Lecture 1: ULDM searches

Gravitational signatures

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ISAPP School - *Quantum Fluids in the Universe*
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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) $\sim 3 \times 10^{16}\,\mathrm{m}$

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)*

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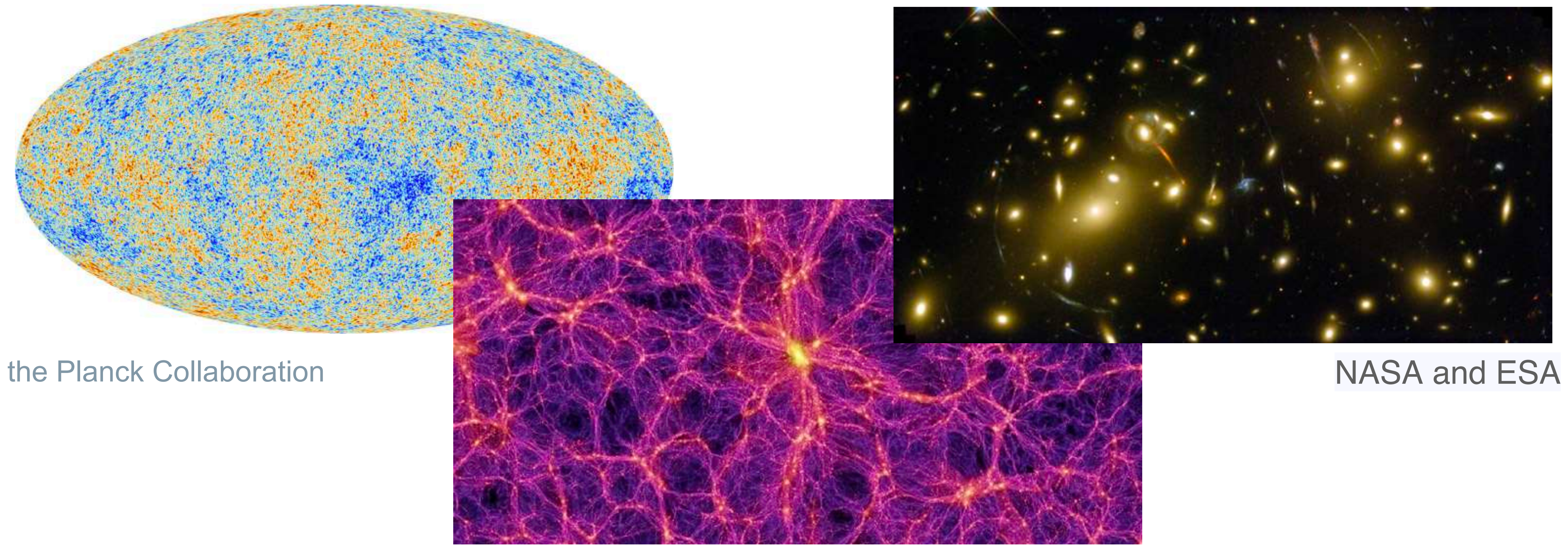
Evidences for dark matter

We can observe its effects in

Galaxies

NASA and ESA

CMB+LSS

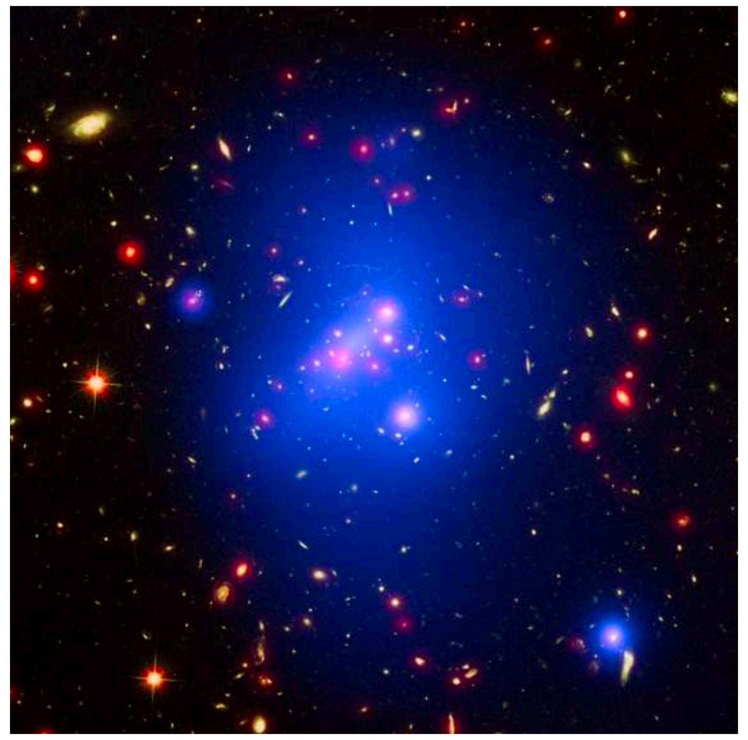


ESA and the Planck Collaboration

NASA and ESA

Springel & others / Virgo Consortium

Clusters

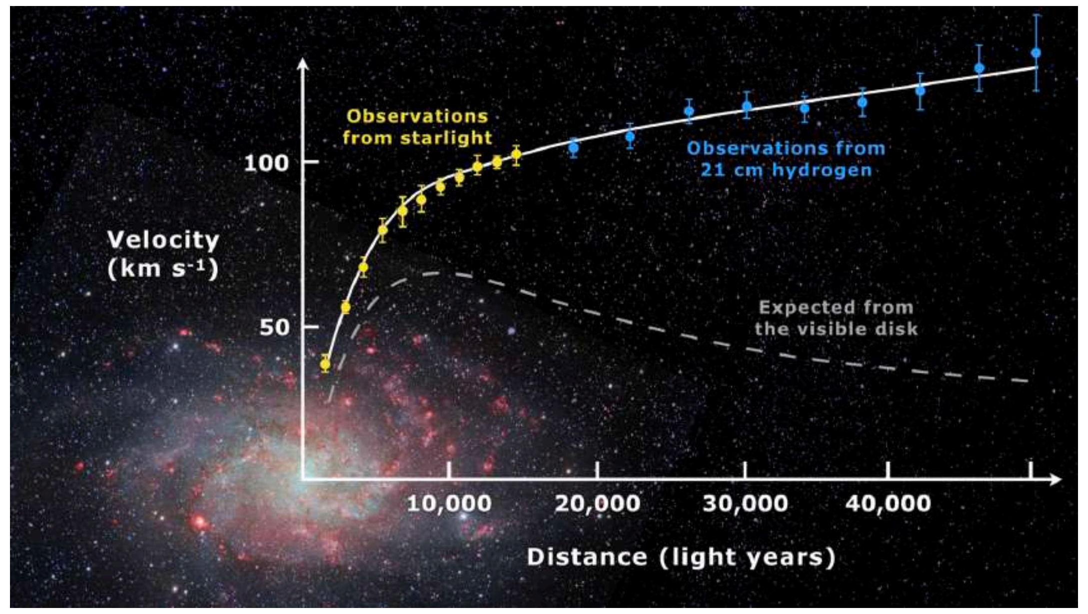


CC BY 4.0

Huge amount of evidence
From all scales

Evidences for dark matter - *properties*

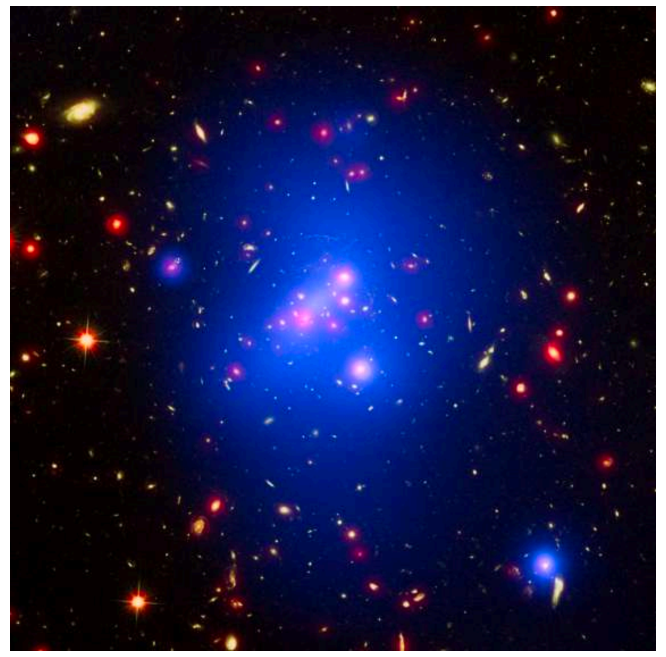
Galaxy rotation curves



Credit: Mario De Leo

- Mass fraction
- Distribution

Clusters



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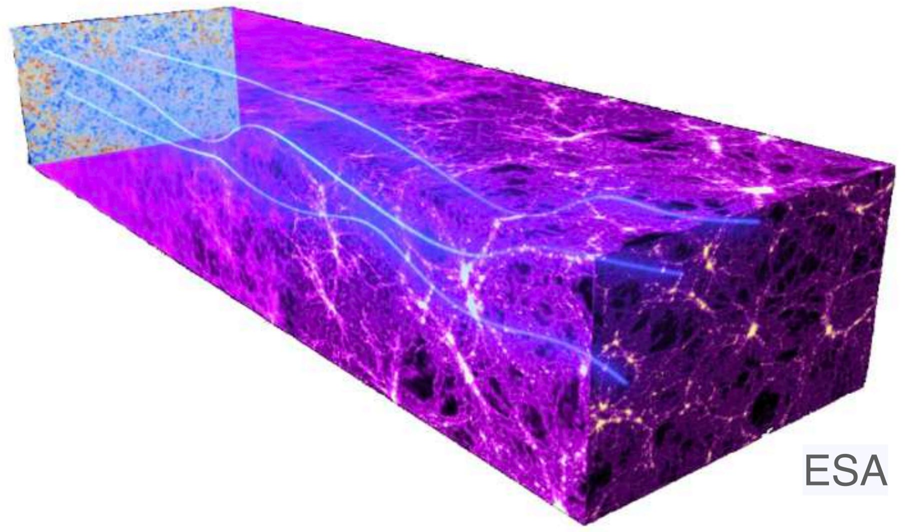
- Mass fraction
- Distribution

Lensing



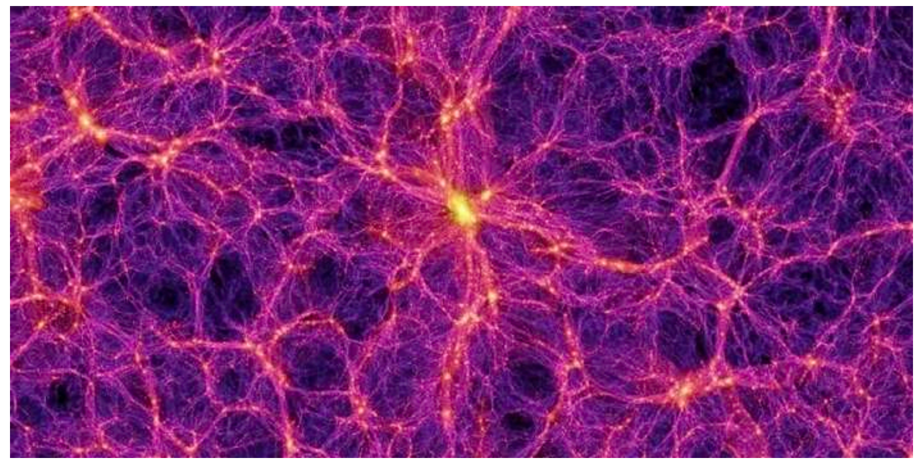
ESA

Strong lensing
- Mass fraction
- Distribution

Weak lensing
- Distribution
- Shape
- Structure

Micro lensing
- Mass fraction
- Smoothness

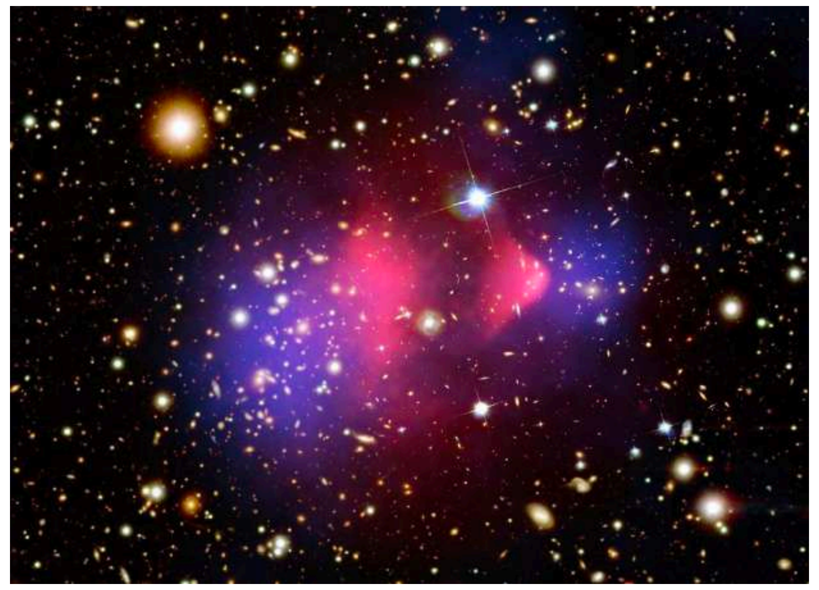
Large Scale Structure



Springel & others / Virgo Consortium

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

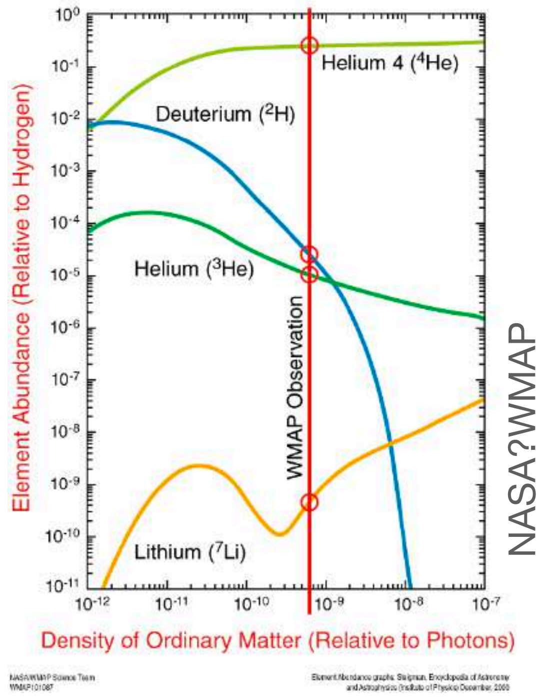
Cluster collision



NASA/CXC/CfA and NASA/STScI

- Distribution
- Separation from collisional matter
- Self-interaction

Big Bang Nucleosynthesis



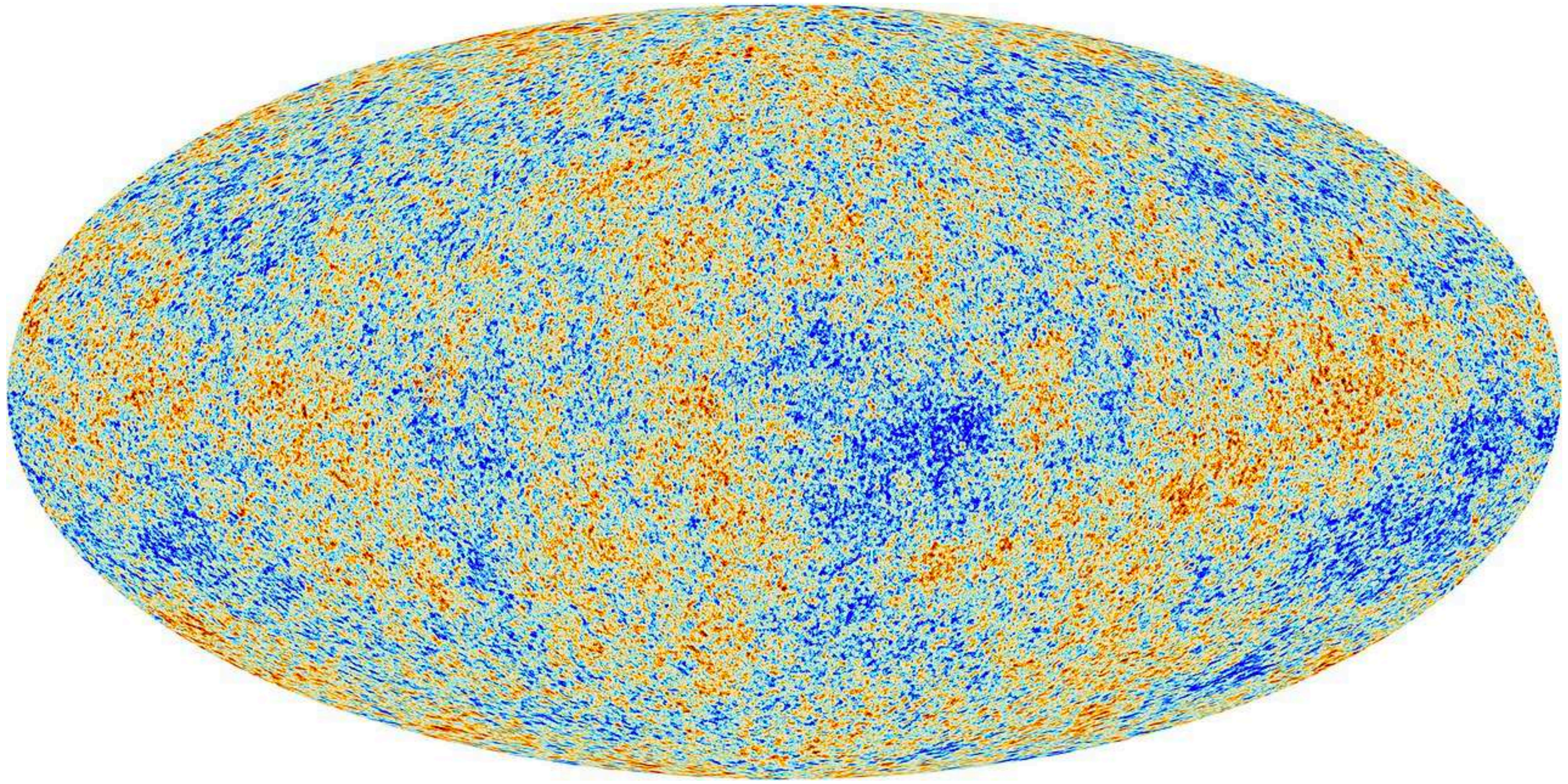
NASA?WMAP

- Amount of baryons

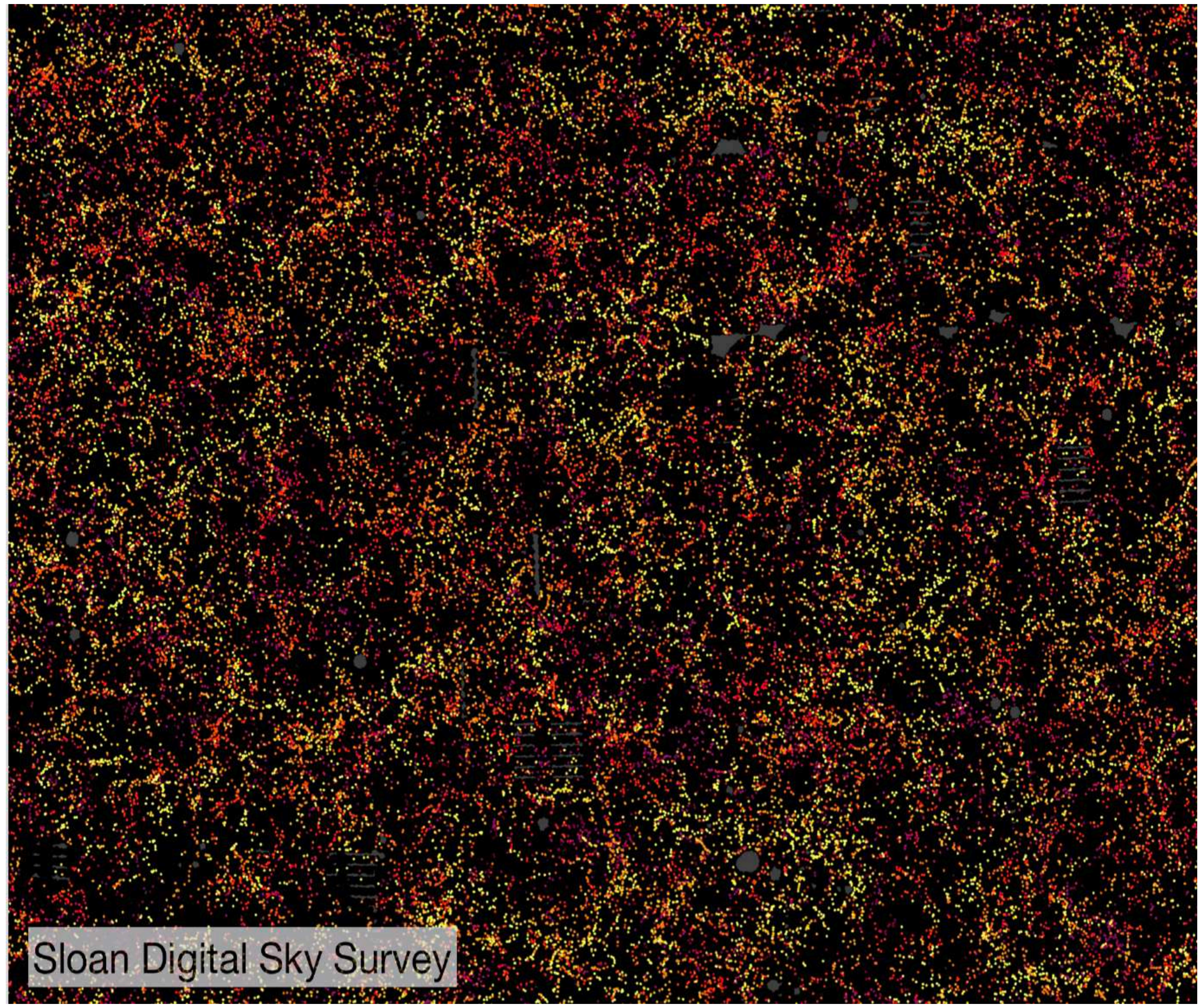
Based on K. Mack

Large scale structure

Cosmic Microwave Background

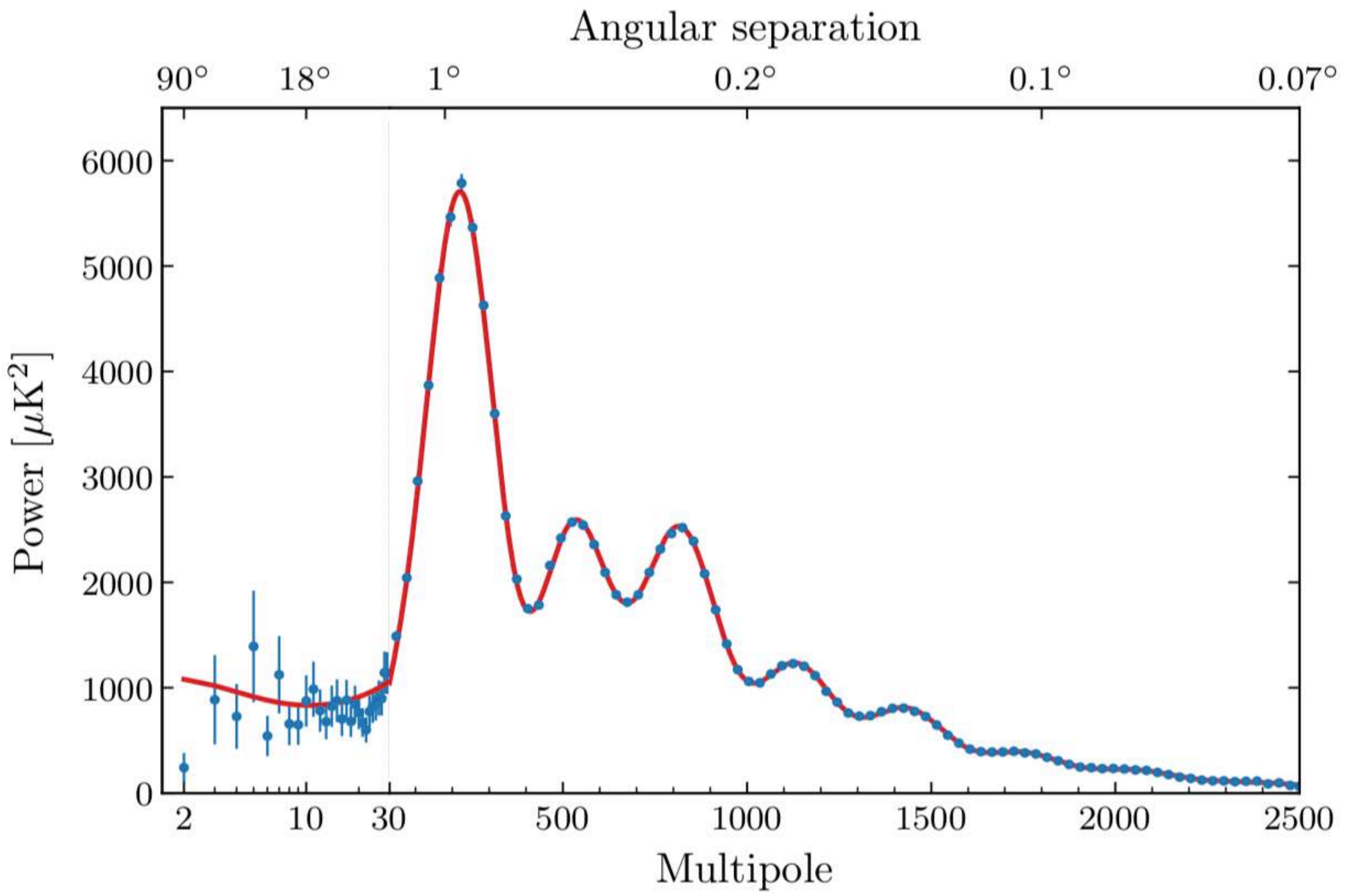


Large Scale Structure



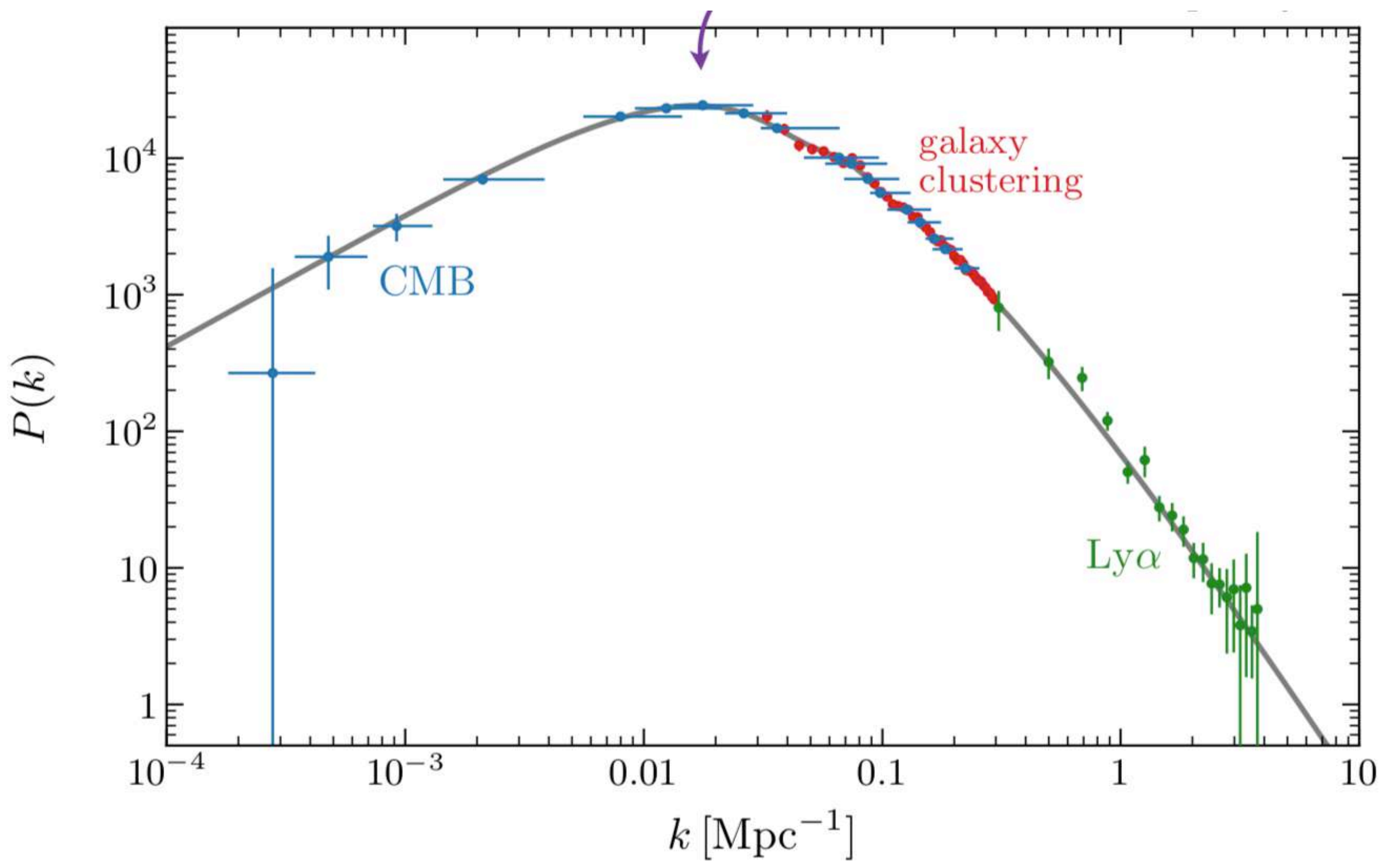
Large scale structure

Cosmic Microwave Background



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

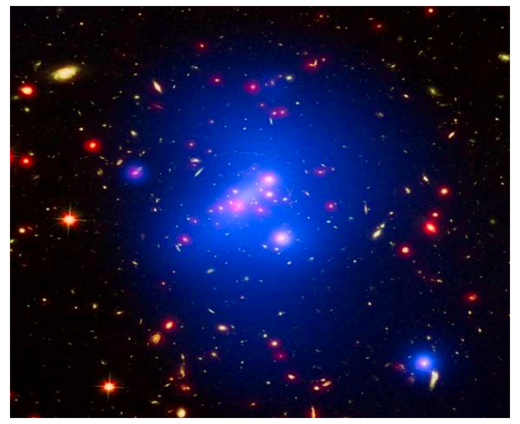
Large Scale Structure



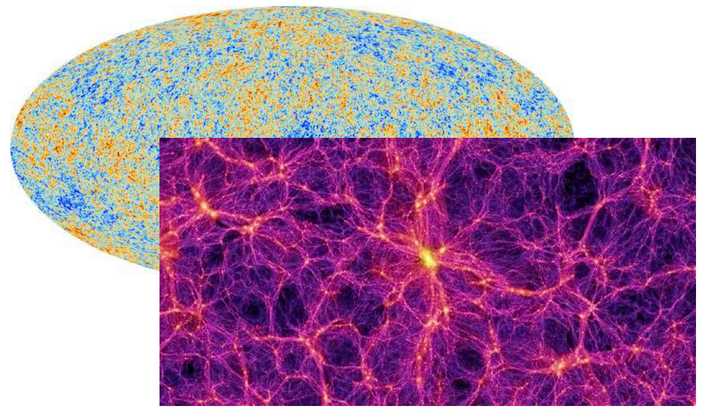
What we know about dark matter

Galaxies

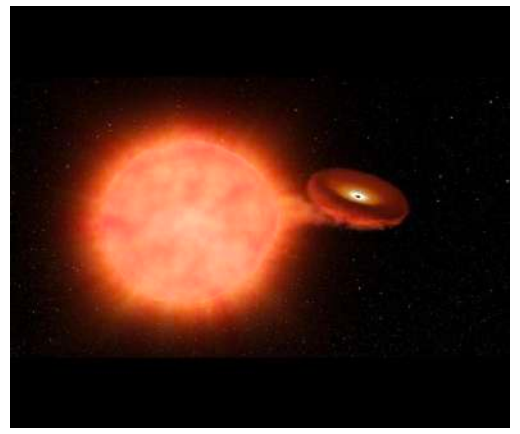
Clusters



Large scales

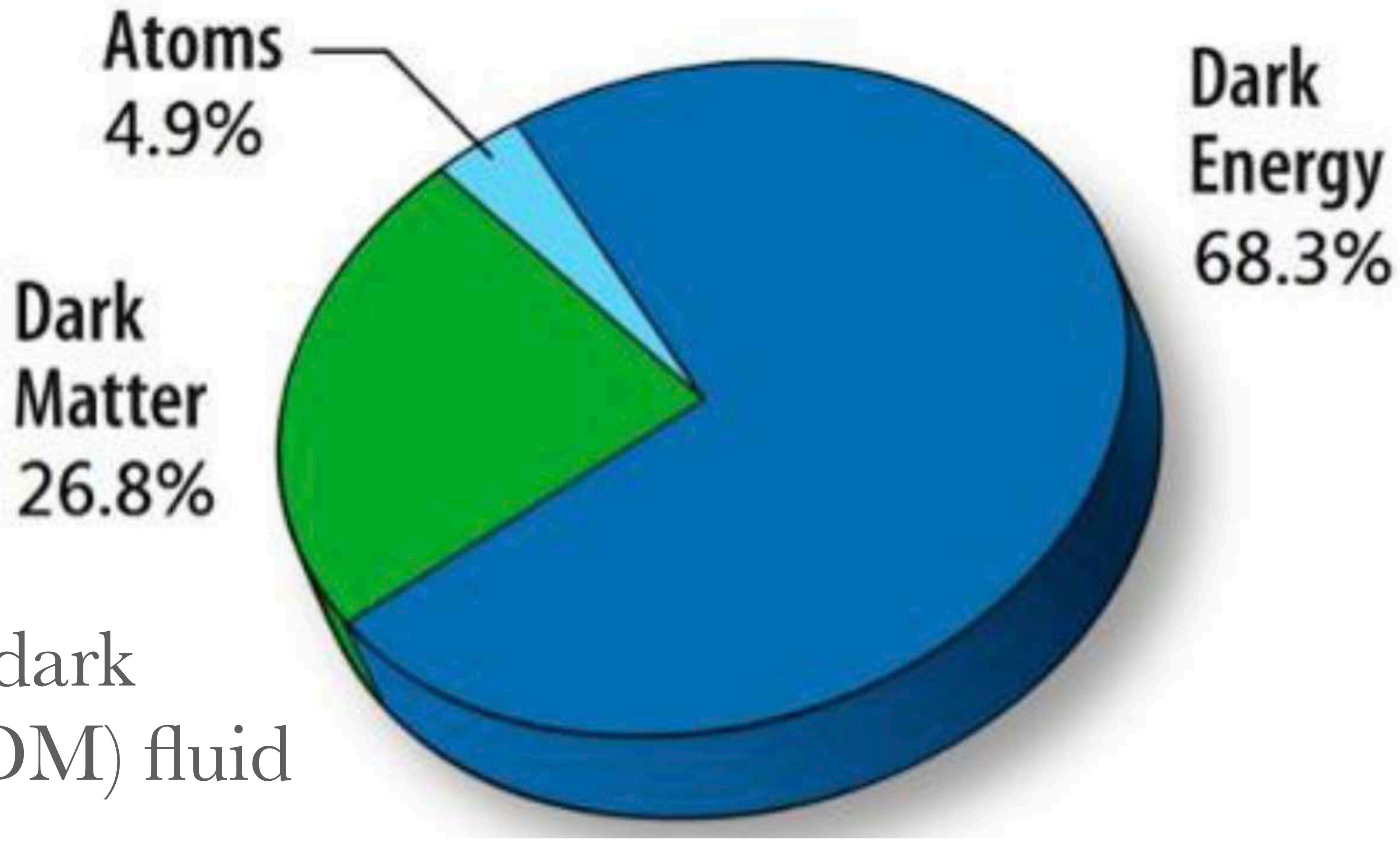


Sn Ia



ΛCDM – the standard cosmological model

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



Λ

DM: cold dark matter (CDM) fluid

ΛCDM

simple but exotic model!

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
- Abundance: amount of dark matter today known

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

Backg.: ρ, P

$w = P/\rho$

with $P = 0 \Rightarrow w = 0$

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

Pert.: δ, θ

with $c_s \sim 0$

Cold dark matter

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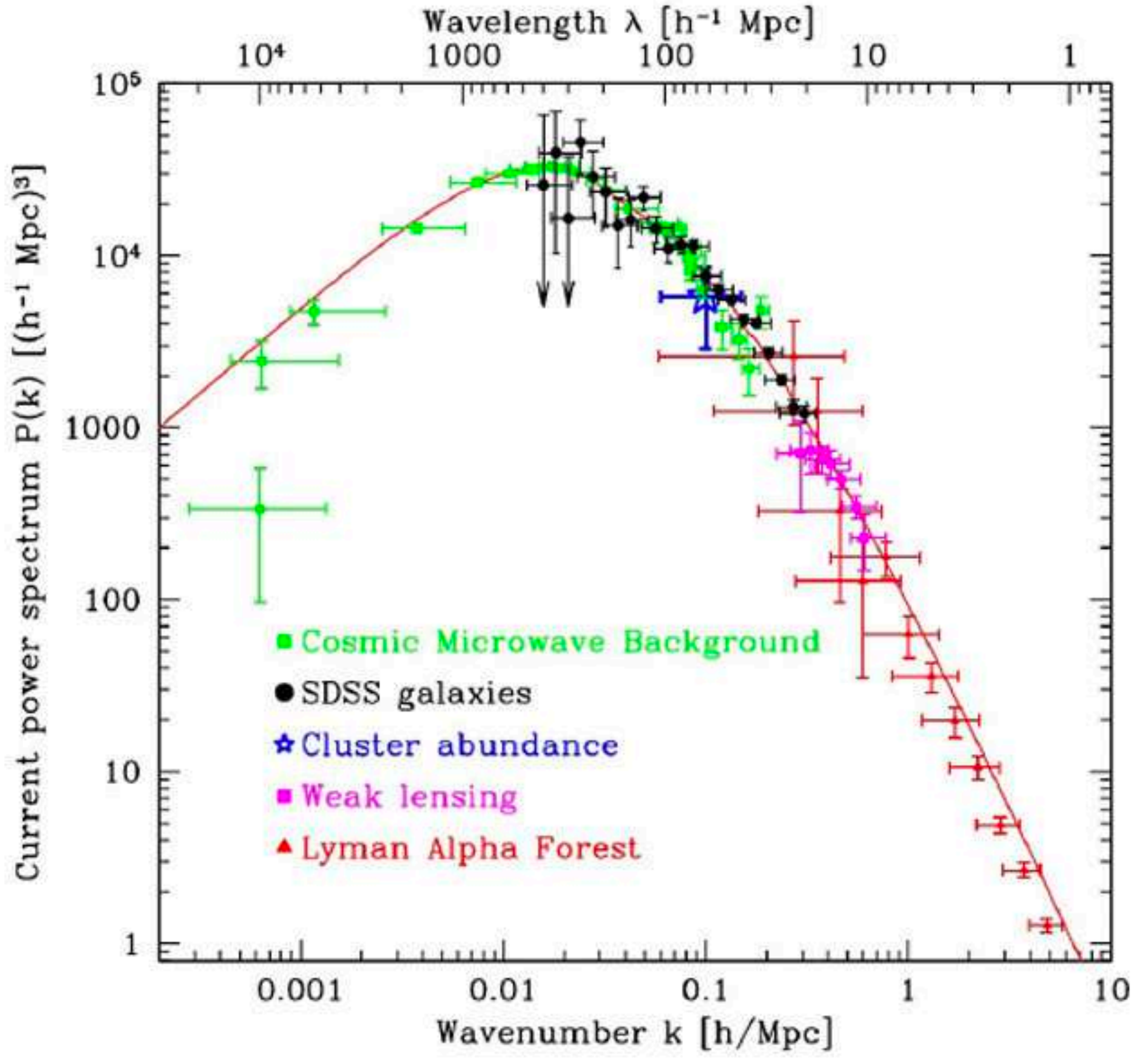


Many observational probes for $k \sim 10^{-3} - 10\,\mathrm{Mpc}^{-1}$

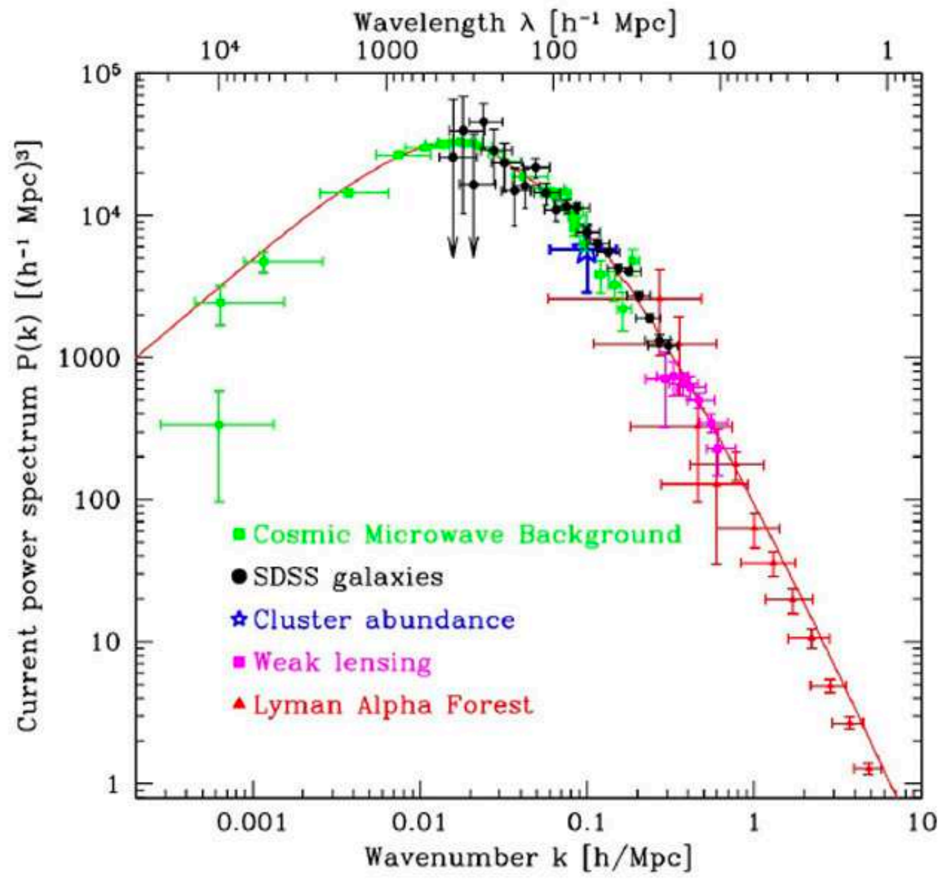
range of redshift $z < 3 - 4$

Incredible agreement to CDM!

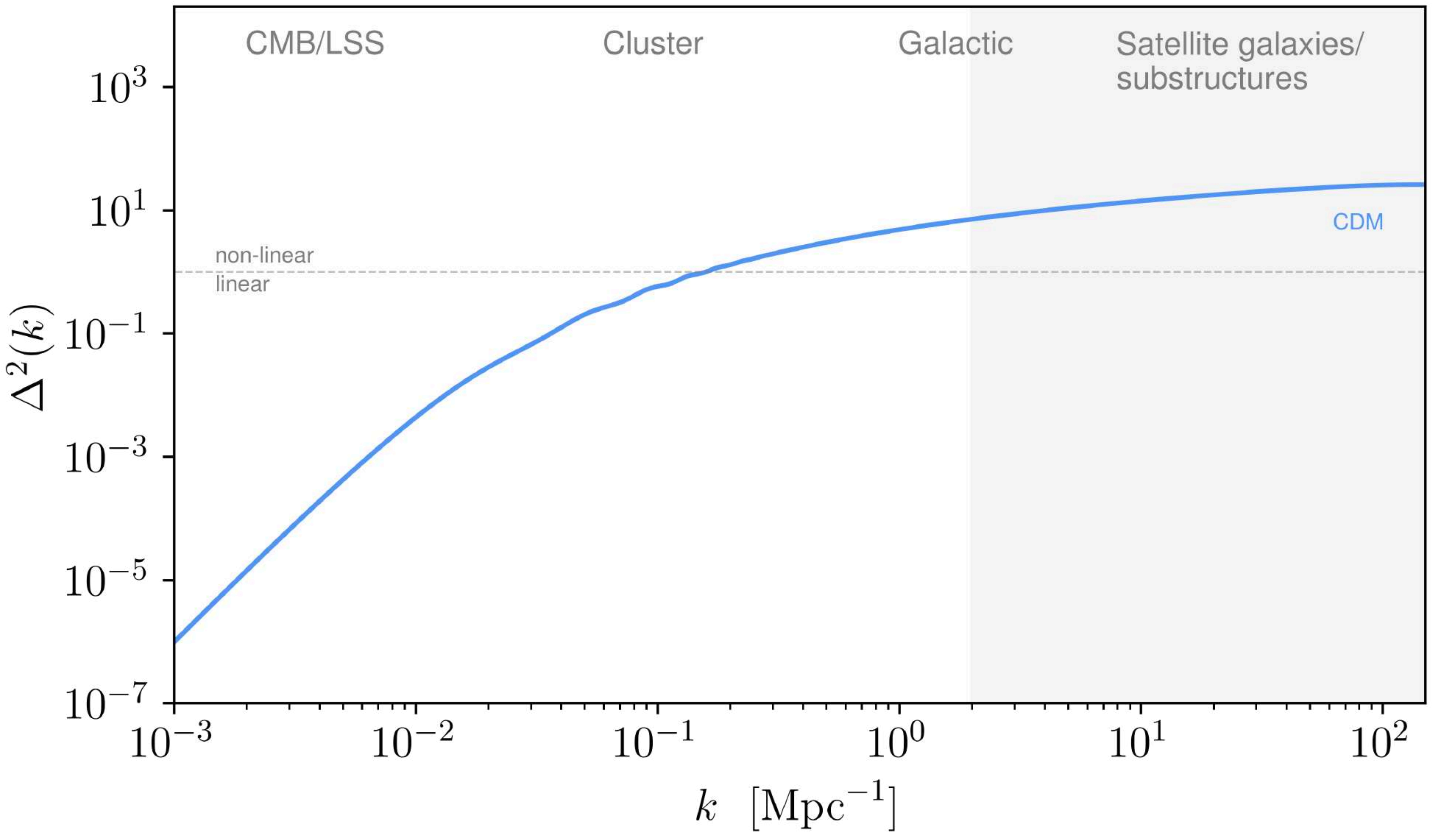
What we know about dark matter

Properties:

From LSS:



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



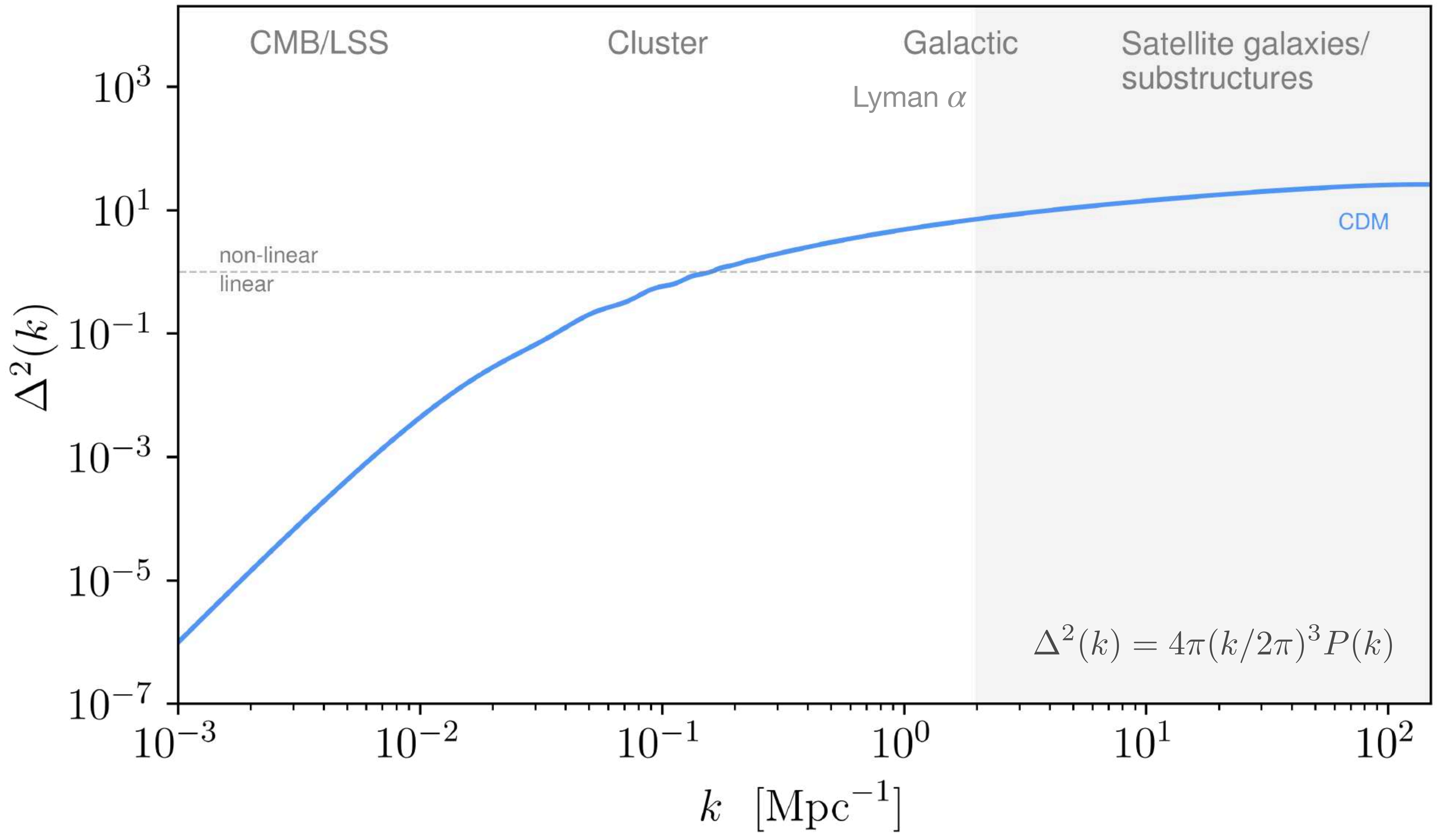
Dimensionless power spectrum

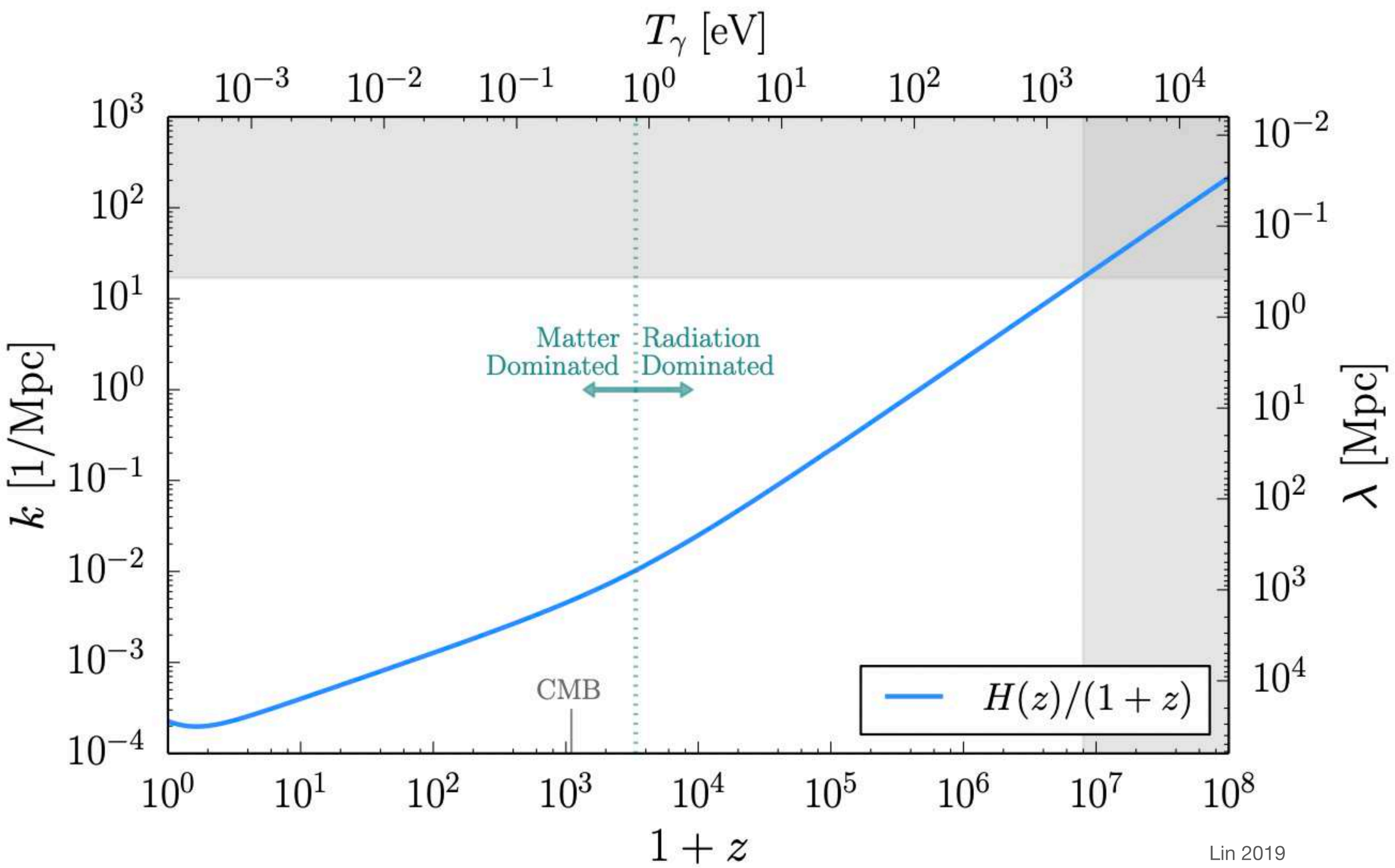
$$\Delta^2(k) = 4\pi(k/2\pi)^3 P(k)$$

What we know about dark matter

Properties:

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





Lin 2019

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 $\lambda_{phys} = a/k = H^{-1}$

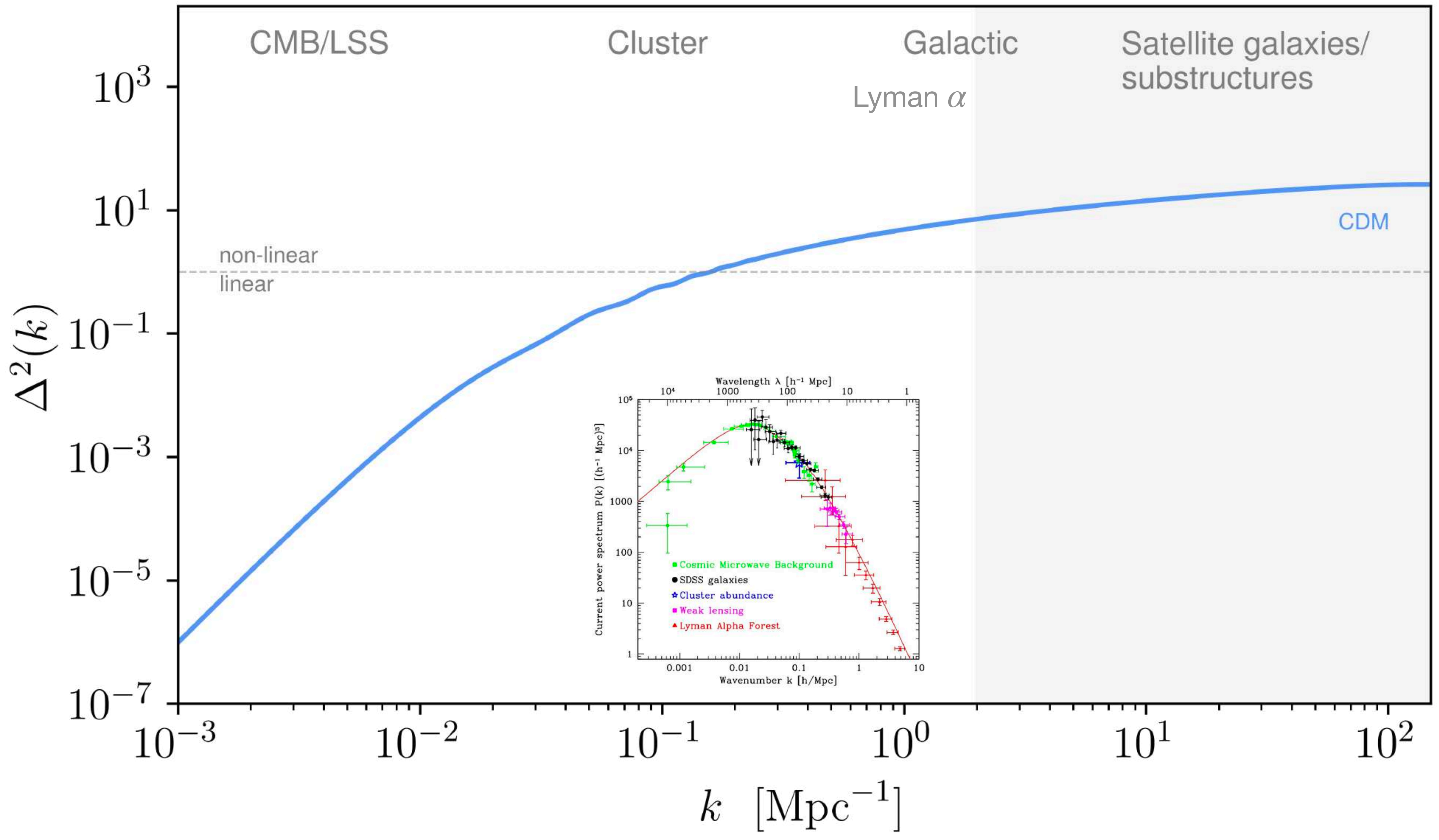
$$k = aH = H/(1+z)$$

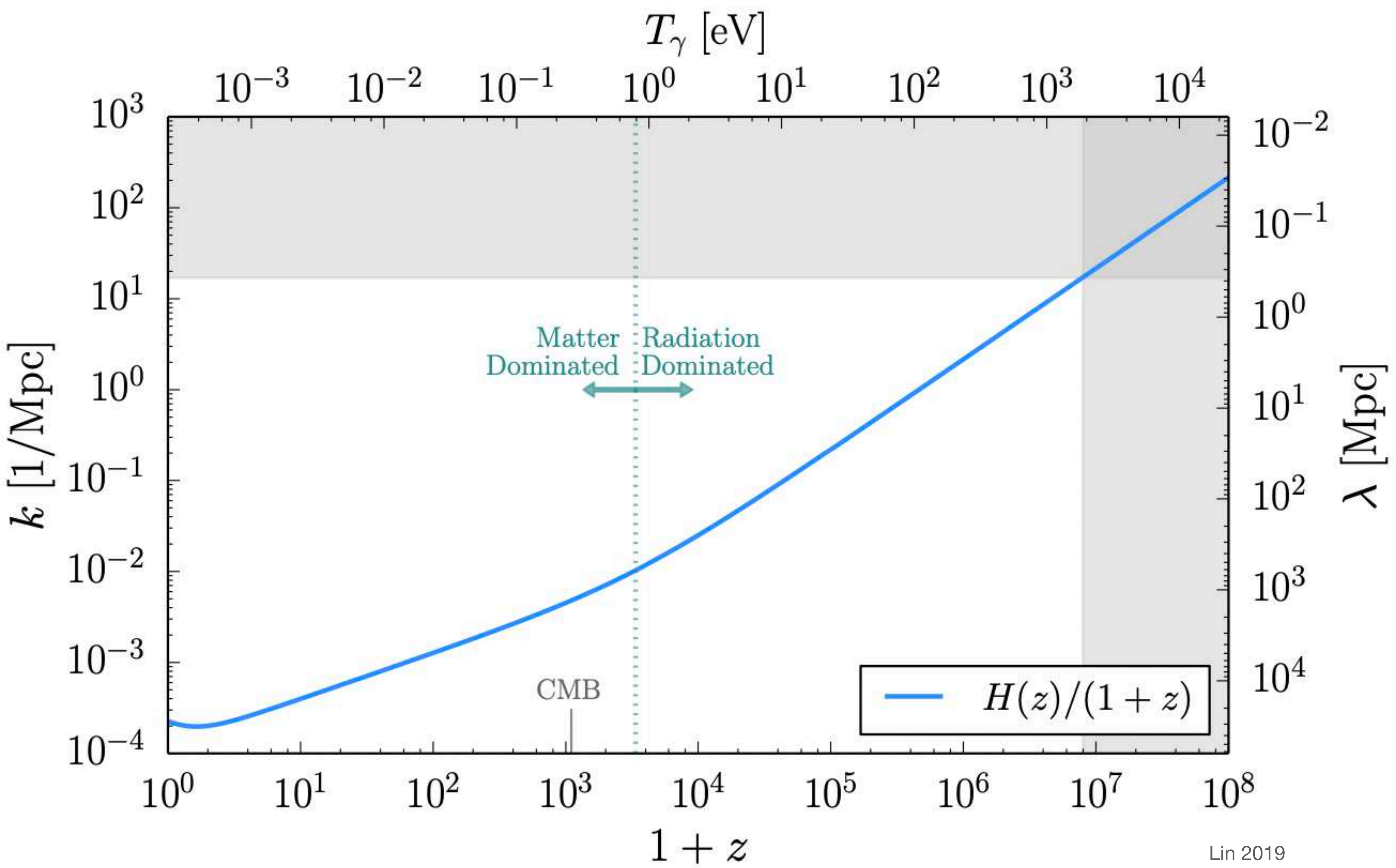
After this, the density pert. of CDM start to evolve, **grow** - contribute to the PS

What we know about dark matter

Properties:

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





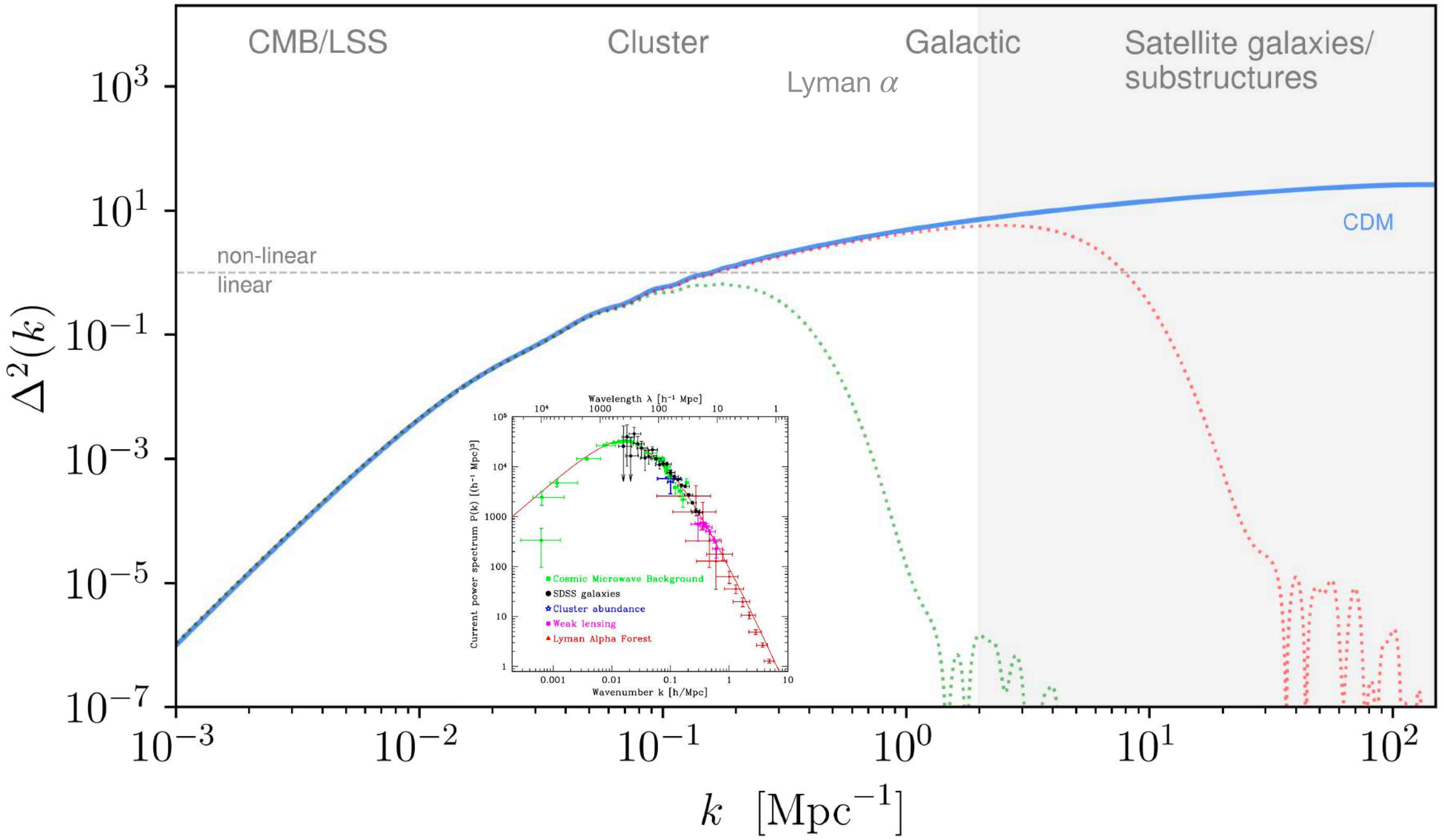
Perturbation modes enter the Hubble radius $\lambda_{phys} = a/k = H^{-1}$

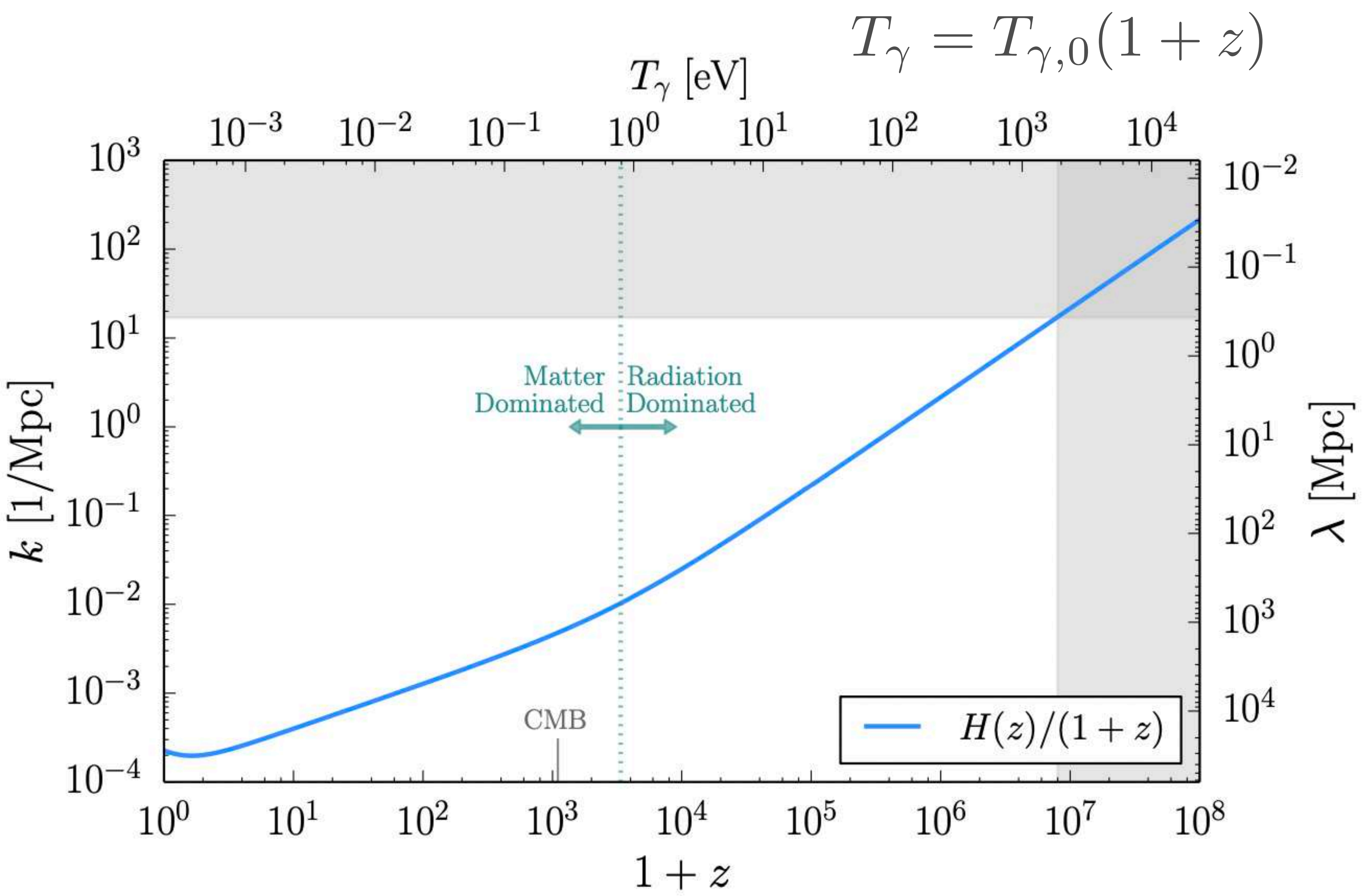
$k = aH = H/(1+z)$

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:





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 $z = 10^7$

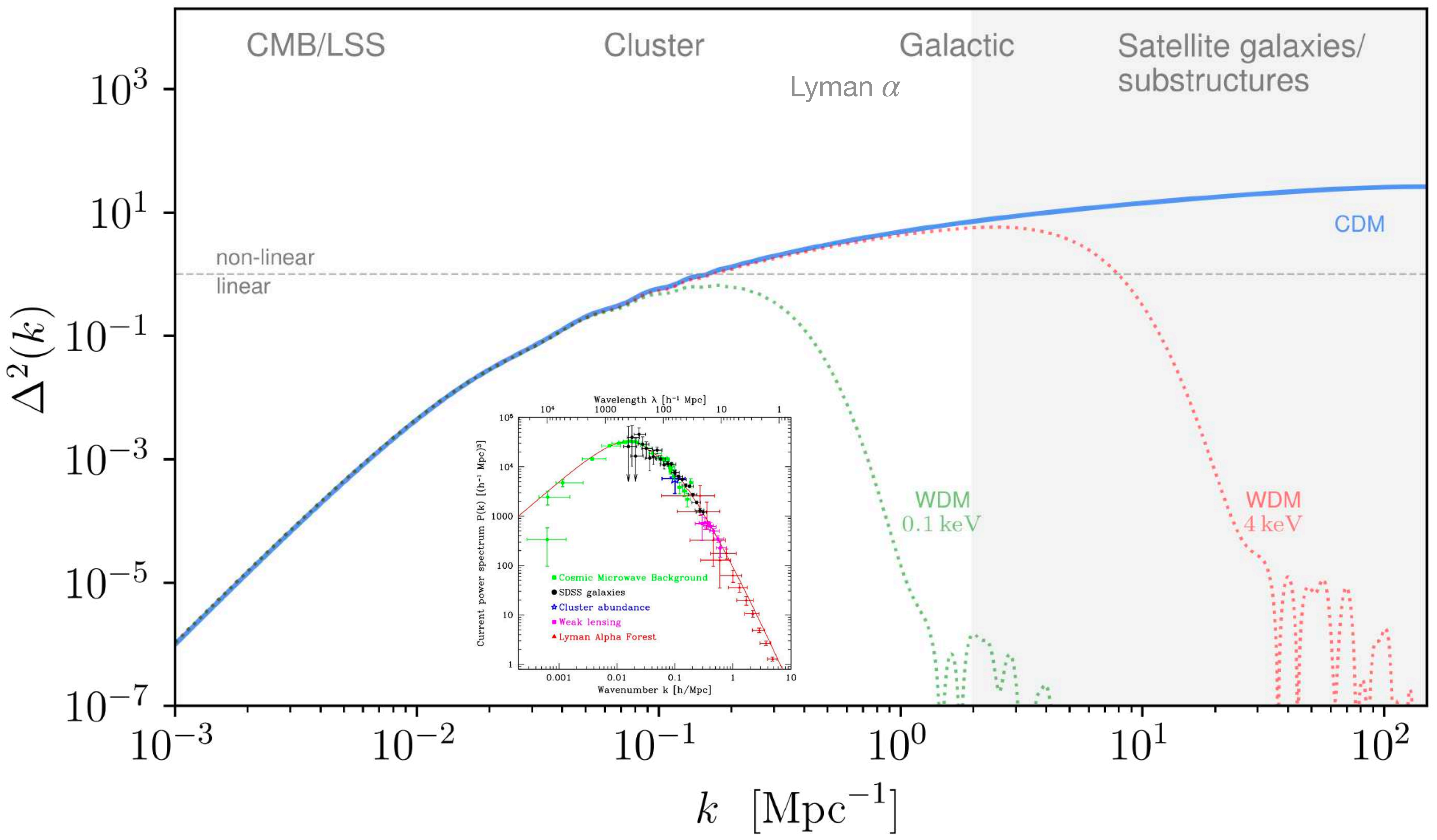
If **DM in thermal equilibrium** with the baryon-photon plasma ($T_{dm} = T_\gamma$)

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

WDM bound

What we know about dark matter

Properties:



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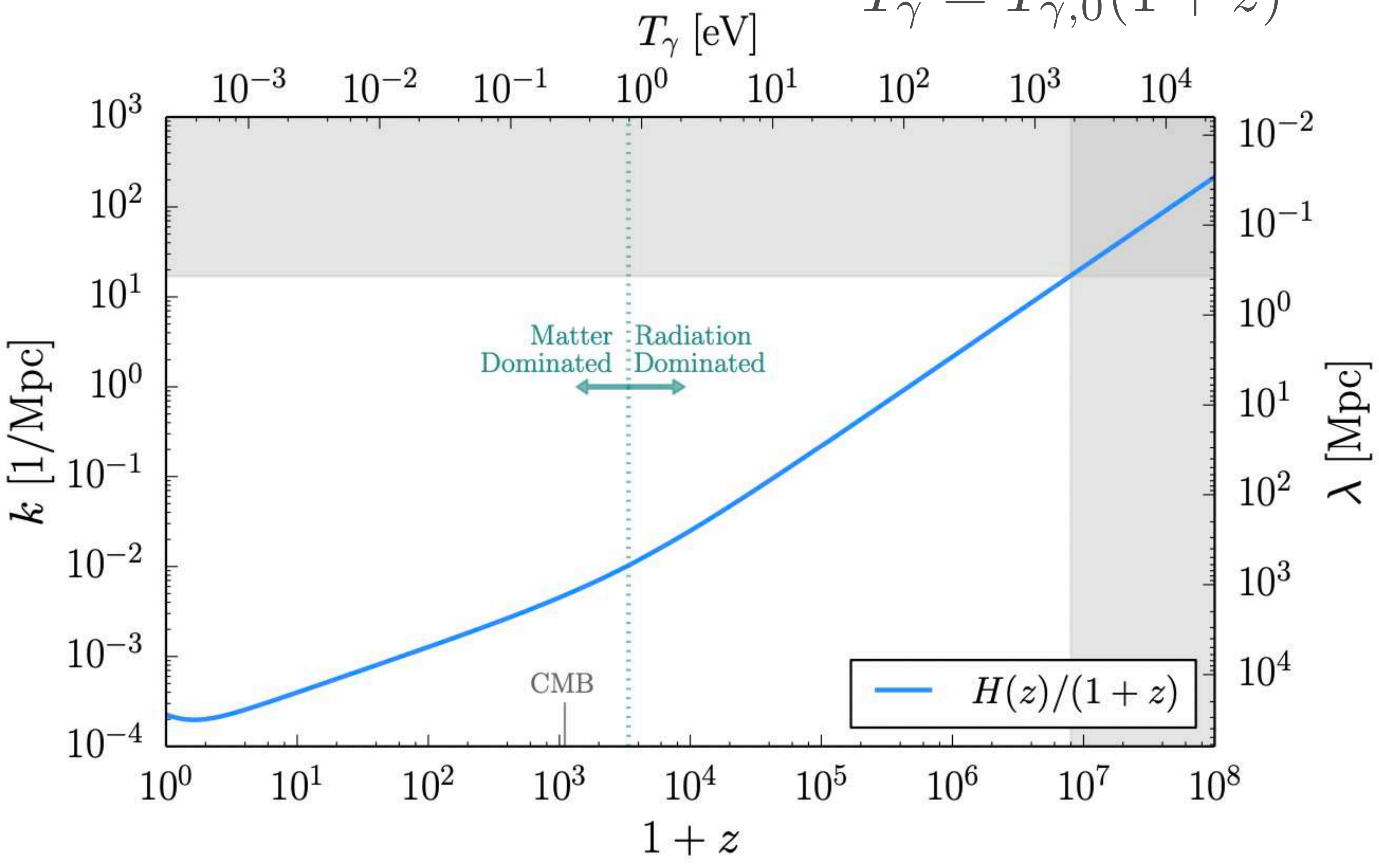

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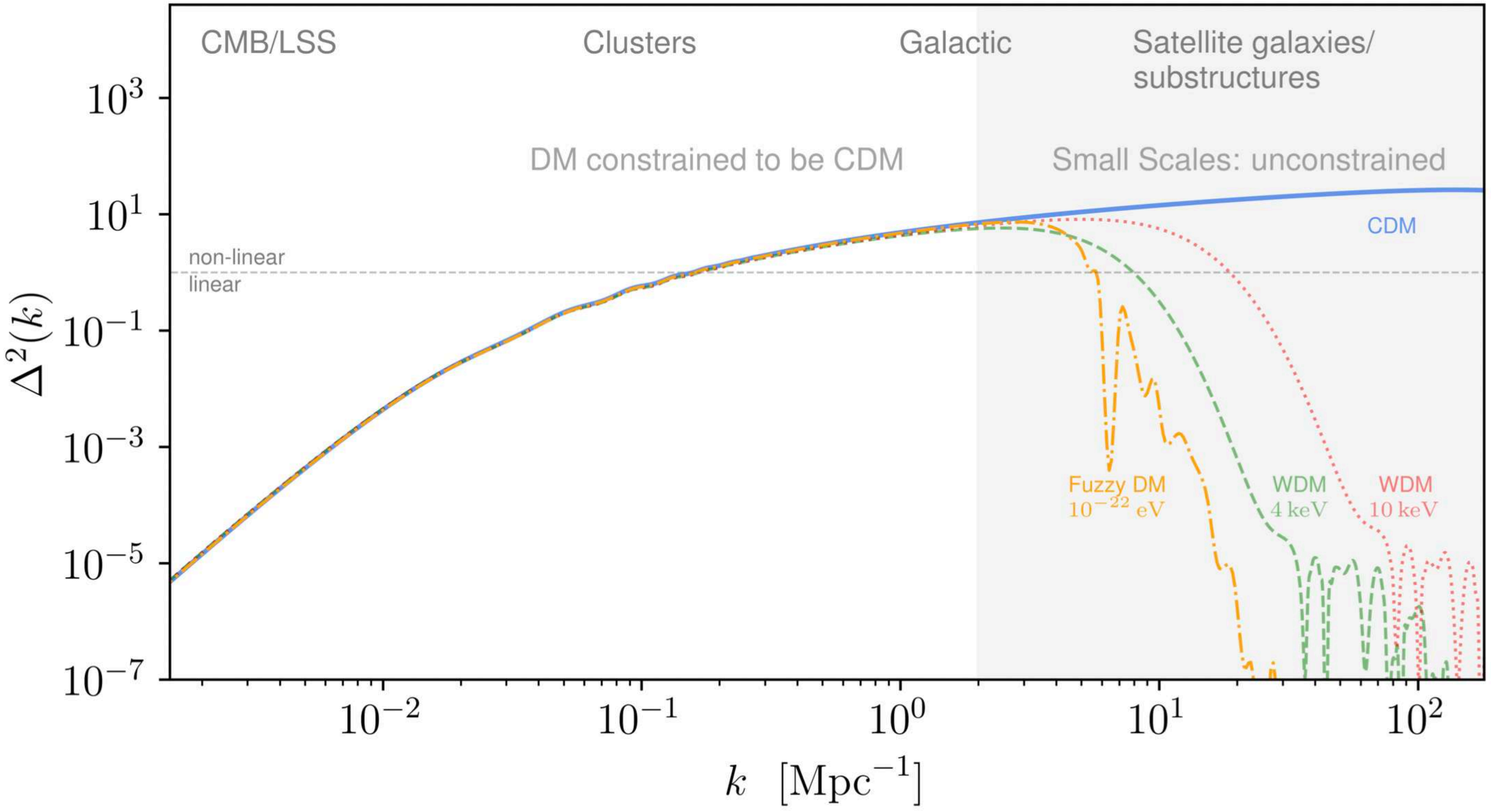
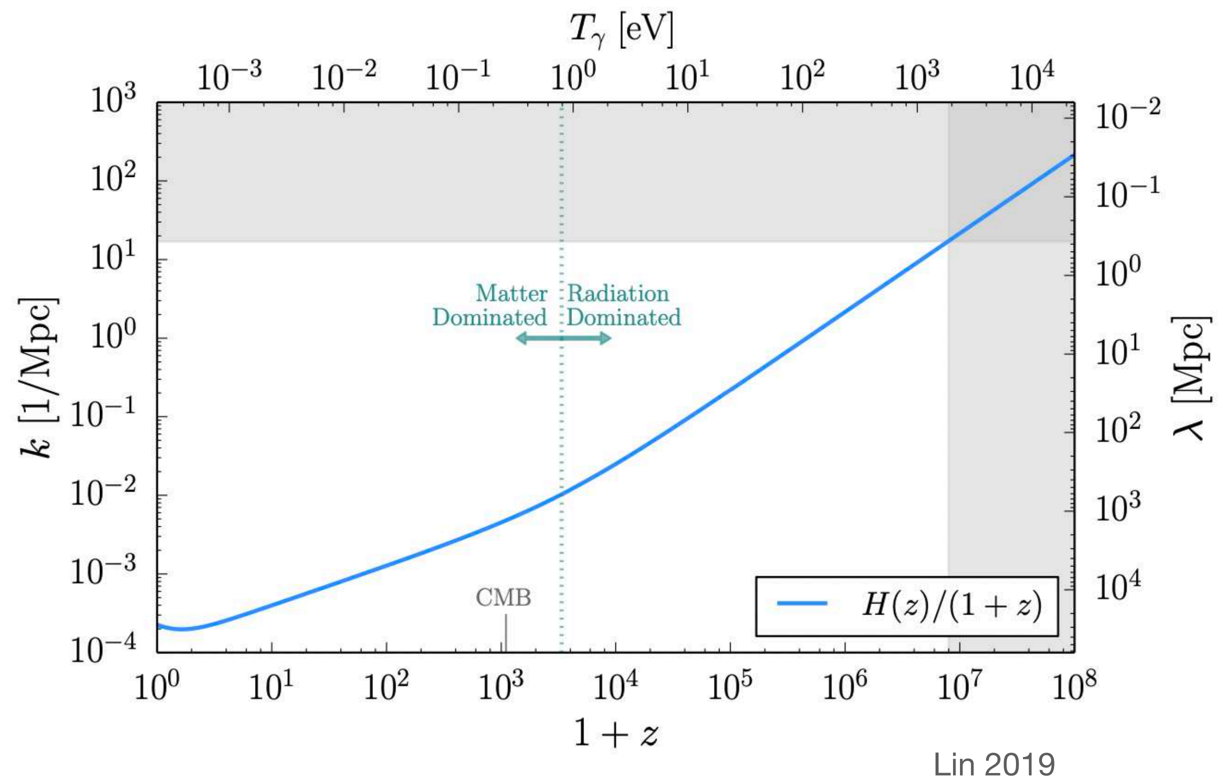




Lin 2019

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

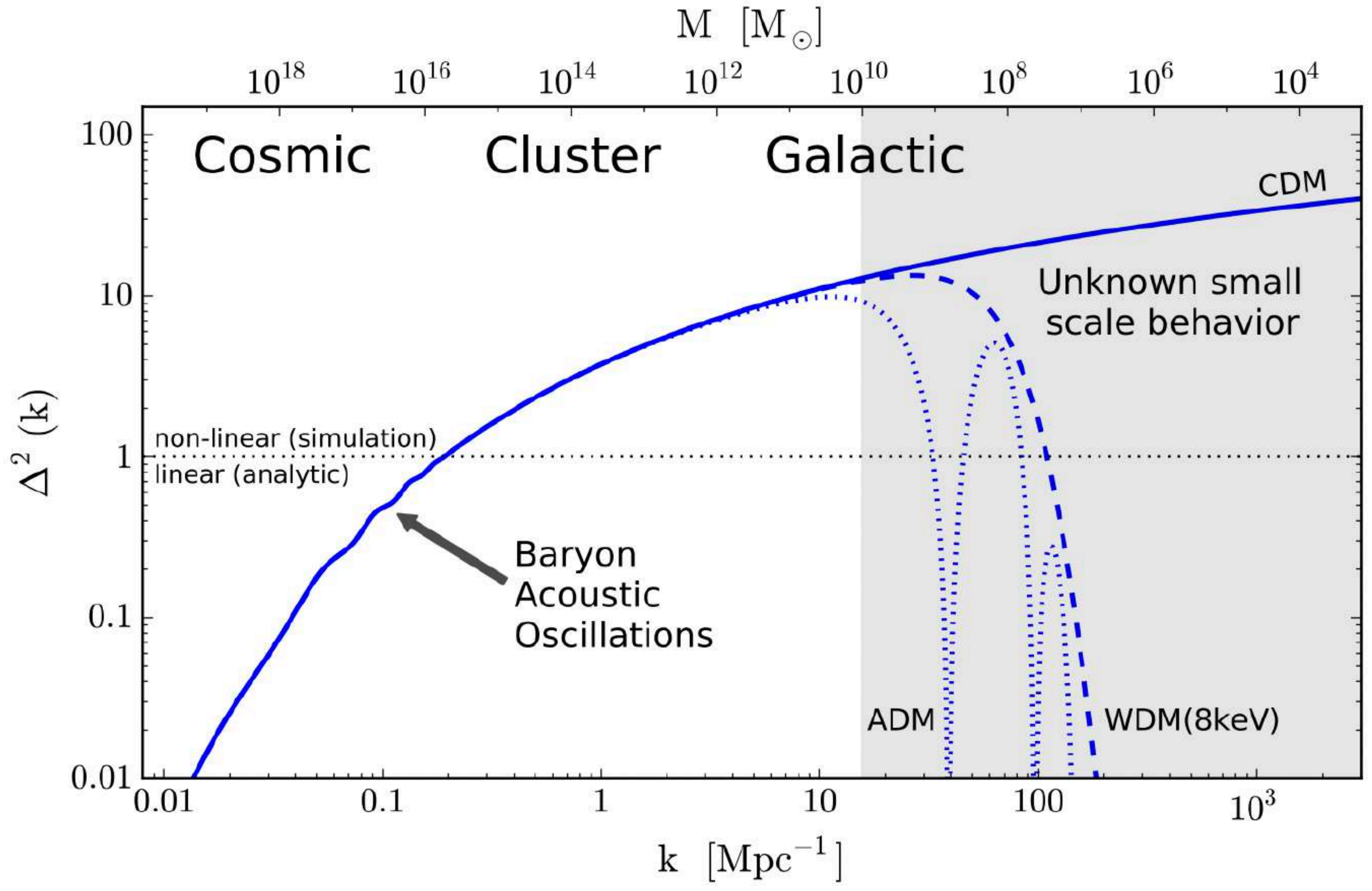
If DM had a *charge* $\epsilon\, e$:

- 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:

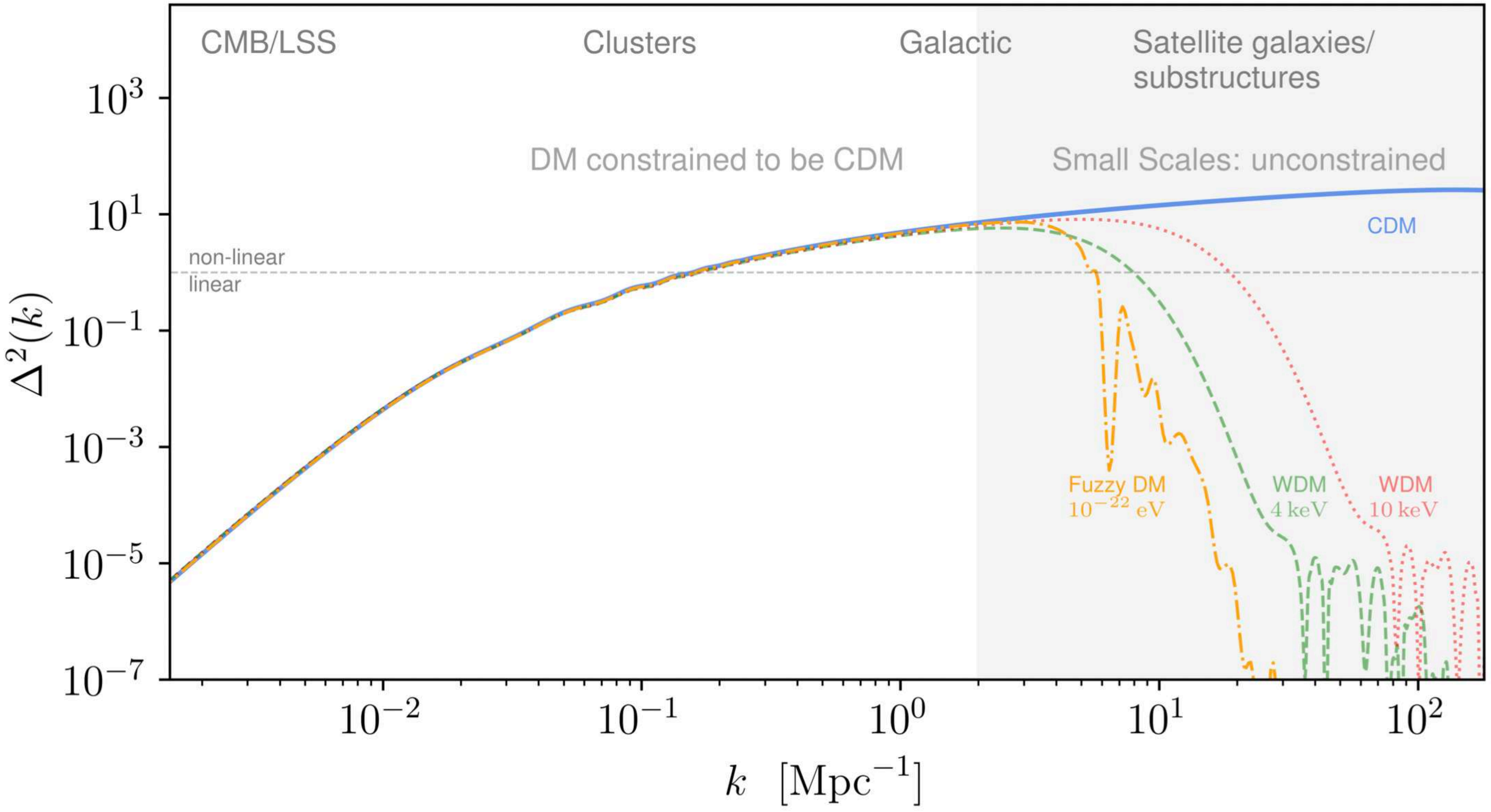
Charge: DM has neutral or charge < mili-charge!

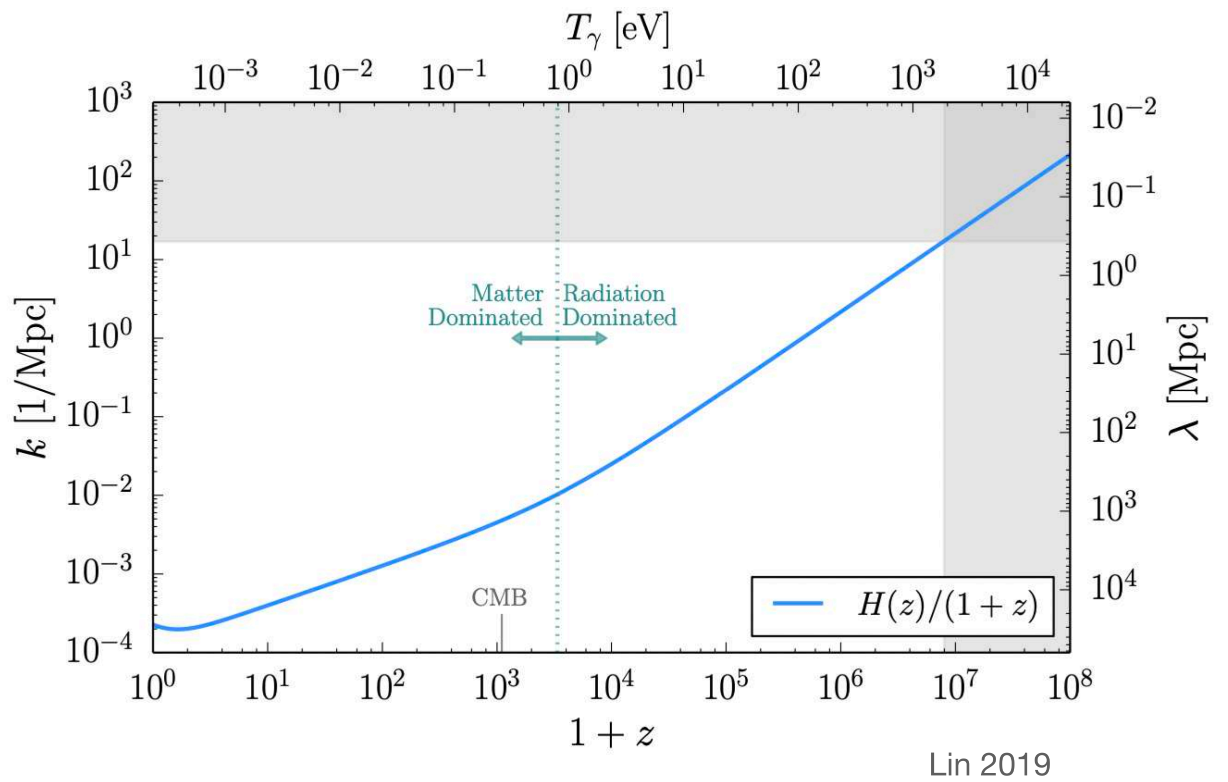
Self-interaction $\sigma/m_{dm} < 0.13\,\mathrm{cm}^2/\mathrm{g}\,,\;\; \sigma/m_{dm} < 0.35\,\mathrm{cm}^2/\mathrm{g}$

From: measured core densities from strong lensing

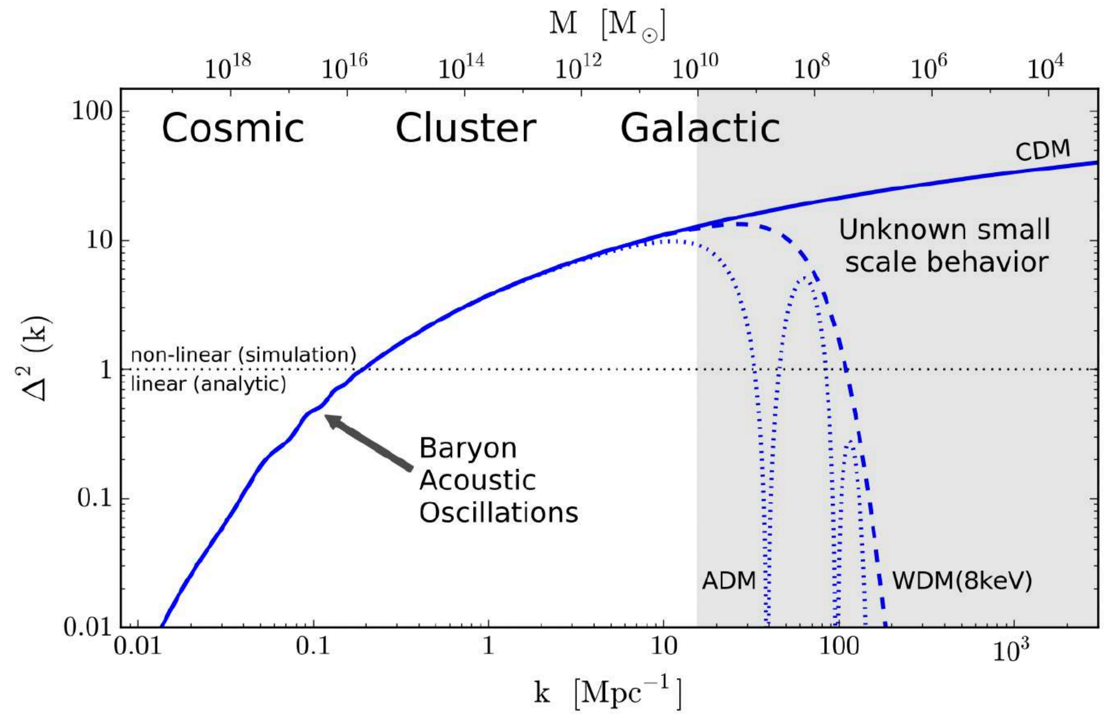
What we know about dark matter

Properties:





Lin 2019

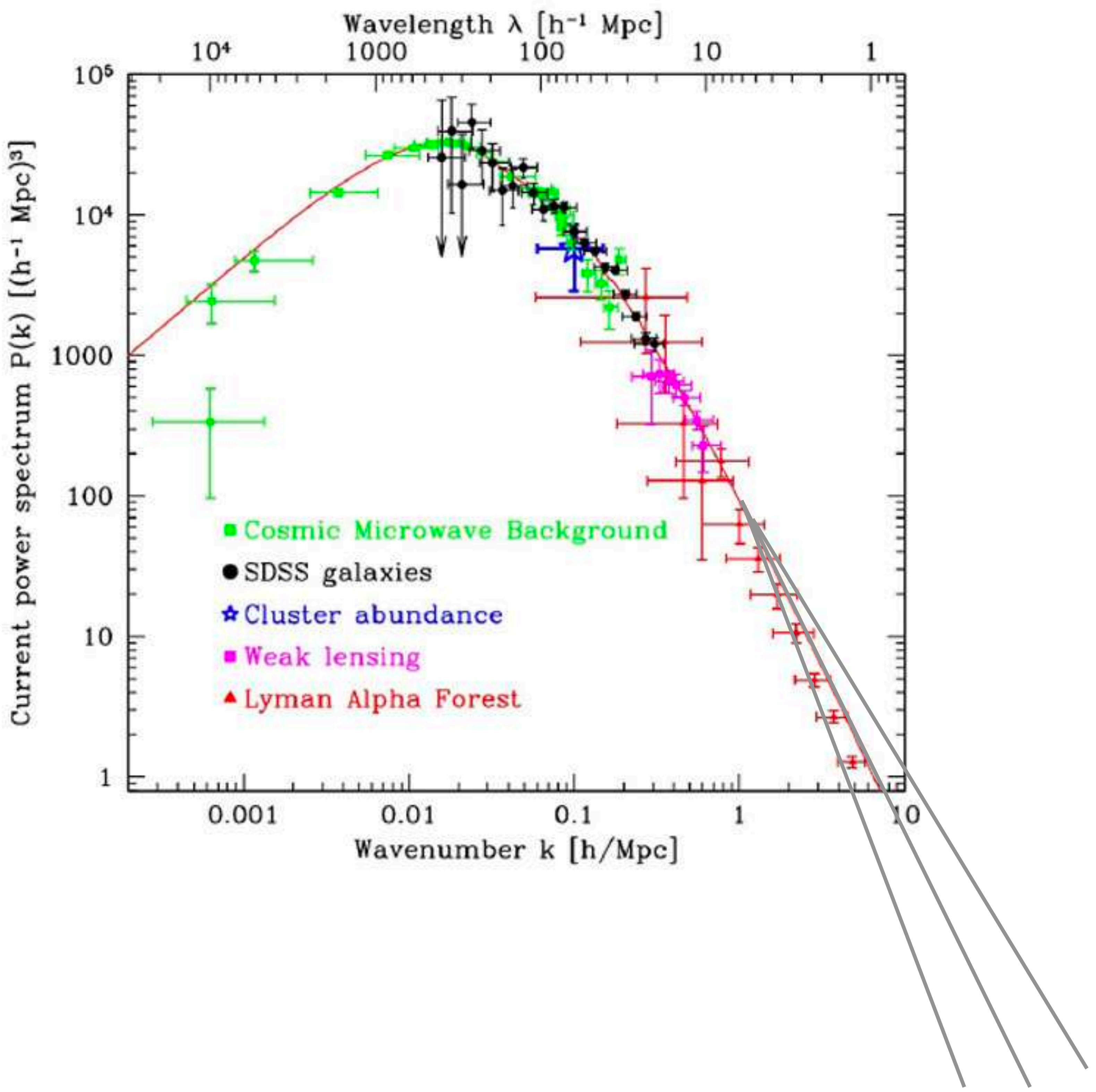


Ref.: Kaplan et al 2009, Cyr-Racine et al 2012

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



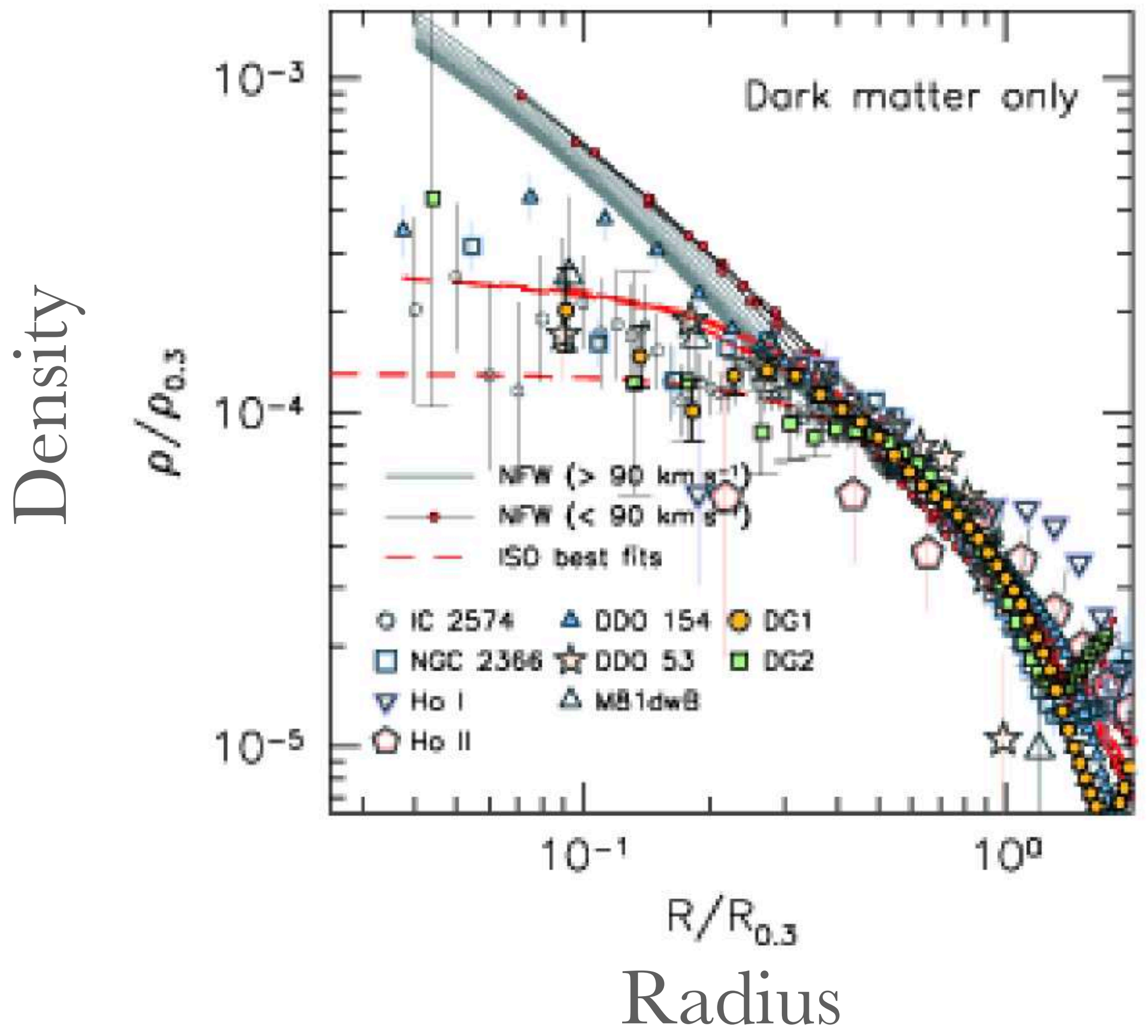
CDM on large scales

Small scale behavior: still weakly constrained and small scale challenges

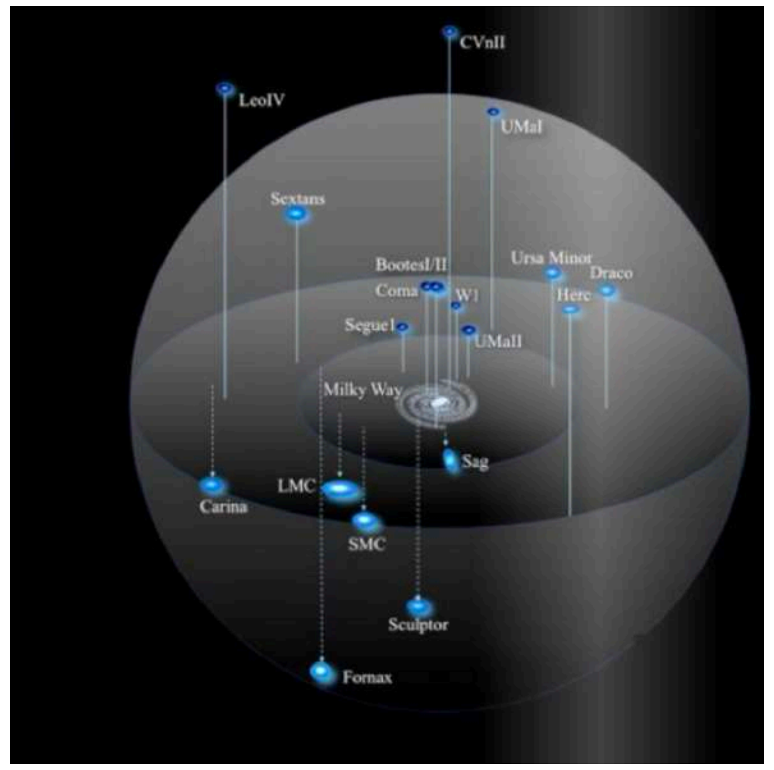
Small scale curiosities: cusp-core, missing satellites, BTFR, …

Small scale challenges

Cusp-core



THINGS (HI Near Galaxy Survey)/LITTLE THINGS

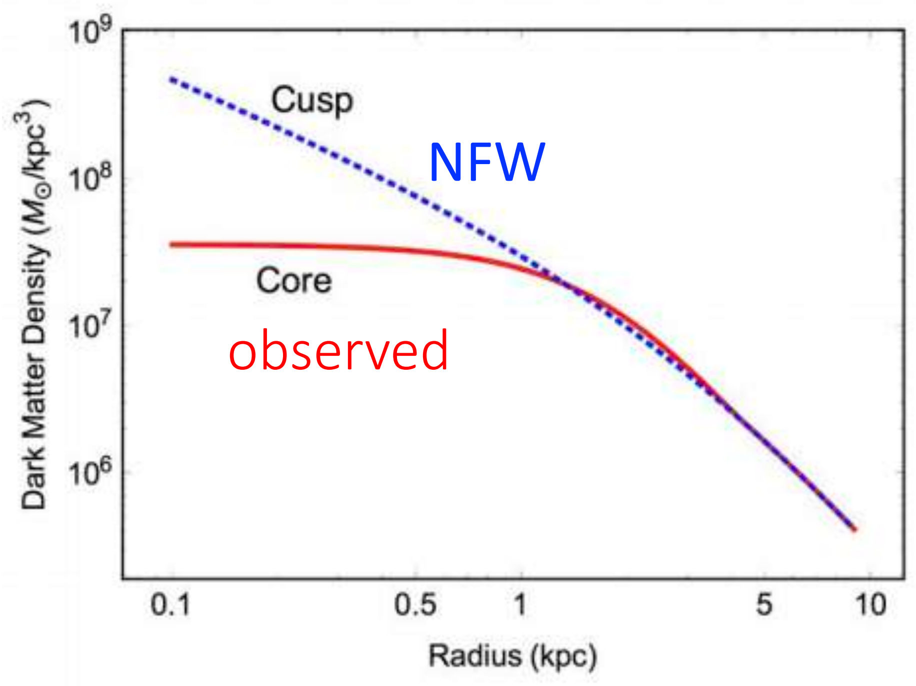


Bullock, Baylon-Kolchin

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)

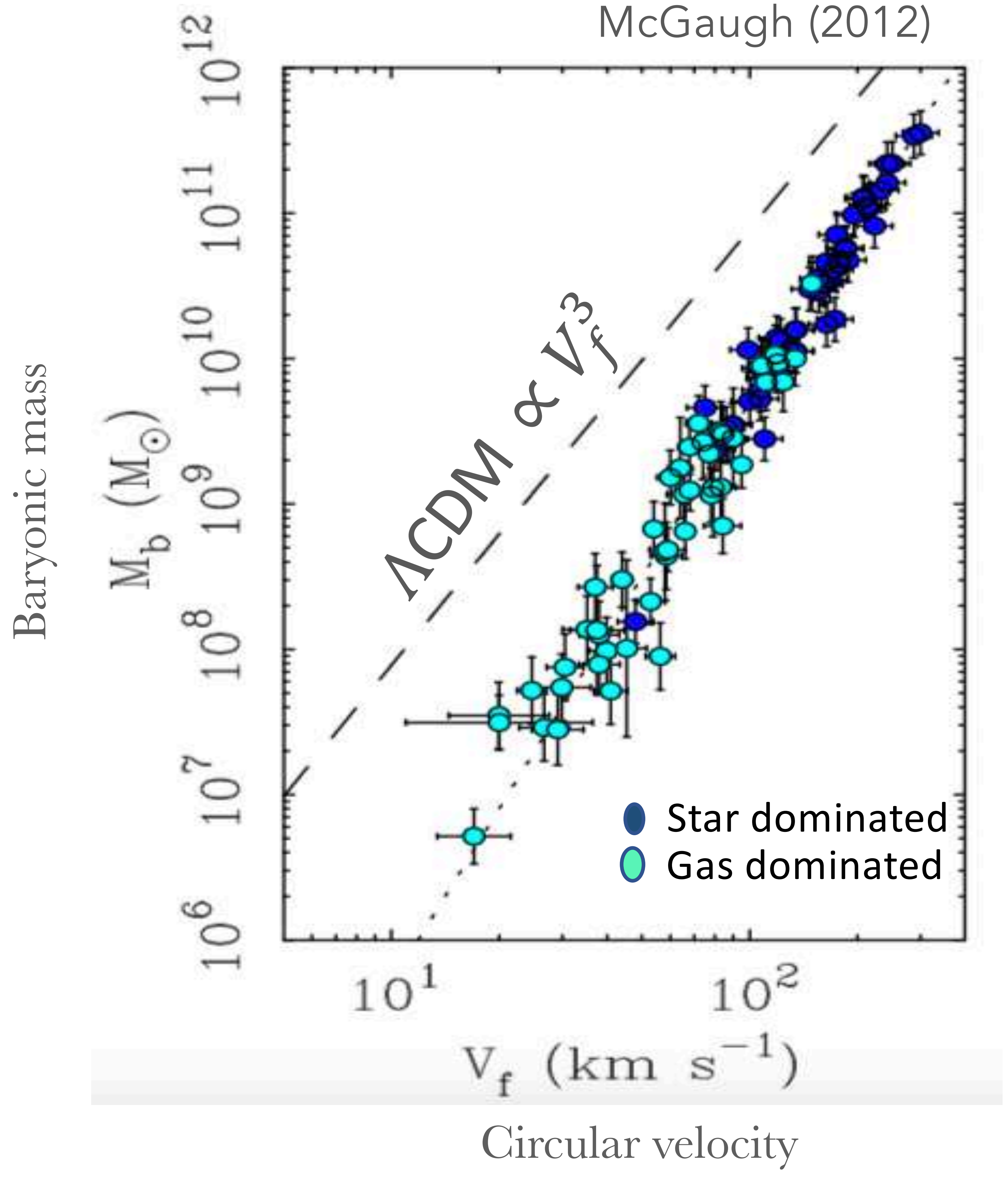
Remarkably tight scaling relations between dynamical and baryonic properties.

Other scaling relations:

✓TRF
✓RAR - Radial acceleration relation
✓…

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

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?
- $\neq$ simulations, $\neq$ 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

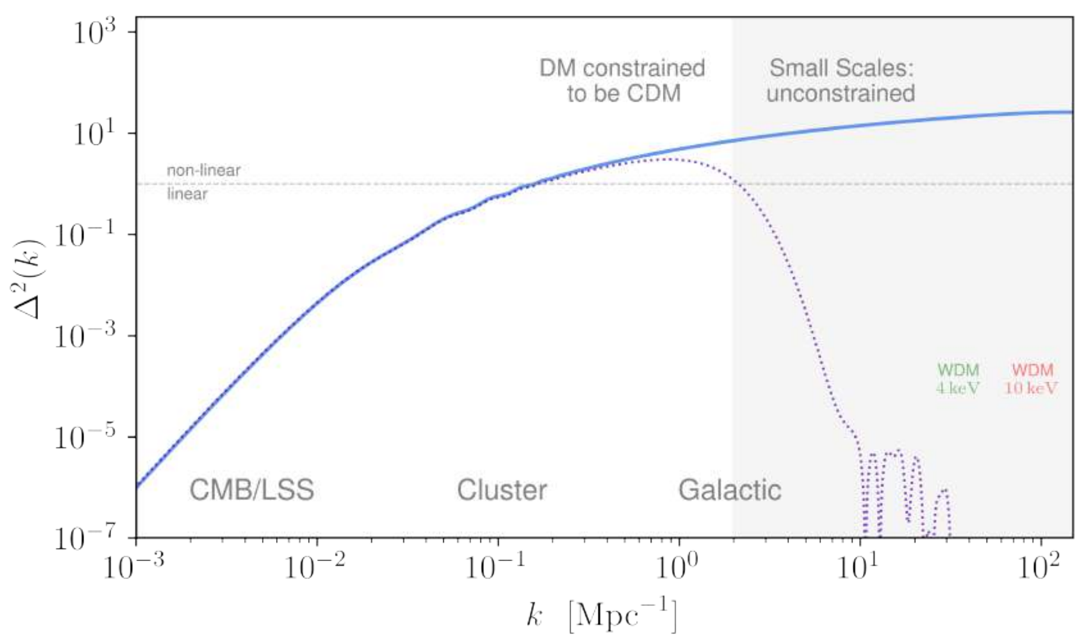
- WDM (Warm DM)

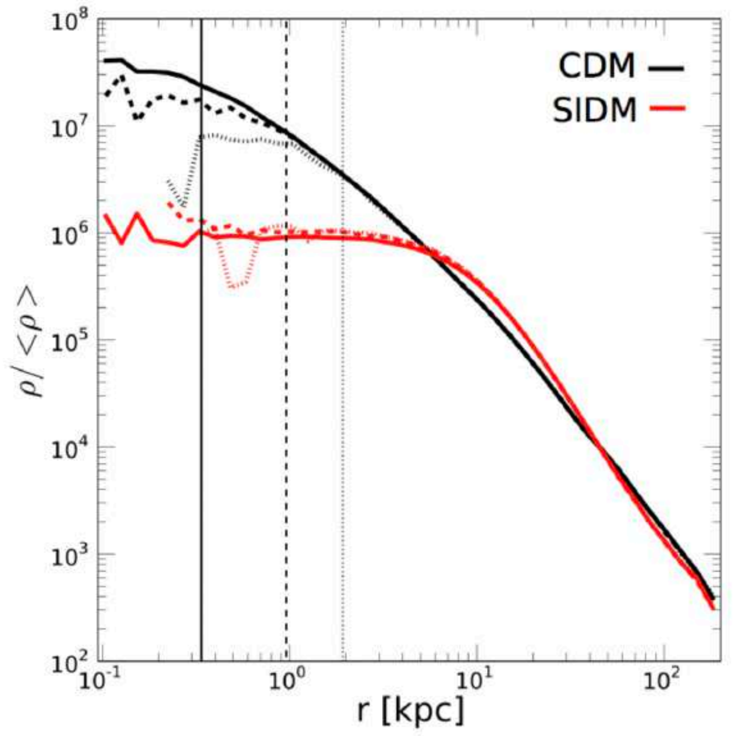
Solve missing satellites

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

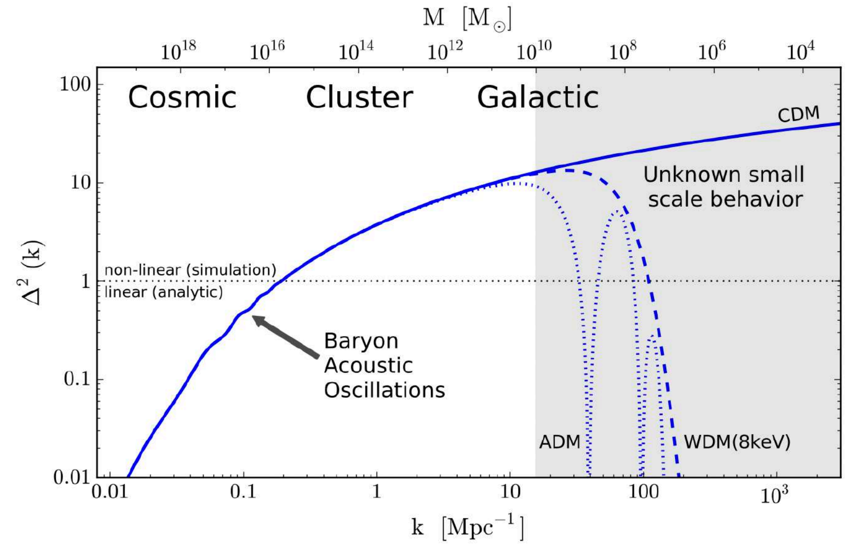
- Cold or warm — Thermal candidate: $m_{dm} \geq \text{keV}$ — Or produced cold by a non-thermal mechanism

  Has to be non-relativistic at BBN

- Reproduce large and small scale distribution

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

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



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

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

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

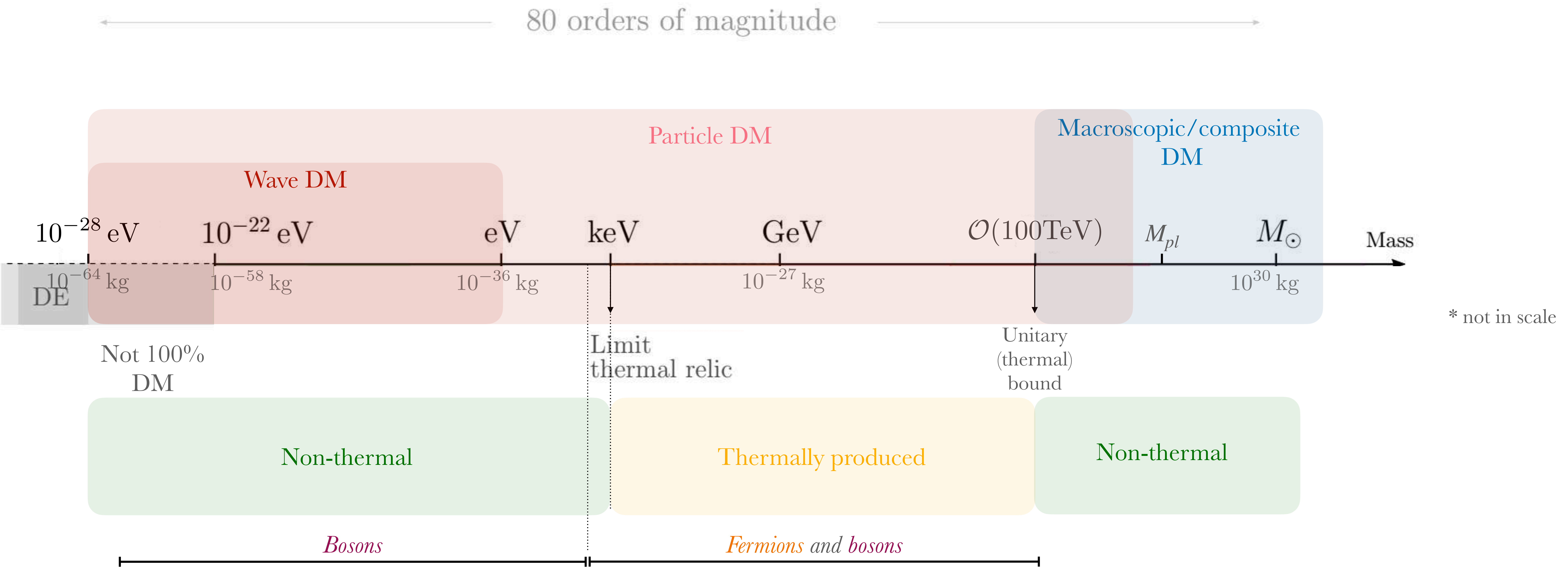
  Can interact via the ***weak force***

- 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!

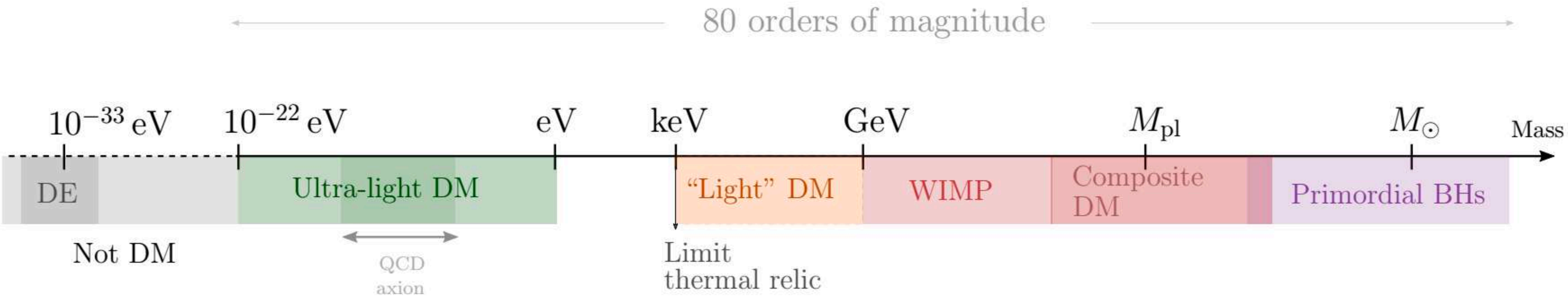
Natural units $(c = 1)$
$1\,\text{kg} \rightarrow \sim 5 \times 10^{35}\,\text{eV}$
$1\,M_\odot \rightarrow \sim 10^{66}\,\text{eV}$

Landscape of dark matter models

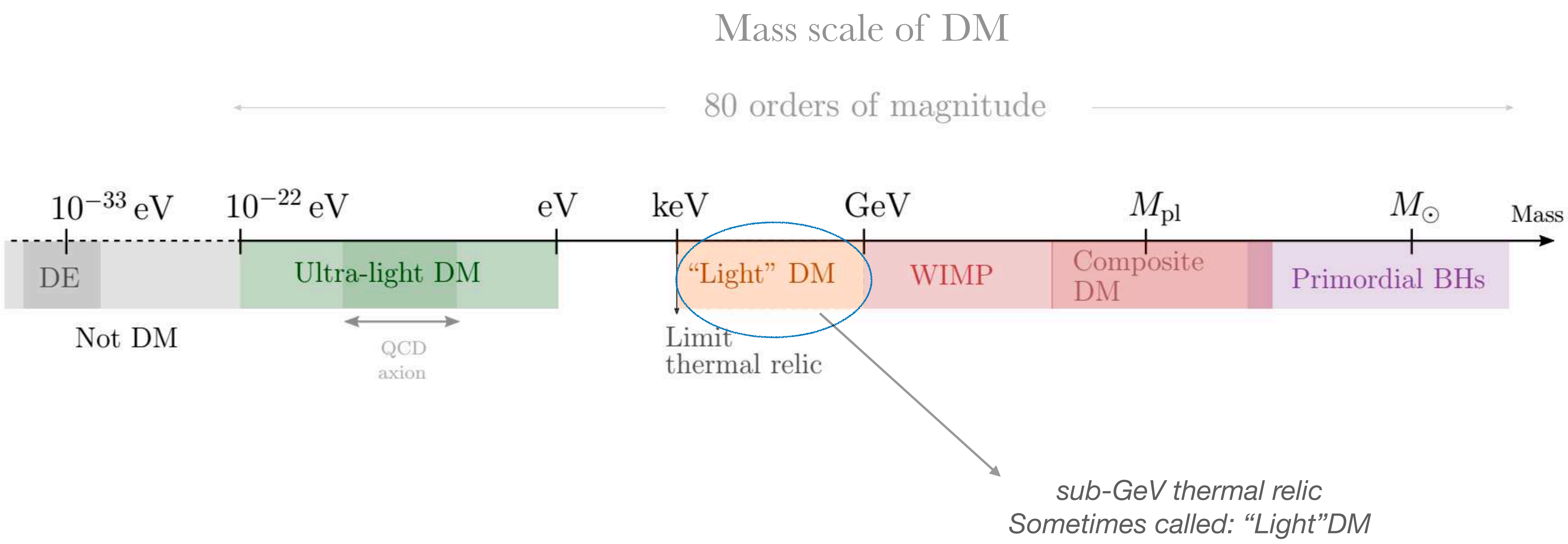
- What is DM? What is the nature of DM?

State of the "art"

Mass scale of DM

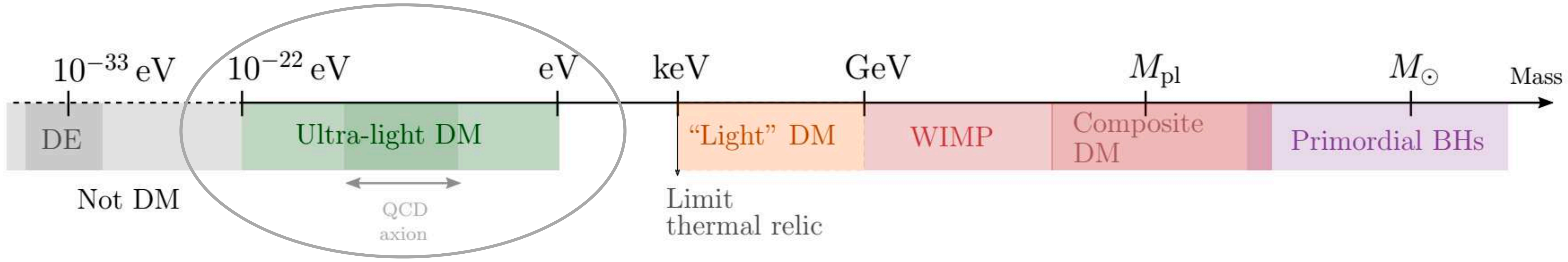


Landscape of dark matter models

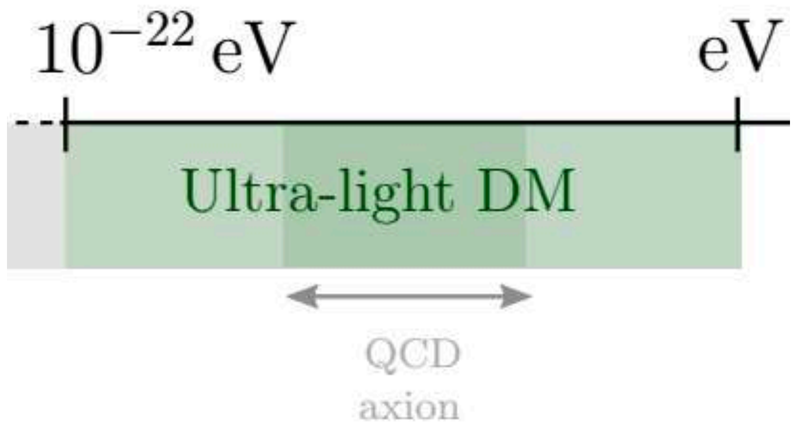


BUT, for us…

Ultra-light dark matter

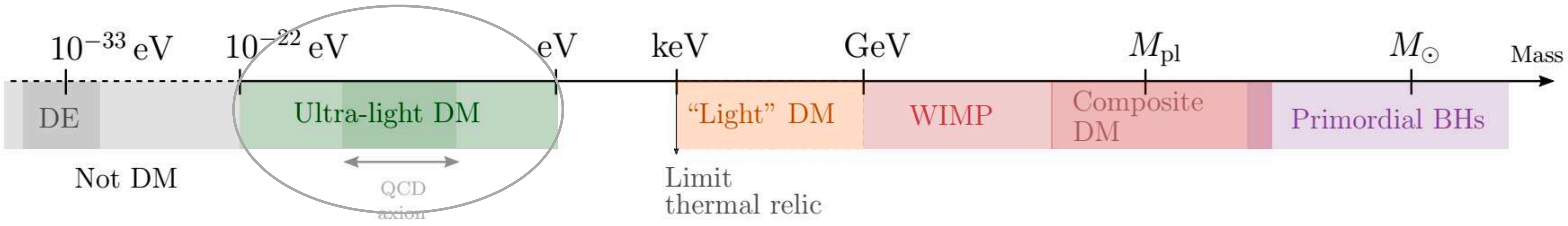


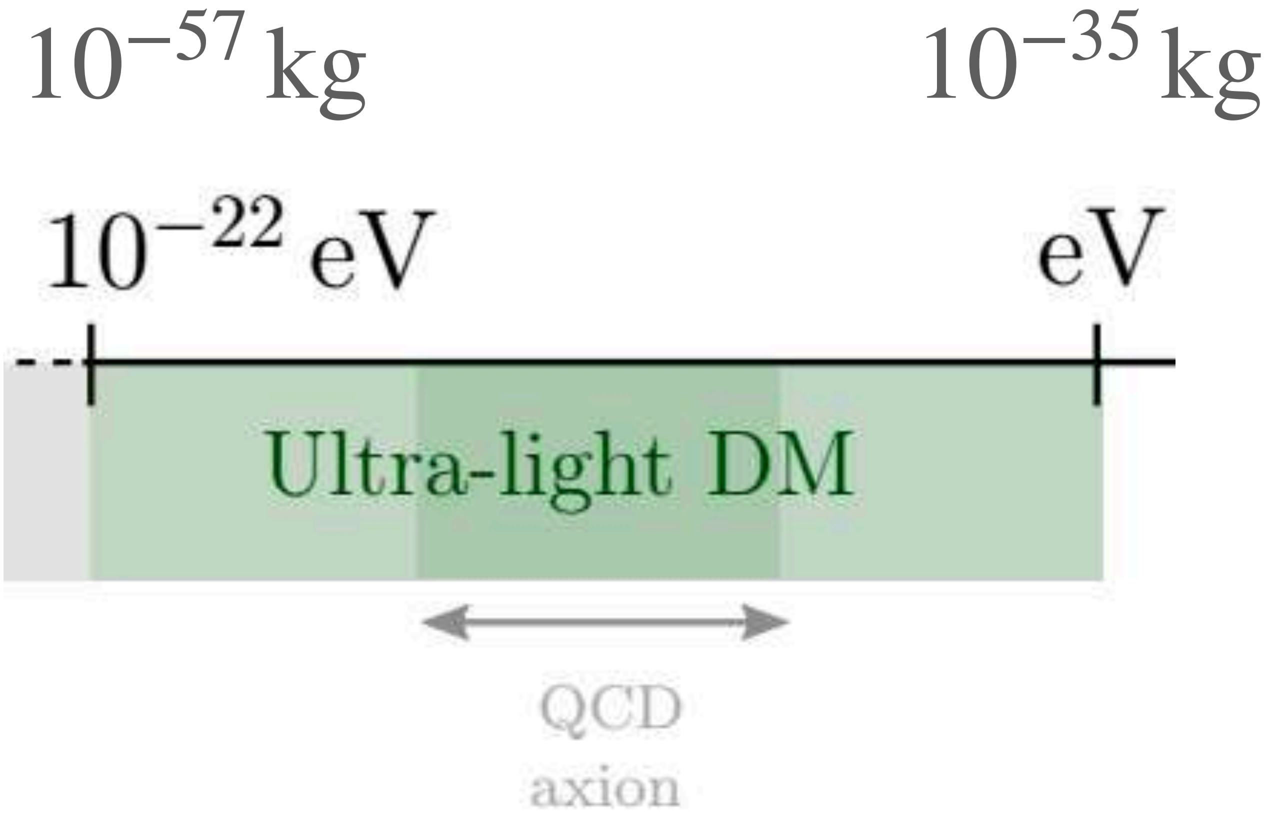
Ultra-light dark matter



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

Lightest possible candidate for DM





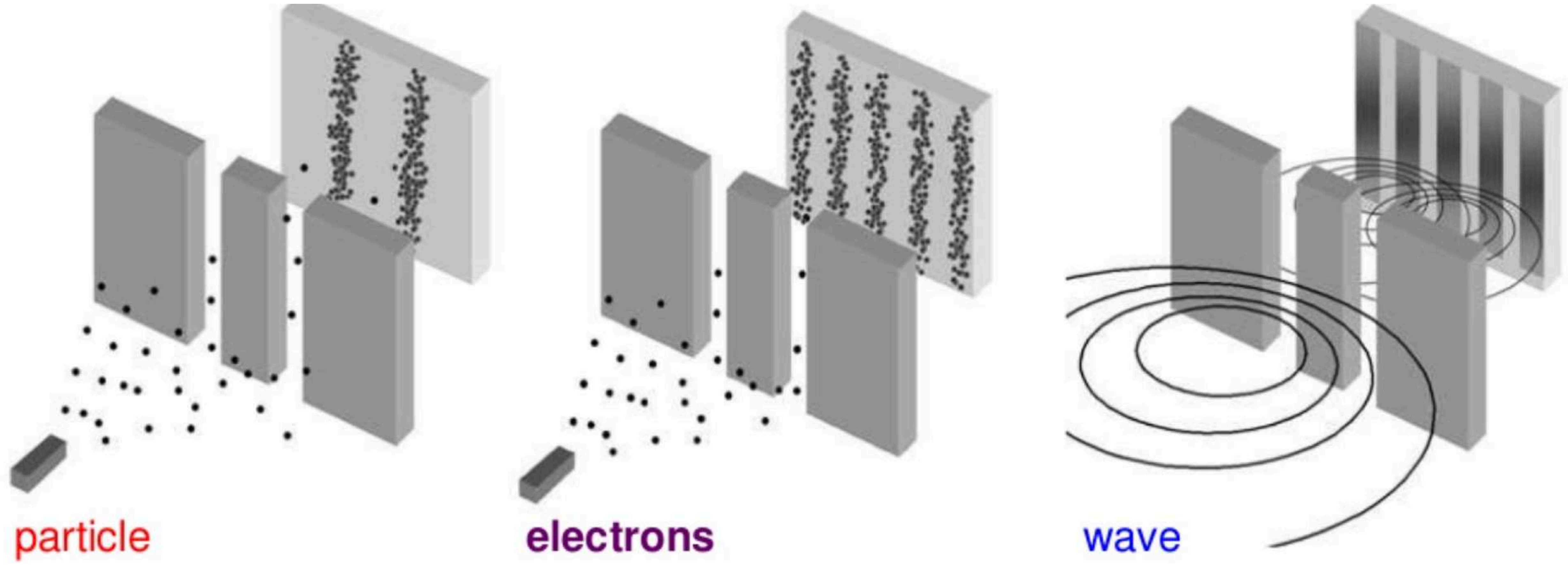
→ Bosons (scalar fields)

Non-thermally produced

Wave-Particle duality

All matter exhibits a wave behaviour

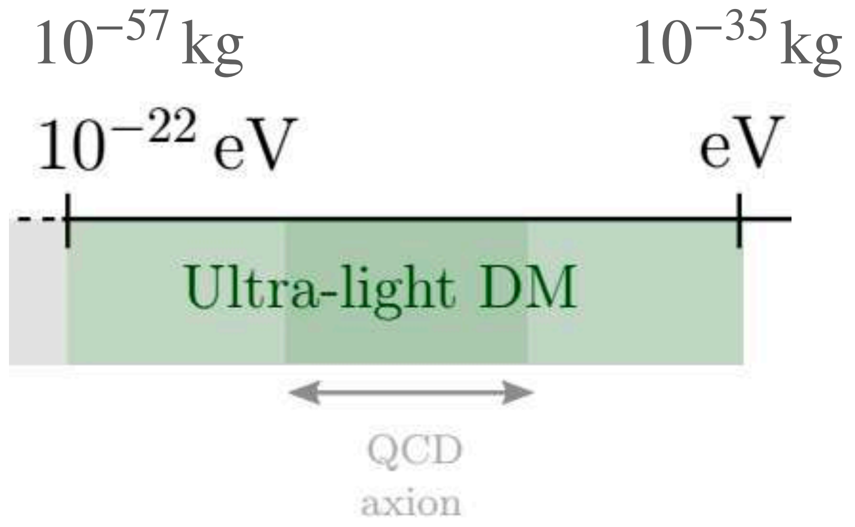
De Broglie 1924



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

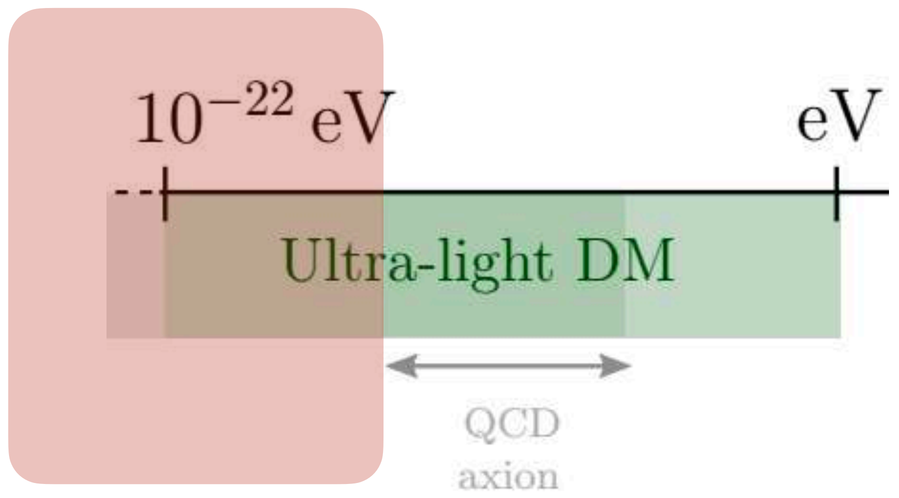
$\lambda_{dB} \sim 1/\sqrt{2\pi m k_B T}$

	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}



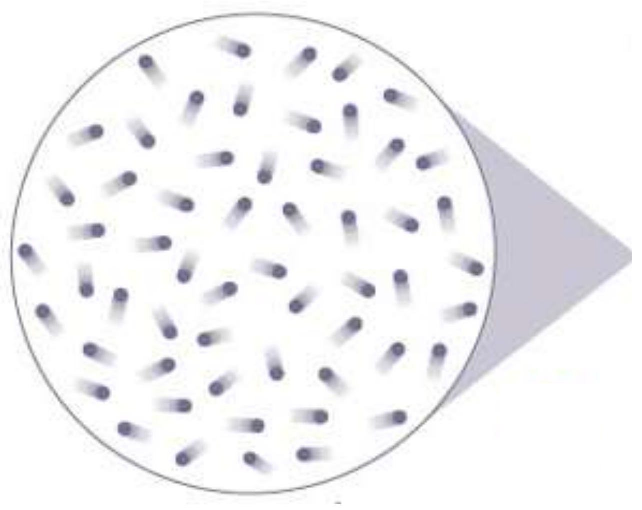
$$\lambda_{dB}^{ULDM} \sim \text{pc} - \text{kpc}$$

Ultra-light dark matter

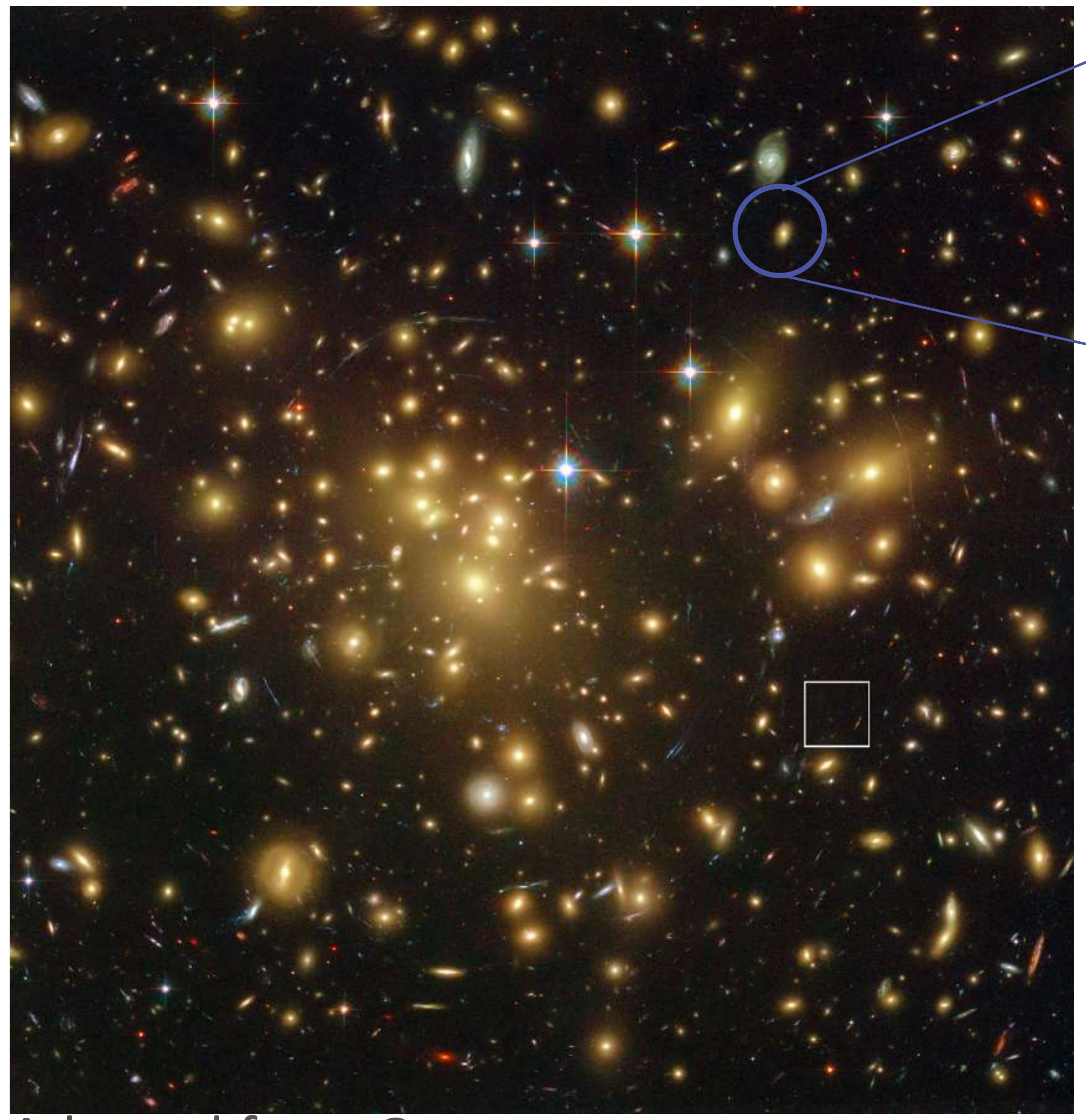


Ultra-light candidate ⟶ Large $\lambda_{\mathrm{dB}} \sim 1/mv$

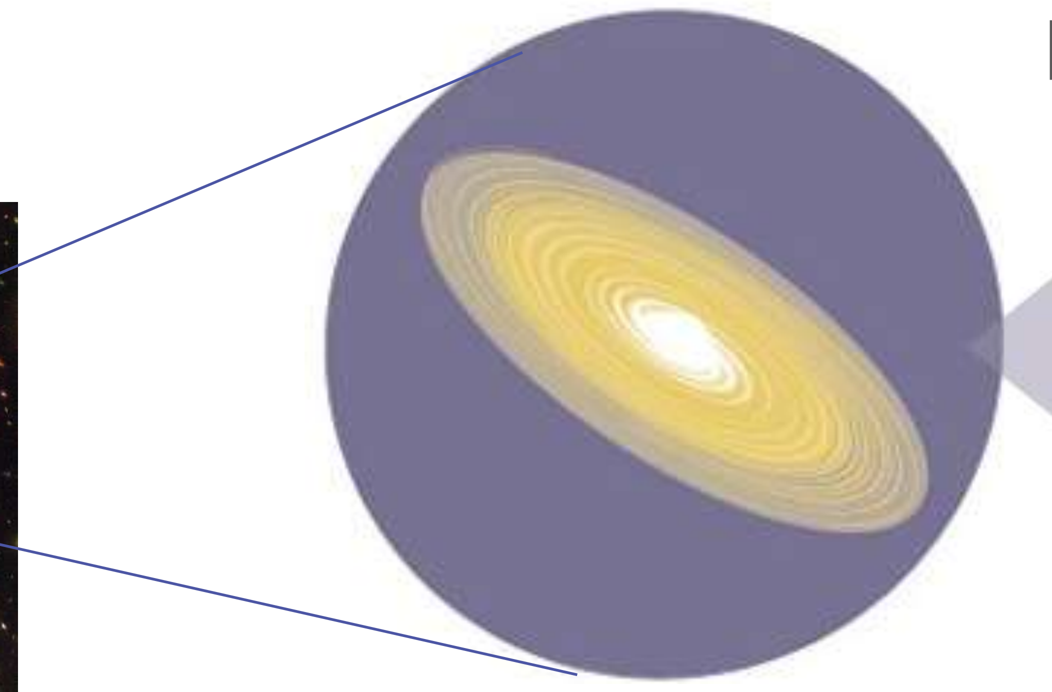
Large scales:
DM behaves like standard particle DM (CDM).



DM: particles
$d \gg \lambda_{dB}$

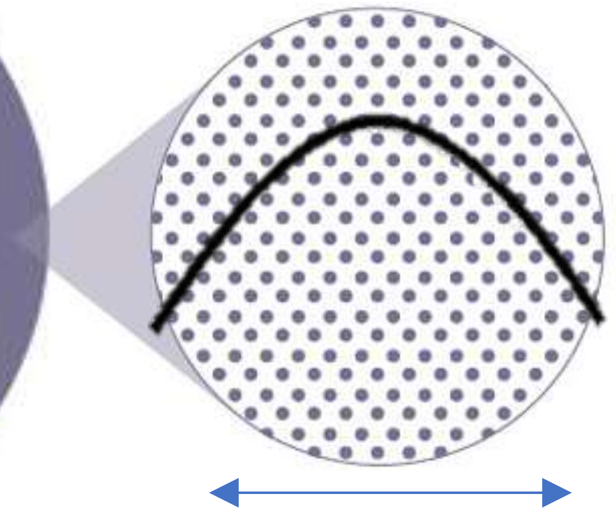


Adapted from Quanta



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

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

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

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

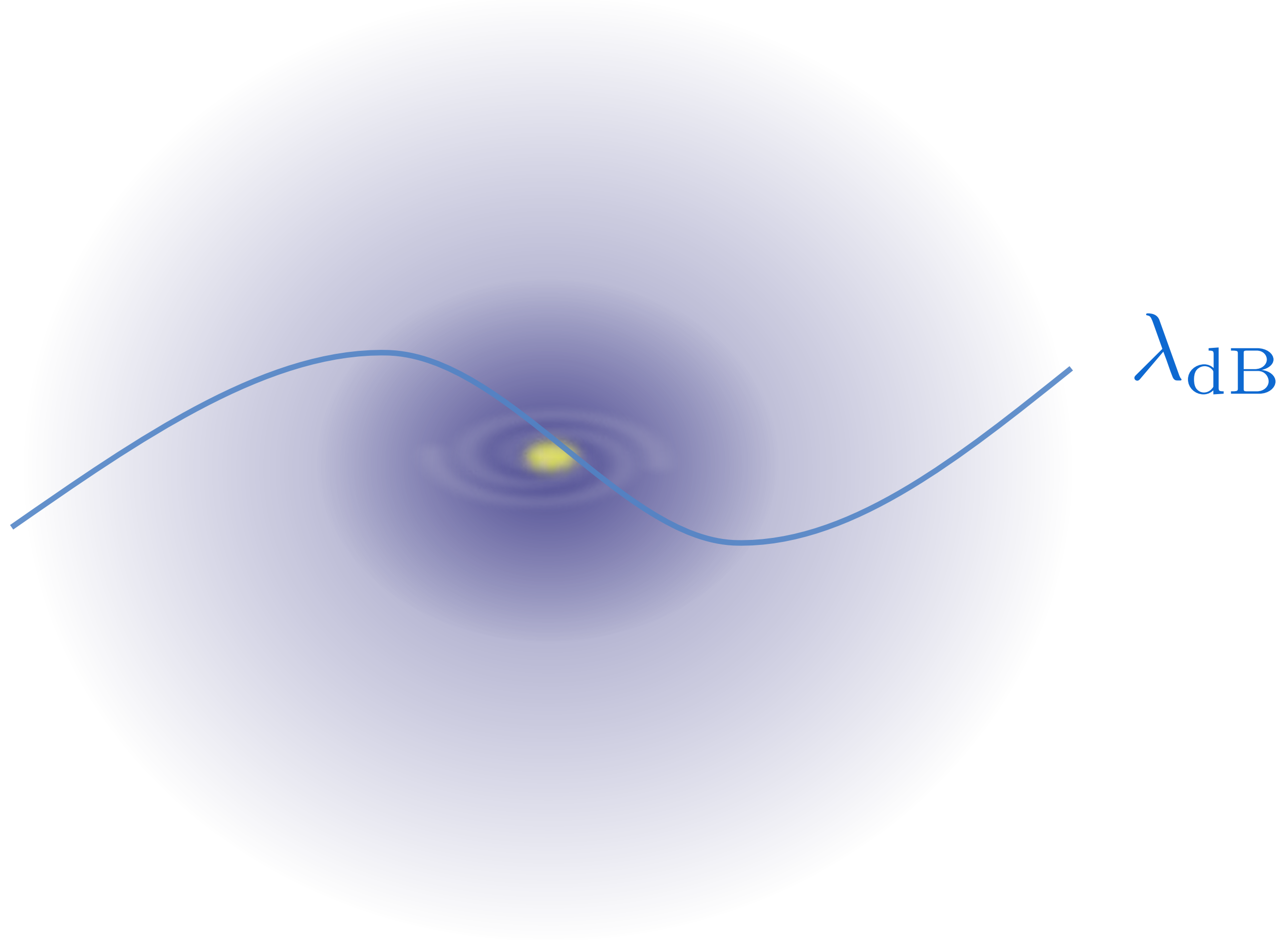
How light is ultra-light?

Behave as wave on galactic scales:

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

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

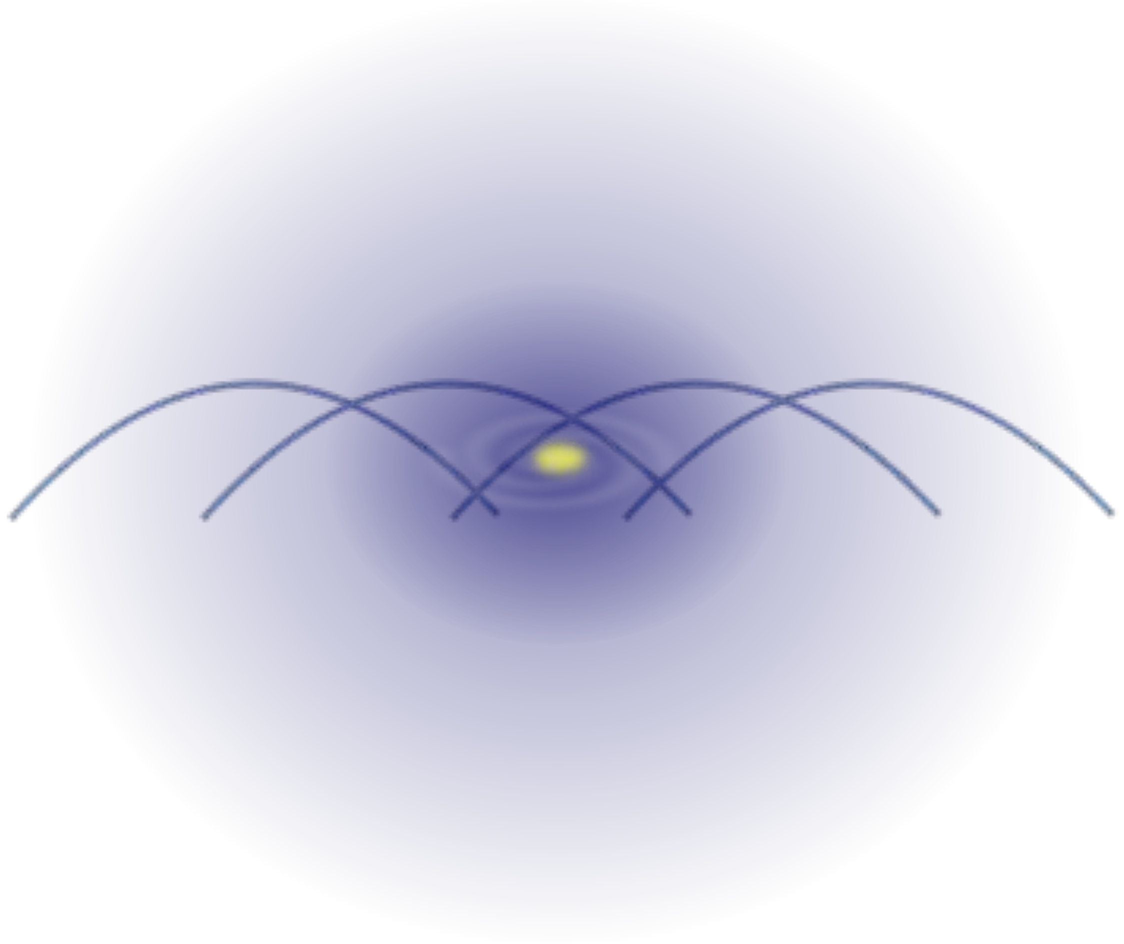
$$\implies \quad m \gtrsim 10^{-25}\,\mathrm{eV}$$



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

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

$$\implies \quad m \leq 2\mathrm{eV}$$



$10^{-60}\,\mathrm{kg}$ $10^{-35}\,\mathrm{kg}$

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

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

Recap

"Light DM" theory

Motivation: particle physics

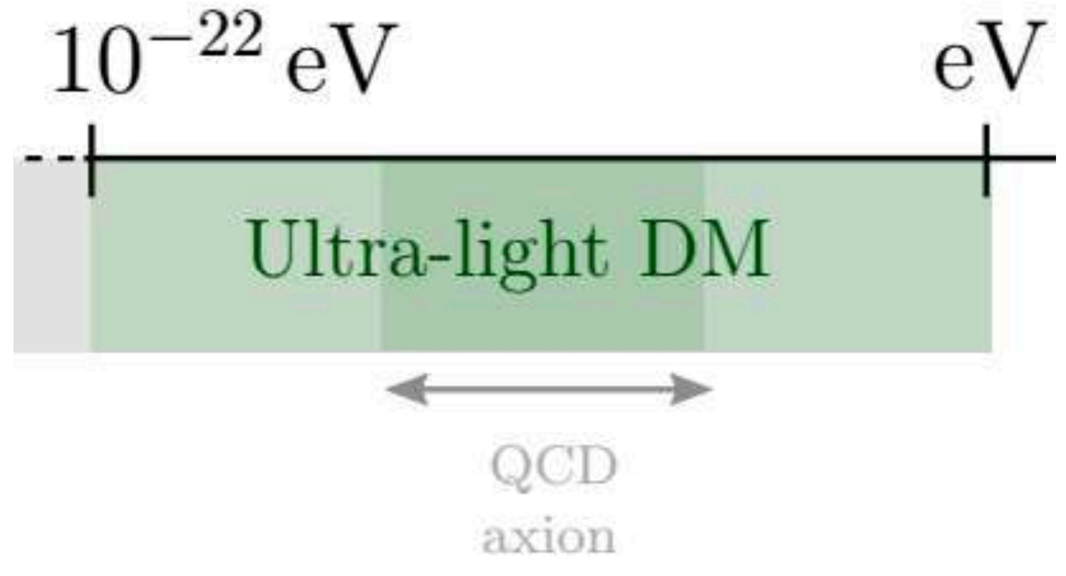
ULDM candidates

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

Known PNGB: QCD axion $\longrightarrow$ 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:

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

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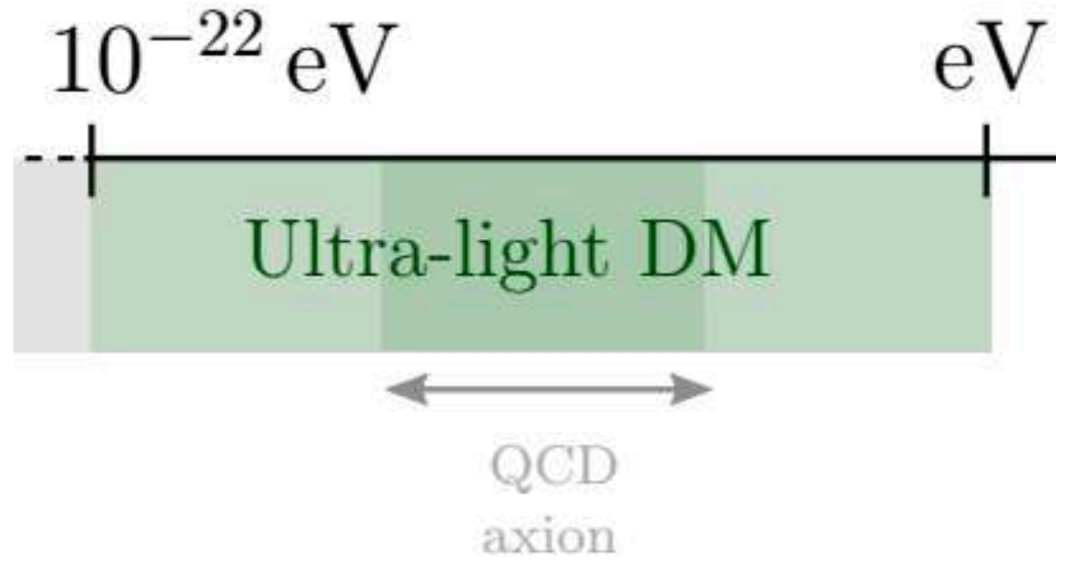
(Peccei and Quinn 1977; Weinberg 1978; Wilczek 1978)



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

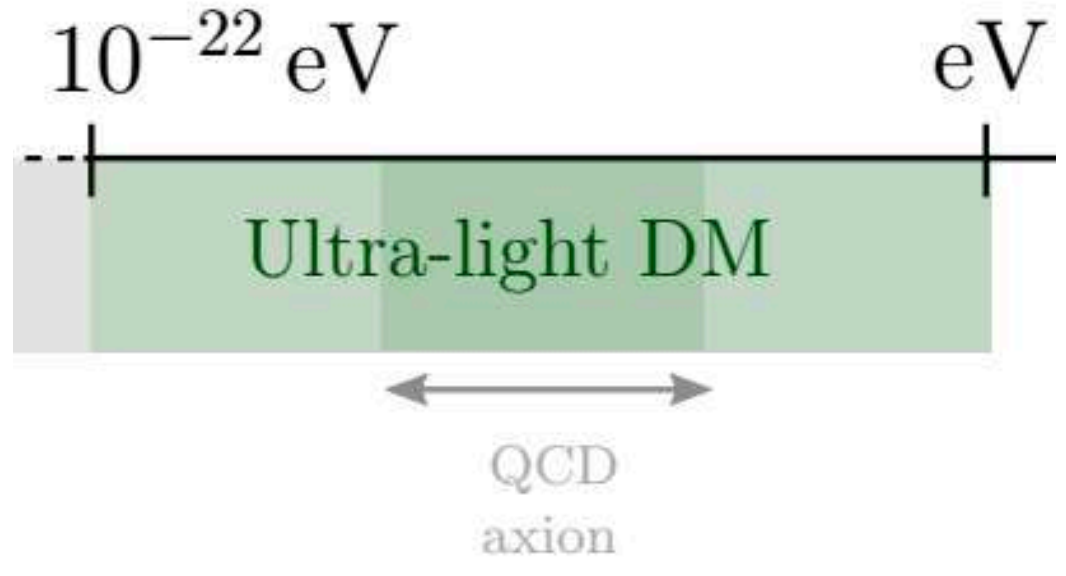
Motivation: particle physics

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)



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

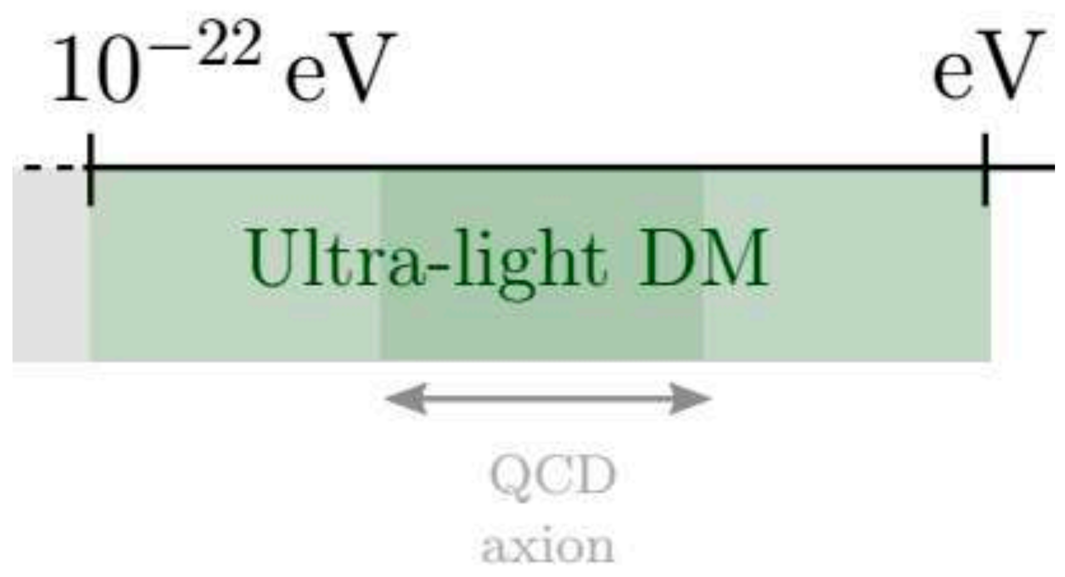
- Formation mechanism: needs to have a relic abundance that gives the correct DM abundance

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

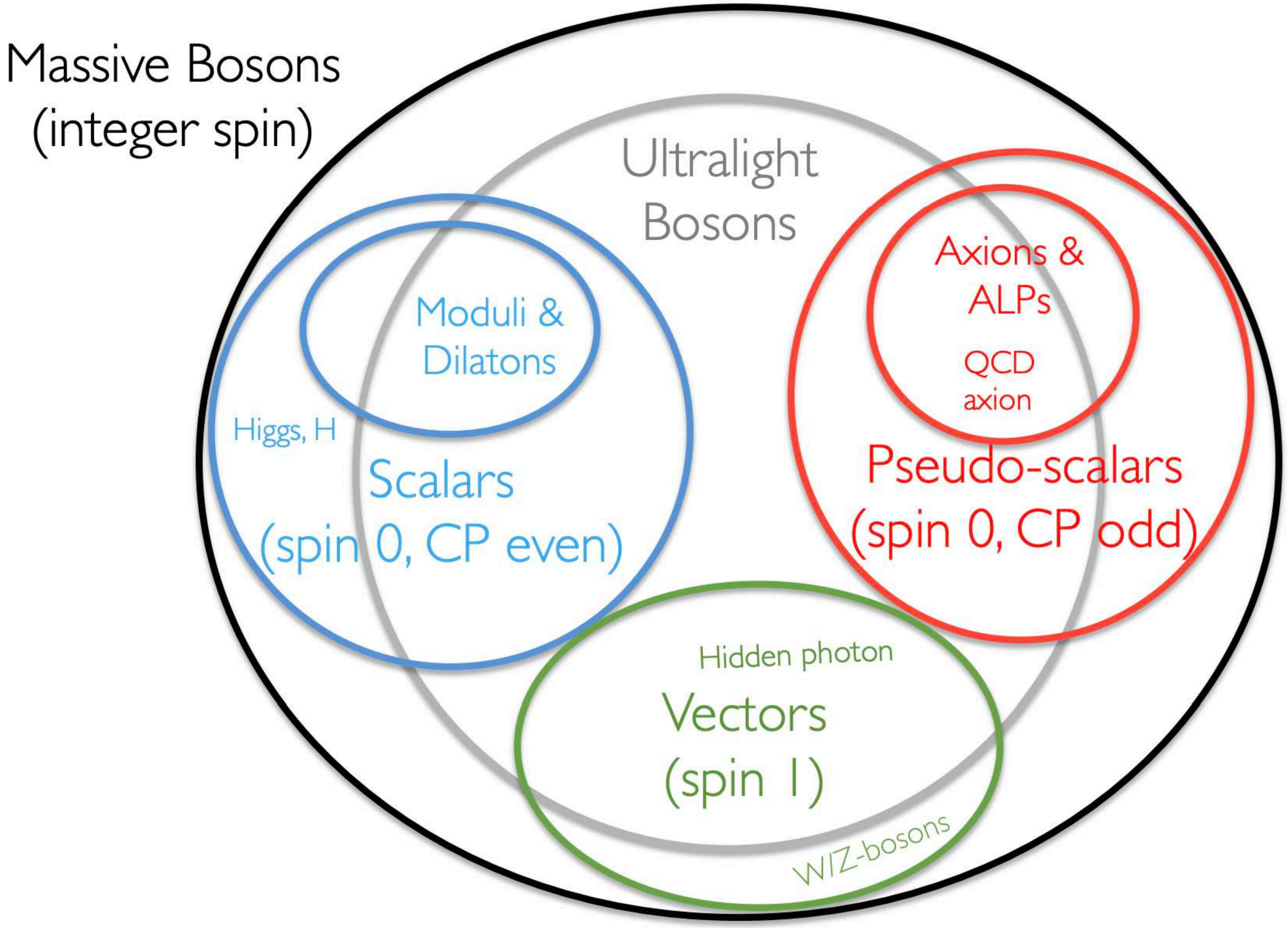
Vector FDM: challenging in the ultra-light regime
(e.g. from misalignment requires non-minimal couplings to Ricci scalar -> viol. of unitarity long. graviton-photon scattering; oscillating Higgs or oscillating misaligned axion - resonant production - choices for couplings for right abundance)
Spin 2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

Motivation: particle physics

ULDM candidates

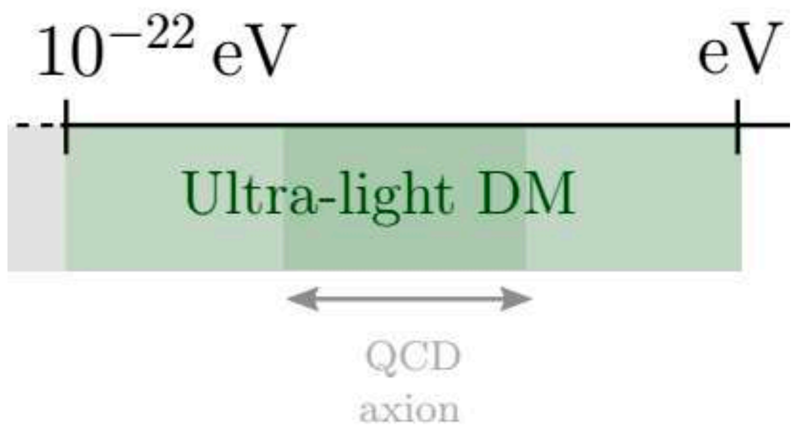


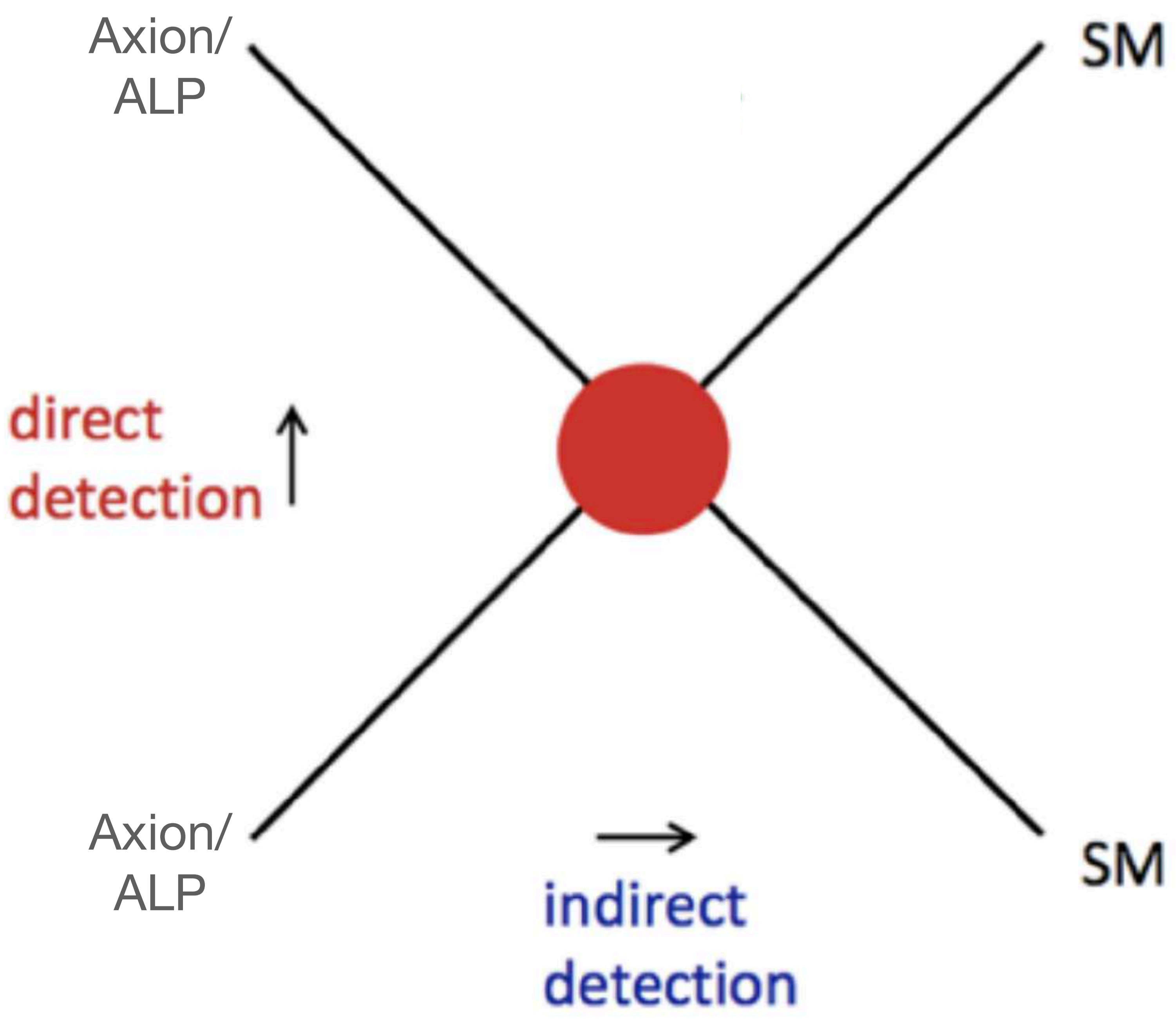
Many extensions of the Standard Model predict additional massive bosons



Ref.: Chadha-Day et al 2022

How to search for ULDM?

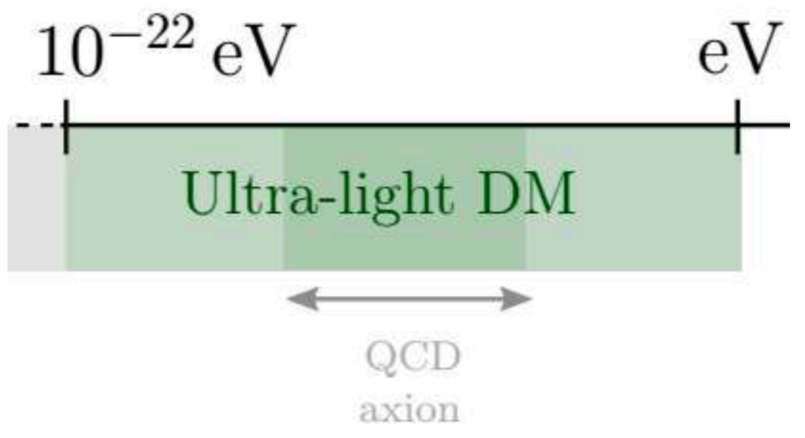




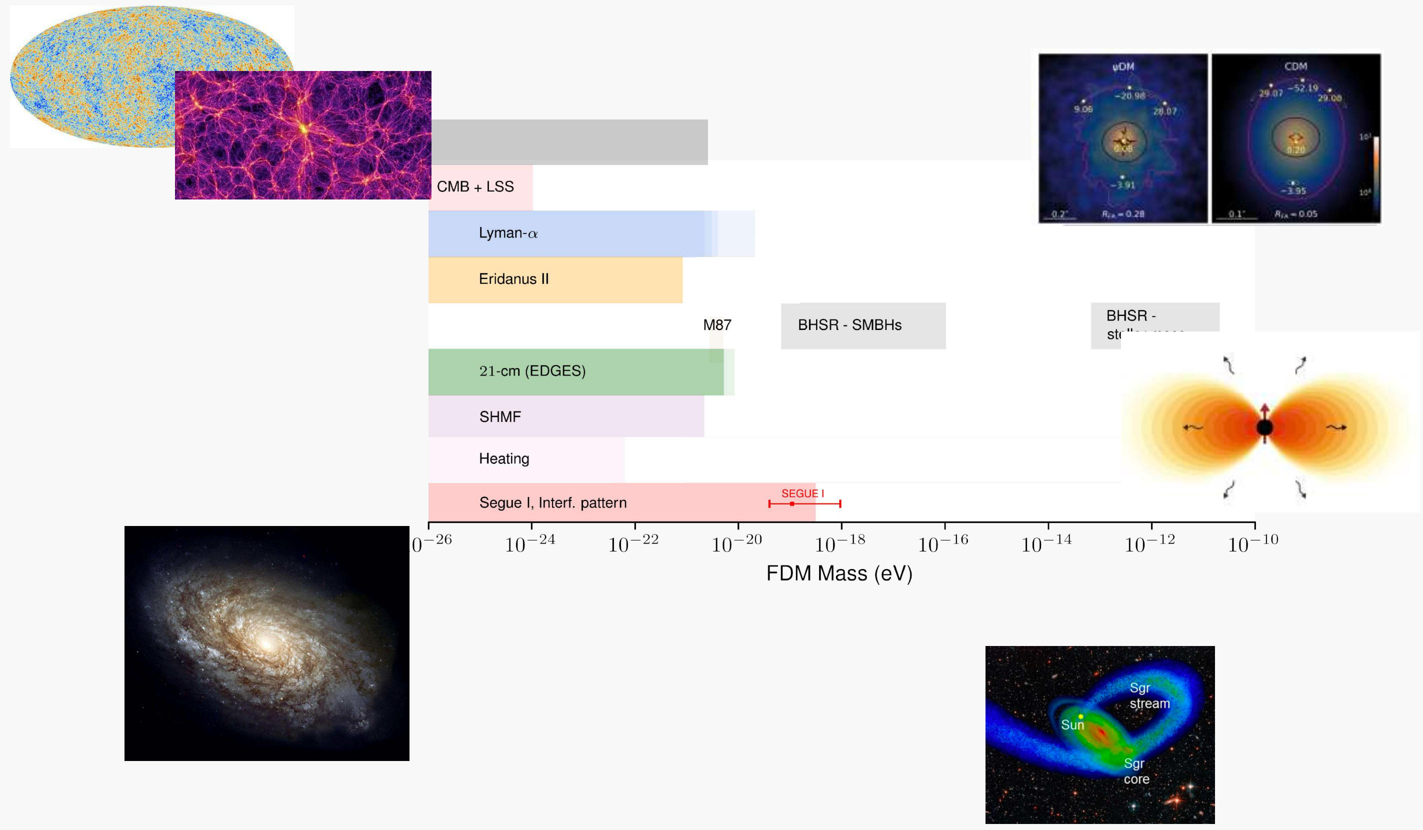
+

Gravitationally
Cosmological and astrophysical searches

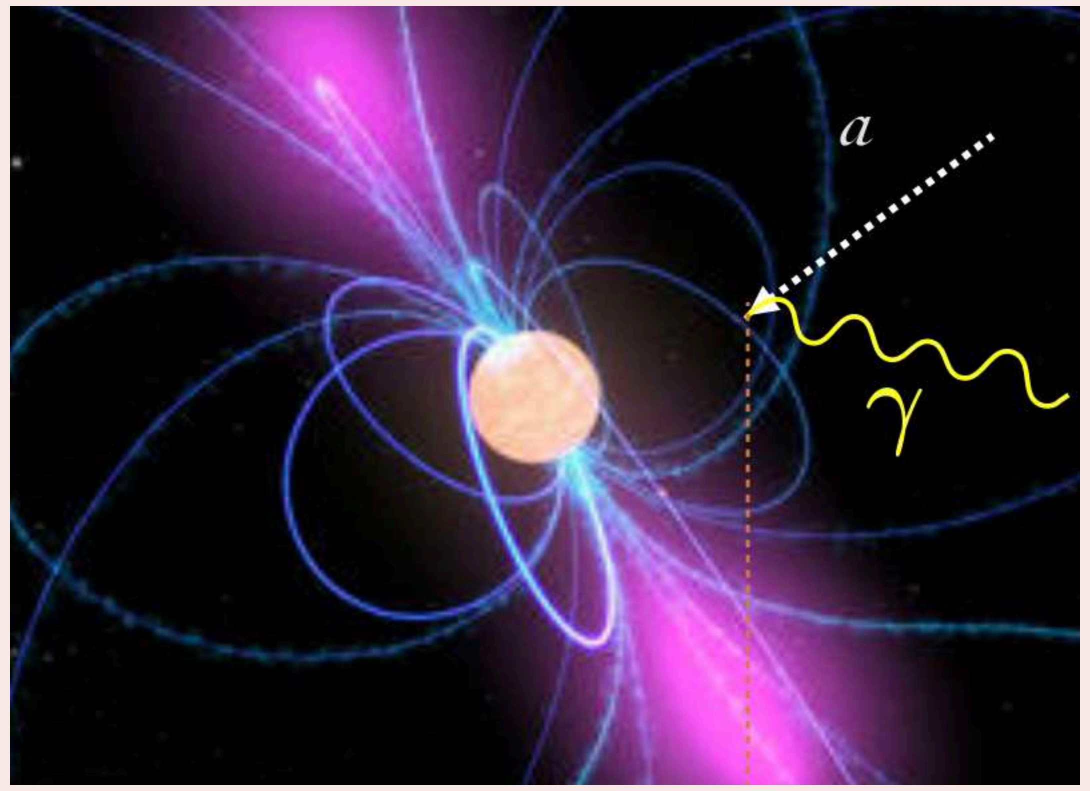
How to search for axions/ALPs?



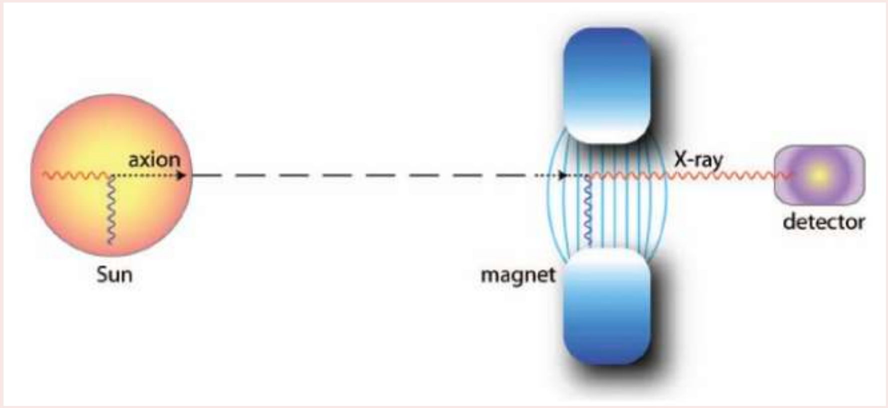
Cosmological and astrophysical searches

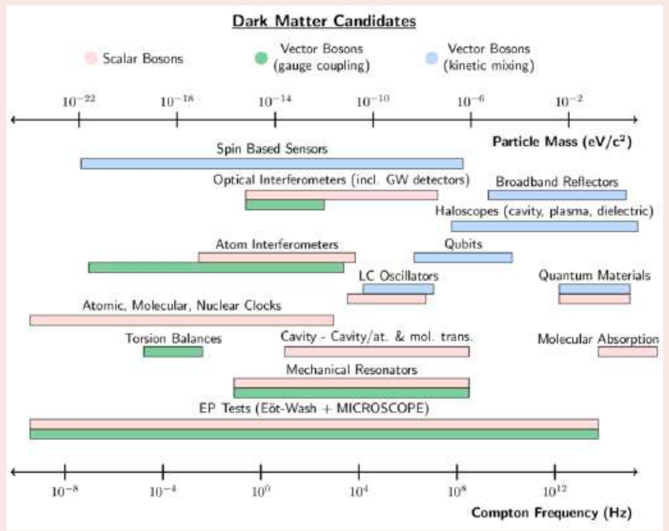


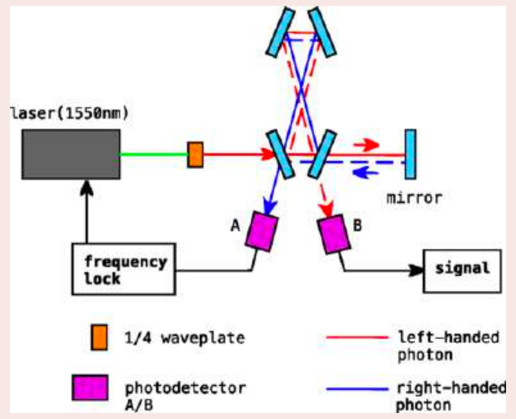
Indirect detection



"Direct detection" Axion/ALPs experiments

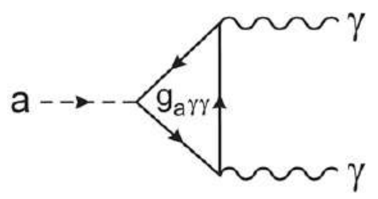


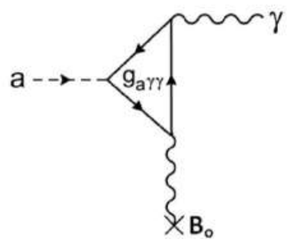




Gravitational

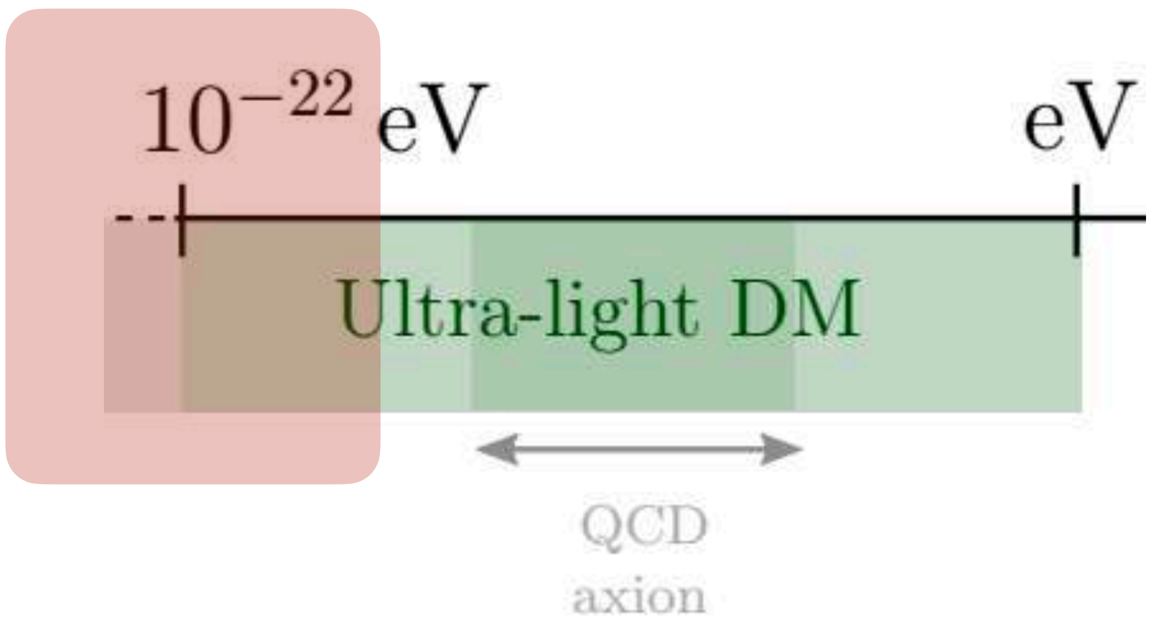
Interactions with the SM



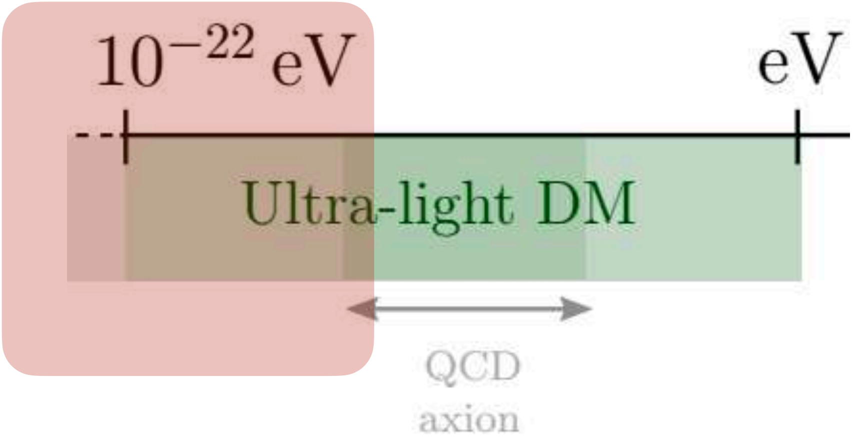


Gravitational signatures

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)

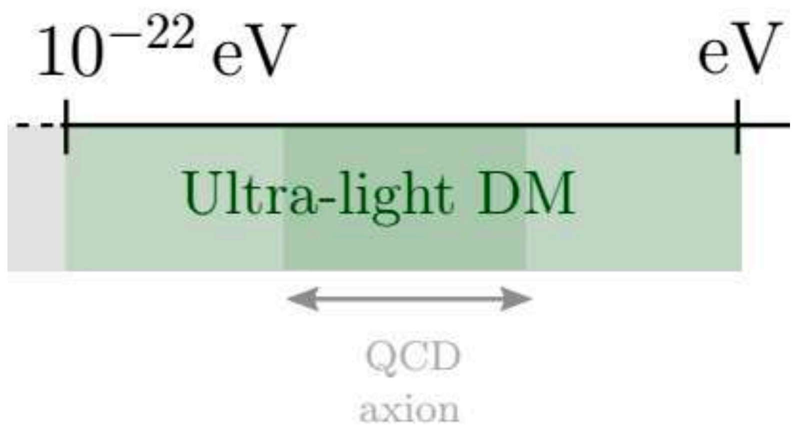
$$i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{g}{8m^2}|\psi|^2 - m\Phi\right)\psi$$

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

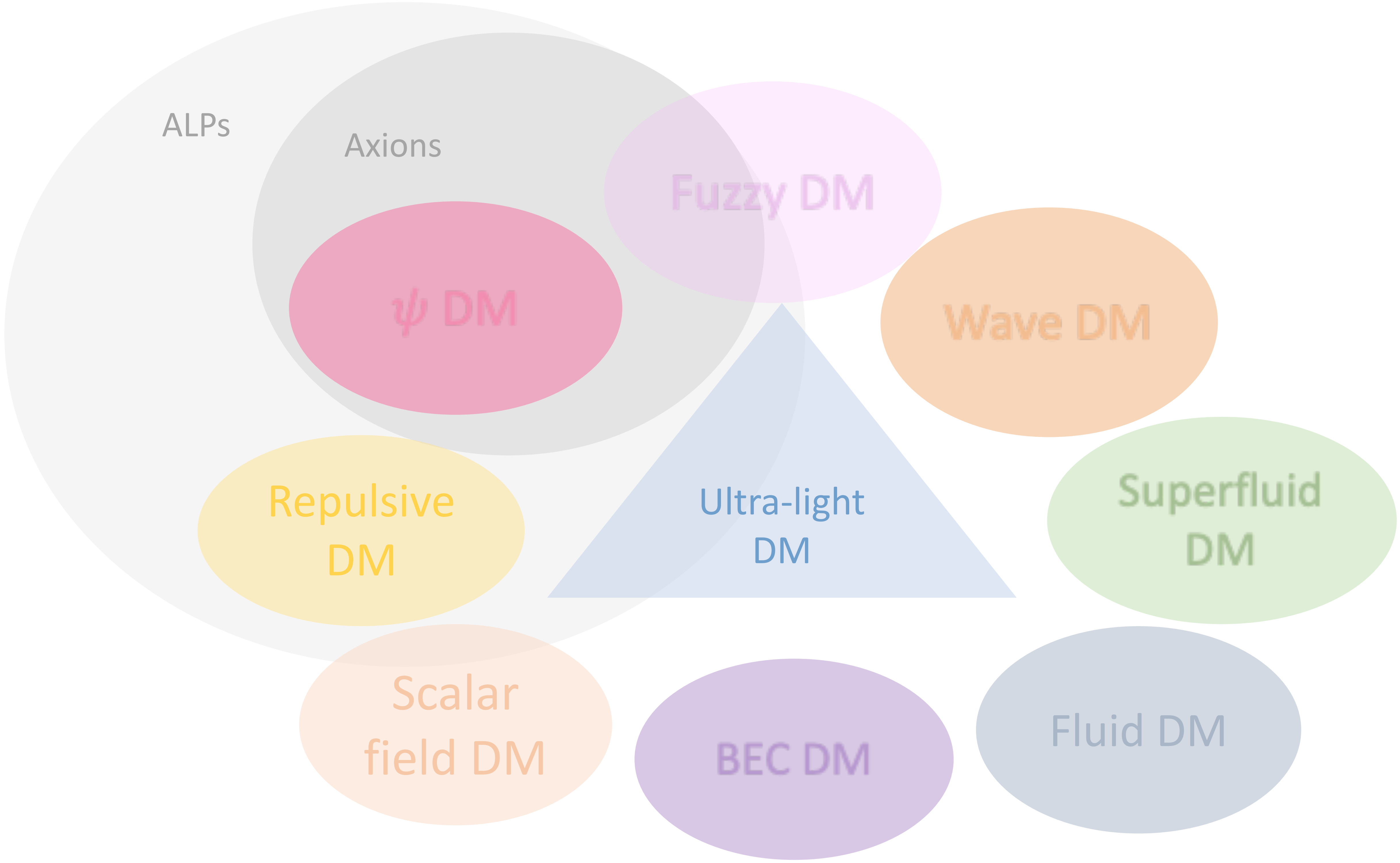
$\longrightarrow$ Connection with condensed matter and particle physics!

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

Ultra-light Dark Matter - models

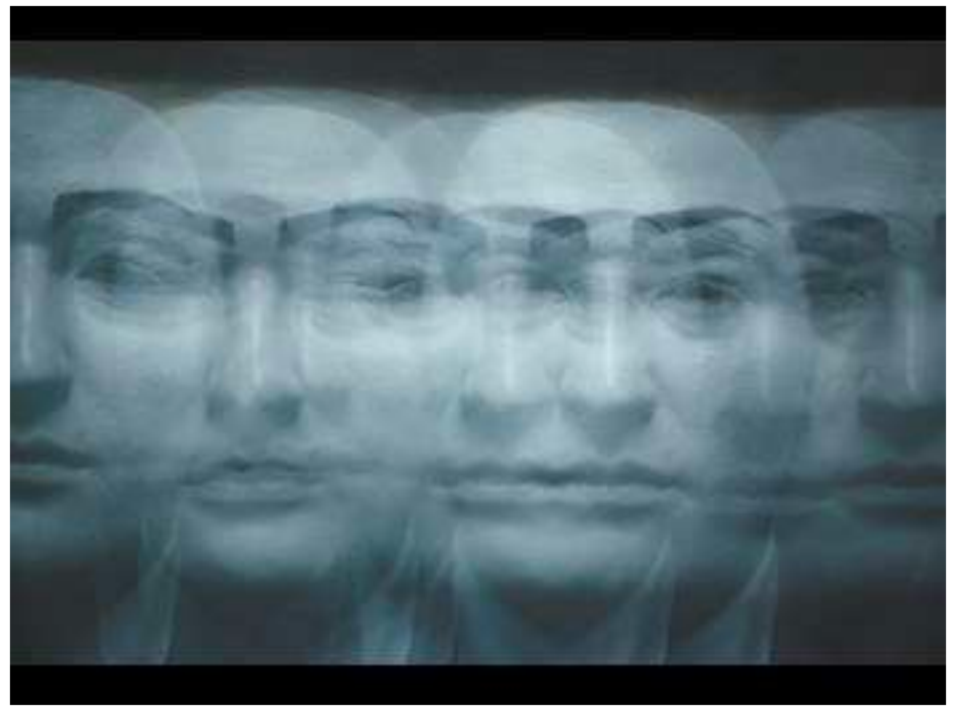


There are many ways to have a DM with this property → many ULDM models in the literature
However, each of these models presents a different dynamics on small scales - different phenomenology

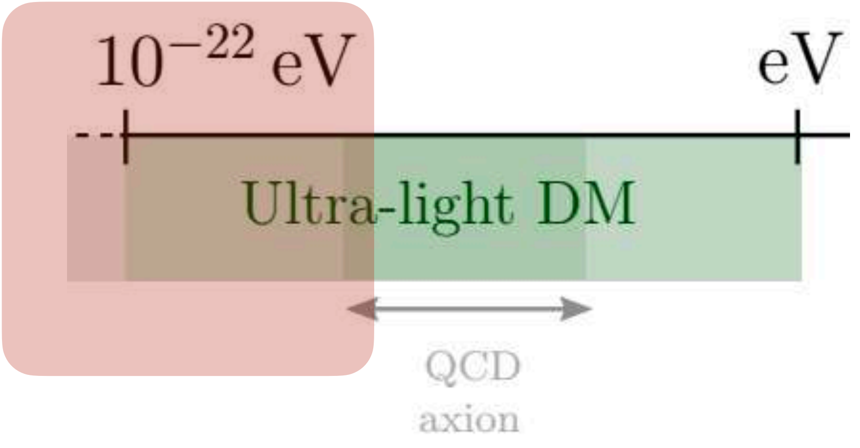


Fuzzy dark matter

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)

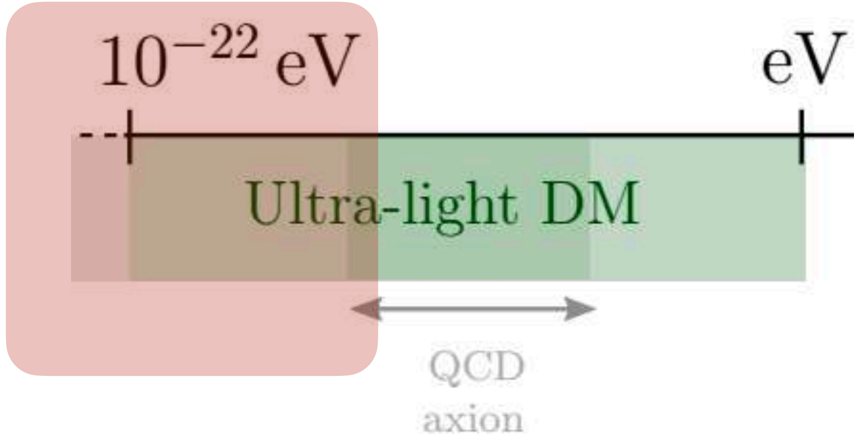
(Reviews: EF (2021), J. Niemeyer (2019), L. Hui (2021))

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!

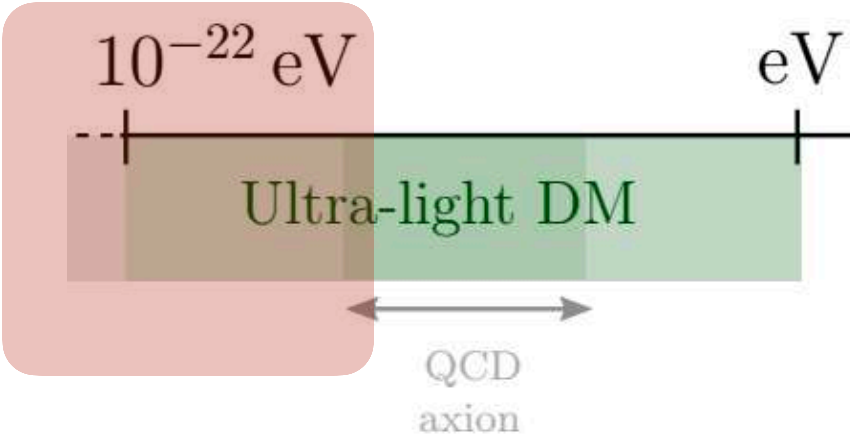
(Some of the grav. phenom. is carried for vectors, for example)

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

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

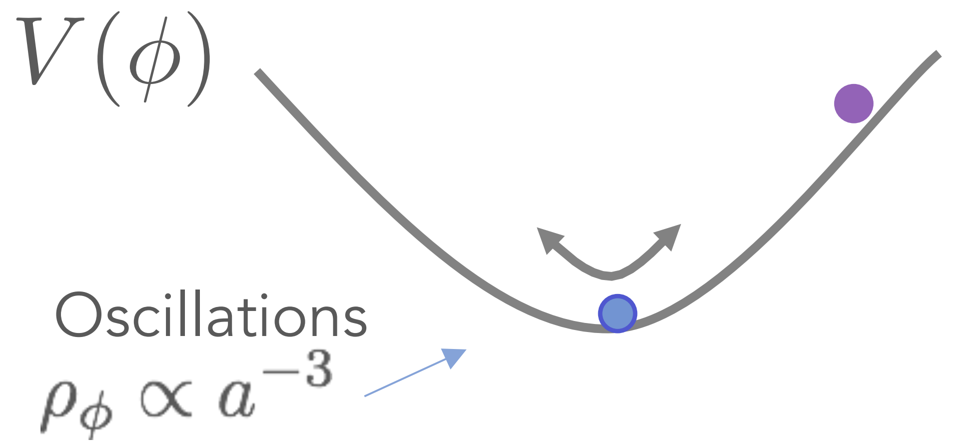
(Reviews: *EF (2021), J. Niemeyer (2019), L. Hui (2021)*)

Cosmological evolution

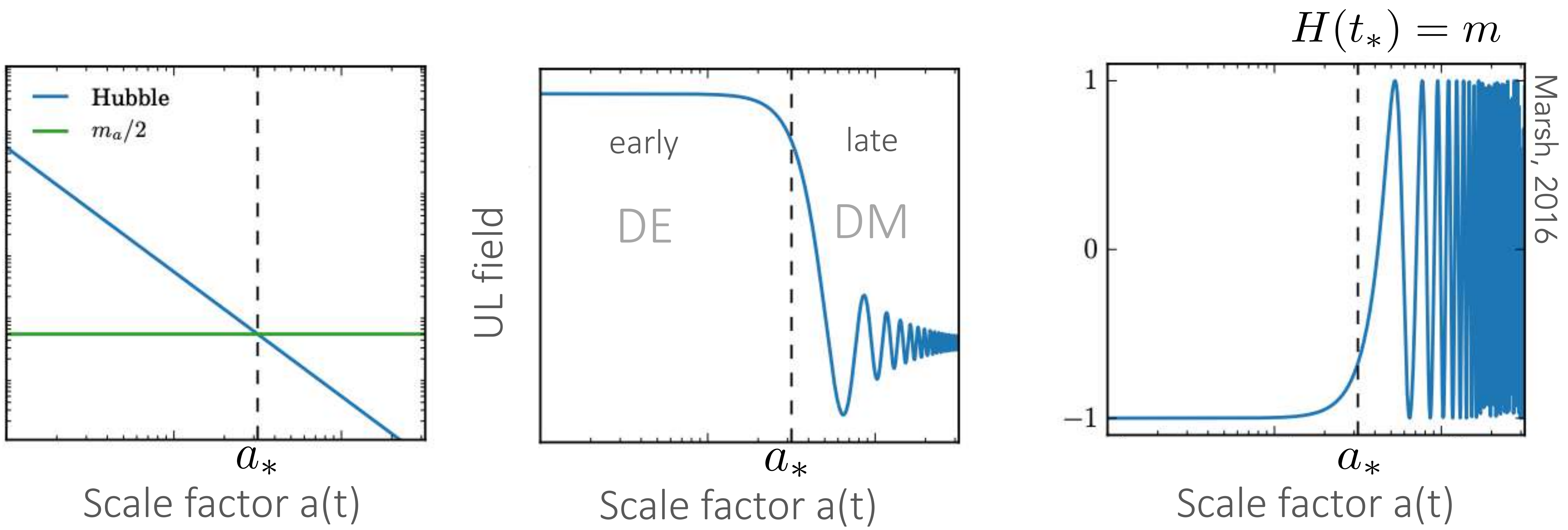


$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

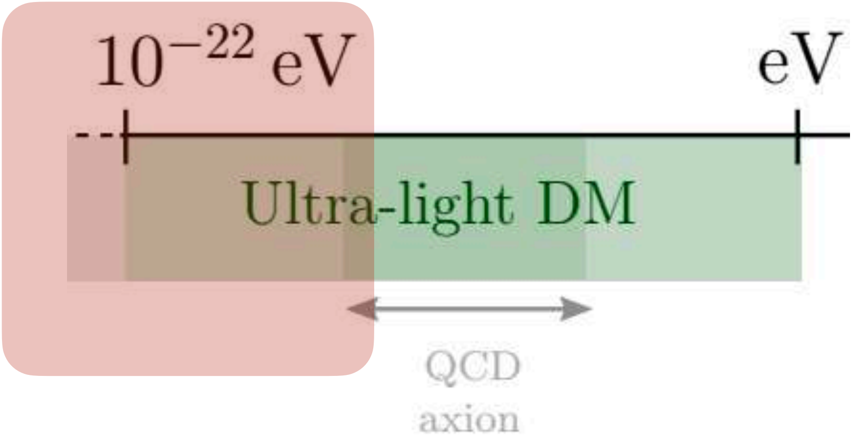
FDM



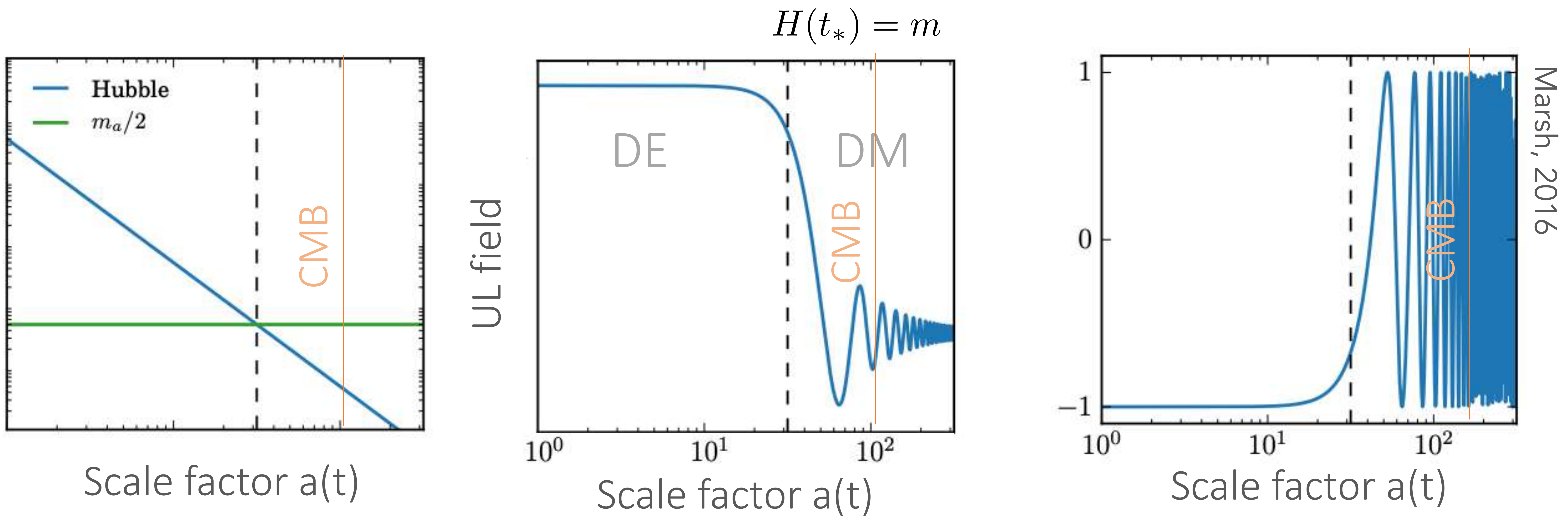
$$\begin{cases} H \gg m \implies \phi_{\text{early}} = \phi(t_i) \longrightarrow \omega = -1 & \text{DE} \\ H \ll m \implies \phi_{\text{late}} \propto e^{imt} \longrightarrow \langle\omega\rangle = 0 & \text{DM} \end{cases}$$



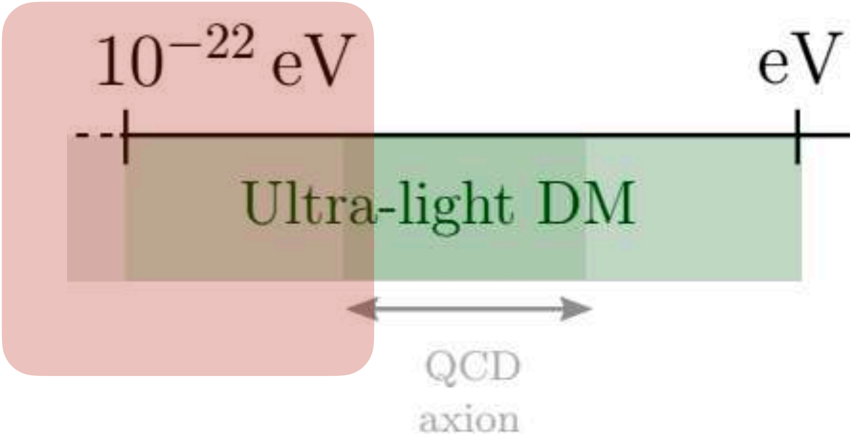
Cosmological evolution



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.

Schrödinger-Poisson system : describe the FDM and the SIFDM

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

Schrödinger equation (Gross-Pitaevskii)

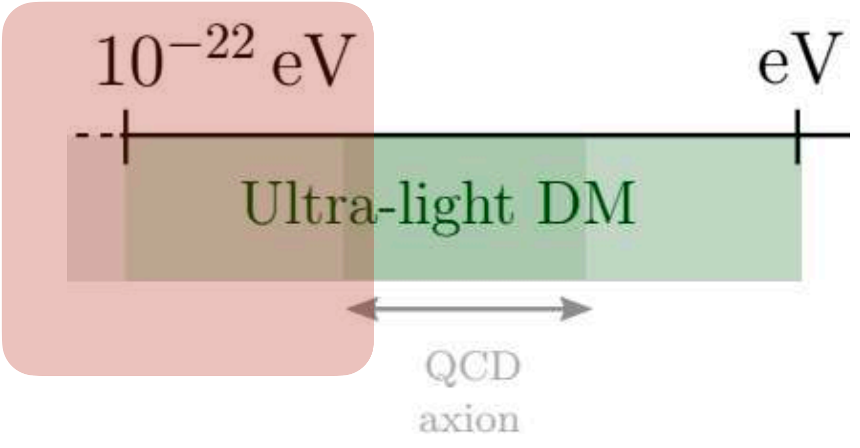
Poisson equation

$g = 0 \longrightarrow$ FDM

$g \neq 0 \longrightarrow$ SIFDM

Fundamentally different than CDM/WDM/SIDM!

Structure formation - non-relativistic regime



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Schrödinger equation (Gross-Pitaevskii)

Poisson equation

$g = 0 \longrightarrow$ FDM

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Fundamentally different than CDM/WDM/SIDM!

<u>Madelung equations</u> $\left(\psi \equiv \sqrt{\rho/m}\, e^{i\theta}\right.$ and $\left.\mathbf{v} \equiv \nabla\theta/m\right)$

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

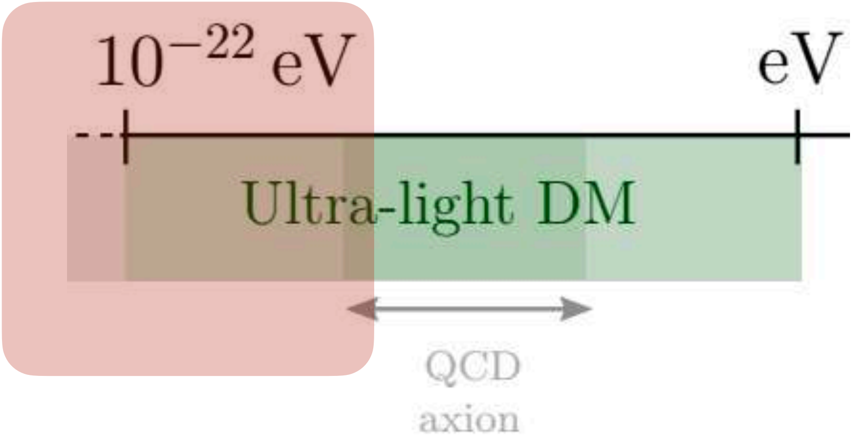
$$\dot{\rho} + \nabla\cdot(\rho\,\mathbf{v}) = 0$$

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

$\longrightarrow$ Quantum pressure

FLUID DESCRIPTION

Structure formation - non-relativistic regime



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

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$g \neq 0 \longrightarrow$ SIFDM

$$\nabla^2\Phi = 4\pi G(m|\psi|^2 - \bar{\rho})$$

Poisson equation

Fundamentally different than CDM/WDM/SIDM!

HOMEWORK

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

From the relativistic action of a scalar field in FRW

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

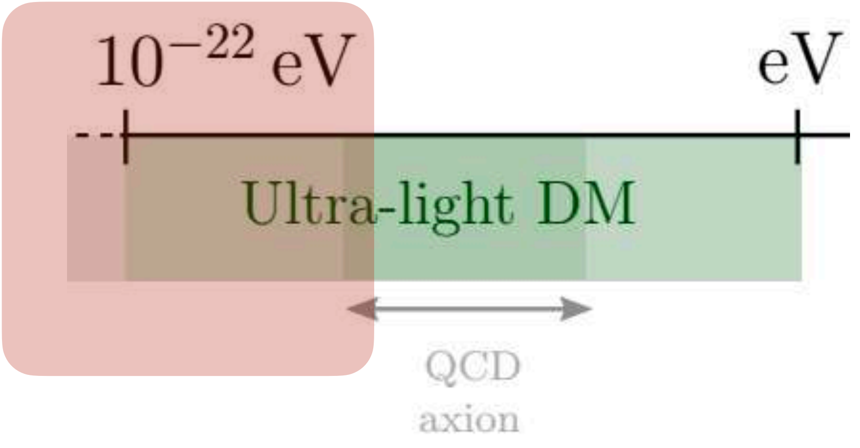
Write the perturbed equation in Newtonian gauge

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

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

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

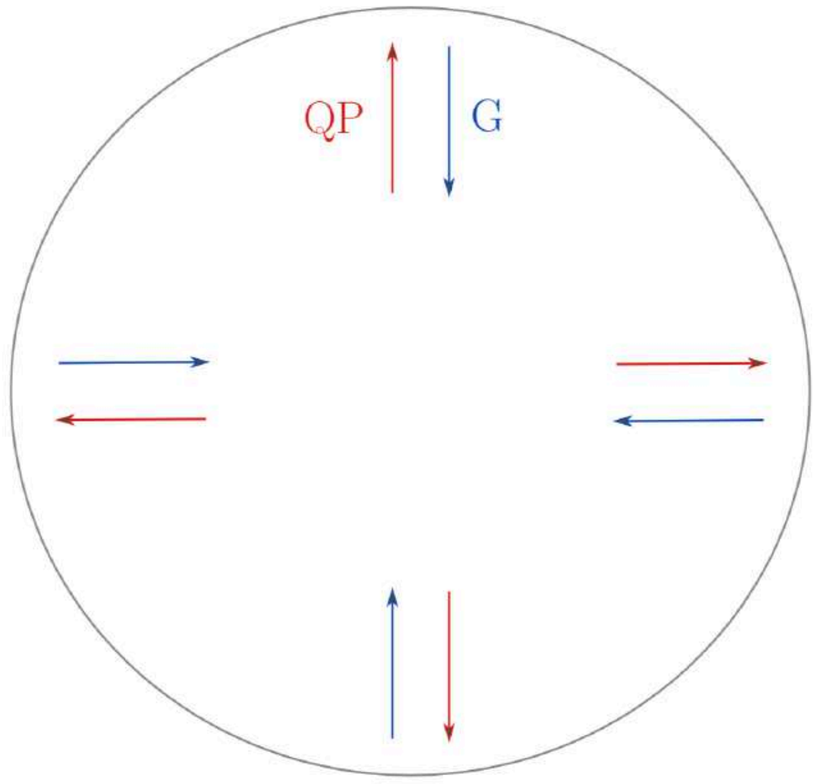
Structure formation - perturbation and stability



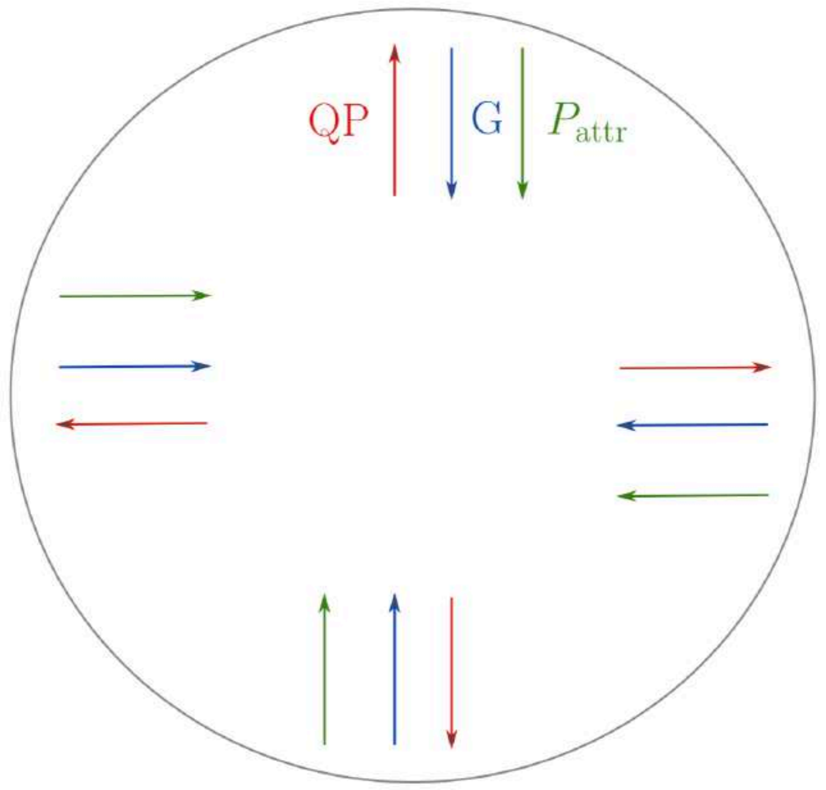
Competition between gravity and pressure (quantum pressure and interaction)

SIFDM

FDM

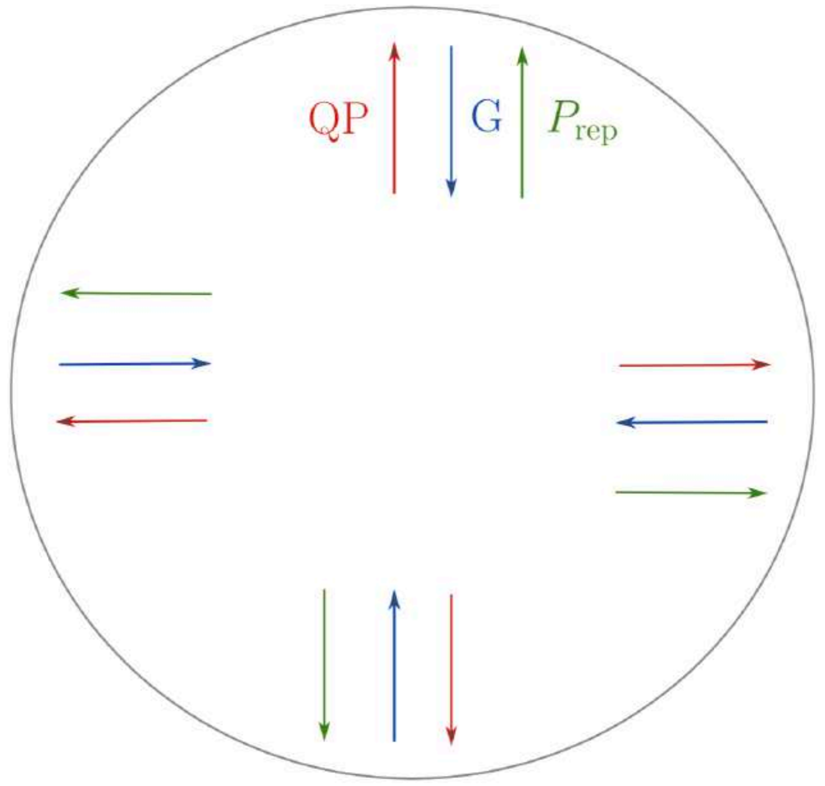


ATTRACTIVE



$g < 0$

REPULSIVE



$g > 0$

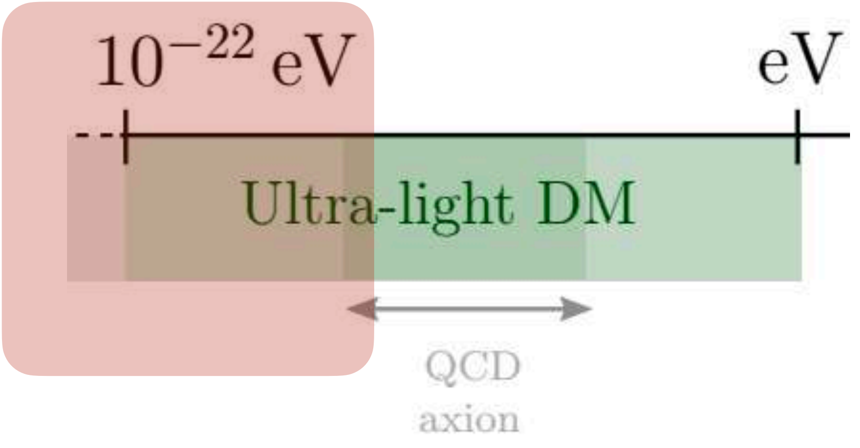
$$\dot{\rho} + \nabla \cdot (\rho\, \mathbf{v}) = 0$$

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

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

Quantum pressure

Structure formation - perturbation and stability

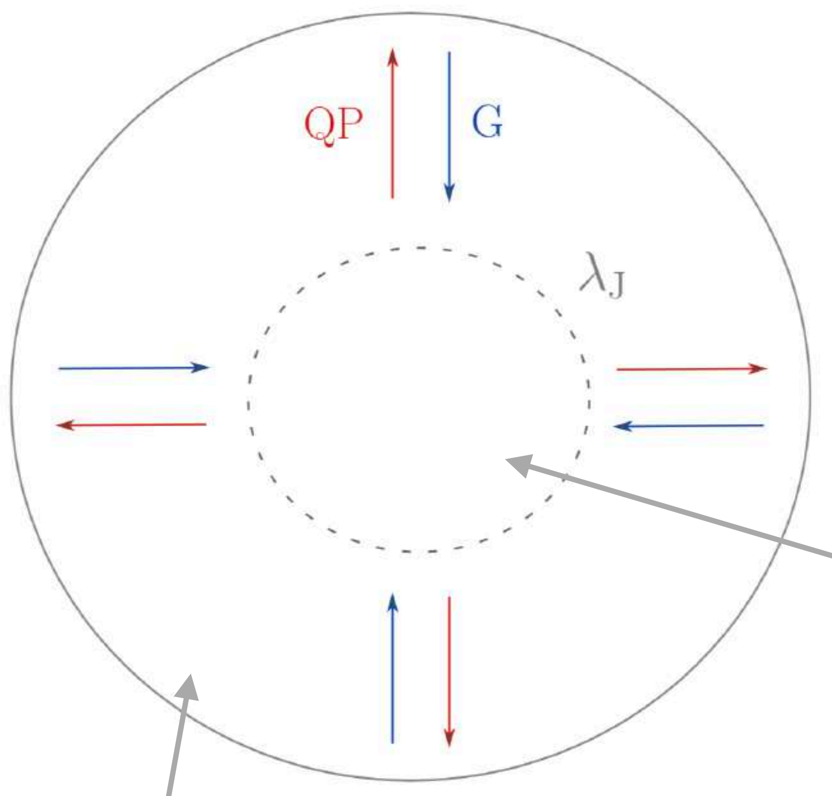


Finite clustering scale (Jeans length)- no structure formation on small scales

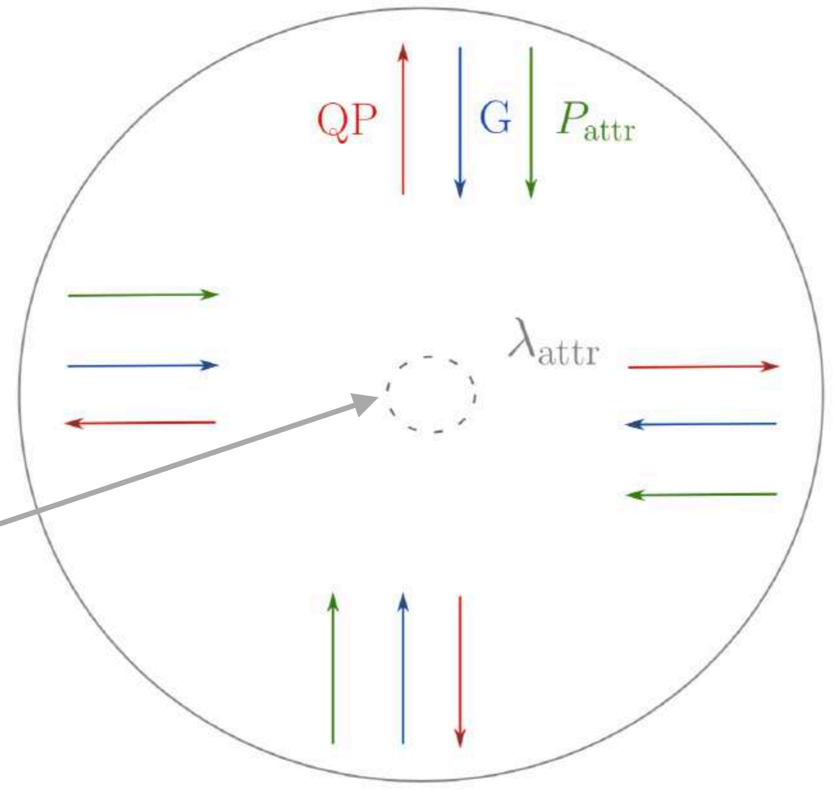
(CDM, λ_J effectively zero)

SIFDM

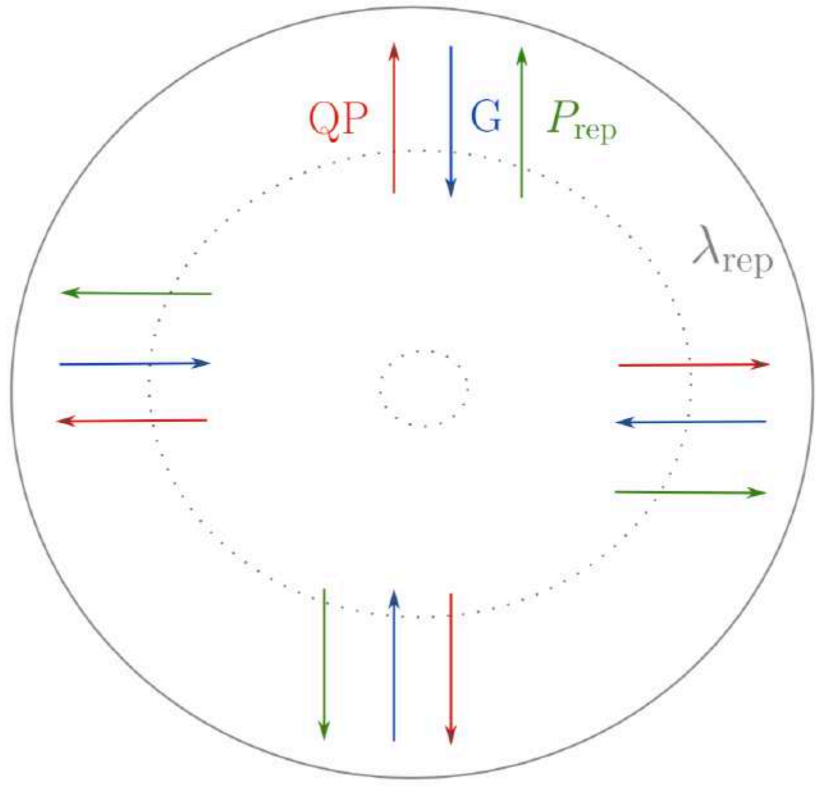
FDM



ATTRACTIVE



REPULSIVE



QP dominates -
Stable solution
NO structure formation

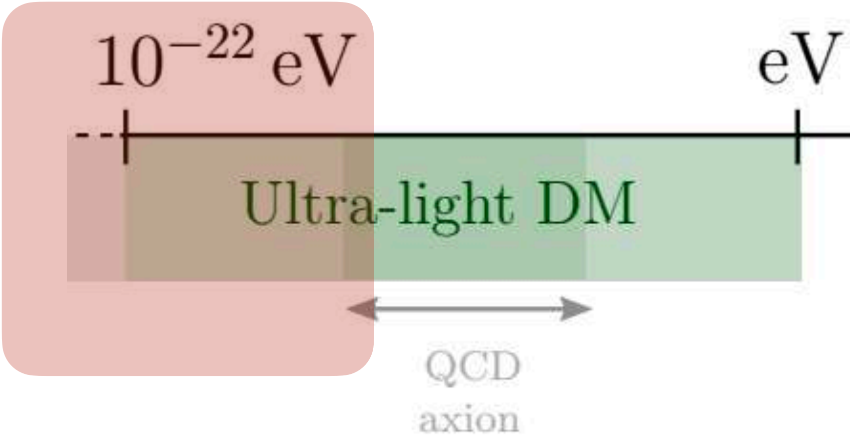
$\lambda < \lambda_J, \lambda_{attr}, \lambda_{rep}$

$g < 0$

$g > 0$

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

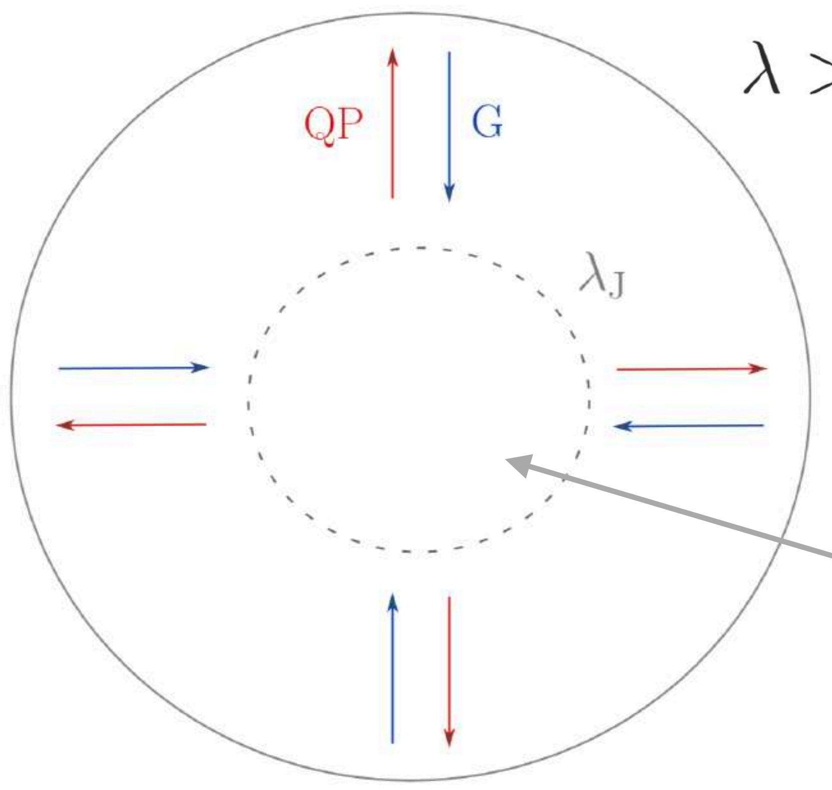
Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

SIFDM

FDM

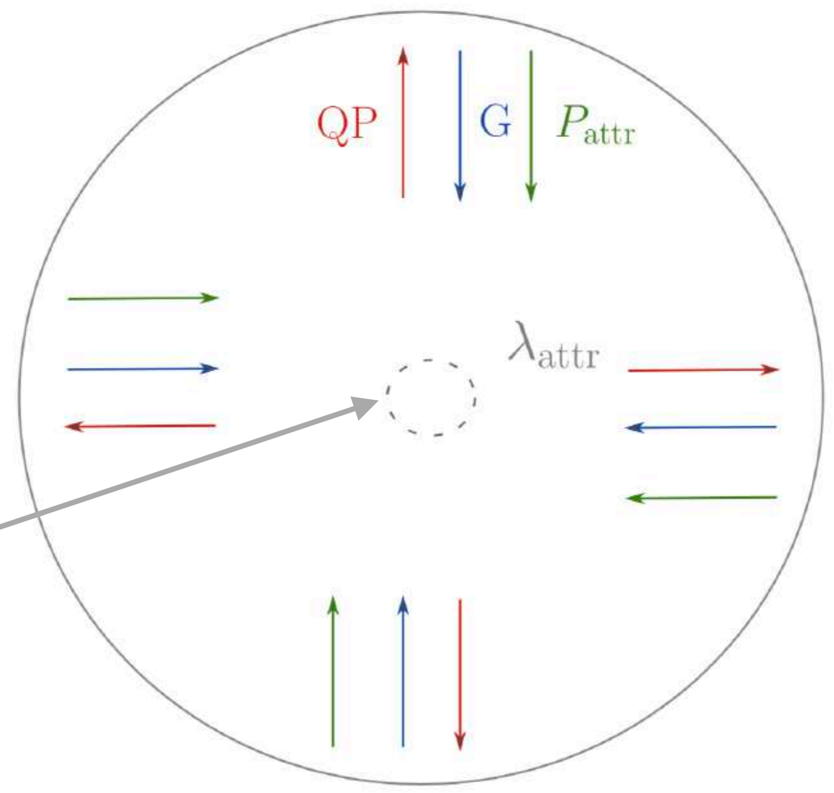


$\lambda > \lambda_J, \lambda_{attr}, \lambda_{rep} \quad \longrightarrow \quad$ CDM

QP dominates -
NO structure formation

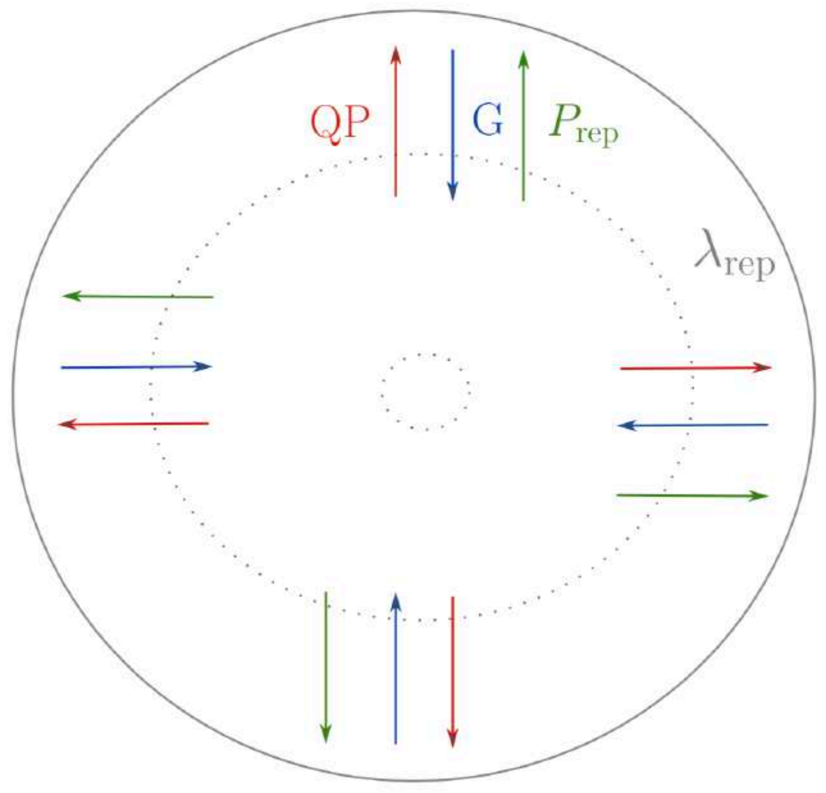
$\lambda < \lambda_J, \lambda_{attr}, \lambda_{rep}$

ATTRACTIVE



$g < 0$

REPULSIVE



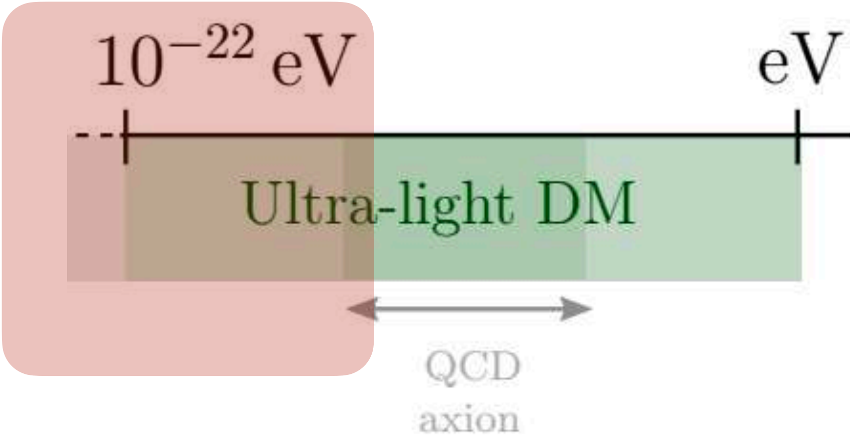
$g > 0$

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



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

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

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

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

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

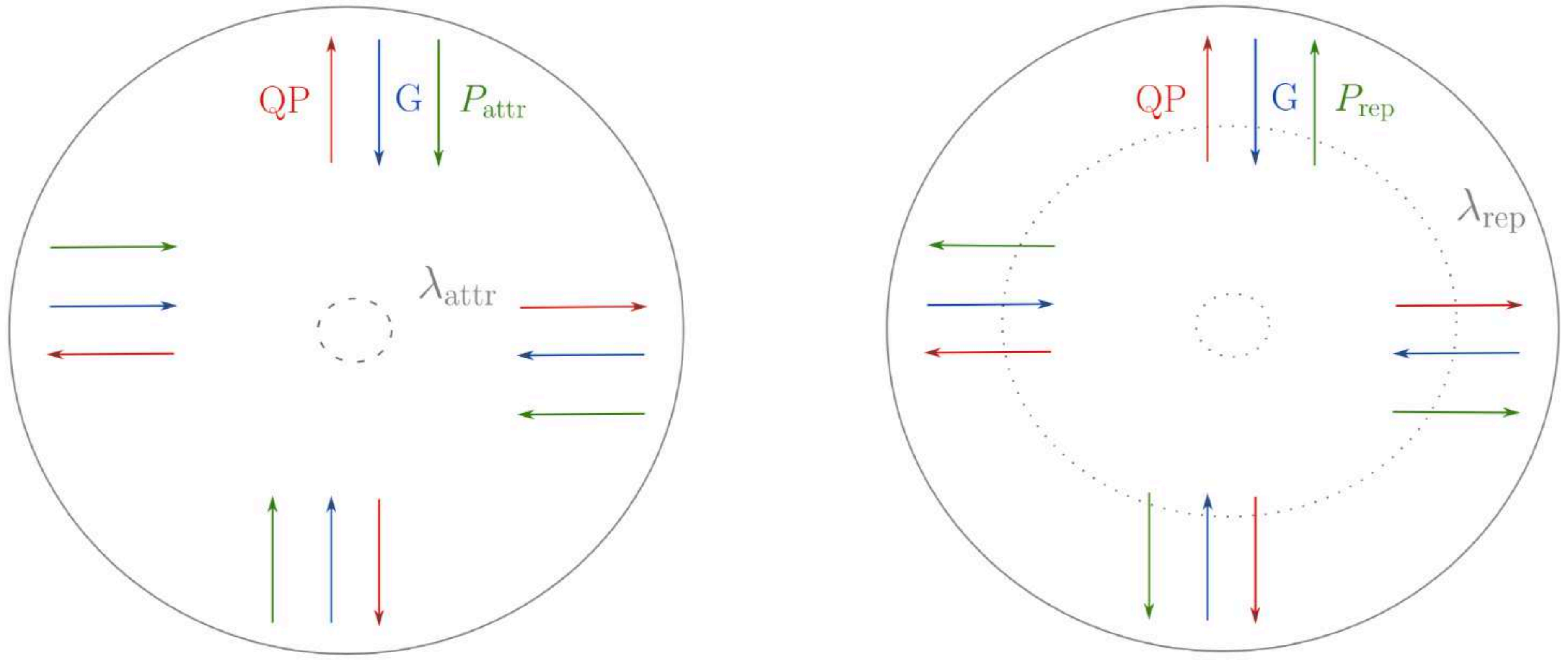
Rewriting $\delta\Psi$ as $\Psi = A + iB$

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

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

SIFDM

ATTRACTIVE REPULSIVE



$g < 0$ $g > 0$

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

Solution:

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

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

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:

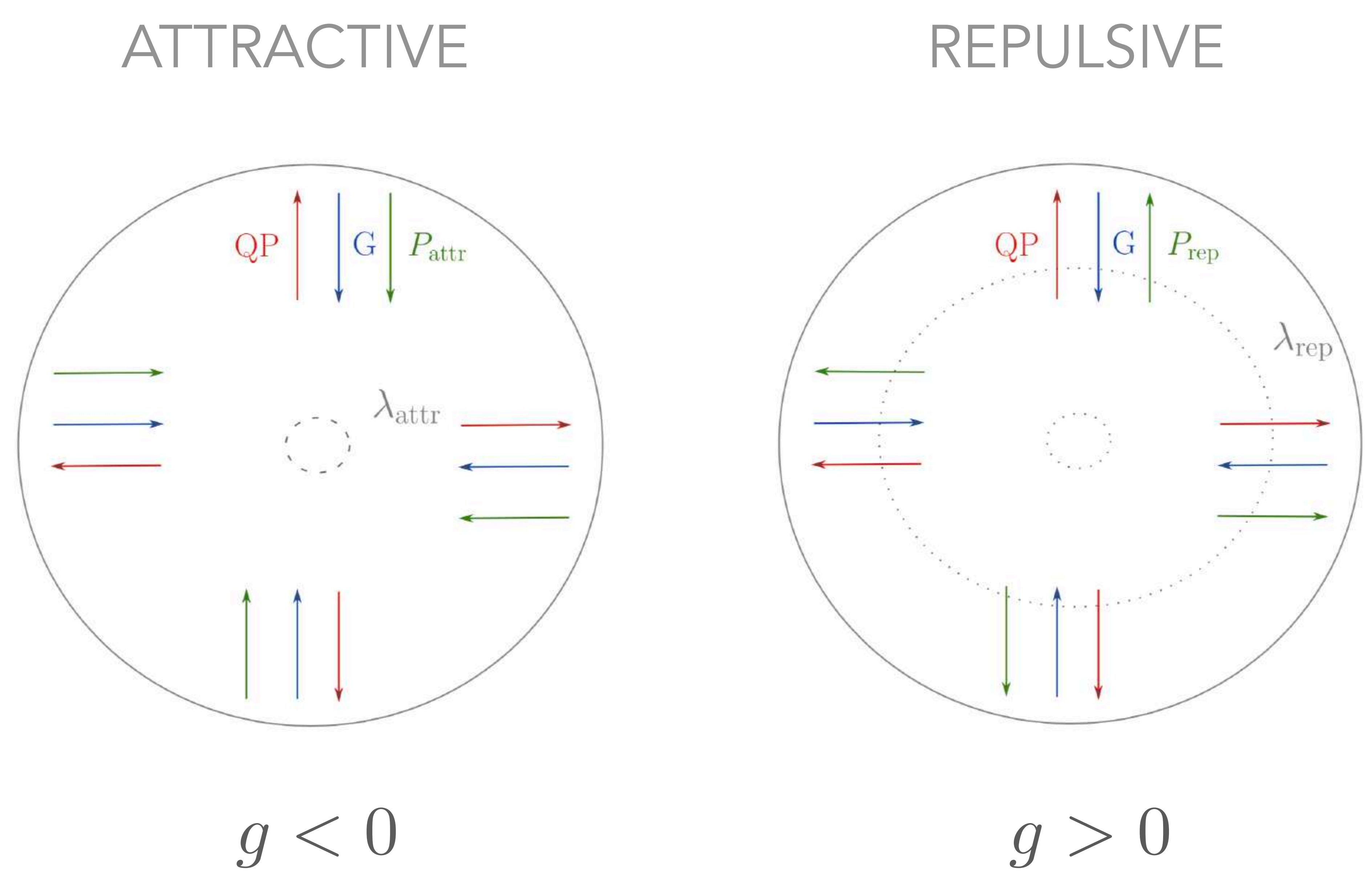
$$i\dot{\psi}_c = \frac{g}{8m^2}|\psi_0|^2\psi_c$$

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

Perturbations:

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

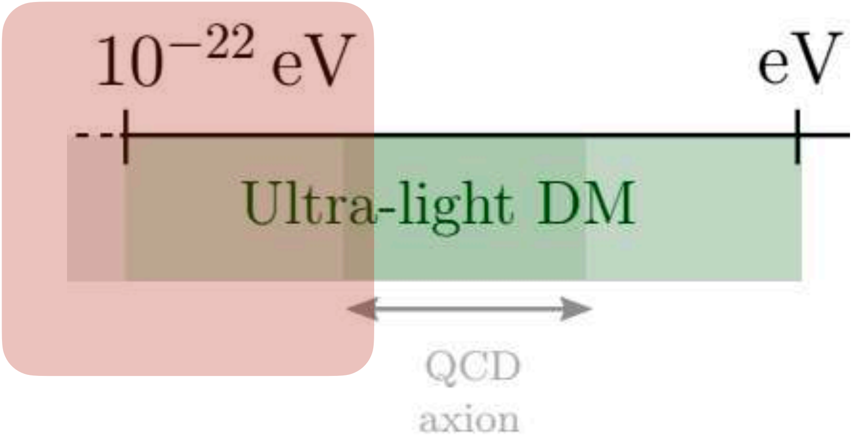
SIFDM



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

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

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

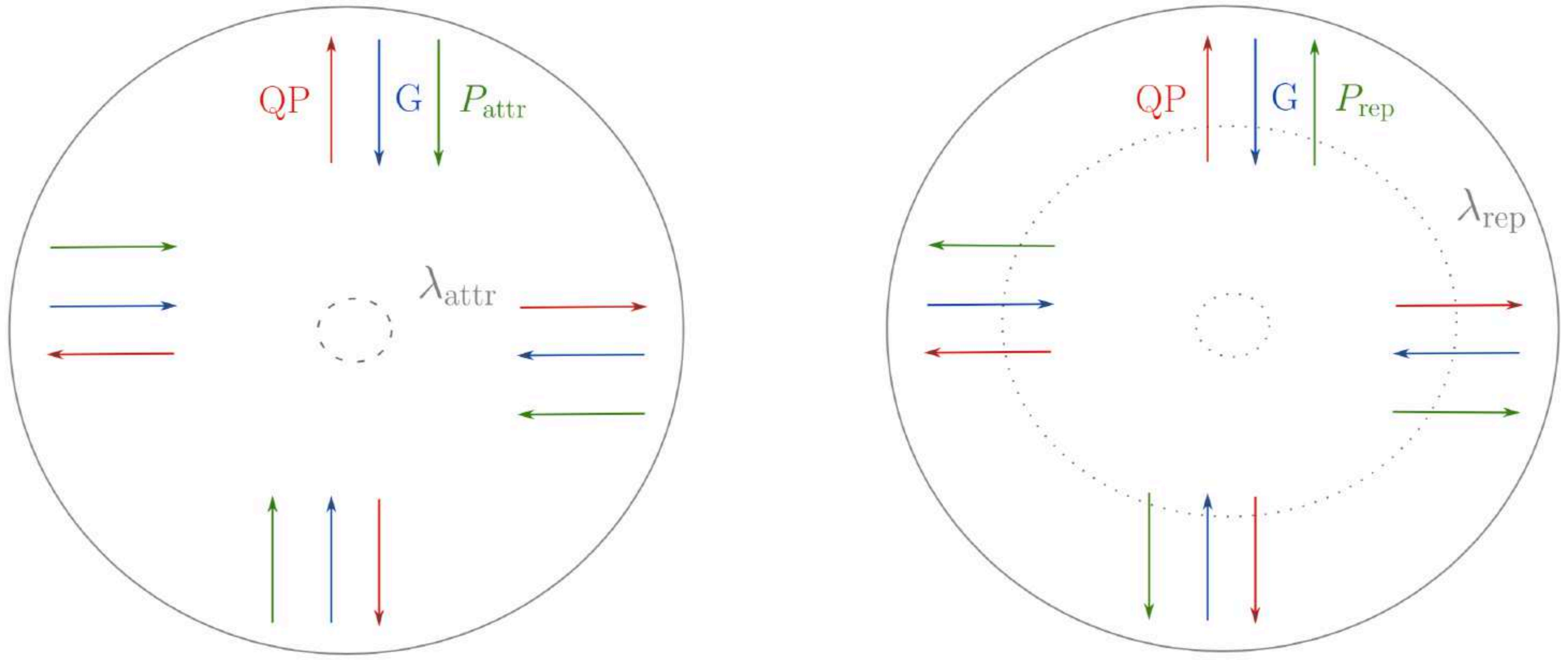
$k > k_c \, (\lambda < \lambda_c)$ $\Rightarrow$ Solution oscillates and is stable

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

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

SIFDM

ATTRACTIVE REPULSIVE



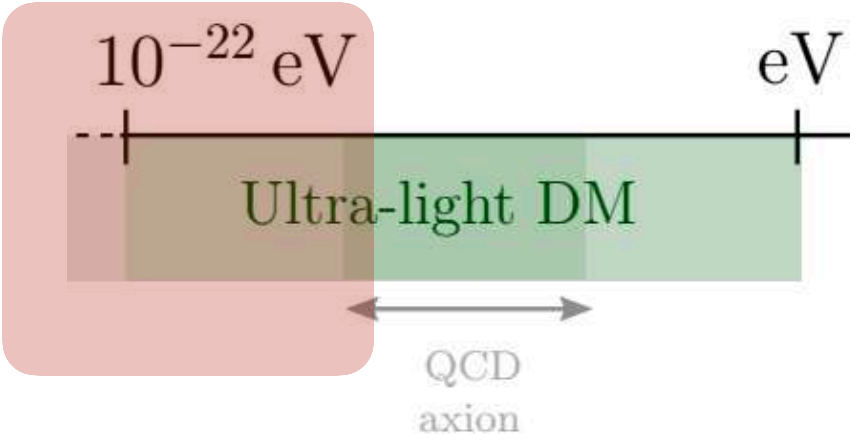
$g < 0$ $g > 0$

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

For attractive interactions can only form localized clumps (solitons)

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

Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

REPULSIVE $\quad g > 0$

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

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

Dispersion relation

Long wavelength regime

$$\lambda \gg \lambda_c$$

$$\omega_k \simeq c_s k$$

Long range - superfluid

Short wavelength regime

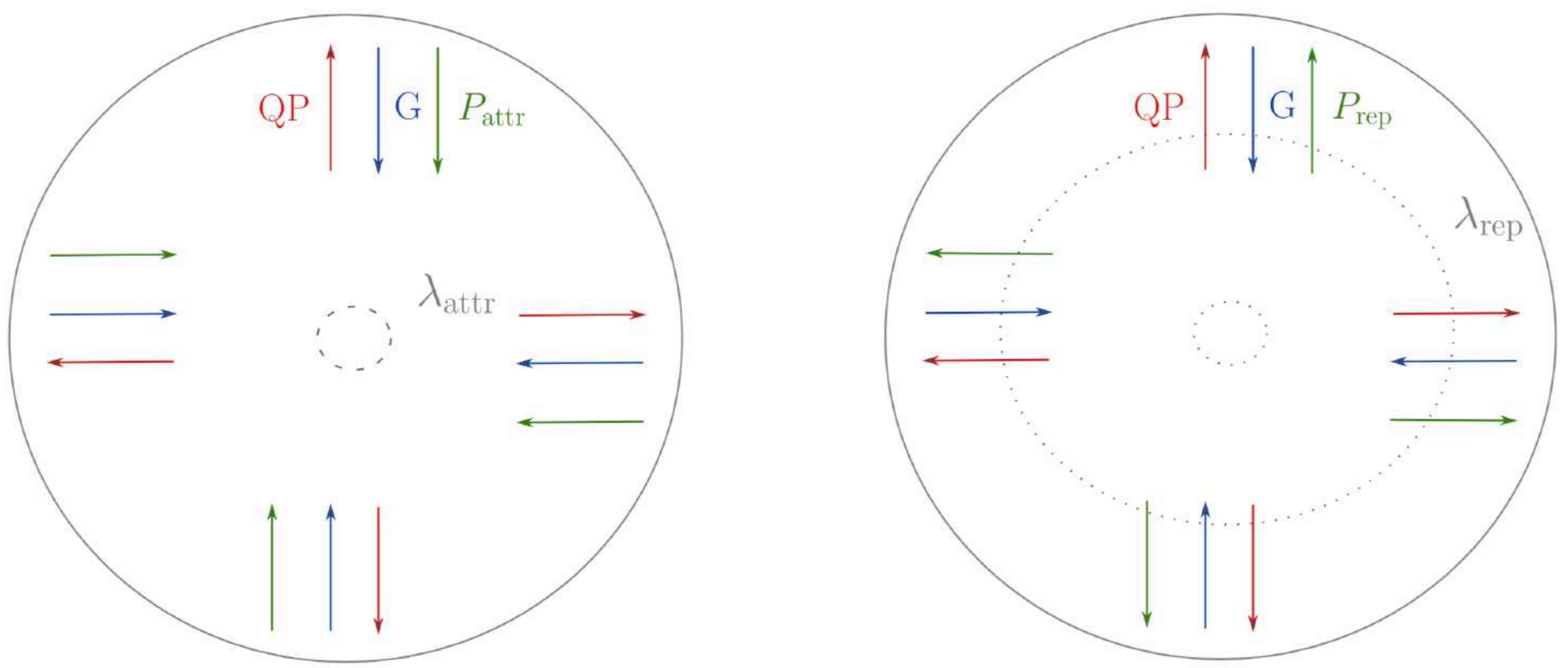
$$\omega_k \simeq k^2/2m$$

Free massive particle

SIFDM

ATTRACTIVE

REPULSIVE



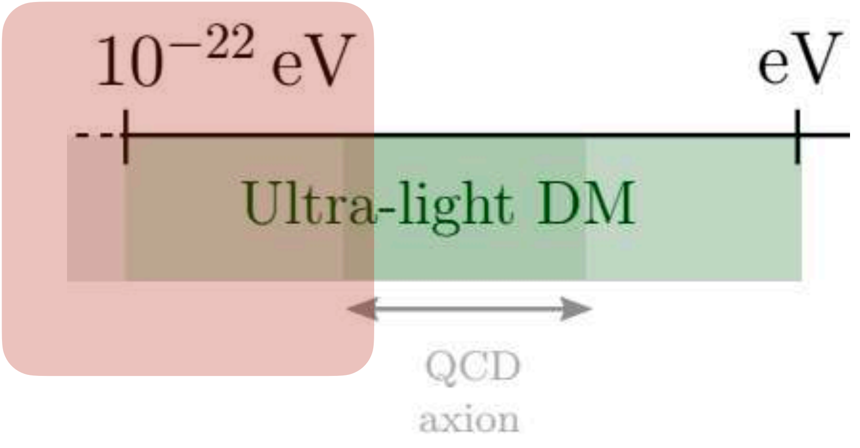
$g < 0$

$g > 0$

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

Superfluid!

Structure formation - perturbation and stability



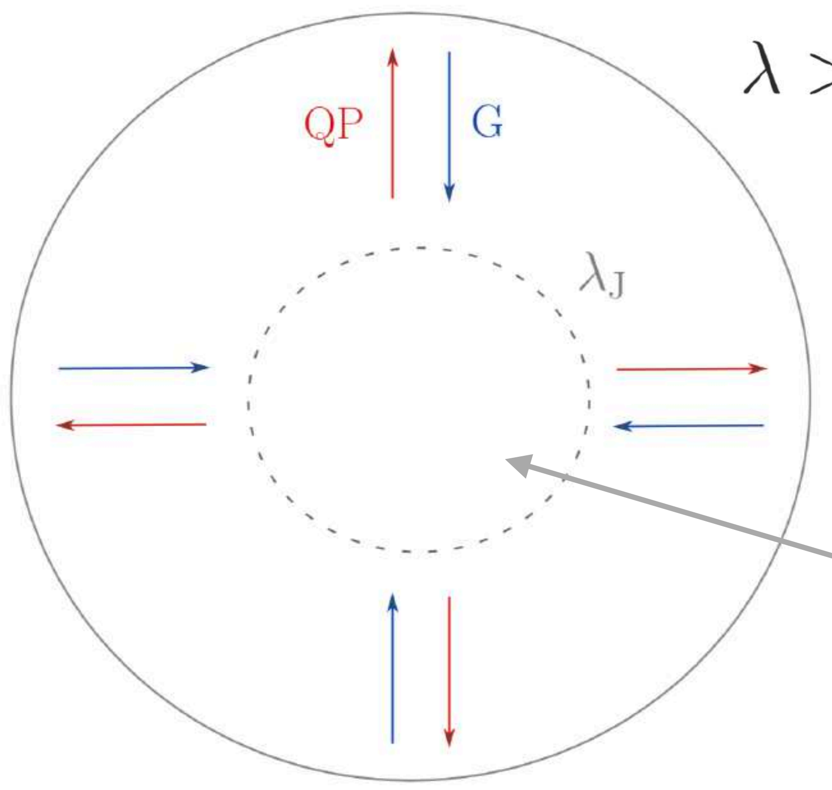
Finite clustering scale - no structure formation on small scales

SIFDM

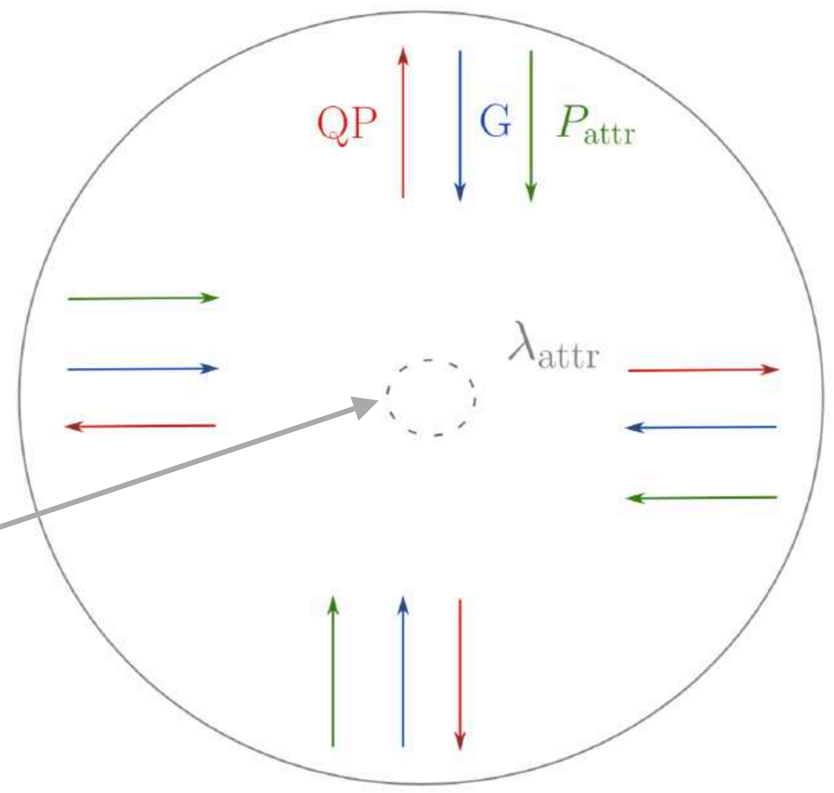
FDM

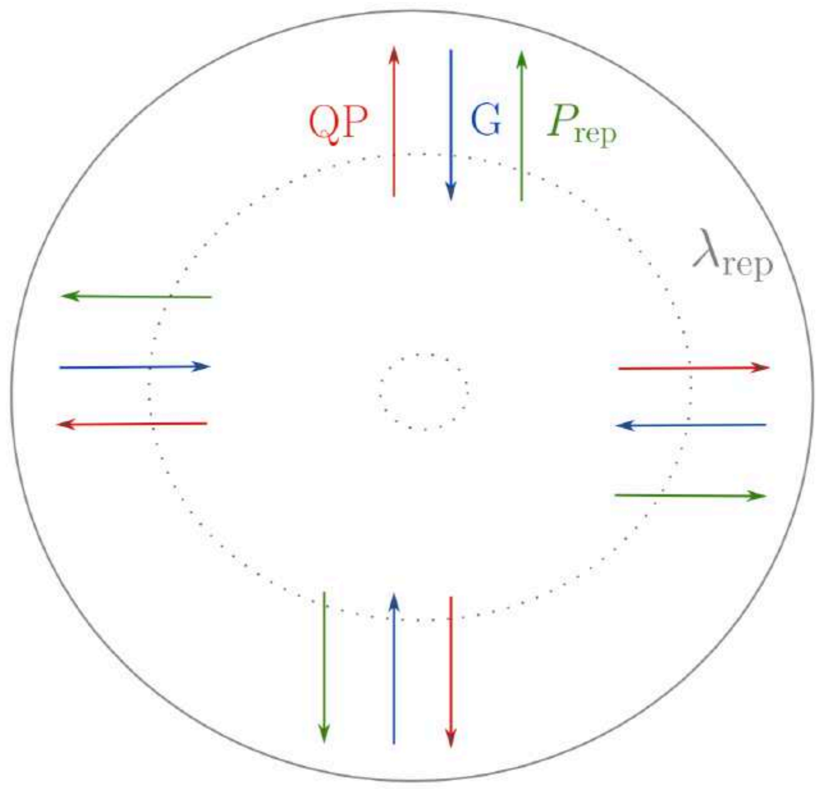
ATTRACTIVE

REPULSIVE



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





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

QP wins -
NO structure formation

$\lambda < \lambda_J, \lambda_{attr}, \lambda_{rep}$

$g < 0$

$g > 0$

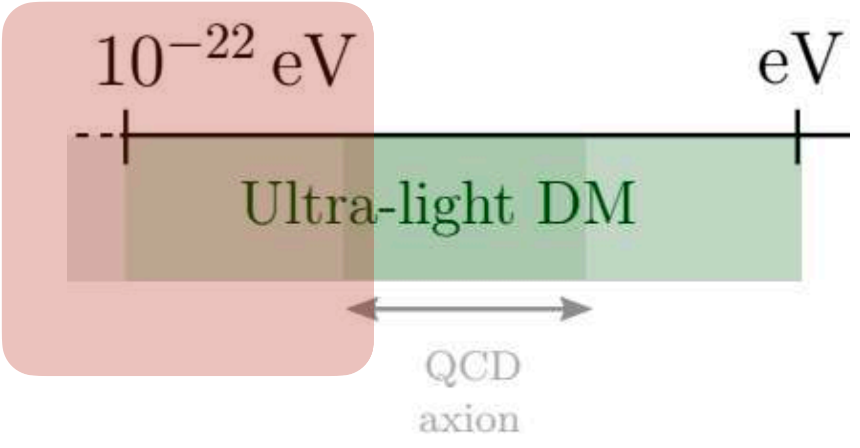
Finite size coherent core – Bose stars

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

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

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

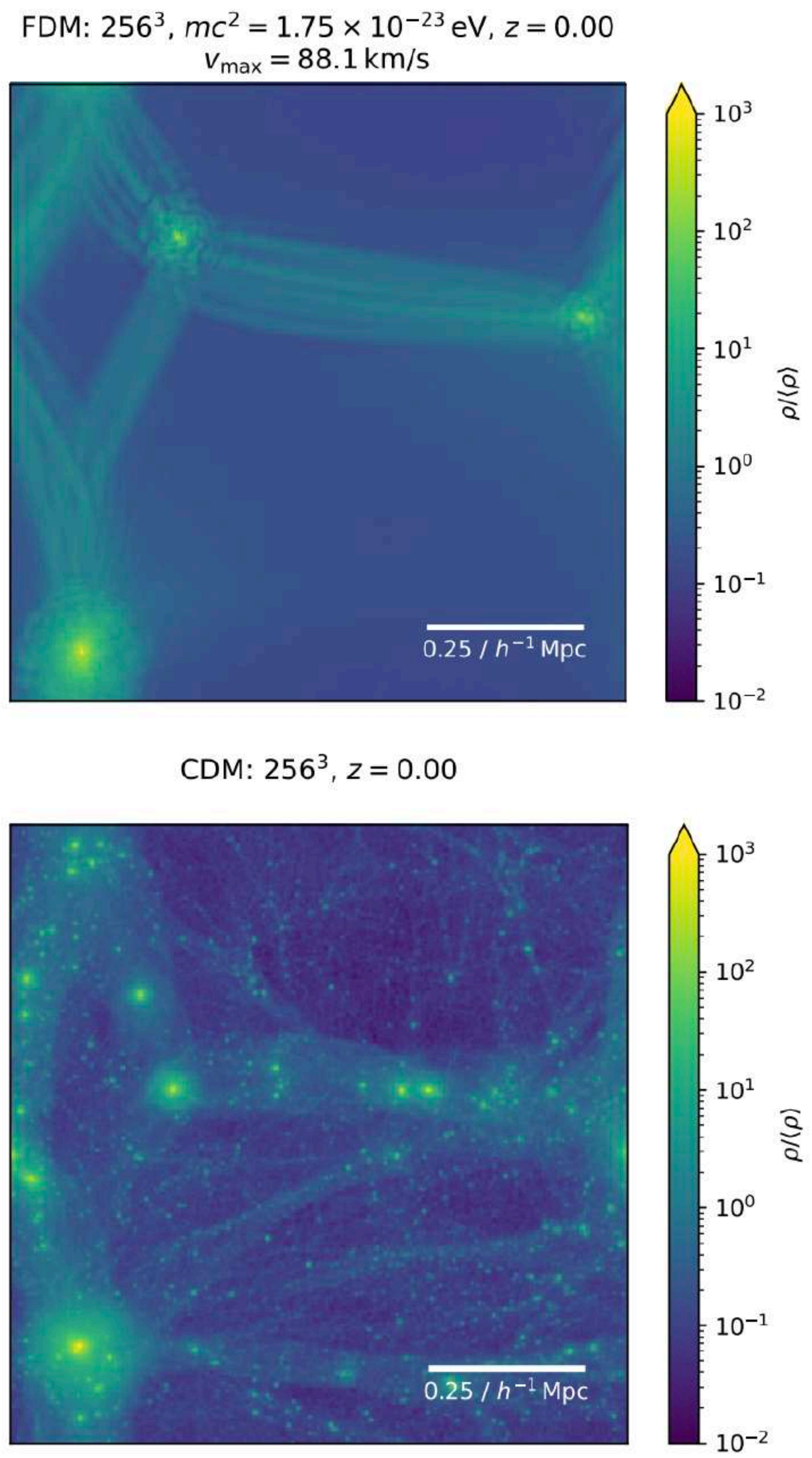
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

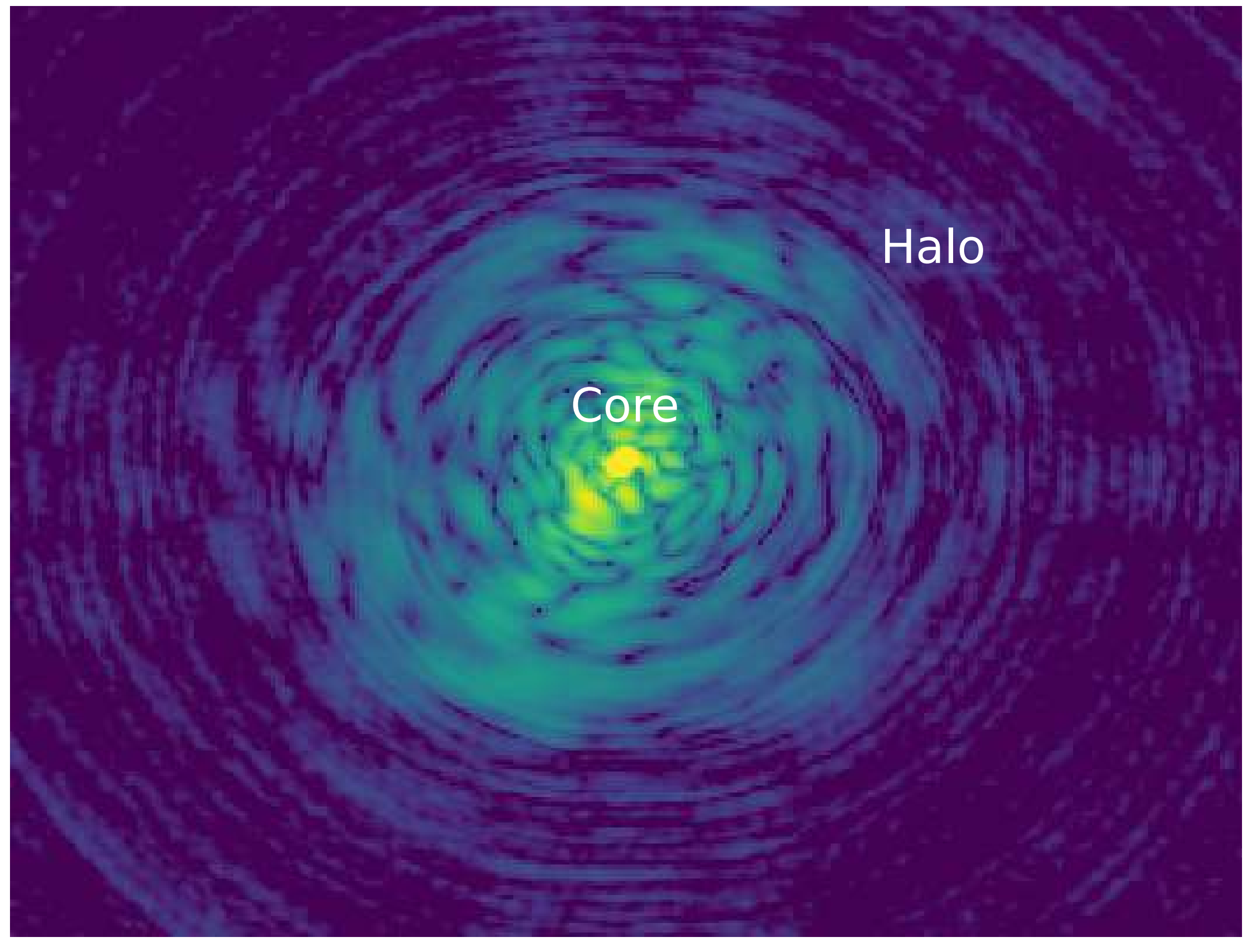
* Focus only in gravitational signatures

Suppression of small structures

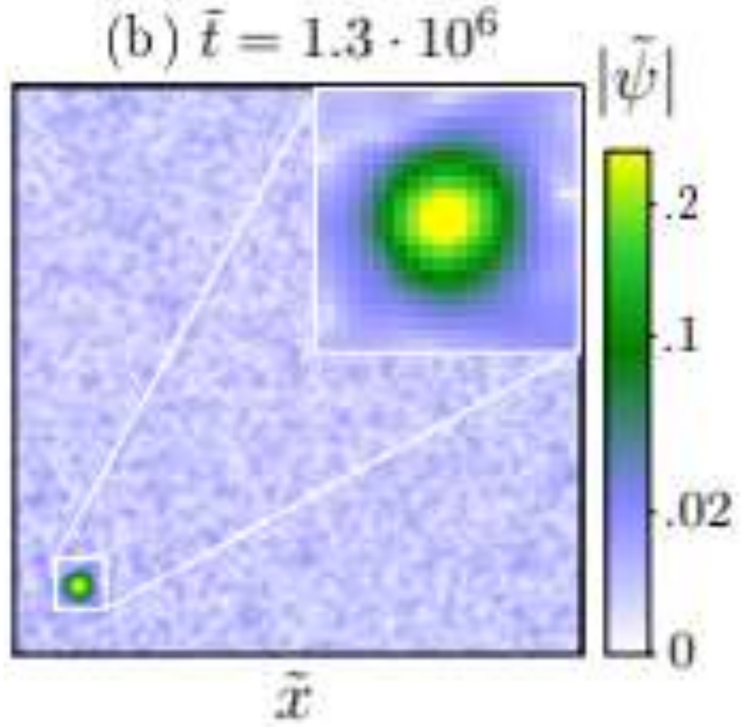


S. May et al. 2021

Formation of a solitonic core

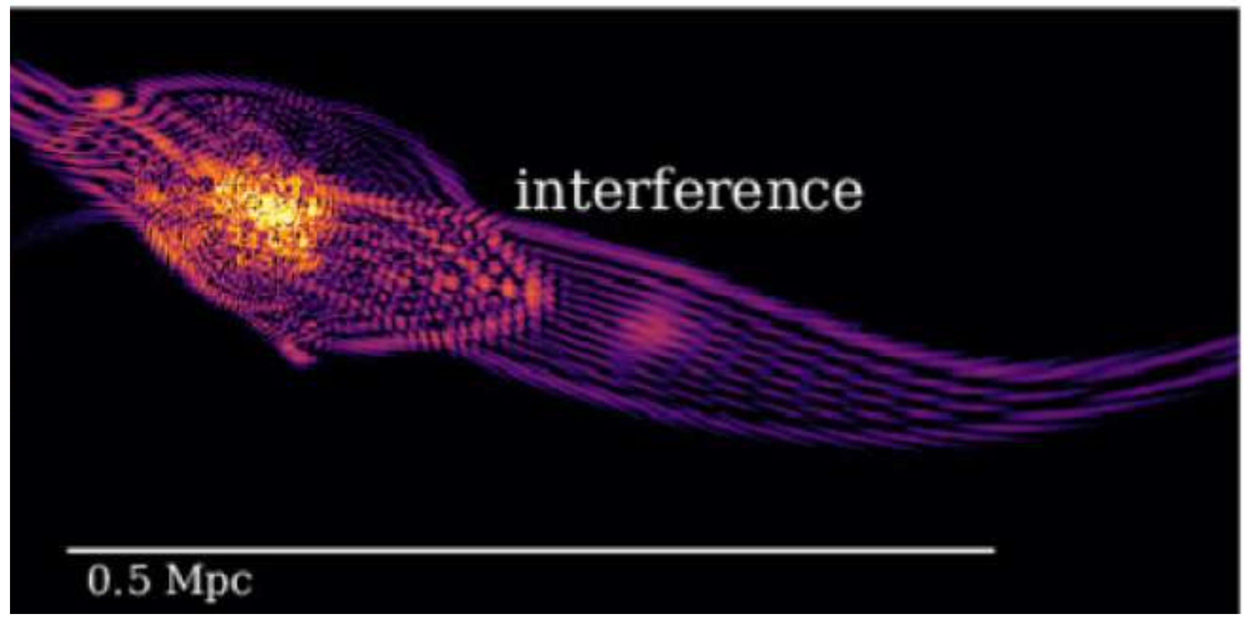


Dynamical effects



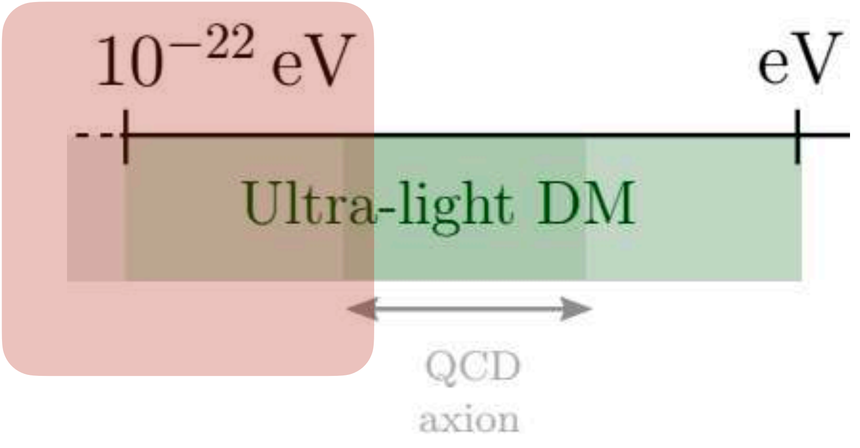
Levkov et al. 2018

Wave interference



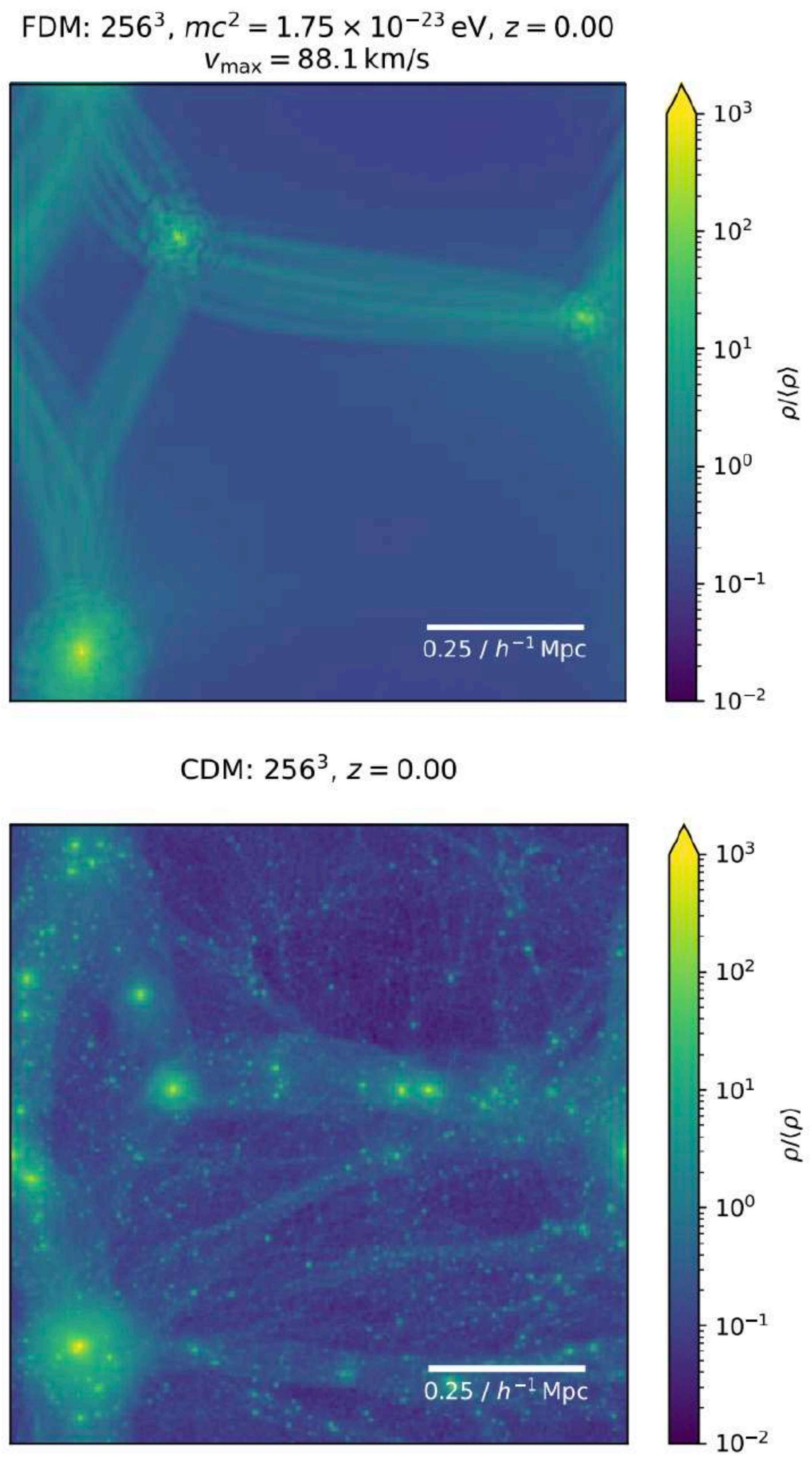
Mocz et al. 2017

Phenomenology



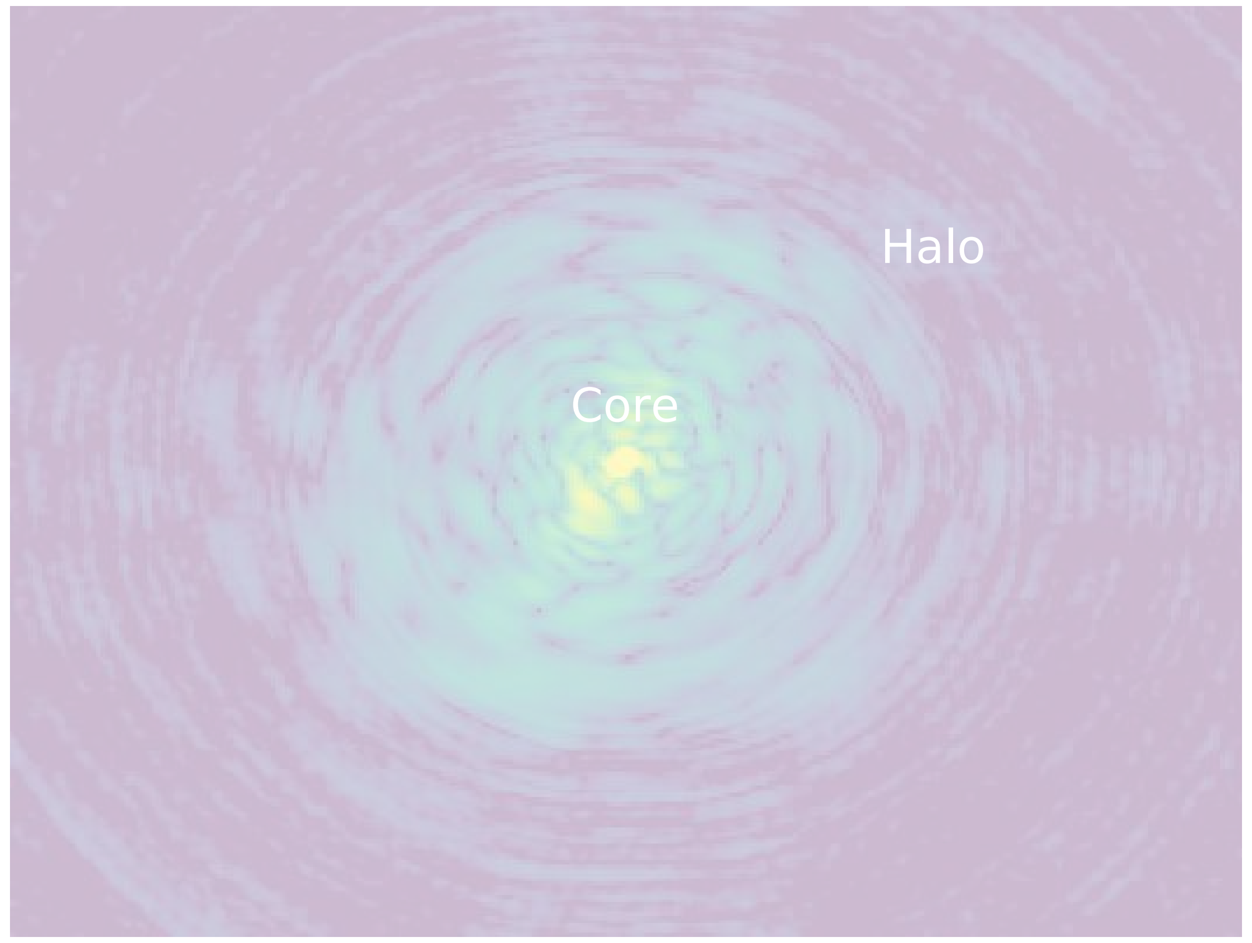
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

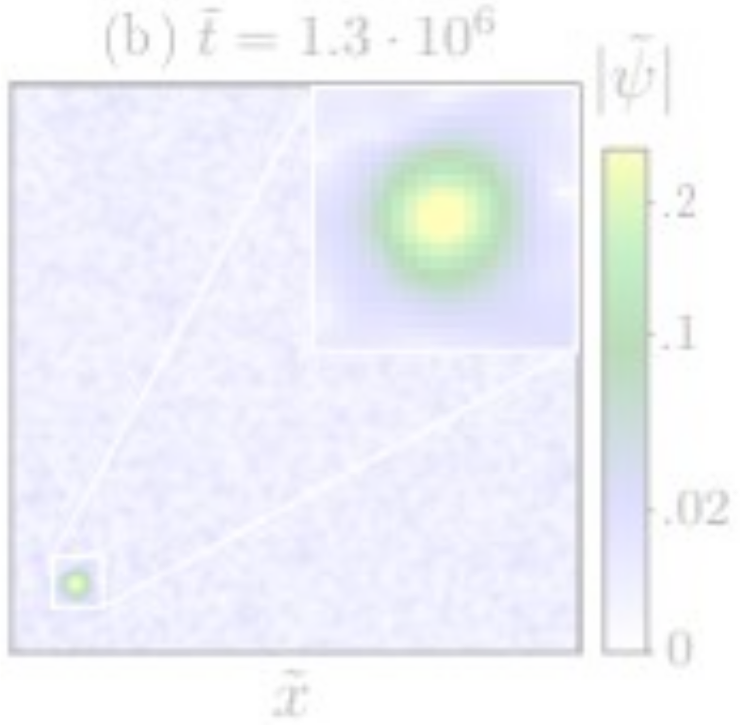


S. May et al. 2021

Formation of a solitonic core



Dynamical effects



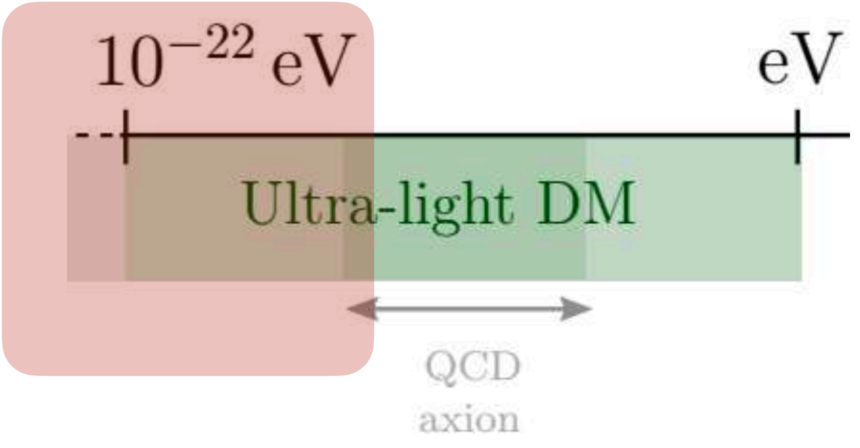
Levkov et al. 2018

Wave interference

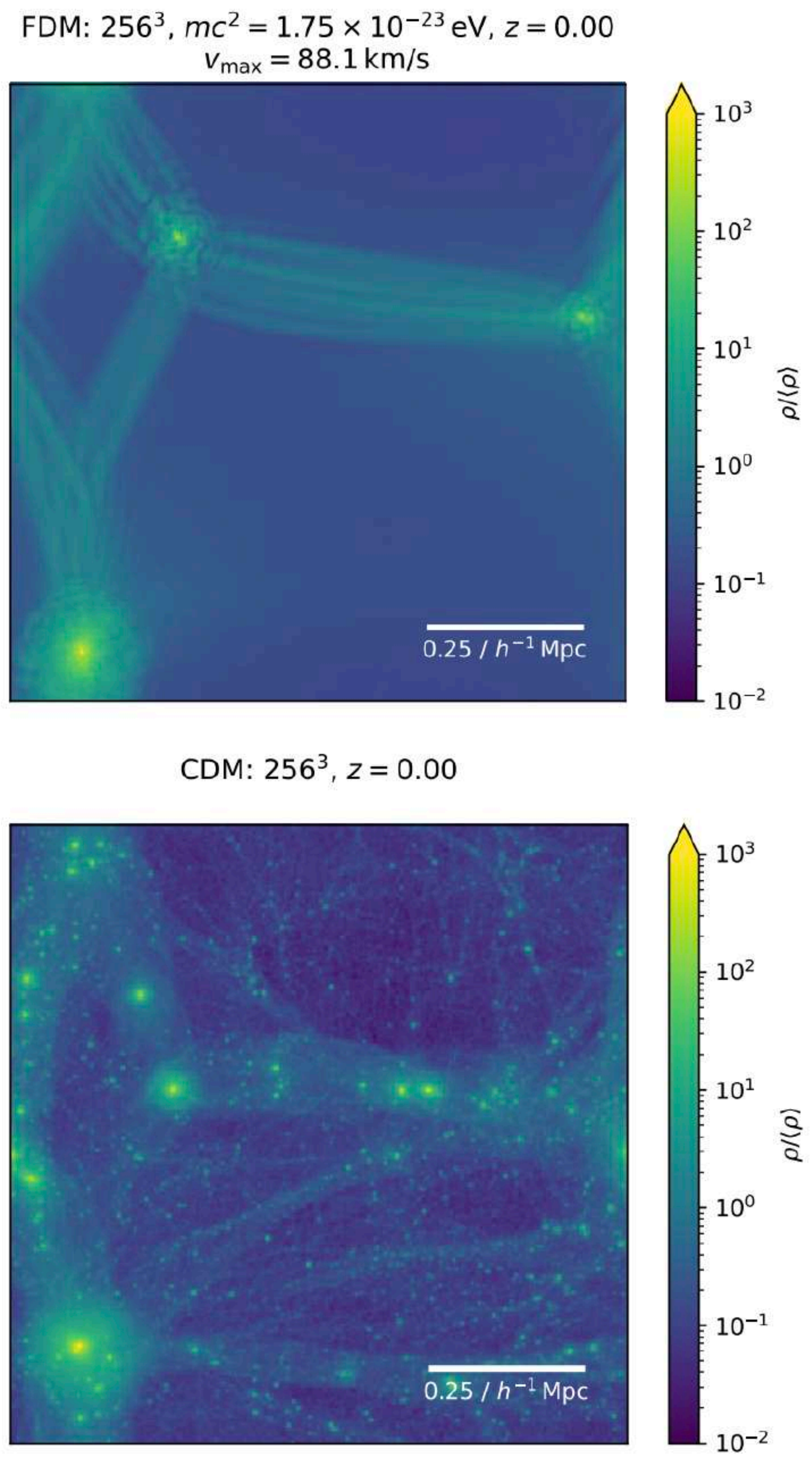
Mocz et al. 2017

Phenomenology

Suppression of small structures



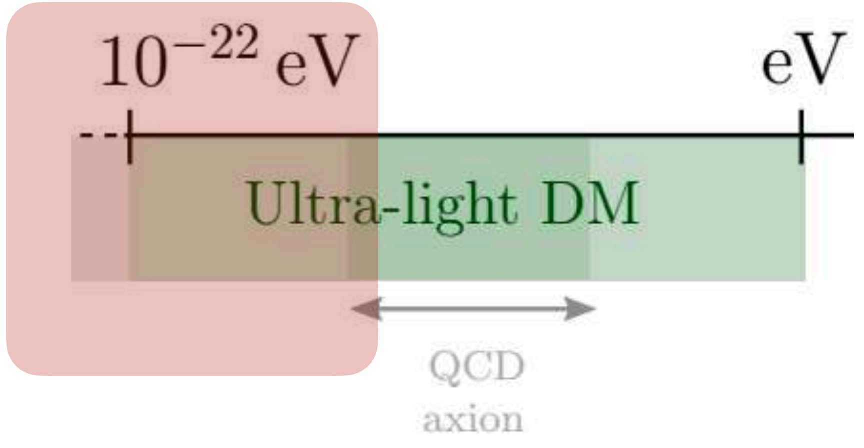
Finite Jeans length λ_J or λ_{attr}, λ_{rep} $\longrightarrow$ No small scale structure



S. May et al. 2021

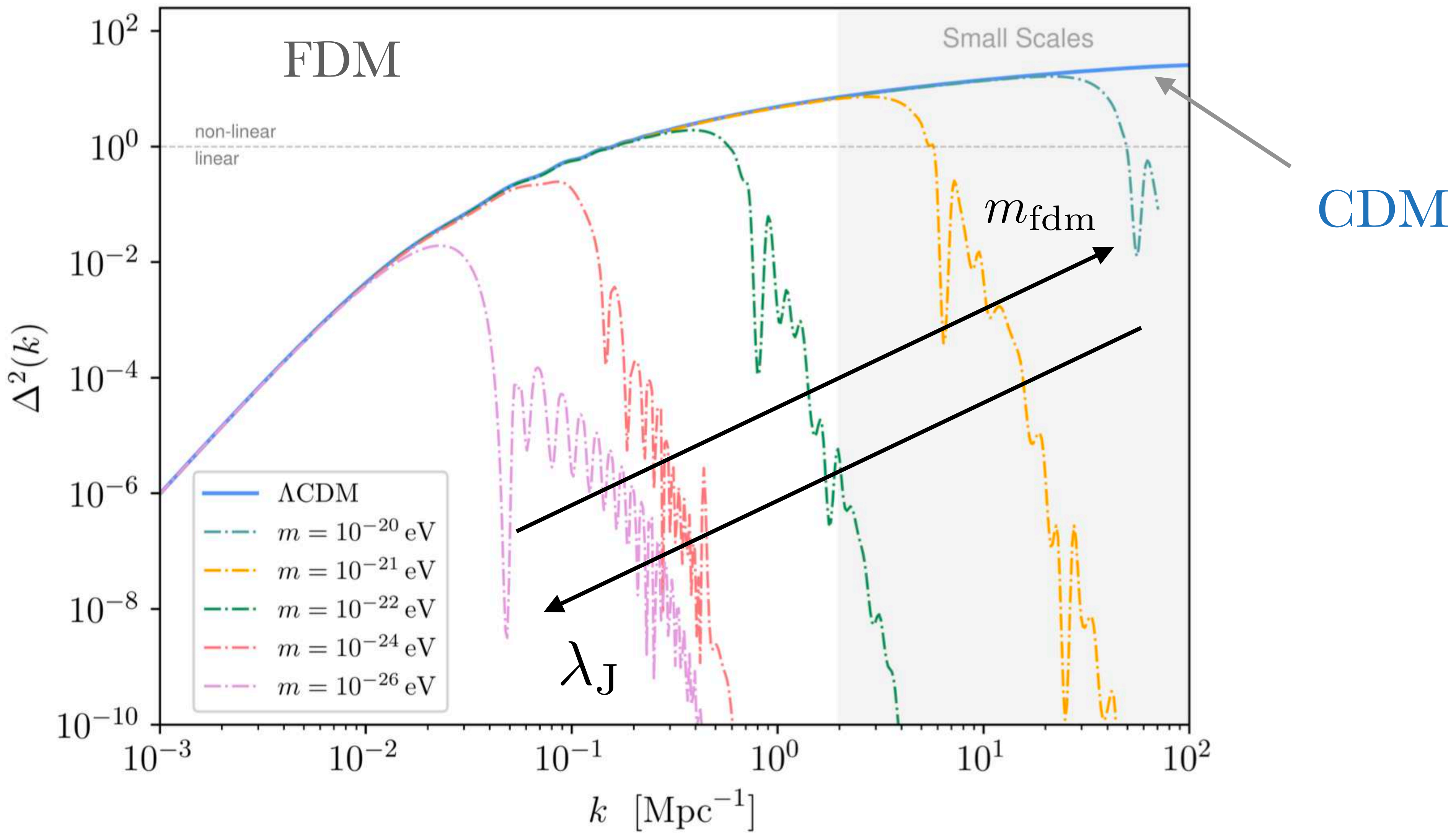
Phenomenology

Suppression of small structures

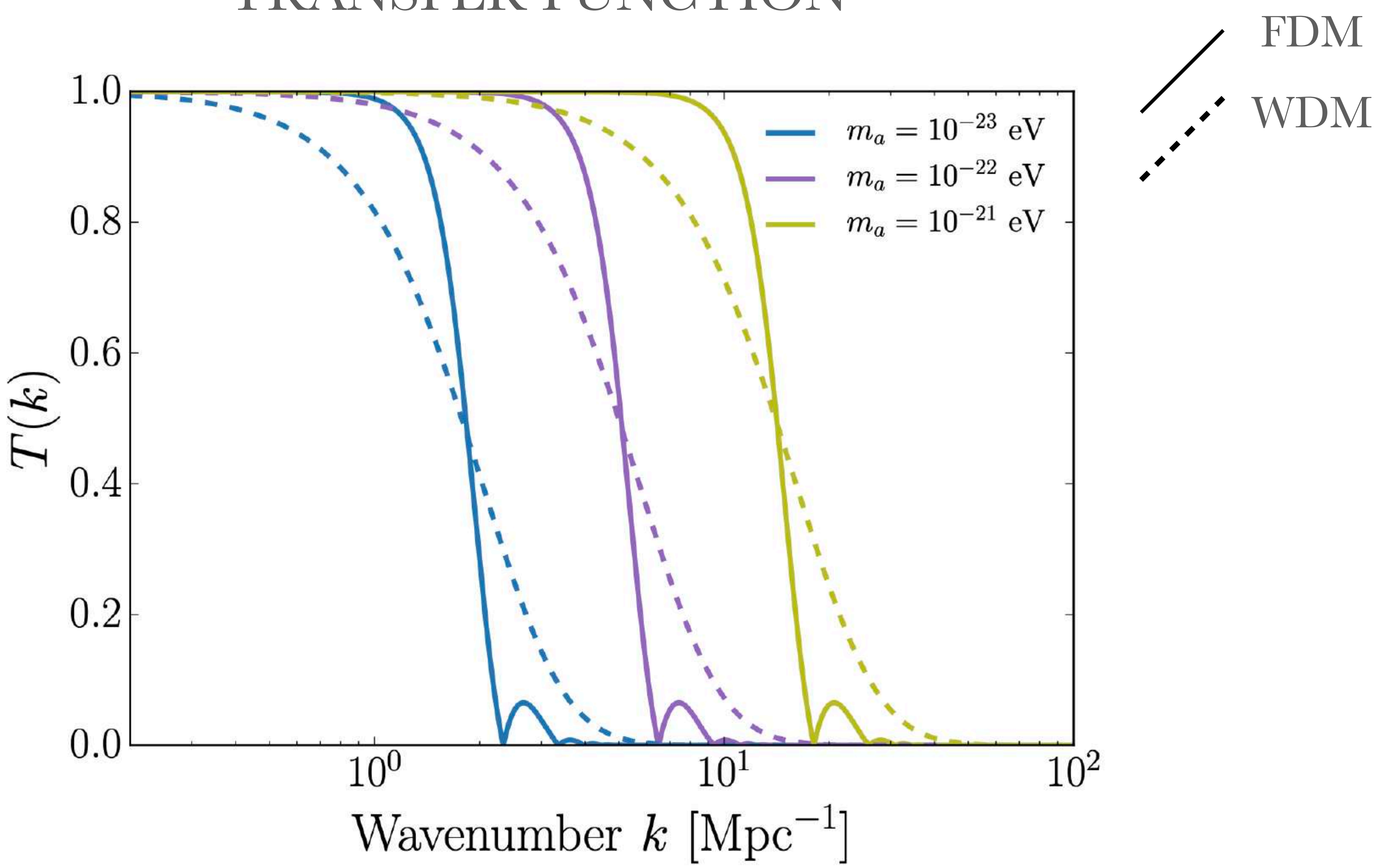


Finite Jeans length λ_J or λ_{attr}, λ_{rep} $\longrightarrow$ Suppresses small scale structure

POWER SPECTRUM



TRANSFER FUNCTION



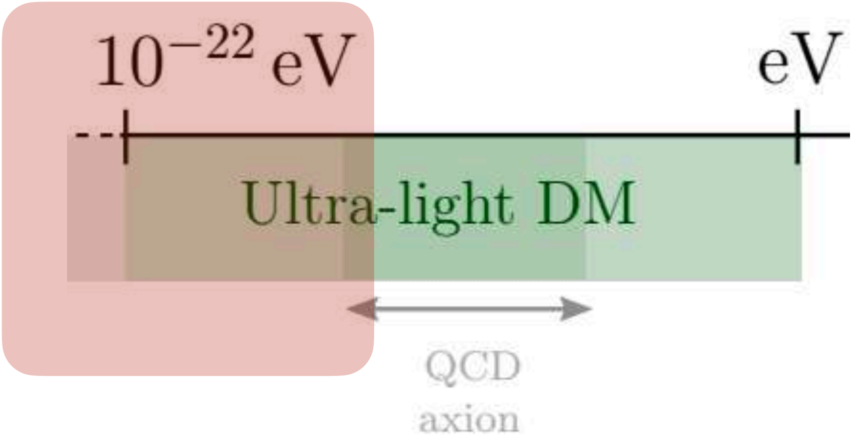
$$P_X(k,z) = T_X^2(k,z)\, P_{\Lambda CDM}(k)$$

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

- Degenerate with WDM

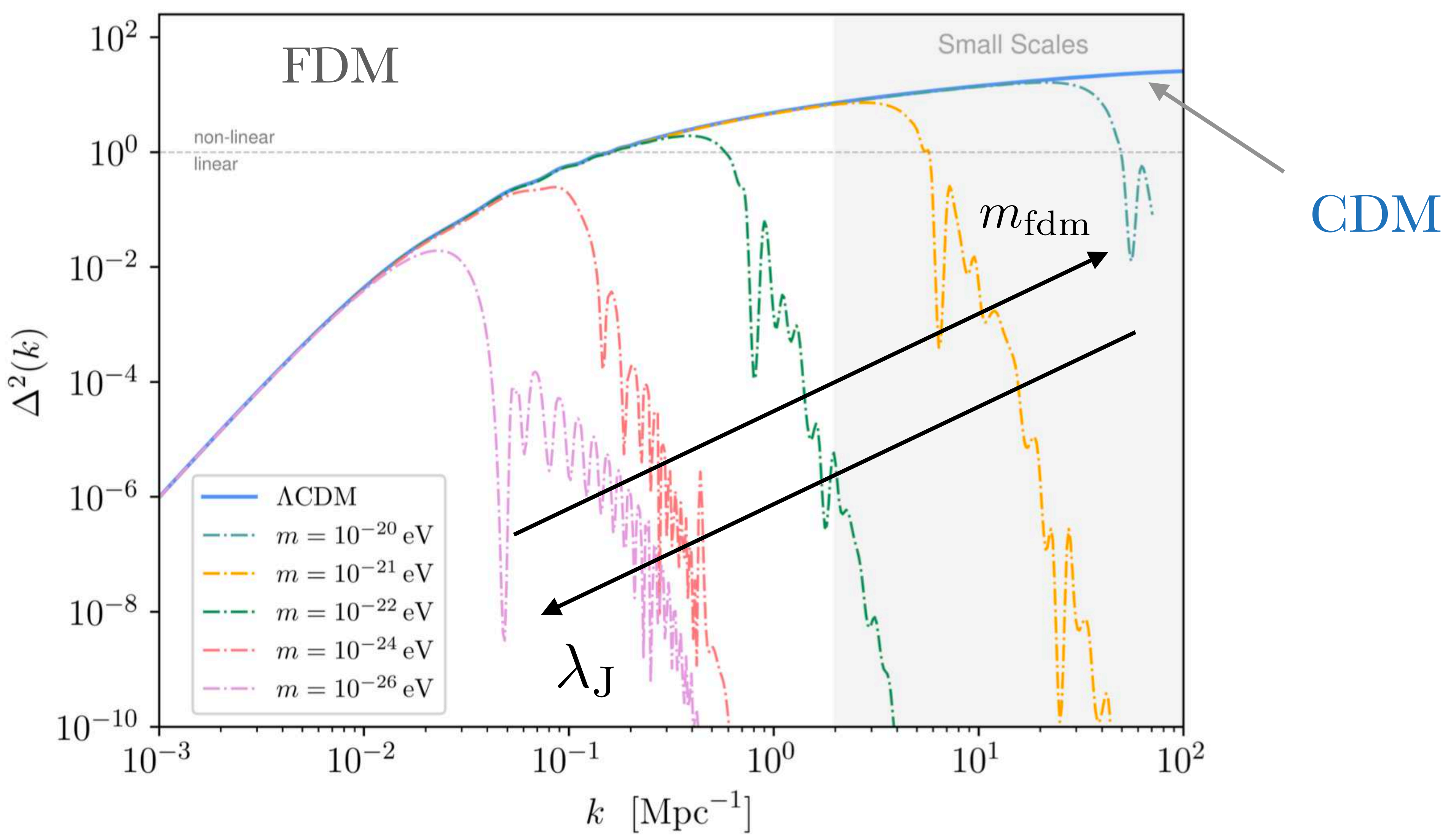
Phenomenology

Suppression of small structures

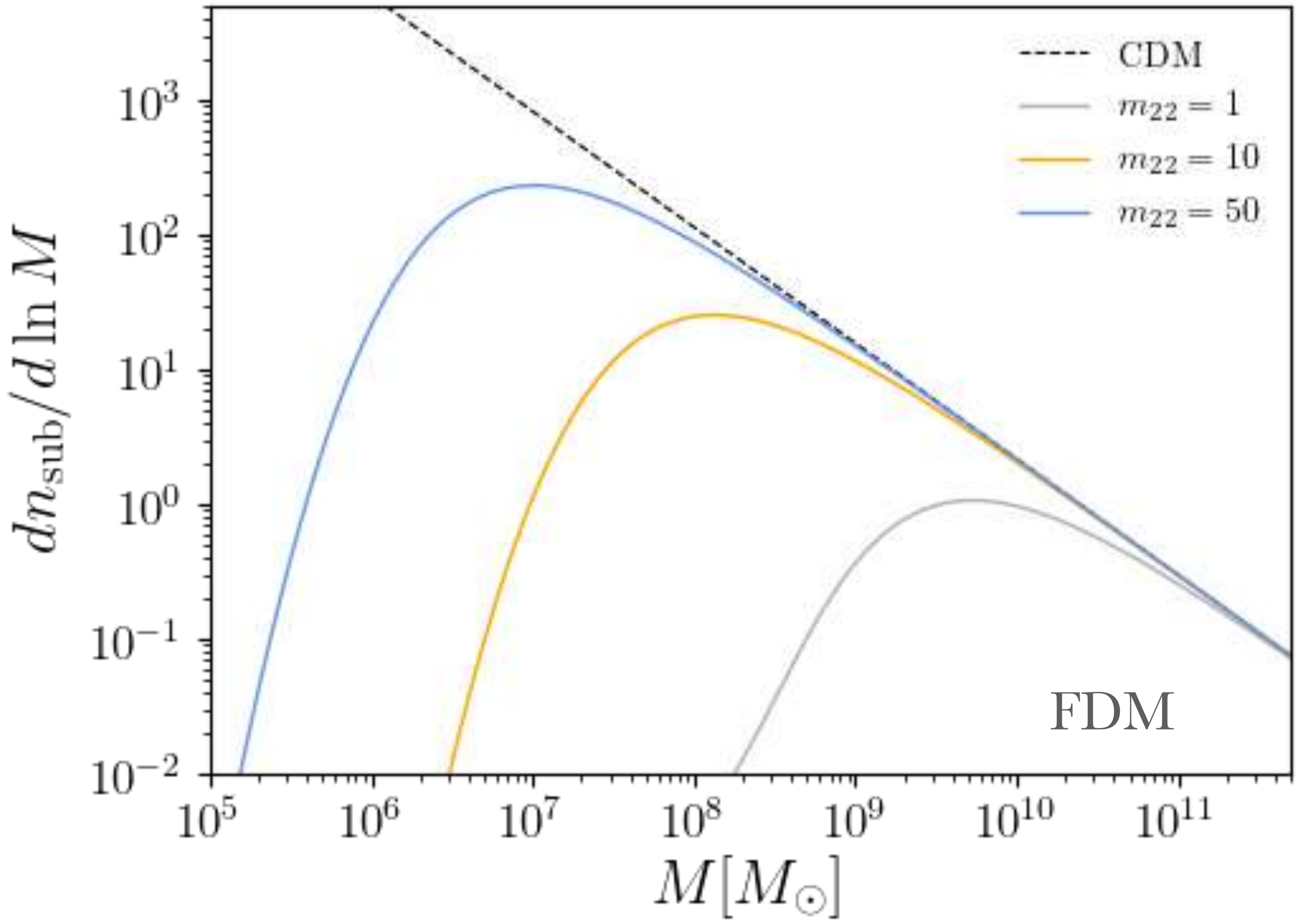


Finite Jeans length λ_J or $\lambda_{\mathrm{attr}}, \lambda_{\mathrm{rep}}$ $\longrightarrow$ Suppresses small scale structure

POWER SPECTRUM

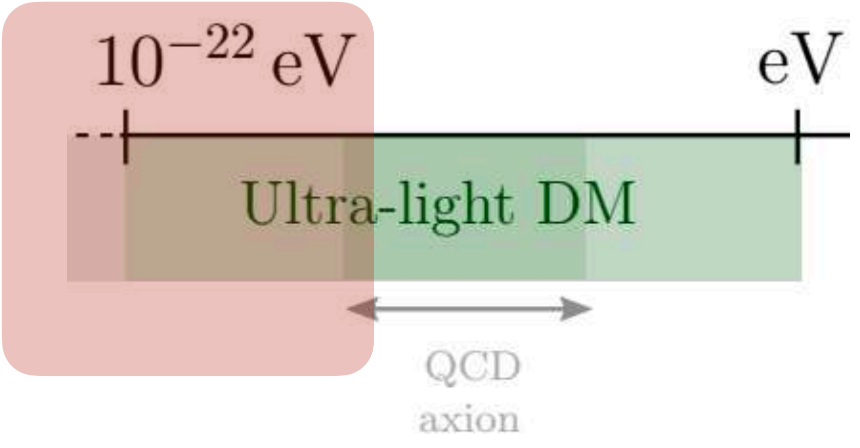


(sub) HALO MASS FUNCTION



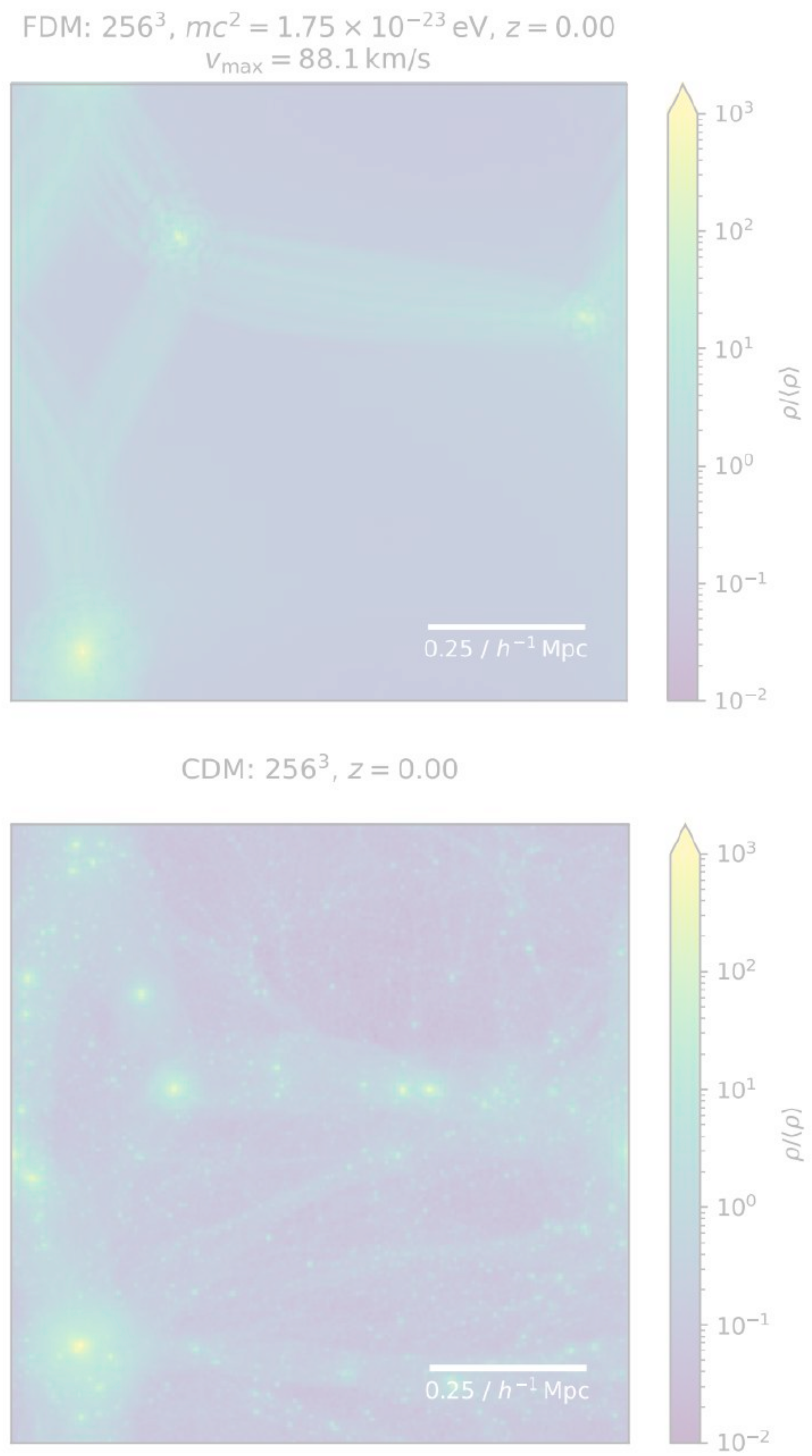
What about the PS from inflation? Practice session!

Phenomenology



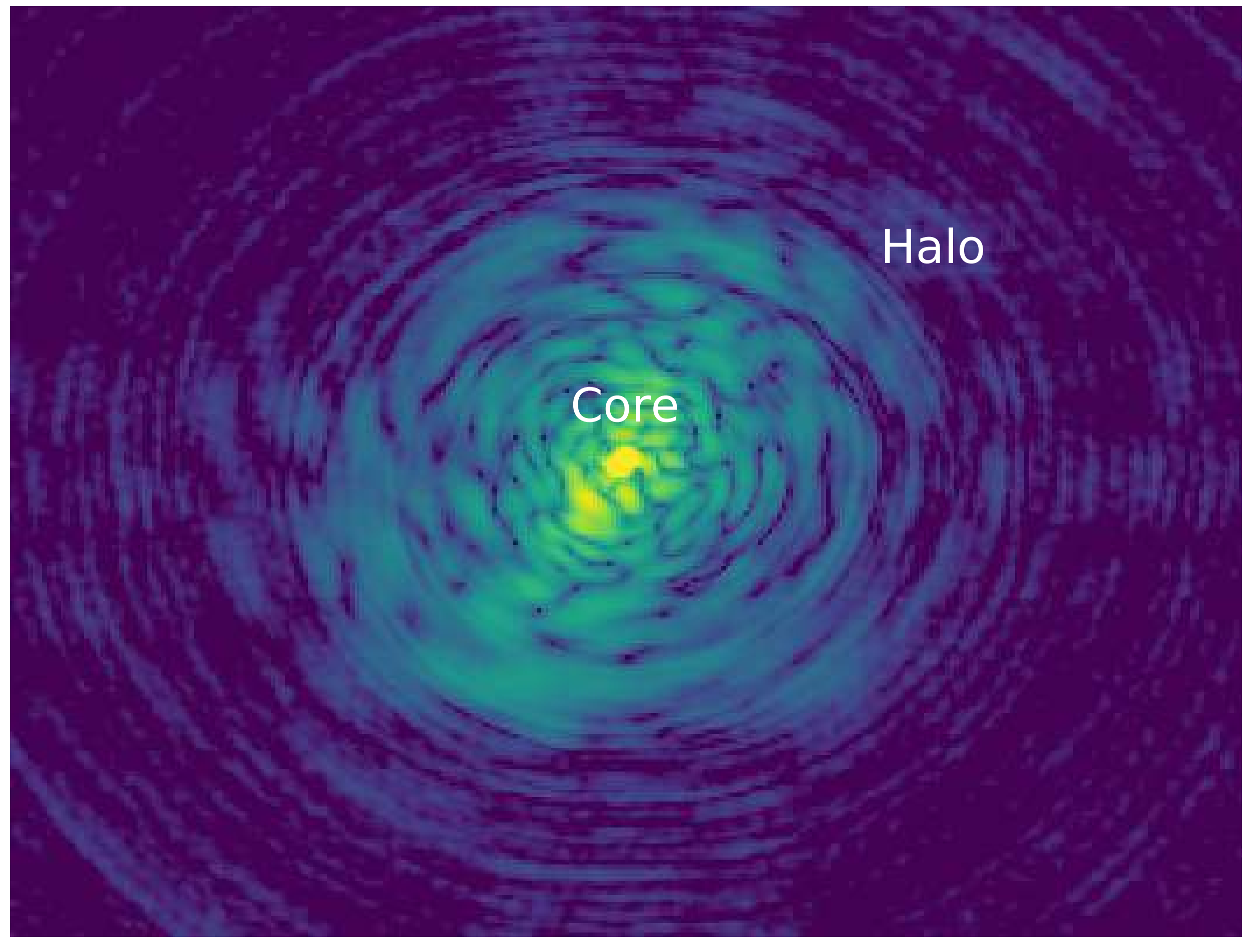
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

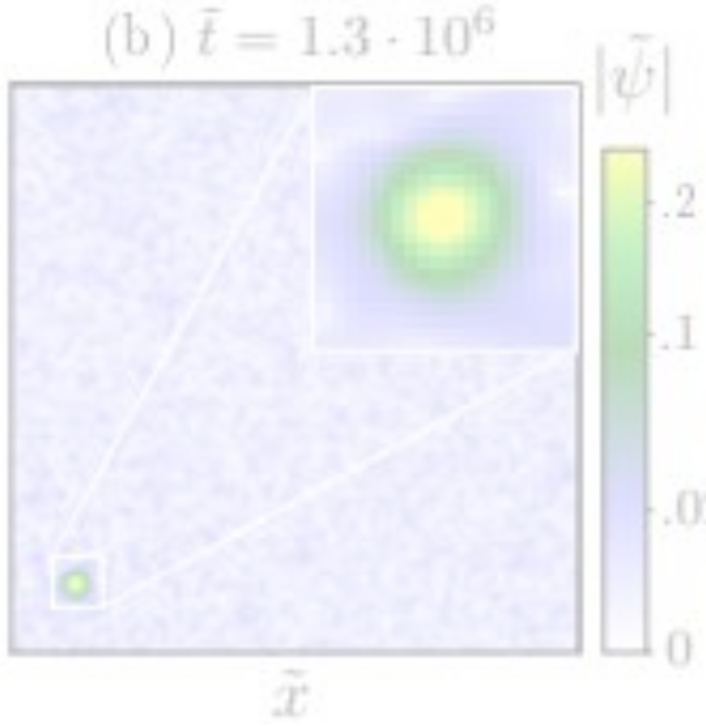


S. May et al. 2021

Formation of a solitonic core



Dynamical effects



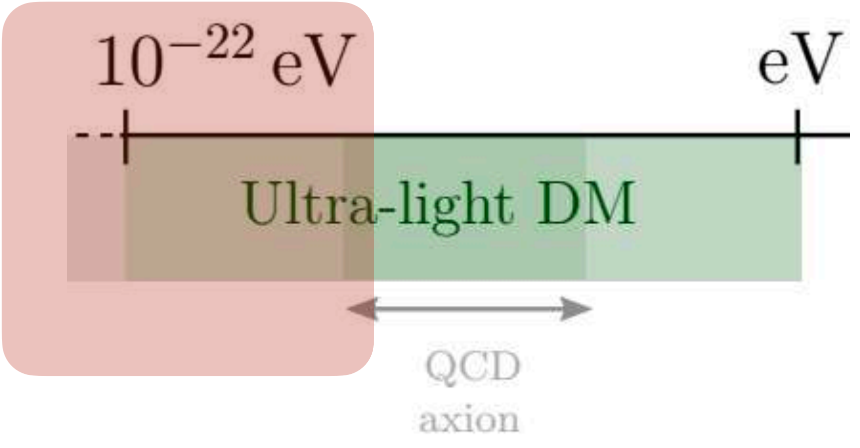
Levkov et al. 2018

Wave interference

Mocz et al. 2017

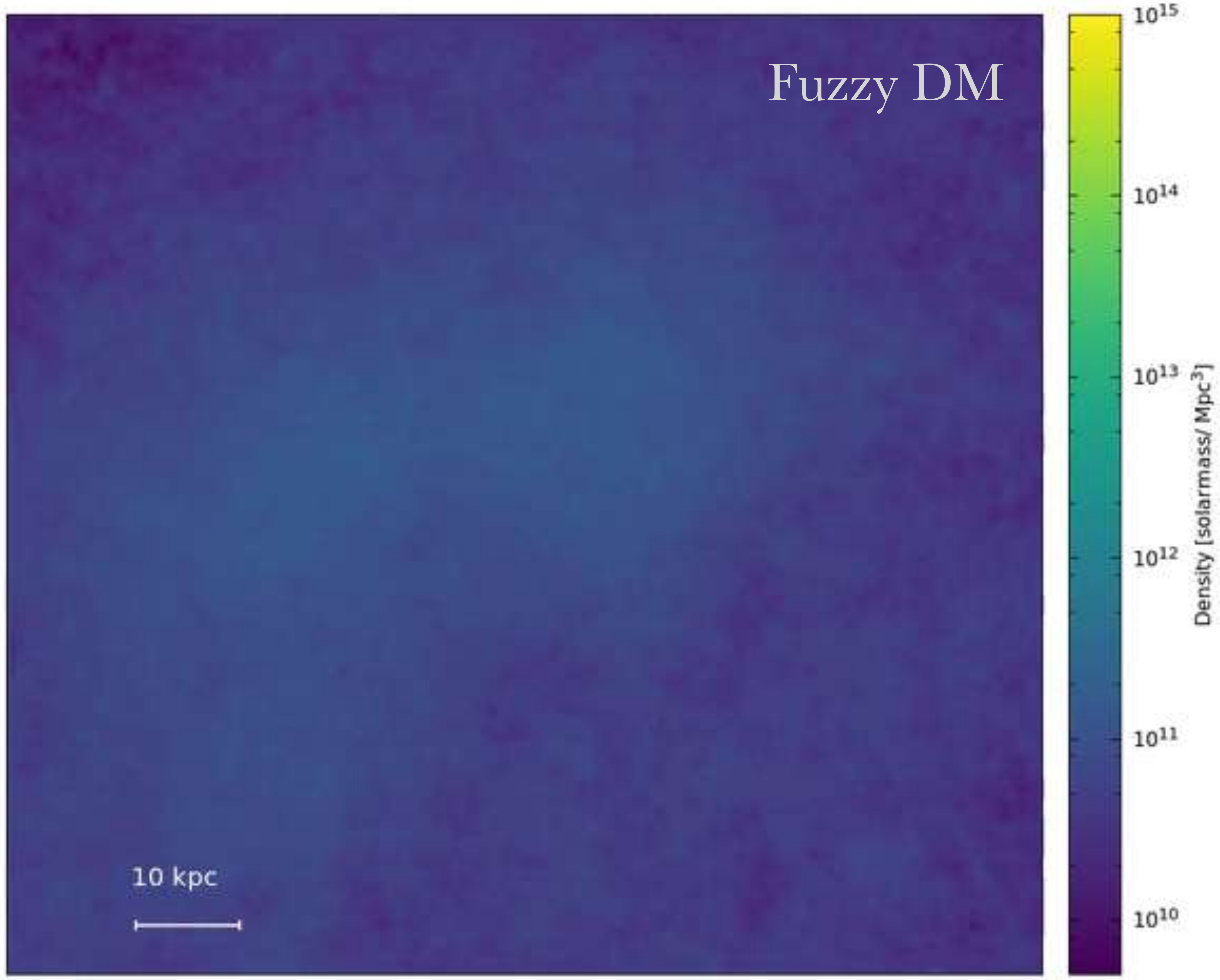
Phenomenology

Formation of cores

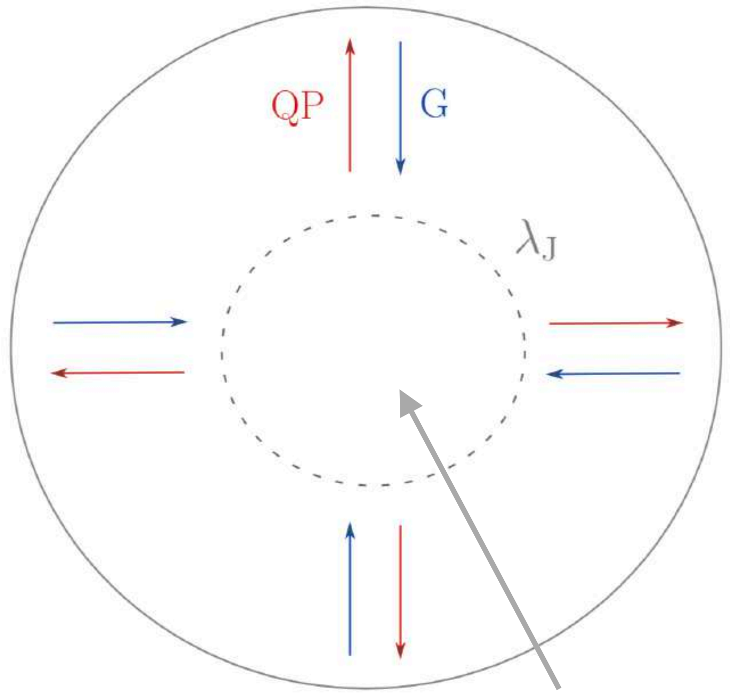


NON-LINEAR evolution: need simulations

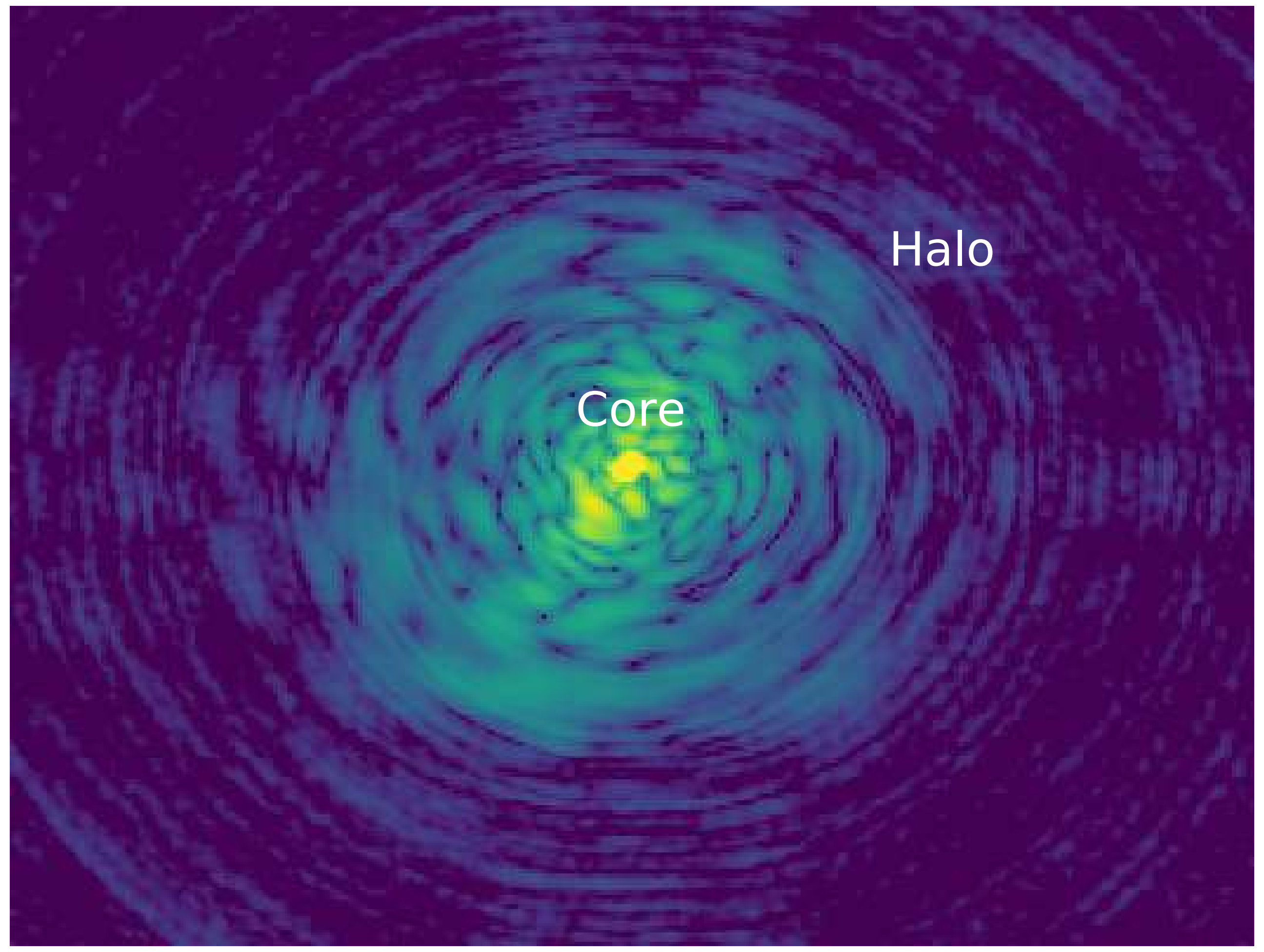
$m = 10^{-22}\,\mathrm{eV}$ $\quad N = 512^3$ $\quad L = 300\,\mathrm{kpc}$



Simulation by Jowett Chan

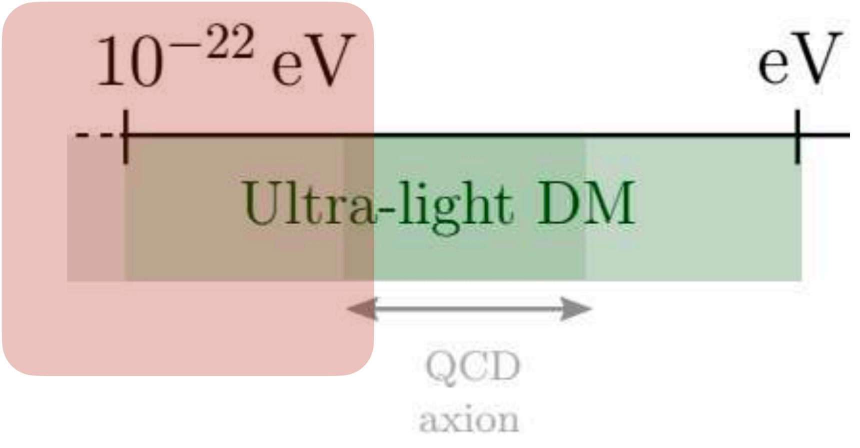


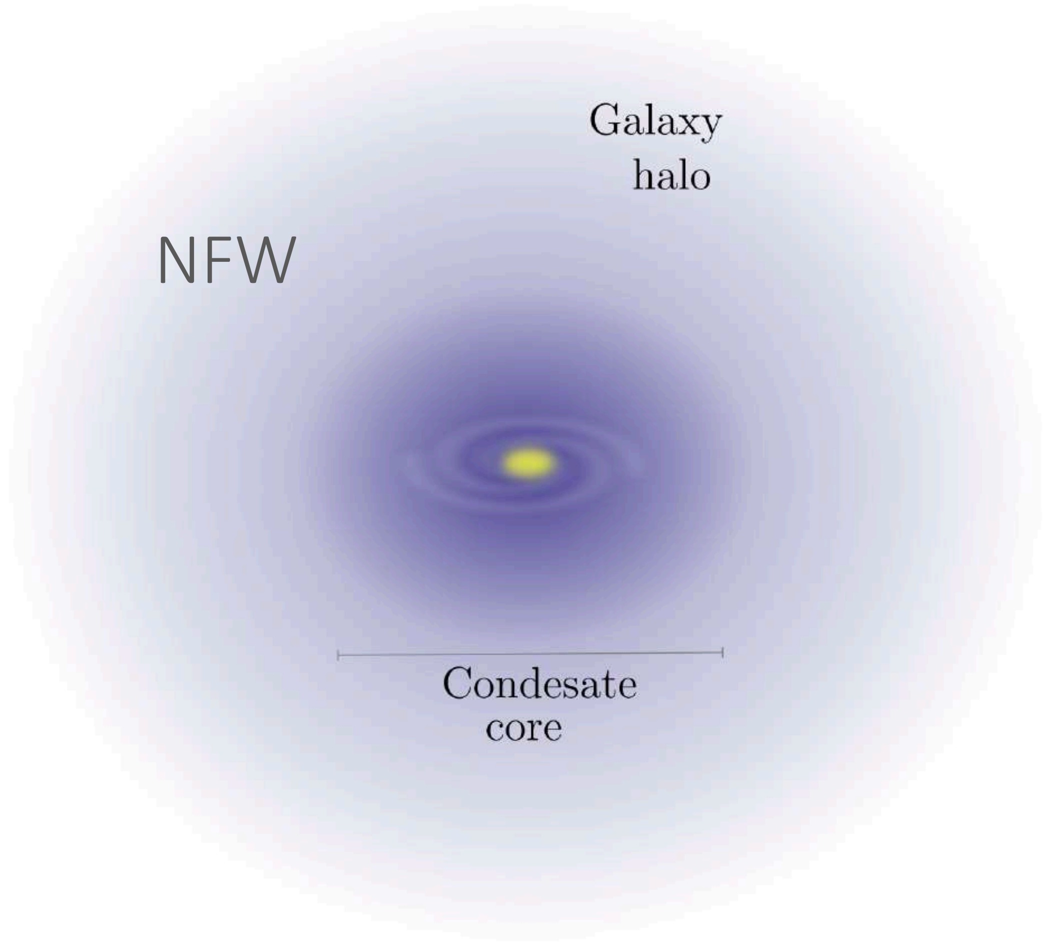
NO structure formation
Stable, oscillating solution



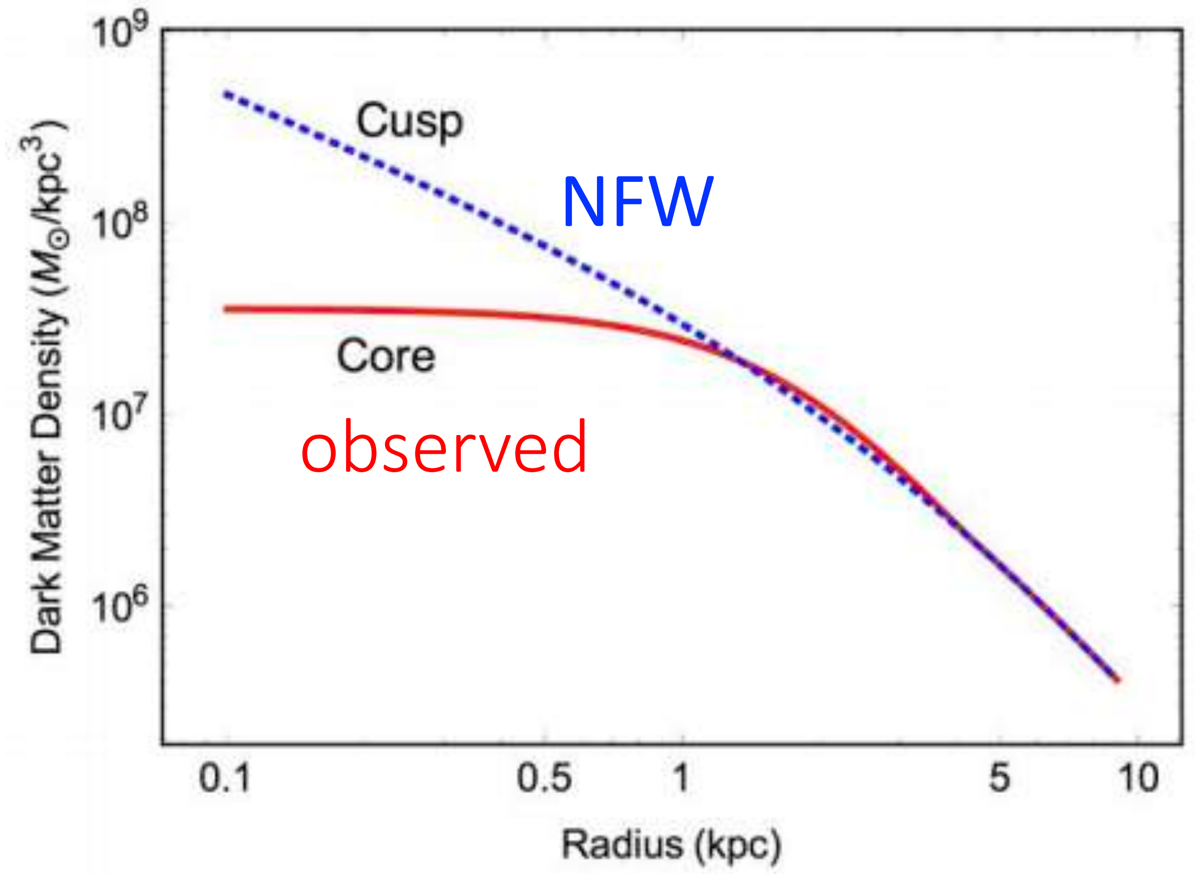
Phenomenology

Formation of cores





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



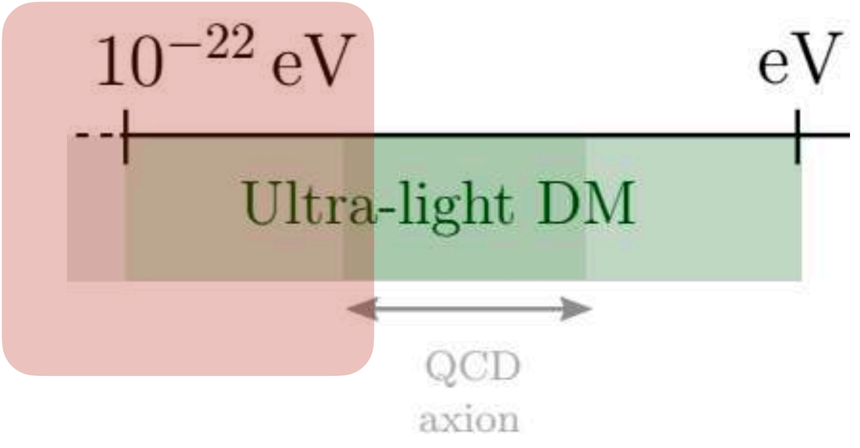
FDM   From simulations Schive et al. 2014, fitting function: Stable core solution

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

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

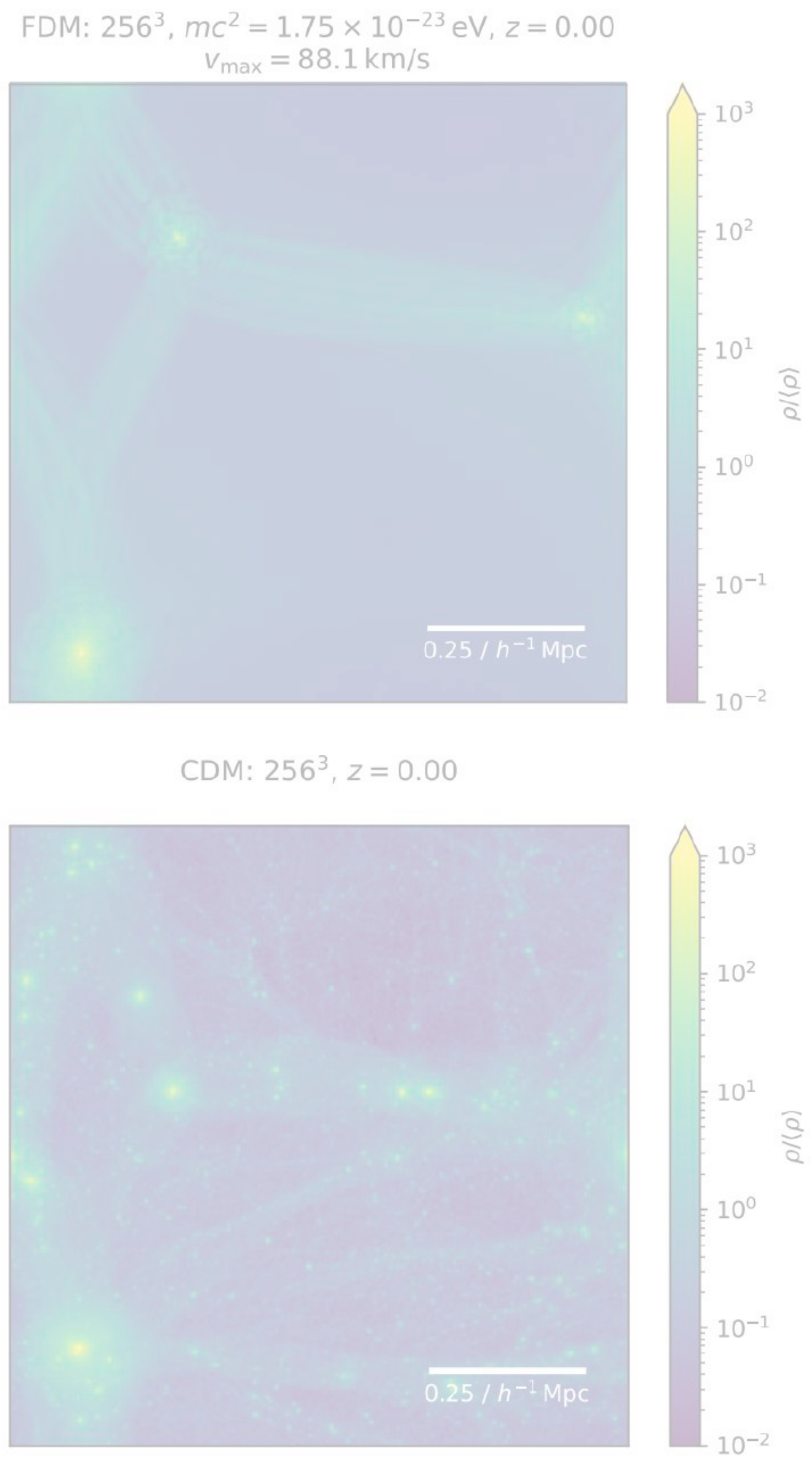
Relations used to compare with observations

Phenomenology



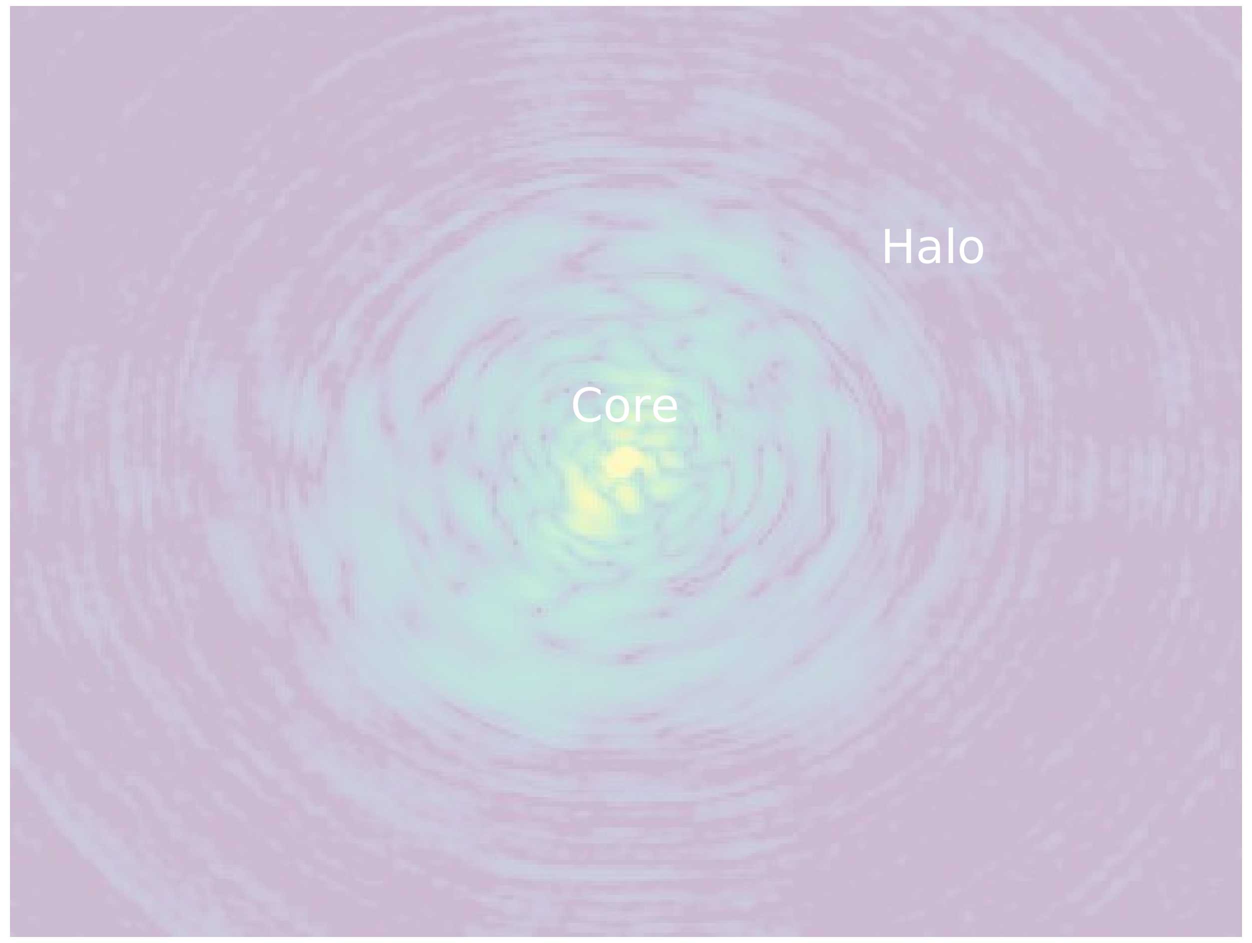
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

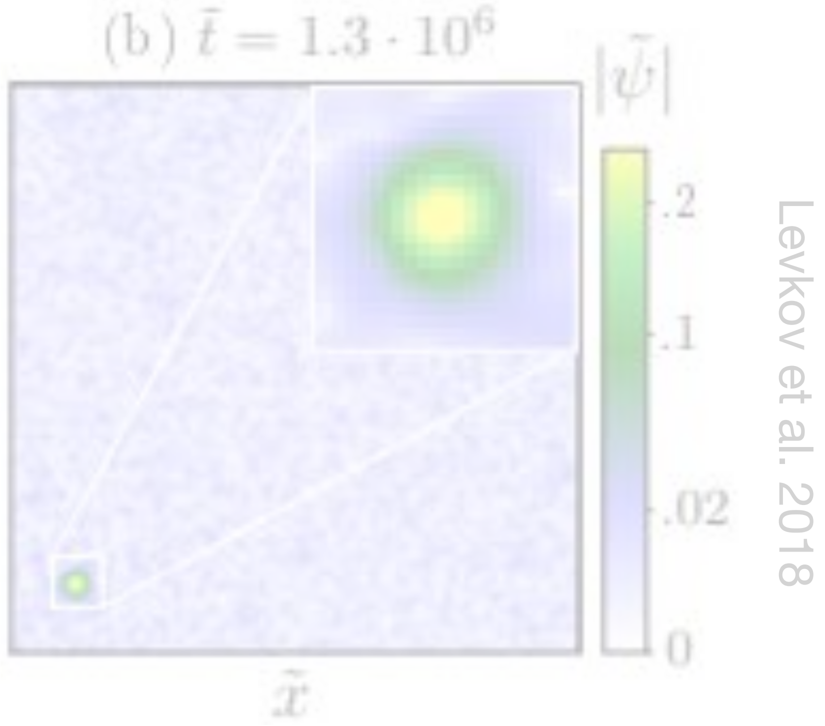


S. May et al. 2021

Formation of a solitonic core

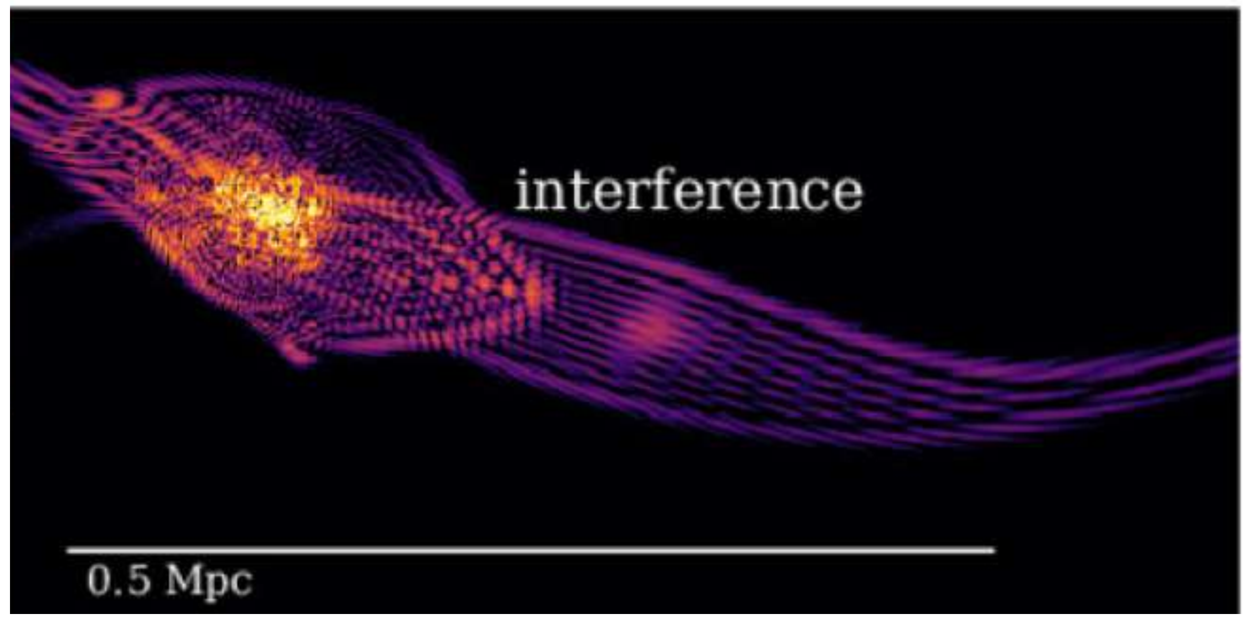


Dynamical effects



Levkov et al. 2018

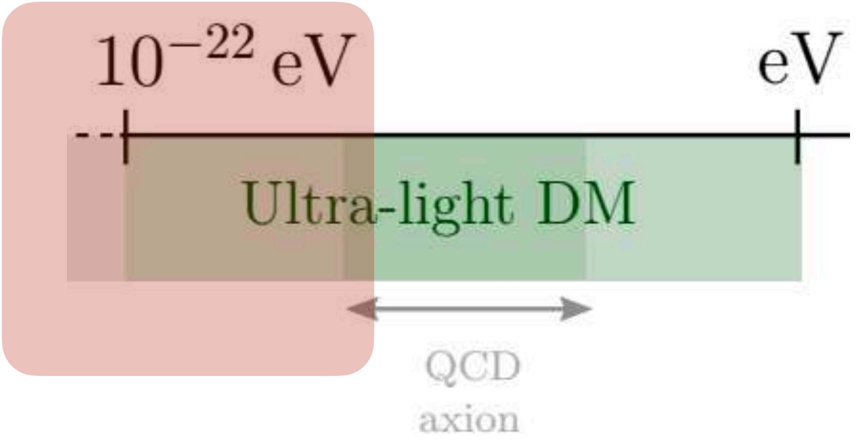
Wave interference

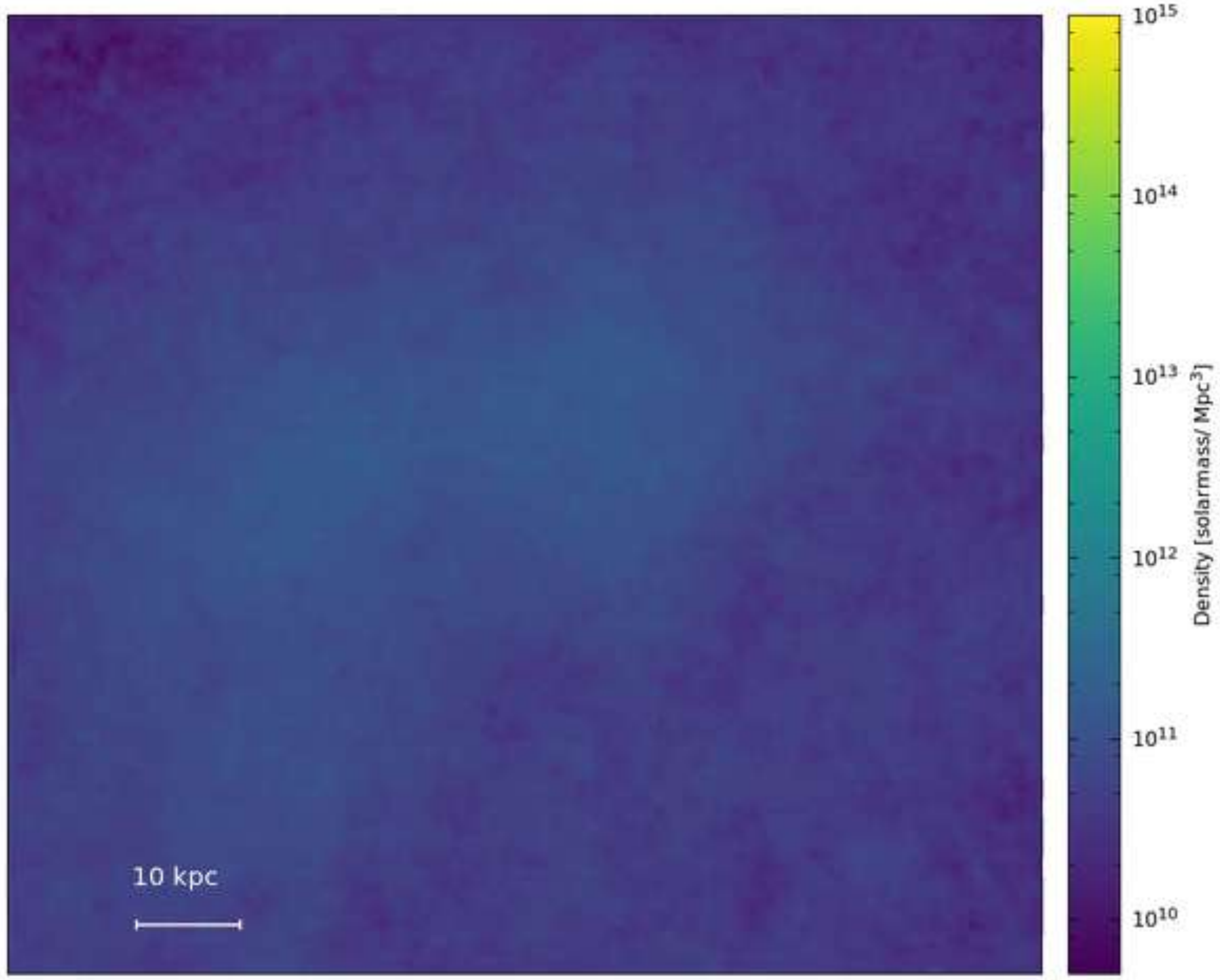


Mocz et al. 2017

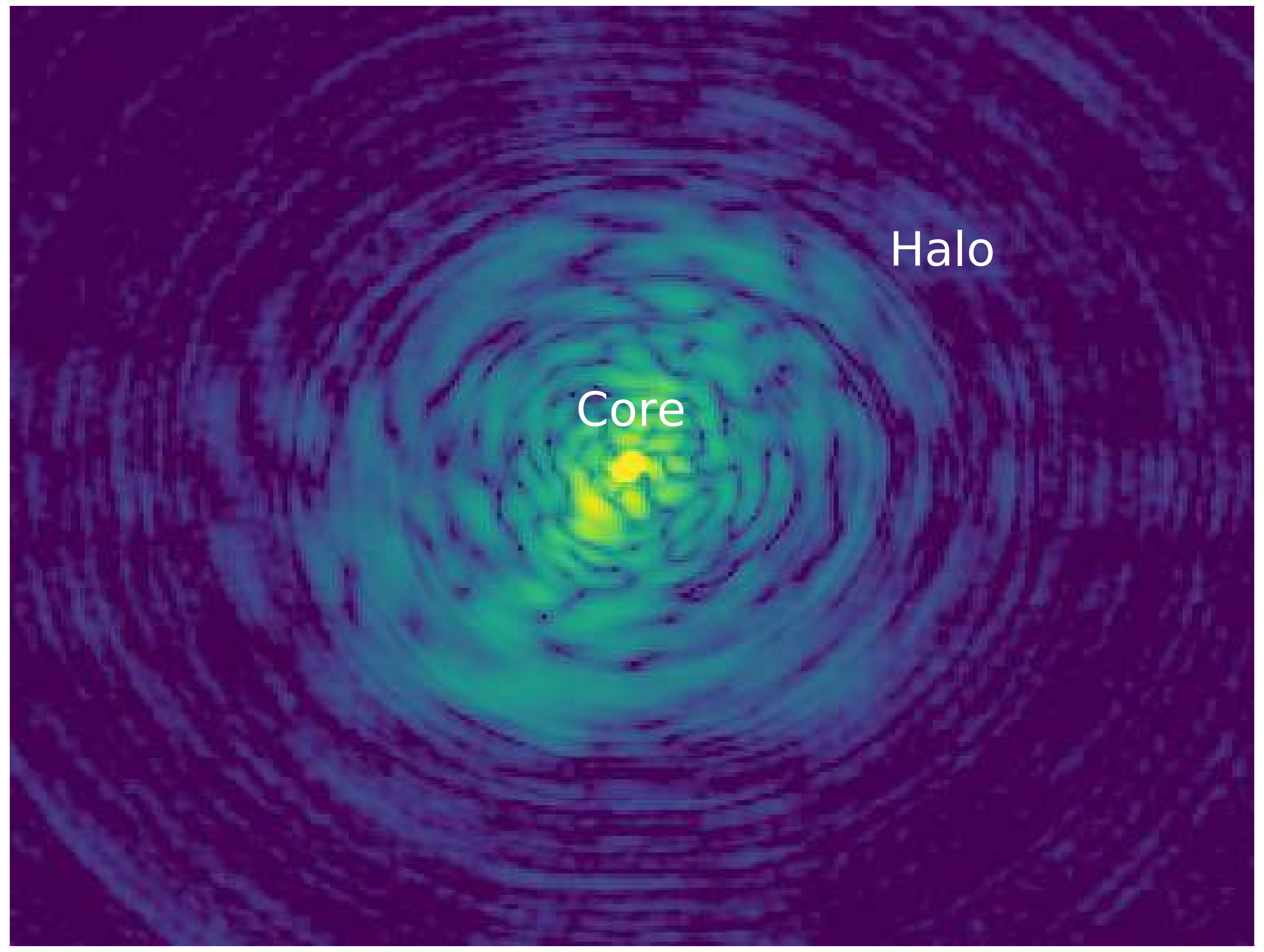
Phenomenology

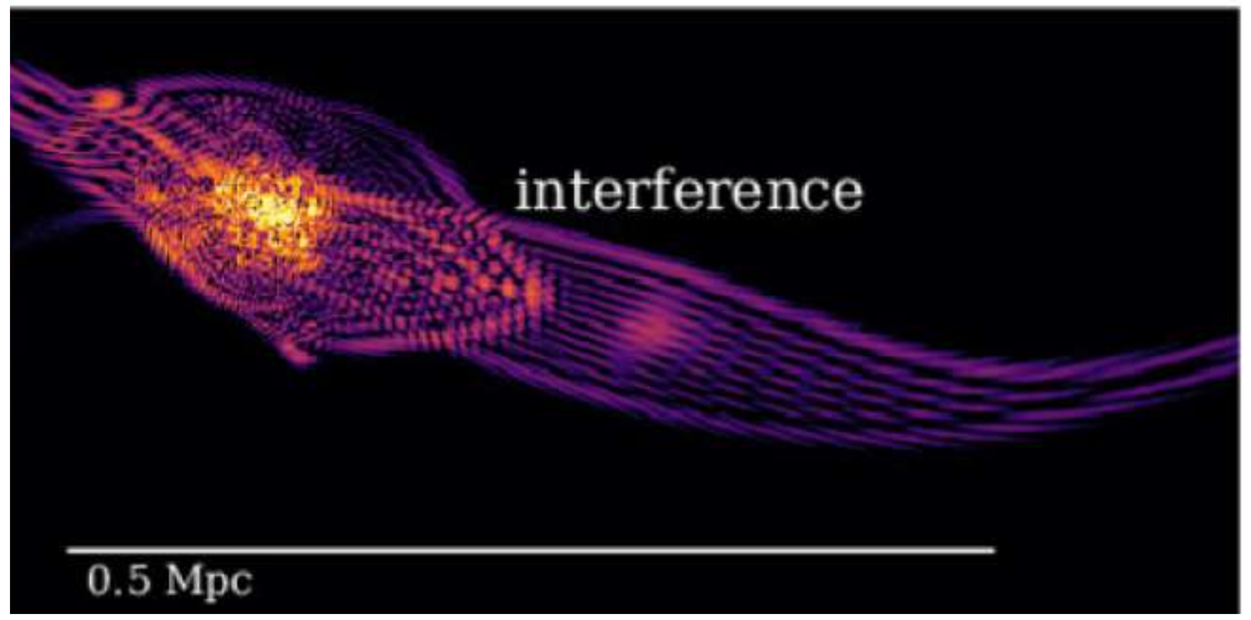
Wave interference: granules and vortices





Simulation by Jowett Chan





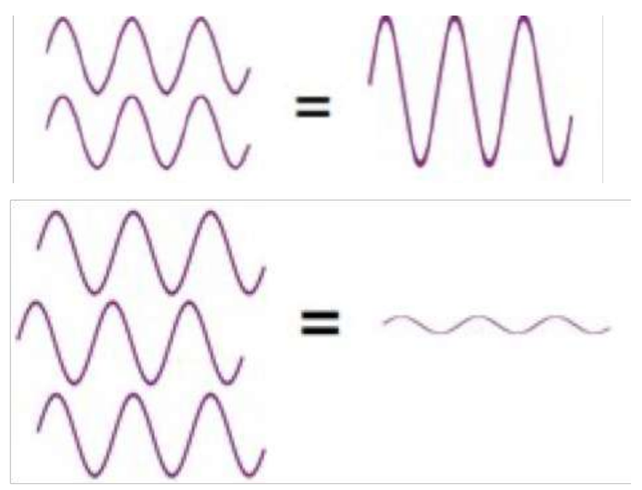
Mocz et al. 2017

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

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

Vector, higher spin or multicomponent FDM

Interference patterns

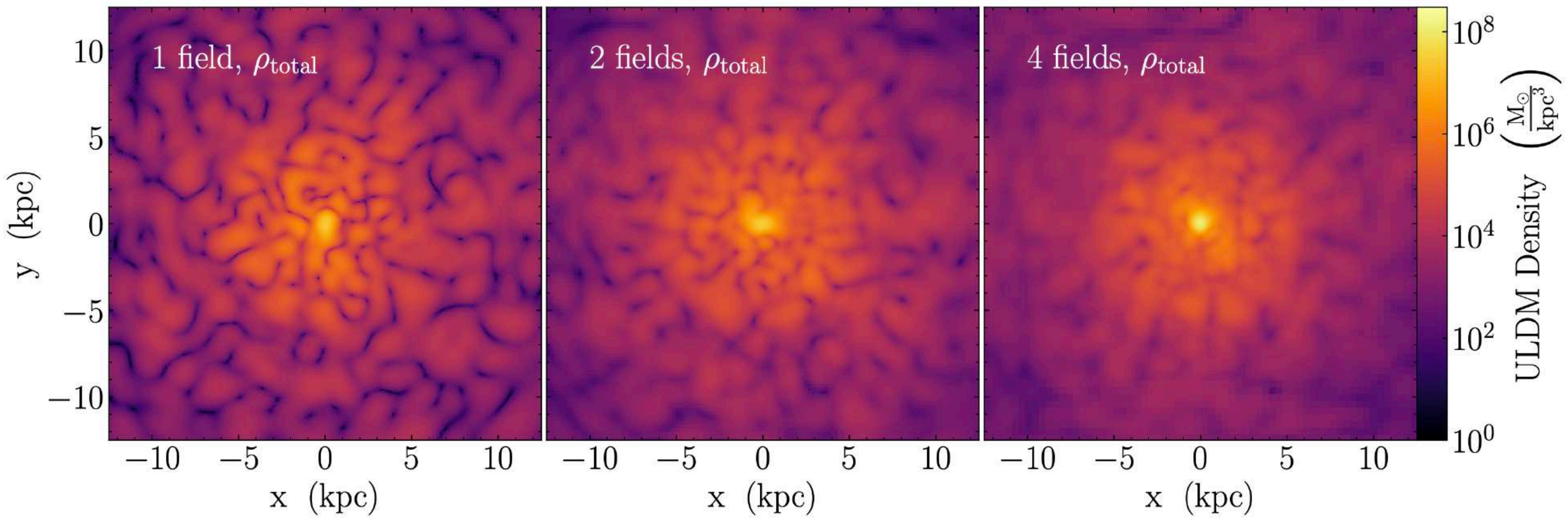


ULDM or ULA are a coherent wave - same frequency and constant phase difference

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)

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

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

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

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

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

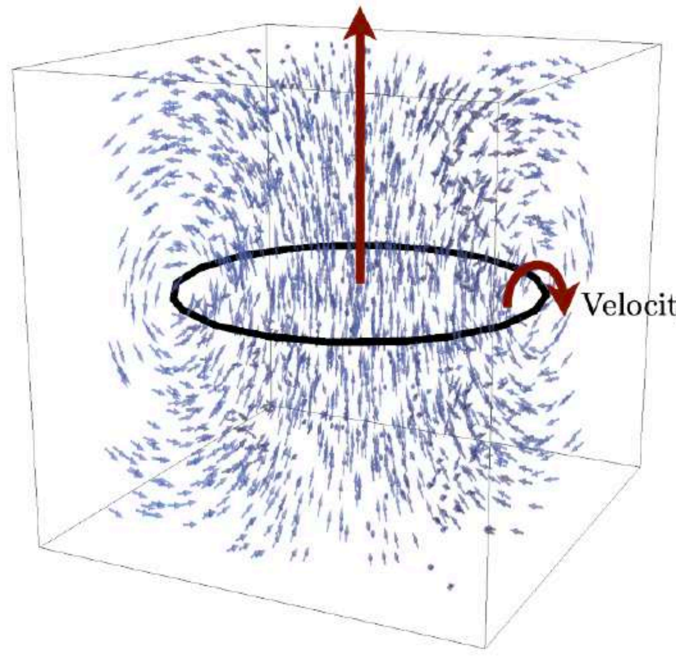
Two ways:
- regions where the density vanishes
- transfer of angular momentum (superfluids only)

Fuzzy DM

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

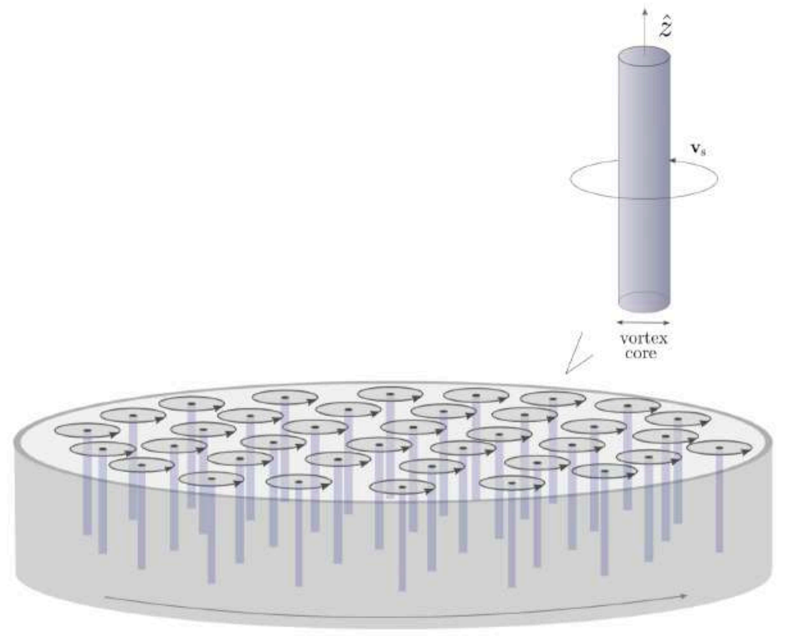
General defet in 3D

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



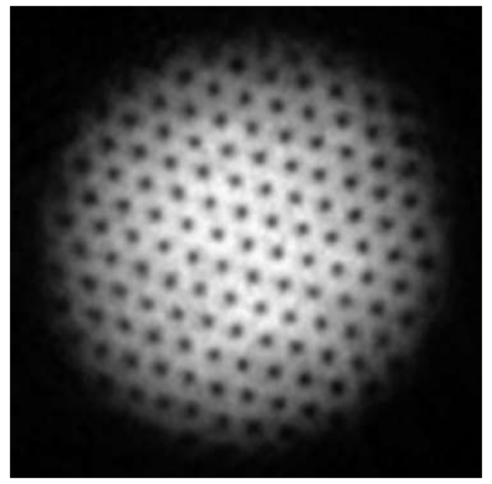
Self-interacting Fuzzy DM

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

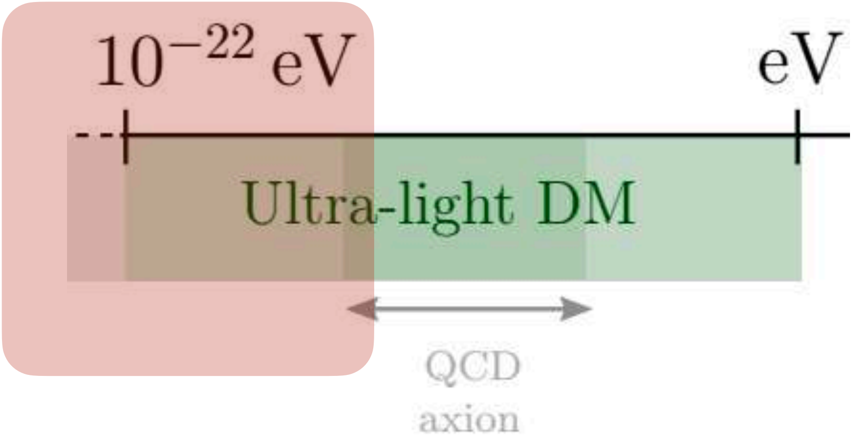


EF, 2020

© Martin Zwierlein.

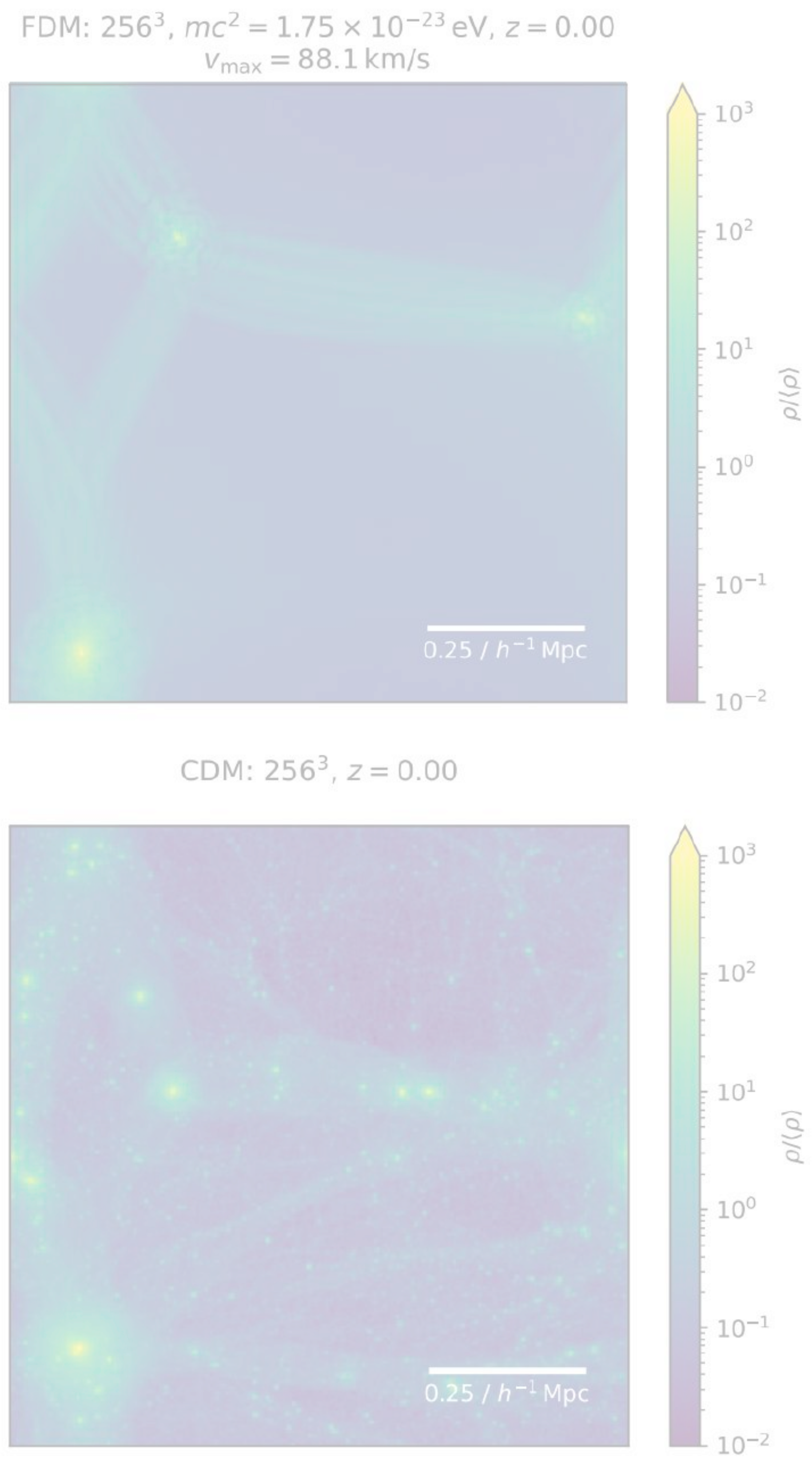


Phenomenology



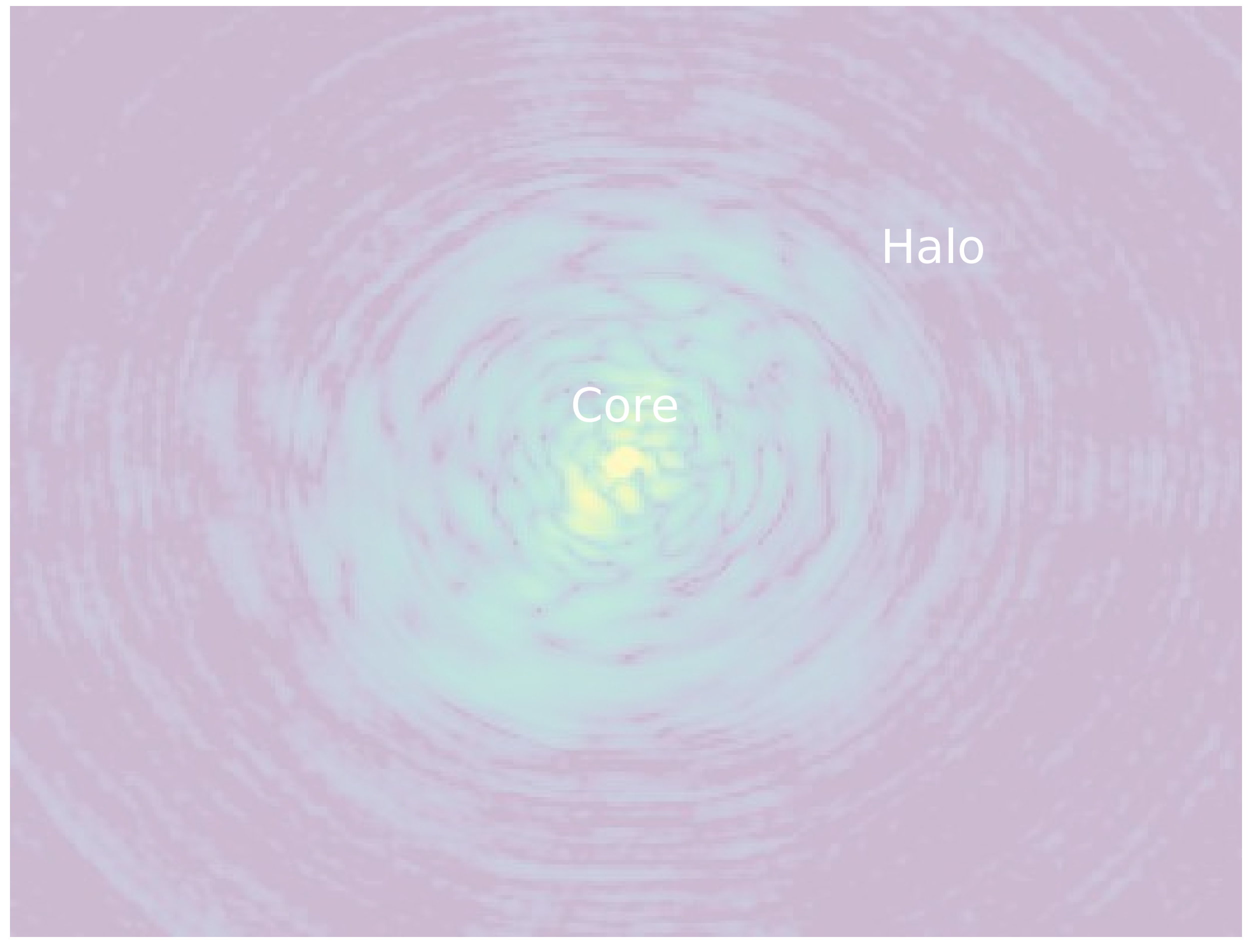
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

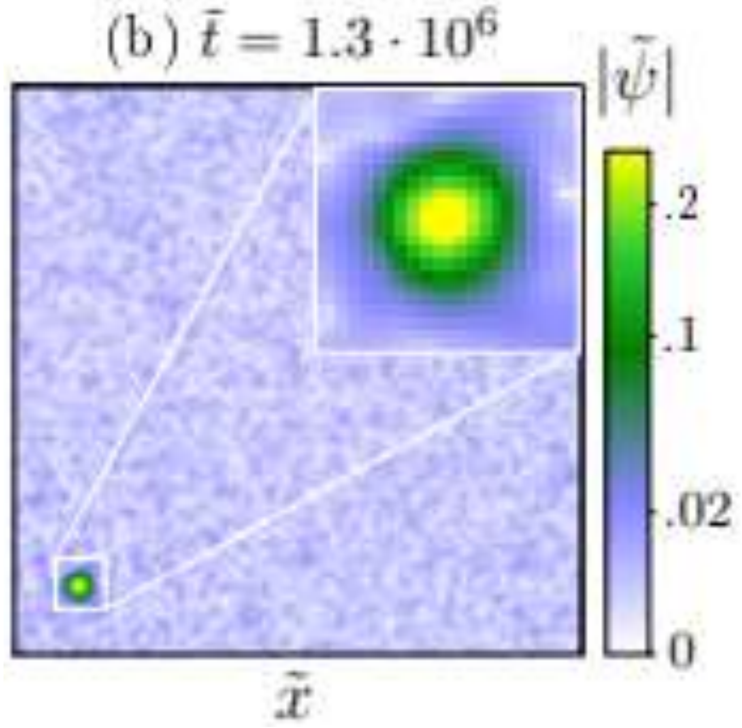


S. May et al. 2021

Formation of a solitonic core



Dynamical effects



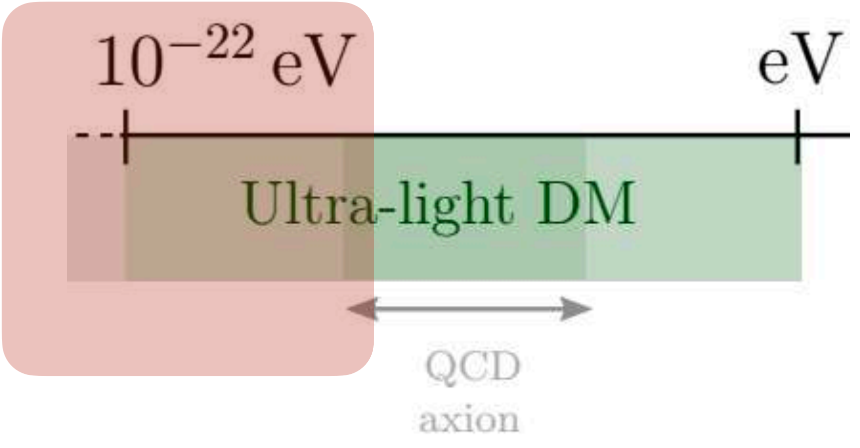
Levkov et al. 2018

Wave interference

Mocz et al. 2017

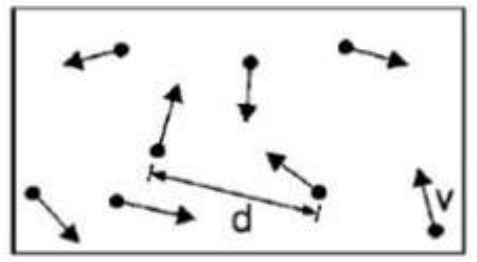
Phenomenology

Dynamical effects

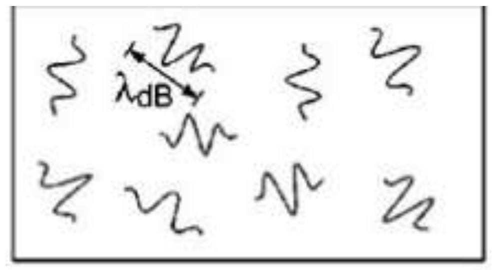


Relaxation, oscillation, friction, and heating

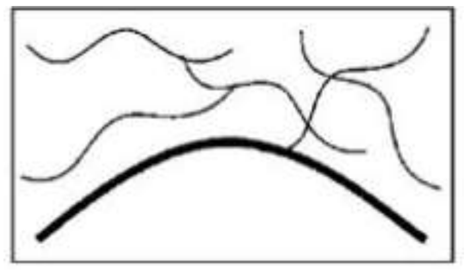
Bose Einstein Condensate



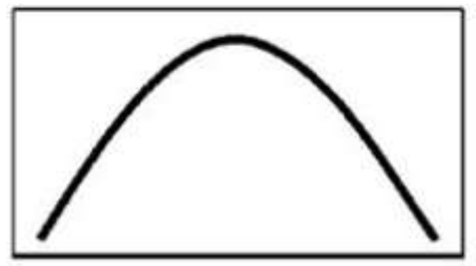
High temperature
Thermal velocities



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

<u>Description</u>

Mean field approximation:
Large N, dilute

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

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

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

classical field "wavefunction of the condensate"

small perturbation: describes depletion of the condensate

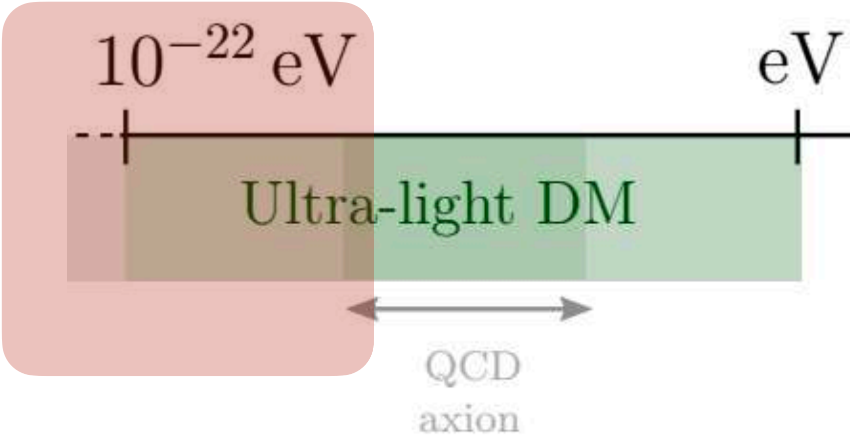
Credit: Peking University

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

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.

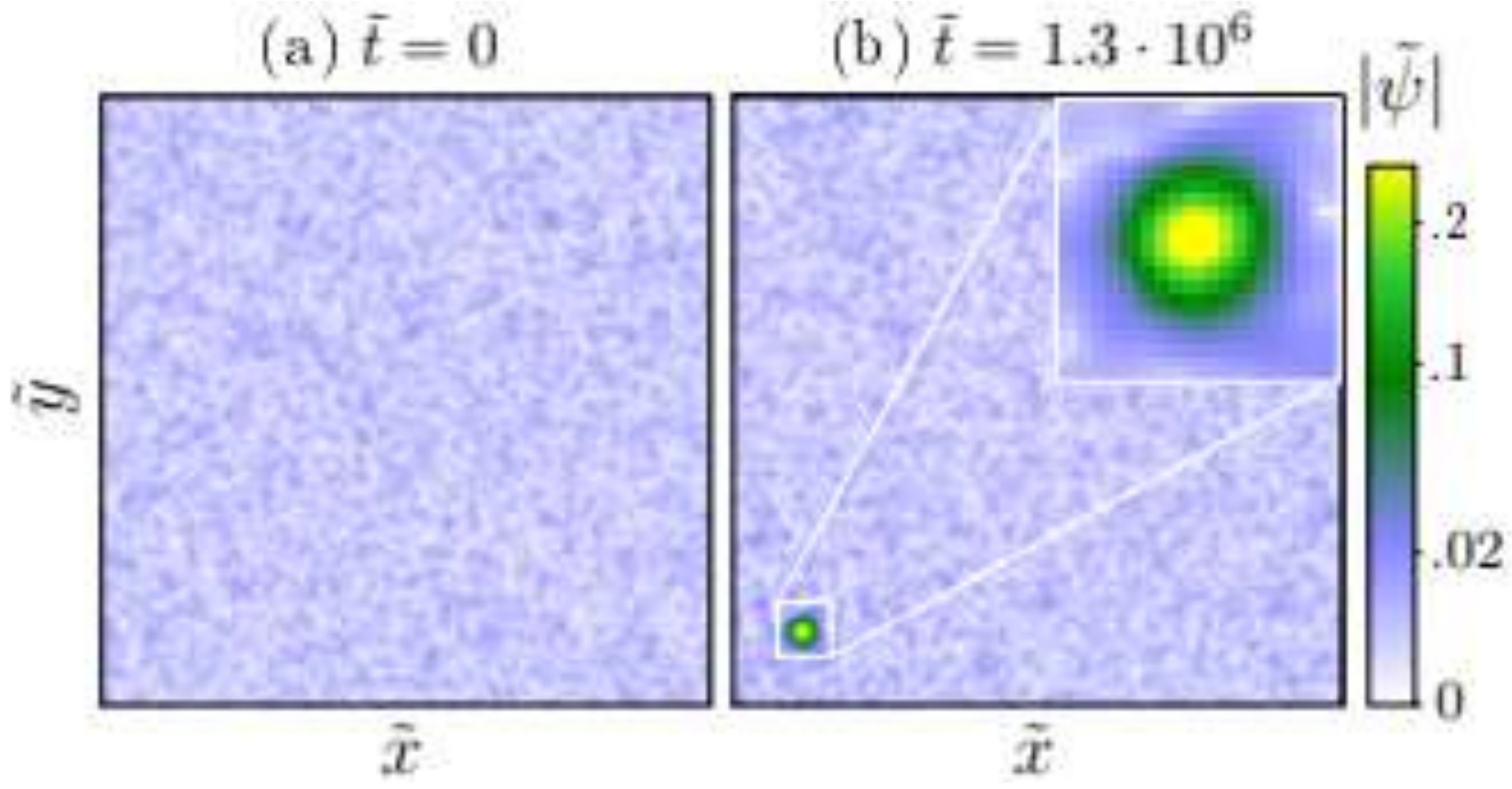
Condensation/relaxation time: $\tau_{\rm gr} \gg \tau_{\rm int}$

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

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

Smaller than the age of the universe!

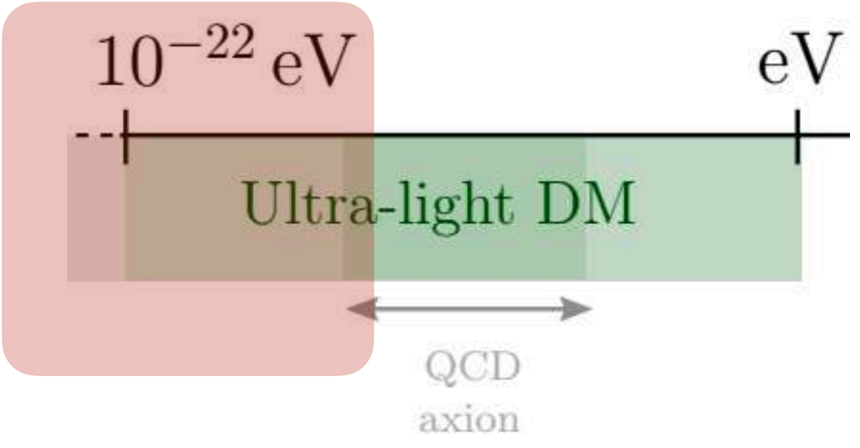
Wave turbulence theory



Levkov et al. 2018, Kirpatrick et al. 2020

Phenomenology

Dynamical effects



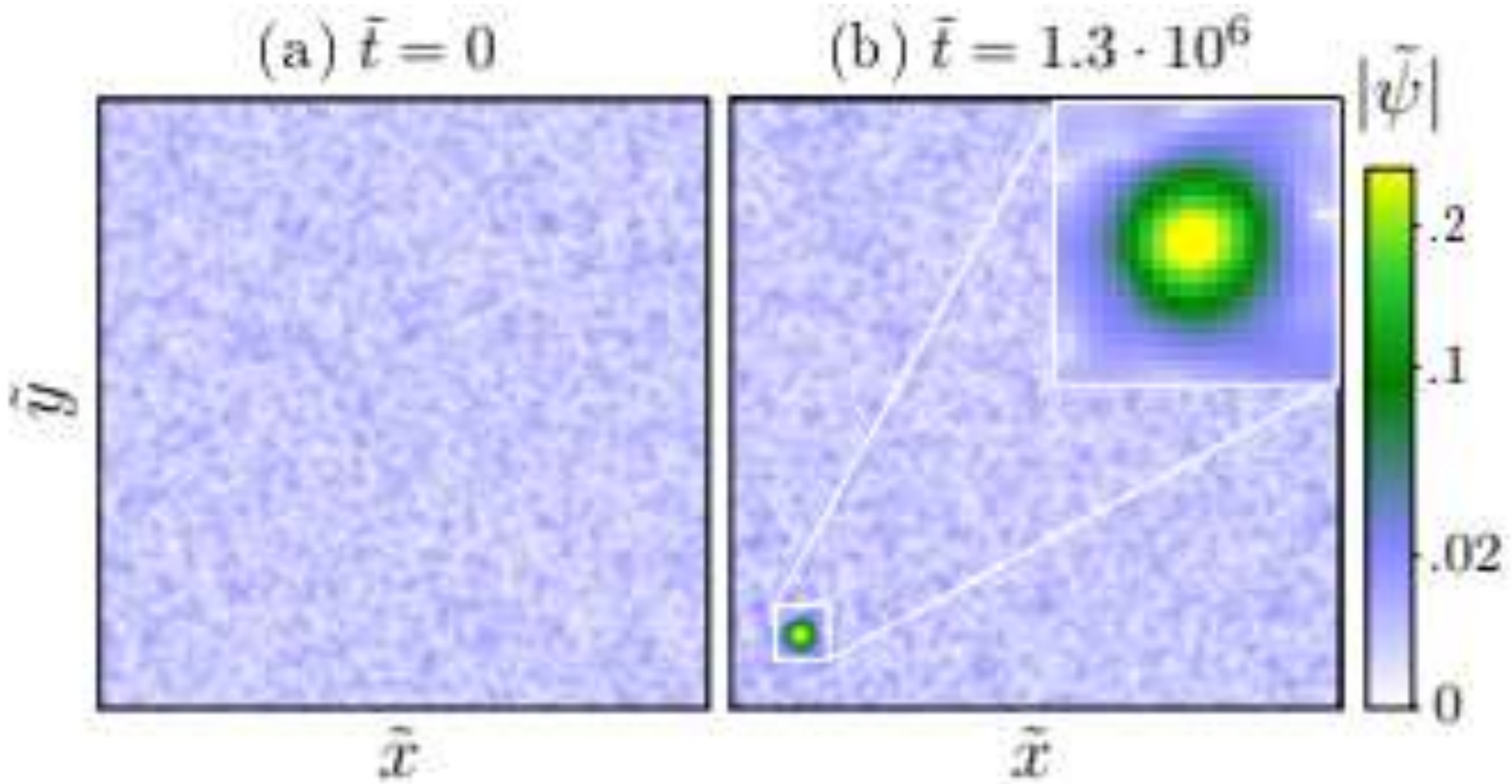
Relaxation, oscillation, friction, and heating

Formation of a BEC / superfluid

Open question!

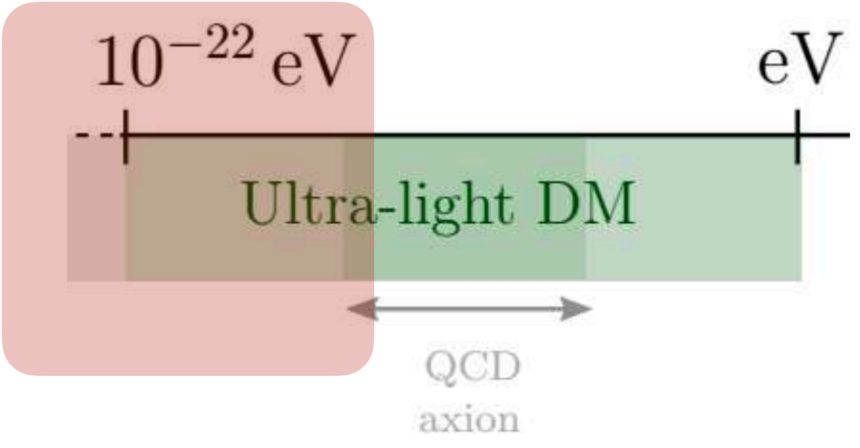
- Need theoretical work to describe *analytically* the formation of these solitons

- Cosmologically, classical or quantum field?

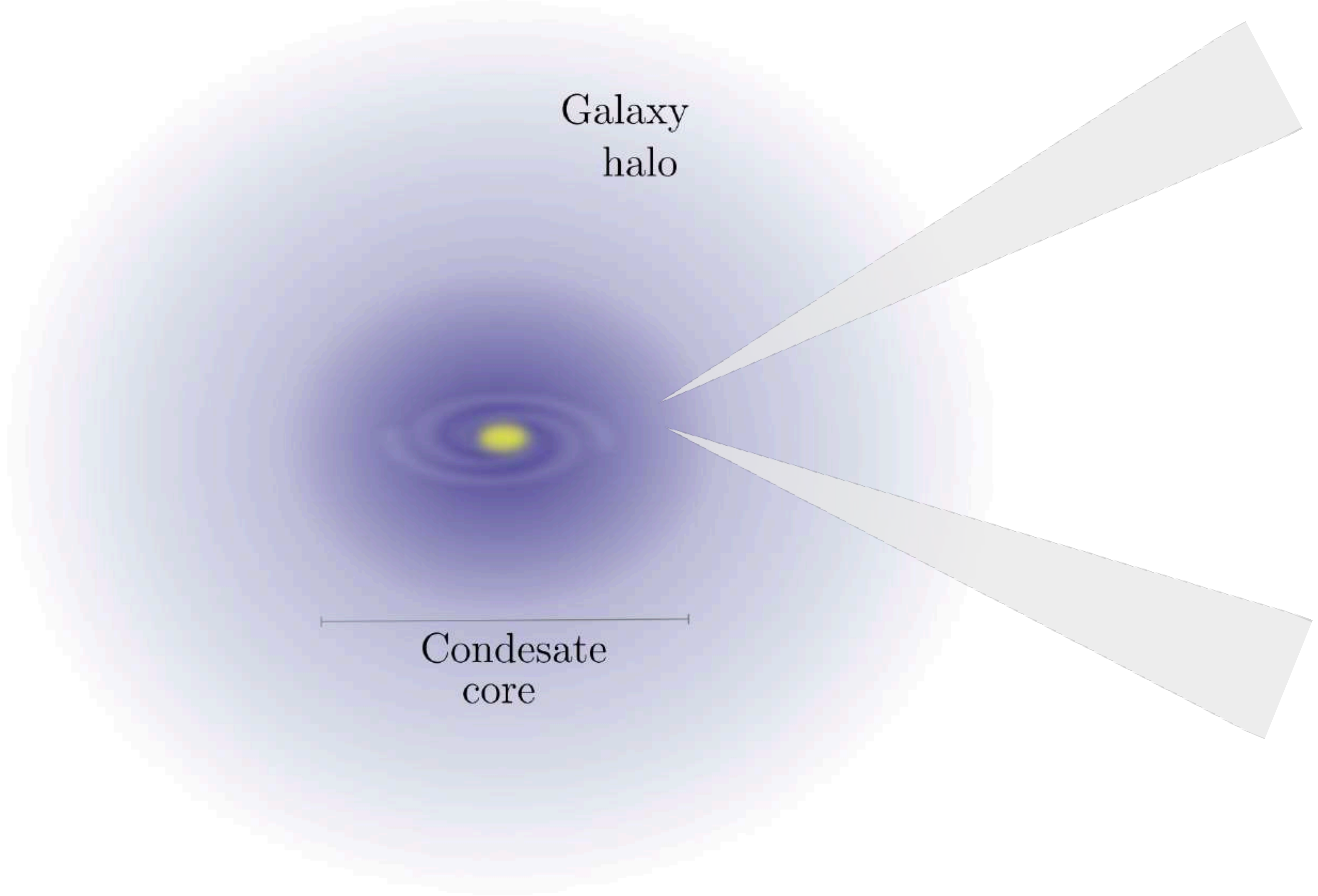


Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

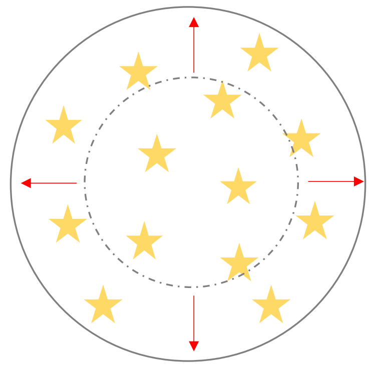


Heating

FDM granule

m_{eff}

System (star)
gains energy



Friction

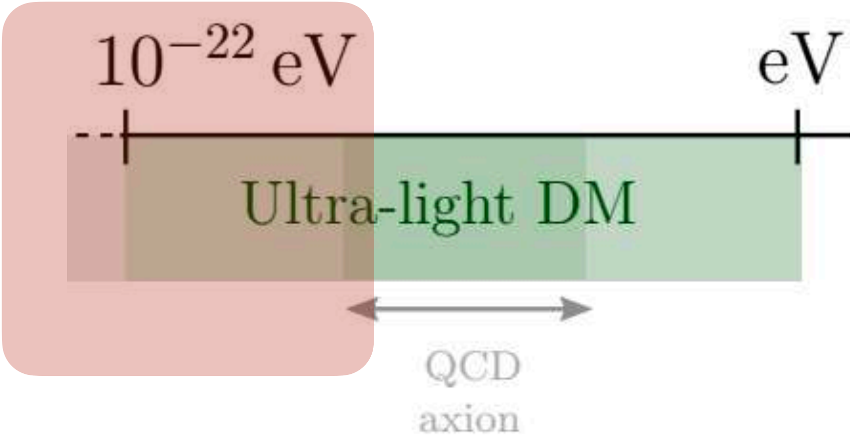
FDM granule

m_{eff}

Globular cluster

System (GC or BH)
loses energy

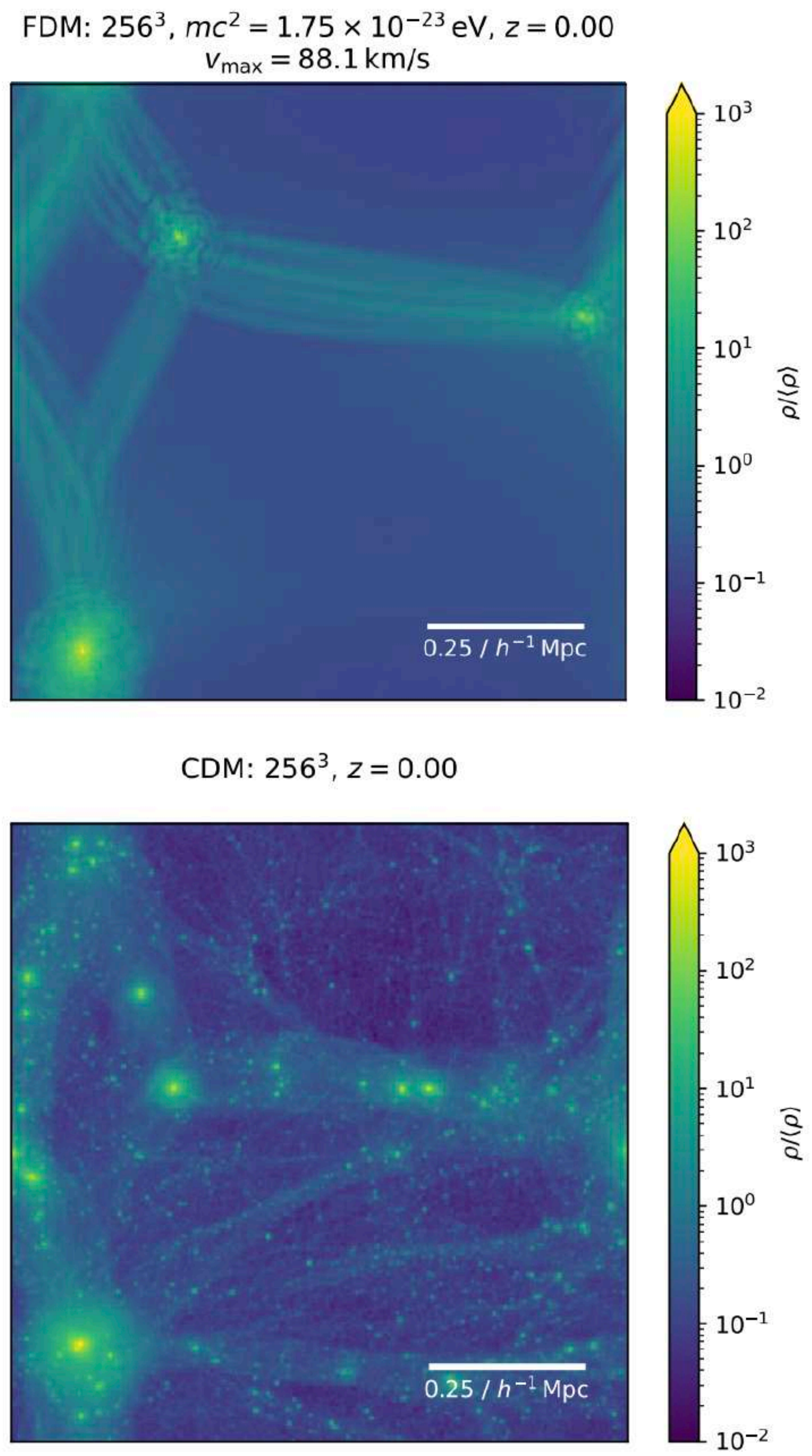
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

* Focus only in gravitational signatures

Suppression of small structures



S. May et al. 2021

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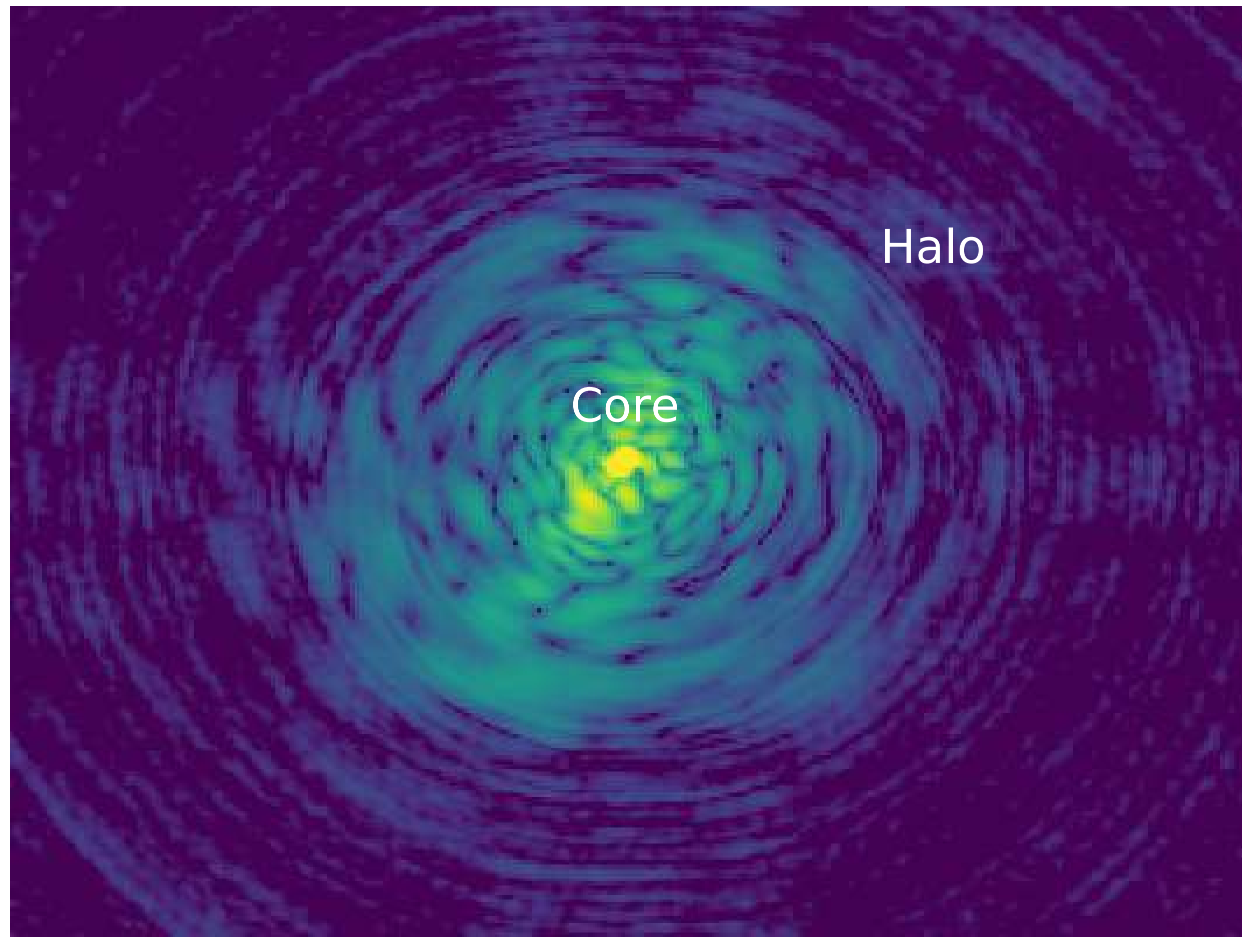
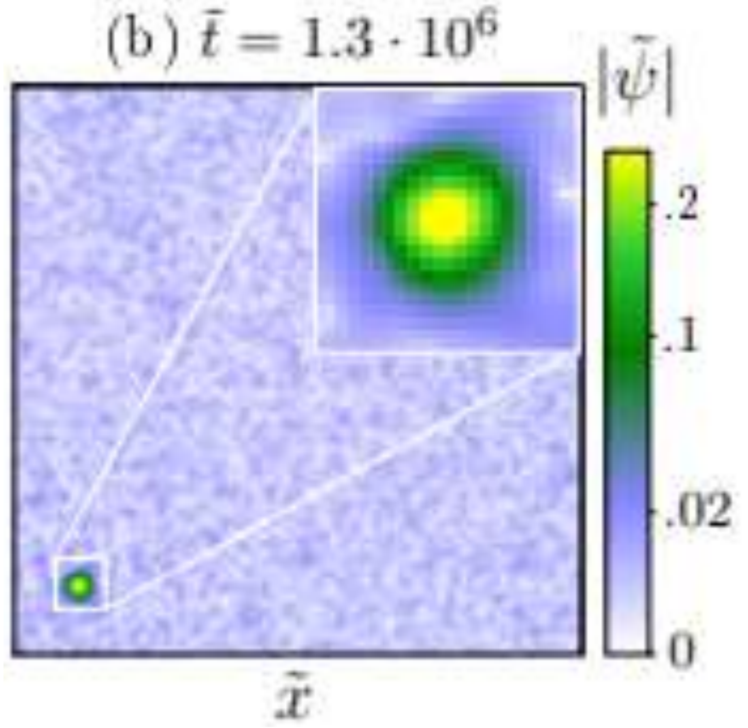
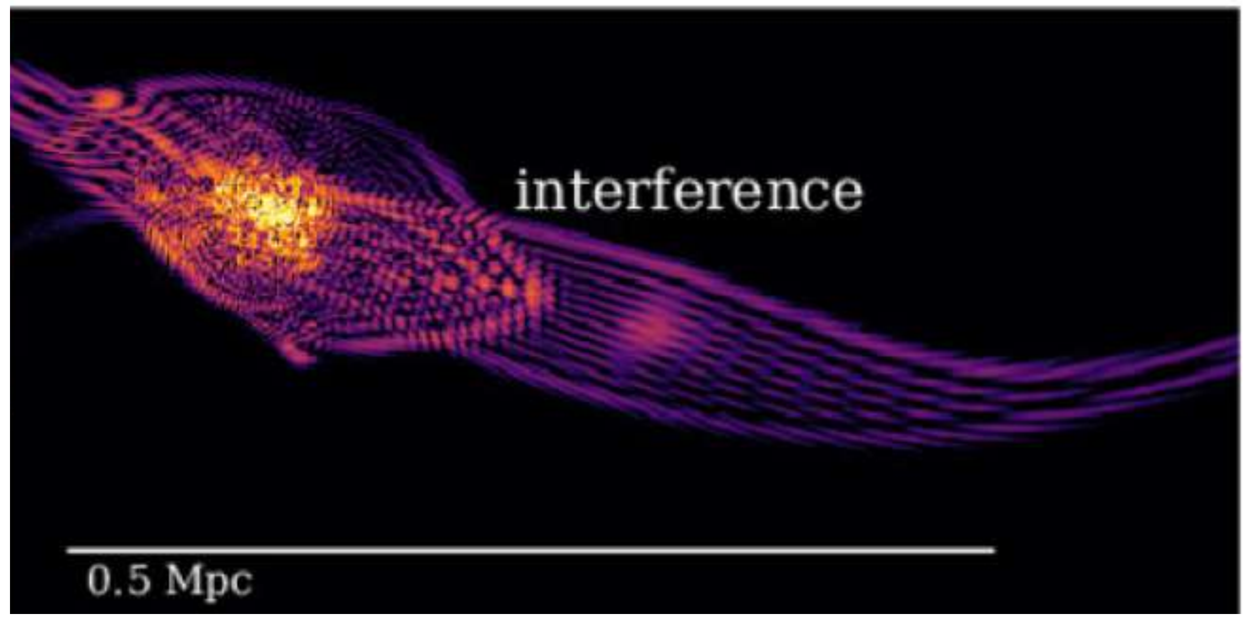


Dynamical effects



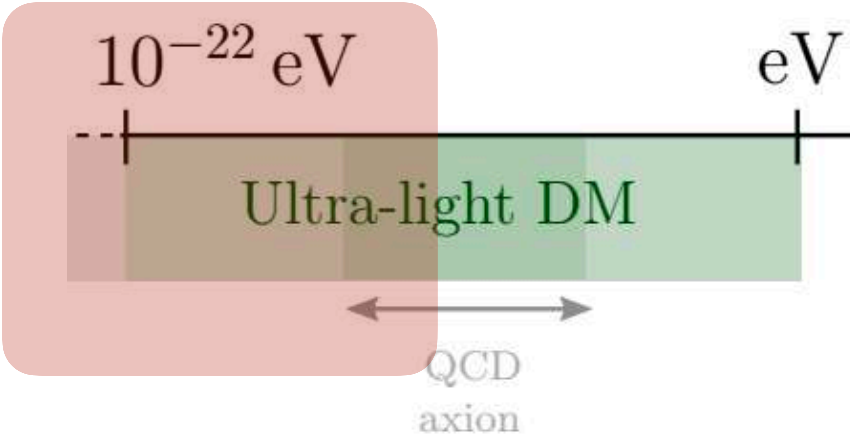
Levkov et al. 2018

Wave interference



Mocz et al. 2017

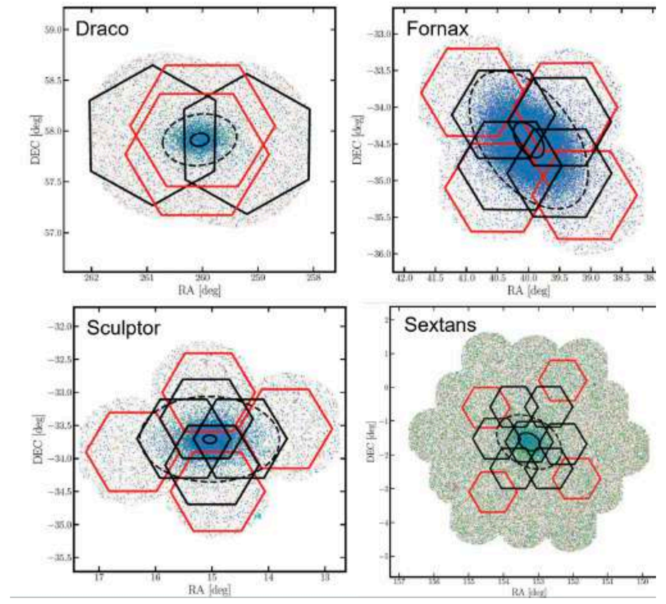
Observational implications and constraints



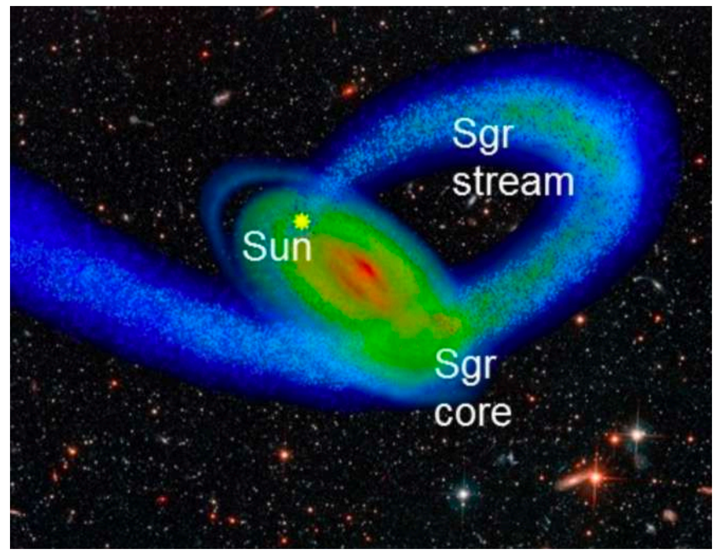
Galaxies

NASA and ESA

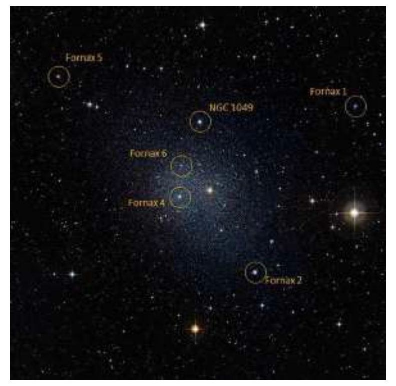
Dwarfs



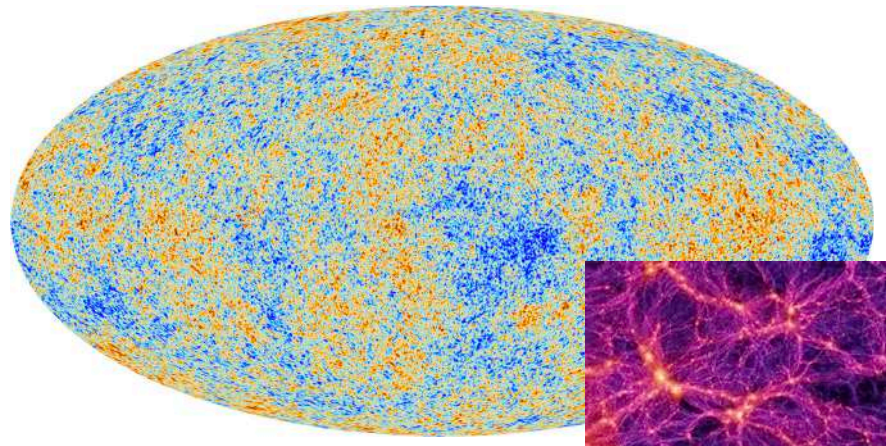
Stellar stream



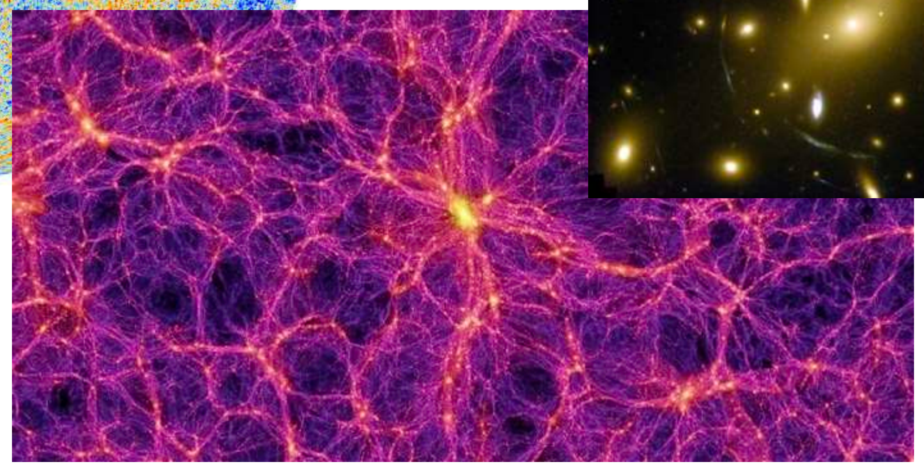
Globular clusters



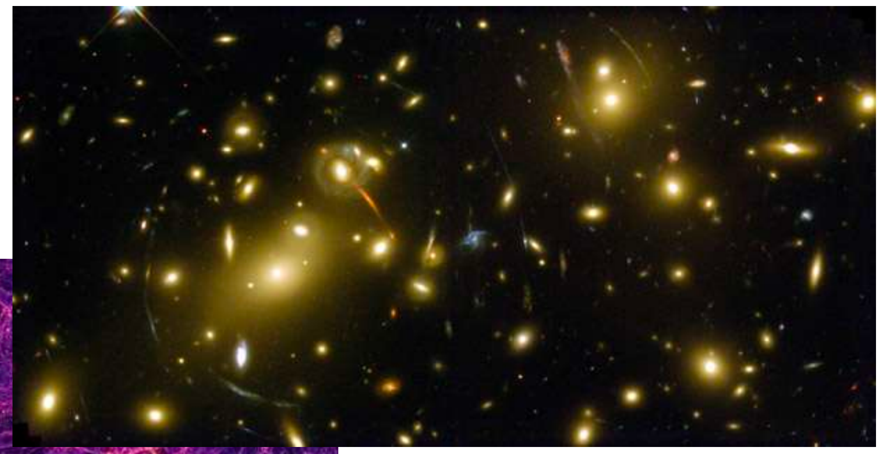
CMB+LSS



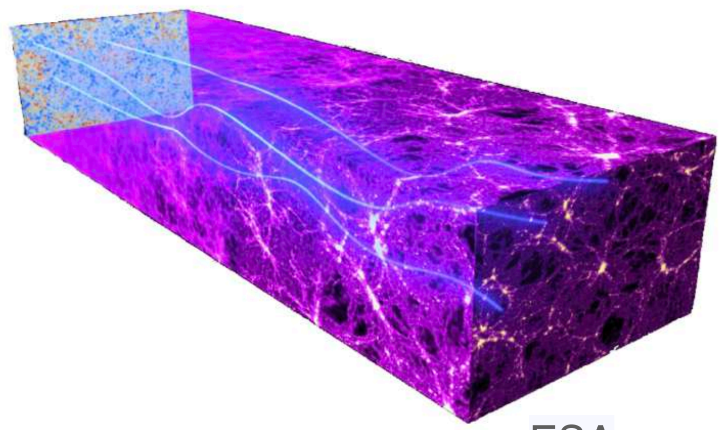
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

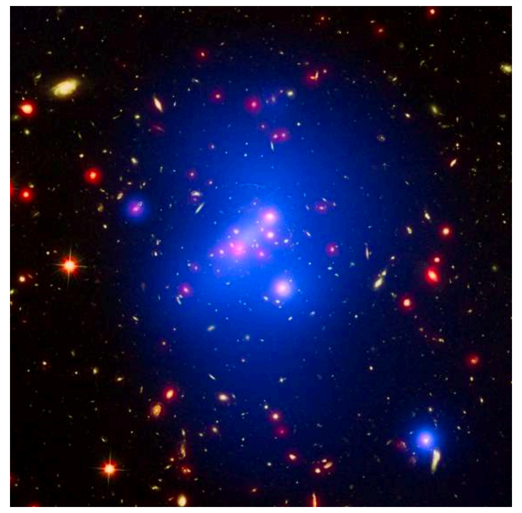


NASA and ESA



ESA

Clusters



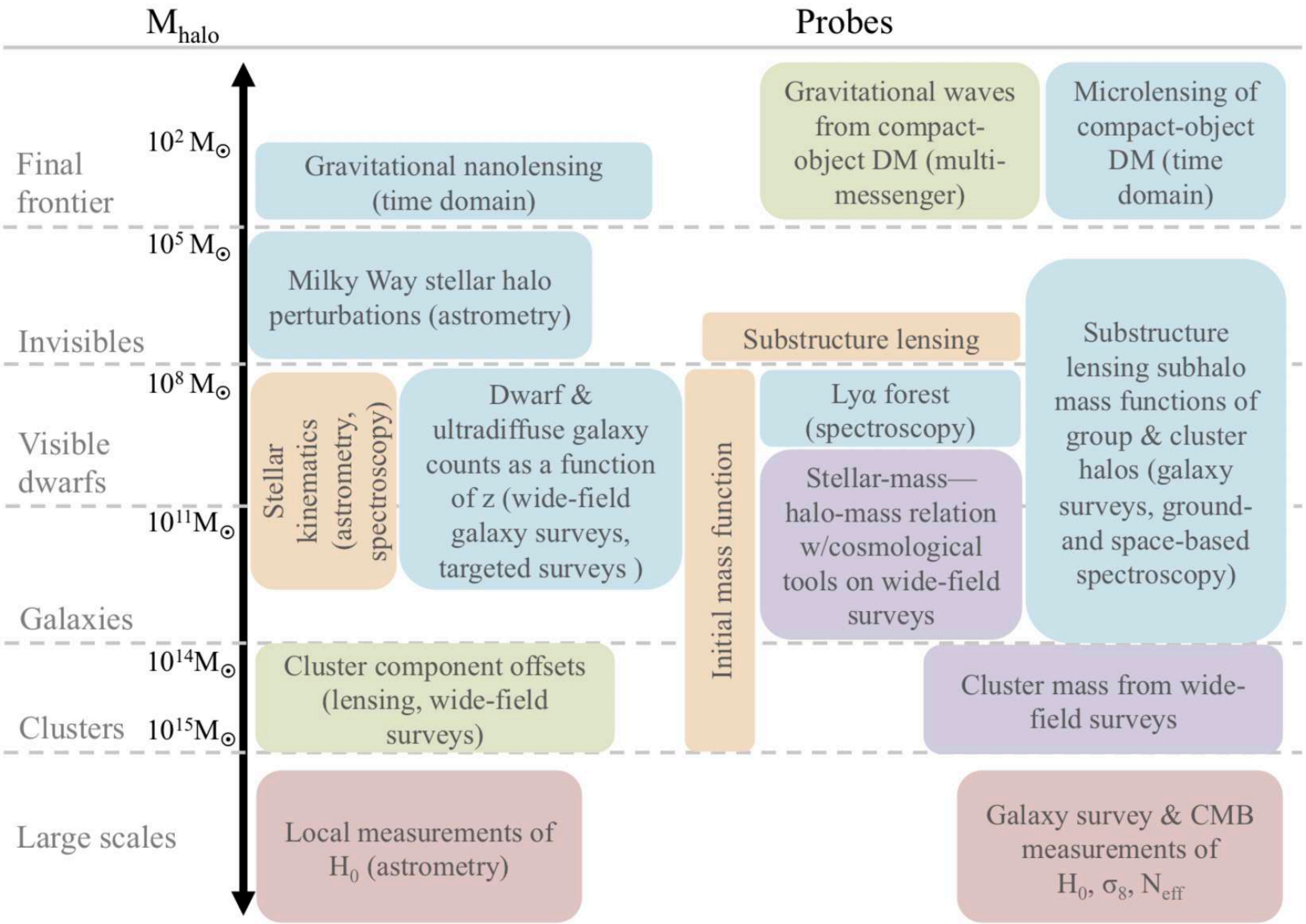
interlude

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*

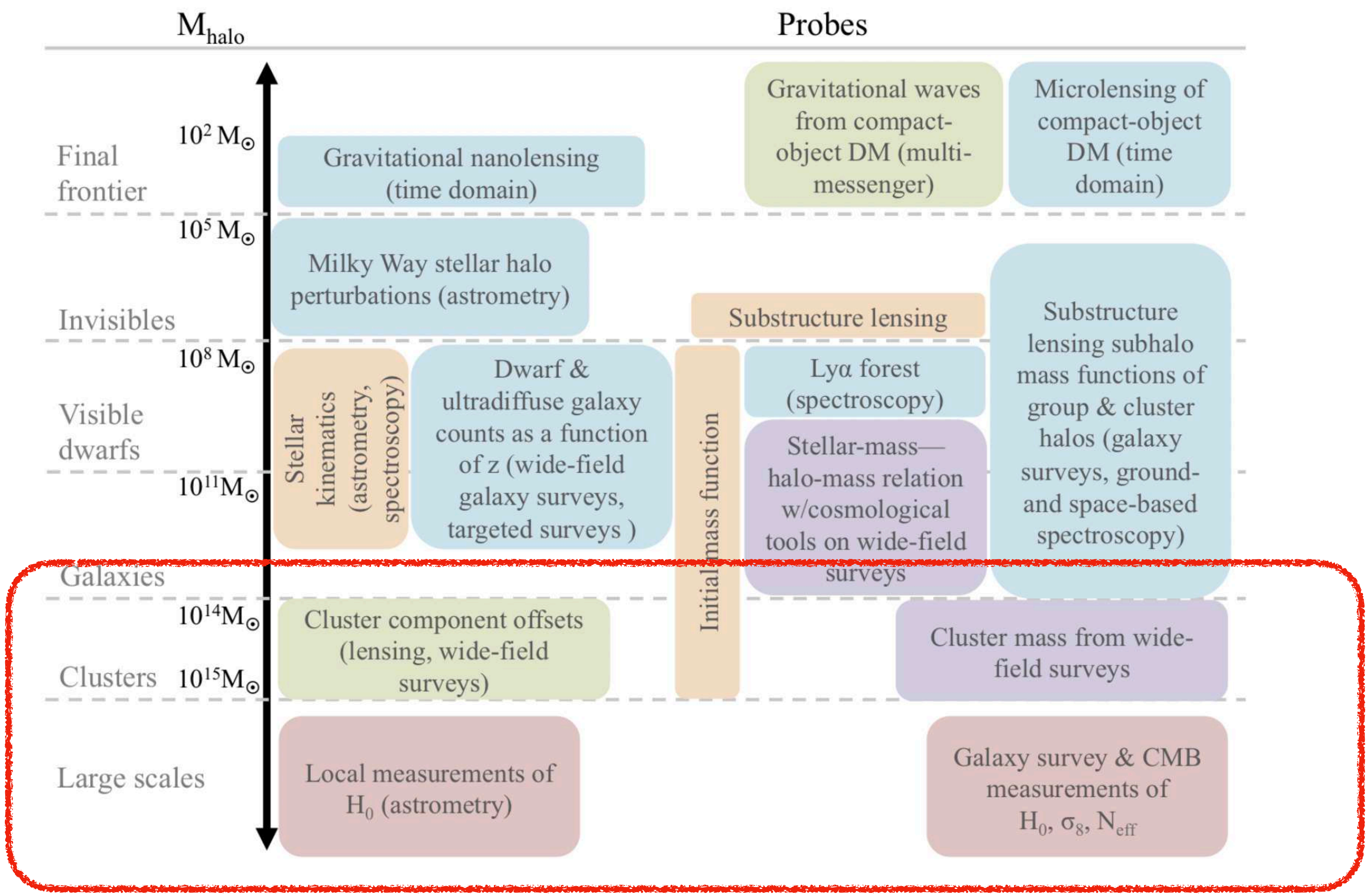


Buckleya et al 2017

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

Planck

SDSS
DES
HSC
KIDS
…



CMB and LSS

Highly constrained

Precise measurements

Buckleya et al 2017

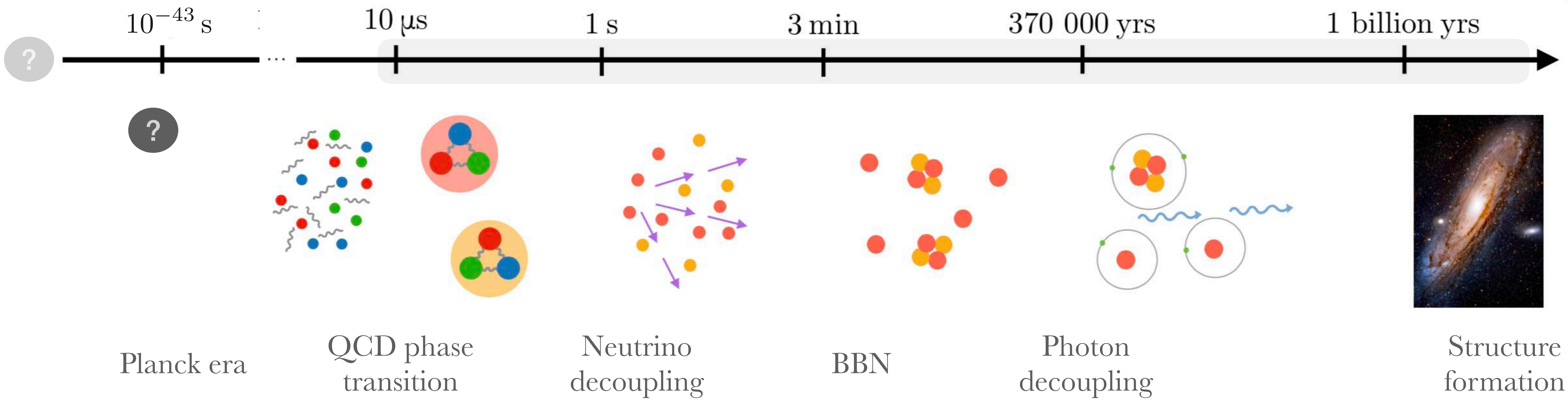
*Cosmological and astrophysical **probes** of dark matter*

CMB and LSS

Thermal history of the universe

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

SCM



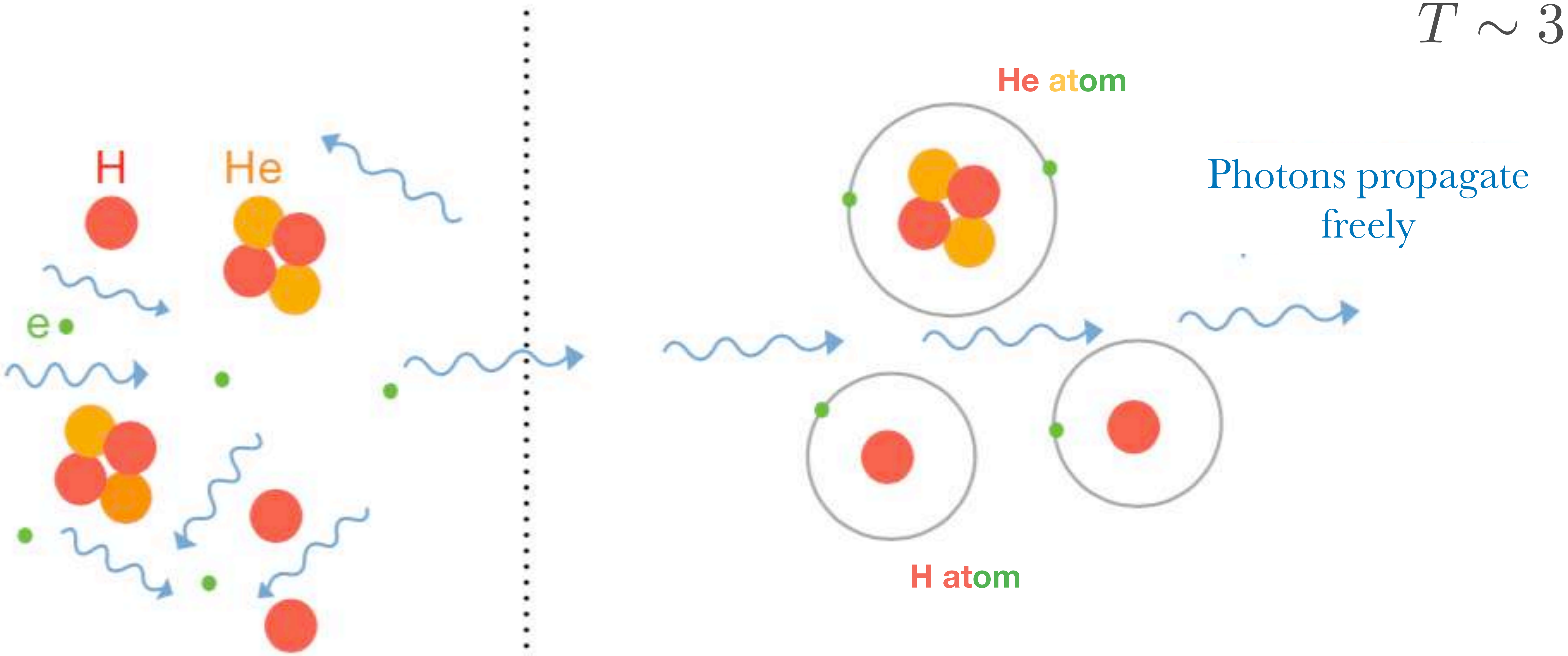
Crédito: D. Baumann

- (Most of them) observationally confirmed by independent measurements

Recombination and photon decoupling

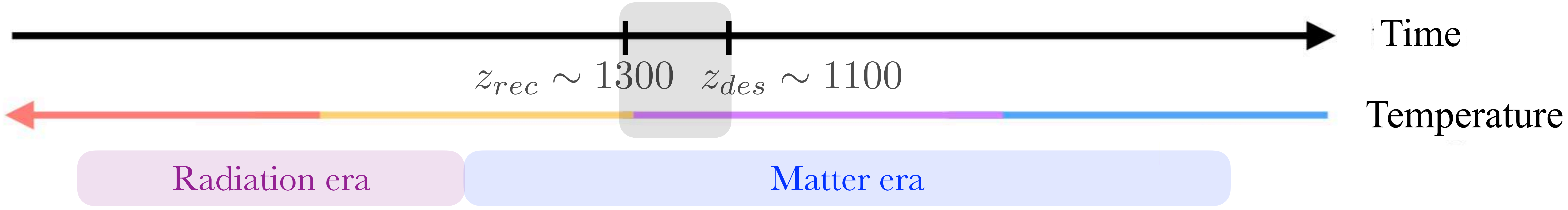
$t \sim 370000\,\mathrm{yrs}$

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



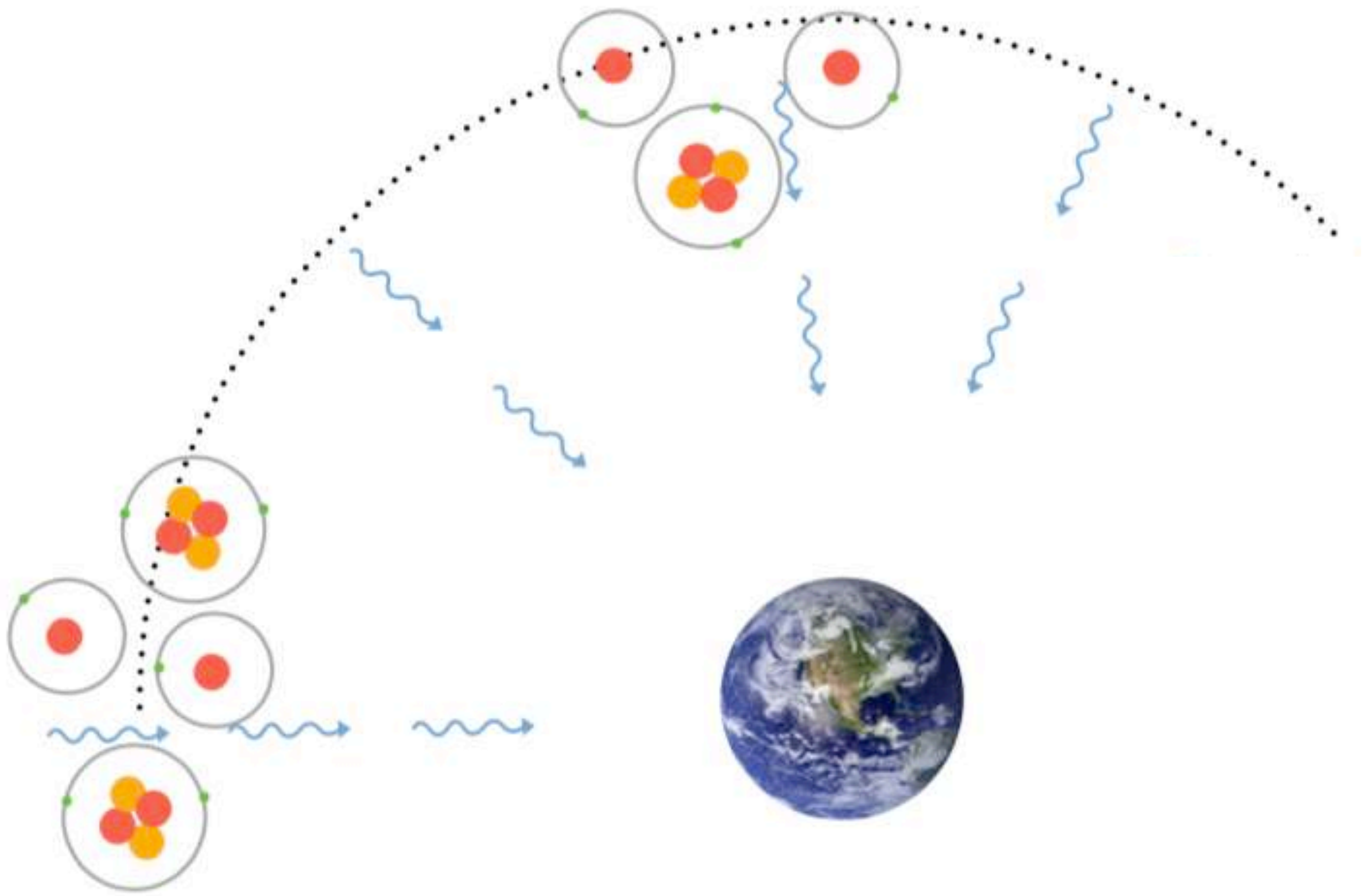
Plasma ("soup") of coupled H, He, elétrons and radiation - thermal equilibrium
- universe is opaque: radiation cannot scape!

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



Crédito: D. Baumann

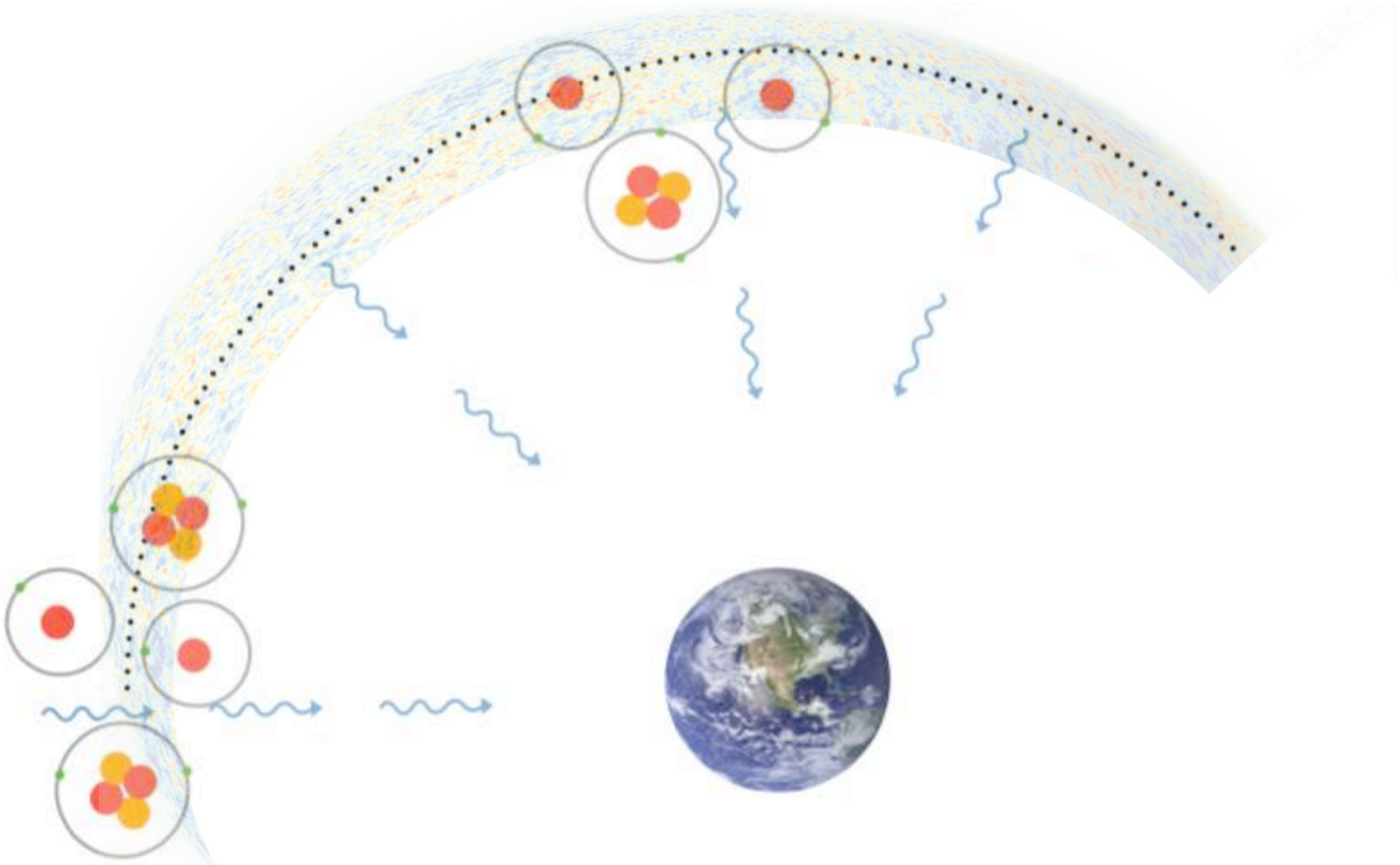
These photons are the first light of our universe…



Crédito: D. Baumann

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

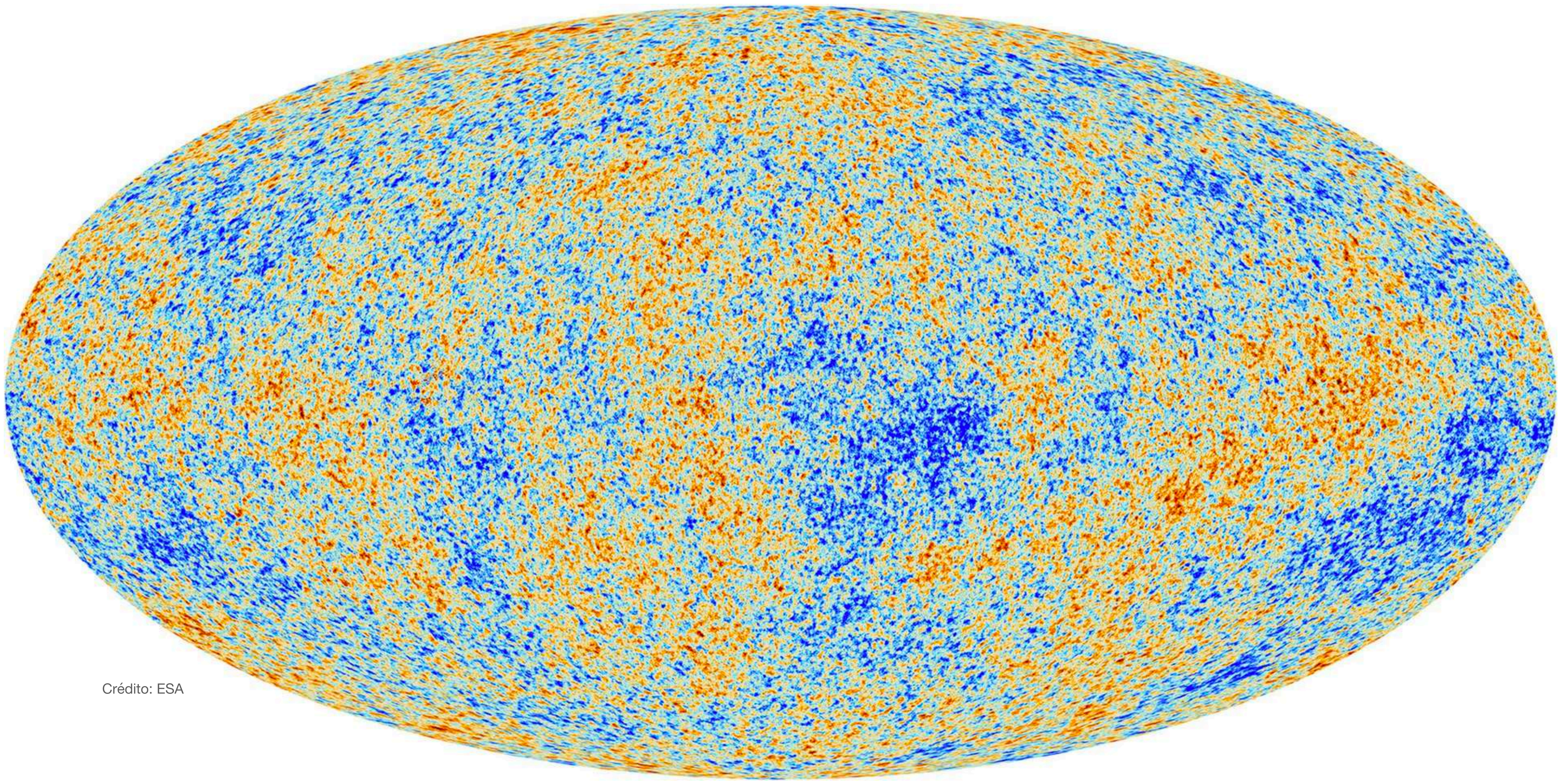
Cosmic **M**icrowave **B**ackground *(CMB)*



Crédito: D. Baumann

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

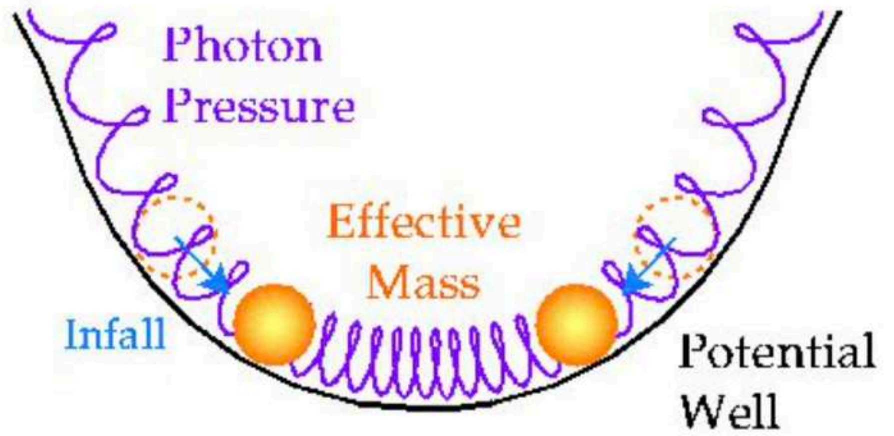
Cosmic **M**icrowave **B**ackground *(CMB)*



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

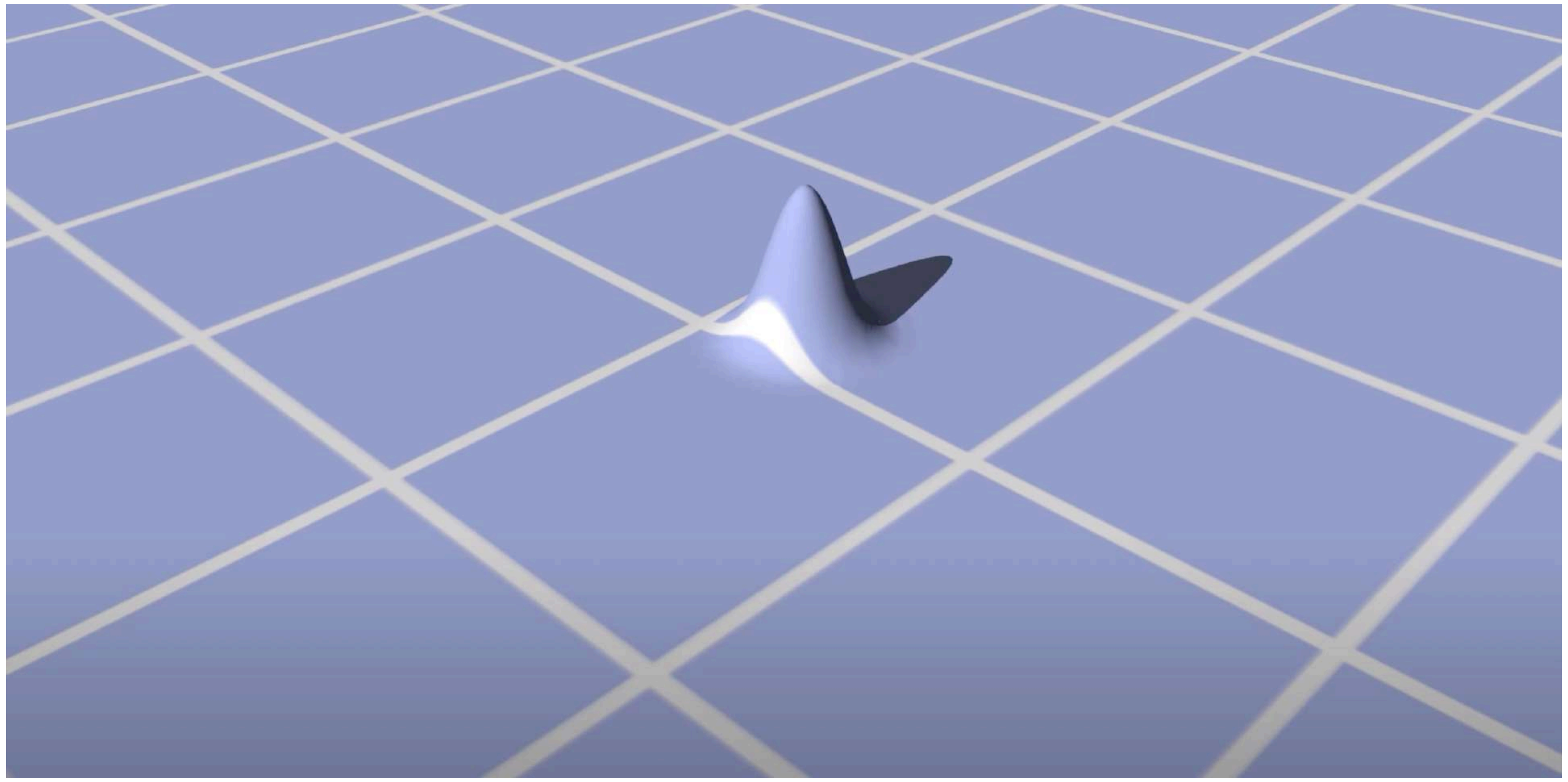
Baryon Acoustic Oscillation (BAO)

- 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)

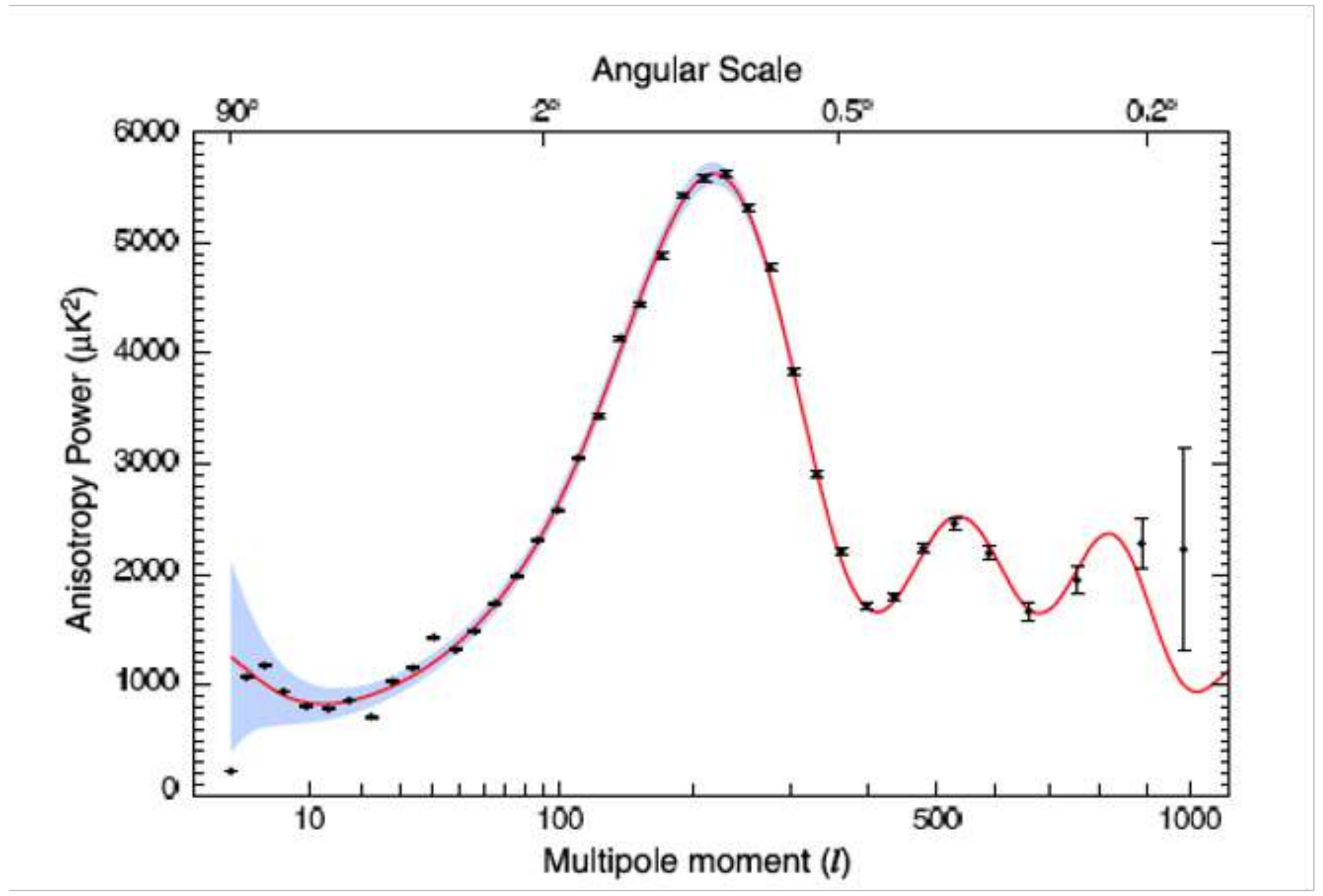
Scale known to 0.2% precision from CMB power spectrum (147.4±0.3 Mpc)



Crédito: CASTRO

Baryon Acoustic Oscillation (BAO)

Cosmic Microwave Background



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

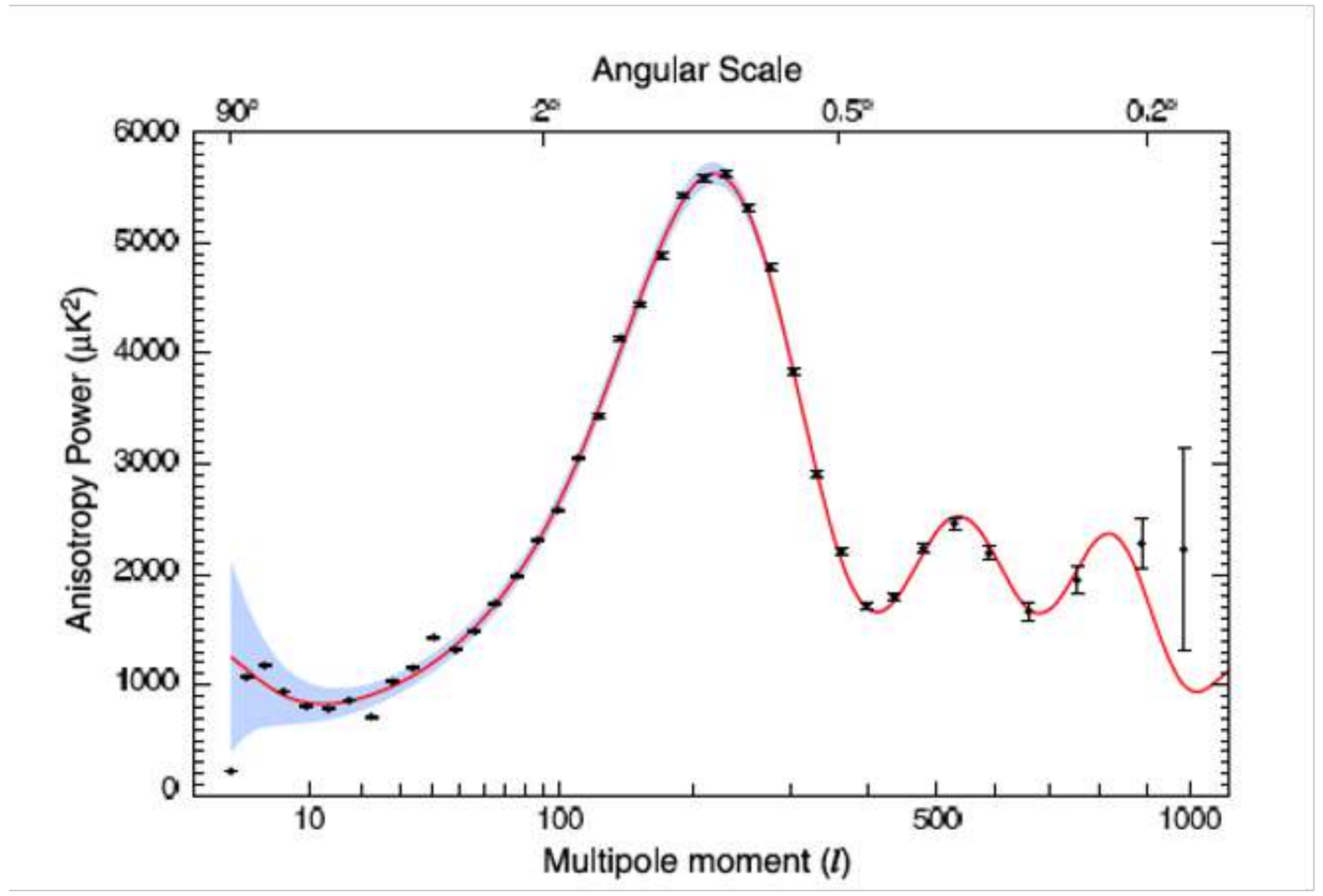
Using CMB and other LSS probes, can constraint the parameters with incredible precision.

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

Standard cosmological model - LCDM model

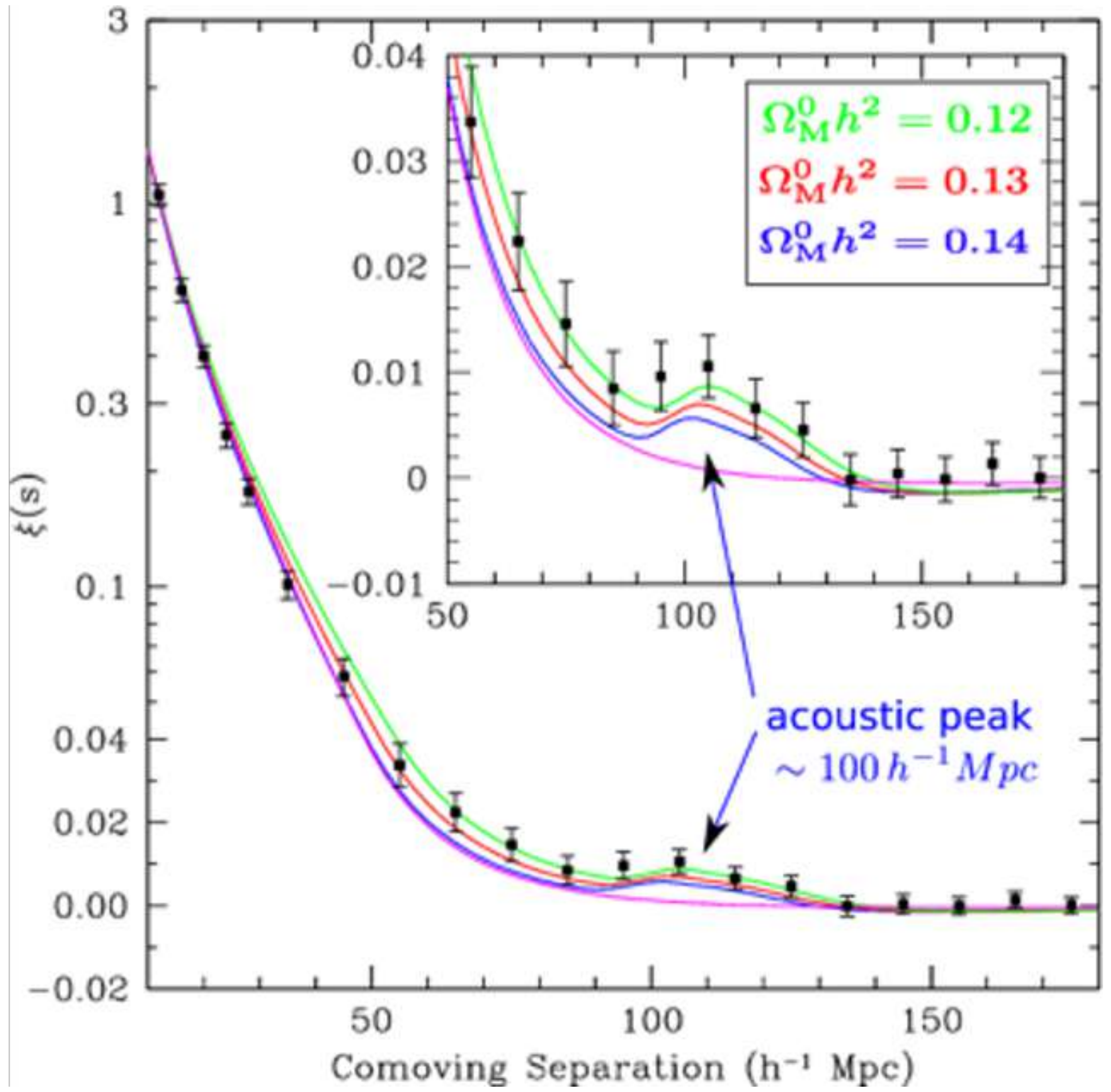
Baryon Acoustic Oscillation (BAO)

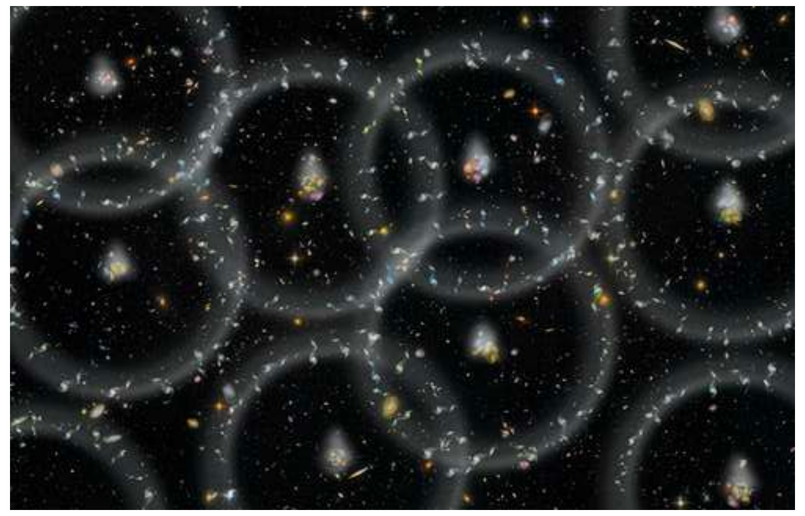
Cosmic Microwave Background



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

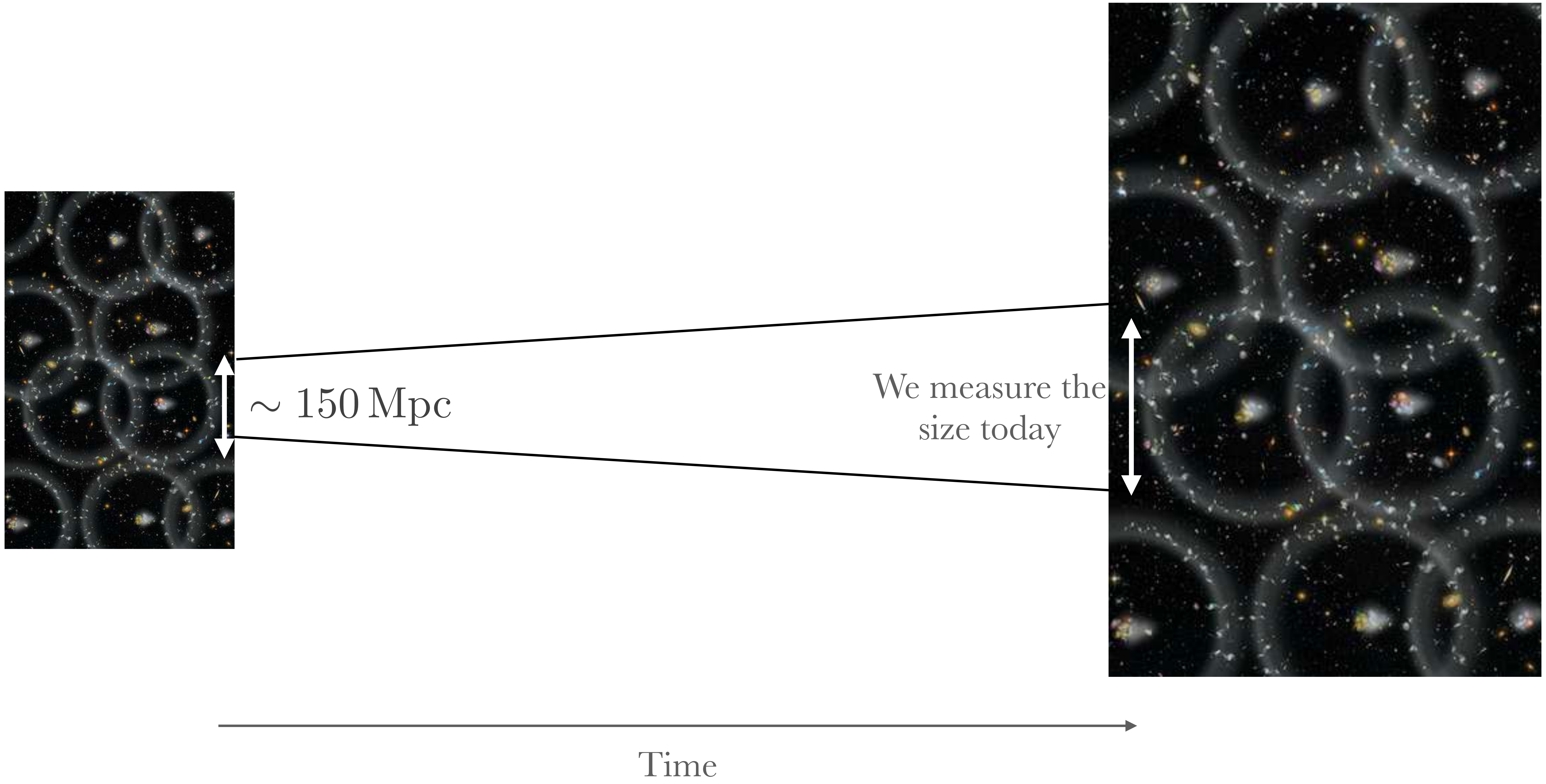
Large Scale Structure





Crédit:LBNL

Baryon Acoustic Oscillation (BAO)

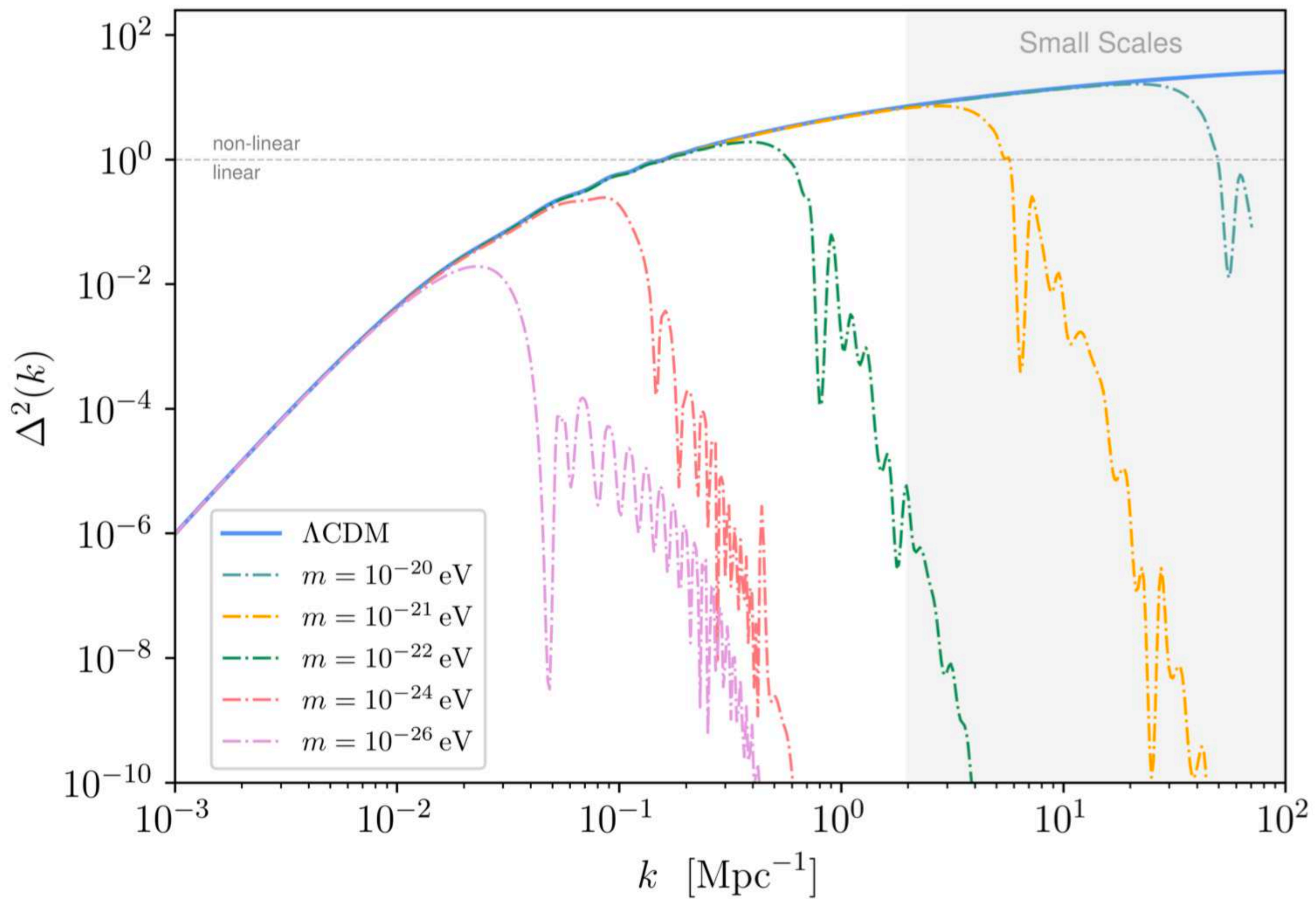


- BAOs are “standard rulers” to measure expansion

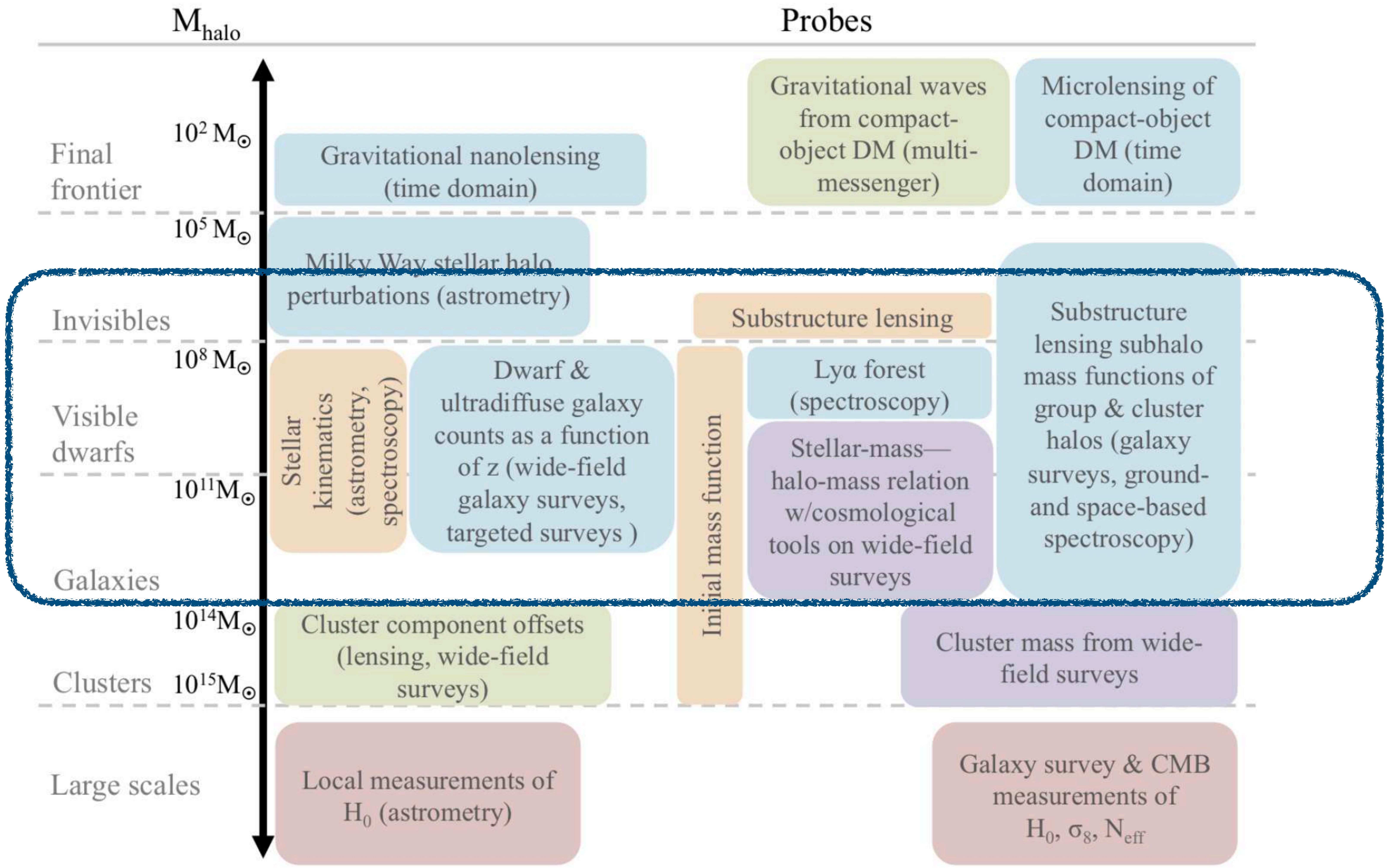
Cosmological and astrophysical ***probes*** *of dark matter*

CMB and LSS

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



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

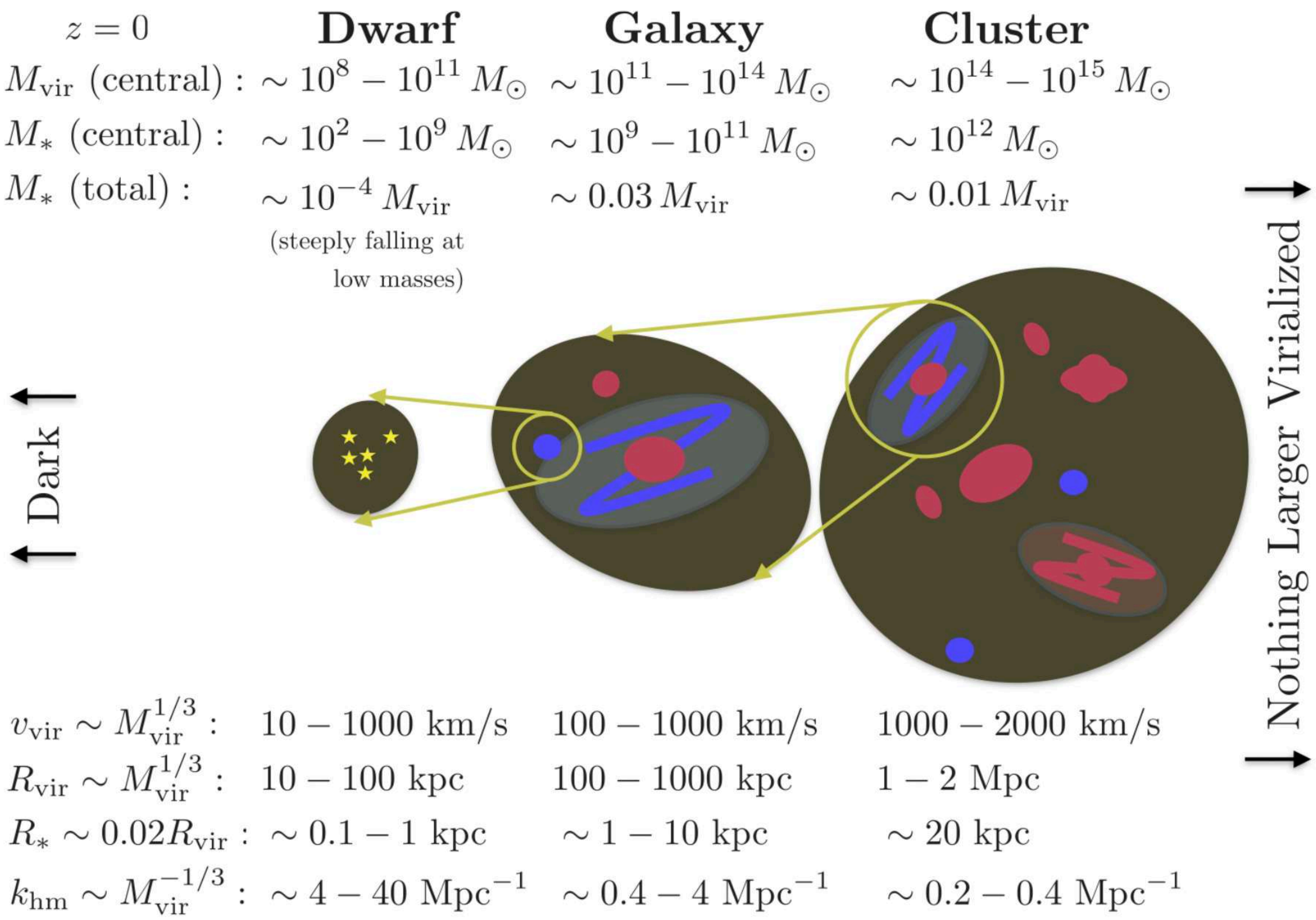


Currently being measured

Precision improving

Buckleya et al 2017

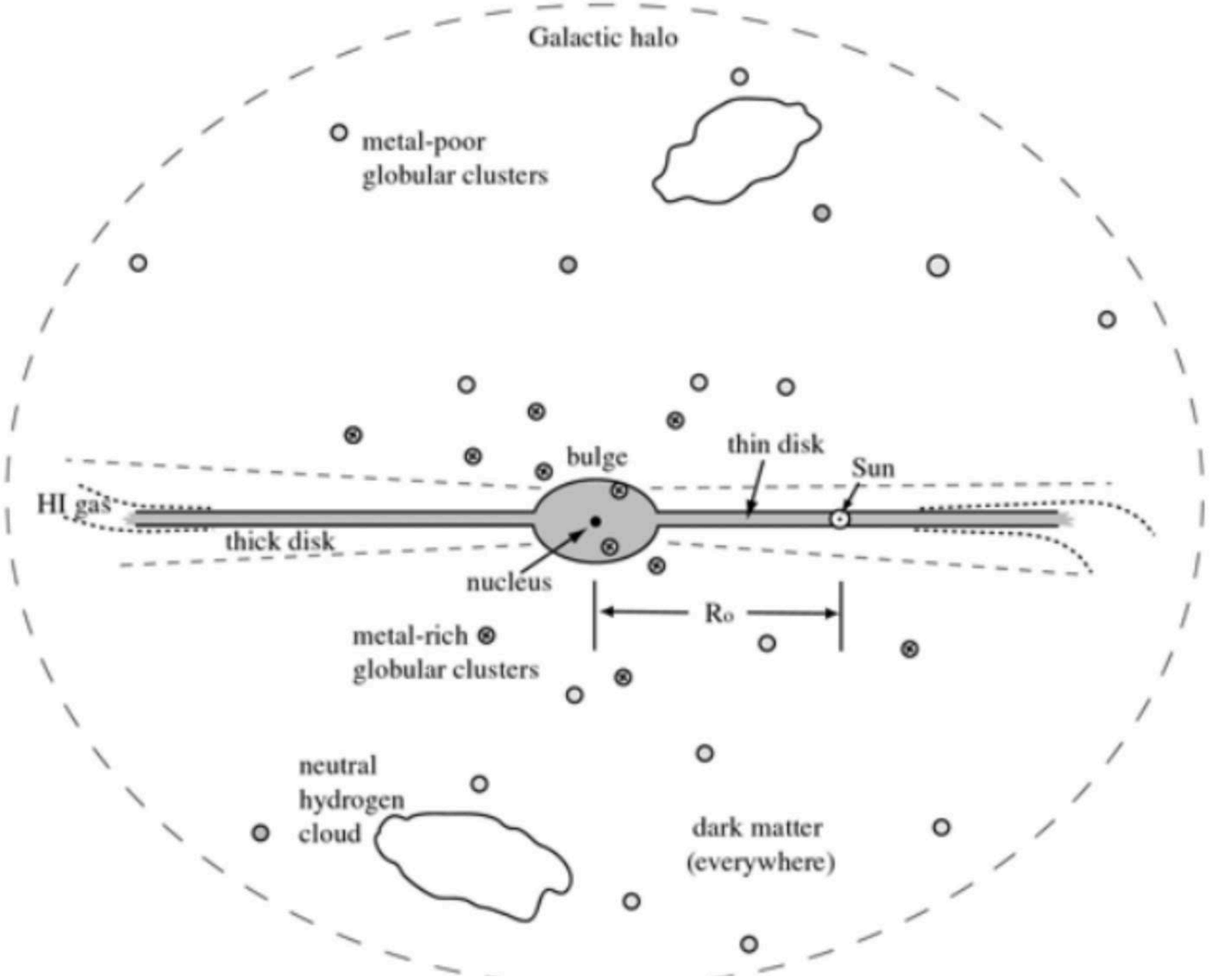
Cosmological and astrophysical **probes** *of dark matter*



Buckleya et al 2017

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

Galaxies



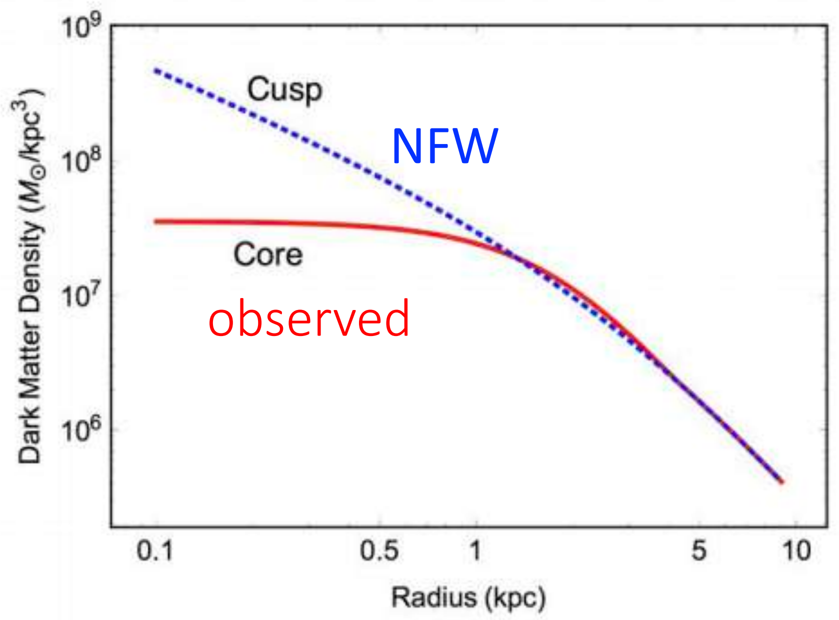
A schematic side view of the Milky Way

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)*
- …

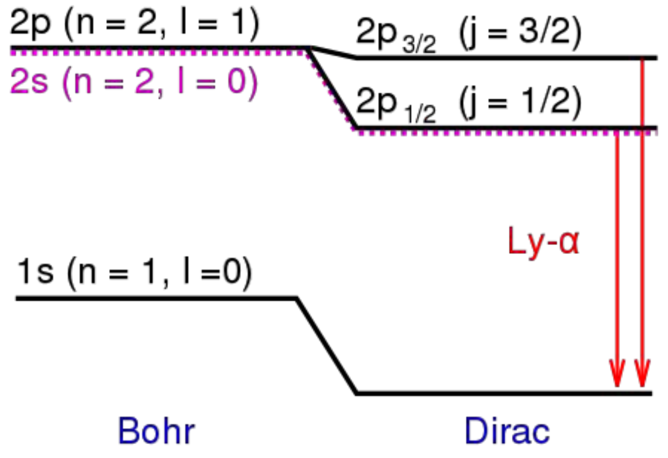
Gravitational lensing

(More later)

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

Lyman α

Spectral line of hydrogen



Tobix10

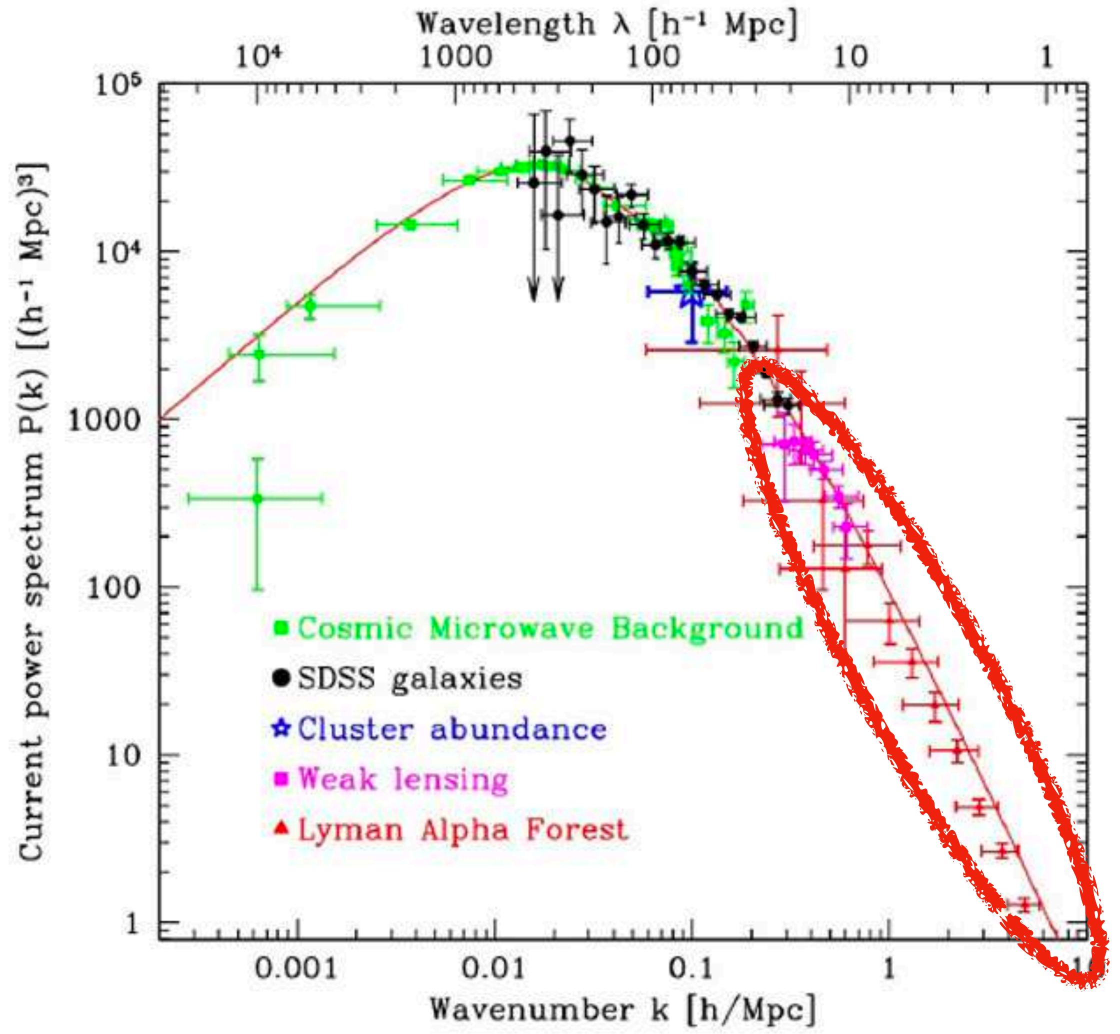
Lyman-alpha forest is a series of absorption lines in the spectra of distant galaxies and quasars arising from the Lyman-alpha electron transition of the neutral hydrogen atom

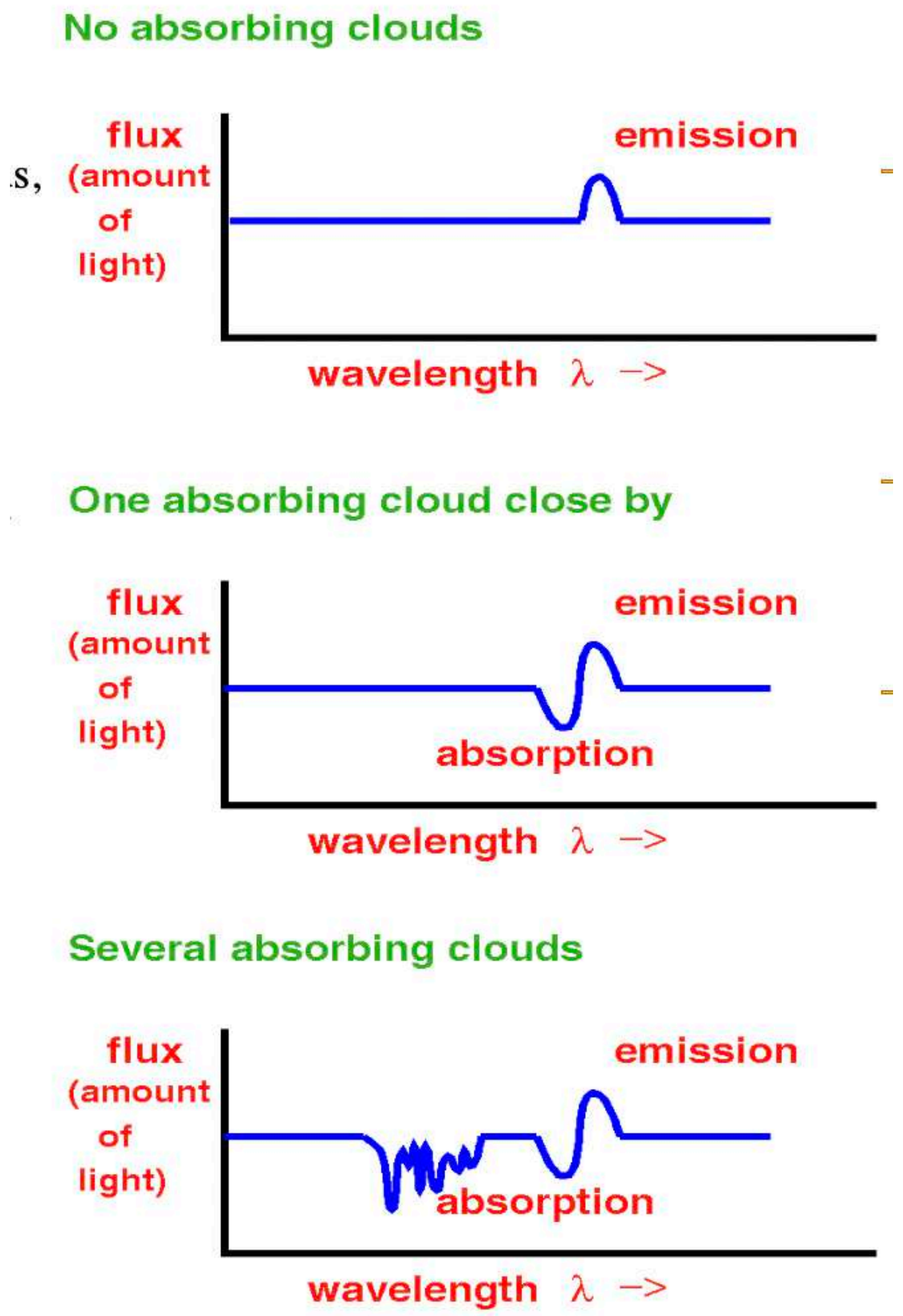
Armengaud

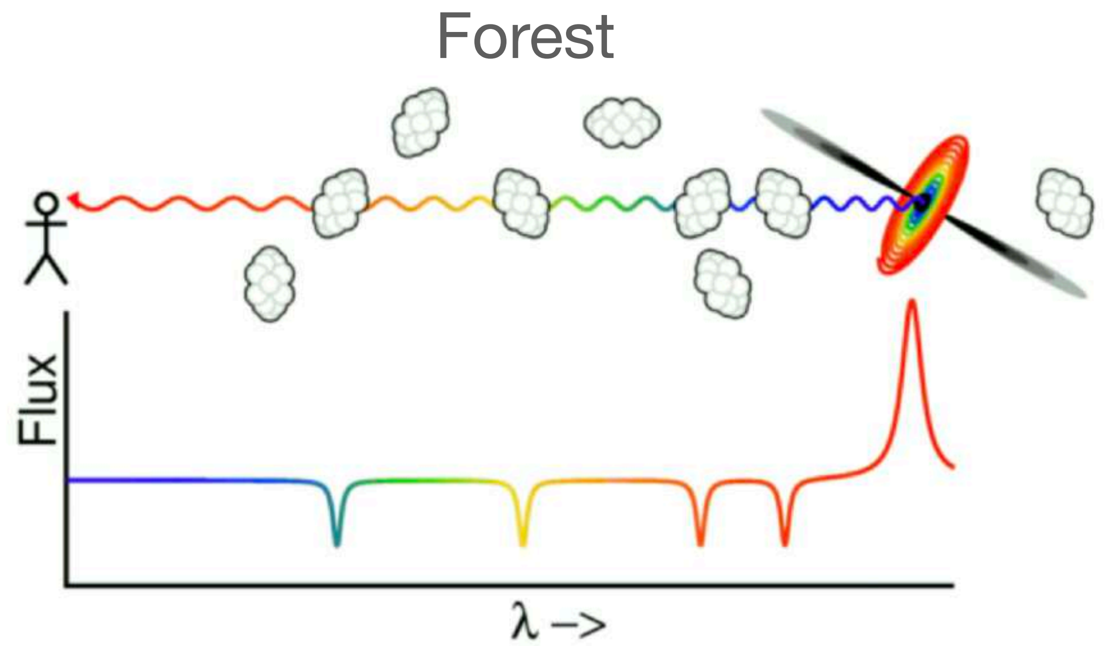
$$\delta(\lambda) = \frac{f(\lambda)}{C_q(\lambda)\bar{f}(z)} - 1$$

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

related to 3D matter P(k)







Lyα forest: series of absorption lines

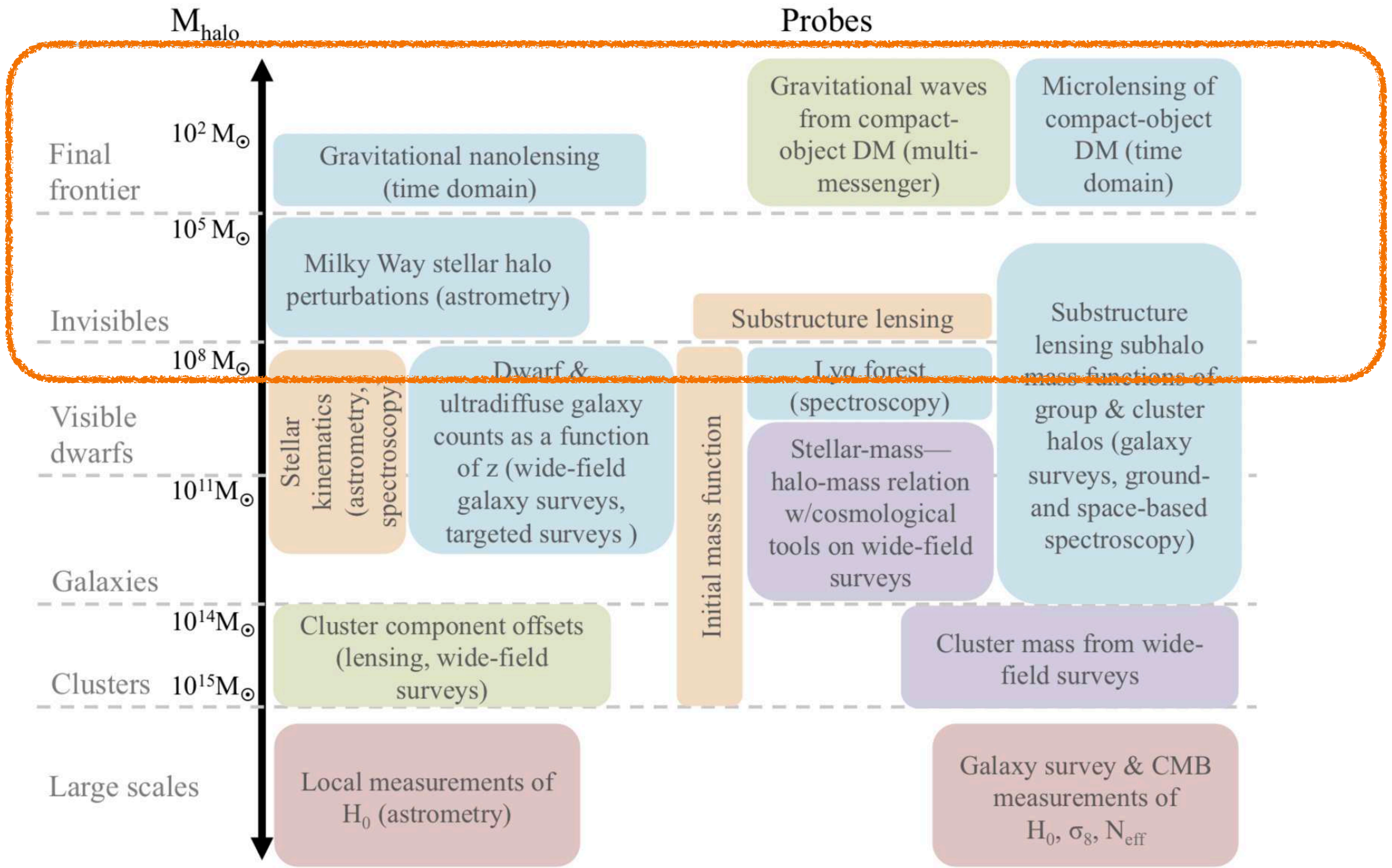
Advantage: provide PS on intermediary scales

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

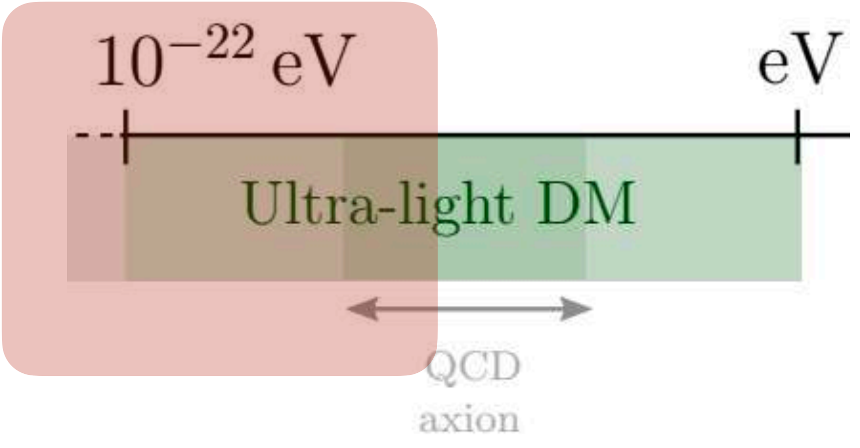
*Cosmological and astrophysical **probes** of dark matter*



Future

Buckleya et al 2017

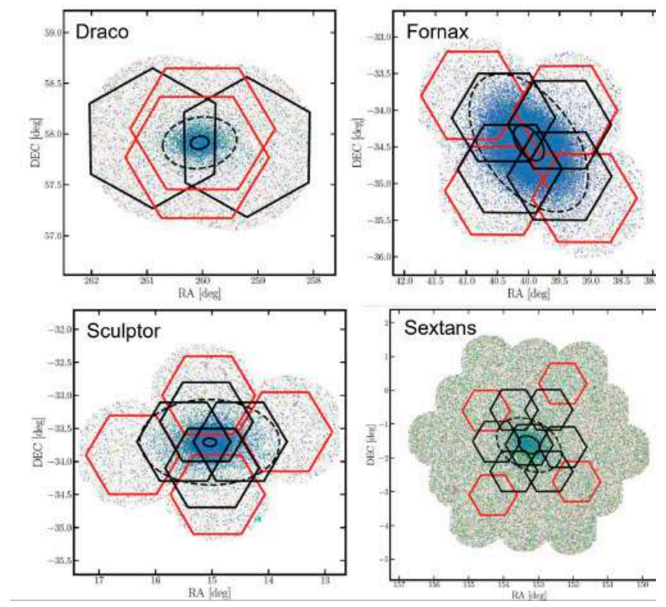
Observational implications and constraints



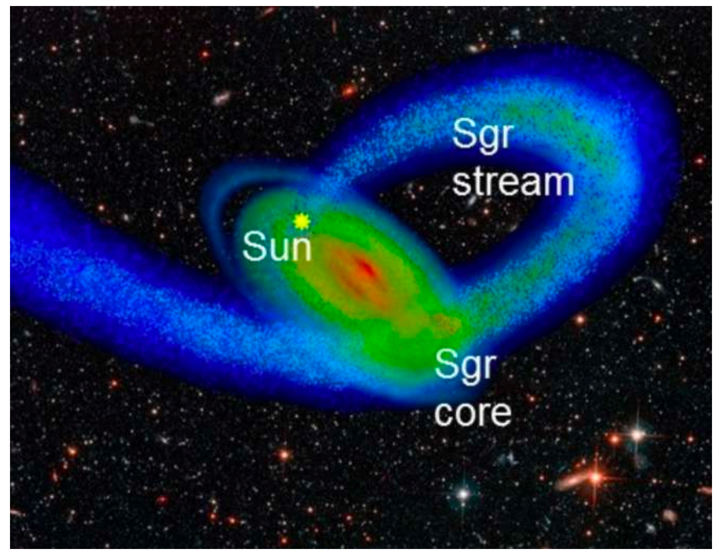
Galaxies

NASA and ESA

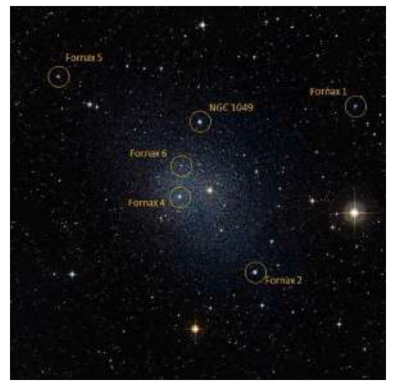
Dwarfs



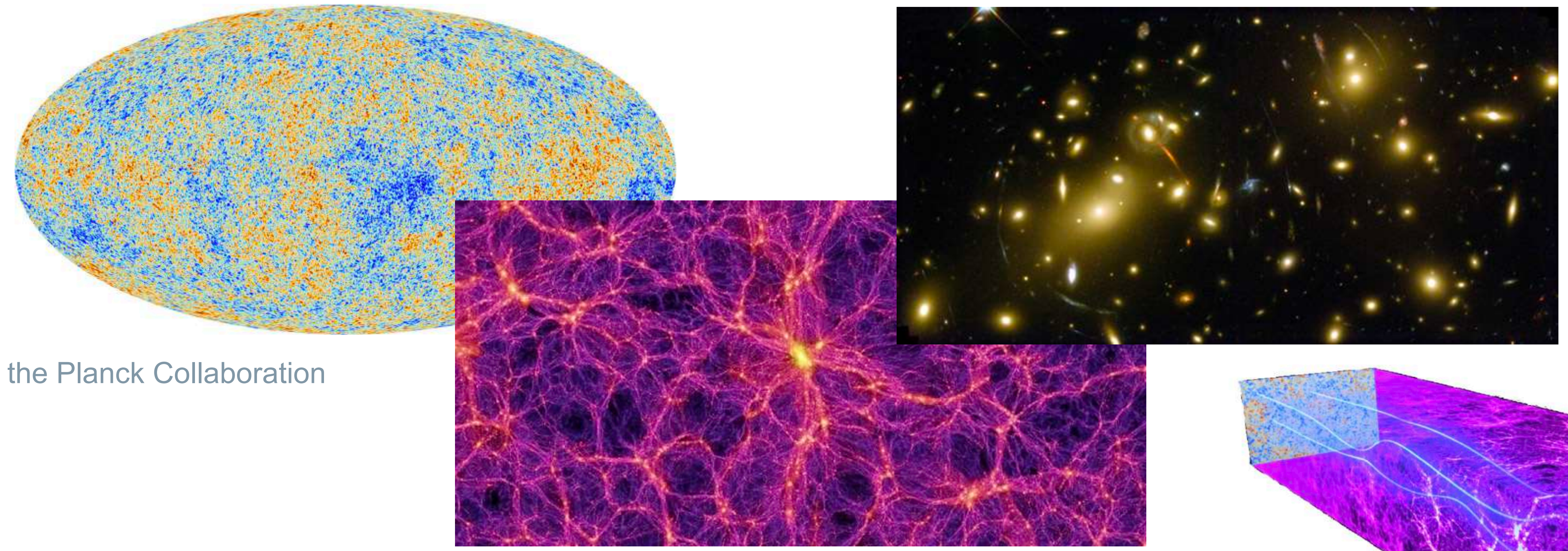
Stellar stream



Globular clusters



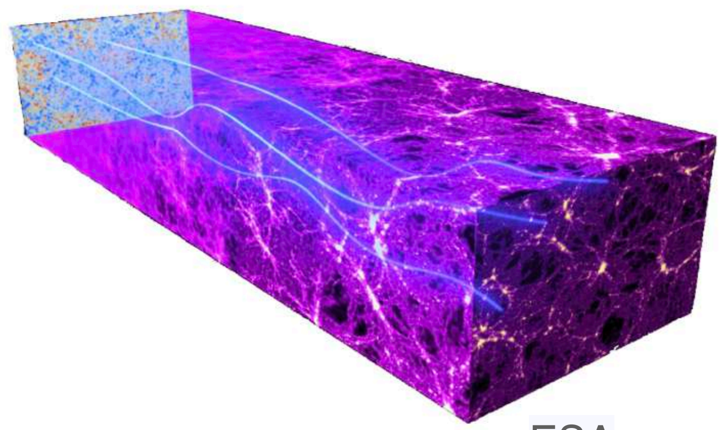
CMB+LSS



ESA and the Planck Collaboration

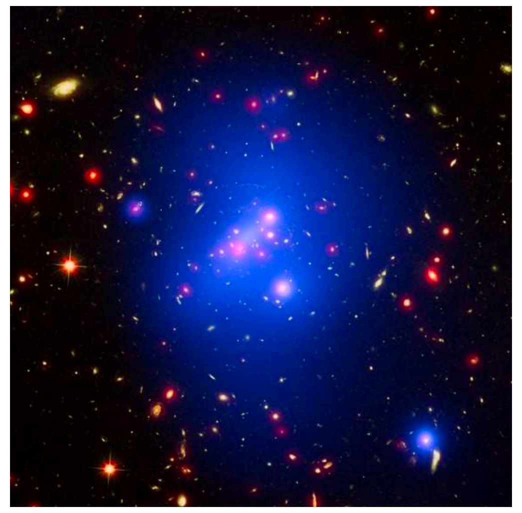
NASA and ESA

Springel & others / Virgo Consortium



ESA

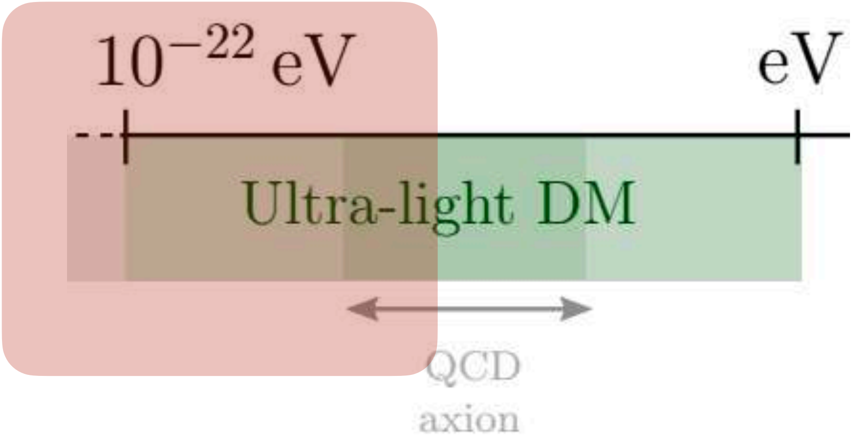
Clusters

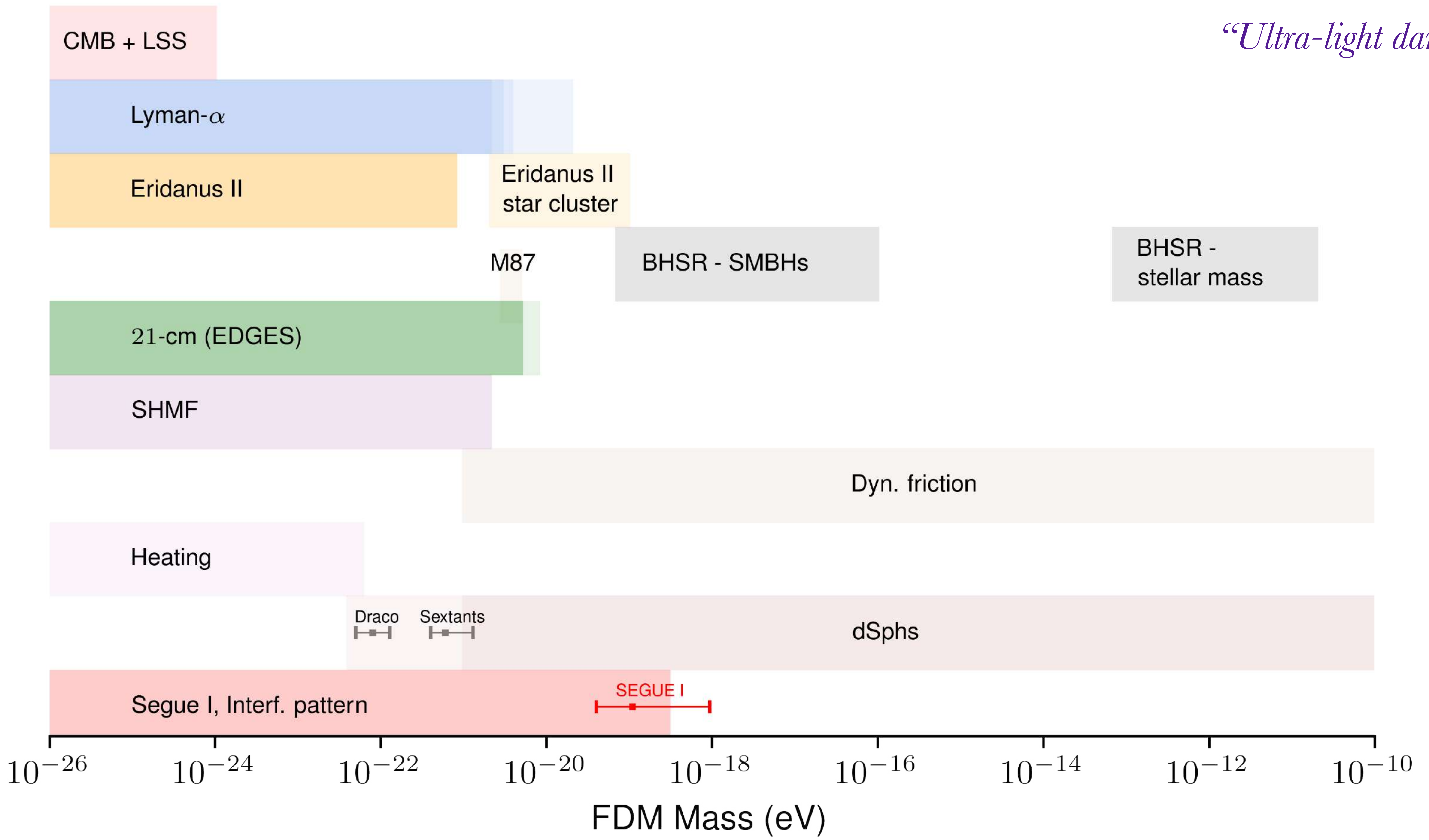


CC BY 4.0

Observational implications and constraints

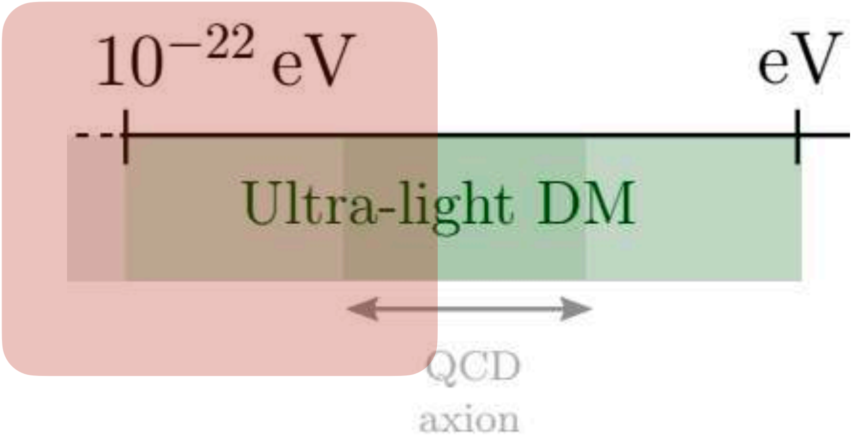
Fuzzy Dark Matter - bounds on the mass





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

Bounds consider FDM is *all* DM

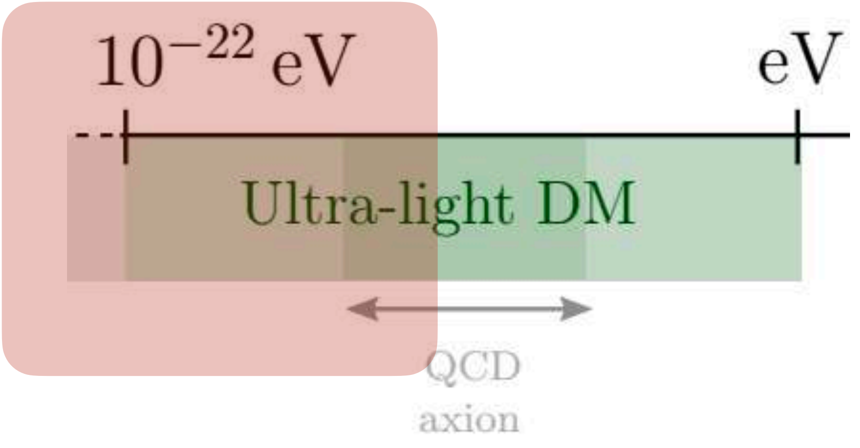


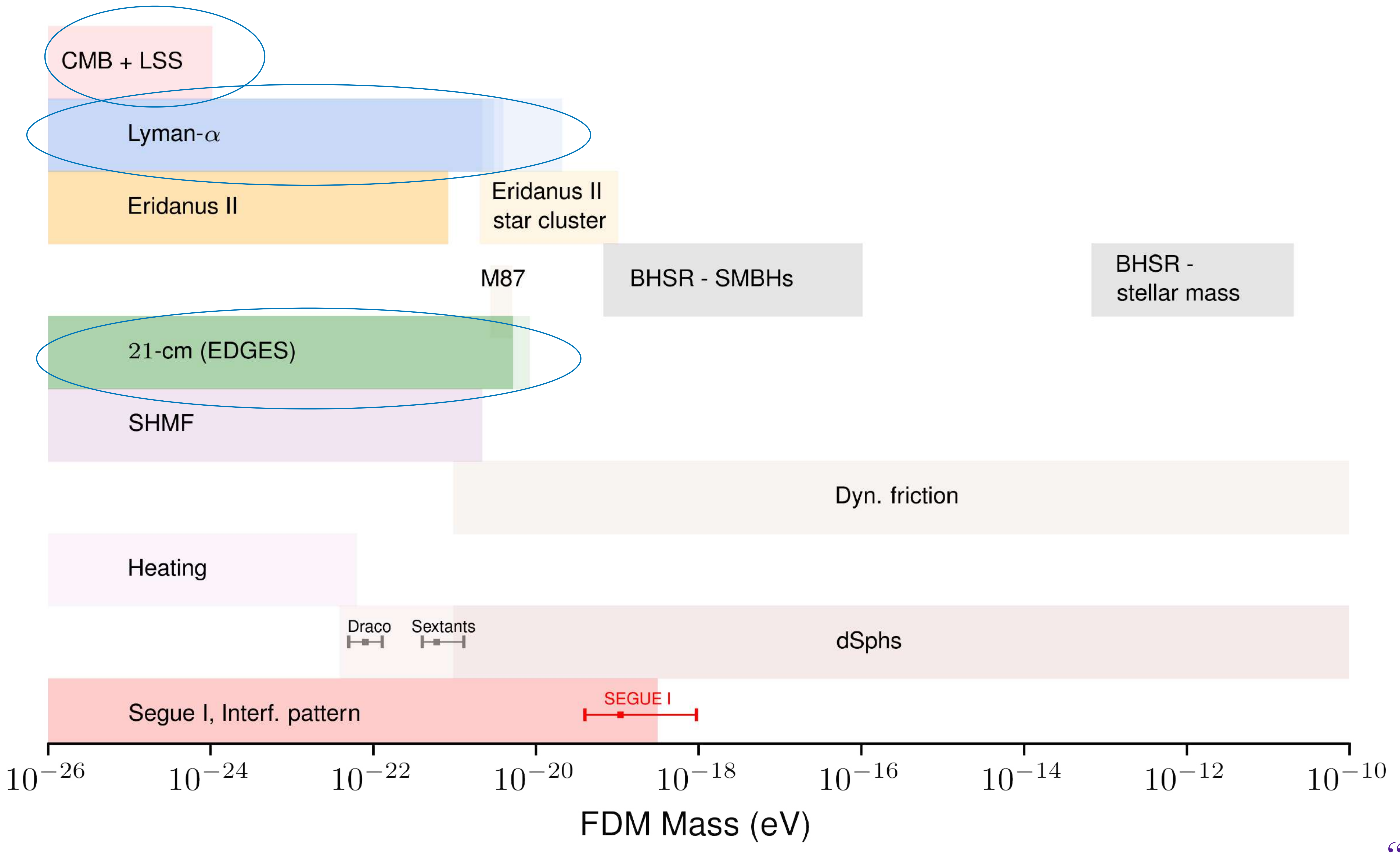
Observational implications and constraints

Suppression of small scale structures

Observational implications and constraints

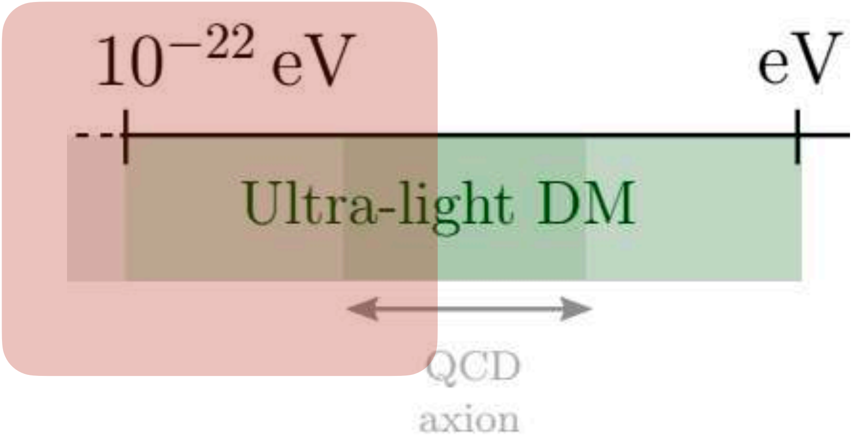
Fuzzy Dark Matter - bounds on the mass





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

Observational implications and constraints

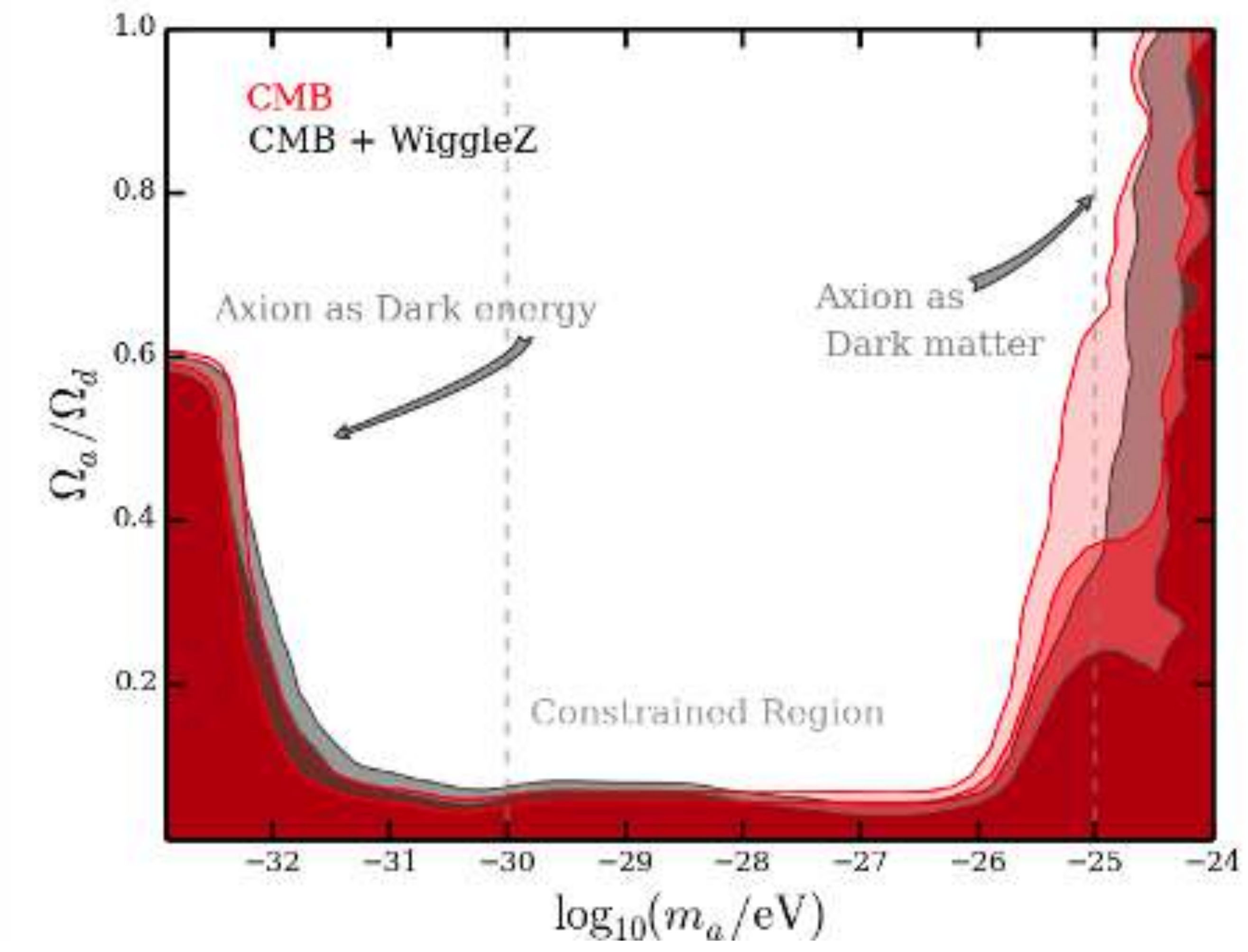


Fuzzy Dark Matter - bounds on the mass

Suppression of small structures

CMB/LSS

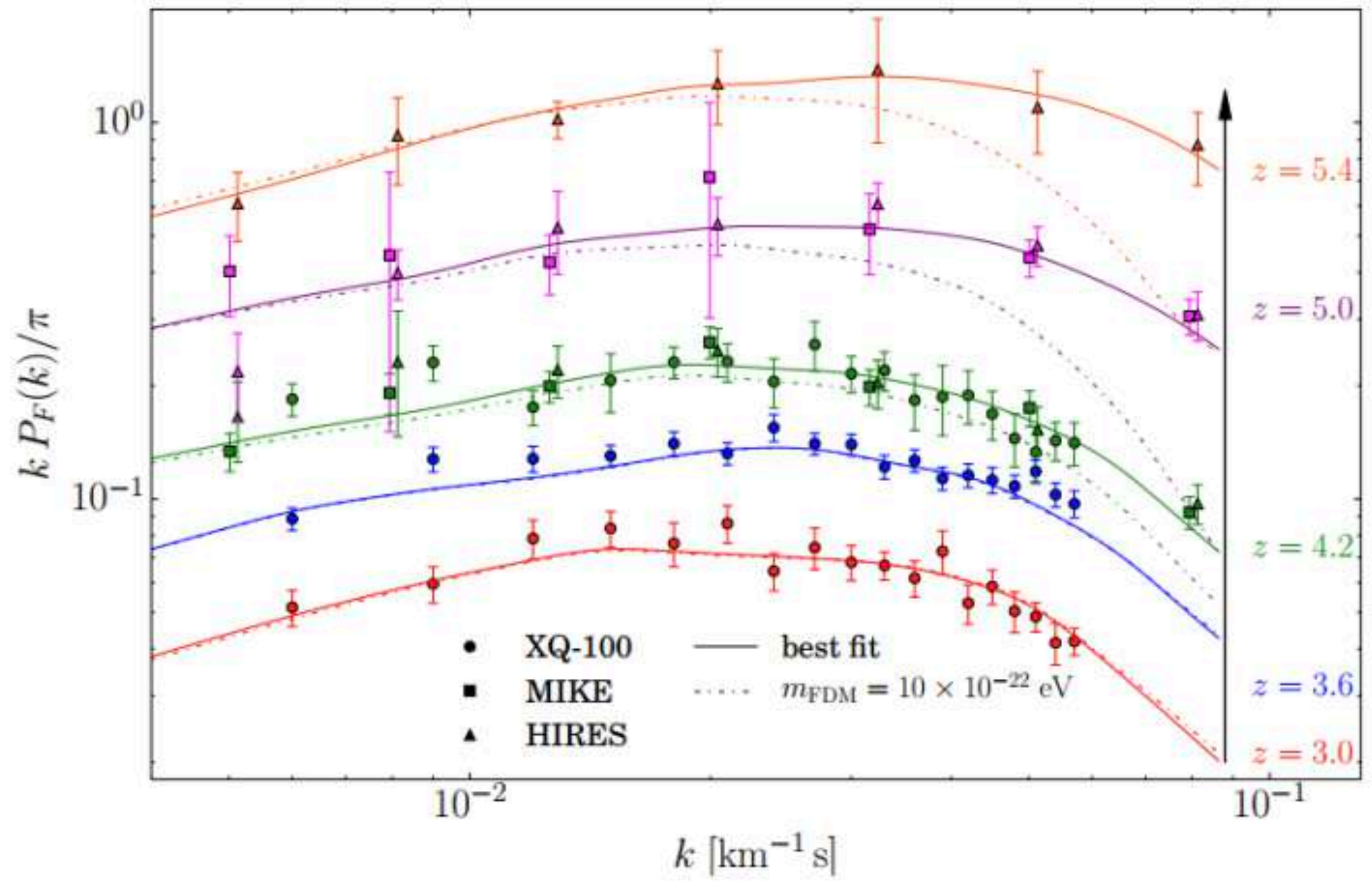
Hlozek et al, (2015, 2018)



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

Lyman alpha

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

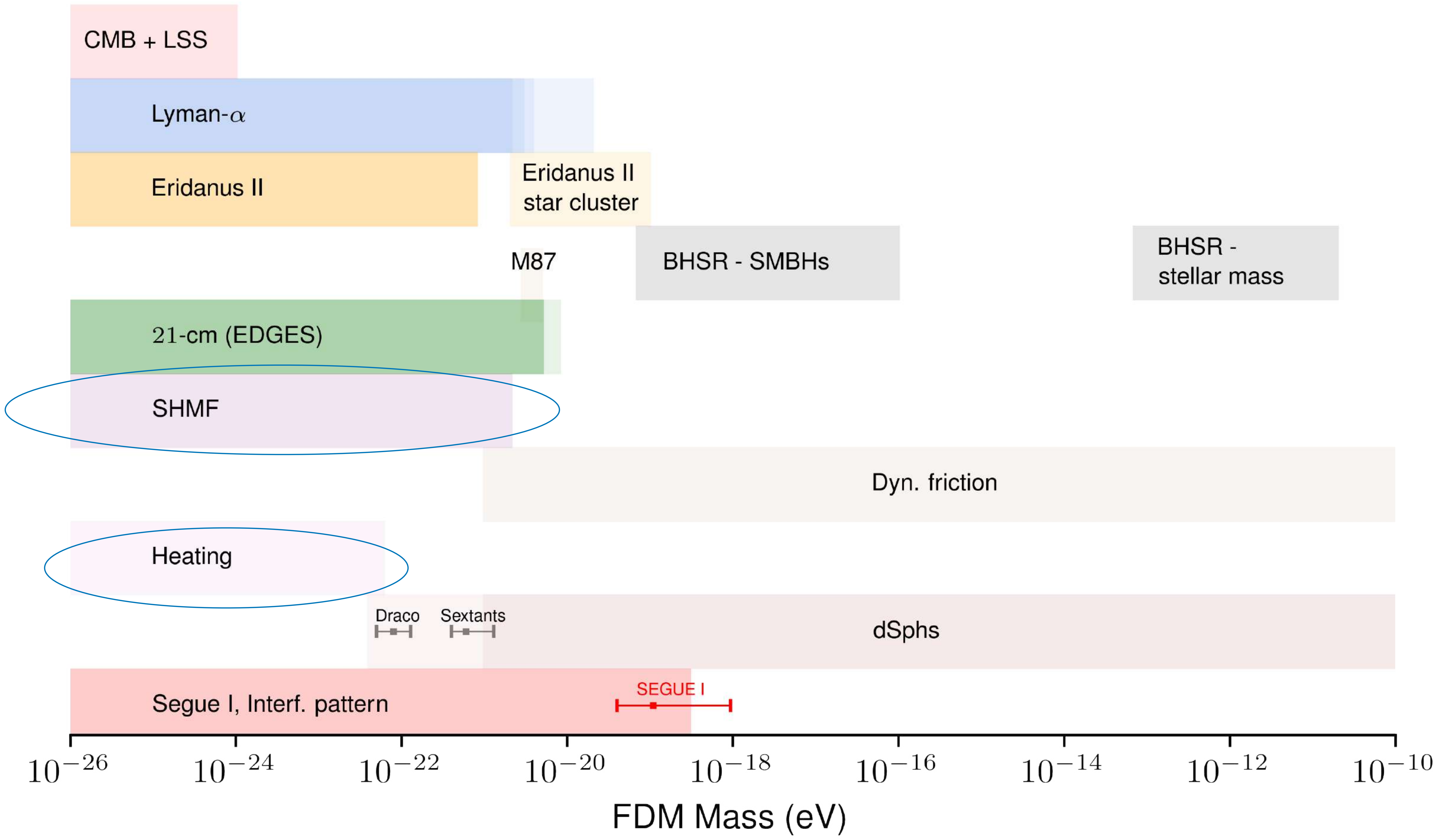


$$m \gtrsim 2 \times 10^{-20}\,\mathrm{eV}$$

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

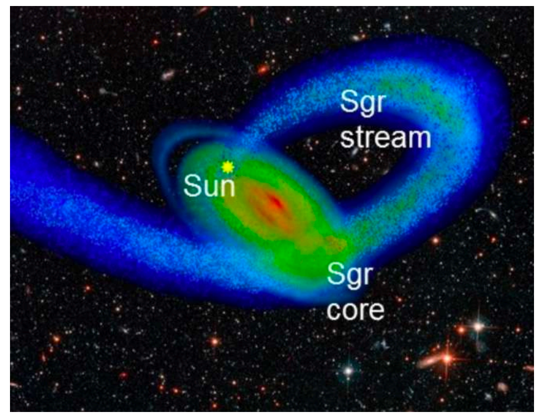
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



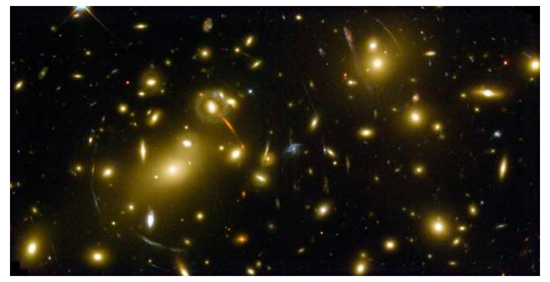
<u>Suppression of small structures</u>

Stellar streams



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

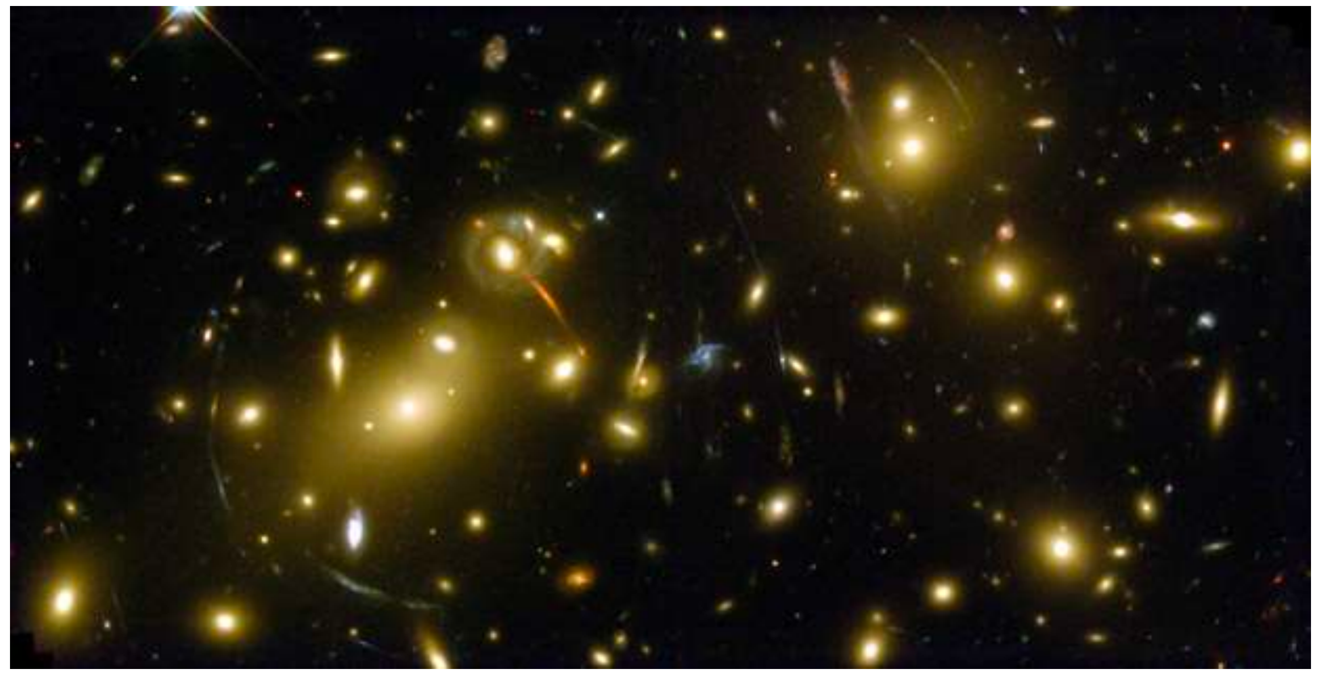
Grav. lensing



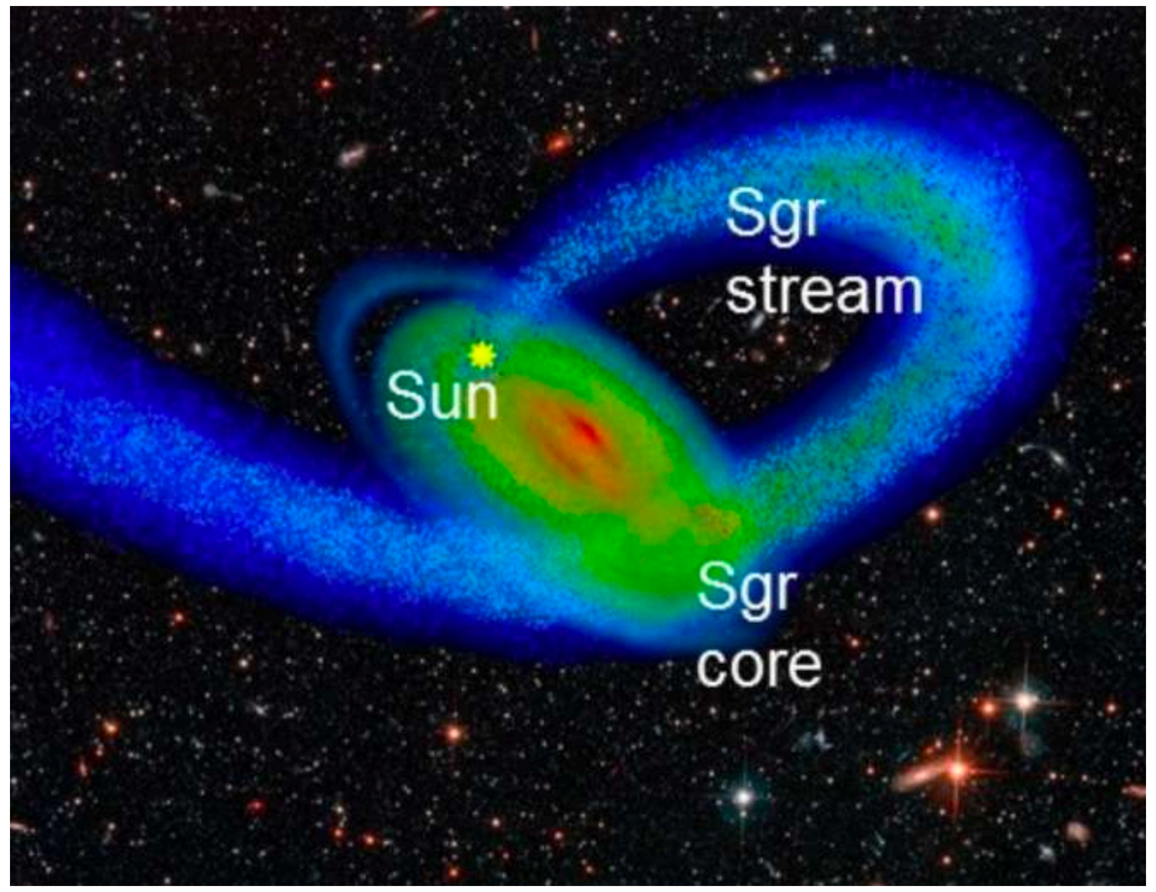
Gravitational probes

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

Gravitational lensing

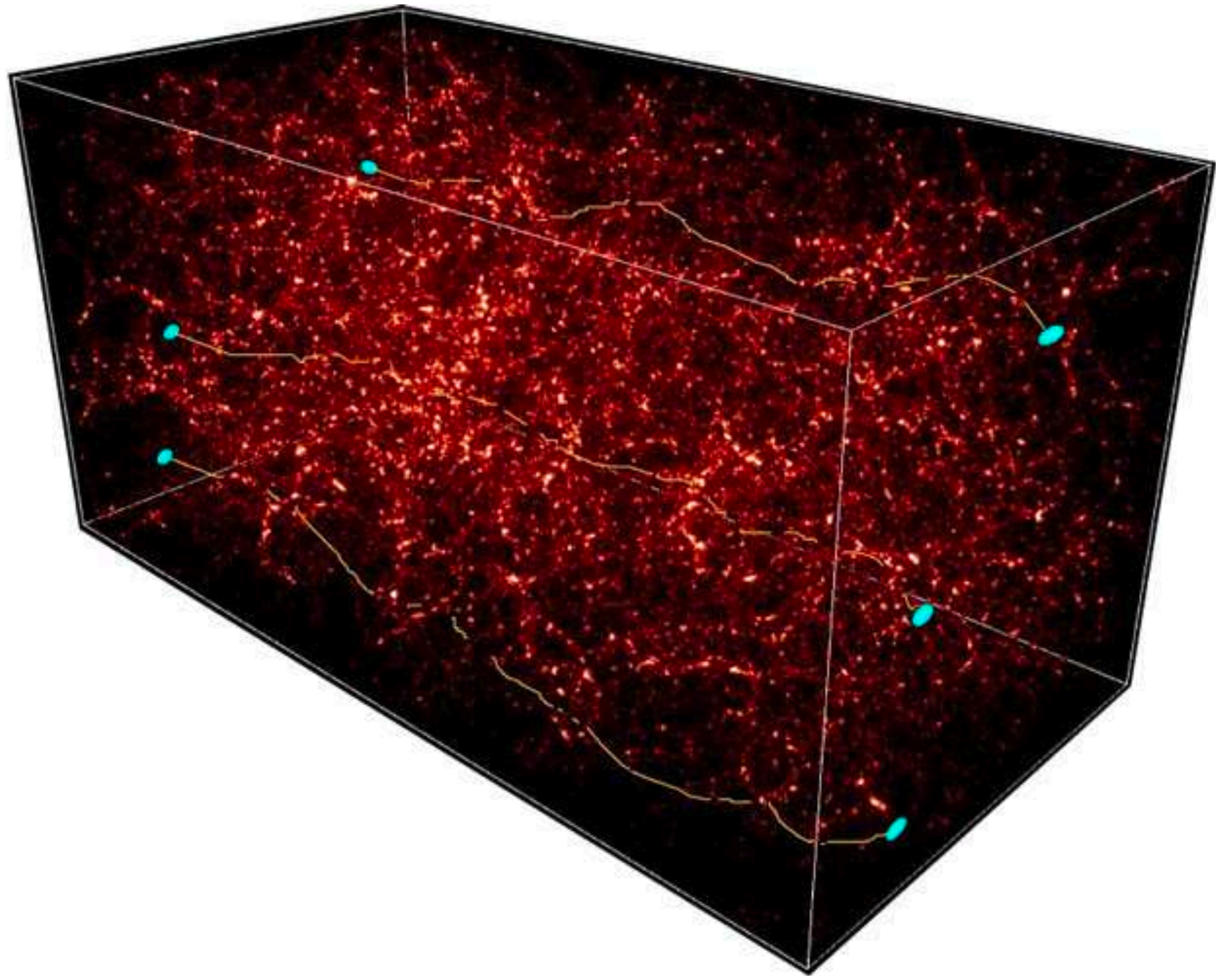


Stellar stream



Gravitational lensing

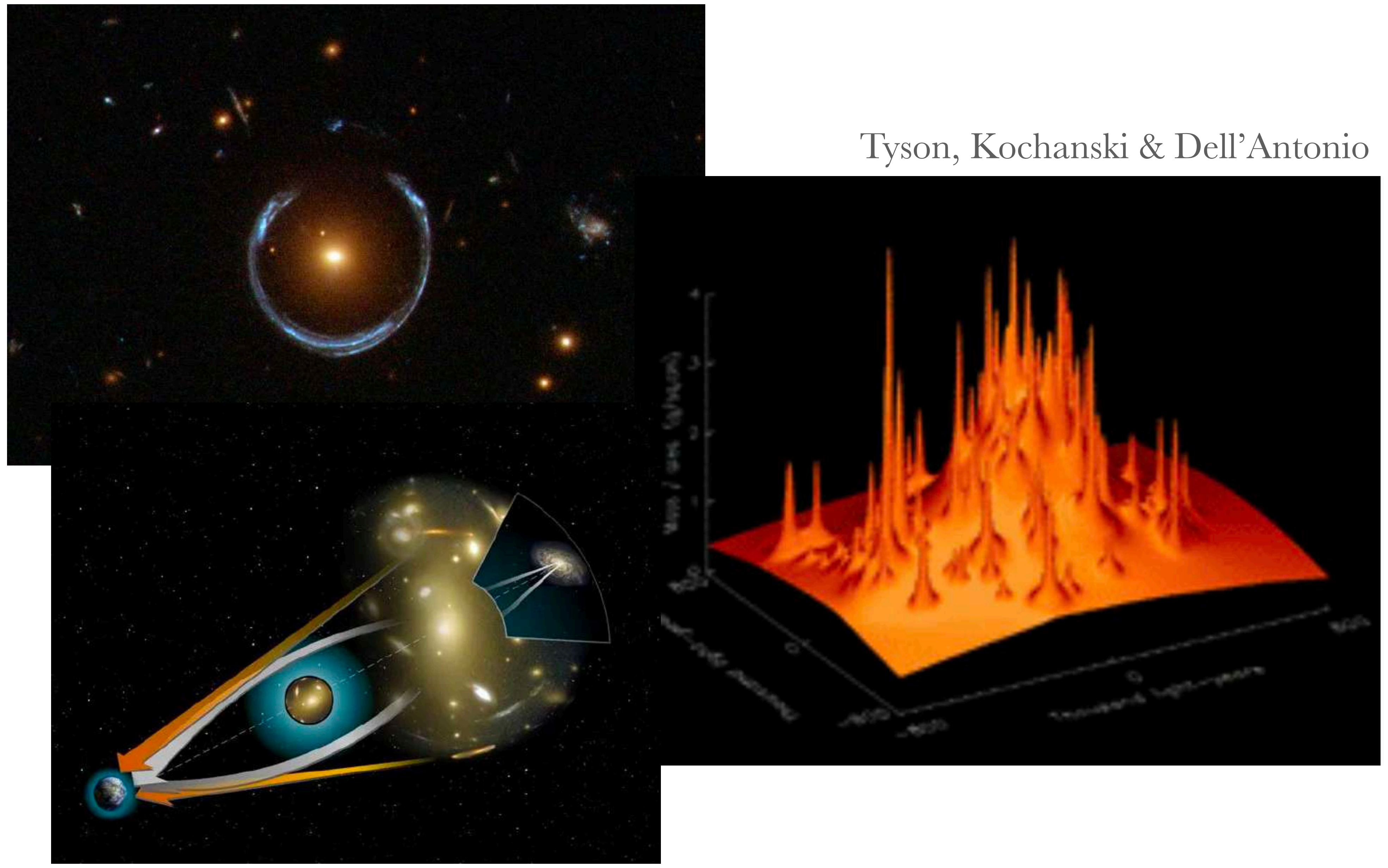
Weak lensing



Strong lensing

Image: © ESA/Hubble/NASA)

Tyson, Kochanski & Dell'Antonio



NASA / STSCI

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

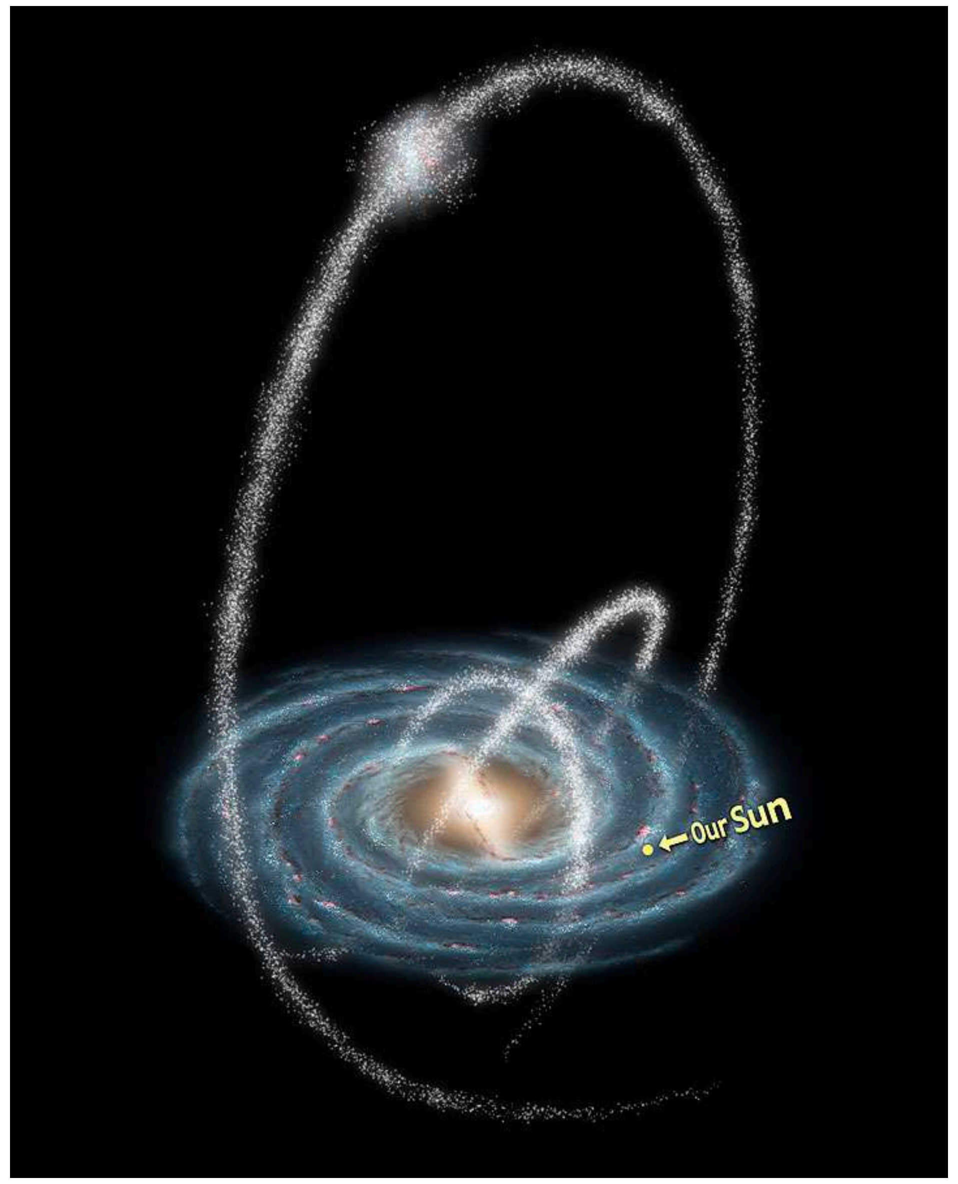
- Reconstruct the gravitational potential (total enclosed mass) of the lens
- Total mass on small scales

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.

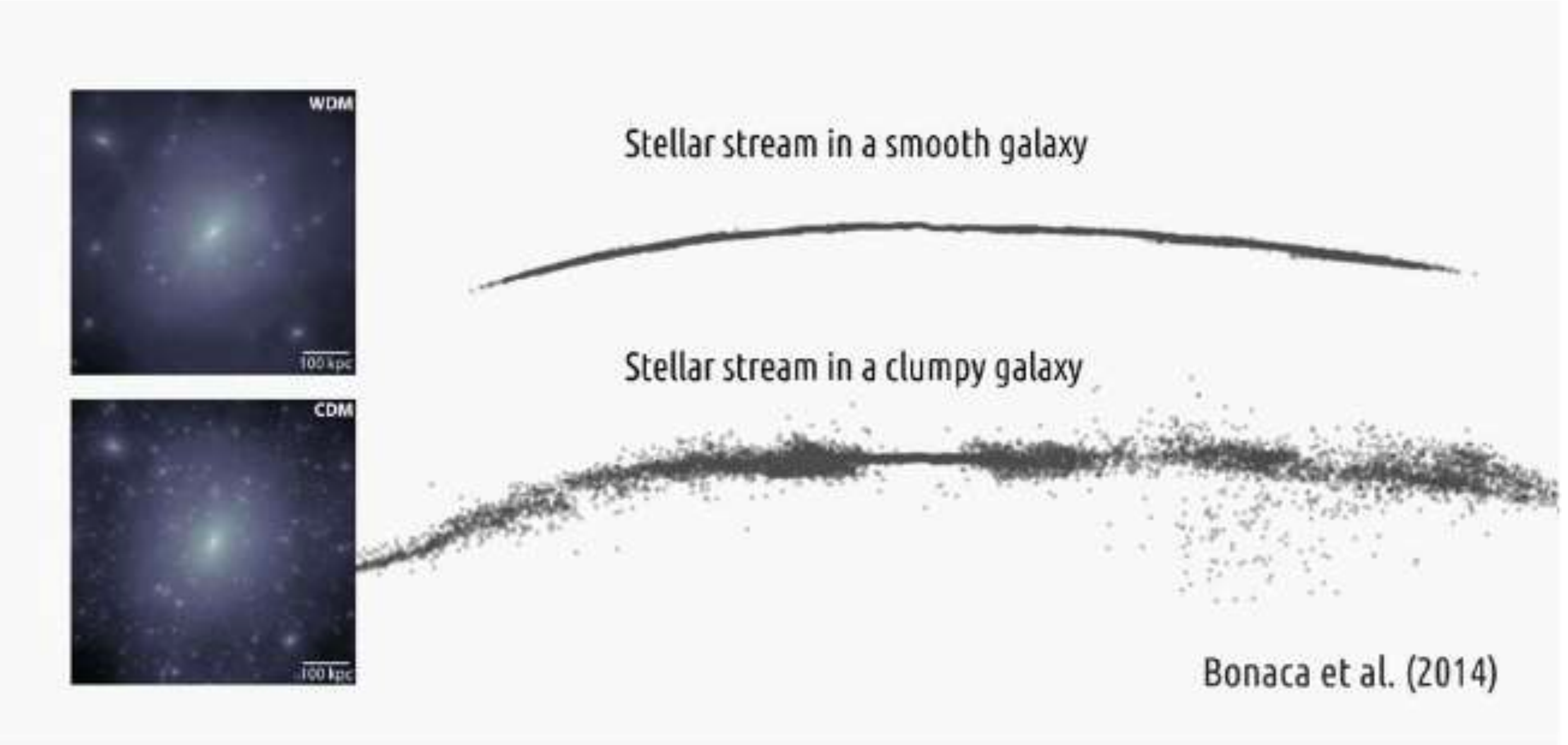
Streams are good dynamical probes since they are initially cold and very sensitive to the gravitational potential



NASA

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

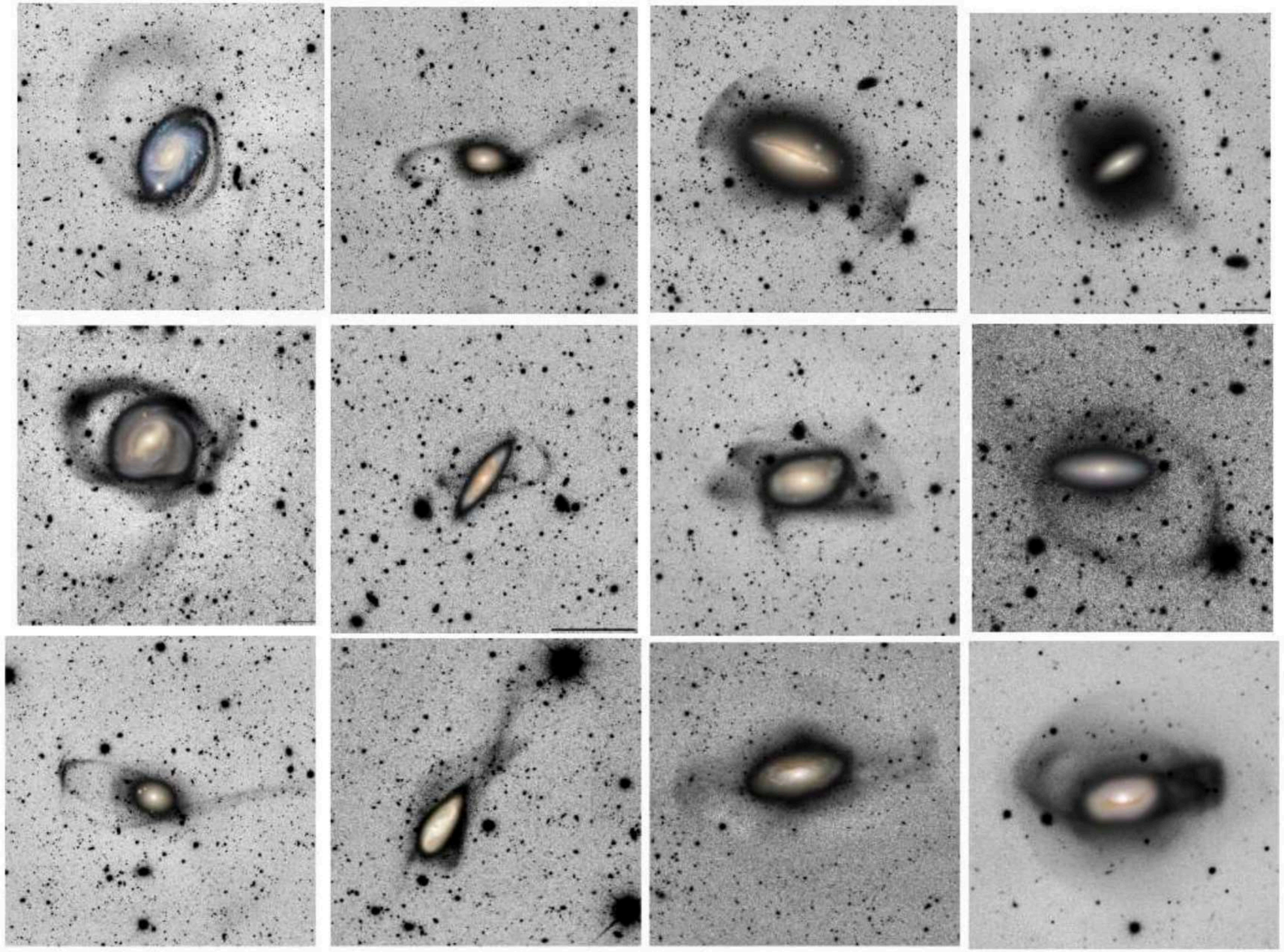
- Dynamical heating: which are changes in the velocities in the stream,
- Disturbances in the morphology of the stream: formation of gaps which are underdensities caused by the sub-halos encountered



Bonaca et al. (2014)

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

Practice session:

Suppression of small scale structures

S8 tension

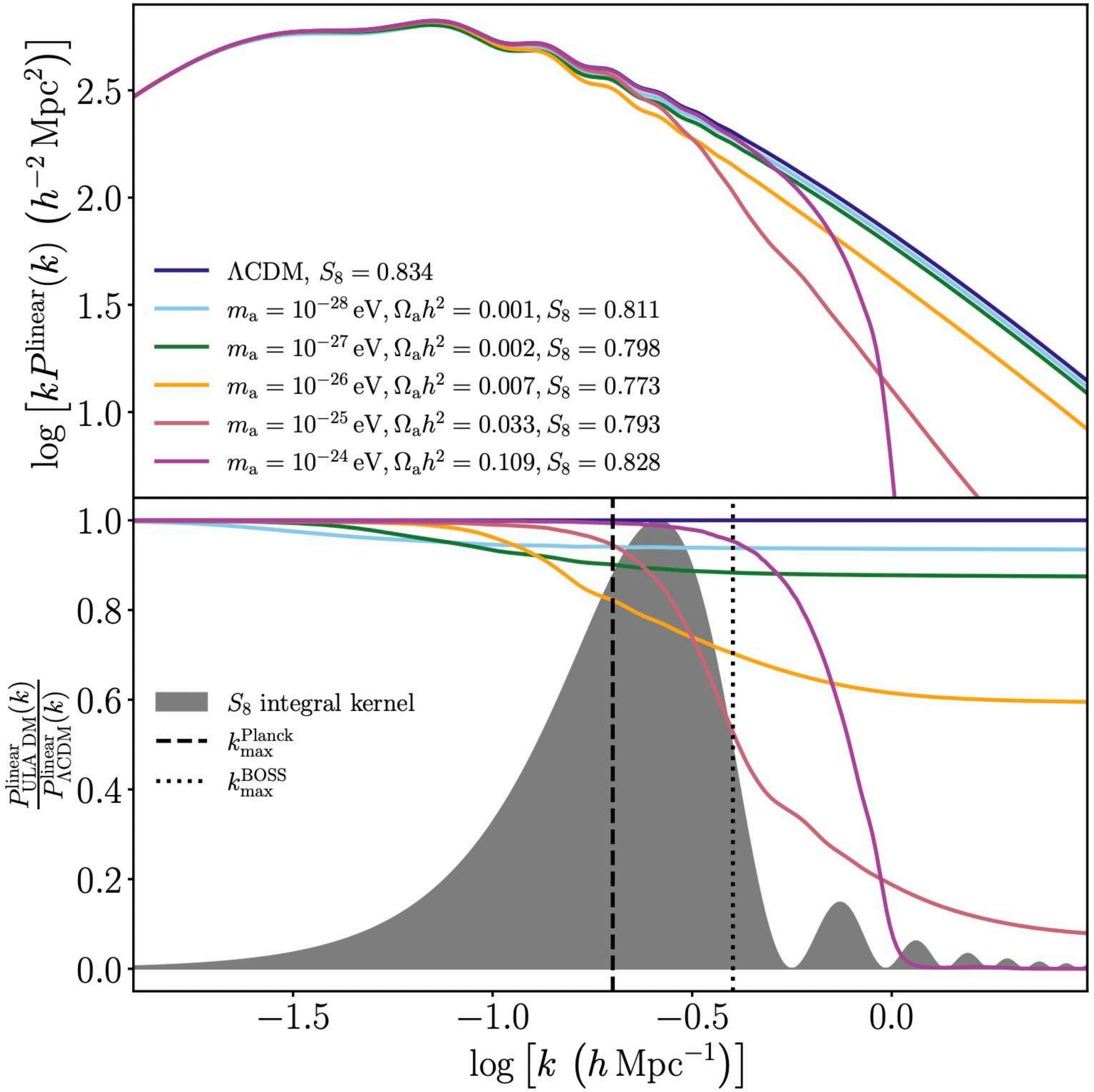
Ref.: K. Rogers et al 2023

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

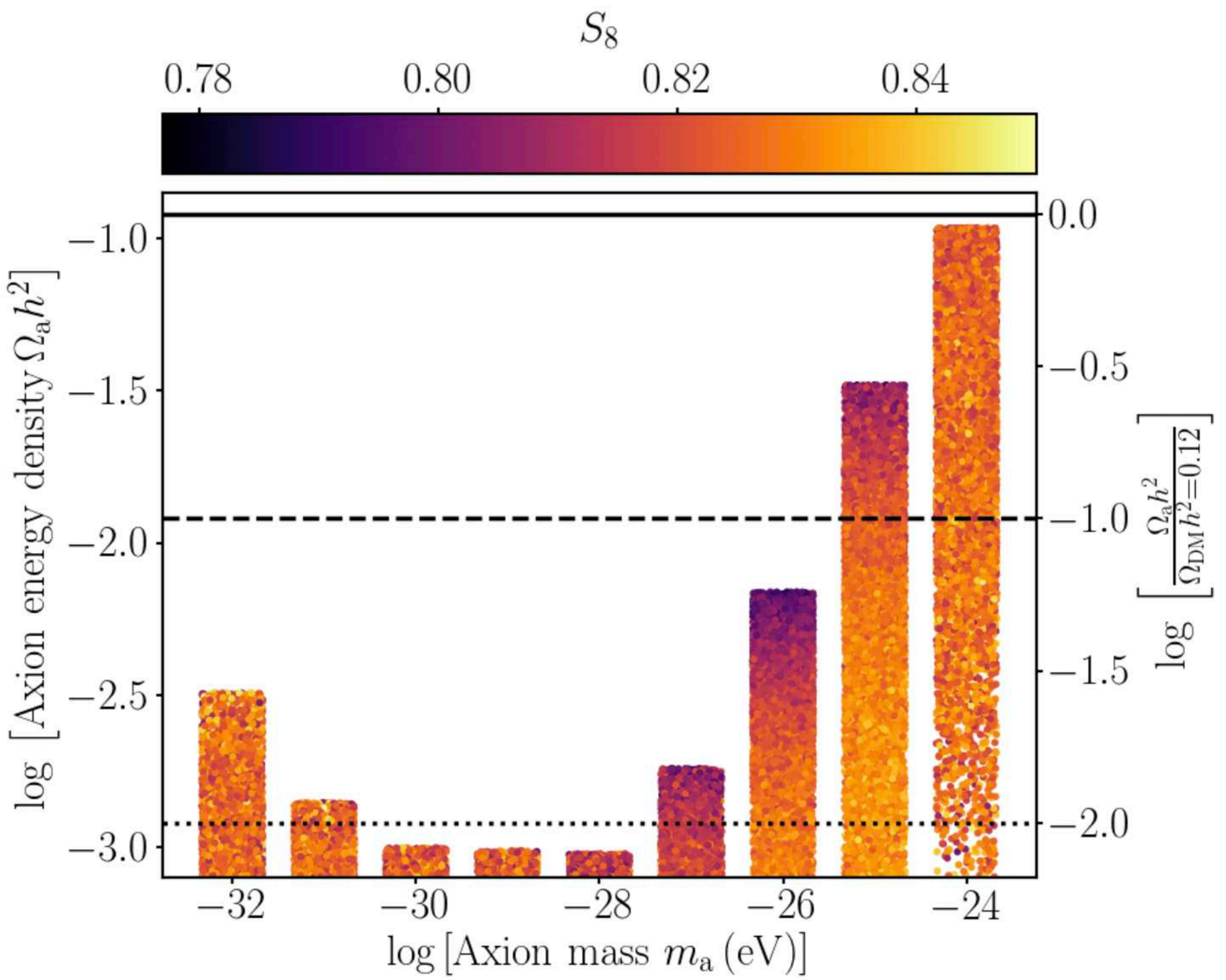
Planck + BOSS

The presence of ULAs with mass

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

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

from 2.6σ to 1.7σ

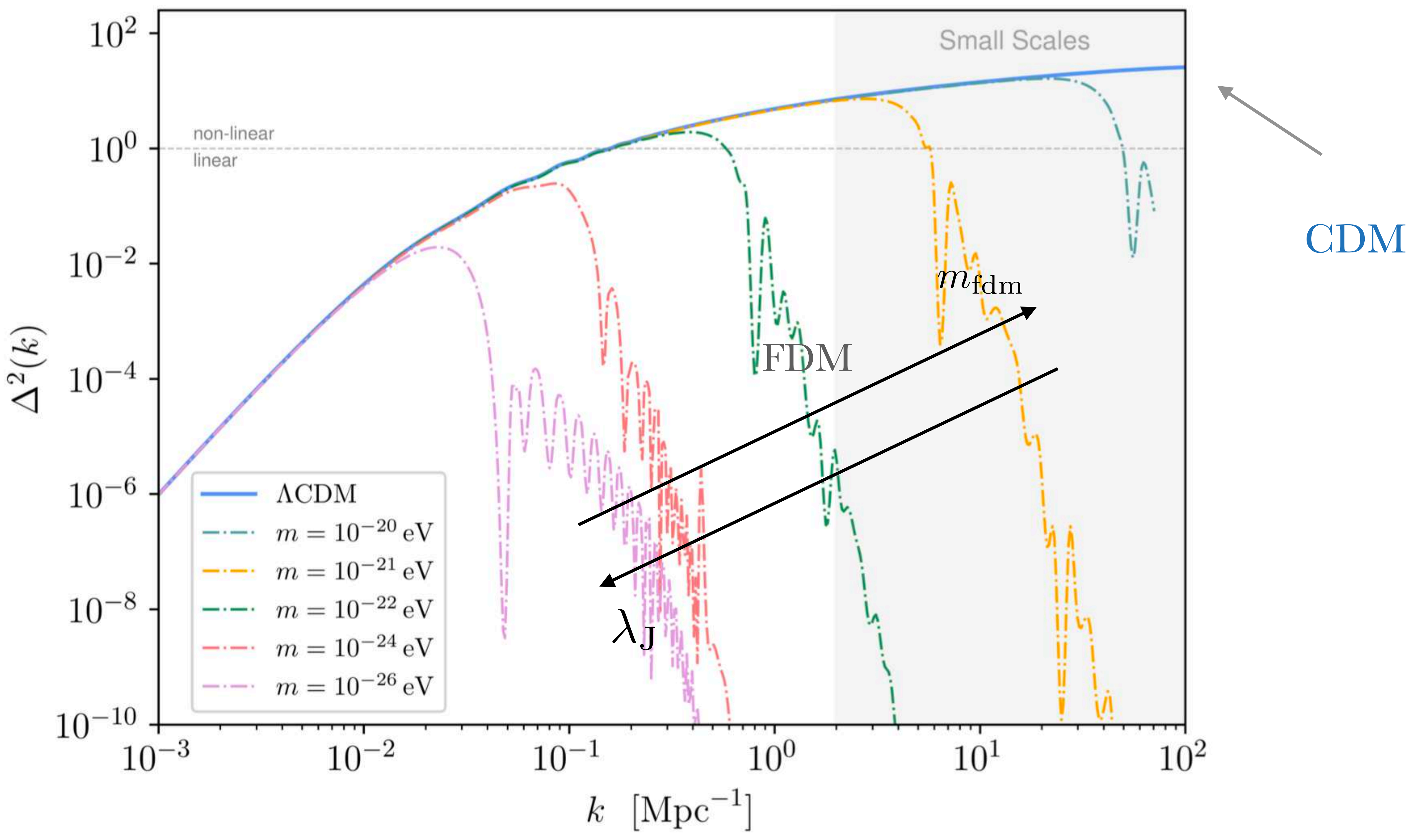


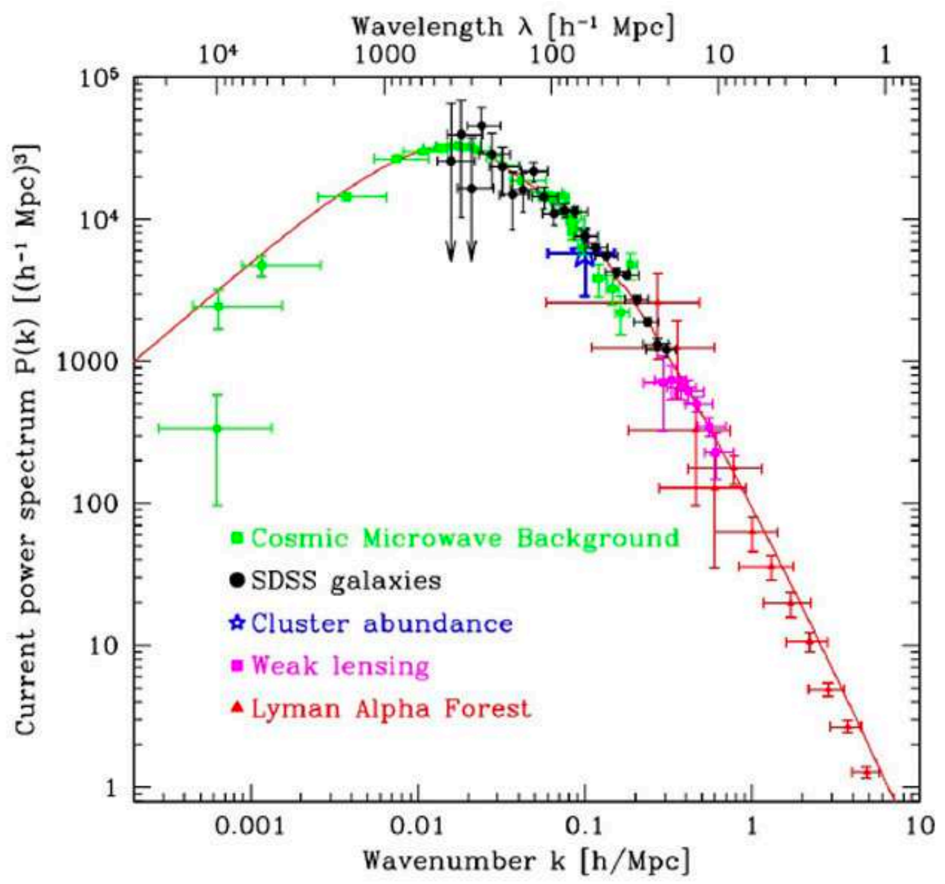
Ex.:
- H0 tension: Early dark energy - axion-like particle
- Model address H0 and S8 tensions: *"Chameleon EDE"*, Karwal et al 2021

Suppression of small scale structure

Can we probe the small scales?

POWER SPECTRUM





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

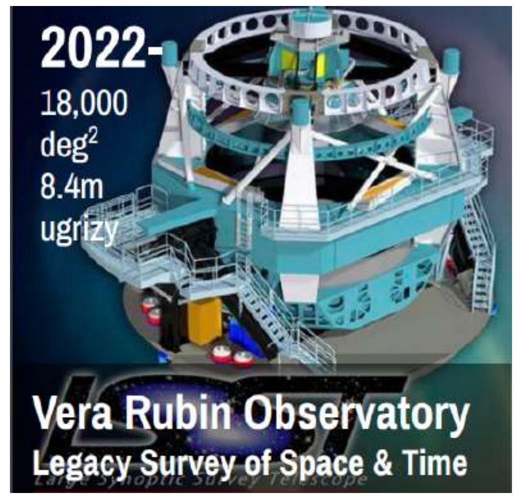
Can we measure the power spectrum on scales
$k < 10\,\mathrm{Mpc}^{-1}$?

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

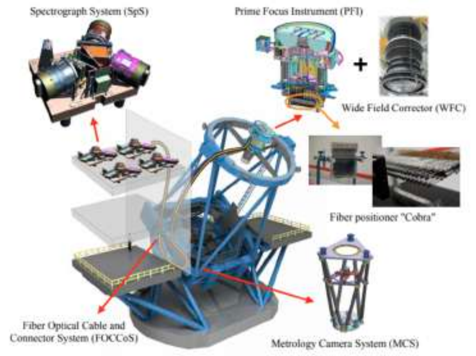
Future - signals in cosmology

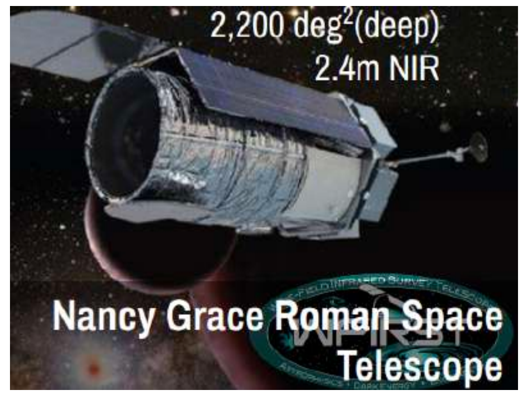
Observations

Photometric and spectroscopic surveys



Prime Focus Spectrograph (PFS)





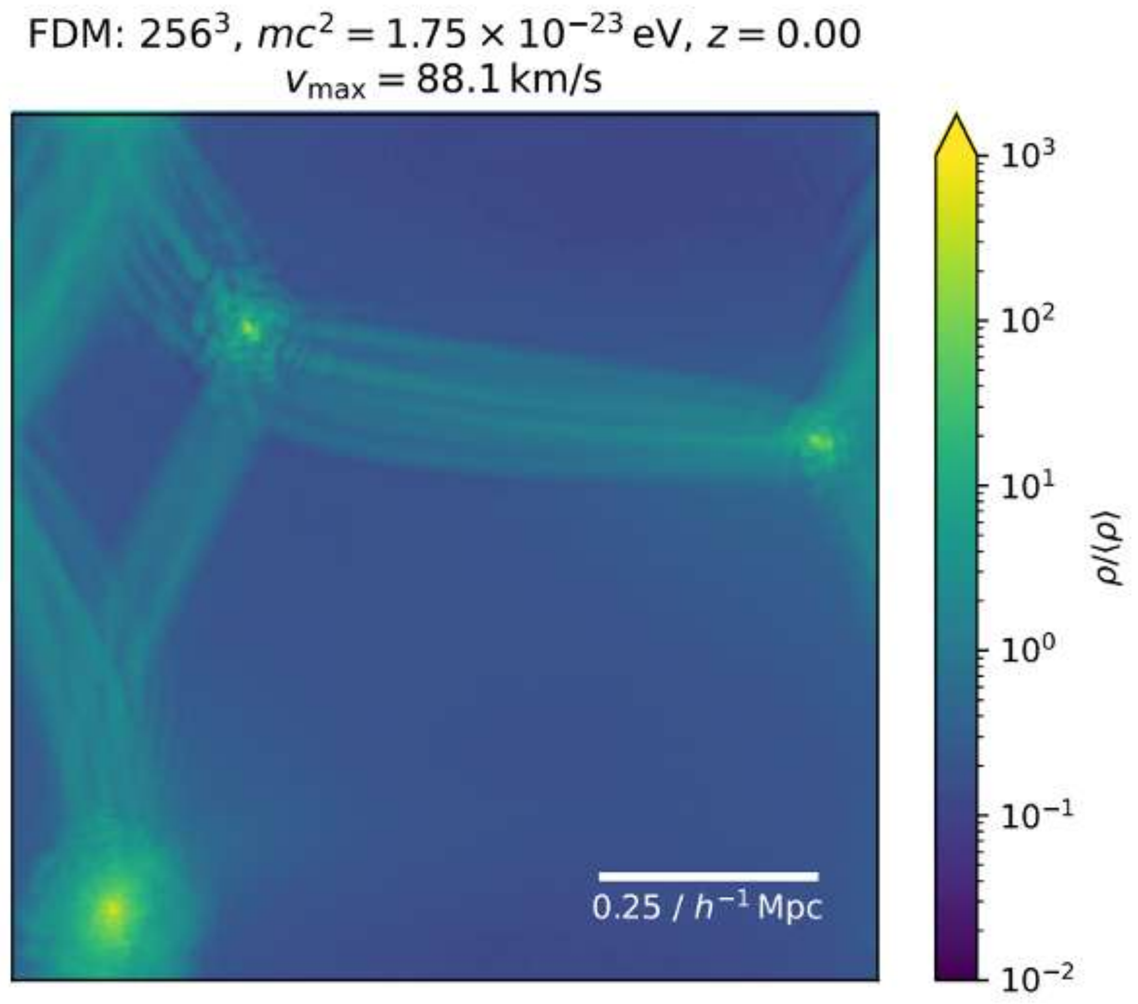
CMB

CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New probes

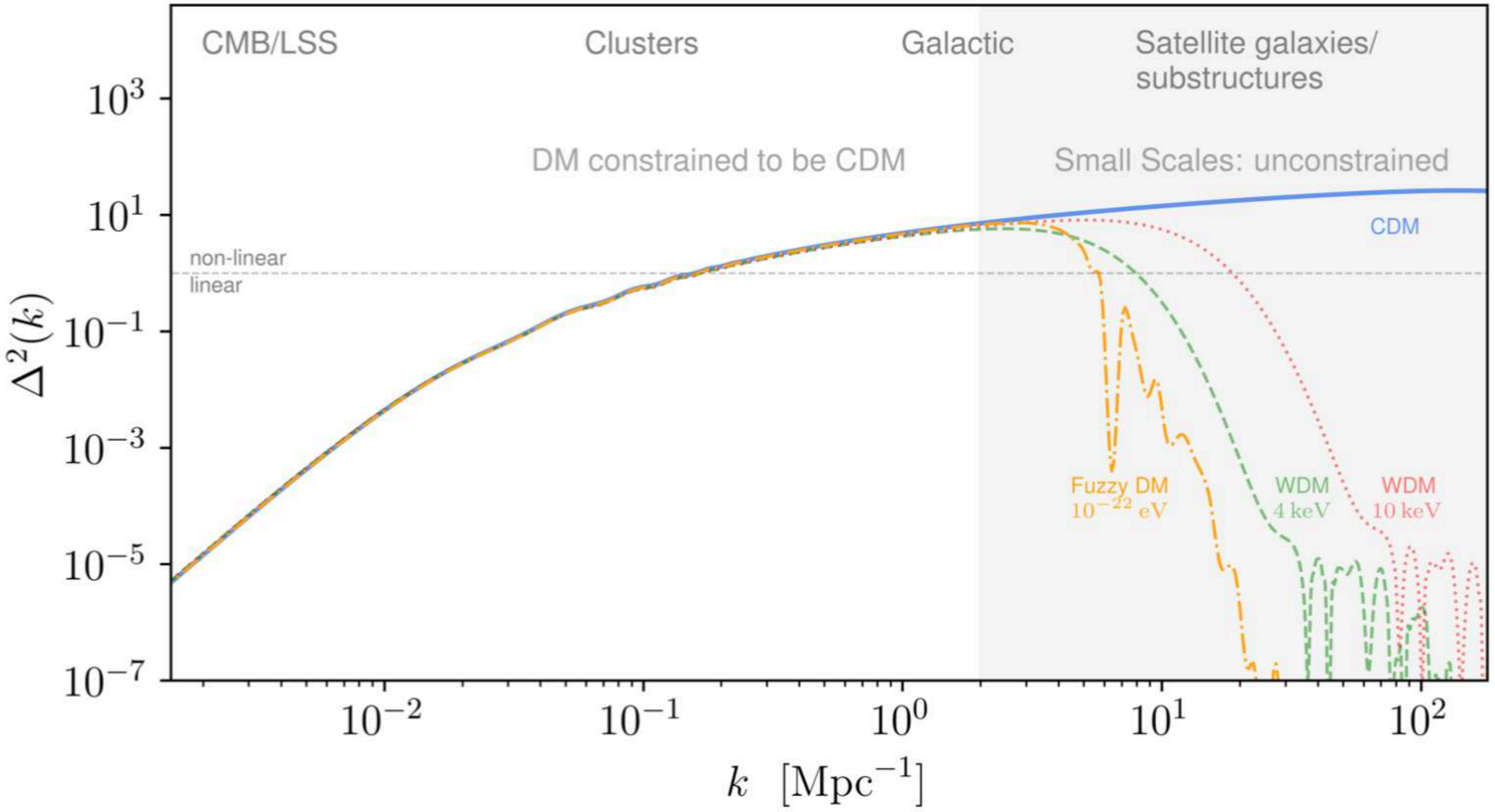
Substructures
- strong lensing
- stellar streams

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)

Substructure convergence power spectrum

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

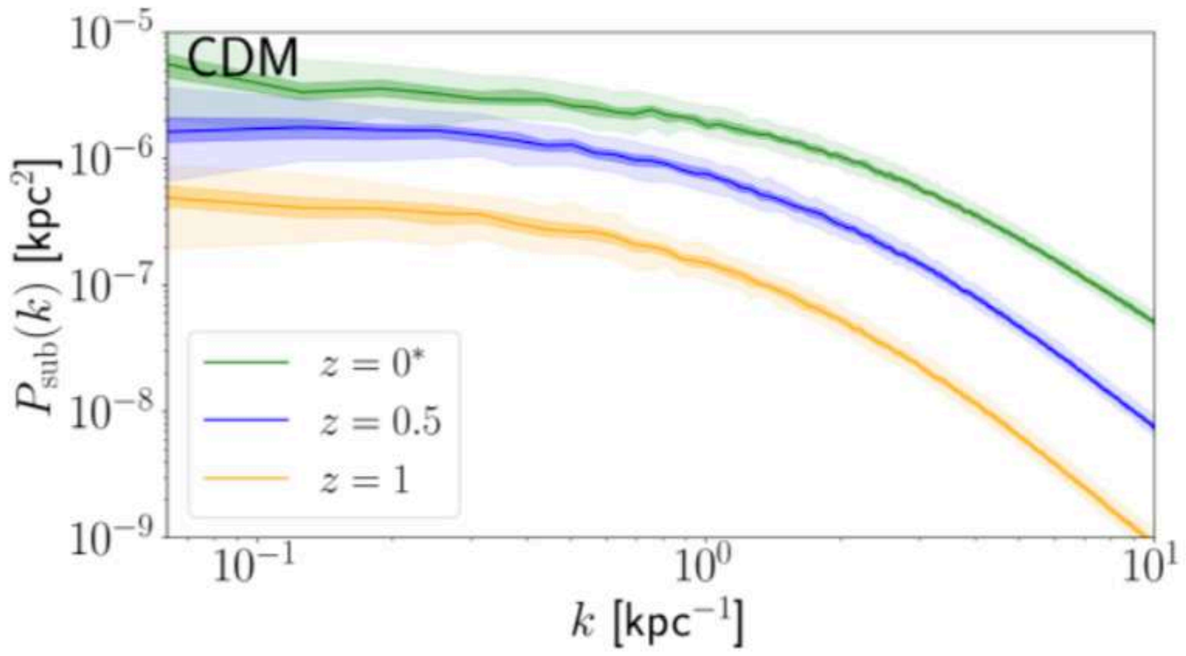
Develop a formalism to compute the substructure convergence power spectrum for different populations of dark matter subhalos.

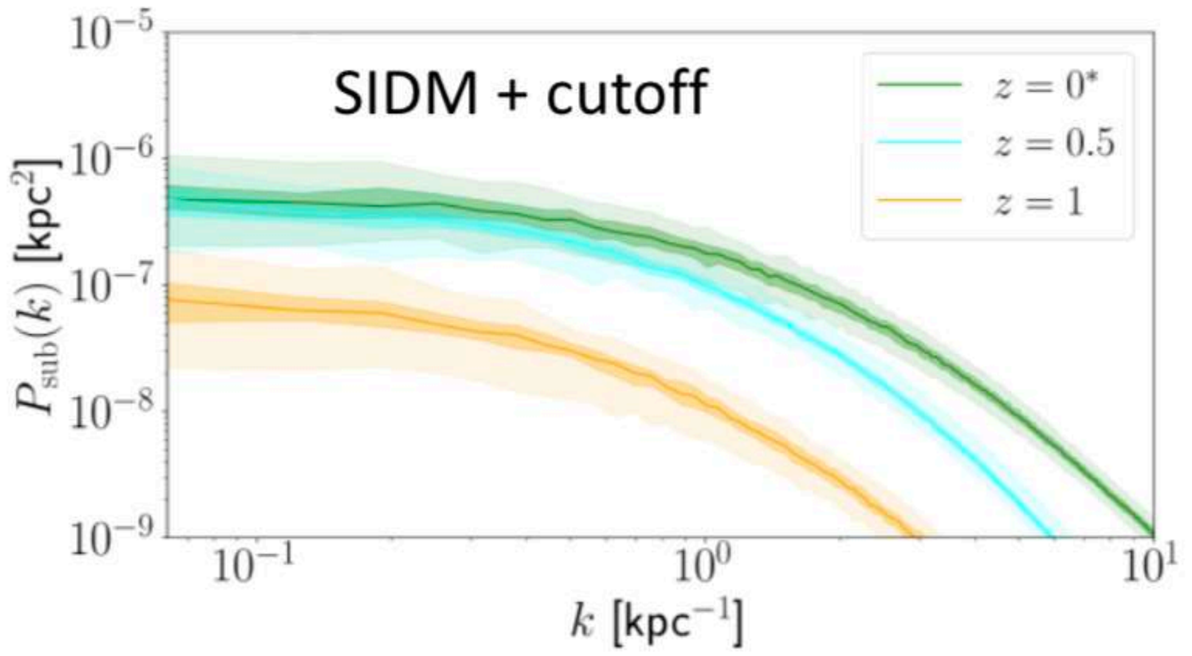
Hezaveh et al. (2016) (projected mPS by using strong lensing)

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

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

<u>Substructure convergence power spectrum</u>

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:

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

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

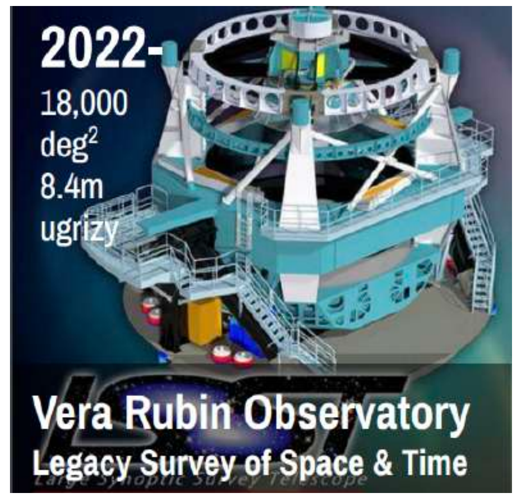
Previous:
- Mostly numerical
- Perturbations $\longrightarrow$ sub-halo mass function

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

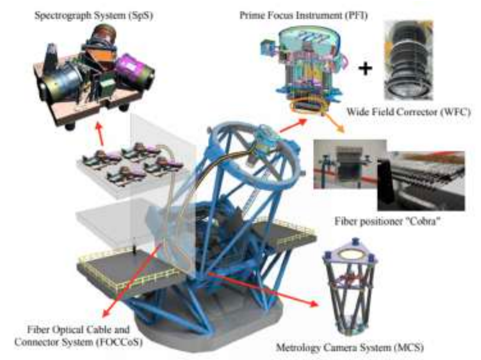
Future - signals in cosmology

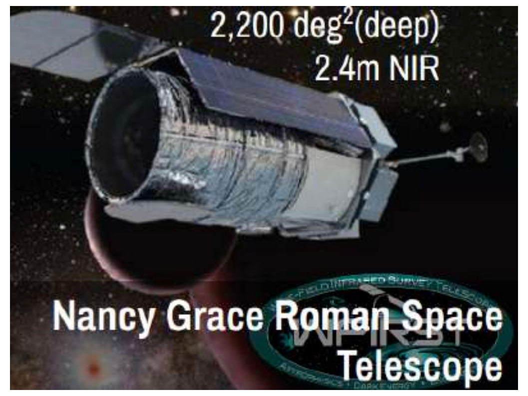
Observations

Photometric and spectroscopic surveys



Prime Focus Spectrograph (PFS)





CMB

CMB-S4
Next Generation CMB Experiment

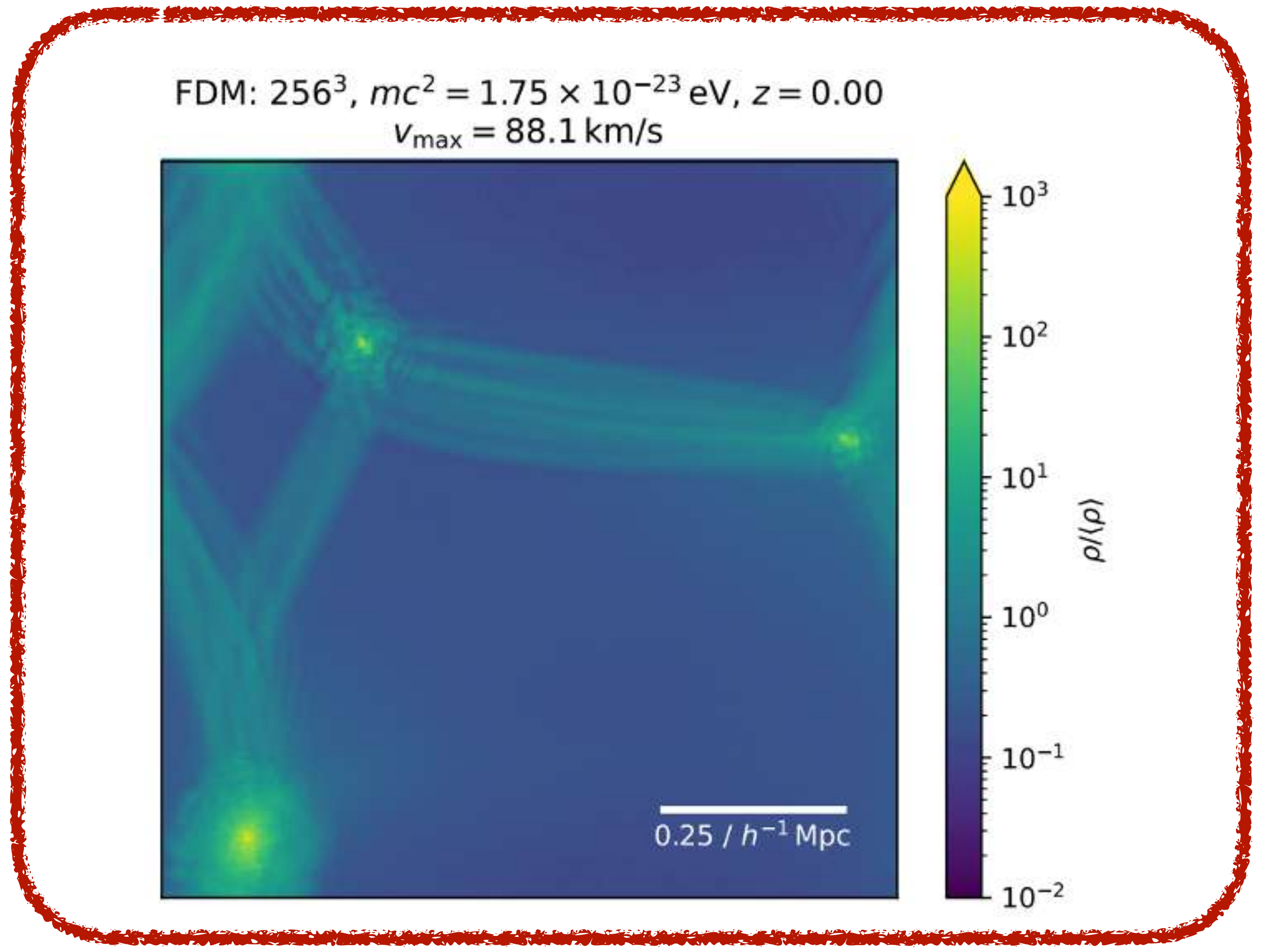
21cm

SKA
SQUARE KILOMETRE ARRAY

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

Simulations

(more later)



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