KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Constraining ultra-light dark matter *with astrophysical and cosmological probes*

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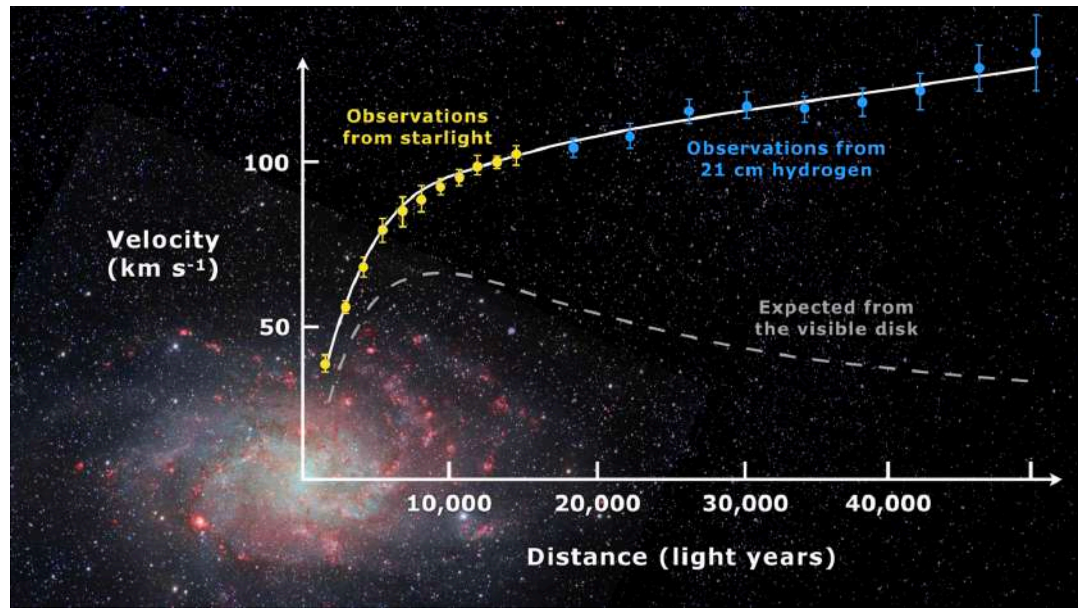
Kavli IPMU

UGAP 2024

05/March/2024

Evidences for dark matter

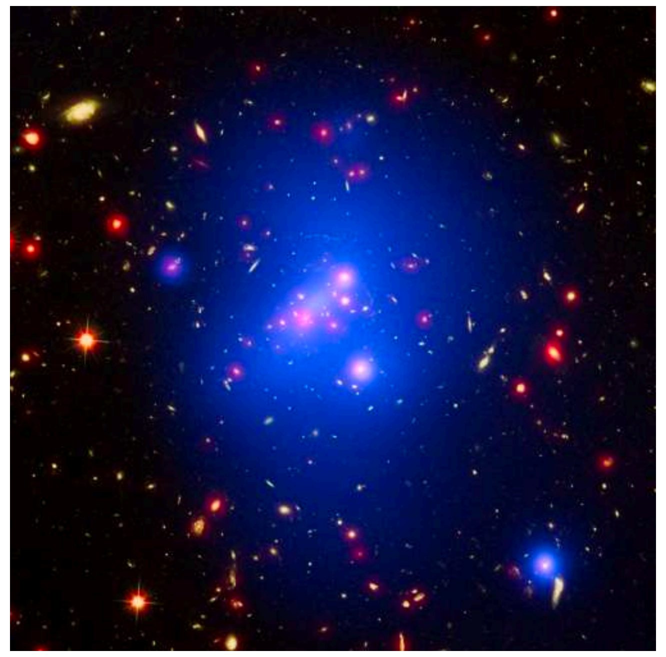
Galaxy rotation curves



Credit: Mario De Leo

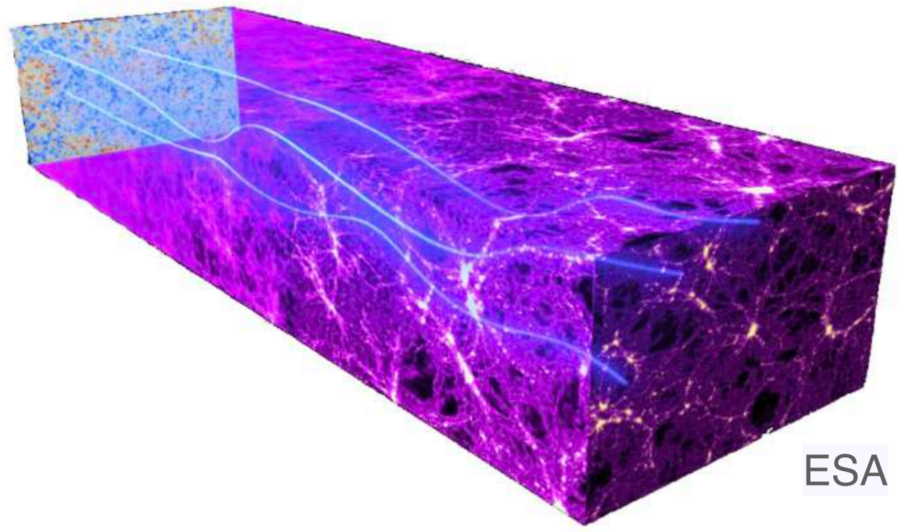
- Mass fraction
- Distribution

Clusters



- Mass fraction
- Distribution

Lensing



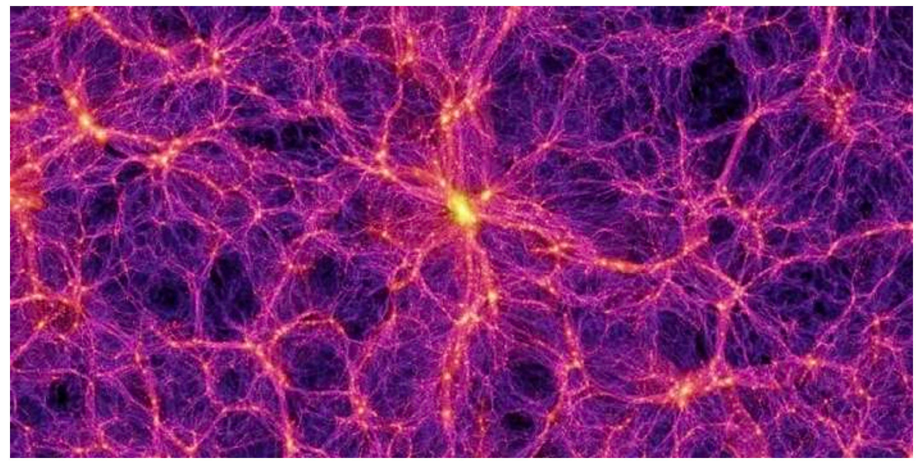
ESA

Strong lensing
- Mass fraction
- Distribution

Weak lensing
- Distribution
- Shape
- Structure

Micro lensing
- Mass fraction
- Smoothness

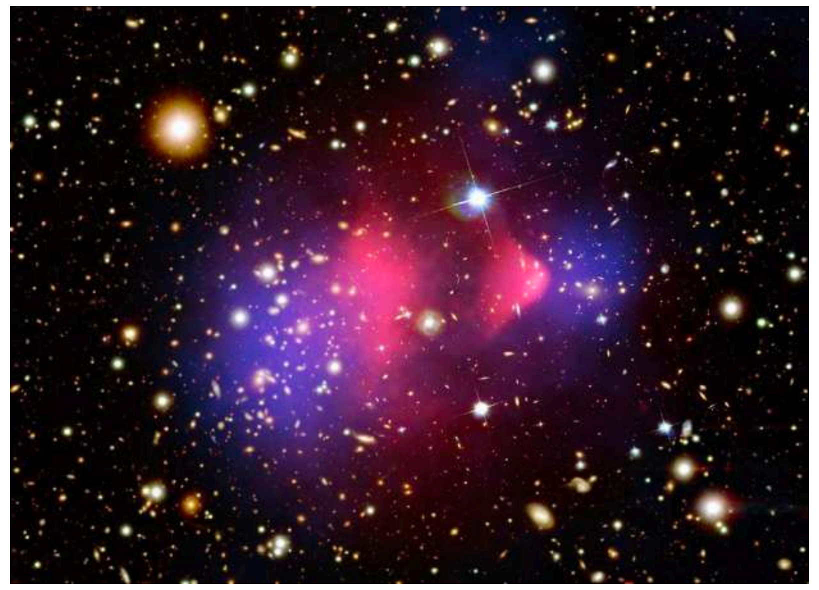
Large Scale Structure



Springel & others / Virgo Consortium

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

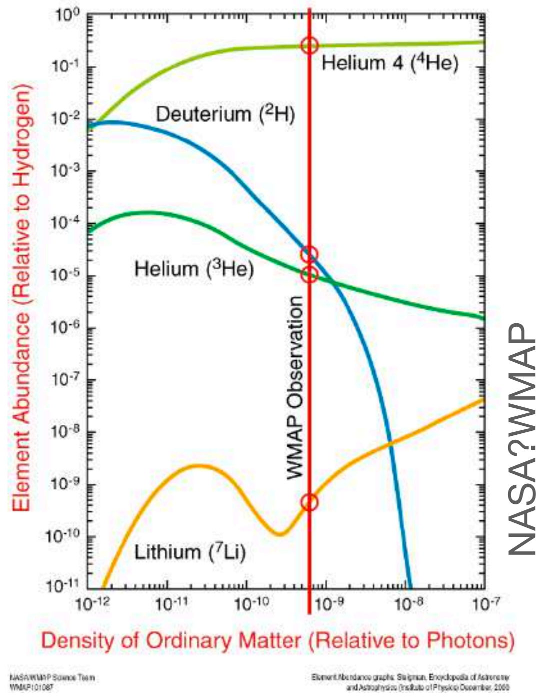
Cluster collision



NASA/CXC/CfA and NASA/STScI

- Distribution
- Separation from collisional matter
- Self-interaction

Big Bang Nucleosynthesis



NASA?WMAP

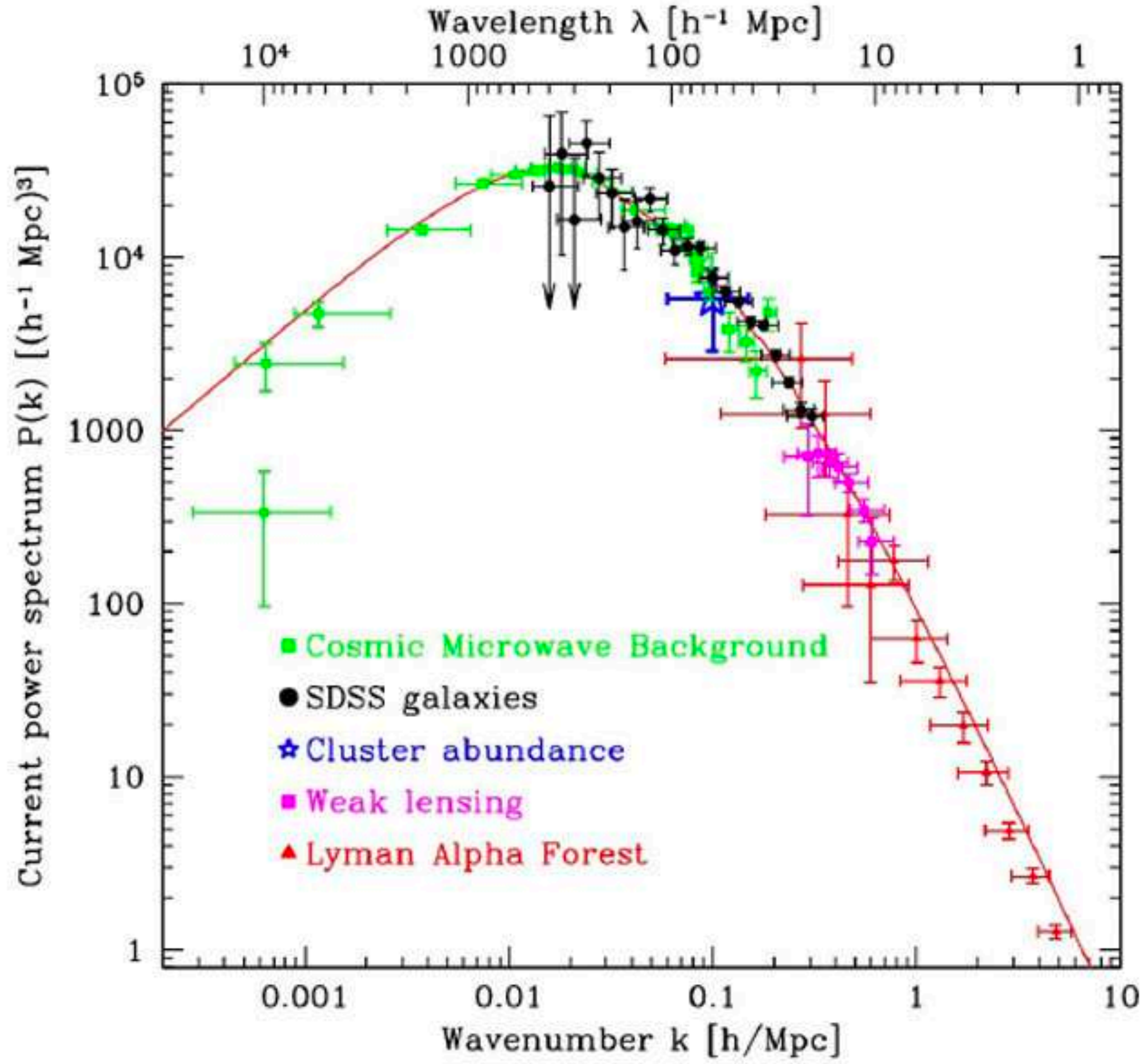
- Amount of baryons

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

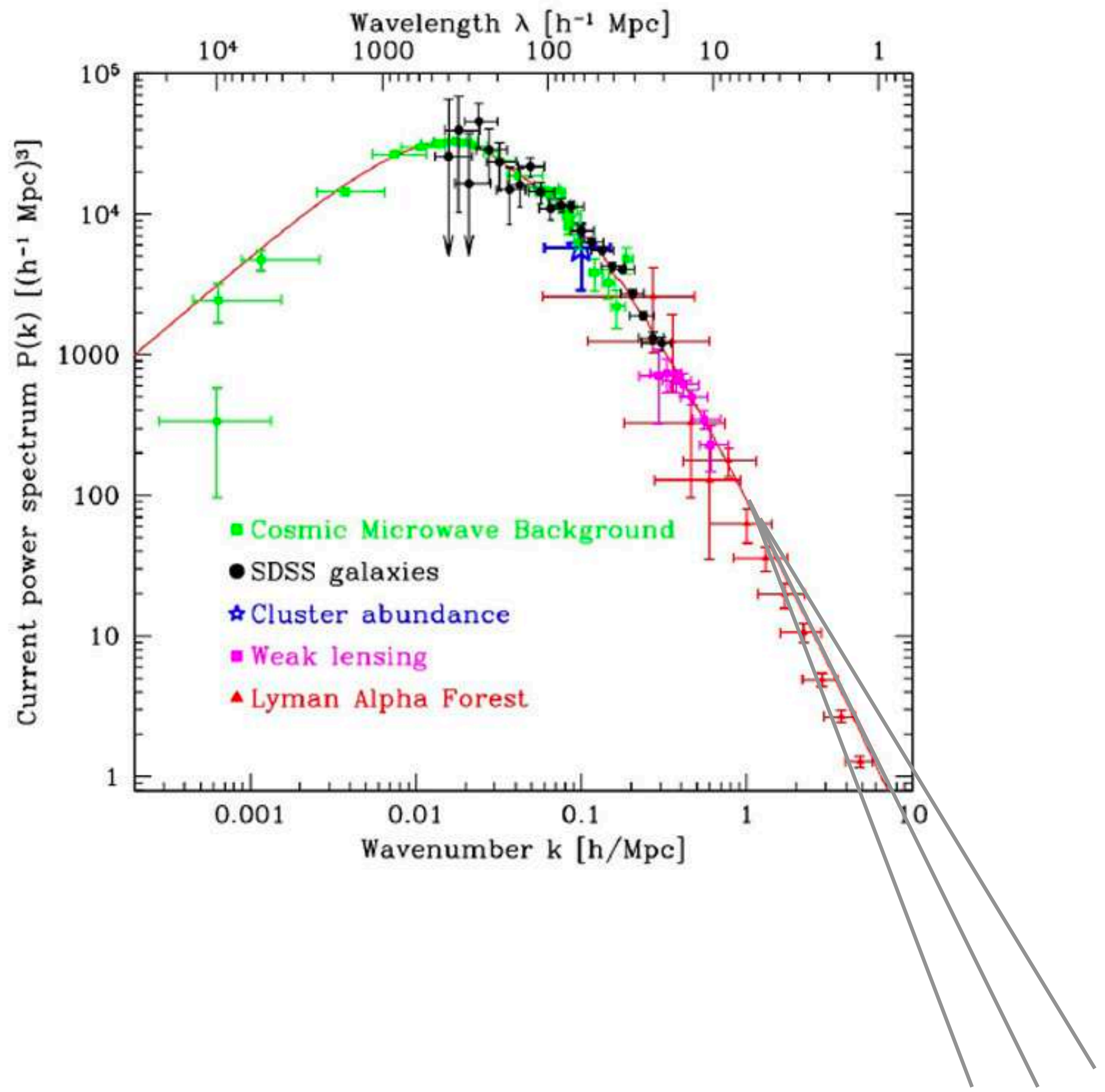


- Abundance: amount of dark matter today known

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

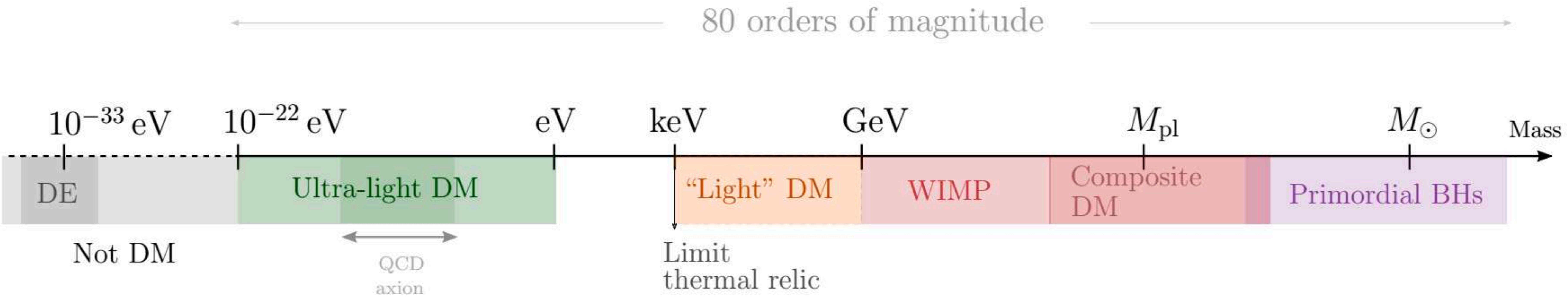
Small scale curiosities: cusp-core, missing satellites, BTFR, …

What is dark matter?

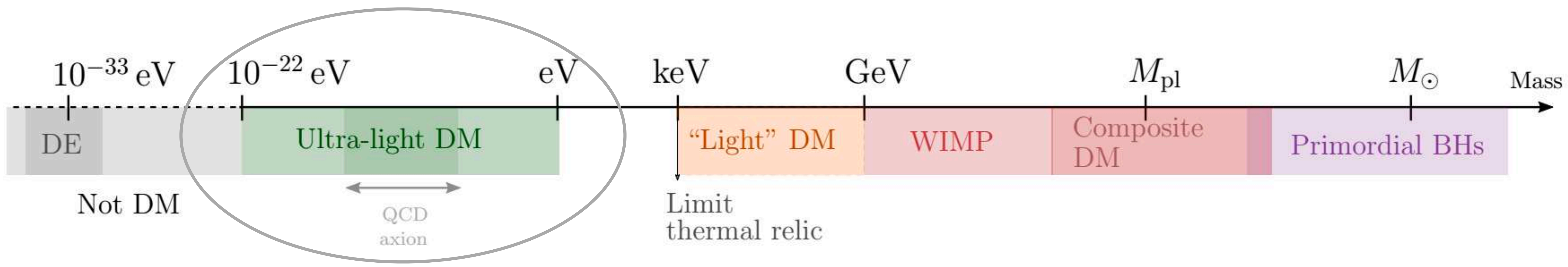
- What is the nature of DM?

State of the “art"

Mass scale of DM



Ultra-light dark matter



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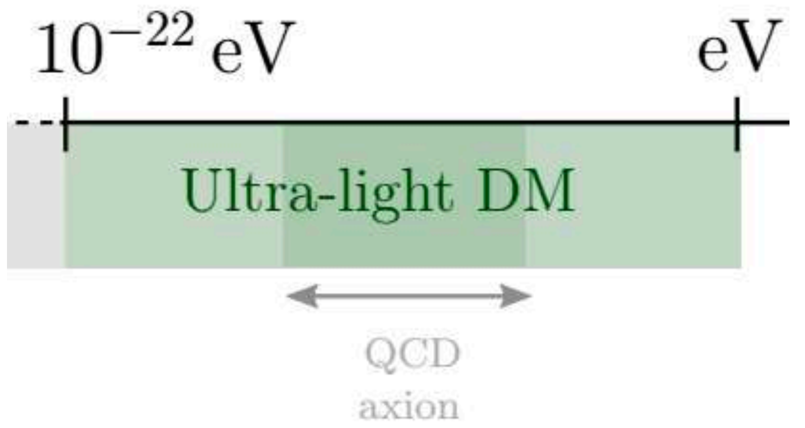
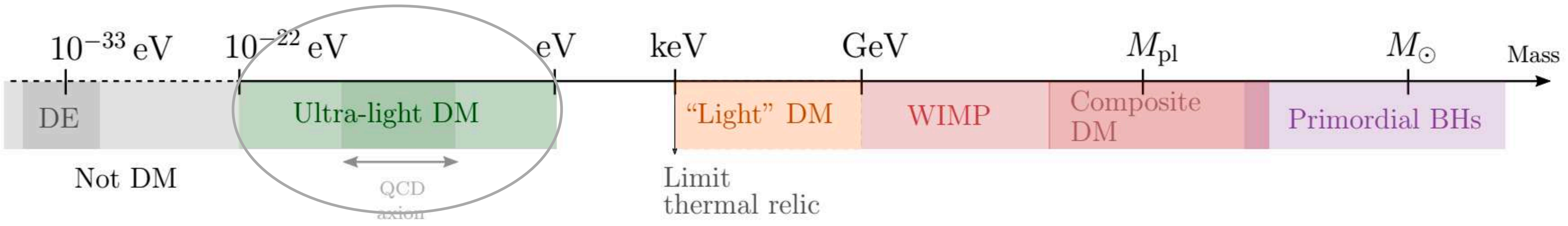
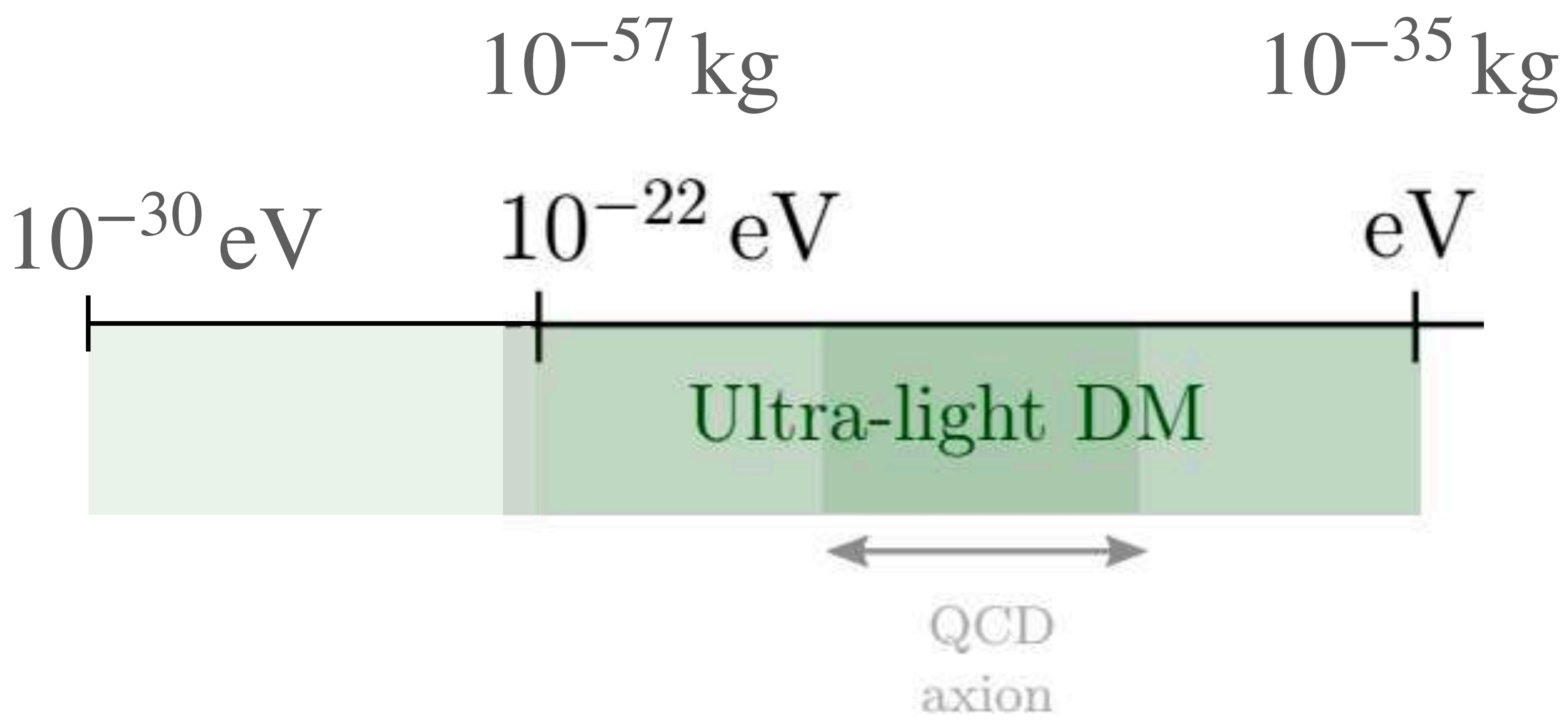


Ultra-light candidate, cold → Large $\lambda_{dB} \sim 1/mv$

Lightest possible candidate for DM





→ Bosons

Non-thermally produced

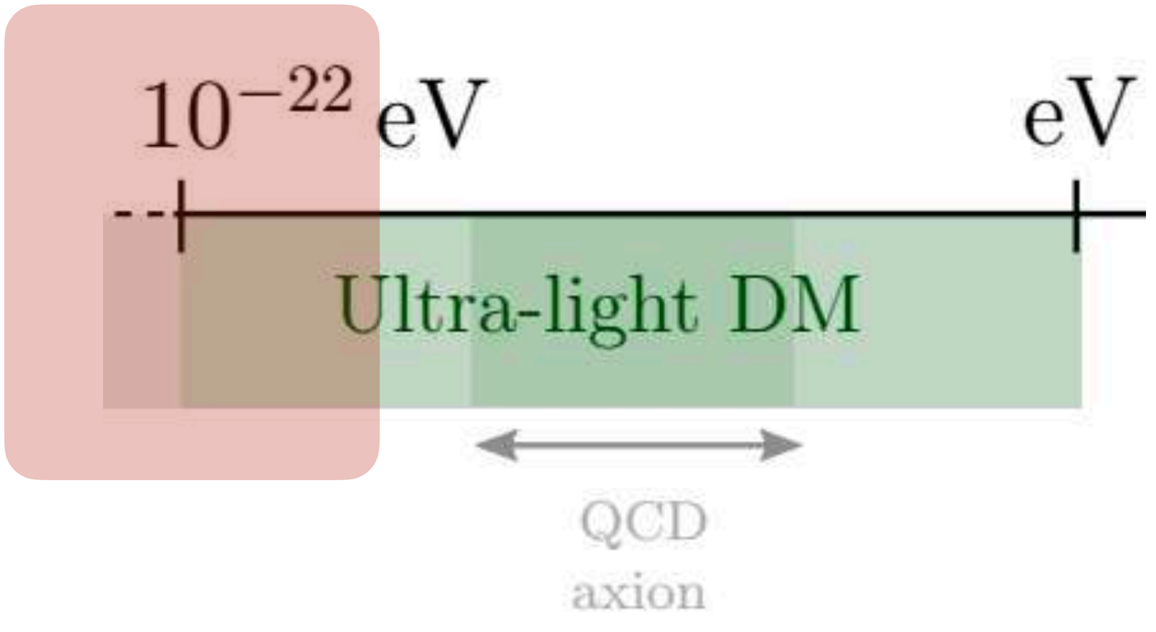
Motivation: particle physics

FDM candidates

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

Known PNGB: QCD axion → Candidate for DM

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



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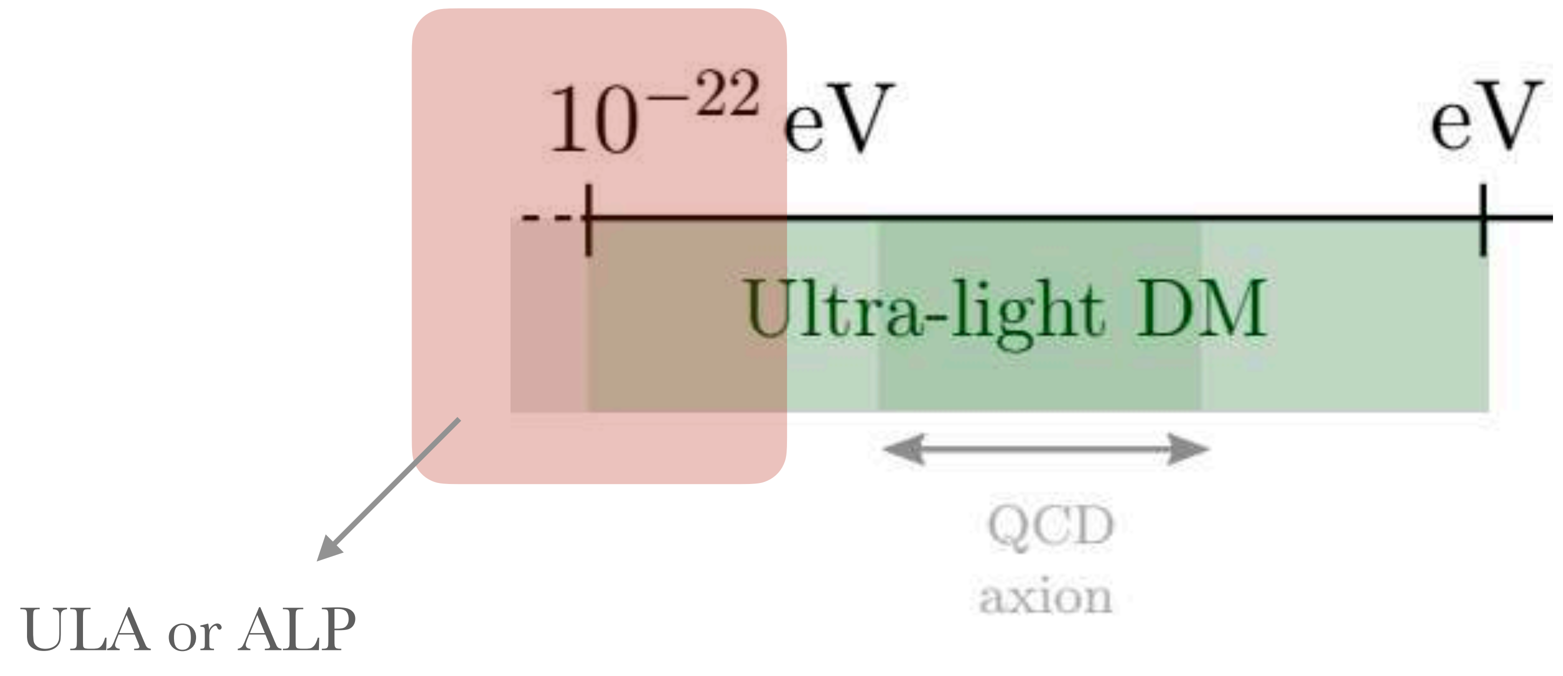

Known PNGB: QCD axion → Candidate for DM

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

Axion-like particles or ultra-light axions:

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

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

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

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

L. Hui

* Axion and ALP interact with photons (and neutrinos)

Motivation: particle physics

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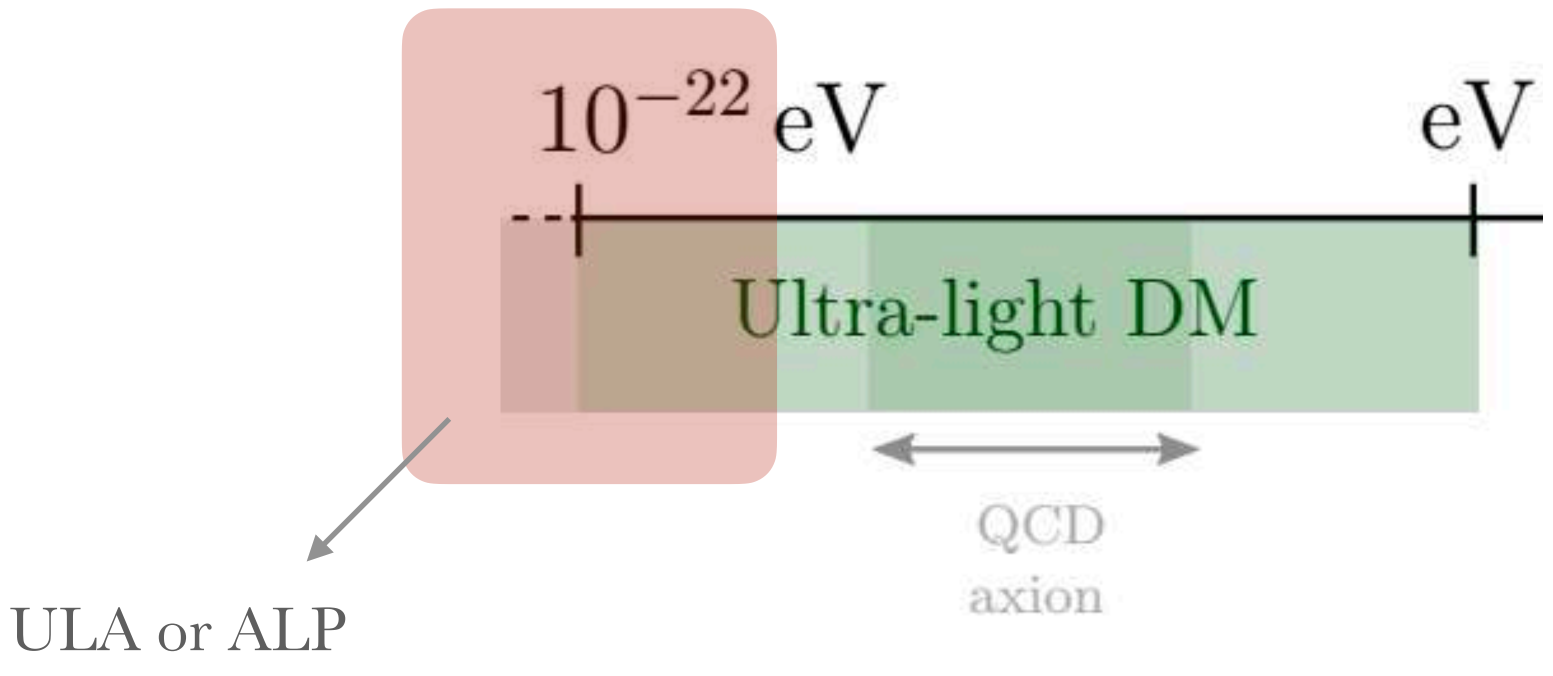

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- Can generate PNGB that are ultra-light

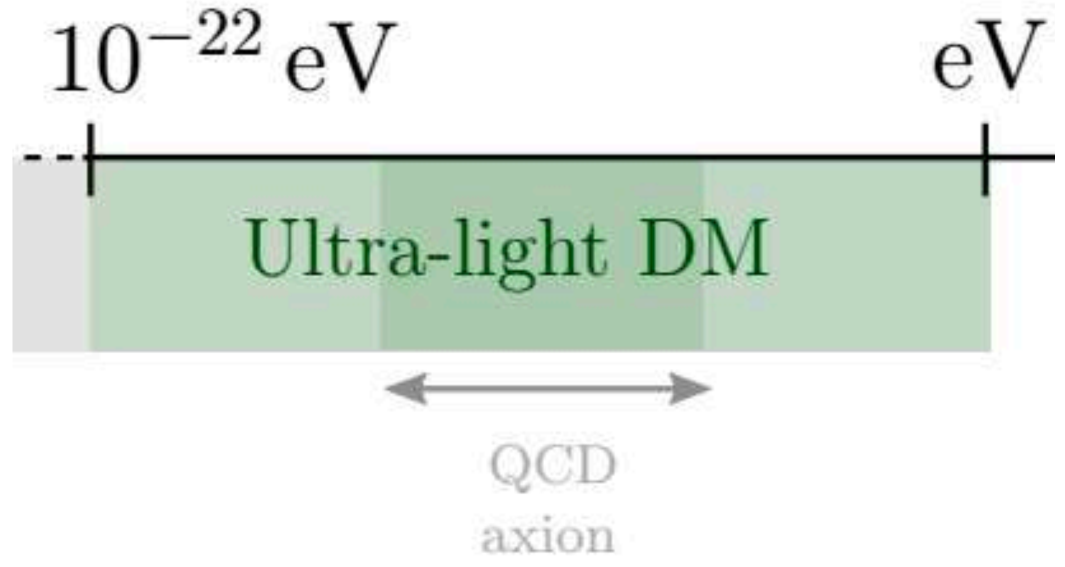
- Formation mechanism: needs to have a relic abundance that gives the correct DM abundance

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

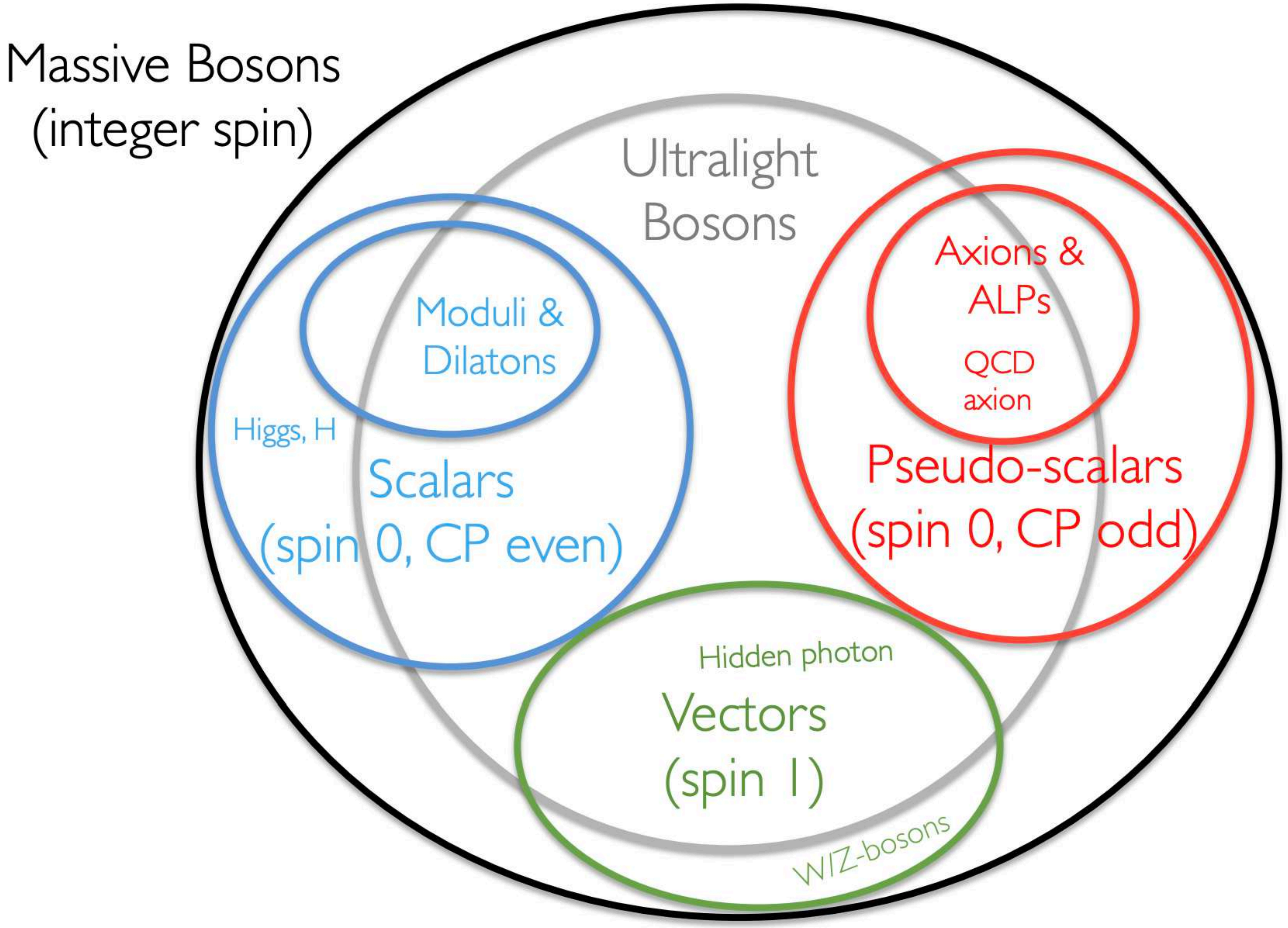
Vector FDM: challenging in the ultra-light regime
(e.g. from misalignment requires non-minimal couplings to Ricci scalar -> viol. of unitarity long. graviton-photon scattering; oscillating Higgs or oscillating misaligned axion - resonant production - choices for couplings for right abundance)
Spin 2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

Motivation: particle physics

ULDM candidates



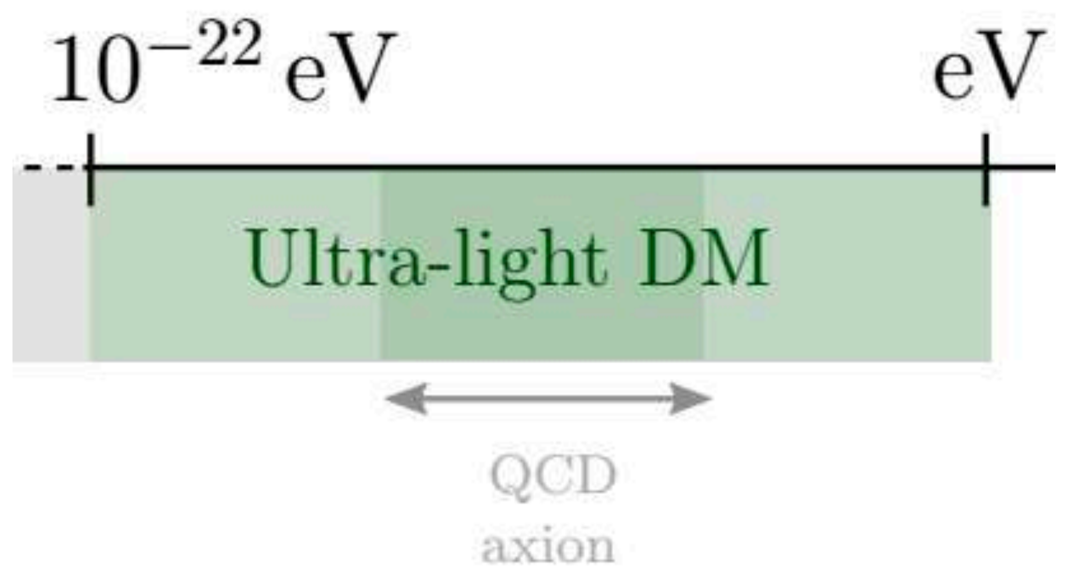
Many extensions of the Standard Model predict additional massive bosons



Ref.: Chadha-Day et al 2022

Motivation: particle physics

ULDM candidates



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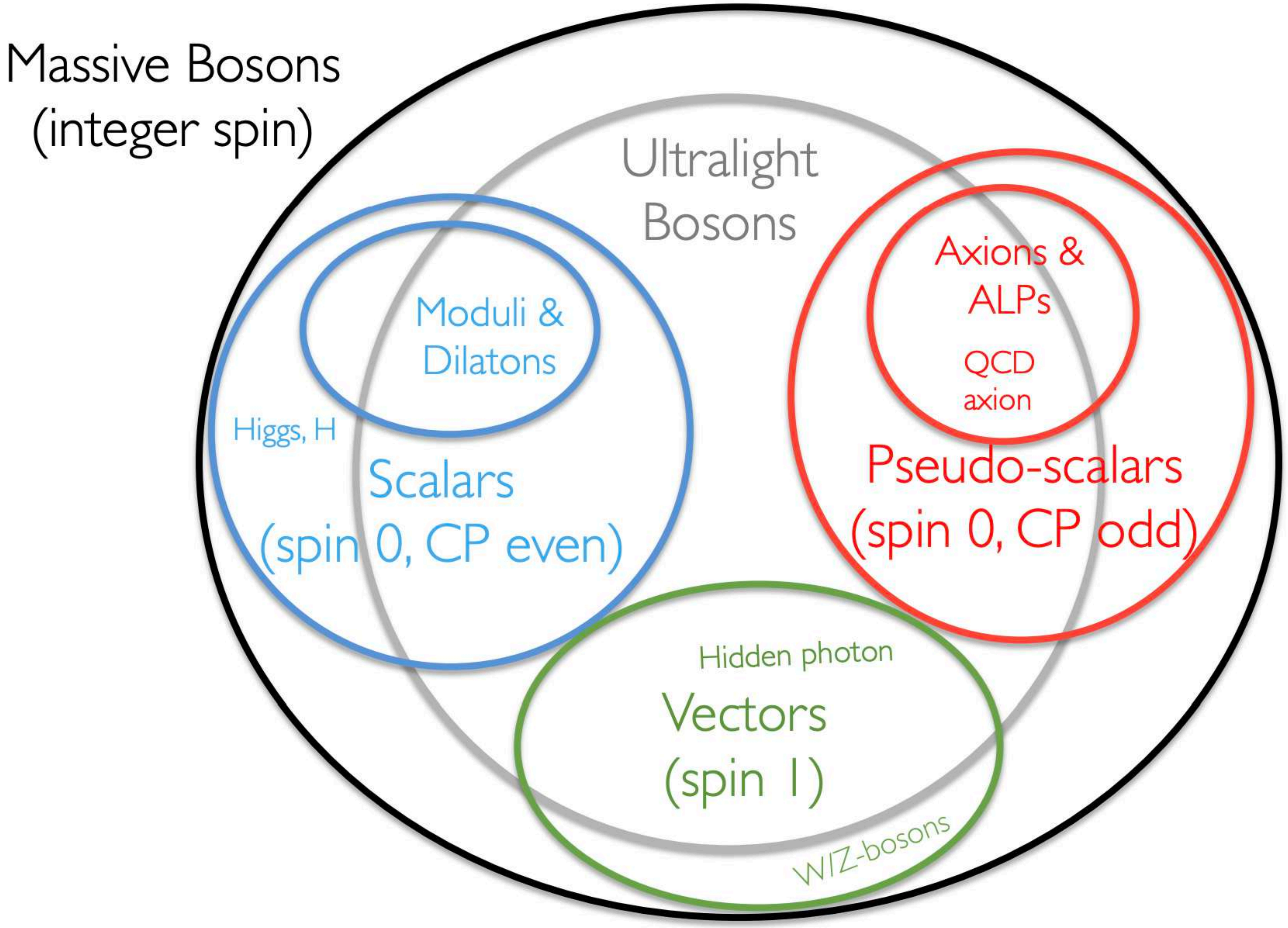
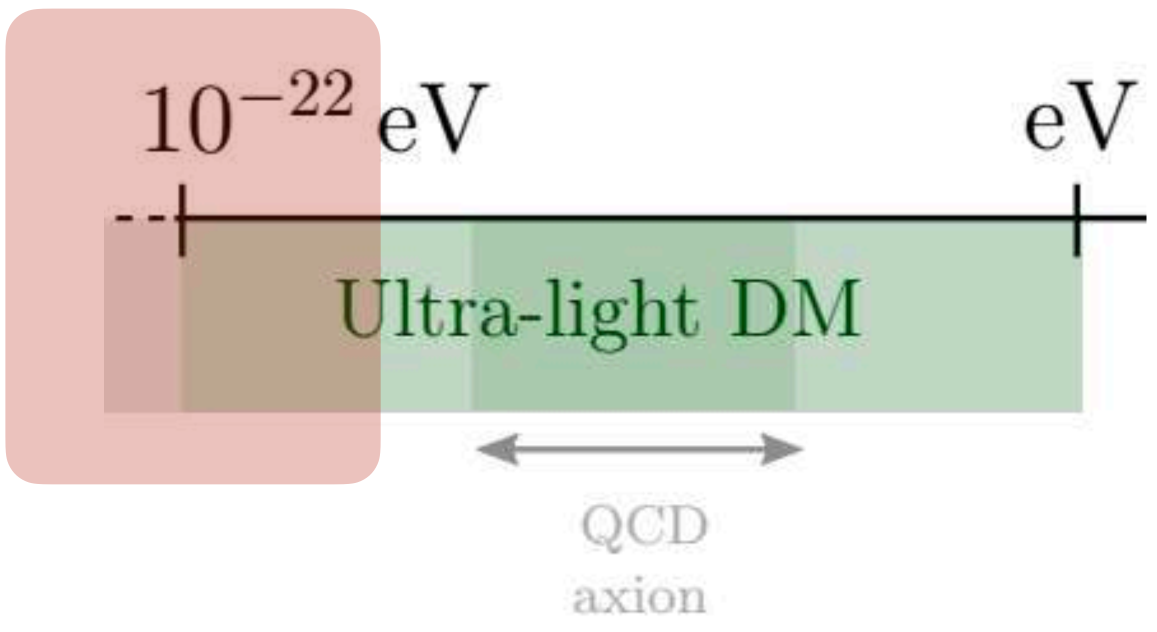


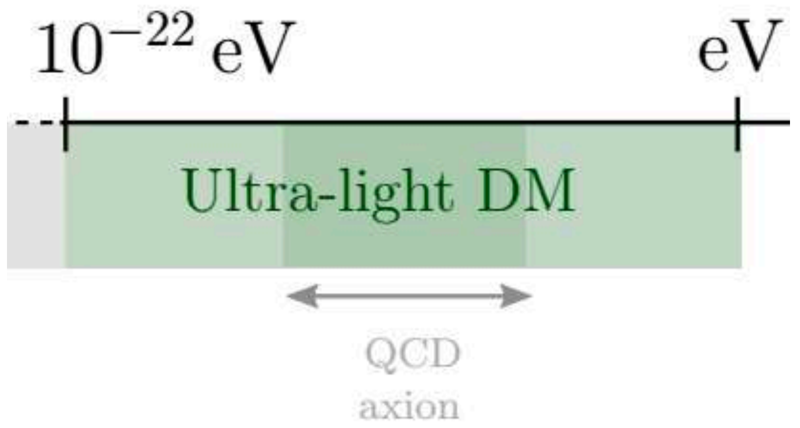
Today:
Gravitational signatures!

Ref.: Chadha-Day et al 2022

Cosmological signatures



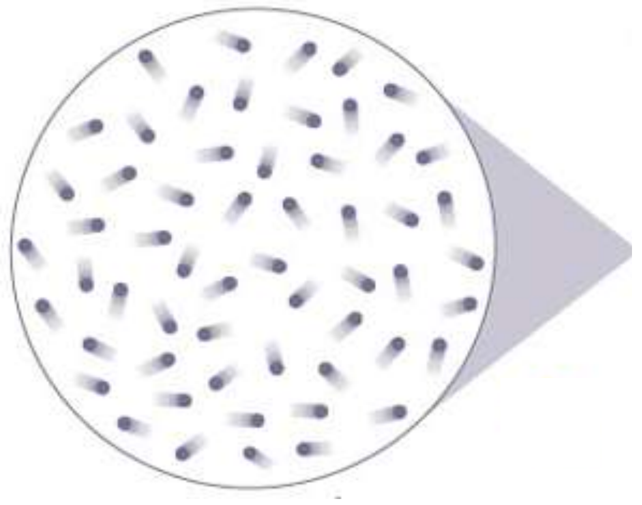
Ultra-light Dark Matter



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

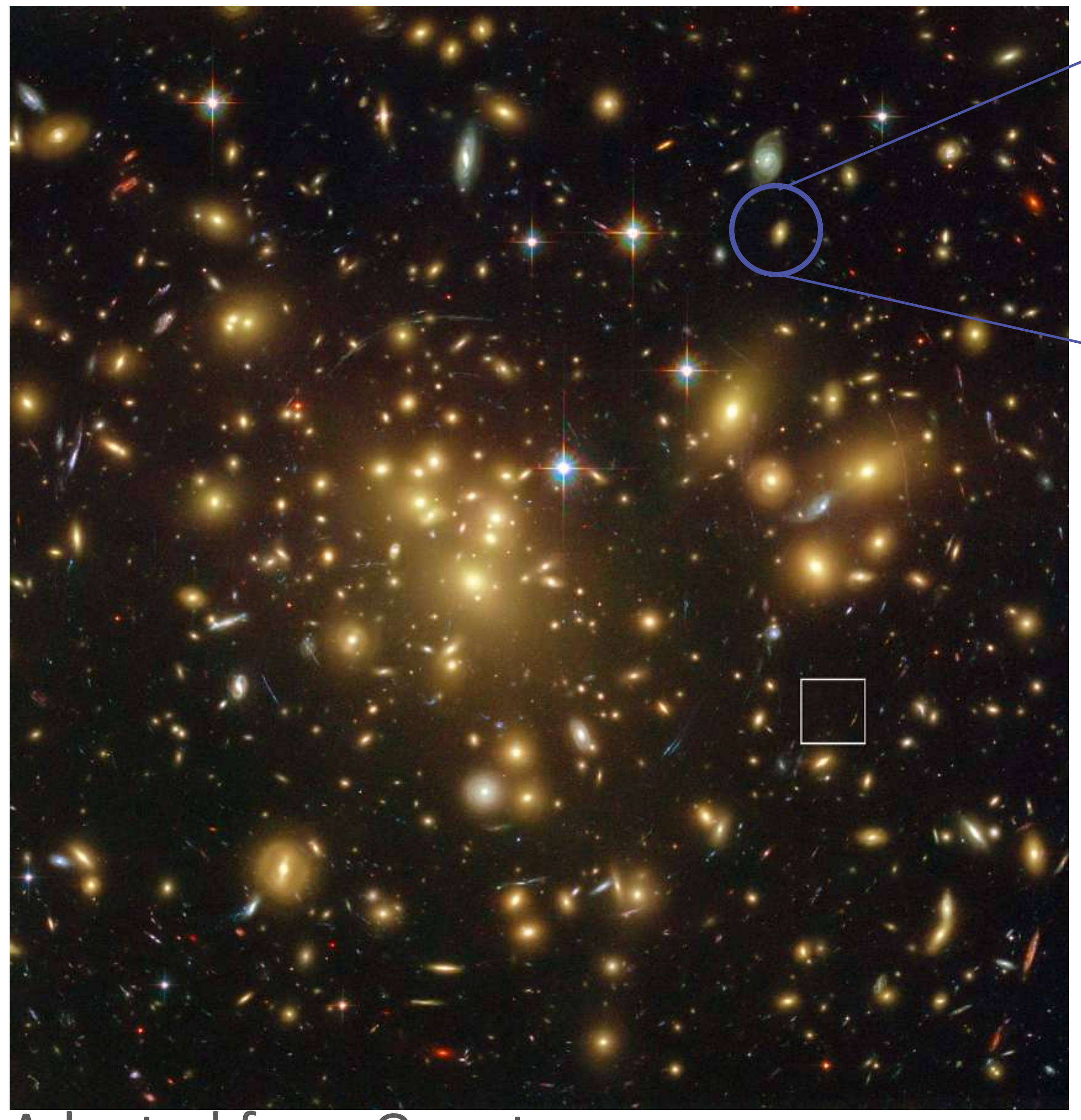
Lightest possible candidate for DM

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



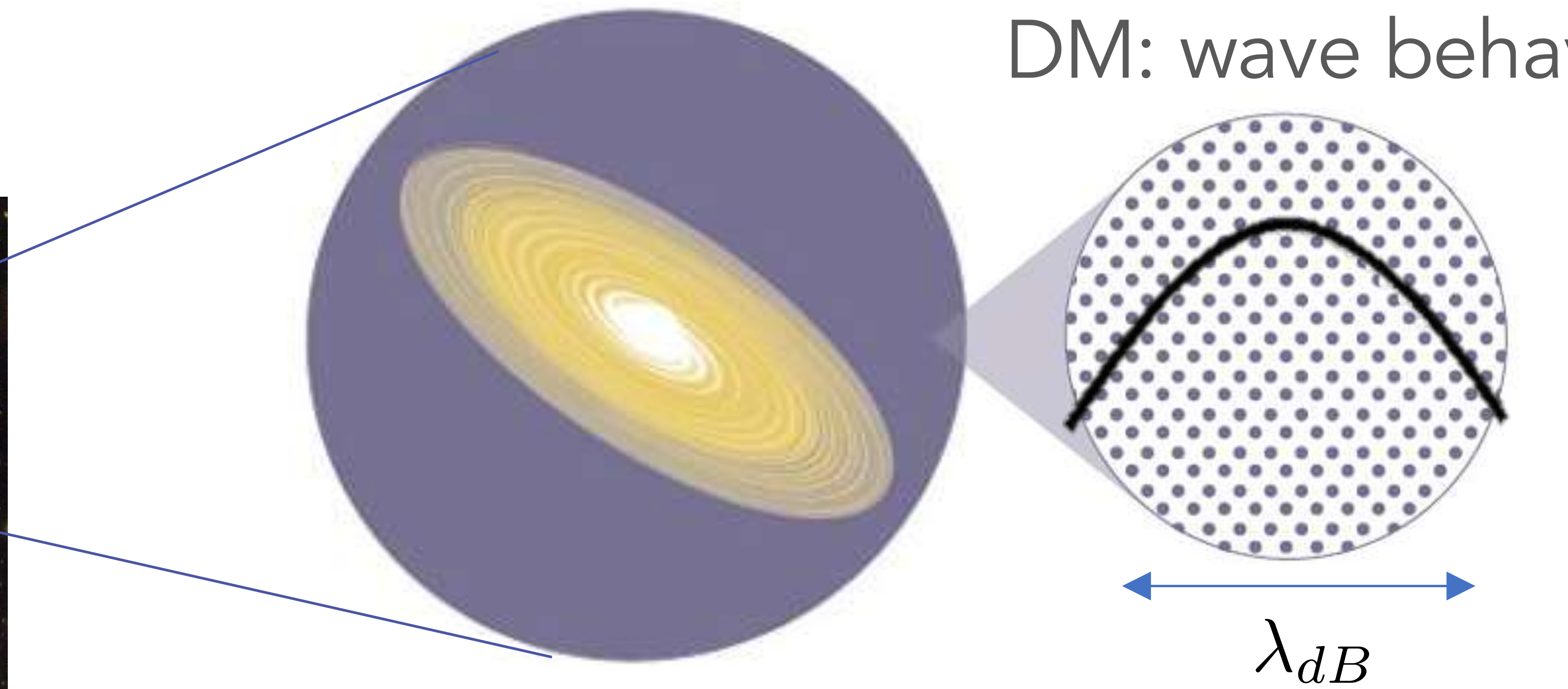
DM: particles

$d \gg \lambda_{dB}$



Adapted from Quanta

DM: wave behaviour



Galaxy halo

λ_{dB}

$d \ll \lambda_{dB}$

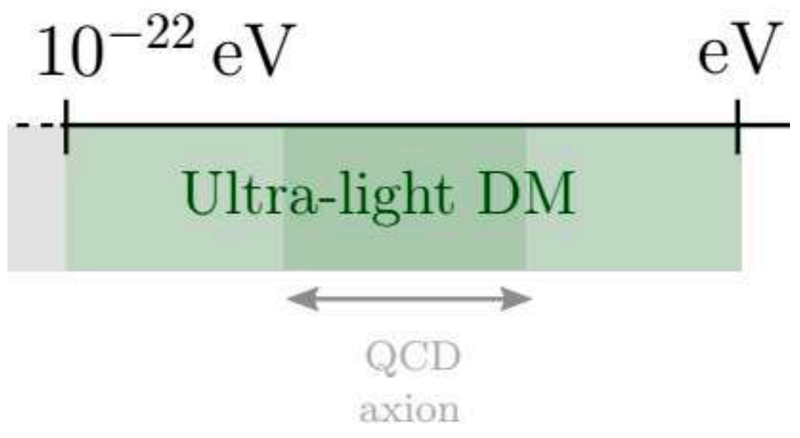
Small scales:
DM behaves like a wave

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

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

$\lambda_{dB}^{ULDM} \sim$ pc – kpc

Ultra-light Dark Matter -classes



3 classes:

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

Axion and ALP (axion like particles)

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

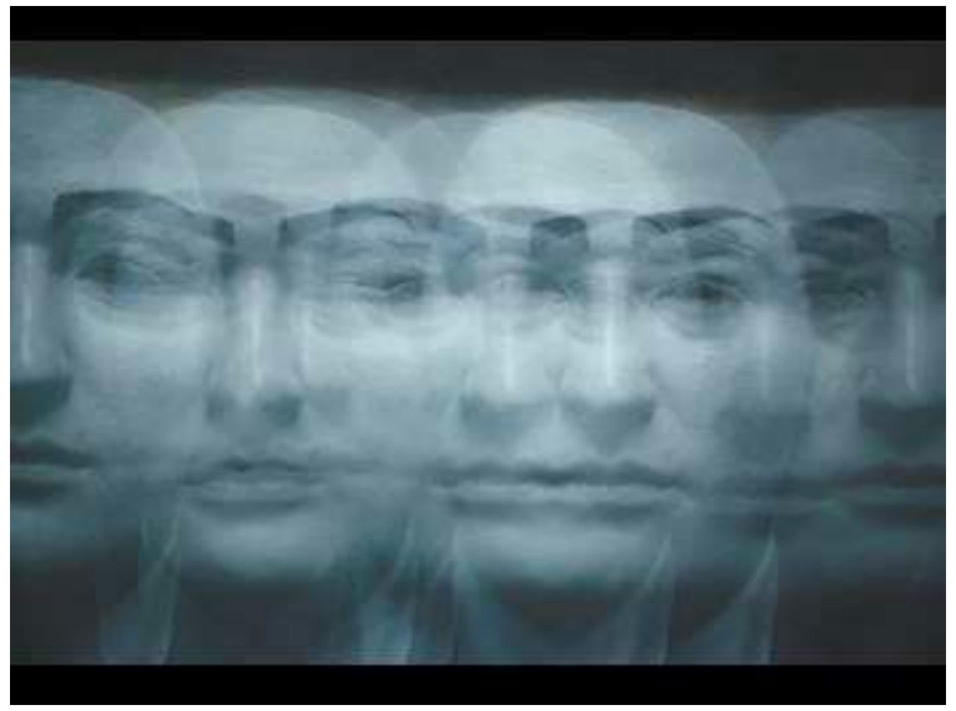
$$\mathcal{L} = P(X)$$

⟶ Connection with condensed matter and particle physics!

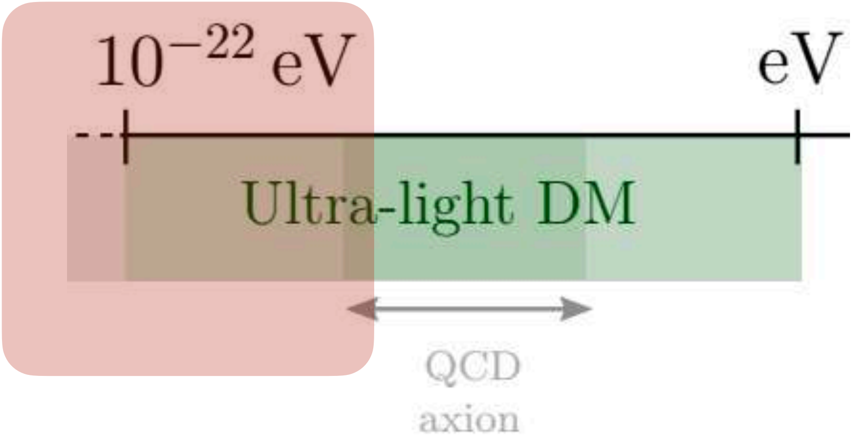
"Ultra-light dark matter", **E.Ferreira**, 2020. The Astronomy and Astrophysics Review.

Fuzzy dark matter

Self interacting fuzzy dark matter



Fuzzy Dark Matter



Fuzzy DM (FDM)

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

m

Wave DM
Ultra-light axions

Self Interacting FDM (SIFDM)

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

m g

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

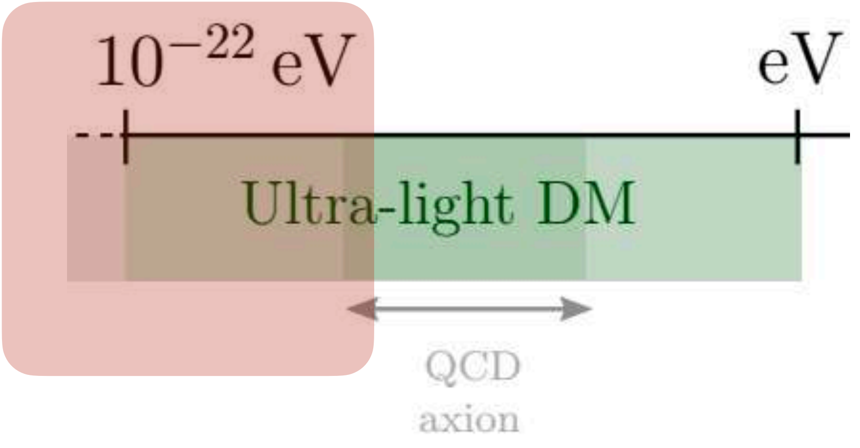
(Reviews: EF (2021), J. Niemeyer (2019), L. Hui (2021))

Idea:

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

address the small scale problems+ rich phenom.

Fuzzy Dark Matter



Fuzzy DM
(FDM)

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

m

Wave DM
Ultra-light axions

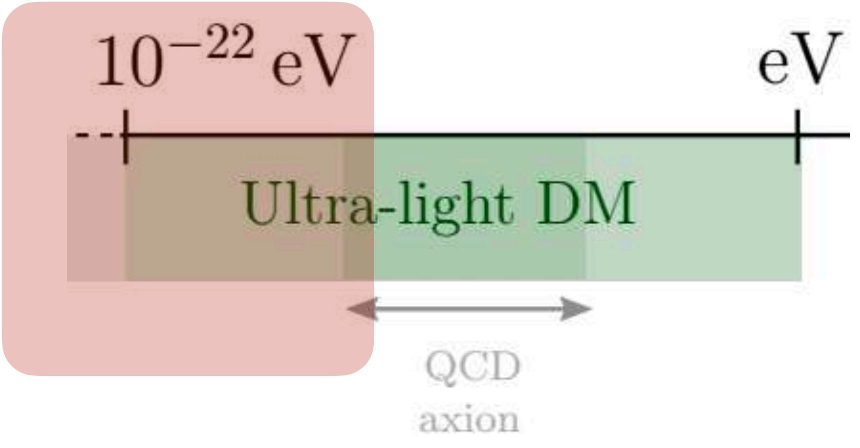
Focus *more* on spin 0 particles here!

$$10^{-22}\,\mathrm{eV} < m < 10^{-18}\,\mathrm{eV}$$

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

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

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

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

Schrödinger equation (Gross-Pitaevskii)

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

Poisson equation

$g = 0$ → 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

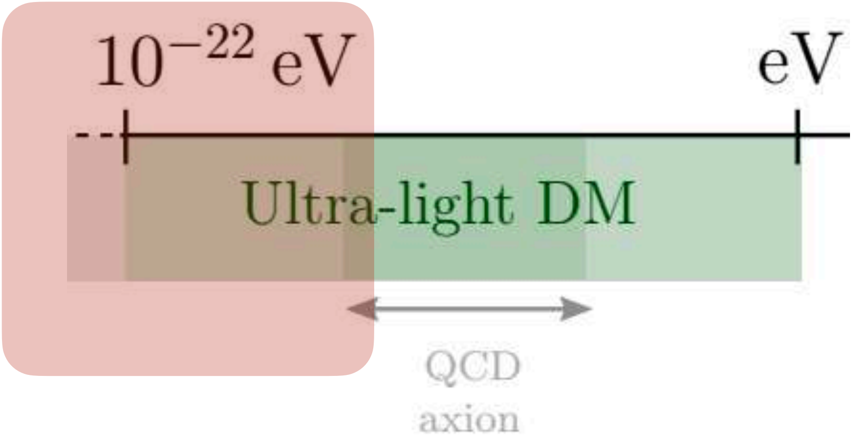
Cosmological evolution

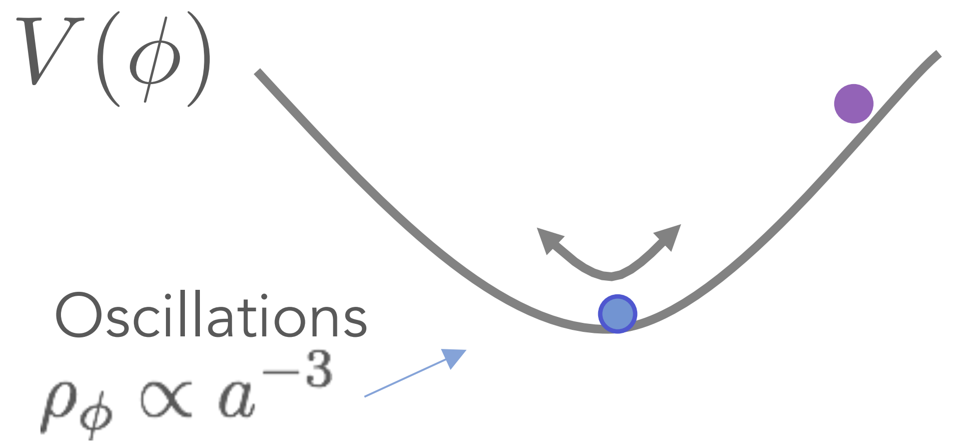
Boson/ Scalar field in a cosmological (FRW) background

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

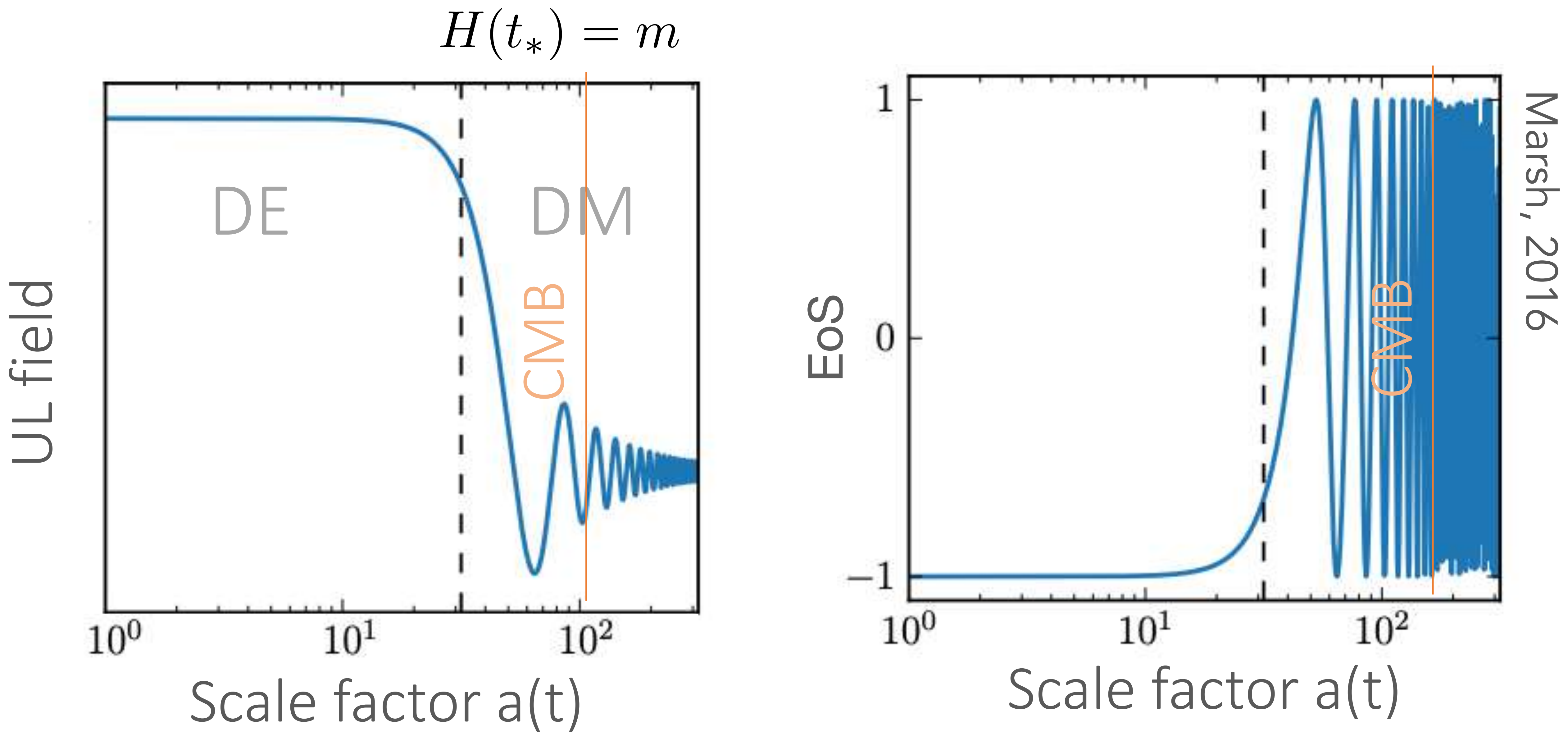
$$\begin{cases} H \gg m \implies \phi_{\rm early} = \phi(t_i) \longrightarrow \omega = -1 & \text{DE} \\ H \ll m \implies \phi_{\rm late} \propto e^{imt} \longrightarrow \langle\omega\rangle = 0 & \text{DM} \end{cases}$$

FDM

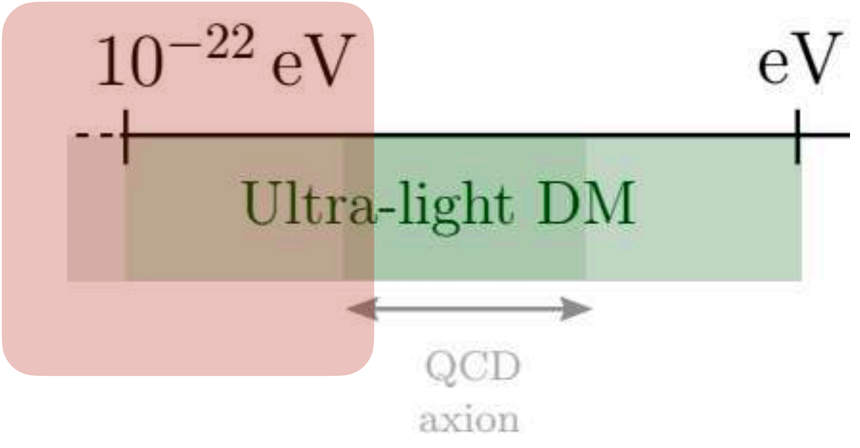




$m > 10^{-28}\,{\rm eV} \sim H(a_{\rm eq})$



Structure formation - non-relativistic regime



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

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

Schrödinger equation (Gross-Pitaevskii)

Poisson equation

$g = 0$ → FDM

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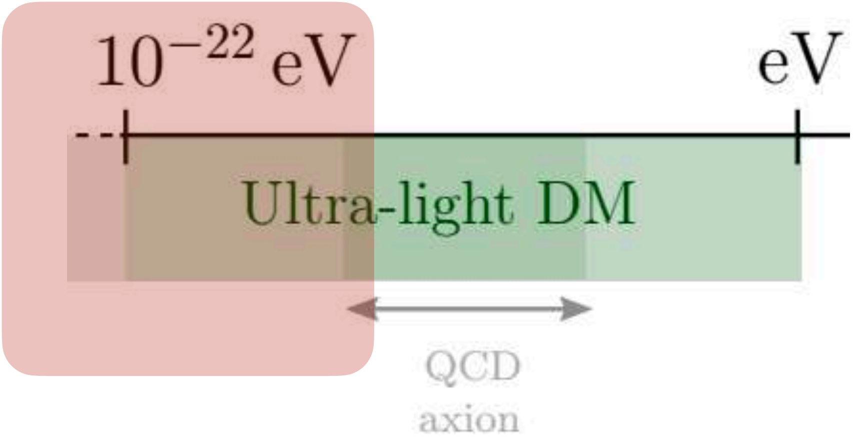
Fundamentally different than CDM/WDM/SIDM!

Structure formation - non-relativistic regime



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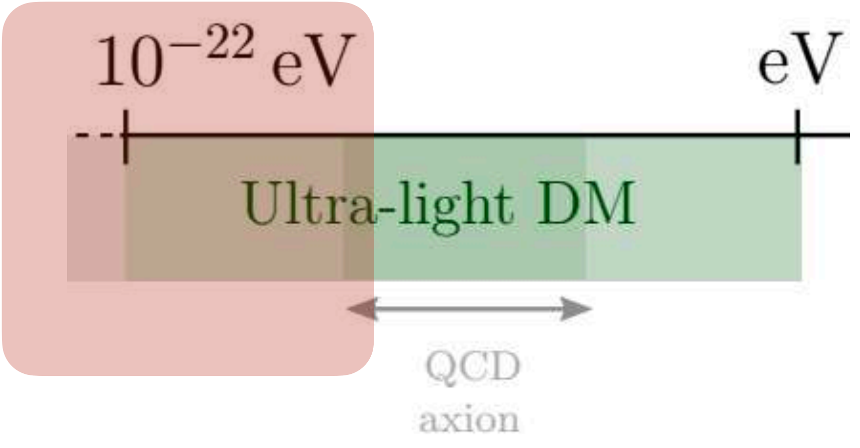
Quantum pressure

FLUID DESCRIPTION

Structure formation - perturbation and stability



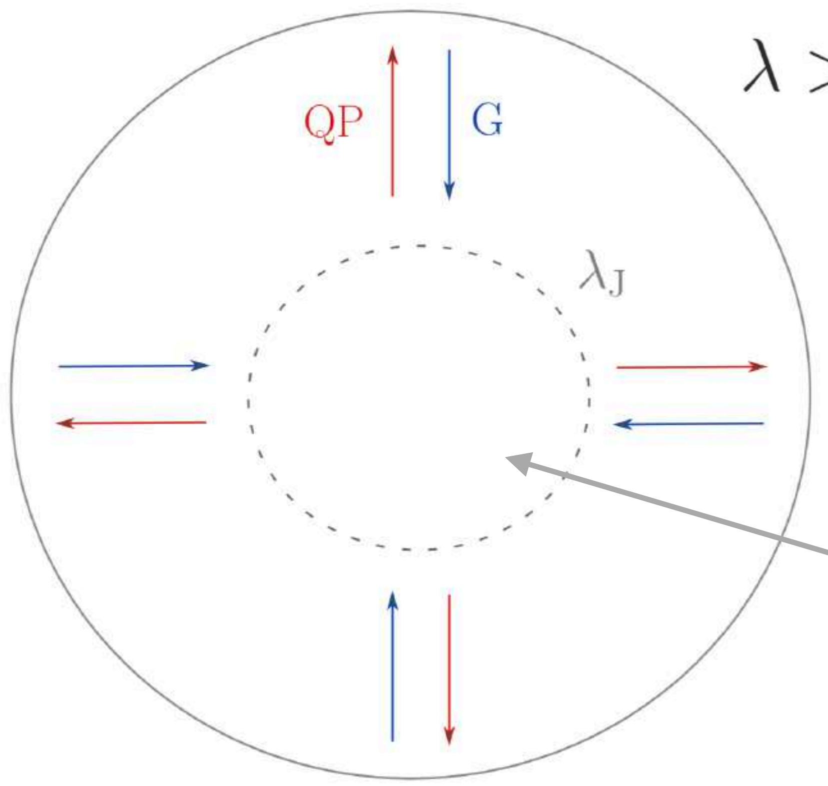
Finite clustering scale - no structure formation on small scales

SIFDM

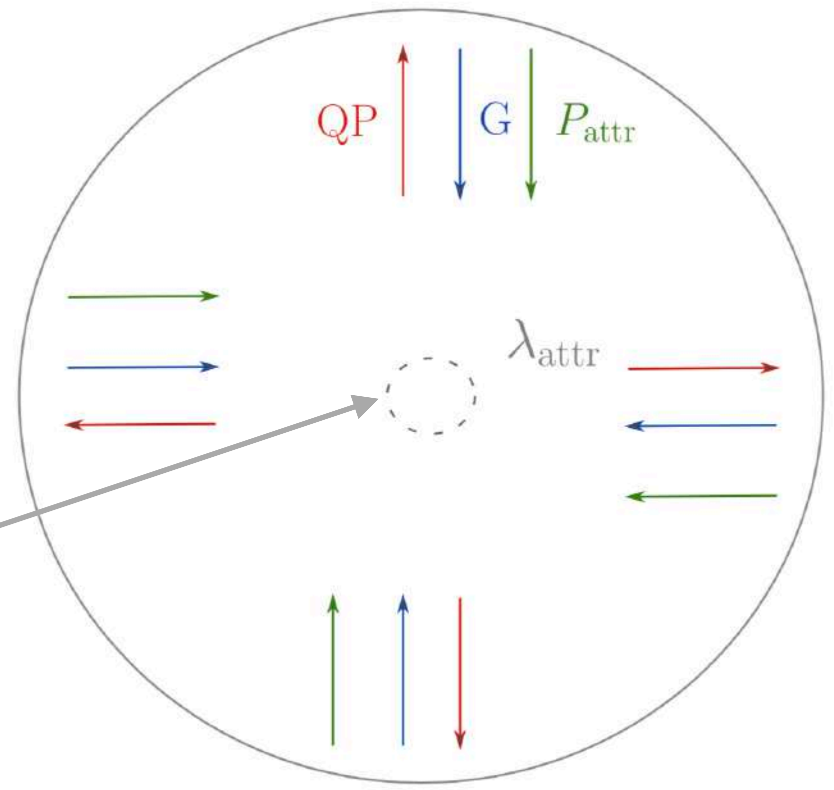
FDM

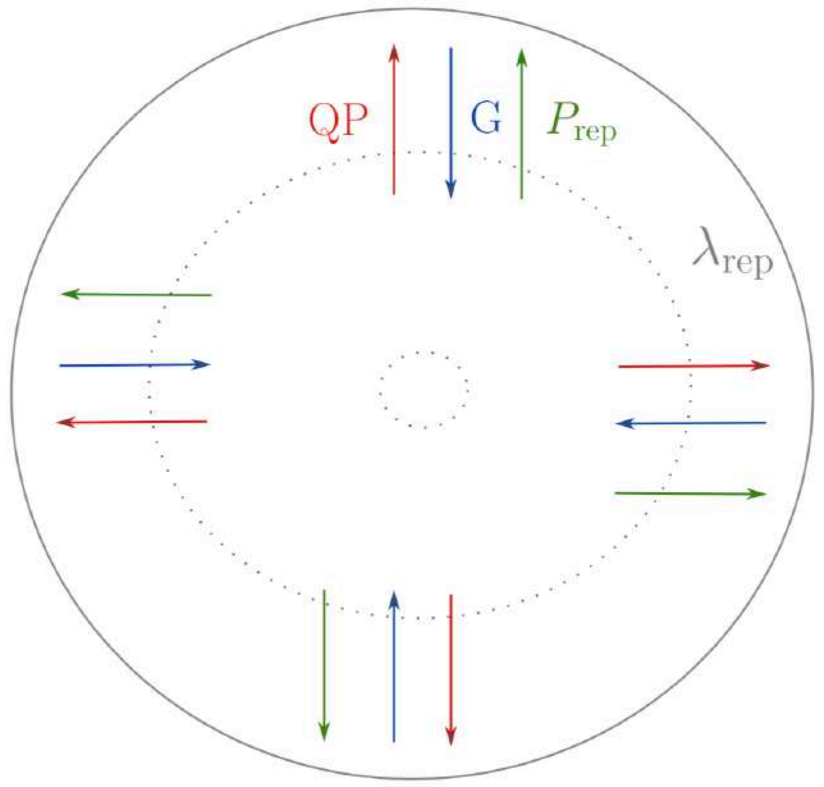
ATTRACTIVE

REPULSIVE



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





QP wins -
NO structure formation

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

$g < 0$

$g > 0$

Finite size coherent core – Bose stars

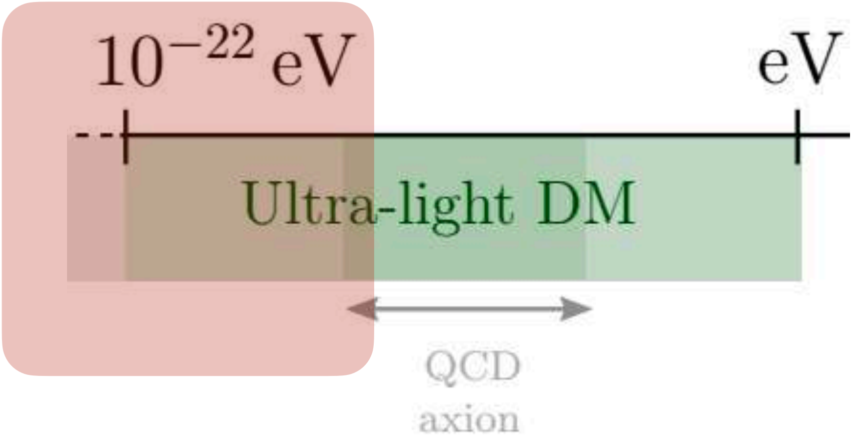
$$\lambda_J = 55 \left(\frac{m}{10^{-22}\,\text{eV}}\right)^{-1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{-1/4} (\Omega_m h)^{-1/4}\,\text{kpc}$$

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

For attractive interactions can only form localized clumps (solitons)

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

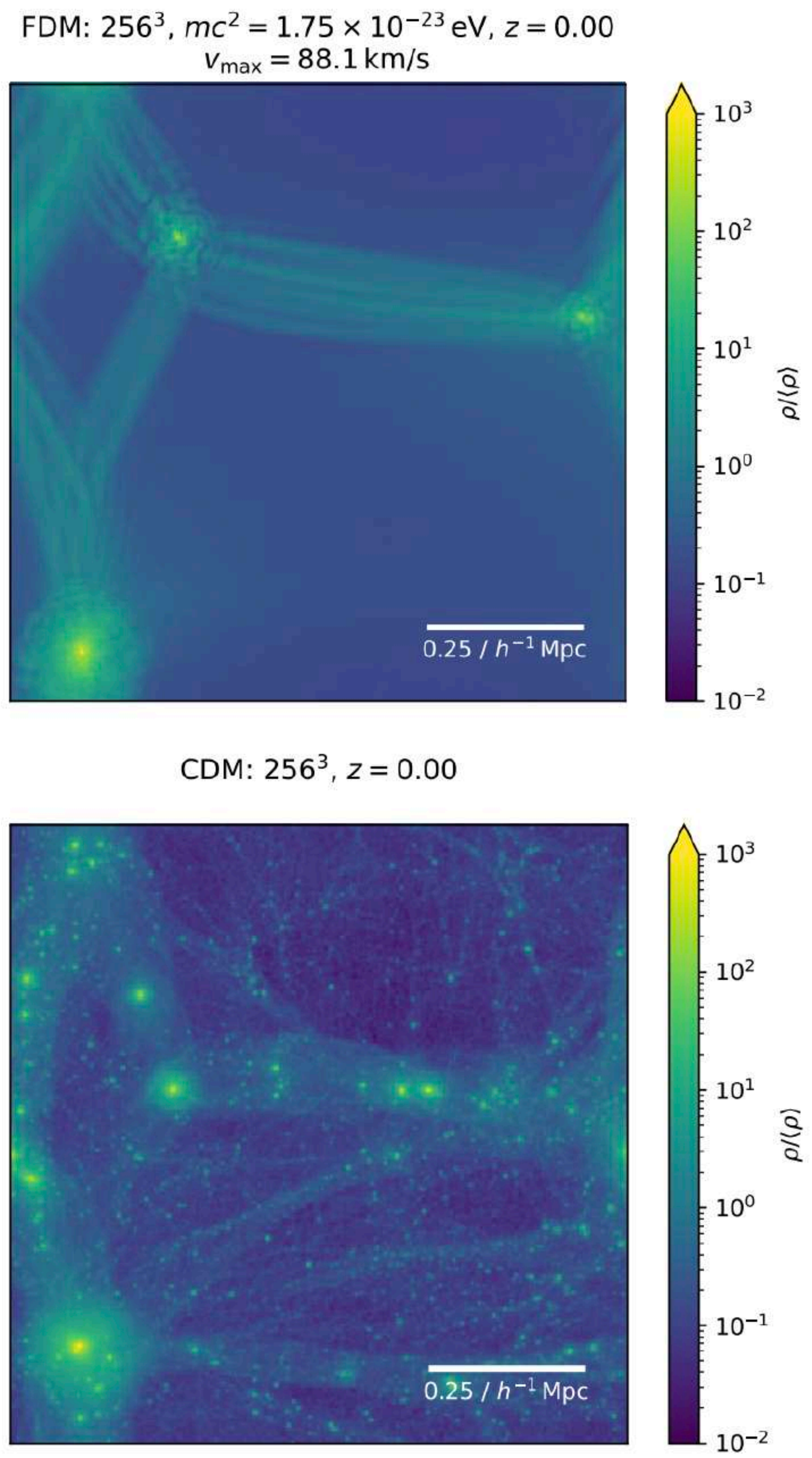
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

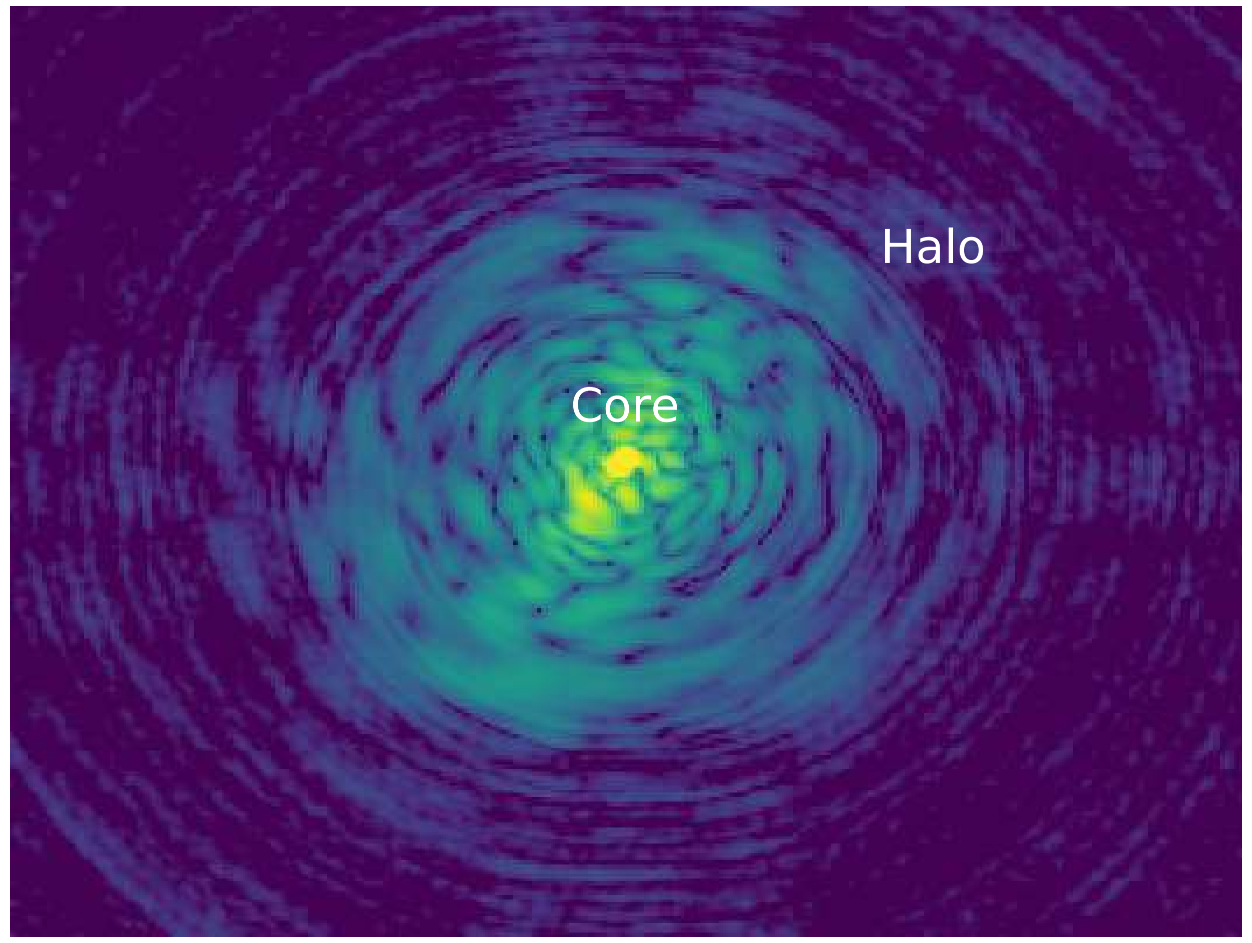
* Focus only in gravitational signatures

Suppression of small structures

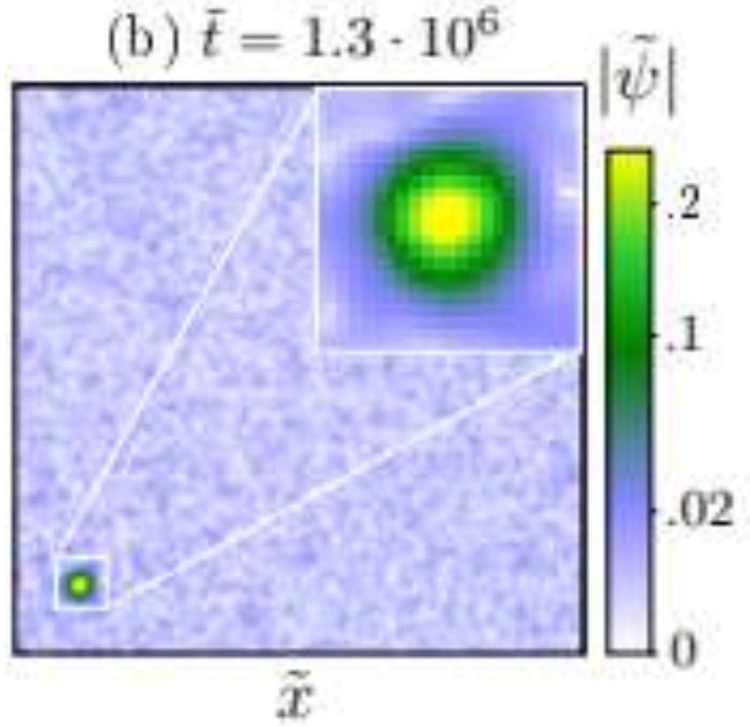


S. May et al. 2021

Formation of a solitonic core

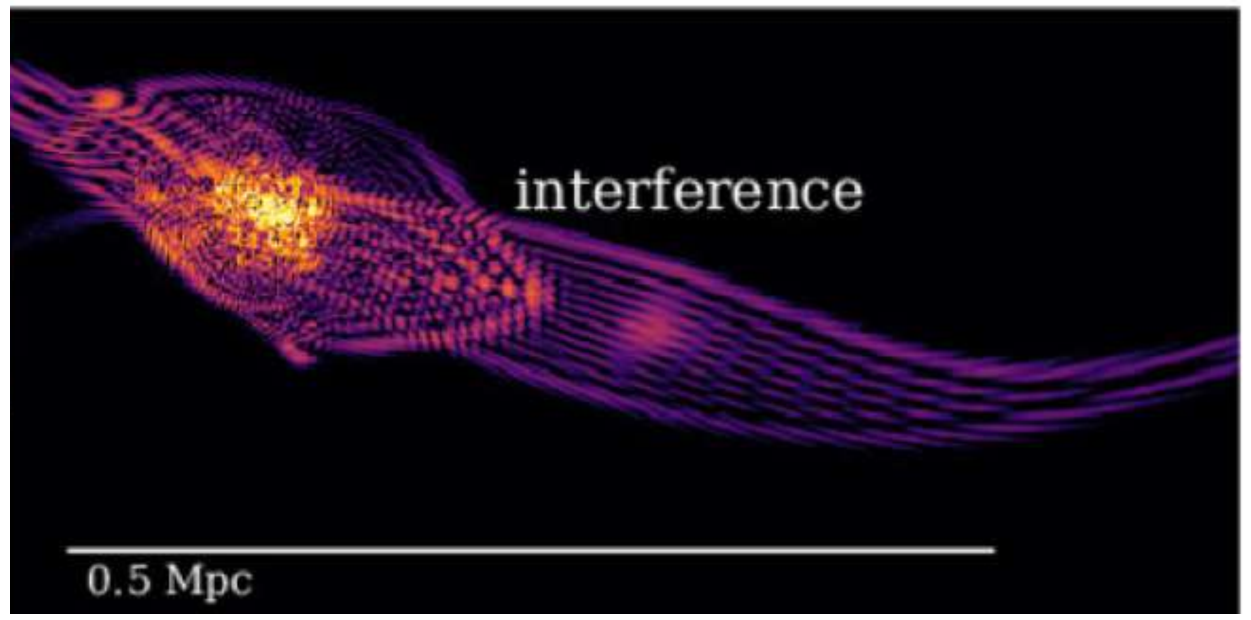


Dynamical effects



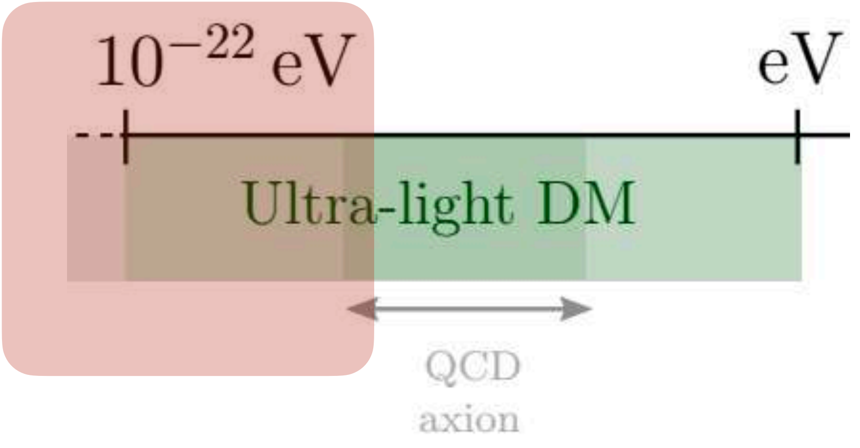
Levkov et al. 2018

Wave interference



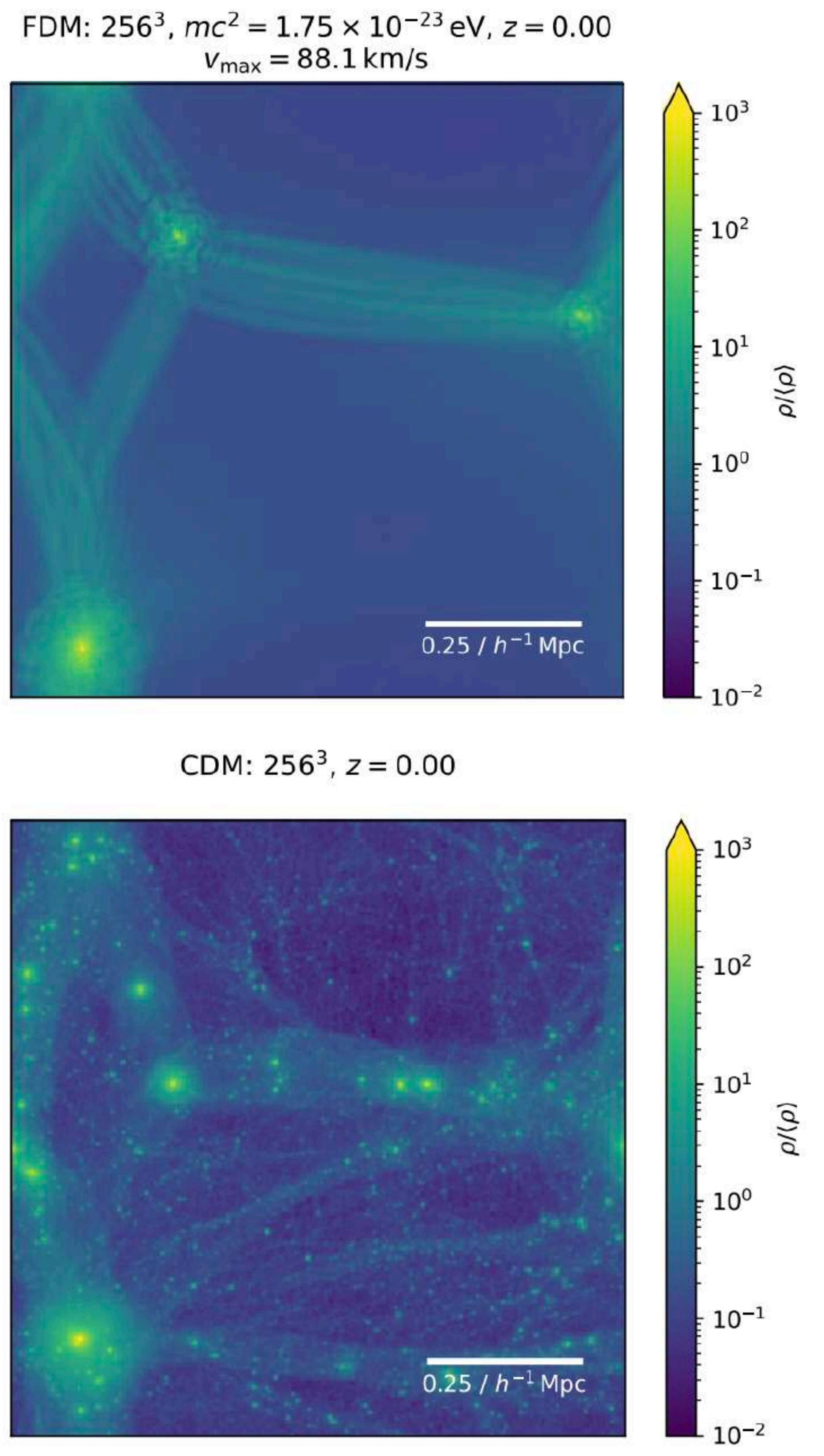
Mocz et al. 2017

Phenomenology



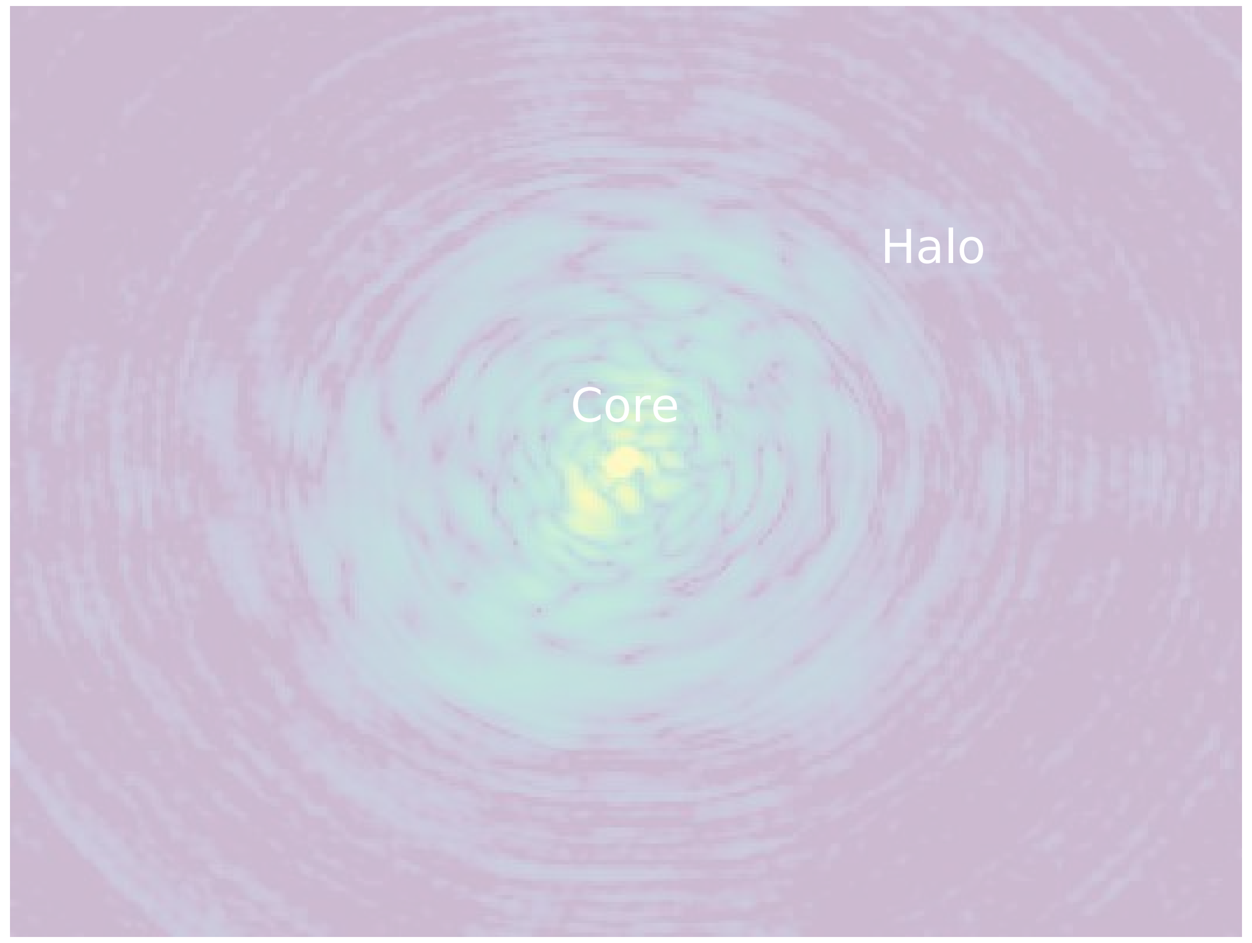
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

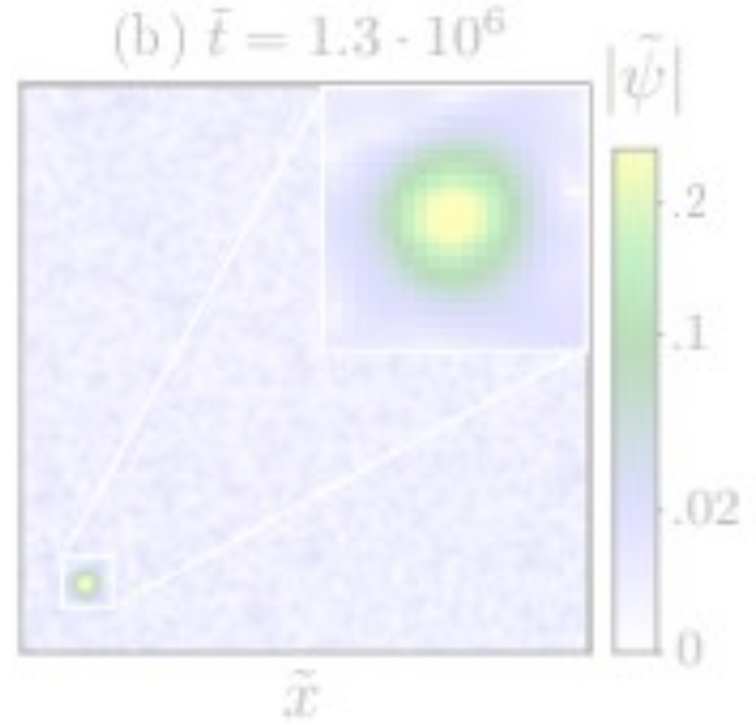


S. May et al. 2021

Formation of a solitonic core



Dynamical effects



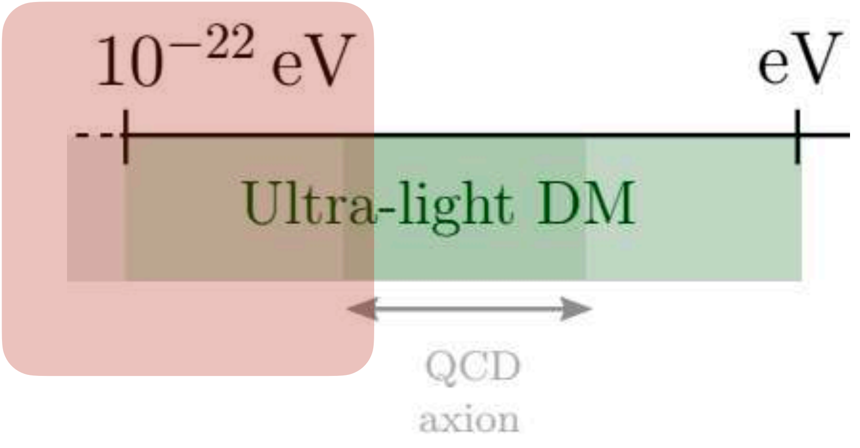
Levkov et al. 2018

Wave interference

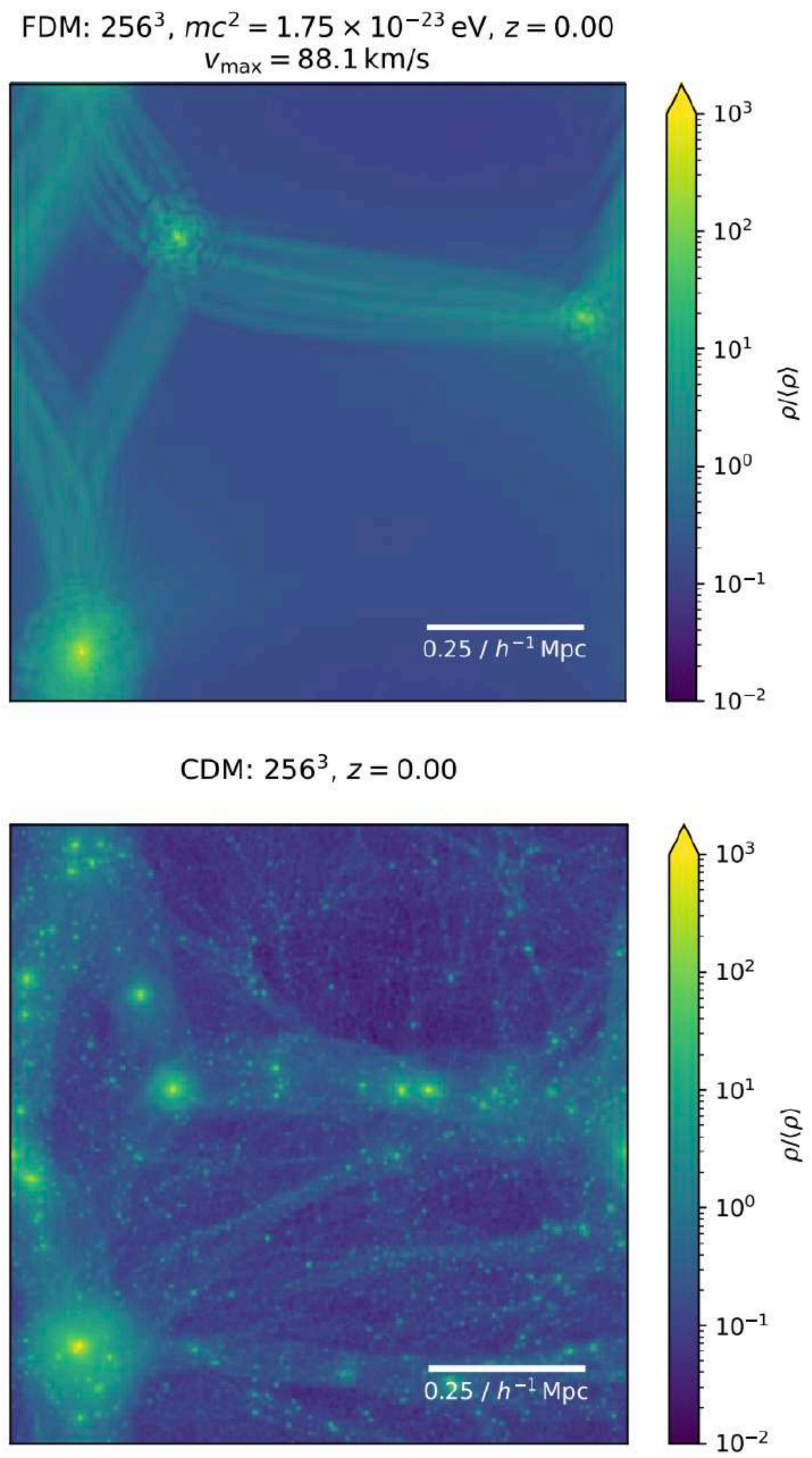
Mocz et al. 2017

Phenomenology

Suppression of small structures



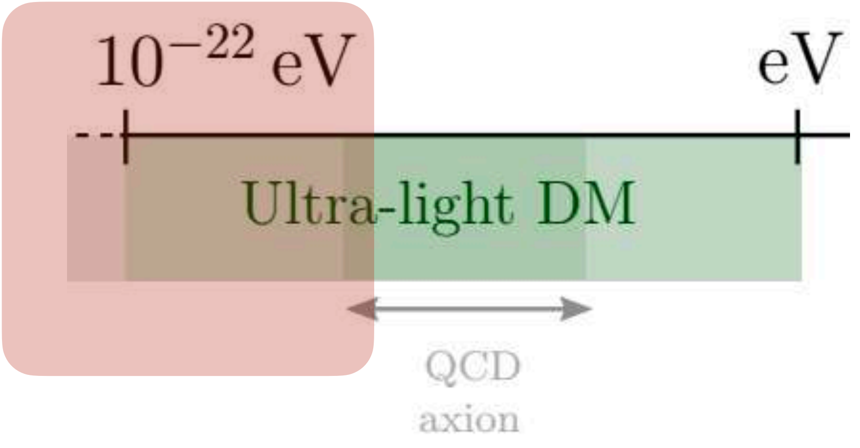
Finite Jeans length λ_J or $\lambda_{attr}, \lambda_{rep}$ → No small scale structure



S. May et al. 2021

Phenomenology

Suppression of small structures



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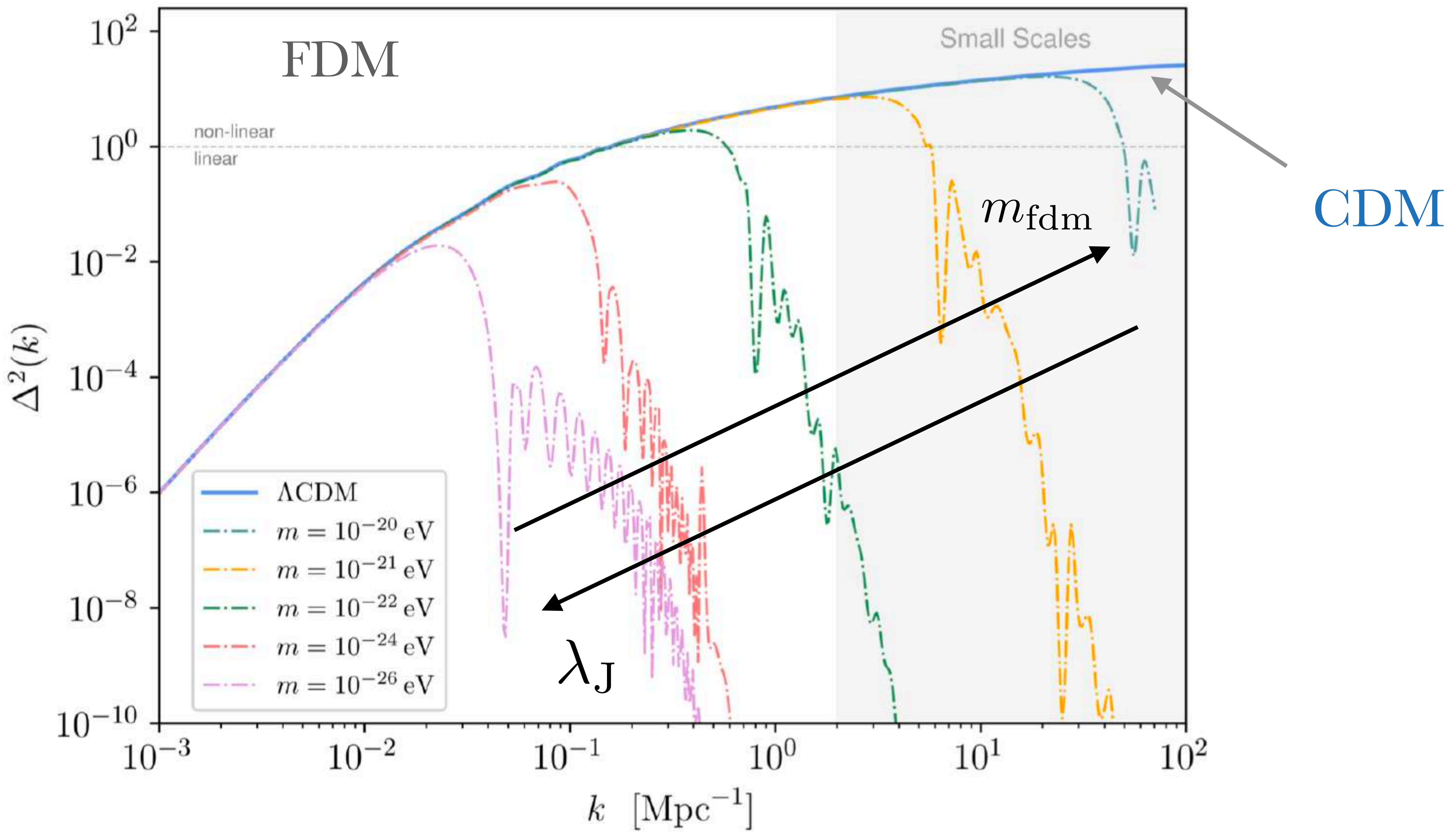
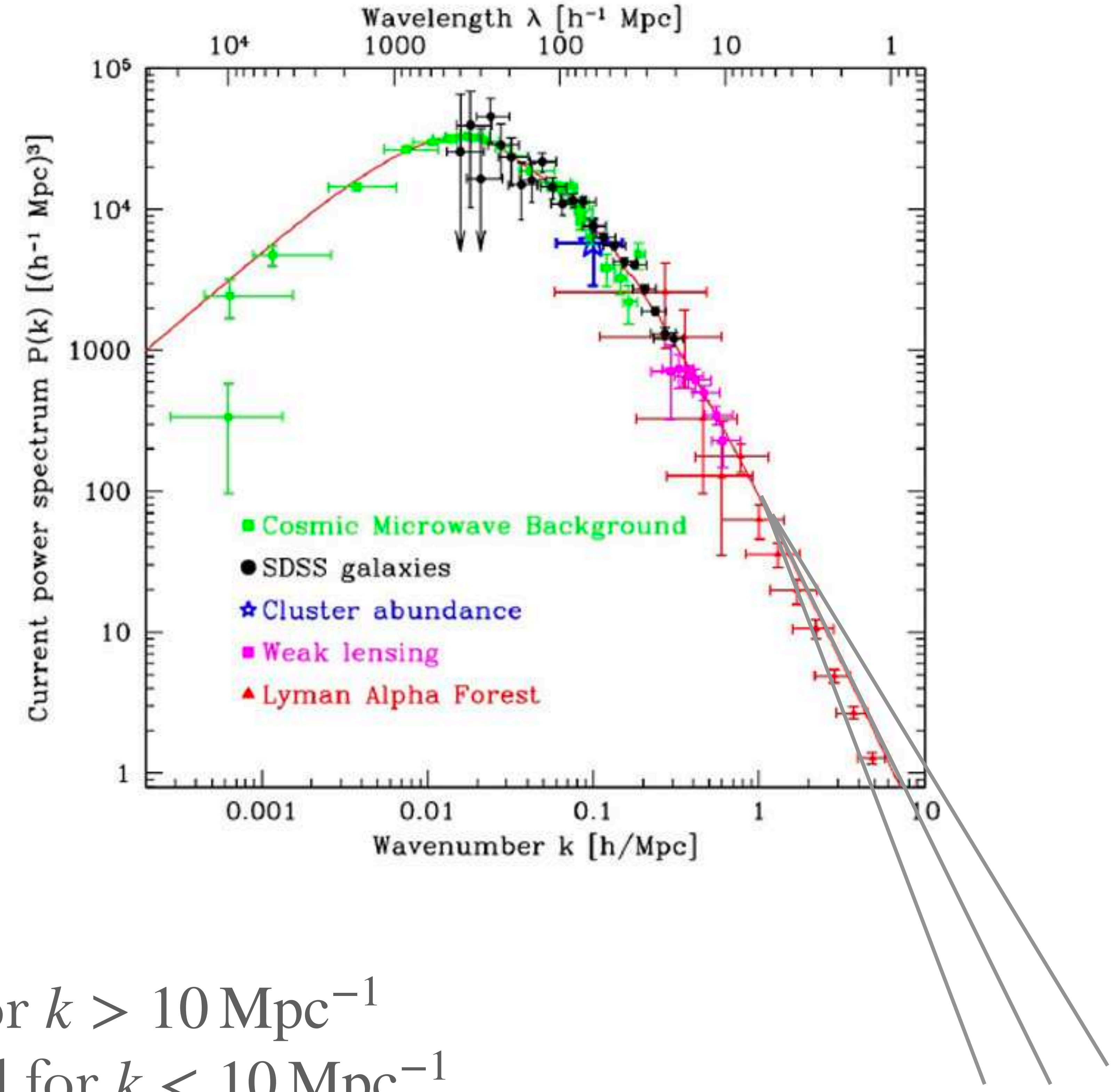
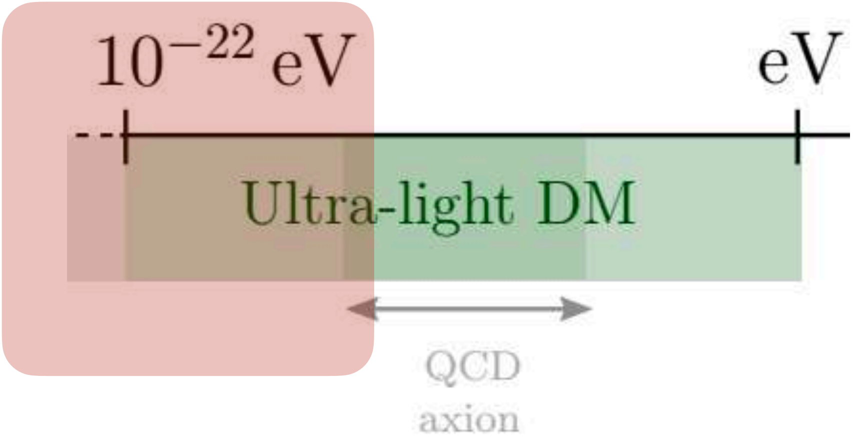
POWER SPECTRUM





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

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

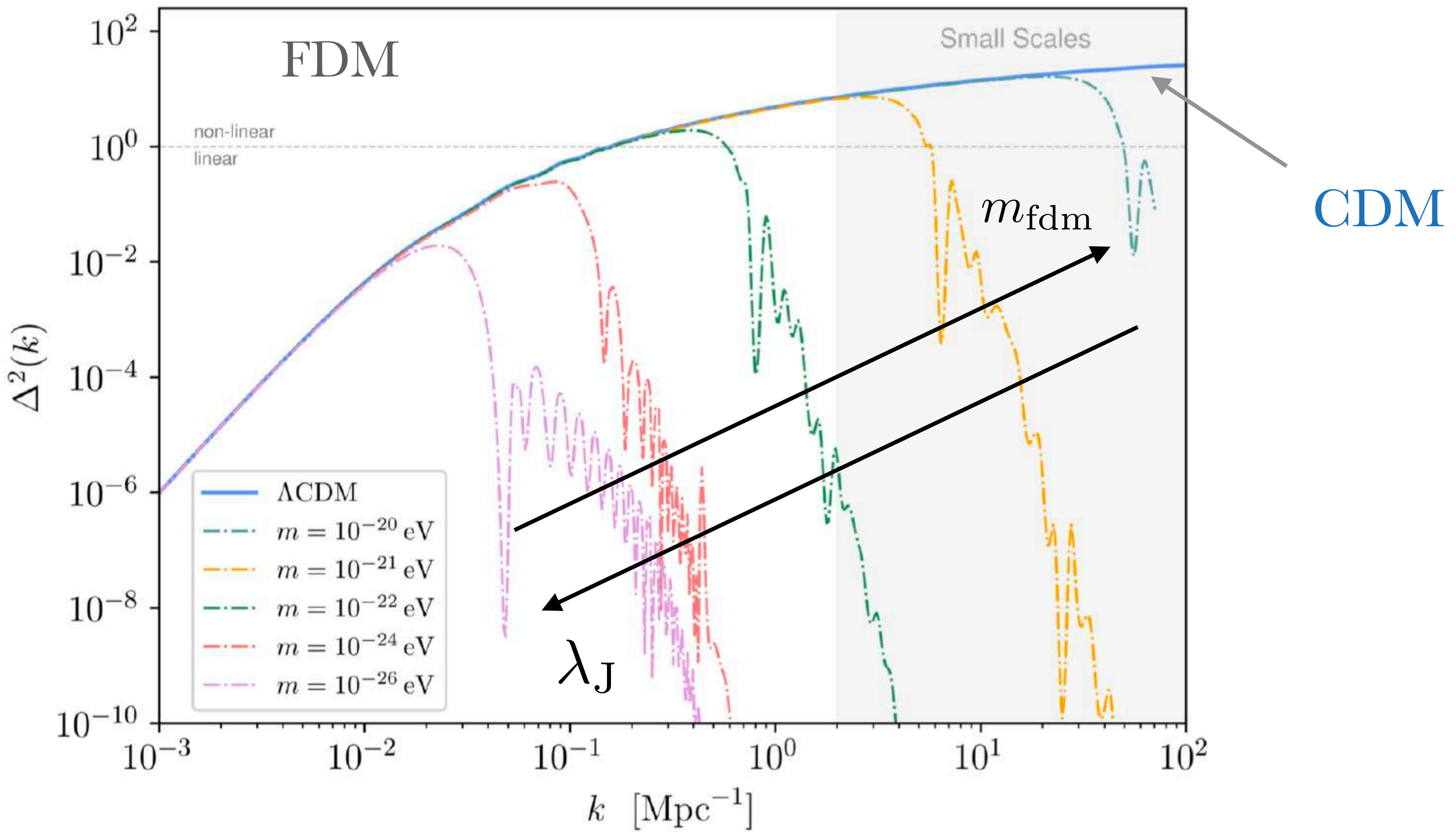


Phenomenology

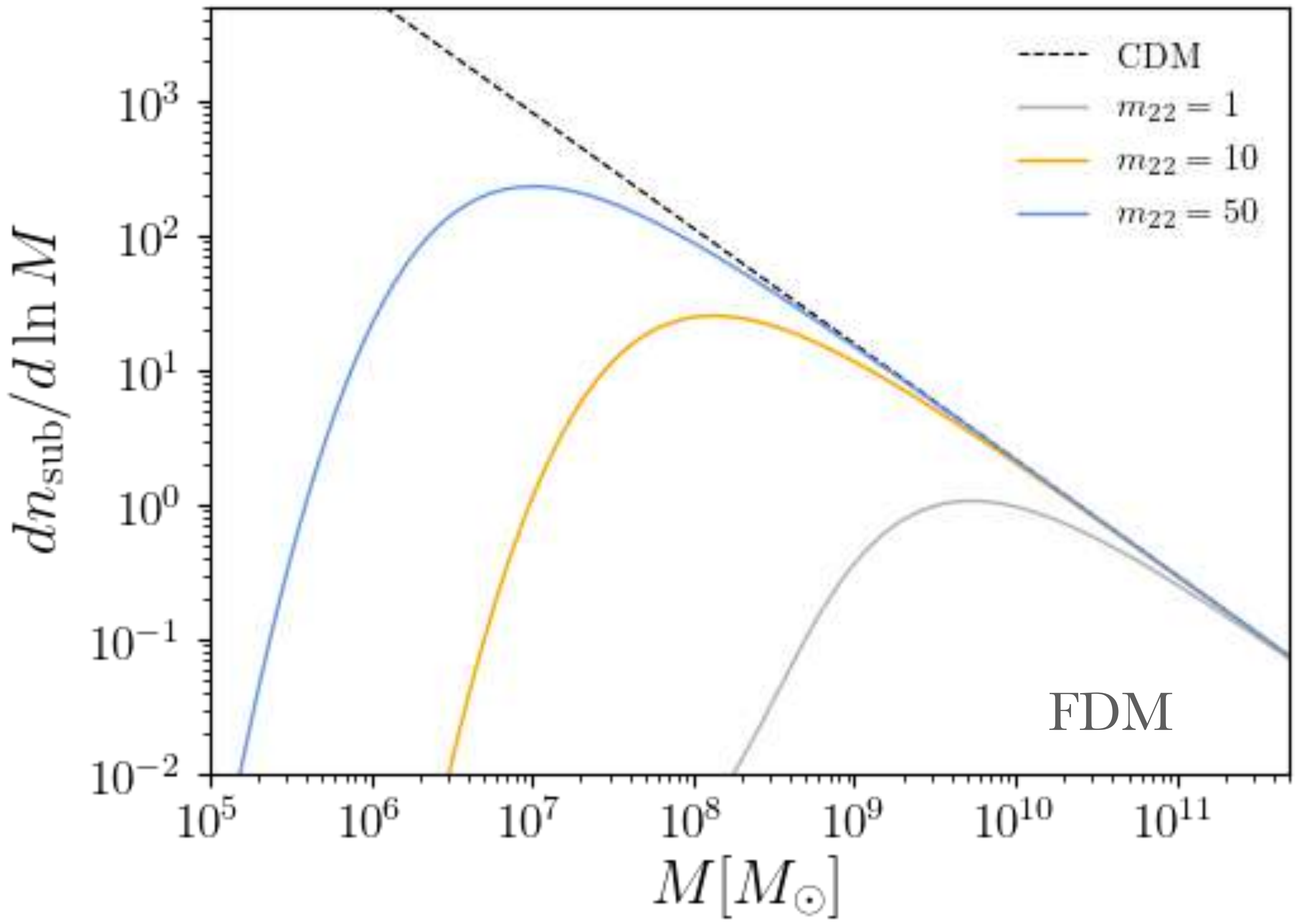
Suppression of small structures

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

POWER SPECTRUM



(sub) HALO MASS FUNCTION



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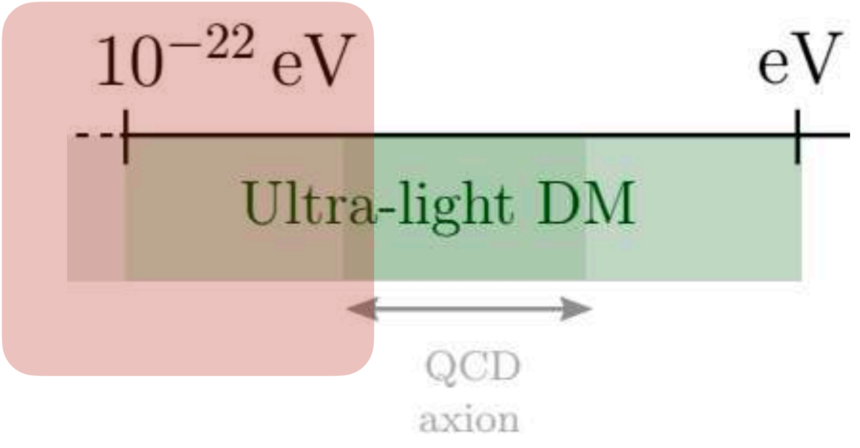
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

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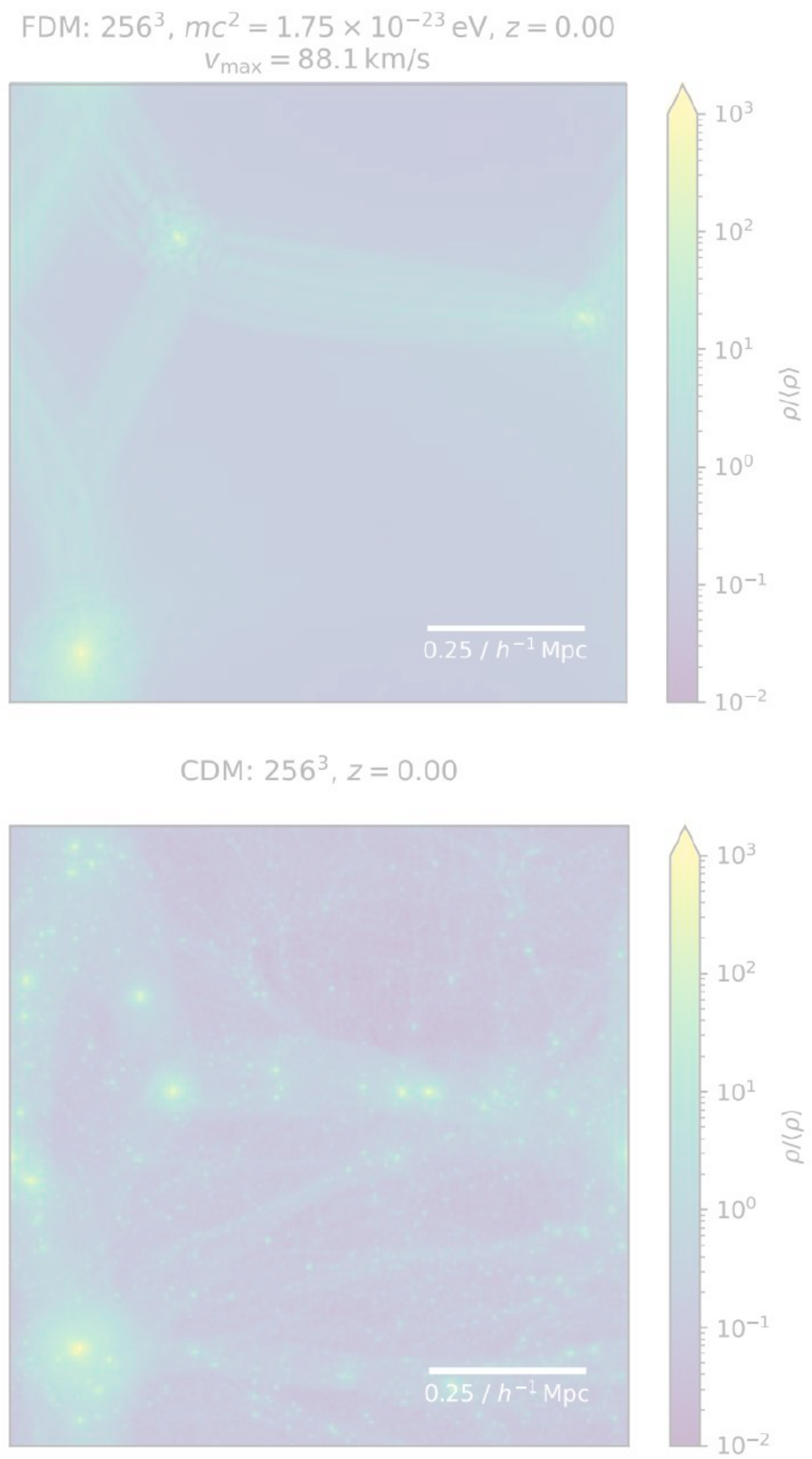
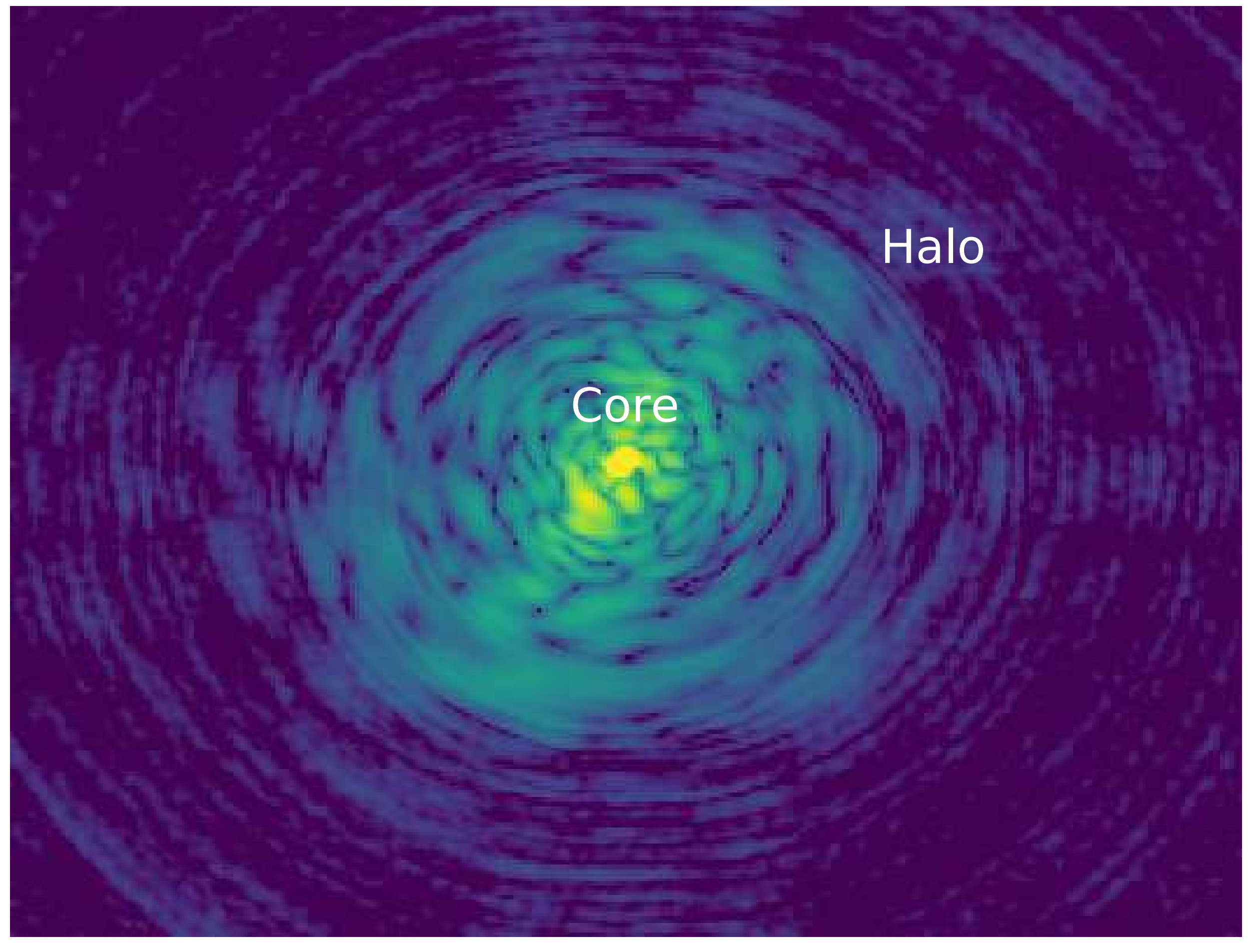
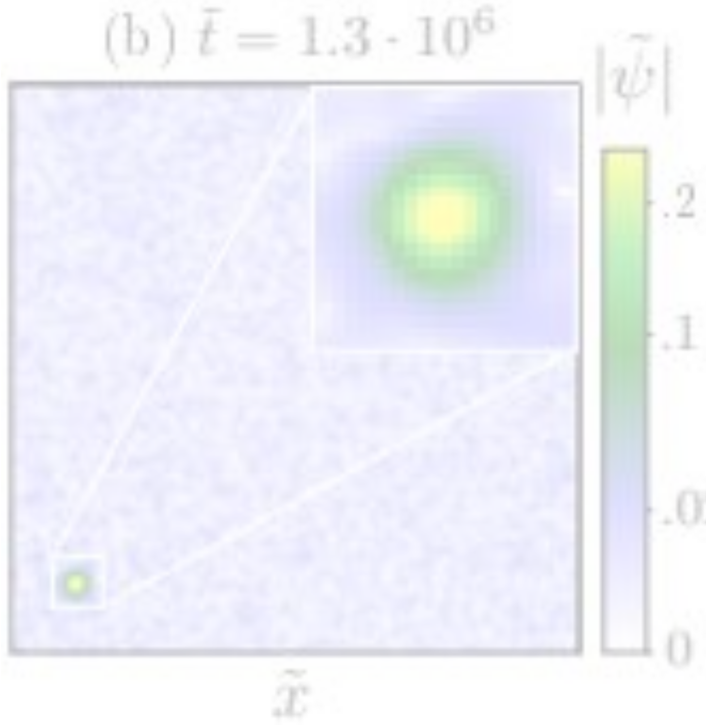


S. May et al. 2021

Formation of a solitonic core



Dynamical effects



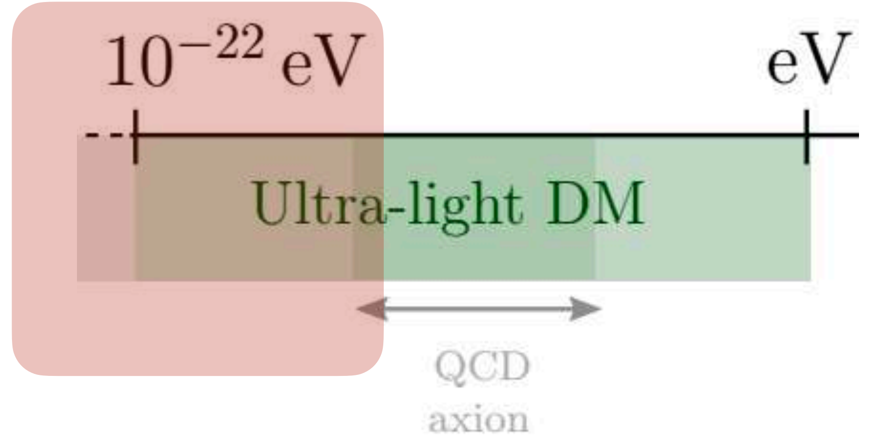
Levkov et al. 2018

Wave interference

Mocz et al. 2017

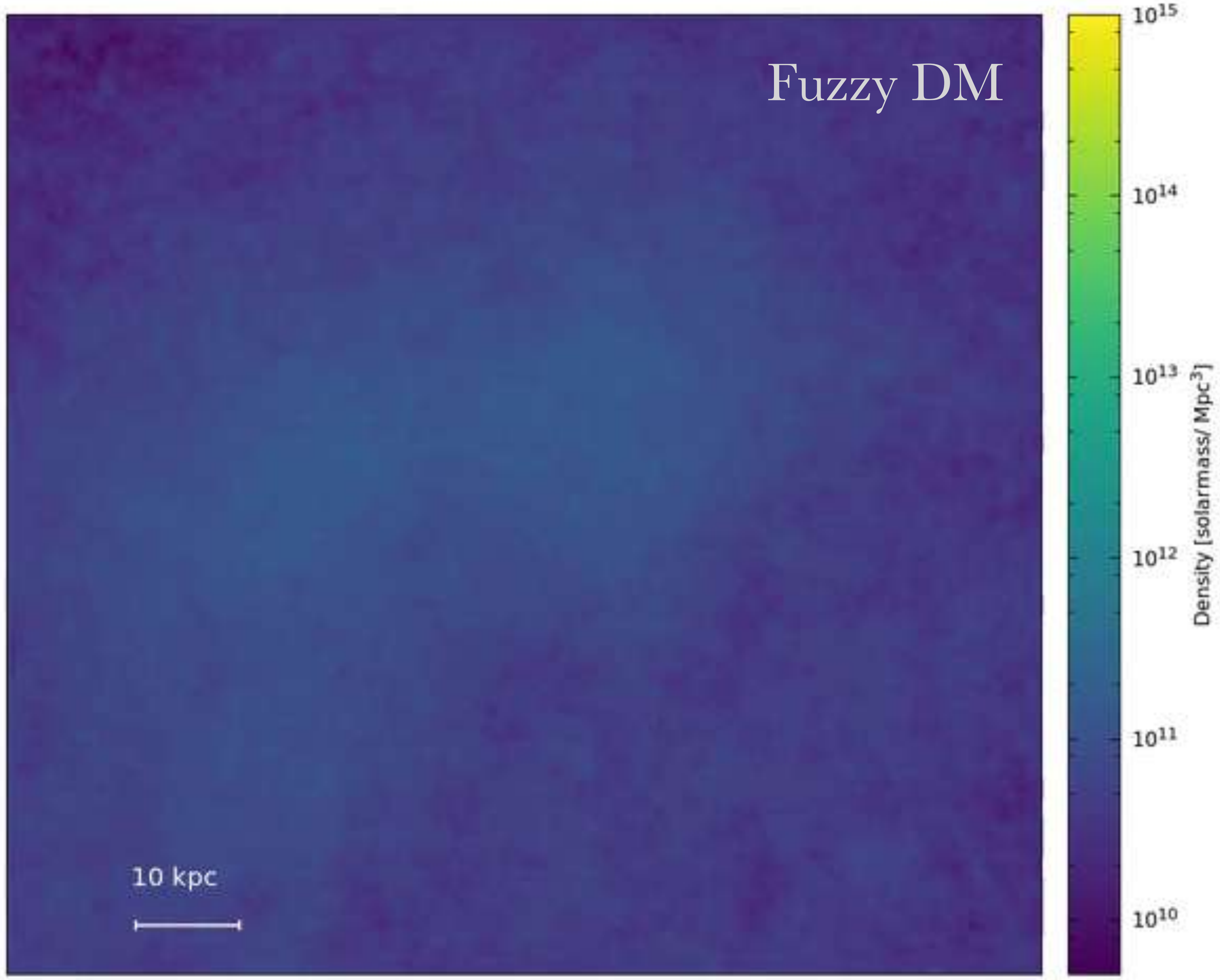
Phenomenology

Formation of cores

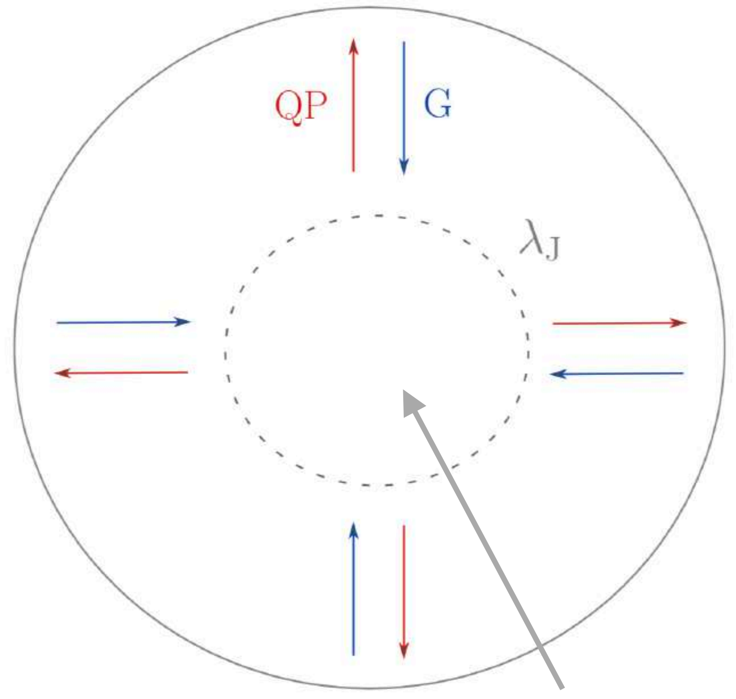


NON-LINEAR evolution: need simulations

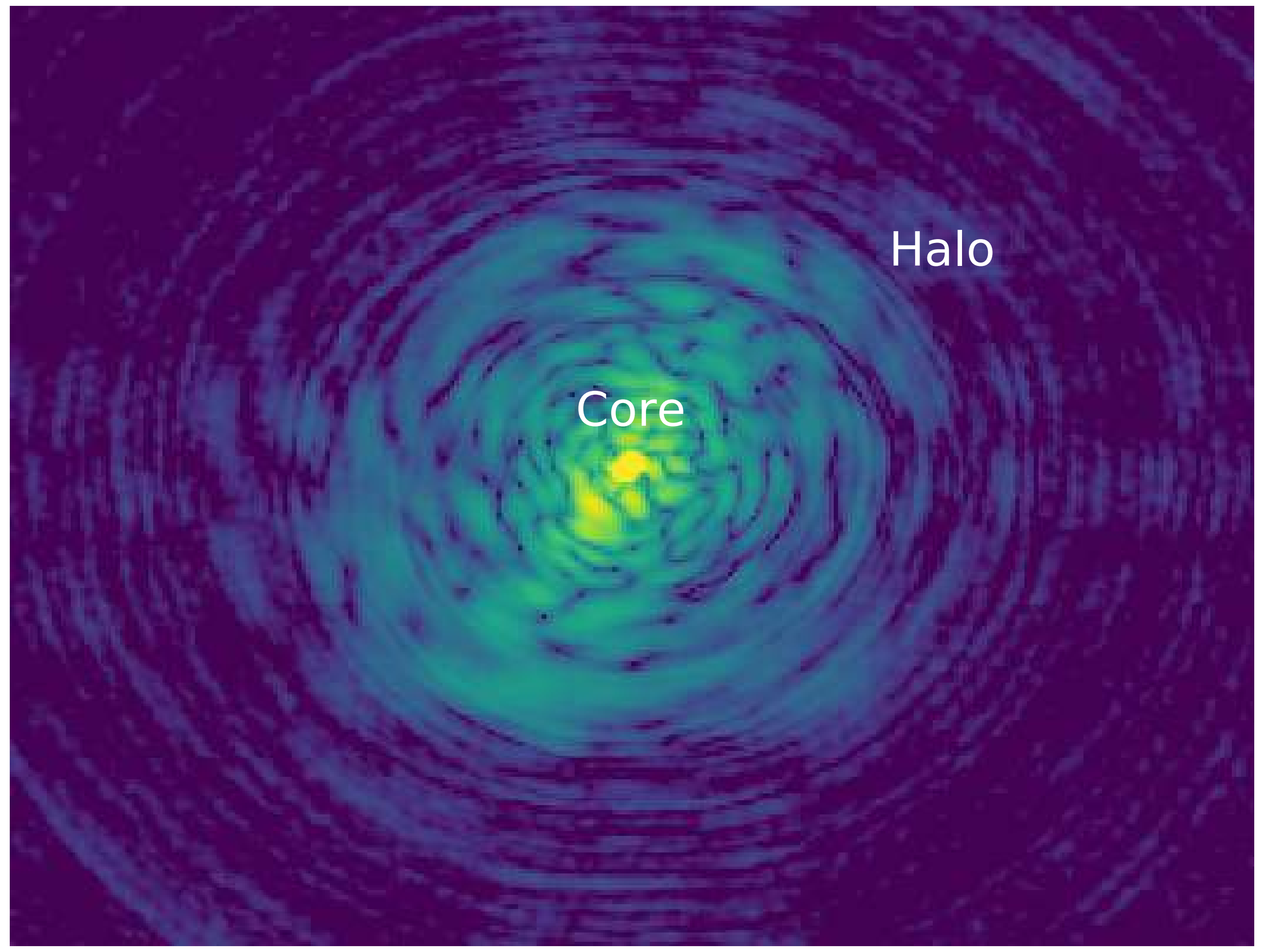
$m = 10^{-22}\,\mathrm{eV}$ $N = 512^3$ $L = 300\,\mathrm{kpc}$



Simulation by Jowett Chan

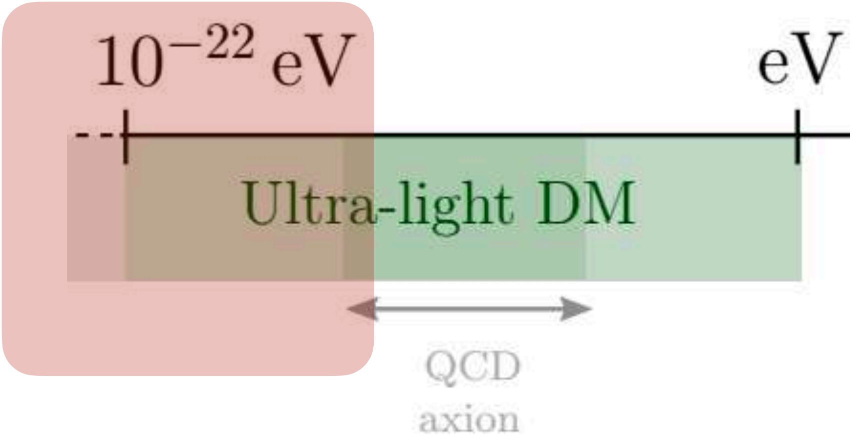


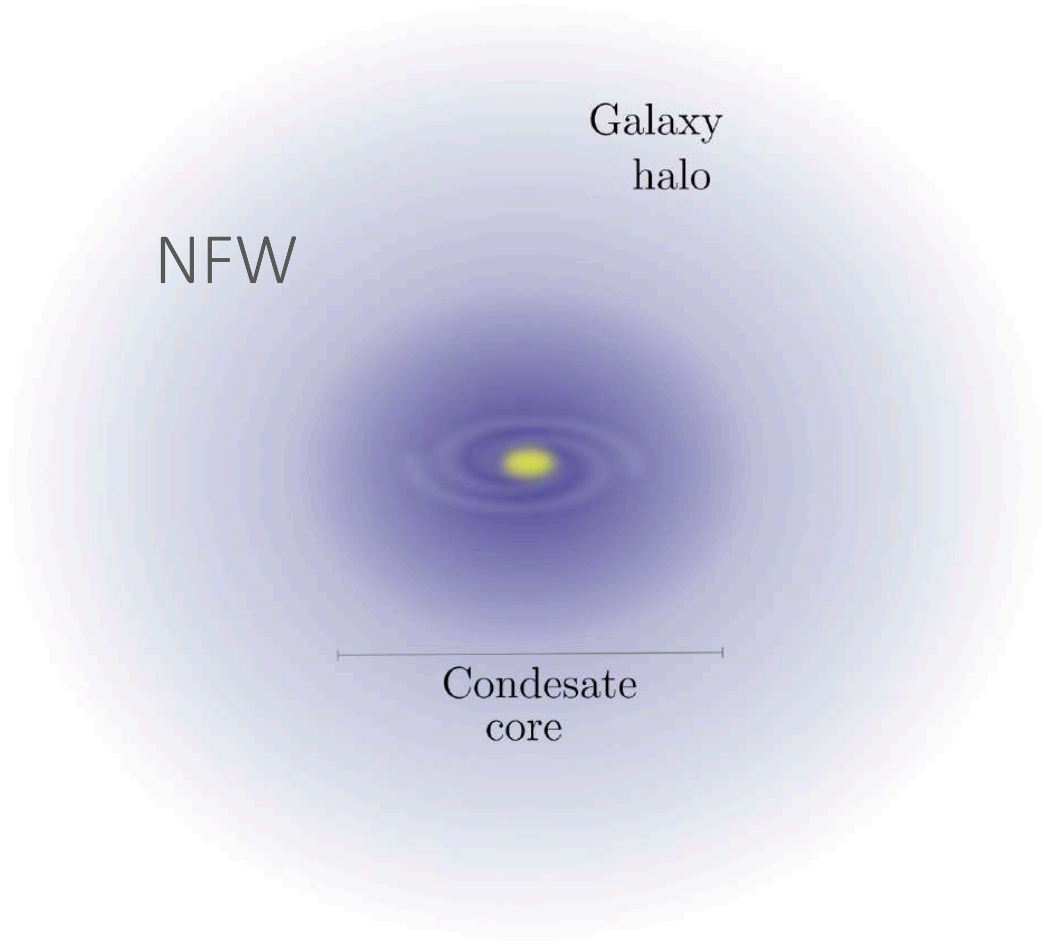
NO structure formation
Stable, oscillating solution



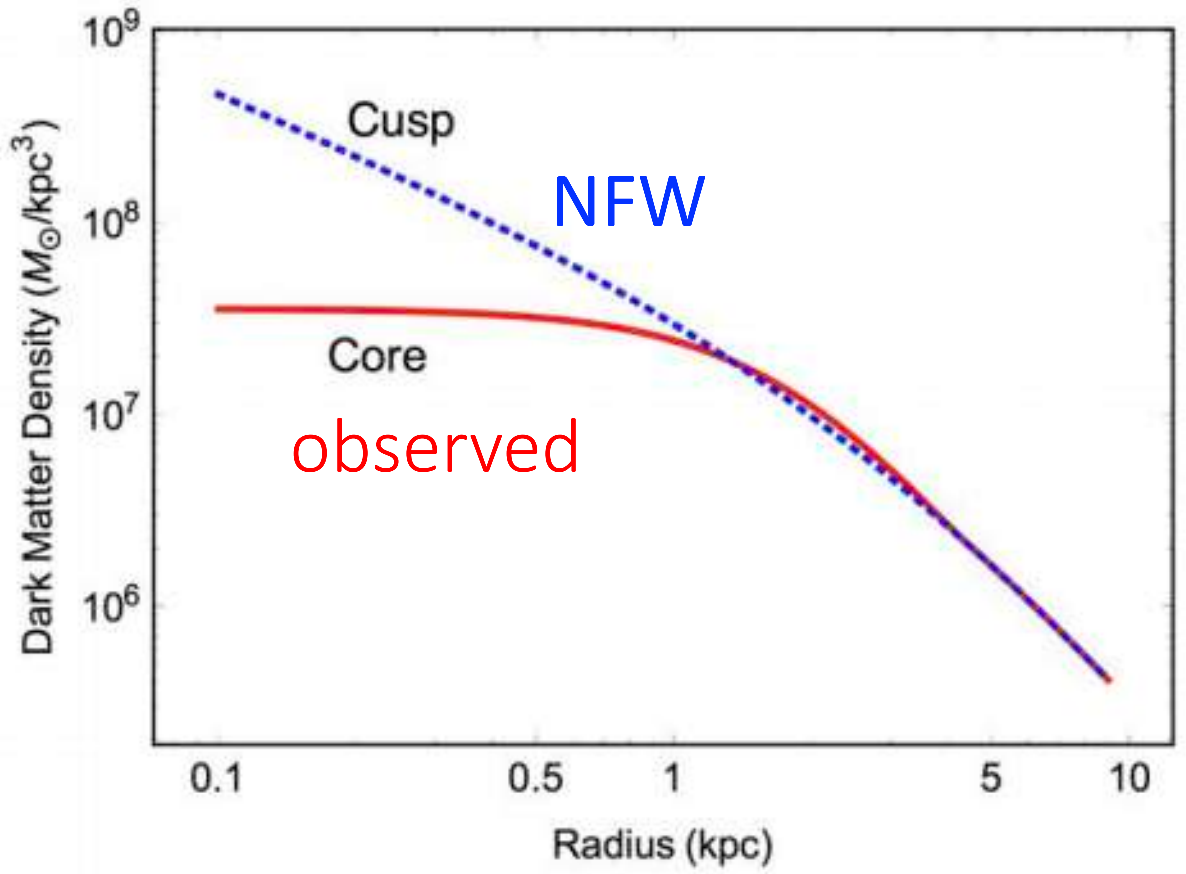
Phenomenology

Formation of cores





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



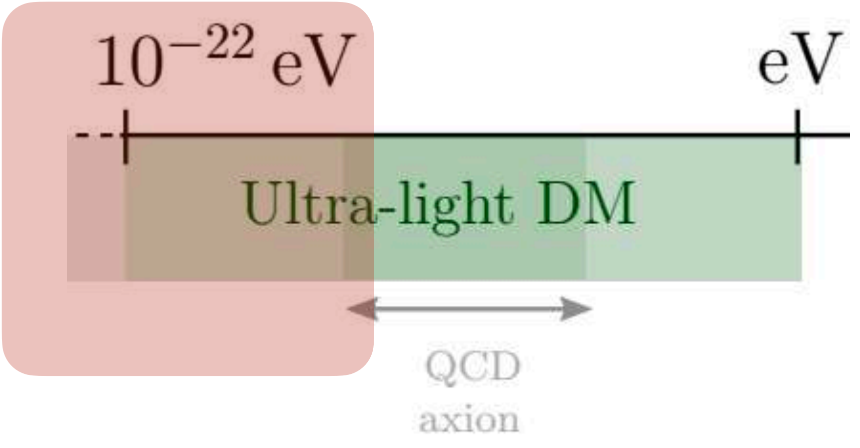
FDM — From simulations Schive et al. 2014, fitting function: Stable core solution

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

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

→ Relations used to compare with observations

Phenomenology



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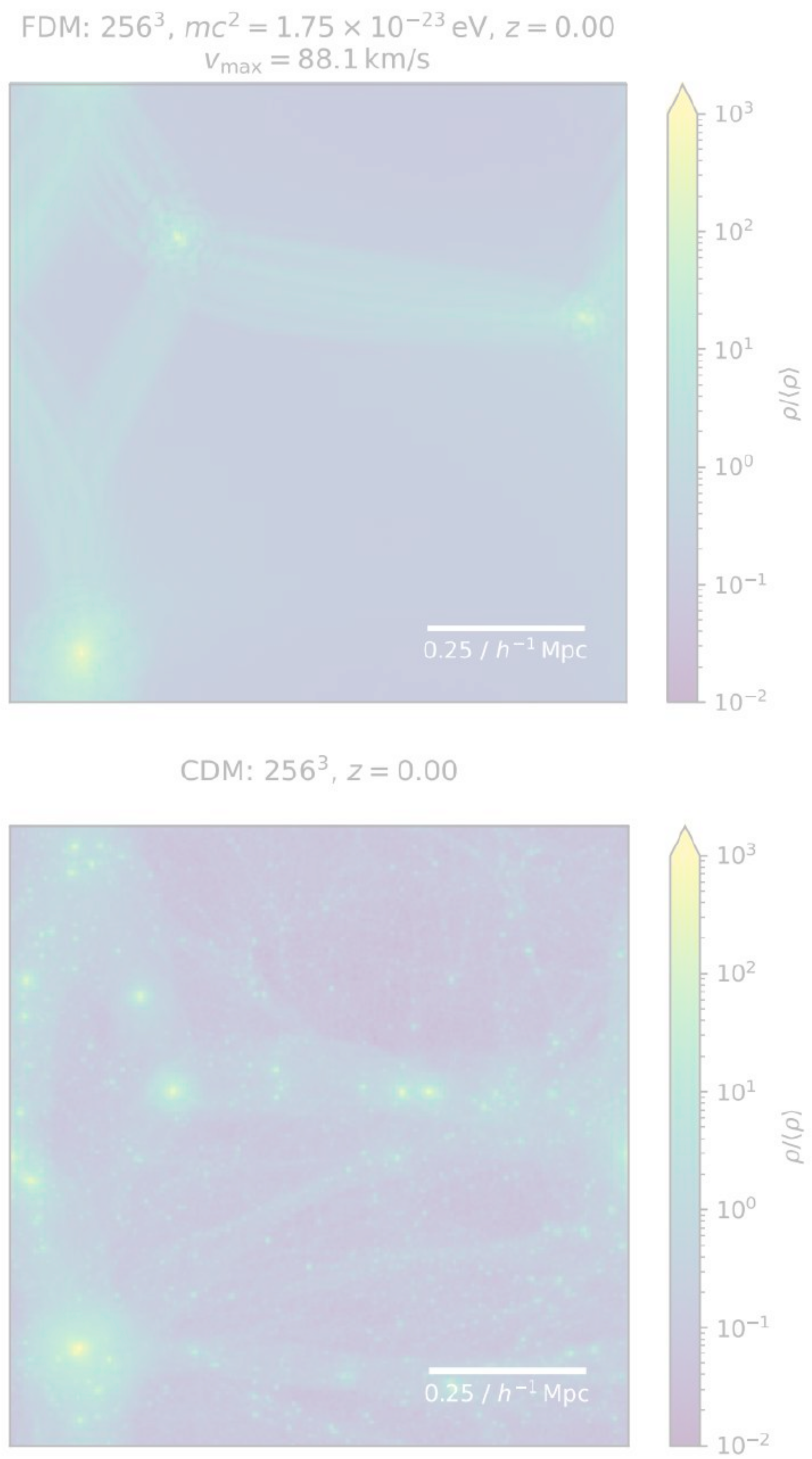
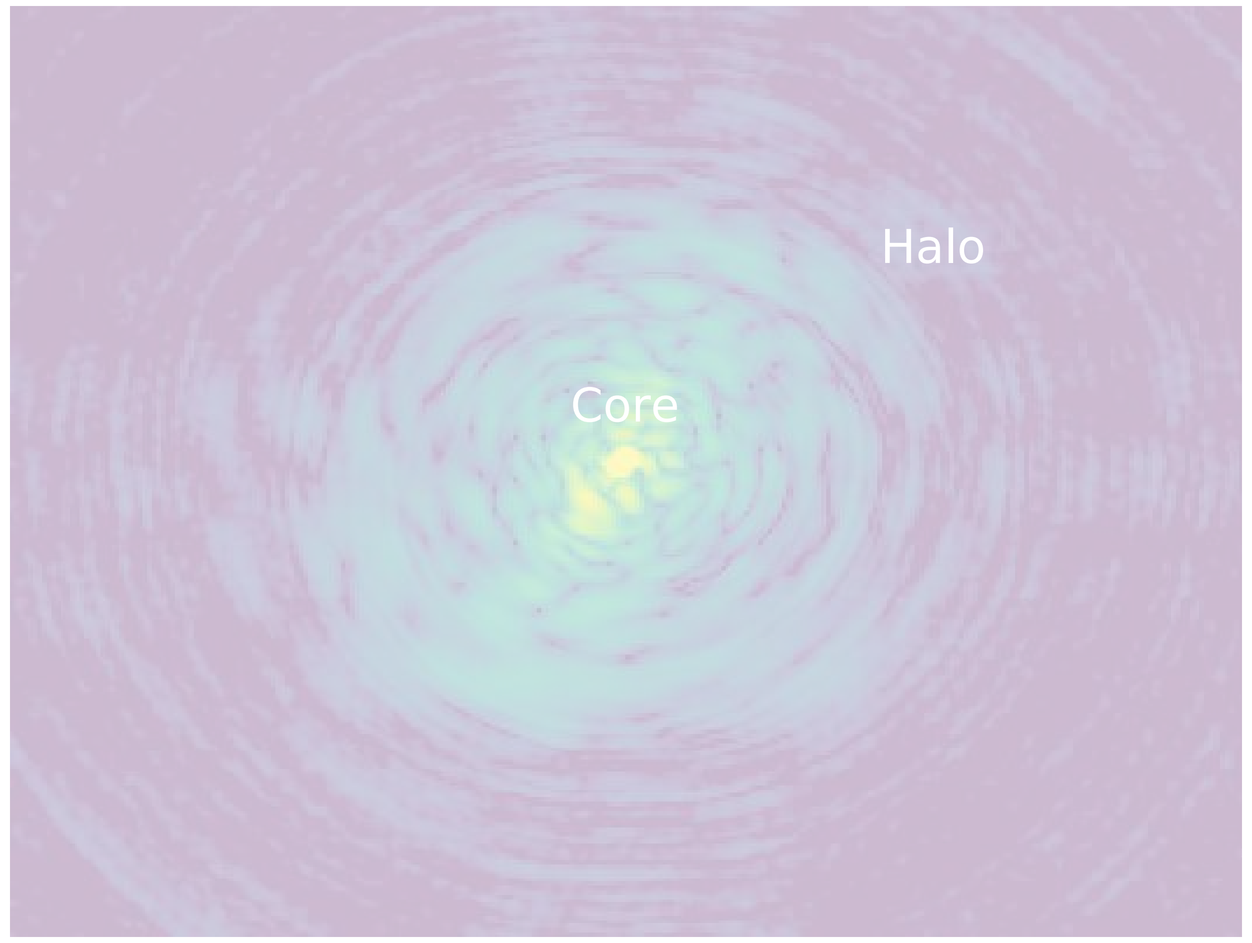
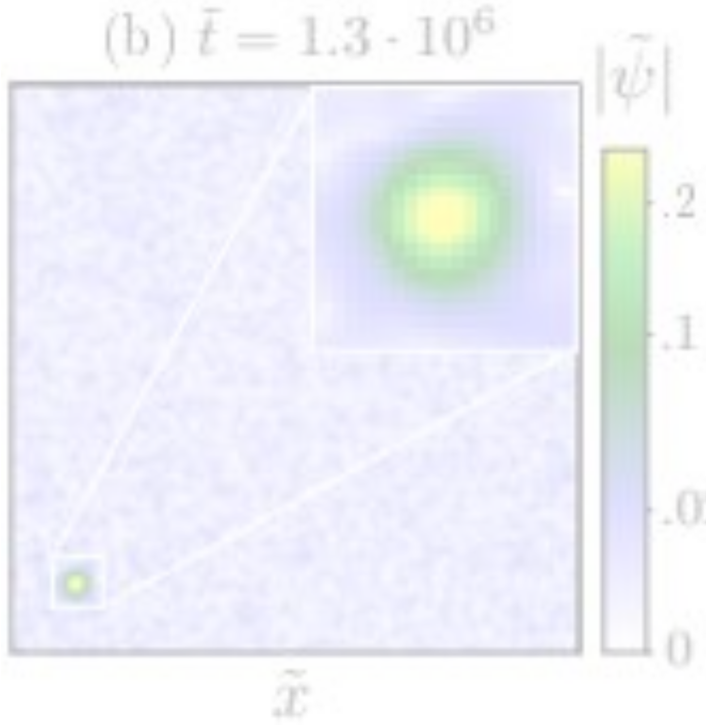


S. May et al. 2021

Formation of a solitonic core

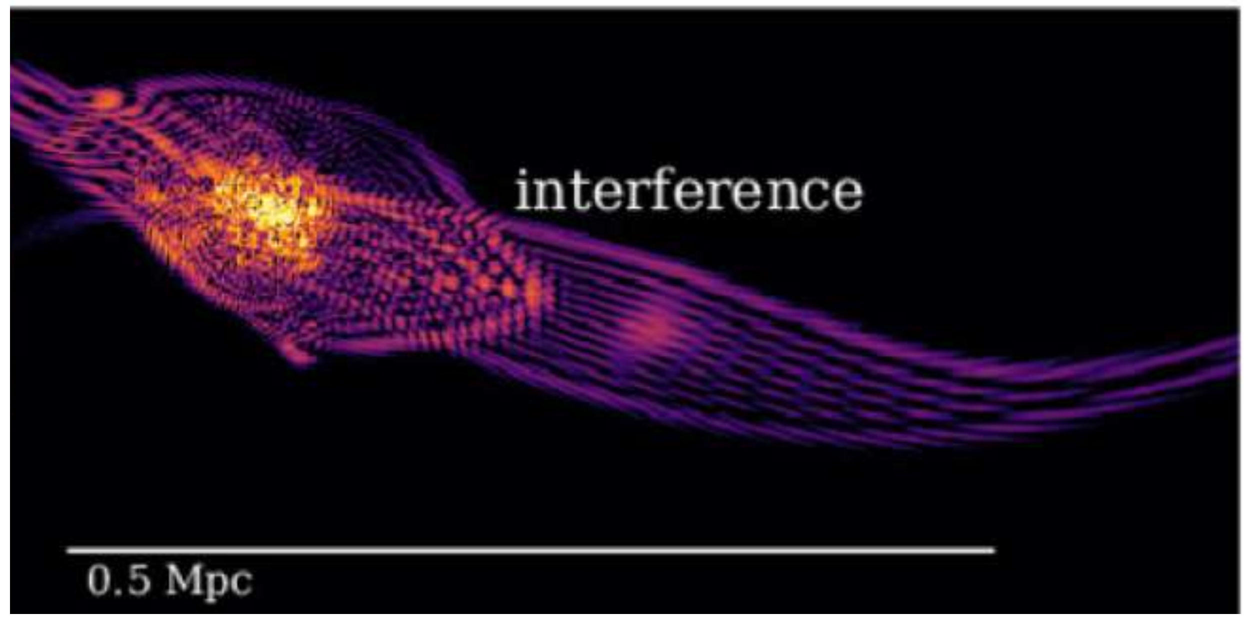


Dynamical effects



Levkov et al. 2018

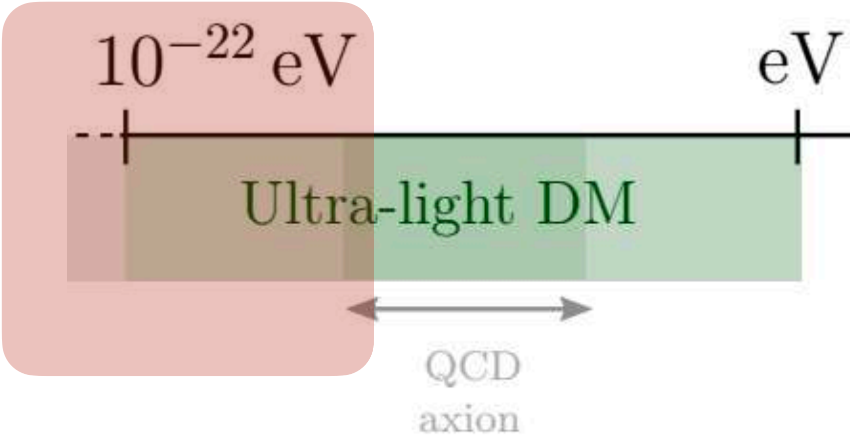
Wave interference

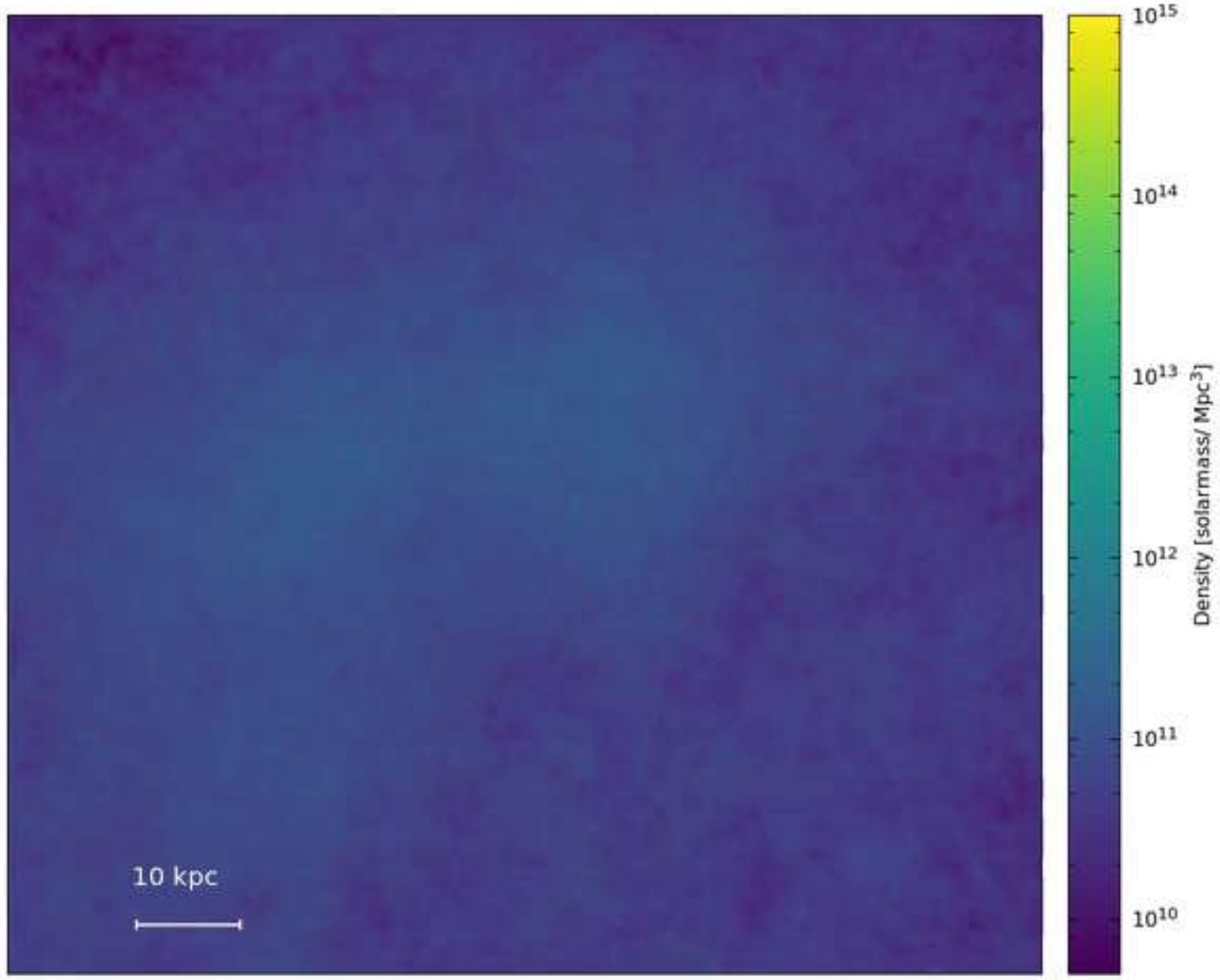


Mocz et al. 2017

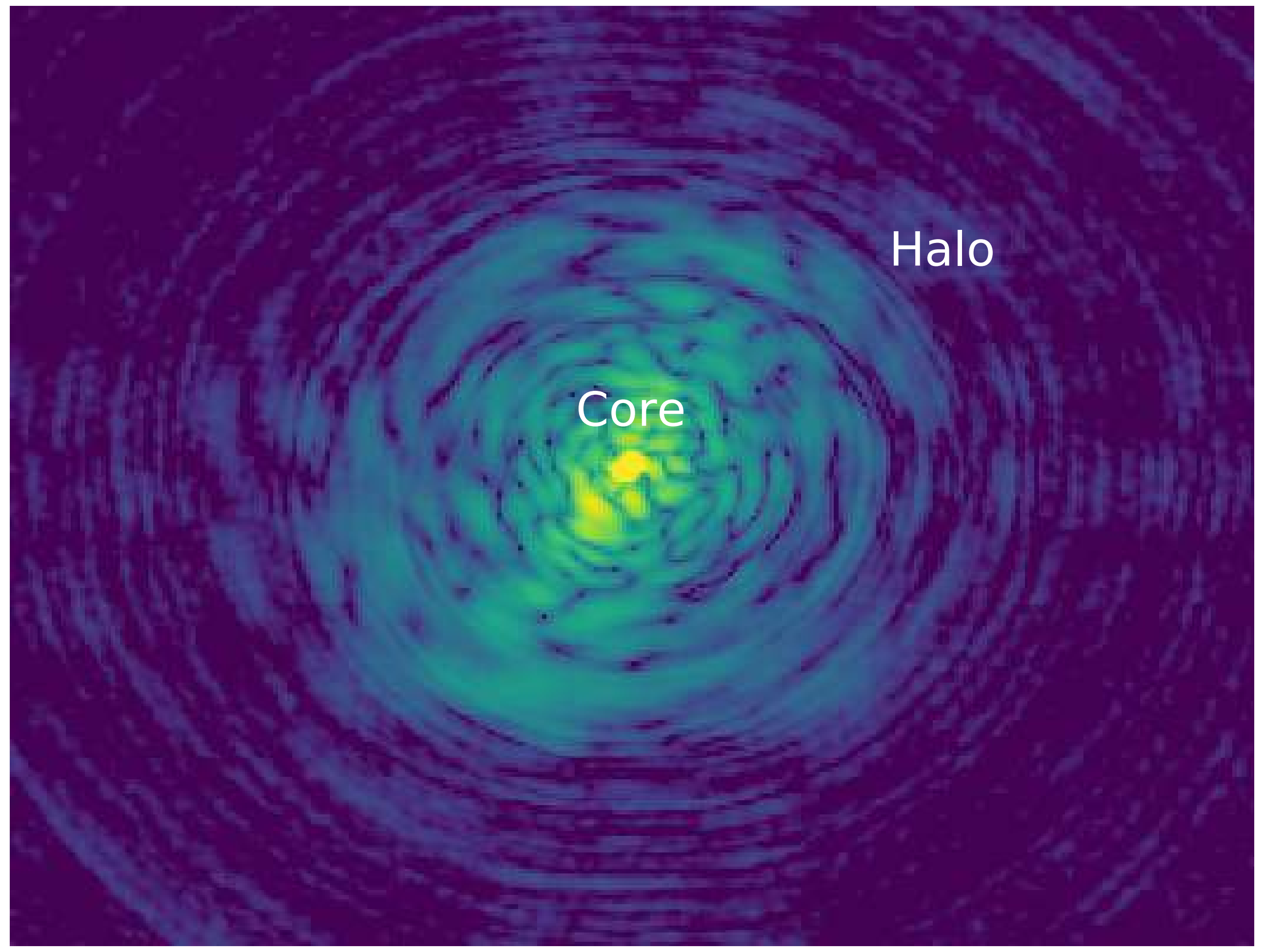
Phenomenology

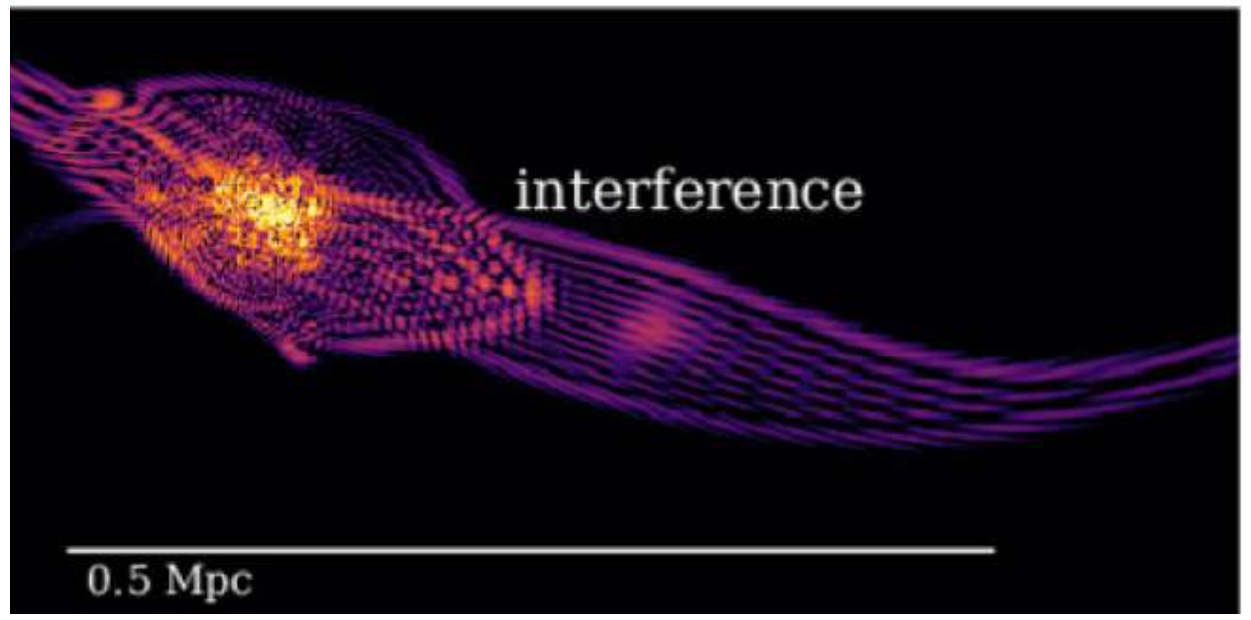
Wave interference: granules and vortices





Simulation by Jowett Chan



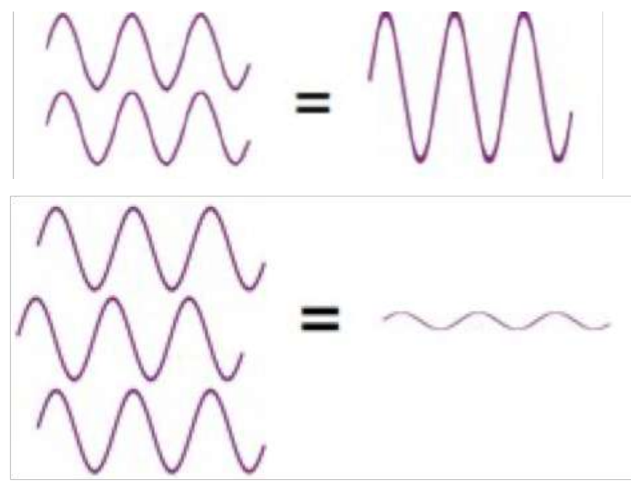


Mocz et al. 2017

Order one fluctuations in density $\longrightarrow$ Constructive interference: granules
Destructive interference $\hookrightarrow$ $\sim \lambda_{\rm dB}$

Vector, higher spin or multicomponent FDM

Interference patterns

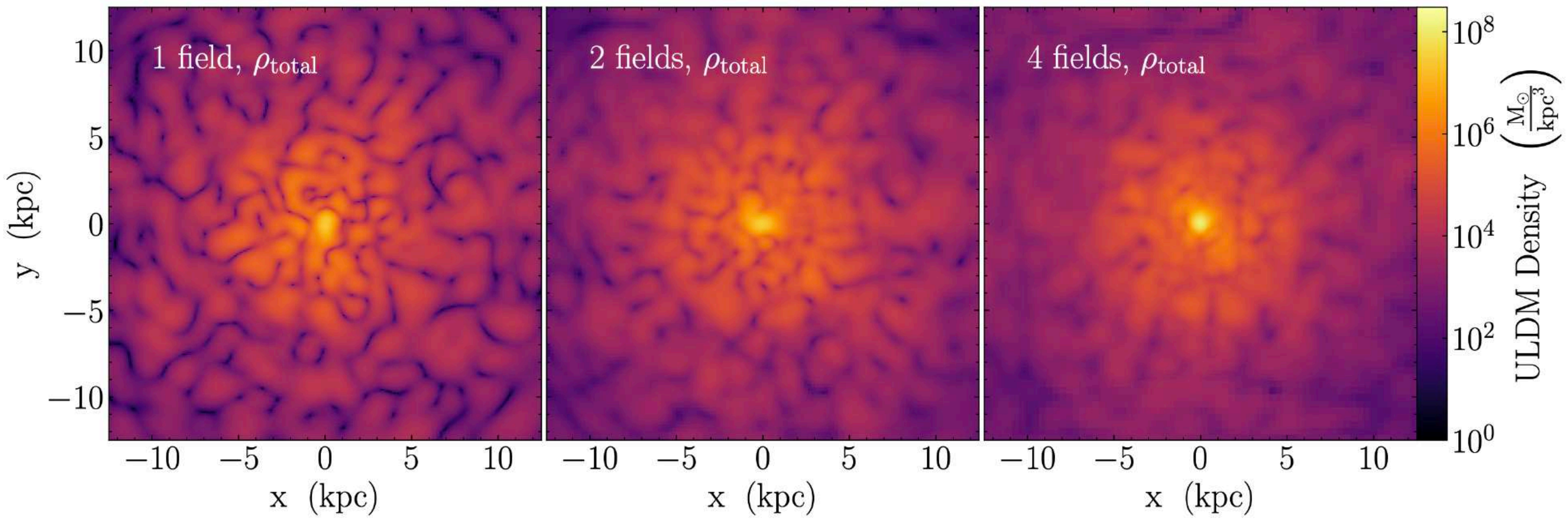


ULDM or ULA are a coherent wave - same frequency and constant phase difference

Multiple coherent waves

Gonseca et al 2023

For ULDM:



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

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

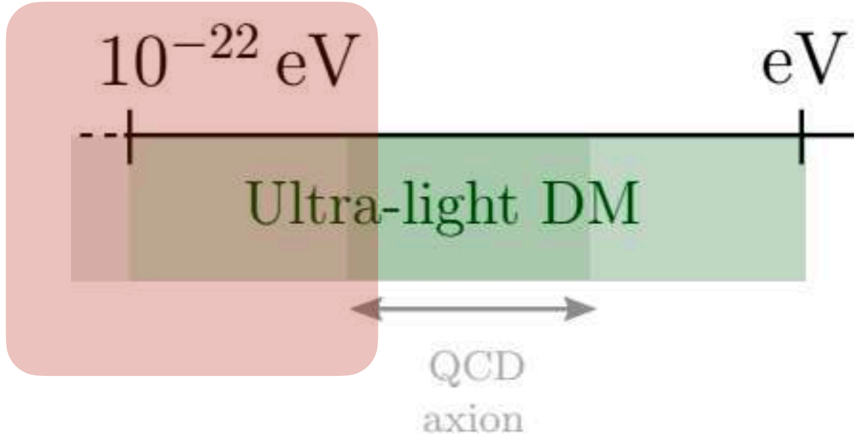
(Amin et al 2022)

Cosmological/astrophysical probes can also given information about the spin!

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

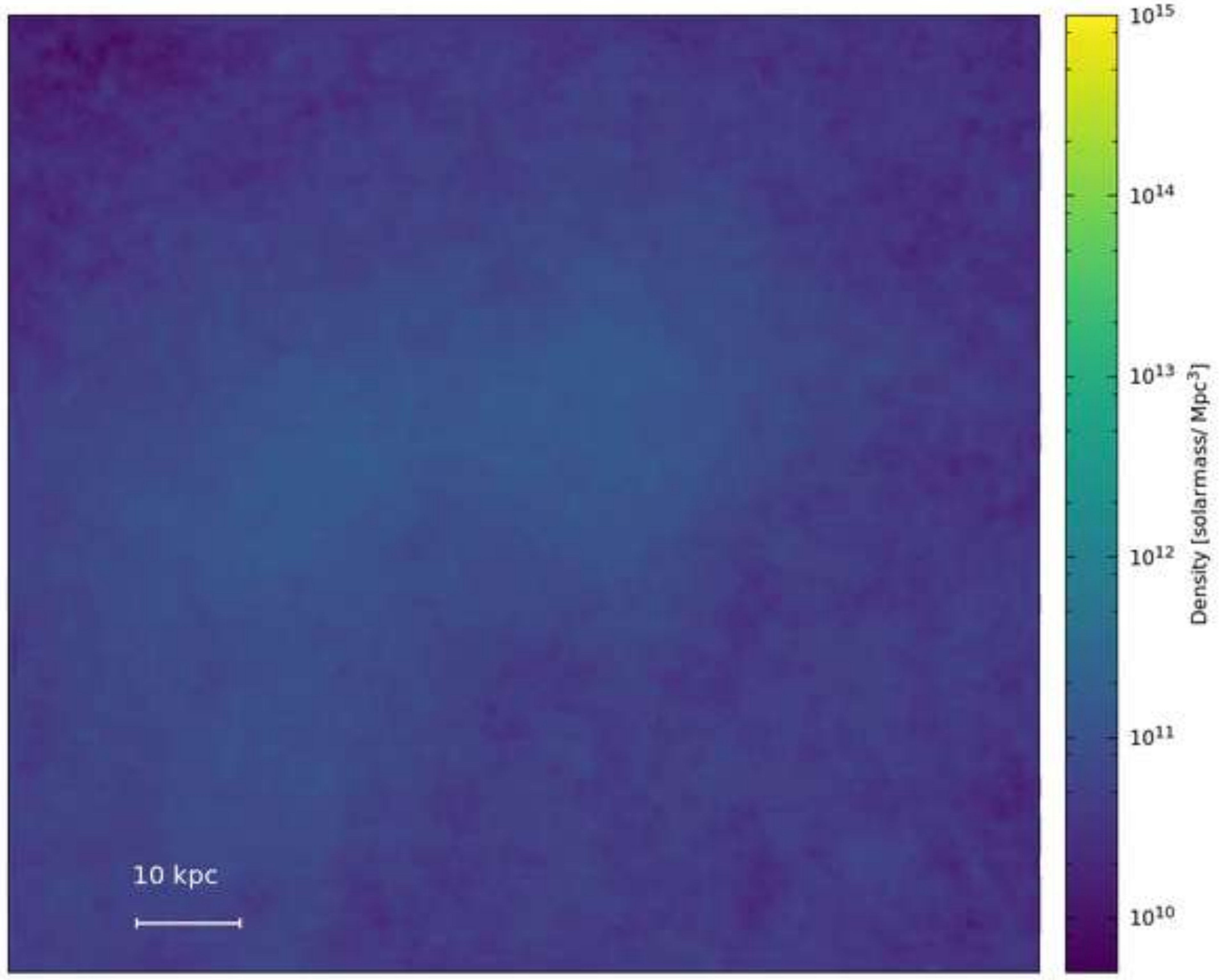
(Vector FDM = 3 x same mass FDM (spin 0))

Multicomponent FDM   Gonseca et al 2023



Phenomenology

Wave interference: granules and vortices



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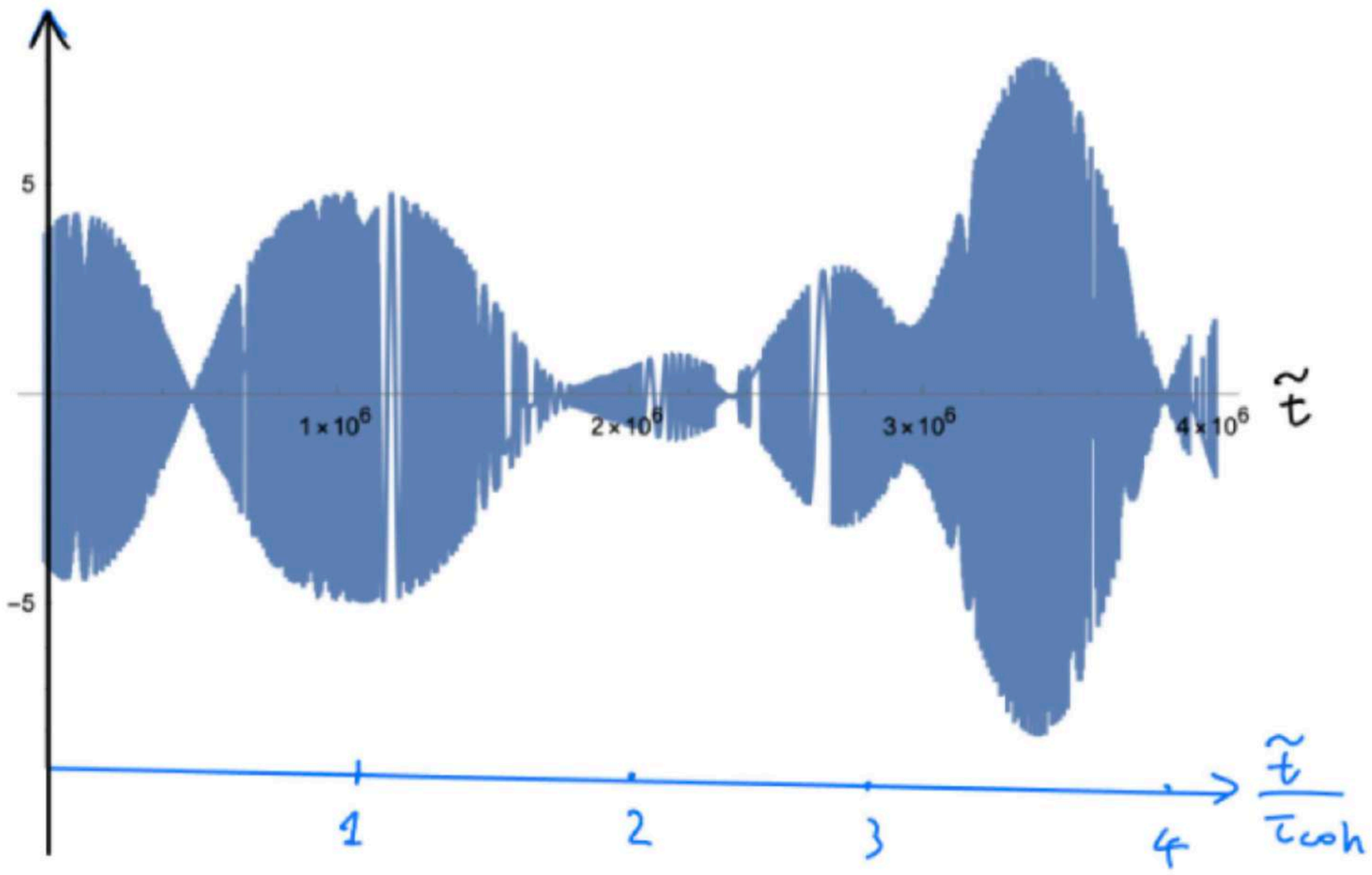


The time dependence of the amplitude and the phase of ULDM

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

$\sim \lambda_{dB}$

Phenomenology

Vortices

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

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

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

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

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

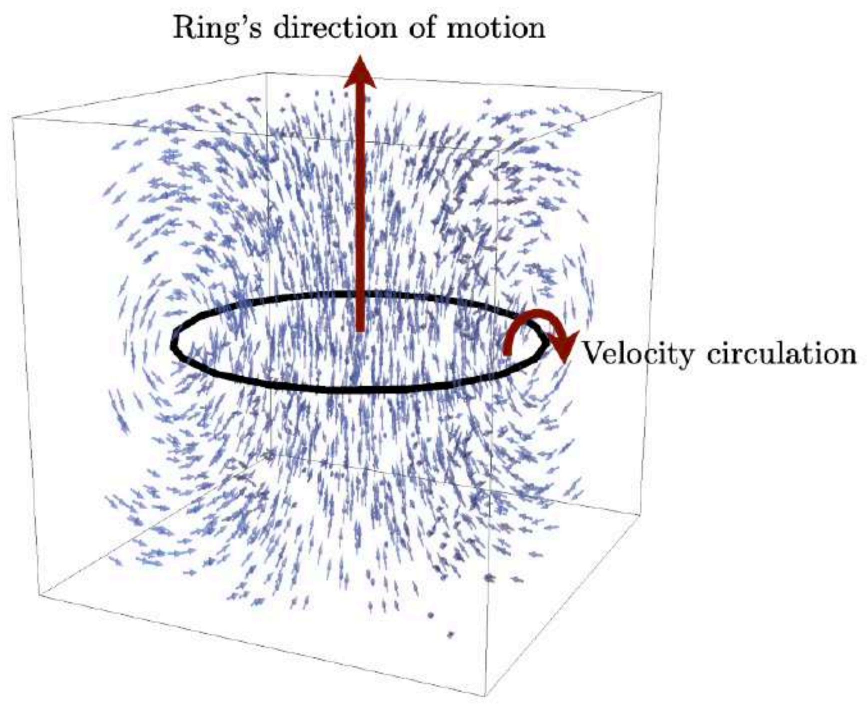
Vel. field is a gradient flow $\longrightarrow$ irrotational fluid, no vorticity

Fuzzy DM

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

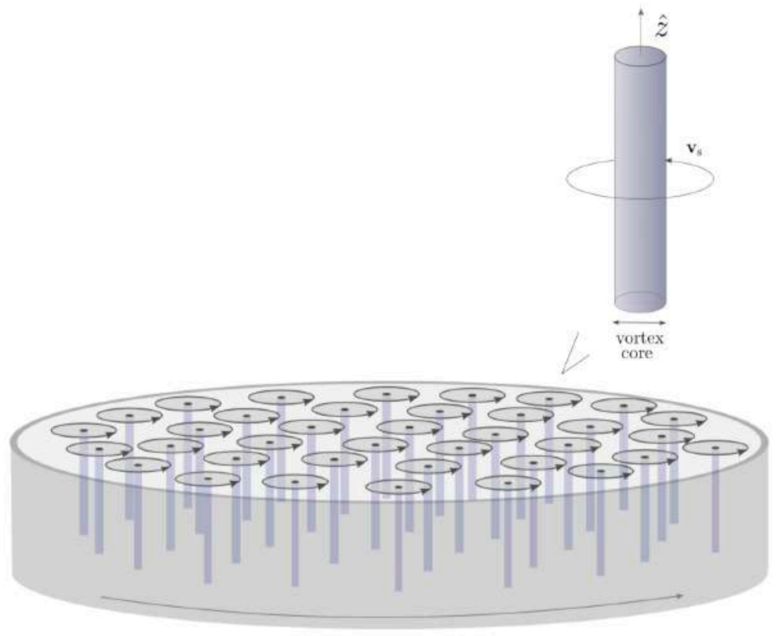
General defet in 3D

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



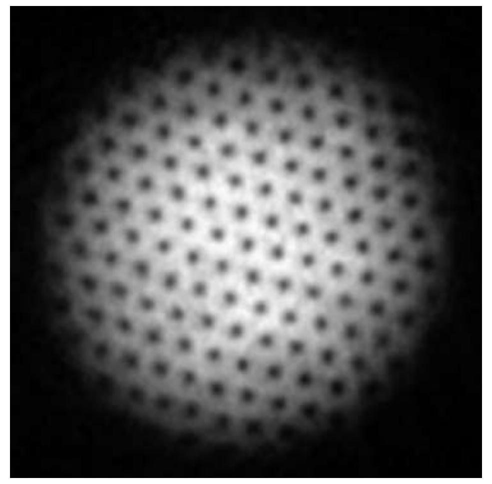
Self-interacting Fuzzy DM

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

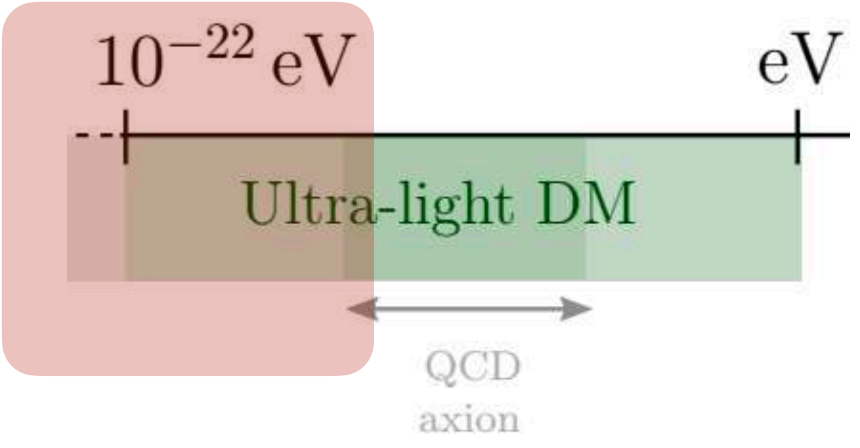


EF, 2020

© Martin Zwierlein.



Phenomenology



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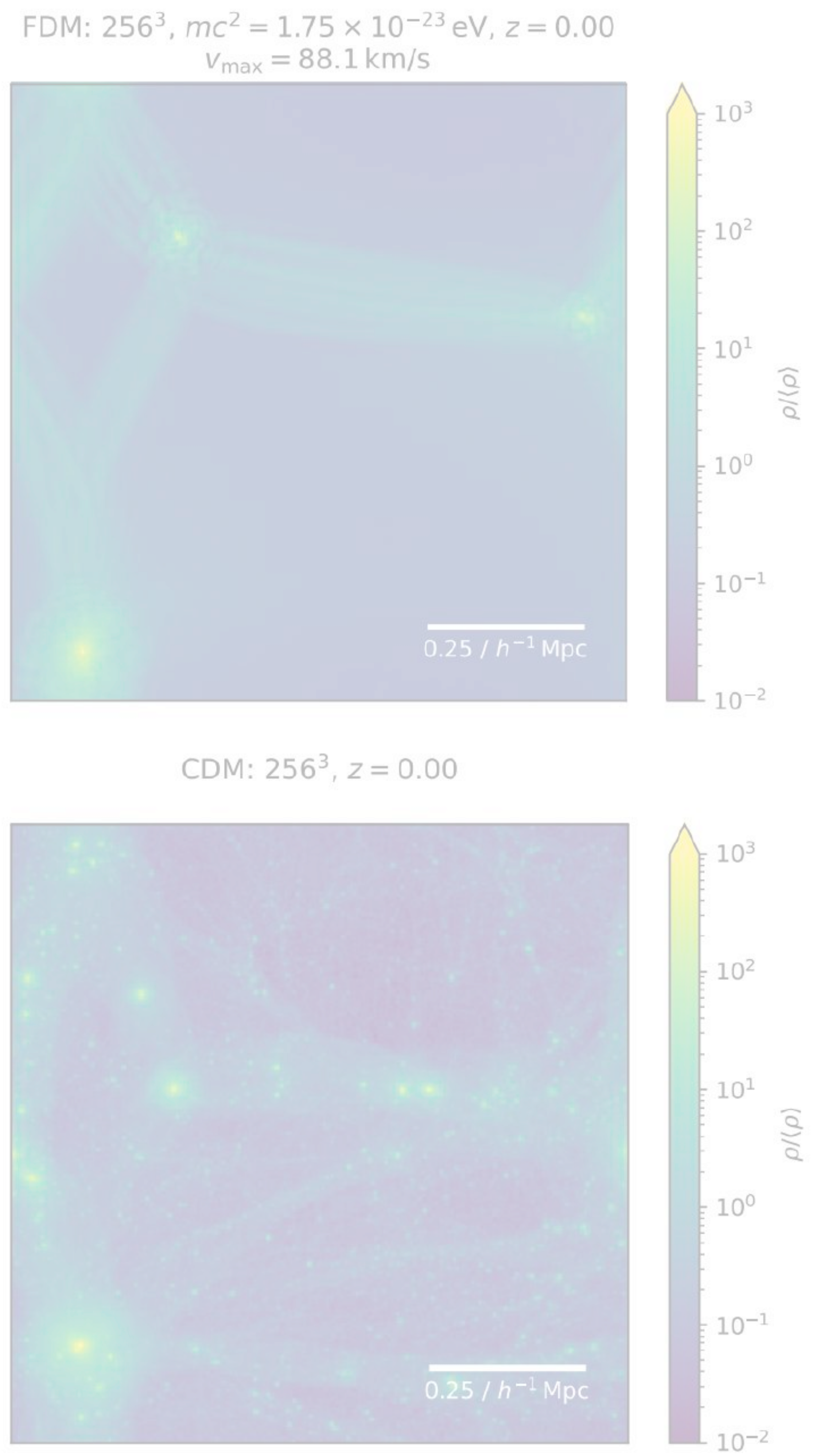

S. May et al. 2021

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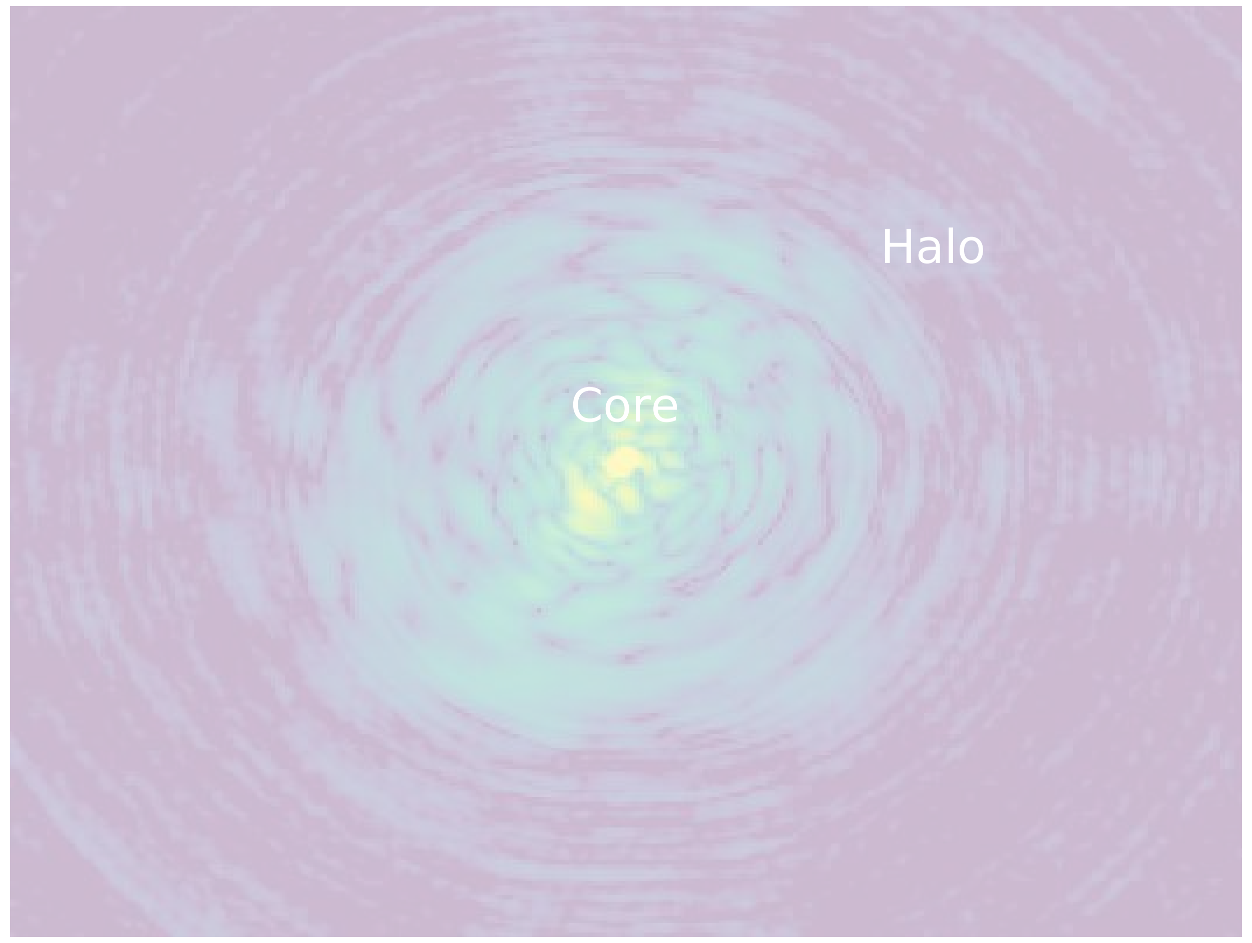
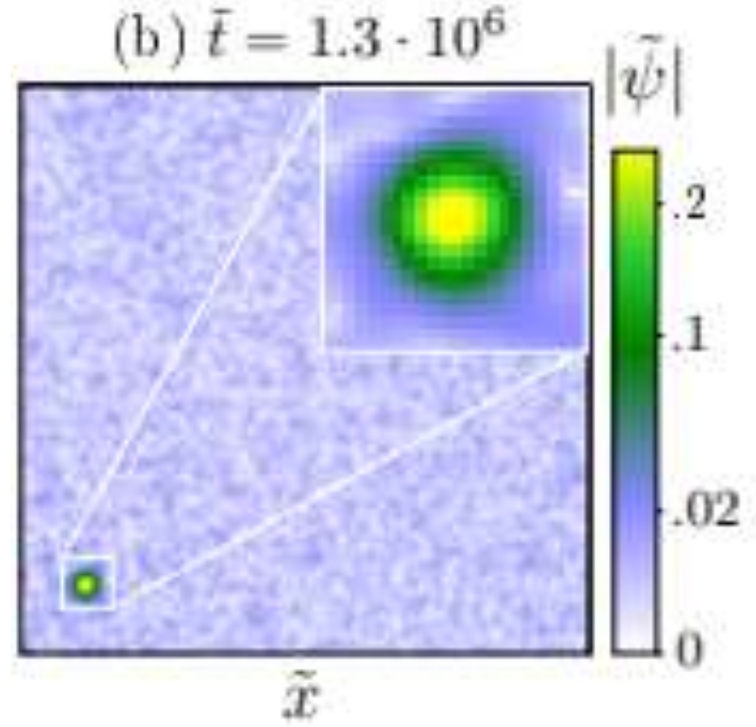


Dynamical effects



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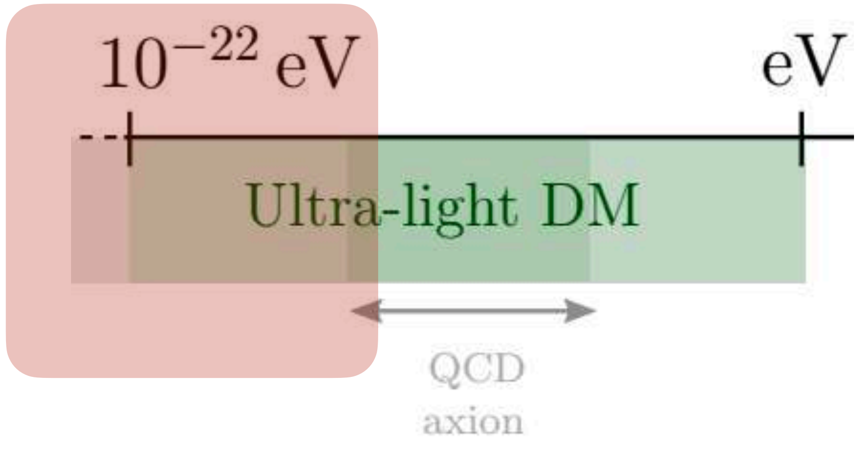
Mocz et al. 2017

Phenomenology

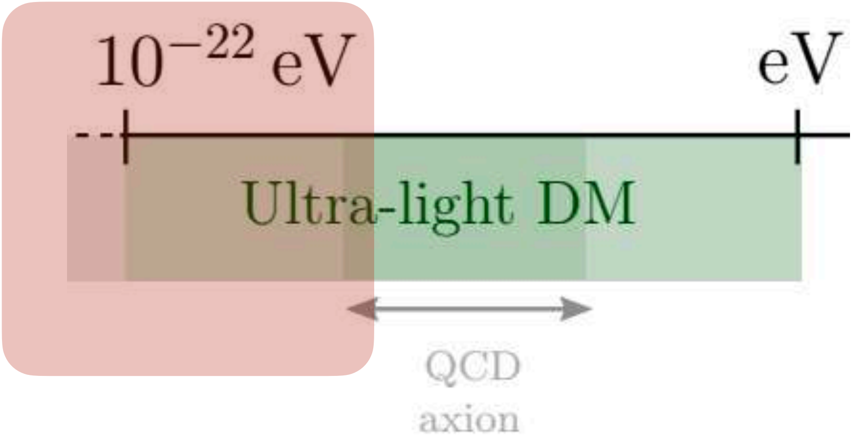
Dynamical effects

Relaxation, oscillation, friction, and heating



Phenomenology

Dynamical effects

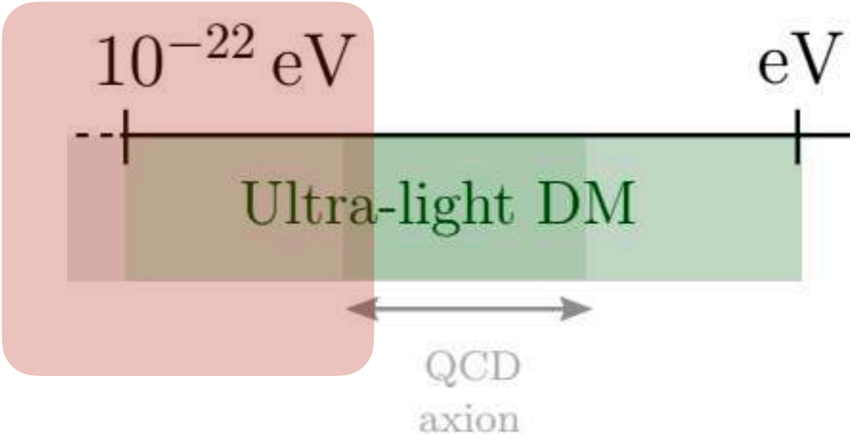


Relaxation, oscillation, friction, and heating

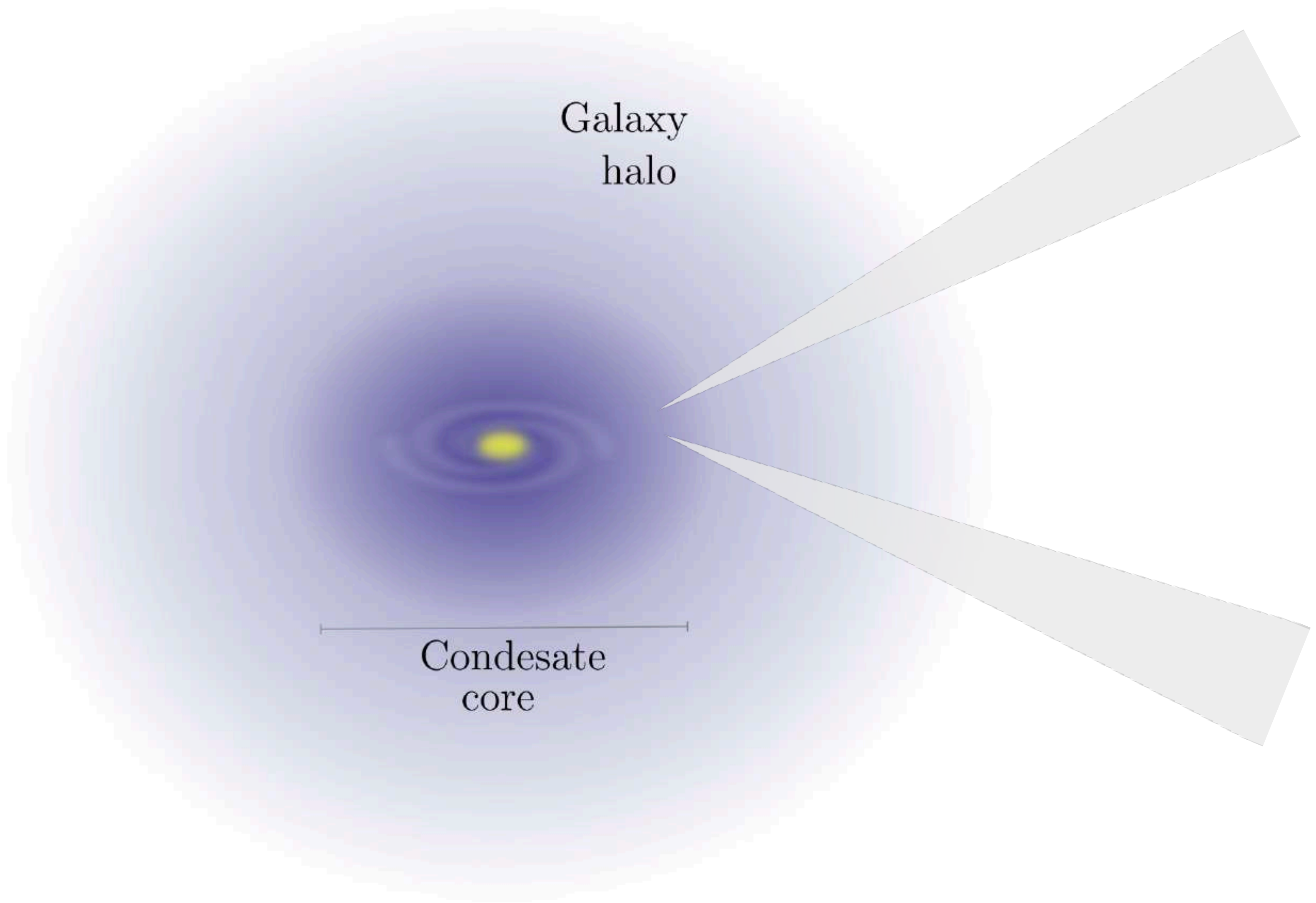
Formation of a BEC / superfluid

Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

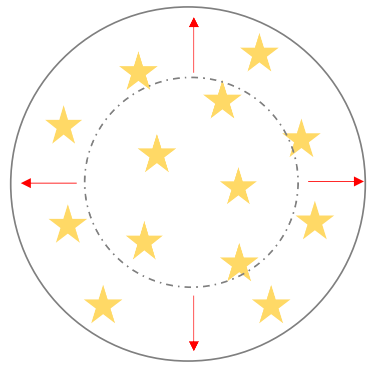


Heating

FDM granule

m_{eff}

System (star)
gains energy



Friction

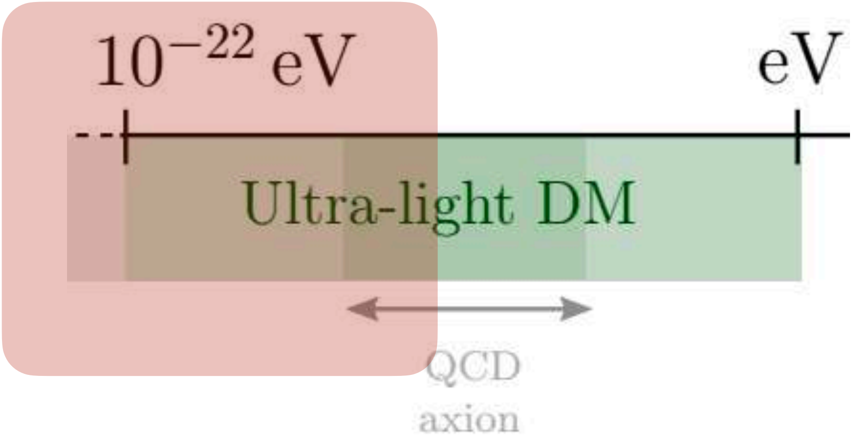
FDM granule

m_{eff}

Globular cluster

System (GC or BH)
loses energy

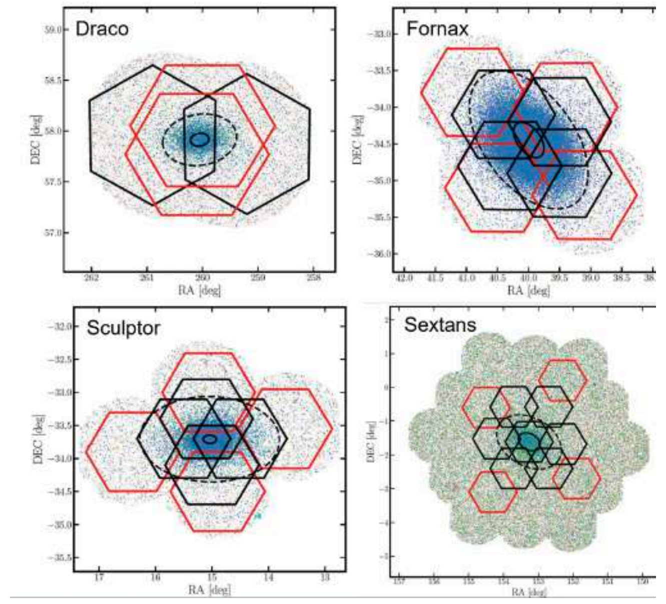
Observational implications and constraints



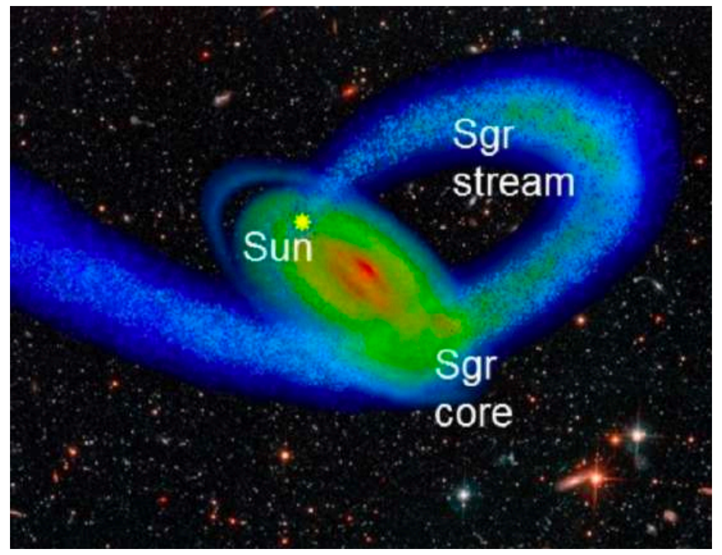
Galaxies

NASA and ESA

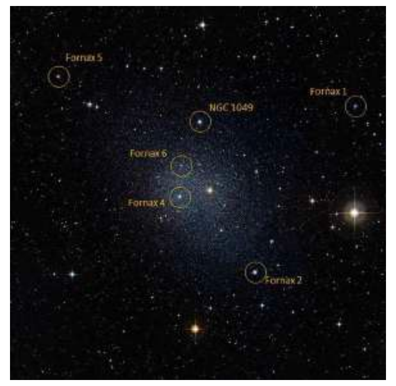
Dwarfs



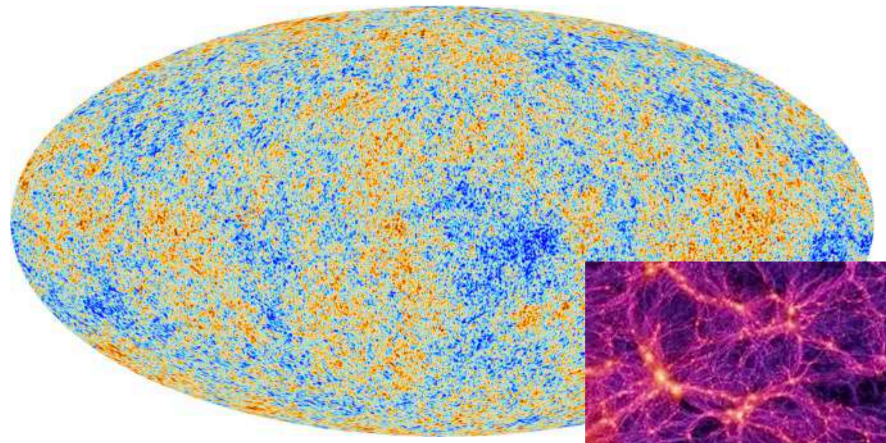
Stellar stream



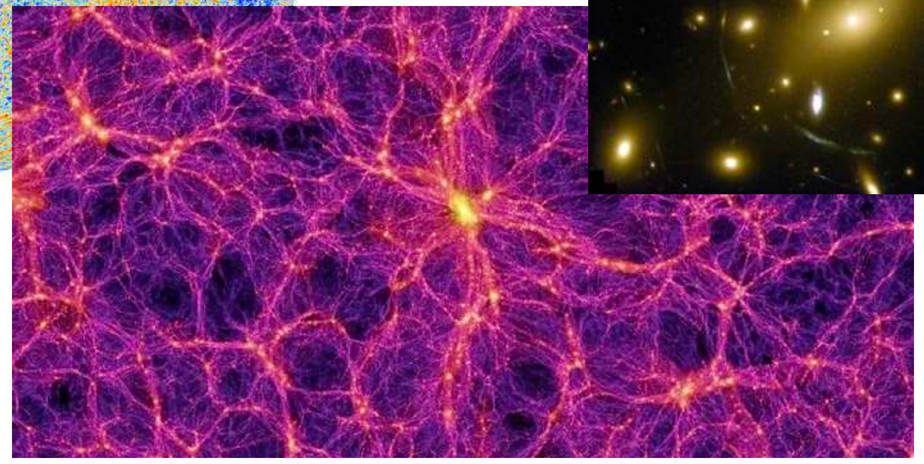
Globular clusters



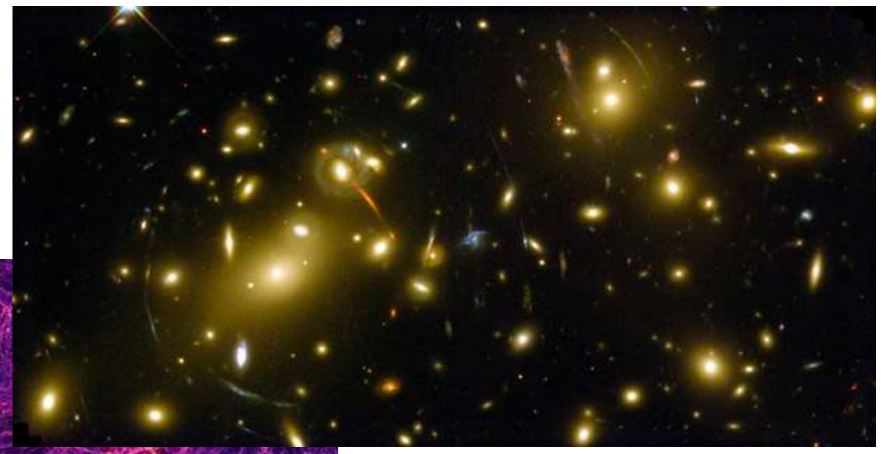
CMB+LSS



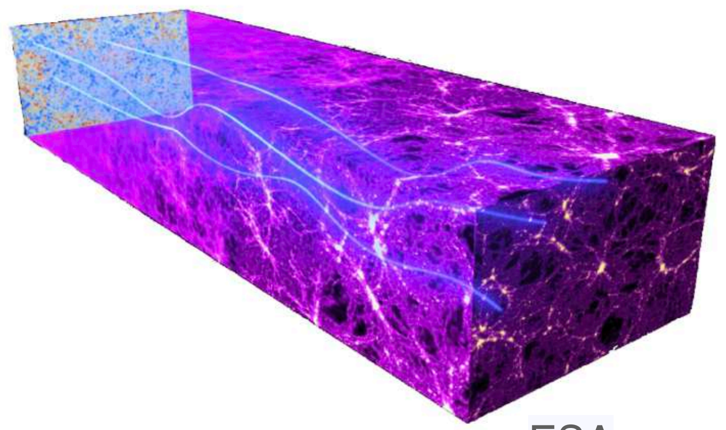
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

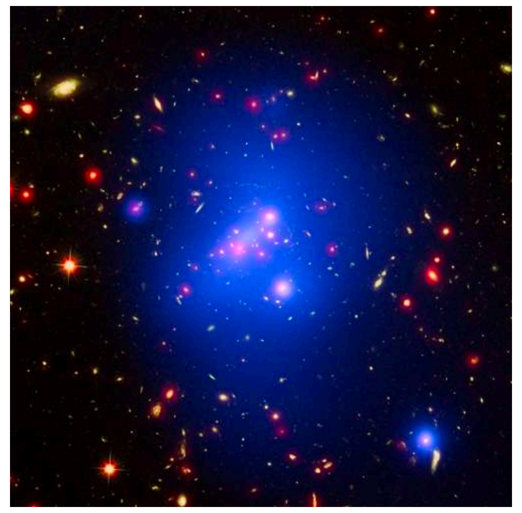


NASA and ESA



ESA

Clusters



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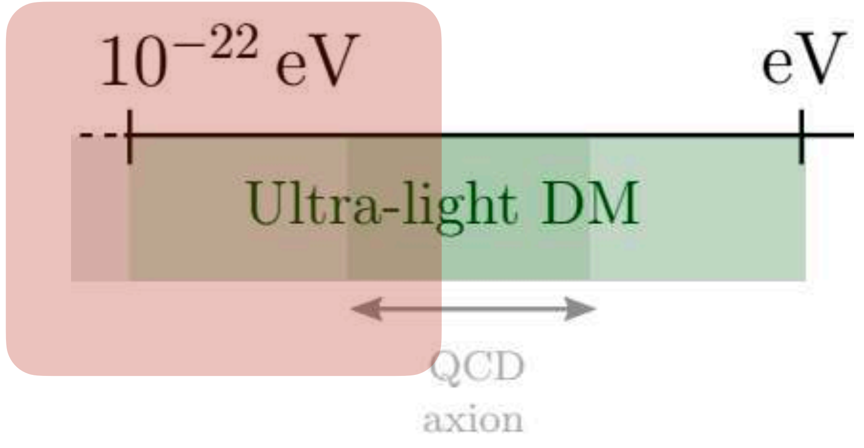
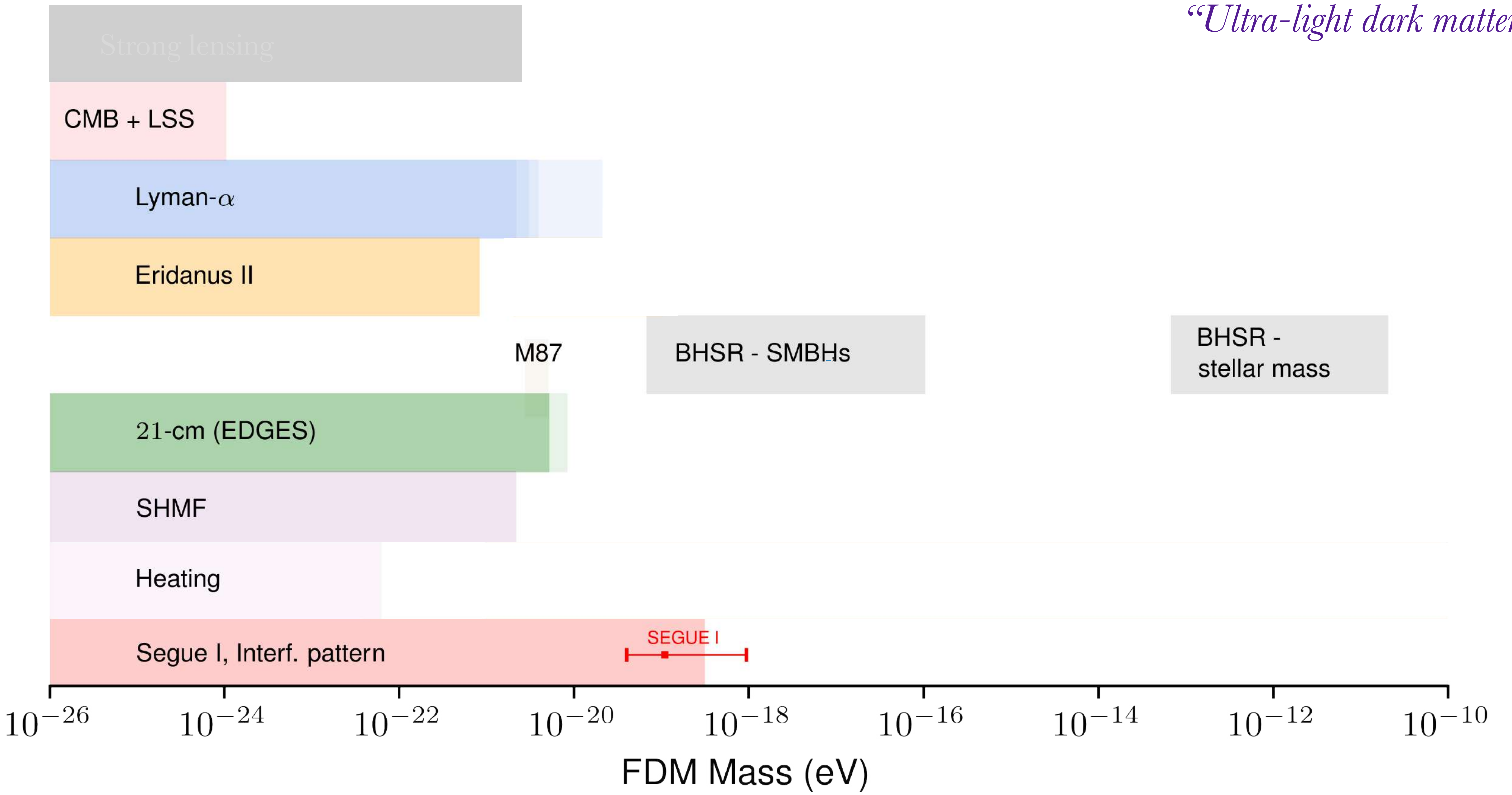
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



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



Bounds consider FDM is *all* DM

Observational implications and constraints

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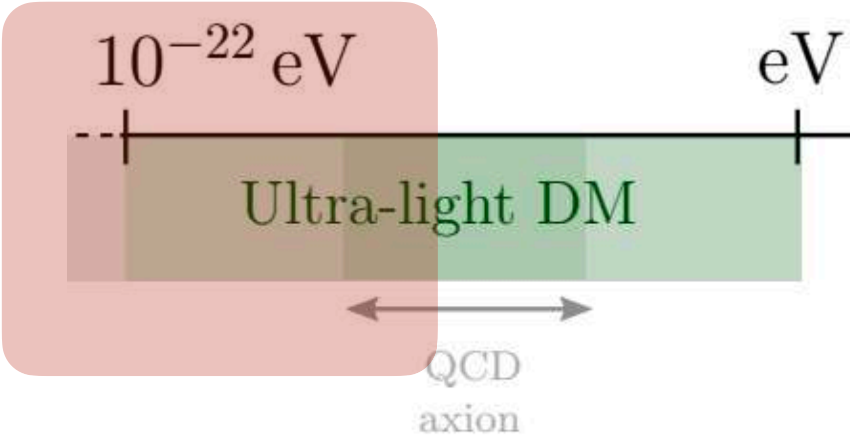
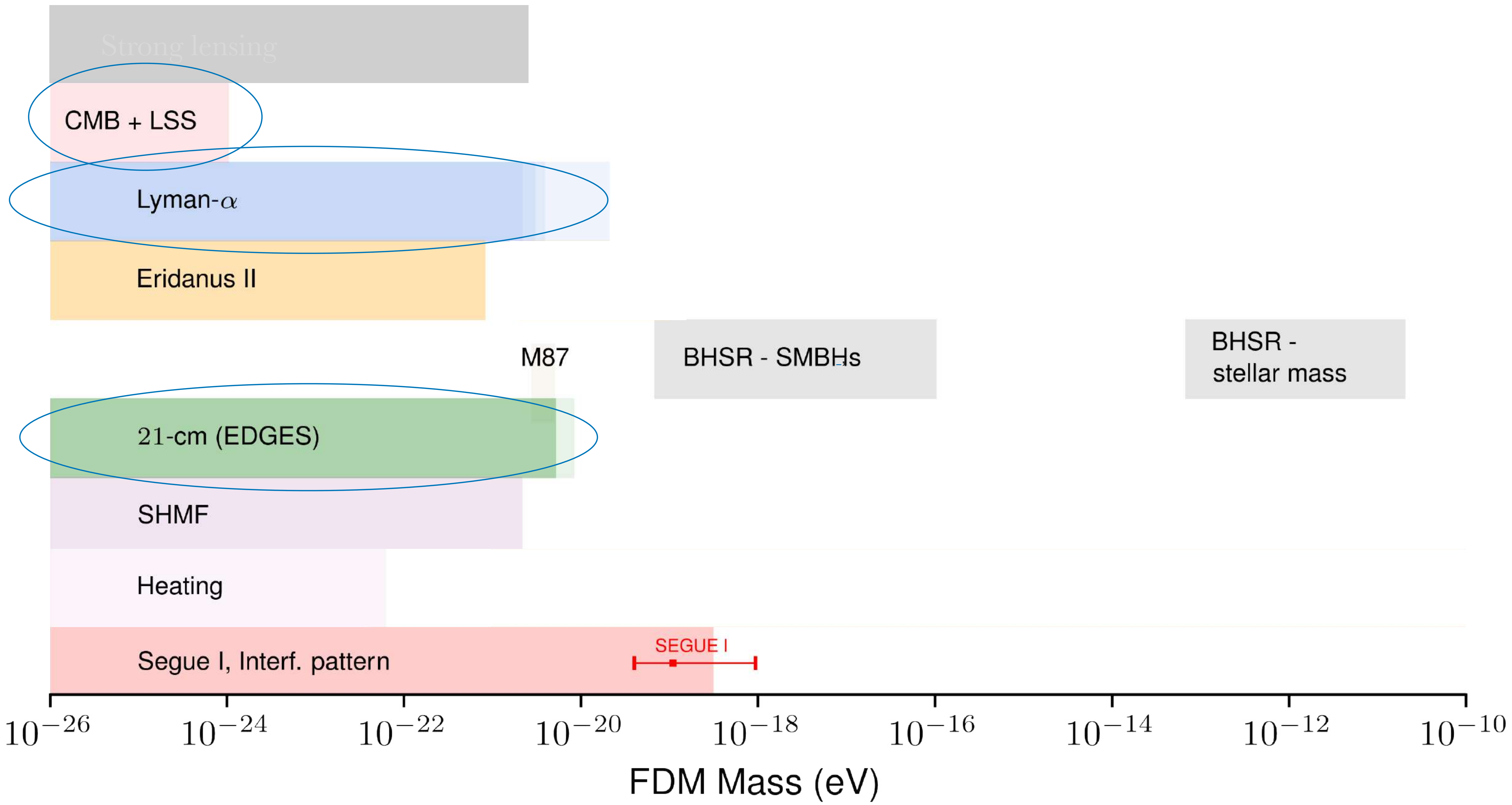
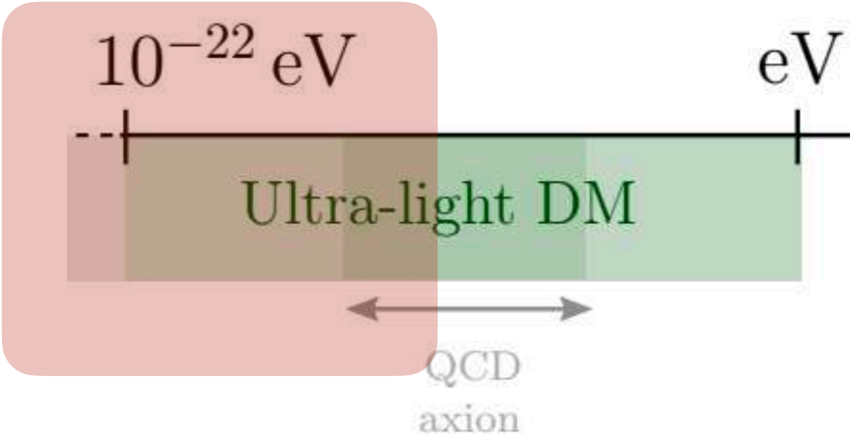




"Ultra-light dark matter", **E.F.**, 2020



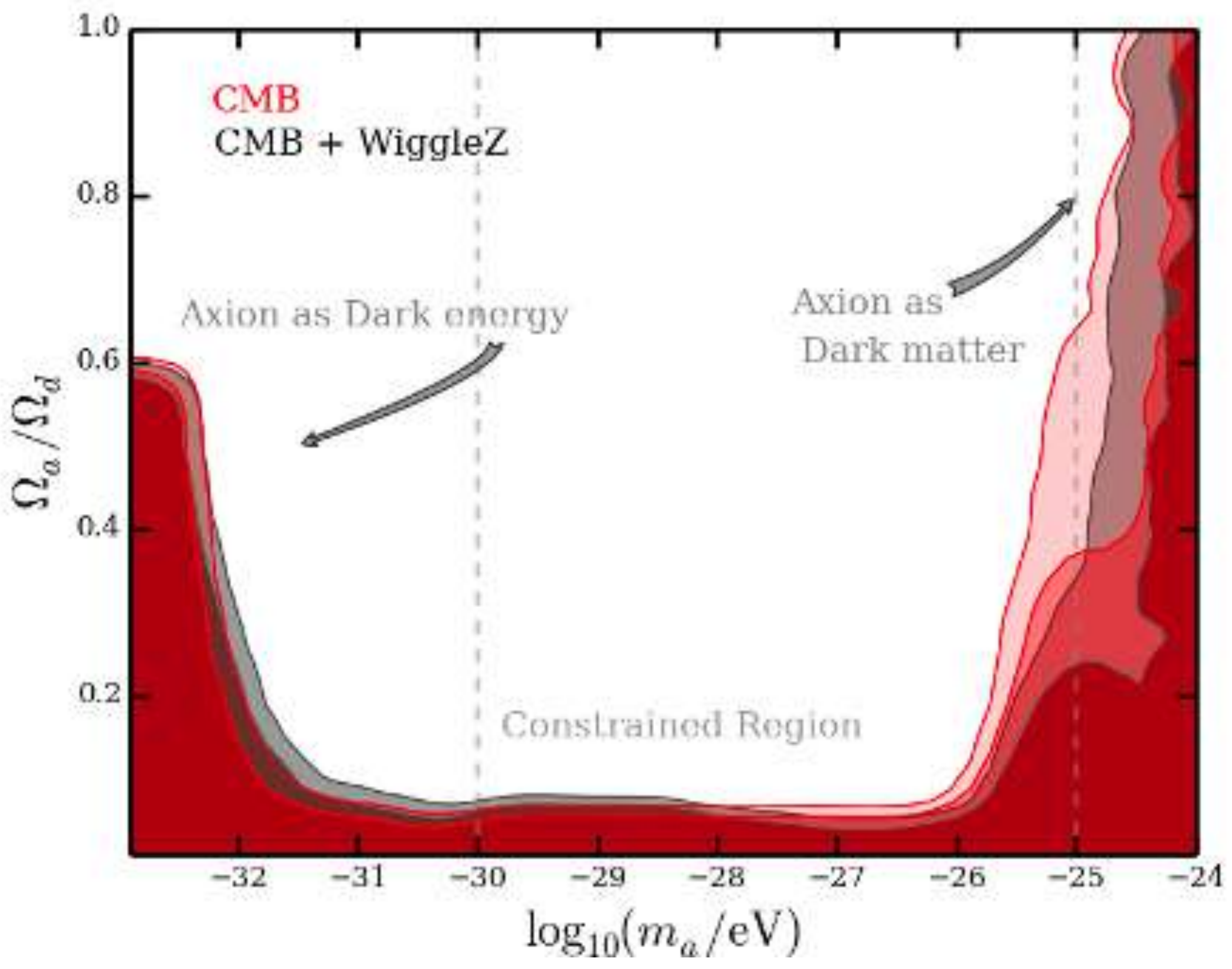
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

Suppression of small structures

CMB/LSS

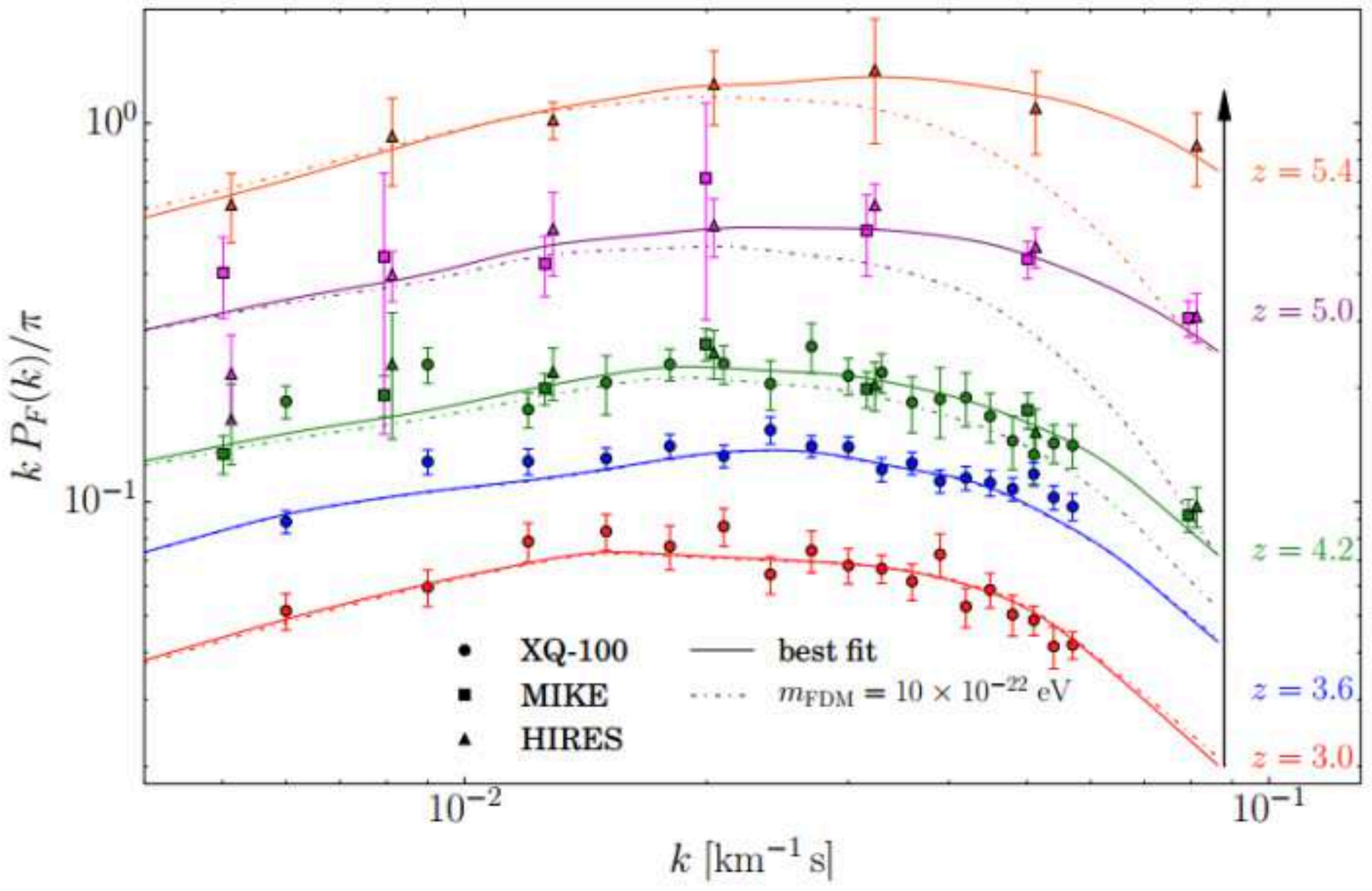
Hlozek et al, (2015, 2018)



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

Lyman alpha

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

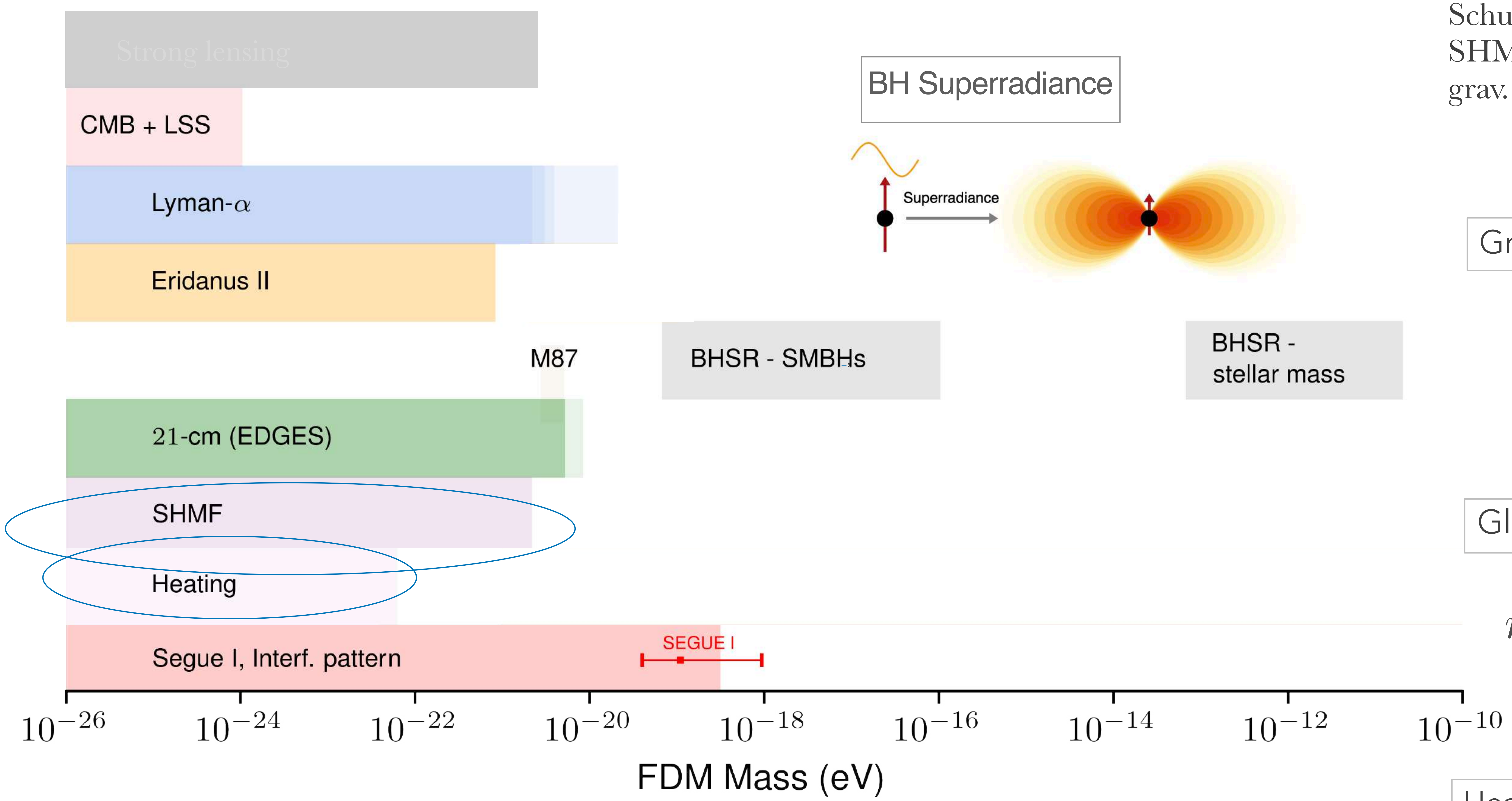


$$m \gtrsim 2 \times 10^{-20}\,\mathrm{eV}$$

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

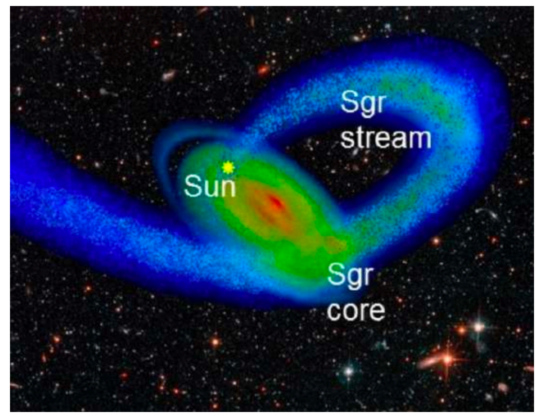
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



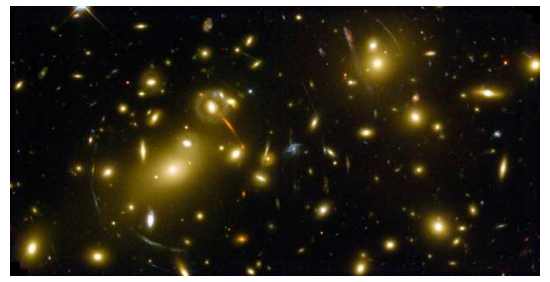
Suppression of small structures

Stellar streams



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

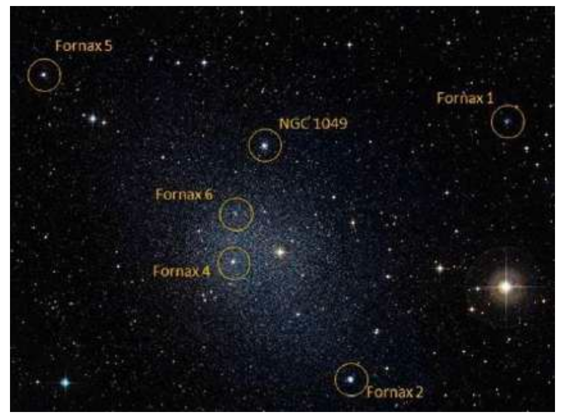
Grav. lensing



Dynamical effects

Globular clusters

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



ESO/Digitized Sky Survey 2

Lancaster et al. 2020

Heating of the MW disk

Church et al. 2019

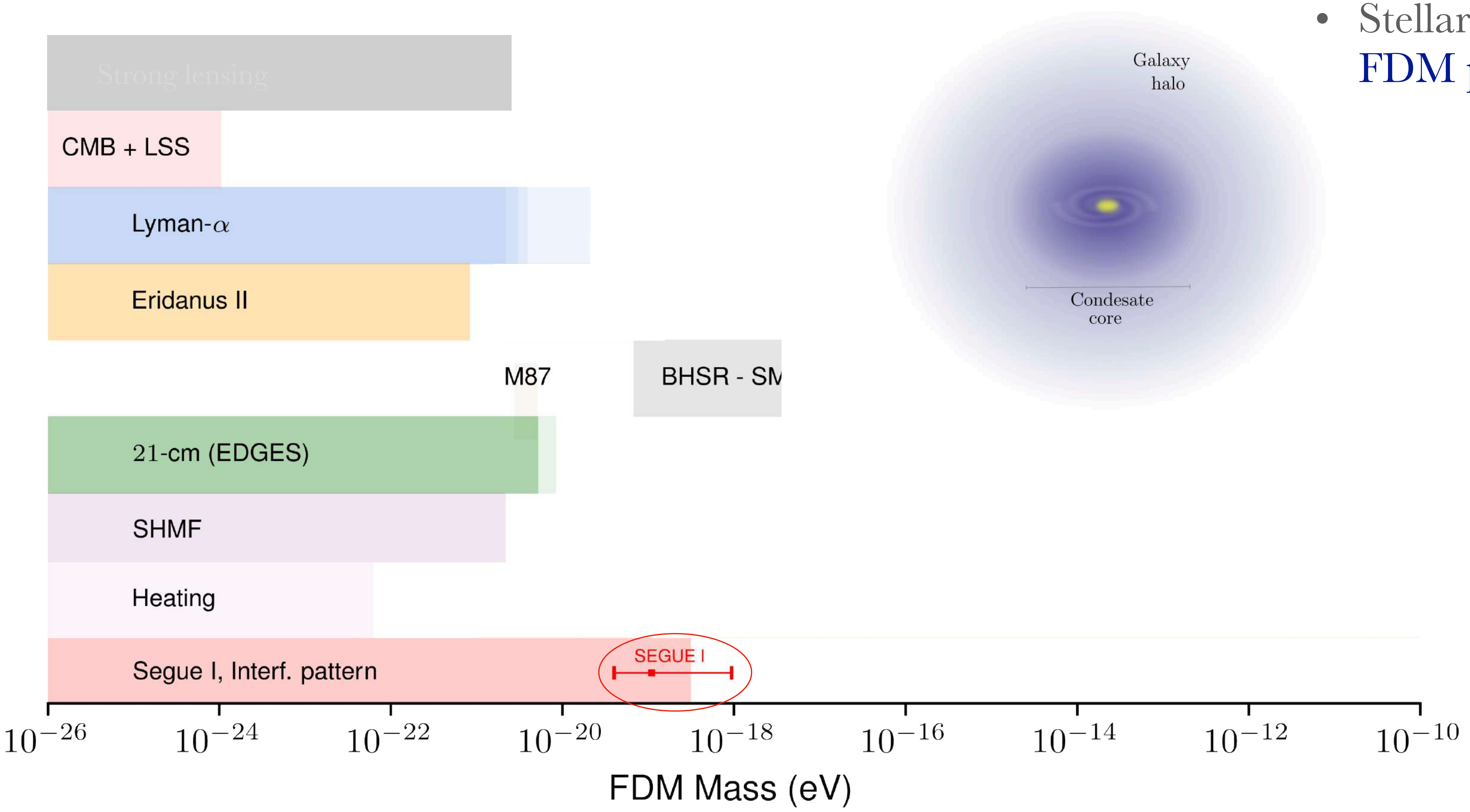
$$m > 0.6 \times 10^{-22}\,\mathrm{eV}$$

Observational implications and constraints

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

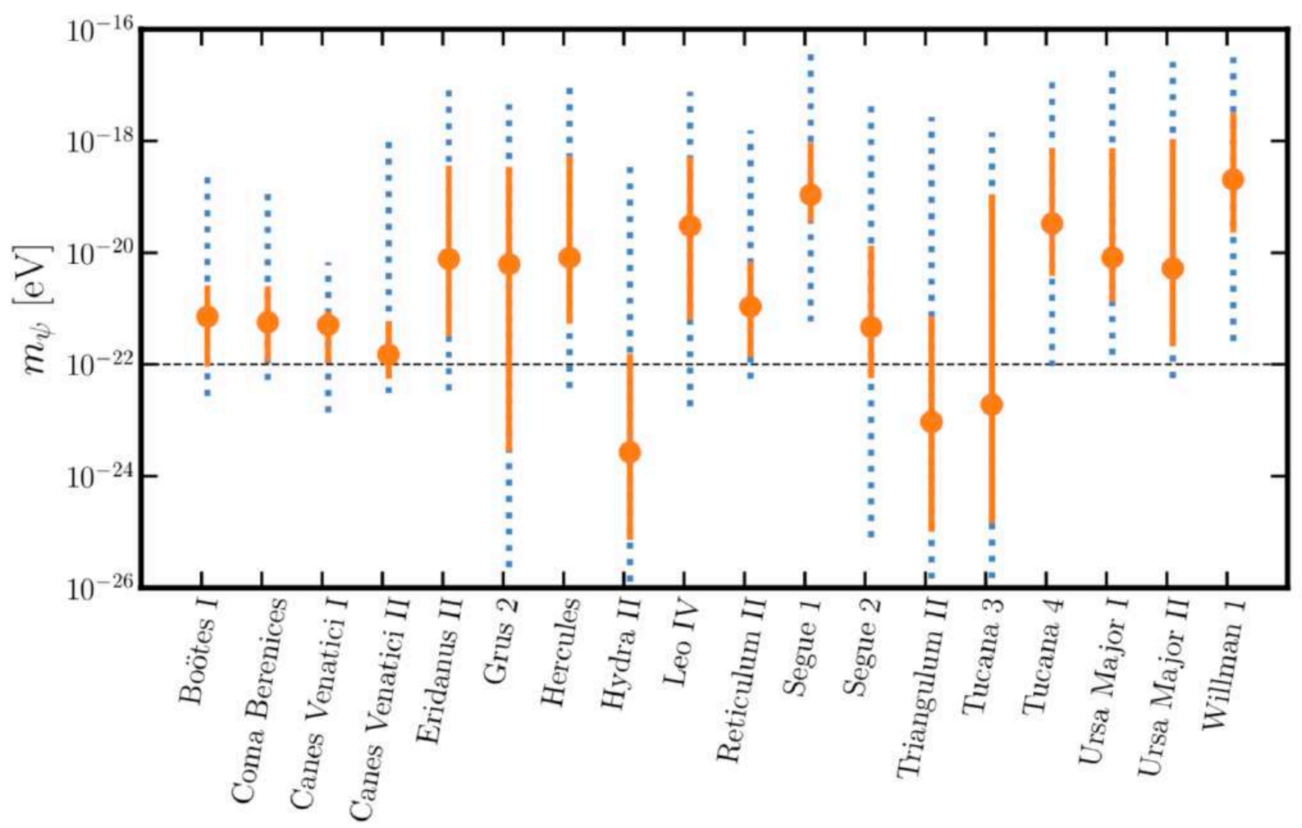


Ultra faint dwarfs

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

FDM SIMULATIONS

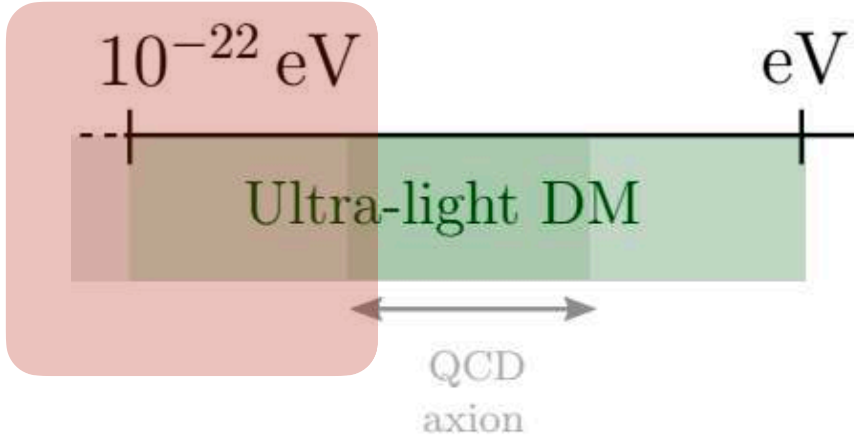
$$\rho(r) = \begin{cases} \rho_{\text{soliton}} \simeq \dfrac{\rho_c}{\left[1 + 0.091(r/r_c)^2\right]^8}, & r < r_\epsilon \\ \rho_{\text{NFW}} = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, & r > r_\epsilon \end{cases}$$

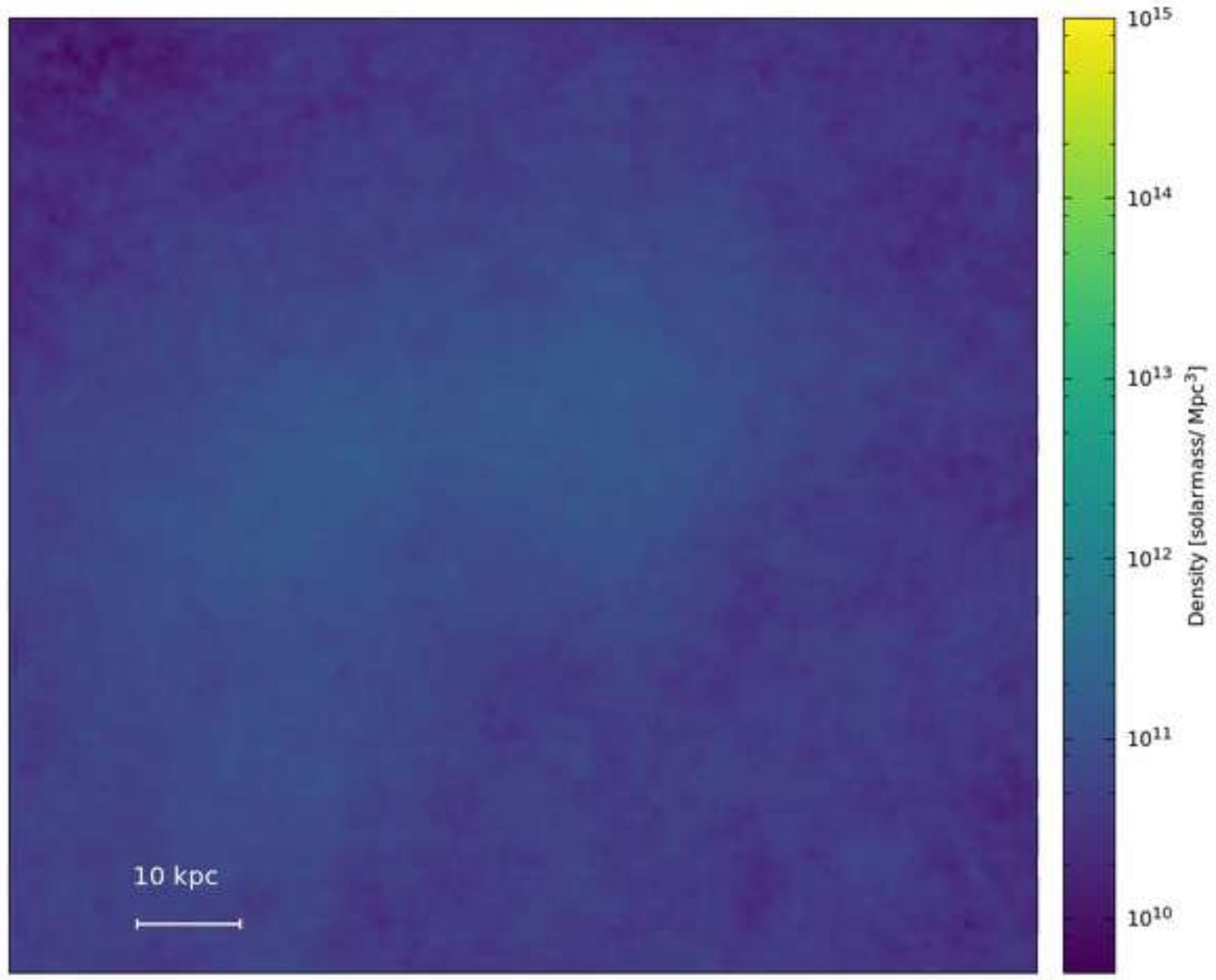


Preference for higher mass

New observables/new probes

Interference pattern





Simulation by Jowett Chan

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

PROBES:

- Strong lensing
- Stellar streams
- Heating

} Gravitational probes

Previous studies:

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

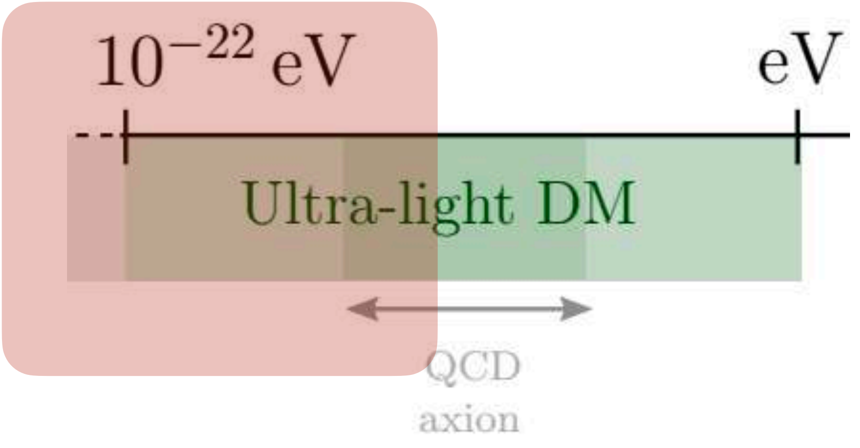
Stellar streams:
Neal Dalal, Jo Bovy Lam Hui, Xinyu Li, 2020

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

Sub-galactic power spectrum
Kawai, Oguri (2021)

Dwarfs
N. Dalal, A. Kravtsov, 2022

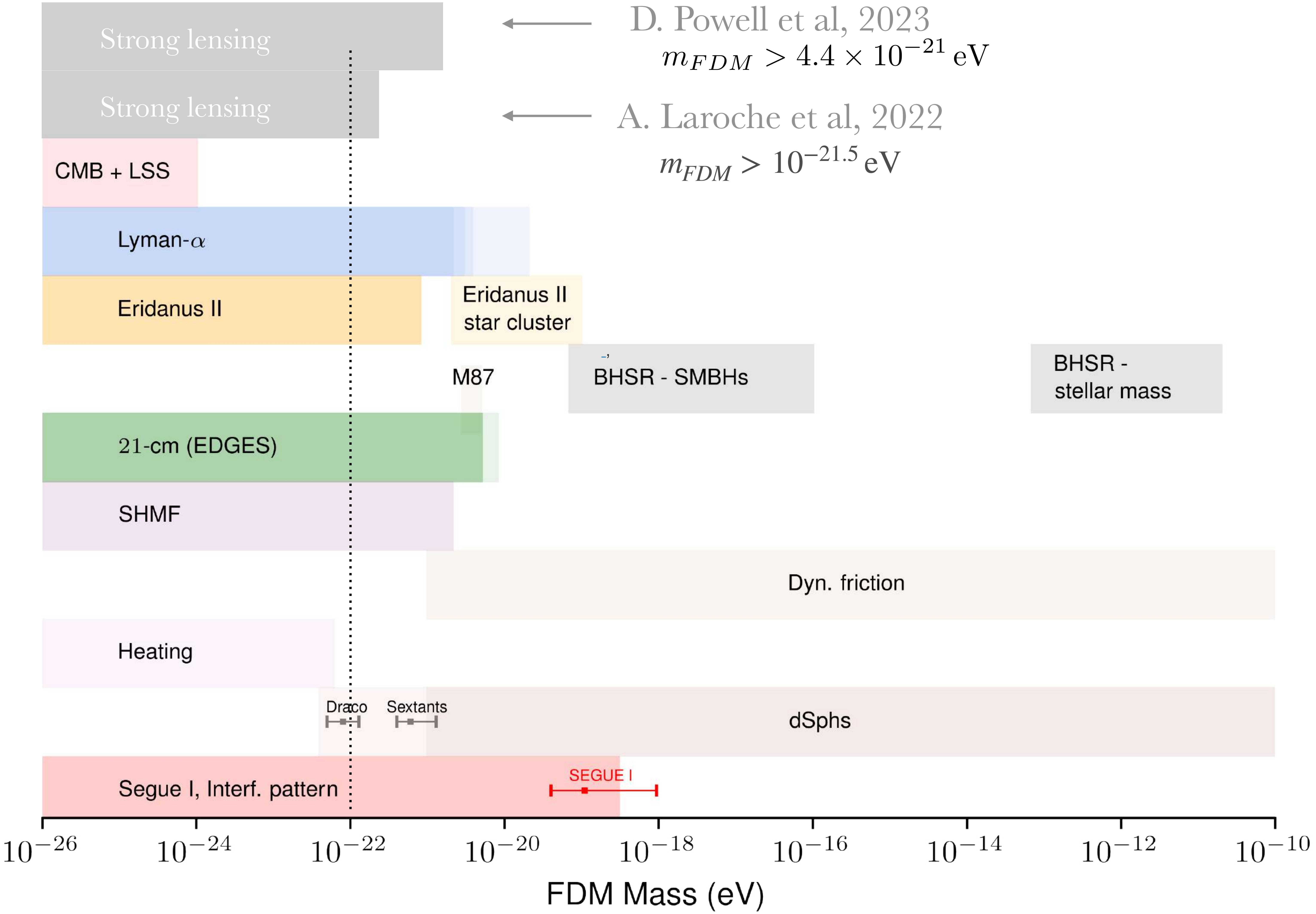
Interference patterns - granules



Strong lensing

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

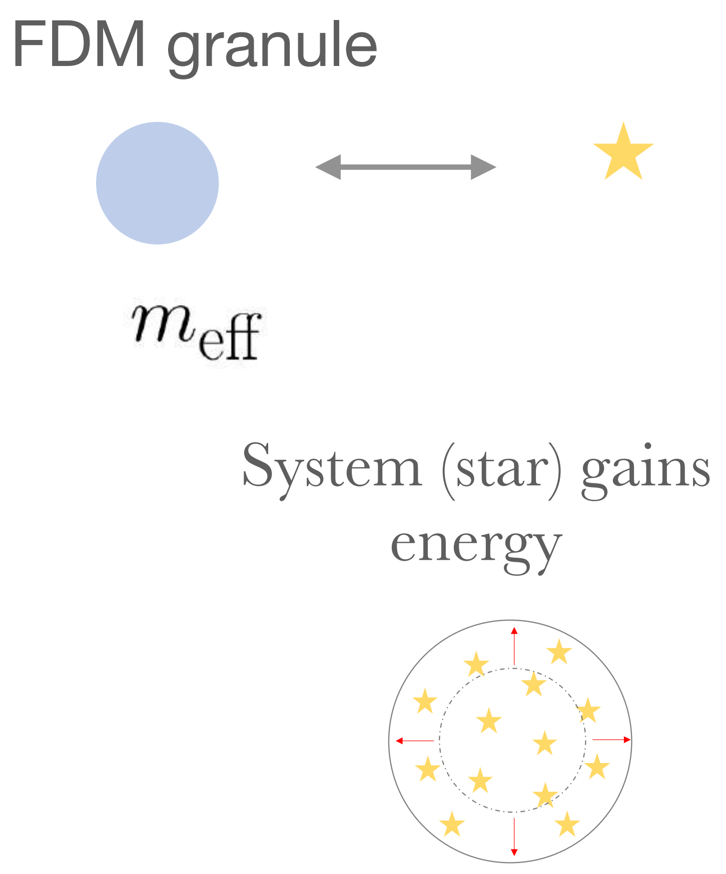
A. Laroche et al, 2022
$m_{FDM} > 10^{-21.5}$ eV



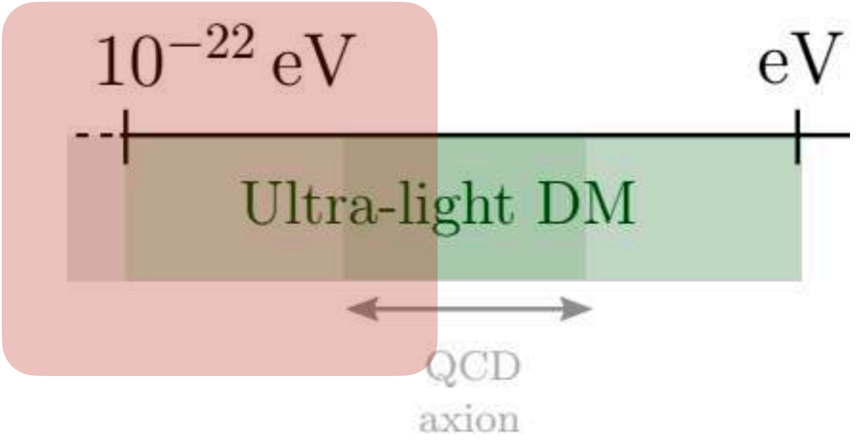
Stellar heating

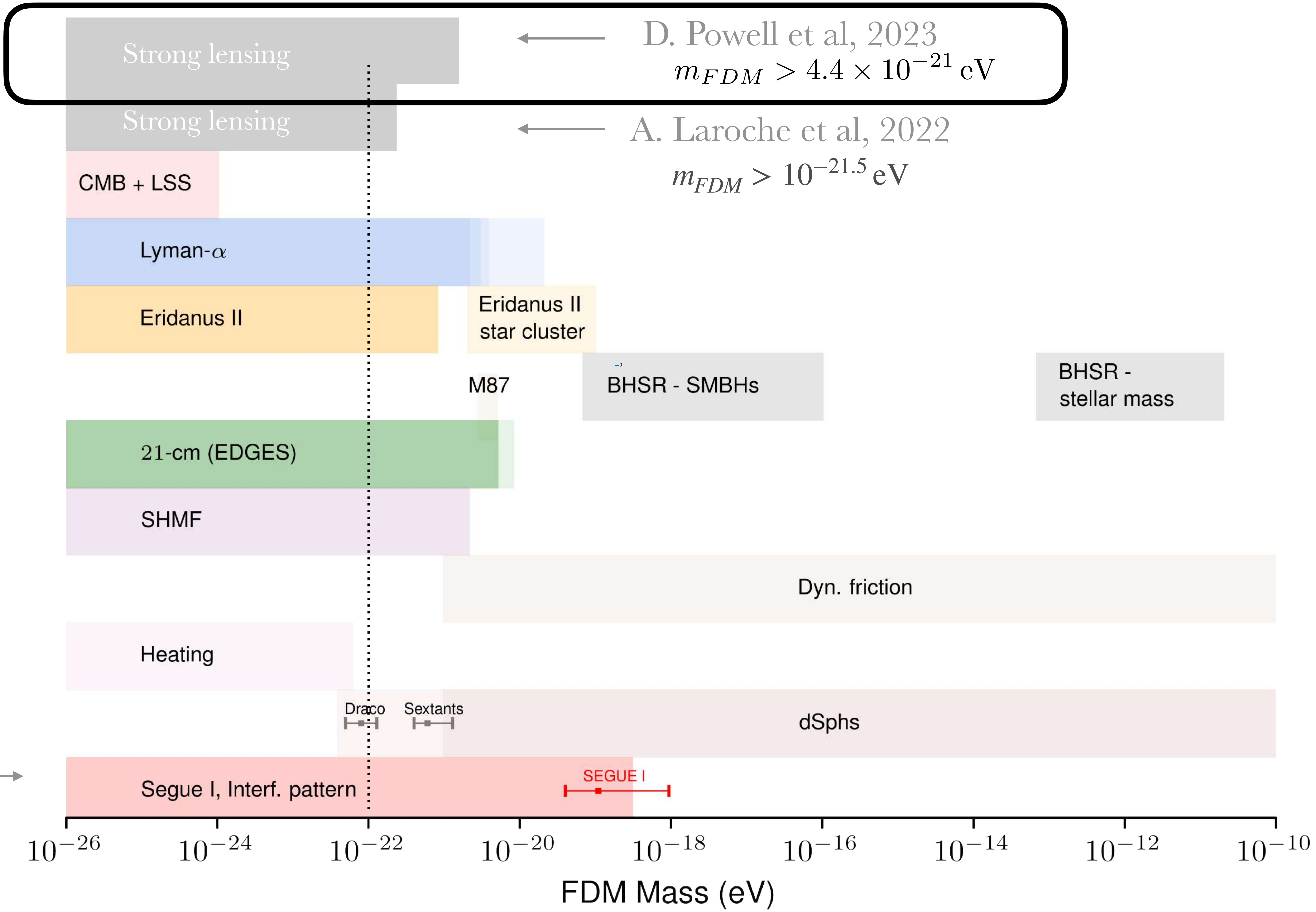
Dalal et al, 2022
$m_{FDM} > 3 \times 10^{-19}$ eV

Heating



Interference patterns - granules



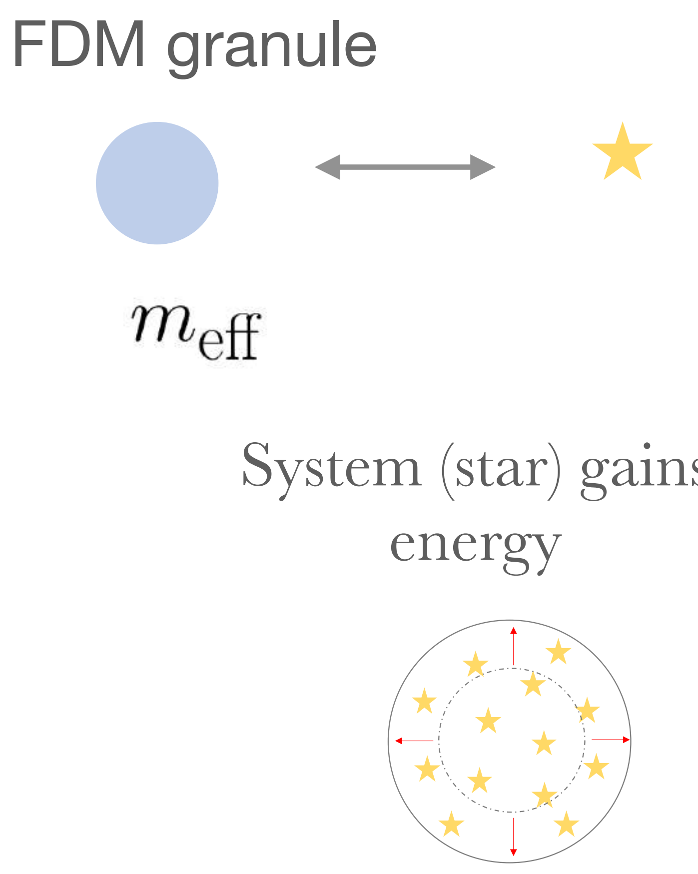


<u>Stellar heating</u>

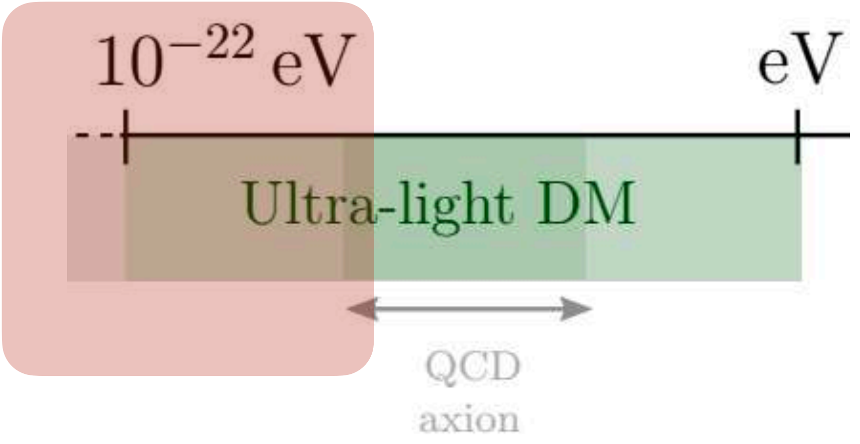
Dalal et al, 2022

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

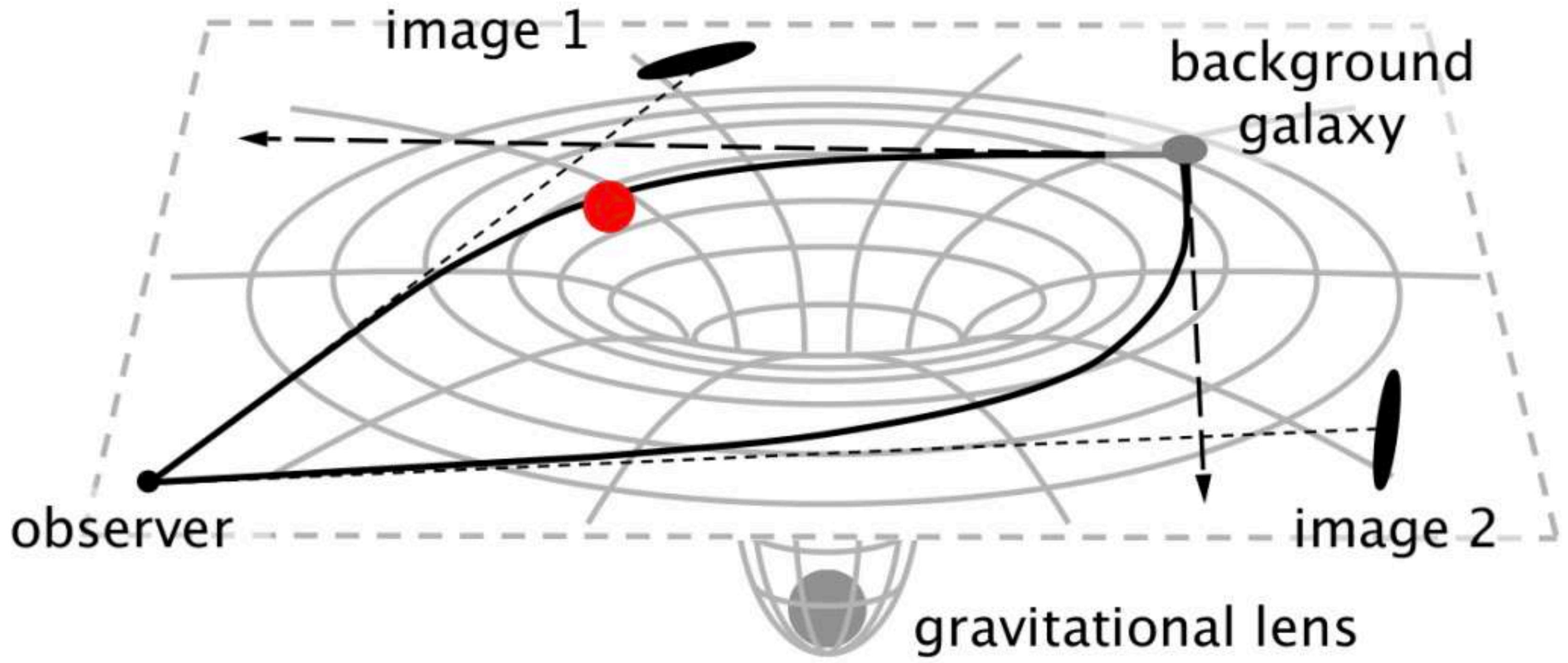
Heating

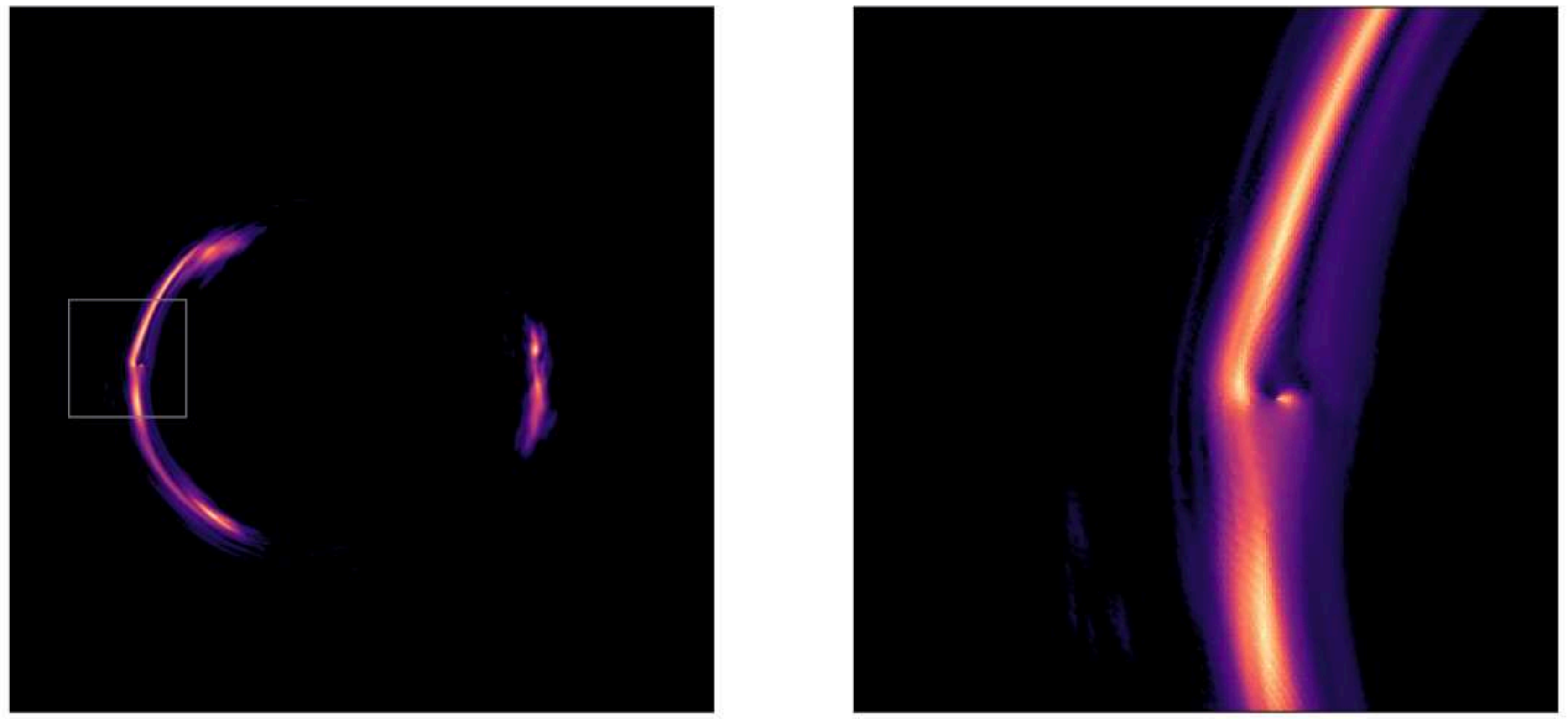


Strong lensing



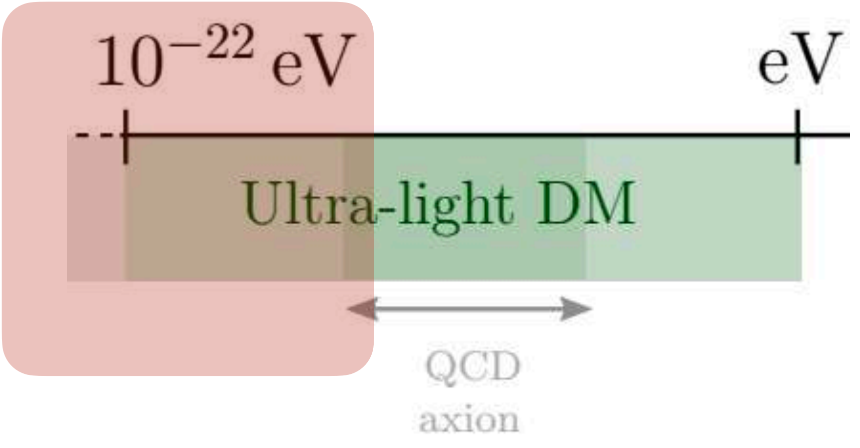
Low mass perturber with lensing



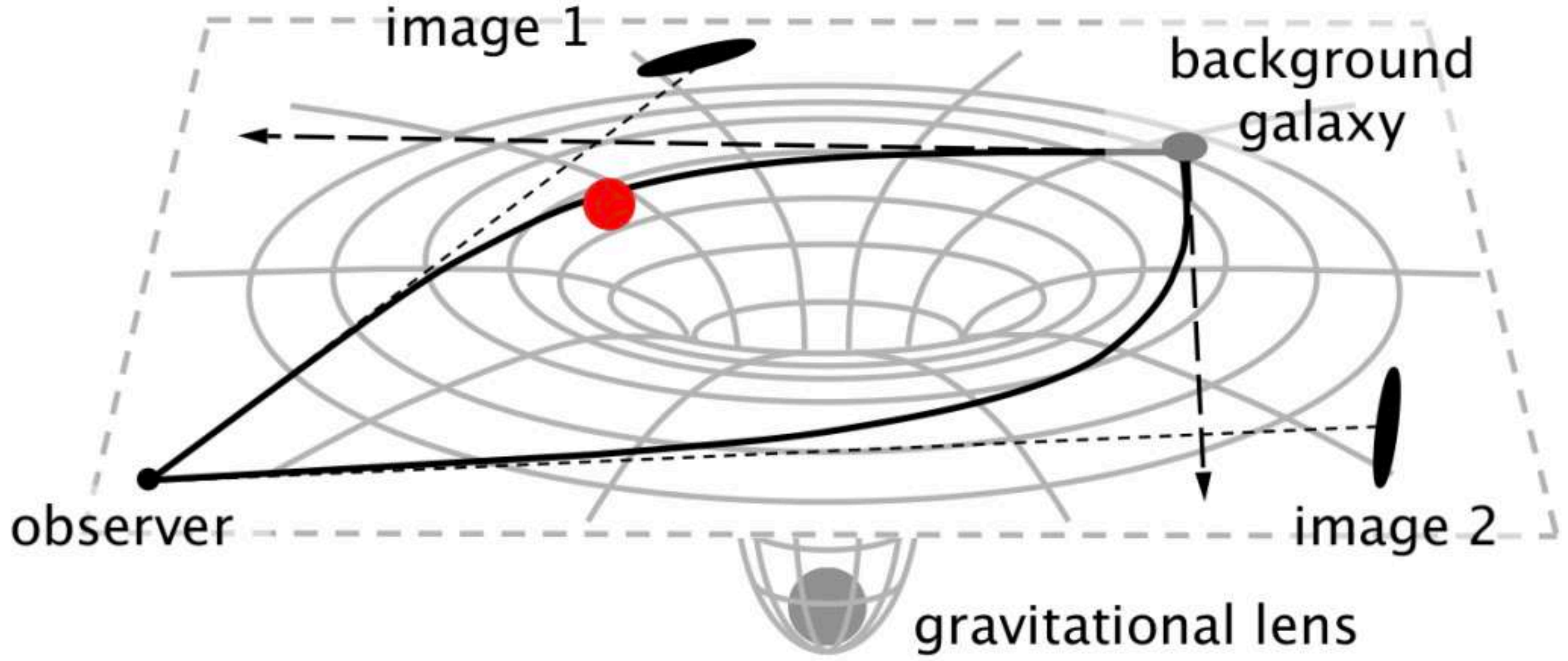


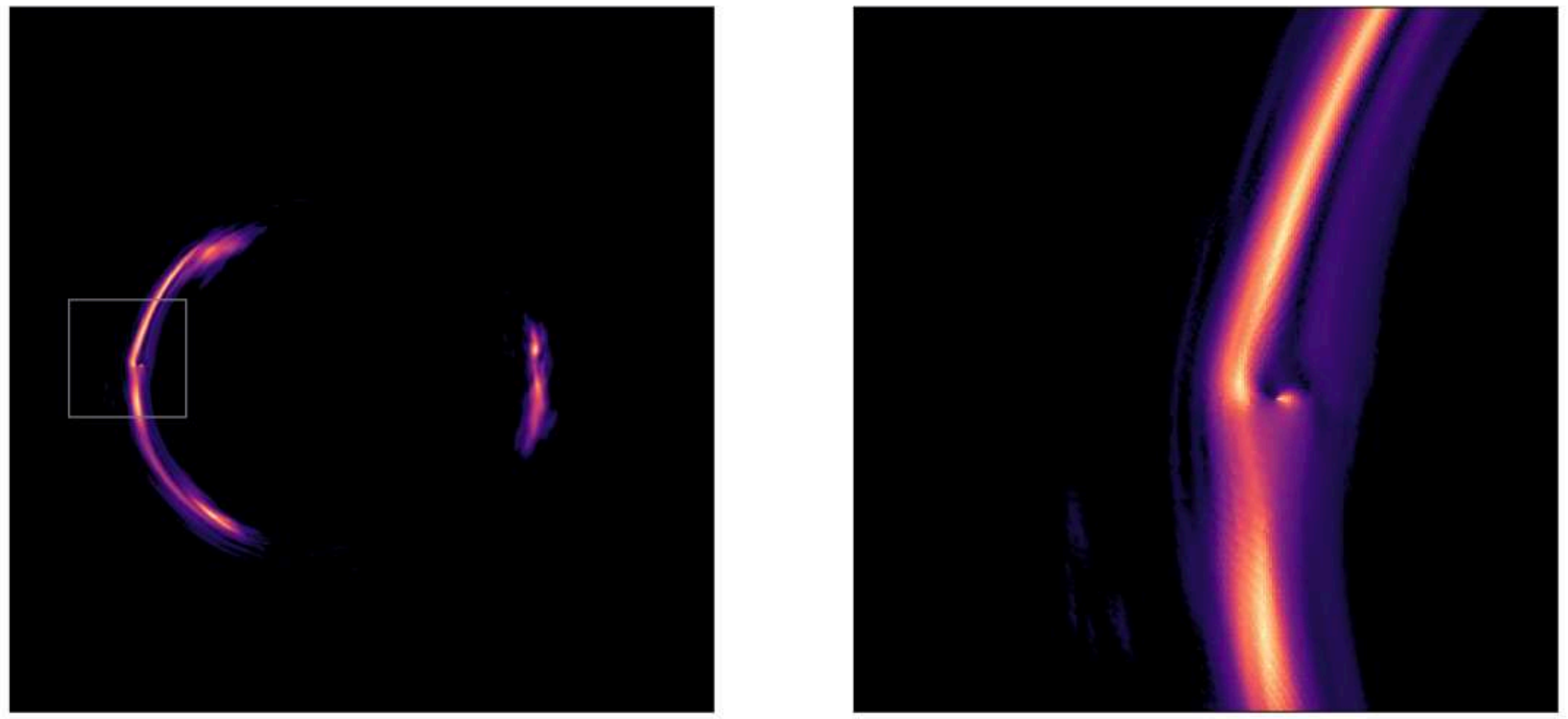
- Strong lensing: powerful probe of substructure
- Sensitivity is limited by angular angular resolution
- Roughly speaking, the resolution must be better than the scale radius of the perturber

Strong lensing



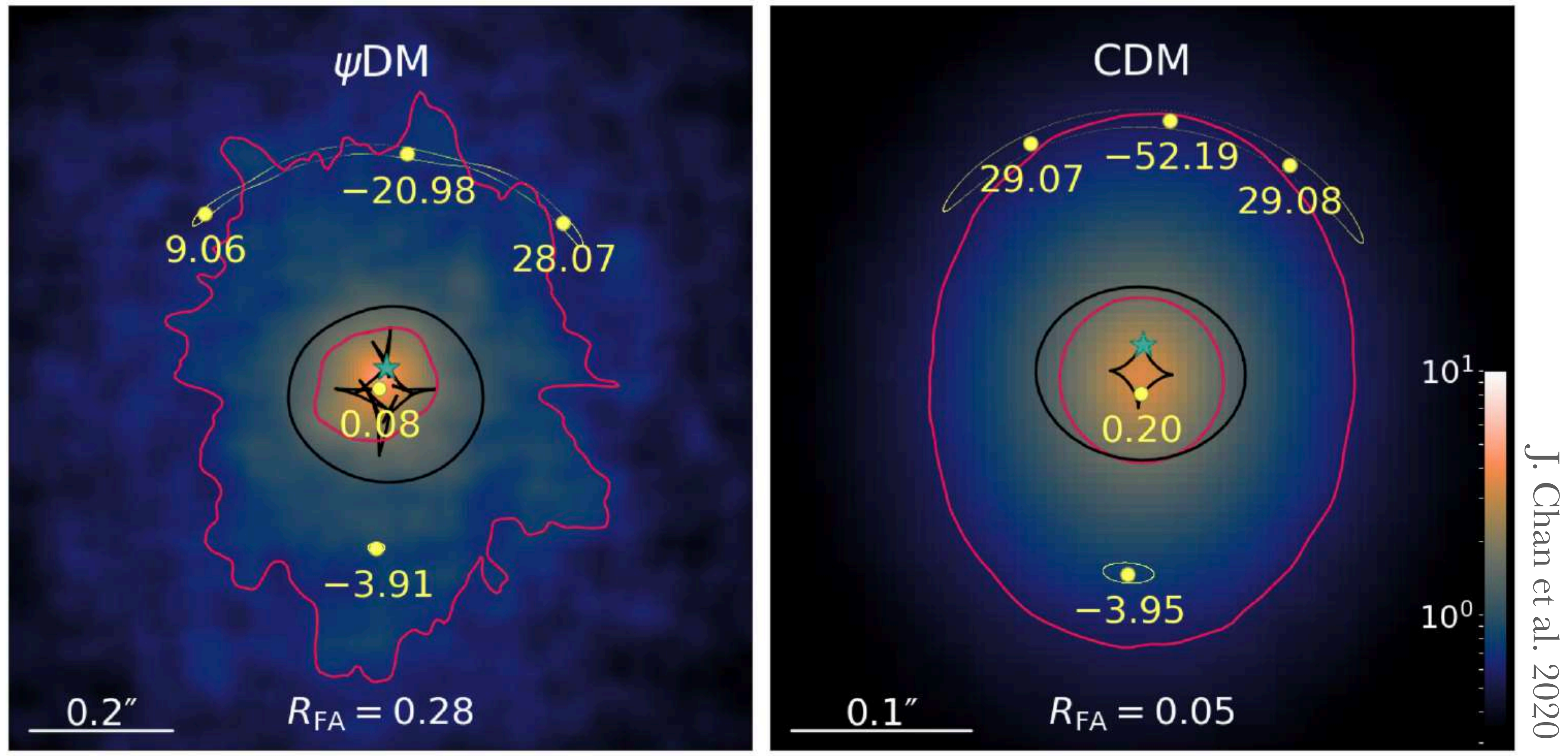
Low mass perturber with lensing





Presence of granules

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



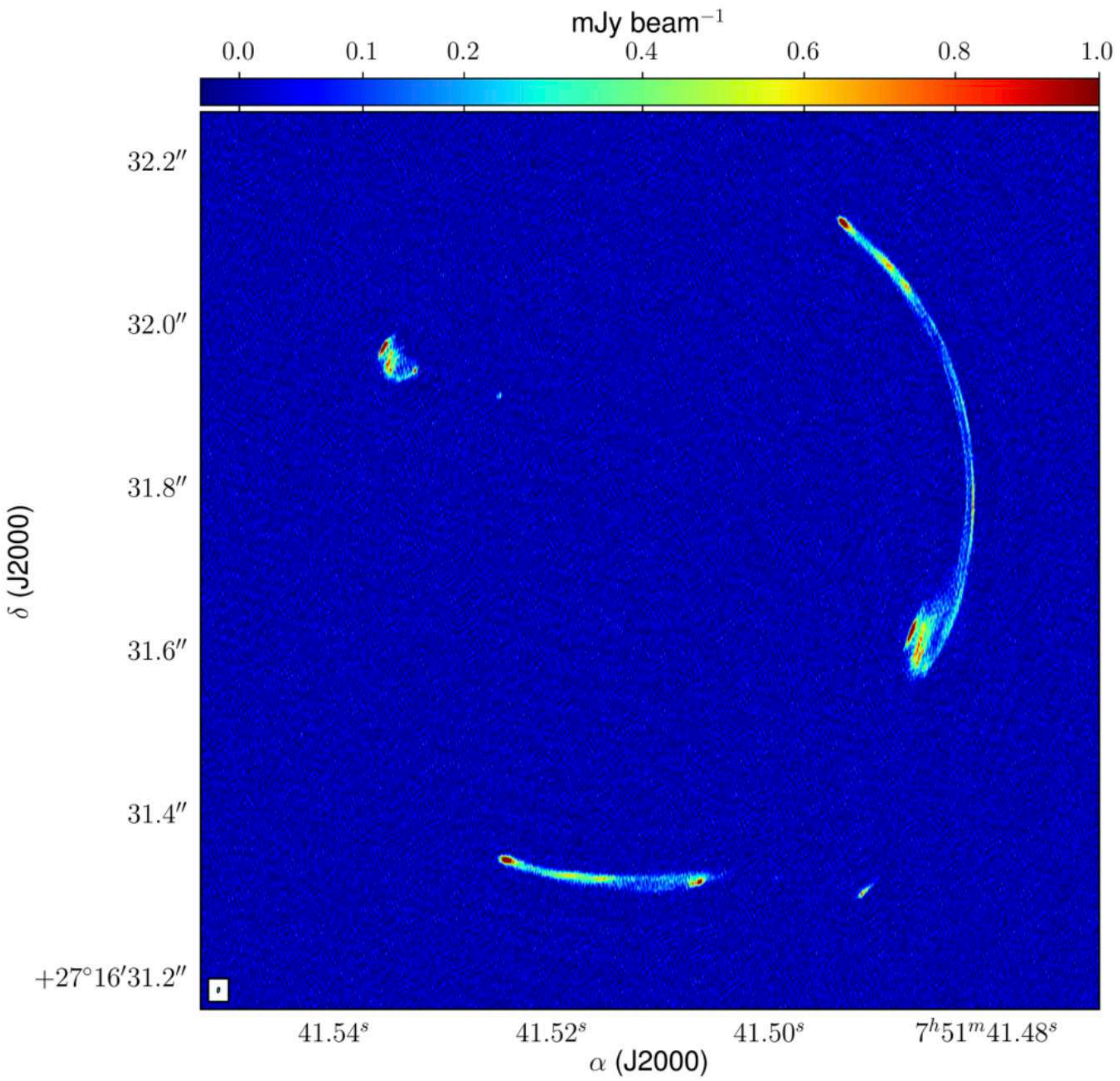
Fuzzy lens: fluctuating tangencial critical curve; flux ratio anomalies also sizable.

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

Strong lensing

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

MG J0751+2716



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

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

Strong lensing

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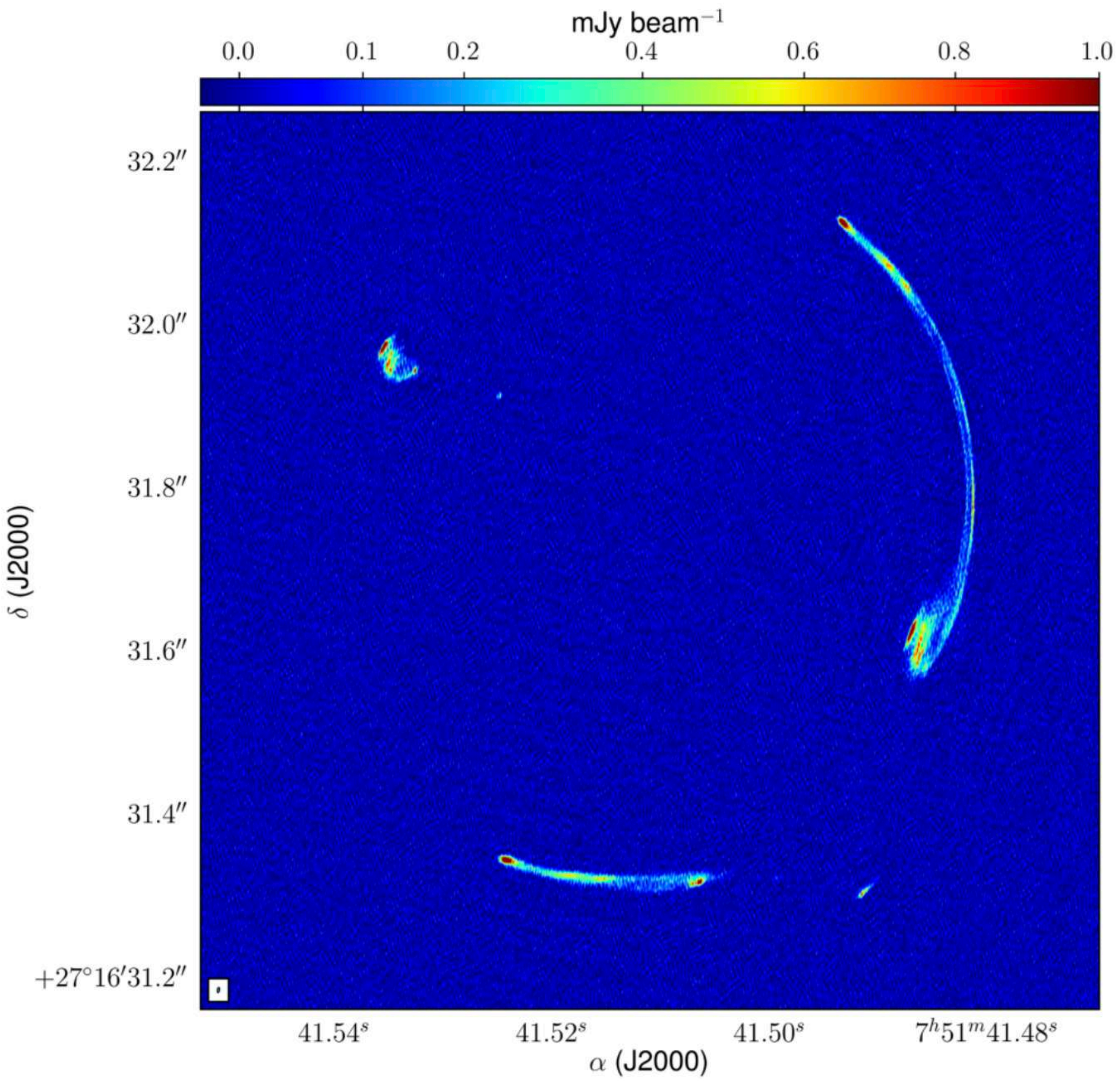

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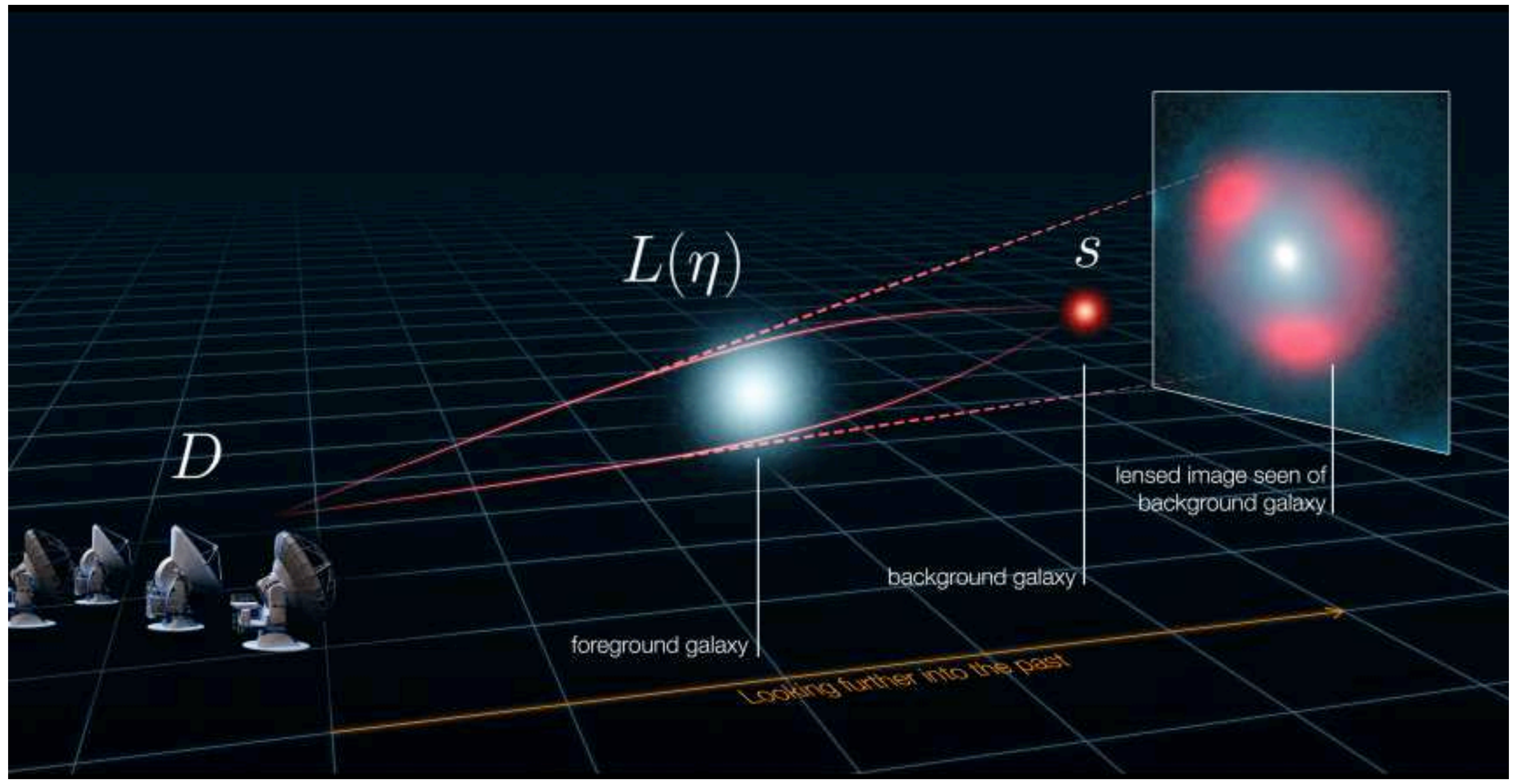
Bayesian approach to jointly inferring the lens mass model and source surface brightness distribution

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

Strong lensing

Forward modeling



Instrumental response

source

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

Lens operator

Smooth lens model

Potential perturbations

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

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

FDM granules:

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

Model by Chan et al 2020

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

Smooth lensing model: from Powell et al 2022

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

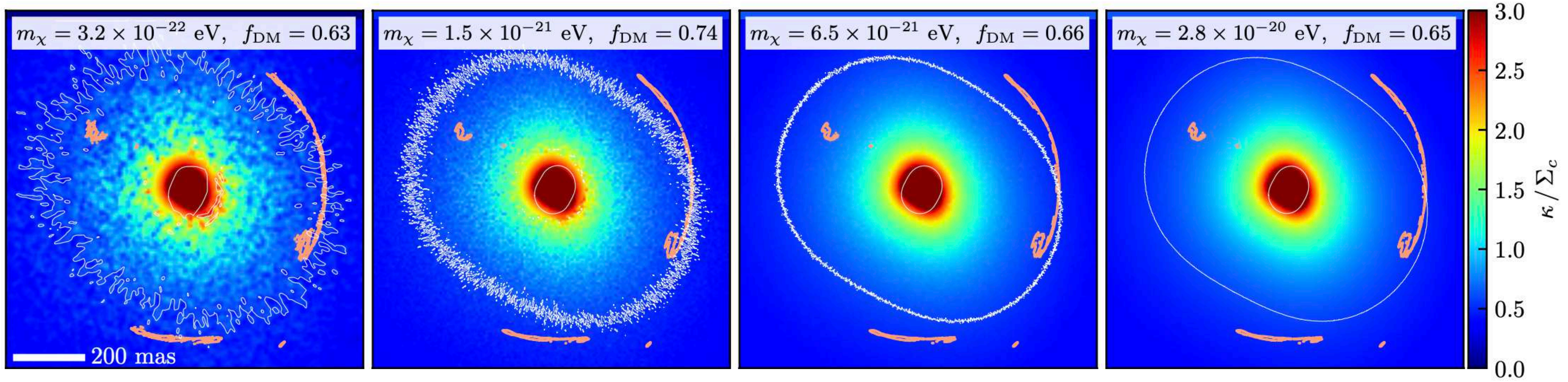
We compute likelihoods for 10^4 sample FDM lens realizations with m_{fdm} drawn from the log-uniform prior range $\log(m_{fdm}/\mathrm{eV}) \in [-21.5, -19.0]$.

Strong lensing

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

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

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



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

Strong *lensing*

A lensed radio jet at milli-arcsecond resolution II: Constraints on fuzzy dark matter from an extended gravitational arc
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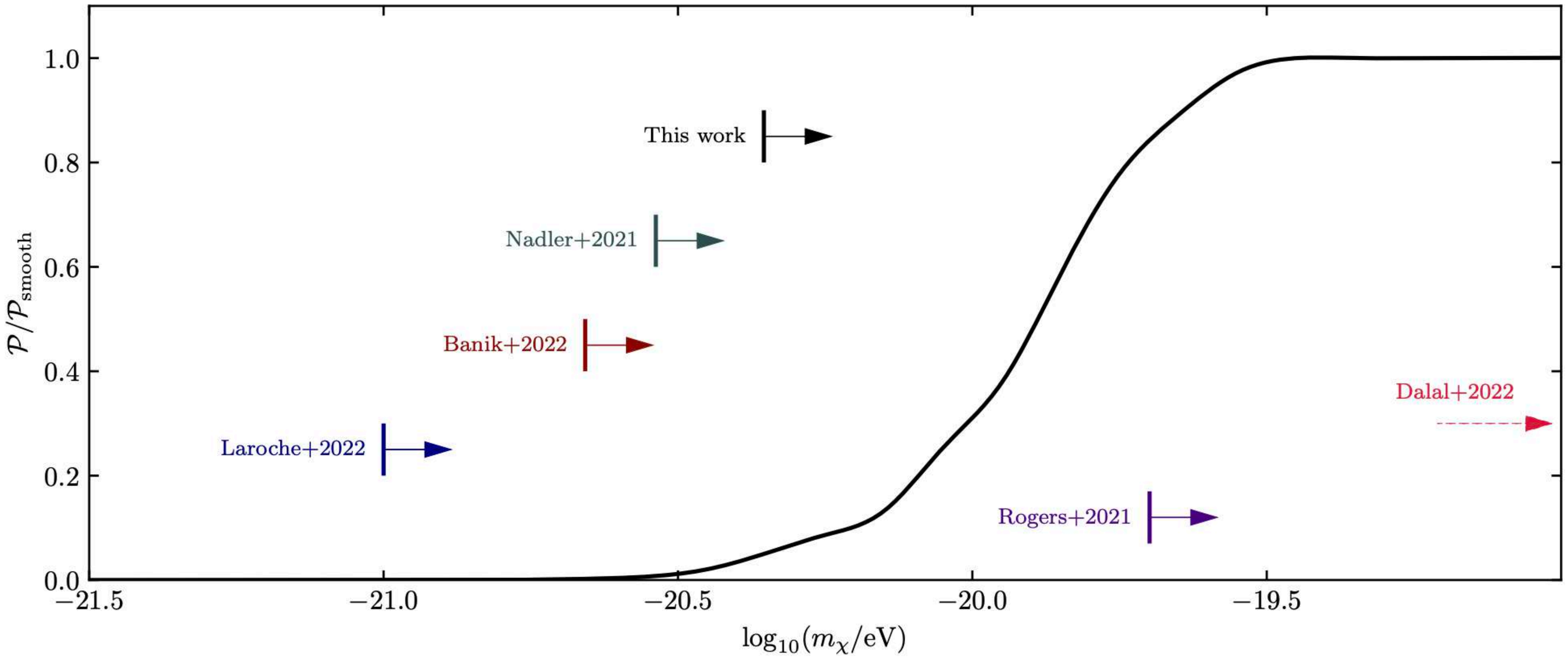
Results quoted in terms of posterior odds ratio (POR) between FDM with a particle mass m_{fdm} and the smooth model, $\mathscr{P}/\mathscr{P}$smooth



Fuzzy dark matter
(Single spin-0 particle)

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

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

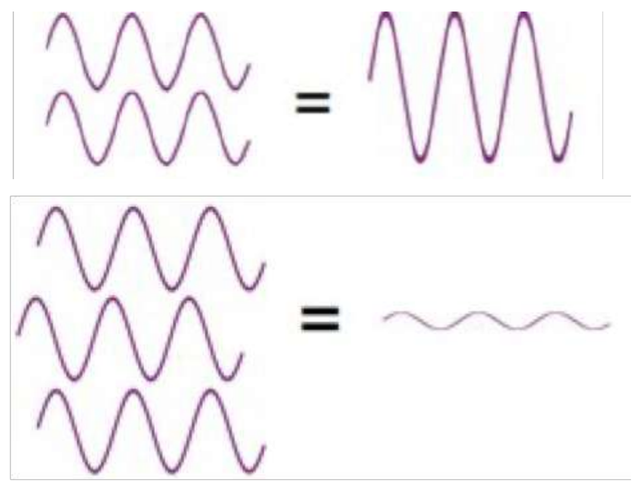
$m_{\rm vdm} > 1.4 \times 10^{-21}$ eV

Spin-2 FDM

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

Vector, higher spin or multicomponent FDM

Interference patterns

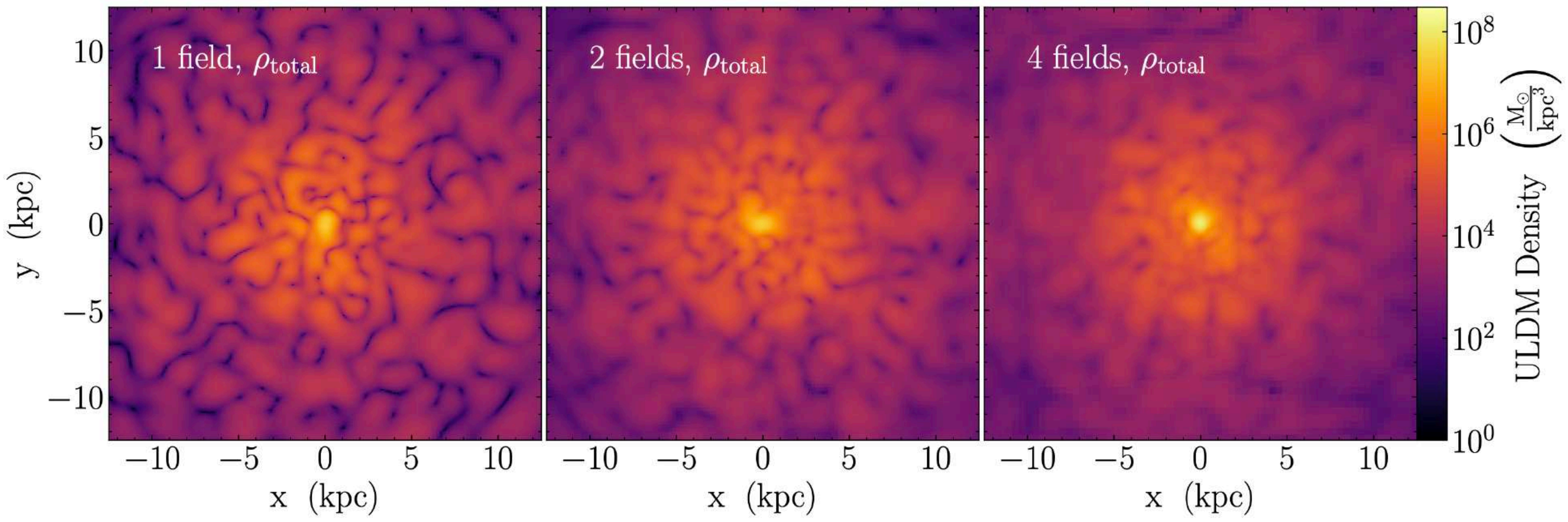


ULDM or ULA are a coherent wave - same frequency and constant phase difference

Multiple coherent waves

Gonseca et al 2023

For ULDM:



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

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

(Amin et al 2022)

Expectation for lensing:

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

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

Detailed simulations and analysis in the future!

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

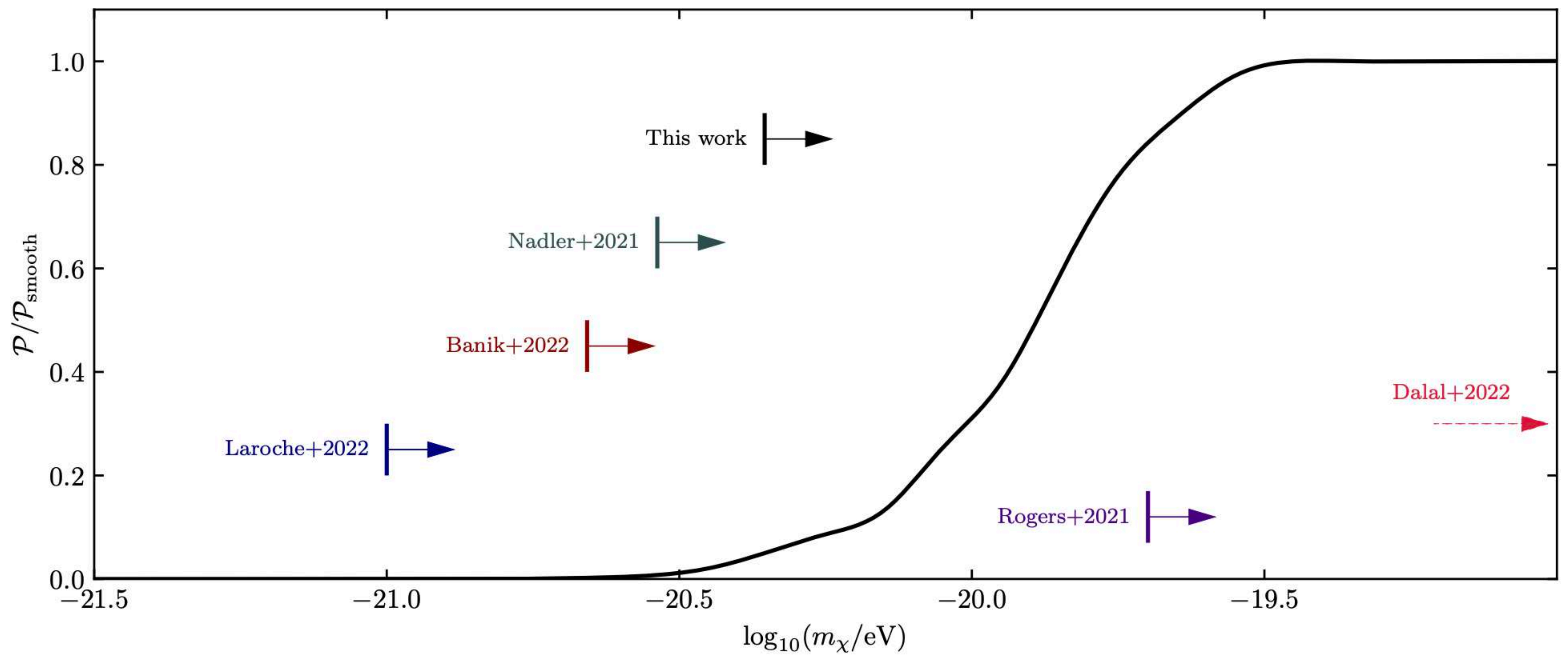
(Vector FDM = 3 x same mass FDM (spin 0))

Multicomponent FDM   Gonseca et al 2023

Strong lensing

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

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



Fuzzy dark matter
(Single spin-0 particle)

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

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

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

Spin-2 FDM

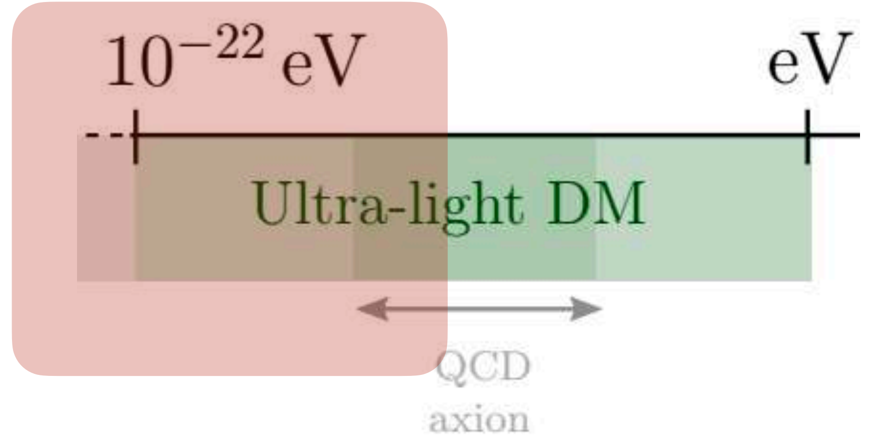
$m_{\rm spin-2} > 8.8 \times 10^{-22}$ eV

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

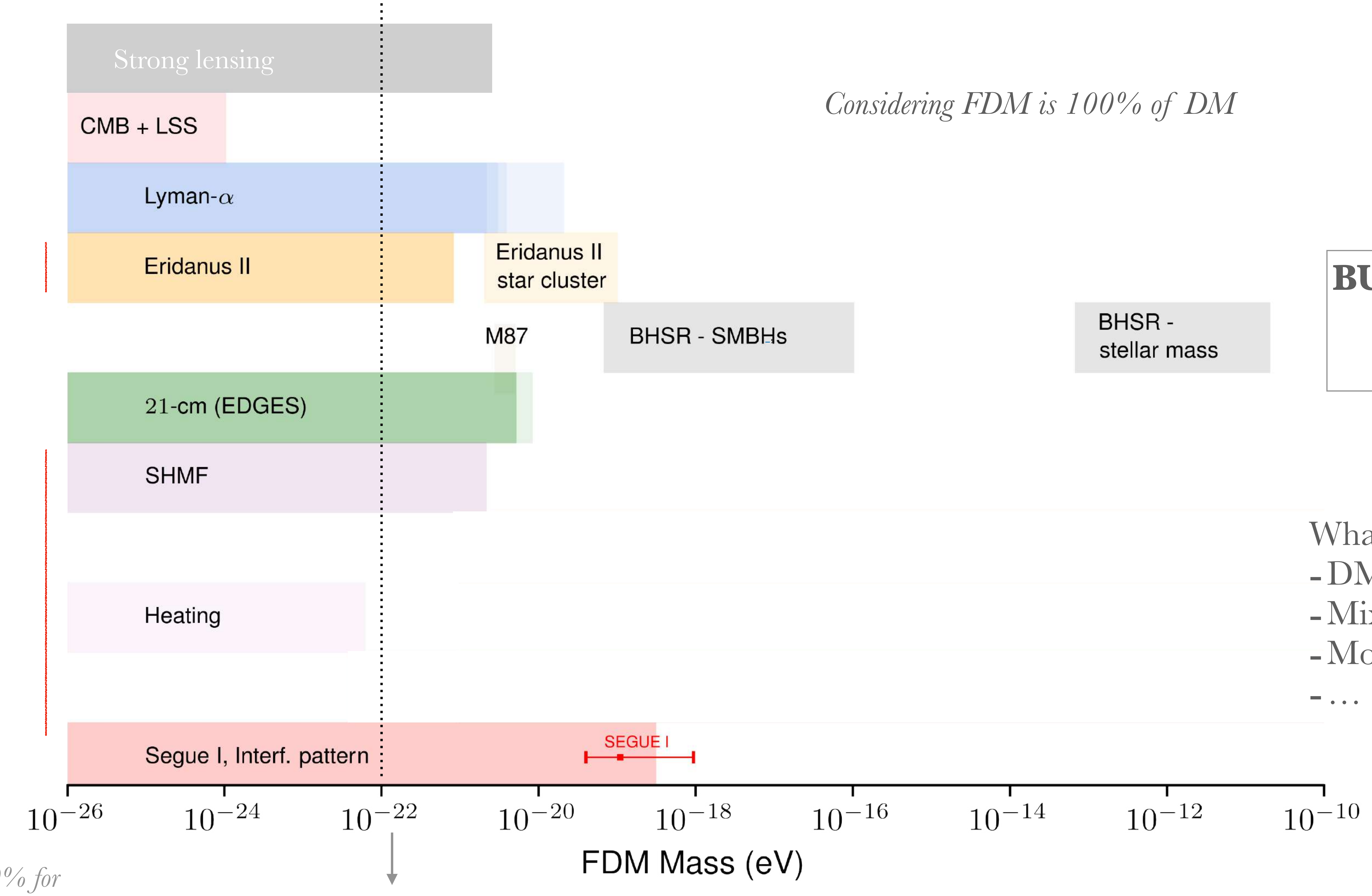
Gravitational effects can give tell us about particle properties of DM (mass, spin, self-interaction, …)

Current status

Fuzzy Dark Matter - bounds on the mass



Considering FDM is 100% of DM



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

What if:
- DM not 100%
- Mixed CDM+ULDM
- More than one field - axiverse
- …

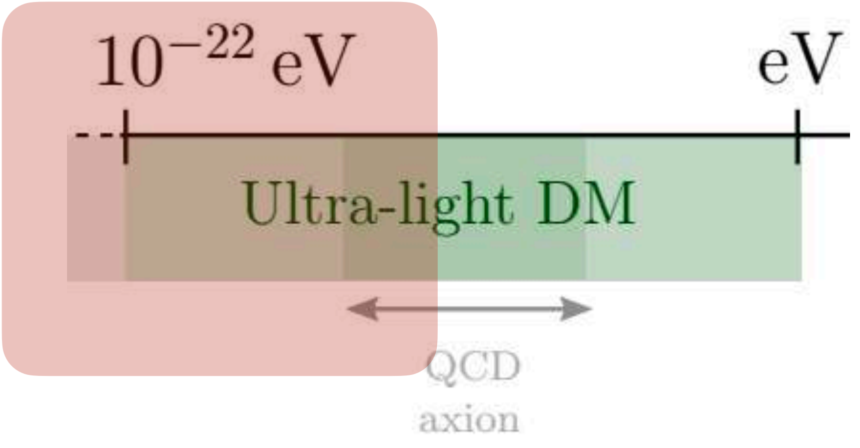
These bounds would change!

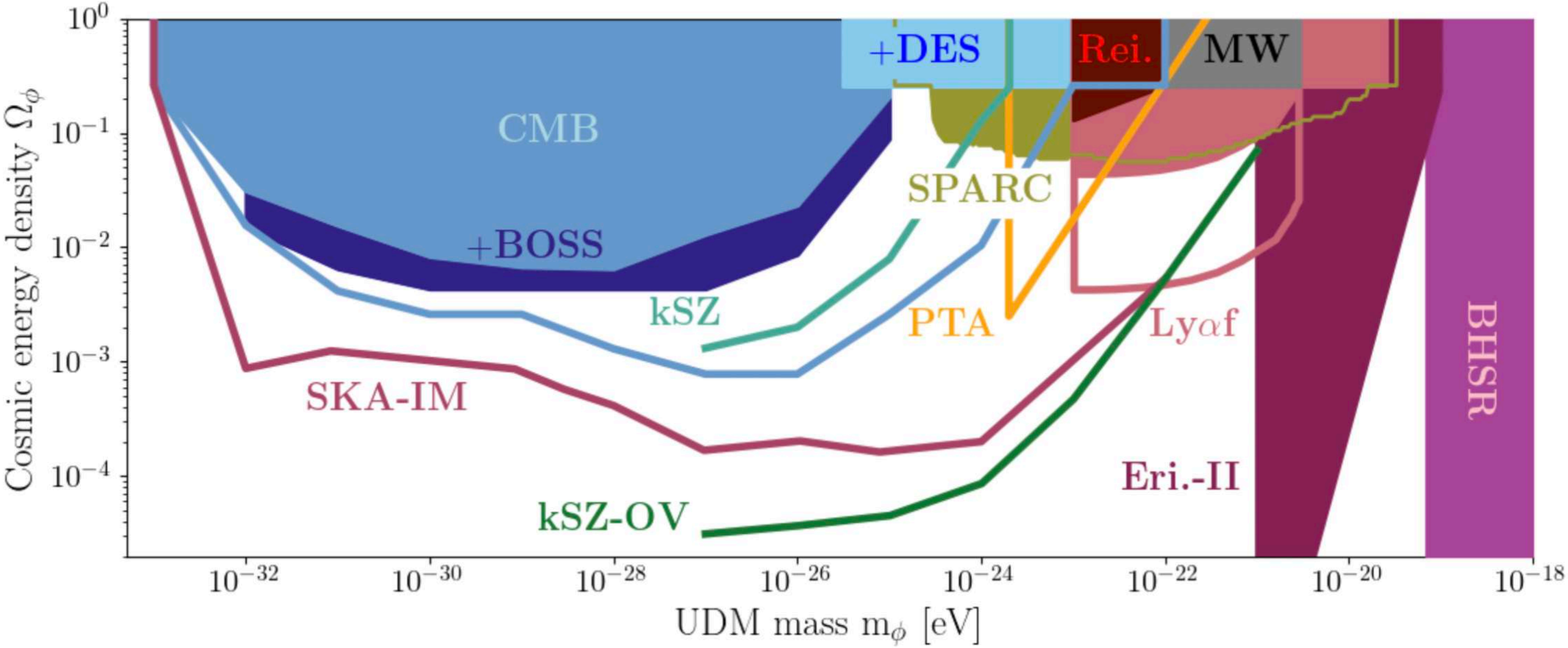
Caner et al: FDM at most 10% for
$10^{-21}\,\text{eV} < m < 10^{-17}\,\text{eV}$

Sweet spot for solving small scale problems

Current status

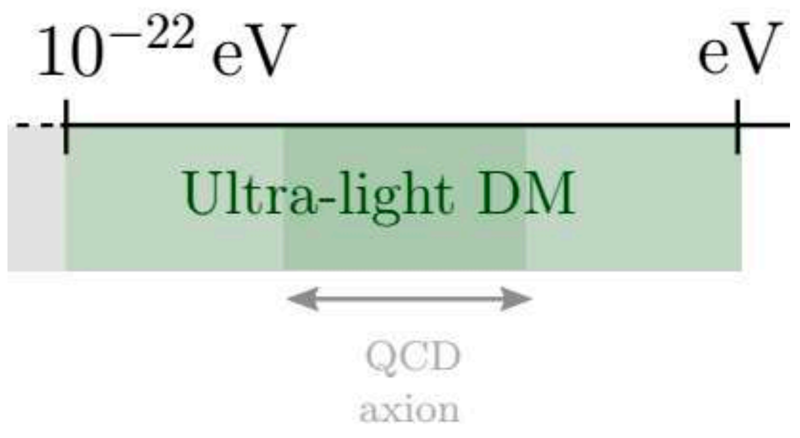
Fuzzy Dark Matter - bounds on the mass





Credit: Keir Rogers

Other probes



- Microlensing to probe the interference patterns *(Work in progress)*

- Using PTA

"Second Data Release from the European Pulsar Timing Array: Challenging the Ultralight Dark Matter Paradigm"
Clemente Smarra *et al.* (European Pulsar Timing Array), Phys. Rev. Lett. **131**, 171001

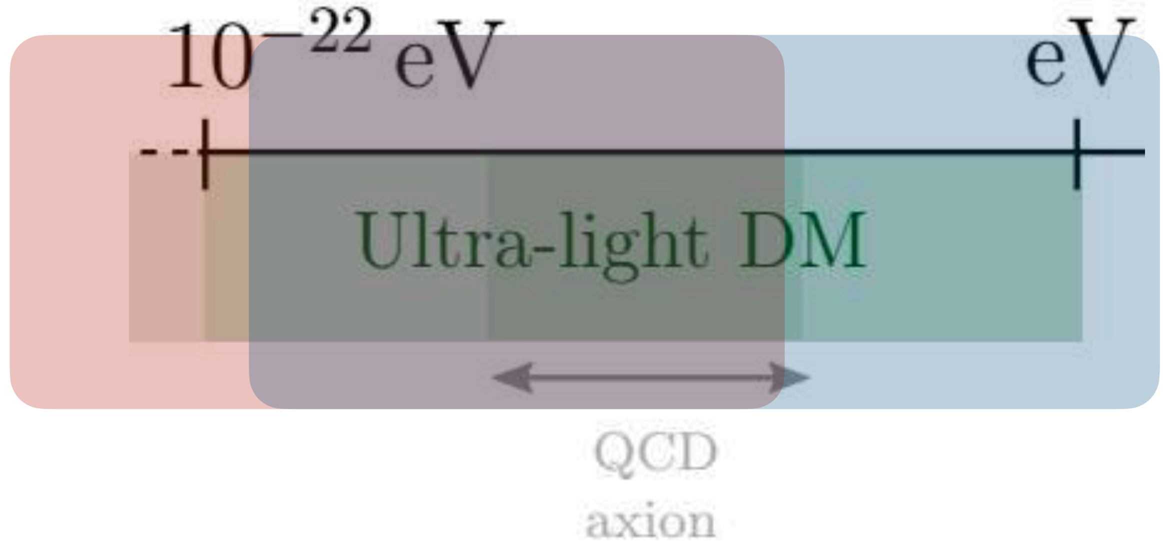
$$10^{-24} \lesssim m \lesssim 10^{-23.3}$$

Cannot be 100% of DM!

  - Considering the interference pattern *(Work in progress)*

- GWs ressonance in ULDM halos Delgado, 2023

- …



Other phenomenology

Solar (Earth) halos

Poisson Gravity

$\nabla^2 V_g = 4\pi G m^2 |\psi|^2$

(Attractive)

Coherent state → Oscillates

Leading time dependence

$\dot{\psi} \sim (m-\omega)\psi \ll m\psi$

$$i\frac{\partial\psi}{\partial t} = \left[-\frac{\nabla^2}{2m} + V_g\left(|\psi|^2\right) + V_{int}\left(|\psi|^2\right)\right]\psi$$

Normalization

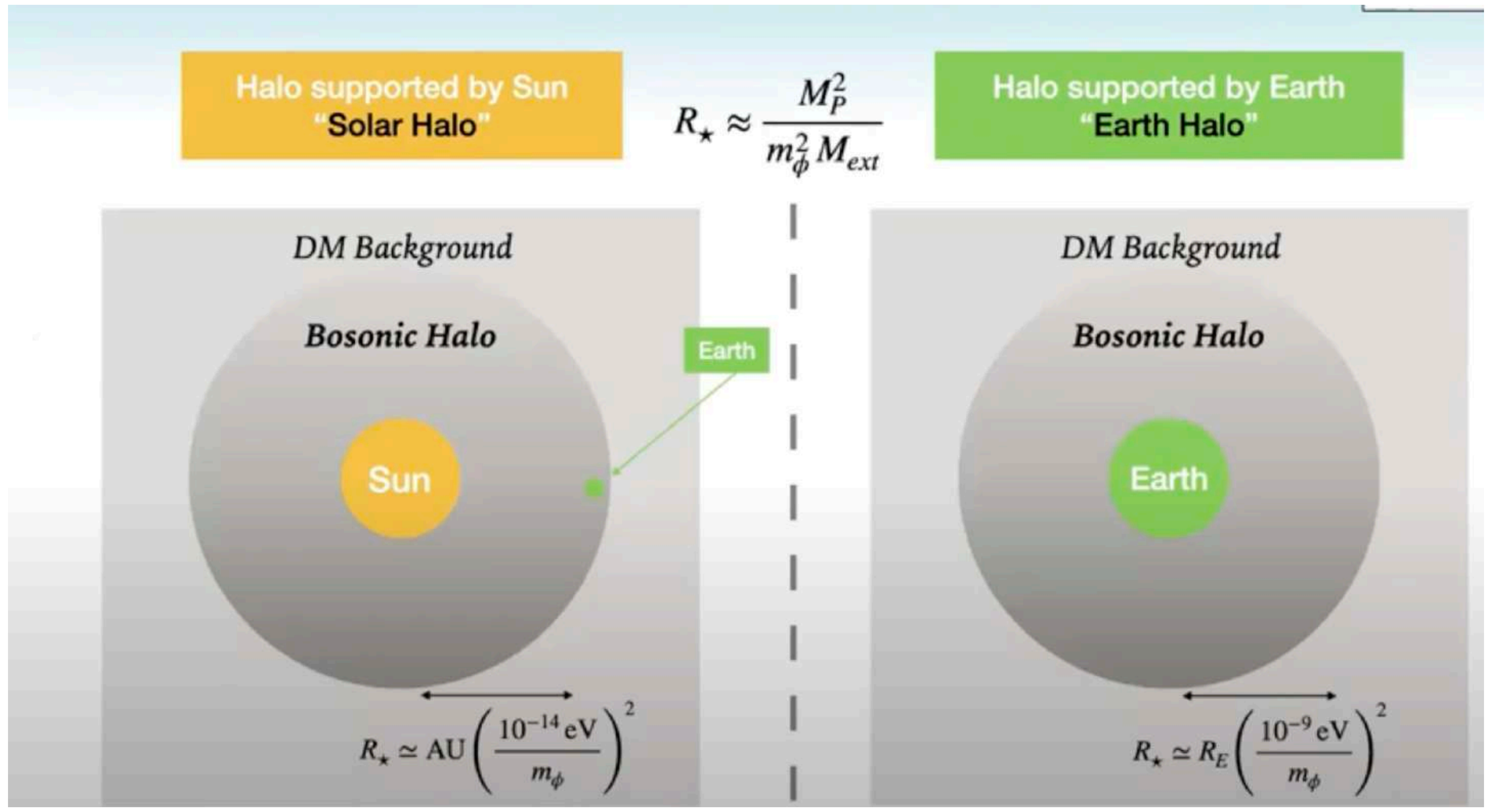
$$m\int d^3r\,|\psi|^2 = M_\star$$

Kinetic energy
(Repulsive)

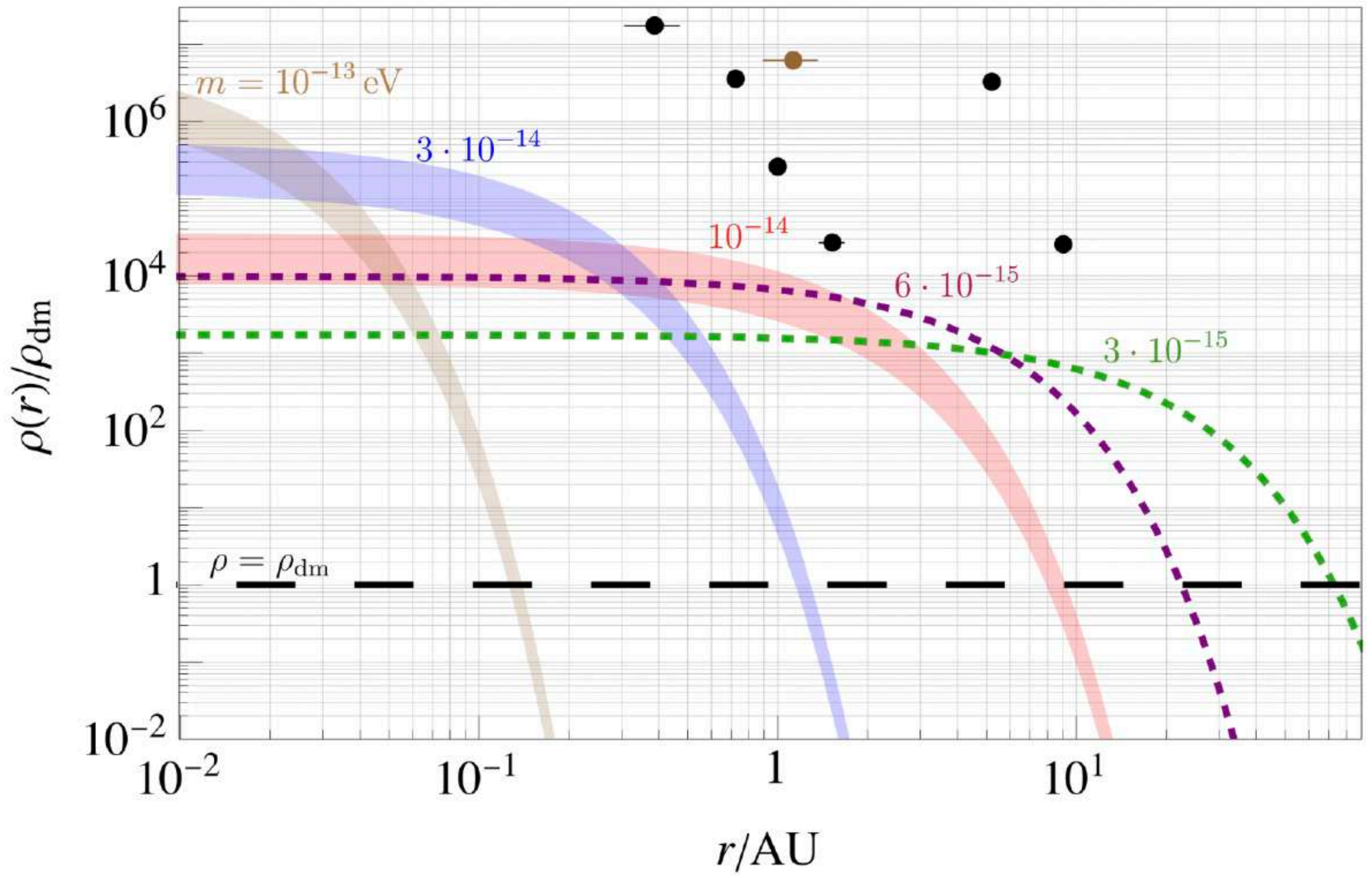
Self-interactions
For axion potential,

$$V(\phi) = m^2 f^2\left[1-\cos\left(\frac{\phi}{f}\right)\right] = \frac{m^2}{2}\phi^2 - \frac{1}{4!}\left(\frac{m}{f}\right)^2\phi^4 + \frac{1}{6!f^2}\left(\frac{m}{f}\right)^2\phi^6 - \dots$$

(Attractive) **(Repulsive)**

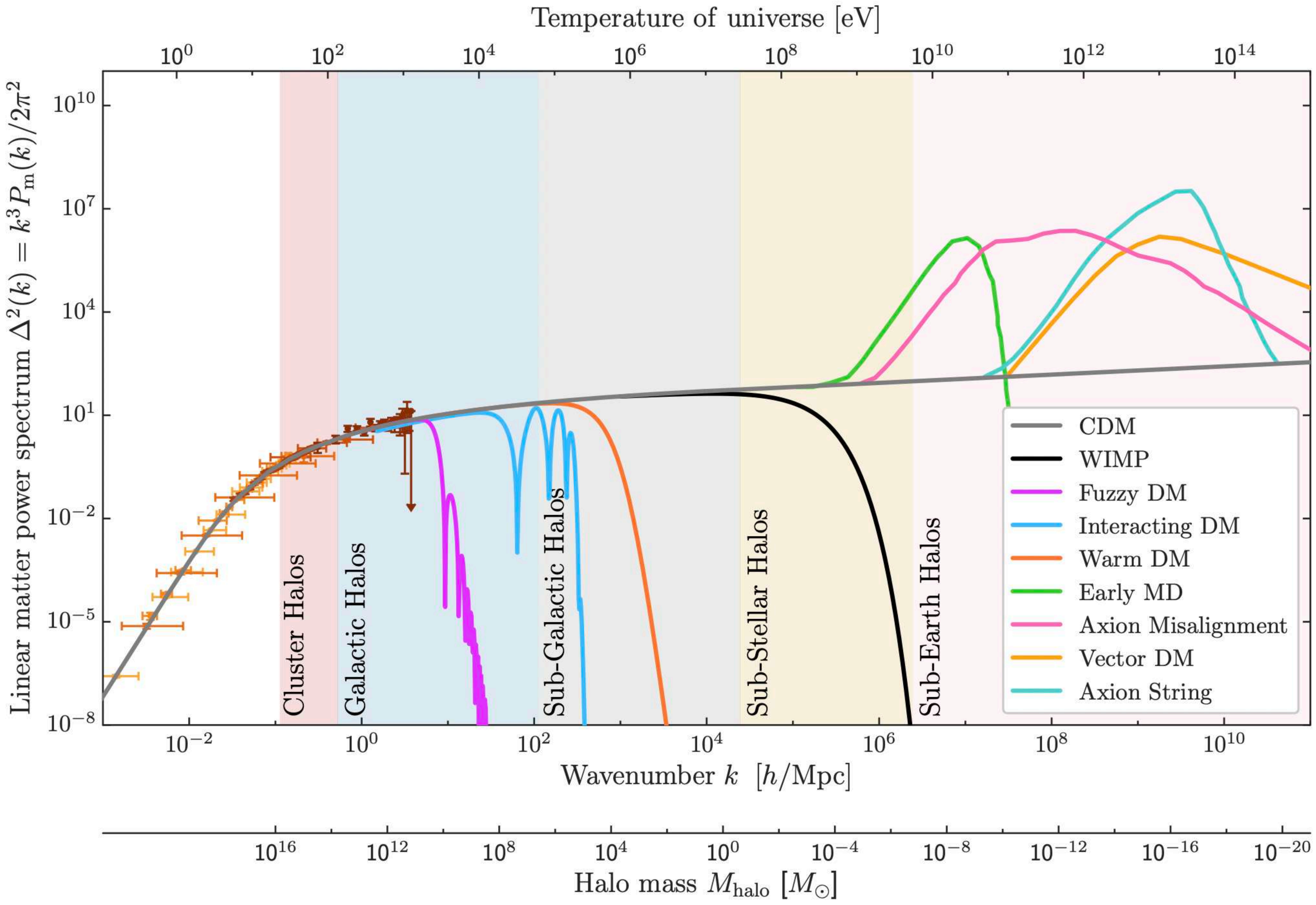


10^{-12} eV $\lesssim m_\phi \lesssim 10^{-7}$

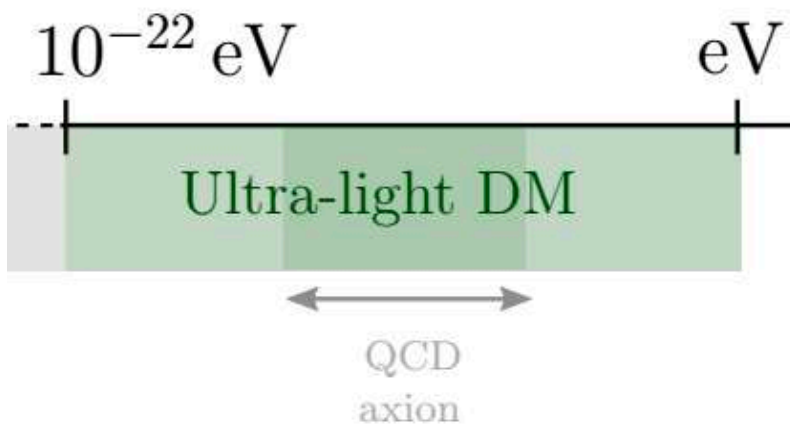


Figures by Josh Eby

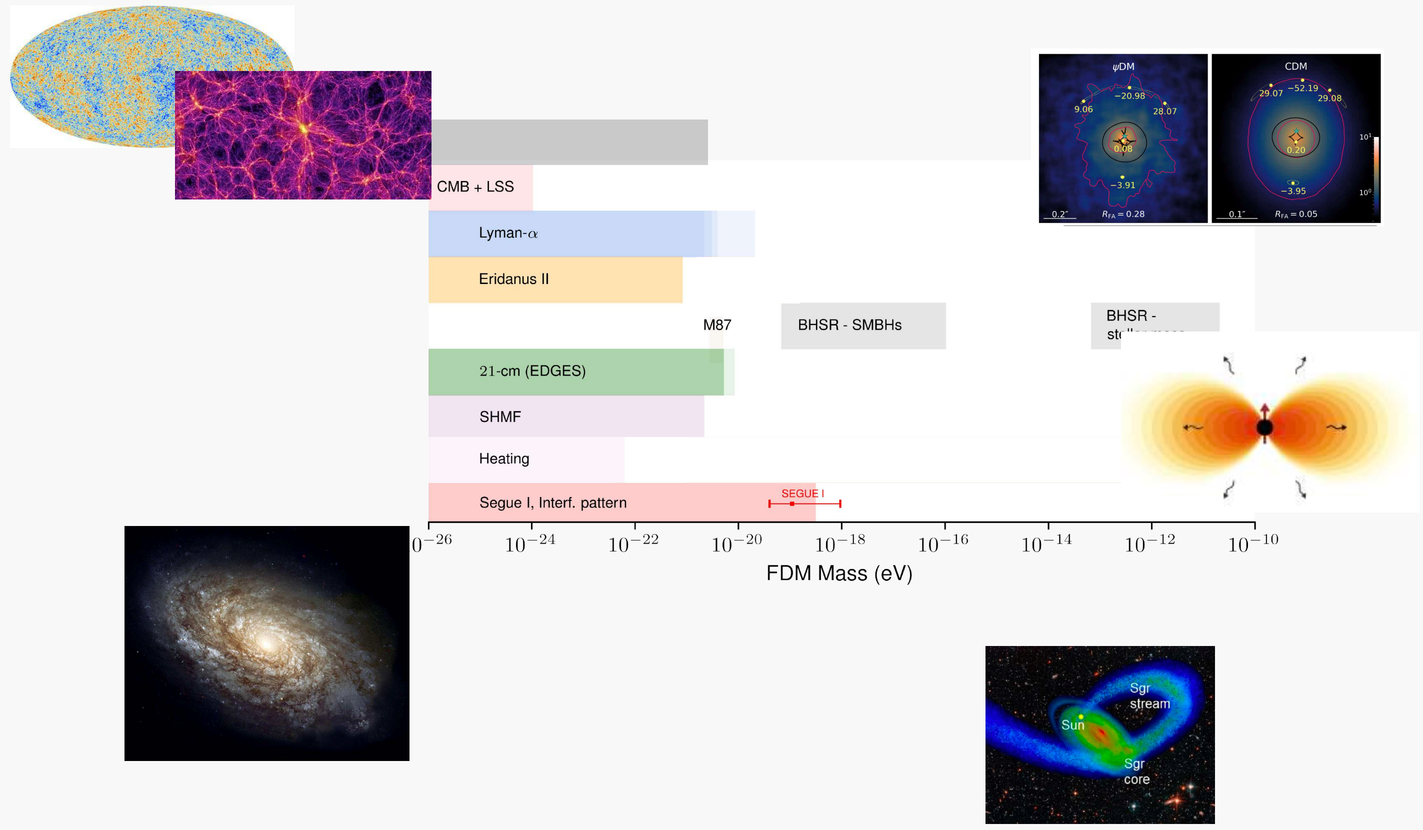
Small scales can offer some hints of the nature of DM



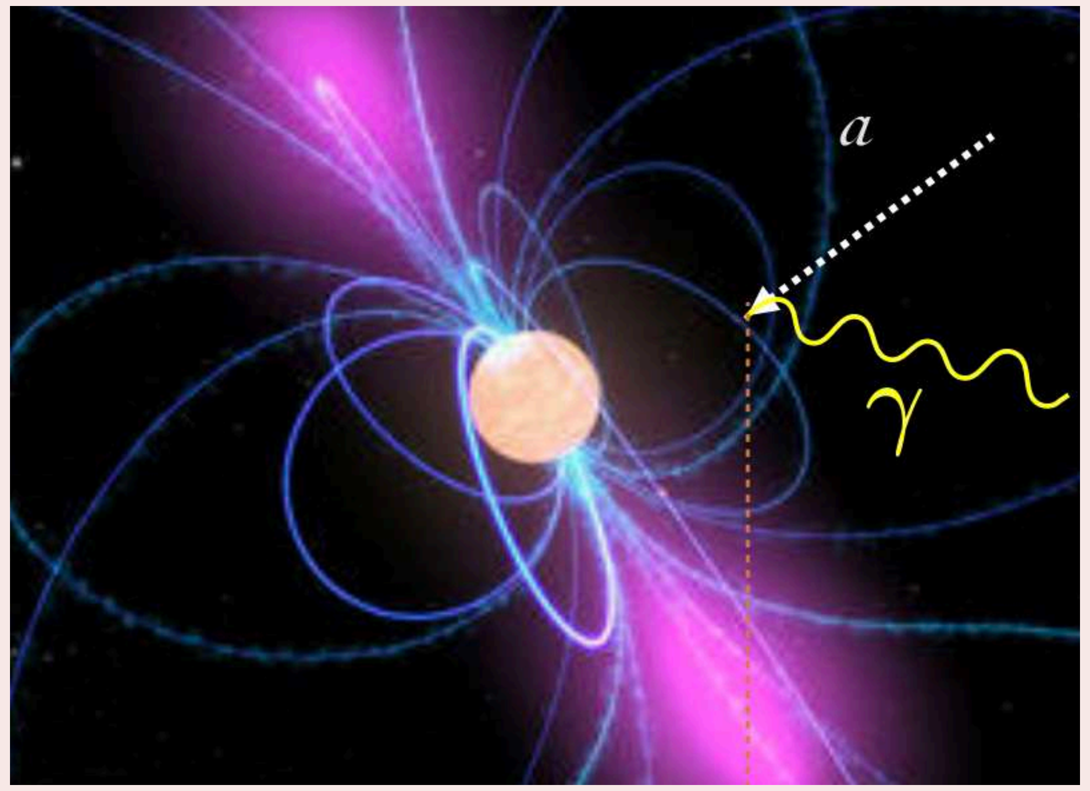
If ULDM are axions/ALPs



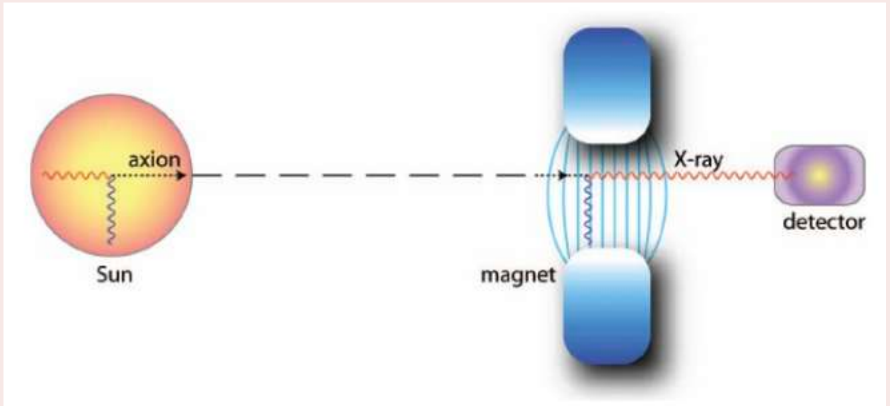
Cosmological and astrophysical searches

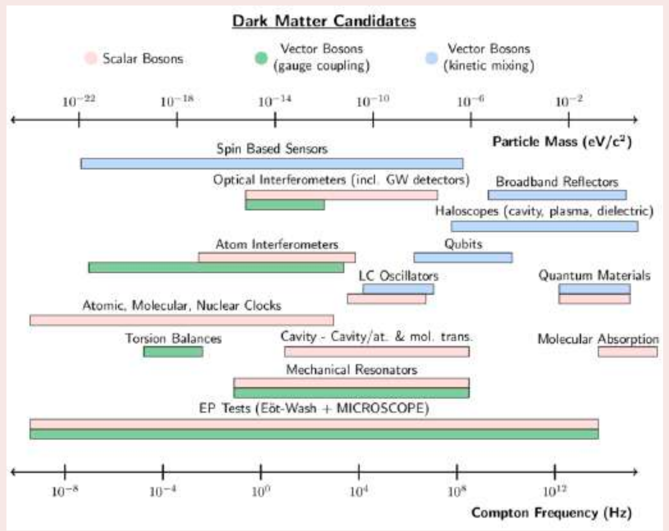


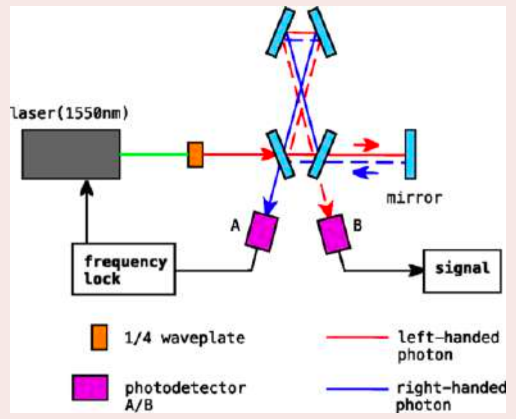
Indirect detection



"Direct detection" Axion/ALPs experiments

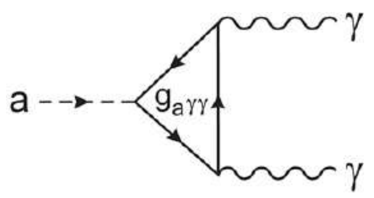


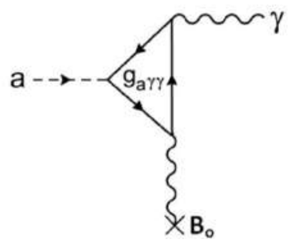




Gravitational

Interactions with the SM



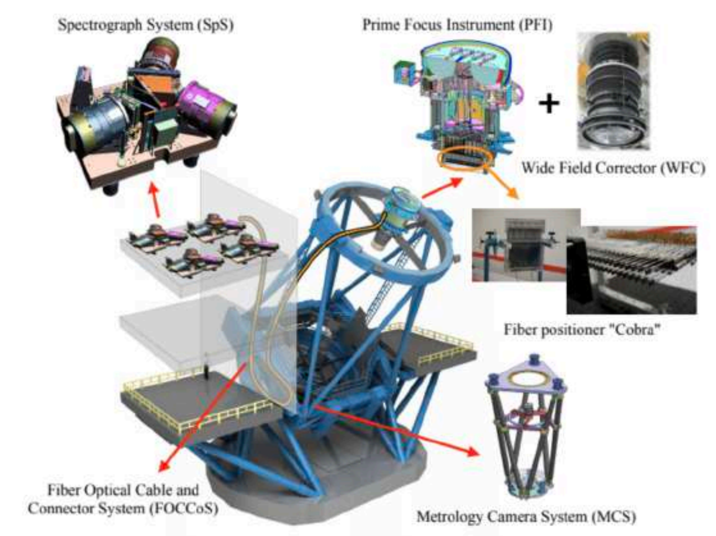


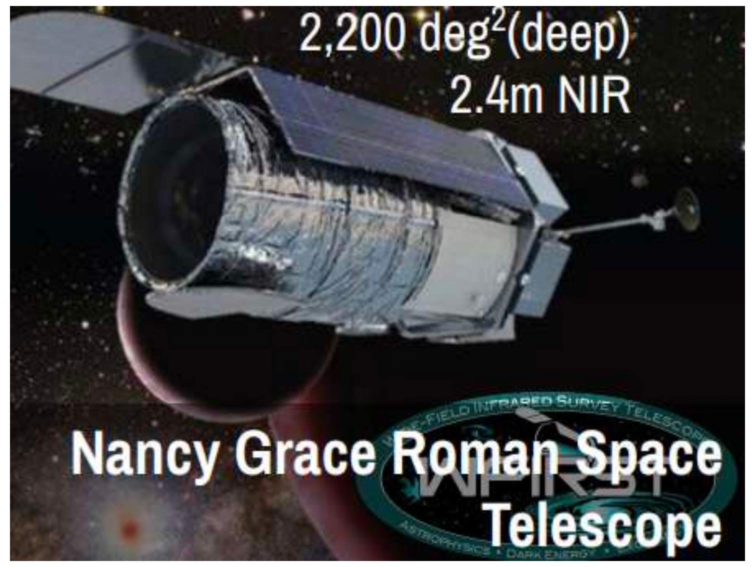
Improving these bounds

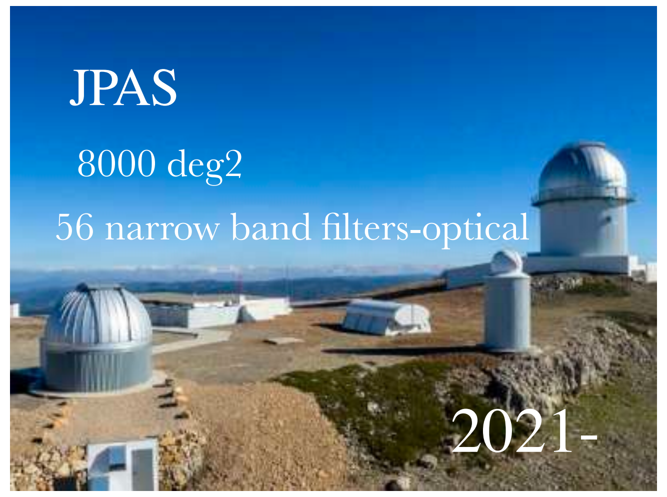
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)

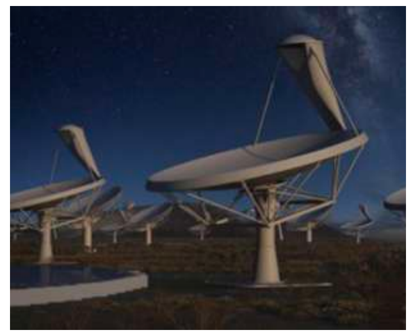






GWs

21cm



SKA
SQUARE KILOMETRE ARRAY

CMB

CMB-S4
Next Generation CMB Experiment

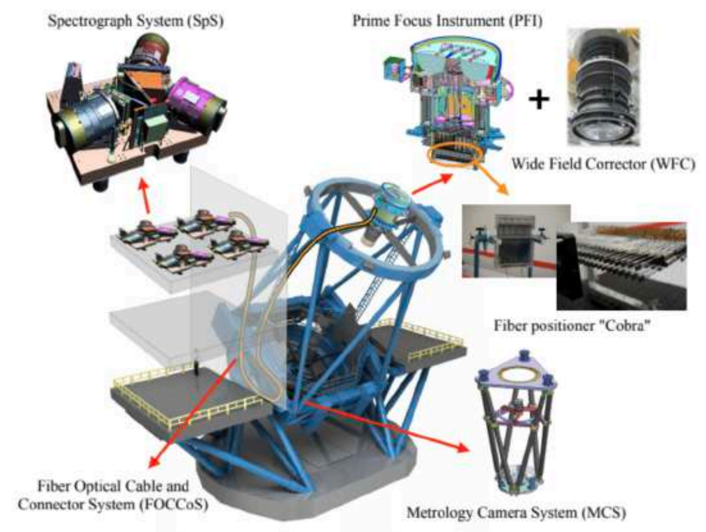
Modified from Jia Liu

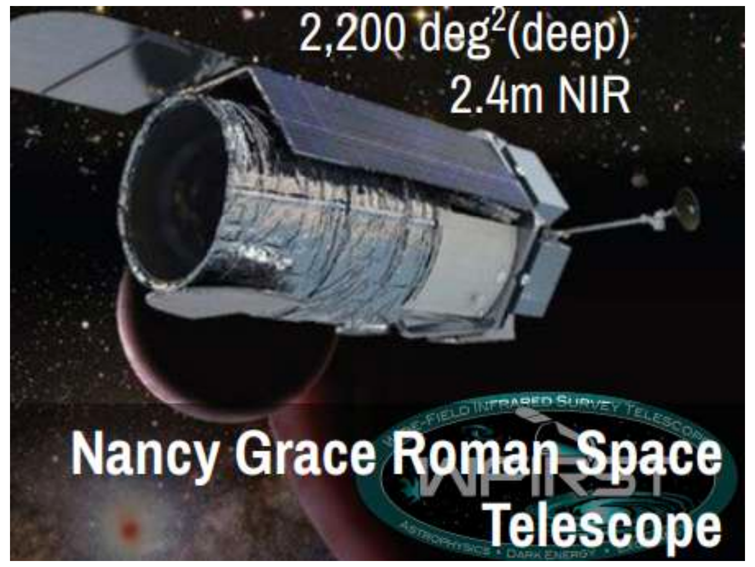
Improving these bounds

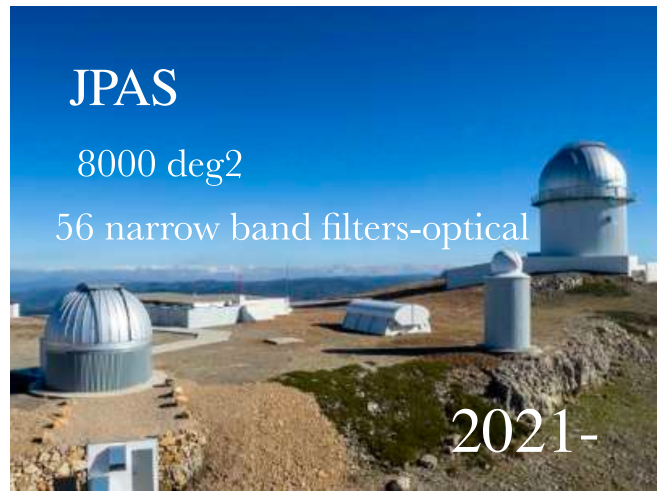
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)







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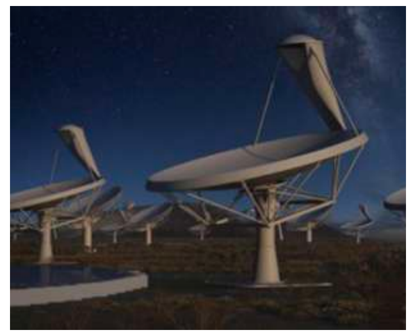

SKA SQUARE KILOMETRE ARRAY

CMB

CMB-S4
Next Generation CMB Experiment

+ direct detection experiments

PFS (Prime Focus Spectrograph)

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

PFS: spectroscopy part of *SuMIRe project*

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

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

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

DM with PFS

Galaxy archeology	Cosmology	Galaxy evolution
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FDM

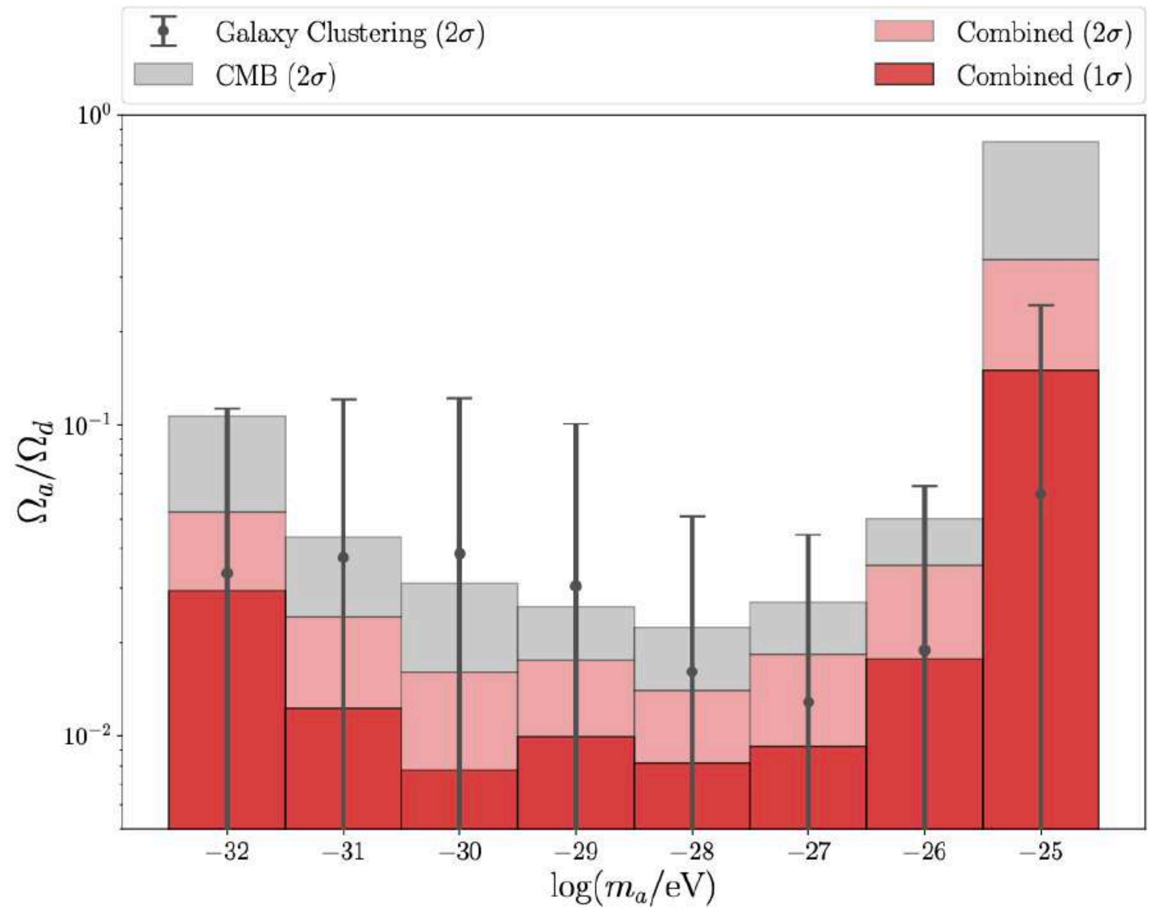
SIDM

ULA

- Science with dwarf galaxies
  Core:
  - Presence of a core or not (slope)
  - Size of the core
  - Profile
    - Inner density
    - Transition radius
  - Abundance data to understand the role of baryons in each system
- *Beyond the core*
  - Granules: heating of stars (dwarfs)
    - Angular momentum
  - Stellar streams

…

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



Lague et al 2021

The small-scale Ly-α forest power spectrum

ULA

FDM

WDM

SIDM

Halo mass function

Constraints on the *optical depth:*

Constraint the ULDM mass

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

Properties of DM

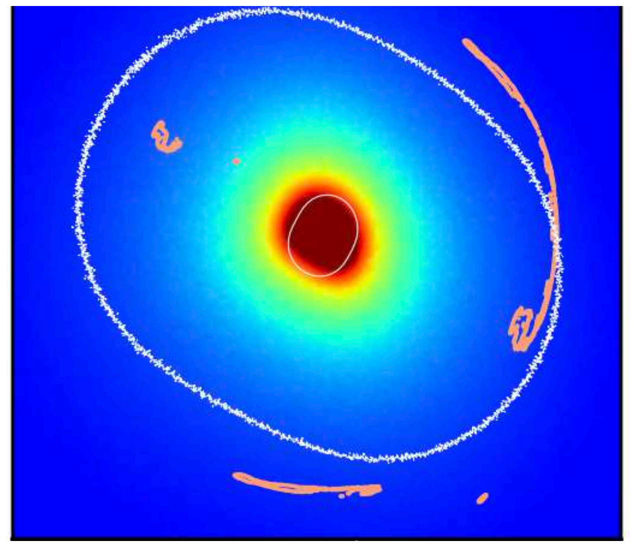
Summary

Ultra-Light Dark Matter

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

Cosmological and astrophysical systems can probe
mass, spin (# of fields), self-interaction, …

Granules



Strong lensing:

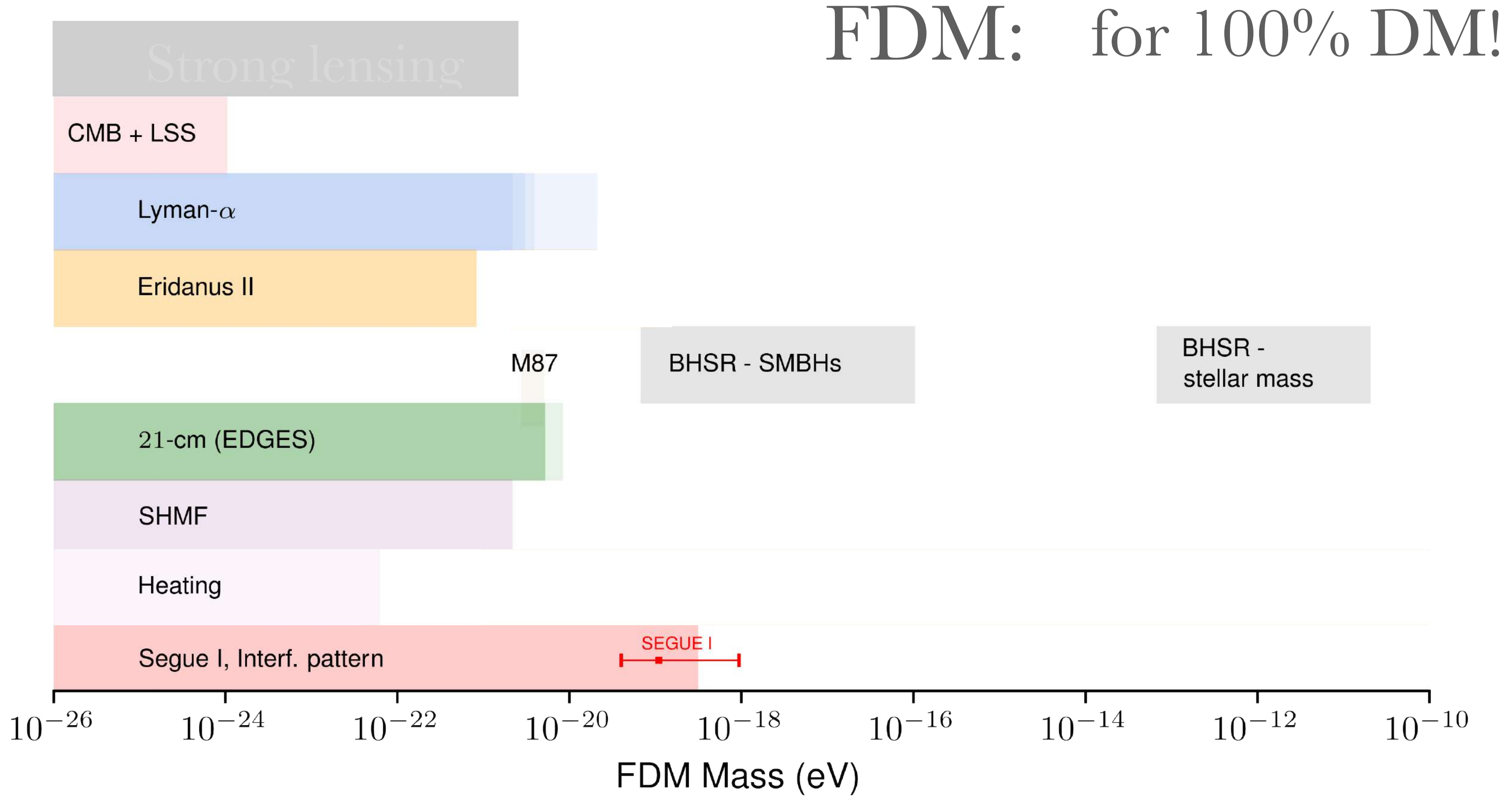
$$m_{\rm fdm} > 4.4 \times 10^{-21}\,{\rm eV}$$

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

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

Current status

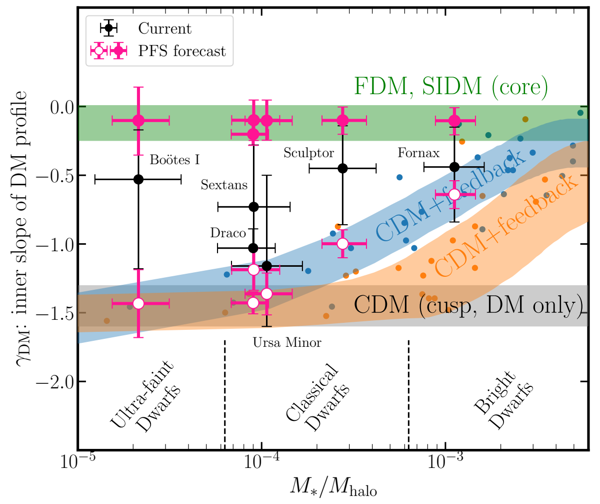
FDM: for 100% DM!

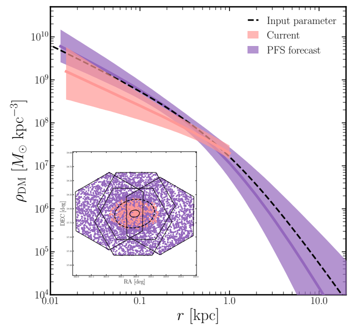


Future

Observations

PFS





Improve in simulations
New probes/observables