

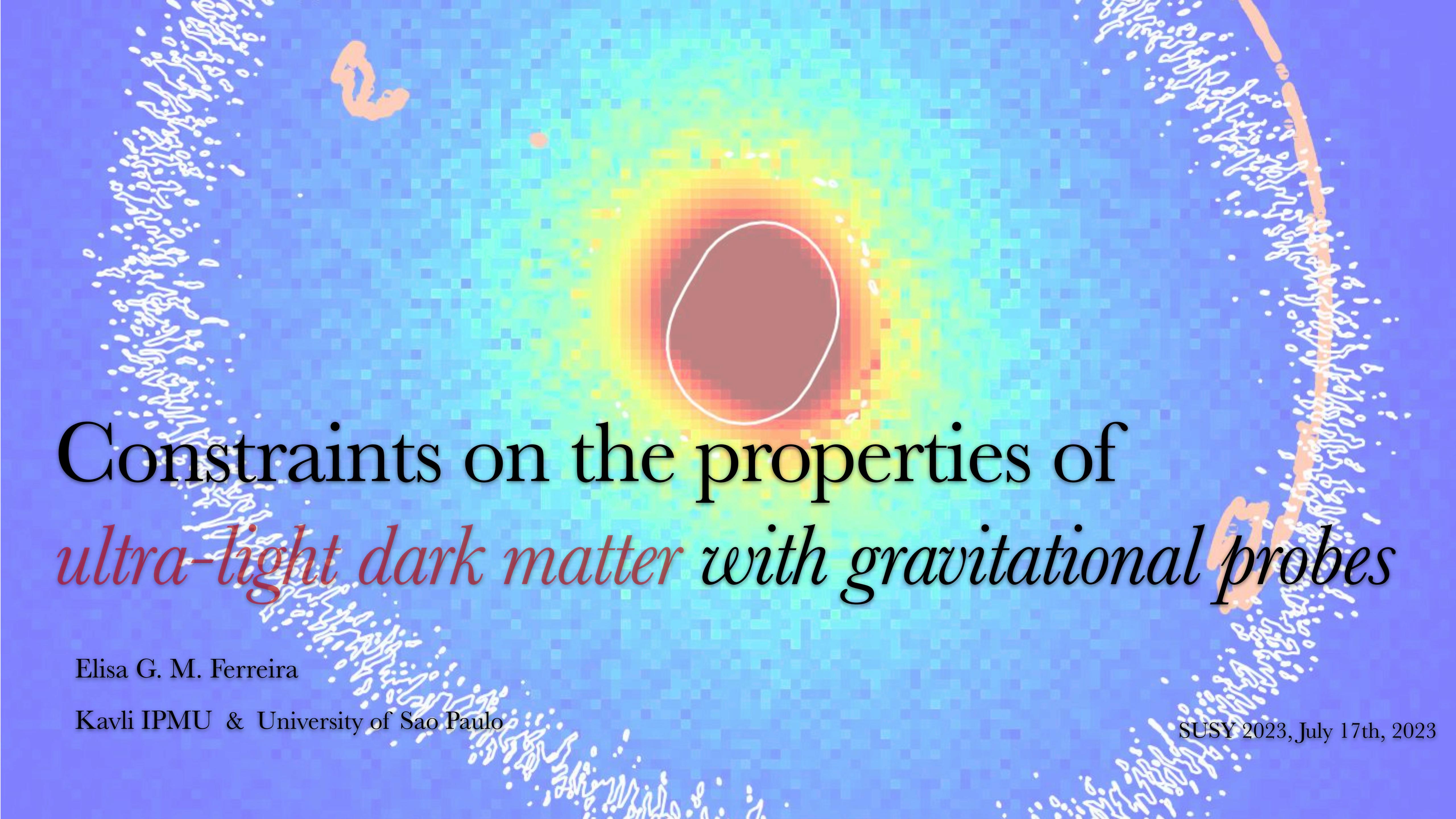


Narrowing down the mass range of *ultra-light dark matter*

Elisa G. M. Ferreira

Kavli IPMU & University of Sao Paulo

SUSY 2023, July 17th, 2023



Constraints on the properties of *ultra-light dark matter with gravitational probes*

Elisa G. M. Ferreira

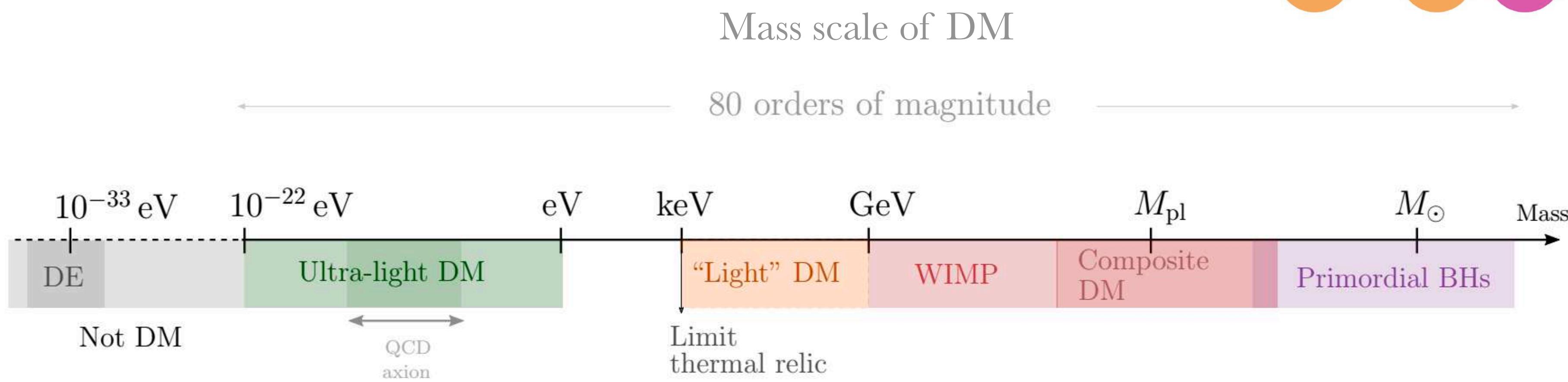
Kavli IPMU & University of São Paulo

SUSY 2023, July 17th, 2023

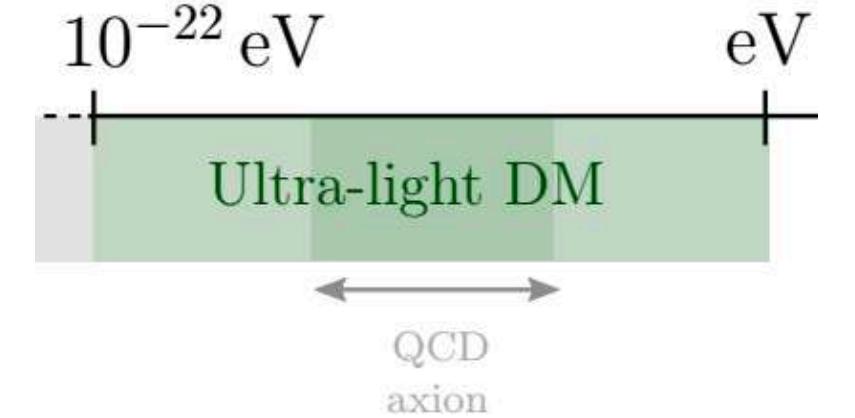
What is dark matter?

- DM Landscape

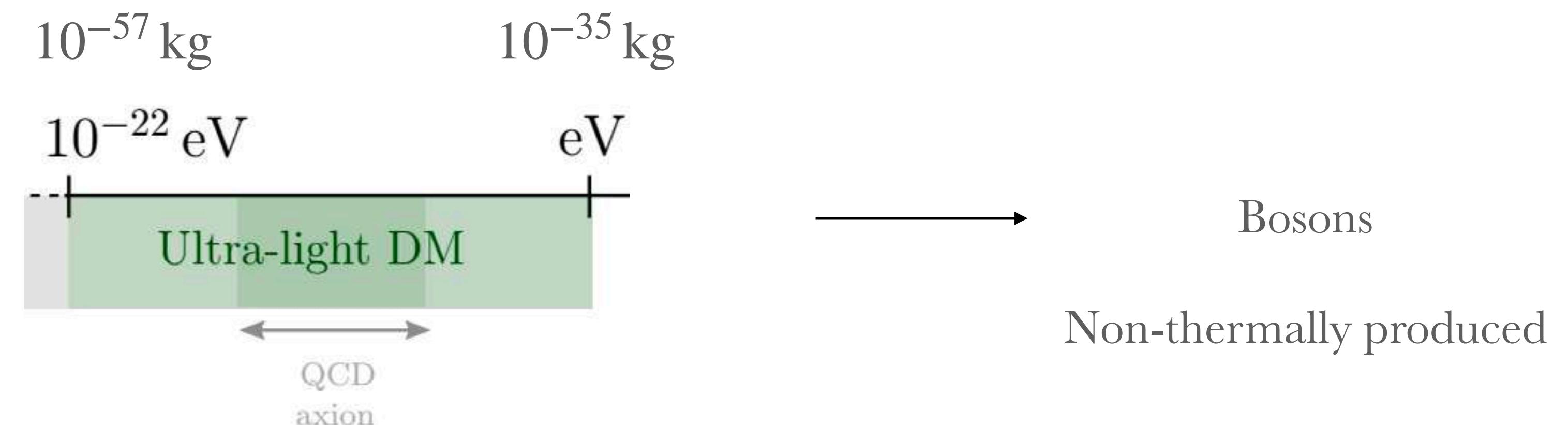
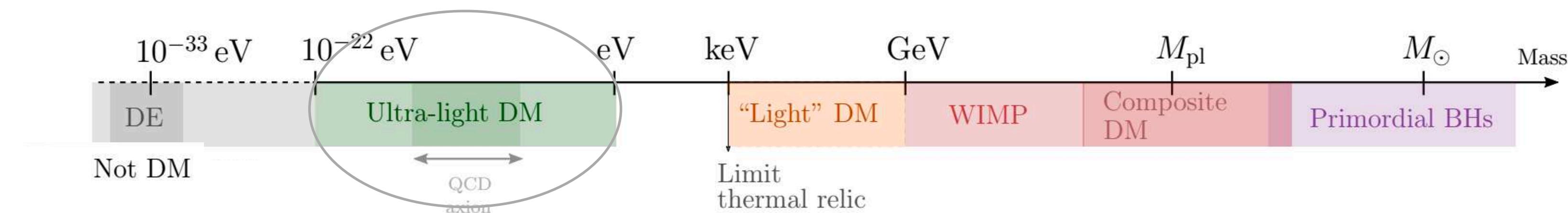
State of the “art”



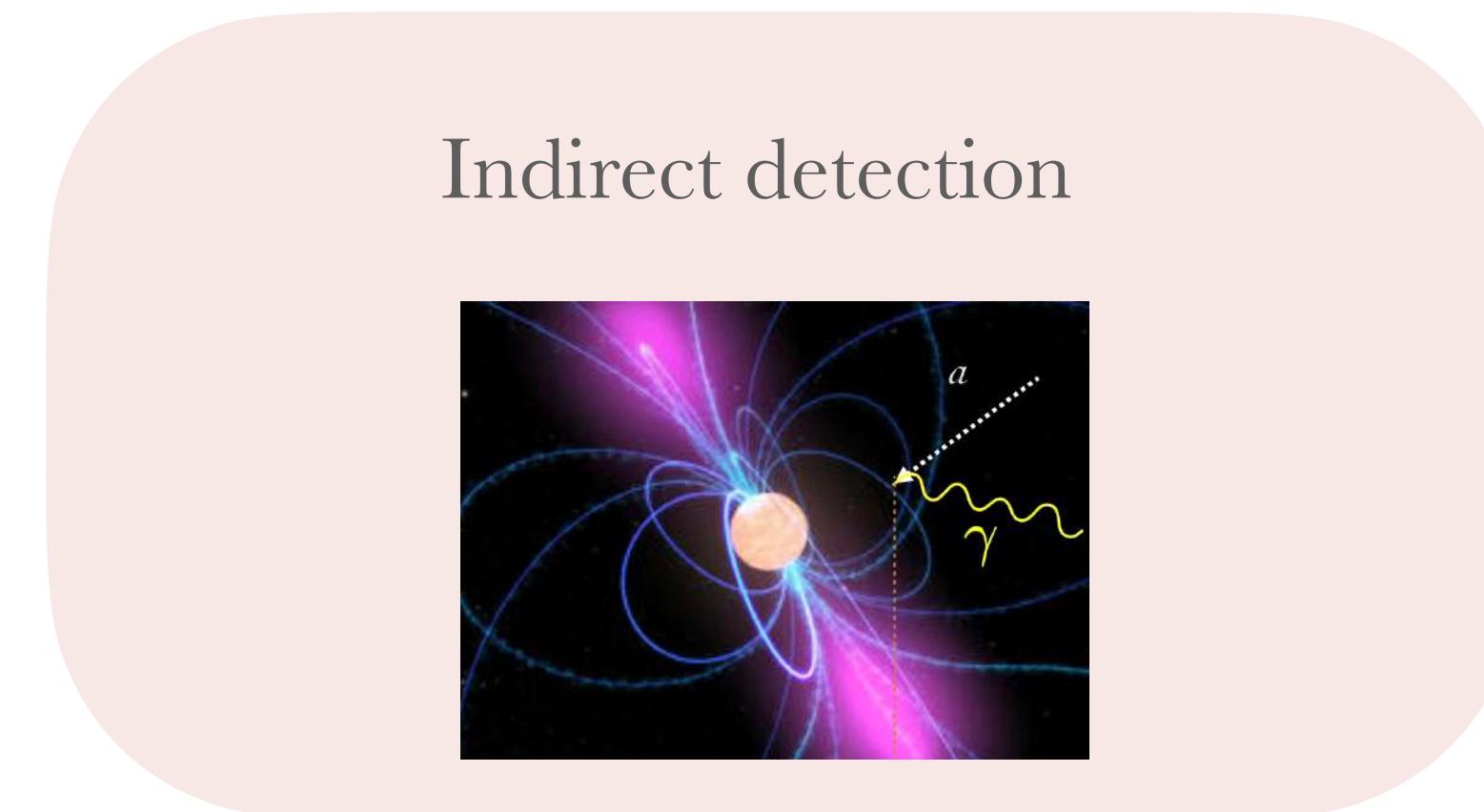
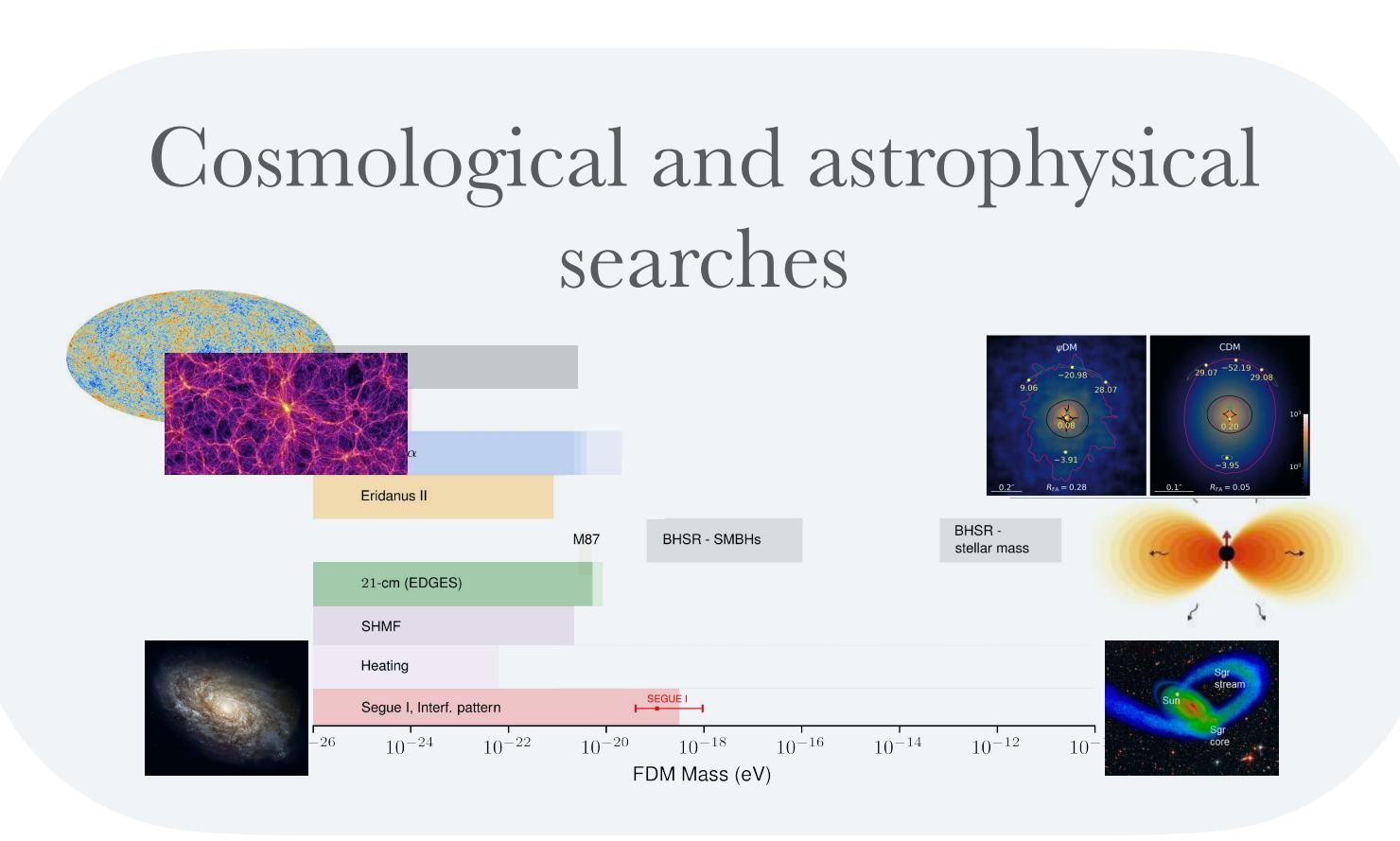
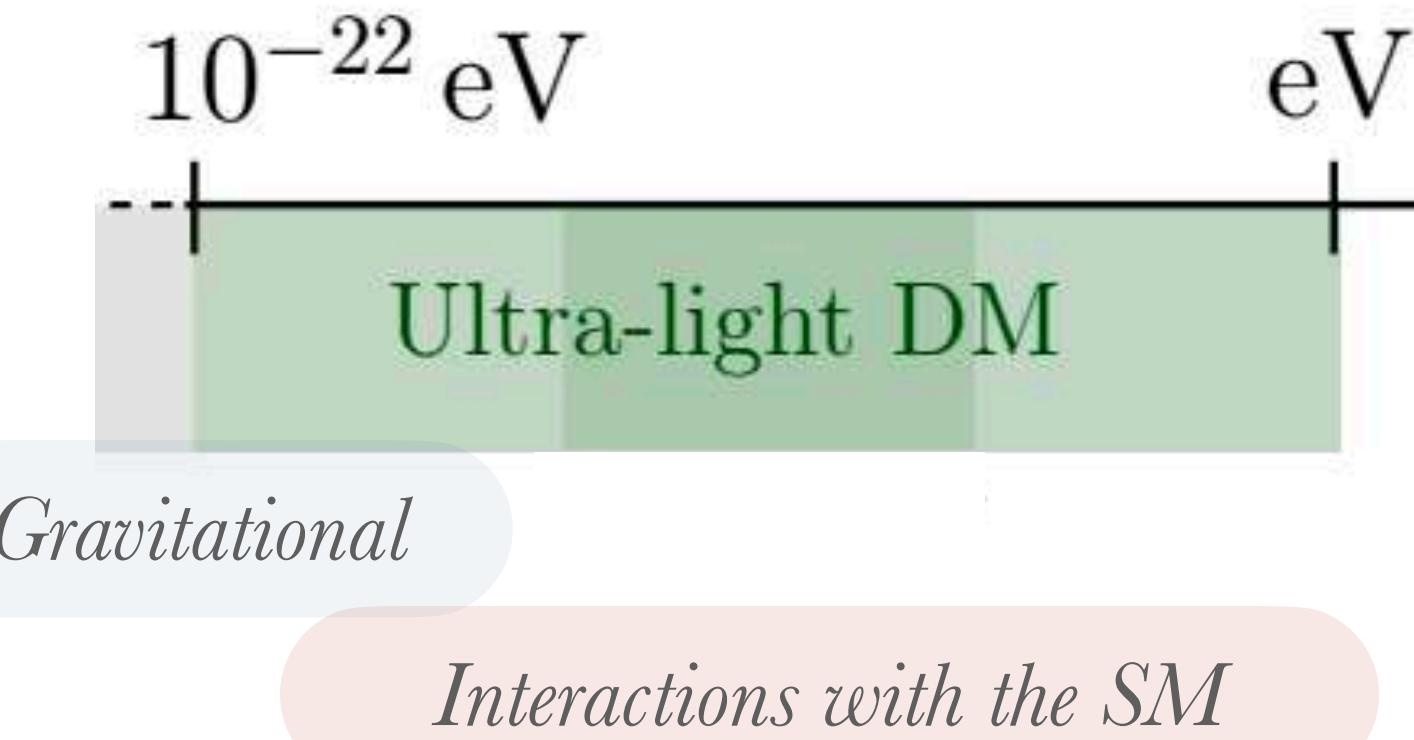
Ultra-light Dark Matter



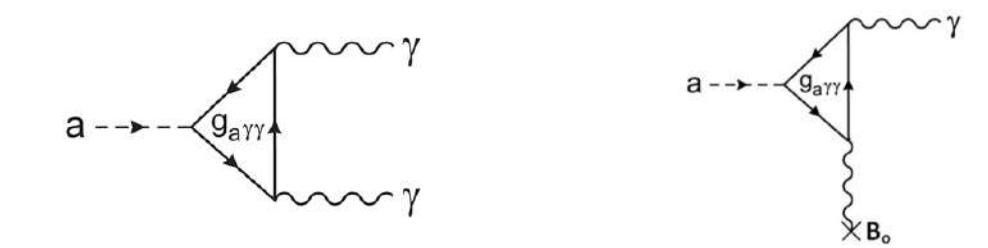
Ultra-light candidate, cold \longrightarrow Large $\lambda_{dB} \sim 1/mv$
 Lightest possible candidate for DM



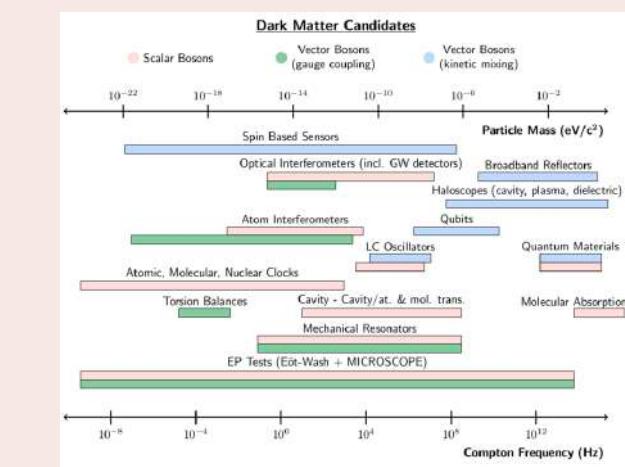
Ultra-light Dark Matter



ALPs or Ultra-light axions

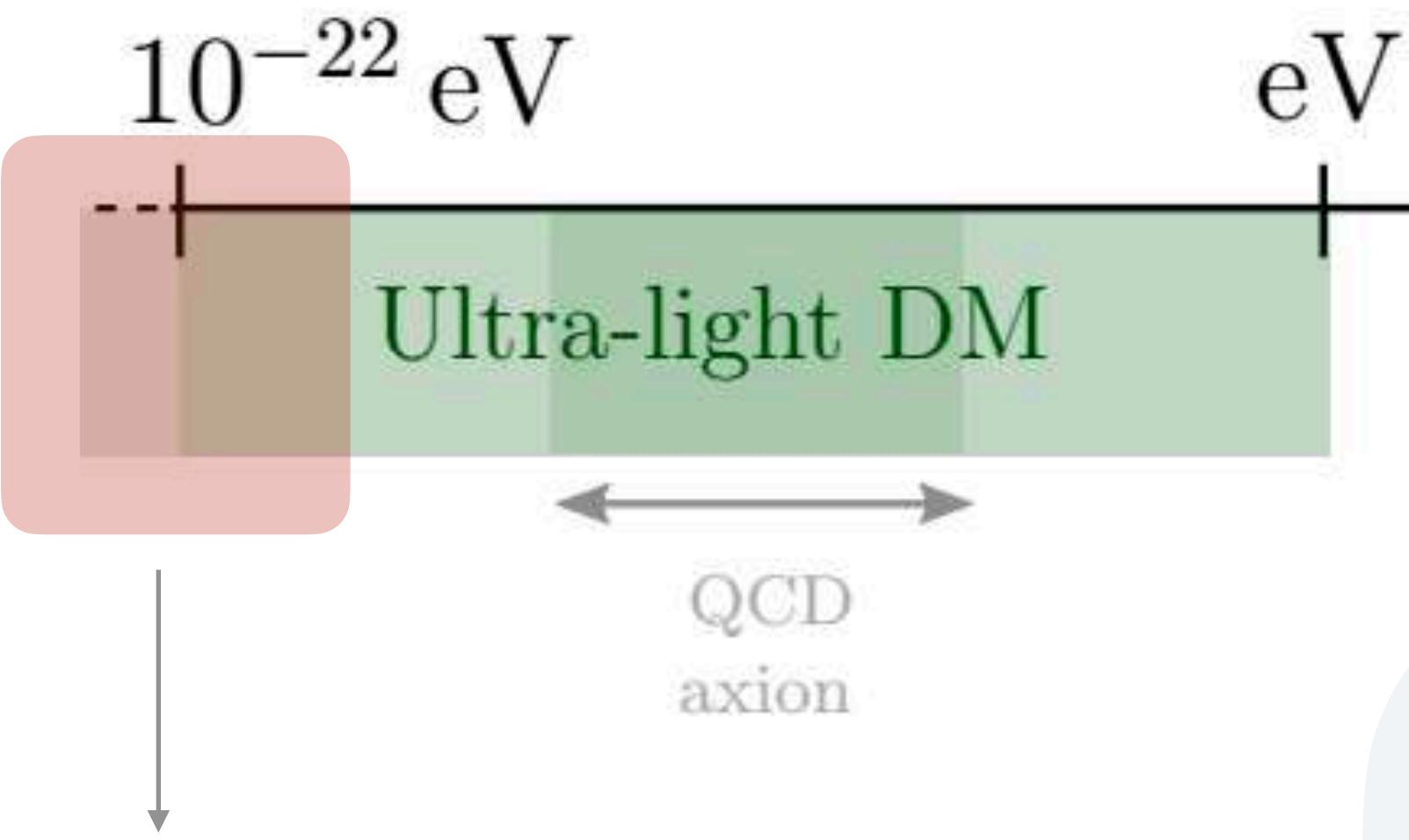
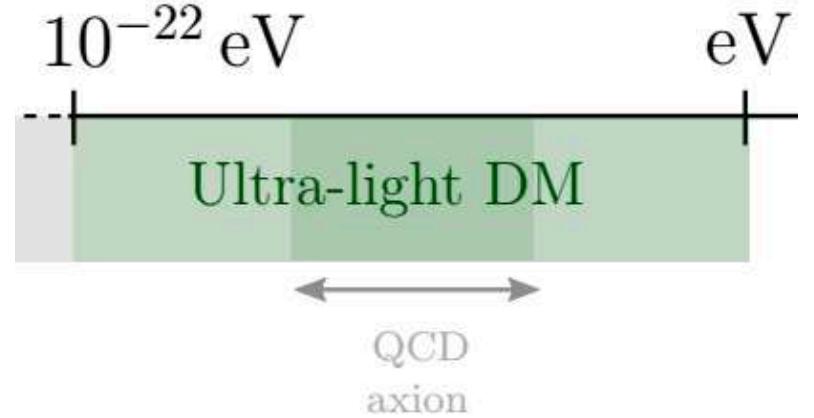


"Direct detection"
Axion/ALPs experiments



$$\mathcal{L} \supset \frac{1}{2} (\partial a)^2 - \frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}_{\mu\nu}$$

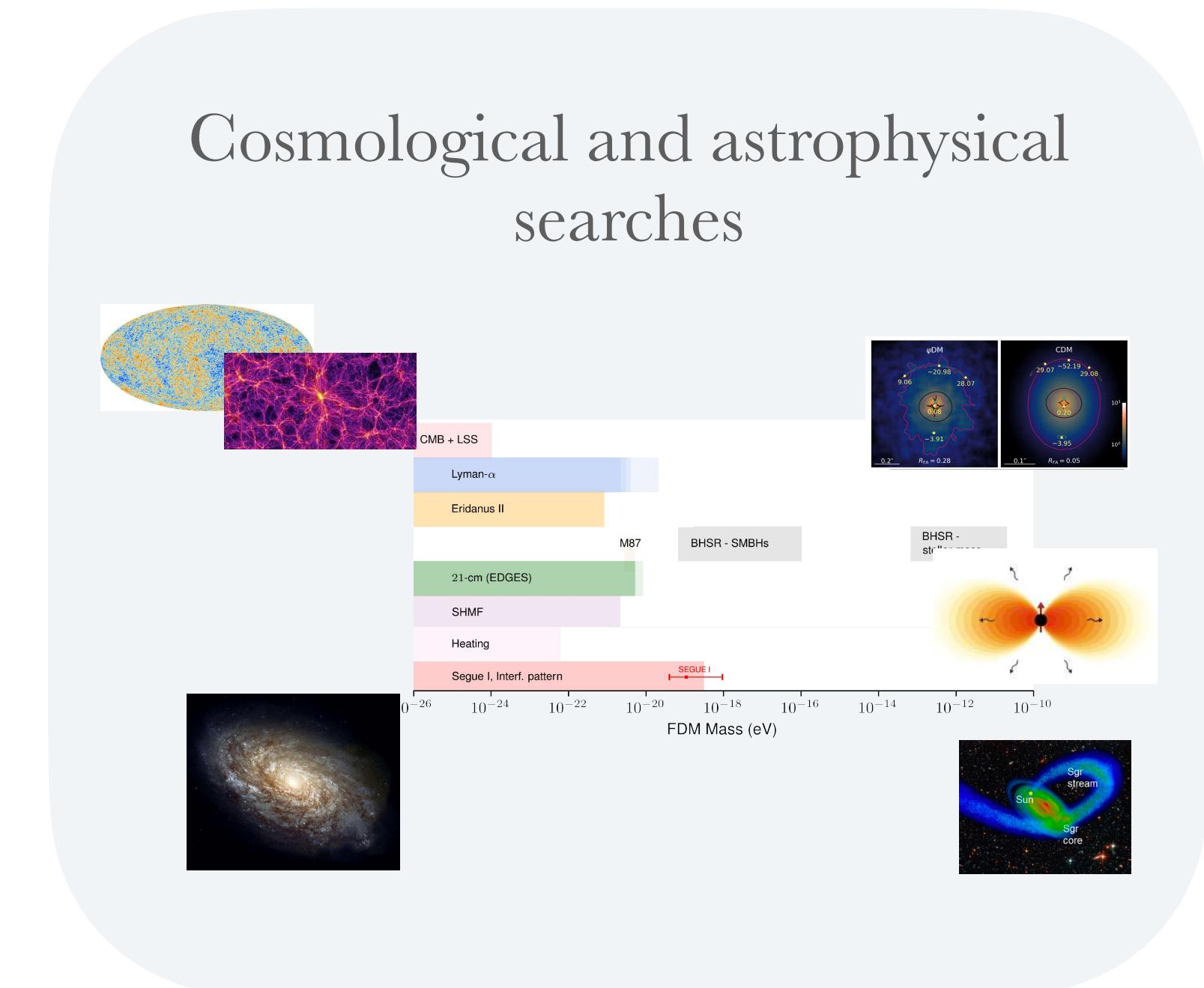
Ultra-light Dark Matter



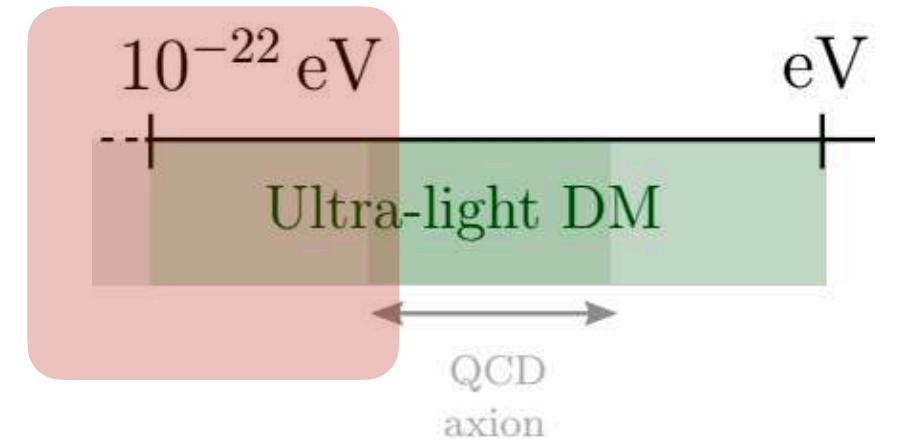
Gravitational probes

$$10^{-24} \text{ eV} \lesssim m_{\text{fdm}} \lesssim 10^{-18} \text{ eV}$$

Particle properties: mass, spin
And also fraction.

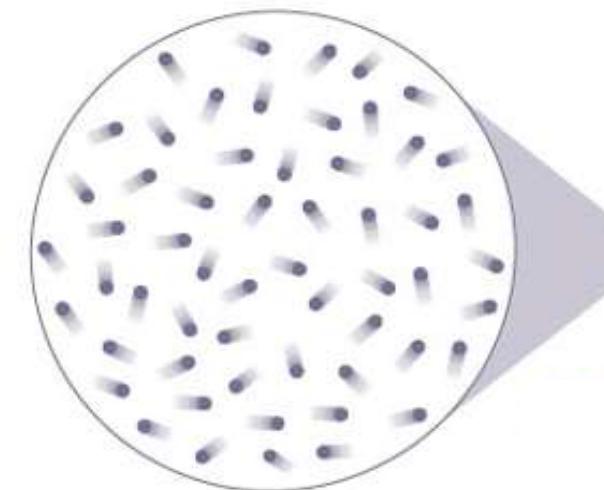


Ultra-light Dark Matter

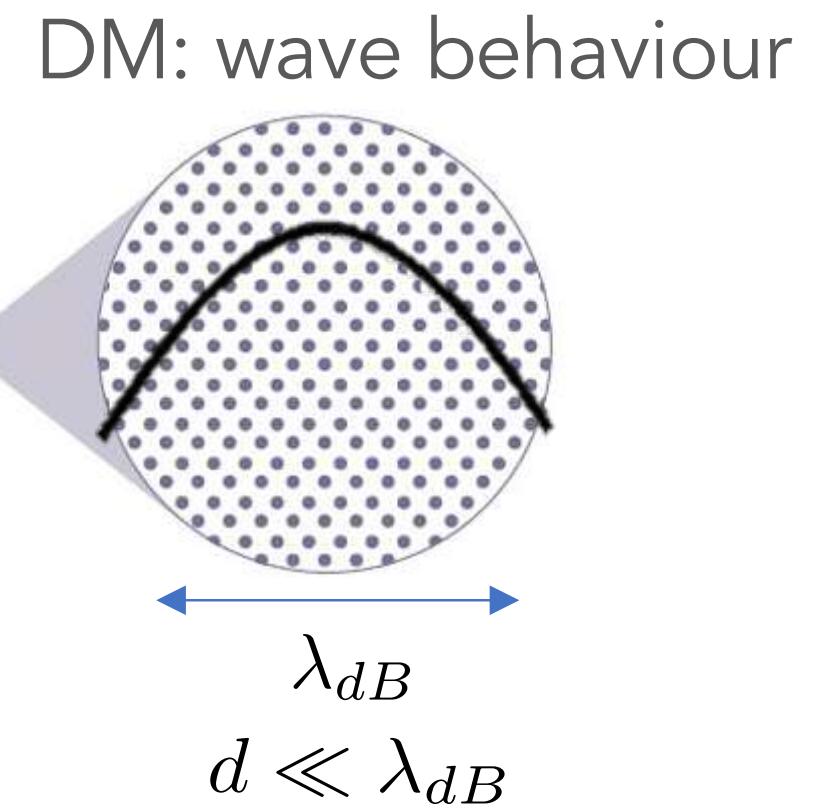
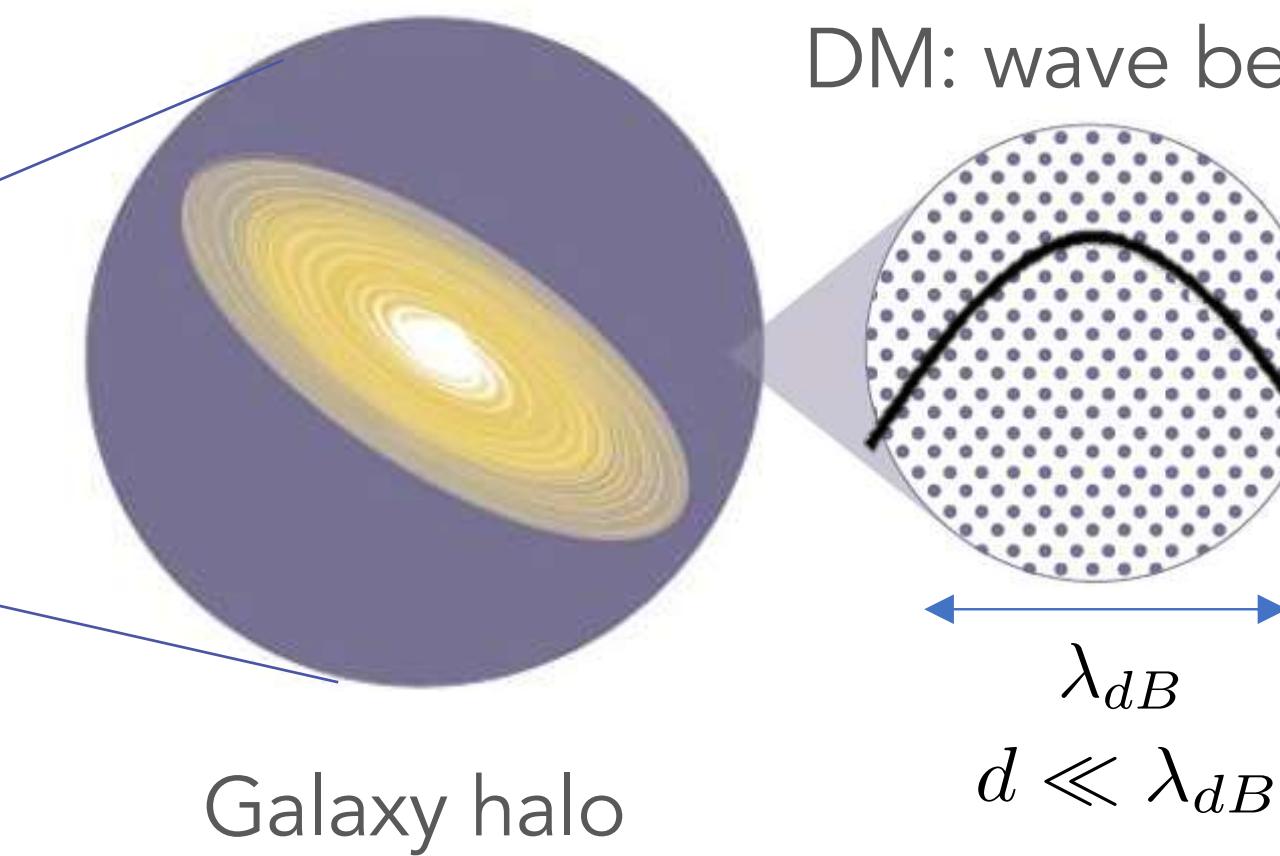
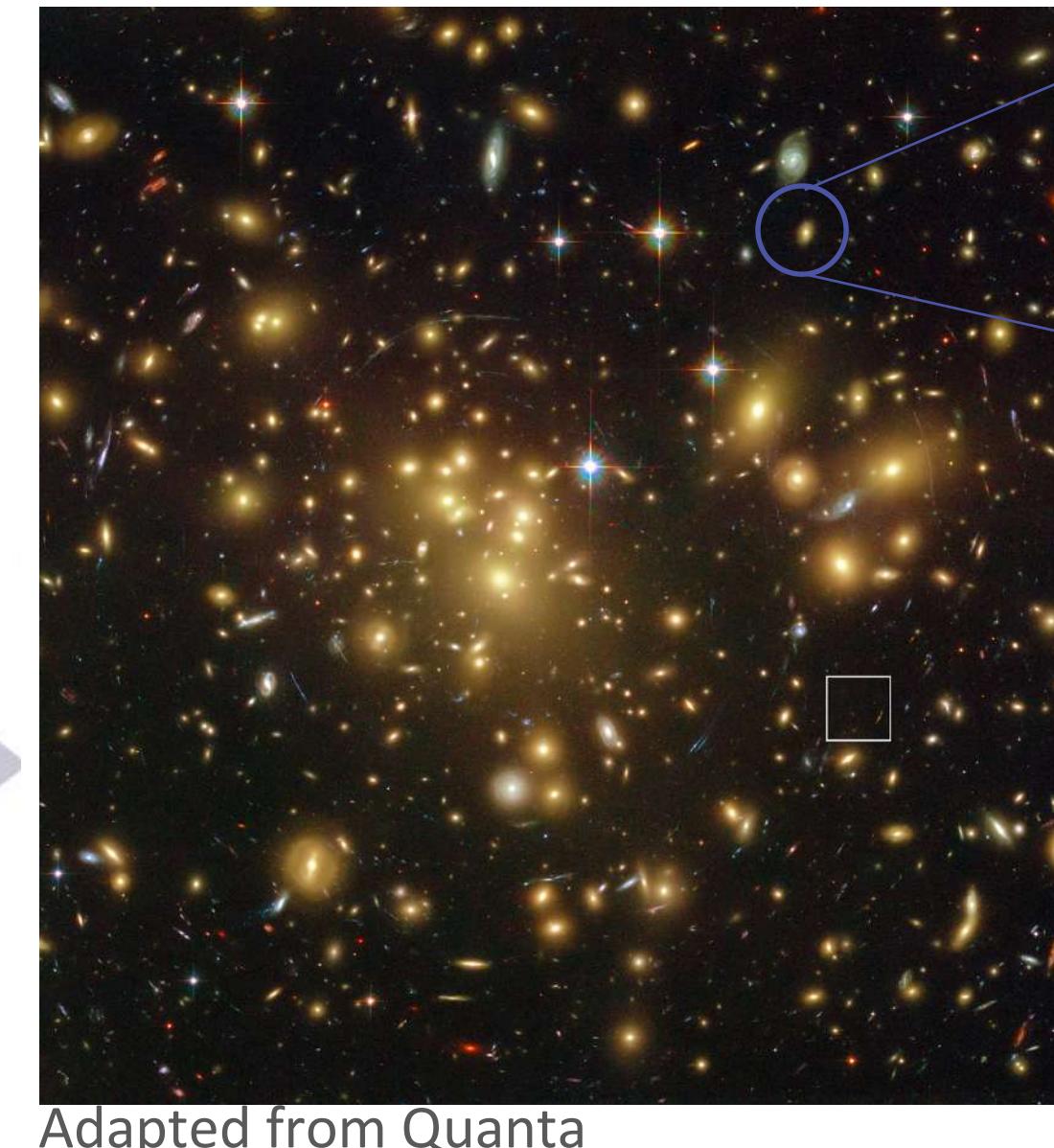


Ultra-light candidate \longrightarrow Large $\lambda_{dB} \sim 1/mv$
Lightest possible candidate for DM

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



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

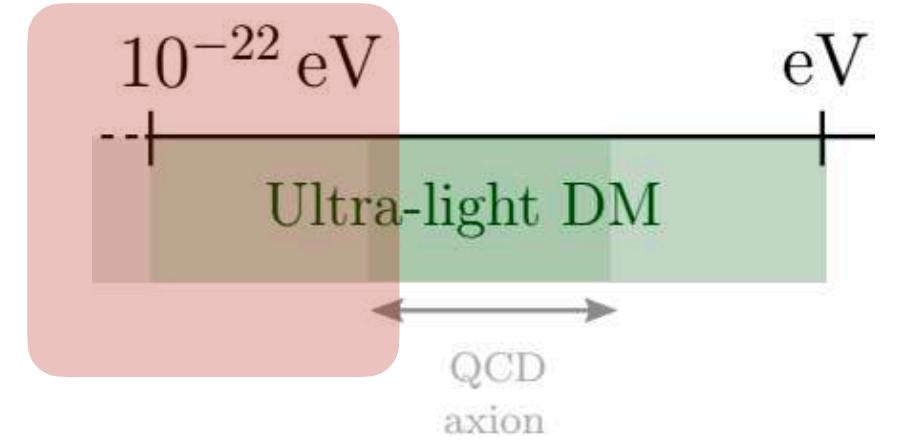


Small scales:
DM behaves like a **wave**

$$10^{-60} \text{ kg} \quad 10^{-35} \text{ kg}$$
$$10^{-25} \text{ eV} \lesssim m \lesssim \text{eV}$$

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

Ultra-light Dark Matter -classes



3 classes:

Fuzzy DM (FDM)

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

m

DOFs

Self Interacting FDM (SIFDM)

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

$m \quad g$

DM Superfluid

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

Axion and ALP (axion like particles)

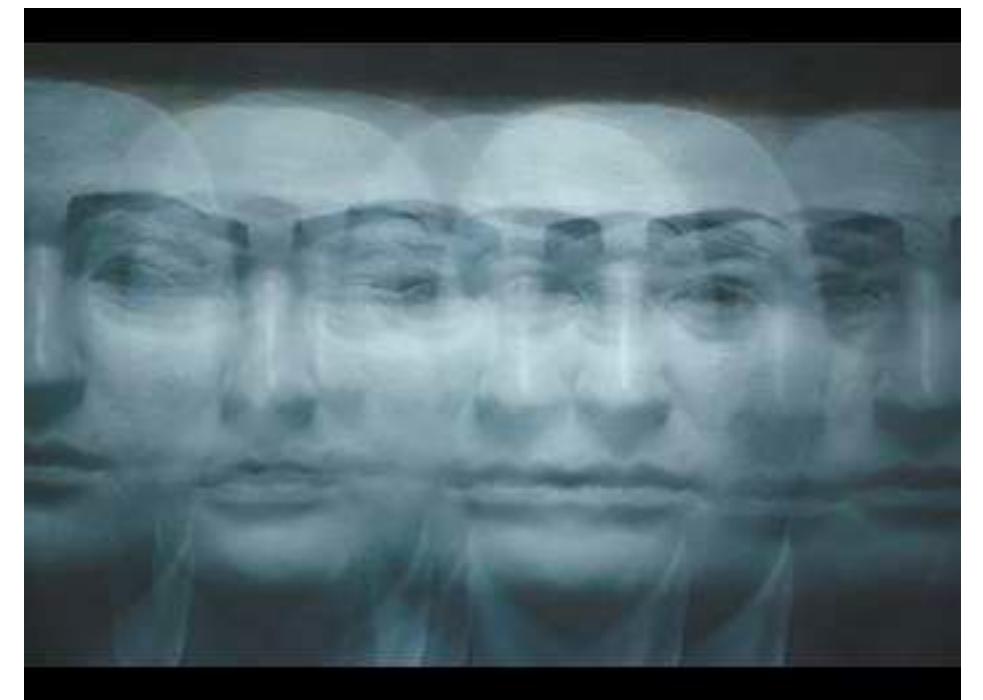
$$i\dot{\psi} = \left(-\frac{1}{2m} \nabla^2 + \frac{g}{8m^2} |\psi|^2 - m\Phi \right) \psi$$

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

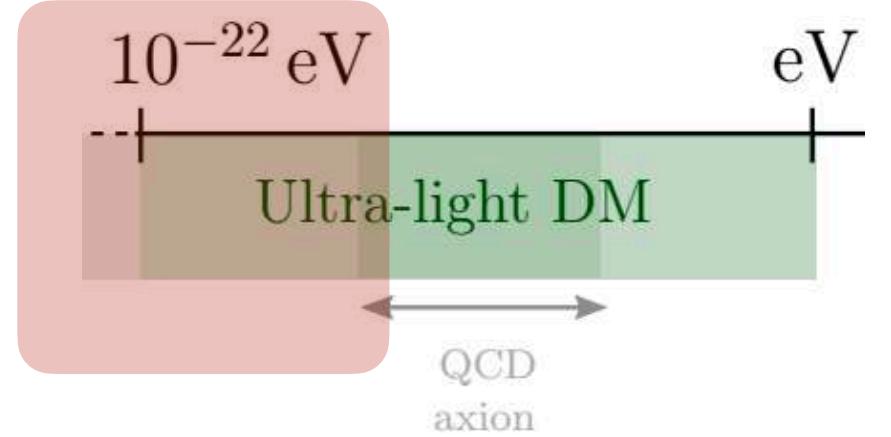
→ Connection with condensed matter and particle physics!

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

Fuzzy dark matter



Structure formation - non-relativistic regime



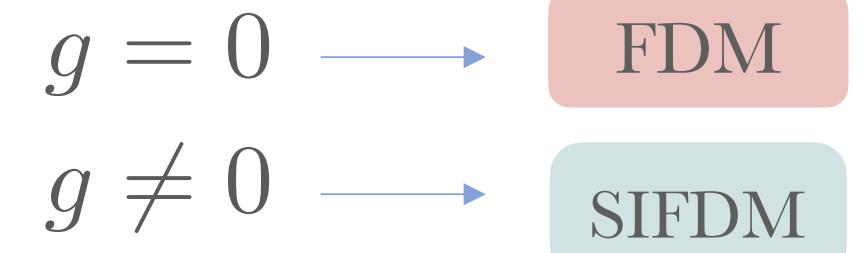
Evolution on small scales: take non-relativistic regime of the theory, relevant for structure formation.

Schrödinger-Poisson system : describe the FDM and the SIFDM

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

Schrödinger equation
(Gross-Pitaevskii)

Poisson equation



Fundamentally different than
CDM/WDM/SIDM!

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

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

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

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

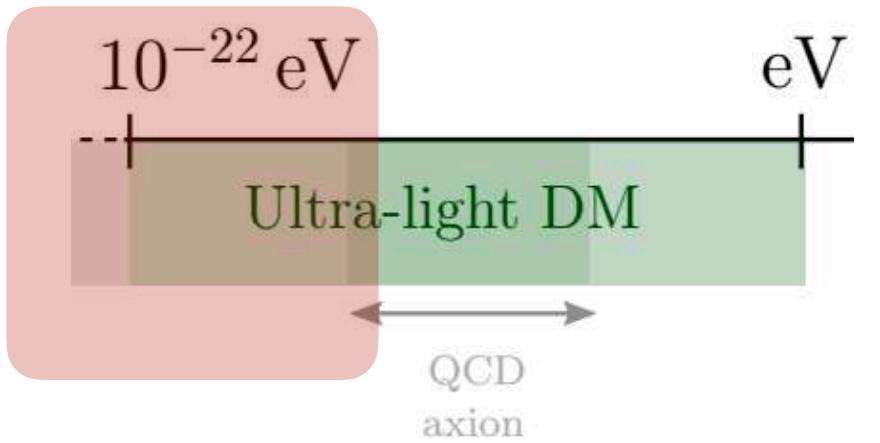
$$\frac{1}{2m} \frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}}$$

Quantum pressure

Finite Jeans length -
Suppresses
structure formation
on small scales

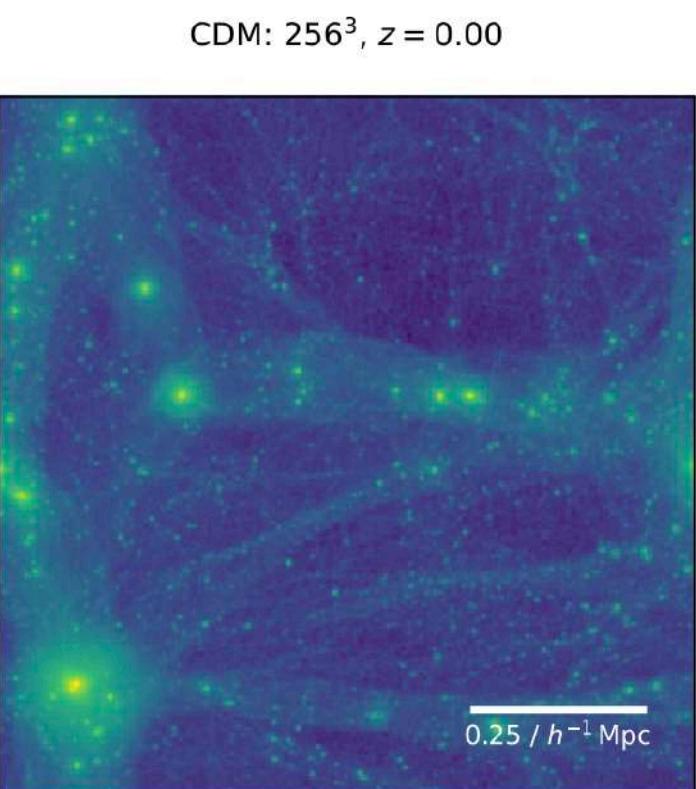
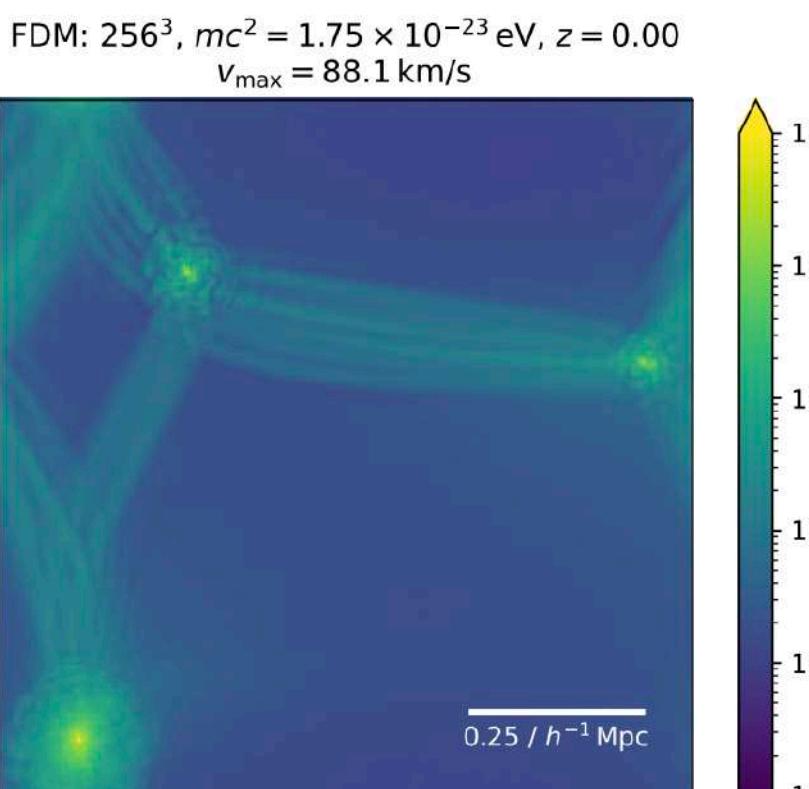
Phenomenology

RICH PHENOMENOLOGY ON SMALL SCALES



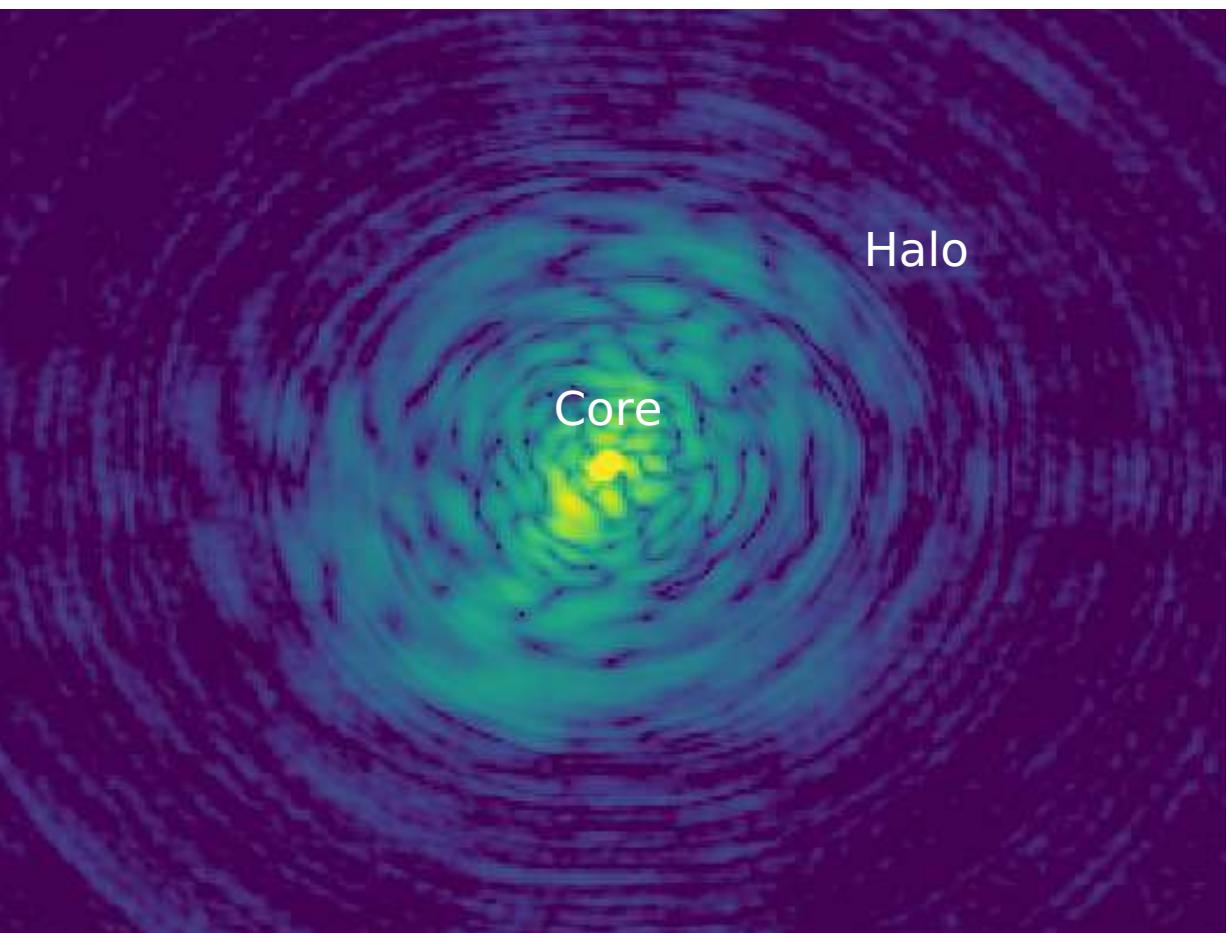
* Focus only in gravitational signatures

Suppression of small structures

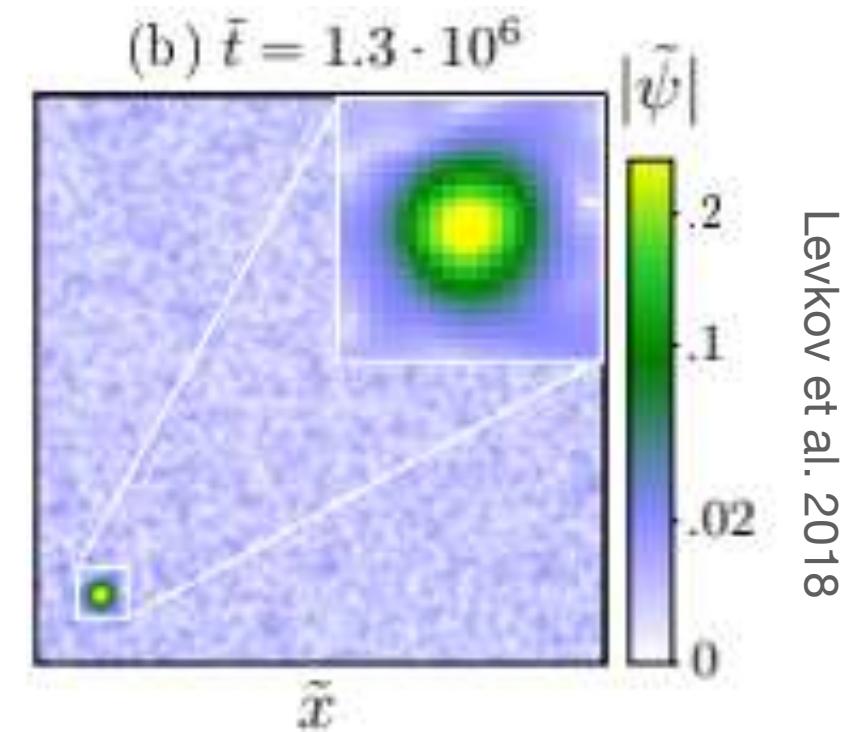


S. May et al. 2021

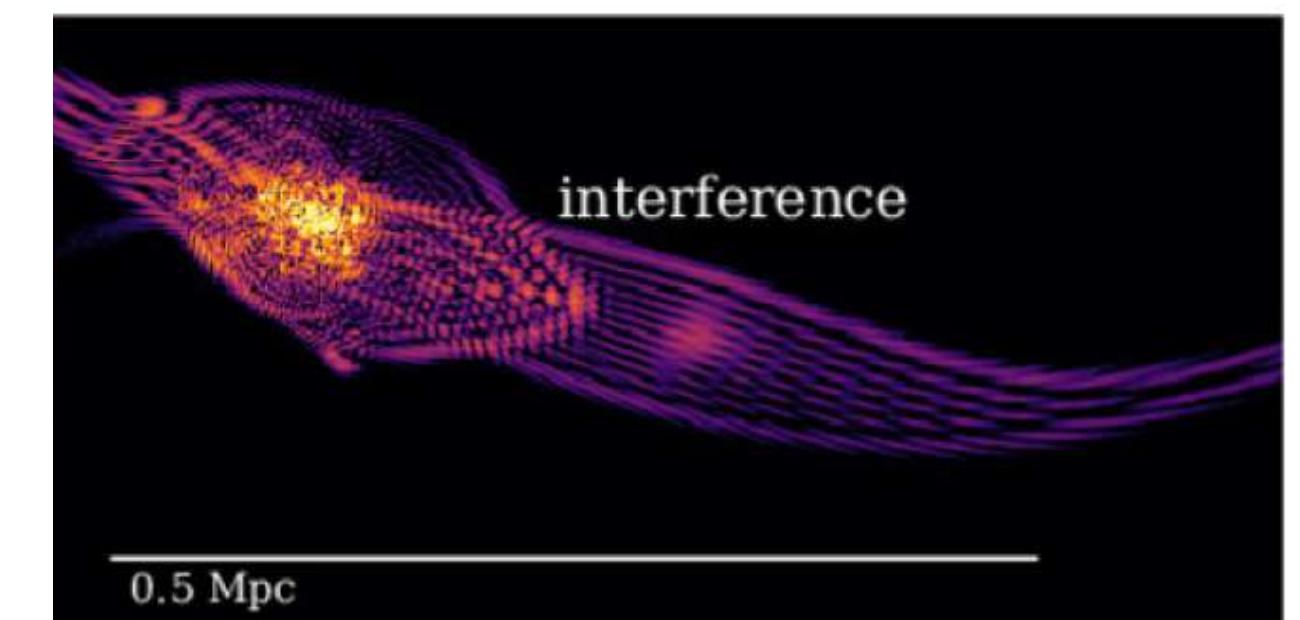
Formation of a solitonic core



Dynamical effects

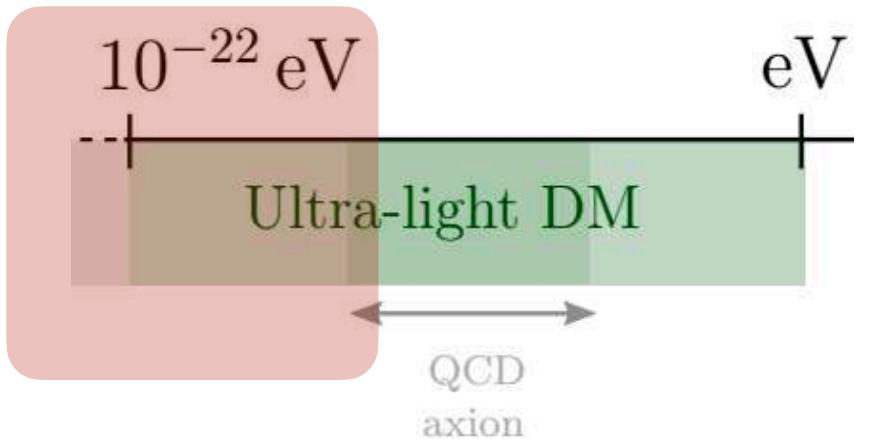


Wave interference

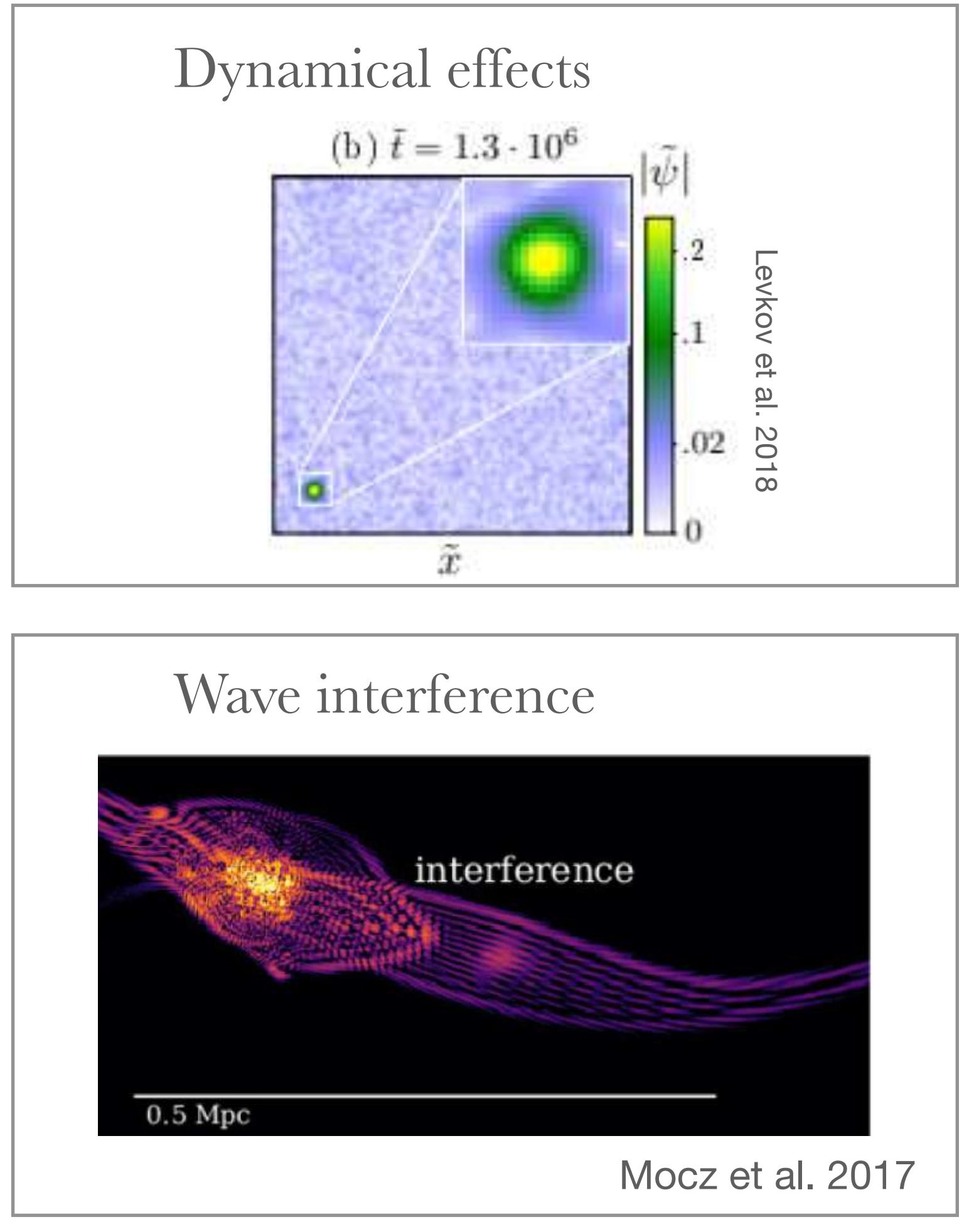
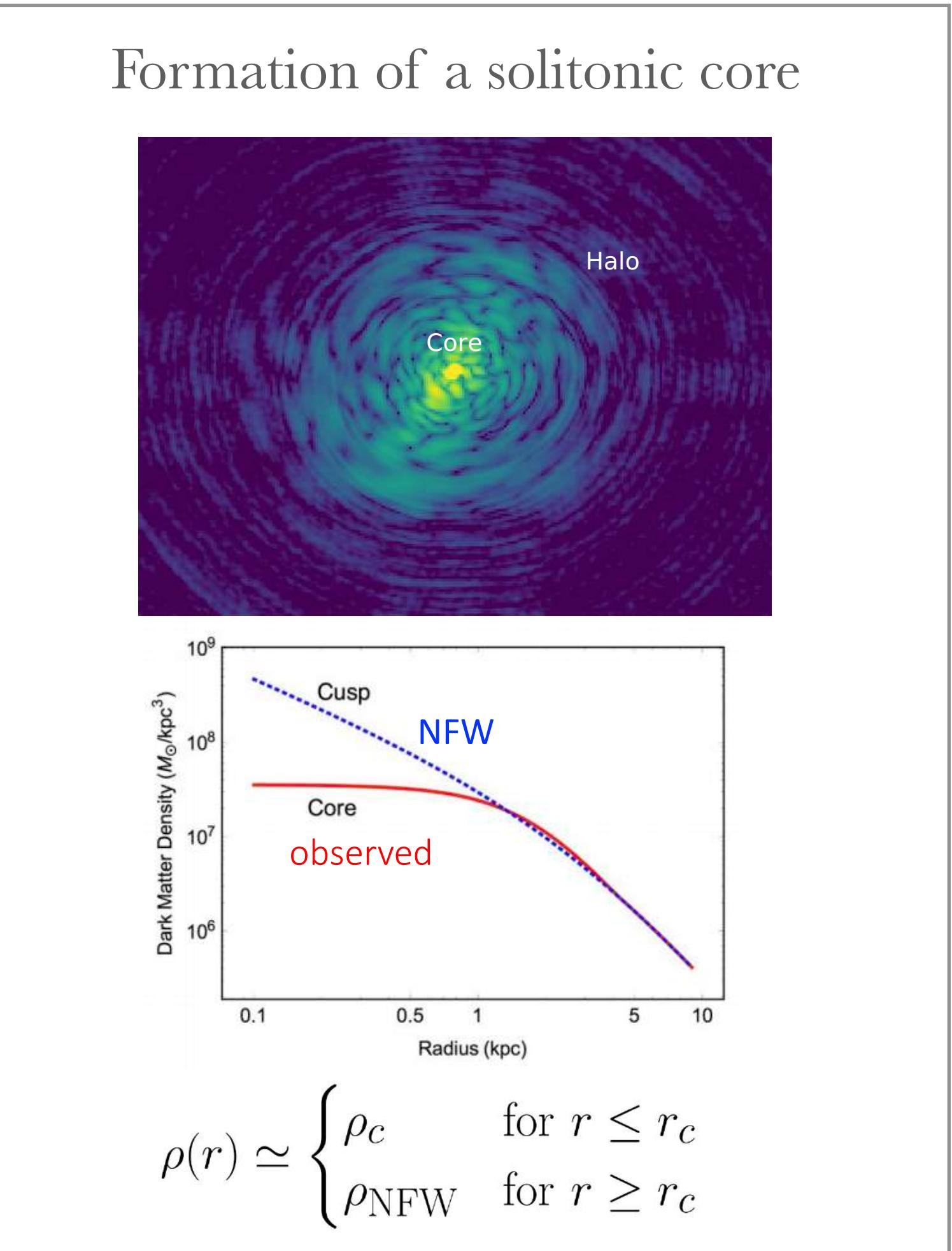
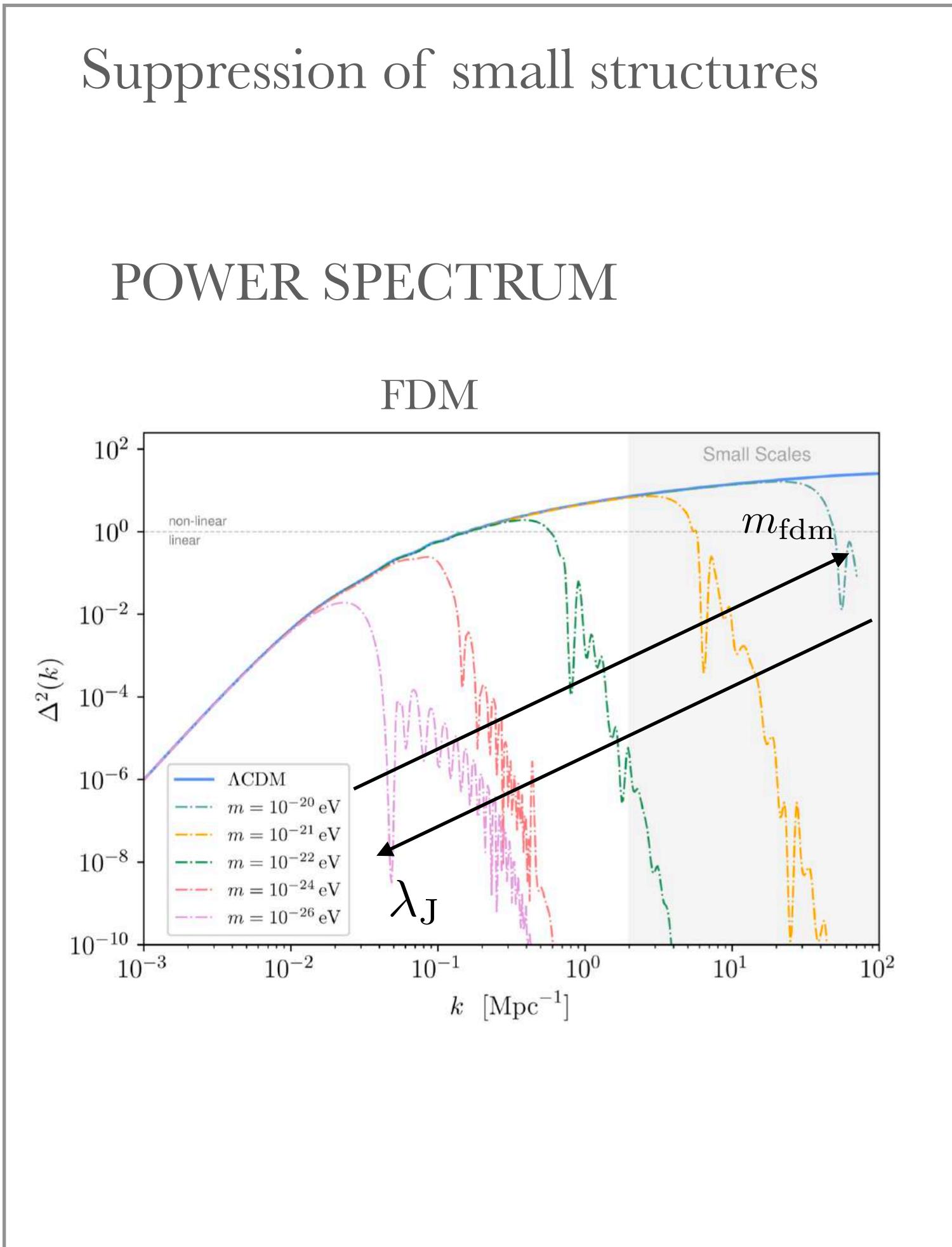


Phenomenology

RICH PHENOMENOLOGY ON SMALL SCALES

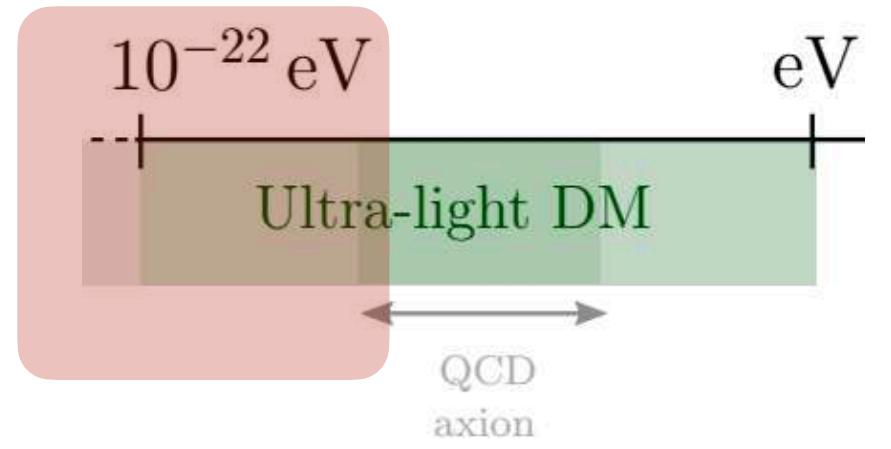


* Focus only in gravitational signatures

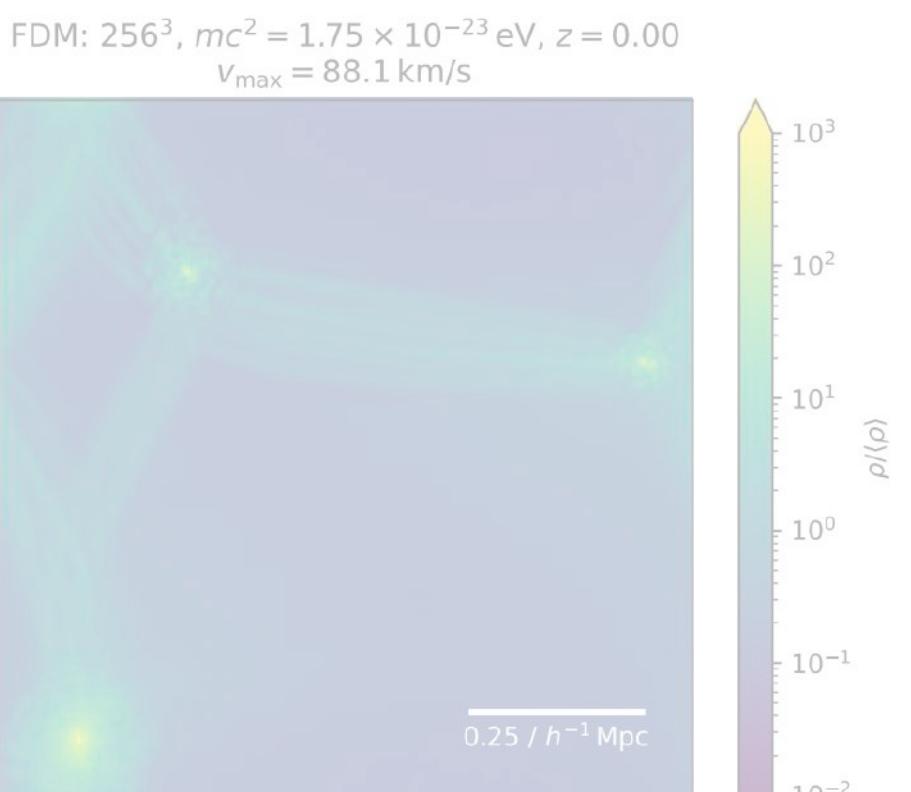


Phenomenology

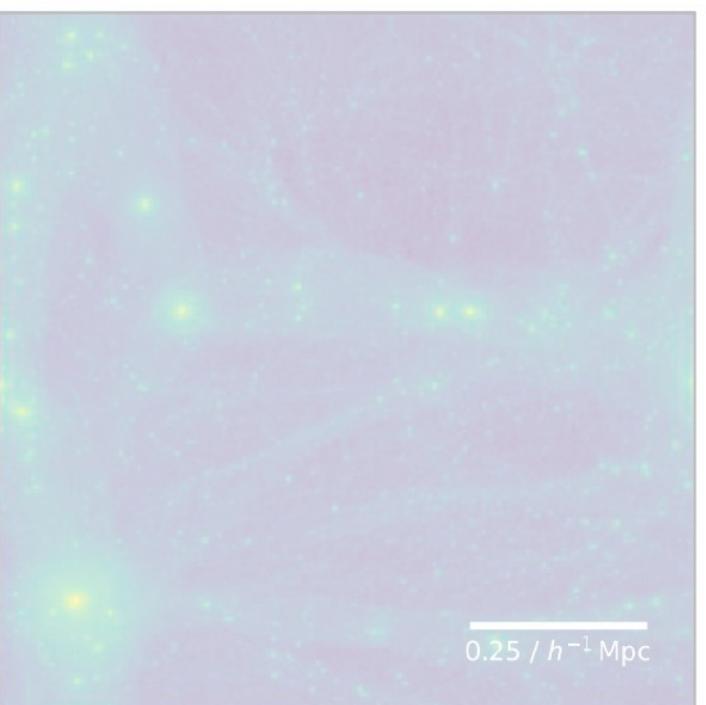
RICH PHENOMENOLOGY ON SMALL SCALES



Suppression of small structures

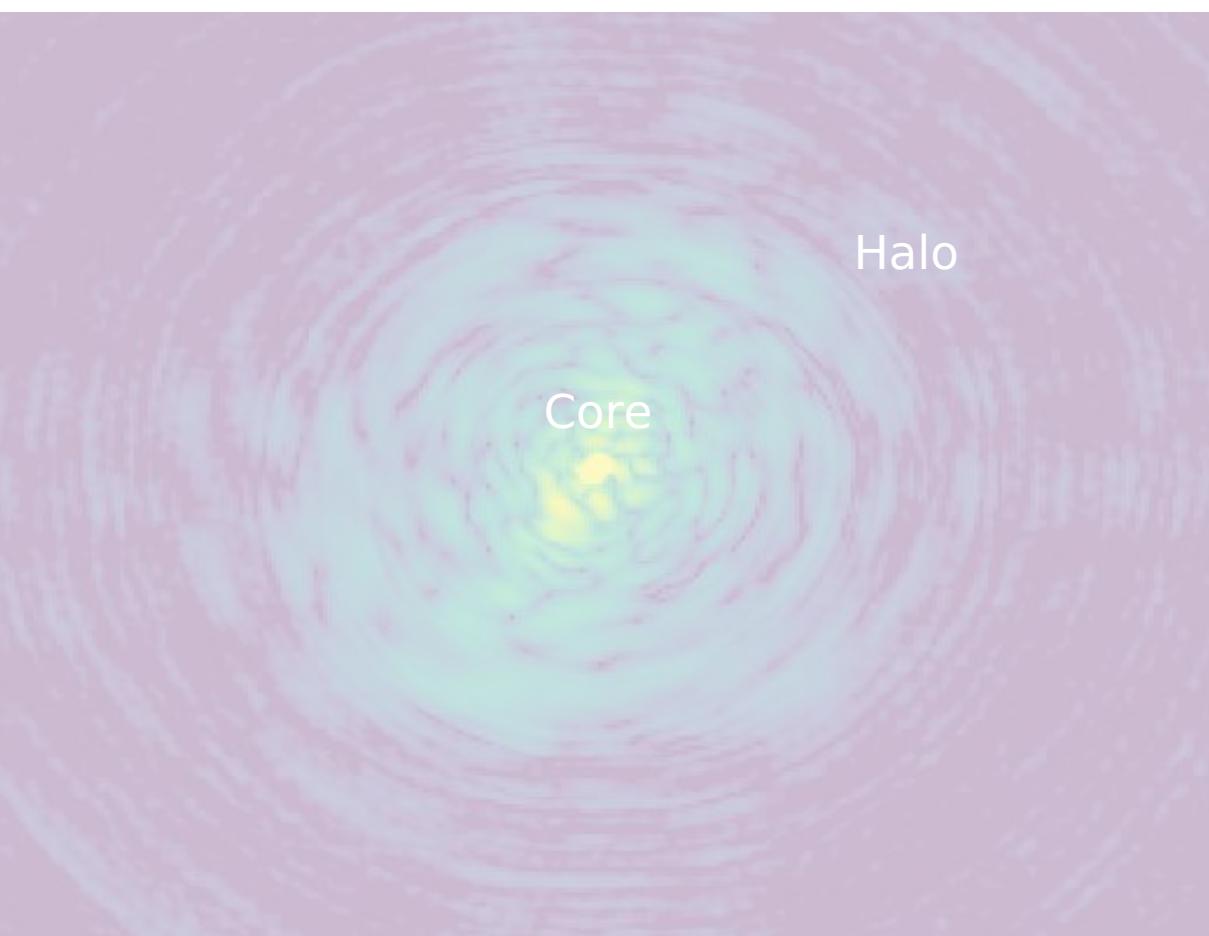


CDM: 256^3 , $z = 0.00$

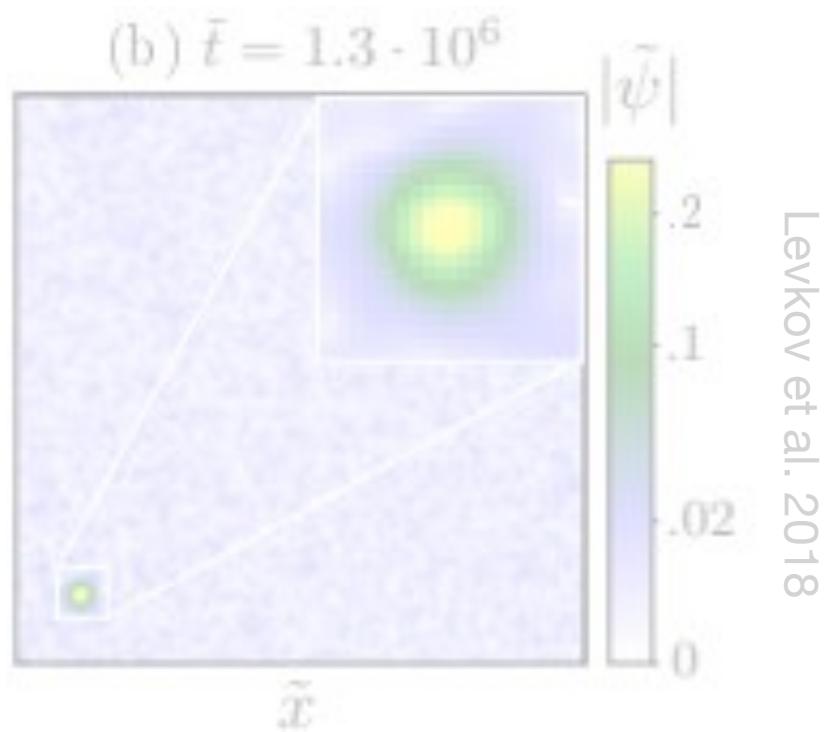


S. May et al. 2021

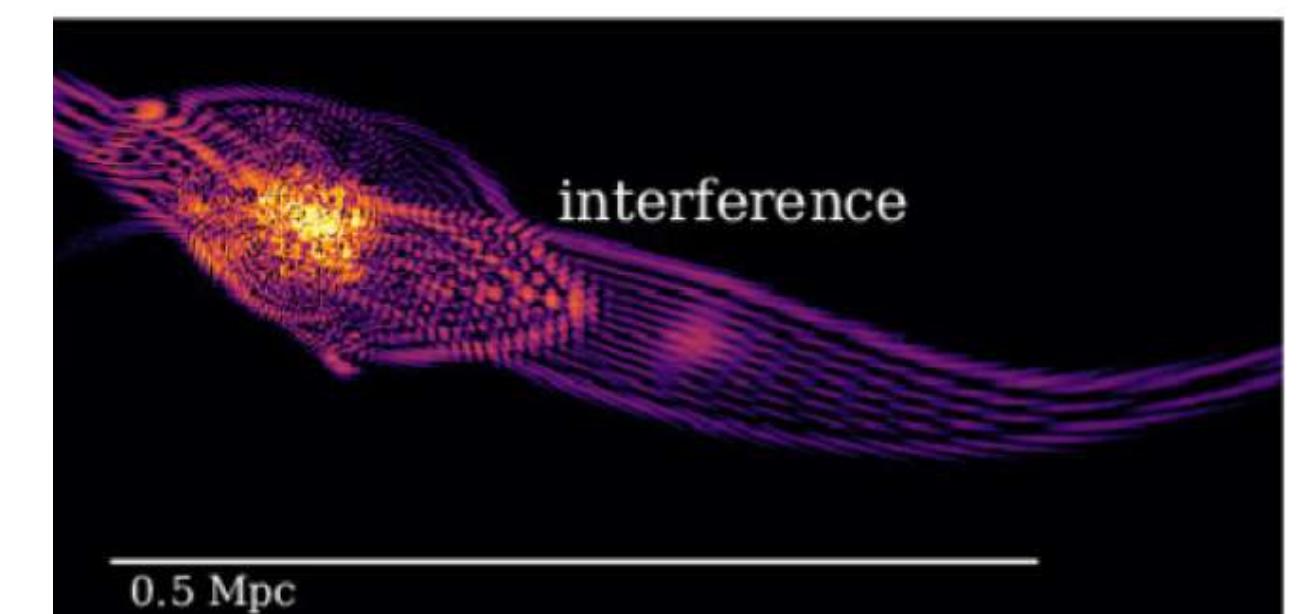
Formation of a solitonic core



Dynamical effects



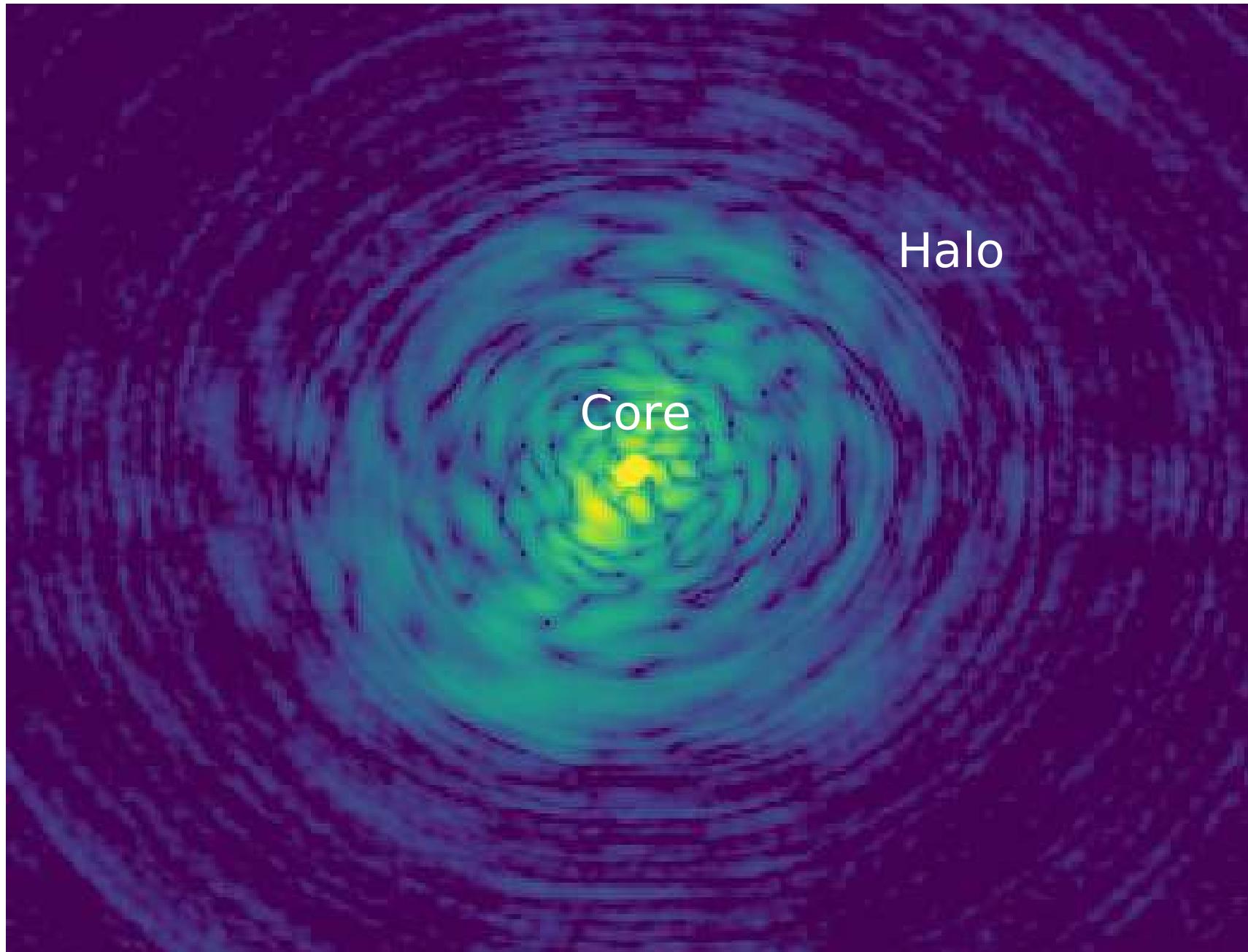
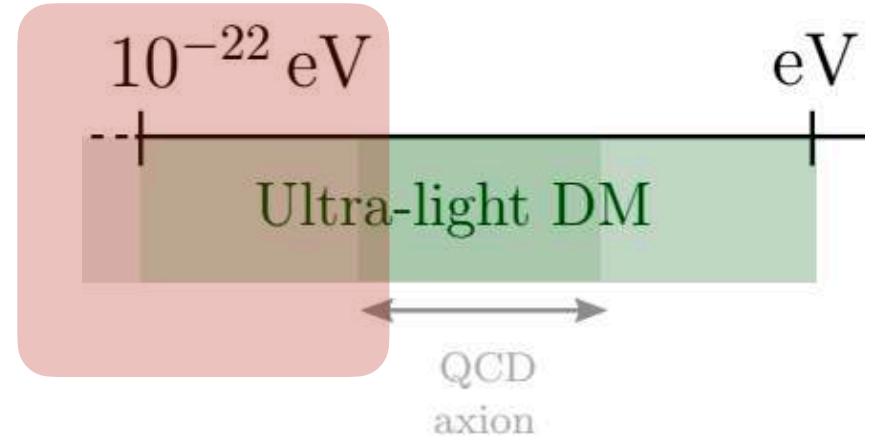
Wave interference



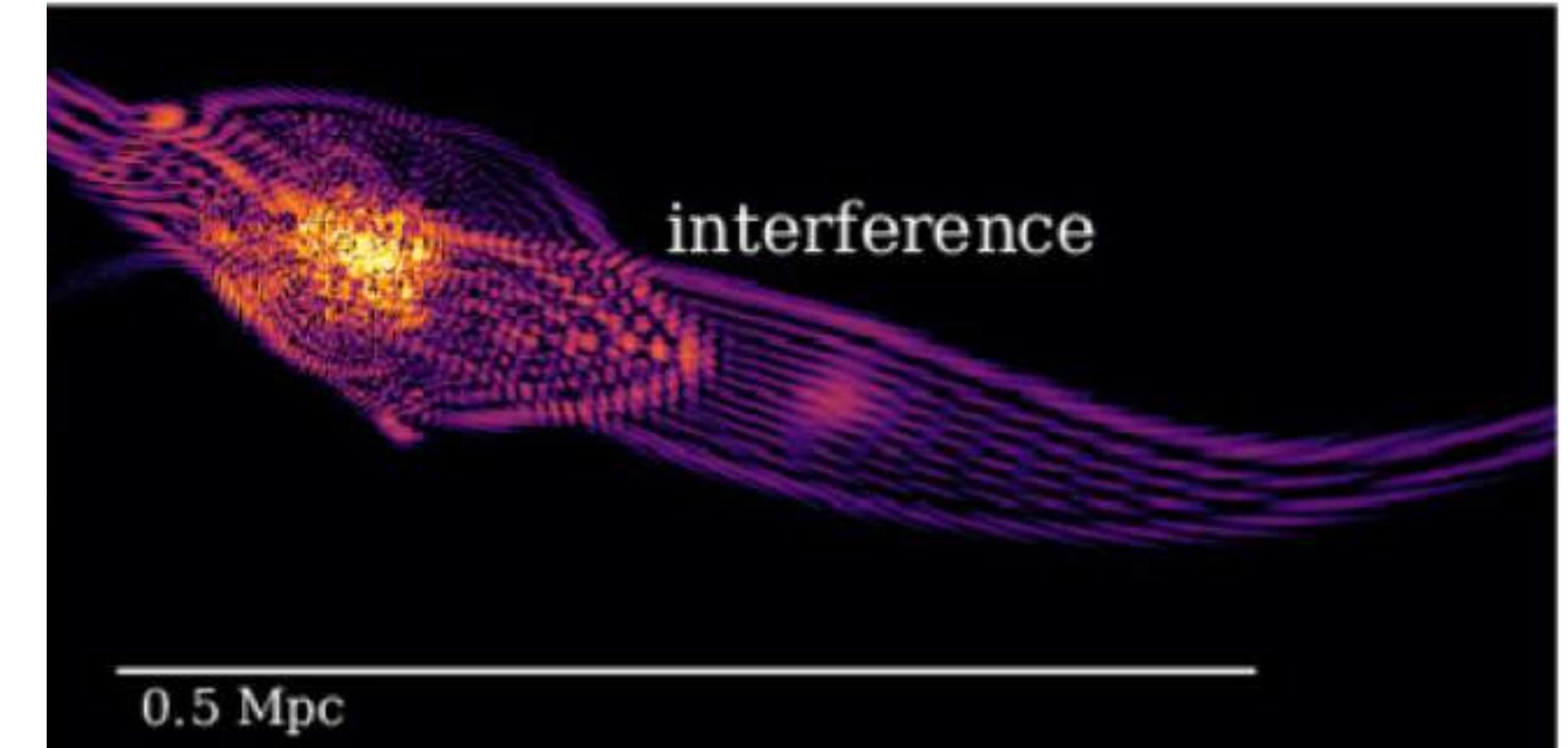
Mocz et al. 2017

Phenomenology

Wave interference: granules and vortices



Jowett Chan



Mocz et al. 2017

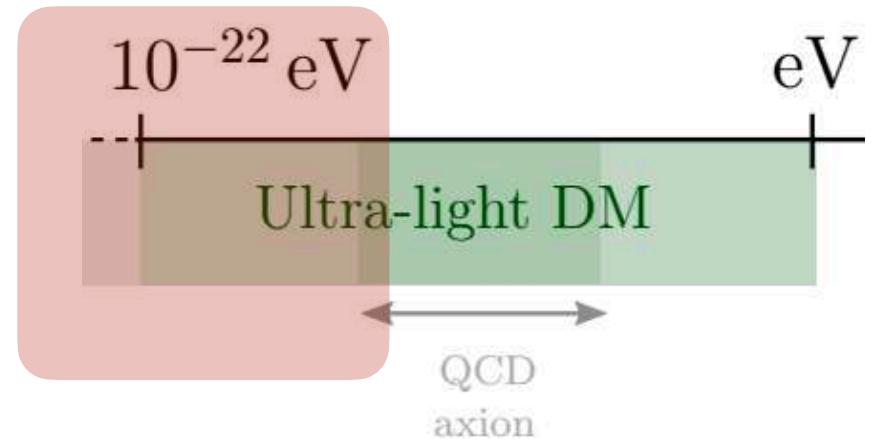
Order one fluctuations in density \longrightarrow

Constructive interference: **granules**
Destructive interference

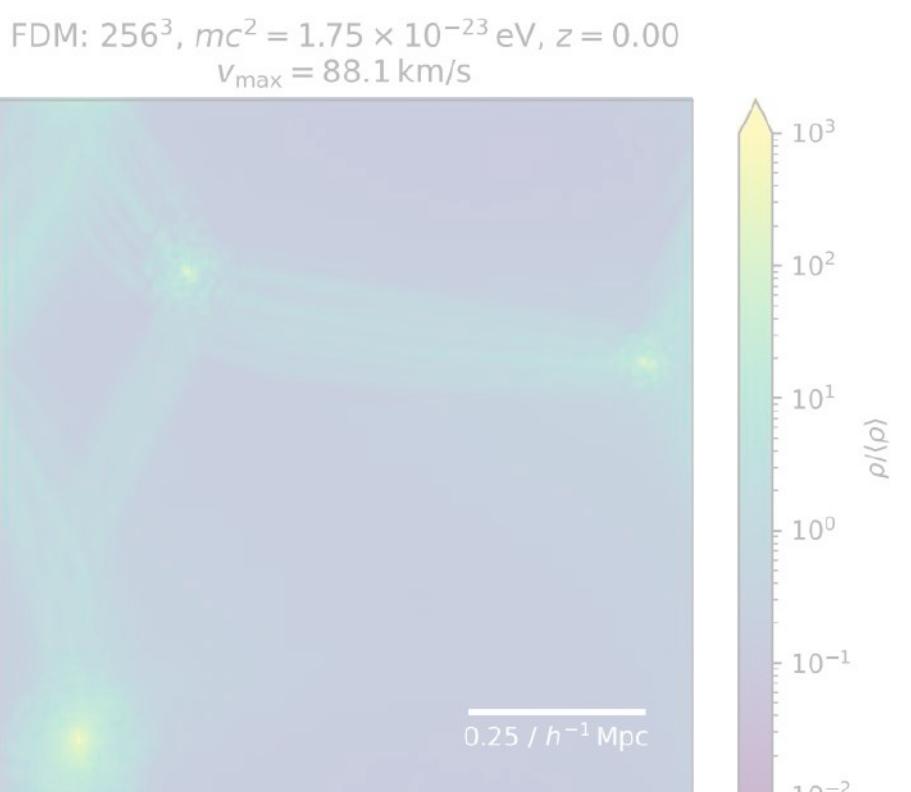
$\sim \lambda_{dB}$ Hard to observe!

Phenomenology

RICH PHENOMENOLOGY ON SMALL SCALES

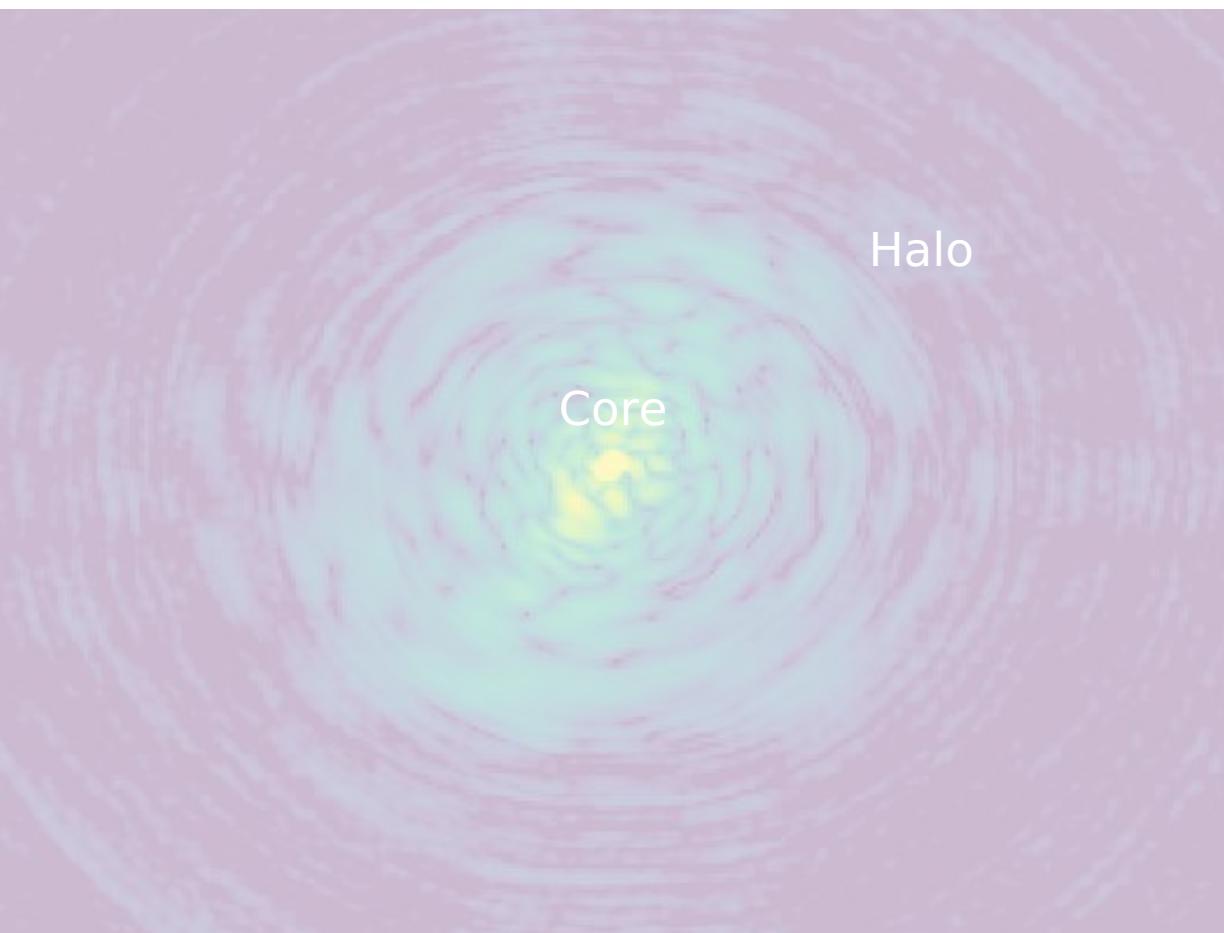


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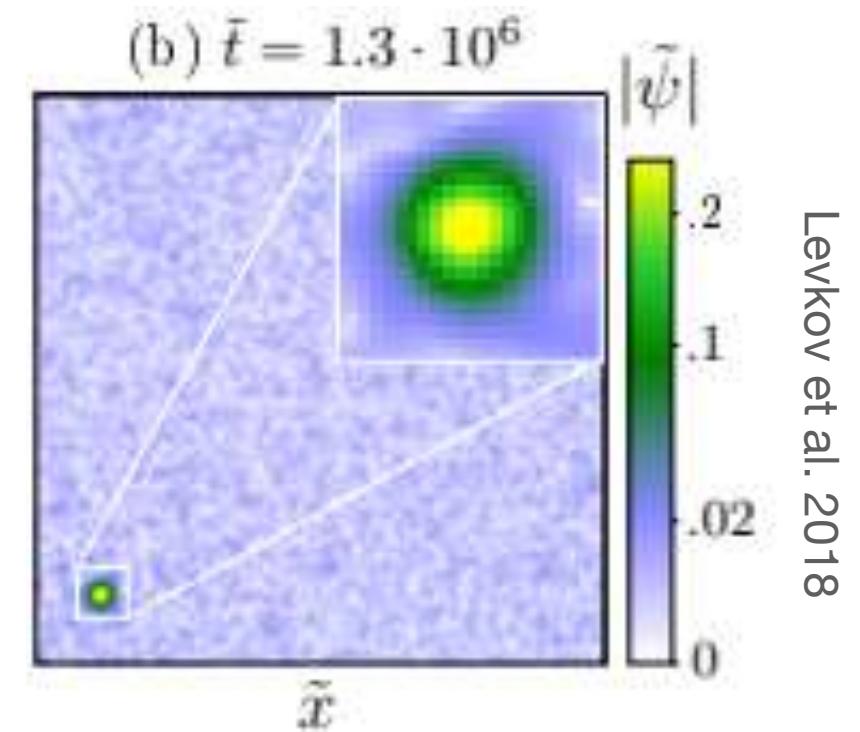


S. May et al. 2021

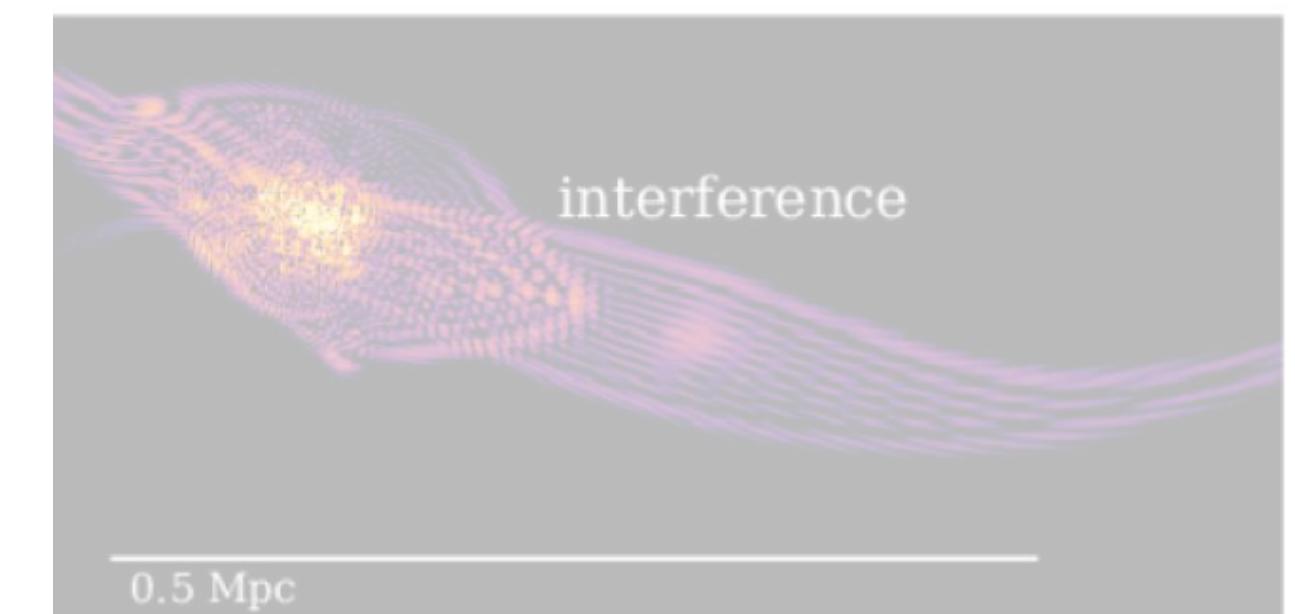
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Wave interference



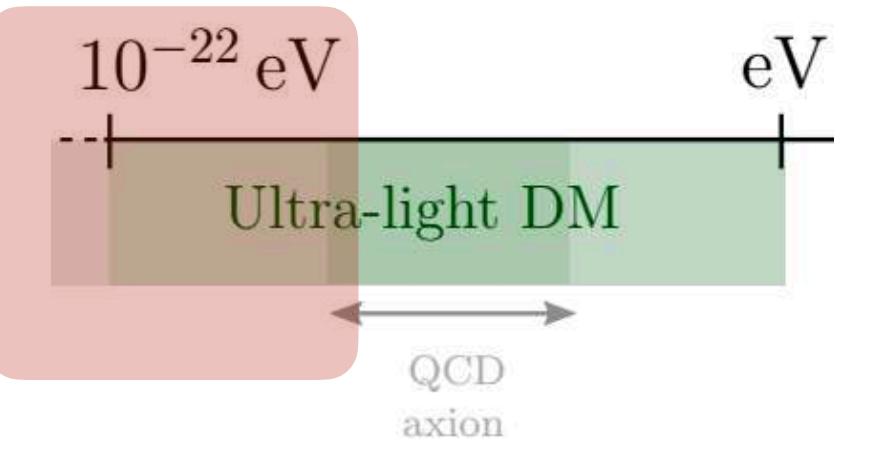
Mocz et al. 2017

S. May et al. 2021

Phenomenology

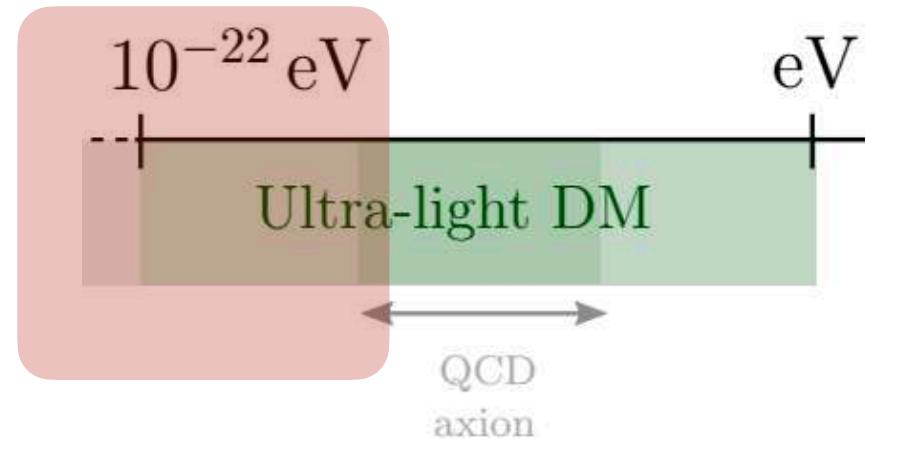
Dynamical effects

Relaxation, oscillation, friction, and heating

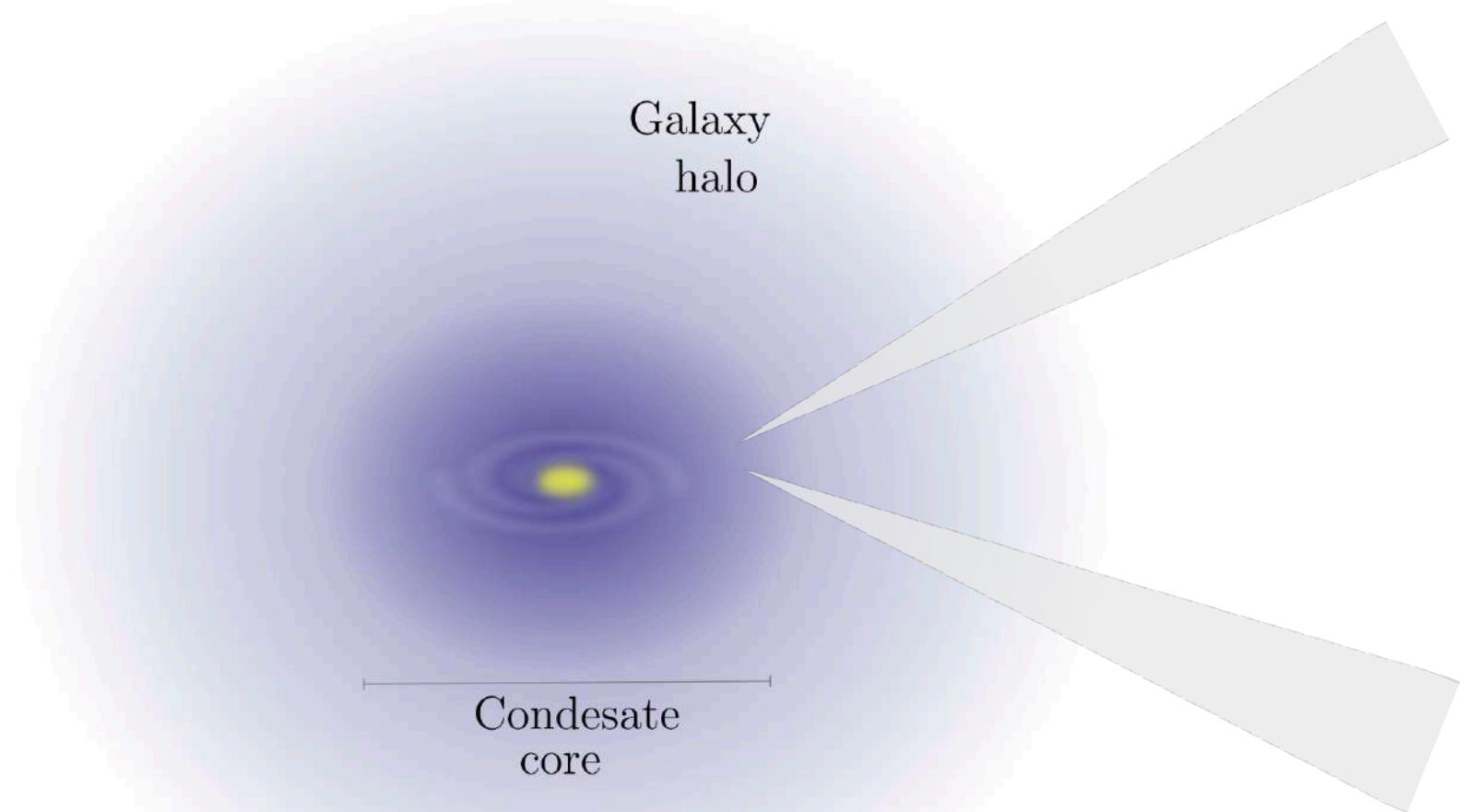


Phenomenology

Dynamical effects



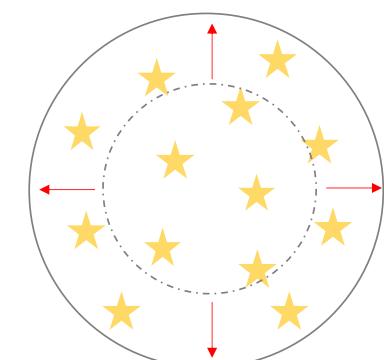
Relaxation, oscillation, friction, and heating



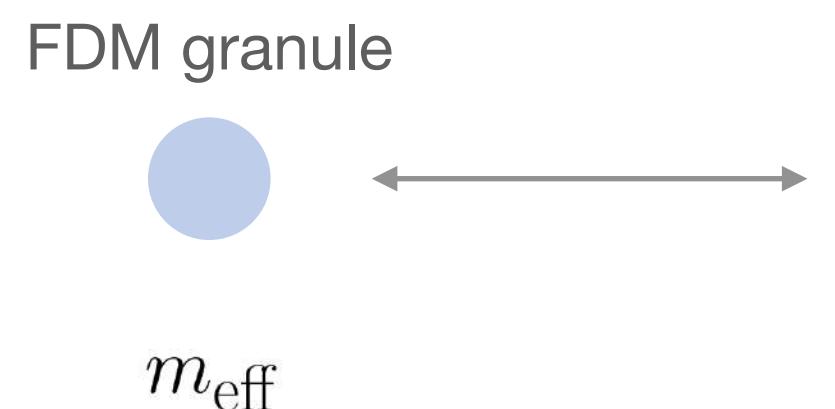
Heating



System (star)
gains energy



Friction

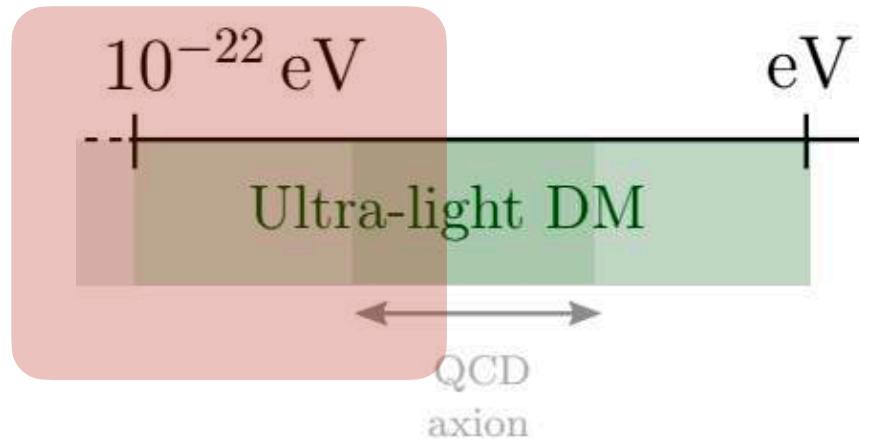


System (GC or BH)
loses energy



Globular cluster

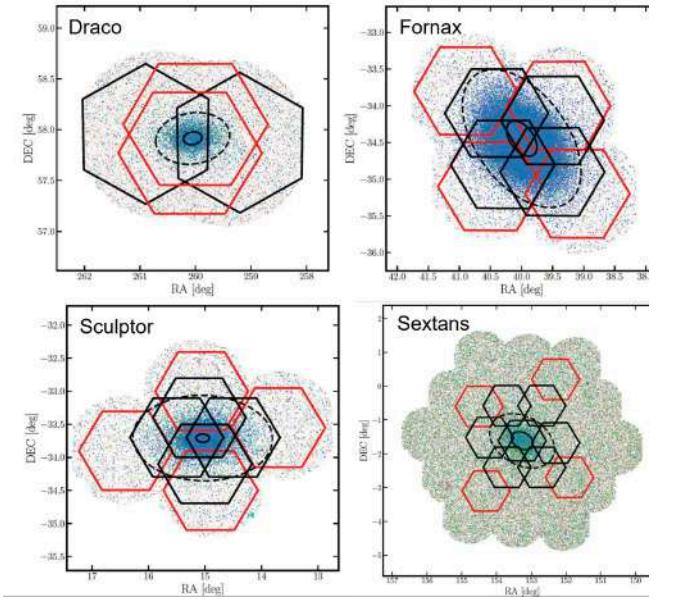
Observational implications and constraints



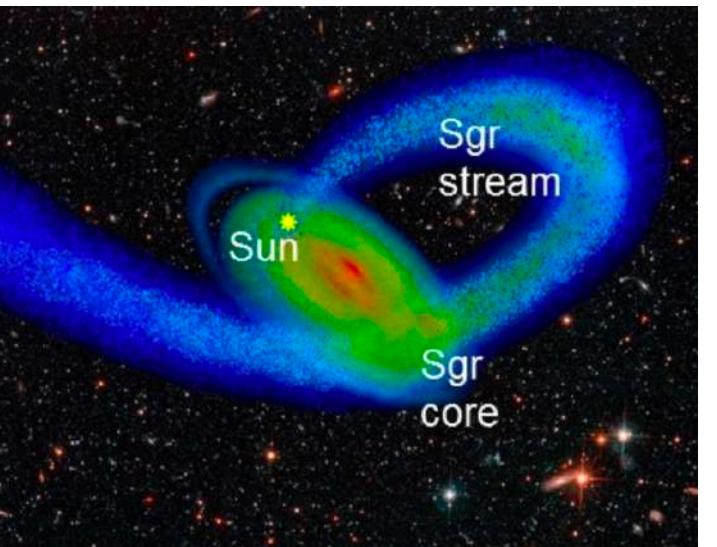
Galaxies



Dwarfs

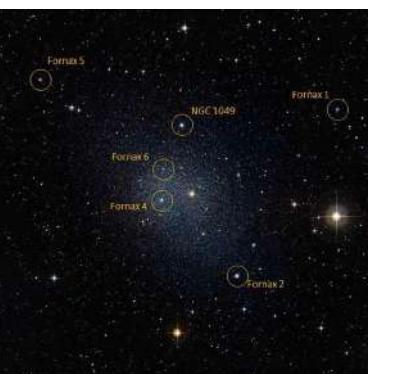


Stellar stream

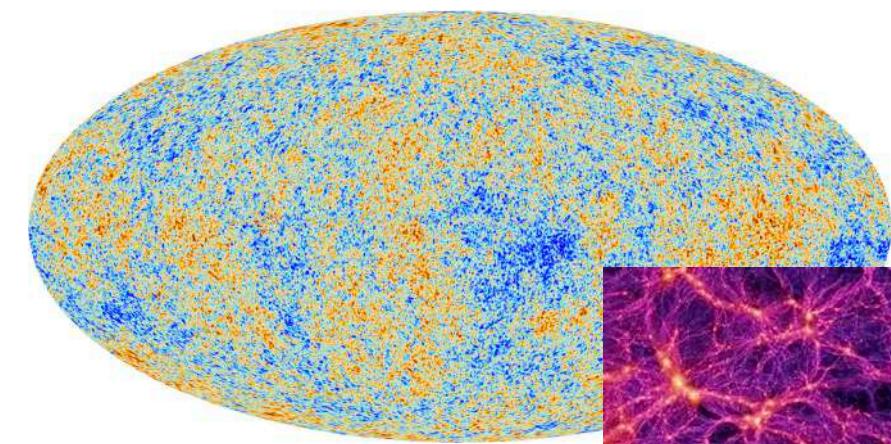


NASA and ESA

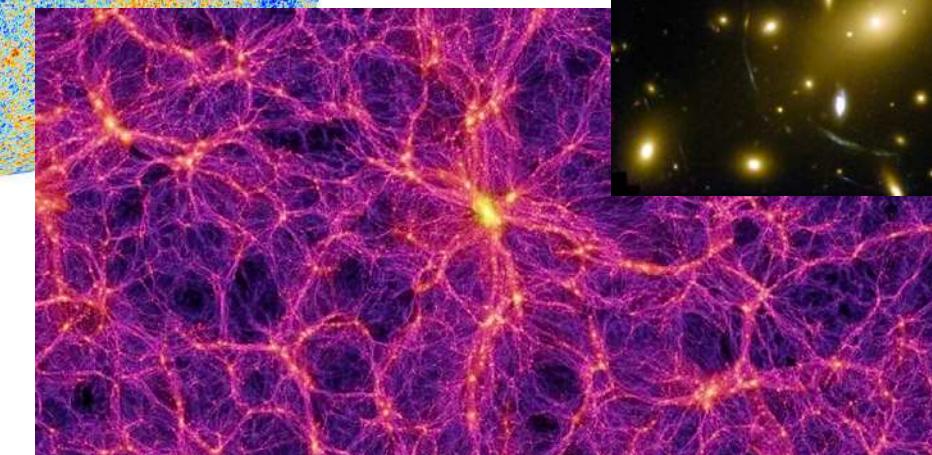
Globular clusters



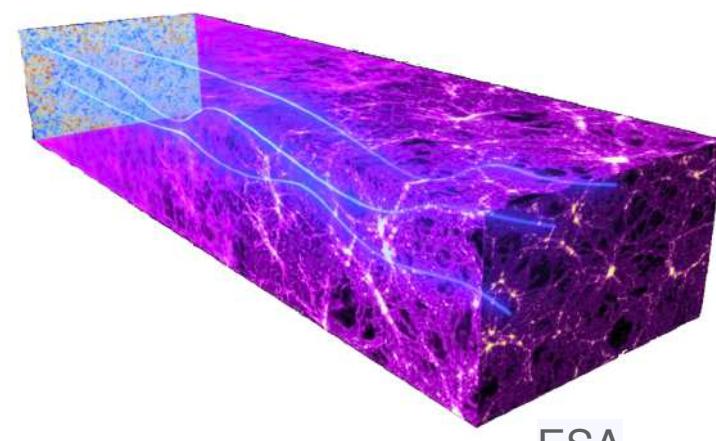
ESA and the Planck Collaboration



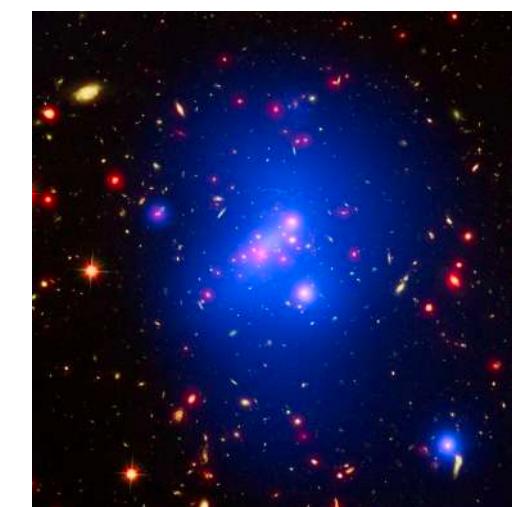
CMB+LSS



Springel & others / Virgo Consortium

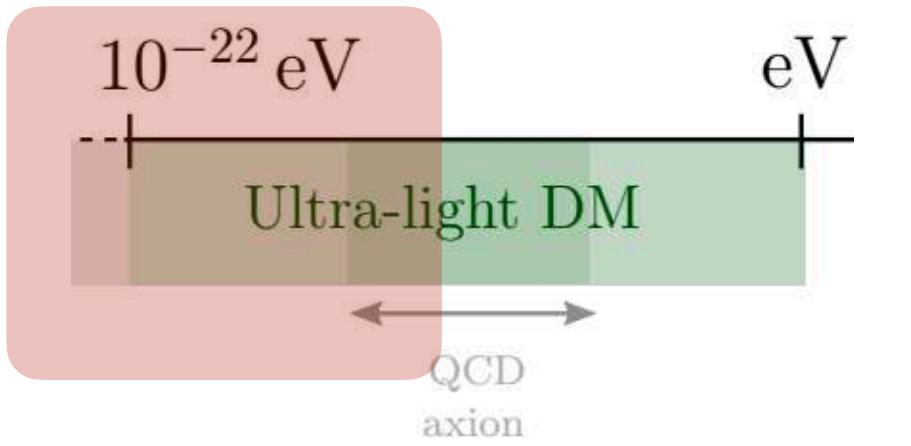


Clusters



NASA and ESA

CC BY 4.0

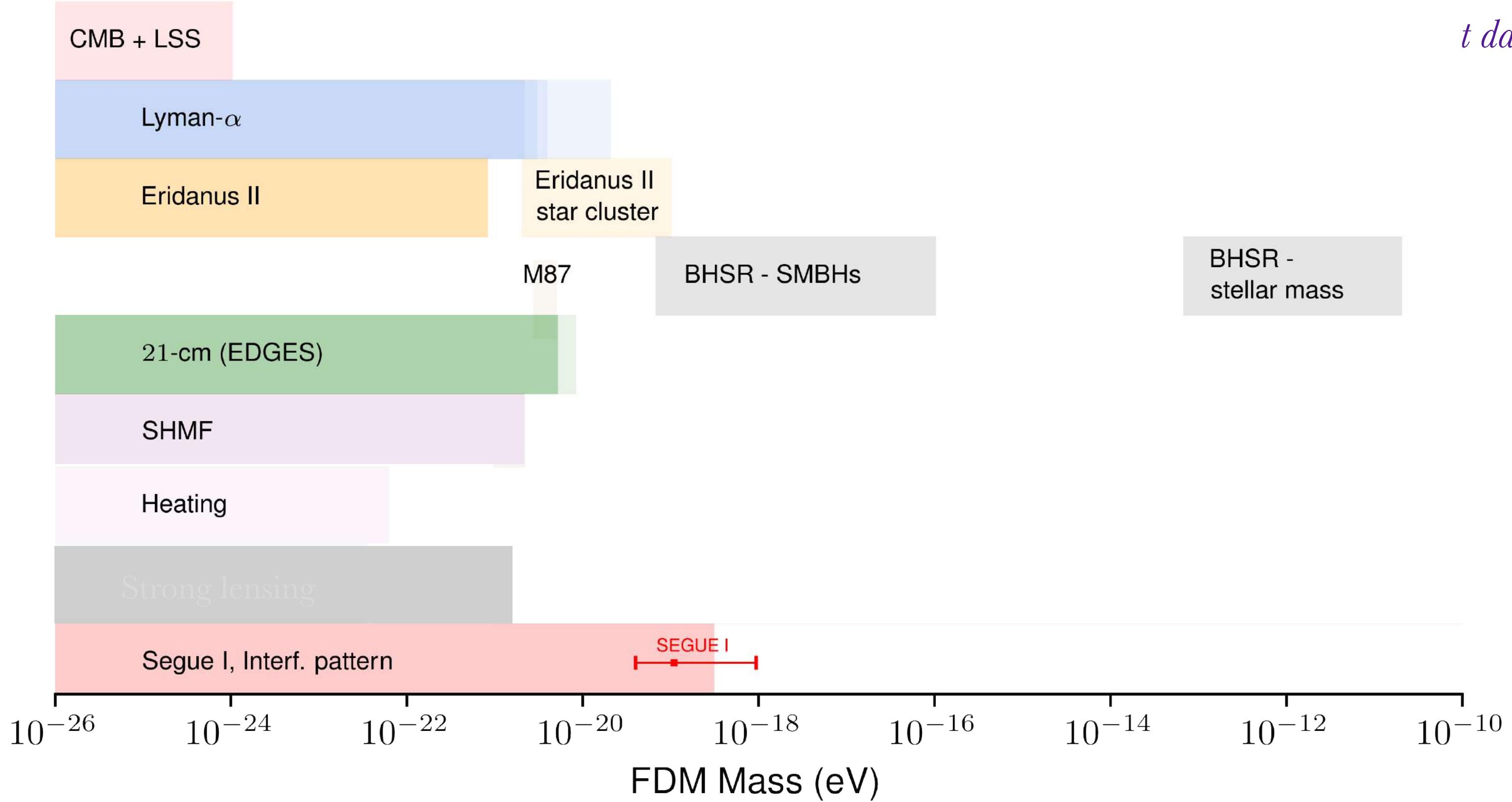
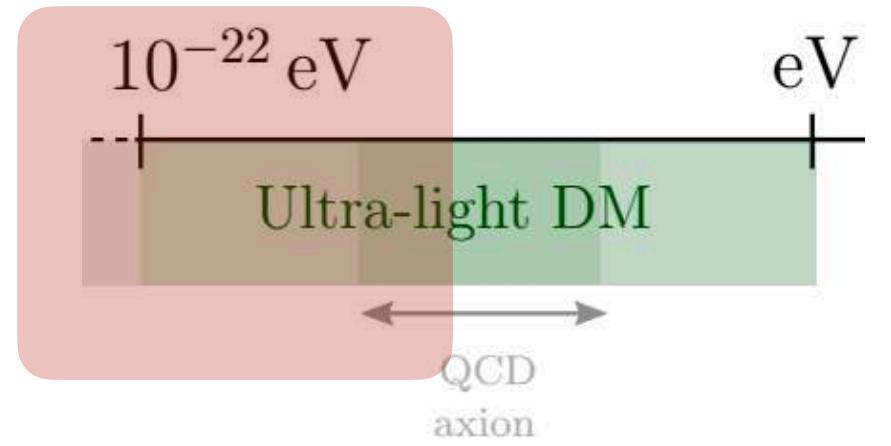


Constraining DM properties

Mass, Spin, fraction

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



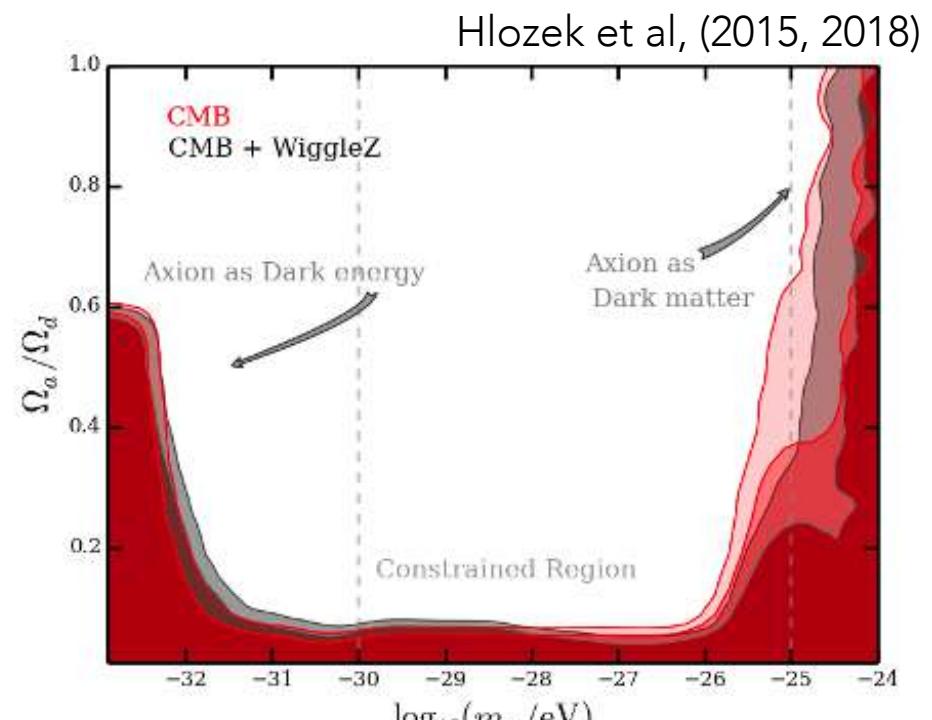
"t dark matter", E.F., 2020. The Astronomy and Astrophysics Review.

Bounds consider FDM is **all** DM

Observational implications and constraints

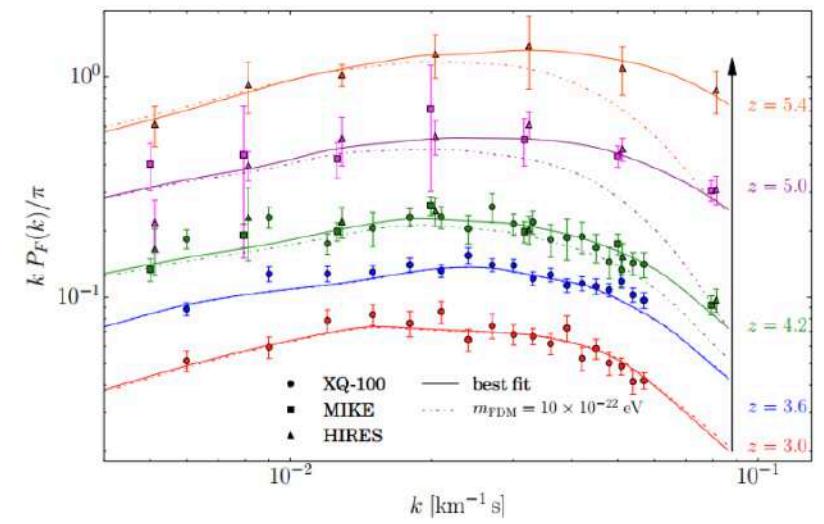
Fuzzy Dark Matter - bounds on the mass

CMB/LSS

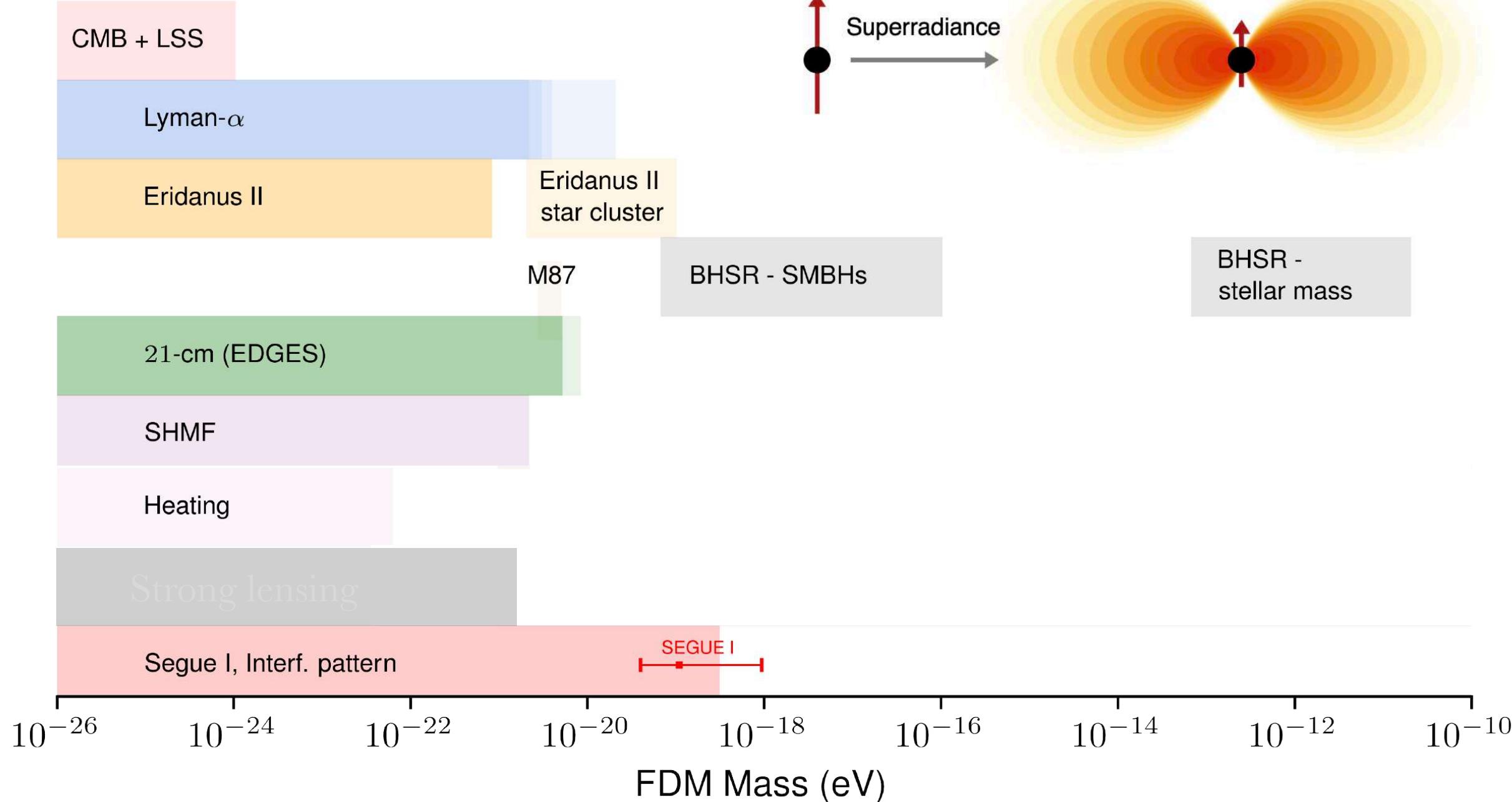


$$m \gtrsim 10^{-24} \text{ eV}$$

Lyman alpha



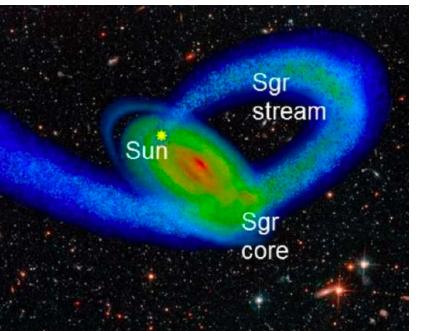
$$m \gtrsim 2 \times 10^{-20} \text{ eV}$$



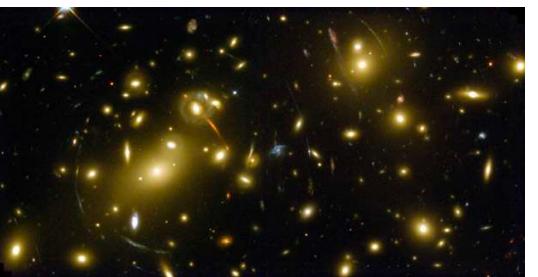
;

Suppression of small structures

Stellar streams



Grav. lensing



Dynamical effects

Globular clusters

$$m < 10^{-21} \text{ eV}$$



ESO/Digitized Sky Survey 2

Lancaster et al. 2020

Heating of the MW disk

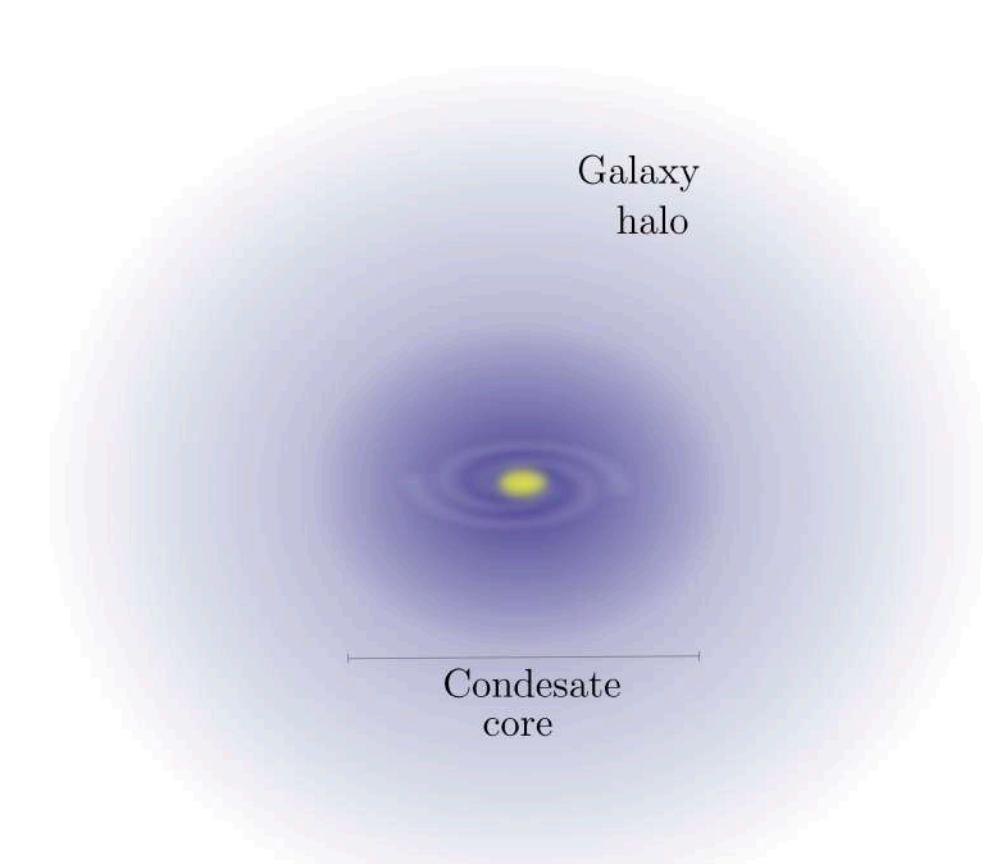
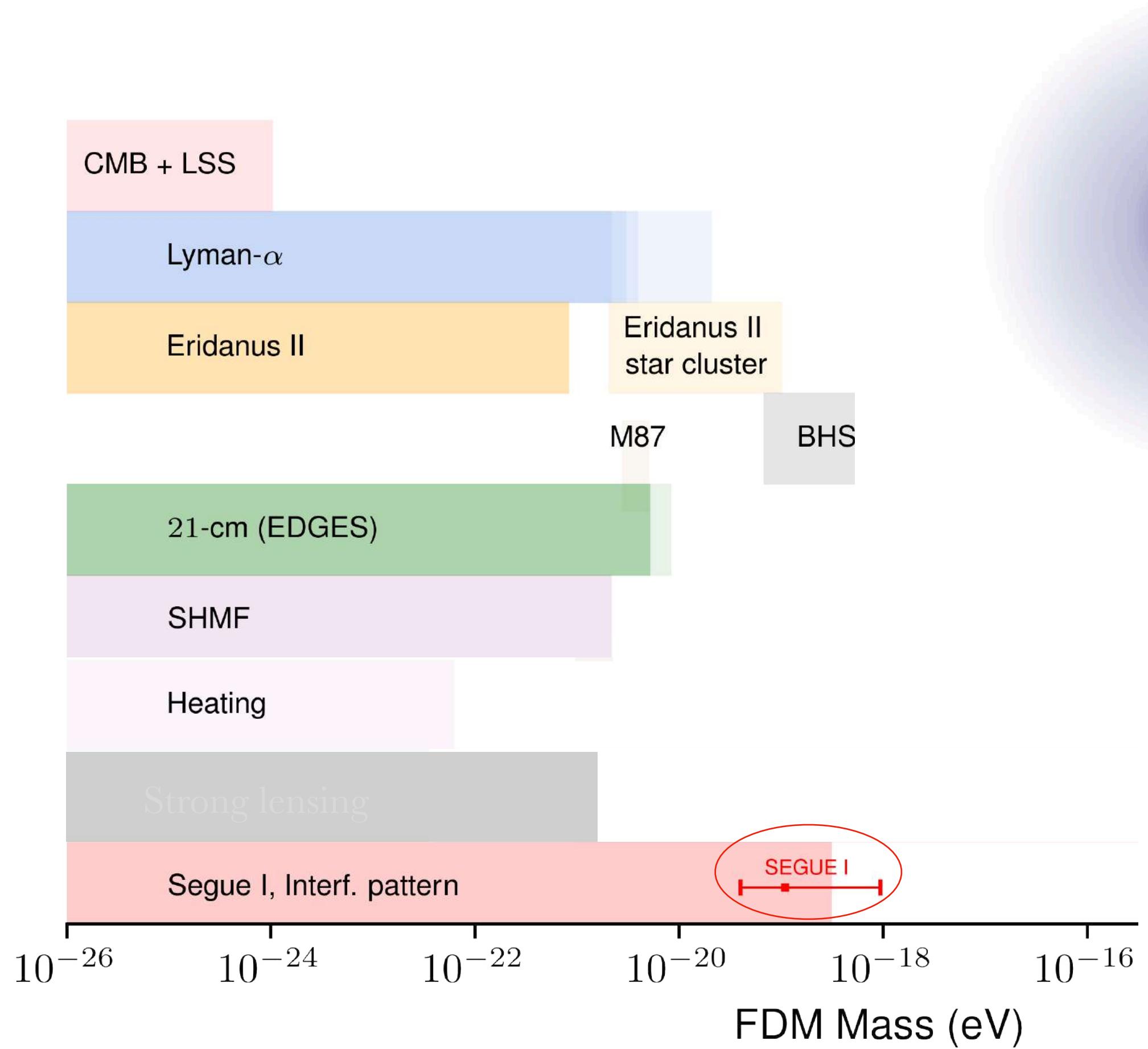
$$m > 0.6 \times 10^{-22} \text{ eV}$$

Church et al. 2019

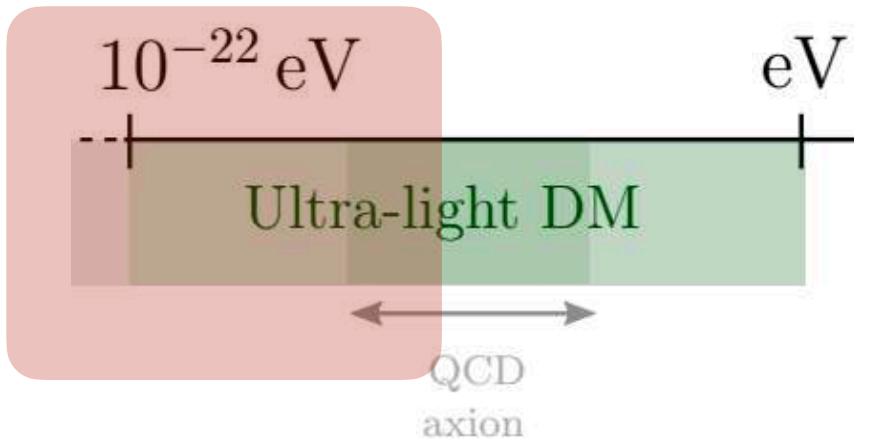
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

Presence of a core



Ultra faint dwarfs



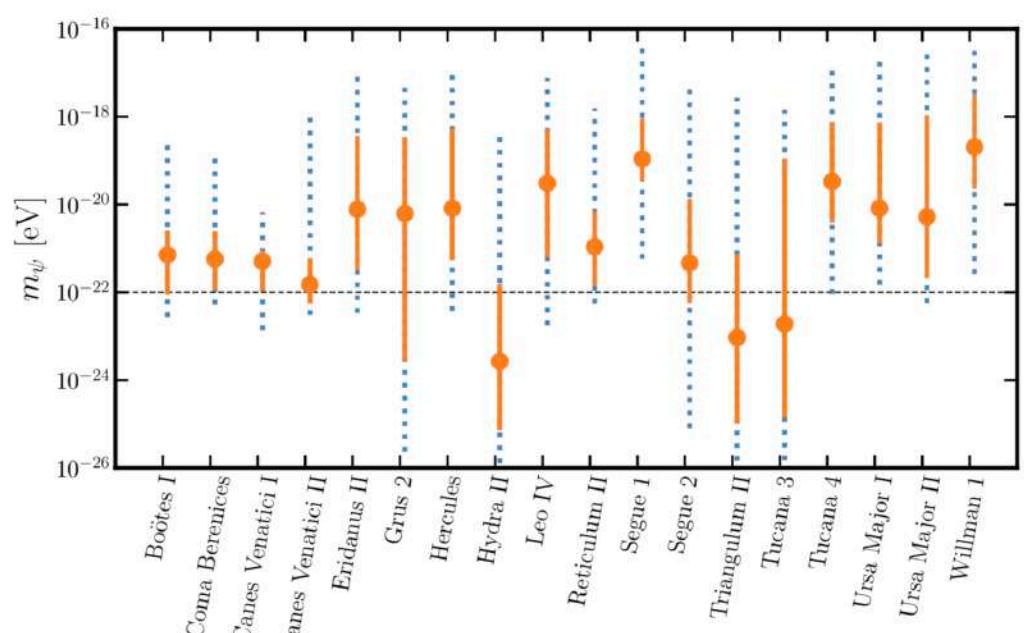
FDM SIMULATIONS

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

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

$$m_{\text{FDM}}^{(\text{Segue 1})} = 1.1^{+8.3}_{-0.7} \times 10^{-19} \text{ eV}$$

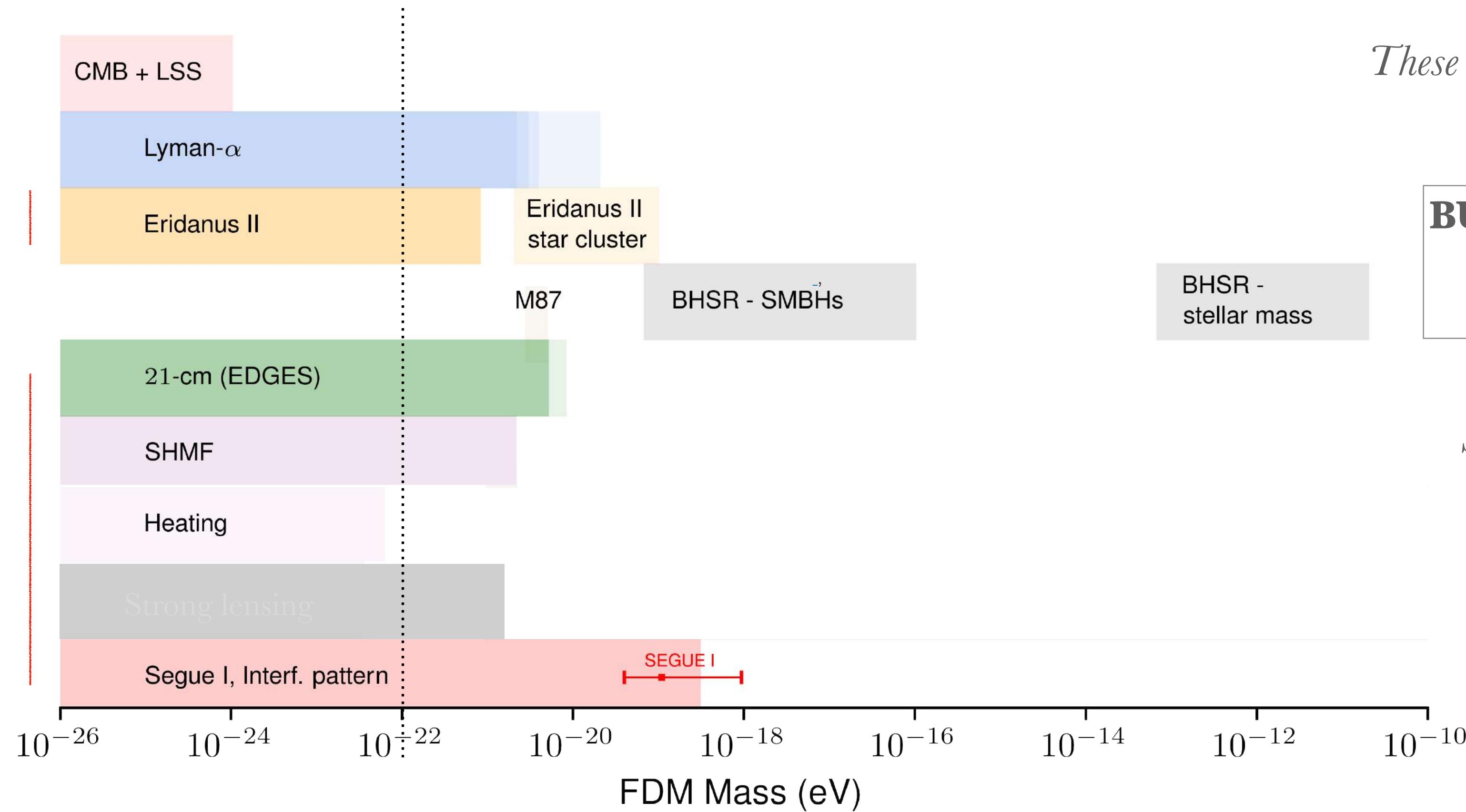
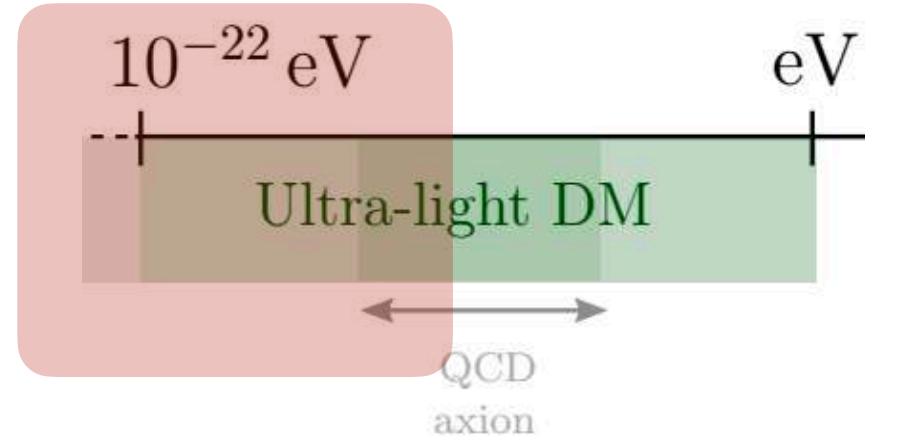
Preference for higher mass



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

Current status

Fuzzy Dark Matter - bounds on the mass



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

Sweet spot for solving small scale problems

These models can be highly constrained

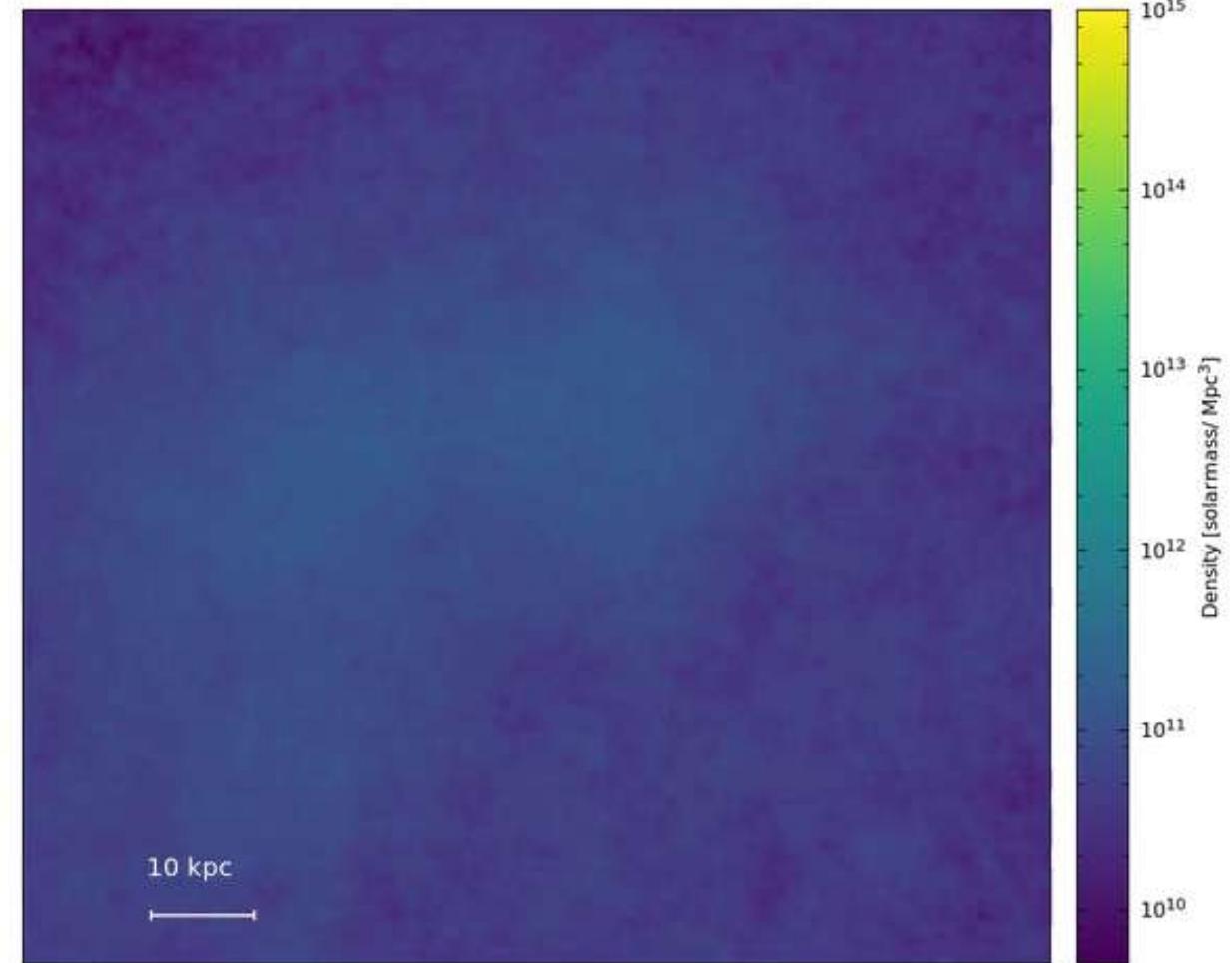
BUT: - systematic effects!!
 - dynamics of FDM not fully understood.

Some bounds are incompatible!

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

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

Interference pattern



Simulation by Jowett Chan

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

PROBES:

- Strong lensing
- Stellar streams
- Heating

} Gravitational probes

ONGOING

- Characterizing the interference patterns using full simulations

In collaboration with Jowett Chan and Simon May

- Strong lensing

In collaboration with: Devon Powel, Simona Vegetti, Simon White

- Stellar streams

In collaboration with: Sten Delos and Fabian Schmidt

Previous studies:

Strong lensing:

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

Stellar streams:

Neal Dalal, Jo Bovy Lam Hui, Xinyu Li, 2020

Sub-galactic power spectrum:

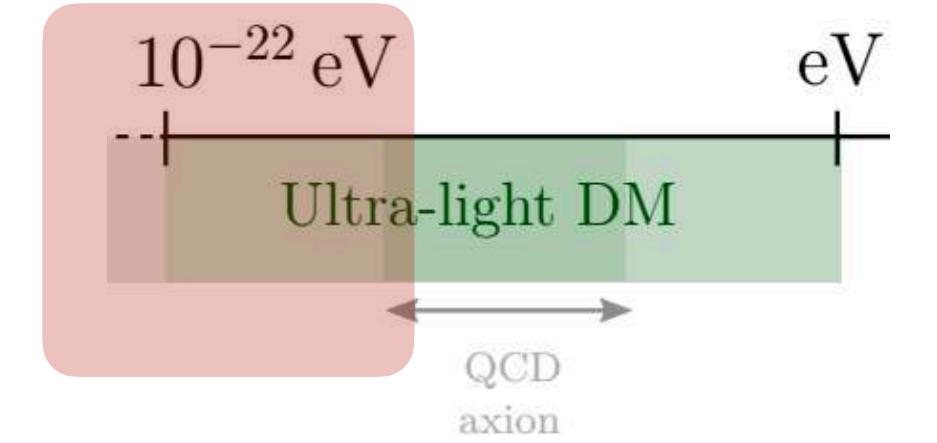
Hezaveh et al. (2016)

Sub-galactic power spectrum

Kawai, Oguri (2021)

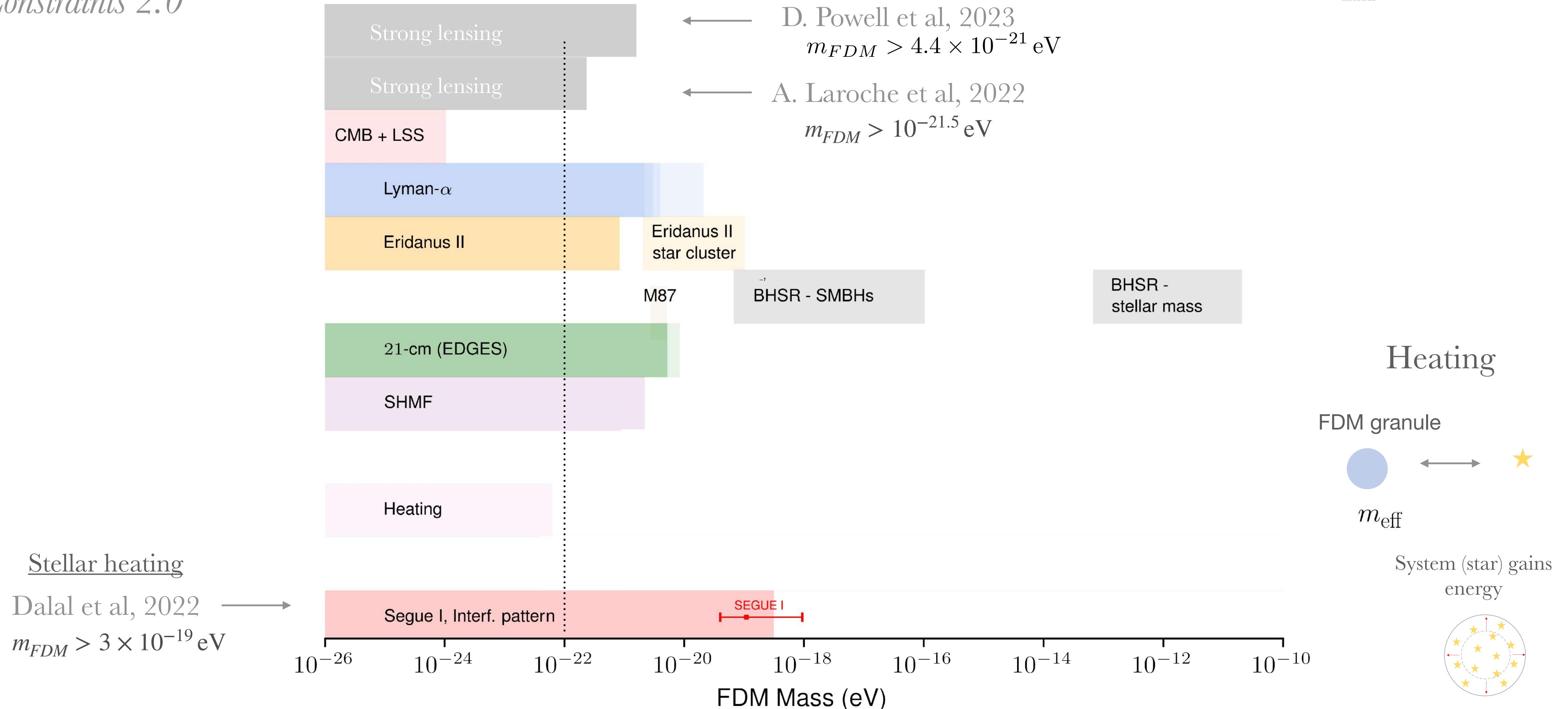
Dwarfs

N. Dalal, A. Kravtsov, 2022

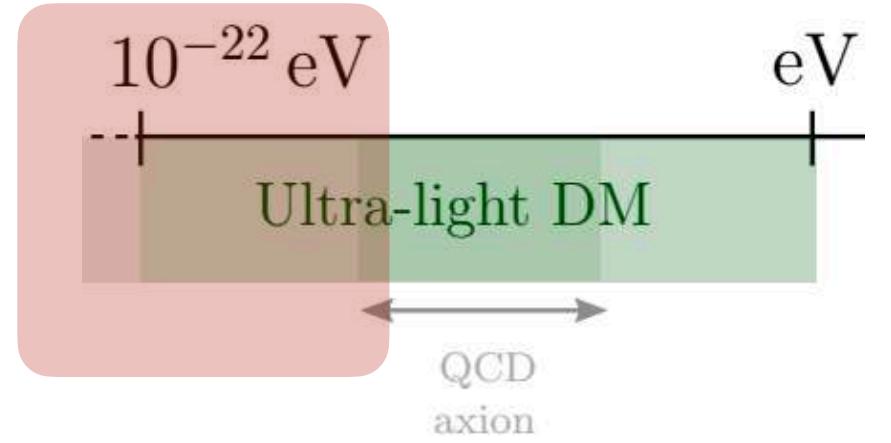


Interference patterns - granules

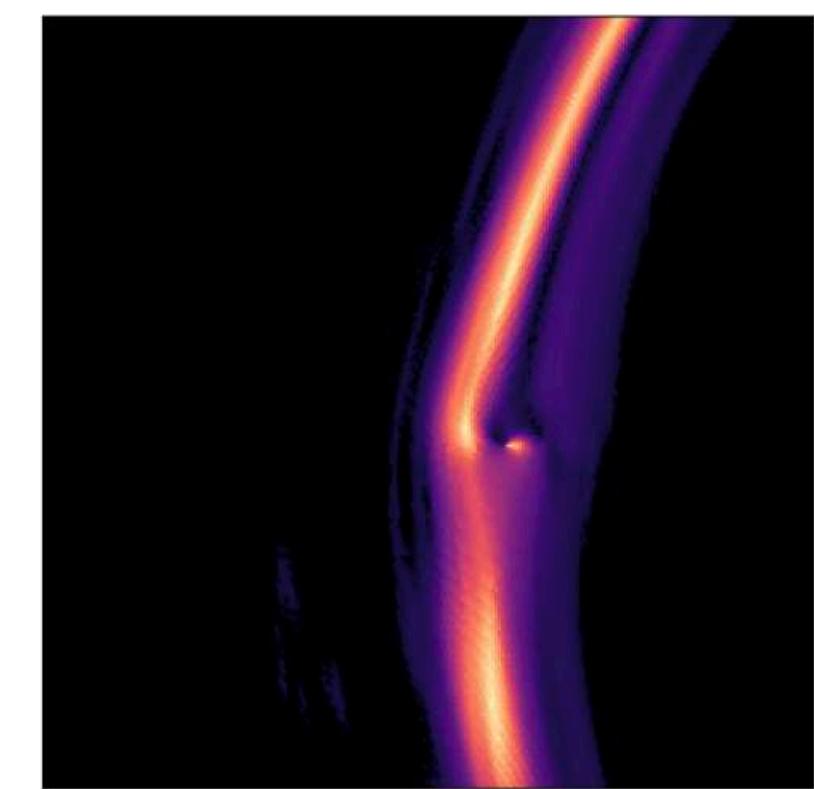
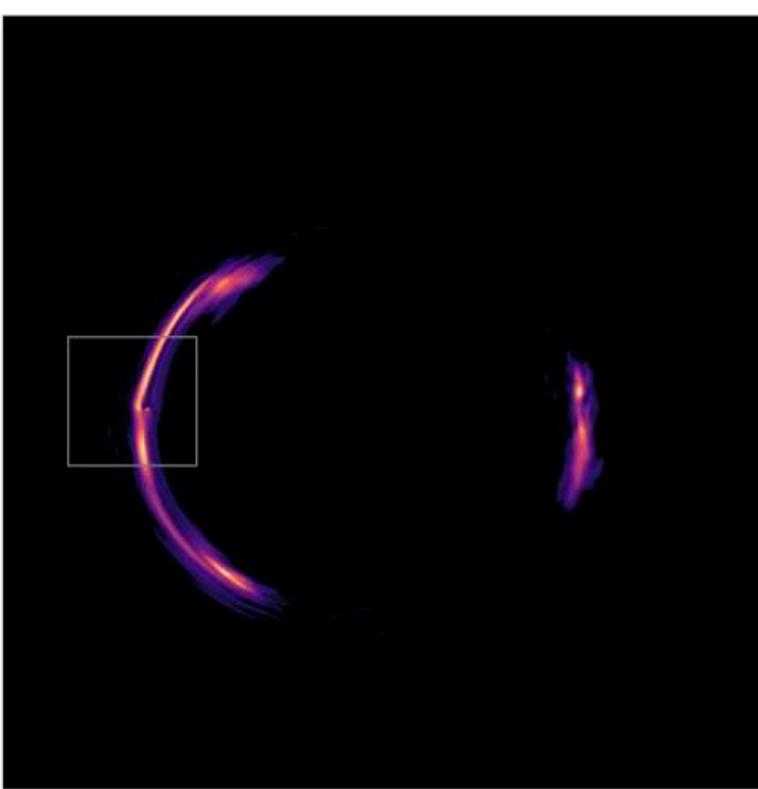
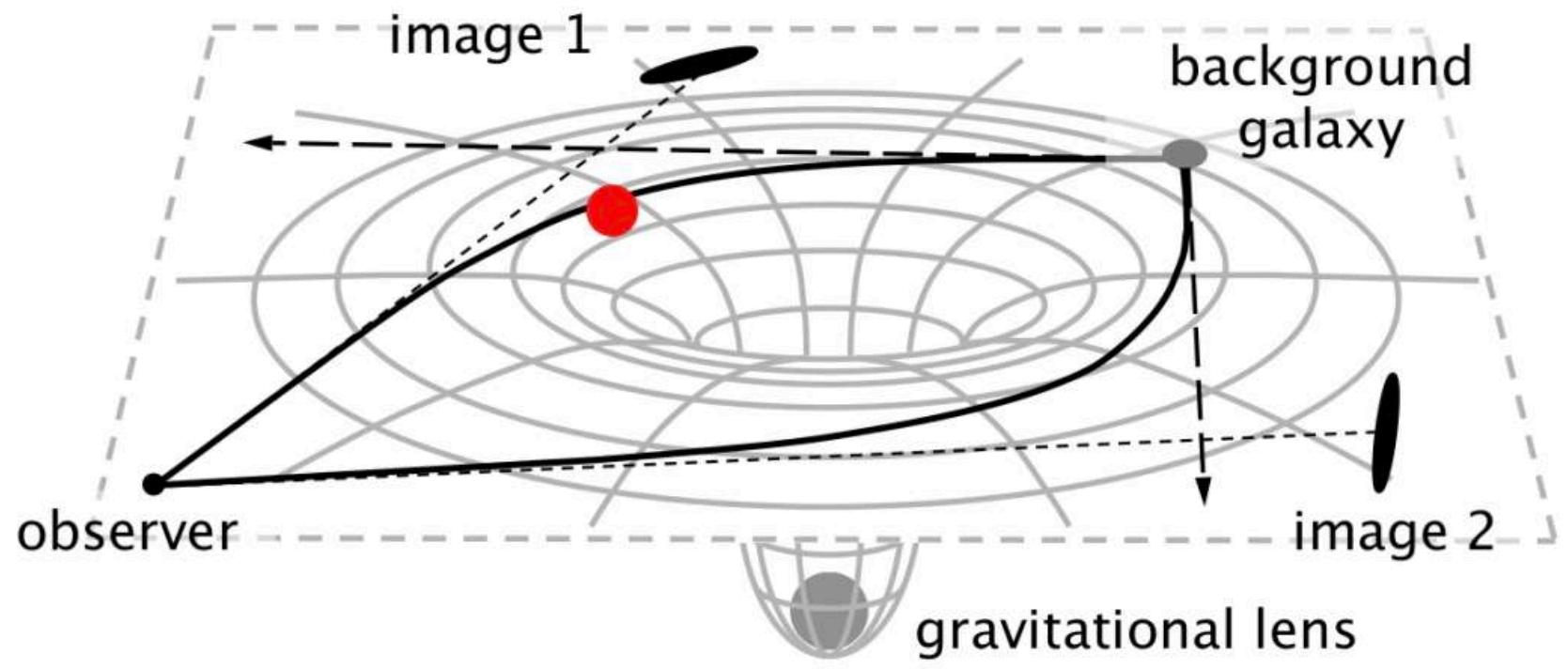
Constraints 2.0



Strong *lensing*



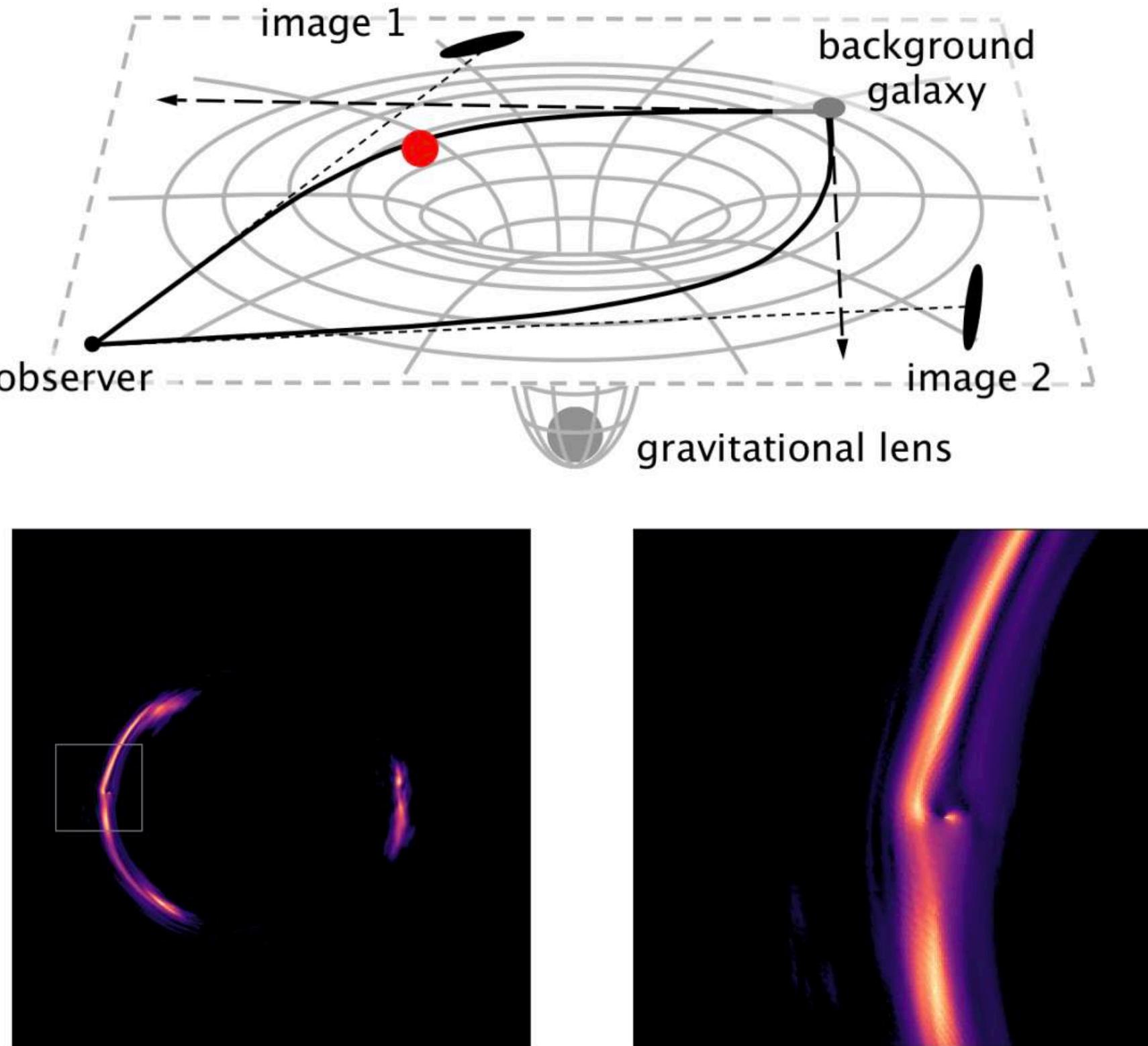
Low mass perturber with lensing



- 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

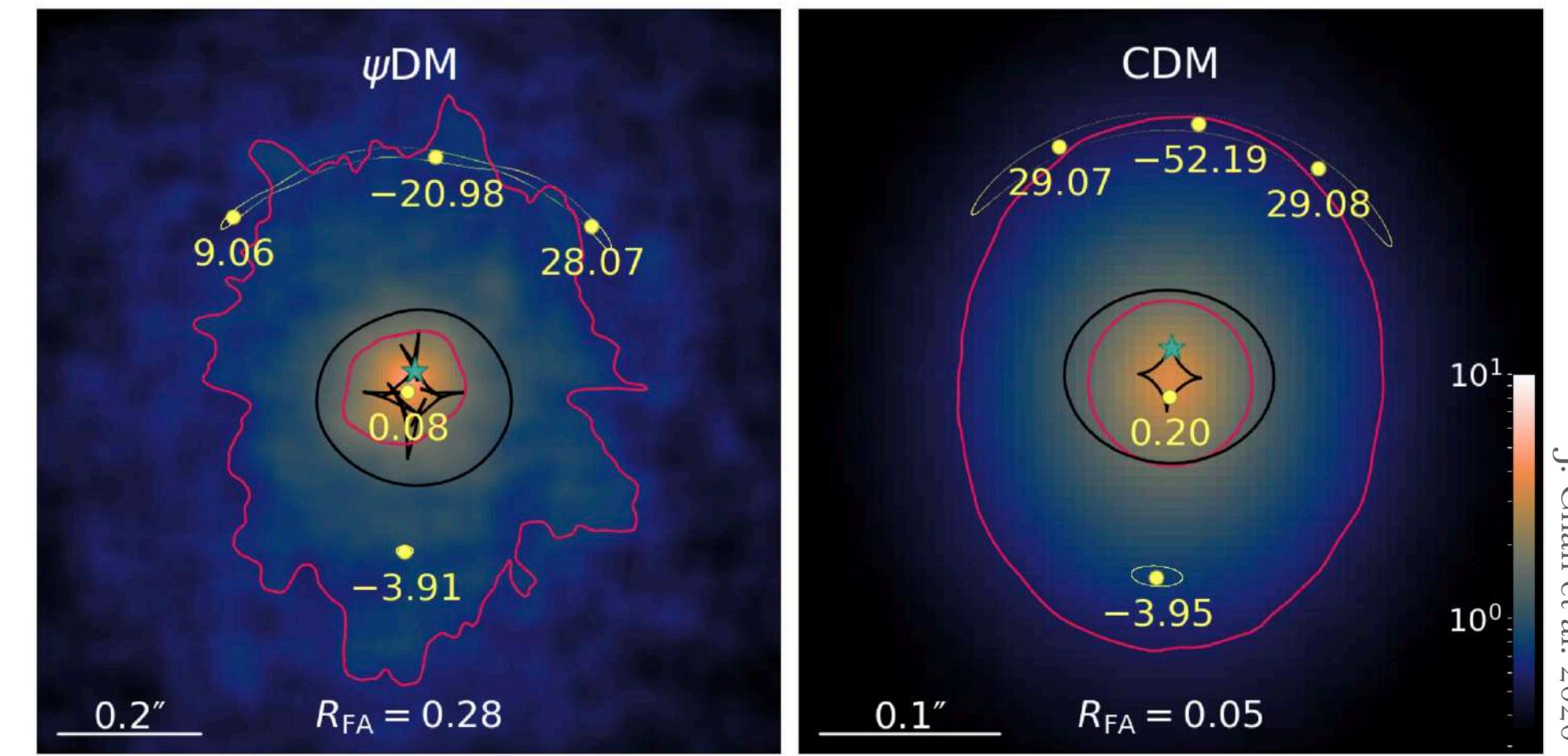
Strong *lensing*

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:

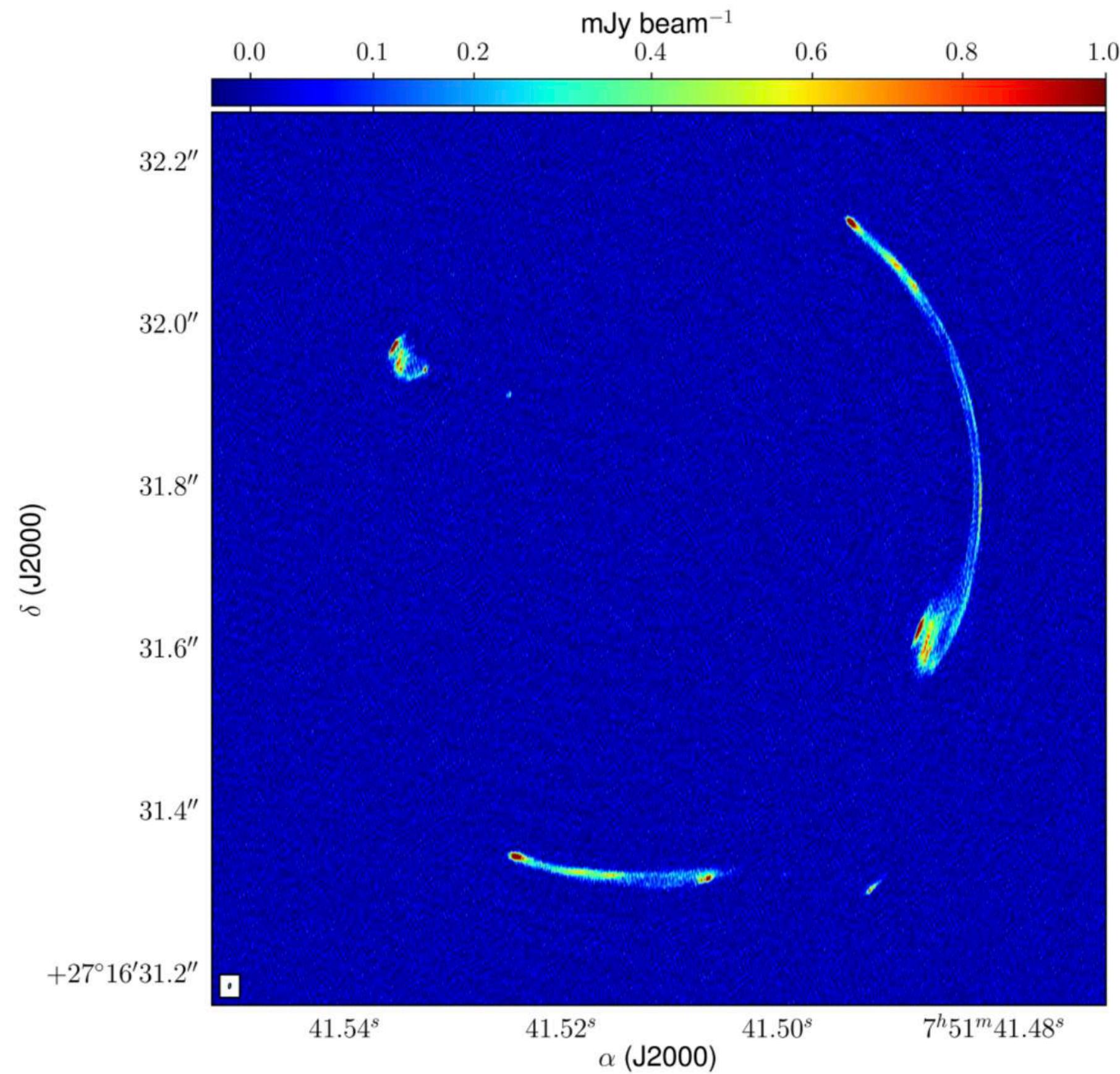
- J. Chan, H. Schive, S.g Wong, T. Chiueh, T. Broadhurst, 2020
- A. Laroche, Daniel Gilman, X. Li, J. Bovy, X. Du, 2022

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

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 mas²

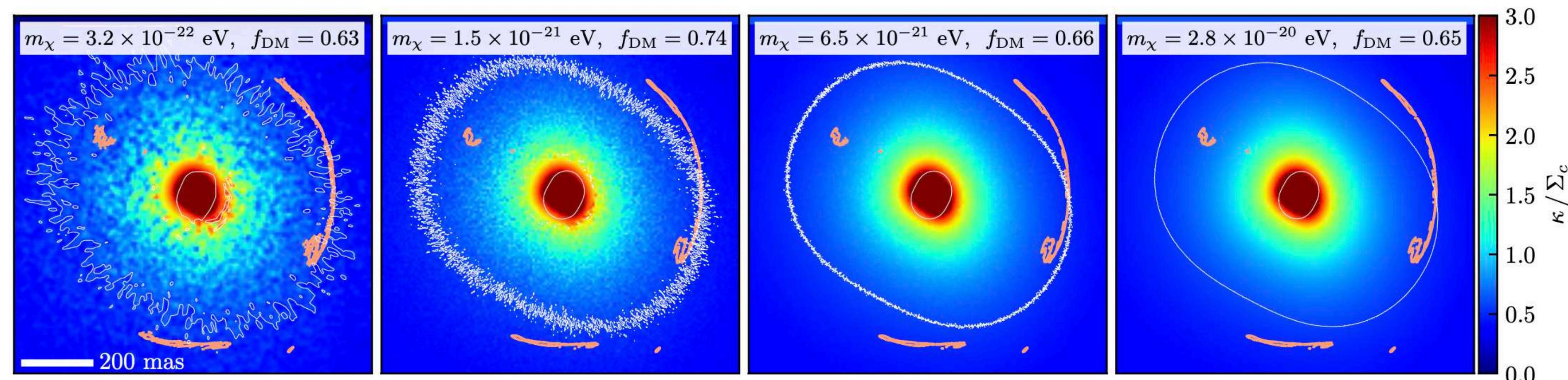
(Suyu et al. 2006; Vegetti & Koopmans 2009; Hezaveh et al. 2016; Rizzo et al. 2018)

Strong *lensing*

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



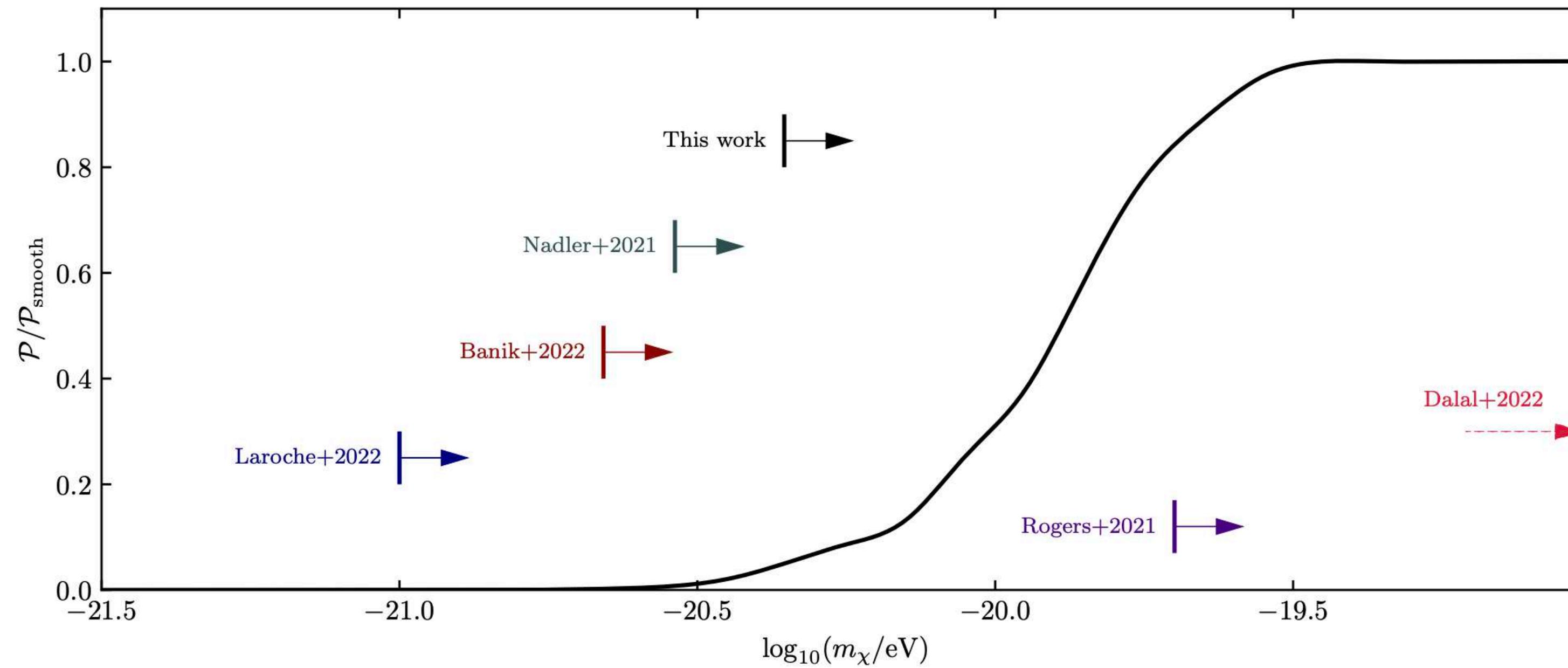
The lensing effect of the FDM granules is apparent: The critical curves wiggle back and forth across the lensed arcs, which would require the presence of multiple images of the same region of the source along the arc.

Strong lensing

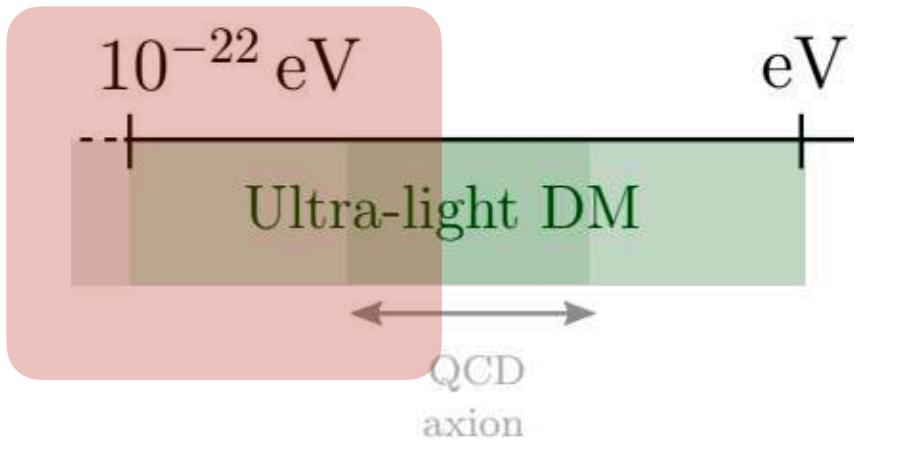
A lensed radio jet at milli-arcsecond resolution II: Constraints on fuzzy dark matter from an extended gravitational arc

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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, $\mathcal{P}/\mathcal{P}_{\text{smooth}}$



Fuzzy dark matter
(Single spin-0 particle)
 $m_{\text{fdm}} > 4.4 \times 10^{-21} \text{ eV}$



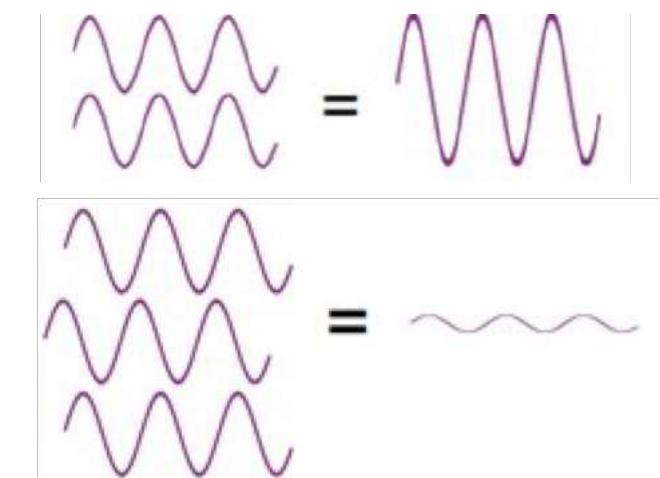
Mass, Spin, fraction

Vector, higher spin or multicomponent FDM

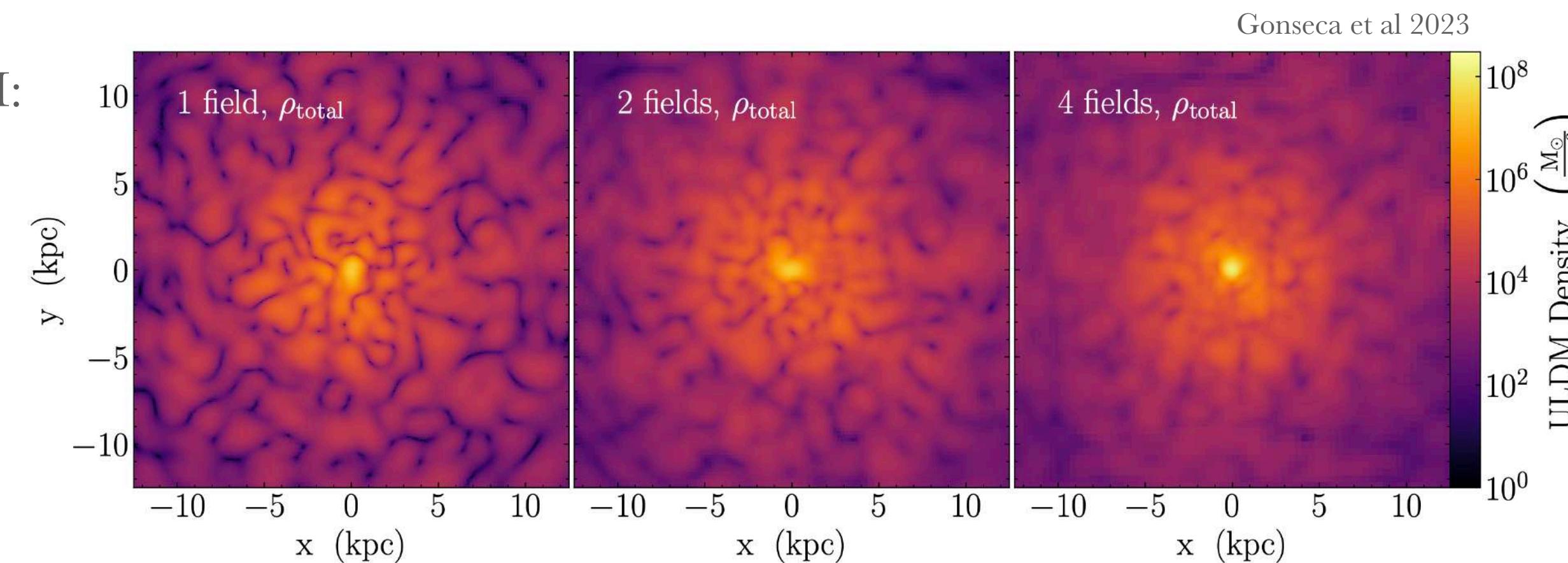
ULDM or ULA are a coherent wave - same frequency and constant phase difference

Multiple coherent waves

Interference patterns



For ULDM:



Gonseca et al 2023

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

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

(Amin et al 2022)

Expectation for lensing:

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

Detailed simulations and analysis in the future!

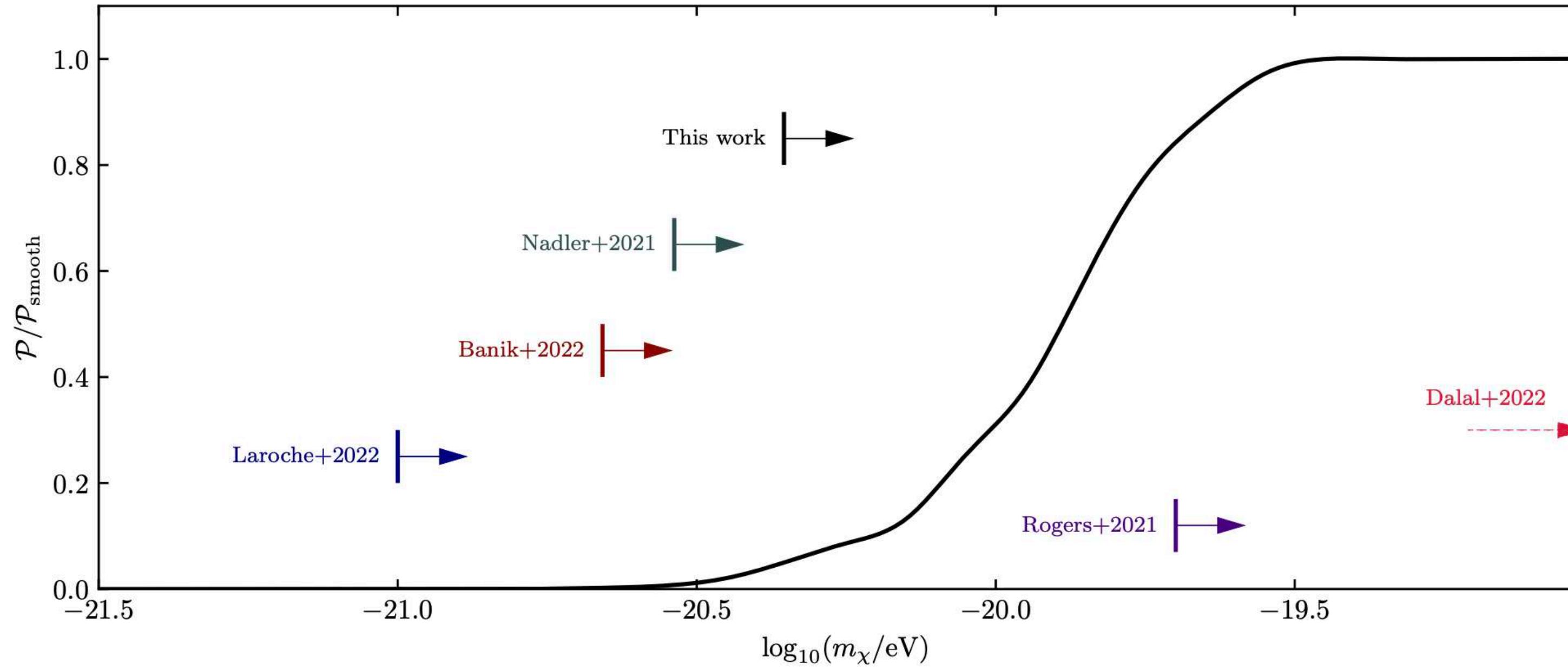
Vector (and higher-spin) FDM Amin et al 2022
(Vector FDM = 3 x same mass FDM (spin 0))

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



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

Fuzzy dark matter
(Single spin-0 particle)

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

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

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

Spin-2 FDM

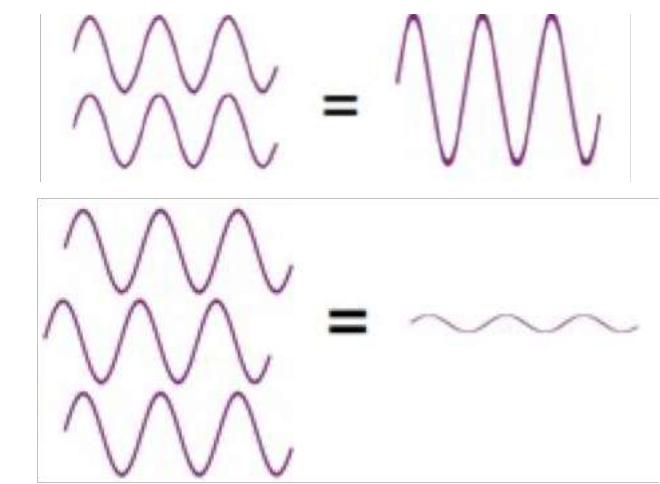
$$m_{\text{spin-2}} > 8.8 \times 10^{-22} \text{ eV}$$

Vector, higher spin or multicomponent FDM

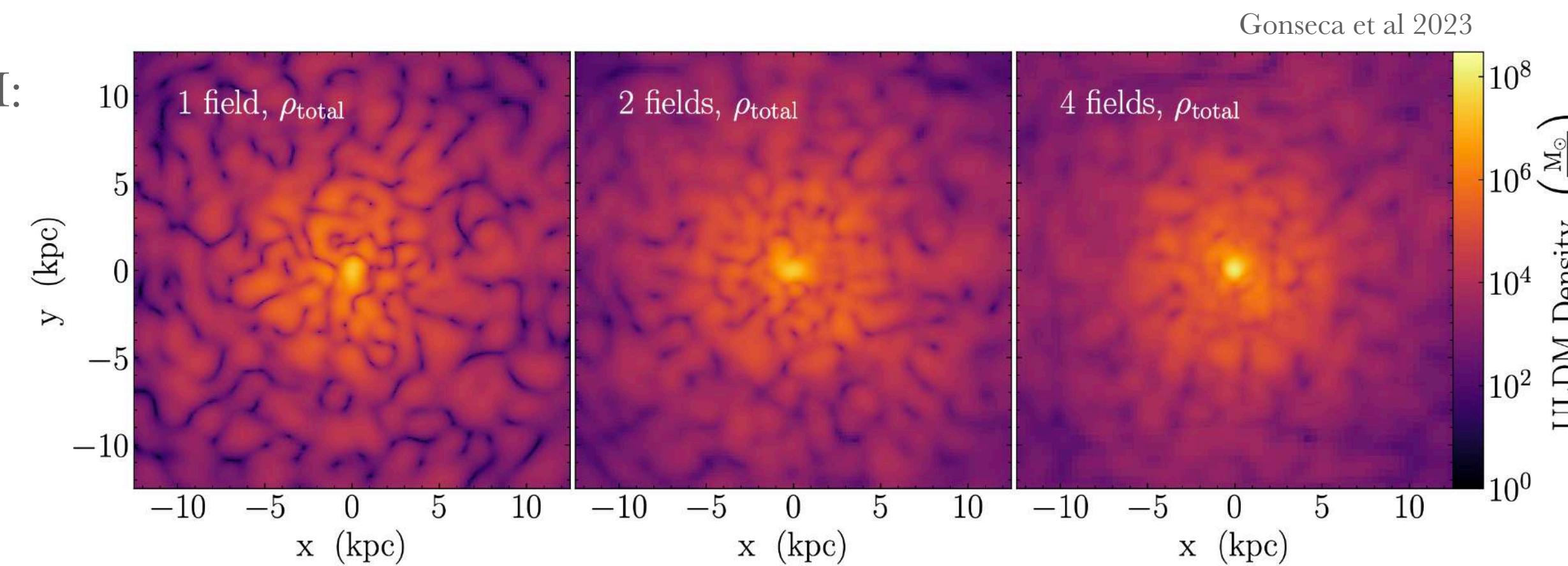
ULDM or ULA are a coherent wave - same frequency and constant phase difference

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Gonseca et al 2023

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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)

Other signatures dependent on *spin*: core-to-halo mass ratio (and its scatter), spin of the core, shape of the central regions of dark matter halos

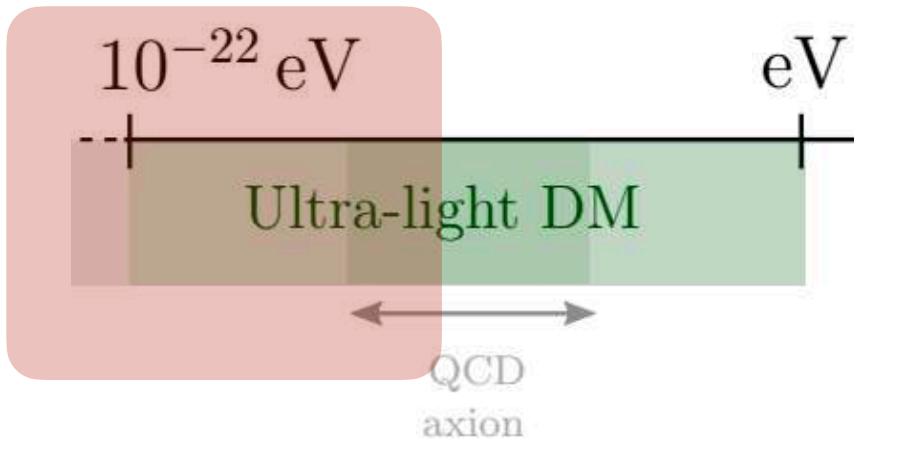
Presence of **self-interaction** leads to different signatures!

Both for the **cores** and *interference patterns*

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

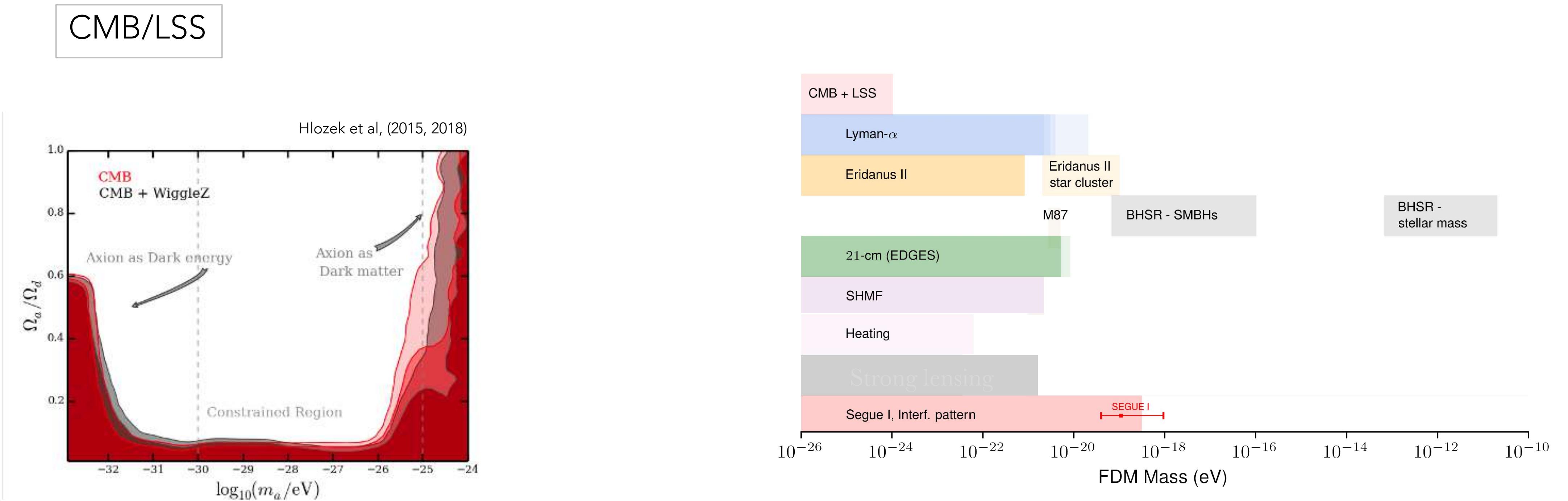
(Vector FDM = 3 x same mass FDM (spin 0))

High spin and self interaction Jain et al 2023



Mass, spin, self-interaction, fraction

Fraction of *ULDM*



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

Degenerate with fraction!!

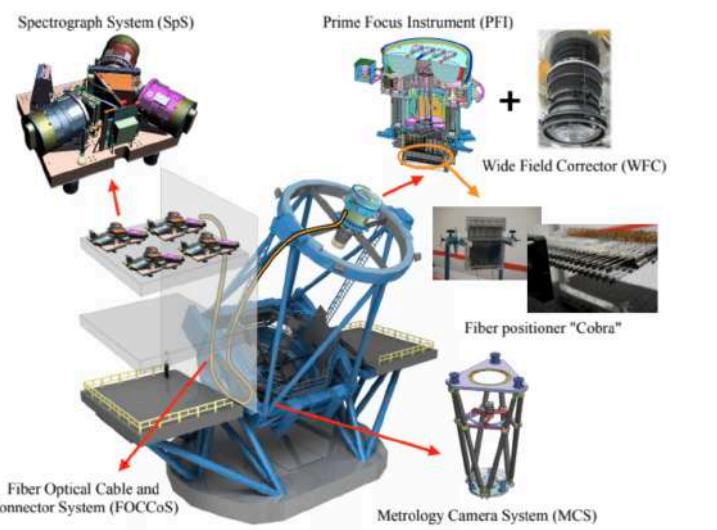
Improving these bounds

Observations

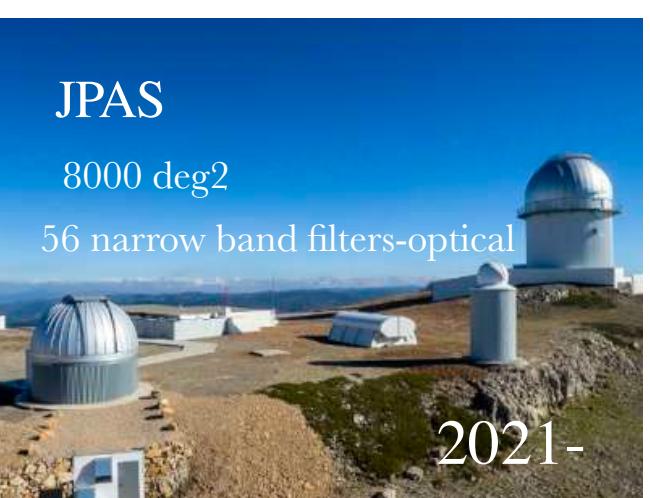
Photometric and spectroscopic surveys



Prime Focus Spectrograph (PFS)



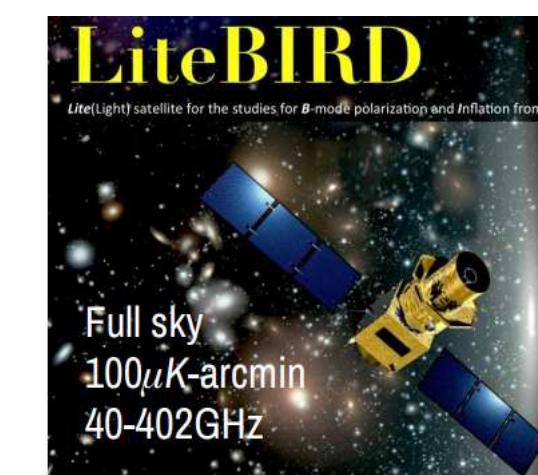
21cm



Modified from Jia Liu



CMB



2021

16,000 deg²
6 μK-arcmin
27-280GHz

CMB-S4
Next Generation CMB Experiment

GWs

+ direct detection experiments

Summary

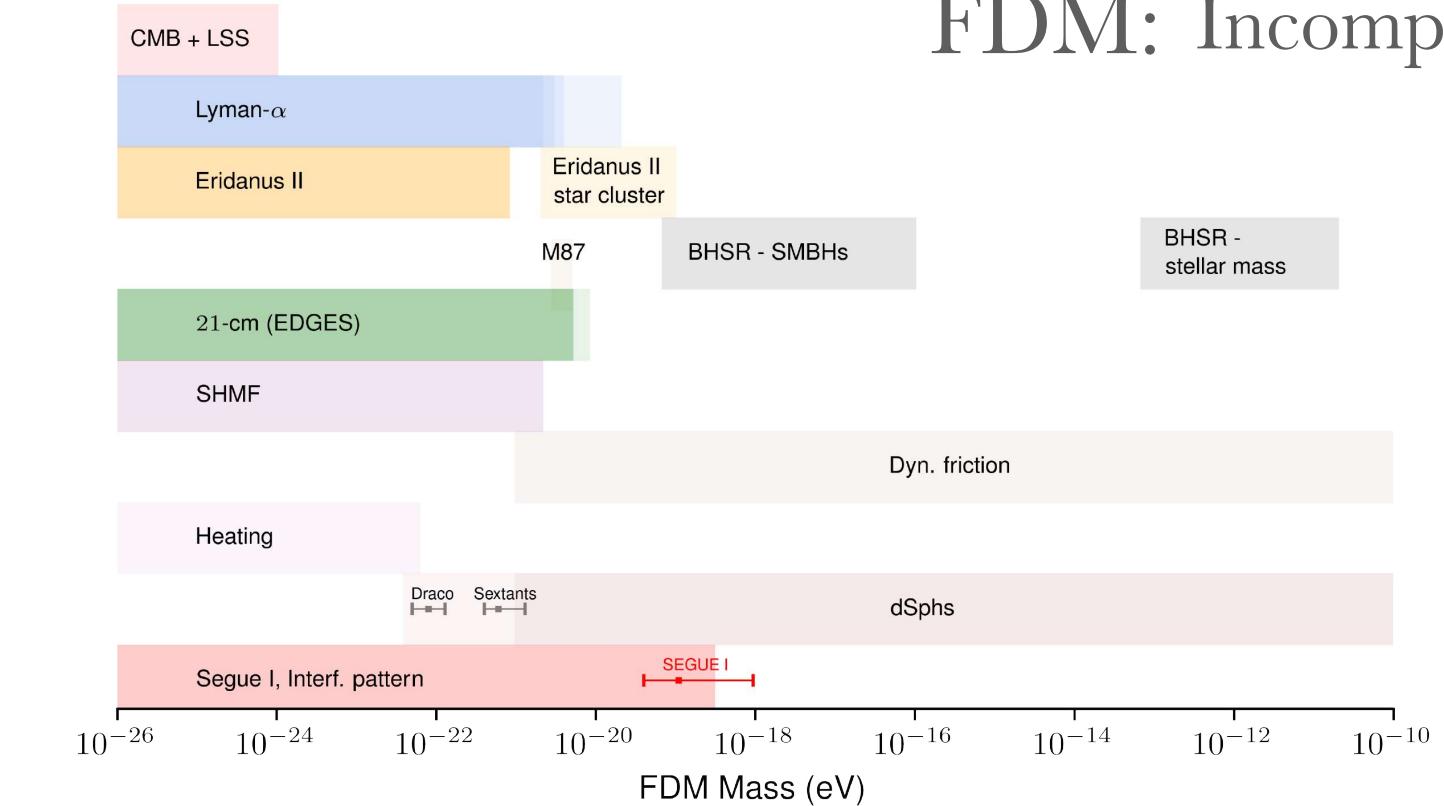
Ultra-Light Dark Matter

Well motivated DM models

Rich and distinct phenomenology on small scales

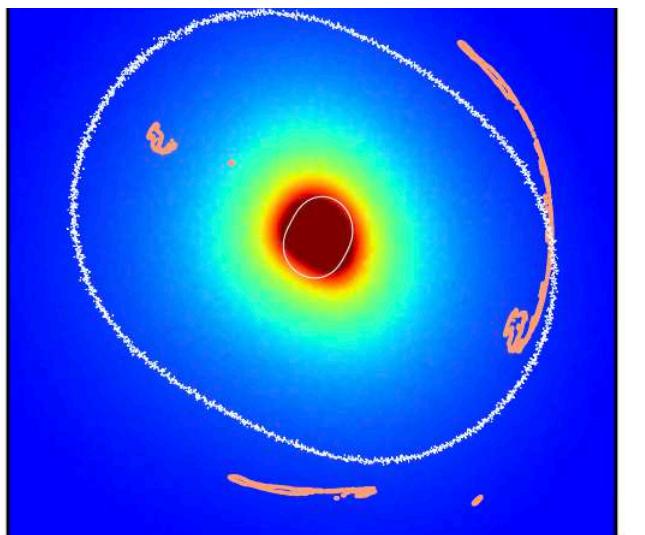
Testable prediction

Current status



FDM: Incompatibilities!

Granules



Strong lensing:

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

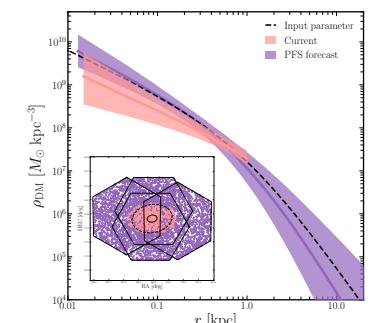
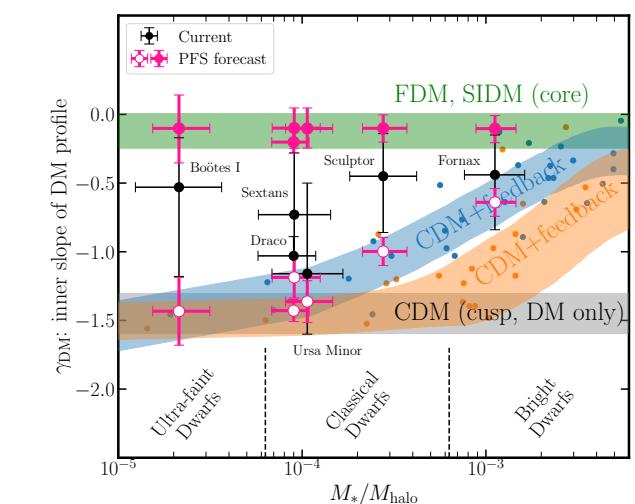
$$m_{\text{vdm}} > 1.4 \times 10^{-21} \text{ eV}$$

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

Future

Observations

PFS



Improve in simulations
New probes/observables