Waves in the sky:

probing ultra-light dark matter wave interference with strong lensing

Elisa G. M. Ferreira

Kavli IPMU & University of Sao Paulo

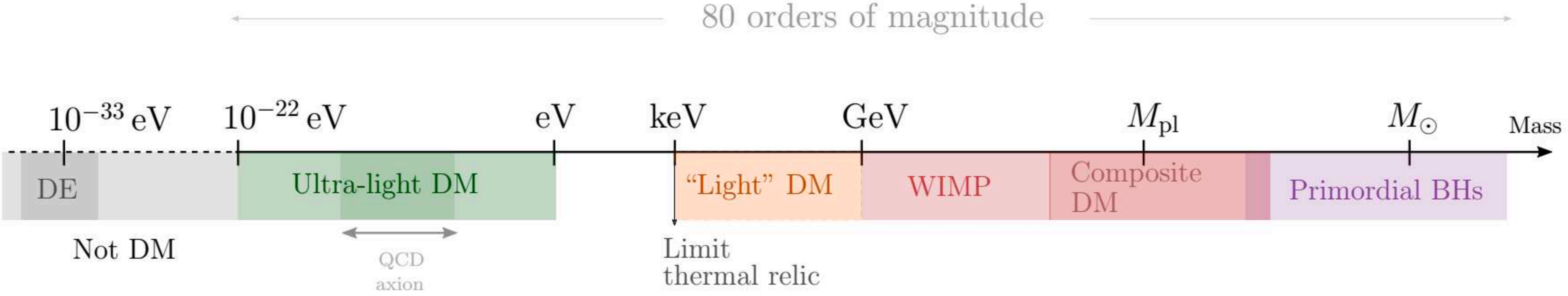
“What is DM" Symposium, March 9th, 2023

What is dark matter?

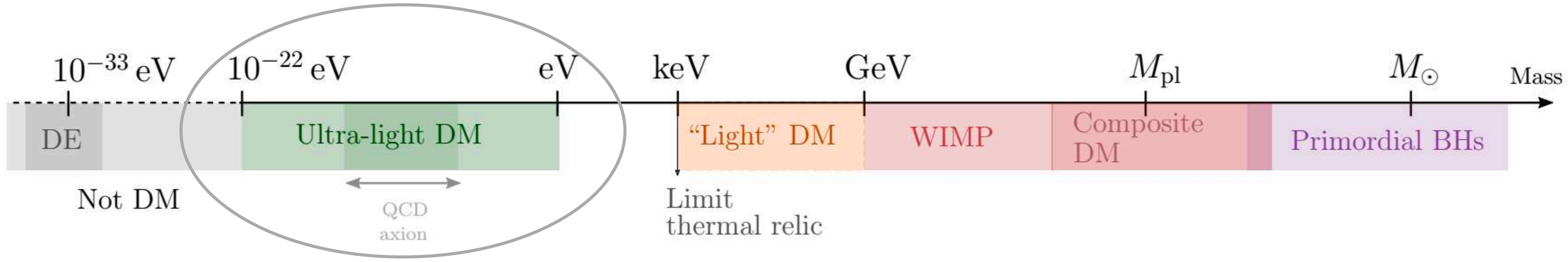
- What is the nature of DM?

State of the "art"

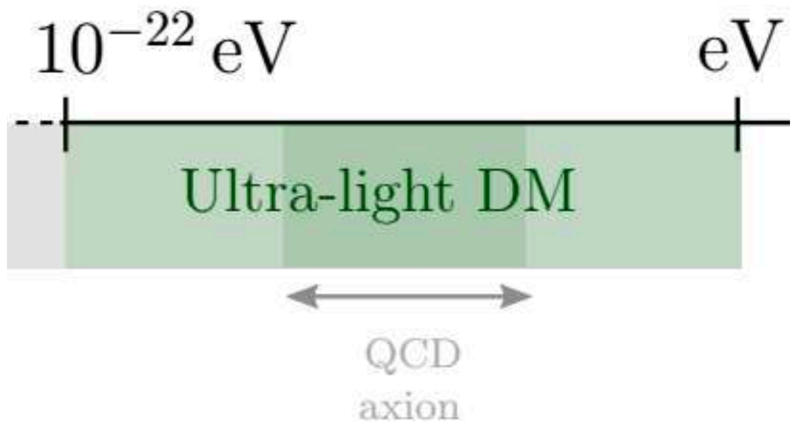
Mass scale of DM



Ultra-light dark matter

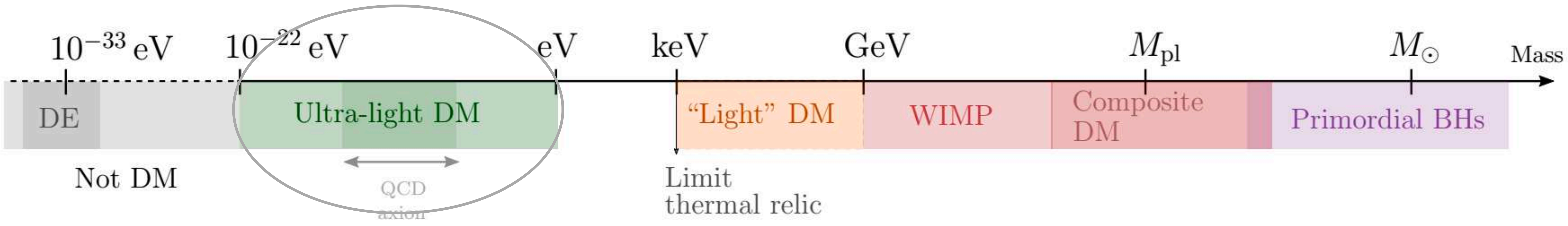


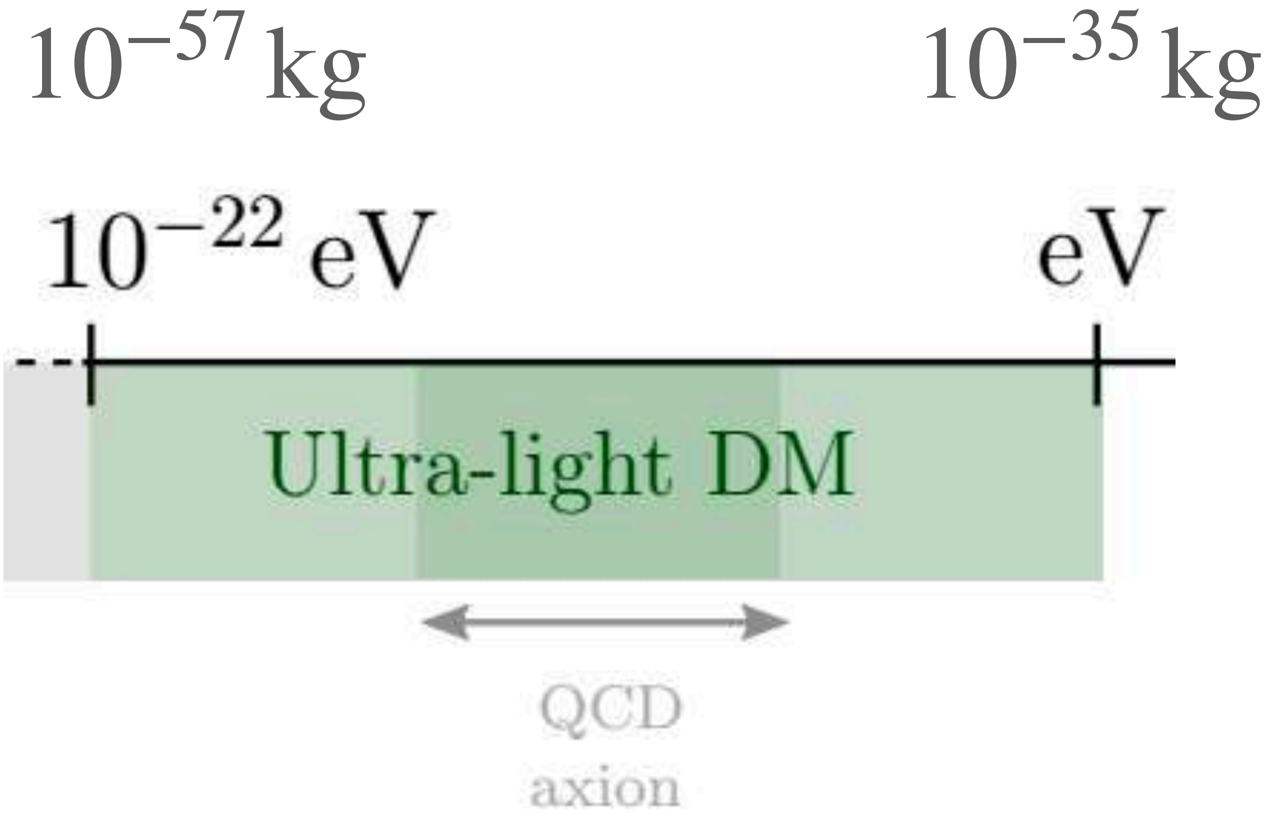
Ultra-light Dark Matter



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

Lightest possible candidate for DM

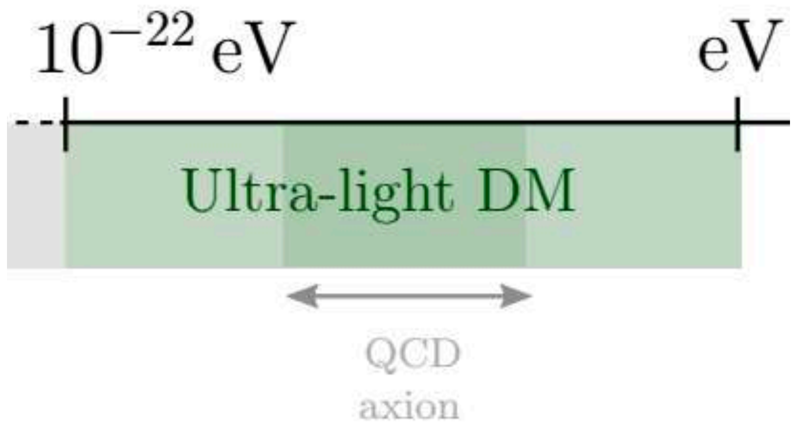




→ Bosons

Non-thermally produced

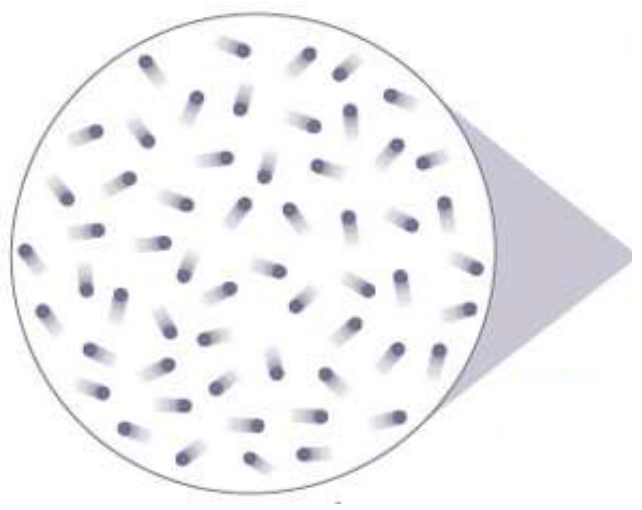
Ultra-light Dark Matter



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

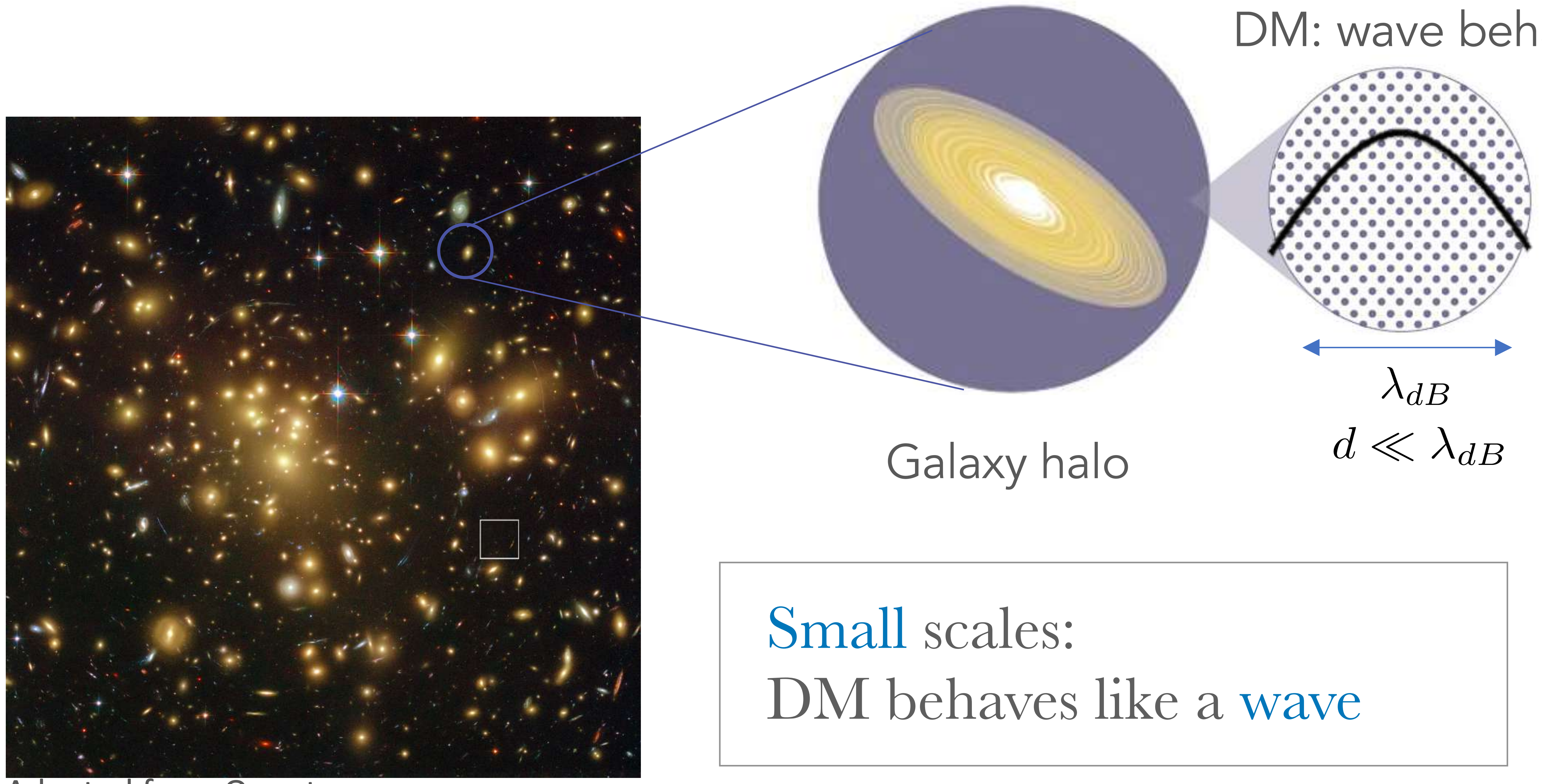
Lightest possible candidate for DM

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



DM: particles

$d \gg \lambda_{dB}$



Adapted from Quanta

DM: wave behaviour

Galaxy halo

λ_{dB}

$d \ll \lambda_{dB}$

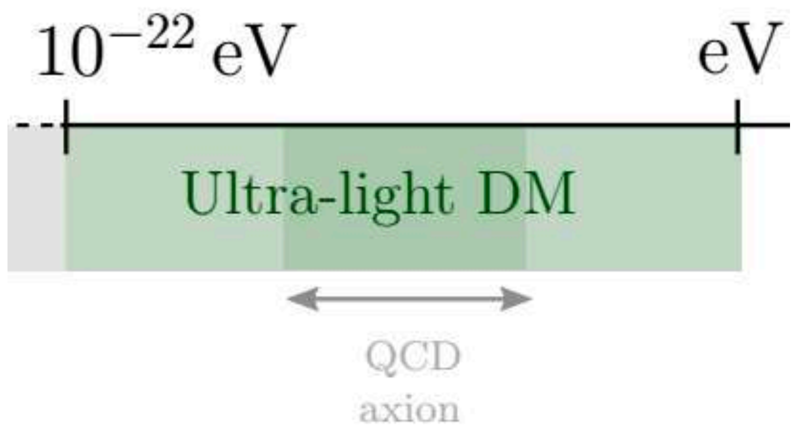
Small scales:
DM behaves like a wave

10^{-60} kg $\qquad 10^{-35}$ 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)

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

DOFs: m

Self Interacting FDM (SIFDM)

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

m g

DM Superfluid

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

Axion and ALP (axion like particles)

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

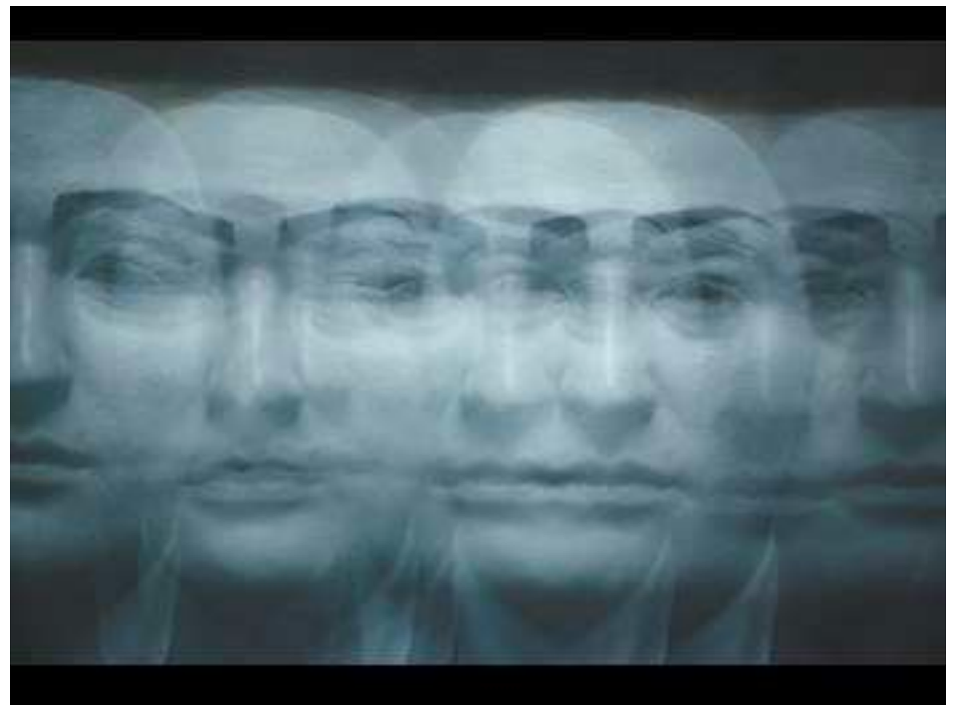
$$\mathcal{L} = P(X)$$

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

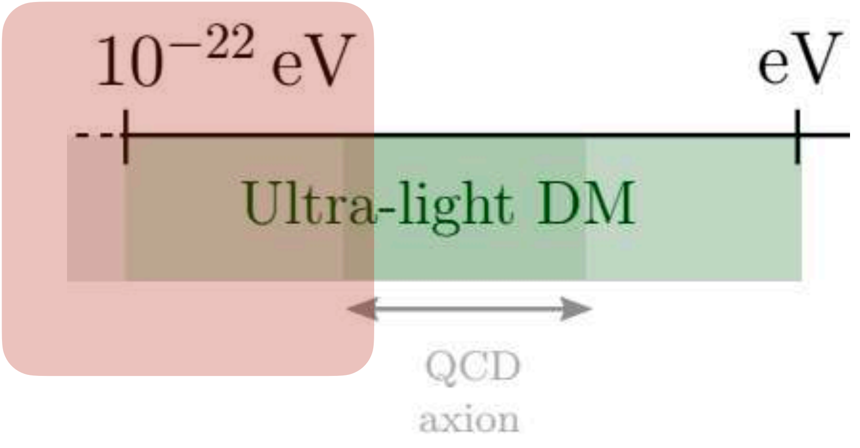
"Ultra-light dark matter", **E.Ferreira**, 2020. The Astronomy and Astrophysics Review.

Fuzzy dark matter

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)

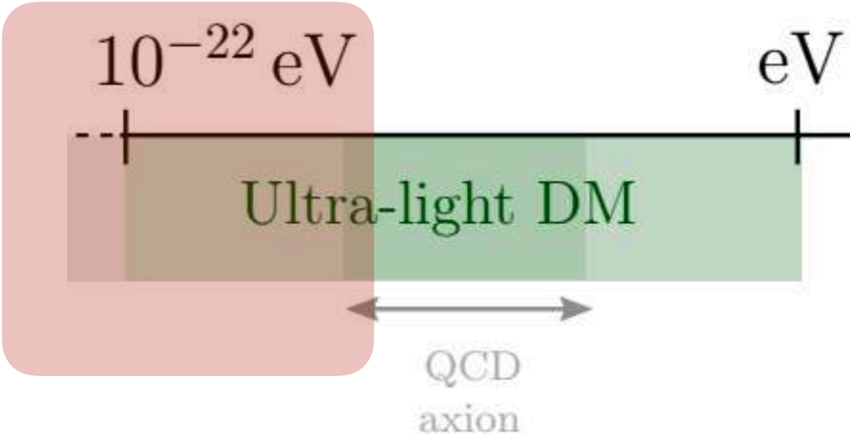
(Reviews: EF (2021), J. Niemeyer (2019), L. Hui (2021))

Idea:

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

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

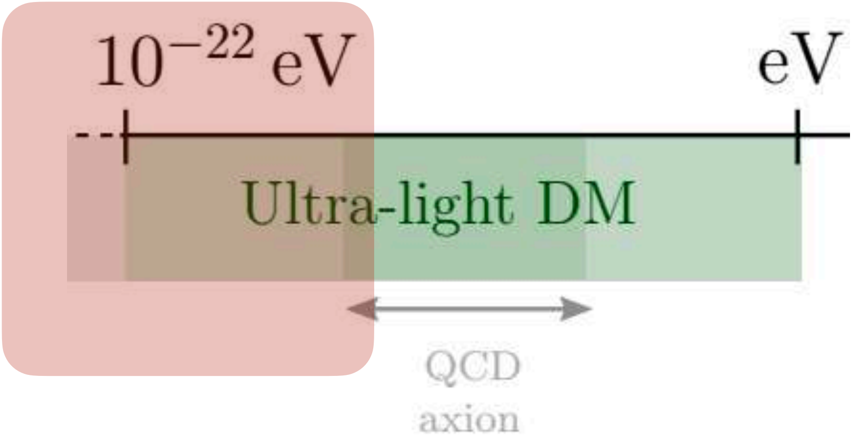
Focus in spin 0 particles here!

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

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

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

Schrödinger equation (Gross-Pitaevskii)

Poisson equation

$g = 0$ → FDM

$g \neq 0$ → SIFDM

Fundamentally different than CDM/WDM/SIDM!

FLUID DESCRIPTION

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

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

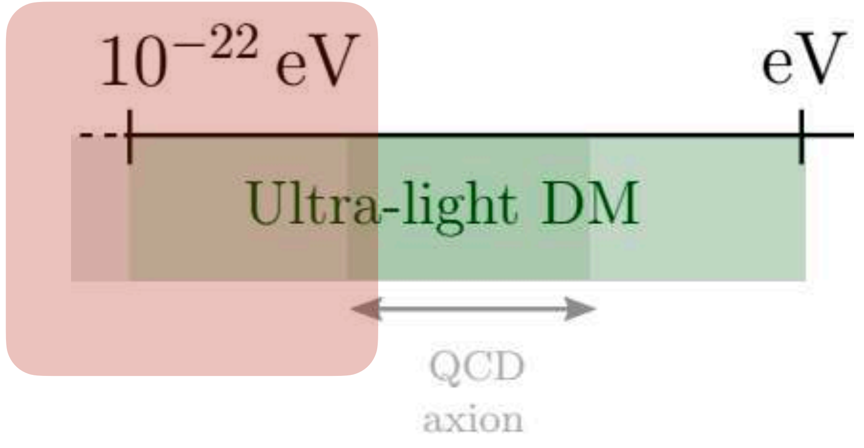
$$\dot{\mathbf{v}} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - P_{int} - \frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

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

Quantum pressure

→ Finite Jeans length - Suppresses structure formation on small scales

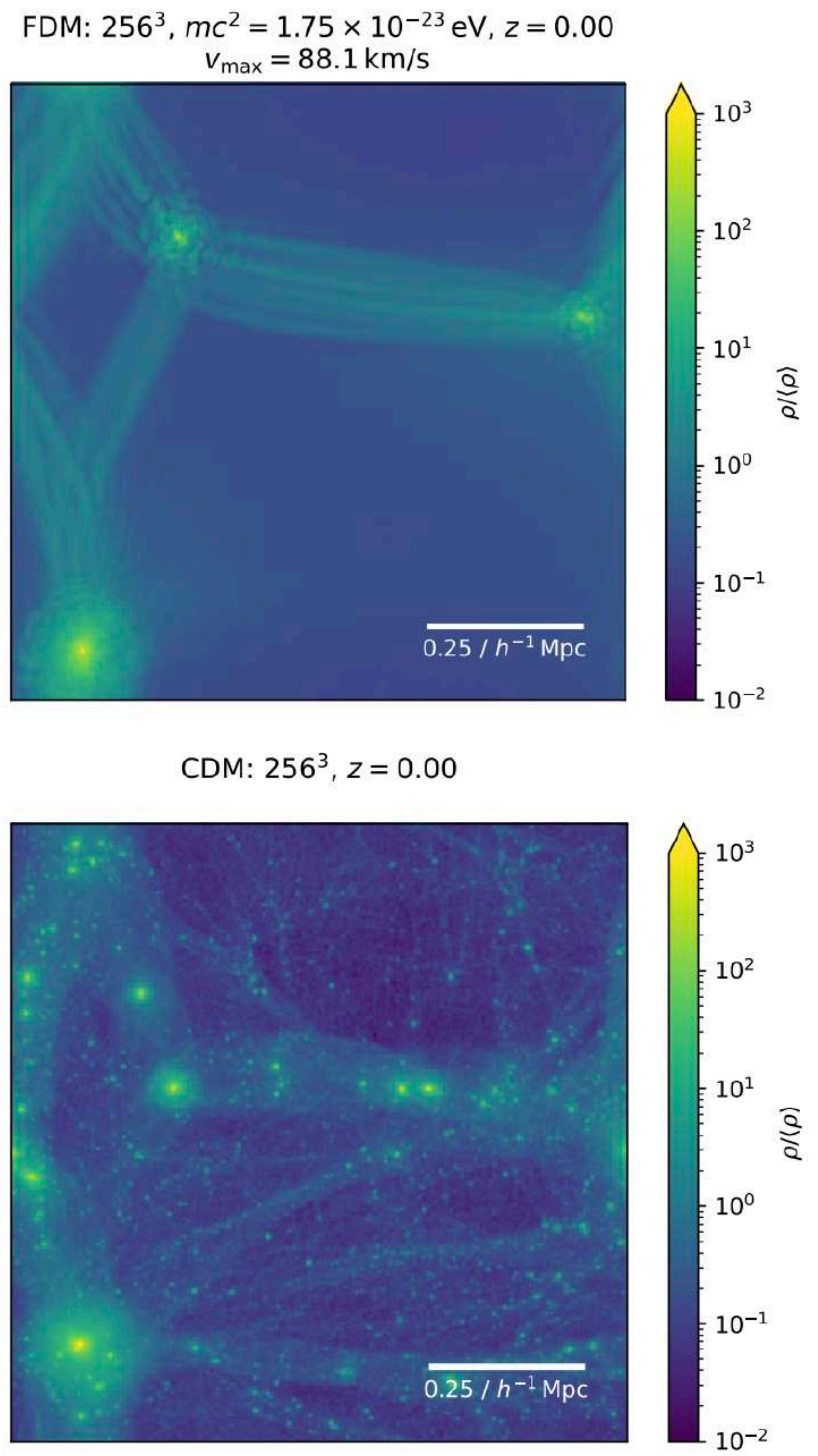
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

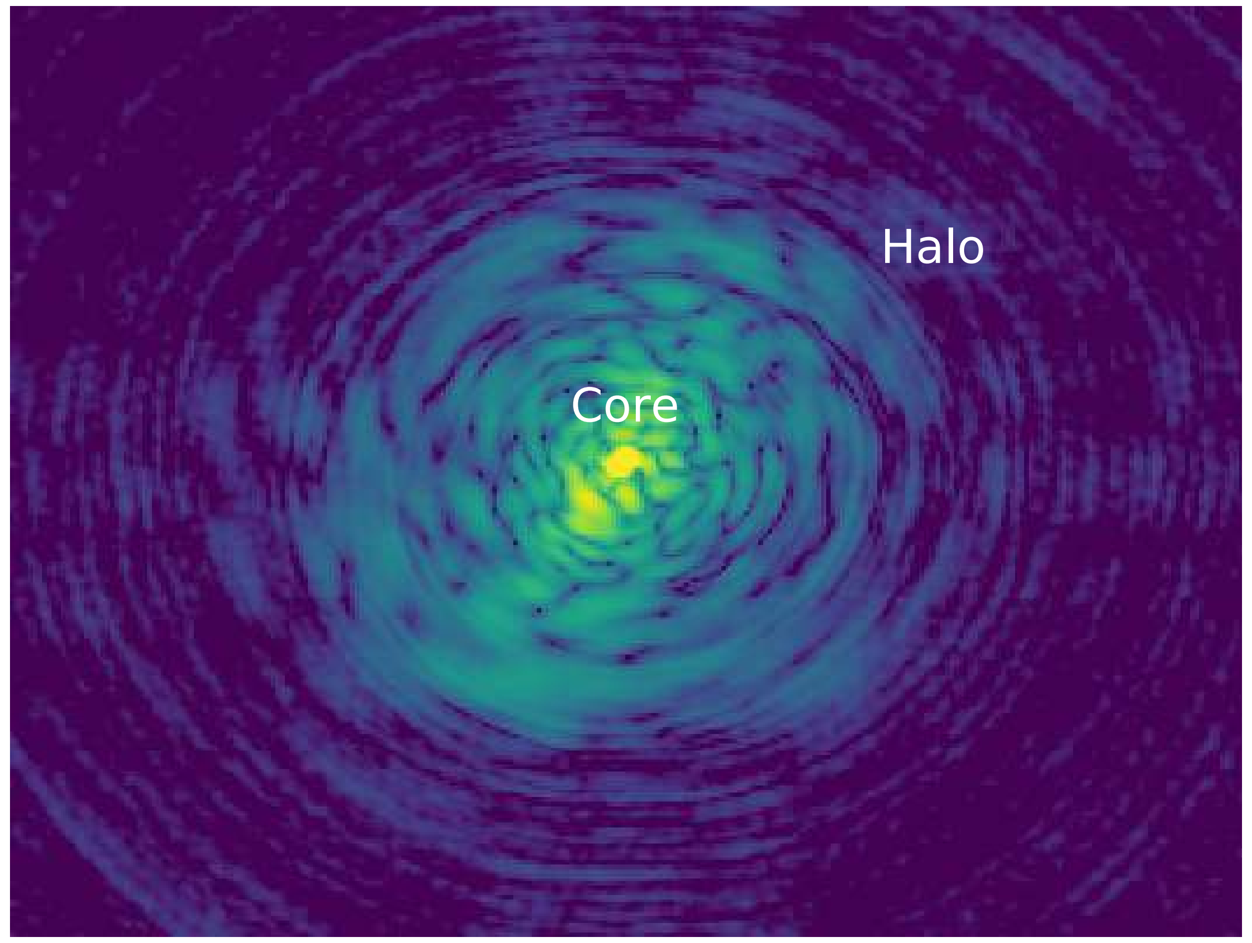
* Focus only in gravitational signatures

Suppression of small structures

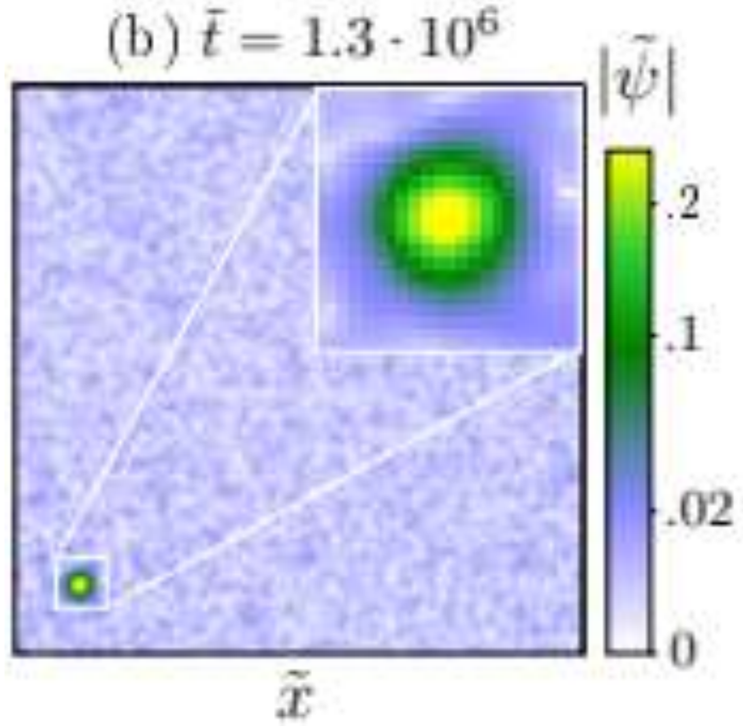


S. May et al. 2021

Formation of a solitonic core

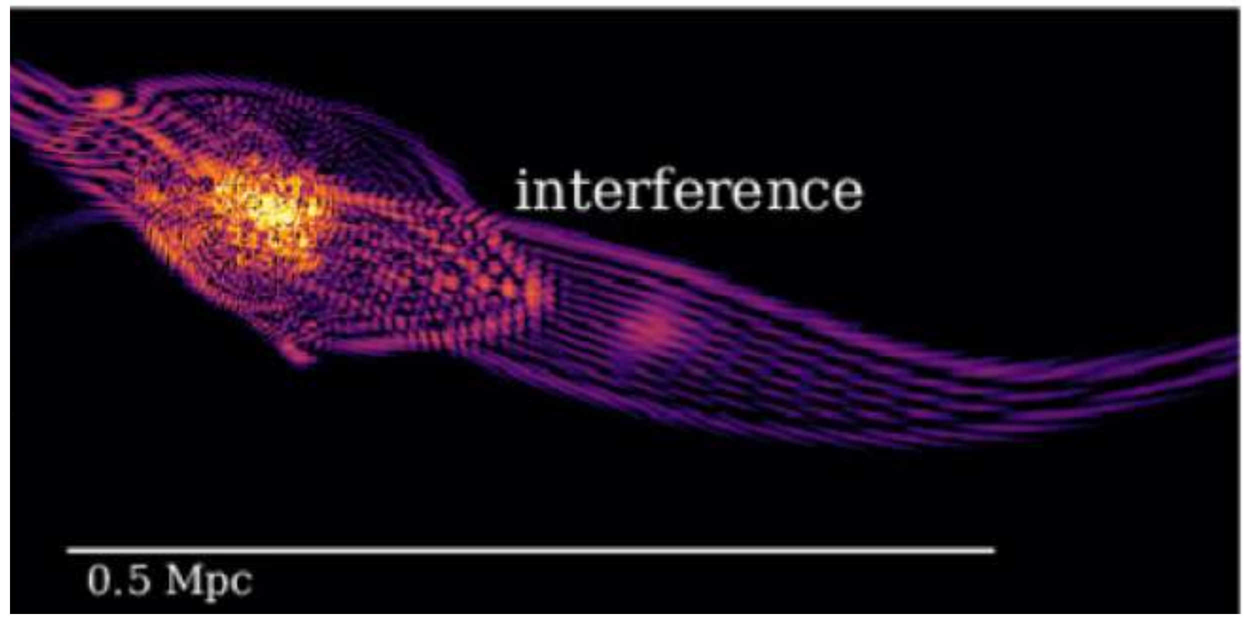


Dynamical effects



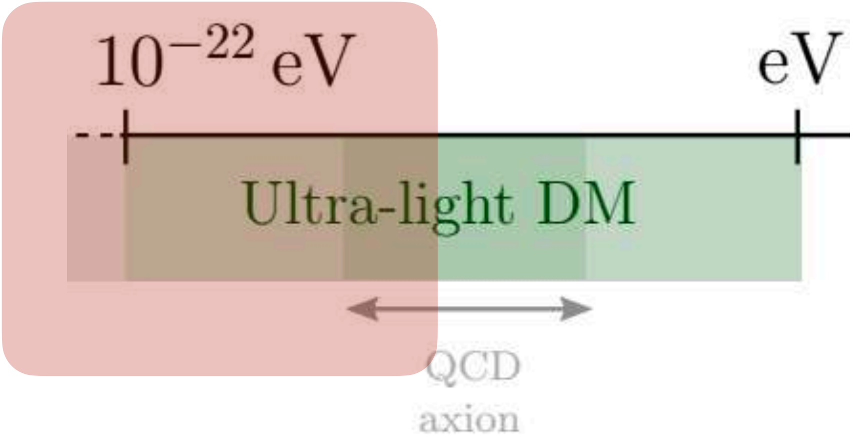
Levkov et al. 2018

Wave interference



Mocz et al. 2017

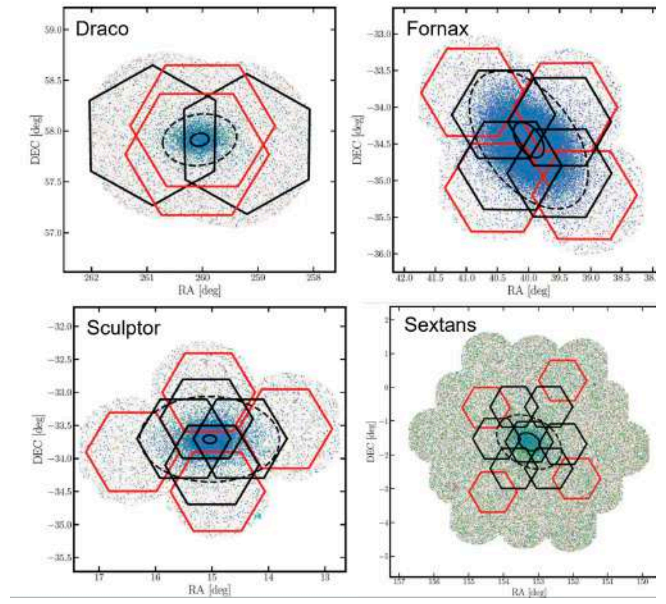
Observational implications and constraints



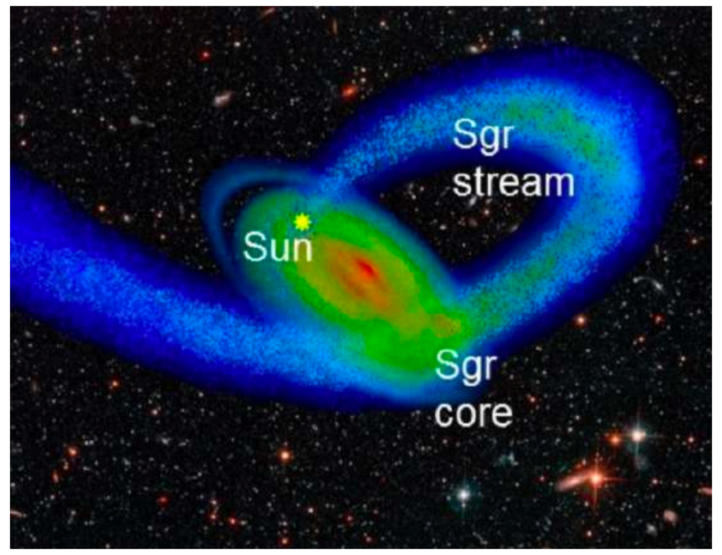
Galaxies

NASA and ESA

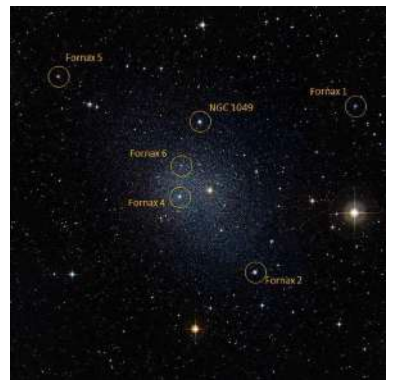
Dwarfs



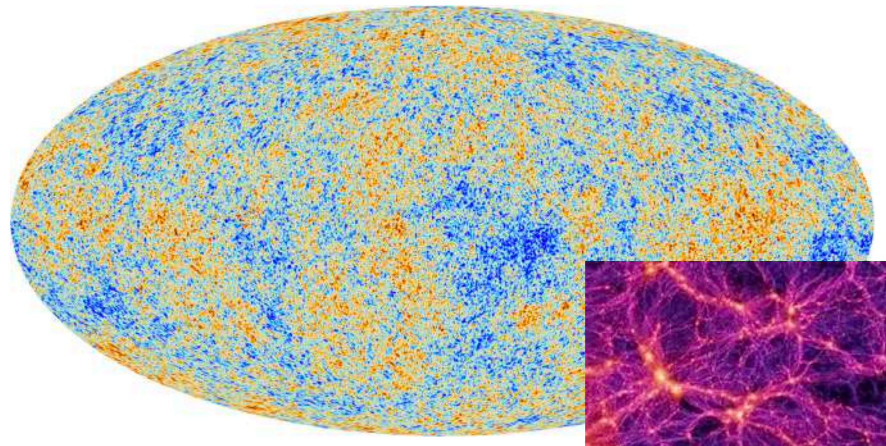
Stellar stream



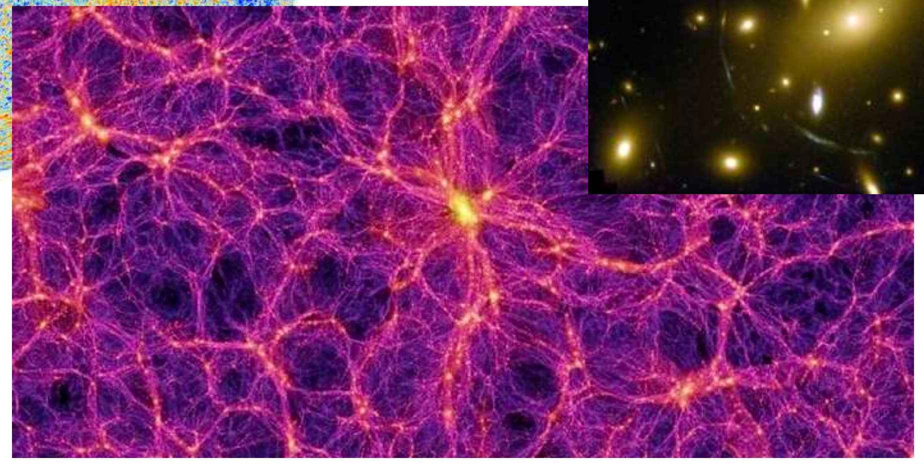
Globular clusters



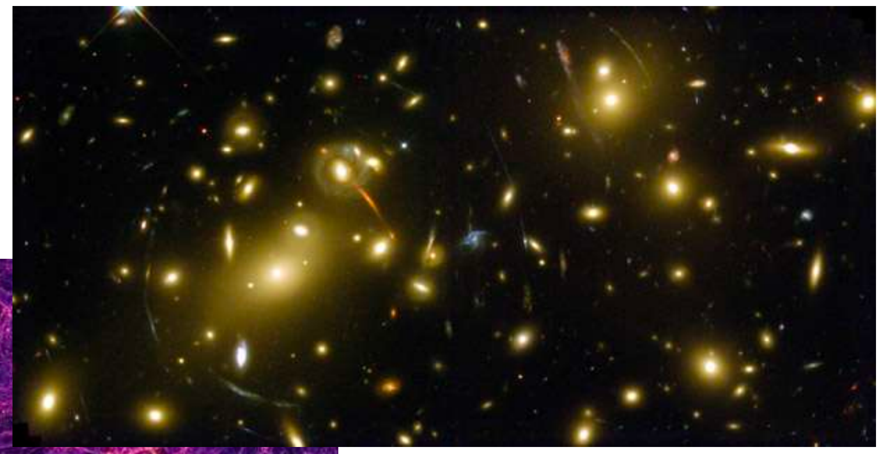
CMB+LSS



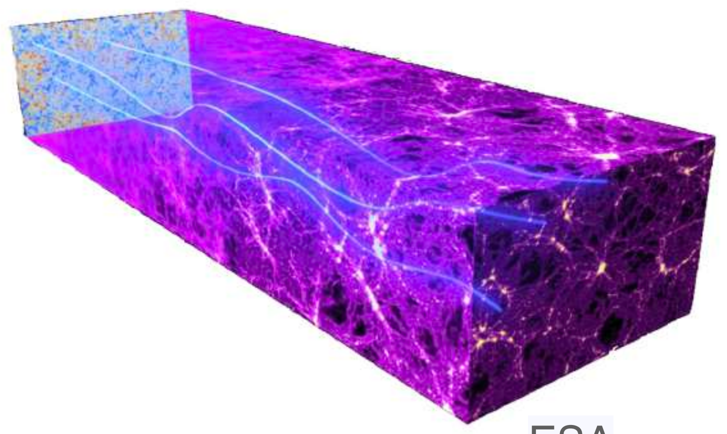
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

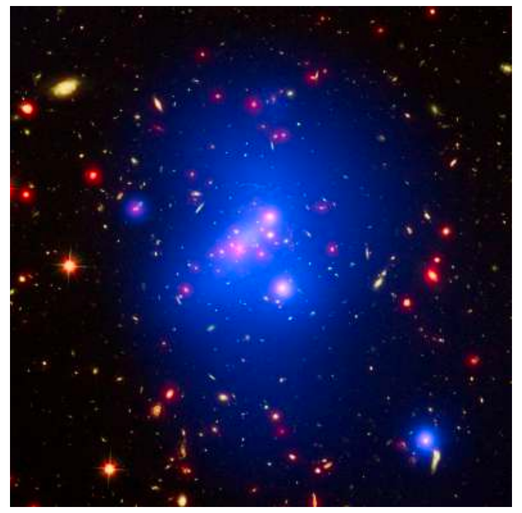


NASA and ESA



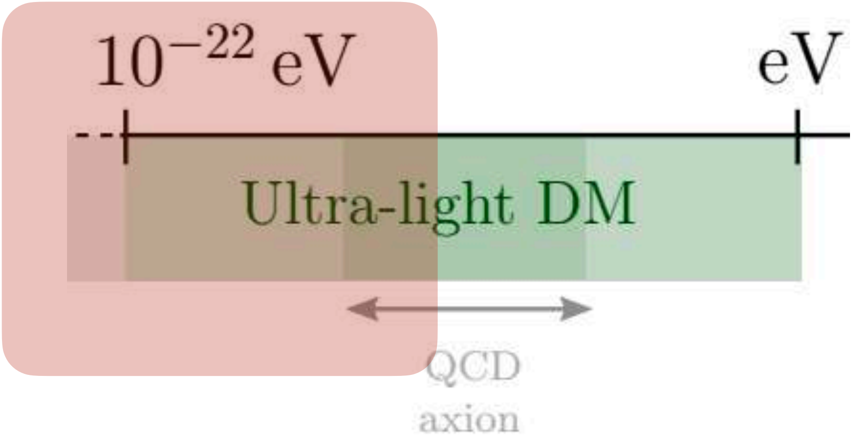
ESA

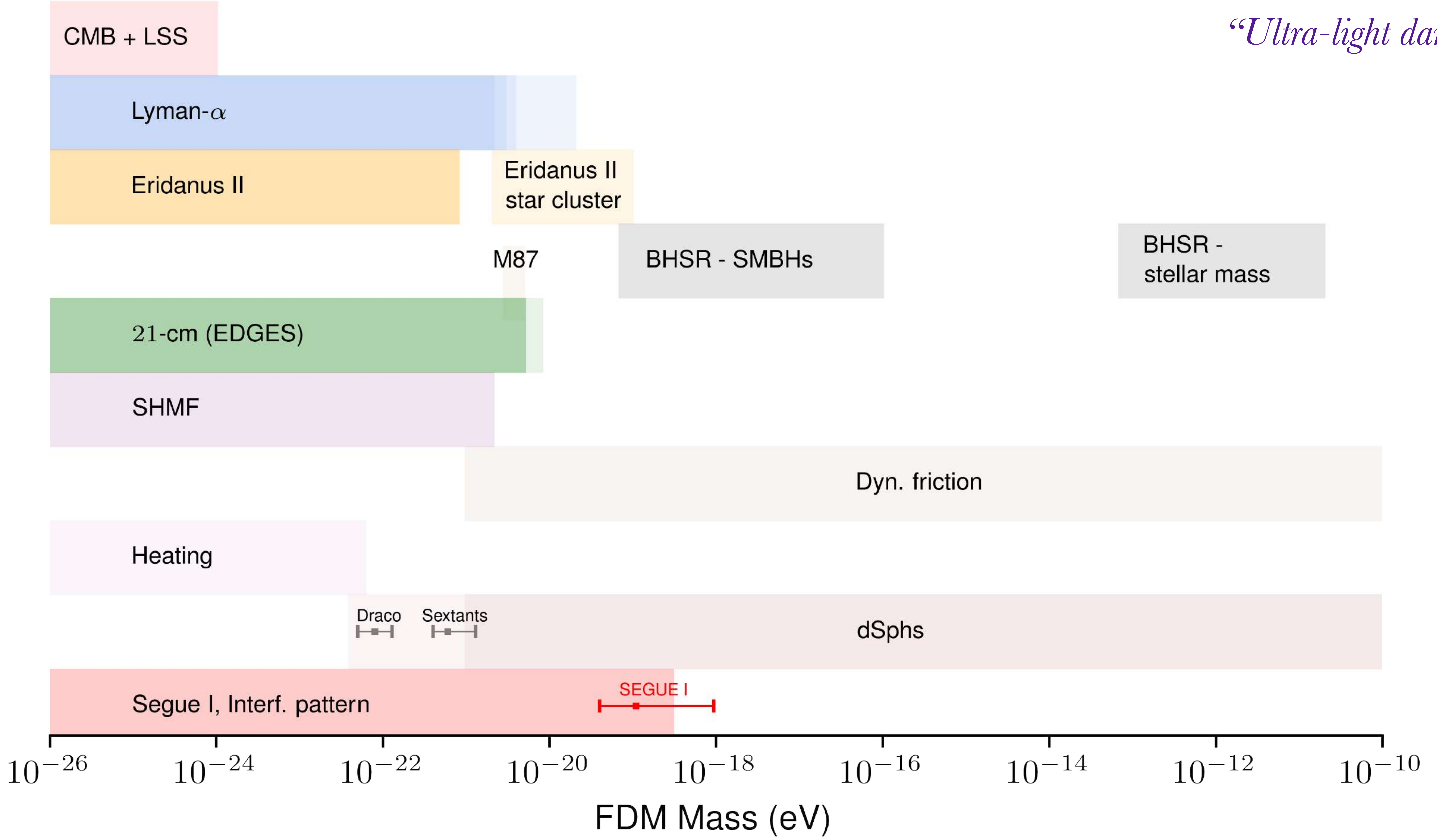
Clusters



Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



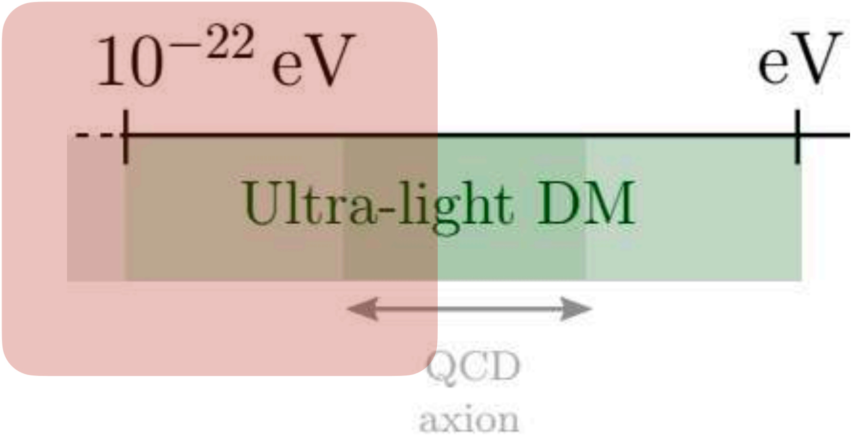


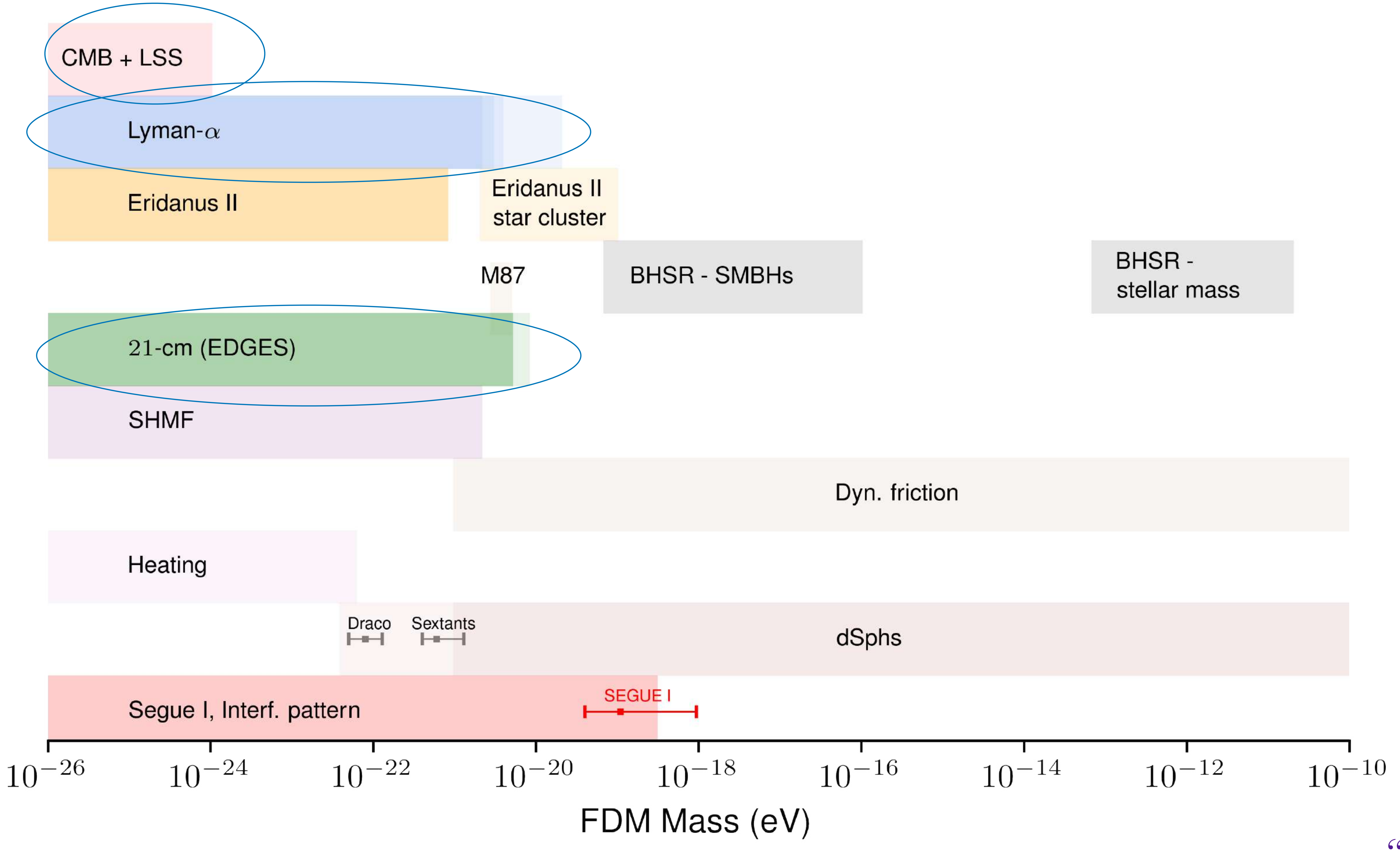
"Ultra-light dark matter", **E.F.**, 2020. The Astronomy and Astrophysics Review.

Bounds consider FDM is *all* DM

Observational implications and constraints

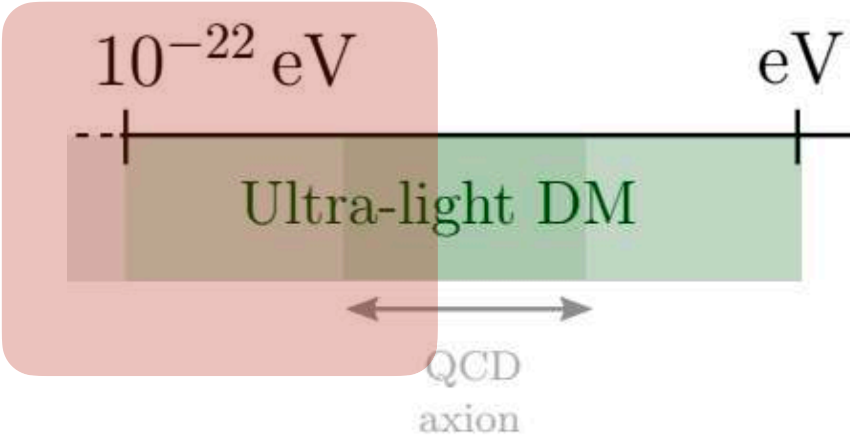
Fuzzy Dark Matter - bounds on the mass





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

Observational implications and constraints

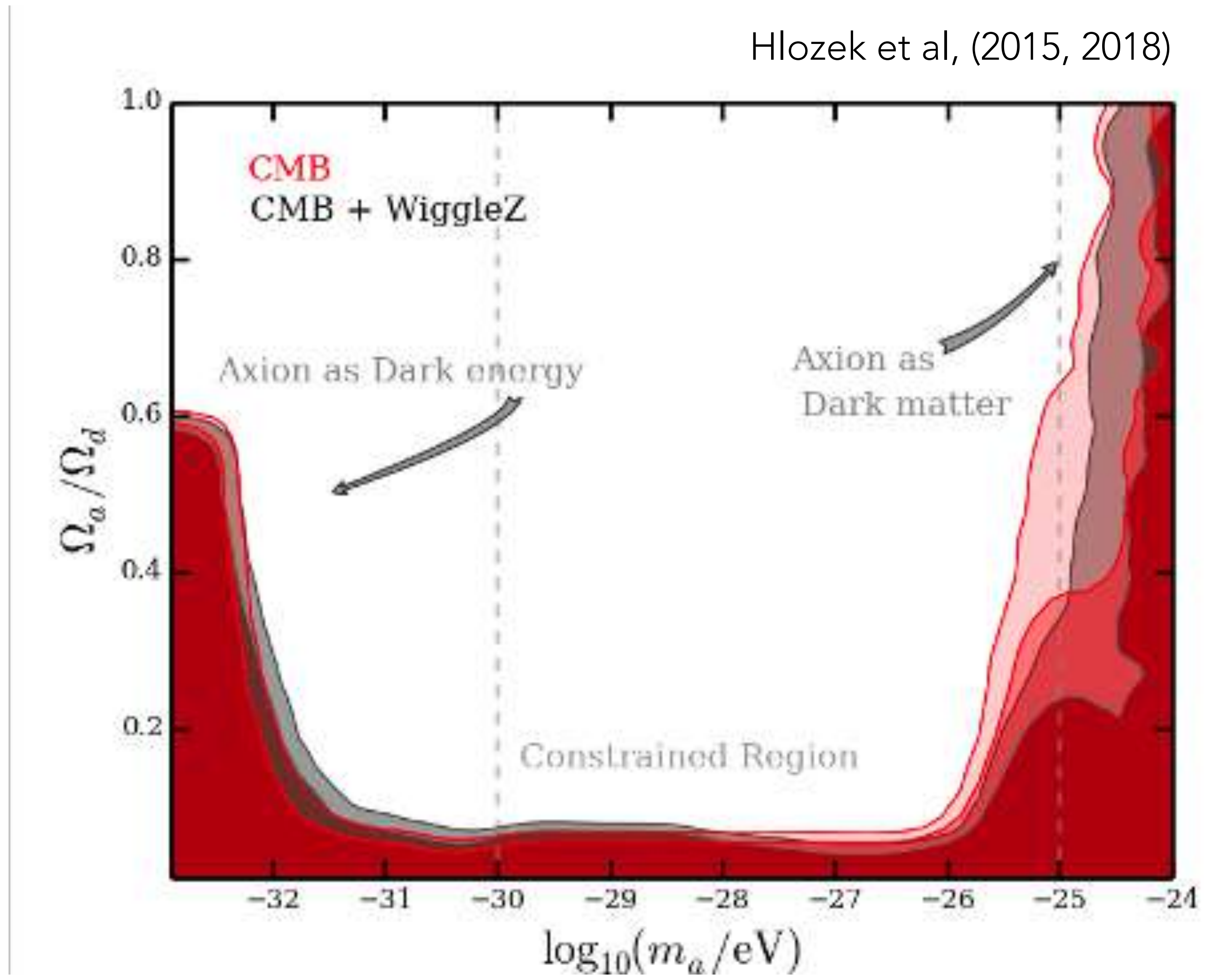


Fuzzy Dark Matter - bounds on the mass

Suppression of small structures

CMB/LSS

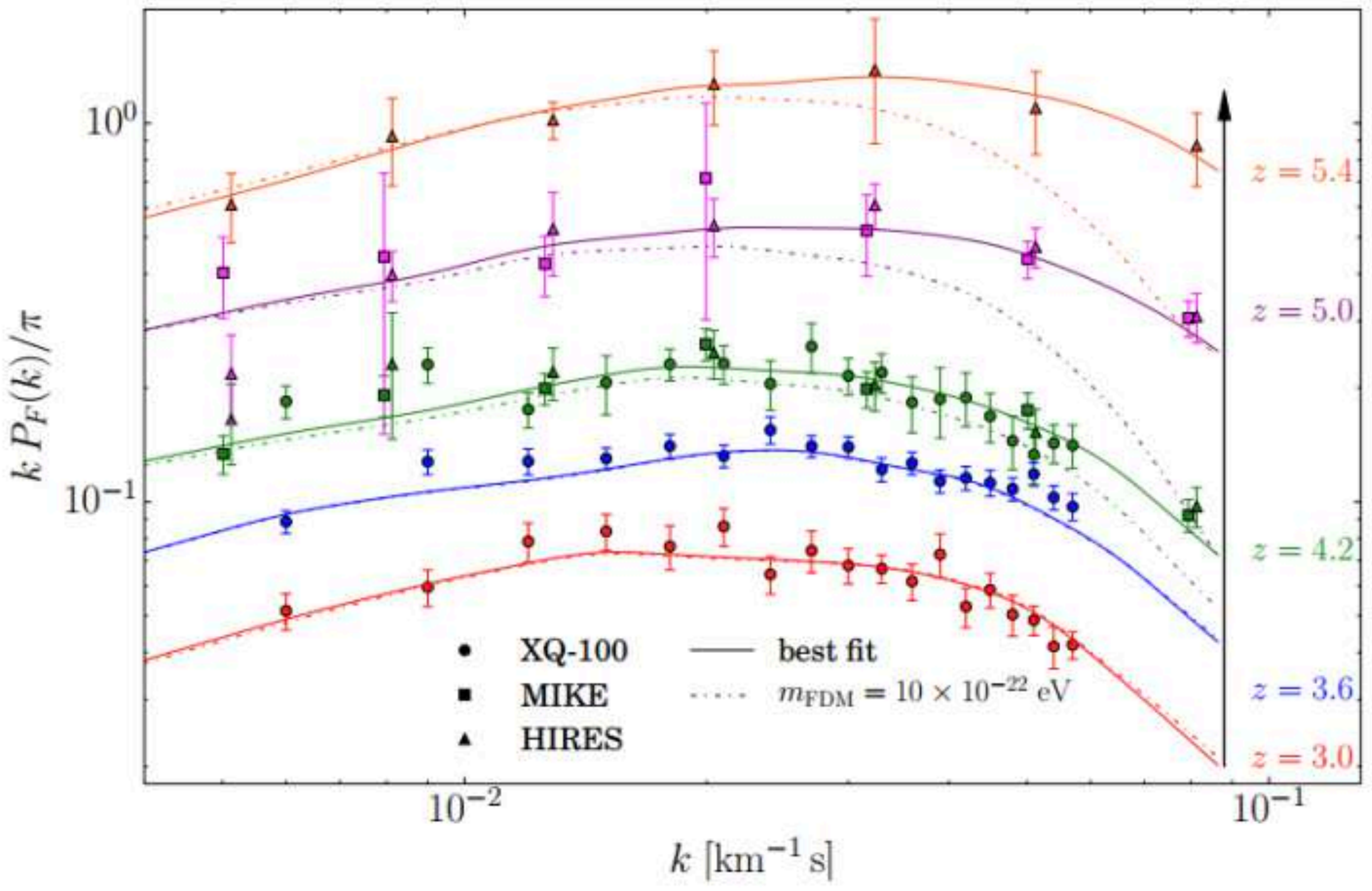
Hlozek et al, (2015, 2018)



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

Lyman alpha

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

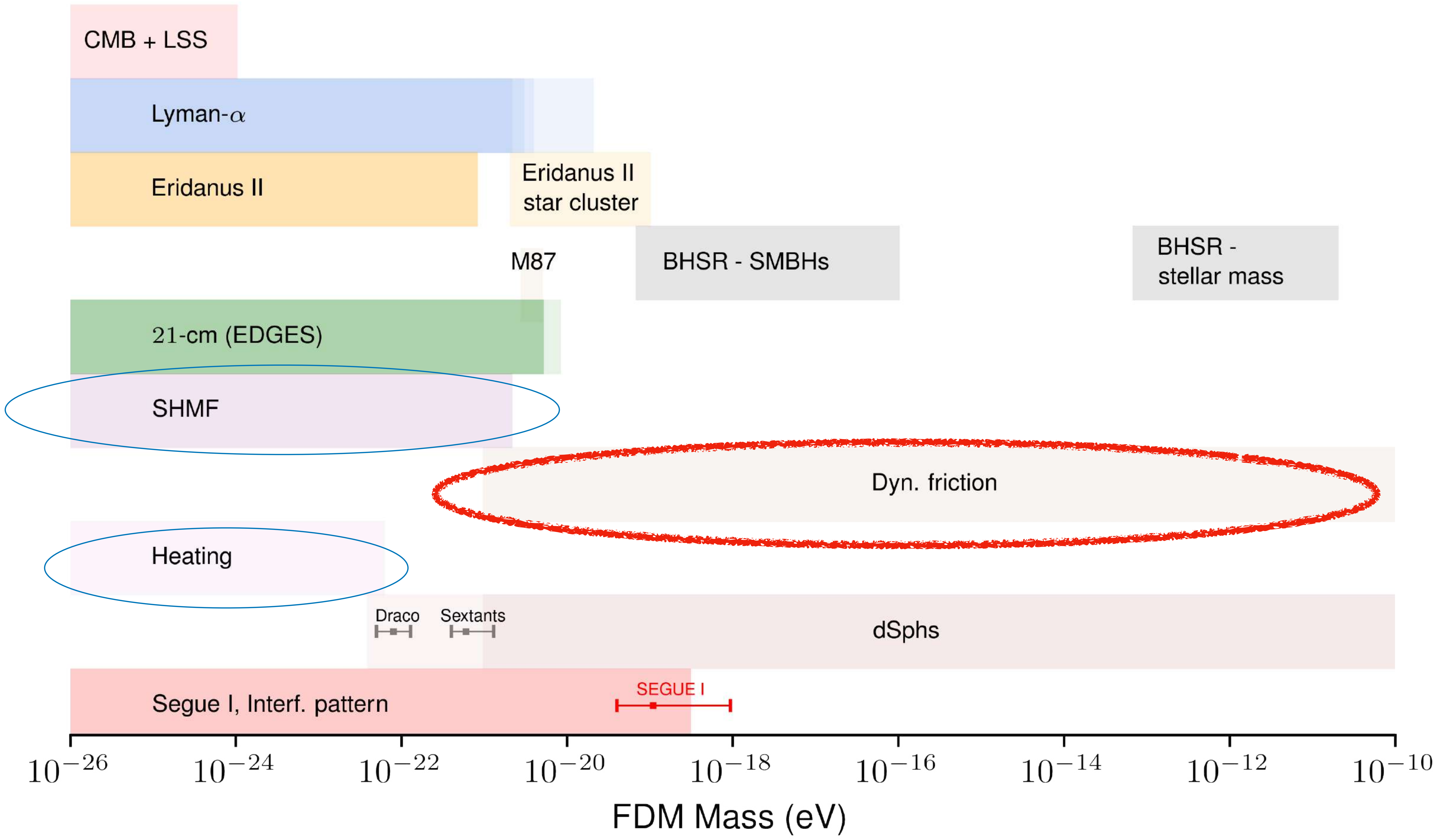


$m \gtrsim 2 \times 10^{-20}\,\mathrm{eV}$

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

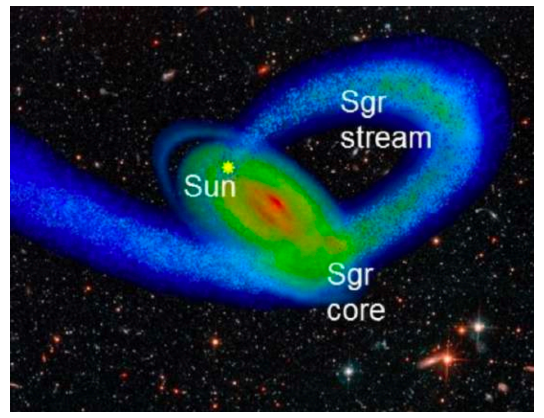
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



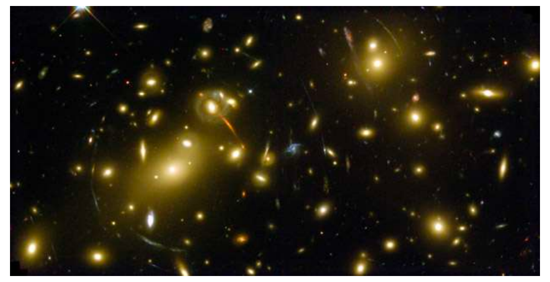
Suppression of small structures

Stellar streams



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

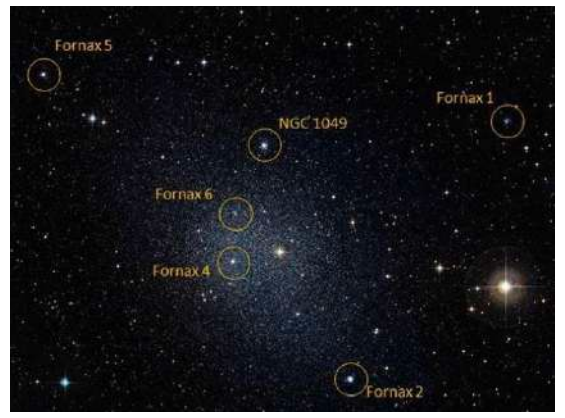
Grav. lensing



Dynamical effects

Globular clusters

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



ESO/Digitized Sky Survey 2

Lancaster et al. 2020

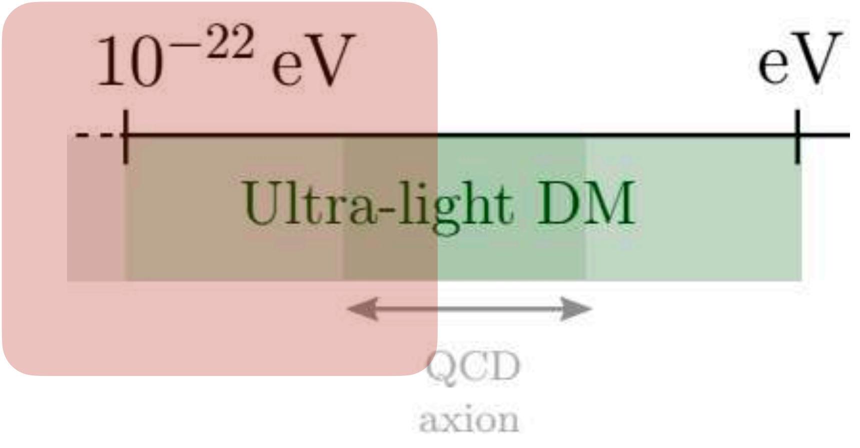
Heating of the MW disk

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

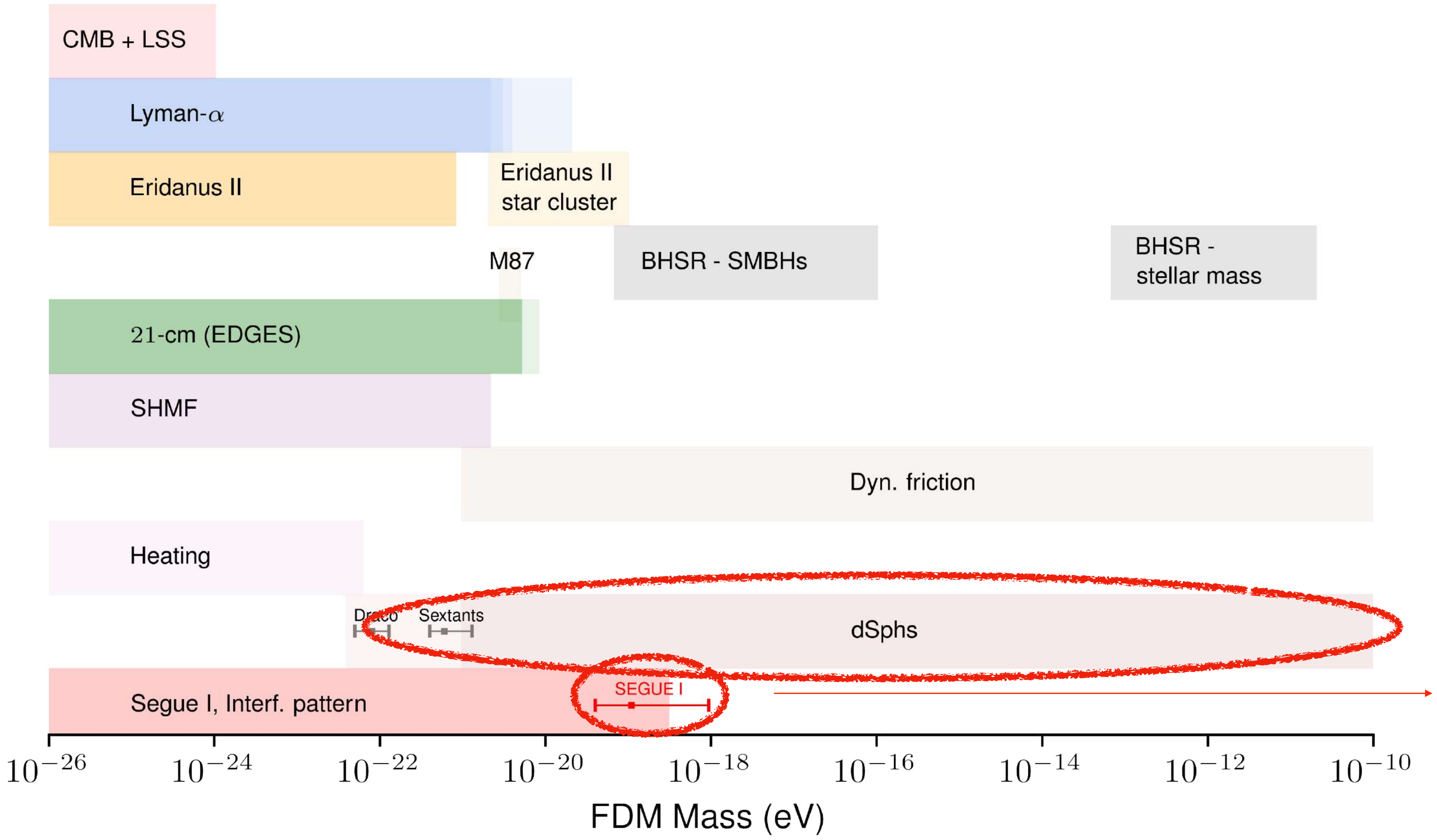
Church et al. 2019

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

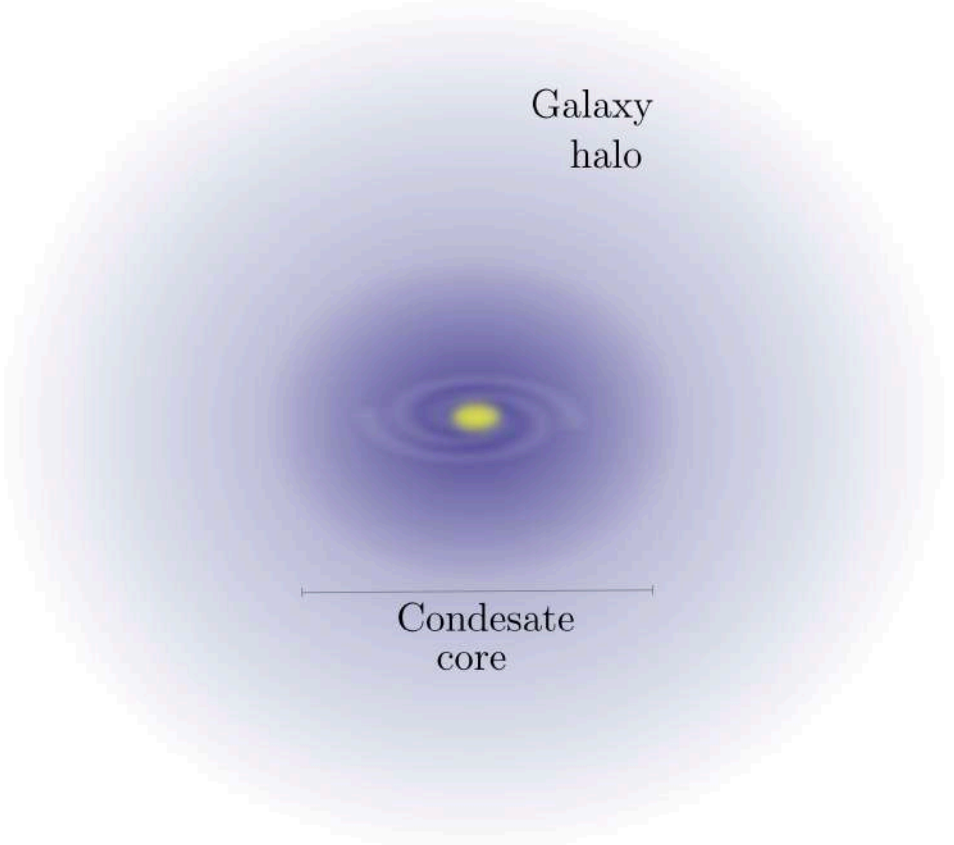


Presence of a core



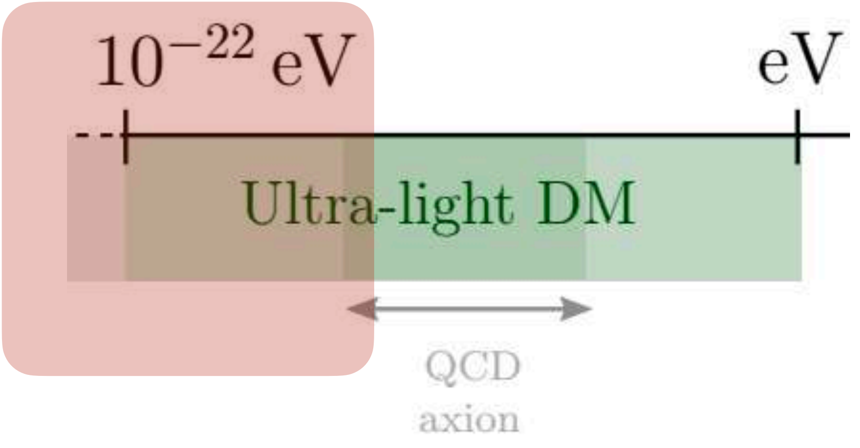
Presence of a core

DWARF GALAXIES



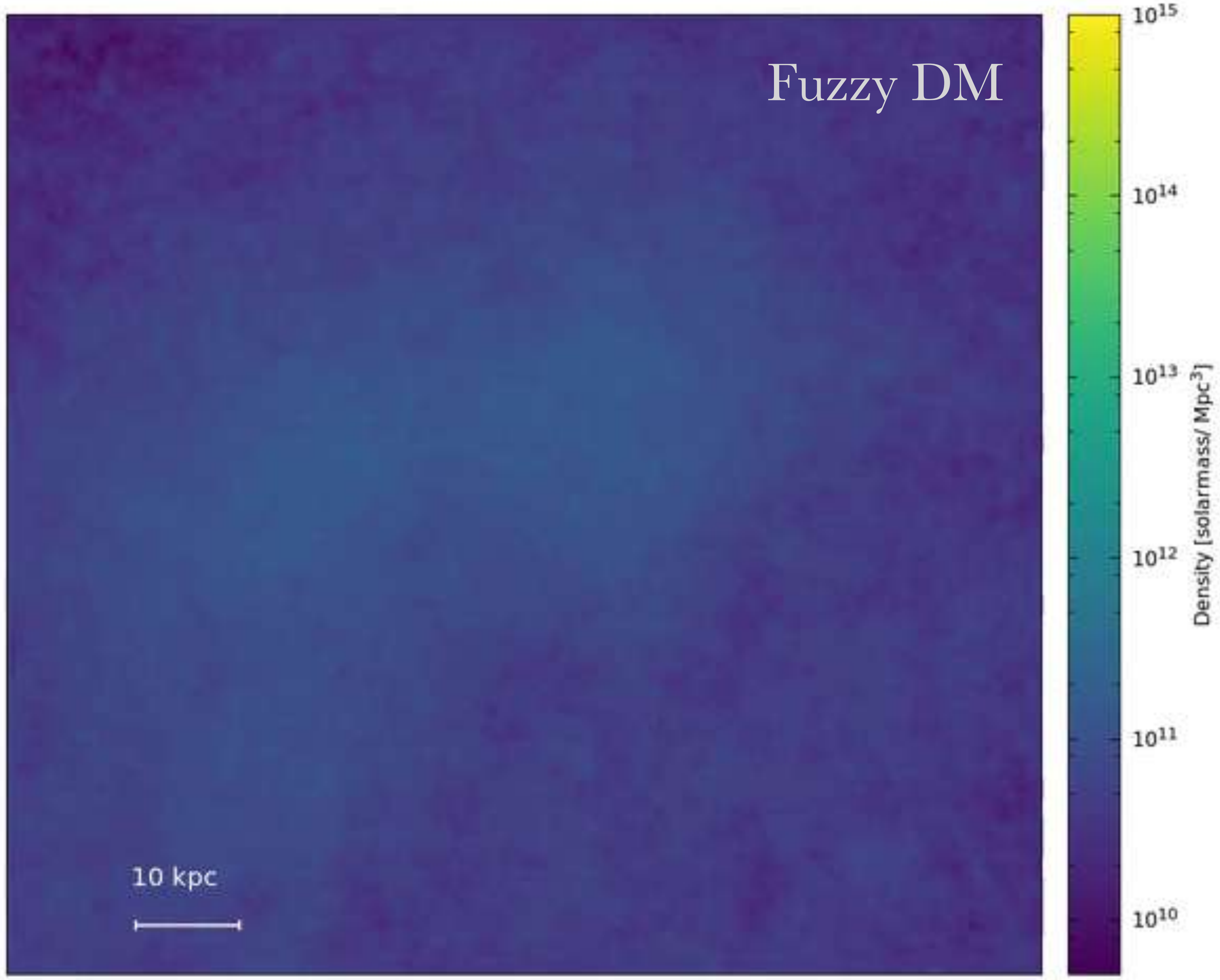
Phenomenology

Formation of cores

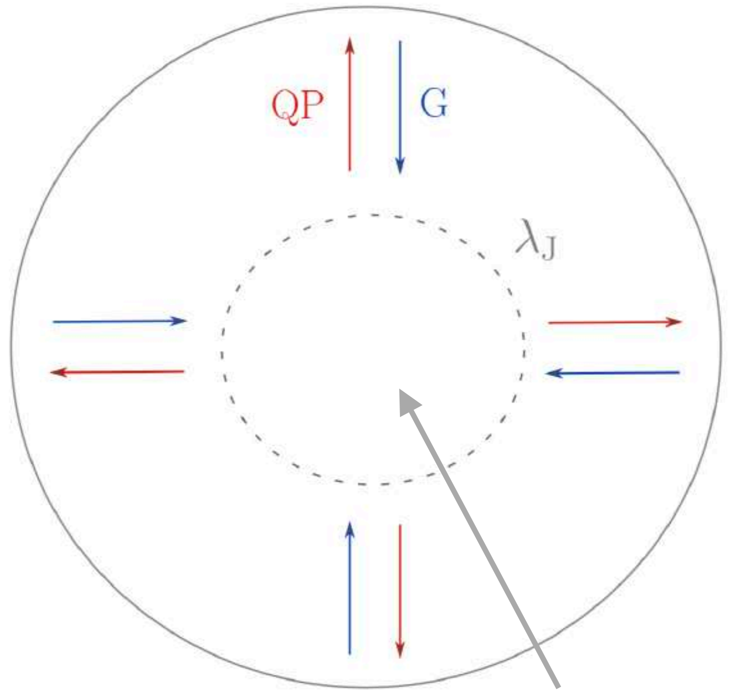


NON-LINEAR evolution: need simulations

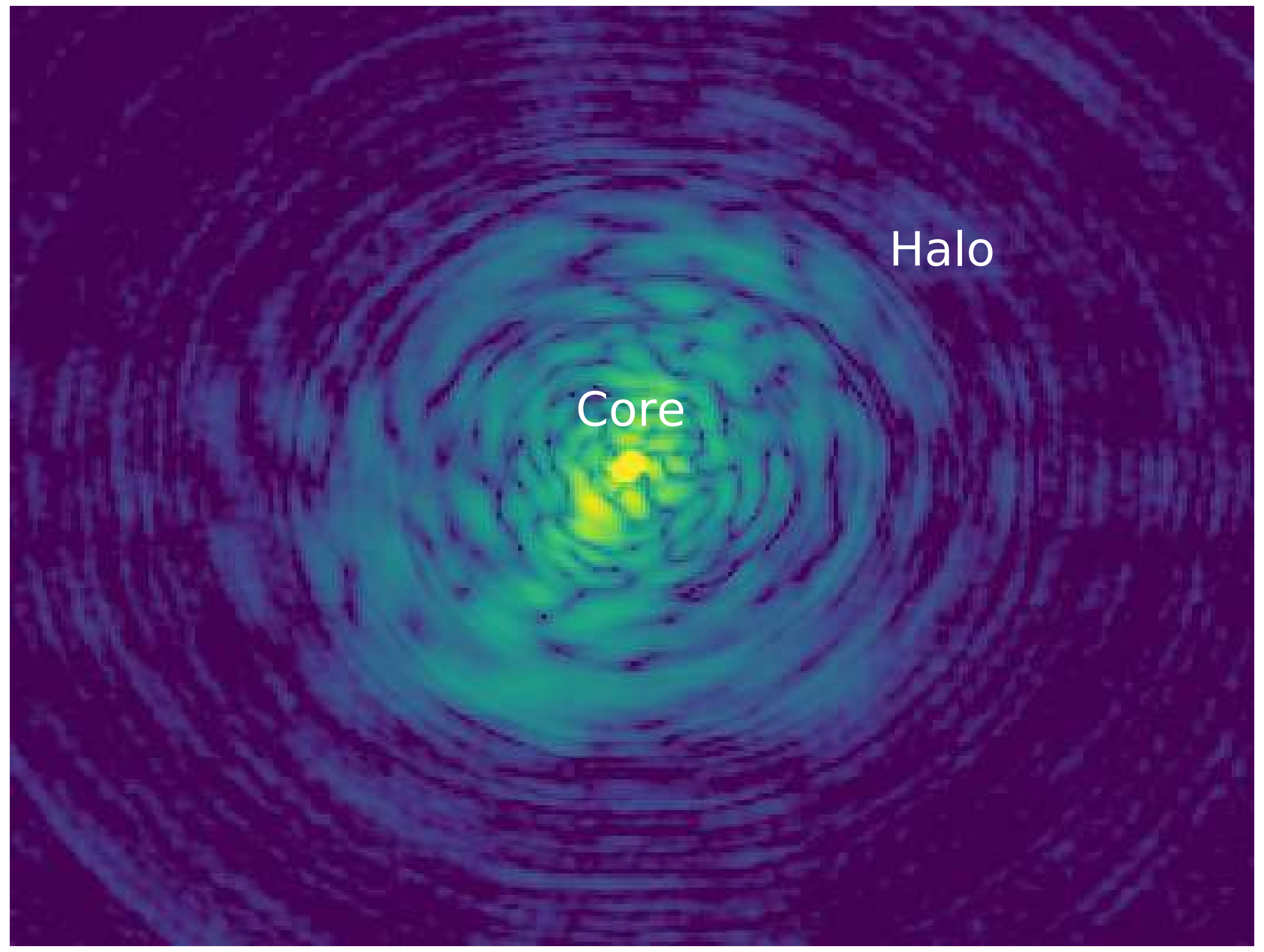
$m = 10^{-22}\,\mathrm{eV}$ $N = 512^3$ $L = 300\,\mathrm{kpc}$

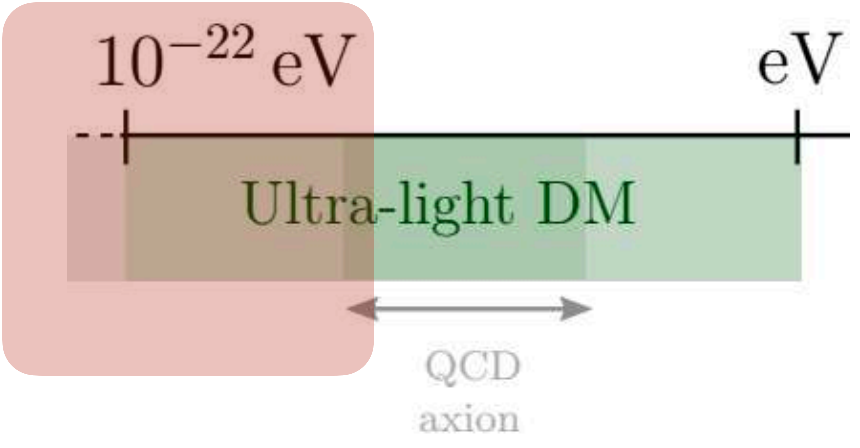


Simulation by Jowett Chan



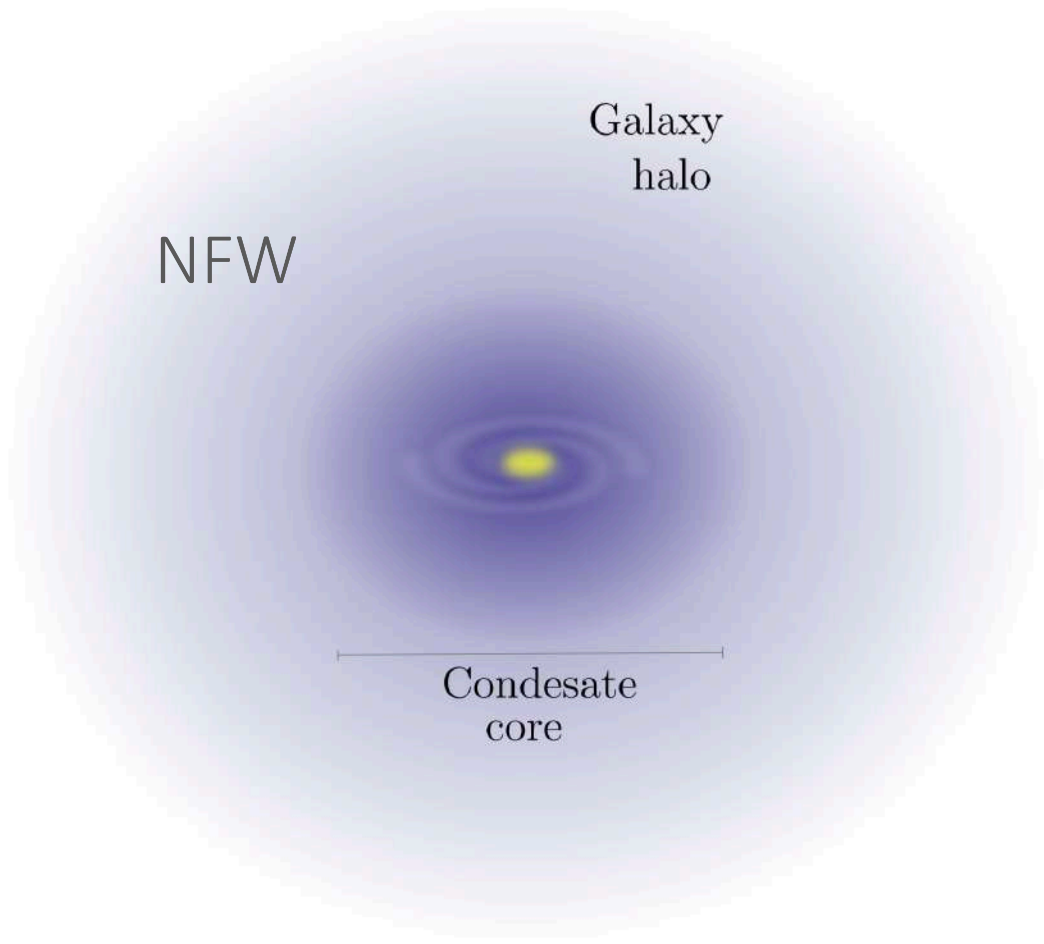
NO structure formation
Stable, oscillating solution





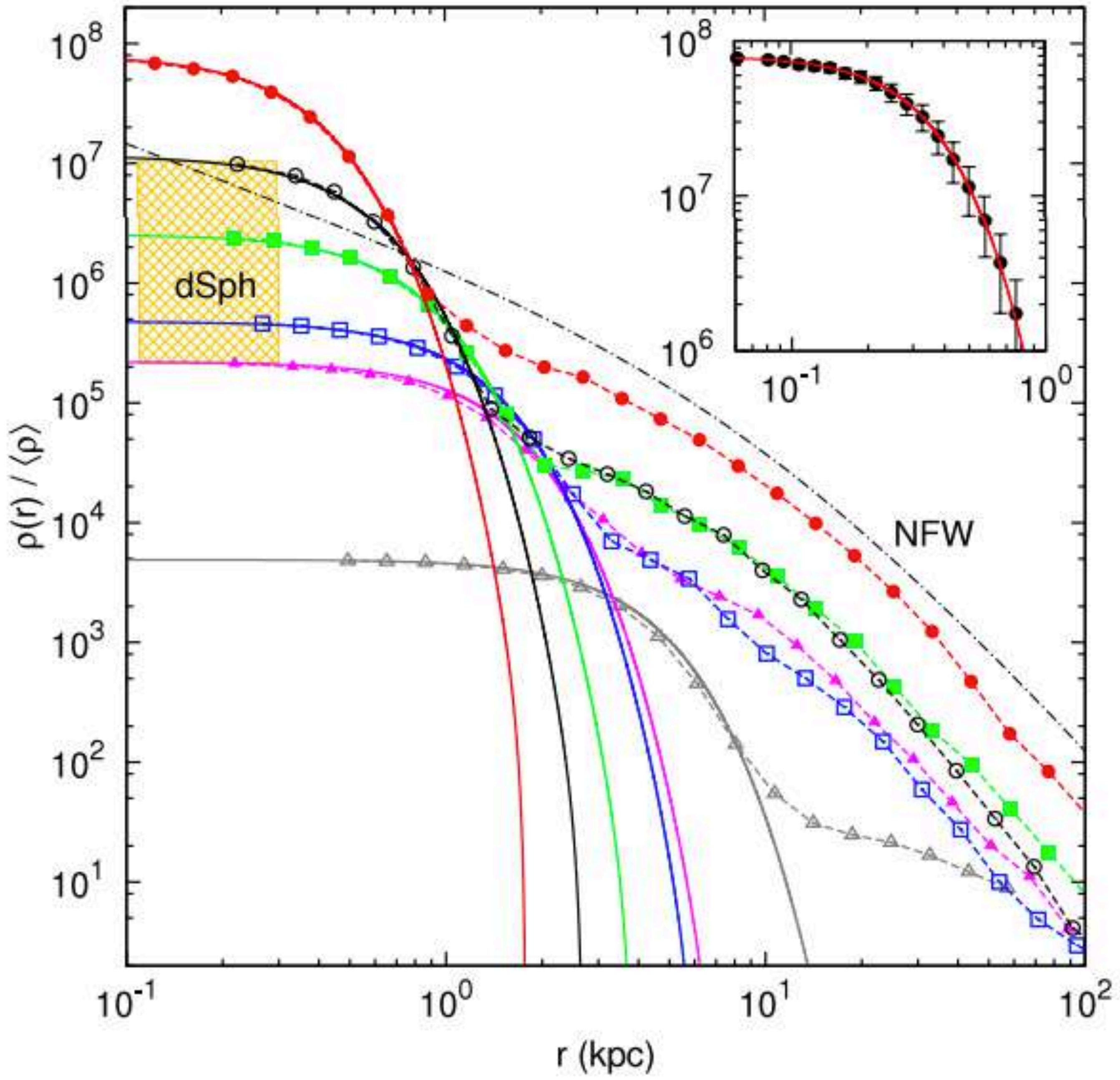
Phenomenology

Formation of cores



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

Schive et al. 2014



FDM

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

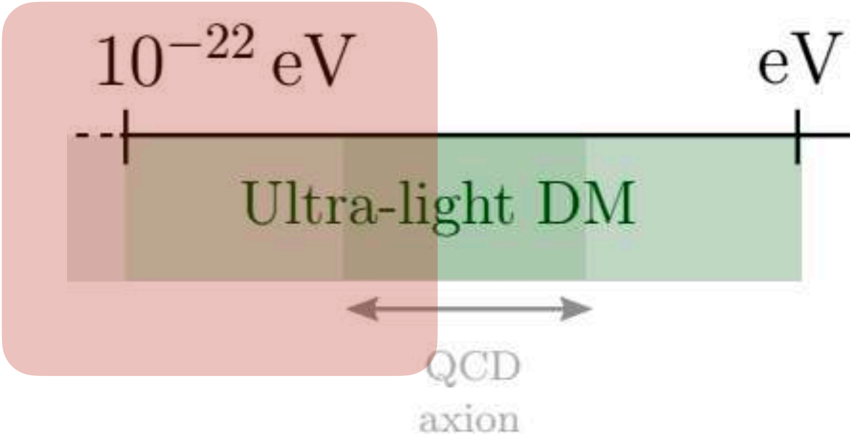
$$\rho_c \simeq \frac{1.9 \times 10^{-2}}{[1 + 0.091\,(r/R_{1/2,c})^2]^8} \left(\frac{m}{10^{-22}\,\text{eV}}\right)^{-2} \left(\frac{r_c}{\text{kpc}}\right)^{-4} M_\odot\,\text{pc}^{-3}\,,$$

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

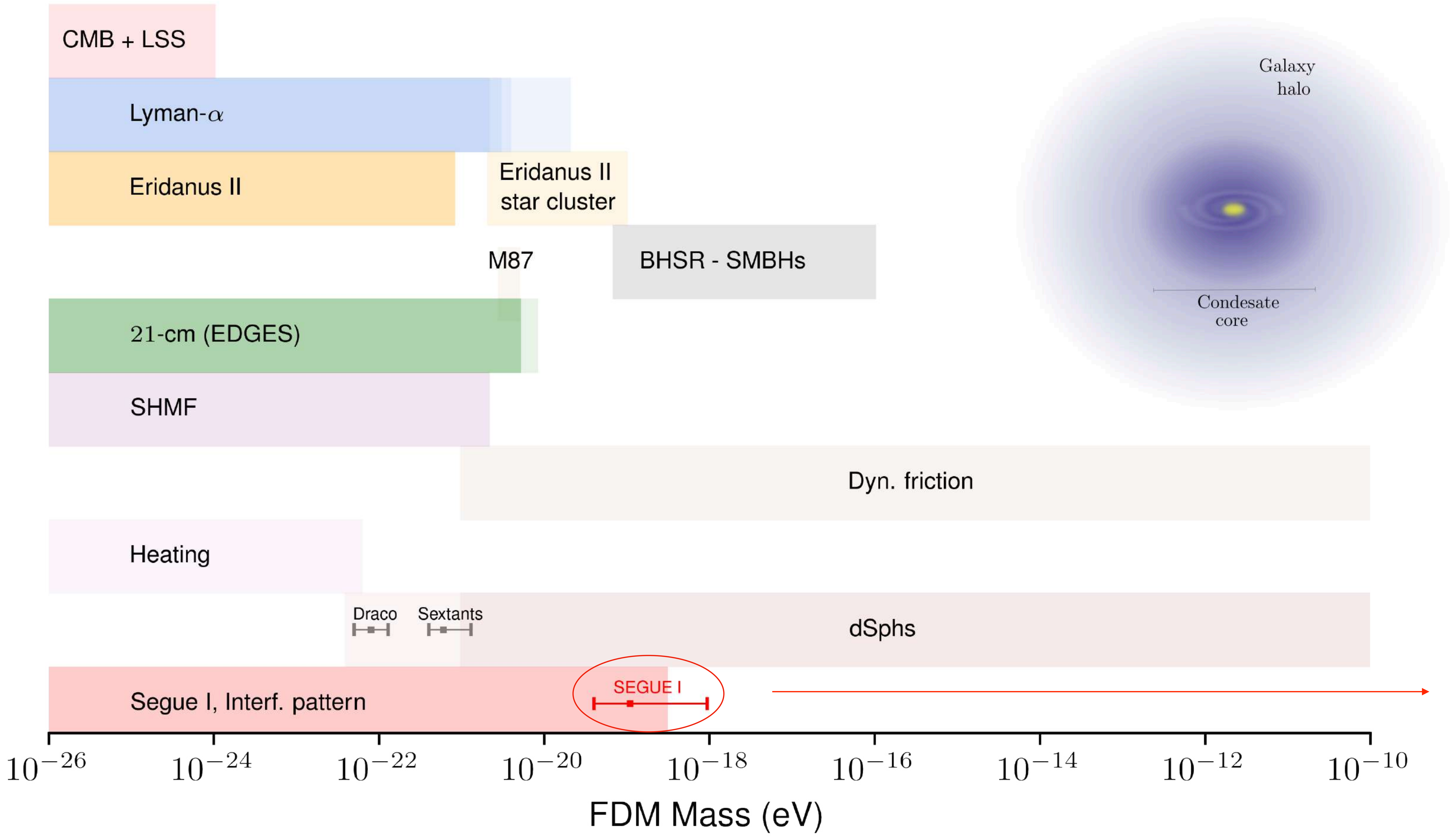
→ Relations used to compare with observations

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



Presence of a core



DWARFS

Ultra faint dwarfs

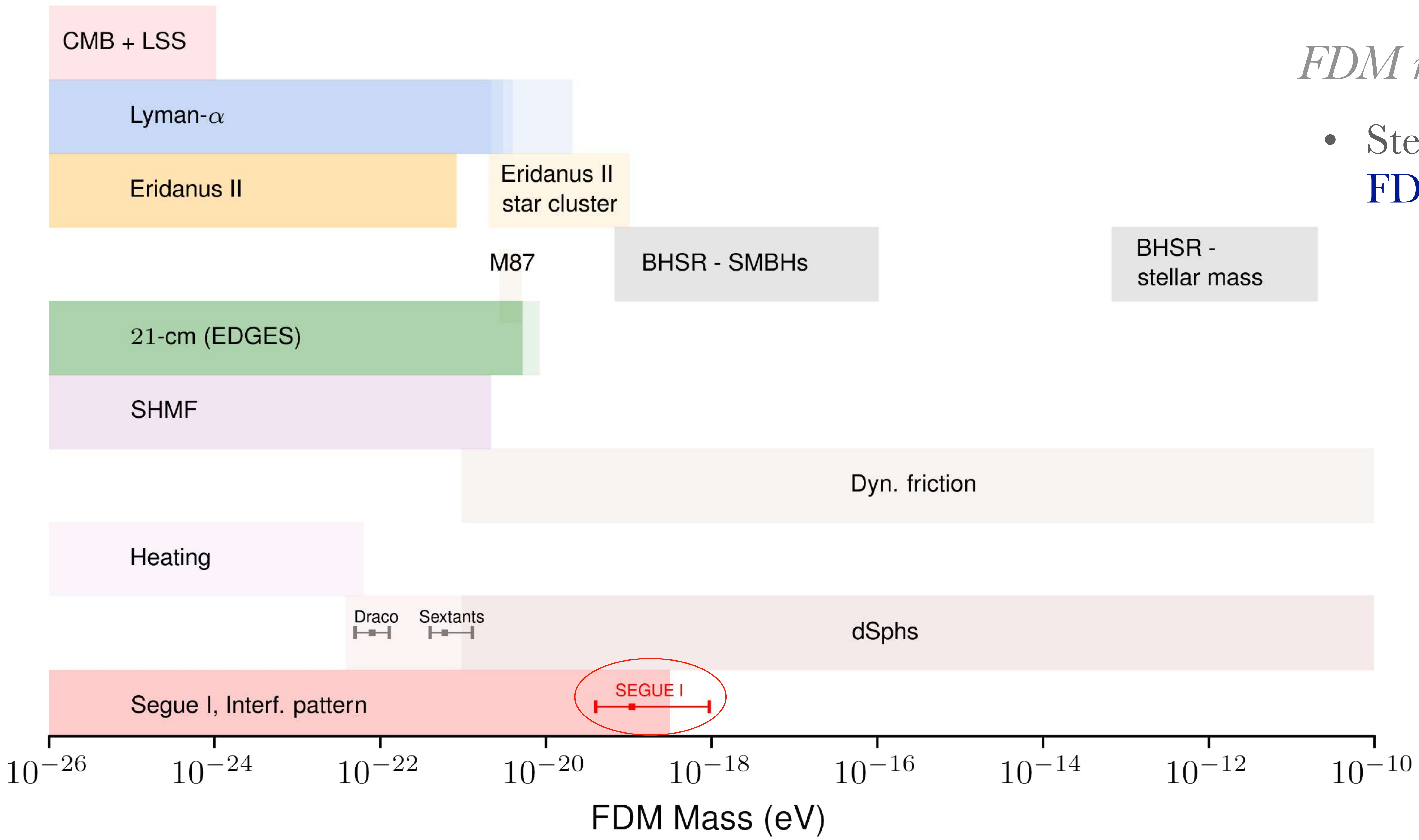
FDM SIMULATIONS

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

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

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass



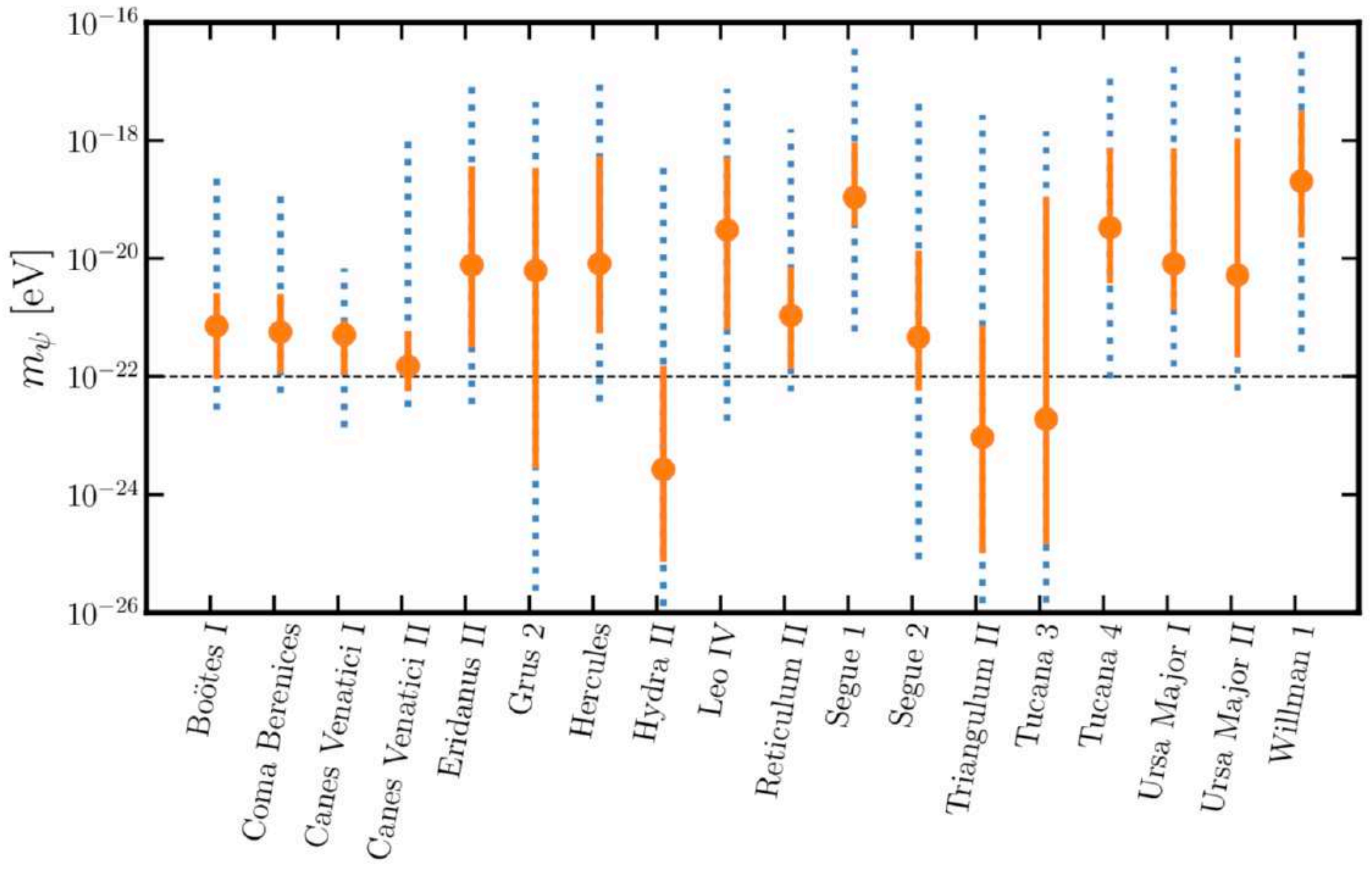
Ultra faint dwarfs

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

FDM mass from Ultra-faint dwarfs

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

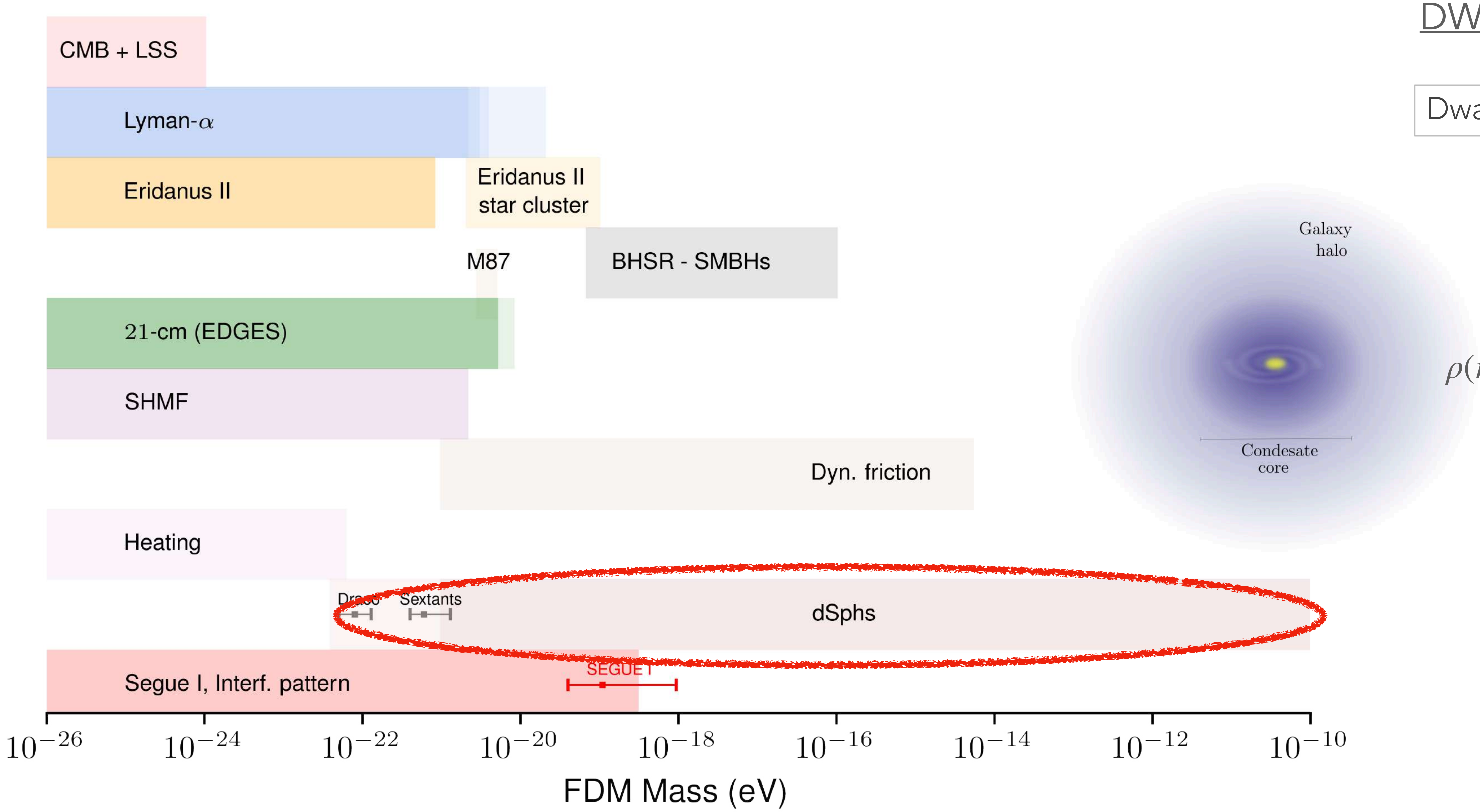
$$m_{\mathrm{FDM}}^{(Seg1)} = 1.1^{+8.3}_{-0.7} \times 10^{-19}\,\mathrm{eV}$$



Preference for higher mass

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



DWARFS

Dwarf Spheroidals (dSphs)

FDM SIMULATIONS

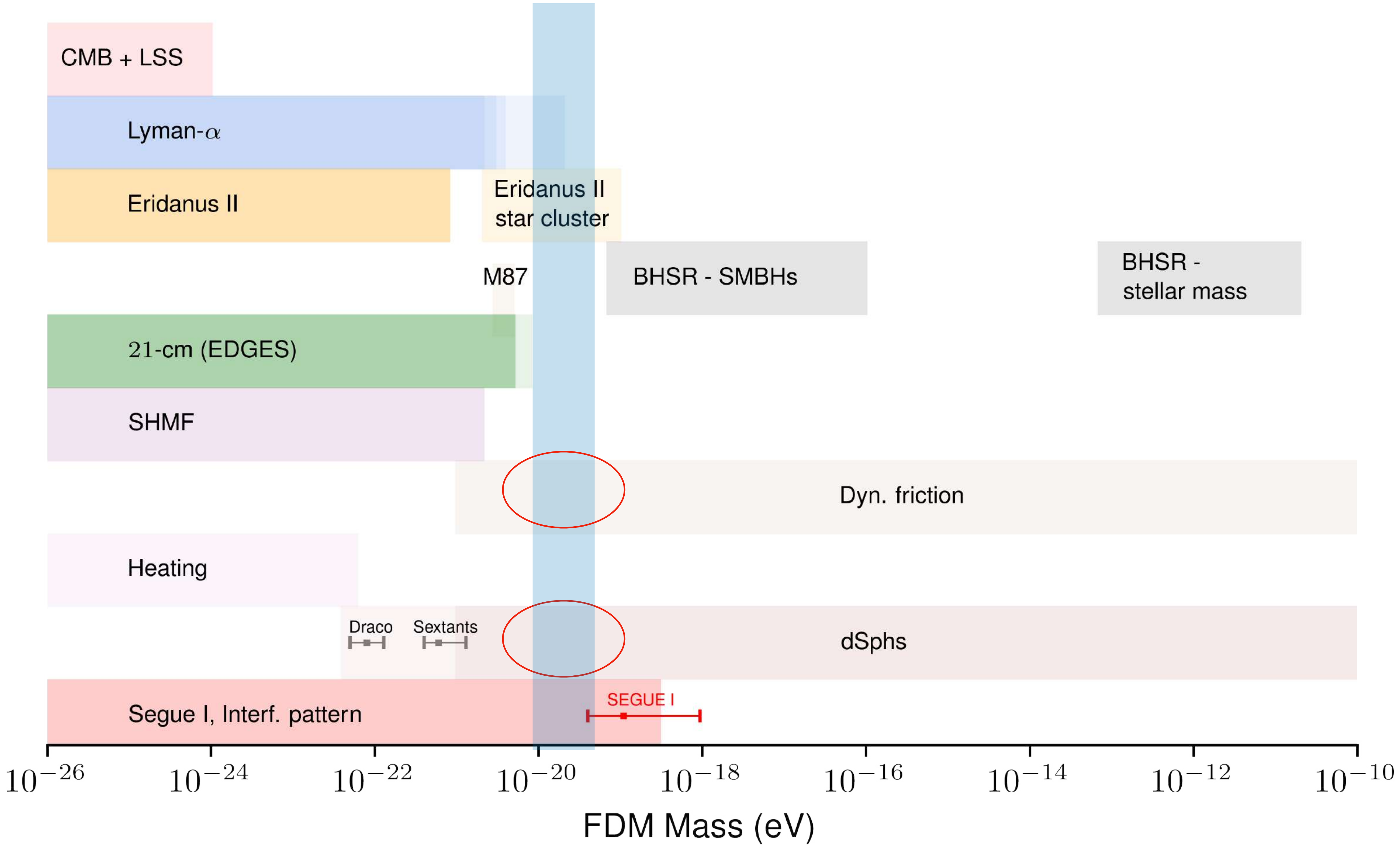
$$\rho(r) = \begin{cases} \rho_{\text{soliton}} \simeq \dfrac{\rho_c}{\left[1 + 0.091(r/r_c)^2\right]^8}, & r < r_\epsilon \\ \rho_{\text{NFW}} = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, & r > r_\epsilon \end{cases}$$

Fornax - Sculptor

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

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

Constraints on the mass



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

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

Possible reasons for this incompatibility:

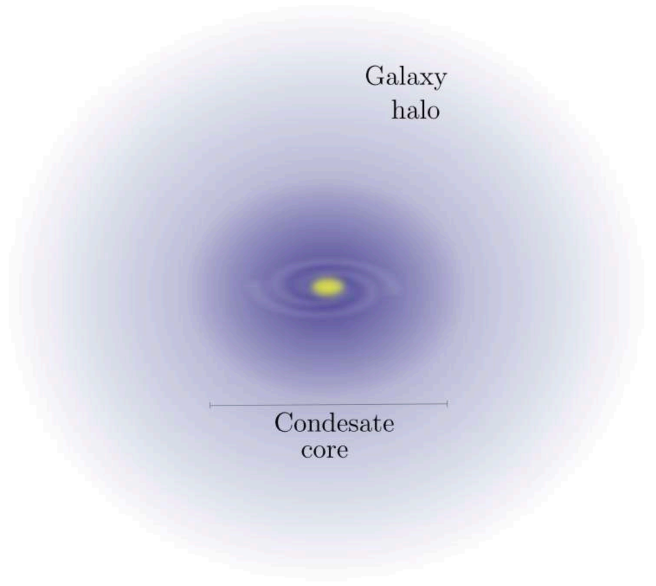
- *Influence of baryons:* baryonic processes can change the density structure of their halo - we are not probing the intrinsic DM profile.
- *Universality of the core profile*: FDM soliton profile might be too simplistic, could change for different systems (might also depend on baryons)
- *Core-mass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

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

FDM - Core-halo mass relation

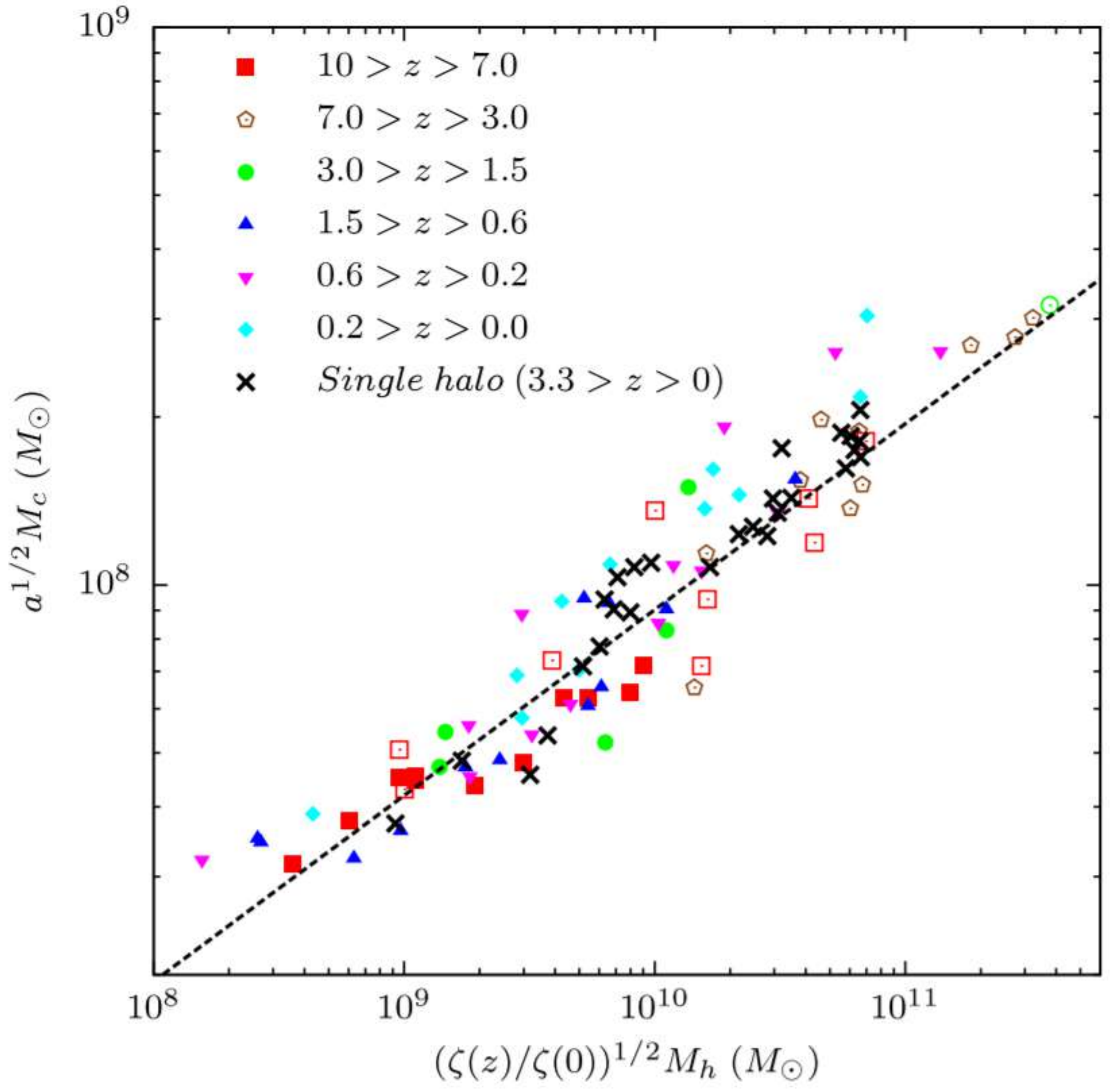
J. Chan et al. 2021

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



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

$\xrightarrow{?} M_h$



Schive et al. 2014

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

Velocity dispersion tracing

$\sigma_c \sim \sigma_h$

Energy tracing

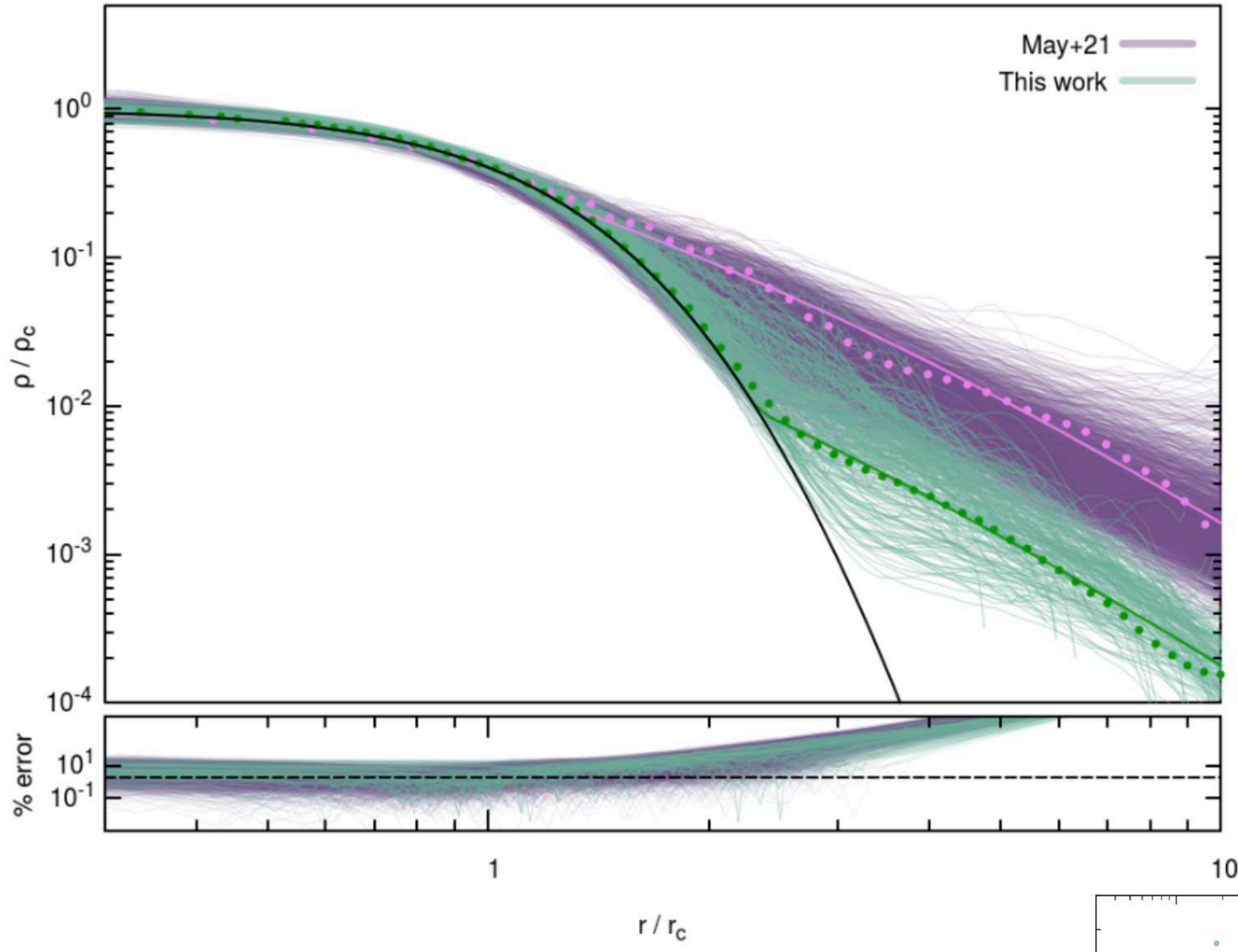
$M_c\,\sigma_c^2 \sim M_h\,\sigma_h^2$

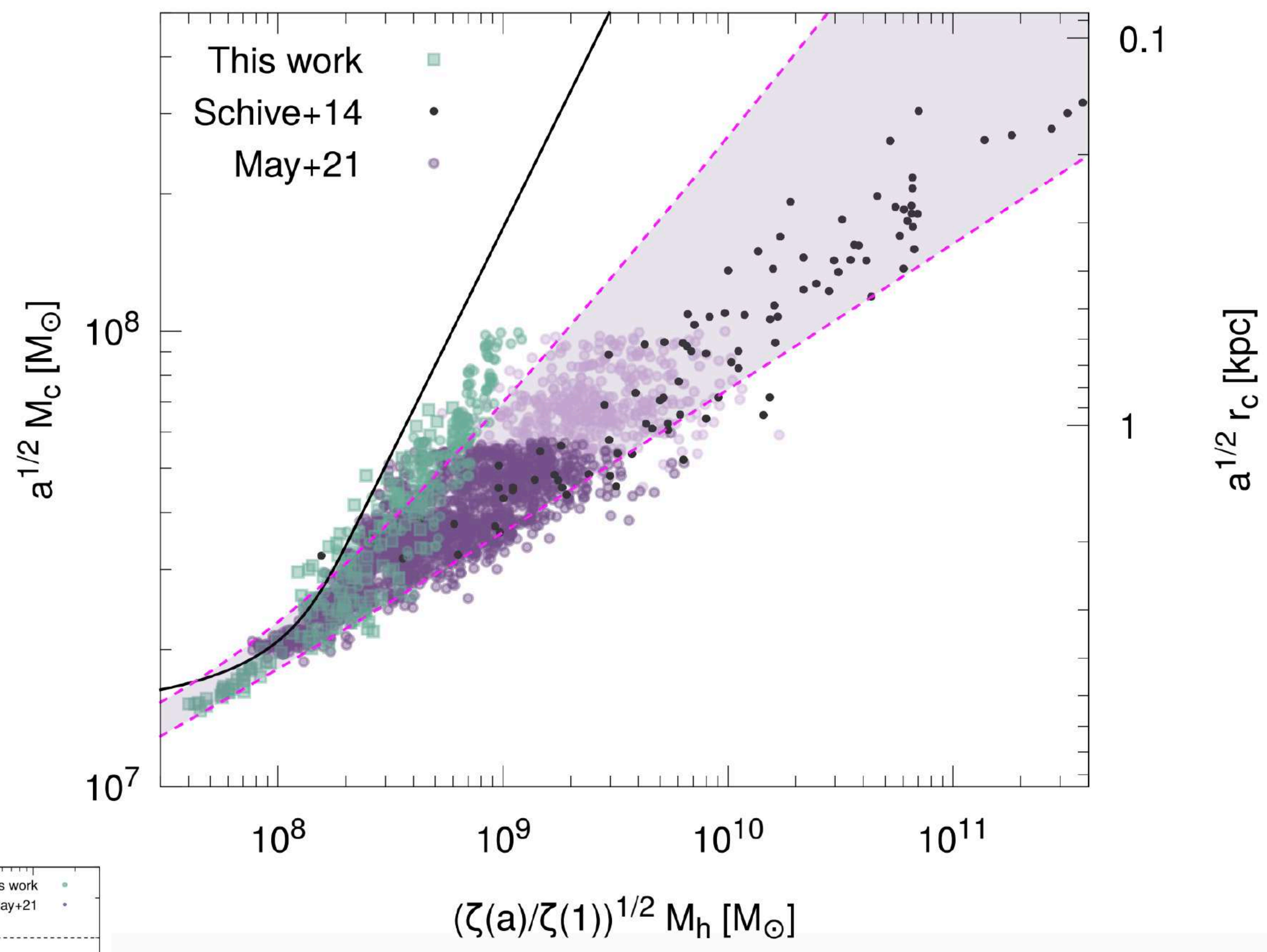
Velmatt et al 2018, Nori et al 2020, Nima et al 2020

= Schive ≠ Schive

FDM - Core-halo mass relation

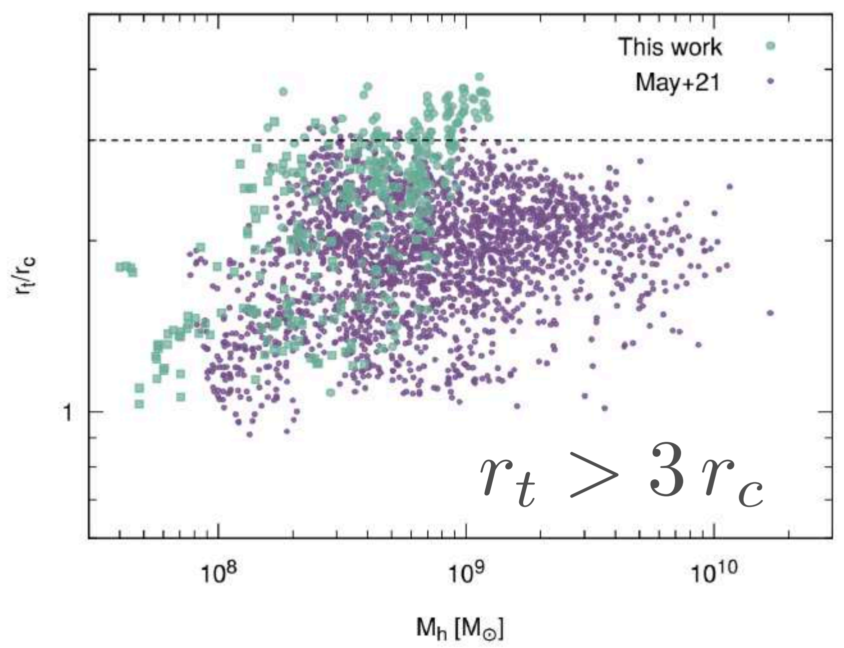
J. Chan, EF, S. May, K. Hayashi, M. Chiba 2021





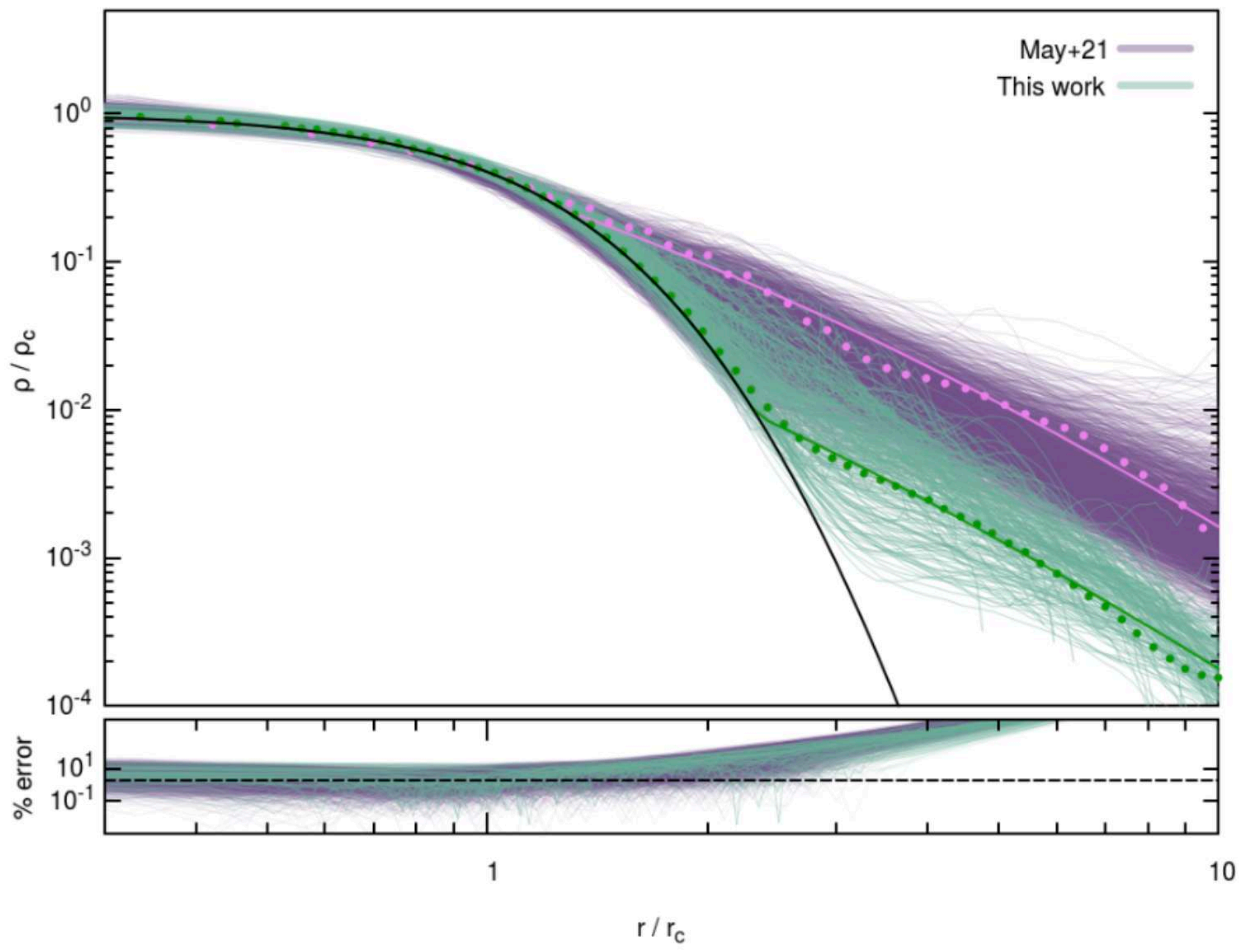
Well fitted by:

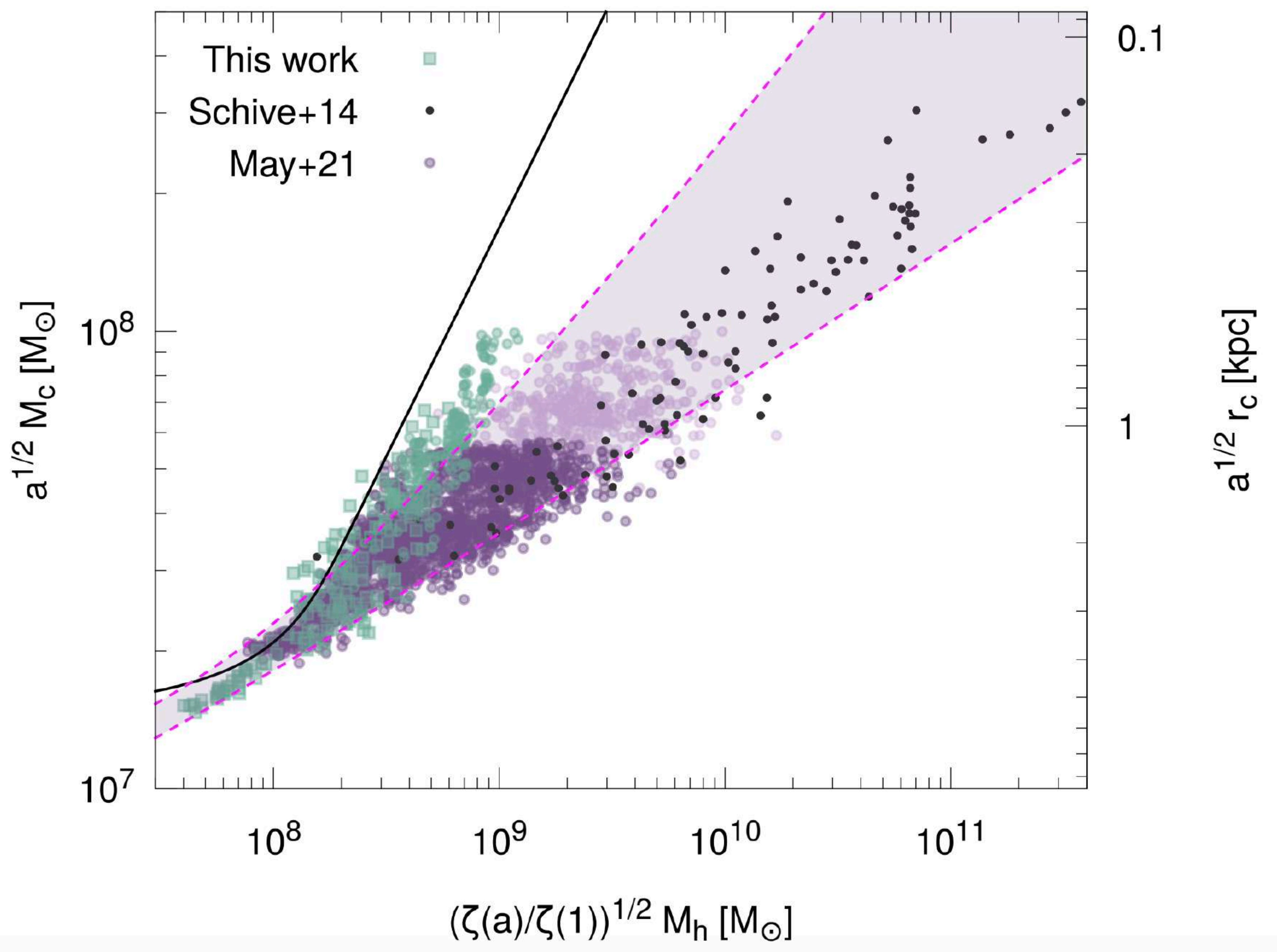
$$\rho(r) = \begin{cases} \rho_{\text{soliton}} \simeq \dfrac{\rho_c}{\left[1 + 0.091(r/r_c)^2\right]^8}, & r < r_\epsilon \\ \rho_{\text{NFW}} = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, & r > r_\epsilon \end{cases}$$



FDM - Core-halo mass relation

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

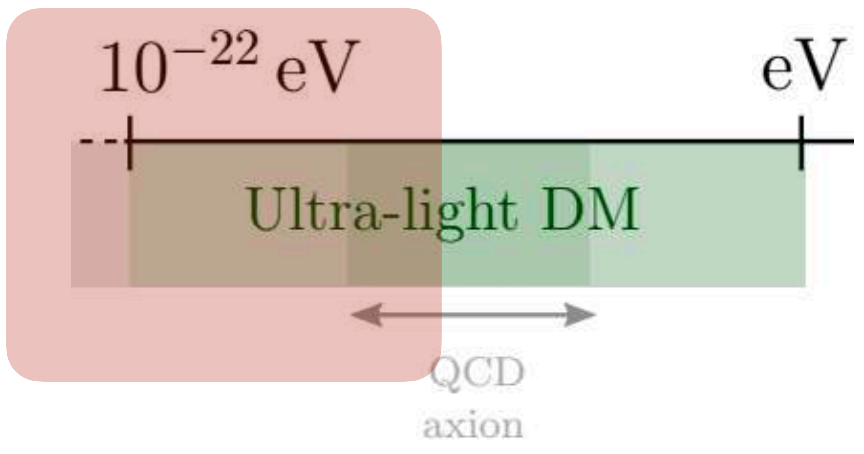




Steeper slope → Smaller core → Smaller mass

Current status

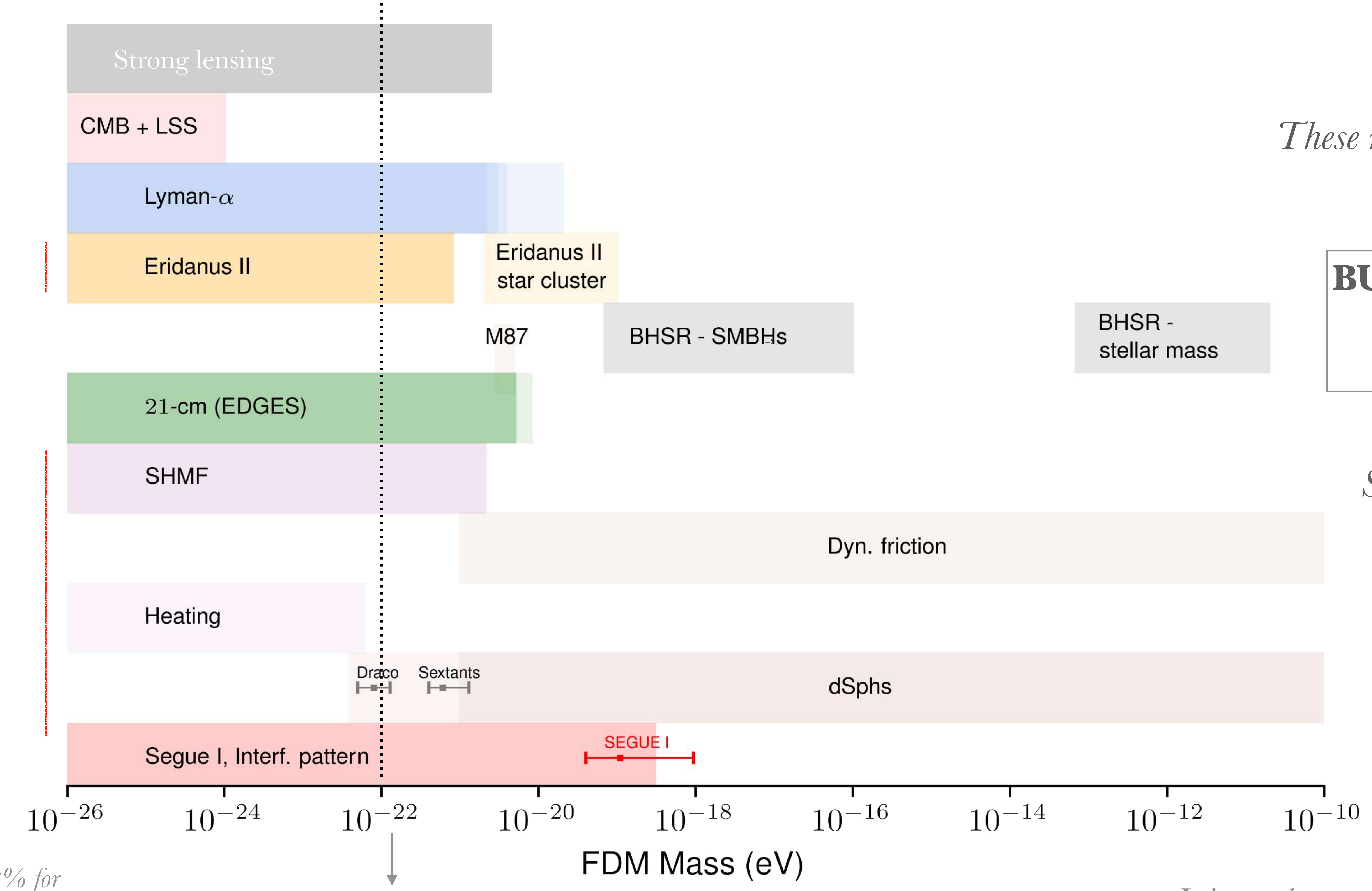
Fuzzy Dark Matter - bounds on the mass



These models can be highly constrained

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

Some bounds are incompatible!



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

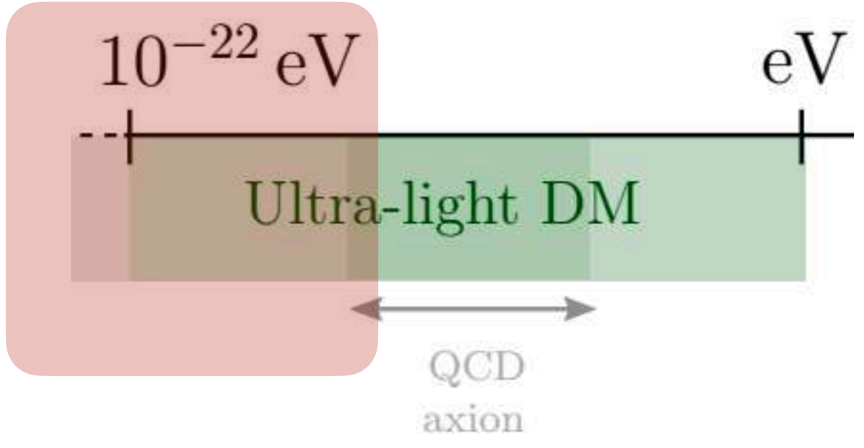
Caner et al: FDM at most 10% for
$10^{-21}\,\mathrm{eV} < m < 10^{-17}\,\mathrm{eV}$

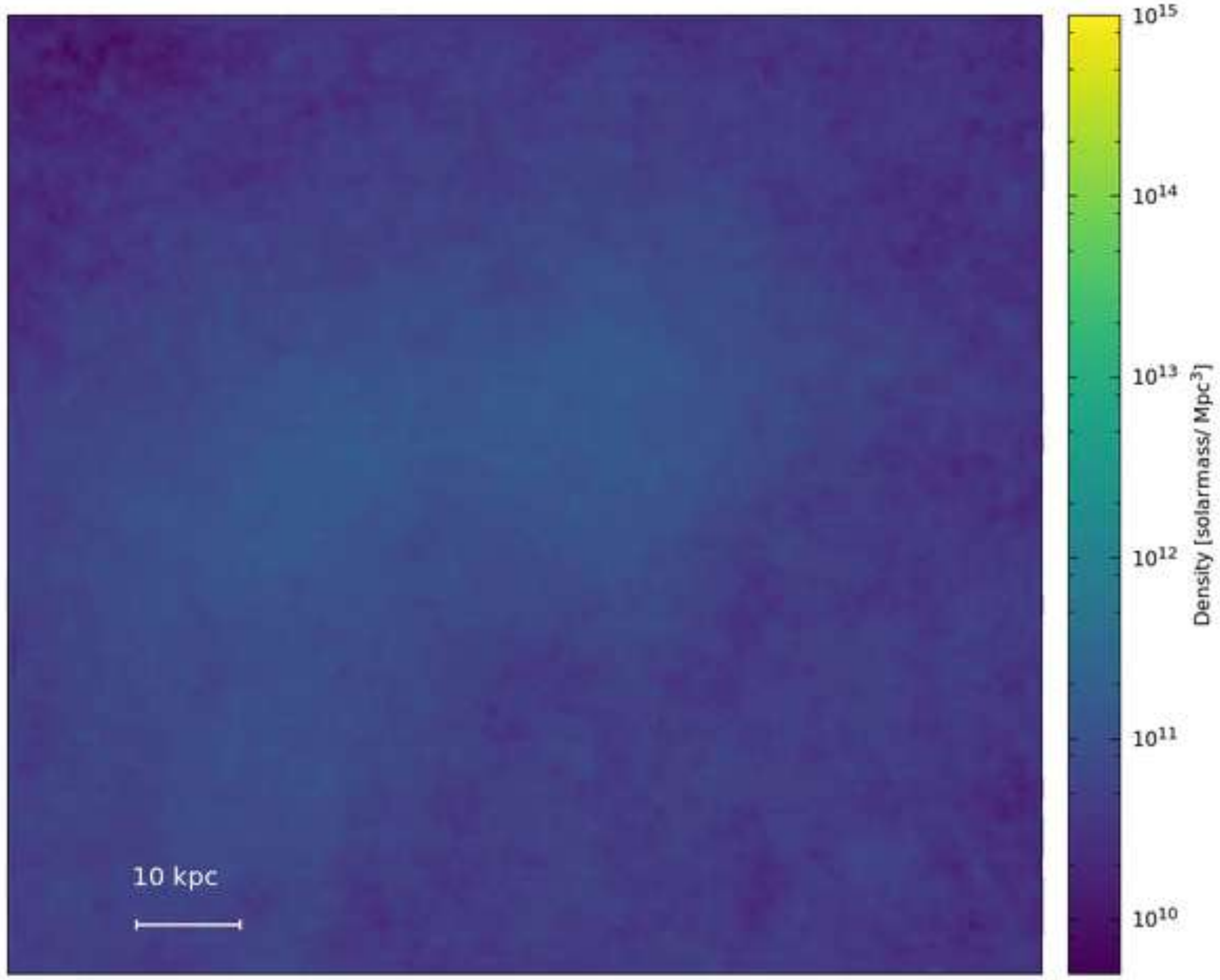
Sweet spot for solving small scale problems

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

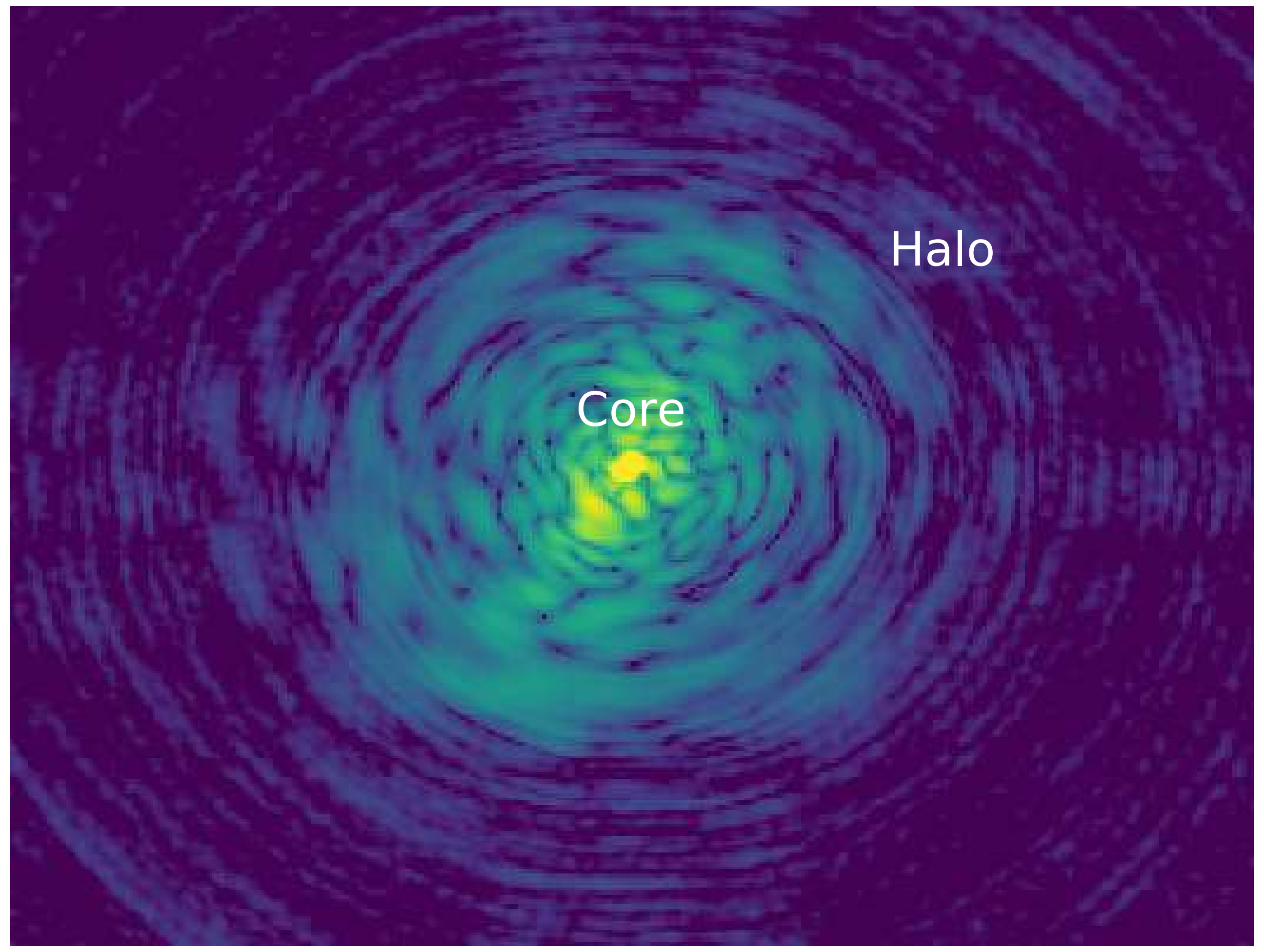
Phenomenology

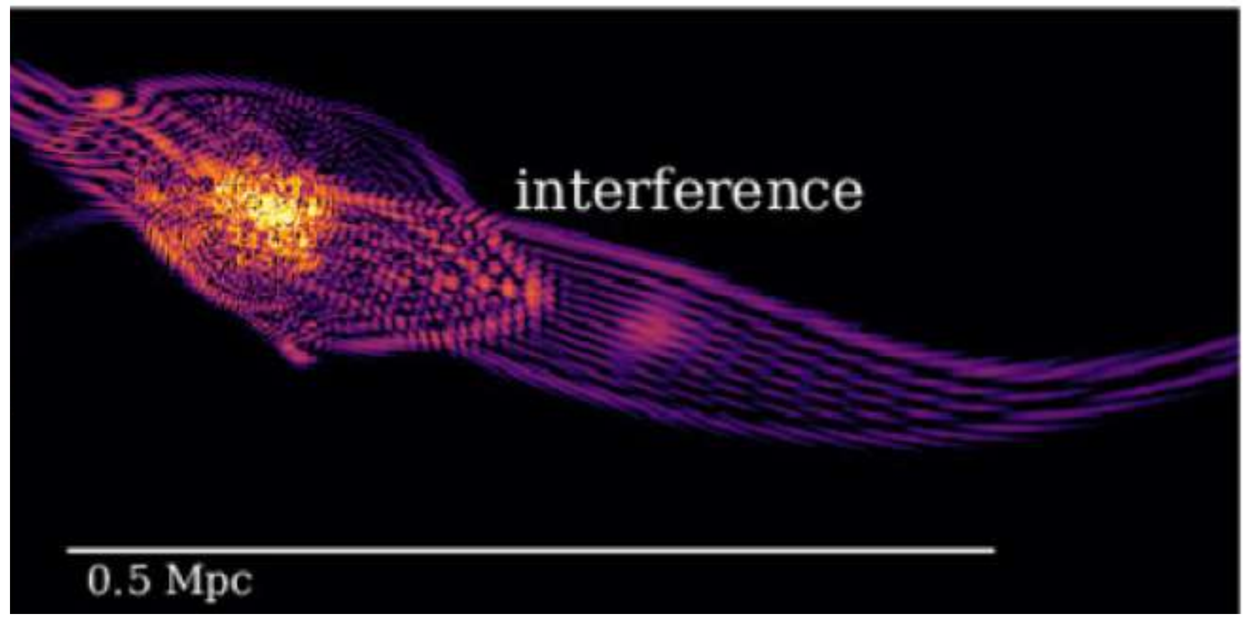
Wave interference: granules and vortices





Simulation by Jowett Chan





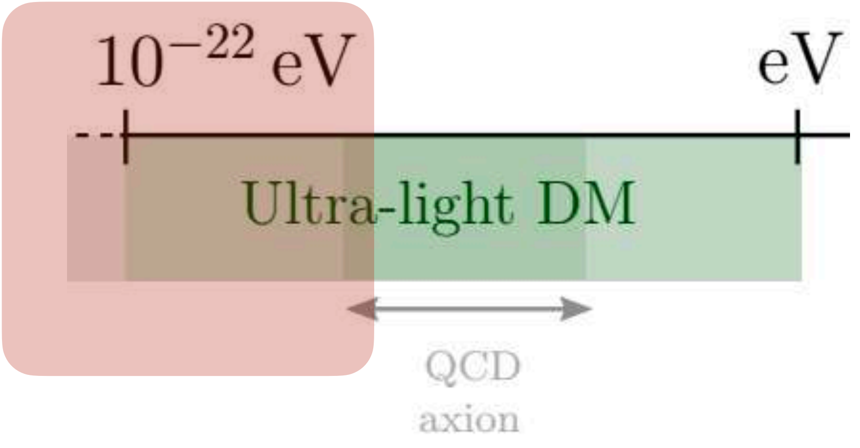
Mocz et al. 2017

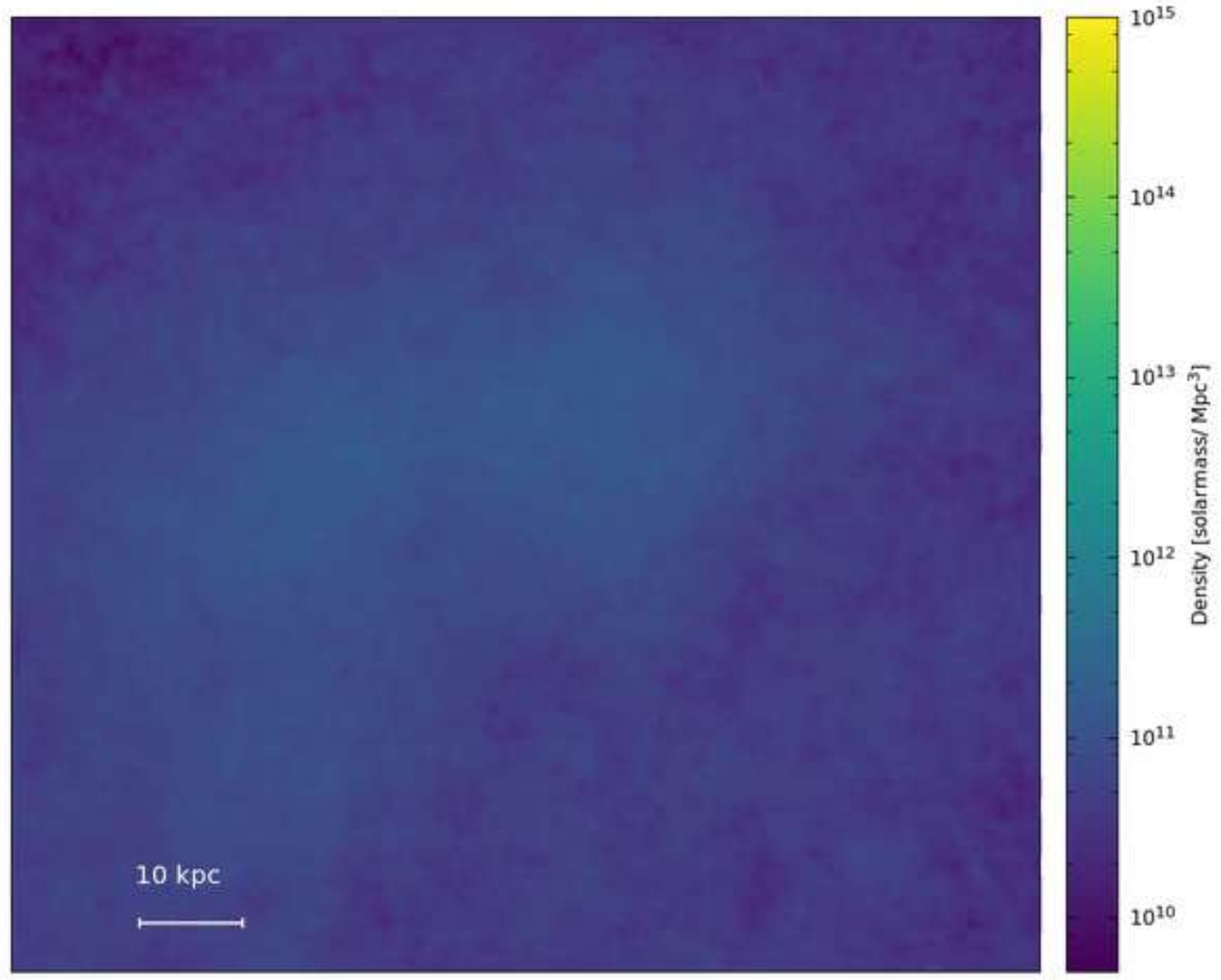
Order one fluctuations in density $\longrightarrow$ Constructive interference: granules
Destructive interference

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

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 (strong lensing, stellar streams)

ONGOING

In collaboration with Jowett Chan and Simon May

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

Previous studies:

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

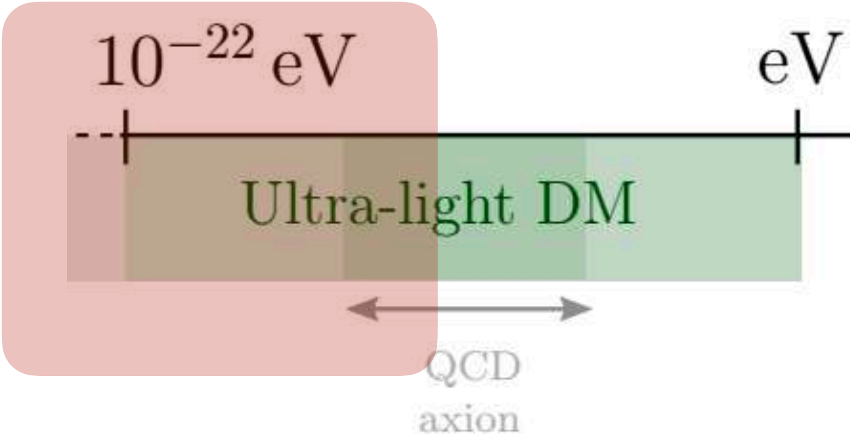
Stellar streams:
Neal Dalal, Jo Bovy Lam Hui, Xinyu Li, 2020

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

Sub-galactic power spectrum
Kawai, Oguri (2021)

Dwarfs
N. Dalal, A. Kravtsov, 2022

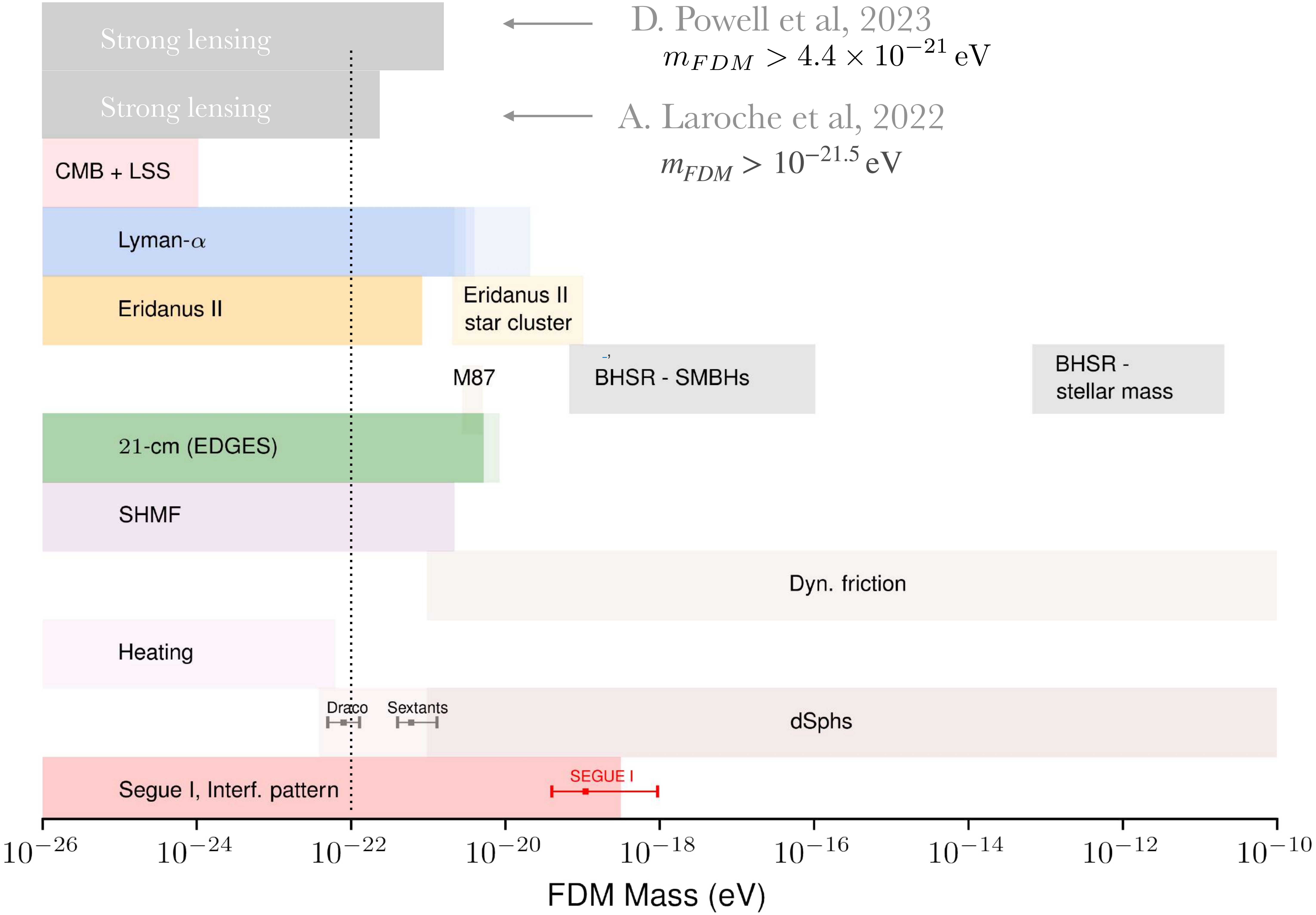
Interference patterns - granules



Strong lensing

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

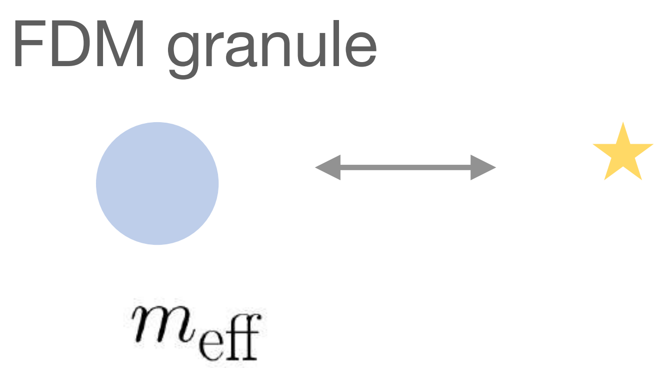
A. Laroche et al, 2022
$m_{FDM} > 10^{-21.5}$ eV



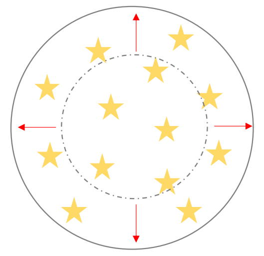
Stellar heating

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

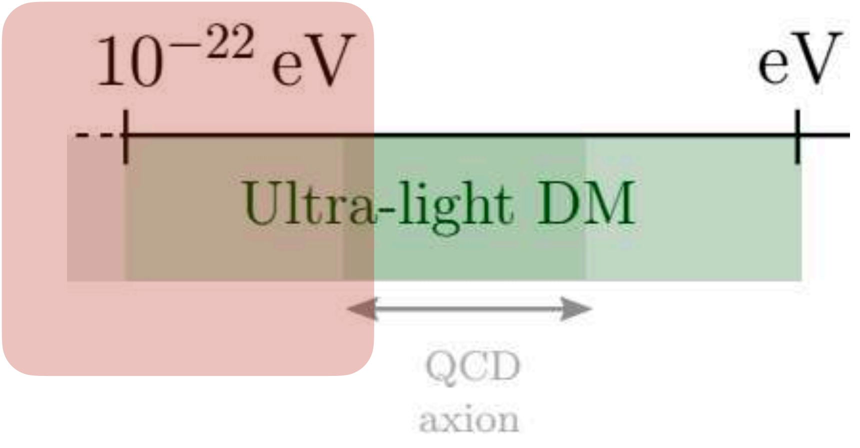
Heating



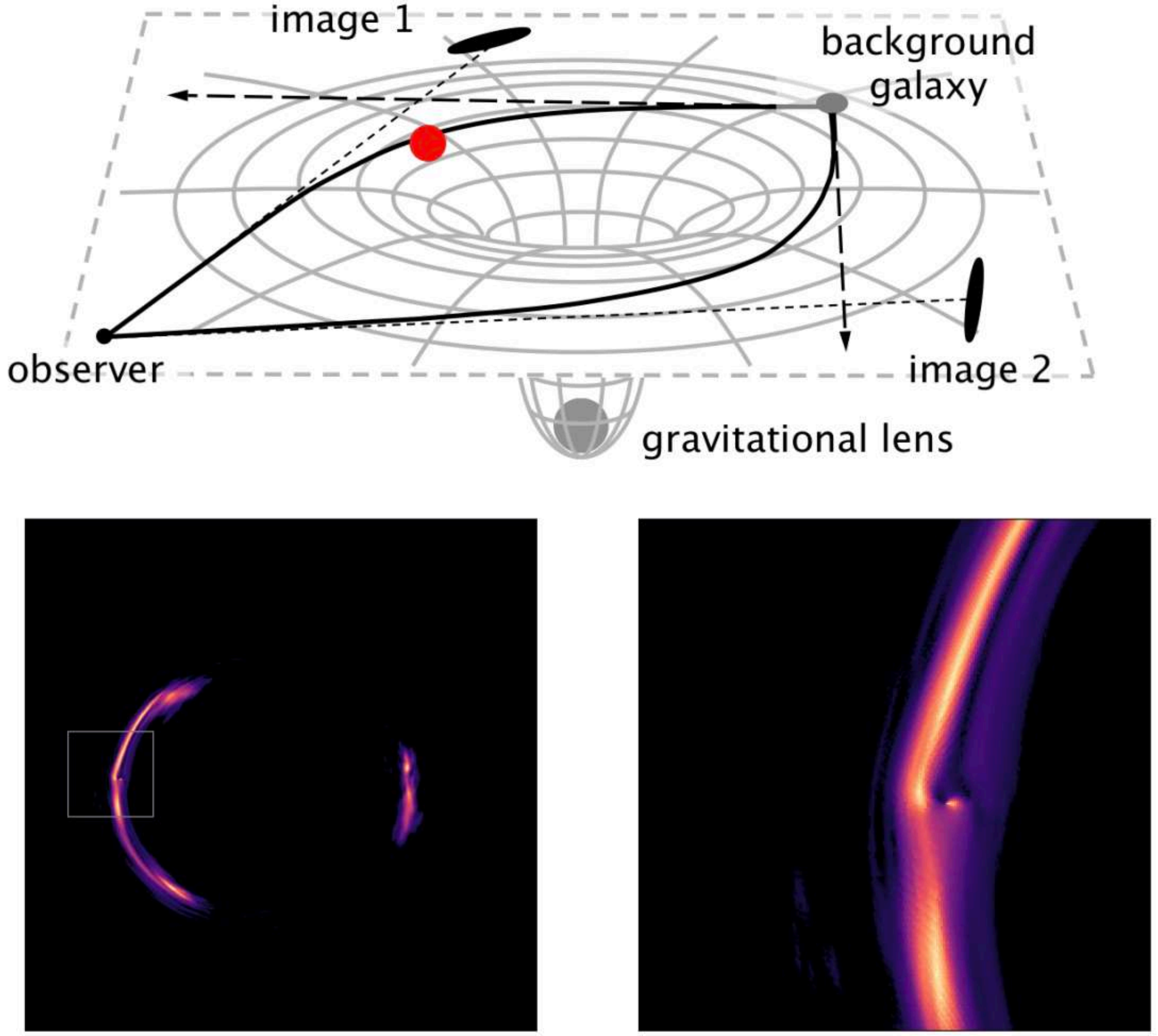
System (star) gains energy



Strong lensing

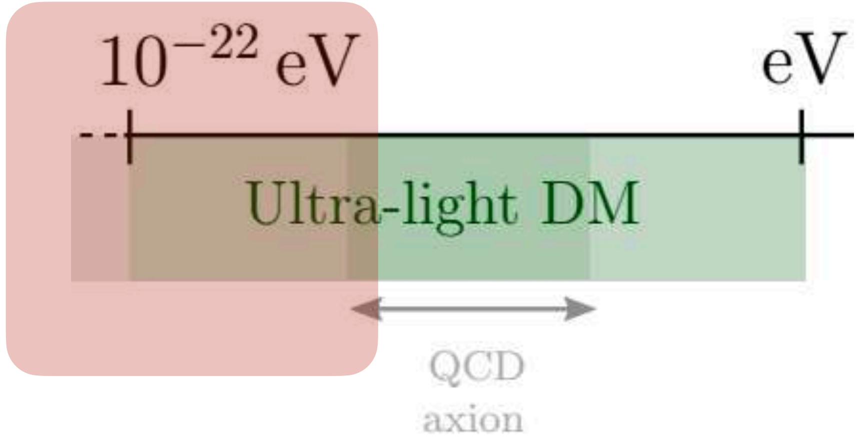


Low mass perturber with lensing

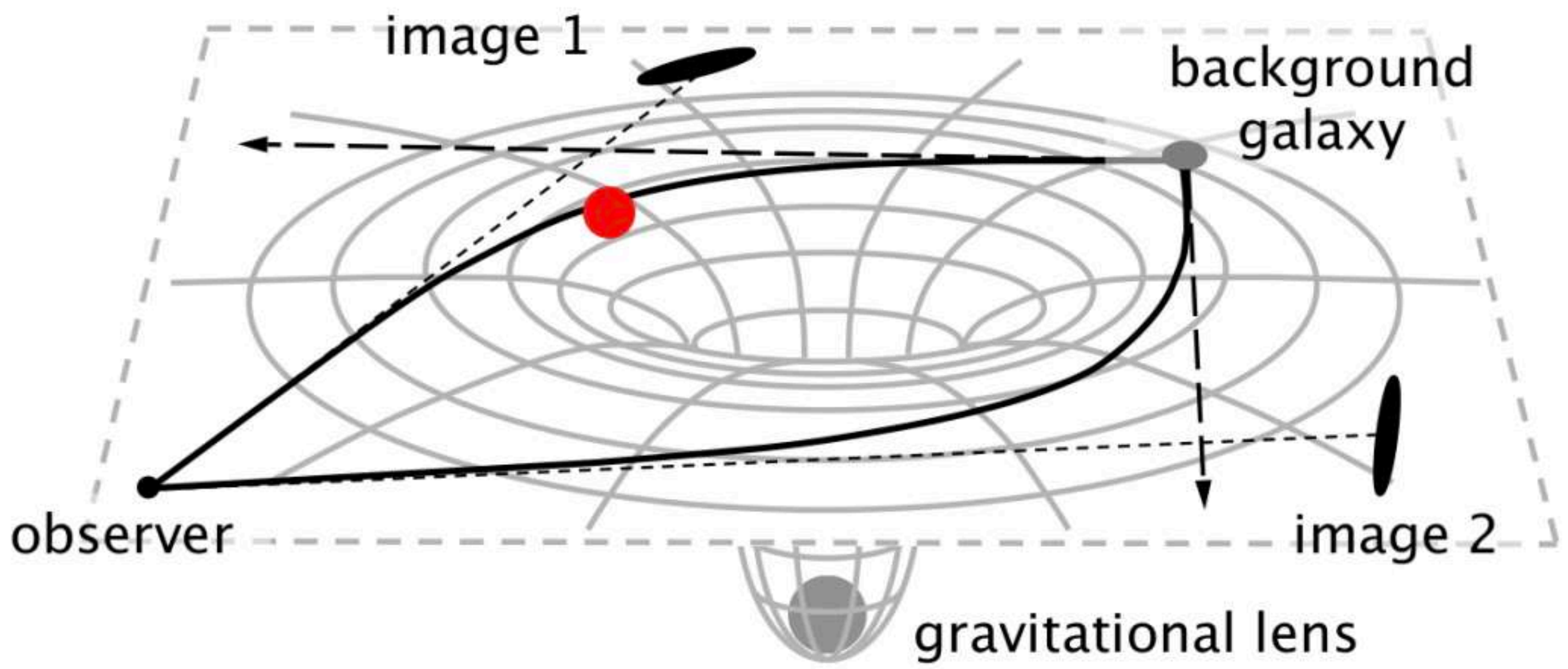


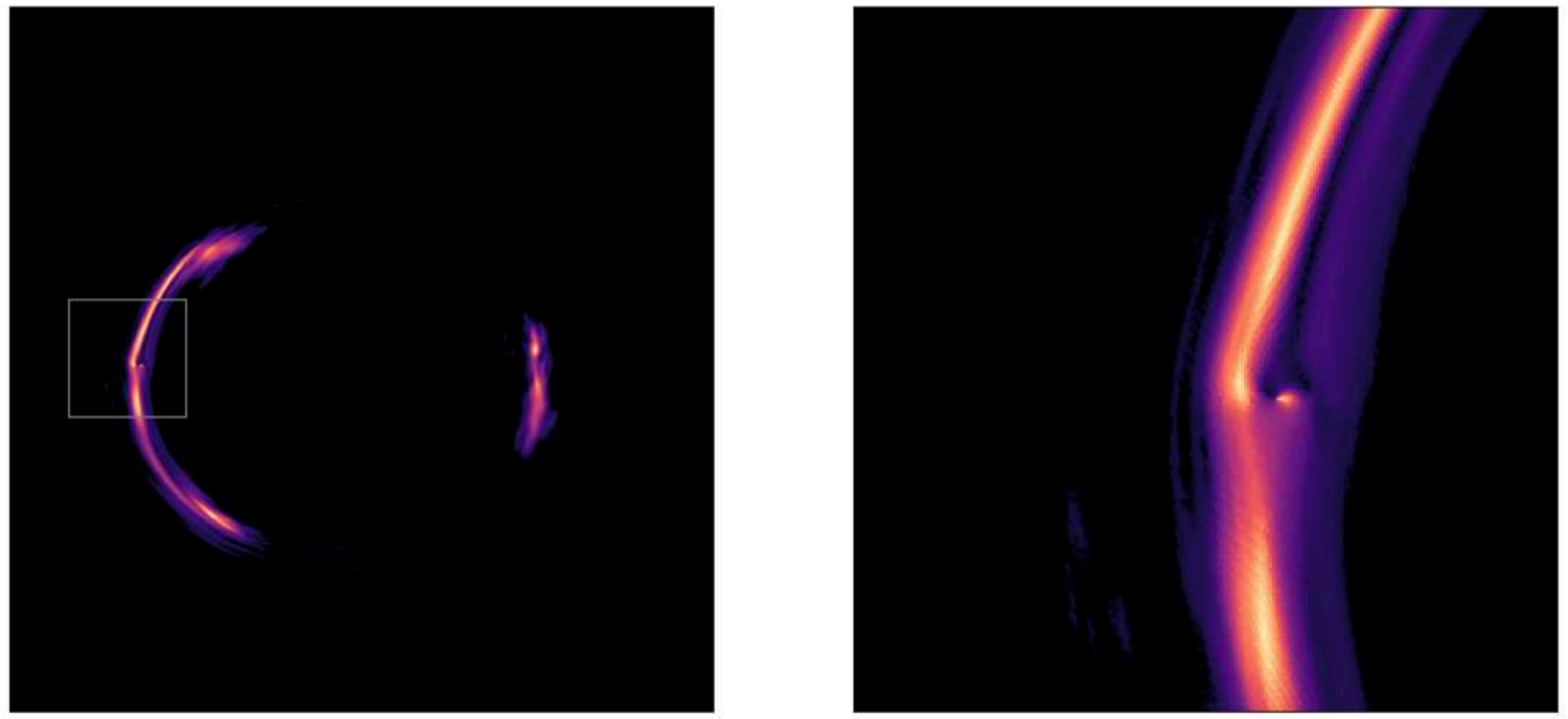
- Strong lensing: powerful probe of substructure
- Sensitivity is limited by angular angular resolution
- Roughly speaking, the resolution must be better than the scale radius of the perturber

Strong lensing



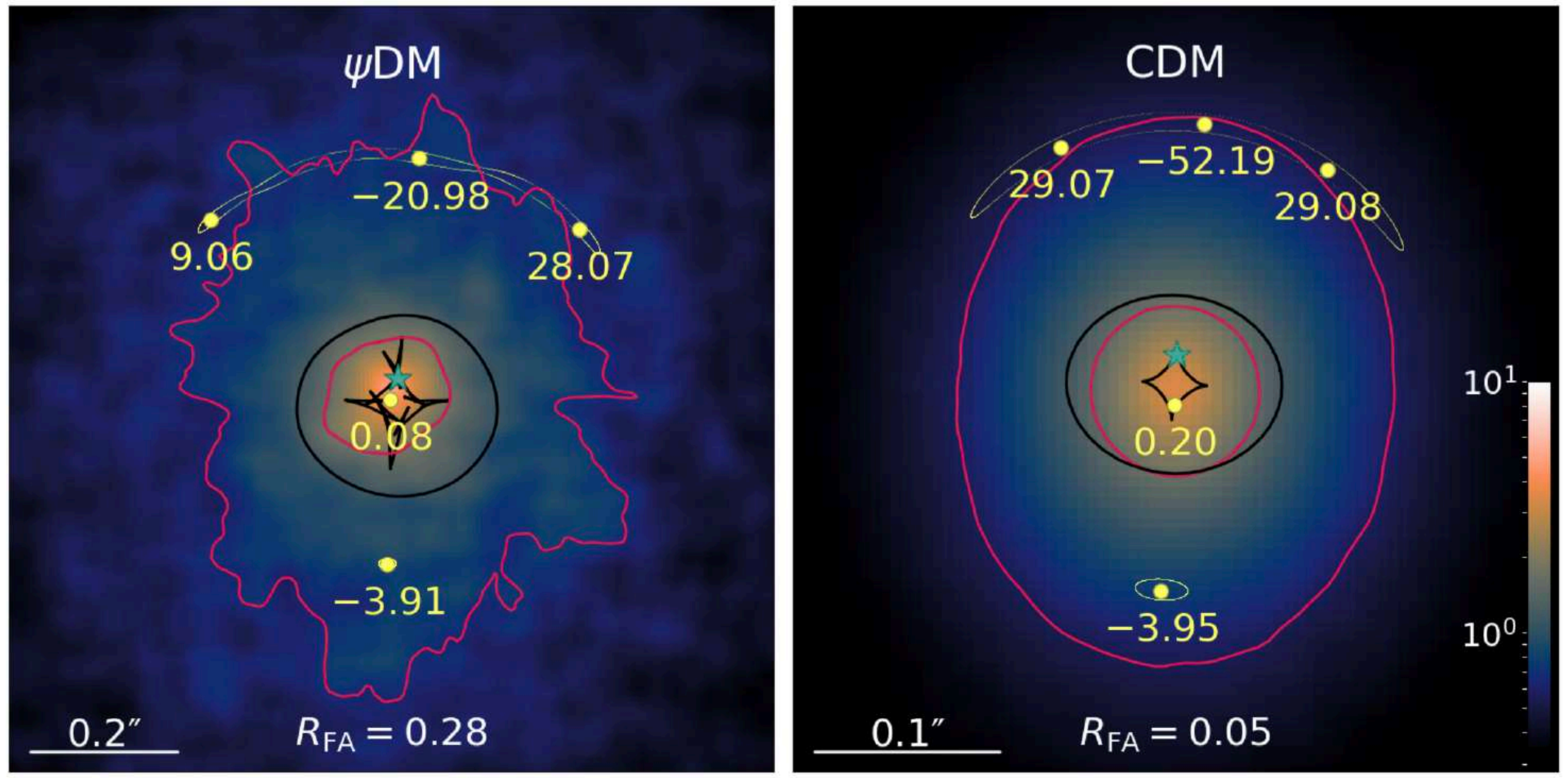
Low mass perturber with lensing





Presence of granules

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



J. Chan et al. 2020

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

Previous works:

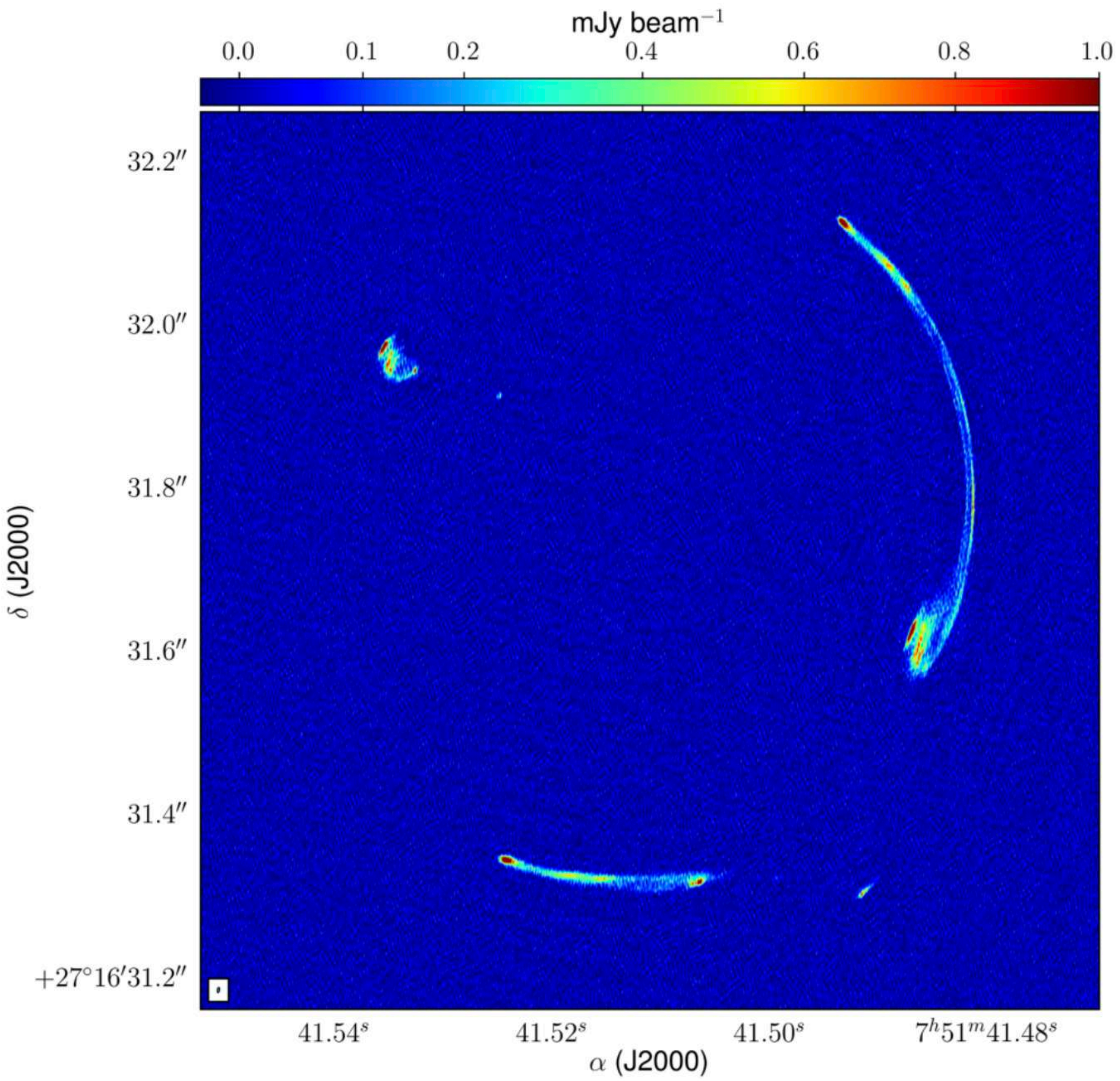
J. Chan, H.Schive, S.g Wong, T. Chiueh, T. Broadhurst, 2020

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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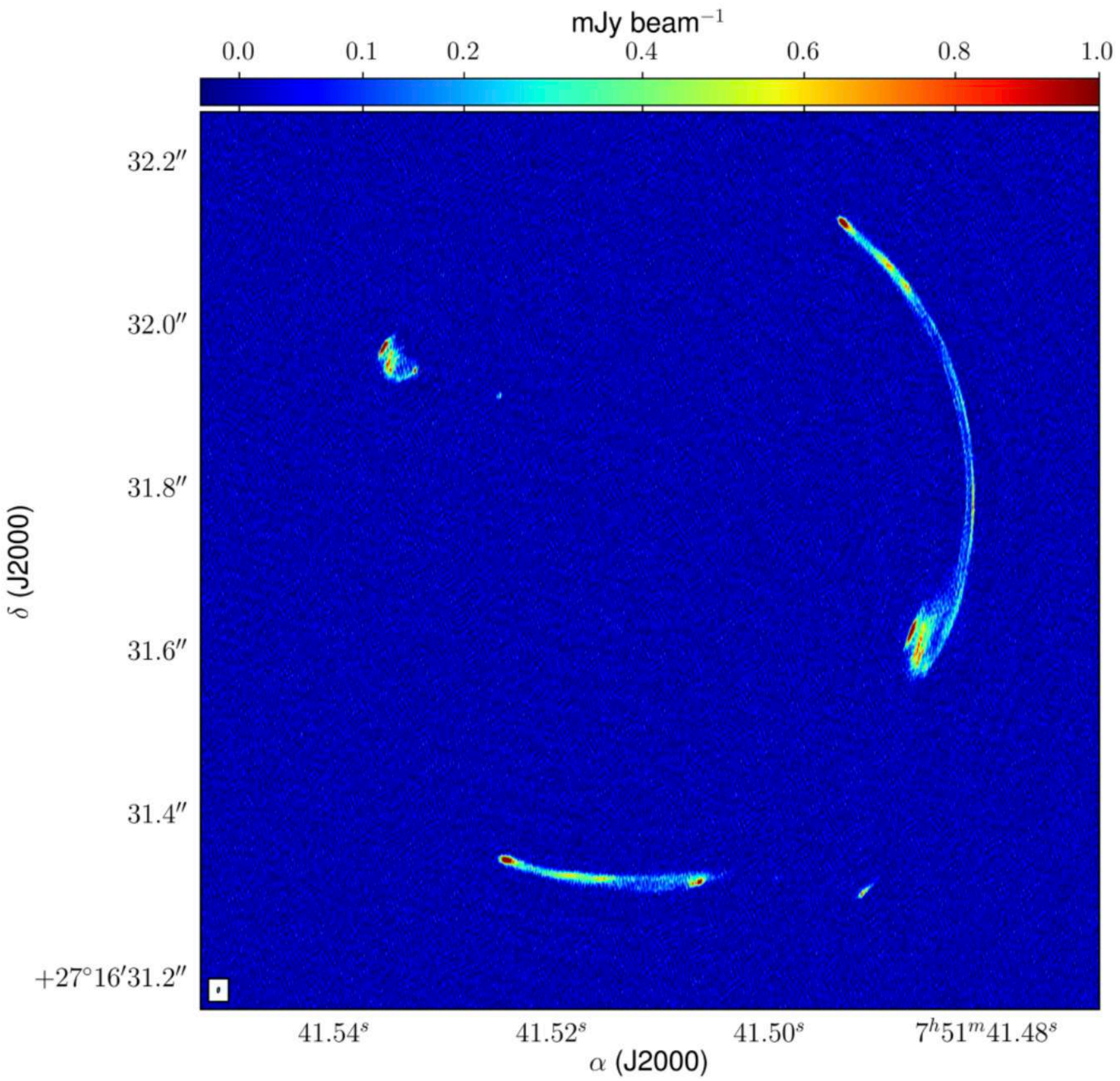

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Bayesian approach to jointly inferring the lens mass model and source surface brightness distribution

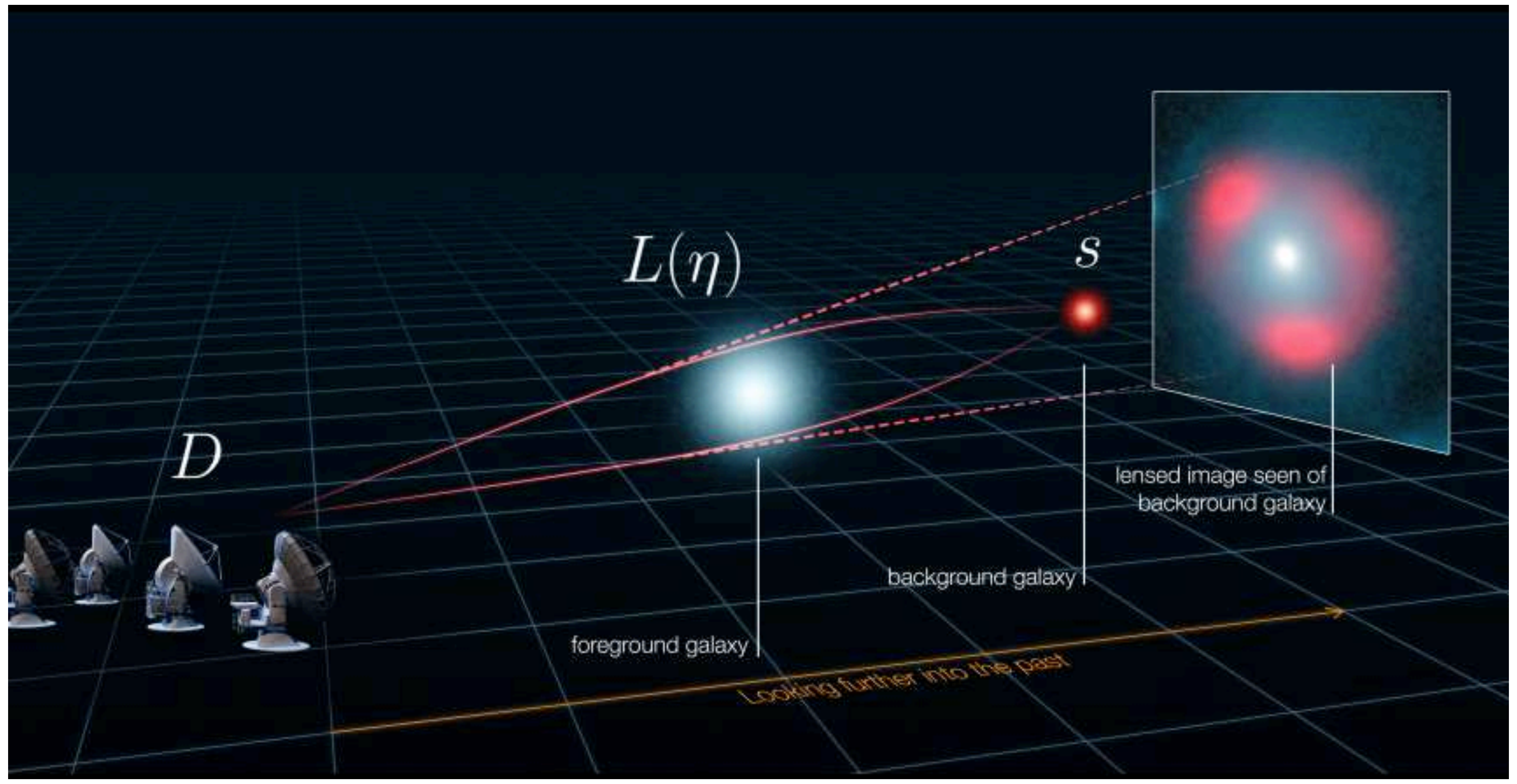
(Suyu et al. 2006; Vegetti & Koopmans 2009; Hezaveh et al. 2016; Rizzo et al. 2018)

Strong *lensing*

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

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

Forward modeling



Instrumental response

source

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

Lens operator

Smooth lens model

Potential perturbations

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

Smooth lensing model: from Powell et al 2022

FDM granules:

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

$\delta\psi(m_{fdm}, f_{dm}, \sigma_v)$ - is the perturbation of the lensing potential - fluctuations in the projected surface mass density written as perturbations in the lensing convergence due to the presence of the granules:

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

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

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

Strong lensing

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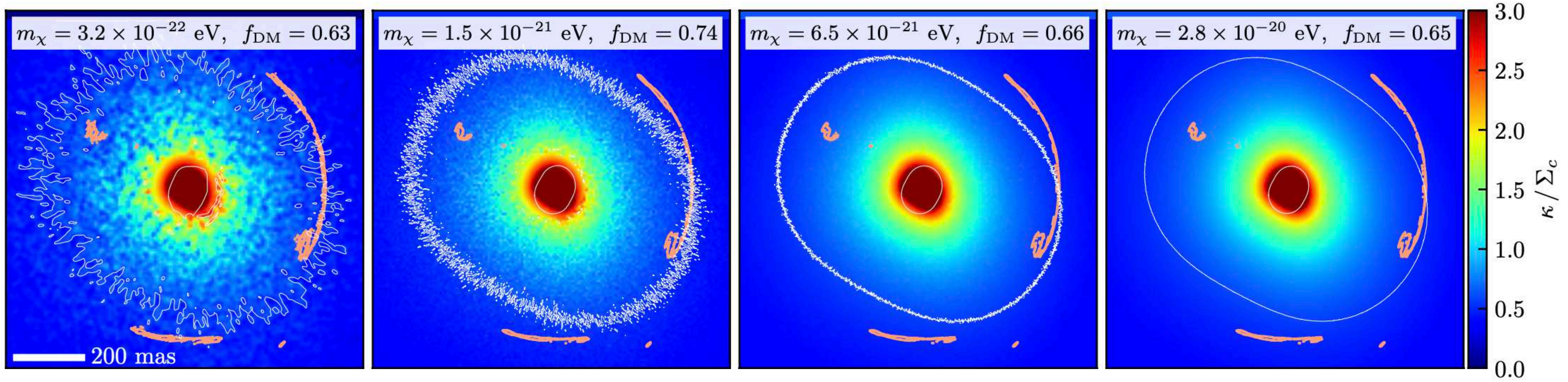
Example convergence maps with corresponding MAP surface mass density maps (κ, in units of the critical density Σc) reconstruction for 4 random realizations of MG J0751+2716 in an FDM cosmology - the model lensed images in orange contours



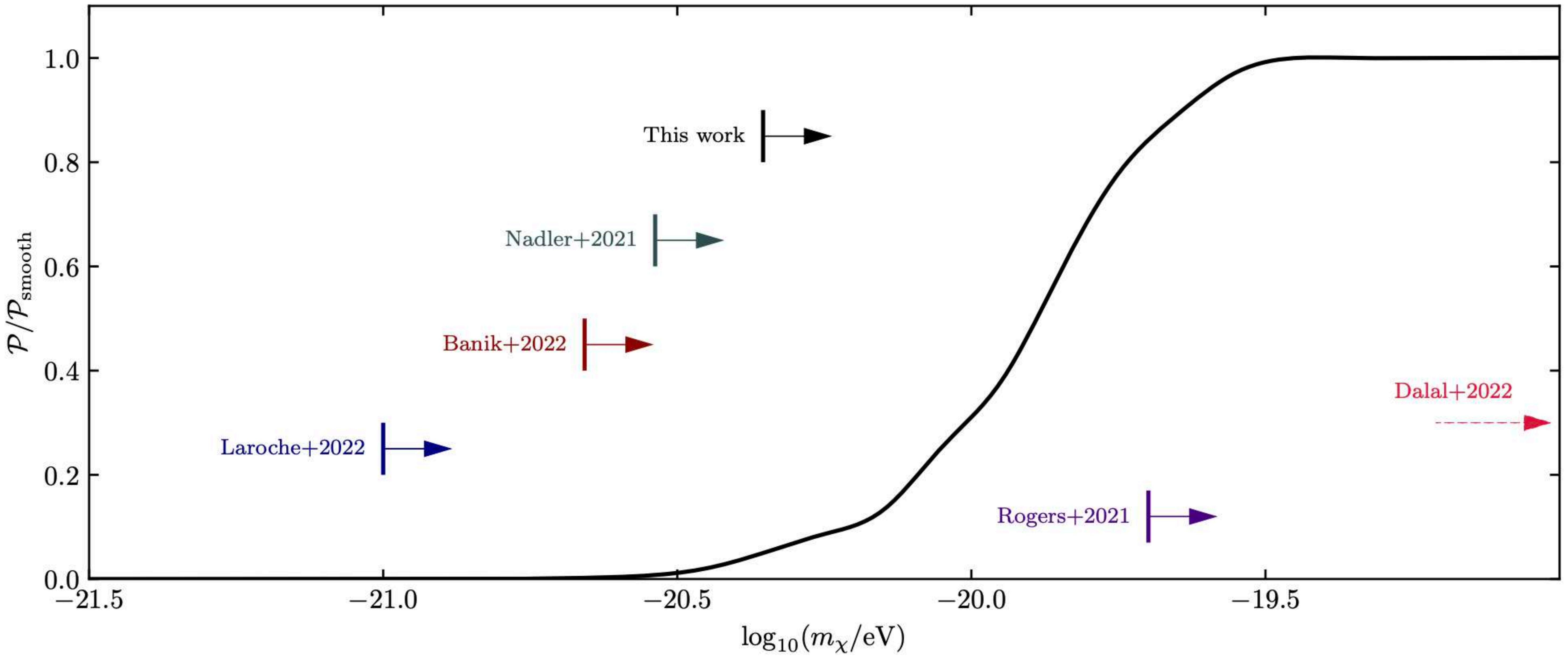
The lensing effect of the FDM granules is apparent: The critical curves wiggle back and forth across the lensed arcs, which would require the presence of multiple images of the same region of the source along the arc.

Strong *lensing*

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

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

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



Fuzzy dark matter
(Single spin-0 particle)

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

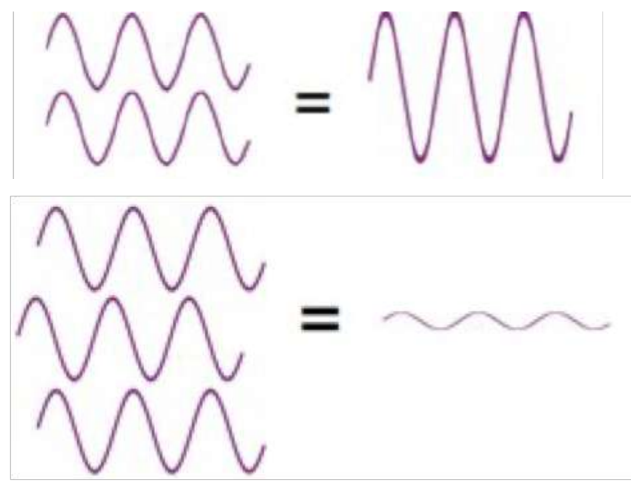
$m_{\rm spin-2} > 8.8 \times 10^{-22}$ eV

Vector, higher spin or multicomponent FDM

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

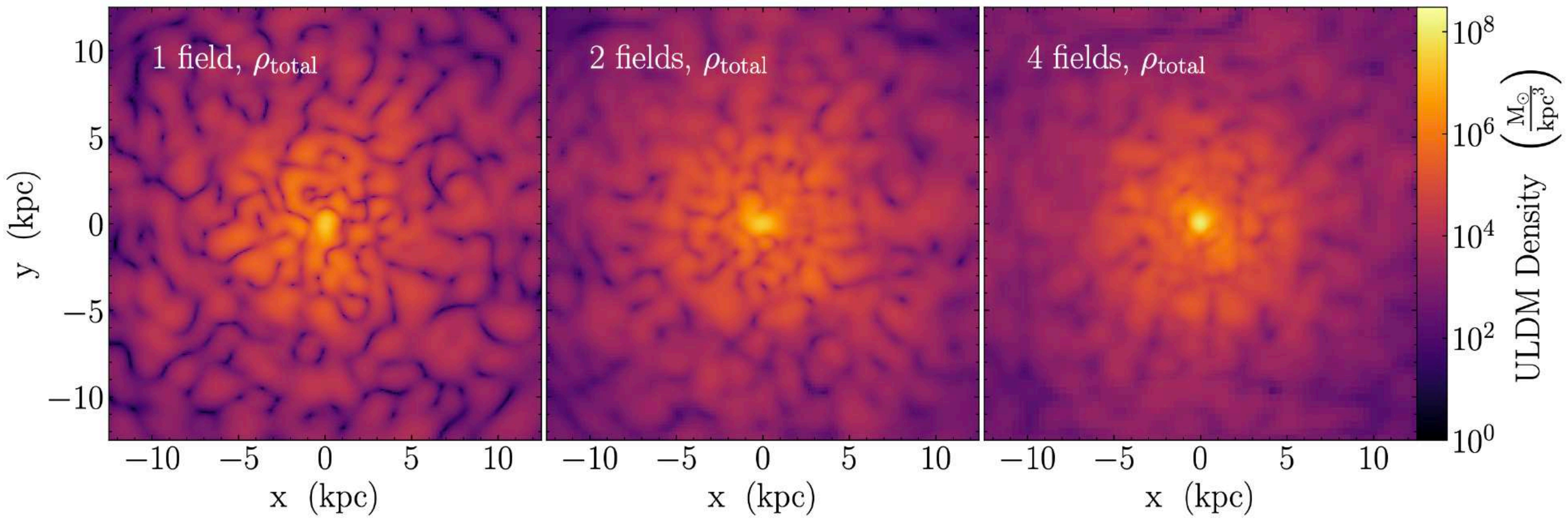
Multiple coherent waves

Interference patterns



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

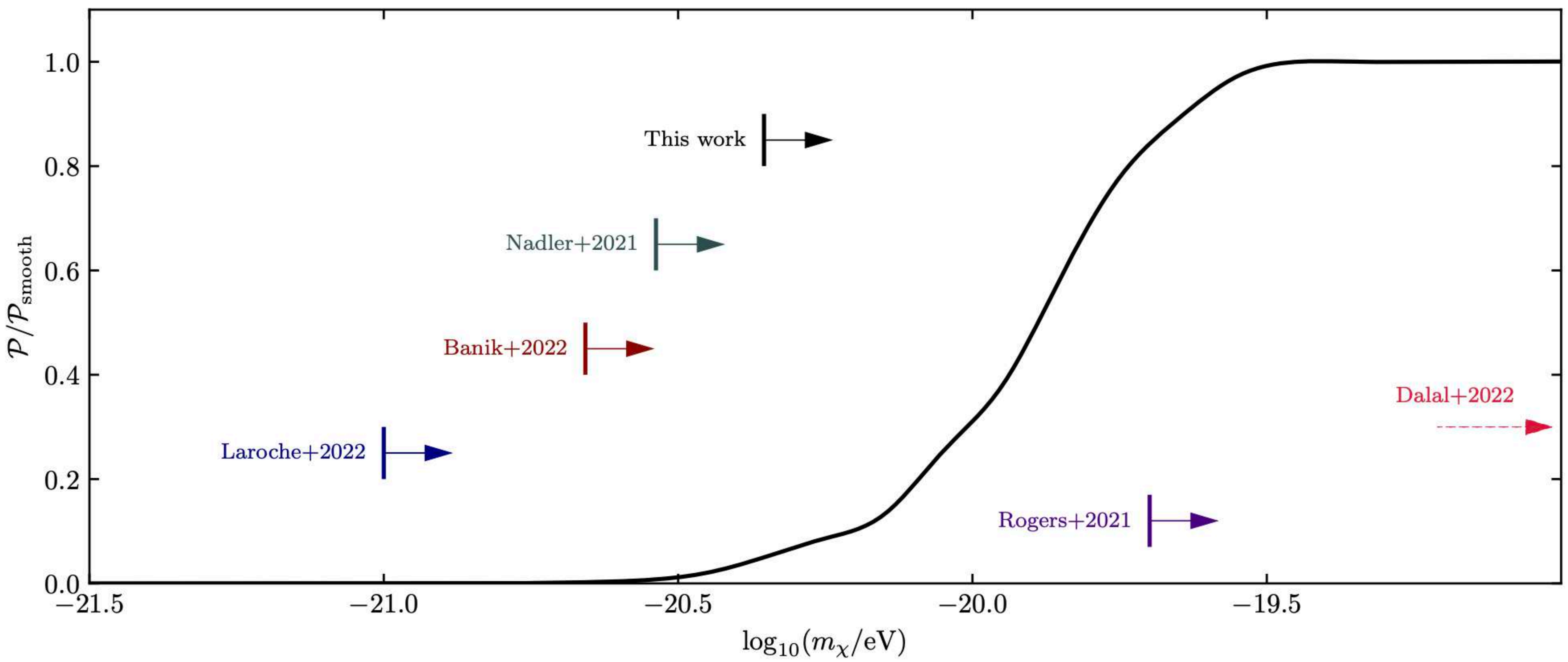
(Vector FDM = 3 x same mass FDM (spin 0))

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



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)

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

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

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

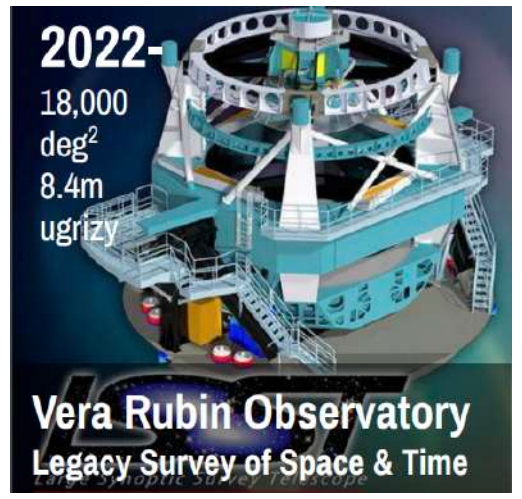
Spin-2 FDM

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

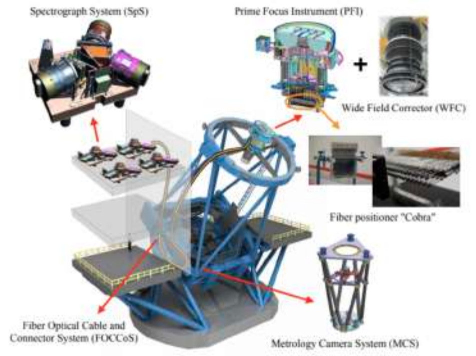
Improving these bounds

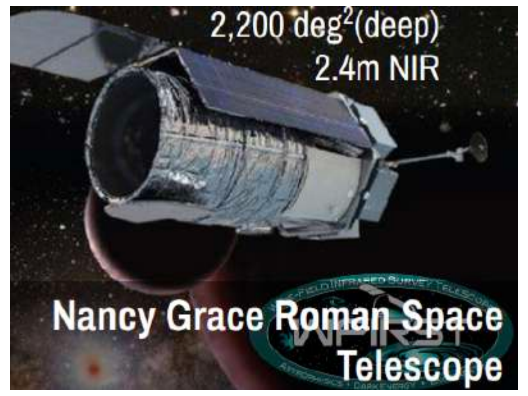
Observations

Photometric and spectroscopic surveys



Prime Focus Spectrograph (PFS)





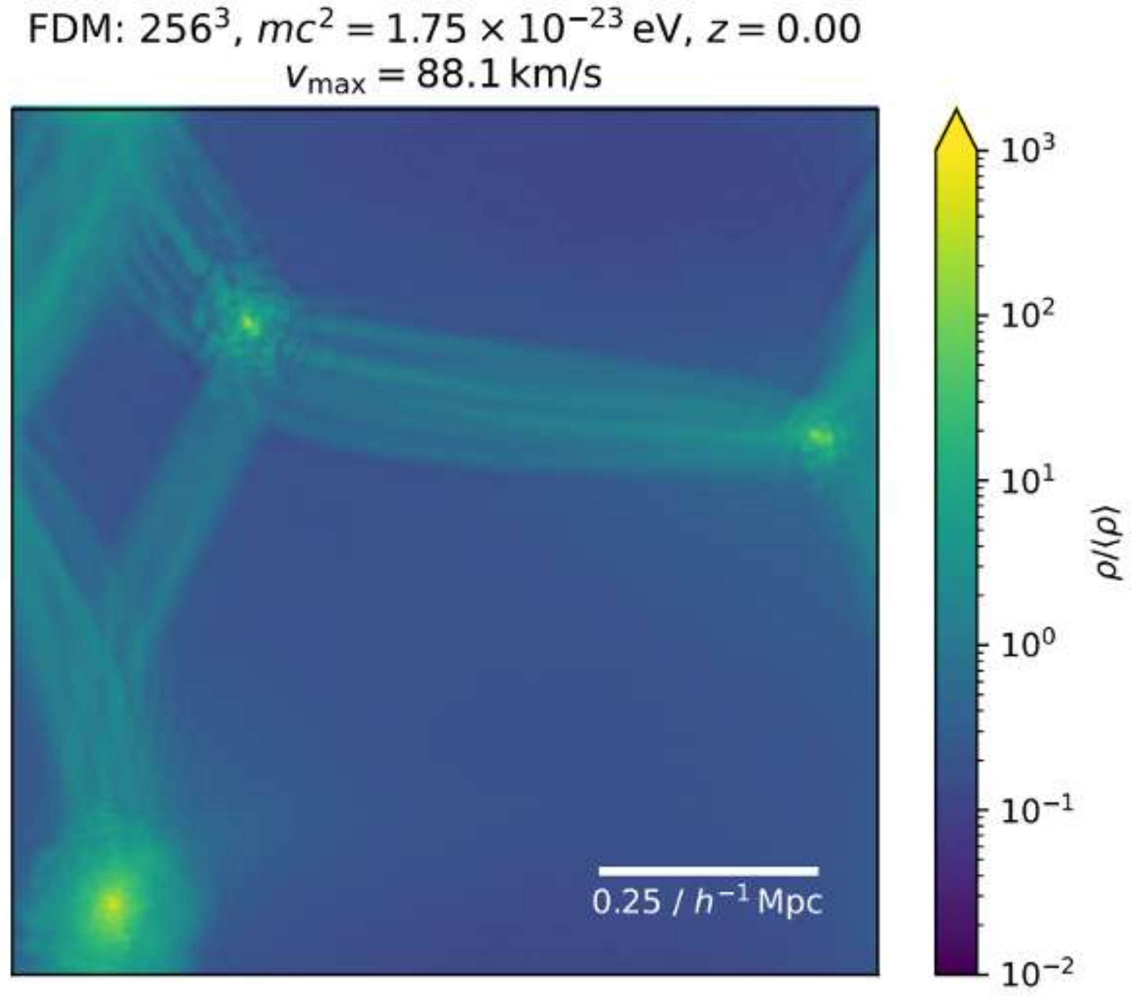
CMB

CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New observables

New probes

Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Modified from Jia Liu

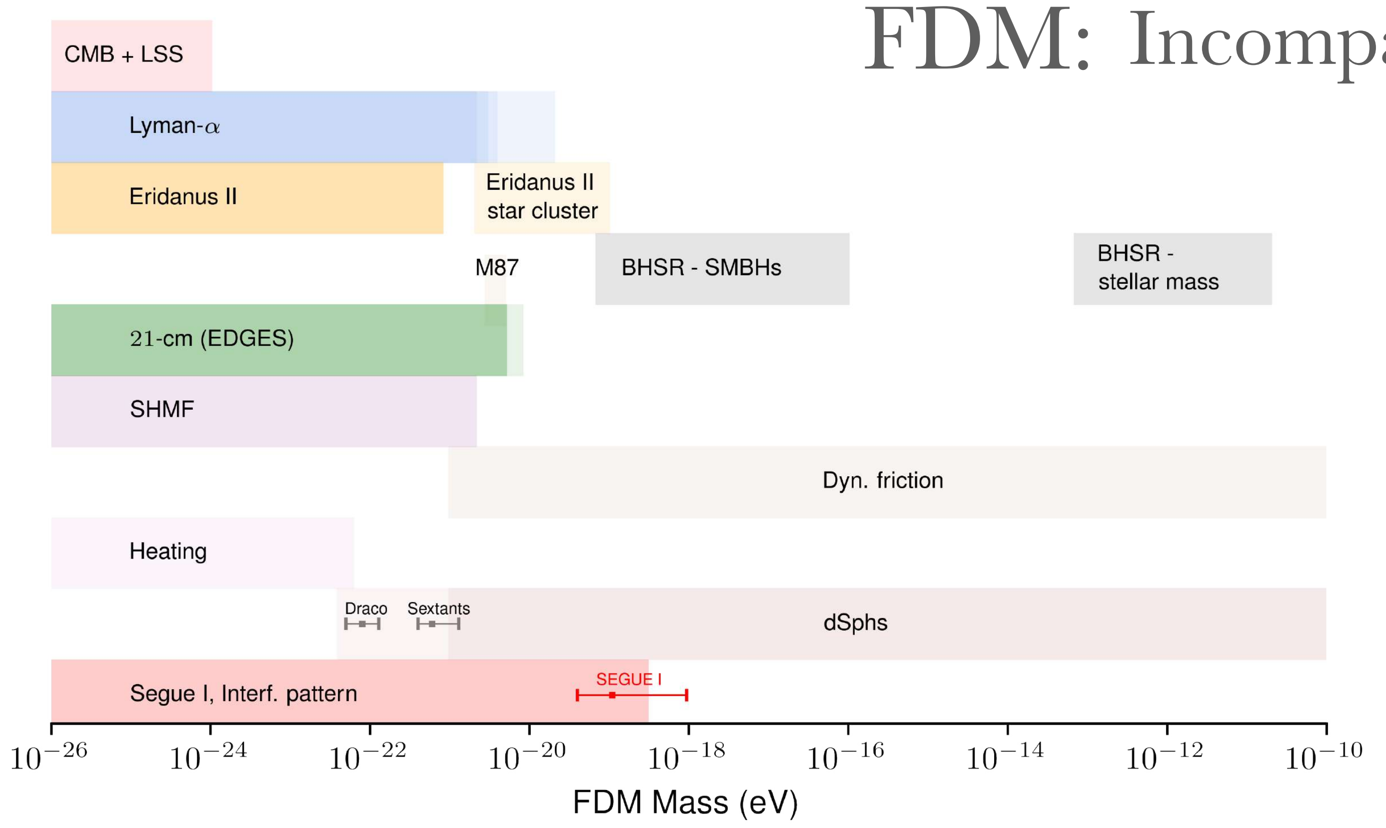
Summary

Ultra-Light Dark Matter

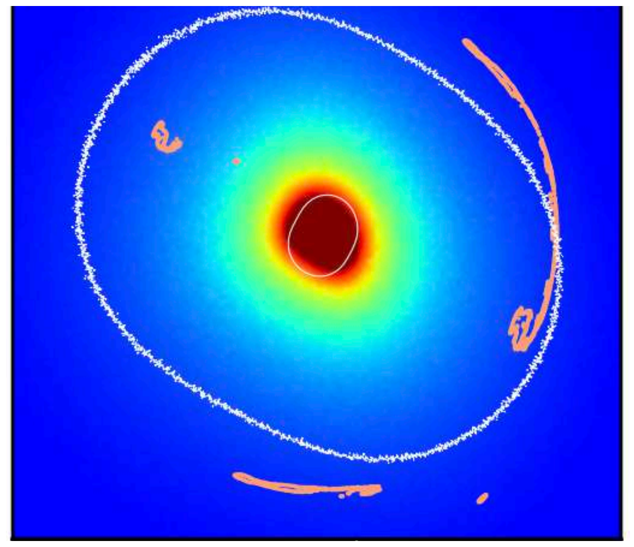
Well motivated DM models
Rich and distinct phenomenology on small scales
Testable prediction

Current status

FDM: Incompatibilities!



Granules



Strong lensing:

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

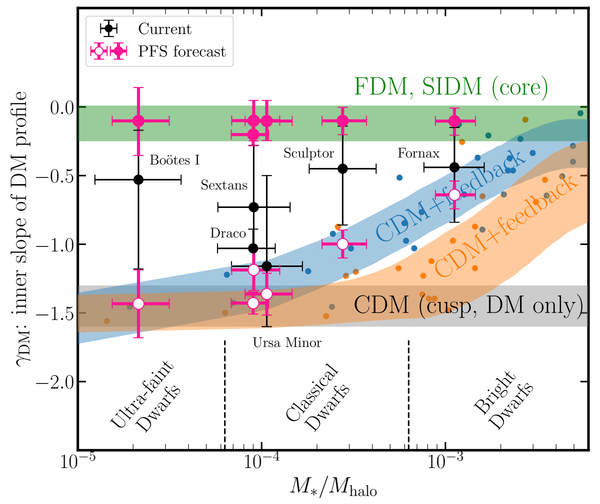
$$m_{\rm vdm} > 1.4 \times 10^{-21}\,{\rm eV}$$

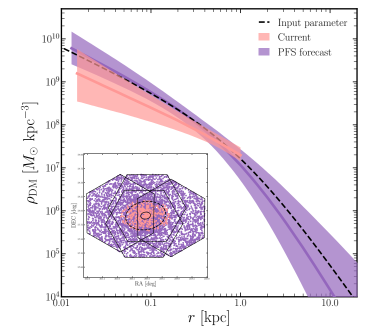
Heating: $m_{FDM} > 3 \times 10^{-19}\,{\rm eV}$

Future

Observations

PFS





Improve in simulations
New probes/observables