Narrowing down the mass range of ultra-light dark matter

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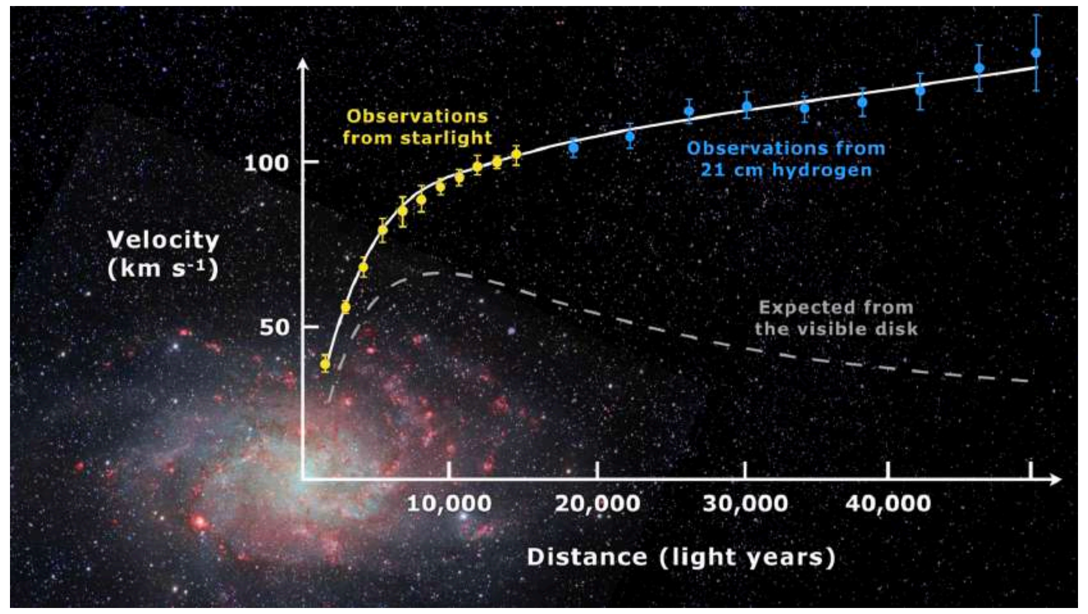
KMI/NITEP School 2026: Dark Matter -
From Ultra Light To Super Massive

11/March/2026

Evidences for dark matter

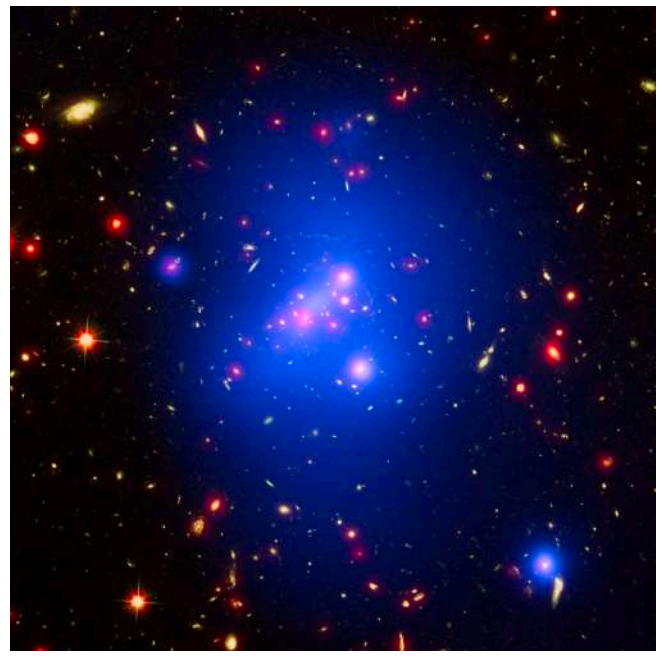
Galaxy rotation curves



Credit: Mario De Leo

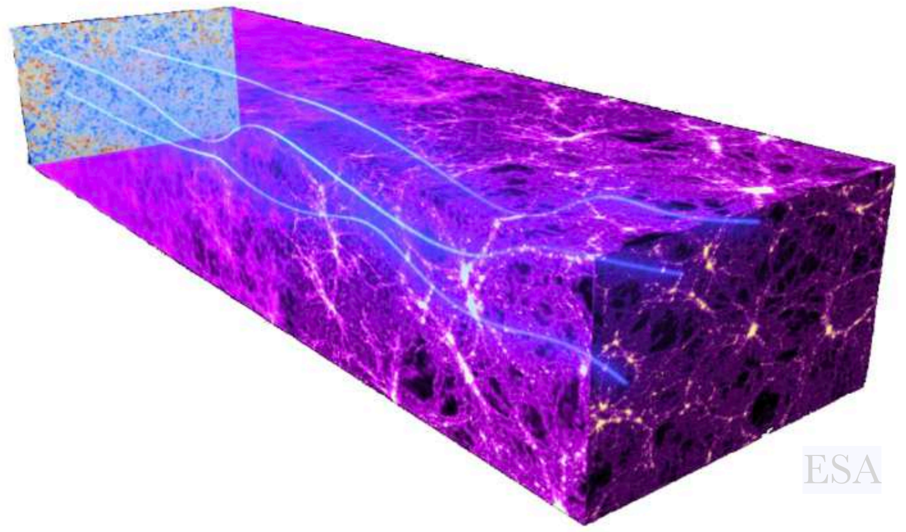
- Mass fraction
- Distribution

Clusters



- Mass fraction
- Distribution

Lensing



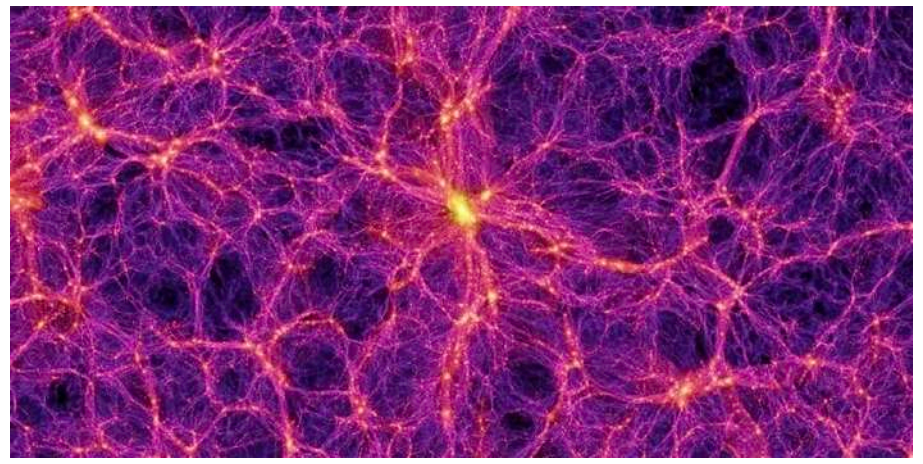
ESA

Strong lensing
- Mass fraction
- Distribution

Weak lensing
- Distribution
- Shape
- Structure

Micro lensing
- Mass fraction
- Smoothness

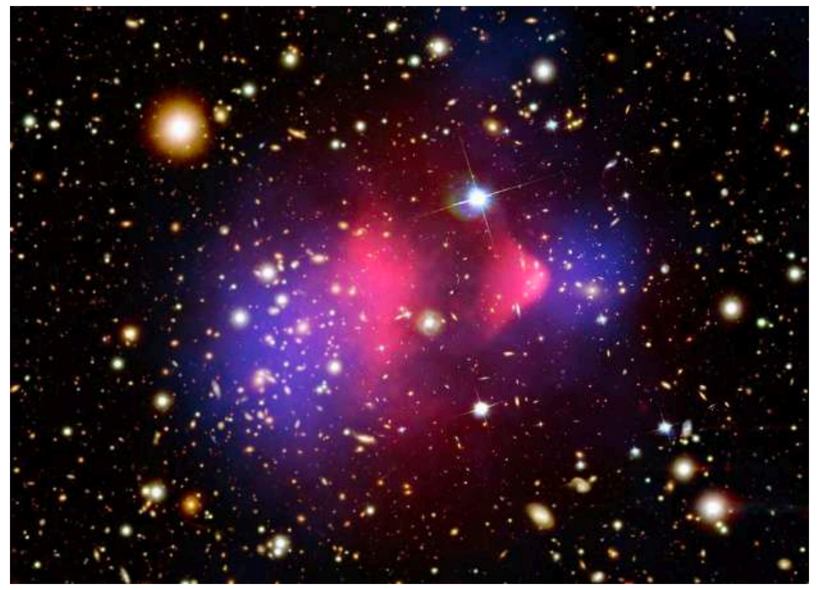
Large Scale Structure



Springel & others / Virgo Consortium

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

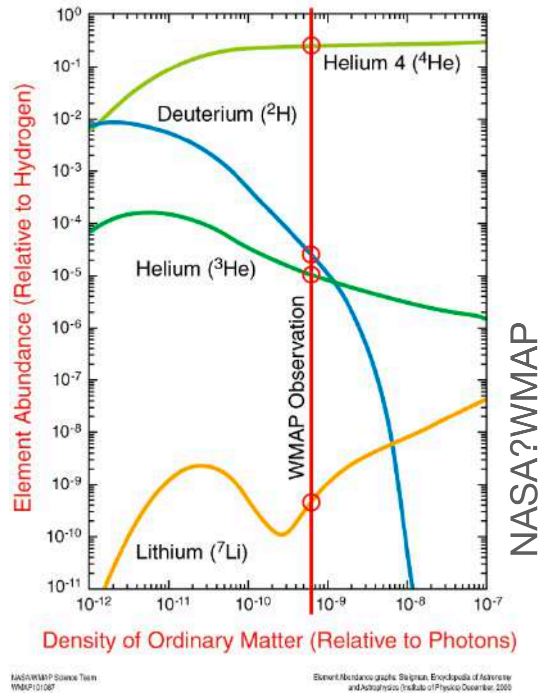
Cluster collision



NASA/CXC/CfA and NASA/STScI

- Distribution
- Separation from collisional matter
- Self-interaction

Big Bang Nucleosynthesis



NASA?WMAP

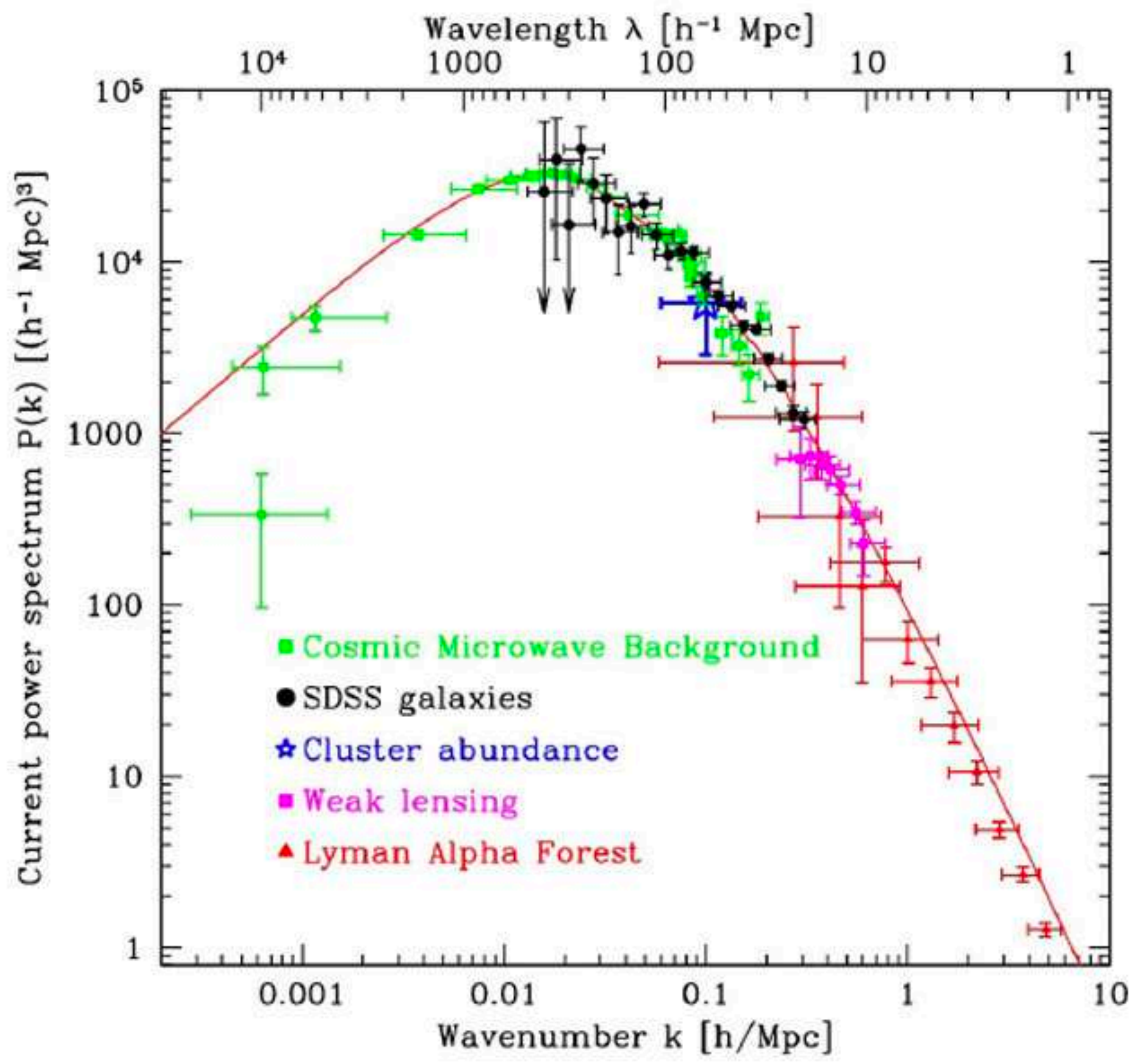
- Amount of baryons

Based on K. Mack

Cold *dark matter*

ΛCDM

- 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

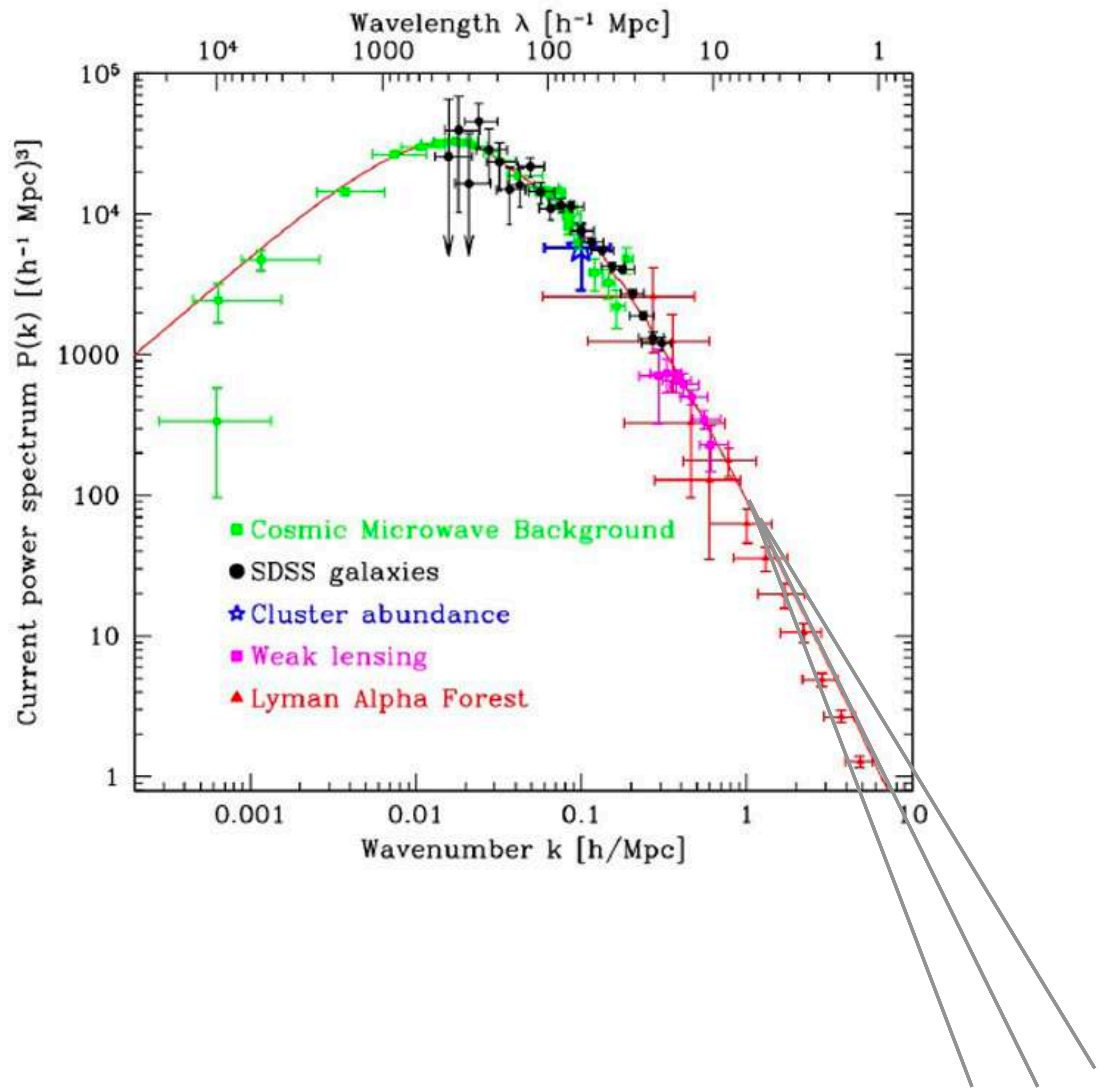


- Abundance: amount of dark matter today known

What we don't know

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

- What is DM? Nature
- ~~Cold~~ → How cold it is? WDM
- ~~Pressureless~~ → Cluster on all scales?
- ~~Dark~~ → Non-gravitational interaction? Milicharged DM
- ~~Collisionless~~ → How small sefl-interaction? SIDM



Although still behaves like CDM on large scales

Small scale behaviour: still "weakly" constrained and small scale challenges

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

Model building: pre-requisites for a dark matter candidate

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

  Has to be non-relativistic at BBN Or produced cold by a non-thermal mechanism

- Abundance

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

- 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

- Stable

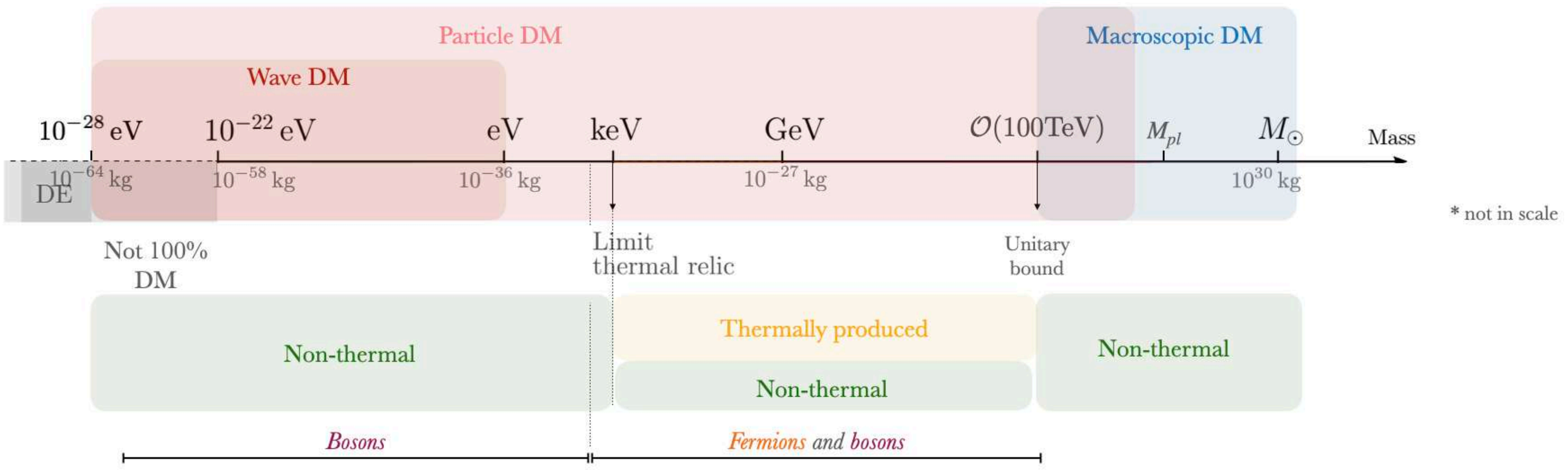
  If it is a particle, it has to be stable with lifetime >> than the age of the universe

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

  Can have a small electromagnetic interaction. Bound < **milicharge** ; Can interact via the ***weak force***

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

Mass scale of dark matter



What we don't know

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

State of the “art"

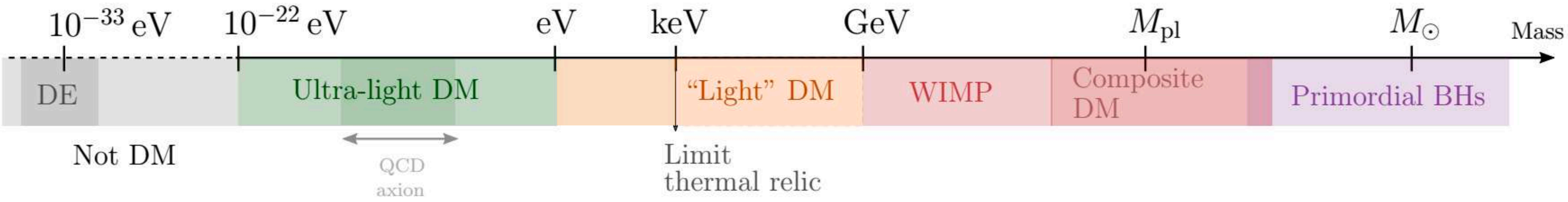
What is dark matter?

- What is the nature of DM?

State of the “art"

Mass scale of DM

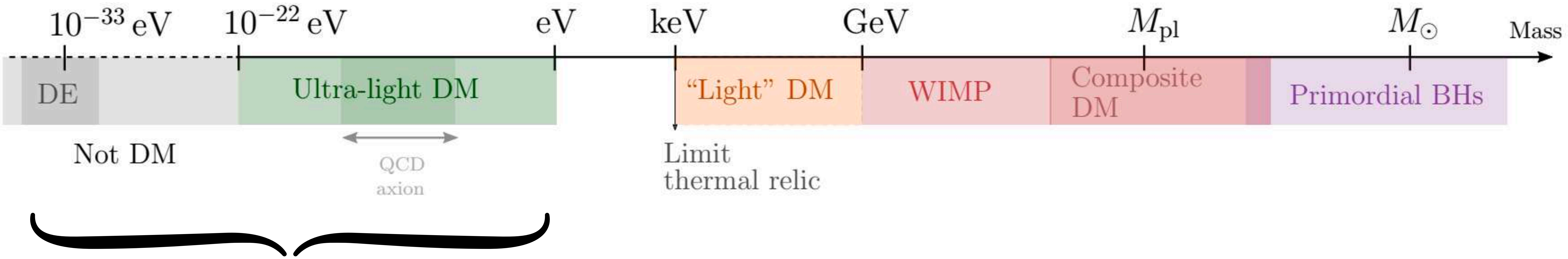
80 orders of magnitude

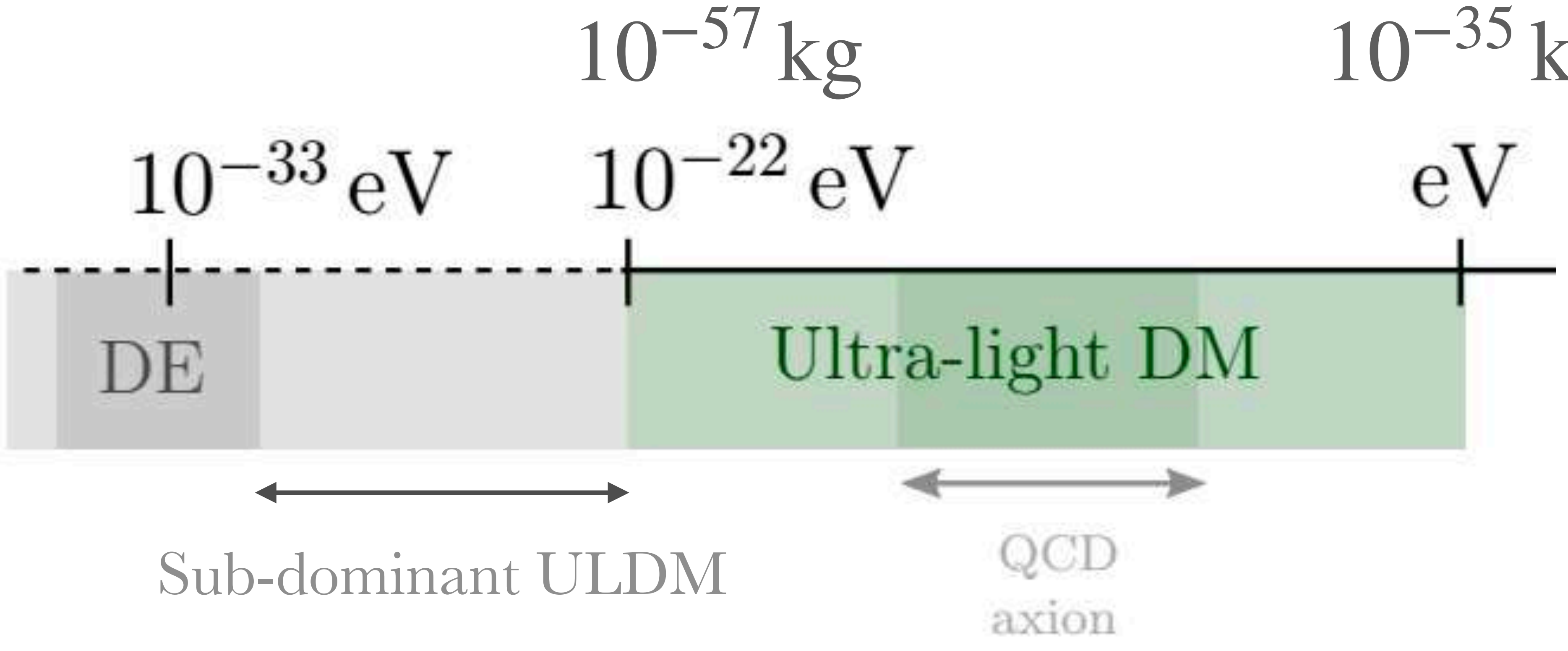


Ultra-light fields

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

Lightest possible candidate for DM or DE



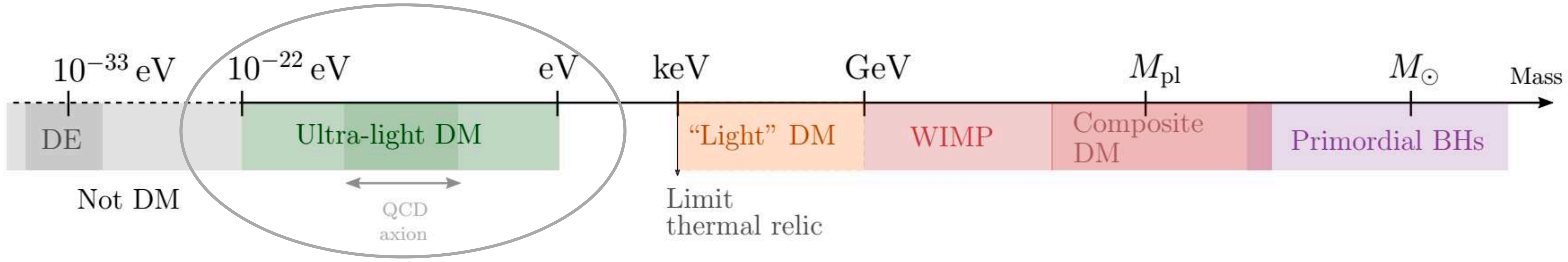


→ Bosons

Non-thermally produced

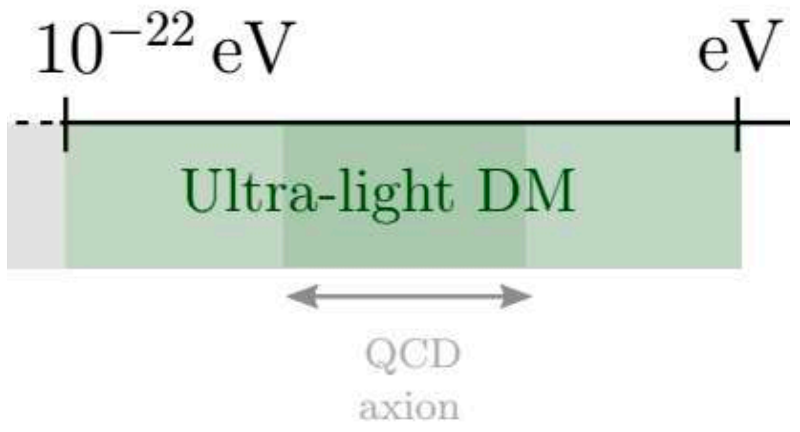
Can be 100% of DM

Ultra-light dark matter



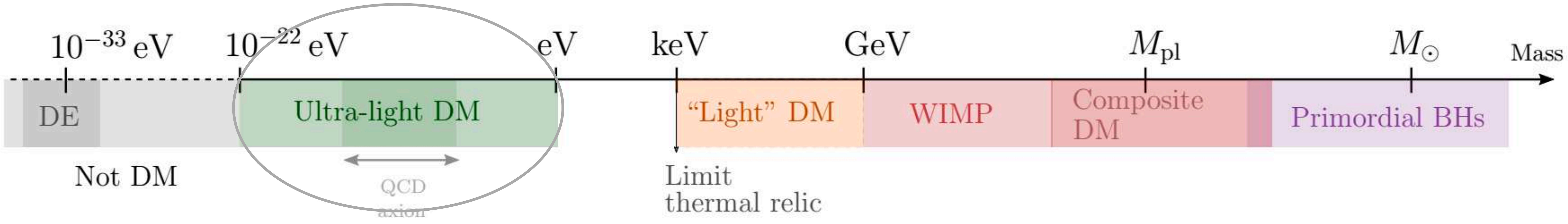
"Ultra-light dark matter", **E.Ferreira**, 2020.
"Wave dark matter", **Lam Hui**, 2020.
New review on ULDM, **Eberhardt, EF** (to appear)

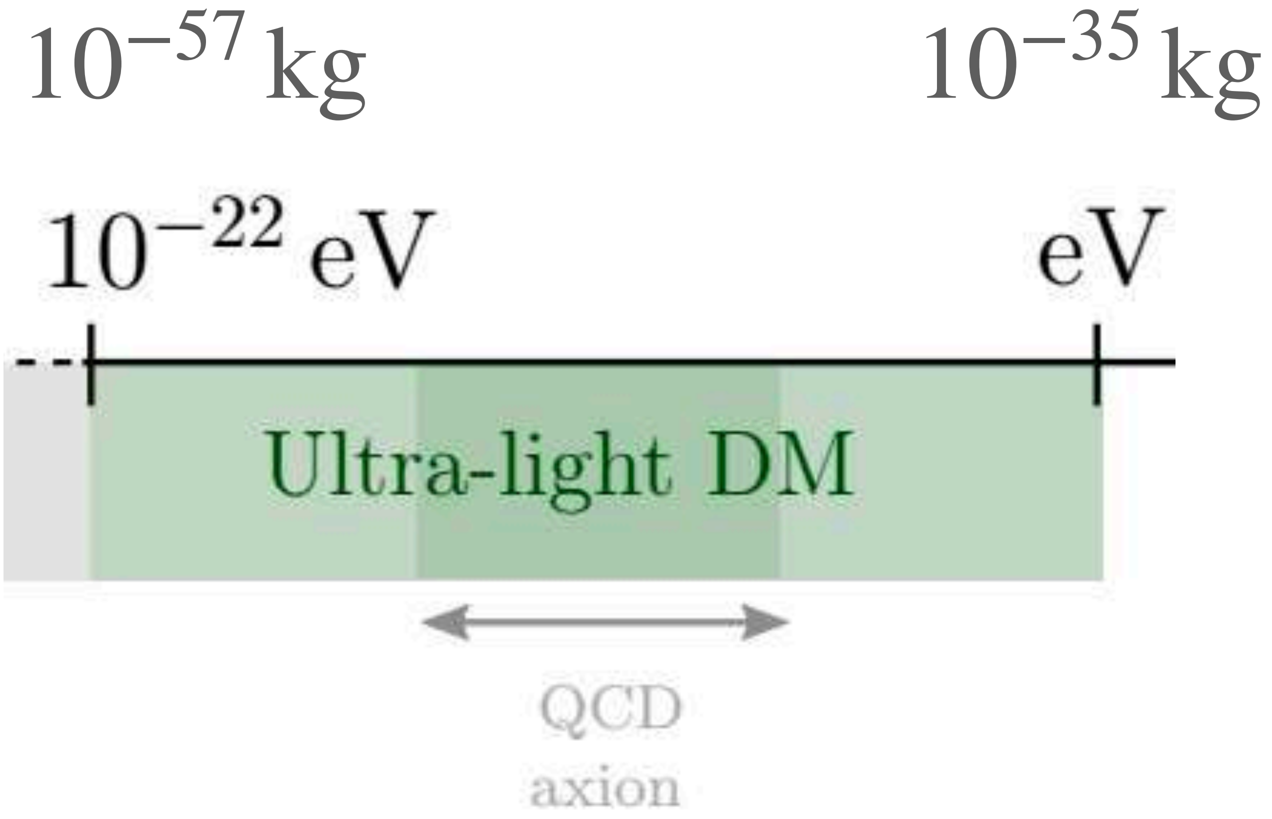
Ultra-light Dark Matter



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

Lightest possible candidate for DM

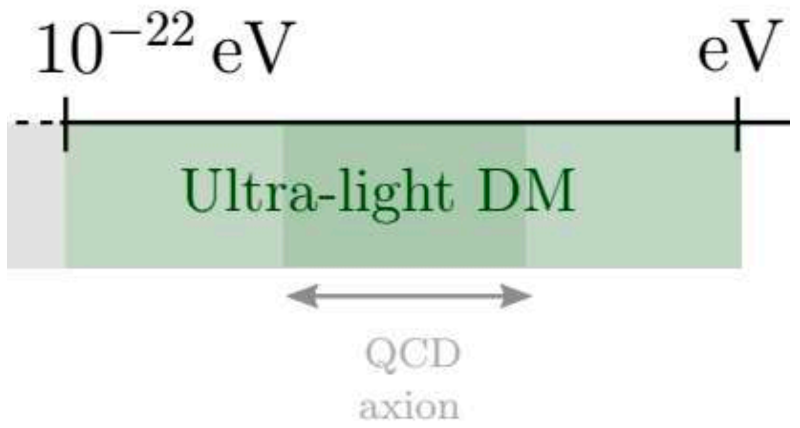




→ Bosons

Non-thermally produced

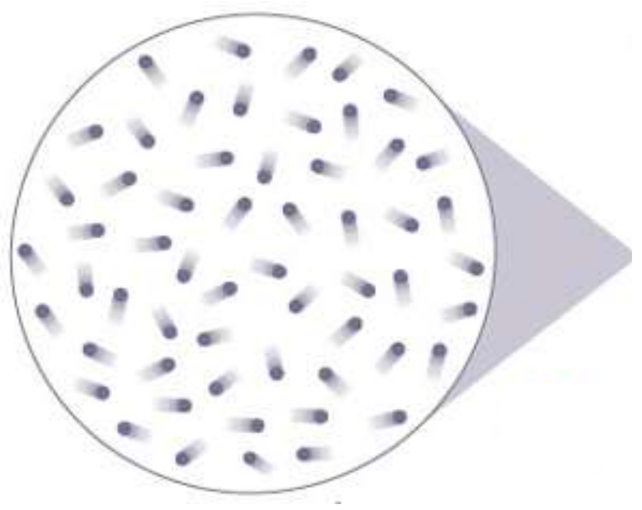
Ultra-light Dark Matter

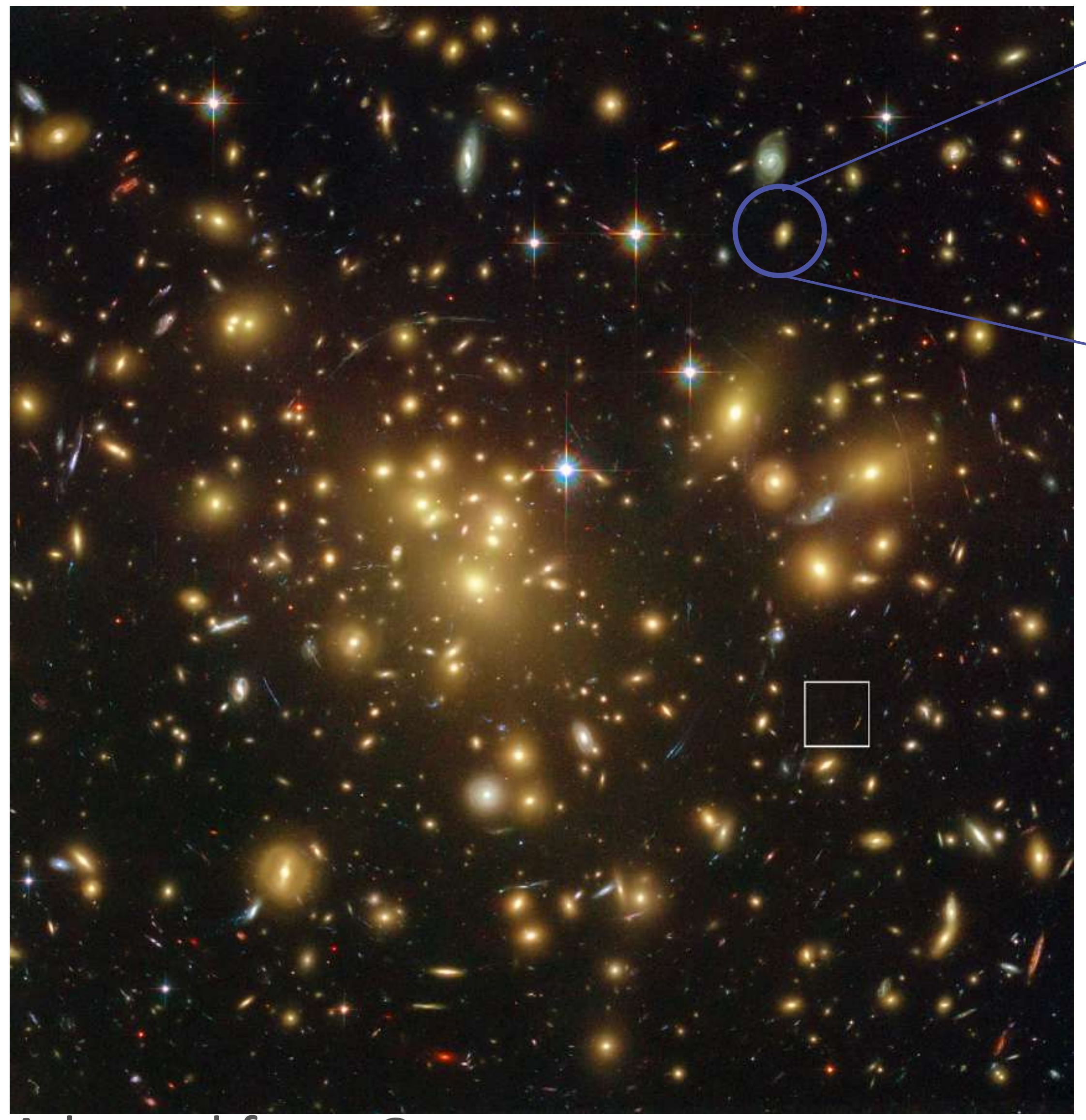


Ultra-light candidate → Large $\lambda_{\rm dB} \sim 1/mv$

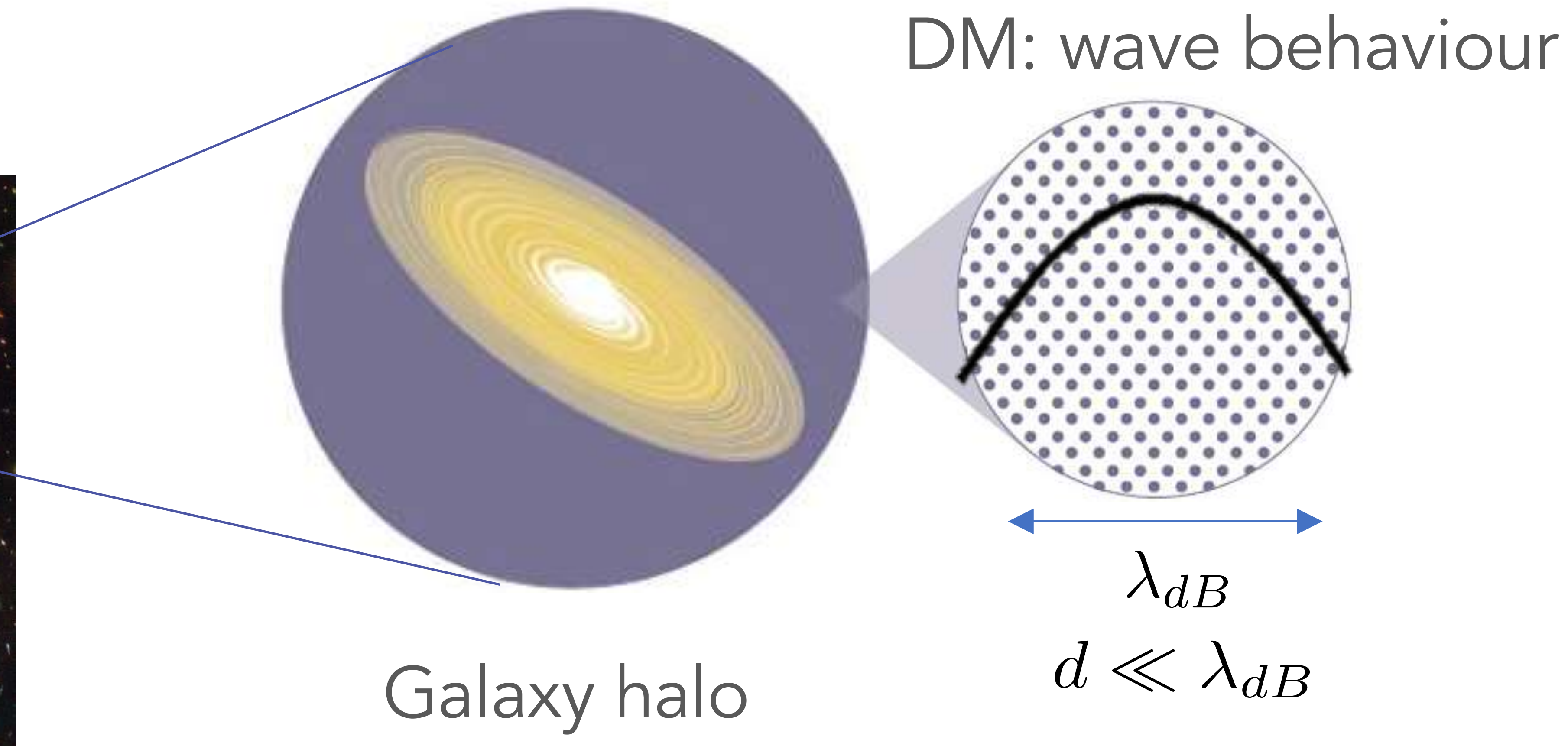
Lightest possible candidate for DM

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





Adapted from Quanta



Small scales:
DM behaves like a wave

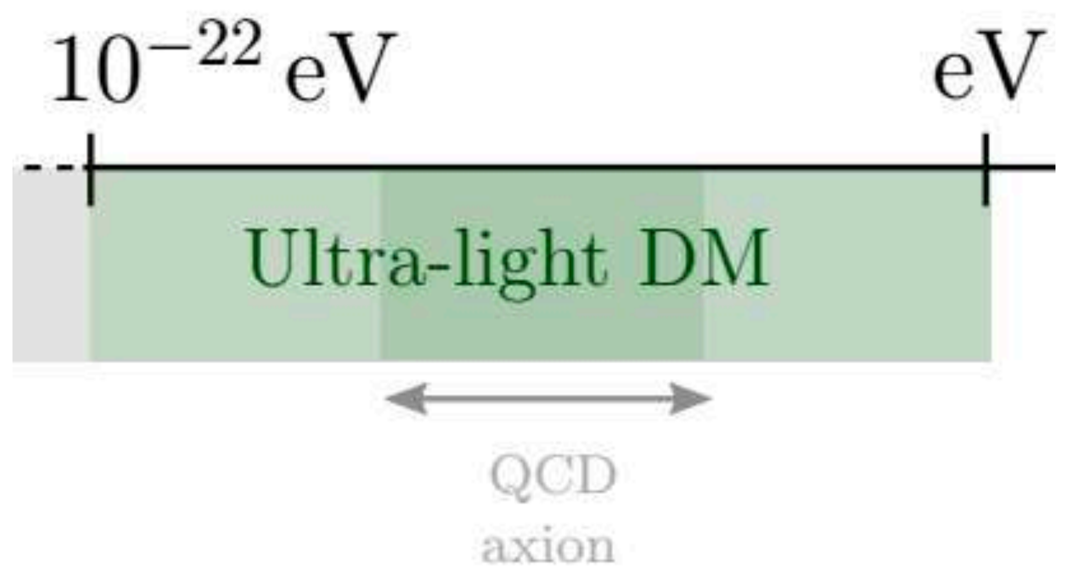
10^{-60} kg 10^{-35} kg

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

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

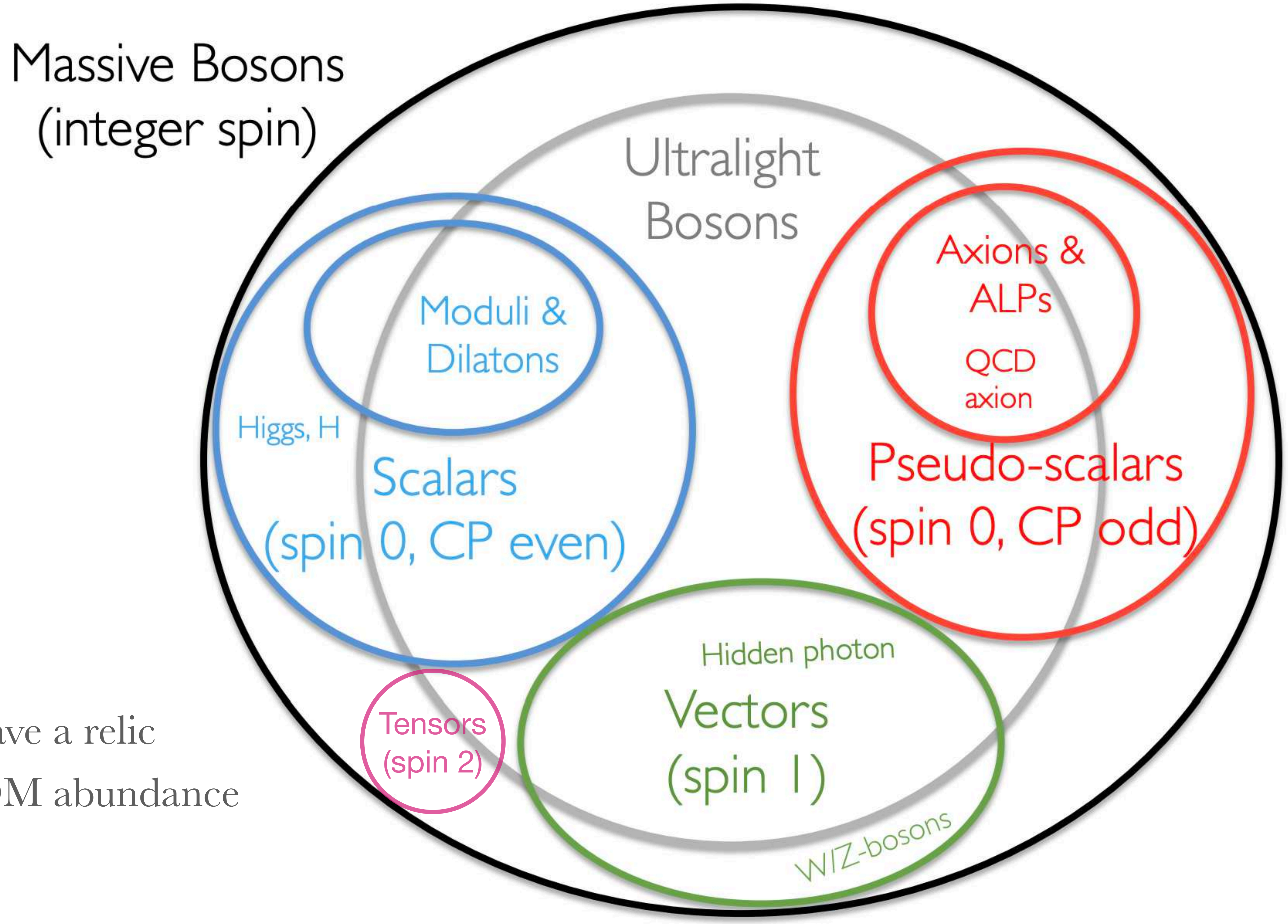
Motivation: particle physics

ULDM candidates



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

Many extensions of the Standard Model predict additional massive bosons



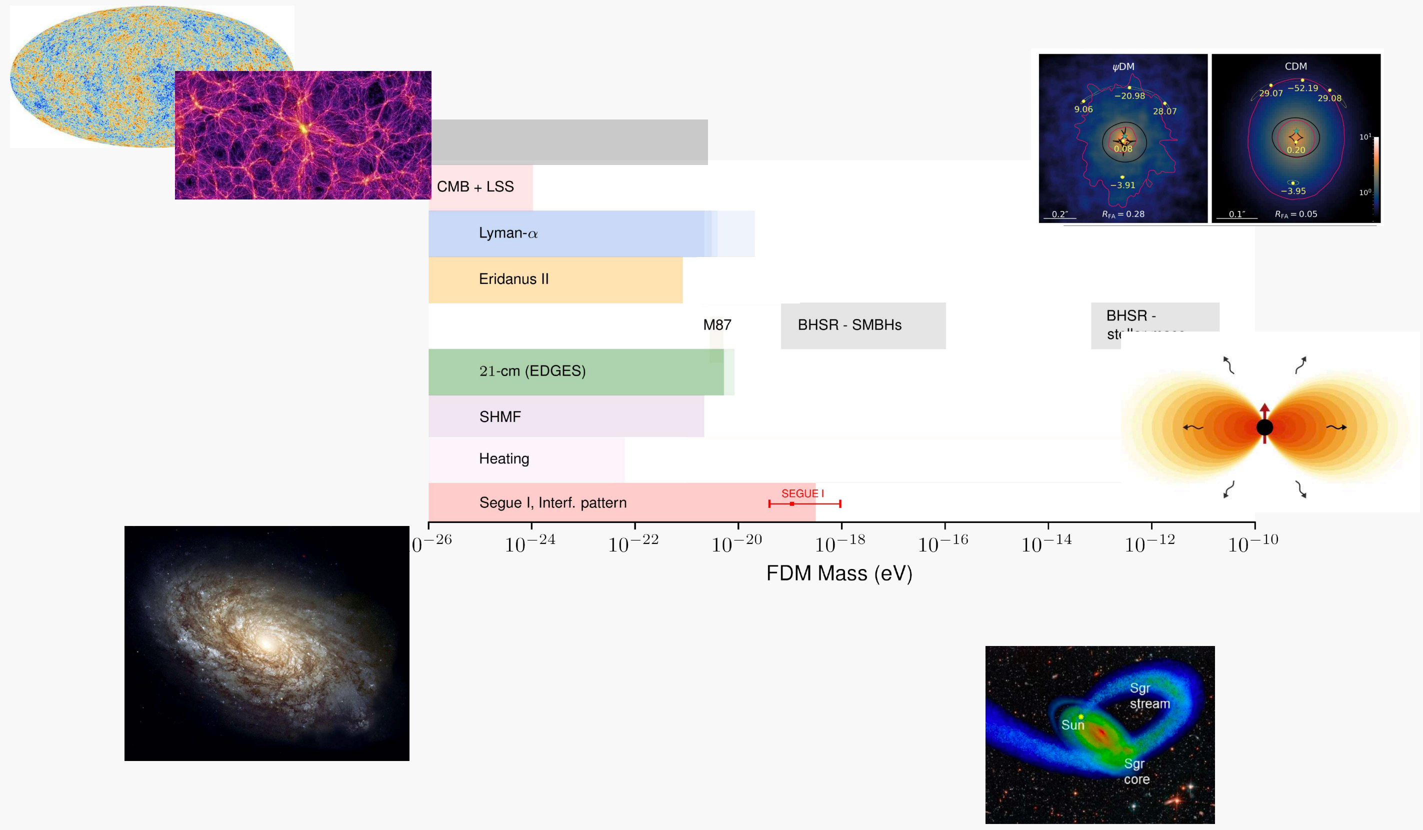
- Formation mechanism: needs to have a relic abundance that gives the correct DM abundance

Ref.: Modified from Chadha-Day et al 2022

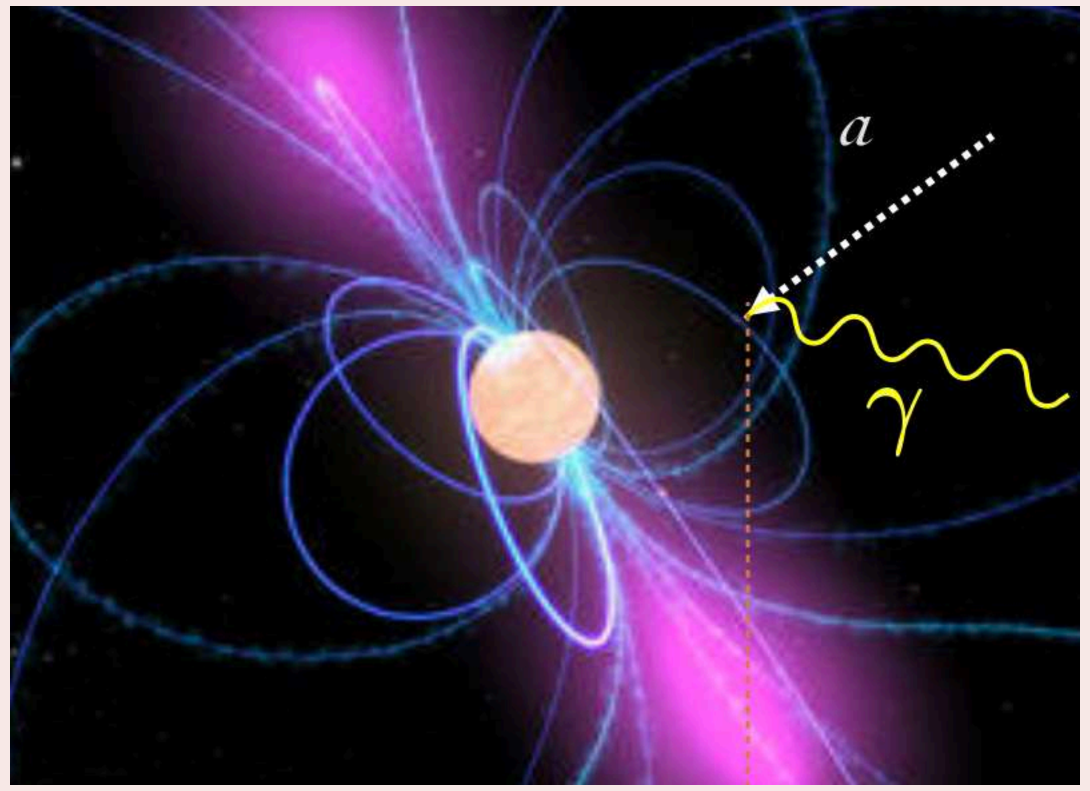
Outline

This talk!

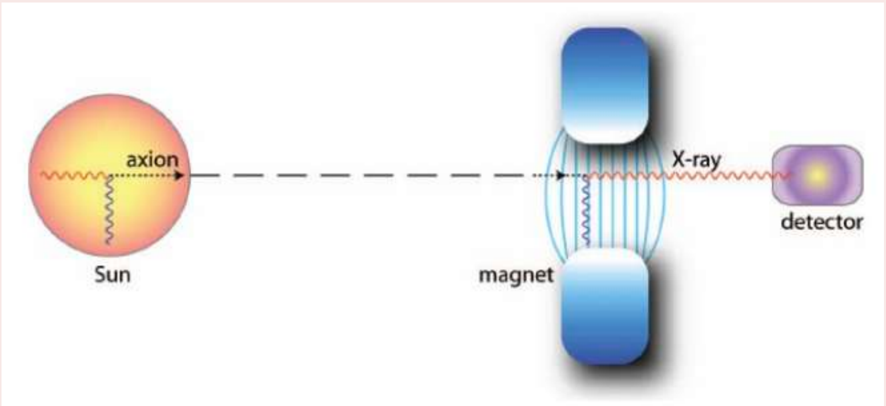
Cosmological and astrophysical searches

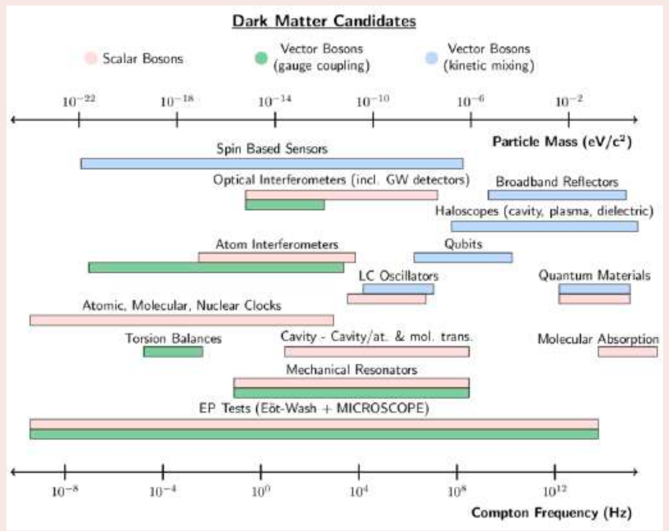


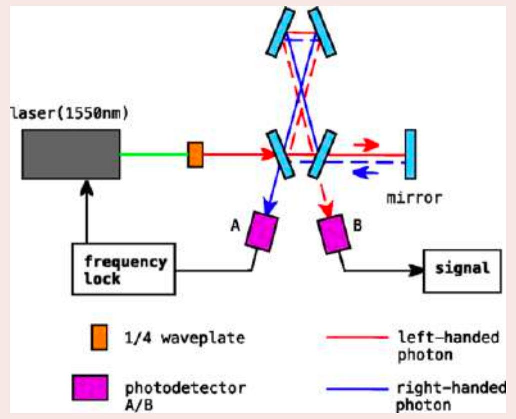
Indirect detection



"Direct detection" Axion/ALPs experiments

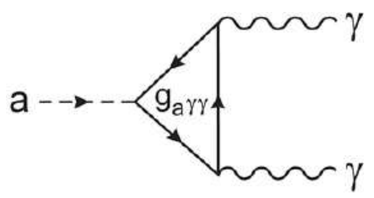


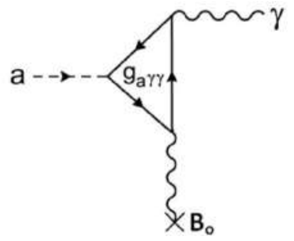




Gravitational

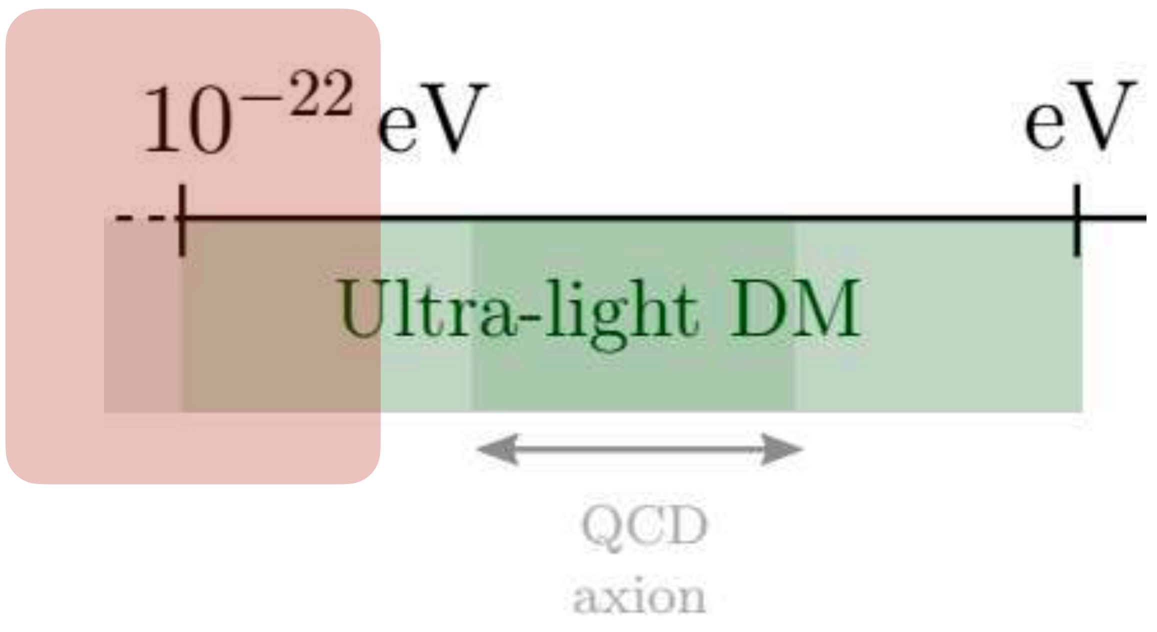
Interactions with the SM



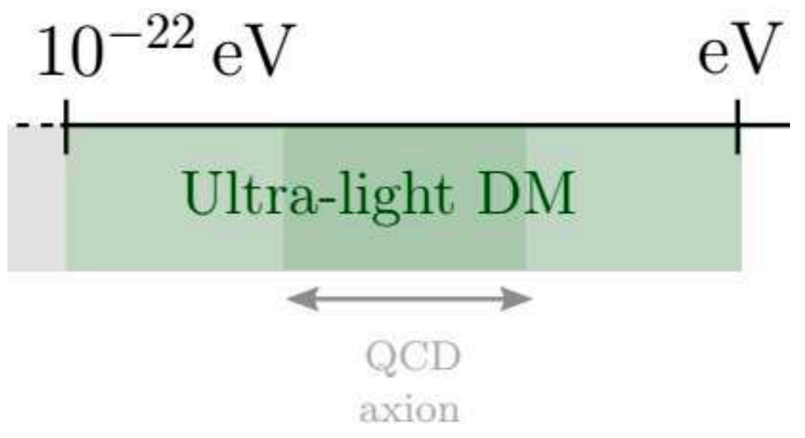


For most of this talk:
Gravitational signatures!

Astrophysical signatures



Ultra-light Dark Matter -classes



3 classes:

Fuzzy DM (FDM)

- Gravitationally bounded ultra-light scalar field model

DOFs: m

Self Interacting FDM (SIFDM)

- Presence of (weakly) self-interaction

DOFs: m g

DM Superfluid

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

Axion and ALP (axion like particles)

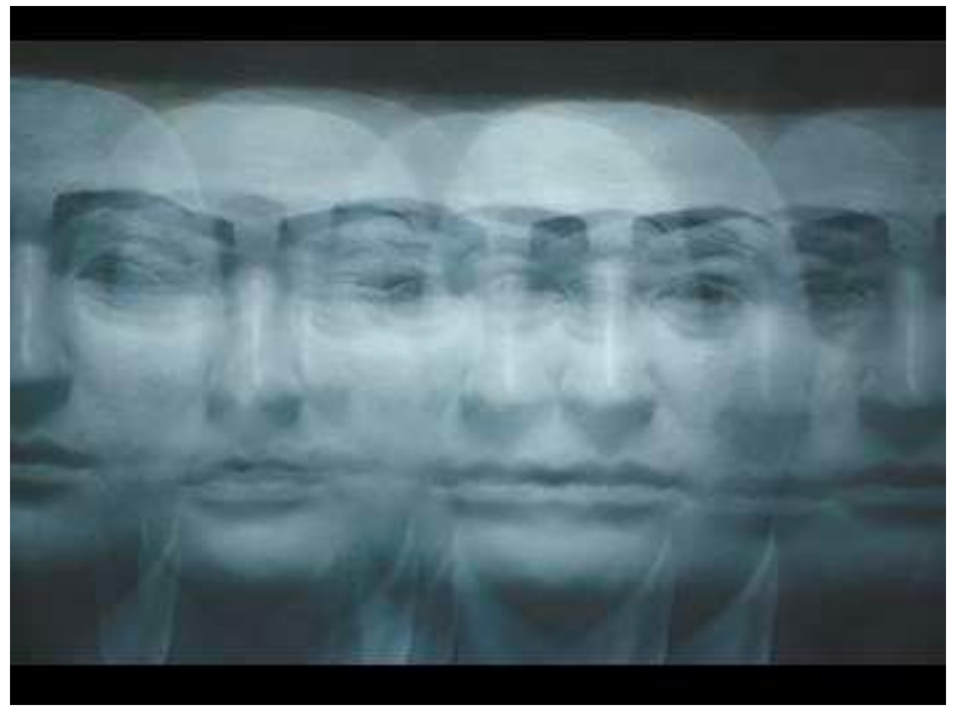
$$i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{g}{8m^2}|\psi|^2 - m\Phi\right)\psi$$

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

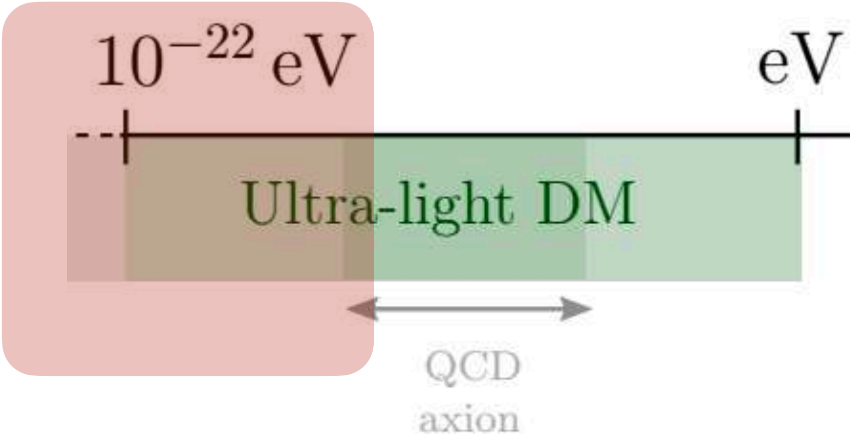
$\longrightarrow$ Connection with condensed matter and particle physics!

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

Fuzzy dark matter



Fuzzy Dark Matter



Fuzzy DM
(FDM)

- Gravitationally bounded ultra-light scalar field model

m

Wave DM
Ultra-light axions

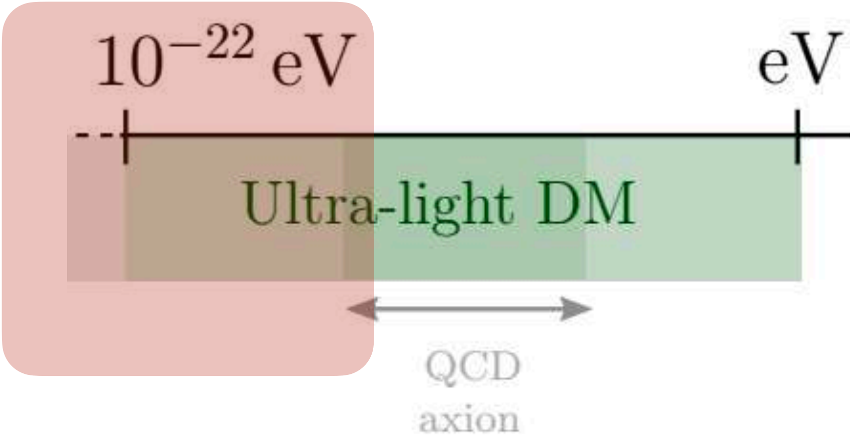
Focus *more* on spin 0 particles here!

$$10^{-22}\,\mathrm{eV} \lesssim m \lesssim 10^{-17}\,\mathrm{eV}$$

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

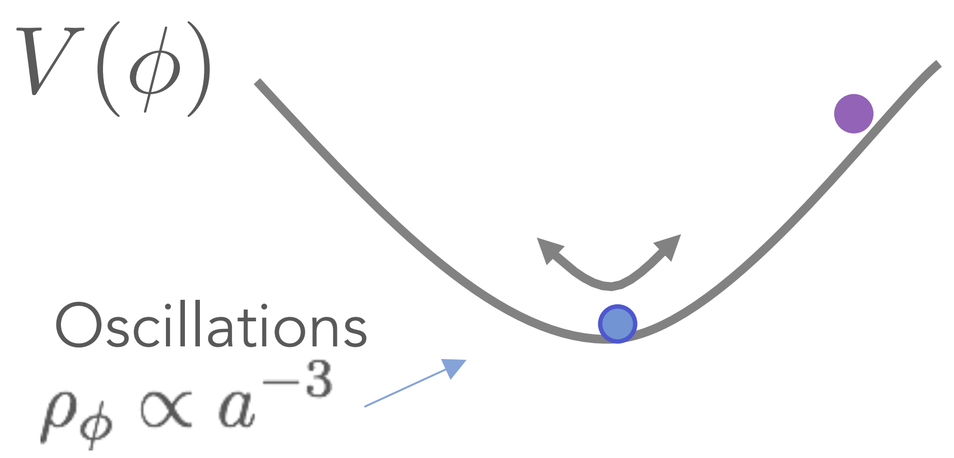
(Reviews: *EF (2021), J. Niemeyer (2019), L. Hui (2021)*)

Cosmological evolution



Boson/ Scalar field in a cosmological (FRW) background

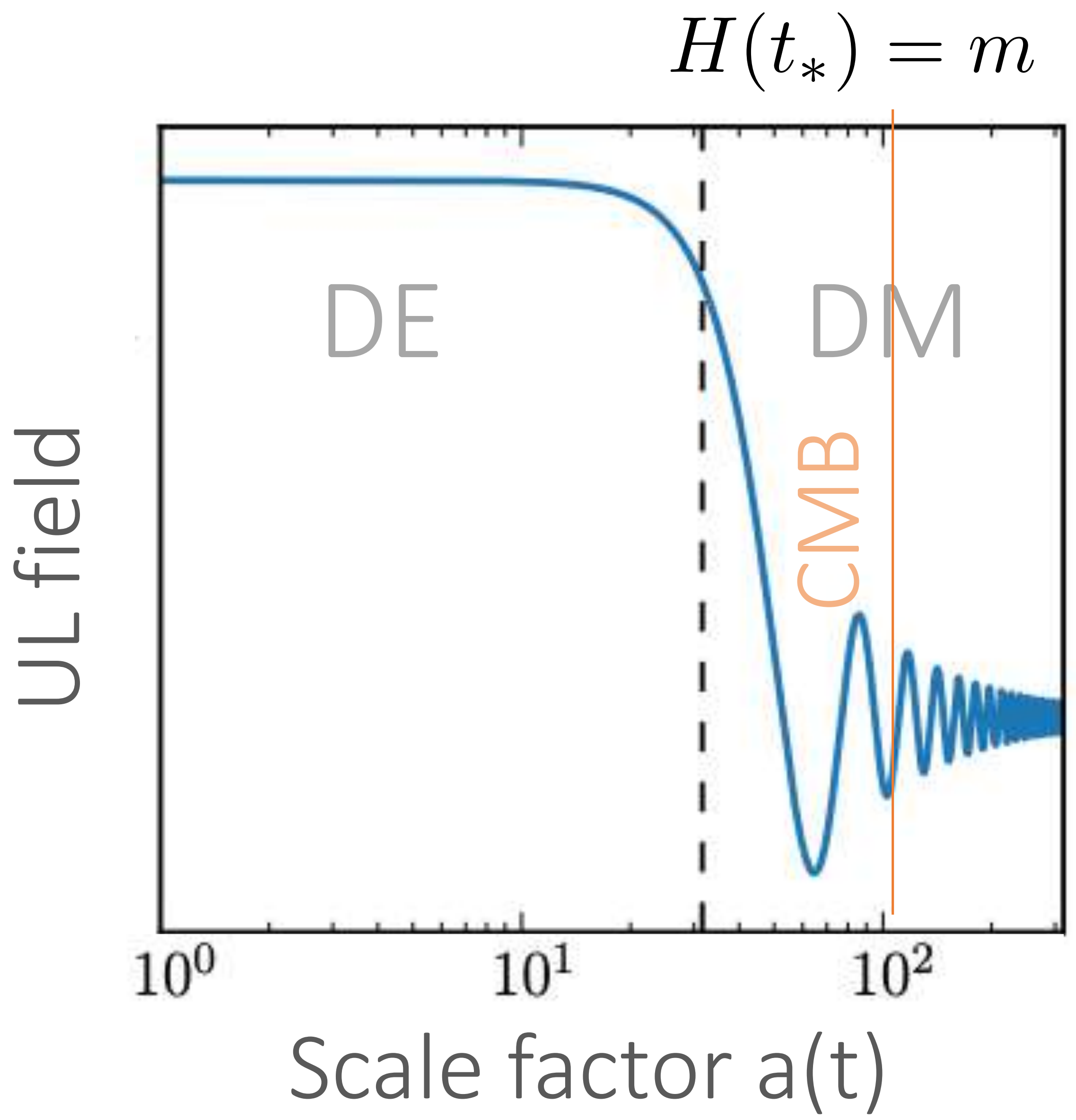
FDM

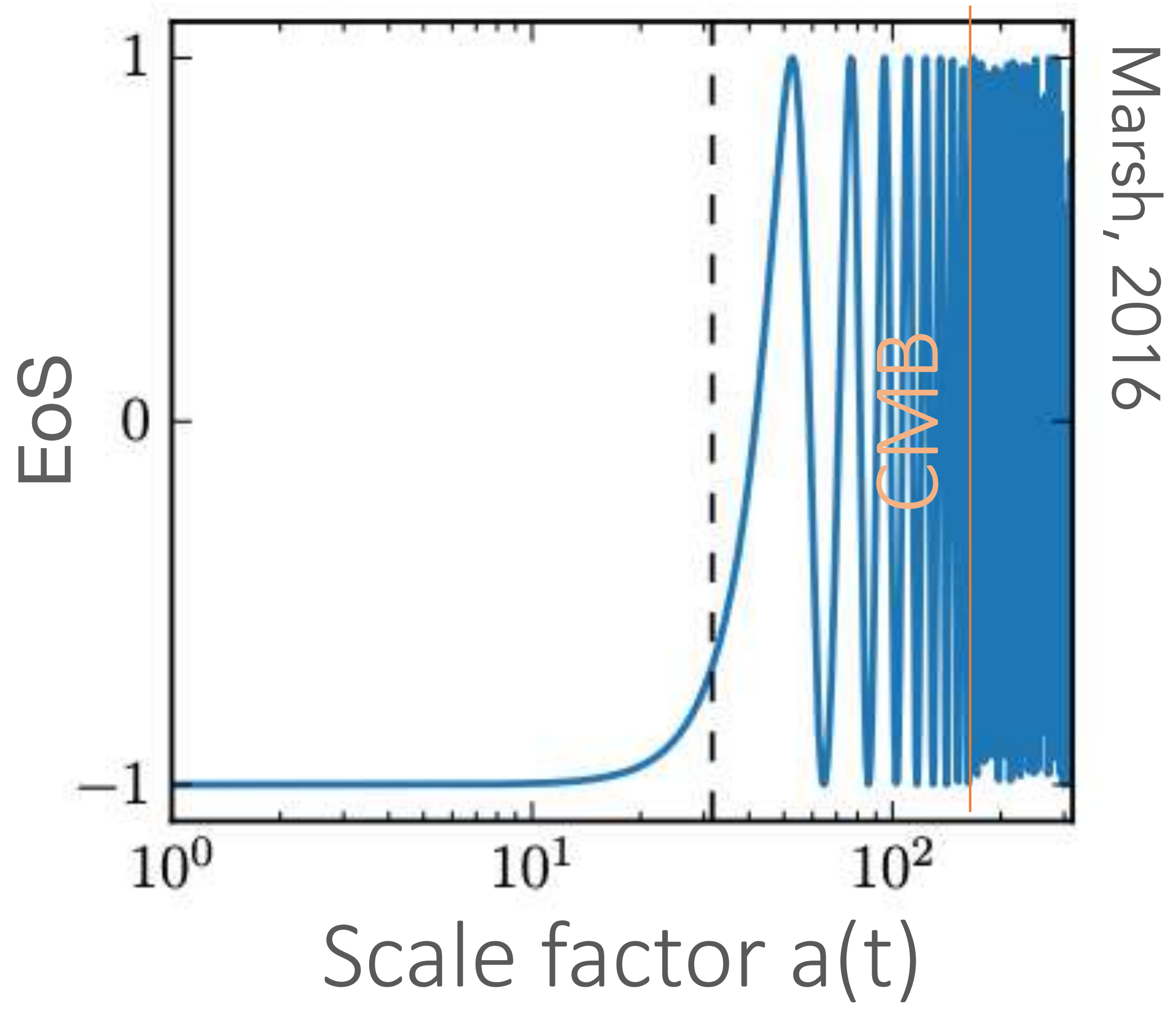


$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

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

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





Ultra-light fields as Dark Energy

Behave as (most of) dynamical dark energy with $w \sim -1$ for

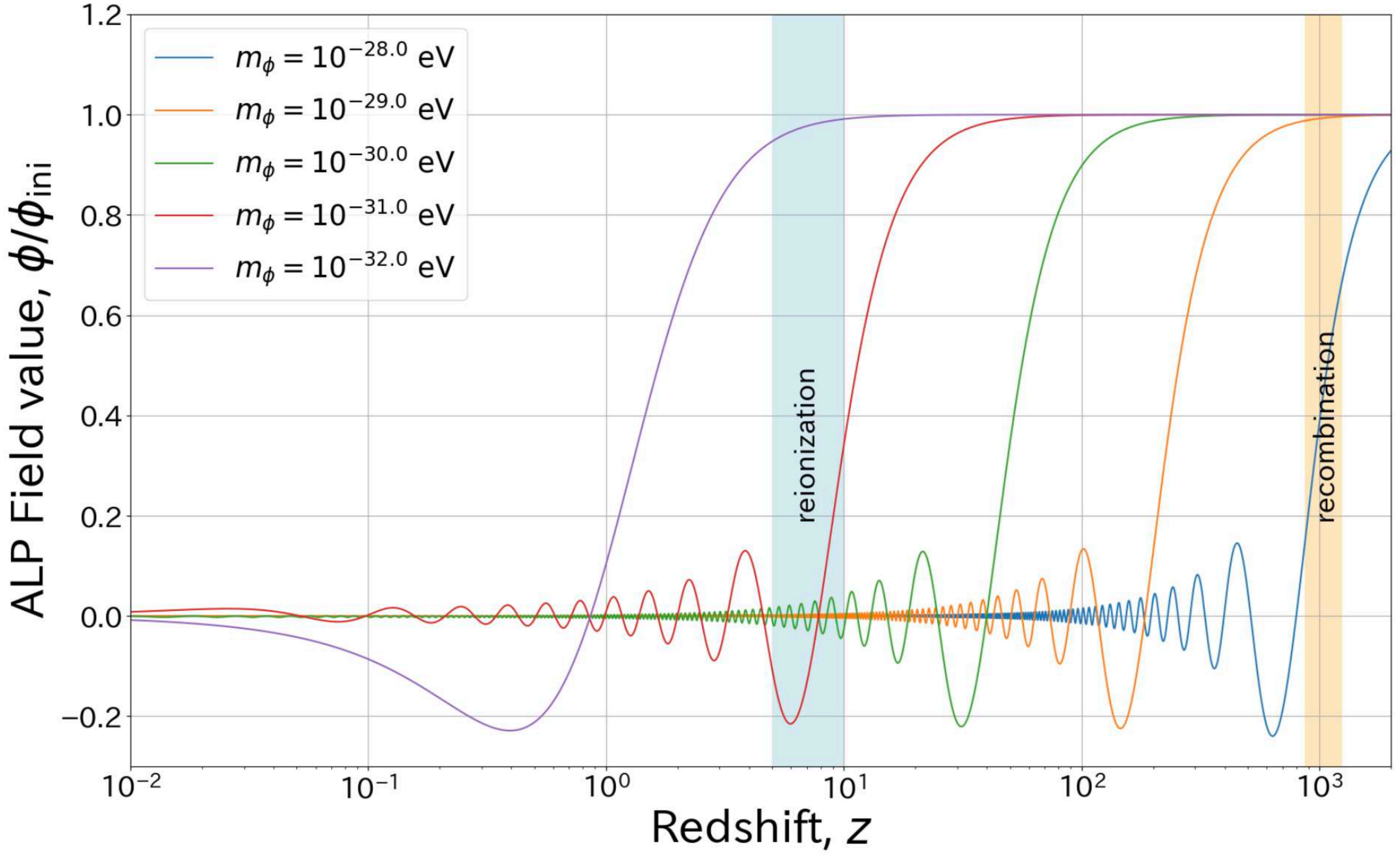
$$m_{\rm fdm} < 10^{-32}\,{\rm eV}$$

Like quintessence with an axion-like potential:

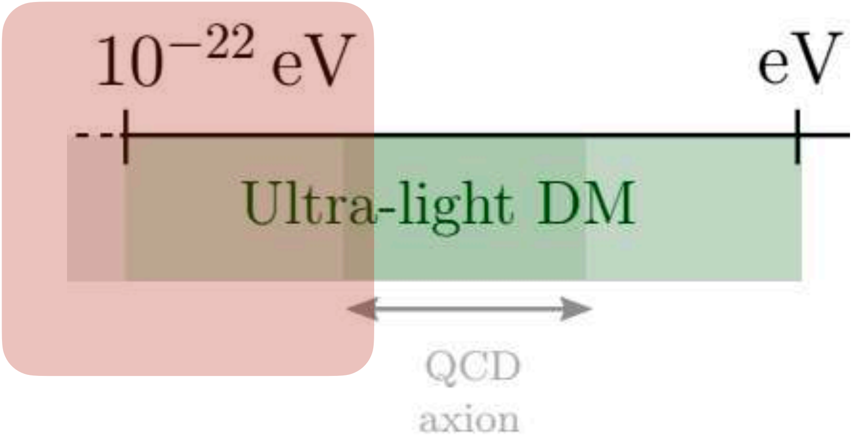
$$V(\phi) = \Lambda^4[1 - \cos(\phi/f_a)]^n$$

$$\Lambda^2 = m_a f_a$$

(Also early dark energy)



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

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

Schrödinger equation (Gross-Pitaevskii)

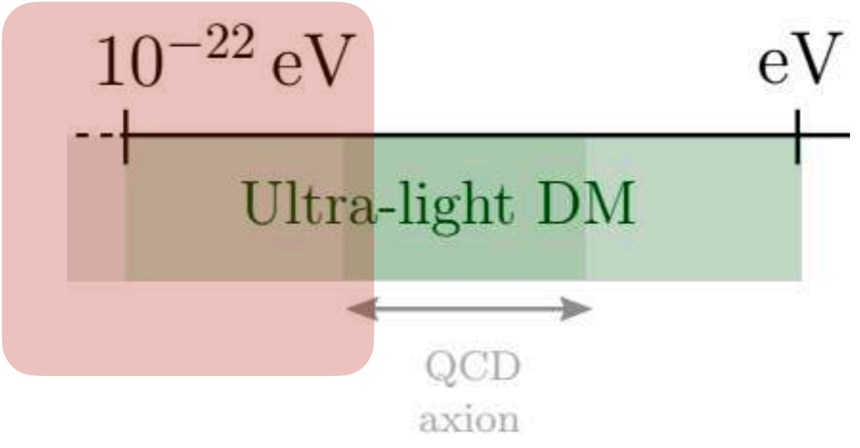
Poisson equation

$g = 0$ → FDM

$g \neq 0$ → SIFDM

Fundamentally different than CDM/WDM/SIDM!

Structure formation - non-relativistic regime



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

$g = 0$ → FDM

$g \neq 0$ → SIFDM

Fundamentally different than CDM/WDM/SIDM!

FLUID DESCRIPTION

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

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

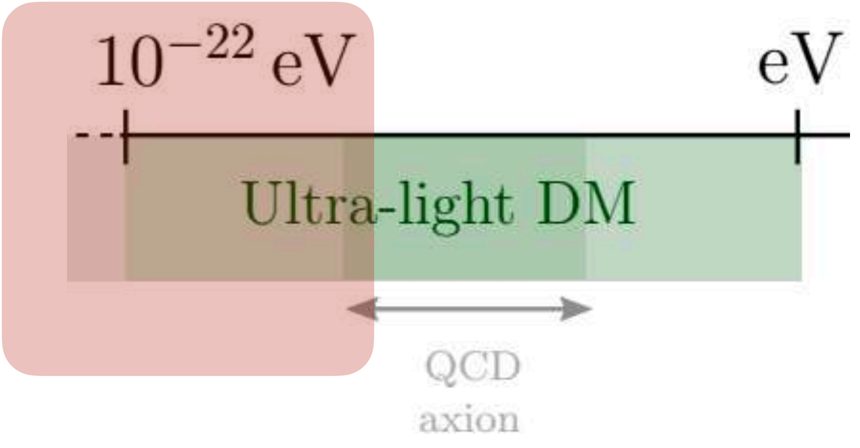
$$\dot{\mathbf{v}} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - P_{int} - \frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

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

Quantum pressure

→ Finite Jeans length - Suppresses structure formation on small scales

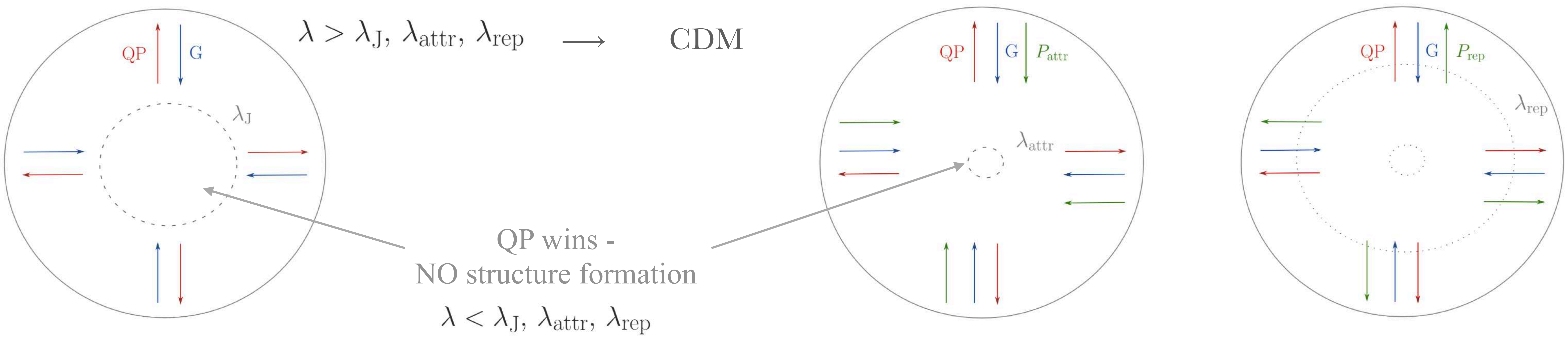
Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

SIFDM

FDM | ATTRACTIVE | REPULSIVE



$g < 0$ | $g > 0$

Finite size coherent core – Bose stars

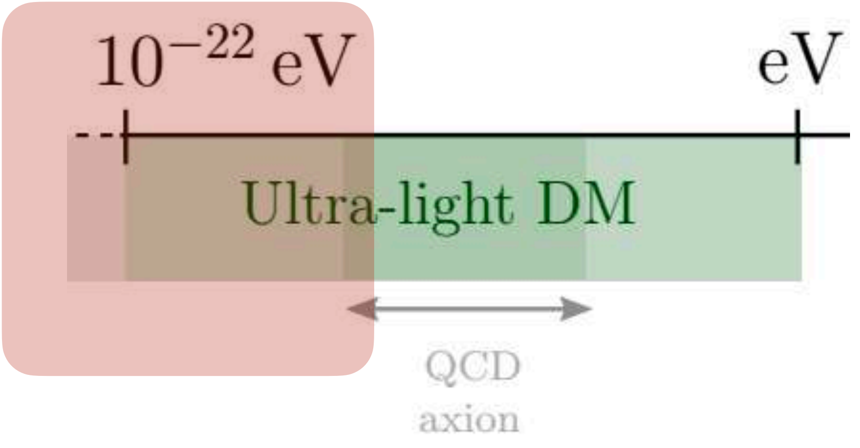
$$\lambda_J = 55 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{-1/4} (\Omega_m h)^{-1/4}\,\mathrm{kpc}$$

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

For attractive interactions can only form localized clumps (solitons)

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

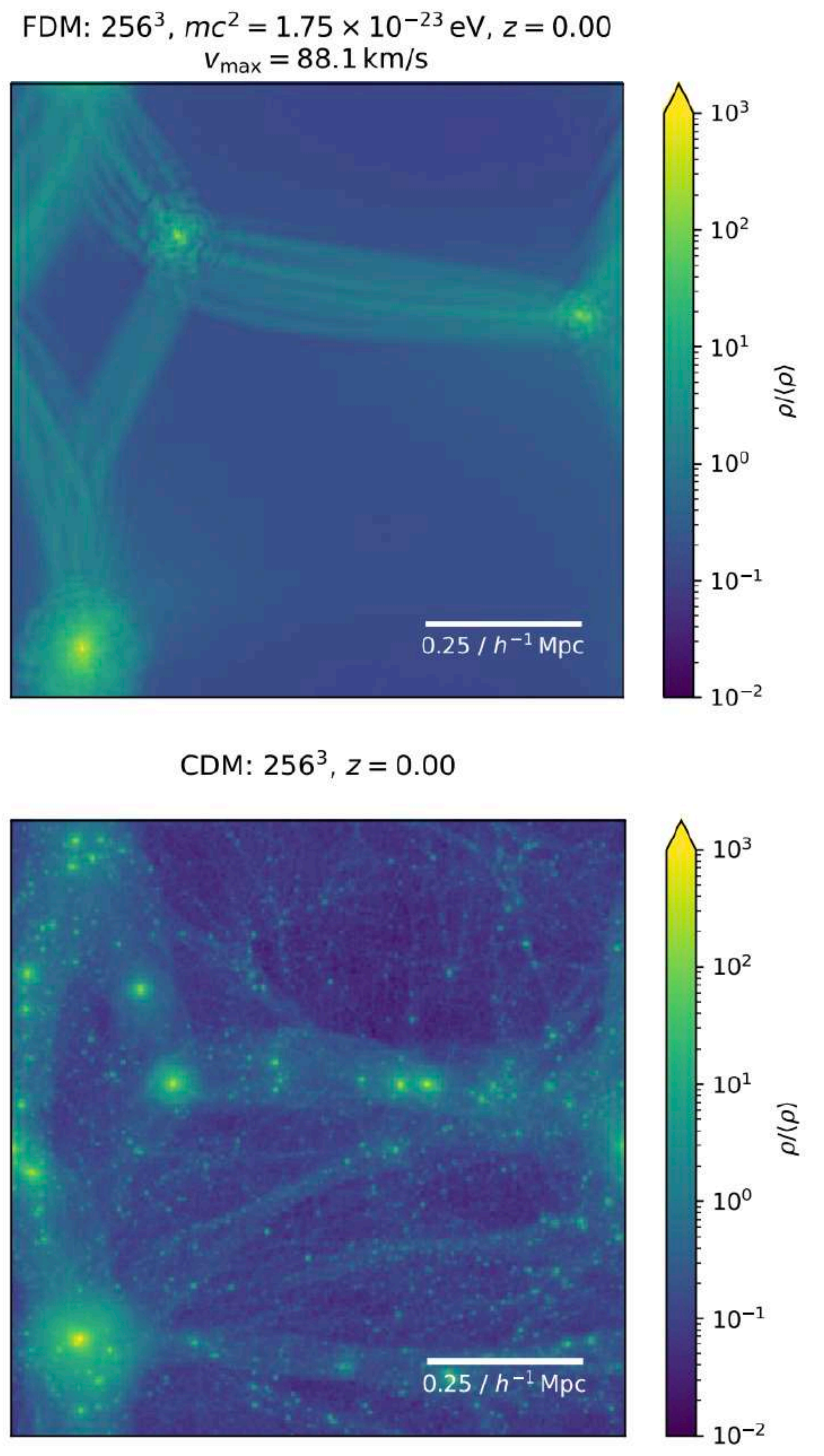
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

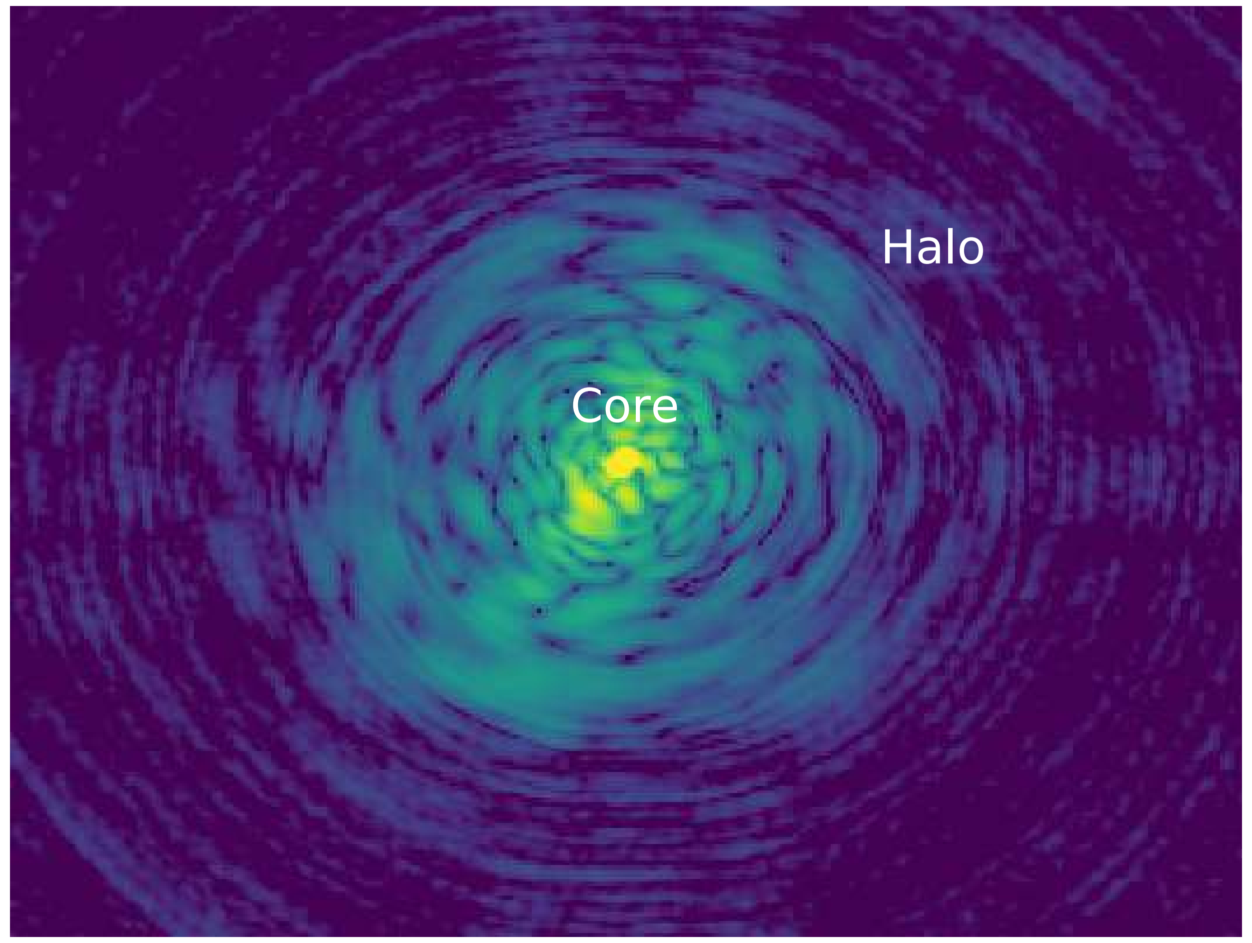
* Focus only in gravitational signatures

Suppression of small structures

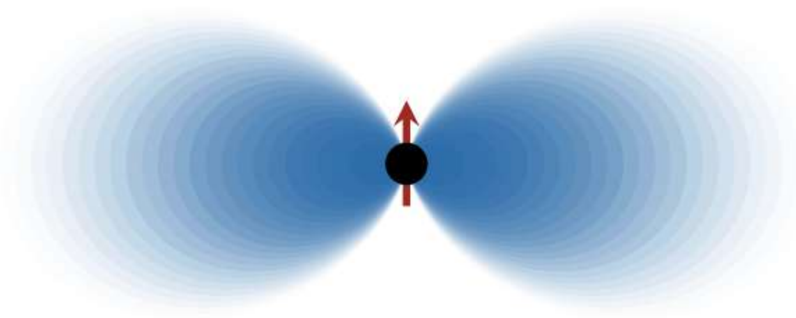


S. May et al. 2021

Formation of a solitonic core

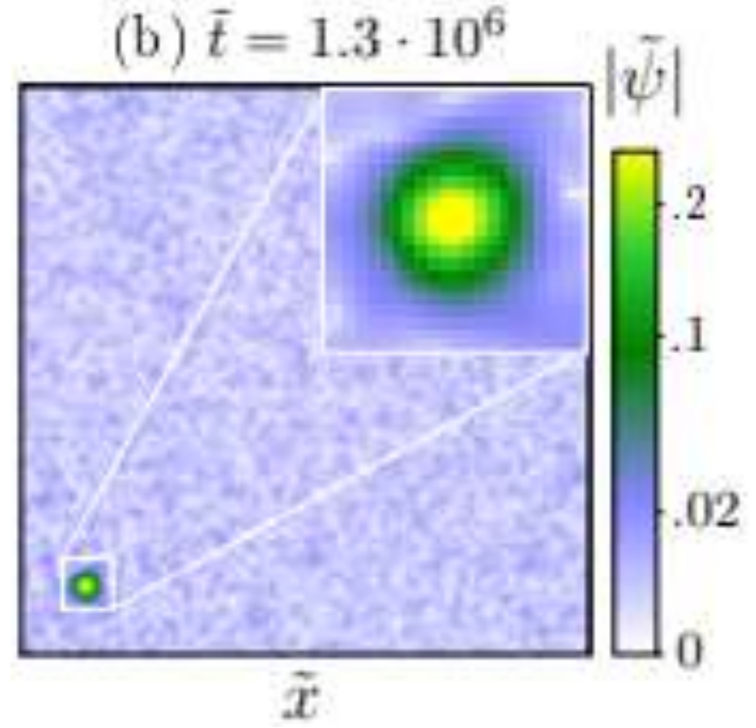


Axion clouds



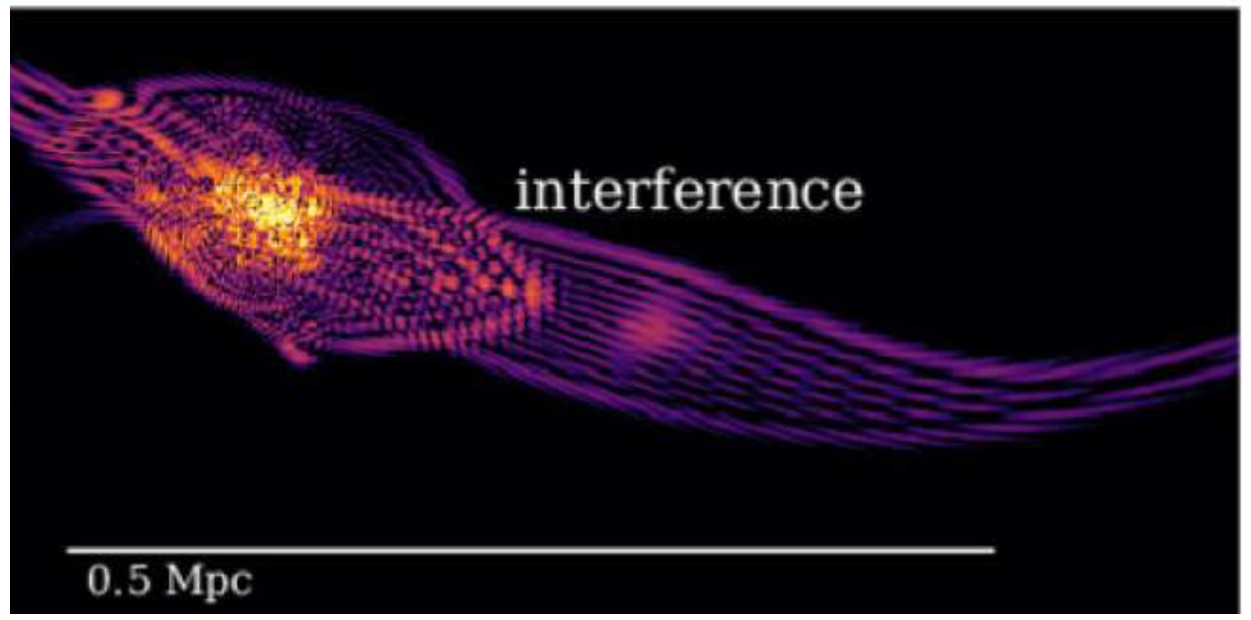
Baumann et al. 2019

Dynamical effects



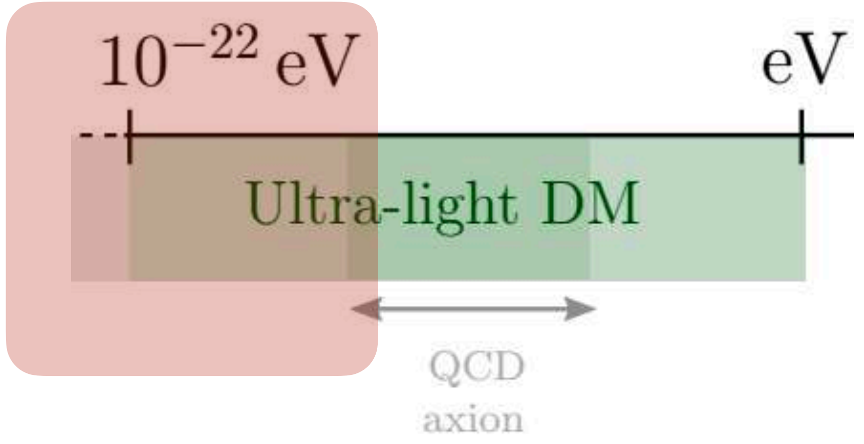
Levkov et al. 2018

Wave interference

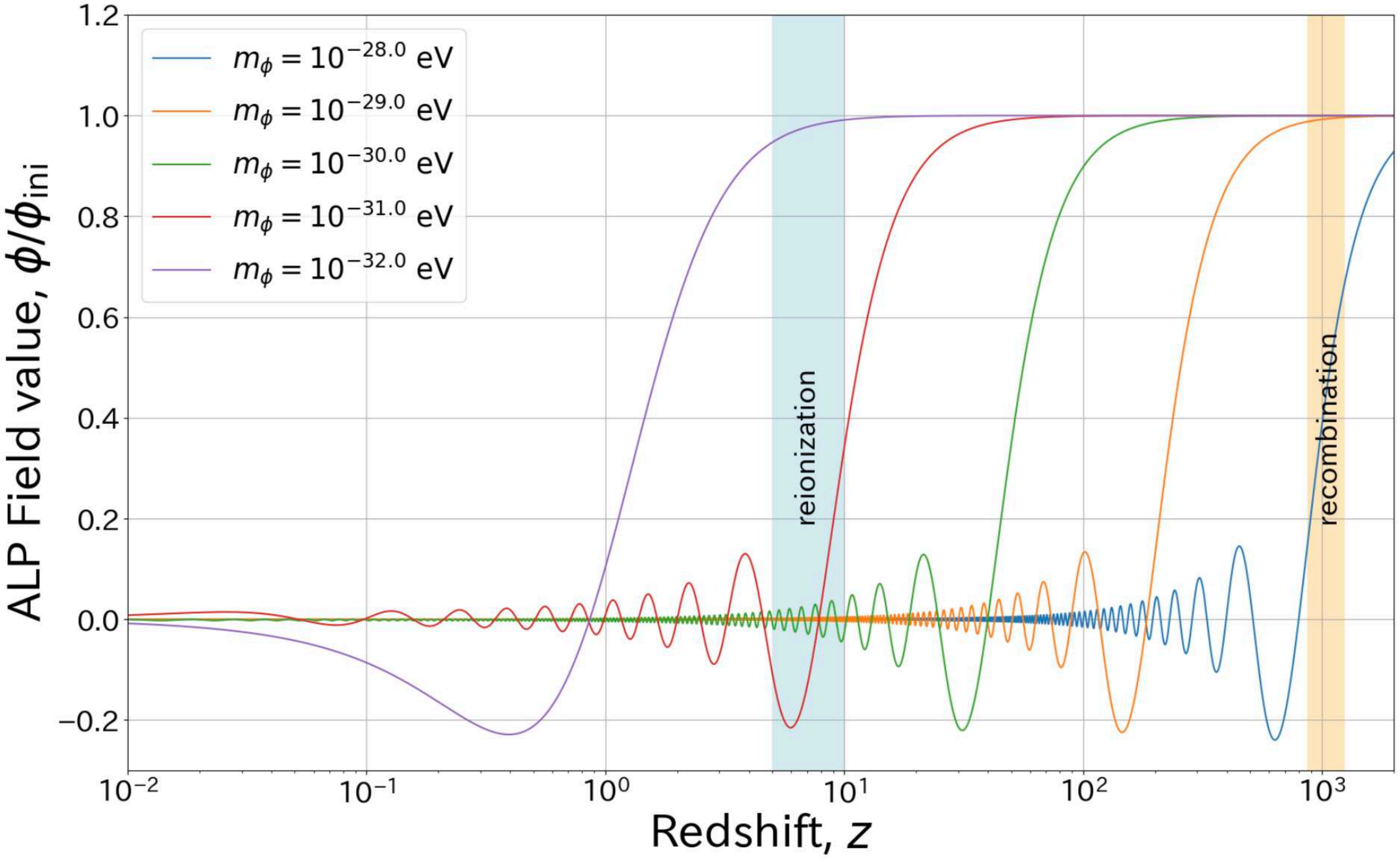


Mocz et al. 2017

Linear evolution



Boson/ Scalar field in a cosmological (FRW) background



Boltzmann codes: axionCAMB, axionECAMB, AxiCLASS

New emulator (to appear *soon*)

Condition DM today:

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

Predictions

Non-linear evolution - simulations

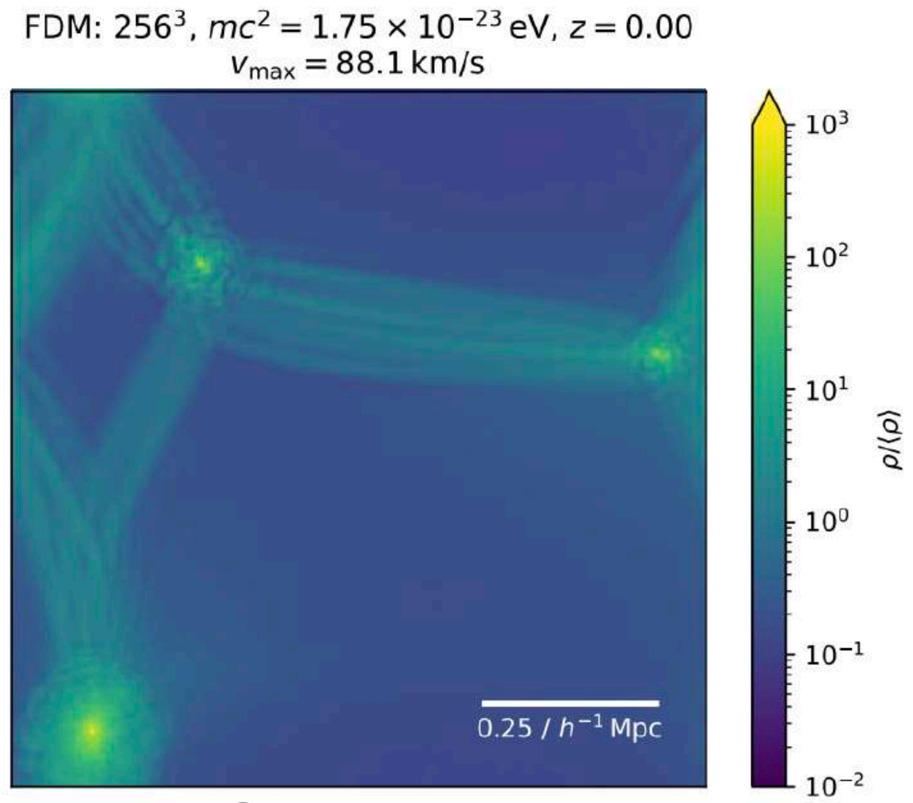
Pseudo-spectral methods

Solves the Schrödinger-Poisson equations.

→ Used widely in the field to simulate: isolated halos, the formation of cores, and cosmological simulations

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

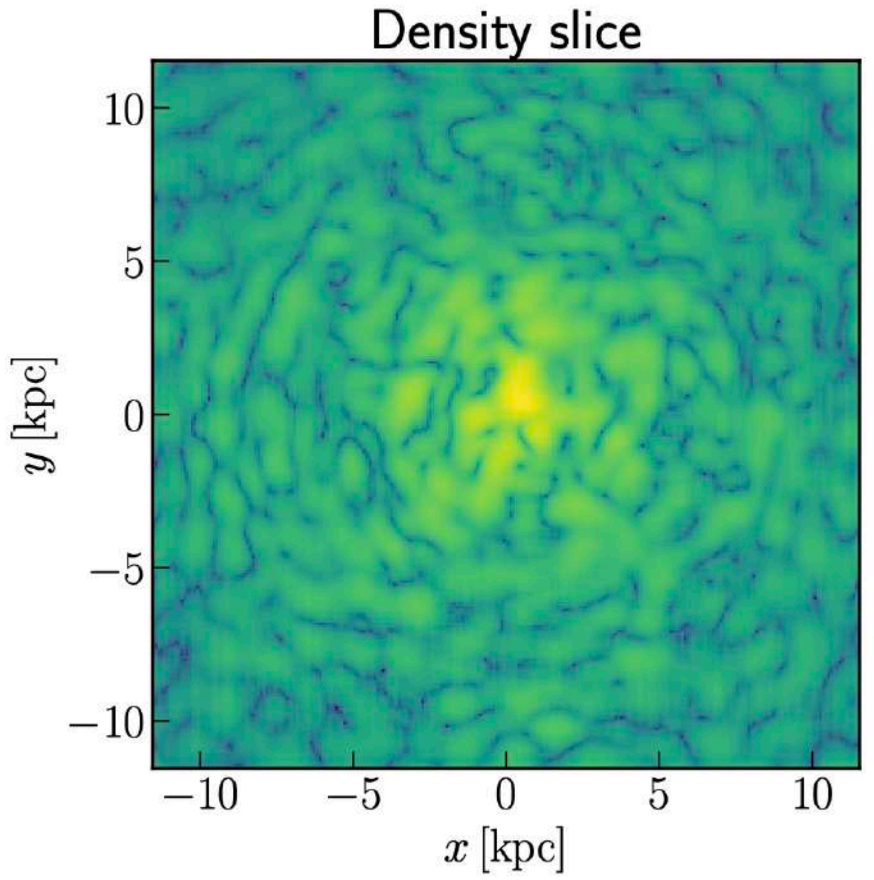
Largest to date: 10/Mpc/h



S. May et al. 2021

Mock halo generation

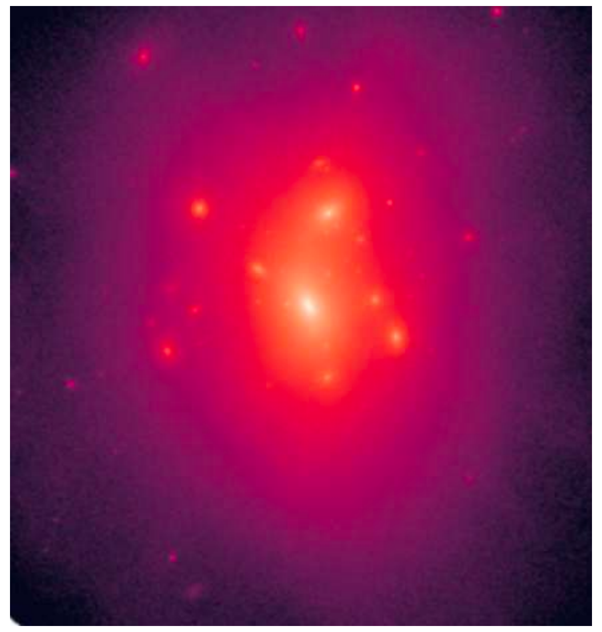
- Soliton collisions
- Eigenvalue decomposition: semi-analytical model to describe the halo



Eberhardt et al. 2024

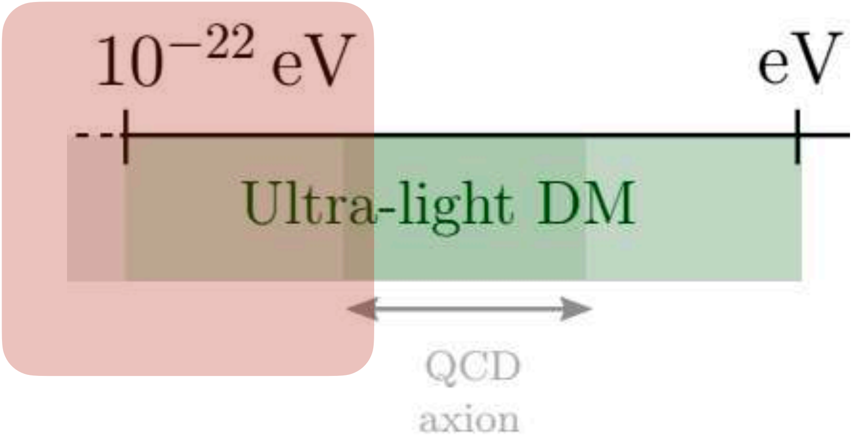
Approximation schemes

- Eigenvalue solvers
- Madelung simulations
- **N-body schemes** (or initial condition sims)



Nadler et al. 2024

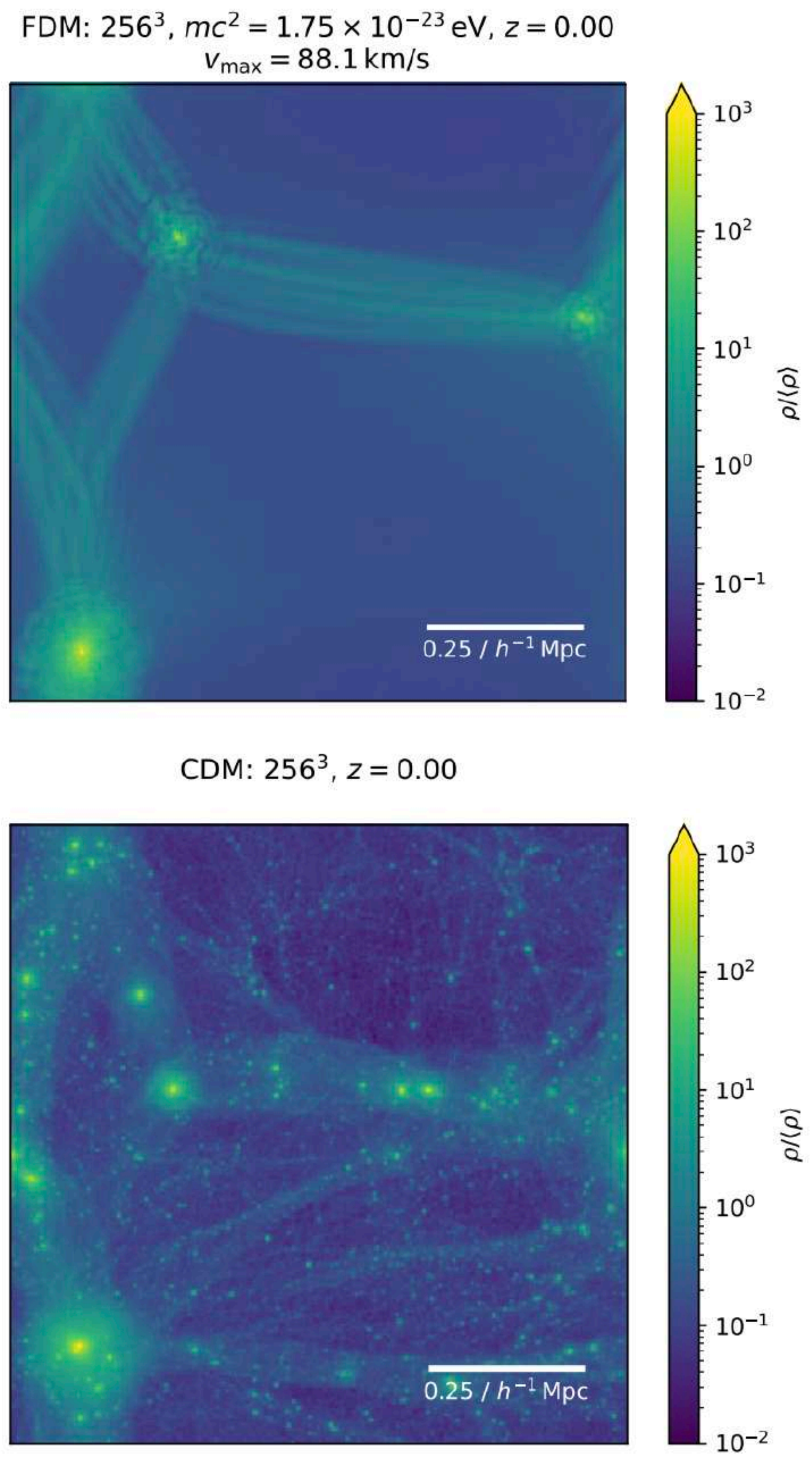
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

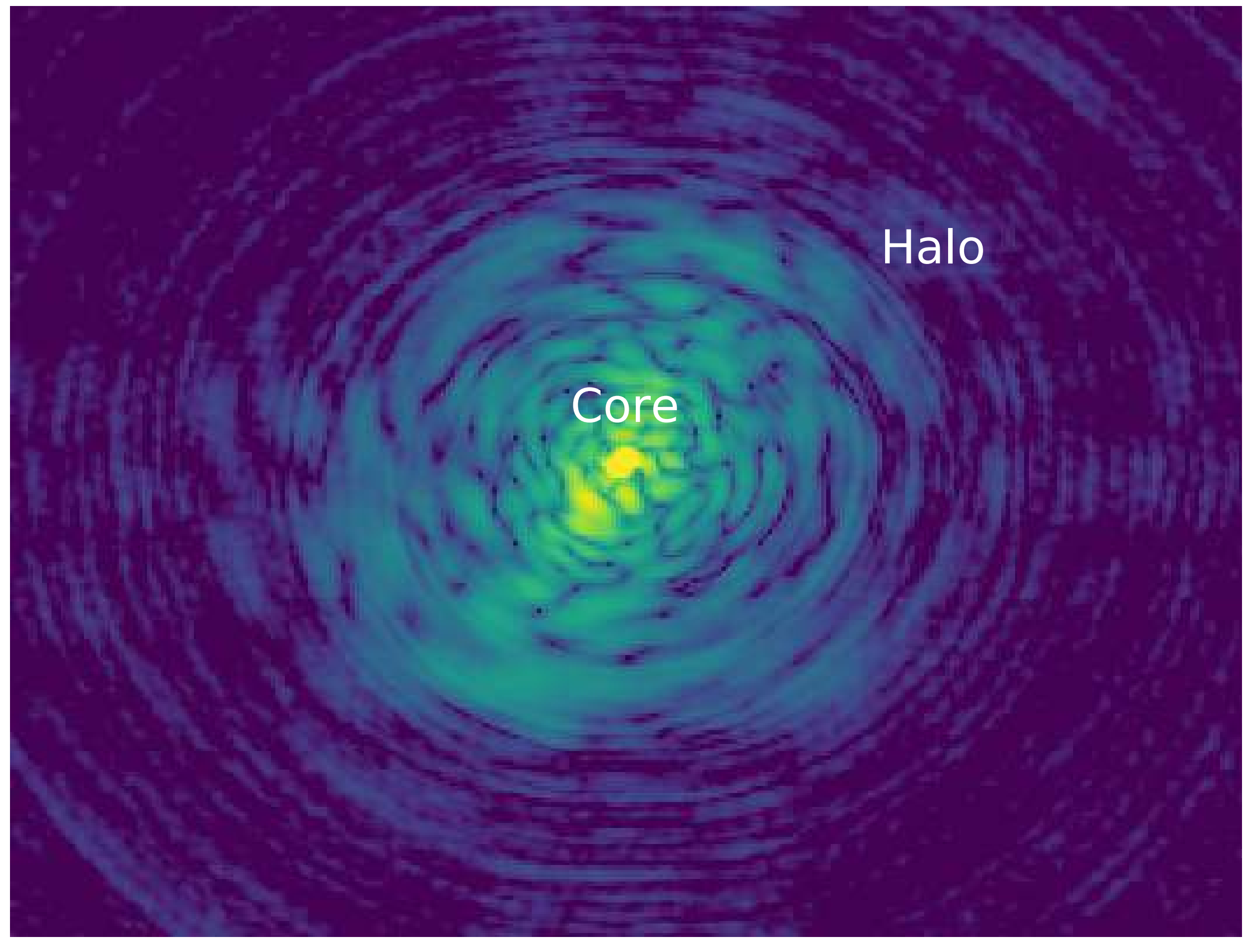
* Focus only in gravitational signatures

Suppression of small structures

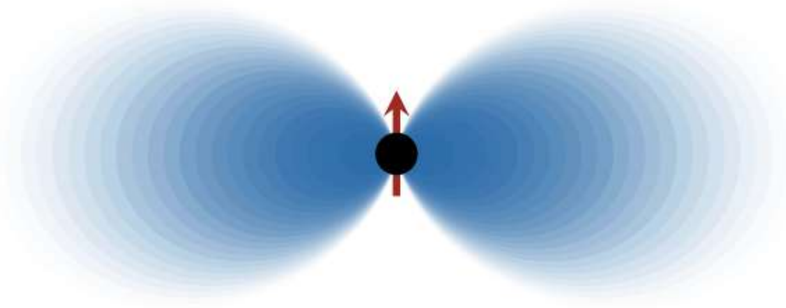


S. May et al. 2021

Formation of a solitonic core

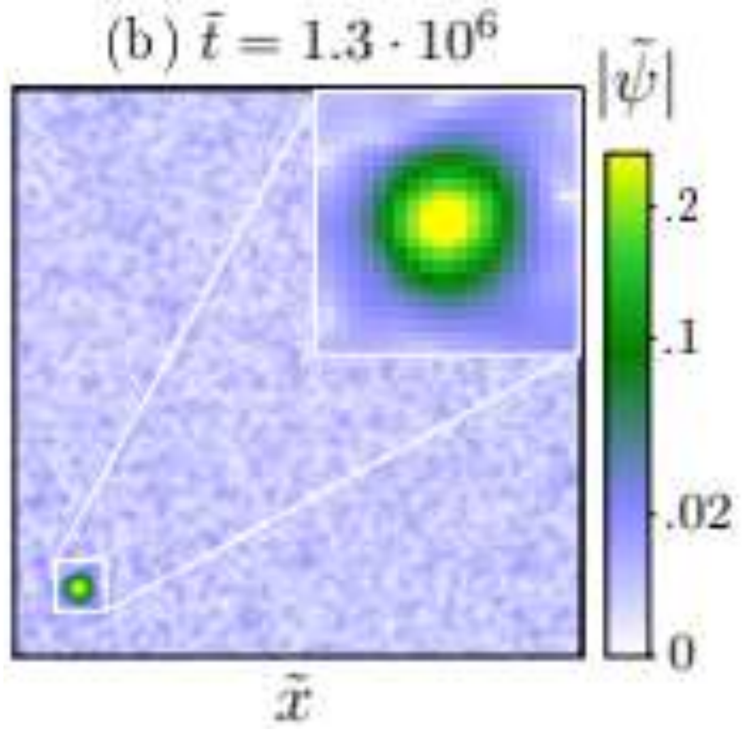


Axion clouds



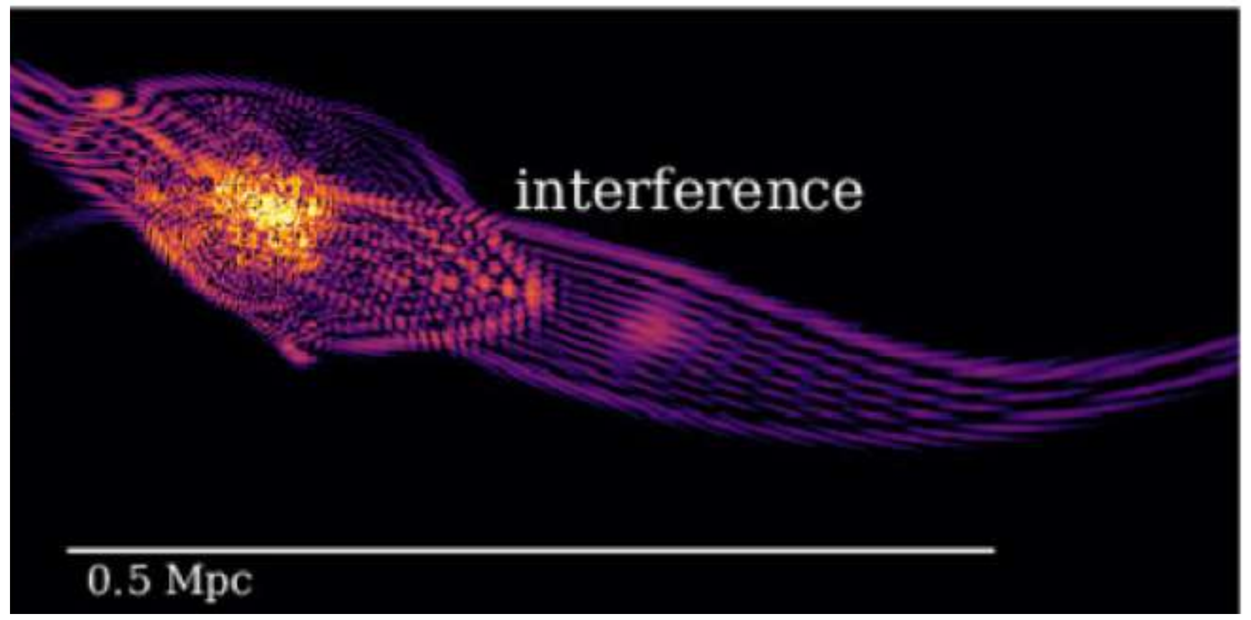
Baumann et al. 2019

Dynamical effects



Levkov et al. 2018

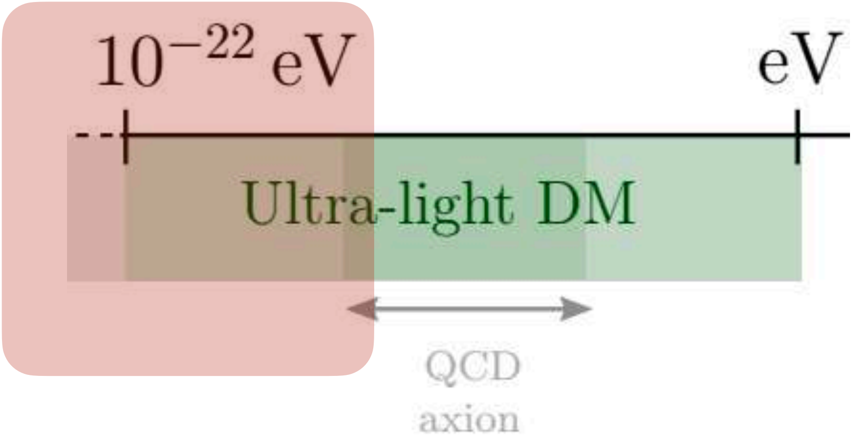
Wave interference



Mocz et al. 2017

Phenomenology

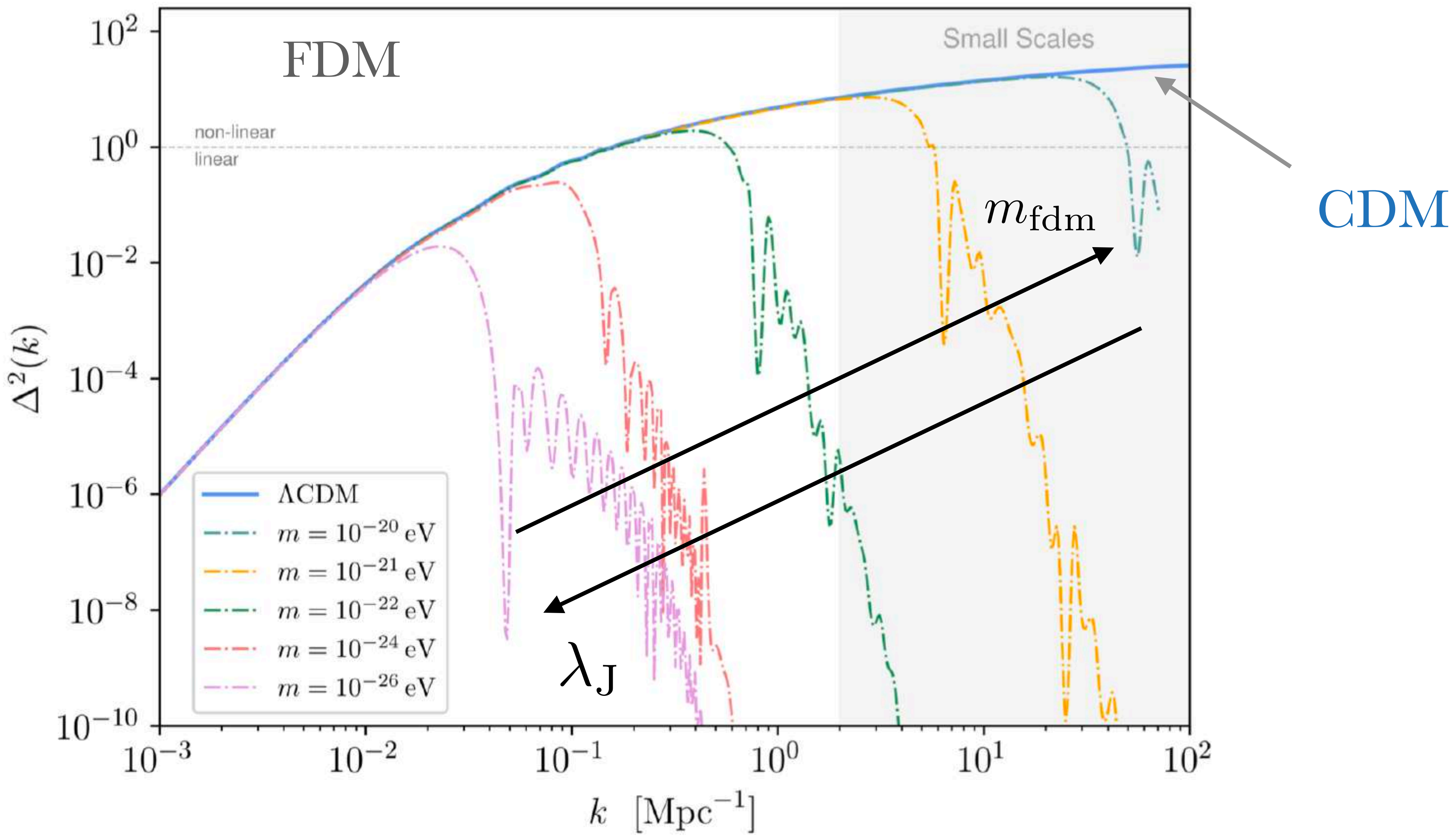
Suppression of small structures



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

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

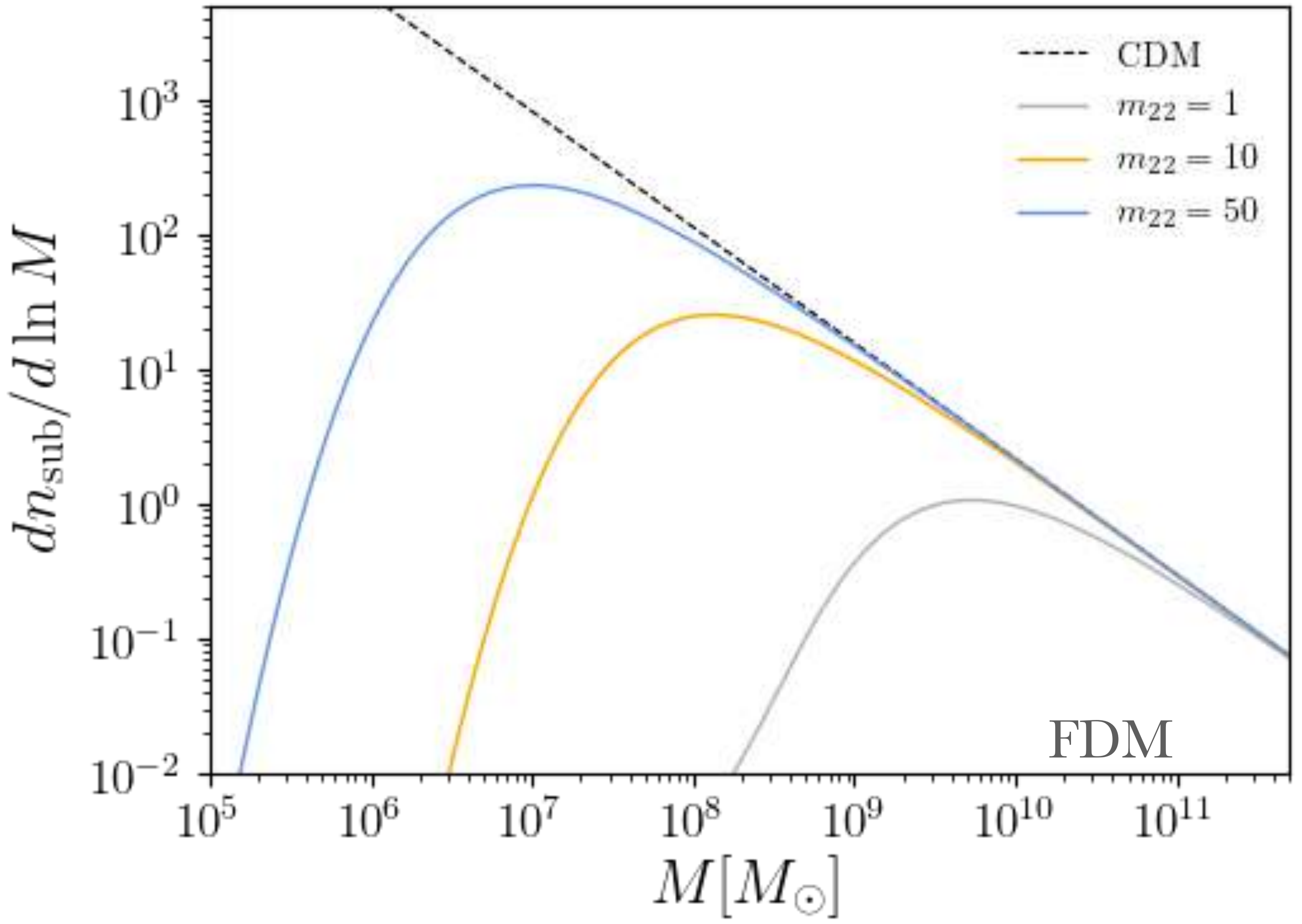
POWER SPECTRUM



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

unconstrained for $k < 10\,\mathrm{Mpc}^{-1}$

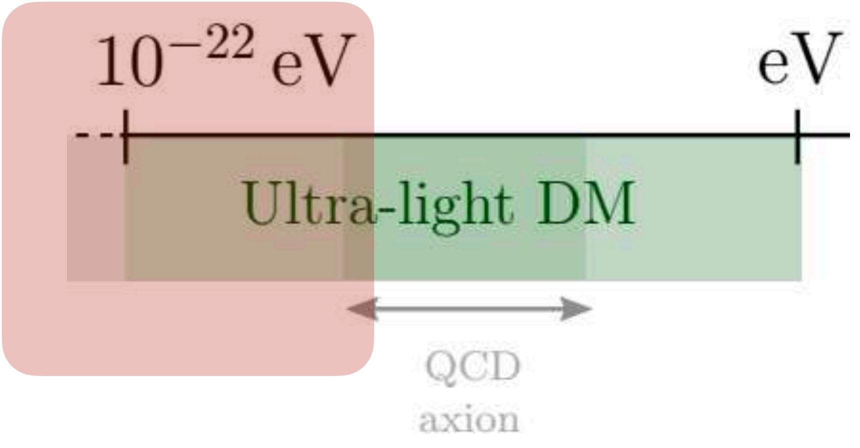
(sub) HALO MASS FUNCTION



* hard to get a proper prediction!

Phenomenology

Suppression of small structures



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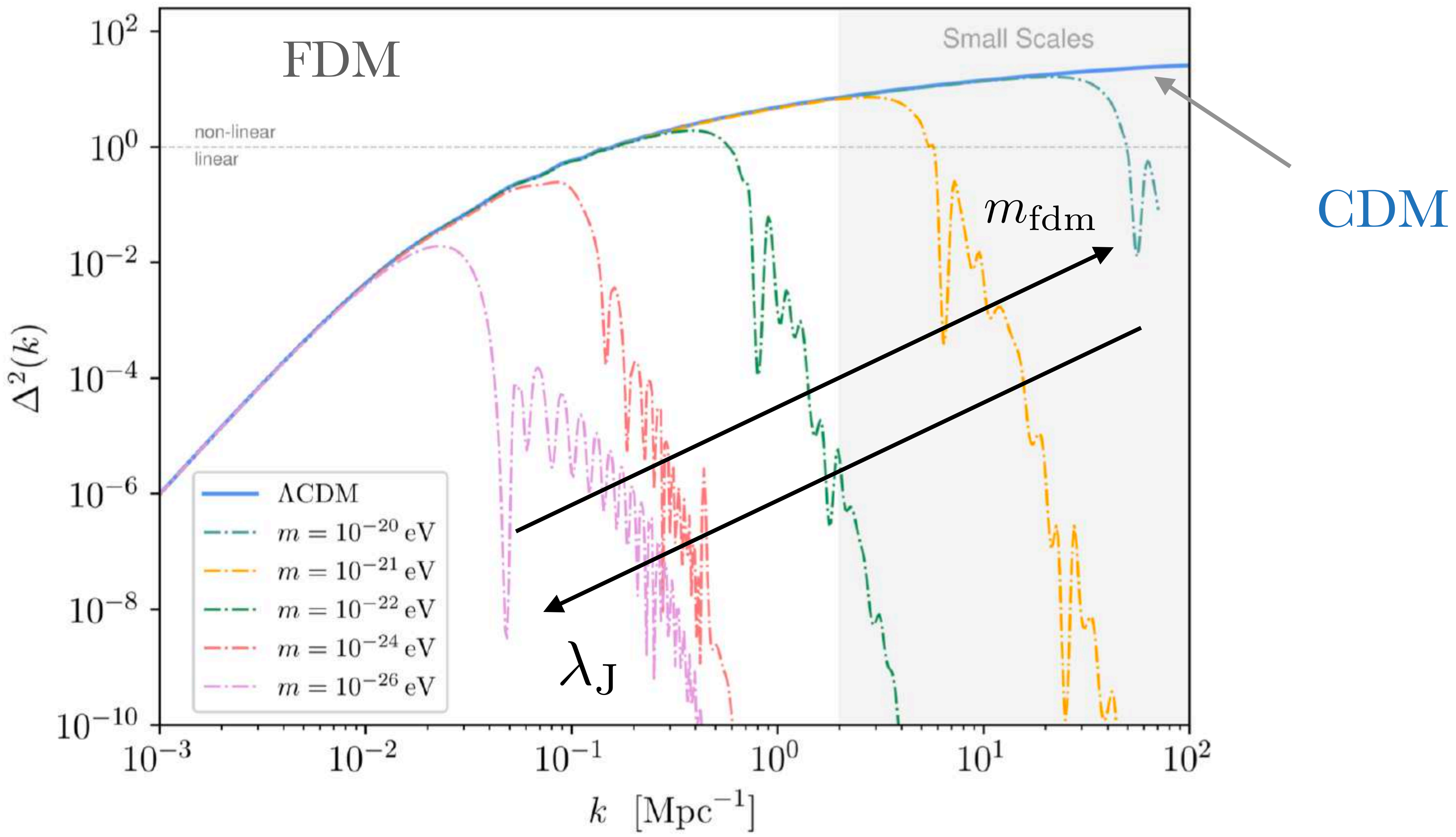
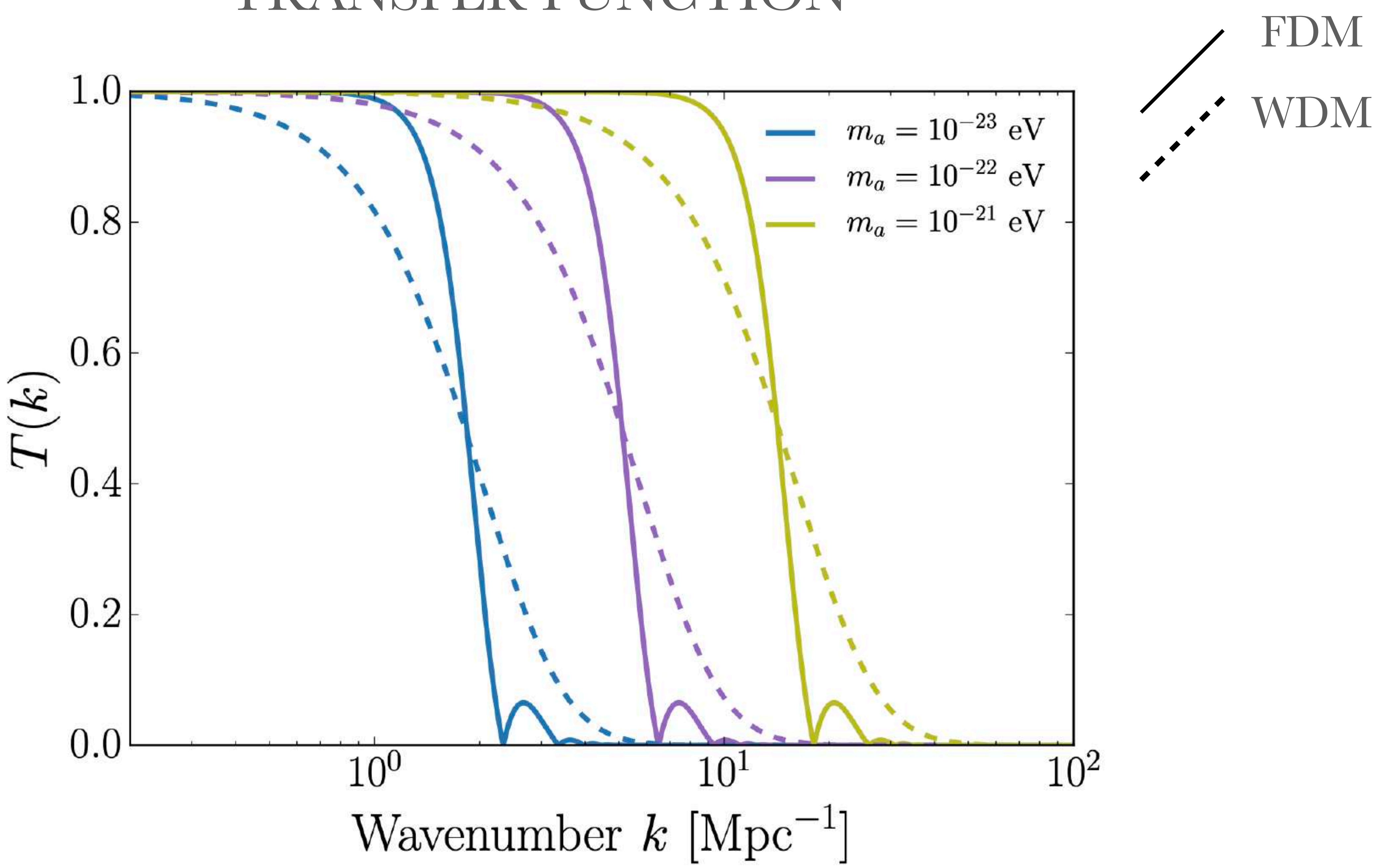
POWER SPECTRUM

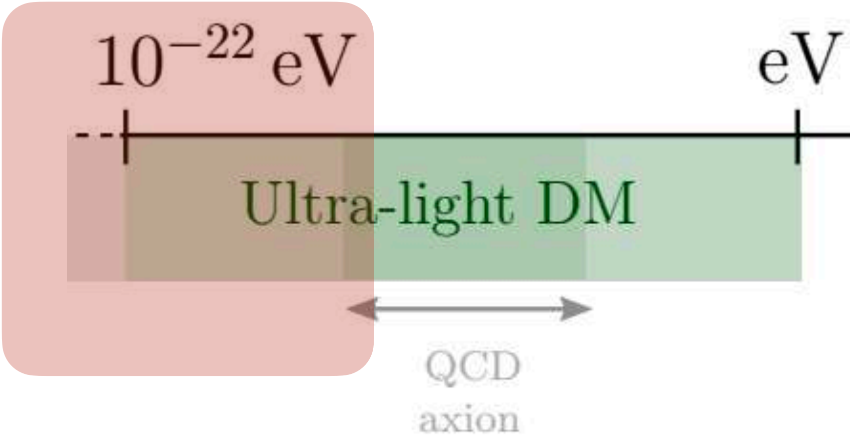


TRANSFER FUNCTION



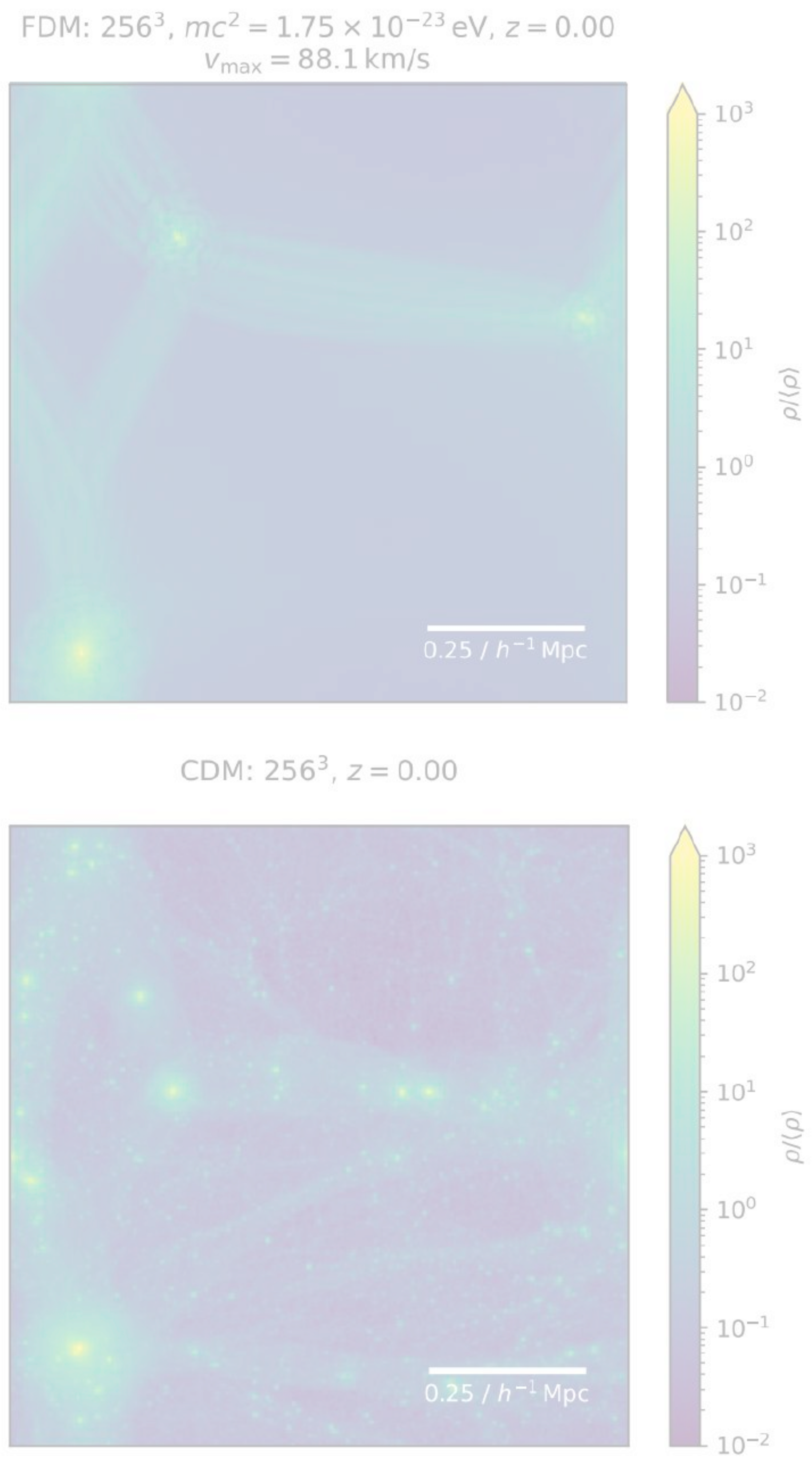
- Degenerate with WDM

Phenomenology



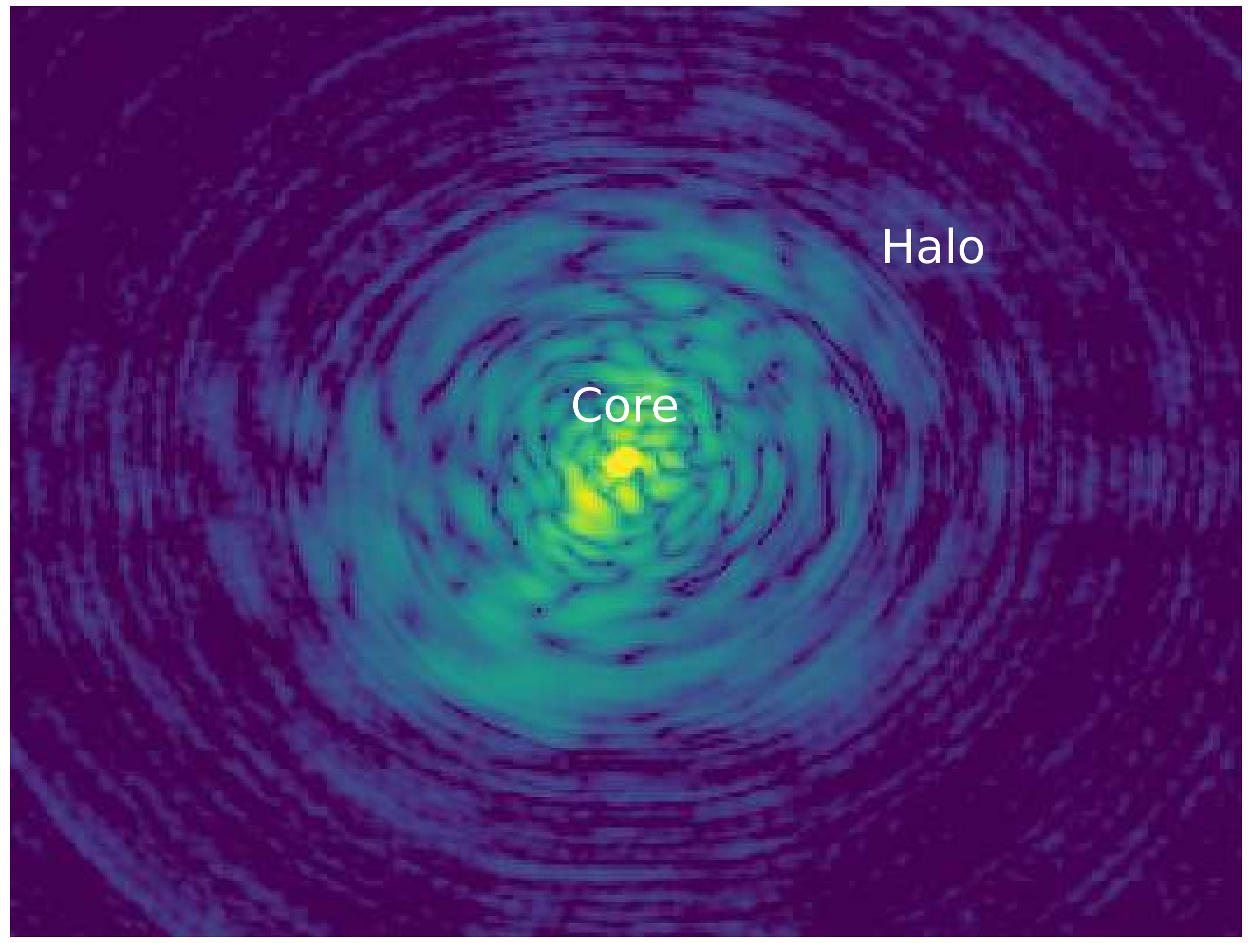
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

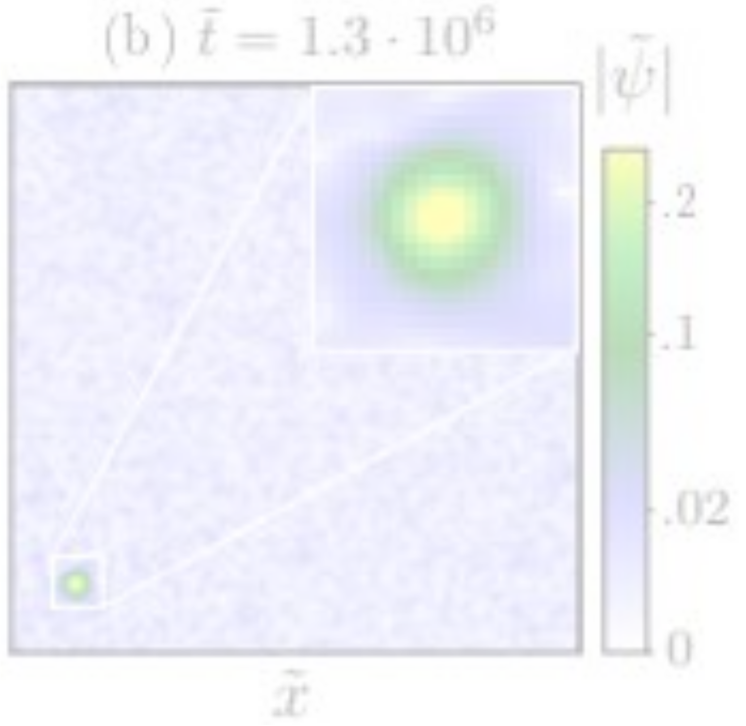


S. May et al. 2021

Formation of a solitonic core



Dynamical effects



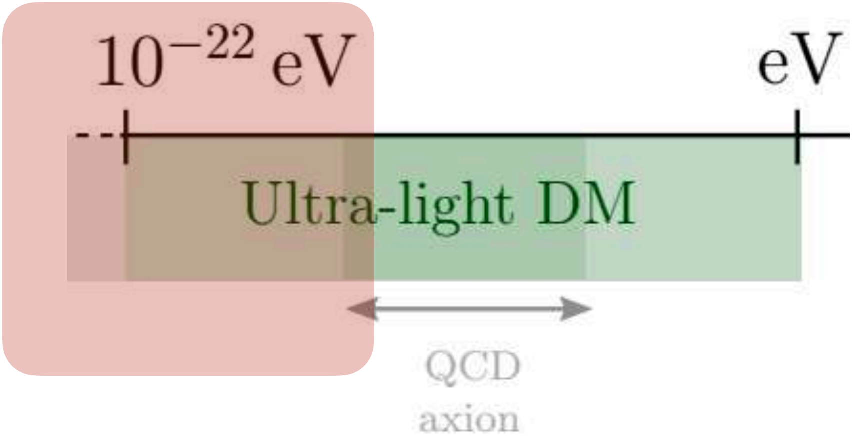
Levkov et al. 2018

Wave interference

Mocz et al. 2017

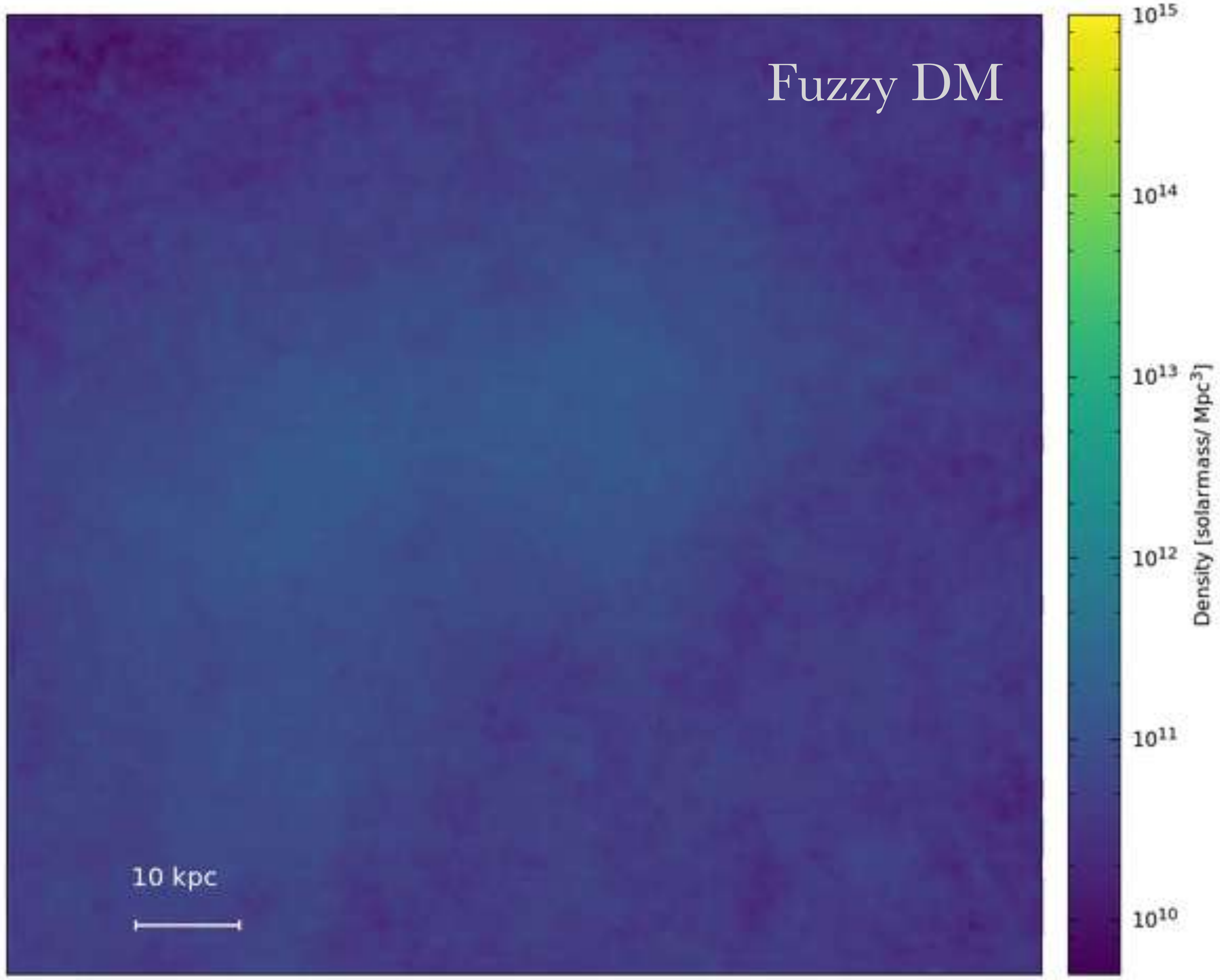
Phenomenology

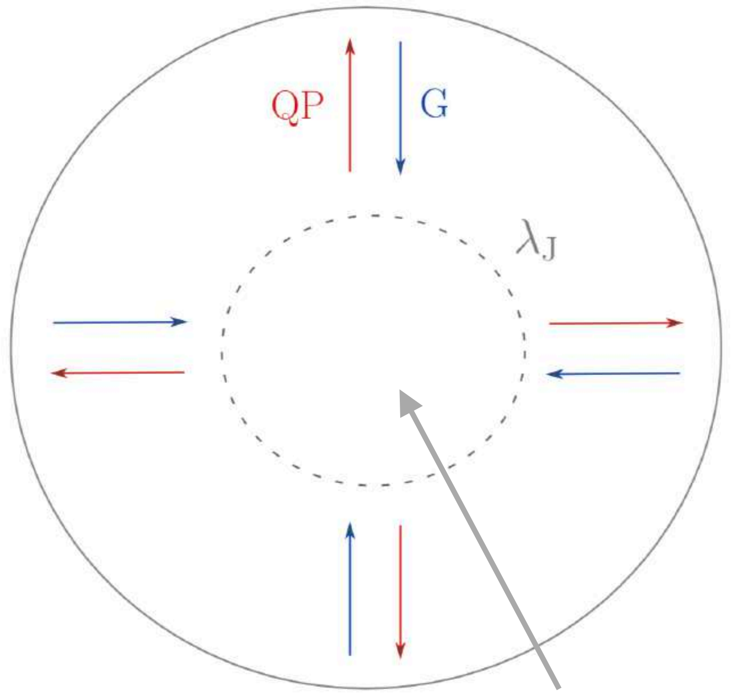
Formation of cores



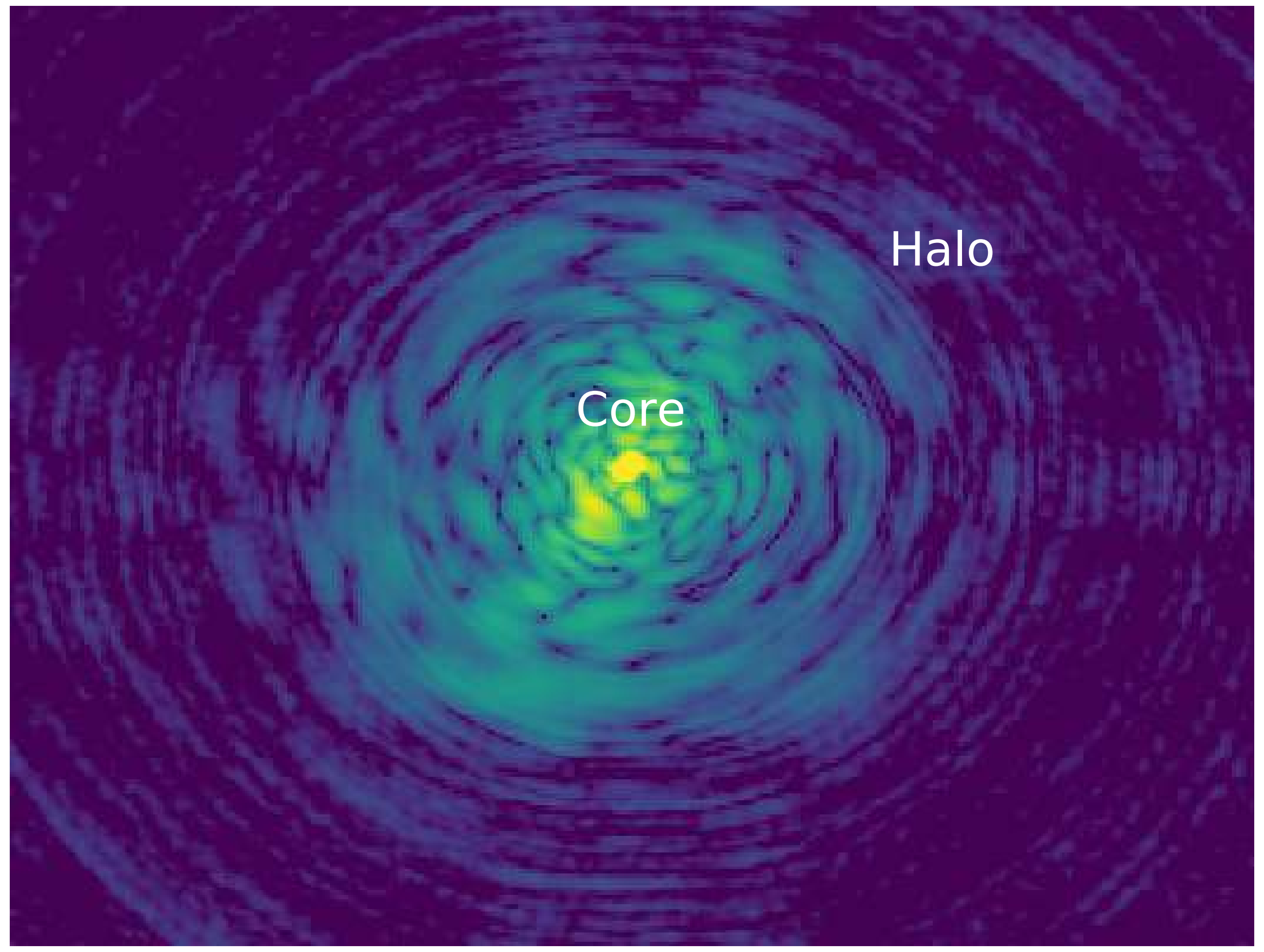
NON-LINEAR evolution: need simulations

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



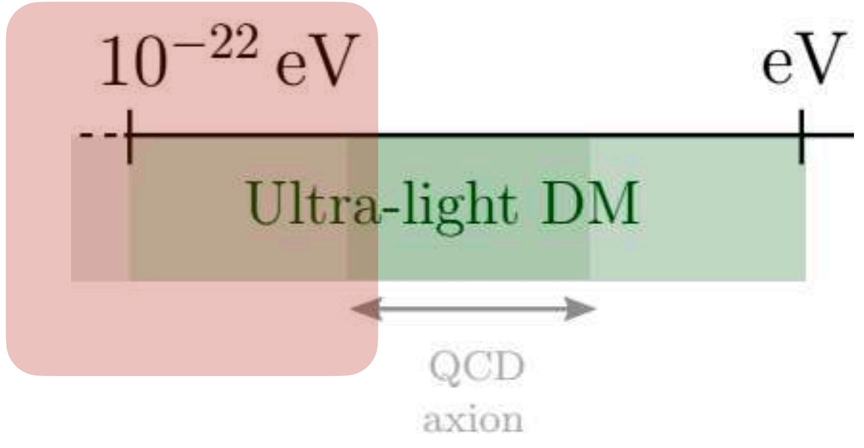


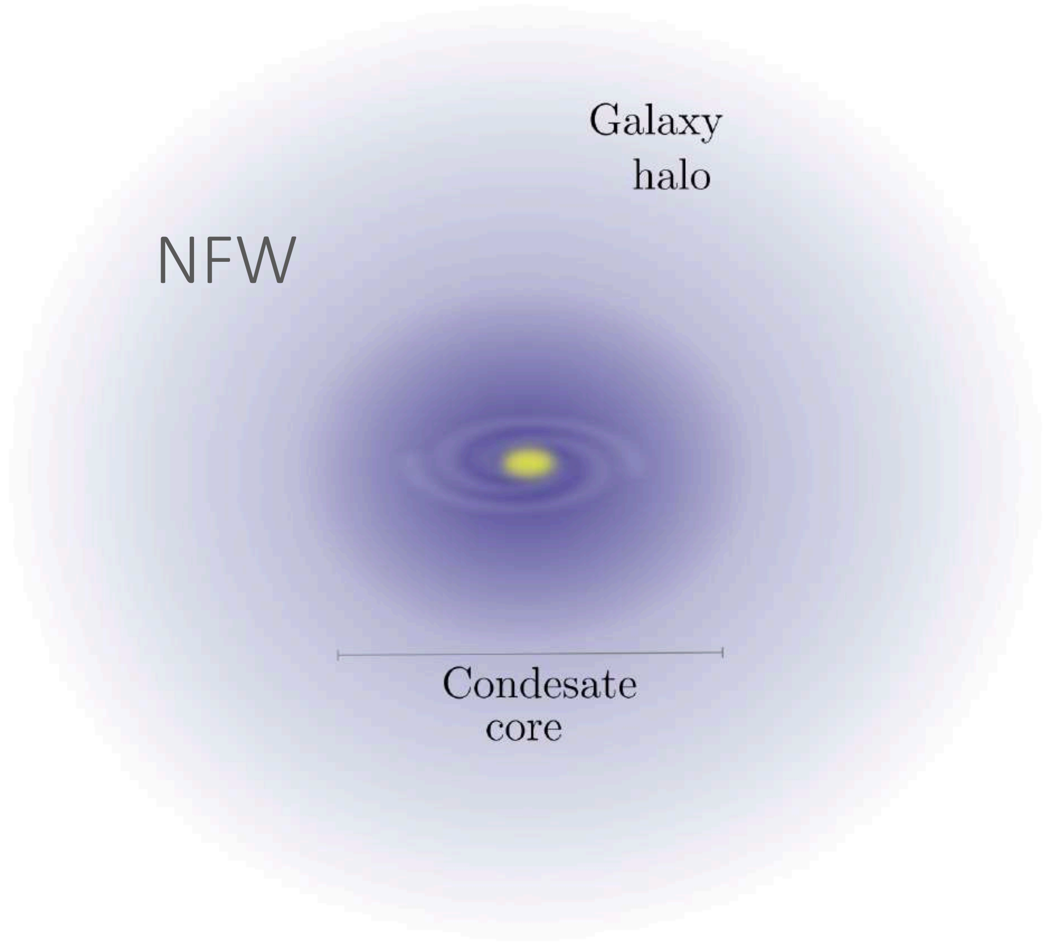
NO structure formation
Stable, oscillating solution



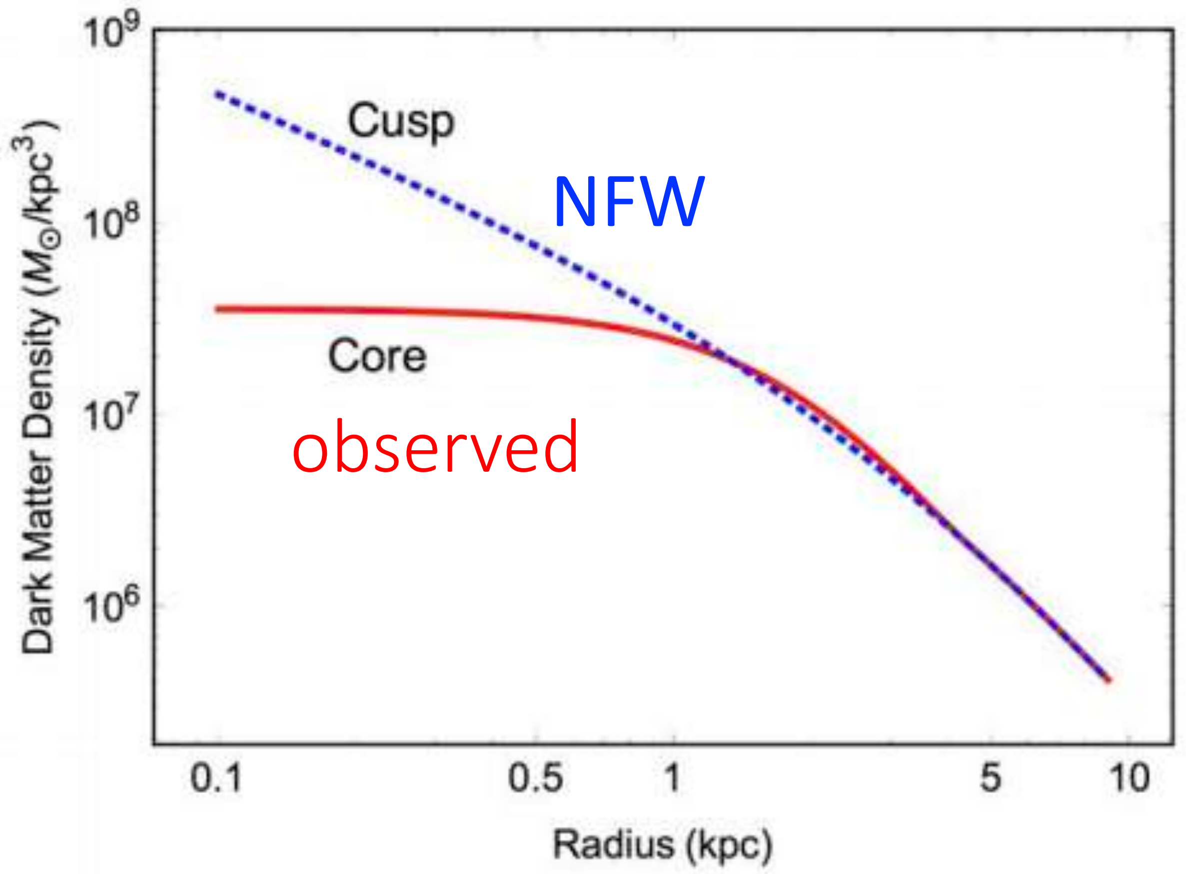
Phenomenology

Formation of cores





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



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

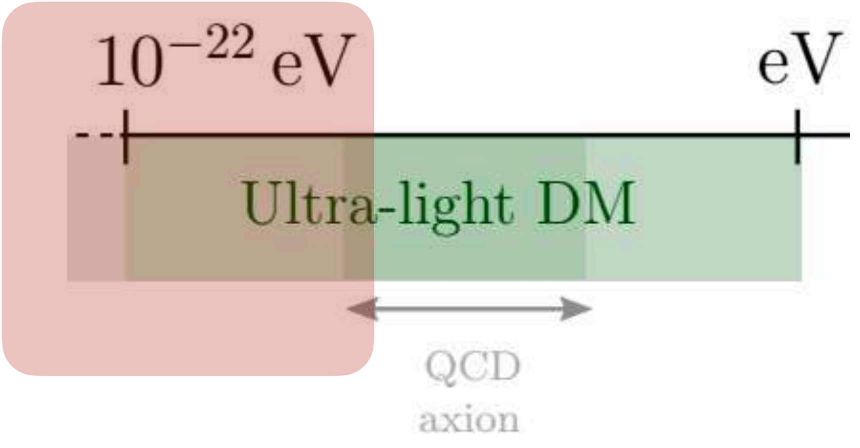
Updated in *Chan, EF et al 2021*

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

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

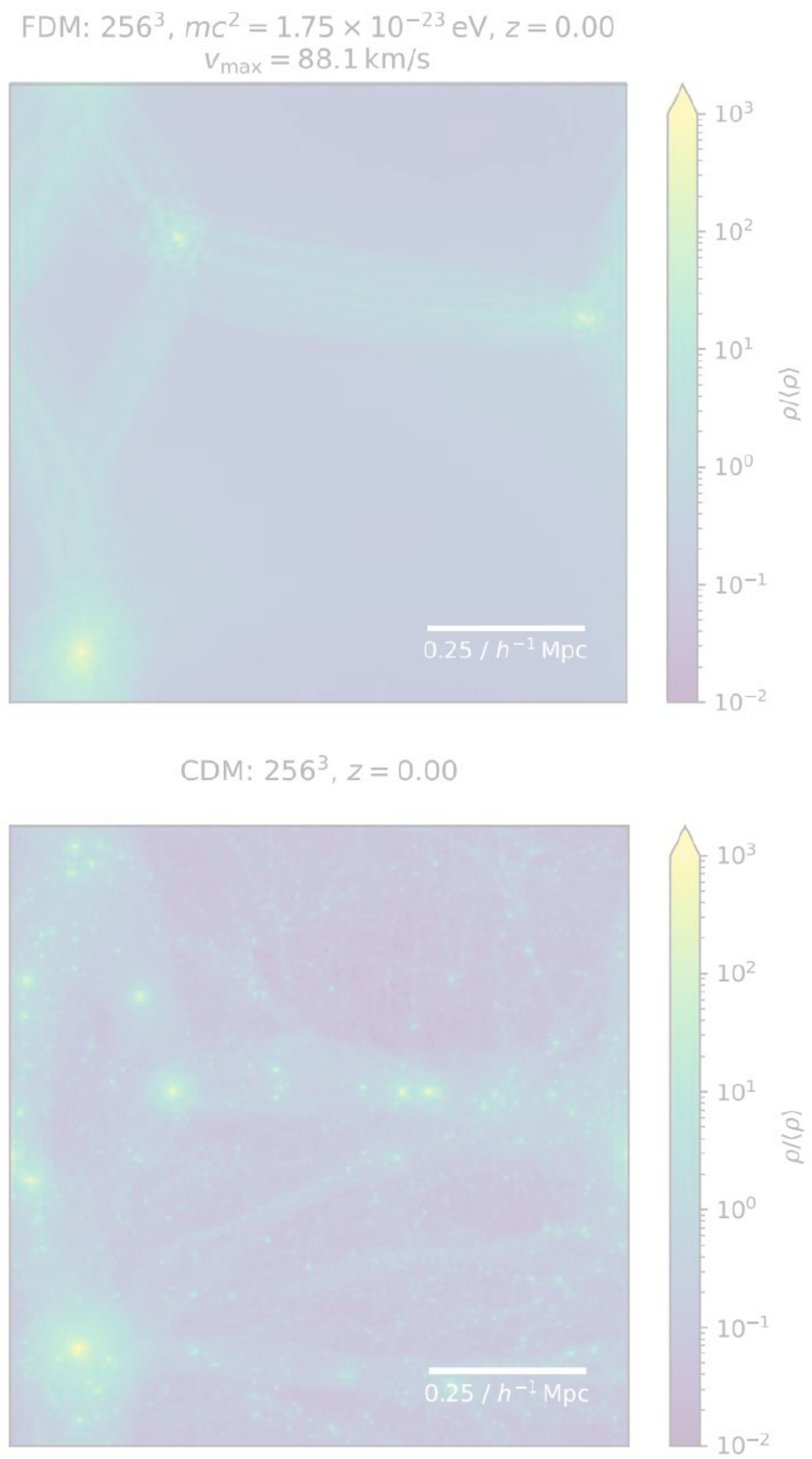
→ Relations used to compare with observations

Phenomenology



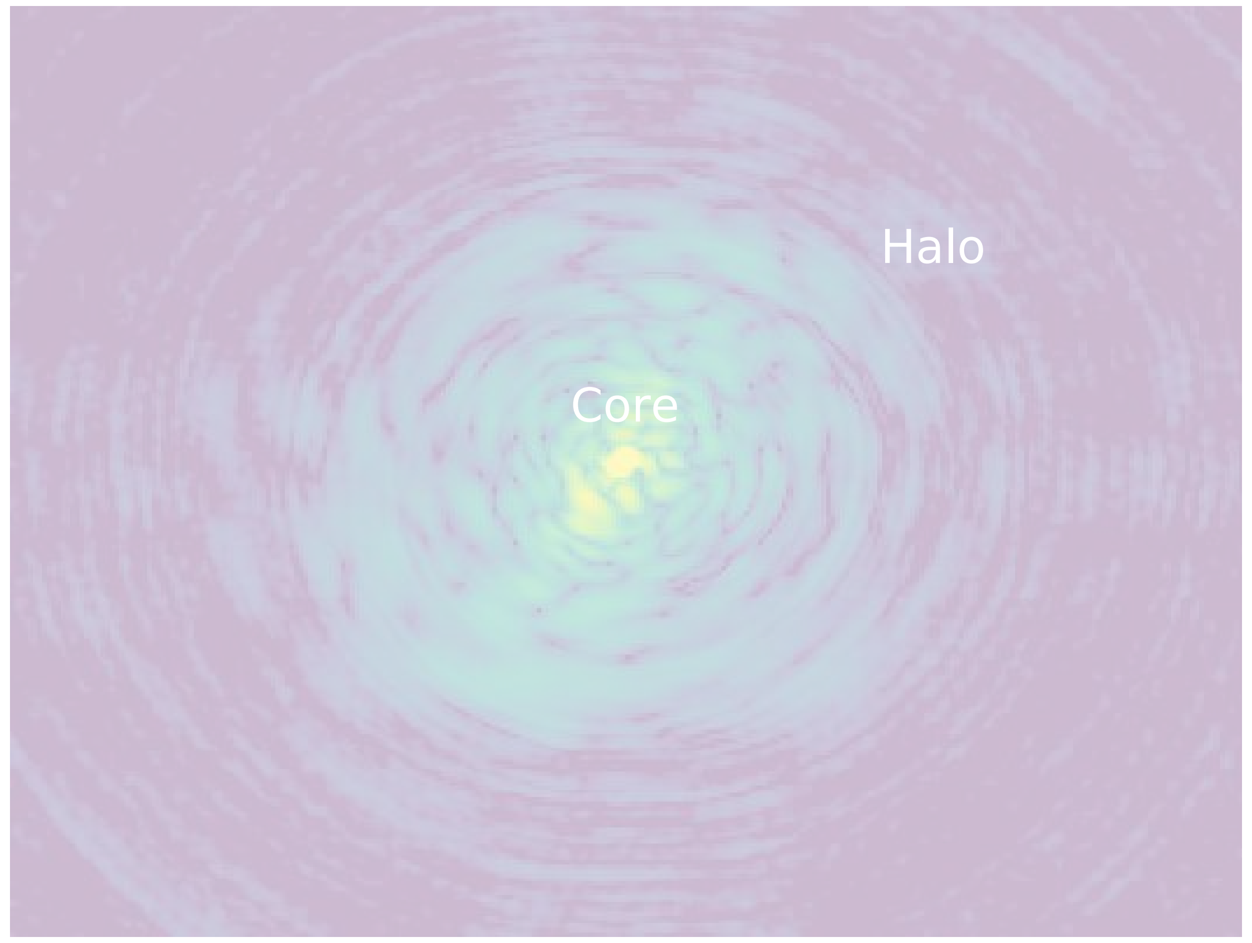
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

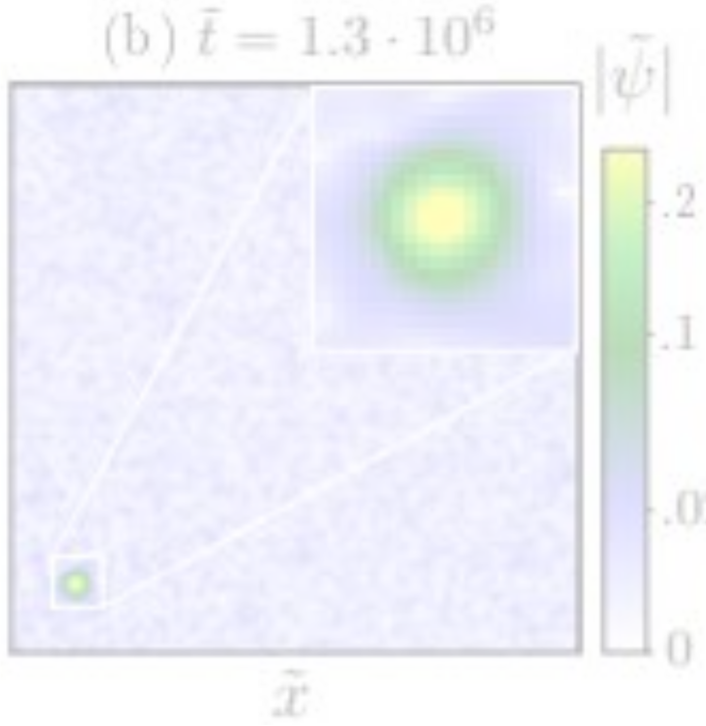


S. May et al. 2021

Formation of a solitonic core

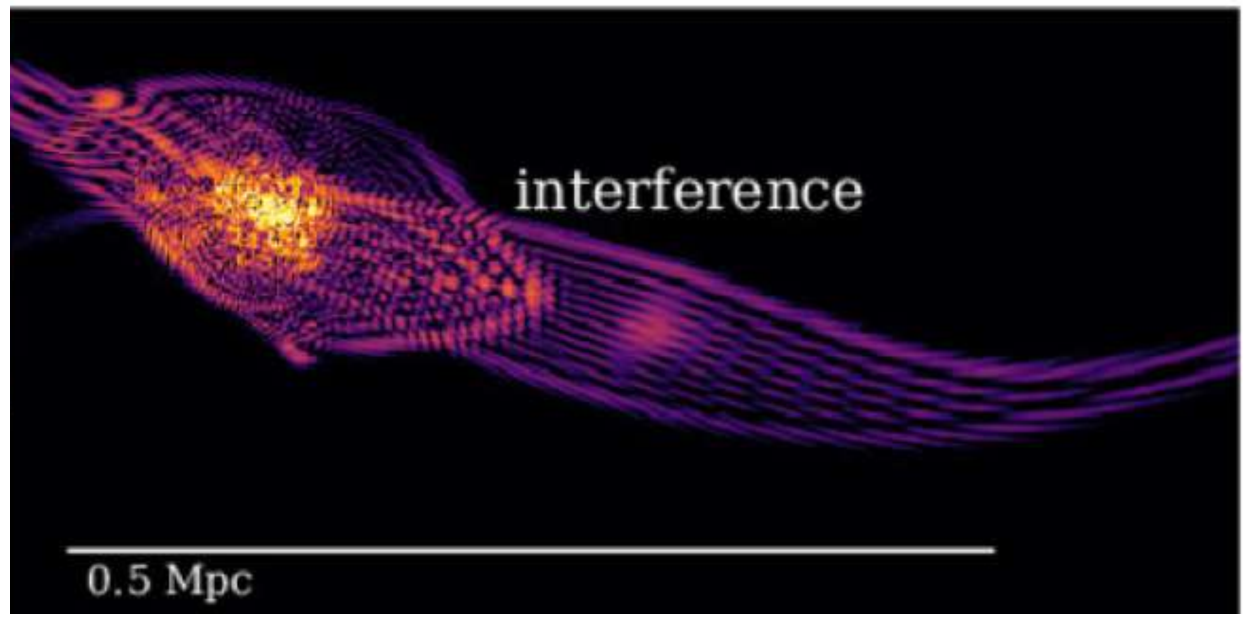


Dynamical effects



Levkov et al. 2018

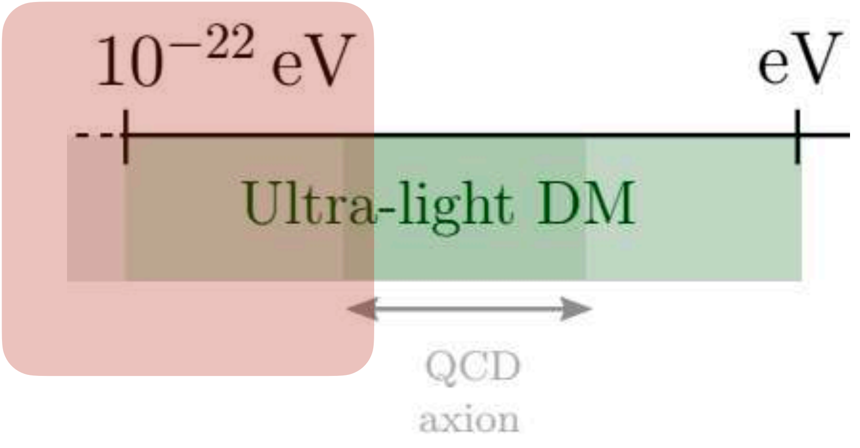
Wave interference

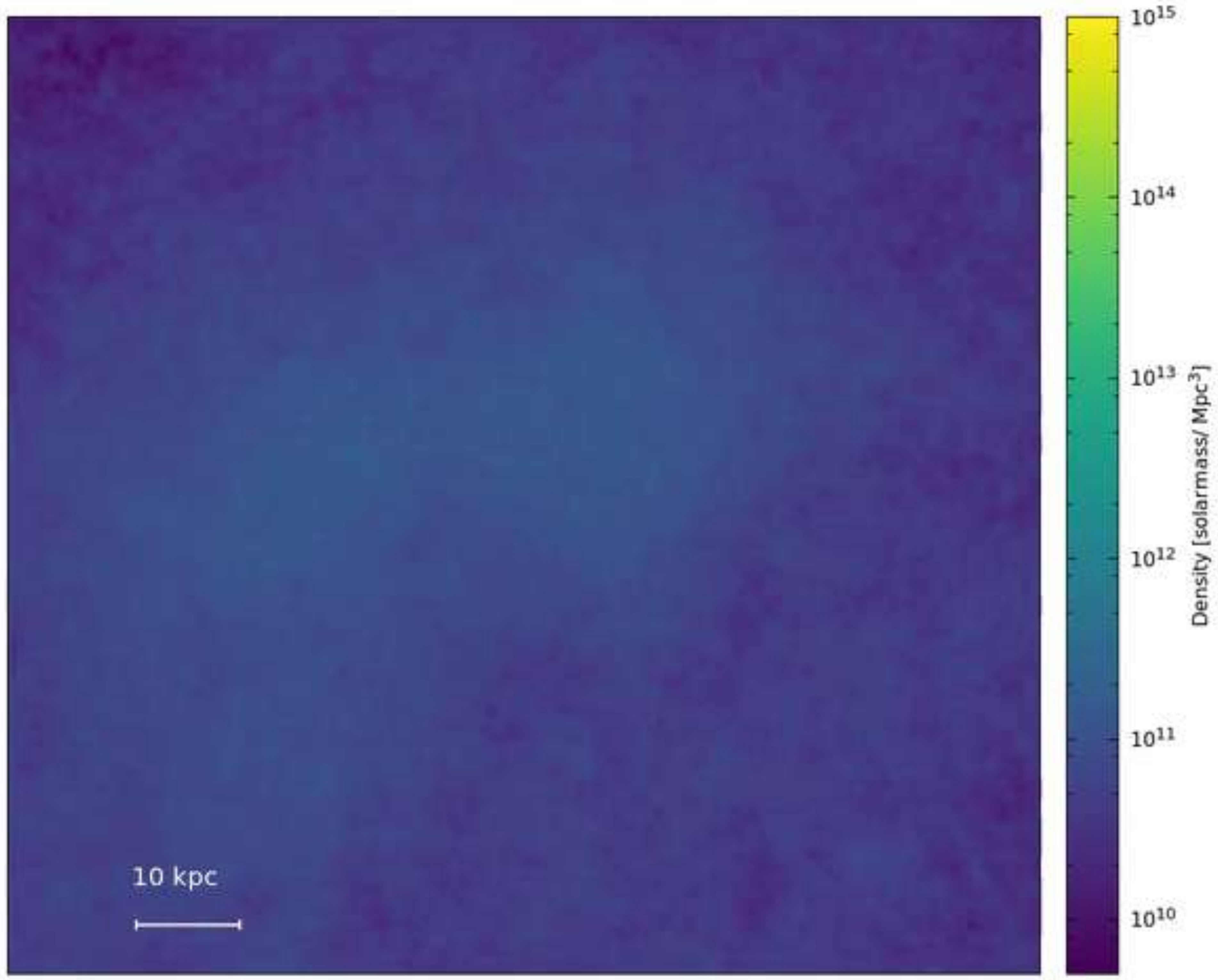


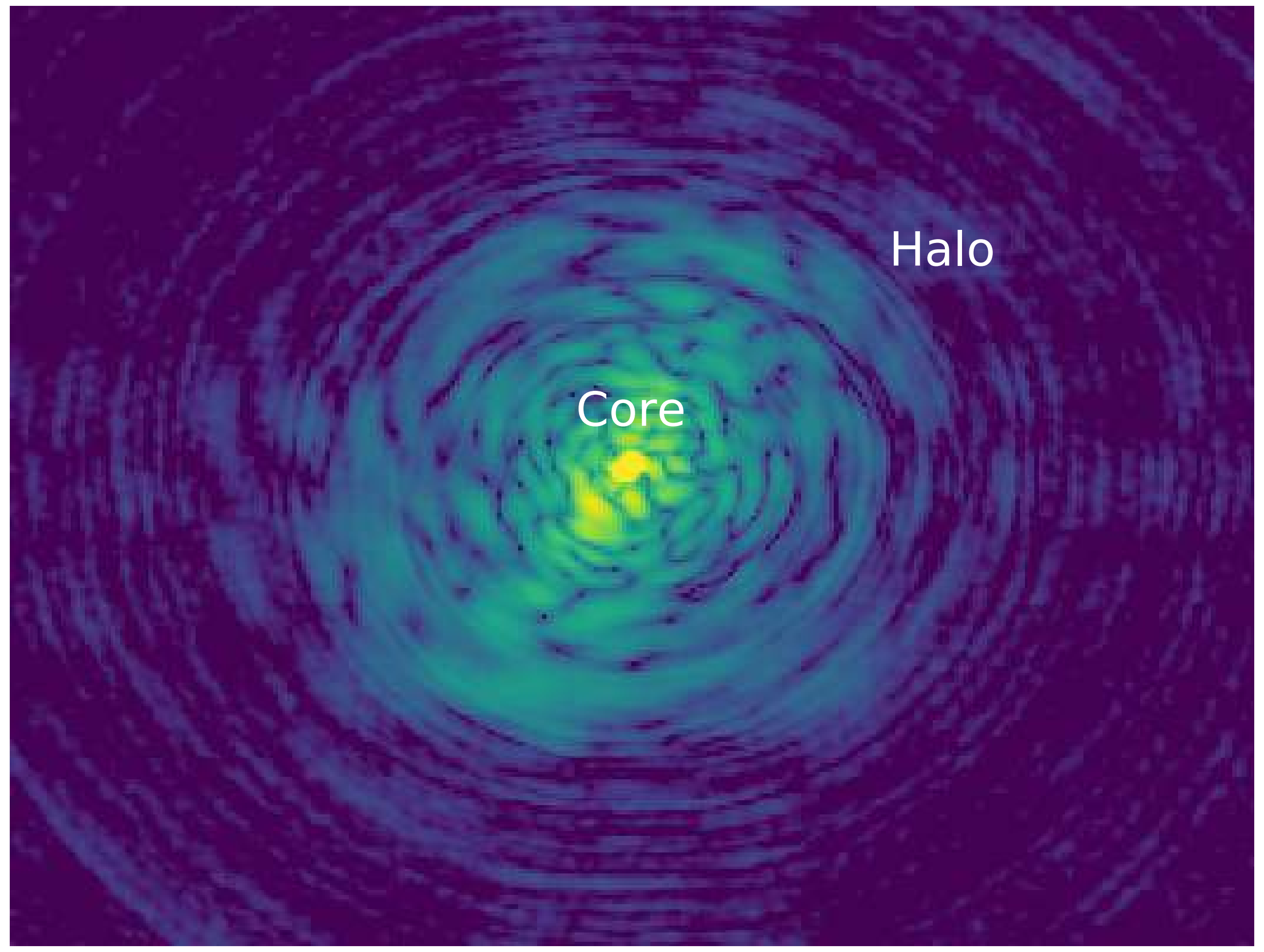
Mocz et al. 2017

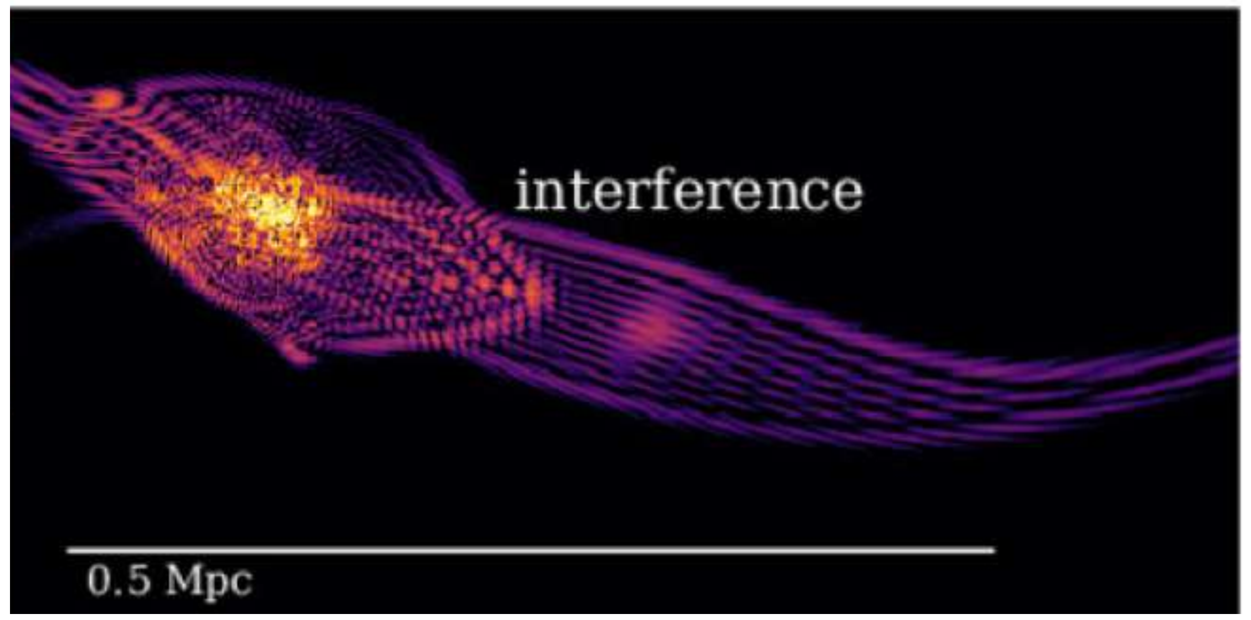
Phenomenology

Wave interference: granules and vortices









Mocz et al. 2017

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

$\hookrightarrow \sim \lambda_{\mathrm{dB}}$

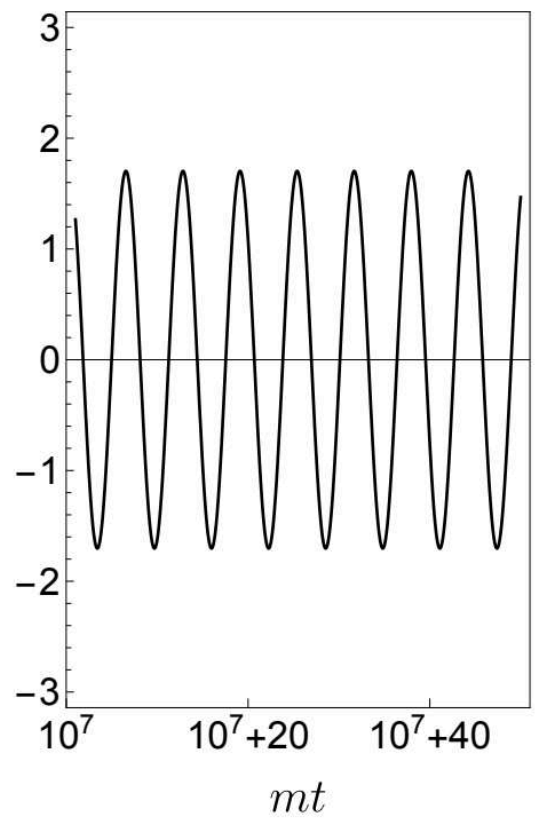
Modeling a granular halo

Coherent wave oscillation of ULDM

$$\phi(t,\vec{x}) = m^{-1}\sqrt{2\rho(t,\vec{x})}\,\cos[mt+\theta]$$

Fixed freq. (mt)

Constant phase (θ)



Modeling a granular halo

Coherent wave oscillation of ULDM

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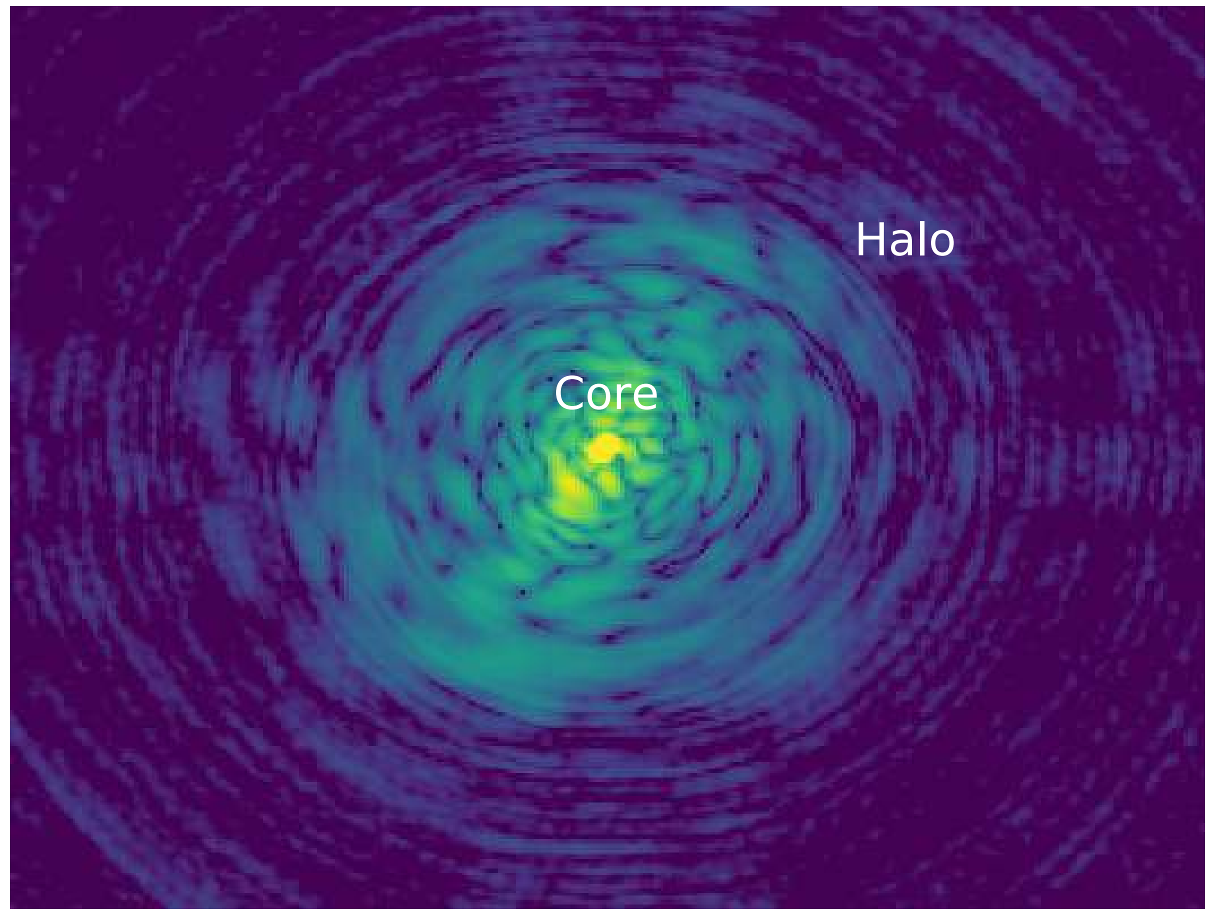
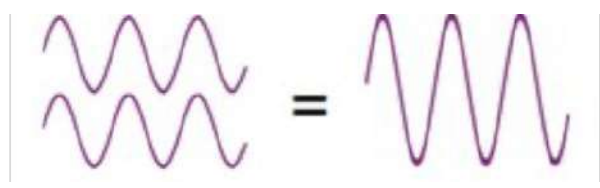
Fixed freq.

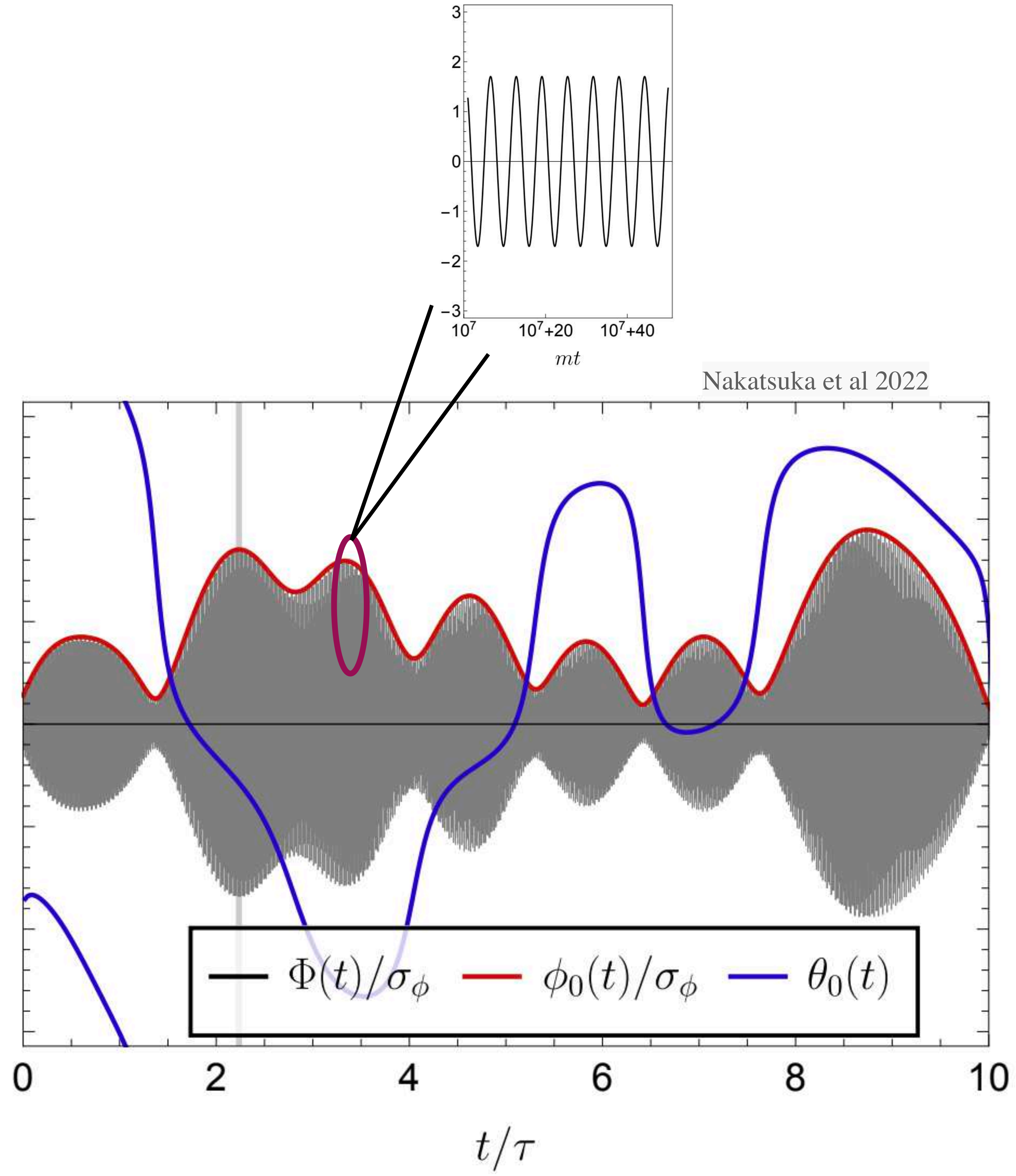
Constant phase

But, the halo in these models is like this:



Superposition of plane waves





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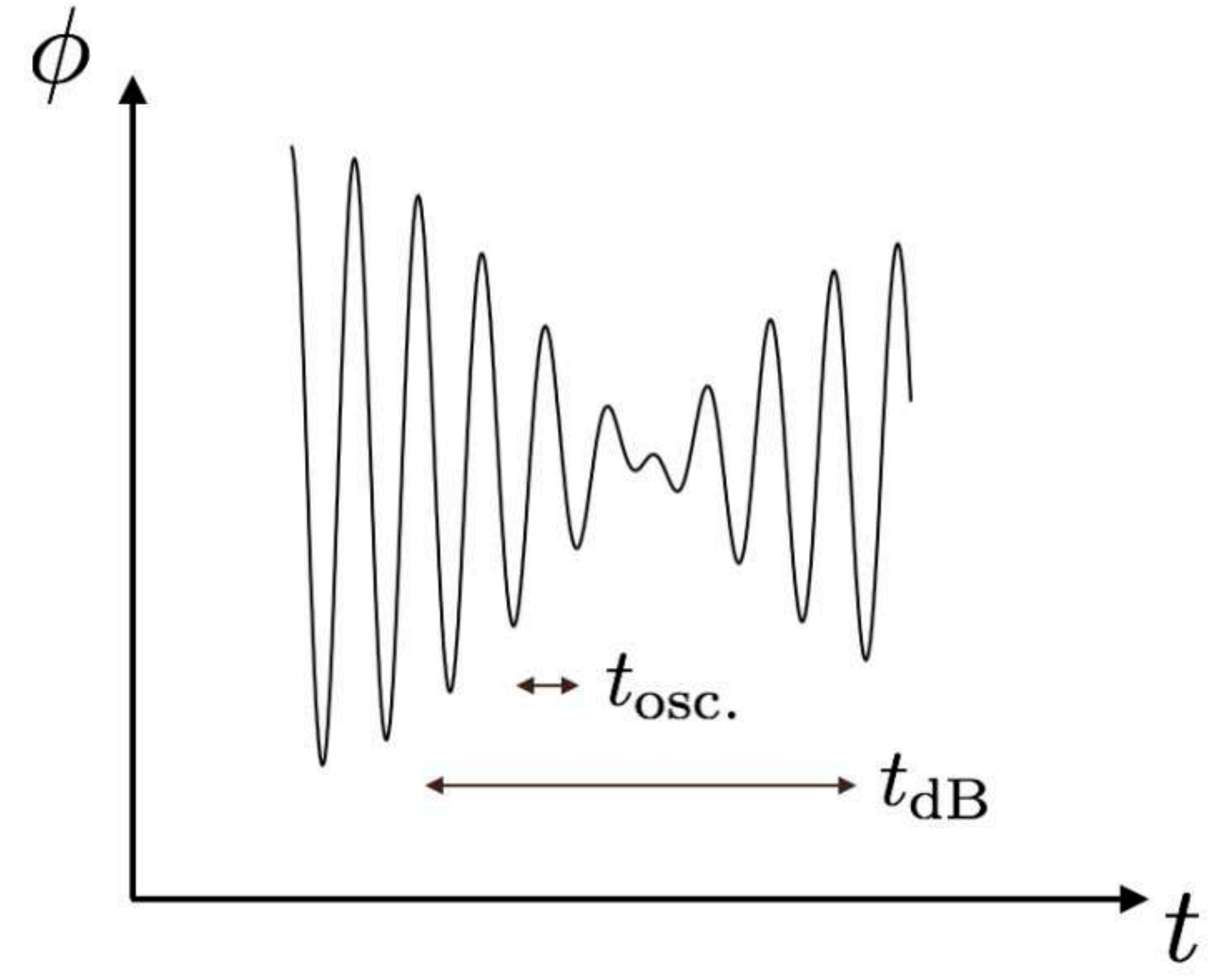

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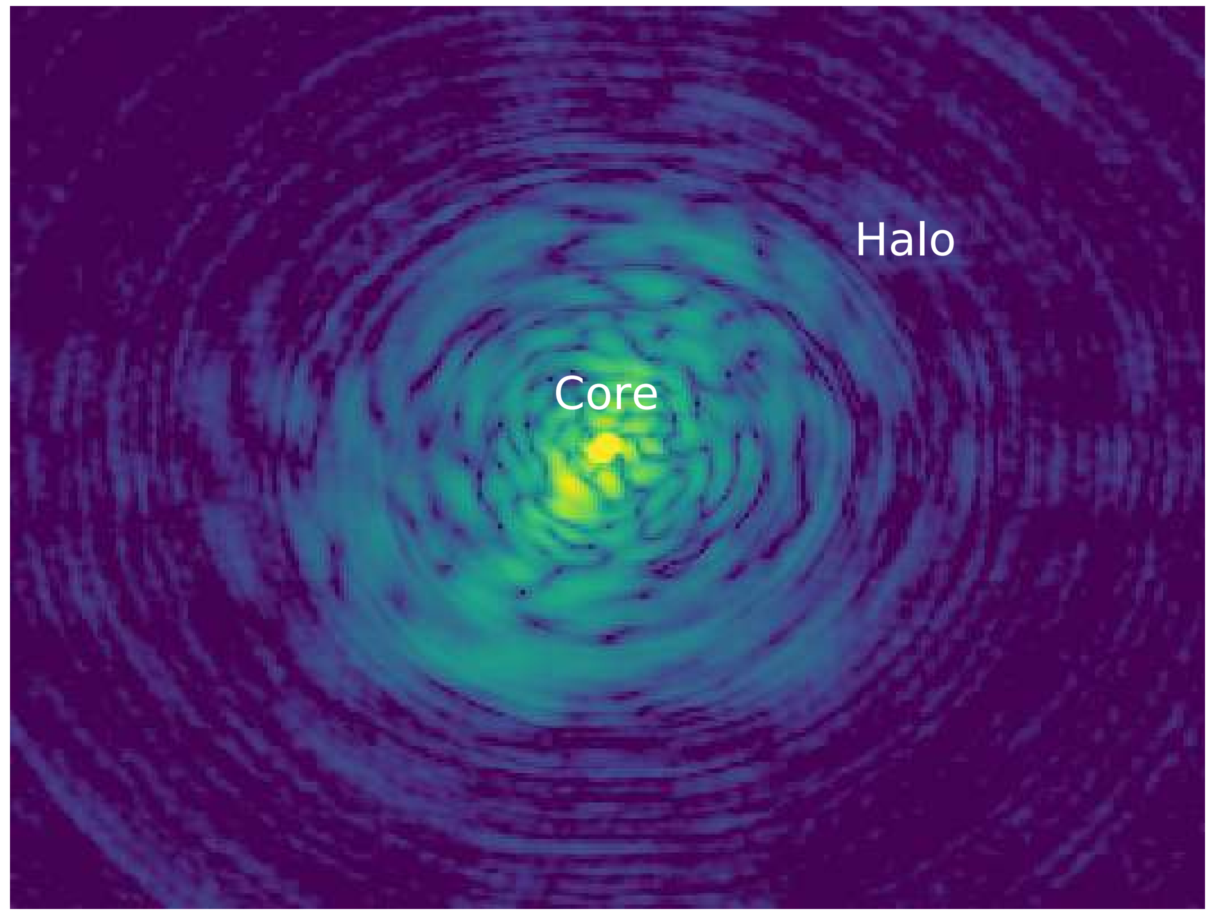

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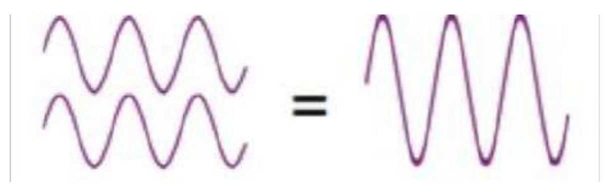


$$t_{osc.} = 2\pi/m$$

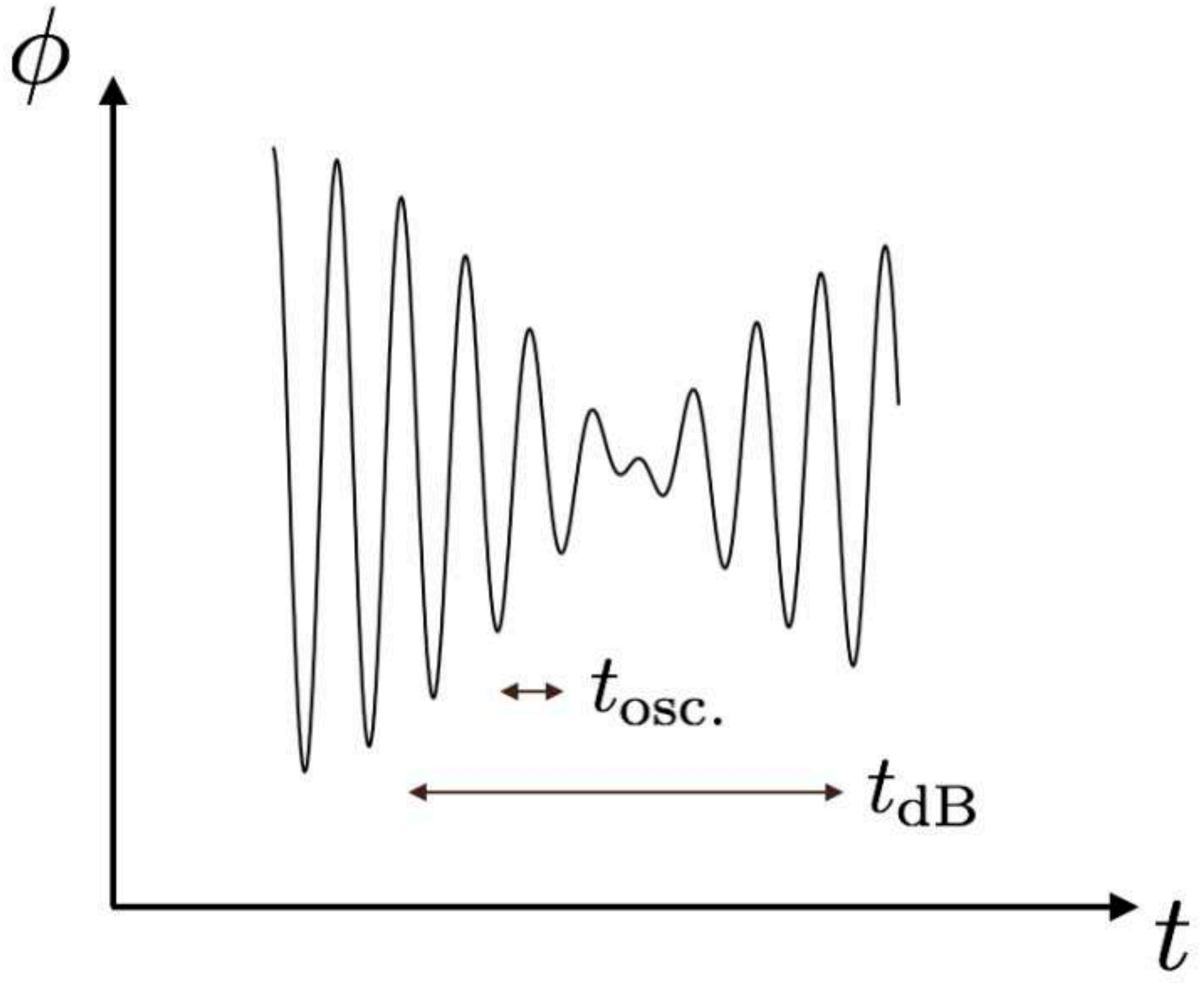
$$t_{dB} = 2\pi/(mv^2)$$

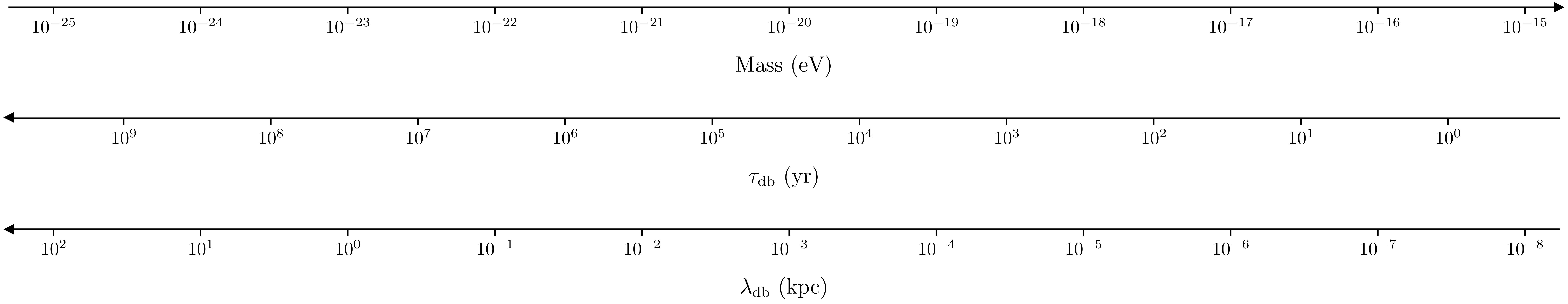
$$= 1.9\times10^6\,\mathrm{yr}\left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)\left(\frac{250\,\mathrm{km/s}}{v}\right)^2$$

Modeling a granular halo

$$t_{\rm osc.} = 2\pi/m$$

$$t_{\rm dB} = 2\pi/(mv^2)$$
$$= 1.9 \times 10^6\,{\rm yr}\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{250\,{\rm km/s}}{v}\right)^2$$





Modeling a granular halo

Full SP simulations can describe perfectly this interference pattern (while fluid ones *cannot* describe it)

OR

We can adopt simpler descriptions of the galactic halo to describe this effect.

1) A simple model of a galactic halo, consider a superposition of plane waves:

Random phase halo model

Randomly distributed

$$\psi(t,\vec{x}) = \sum_{\vec{k}} A_{\vec{k}} e^{iB_{\vec{k}}} e^{i\vec{k}\cdot\vec{x} - i\omega_k t}$$

Wave interference produces de-Broglie-scale, order unity density fluctuations which vary on time scale of t_{dB}

This collection of plane waves can also be represented like this:

$$\phi(t,\vec{x}) = A(\vec{x})\cos(m\,t + \alpha(\vec{x}))$$

describes the interference patterns

2) Another model would superimpose eigenstates of a desired gravitational potential (Lin et al. 2018, Li et al. 2021)

Perform an eigenmode decomposition of the halo wavefunction, where the eigenmodes are for a fixed gravitational potential
→ ω_k is the energy of each eigenmode (labeled abstractly by k), with $e^{i\vec{k}\cdot\vec{x}}$ replaced by the corresponding eigenfunction.

Energy eigenvalue

$$\psi(r,\theta,\phi,t) = \sum_{n,l,m} A_{nlm} F_{nlm}(r,\theta,\phi) e^{-iE_{nl}t/\hbar}$$

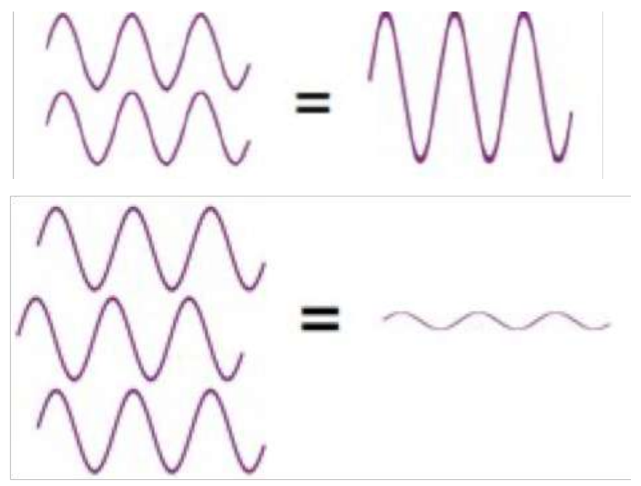
$$F_{nlm}(r,\theta,\phi) = R_{nl}(r) Y_l^m(\theta,\phi)$$

Radial eigenfunction

energy eigenmodes of the gravitational potential of the virialized halo

Vector, higher spin or multicomponent FDM

Interference patterns

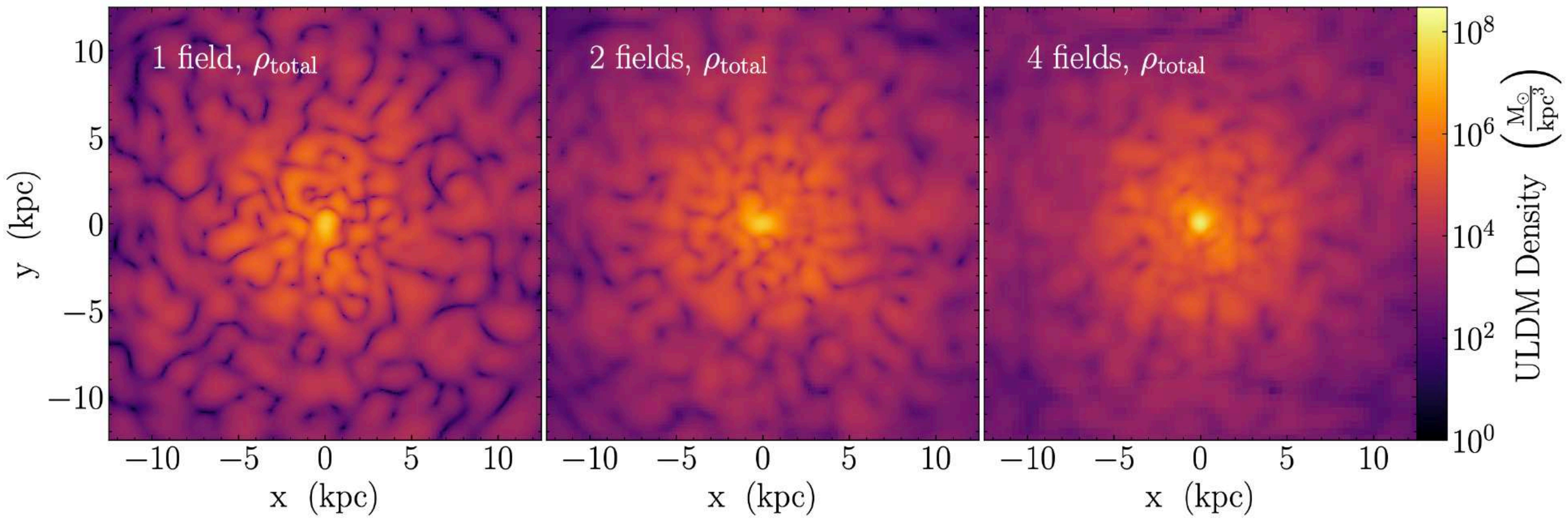


ULDM or ULA are a coherent wave - same frequency and constant phase difference

Multiple coherent waves

Gonseca et al 2023

For ULDM:



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

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

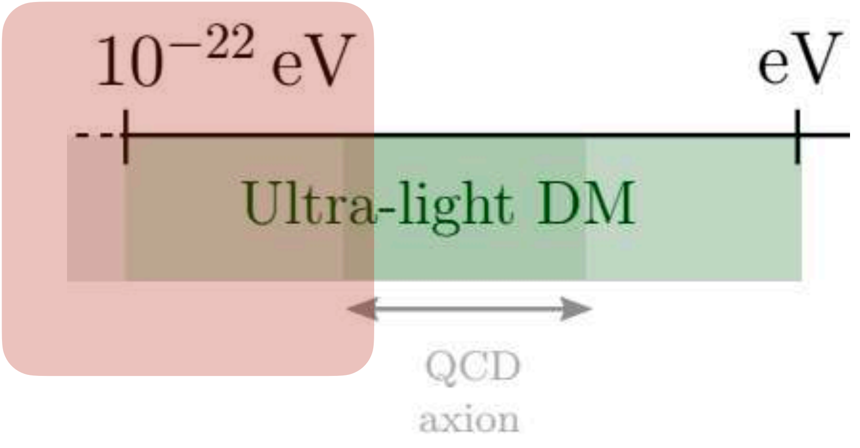
(Amin et al 2022)

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

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

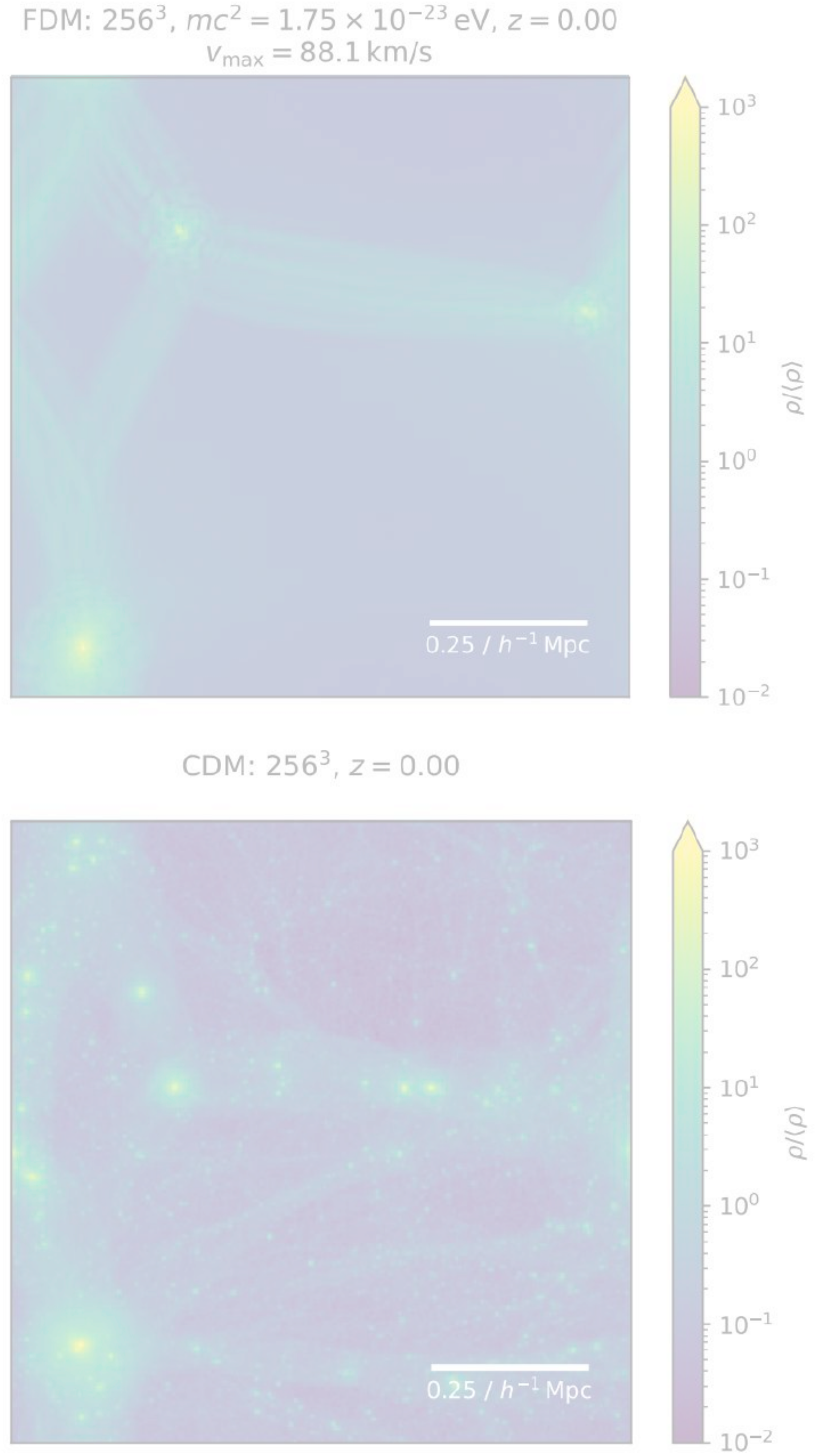
Multicomponent FDM   Gonseca et al 2023

Phenomenology



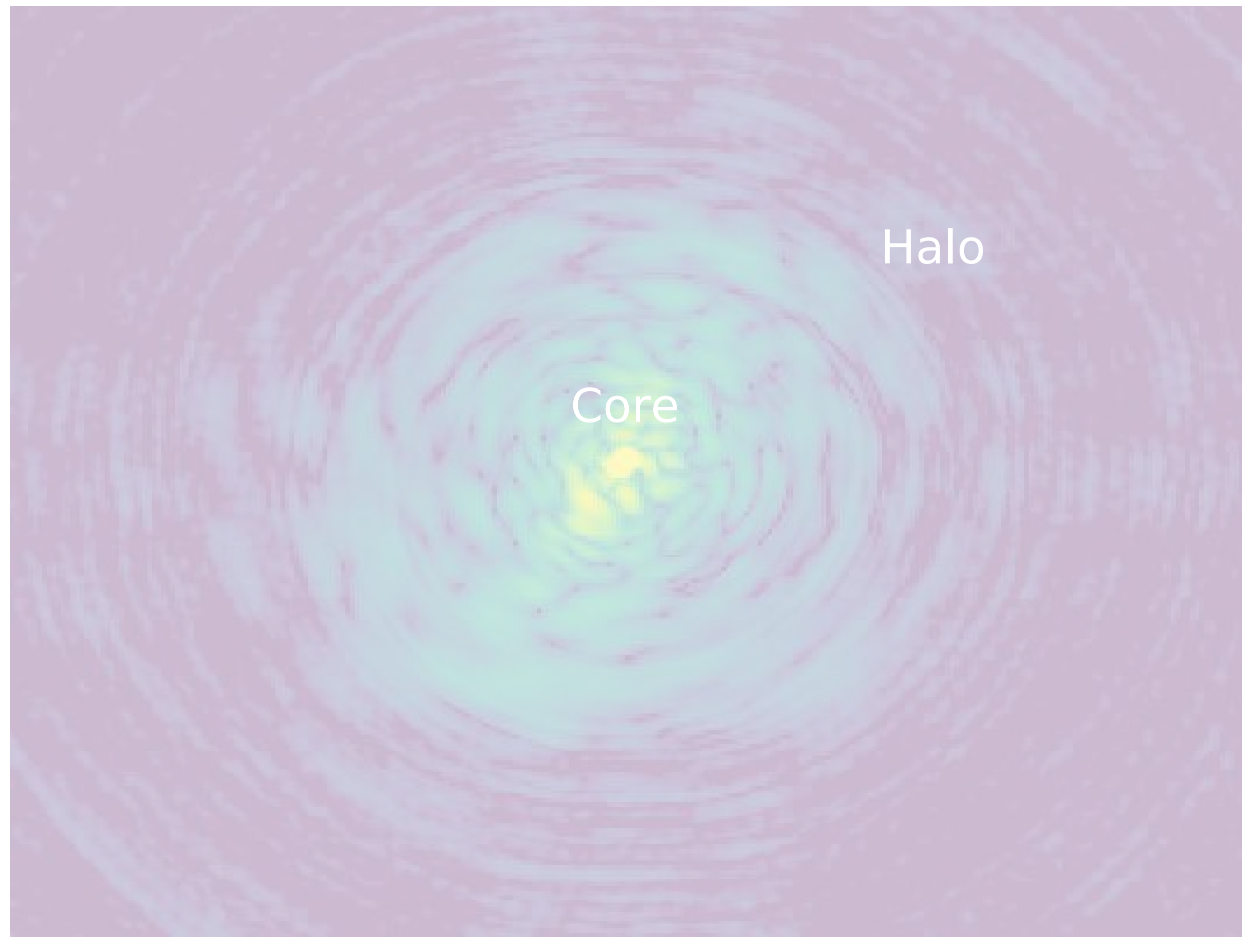
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

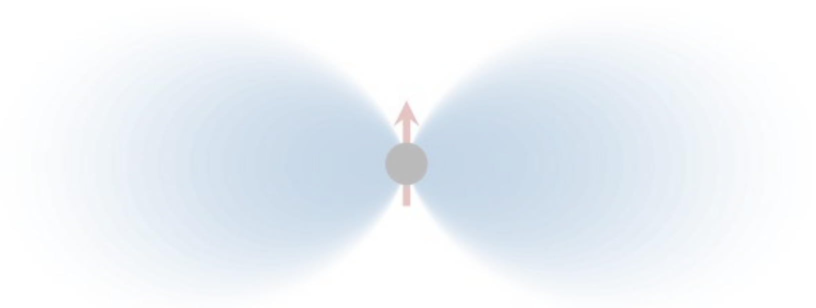


S. May et al. 2021

Formation of a solitonic core

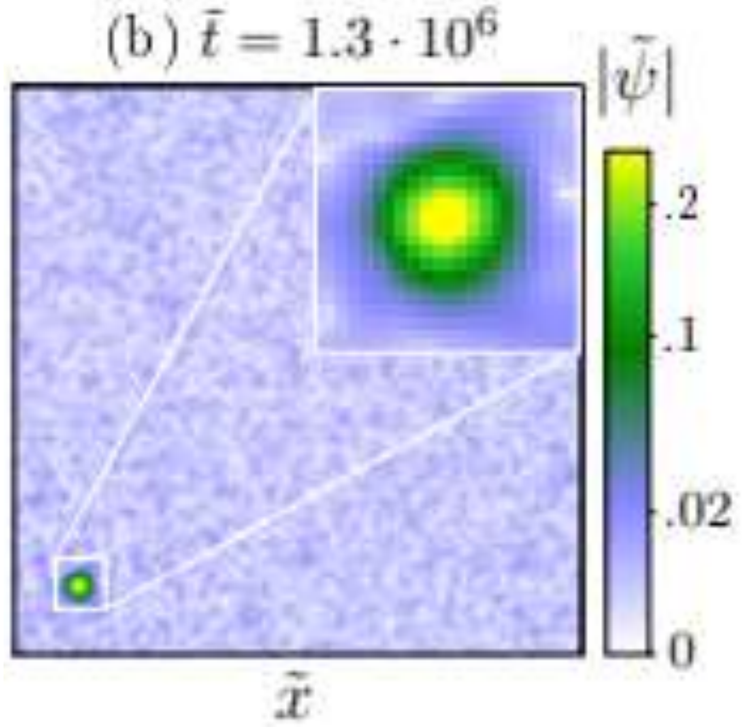


Axion clouds



Baumann et al. 2019

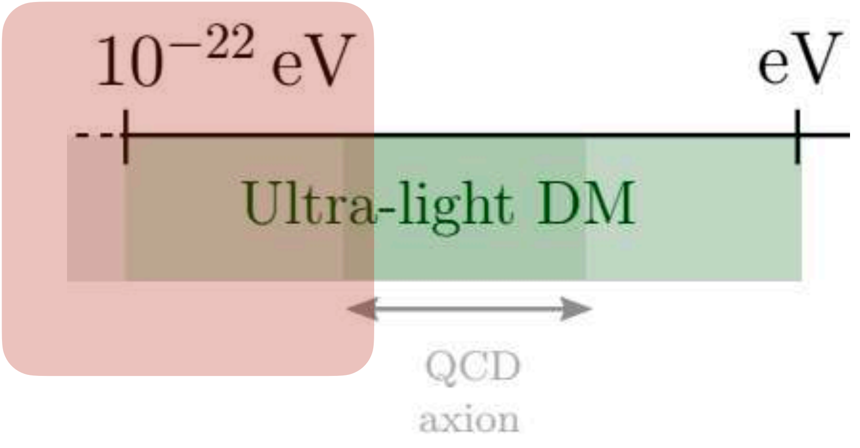
Dynamical effects



Levkov et al. 2018

Wave interference

Mocz et al. 2017



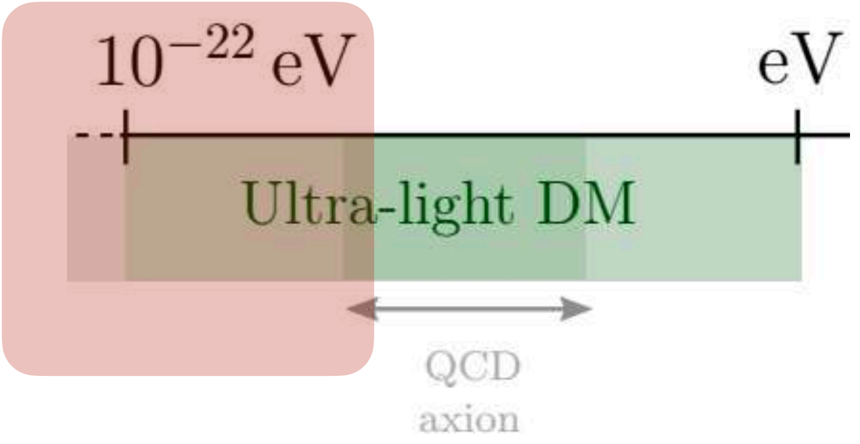
Phenomenology

Dynamical effects

Relaxation, oscillation, friction, and heating

Phenomenology

Dynamical effects

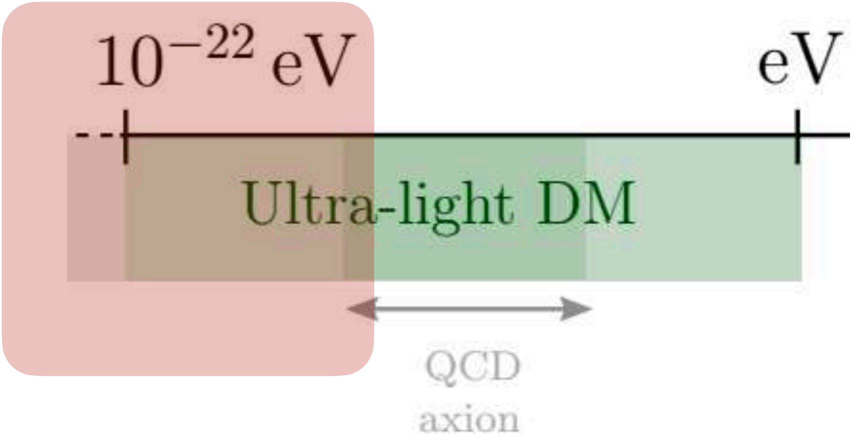


Relaxation, oscillation, friction, and heating

Formation of a BEC / superfluid

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.

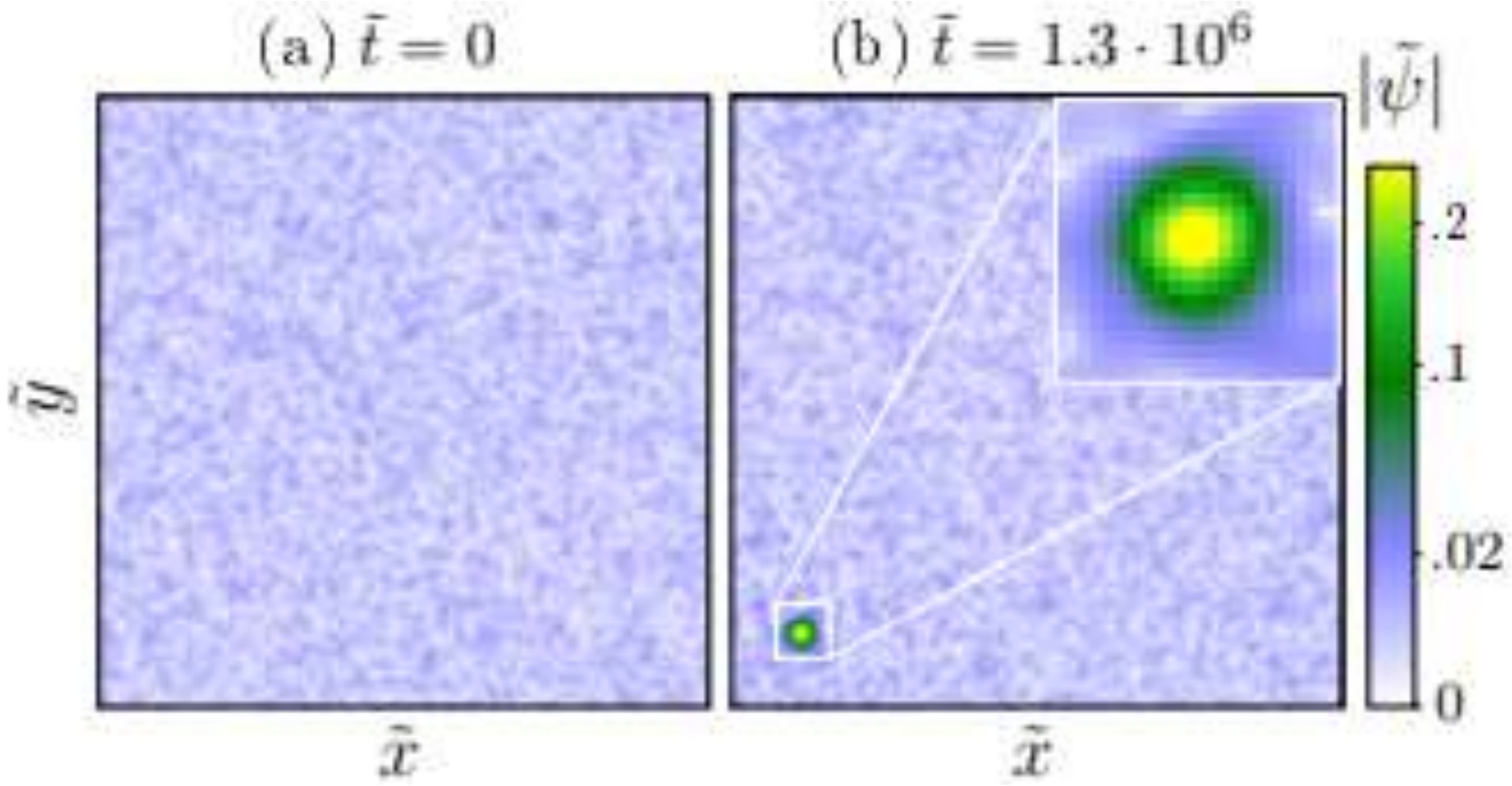
Condensation/relaxation time: $\tau_{\rm gr} \gg \tau_{\rm int}$

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

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

Smaller than the age of the universe!

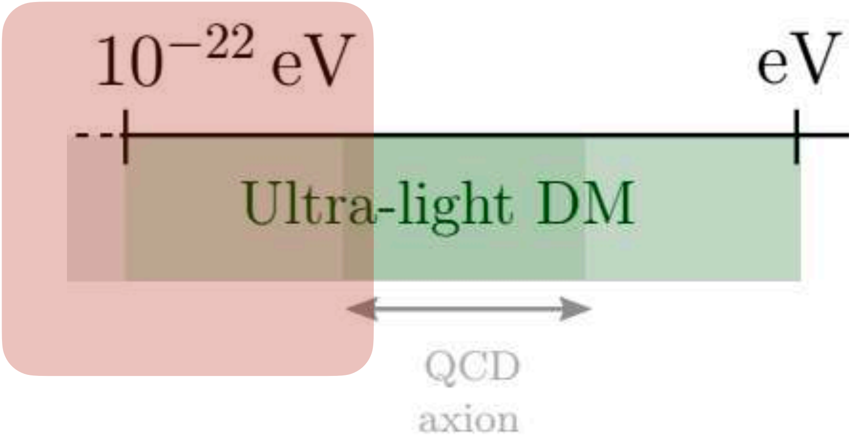
Wave turbulence theory



Levkov et al. 2018, Kirpatrick et al. 2020

Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

Formation of a BEC / superfluid

(Work in progress)

In collaboration with Yuta Sekino and Ryo Namba

Open question!

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

- Evolution all classical?

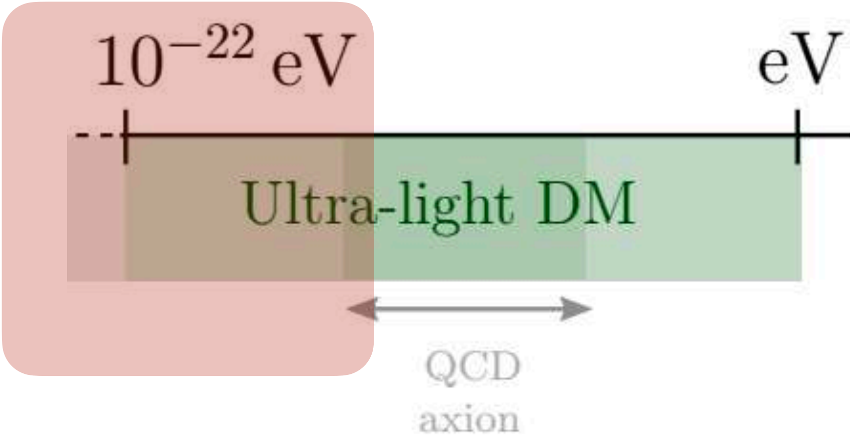
  - *Allali and Hertzberg 2020*
  - *Dvali and Zell 2018*
  - *A. Eberhardt et al. 2022, 2023*
  - *M. Yamaguchi et al.*

Re-thermalization or not: (Sikivie and Yang 2009; Erken et al. 2012; Marsh 2016; Guth et al. 2015; Castellanos et al. 2014; Davidson and Elmer 2013; Davidson 2015)

For an overdensity whose size is the typical DM de Broglie wavelength, we find that the decoherence rate in the halo is higher than the present Hubble rate for DM masses m≲5×10^{−7} eV and in earth based experiments it is higher than the classical field coherence rate for m≲10^{−6}eV. When spreading of the states occurs, the rates can become much faster, as we quantify. Also, we establish that DM BECs decohere very rapidly and so are very well described by classical field theory.

Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

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Here: gravitational interactions only; with baryons, much faster!

- Allali and Hertzberg 2020
- Dvali and Zell 2018
- A. Eberhardt et al. 2022, 2023
- M. Yamaguchi et al.

Re-thermalization or not: (Sikivie and Yang 2009; Erken et al. 2012; Marsh 2016; Guth et al. 2015; Castellanos et al. 2014; Davidson and Elmer 2013; Davidson 2015)

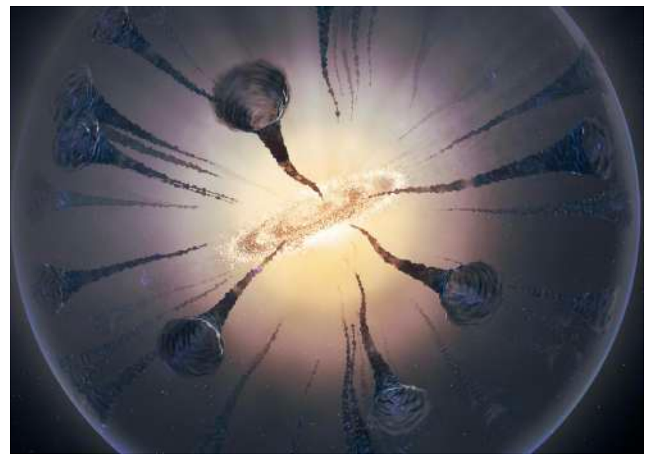
Phenomenology

Vortices

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

Vel. field is a gradient flow ⟶ irrotational fluid, no vorticity

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



Quanta magazine

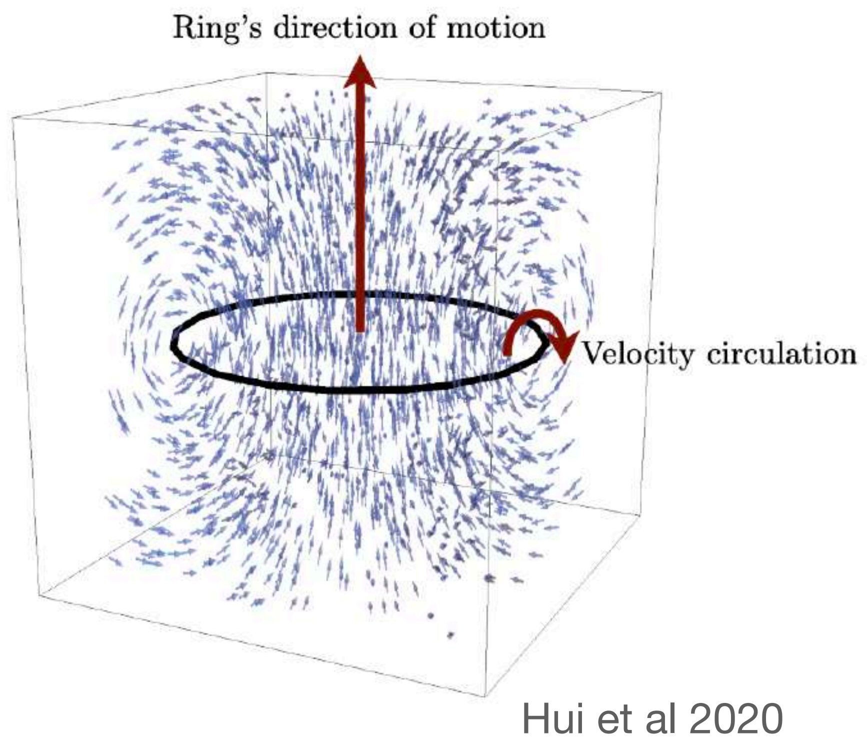
Two ways:
- regions where the density vanishes
- transfer of angular momentum (superfluids only)

Fuzzy DM

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

General defet in 3D

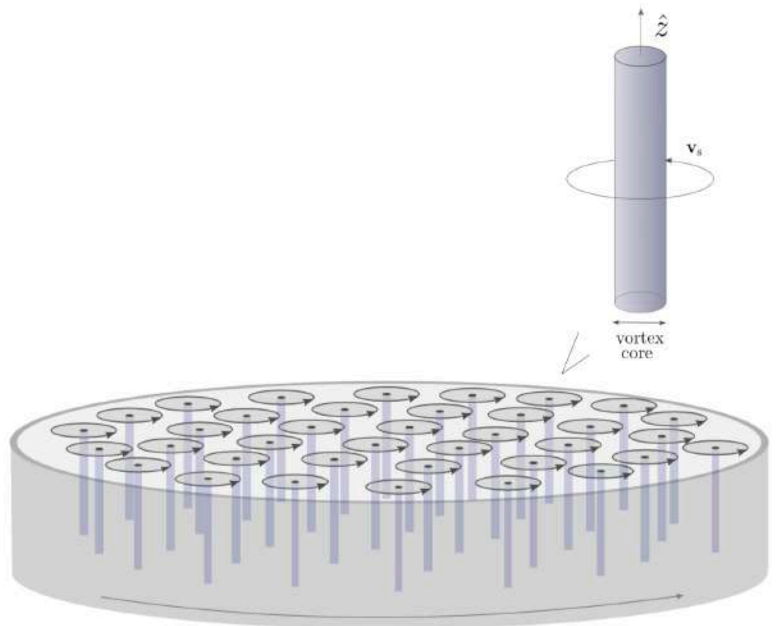
$$\mathcal{C} = \frac{1}{m}\oint_{\partial A} \mathrm{d}\theta = \frac{2\pi n}{m}$$



Hui et al 2020

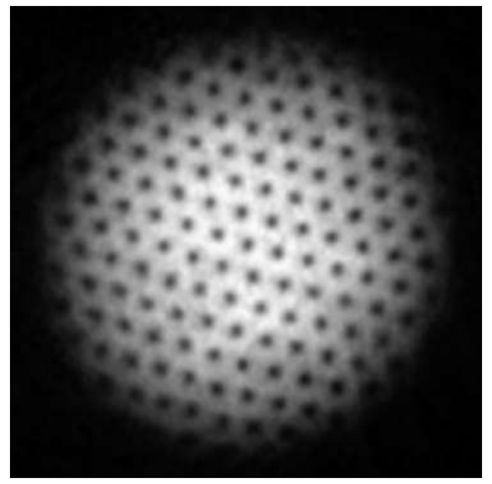
Self-interacting Fuzzy DM

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



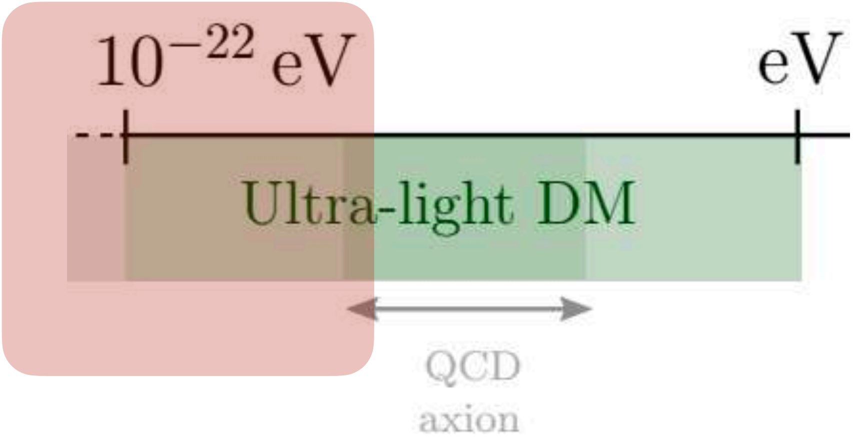
EF, 2020

© Martin Zwierlein.

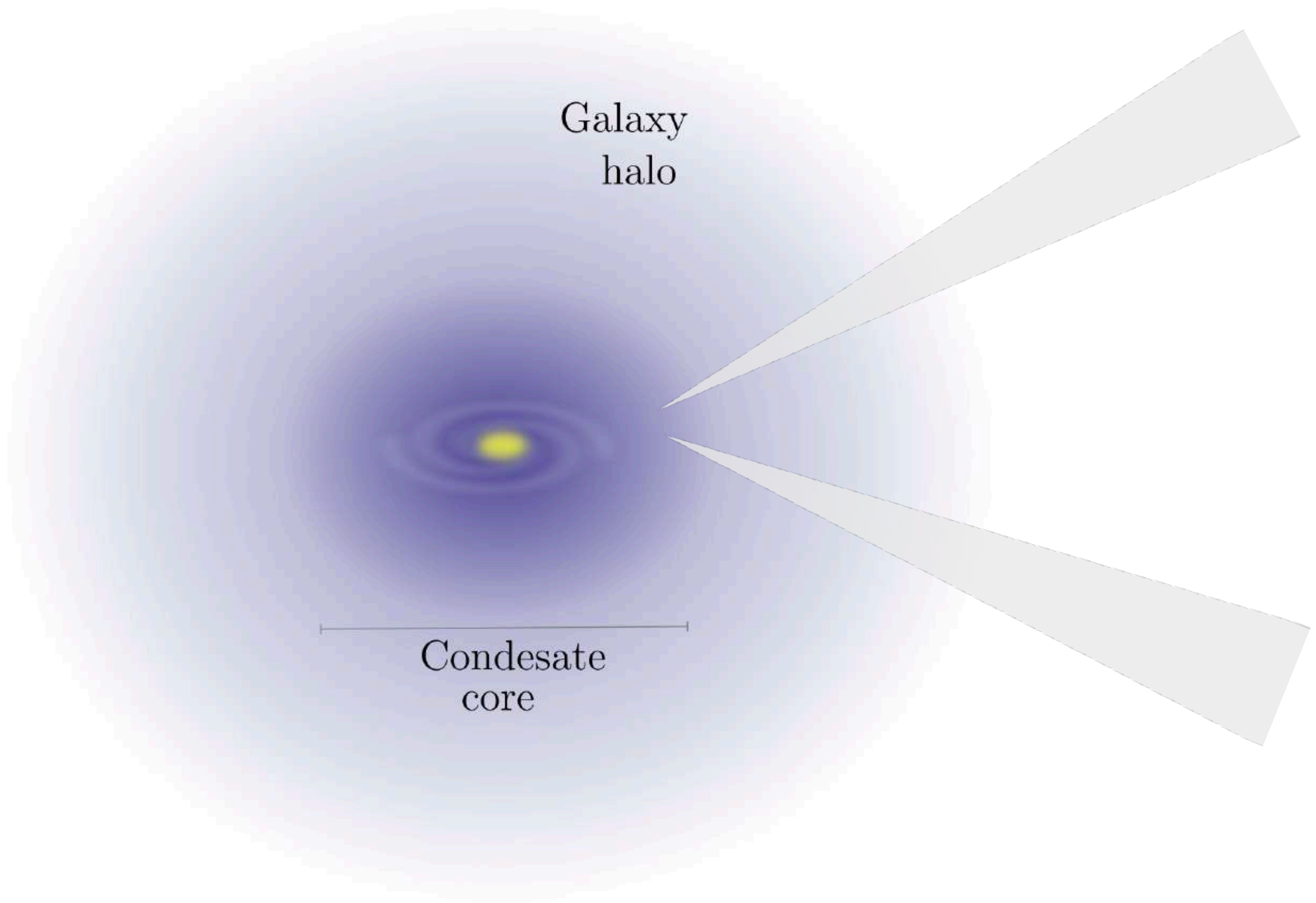


Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

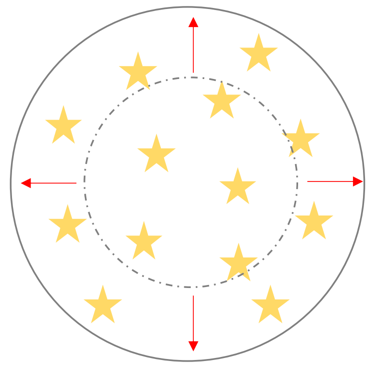


Heating

FDM granule

m_{eff}

System (star)
gains energy



Friction

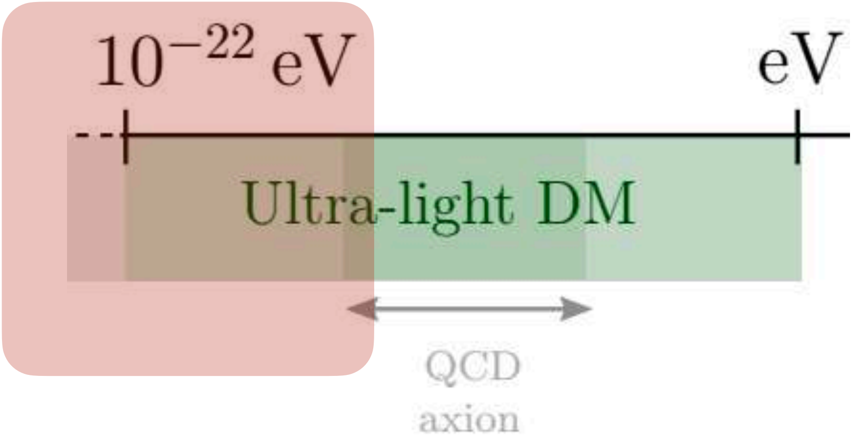
FDM granule

m_{eff}

Globular cluster

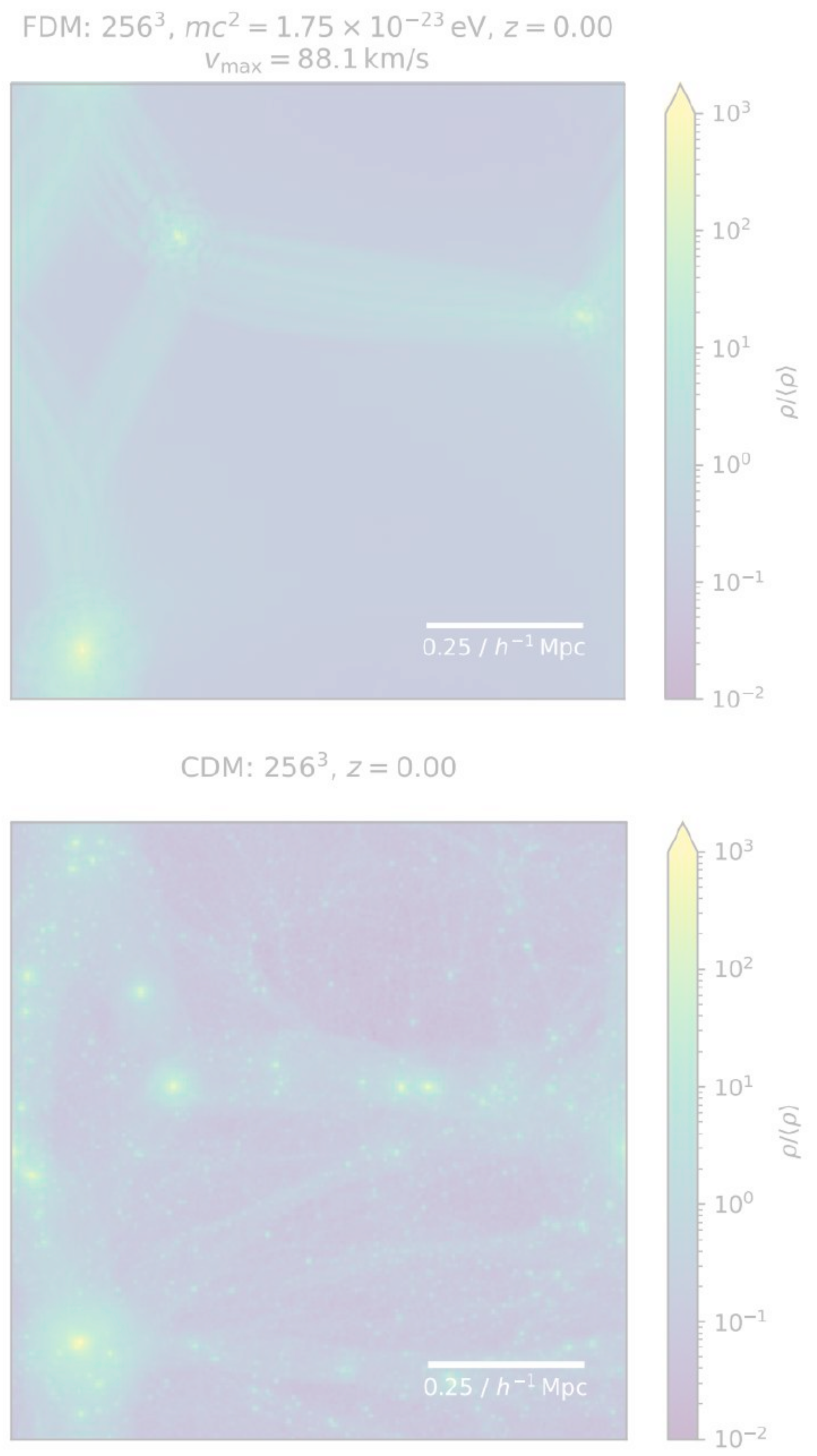
System (GC or BH)
loses energy

Phenomenology



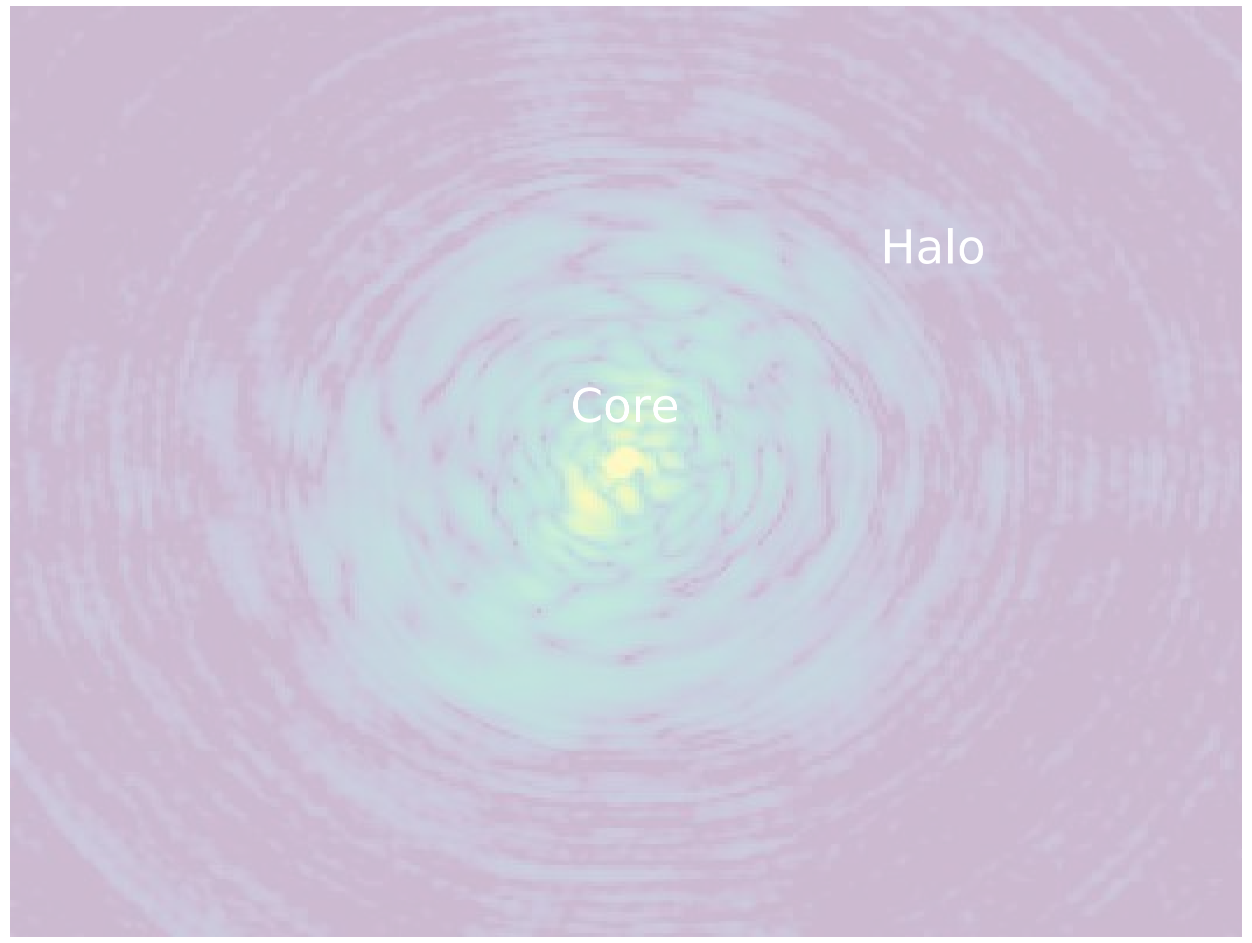
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

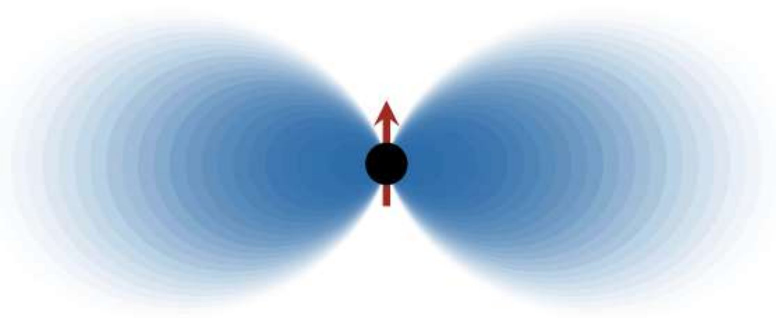


S. May et al. 2021

Formation of a solitonic core

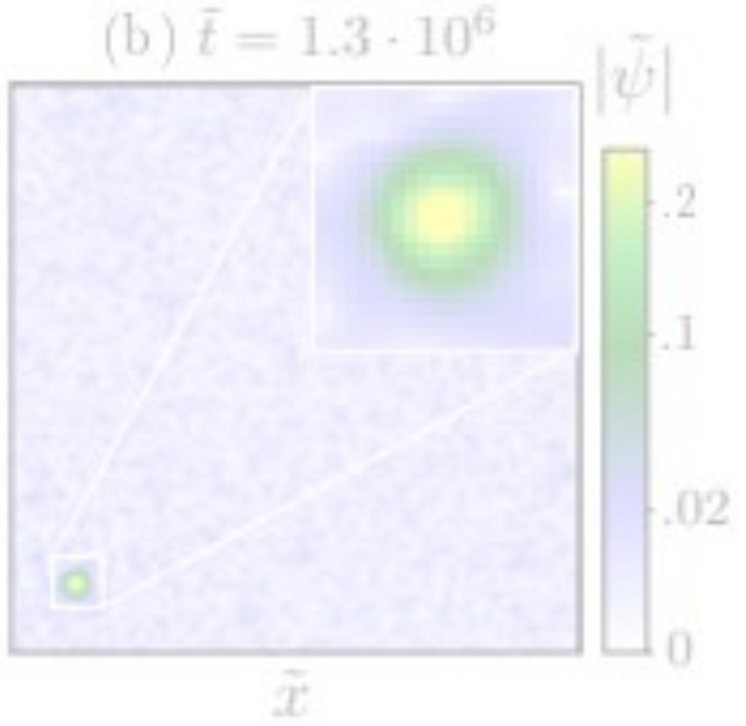


Axion clouds



Baumann et al. 2019

Dynamical effects



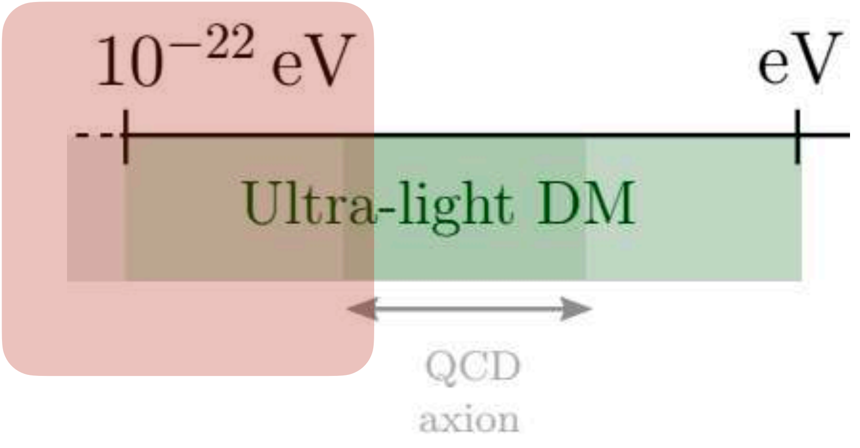
Levkov et al. 2018

Wave interference

Mocz et al. 2017

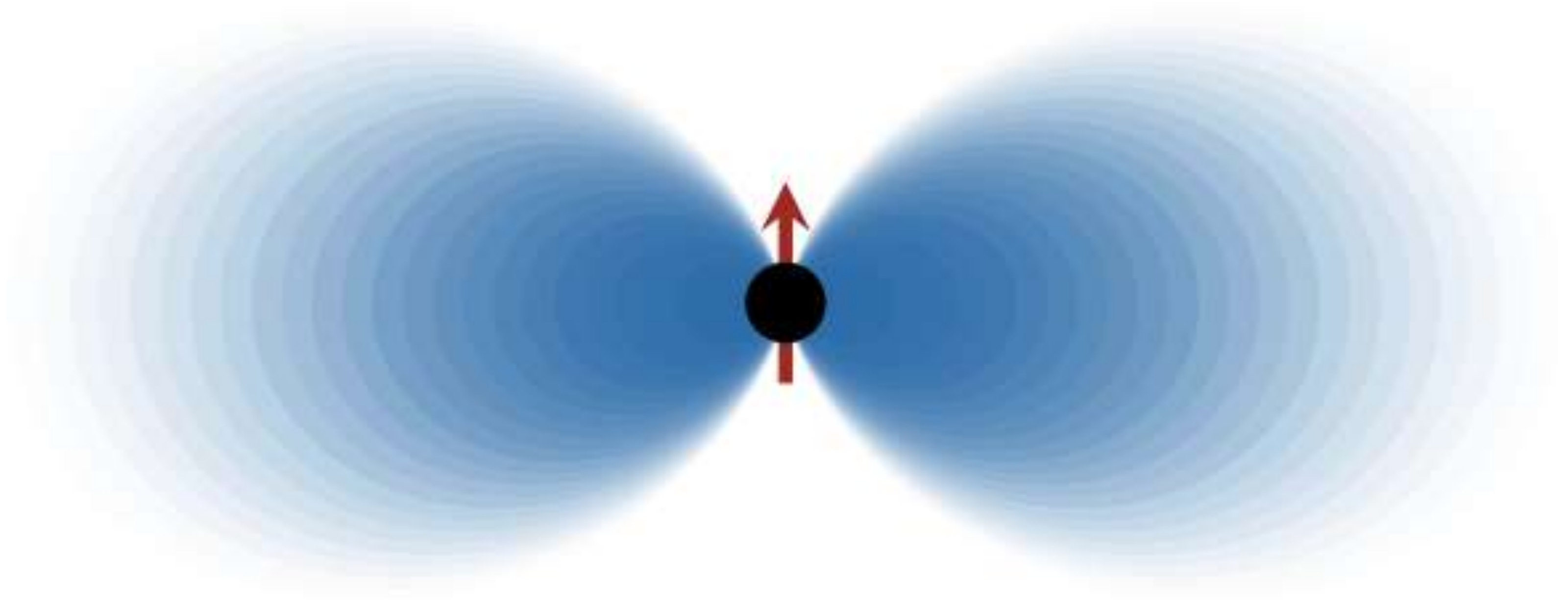
Phenomenology

Axion clouds



- Superradiance

Cloud created around rotating BHs



Baumann et al. 2019

- External potential

Self-gravity

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

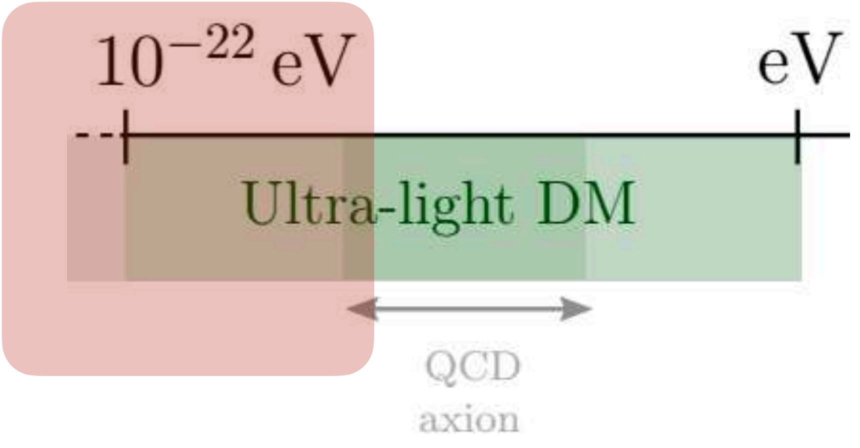
$$\nabla^2\Phi = 4\pi G(m|\psi|^2 - \bar{\rho})$$

$+$

External potential

Ex.: BHs, neutron stars, stars, planets, …

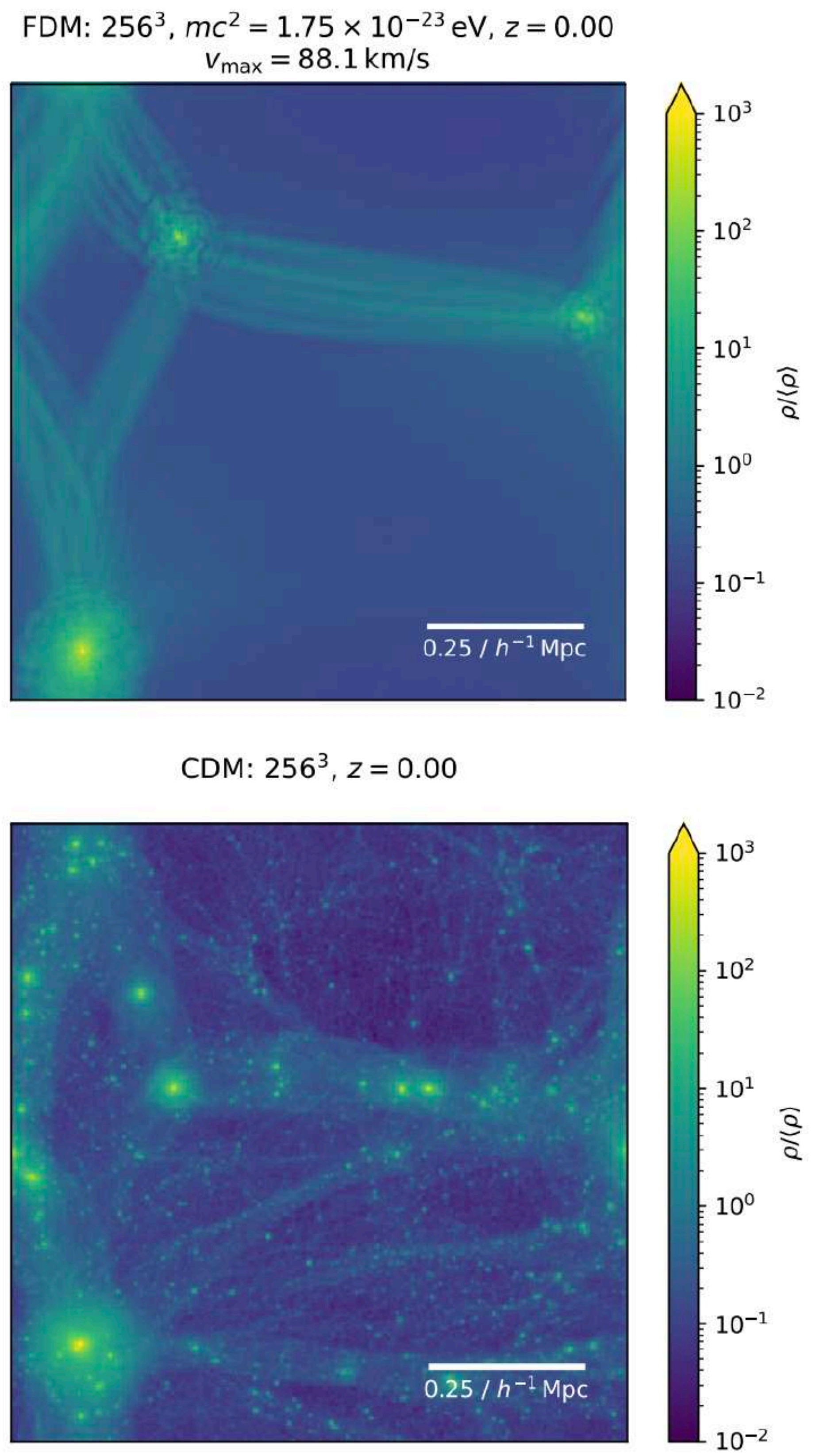
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

* Focus only in gravitational signatures

Suppression of small structures



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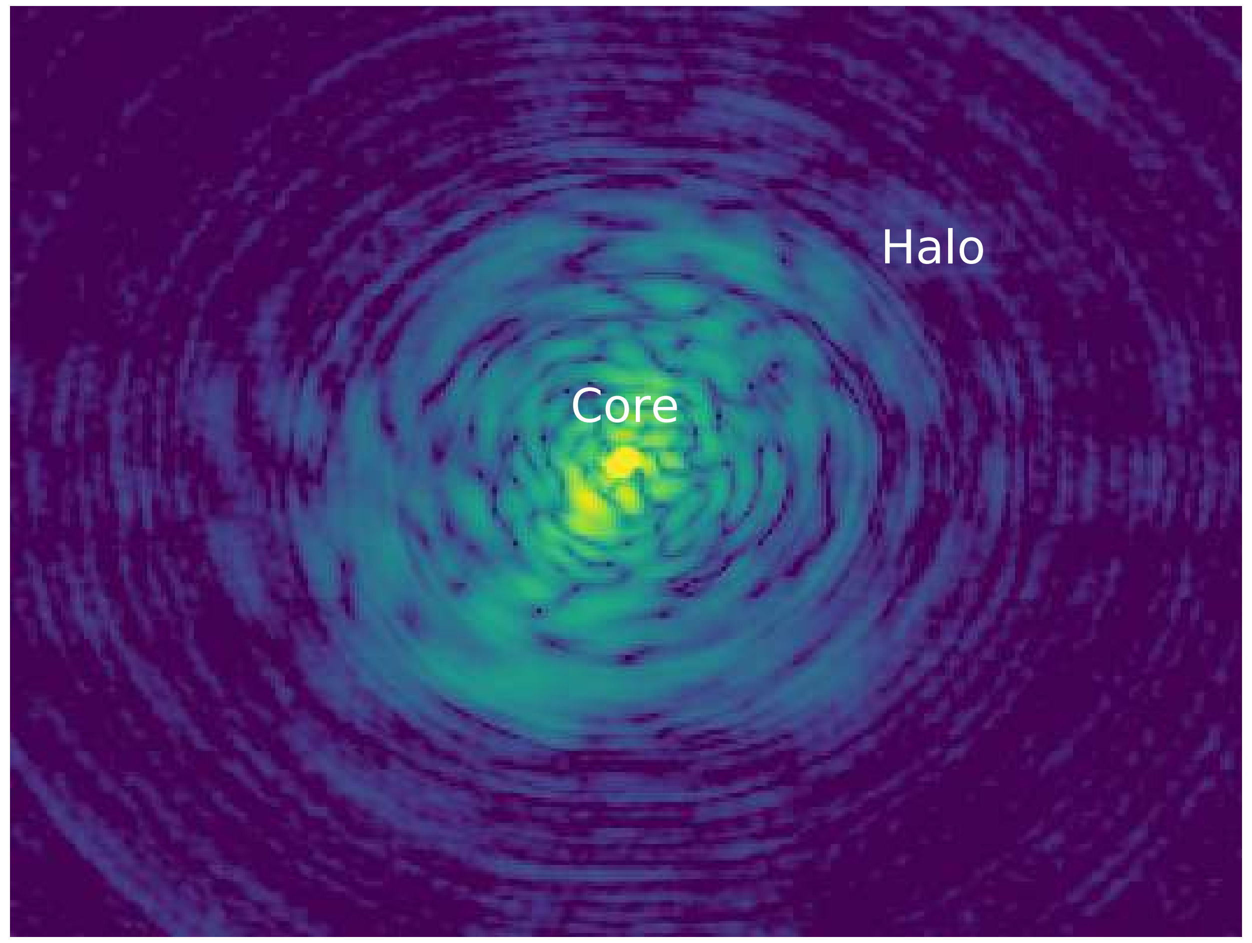
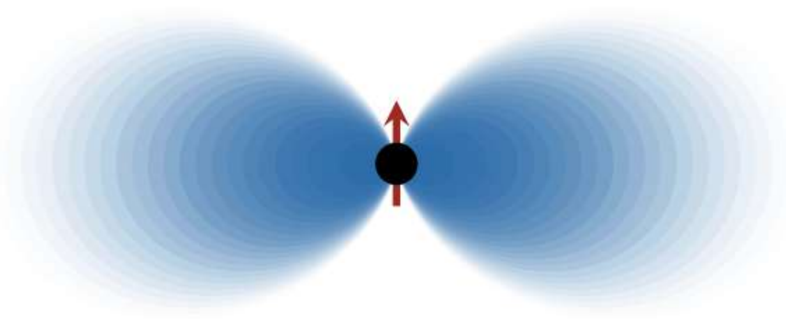
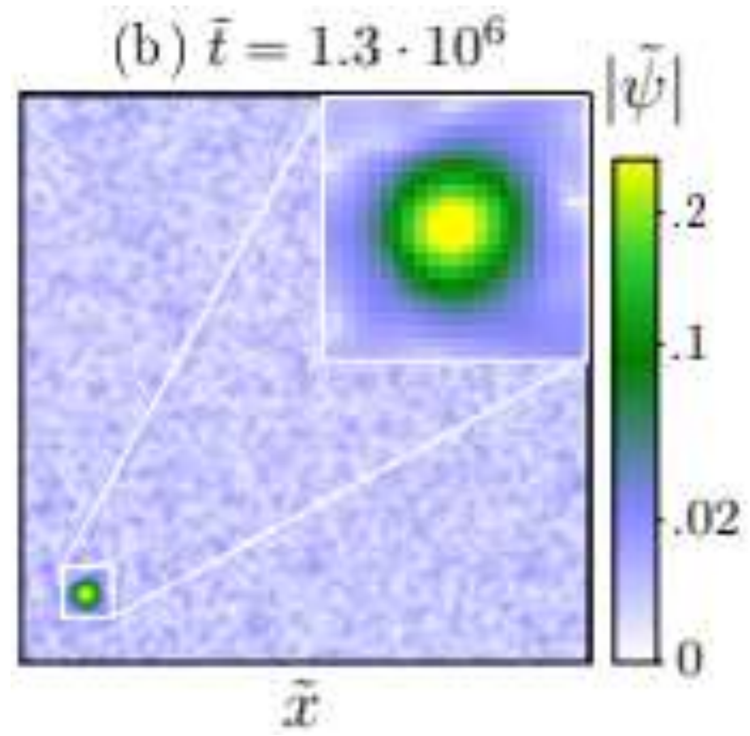


Axion clouds



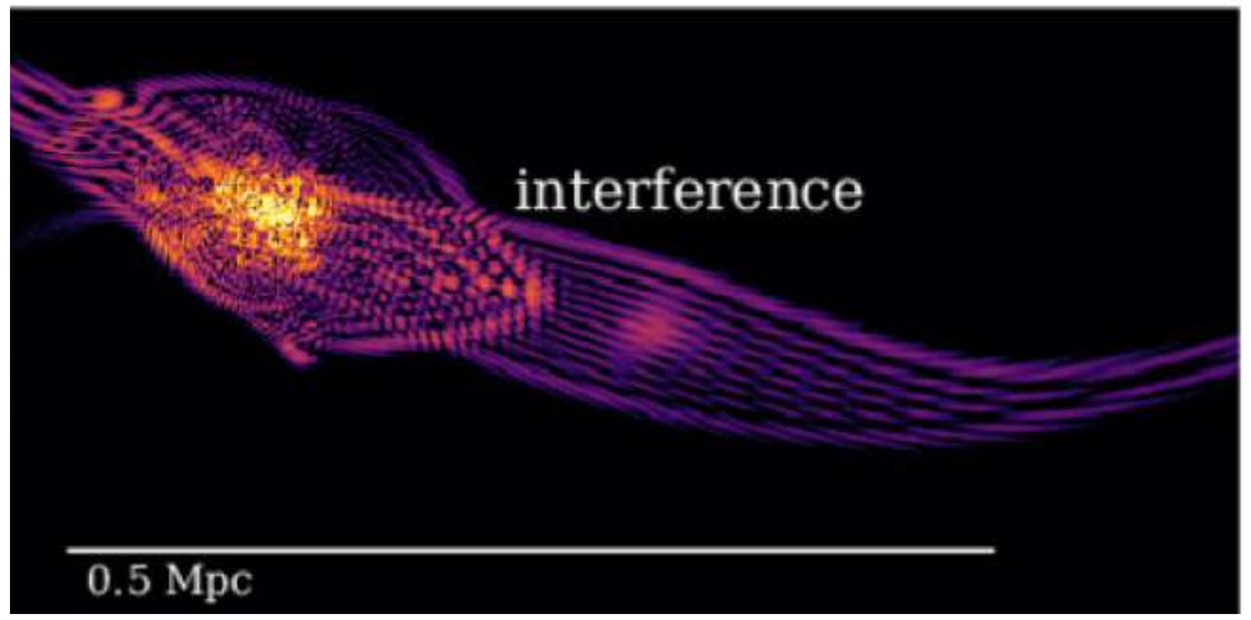
Baumann et al. 2019

Dynamical effects



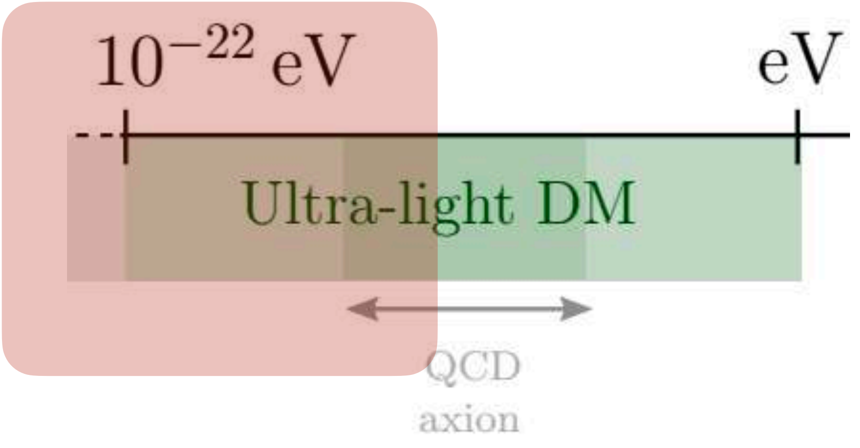
Levkov et al. 2018

Wave interference



Mocz et al. 2017

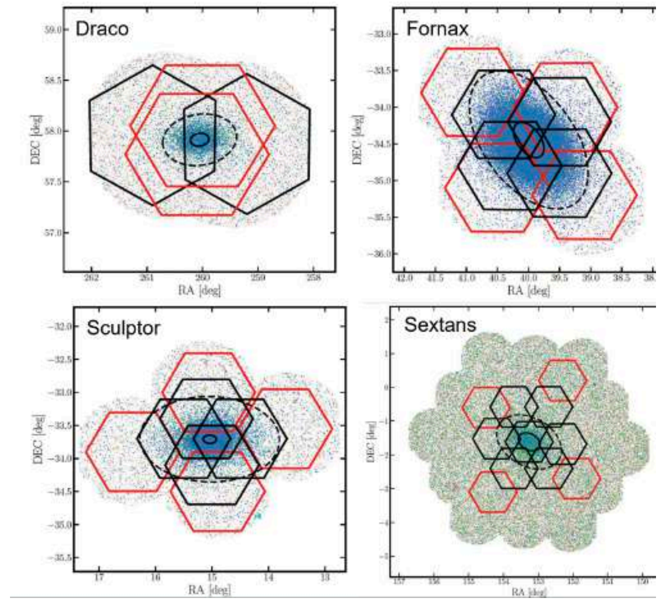
Observational implications and constraints



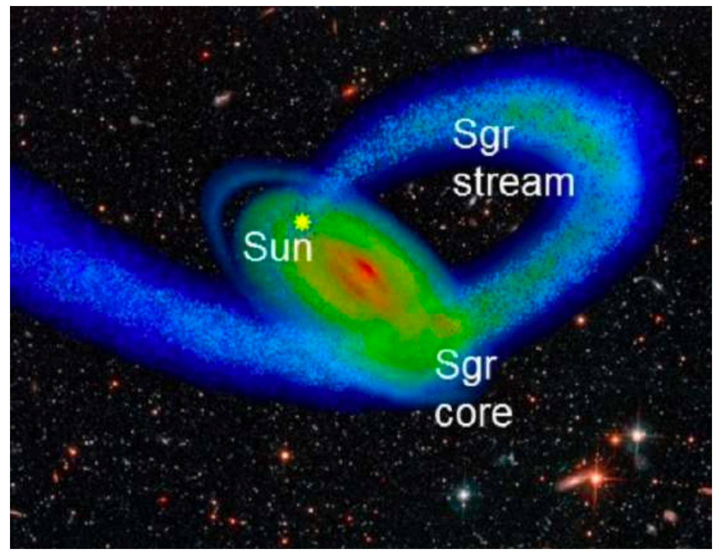
Galaxies

NASA and ESA

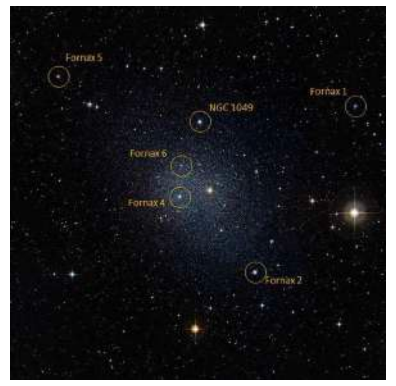
Dwarfs



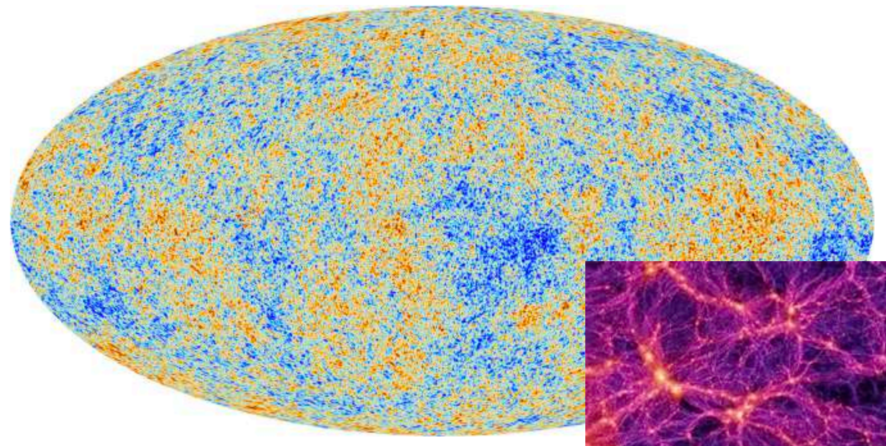
Stellar stream



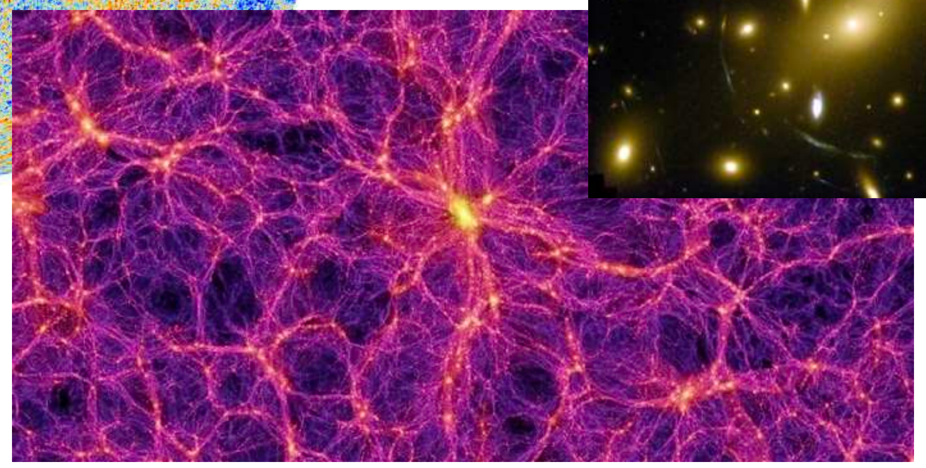
Globular clusters



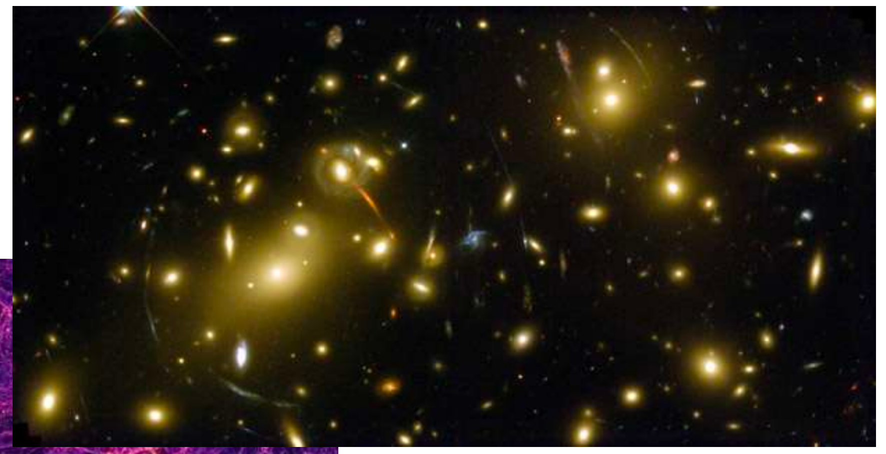
CMB+LSS



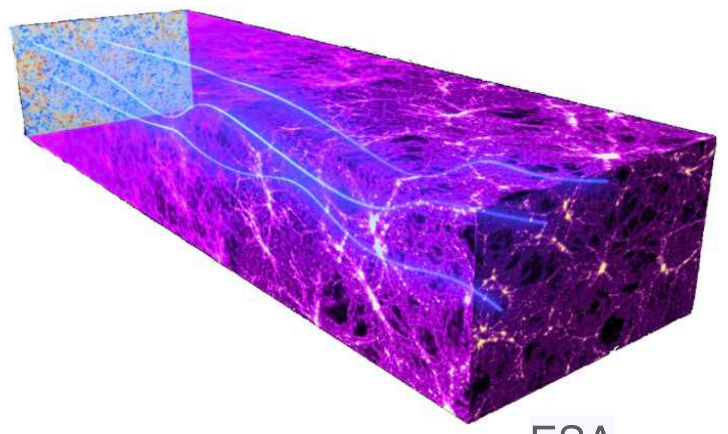
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

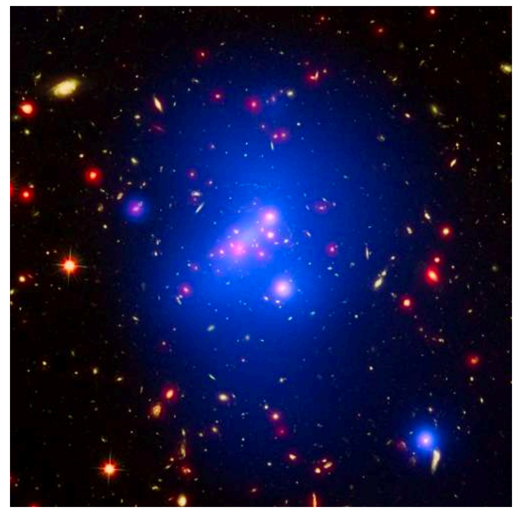


NASA and ESA



ESA

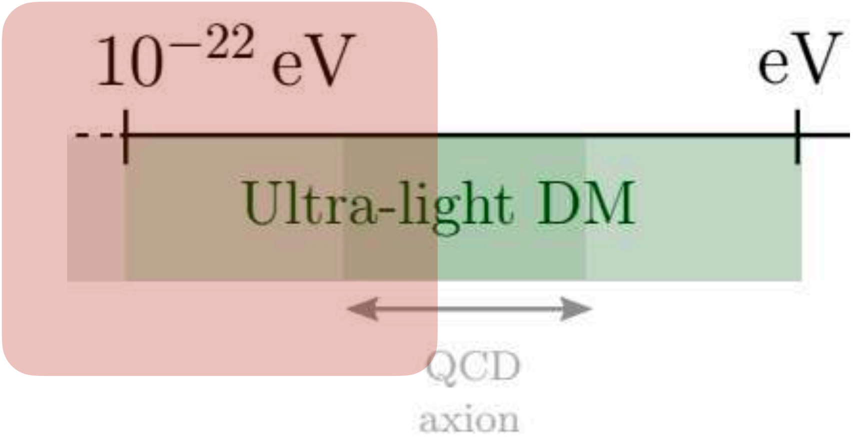
Clusters

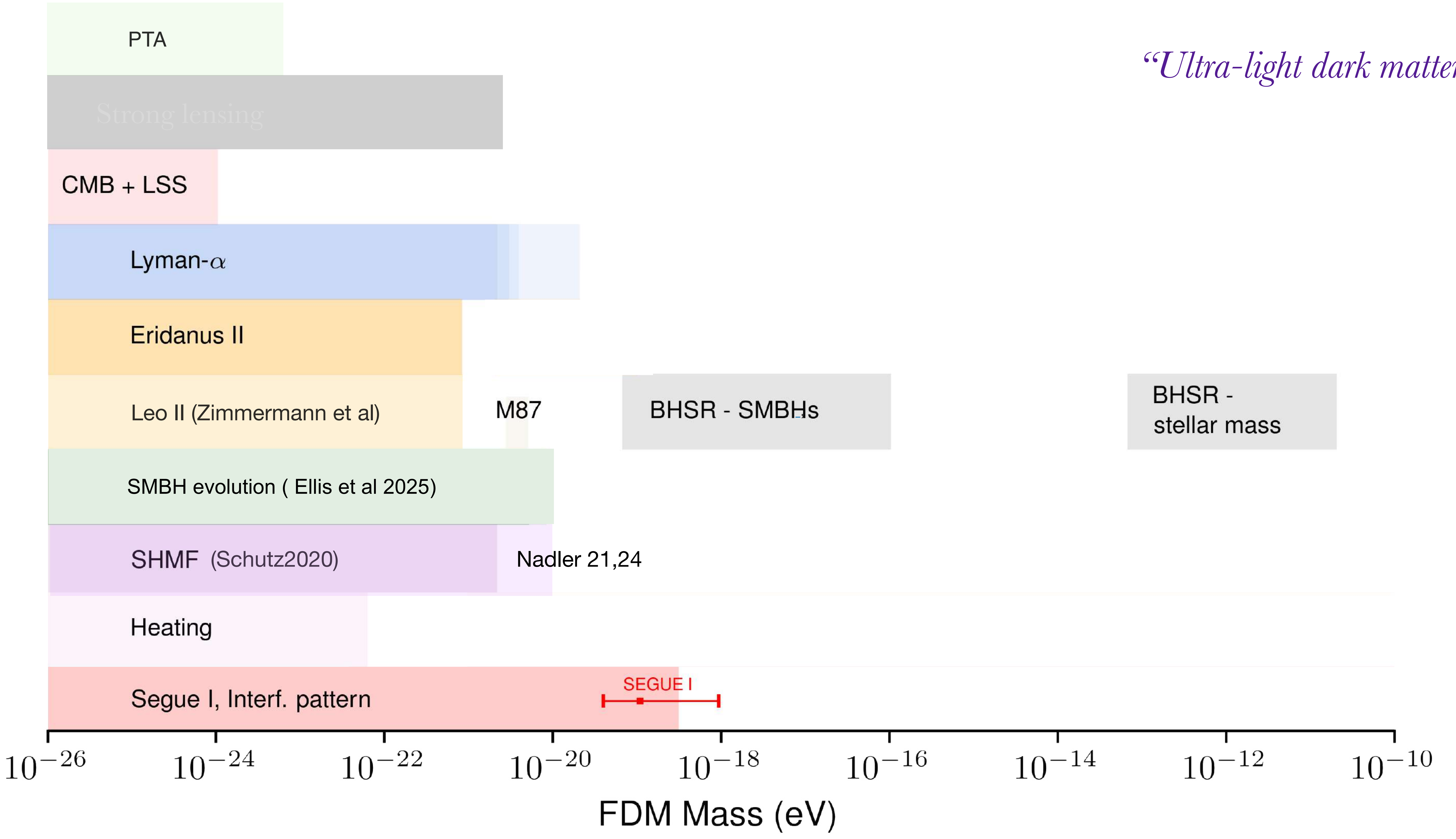


CC BY 4.0

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



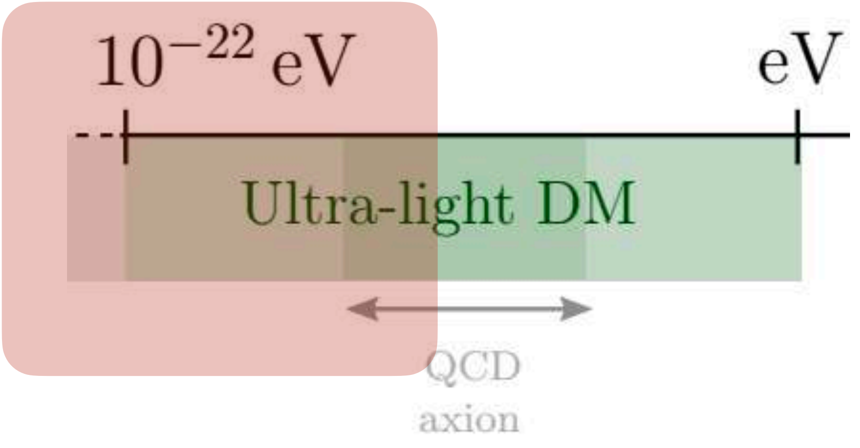


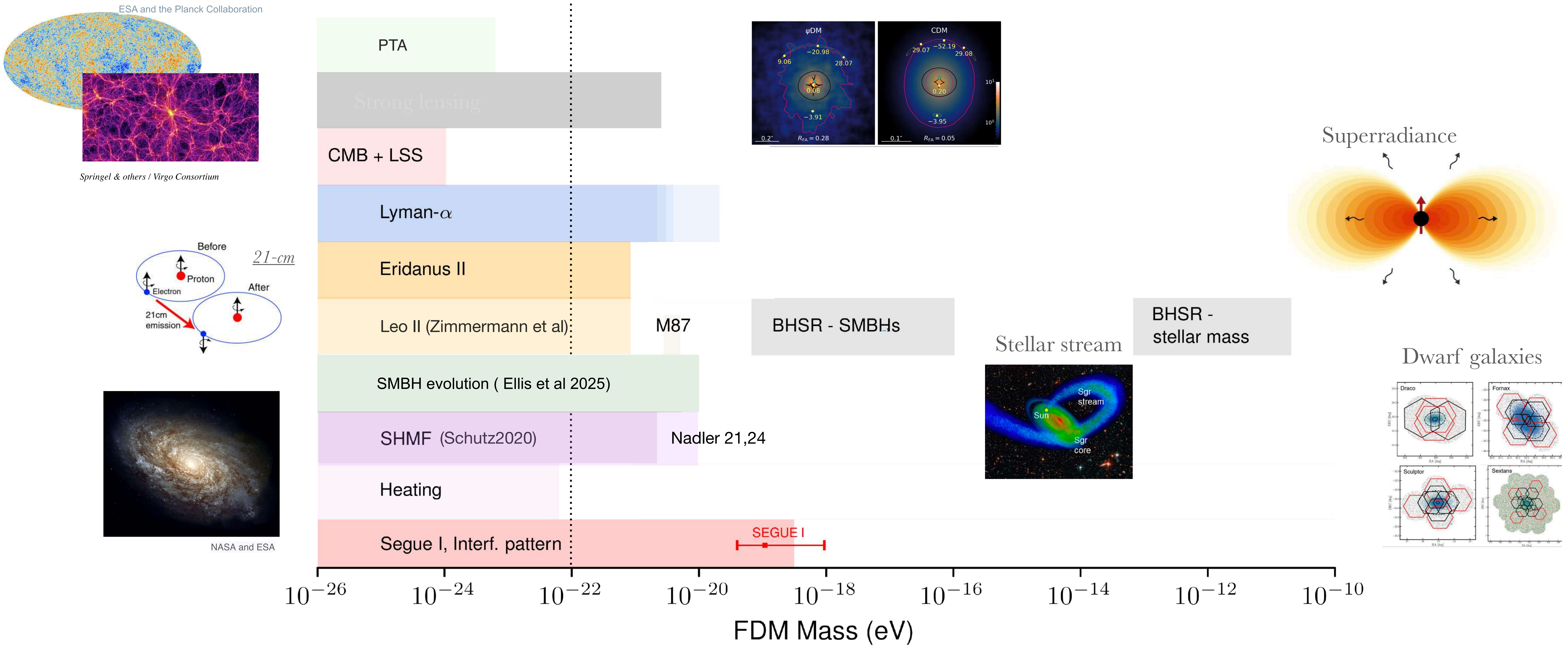
"Ultra-light dark matter", **E.F.**, 2020. The Astronomy and Astrophysics Review.

Bounds consider FDM is *all* DM

Current status

Fuzzy Dark Matter - bounds on the mass





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

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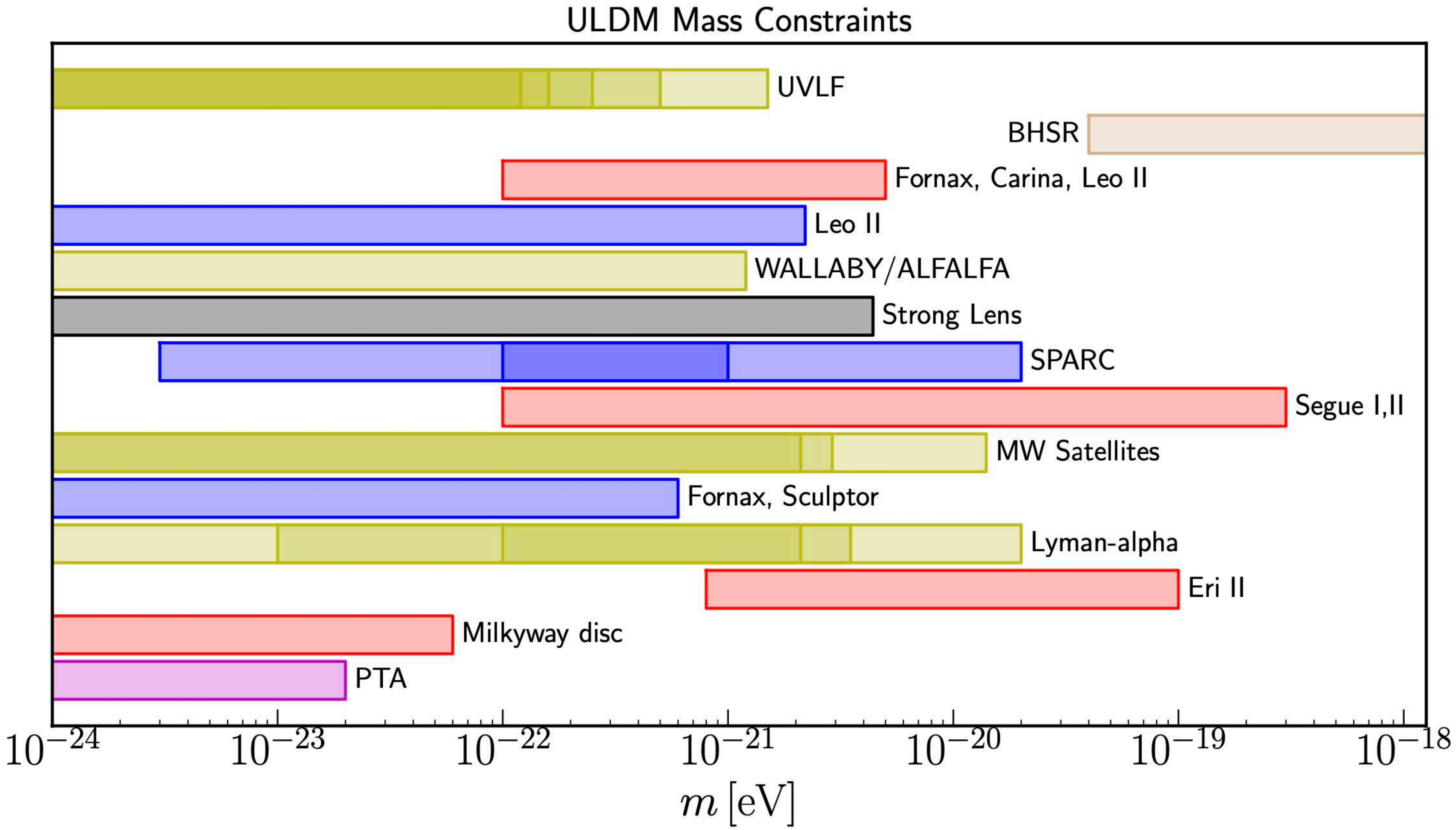
Fuzzy Dark Matter - bounds on the mass

Review: Eberhardt, EF, 2025



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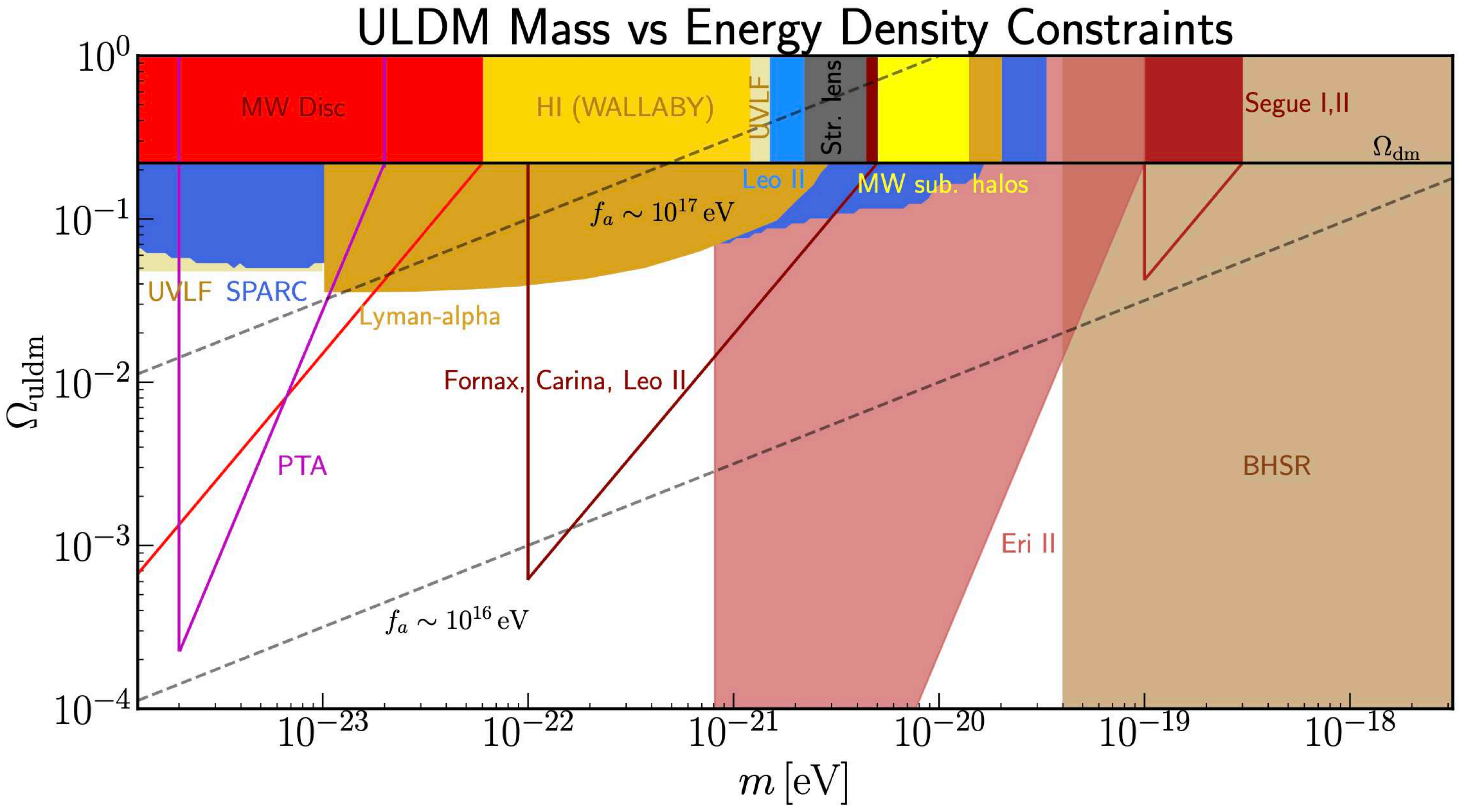
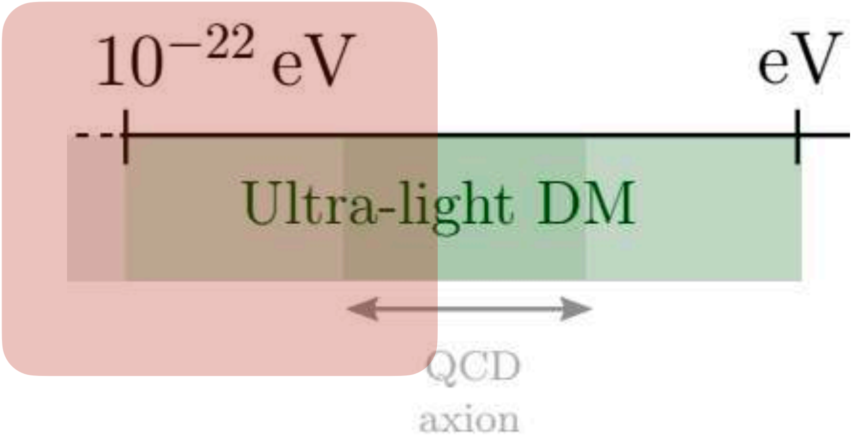


How to probe these?

Evolution and suppression: CMB and LSS

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

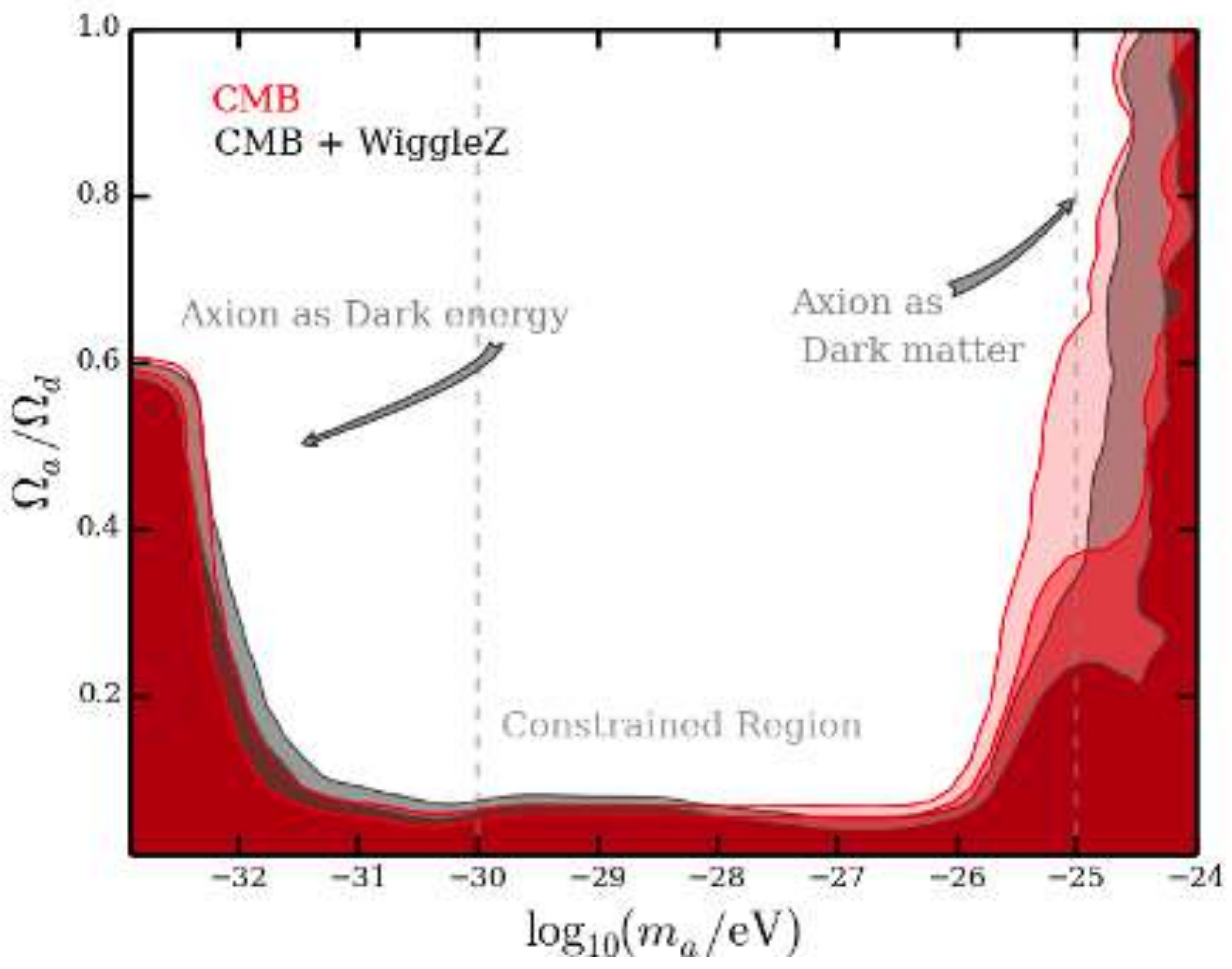


Suppression of small structures + evolution

<u>*Extremely light dark matter or axion DE*</u>

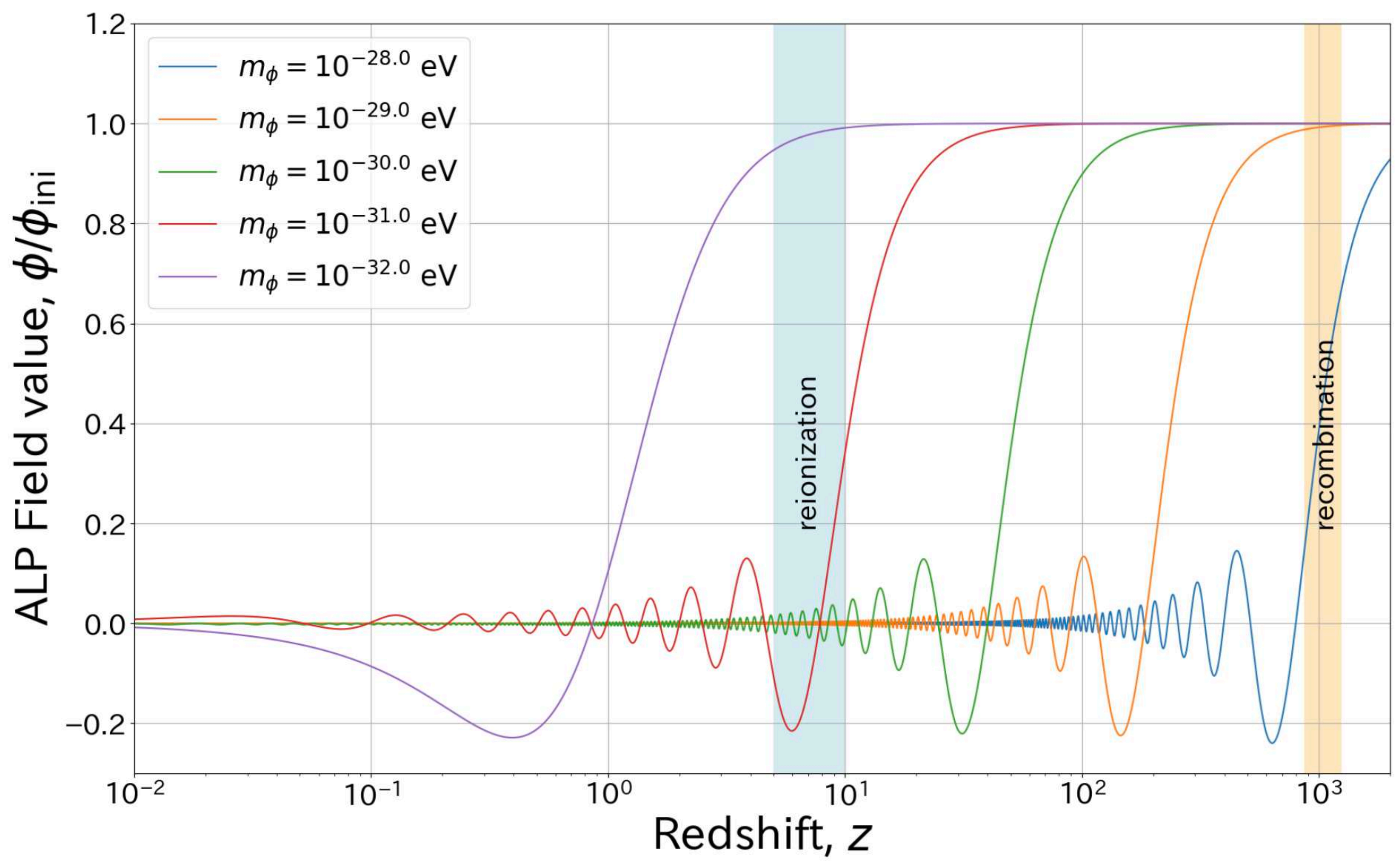
CMB/LSS

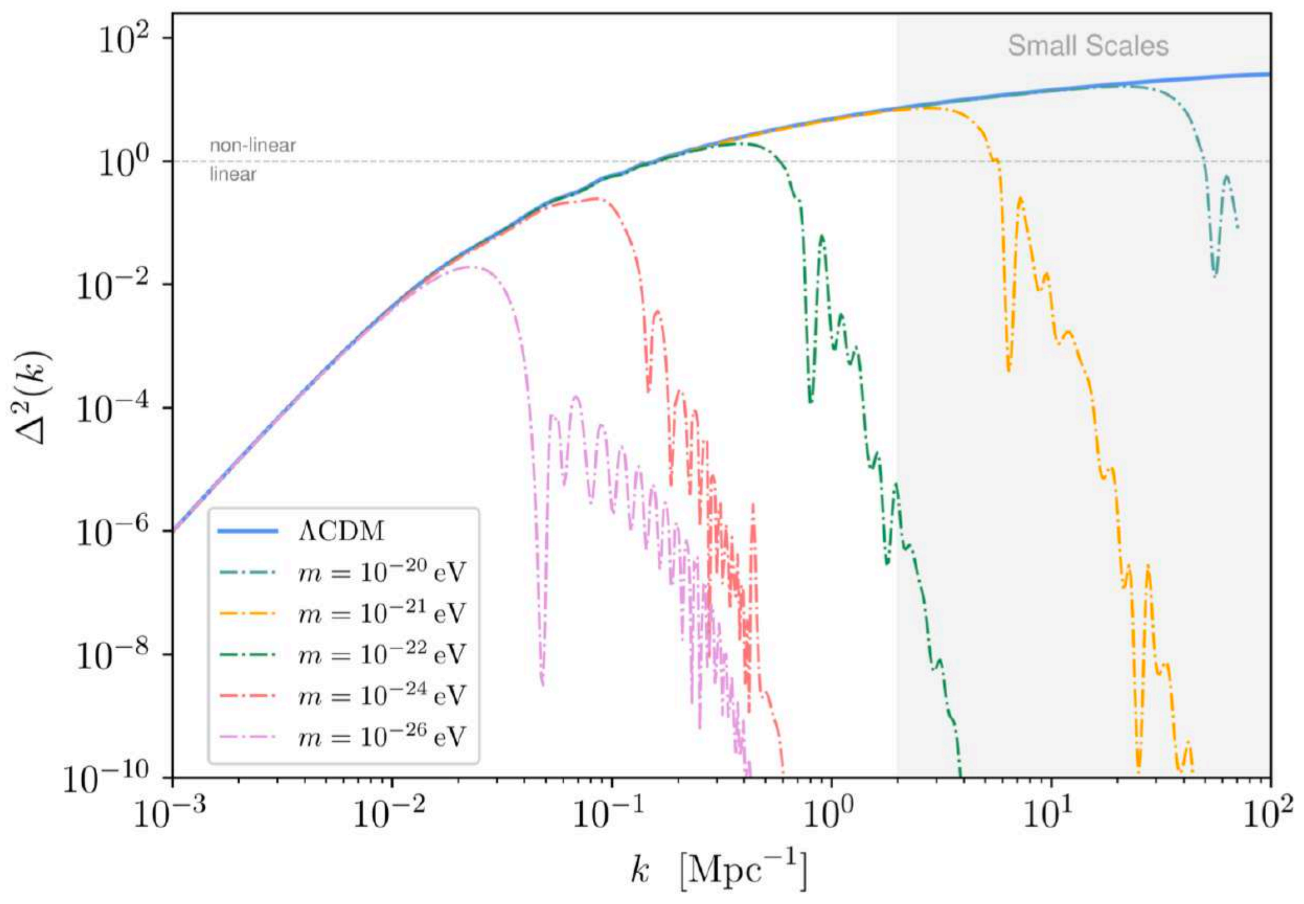
Hlozek et al, (2015, 2018)



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

Atacama Cosmology Telescope (ACT) Data Release 6 (DR6) (2025) improved over these bounds

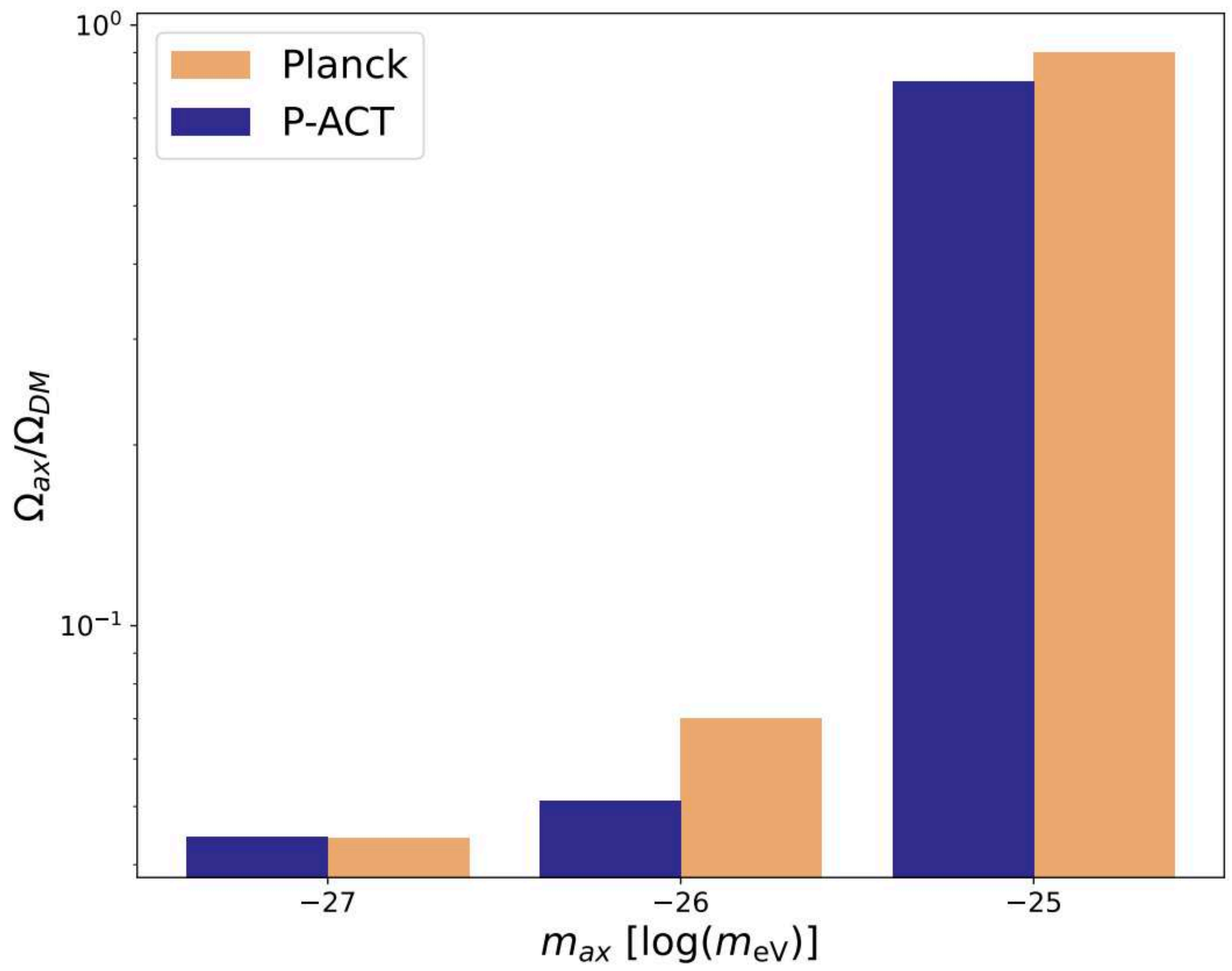




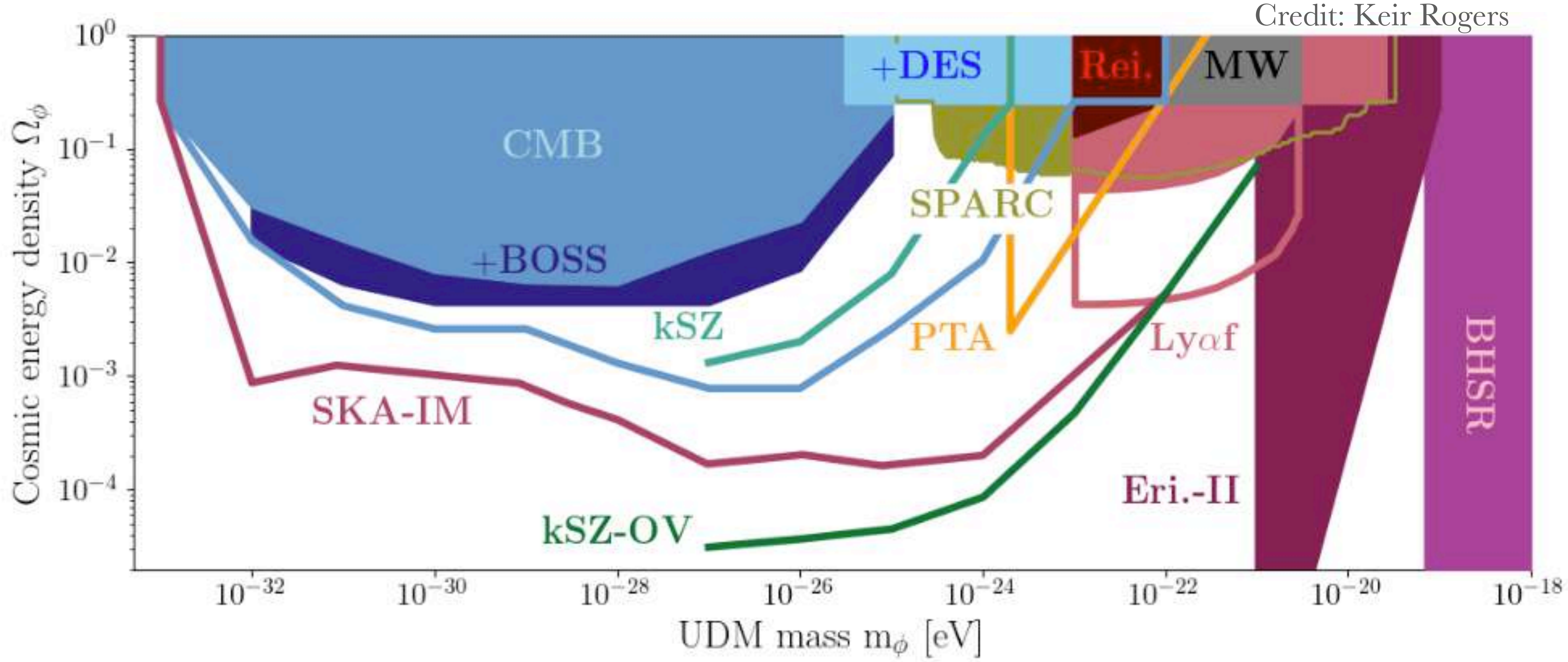
CMB and LSS

Evolution and shape of PS

Atacama Cosmology Telescope (ACT) Data Release 6 (DR6) (2025) improved over these bounds



Calabrese et al 2025

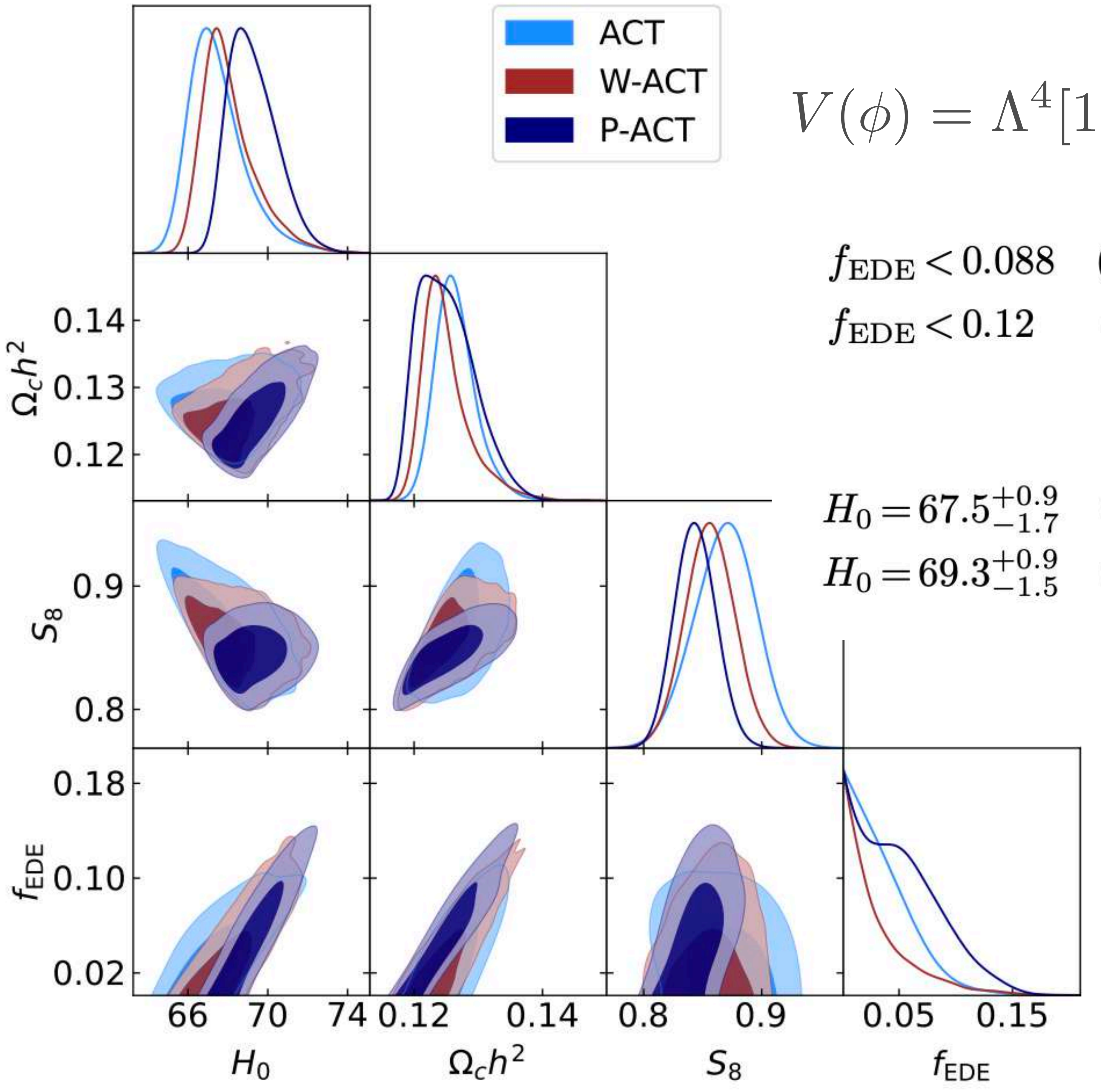


$$m_{\rm ax} = 10^{-26}\ {\rm eV}:$$

$$\Omega_{\rm ax}/(\Omega_{\rm ax}+\Omega_c) < 0.070 \quad (95\%,\ \text{Planck})$$
$$< 0.052 \quad (95\%,\ \text{P-ACT}). \quad (51)$$

ACT DR6

Early dark energy



$$V(\phi) = \Lambda^4[1 - \cos(\phi/f_a)]^3$$

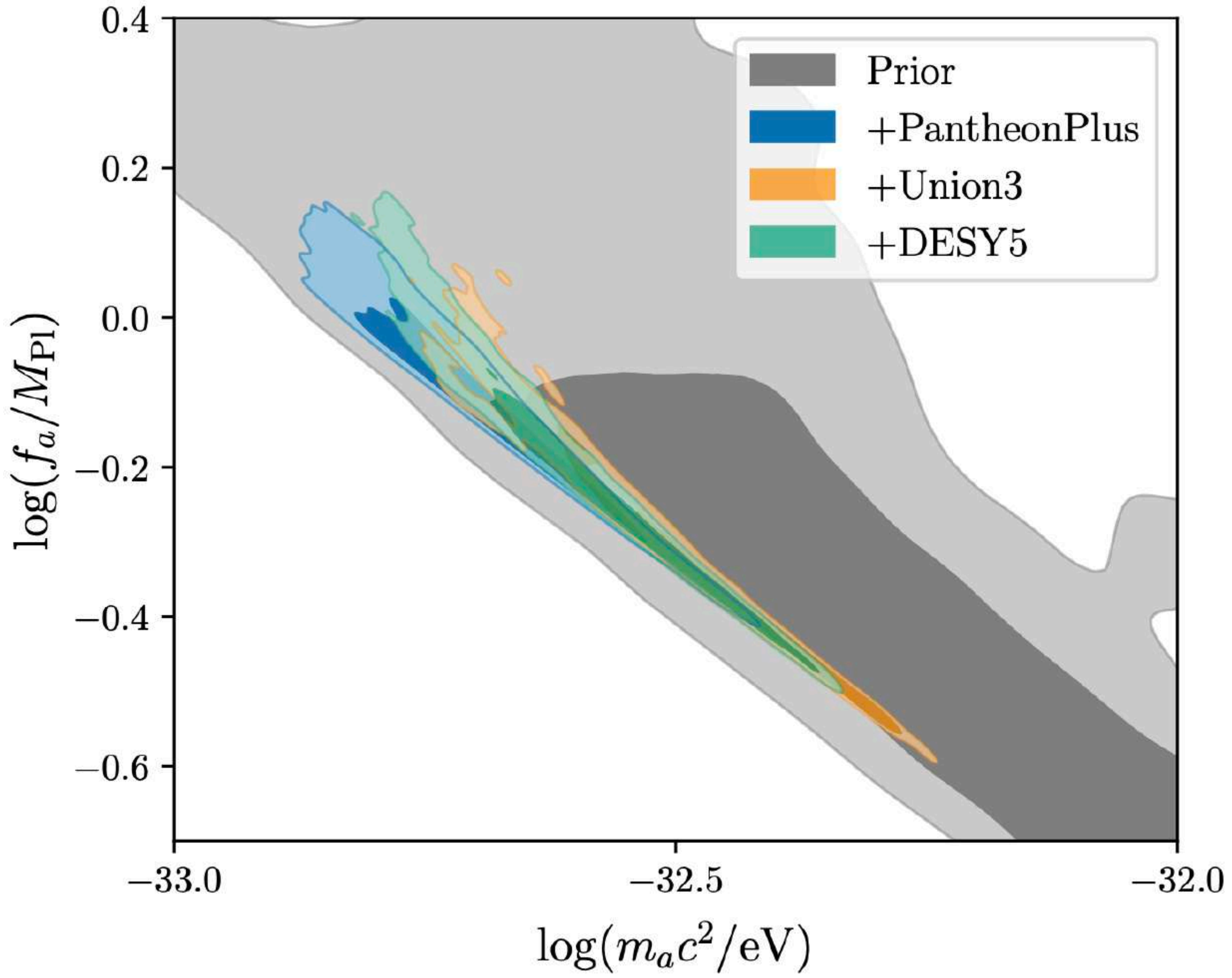
$$f_{\rm EDE} < 0.088 \quad (95\%, \text{ACT}),$$
$$f_{\rm EDE} < 0.12 \quad (95\%, \text{P-ACT}),$$

$$H_0 = 67.5^{+0.9}_{-1.7} \quad (68\%, \text{ACT}),$$
$$H_0 = 69.3^{+0.9}_{-1.5} \quad (68\%, \text{P-ACT}),$$

Calabrese et al 2025

DESI

Axion dark energy



DESI

$\log(m_a c^2/\text{eV}) \simeq -32.6$

$\log(f_a/M_{\rm Pl}) \simeq -0.22$

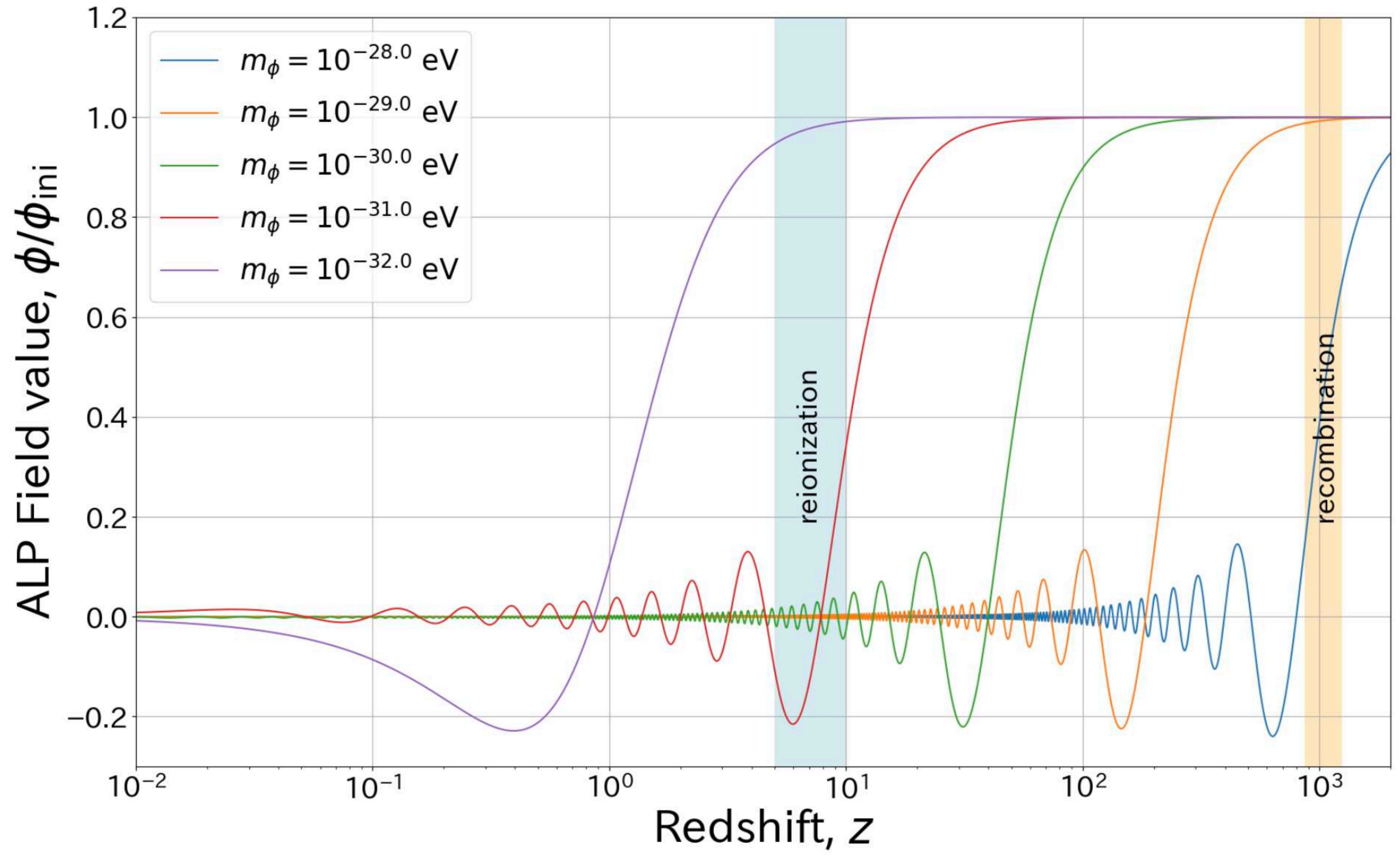
Previous: Planck

$m_a^2 f_a^2 \simeq 2.3 \times 10^{-11} \text{eV}^4$

$f_a/M_{\rm Pl} > 0.67$

Urena-Lopez et al 2025

Emulator for FDM



Linear predictions:

Boltzmann codes: axionCAMB, AxionECAMB, AxiCLASS

Very slow!! 1 - 8 min per spectrum

Parameter inference → very hard!

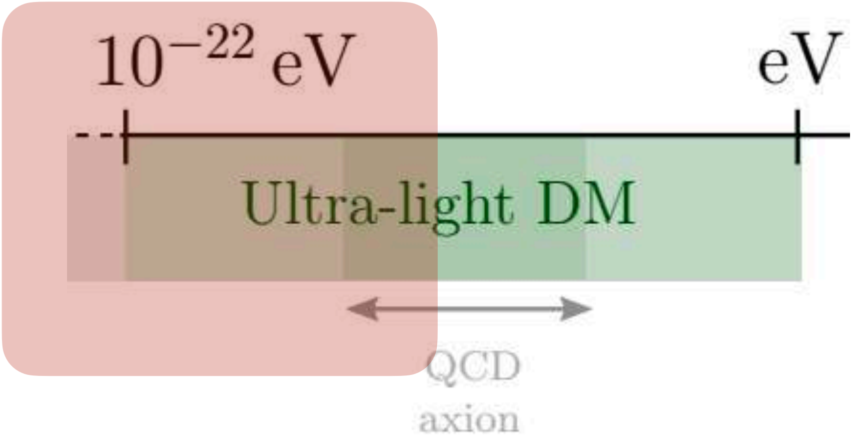
New emulator (to appear) (Work in progress) *with Fernanda Matos*

Phase 1 - linear emulator

Most complete ULDM emulator in the market!

Phase 2 - non-linear emulator

Observational implications and constraints

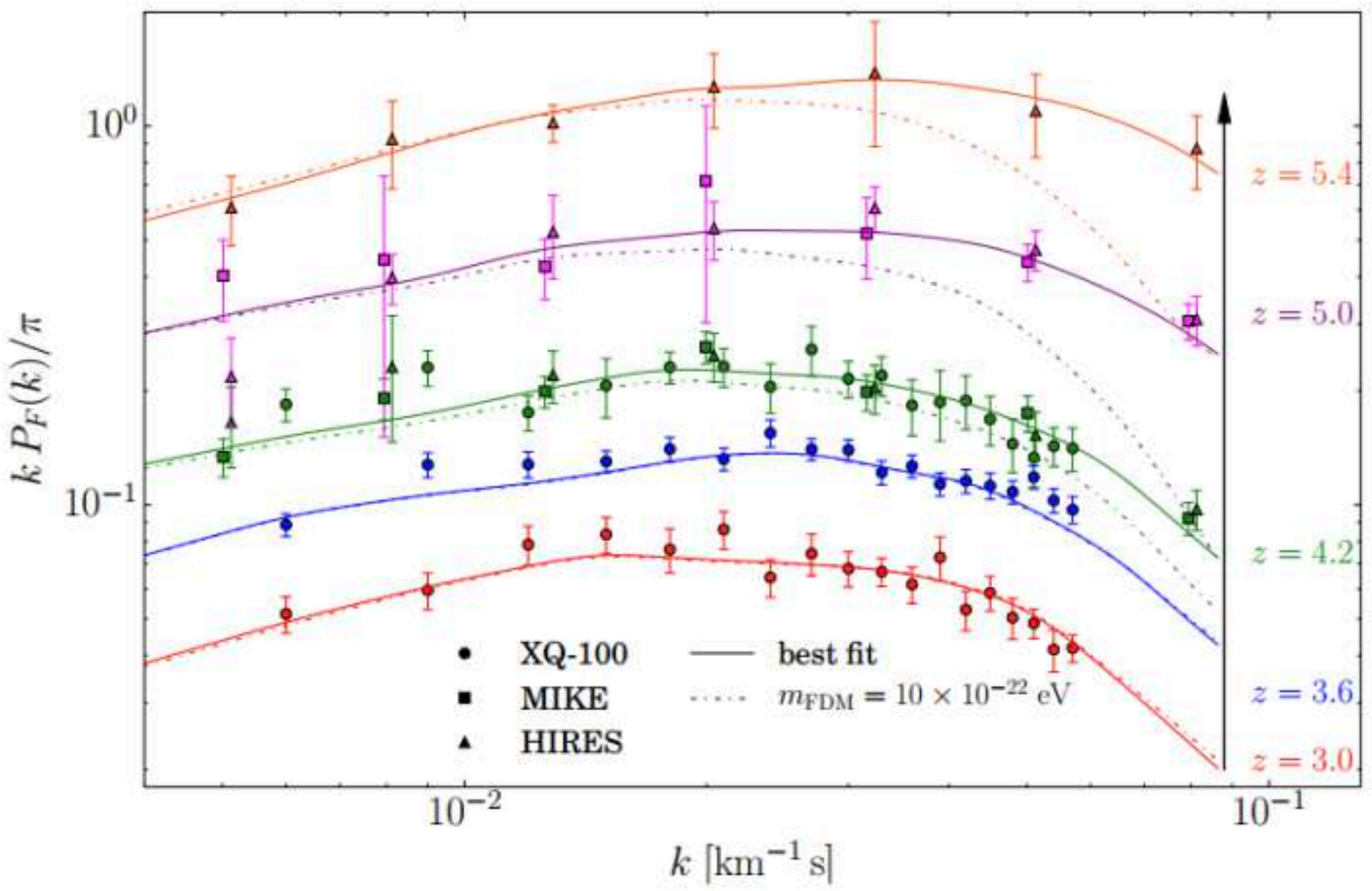


Fuzzy Dark Matter - bounds on the mass

Suppression of small structures + evolution

Lyman alpha

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



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

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

One of the strongest bounds on ULDM!

Constraints depends on:

- IGM modelling - simplifying assumptions
- Trusts on IC sims

(Work in progress) with Simon May

New cosmological fuzzy dark matter simulations including baryons, using the IllustrisTNG galaxy formation model

Revise these bounds + study the evolution of IGM as a way of constraining FDM.
IGM properties not so influenced by feedback
Filaments and interference patterns important here!

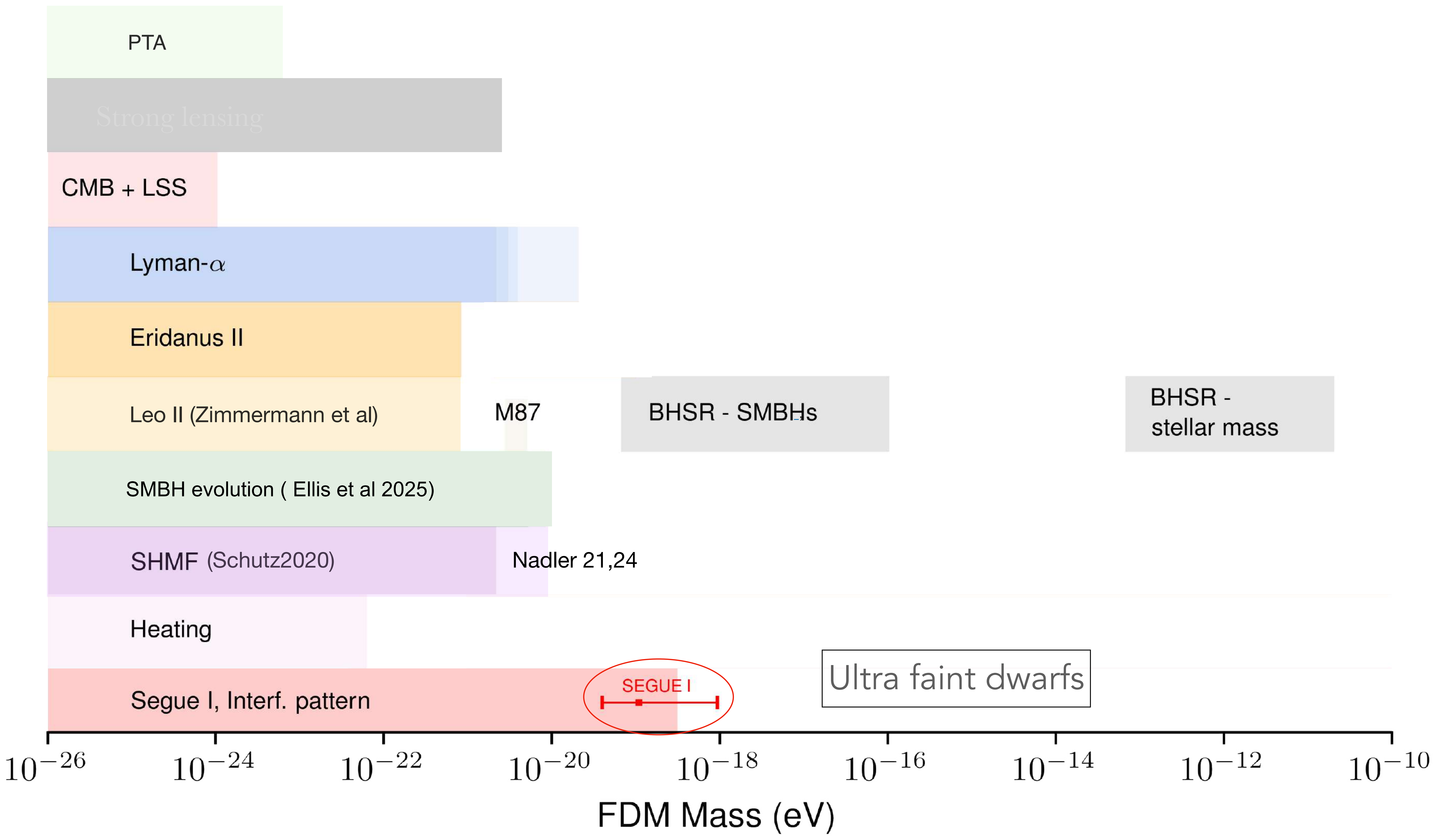
How to probe these?

Presence of a core

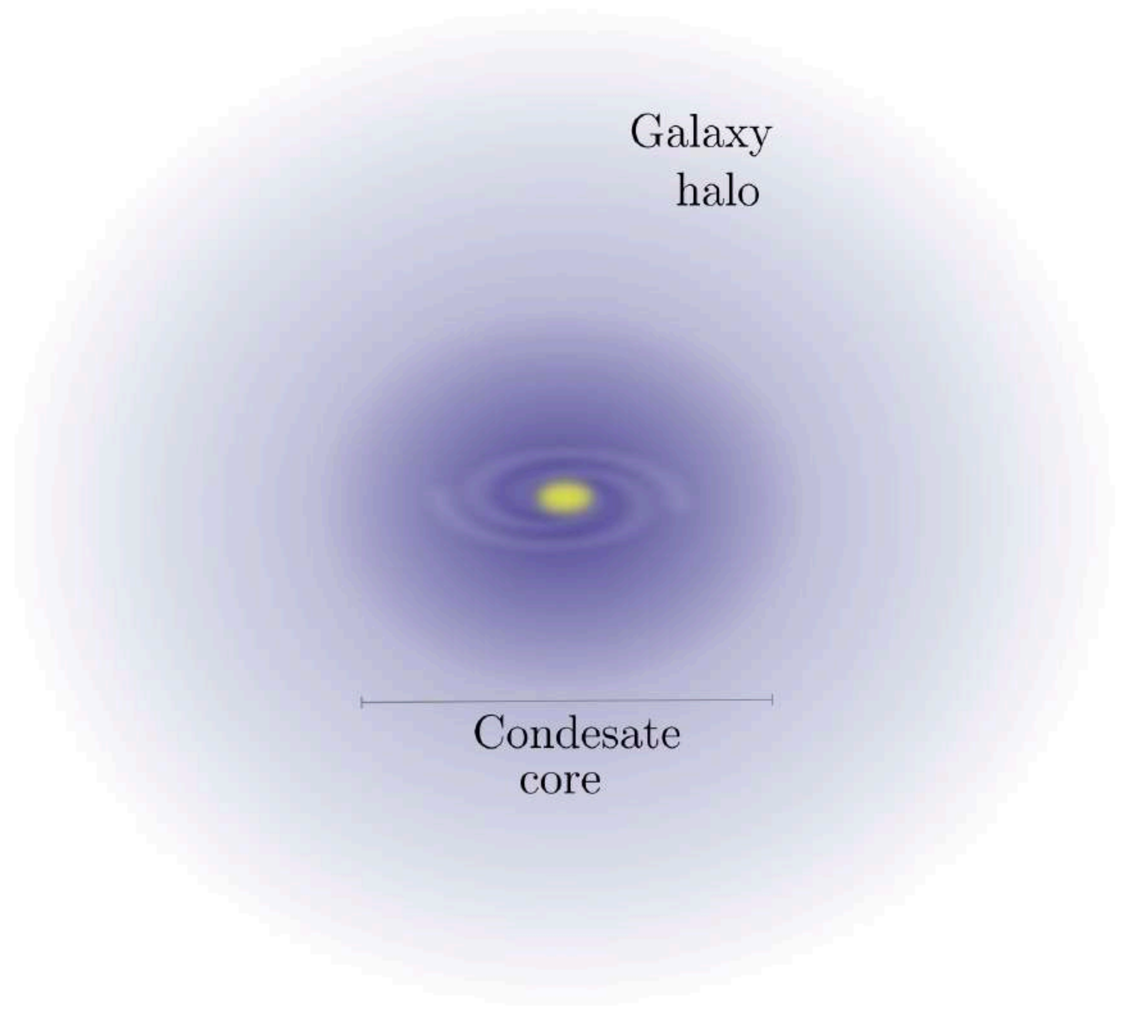
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

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



Presence of a core



Ultra-light Dark Matter

FDM mass from Ultra-faint dwarfs

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

Ultra-faint dwarfs (UFD): ideal laboratory to study DM

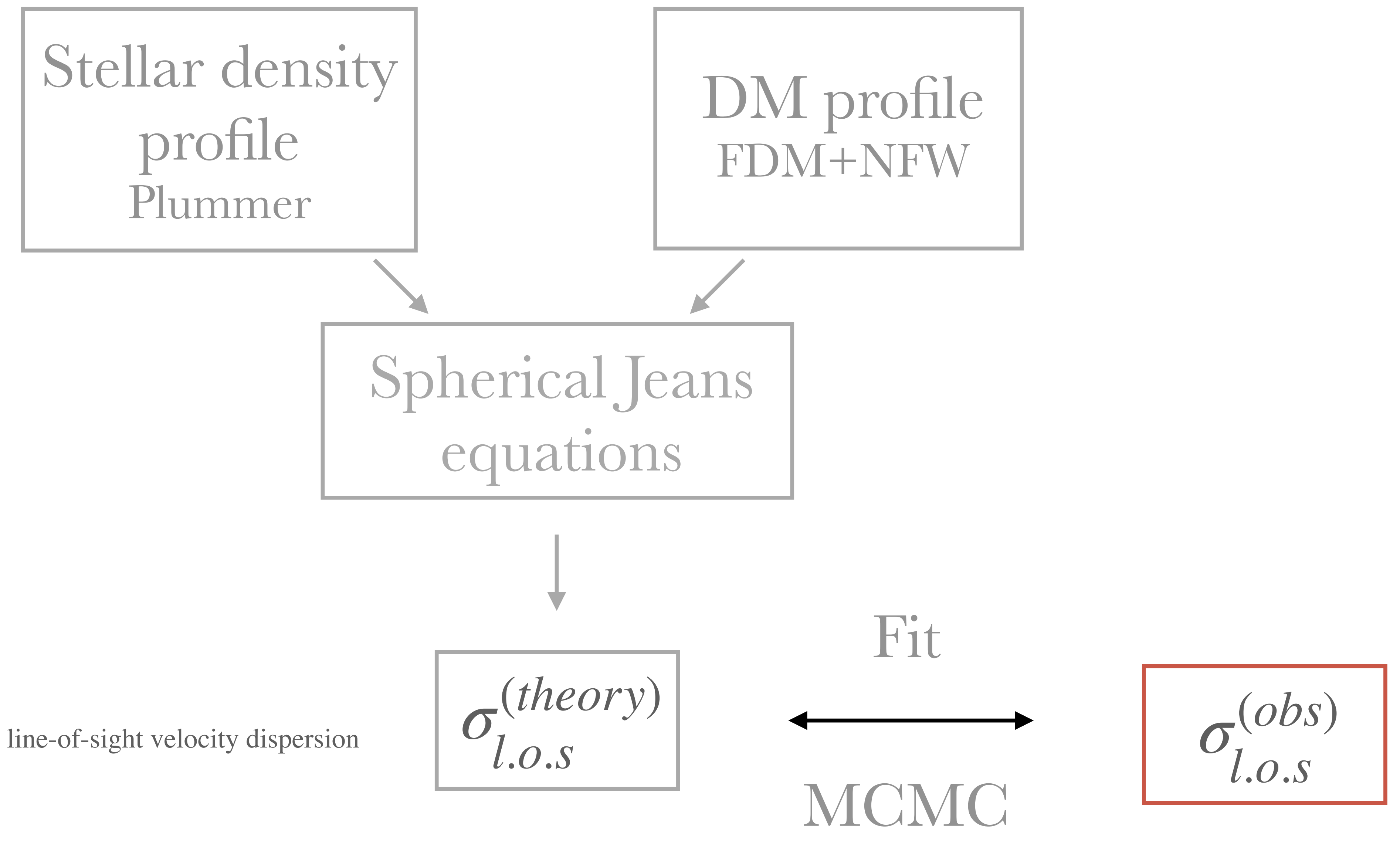
Stellar kinematic data from 18 UFDs to fit the FDM profile:

FDM SIMULATIONS

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

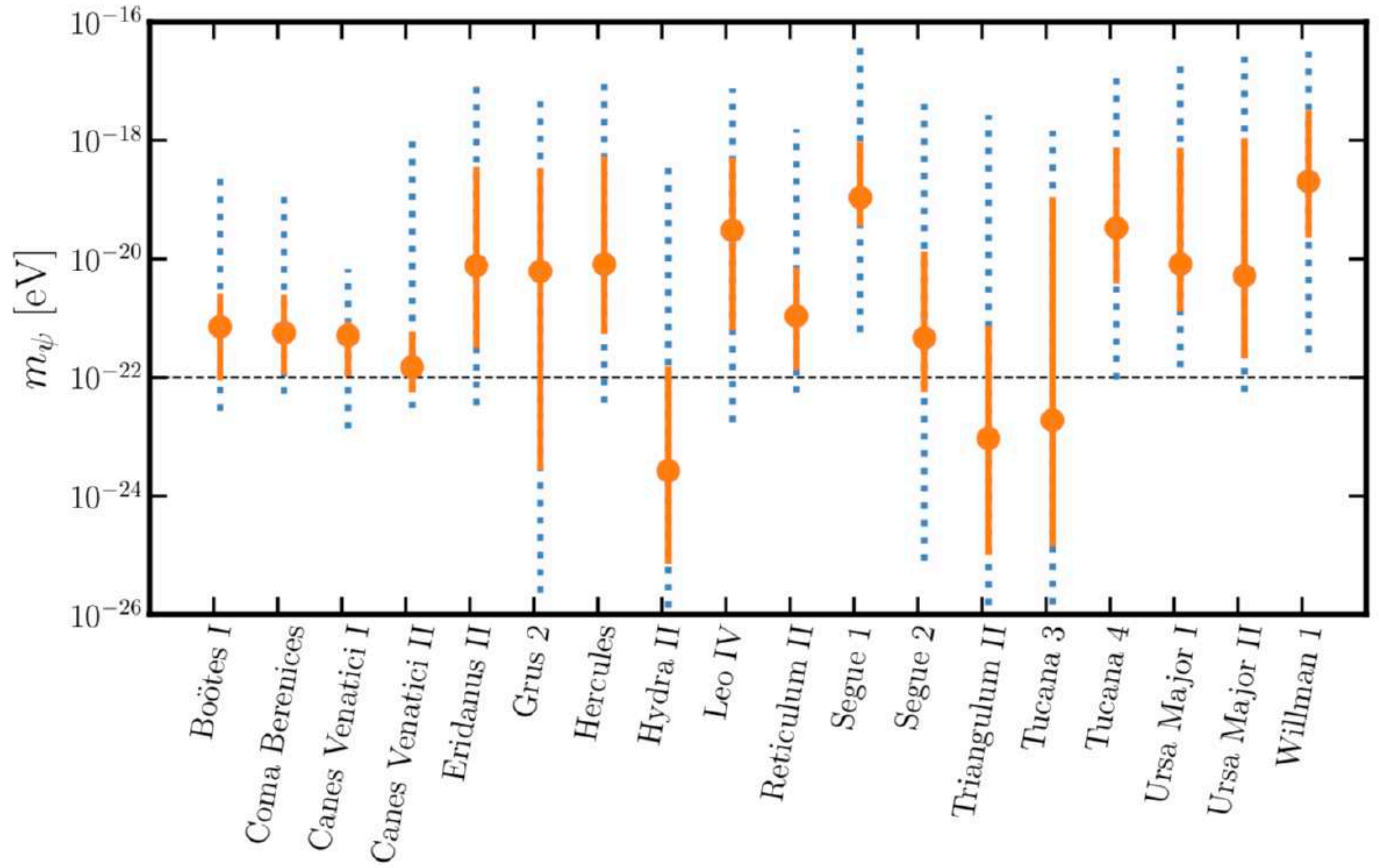
$$\rho_c(r) = 1.9 \times 10^{12} \left(\frac{m}{10^{-23}\,{\rm eV}}\right)^{-2} \left(\frac{r_c}{\rm pc}\right)^{-4} \; [M_\odot\,{\rm pc}]$$

$$r_c \simeq 1600 \left(\frac{m}{10^{-23}\,{\rm eV}}\right)^{-1} \left(\frac{M_{\rm halo}}{10^{12}\,M_\odot}\right)^{-1/3} \; [{\rm pc}]$$



Parameter space (10): $\left\{m, M_{\rm halo}, r_\epsilon, r_s, r_\beta, \beta_0, \beta_\infty, \eta, r_h, v_{sys}\right\}$

Stellar velocity anisotropy



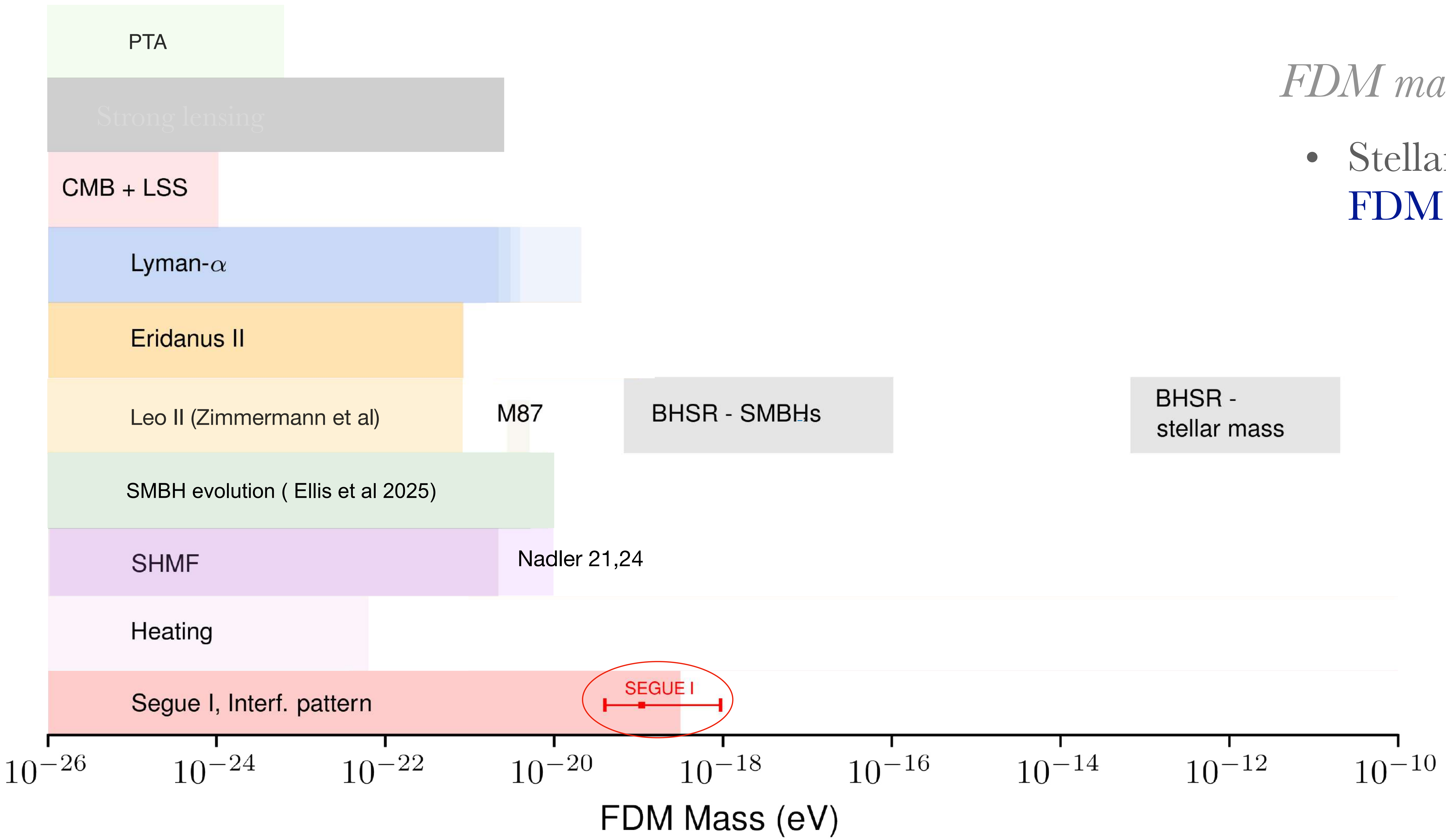
Strongest constraint on $m_{\rm FDM}$ to date!

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass

Ultra faint dwarfs

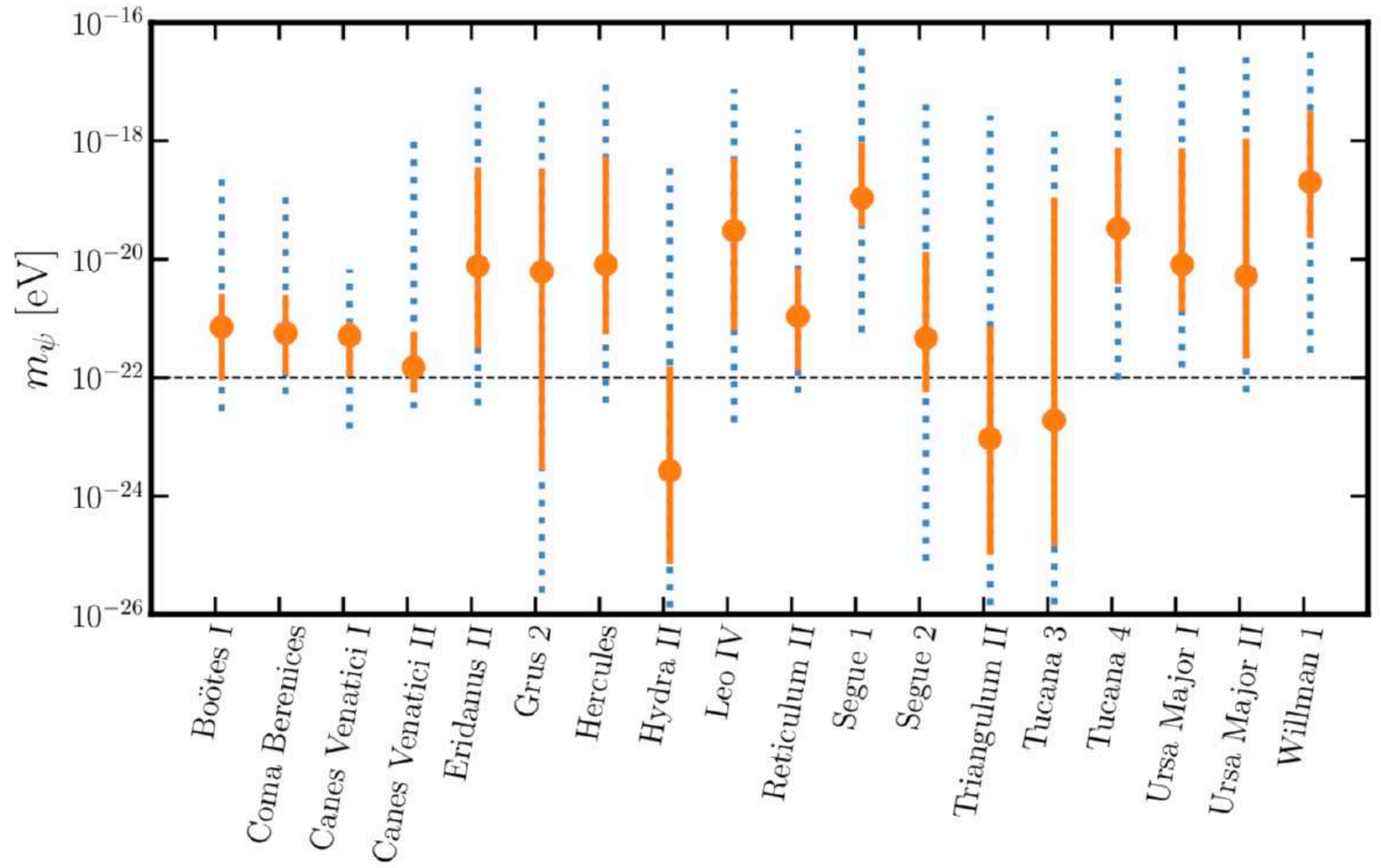
Hayashi, **E.F**,Chan, 2021.



FDM mass from Ultra-faint dwarfs

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

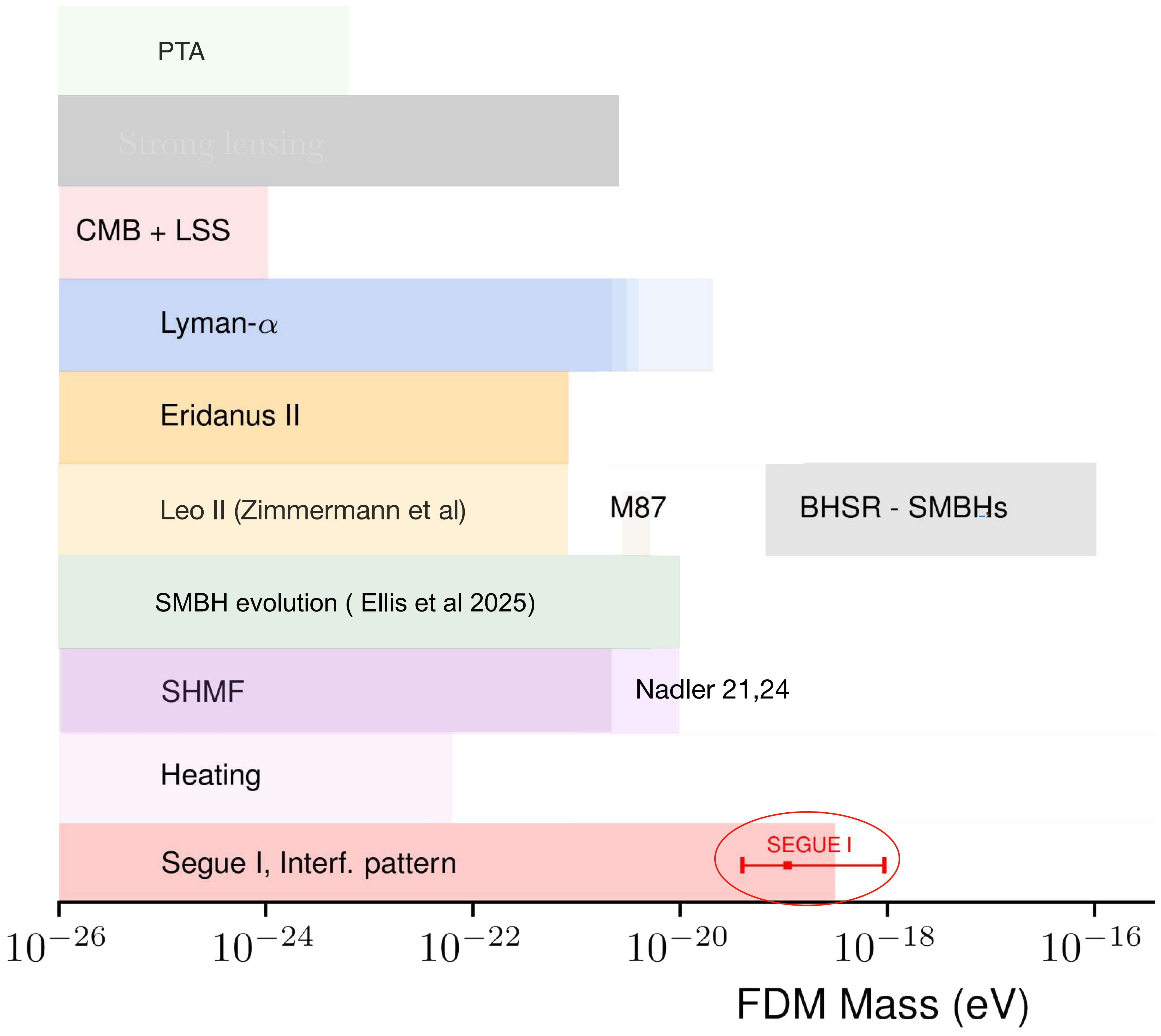
$$m_{\rm FDM}^{(Seg1)} = 1.1^{+8.3}_{-0.7} \times 10^{-19}\,{\rm eV}$$



Preference for higher mass

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass



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Important:

- Bayesian analysis - reason for a constraint
- 'Bad' assumption
- Systematic effects !

Ultra-light Dark Matter

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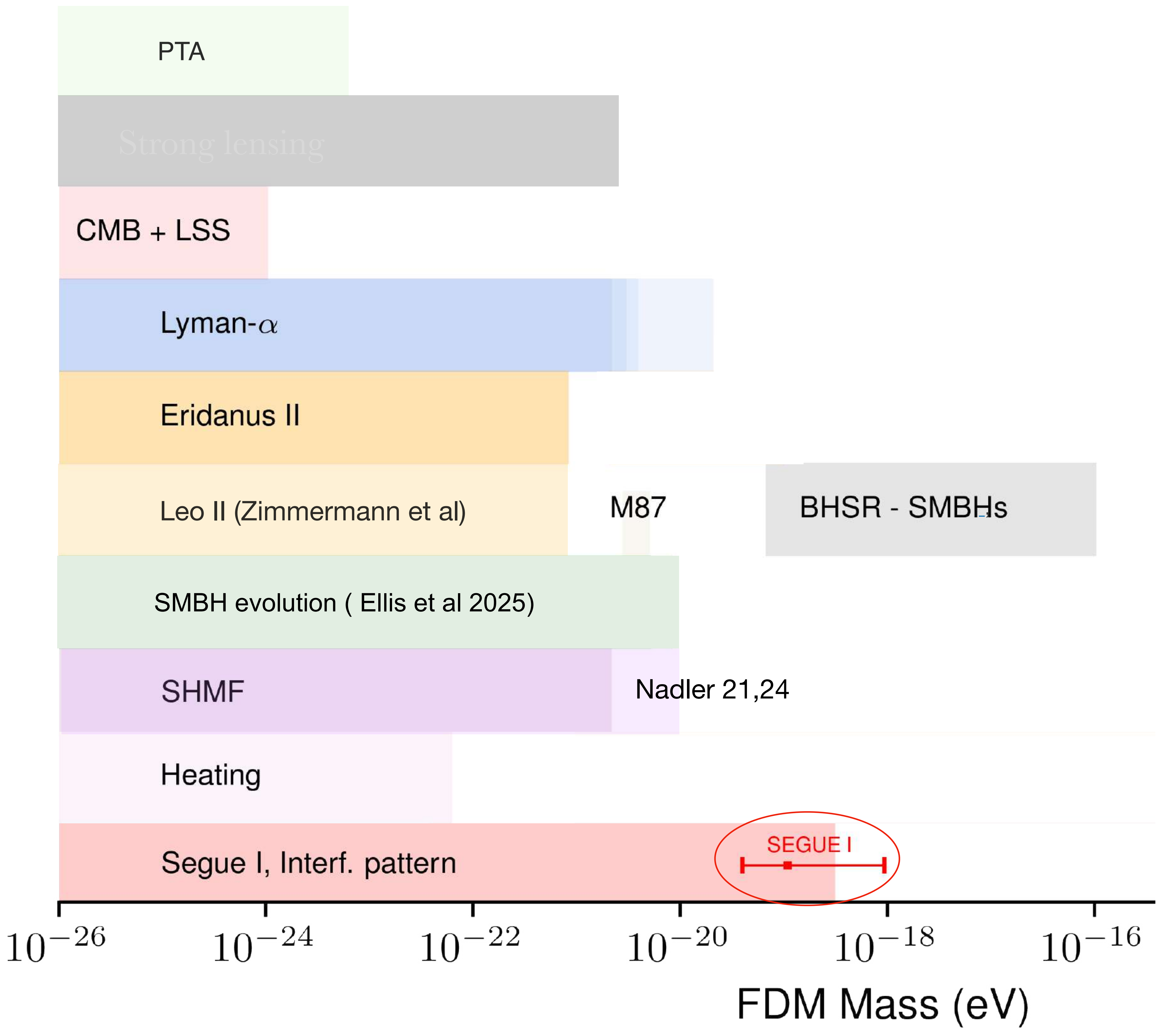

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Important:

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- 'Bad' assumption
- Systematic effects !

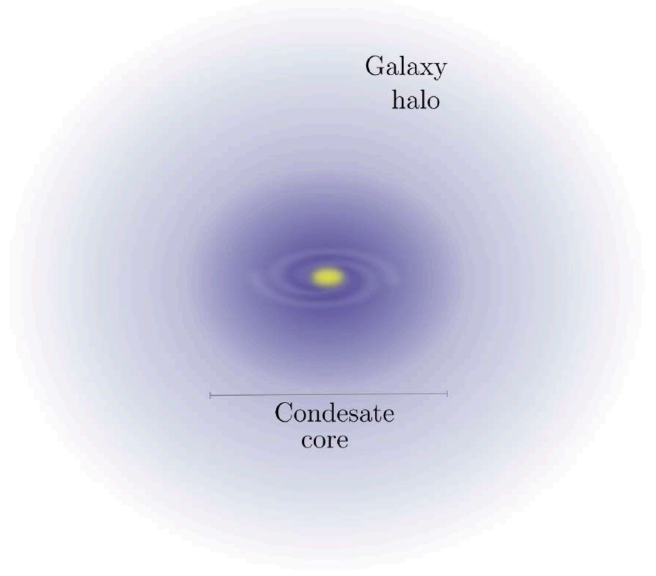
FDM - *Core-halo mass relation*

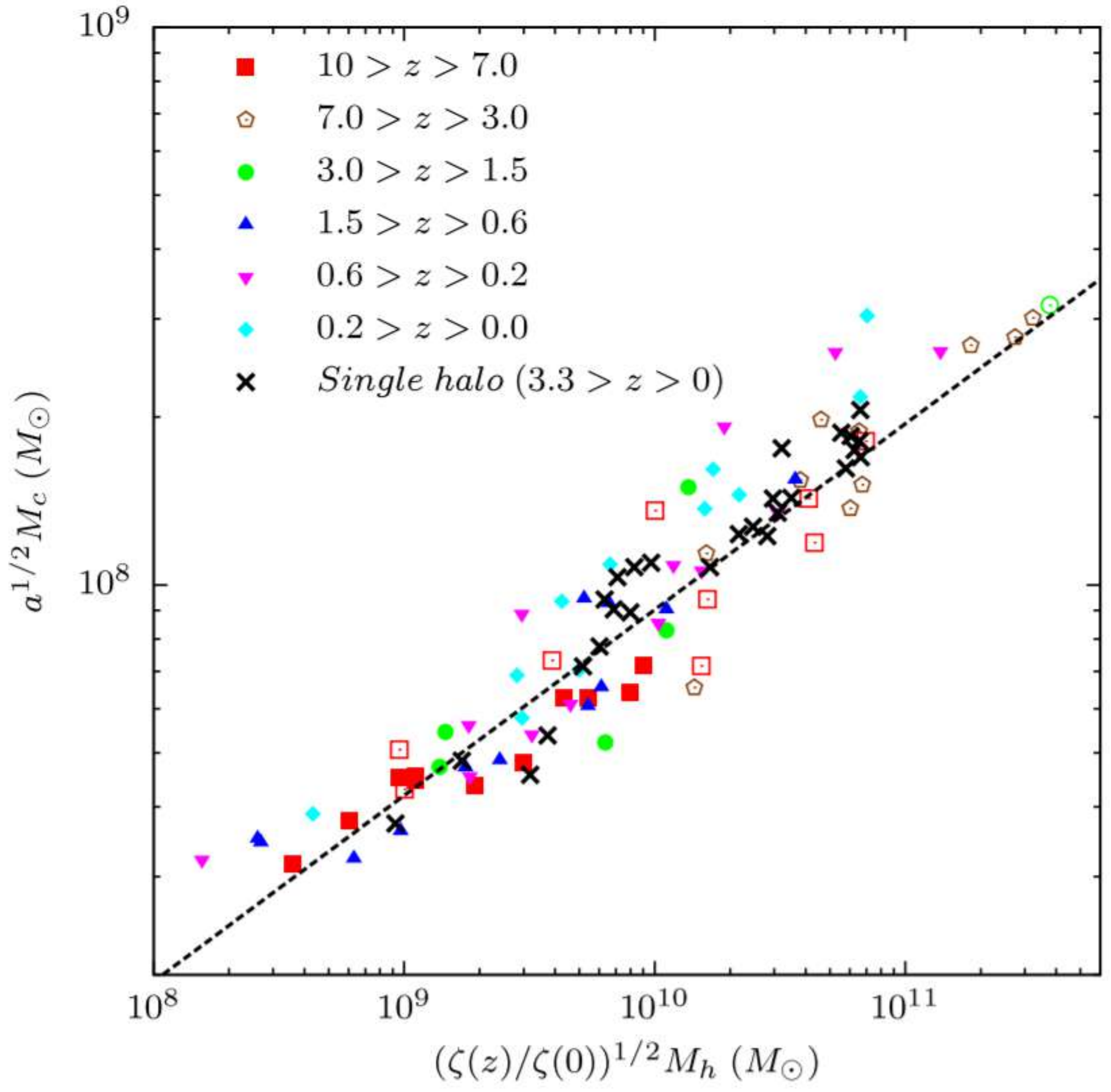
J. Chan et al. 2021

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

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

$\xrightarrow{?}$ 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

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

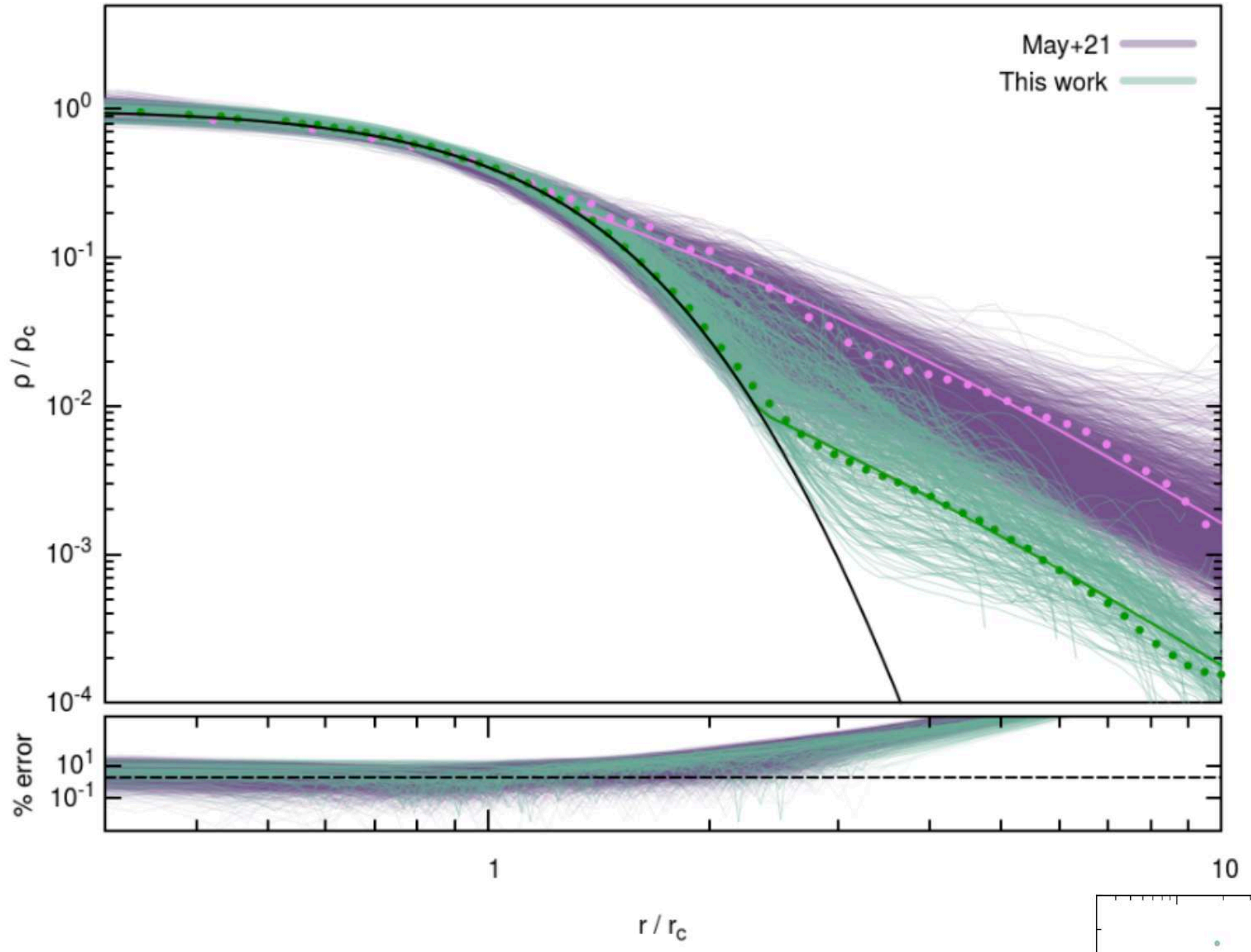
Velmatt et al 2018, Nori et al 2020, Nima et al 2020

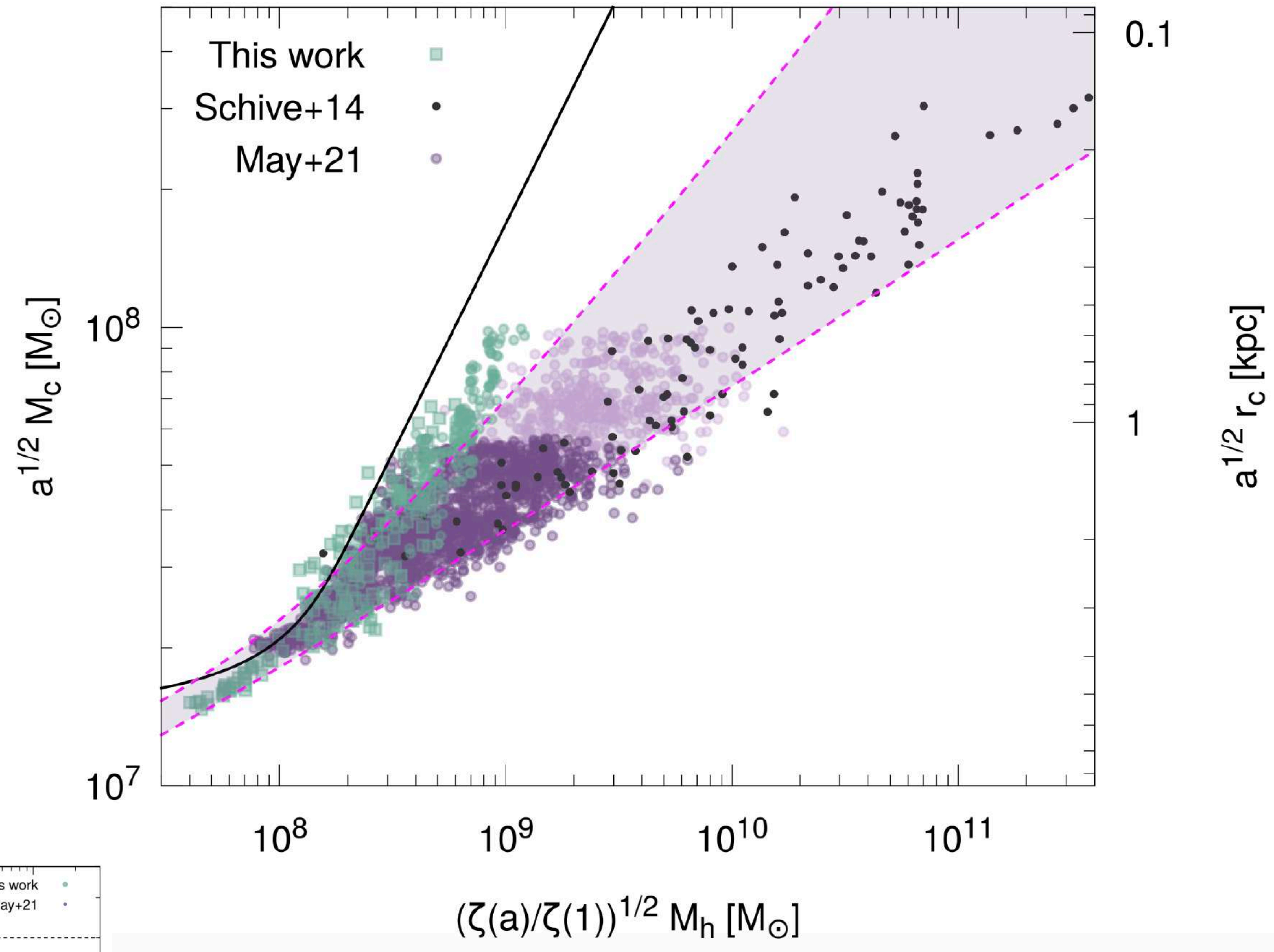
= Schive (Velmatt et al 2018)

≠ Schive (Nori et al 2020, Nima et al 2020)

FDM - Core-halo mass relation

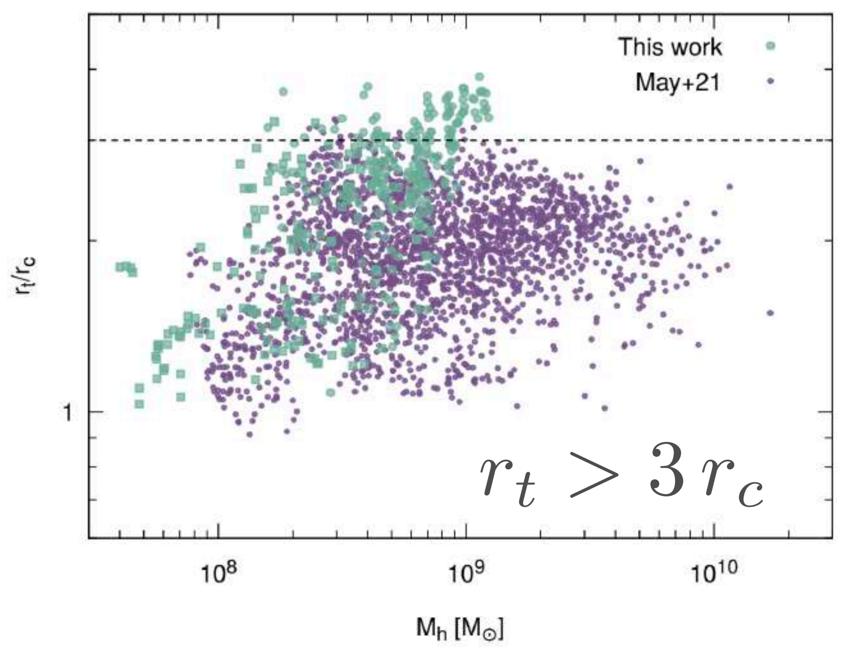
J. Chan, EF, S. May, K. Hayashi, M. Chiba 2021





Well fitted by:

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



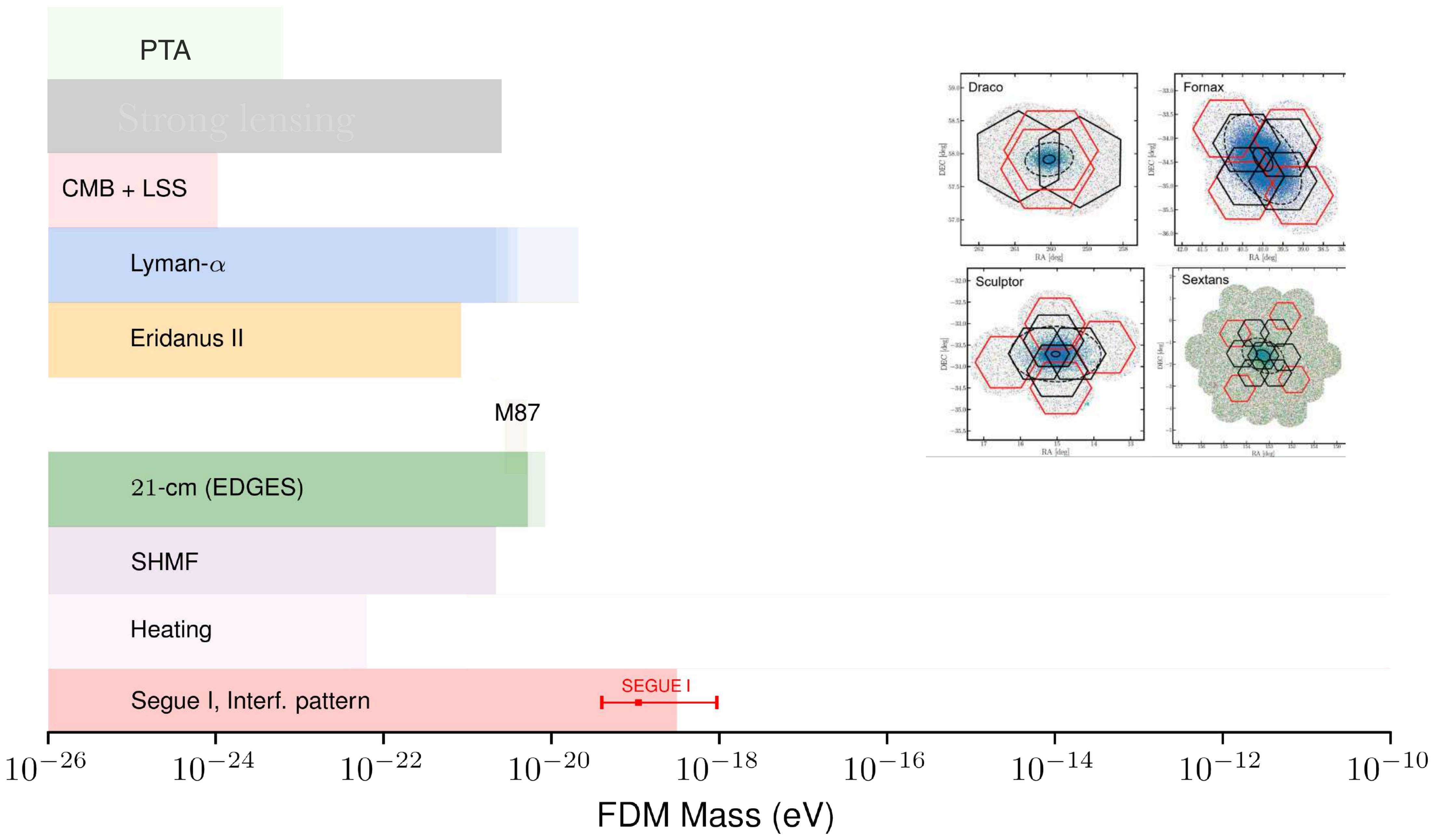
Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass

(Work in progress)

Shun'ichi Horigome

Shin'ichiro Ando



FDM mass from Ultra-faint dwarfs

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

- New analysis:

  - Improved modelling of FDM based on previous work and simulation from our group

  - Using environmental effects to put informed priors for Bayesian analysis the dwarfs quantities - SASHIMI

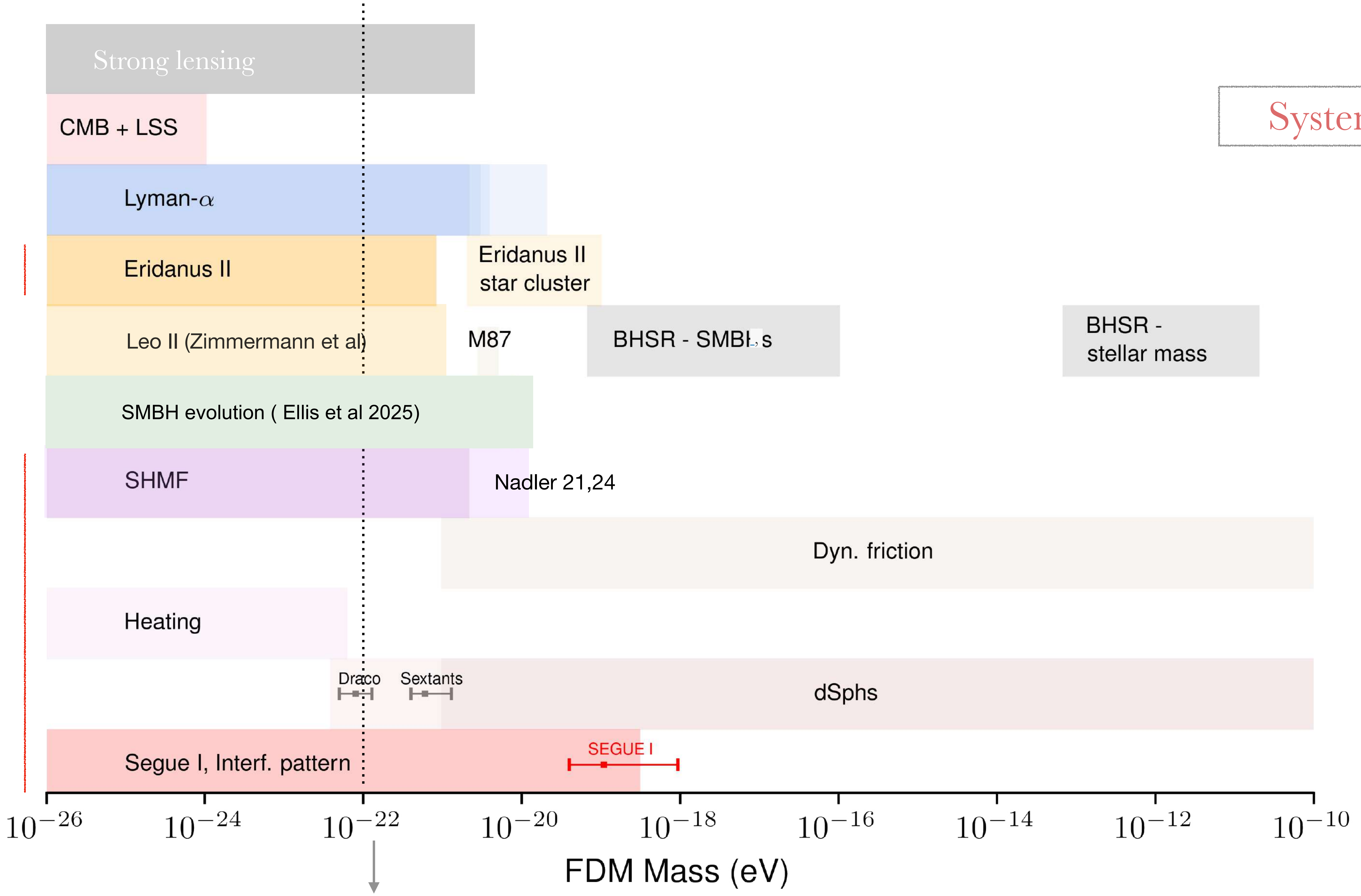
↓

Result: more conservative and improved bounds

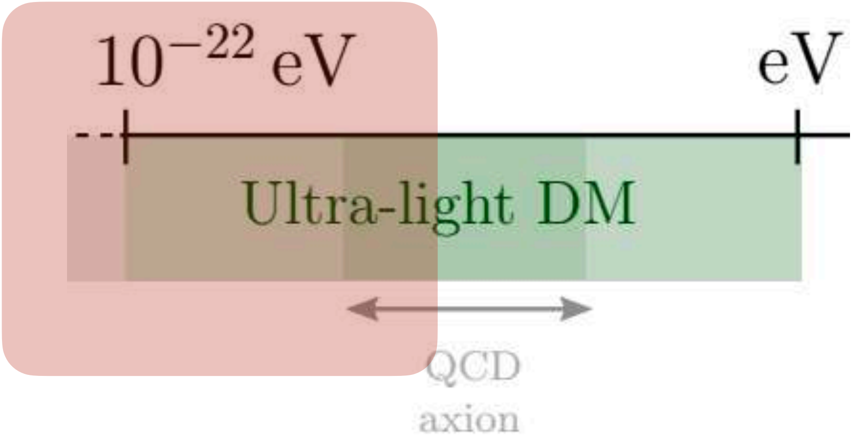
+ Improved **zoom in** simulations to understand sub-halo properties

Current status

Fuzzy Dark Matter - bounds on the mass



Sweet spot for solving small scale problems



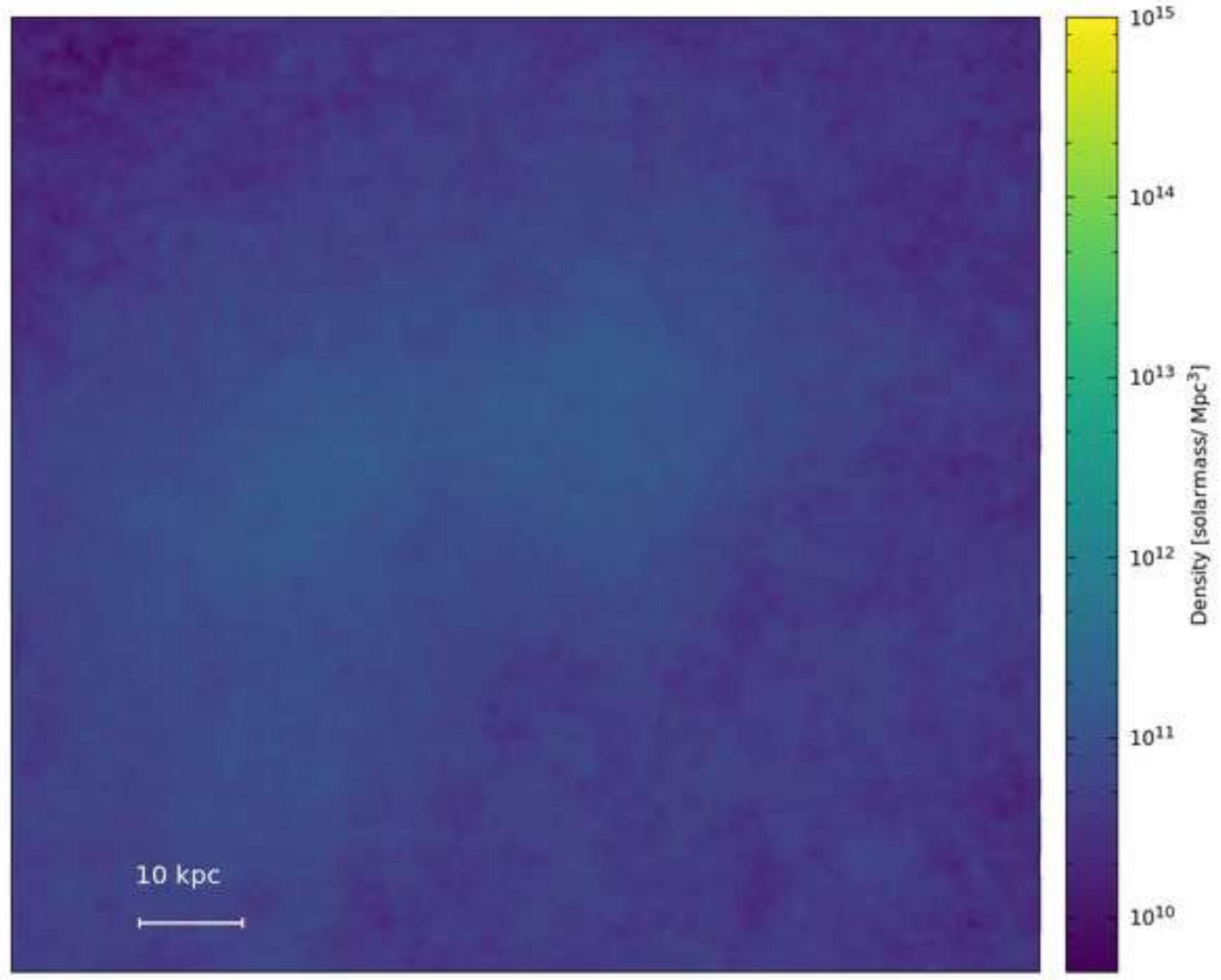
Systematics everywhere!

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

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

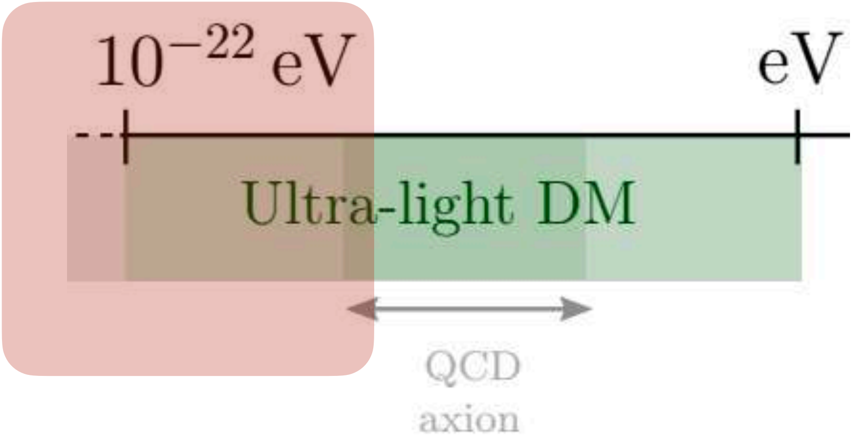
It is not because a bound is here that is correct!

interference patterns



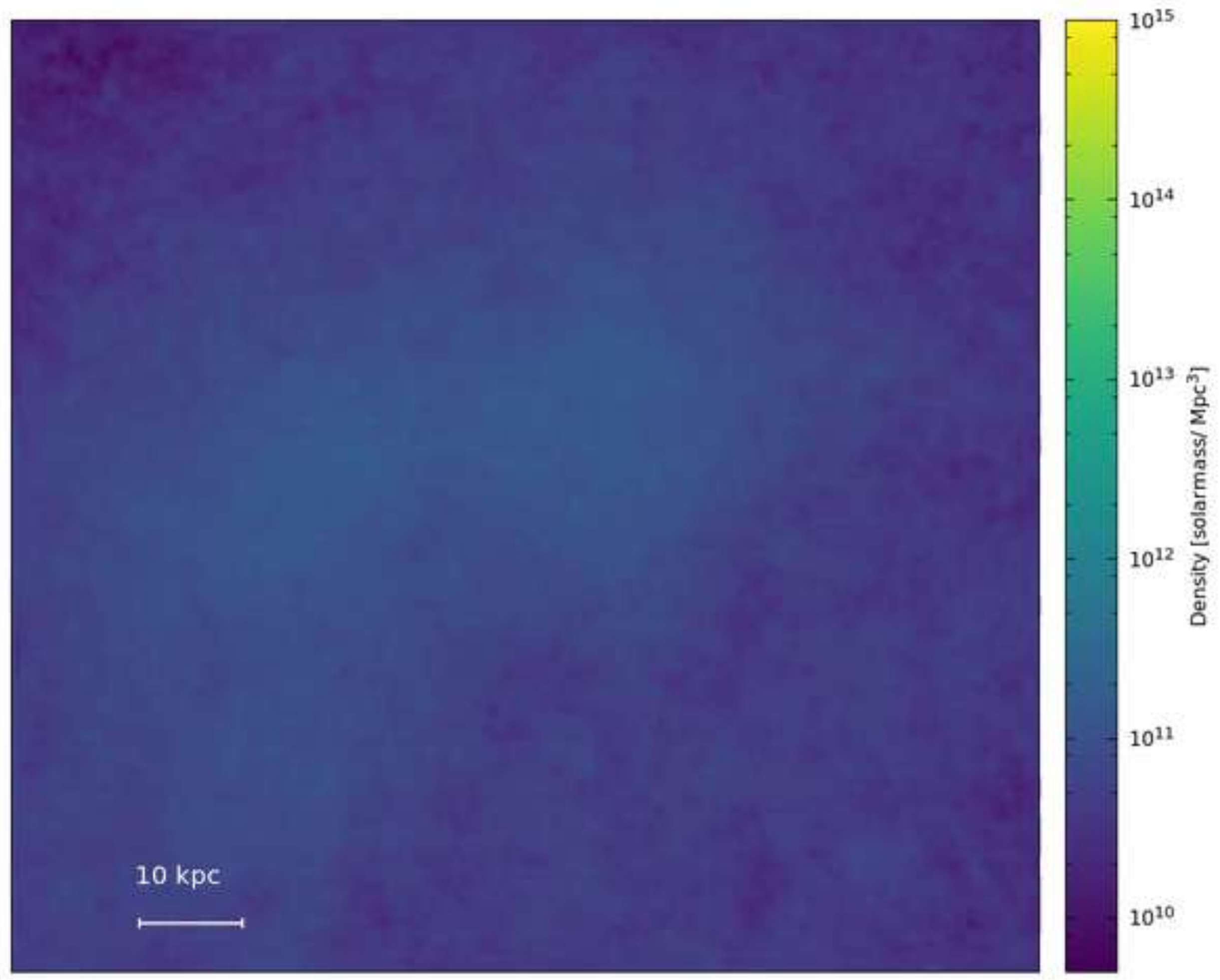
FDM constraints 2.0

Interference pattern



PROBES:

- Strong lensing
- Stellar streams
- Heating
- Dynamical friction



Simulation by Jowett Chan

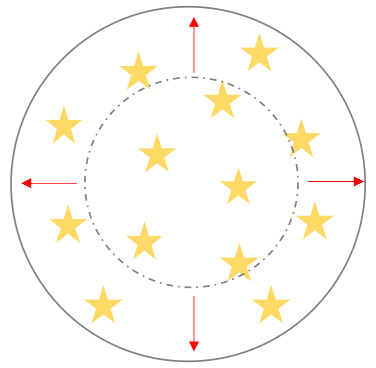
$\mathcal{O}(1)$ fluctuations in density $\longrightarrow \sim \lambda_{\rm dB}$

Heating

FDM granule

$m_{\rm eff}$

System (star) gains energy



Friction

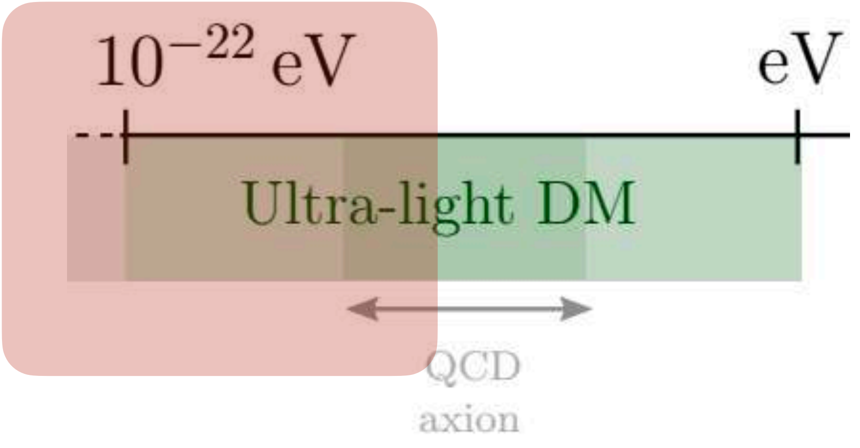
FDM granule

$m_{\rm eff}$

Globular cluster

System (GC or BH) loses energy

Interference patterns - granules



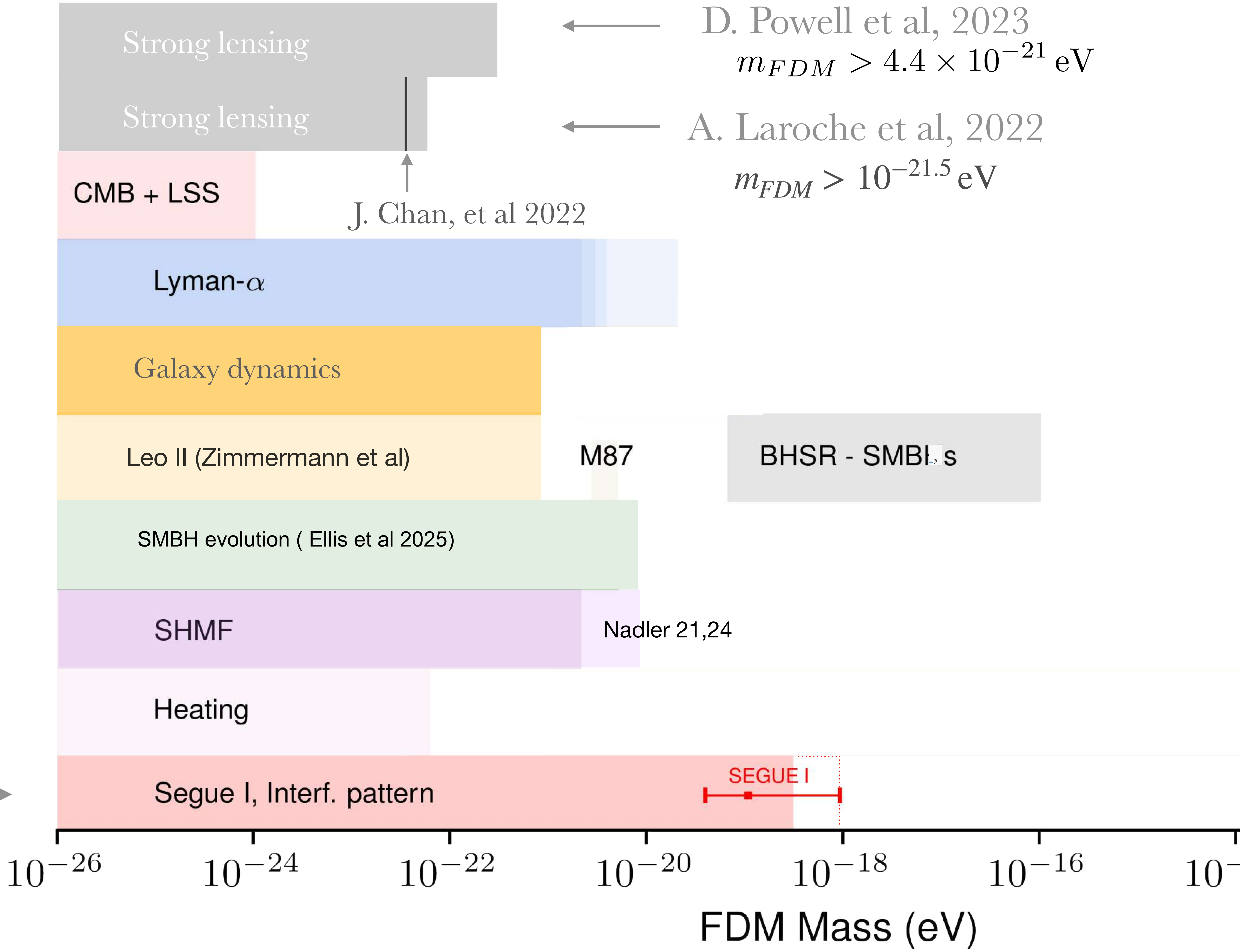
Strong lensing

D. Powell et al, 2023

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

A. Laroche et al, 2022

$m_{FDM} > 10^{-21.5}$ eV



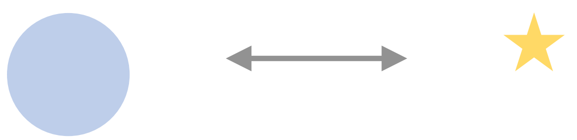
Stellar heating

Dalal et al, 2022

$m_{FDM} > 3 \times 10^{-19}$ eV

Heating

FDM granule



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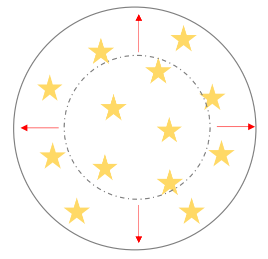
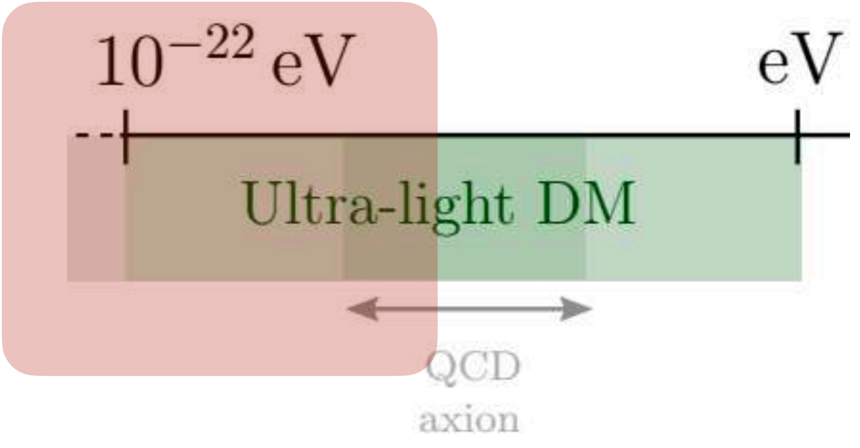


See Peter Graham talk

Interference patterns - granules



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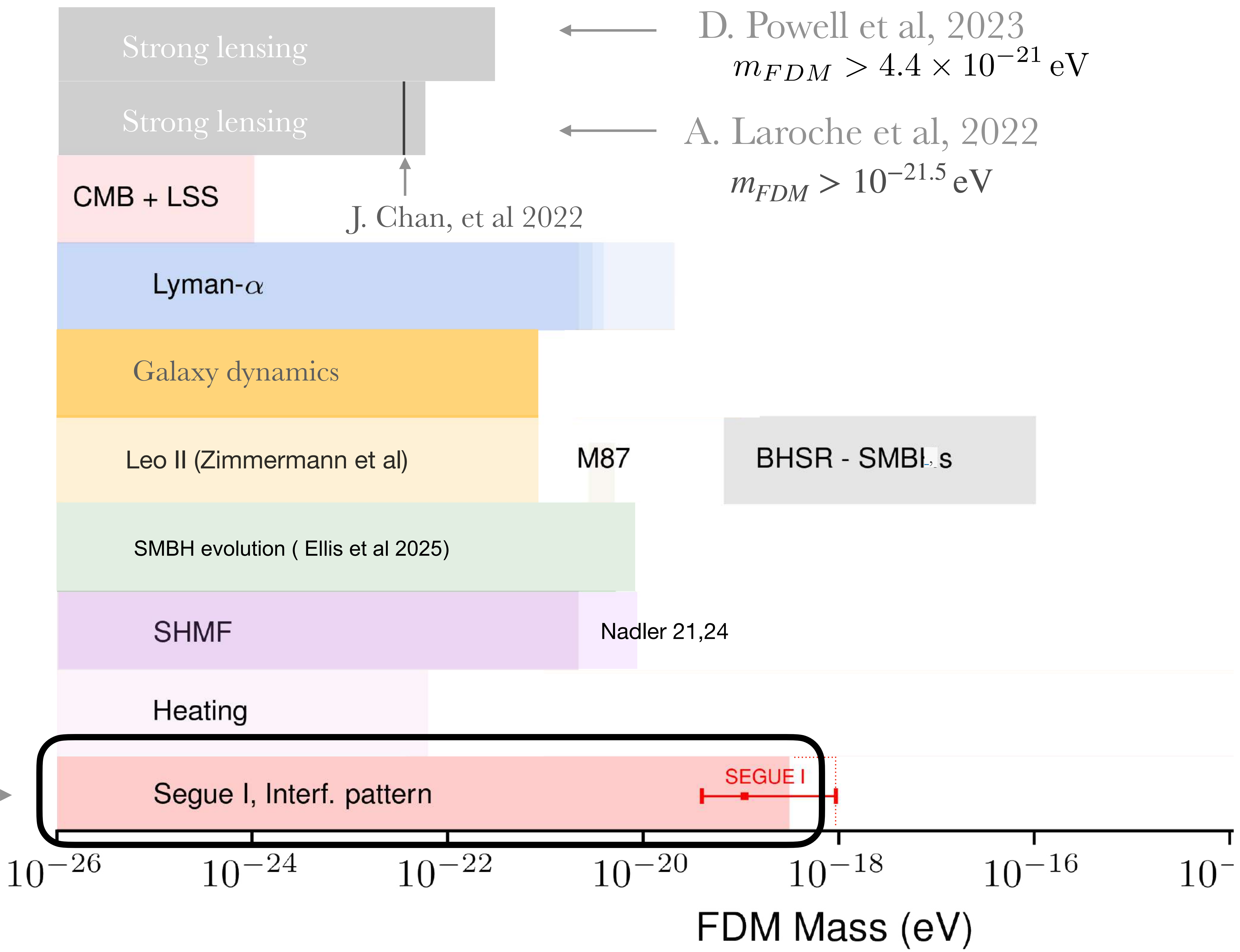

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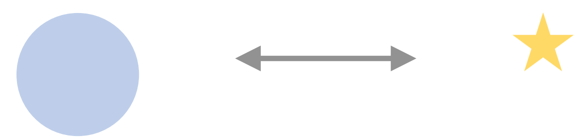

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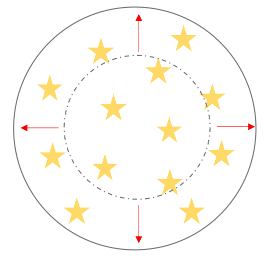
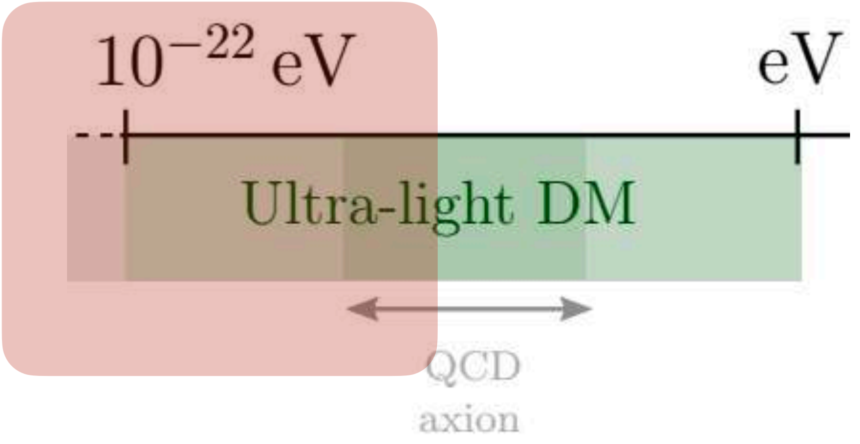


See Peter Graham talk

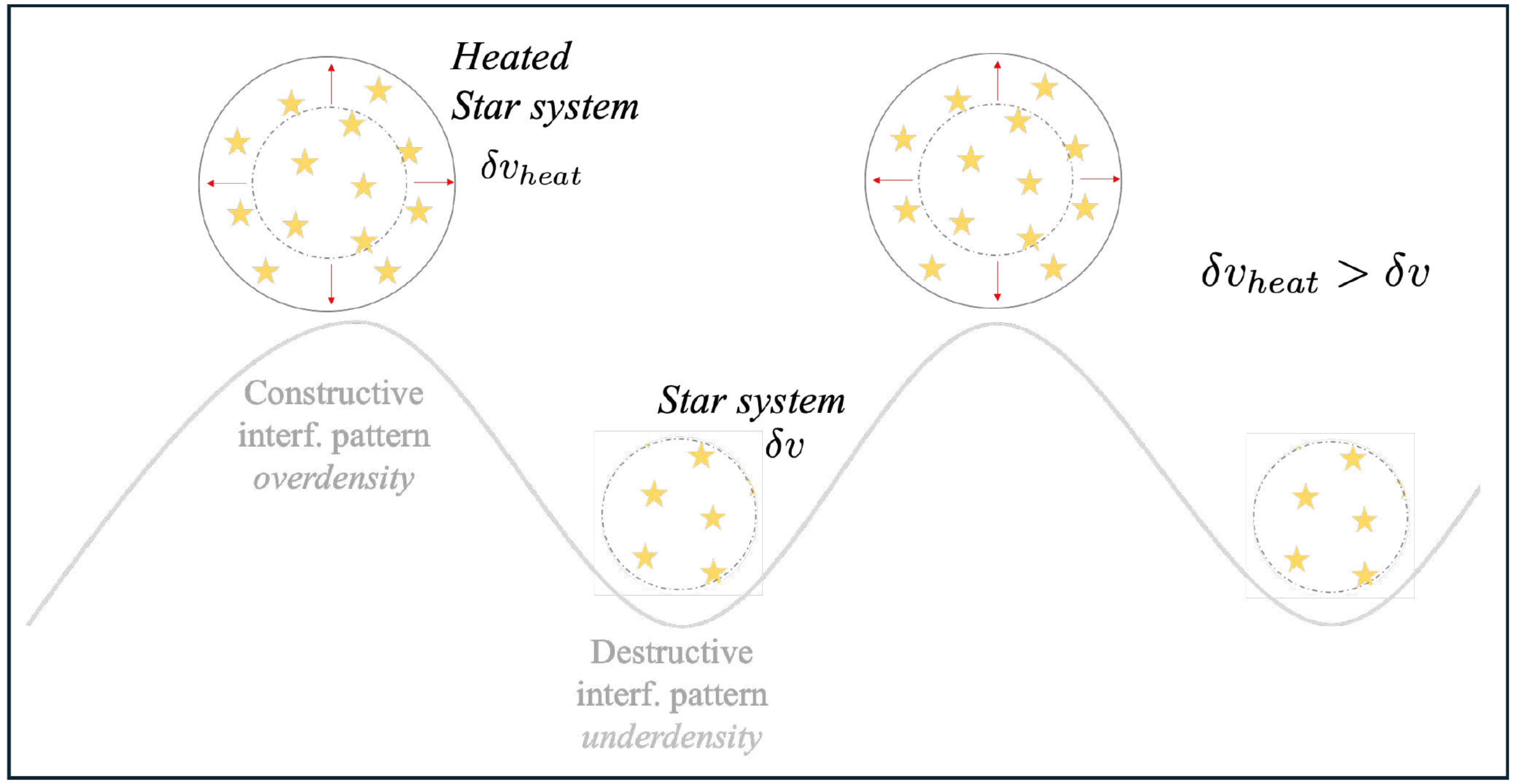
Stellar heating - ultra-faint dwarfs



Dalal et al 2022

- Study stellar heating on UFD due to the presence of granules
- Track the half-light radius and stellar dispersion
- Compared with observations of Segue I and II

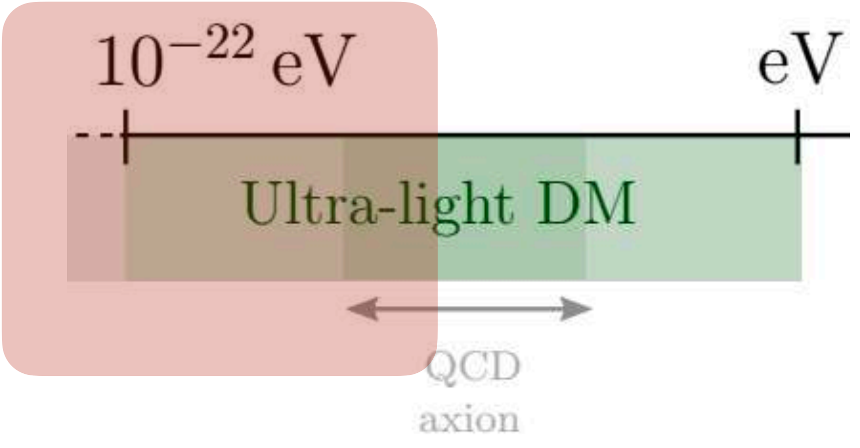
$$m > 3 \times 10^{-19}\,\text{eV}$$



Details:

- Soliton excluded (authors claim conservative bounds)
- Tidally stripped halo? Alters the granules

Stellar heating - ultra-faint dwarfs



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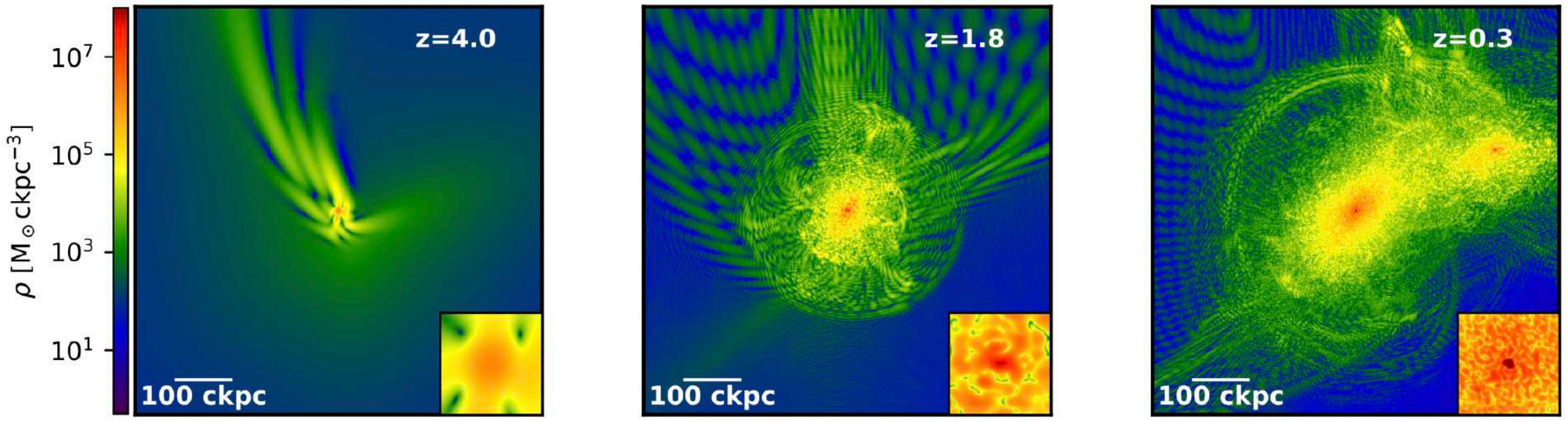

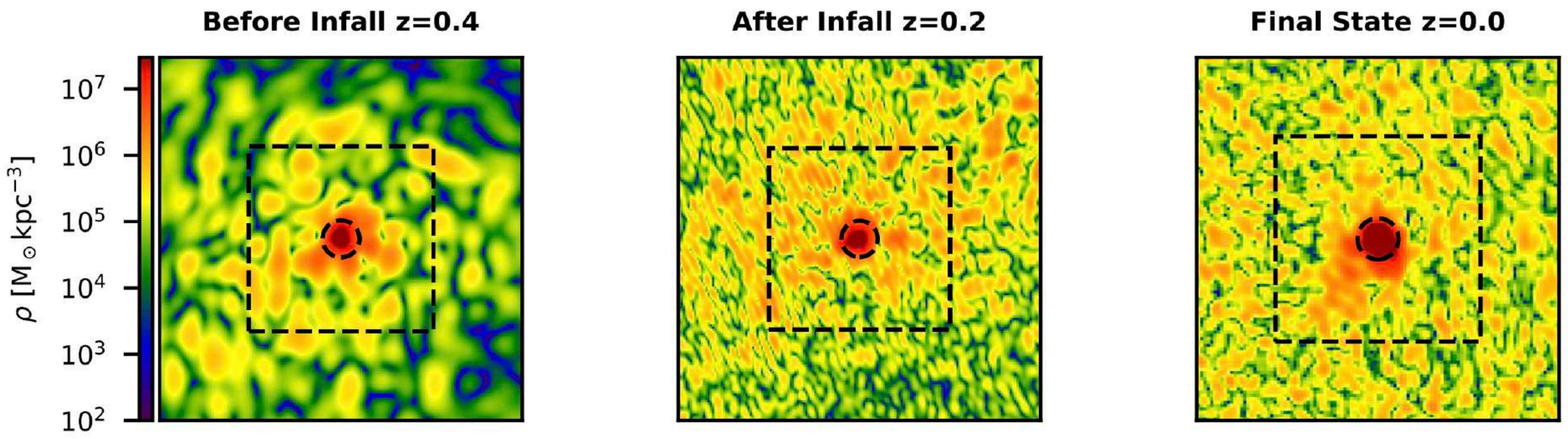

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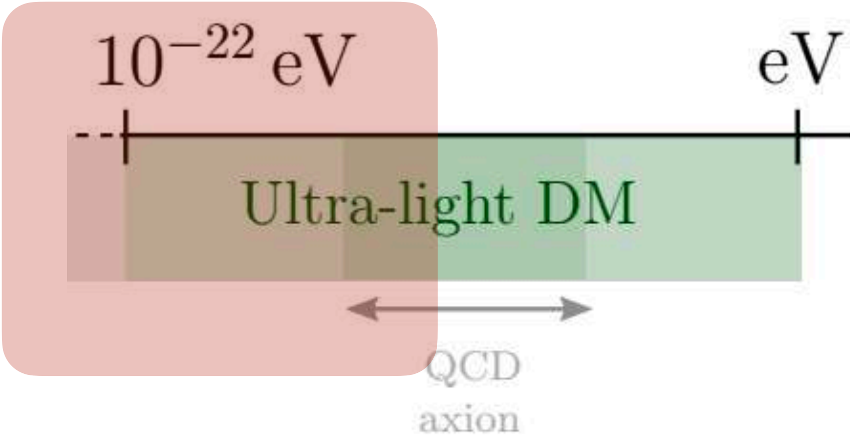
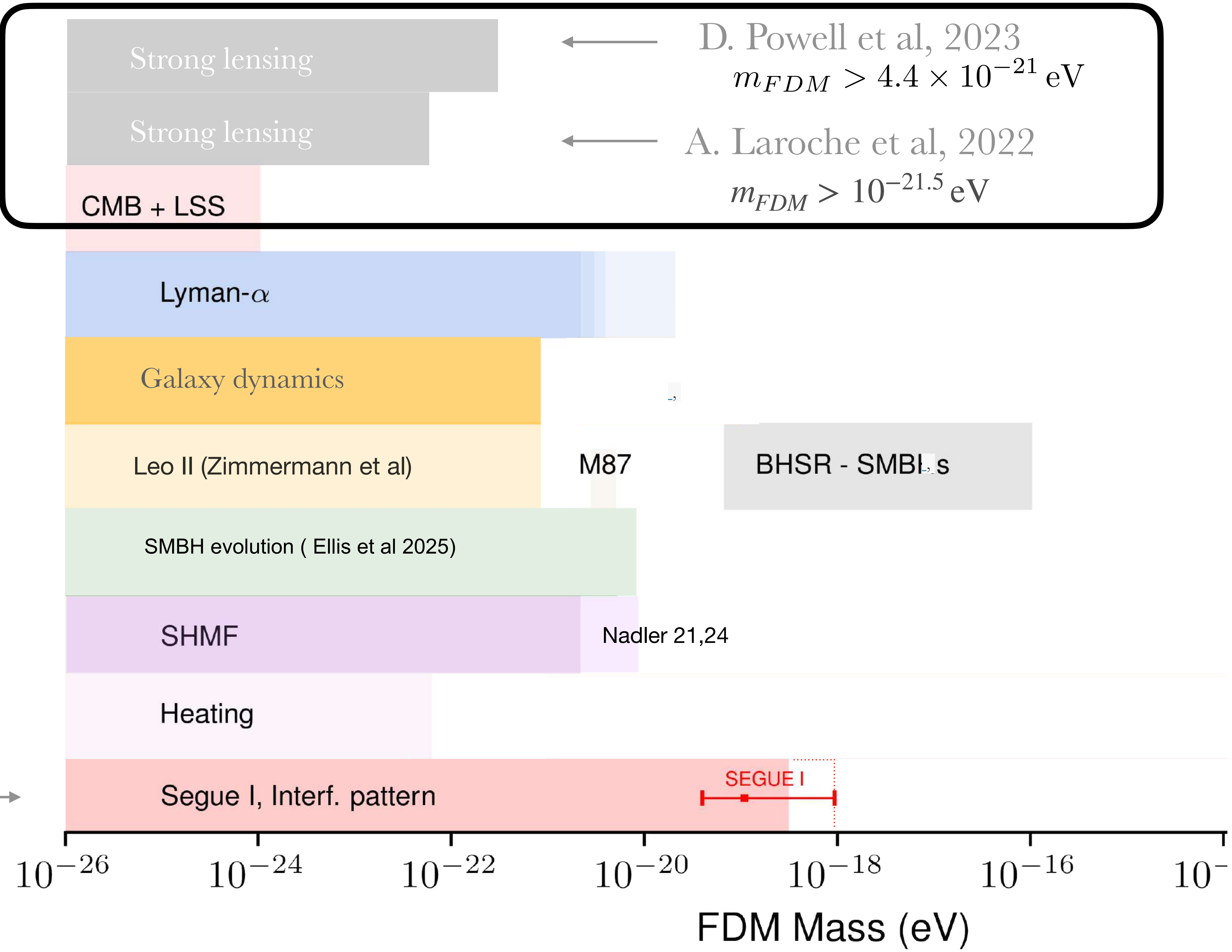
(In progress)

Jowett et al, 2024

Interference patterns - granules



Strong lensing



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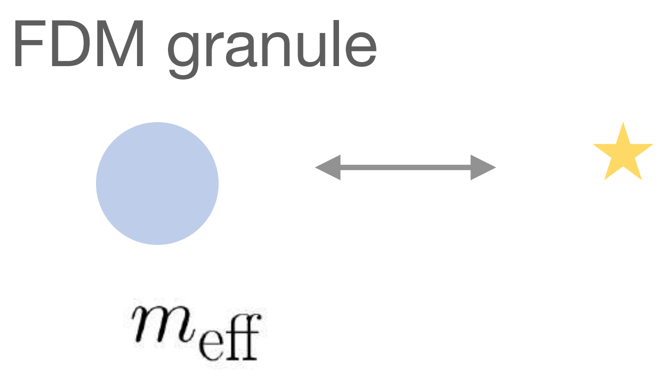

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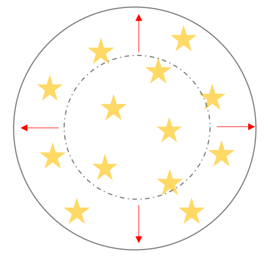

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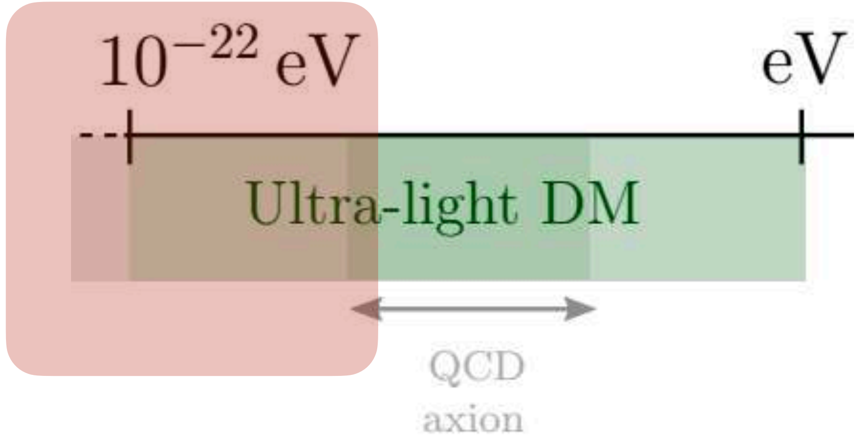
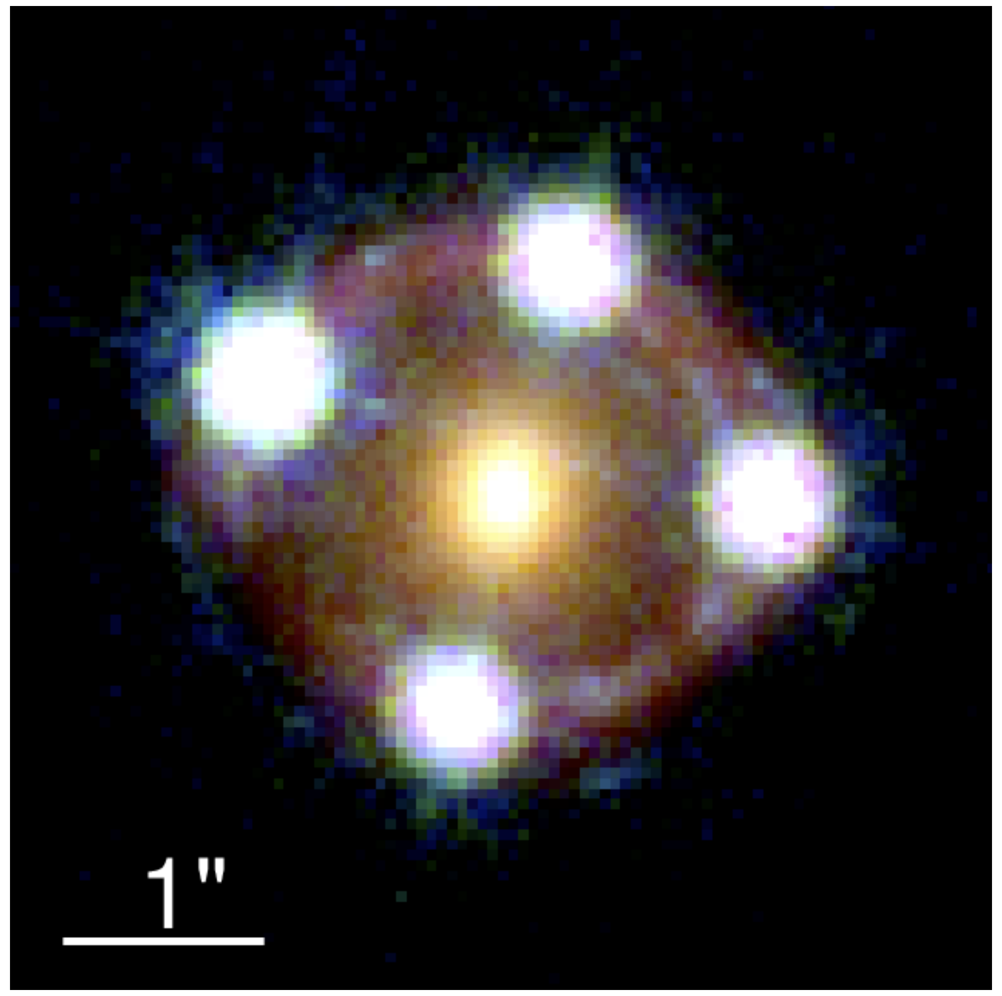


Strong lensing: sensitive to the mass distribution of the total matter in the lens system

Flux anomaly

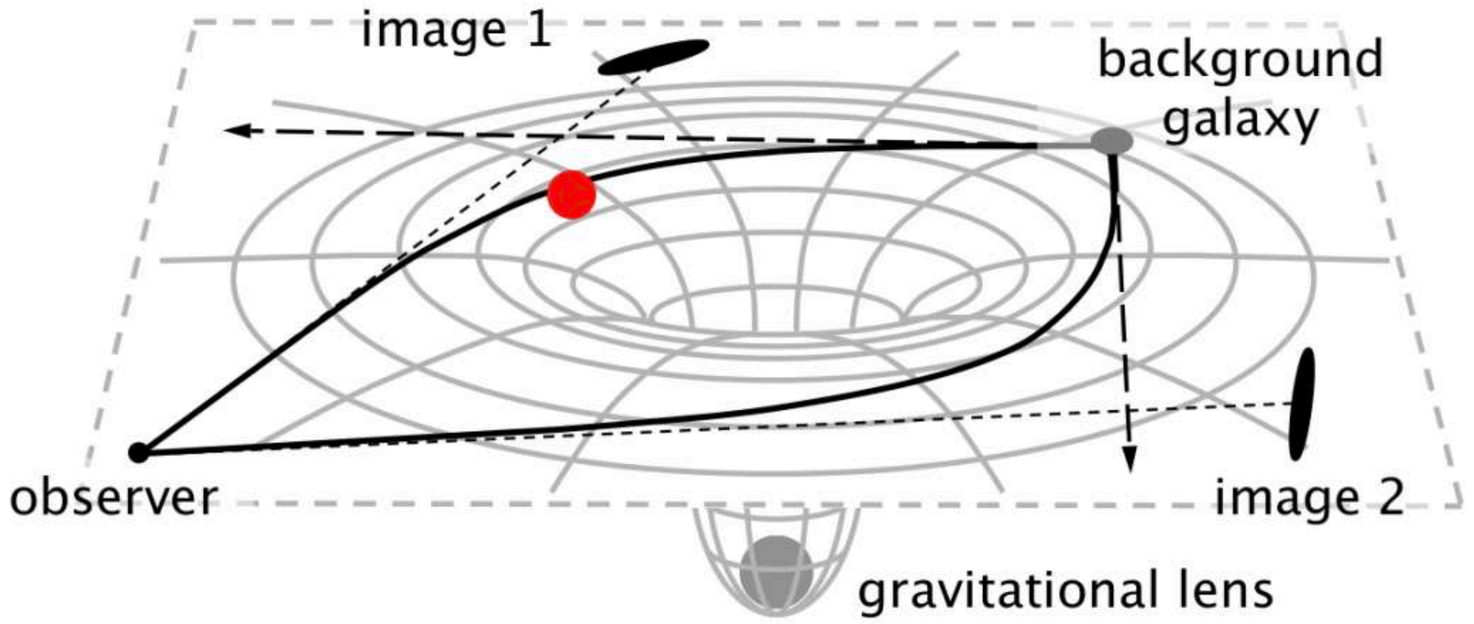
Unresolved strong lensed system

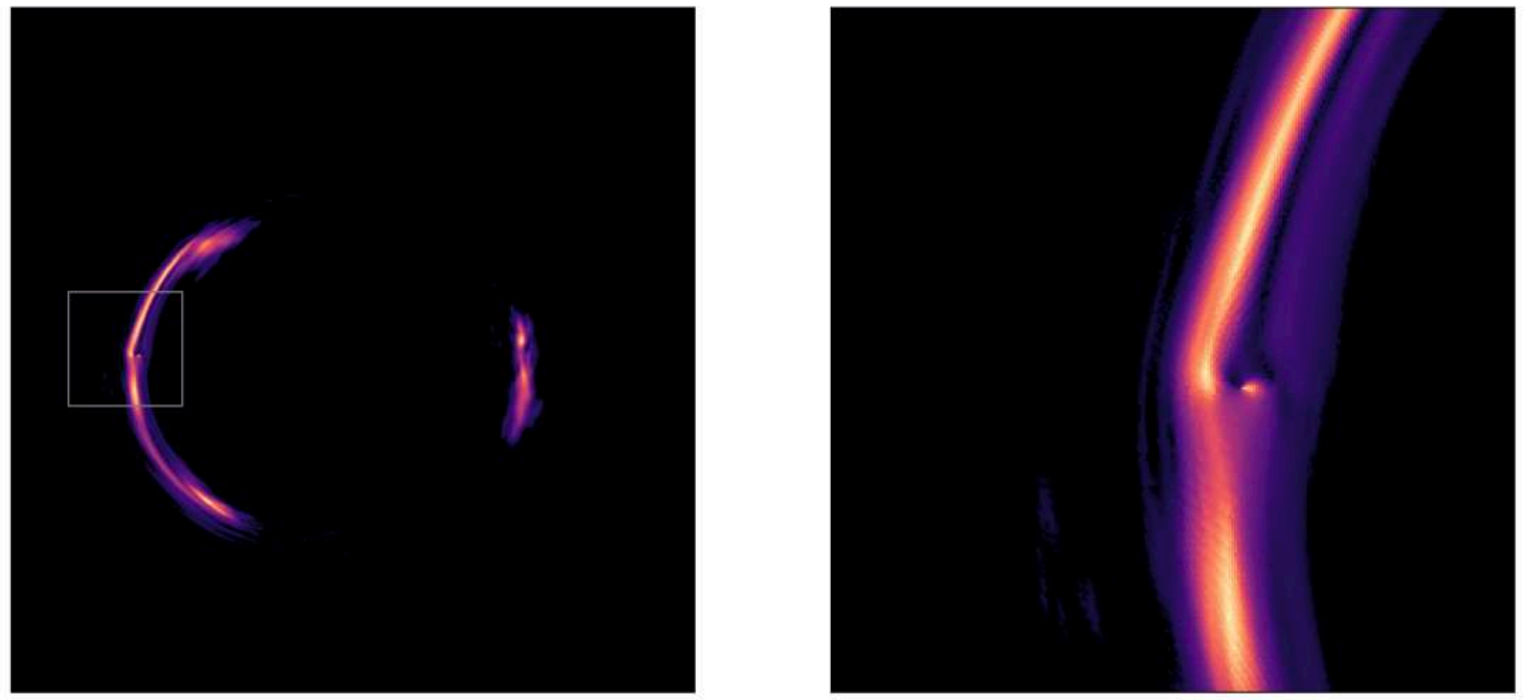


Any asymmetry in the structure in the lens, can break the symmetry that yielded the flux ratio predictions

Resolved imaging

Resolved strong lensing from galaxy surface brightness





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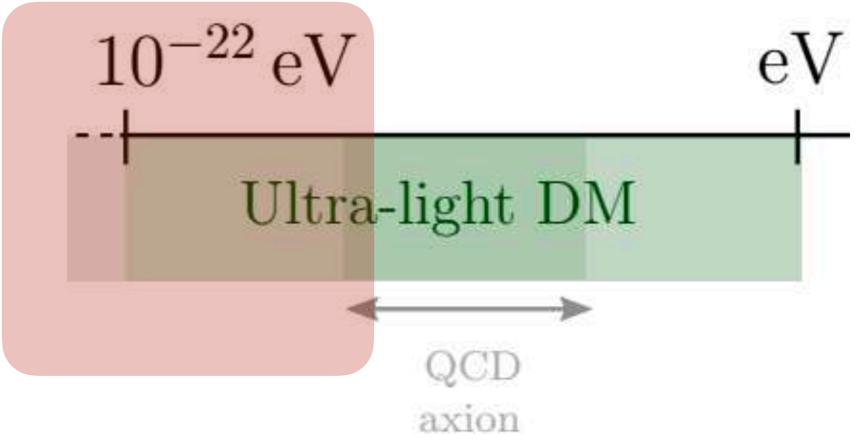
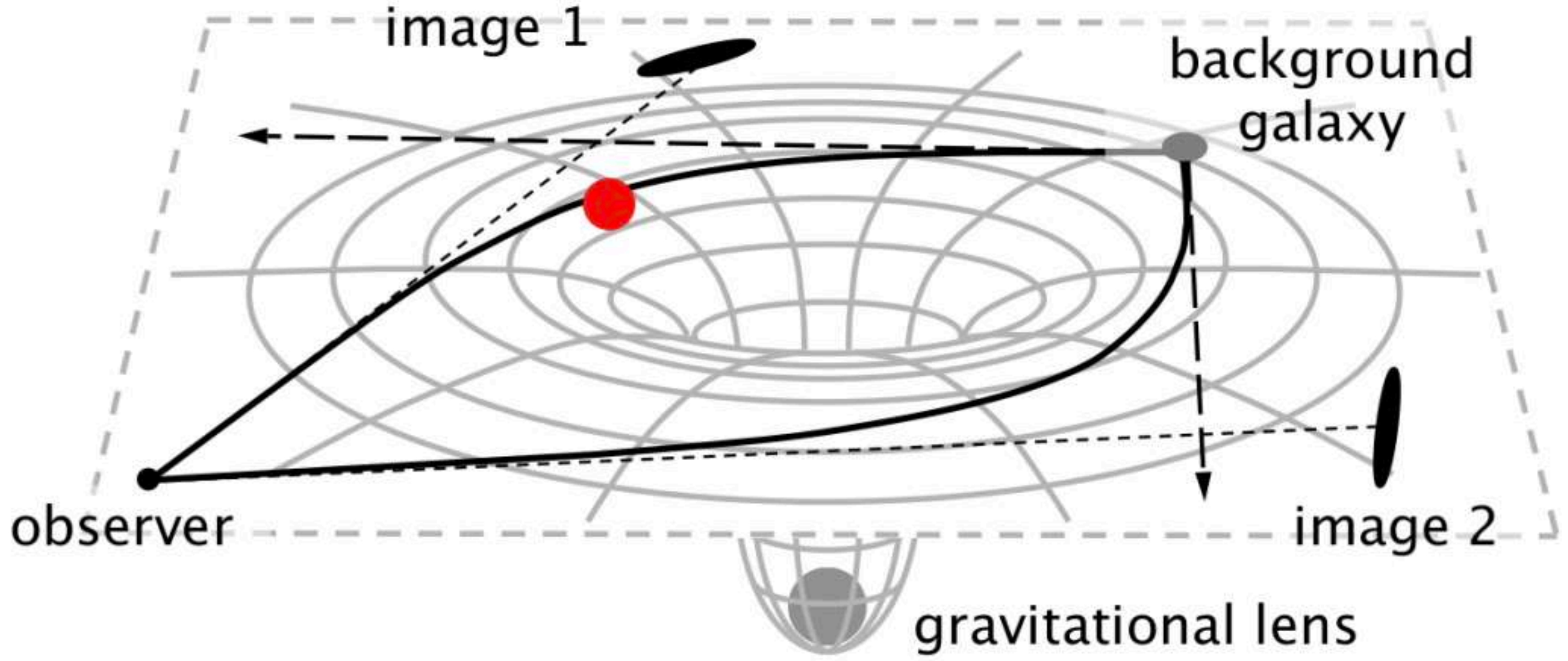
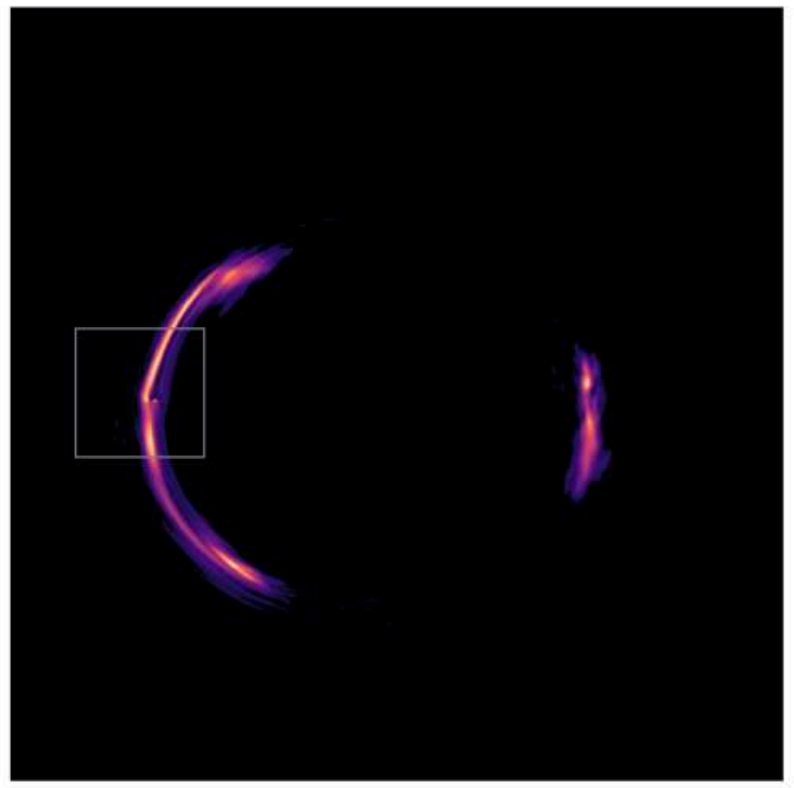
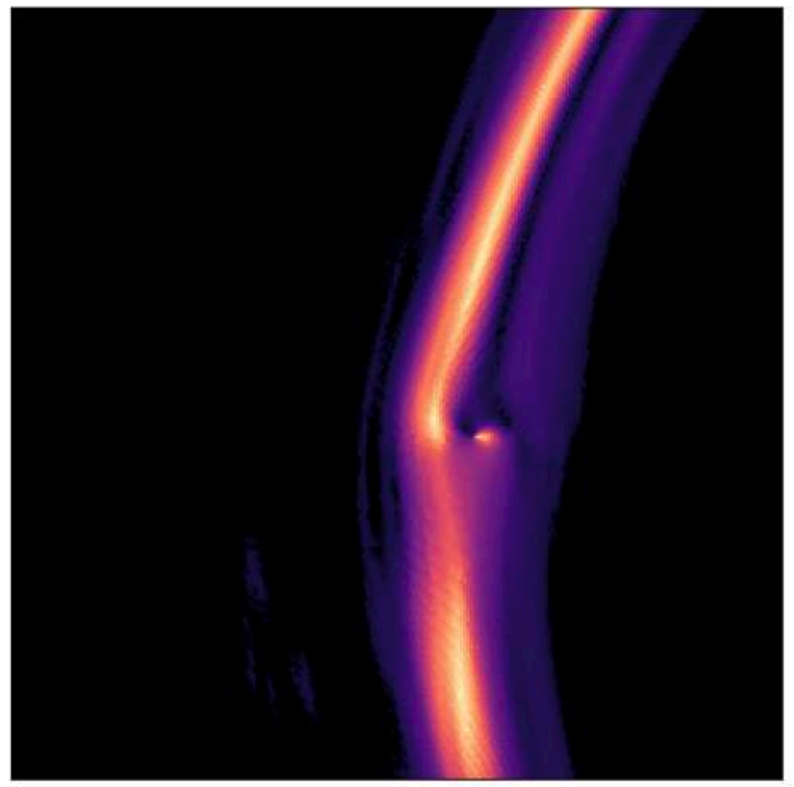


Low mass perturber with lensing

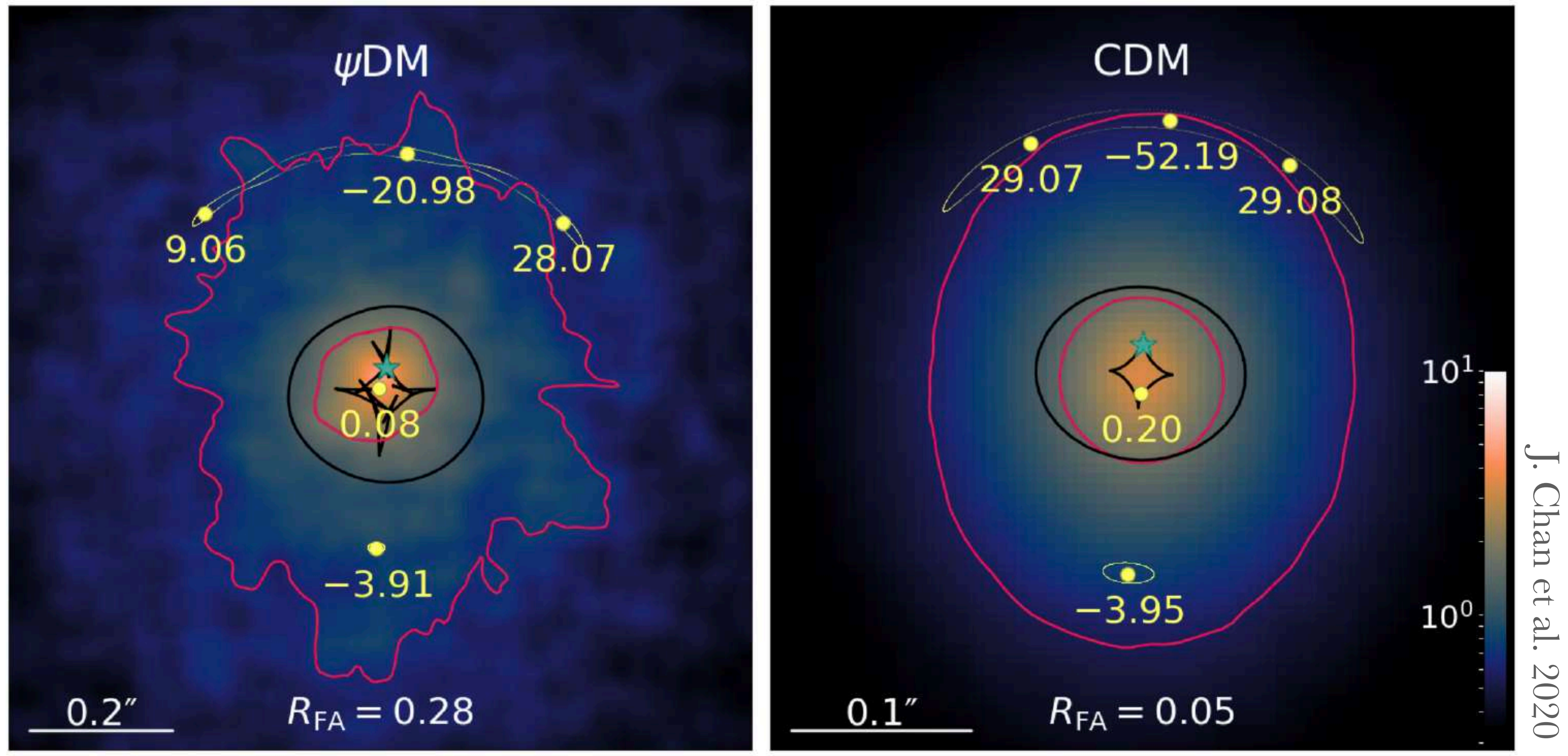






Presence of granules

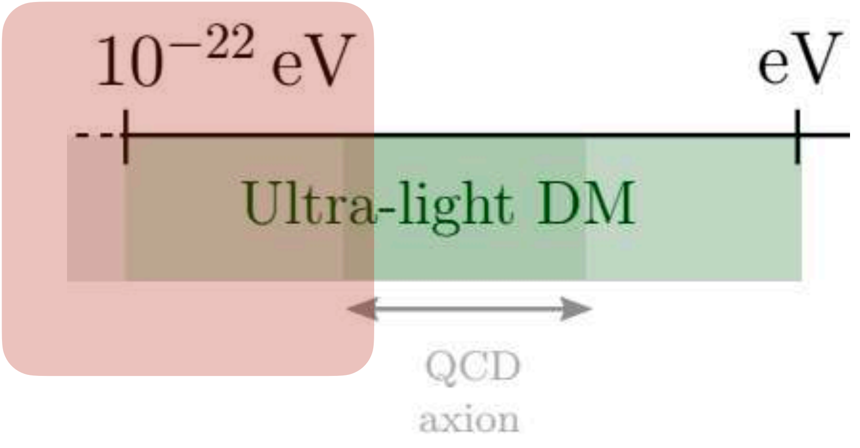
Surface densities overlaid with sources and quad images for fuzzy and smooth lenses



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



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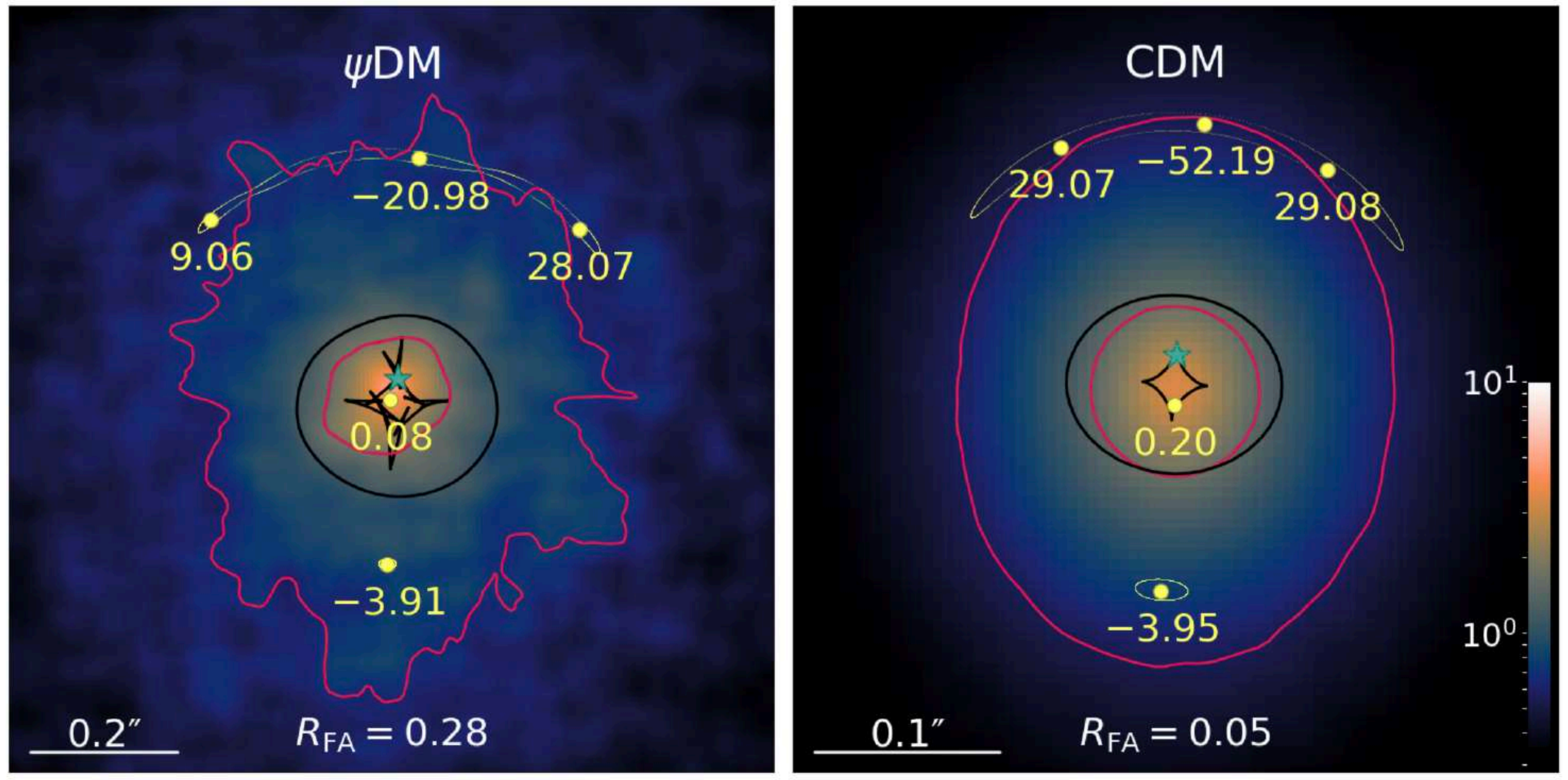

J. Chan et al. 2020

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Laroche et al

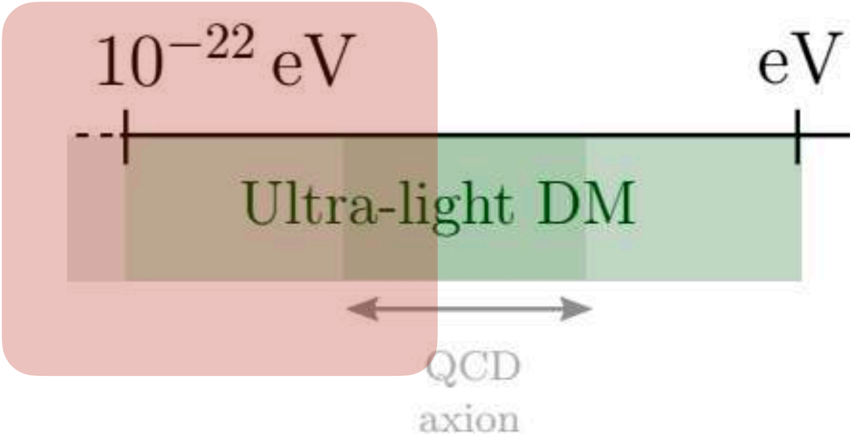
- 11 quadruply imaged quasars
- granularity arising from FDM can significantly affect flux ratios

$$m_{FDM} > 10^{-21.5}\,\text{eV}$$

Chan et al

- 11 quadruply imaged quasars
- quadruply lensed system HS 0810+2554
- successfully reproduce both the positions and fluxes of the observed images, including anomalies that CDM models fail to explain

Interference patterns - granules



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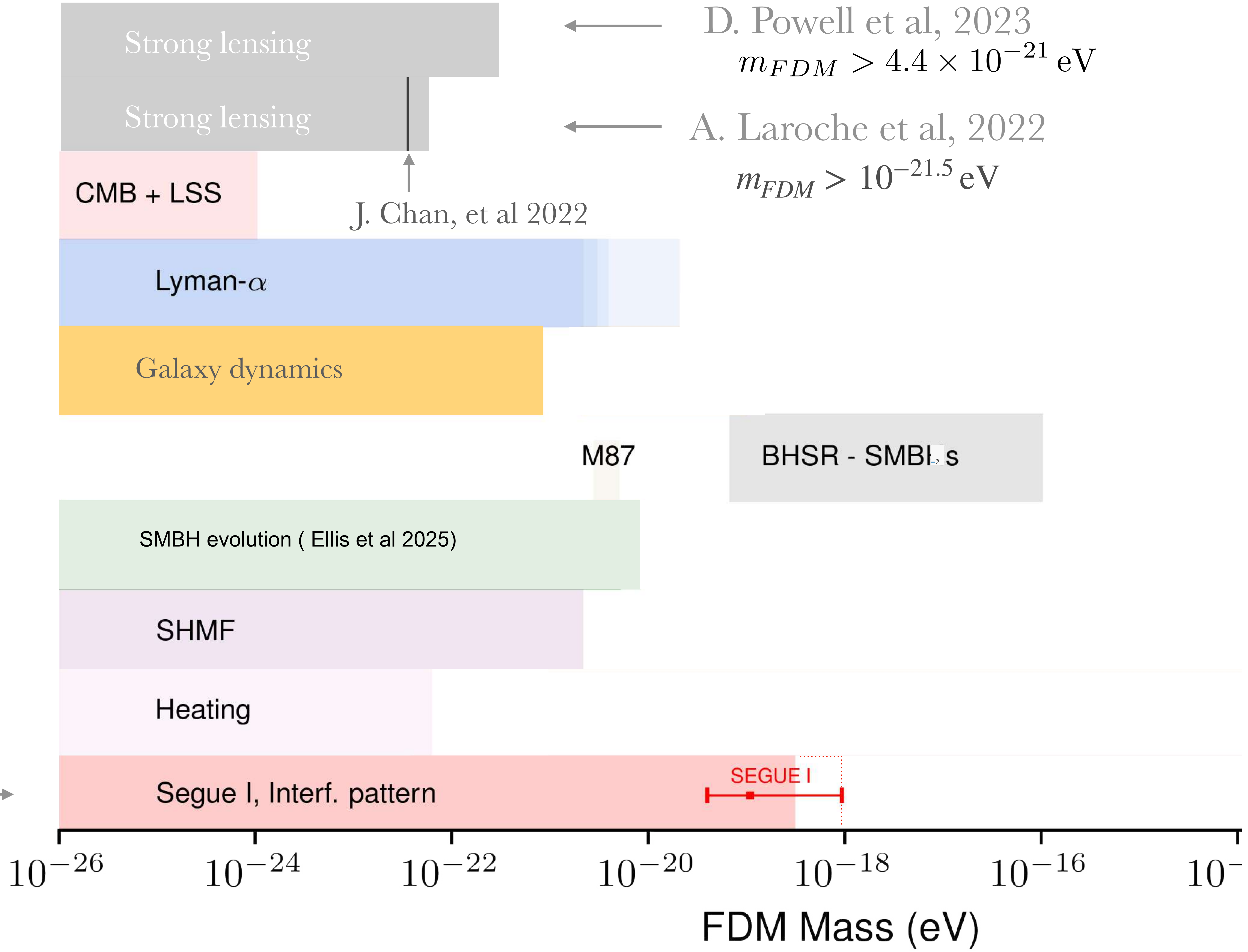

Stellar heating

Dalal et al, 2022
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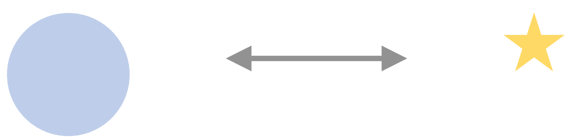
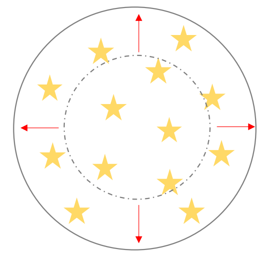
Heating

FDM granule



$m_{\rm eff}$

System (star) gains energy

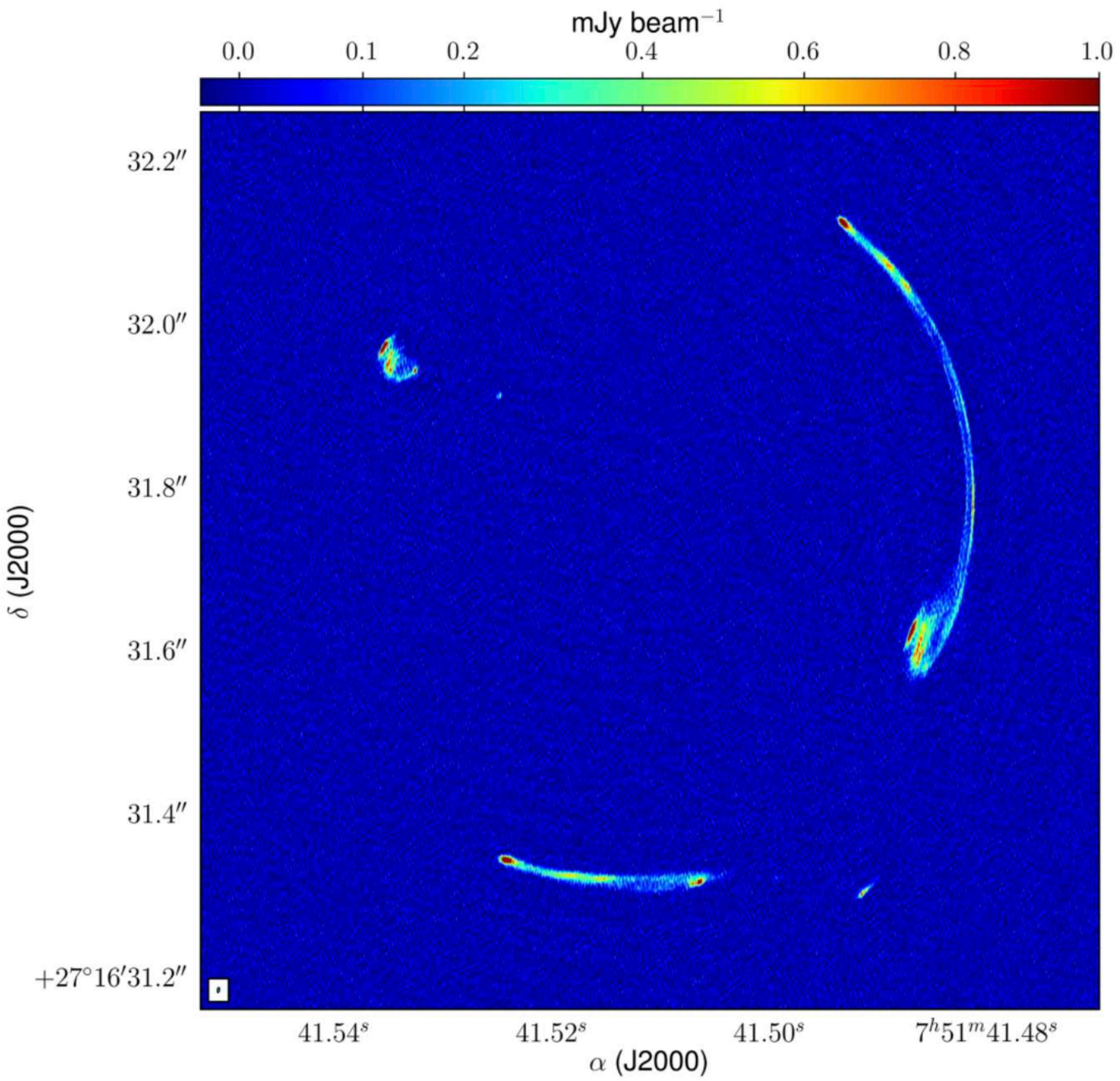


See Peter Graham talk

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

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

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

(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

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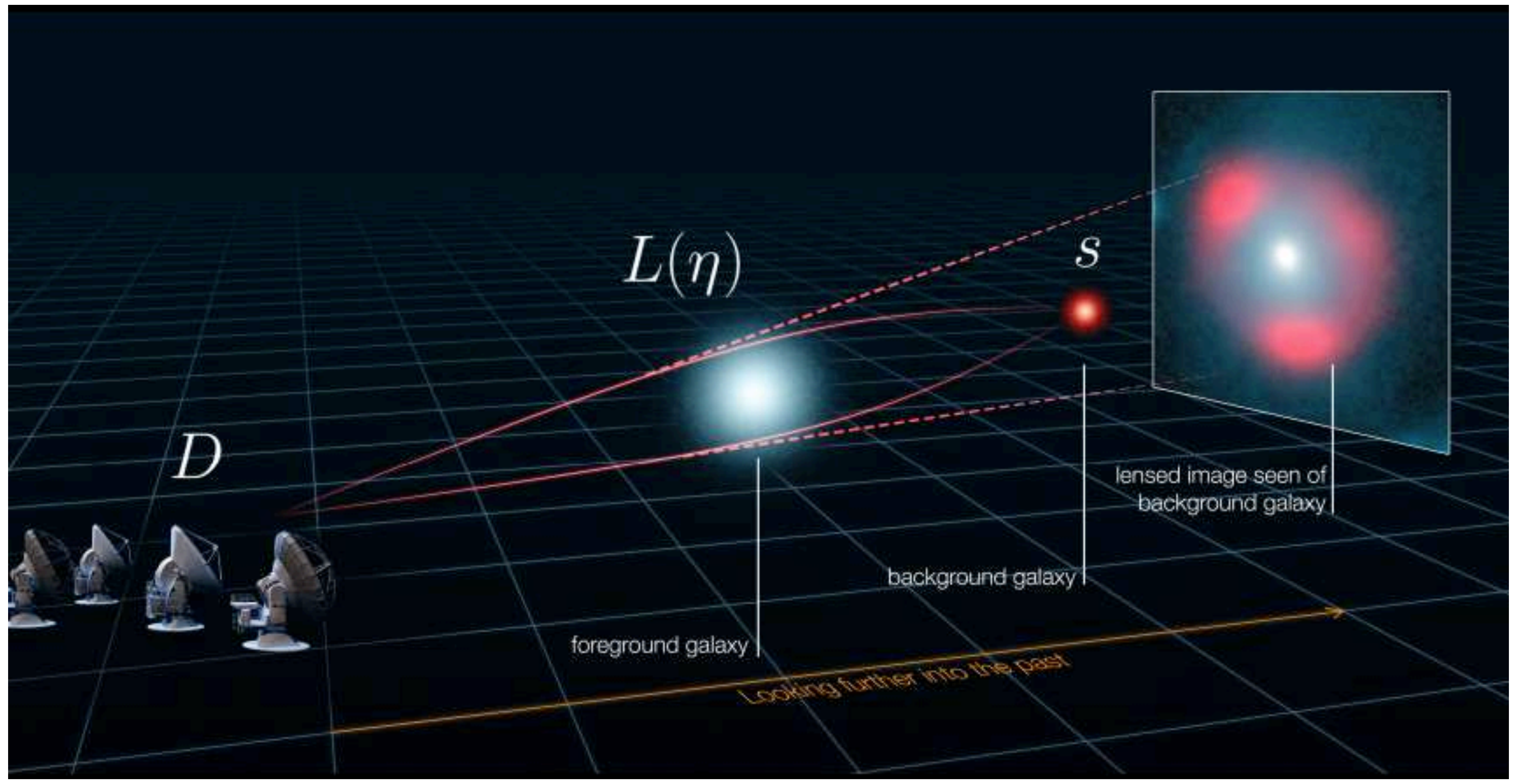
Forward modelling



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

$\delta\psi(m_{fdm}, f_{dm}, \sigma_v)$ - is the 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 $\mathcal{P}(m_{fdm})$

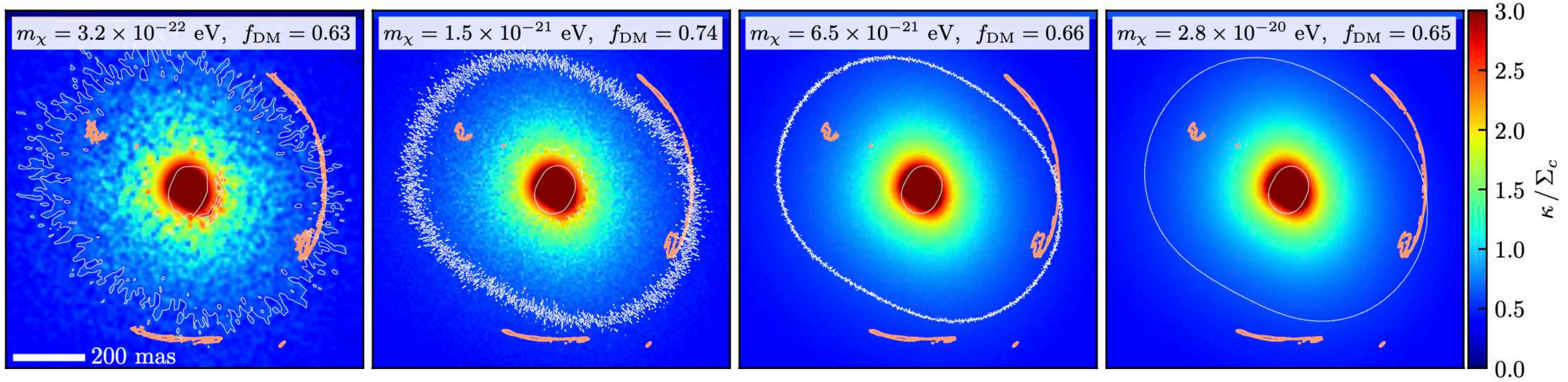
We compute likelihoods for 10^4 sample FDM lens realizations with m_{fdm} drawn from the log-uniform prior range $\log(m_{fdm}/\mathrm{eV}) \in [-21.5, -19.0]$.

Free parameters: $\{m, f_{\mathrm{DM},\sigma_v,\eta}, \lambda_s\}$

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



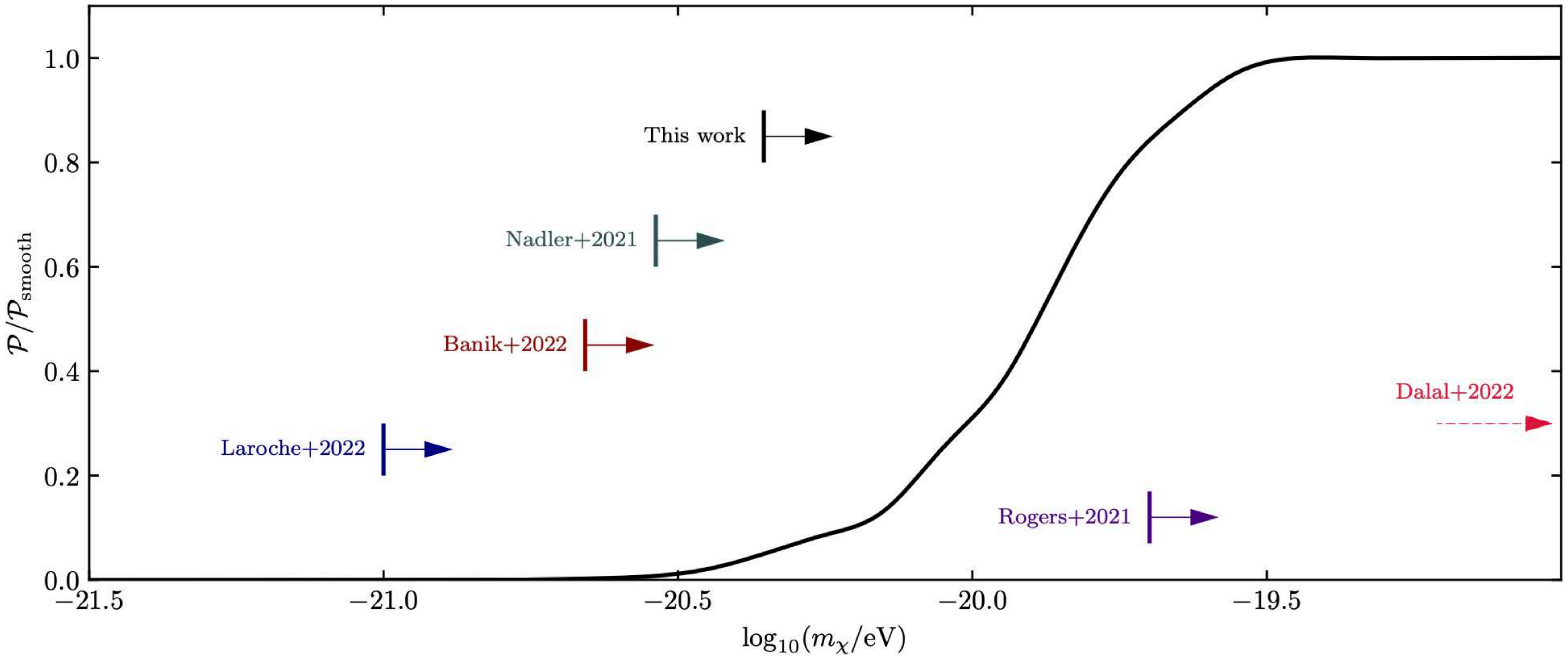
The lensing effect of the FDM granules is apparent: The critical curves wiggle back and forth across the lensed arcs, which would require the presence of multiple images of the same region of the source along the arc.

Strong *lensing*

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

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

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)

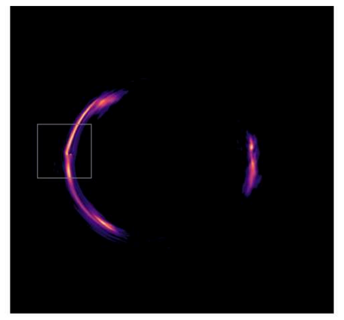
$$m_{\rm fdm} > 4.4 \times 10^{-21}\ \mathrm{eV}$$

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

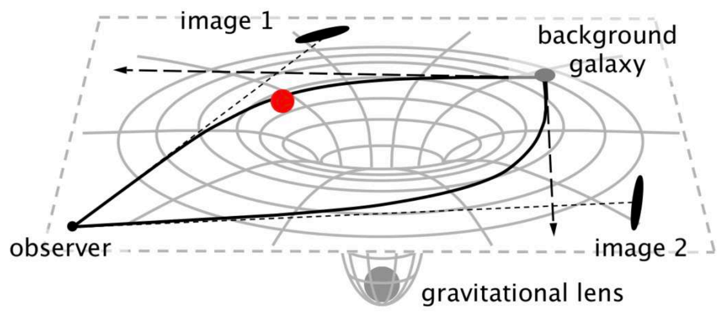
$$m_{\rm vdm} > 1.4 \times 10^{-21}\ \mathrm{eV}$$

Spin-2 FDM

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



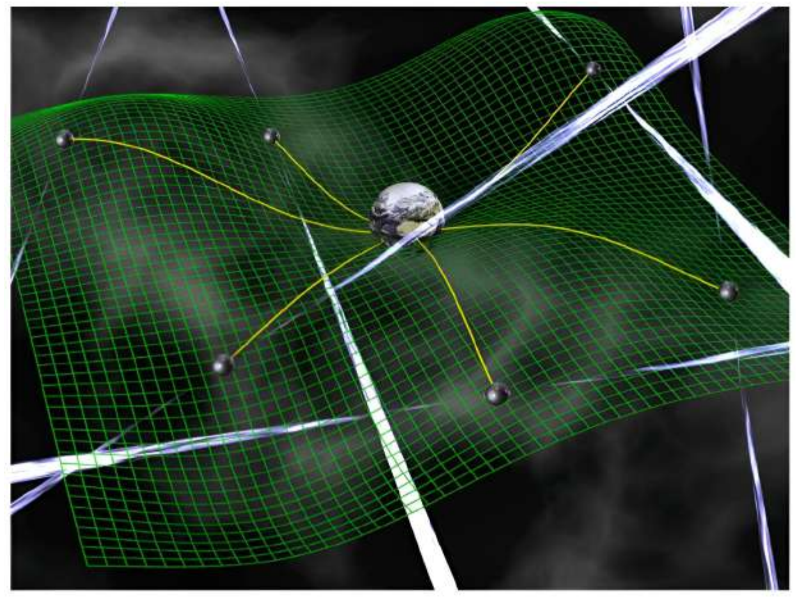
Strong lensing



axion-photon coupling

$m \sim 10^{-[22-17]}\,\mathrm{eV}$

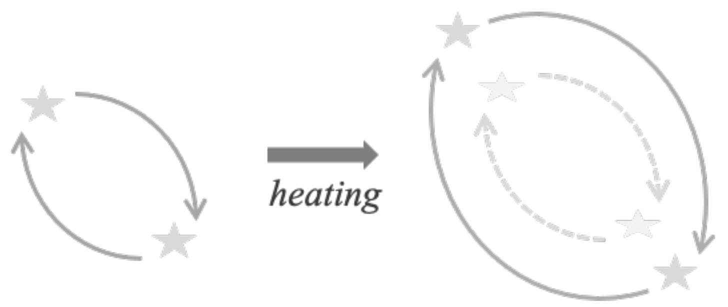
Pulsar Timing Array



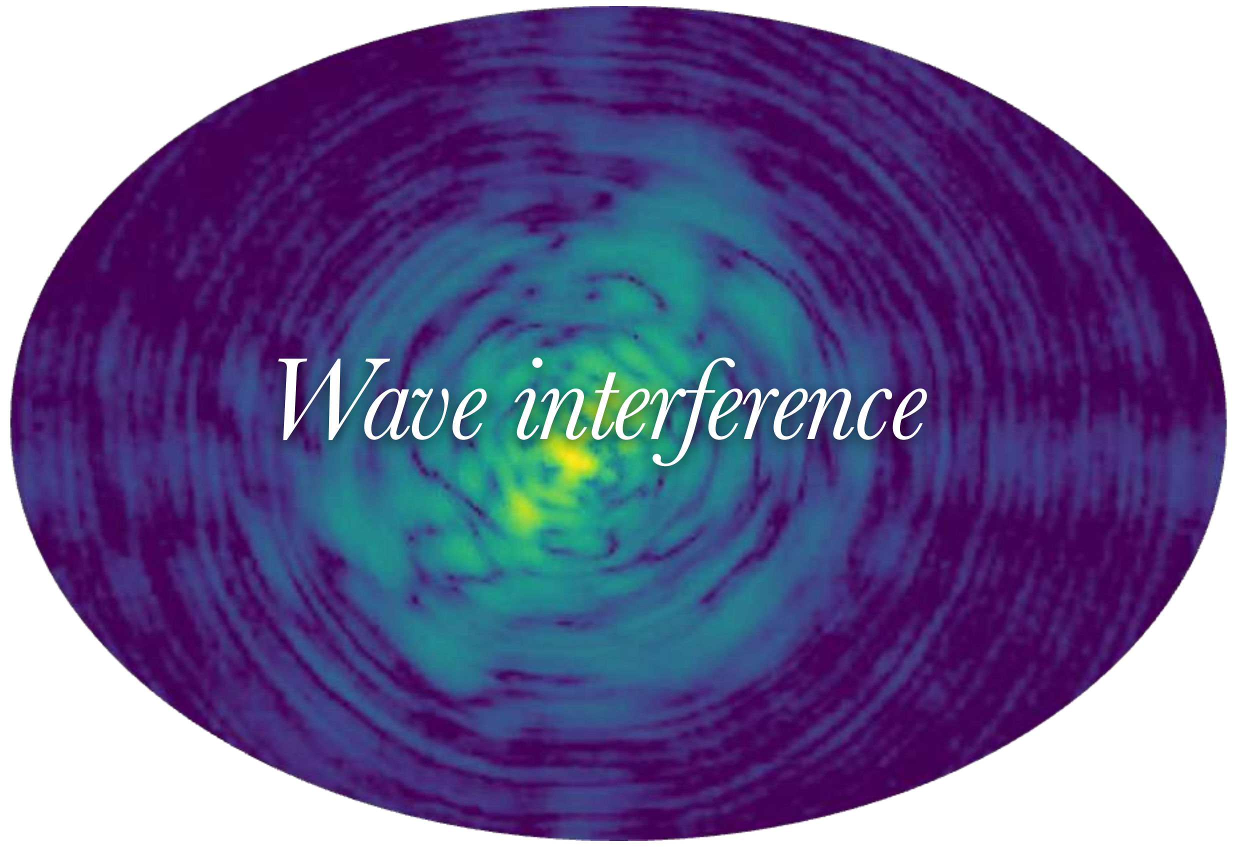
Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

$m \sim 10^{-[22-17]}\,\mathrm{eV}$

Binary stars



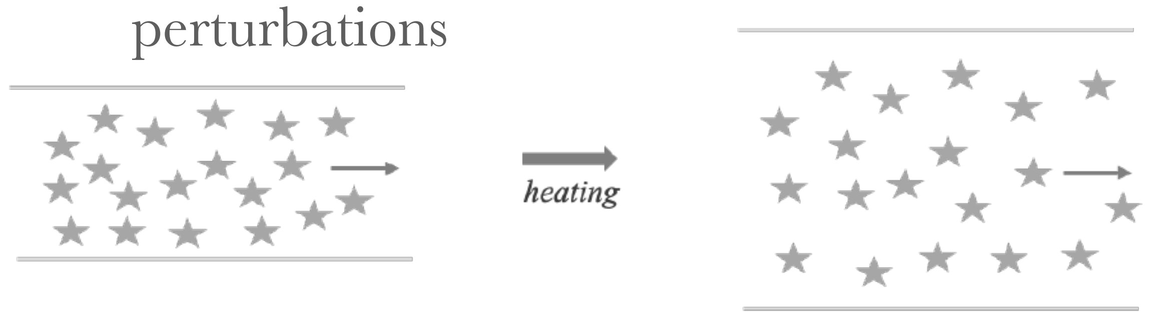
$m \sim 10^{-[16-10]}\,\mathrm{eV}$



Mass, spin (# particles), fraction self interaction

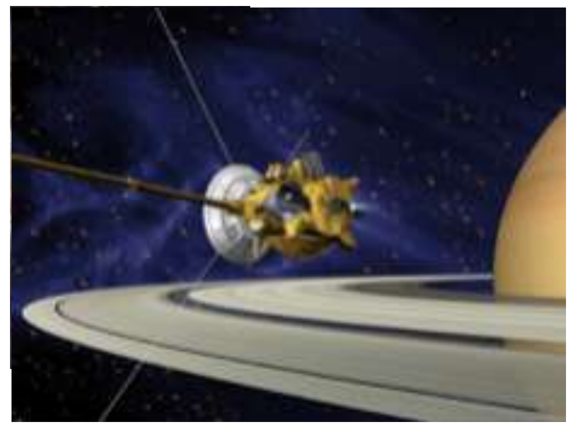
Stellar streams

Heating + coherent perturbations



$m \sim 10^{-[23-18]}\,\mathrm{eV}$

Solar system



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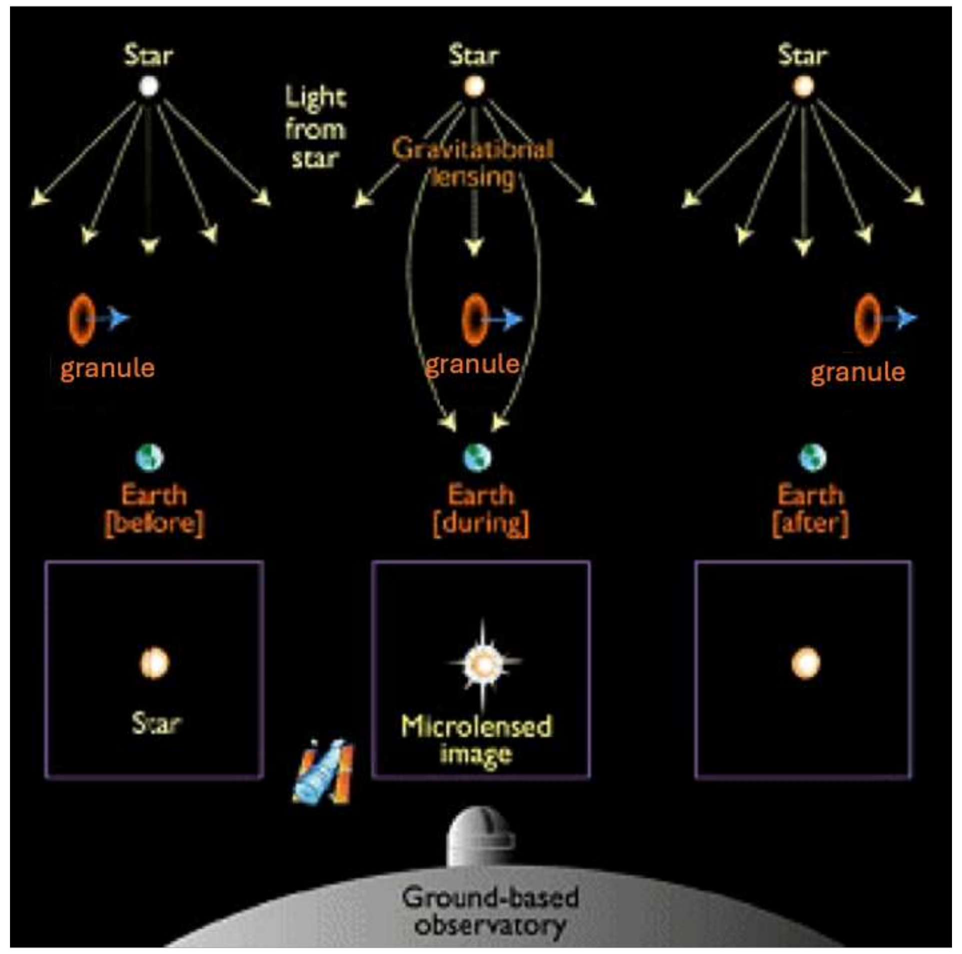
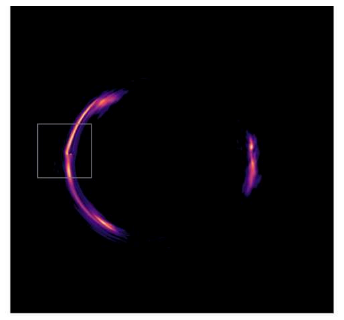
axion-photon coupling

Stochastic lensing

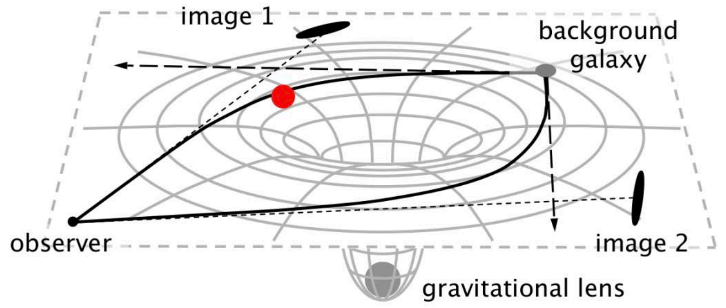


Modified from: https://i.astro.tsinghua.edu.cn/~smao/contents/microlens.html

$m \sim 10^{-[23-18]}\,\mathrm{eV}$



Strong lensing



$m \sim 10^{-[22-17]}$ eV

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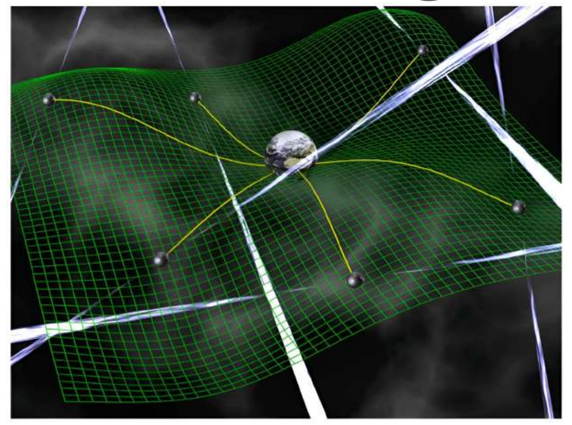
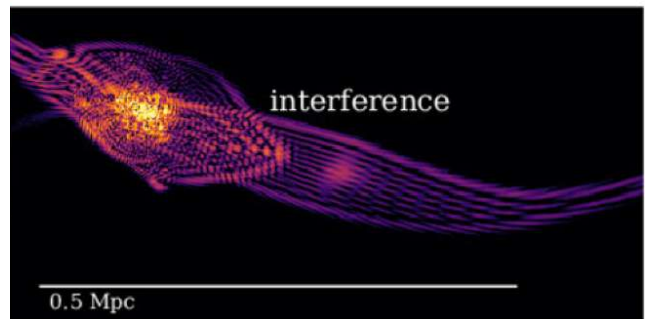


Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

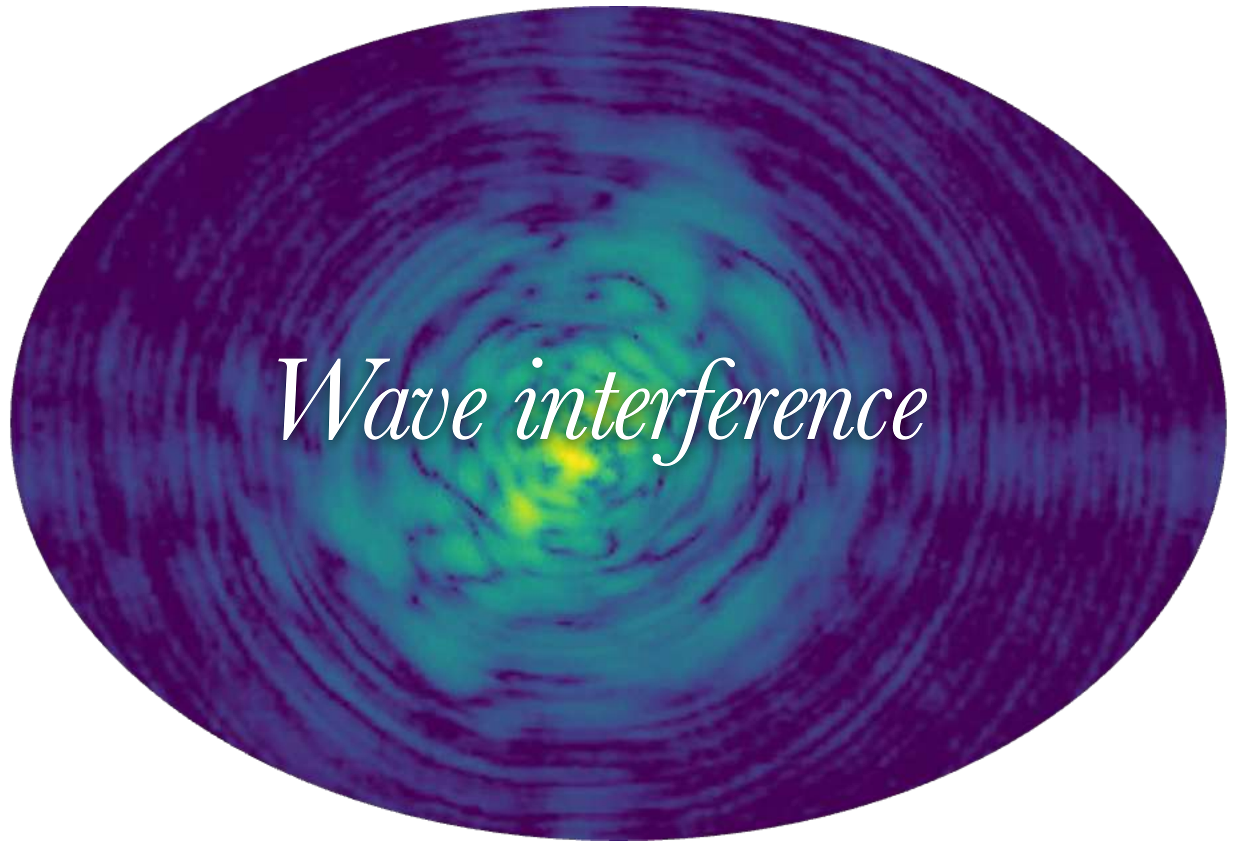
$m \sim 10^{-[22-17]}$ eV

de Broglie scale time delays in pulsar networks for ultralight dark matter
Andrew Eberhardt, Qiuyue Liang, **EF**, 2411.18051

Filaments

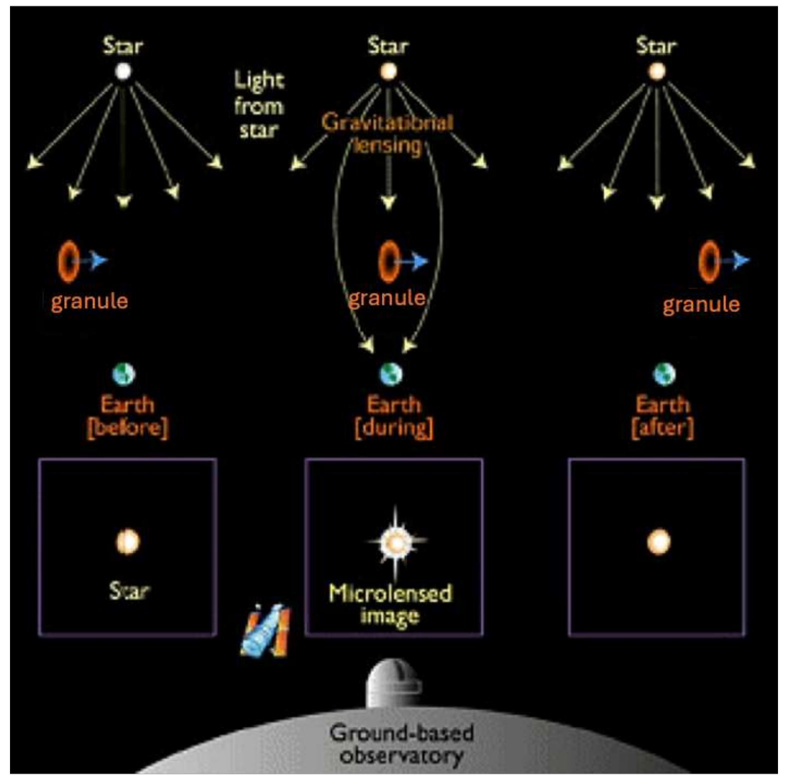


Cosmic filament spin from DM vortices
S. Alexander, C. Capanelli, **EF**, E. McDonough, 2022



Mass, spin (# particles), fraction self interaction
axion-photon coupling

Stochastic lensing



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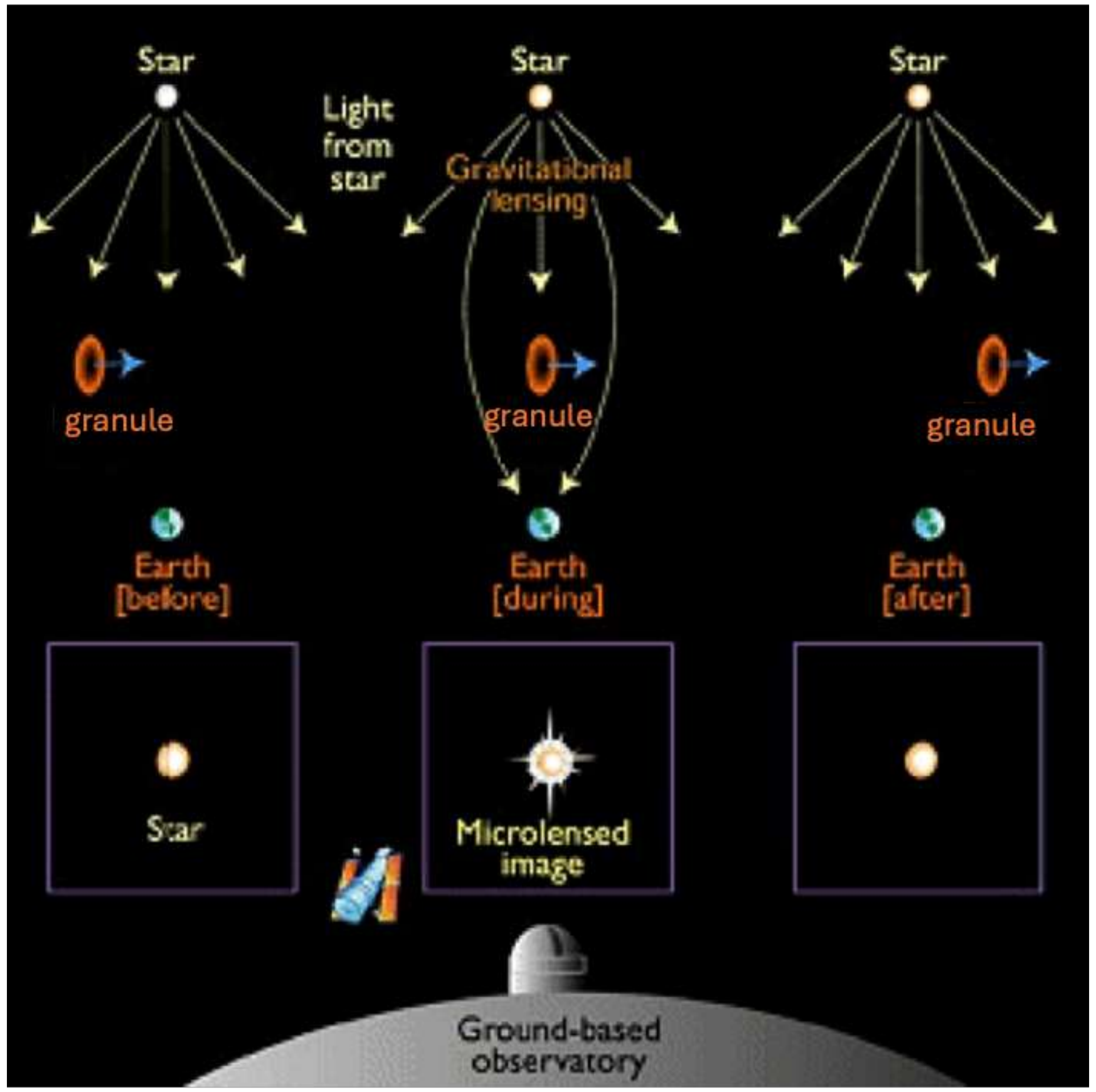
$m \sim 10^{-[23-18]}$ eV

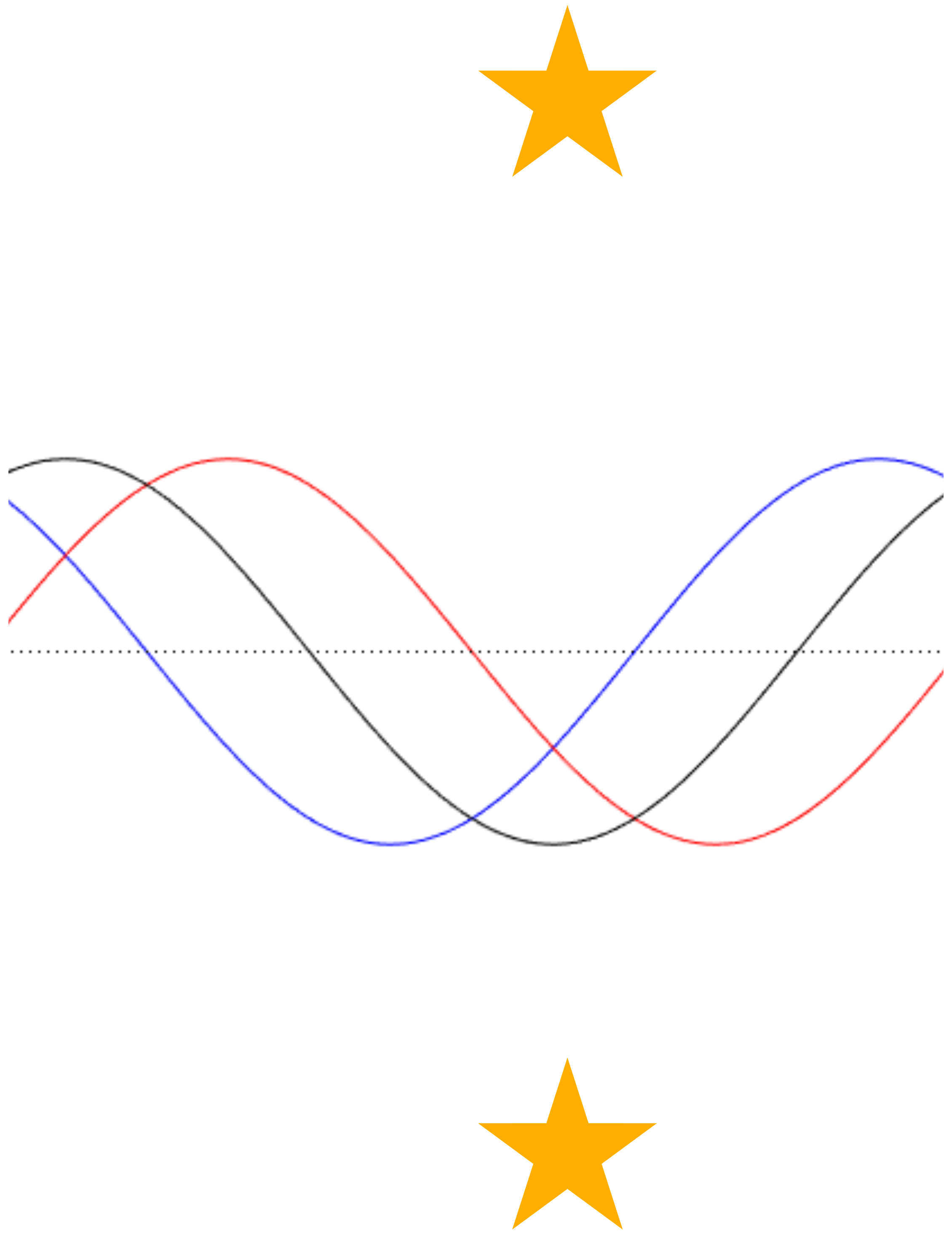
Stochastic *lensing*

Stochastic lensing of stars by ultralight dark matter halos, A. Eberhardt, **EF**, W. Luo, S. Lin, Y. Li, 2025

Microlensing



Stochastic lensing



Every source in the galaxy will flicker with a period given by the mass

$$\tau_{\rm db} = 2\pi\hbar/m\sigma^2 \sim 30 \left(\frac{10^{-17}\,{\rm eV}}{m}\right)\left(\frac{200\,{\rm km/s}}{\sigma}\right)^2 \,{\rm yrs}\,,$$

BUT, very small!

Stochastic lensing

Andrew Eberhardt, Wentao Lui, Yin Li and Shurui Lin, 2025

ULDM

$$\lambda_{\rm db} = \hbar/m\sigma \sim 6\times 10^{-6}\left(\frac{10^{-17}\,{\rm eV}}{m}\right)\left(\frac{200\,{\rm km/s}}{\sigma}\right)\,{\rm kpc}\,.$$

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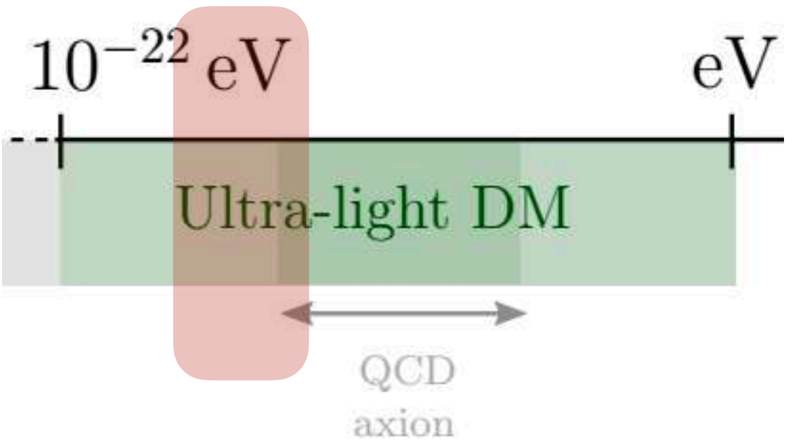


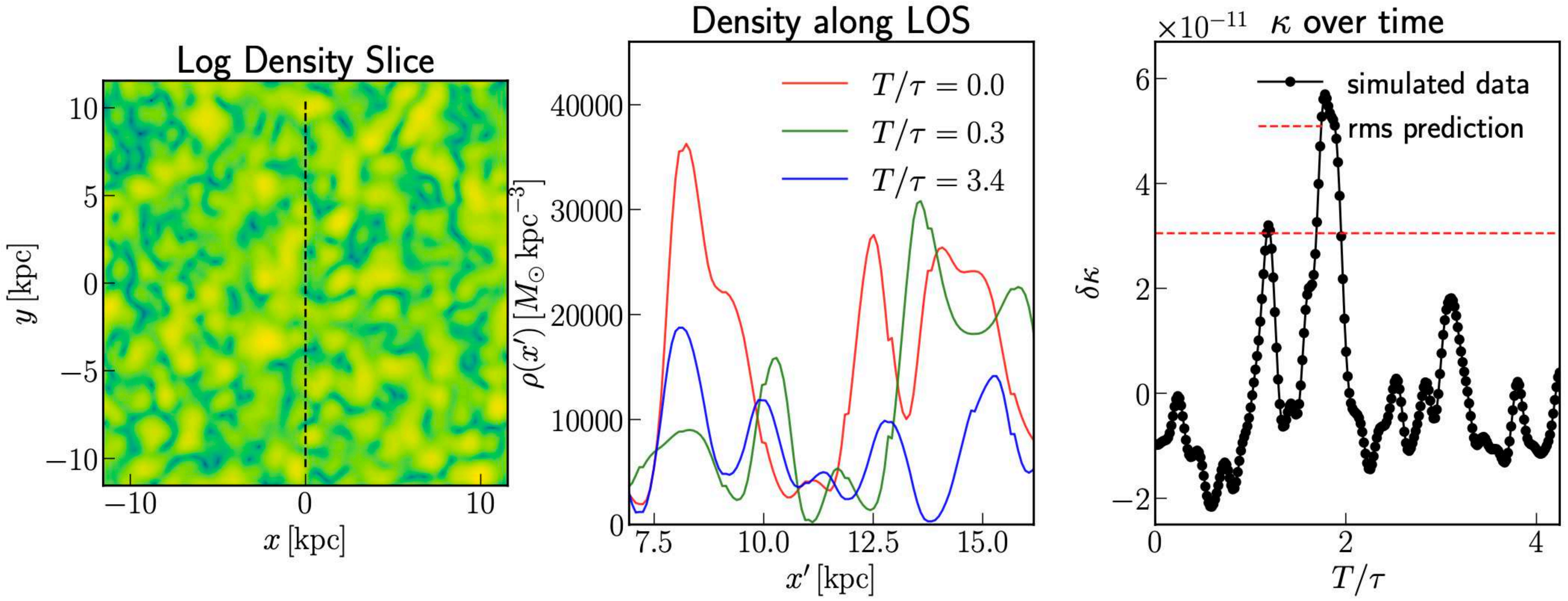
Lensing

Lensing convergence:

observer at the origin and source a distance D away along the line of sight

$$\delta\kappa_{\rm gr} = \frac{4\pi G}{c^2}\int_0^D dx\,\frac{x(D-x)}{D}\,\delta\rho(x)$$

$\rho - \rho_{sm}$



We approximate the dark matter granules as a Gaussian random field with correlation length equal to the de Broglie wavelength, $\lambda = \hbar/m\sigma$, and expectation and variance given

$$\langle\delta\rho\rangle = 0 \text{ and } \langle\delta\rho^2\rangle = \rho_{sm}^2$$

$$\delta\kappa^{\rm gr}_{\rm rms} \sim 3\times 10^{-12}\left(\frac{m}{10^{-17}\,{\rm eV}}\right)^{-1/2}\left(\frac{\sigma}{200\,{\rm km/s}}\right)^{-1/2}\left(\frac{\rho}{10^7\,{\rm M_\odot/kpc^3}}\right)\left(\frac{D}{\rm kpc}\right)^{3/4}$$

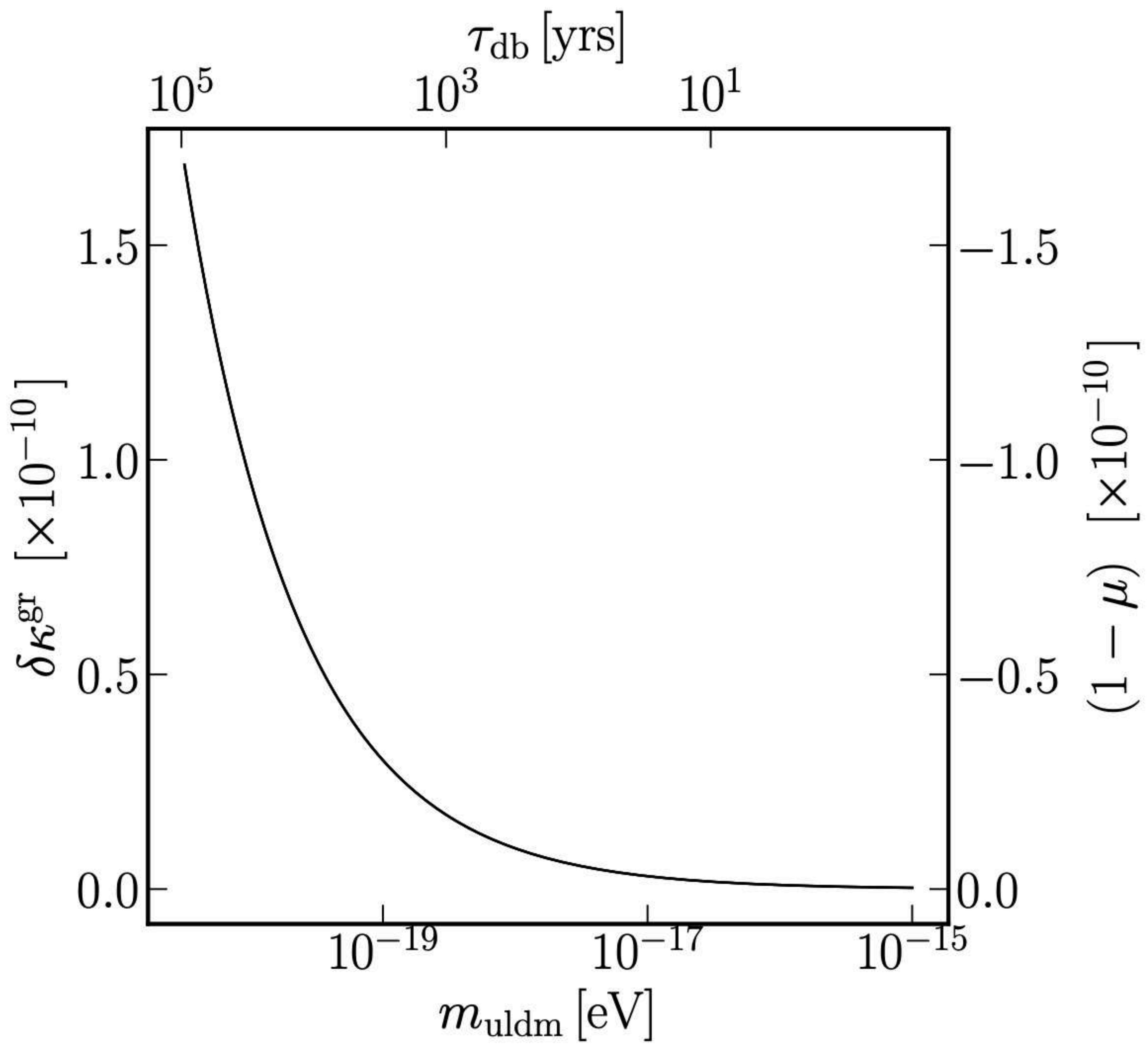
Stochastic lensing

Andrew Eberhardt, Wentao Lui, Yin Li
and Shurui Lin, 2025

ULDM

$$\lambda_{db} = \hbar/m\sigma \sim 6 \times 10^{-6} \left(\frac{10^{-17}\,\mathrm{eV}}{m}\right)\left(\frac{200\,\mathrm{km/s}}{\sigma}\right)\,\mathrm{kpc}\,.$$

$$\tau_{db} = 2\pi\hbar/m\sigma^2 \sim 30 \left(\frac{10^{-17}\,\mathrm{eV}}{m}\right)\left(\frac{200\,\mathrm{km/s}}{\sigma}\right)^2\,\mathrm{yrs}\,,$$



Lensing

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Stochastic lensing

Andrew Eberhardt, Wentao Lui, Yin Li and Shurui Lin, 2025

Lensing

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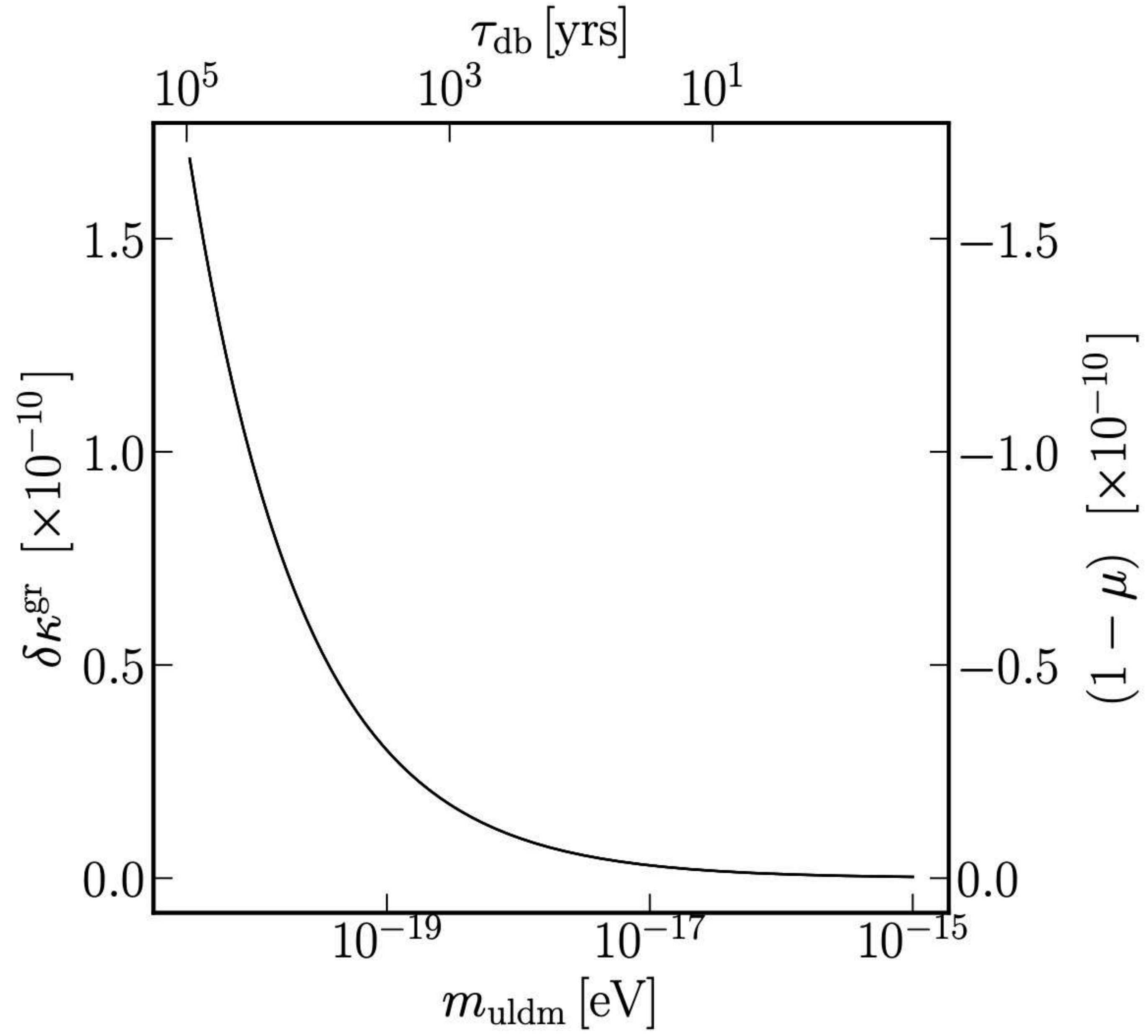


Observational effect

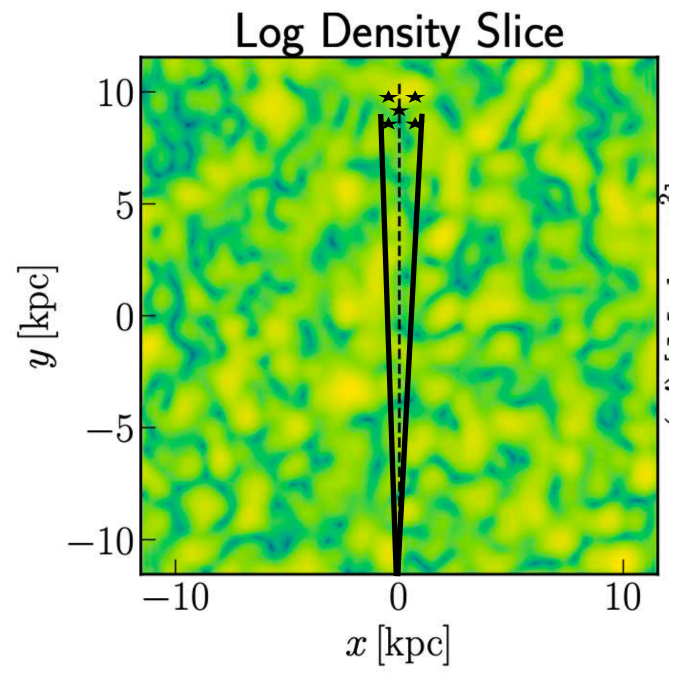
Every source in the galaxy will flicker with a period given by the mass

$$\tau_{\rm db} = 2\pi\hbar/m\sigma^2 \sim 30\left(\frac{10^{-17}\,{\rm eV}}{m}\right)\left(\frac{200\,{\rm km/s}}{\sigma}\right)^2 {\rm yrs}\,,$$

Objects to use?

Ex.: globular cluster, star, …

(Work in progress)
FRB diffraction
W/ Ue-li Pen

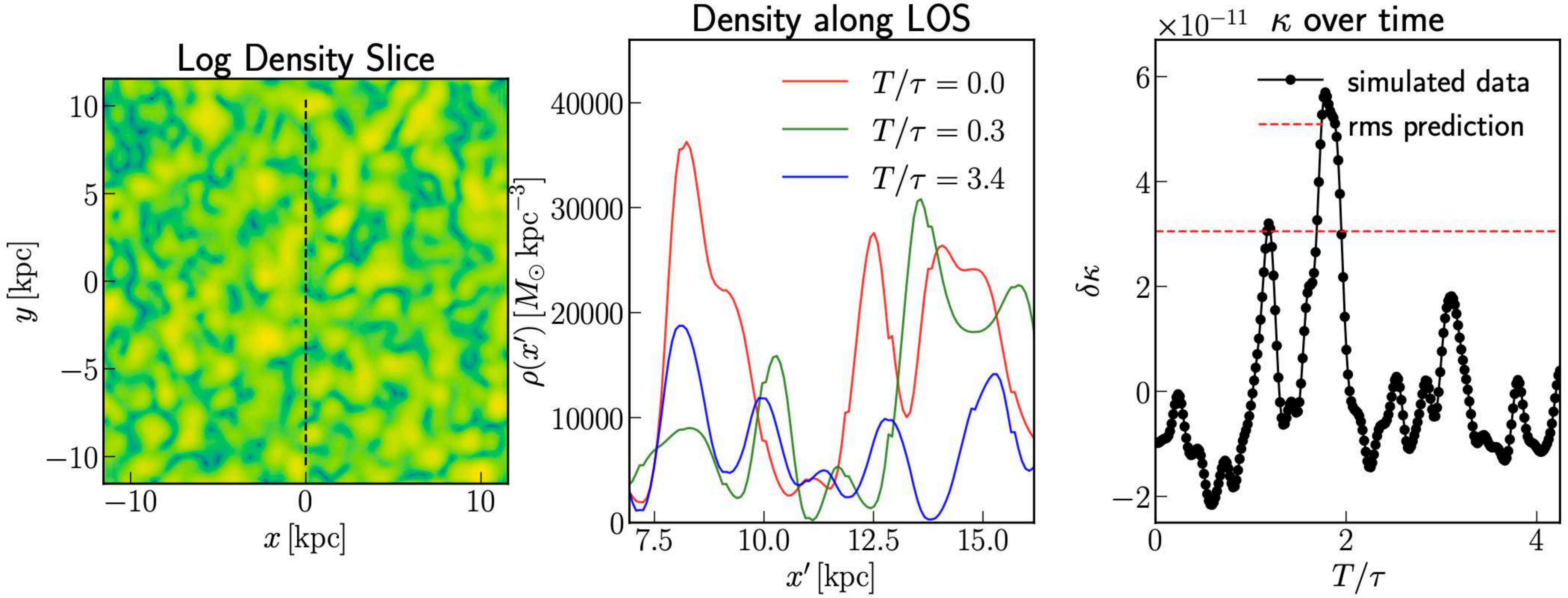


Stochastic lensing

Andrew Eberhardt, Wentao Lui, Yin Li and Shurui Lin, 2025

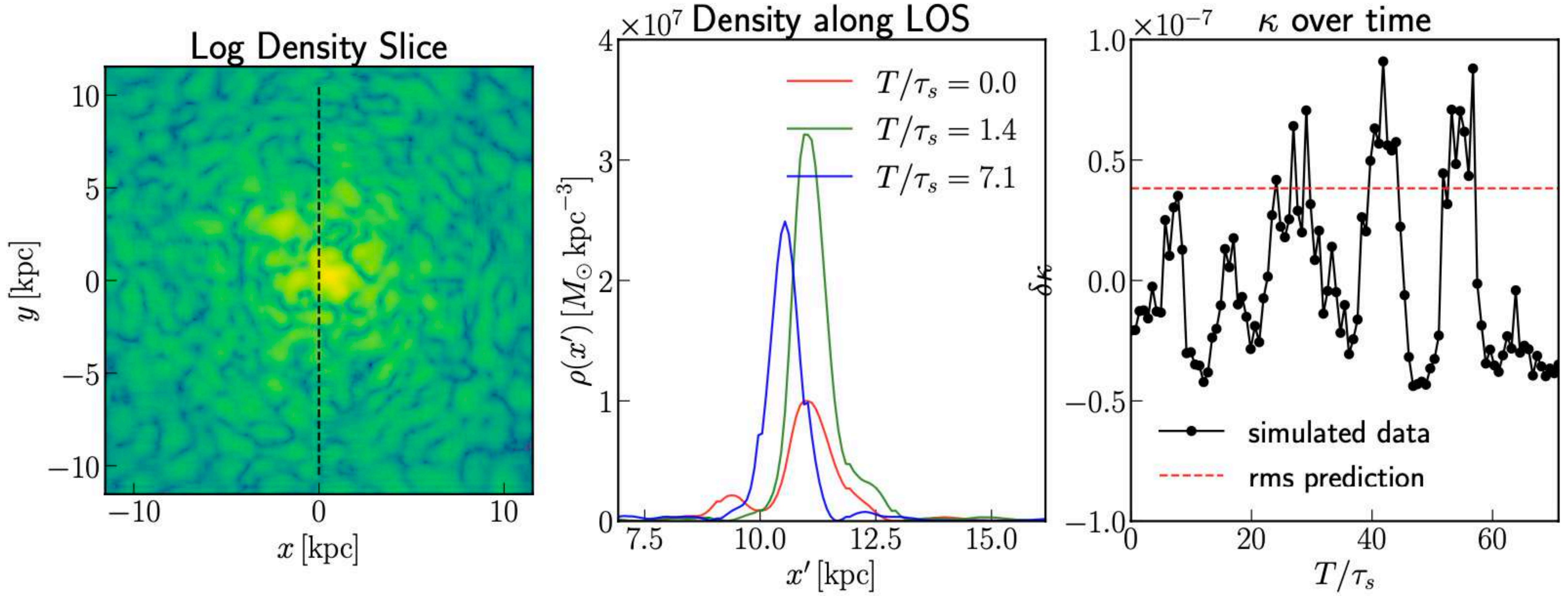
Granules $\sim \mathcal{O}(10^{-17})\,\mathrm{eV}$

$$\delta\kappa^{\rm gr}_{\rm rms} \sim 3\times 10^{-12}\left(\frac{m}{10^{-17}\,\mathrm{eV}}\right)^{-1/2}\left(\frac{\sigma}{200\,\mathrm{km/s}}\right)^{-1/2} \times \left(\frac{\rho}{10^{7}\,\mathrm{M_\odot/kpc^3}}\right)\left(\frac{D}{\mathrm{kpc}}\right)^{3/4}$$

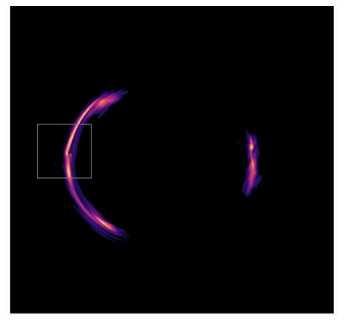


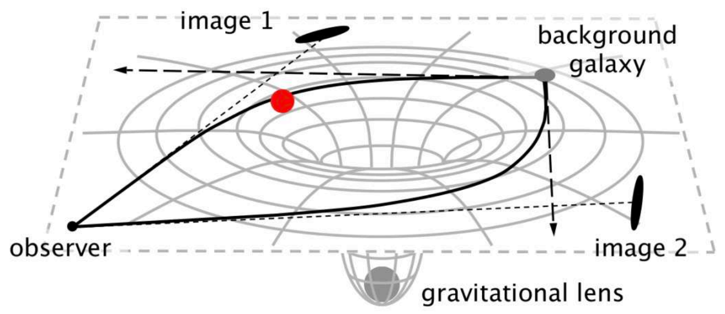
Soliton oscillation $\sim \mathcal{O}(10^{-23} - 10^{-22})\,\mathrm{eV}$

$$\kappa^{\rm s}_{\rm rms} \sim 10^{-8}\left(\frac{m}{10^{-23}\,\mathrm{eV}}\right)^{-2}\left(\frac{r_c}{\mathrm{kpc}}\right)^{-3}\left(\frac{D_s(D-D_s)/D}{\mathrm{kpc}}\right)$$



Strong lensing

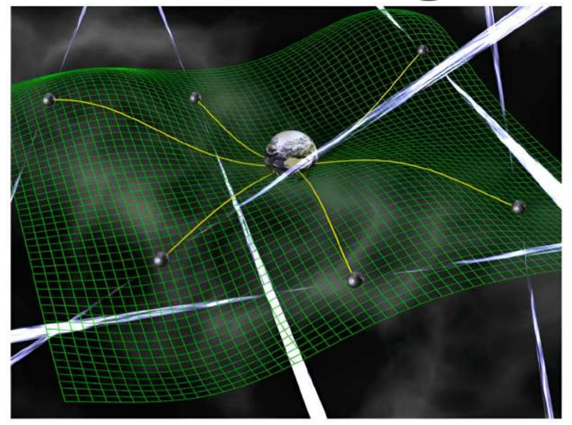




axion-photon coupling

$m \sim 10^{-[22-17]}$ eV

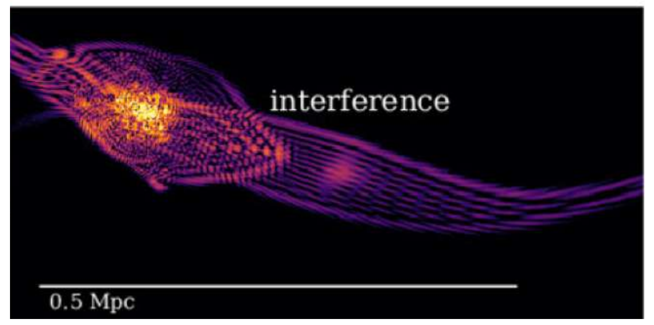
Pulsar Timing Array



Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

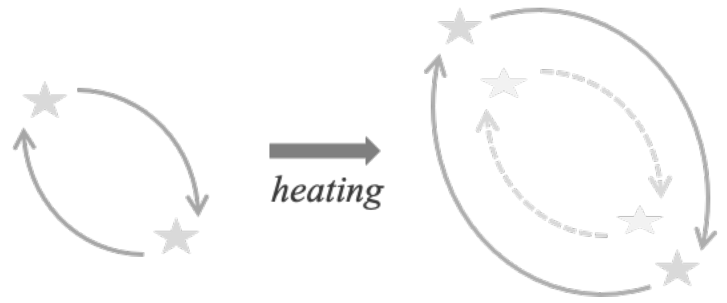
$m \sim 10^{-[22-17]}$ eV

Filaments

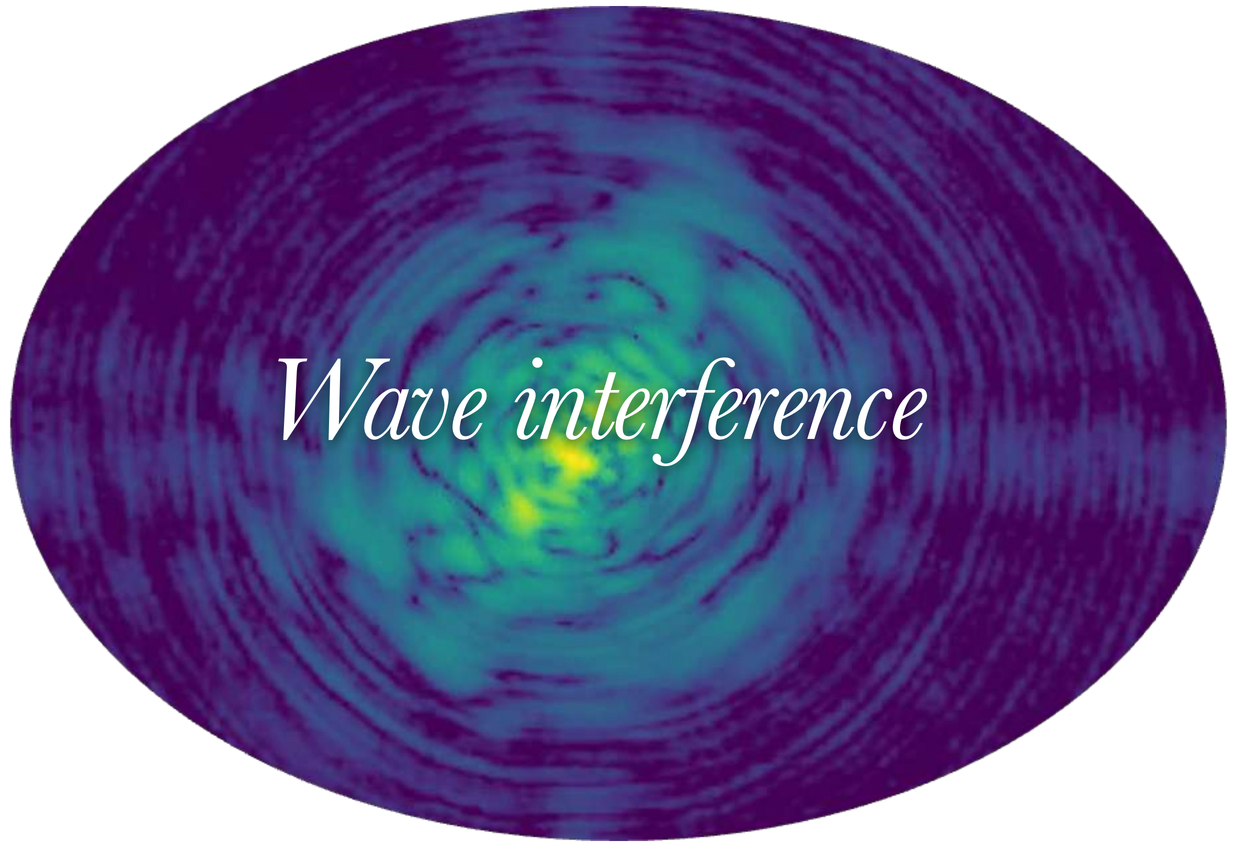


Cosmic filament spin from DM vortices
S. Alexander, C. Capanelli, **EF**, E. McDonough, 2022

Binary stars



$m \sim 10^{-[16-10]}$ eV

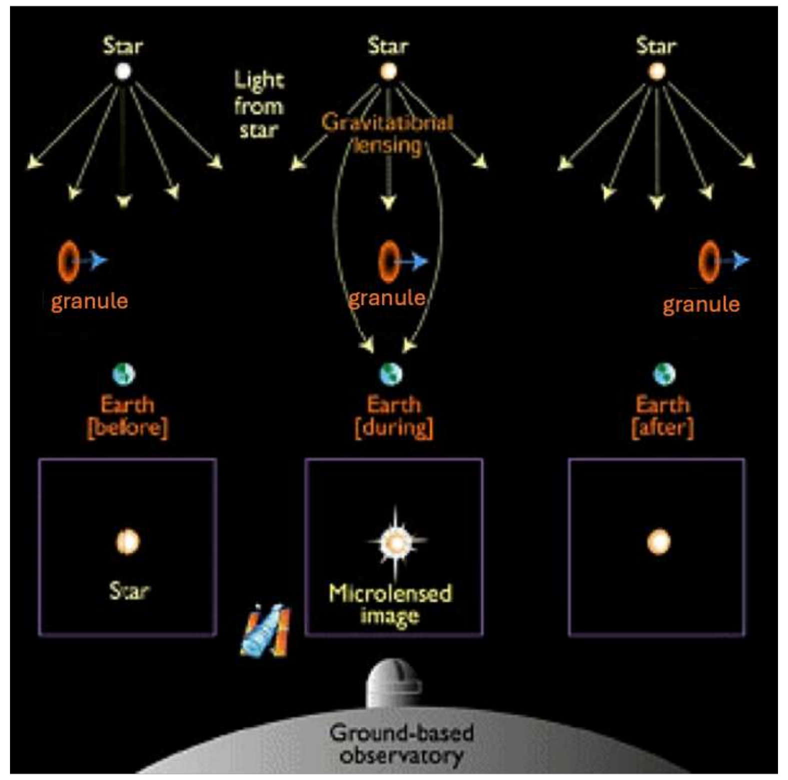


Mass, spin (# particles), fraction self interaction

Stellar streams

$m \sim 10^{-[23-18]}$ eV

Stochastic lensing



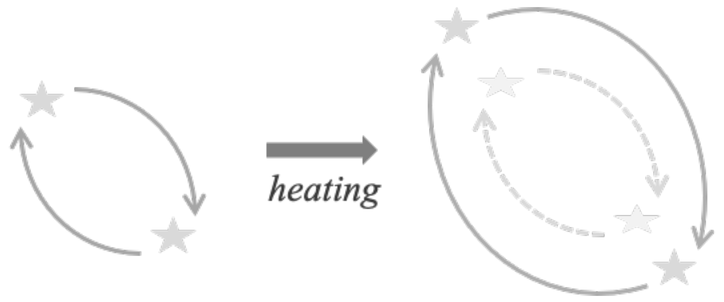
Modified from: https://i.astro.tsinghua.edu.cn/~smao/contents/microlens.html

$m \sim 10^{-[23-18]}$ eV

(Work in progress)

In collaboration with Andrew Eberhardt, Margot Imbach and Naoki Yoshida

Binary stars



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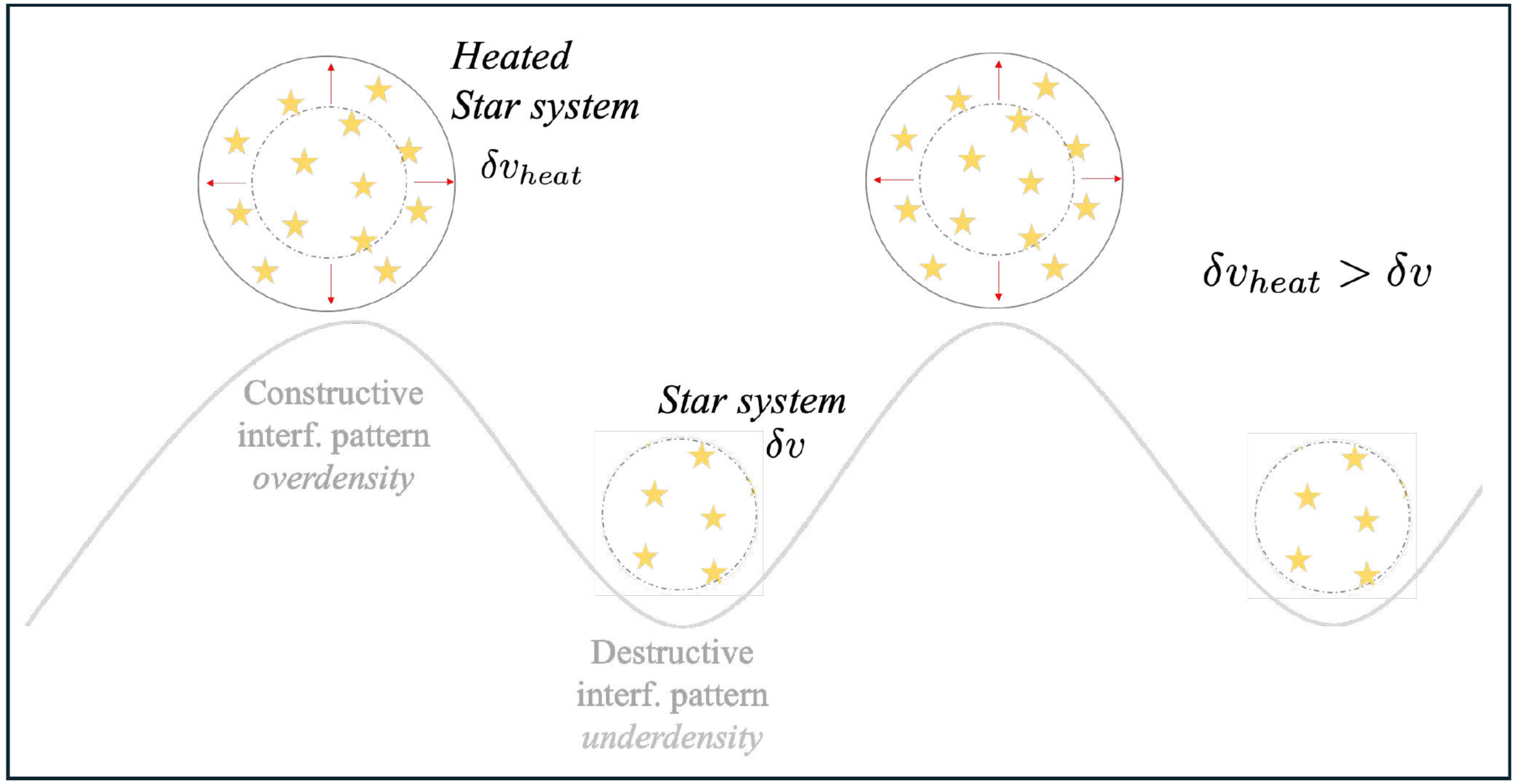
Stellar streams

$m \sim 10^{-[23-18]}$ eV

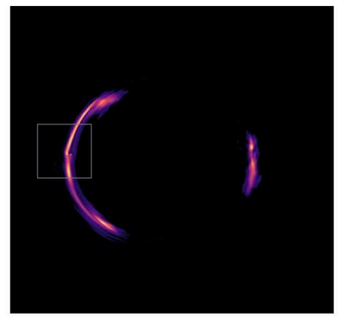
Stellar *heating*



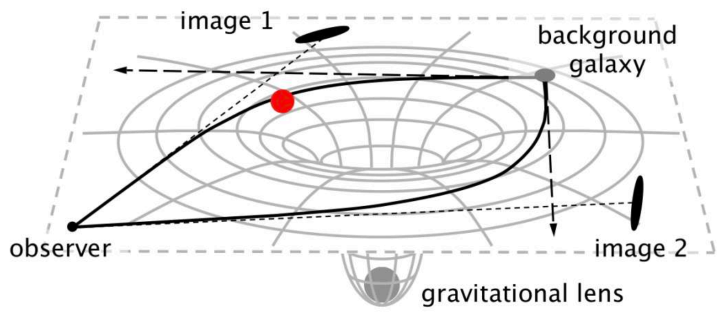
(Work in progress)

In collaboration with Andrew Eberhardt, and Fabian Schmidt

Preparation for PFS!



Strong lensing



axion-photon coupling

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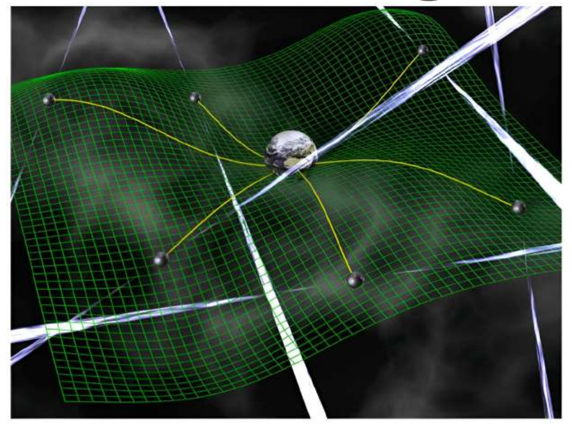

Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

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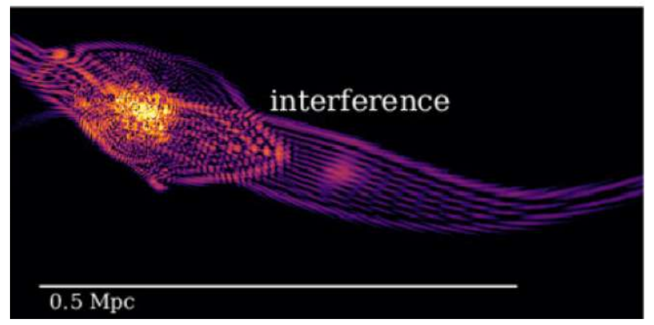
Filaments



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S. Alexander, C. Capanelli, **EF**, E. McDonough, 2022

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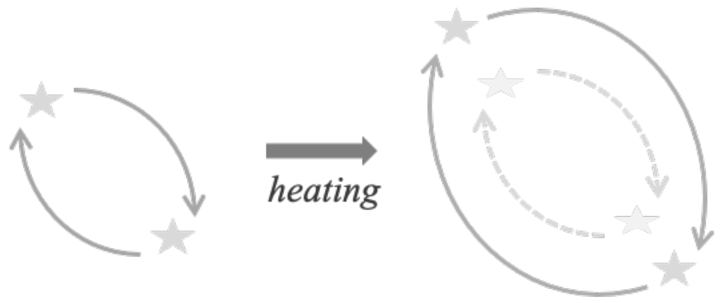

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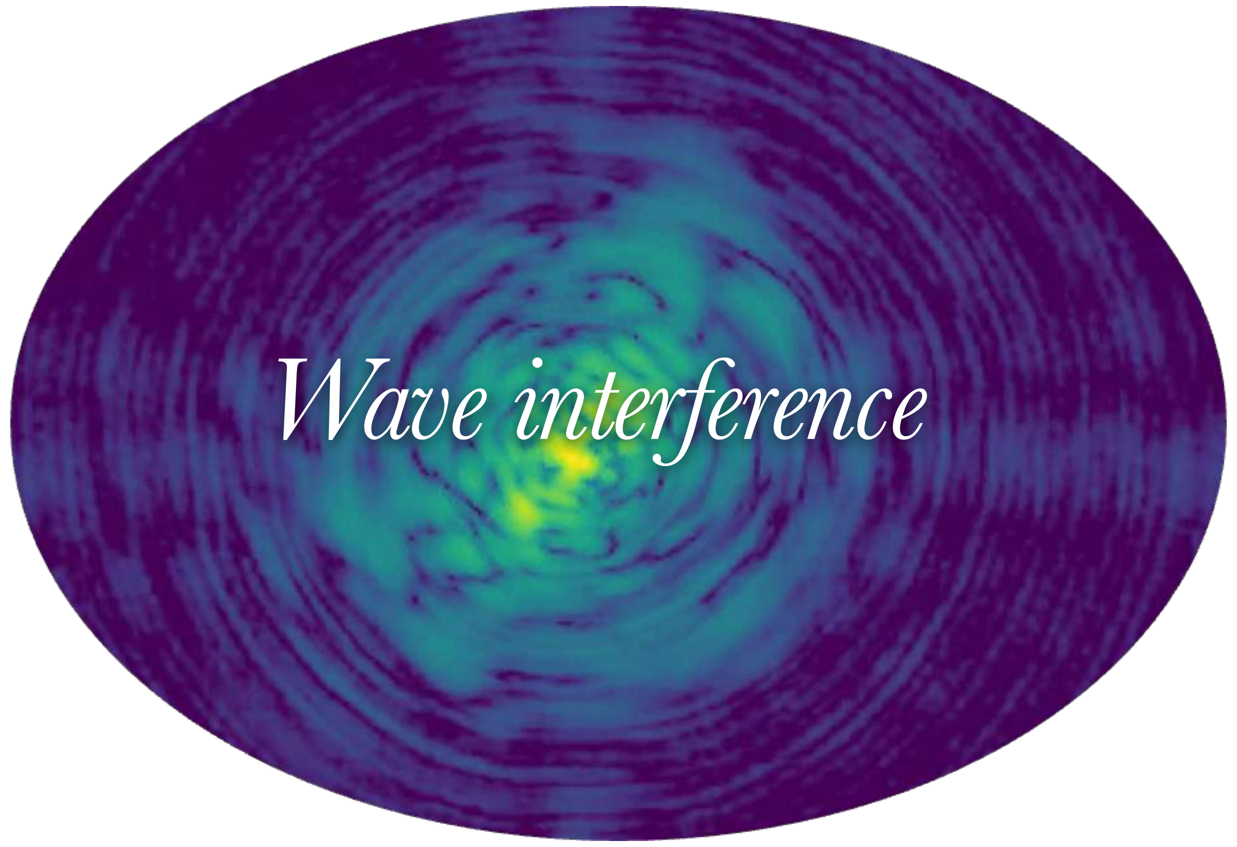
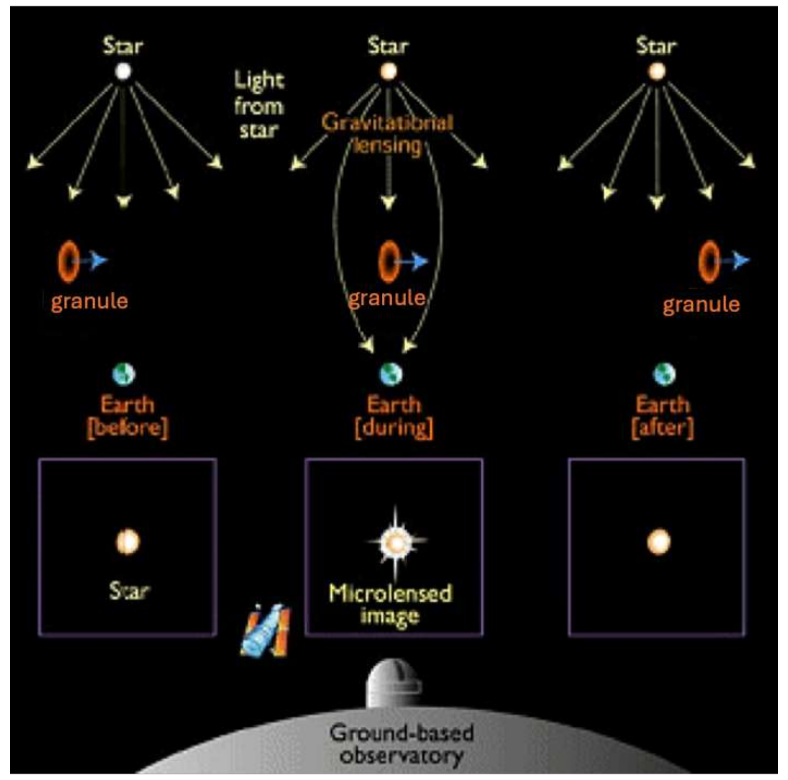


Mass, spin (# particles), fraction self interaction

Stochastic lensing



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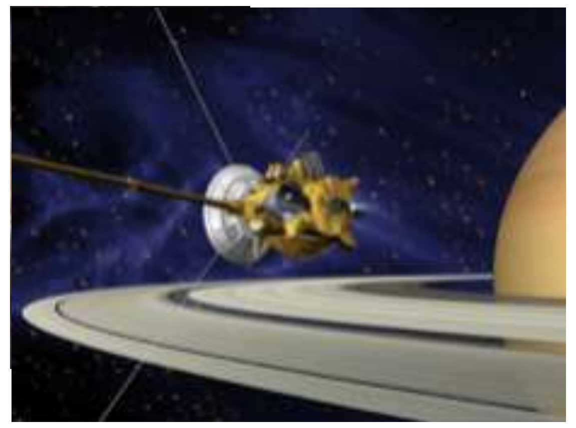
Stellar streams

$m \sim 10^{-[23-18]}$ eV

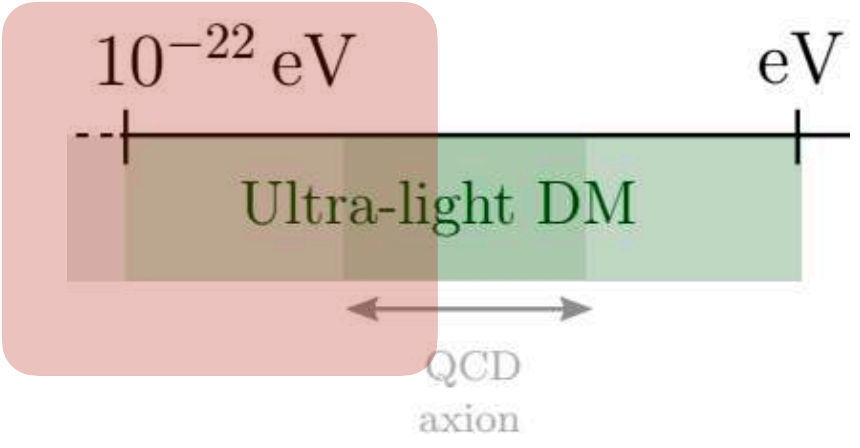
Solar system



$m \sim 10^{-[16-10]}$ eV

axion-photon coupling

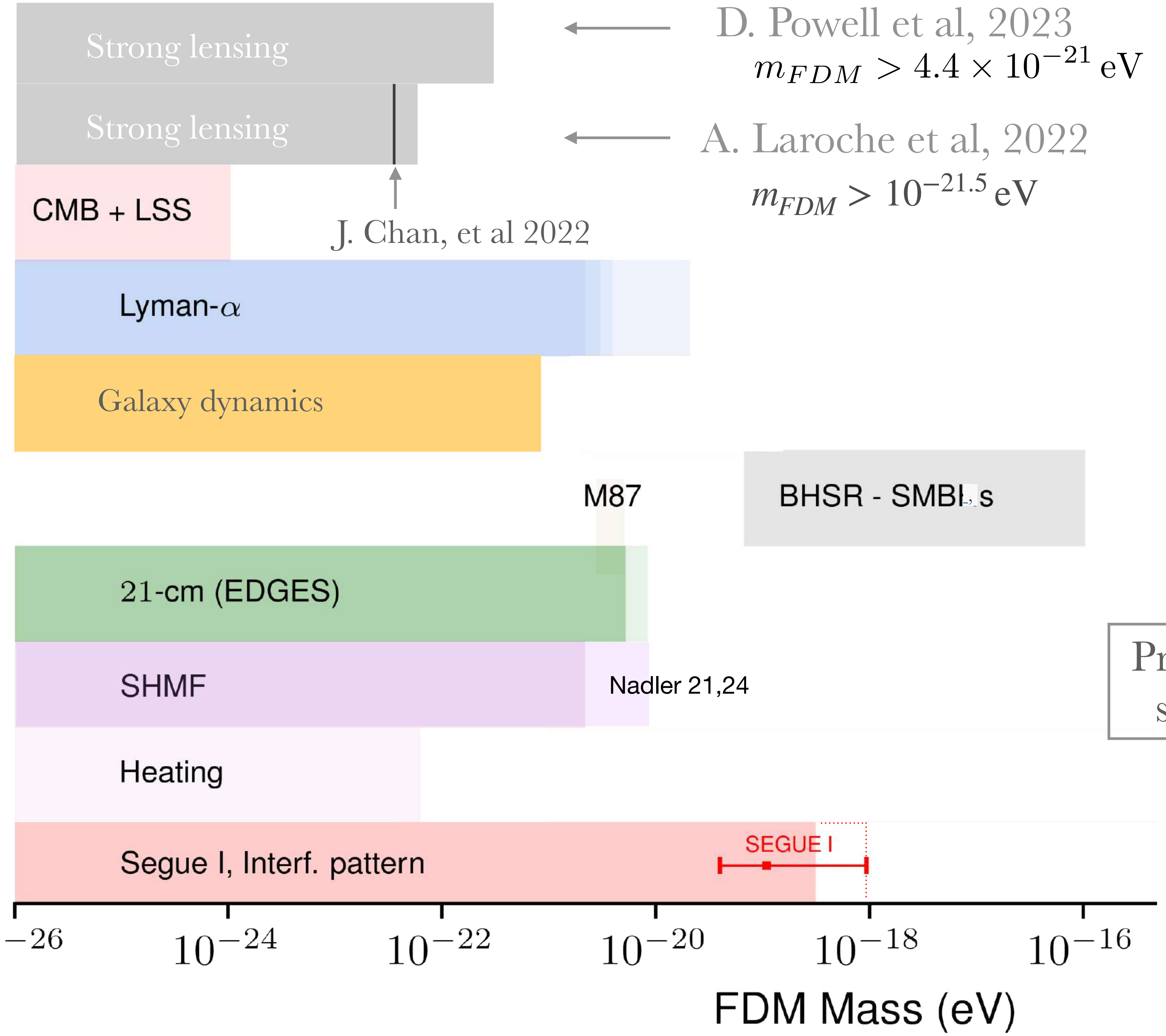
Interference patterns - granules



Strong lensing

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

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

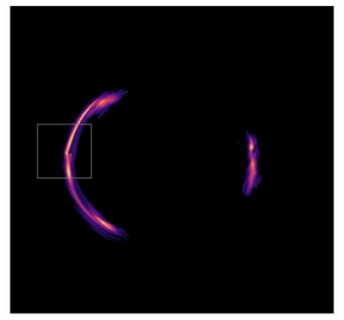


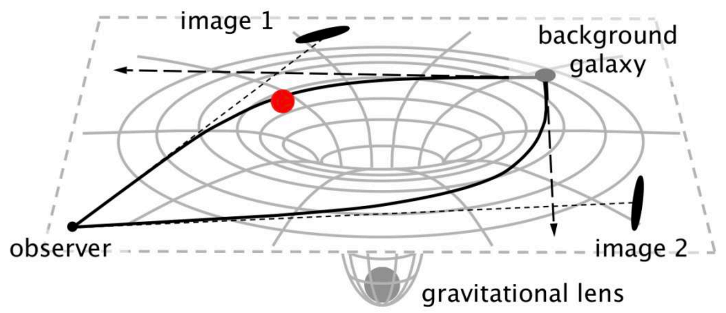
Probing the fuzziness on smaller and smaller scales (larger masses) - still wave behavior!

Stellar heating

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

Strong lensing





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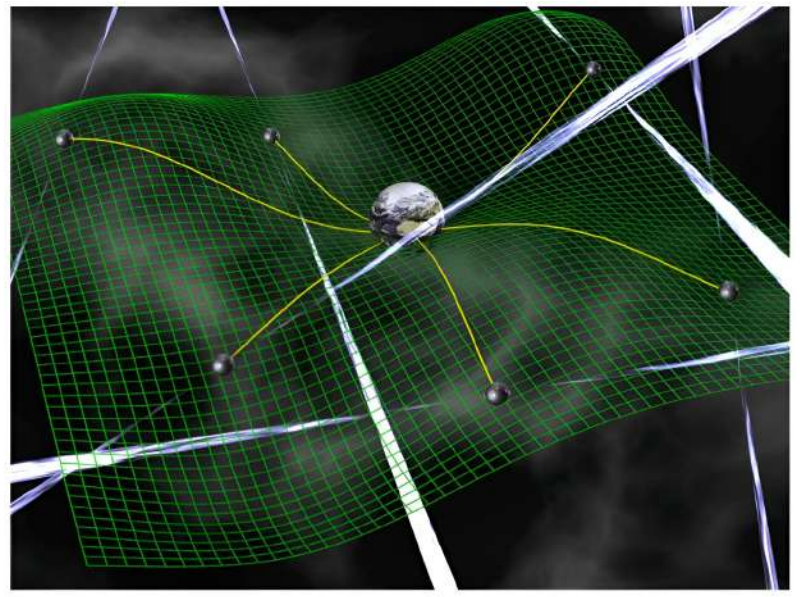
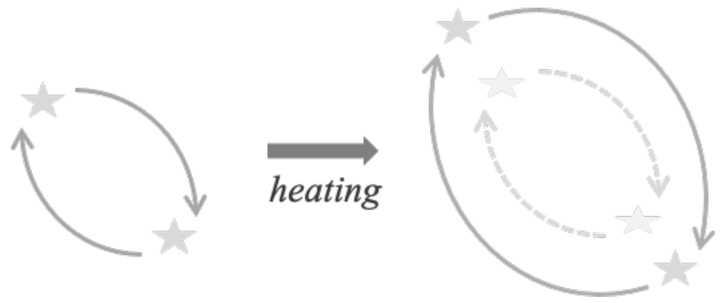
Pulsar Timing Array



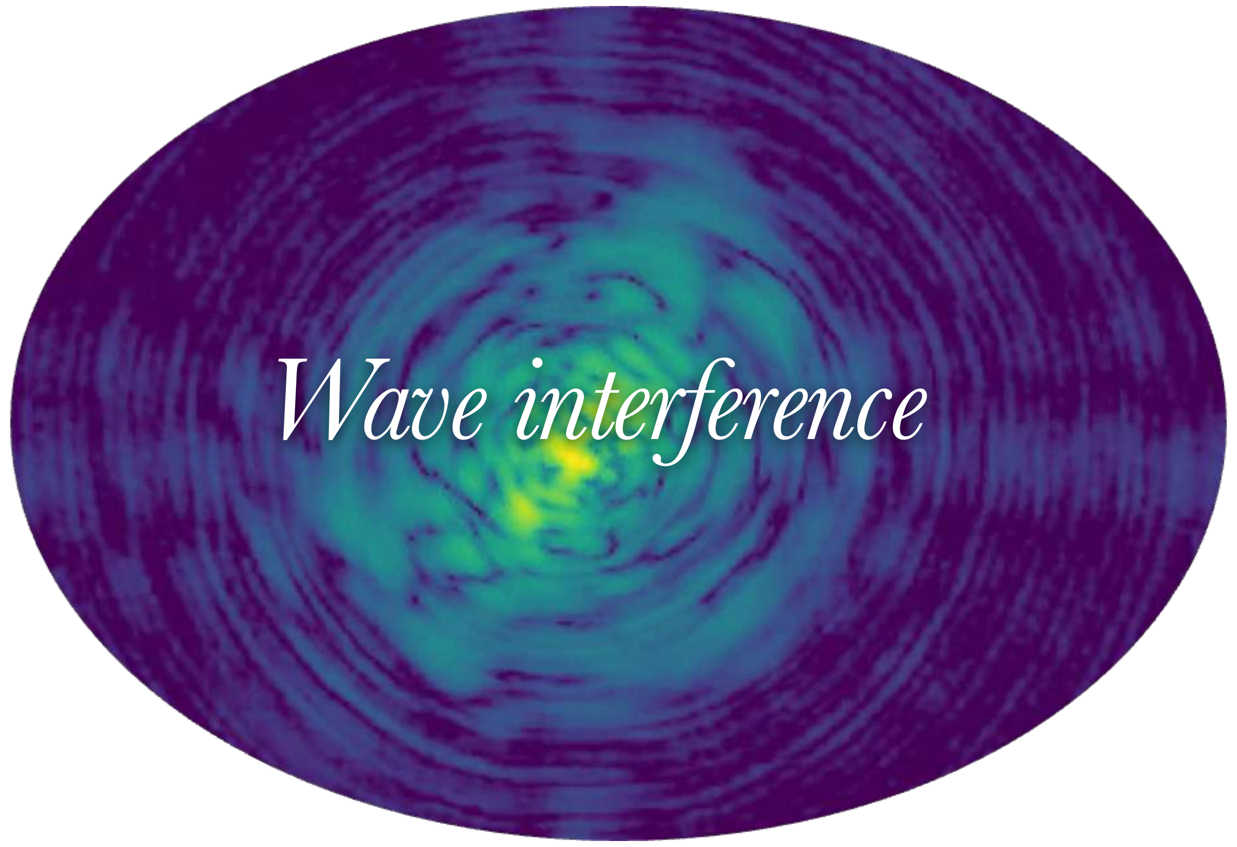
Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

$m \sim 10^{-[22-17]}$ eV

Binary stars



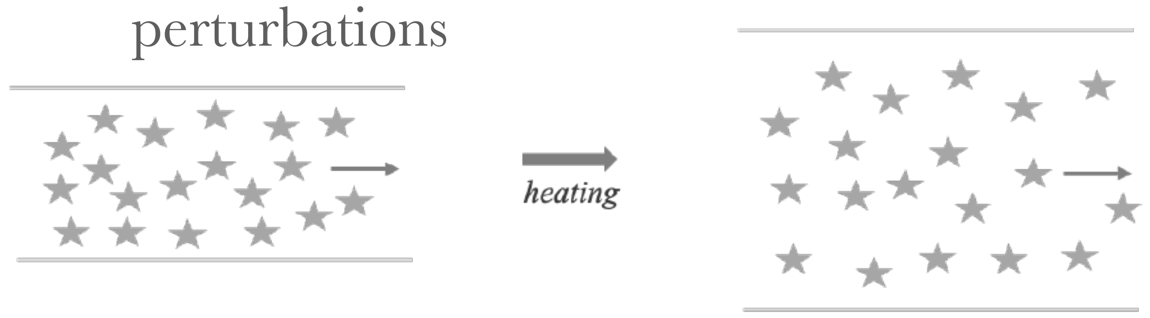
$m \sim 10^{-[16-10]}$ eV



Mass, spin (# particles), fraction self interaction

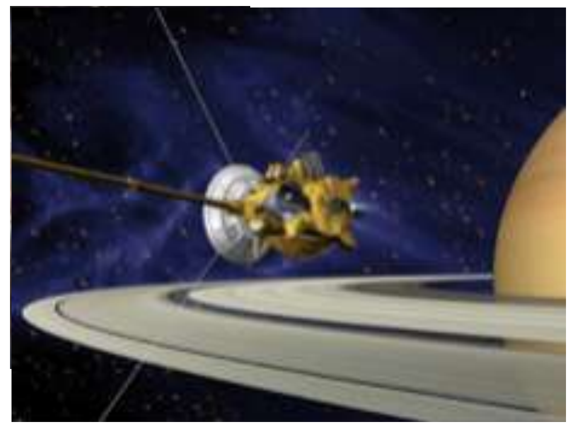
Stellar streams

Heating + coherent perturbations



$m \sim 10^{-[23-18]}$ eV

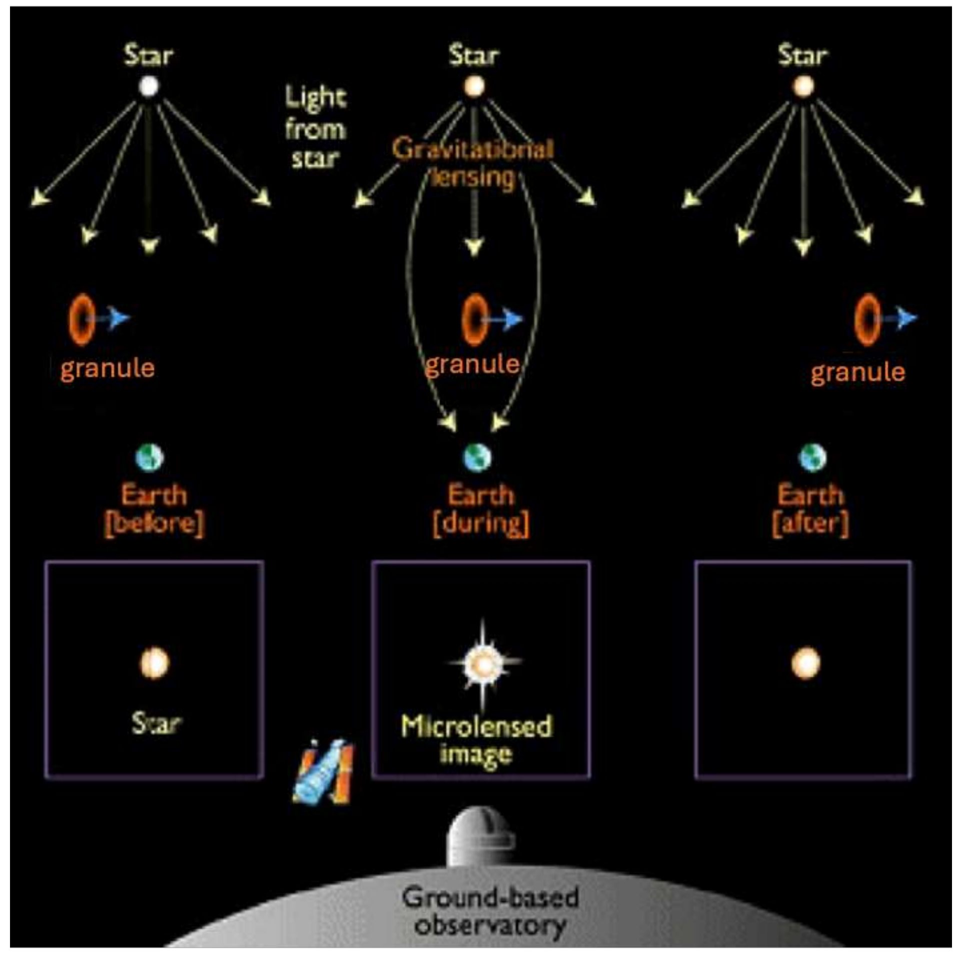
Solar system



$m \sim 10^{-[16-10]}$ eV

axion-photon coupling

Stochastic lensing



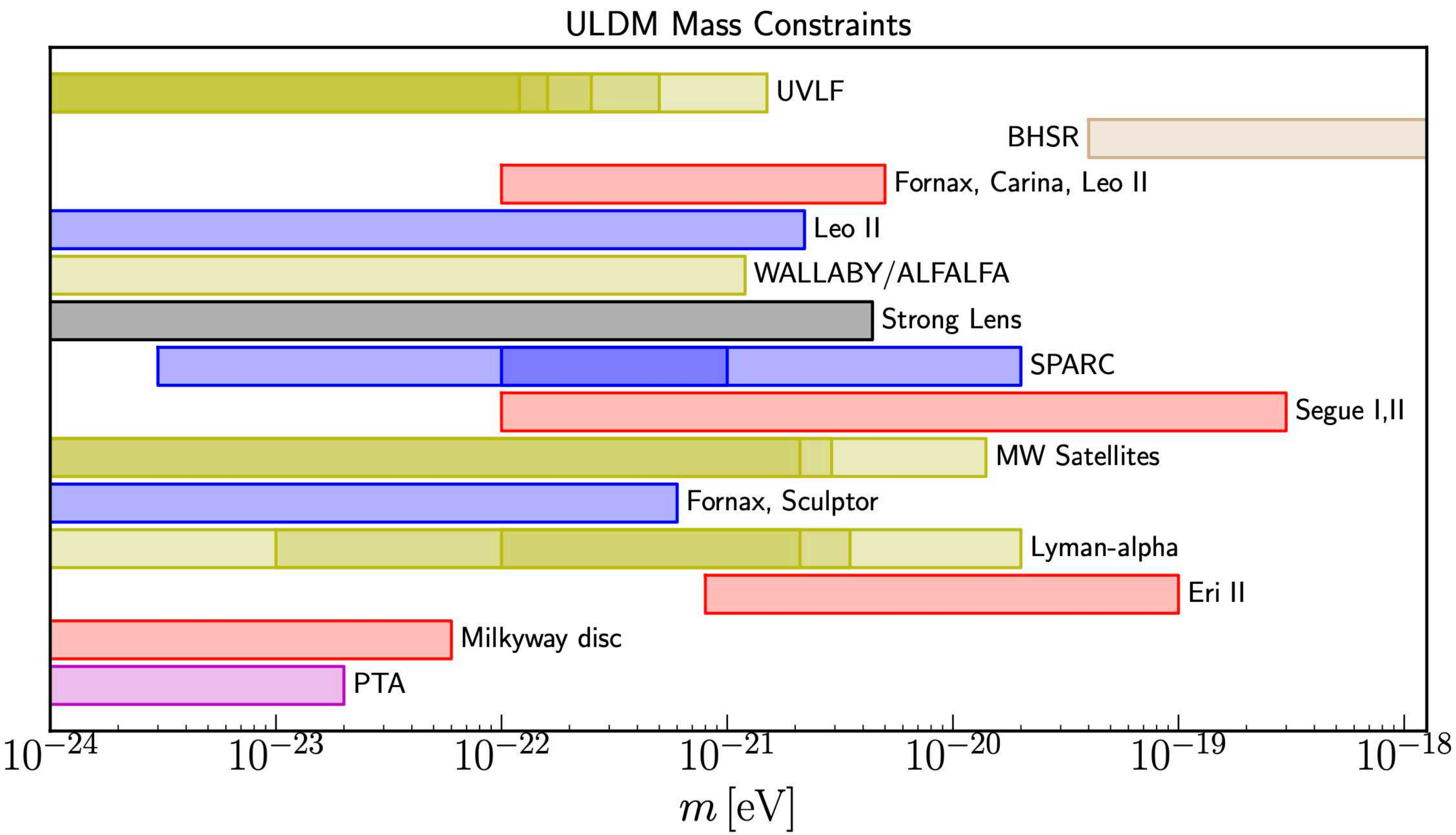
Modified from: https://i.astro.tsinghua.edu.cn/~smao/contents/microlens.html

$m \sim 10^{-[23-18]}$ eV

Current status

Fuzzy Dark Matter - bounds on the mass

Review: Eberhardt, EF (to appear)

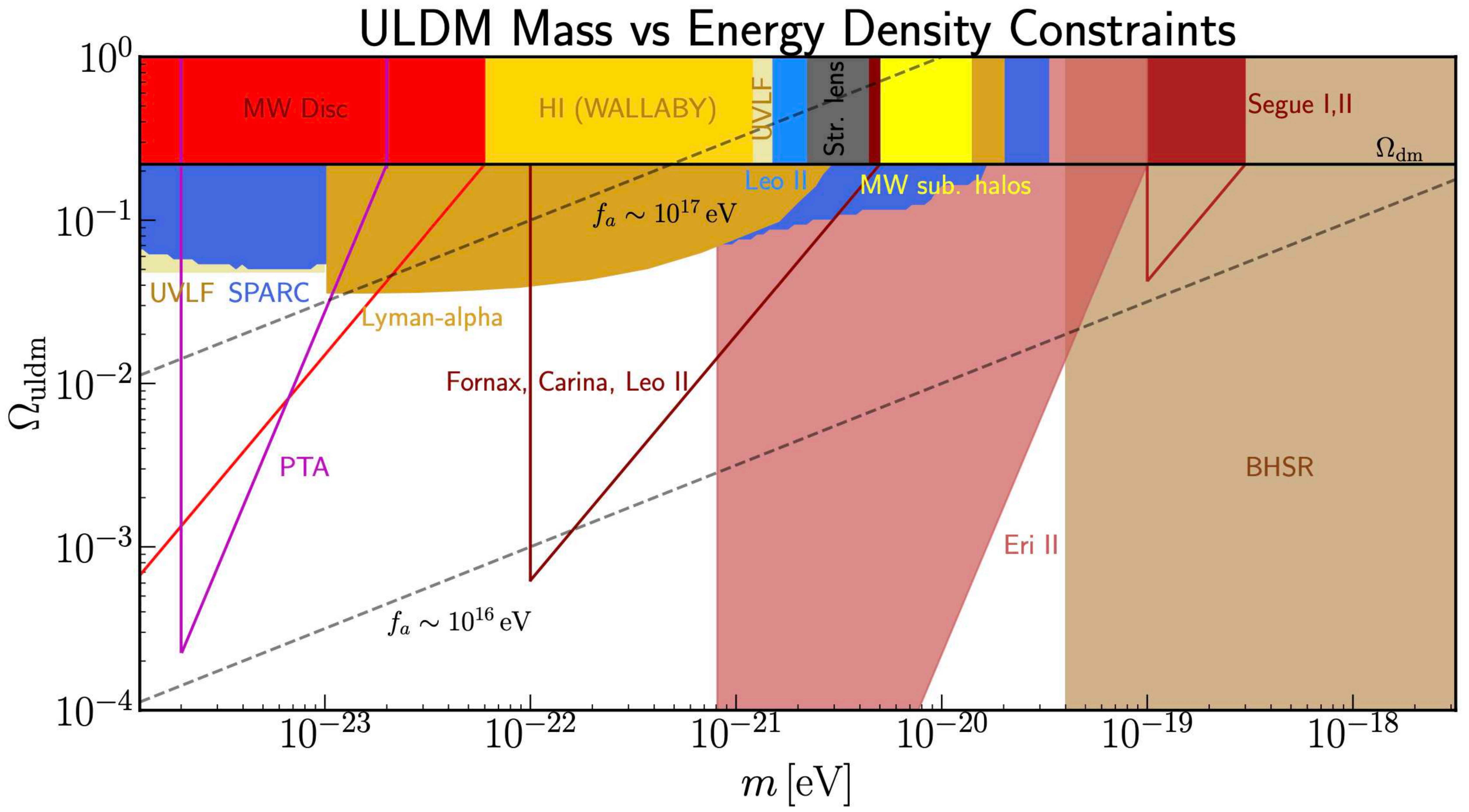


Bounds depend on assumptions, simplifications, simulations, …
And can be conservative or best case scenario.
Systematic effects!
Careful when interpreting them!

Current status

Fuzzy Dark Matter - bounds on the mass

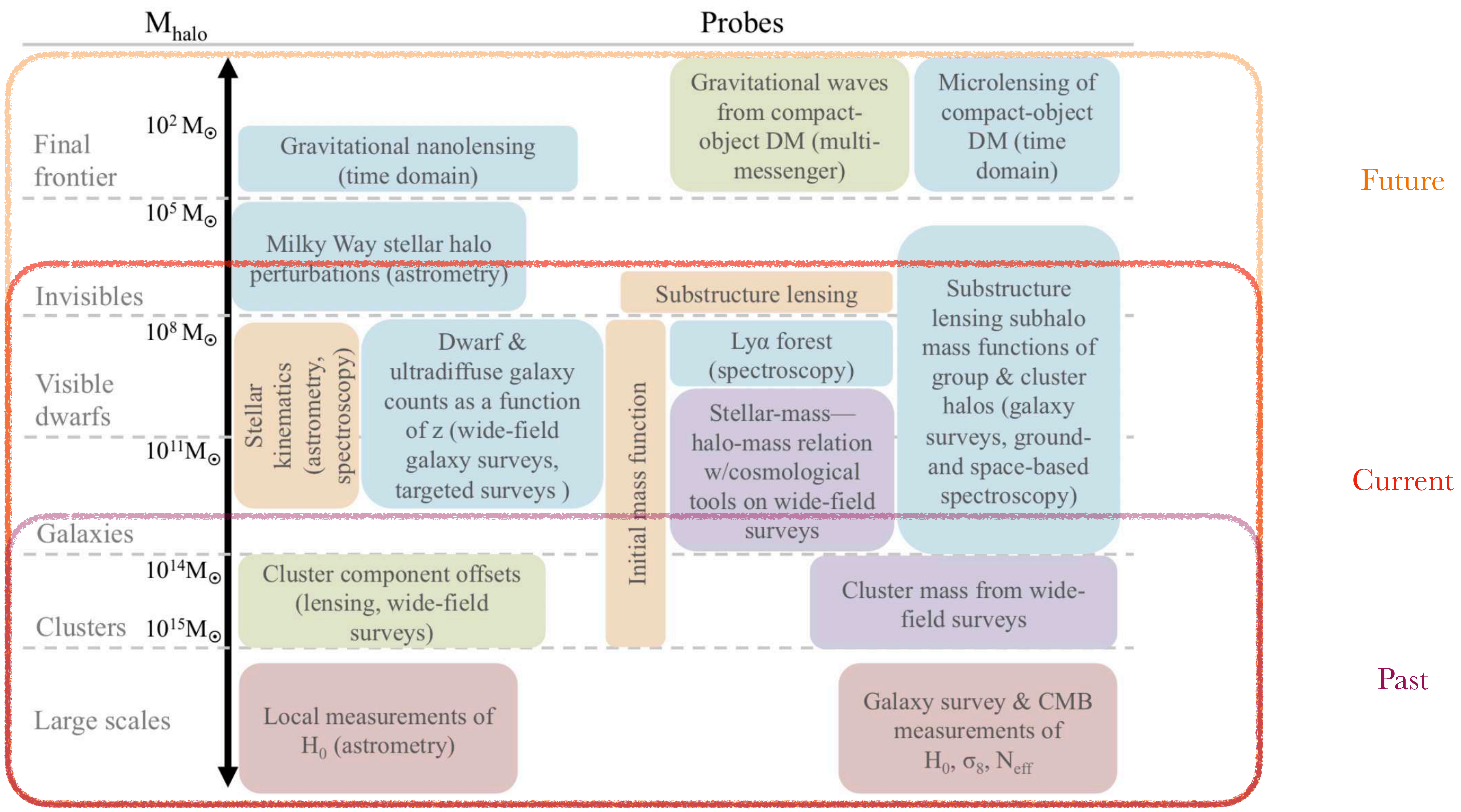
Review: Eberhardt, EF (to appear)



Much more:
- ULDM not 100%
- Multiple axions
- Add self-interaction
- Couplings
- Spin

The search for dark matter (ULDM) is a multi-probe/multi-scale endeavour…

Small scales can offer some hints of the nature of DM



Bucklеya et al 2017

The search for dark matter (ULDM) is a multi-probe/multi-scale endeavour…

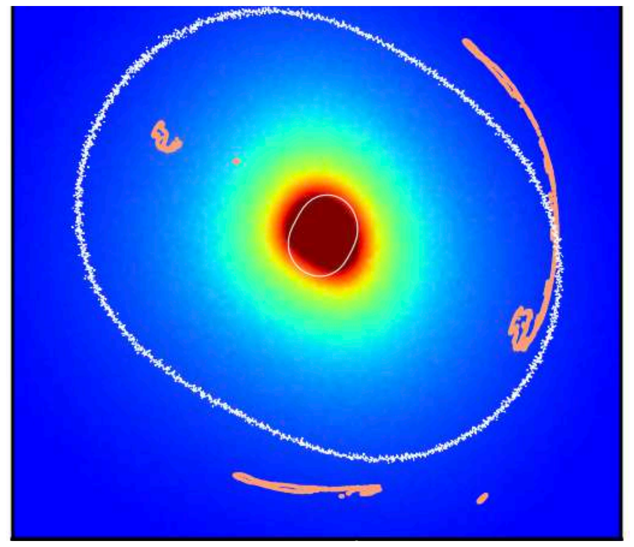
exciting times for axion dark matter

Summary

Ultra-Light Dark Matter

Well motivated DM models
Rich and distinct phenomenology on small scales
Testable prediction

Granules



Strong lensing:

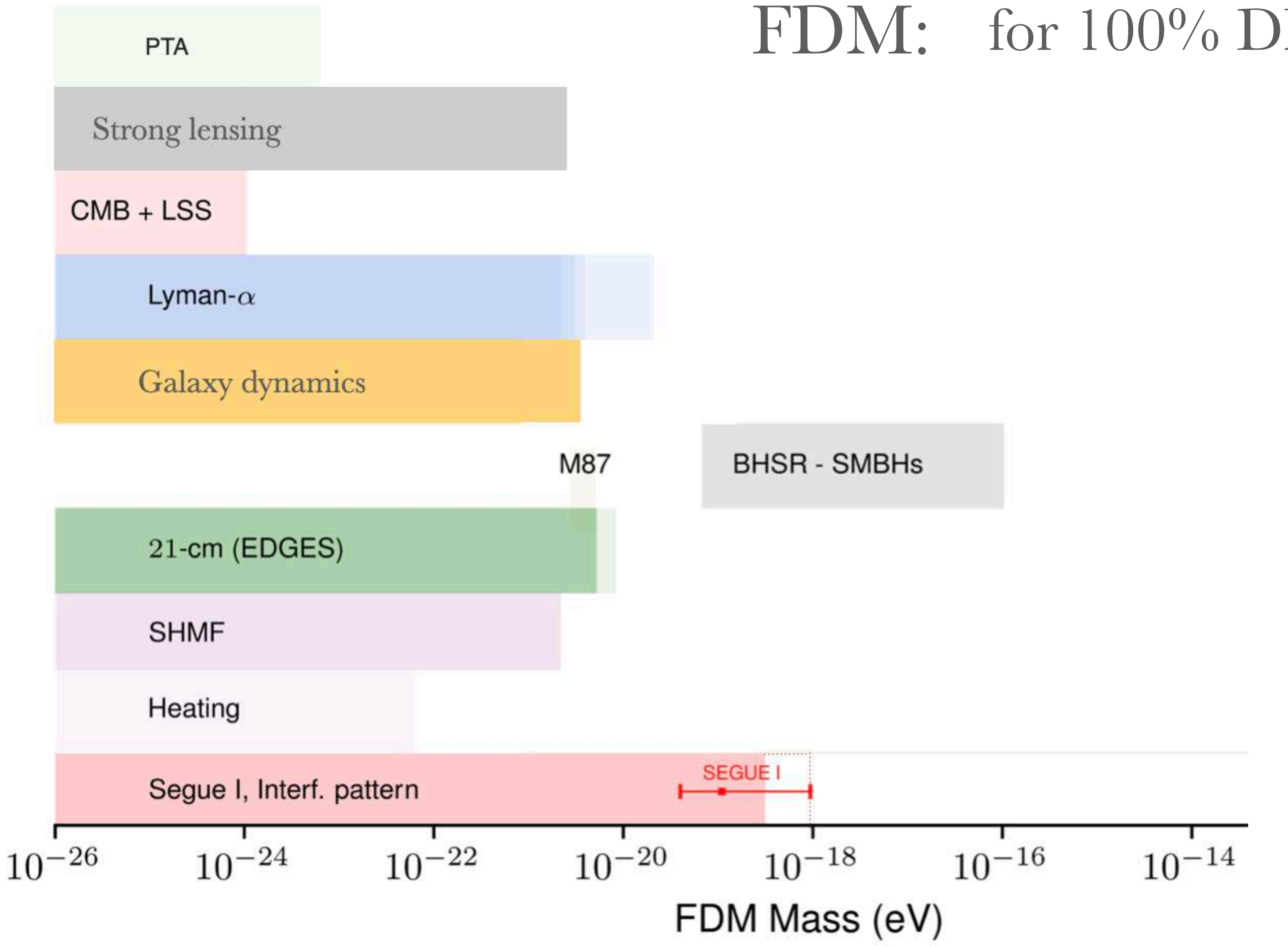
$$m_{\rm fdm} > 4.4 \times 10^{-21}\ \rm eV$$

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

Heating: $m_{FDM} > 3 \times 10^{-19}\,\rm eV$

Current status

FDM: for 100% DM!



Future

Observations

Improve in simulations
New probes/observables


Thank you!