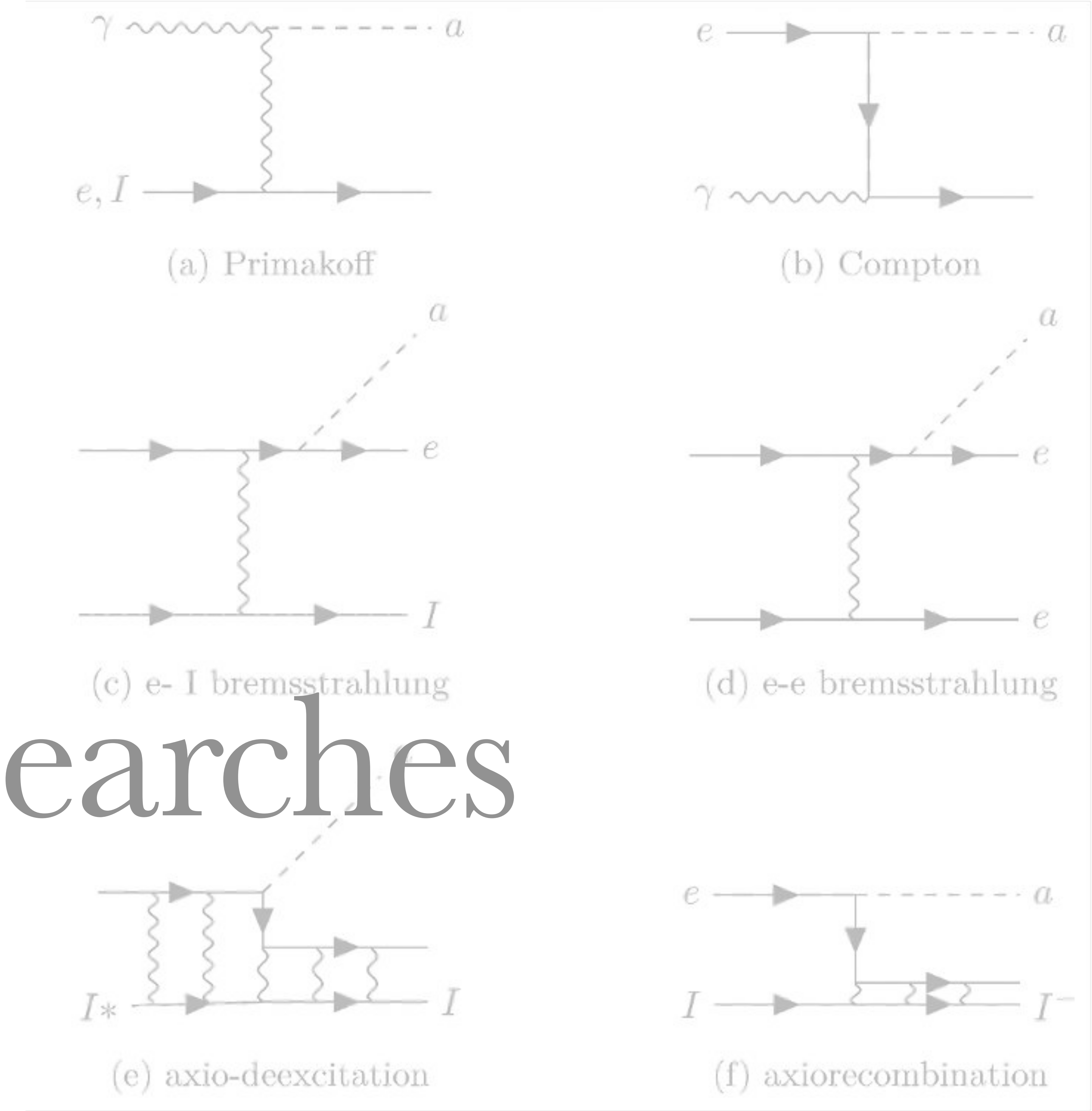


Lecture 3: ULDM searches

Interactions with SM

Elisa G. M. Ferreira

Kavli IPMU & University of Sao Paulo

ISAPP School - *Quantum Fluids in the Universe*
June 15, 2023

Outline

Lecture 1: Cosm. Signatures 1

Part I:

- Evidences
- ULDM models
- Observational signatures
- GravitationalBounds

Part II: *Practice!*

Notebook 1: linear

- Linear observational signature of ULDM: suppression of structures

Lecture 2: Cosm. Signatures 2

Part I:

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

Part II:

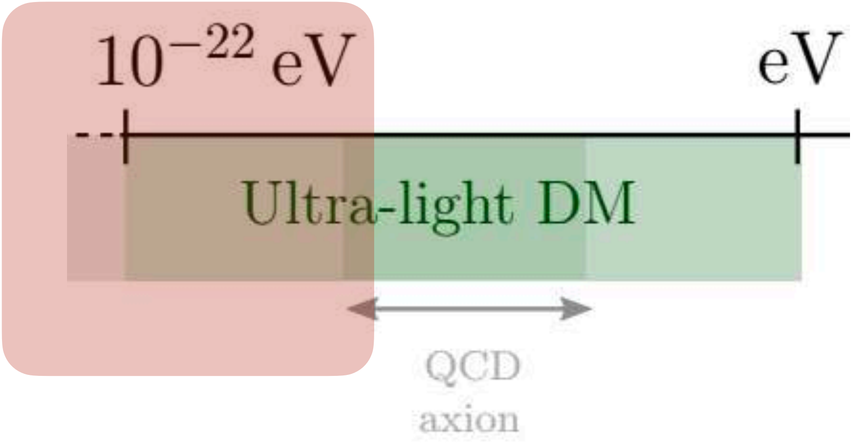
Notebook 2: non-linear

- Consequences on small scales

Lecture 3: interac. with SM

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

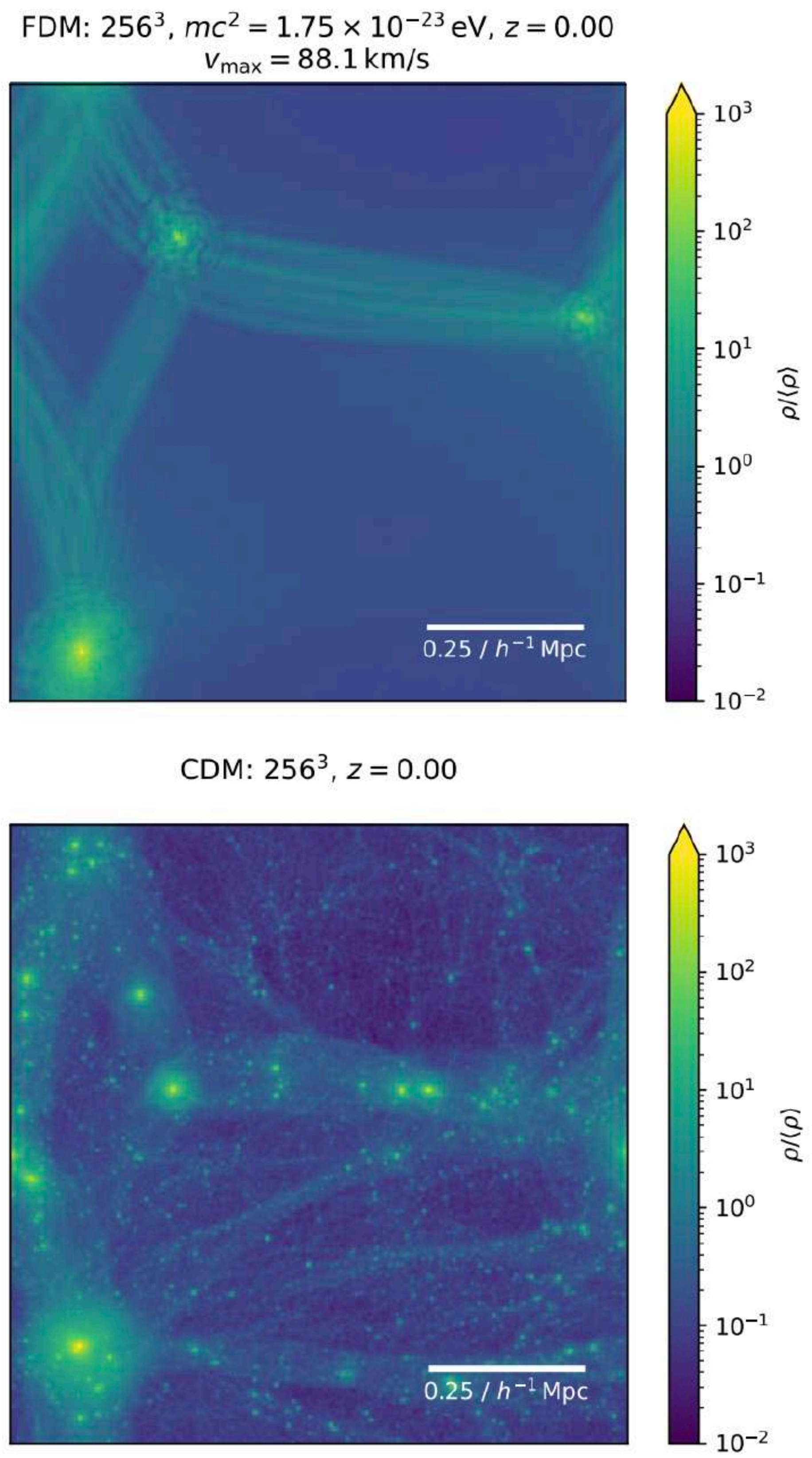
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

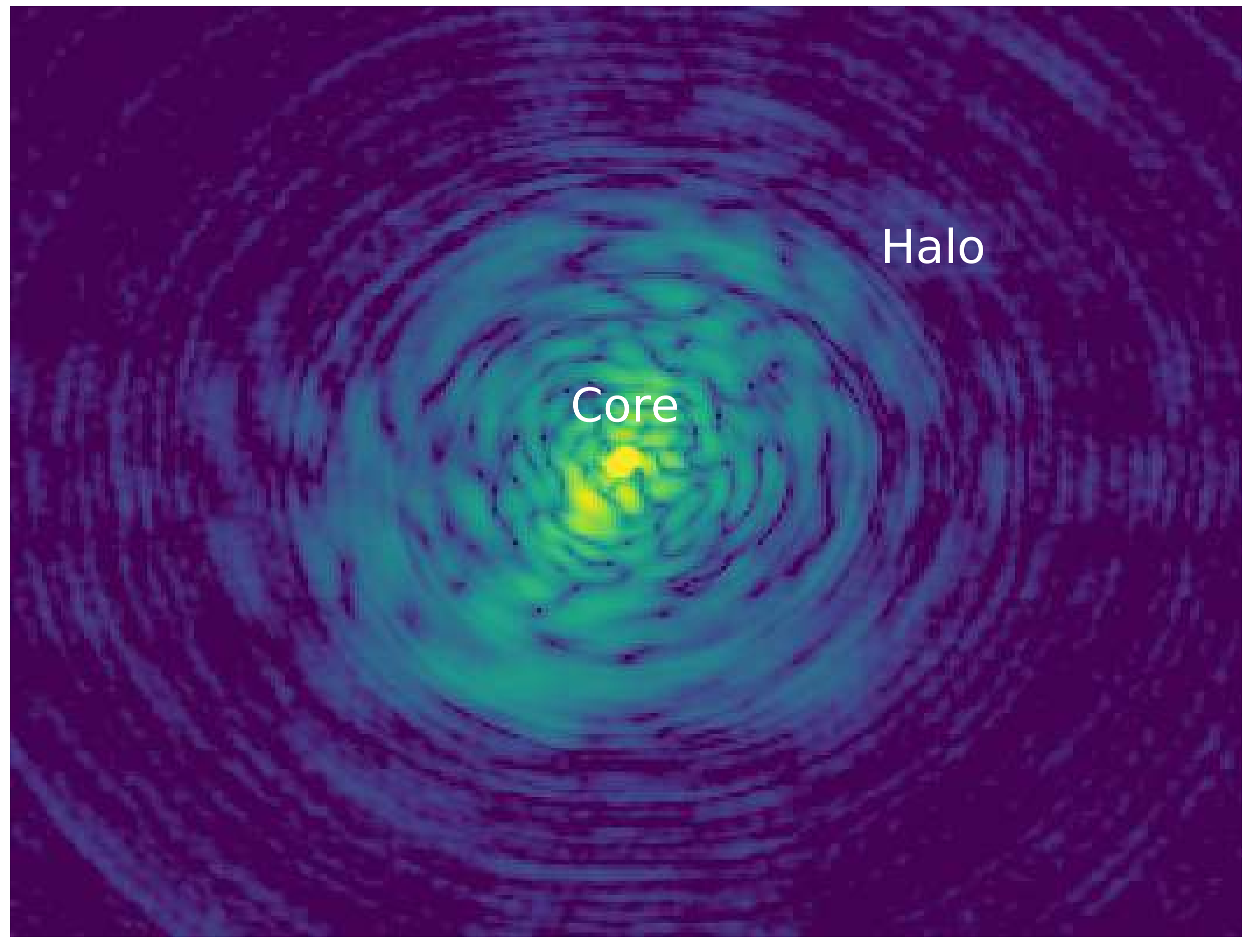
* Focus only in gravitational signatures

Suppression of small structures

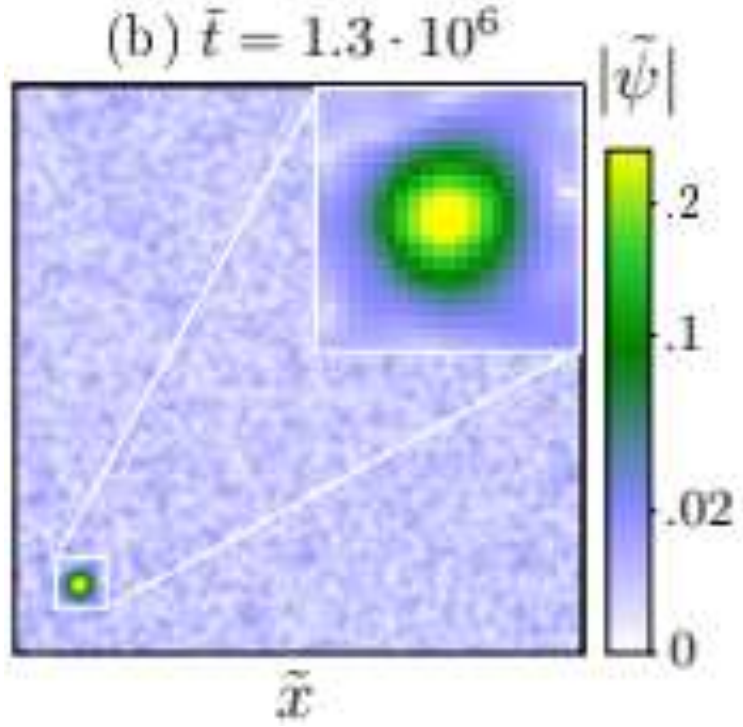


S. May et al. 2021

Formation of a solitonic core

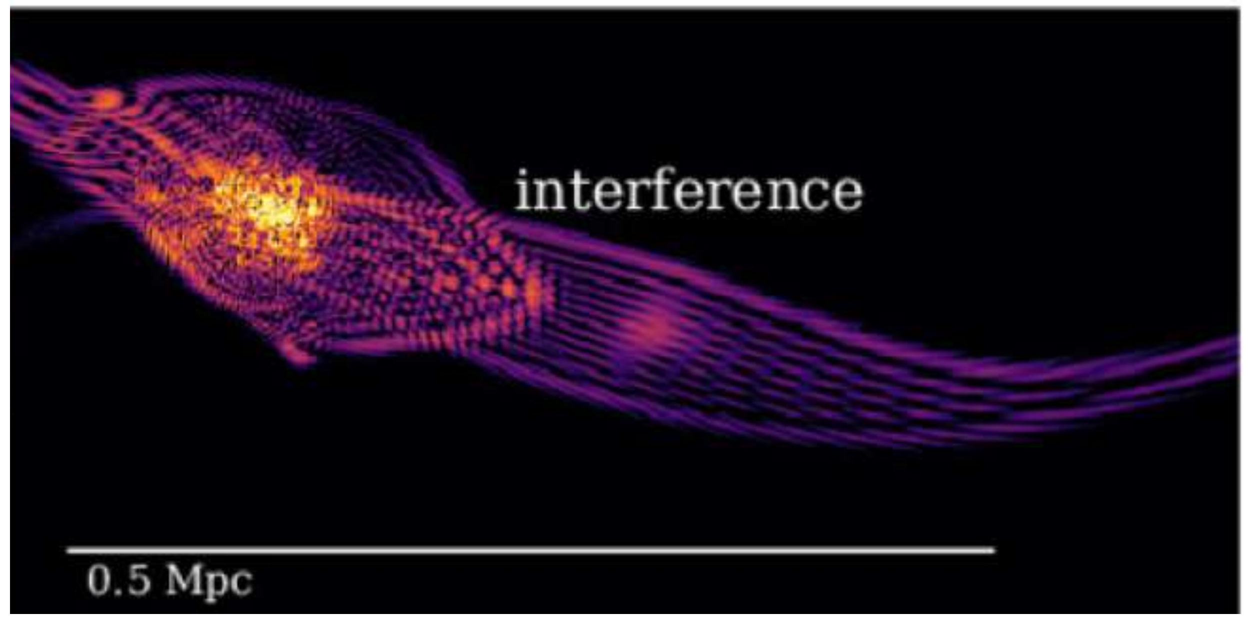


Dynamical effects



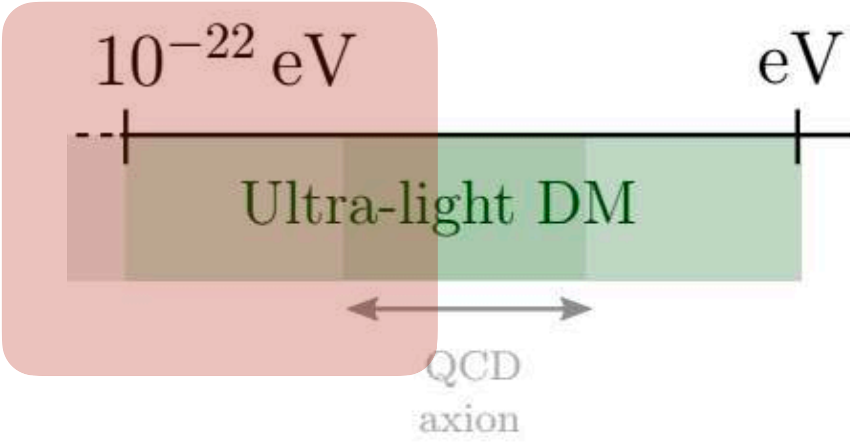
Levkov et al. 2018

Wave interference



Mocz et al. 2017

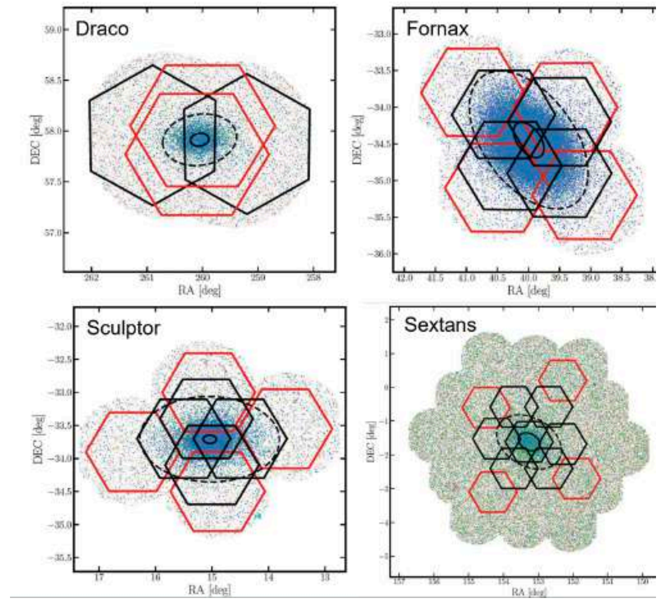
Observational implications and constraints



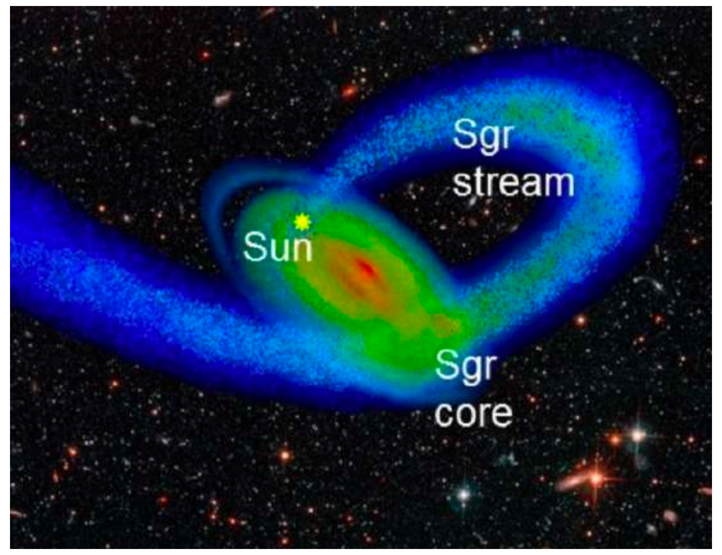
Galaxies

NASA and ESA

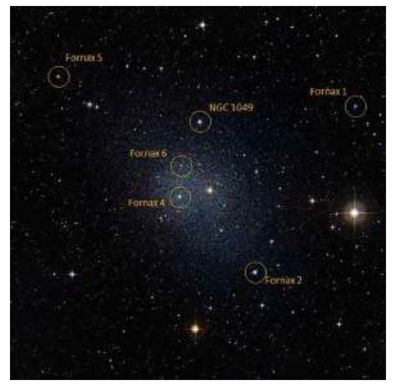
Dwarfs



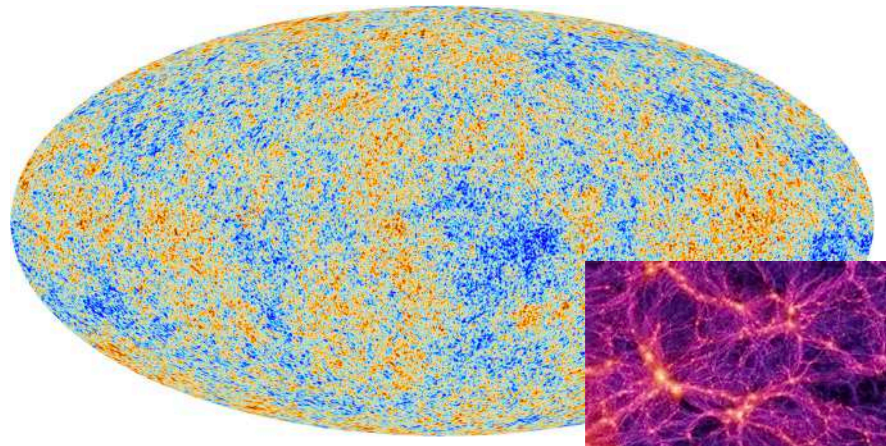
Stellar stream



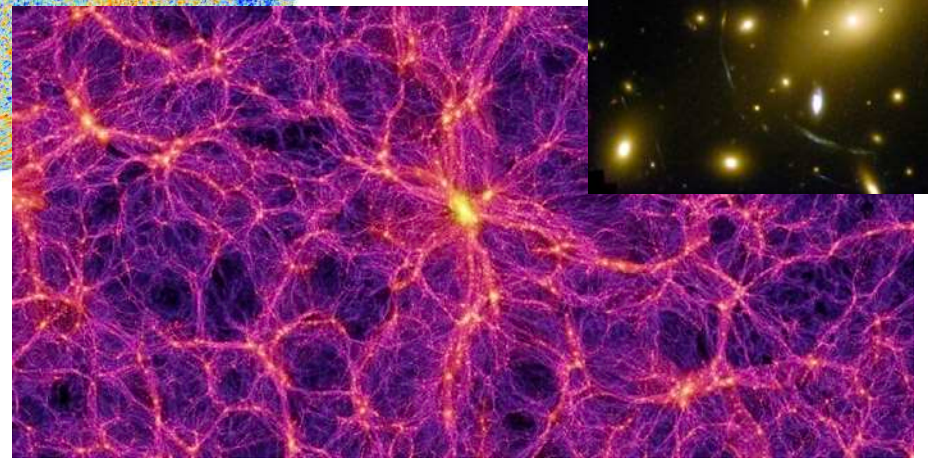
Globular clusters



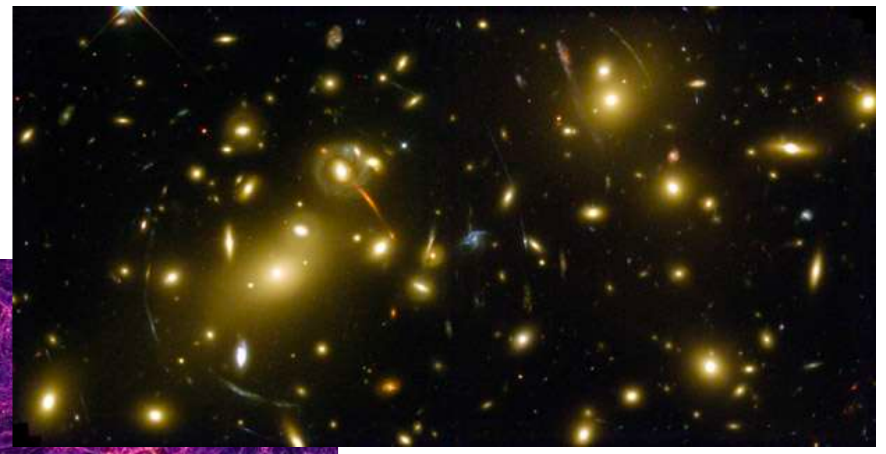
CMB+LSS



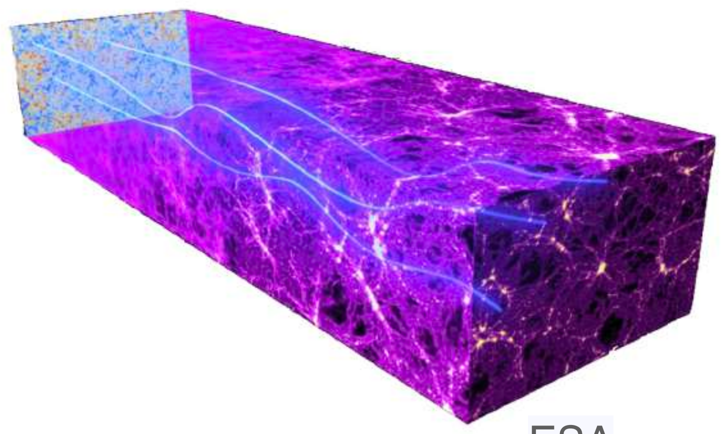
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

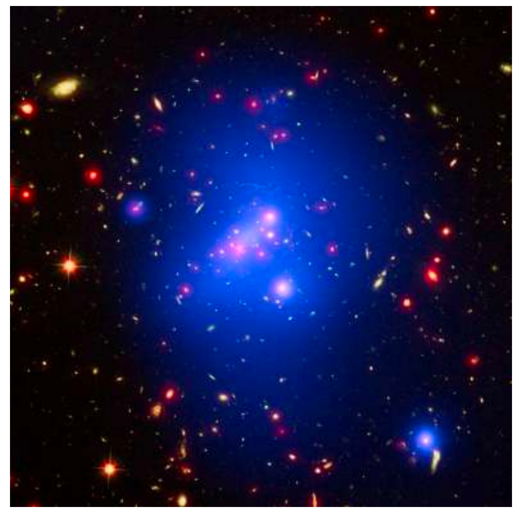


NASA and ESA



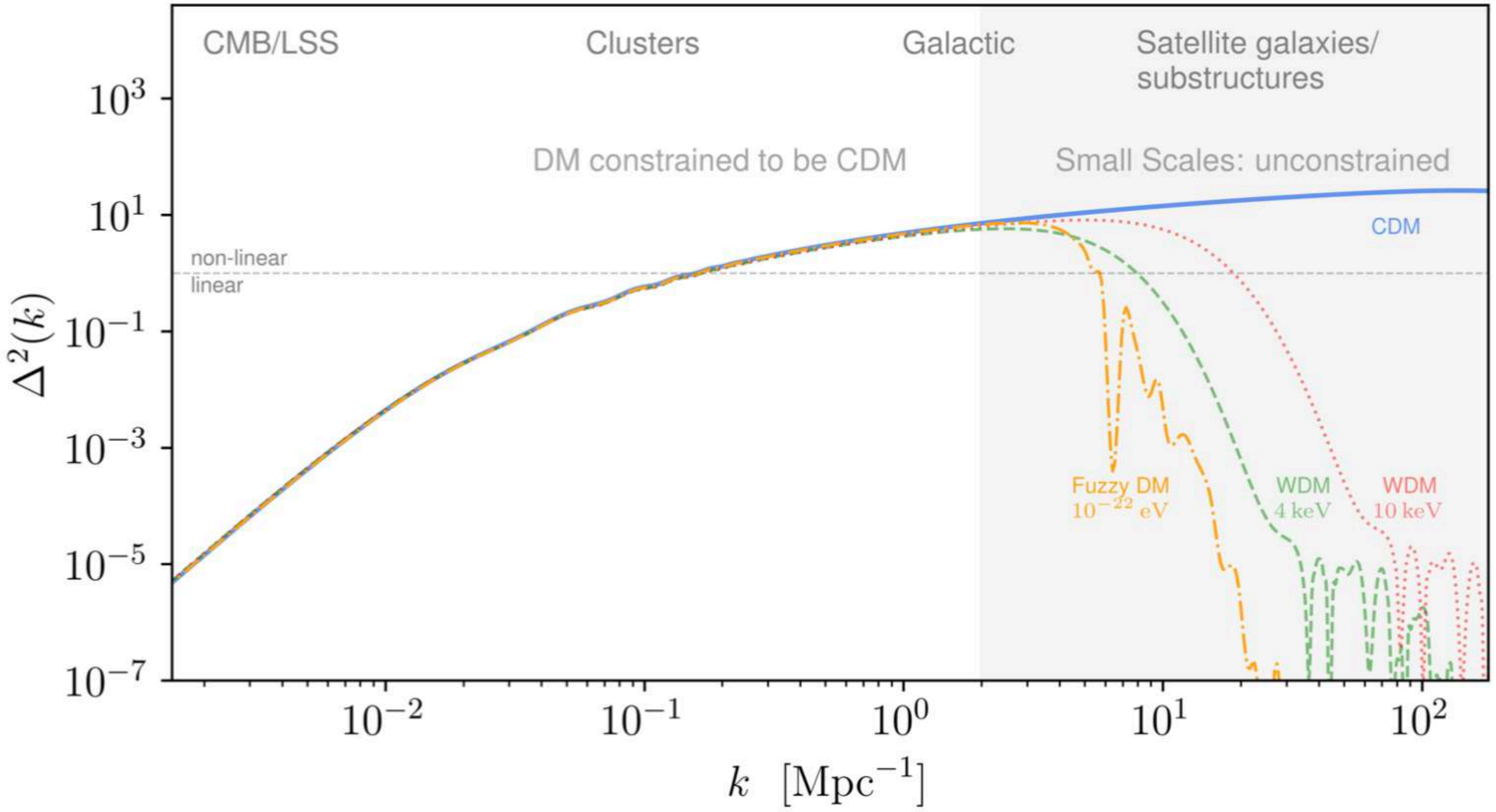
ESA

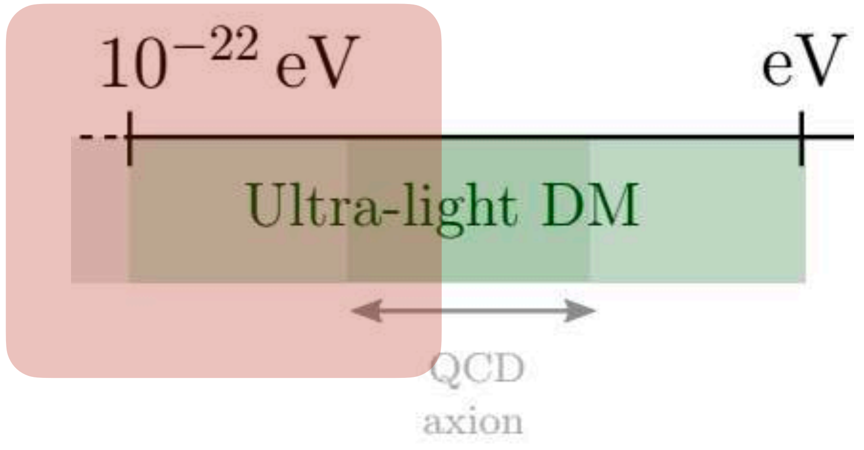
Clusters



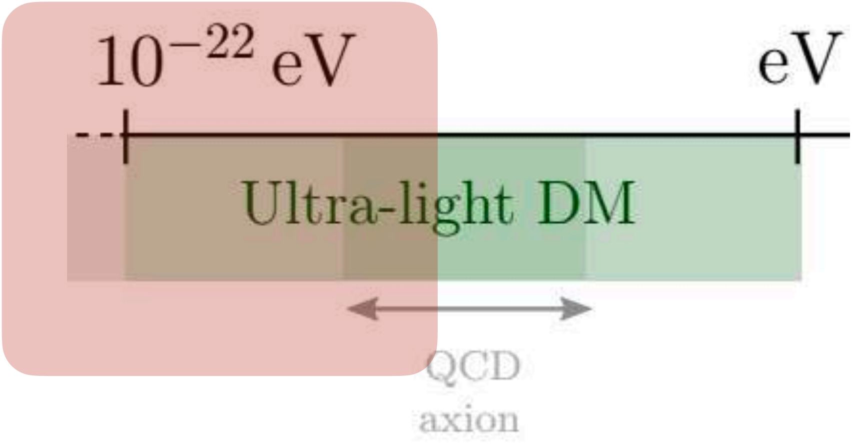
CC BY 4.0

Power spectrum





Cont. Observational implications and constraints

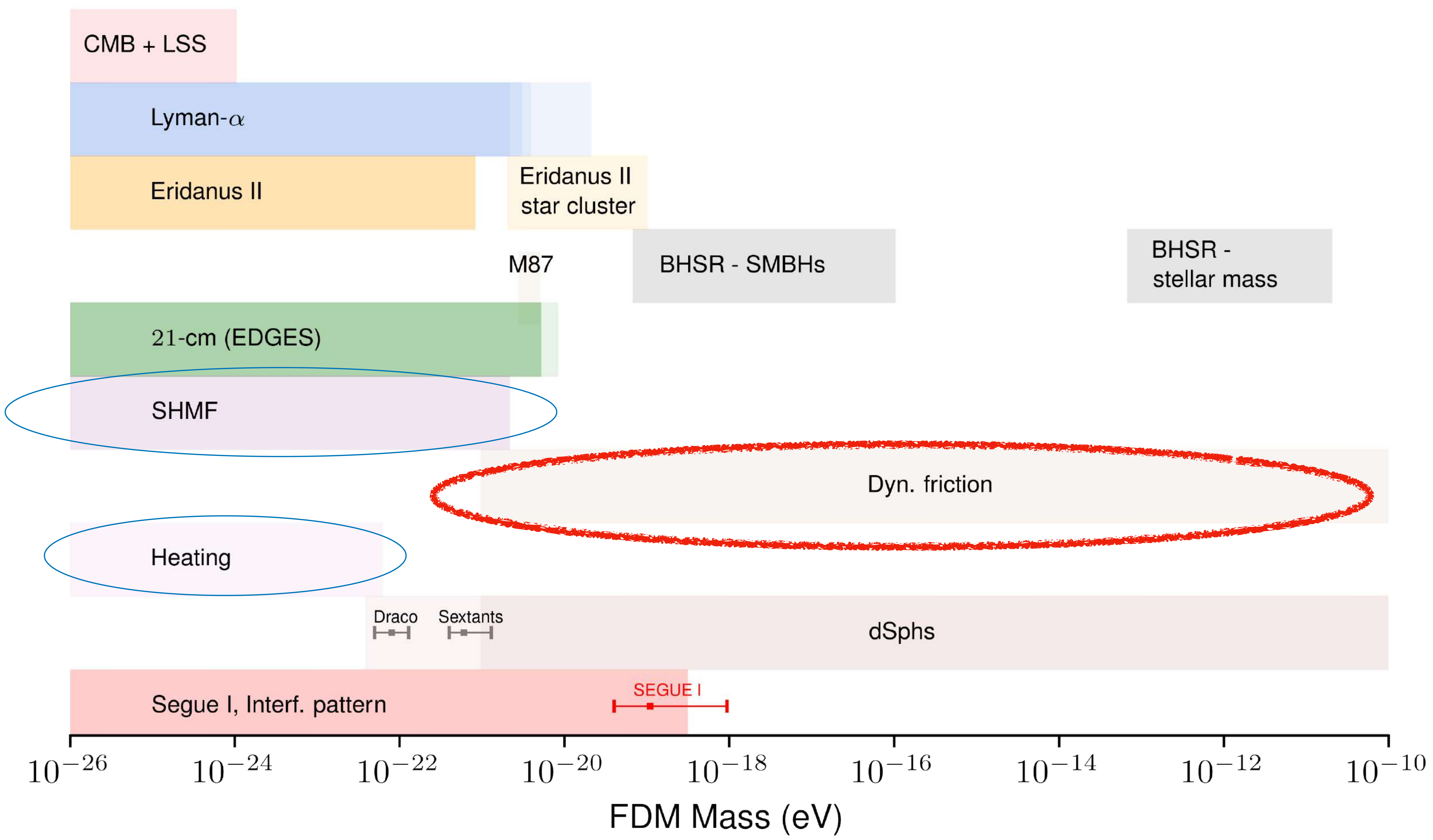


Observational implications and constraints

Dynamical effects

Observational implications and constraints

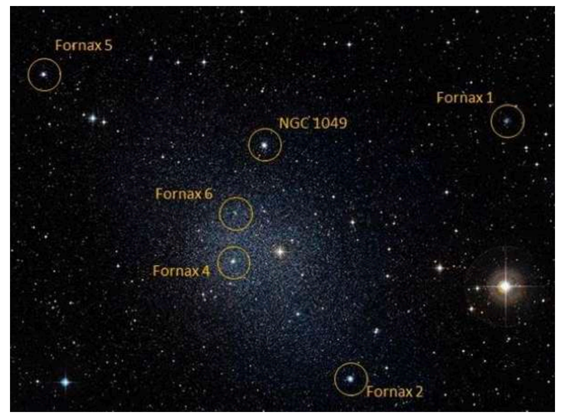
Fuzzy Dark Matter - bounds on the mass



Dynamical effects

Globular clusters

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



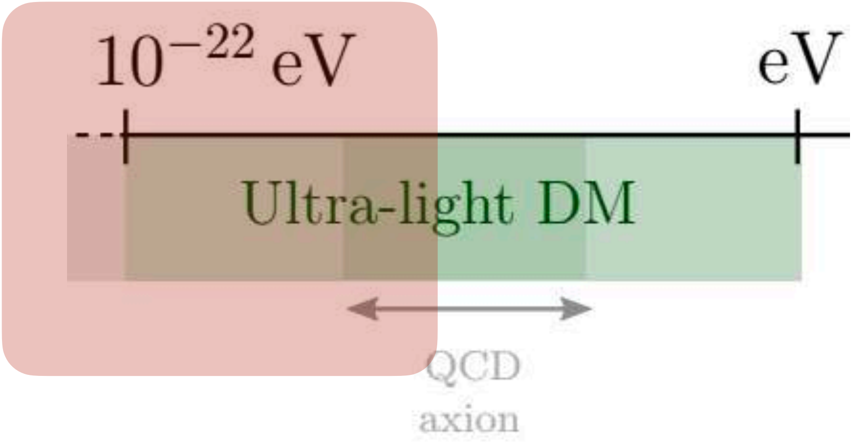
ESO/Digitized Sky Survey 2

Lancaster et al. 2020

Heating of the MW disk

Church et al. 2019

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

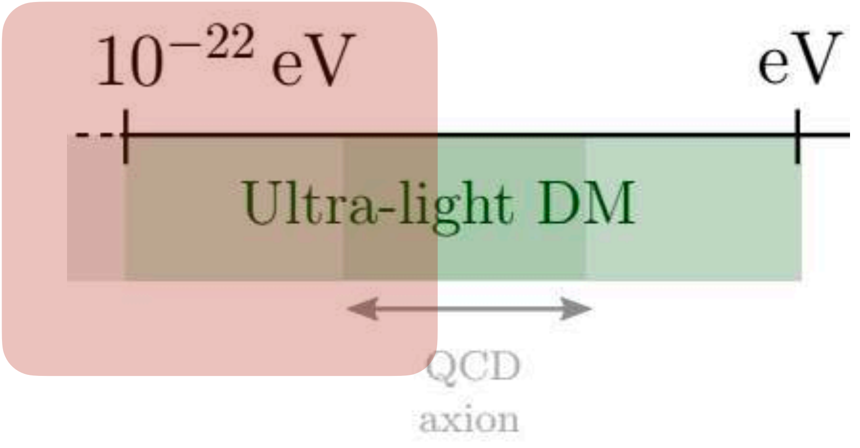


Observational implications and constraints

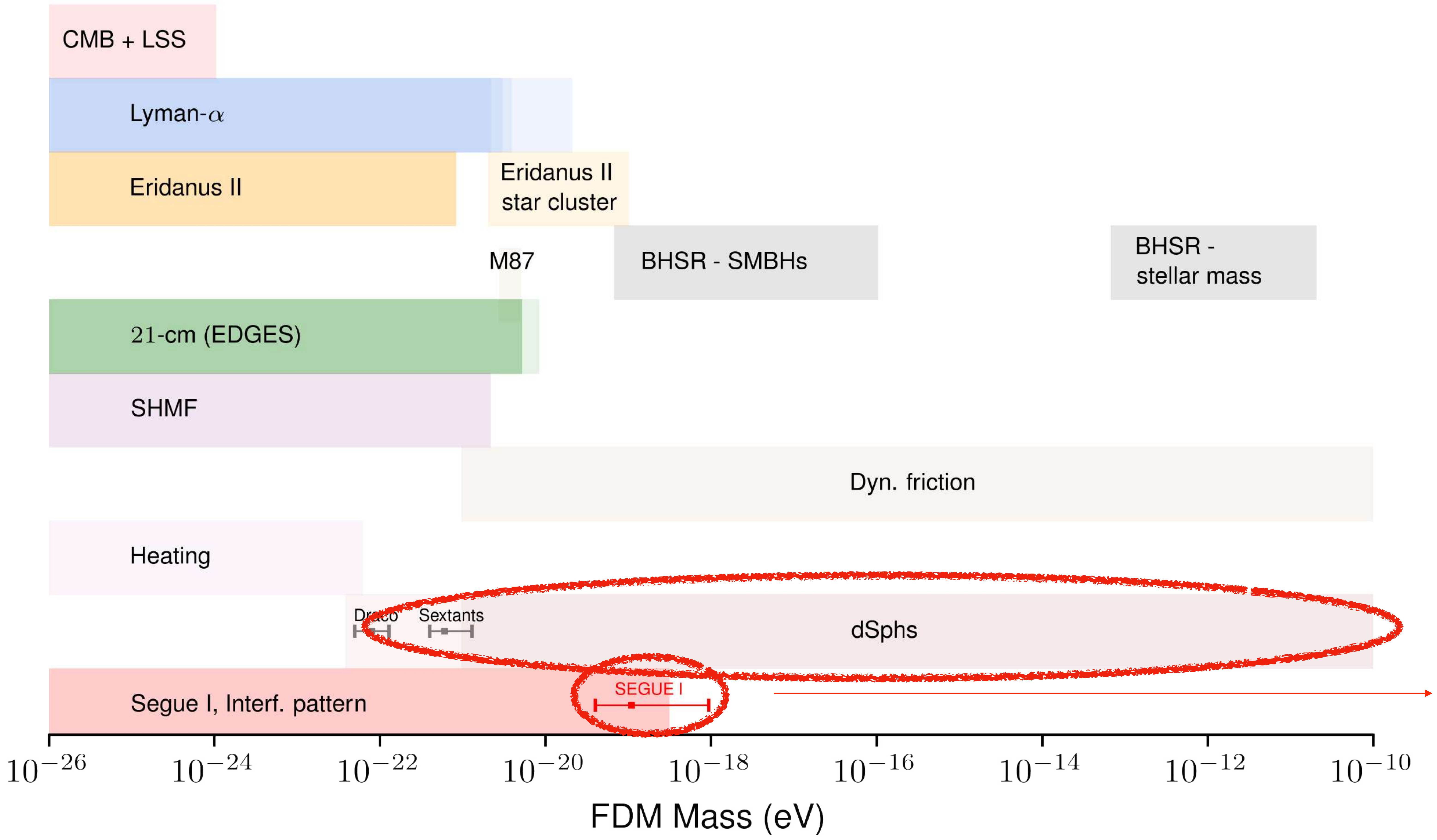
Core in the interior of galaxies

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

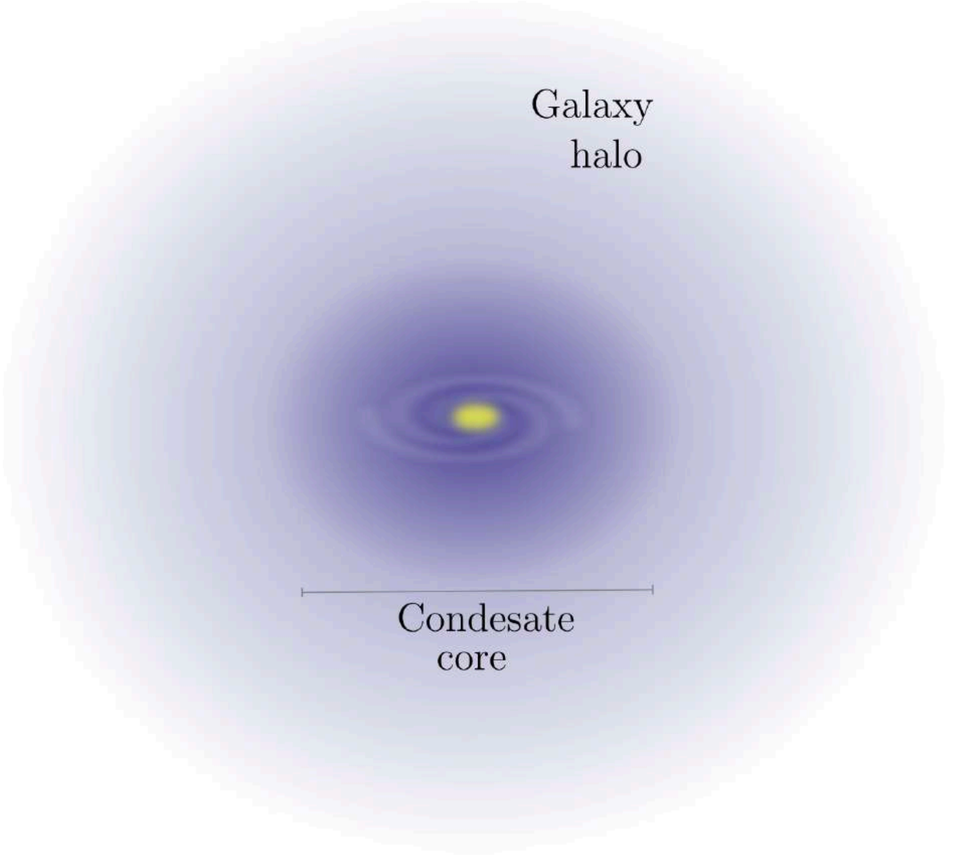


Presence of a core



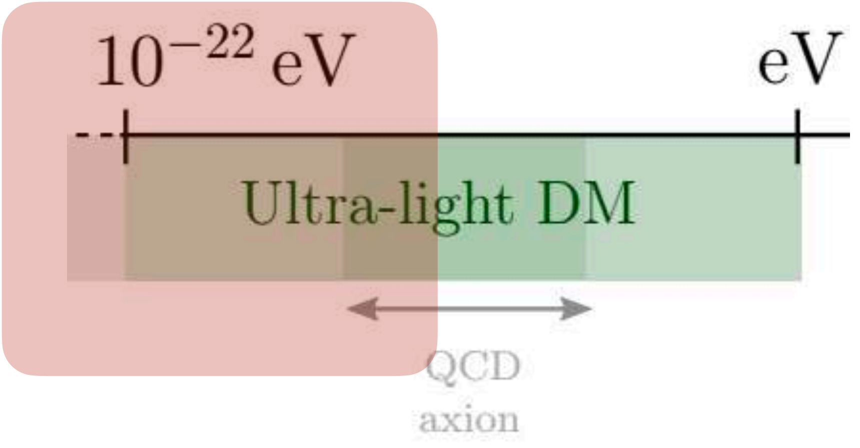
Presence of a core

DWARF GALAXIES

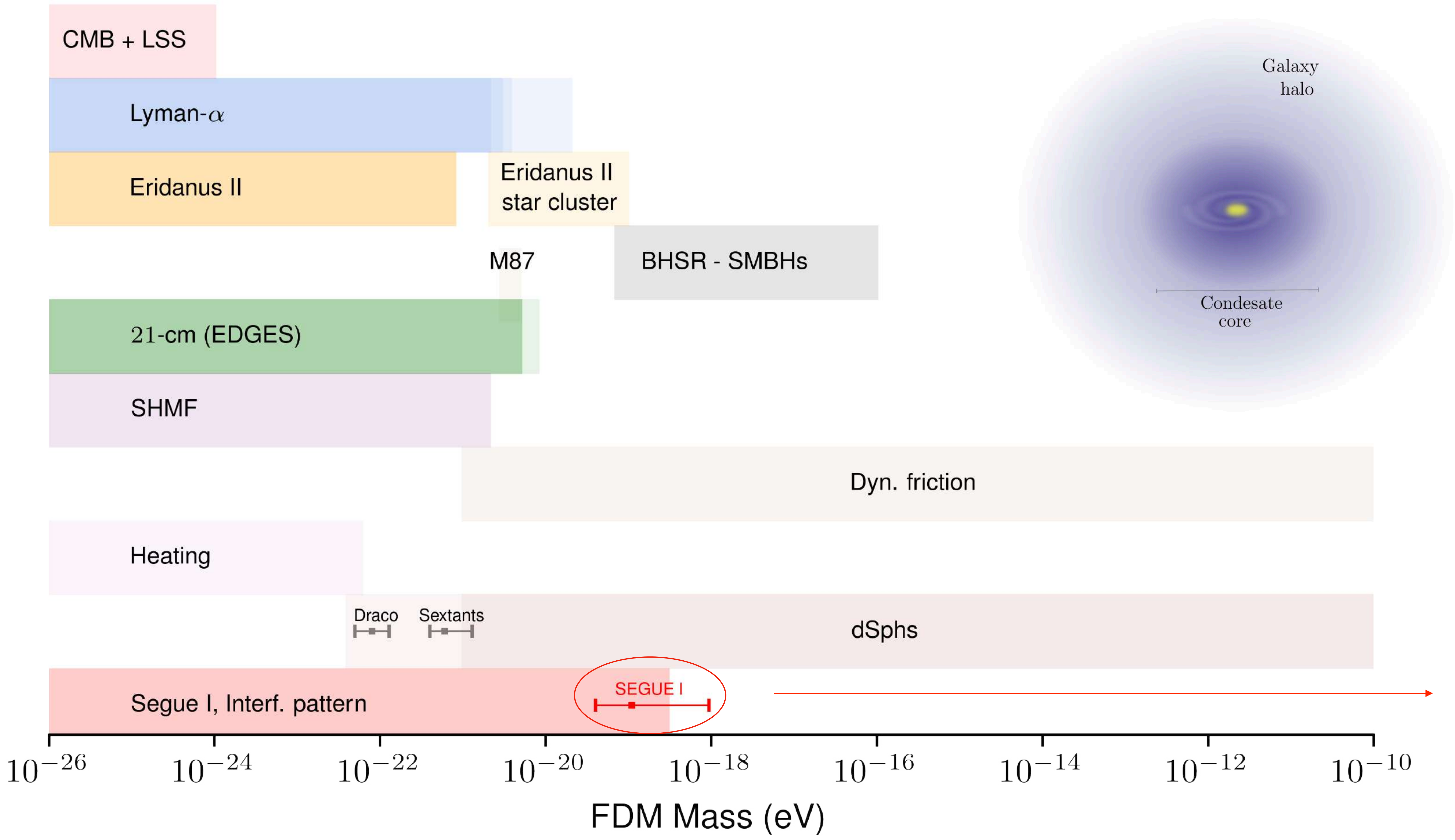


Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



Presence of a core



DWARFS

Ultra faint dwarfs

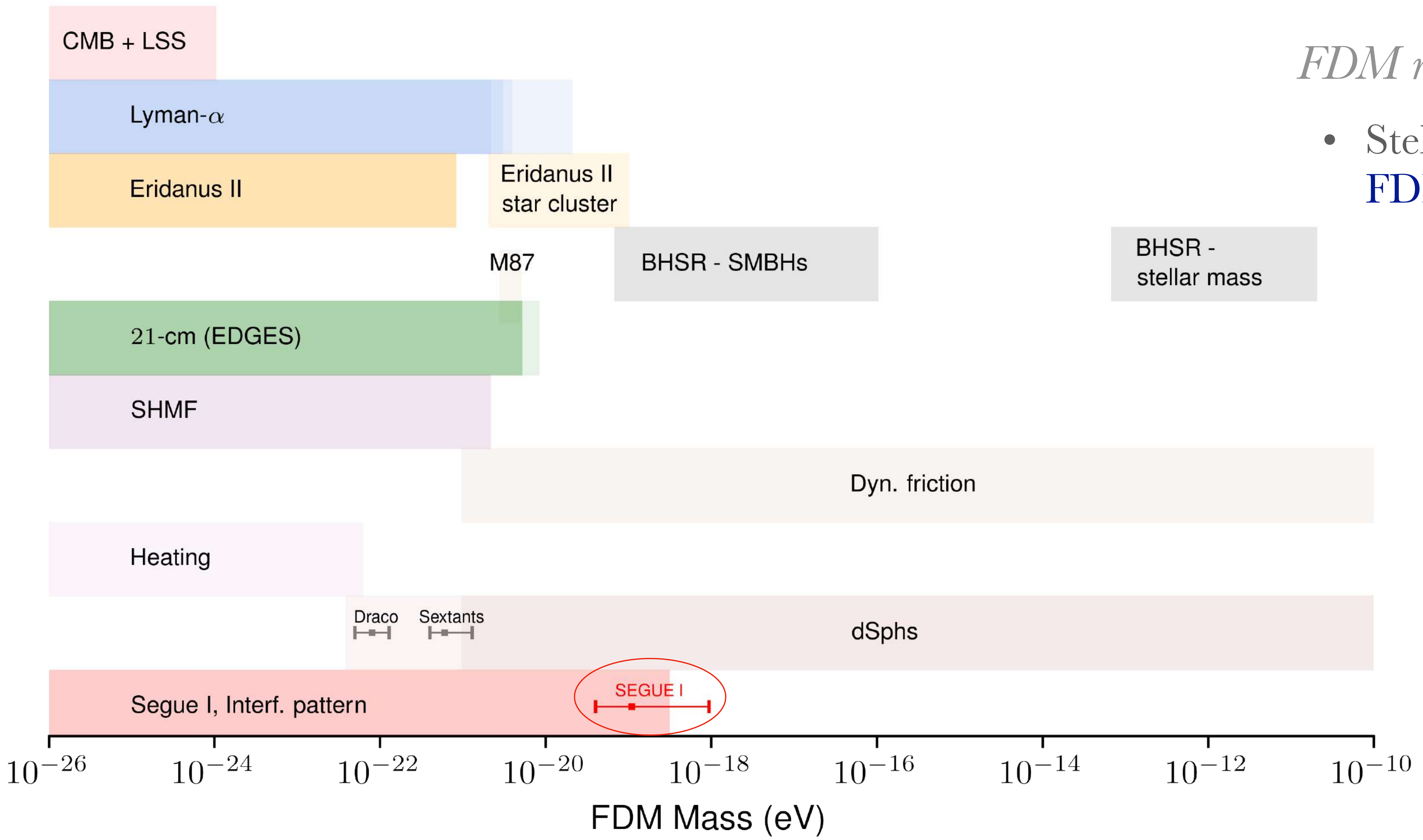
FDM SIMULATIONS

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

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

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass



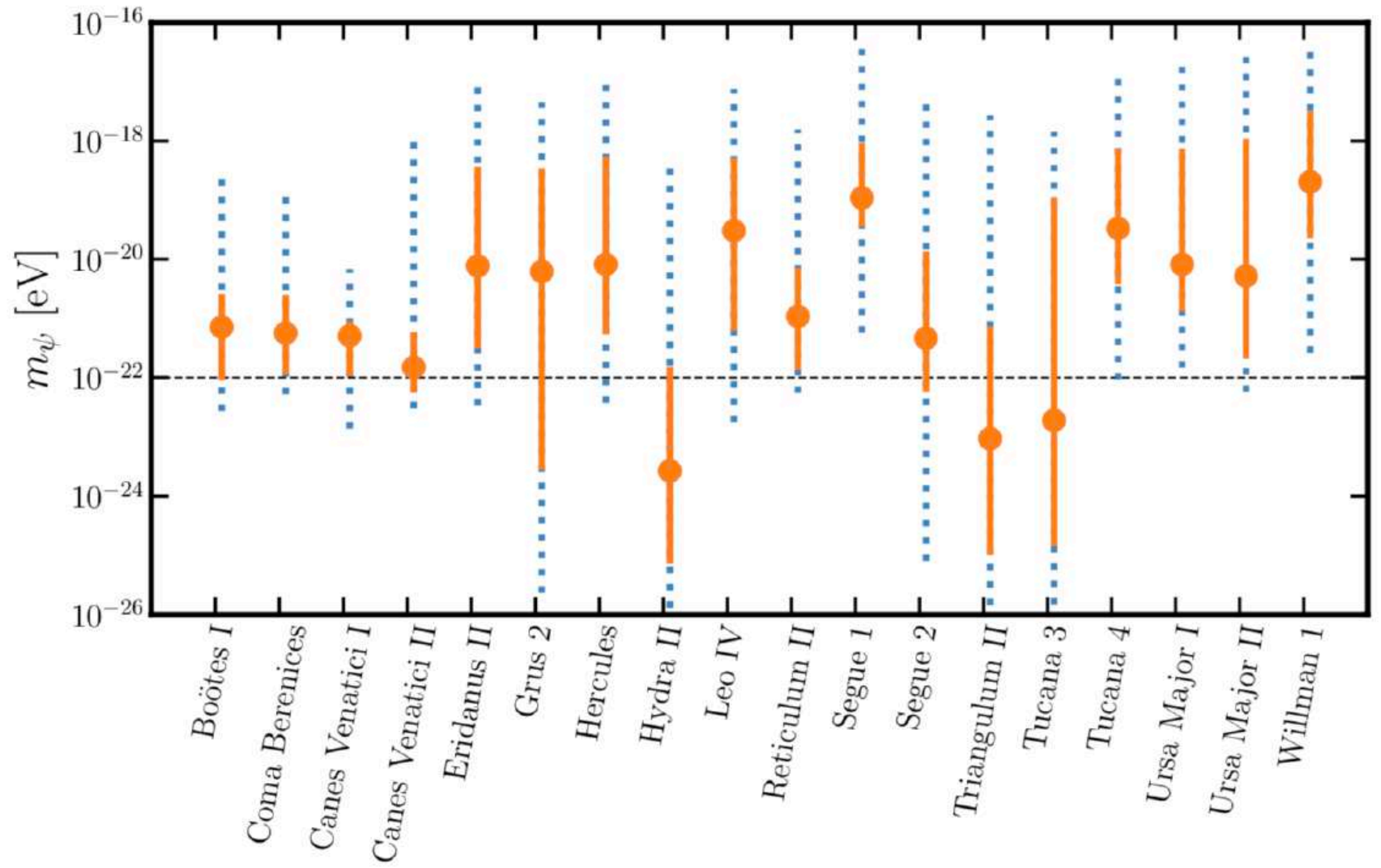
Ultra faint dwarfs

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

FDM mass from Ultra-faint dwarfs

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

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

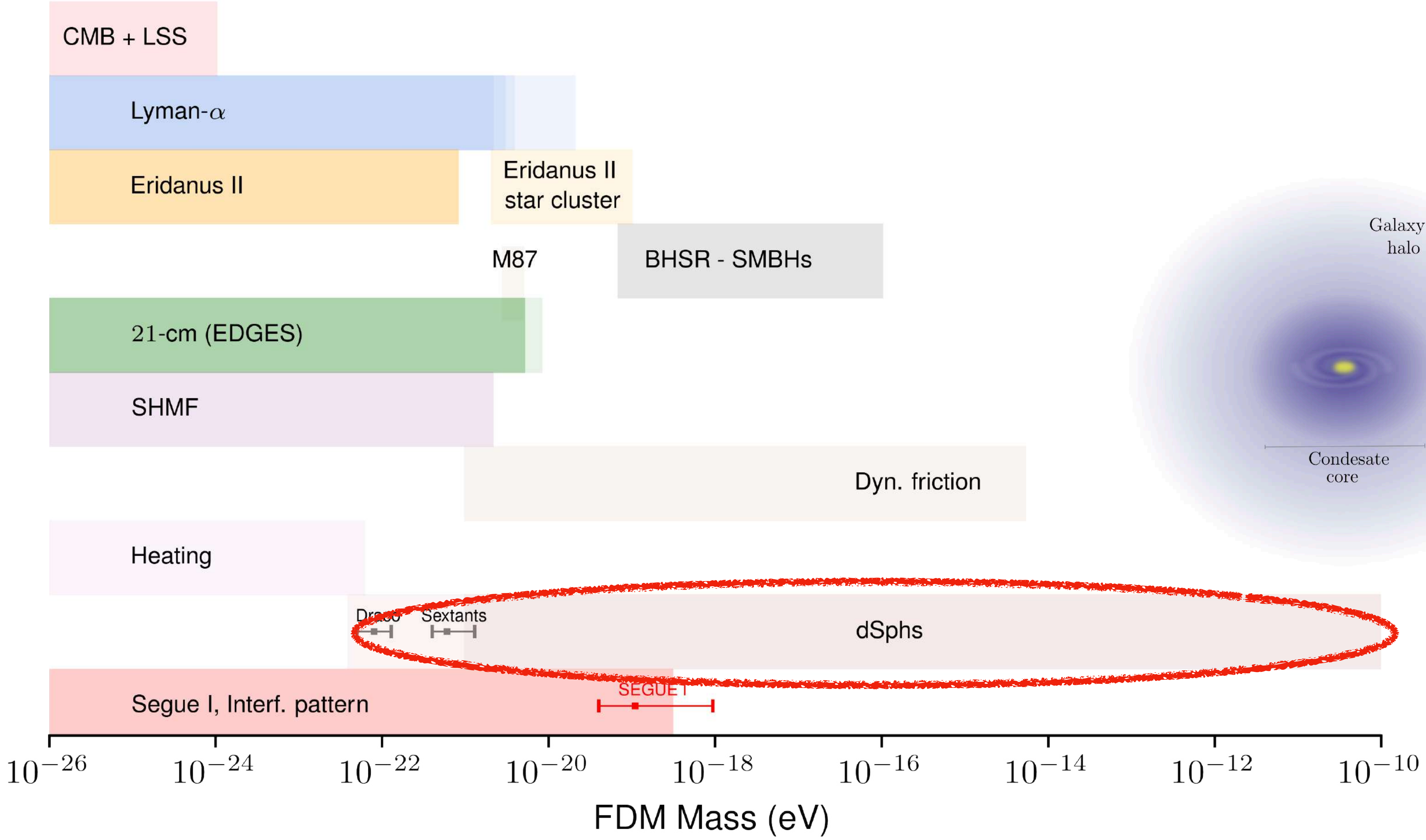


Preference for higher mass

Observational implications and constraints

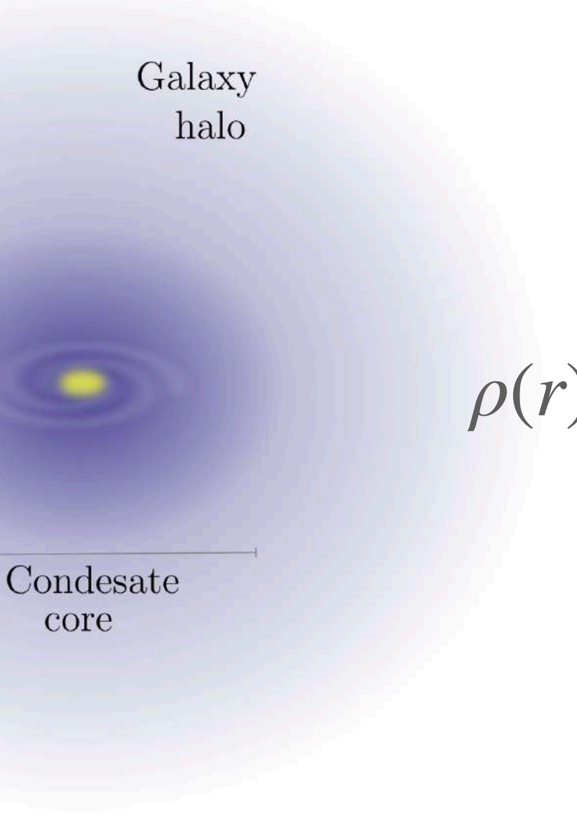
Fuzzy Dark Matter - bounds on the mass

Presence of a core



DWARFS

Dwarf Spheroidals (dSphs)



FDM SIMULATIONS

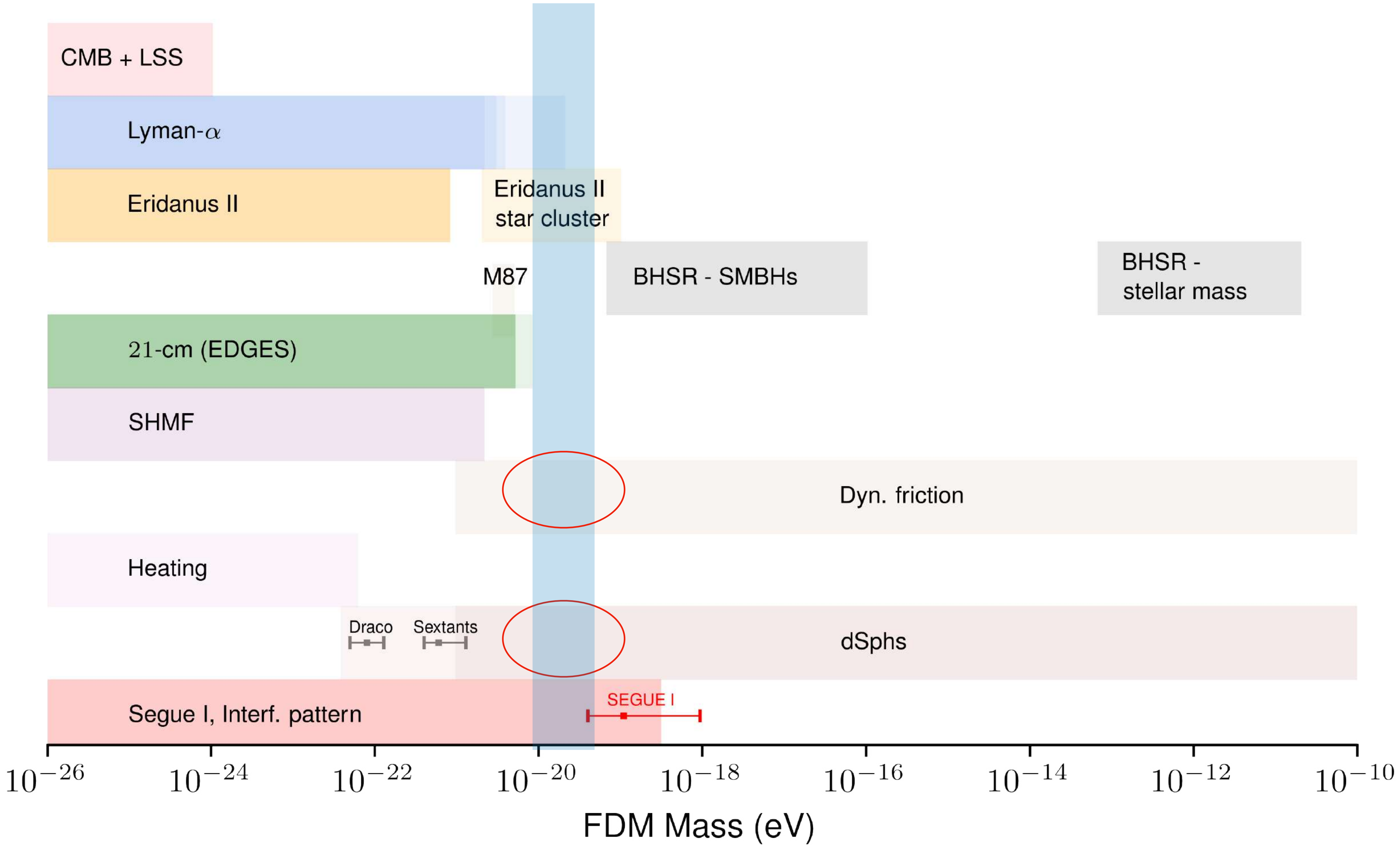
$$\rho(r) = \begin{cases} \rho_{\text{soliton}} \simeq \dfrac{\rho_c}{\left[1 + 0.091 (r/r_c)^2\right]^8}, & r < r_\epsilon \\ \rho_{\text{NFW}} = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, & r > r_\epsilon \end{cases}$$

Fornax - Sculptor

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

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

Constraints on the mass



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

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

Possible reasons for this incompatibility:

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

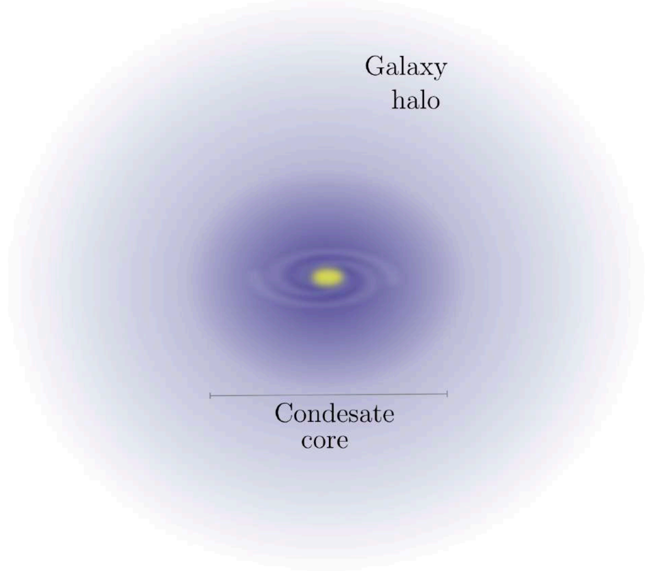
J. Chan, EF, S. May, K. Hayashi, M. Chiba 2021

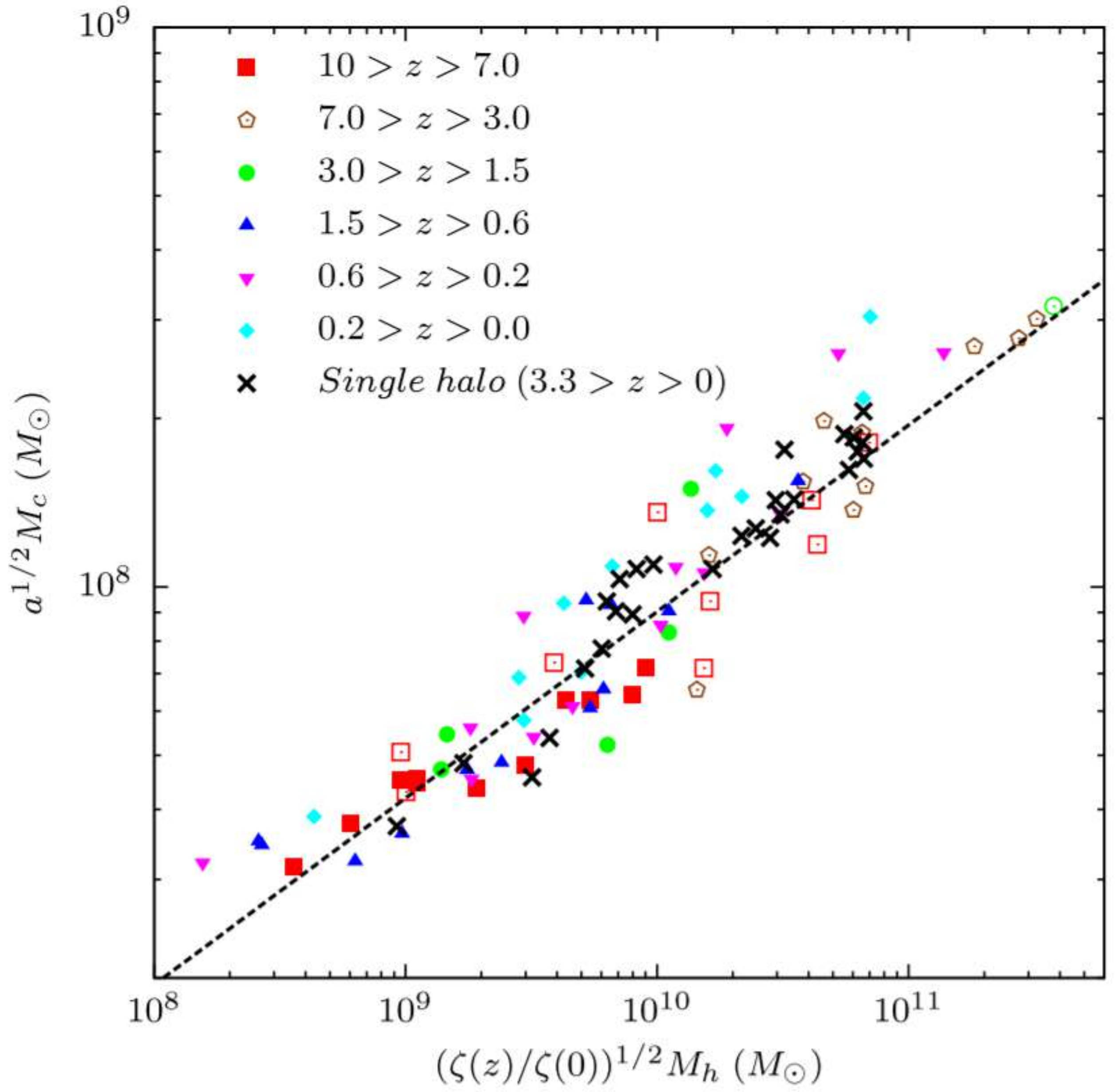
FDM - Core-halo mass relation

J. Chan et al. 2021

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

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





Schive et al. 2014

Schive et al 2014	Mocz et al 2017
$M_c \propto M_h^{1/3}$	$M_c \propto M_h^{5/9}$

Velocity dispersion tracing

$$\sigma_c \sim \sigma_h$$

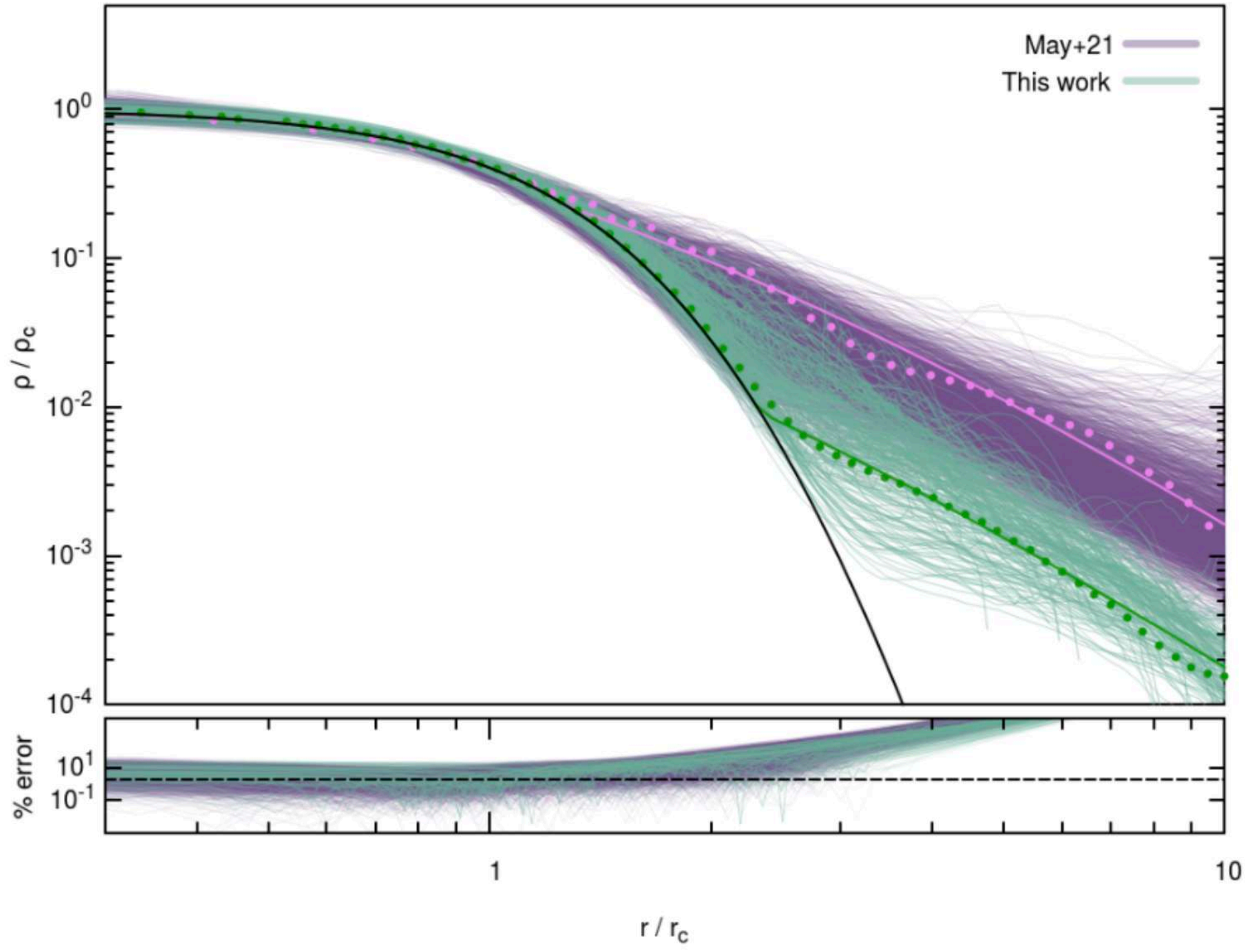
Energy tracing

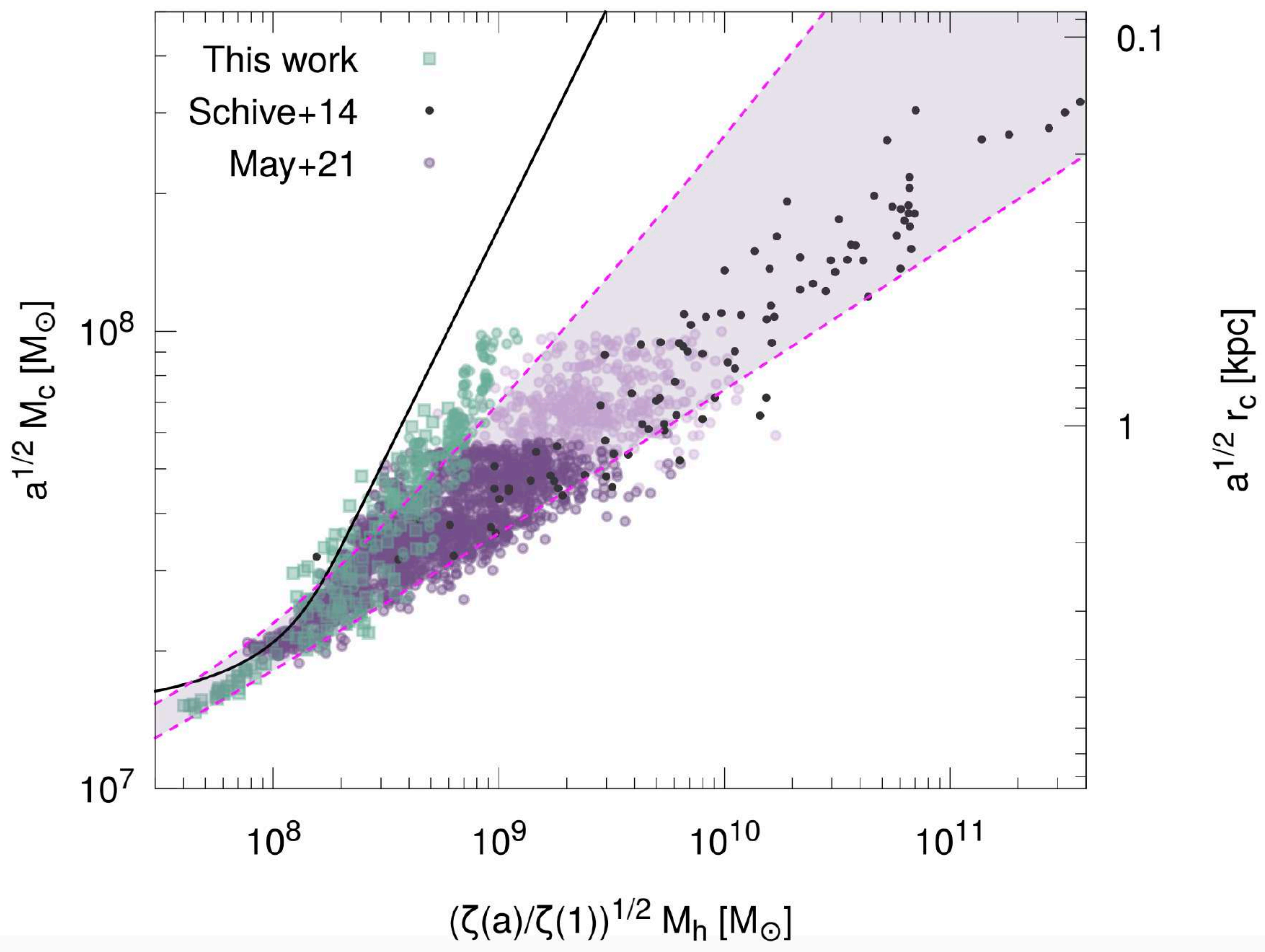
$$M_c\,\sigma_c^2 \sim M_h\,\sigma_h^2$$

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

FDM - Core-halo mass relation

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



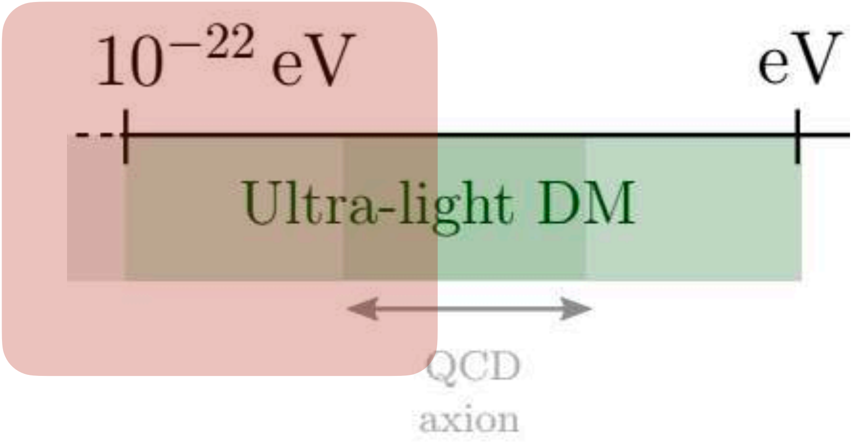


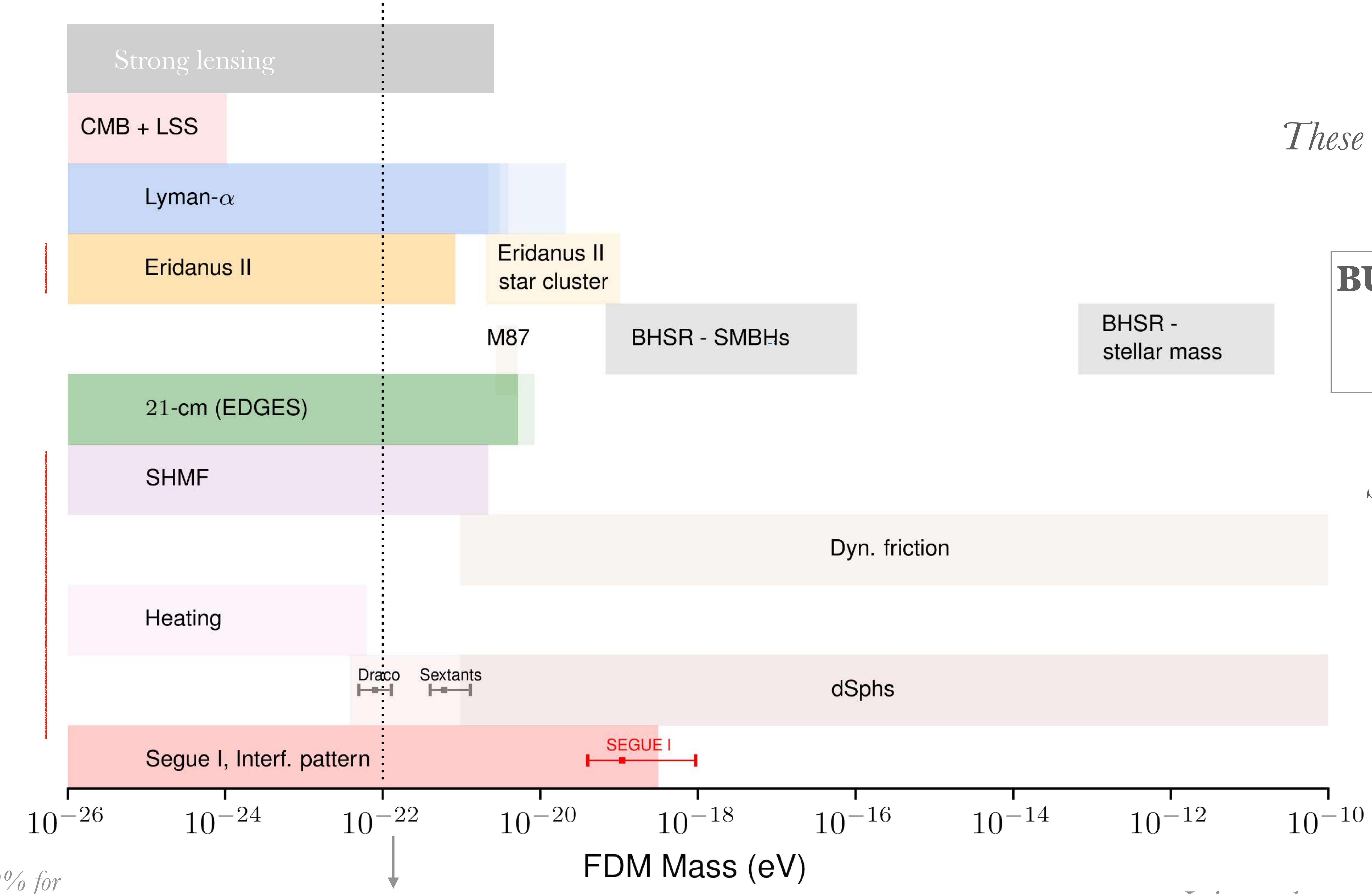
Well fitted by:
$$\rho(r) = \begin{cases} \rho_{\rm soliton} \simeq \dfrac{\rho_c}{\left[1+0.091(r/r_c)^2\right]^8}, & r < r_\epsilon \\ \rho_{\rm NFW} = \dfrac{\rho_s}{(r/r_s)(1+r/r_s)^2}, & r > r_\epsilon \end{cases}$$

Steeper slope → Smaller core → Smaller mass

Current status

Fuzzy Dark Matter - bounds on the mass





These models can be highly constrained

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

Some bounds are incompatible!

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

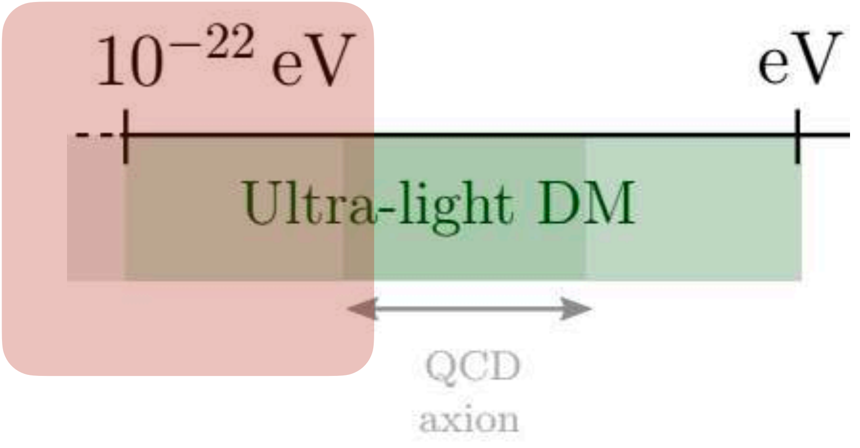
Caner et al: FDM at most 10% for
$10^{-21}\,\mathrm{eV} < m < 10^{-17}\,\mathrm{eV}$

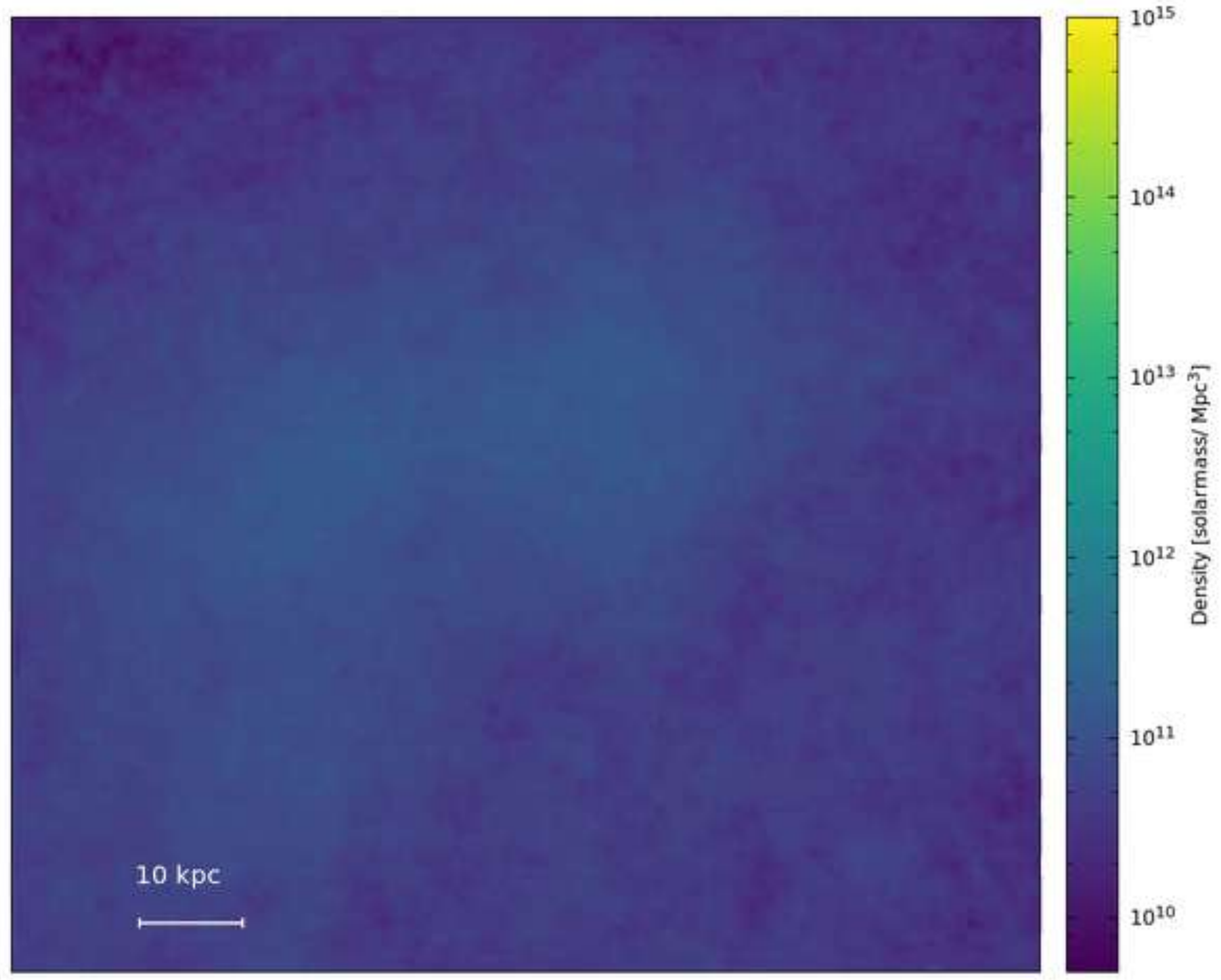
Sweet spot for solving small scale problems

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

New observables/new probes

Interference pattern





Simulation by Jowett Chan

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

PROBES:

- Strong lensing
- Stellar streams
- Heating

Gravitational probes

ONGOING

In collaboration with Jowett Chan and Simon May

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

Previous studies:

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

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

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

Sub-galactic power spectrum
Kawai, Oguri (2021)

Dwarfs
N. Dalal, A. Kravtsov, 2022

Interference patterns - granules

Strong lensing

Suppression of
small scale structures

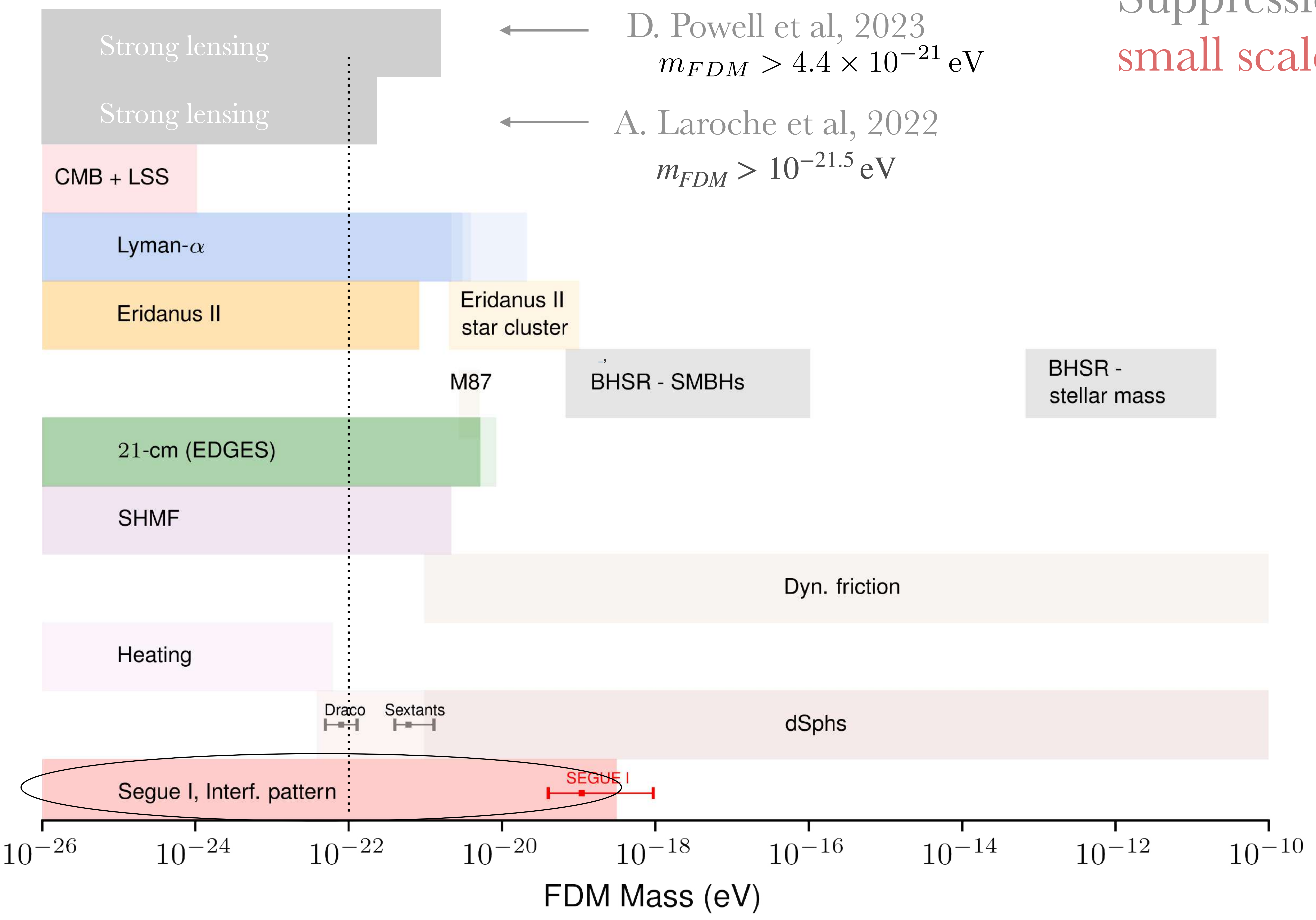
D. Powell et al, 2023
$m_{FDM} > 4.4 \times 10^{-21}$ eV

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

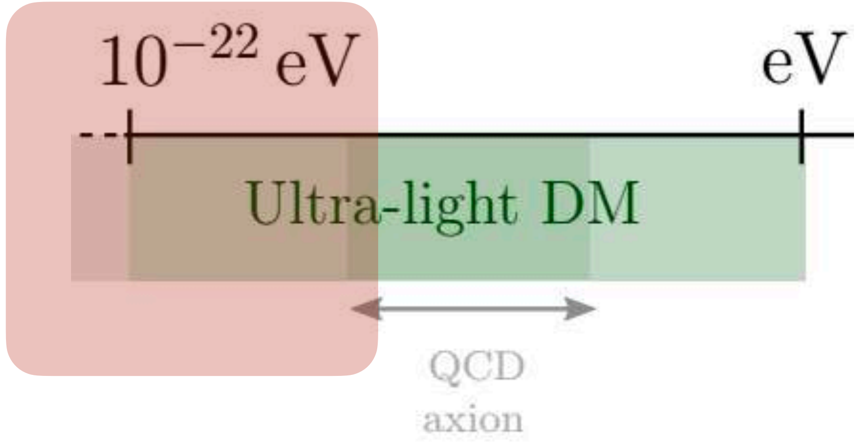
Dynamical effects

Stellar heating

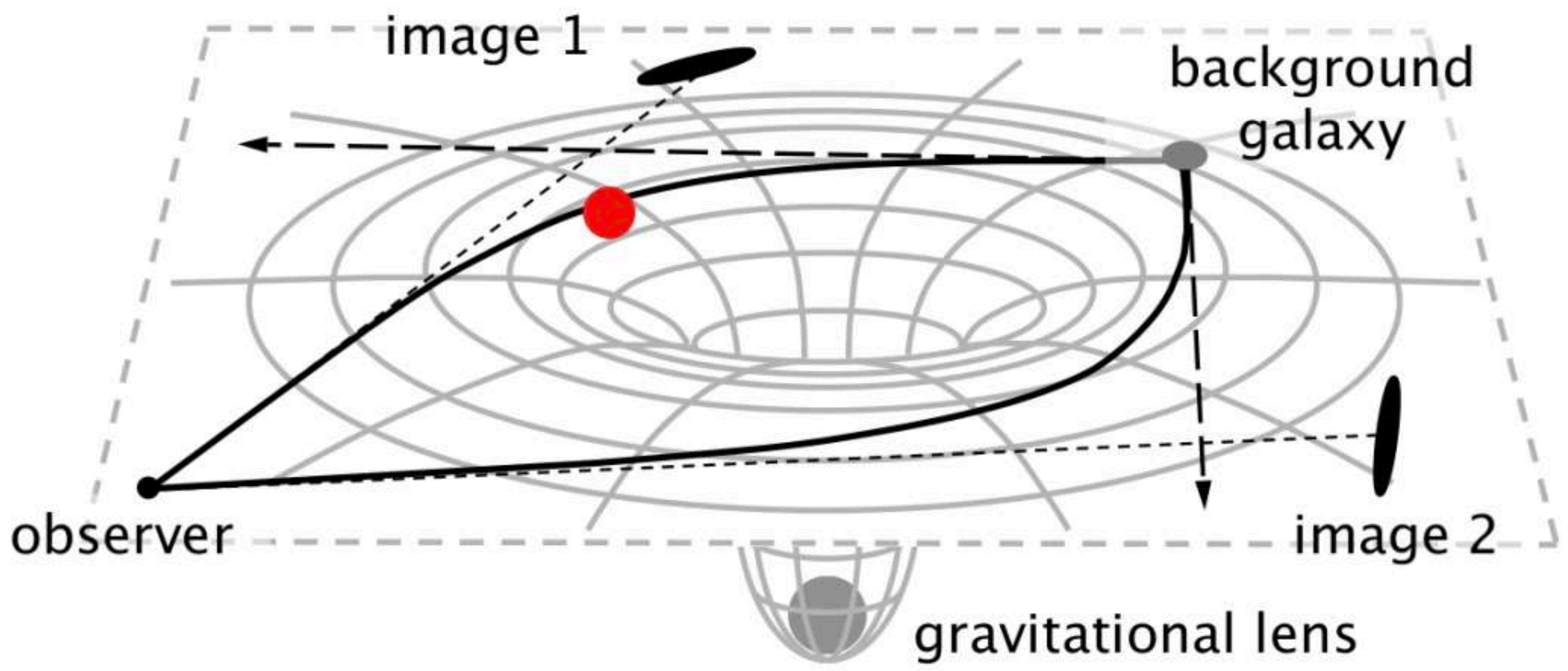
Dalal et al, 2022
$m_{FDM} > 3 \times 10^{-19}$ eV

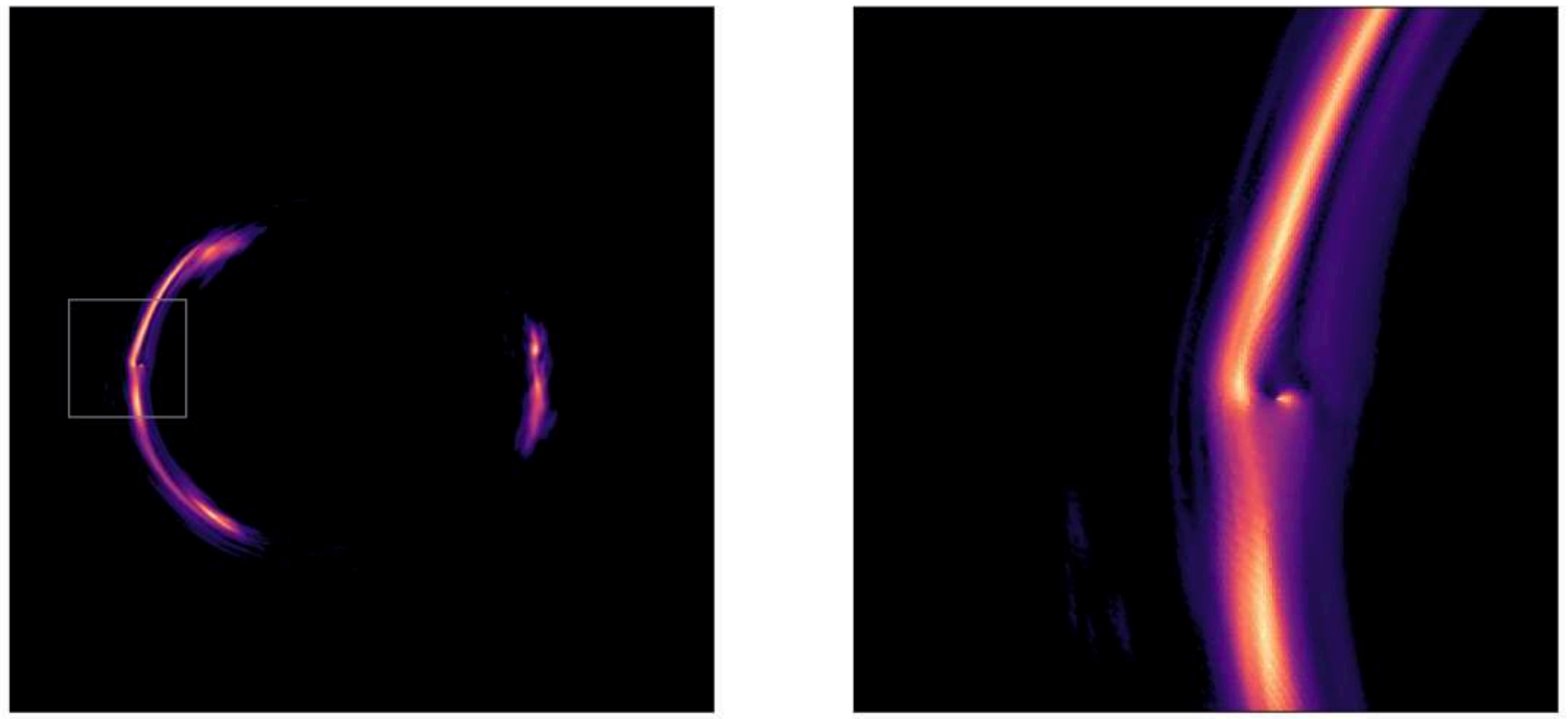


Strong lensing



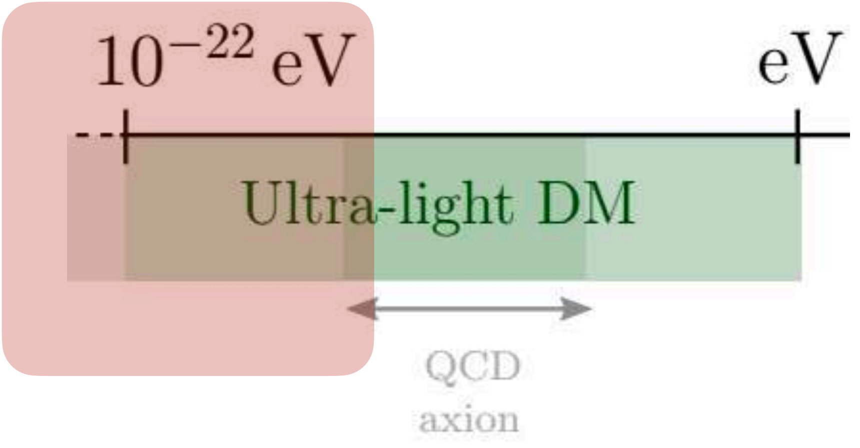
Low mass perturber with lensing



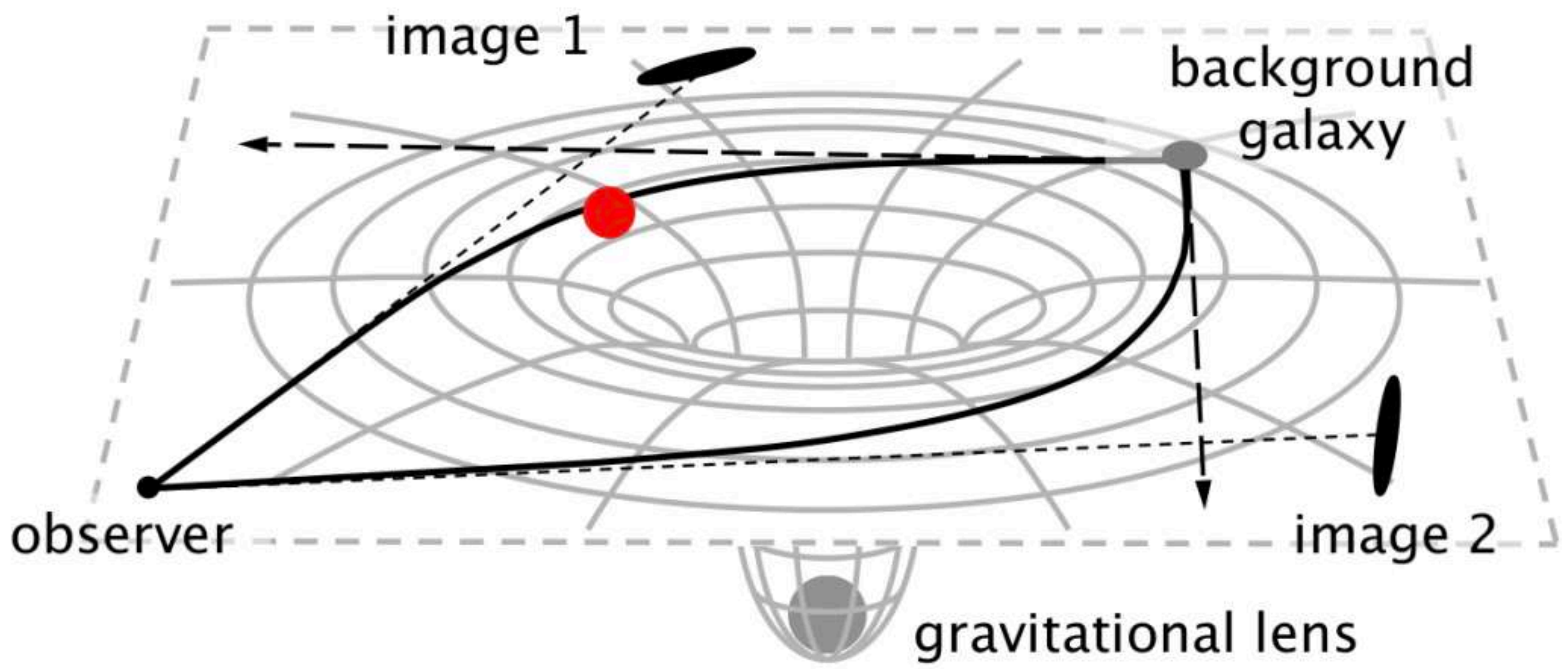


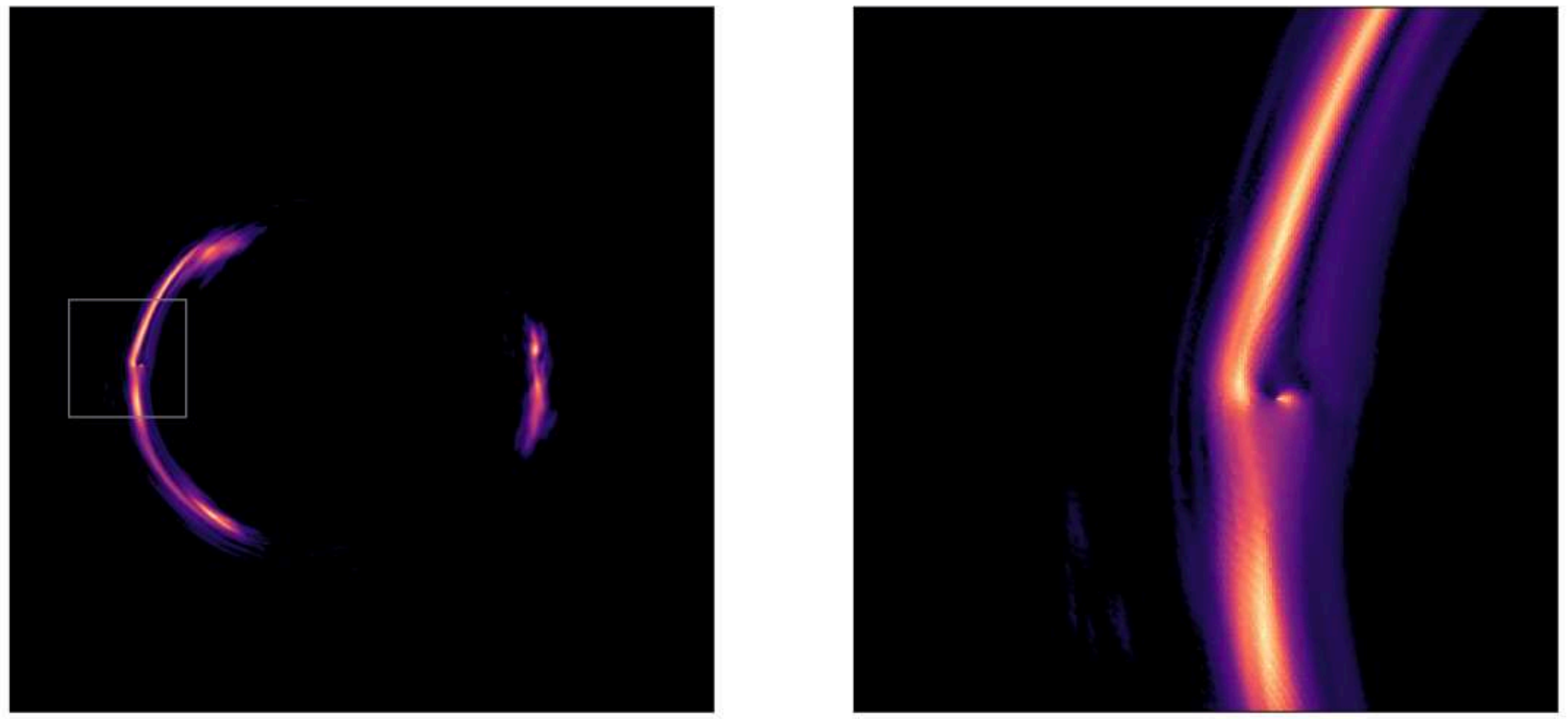
- Strong lensing: powerful probe of substructure
- Sensitivity is limited by angular angular resolution
- Roughly speaking, the resolution must be better than the scale radius of the perturber

Strong lensing



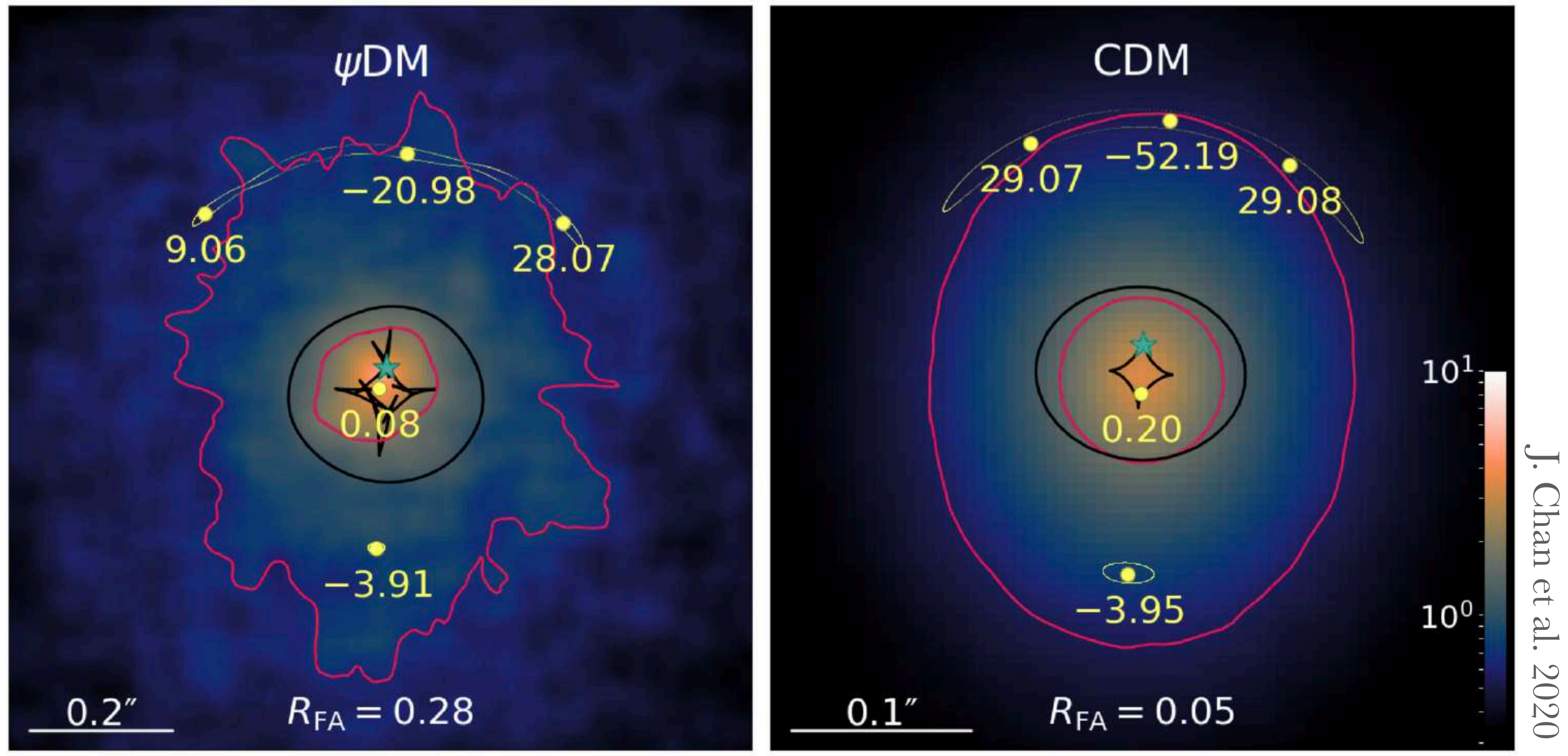
Low mass perturber with lensing





Presence of granules

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



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

Previous works:

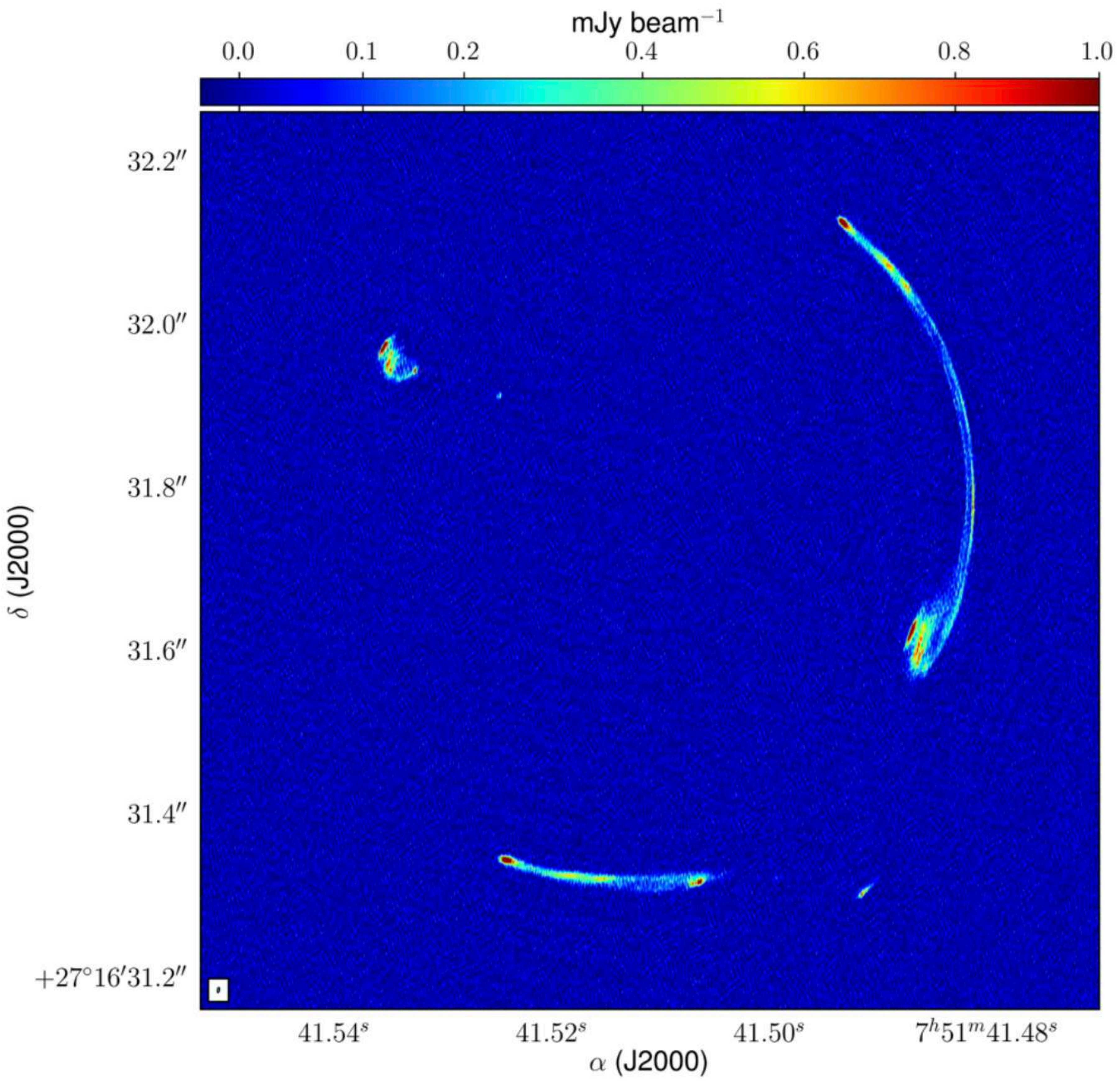
J. Chan, H.Schive, S.g Wong, T. Chiueh, T. Broadhurst, 2020

A. Laroche, Daniel Gilman, X. Li, J. Bovy, X. Du, 2022

Strong lensing

A lensed radio jet at milli-arcsecond resolution II: Constraints on fuzzy dark matter from an extended gravitational arc
D. Powell, S. Vegetti, J.P. McKean, S. White, EF, S. May, C. Spingola

MG J0751+2716



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

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

Strong lensing

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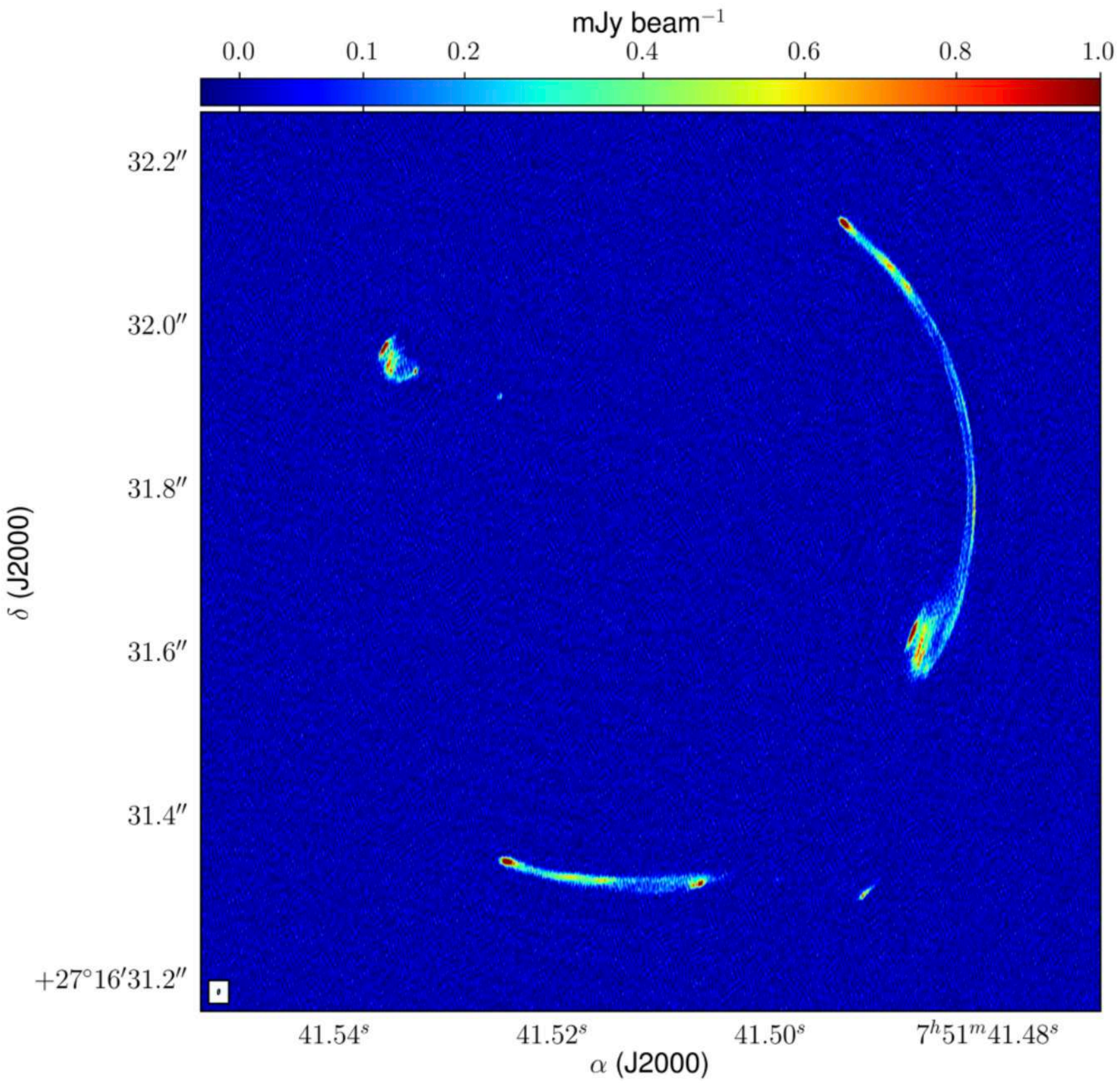

- Lensed radio jet, observed with global VLBI
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Bayesian approach to jointly inferring the lens mass model and source surface brightness distribution

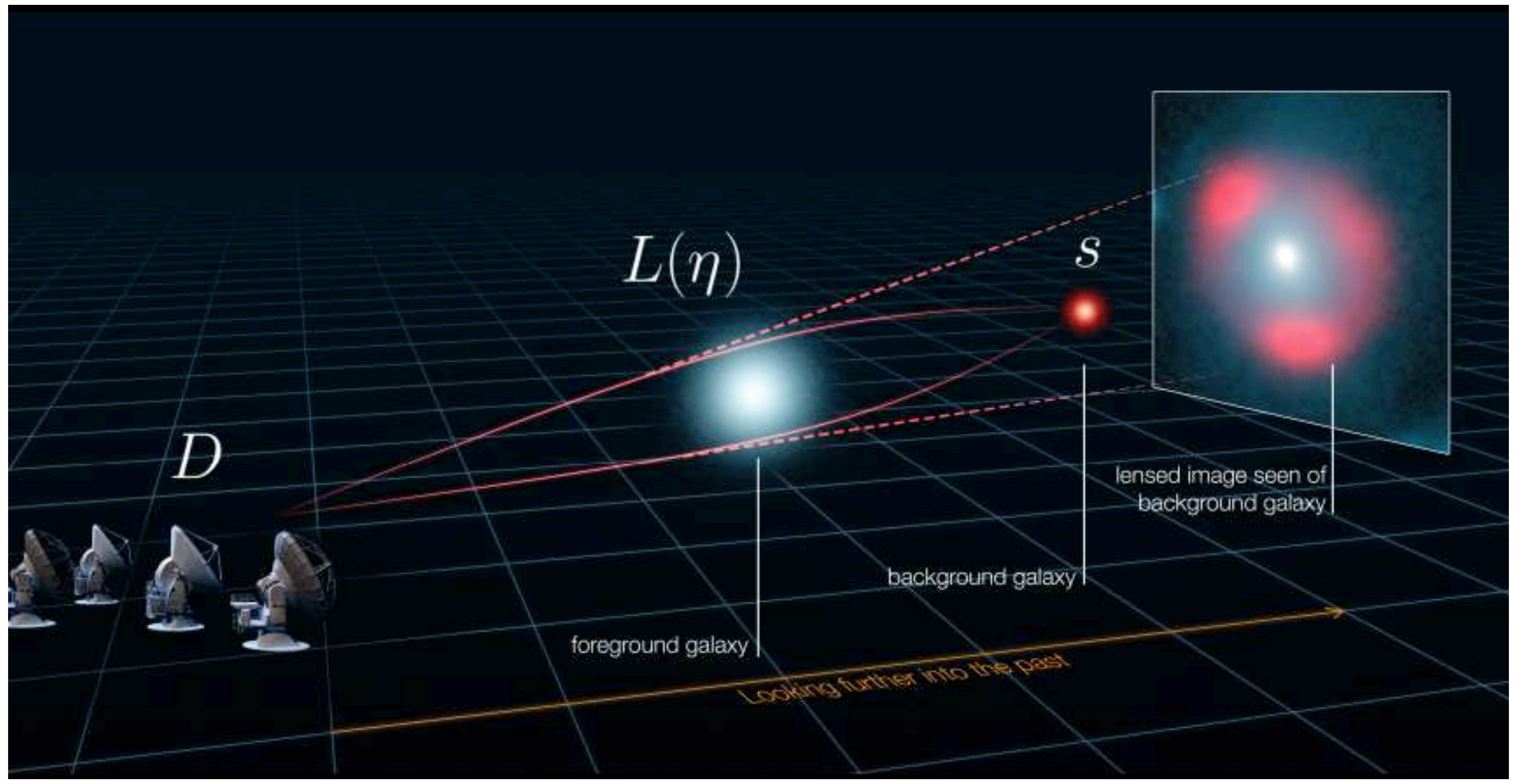
(Suyu et al. 2006; Vegetti & Koopmans 2009; Hezaveh et al. 2016; Rizzo et al. 2018)

Strong lensing

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

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

Forward modeling



Instrumental response

source

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

Lens operator

Smooth lens model

Potential perturbations

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

Smooth lensing model: from *Powell et al 2022*

FDM granules:

Model by Chan et al 2020: statistics of spatially-varying surface mass density fluctuations, given the density profile of the dark matter, as well as some basic assumptions on the behavior of scalar fields in a potential well

$\delta\psi(m_{fdm}, f_{dm}, \sigma_v)$ (perturbation of the lensing potential)

fluctuations in the projected surface mass density written as perturbations in the lensing convergence due to the presence of the granules:

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

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

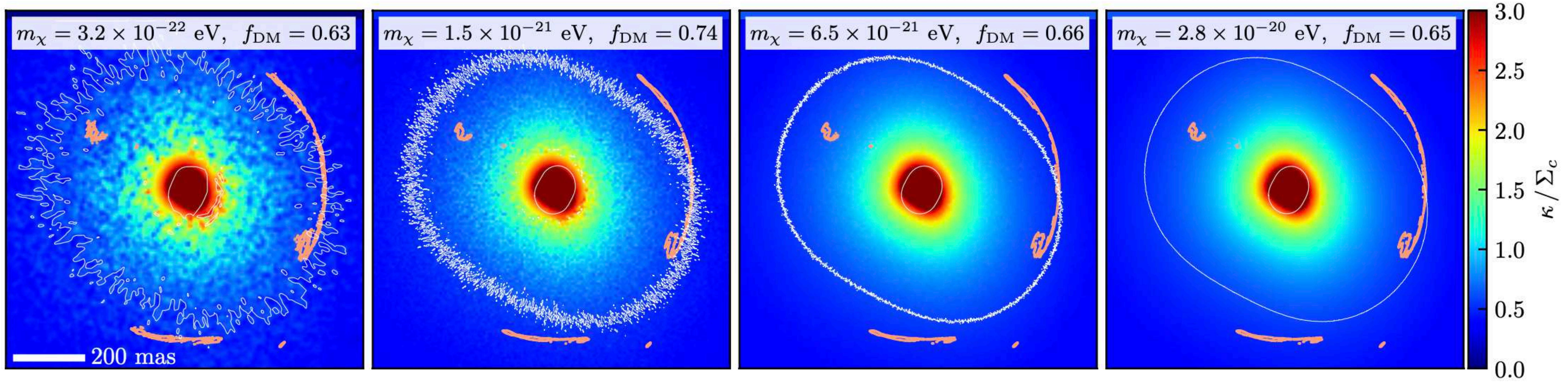
We compute likelihoods for 10^4 sample FDM lens realizations with m_{fdm} drawn from the log-uniform prior range $\log(m_{fdm}/\mathrm{eV}) \in [-21.5, -19.0]$.

Strong lensing

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

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

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



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

Strong *lensing*

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

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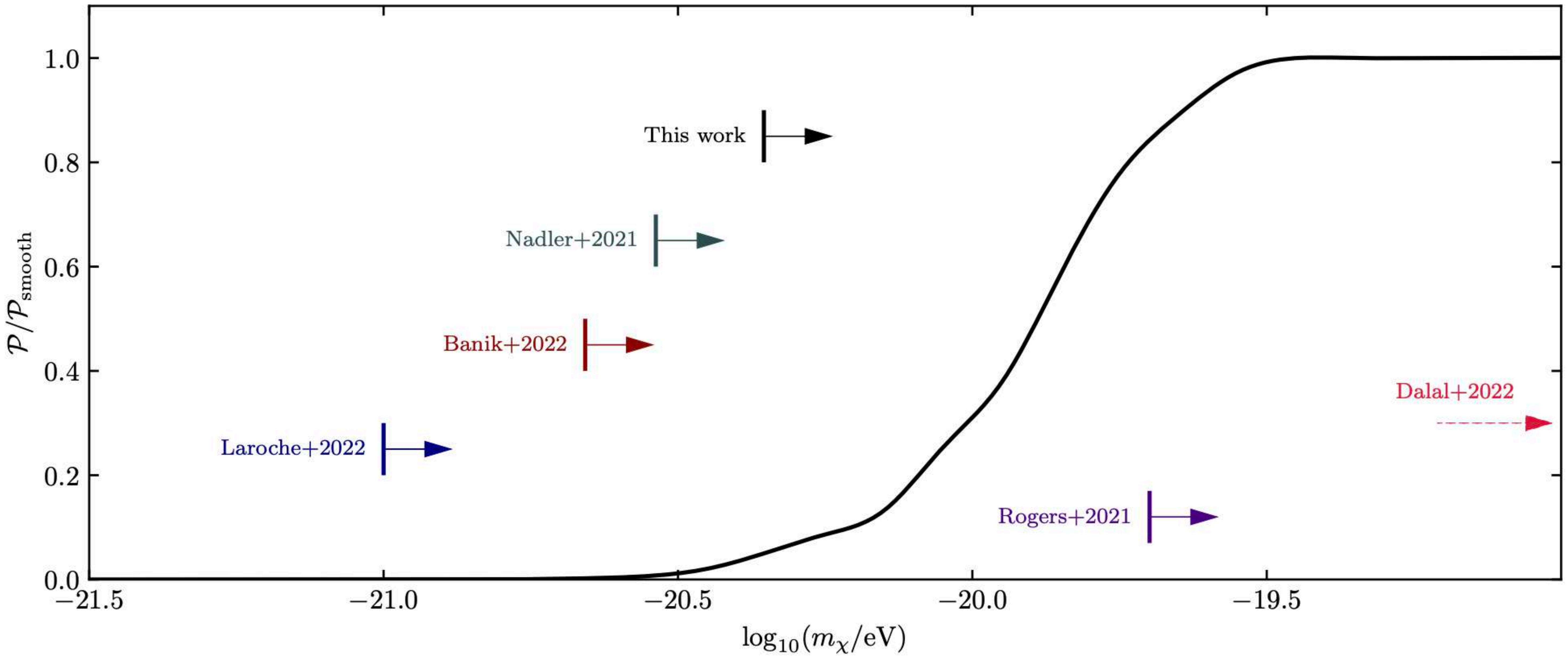
Results quoted in terms of posterior odds ratio (POR) between FDM with a particle mass m_{fdm} and the smooth model, $\mathscr{P}/\mathscr{P}$smooth



Fuzzy dark matter
(Single spin-0 particle)

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

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

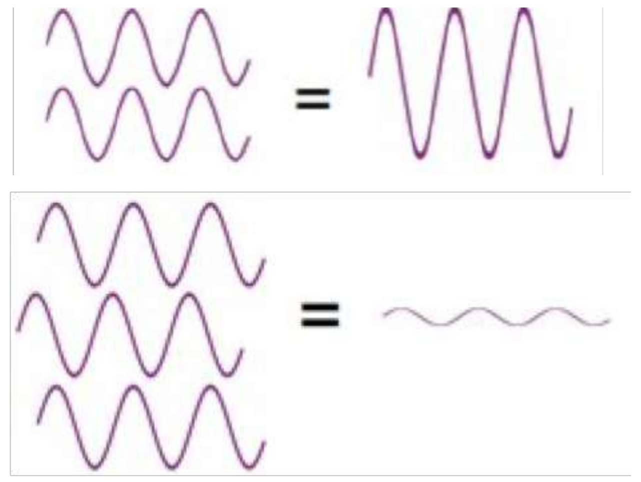
$m_{\rm vdm} > 1.4 \times 10^{-21}$ eV

Spin-2 FDM

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

Vector, higher spin or multicomponent FDM

Interference patterns

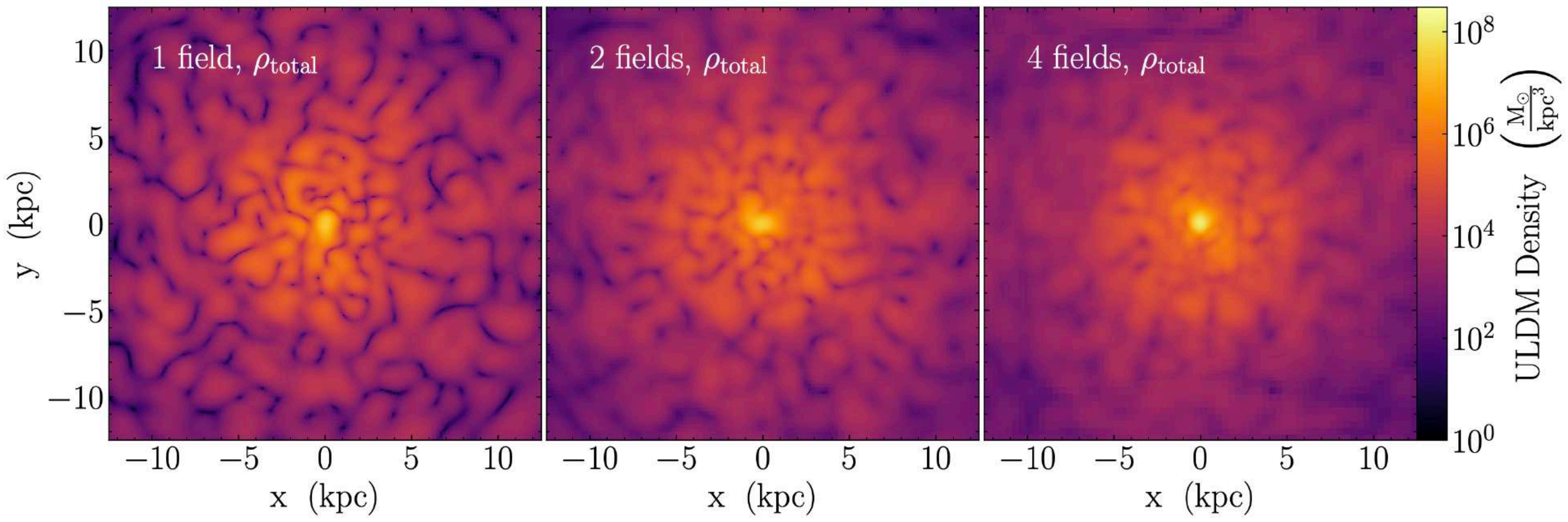


ULDM or ULA are a coherent wave - same frequency and constant phase difference

Multiple coherent waves

Gonseca et al 2023

For ULDM:



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

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

(Amin et al 2022)

Expectation for lensing:

$$\langle \delta\kappa^2 \rangle = \frac{\lambda_{dB}}{2\sqrt{\pi}\,\Sigma_c^2} \int \rho_{\mathrm{DM}}^2 \, dl$$

$$m_{nfdm,s} = \frac{m_{fdm}}{N} = \frac{m_{fdm}}{2s+1}$$

Detailed simulations and analysis in the future!

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

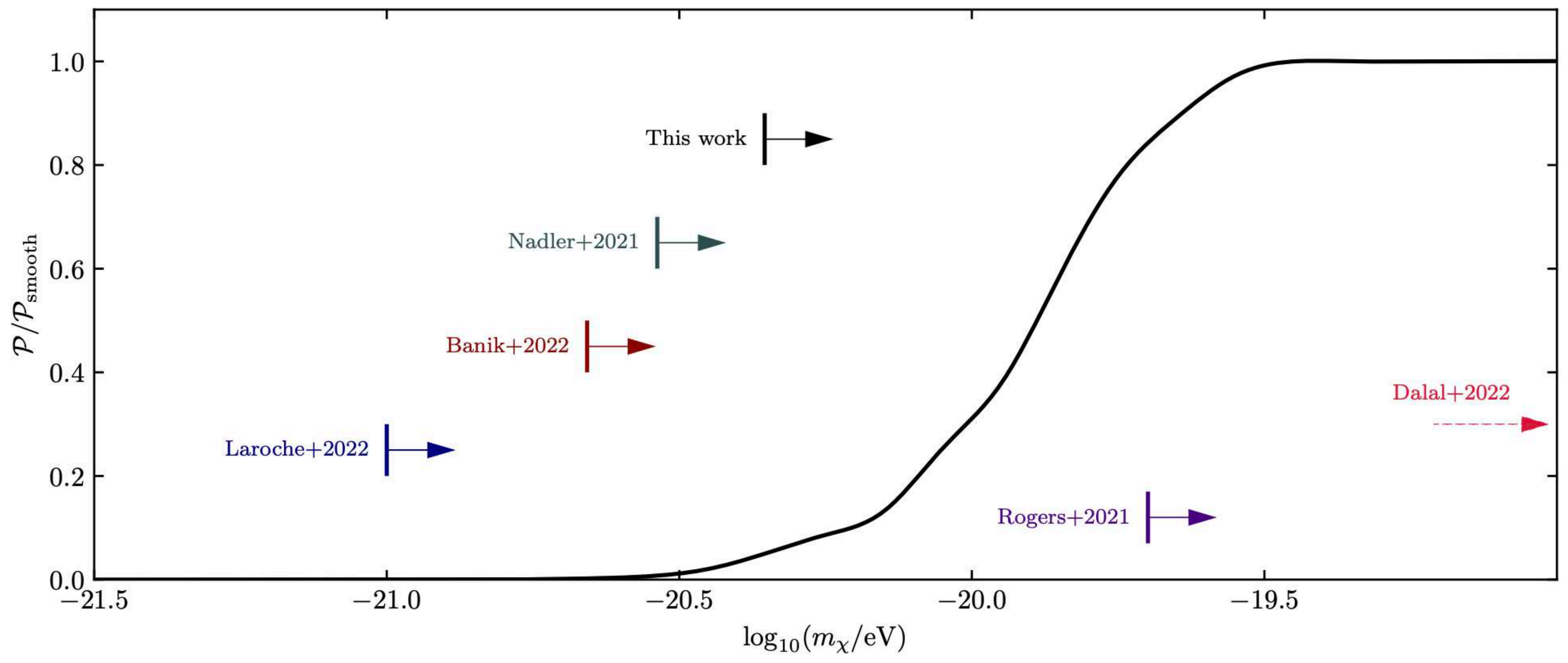
(Vector FDM = 3 x same mass FDM (spin 0))

Multicomponent FDM Gonseca et al 2023

Strong lensing

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

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



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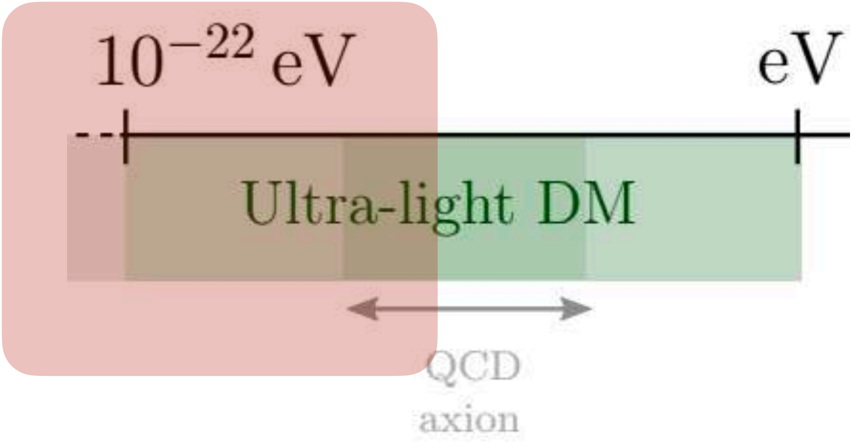
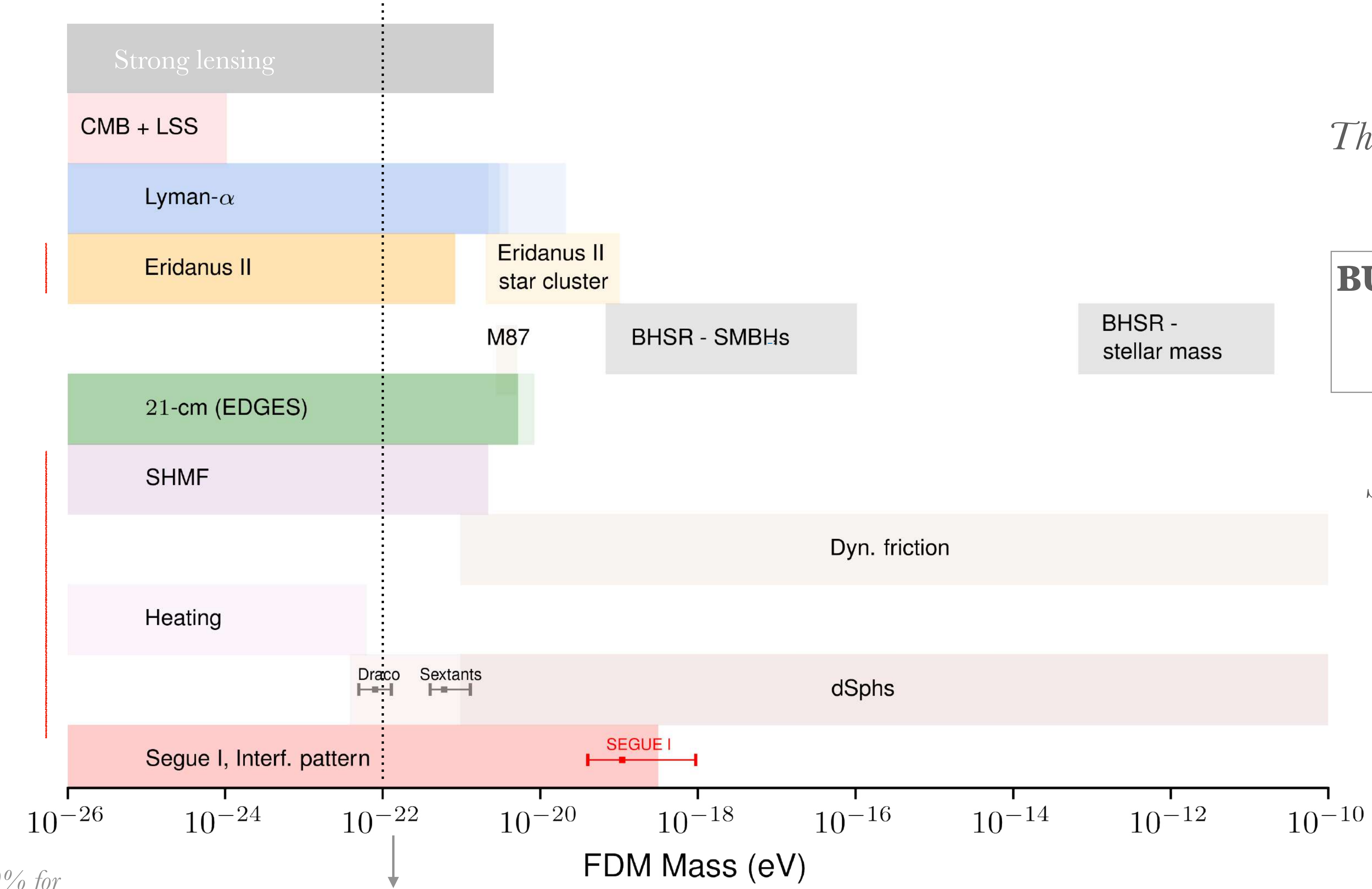
Milli-arcsecond angular resolution of VLBI, competitive constraints on dark matter models can be inferred using a single strong gravitational lens observation

More lenses in the future!

Current status

Fuzzy Dark Matter - bounds on the mass





Sweet spot for solving small scale problems

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

These models can be constrained

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

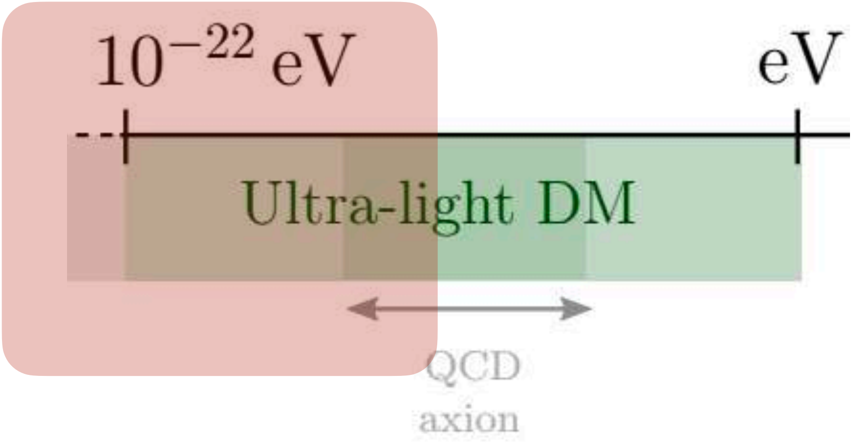
Some bounds are incompatible!

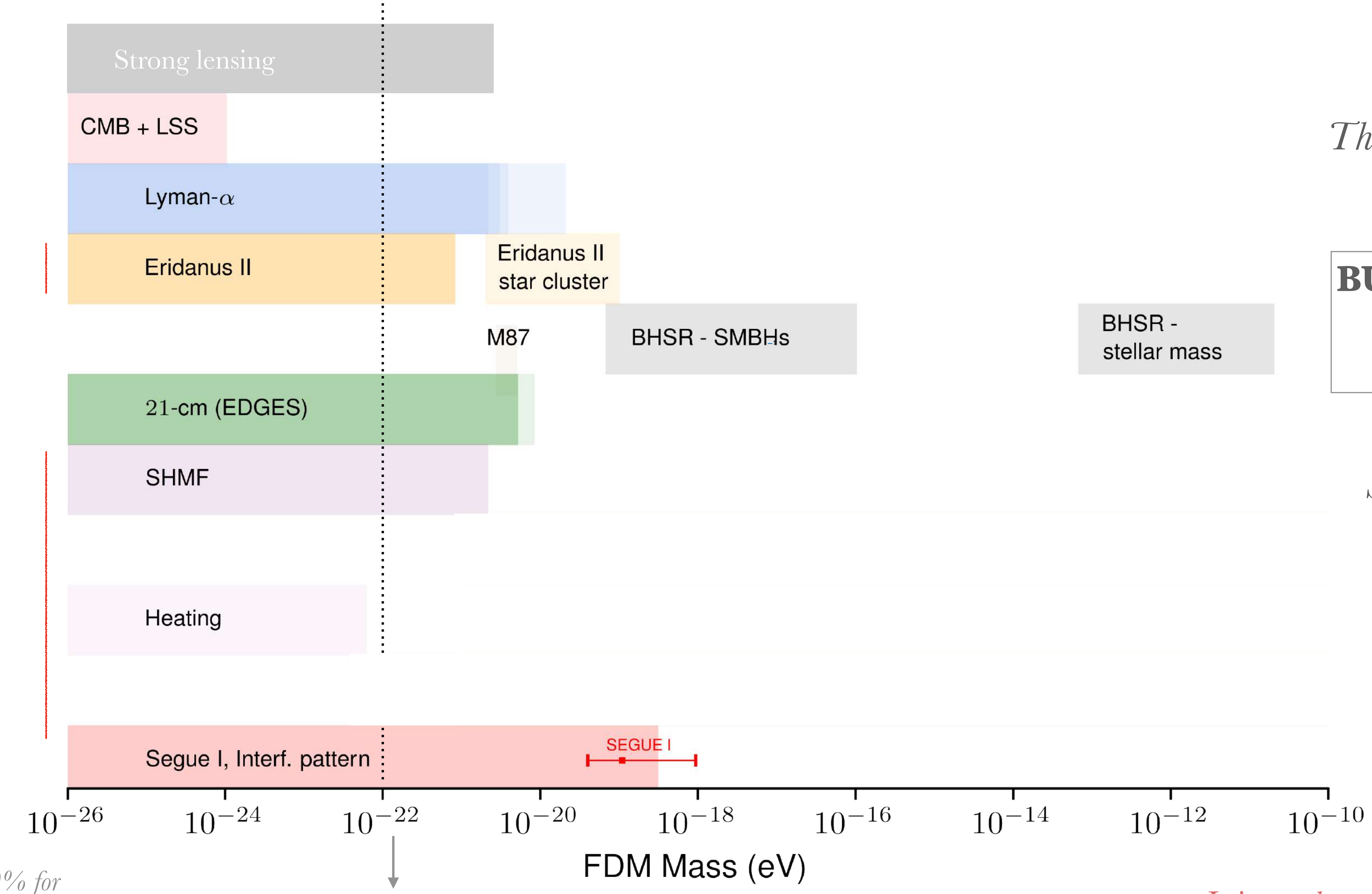
Need:
- Observations
- Improve sims
- New observables
- New probes

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

Current status

Fuzzy Dark Matter - bounds on the mass





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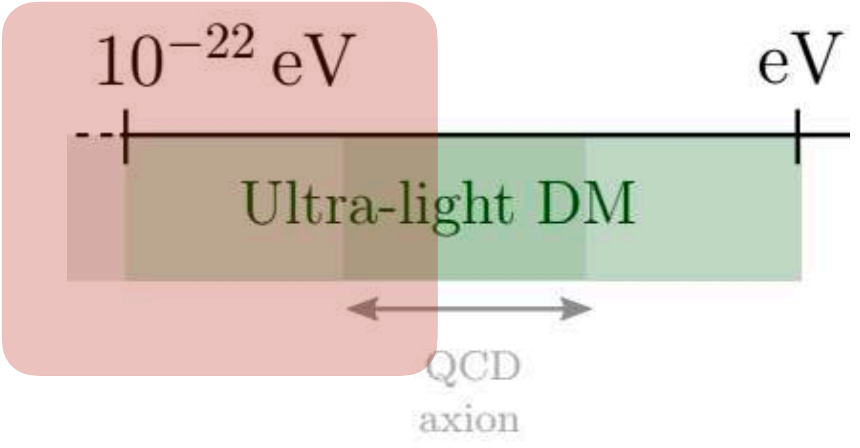
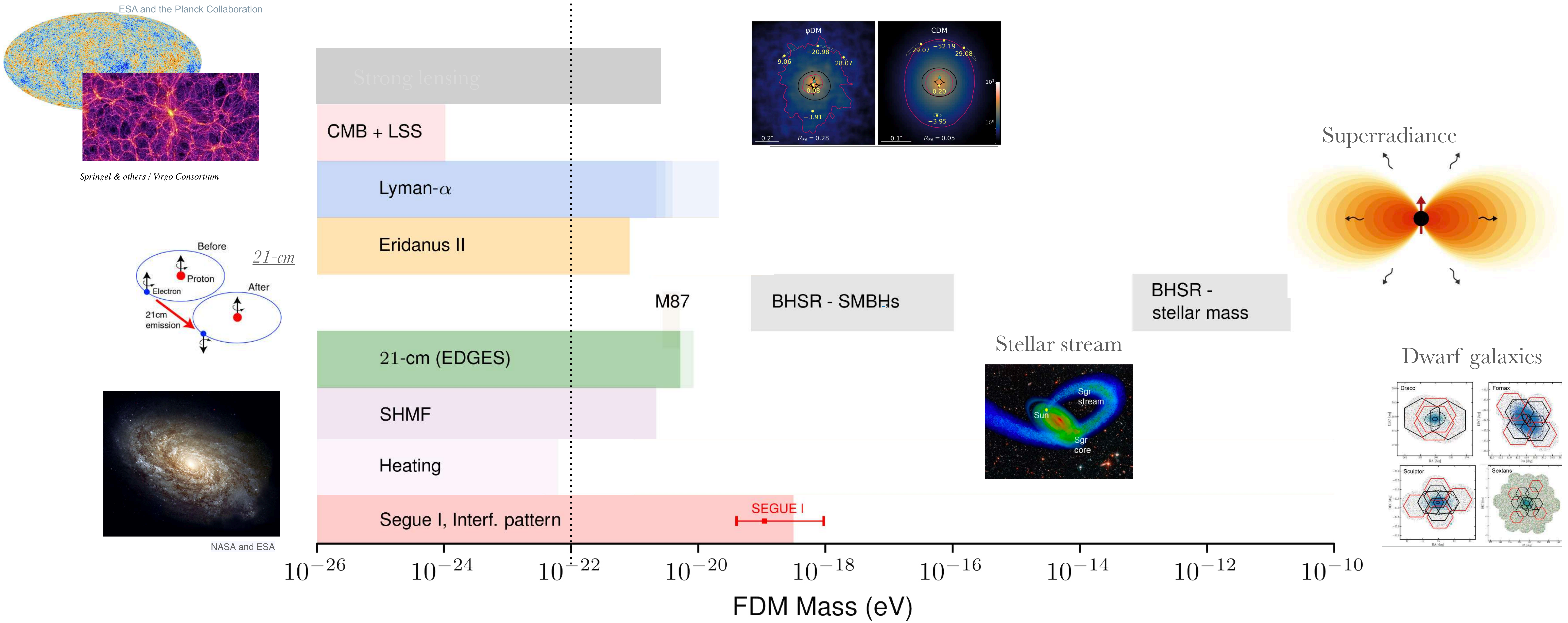
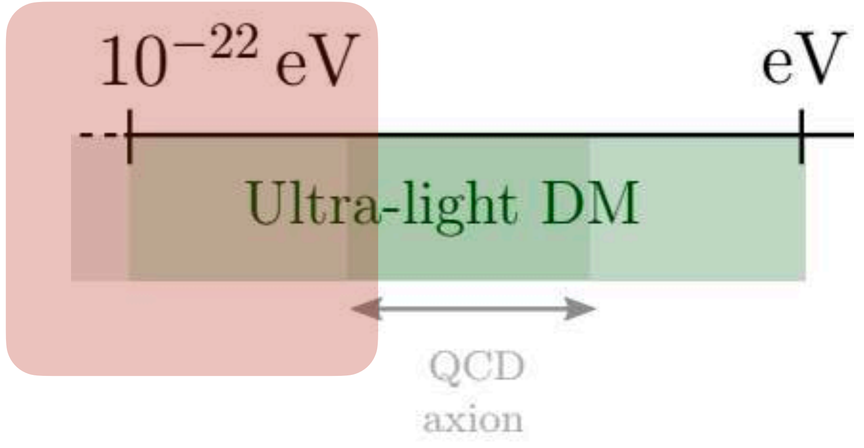




"Ultra-light dark matter", **E.F.**, 2020

Fuzzy Dark Matter



Open questions:

-Condensation?

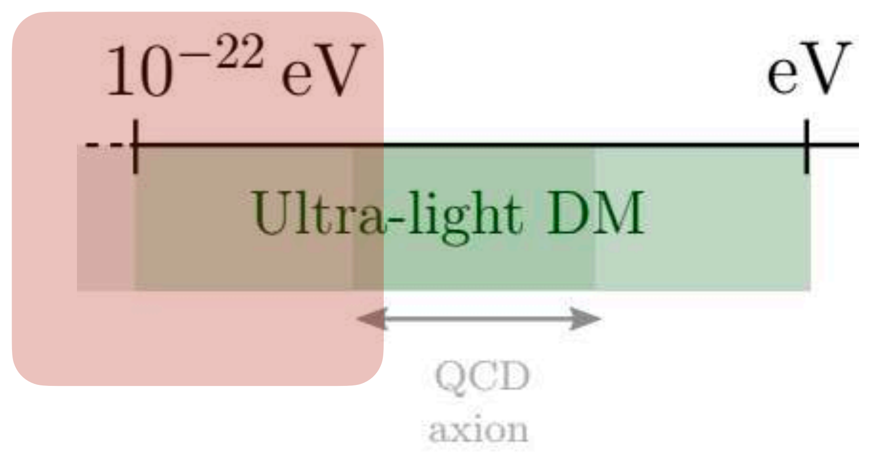
-Quantum mechanical?

-Vortice description

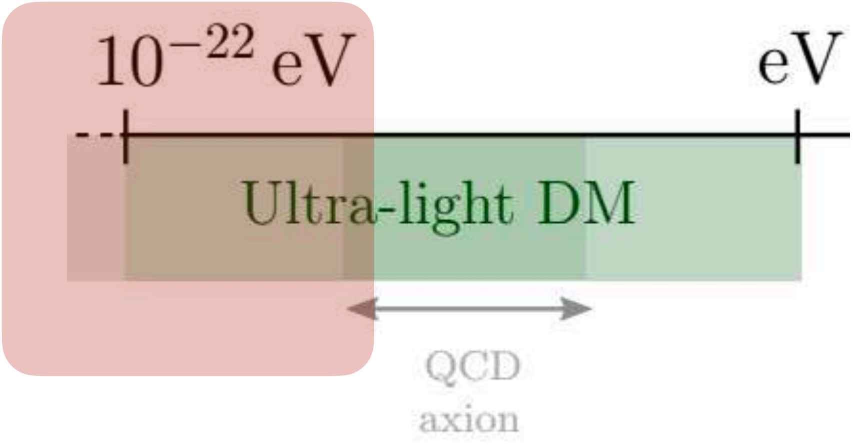
-Baryons influence

-…

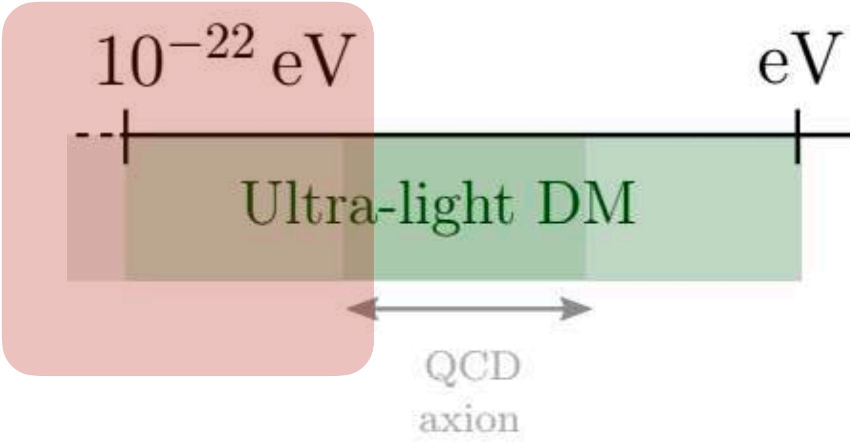
Role of baryons



Role of baryons

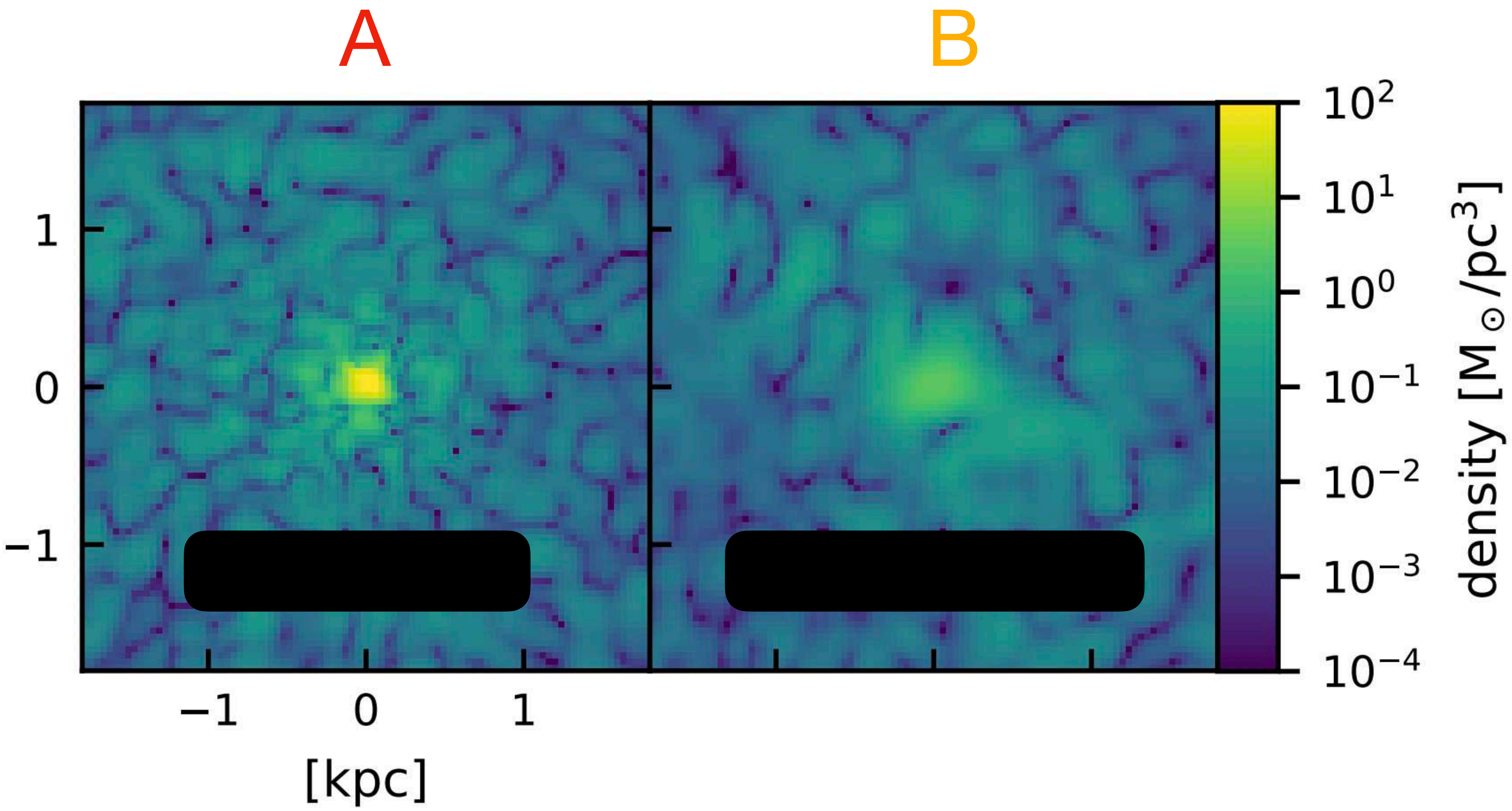


Quiz time!!

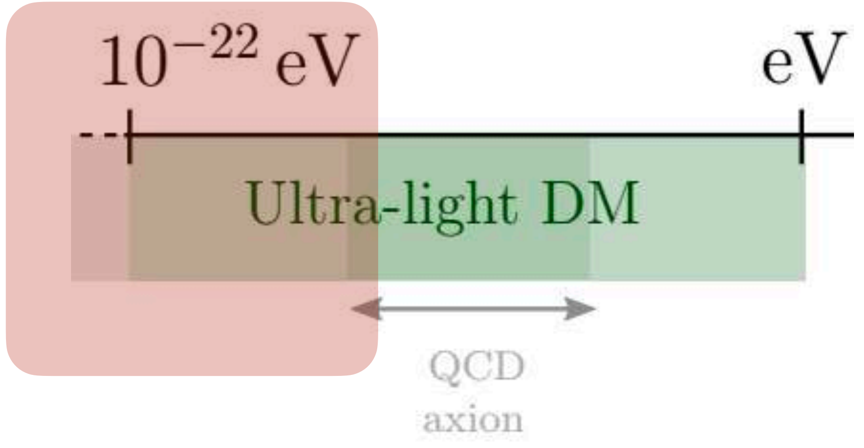


Role of baryons

From those two images, which one do you think has the influence of baryons?



Veltmaat et al 2020



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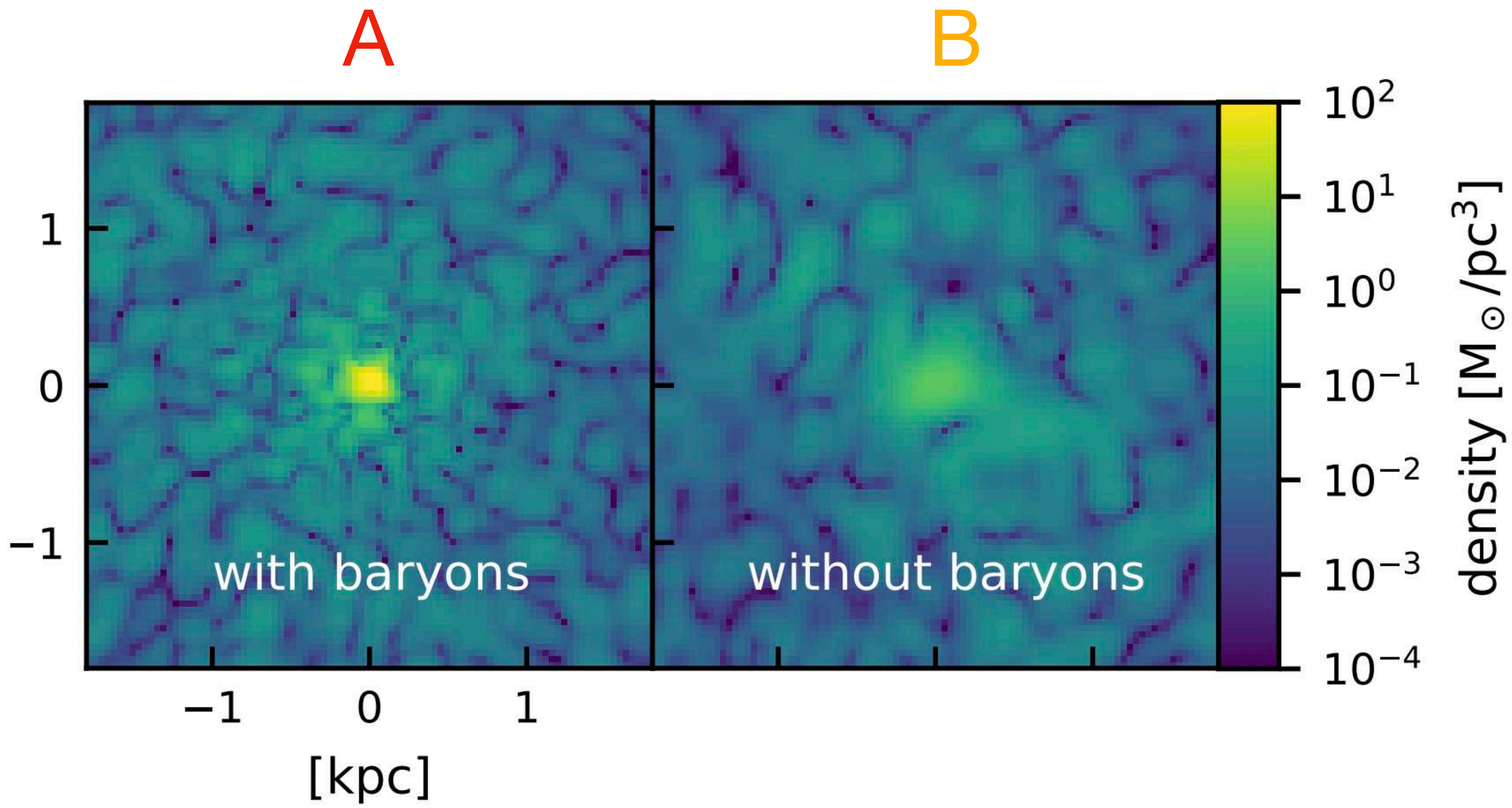
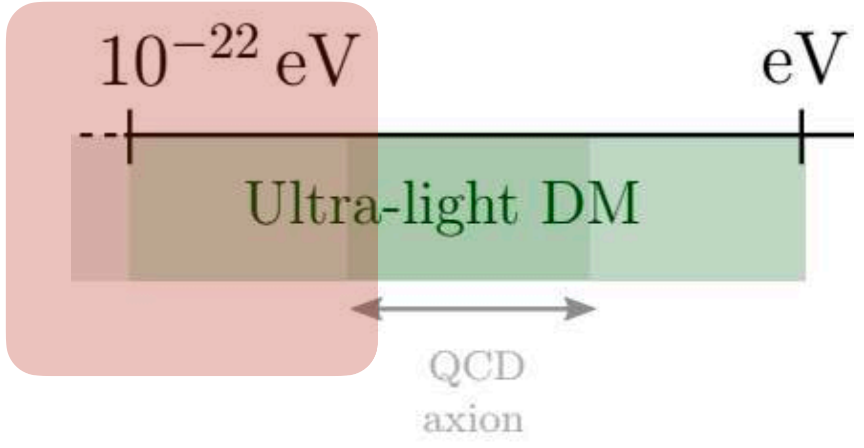


Veltmaat et al 2020

Role of baryons



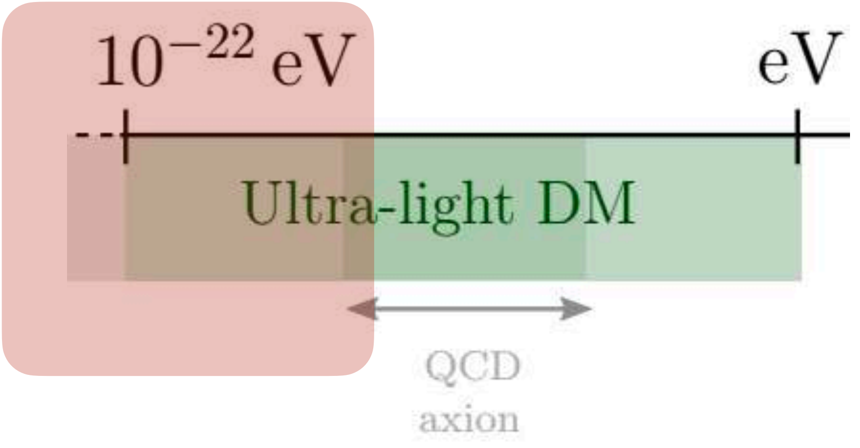
How baryons influence the behavior of ULDM?

A) Enhance the small scale structures

C) Suppress small scale structure

B) Eject matter from galaxies

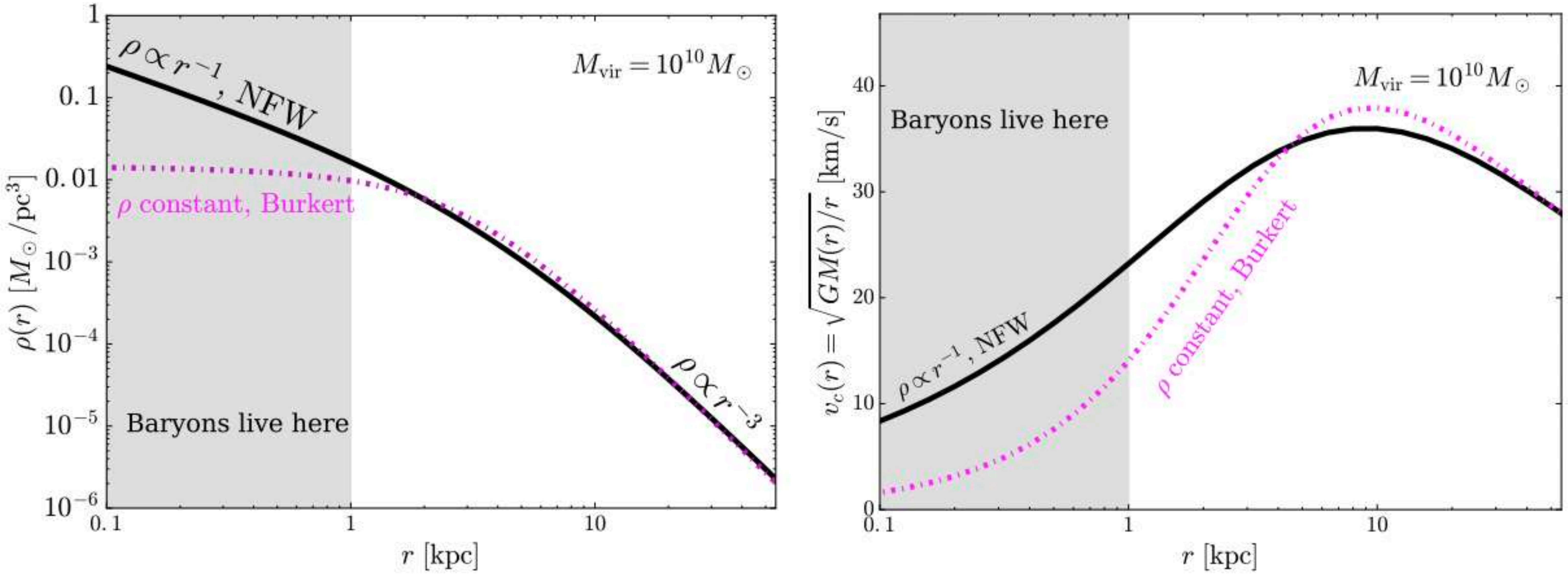
D) All of the above



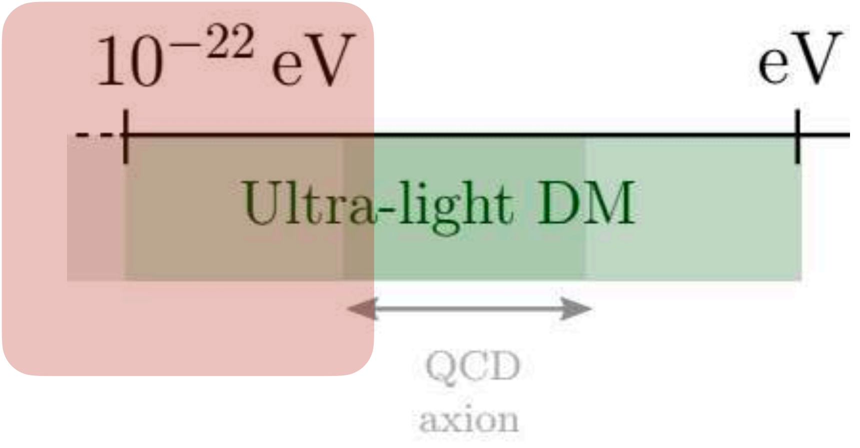
Role of baryons

Core

Baryonic feedback

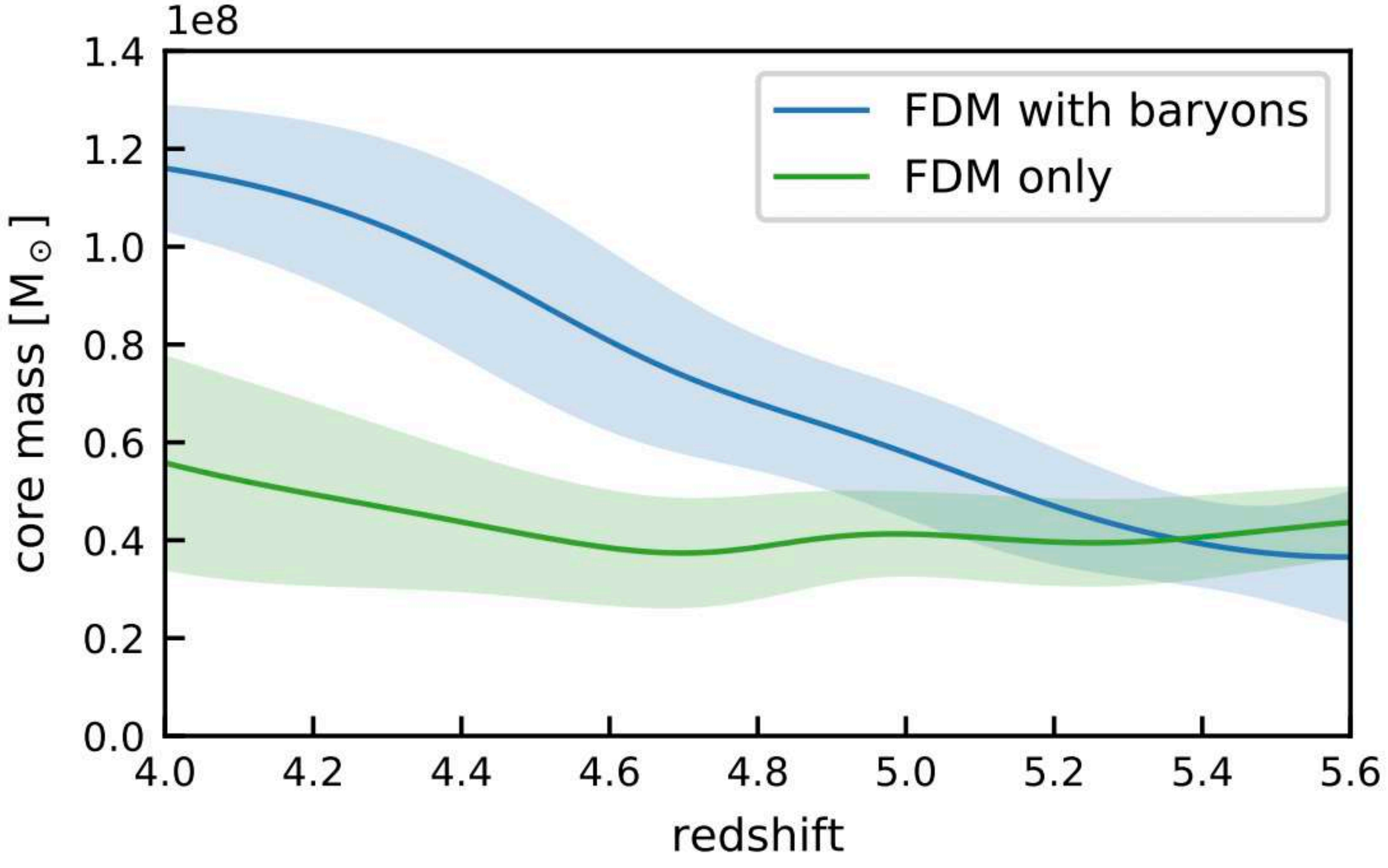


Role of baryons



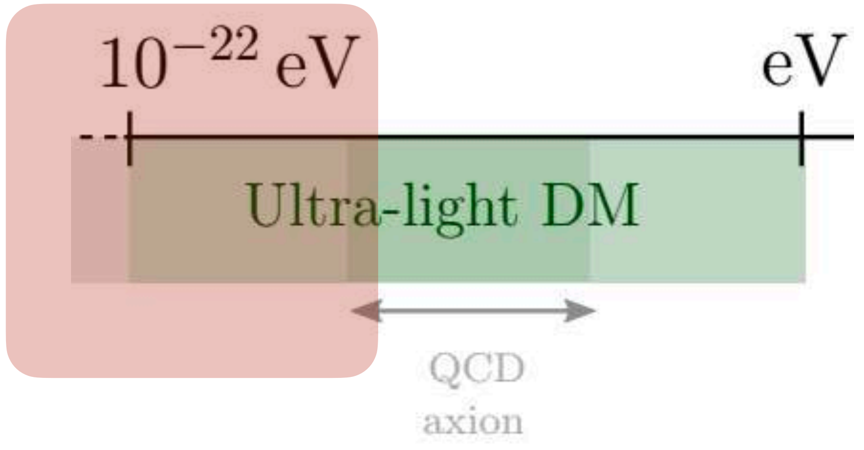
Core

Adding baryons: increase in the gravitational potential in the interior of the halo



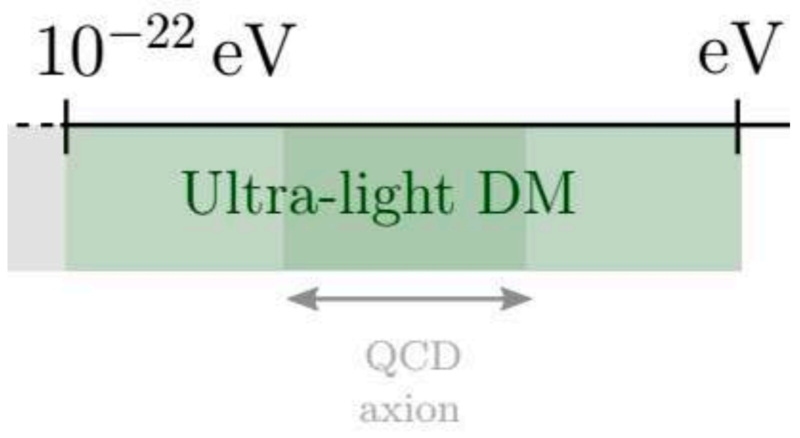
More massive and larger core than without baryons

Role of baryons



Interference pattern

Observational implications and constraints



Bounds on the mass and other parameters

Self interacting FDM

m g

DM Superfluid

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

Still highly unconstrained

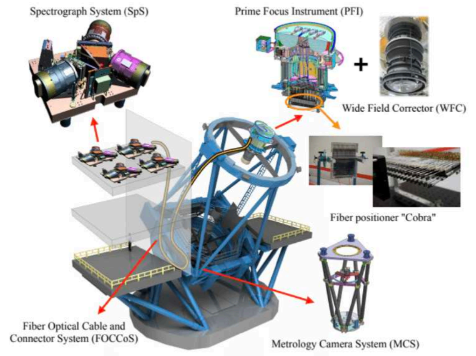
* Check: Lasha Berezhiani et al (2020)

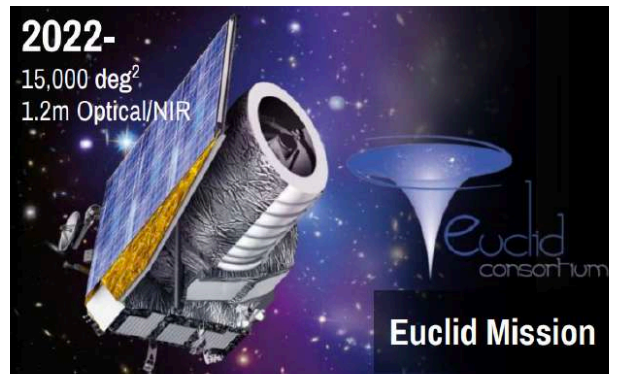
Future - *signals in cosmology*

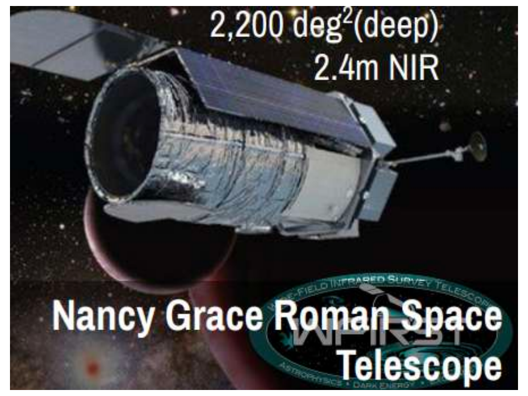
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)







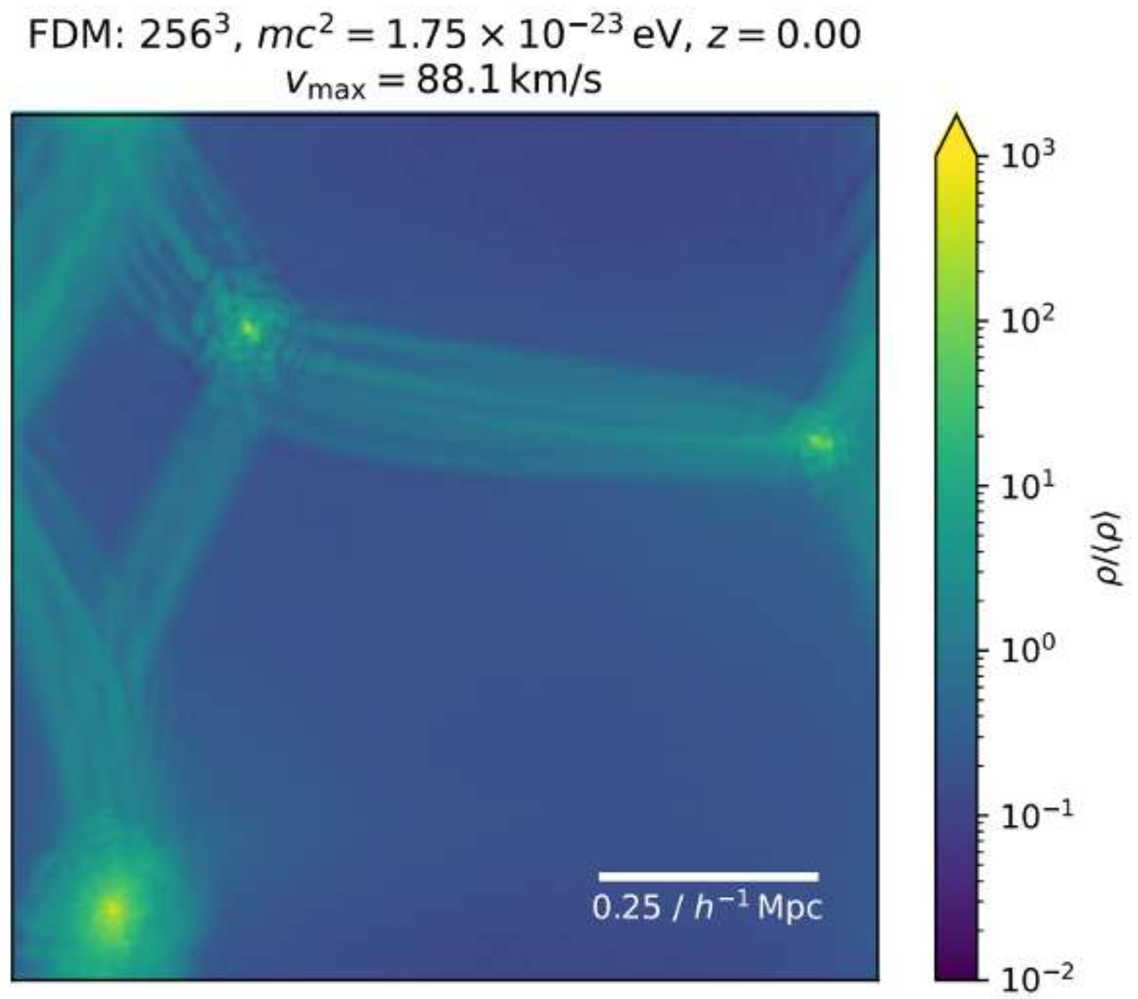
CMB

CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New observables

New probes

Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

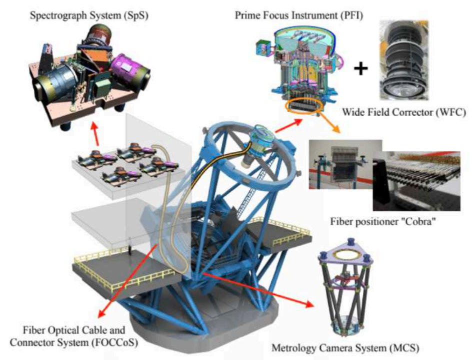
Modified from Jia Liu

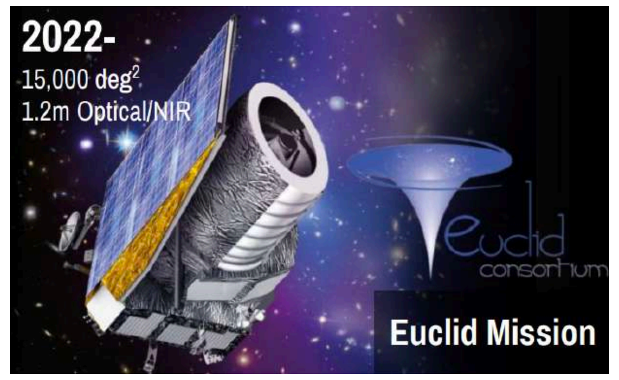
Future - *signals in cosmology*

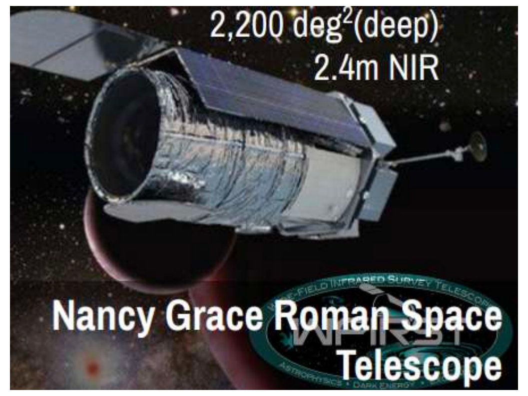
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)







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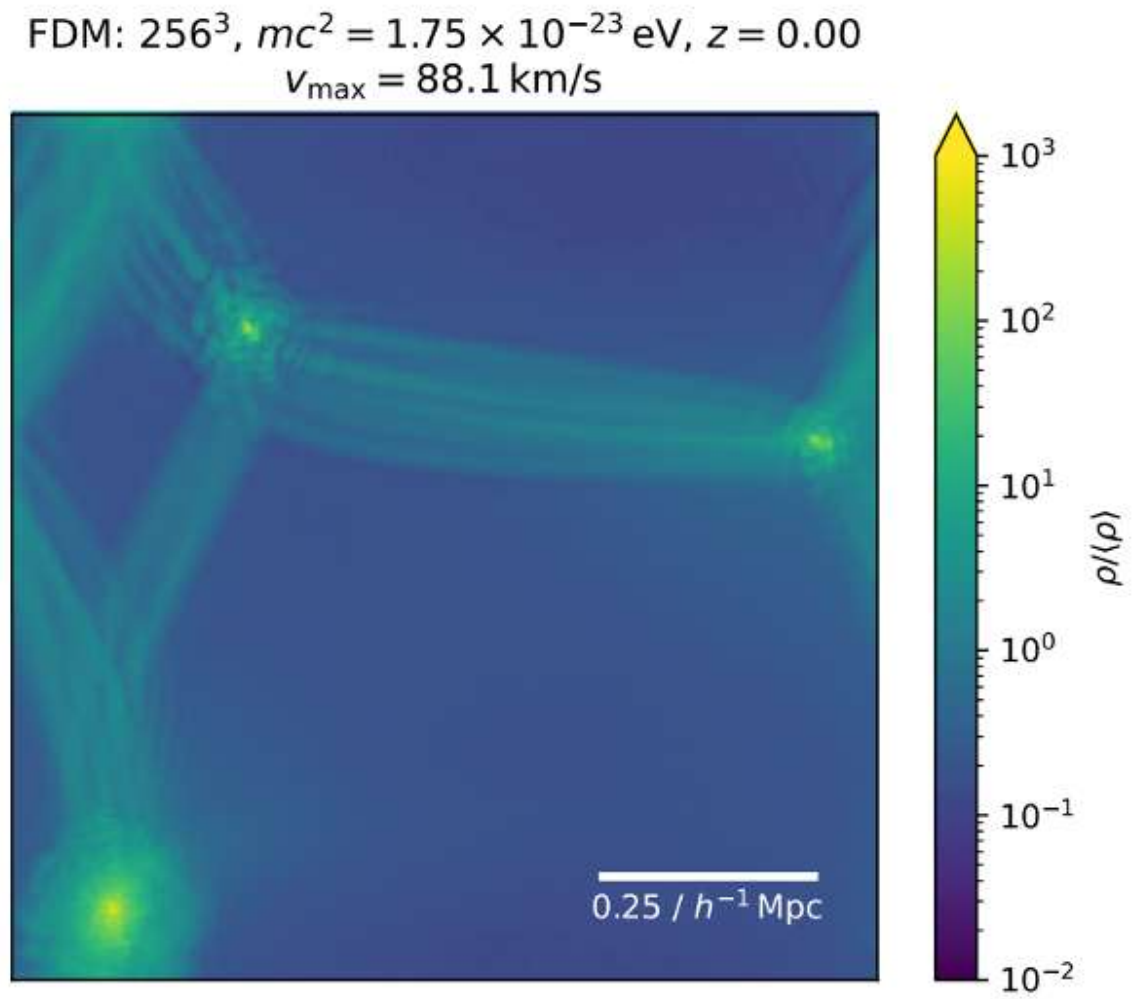


New observables

New probes

Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Modified from Jia Liu

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

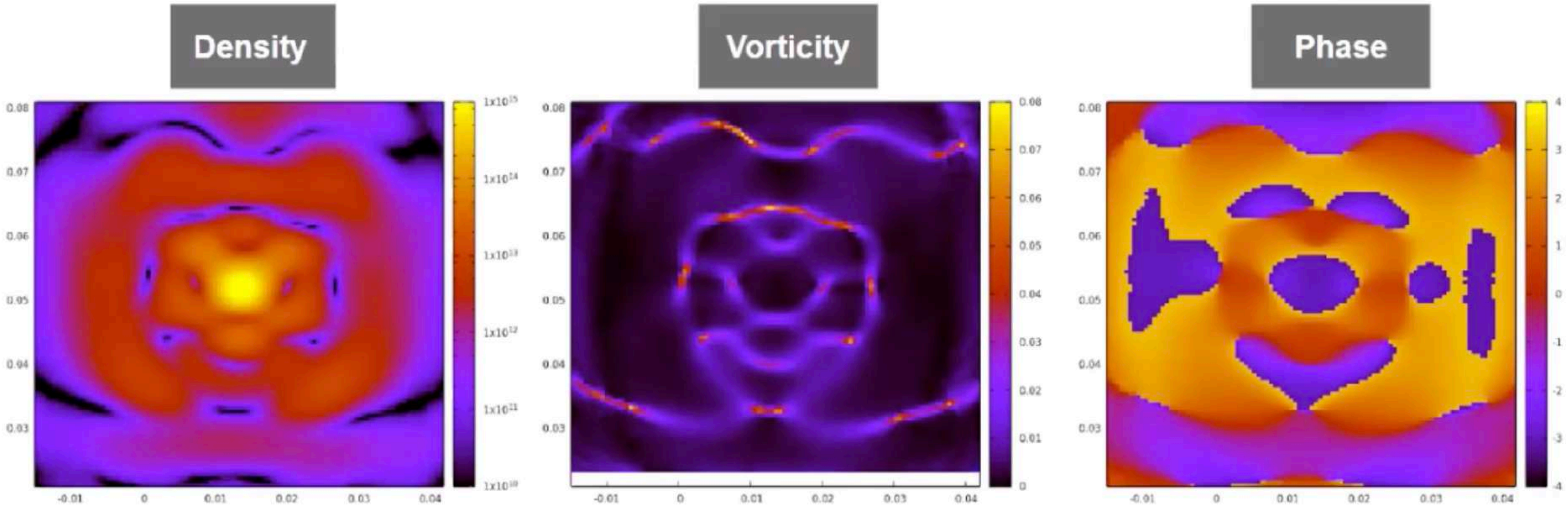
New observables

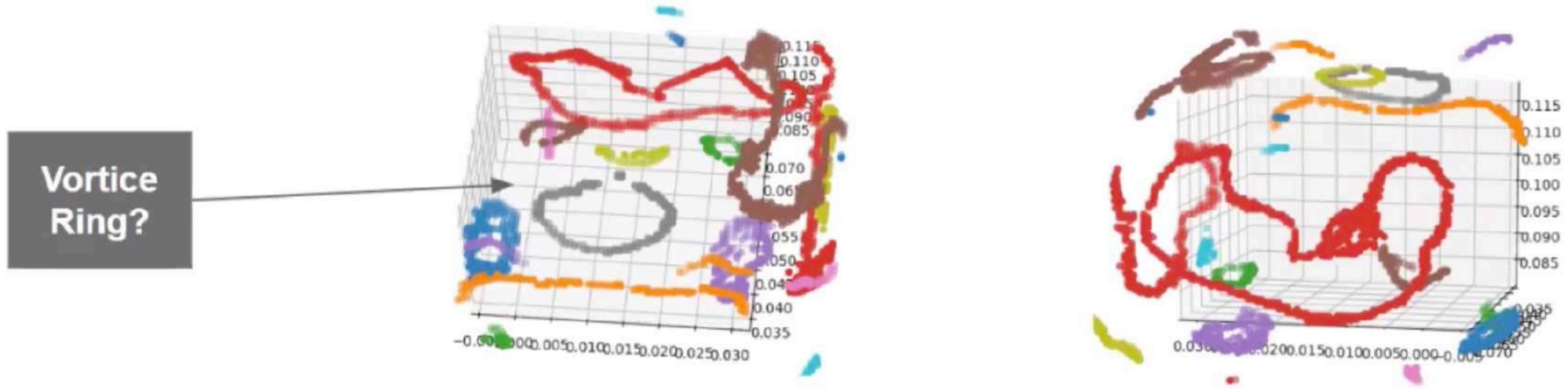
Vortices

PRELIMINARY

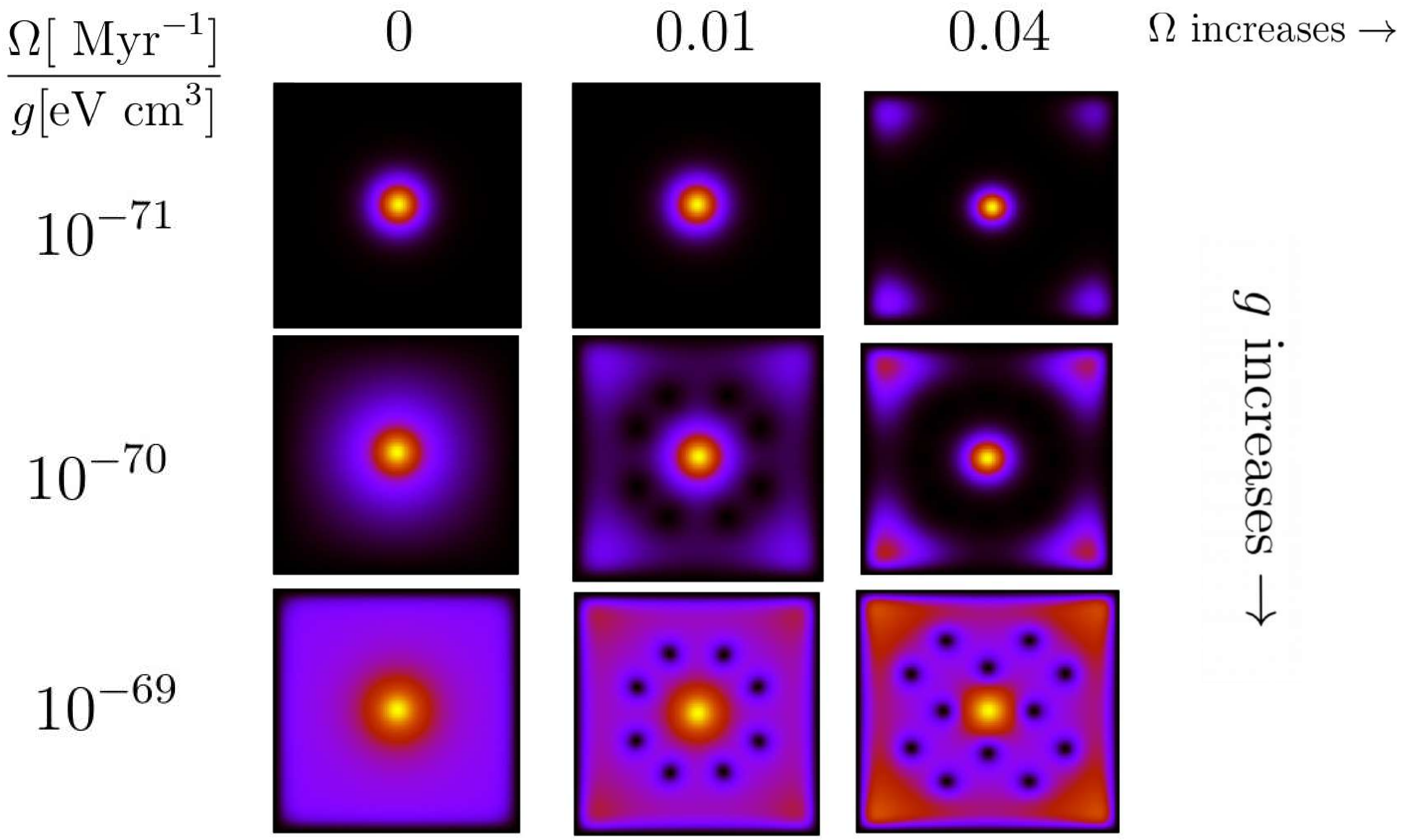
In collaboration with Jowett Chan

Fuzzy DM





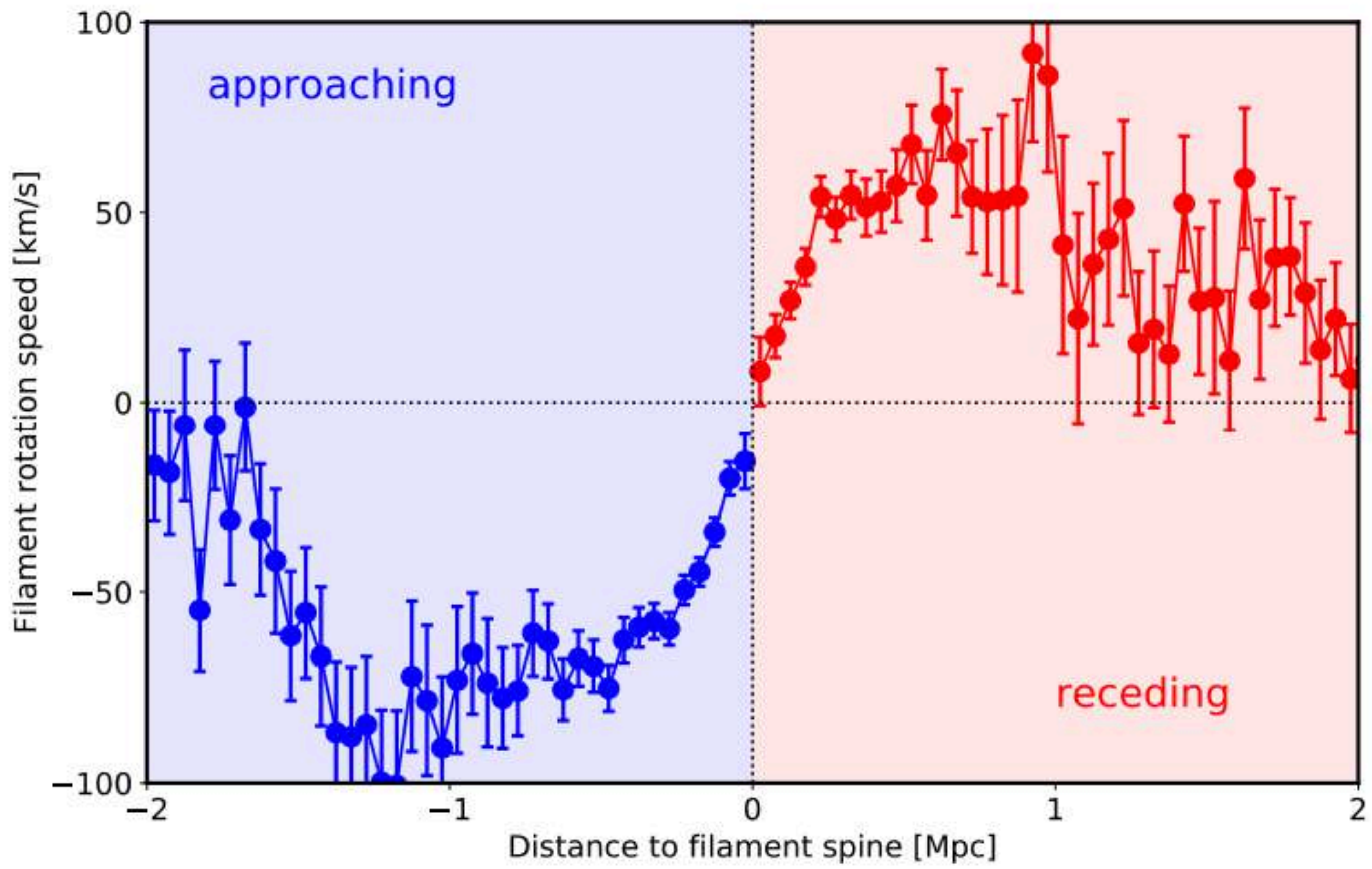
Self-interacting Fuzzy DM



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

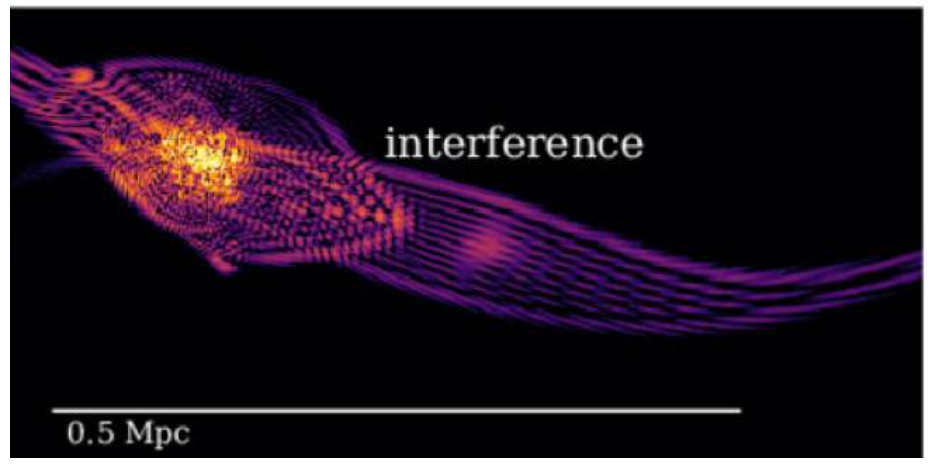
Rotation of filaments: vortices

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



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

Rotation of filaments: vortices

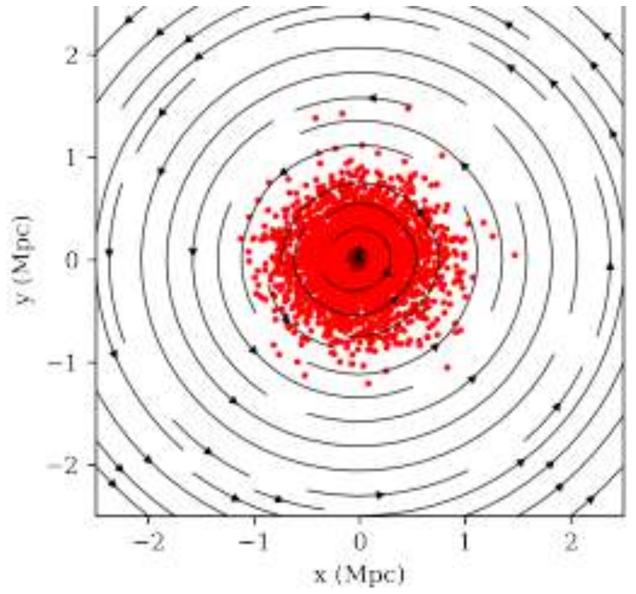


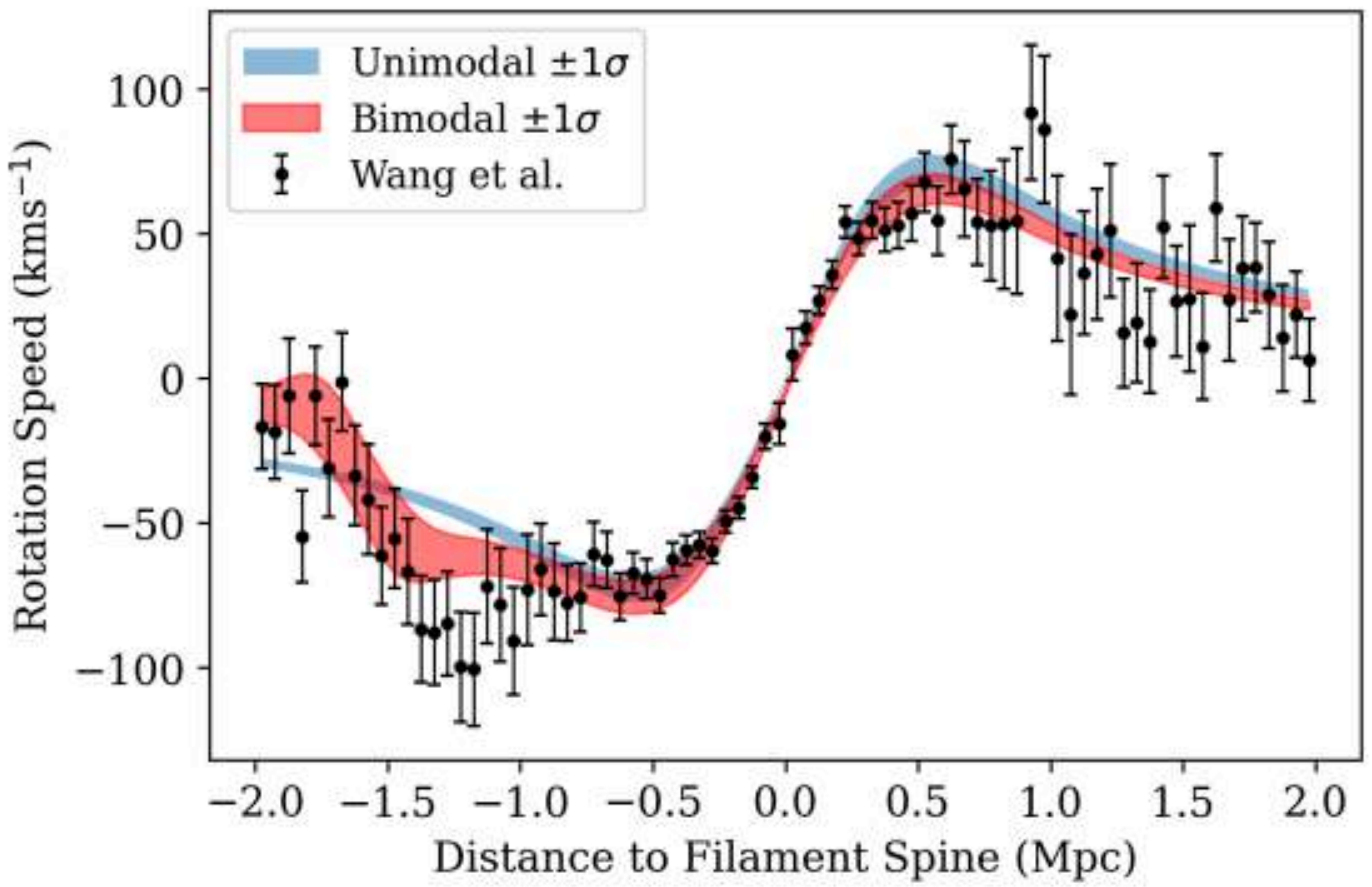
Mocz et al. 2017

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

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

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





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

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

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

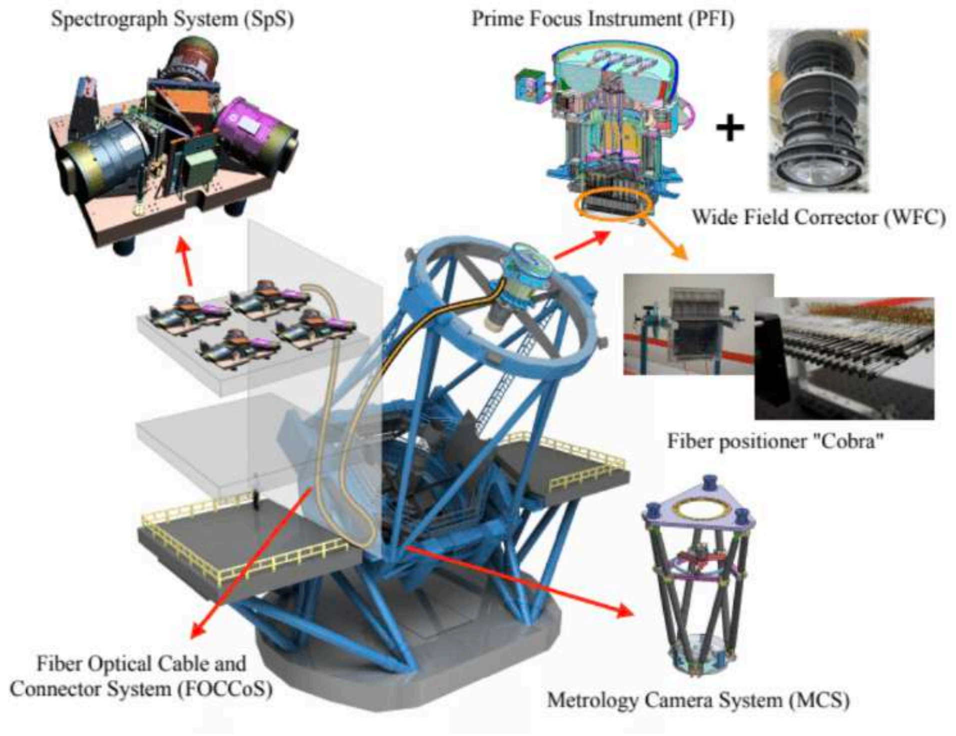
Compatible with:
- in regions where the density vanishes (*Hui et al 2020, Lague et al 2020*)
- Transfer of angular momentum (*Berezhiani, 2015*)

Future

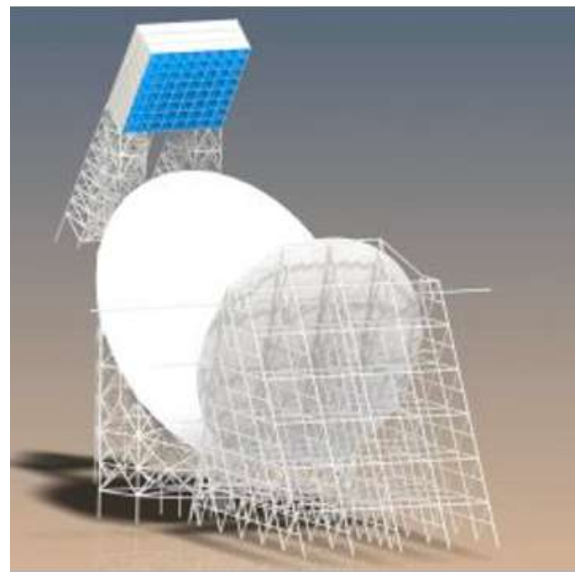
Observations

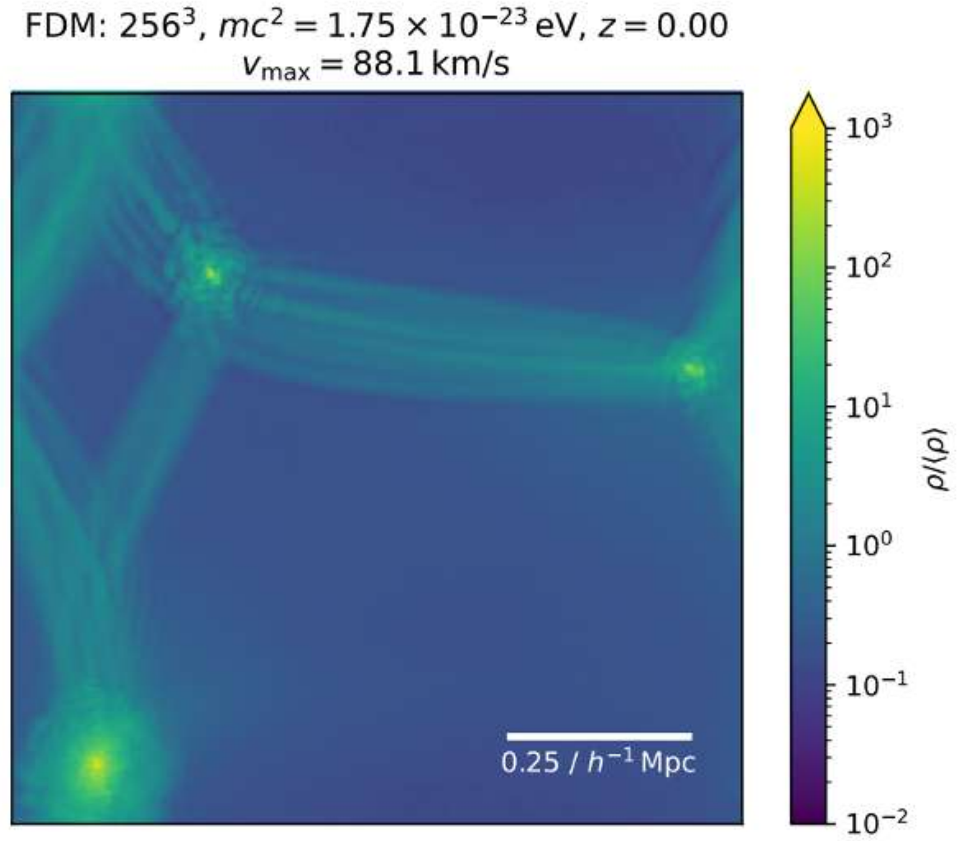
Simulations

Prime Focus Specctrograph (PFS)



BINGO telescope

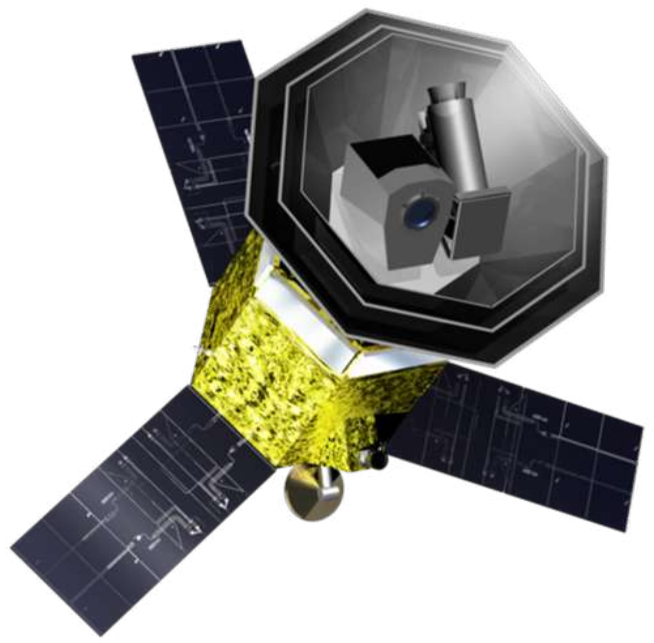




CMB-S4

LiteBIRD

CMB-S4
Next Generation CMB Experiment



Vera Rubin observatory (LSST)

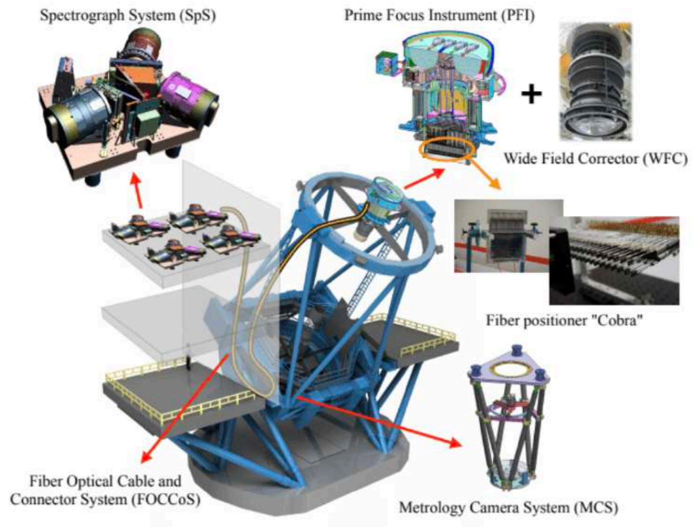
New probes

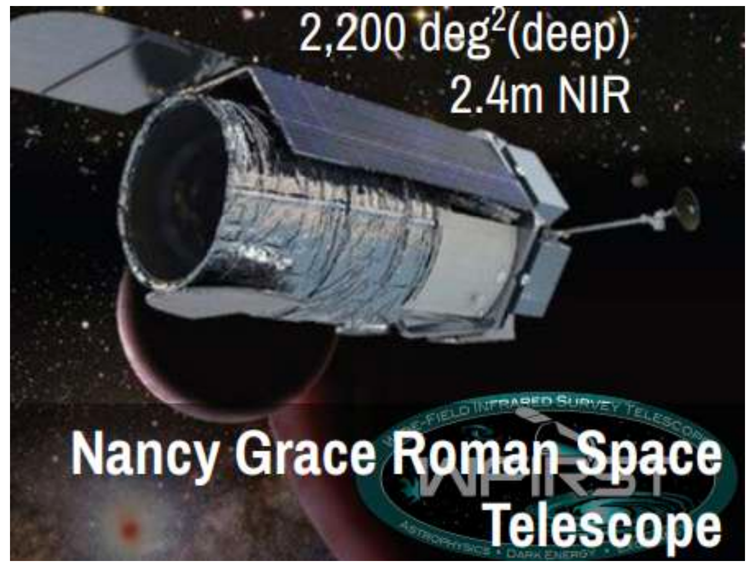
Future - signals in cosmology

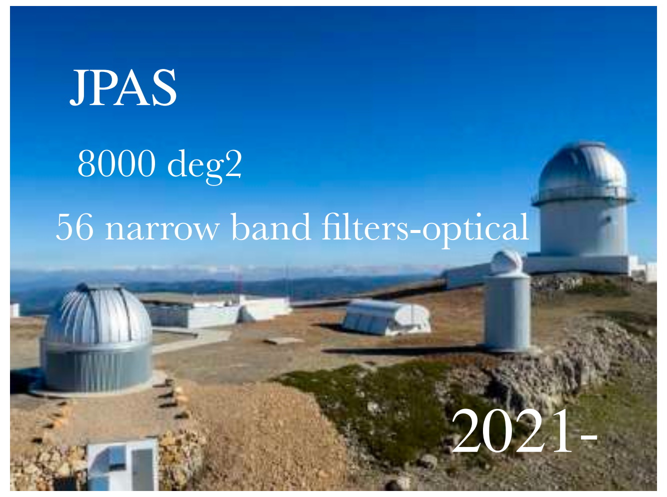
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)

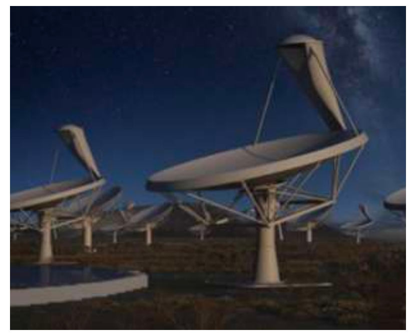






GWs

21cm



SKA SQUARE KILOMETRE ARRAY

CMB

CMB-S4
Next Generation CMB Experiment

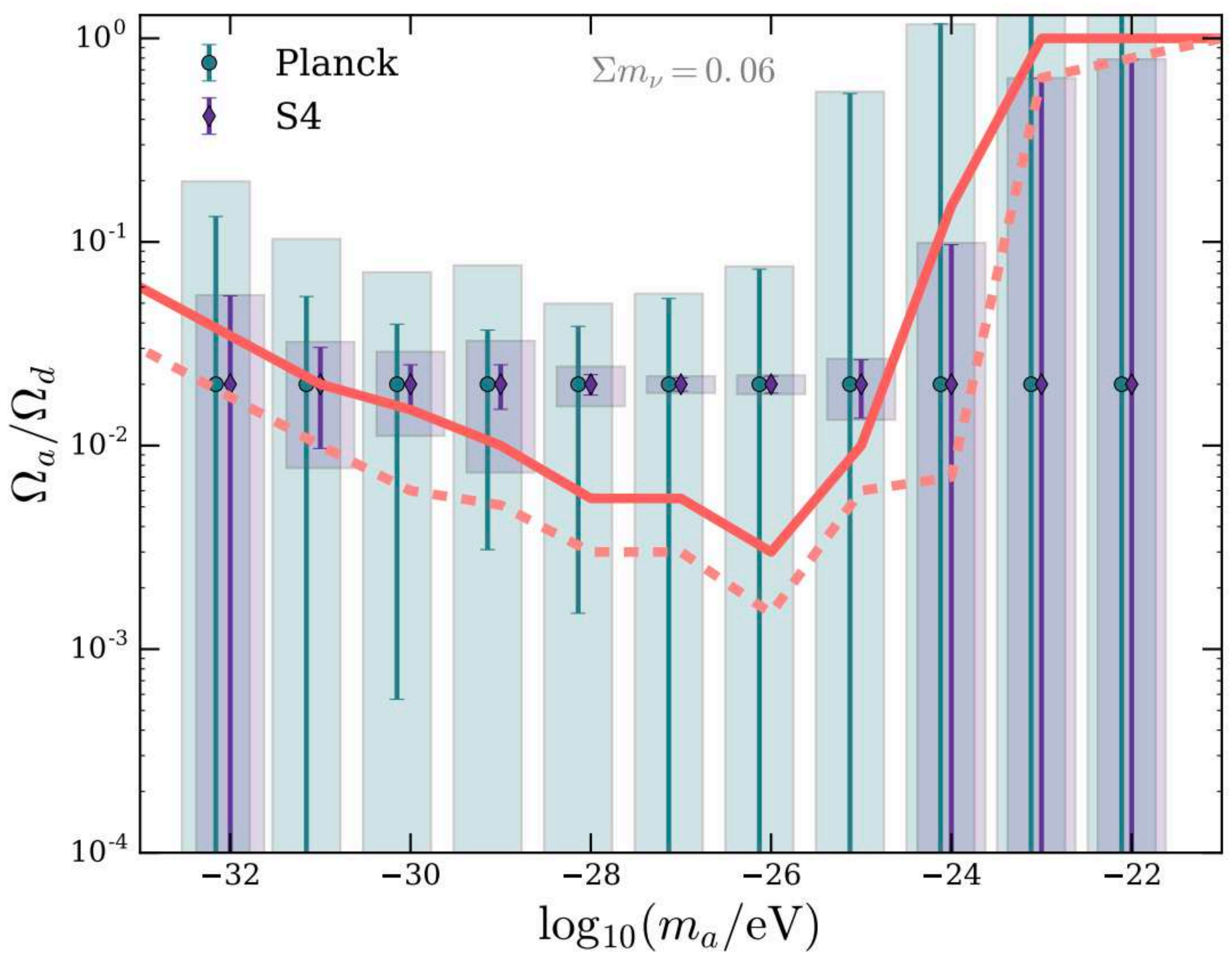
Modified from Jia Liu

Future - *Cosmic Microwave Background*

TESTING ULTRA LIGHT DM CMB

CMB - S4

Constraints on Ω_a/Ω_d



Hlozek et al., 2016

Significantly improve constraints on the composition of the dark sector!

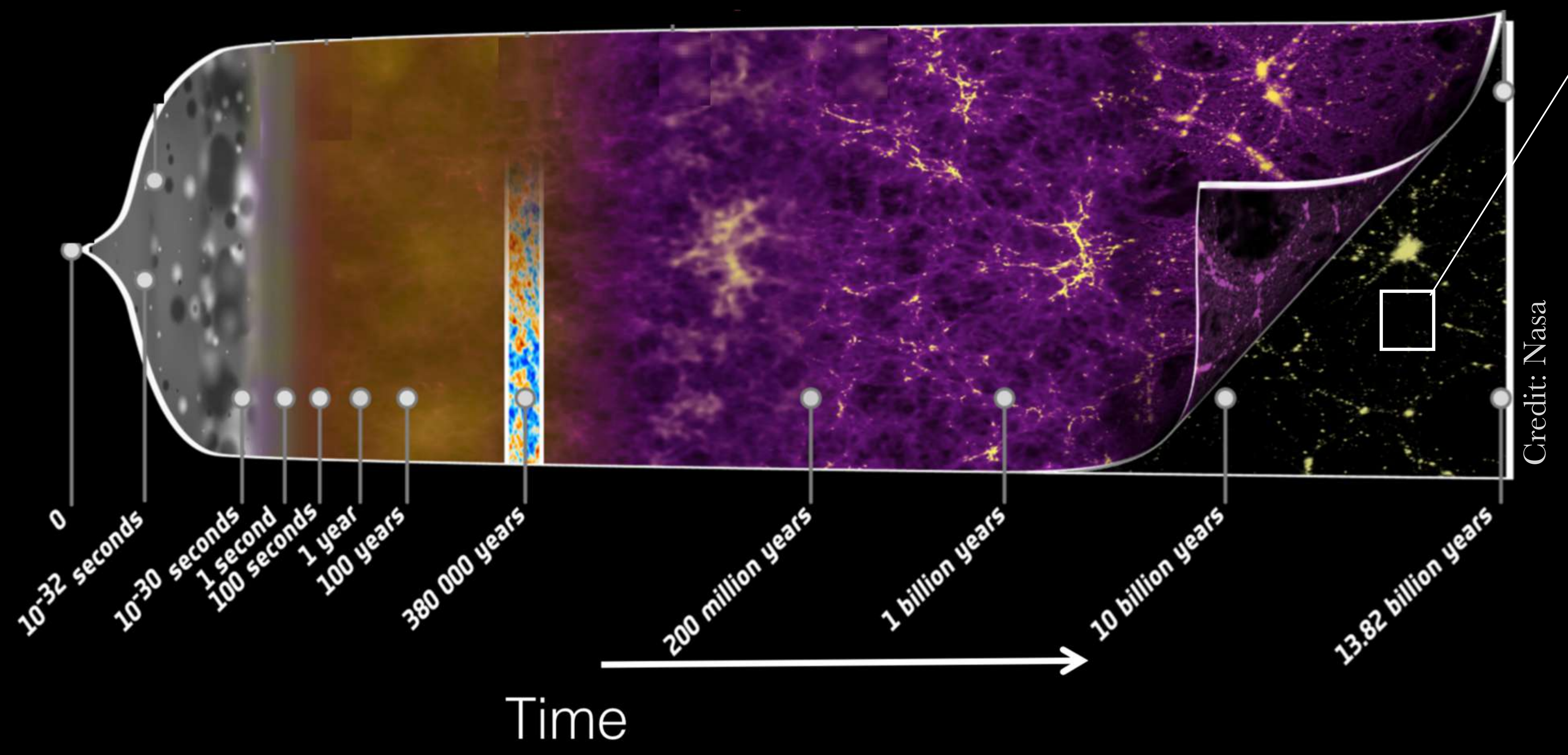
Constraints on the *optical depth* $\tau(r_{\rm rec})$

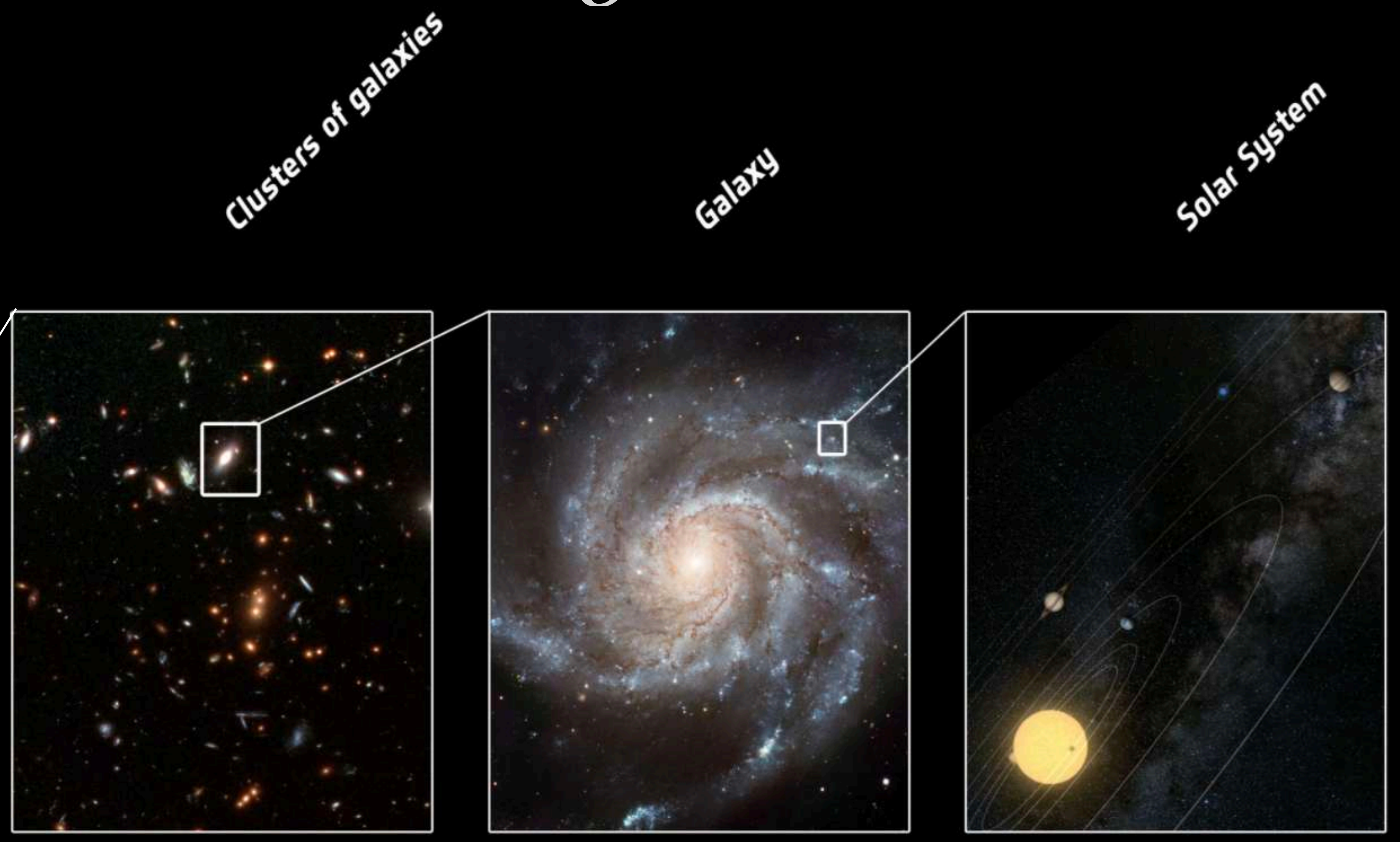
Constraint the ULDM mass

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

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

Small scales can offer some hints of the nature of DM



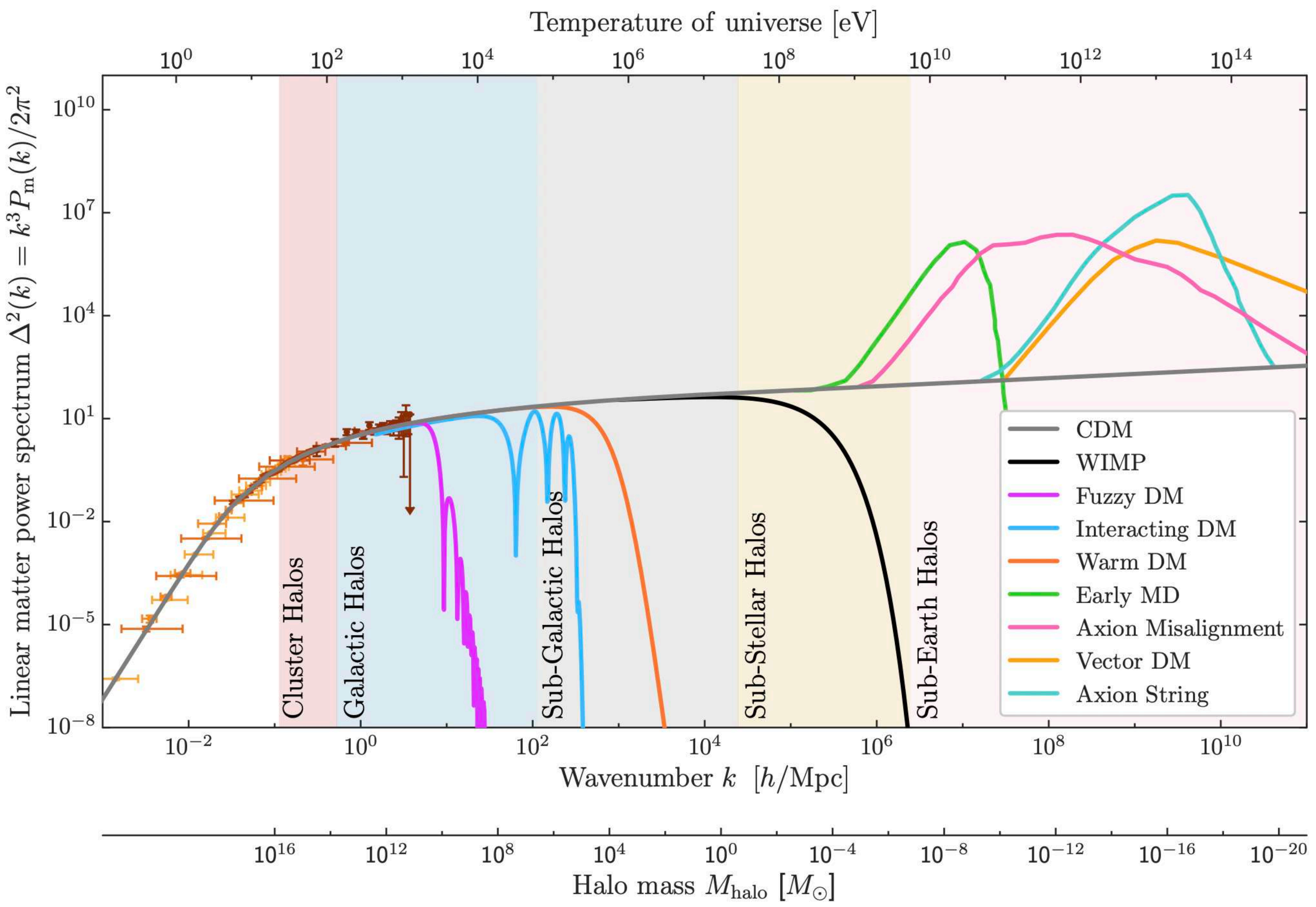


Small Scales

Opportunity to probe the nature of DM!

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

Small scales can offer some hints of the nature of DM

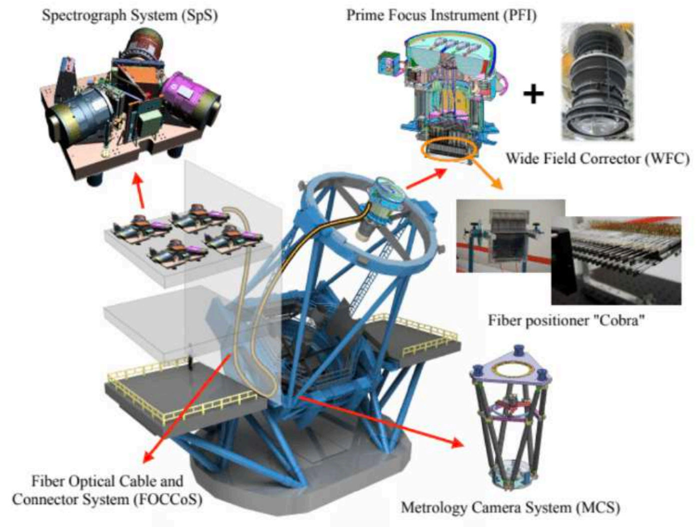


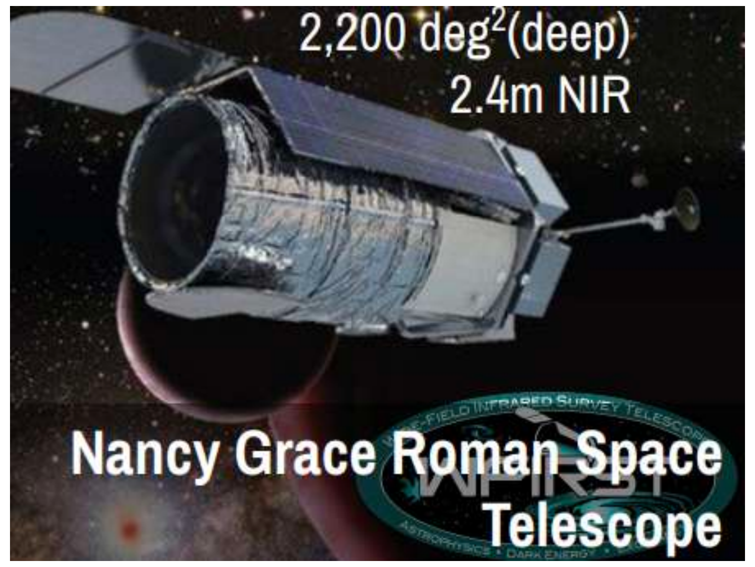
Future - signals in cosmology

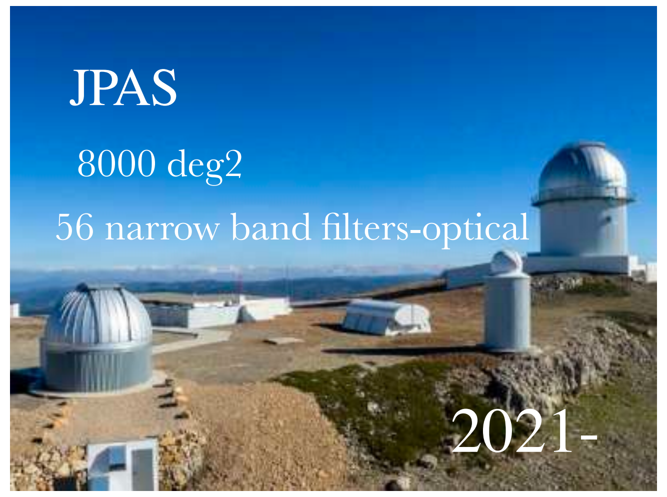
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)

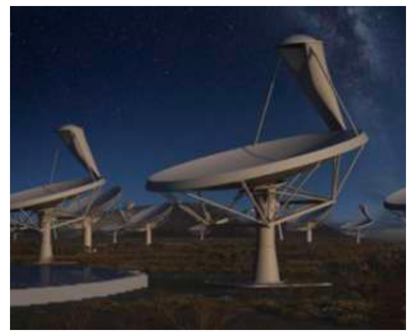






GWs

21cm



SKA
SQUARE KILOMETRE ARRAY

CMB

CMB-S4
Next Generation CMB Experiment

Modified from Jia Liu

PFS (Prime Focus Spectrograph)

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

GOAL

PFS: spectroscopy part of *SuMIRe project*

DM with PFS $\longrightarrow$ *synergy between science goals*

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

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

DM with PFS

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

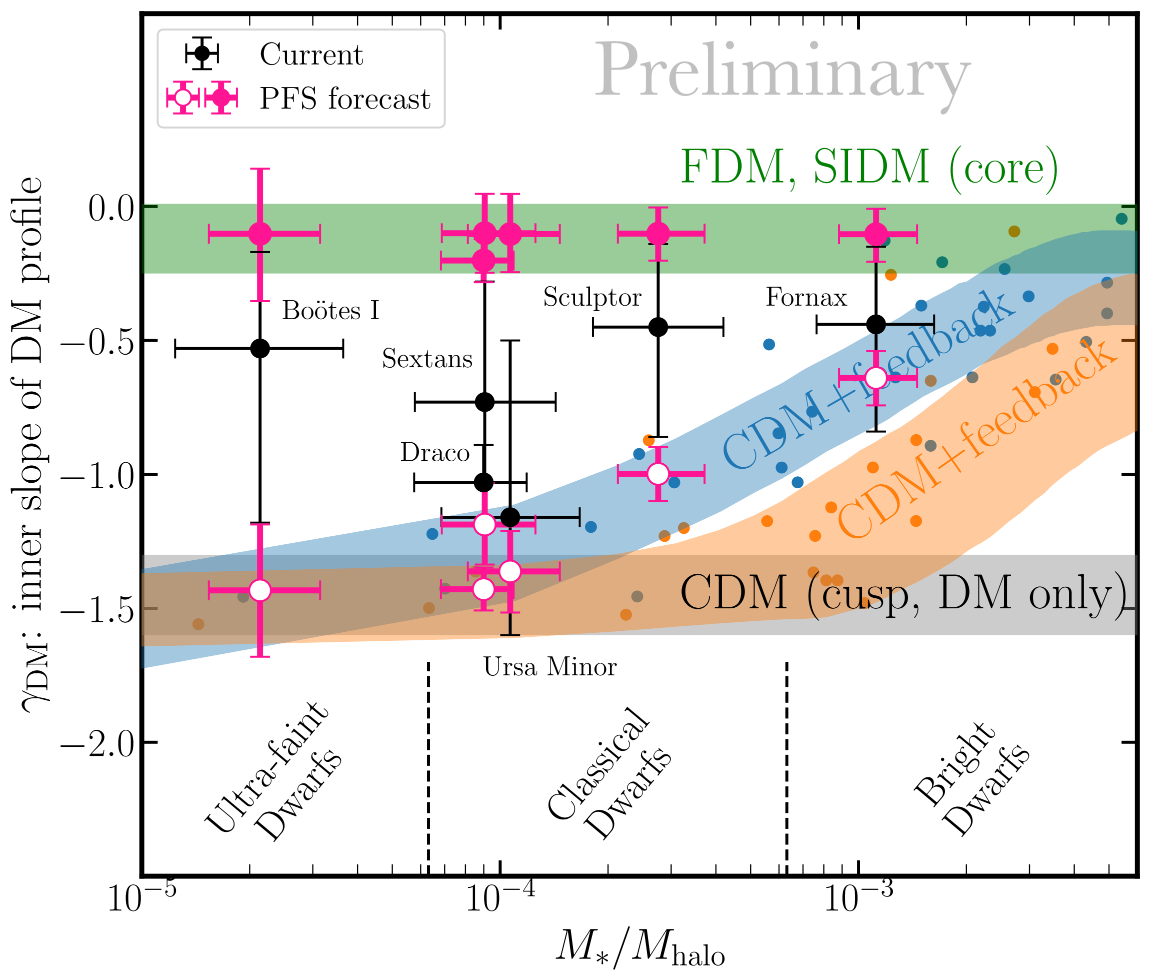
FDM

SIDM

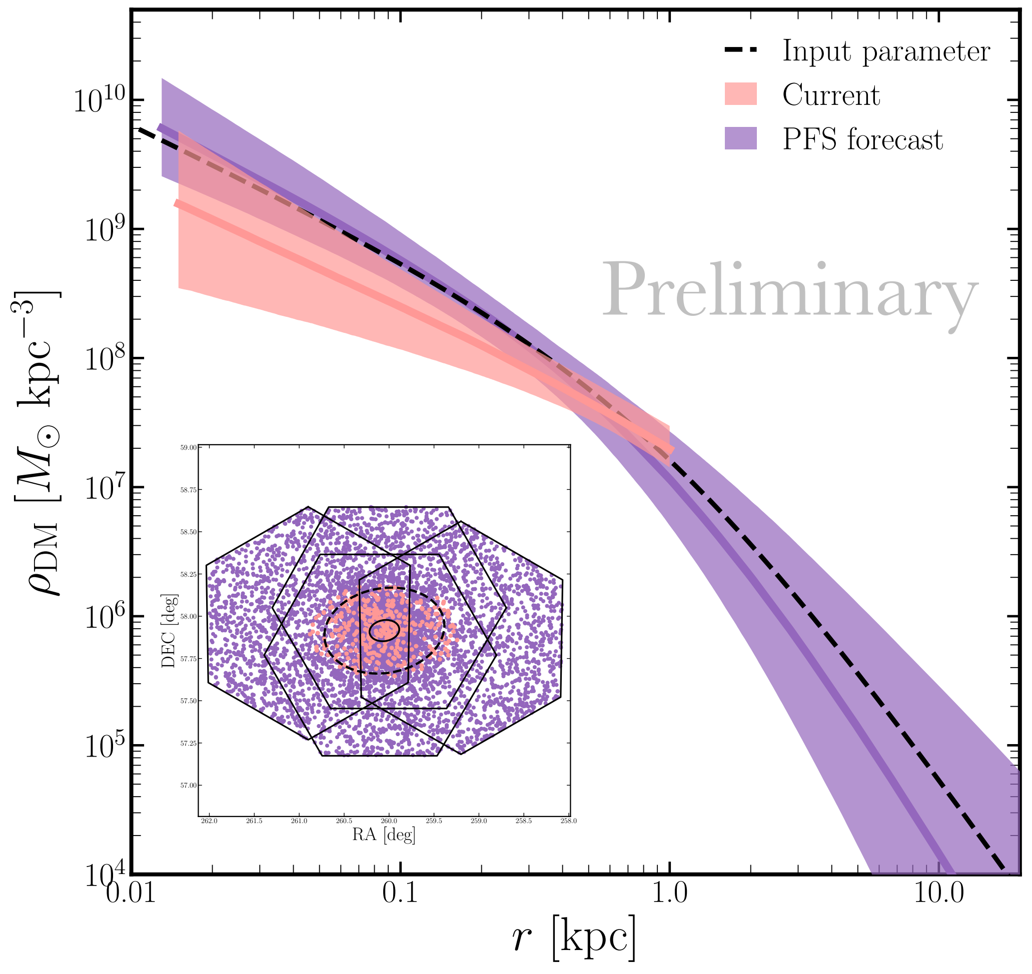
ULA

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

…



Kohei Hayashi' and Masashi Chibas talk



Figures by Kohei Hayashi

DM with PFS

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

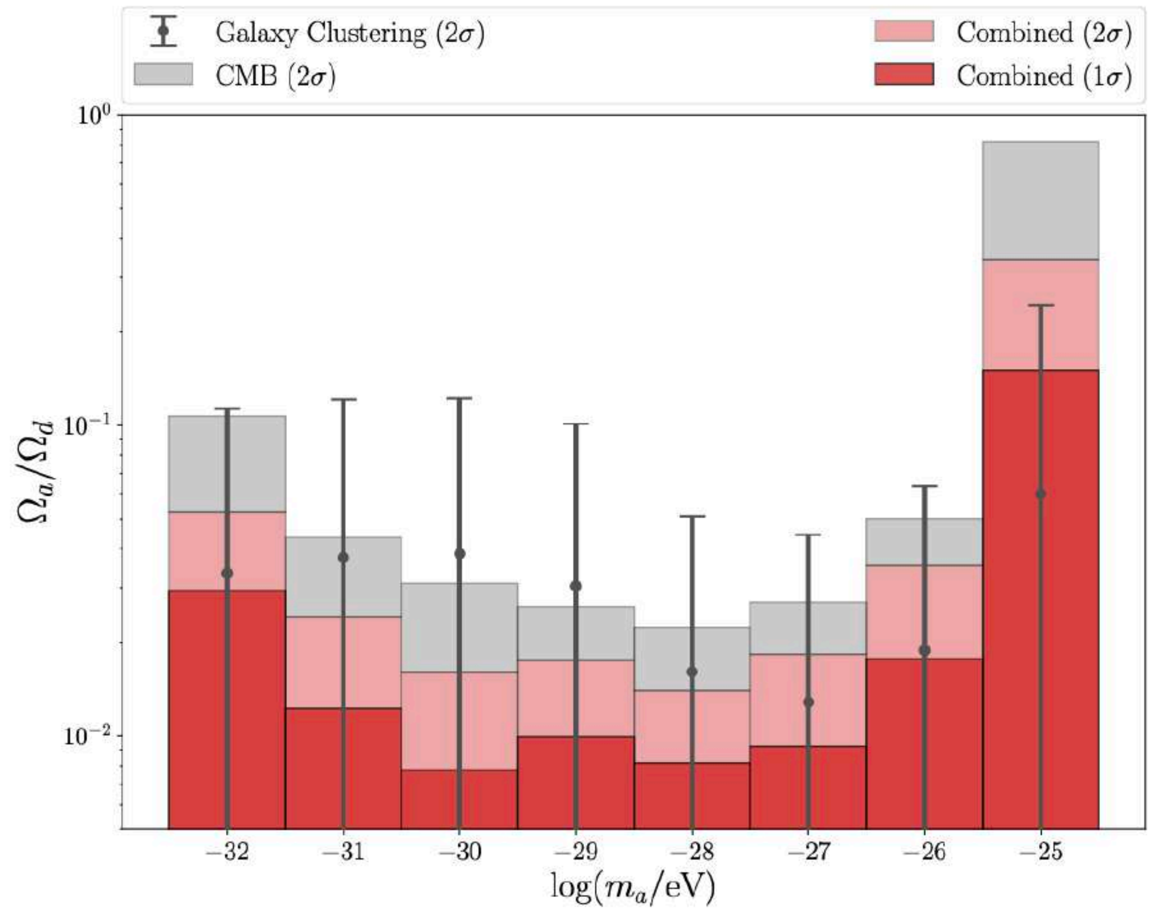
…

FDM

SIDM

ULA

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



Lague et al 2021

ULA

FDM

WDM

SIDM

The small-scale Ly-α forest power spectrum

Halo mass function

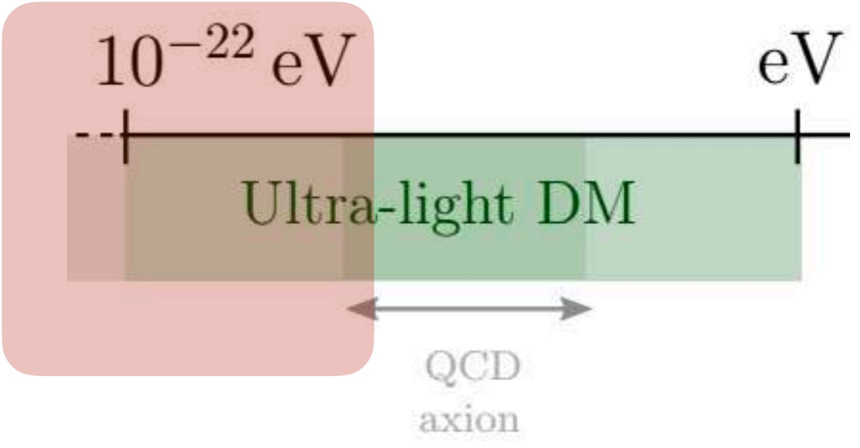
Constraints on the *optical depth:*

Constraint the ULDM mass

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

Properties of DM

Ultra-light Dark Matter -classes



3 classes:

Fuzzy DM (FDM)

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

DOFs: m

Self Interacting FDM (SIFDM)

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

DOFs: m g

DM Superfluid

- Forms a superfluid in galaxies
- MOND behaviour interior of galaxies

Axion and ALP (axion like particles)

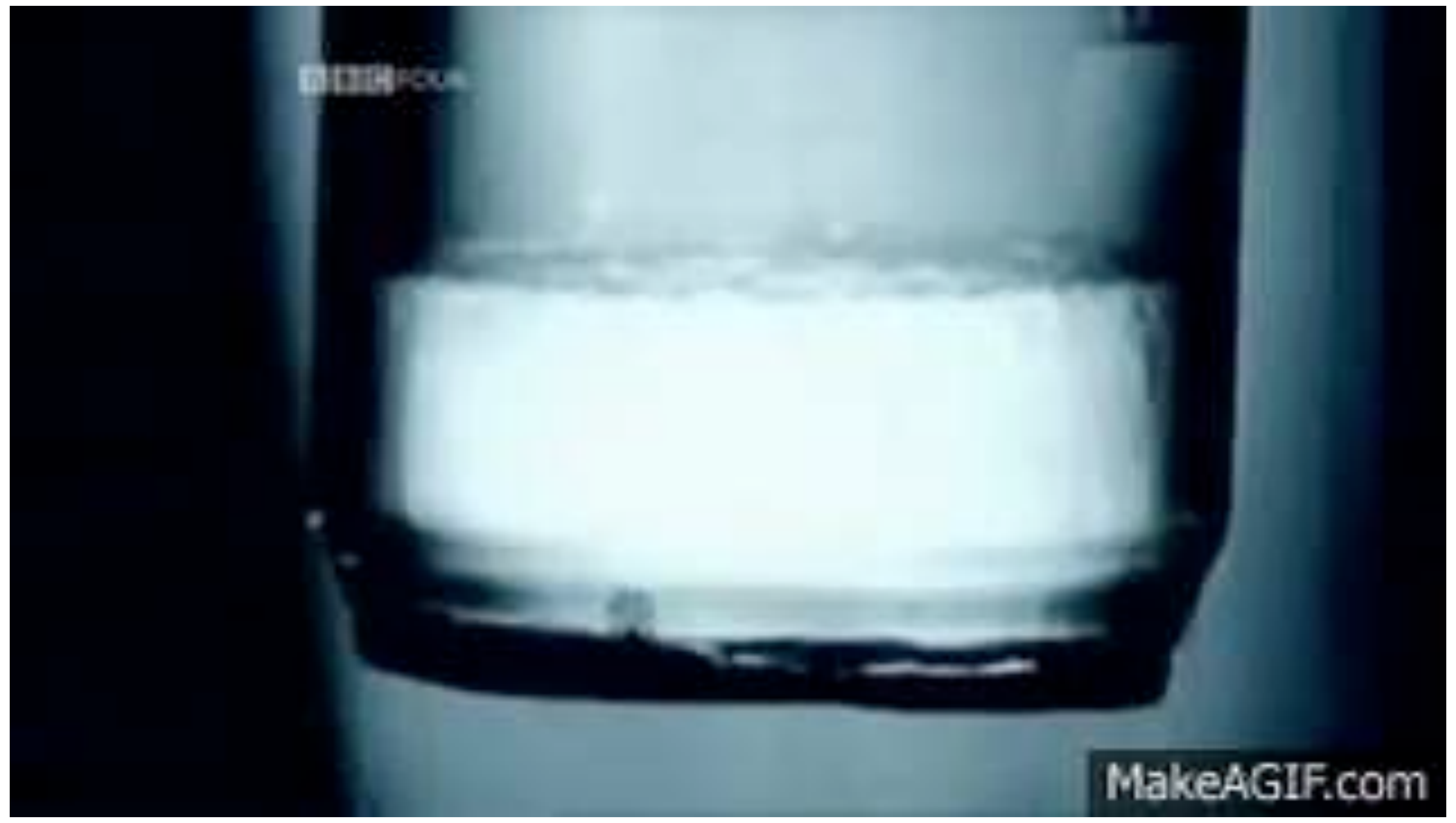
$$i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{g}{8m^2}|\psi|^2 - m\Phi\right)\psi$$

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

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

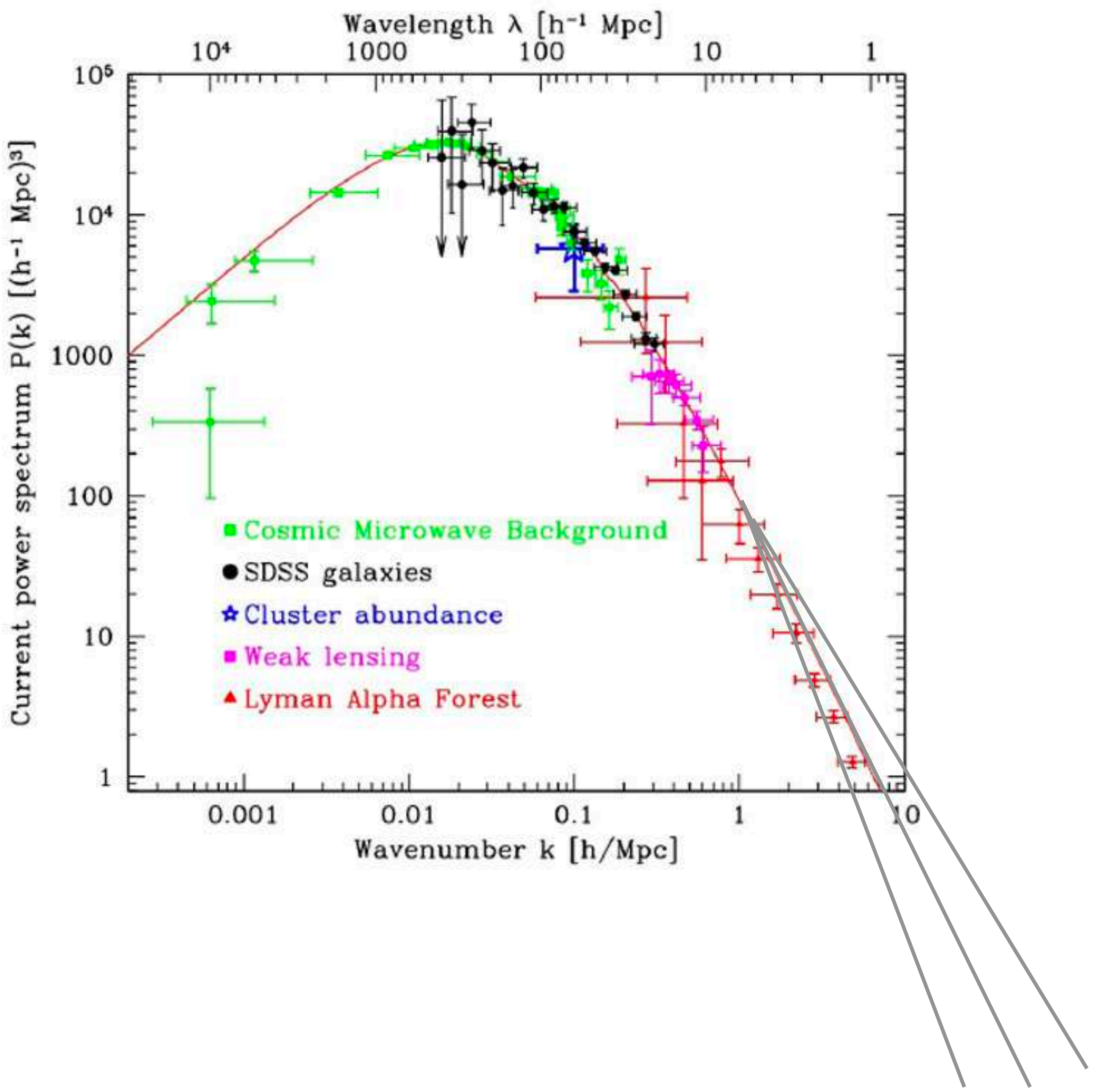
"Ultra-light dark matter", **E.Ferreira**, 2020. The Astronomy and Astrophysics Review.

Superfluid Dark Matter



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

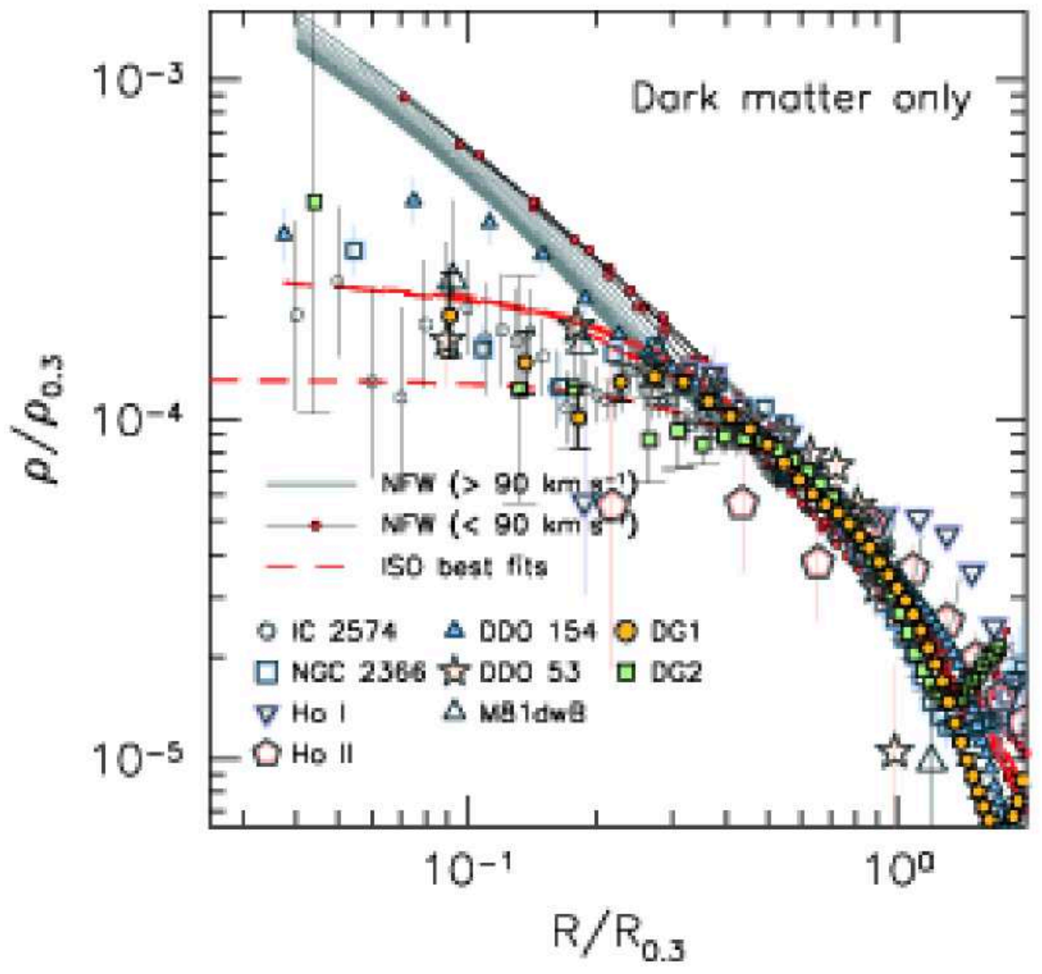
Small scale behavior: still weakly constrained and small scale challenges

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

Small scale challenges

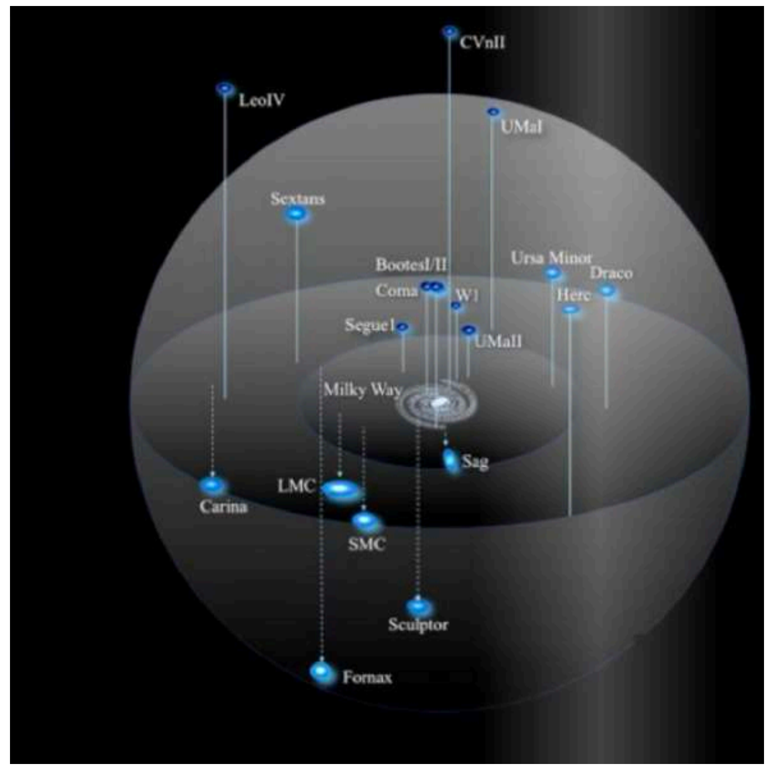
Cusp-core

Density



Radius

THINGS (HI Near Galaxy Survey)/LITTLE THINGS

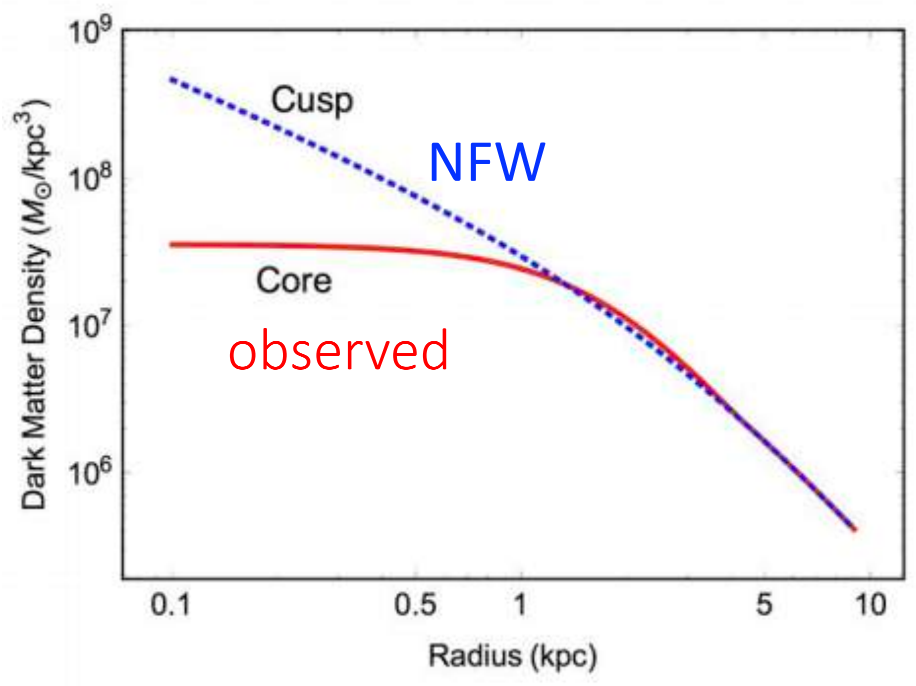


Bullock, Baylon-Kolchin

Missing satellites

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

CDM - NFW profile



Regularity/diversity of rotation curves

Regularity and diversity of rotation curves

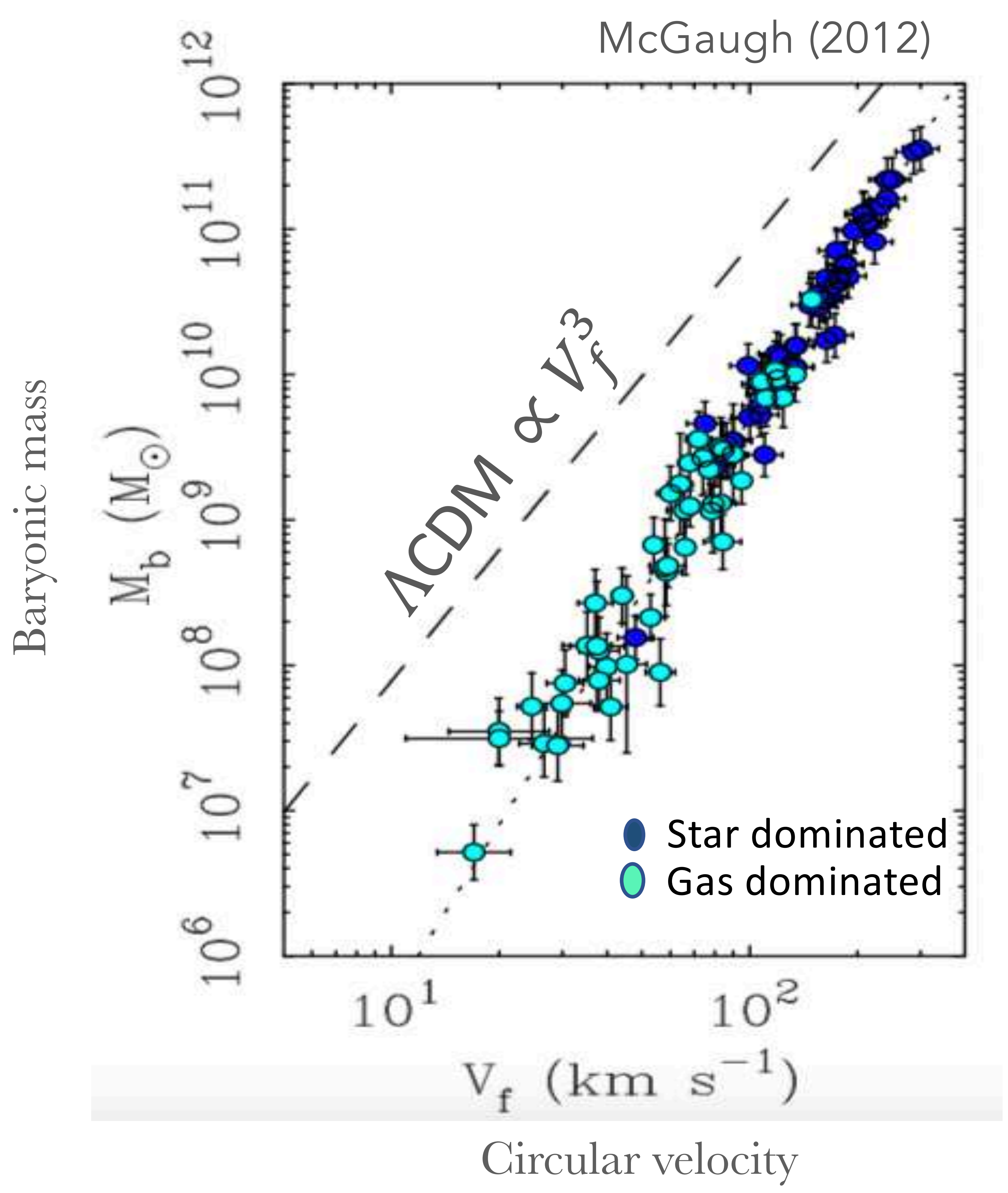
- Baryonic Tully-Fisher relation (BTFR)

Remarkably tight scaling relations between dynamical and baryonic properties.

Other scaling relations:

✓TRF
✓RAR - Radial acceleration relation
✓…

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



Dark matter- Large scales: CDM

Small scales:

Both?

- **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!

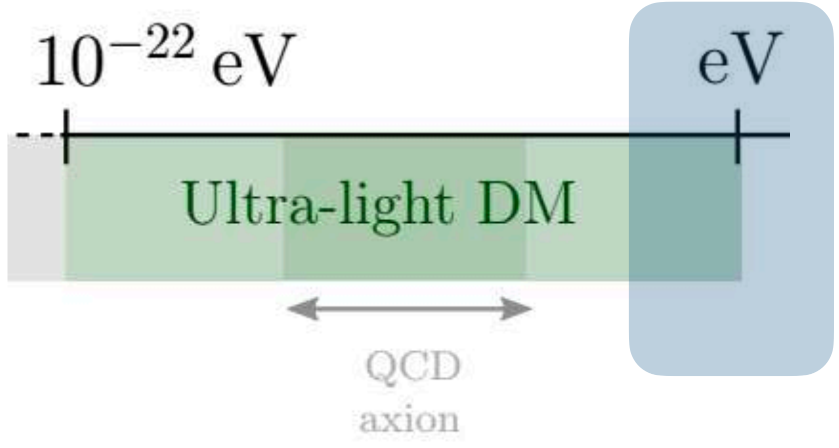
Works extremely well for: (1) rotation curves; (2) scaling relations

BUT: ~~MOND without DM~~

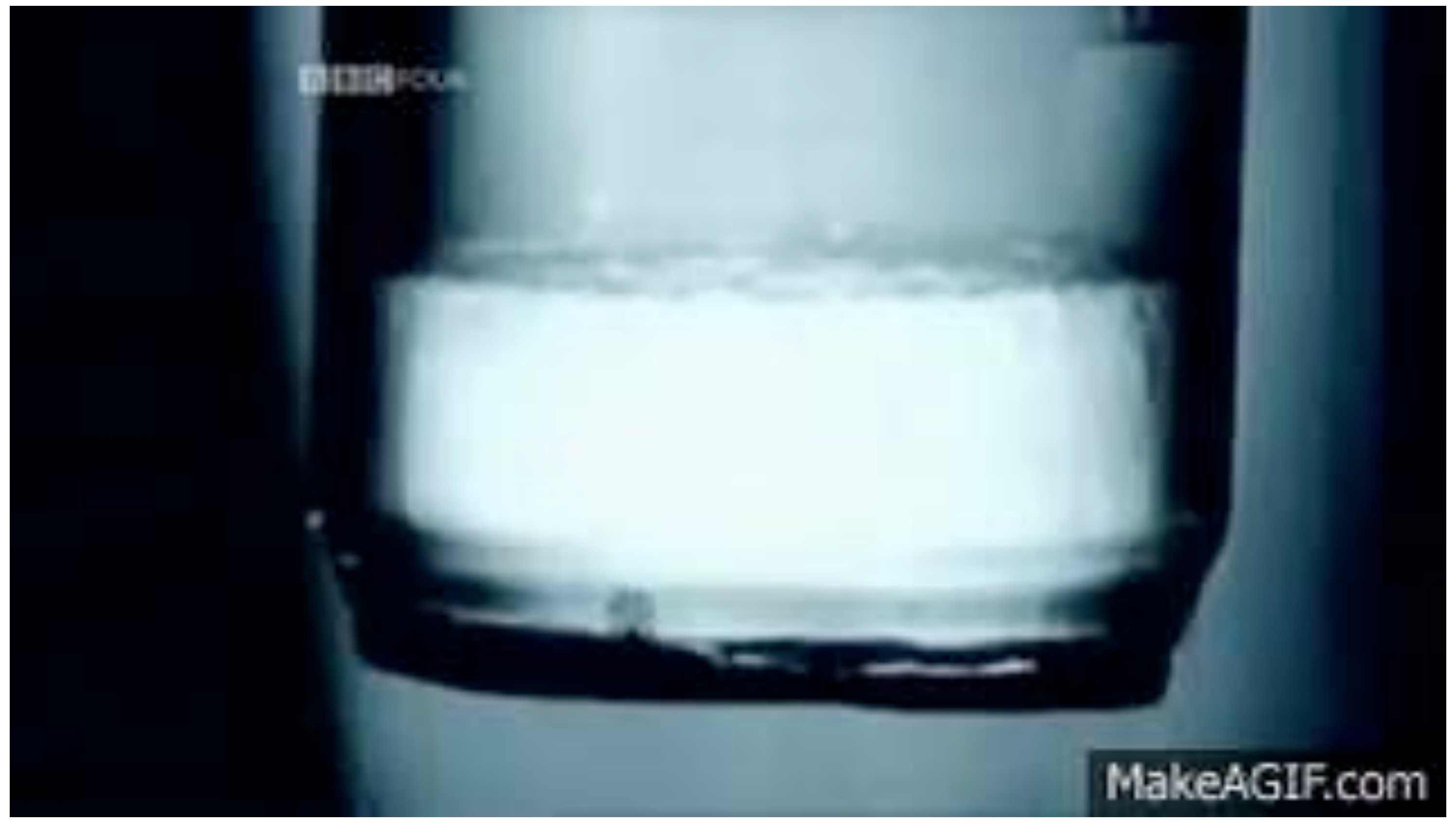
Problems explaining large scales

- **Modify dark matter:**

DM with different properties on small scales



Superfluid Dark Matter



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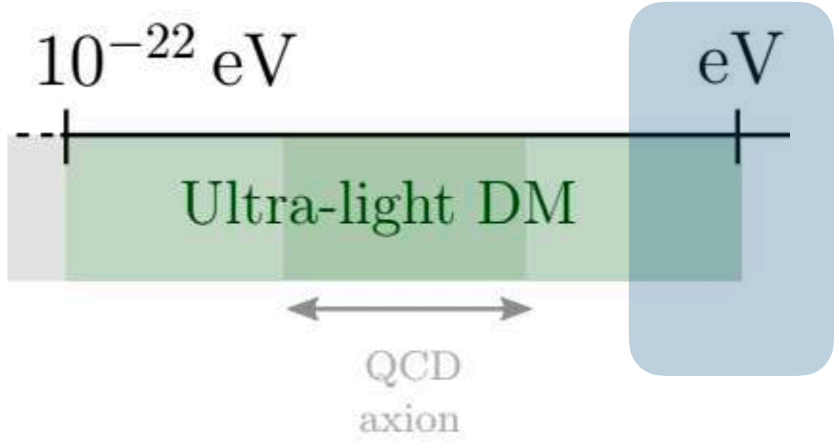
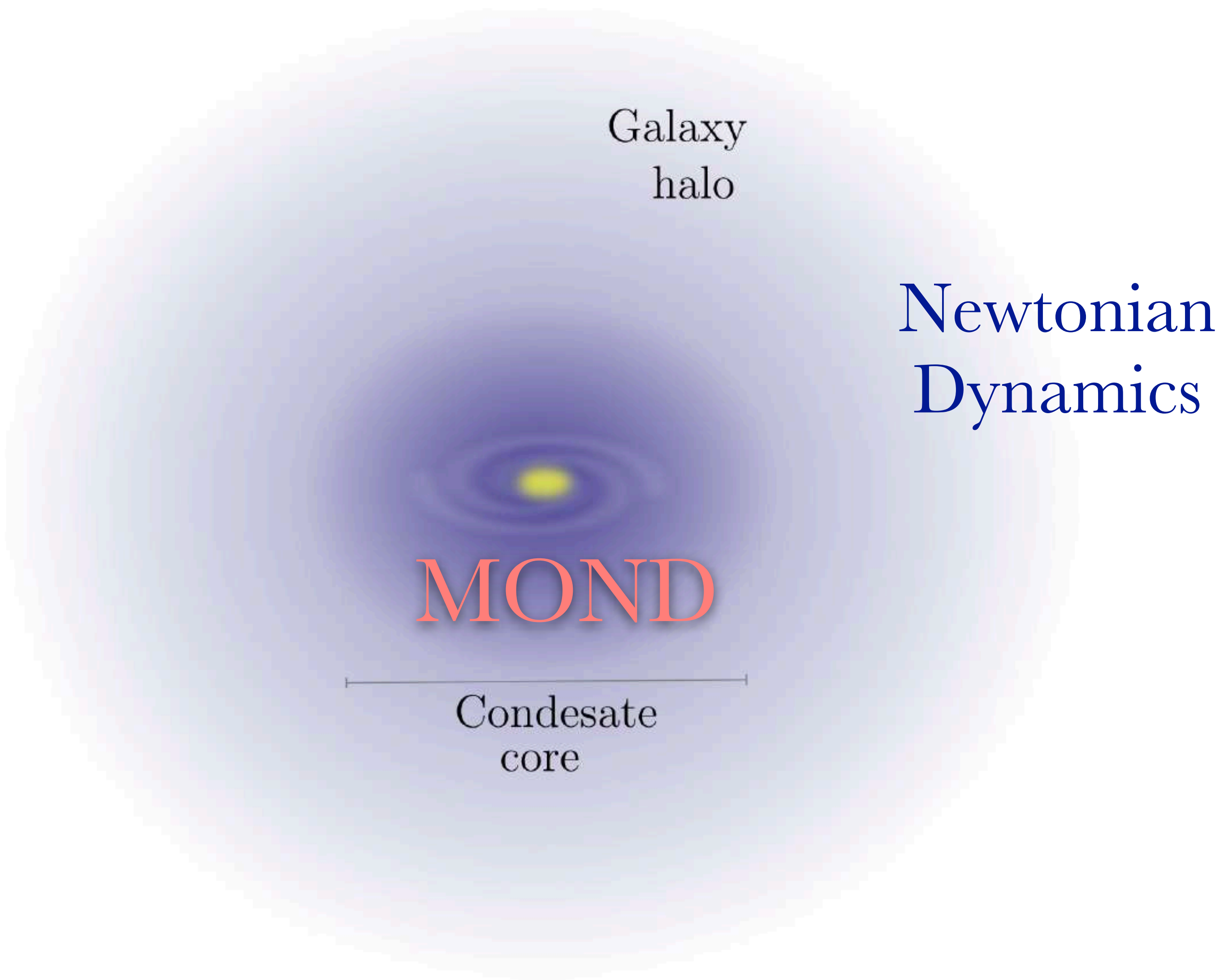


Lasha Berezhiani and Justin Khoury (2016)

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



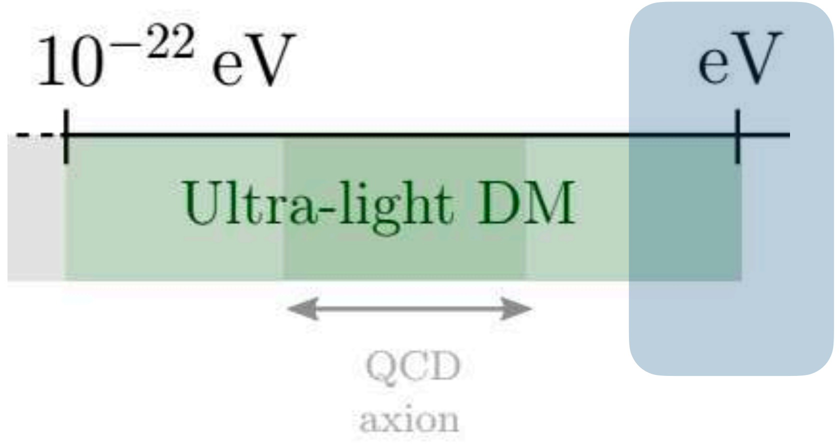
Galactic scales:
DM forms a superfluid
$\longrightarrow$ emergent MOND dynamics in galaxies

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

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

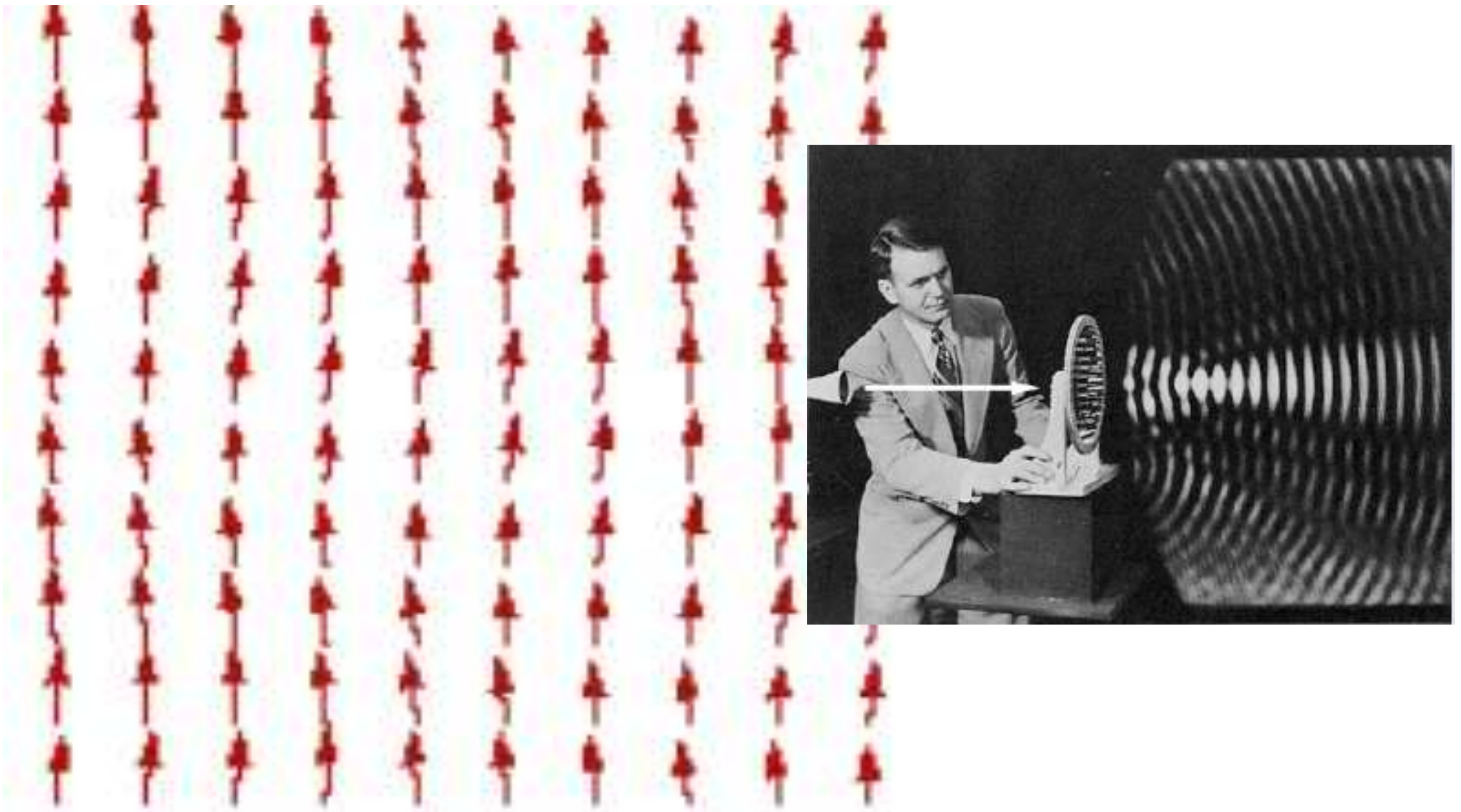
Suppresses small structures, dyn. effects, formation of cores

Collective modes



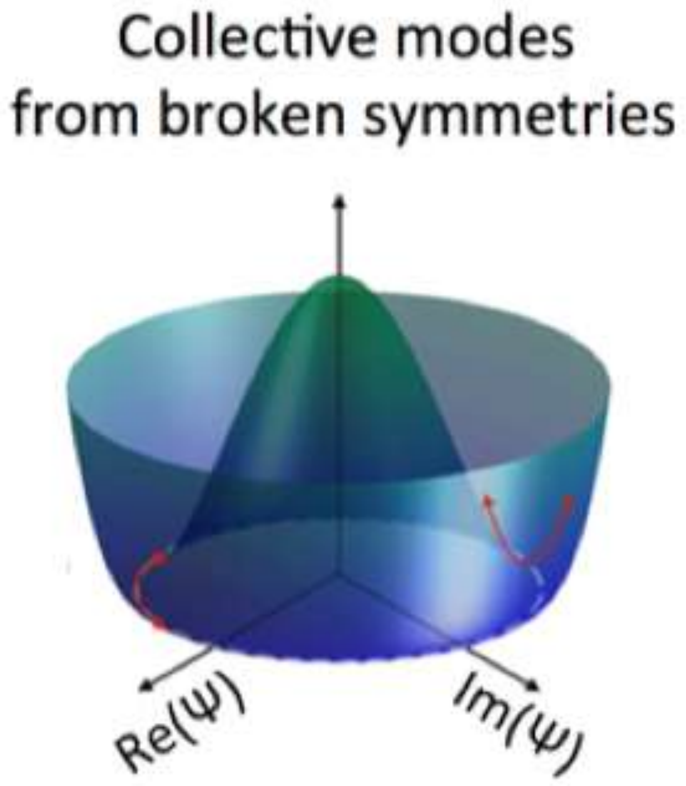
- Described by the collective behavior of the particles.

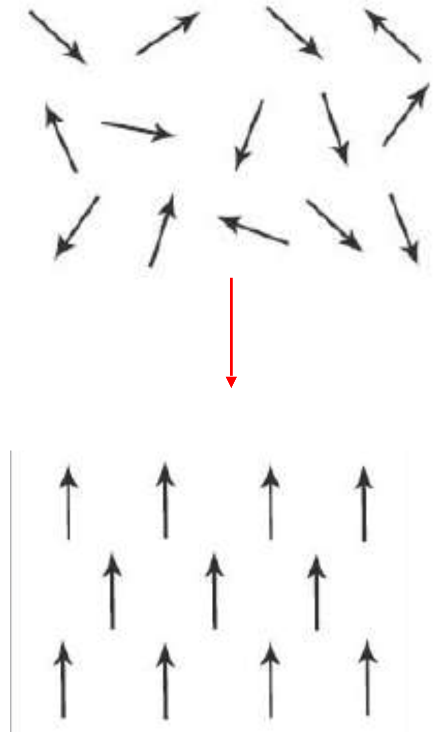
- No need for microphysics: symmetry alone describes the system.



Tom‡š Brauner

- Collective modes related to symmetry = Nambu–Goldstone bosons





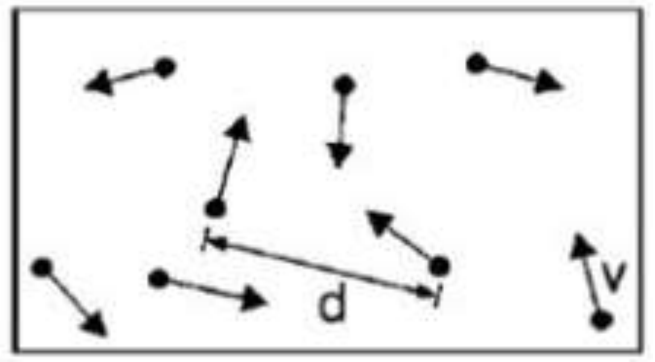
Order parameter

Effective degree of freedom

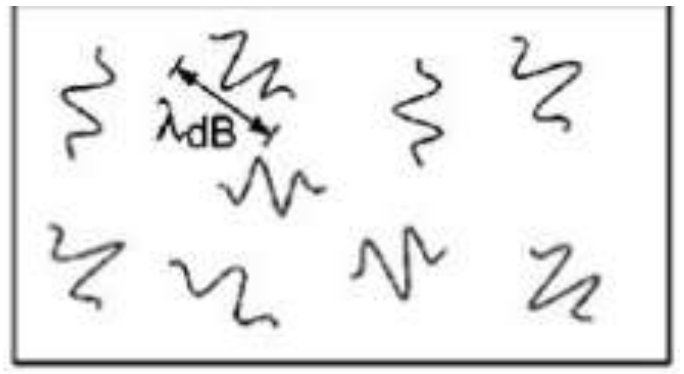
Effective dynamics

Superfluid

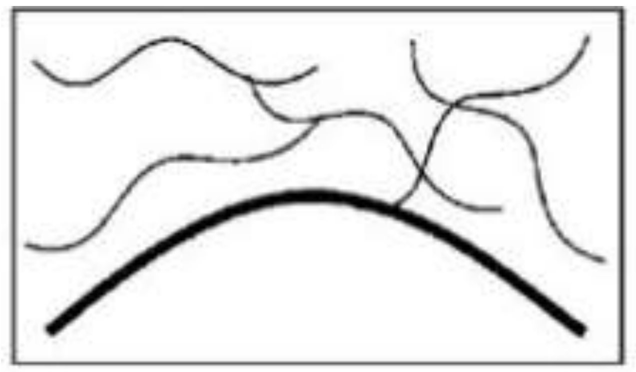
- At low temperatures, a superfluid condensates into a Bose-Einstein condensate (BEC).
- De Broglie wavelength (λ_B) of each particle is large enough that their quantum wave function overlap, and a single wave function describes the entire liquid.
- Quantum phenomenon that appears at low temperatures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



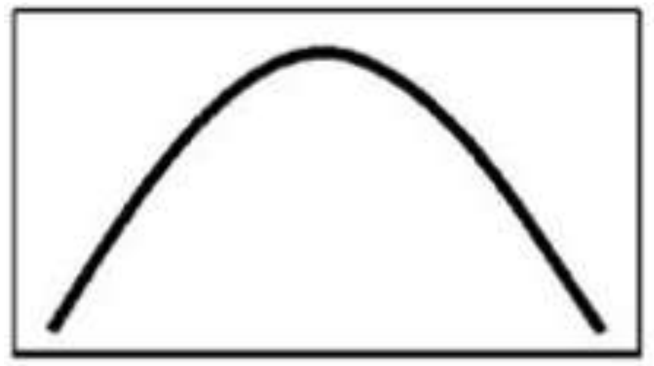
High temperature
Thermal velocities



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



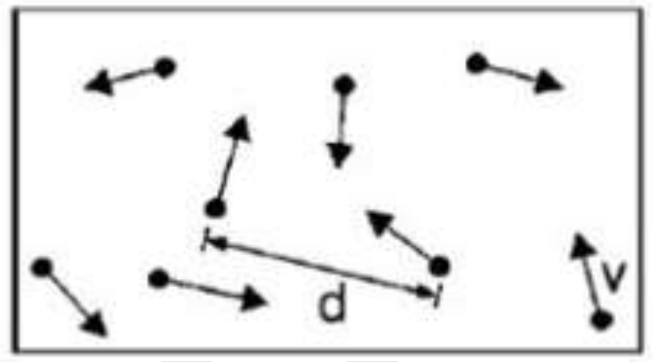
$T = T_c$
BEC
"matter wave overlap"



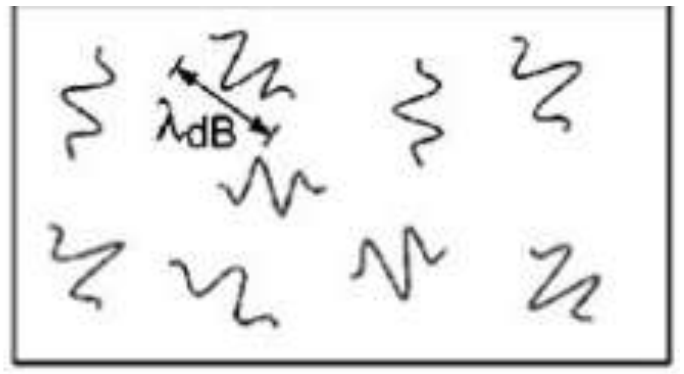
$T = 0$
Pure BEC
"giant matter wave"

Goal:

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

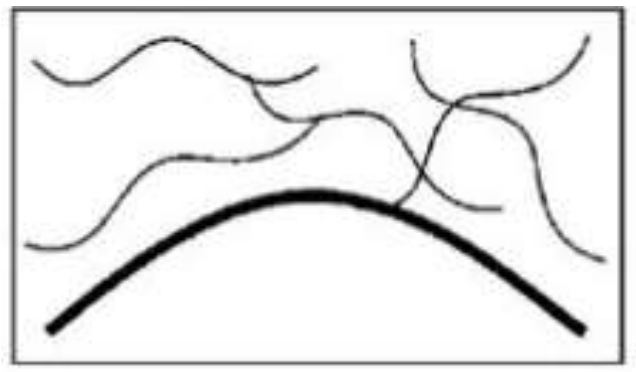


$T \gg T_c$



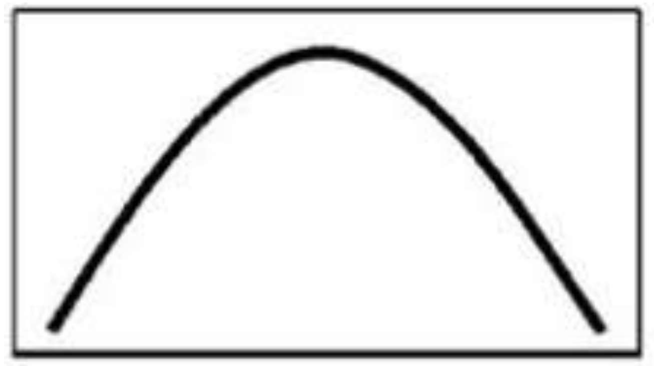
Low temperature

$\lambda_B \sim T^{-1/2}$



$T = T_c$

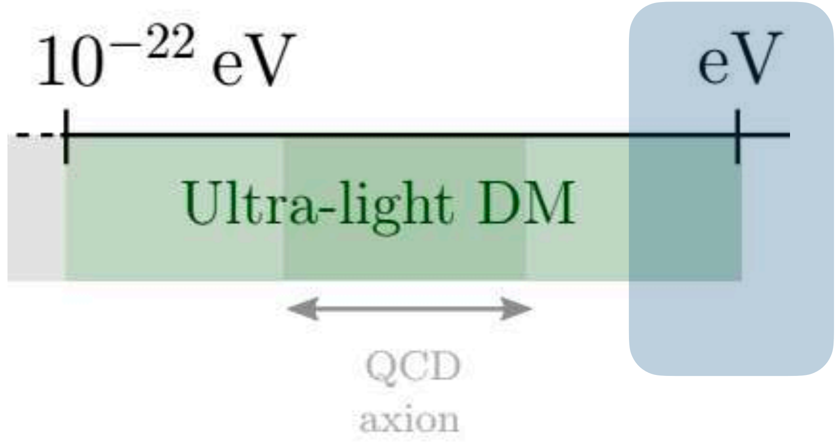
BEC



$T = 0$

Pure BEC

Superfluid Dark Matter



Lasha Berezhiani and Justin Khoury (2016)

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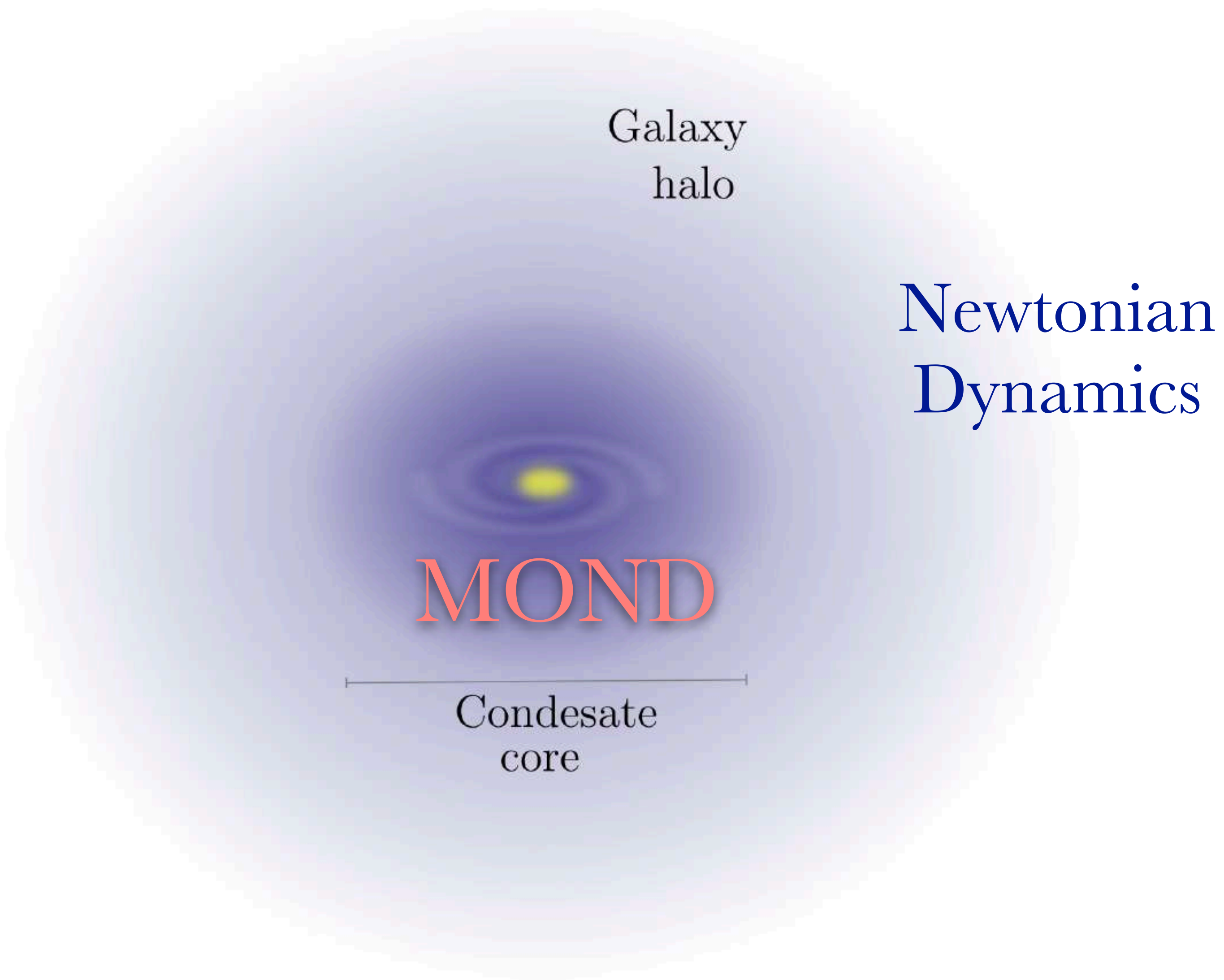

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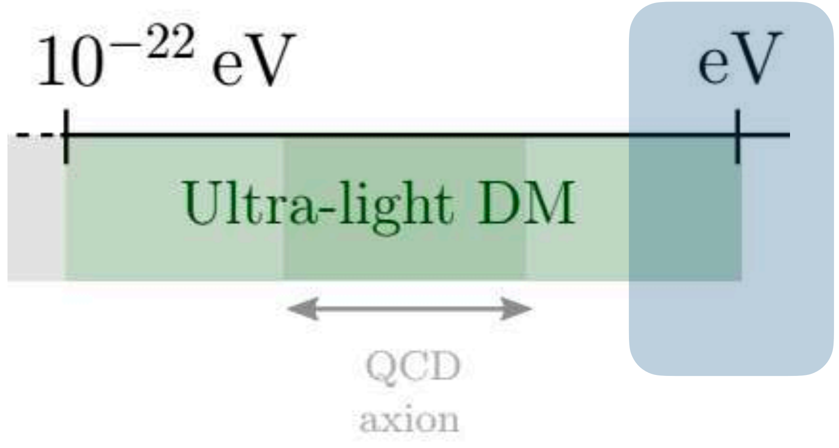
DM forms a superfluid
⟶ emergent MOND dynamics in galaxies

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

Suppresses small structures, dyn. effects, formation of cores

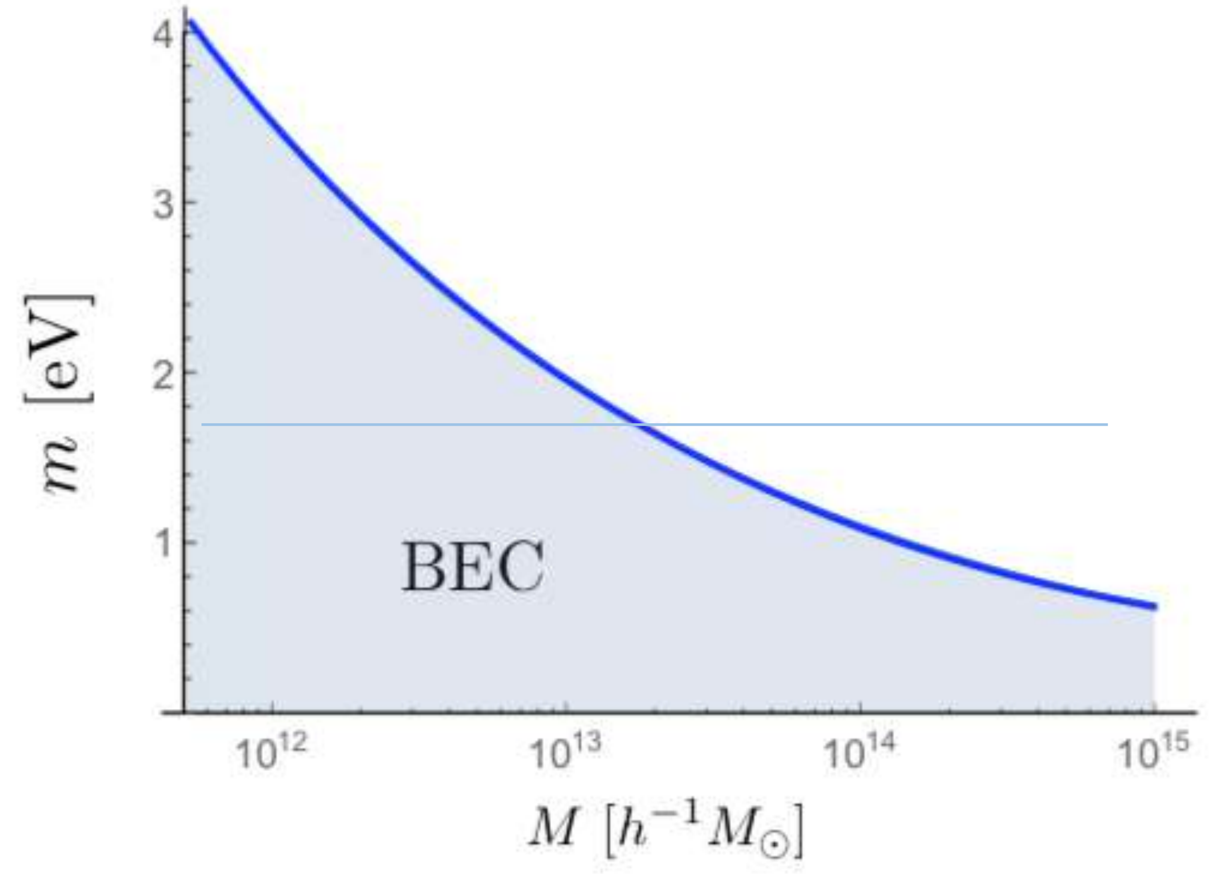
Condition for Superfluidity



DM has to condensate in galaxies:

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

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



- Thermalization

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

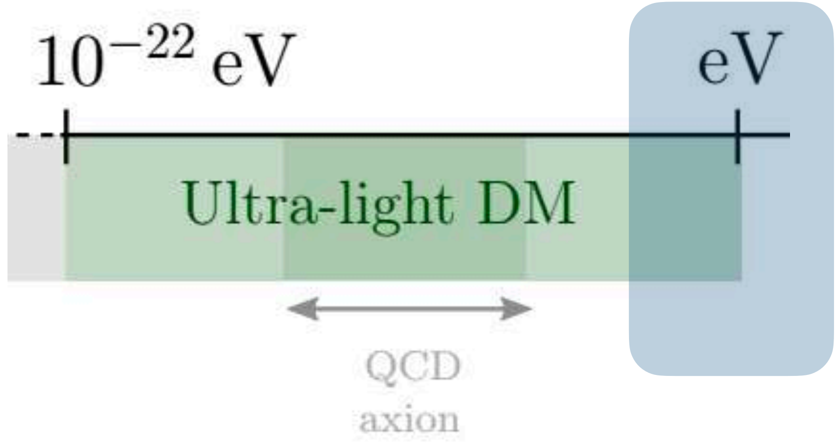
Cold atoms in the lab

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

Condition for superfluidity (Landau criteria):

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

Description of the Superfluid



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

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

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

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

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

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

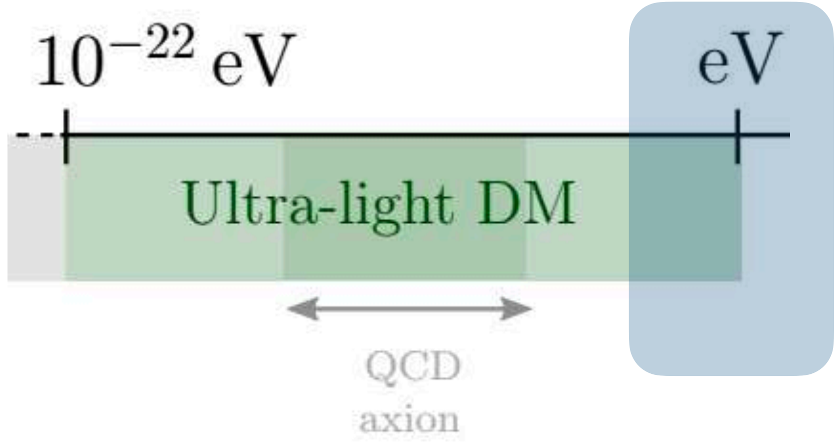
Current: $\dot{j}_0 = v^2\dot{\pi} = \text{const.} \Rightarrow \dot{\pi} = \mu$

The stationary solution determines the ground state of the system

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

$$\begin{cases} \mu^2 < m^2 & \text{Symmetry restoring phase} \\ \mu^2 > m^2 & \text{Bose Einstein condensation} \end{cases}$$

Description of the Superfluid



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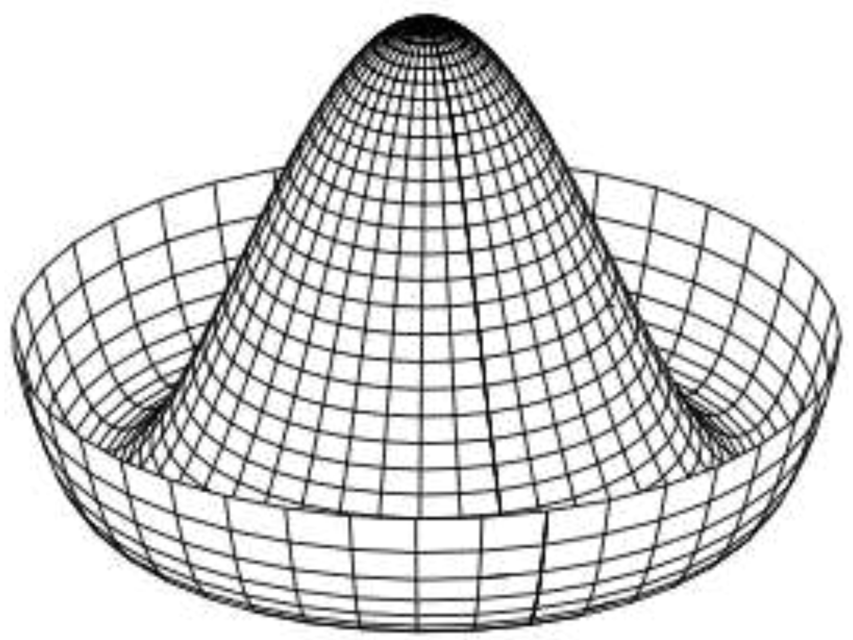
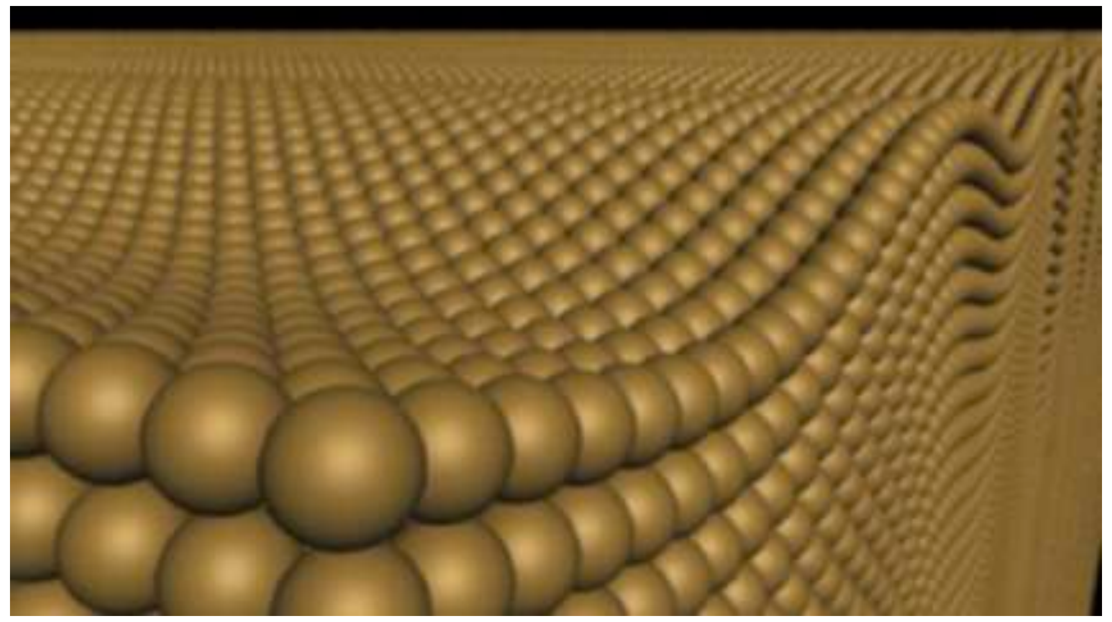


$$\Psi = \Psi_0 + \delta\Psi \quad \begin{cases} \text{Condensate:} & \Psi_0 = v\, e^{i\mu t} \\ \text{Excitations:} & \Psi = (v+\rho)e^{i\overbrace{(\mu t+\theta)}^{\Theta}} \end{cases}$$



Crystal Lens

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

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

* Recover the previous description in the non-relativistic regime

Description of the Superfluid

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

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

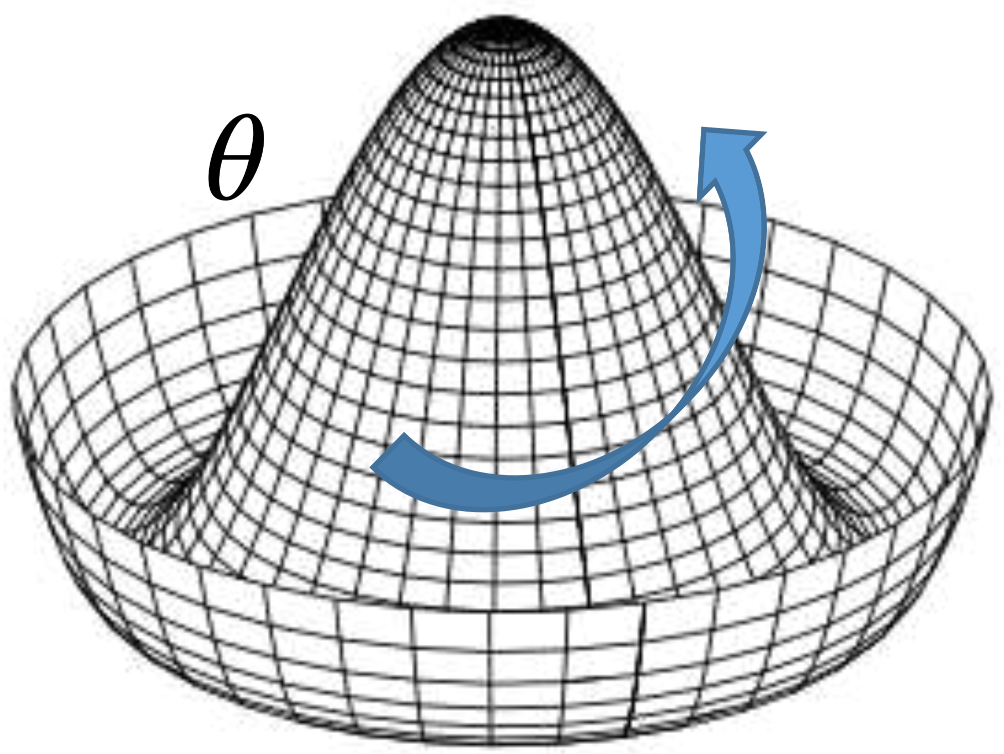
- Low energy DOF: Only massless Goldstone bosons excited θ

Shift symmetry $\theta \rightarrow \theta + c$

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

Chemical potential

Phonon excitations



$c = \mu t$

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

+ Galilean invariance

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

Gravitational potential

MOND from phonons

Lasha Berezhiani and Justin Khoury (2016)

This description represents different phenomena:

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

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

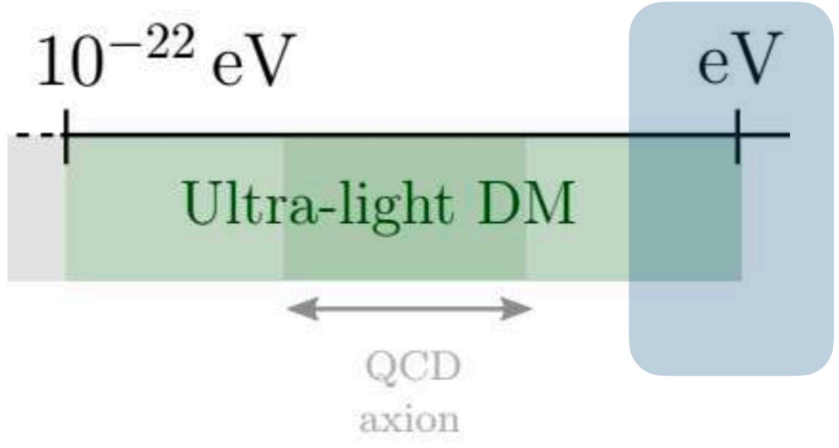
BEC

MOND

Unitary Fermi Gas

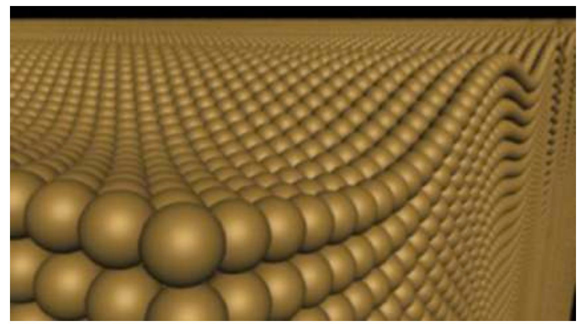
Superfluid Dark Matter

How to construct - MOND from phonons



Lasha Berezhiani and Justin Khoury (2016)

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


Crystal Lens

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

Low energy: only θ excited - phonon
Nambu Goldstone boson

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

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

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

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

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

To mediate the MONDian force, couple phonons to baryons:

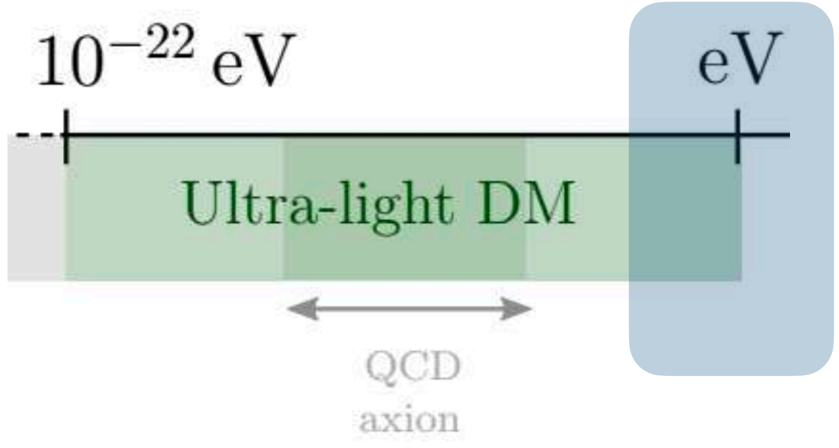
$$\mathcal{L}_{int} \sim \frac{\Lambda}{M_{pl}}\theta\rho_b$$

Softly breaks shift symmetry

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

Description of the Superfluid

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



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

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

+ Galilean invariance

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

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

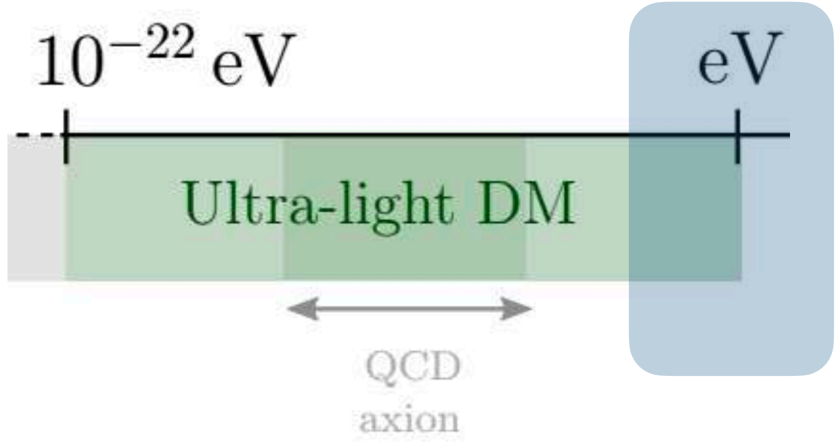
$n = 2:$	$P \sim \rho^2$	BEC
$n = 3/2:$	$P \sim \rho^3$	"MOND"
$n = 5/2:$	$P \sim \rho^{5/3}$	Unitary Fermi gas

Equivalence (low energies)

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

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

Superfluid Dark Matter



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

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

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

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

Only DM

Mostly DM

"MOND"

No MOND

Higher order correction

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

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

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

Strong coupling scale, the scale suppressing higher order terms:

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

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

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

Higher order corr. → neglected when

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

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

Fiducial parameters (galaxies):

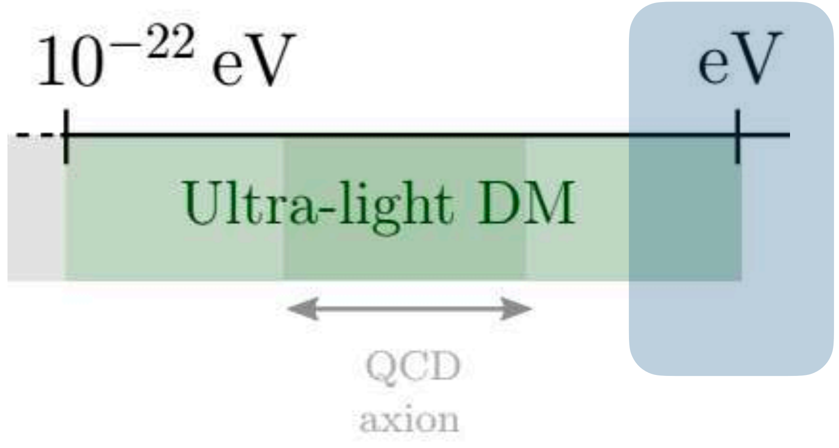
$$\Lambda_s \sim \mathrm{meV}$$

HO corr. neglected ↓

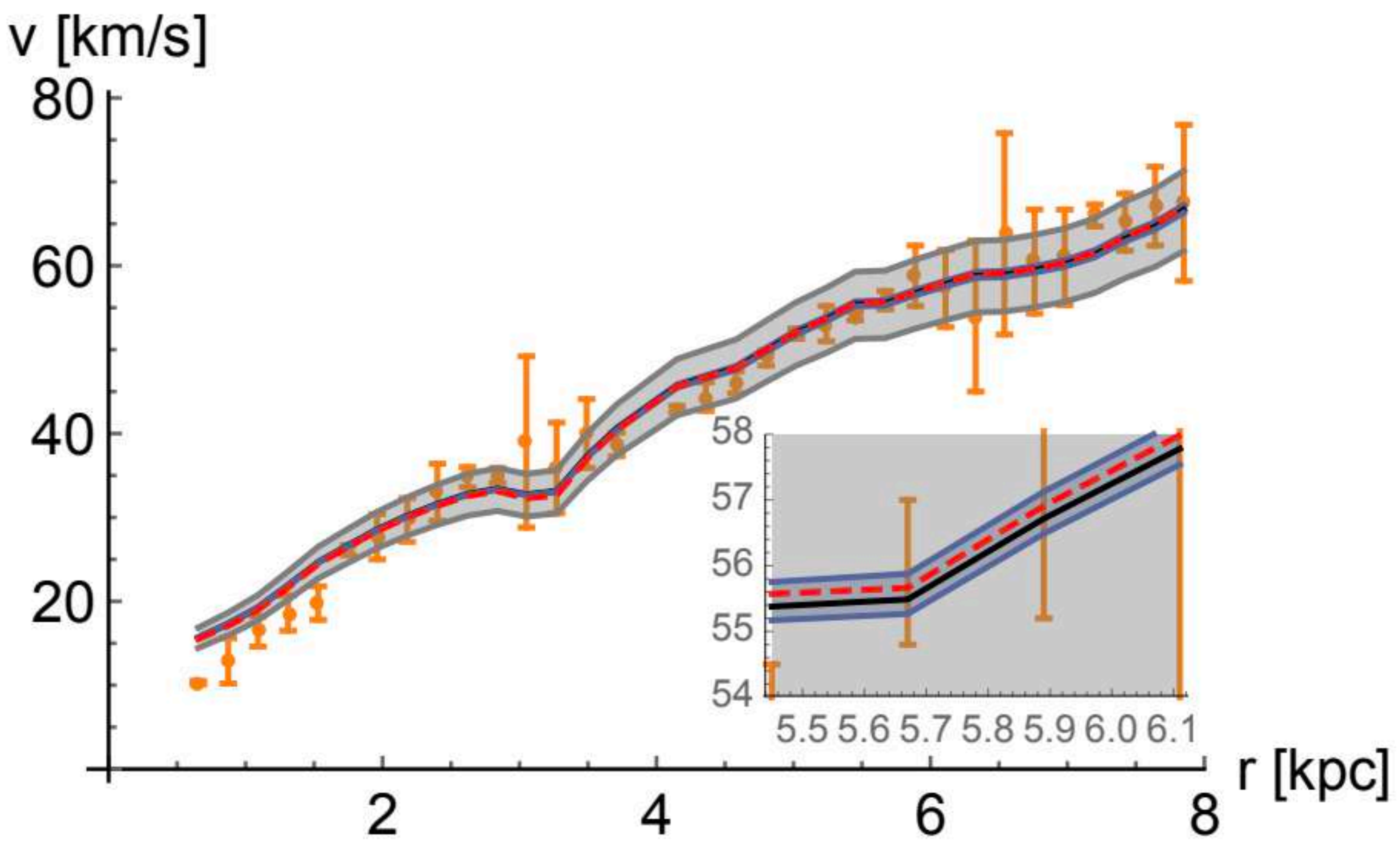
$$r \gg 0.2\mathrm{mm}$$

Superfluid Dark Matter

Rotation curves



Low surface brightness

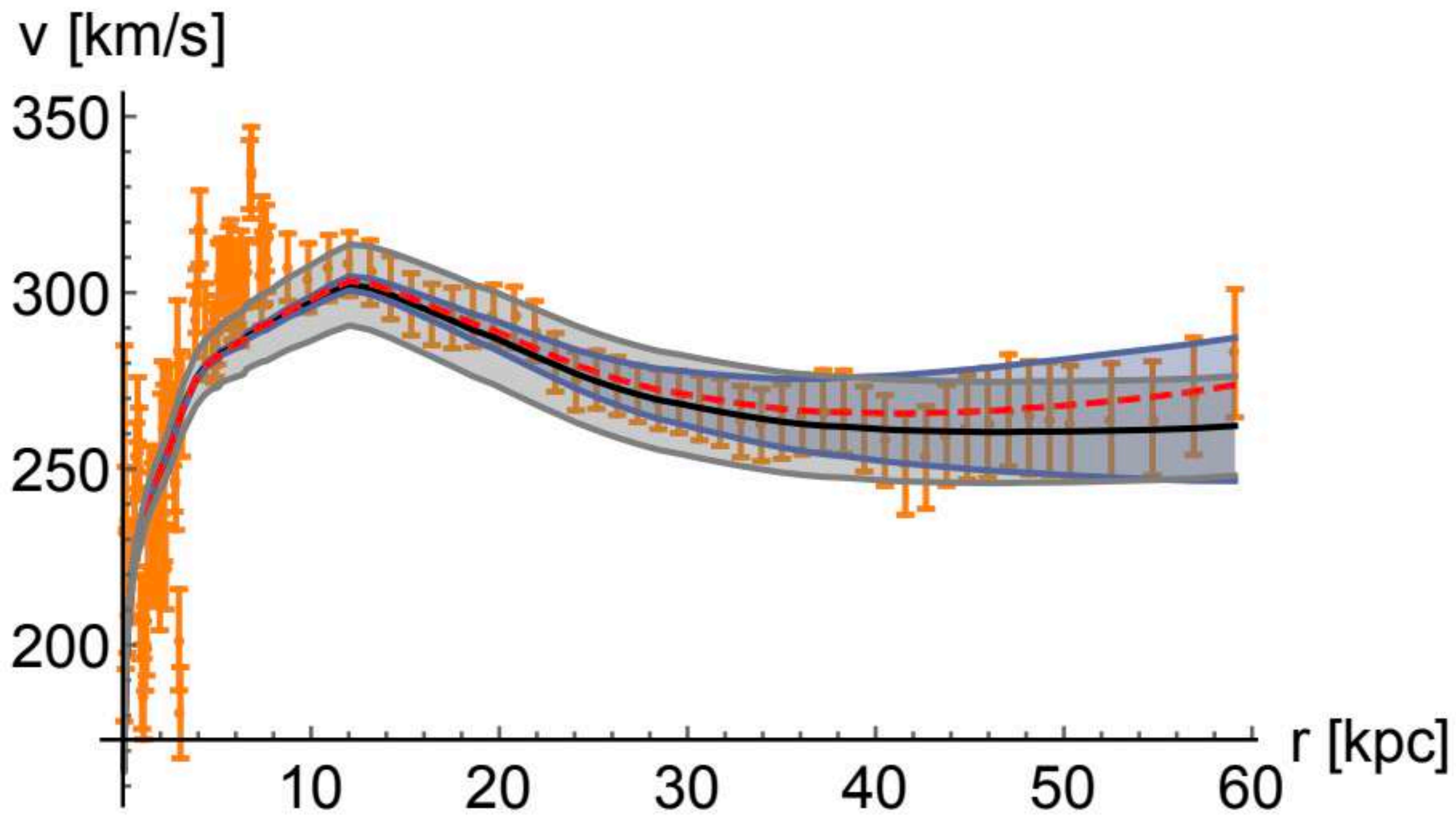


Superfluid core:

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

58% of the total mass of the halo

High surface brightness



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

25% of the total mass of the halo

Superfluid Dark Matter

Observational consequences

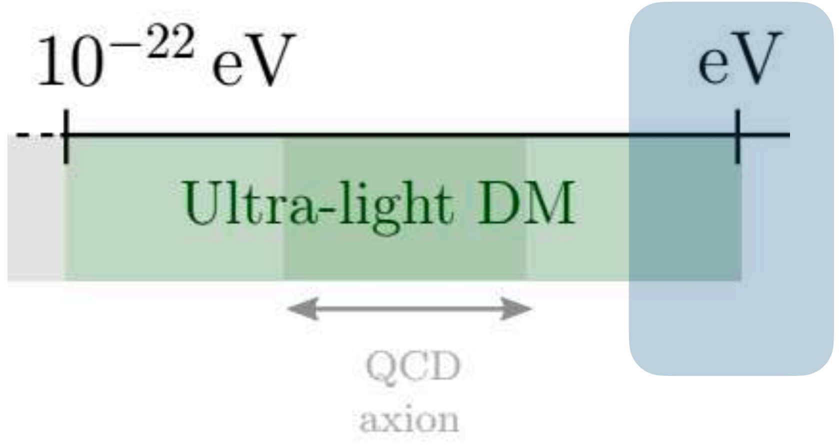


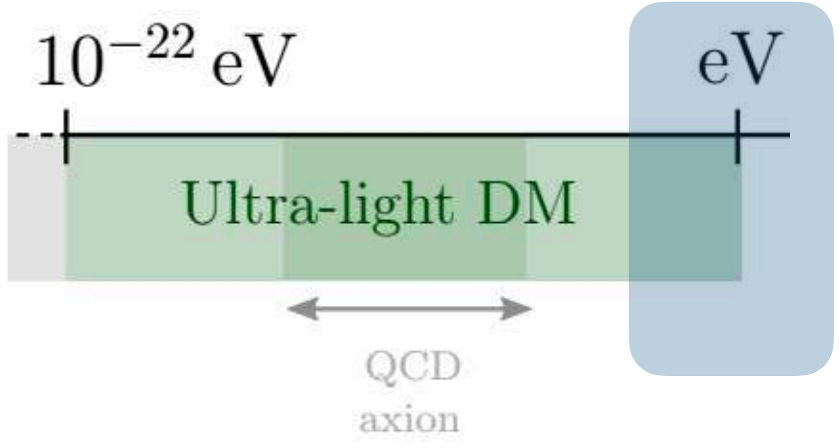
Table 2: Summary of observational consequences of superfluid DM from [124].

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

Berezhiani et al. 2018)

Superfluid Dark Matter

Dynamical Friction

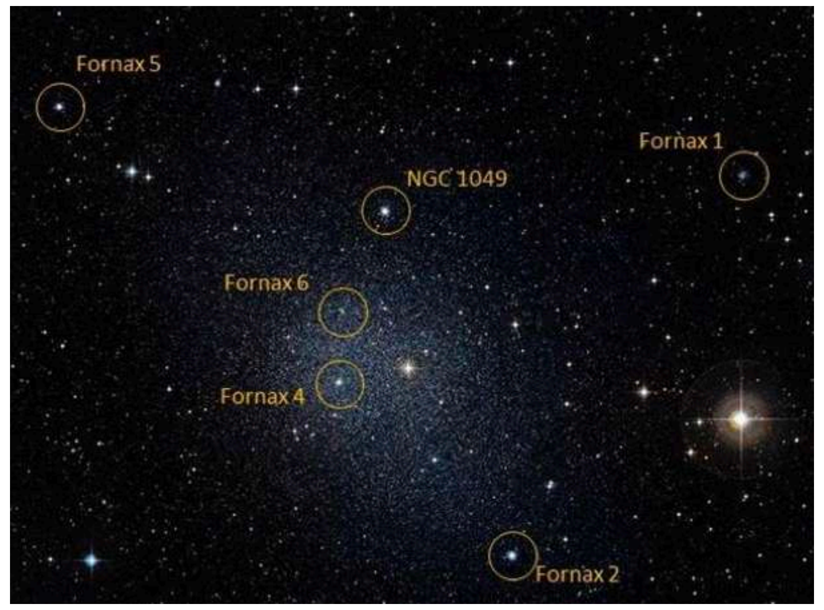


Inner region of galaxy:
Superfluid core

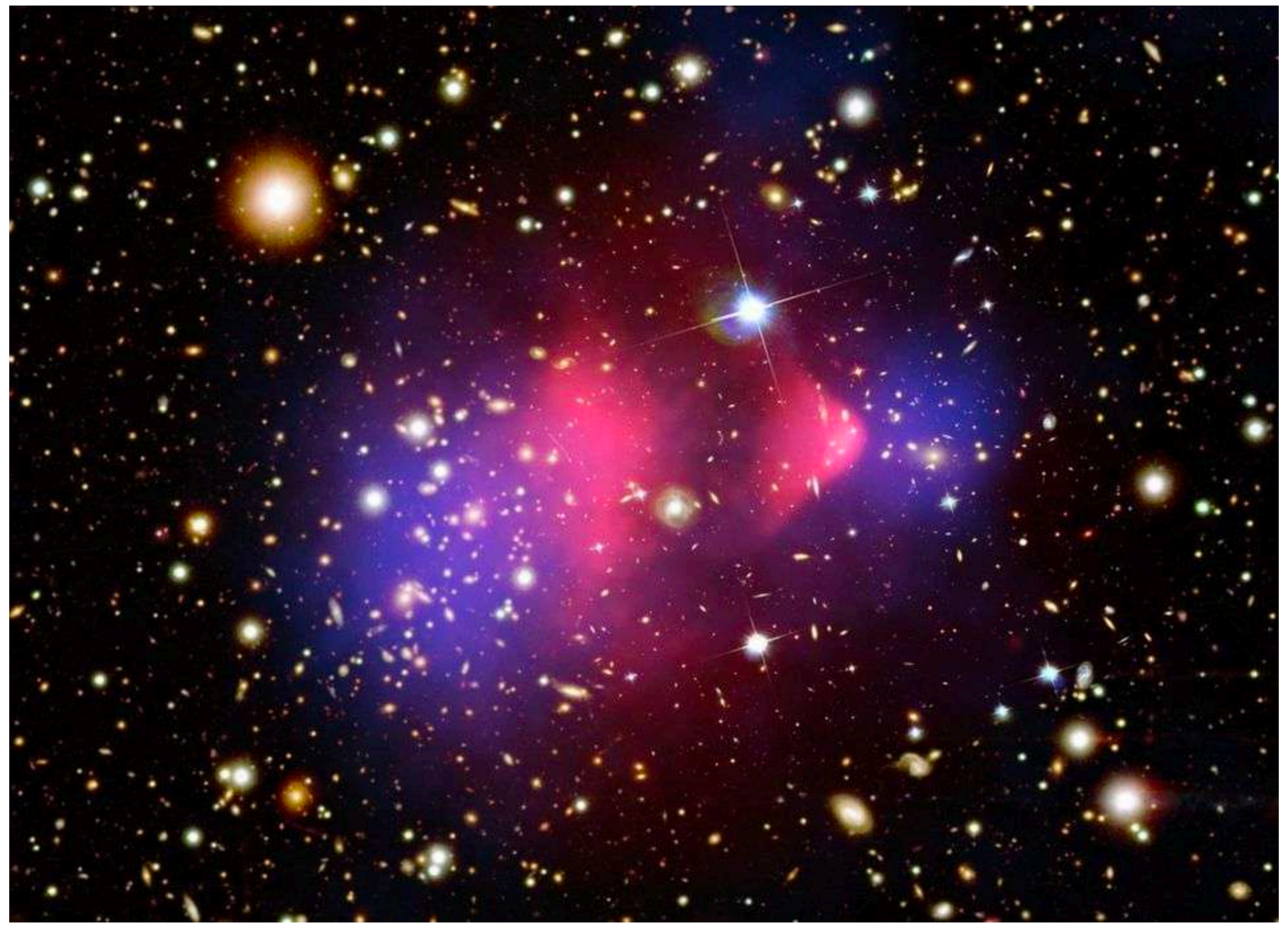
Superfluid flows without friction

BUT: what about the Bullet Cluster?

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



ESO/Digitized Sky Survey 2



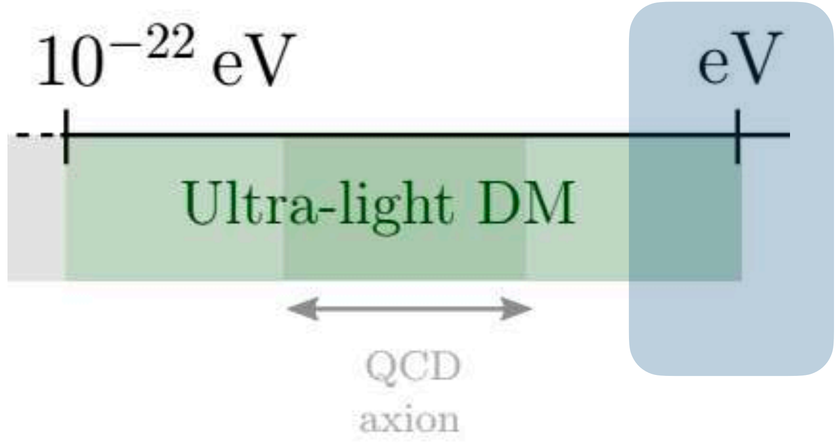
Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al. Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.;

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

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

Landa criteria for superfluid
$v < v_c$

Superfluid Dark Matter



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

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

$\Longrightarrow$ need a microscopic description

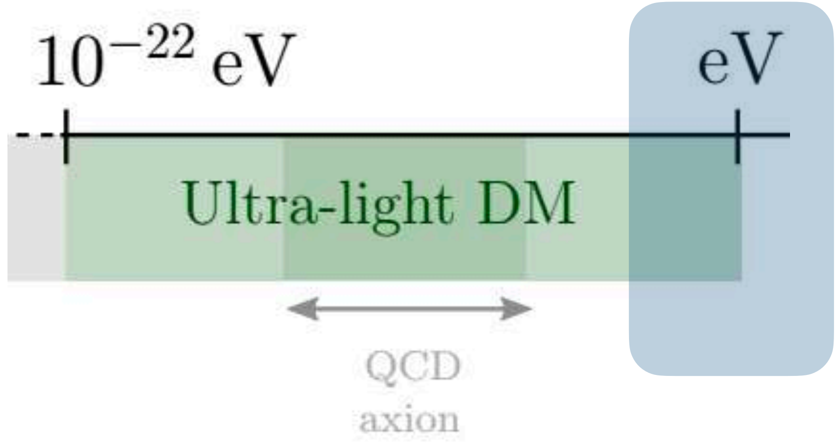
- Does not present many constraints yet.

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

Presents opportunities of theoretical and observational advances!

Superfluid Dark Matter

Vertical dynamics



High Energy Physics – Phenomenology

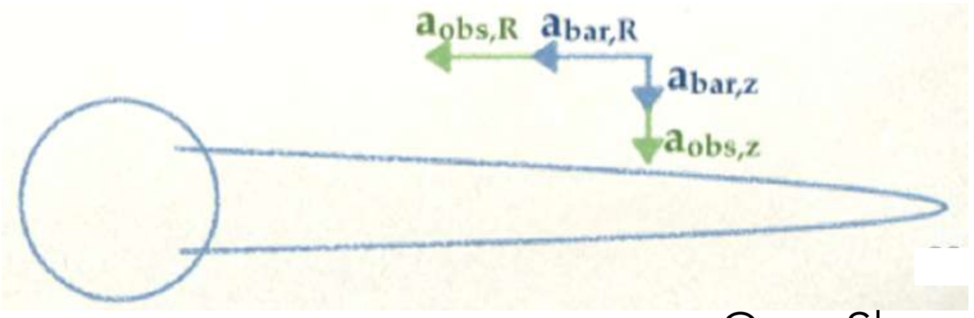
The Inconsistency of Superfluid Dark Matter with Milky Way Dynamics

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

(Submitted on 27 Nov 2019)

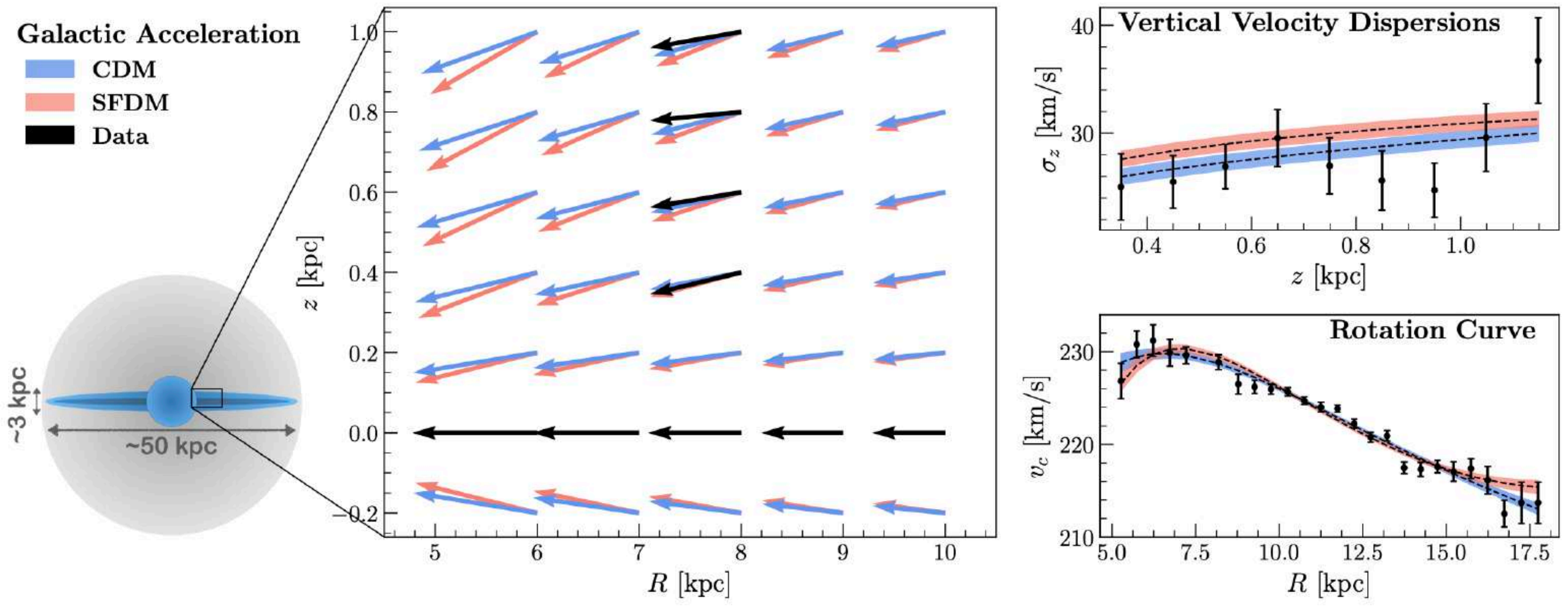
There are many well-known correlations between dark matter and baryons that exist on galactic scales. These correlations can essentially be encompassed by a simple scaling relation between observed and baryonic accelerations, historically known as the Mass Discrepancy Acceleration Relation (MDAR). The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

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



Oren Slone

MOND-like force amplifies:
a_R not enough
a_z too much



Ultra-light fields as Dark Energy

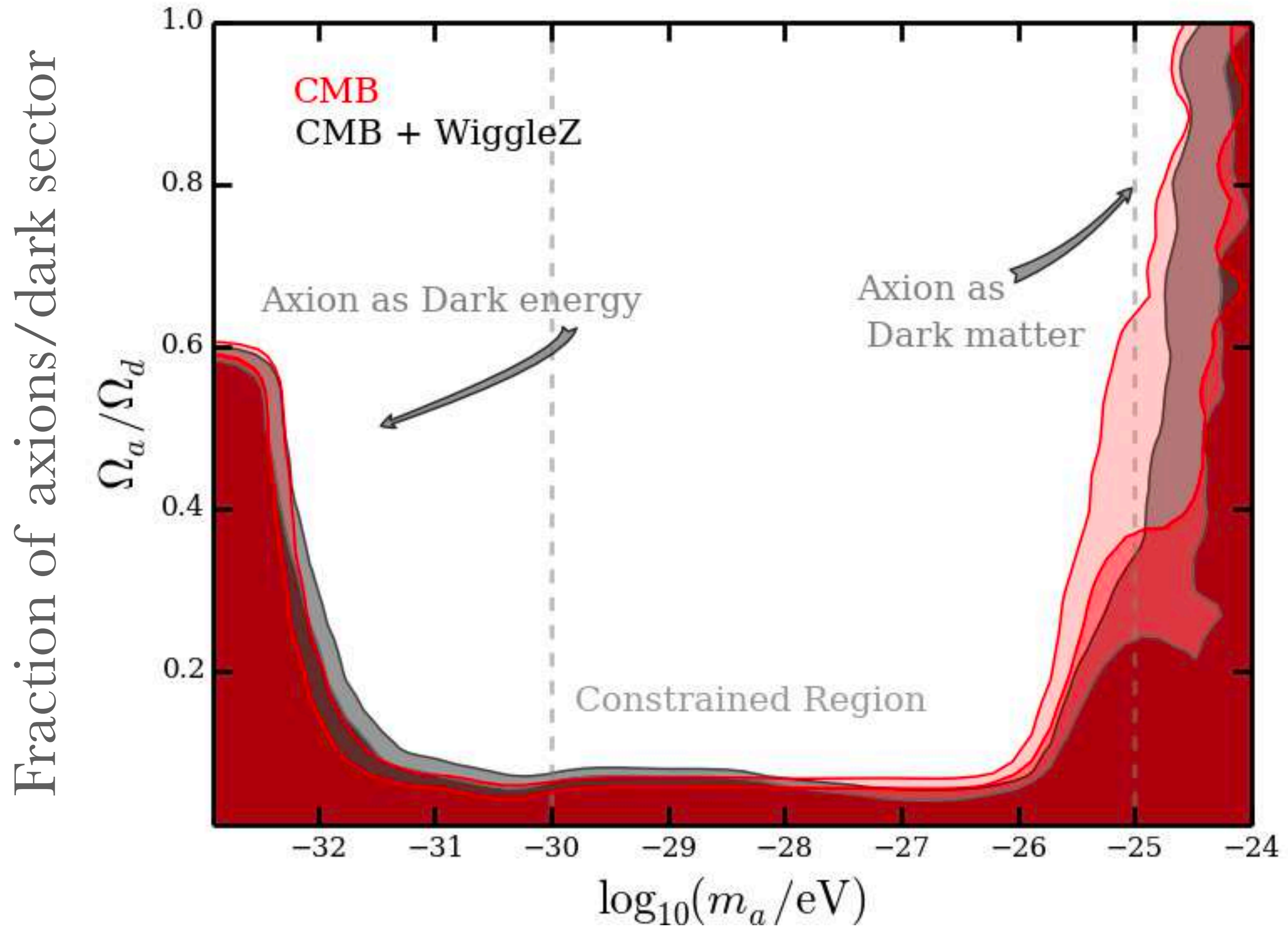
Ultra-light fields as Dark Energy

Fuzzy Dark Matter

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

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

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



Ultra-light fields as Dark Energy



Unified superfluid dark sector

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

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

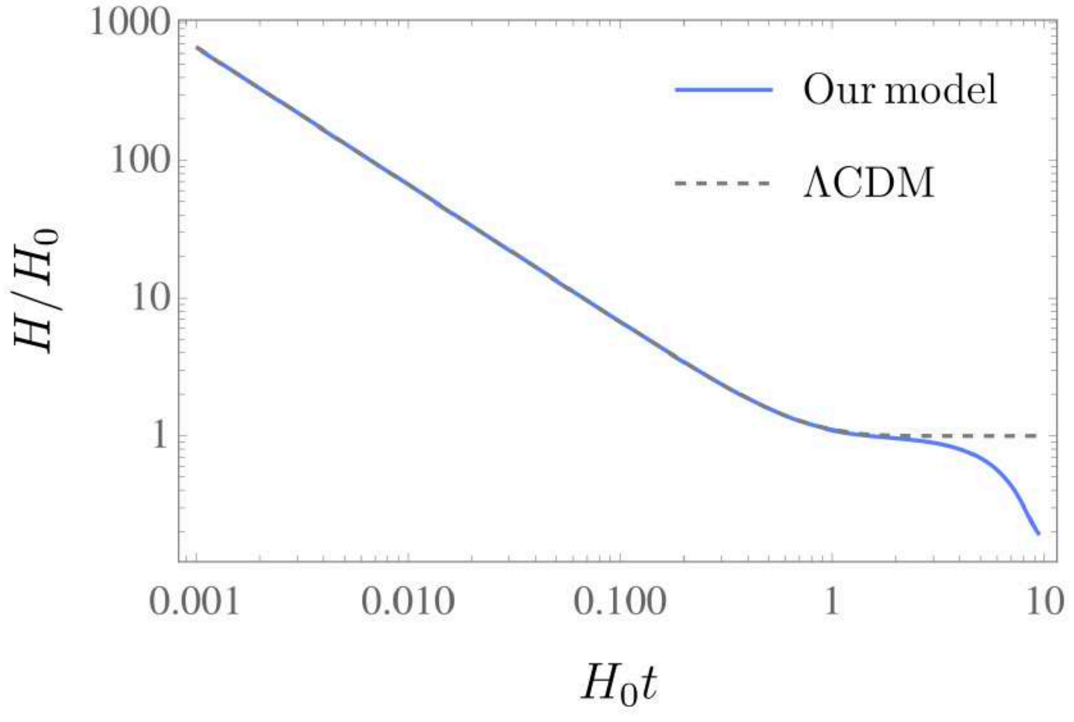
  $\longrightarrow$ Potential for the $(\theta_1 - \theta_2)$
- Prediction for clustering

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

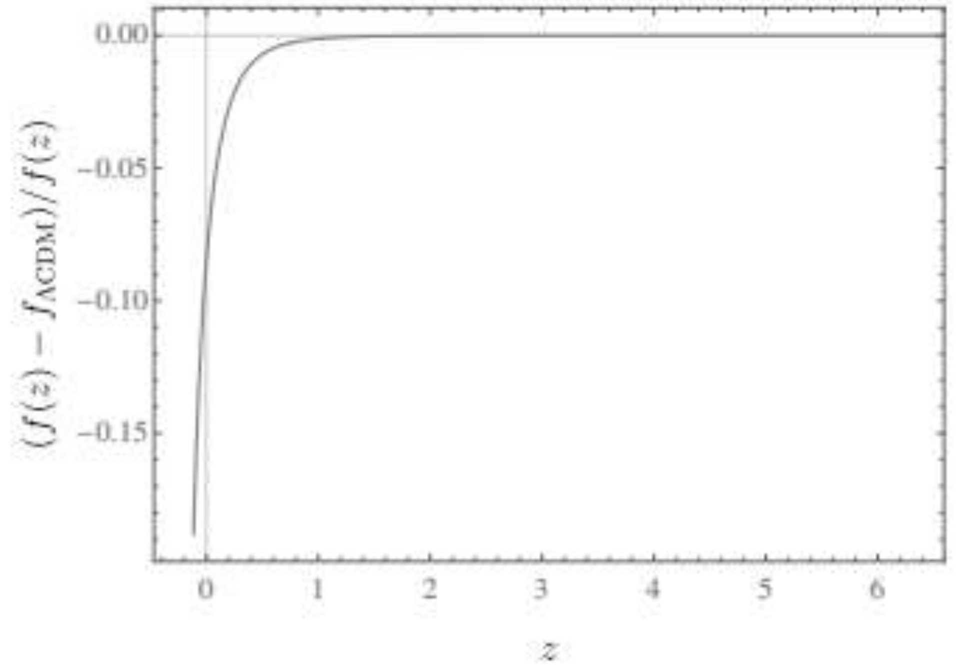
Unified framework
w/ DM alone!

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

Background evolution

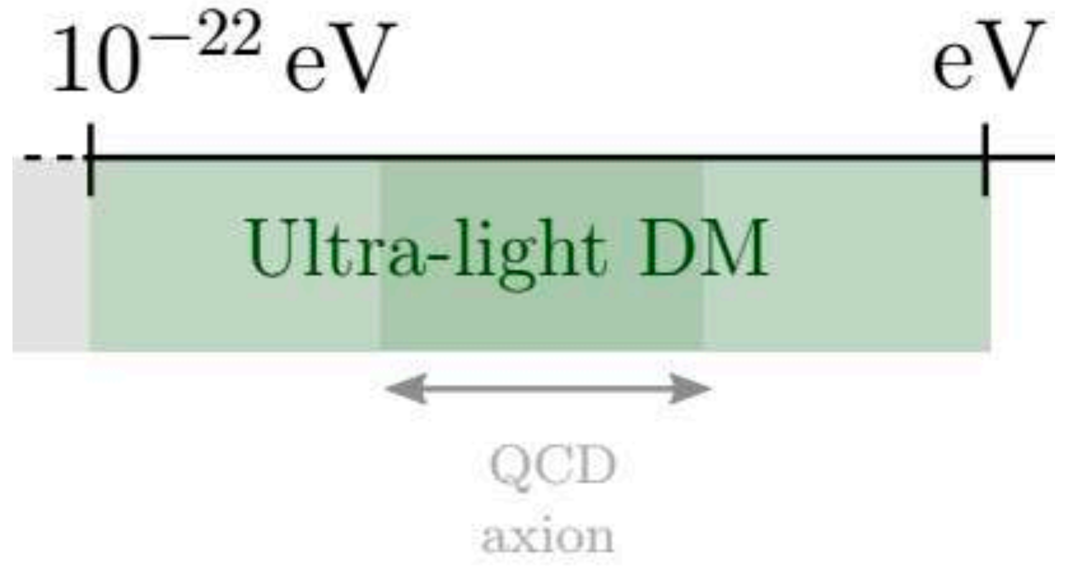


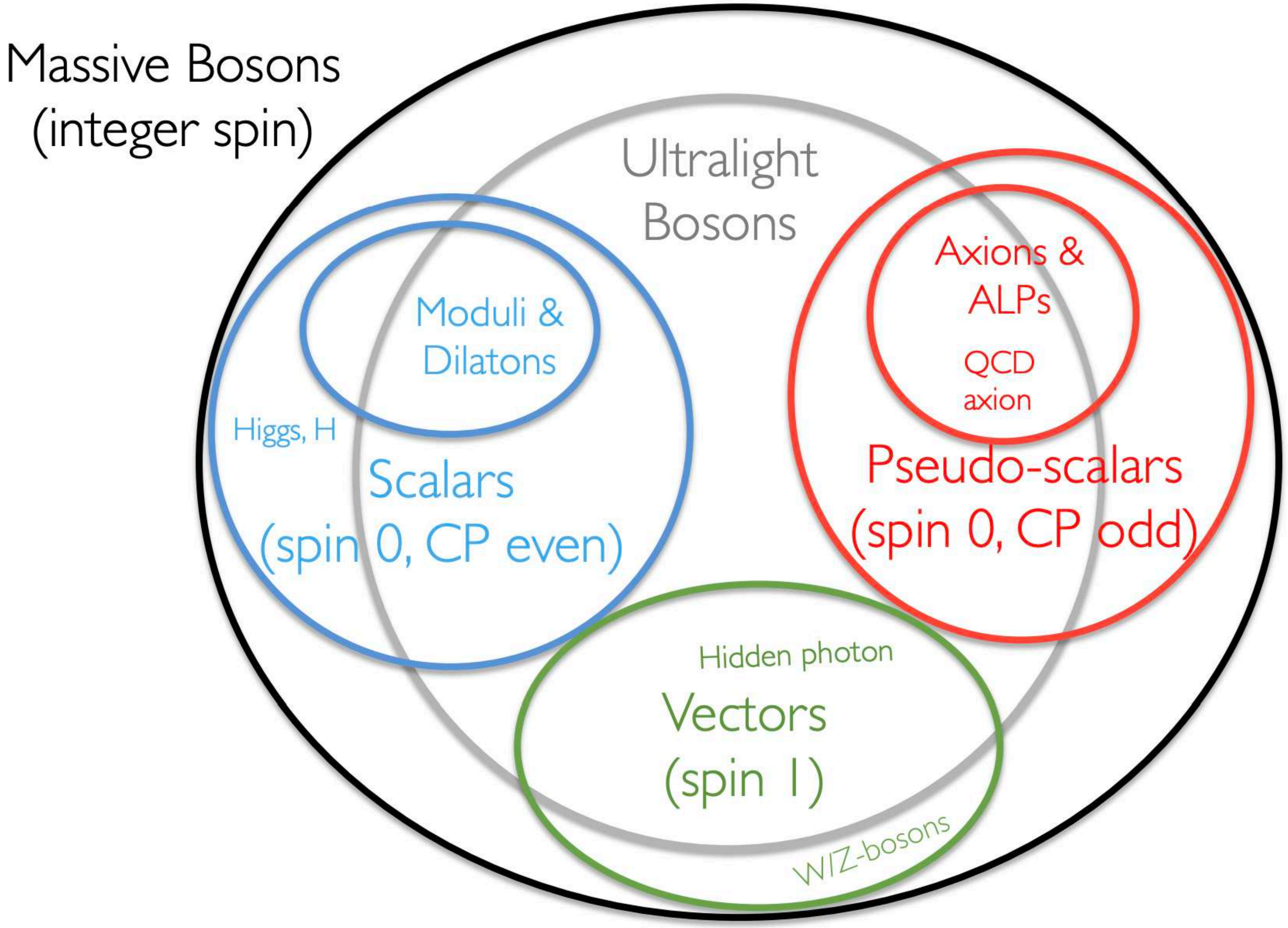
Clustering:
growth factor



ULDM candidates

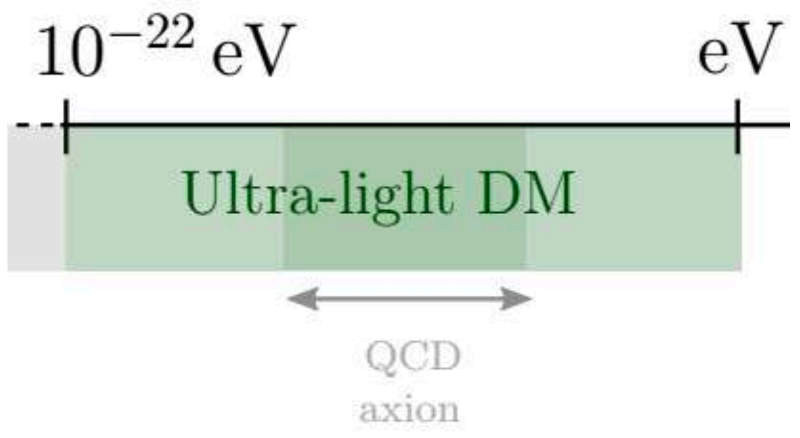
Many extensions of the Standard Model predict additional massive bosons

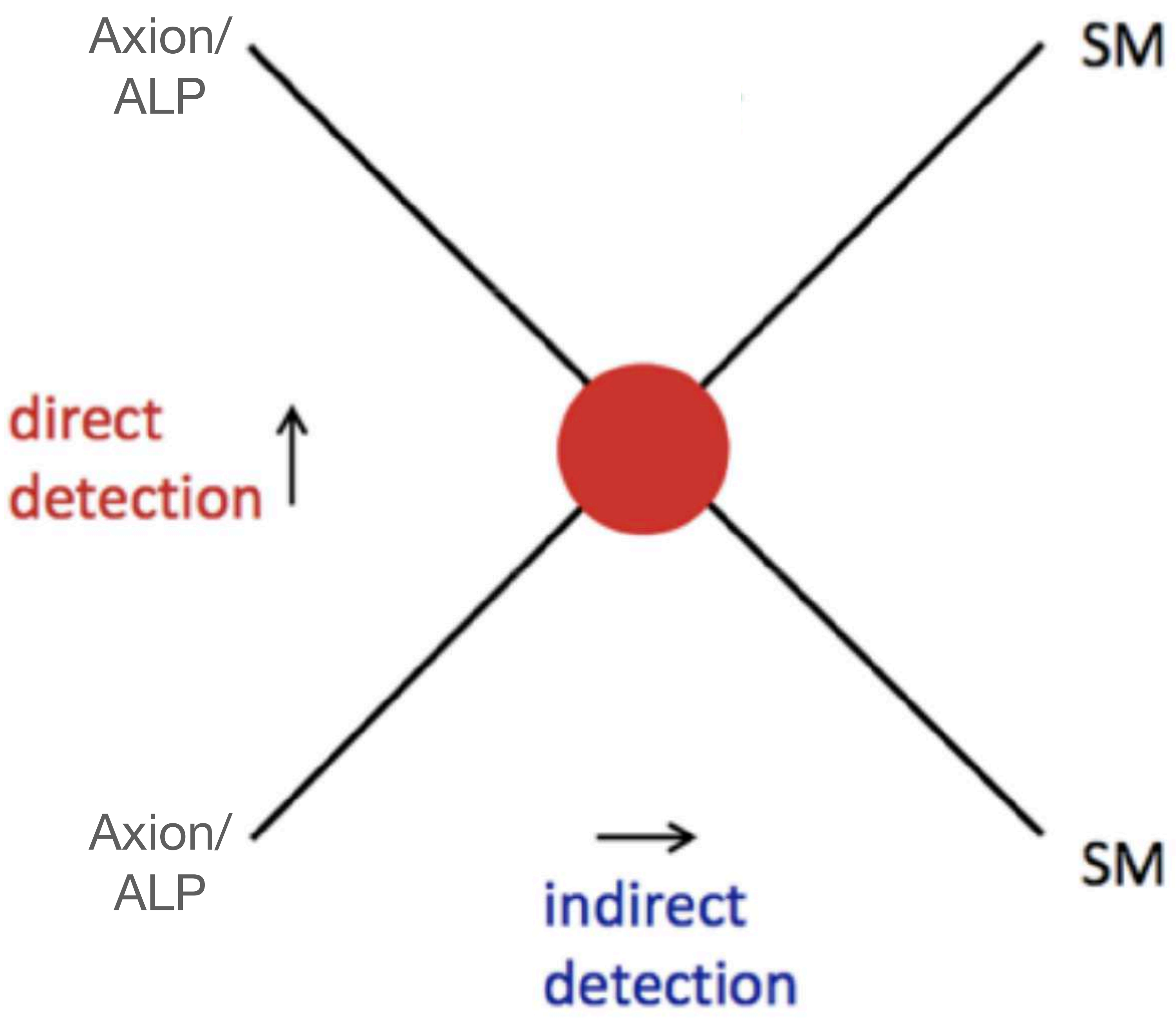




Ref.: Chadha-Day et al 2022

How to search for ULDM?



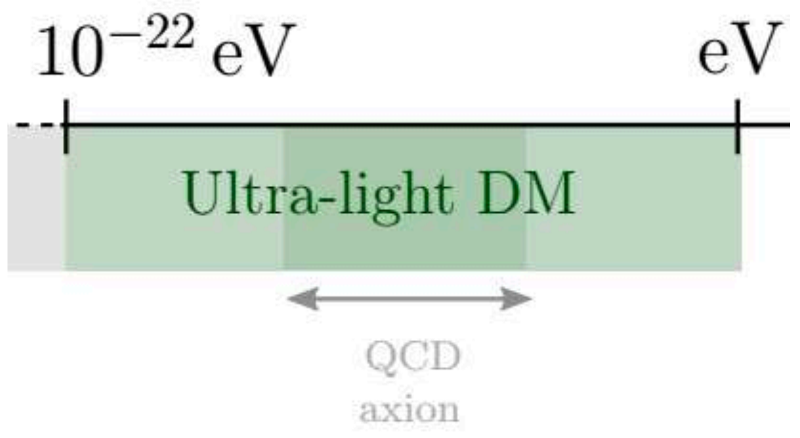


+

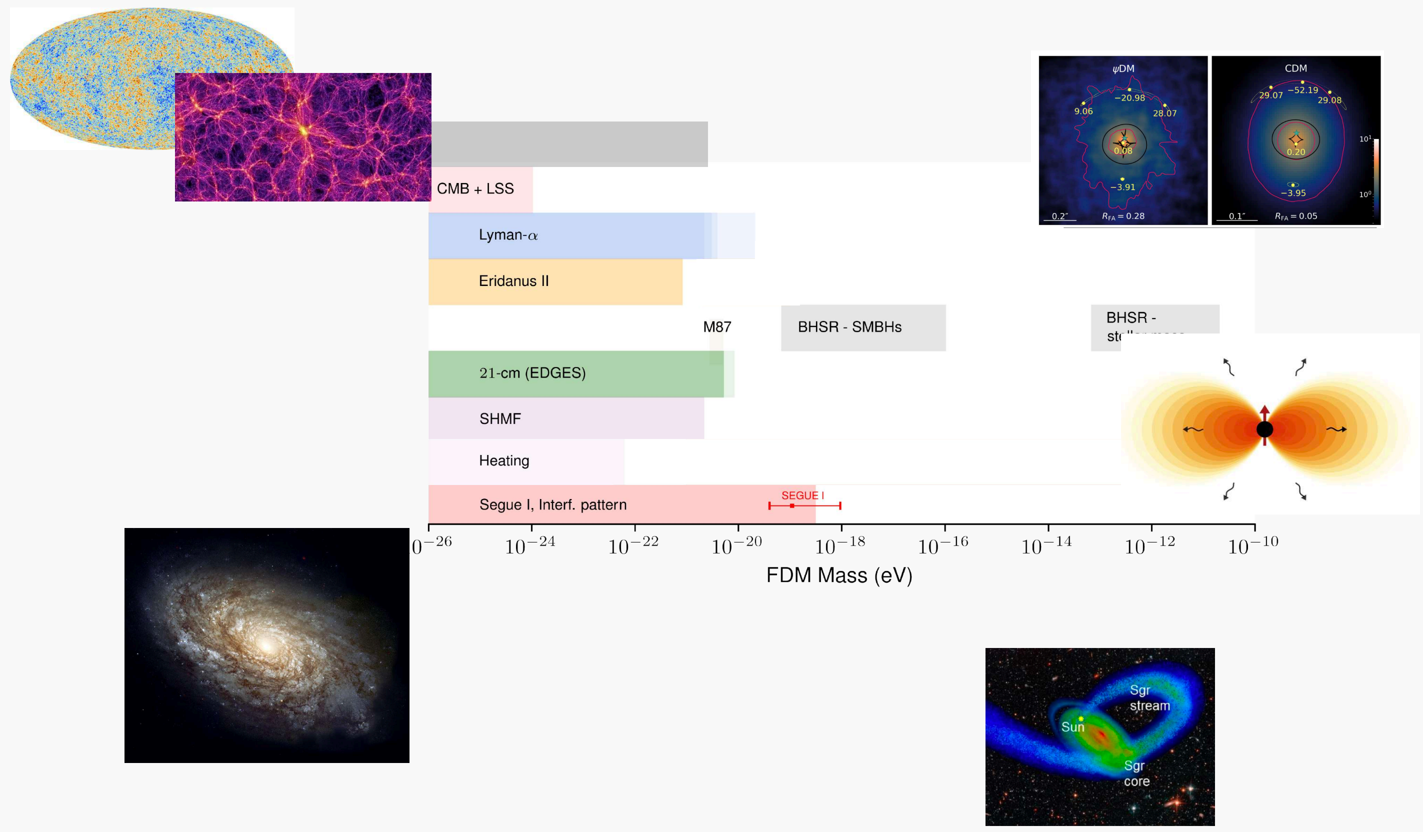
Gravitationally

Cosmological and astrophysical searches

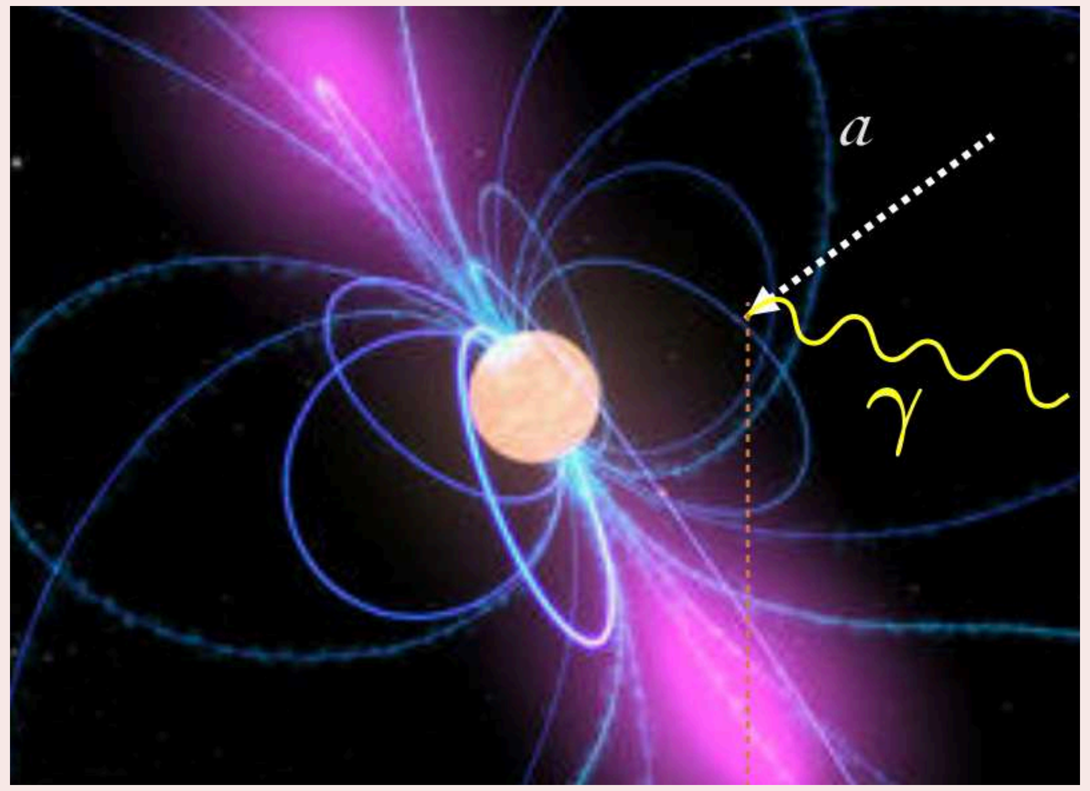
How to search for axions/ALPs?



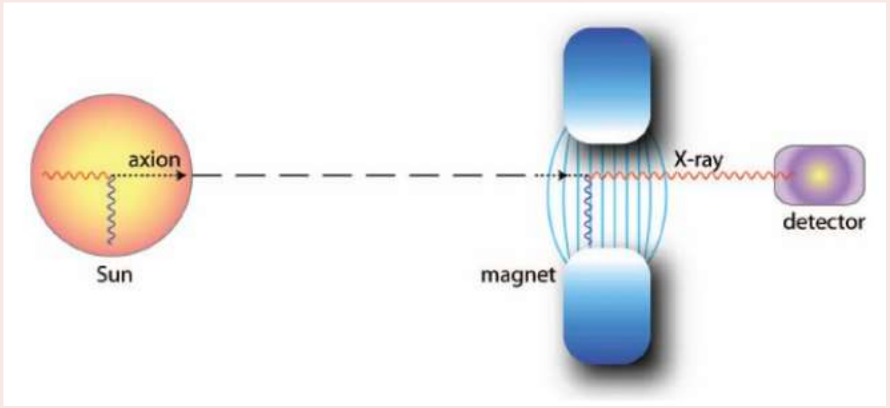
Cosmological and astrophysical searches

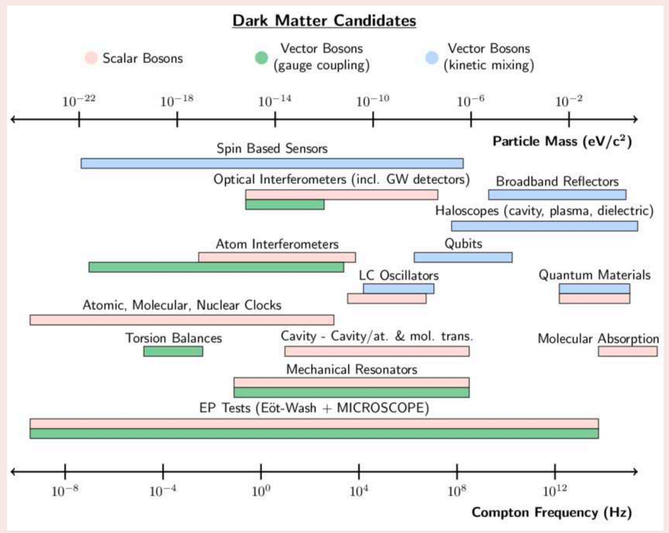


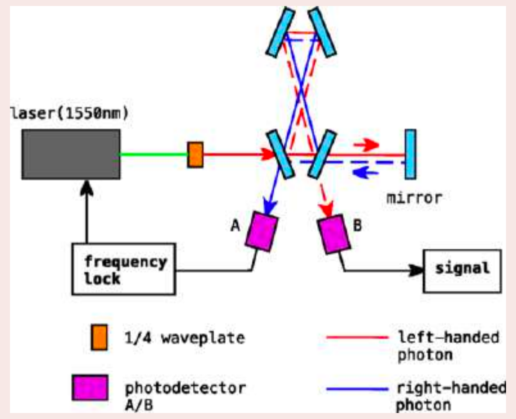
Indirect detection



"Direct detection" Axion/ALPs experiments

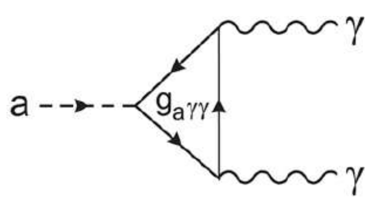


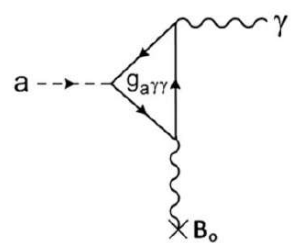


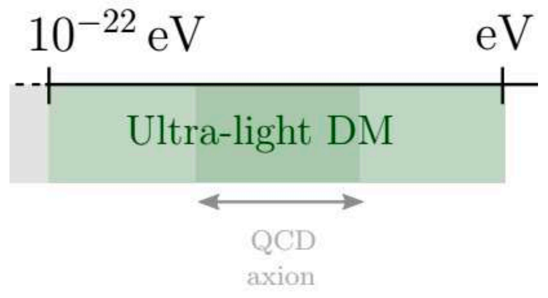


Gravitational

Interactions with the SM

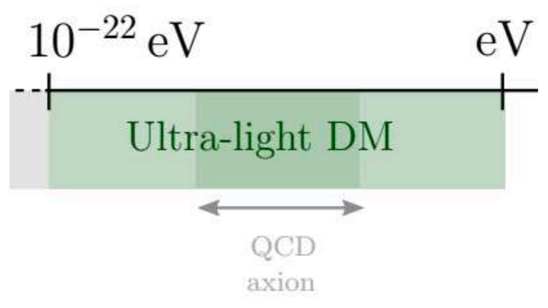






Axion and ALPs interaction with the SM

Axion and ALPs interaction with the SM



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

Axions and ALPs interact with the standard model particles

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

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

Not considering here

+ a few model-dependent assumptions

Axion and ALPs interaction with the SM

Axions and ALPs interact with the standard model particles

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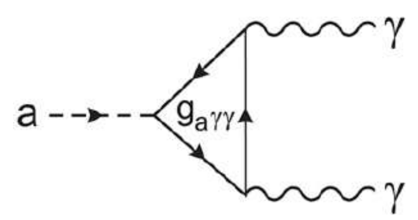
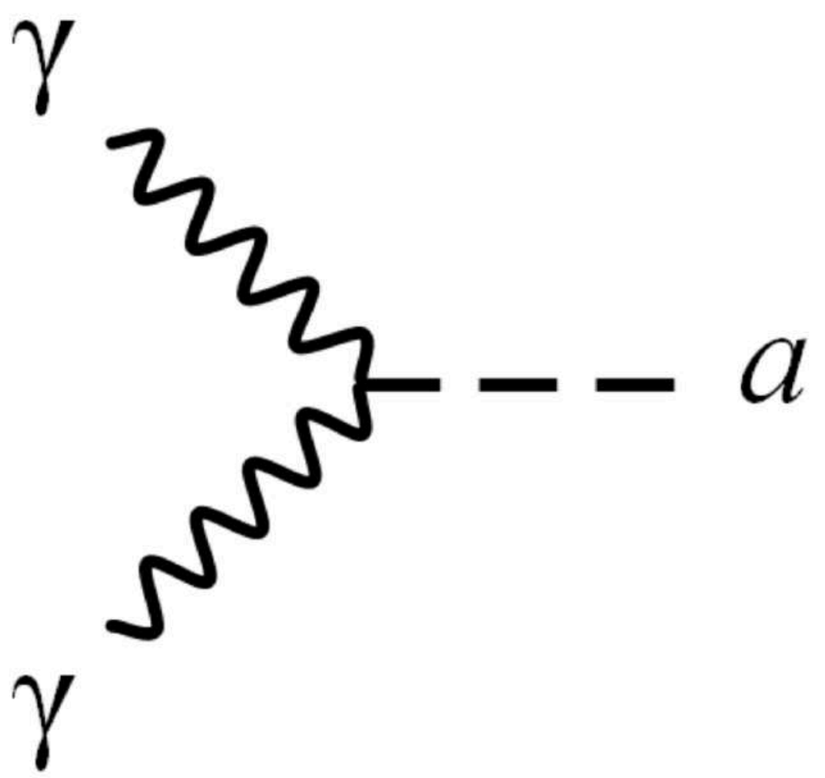
$$\mathbf{B} = \nabla \times \mathbf{A}$$

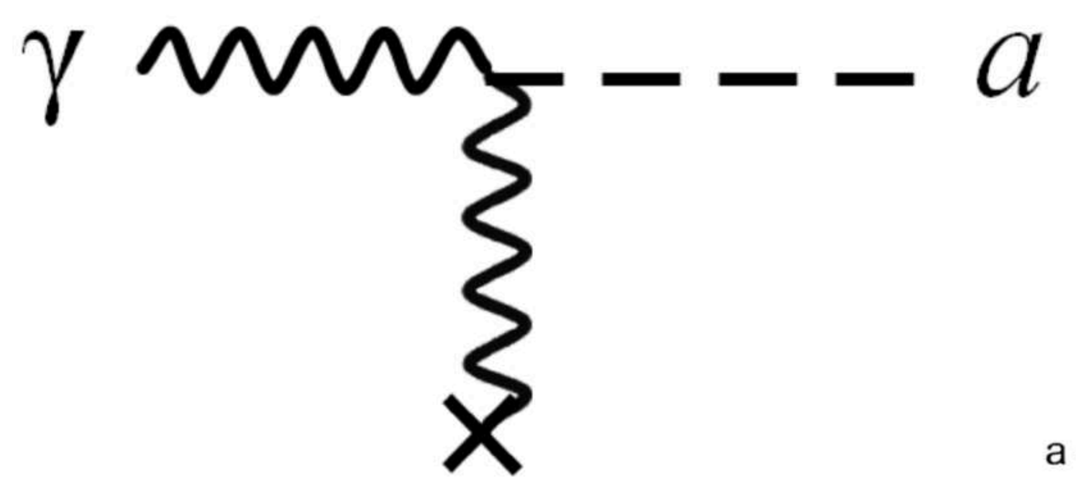
Photon - Axion electrodynamics

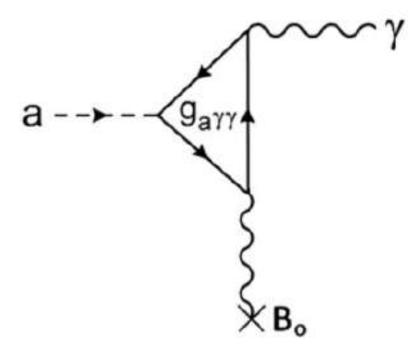
$$\mathcal{L}_{ALP} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}_{\mu\nu} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 + g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}\, a$$





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





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

Other diagrams…

Axion and ALPs interaction with the SM

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$
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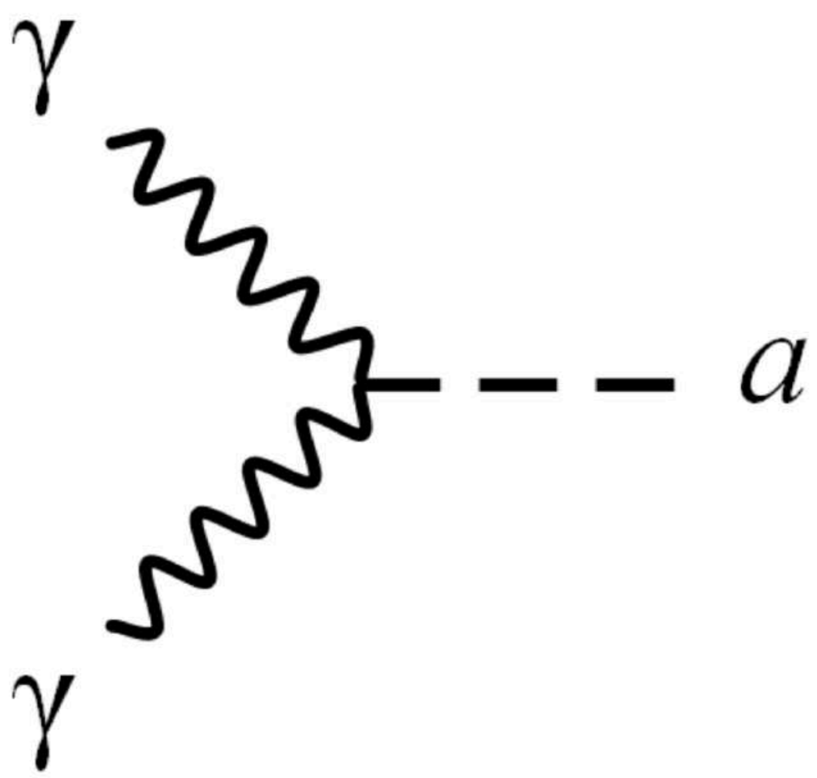

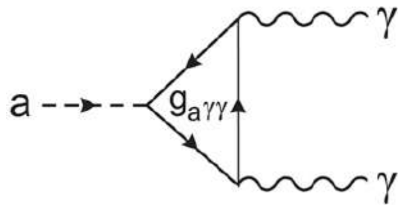

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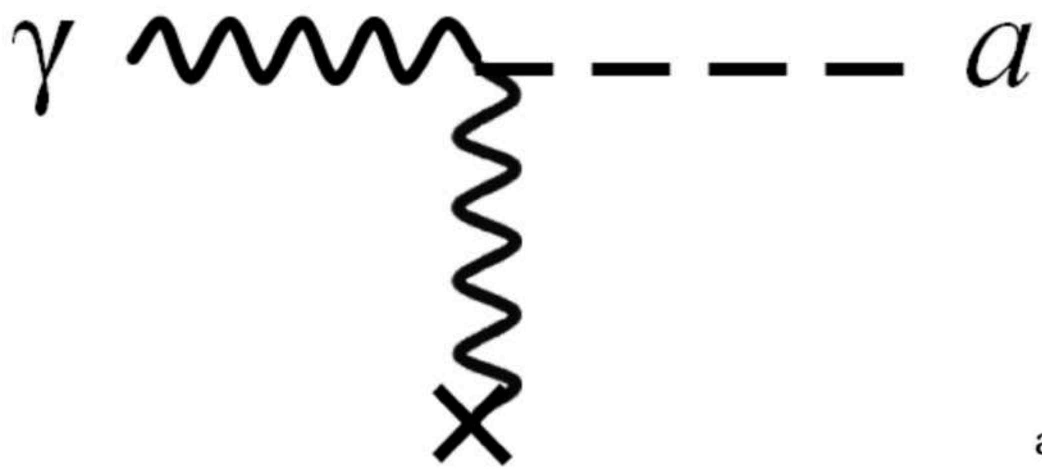

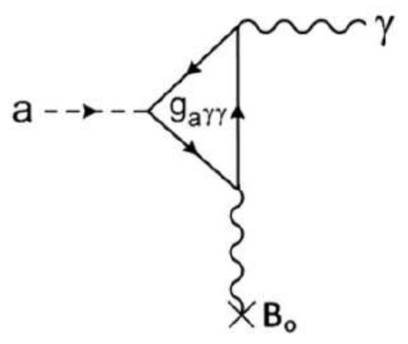

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Axions and ALPs interact with the standard model particles

Axion electrodynamics

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

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

$$\partial_\mu F^{\mu\nu} = J^\nu \underbrace{- g_{a\gamma}\widetilde{F}_{\mu\nu}\partial_\mu a}$$

$$J_a^\mu = g_{a\gamma}(-\mathbf{B}\cdot\nabla a,\ -\mathbf{E}\times\nabla a + \partial_t a\mathbf{B})$$

Maxwell's equations:

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

Extended Maxwell's equations:

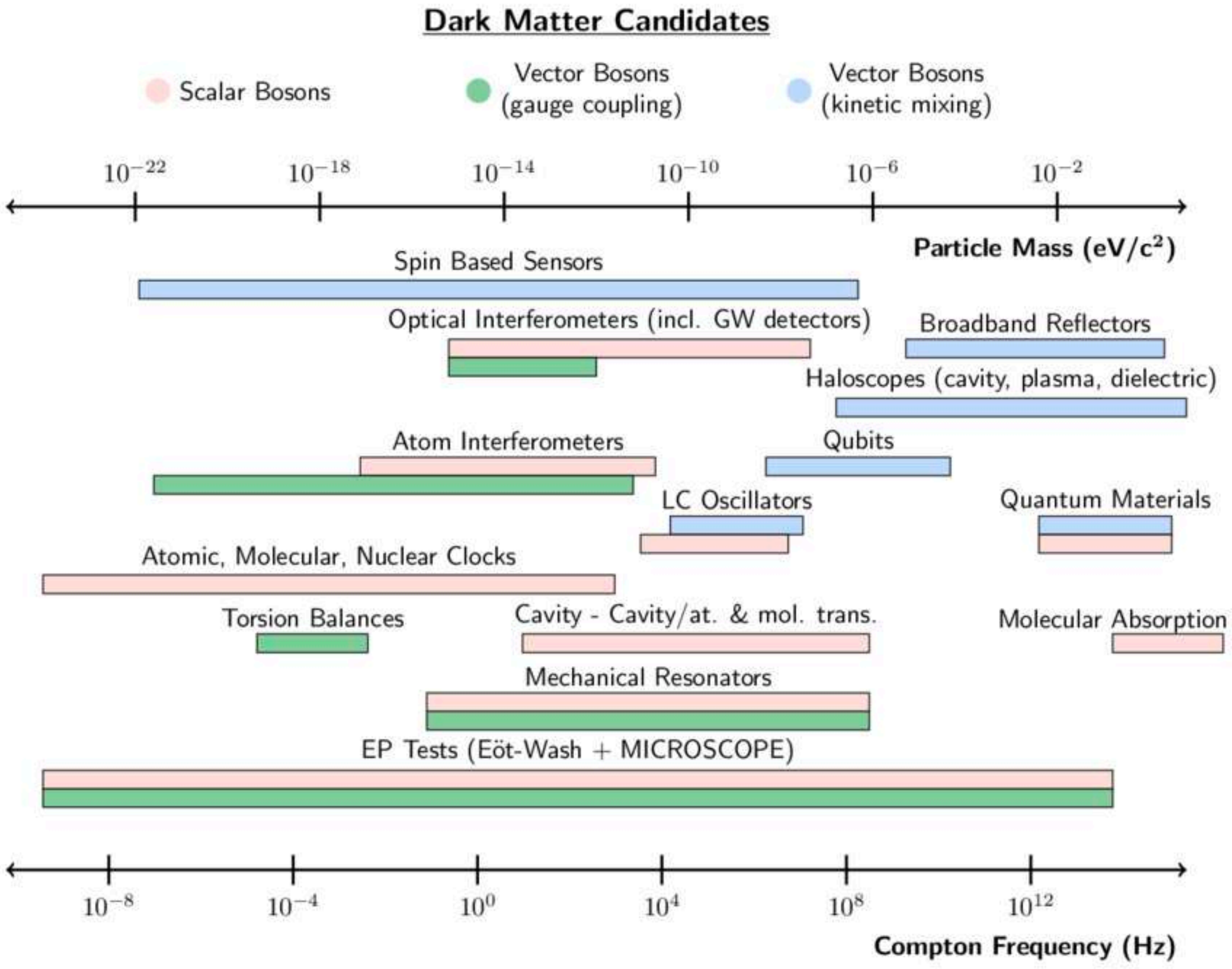
$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma}\,\mathbf{B}\cdot\nabla a$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} - g_{a\gamma}\left(\mathbf{E}\times\nabla a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

Adapted from: Cyaran O'Hare

Axion and ALPs interaction with the SM

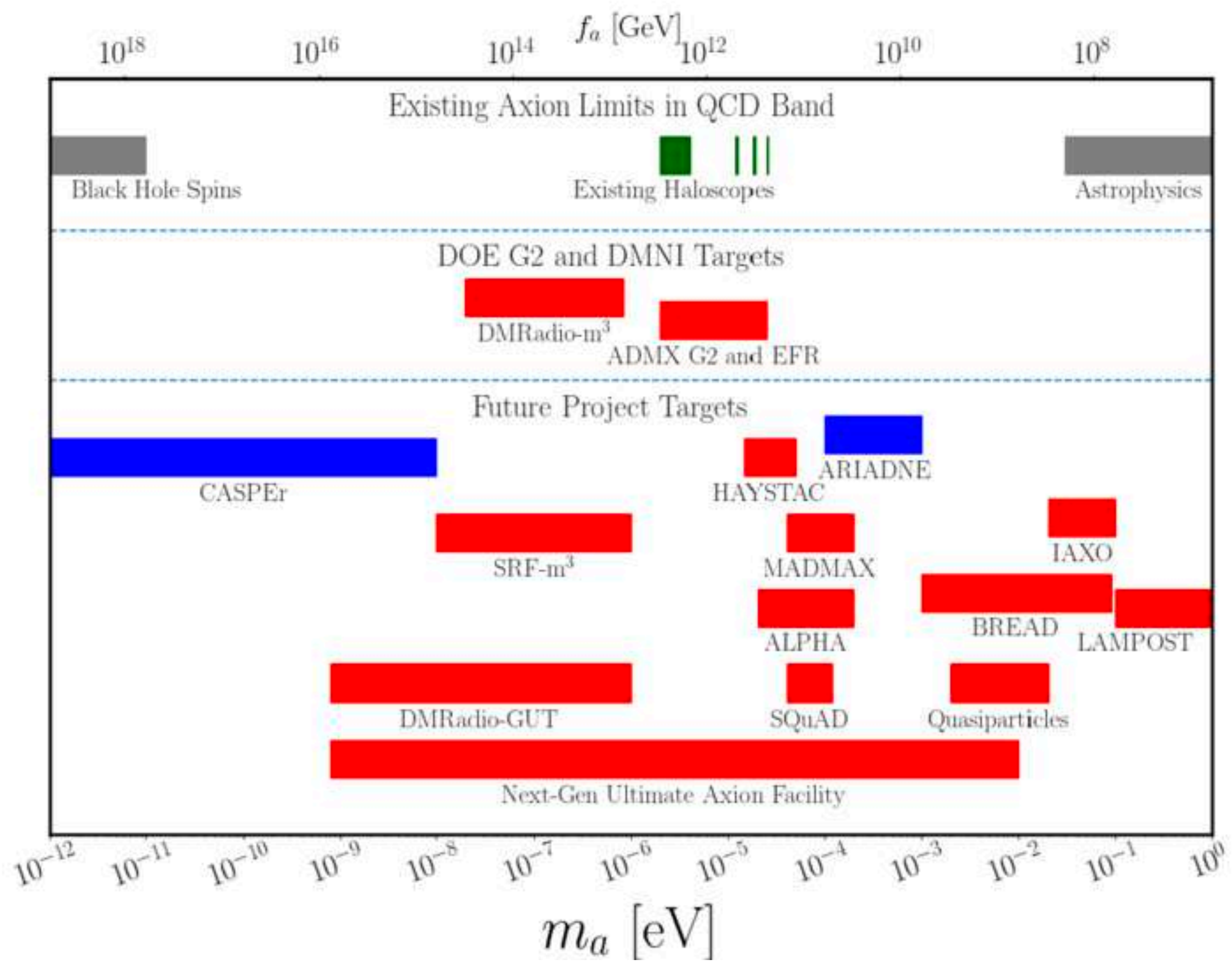
"Direct Detection": axion/ALPs experiments

Overview of experimental techniques and the mass ranges they target

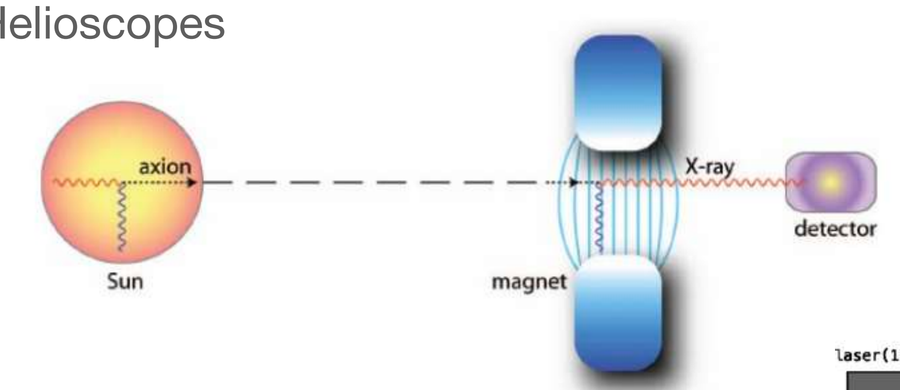


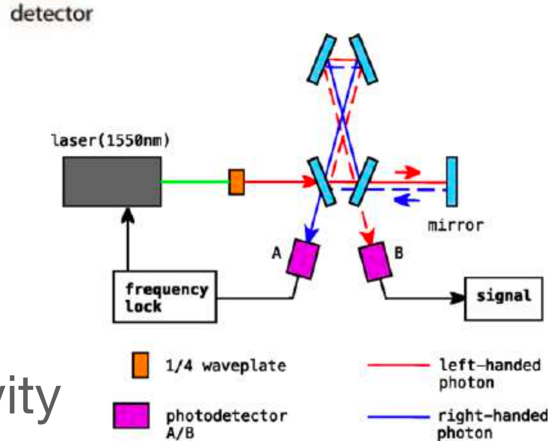
Ref. Jaeckel et al 2021

Experiments

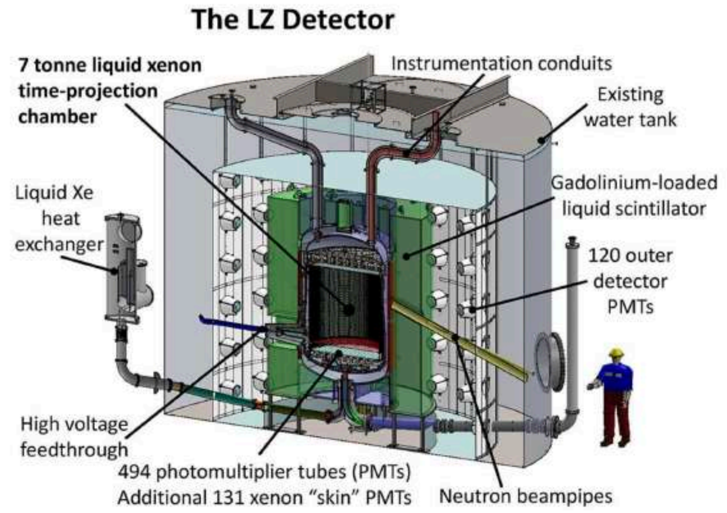


Helioscopes





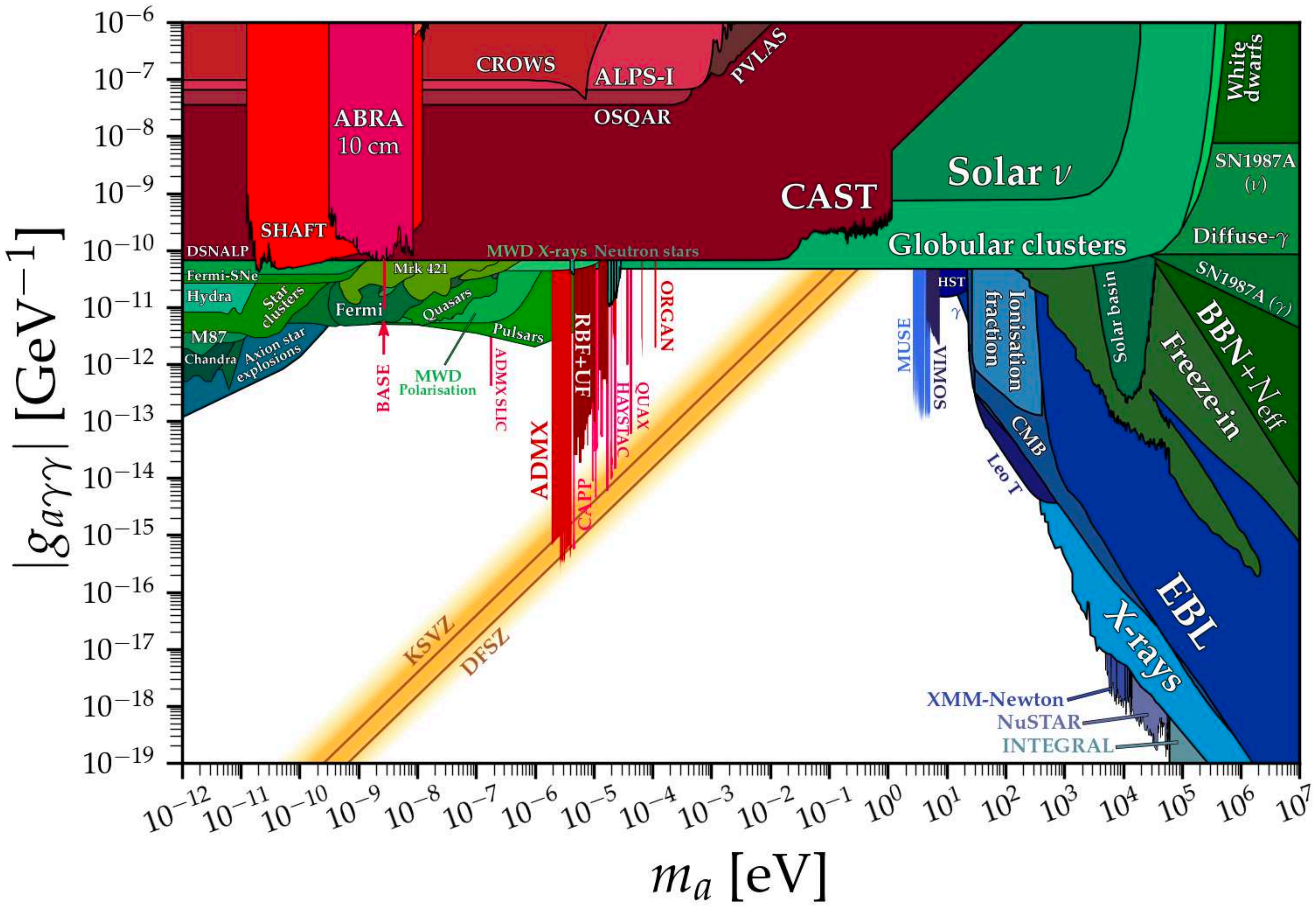
Optical cavity



Axion and ALPs interaction with the SM

Bounds on Axion-photon coupling

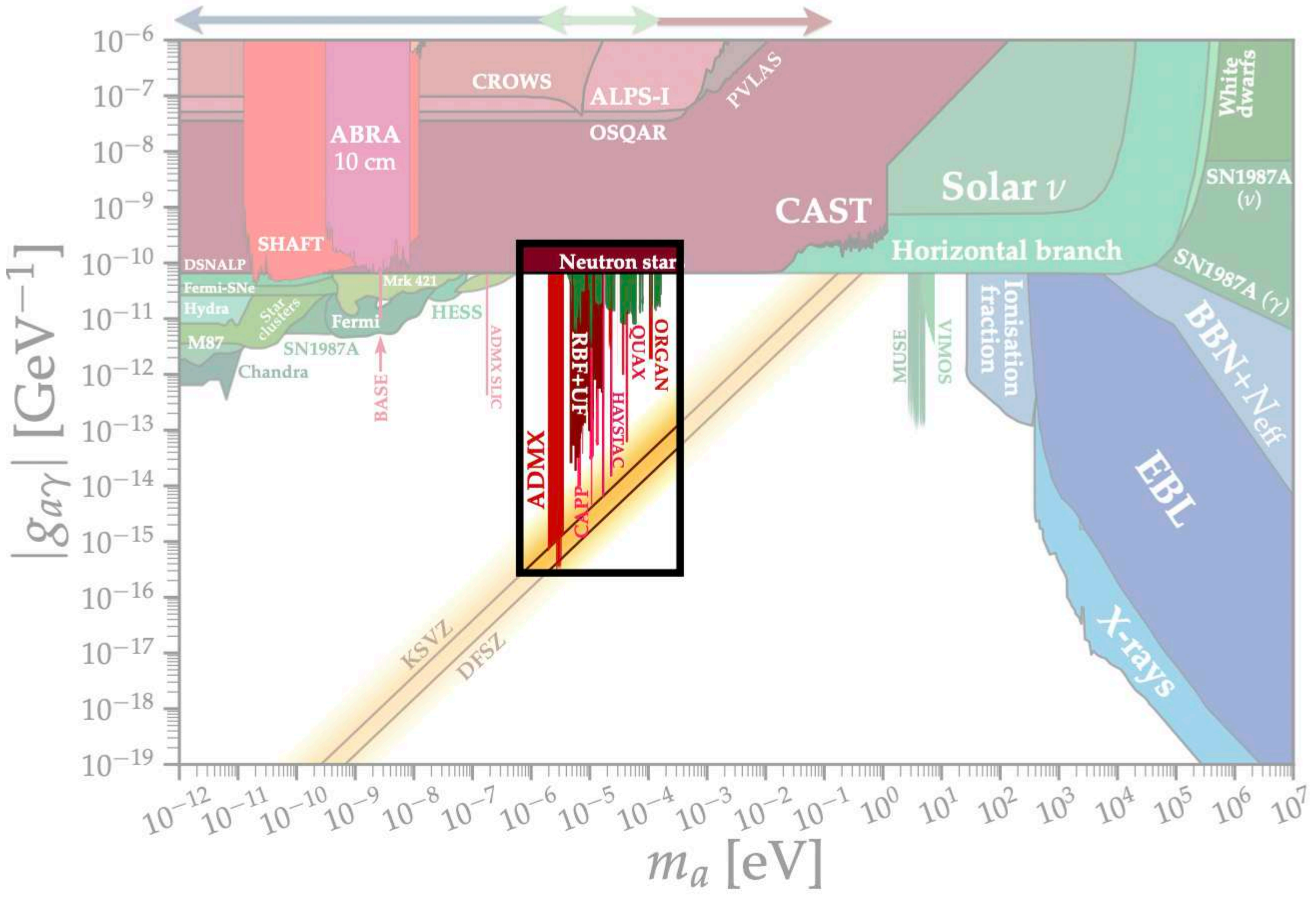
Includes direct and indirect detection



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

Axion and ALPs interaction with the SM

Bounds on Axion-photon coupling



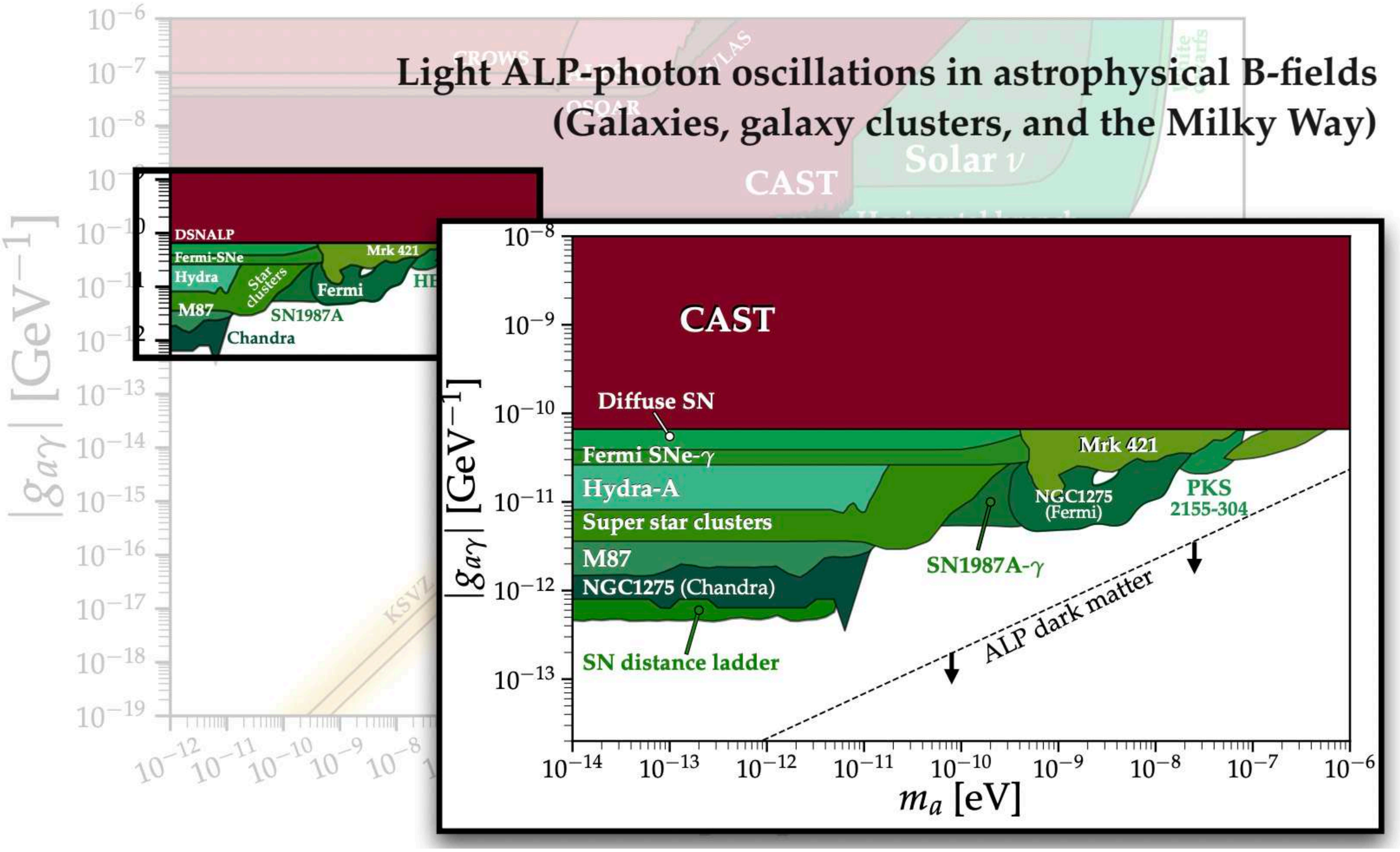
$$\boxed{\boxed{\nabla \times \mathbf{B}_a} = \boxed{\frac{\partial \mathbf{E}_a}{\partial t} \boxed{- g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}}}}$$

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

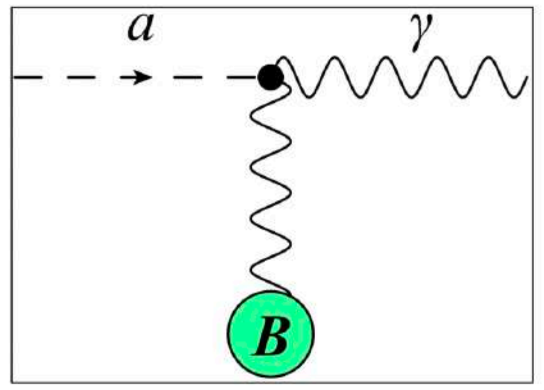
Axion and ALPs interaction with the SM

Indirect Detection

In astrophysical systems



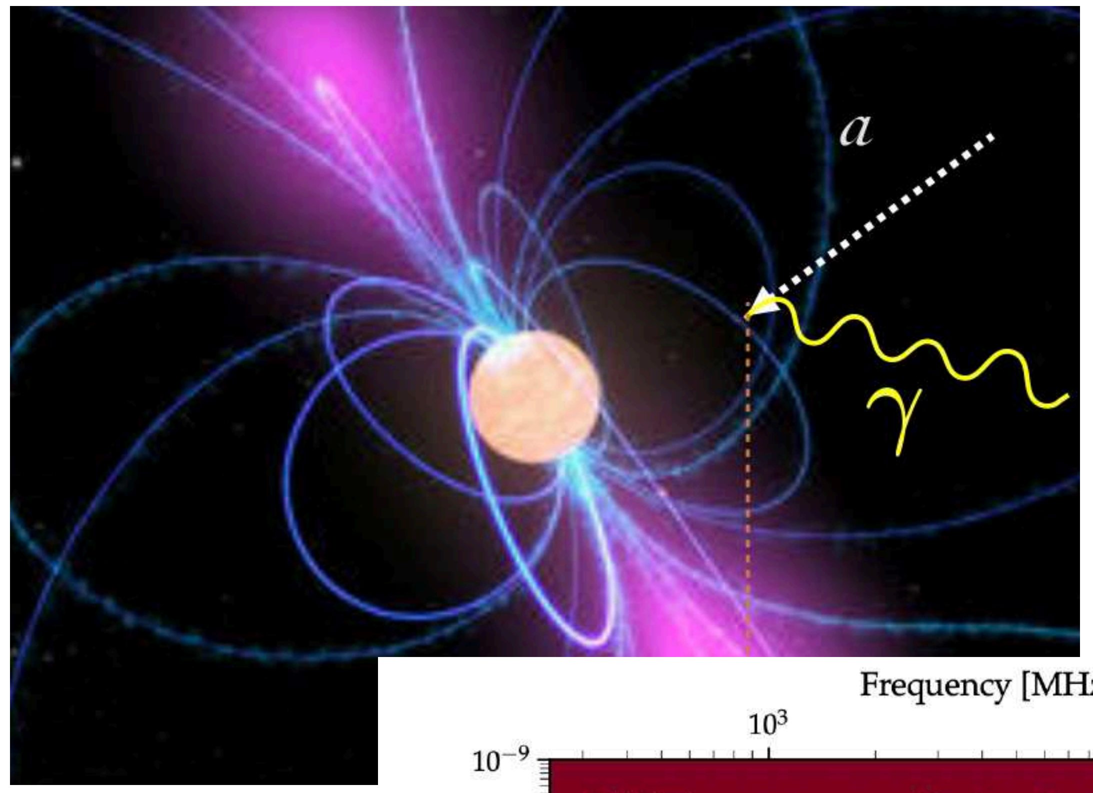
+

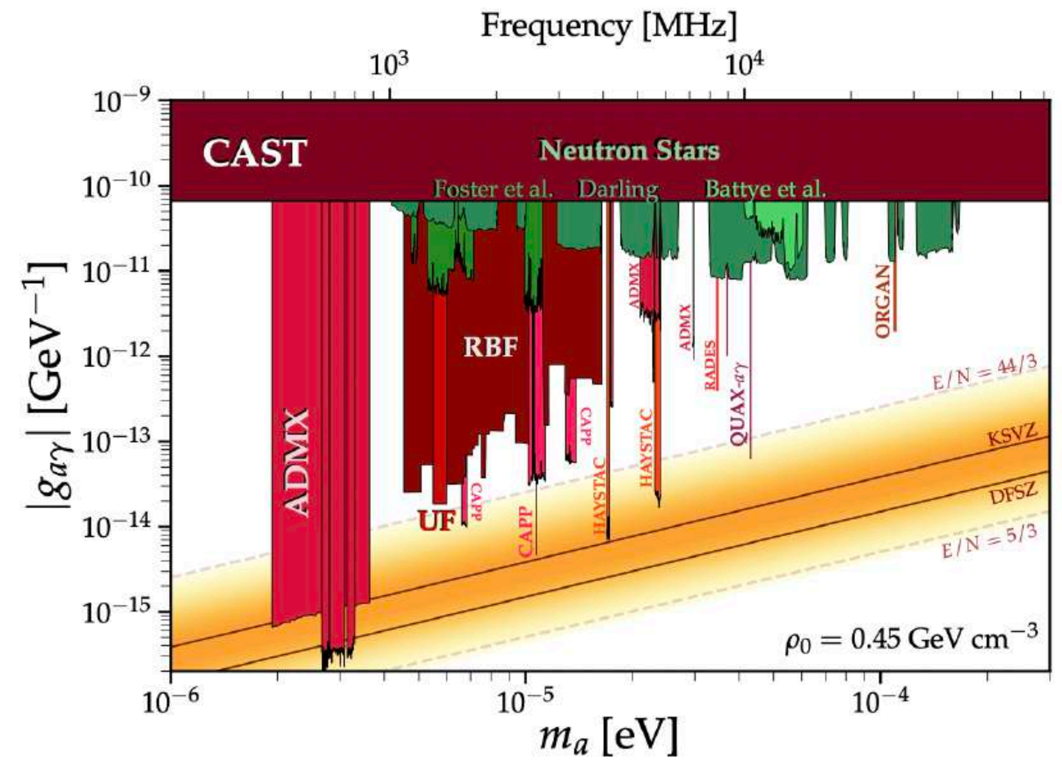


Axion-photon conversion (Primakoff effect)

a : axion
γ : photon
B : magnetic field

DM axions in neutron star magnetospheres



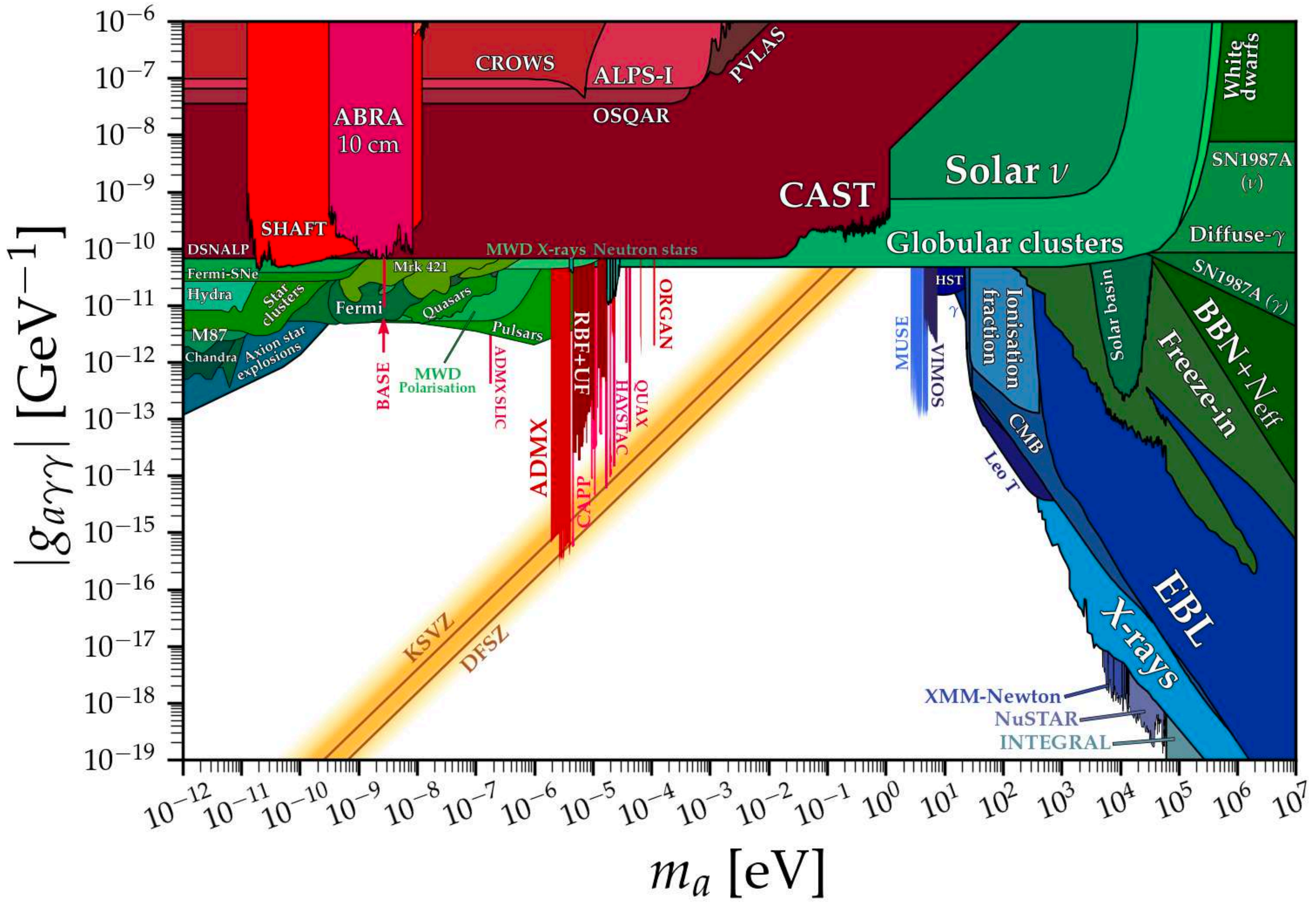


Axion and ALPs interaction with the SM

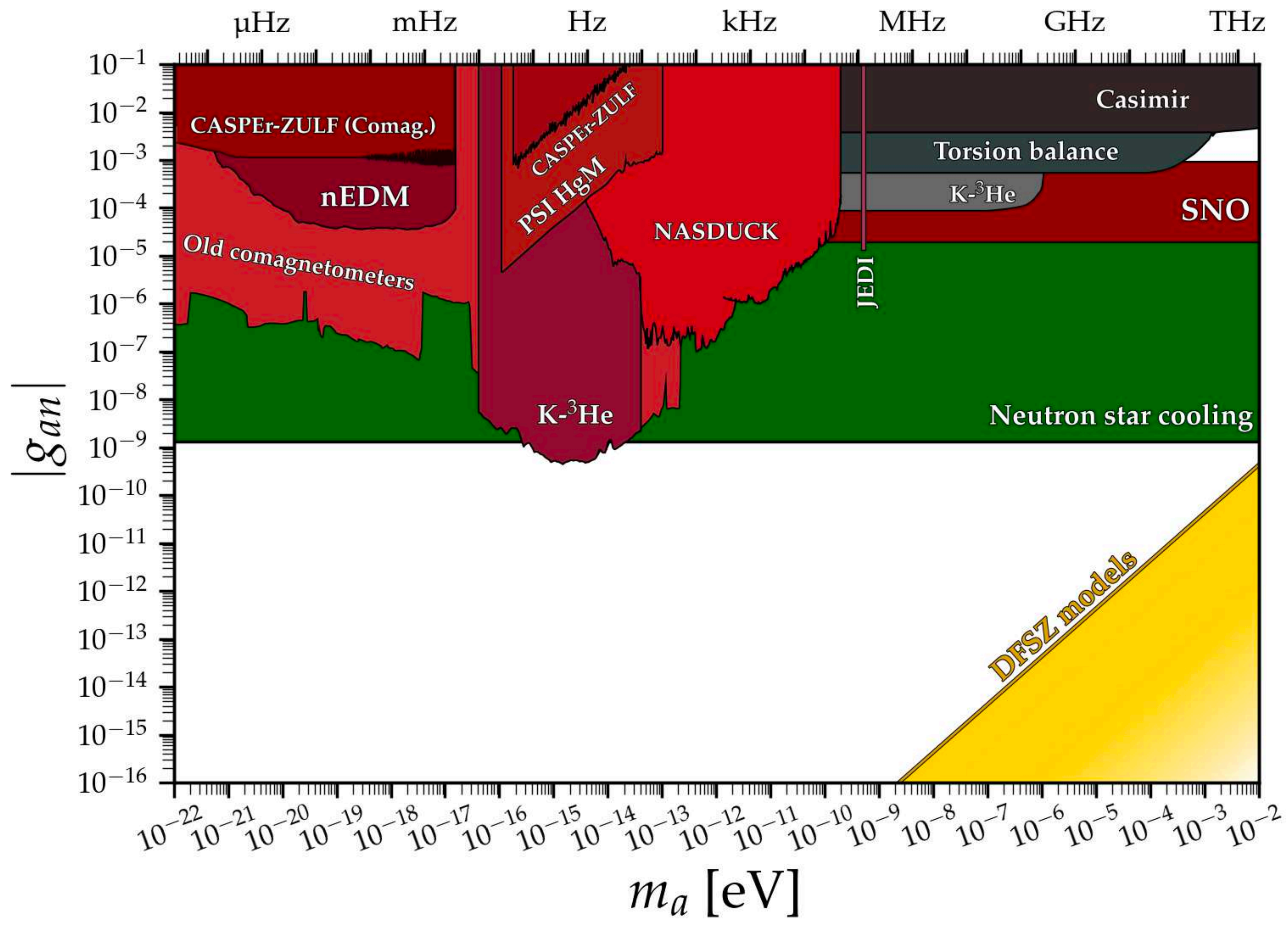
Bounds

Includes direct and indirect detection

Axion-electron coupling



Axion-neutron coupling



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

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

Summary

DM builder's guide

What we learned from observations

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

  Or produced cold by a non-thermal mechanism

- Reproduce large and small scale distribution

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

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

- Non-interacting or weakly interacting

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

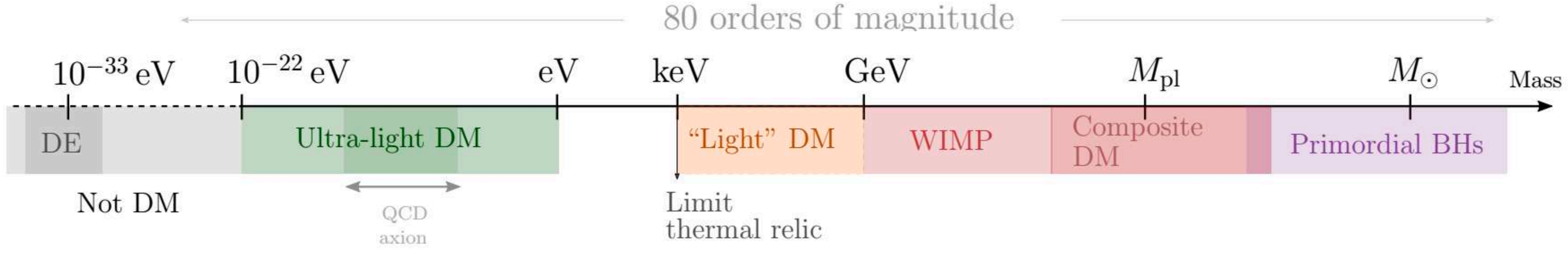
  Can have a small **self interaction**.

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

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

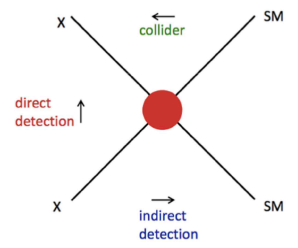
- Stable

Mass scale of DM

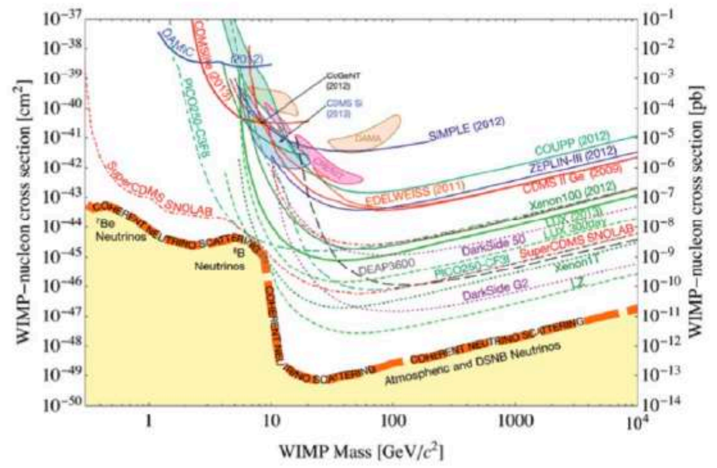


DM Landscape

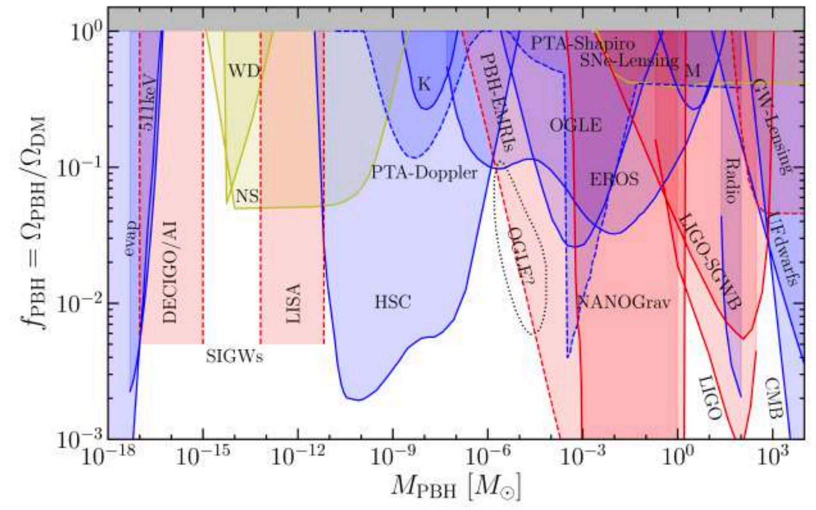
Search for DM



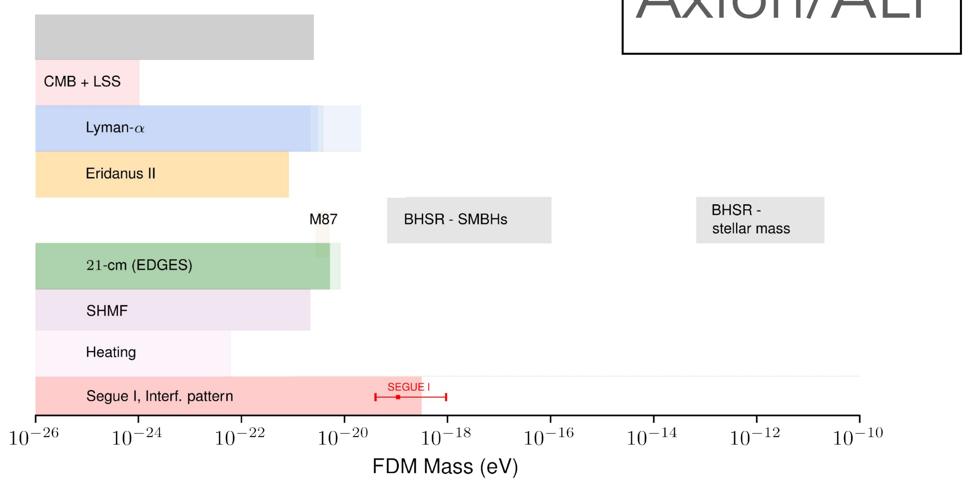
WIMPS

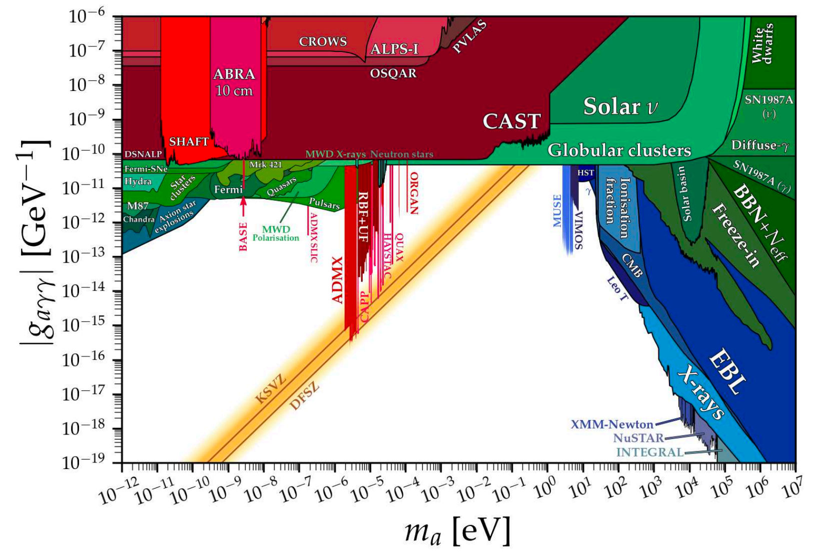


PBHs



Axion/ALP






Thank you very much!

EXTRA slides

EXTRA slides

FDM *simulation*

Spectral technique to solve the SP system

$$i\hbar\partial_t\psi_c(t,\mathbf{x}) = -\frac{\hbar^2}{2m\,a(t)^2}\nabla_c^2\psi_c(t,\mathbf{x}) + \frac{m}{a(t)}\Phi_c\,\psi_c(t,\mathbf{x})$$

$$\nabla_c^2\Phi_c(t,\mathbf{x}) = 4\pi G m\left(|\psi_c(t,\mathbf{x})|^2 - \langle|\psi_c|^2\rangle(t)\right)$$

Time evolution of the wave function

$$\Psi(\boldsymbol{x}, t+\Delta t) = T\exp\left[-\frac{\mathrm{i}\Delta t}{\hbar}\int \mathrm{d}t'\left(-\frac{\hbar^2}{2m}\nabla^2 + mV(\boldsymbol{x}, t')\right)\right]\Psi(\boldsymbol{x}, t)$$

Small Δt:

$$\Psi(\boldsymbol{x}, t+\Delta t) = \exp\left(\frac{\mathrm{i}\hbar\Delta t}{2m}\nabla^2 - \frac{\mathrm{i}m\Delta t}{2\hbar}V(\boldsymbol{x}, t+\Delta t) - \frac{\mathrm{i}m\Delta t}{2\hbar}V(\boldsymbol{x}, t)\right)\Psi(\boldsymbol{x}, t)\,,$$

Split into 3 operations (Baker-Campbell-Haussdorff formula)

$$\Psi(\boldsymbol{x}, t+\Delta t) = \exp\left(-\frac{\mathrm{i}m\Delta t}{2\hbar}V(\boldsymbol{x}, t+\Delta t)\right)\exp\left(\frac{\mathrm{i}\hbar\Delta t}{2m}\nabla^2\right)\exp\left(-\frac{\mathrm{i}m\Delta t}{2\hbar}V(\boldsymbol{x}, t)\right)\Psi(\boldsymbol{x}, t)$$

Operator Splitting Spectral Method

$$\psi_c^{n+1} \approx \underbrace{e^{i\Phi_c\,\Delta t/2}}_{3^{\mathrm{rd}}}\,\underbrace{\mathcal{F}^{-1}\left[e^{ik^2\Delta t}\right.}_{2^{\mathrm{nd}}}\,\underbrace{\left.\mathcal{F}^{-1}\left[e^{i\Phi_c\,\Delta t/2}\,\psi_c^n\right]\right]}_{1^{\mathrm{st}}}$$

$$\Delta t \sim \Delta x^2$$

Timestep criteria

FDM simulation

Spectral technique to solve the SP system

$$i\hbar\partial_t\psi_c(t,\mathbf{x}) = -\frac{\hbar^2}{2m\,a(t)^2}\nabla_c^2\psi_c(t,\mathbf{x}) + \frac{m}{a(t)}\Phi_c\,\psi_c(t,\mathbf{x})$$

$$\nabla_c^2\Phi_c(t,\mathbf{x}) = 4\pi G m\left(|\psi_c(t,\mathbf{x})|^2 - \langle|\psi_c|^2\rangle(t)\right)$$

Operator Splitting Spectral Method

$$\psi_c^{n+1} \approx \underbrace{e^{i\Phi_c\,\Delta t/2}}_{3^{\mathrm{rd}}}\,\underbrace{\mathcal{F}^{-1}\left[e^{ik^2\Delta t}\right.}_{2^{\mathrm{nd}}}\,\underbrace{\left.\mathcal{F}^{-1}\left[e^{i\Phi_c\,\Delta t/2}\,\psi_c^n\right]\right]}_{1^{\mathrm{st}}}$$

$$\Delta t \sim \Delta x^2$$

Timestep criteria

FDM simulation

The fields ψ and Φ are discretised on a uniform Cartesian mesh with N^3 grid points - allow numerical computations using Fast Fourier transform. It follows the operations:

Schrödinger-Poisson system

$$i\hbar\partial_t\psi_c(t,\mathbf{x}) = -\frac{\hbar^2}{2m\,a(t)^2}\nabla_c^2\psi_c(t,\mathbf{x}) + \frac{m}{a(t)}\Phi_c\,\psi_c(t,\mathbf{x})$$
$$\nabla_c^2\Phi_c(t,\mathbf{x}) = 4\pi G m\left(|\psi_c(t,\mathbf{x})|^2 - \langle|\psi_c|^2\rangle(t)\right)$$

- Calculate the potential
- $$\psi_c \leftarrow e^{-i\frac{m}{\hbar}\frac{1}{a}\frac{\Delta t}{2}\Phi_c}\psi_c \quad \text{(kick)} \qquad (20a)$$
- $$\psi_c \leftarrow \mathrm{FFT}^{-1}\left(e^{-i\frac{\hbar}{m}\frac{1}{a^2}\frac{\Delta t}{2}k^2}\,\mathrm{FFT}(\psi_c)\right) \quad \text{(drift)} \qquad (20b)$$
- $$\Phi_c \leftarrow \mathrm{FFT}^{-1}\left(-\frac{1}{k^2}\,\mathrm{FFT}\left(4\pi G m\left(|\psi_c|^2 - \langle|\psi_c|^2\rangle\right)\right)\right) \quad \text{(update potential)} \qquad (20c)$$
- $$\psi_c \leftarrow e^{-i\frac{m}{\hbar}\frac{1}{a}\frac{\Delta t}{2}\Phi_c}\psi_c \quad \text{(kick)} \qquad (20d)$$
- Go to step (20a) (20e)

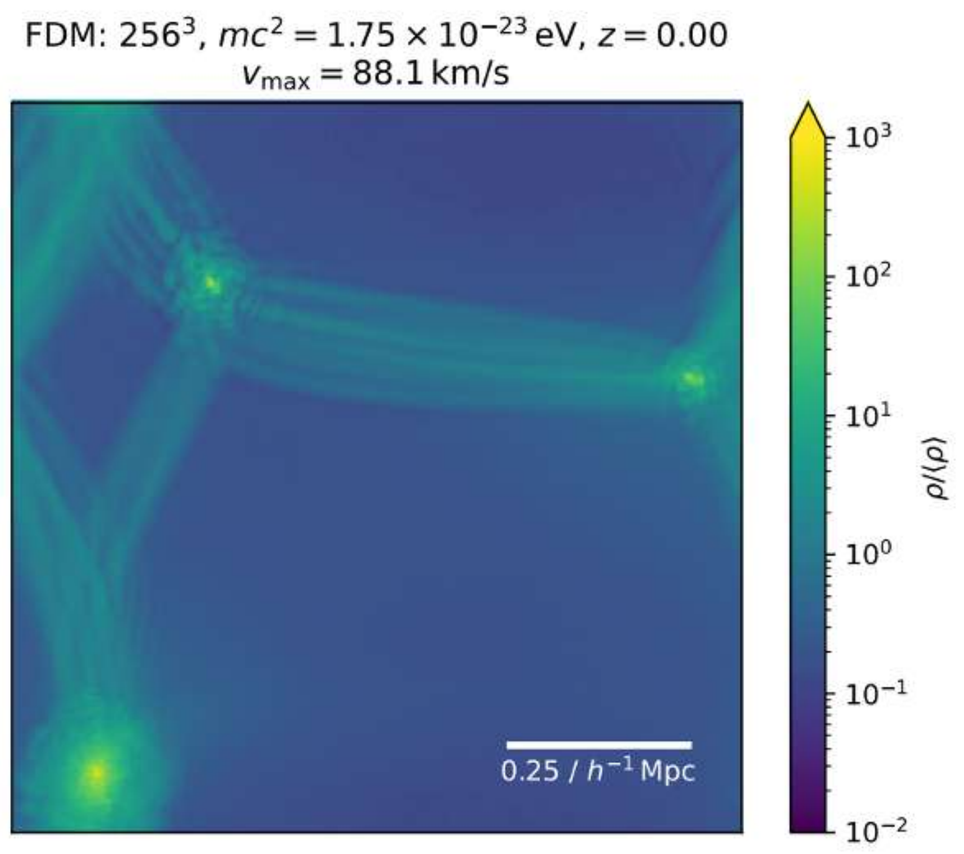
May et al. 2020
Steps (20a) to (20e) implemented as a module in the AREPO code

Jowett
Own implementation

FDM simulation

May et al 2020: Box size and resolution

Largest three-dimensional cosmological simulations of FDM structure formation to low redshifts



Type	Res. el.	L / h^{-1} Mpc	mc^2 / eV	Resolution
FDM	8640^3	10	7×10^{-23}	$1.16\, h^{-1}$ kpc
FDM	4320^3	10	$(3.5, 7) \times 10^{-23}$	$2.31\, h^{-1}$ kpc
FDM	3072^3	10	$(3.5, 7) \times 10^{-23}$	$3.26\, h^{-1}$ kpc
FDM	2048^3	10	$(3.5, 7) \times 10^{-23}$	$4.88\, h^{-1}$ kpc
FDM	4320^3	5	7×10^{-23}	$1.16\, h^{-1}$ kpc
FDM	3072^3	5	$(3.5, 7) \times 10^{-23}$	$1.63\, h^{-1}$ kpc
FDM	2048^3	5	$(3.5, 7) \times 10^{-23}$	$2.44\, h^{-1}$ kpc
FDM	1024^3	5	$(3.5, 7) \times 10^{-23}$	$4.88\, h^{-1}$ kpc
CDM	2048^3	10	—	$9.69 \times 10^3\, h^{-1}\, M_\odot$
CDM	1024^3	10	—	$7.75 \times 10^4\, h^{-1}\, M_\odot$
CDM	512^3	10	—	$6.20 \times 10^5\, h^{-1}\, M_\odot$
CDM	1024^3	5	—	$9.69 \times 10^3\, h^{-1}\, M_\odot$
CDM	512^3	5	—	$7.75 \times 10^4\, h^{-1}\, M_\odot$

Table 1. List of performed simulations with important characteristics. The lengths given for the box sizes and resolutions are comoving.

Simulations: $\{\Omega_m = 0.3,\ \Omega_b = 0,\ \Omega_\Lambda = 0.7,\ H_0 = 70\,\mathrm{km\,s}^{-1} (h = 0.7),\ \sigma_8 = 0.9\}$

IC: $z = 127$