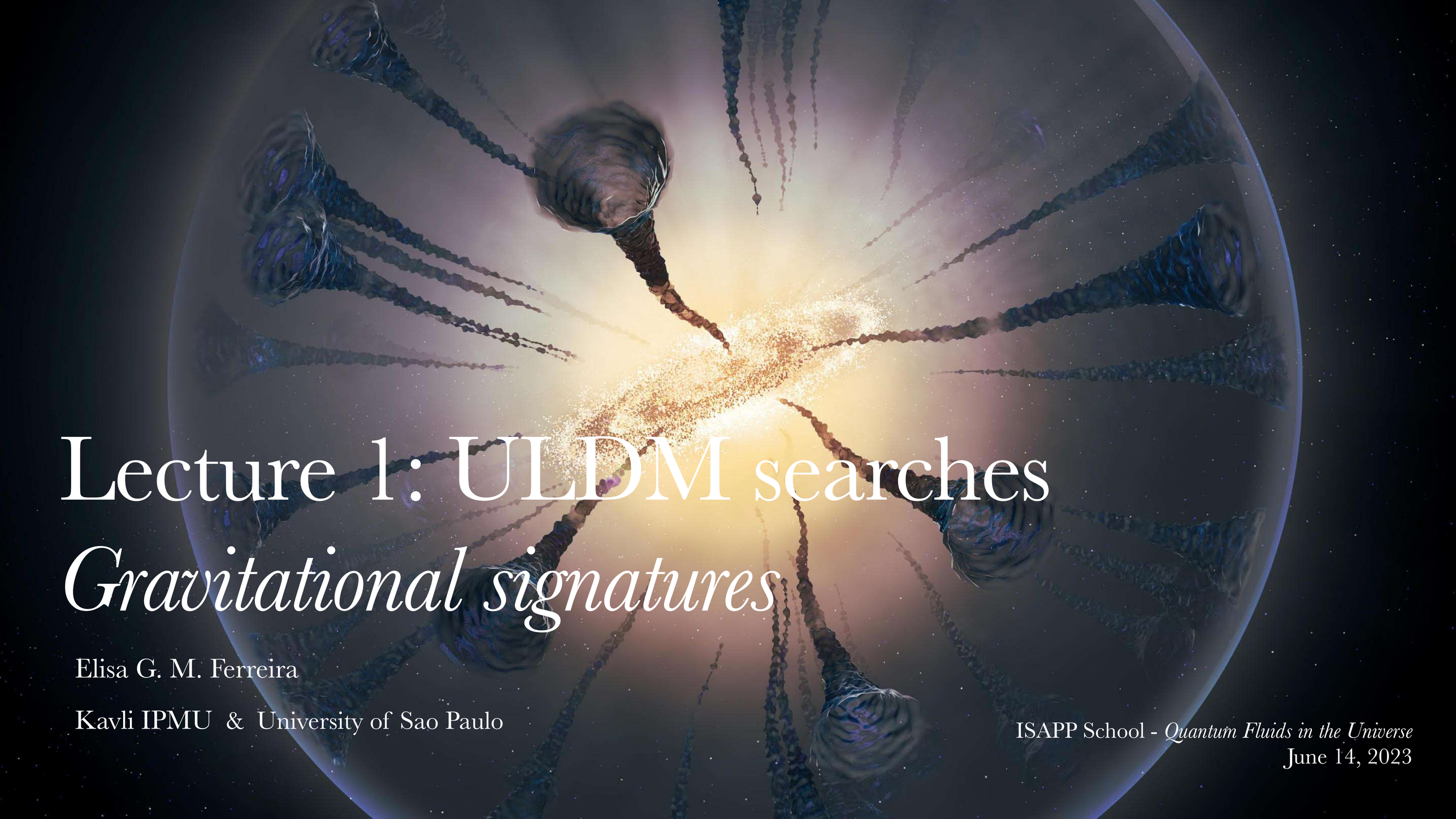

Lecture 1: ULDM searches

Gravitational signatures

Elisa G. M. Ferreira

Kavli IPMU & University of Sao Paulo

ISAPP School - *Quantum Fluids in the Universe*
June 14, 2023

Outline

Lecture 1: Cosm. Signatures 1

Part I:

- Evidences
- ULDM models
- Observational signatures
- GravitationalBounds

Part II: *Practice!*

Notebook 1: linear

- Linear observational signature of ULDM: suppression of structures

Lecture 2: Cosm. Signatures 2

Part I:

- Cont. ULDM gravitational bounds
- Future of grav. observations

Part II:

Notebook 2: non-linear

- Consequences on small scales

Lecture 3: interac. with SM

- Cont. ULDM gravitational bounds
- DM Superfluid
- Interaction of ULDM with SM
  - Axion/ALPs interaction in astrophysical systems
  - Direct detection

Disclaimer

- Impossible to cover all the possible searches there are now! But I will do my best to give a general view.

- Biased review of the ULDM field

- Field that is changing rapidly, so my apologies for not mentioning your model or reference

- Lectures are going to have a practical component. Hope it is useful in your research!

Units of mass, energy and momentum = eV
Length = eV^{-1}

BUT sometimes (astro/cosmology)
1parsec (pc) $\sim 3 \times 10^{16}\,\mathrm{m}$

$$\text{Natural units}(c = \bar{h} = 1)$$
$$1\,\mathrm{kg} \to 5 \times 10^{35}\,\mathrm{eV}$$
$$1\,M_{\odot} \to\sim 10^{66}\,\mathrm{eV}$$

Further reading

Reviews!!!

Main reference for gravitational searches:

- **Elisa Ferreira**, *Ultra-light dark matter*, The Astronomy and Astrophysics Review. 29 (2021) 1, 7, arXIv:2005.03254

Other very good reviews

- Lam Hui, *Wave dark matter,* Ann.Rev.Astron.Astrophys. 59 (2021) 247-289, arXiv: 2101.11735
- Jens C., *Niemeyer Small-scale structure of fuzzy and axion-like dark matter*, Prog.Part.Nucl.Phys. 103787, arXiv:1912.07064
- David Marsh, *Axion cosmology*, Phys.Rept. 643 (2016) 1-79, arXiv:1510.07633

Reference for non-gravitational searches:

- Francesca Chadha-Day et al., *Axion dark matter: What is it and why now?*, Sci.Adv. 8 (2022) 8, abj3618, arXiv: 2105.01406

+ many references *(in the slides)*

Outline

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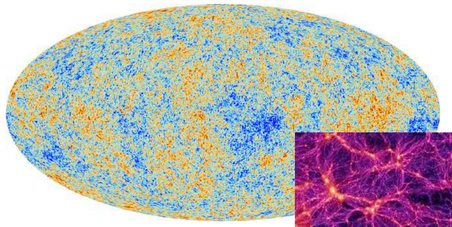
Evidences for dark matter

We can observe its effects in

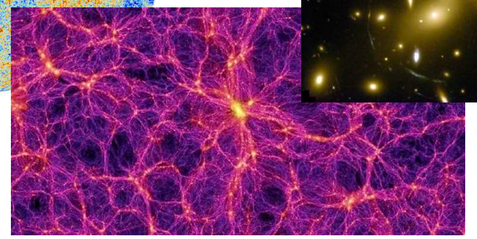
Galaxies

NASA and ESA

CMB+LSS



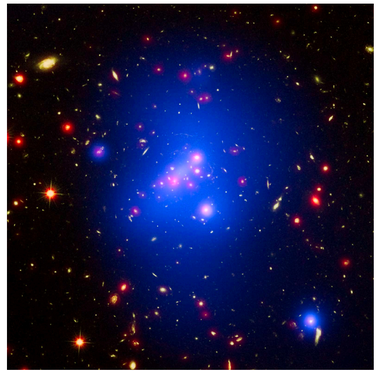
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

NASA and ESA

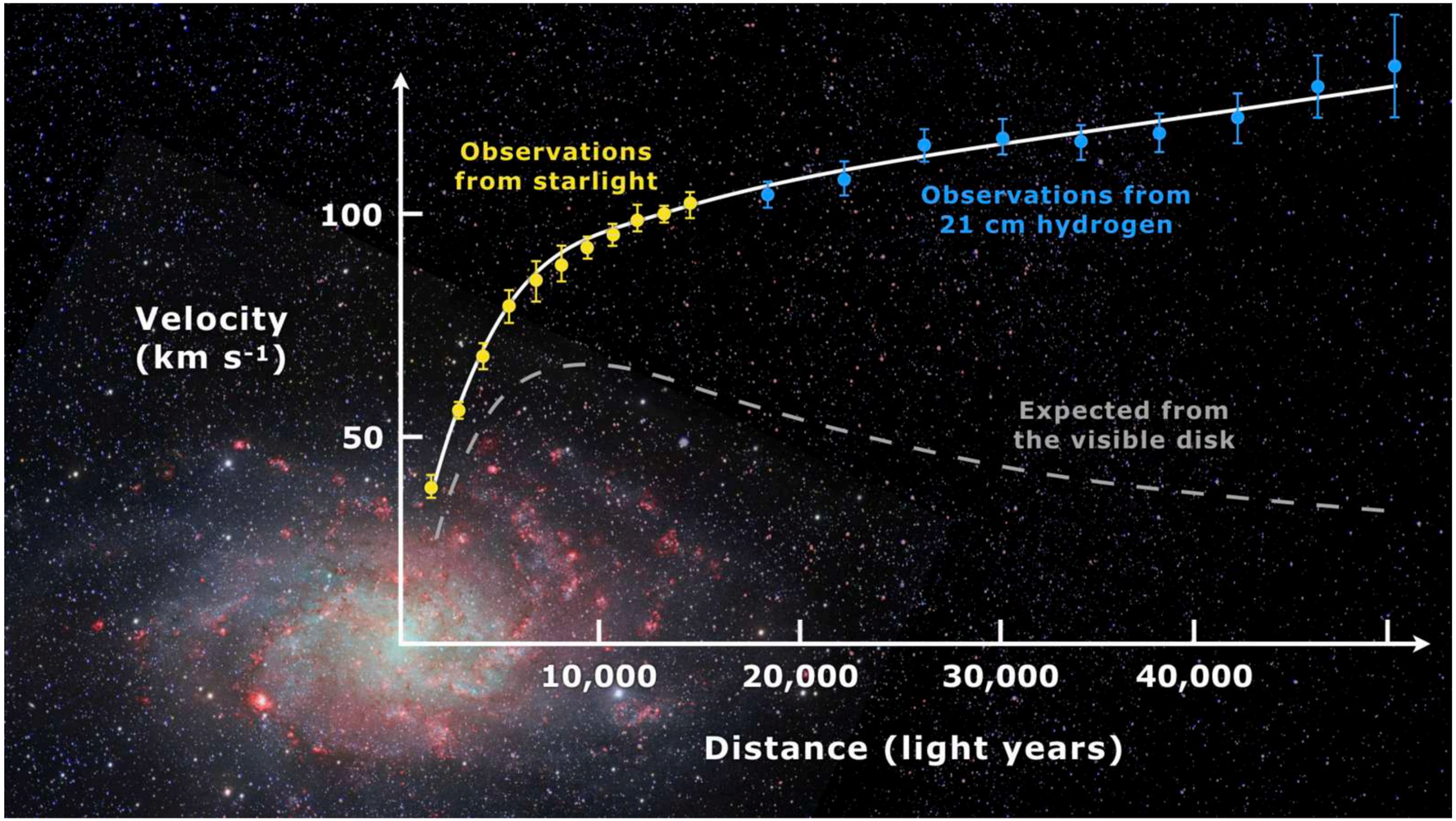
Clusters



CC BY 4.0

Huge amount of evidence
From all scales

Galaxy rotation curves



Credit: Mario De Leo

Missing mass

$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

OR this formula is wrong!

Clusters of galaxies

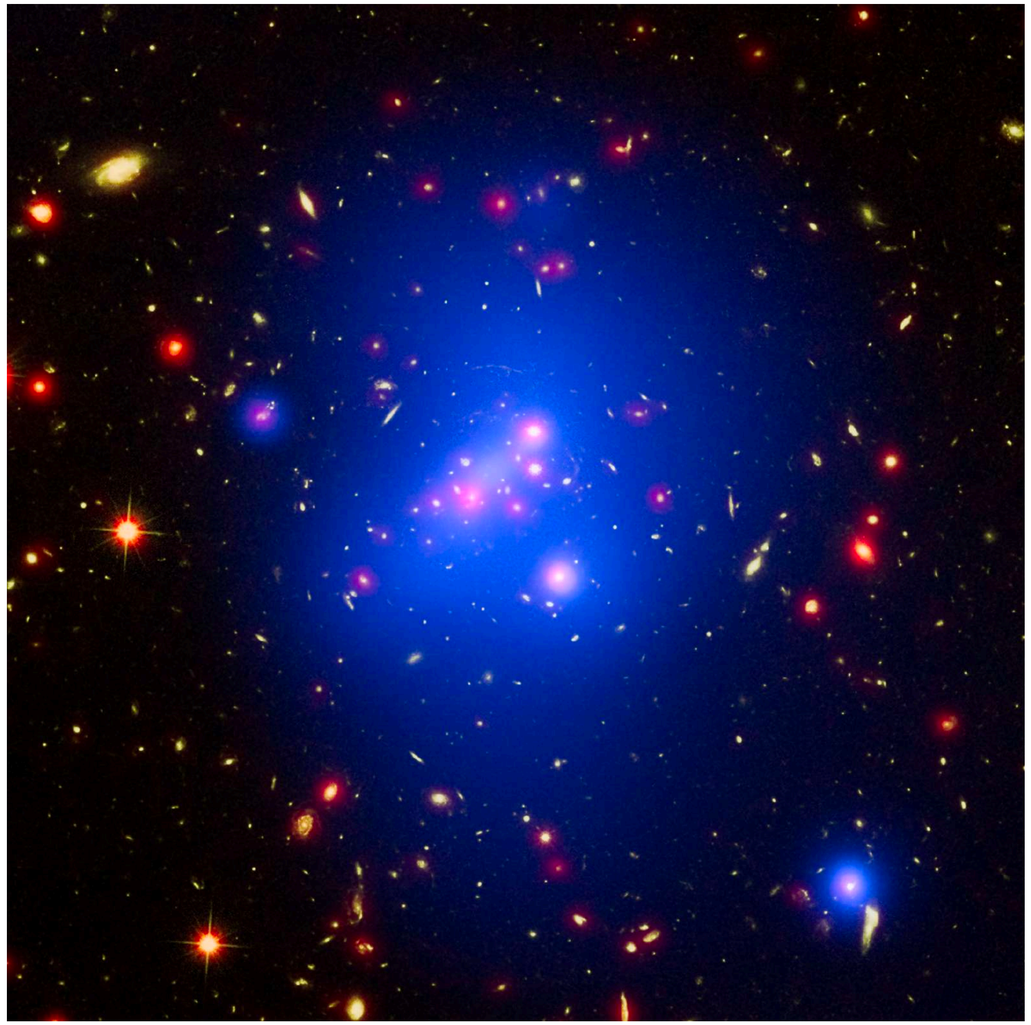
Largest gravitationally bound structures.
Contain 100s/1000s of galaxies and hot x-ray emitting gas

(Zwicky 1933)

~ 1 % Galaxies

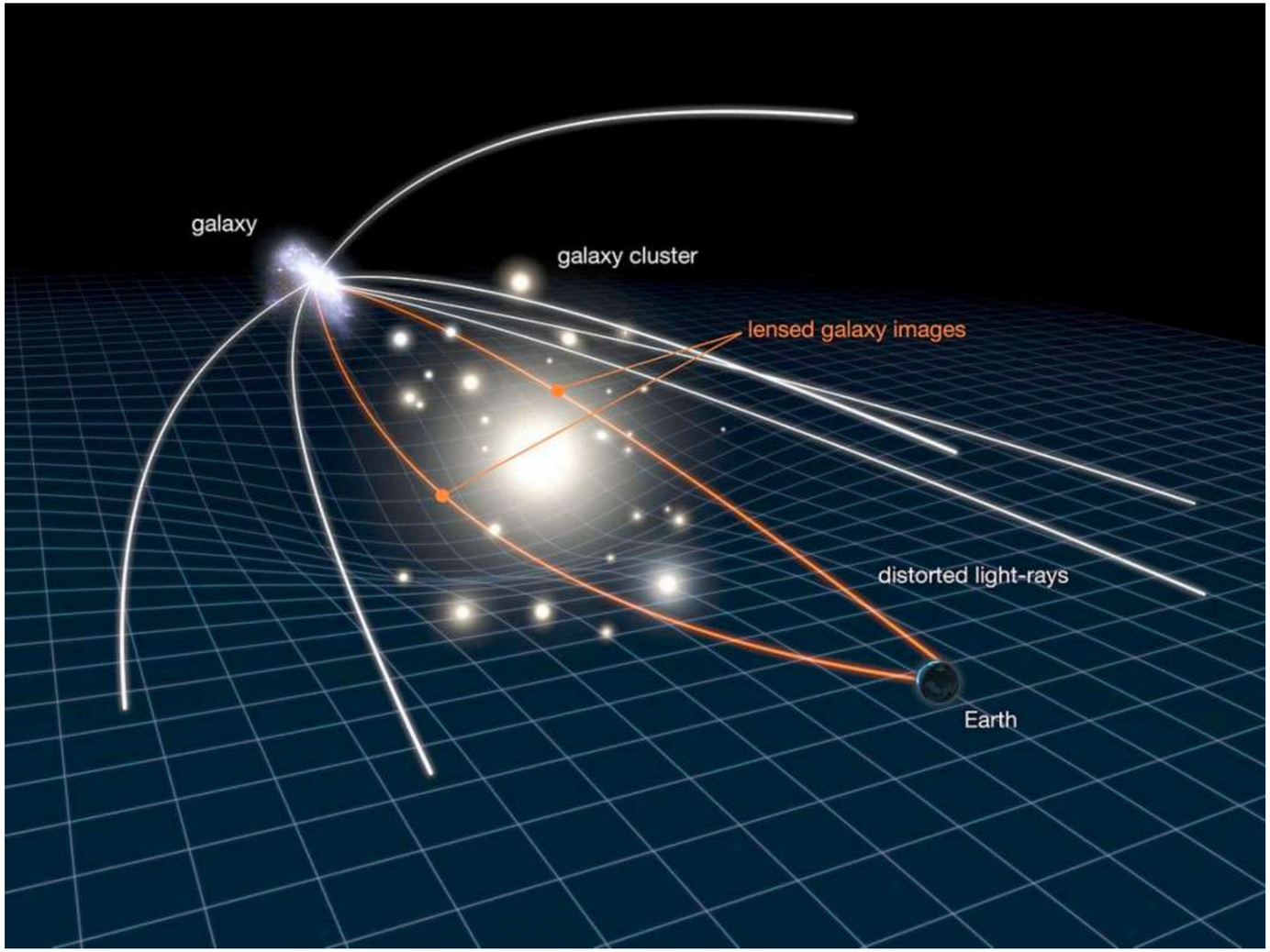
~ 10 % Gas

~ 90 % Dark matter

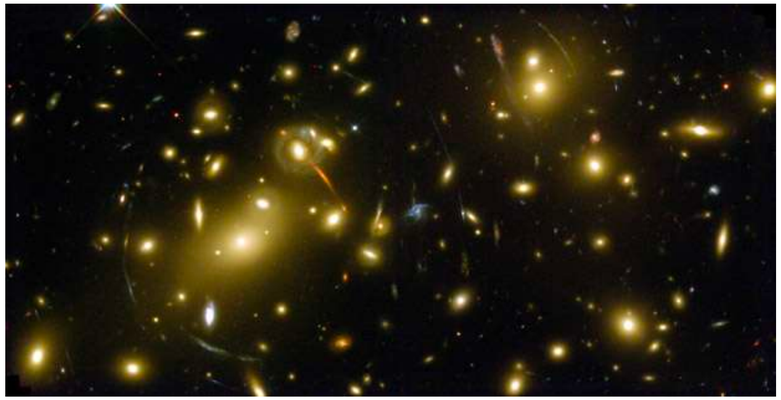


CC BY 4.0

Gravitational lensing



mage: NASA/ESA



NASA and ESA

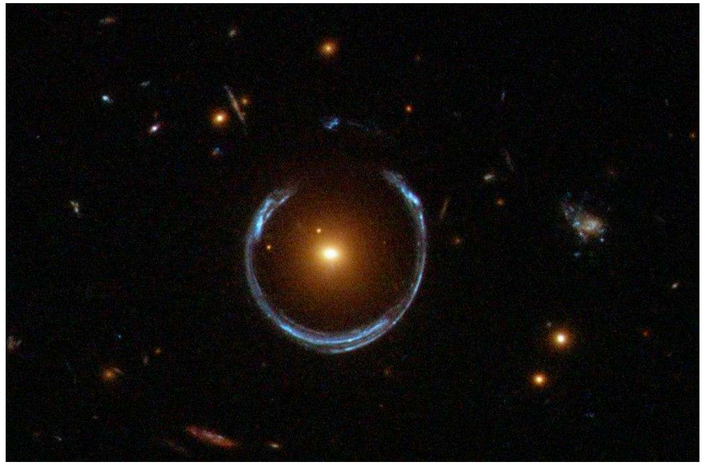
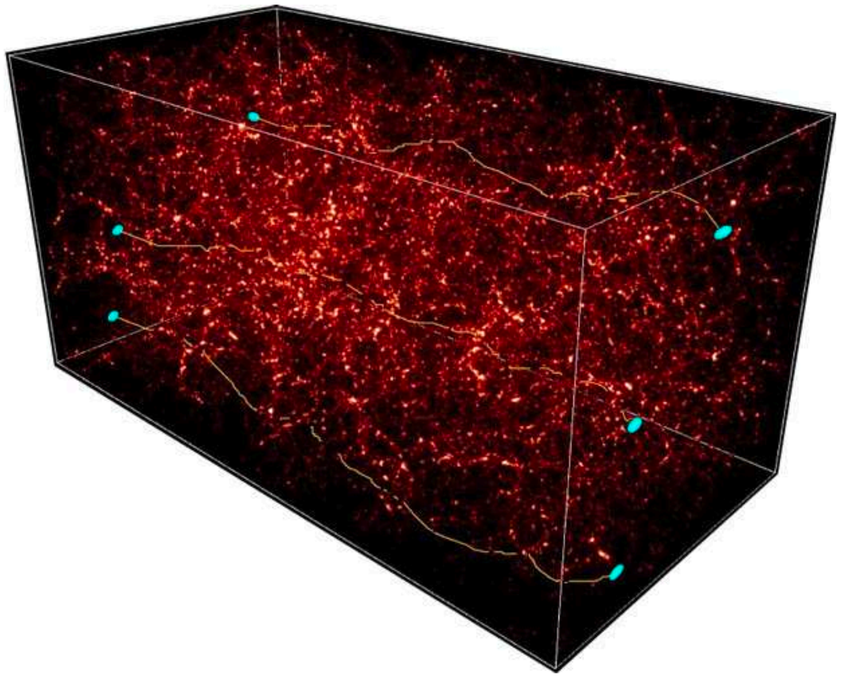


Image: © ESA/Hubble/NASA)

Gravitational lensing

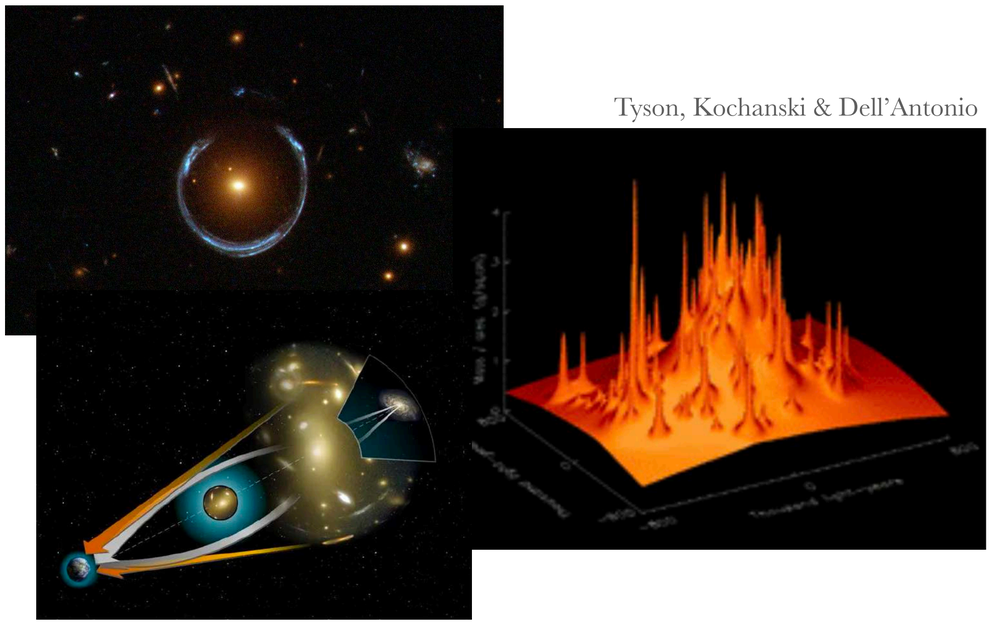
Weak lensing



- Background image is perturbed by matter in its path
- Statistical signal
- Total mass on large scales

Strong lensing

Image: © ESA/Hubble/NASA)

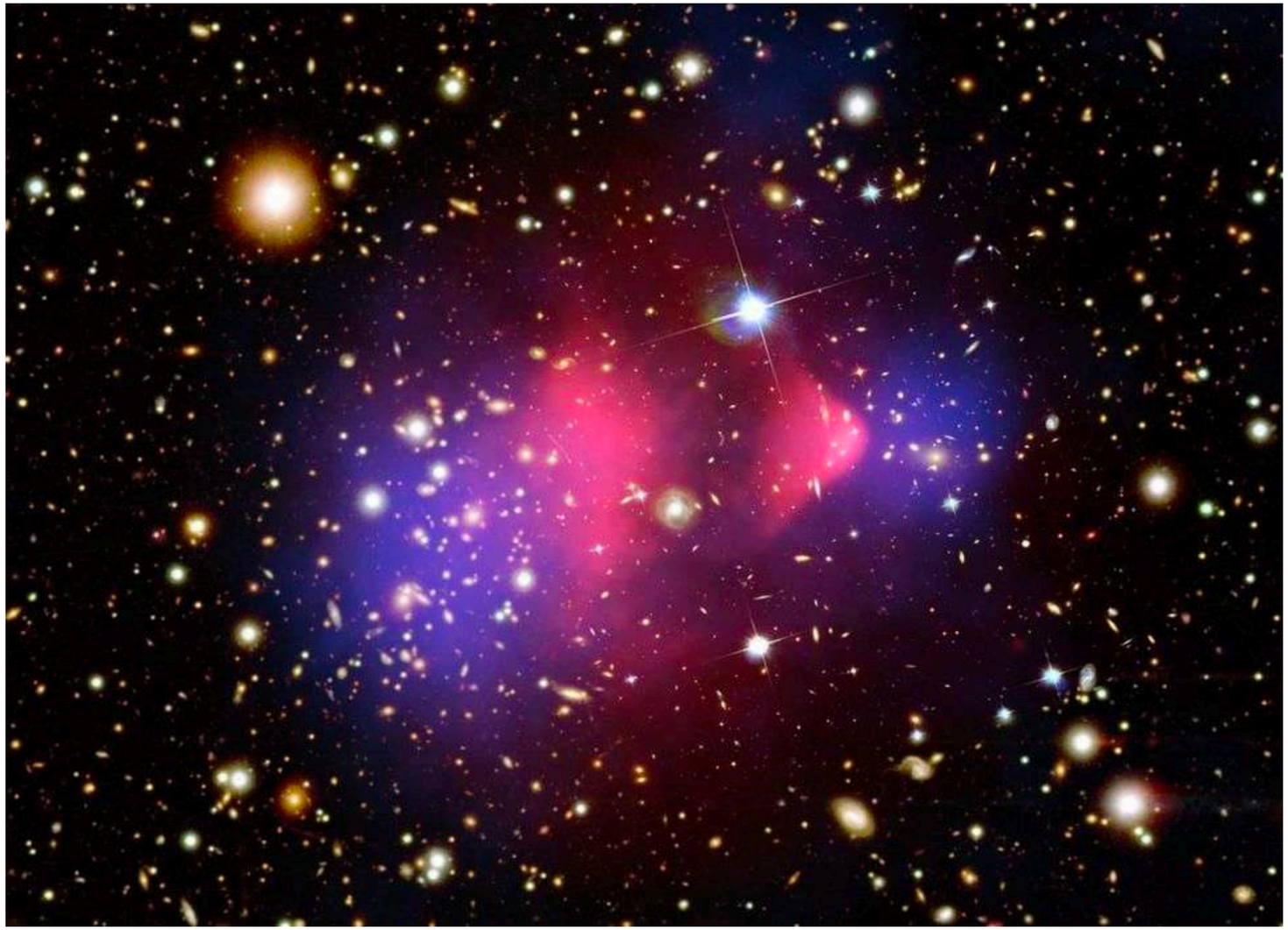


Tyson, Kochanski & Dell'Antonio

NASA / STSCI

- Reconstruct the gravitational potential (total enclosed mass) of the lens
- Total mass on small scales

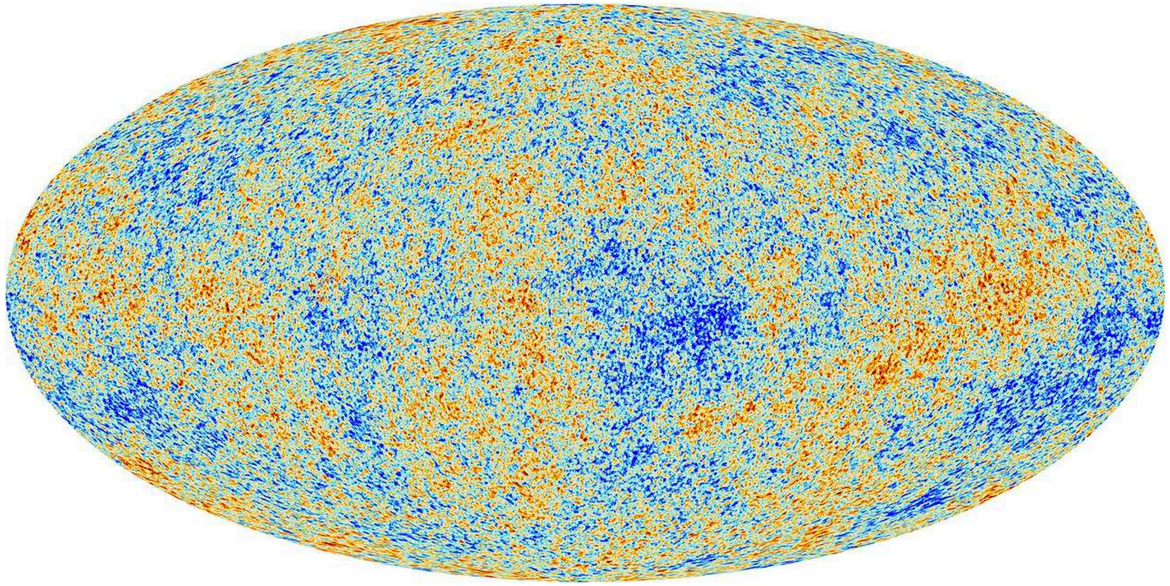
Clusters/lensing

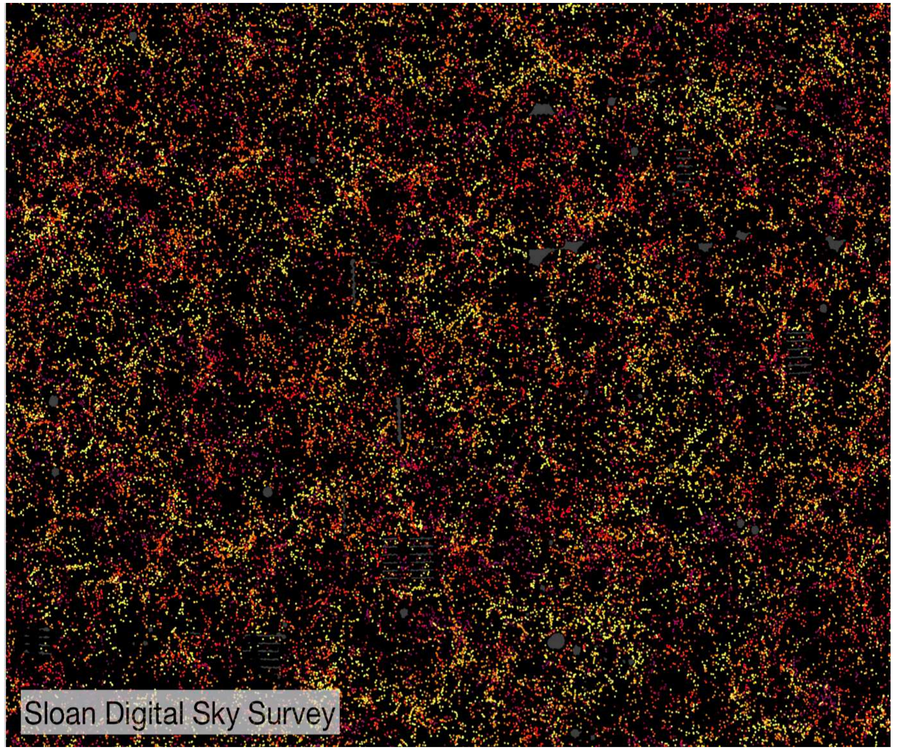


Bullet cluster: aftermath of the collision of two clusters

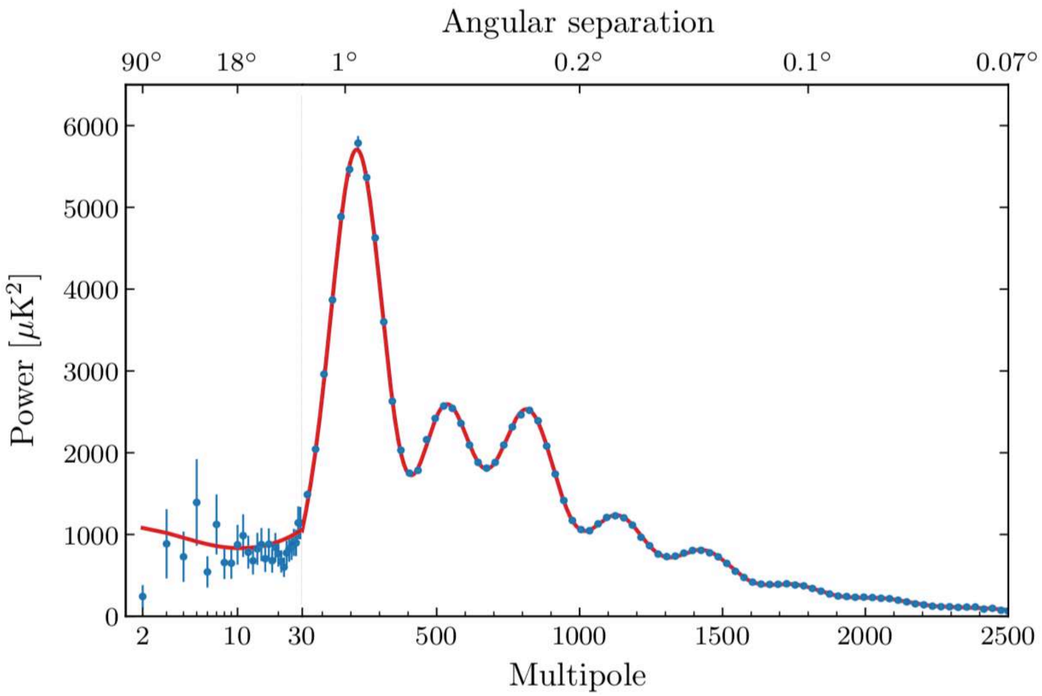
Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

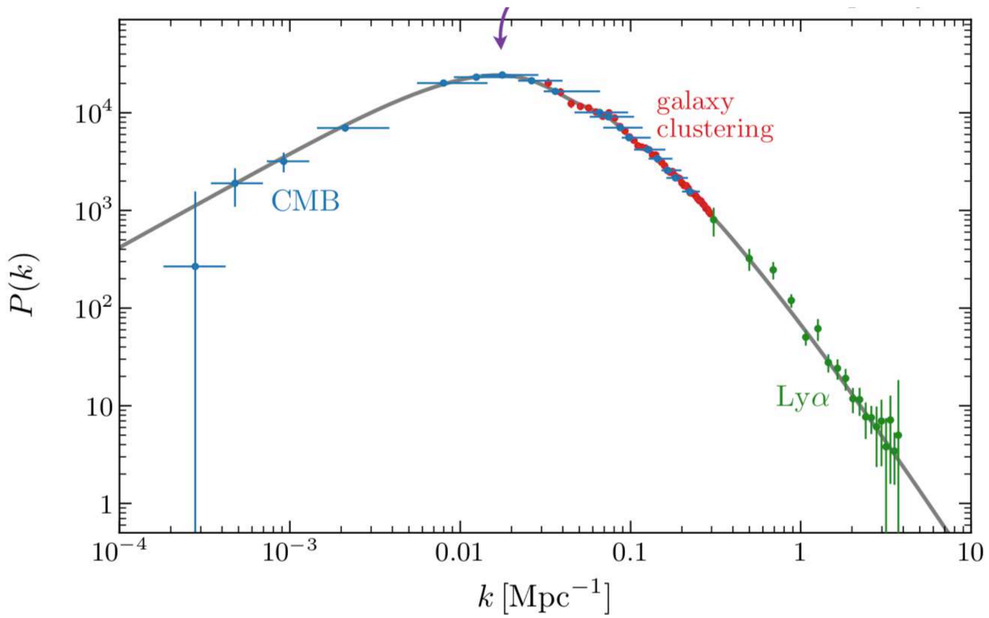
Large scale structure





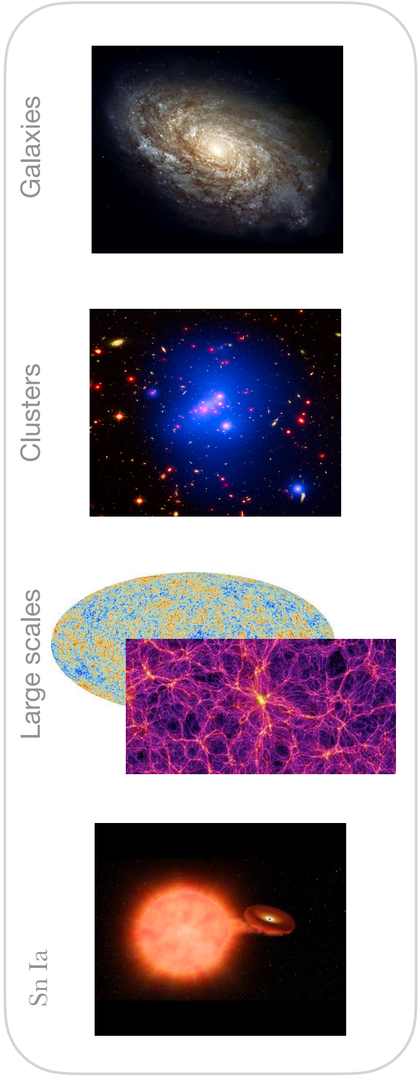
Large scale structure





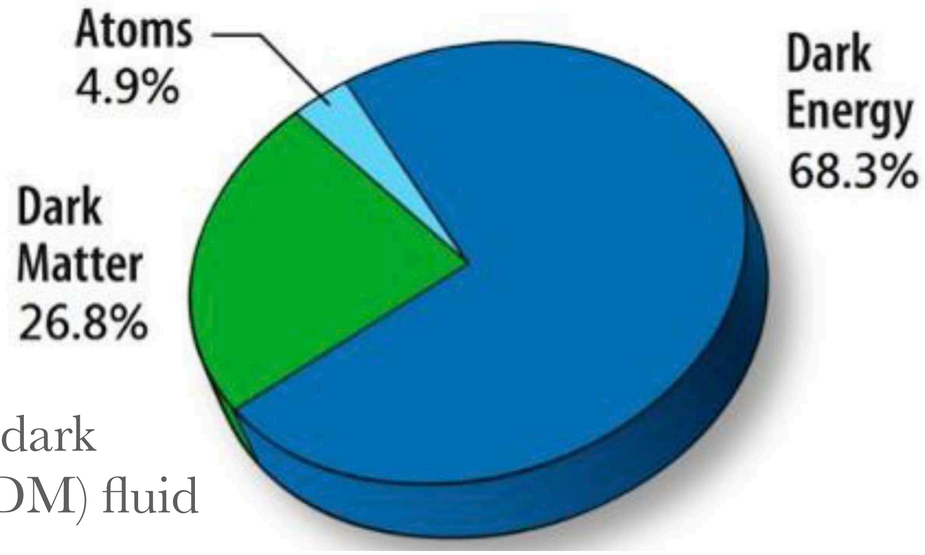
$$\Omega_m = 0.308 \pm 0.012$$ *(Planck 2018)*

What we know about dark matter



ΛCDM – the standard cosmological model

Successful description of our universe with 6 free parameters, tested to sub-percent precision.



Λ

ΛCDM

simple but exotic model!

DM: cold dark matter (CDM) fluid

Cold dark matter

- Cold: moves much slower than c
- Presureless: gravitational attractive, clusters
- Dark (transparent): no/weakly electromagnetic interaction
- Collisionless: no/weakly self-interaction or interaction with baryons

CDM on large scales described by a ***perfect fluid***:

Backg.: ρ, P $\quad w = P/\rho$

with $P = 0 \Rightarrow w = 0$

$\Rightarrow \rho \propto a^{-3}$

Pert.: δ, θ

with $c_s \sim 0$

- Abundance: amount of dark matter today known

Cold dark matter

- Cold: moves much slower than c
- Presureless: gravitational attractive, clusters
- Dark (transparent): no/weakly electromagnetic interaction
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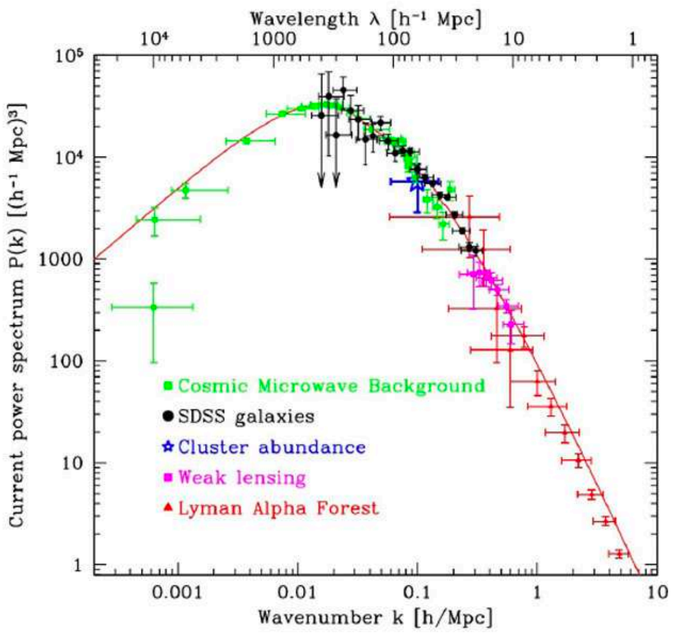


Many observational probes for $k \sim 10^{-3} - 10\,\mathrm{Mpc}^{-1}$

range of redshift $z < 3 - 4$

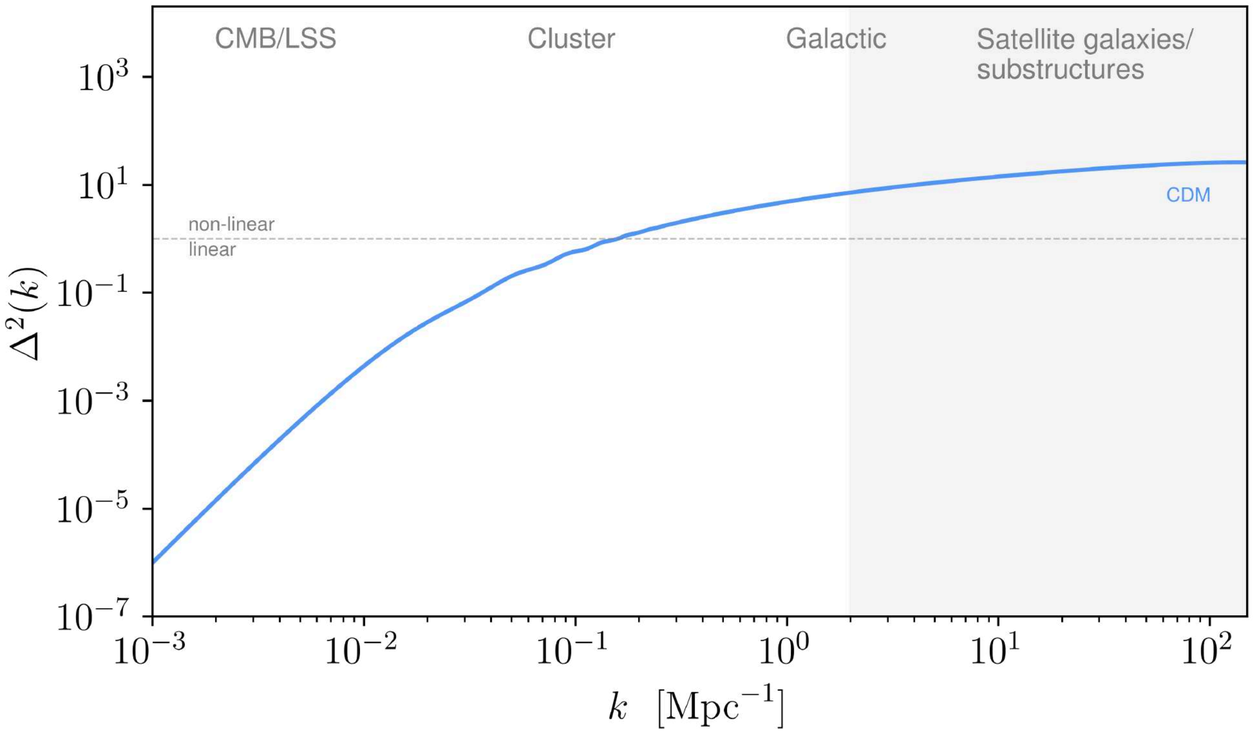
- Abundance: amount of dark matter today known

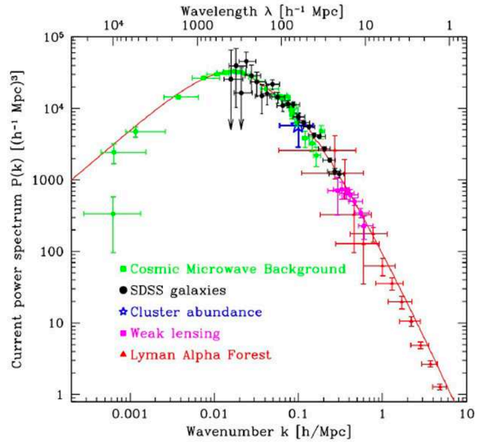
Incredible agreement to CDM!

What we know about dark matter

Properties:

From LSS:





Measure PS well until scales $k \sim 10 - 20\,\mathrm{Mpc}^{-1}$

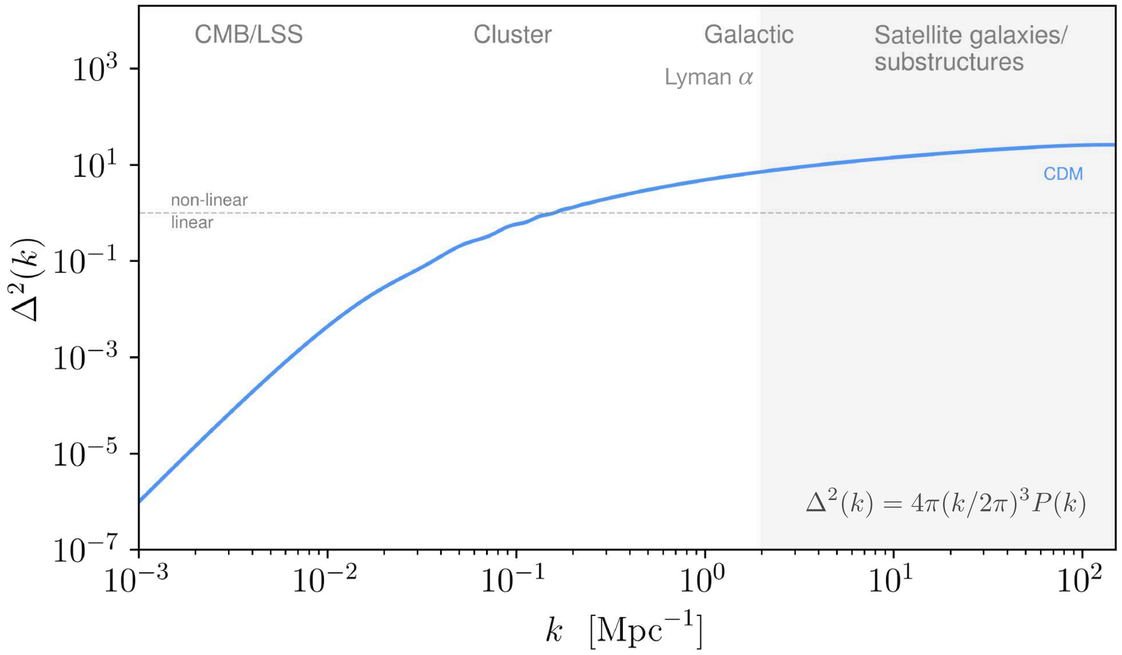
Dimensionless power spectrum

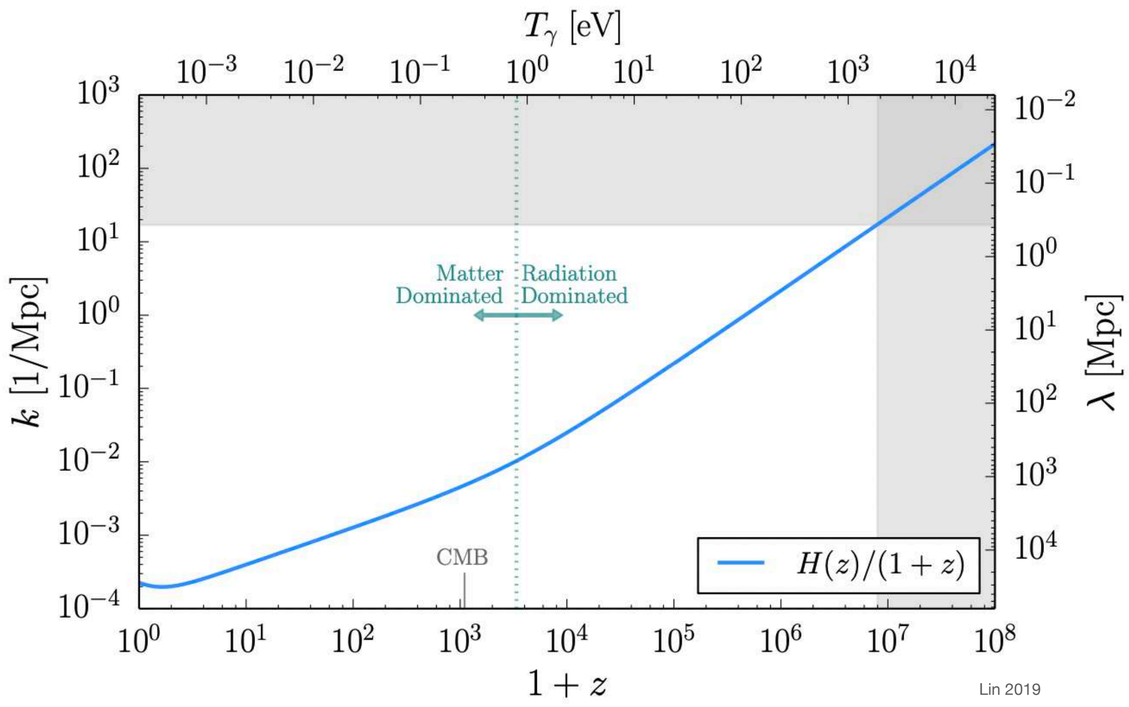
$$\Delta^2(k) = 4\pi(k/2\pi)^3 P(k)$$

What we know about dark matter

Properties:

$$T_\gamma = T_{\gamma,0}(1+z)$$





CDM pert. ($c_s = 0$) inside Hubble radius:

$$\delta \propto \begin{cases} \log a & \text{rad. domination} \\ a & \text{matter domination} \end{cases}$$

Perturbation modes enter the Hubble radius $\lambda_{phys} = a/k = H^{-1}$

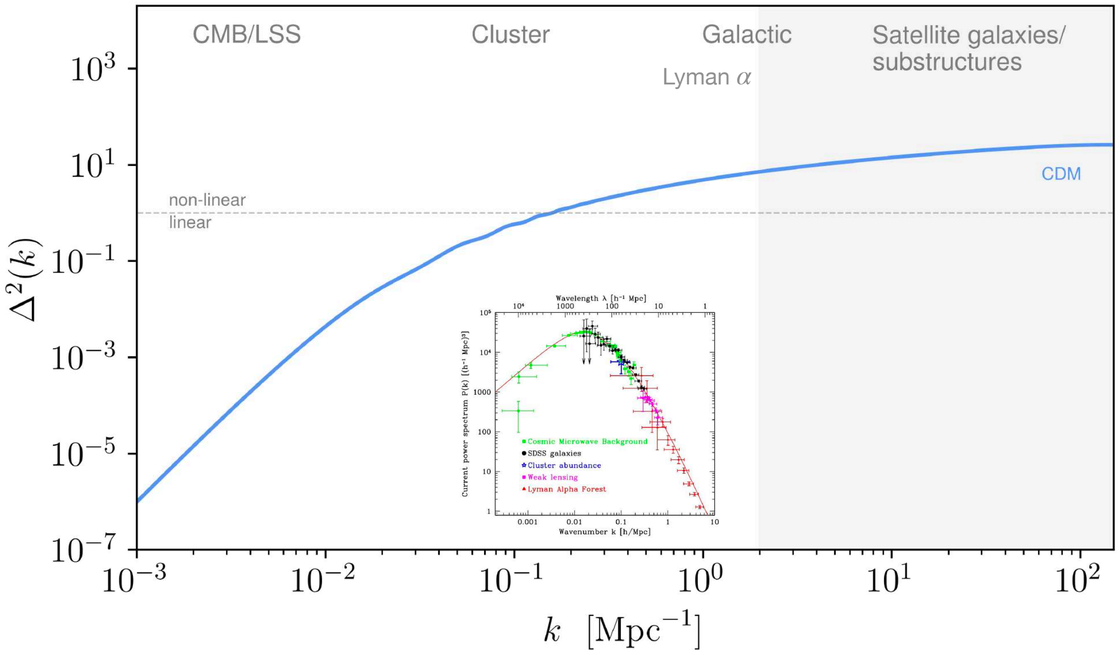
$$k = aH = H/(1+z)$$

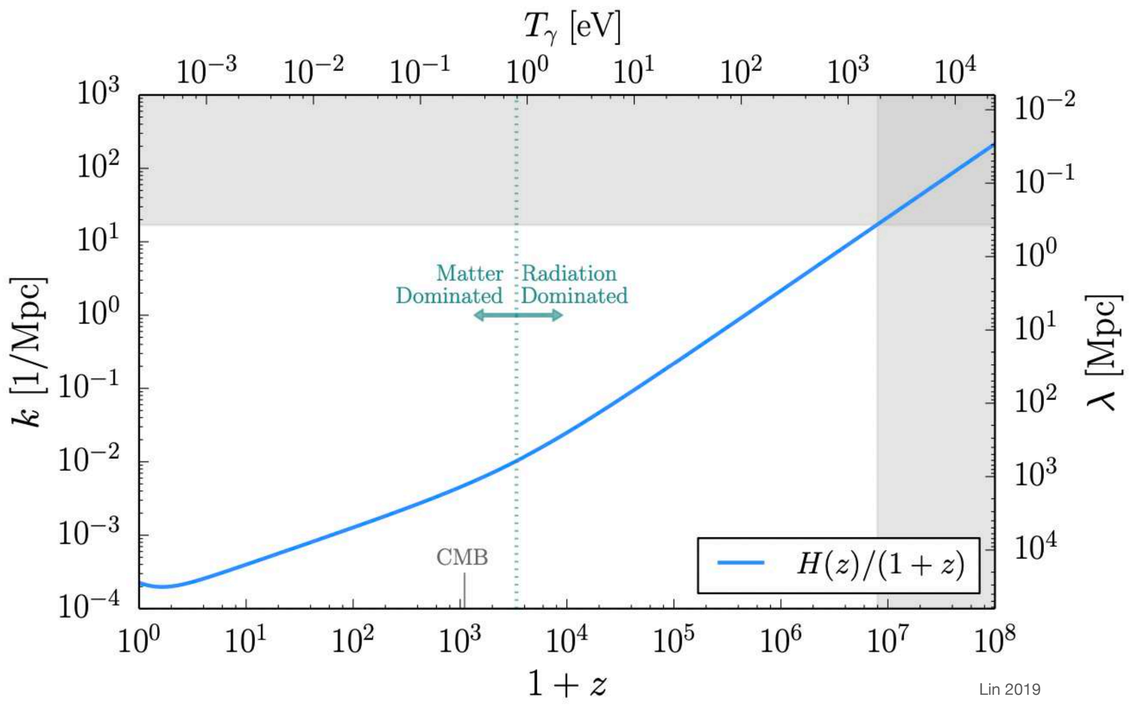
After this, the density pert. of CDM start to evolve, **grow** - contribute to the PS

What we know about dark matter

Properties:

$$T_\gamma = T_{\gamma,0}(1+z)$$





Lin 2019

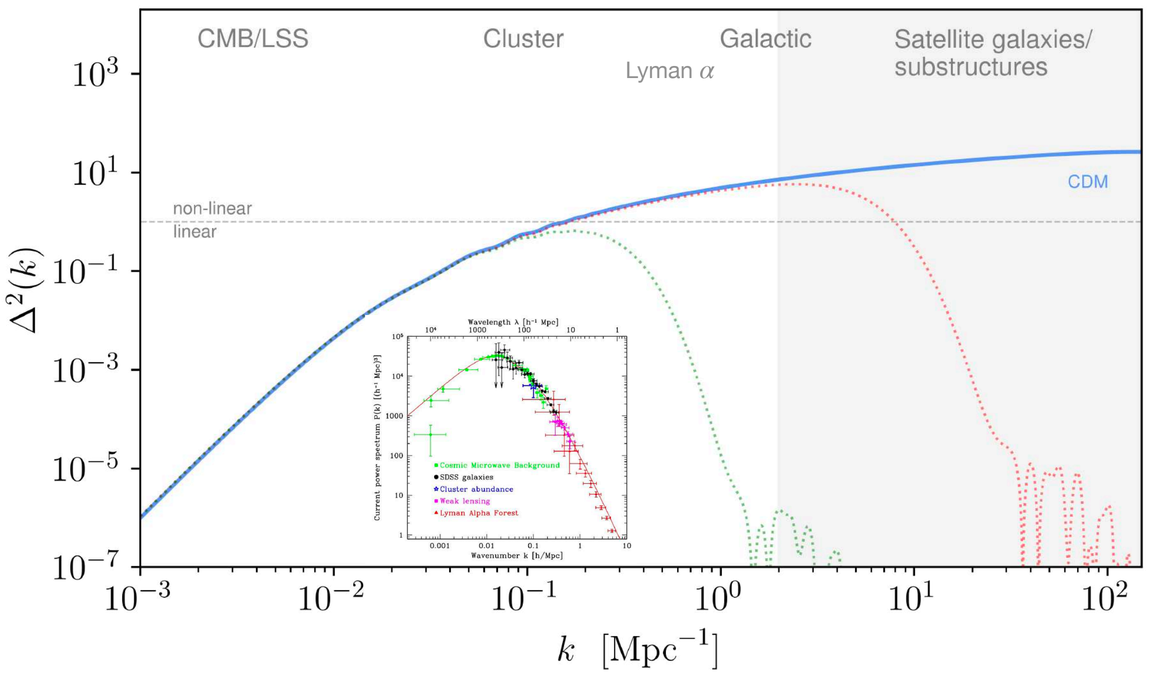
Perturbation modes enter the Hubble radius $\lambda_{phys} = a/k = H^{-1}$

$$k = aH = H/(1+z)$$

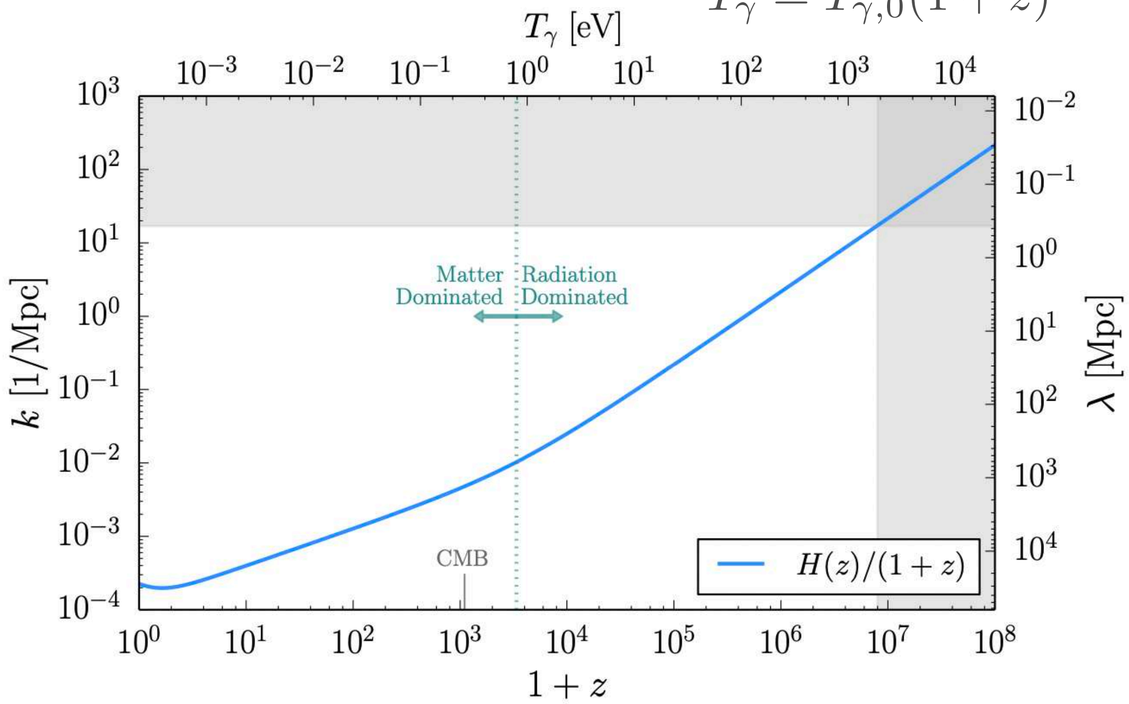
So we can describe the observations, all the modes in the white region ($< 10\,\mathrm{Mpc}^{-1}$) are inside the Hubble radius and contribute to the PS, and are very precisely described by CDM $\Rightarrow$ cold and pressureless

What we know about dark matter

Properties:



$$T_\gamma = T_{\gamma,0}(1+z)$$



Lin 2019

If DM relativistic (or hot) when $z < 10^7$, this mode is inside R_H, so it will contribute to the PS - since relativ. pert. DO NOT cluster, we would have a **suppression in the power spectrum** for $k < 10 - 20\,\mathrm{Mpc}^{-1}$ - *not in agreement with observations!*

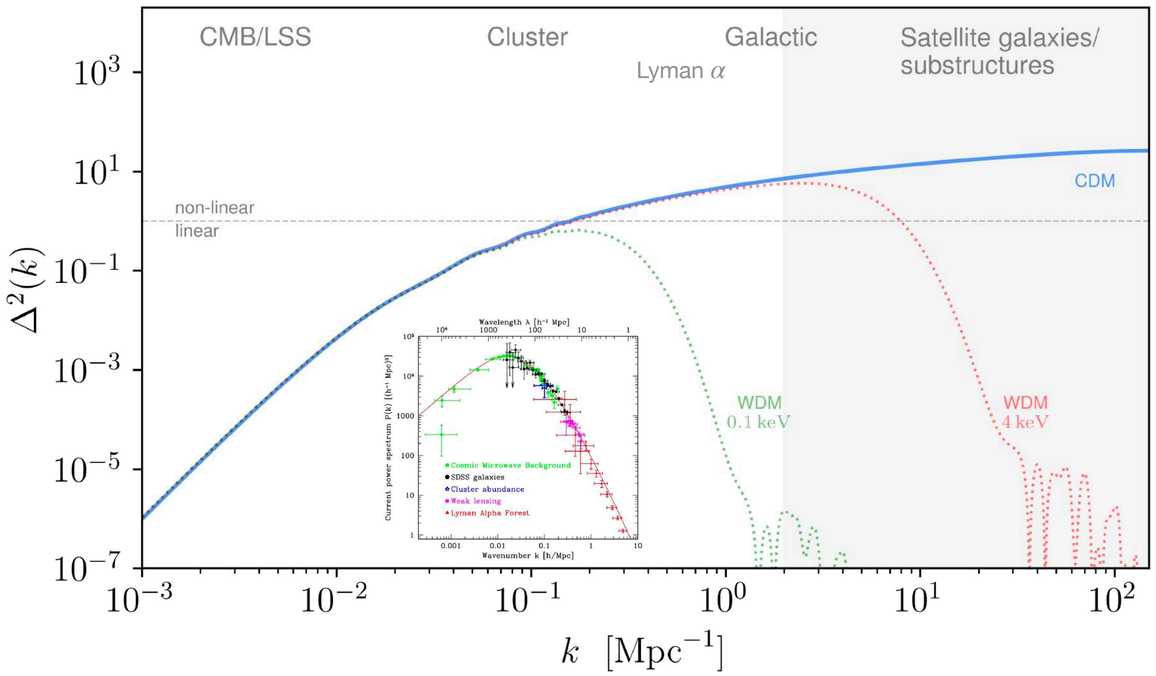
$\Rightarrow$ DM has to be non-relativistic before $z = 10^7$

If **DM in thermal equilibrium** with the baryon-photon plasma ($T_{dm} = T_\gamma$)

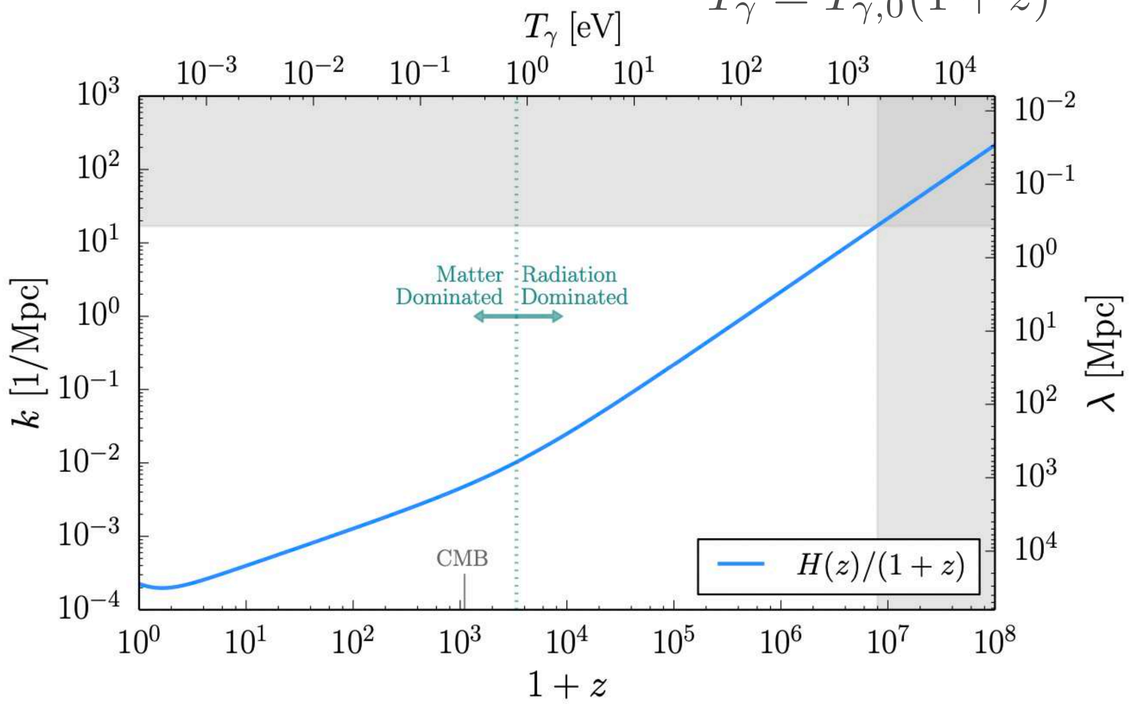
$\Rightarrow m_{dm} > \mathrm{keV}$ WDM bound

What we know about dark matter

Properties:



$T_\gamma = T_{\gamma,0}(1+z)$



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WDM bound

What we know about dark matter

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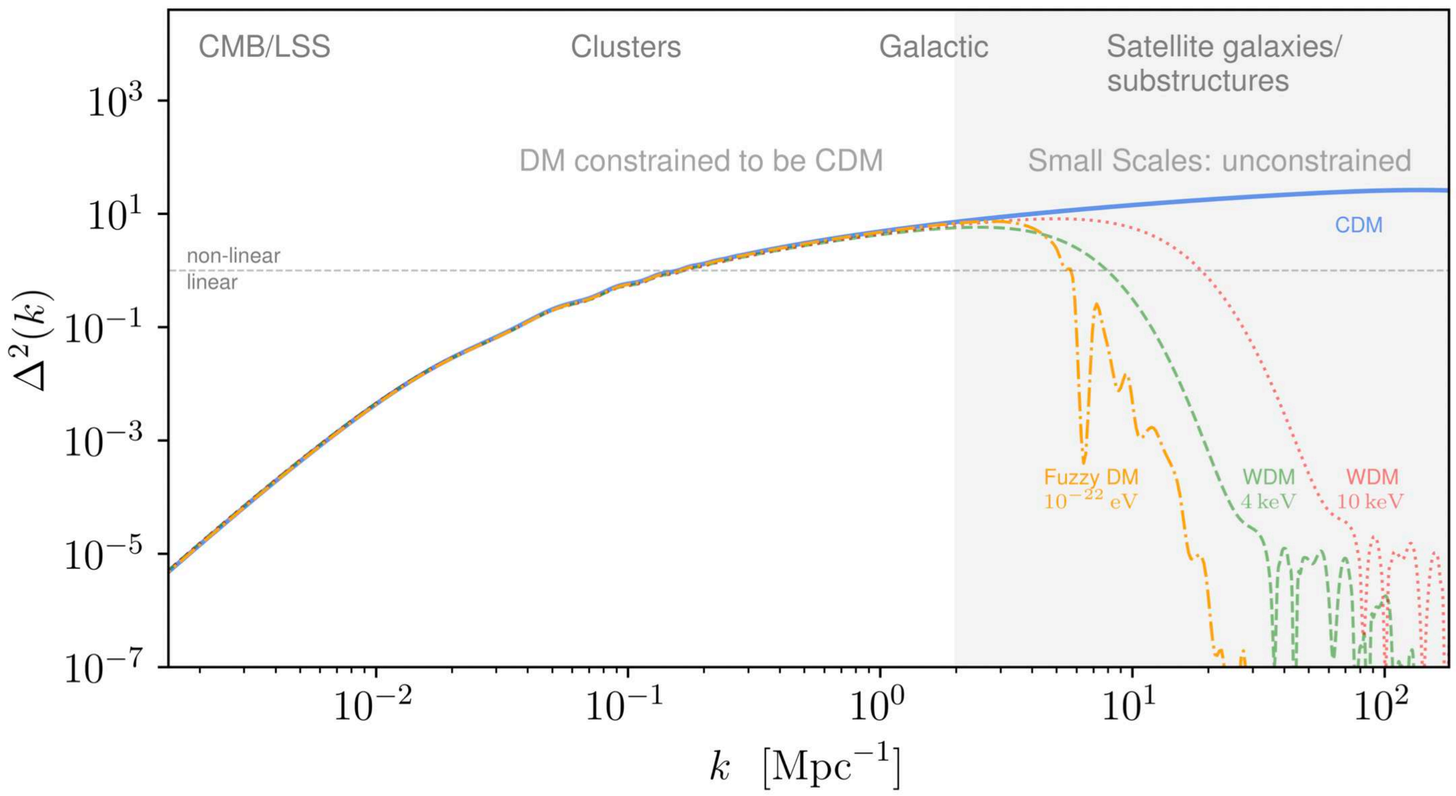
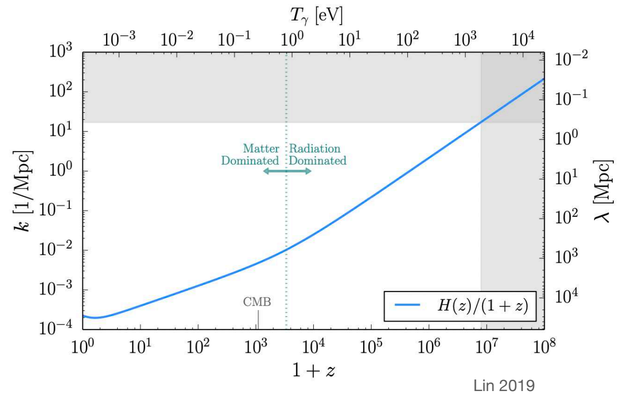




Deviations from CDM in the highlighted region are allowed, since highly unconstrained!

What we know about dark matter

- Dark (transparent/neutral): DM does not interact electromagnetically
- Collisionless: no/weakly self-interaction; non-interacting

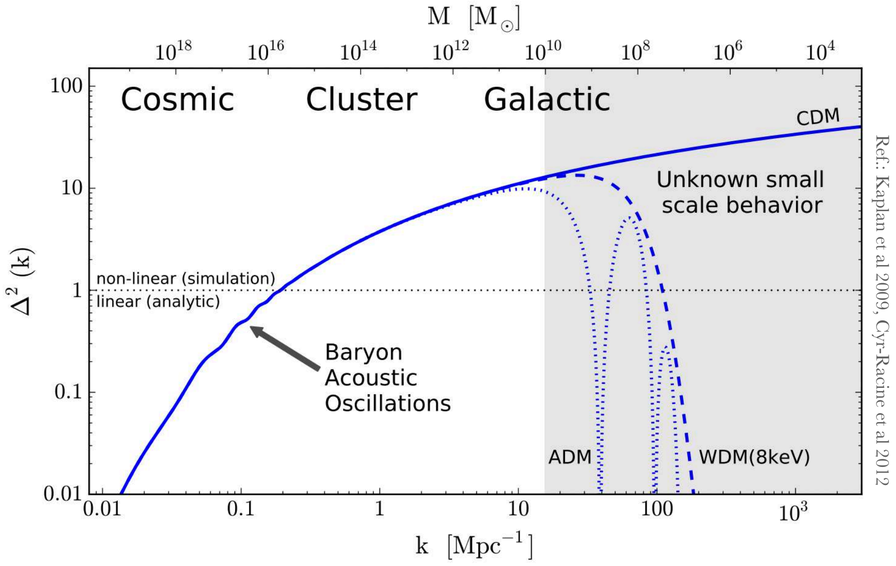
If DM had a *charge* ϵe :

- Suppression of the power spectrum

Charged DM particles interact with the Standard Model via a small coupling through the photon

If the DM is coupled with the baryon-photon plasma during *recombination*, the DM density fluctuations can be washed out due to the radiation pressure and the photon diffusion (Silk damping). The BAO structure will also be directly altered through the coupling.

Ex: ADM - atomic dark matter



Ref.: Kaplan et al 2009, Cyr-Racine et al 2012

Interactions of DM with SM particles and itself at early times would **suppress** the power spectrum, since the radiation pressure of the baryons and photons would prevent DM density perturbations from growing and lead to the presence of "dark acoustic oscillations"

Current bounds:

DM has neutral or charge < mili-charge!

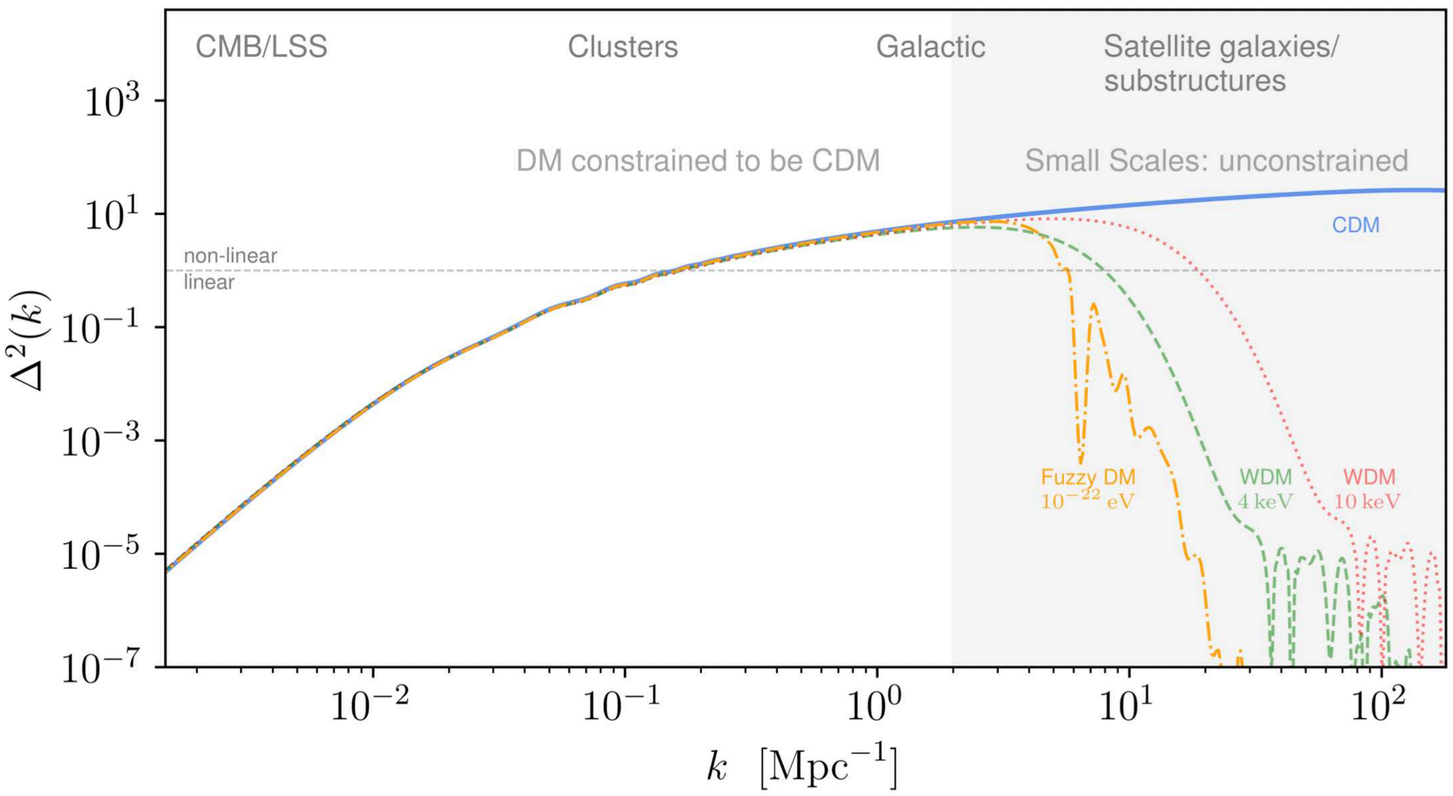
Charge:

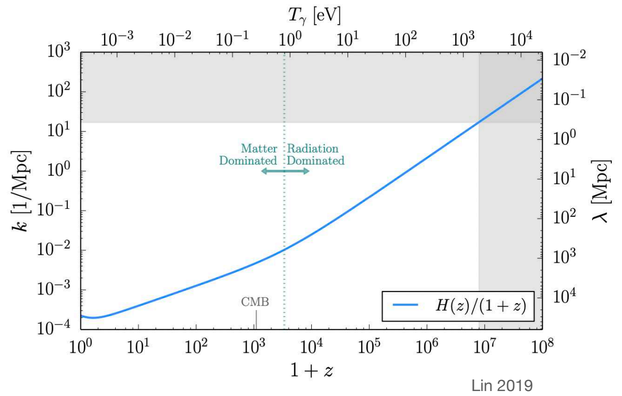
Self-interaction $\sigma/m_{dm} < 0.13\,\mathrm{cm}^2/\mathrm{g}\,,\ \sigma/m_{dm} < 0.35\,\mathrm{cm}^2/\mathrm{g}$

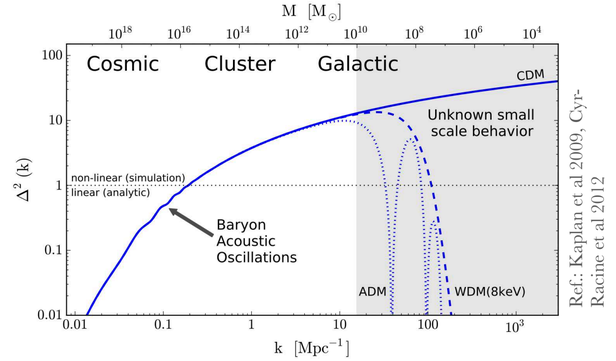
From: measured core densities from strong lensing

What we know about dark matter

Properties:



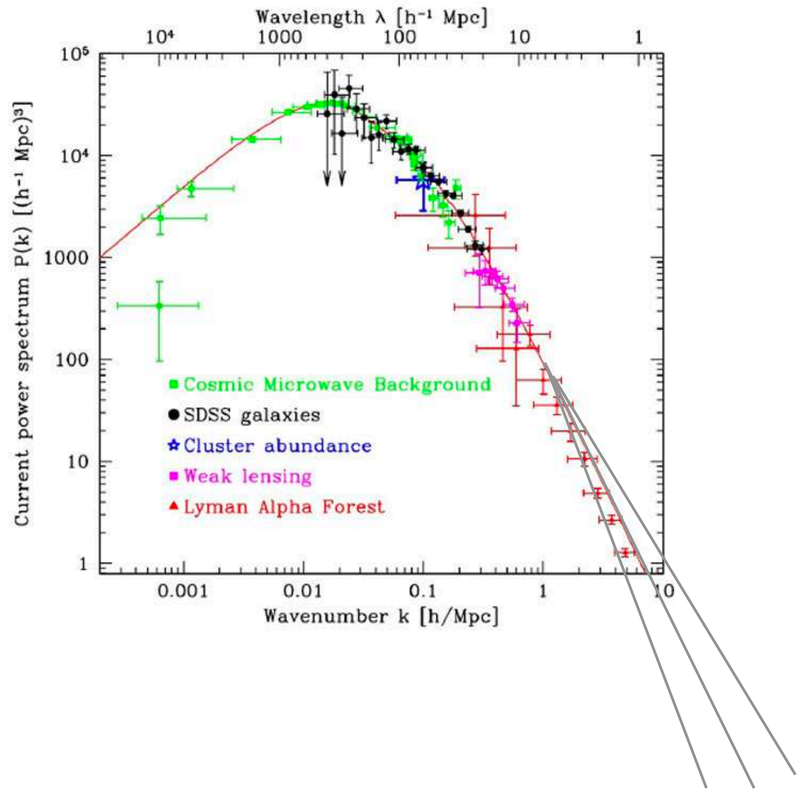




Deviations from CDM in the highlighted region are allowed, since highly unconstrained!

What we don't know about dark matter

- ~~Cold~~ → How cold it is? WDM $m \sim \mathrm{keV}$
- ~~Pressureless~~ → Cluster on all scales?
- ~~Dark~~ → Non-gravitational interaction? Milicharged DM
- ~~Collisionless~~ → How small sefl-interaction? SIDM



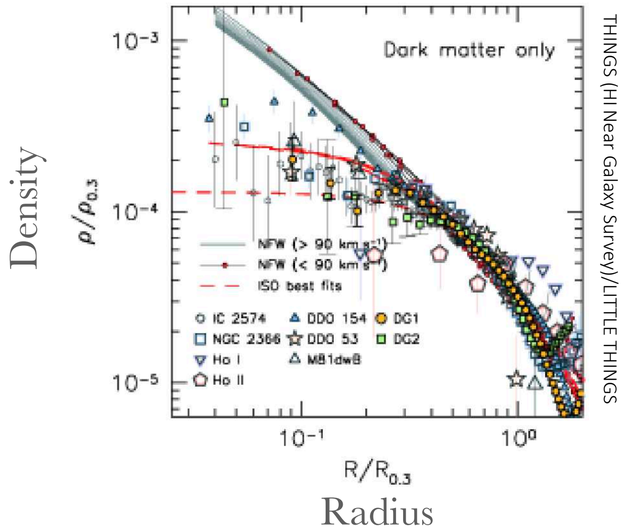
CDM on large scales

Small scale behavior: still weakly constrained and small scale challenges

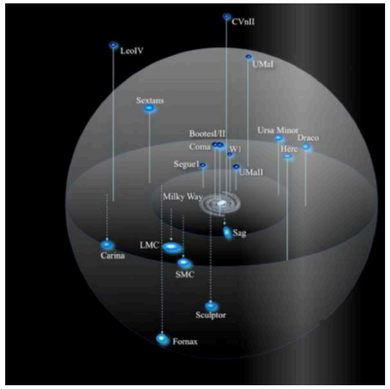
Small scale curiosities: cusp-core, missing satellites, BTFR, …

Small scale challenges

Cusp-core



THINGS (HI Near Galaxy Survey)/LITTLE THINGS

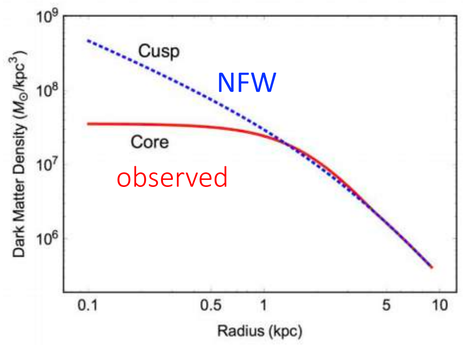


Bullock, Baylon-Kolchin

Missing satellites

Incompatibility between the # of satellites predicted by simulations using LCDM and the # of observed satellites

CDM -
NFW profile



Regularity/diversity of rotation curves

Regularity and diversity of rotation curves

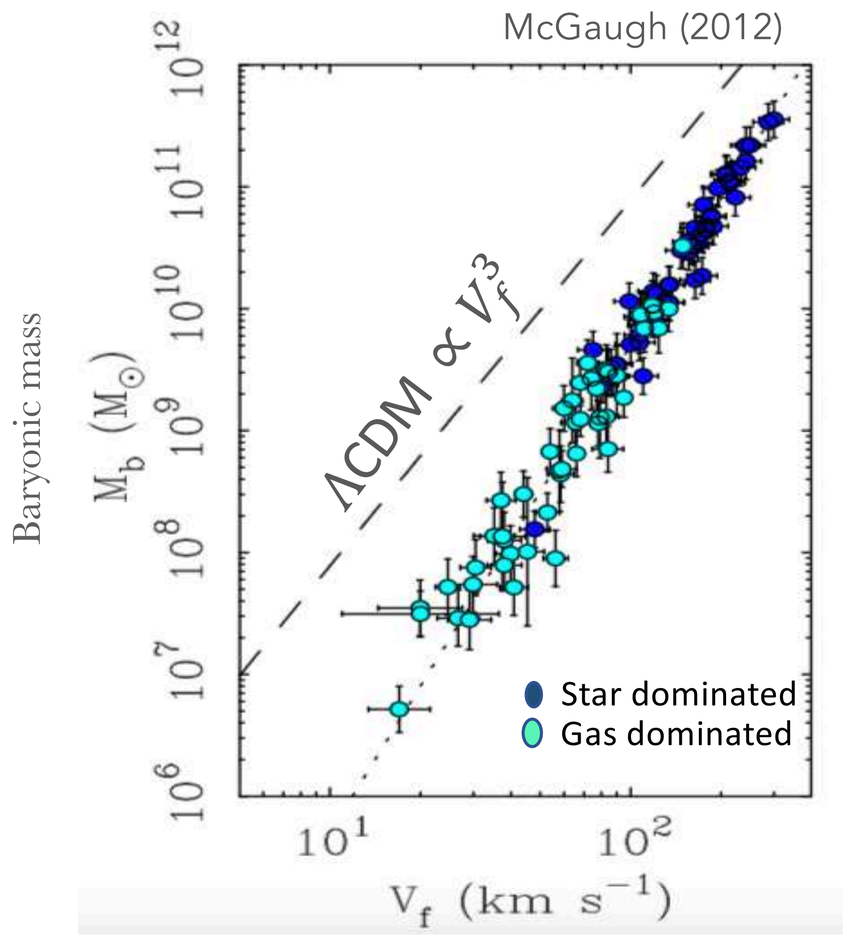
- Baryonic Tully-Fisher relation (BTFR)

Remarkably tight scaling relations between dynamical and baryonic properties.

Other scaling relations:

✓TRF
✓RAR - Radial acceleration relation
✓…

$$a_0 \simeq \frac{1}{6} H_0 \simeq 1.2 \times 10^{-8}\ \mathrm{cm/s^2} = 2.7 \times 10^{-34}\ \mathrm{eV}\,.$$



Dark matter- Large scales: CDM

Small scales:

- **Feedback:** Within ΛCDM

  - Star formation
  - Stellar evolution
  - Sn rates
  - BH and AGN feedback
  - Stellar feedback
  - …

Questions:

- Can it solve all these?
- ≠ simulations, ≠ parametrizations
- Enough feedback?
- Explains tight scaling relation?

- **MOND:**

Modified Newtonian Dynamics

Empirical relation

$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

Curiosity: Baryons drive the dynamics!

Works extremely well for: (1) rotation curves; (2) scaling relations

BUT: ~~MOND without DM~~

Problems explaining large scales

- **Modify dark matter:**

DM with different properties on small scales

- SIDM (Self-interacting DM)

Solve cusp-core and missing satellites

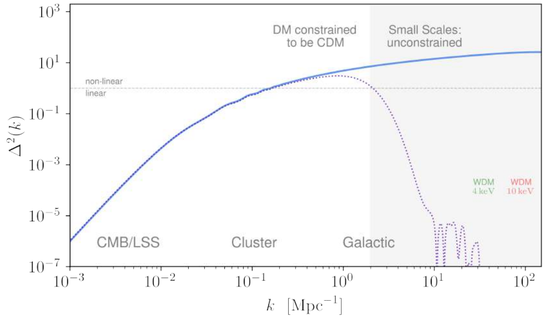
- WDM (Warm DM)

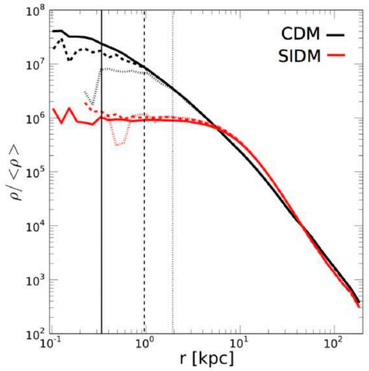
Solve missing satellites

What we know about dark matter

- ~~Cold~~ → How cold it is? WDM (missing sat.)
- ~~Pressureless~~ → Cluster on all scales?
- ~~Dark~~ → Non-gravitational interaction? Milicharged DM
- ~~Collisionless~~ → How small sefl-interaction? SIDM (changes the profile in galaxies - cored; missing sat.)

Solve SSP: $\sigma/m_{dm} \sim 1\,\mathrm{cm}^2\mathrm{g}$





Adhikari et al. 2022

CDM on large scales!

Small scale behavior: still weakly constrained and small scale challenges

Small scale curiosities: cusp-core, missing satellites, BTFR, …

DM builder's guide

Pre-requisites for a dark matter candidate

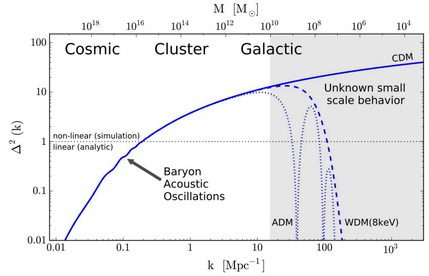
- Cold or warm — Thermal candidate: $m_{dm} \geq \mathrm{keV}$ — Or produced cold by a non-thermal mechanism

  Has to be non-relativistic at BBN

- Reproduce large and small scale distribution

  Clusters like pressure-less fluid on large scales $k \lesssim 10\,\mathrm{Mpc}^{-1}$

  Clustering on scales smaller than $k \gtrsim 10\,\mathrm{Mpc}^{-1}$ highly unconstrained



- Non-interacting or weakly interacting (~~Dark, colissionless~~)

  Can have a small electromagnetic interaction. Bound < **milicharge**

  Can have a **self interaction**. Bounds: $\sigma/m_{dm} < 0.13\,\mathrm{cm}^2/\mathrm{g}\,,\ \sigma/m_{dm} < 0.35\,\mathrm{cm}^2/\mathrm{g}$

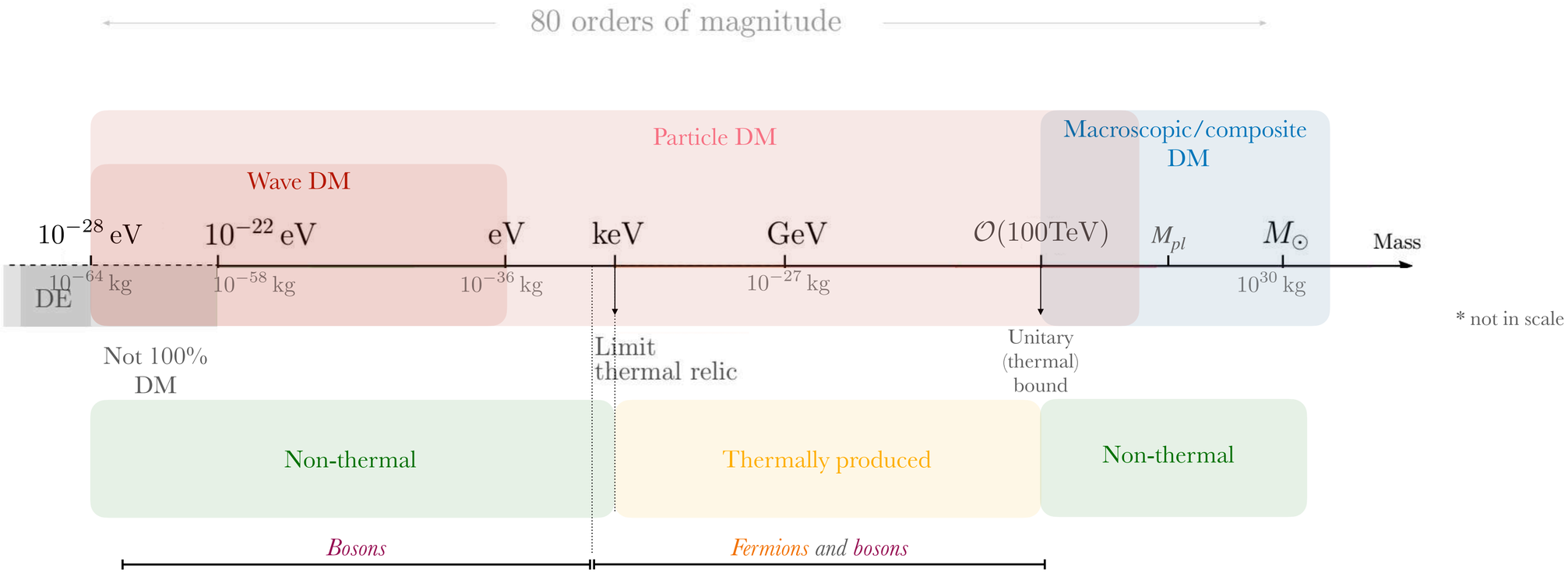
  Can interact via the ***weak force***

- Abundance $\Omega_m = 0.308 \pm 0.012$ (*Planck 2018*)

- Stable **If** it is a particle, it has to be stable with lifetime of DM should be much greater than the age of the universe

Mass scale of dark matter

We can use observations of LSS and galaxies to put bounds in the “particle" physics properties, like mass and spin, of the DM candidate



There are ways to evade some of these bounds!

Natural units ($c = 1$)

$1\,\text{kg} \to \sim 5 \times 10^{35}\,\text{eV}$

$1\,M_\odot \to \sim 10^{66}\,\text{eV}$

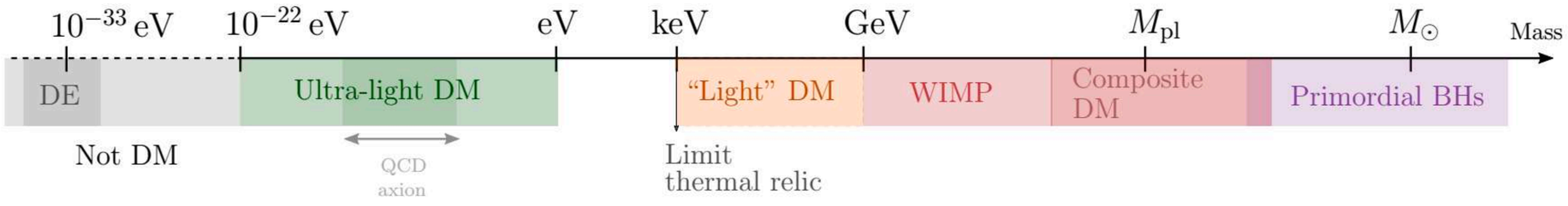
Landscape of dark matter models

- What is DM? What is the nature of DM?

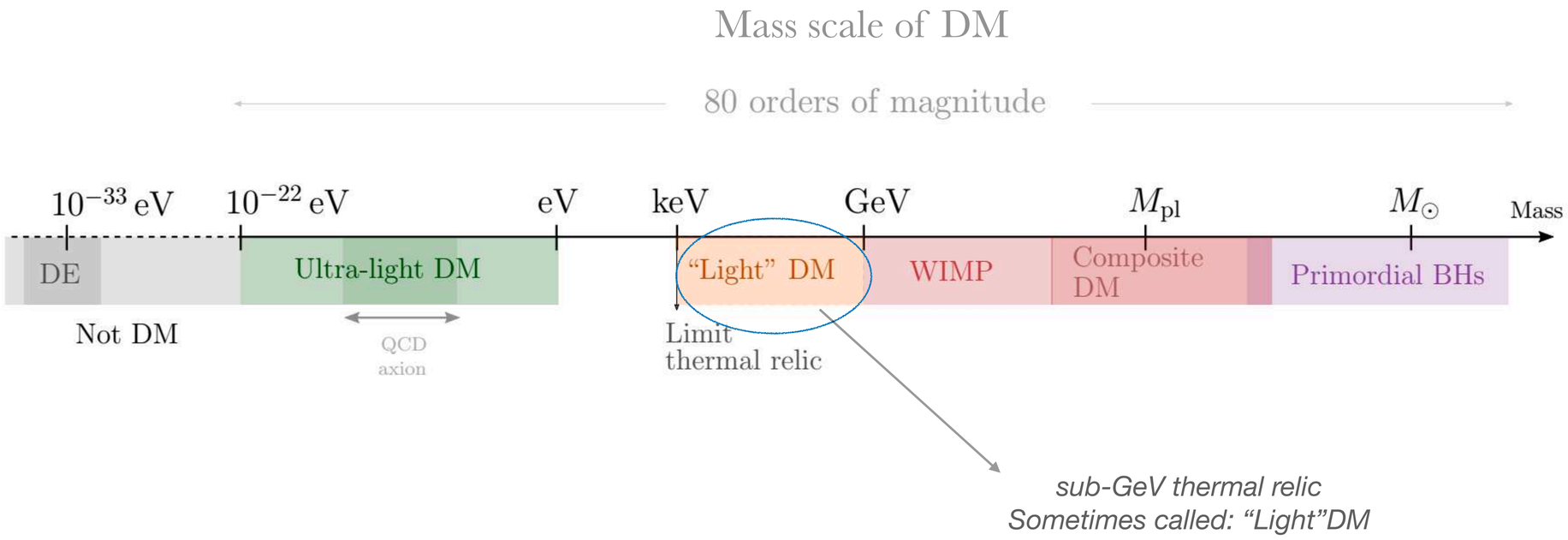
State of the "art"

Mass scale of DM

80 orders of magnitude

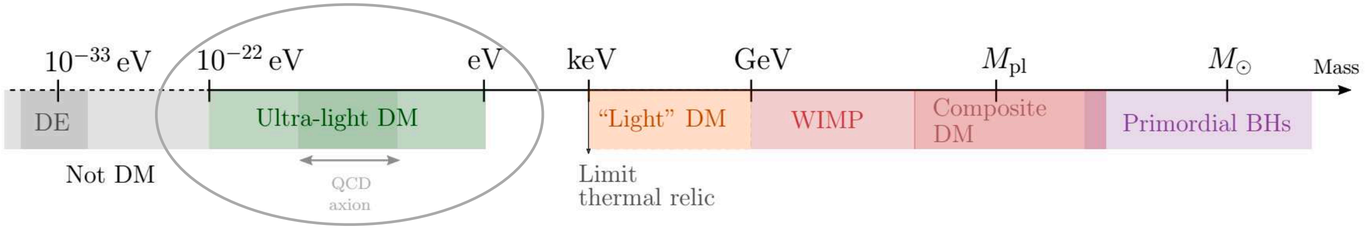


Landscape of dark matter models

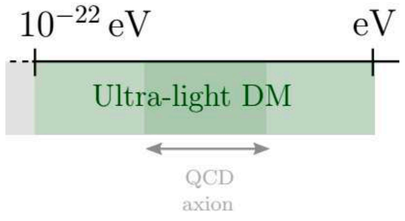


BUT, for us…

Ultra-light dark matter

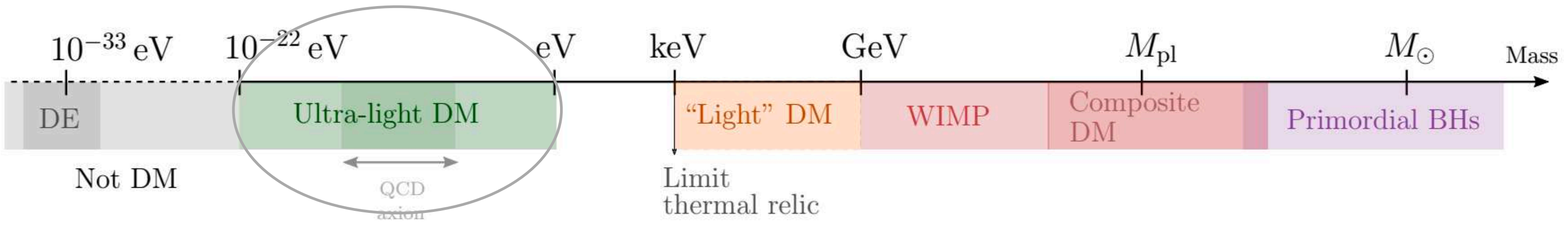


Ultra-light dark matter

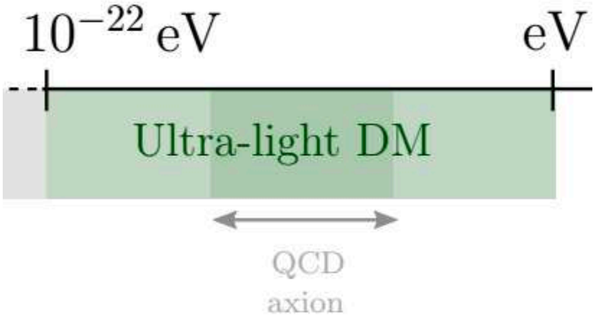


Ultra-light candidate, cold → Large $\lambda_{dB} \sim 1/mv$

Lightest possible candidate for DM



10^{-57} kg 10^{-35} kg



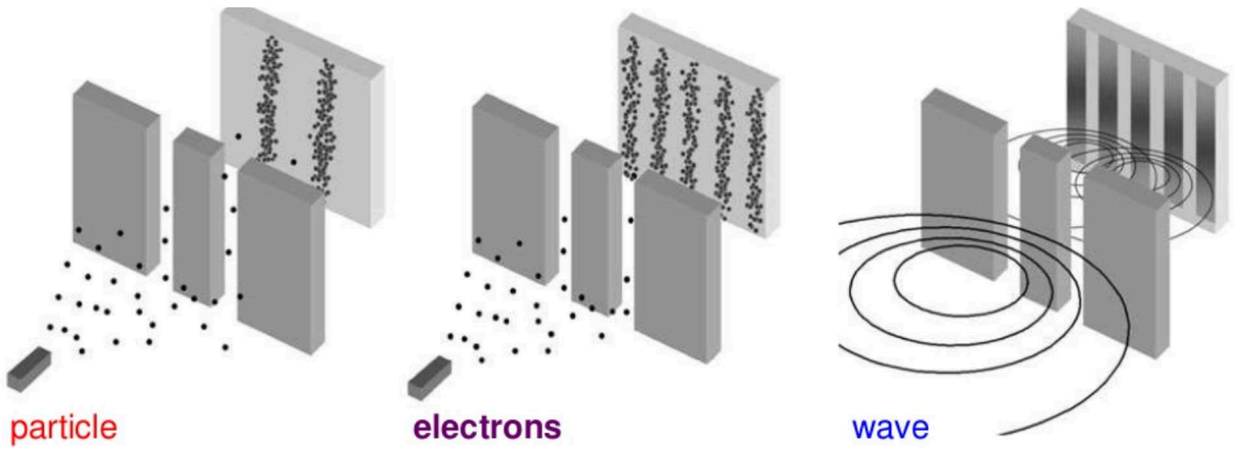
→ Bosons (scalar fields)

Non-thermally produced

Wave-Particle duality

All matter exhibits a wave behaviour

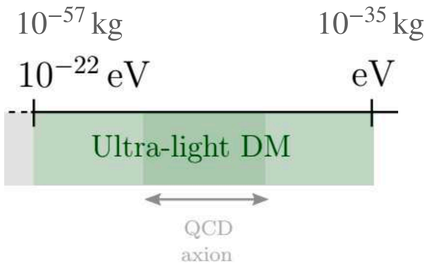
De Broglie 1924



$$\lambda_{dB} \sim \frac{1}{mv}$$

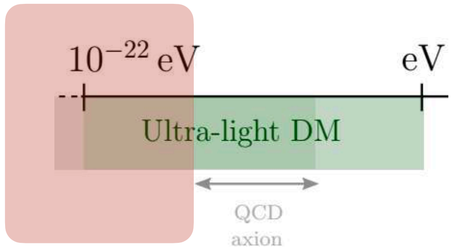
$$\lambda_{dB} \sim 1/\sqrt{2\pi m k_B T}$$

	Mass (kg)	Speed (m/s)	λ_{dB} (m)
Accelerated e-	9.1×10^{-31}	5.9×10^{6}	1.2×10^{-10}
Golf ball	0.045	220	4.8×10^{-30}



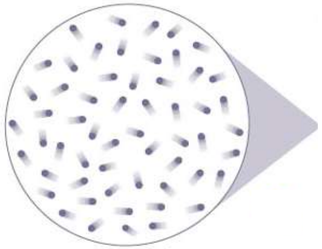
$$\lambda_{dB}^{ULDM} \sim \text{pc} - \text{kpc}$$

Ultra-light dark matter



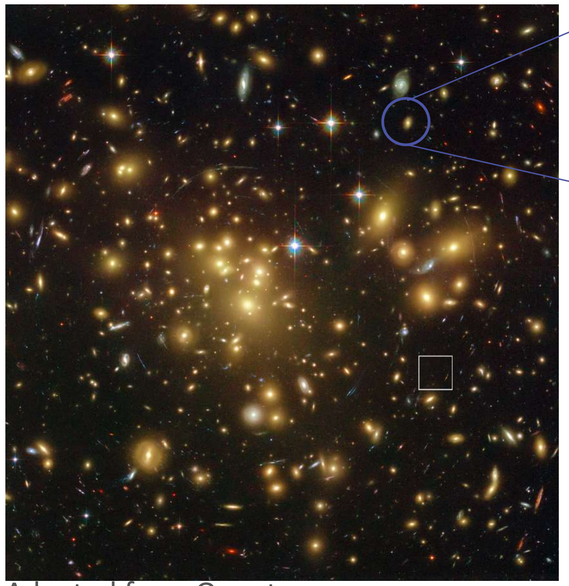
Ultra-light candidate → Large $\lambda_{\rm dB} \sim 1/mv$

Large scales:
DM behaves like standard particle DM (CDM).

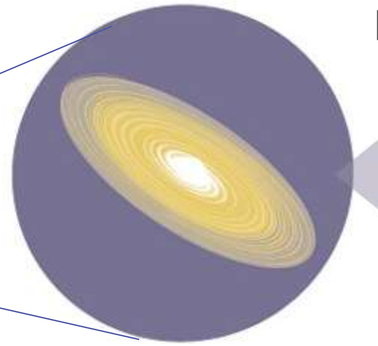


DM: particles

$d \gg \lambda_{dB}$

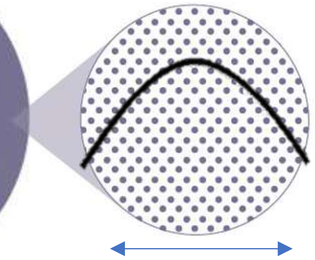


Adapted from Quanta



Galaxy halo

DM: wave behaviour



λ_{dB}

$d \ll \lambda_{dB}$

Small scales:
DM behaves like a wave

10^{-60} kg $\qquad$ 10^{-35} kg

$$10^{-25}\ \text{eV} \lesssim m \lesssim \text{eV}$$

$\lambda_{dB}^{ULDM} \sim$ pc – kpc

How light is ultra-light?

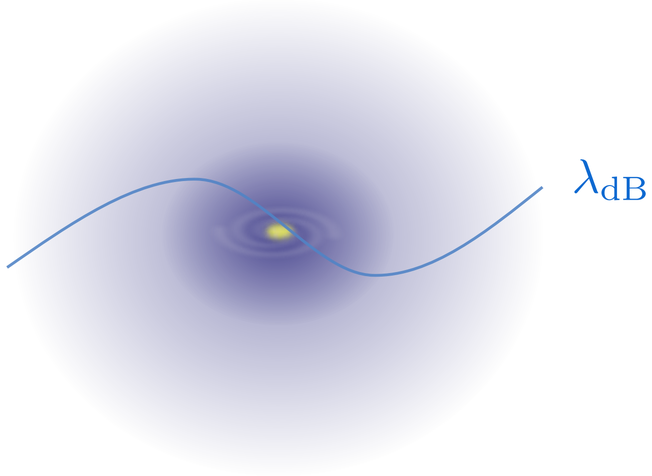
"Ultra-light dark matter", **EF**, 2020.

Behave as wave on galactic scales:

- $\lambda_{\rm dB}$ must be smaller than the halo

$$\lambda_{\rm dB} < R_{\rm halo}$$

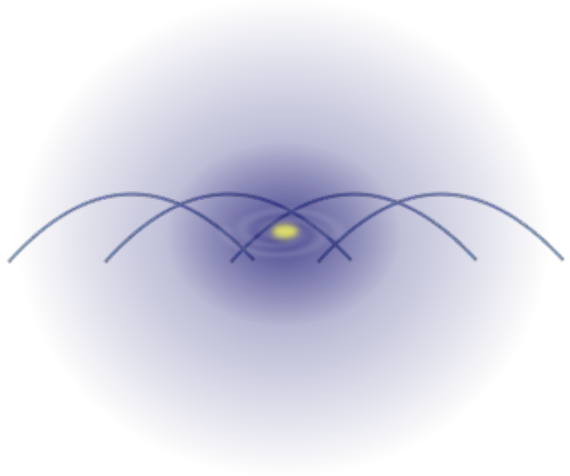
$$\Longrightarrow \quad m \gtrsim 10^{-25}\,{\rm eV}$$



- $\lambda_{\rm dB}$ overlap to be of halo size

$$\lambda_b \sim \frac{1}{mv} \geq d \sim \left(\frac{m}{\rho_{vir}}\right)^{\frac{1}{3}}$$

$$\Longrightarrow \quad m \leq 2{\rm eV}$$



10^{-60} kg $\qquad\qquad$ 10^{-35} kg

$$\boxed{10^{-25}\,{\rm eV} \lesssim m \lesssim {\rm eV}}$$

$$\lambda_{dB}^{ULDM} \sim {\rm pc} - {\rm kpc}$$

Recap

"Light DM" theory

Motivation: particle physics

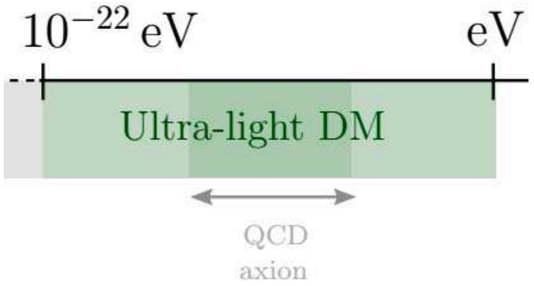
ULDM candidates

- Natural candidate for a light scalar field is a pseudo-Nambu Goldstone boson (breaking of an approximate symmetry)

Known PNGB: QCD axion → Candidate for DM

(Peccei and Quinn 1977; Weinberg 1978; Wilczek 1978)

Axion-like particles



Axions or Axion like particles (ALP)

Axions and ALPs are pseudo Nambu Goldstone bosons from the spontaneous symmetry breaking of a $U_{PQ}(1)$ (U(1)) symmetry, and are described by the complex field: $\Psi = v\, e^{i\phi/f_a}$

$$v_{0,ssb} = f_a/\sqrt{2} \longrightarrow \phi \to \phi + c$$

Non-perturbative effects (from string theory or instatons) induce a potential:

$$V(\phi) = \Lambda_a^4\,[1 - \cos(\phi/f_a)] \xrightarrow[\phi \ll f_a]{} \frac{1}{2}m^2\phi^2 + \frac{g}{4}\phi^4 + \cdots$$

Motivation: particle physics

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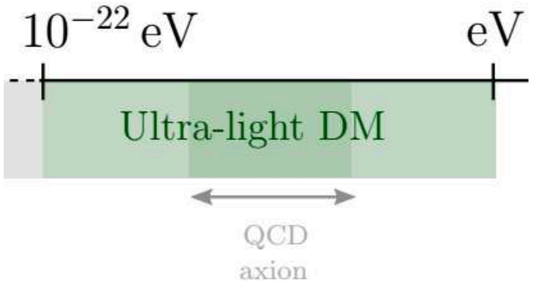
(Peccei and Quinn 1977; Weinberg 1978; Wilczek 1978)



Axion-like particles or ultra-light axions:

- ALPs expected in string theory *(Arvanitaki et al., Svrcek, Witten)*
- Can generate PNGB that are ultra-light
- Formation mechanism: needs to have a relic abundance that gives the correct DM abundance

Non-thermal mechanism (e.g. mis-alignement)

$$\Omega_{axion} \sim 0.15 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \theta_1^2$$

$$\Omega_{ALP} \sim 0.1 \left(\frac{f_a}{10^{17}\,\mathrm{GeV}}\right)^{2} \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)$$

L. Hui

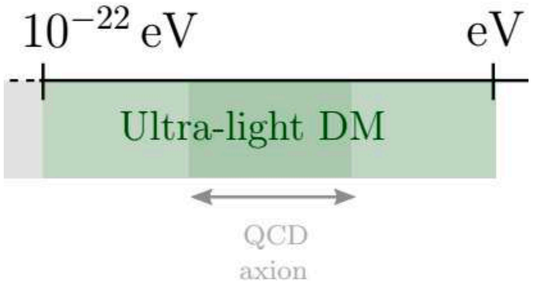
Motivation: particle physics

ULDM candidates

- Natural candidate for a light scalar field is a pseudo-Nambu Goldstone boson

Known PNGB: QCD axion → Candidate for DM

(Peccei and Quinn 1977; Weinberg 1978; Wilczek 1978)



Axion-like particles or ultra-light axions:

- ALPs expected in string theory *(Arvanitaki et al., Svrcek, Witten)*
- Can generate PNGB that are ultra-light

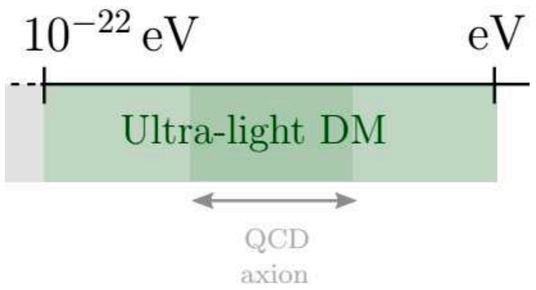
- Formation mechanism: needs to have a relic abundance that gives the correct DM abundance

Spin-0: Non-thermal mechanism (e.g. misalignement)

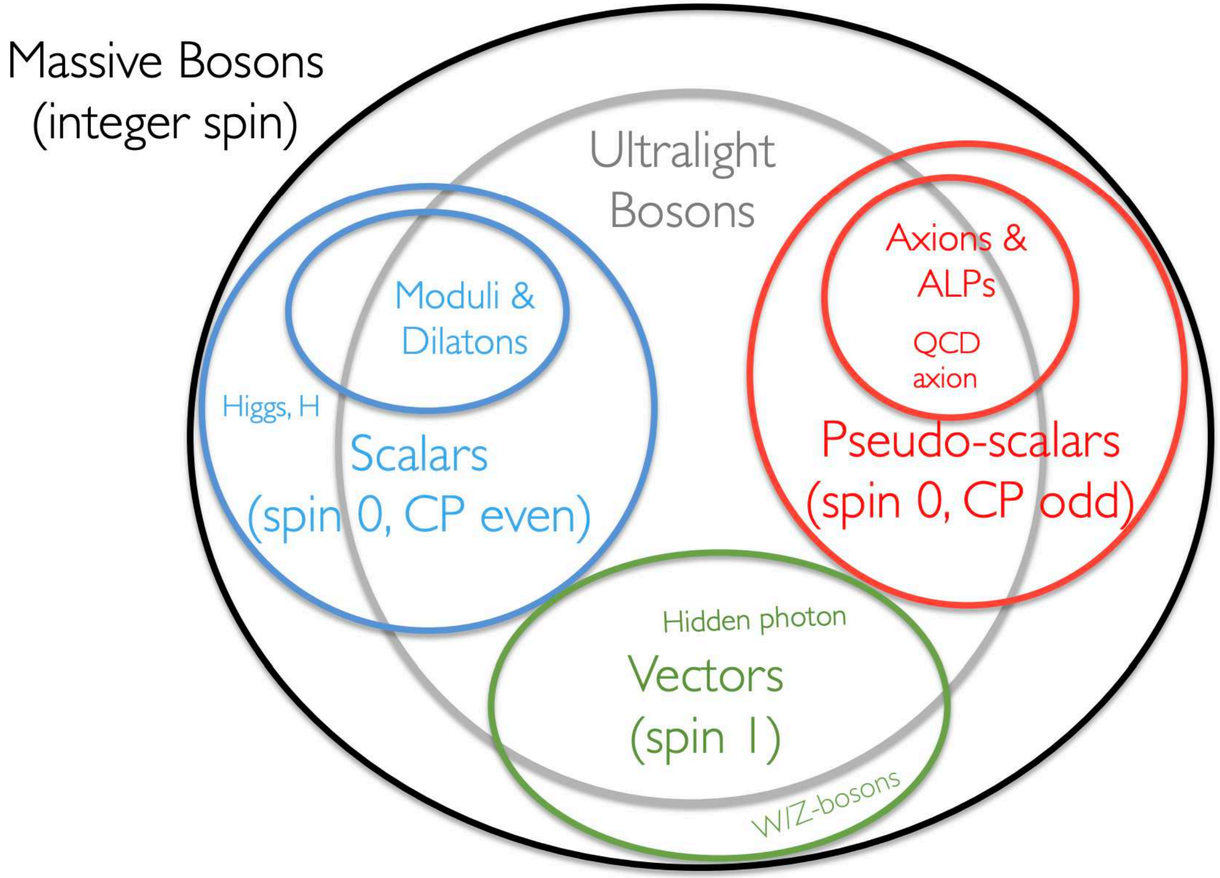
Vector FDM: challenging in the ultra-light regime
(e.g. from misalignment requires non-minimal couplings to Ricci scalar -> viol. of unitarity long. graviton-photon scattering; oscillating Higgs or oscillating misaligned axion - resonant production - choices for couplings for right abundance)
Spin 2 FDM: (e.g bigravity)

Motivation: particle physics

ULDM candidates

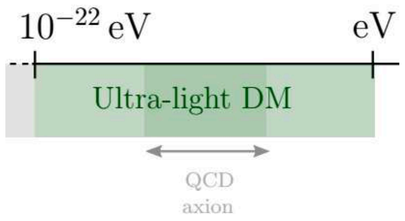


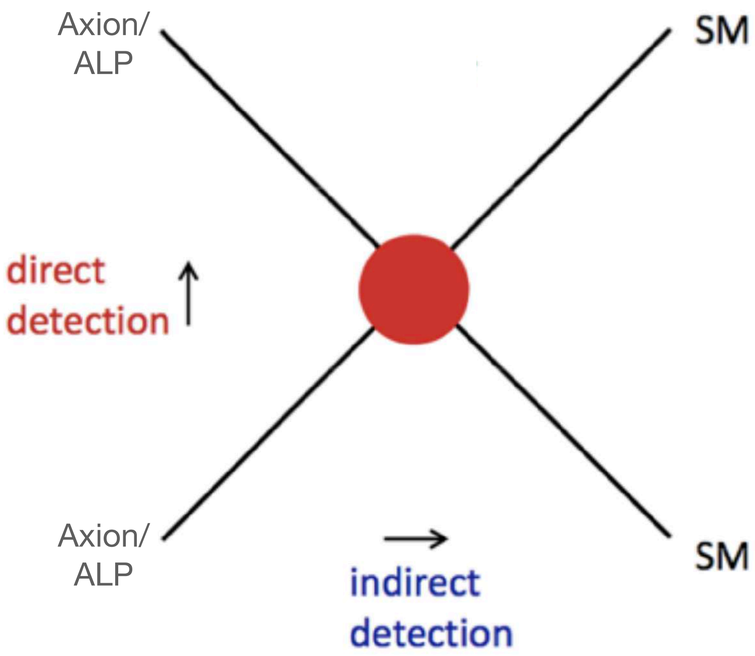
Many extensions of the Standard Model predict additional massive bosons



Ref.: Chadha-Day et al 2022

How to search for ULDM?





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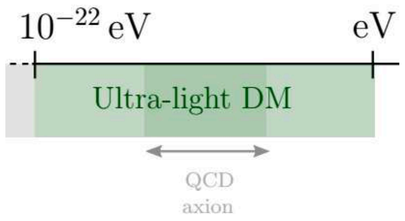
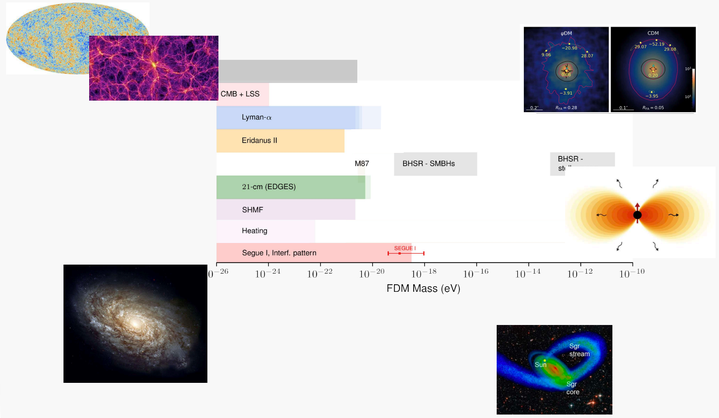
Gravitationally
Cosmological and astrophysical searches

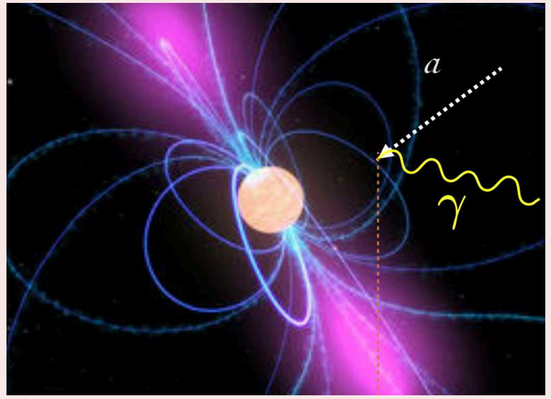
How to search for axions/ALPs?



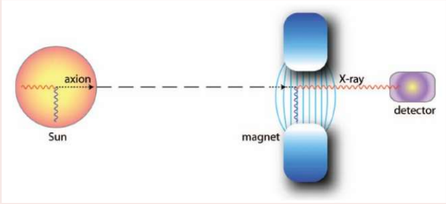
Cosmological and astrophysical searches

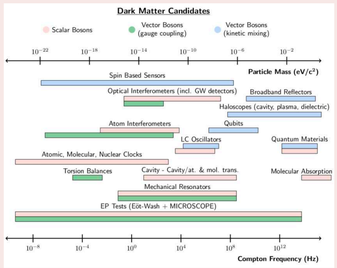


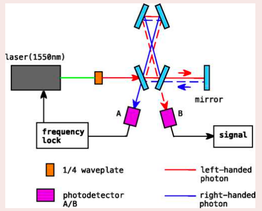
Indirect detection



"Direct detection" Axion/ALPs experiments





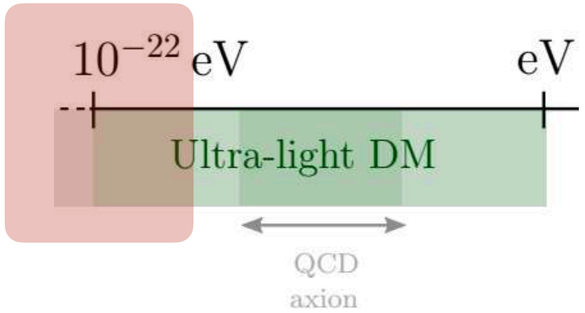


Gravitational

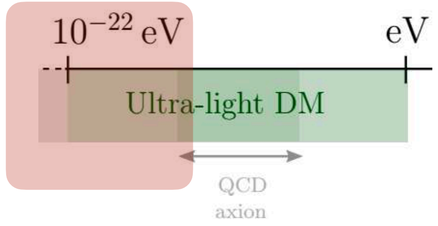
Interactions with the SM

Gravitational signatures

Cosmological and astrophysical



Ultra-light Dark Matter -classes



3 classes:

	Fuzzy DM (FDM)	Self Interacting FDM (SIFDM)	DM Superfluid
	- Gravitationally bounded ultra-light scalar field model - Condensation under gravity (BEC)	- Presence of (weakly) self-interaction - Condensation under gravity + SI (superfluid)	- Forms a superfluid in galaxies - MOND behaviour interior of galaxies
DOFs	m	m g	

Axion and ALP (axion like particles)

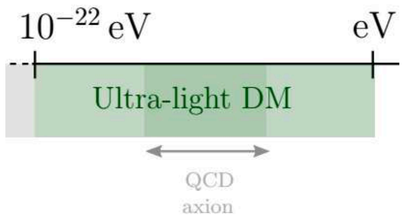
$$i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{g}{8m^2}|\psi|^2 - m\Phi\right)\psi$$

$$\mathcal{L} = P(X)$$

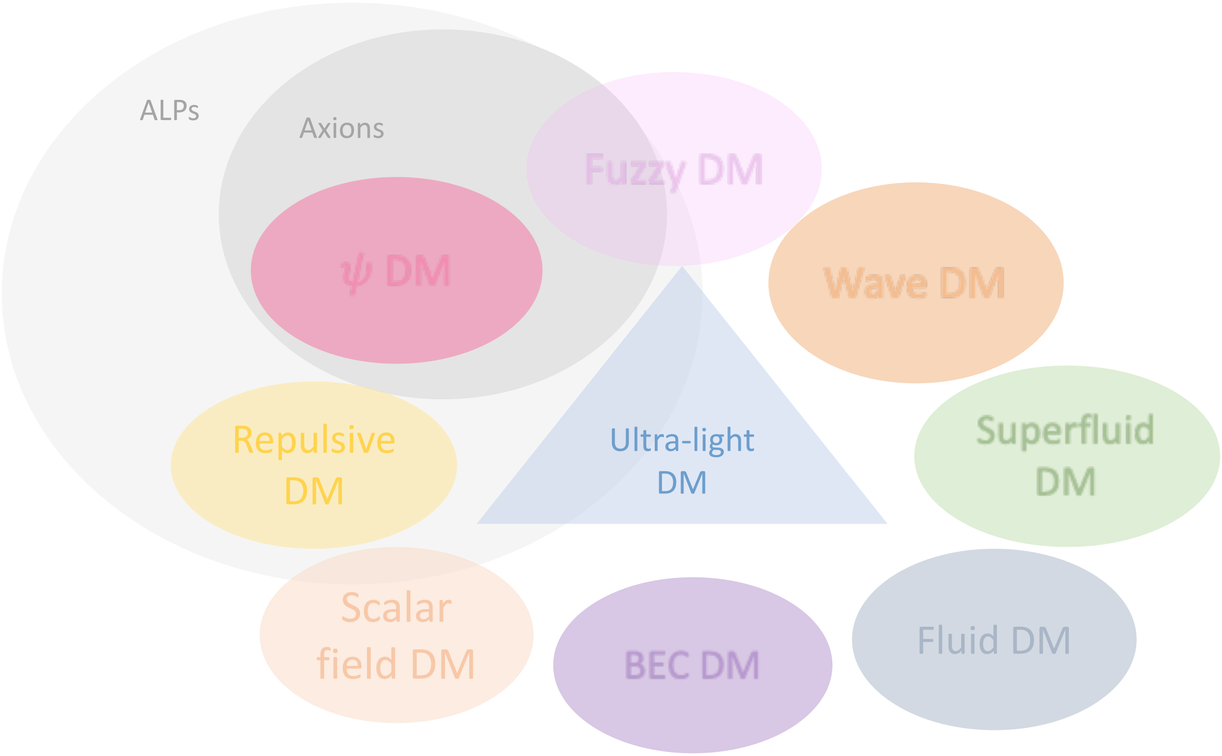
$\longrightarrow$ Connection with condensed matter and particle physics!

"Ultra-light dark matter", **E.Ferreira**, 2020. The Astronomy and Astrophysics Review.

Ultra-light Dark Matter - models

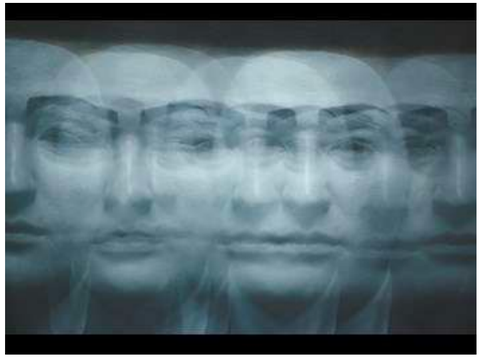


There are many ways to have a DM with this property → many ULDM models in the literature
However, each of these models presents a different dynamics on small scales - different phenomenology

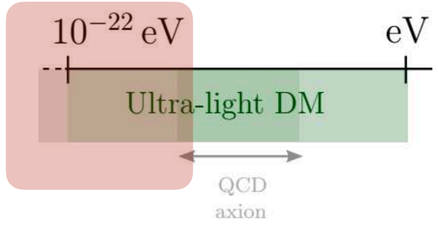


Fuzzy dark matter

Self interacting fuzzy dark matter



Fuzzy dark matter



Fuzzy DM (FDM)

- Gravitationally bounded ultra-light scalar field model
- Condensation under gravity (BEC)

m

Wave DM
Ultra-light axions

Self Interacting FDM (SIFDM)

- Presence of (weakly) self-interaction
- Condensation under gravity + SI (superfluid)

m g

Hu W, Barkana R, Gruzinov A (2000 a,b)

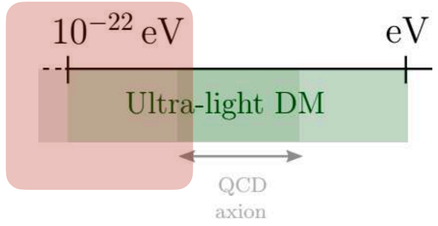
(Reviews: EF (2021), J. Niemeyer (2019), L. Hui (2021))

Idea:

$$m_{\rm fdm} \sim 10^{-22}\,{\rm eV}$$

address the small scale problems+ rich phenom.

Fuzzy dark matter



Fuzzy DM
(FDM)

- Gravitationally bounded ultra-light scalar field model
- Condensation under gravity (BEC)

m

Wave DM
Ultra-light axions

Focus more on spin 0 particles here!

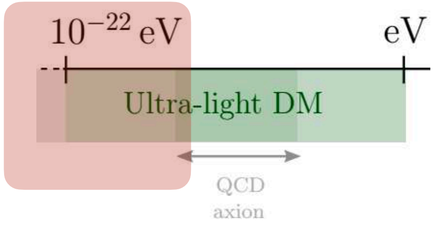
(Some of the grav. phenom. is carried for vectors, for example)

- Spin 0 - FDM
- Spin 1 - Vector FDM
- Higher spin FDM

Hu W, Barkana R, Gruzinov A (2000 a,b)

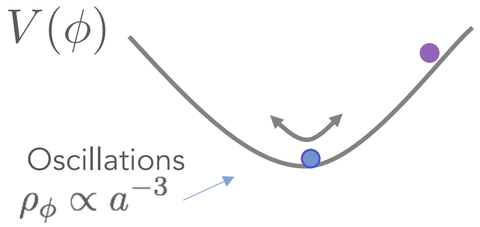
(Reviews: *EF (2021), J. Niemeyer (2019), L. Hui (2021)*)

Cosmological evolution



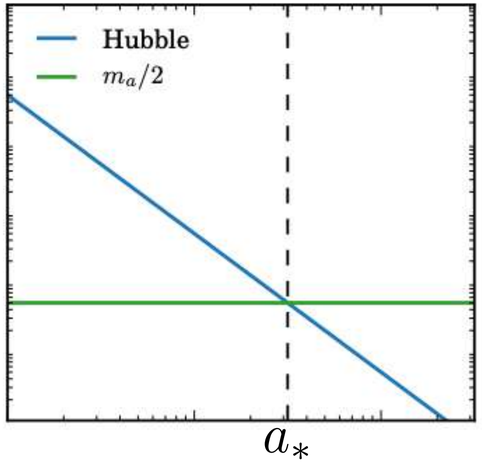
$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

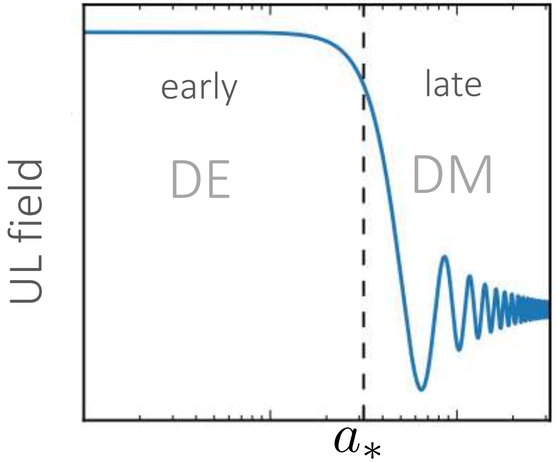
FDM

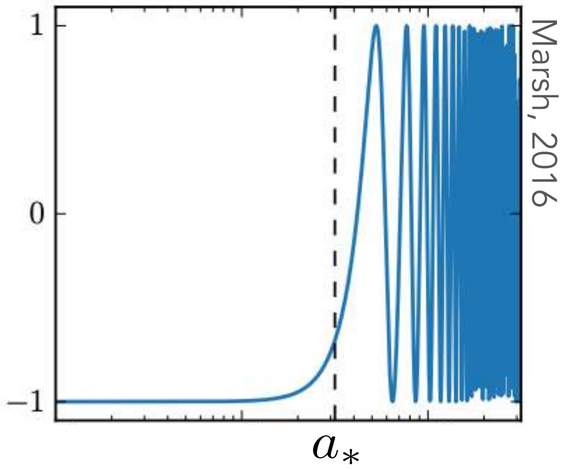


$$\begin{cases} H \gg m \implies \phi_{\text{early}} = \phi(t_i) \longrightarrow \omega = -1 & \text{DE} \\ H \ll m \implies \phi_{\text{late}} \propto e^{imt} \longrightarrow \langle\omega\rangle = 0 & \text{DM} \end{cases}$$

$H(t_*) = m$

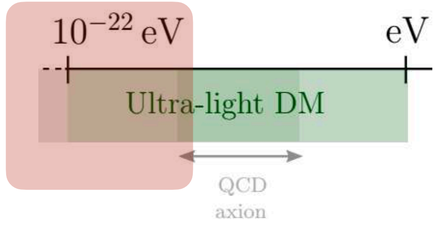




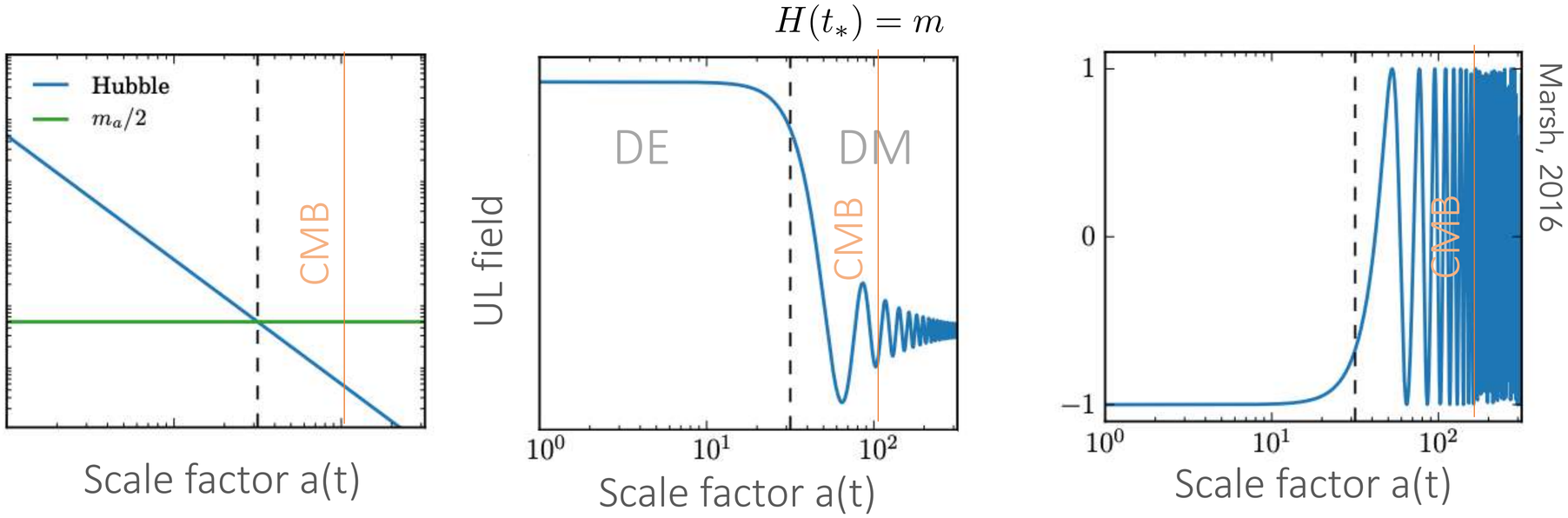


Marsh, 2016

Cosmological evolution

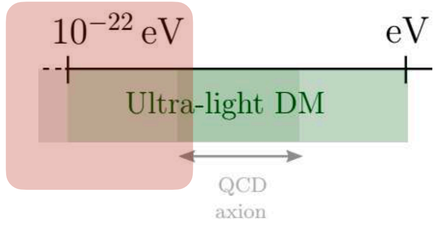


In order to behave like DM: start oscillating before matter-radiation equality



$$m > 10^{-28}\,\mathrm{eV} \sim H(a_{\mathrm{eq}})$$

Structure formation - non-relativistic regime



Evolution on small scales: take non-relativistic regime of the theory, relevant for structure formation.

<u>Schrödinger-Poisson system</u> : describe the FDM and the SIFDM

$$\begin{cases} i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{g}{8m^2}|\psi|^2 - m\Phi\right)\psi \\ \nabla^2\Phi = 4\pi G(m|\psi|^2 - \bar{\rho}) \end{cases}$$

Schrödinger equation (Gross-Pitaevskii)

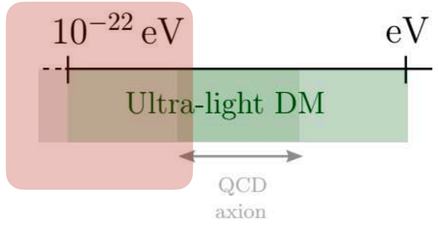
Poisson equation

$g = 0 \longrightarrow$ FDM

$g \neq 0 \longrightarrow$ SIFDM

Fundamentally different than CDM/WDM/SIDM!

Structure formation - non-relativistic regime



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Poisson equation

$g = 0 \longrightarrow$ FDM

$g \neq 0 \longrightarrow$ SIFDM

Fundamentally different than CDM/WDM/SIDM!

Madelung equations $\quad (\psi \equiv \sqrt{\rho/m}\, e^{i\theta}$ and $\mathbf{v} \equiv \nabla\theta/m)$

$$\dot{\rho} + \nabla\cdot(\rho\,\mathbf{v}) = 0$$

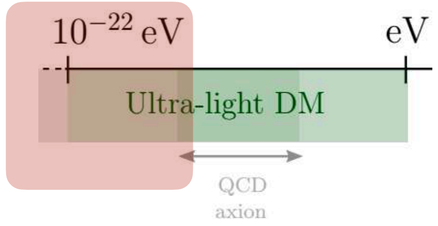
$$\dot{\mathbf{v}} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - P_{int} - \frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

$P_{int} = K\rho^{(j+1)/j} = \frac{g}{2m^2}\rho^2$

Quantum pressure

FLUID DESCRIPTION

Structure formation - non-relativistic regime



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Schrödinger equation (Gross-Pitaevskii)

Poisson equation

$g = 0 \longrightarrow$ FDM

$g \neq 0 \longrightarrow$ SIFDM

Fundamentally different than CDM/WDM/SIDM!

HOMEWORK

Refs.: EF, "ULDM" review
Niemeyer 2019 review

From the relativistic action of a scalar field in FRW

$$S_\phi = \int d^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V(\phi)\right]$$

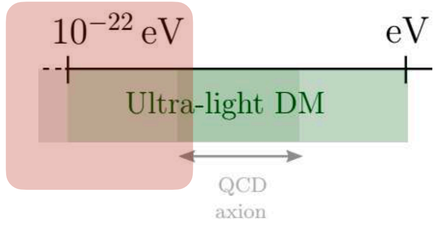
Write the perturbed equation in Newtonian gauge

$$S_\phi = \int d^4x\, a^3\left[\frac{1}{2}(1-4\Phi)\,\dot{\phi}^2 - \frac{1}{a^2}(\partial_i\phi)^2 - (1-2\Phi)V(\phi)\right]$$

Compute the non-relativistic action and EoM (Schrödinger-Poisson system)

$$S = \int d^4x\left[\frac{i}{2}(\psi\partial_t\psi^* - \psi^*\partial_t\psi) - \frac{|\nabla\psi|^2}{2m} - \frac{g}{16m^2}|\psi|^4 - m(\psi\psi^* - \langle\psi\psi^*\rangle)\Phi - \frac{a}{8\pi G}(\partial_i\Phi)^2\right]$$

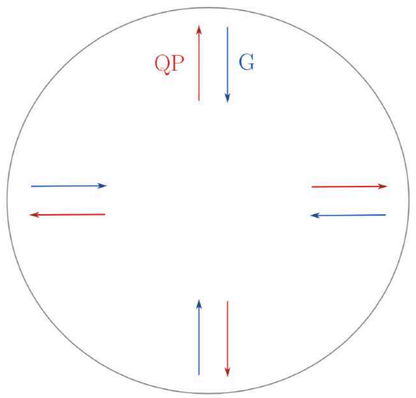
Structure formation - perturbation and stability



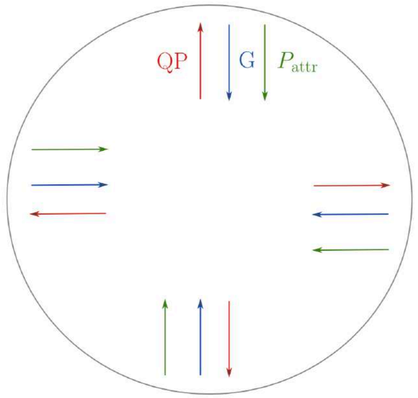
Competition between gravity and pressure (quantum pressure and interaction)

SIFDM

FDM

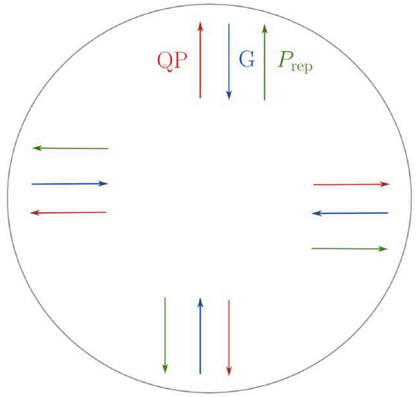


ATTRACTIVE



$g < 0$

REPULSIVE



$g > 0$

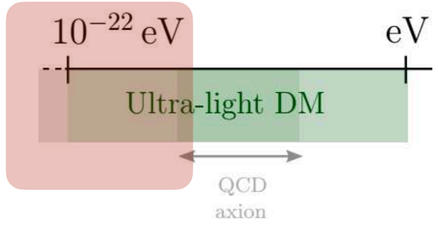
$$\dot{\rho} + \nabla \cdot (\rho\, \mathbf{v}) = 0$$

$$\dot{\mathbf{v}} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - P_{int} - \frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

$P_{\rm int} = \frac{g}{2m^2}\rho^2$

Quantum pressure

Structure formation - perturbation and stability



Finite clustering scale (Jeans length)- no structure formation on small scales

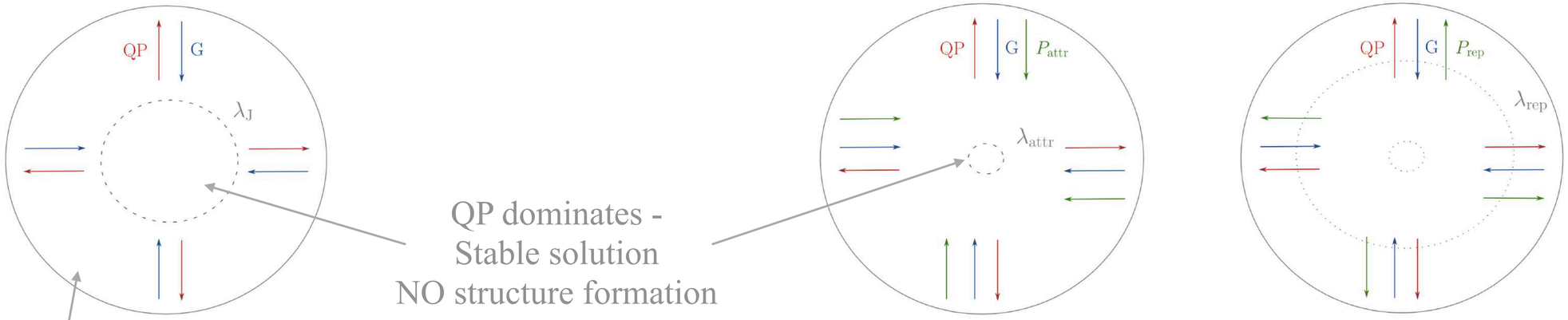
(CDM, λ_J effectively zero)

SIFDM

FDM

ATTRACTIVE

REPULSIVE



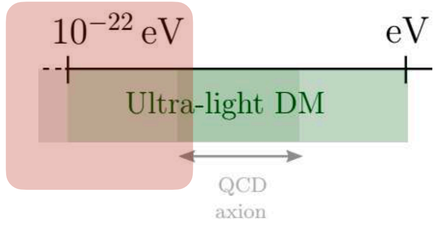
QP dominates -
Stable solution
NO structure formation
$\lambda < \lambda_J,\ \lambda_{attr},\ \lambda_{rep}$

$g < 0$

$g > 0$

For $\lambda > \lambda_J,\ \lambda_{attr},\ \lambda_{rep}$ $\longrightarrow$ CDM

Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

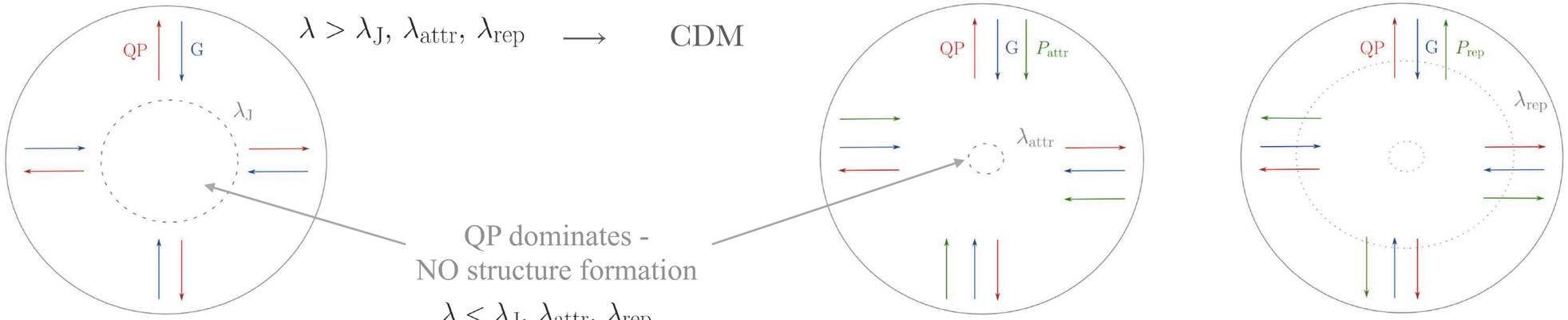
SIFDM

FDM

ATTRACTIVE

REPULSIVE

$\lambda > \lambda_J,\ \lambda_{\rm attr},\ \lambda_{\rm rep} \longrightarrow$ CDM



QP dominates -
NO structure formation
$\lambda < \lambda_J,\ \lambda_{\rm attr},\ \lambda_{\rm rep}$

$g < 0$

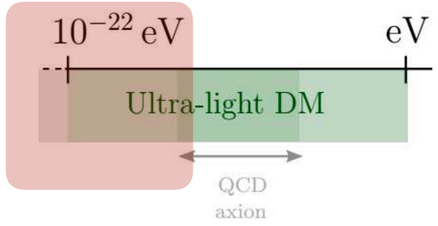
$g > 0$

Finite size coherent core – Bose stars

$$\lambda_J = 55 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{-1/4} (\Omega_m h)^{-1/4}\,\mathrm{kpc}$$

$m \leq 10^{-20}\mathrm{eV} \ \Rightarrow\ \lambda_{dB} > \mathcal{O}(\mathrm{kpc})$ Galactic scales

Structure formation - perturbation and stability

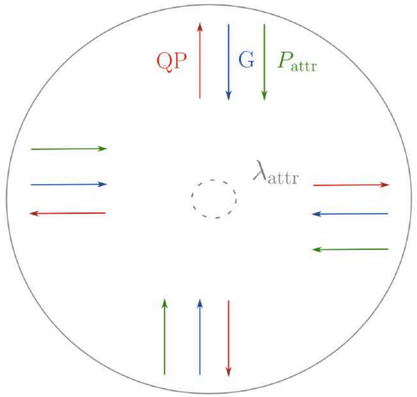


Quiz

What about in the case where there is self-interaction?

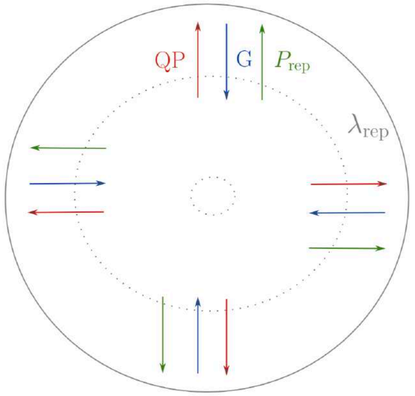
SIFDM

ATTRACTIVE



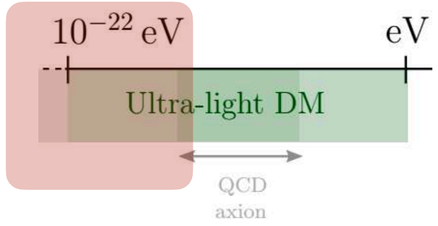
$g < 0$

REPULSIVE



$g > 0$

Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

In the limit where only self-interaction is important:

$$i\dot{\psi} = -\frac{1}{2m}\nabla^2\psi + \frac{g}{8m^2}|\psi|^2\psi\,.$$

We can decompose as: $\psi(\mathbf{x},t) = \psi_c(t) + \delta\bar{\Psi}(\mathbf{x},t)$

<u>Homogeneous:</u> $i\dot{\psi}_c = \frac{g}{8m^2}|\psi_0|^2\psi_c$

Periodic solution $\psi_c(t) = \psi_0\, e^{-i\mu_c t}$

where $|\psi_0|^2 = n_0$ fixes the amplitude and $\mu_c = gn_0/8m^2$

<u>Perturbations:</u>

$$i\delta\Psi = -\frac{1}{2m}\nabla^2\delta\Psi + \frac{gn_0}{8m^2}\left(\delta\Psi + \delta\Psi^*\right)$$

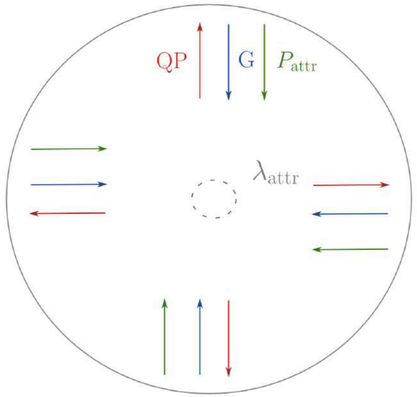
Rewriting $\delta\Psi$ as $\Psi = A + iB$

$$\Rightarrow \quad \frac{d}{dt}\begin{pmatrix} A_k \\ B_k \end{pmatrix} = \begin{pmatrix} 0 & \frac{k^2}{2m} \\ -\frac{k^2}{2m} - \frac{gn_0}{4m^2} & 0 \end{pmatrix}\begin{pmatrix} A_k \\ B_k \end{pmatrix}$$

Dispersion relation $\omega_k^2 = \frac{gn_0}{4m^2}\frac{k^2}{2m} + \frac{k^4}{4m^2}$

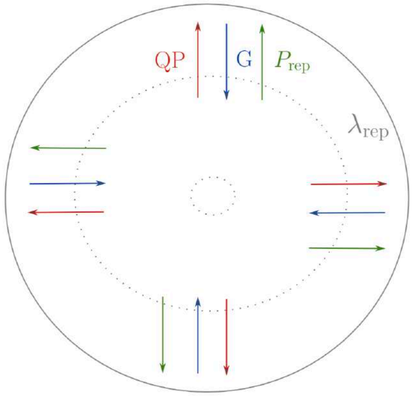
SIFDM

ATTRACTIVE



$g < 0$

REPULSIVE



$g > 0$

$$k_c^2 = -\frac{g\,n_0}{2m}$$

<u>Solution:</u>

$(\omega_k^2 > 0)$ $\quad \delta\Psi_k = Z\left(\omega_k + \zeta_k\right)e^{i\omega_k t} + Z^*\left(\omega_k - \zeta_k\right)e^{-i\omega_k t}$

$(\omega_k^2 < 0)$ $\quad \delta\Psi_k = c_1\left(\gamma_k - i\zeta_k\right)e^{\gamma_k t} + c_2\left(\gamma_k + i\zeta_k\right)e^{-\gamma_k t}$

Structure formation - perturbation and stability

HOMEWORK

EXERCISE:

In the limit where only self-interaction is important:

$$i\dot{\psi} = -\frac{1}{2m}\nabla^2\psi + \frac{g}{8m^2}|\psi|^2\psi\,.$$

We can decompose as: $\psi(\mathbf{x},t) = \psi_c(t) + \delta\bar{\Psi}(\mathbf{x},t)$

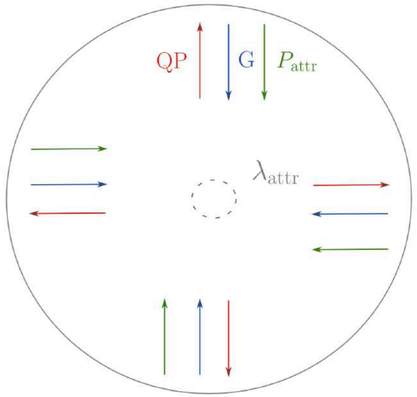
Homogeneous: $i\dot{\psi}_c = \frac{g}{8m^2}|\psi_0|^2\psi_c$

$$\psi_c(t) = \psi_0\, e^{-i\mu_c t}$$

Perturbations: $i\delta\Psi = -\frac{1}{2m}\nabla^2\delta\Psi + \frac{g n_0}{8m^2}\left(\delta\Psi + \delta\Psi^*\right)$

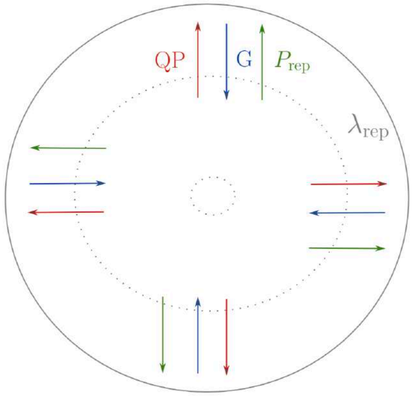
SIFDM

ATTRACTIVE



$g < 0$

REPULSIVE

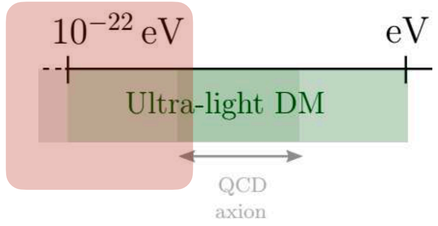


$g > 0$

$$k_c^2 = -\frac{g\, n_0}{2m}$$

Derive the solutions to the Schrodinger equation above for an attractive and repulsive potential.
Identify the different scales of the problem and where we have clustering or a stable, oscillatory solution.

Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

ATTRACTIVE

$$k_c^2 = -\frac{|g|\, n_0}{2m}$$

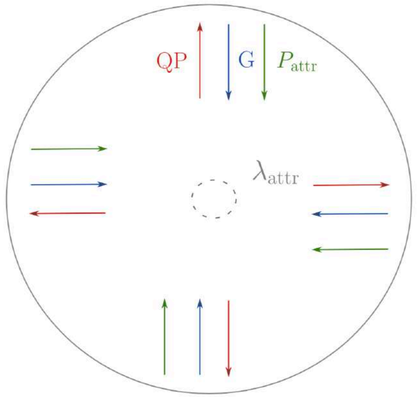
$k > k_c \, (\lambda < \lambda_c) \quad \Rightarrow \quad$ Solution oscillates and is stable

This stable configuration, however, is different than in the case for repulsive interaction, forming a localized object, with maximum size given by λ_c

$k < k_c \, (\lambda > \lambda_c) \quad \Rightarrow \quad$ Exponential growth (like CDM)

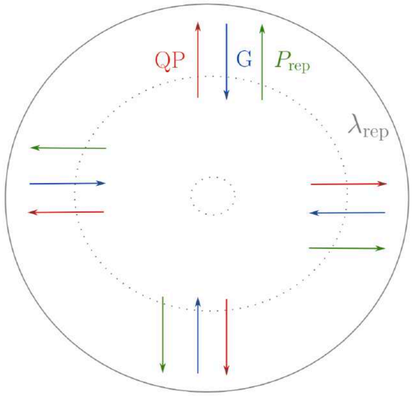
SIFDM

ATTRACTIVE



$g < 0$

REPULSIVE



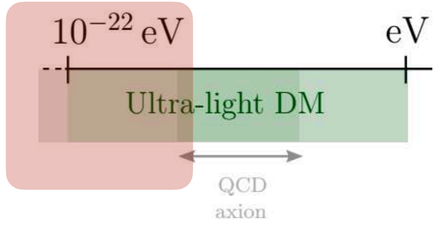
$g > 0$

$$k_c^2 = -\frac{g\, n_0}{2m}$$

For attractive interactions can only form localized clumps (solitons)

QCD axion: $m \sim 10^{-5}$ eV, $\lambda_a \sim -10^{-48}$ $\rightarrow$ $l_{soliton} \sim 10^{-5}$ kpc

Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

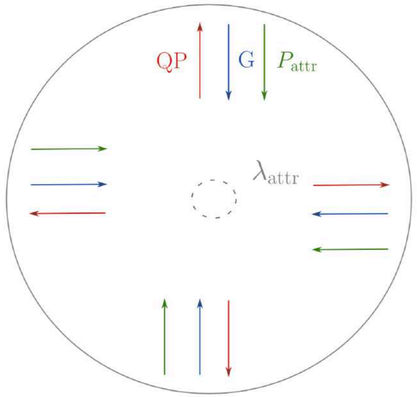
REPULSIVE $g > 0$

$$k_c^2 = \frac{g\, n_0}{2m}$$

Homogeneous configuration is always stable, and it is always going to be described by an oscillatory solution, either if λ is bigger or smaller than λ_c

SIFDM

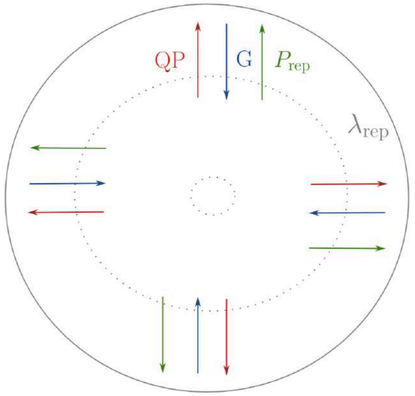
ATTRACTIVE



$g < 0$

Superfluid!

REPULSIVE



$g > 0$

$$k_c^2 = -\frac{g\, n_0}{2m}$$

Dispersion relation

Long wavelength regime

$$\lambda \gg \lambda_c$$

$$\omega_k \simeq c_s k$$

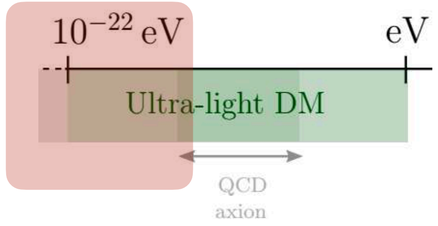
Long range - superfluid

Short wavelength regime

$$\omega_k \simeq k^2/2m$$

Free massive particle

Structure formation - perturbation and stability



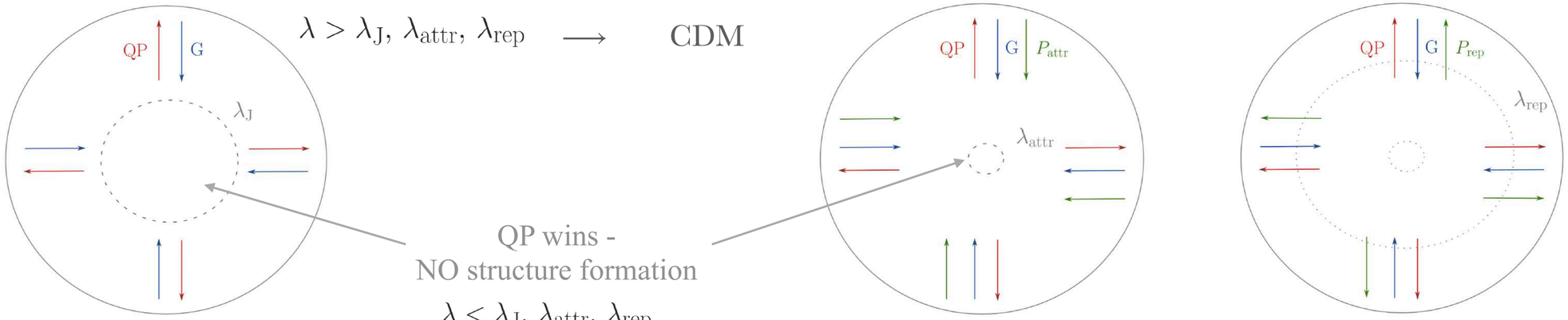
Finite clustering scale - no structure formation on small scales

SIFDM

FDM

ATTRACTIVE

REPULSIVE



$$k_c^2 = -\frac{g\, n_0}{2m}$$

$g < 0$

$g > 0$

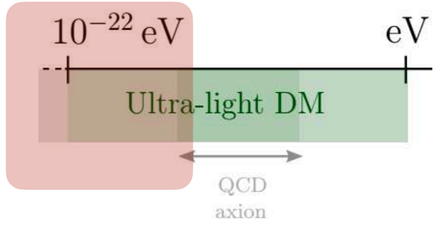
Finite size coherent core – Bose stars

$$\lambda_J = 55 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{-1/4} (\Omega_m h)^{-1/4}\,\mathrm{kpc}$$

$m \leq 10^{-20}\mathrm{eV} \;\Rightarrow\; \lambda_{dB} > \mathcal{O}(\mathrm{kpc})$ Galactic scales

$g > 0$	$\longrightarrow$	$\forall \lambda$	Solution oscillates. Condensate (long range)
$g < 0$	$\longrightarrow$	$\lambda > \lambda_*$	Structures grow. No condensate.
		$\lambda < \lambda_*$	Solution oscillates. Condensate (finite size)

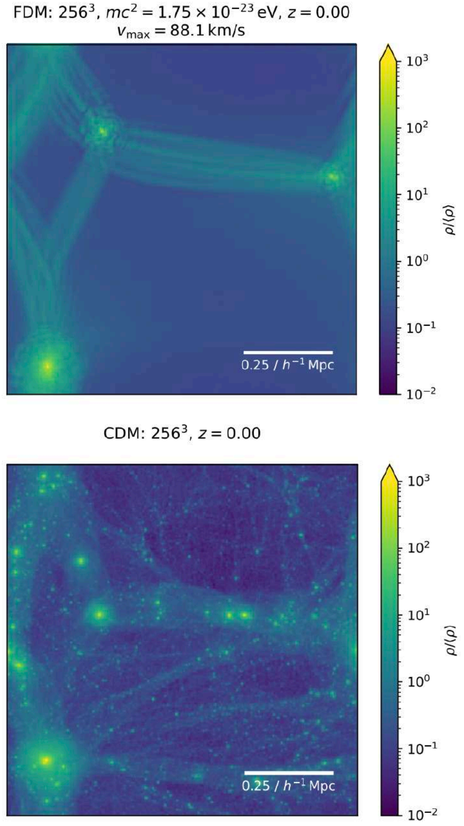
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

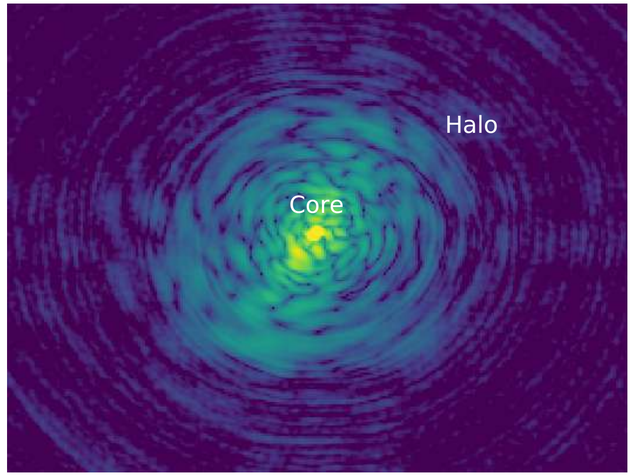
* Focus only in gravitational signatures

Suppression of small structures

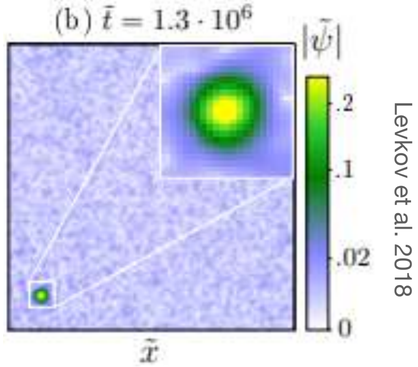


S. May et al. 2021

Formation of a solitonic core

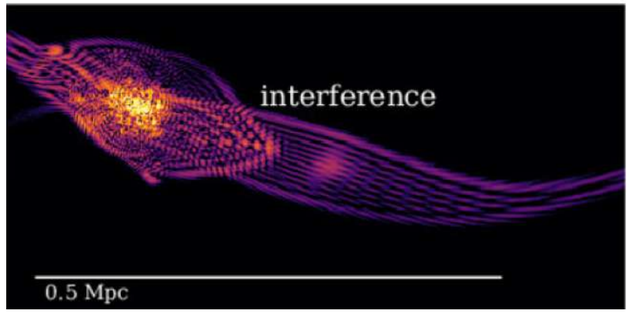


Dynamical effects



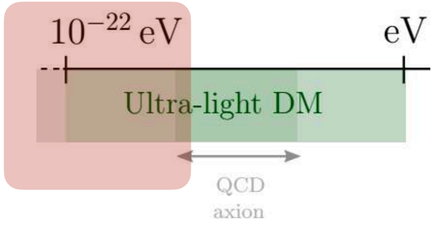
Levkov et al. 2018

Wave interference



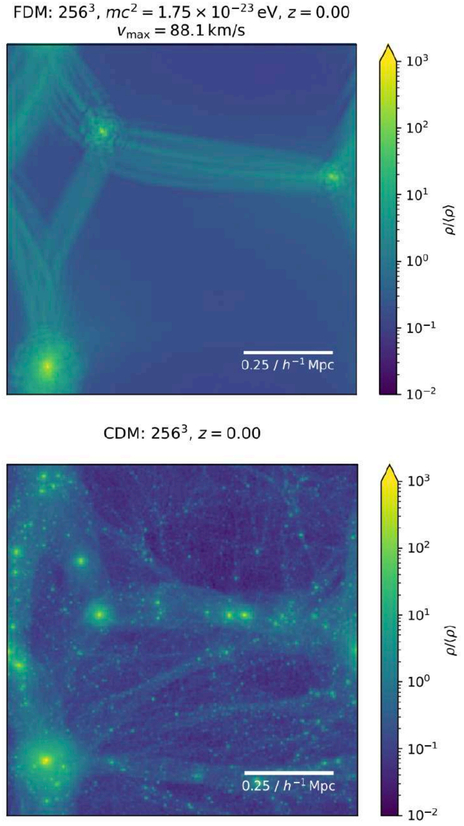
Mocz et al. 2017

Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures



S. May et al. 2021

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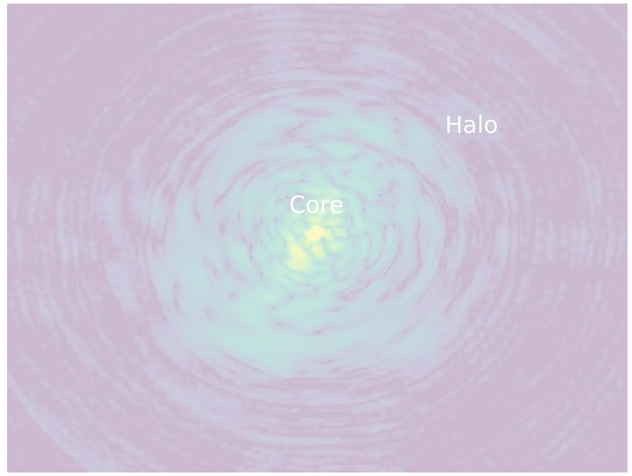
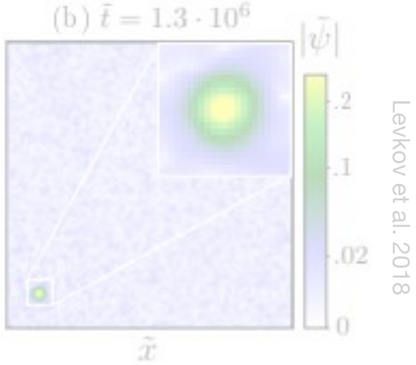


Dynamical effects



Levkov et al. 2018

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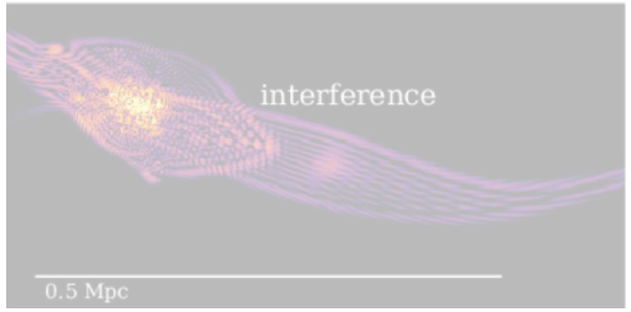
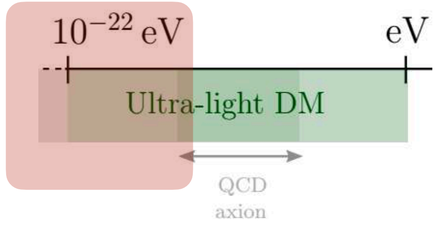


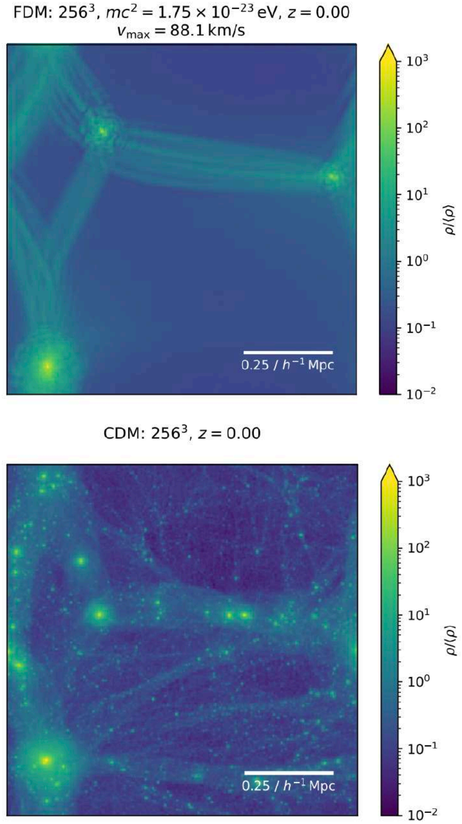
Mocz et al. 2017

Phenomenology

Suppression of small structures



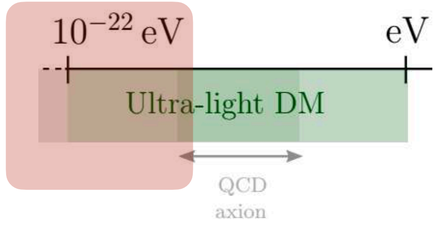
Finite Jeans length λ_J or λ_{attr}, λ_{rep} ⟶ No small scale structure



S. May et al. 2021

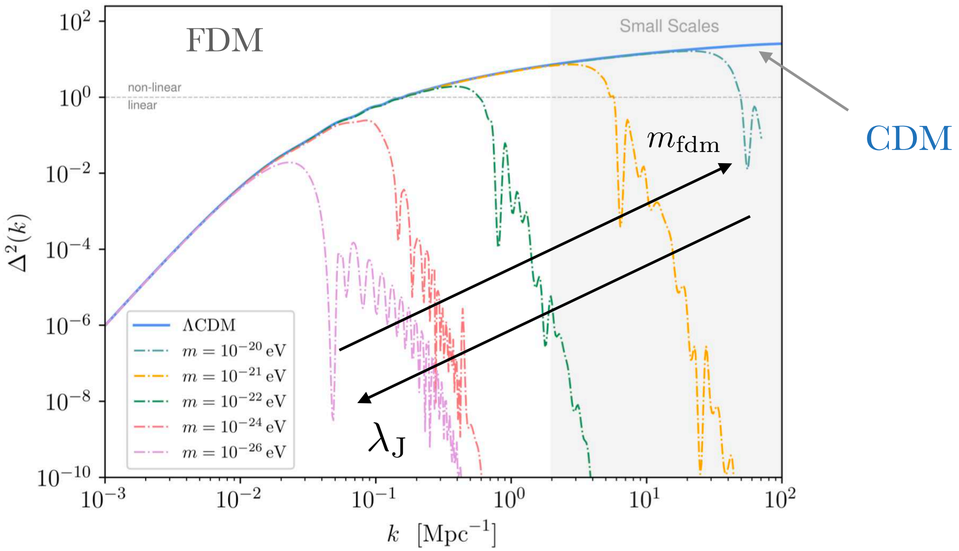
Phenomenology

Suppression of small structures

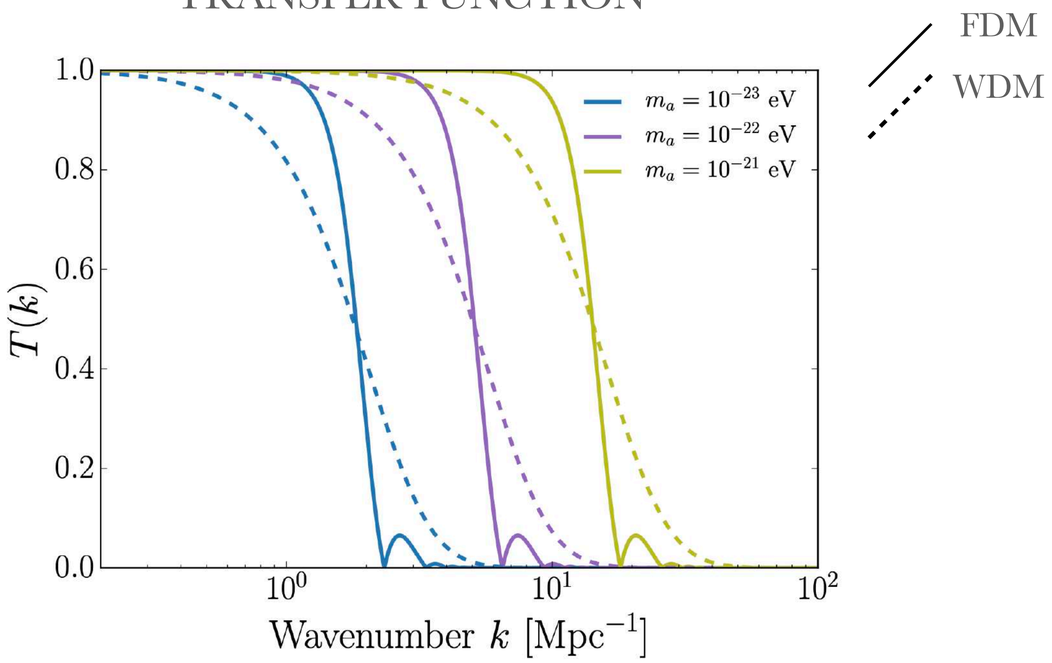


Finite Jeans length λ_J or $\lambda_{attr}, \lambda_{rep}$ ⟶ Suppresses small scale structure

POWER SPECTRUM



TRANSFER FUNCTION



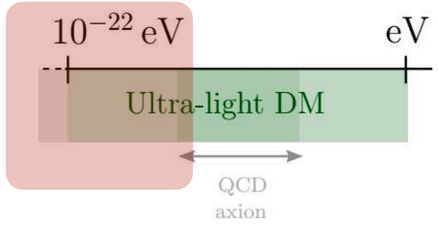
$$P_X(k,z) = T_X^2(k,z)\, P_{\Lambda CDM}(k)$$

$$\begin{cases} T_{WDM} = [1 + (\alpha k)^{2\mu}]^{-5/\mu} \\ T_{FDM} = \frac{\cos x_J^3(k)}{1 + x_J^8(k)} \end{cases}$$

- Degenerate with WDM

Phenomenology

Suppression of small structures



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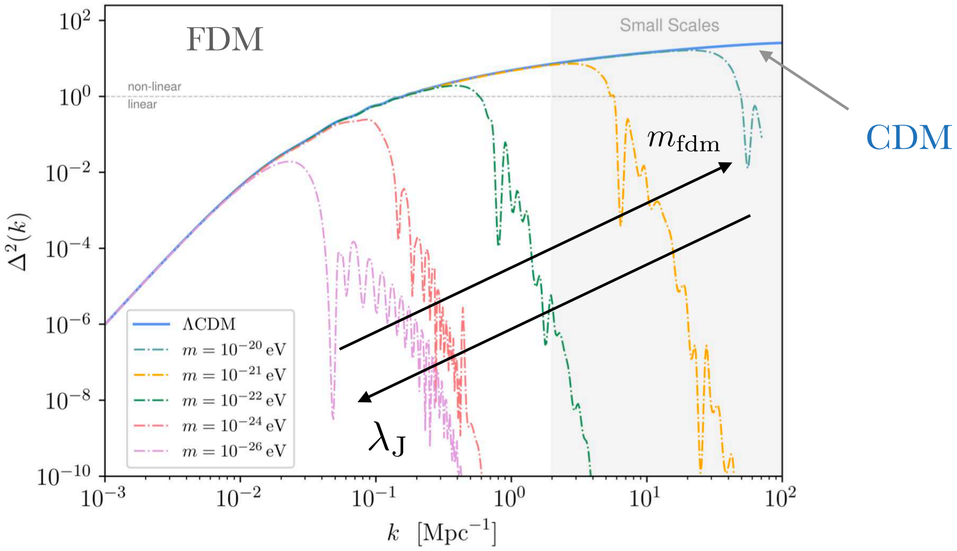
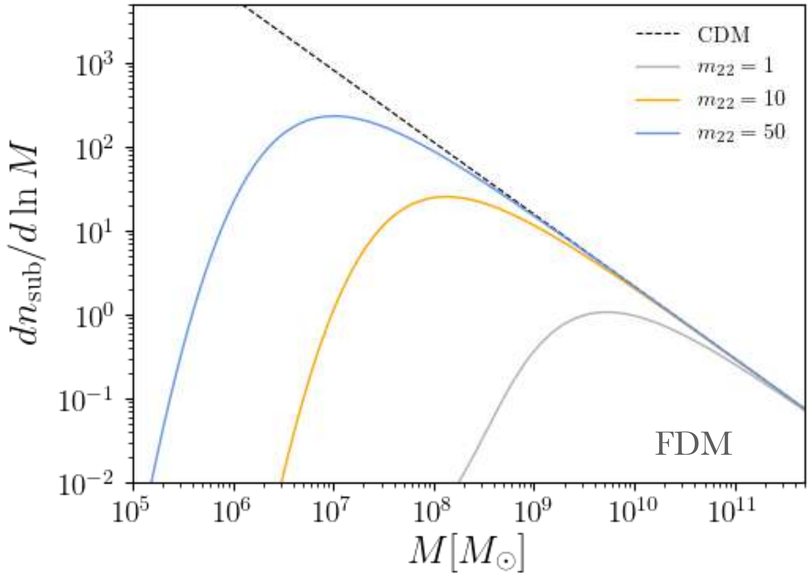
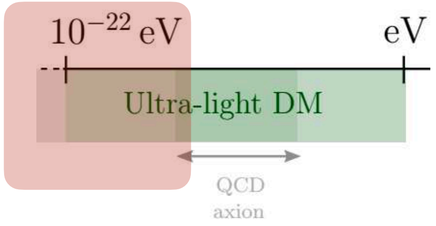


(sub) HALO MASS FUNCTION



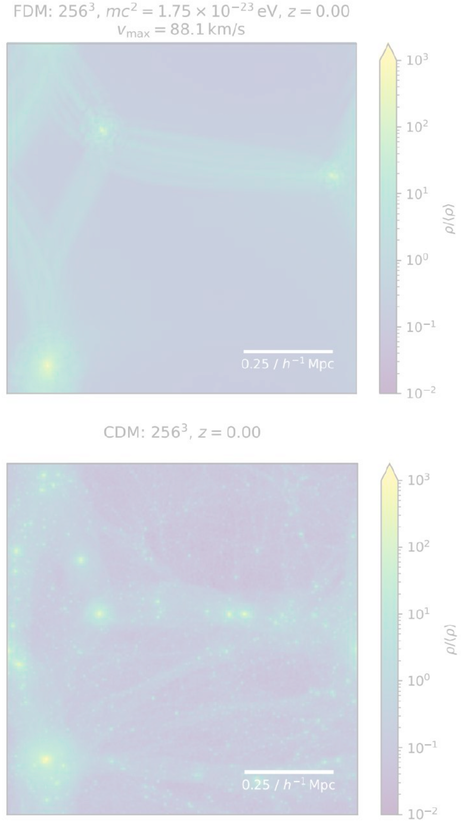
What about the PS from inflation? Practice session!

Phenomenology



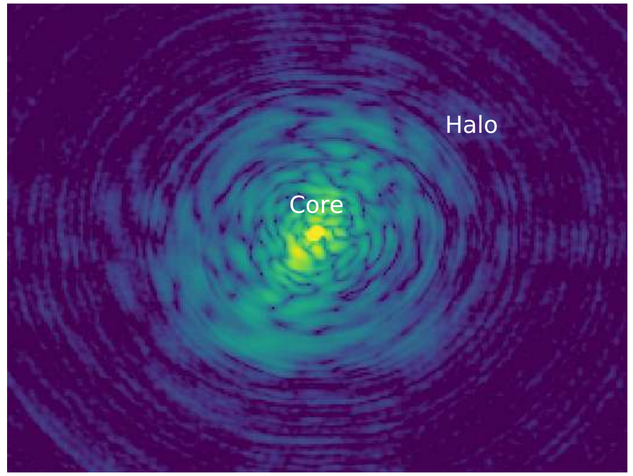
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

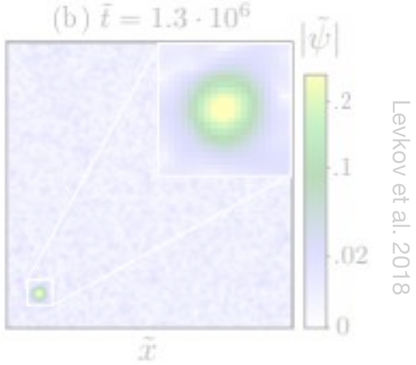


S. May et al. 2021

Formation of a solitonic core

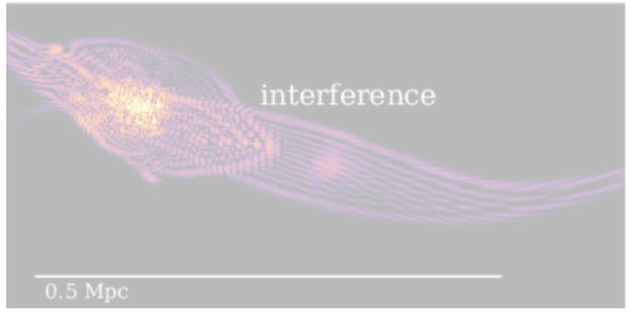


Dynamical effects



Levkov et al. 2018

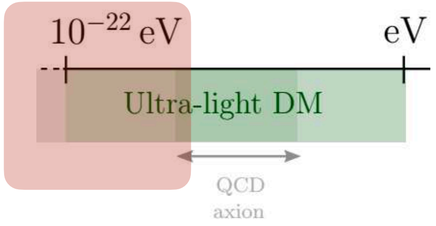
Wave interference



Mocz et al. 2017

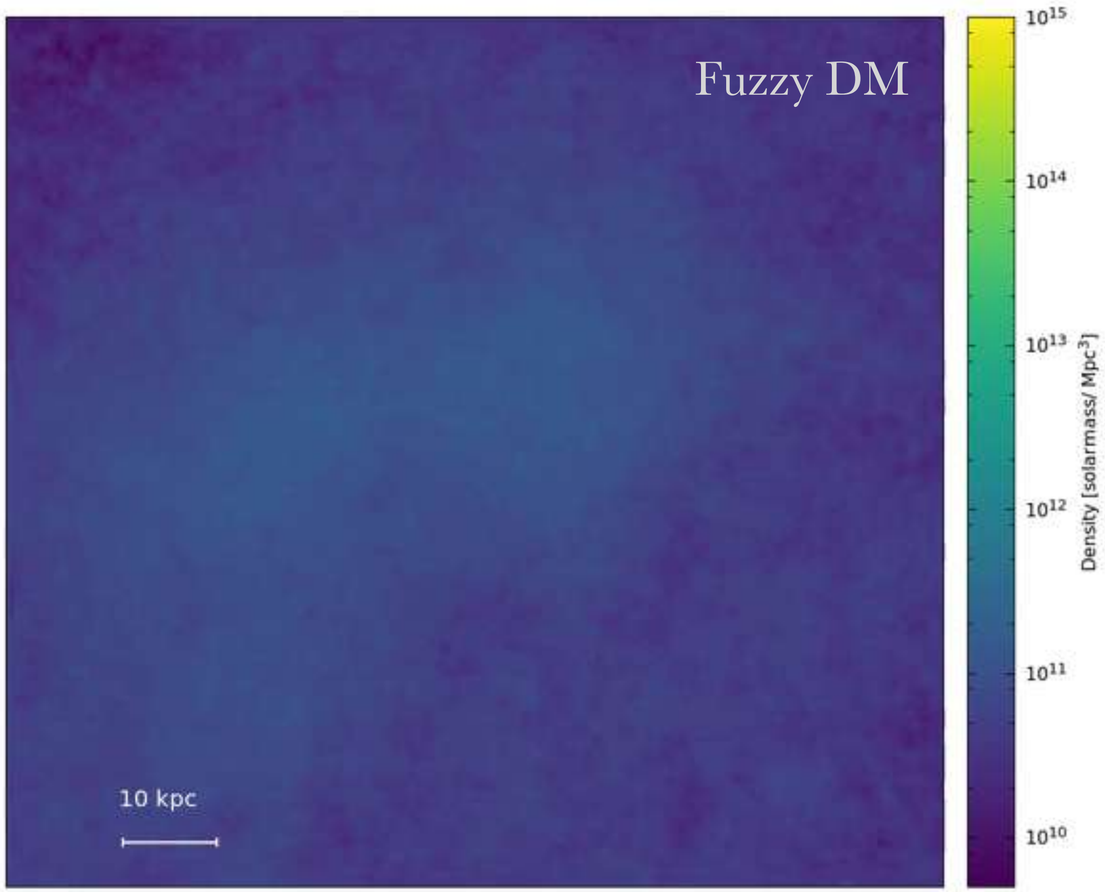
Phenomenology

Formation of cores

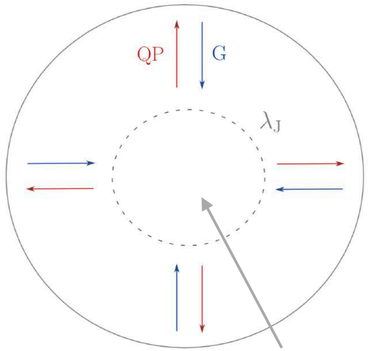


NON-LINEAR evolution: need simulations

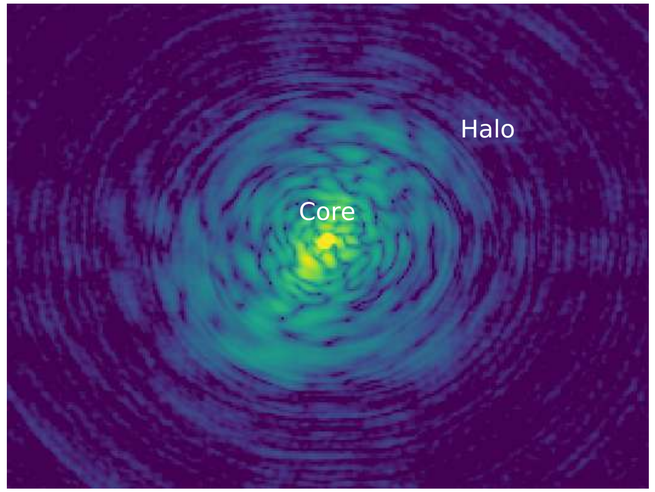
$m = 10^{-22}\,\mathrm{eV}$ $N = 512^3$ $L = 300\,\mathrm{kpc}$



Simulation by Jowett Chan

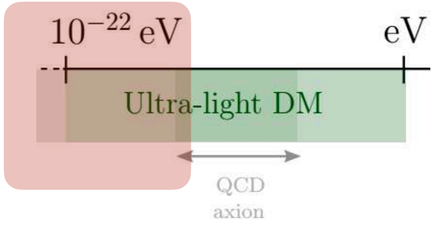


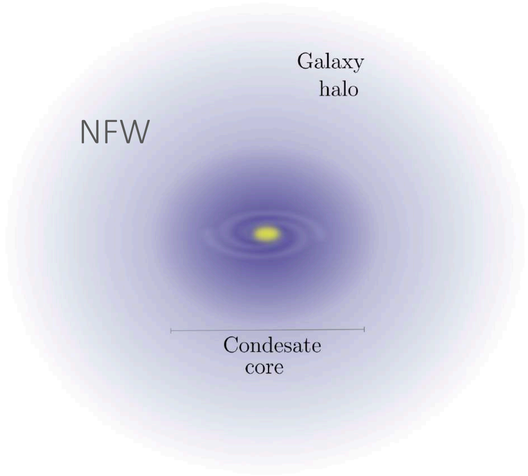
NO structure formation
Stable, oscillating solution



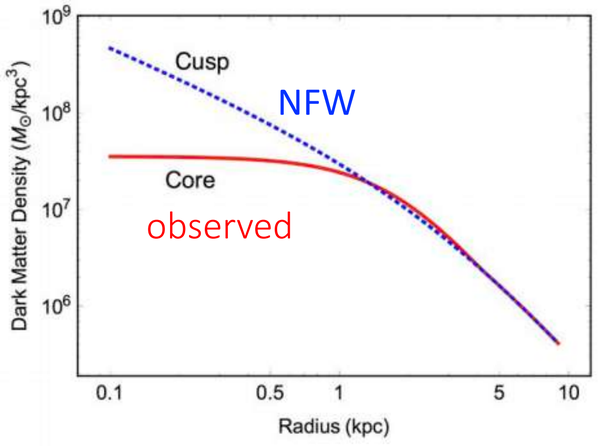
Phenomenology

Formation of cores





$$\rho(r) \simeq \begin{cases} \rho_c & \text{for } r \leq r_c \\ \rho_{\rm NFW} & \text{for } r \geq r_c \end{cases}$$



FDM

From simulations Schive et al. 2014, fitting function:

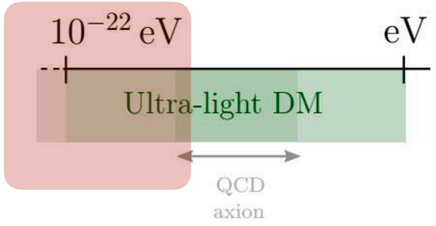
Stable core solution

$$\rho_c \simeq \frac{1.9 \times 10^{-2}}{[1 + 0.091\,(r/R_{1/2,c})^2]^8} \left(\frac{m}{10^{-22}\,\text{eV}}\right)^{-2} \left(\frac{r_c}{\text{kpc}}\right)^{-4} M_\odot\,\text{pc}^{-3}\,,$$

$$r_c \simeq 0.16 \left(\frac{m}{10^{-22}\,\text{eV}}\right)^{-1} \left(\frac{M}{10^{12}\,M_\odot}\right)^{-1/3} \text{kpc}\,.$$

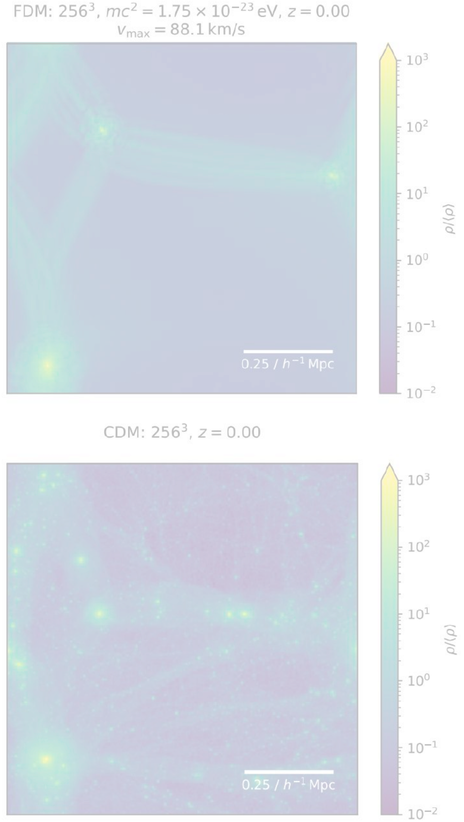
$\longrightarrow$ Relations used to compare with observations

Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures



S. May et al. 2021

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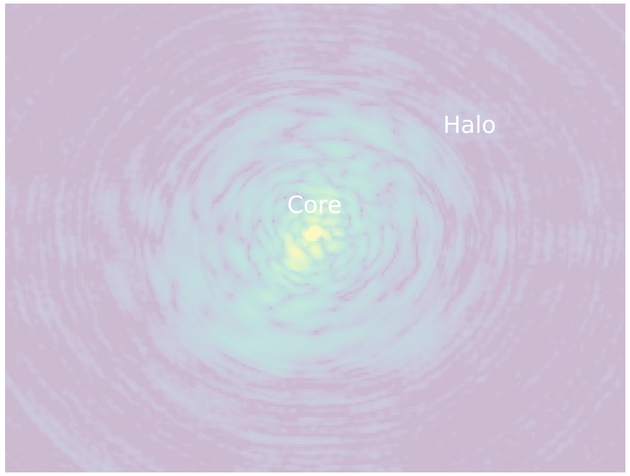
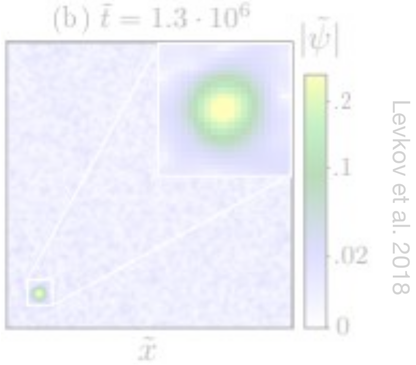
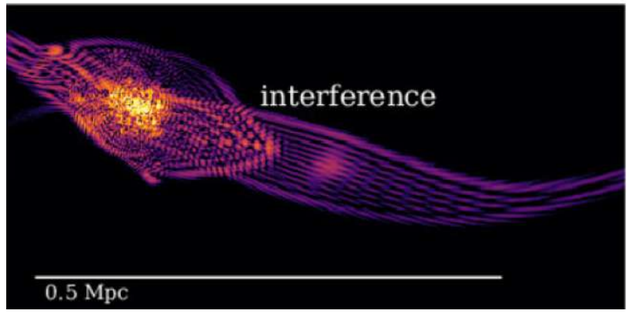


Dynamical effects



Levkov et al. 2018

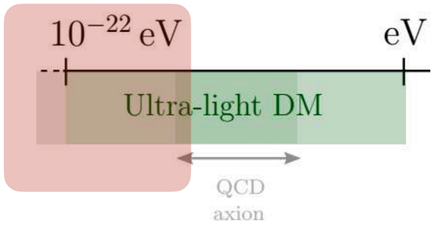
Wave interference

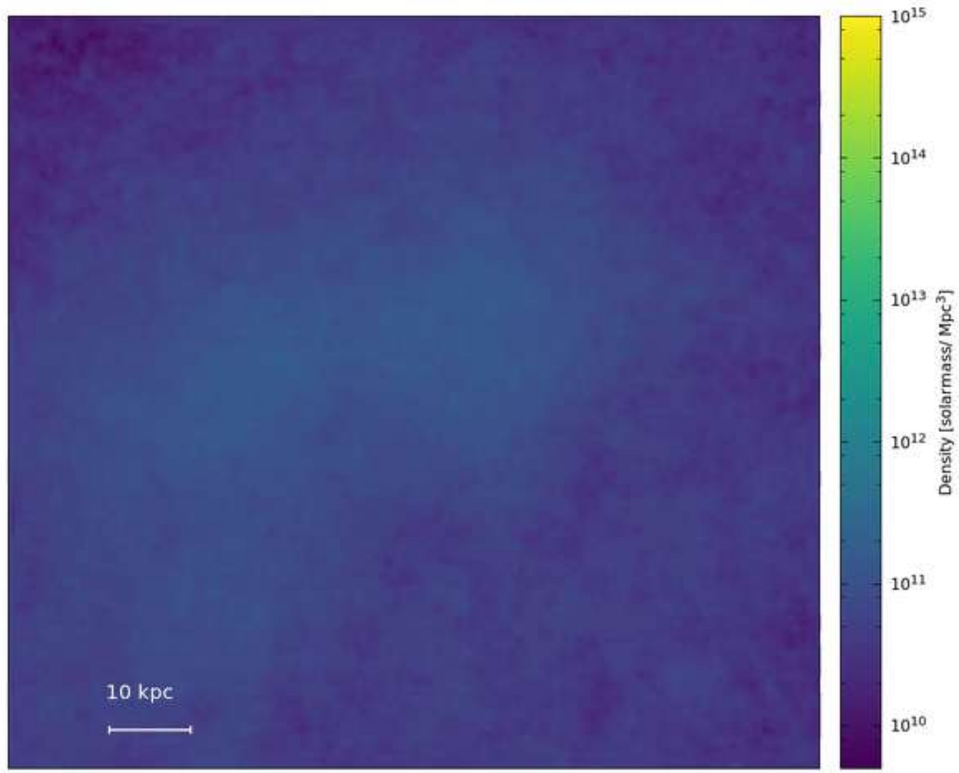


Mocz et al. 2017

Phenomenology

Wave interference: granules and vortices





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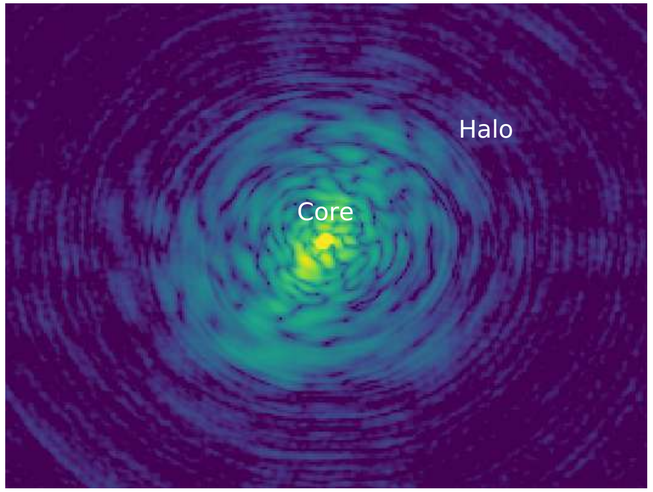
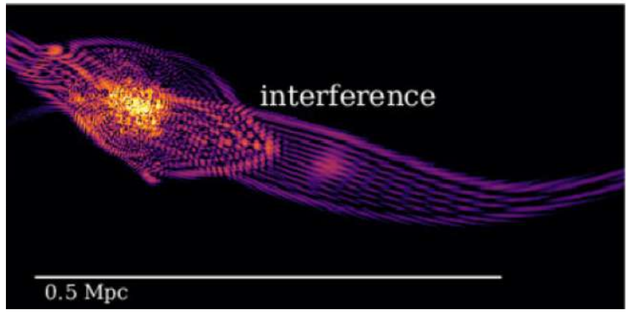




Mocz et al. 2017

Order one fluctuations in density $\longrightarrow$ Constructive interference: granules
Destructive interference

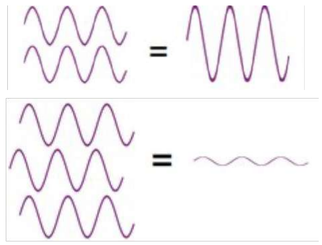
$\hookrightarrow \sim \lambda_{\rm dB}$ Hard to observe!

Vector, higher spin or multicomponent FDM

ULDM or ULA are a coherent wave - same frequency and constant phase difference

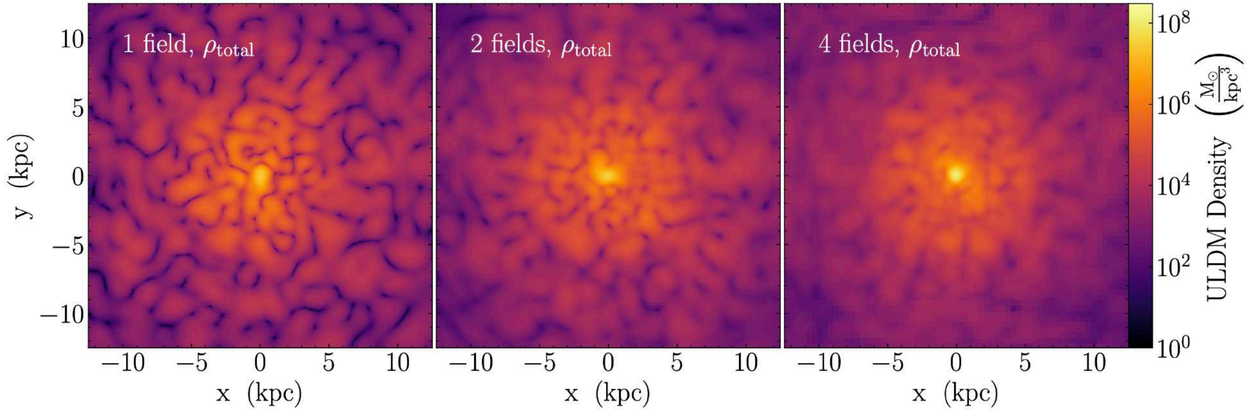
Multiple coherent waves

Interference patterns



For ULDM:

Gonseca et al 2023



Multiple FDM or VFDM (or higher spin s FDM) *attenuates* the granule amplitude by

$$\frac{[\delta\rho/\rho]_{\rm nfdm,s}}{[\delta\rho/\rho]_{\rm fdm}} \propto \frac{1}{\sqrt{(2s+1)}} = \frac{1}{\sqrt{N}}$$

(Amin et al 2022)

Vector (and higher-spin) FDM Amin et al 2022

(Vector FDM = 3 x same mass FDM (spin 0))

Multicomponent FDM Gonseca et al 2023

Phenomenology

Vortices

Vortices are sites where the fluid velocity has a non-vanishing curl

Two ways:
- regions where the density vanishes
- transfer of angular momentum (superfluids only)

$$(\psi \equiv \sqrt{\rho/m}\, e^{i\theta} \;\text{ and }\; \mathbf{v} \equiv \nabla\theta/m)$$

$$\dot{\rho} + \nabla \cdot (\rho\, \mathbf{v}) = 0$$

$$\dot{\mathbf{v}} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - P_{int} - \frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

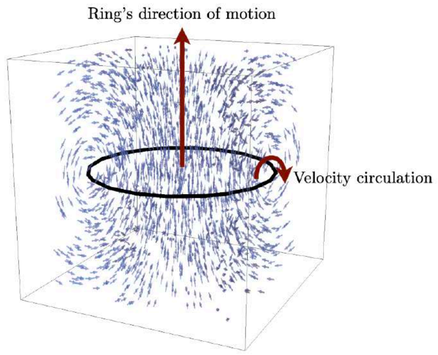
Vel. field is a gradient flow $\longrightarrow$ irrotational fluid, no vorticity

Fuzzy DM

Interference of waves leads to vortices - where there is destructive interference

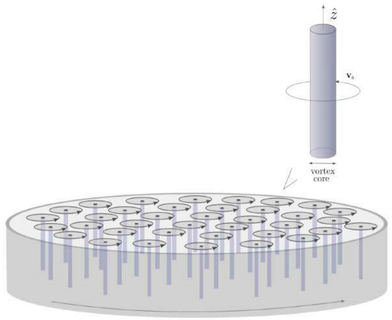
General defet in 3D

$$\mathcal{C} = \frac{1}{m}\oint_{\partial A} \mathrm{d}\theta = \frac{2\pi n}{m}$$

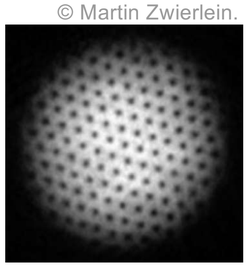


Self-interacting Fuzzy DM

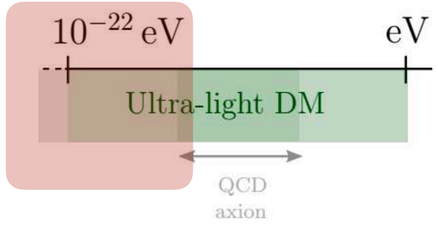
Superfluid cannot rotate uniformly. If the superfluid rotates faster than the critical vel., network of vortices are formed.



EF, 2020

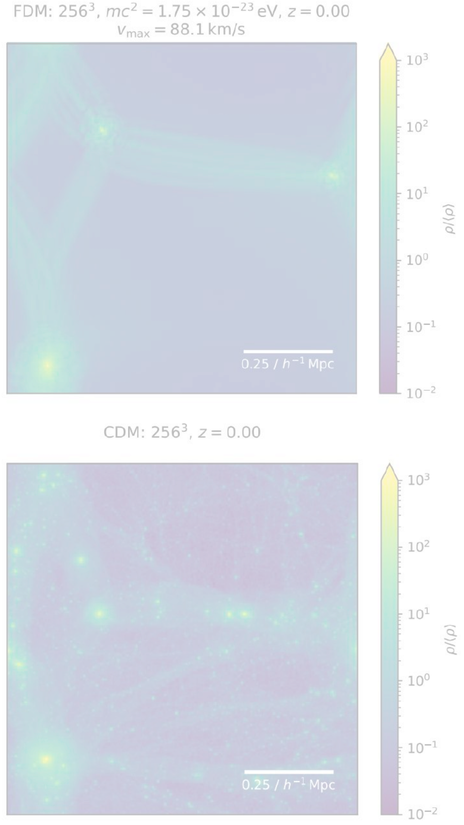


Phenomenology



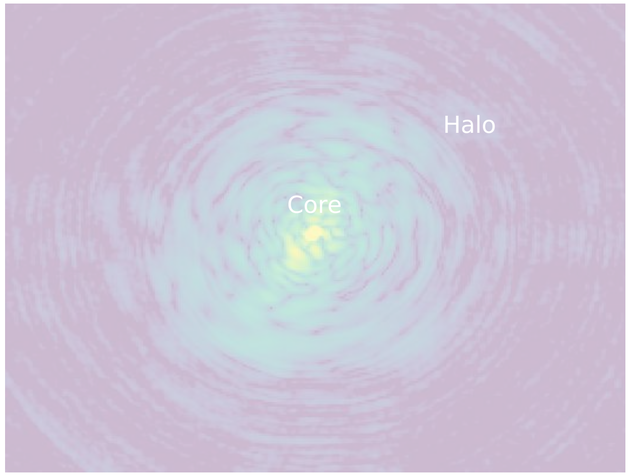
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

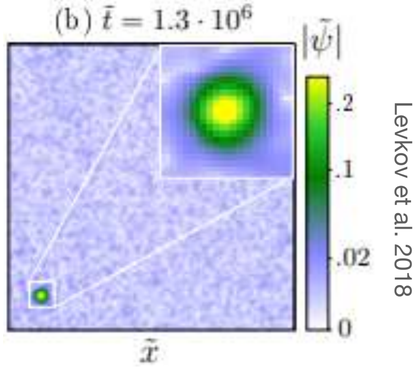


S. May et al. 2021

Formation of a solitonic core

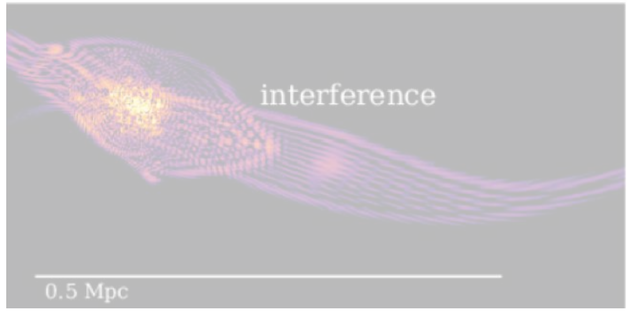


Dynamical effects



Levkov et al. 2018

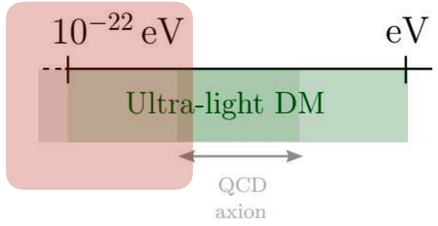
Wave interference



Mocz et al. 2017

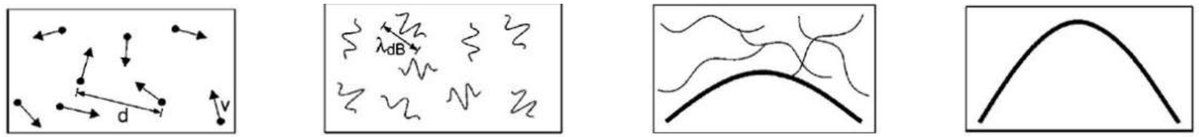
Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

Bose Einstein Condensate



High temperature
Thermal velocities

Low temperature
$\lambda_B \sim T^{-1/2}$
"wave packets"

$T = T_c$
BEC
"matter wave overlap"
$d \sim \lambda_{dB}$

$T = 0$
Pure BEC
"giant matter wave"

- Bose Einstein condensate (BEC): macroscopic occupation of the ground state
- At low temperatures, each particle wave function overlap - single wave function describes the entire fluid.

Superfluid

- Appears at low T after the superfluid condenses into a BEC.
- Effective dynamics: fluid flows without friction

Description

Mean field approximation:
Large N, dilute

$$\hat{\Psi}(\mathbf{r},t) = \psi(\mathbf{r},t) + \delta\hat{\Psi}(\mathbf{r},t)$$

classical field
"wavefunction of the condensate"

small perturbation: describes depletion of the condensate

with $\psi(\mathbf{r},t) = \langle\hat{\Psi}(\mathbf{r},t)\rangle$

Fixed $n_0 = |\psi(\mathbf{r},t)|^2$

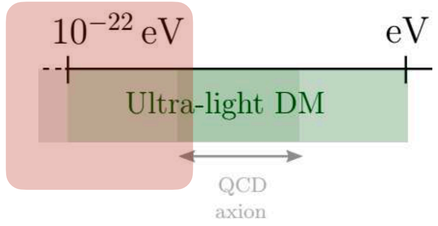
Credit: Peking University

$$i\partial_t\psi(\mathbf{r},t) = \left(-\frac{\nabla^2}{2m} + V_{trap}(\mathbf{r}) + U_0|\psi(\mathbf{r},t)|^2\right)\psi(\mathbf{r},t)$$

Non-linear Schrödinger equation - Gross-Pitaevskii equation

Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

Formation of a BEC / superfluid

- Thermalization (and condensation) *seem* to happen inside the galaxy!
Formation of a soliton (ground state) or Bose star in the interior of galaxies

A. Guth M. Hertzberg, C. Prescod-Weinstein (2014)

- Formation of a condensate and a core occur from gravitational interaction.

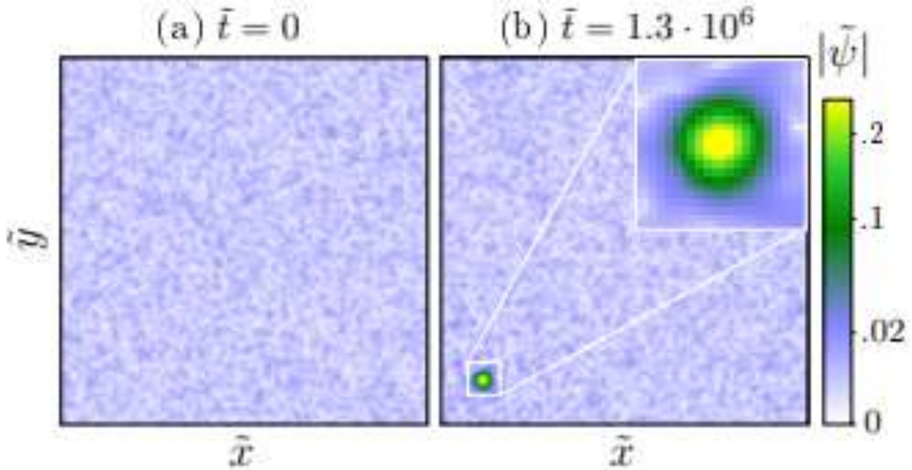
Condensation/relaxation time: $\tau_{\rm gr} \gg \tau_{\rm int}$

$$\tau_{\rm gr} \sim 10^6\,{\rm yr}\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^3\left(\frac{v}{30\,{\rm km/s}}\right)^6\left(\frac{\rho}{0.1\,M_\odot/{\rm pc}^3}\right)^{-2}$$

$$\tau_{\rm int} = \frac{1}{\sqrt{8}|g|n}$$

Smaller than the age of the universe!

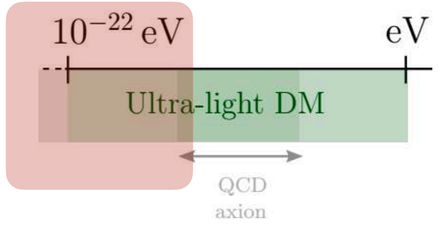
Wave turbulence theory



Levkov et al. 2018, Kirpatrick et al. 2020

Phenomenology

Dynamical effects



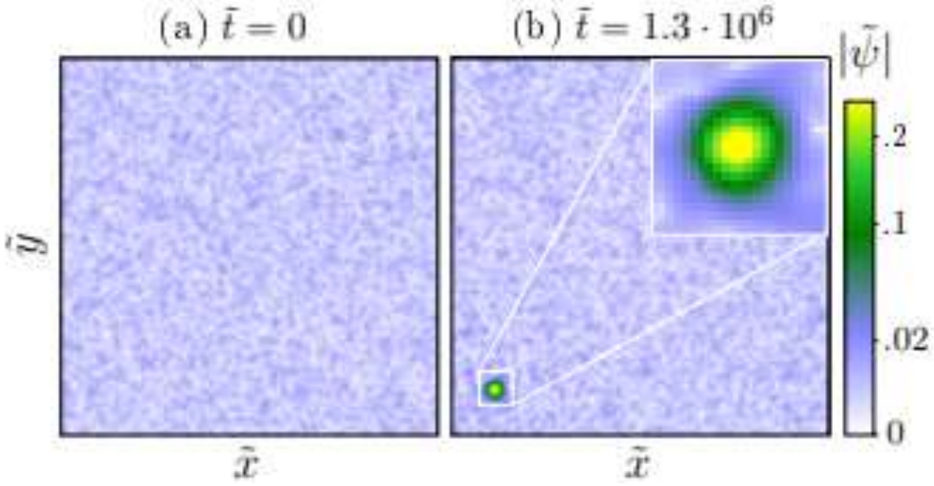
Relaxation, oscillation, friction, and heating

Formation of a BEC / superfluid

Open question!

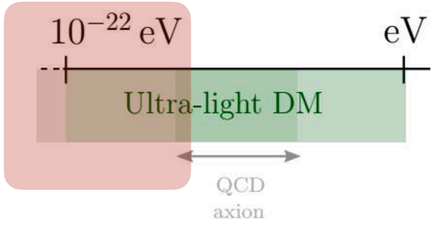
- Need theoretical work to describe *analytically* the formation of these solitons

- Cosmologically, classical or quantum field?

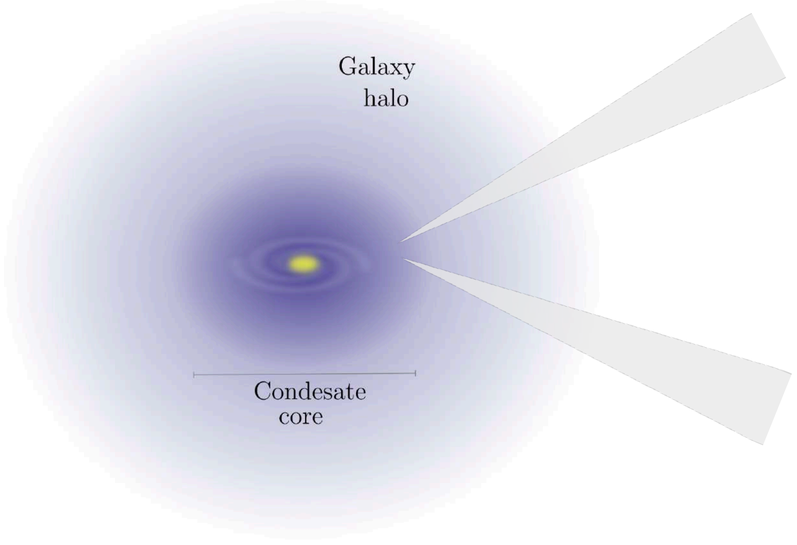


Phenomenology

Dynamical effects



Relaxation, oscillation, <u>friction, and heating</u>

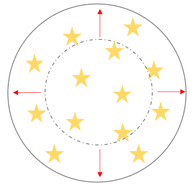


Heating

FDM granule

m_{eff}

System (star)
gains energy



Friction

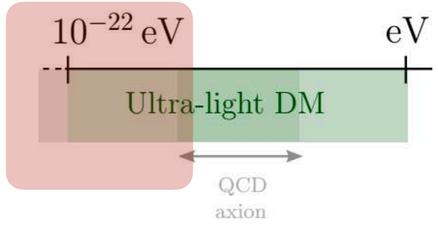
FDM granule

m_{eff}

Globular cluster

System (GC or BH)
loses energy

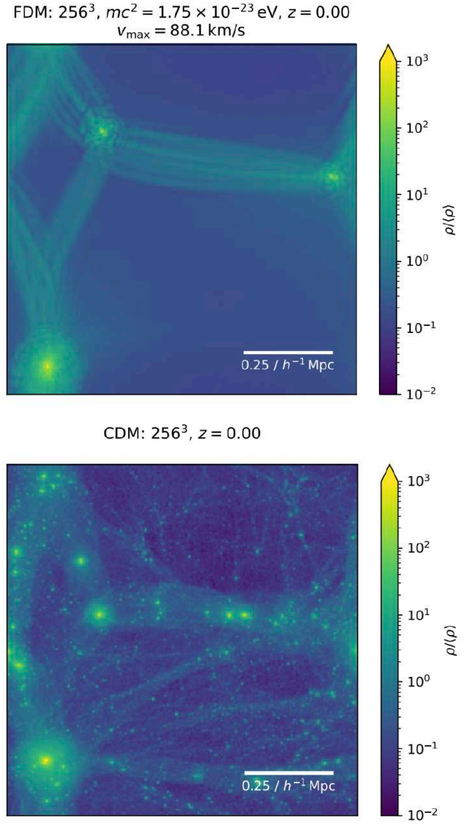
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

* Focus only in gravitational signatures

Suppression of small structures



S. May et al. 2021

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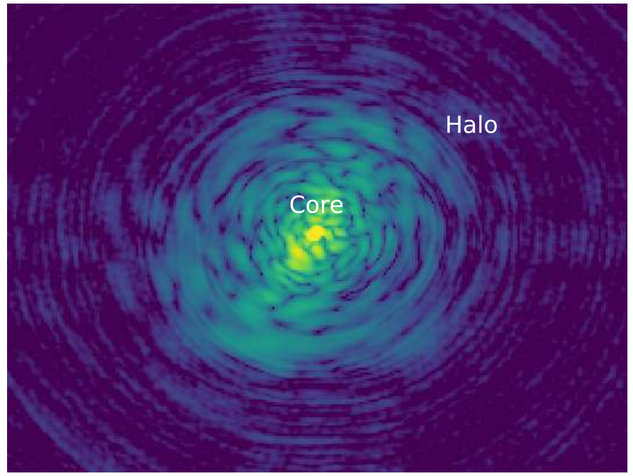
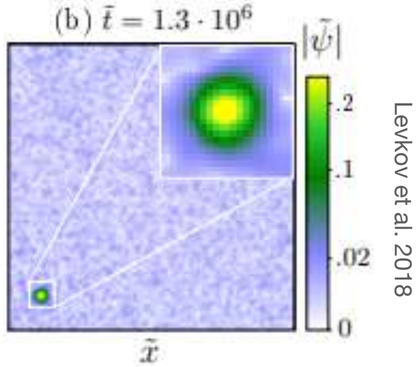
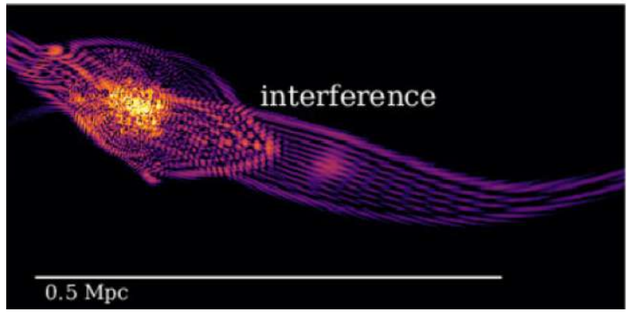


Dynamical effects



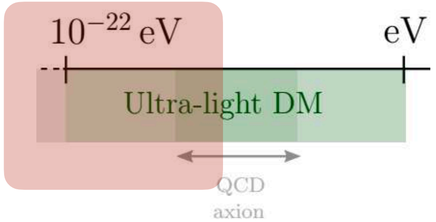
Levkov et al. 2018

Wave interference



Mocz et al. 2017

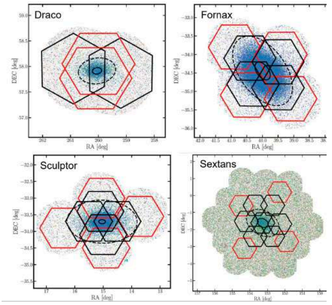
Observational implications and constraints



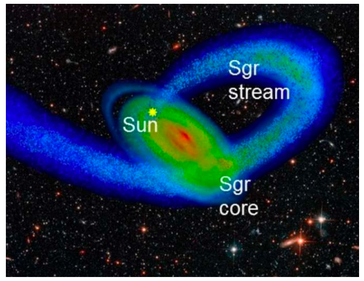
Galaxies

NASA and ESA

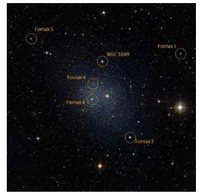
Dwarfs



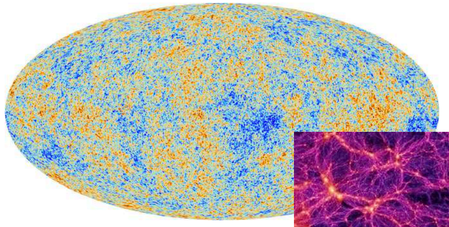
Stellar stream



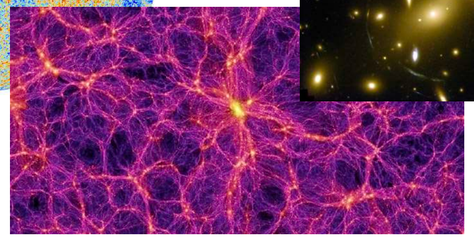
Globular clusters



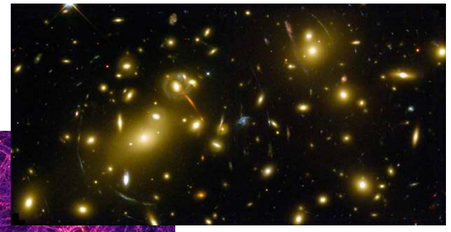
CMB+LSS



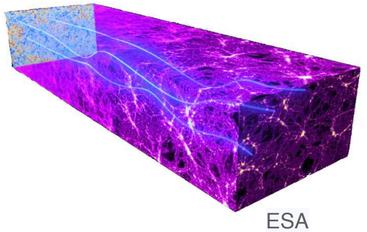
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

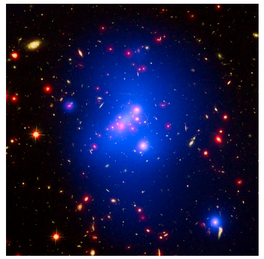


NASA and ESA



ESA

Clusters



CC BY 4.0

interlude

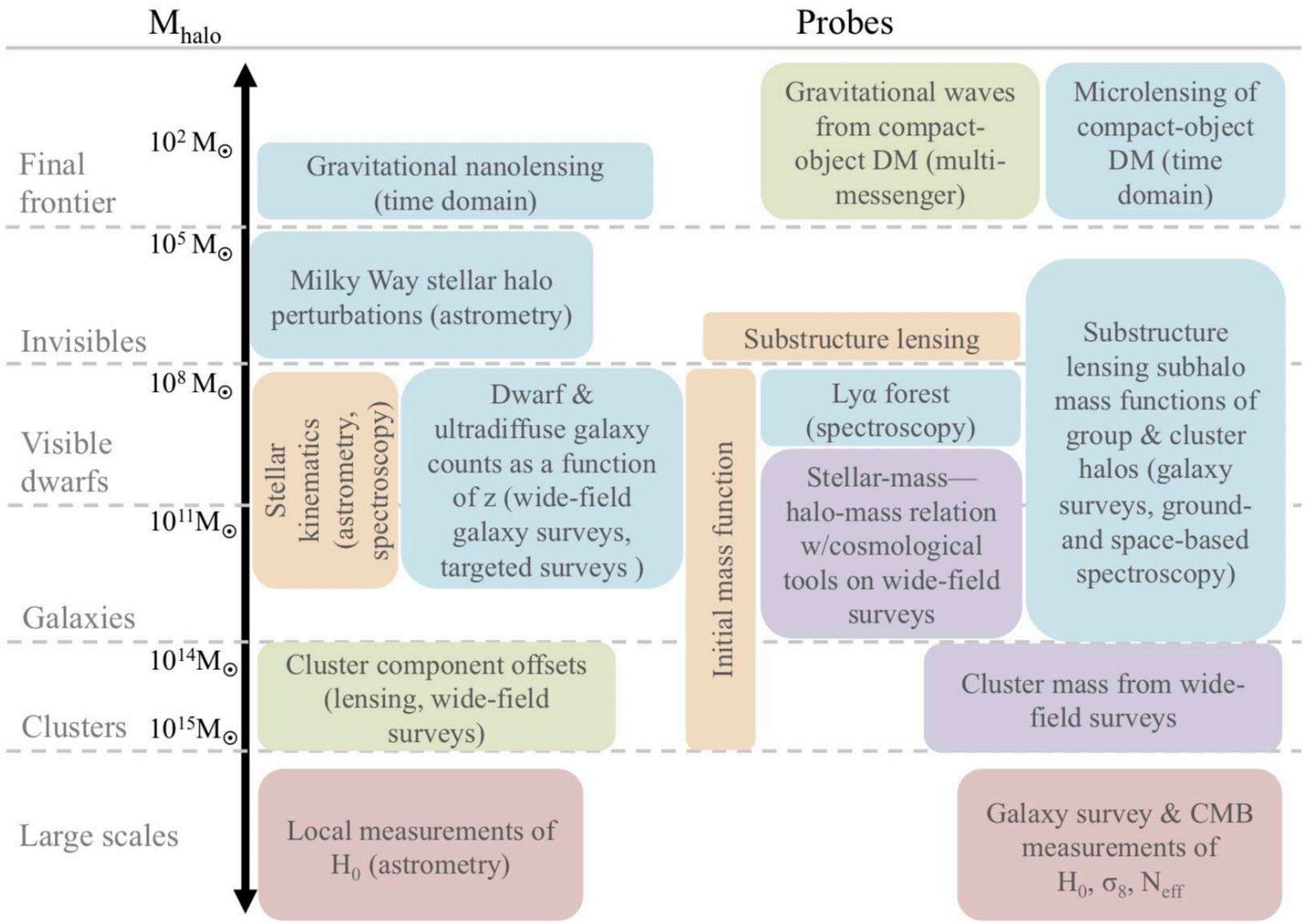
Cosmological and astrophysical ***probes*** *of dark matter*

interlude

Cosmological and astrophysical ***probes*** *of dark matter*

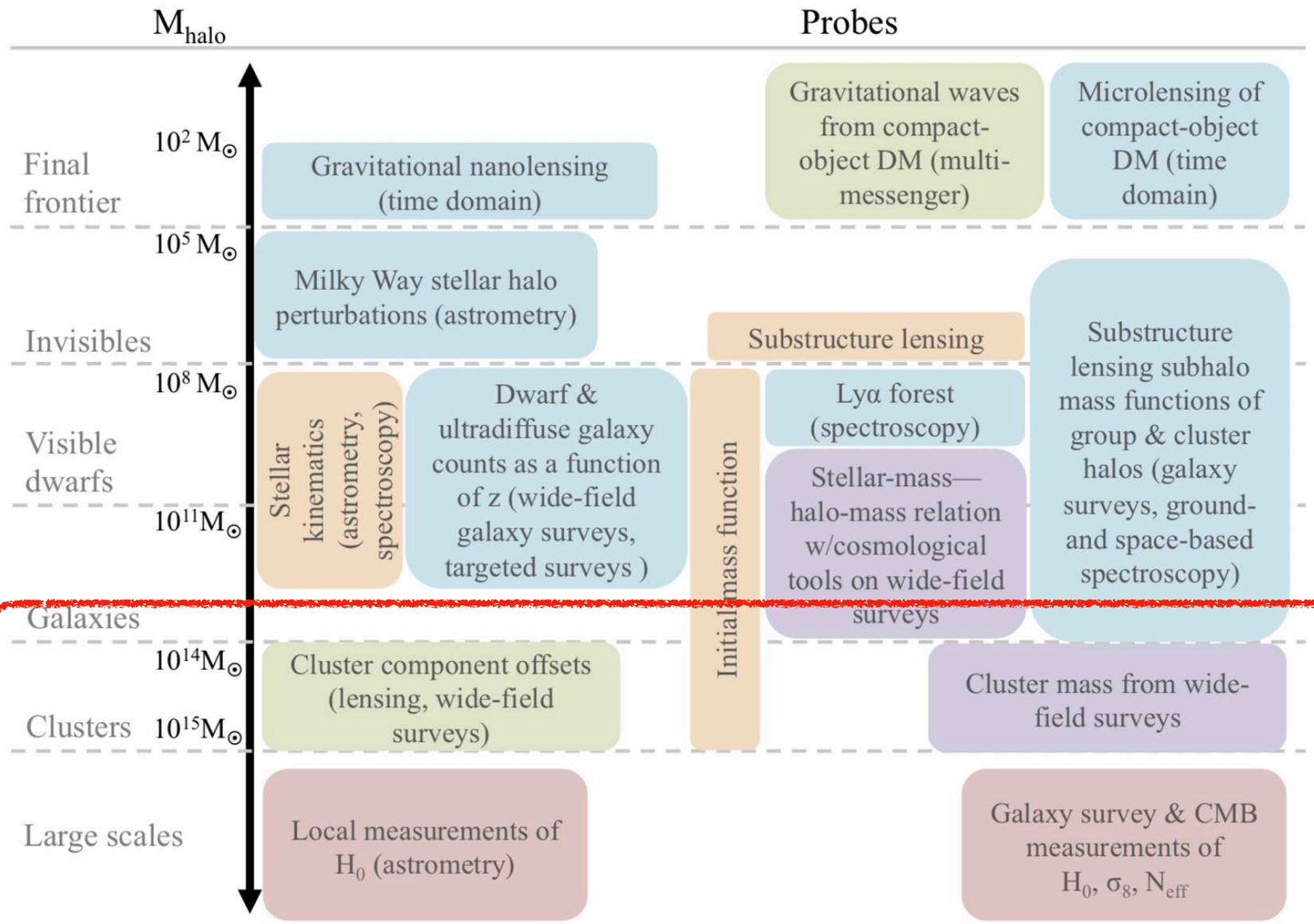
Good reference:
"Gravitational probes of dark matter physics", Matthew R. Buckley , Annika H. G. Peter, 2017

Cosmological and astrophysical ***probes*** *of dark matter*



Buckleya et al 2017

Cosmological and astrophysical ***probes*** *of dark matter*



Planck

SDSS
DES
HSC
KIDS
...

CMB and LSS

Highly constrained

Precise measurements

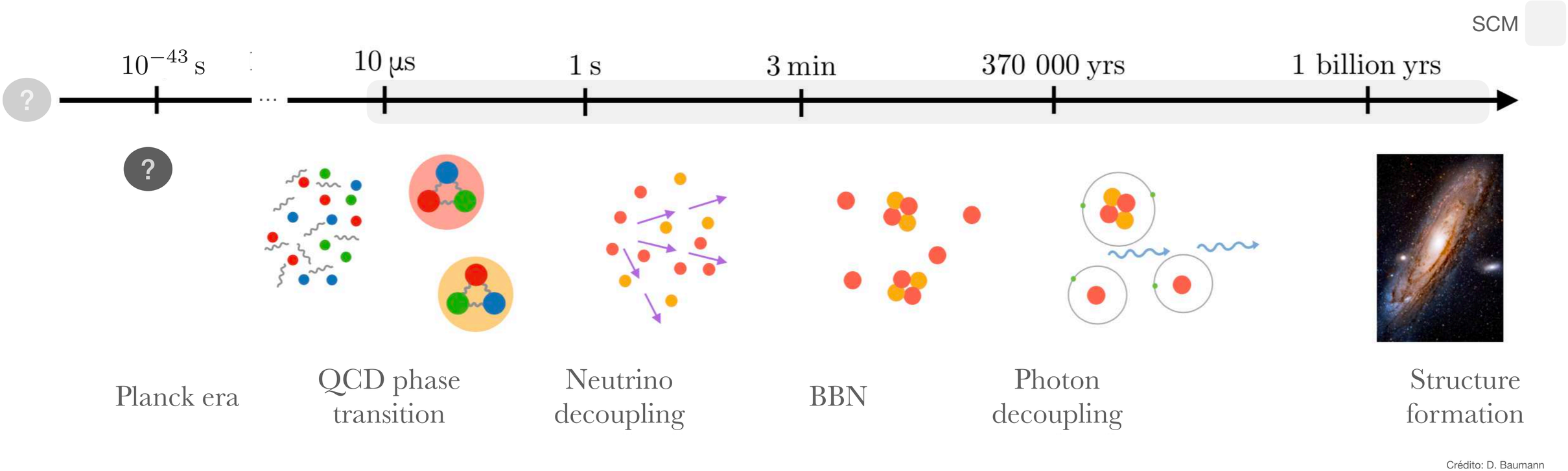
Buckleya et al 2017

Cosmological and astrophysical ***probes*** *of dark matter*

CMB and LSS

Thermal history of the universe

The universe“started" hot e **dense** → As it cools, the structures we know start to form



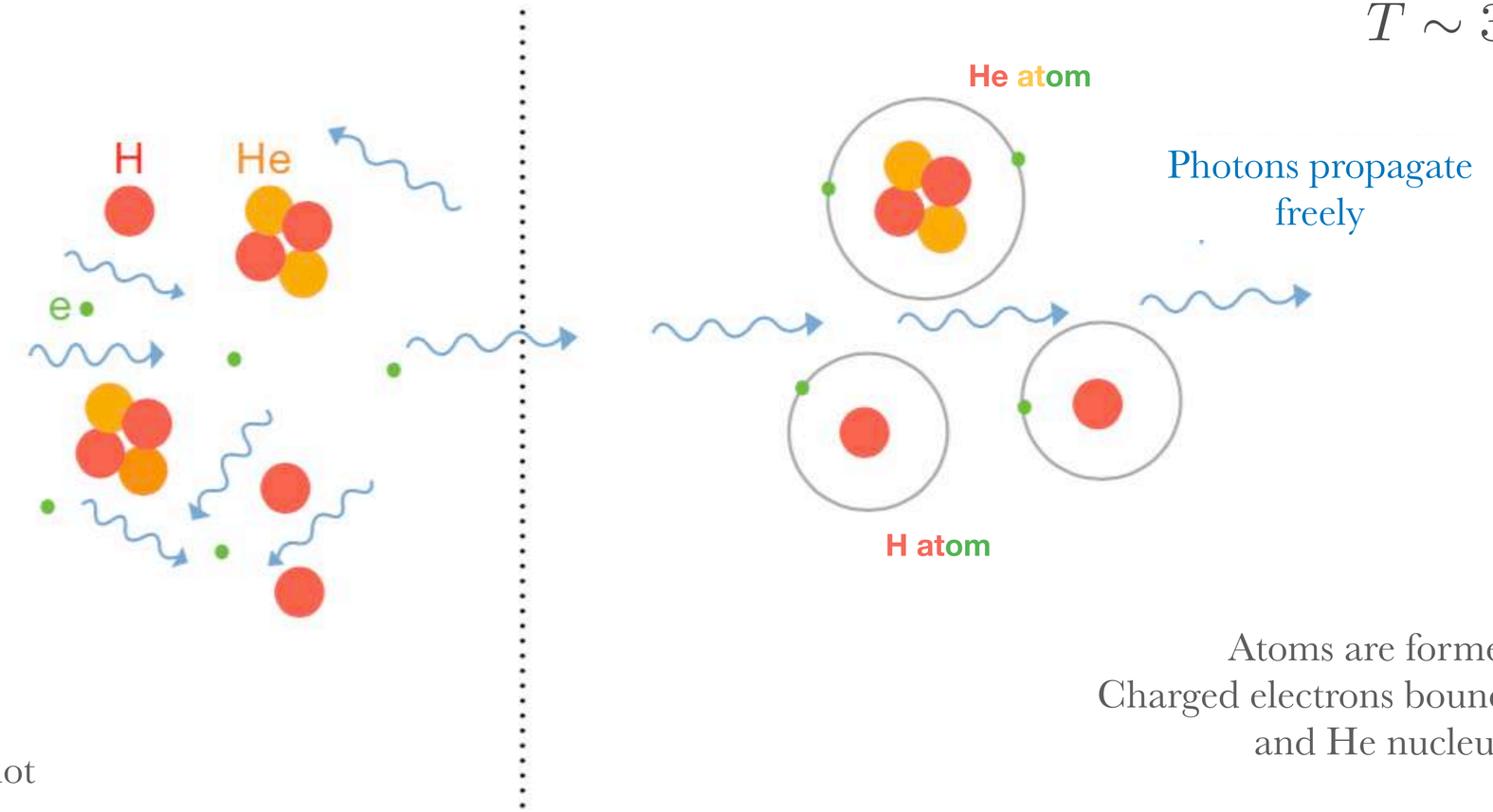
Crédito: D. Baumann

- (Most of them) observationally confirmed by independent measurements

Recombination and photon decoupling

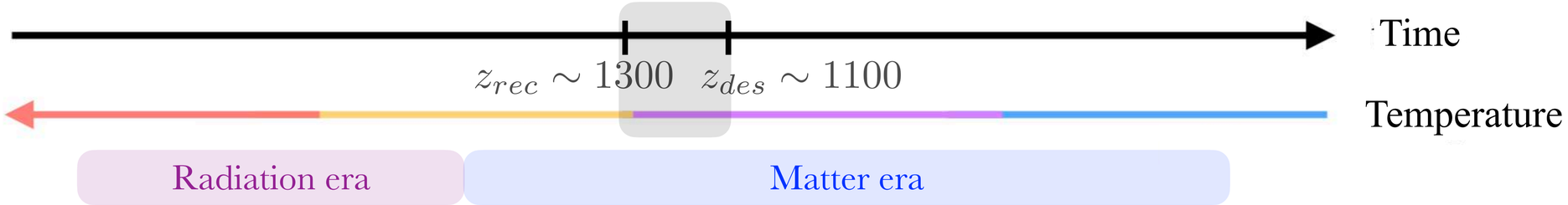
$t \sim 370000\,\text{yrs}$

$T \sim 3000\,\text{K}$



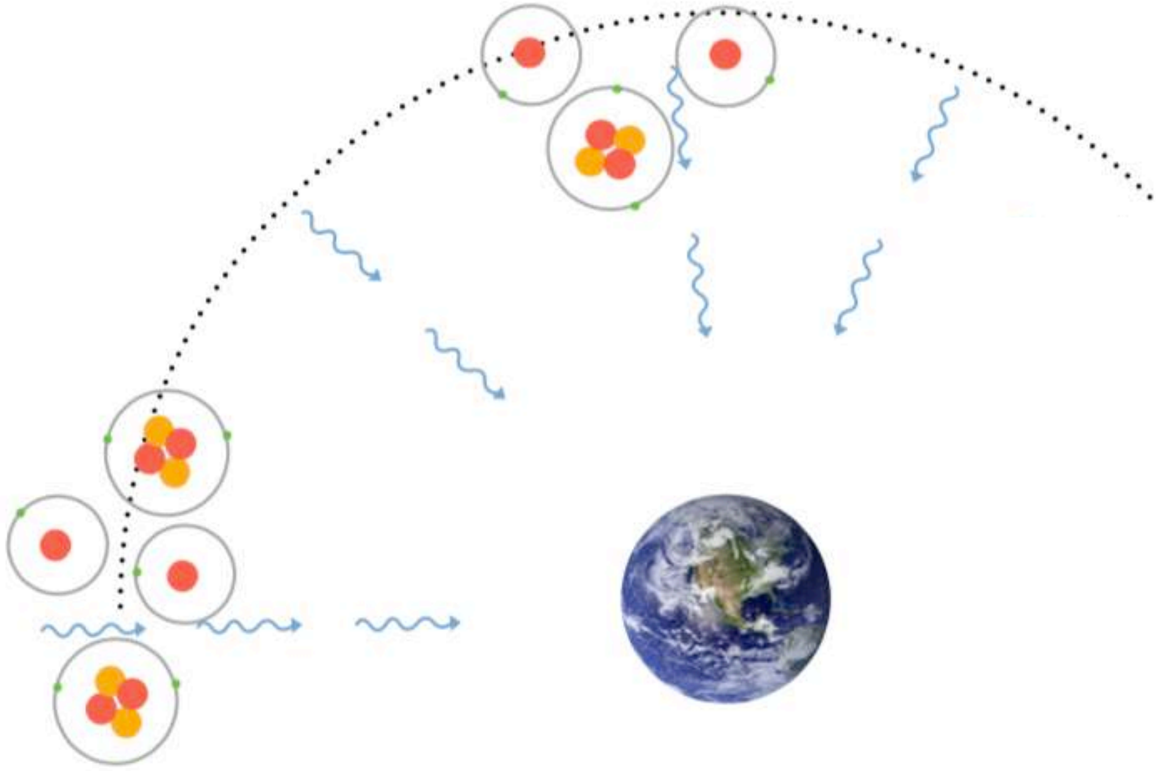
Plasma ("soup") of coupled H, He, elétrons and radiation - thermal equilibrium
- universe is opaque: radiation cannot scape!

Atoms are formed!
Charged electrons bound with n H and He nucleus



Crédito: D. Baumann

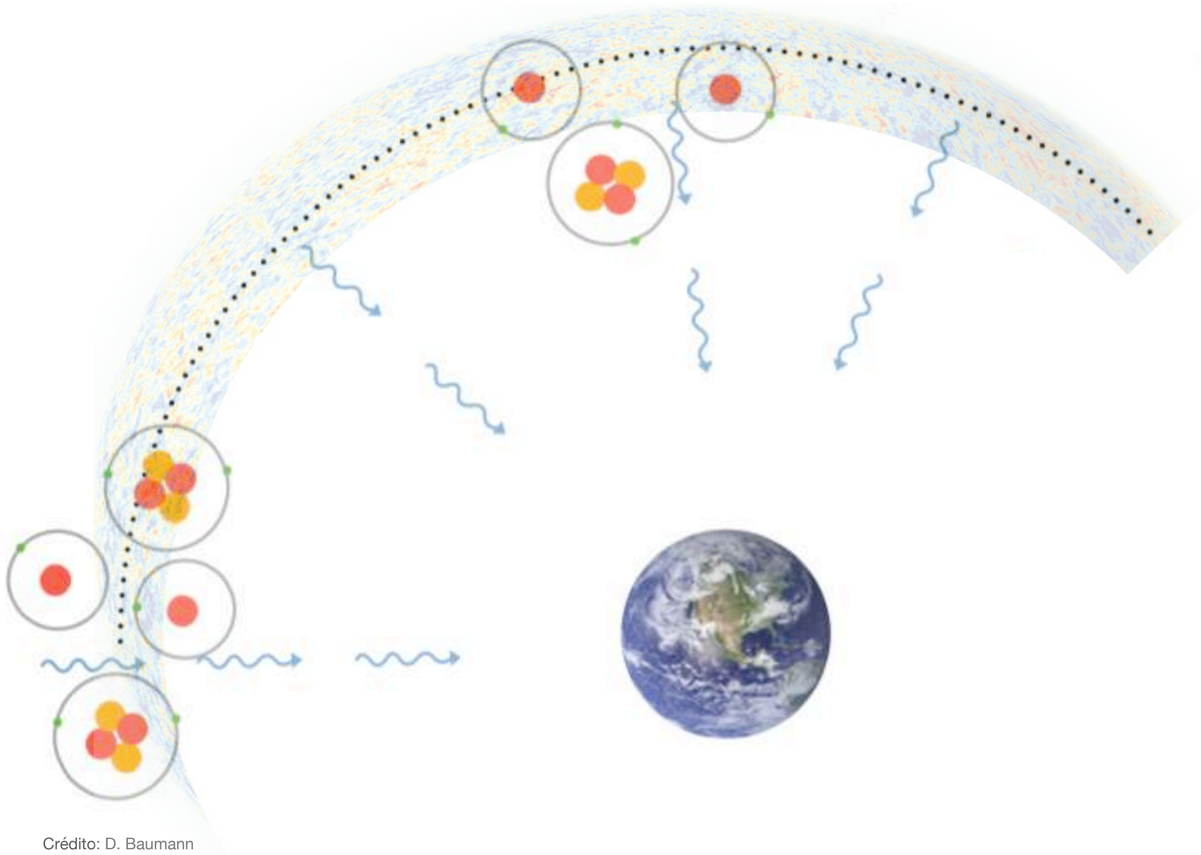
These photons are the first light of our universe…



Crédito: D. Baumann

… e tell us how the universe was at early times.

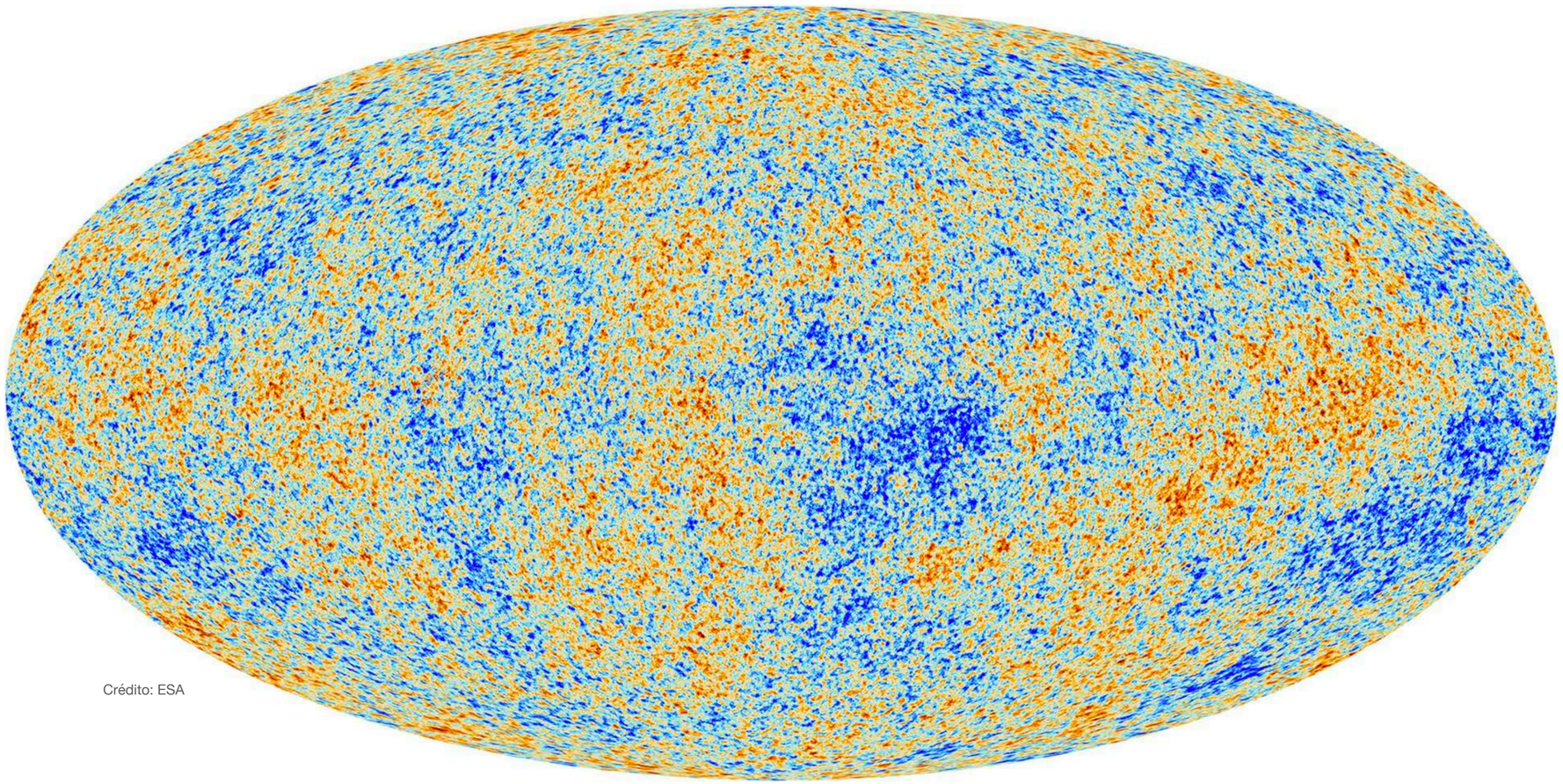
Cosmic **M**icrowave **B**ackground *(CMB)*



Crédito: D. Baumann

Given the expansion of the universe, we observe these photons in microwave.

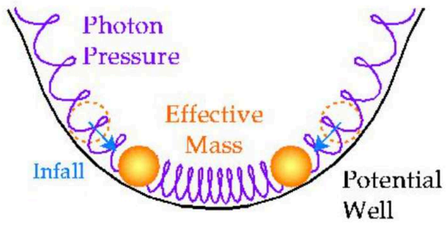
Cosmic **M**icrowave **B**ackground *(CMB)*



Temperature 2.7 K. Small fluctuations - initial condition for the structures of our universe

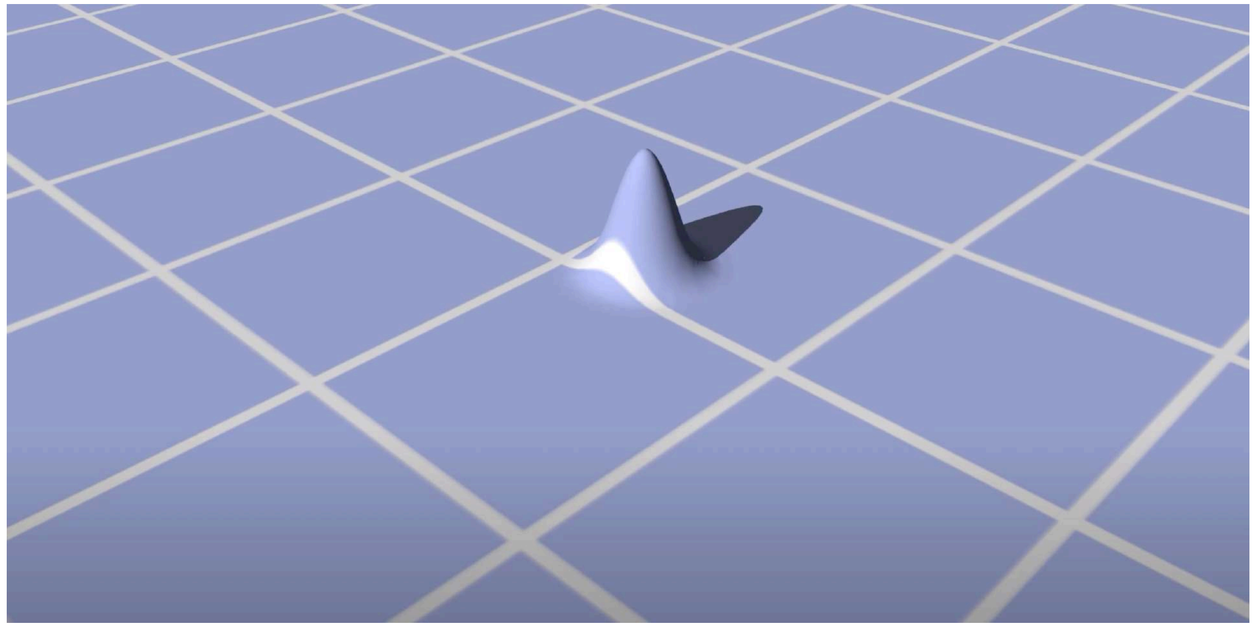
Baryon Acoustic Oscillation (BAO)

- Oscillation in the baryon-photon fluid: pressure vs gravity
- This wave propagates until matter/radiation decoupling
- Its signature is imprinted in the CMB and the distribution of galaxies



(Wayne Hu)

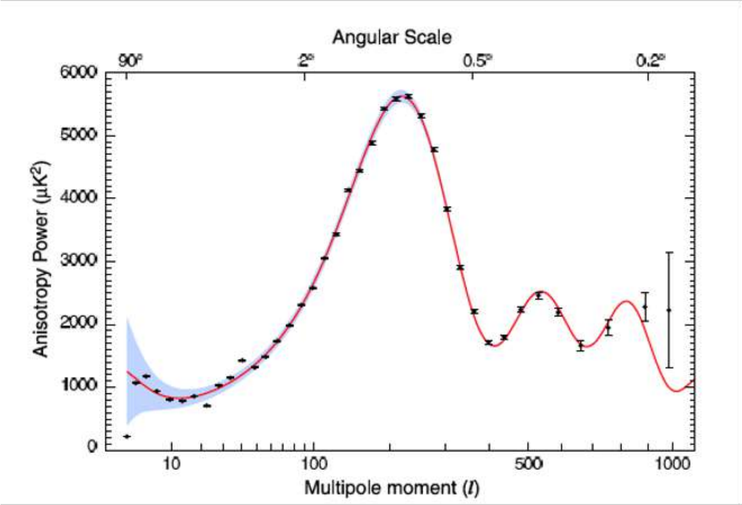
Scale known to 0.2% precision from
CMB power spectrum (147.4±0.3 Mpc)



Crédito: CASTRO

Baryon Acoustic Oscillation (BAO)

Cosmic Microwave Background



Using CMB and other LSS probes, can constraint the parameters with incredible precision.

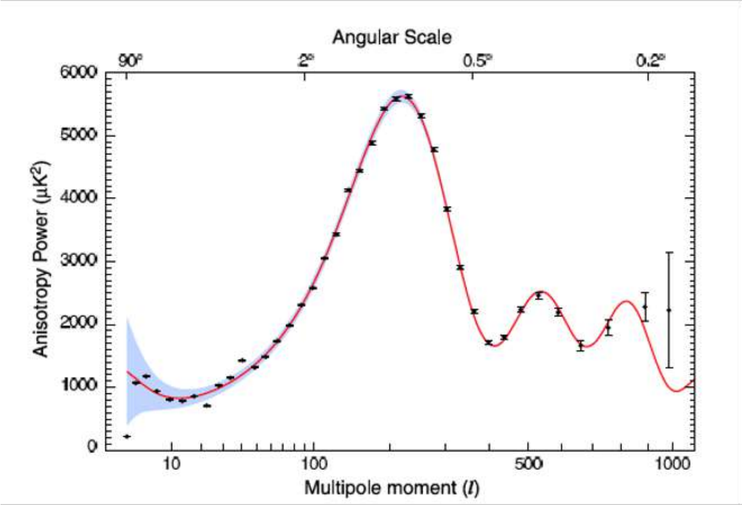
$$\Omega_b = 0.0484 \pm 0.0003$$
$$\Omega_m = 0.308 \pm 0.012$$
$$\Omega_\Lambda = 0.692 \pm 0.012$$
$$\mathrm{n}_s = 0.9626 \pm 0.0057$$
$$10^9\, A_s = 2.092 \pm 0.034$$
$$\tau = 0.0522 \pm 0.0080$$

Scale known to 0.2% precision from CMB power spectrum (147.4±0.3 Mpc)

Standard cosmological model - LCDM model

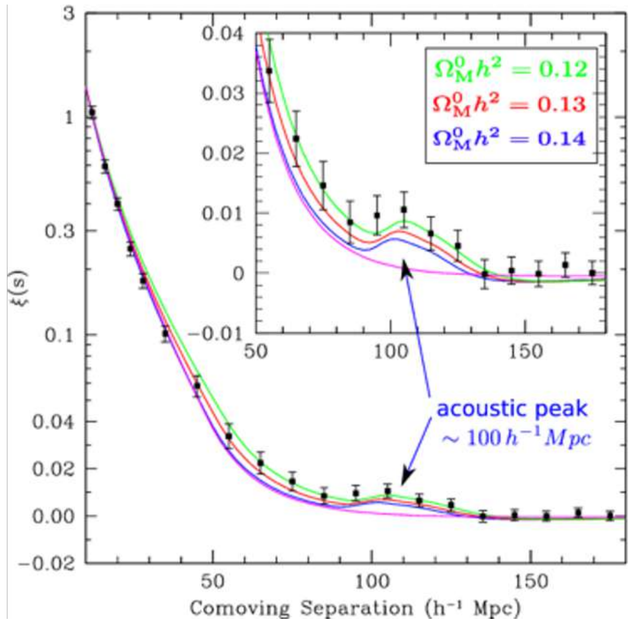
Baryon Acoustic Oscillation (BAO)

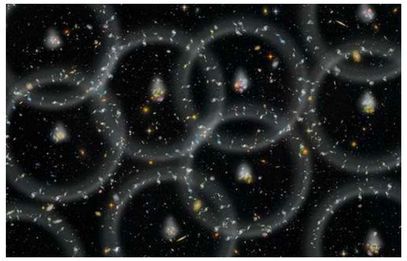
Cosmic Microwave Background



Scale known to 0.2% precision from CMB power spectrum (147.4±0.3 Mpc)

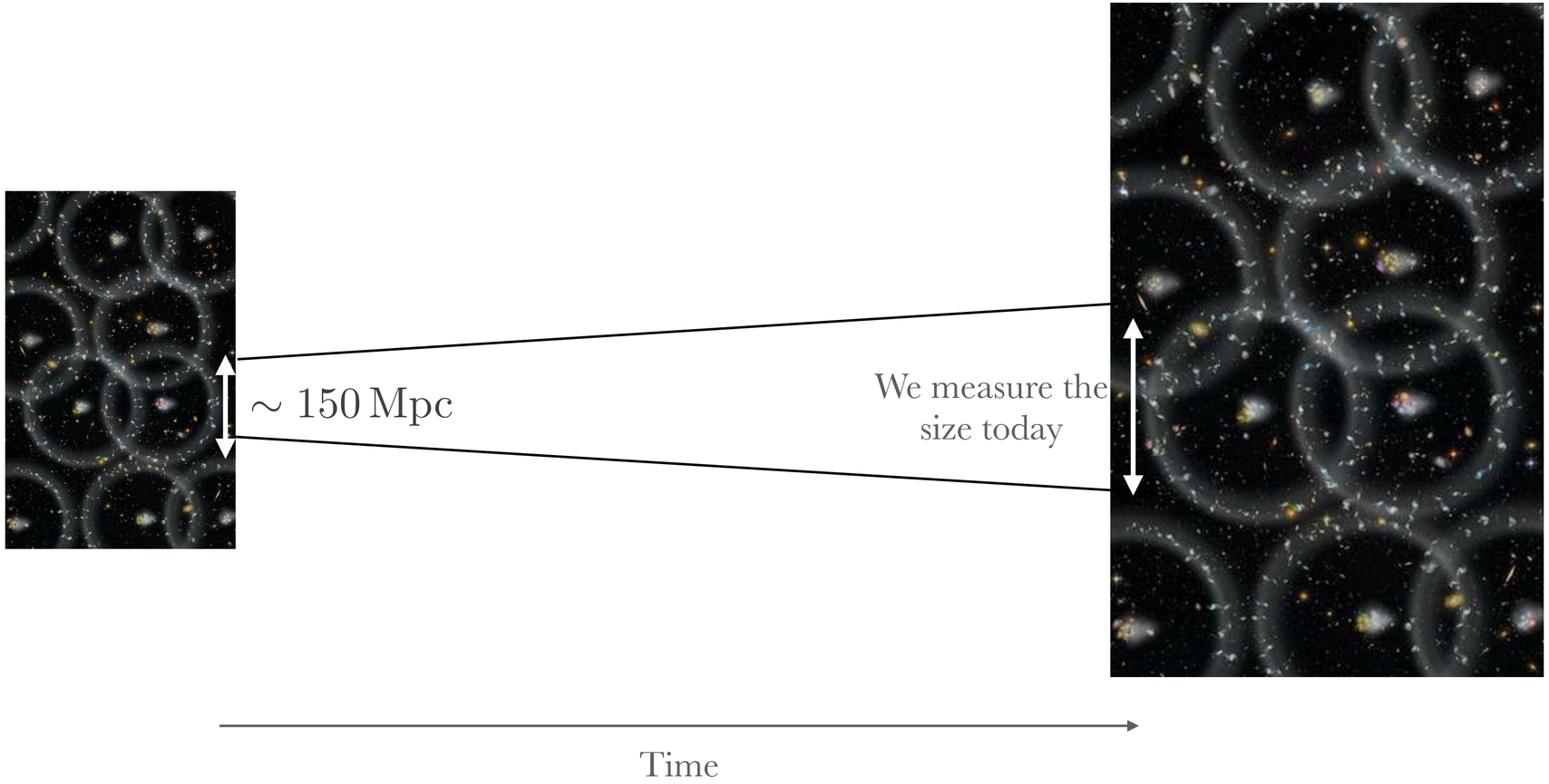
Large Scale Structure





Crédit:LBNL

Baryon Acoustic Oscillation (BAO)

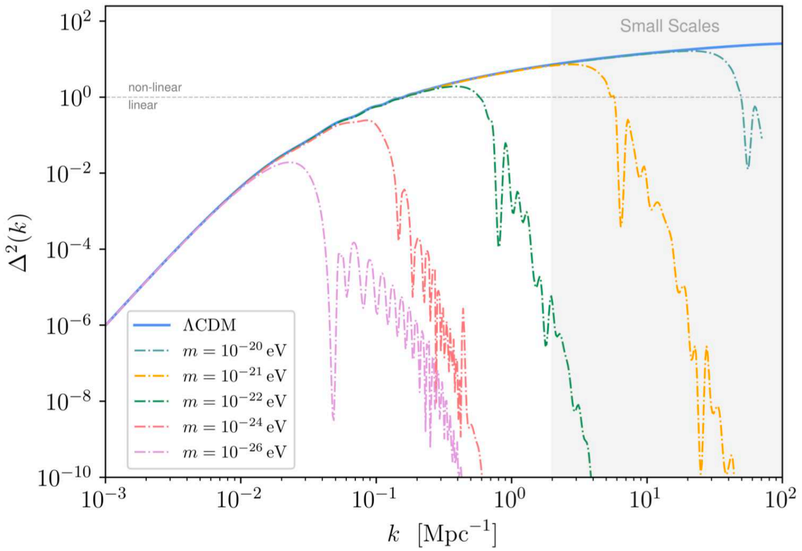


- BAOs are “standard rulers” to measure expansion

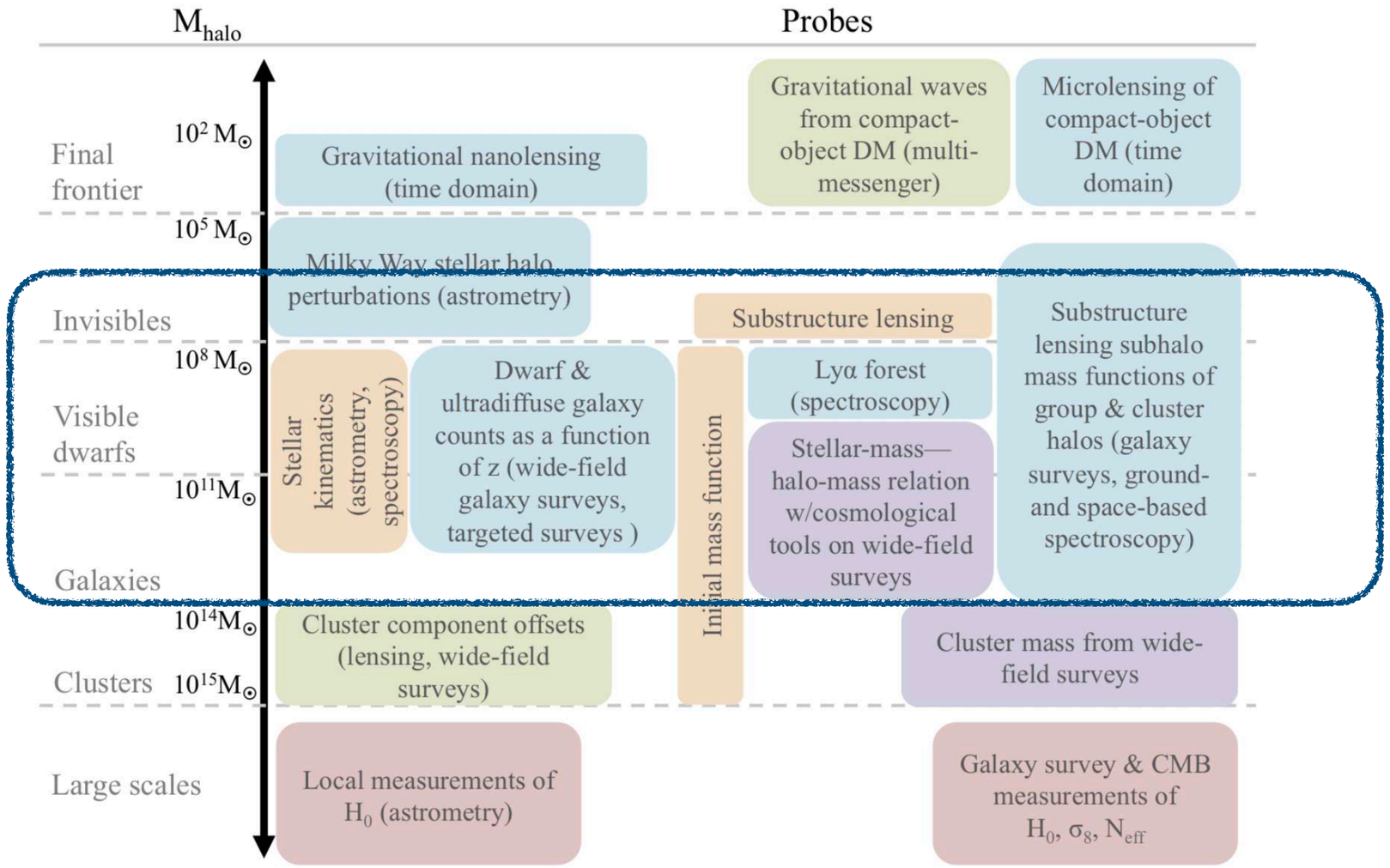
Cosmological and astrophysical ***probes*** *of dark matter*

CMB and LSS

Depends on the amount of CDM - a cold fluid
Damping/suppression
…



Cosmological and astrophysical ***probes*** *of dark matter*



Currently being measured

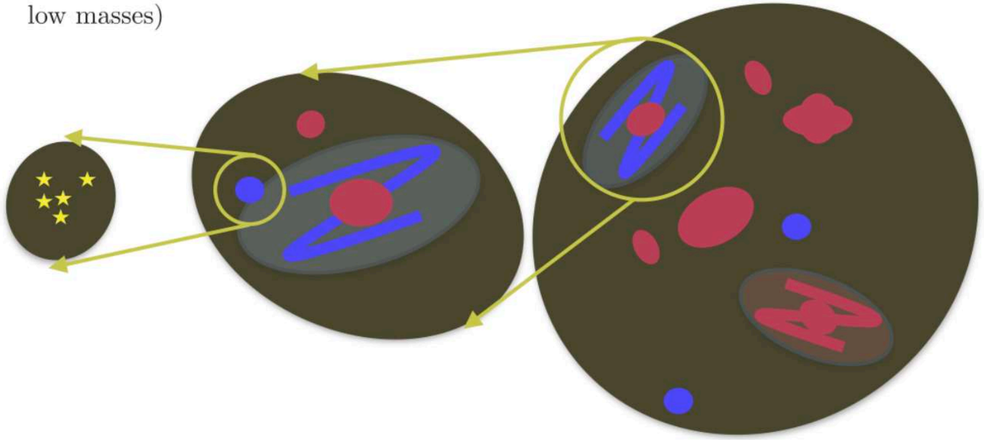
Precision improving

Buckleya et al 2017

Cosmological and astrophysical ***probes*** *of dark matter*

$z = 0$	**Dwarf**	**Galaxy**	**Cluster**
$M_{\rm vir}$ (central) :	$\sim 10^8 - 10^{11}\, M_\odot$	$\sim 10^{11} - 10^{14}\, M_\odot$	$\sim 10^{14} - 10^{15}\, M_\odot$
M_* (central) :	$\sim 10^2 - 10^9\, M_\odot$	$\sim 10^9 - 10^{11}\, M_\odot$	$\sim 10^{12}\, M_\odot$
M_* (total) :	$\sim 10^{-4}\, M_{\rm vir}$ (steeply falling at low masses)	$\sim 0.03\, M_{\rm vir}$	$\sim 0.01\, M_{\rm vir}$

Dark



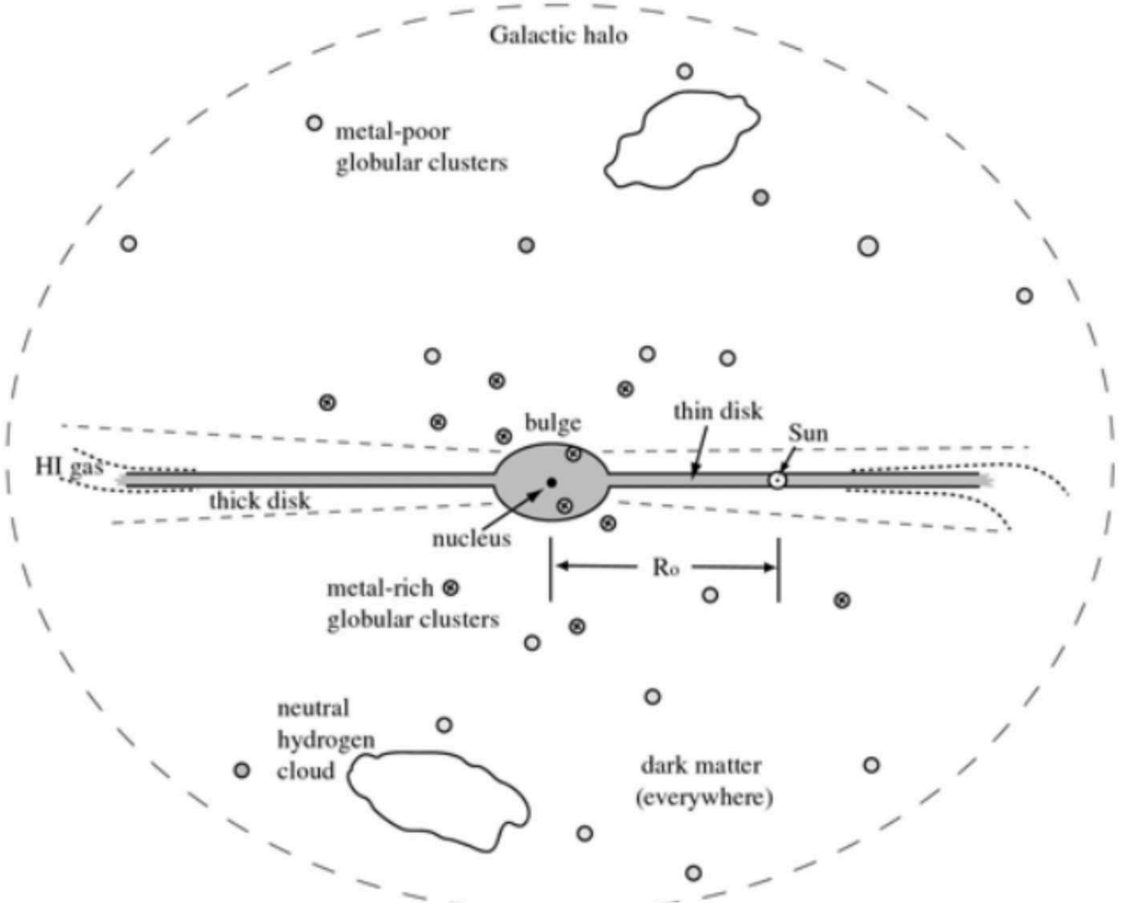
Nothing Larger Virialized

$v_{\rm vir} \sim M_{\rm vir}^{1/3}$:	$10 - 1000$ km/s	$100 - 1000$ km/s	$1000 - 2000$ km/s
$R_{\rm vir} \sim M_{\rm vir}^{1/3}$:	$10 - 100$ kpc	$100 - 1000$ kpc	$1 - 2$ Mpc
$R_* \sim 0.02 R_{\rm vir}$:	$\sim 0.1 - 1$ kpc	$\sim 1 - 10$ kpc	~ 20 kpc
$k_{\rm hm} \sim M_{\rm vir}^{-1/3}$:	$\sim 4 - 40$ Mpc^{-1}	$\sim 0.4 - 4$ Mpc^{-1}	$\sim 0.2 - 0.4$ Mpc^{-1}

Buckleya et al 2017

Cosmological and astrophysical ***probes*** *of dark matter*

Galaxies



A schematic side view of the Milky Way

Sparke & Gallagher

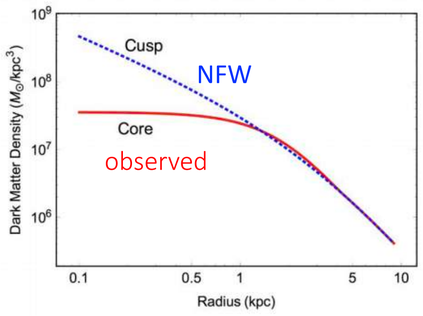
Cosmological and astrophysical ***probes*** *of dark matter*

Galaxies/dwarf galaxies

Local Milky Way observables and stellar streams

- Density profile
  - MW gravitational profile
  - Dwarfs density profile

- Vertical dynamics
- Velocity dispersion
- Dynamical effect
  - Heating
  - Dynamical friction
- Counting small galaxies
- Stellar stream *(More later)*
- …



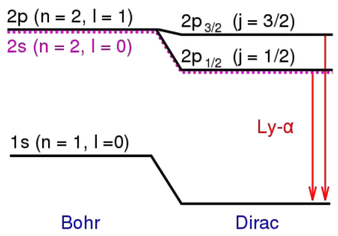
Gravitational lensing

(More later)

Cosmological and astrophysical ***probes*** *of dark matter*

Lyman α

Spectral line of hydrogen



Tobix10

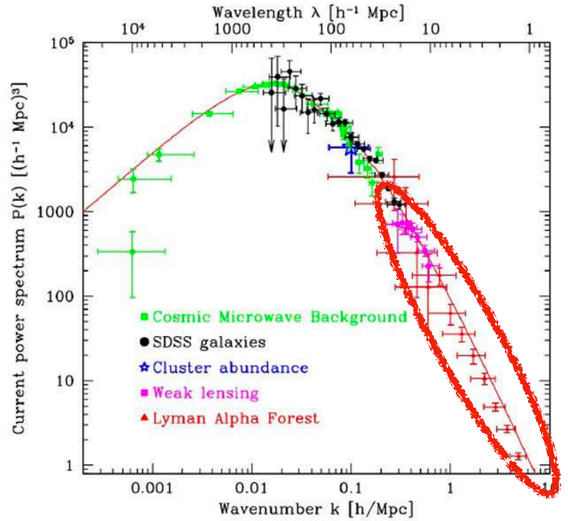
Lyman-alpha forest is a series of absorption lines in the spectra of distant galaxies and quasars arising from the Lyman-alpha electron transition of the neutral hydrogen atom

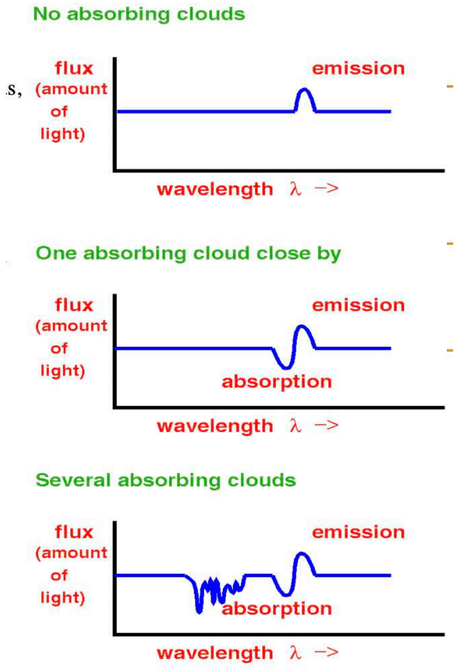
Armengaud

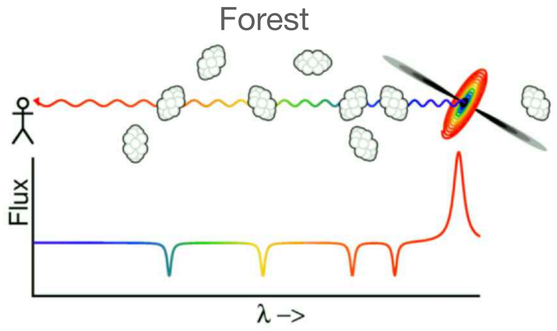
$$\delta(\lambda) = \frac{f(\lambda)}{C_q(\lambda)\bar{f}(z)} - 1$$

$P_{1D}(k) = < (FFT(\delta))^2 >$

related to 3D matter P(k)







Advantage: provide PS on intermediary scales

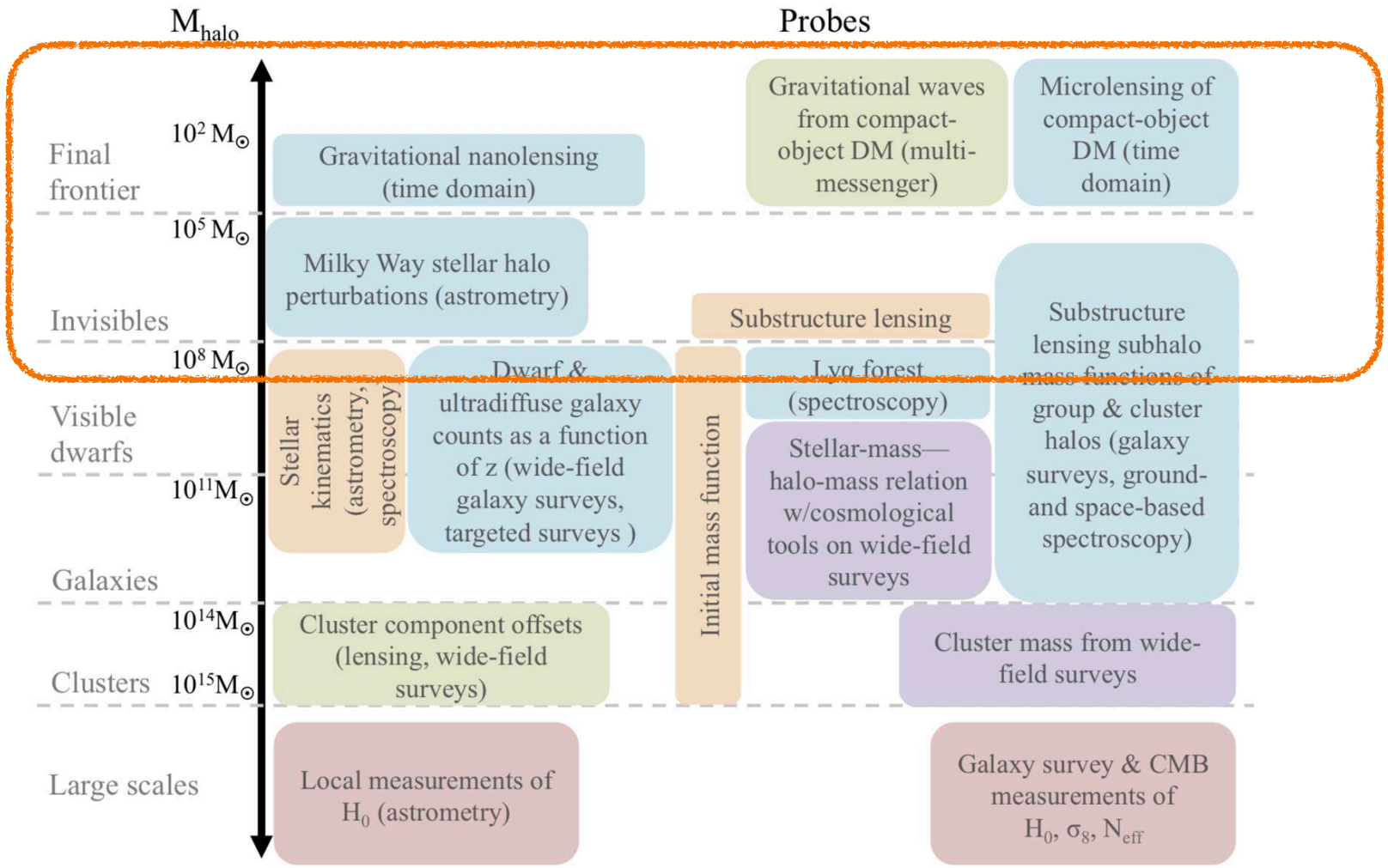
It probes the matter power spectrum in the mildly nonlinear regime over a large range of redshifts ($z = 2 - 6$) down to small scales ($1 - 80\ h^{-1}$ Mpc)

Challenges:

- Modelling/simulating of DM on NL scales
- Modelling/simulating Lyα
  - Reionization

Lyα forest: series of absorption lines

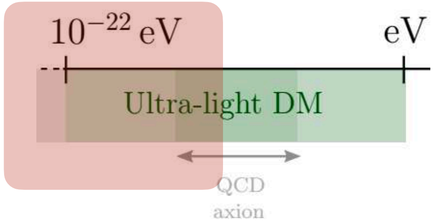
Cosmological and astrophysical ***probes*** *of dark matter*



Future

Buckleya et al 2017

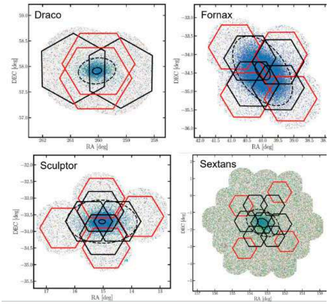
Observational implications and constraints



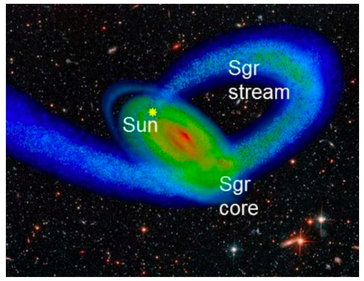
Galaxies

NASA and ESA

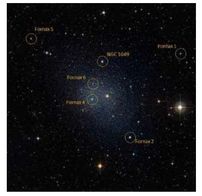
Dwarfs



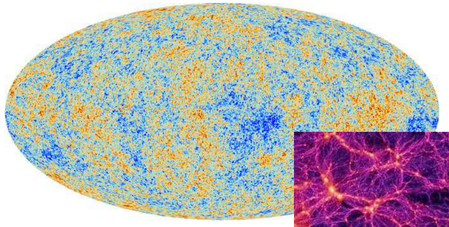
Stellar stream



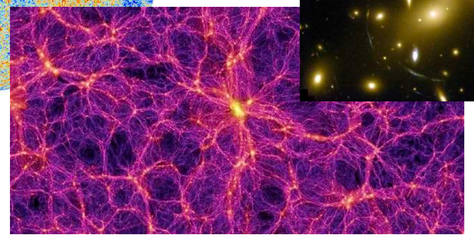
Globular clusters



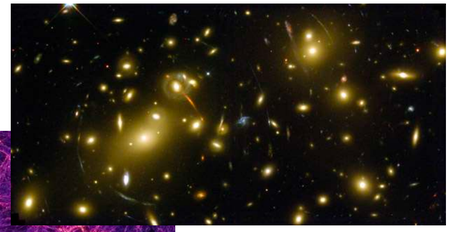
CMB+LSS



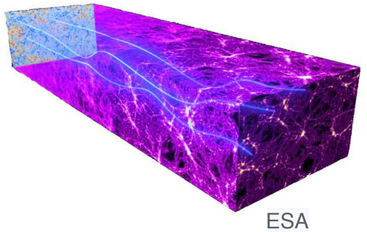
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

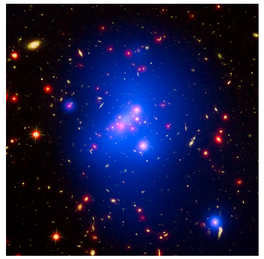


NASA and ESA



ESA

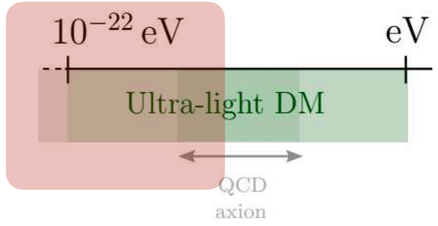
Clusters



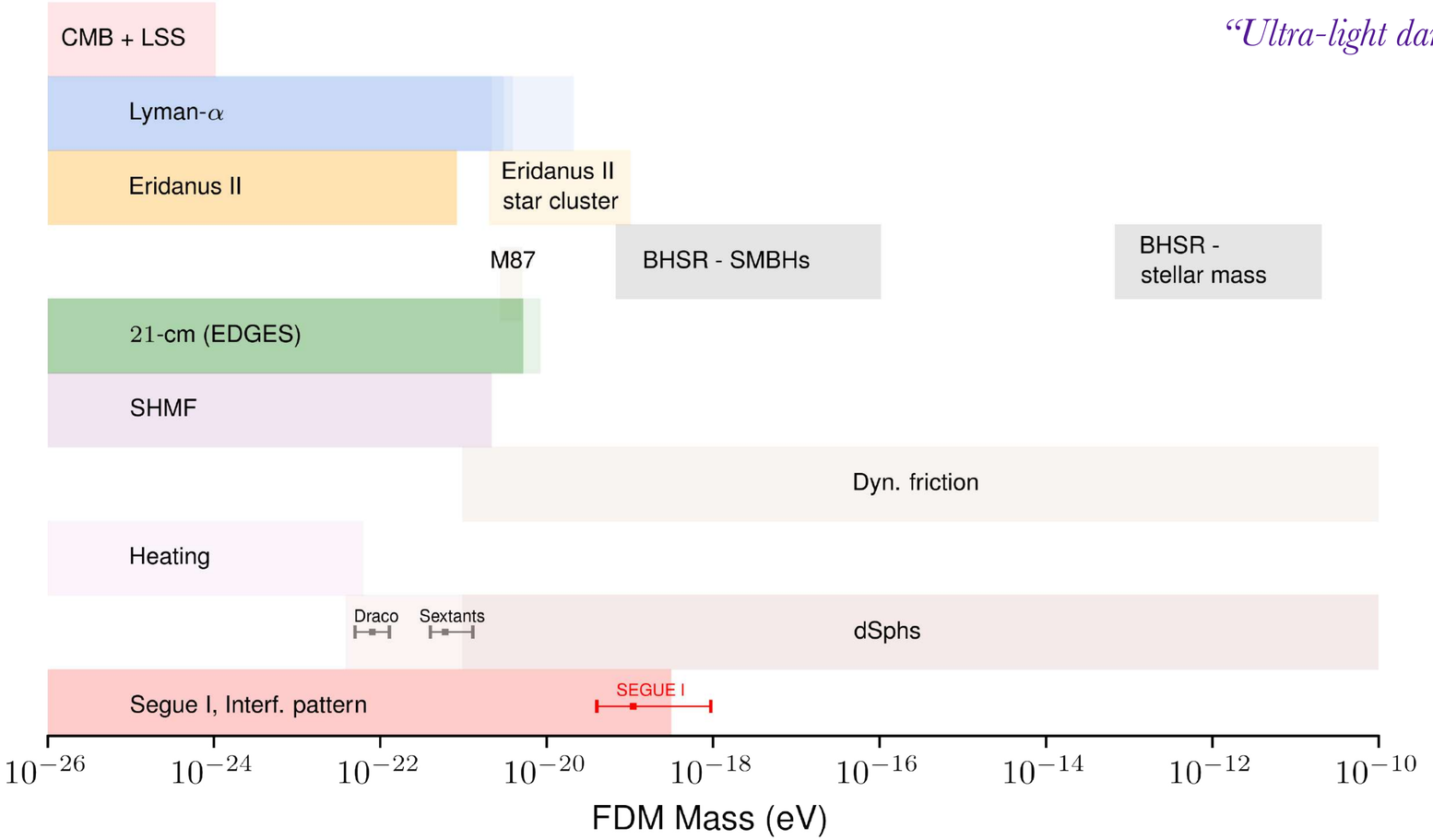
CC BY 4.0

Observational implications and constraints

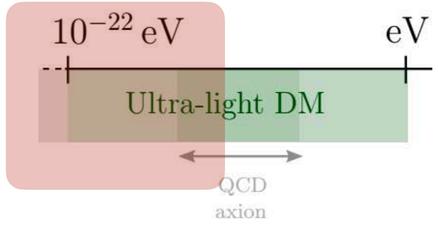
Fuzzy Dark Matter - bounds on the mass



"Ultra-light dark matter", **E.F.**, 2020. The Astronomy and Astrophysics Review.



Bounds consider FDM is *all* DM

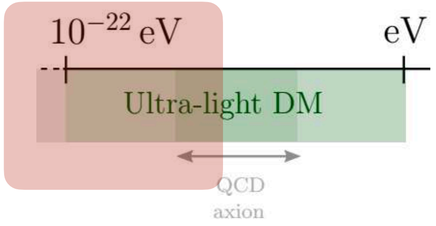


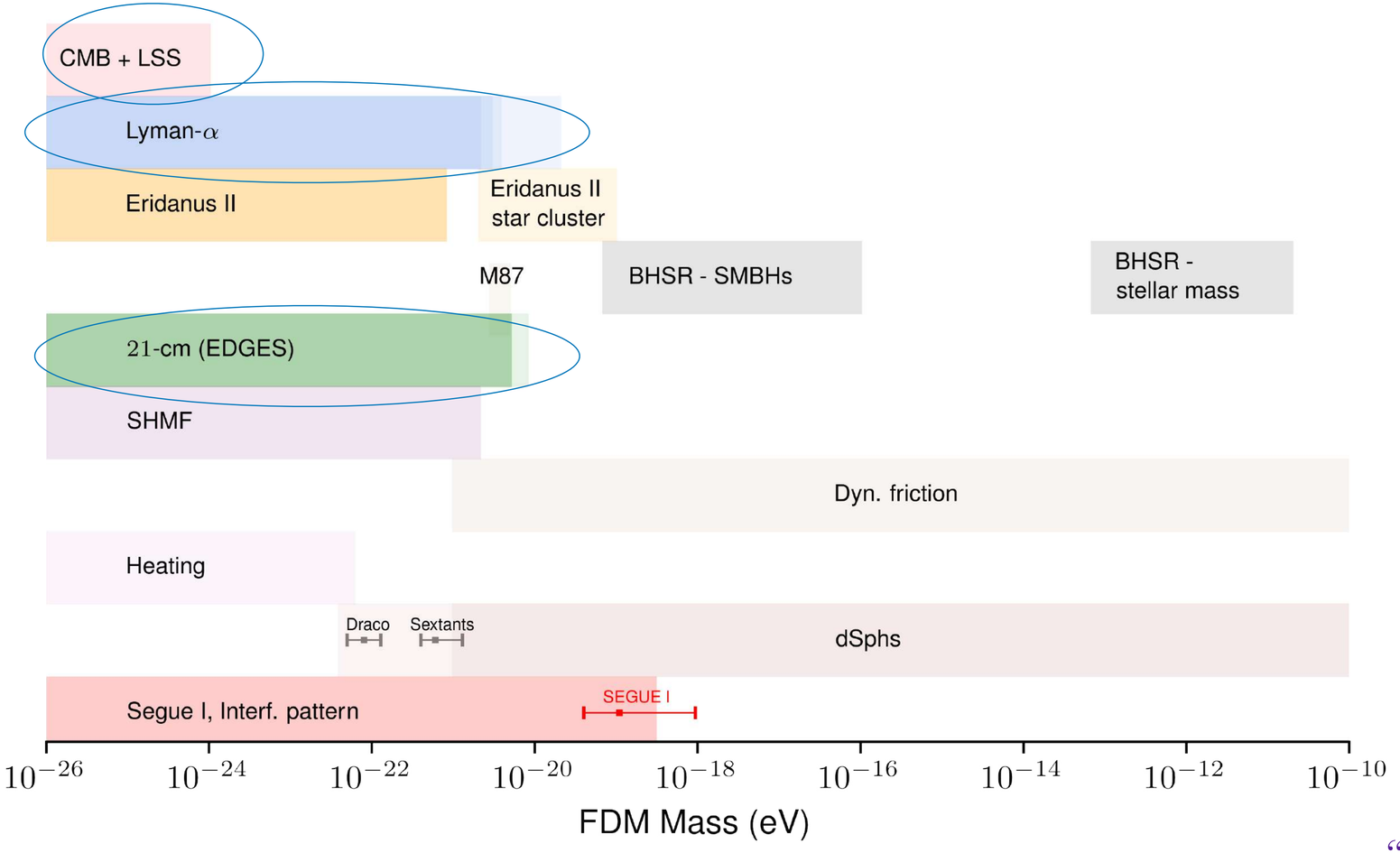
Observational implications and constraints

Suppression of small scale structures

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

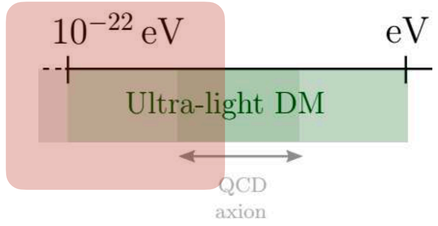




"Ultra-light dark matter", **E.F.**, 2020

Observational implications and constraints

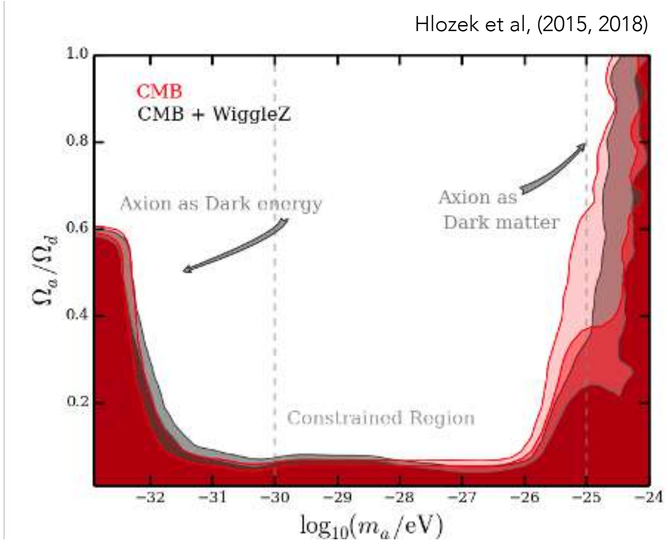
Fuzzy Dark Matter - bounds on the mass



Suppression of small structures

CMB/LSS

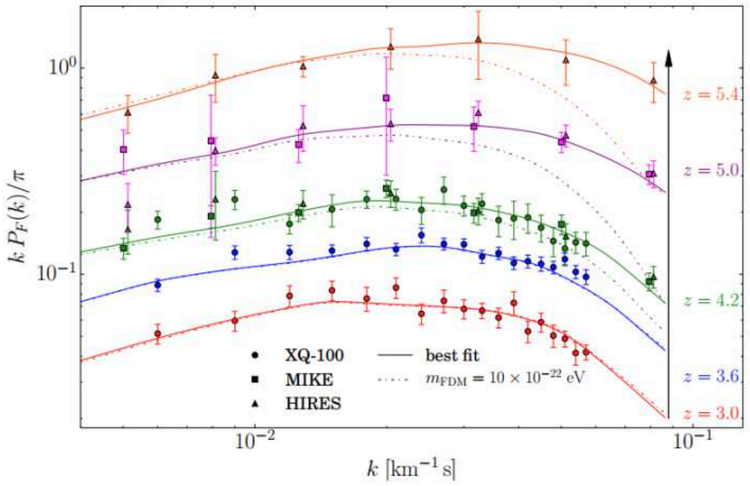
Hlozek et al, (2015, 2018)



$m \gtrsim 10^{-24}$ eV

Lyman alpha

Armengaud et al. (2017); Iršič et al. (2017);
Rogers et al. (2020)

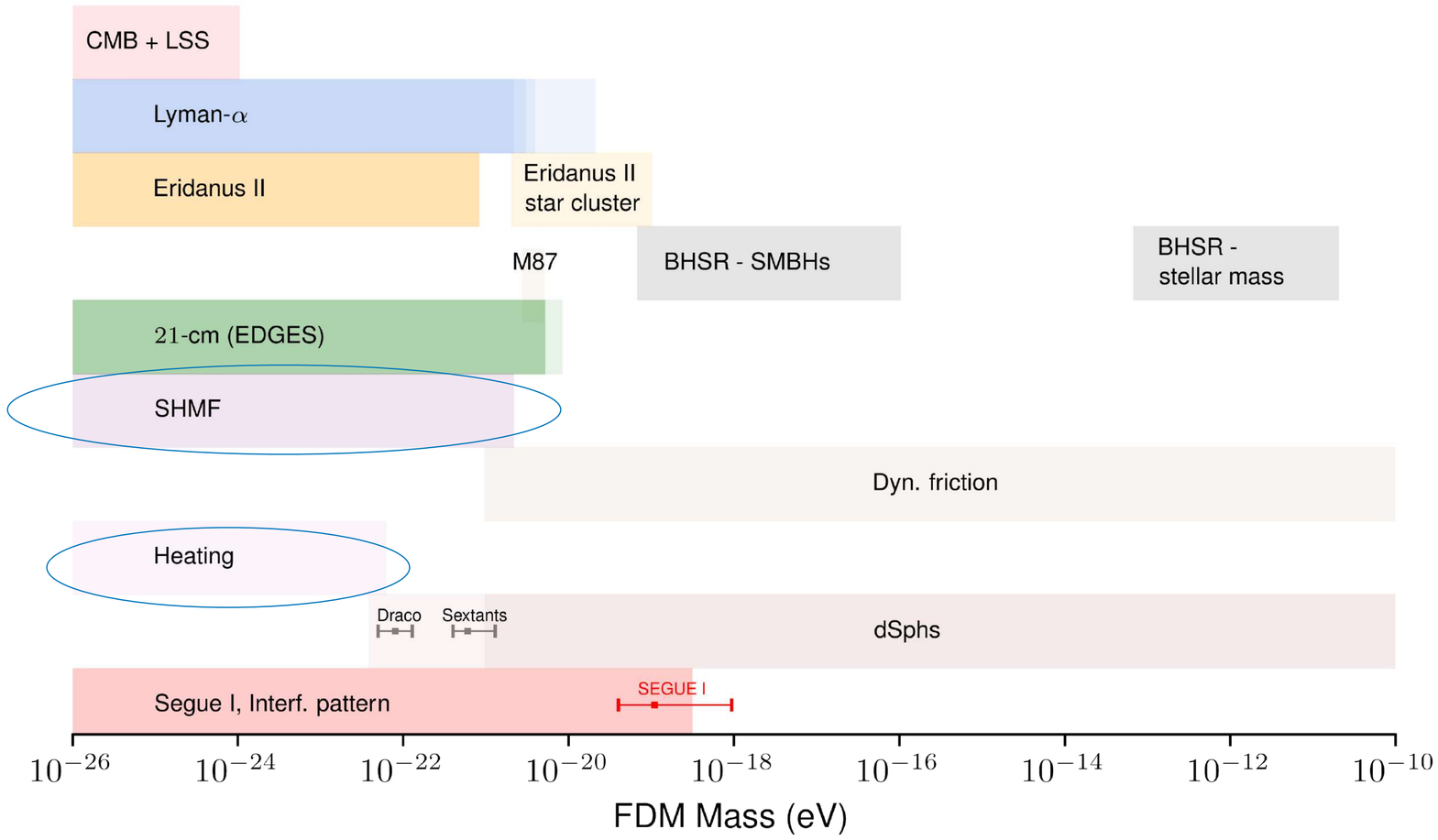


$m \gtrsim 2 \times 10^{-20}$ eV

so enough Mpc-scale power in Ly-α forest at z = 5.

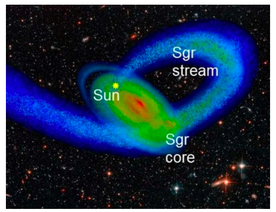
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



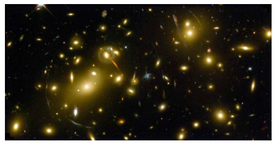
Suppression of small structures

Stellar streams



Schutz 2020: bound in the FDM SHMF using stellar streams and grav. lensing

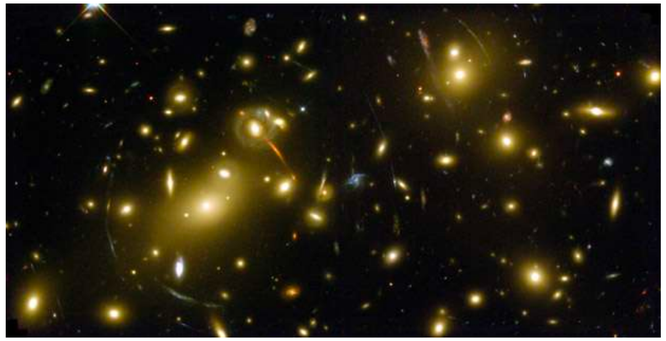
Grav. lensing



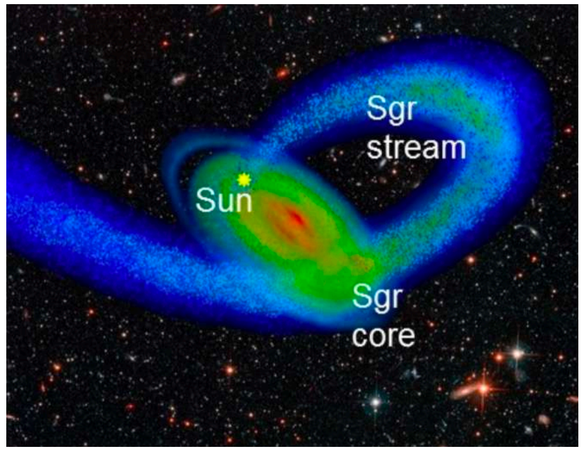
Gravitational probes

Probes that are sensitive to changes in the gravitational potential - total mass

Gravitational lensing

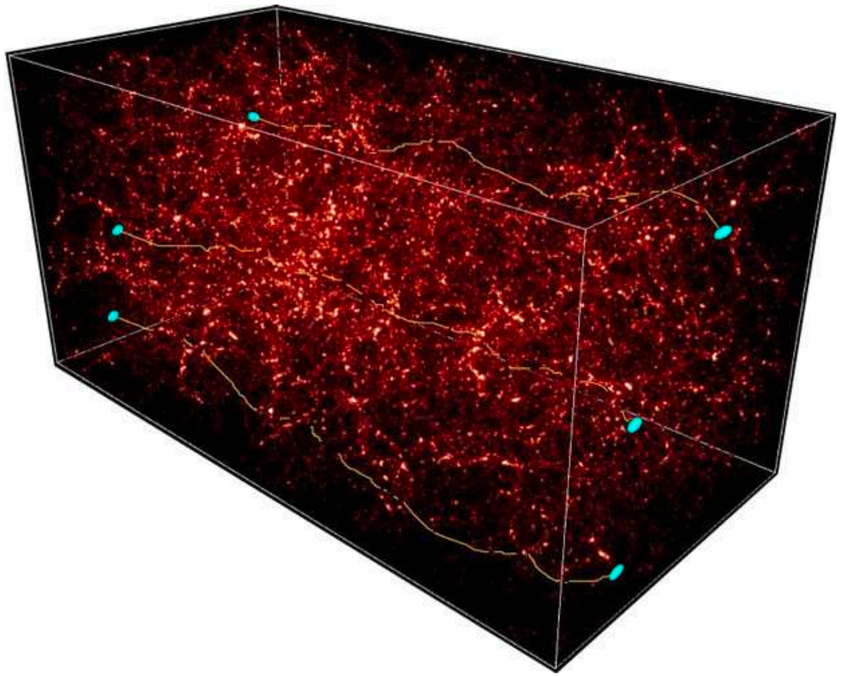


Stellar stream



Gravitational lensing

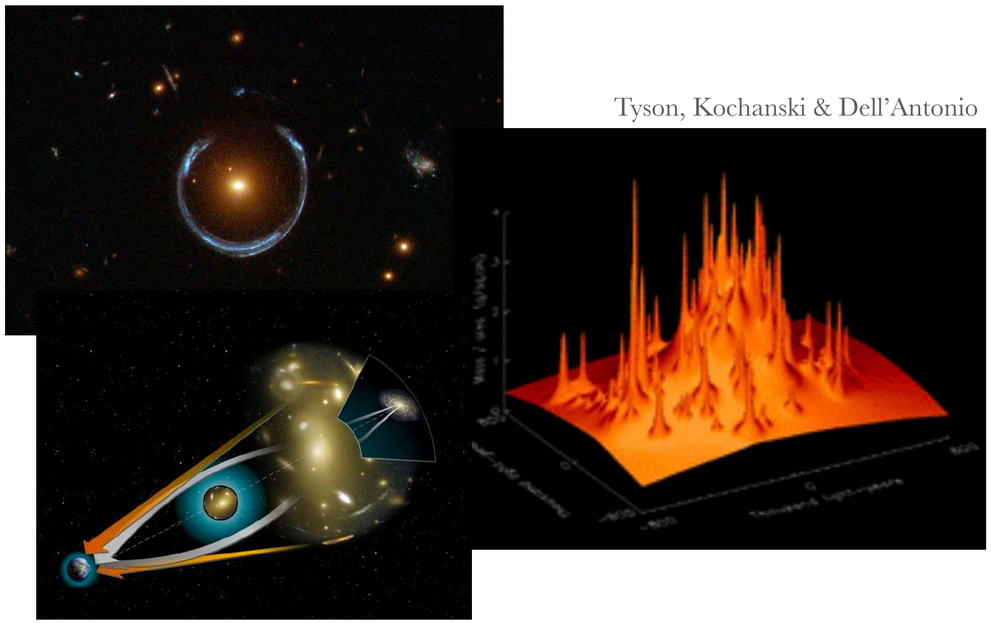
Weak lensing



- Background image is perturbed by matter in its path
- Statistical signal
- Total mass on large scales

Strong lensing

Image: © ESA/Hubble/NASA)



Tyson, Kochanski & Dell'Antonio

NASA / STSCI

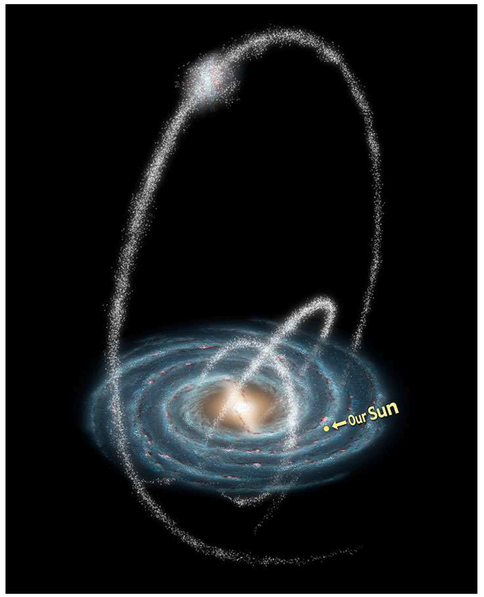
- Reconstruct the gravitational potential (total enclosed mass) of the lens
- Total mass on small scales

Stellar streams

Stellar streams are a stream of stars orbiting a galaxy which are remnants of a tidally disrupted globular clusters or dwarf galaxies, that was torn apart by a more massive system.

These streams are usually thin and very long, extending to dozens of kpc across the 3-dimensions of the halo, and wrap around the disrupting galaxy.

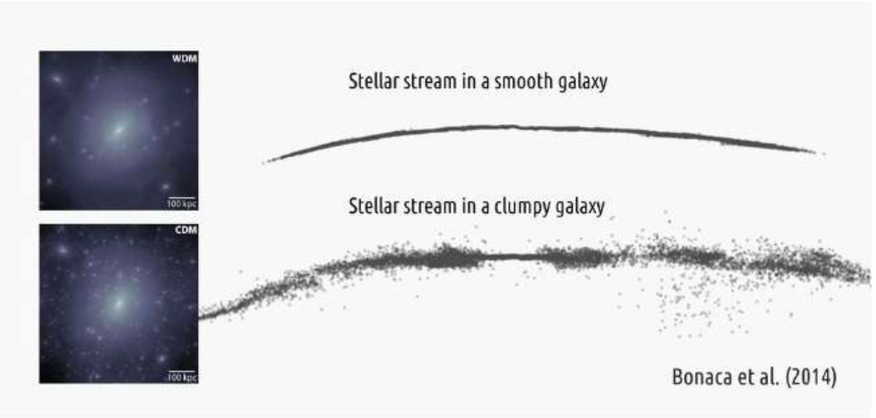
Streams are good dynamical probes since they are initially cold and very sensitive to the gravitational potential



NASA

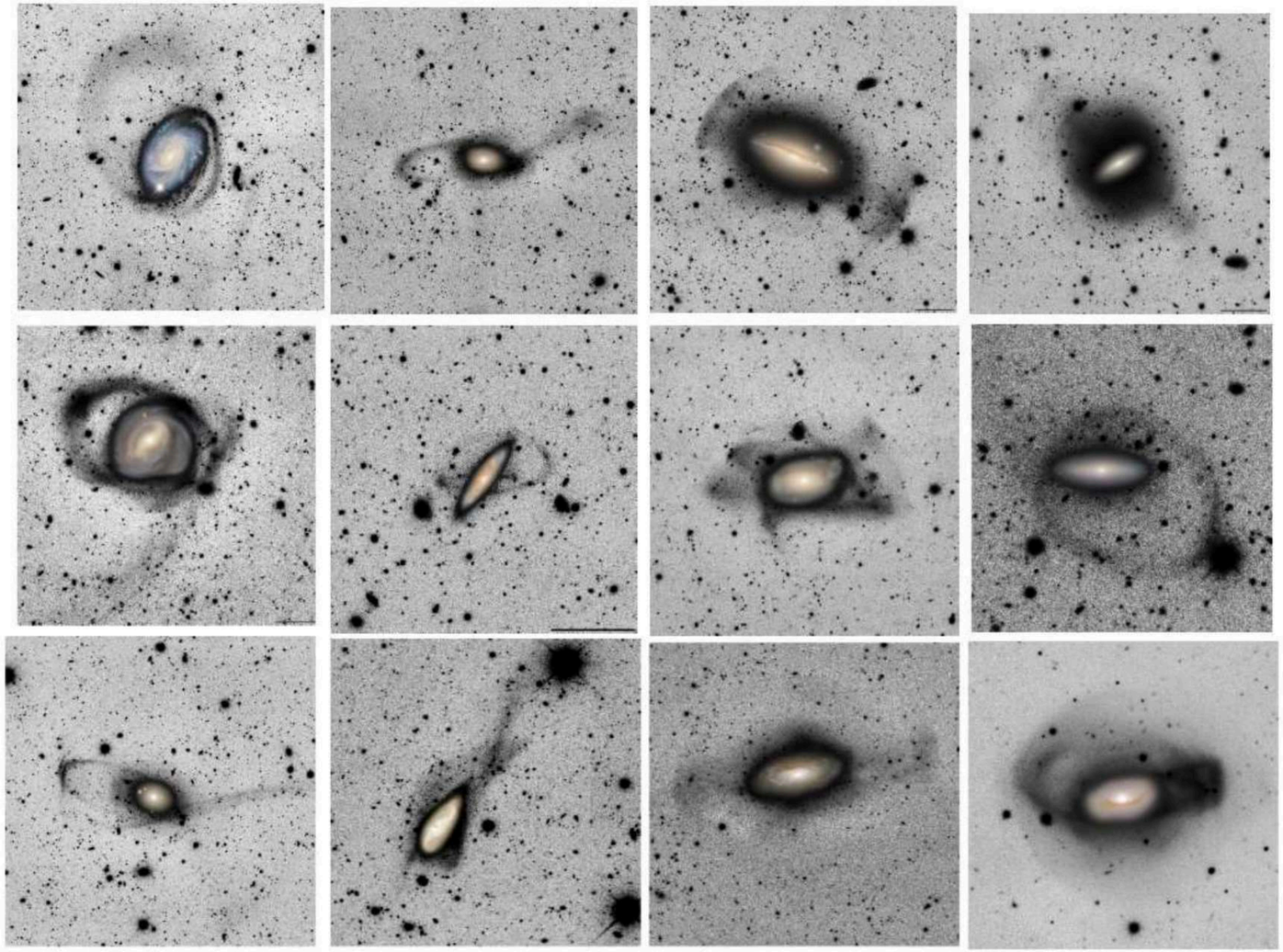
⟶ Substructures present in the halo when encounter the streams disturb it causing:

- Dynamical heating: which are changes in the velocities in the stream,
- Disturbances in the morphology of the stream: formation of gaps which are underdensities caused by the sub-halos encountered



It is estimated that we can observe gaps in streams cause by substructures with mas as low as $M \sim 10^5 - 10^6\, M_\odot$ (Erkal and Belokurov 2015; Erkal et al. 2016; Bovy et al. 2017)

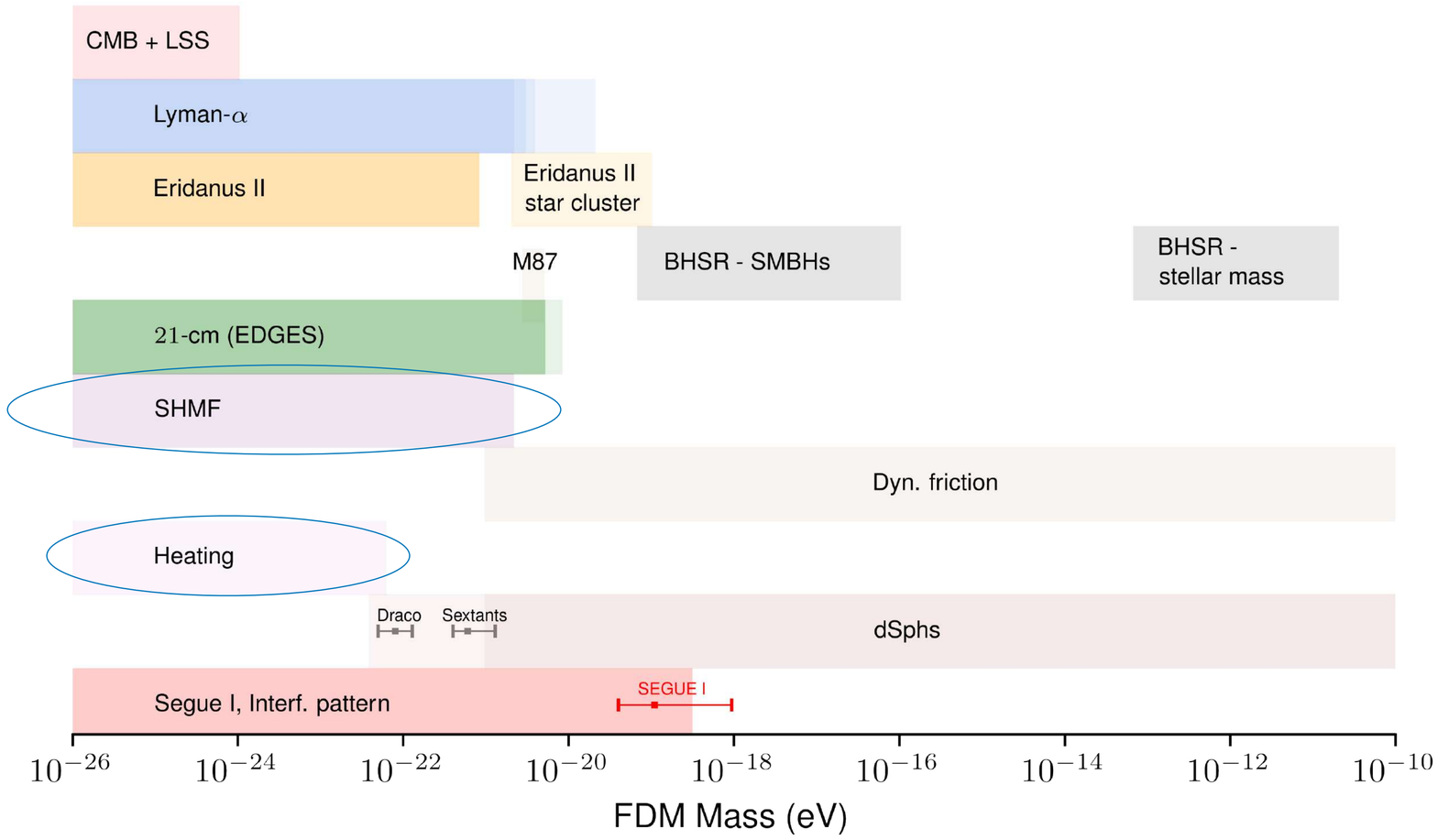
Stellar streams



Martinez-Delgado et al. 2021;arXiv:2104.06071

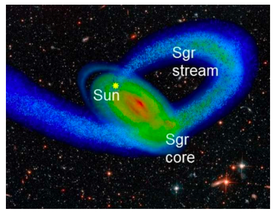
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



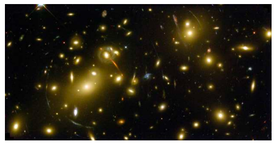
Suppression of small structures

Stellar streams



Schutz 2020: bound in the FDM SHMF using stellar streams and grav. lensing

Grav. lensing



Practice session:

Suppression of small scale structures

S8 tension

Ref.: K. Rogers et al 2023

Changes in the small scale paradigm can change the behaviour of DM in many scales, including cosmology

Ex.: Fuzzy DM

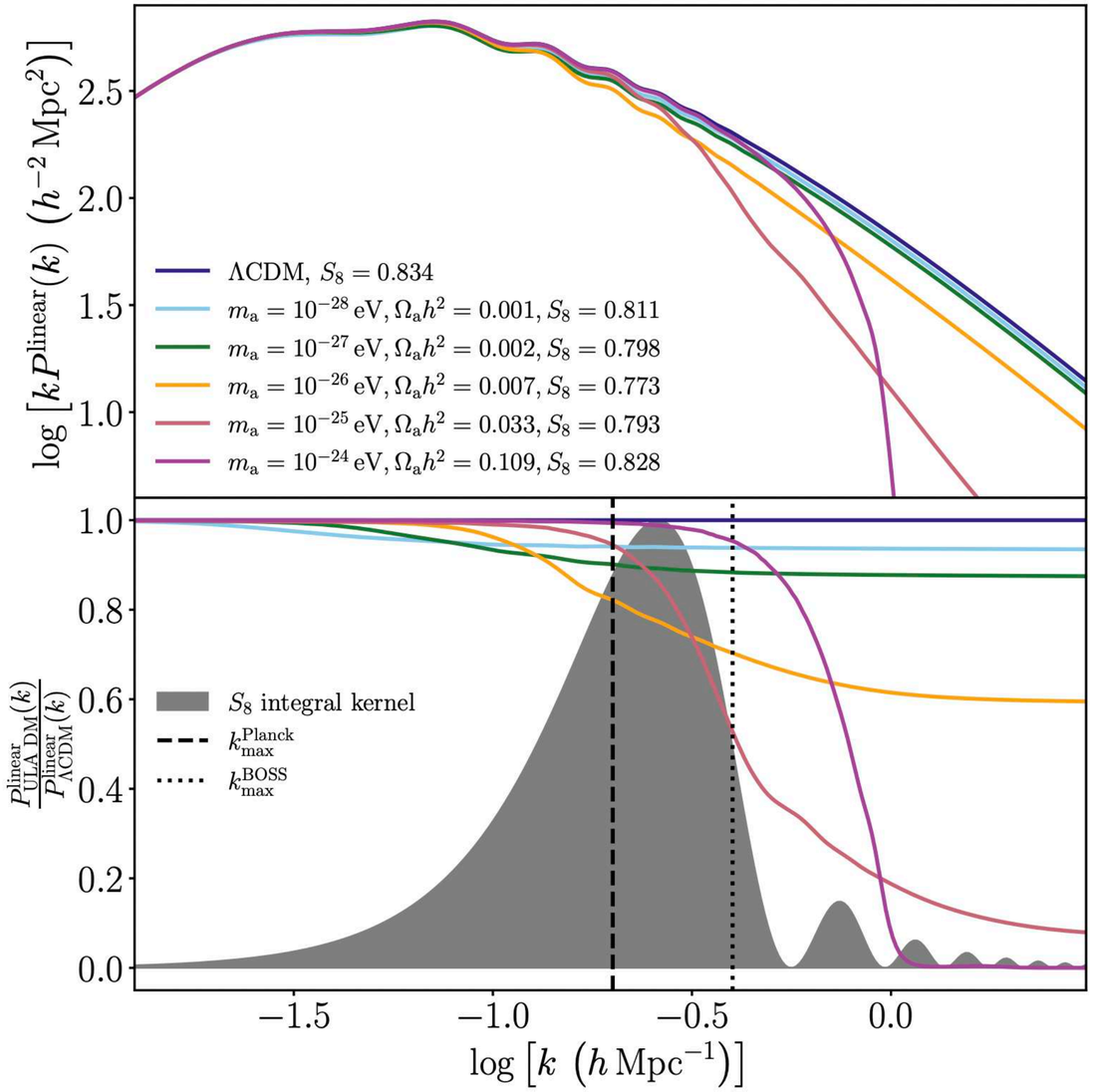
$$\sigma_8 = \int \mathrm{dln}k \, \frac{k^3}{2\pi} W^2(k) P^{\mathrm{linear}}(k)$$

$$S_8 = \sqrt{\frac{\Omega_{\mathrm{m}}}{0.3}} \sigma_8$$

The presence of ULAs can significantly lowers S8 for:

$$m_{\mathrm{a}} \in [10^{-27}, 10^{-25}]\,\mathrm{eV}$$

S8 is lowered because the Jeans scale today for $m_a = 10^{-25} - 10^{-26}\,\mathrm{eV}$ is about $\lambda_J = 4 - 12\,h^{-1}\,\mathrm{Mpc}$



S8 tension

Ref.: K. Rogers et al 2023

Ex.: Fuzzy DM

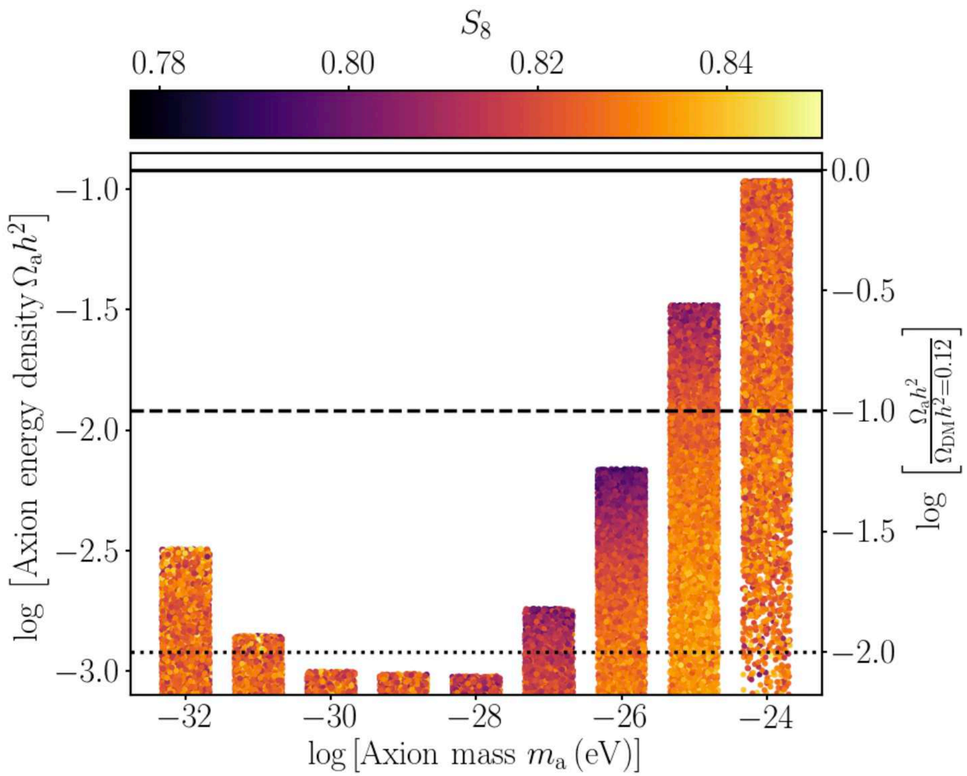
Planck + BOSS

The presence of ULAs with mass

$$10^{-28}\,\mathrm{eV} \leq m_a \leq 10^{-25}\,\mathrm{eV}$$

can improve consistency between CMB and galaxy clustering
(reduce the S8 discrepancy)

from 2.6σ to 1.7σ

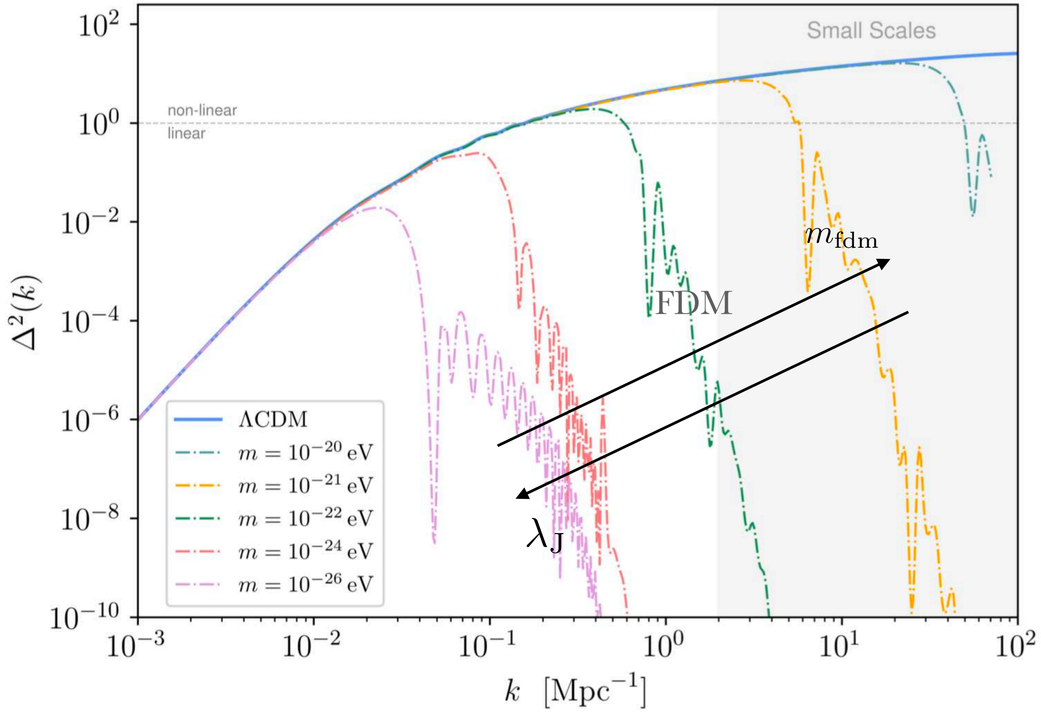


Ex.:
- H0 tension: Early dark energy - axion-like particle
- Model address H0 and S8 tensions: *"Chameleon EDE"*, Karwal et al 2021

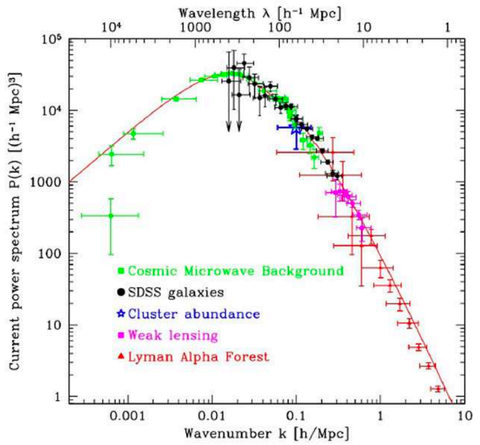
Suppression of small scale structure

Can we probe the small scales?

POWER SPECTRUM



CDM



Measure PS well until scales
$k \sim 10 - 20\,\mathrm{Mpc}^{-1}$

Can we measure the power spectrum on scales
$k < 10\,\mathrm{Mpc}^{-1}$?

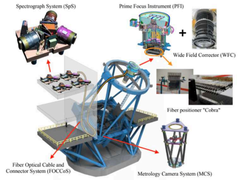
Power spectrum: highly constrained for $k > 10\,\mathrm{Mpc}^{-1}$
highly unconstrained for $k < 10\,\mathrm{Mpc}^{-1}$

Future - *signals in cosmology*

Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)



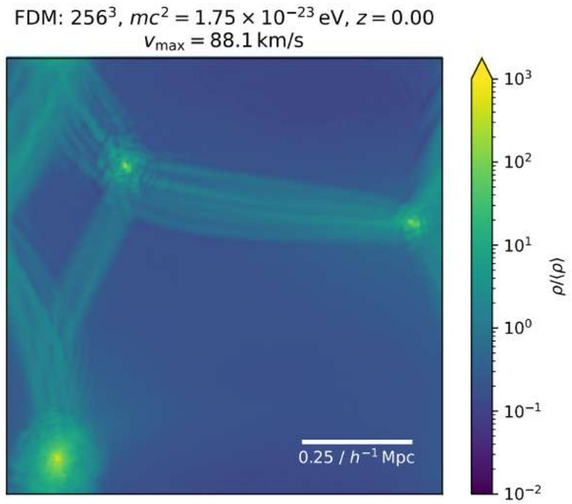
CMB

CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New probes

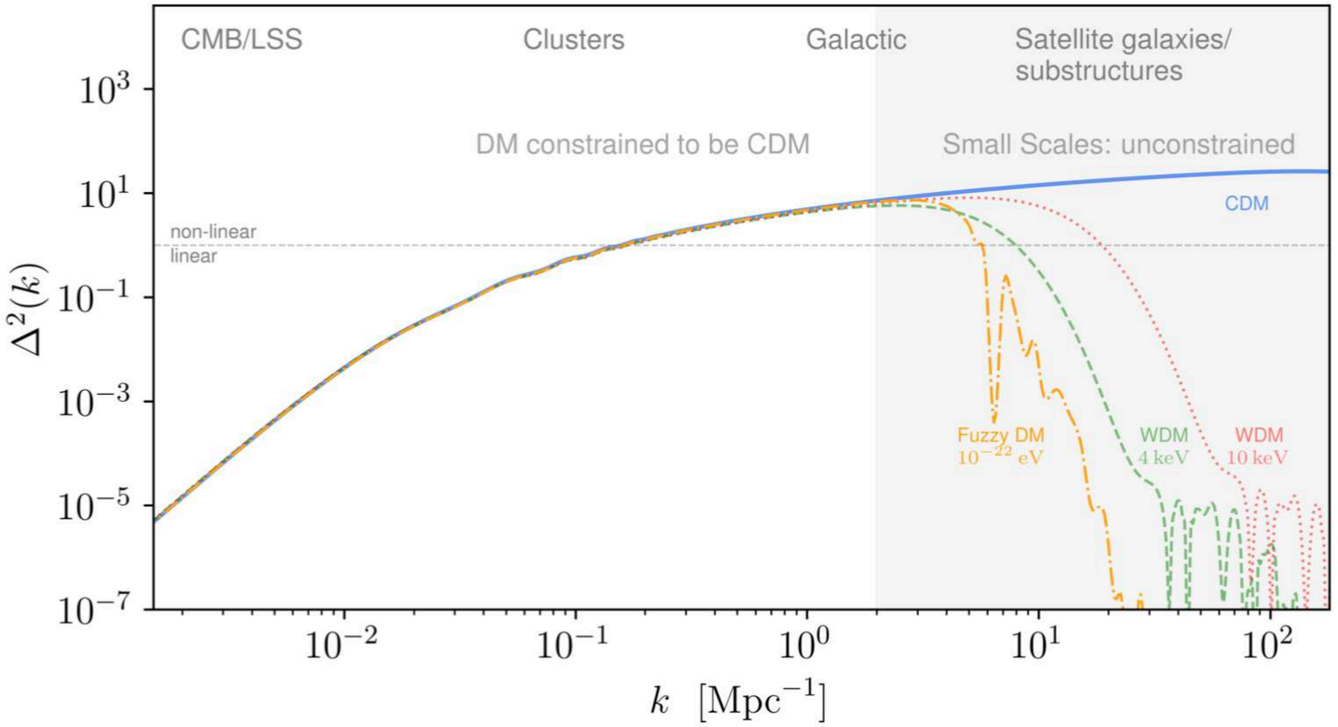
Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Modified from Jia Liu

Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures



Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures

A. Diaz Rivero, et al. (2017); Diaz Rivero, et al. , (2018)

Bayer et al. (2018) ; Auger et al. 2009
FDM*: Kawai et al. (2021)*

Hezaveh et al. (2016) (projected mPS by using strong lensing)

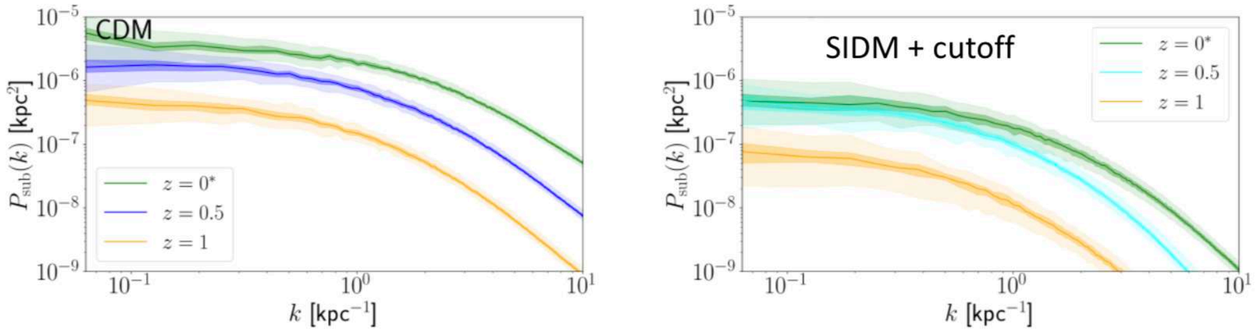
Substructure convergence power spectrum

Develop a formalism to compute the substructure convergence power spectrum for different populations of dark matter subhalos.

Change of language: instead of talking about lensing perturbations in terms of individual subhalos, look at the correlation function of the projected density field.

(based on Dvorkin's slide)

$$P_{\rm sub}(k) = P_{\rm 1sh}(k) + P_{\rm 2sh}(k)$$



Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures

Substructure convergence power spectrum

Sten Delos and Fabian Schmidt (2021)

Stellar streams: perturbed by passing substructure. Good gravitational probe, since given their low dynamical temperature and negligible self-interaction, it retains the memory of those encounters.

THIS WORK: Fully analytical understanding of the stream perturbations!

Power spectrum of a stream's stellar density is analytically related to that of the substructure background:

$$\boxed{P_*(k,t)} = \chi_*\left(k\sigma_0 t, \frac{D}{k\sigma_0^3}\right)\frac{k^2t^2}{3}P_{\Delta v}(k,t)$$

Stream power

Substructure power

$$P_{\Delta v}(k,t) = 16\pi^4 G^2\bar{\rho}^2 k^2 t \int_k^\infty \frac{\mathrm{d}q}{q}\frac{\boxed{\mathcal{P}(q)}}{q^6}\int \mathrm{d}^3\boldsymbol{u}\frac{f(\boldsymbol{u})}{u}\theta_H(qu-kv)$$

Previous:
- Mostly numerical
- Perturbations $\longrightarrow$ sub-halo mass function

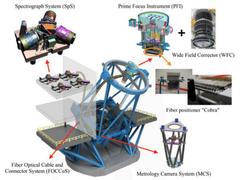
Relates the stellar stream perturbation to the surrounding matter distribution, from dark and luminous substructure

Future - signals in cosmology

Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)



CMB

CMB-S4
Next Generation CMB Experiment

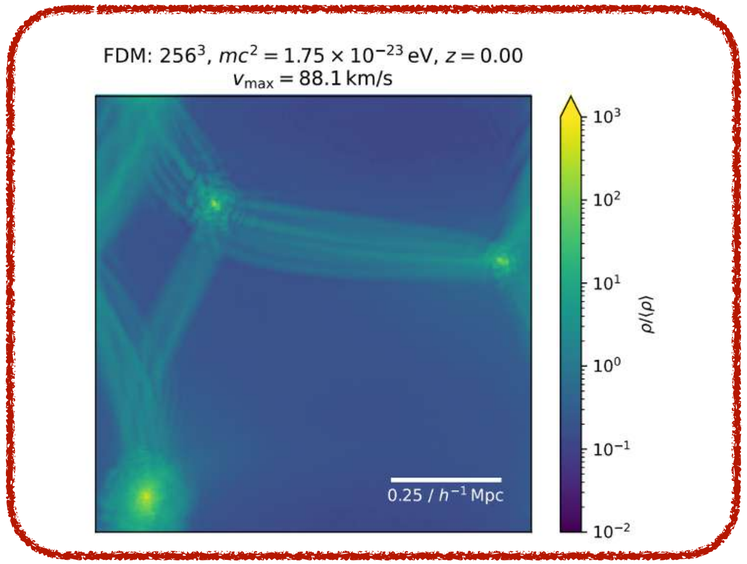
21cm

SKA
SQUARE KILOMETRE ARRAY

How to model the PS on these small scales?
Highly non-liner scales!
Challenge!

(more later)

Simulations



New probes

Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Modified from Jia Liu

Future - signals in cosmology

All we computed in lecture 1 was the LINEAR power spectrum

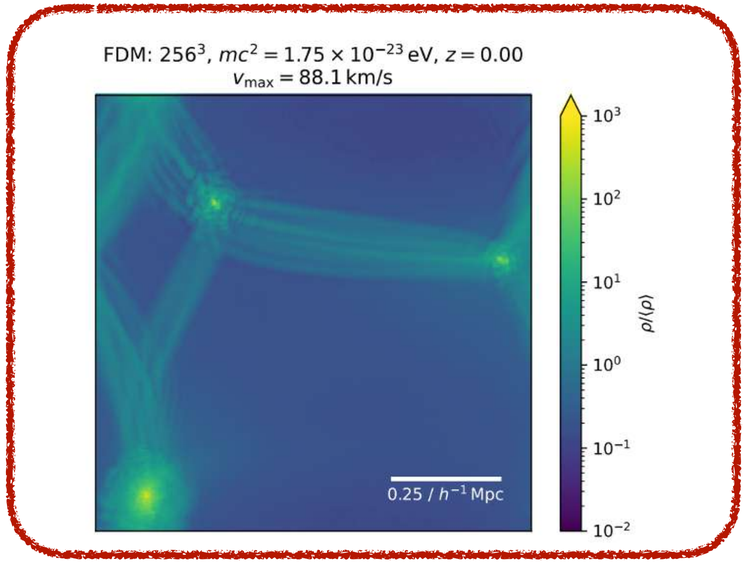
How to model the PS on these small scales?
Highly non-liner scales!
Hard!

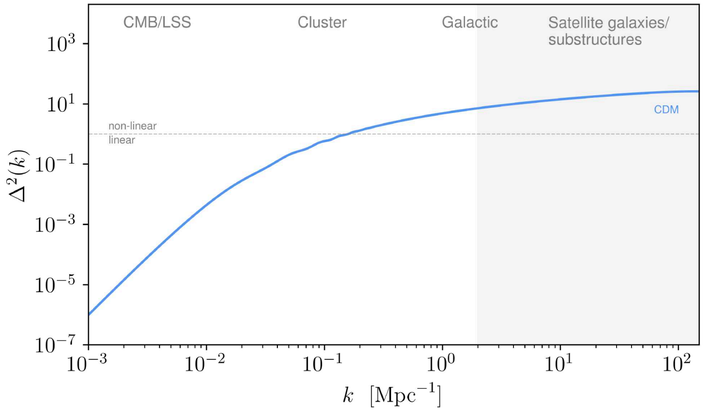
We can use EFT of LSS to compute mildly non-linear scales, but smaller scales are non-linear - Need simulations!

Need to improve simulations!
Challenge!

(more later)

Simulations





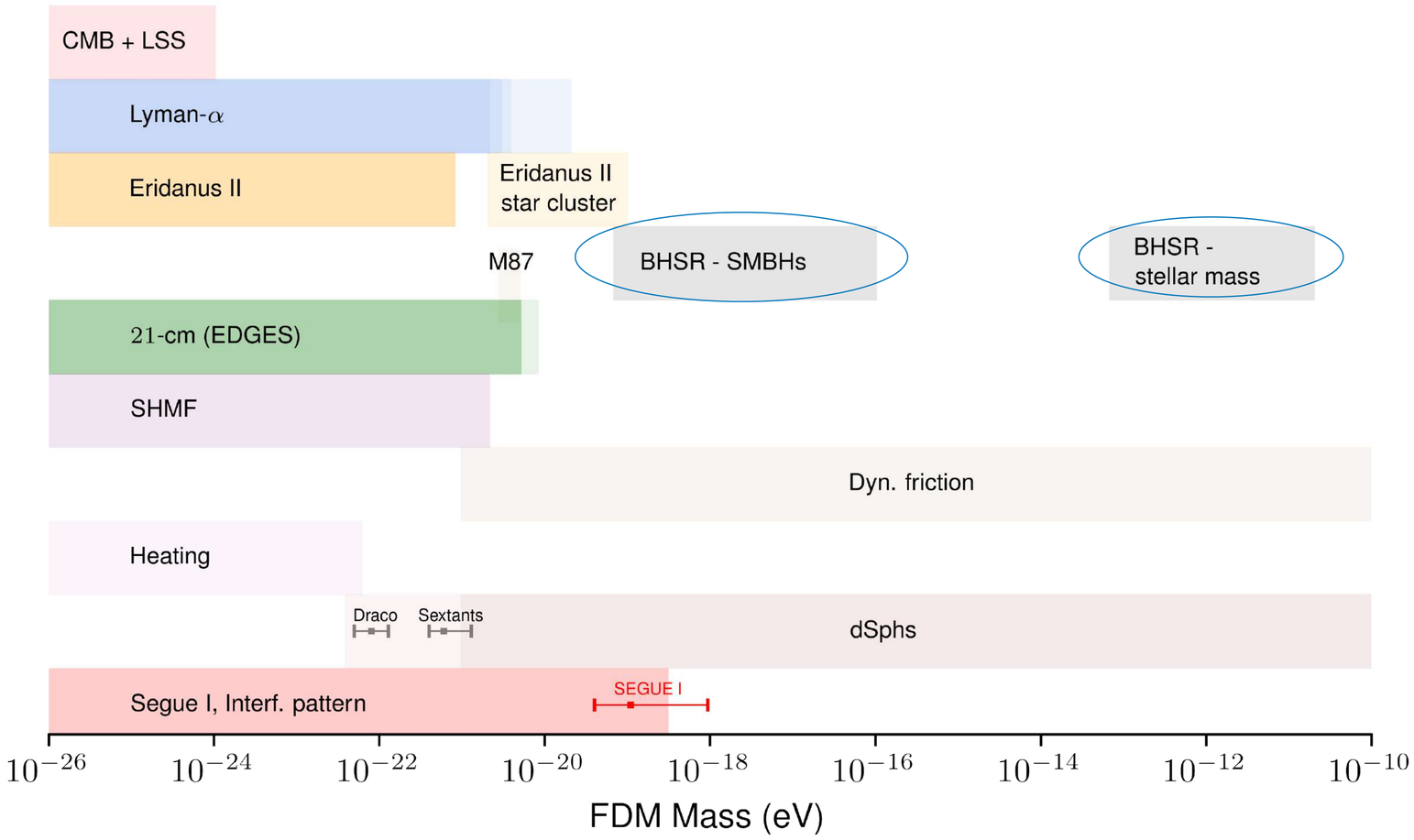
Lecture 2

Continuing:

Observational implications and constraints

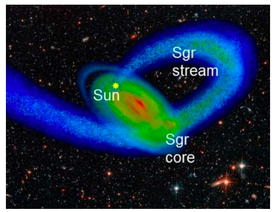
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



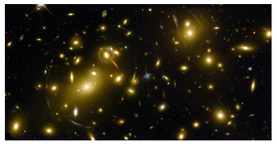
Suppression of small structures

Stellar streams



Schutz 2020: bound in the FDM SHMF using stellar streams and grav. lensing

Grav. lensing

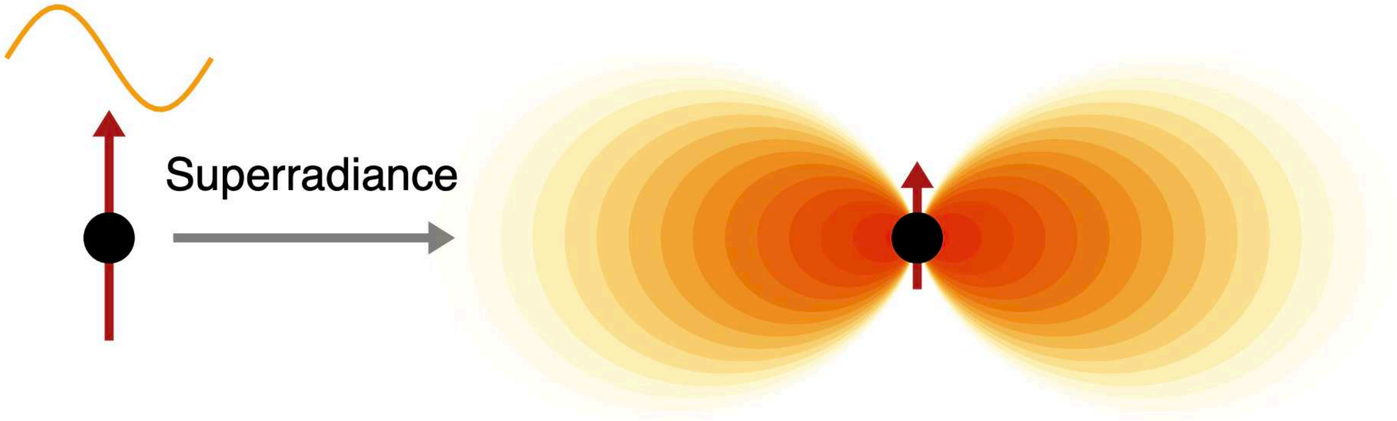


Black Hole Superradiance

Zeldovich (1972) Starobinsky (1973) Arvanitaki et al. [0905.4720]

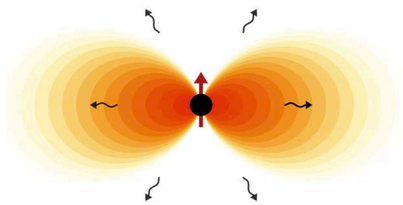
A cloud of ultra-light bosons (and vector fields) can be created around rotating black holes - if the particle Compton wavelength is of the order of the size of the BH

Structure like a "gravitational atom"

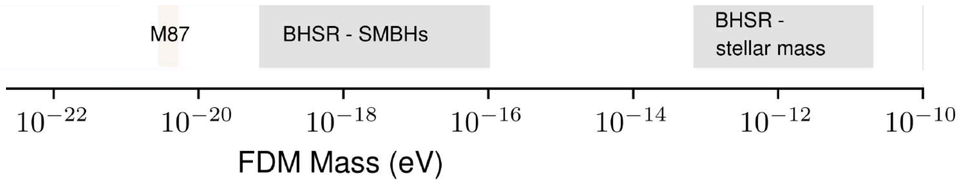


H. Chia et al, 2018

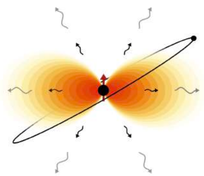
Emits gravitational waves



H. Chia et al, 2018

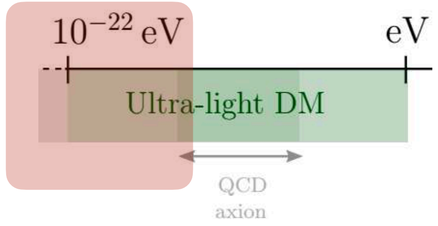


Dynamics can be altered by the presence of a companion - binary



H. Chia et al, 2018

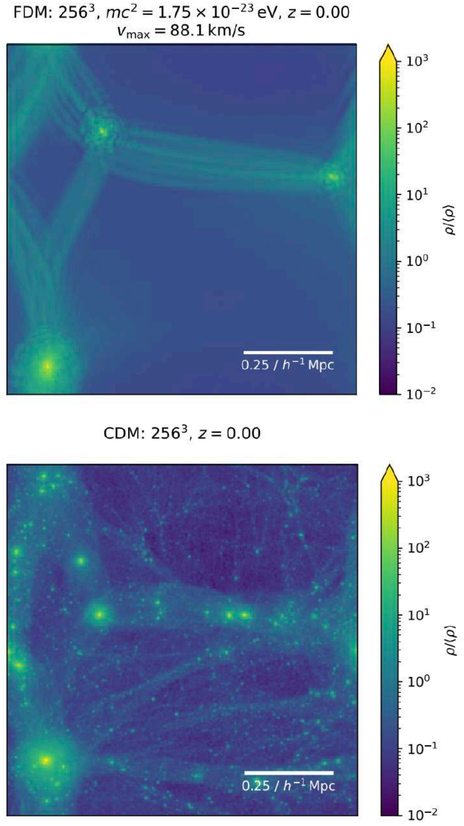
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

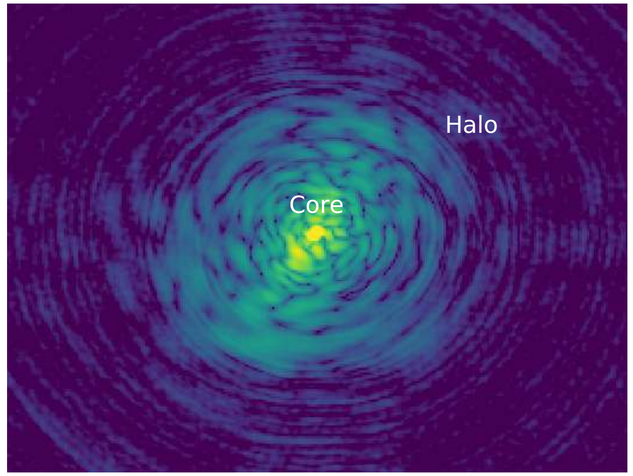
* Focus only in gravitational signatures

Suppression of small structures

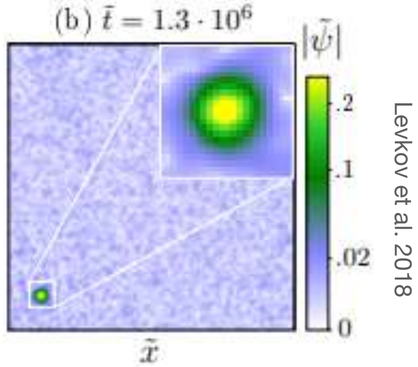


S. May et al. 2021

Formation of a solitonic core

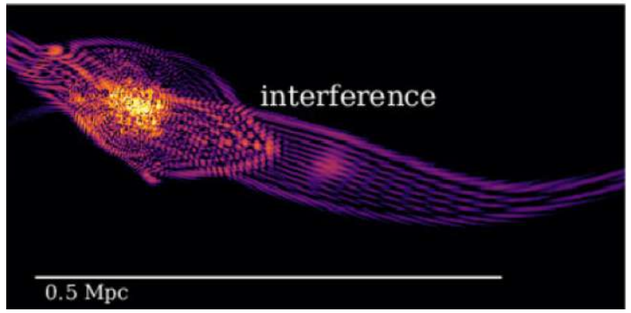


Dynamical effects



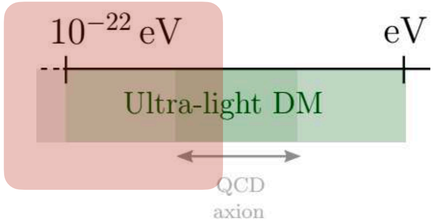
Levkov et al. 2018

Wave interference



Mocz et al. 2017

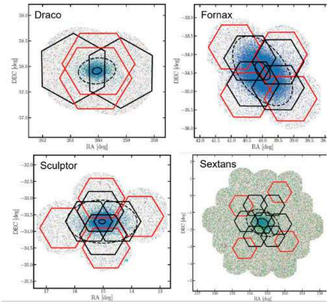
Observational implications and constraints



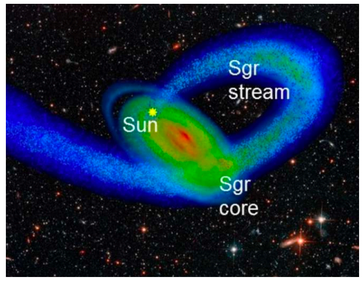
Galaxies

NASA and ESA

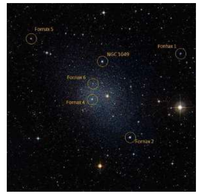
Dwarfs



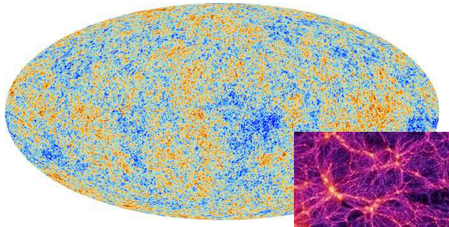
Stellar stream



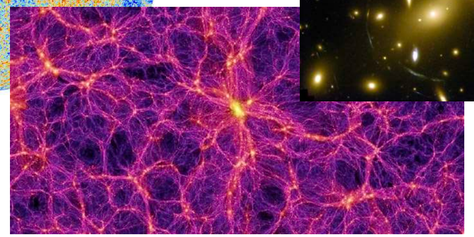
Globular clusters



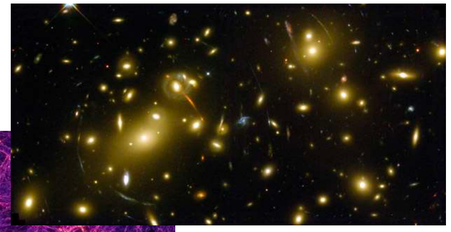
CMB+LSS



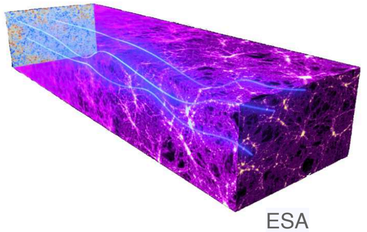
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

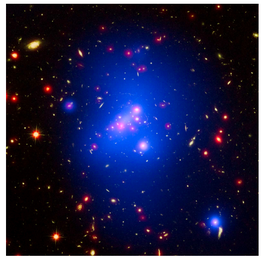


NASA and ESA

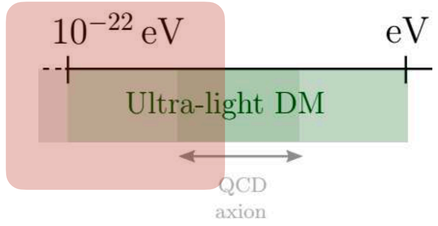


ESA

Clusters



CC BY 4.0

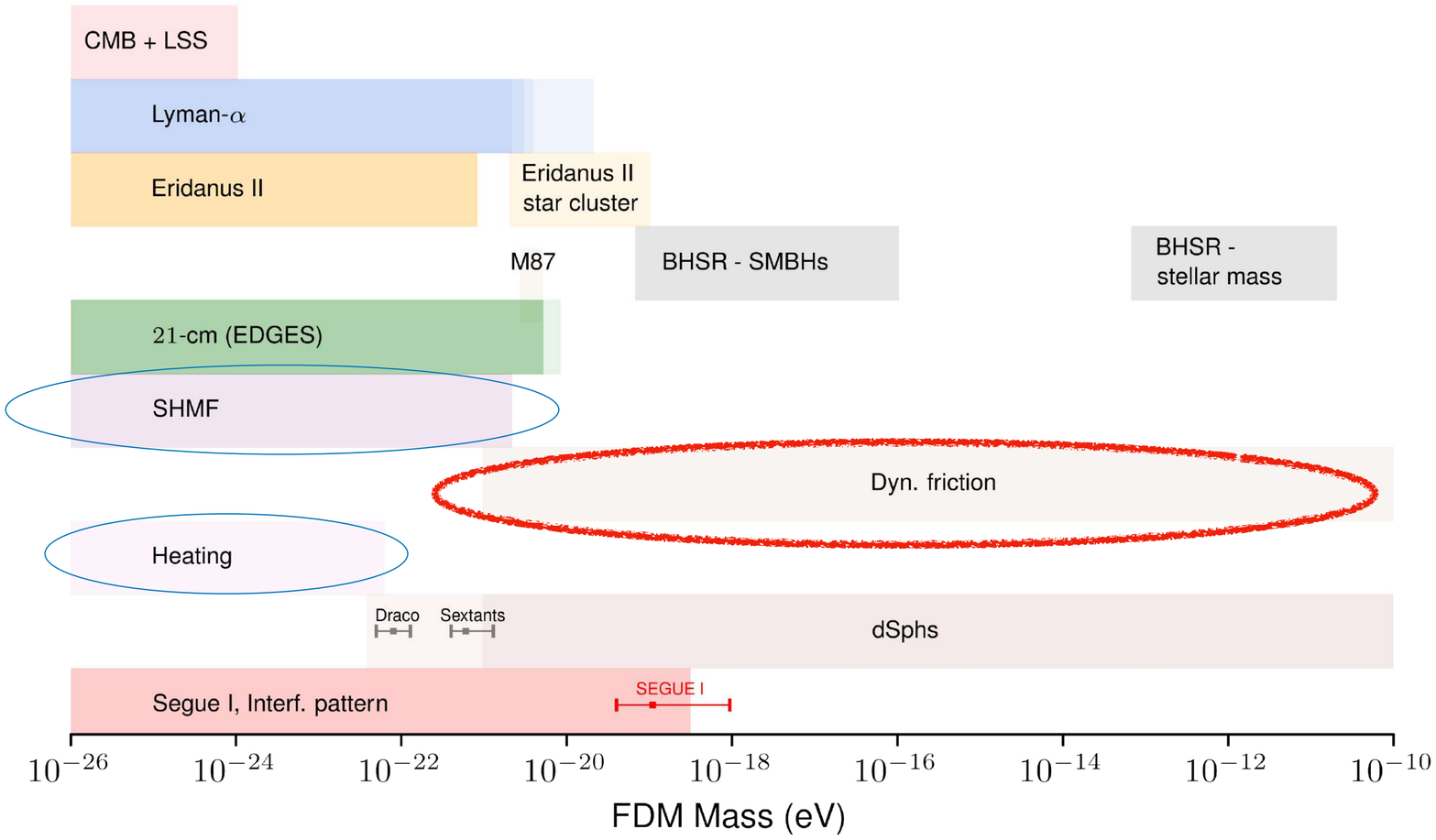


Observational implications and constraints

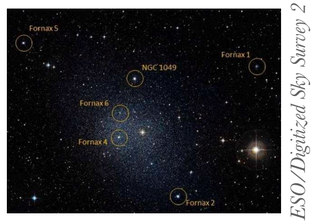
Dynamical effects

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



Dynamical effects



Lancaster et al. 2020

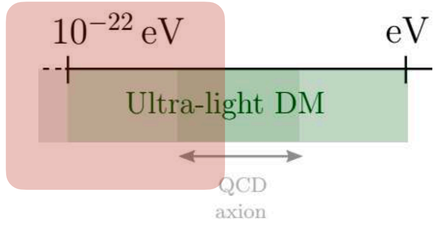
Globular clusters

$$m < 10^{-21}\,\mathrm{eV}$$

Heating of the MW disk

Church et al. 2019

$$m > 0.6 \times 10^{-22}\,\mathrm{eV}$$

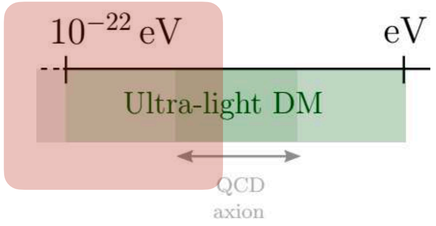


Observational implications and constraints

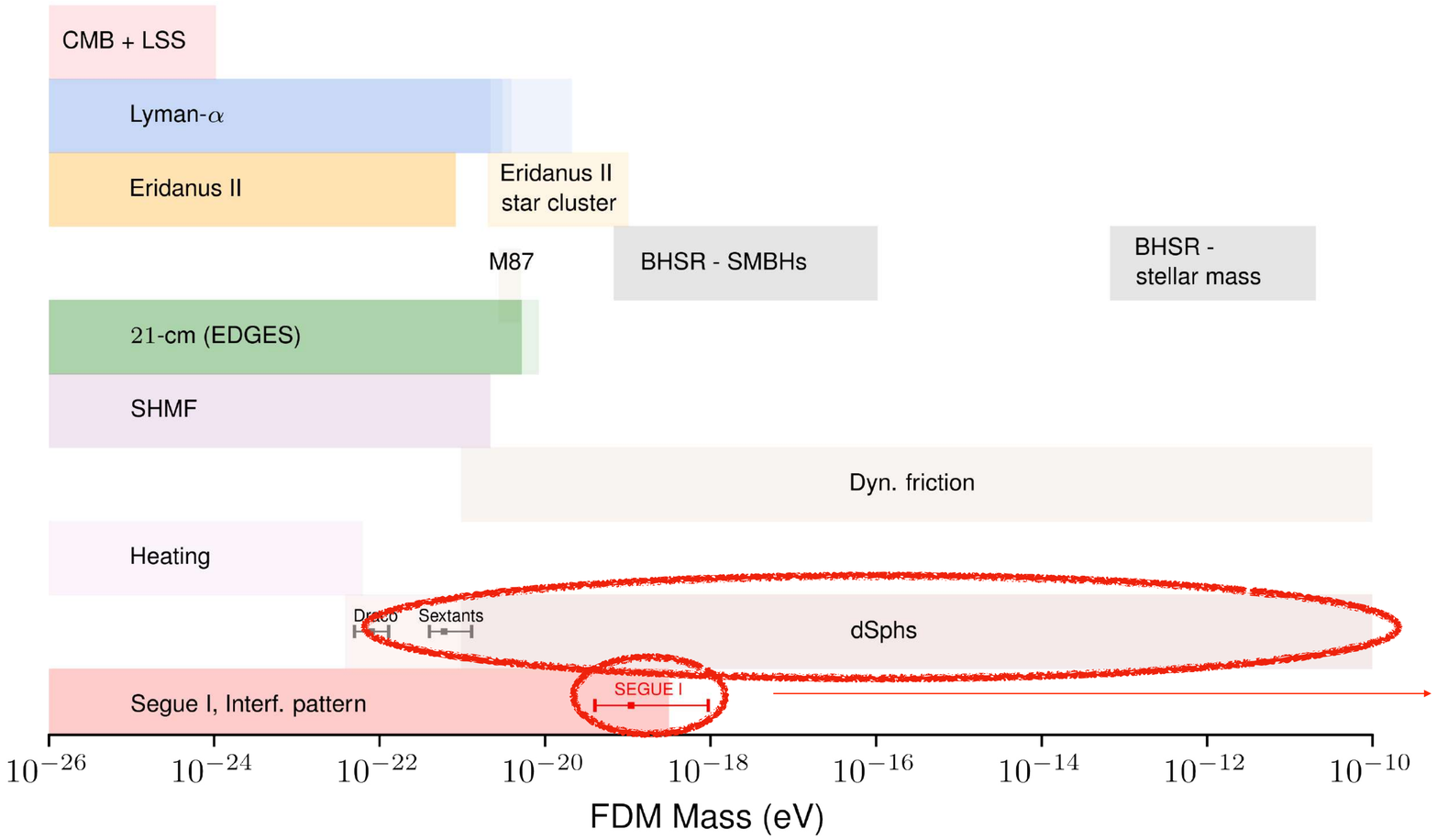
Core in the interior of galaxies

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

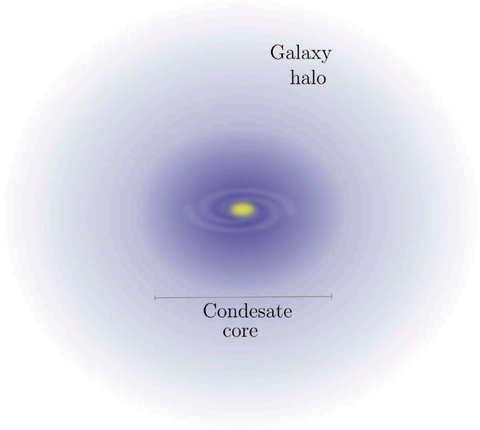


Presence of a core



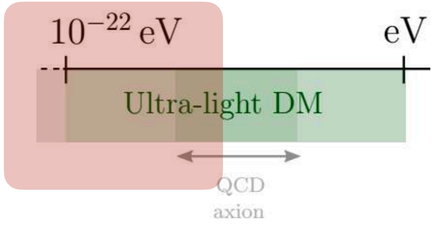
Presence of a core

DWARF GALAXIES



Observational implications and constraints

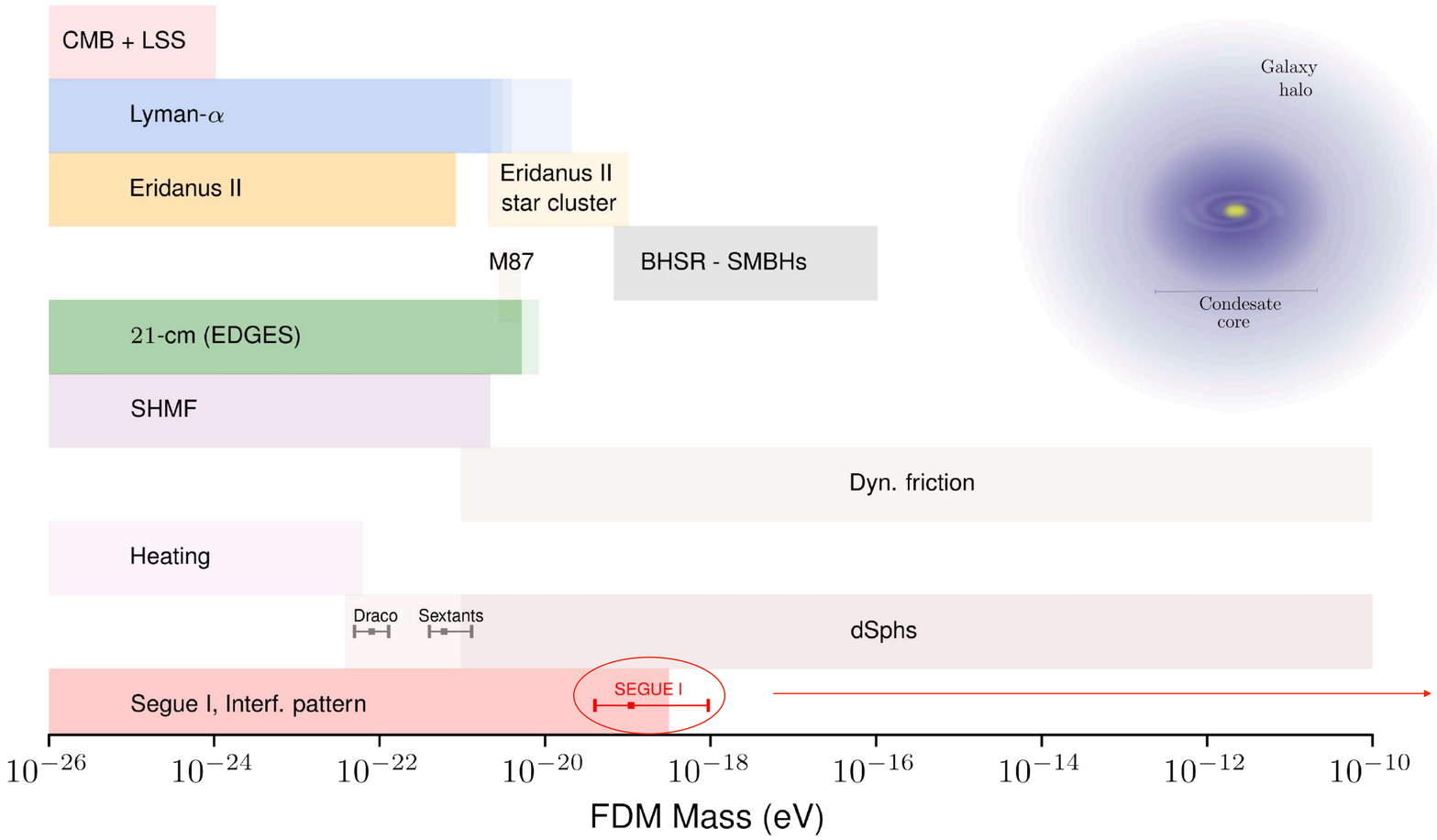
Fuzzy Dark Matter - bounds on the mass



DWARFS

Ultra faint dwarfs

Presence of a core



FDM SIMULATIONS

$$\rho(r) = \begin{cases} \rho_{\text{soliton}} \simeq \dfrac{\rho_c}{\left[1 + 0.091 (r/r_c)^2\right]^8}, & r < r_\epsilon \\ \rho_{\text{NFW}} = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, & r > r_\epsilon \end{cases}$$

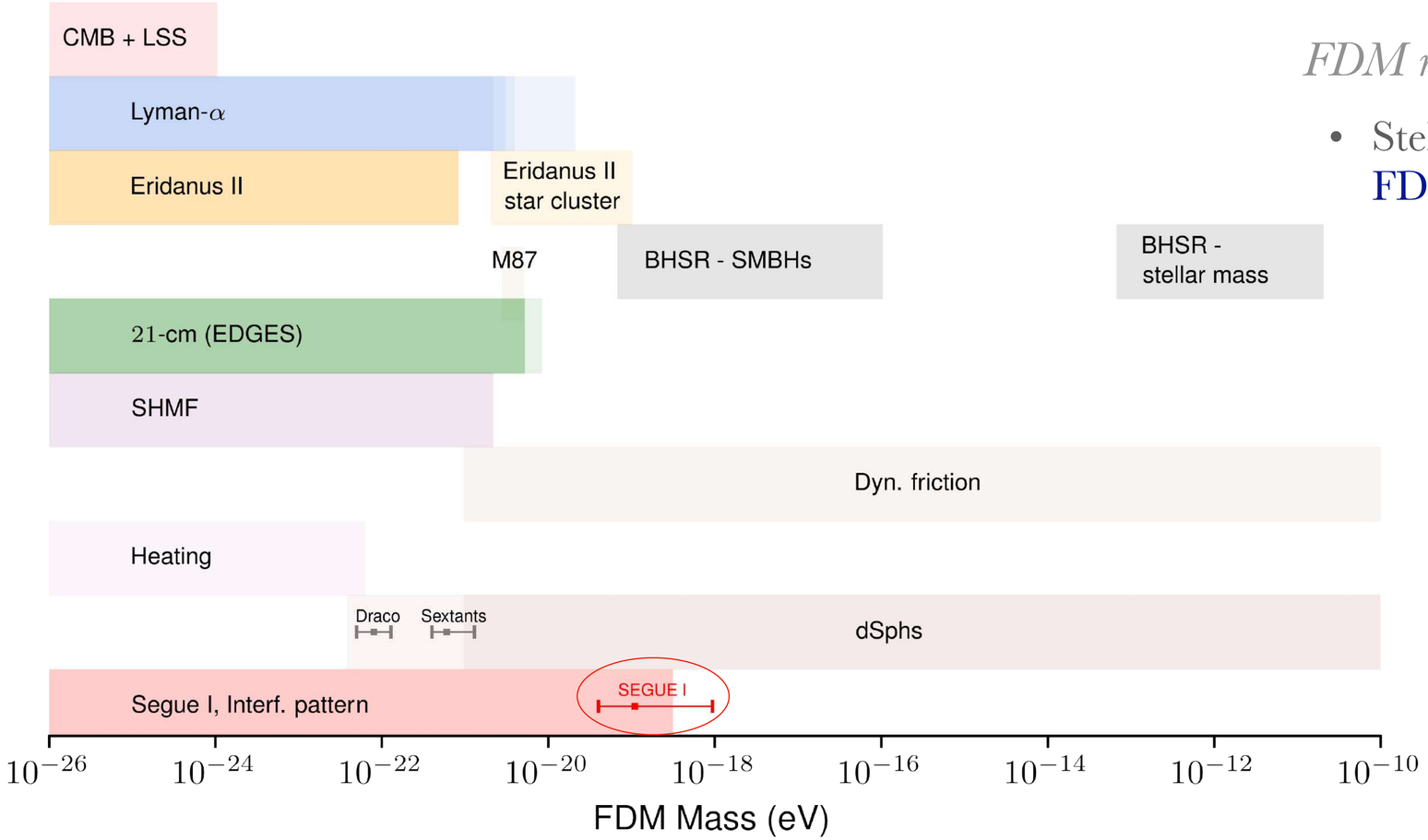
"Narrowing the mass range of Fuzzy Dark Matter with Ultra-faint Dwarfs", J. Chan, **E.F.**, K. Hayashi, 2021.

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass

Ultra faint dwarfs

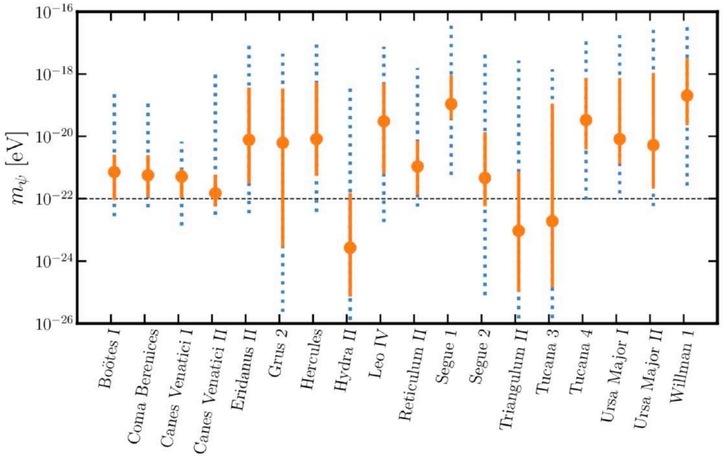
Hayashi, **E.F**,Chan, 2021.



FDM mass from Ultra-faint dwarfs

- Stellar kinematic data from 18 UFDs to fit the FDM profile from simulations

$$m_{\rm FDM}^{(Seg1)} = 1.1^{+8.3}_{-0.7} \times 10^{-19}\,{\rm eV}$$

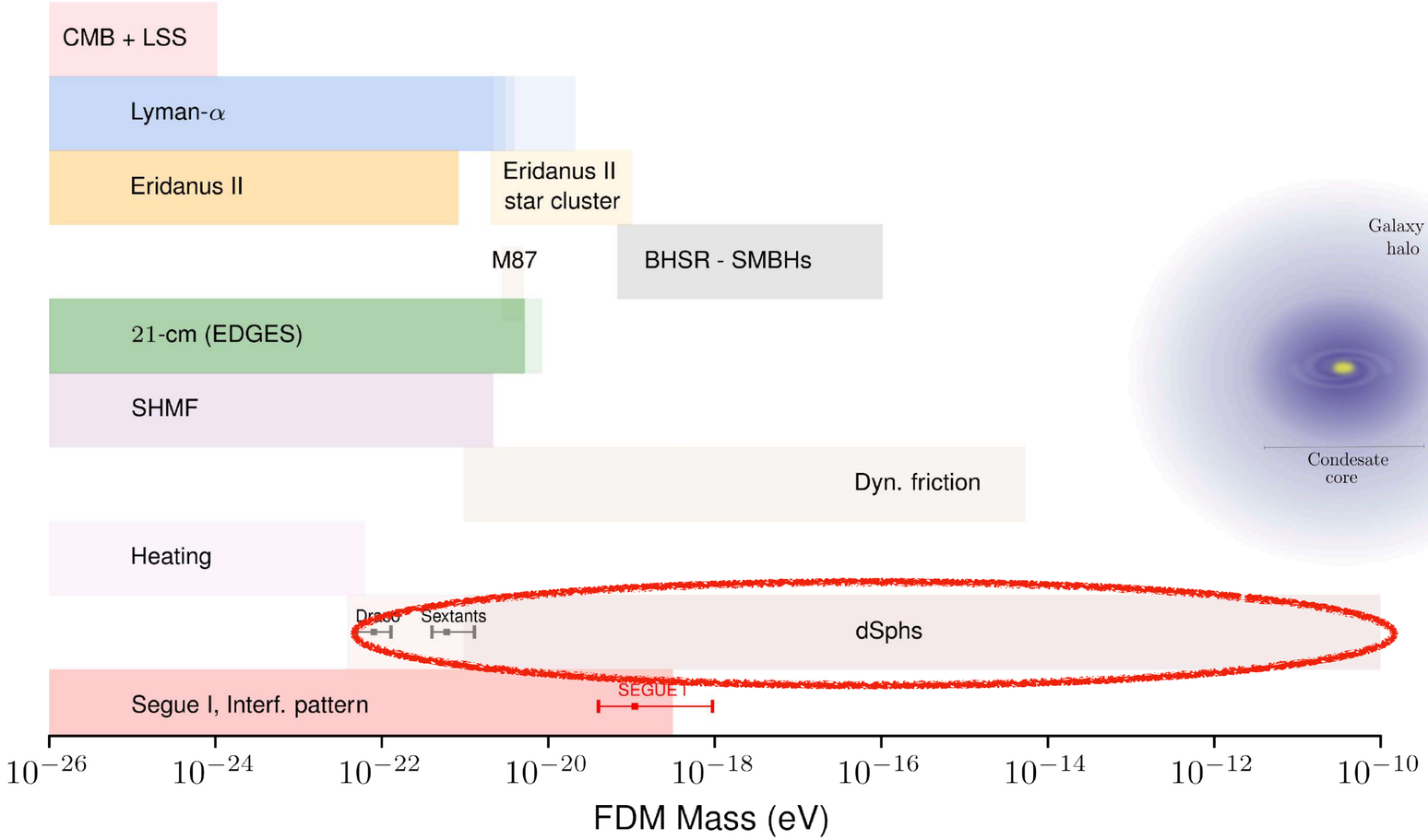


Preference for higher mass

Observational implications and constraints

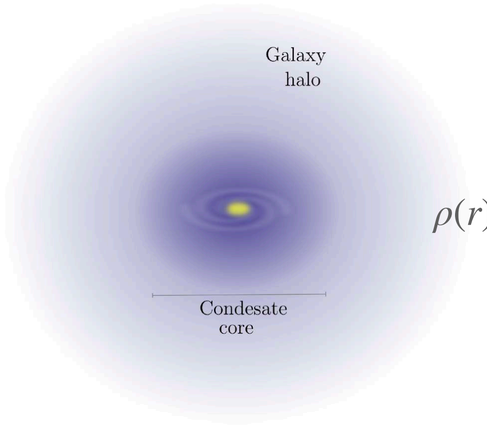
Fuzzy Dark Matter - bounds on the mass

Presence of a core



DWARFS

Dwarf Spheroidals (dSphs)



FDM SIMULATIONS

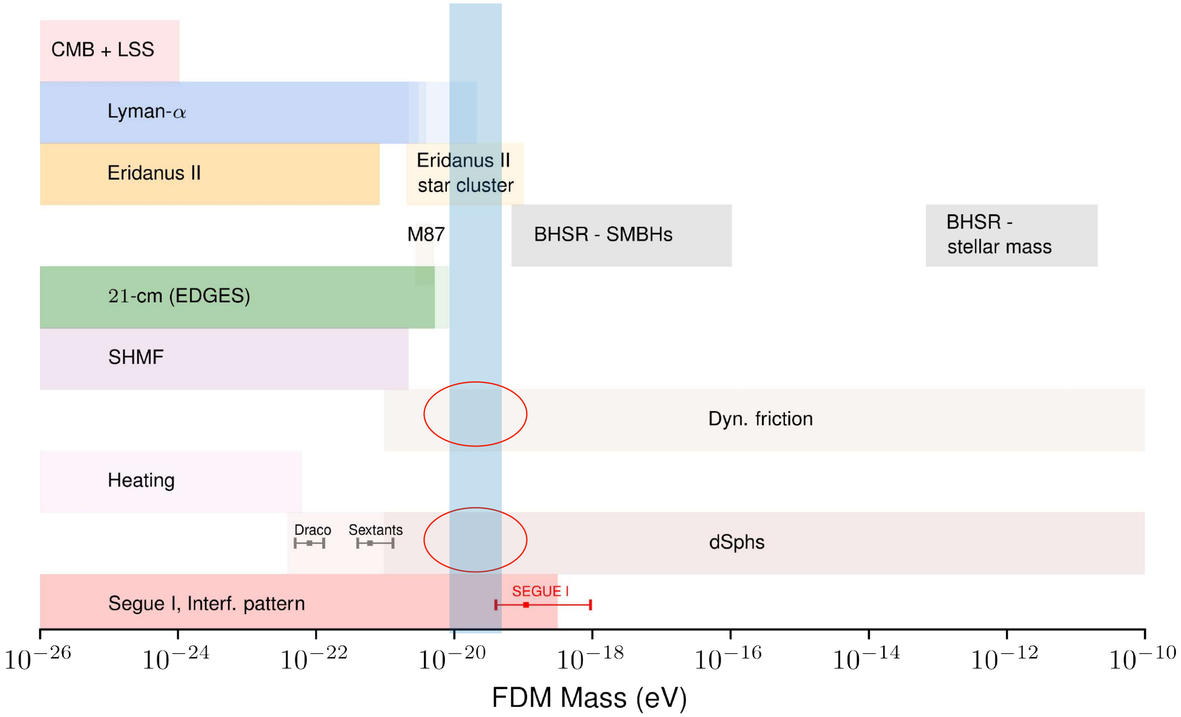
$$\rho(r) = \begin{cases} \rho_{\text{soliton}} \simeq \dfrac{\rho_c}{\left[1 + 0.091(r/r_c)^2\right]^8}, & r < r_\epsilon \\ \rho_{\text{NFW}} = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, & r > r_\epsilon \end{cases}$$

Fornax - Sculptor

$$m < 0.8 \times 10^{-22}\ \text{eV}$$

Gonzalez-Morales et al. 2017, Safarzadeh and Spergel 2019

Constraints on the mass



$$m_{\rm FDM}^{(Seg1)} = 1.1^{+8.3}_{-0.7} \times 10^{-19}\,{\rm eV}$$

Incompatibility between all bounds and the dSphs (Fornax and Sculptor) bounds

Possible reasons for this incompatibility:

- *Influence of baryons:* baryonic processes can change the density structure of their halo - we are not probing the intrinsic DM profile.
- *Universality of the core profile*: FDM soliton profile might be too simplistic, could change for different systems (might also depend on baryons)
- *Core-mass relation:* might need to be better understood. ≠ relation in ≠ simulations
- *Challenge for the FDM model*

J. Chan, EF, S. May, K. Hayashi, M. Chiba 2021

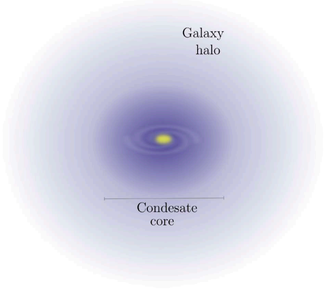
FDM - Core-halo mass relation

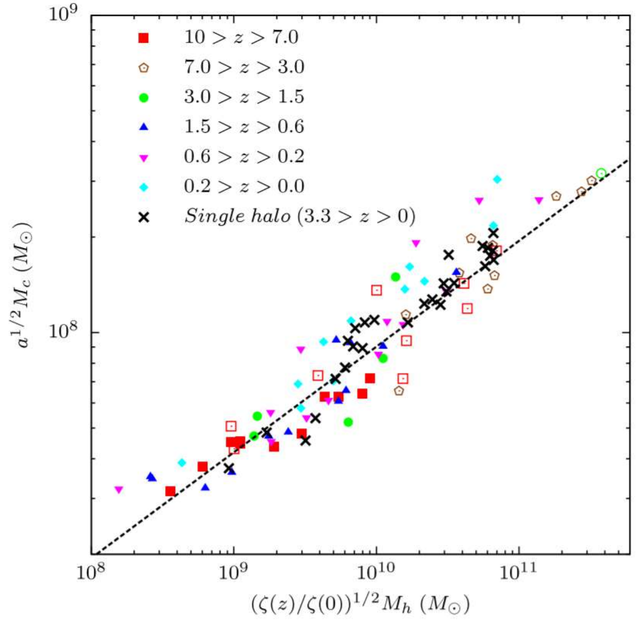
J. Chan et al. 2021

We want to study how the core relates to the halo mass - might be one part this puzzle

$$\rho_c \simeq \frac{1.9\times10^{-2}}{[1+0.091\,(r/R_{1/2,c})^2]^8}\left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-2}\left(\frac{r_c}{\mathrm{kpc}}\right)^{-4} M_\odot\,\mathrm{pc}^{-3}\,,$$

$$\xrightarrow[\quad ? \quad]{} M_h$$





Schive et al. 2014

Schive et al 2014

$$M_c \propto M_h^{1/3}$$

Velocity dispersion tracing

$$\sigma_c \sim \sigma_h$$

Mocz et al 2017

$$M_c \propto M_h^{5/9}$$

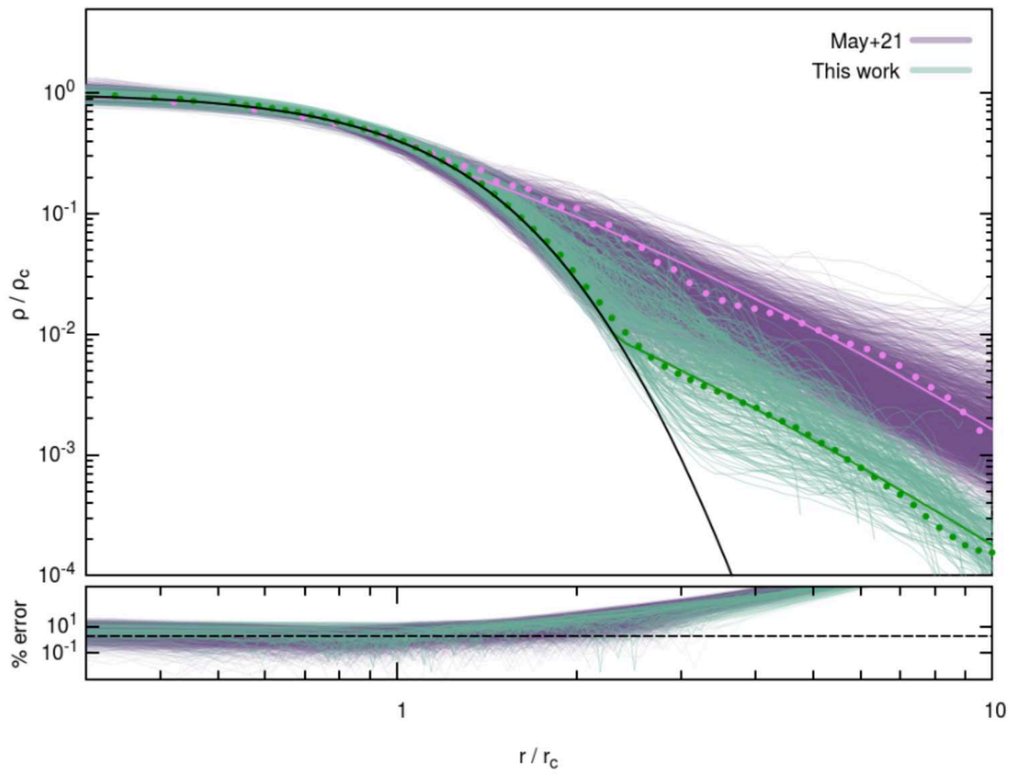
Energy tracing

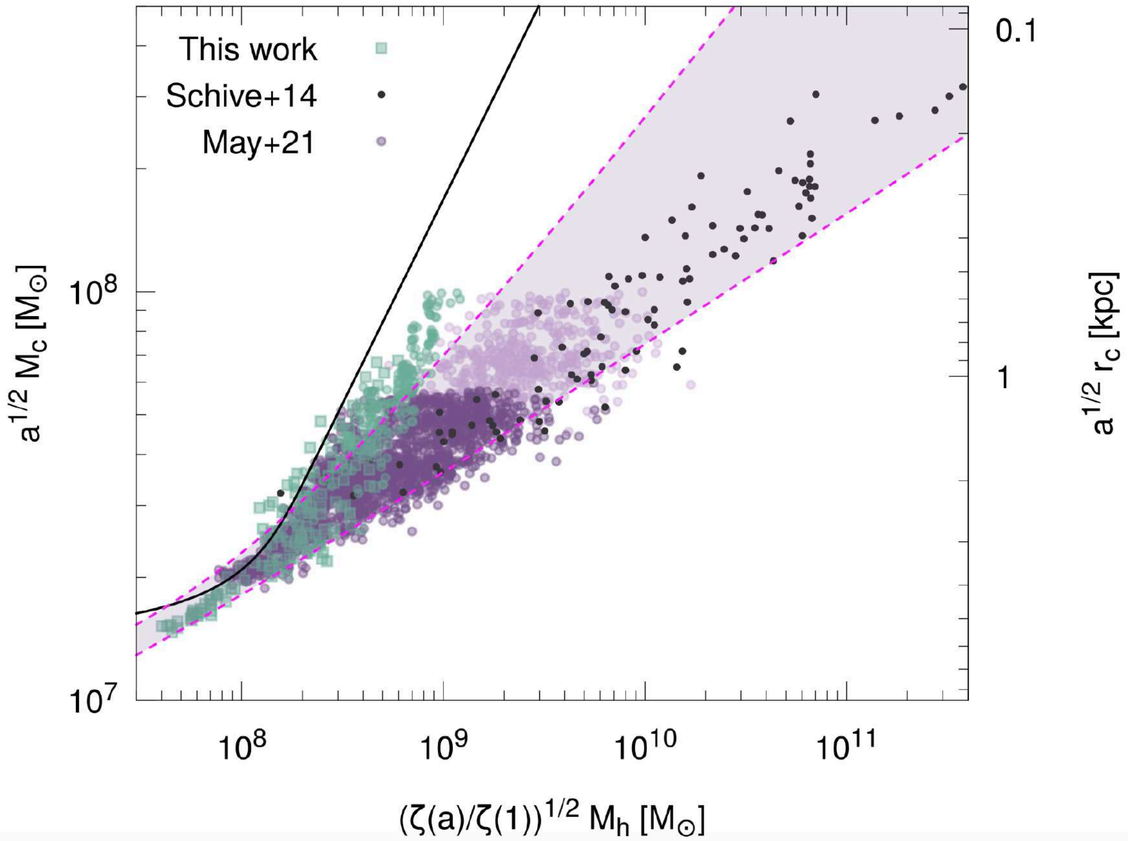
$$M_c\,\sigma_c^2 \sim M_h\,\sigma_h^2$$

$\underbrace{\text{Velmatt et al 2018}}_{=\text{ Schive}}$, $\underbrace{\text{Nori et al 2020, Nima et al 2020}}_{\neq\text{ Schive}}$

FDM - Core-halo mass relation

J. Chan, EF, S. May, K. Hayashi, M. Chiba 2021





Well fitted by:

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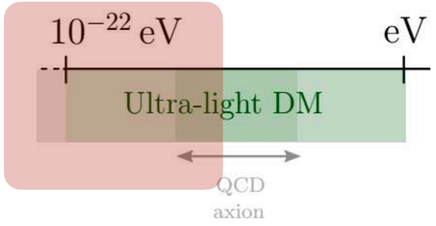
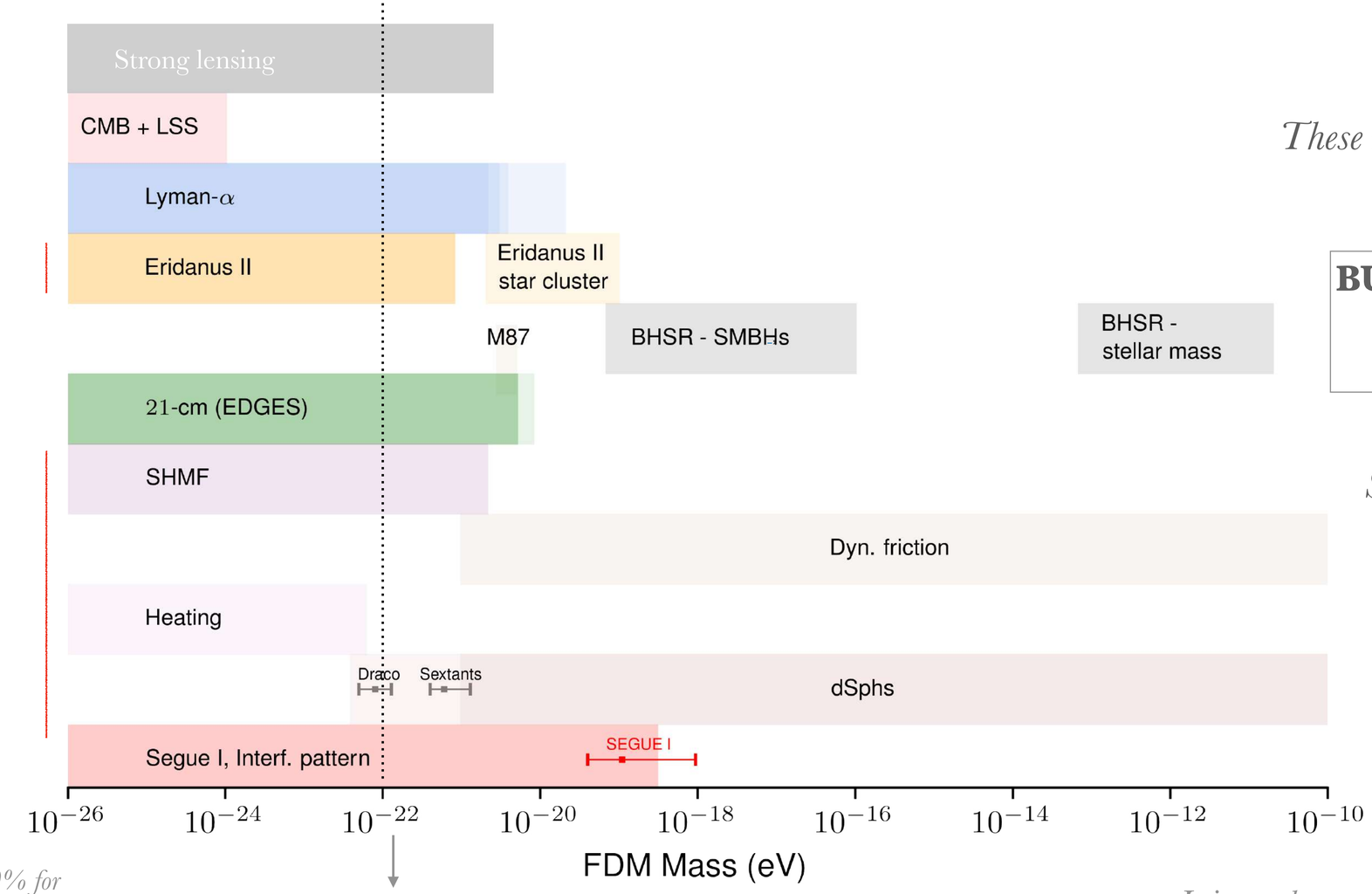
Steeper slope → Smaller core → Smaller mass

Current status

Fuzzy Dark Matter - bounds on the mass





These models can be highly constrained

BUT: - systematic effects!!
- dynamics of FDM not fully understood.

Some bounds are incompatible!

Need:
- Observations
- Improve sims
- New observables
- New probes

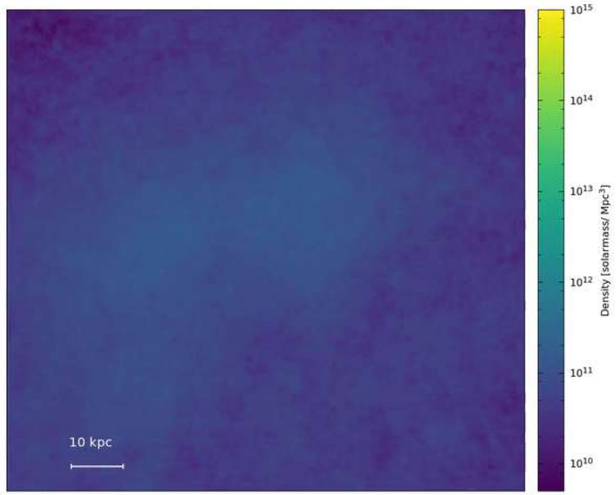
Caner et al: FDM at most 10% for
$10^{-21}\,\mathrm{eV} < m < 10^{-17}\,\mathrm{eV}$

Sweet spot for solving small scale problems

It is not because the bound is here that it is correct!

New observables/new probes

Interference pattern



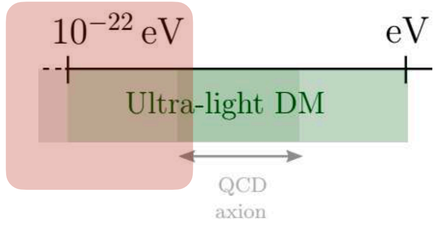
Simulation by Jowett Chan

$\mathcal{O}(1)$ fluctuations in density $\longrightarrow$ $\sim \lambda_{\rm dB}$

PROBES:

- Strong lensing
- Stellar streams
- Heating

} Gravitational probes



ONGOING

In collaboration with Jowett Chan and Simon May

- Characterizing the interference patterns using full simulations
- Strong lensing — *In collaboration with: Devon Powel, Simona Vegetti, Simon White*
- Stellar streams — *In collaboration with: Sten Delos and Fabian Schmidt*

Previous studies:

Strong lensing:
J. Chan, H.Schive, S.g Wong, T. Chiueh, T. Broadhurst, 2020
A. Laroche, Daniel Gilman, X. Li, J. Bovy, X. Du, 2022

Stellar streams:
Neal Dalal, Jo Bovy Lam Hui, Xinyu Li, 2020

Sub-galactic power spectrum:
Hezaveh et al. (2016)

Sub-galactic power spectrum
Kawai, Oguri (2021)

Dwarfs
N. Dalal, A. Kravtsov, 2022

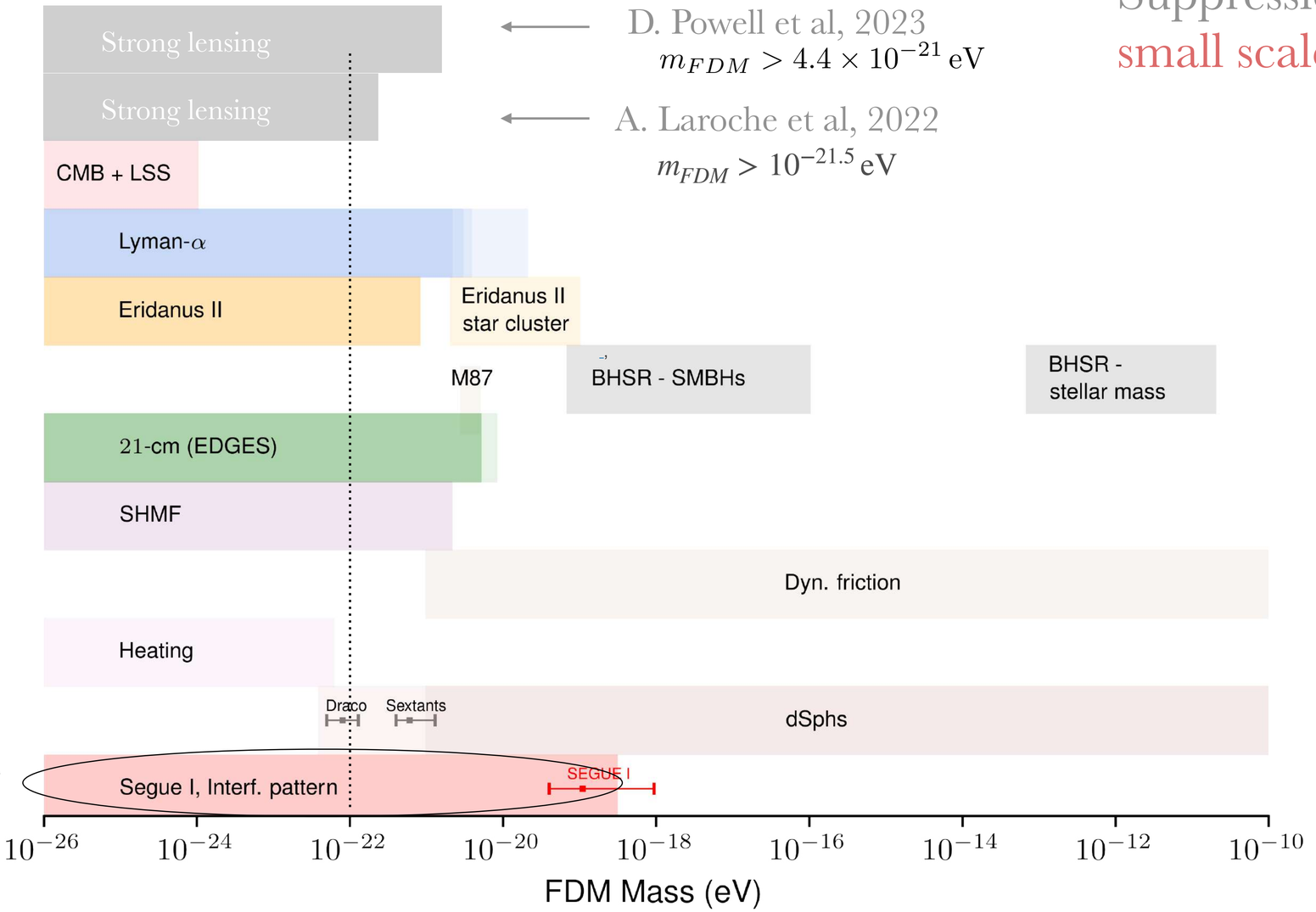
Interference patterns - granules

Strong lensing

D. Powell et al, 2023
$m_{FDM} > 4.4 \times 10^{-21}$ eV

A. Laroche et al, 2022
$m_{FDM} > 10^{-21.5}$ eV

Suppression of
small scale structures

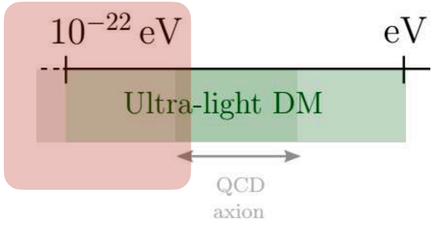


Dynamical effects

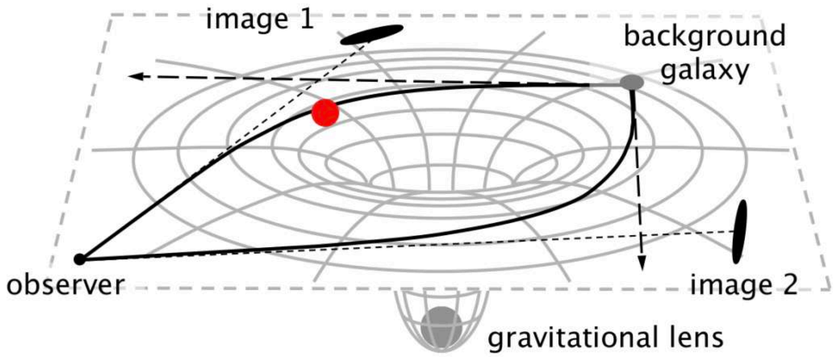
Stellar heating

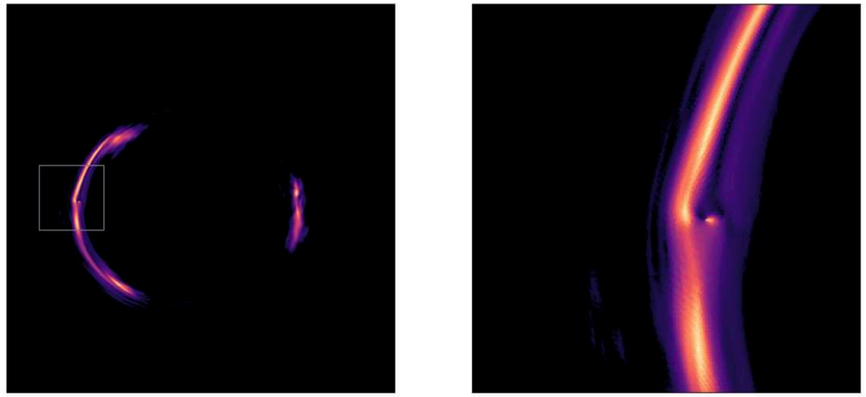
Dalal et al, 2022
$m_{FDM} > 3 \times 10^{-19}$ eV

Strong lensing



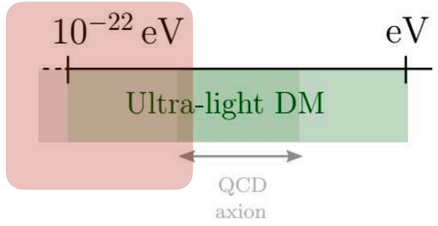
Low mass perturber with lensing





- Strong lensing: powerful probe of substructure
- Sensitivity is limited by angular angular resolution
- Roughly speaking, the resolution must be better than the scale radius of the perturber

Strong lensing



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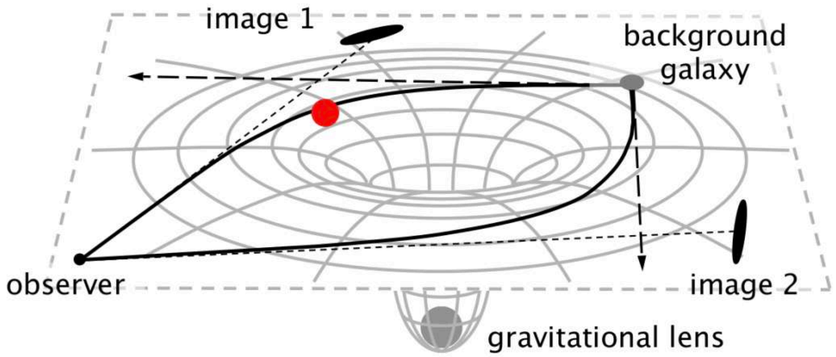
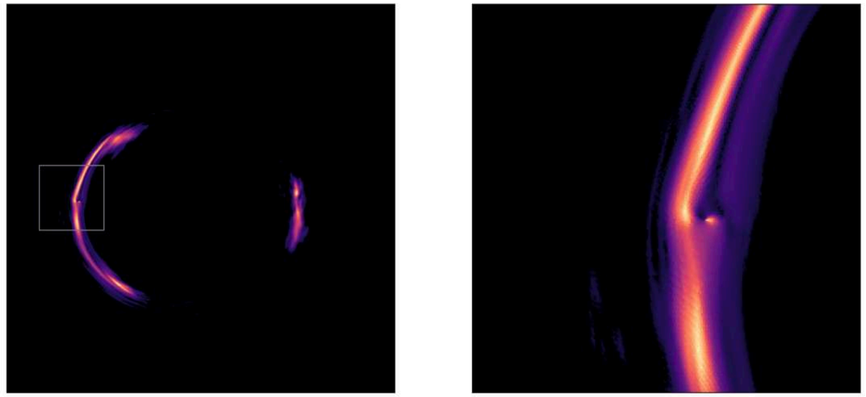
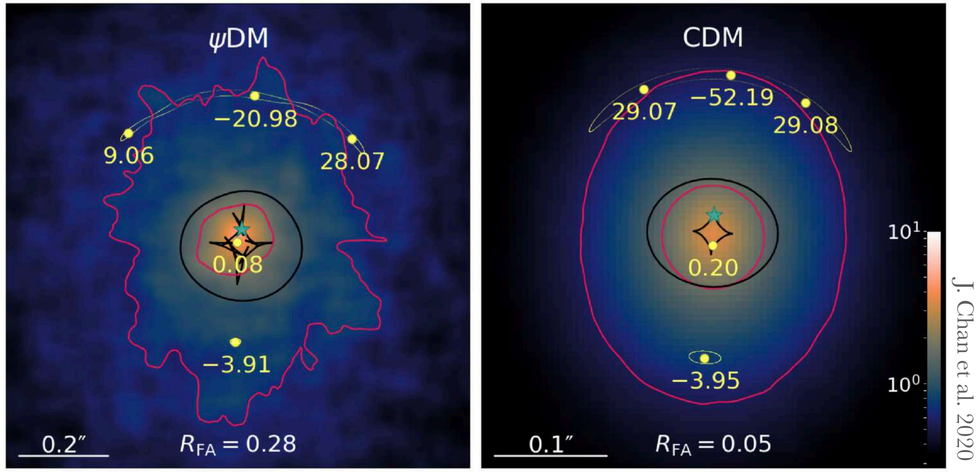




Presence of granules

Surface densities overlaid with sources and quad images for fuzzy and smooth lenses



J. Chan et al. 2020

Fuzzy lens: fluctuating tangencial critical curve; flux ratio anomalies also sizable.

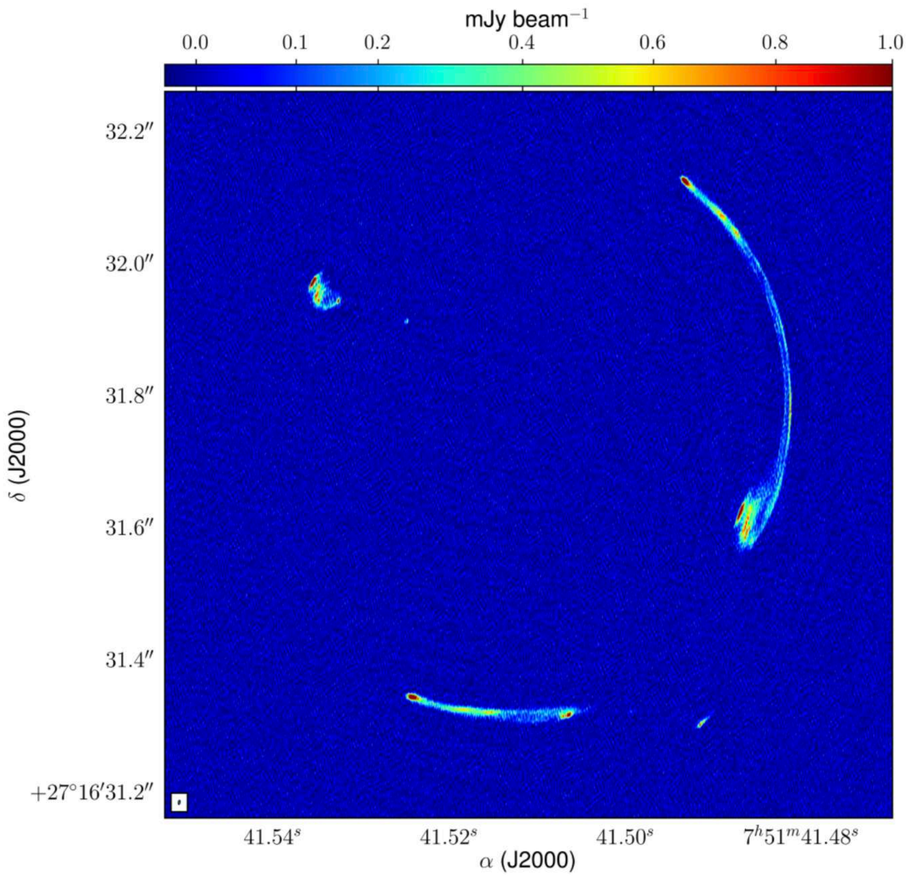
Previous works:
J. Chan, H.Schive, S.g Wong, T. Chiueh, T. Broadhurst, 2020
A. Laroche, Daniel Gilman, X. Li, J. Bovy, X. Du, 2022

Strong lensing

A lensed radio jet at milli-arcsecond resolution II: Constraints on fuzzy dark matter from an extended gravitational arc

D. Powell, S. Vegetti, J.P. McKean, S. White, EF, S. May, C. Spingola

MG J0751+2716



- Lensed radio jet, observed with global VLBI
- First image of a lensed radio jet!
- Source structure allows us to "image" the lens surface density
- Extended lensed radio arcs and the milli-arcsecond resolution provide direct sensitivity to the presence of FDM granules in the halo of the lens galaxy

Data taken at 1.6 GHz using global very long baseline interferometry (VLBI) with an angular resolution, measured as the full width at half maximum (FWHM) of the main lobe of the dirty beam response, of 5.5×1.8 mas^2

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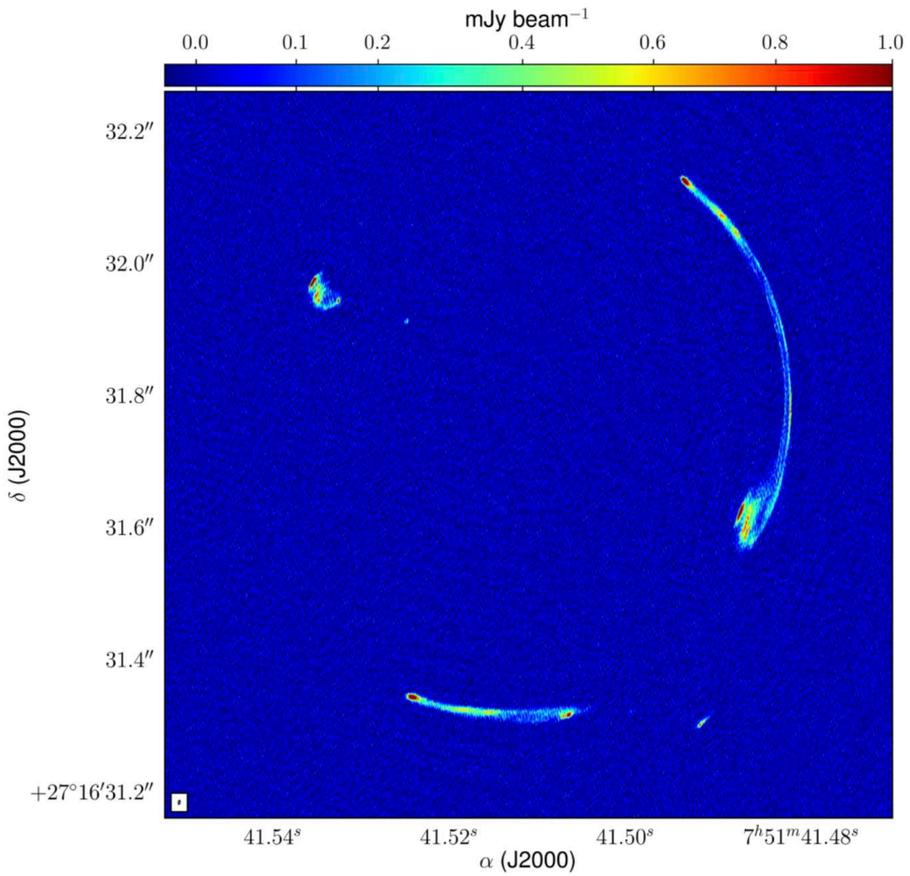

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Bayesian approach to jointly inferring the lens mass model and source surface brightness distribution

(Suyu et al. 2006; Vegetti & Koopmans 2009; Hezaveh et al. 2016; Rizzo et al. 2018)

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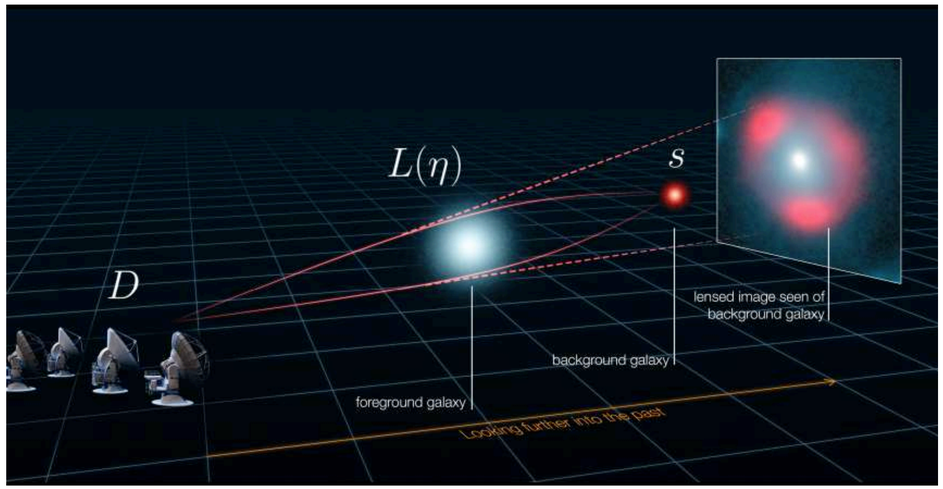
Forward modeling



Instrumental response

source

$$\mathbf{m} = \mathbf{D}\,\mathbf{L}(\delta\psi, \eta)\,\mathbf{s}$$

Lens operator

Smooth lens model

Potential perturbations

$$\delta\psi(m_{fdm}, f_{dm}, \sigma_v)$$

Smooth lensing model: from *Powell et al 2022*

FDM granules:
Model by Chan et al 2020: statistics of spatially-varying surface mass density fluctuations, given the density profile of the dark matter, as well as some basic assumptions on the behavior of scalar fields in a potential well $\delta\psi(m_{fdm}, f_{dm}, \sigma_v)$ (perturbation of the lensing potential) fluctuations in the projected surface mass density written as perturbations in the lensing convergence due to the presence of the granules:

$$\langle \delta\kappa^2 \rangle = \frac{\lambda_{db}}{2\sqrt{\pi}\Sigma_c^2} \int_{los} \rho_{DM}^2 \, dl$$

We wish to infer a posterior distribution on the dark matter particle mass $\mathcal{P}(m_{fdm})$

We compute likelihoods for 10^4 sample FDM lens realizations with m_{fdm} drawn from the log-uniform prior range $\log(m_{fdm}/\mathrm{eV}) \in [-21.5, -19.0]$.

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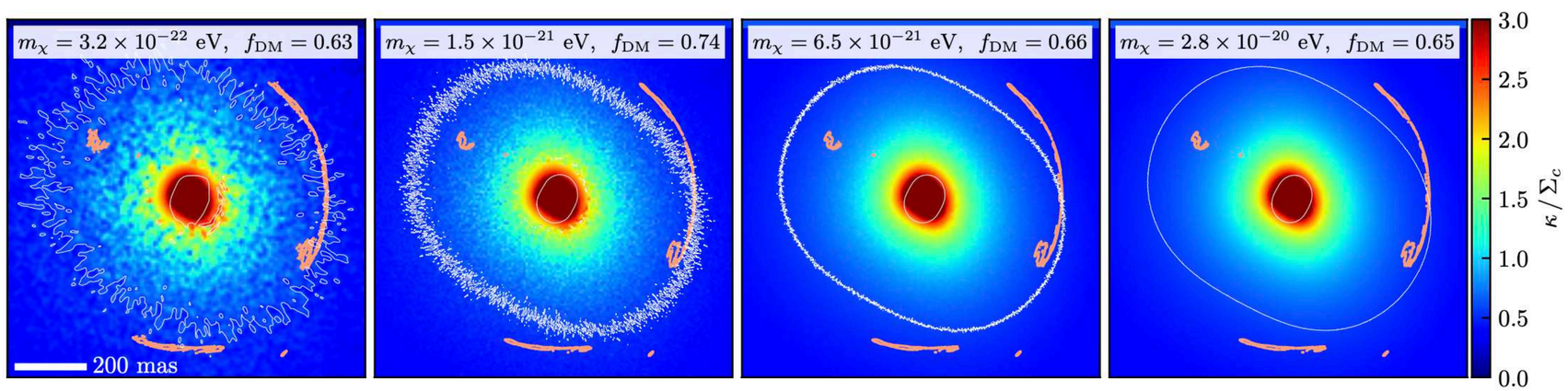
Example convergence maps with corresponding MAP surface mass density maps (κ, in units of the critical density Σc) reconstruction for 4 random realizations of MG J0751+2716 in an FDM cosmology - the model lensed images in orange contours



The lensing effect of the FDM granules is apparent: The critical curves wiggle back and forth across the lensed arcs, which would require the presence of multiple images of the same region of the source along the arc.

Strong lensing

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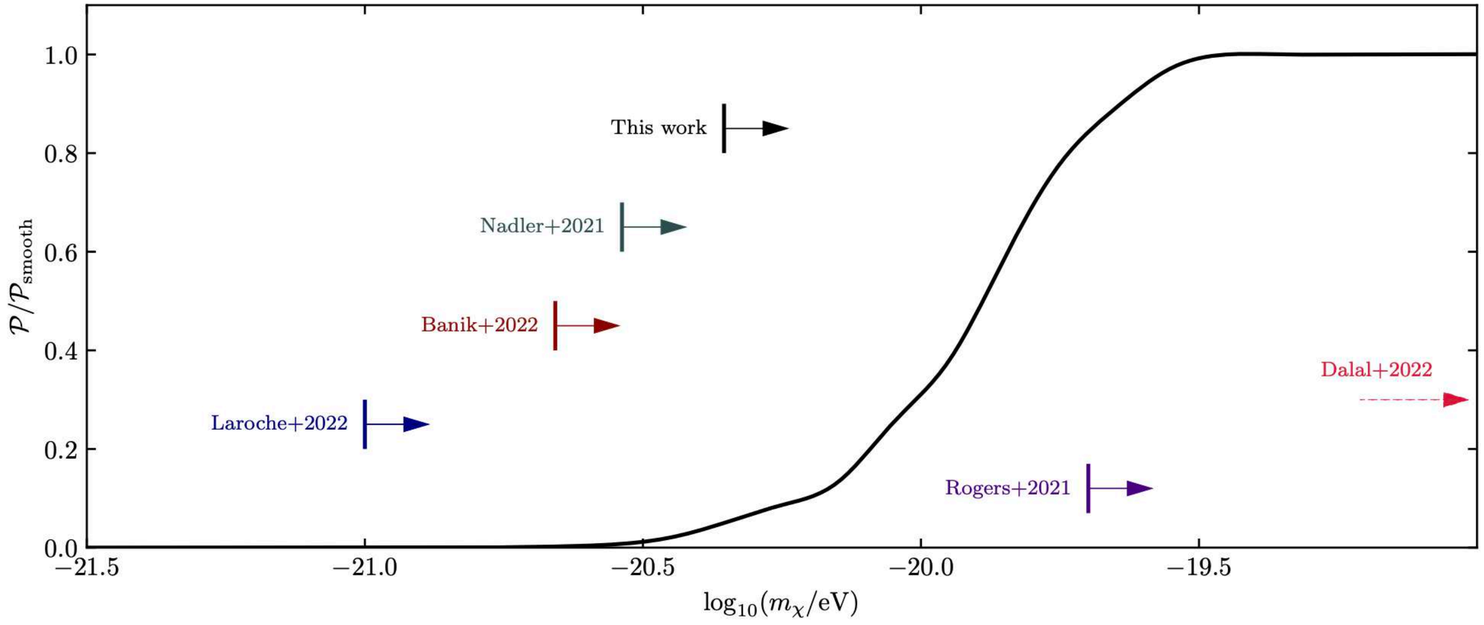
Results quoted in terms of posterior odds ratio (POR) between FDM with a particle mass m_{fdm} and the smooth model, $\mathscr{P}/\mathscr{P}$smooth



Fuzzy dark matter
(Single spin-0 particle)

$$m_{\rm fdm} > 4.4 \times 10^{-21}\ {\rm eV}$$

Vector fuzzy dark matter
(spin-1 particle)
OR 3 same mass FDM

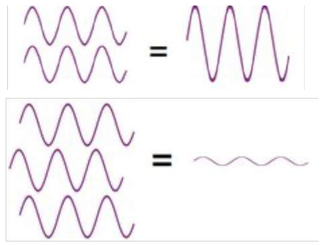
$$m_{\rm vdm} > 1.4 \times 10^{-21}\ {\rm eV}$$

Spin-2 FDM

$$m_{\rm spin-2} > 8.8 \times 10^{-22}\ {\rm eV}$$

Vector, higher spin or multicomponent FDM

Interference patterns

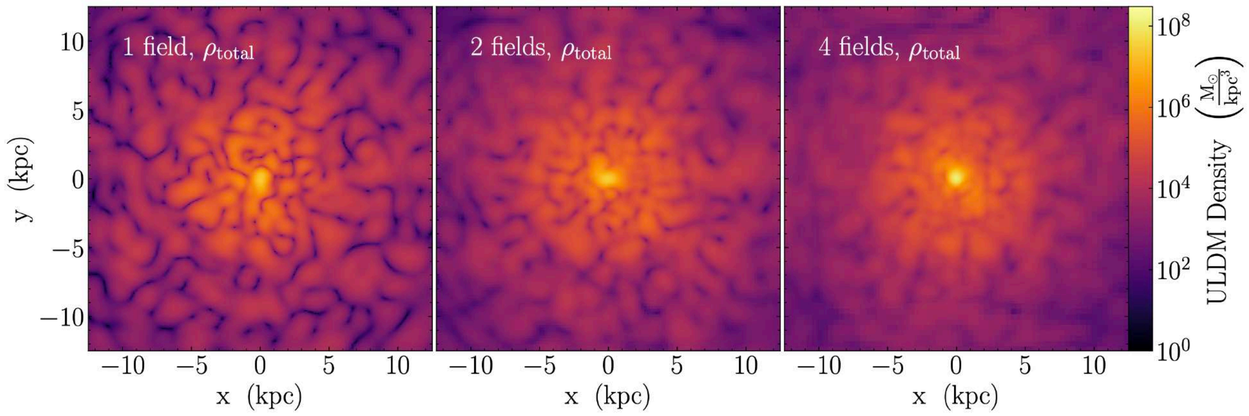


ULDM or ULA are a coherent wave - same frequency and constant phase difference

Multiple coherent waves

Gonseca et al 2023

For ULDM:



Multiple FDM or VFDM (or higher spin s FDM) *attenuates* the granule amplitude by

$$\frac{[\delta\rho/\rho]_{\rm nfdm,s}}{[\delta\rho/\rho]_{\rm fdm}} \propto \frac{1}{\sqrt{(2s+1)}} = \frac{1}{\sqrt{N}}$$

(Amin et al 2022)

Expectation for lensing:

$$\langle \delta\kappa^2 \rangle = \frac{\lambda_{dB}}{2\sqrt{\pi}\,\Sigma_c^2} \int \rho_{\rm DM}^2 \, dl \quad \Rightarrow \quad m_{nfdm,s} = \frac{m_{fdm}}{N} = \frac{m_{fdm}}{2s+1}$$

Detailed simulations and analysis in the future!

Vector (and higher-spin) FDM Amin et al 2022

(Vector FDM = 3 x same mass FDM (spin 0))

Multicomponent FDM Gonseca et al 2023

Strong lensing

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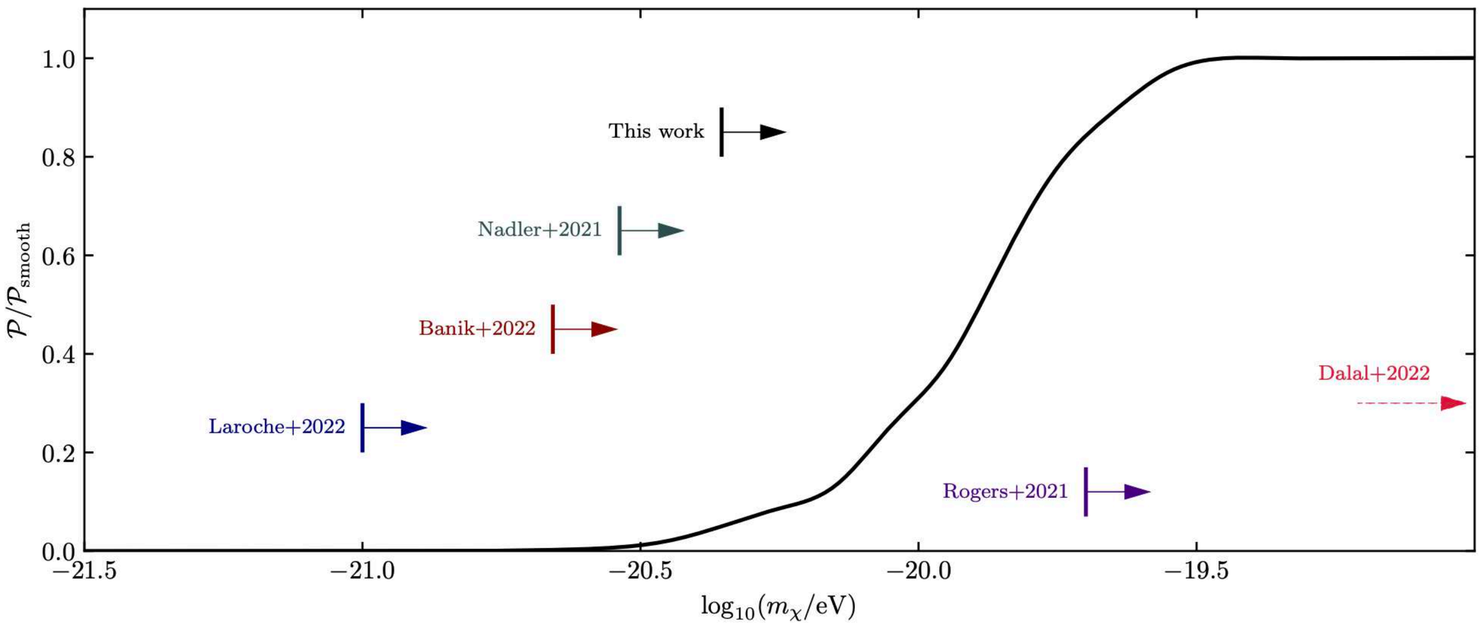

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Spin-2 FDM

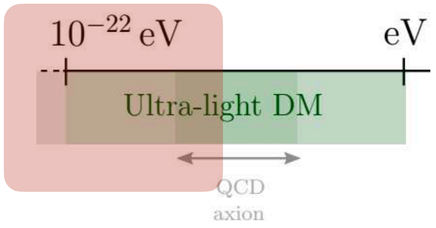
$$m_{\rm spin-2} > 8.8 \times 10^{-22}\ {\rm eV}$$

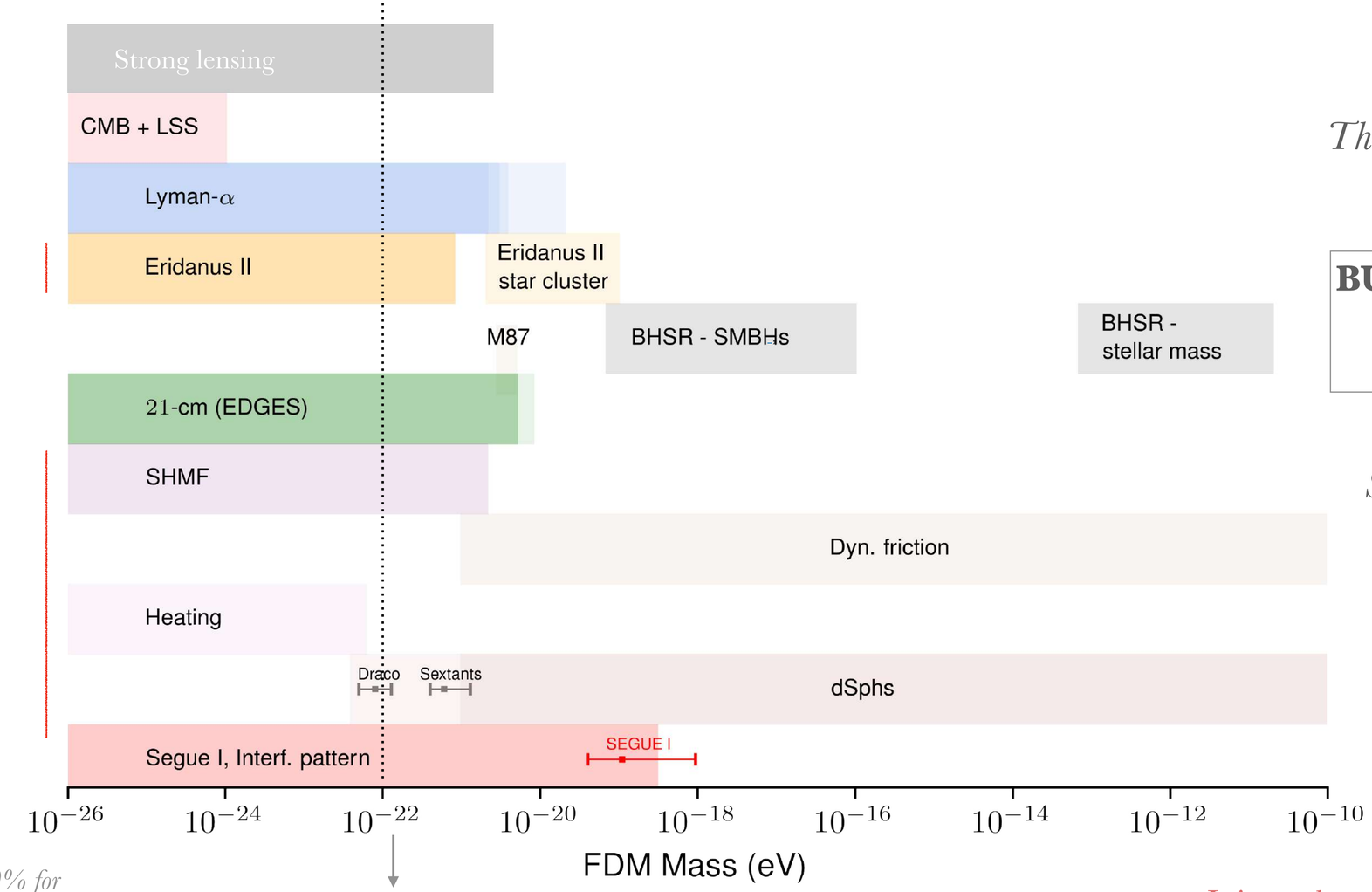
Milli-arcsecond angular resolution of VLBI, competitive constraints on dark matter models can be inferred using a single strong gravitational lens observation

More lenses in the future!

Current status

Fuzzy Dark Matter - bounds on the mass





These models can be constrained

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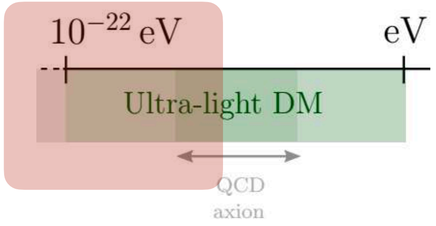

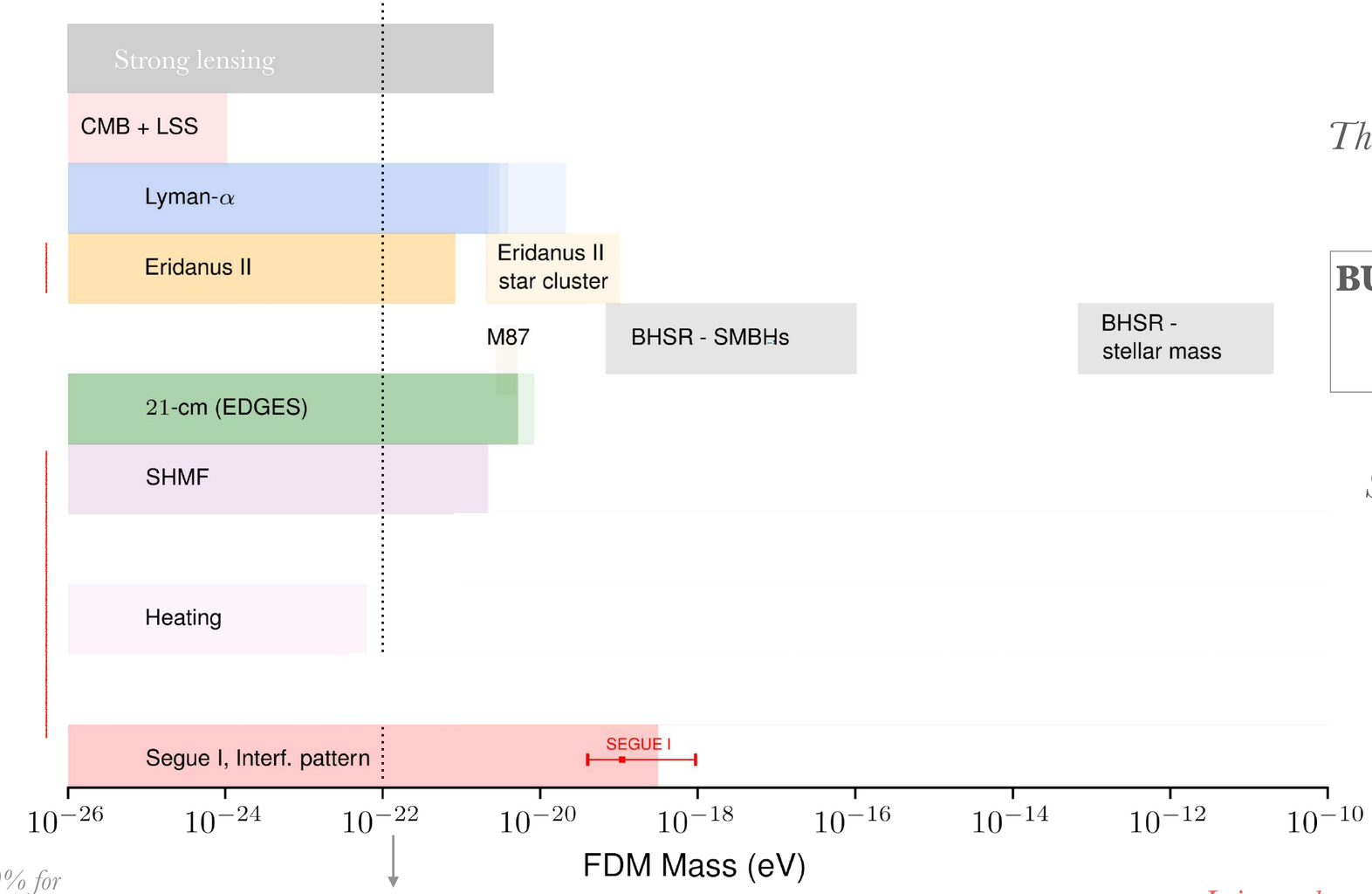

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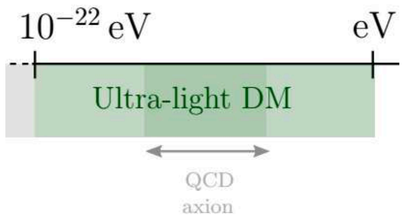
It is not because a bound is here that is correct!

Observational implications and constraints



Bounds on the mass and other parameters

Self interacting FDM

m g

DM Superfluid

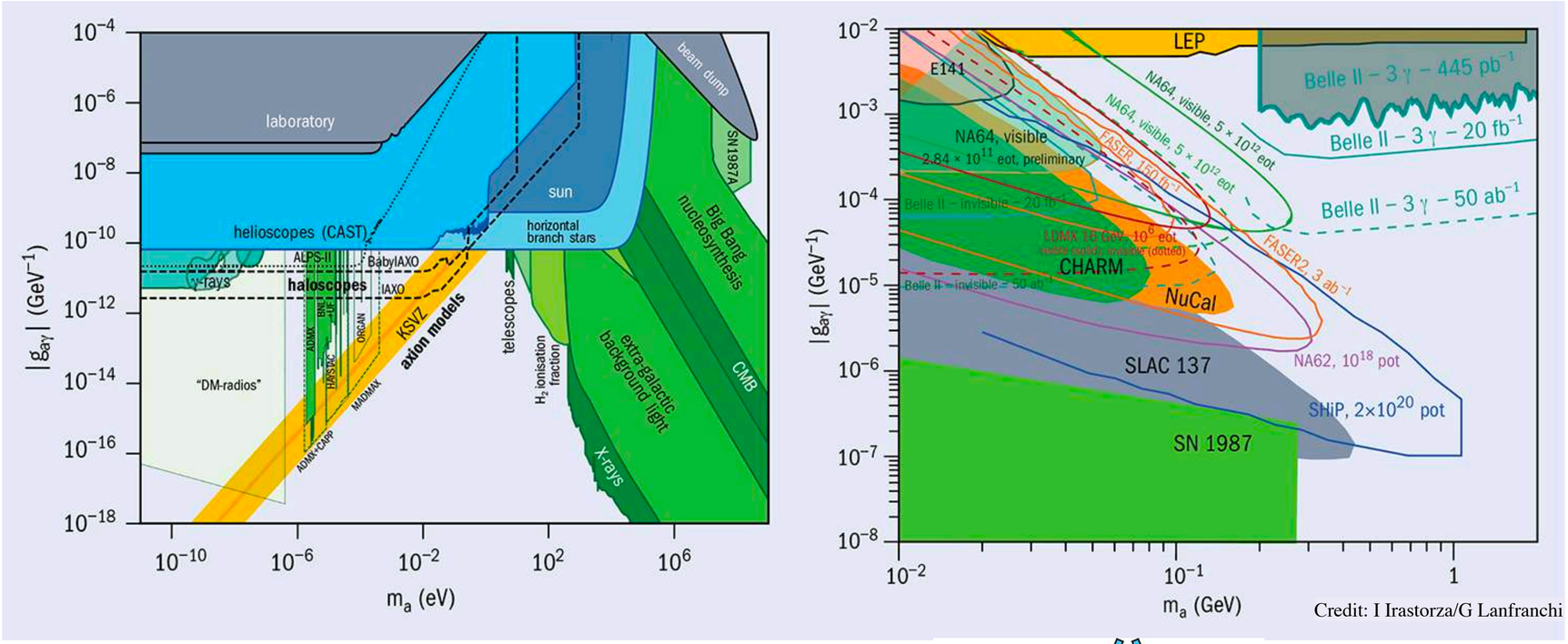
$$\mathcal{L} = P(X)$$

* Check: Lasha Berezhiani et al (2020)

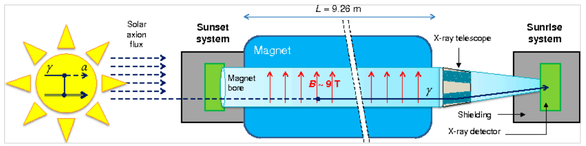
Still highly unconstrained

Axion - direct and indirect detection

Axion and ALP interacts with photons

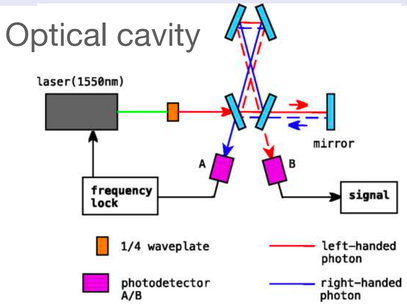


Credit: I Irastorza/G Lanfranchi



CAST

Optical cavity



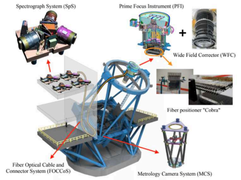
Obata et al 2018

Future - *signals in cosmology*

Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)



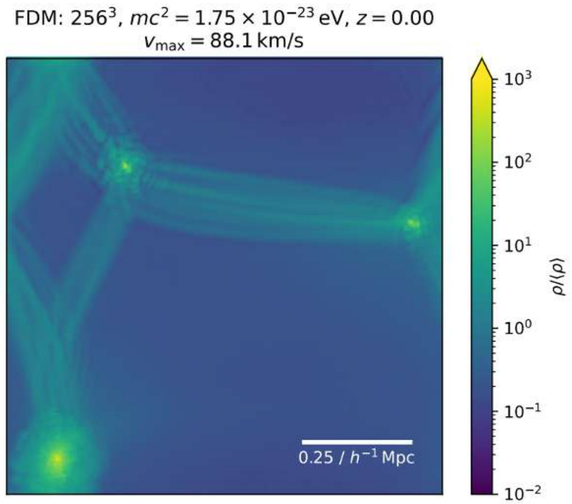
CMB

CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New observables

New probes

Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Modified from Jia Liu

What is the predicted size and abundance of vortices in the halo?
Are they observable?
Strong lensing? Stellar streams?
Can they be formed in the filaments?

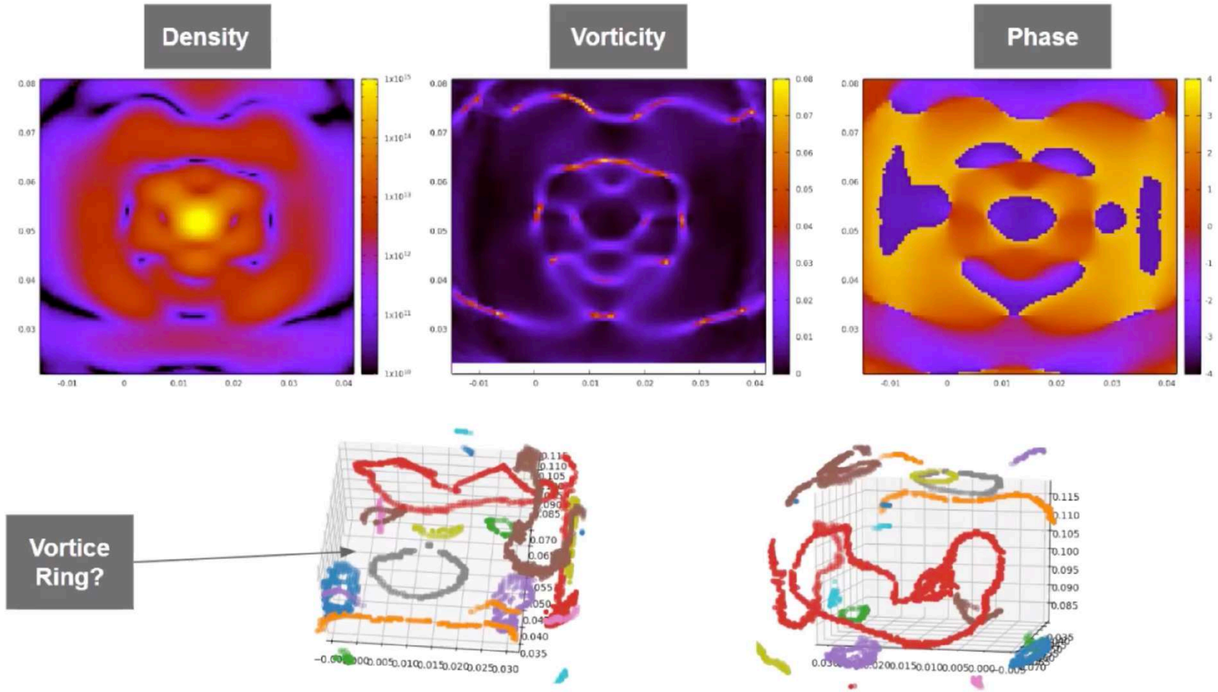
New observables

Vortices

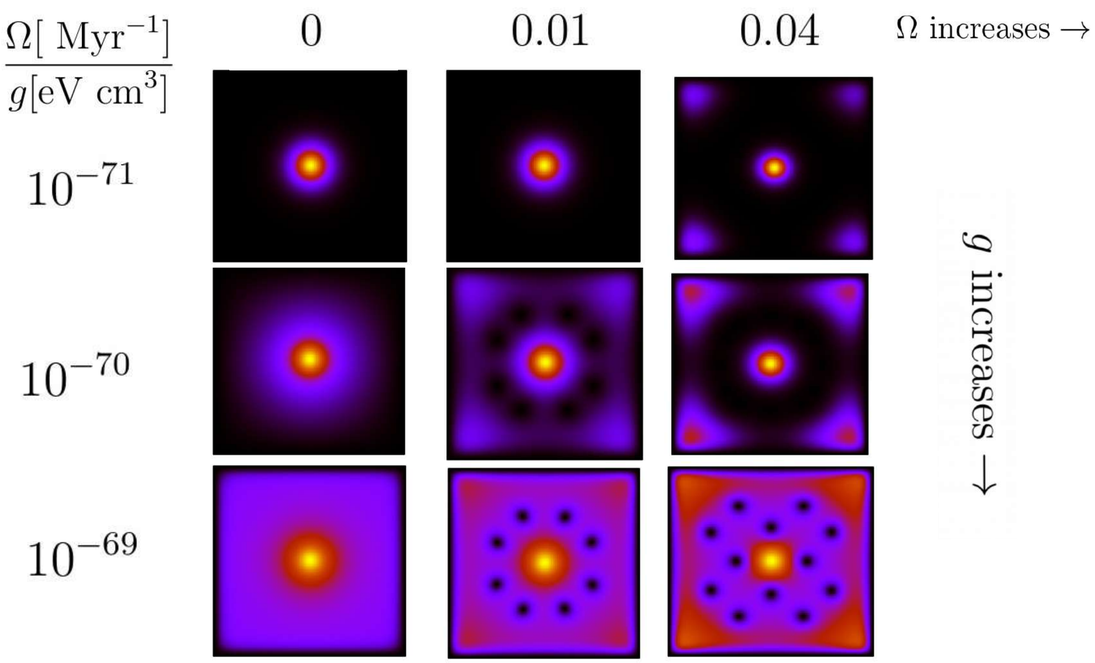
PRELIMINARY

In collaboration with Jowett Chan

Fuzzy DM



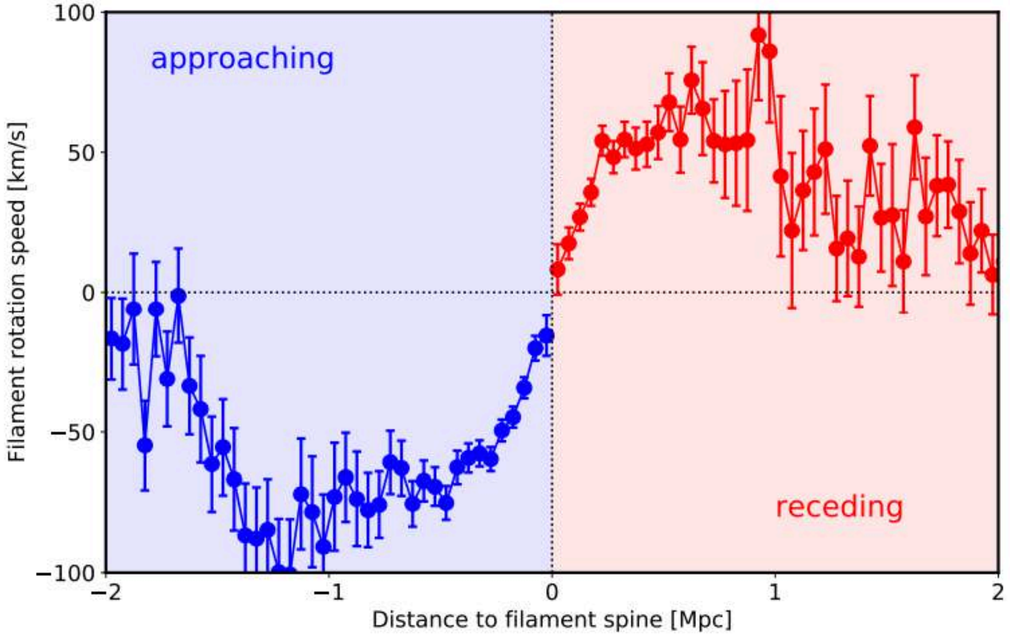
Self-interacting Fuzzy DM



\+ Improve theoretical understanding of these DM vortices *In collaboration with P. Bittar*

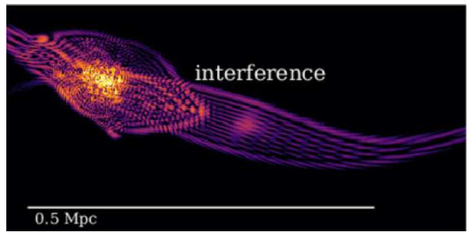
Rotation of filaments: vortices

Peng Wang, Noam I. Libeskind, Elmo Tempel, Xi Kang, Quan Guo, "*Possible observational evidence that cosmic filaments spin*" (2021)



- Stacking thousands of filaments and examining the velocity of galaxies perpendicular to the filament's axis (via their red and blue shift)
- Found that filaments display motion consistent with rotation ⟶ largest objects known to have angular momentum

Rotation of filaments: vortices

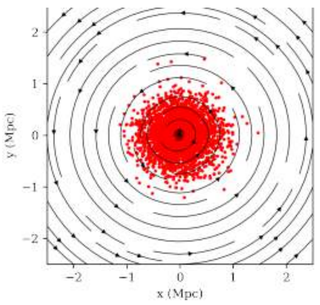


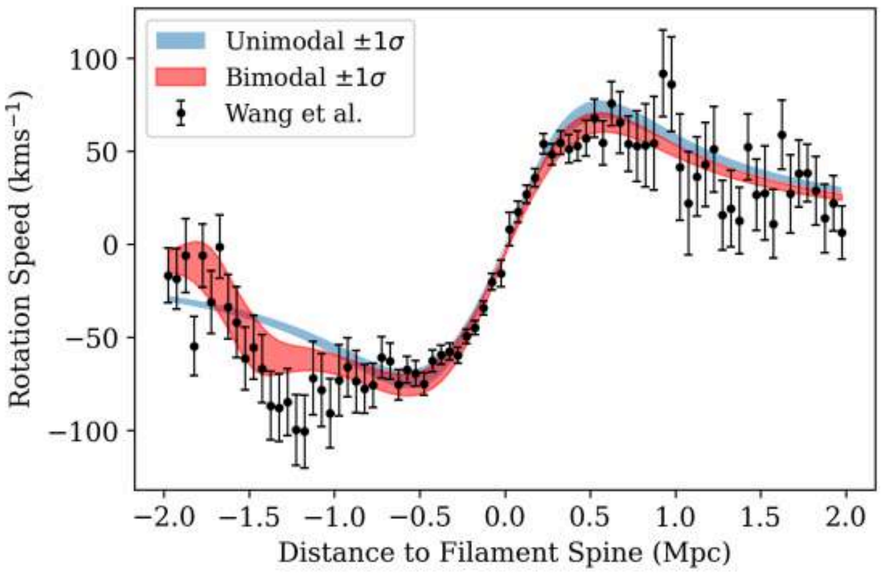
Mocz et al. 2017

- Not clear that we can get spinning cosmic filaments in LCDM
  - Seems to be difficult to theoretically explain the acquisition of angular momentum on megaparsec scales
  - Some simulations seem to be finding spinning cosmic filaments

Stephon Alexander, Christian Capanelli, Elisa G. M. Ferreira, and Evan McDonough, *"Cosmic Filament Spin from Dark Matter Vortices"* (2021)

- Suggest that a collection of (ULDM) vortices enclosed in a cylindrical volume aligned with the axis of a filament are able to generate rotations at the Mpc scale and reproduce the result of Wang et al (2021)





$$R = 0.51^{+0.02}_{-0.02}\ \text{Mpc}$$

$$\frac{N_V}{m} = 2.9^{+0.2}_{-0.2} \times 10^{25}\ \text{eV}^{-1}.$$

For example, for a $m \sim 10^{-22}\text{eV}$ $\longrightarrow$ $N_V \sim 3000$

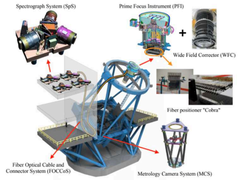
Compatible with:
- in regions where the density vanishes (*Hui et al 2020, Lague et al 2020*)
- Transfer of angular momentum (*Berezhiani, 2015*)

Future - *signals in cosmology*

Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)



CMB

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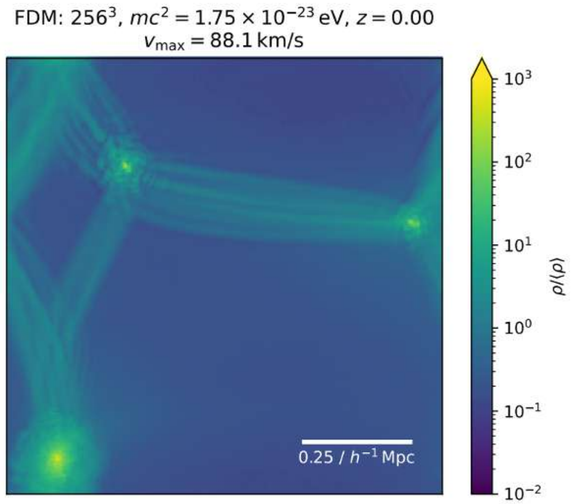


New probes

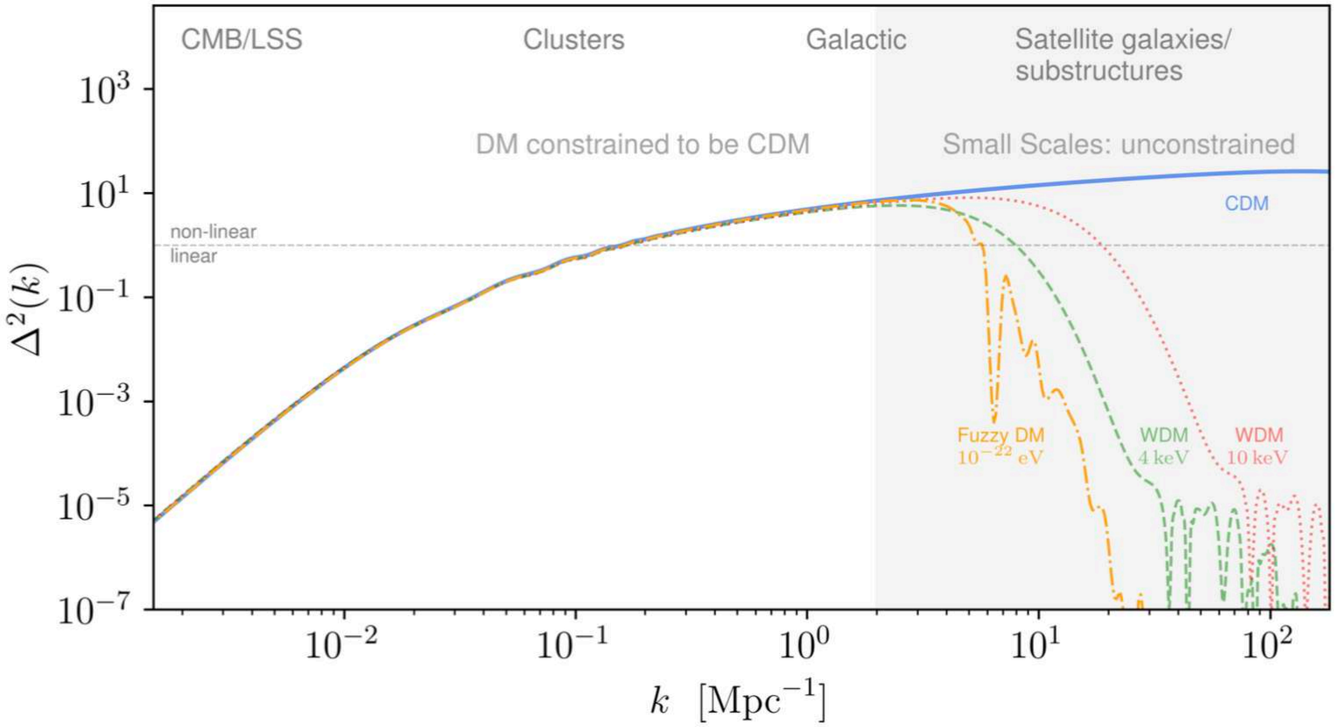
Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Modified from Jia Liu

Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures



Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures

A. Diaz Rivero, et al. (2017); Diaz Rivero, et al. , (2018)

Bayer et al. (2018) ; Auger et al. 2009
FDM*: Kawai et al. (2021)*

Hezaveh et al. (2016) (projected mPS by using strong lensing)

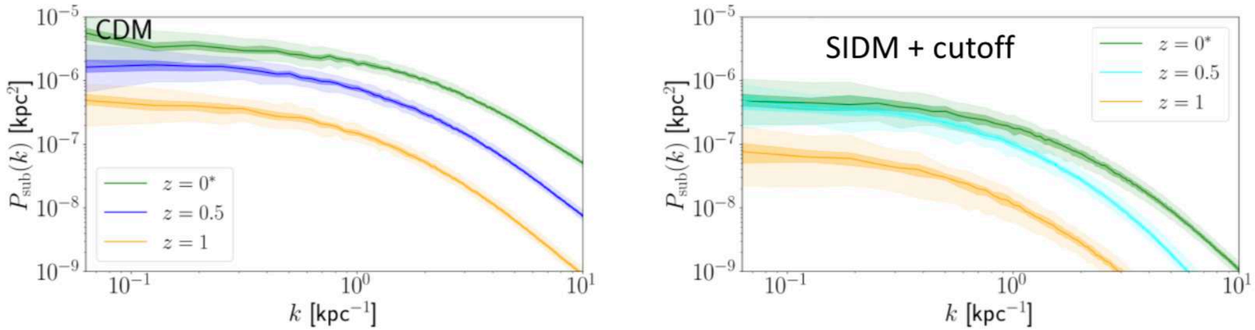
Substructure convergence power spectrum

Develop a formalism to compute the substructure convergence power spectrum for different populations of dark matter subhalos.

Change of language: instead of talking about lensing perturbations in terms of individual subhalos, look at the correlation function of the projected density field.

(based on Dvorkin's slide)

$$P_{\rm sub}(k) = P_{\rm 1sh}(k) + P_{\rm 2sh}(k)$$



Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures

Substructure convergence power spectrum

Sten Delos and Fabian Schmidt (2021)

Stellar streams: perturbed by passing substructure. Good gravitational probe, since given their low dynamical temperature and negligible self-interaction, it retains the memory of those encounters.

THIS WORK: Fully analytical understanding of the stream perturbations!

Power spectrum of a stream's stellar density is analytically related to that of the substructure background:

$$\boxed{P_*(k,t)} = \chi_*\left(k\sigma_0 t, \frac{D}{k\sigma_0^3}\right)\frac{k^2t^2}{3}P_{\Delta v}(k,t)$$

Stream power

Substructure power

$$P_{\Delta v}(k,t) = 16\pi^4 G^2\bar{\rho}^2 k^2 t \int_k^\infty \frac{\mathrm{d}q}{q}\frac{\boxed{\mathcal{P}(q)}}{q^6}\int \mathrm{d}^3\boldsymbol{u}\frac{f(\boldsymbol{u})}{u}\theta_H(qu-kv)$$

Previous:
- Mostly numerical
- Perturbations $\longrightarrow$ sub-halo mass function

Relates the stellar stream perturbation to the surrounding matter distribution, from dark and luminous substructure

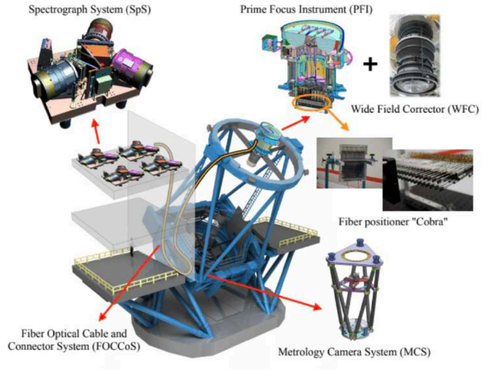
Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures

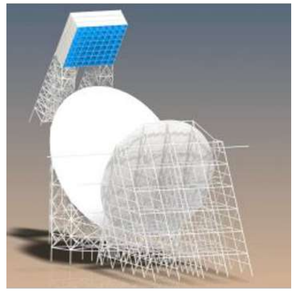
Future

Observations

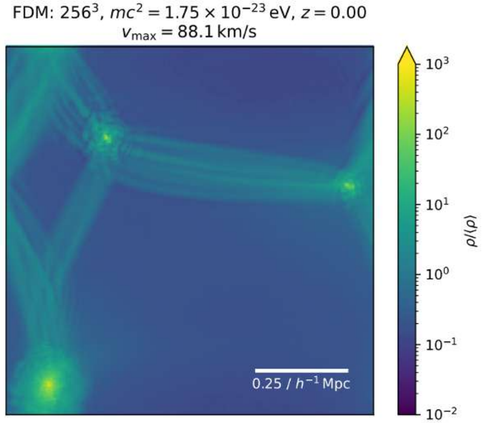
Prime Focus Specctrograph (PFS)



BINGO telescope



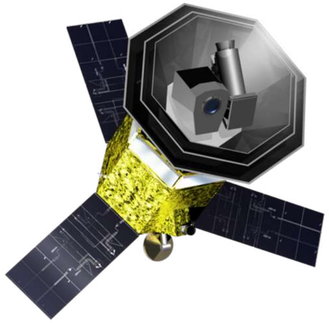
Simulations



Vera Rubin observatory (LSST)

CMB-S4

LiteBIRD

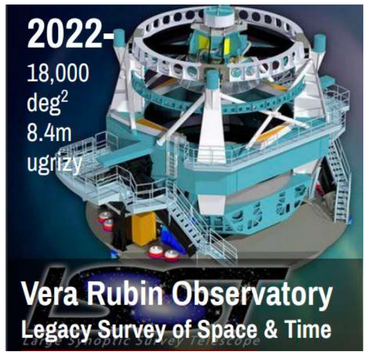


New probes

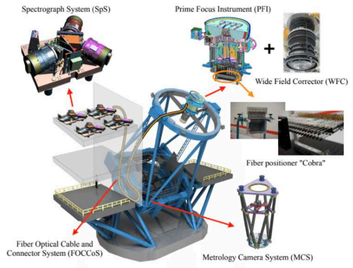
Future - signals in cosmology

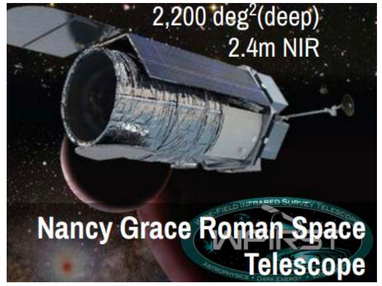
Observations

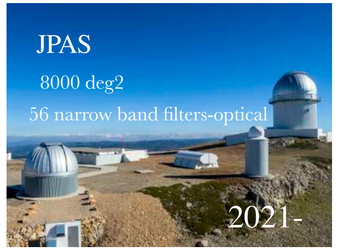
Photometric and spectroscopic surveys



Prime Focus Spectrograph (PFS)







21cm

SKA
SQUARE KILOMETRE ARRAY

CMB

CMB-S4
Next Generation CMB Experiment

GWs

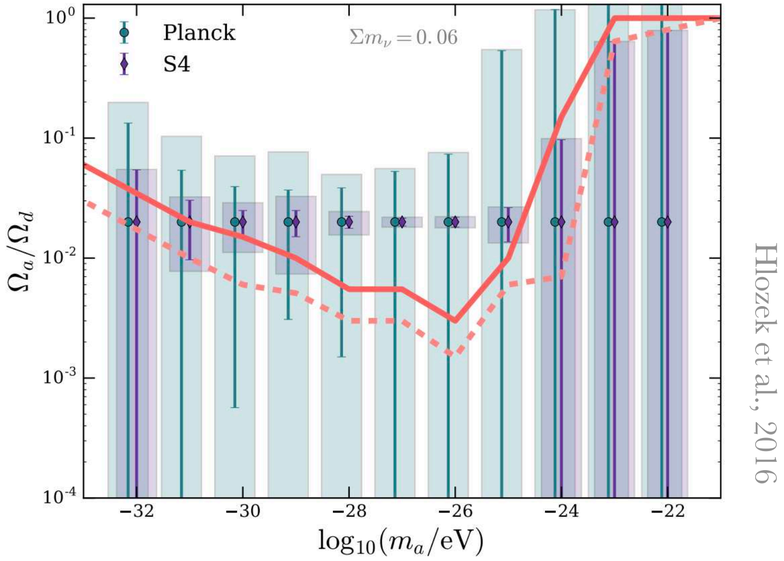
Modified from Jia Liu

Future - Cosmic Microwave Background

TESTING ULTRA LIGHT DM CMB

CMB - S4

Constraints on Ω_a/Ω_d



Hlozek et al., 2016

Significantly improve constraints on the composition of the dark sector!

Constraints on the *optical depth* $\tau(r_{\mathrm{rec}})$

Constraint the ULDM mass

Kinematic Sunyaev–Zel'dovich effect: sensitive to the duration of the reionization

- *LiteBIRD*
- *Advances ACTPol*
- *CMB-S4*

PFS (Prime Focus Spectrograph)

PFS is going to be exquisite to measure the properties of DM

GOAL

PFS: spectroscopy part of *SuMIRe project*

DM with PFS ⟶ *synergy between science goals*

Galaxy archeology	Cosmology	Galaxy evolution
• Nature of DM (dSphs) • Structure of MW dark halo • Streams • Stellar kinematics and chemical abundances – MW & M31	• Power spectrum • HSC+PFS • Linear growth (RSD)	• Small-scale tests of structure growth • Halo-galaxy connection M_*/M_{200} • Physics of cosmic reionization via LAEs & 21cm studies • Tomography of gas and DM

Wide & deep survey of MW dwarf galaxies w. Subaru/PFS

DM with PFS

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- Science with dwarf galaxies
  Core:
  - Presence of a core or not (slope)
  - Size of the core
  - Profile
    - Inner density
    - Transition radius
  - Abundance data to understand the role of baryons in each system

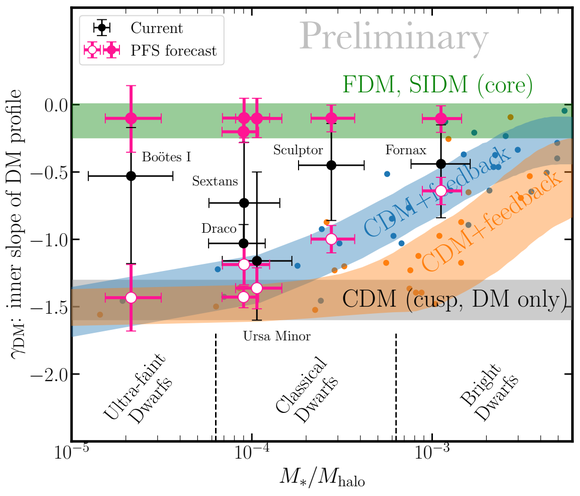
FDM

SIDM

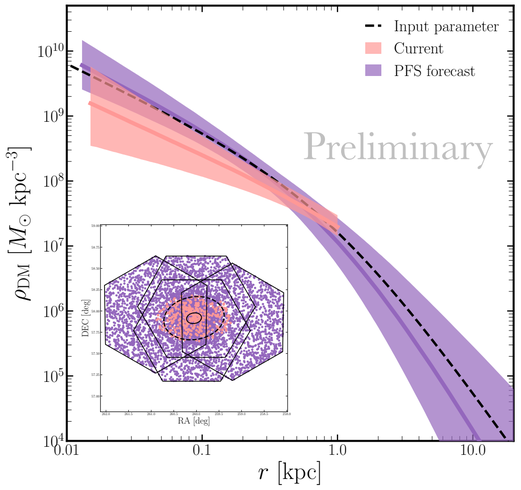
ULA

- *Beyond the core*
  - Granules: heating of stars (dwarfs)
    - Angular momentum
  - Stellar streams

…



Kohei Hayashi' and Masashi Chibas talk



Figures by Kohei Hayashi

DM with PFS

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  FDM

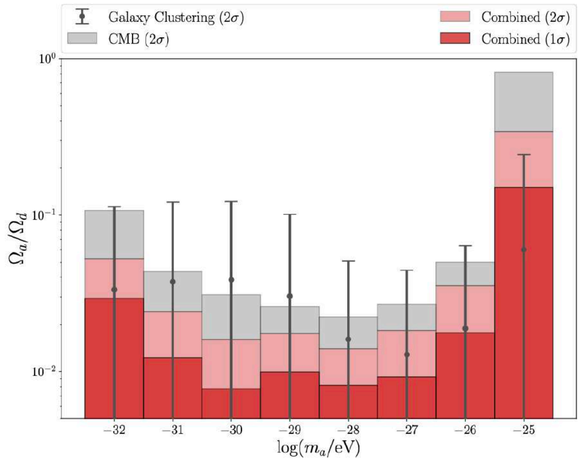
  SIDM

  ULA

- *Beyond the core*
  - Granules: heating of stars (dwarfs)
    - Angular momentum
  - Stellar streams

  …

Fraction of axions in the dark sector: $10^{-32}\,\mathrm{eV} < m < 10^{-25}\,\mathrm{eV}$



Lague et al 2021

The small-scale Ly-α forest power spectrum

ULA

FDM

WDM

SIDM

Halo mass function

Constraints on the *optical depth:*

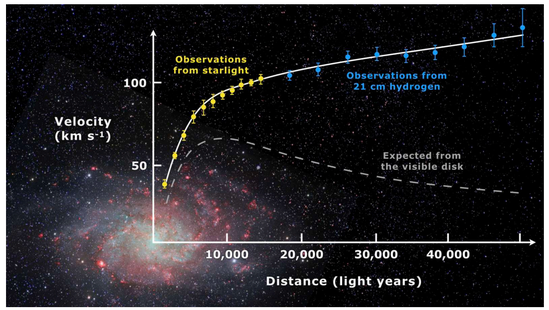
Constraint the ULDM mass

Kinematic Sunyaev–Zel'dovich effect: sensitive to the duration of the reionization

Superfluid Dark Matter

Evidences for dark matter - properties

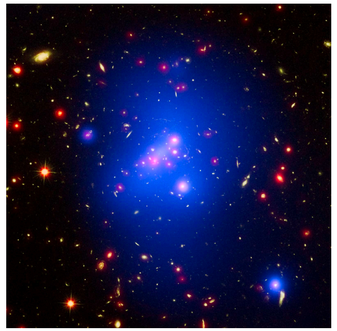
Galaxy rotation curves



Credit: Mario De Leo

- Mass fraction
- Distribution

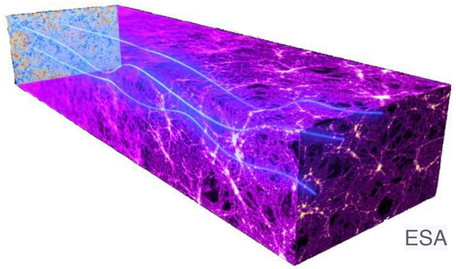
Clusters



CC BY 4.0

- Mass fraction
- Distribution

Lensing



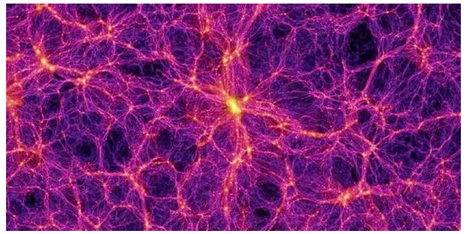
ESA

Strong lensing
- Mass fraction
- Distribution

Weak lensing
- Distribution
- Shape
- Structure

Micro lensing
- Mass fraction
- Smoothness

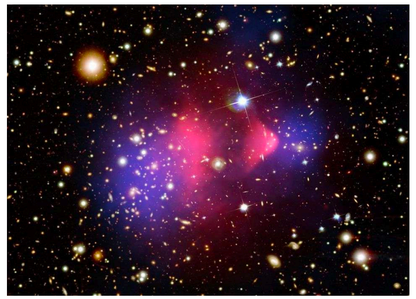
Large Scale Structure



Springel & others / Virgo Consortium

CMB/LSS
- Ratio of DM/collisional matter
- Thermal history

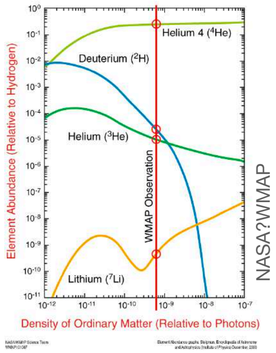
Cluster collision



NASA/CXC/CfA and NASA/STScI

- Distribution
- Separation from collisional matter
- Self-interaction

Big Bang Nucleosynthesis



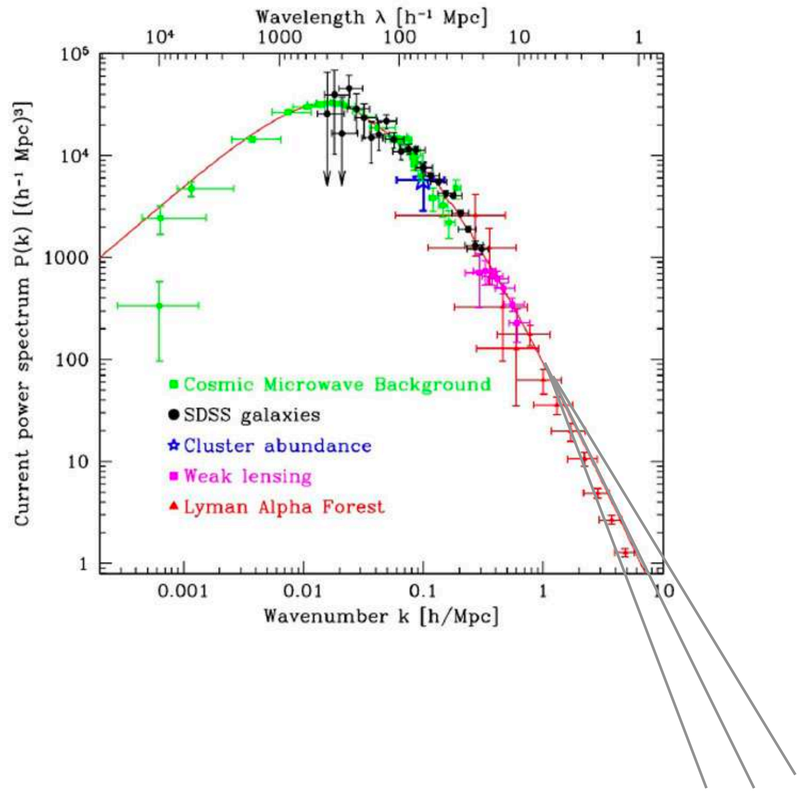
NASA?WMAP

- Amount of baryons

Based on K. Mack

What we don't know about dark matter

- ~~Cold~~ → How cold it is? WDM $m \sim \mathrm{keV}$
- ~~Pressureless~~ → Cluster on all scales?
- ~~Dark~~ → Non-gravitational interaction? Milicharged DM
- ~~Collisionless~~ → How small sefl-interaction? SIDM



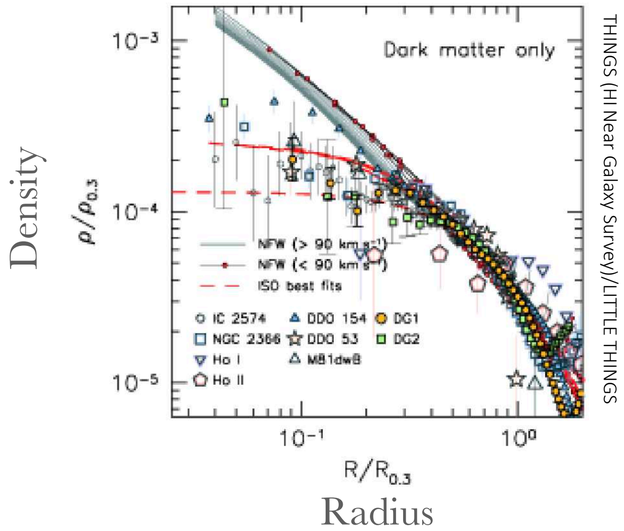
CDM on large scales

Small scale behavior: still weakly constrained and small scale challenges

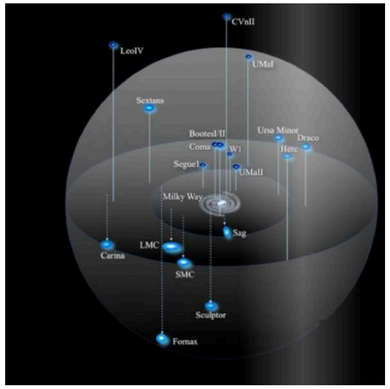
Small scale curiosities: cusp-core, missing satellites, BTFR, …

Small scale challenges

Cusp-core



THINGS (HI Near Galaxy Survey)/LITTLE THINGS

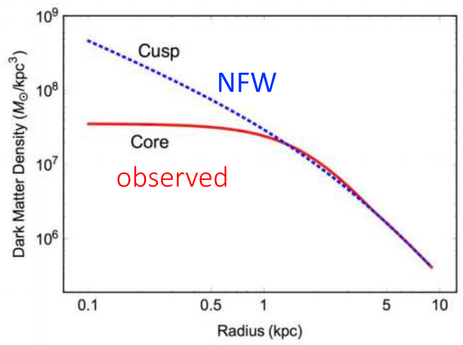


Bullock, Baylon-Kolchin

Missing satellites

Incompatibility between the # of satellites predicted by simulations using LCDM and the # of observed satellites

CDM -
NFW profile



Regularity/diversity of rotation curves

Regularity and diversity of rotation curves

- Baryonic Tully-Fisher relation (BTFR)

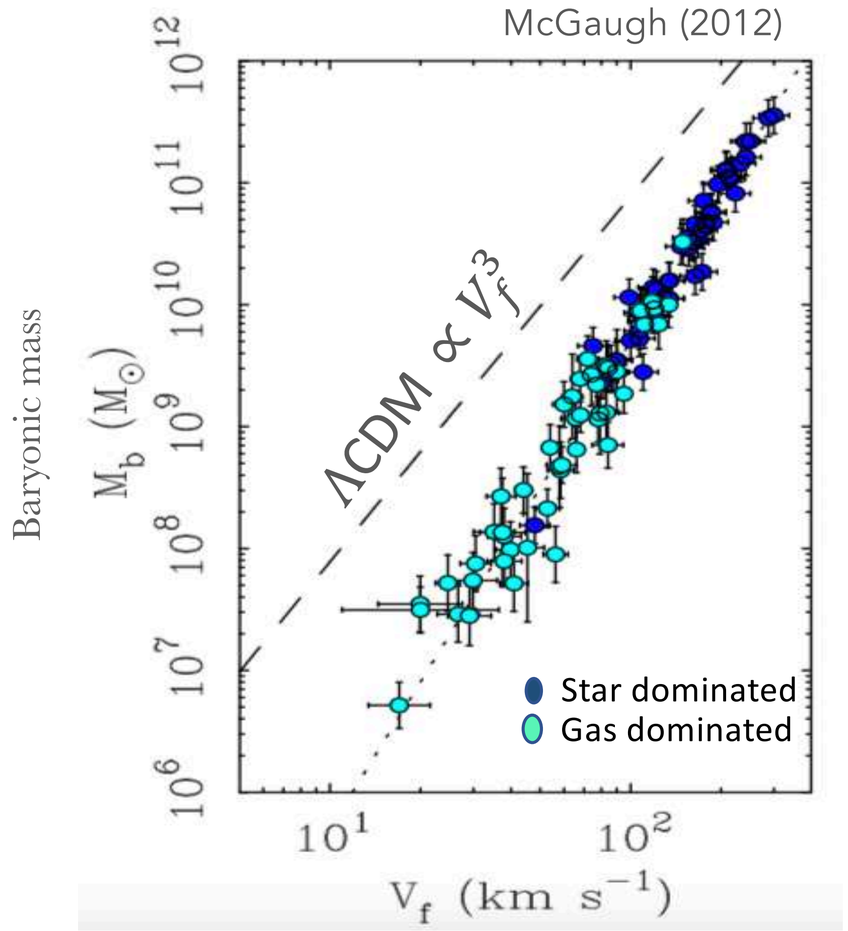
Remarkably tight scaling relations between dynamical and baryonic properties.

Other scaling relations:

✓TRF
✓RAR - Radial acceleration relation
✓…

$$a_0 \simeq \frac{1}{6} H_0 \simeq 1.2 \times 10^{-8}\ \mathrm{cm/s^2} = 2.7 \times 10^{-34}\ \mathrm{eV}\,.$$

McGaugh (2012)



Dark matter- Large scales: CDM

Small scales:

- **Feedback:** Within ΛCDM

  - Star formation
  - Stellar evolution
  - Sn rates
  - BH and AGN feedback
  - Stellar feedback
  - …

Questions:

- Can it solve all these?
- ≠ simulations, ≠ parametrizations
- Enough feedback?
- Explains tight scaling relation?

- **MOND:**

Modified Newtonian Dynamics

Empirical relation

$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

Curiosity: Baryons drive the dynamics!

Works extremely well for: (1) rotation curves; (2) scaling relations

BUT: ~~MOND without DM~~

Problems explaining large scales

- **Modify dark matter:**

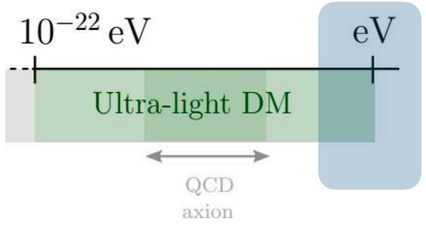
DM with different properties on small scales

- SIDM (Self-interacting DM)

Solve cusp-core and missing satellites

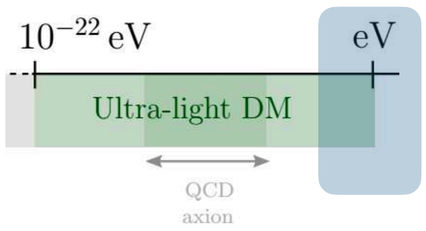
- WDM (Warm DM)

Solve missing satellites



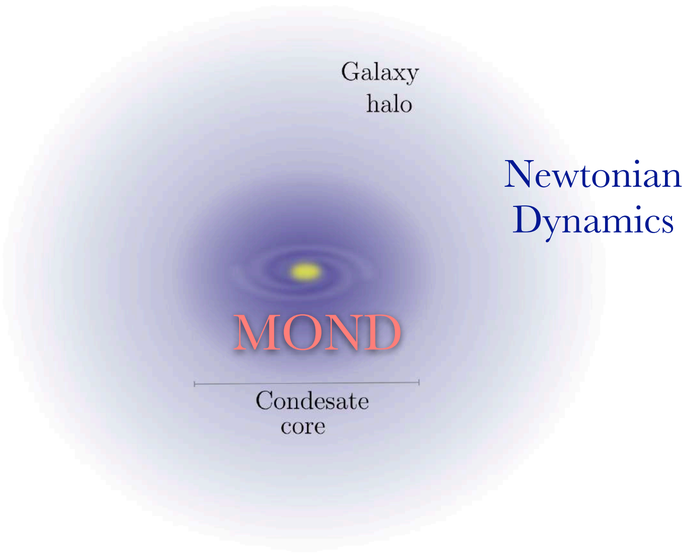
Superfluid Dark Matter

Superfluid Dark Matter



Lasha Berezhiani and Justin Khoury (2016)

Large scales:
DM behaves like standard particle DM (CDM).



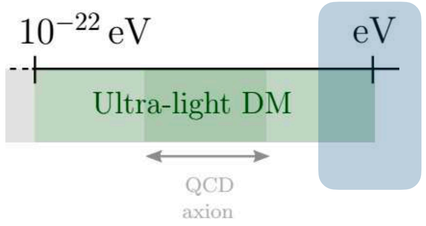
Galactic scales:
DM forms a superfluid
$\longrightarrow$ emergent MOND dynamics in galaxies

$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

Similar phenomenology than the FDM & SIFDM + explains the rotations curves and scaling relations

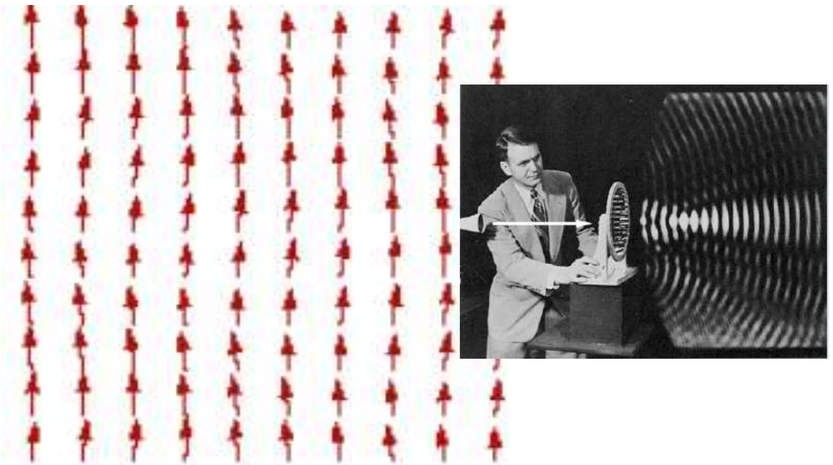
Suppresses small structures, dyn. effects, formation of cores

Collective modes



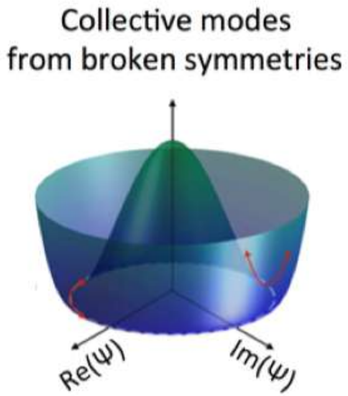
- Described by the collective behavior of the particles.

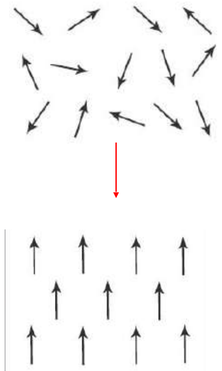
- No need for microphysics: symmetry alone describes the system.



Tom‡š Brauner

- Collective modes related to symmetry = Nambu–Goldstone bosons



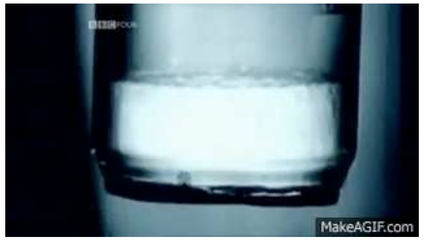


Order parameter

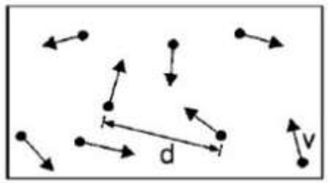
Effective degree of freedom

Effective dynamics

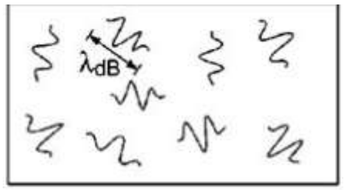
Superfluid



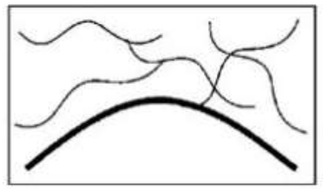
- At low temperatures, a superfluid condensates into a Bose-Einstein condensate (BEC).
- De Broglie wavelength (λ_B) of each particle is large enough that their quantum wave function overlap, and a single wave function describes the entire liquid.
- Quantum phenomenon that appears at low temperatures and macroscopic scales.
- **Effective dynamics**: fluid that can flow without friction.



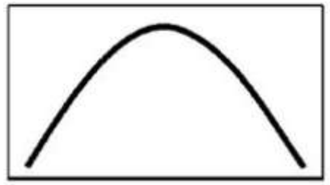
High temperature
Thermal velocities



Low temperature
$\lambda_B \sim T^{-1/2}$
"wave packets"



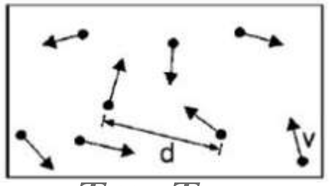
$T = T_c$
BEC
"matter wave overlap"



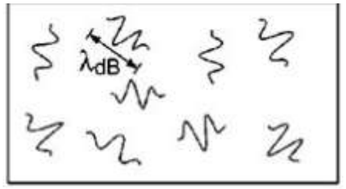
$T = 0$
Pure BEC
"giant matter wave"

Goal:

Use this property of the collective behaviour to explain the modified dynamics at certain scales/times in the evolution of the universe.



$T \gg T_c$



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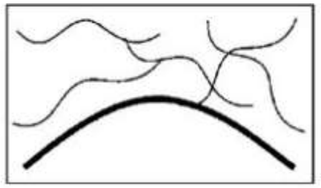
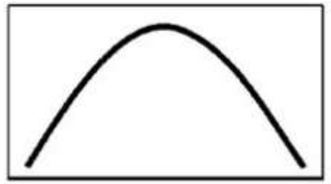


$T = T_c$

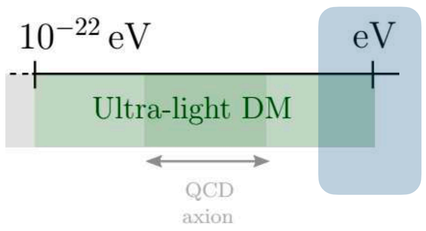
BEC



$T = 0$

Pure BEC

Superfluid Dark Matter



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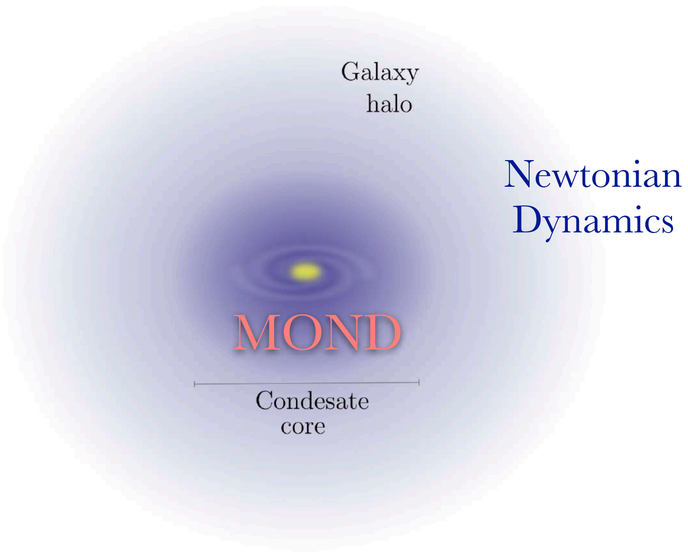

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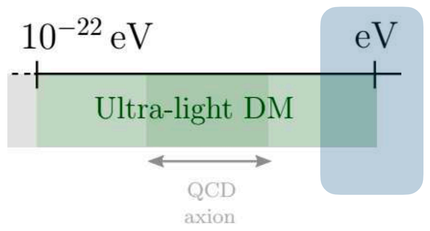
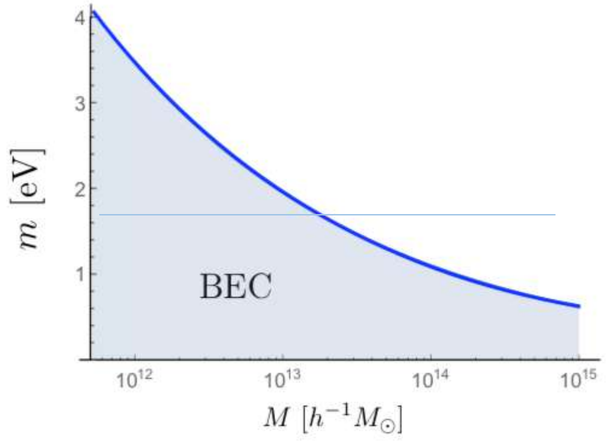
Condition for Superfluidity



DM has to condensate in galaxies:

- de Broglie wavelength of the particles must overlap ($N_0/N = 1 - (T/T_c)^{3/2}$)

$$\lambda_b \sim \frac{1}{mv} \geq d \sim \left(\frac{m}{\rho_{vir}}\right)^{\frac{1}{3}} \quad \Longrightarrow \quad \boxed{m \leq 2\text{eV}}$$



- Thermalization

Strongly interacting axion-like particle.
DM is cold: $T_c \sim \text{mK}$

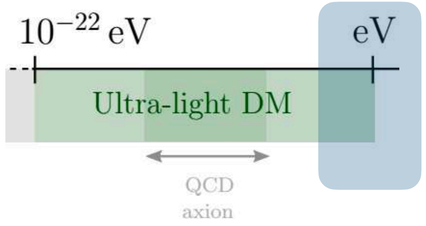
Cold atoms in the lab

$$\frac{\sigma}{m} \gtrsim 0.1 \, \frac{\text{cm}^2}{g}$$

Condition for superfluidity (Landau criteria):

$$v_s < v_c (\neq 0)$$

Description of the Superfluid



Effective field theory that describes a superfluid is represented by a:

- System with a U(1) global symmetry that is spontaneously broken.

$$\mathcal{L} = -|\partial\Psi|^2 - m_\Psi^2|\Psi|^2 - \frac{\lambda}{2}|\Psi|^4 + (...) \qquad \Psi = \Psi_0 + \delta\Psi$$

- Condensate: $\Psi_0 = v e^{\pi(x,t)}$

$$\mathcal{L}_0 = (\partial_\mu v)^2 + v^2[(\partial_\mu \pi)^2 - m^2] - \frac{\lambda}{2}v^4$$

Current: $\dot{j}_0 = v^2\dot{\pi} = \text{const.} \Rightarrow \dot{\pi} = \mu$

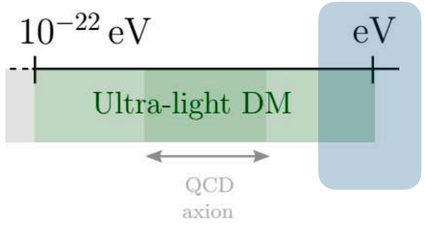
The stationary solution determines the ground state of the system

$$\Psi_0 = v\, e^{i\mu t}$$

$\mu^2 < m^2$ Symmetry restoring phase

$\mu^2 > m^2$ Bose Einstein condensation

Description of the Superfluid



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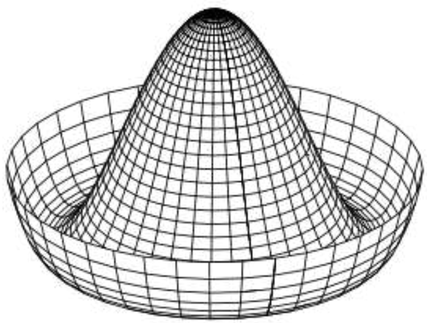
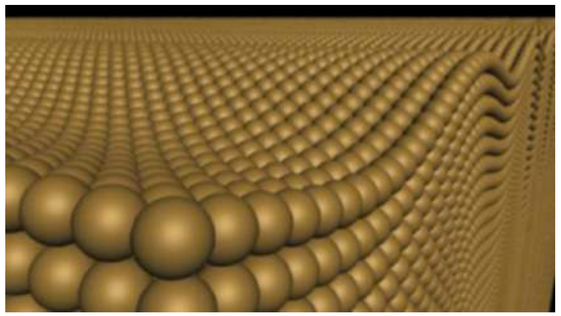


$$\Psi = \Psi_0 + \delta\Psi$$

Condensate: $\Psi_0 = v\, e^{i\mu t}$

Excitations: $\Psi = (v+\rho)e^{i\overbrace{(\mu t+\theta)}^{\Theta}}$



Crystal Lens

Collective excitations: massless Goldstone and massive quasi-particles. $\omega_k^2 = c_s^2 k^2 + \frac{1}{(2\mu)^2}\, k^4$

Low energy: only θ excited - phonon $\omega \sim c_s k$

* Recover the previous description in the non-relativistic regime

Description of the Superfluid

Low energies $(\dot{\theta}/m \ll 1)$

Greiter, Wilczek & Witten (1989);
Son and Wingate (2005)

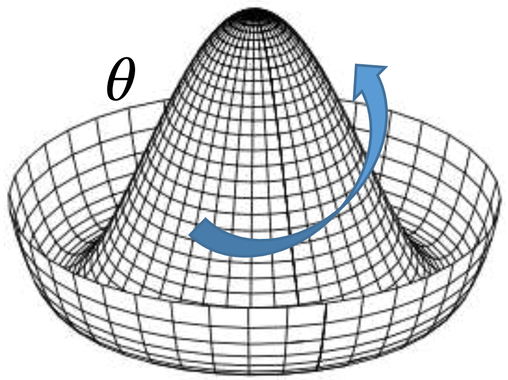
- Low energy DOF: Only massless Goldstone bosons excited θ

Shift symmetry $\theta \to \theta + c$

$$\Theta = \mu t + \theta$$

Chemical potential

Phonon excitations



$c = \mu t$

In the non-relativistic regime and at lowest order in derivatives:

+ Galilean invariance

$$\mathcal{L} = P(X), \qquad X = \dot{\theta} - m\Phi - \frac{(\vec{\nabla}\theta)^2}{2m} \qquad \dot{\theta}/m \ll 1$$

Gravitational potential

MOND from phonons

Lasha Berezhiani and Justin Khoury (2016)

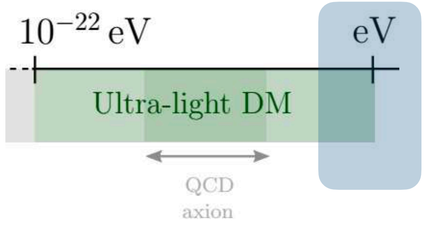
This description represents different phenomena:

$$\mathcal{L} = P(X) = \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}}{m}\right)^n$$

- $n = 2: \quad P \sim \rho^2$ BEC
- $n = 3/2: \quad P \sim \rho^3$ MOND
- $n = 5/2: \quad P \sim \rho^{5/3}$ Unitary Fermi Gas

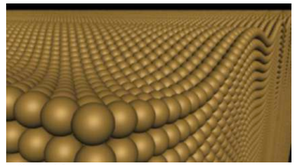
Superfluid Dark Matter

How to construct - MOND from phonons



Lasha Berezhiani and Justin Khoury (2016)

EFT of superfluids $\mathcal{L} = P(X)$ $\quad X = \dot{\theta} - m\Phi - \frac{(\vec{\nabla}\theta)^2}{2m}$


Crystal Lens

$$\Psi = (v + \rho)e^{i(\mu t + \theta)}$$

Low energy: only θ excited - phonon
Nambu Goldstone boson

Different phenomena $P(X) \propto \left(\dot{\theta}/m\right)^n$

$n = 2:$	$P \sim \rho^2$	BEC
$n = 3/2:$	$P \sim \rho^3$	"MOND"
$n = 5/2:$	$P \sim \rho^{5/3}$	Unitary Fermi gas

To describe non-relativistic MOND, it is imposed that:

$\longrightarrow$ Leads to an equation of state $P \sim \rho^3$ required to describe MOND

$$P(X) = \frac{2\Lambda\,(2m)^{3/2}}{3} X\sqrt{|X|}$$

To mediate the MONDian force, couple phonons to baryons:

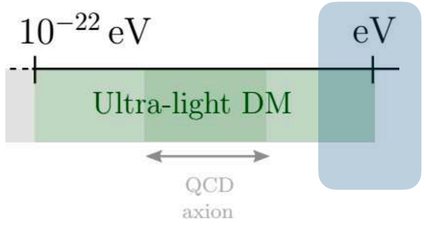
$$\mathcal{L}_{int} \sim \frac{\Lambda}{M_{pl}}\,\theta\rho_b$$

Softly breaks shift symmetry

$$\Lambda = \sqrt{a_0 M_{pl}} \sim 0.8\,\mathrm{meV}$$

Description of the Superfluid

Low energies $(\dot{\theta}/m \ll 1)$



- Low energy DOF: Only massless Goldstone bosons excited θ - Shift symmetry $\theta \to \theta + c$

In the non-relativistic regime and at lowest order in derivatives:

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Different phenomena $P(X) \propto \left(\dot{\theta}/m\right)^n$

$$\begin{cases} n = 2: & P \sim \rho^2 \\ n = 3/2: & P \sim \rho^3 \\ n = 5/2: & P \sim \rho^{5/3} \end{cases}$$

BEC

"MOND"

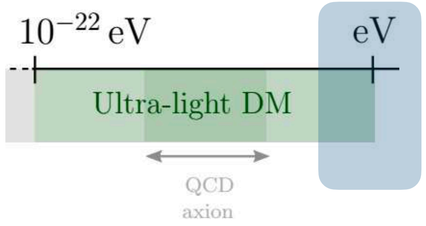
Unitary Fermi gas

Equivalence (low energies)

2-body $\mathcal{L} = -|\partial\Psi| - m^2|\Psi|^2 - \frac{\lambda}{2}|\Psi|^4 \Longleftrightarrow \mathcal{L} = P(X) \propto X^2 \longrightarrow p \propto \rho^2$

3-body $\mathcal{L} = -|\partial\Psi| - m^2|\Psi|^2 - \frac{g_3}{3}|\Psi|^6 \Longleftrightarrow \mathcal{L} = P(X) \propto X^{3/2} \longrightarrow p \propto \rho^3$

Superfluid Dark Matter



- Newtonian limit: $|\vec{\nabla}\Phi| > 3\,a_0$

$$\Longrightarrow \quad \boxed{\vec{\nabla}^2\Phi = \frac{\rho_s + \rho_b}{2M_{pl}^2}}$$

- MOND limit: $|\vec{\nabla}\Phi| < 3\,a_0$

$$\Longrightarrow \quad \boxed{\vec{\nabla}\cdot\left(\frac{|\vec{\nabla}\Phi|}{a_0}\vec{\nabla}\Phi\right) = \frac{\rho_s + \rho_b}{2M_{pl}^2}}$$

Only DM

Mostly DM

"MOND"

No MOND

Higher order correction

- Higher order contributions to the quadratic Lagrangian for the phonon, can contain terms of the form:

$$\mathcal{L}_{\mathrm{higher-order}} \supset \left(\Lambda m^{3/2}\mu^{3/2}\right)^{1-\frac{n}{2}} \partial^n \phi_c^n$$

where $\partial \to \partial_t \text{ or } c_s\vec{\nabla}$ and the canonical variable is $\phi_c = \Lambda^{1/2} m^{3/4} \mu^{-1/4} \phi$

Strong coupling scale, the scale suppressing higher order terms:

$$\Lambda_s = \left(\Lambda m^{3/2}\mu^{3/2}\right)^{1/4} \simeq \left(\Lambda m^3 c_s^3\right)^{1/4}$$

$$(c_s^2 = 2\mu/m \sim \dot{\theta}/m \ll 1)$$

Higher order corr. $\longrightarrow$ neglected when

$$\frac{1}{\Lambda_s}\frac{\partial_r^2 \phi}{\partial \phi} \sim \frac{1}{\Lambda_s r} \ll 1$$

$$\Lambda_s \sim \mathrm{meV}\left(\frac{M_{DM}}{10^{12} M_\odot}\right)^{3/10}\left(\frac{m}{\mathrm{eV}}\right)^{6/5}\left(\frac{\Lambda}{\mathrm{meV}}\right)^{2/5}$$

Fiducial parameters (galaxies):

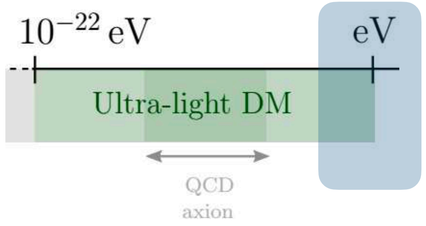
$$\Lambda_s \sim \mathrm{meV}$$

HO corr. neglected $\downarrow$

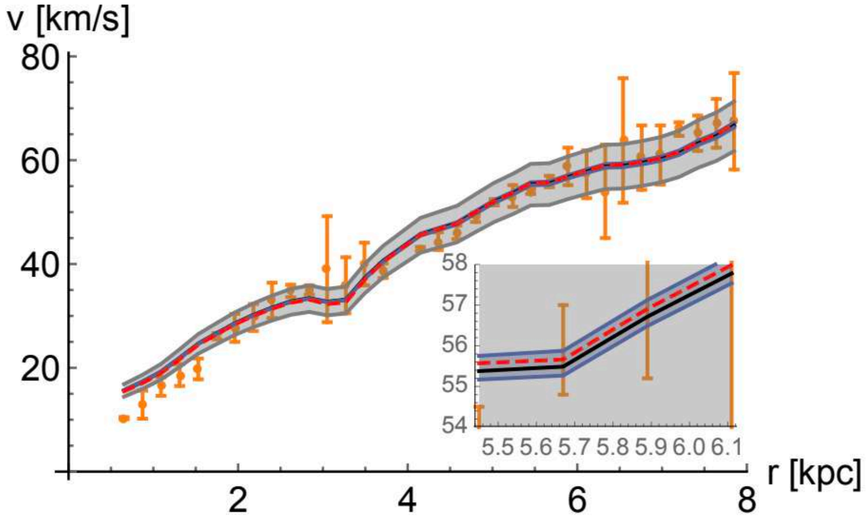
$$r \gg 0.2\mathrm{mm}$$

Superfluid Dark Matter

Rotation curves



Low surface brightness



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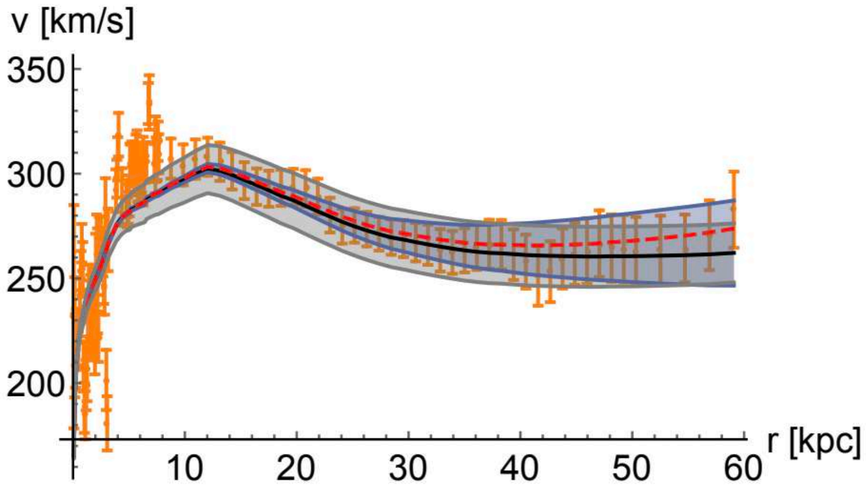


Superfluid core:

$$R_{halo} = 57\,\mathrm{kpc}$$
$$R_{Sf} = 40\,\mathrm{kpc}$$

58% of the total mass of the halo

$$R_{halo} = 445\,\mathrm{kpc}$$
$$R_{Sf} = 79\,\mathrm{kpc}$$

25% of the total mass of the halo

Superfluid Dark Matter

Observational consequences

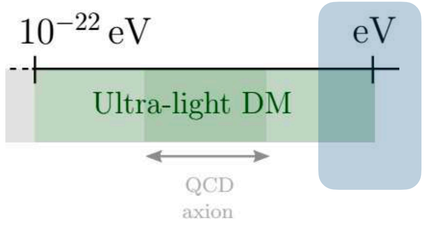


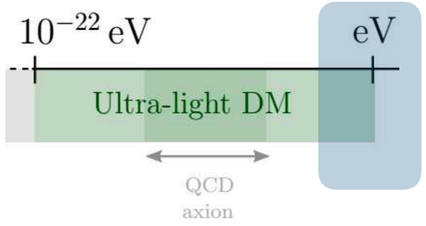
Table 2: Summary of observational consequences of superfluid DM from [124].

System	Behavior
Rotating Systems	
Solar system	Newtonian
Galaxy rotation curve shapes	MOND (+ small DM component making HSB curves rise)
Baryonic Tully–Fisher Relation	MOND for rotation curves (but particle DM for lensing)
Bars and spiral structure in galaxies	MOND
Interacting Galaxies	
Dynamical friction	Absent in superfluid core
Tidal dwarf galaxies	Newtonian when outside of superfluid core
Spheroidal Systems	
Star clusters	MOND with EFE inside galaxy host core — Newton outside of core
Dwarf Spheroidals	MOND with EFE inside galaxy host core — MOND+DM outside of core
Clusters of Galaxies	Mostly particle DM (for both dynamics and lensing)
Ultra-diffuse galaxies	MOND without EFE outside of cluster core
Galaxy-galaxy lensing	Driven by DM enveloppe $\implies$ not MOND
Gravitational wave observations	As in General Relativity

Berezhiani et al. 2018)

Superfluid Dark Matter

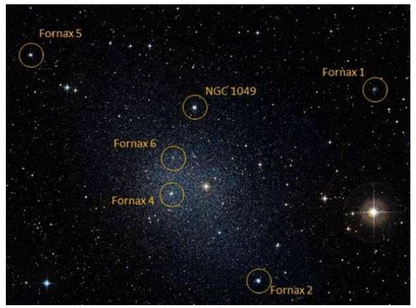
Dynamical Friction



Inner region of galaxy:
Superfluid core

Superfluid flows without friction

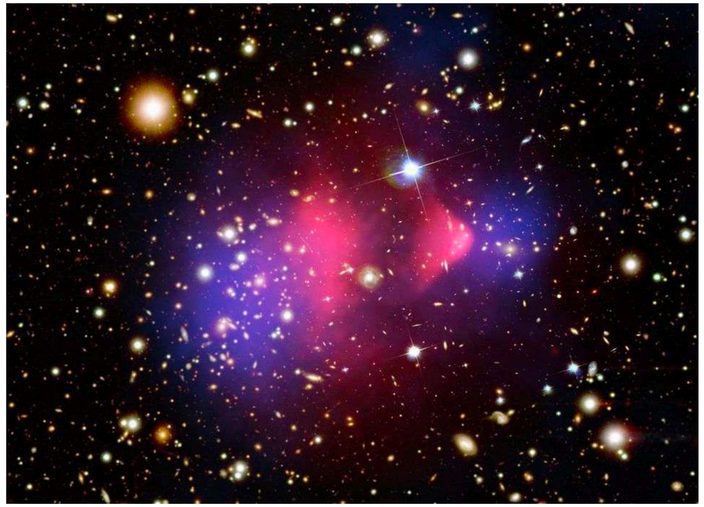
- Fornax: globular cluster should have merged with Fornax due to dynamical friction.
  Superfluid → no friction
  Can explain these glob. Clusters



ESO/Digitized Sky Survey 2

Complete analysis in: B. Elder et al., JCAP 1910 (2019) no.10, 074

BUT: what about the Bullet Cluster?

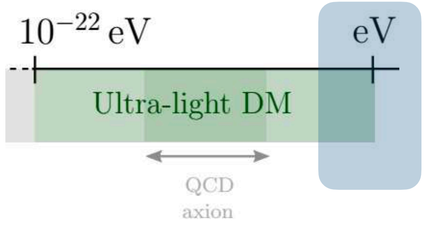


Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al. Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

Large cluster subsonic and small cluster supersonic (Sf core)
Bullet cluster as expected!

Landa criteria for superfluid
$v < v_c$

Superfluid Dark Matter



Superfluid DM model presents a very interesting behaviour in galaxies, being able to reproduce MOND from DM , BUT…

- Presents only a phenomenological non-relativistic description
- Need to develop cosmology

  $\Longrightarrow$ need a microscopic description

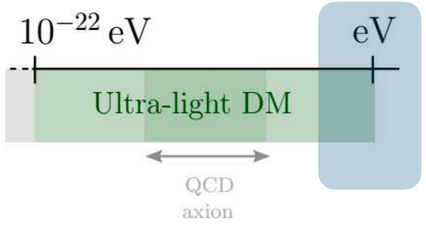
- Does not present many constraints yet.

(SAME AS IN FDM) Does condensation really takes place?

Presents opportunities of theoretical and observational advances!

Superfluid Dark Matter

Vertical dynamics



High Energy Physics – Phenomenology

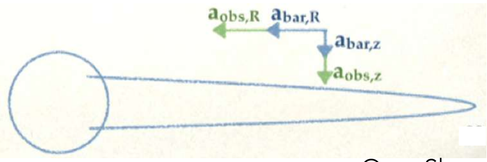
The Inconsistency of Superfluid Dark Matter with Milky Way Dynamics

Mariangela Lisanti, Matthew Moschella, Nadav Joseph Outmezguine, Oren Slone

(Submitted on 27 Nov 2019)

There are many well-known correlations between dark matter and baryons that exist on galactic scales. These correlations can essentially be encompassed by a simple scaling relation between observed and baryonic accelerations, historically known as the Mass Discrepancy Acceleration Relation (MDAR). The existence of such a relation has prompted many theories that attempt to explain the correlations by invoking additional fundamental forces on baryons. The standard lore has been that a theory that reduces to the MDAR on galaxy scales but behaves like cold dark matter (CDM) on larger scales provides an excellent fit to data, since CDM is desirable on scales of clusters and above. However, this statement should be revised in light of recent results showing that a fundamental force that reproduces the MDAR is challenged by Milky Way dynamics. In this study, we test this claim on the example of Superfluid Dark Matter. We find that a standard CDM model is strongly preferred over a static superfluid profile. This is due to the fact that the superfluid model over-predicts vertical accelerations, even while reproducing galactic rotation curves. Our results establish an important criterion that any dark matter model must satisfy within the Milky Way.

Comments: 6+5 pages, 2+4 figures
Subjects: **High Energy Physics – Phenomenology (hep-ph)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); Astrophysics of Galaxies (astro-ph.GA)
Cite as: arXiv:1911.12365 [hep-ph]
(or arXiv:1911.12365v1 [hep-ph] for this version)

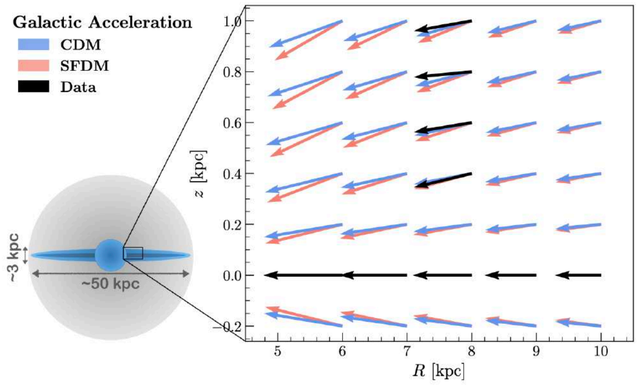


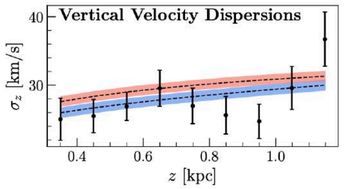
Oren Slone

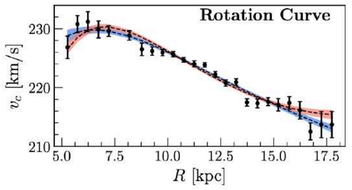
MOND-like force amplifies:

a_R not enough

a_z too much







Ultra-light fields as Dark Energy

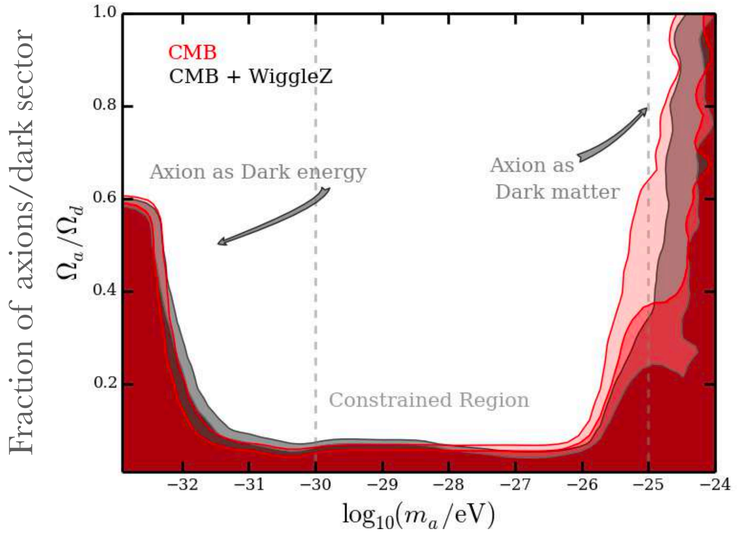
Ultra-light fields as Dark Energy

Fuzzy Dark Matter

Behave as dark energy with $w \sim -1$ for

$$m_{\rm fdm} < 10^{-32}\,{\rm eV}$$

Hlozek et al, 2015; Jiangang Kang et al. (2019)



Ultra-light fields as Dark Energy

Unified superfluid dark sector

"Unified superfluid dark sector", EF, G. Franzmann, J. Khoury, R. Brandenberger, 2018

- DM superfluid with two interacting distinguishable states.
- Phonons: propagate with different phases for each species

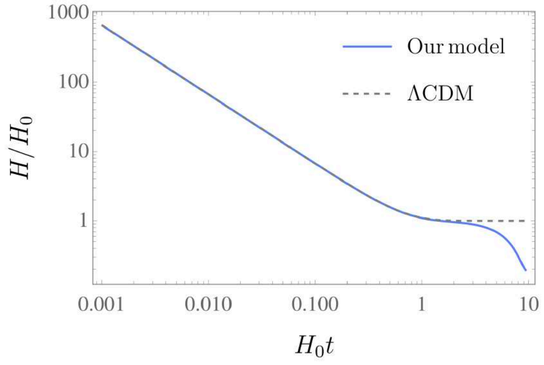
  $\longrightarrow$ Potential for the $(\theta_1 - \theta_2)$
- Prediction for clustering

$$\mathscr{L} = \underbrace{P(X_1) + P(X_2)}_{\text{Dark matter}} - \underbrace{M^4\left[1 + \cos(\theta_1 - \theta_2)/f\right]}_{\text{Potential - dark energy}}$$

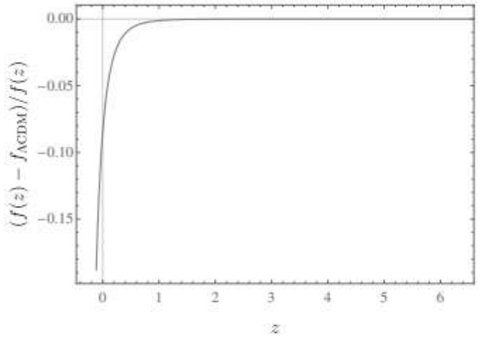
Unified framework
w/ DM alone!

- Acceleration from interactions (no dark energy)
- Use condensed matter methods in cosmology – effective change of the dynamics, no change in the fundamental theory.

Background evolution

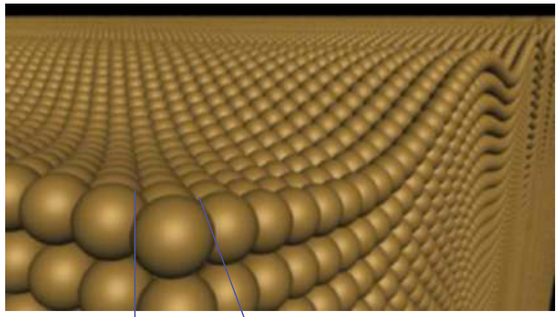


Clustering:
growth factor

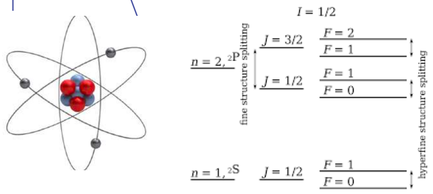


Ultra-light fields as Dark Energy

Phonon



Low energy: phonon, vibration quanta- can be understood as sound waves*.

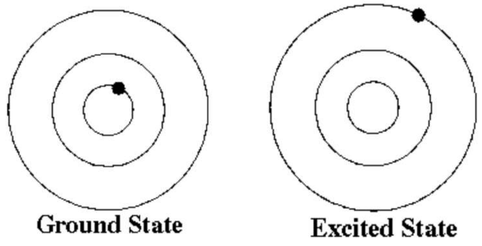


But, not the entire story…

Taking a closer look into the superfluid: atoms.

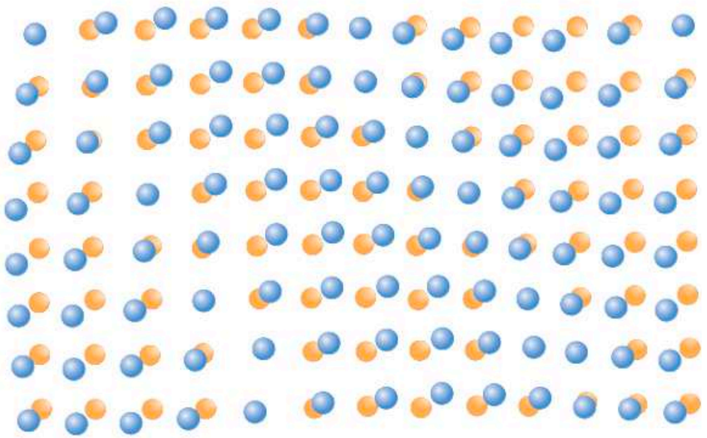
Full richness of the internal DOF needs to be takes into consideration. (Out of lab!)

Components of the (same) superfluid can be in two distinguishable states. (Refinement)



Ultra-light fields as Dark Energy

But, not the entire story…

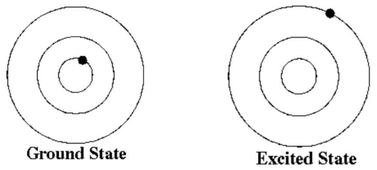


Callister & Rethwisch (2010)

Taking a closer look into the superfluid: atoms.

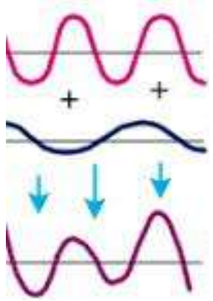
Superfluid with two distinguishable states.

Phonons that propagate with different phases for each species



Atoms in these states are in contact, interact!

Phonons interact!
The complex field interacts!



Analogous to interference of waves

Description of the superfluid

$$\Phi = (v+\rho)e^{i(\mu_1 t+\pi)}$$
$$\Psi = (v+\bar{\rho})e^{i(\mu_2 t+\bar{\pi})}$$

Model by two superfluids: $U(1)\times U(1)$ global symmetry

$$\mathcal{L}_0 = -|\partial\Phi|^2 - m_\Phi^2|\Phi|^2 - \frac{\lambda}{2}|\Phi|^4 - |\partial\Psi|^2 - m_\Psi^2|\Psi|^2 - \frac{\lambda}{2}|\Psi|^4$$

Interaction: breaks $U(1)\times U(1) \longrightarrow U_r(1)$

$$\mathcal{L}_{int} = -\alpha\frac{\Phi^*\Psi + \Psi^*\Phi}{|\Phi||\Psi|}$$

Josephson or Rabi coupling:
- Contact interaction;
- Long-range phase coherence b/ components;
- Conversion of species.

Low-energies: $\Theta_2 - \Theta_1$

$$\mathcal{L} = P(X) + 2\alpha\cos(\Theta_2 - \Theta_1)$$

- From condensed matter:
  - Josephson tunneling
  - Iron-based superconductors
  - MgB2
  - High Tc cuprate superconductor
  - XY model

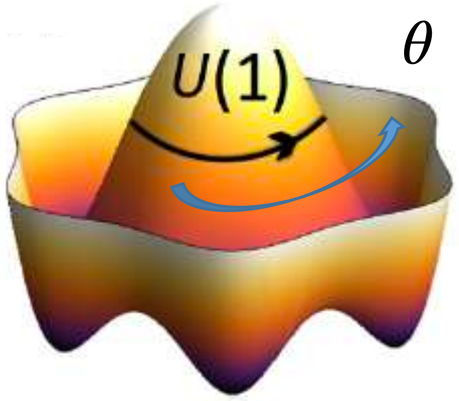
Unified Dark Energy/Dark Matter Superfluid

- Massless Goldstone bosons θ_i, non-relativistic regime $\Rightarrow \dot{\theta}/m \ll 1$

$$\mathcal{L} = P(X_1) + P(X_2) - \frac{M^4}{2}\left[1 + \cos\left(\frac{\theta_2 - \theta_1 + \Delta E\, t}{f}\right)\right]$$

$$X = \dot{\theta} - m\Phi - (\vec{\nabla}\theta)^2/2m$$

- Oscillatory potential is well motivated from the condensed matter description and phenomenologically.



⇒ Breaks shift symmetry weakly into a discrete symmetry.

- Still protects the potential from quantum corrections.

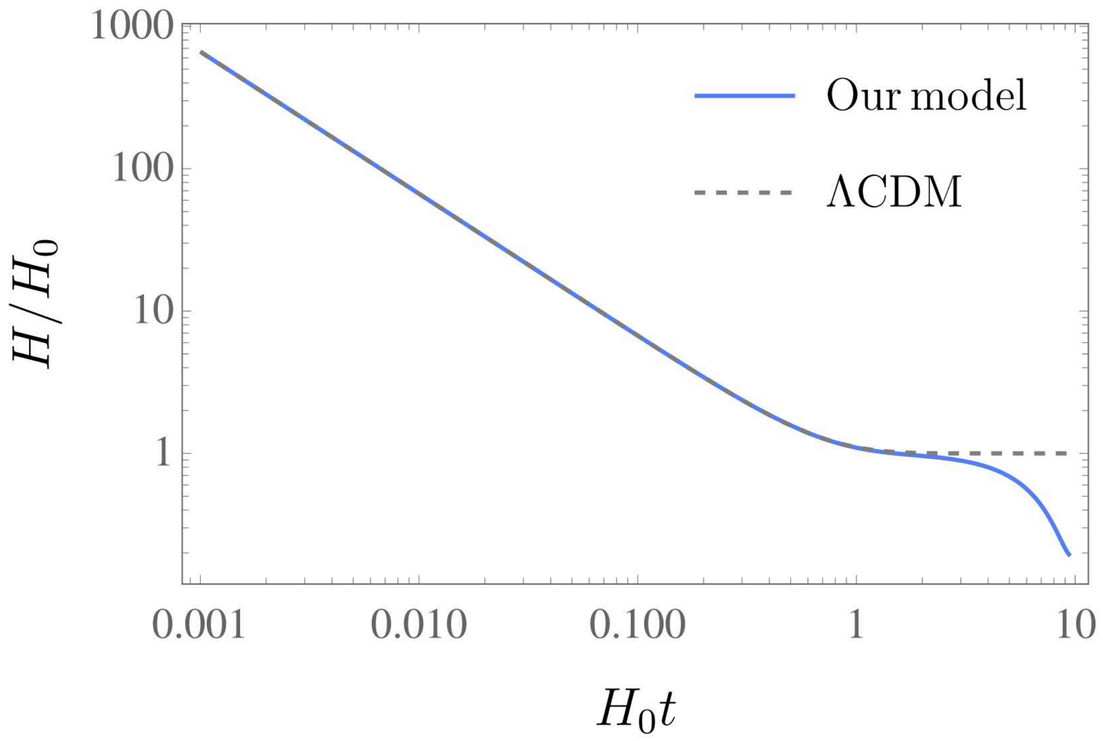
Analogous to a pNGB potential in θ.

Frieman et al 1995

Background evolution

In a FRW universe, for any P(X) superfluid in the NR limit:

$$2\dot{H} + 3H^2 = \frac{V(\Delta E\, t)}{M_{\rm Pl}^2}$$



Any $P(X)$ w/ $P_{i,X_iX_i} \geq 0$

Assume: $|\dot{\theta}_2 - \dot{\theta}_1| \ll \Delta E$

Equation of state

$$P(X_i) = \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^n$$

$$w = \frac{p}{\rho} = \frac{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^n - V(\Delta E\, t)}{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^{n-1} + V(\Delta E\, t)}$$

For $1 < n \leq 2$:

- As $\dot{\theta}$ decays → Past: kinetic term dominates;
  Late times: potential term dominates.

Equation of state

$$w = \frac{p}{\rho} = \frac{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^n - V(\Delta E\, t)}{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^{n-1} + V(\Delta E\, t)}$$

Past

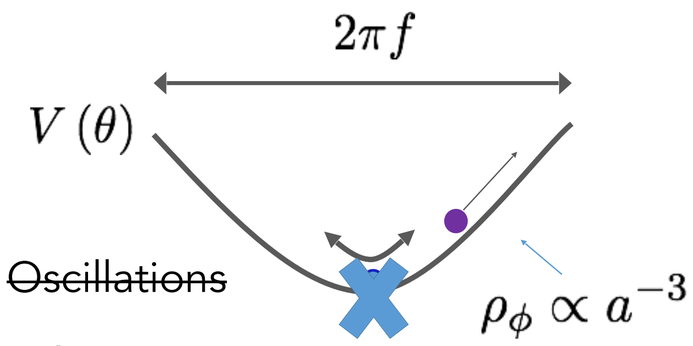
For $1 < n \leq 2$:

- As $\dot{\theta}$ decays → Past: kinetic term dominates;
  Late times: potential term dominates.
- Pressure has a higher power of $\dot{\theta}/m$ than the energy density.

$$w \to \frac{\dot{\theta}}{m} \ll 1$$

Dark matter!

* Naturally provides an EoS of matter- "Overdamped"
* No damped oscillations around the minimum of the potential, e.g., spintessence, pNGB, …



* It will always have small EoS and decaying, until potential term dominates.

Equation of state

$$w = \frac{p}{\rho} = \frac{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^n - V(\Delta E\, t)}{\sum \frac{\Lambda^4}{n}\left(\frac{\dot{\theta}_i}{m_i}\right)^{n-1} + V(\Delta E\, t)}$$

Today

For $1 < n \leq 2$:

- As $\dot{\theta}$ decays, the kinetic term will be important in the past and the potential term at late times.
- Pressure has a higher power of $\dot{\theta}/m$ than the energy density. So, in the regimes where the kinetic term dominates (past):

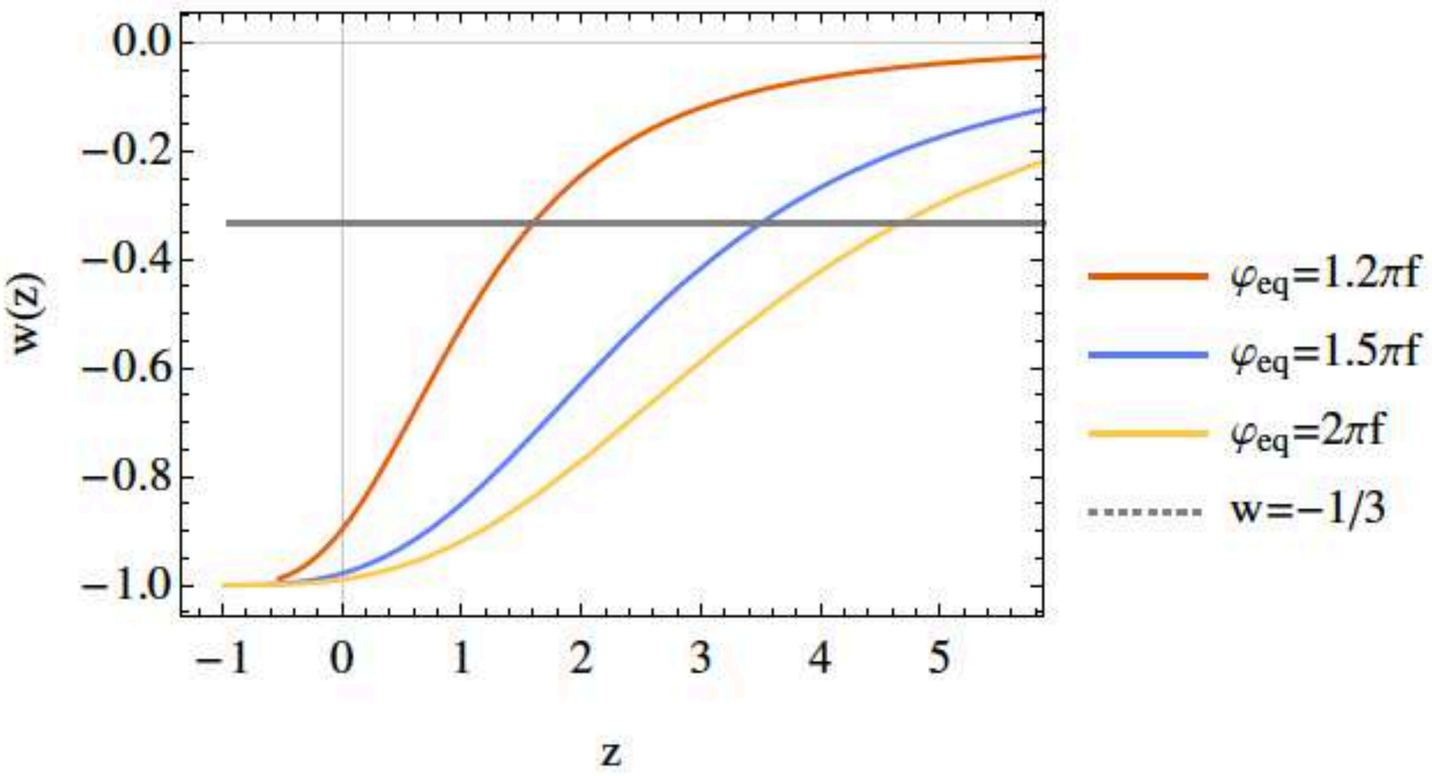
$$w \to \frac{\dot{\theta}}{m} \ll 1$$

Dark matter!

- As $\dot{\theta}$ decays, when the potential term dominates we can have an EoS of acceleration, denoting the dark energy.

Any $P(X)$ w/ $P_{i,X_iX_i} \geq 0$

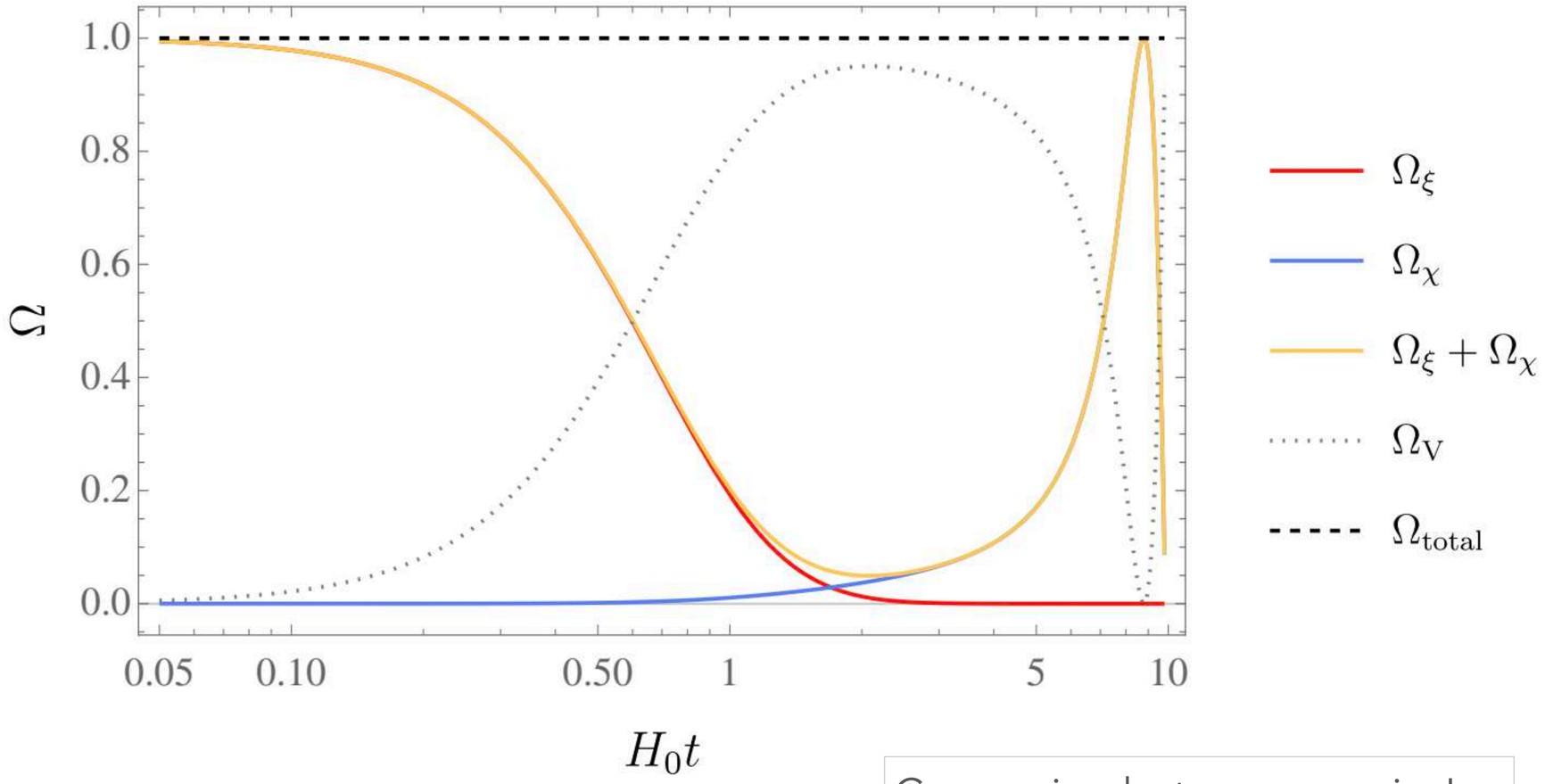
Equation of state



- Apparently it does not depend too much on the initial conditions: gets acceleration today – different instance to the coincidence problem. (Ongoing analysis)
- Exception: bottom of the potential $(2n+1)\pi f$ - takes too long to accelerate

Densities Evolution

Initial condition (eq): All DM in the ground state (θ_1) at eq.

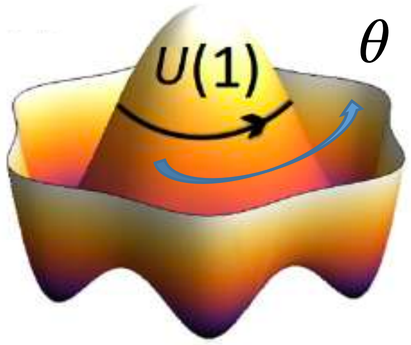


Conversion between species!

Cosmological Evolution

- Radiation: $\dot{\theta}/m \sim 1$ (not described by the NR theory)

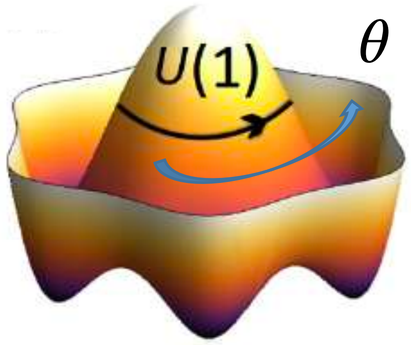
Field rotates fast for many cycles and does not feel the potential.



Cosmological Evolution

- Radiation: $\dot{\theta}/m \sim 1$ (not described by the NR theory)

Field rotates fast for many cycles and does not feel the potential.



$$\dot{\theta}/m \ll 1$$

- Matter:

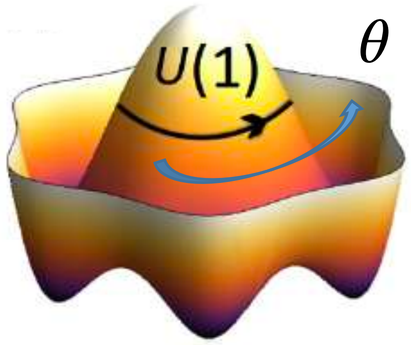
$$w \to \frac{\dot{\theta}}{m} \ll 1$$

Kinetic term dominates with

Cosmological Evolution

- Radiation: $\dot{\theta}/m \sim 1$ (not described by the NR theory)

Field rotates fast for many cycles and does not feel the potential.



$$\dot{\theta}/m \ll 1$$

- Matter:

$$w \to \frac{\dot{\theta}}{m} \ll 1$$

Kinetic term dominates with

- Dark Energy: $V(\theta)$ dominates.

Cosmological Evolution

Radiation

t_{eq}

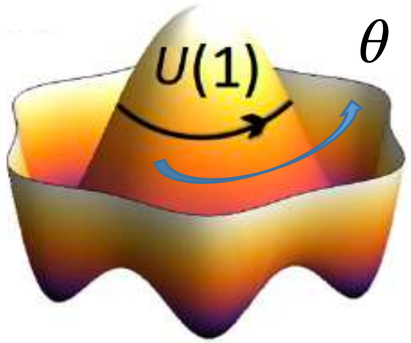
Matter

$t_{dm/de}$

Dark Energy

- Radiation: $\dot{\theta}/m \sim 1$ (not described by the NR theory)

Field rotates fast for many cycles and does not feel the potential.



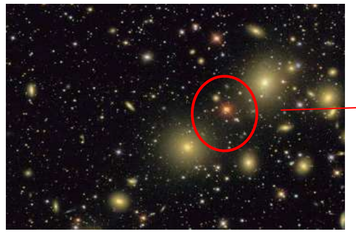
$$\dot{\theta}/m \ll 1$$

- Matter:

$$w \to \frac{\dot{\theta}}{m} \ll 1$$

Kinetic term dominates with

- Dark Energy: $V(\theta)$ dominates.



Small scales: gradients important
DM behaviour on galactic scales

EXTRA slides

EXTRA slides

Outline

Lecture 1: evidence and model building

- Evidence for dark matter
- Dark matter model building
  - What we know about DM
  - Pre-requisites for a DM model
- Mass bounds
- Landscape of models
- MOND

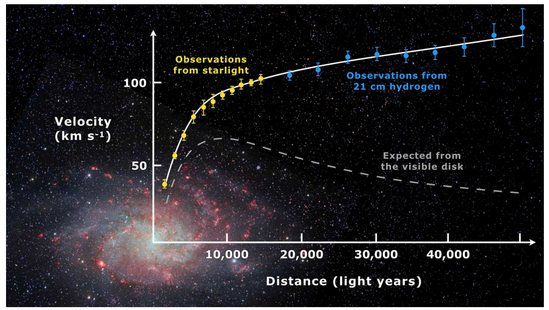
Lecture 2: DM models

- DM models
  - Particle DM: WIMPS
  - Macroscopic DM: MACHOS, Primordial BHs
  - Wave DM

Recap - lecture 1

Evidences for dark matter - properties

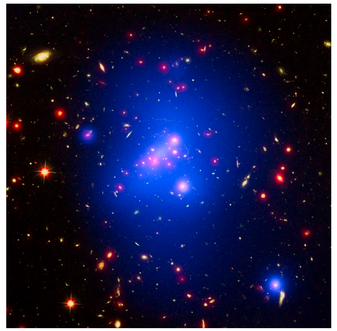
Galaxy rotation curves



Credit: Mario De Leo

- Mass fraction
- Distribution

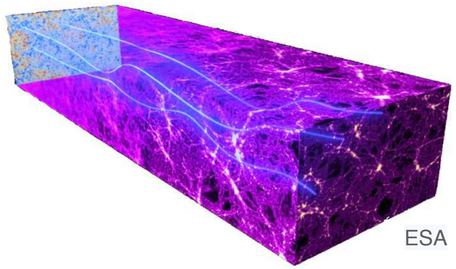
Clusters



CC BY 4.0

- Mass fraction
- Distribution

Lensing



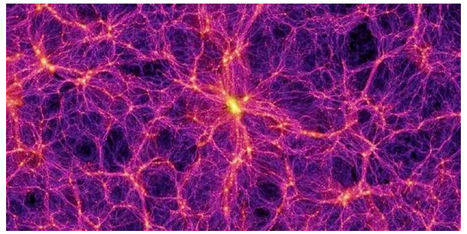
ESA

Strong lensing
- Mass fraction
- Distribution

Weak lensing
- Distribution
- Shape
- Structure

Micro lensing
- Mass fraction
- Smoothness

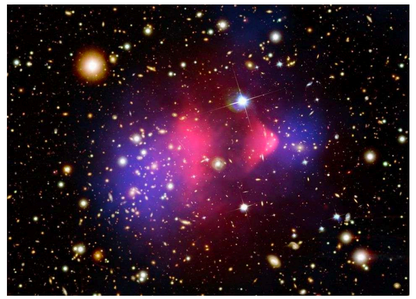
Large Scale Structure



Springel & others / Virgo Consortium

CMB/LSS
- Ratio of DM/collisional matter
- Thermal history

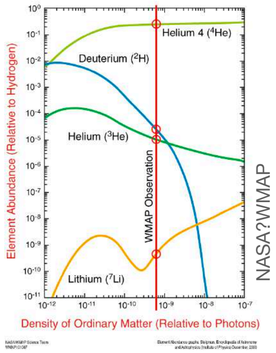
Cluster collision



NASA/CXC/CfA and NASA/STScI

- Distribution
- Separation from collisional matter
- Self-interaction

Big Bang Nucleosynthesis



NASA?WMAP

- Amount of baryons

Based on K. Mack

DM builder's guide

Pre-requisites for a dark matter candidate

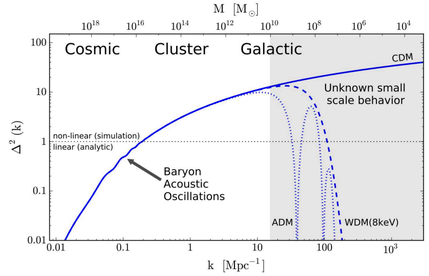
- Cold or warm — Thermal candidate: $m_{dm} \geq \mathrm{keV}$ — Or produced cold by a non-thermal mechanism

  Has to be non-relativistic at BBN

- Reproduce large and small scale distribution

  Clusters like pressure-less fluid on large scales $k \lesssim 10\,\mathrm{Mpc}^{-1}$

  Clustering on scales smaller than $k \gtrsim 10\,\mathrm{Mpc}^{-1}$ highly unconstrained



- Non-interacting or weakly interacting (~~Dark, colissionless~~)

  Can have a small electromagnetic interaction. Bound < **milicharge**

  Can have a **self interaction**. Bounds: $\sigma/m_{dm} < 0.13\,\mathrm{cm}^2/\mathrm{g}\,,\ \sigma/m_{dm} < 0.35\,\mathrm{cm}^2/\mathrm{g}$

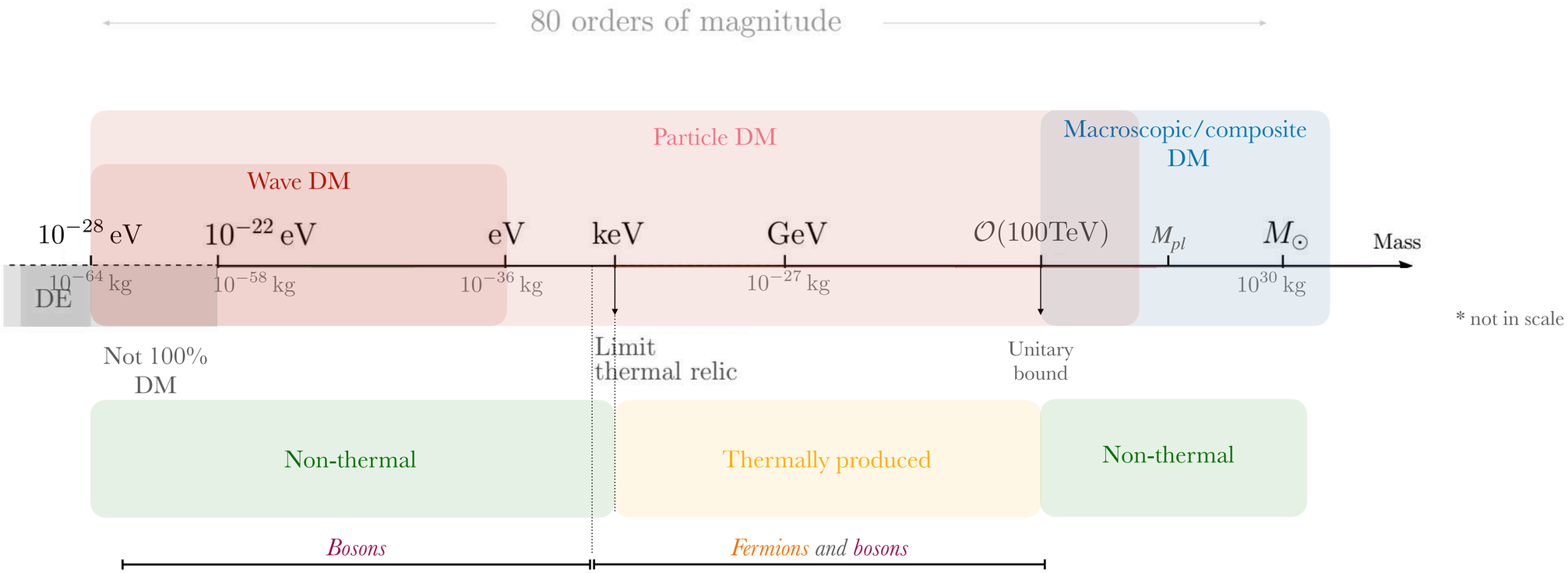
  Can interact via the ***weak force***

- Abundance $\Omega_m = 0.308 \pm 0.012$ (*Planck 2018*)

- Stable **If** it is a particle, it has to be stable with lifetime of DM should be much greater than the age of the universe

Mass scale of dark matter

We can use observations of LSS and galaxies to put bounds in the “particle" physics properties, like mass and spin, of the DM candidate



There are ways to evade some of these bounds!

Natural units ($c = 1$)

$1\,\text{kg} \to \sim 5 \times 10^{35}\,\text{eV}$

$1\,M_\odot \to \sim 10^{66}\,\text{eV}$

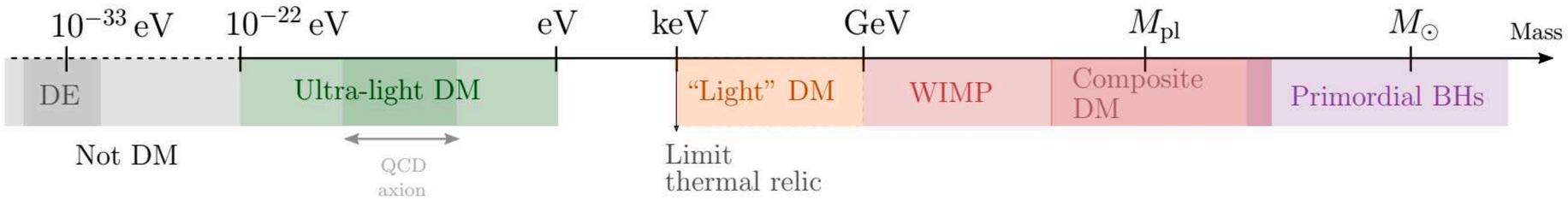
Landscape of dark matter models

- What is DM? What is the nature of DM?

State of the "art"

Mass scale of DM

80 orders of magnitude



MOND

Milgrom, 1983.

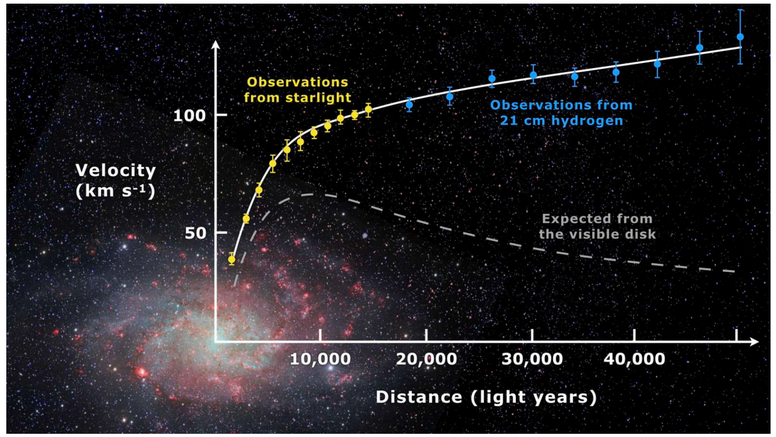
Modified Newtonian Dynamics

Empirical relation

$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

$$a_N^b = \frac{G_N M_b}{r^2}$$

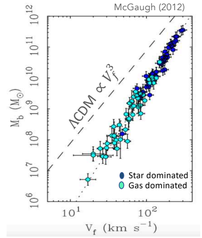
$$a_0 \simeq 1.2 \times 10^{-8}\,\mathrm{cm/s^2}$$



~~Missing mass~~

$$\cancel{v_c(r) = \sqrt{\frac{G_N M(r)}{r}}}$$

Curiosity: Baryons lead the dynamics!



BTFR

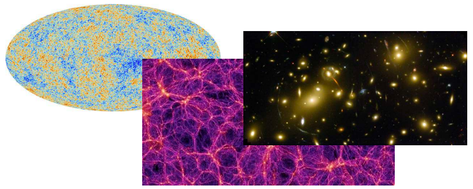
Works really well to: (1) Fit galaxy rotation curves; (2) Explain the scaling relations

BUT: Modified theory of gravity

Milgrom, 1983.

~~MOND without DM~~

Clusters



Large scales

Relativistic extension: TeVeS, (BIMOND)

2020: "*A new relativistic theory for Modified Newtonian Dynamics*", C. Skordis, T. Zlosnik ⟶ Agreement with CMB

Outline

Lecture 1: evidence and model building

- Evidence for dark matter
- Dark matter model building
  - What we know about DM
  - Pre-requisites for a DM model
- Mass bounds
- Landscape of models
- MOND

Lecture 2: DM models

- DM models
  - Particle DM: WIMPS, WIMPzillas
  - Macroscopic DM: MACHOS, Primordial BHs
  - Wave DM

* Biased review of the DM models

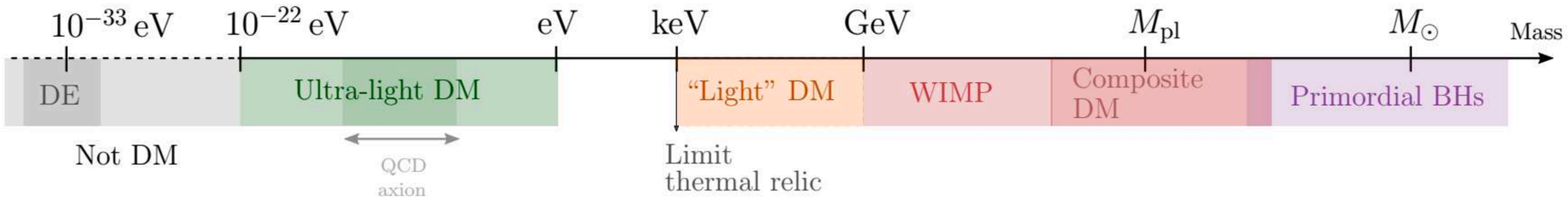
Landscape of dark matter models

- What is DM? What is the nature of DM?

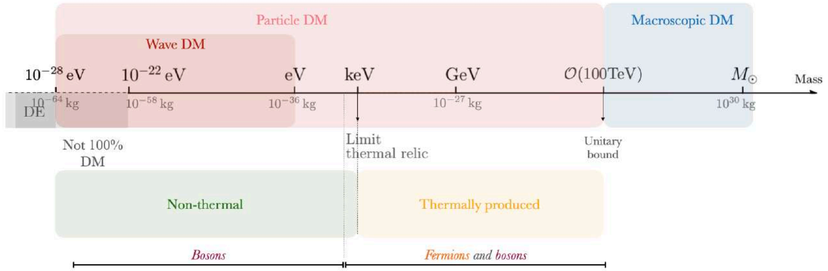
State of the "art"

Mass scale of DM

80 orders of magnitude



Particle DM


Particle DM
Macroscopic DM
Wave DM
10^{-28} eV
10^{-22} eV
eV
keV
GeV
$\mathcal{O}$(100TeV)
$M_\odot$
Mass
10^{-64} kg
10^{-58} kg
10^{-36} kg
10^{-27} kg
10^{30} kg
DE
Not 100% DM
Limit thermal relic
Unitary bound
Non-thermal
Thermally produced
Bosons
Fermions and bosons

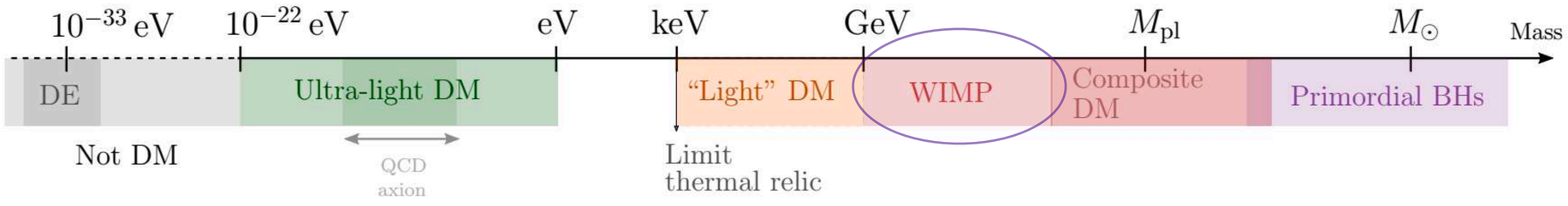
Landscape of dark matter models

- What is DM? What is the nature of DM?

State of the "art"

Mass scale of DM

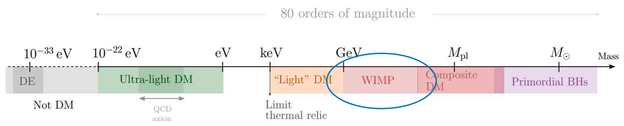
80 orders of magnitude



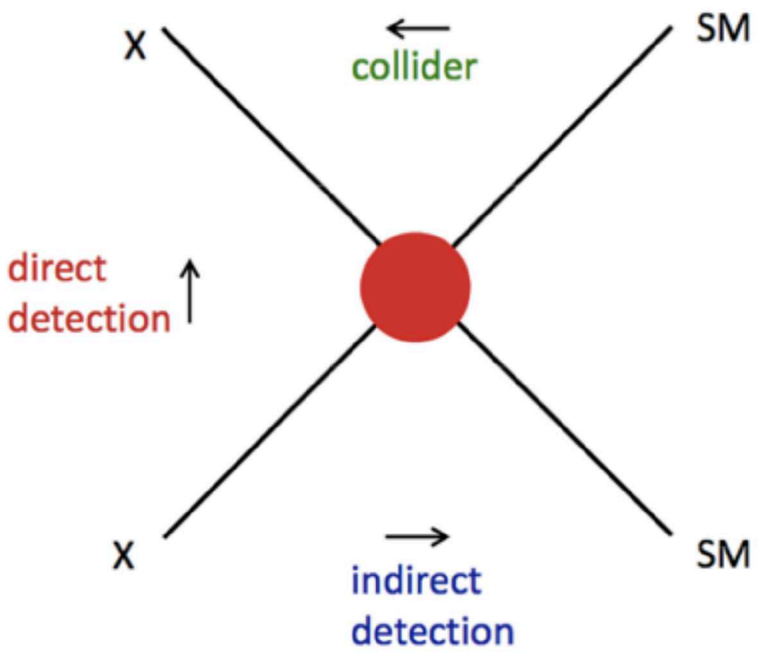
WIMPS

weakly interacting massive particles

WIMP - weakly interacting massive particle

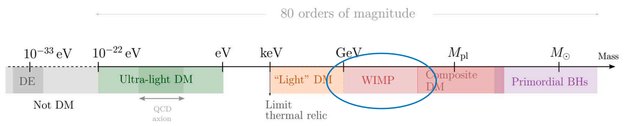


- Most accepted candidate
- (Beyond standard model) massive particle
- "WIMP miracle"
  - Thermally produced
  - m ~ weak scale → abundance of DM



Credito: F. Iocco

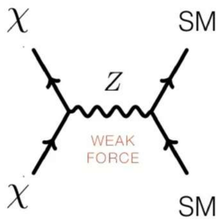
WIMP miracle

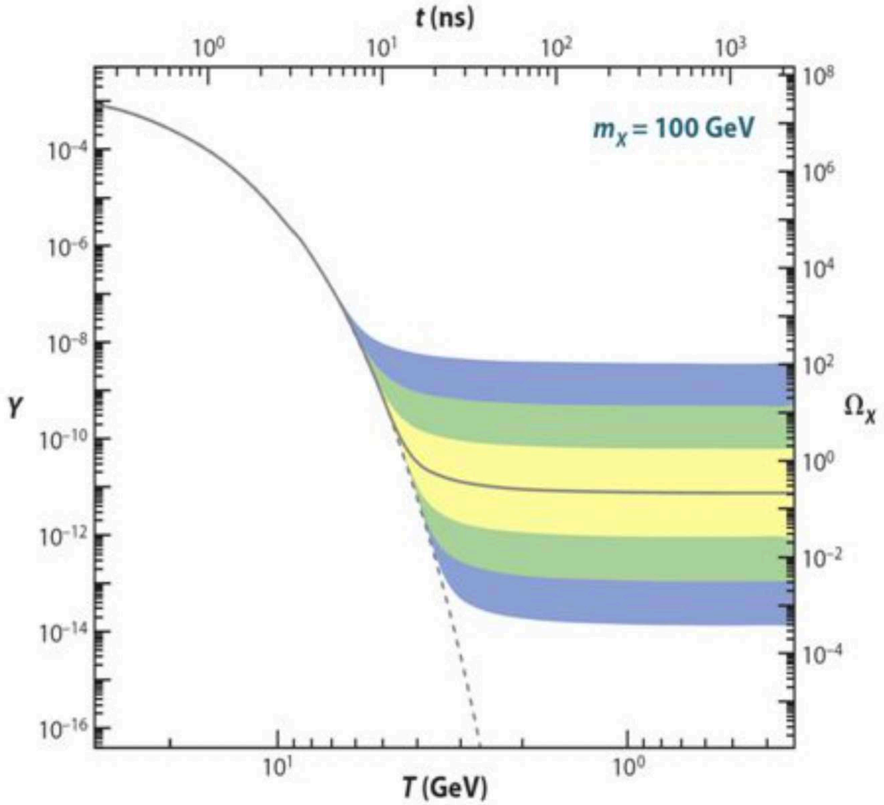


A thermal relic with cross-section ~weak interaction would freeze out with the ~ density of the obs. DM today

$$\Omega_\chi h^2 \simeq 0.1 \left(\frac{3 \times 10^{-9}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

Annihilation cross-section





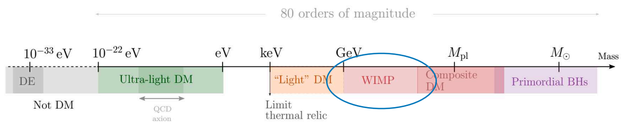
So we can have the correct abundance today:

$$\langle \sigma v \rangle \simeq 3 \times 10^{-9}\,\mathrm{GeV}^{-2} \simeq G_F \times \frac{v_{wimp}}{c}$$

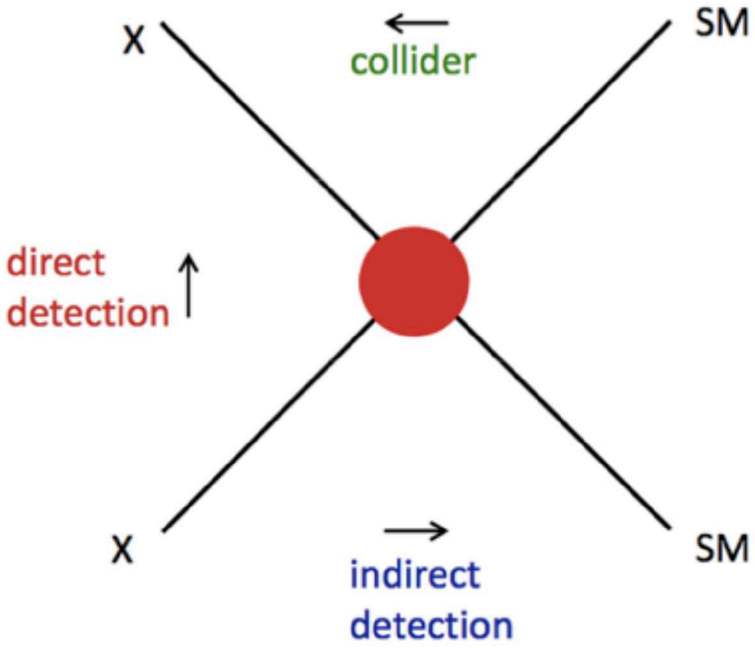
Expected cross-section for the weak interactions!

Therefore, if DM interacts through the weak force, we have the correct abundance of DM! Miracle!?

WIMP - weakly interacting massive particle



How can we measure it?

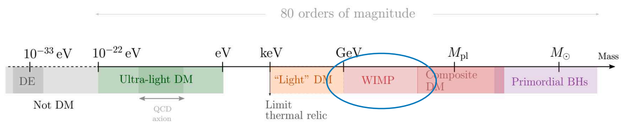


Credito: F. Iocco

+

Gravitationally
Cosmological and astrophysical searches

WIMP - weakly interacting massive particle



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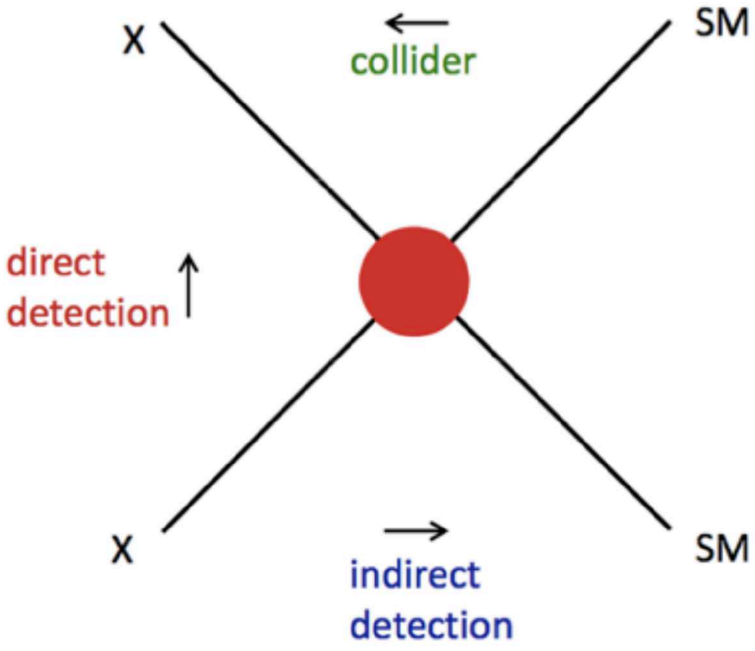


Credito: F. Iocco

\+

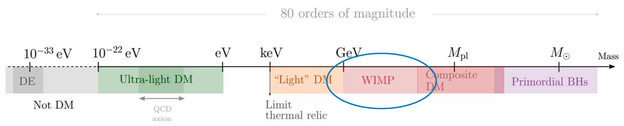
Gravitationally
Cosmological and astrophysical searches

<u>Direct detection</u>:
- DM scattering against nuclei, recoil

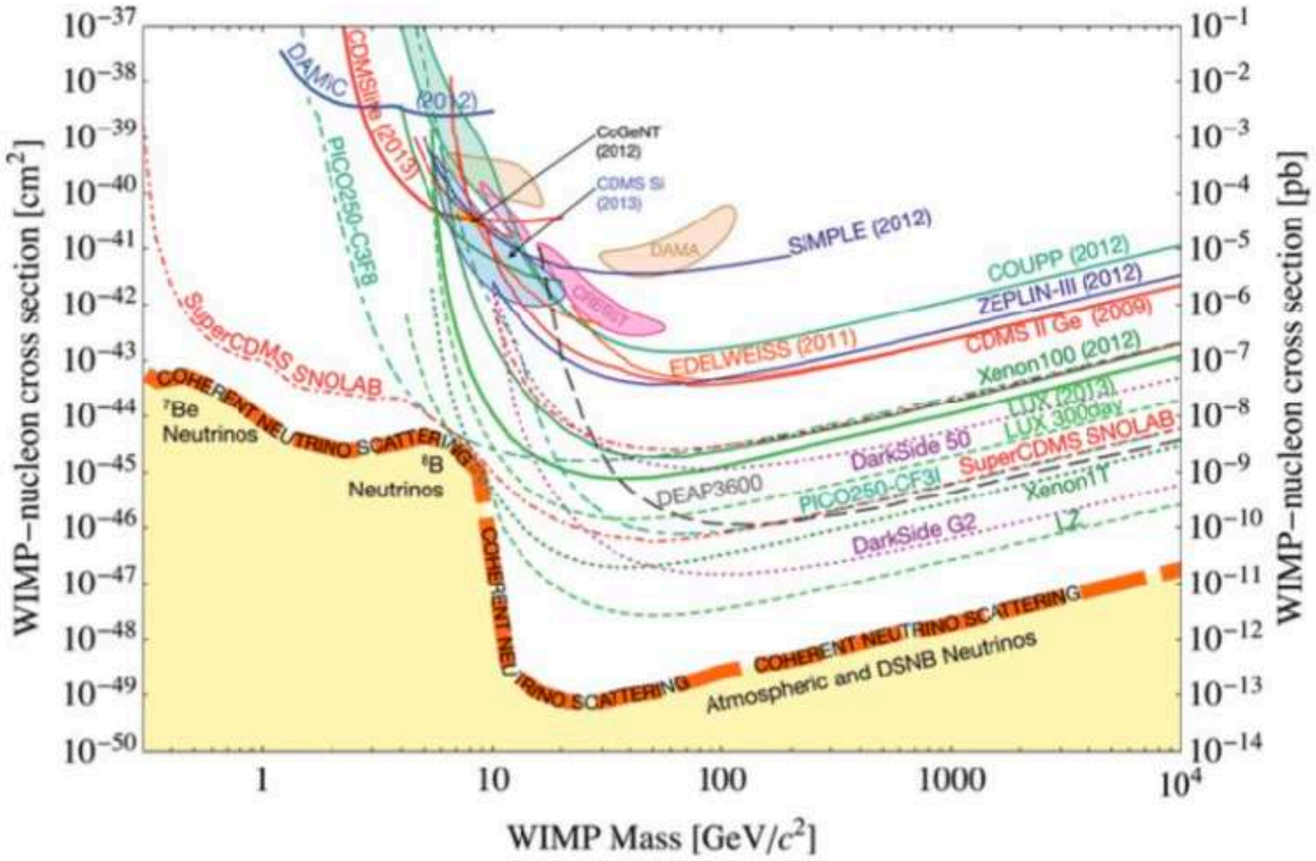
<u>Indirect detection</u>:
- Annihilation in astrophysical environment
- Observation of SM products of annihilation

<u>Production at collider</u> (LHC)

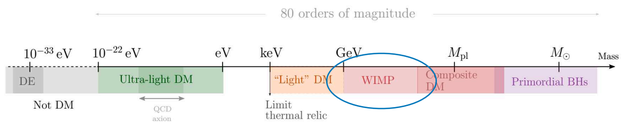
WIMP - weakly interacting massive particle



Bounds

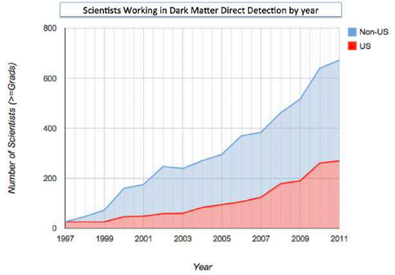


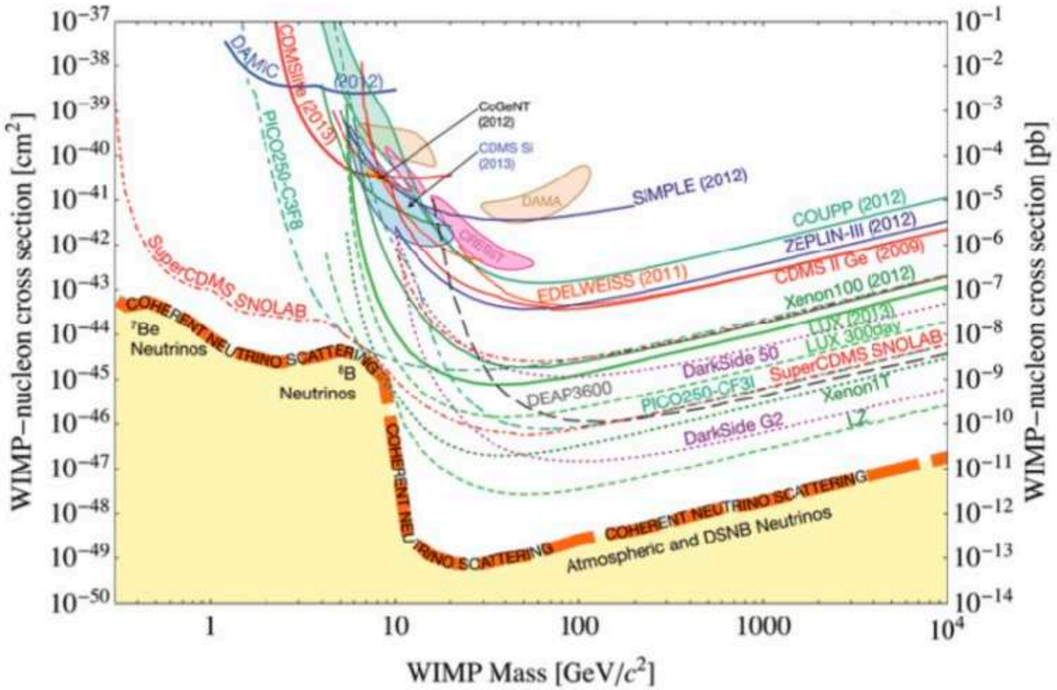
WIMP - weakly interacting massive particle



Bounds

Snowmass 2013

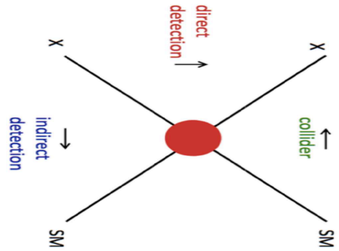




HUGE experimental effort for discovery/bound

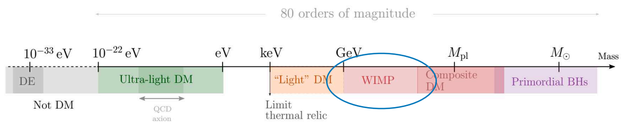
Still not detected!

Exclusion limits/bounds are of difficult interpretation for WIMPs



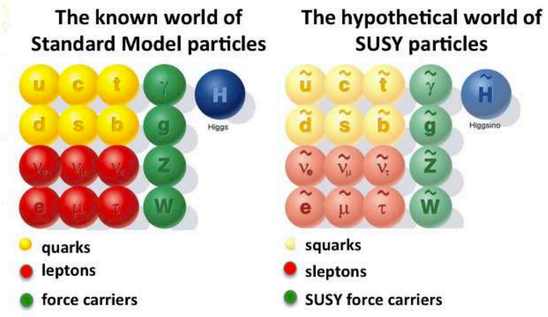
Supersymmetry

DM from supersymmetry

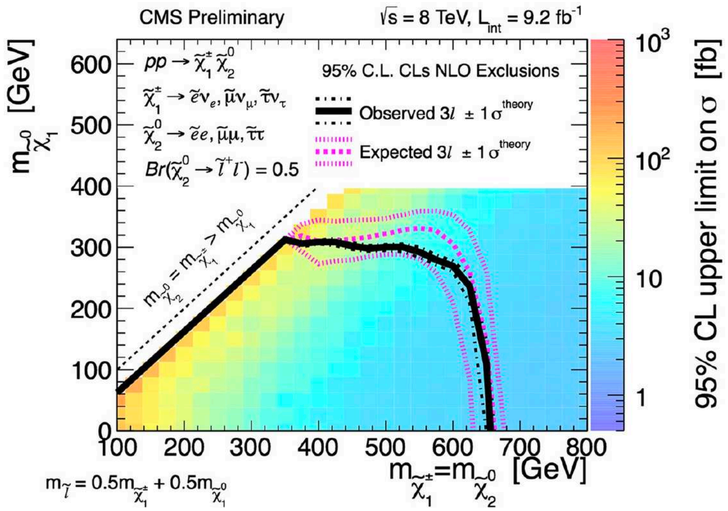


Lightest supersymmetric partner is stable

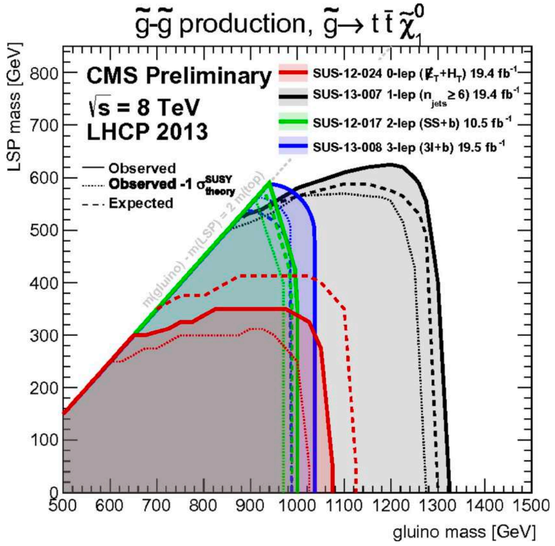
- Neutralino
- Gravitino
- Chargino
- Bino
- …



Search at colliders!

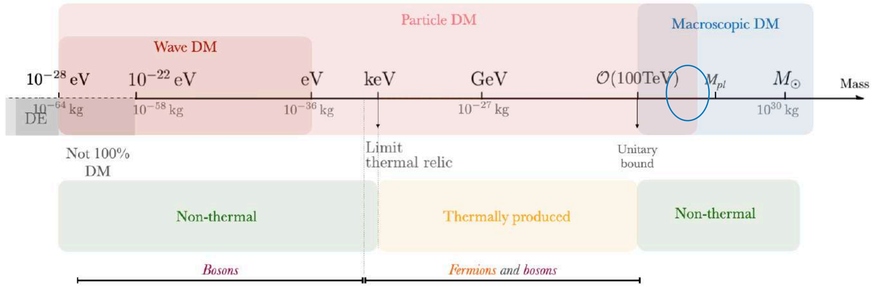


Neutralino and chargino

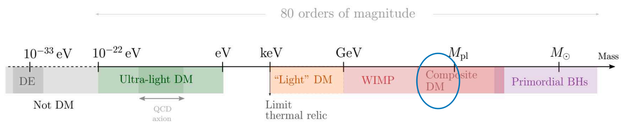


Gluino

WIMPzillas

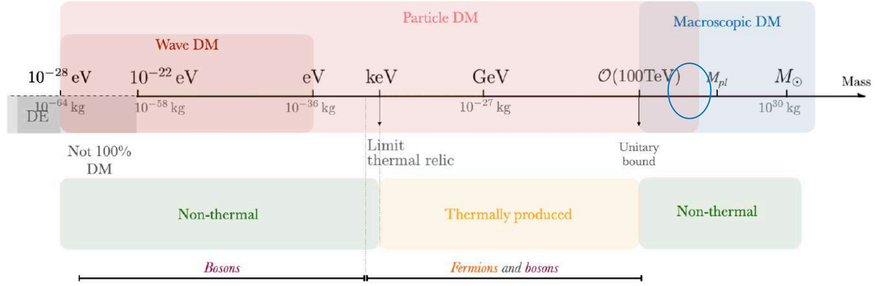

Particle DM
Macroscopic DM
Wave DM
10^{-28} eV
10^{-22} eV
eV
keV
GeV
$\mathcal{O}(100\text{TeV})$
M_{pl}
$M_\odot$
Mass
10^{-54} kg
10^{-58} kg
10^{-36} kg
10^{-27} kg
10^{30} kg
DE
Not 100% DM
Limit thermal relic
Unitary bound
Non-thermal
Thermally produced
Non-thermal
Bosons
Fermions and bosons

WIMPzillas



Not a lot of superheavy candidates between $\mathcal{O}(100)$ TeV – $\mathcal{O}(10^{40})$ eV

WIPMzillas: superheavy **particle** Ref.: Kolb et al 1998



2 necessary conditions:

- Must be stable (Condition for being particle DM)
- Must not have been in equilibrium when it froze out (i.e., it is **not** a thermal relic), otherwise $\Omega_X h^2$ would be much larger than one
  - A sufficient condition for nonequilibrium is that the annihilation rate (per particle) must be smaller than the expansion rate: $n_X \sigma v < H$ (Condition for being non-thermal relic)

Produced non-thermally!!

(Not subjected to the unitary bound)

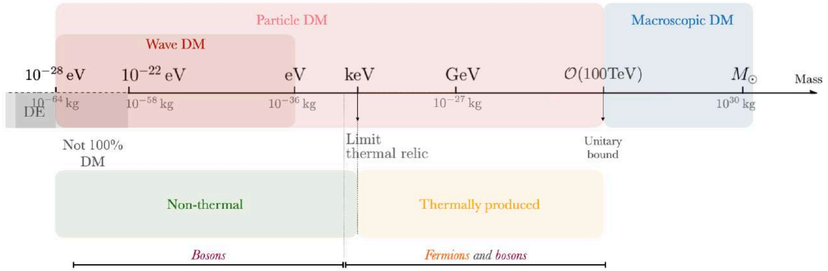
$\Rightarrow$ Produced during inflation - 10^9 GeV – 10^{16} GeV (GUT scale)

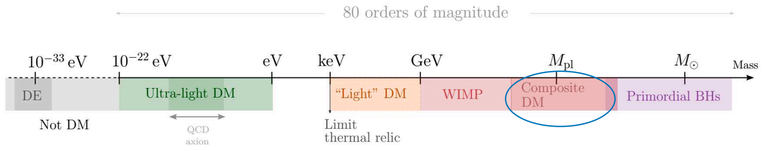
There are no experiments looking for WIMPzillas

(Size does matter)

$M_{pl} \sim 10^{19}$ GeV

Macroscopic/composite DM



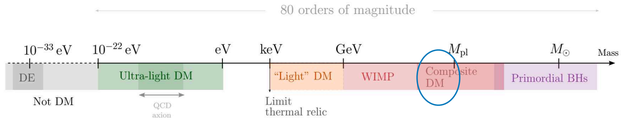


Composite DM

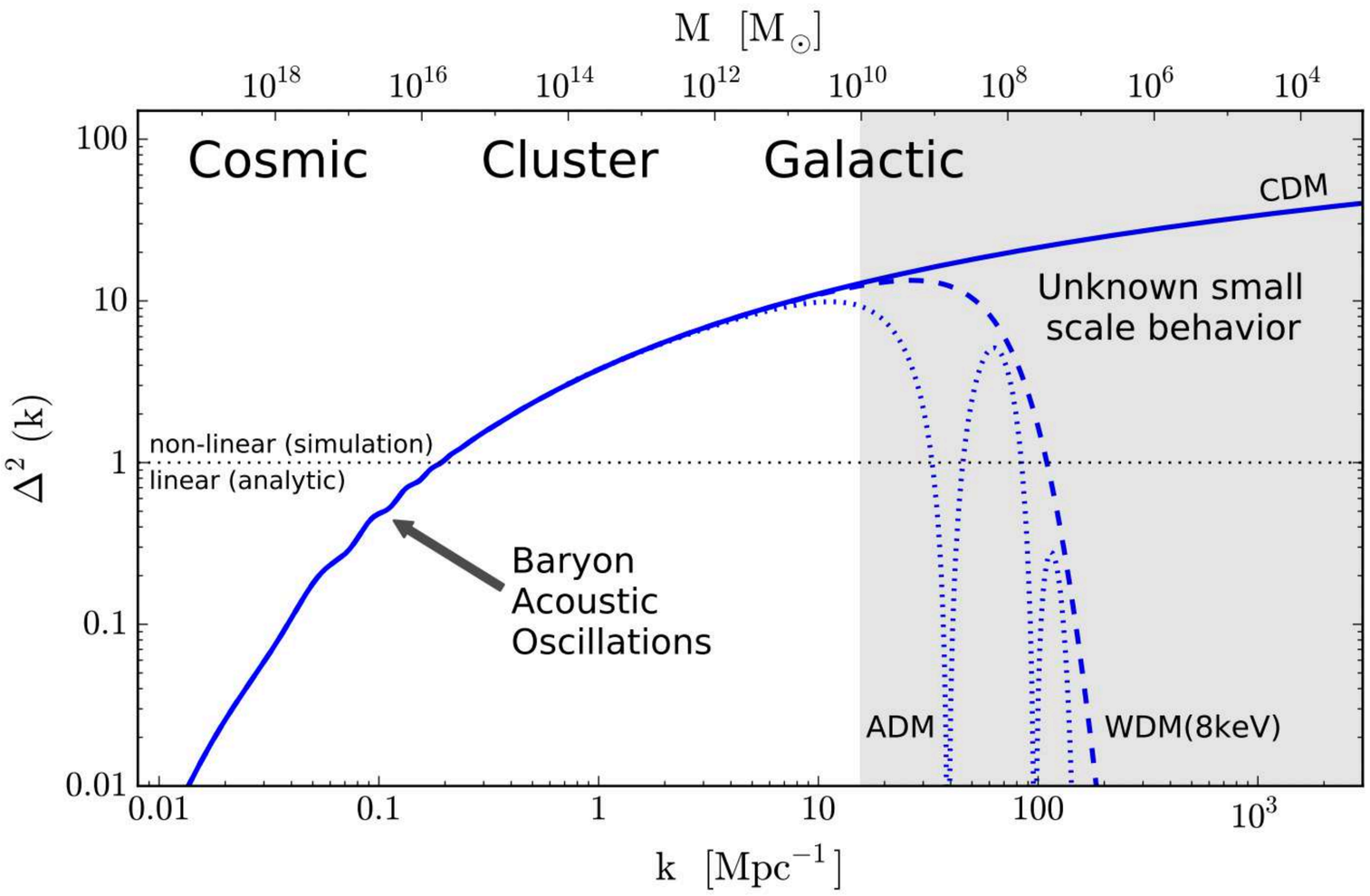
Dark atoms, (dark) glueballs, nuggets of baryons or other fermions …

(an entire "SM" dark sector)

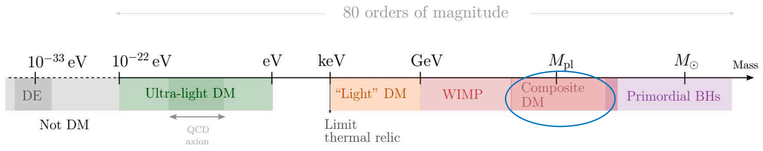
Atomic dark matter



Ref.: Kaplan et al 2009
Cyr-Racine et al 2012



Dark Acoustic Oscillations



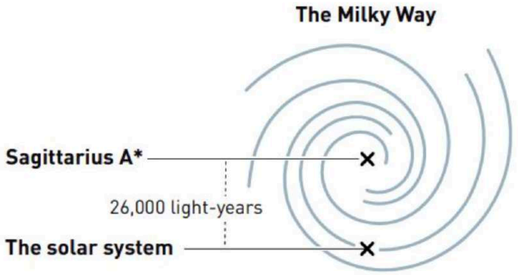
MACHOS

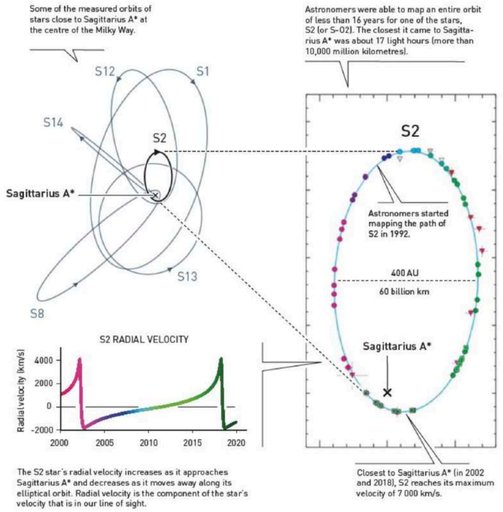
massive compact halo object

Primordial Black Holes

We know BHs exist!

Star motion

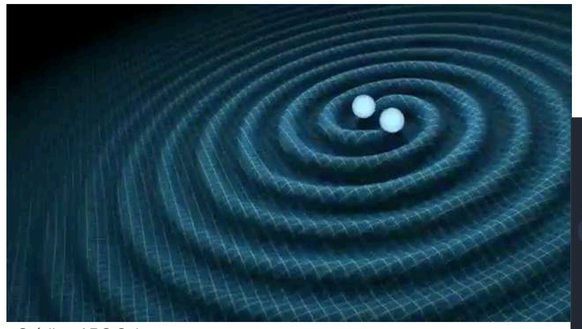




Crédito: Nobel Prize

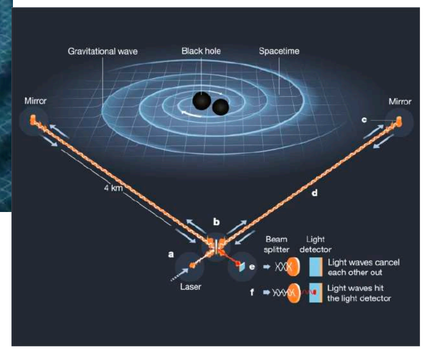
Nobel prize (2021)

Gravitational waves



Crédito: ABC Science

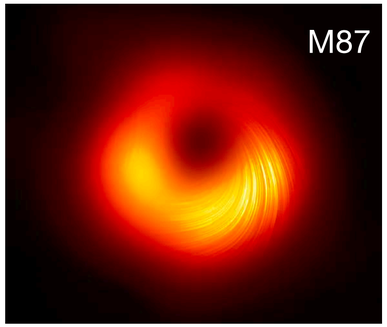
LIGO



+ VIRGO + KAGRA

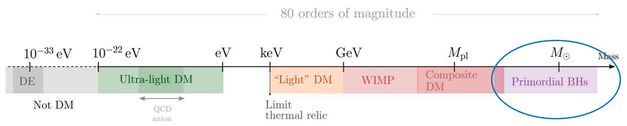
Credito: ©Johan Jarnestad/The Royal Swedish Academy of Sciences.

Event Horizon Telescope

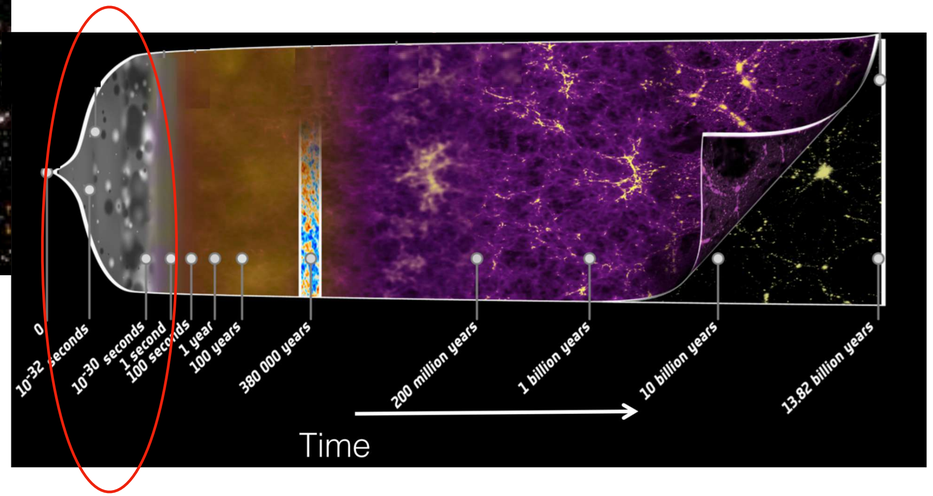


Crédito: ESO

Primordial Black Holes

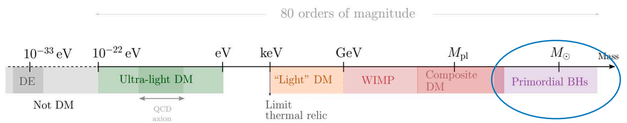


- BHS formed at early times
- BHs with mass $10^{-15}\, M_\odot \lesssim M_{\rm PBH} \lesssim \mathcal{O}(1)\, M_\odot$
- Can explain part or all of the DM



$M_\odot \sim 2 \times 10^{30}$ kg

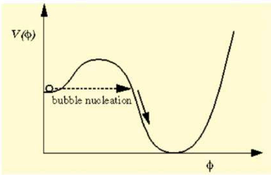
Primordial Black Holes



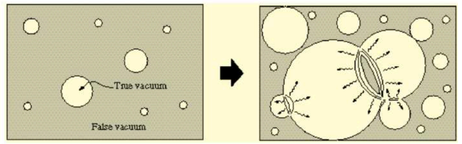
Formation mechanisms

- Bubble collision (Hawking et al, 1982)

1st order phase transitions occur via the nucleation of bubbles



Bubbles



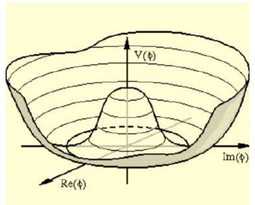
© Cambridge cosmology group

PBHs can form when bubbles collide (but bubble formation rate must be fine tuned)

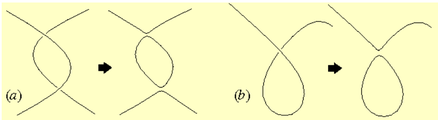
⇒ PBH mass ~ order horizon mass at phase transition.

- Cosmic string loops (Hawking 1987)

Cosmic strings:1d topological defects formed during symmetry breaking phase transition



Loops



© Cambridge cosmology group

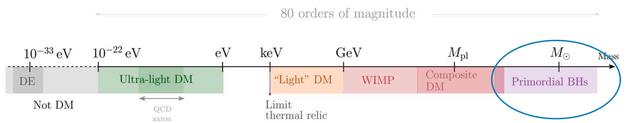
Small probability that loop will get into configuration of size ~ Schwarzschild radius

⇒ hence collapse to from a PBH with mass of order the horizon mass at that time

- Collapse of density perturbations (Carr and Hawking 1974)

Based on Anne Green

Primordial Black Holes



<u>Formation mechanisms:</u> collapse of large density perturbations (during radiation domination)

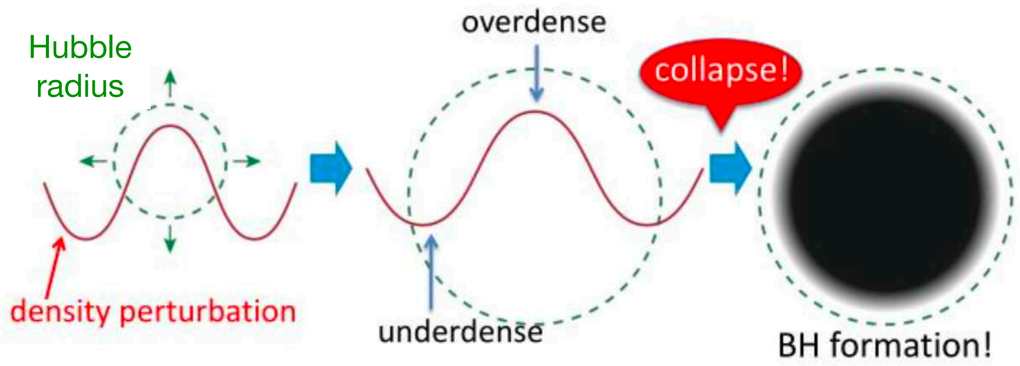
(0th order argument)

If a density perturbation is sufficiently large (at Hubble radius entry) it can collapse to form a PBH

Threshold for formation:

$$\delta_{hc} \geq \delta_c \sim w = \frac{P}{\rho} = \frac{1}{3}$$

Typically requires $\delta \sim 1$



Kawasaki et al 2012

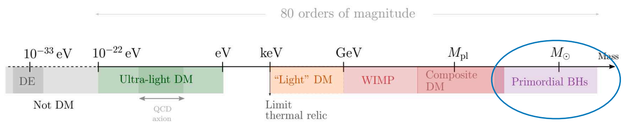
$\Rightarrow$ Form a PBH with $M_{\rm PBH} \sim M_{R_H}$

$$M_{R_H} = \frac{4\pi}{3}\rho(cH^{-1}) = \frac{c^3}{2GH} = \frac{tc^3}{G} \sim 10^{15}\,\mathrm{g}\left(\frac{t}{10^{-23}\,\mathrm{s}}\right) \sim M_\odot\left(\frac{t}{10^{-6}\,\mathrm{s}}\right) \sim M_{\rm PBH}$$

Mass contained in the Hubble radius

* Here not in natural units!!

Primordial Black Holes



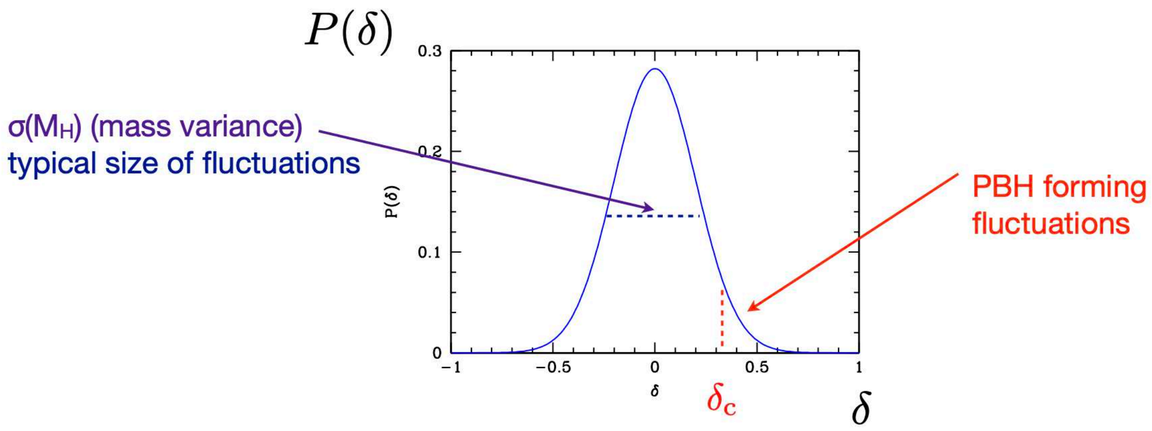
Initial PBH mass fraction: fraction of universe in regions dense enough to form PBHs

(0th order argument)

$$\beta(M) = \left(\frac{\rho_{\rm PBH}}{\rho_{tot}}\right)_i \sim \int_{\delta_c}^{\infty} P(\delta(M_{R_H}))d\delta(M_{R_H}) \sim \sigma(M_{R_H})\exp\left(-\frac{\delta_c^2}{2\sigma^2(M_{R_H})}\right)$$

density contrast, smoothed on a scale R_H

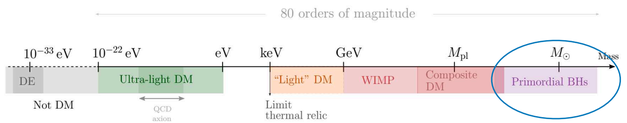
Assuming Gaussian prob. distribution



Credit: Anne Green

* Here not in natural units!!

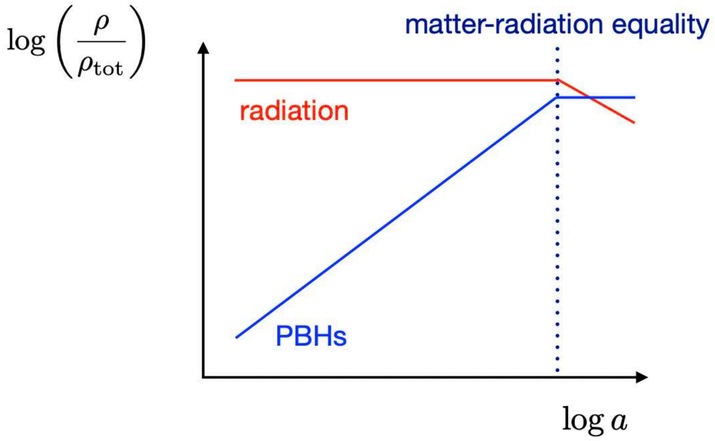
Primordial Black Holes



PBH abundance

Since PBHs are matter, during radiation domination the fraction of energy in PBHs grows

$$\frac{\rho_{\rm PBH}}{\rho_{rad}} \propto \frac{a^{-3}}{a^{-4}} \propto a$$

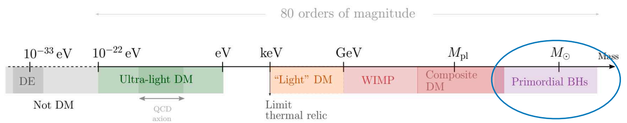


The PBH initial mass fraction, β, and **fraction of DM in form of** PBH are related by:

$$\beta(M) \sim 10^{-9} f_{\rm PBH} \left(\frac{M}{M_\odot}\right)^{1/2}$$

$\Rightarrow$ initial mass fraction must be small, but non-negligible.

Primordial Black Holes



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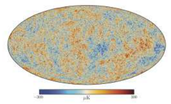
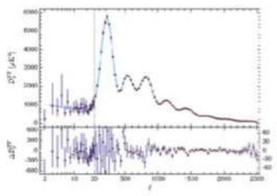
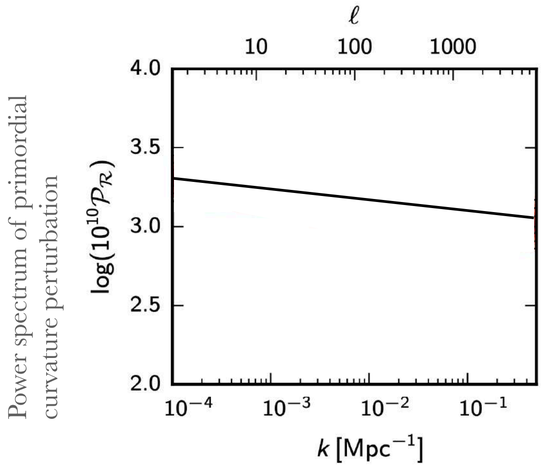
Initial perturbation:

Can the (nearly) scale-invariant primordial pert from early times (same that is the seed to LSS) source PBH and give a sizeable initial fraction? NO!

From CMB: $\sigma(M_{R_H}) \sim 10^{-5}$







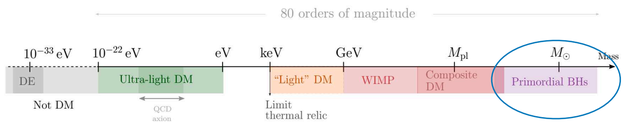
$$\mathcal{P}_\mathcal{R} = A_S \left(\frac{k}{k_p}\right)^{n_s - 1}$$

$$\beta(M) = \sigma(M_{R_H}) \exp\left(-\frac{\delta_c^2}{2\sigma^2 M_{R_H})}\right)$$

$$\sim \exp(10^{-10}) \ll 1$$

Negligible!

Primordial Black Holes



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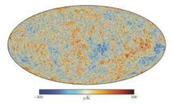
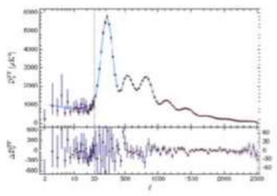
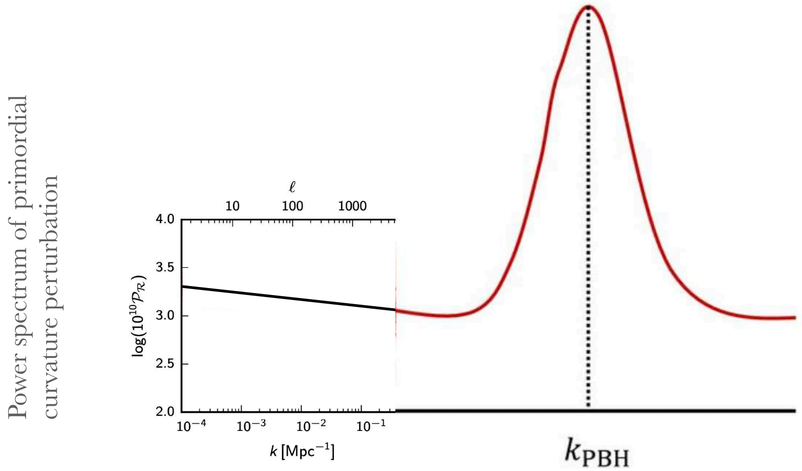






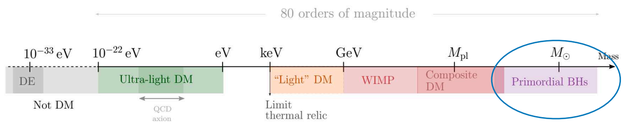
$$\beta(M) = \sigma(M_{R_H}) \exp\left(-\frac{\delta_c^2}{2\sigma^2 M_{R_H})}\right)$$

$$\sim \exp(-10^{10}) \ll 1$$

Negligible!

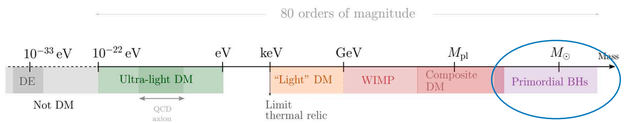
To form an interesting number of PBHs amplitude of primordial perturbations must be 2-3 orders of larger on small scales than on cosmological scales and fine-tuned.

Primordial Black Holes

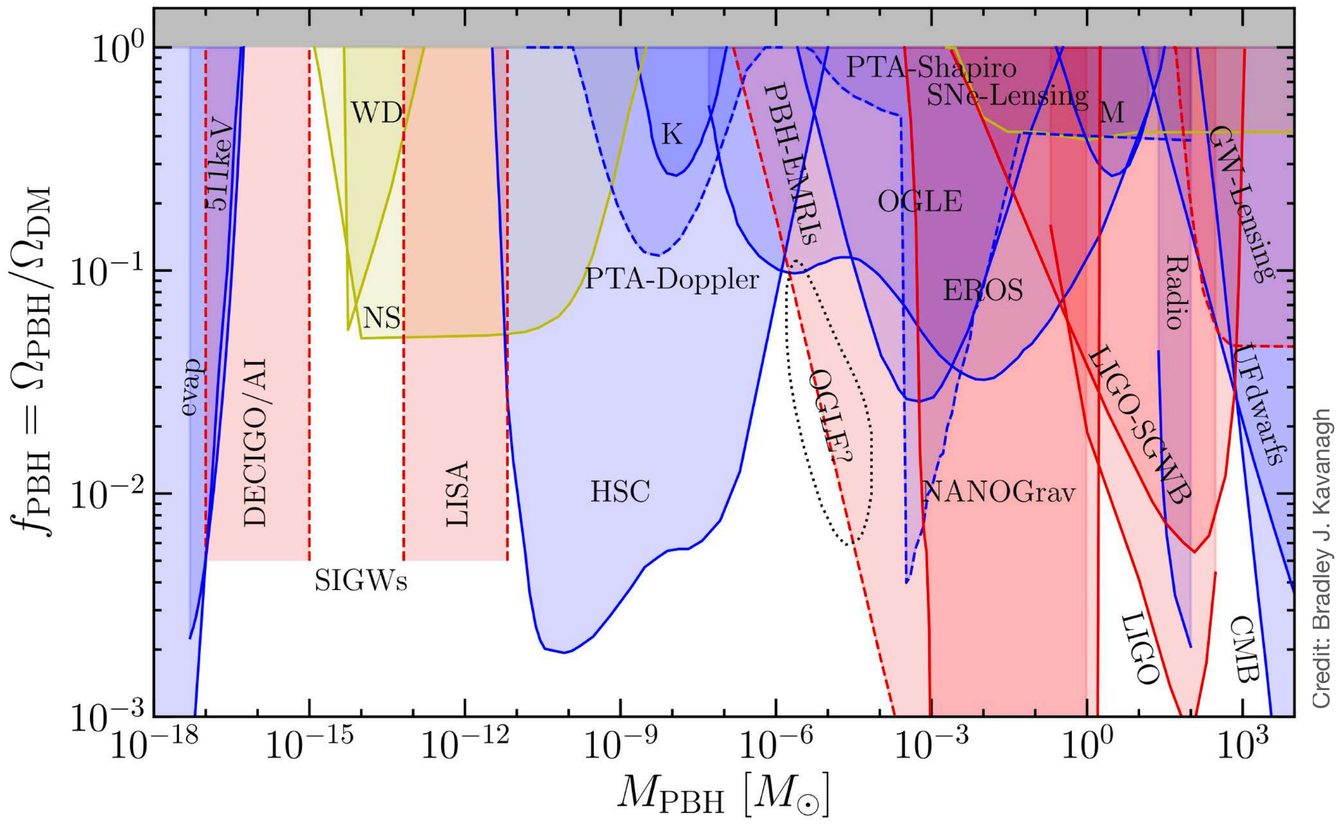


On cosmological scales PBH DM would behave like particle DM, however on galactic and smaller scales its granularity can have *observable consequences.*

Primordial Black Holes



Bounds

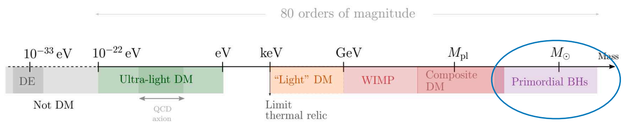


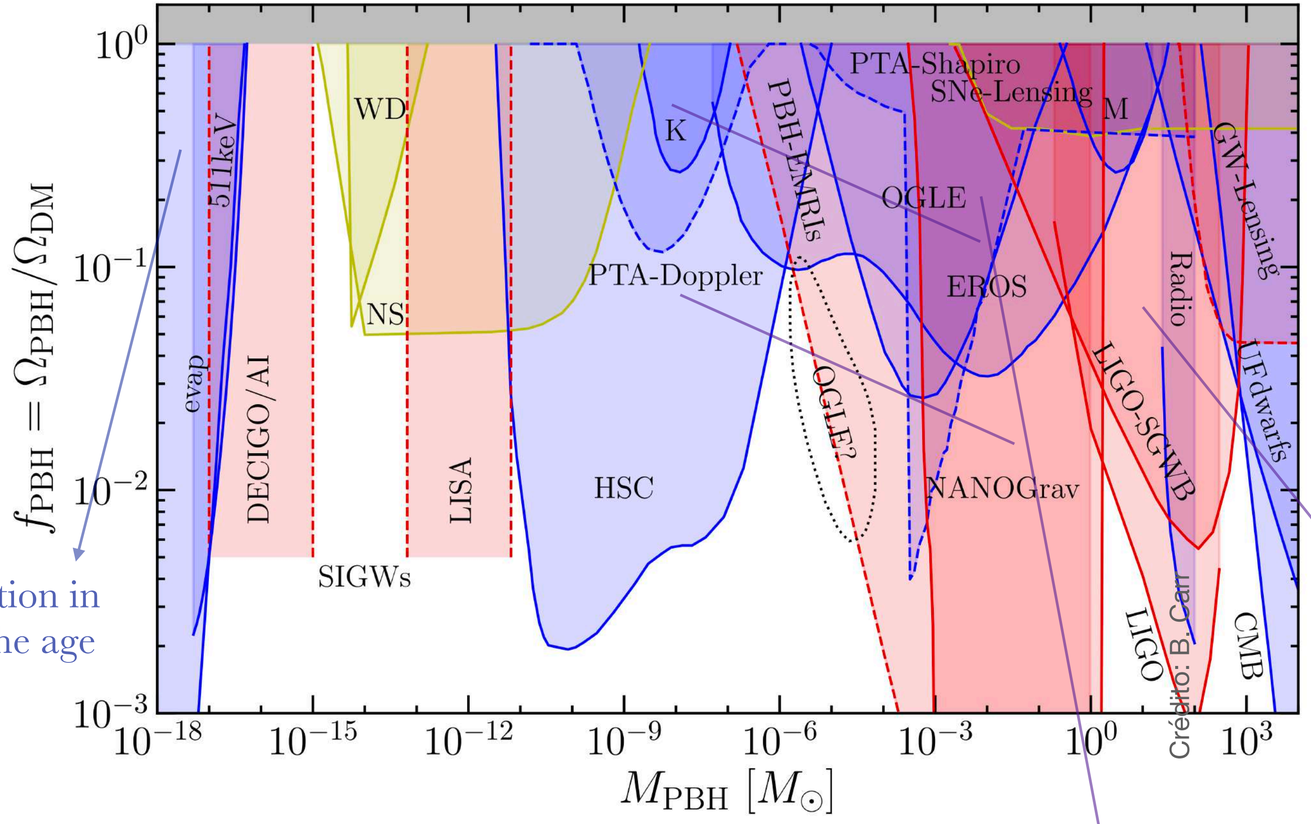
Credit: Bradley J. Kavanagh

$M_\odot \sim 2 \times 10^{30}$ kg

Notebook to plot the PBH bounds: https://github.com/bradkav/PBHbounds

Primordial Black Holes





Crédito: B. Carr

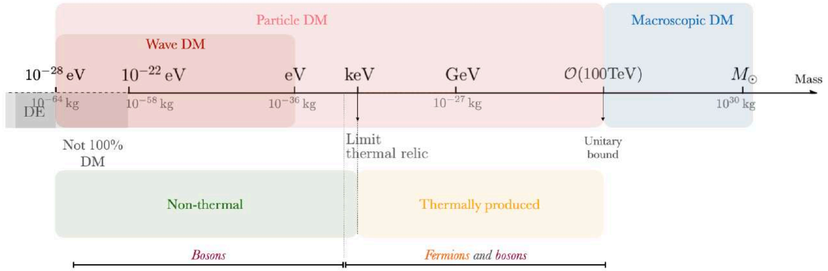
PBH evaporate, emits gamma radiation in scales or the order of smaller than the age of the universe

GW from LIGO

Direct searches via microlensingin our galaxy and M31,… (does not require that it is a BH - scalar bound system)

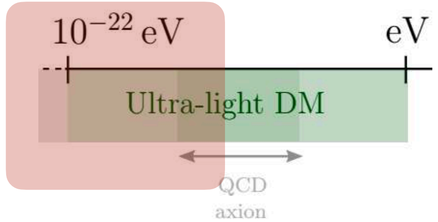
$M_\odot \sim 2 \times 10^{30}$ kg

Wave DM

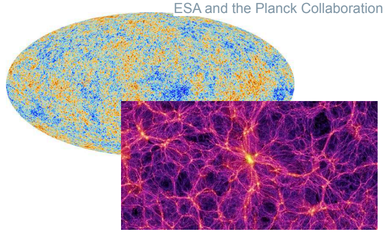

Particle DM
Macroscopic DM
Wave DM
10^{-28} eV
10^{-22} eV
eV
keV
GeV
$\mathcal{O}(100\text{TeV})$
$M_\odot$
Mass
10^{-64} kg
10^{-58} kg
10^{-36} kg
10^{-27} kg
10^{30} kg
DE
Not 100% DM
Limit thermal relic
Unitary bound
Non-thermal
Thermally produced
Bosons
Fermions and bosons

Current status

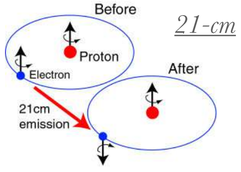
Fuzzy Dark Matter - bounds on the mass



ESA and the Planck Collaboration

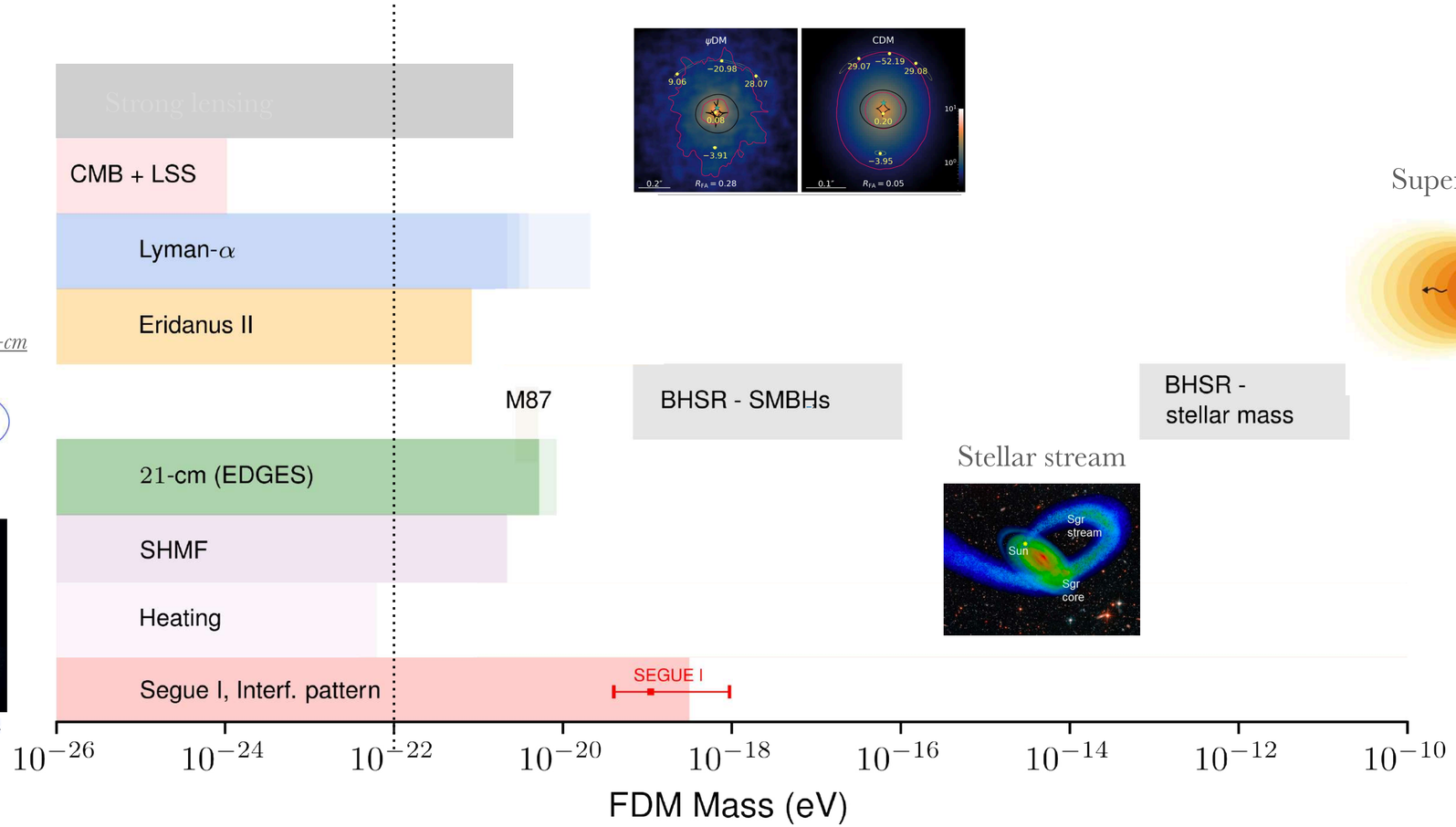


Springel & others / Virgo Consortium

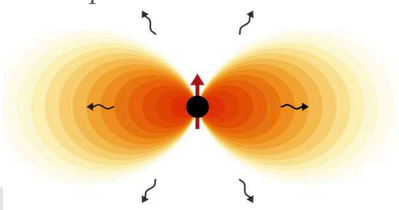


21-cm

NASA and ESA

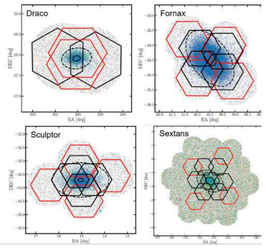


Superradiance



Stellar stream

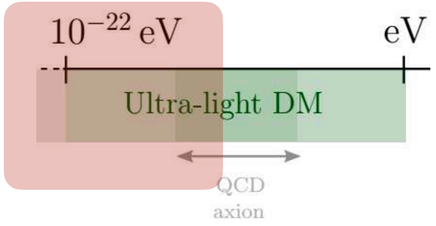
Dwarf galaxies

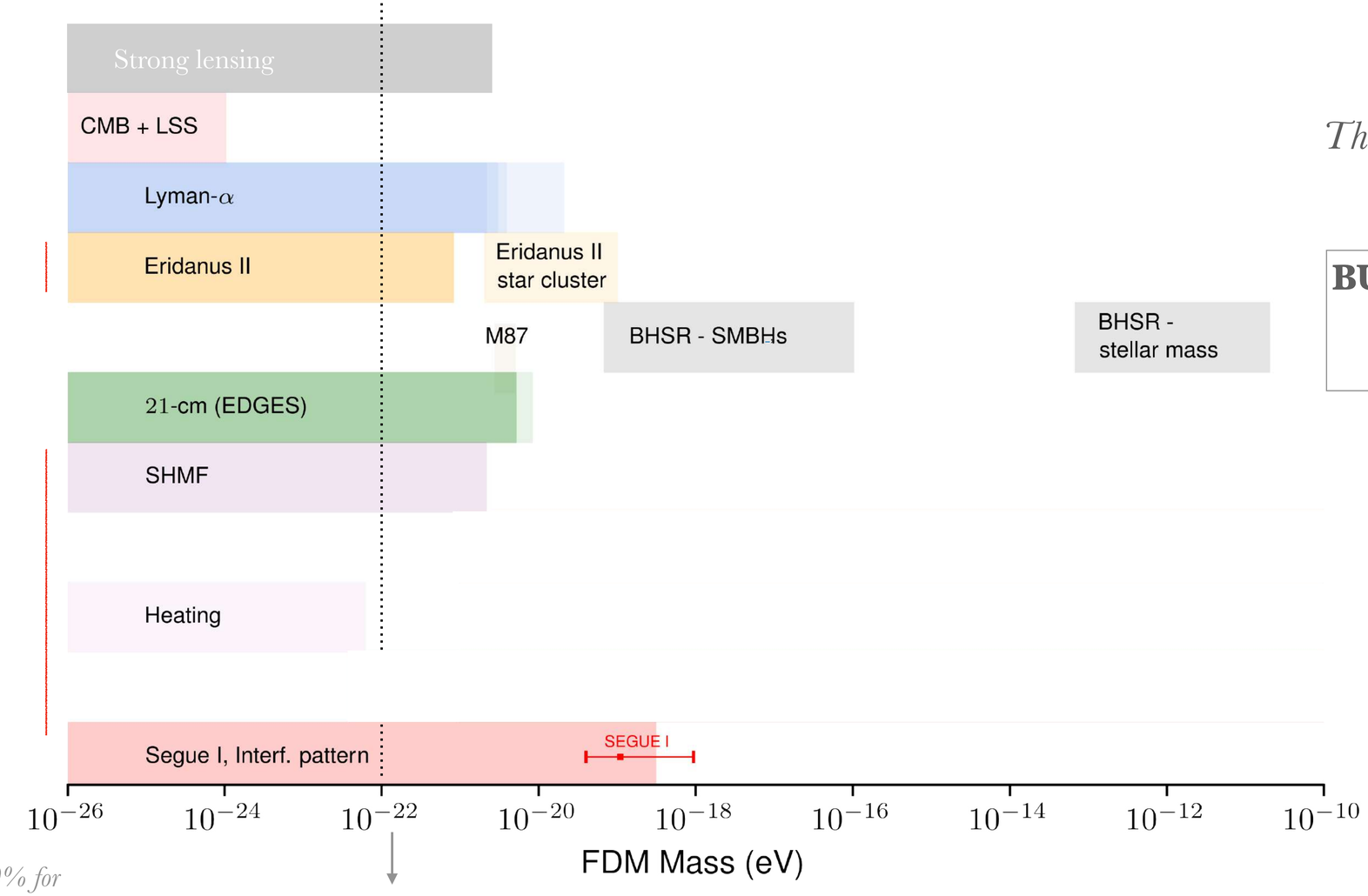


"Ultra-light dark matter", **E.F.**, 2020

Current status

Fuzzy Dark Matter - bounds on the mass





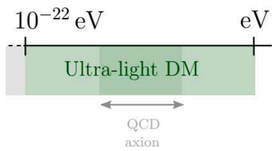
These models can be constrained

BUT: - systematic effects!!
- dynamics of FDM not fully understood.

Need:
- Observations
- Improve sims
- New observables
- New probes

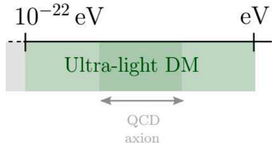
Caner et al: FDM at most 10% for
$10^{-21}\,\mathrm{eV} < m < 10^{-17}\,\mathrm{eV}$

Sweet spot for solving small scale problems



Axion and ALPs interaction with the SM

Axion and ALPs interaction with the SM



Axions and ALPs interact with the standard model particles

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$
$$\widetilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$$
$$\mathbf{E} = -\nabla A_0 - \dot{\mathbf{A}}$$
$$\mathbf{B} = \nabla \times \mathbf{A}$$

Minimal definition: New light pseudoscalar, with coupling to photons and/or derivative couplings to fermions

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma}}{4} a F_{\mu\nu}\widetilde{F}^{\mu\nu} + \partial_\mu a \sum_\psi \frac{g_{a\psi}}{2m_\psi}\left(\bar{\psi}\gamma^\mu\gamma^5\psi\right)$$

Not considering here

+ a few model-dependent assumptions

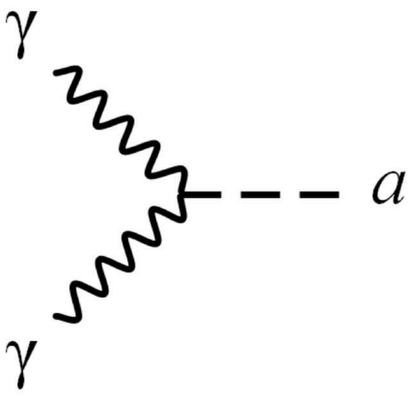
Axion and ALPs interaction with the SM

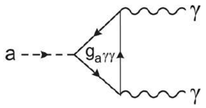
$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$
$$\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$$
$$\mathbf{E} = -\nabla A_0 - \dot{\mathbf{A}}$$
$$\mathbf{B} = \nabla \times \mathbf{A}$$

Axions and ALPs interact with the standard model particles

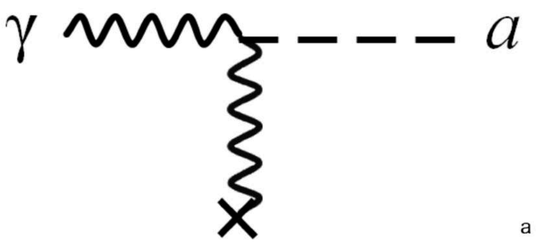
<u>Photon</u> - Axion electrodynamics

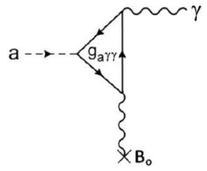
$$\mathcal{L}_{ALP} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}_{\mu\nu} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 + g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}\, a$$





Photon-photon-ALP vertex with coupling constant $g_{a\gamma\gamma}$





$\gamma \to a$ conversion in the external magnetic field **B**
(Primakoff effect)

Other diagrams…

Axion and ALPs interaction with the SM

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$
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$$\mathbf{B} = \nabla \times \mathbf{A}$$

Axions and ALPs interact with the standard model particles

<u>Photon</u> - Axion electrodynamics

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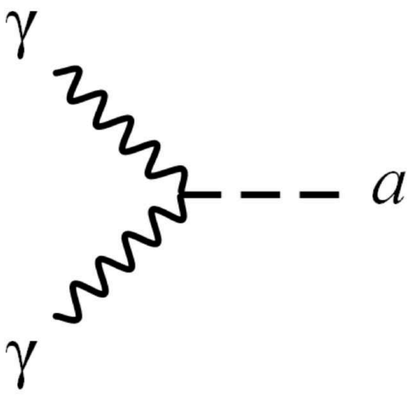

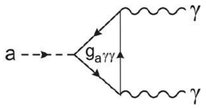

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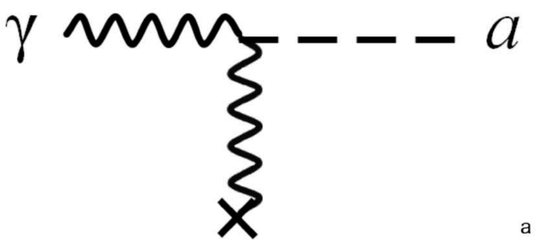

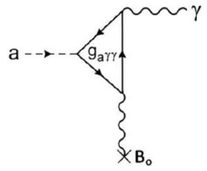

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Axions and ALPs interact with the standard model particles

<u>Axion electrodynamics</u>

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^\mu A_\mu - \frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a$$

- We can interpret axion as the source of an effective current:

$$\partial_\mu F^{\mu\nu} = J^\nu \underbrace{- g_{a\gamma}\widetilde{F}_{\mu\nu}\partial_\mu a}_{J_a^\mu = g_{a\gamma}(-\mathbf{B}\cdot\nabla a,\ -\mathbf{E}\times\nabla a + \partial_t a\mathbf{B})}$$

Maxwell's equations:

$$\nabla \cdot \mathbf{E} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J}$$

Extended Maxwell's equations:

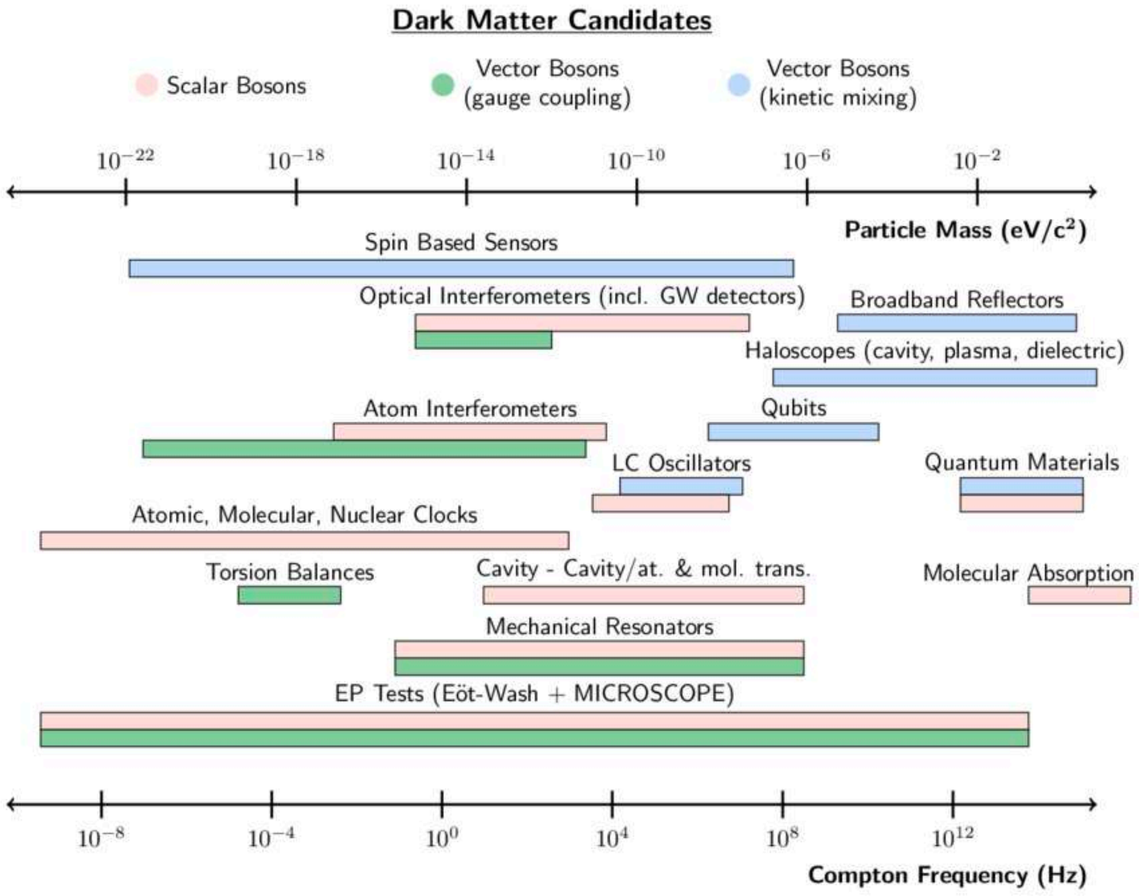
$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma}\,\mathbf{B}\cdot\nabla a$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} - g_{a\gamma}\left(\mathbf{E}\times\nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right)$$

Adapted from: Cyaran O'Hare

Axion and ALPs interaction with the SM

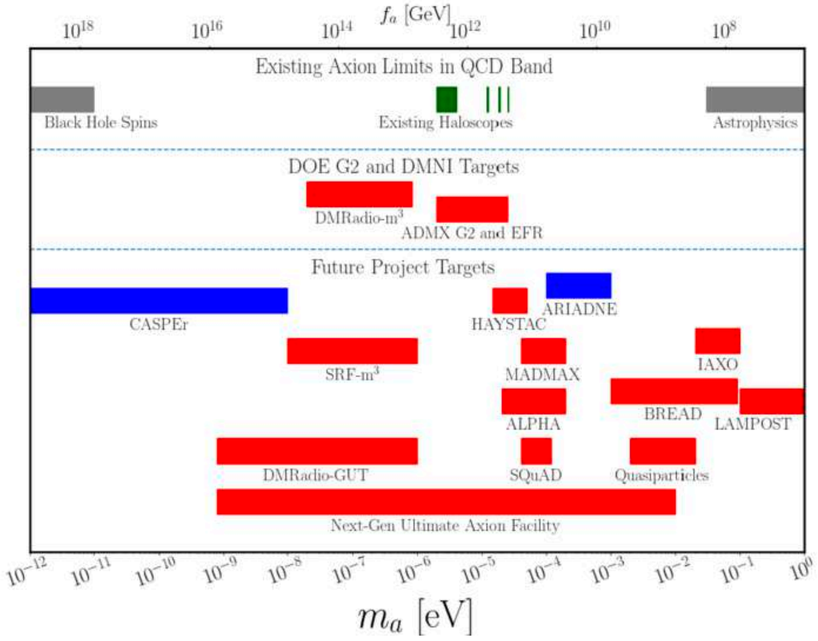
"Direct Detection": axion/ALPs experiments

Overview of experimental techniques and the mass ranges they target

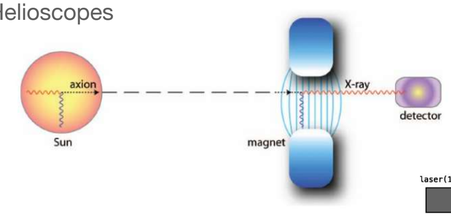


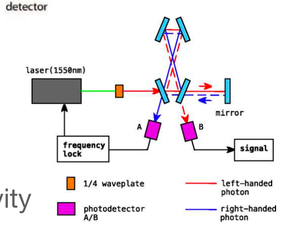
Ref. Jaeckel et al 2021

Experiments

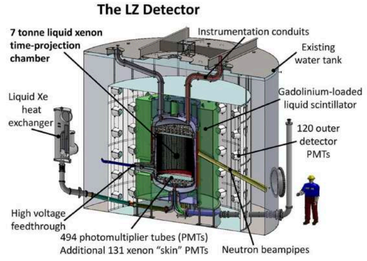


Helioscopes





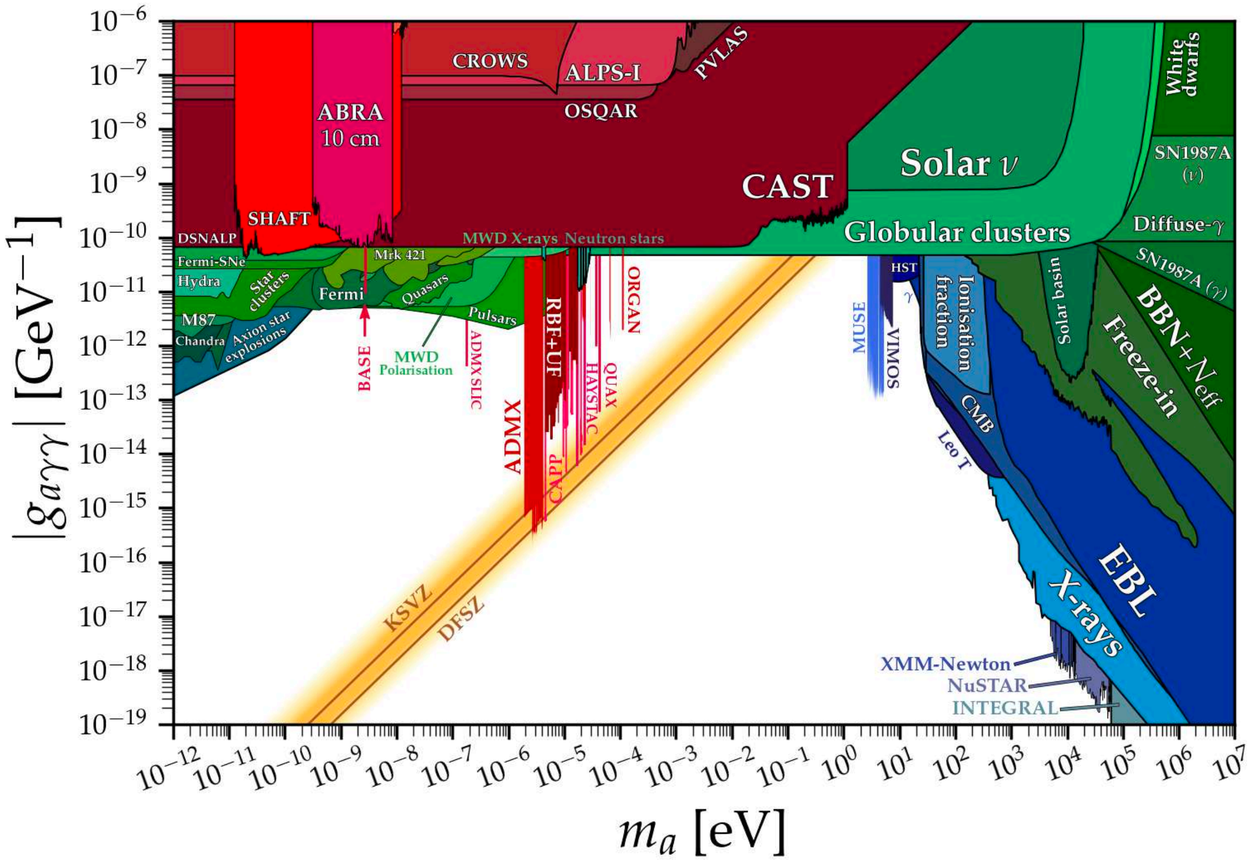
Optical cavity



Axion and ALPs interaction with the SM

Bounds on Axion-photon coupling

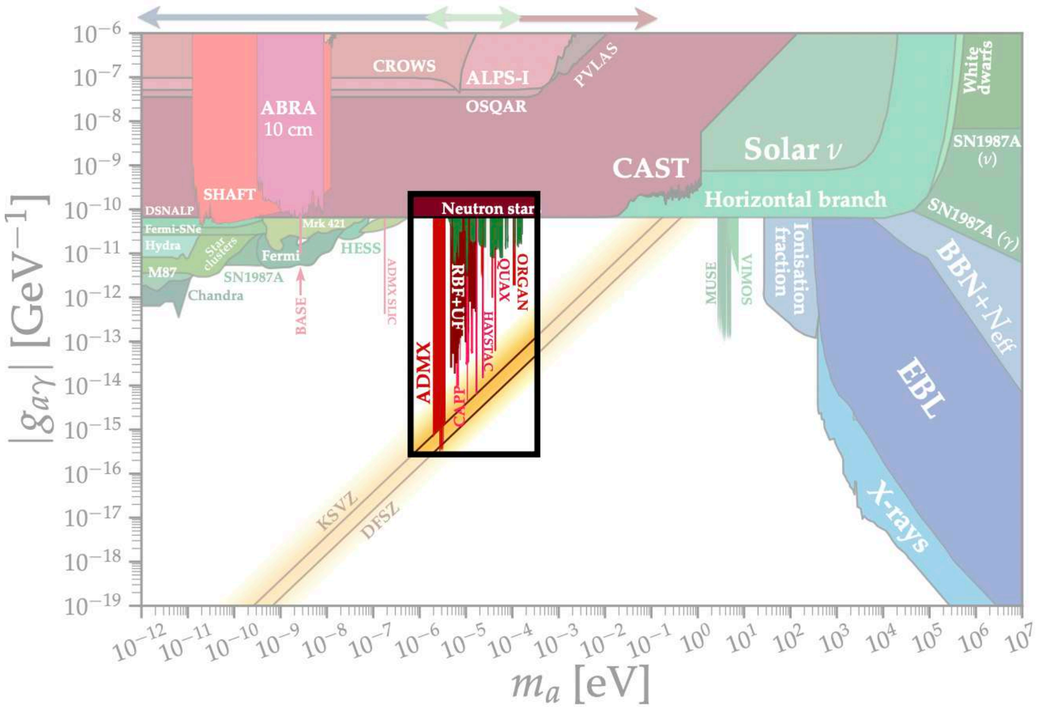
Includes direct and indirect detection



Website with up-to-date with axion/ALP bounds: https://cajohare.github.io/AxionLimits

Axion and ALPs interaction with the SM

Bounds on Axion-photon coupling



$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

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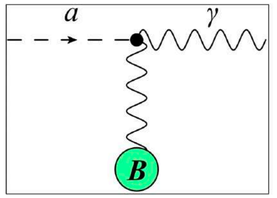
Axion and ALPs interaction with the SM

Indirect Detection

In astrophysical systems

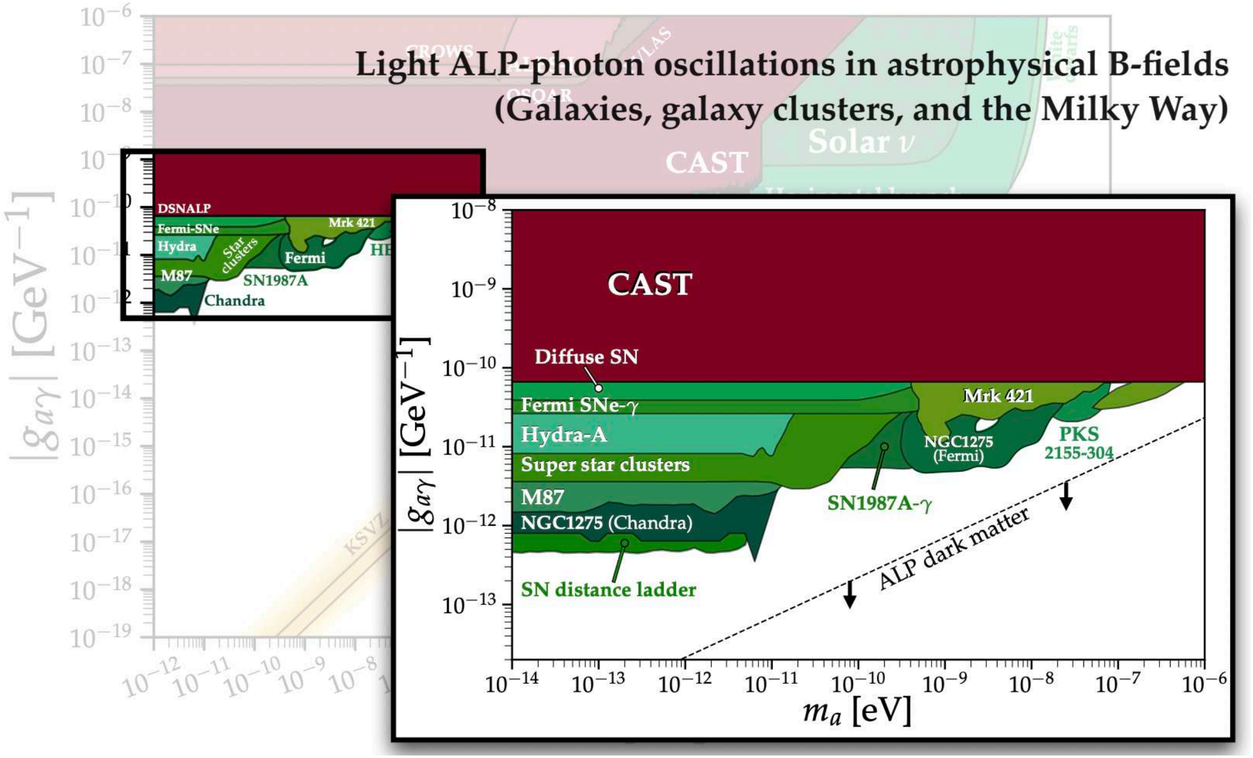


Axion-photon conversion (Primakoff effect)

a : axion

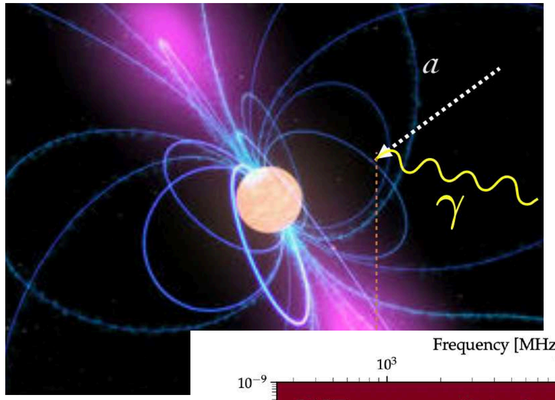
γ : photon

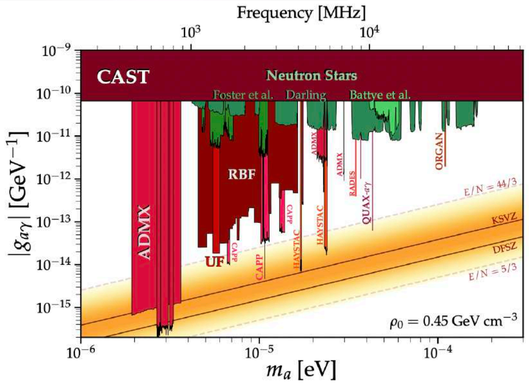
B : magnetic field



+

DM axions in neutron star magnetospheres



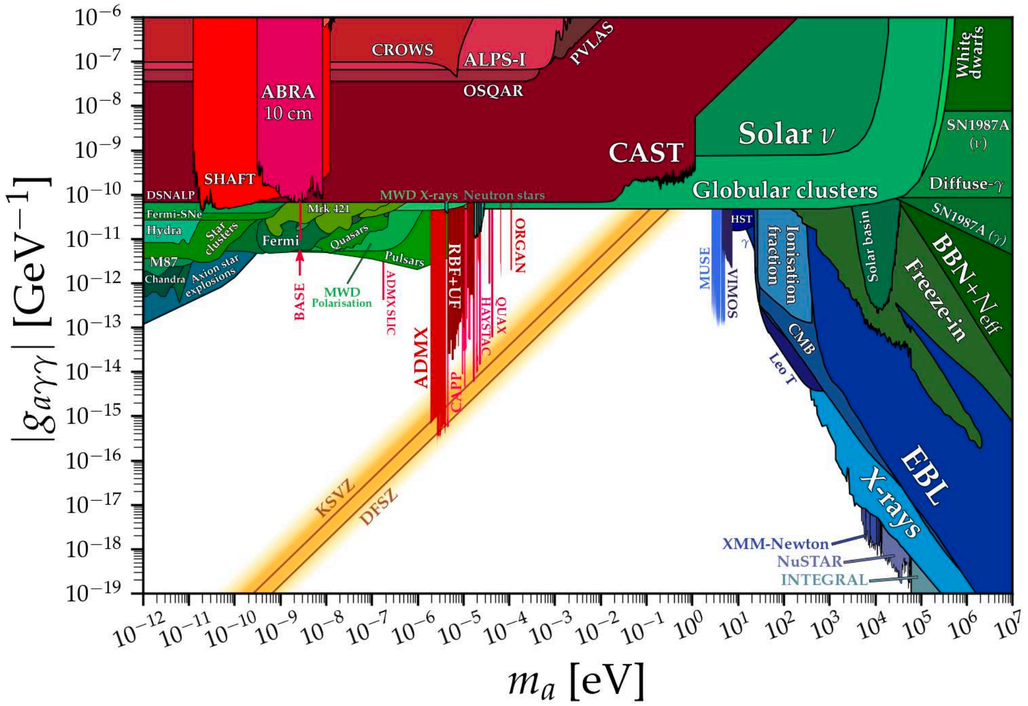


Axion and ALPs interaction with the SM

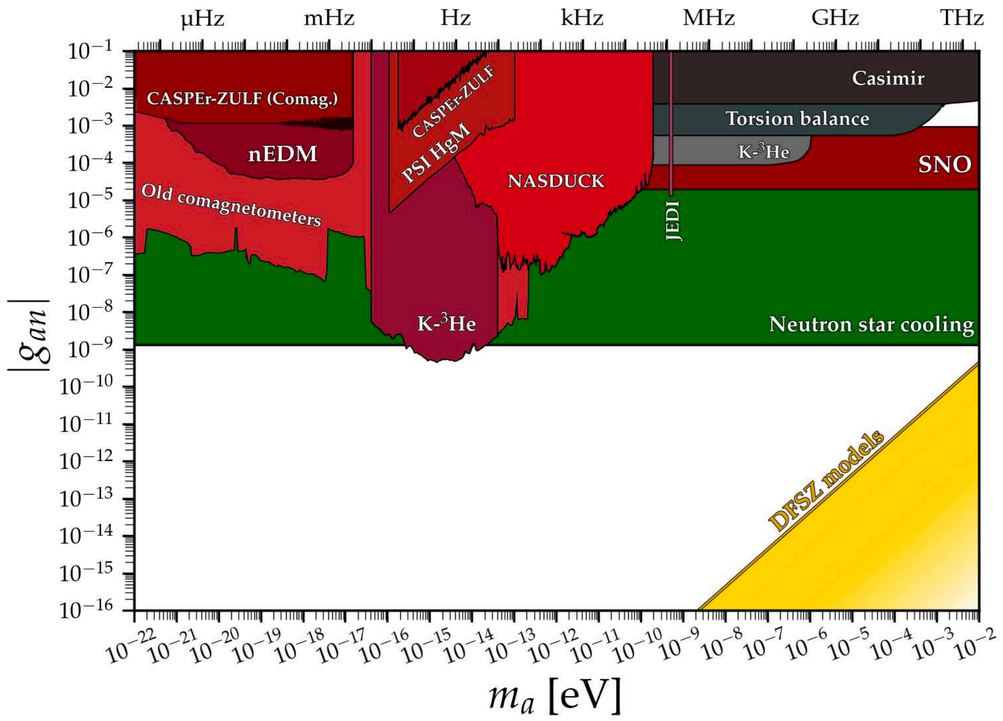
Bounds

Includes direct and indirect detection

Axion-electron coupling



Axion-neutron coupling



+ many more: axion-proton, dark photon, …

Website with up-to-date with axion/ALP bounds: https://cajohare.github.io/AxionLimits
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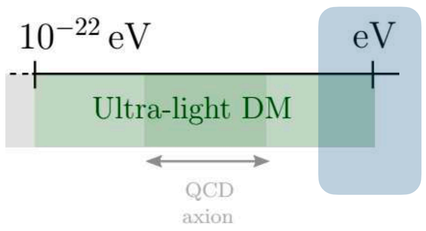
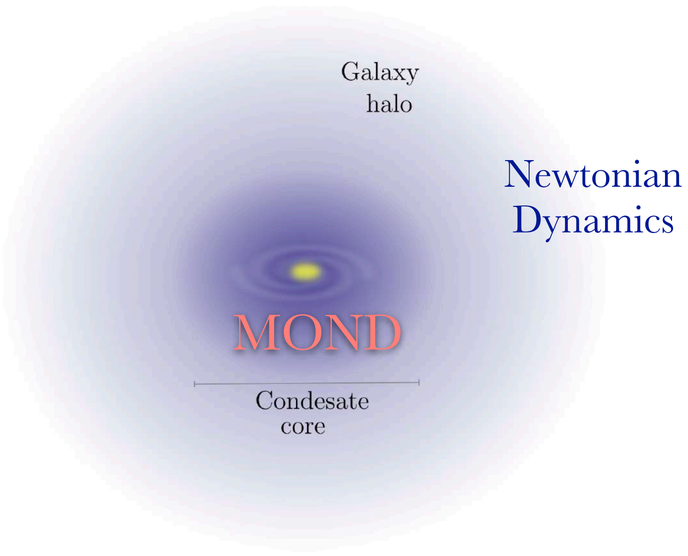
Superfluid Dark Matter

Superfluid Dark Matter



Lasha Berezhiani and Justin Khoury (2016)

Large scales:
DM behaves like standard particle DM (CDM).



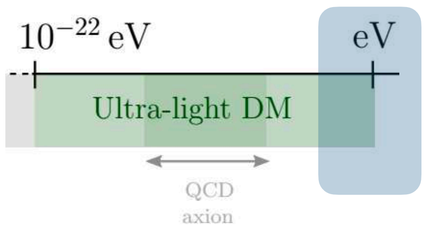
Galactic scales:
DM forms a superfluid
$\longrightarrow$ emergent MOND dynamics in galaxies

$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

Similar phenomenology than the FDM & SIFDM + explains the rotations curves and scaling relations

Suppresses small structures, dyn. effects, formation of cores

Superfluid Dark Matter



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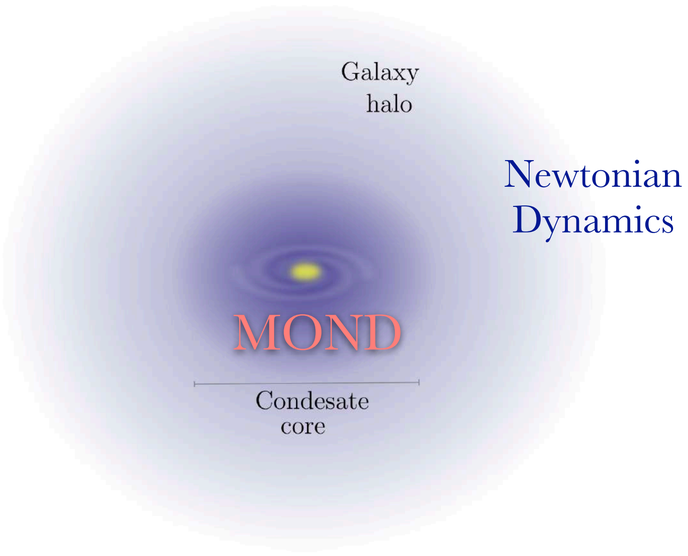


Galactic scales:
DM forms a superfluid
$\longrightarrow$ emergent MOND dynamics in galaxies

To describe non-relativistic MOND, it is imposed that:

$$\mathcal{L} = P(X)\,, \qquad P(X) = \frac{2\Lambda\,(2m)^{3/2}}{3} X\sqrt{|X|}$$

Dark photon

New gauge dark sector - spin 1

Extend SM gauge group: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times U(1)'$

with vector X^μ

Below EW $\longrightarrow$ $$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} \boxed{-\frac{\chi}{2}F_{\mu\nu}X^{\mu\nu}} + \frac{m_X^2}{2}X_\mu X^\mu + j_\mu A^\mu$$

"Kinetic mixing"

$A^\mu \to A^\mu - \chi X^\mu$

$$\frac{m_X^2}{2}X_\mu X^\mu + j_\mu(A^\mu - \chi X^\mu)$$

→ X is massive force carrying vector,
→ SM Particles get dark millicharge ~ χe
→ Can also be coupled to other dark sector particles to create millicharged DM

$X^\mu \to X^\mu - \chi A^\mu$

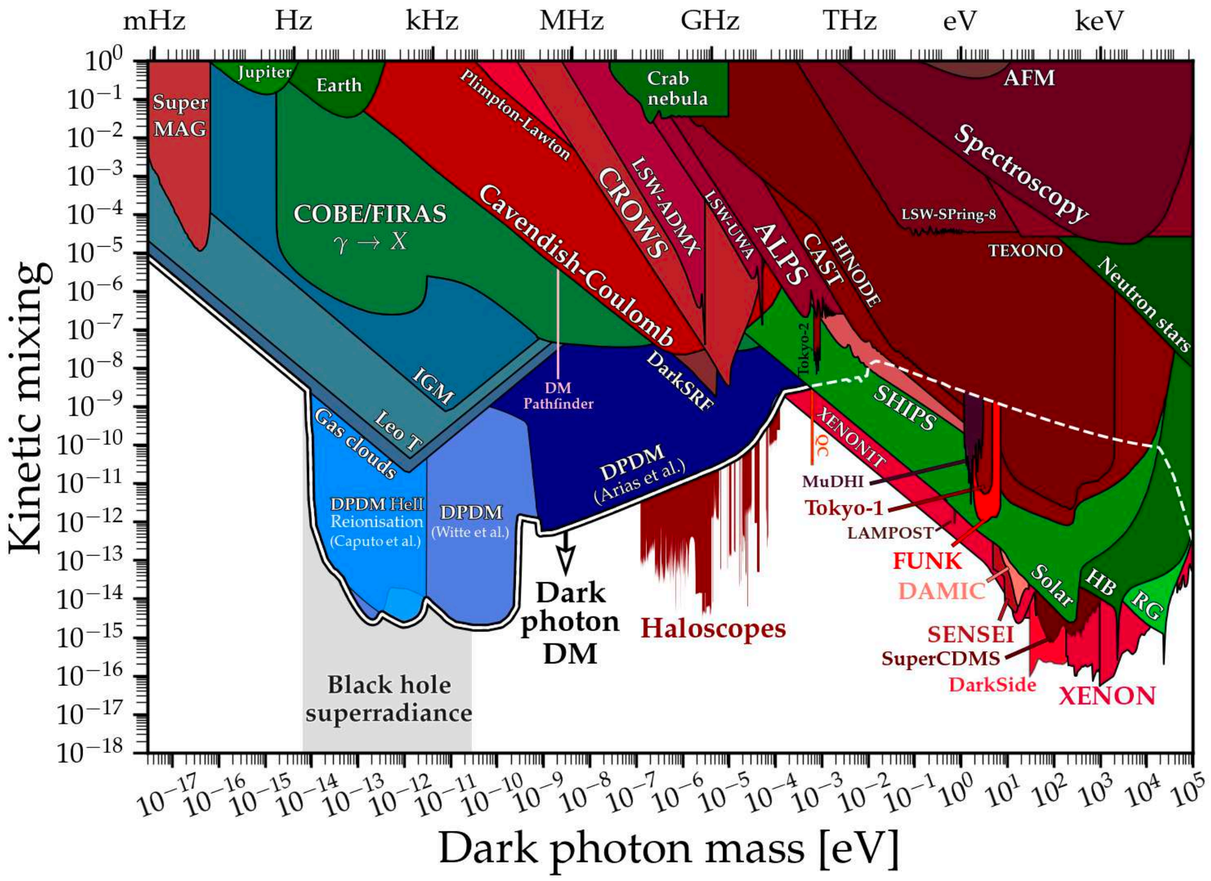
$$\frac{m_X^2}{2}(X_\mu X^\mu - 2\chi X_\mu A^\mu + \chi^2 A_\mu A^\mu) + j_\mu A^\mu$$

→ Non-diagonal mass term
→ SM photon-dark photon mixing

Adapted from: Cyaran O'Hare

Dark photon

New gauge dark sector - spin 1



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(Includes notebooks)

S8 tension

Ref.: K. Rogers et al 2023

Changes in the small scale paradigm can change the behaviour of DM in many scales, including cosmology

Ex.: Fuzzy DM

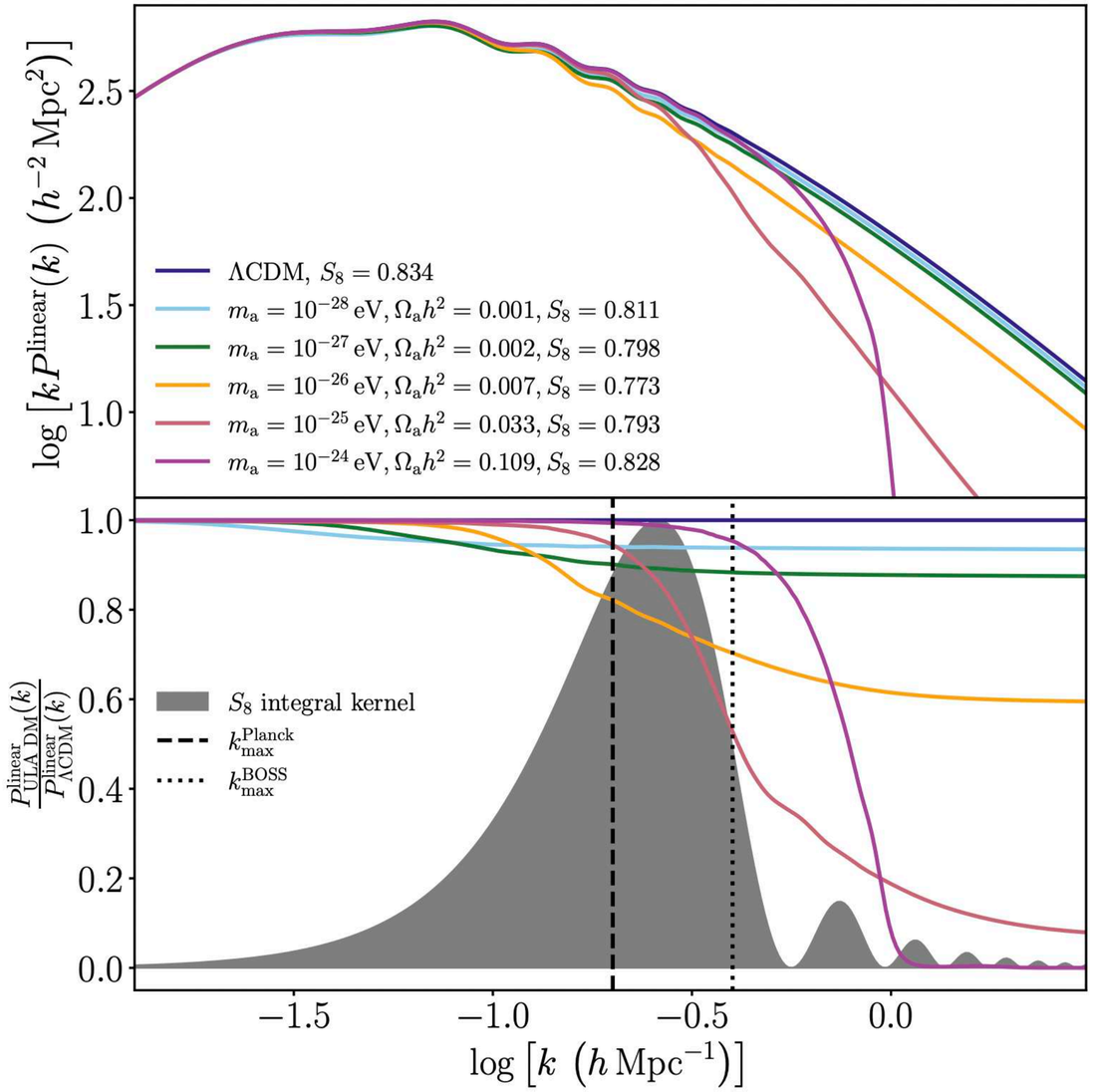
$$\sigma_8 = \int \mathrm{dln}k \, \frac{k^3}{2\pi} W^2(k) P^{\mathrm{linear}}(k)$$

$$S_8 = \sqrt{\frac{\Omega_{\mathrm{m}}}{0.3}} \sigma_8$$

The presence of ULAs can significantly lowers S8 for:

$$m_{\mathrm{a}} \in [10^{-27}, 10^{-25}]\,\mathrm{eV}$$

S8 is lowered because the Jeans scale today for $m_a = 10^{-25} - 10^{-26}\,\mathrm{eV}$ is about $\lambda_J = 4 - 12\,h^{-1}\,\mathrm{Mpc}$



S8 tension

Ref.: K. Rogers et al 2023

Ex.: Fuzzy DM

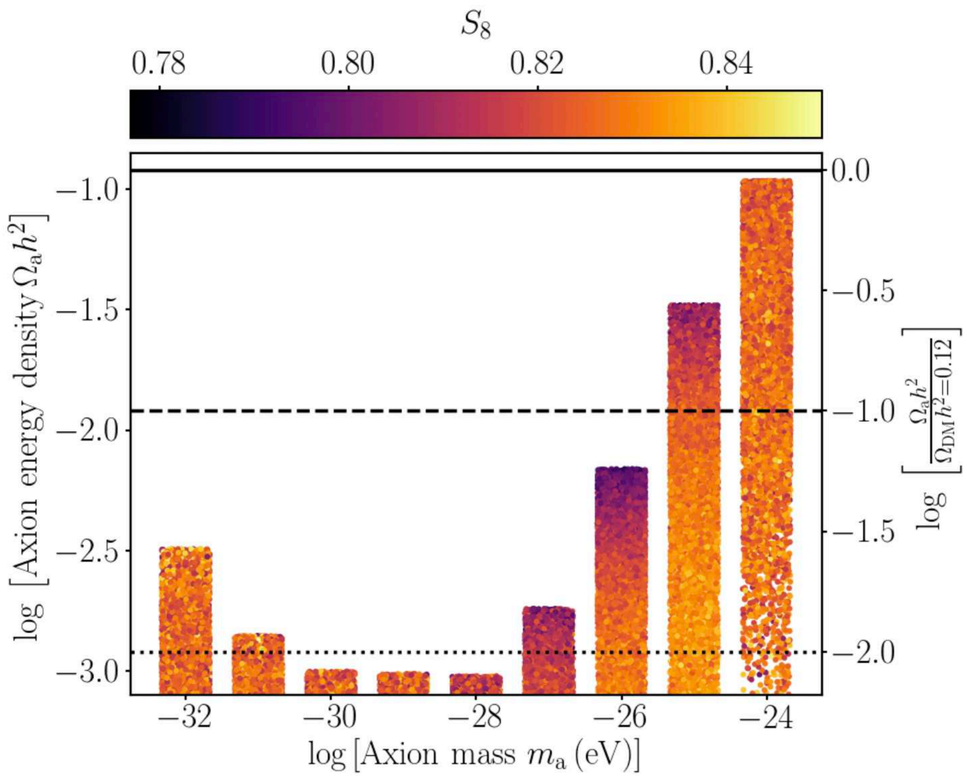
Planck + BOSS

The presence of ULAs with mass

$$10^{-28}\,\mathrm{eV} \leq m_a \leq 10^{-25}\,\mathrm{eV}$$

can improve consistency between CMB and galaxy clustering
(reduce the S8 discrepancy)

from 2.6σ to 1.7σ

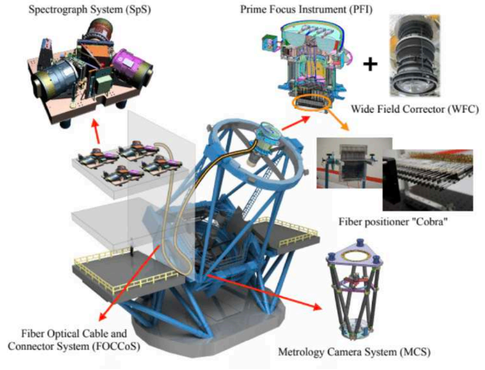


Ex.:
- H0 tension: Early dark energy - axion-like particle
- Model address H0 and S8 tensions: *"Chameleon EDE"*, Karwal et al 2021

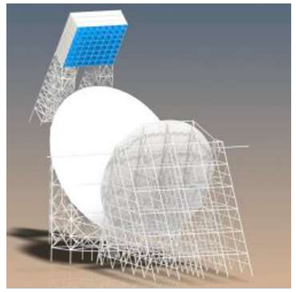
Future

Observations

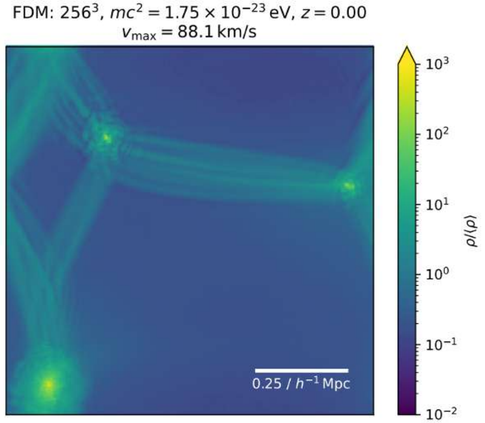
Prime Focus Specctrograph (PFS)



BINGO telescope



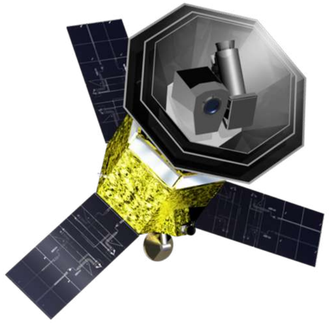
Simulations



Vera Rubin observatory (LSST)

CMB-S4

LiteBIRD

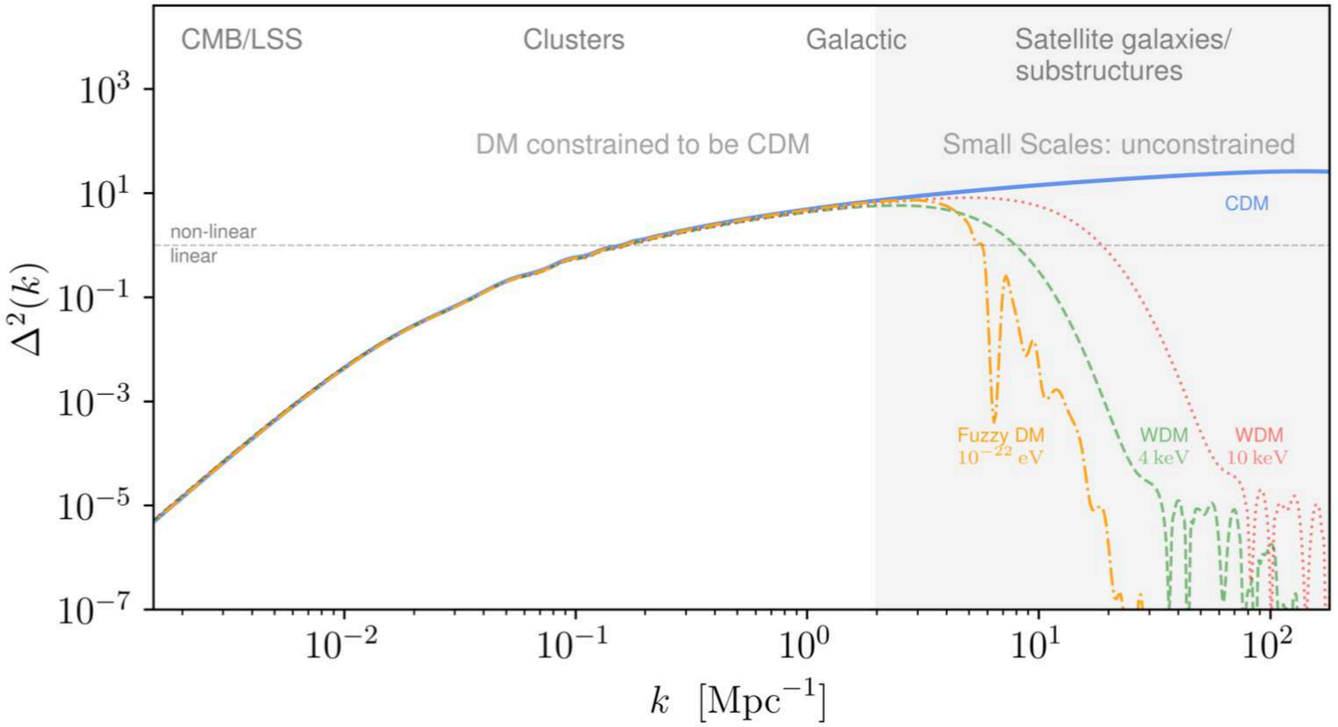


New probes

New probes

Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures



Sub-galactic power spectrum

New probes

Using gravitational probes, strong lensing and stellar streams, to describe substructures

A. Diaz Rivero, et al. (2017); Diaz Rivero, et al. , (2018)

Substructure convergence power spectrum

Bayer et al. (2018) ; Auger et al. 2009
FDM*: Kawai et al. (2021)*

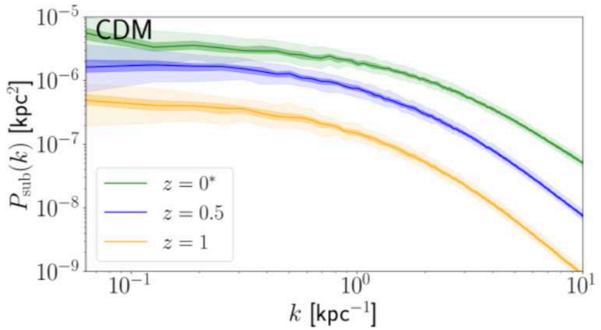
Develop a formalism to compute the substructure convergence power spectrum for different populations of dark matter subhalos.

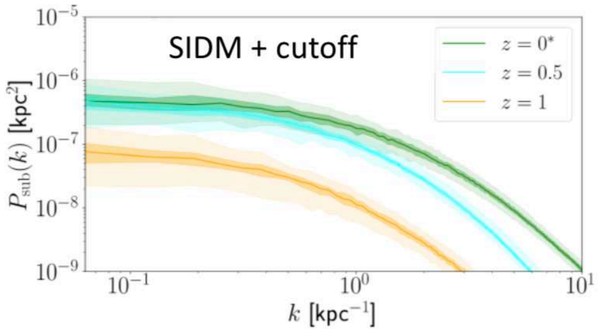
Hezaveh et al. (2016) (projected mPS by using strong lensing)

Change of language: instead of talking about lensing perturbations in terms of individual subhalos, look at the correlation function of the projected density field.

(based on Dvorkin's slide)

$$P_{\rm sub}(k) = P_{\rm 1sh}(k) + P_{\rm 2sh}(k)$$





Sub-galactic power spectrum

New probes

Using gravitational probes, strong lensing and stellar streams, to describe substructures

Substructure convergence power spectrum

Sten Delos and Fabian Schmidt (2021)

Stellar streams: perturbed by passing substructure. Good gravitational probe, since given their low dynamical temperature and negligible self-interaction, it retains the memory of those encounters.

THIS WORK: Fully analytical understanding of the stream perturbations!

Power spectrum of a stream's stellar density is analytically related to that of the substructure background:

$$\boxed{P_*(k,t)} = \chi_*\left(k\sigma_0 t, \frac{D}{k\sigma_0^3}\right)\frac{k^2t^2}{3}P_{\Delta v}(k,t)$$

Stream power

Substructure power

$$P_{\Delta v}(k,t) = 16\pi^4 G^2\bar{\rho}^2 k^2 t \int_k^\infty \frac{\mathrm{d}q}{q}\frac{\boxed{\mathcal{P}(q)}}{q^6}\int \mathrm{d}^3\boldsymbol{u}\frac{f(\boldsymbol{u})}{u}\theta_H(qu-kv)$$

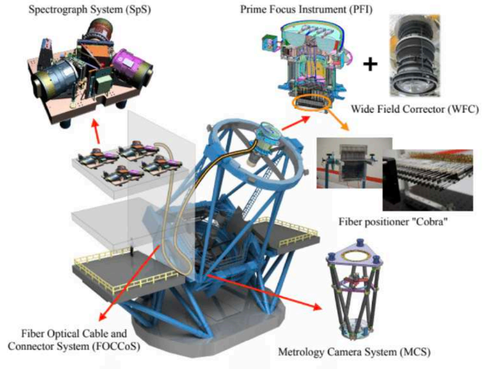
Previous:
- Mostly numerical
- Perturbations $\longrightarrow$ sub-halo mass function

Relates the stellar stream perturbation to the surrounding matter distribution, from dark and luminous substructure

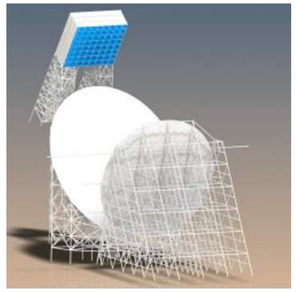
Future

Observations

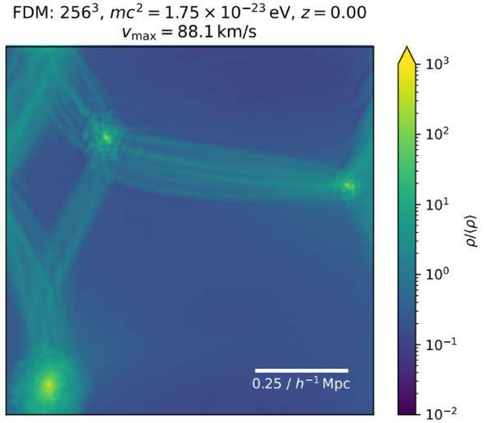
Prime Focus Specctrograph (PFS)



BINGO telescope



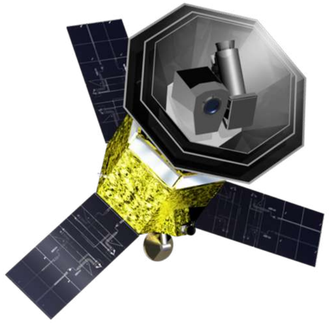
Simulations



Vera Rubin observatory (LSST)

CMB-S4

LiteBIRD

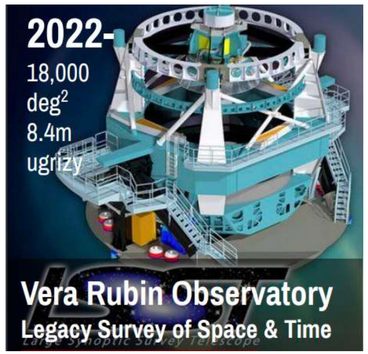


New probes

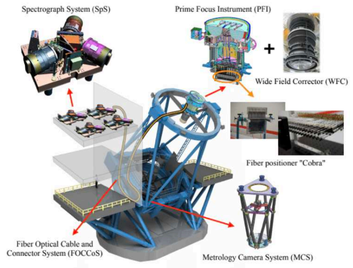
Future - signals in cosmology

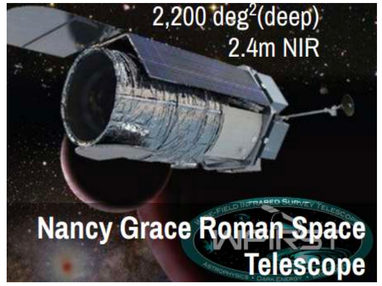
Observations

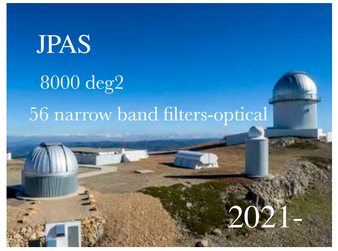
Photometric and spectroscopic surveys



Prime Focus Spectrograph (PFS)







21cm

SKA
SQUARE KILOMETRE ARRAY

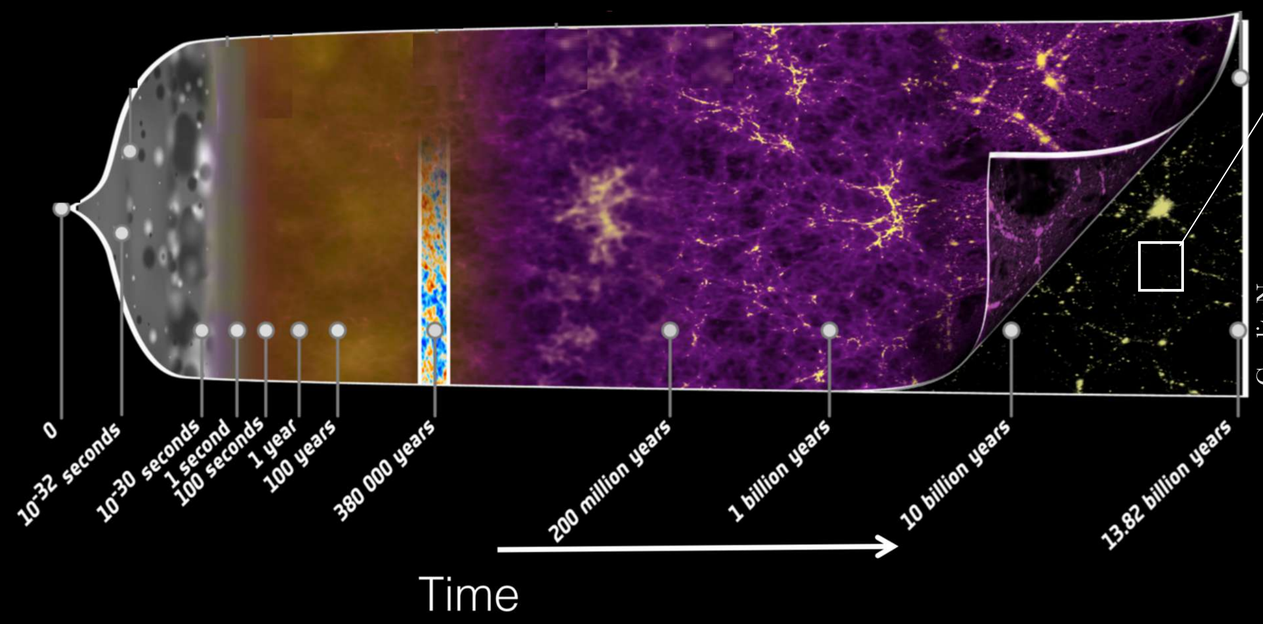
CMB

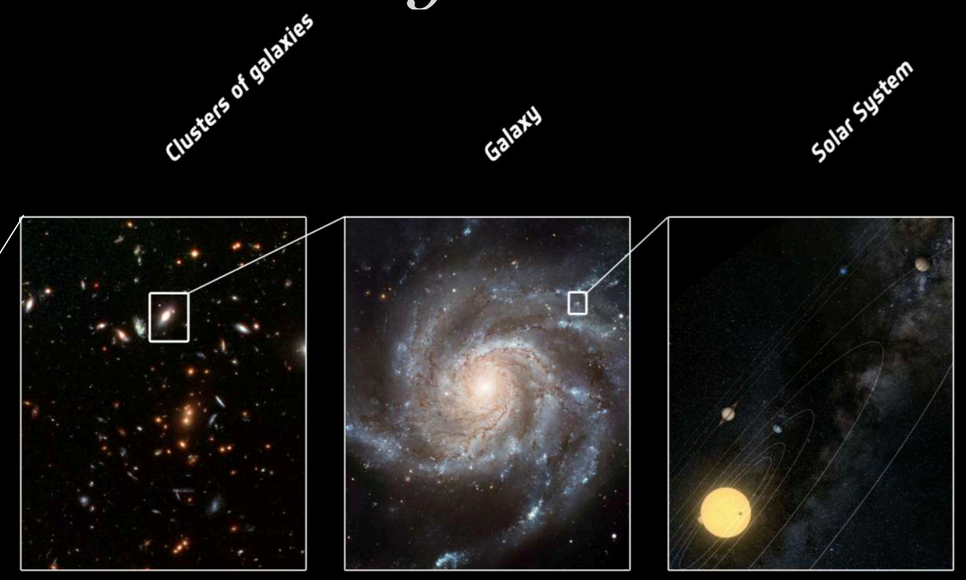
CMB-S4
Next Generation CMB Experiment

GWs

Modified from Jia Liu

Small scales can offer some hints of the nature of DM





Small Scales

Opportunity to probe the nature of DM!

Astrophysical Observables → DM Distribution → Nature of DM Microphysics Particle physics

Summary

DM builder's guide

What we learned from observations

- Cold or warm — Thermal candidate: $m_{dm} \geq \text{keV}$

  Or produced cold by a non-thermal mechanism

- Reproduce large and small scale distribution

  Clusters like CDM on large scales $k \lesssim 10\,\text{Mpc}^{-1}$

  Clustering on scales smaller than $k \gtrsim 10\,\text{Mpc}^{-1}$ highly unconstrained

- Non-interacting or weakly interacting

  Can have a small electromagnetic interaction. Bound < **milicharge**

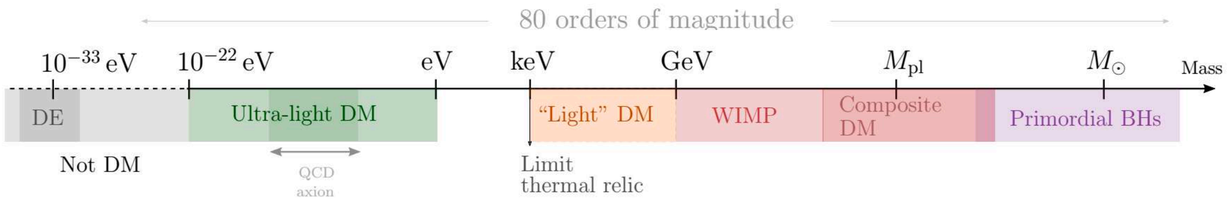
  Can have a small **self interaction**.

  Can interact via the ***weak force***

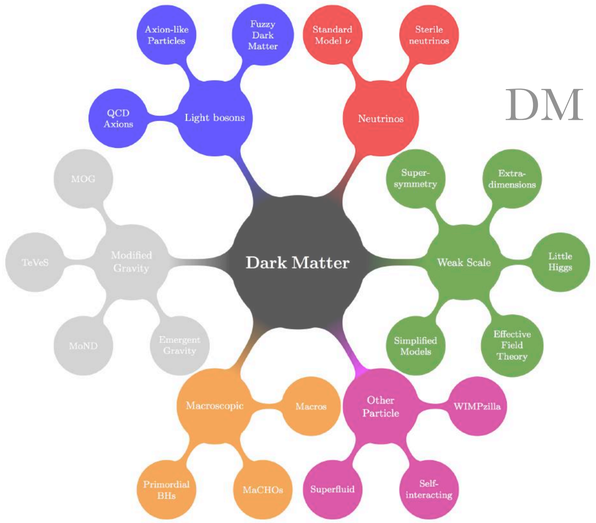
- Abundance $\Omega_m = 0.308 \pm 0.012$ *(Planck 2018)*

- Stable

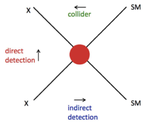
Mass scale of DM



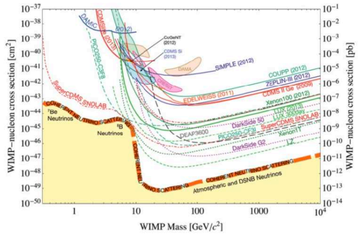
DM Landscape



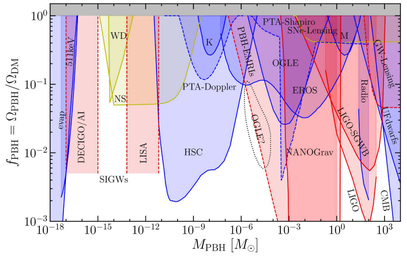
Search for DM



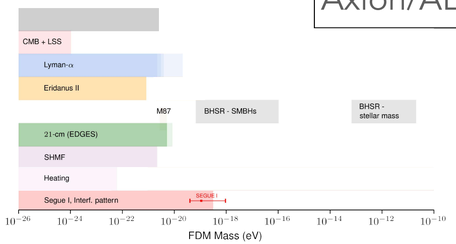
WIMPS

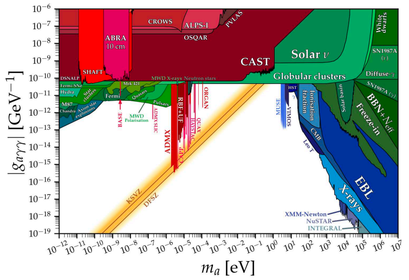


PBHs



Axion/ALP





Thank you very much!