Ultra-light dark matter:

the light and fuzzy side of dark matter

Elisa G. M. Ferreira

Kavli IPMU & University of Sao Paulo

Cosmology from Home 2022

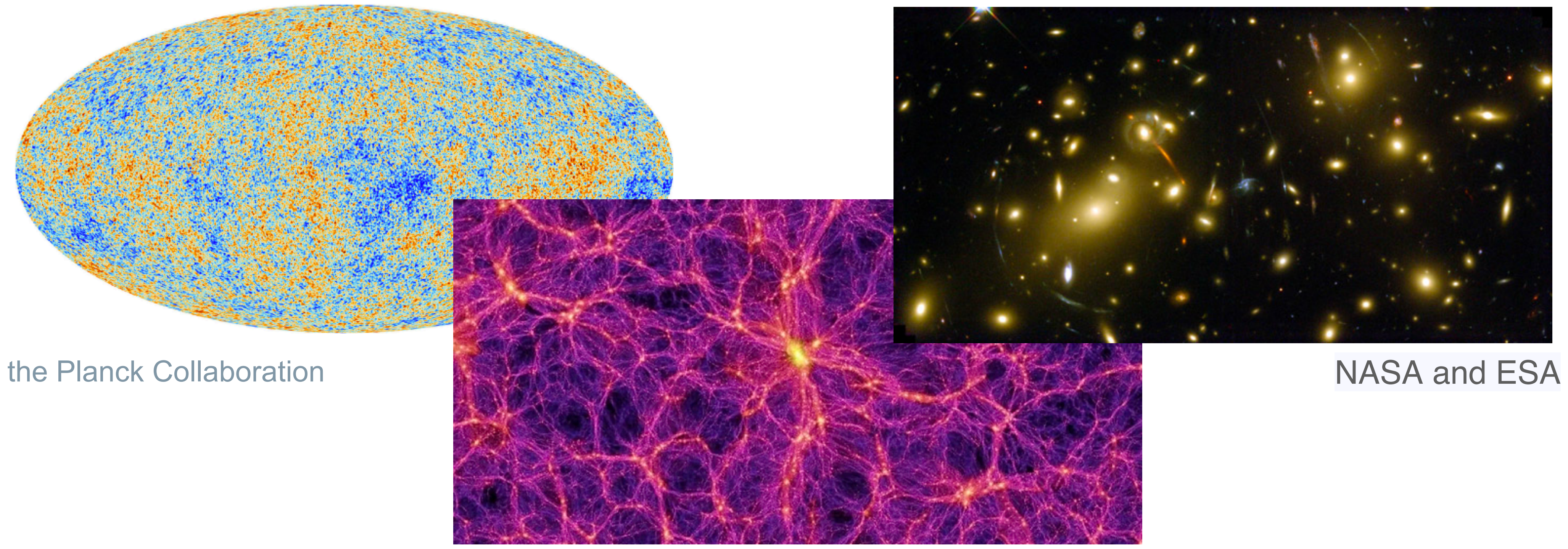
Evidences for dark matter

We can observe its effects in

Galaxies

NASA and ESA

CMB+LSS

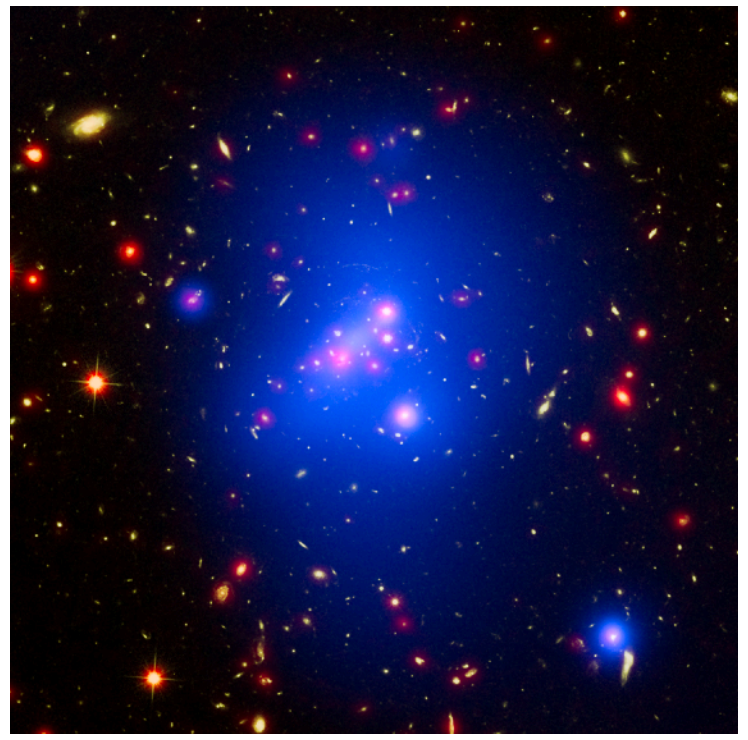


ESA and the Planck Collaboration

NASA and ESA

Springel & others / Virgo Consortium

Clusters

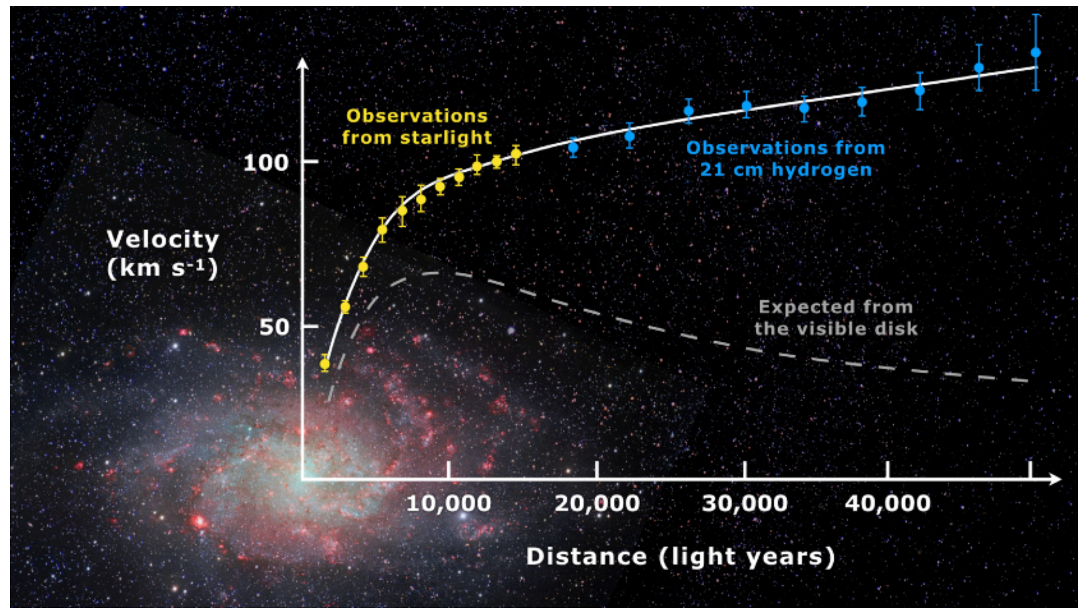


CC BY 4.0

Huge amount of evidence
From all scales

Evidences for dark matter

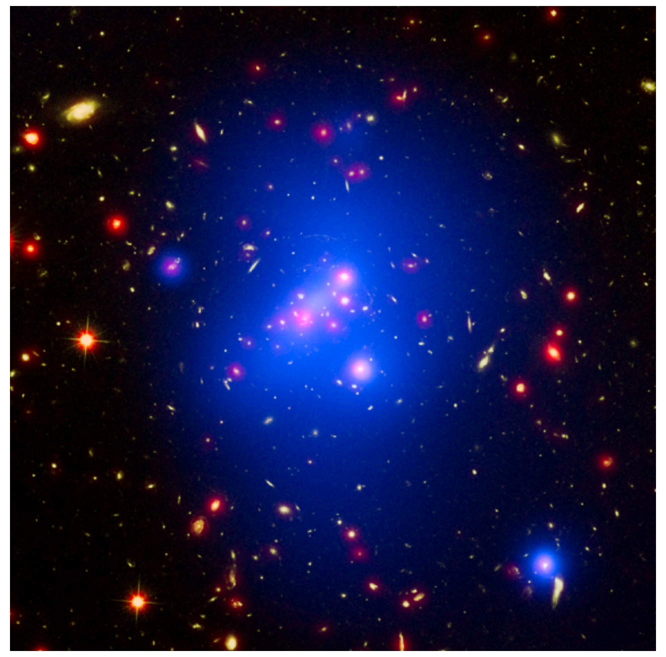
Galaxy rotation curves



Credit: Mario De Leo

- Mass fraction
- Distribution

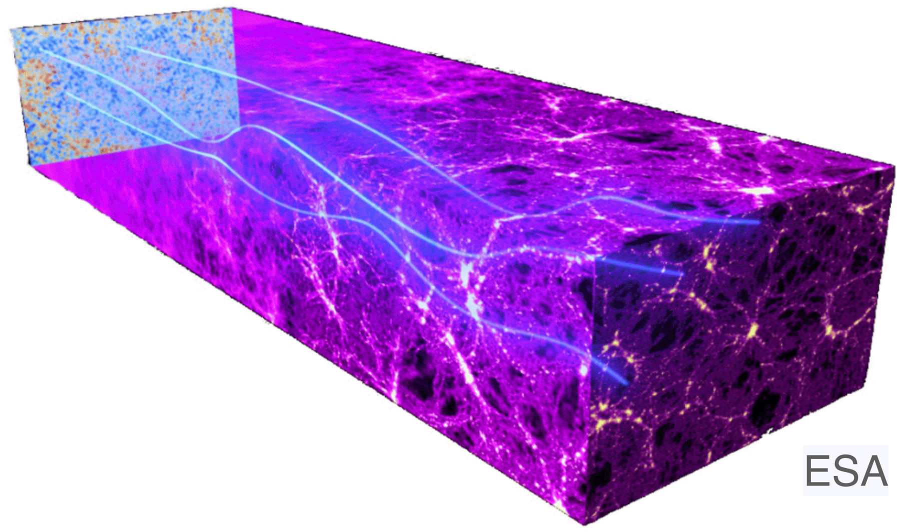
Clusters



CC BY 4.0

- Mass fraction
- Distribution

Lensing



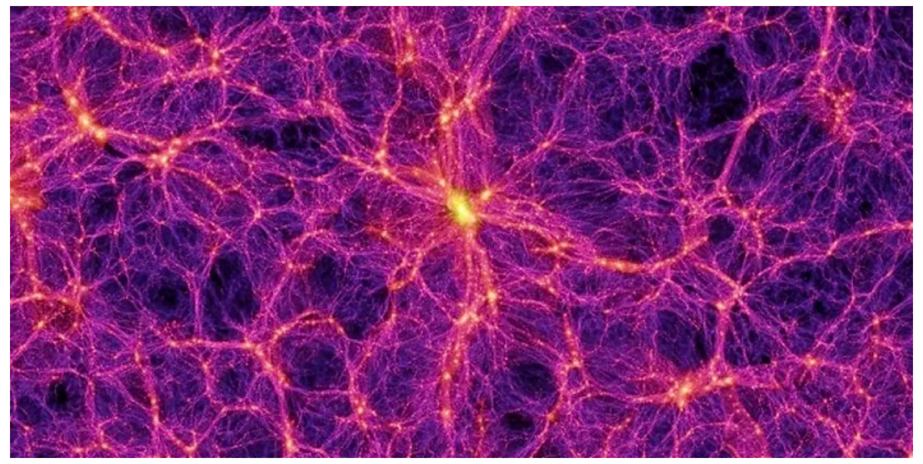
ESA

Strong lensing
- Mass fraction
- Distribution

Weak lensing
- Distribution
- Shape
- Structure

Micro lensing
- Mass fraction
- Smoothness

Large Scale Structure



Springel & others / Virgo Consortium

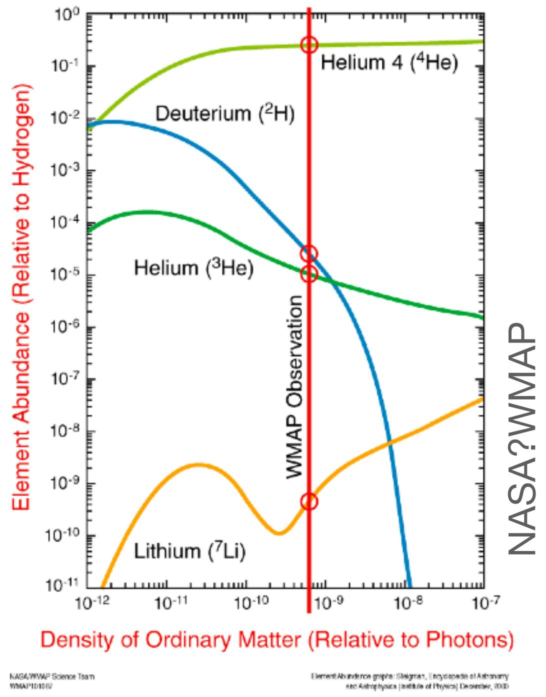
CMB/LSS
- Ratio of DM/collisional matter
- Thermal history

Cluster collision

NASA/CXC/CfA and NASA/STScI

- Distribution
- Separation from collisional matter
- Self-interaction

Big Bang Nucleosynthesis

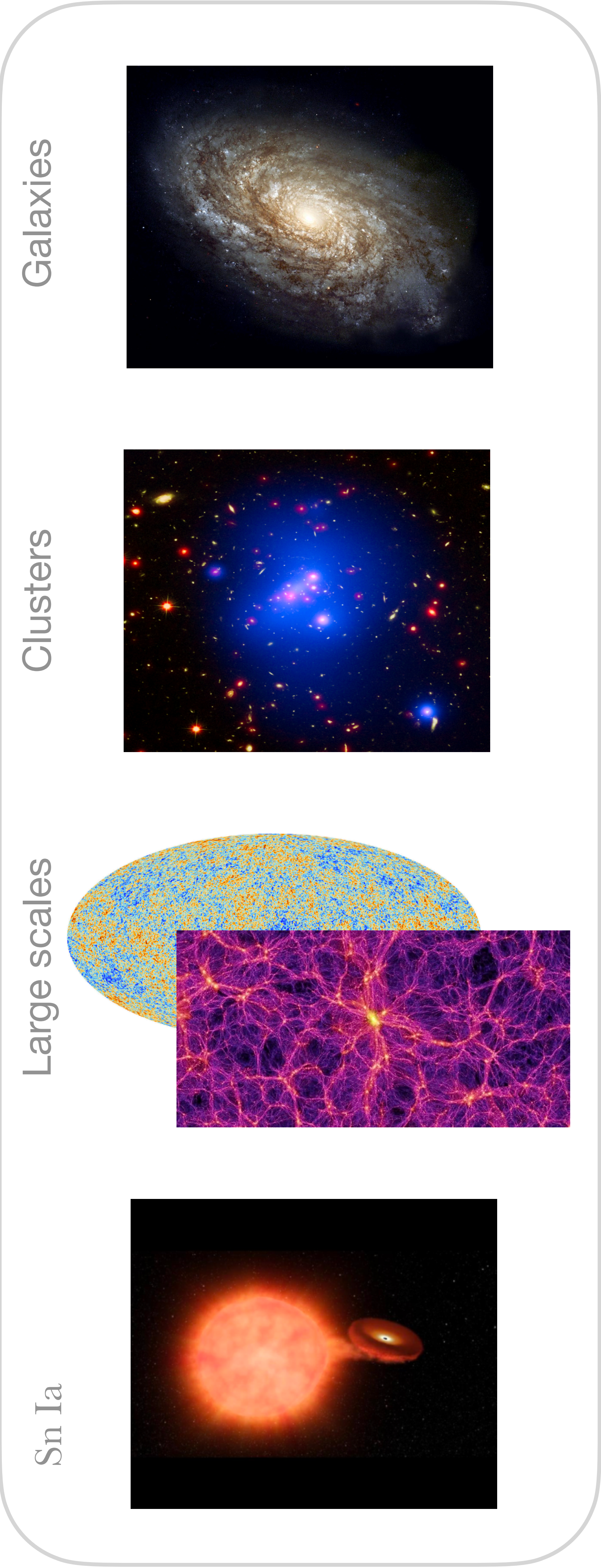


NASA?WMAP

- Amount of baryons

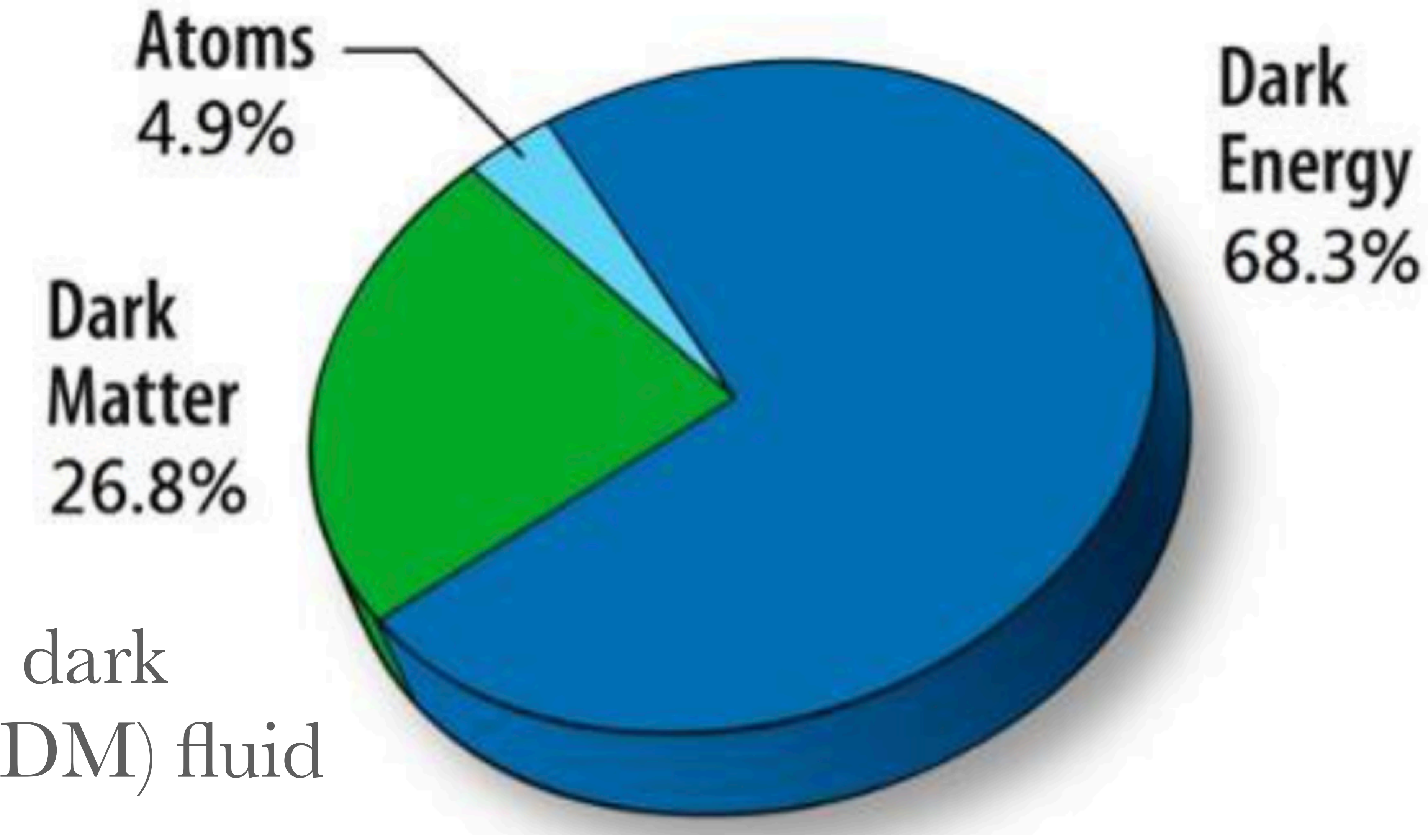
Based on K. Mack

What we know about dark matter



ΛCDM – the standard cosmological model

Successful description of our universe with 6 free parameters, tested to sub-percent precision.



Λ

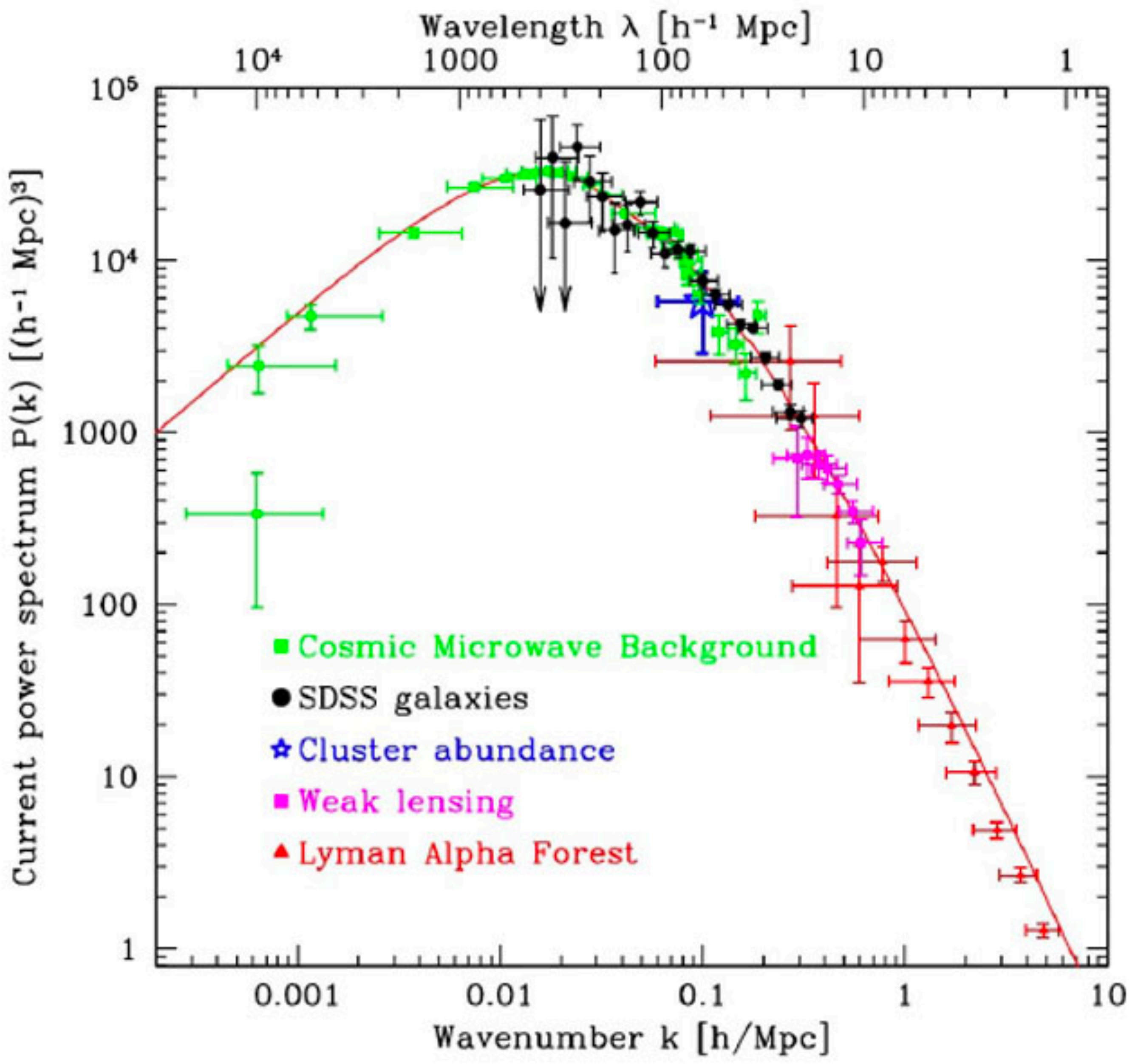
DM: cold dark
matter (CDM) fluid

ΛCDM

simple but exotic model!

Cold dark matter

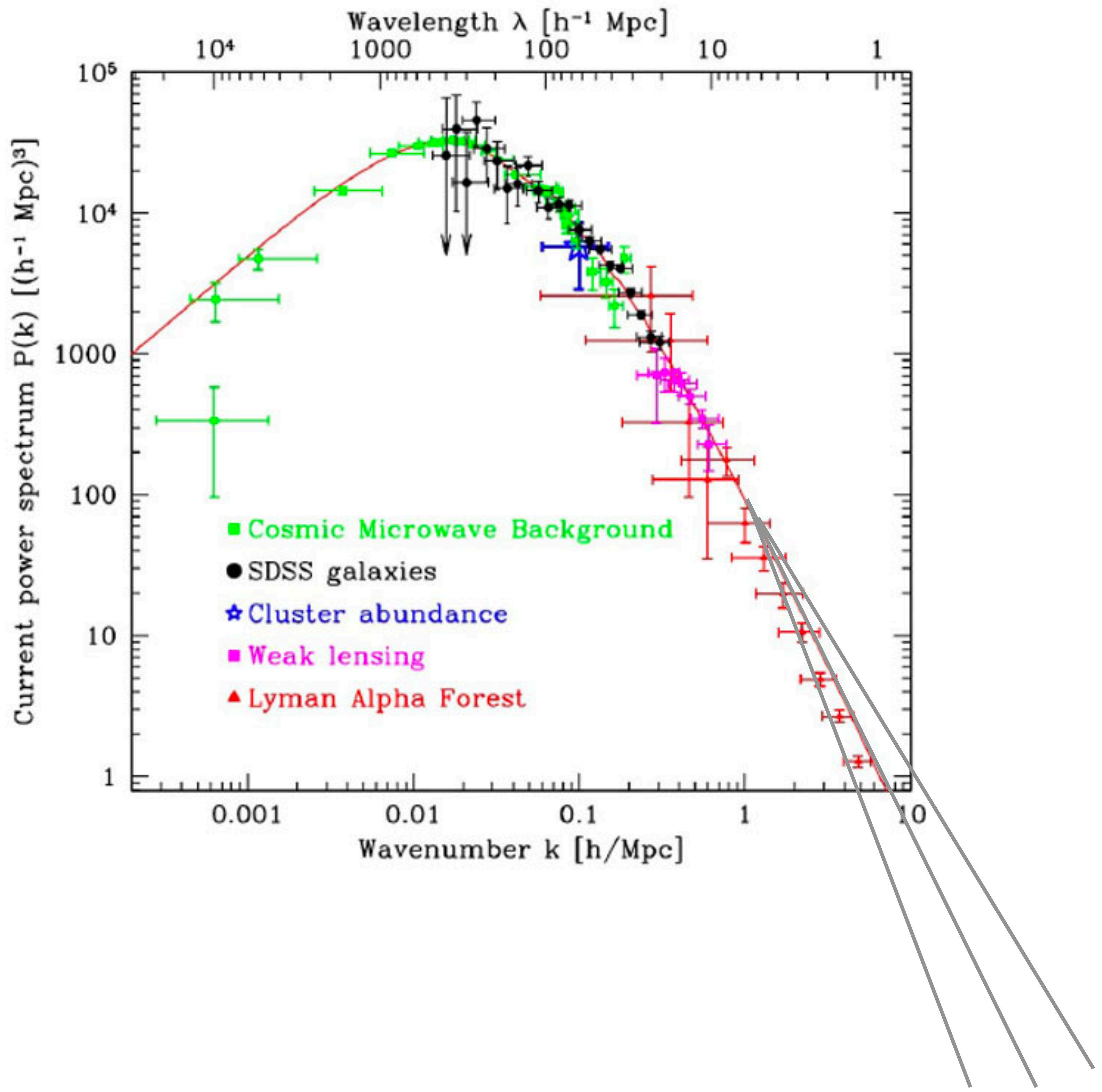
- Cold: moves much slower than *c*
- Presureless: gravitational attractive, clusters
- Dark (transparent): no/weakly electromagnetic interaction
- Collisionless: no/weakly self-interaction or interaction with baryons



- Abundance: amount of dark matter today known

What we don’t know

- 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 we don't know

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

State of the "art"


Dark Matter

Light bosons
Axion-like Particles
Fuzzy Dark Matter
QCD Axions

Neutrinos
Standard Model ν
Sterile neutrinos

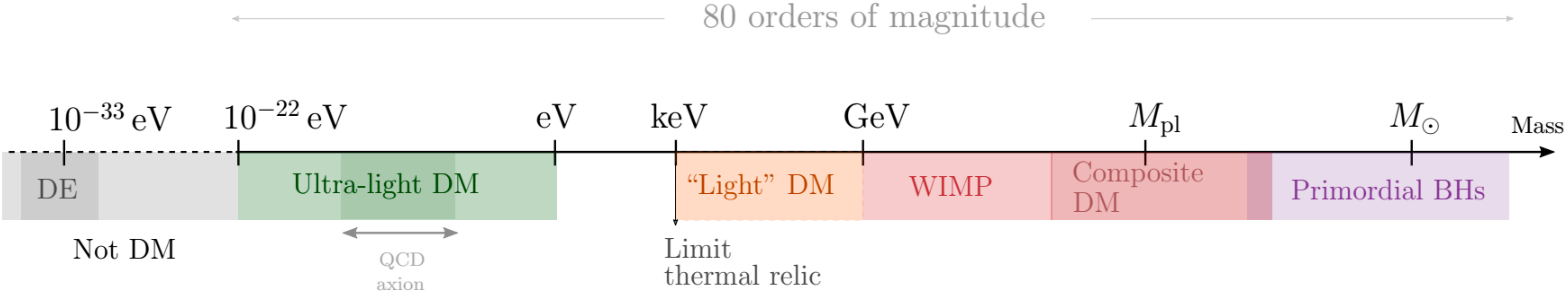
Weak Scale
Super-symmetry
Extra-dimensions
Little Higgs
Simplified Models
Effective Field Theory

Other Particle
WIMPzilla
Superfluid
Self-interacting

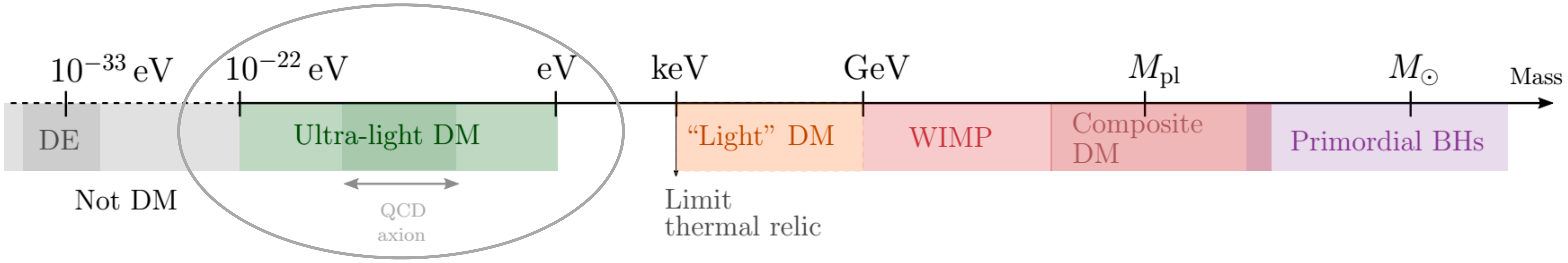
Macroscopic
Macros
Primordial BHs
MaCHOs

Modified Gravity
MOG
TeVeS
MoND
Emergent Gravity

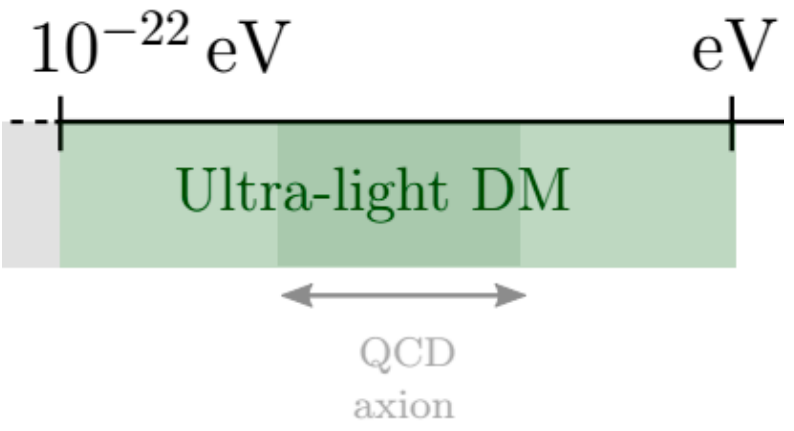
Mass scale of DM



Ultra-light dark matter

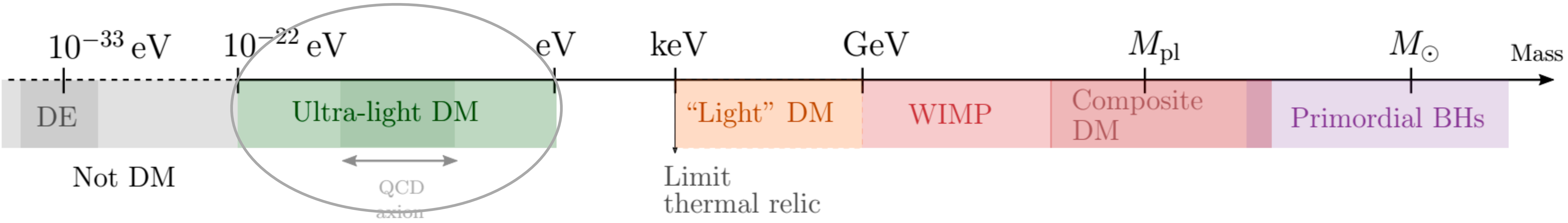


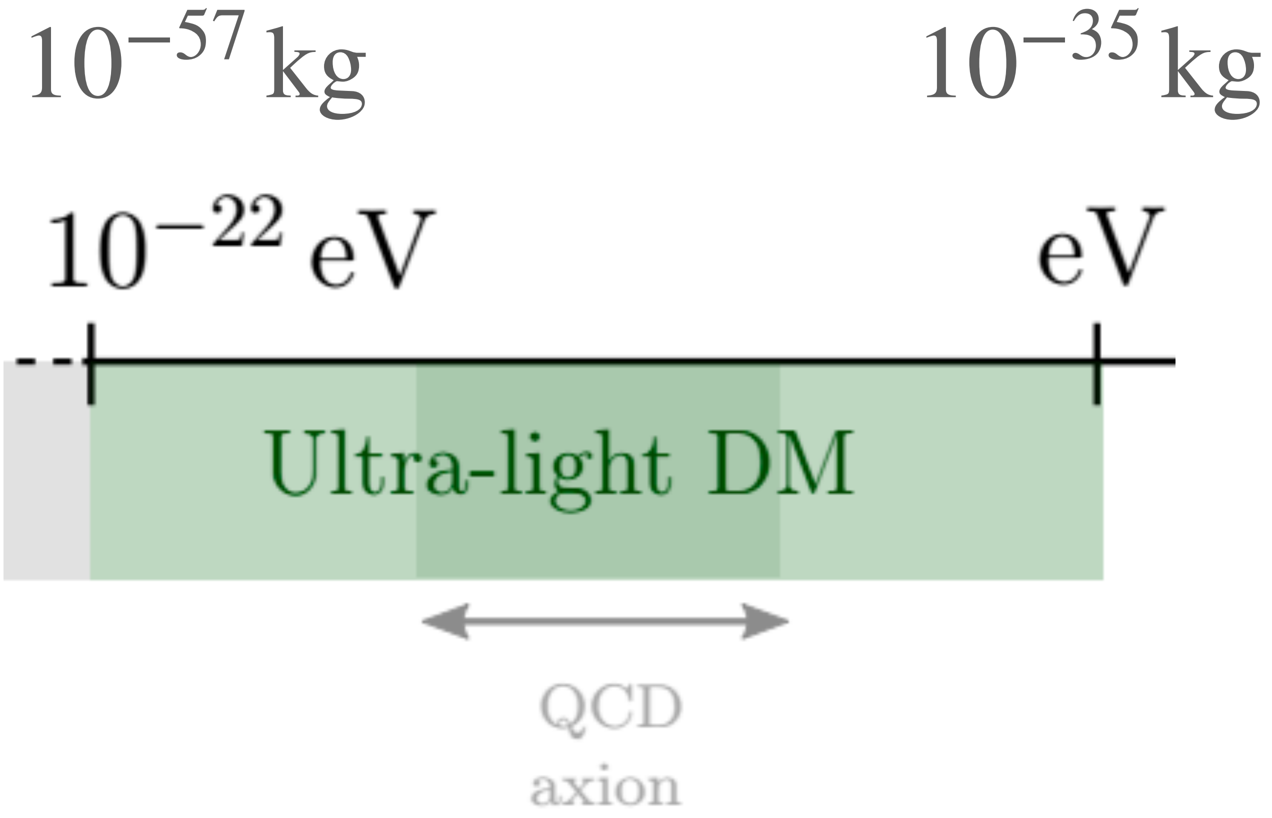
Ultra-light Dark Matter



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

Lightest possible candidate for DM





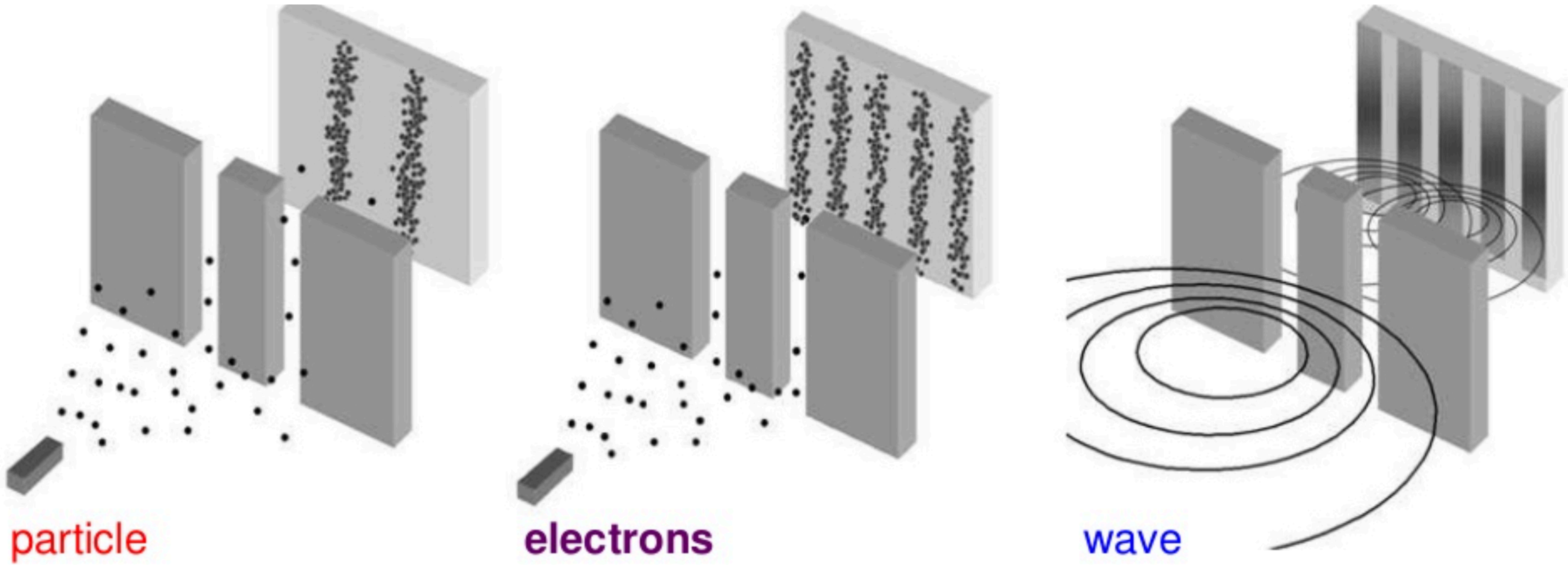
$\longrightarrow$ Bosons

Non-thermally produced

Wave-Particle duality

All matter exhibits a wave behaviour

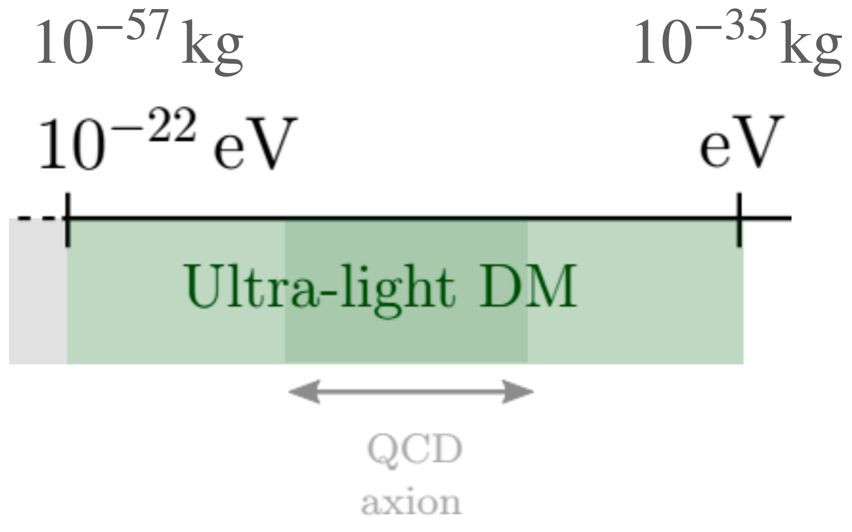
De Broglie 1924



$$\lambda_{dB} \sim \frac{1}{mv}$$

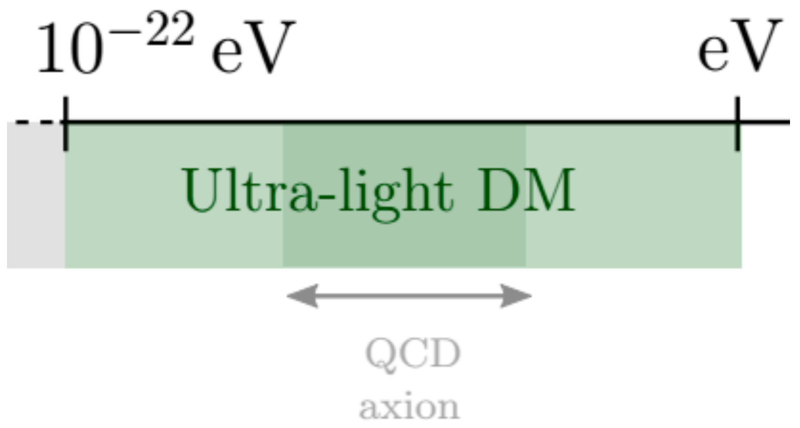
$$\lambda_{dB} \sim 1/\sqrt{2\pi m k_B T}$$

	Mass (kg)	Speed (m/s)	λ_{dB} (m)
Accelerated e-	9.1×10^{-31}	5.9×10^{6}	1.2×10^{-10}
Golf ball	0.045	220	4.8×10^{-30}



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

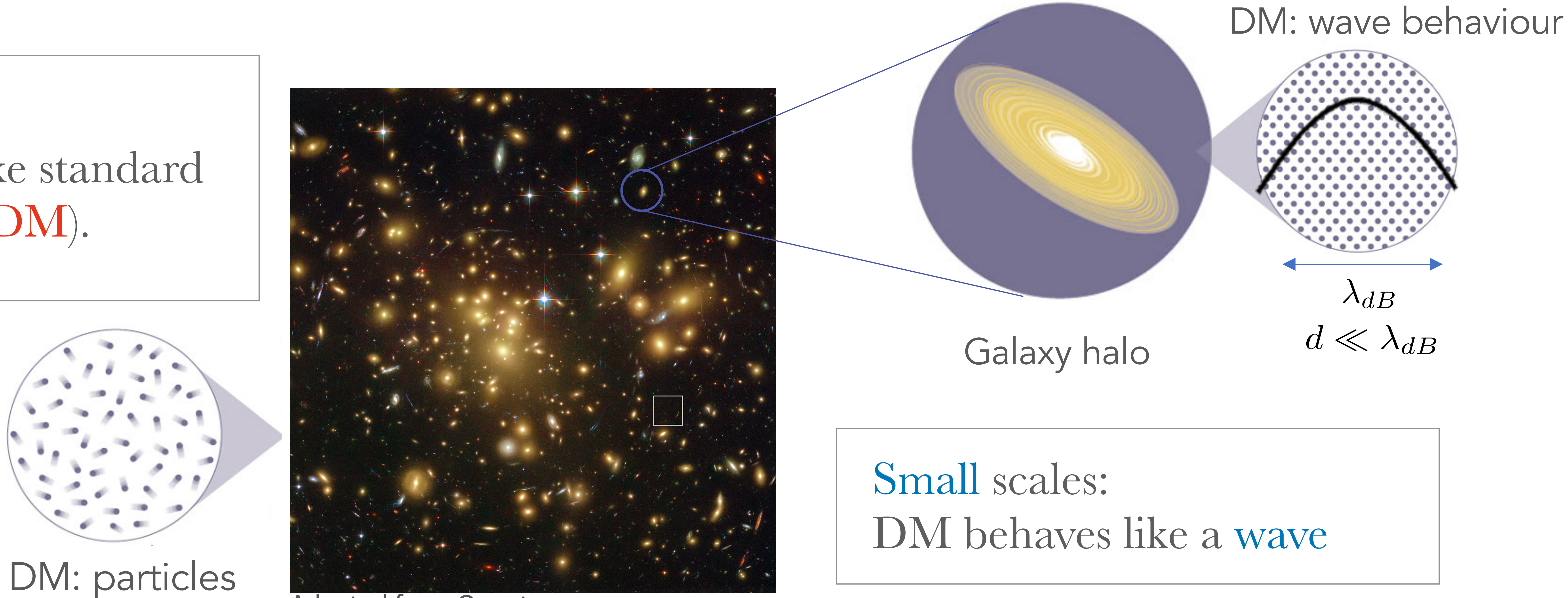
Ultra-light Dark Matter



Ultra-light candidate $\longrightarrow$ Large $\lambda_{\mathrm{dB}} \sim 1/mv$

Lightest possible candidate for DM

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



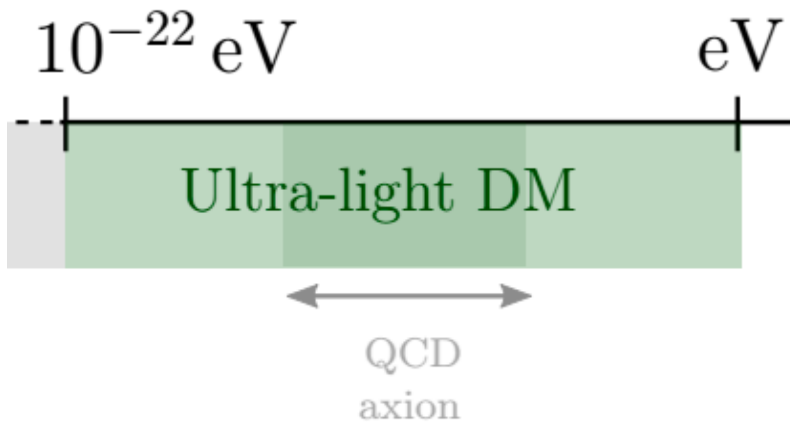
Adapted from Quanta

Small scales:
DM behaves like a wave

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

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

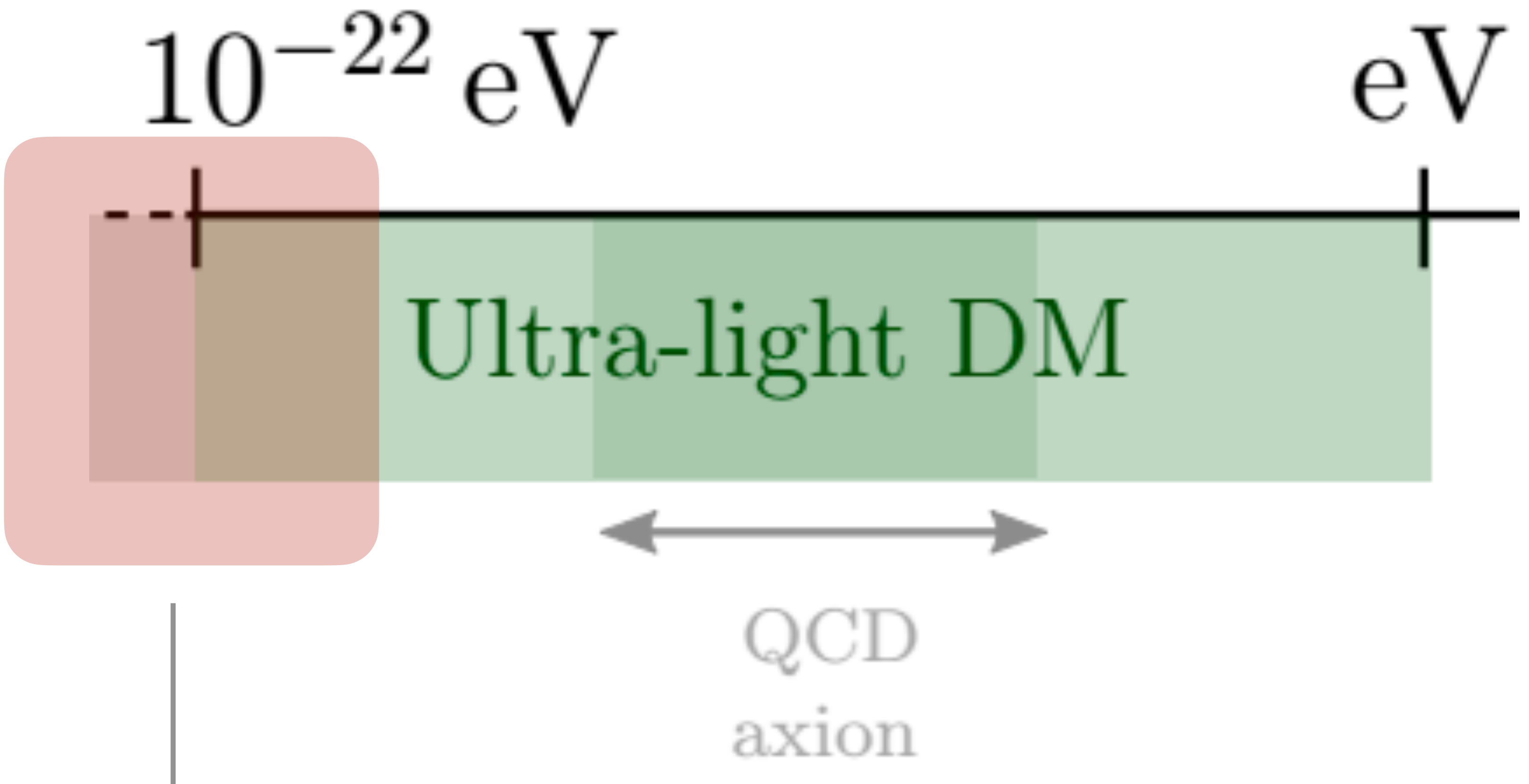
$\lambda_{dB}^{ULDM} \sim \mathrm{pc} - \mathrm{kpc}$



Ultra-light Dark Matter

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

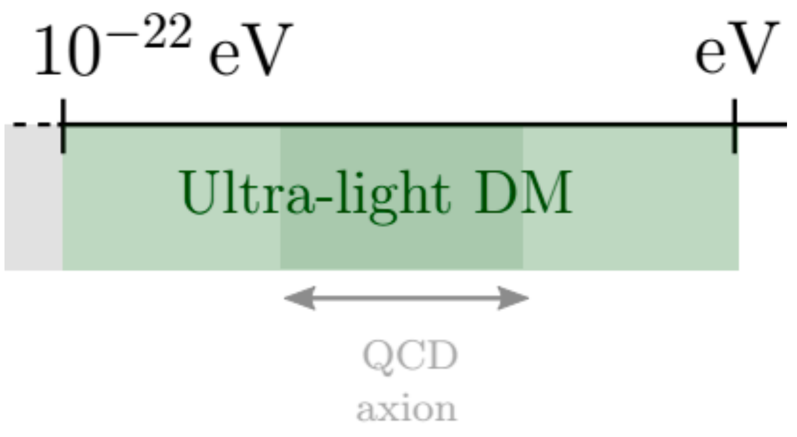
$10^{-57}\,\mathrm{kg}$ $10^{-35}\,\mathrm{kg}$



Gravitational probes

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

Motivations of the ULDM



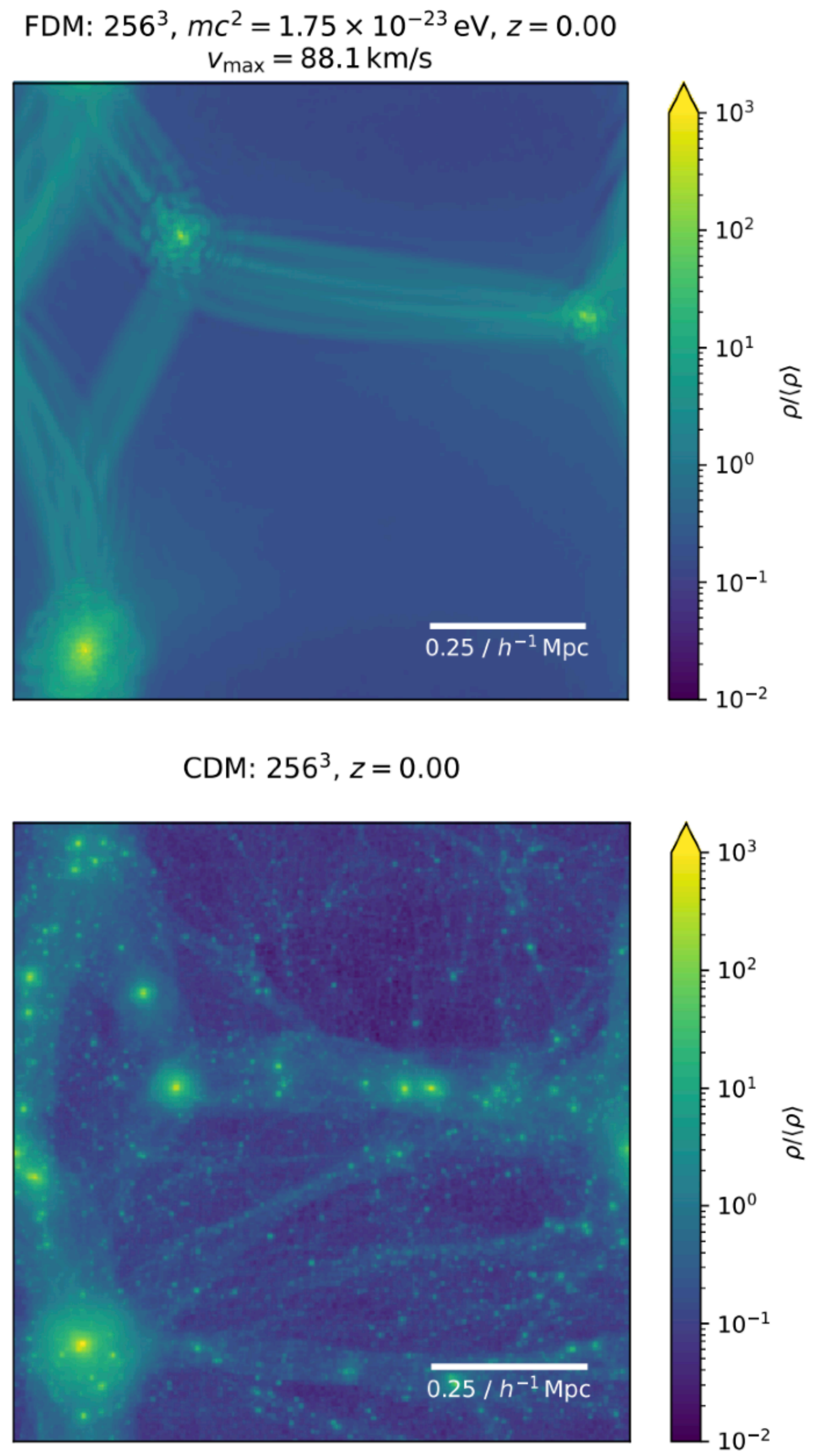
- **Rich phenomenology on small scales:**

  - Wave nature manifest on galactic scales

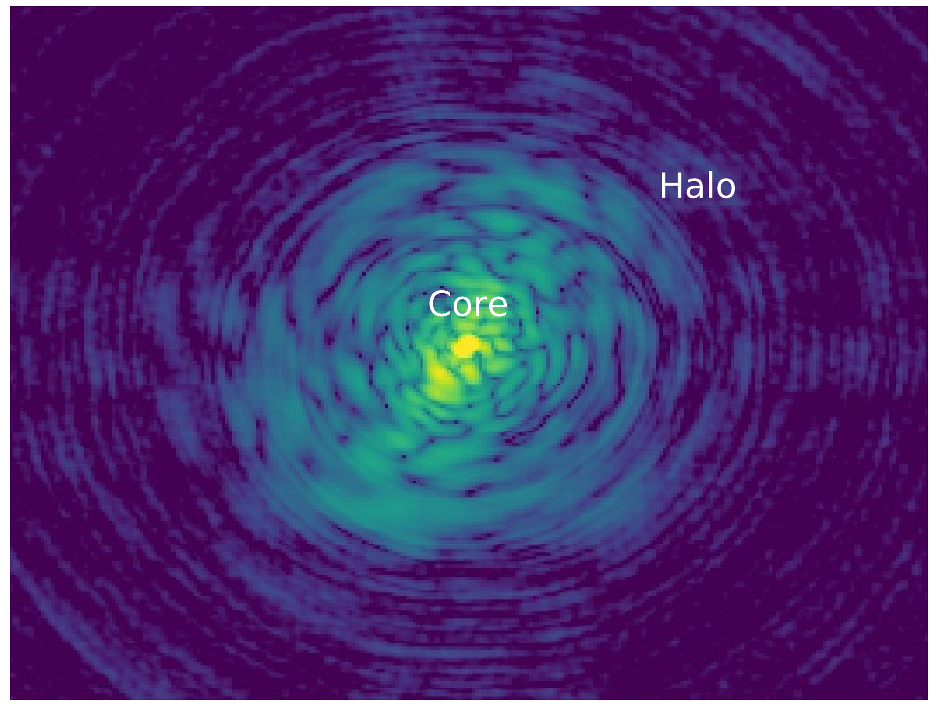
- Particle physics/HEP/condensed matter motivation

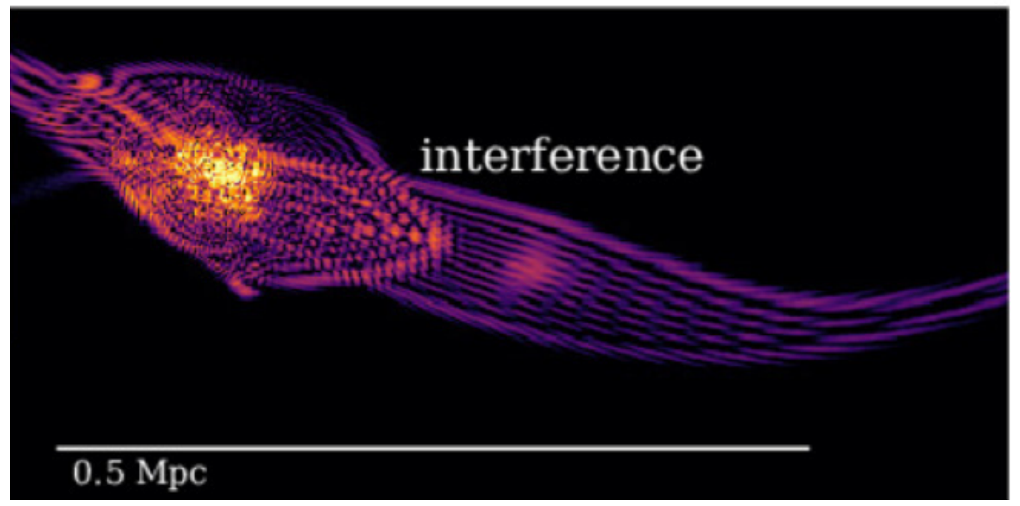
  Candidates: Axions, ALPs, UL particles, …

- Might address small scales problems



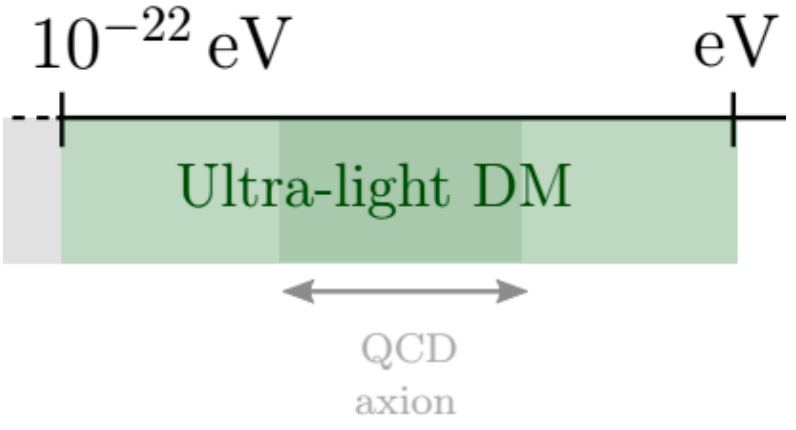
S. May et al. 2021



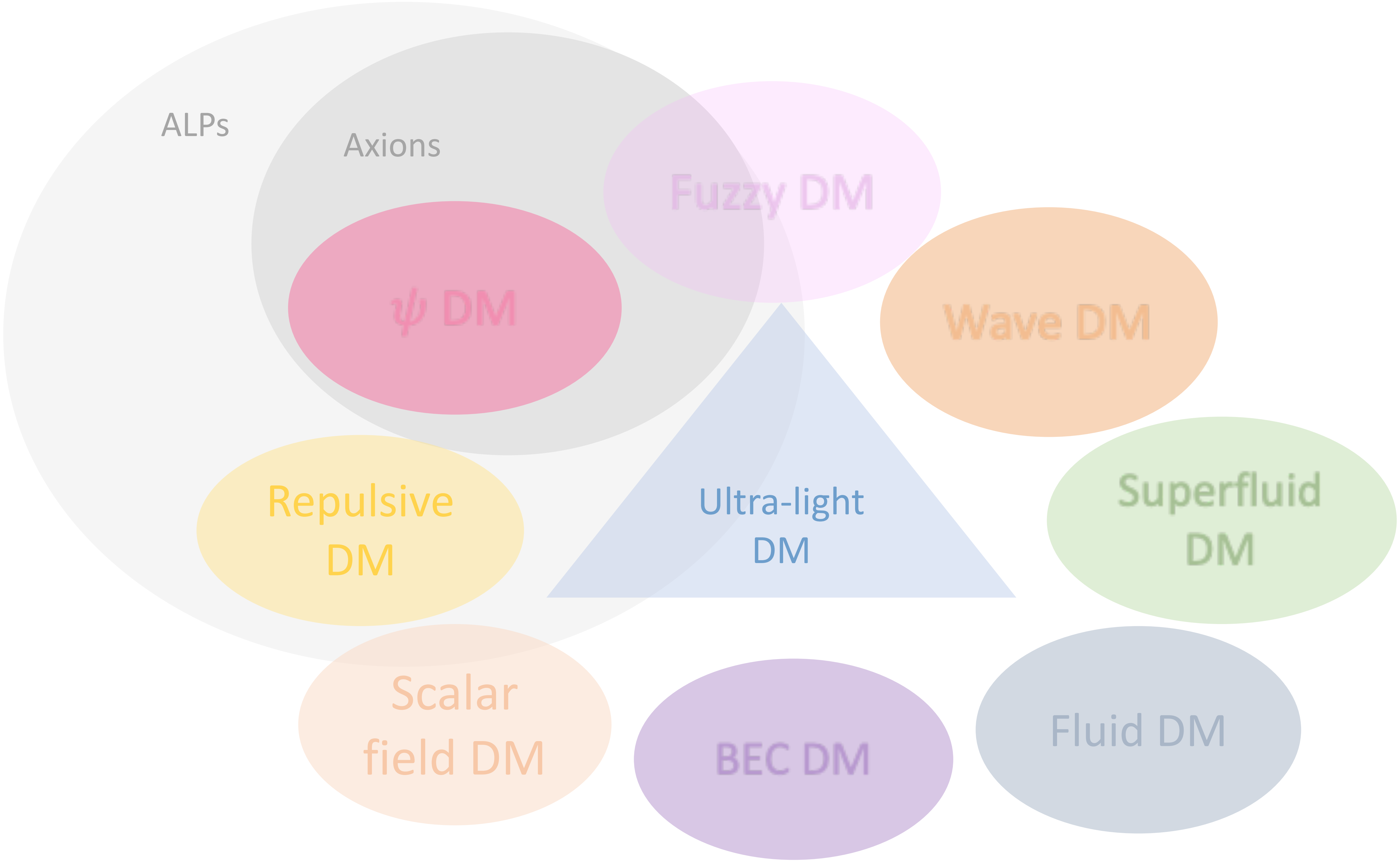


Mocz et al. 2017

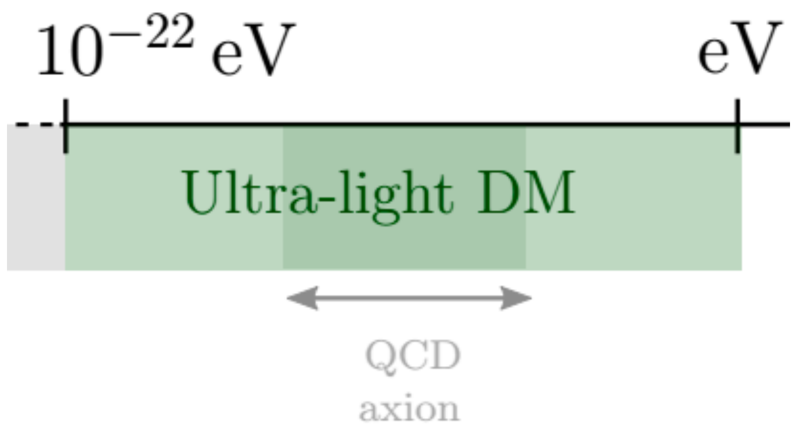
Ultra-light Dark Matter - models



There are many ways to have a DM with this property → many ULDM models in the literature
However, each of these models presents a different dynamics on small scales - different phenomenology



Ultra-light Dark Matter -classes



3 classes:

Fuzzy DM
(FDM)

- Gravitationally bounded ultra-light scalar field model

DOFs

m

Self Interacting FDM
(SIFDM)

- Presence of (weakly) self-interaction

m g

DM Superfluid

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

Axion and ALP (axion like particles)

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

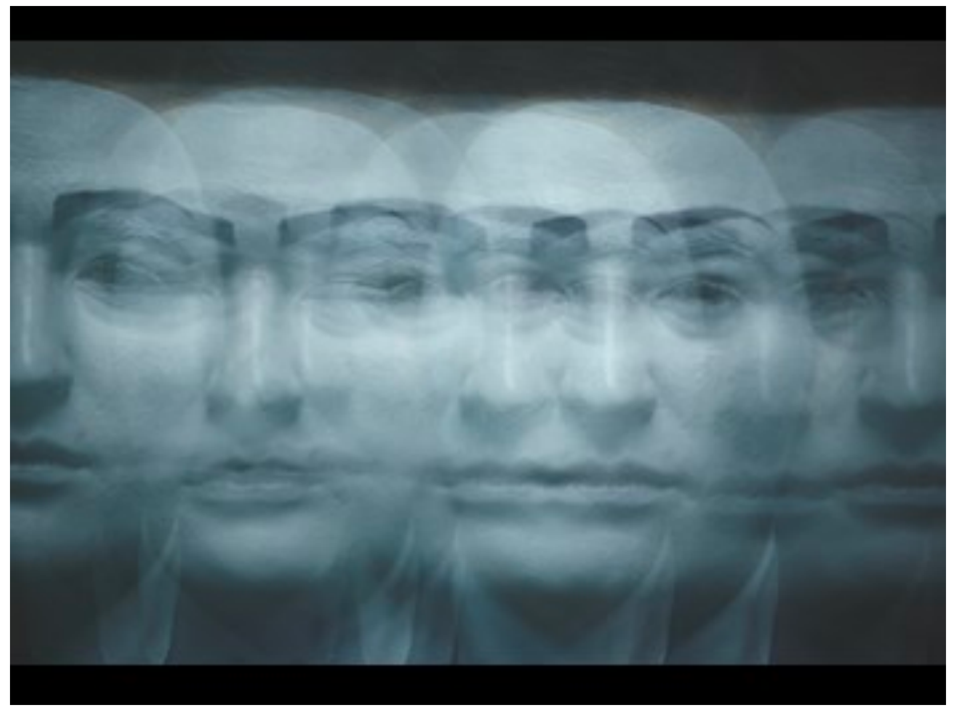
$$\mathcal{L} = P(X)$$

⟶ Connection with condensed matter and particle physics!

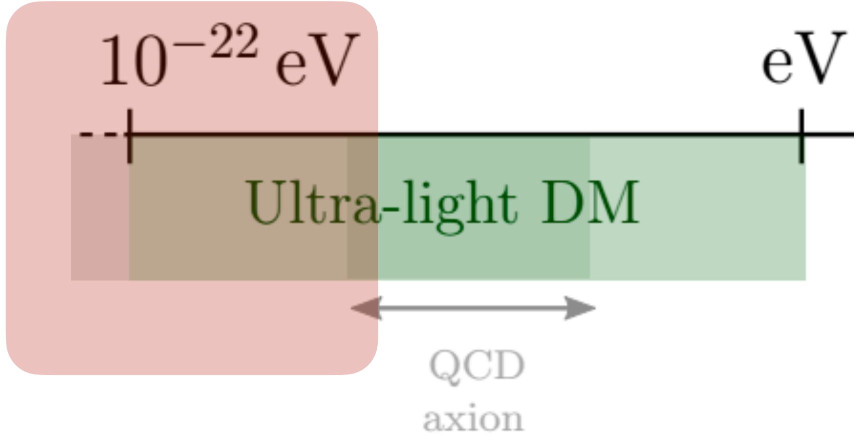
"Ultra-light dark matter", **E.Ferreira**, 2020. The Astronomy and Astrophysics Review.

Fuzzy dark matter

Self interacting fuzzy dark matter



Fuzzy dark matter



Fuzzy DM
(FDM)

- Gravitationally bounded ultra-light scalar field model

m

Wave DM
Ultra-light axions

Self Interacting FDM
(SIFDM)

- Presence of (weakly) self-interaction

m g

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

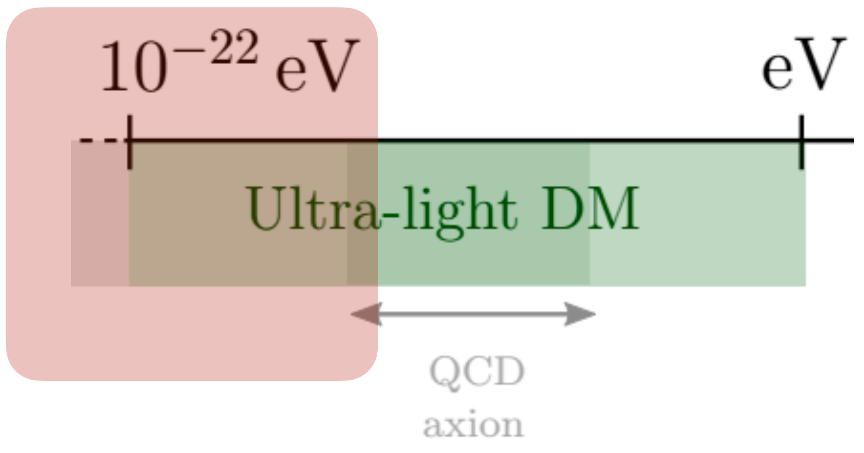
(Reviews: EF (2021), J. Niemeyer (2019), L. Hui (2021))

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

m

Wave DM
Ultra-light axions

Focus in spin 0 particles here!

(Some of the grav. phenom. is carried for vectors, for example)

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

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

Idea:

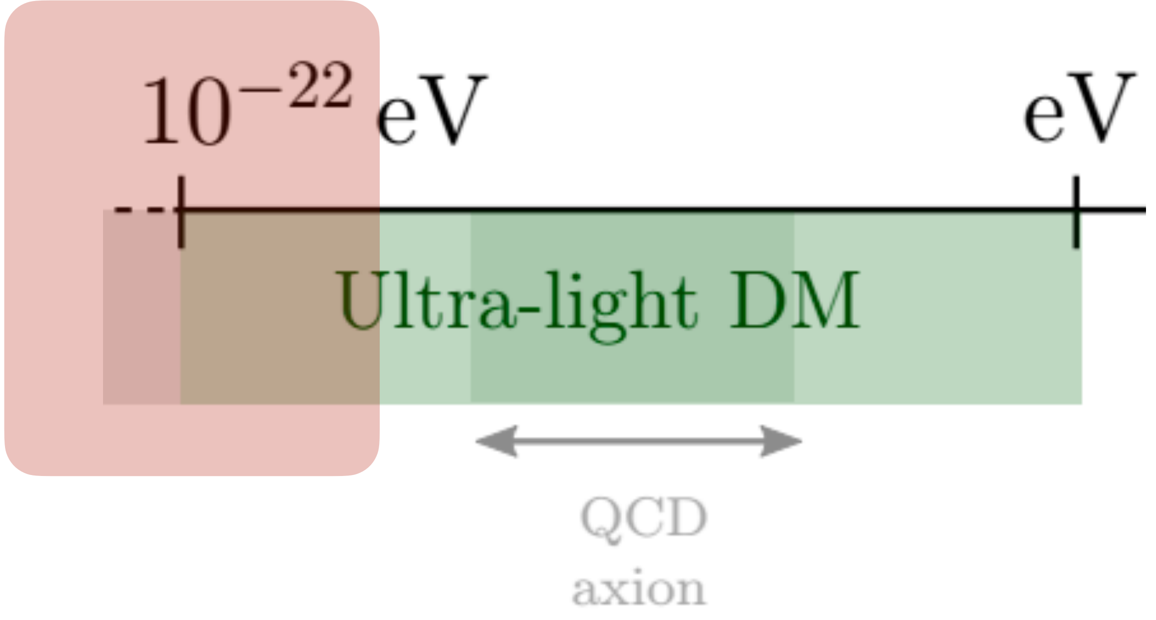
$$m_{\mathrm{fdm}} \sim 10^{-22}\,\mathrm{eV}$$

address the small scale problems+ rich phenom.

Motivation: particle physics

FDM candidates

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



Known PNGB: QCD axion → Candidate for DM

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

Axion-like particles

Axions or Axion like particles (ALP)

Axions and ALPs are pseudo Nambu Goldstone bosons from the spontaneous symmetry breaking of a $U_{PQ}(1)$ (U(1)) symmetry, and are described by the complex field: $\Psi = v\, e^{i\phi/f_a}$

$$v_{0,ssb} = f_a/\sqrt{2} \longrightarrow \phi \rightarrow \phi + c$$

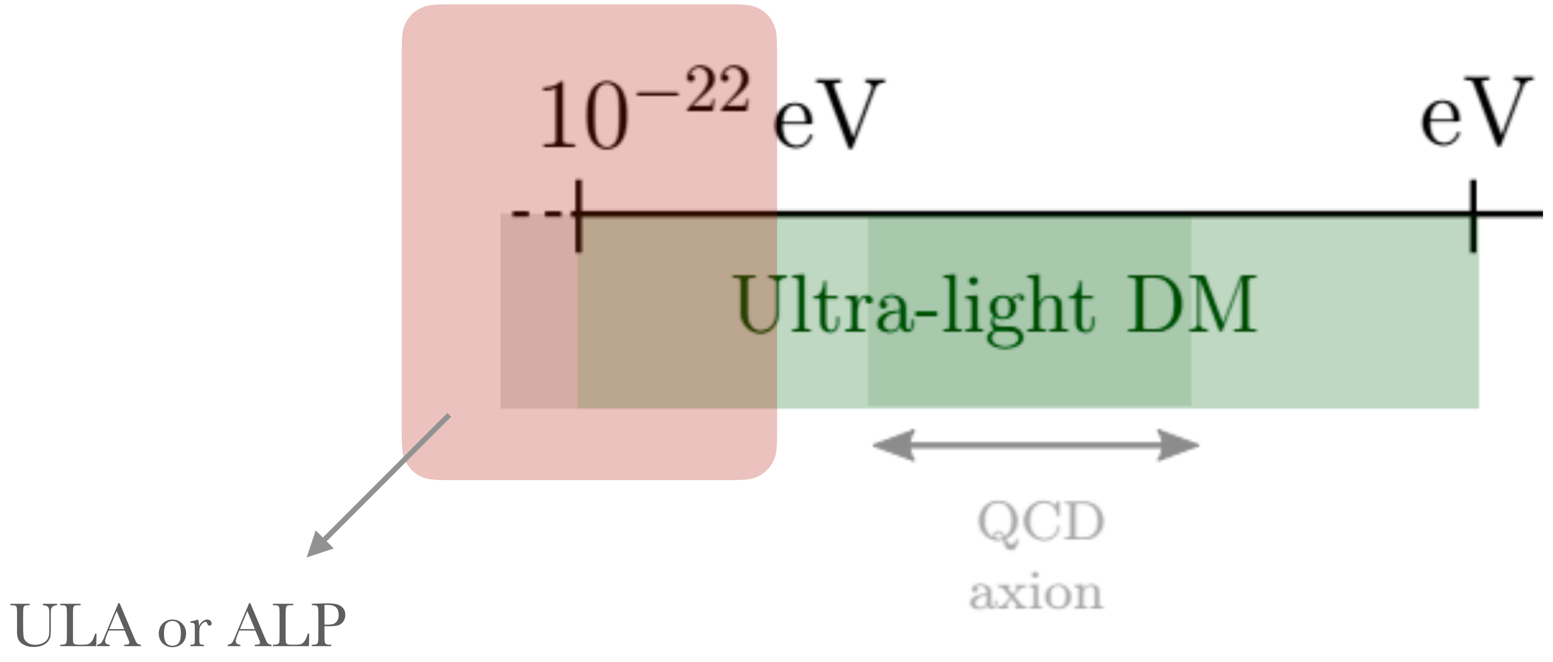
Non-perturbative effects (from string theory or instatons) induce a potential:

$$V(\phi) = \Lambda_a^4\,[1 - \cos(\phi/f_a)] \xrightarrow[\phi \ll f_a]{} \frac{1}{2}m^2\phi^2 + \frac{g}{4}\phi^4 + \cdots$$

Motivation: particle physics

FDM candidates

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



Known PNGB: <u>QCD axion</u> → Candidate for DM

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

<u>Axion-like particles or ultra-light axions:</u>

- 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

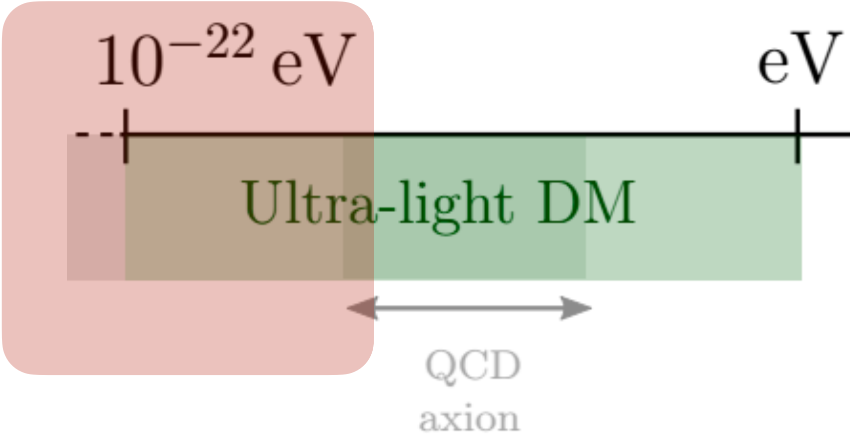
  Non-thermal mechanism (e.g. mis-alignement)

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

L. Hui

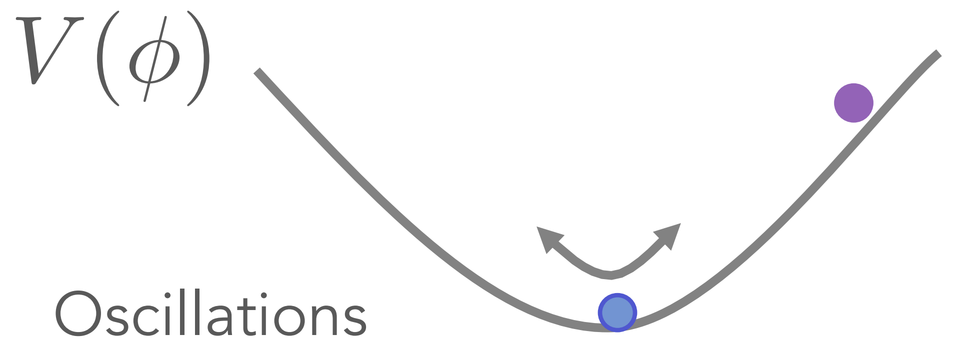
* Axion and ALP interact with photons (and neutrinos)

Cosmological evolution



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

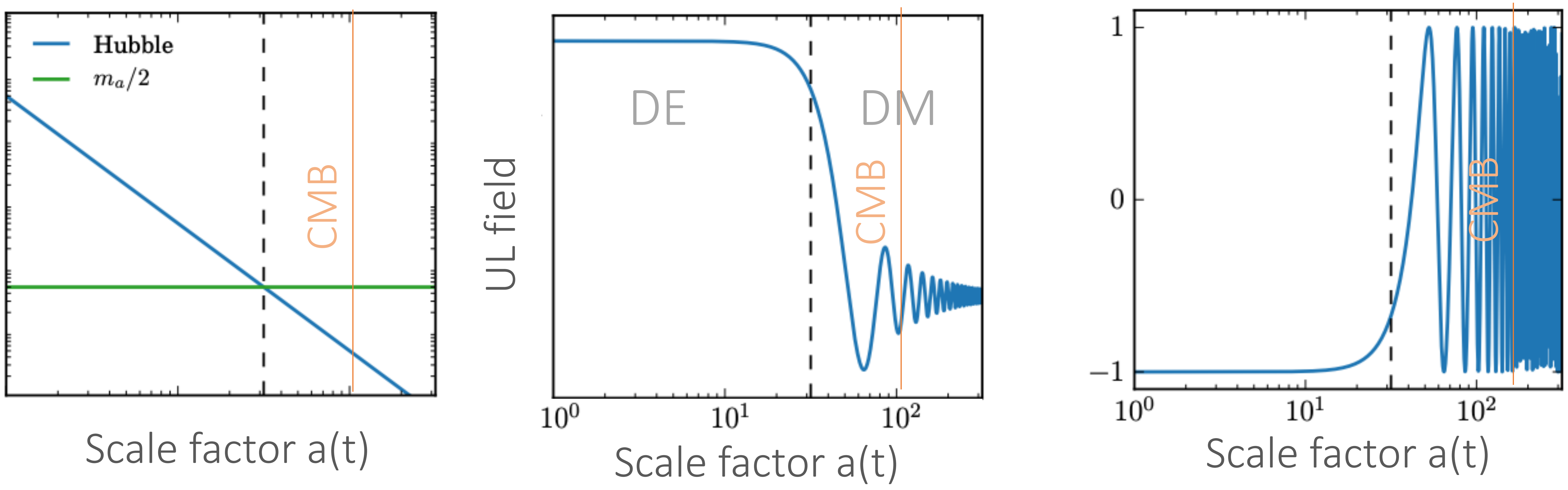
FDM



Oscillations $\rho_\phi \propto a^{-3}$

$$\left\{\begin{array}{llll} H \gg m & \Longrightarrow \quad \phi_{\rm early} = \phi(t_i) & \longrightarrow \quad \omega = -1 & \text{DE} \\ H \ll m & \Longrightarrow \quad \phi_{\rm late} \propto e^{imt} & \longrightarrow \quad \langle\omega\rangle = 0 & \text{DM} \end{array}\right.$$

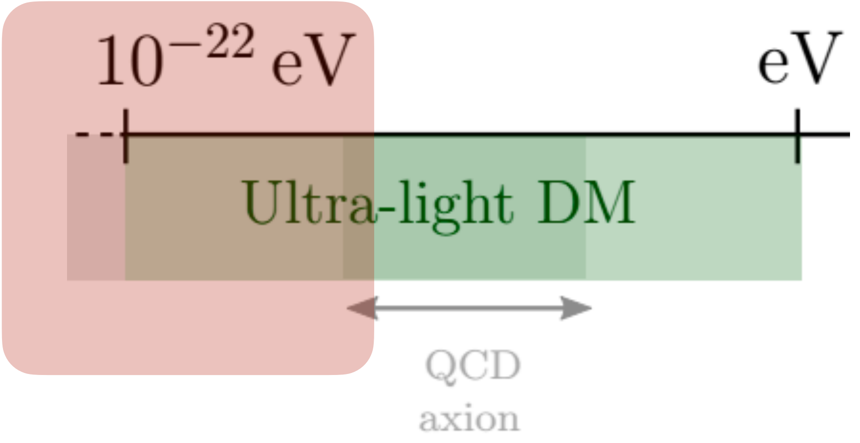
$H(t_*) = m$



Marsh, 2016

In order to behave like DM: start oscillating before matter-radiation equality $m > 10^{-28}\,\text{eV} \sim H(a_{\rm eq})$

Structure formation - *non-relativistic regime*



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

Schrödinger-Poisson system : describe the FDM and the SIFDM

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

Schrödinger equation
(Gross-Pitaevskii)

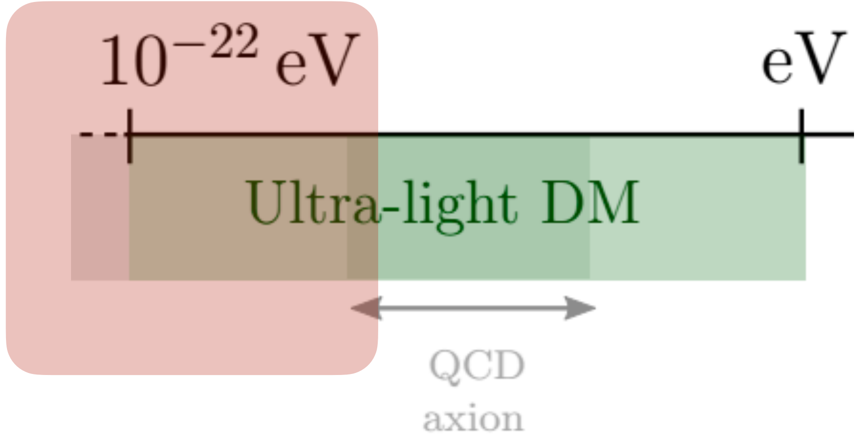
Poisson equation

$g = 0$ → FDM

$g \neq 0$ → SIFDM

Fundamentally different than
CDM/WDM/SIDM!

Structure formation - non-relativistic regime



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

Schrödinger-Poisson system : describe the FDM and the SIFDM

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

Schrödinger equation (Gross-Pitaevskii)

Poisson equation

$g = 0 \rightarrow$ FDM

$g \neq 0 \rightarrow$ SIFDM

Fundamentally different than CDM/WDM/SIDM!

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

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

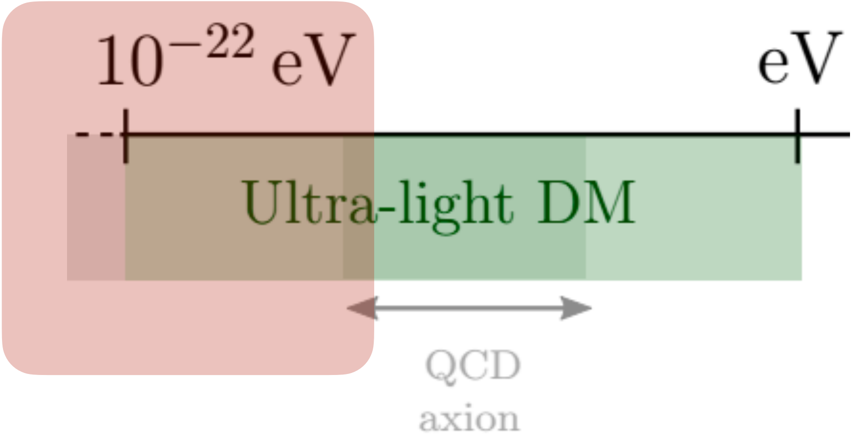
$$\dot{\rho} + \nabla\cdot(\rho\,\mathbf{v}) = 0$$

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

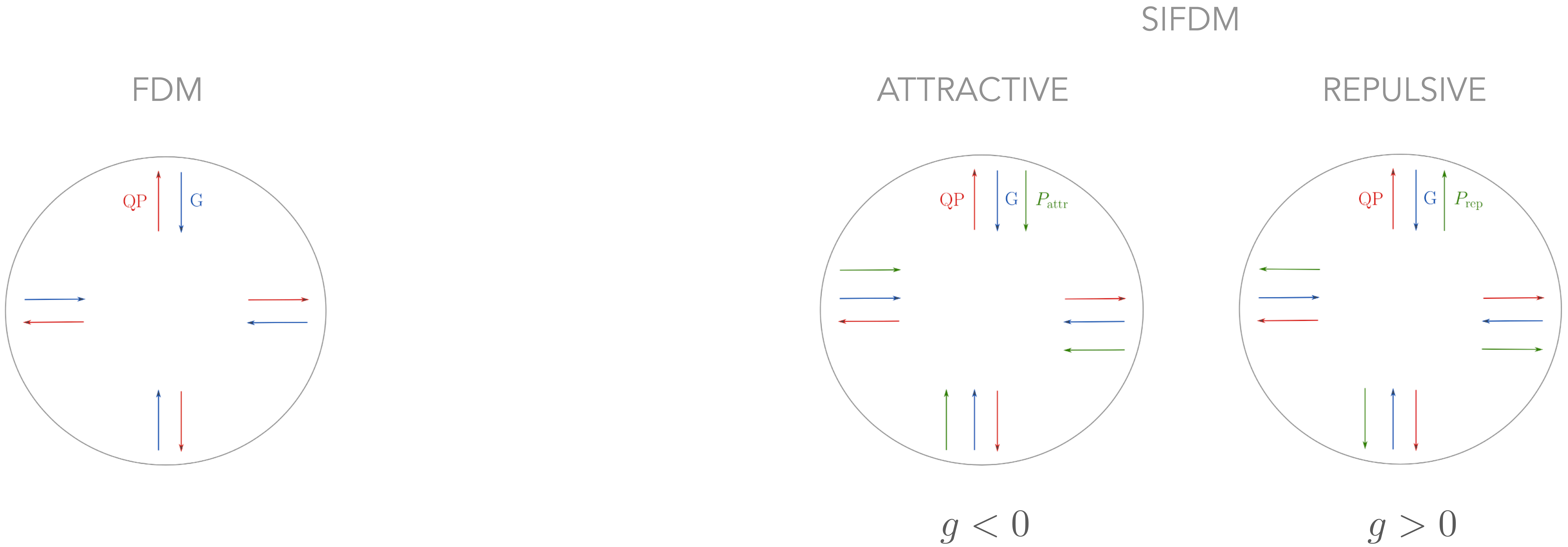
Quantum pressure

FLUID DESCRIPTION

Structure formation - perturbation and stability



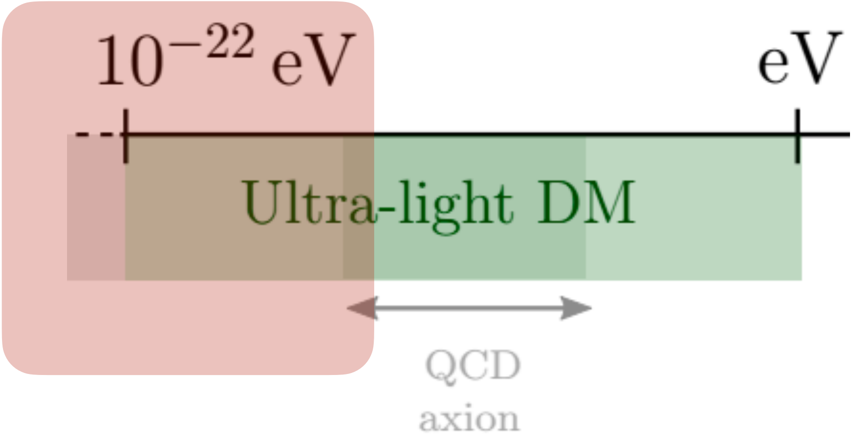
Competition between gravity and pressure (quantum pressure and interaction)



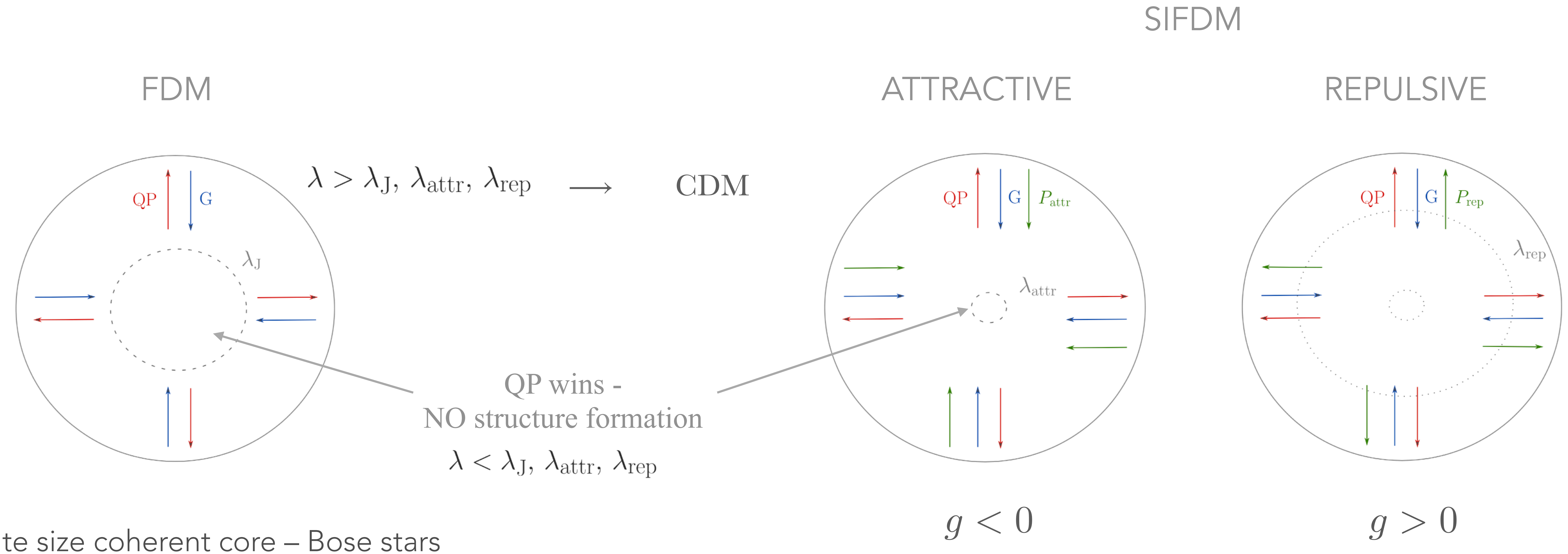
$$\dot{\rho} + \nabla \cdot (\rho\, \mathbf{v}) = 0$$

$$\dot{\mathbf{v}} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - \overset{P_{\rm int} = \frac{g}{2m^2}\rho^2}{\boxed{P_{int}}} - \underbrace{\boxed{\frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}}}_{\text{Quantum pressure}}\right)$$

Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales



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

QP wins -
NO structure formation
$\lambda < \lambda_\mathrm{J},\ \lambda_\mathrm{attr},\ \lambda_\mathrm{rep}$

$g < 0$

$g > 0$

Finite size coherent core – Bose stars

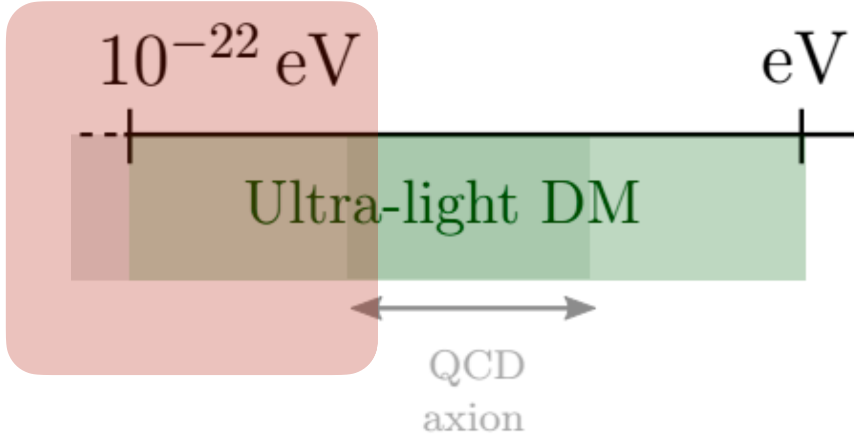
$$\boxed{\lambda_J = 55 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{-1/4} (\Omega_m h)^{-1/4}\,\mathrm{kpc}}$$

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

For attractive interactions can only form localized clumps (solitons)

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

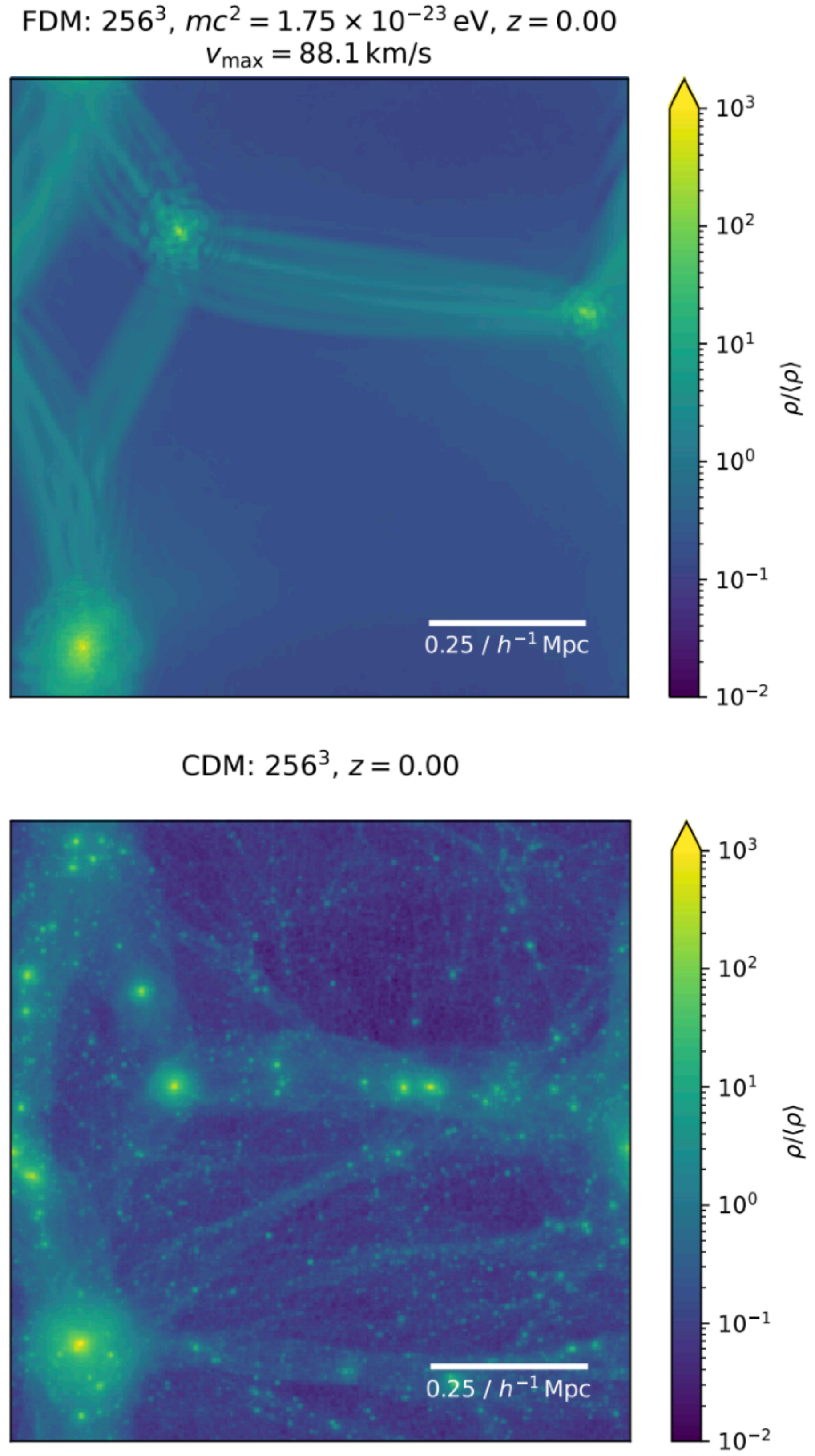
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

* Focus only in gravitational signatures

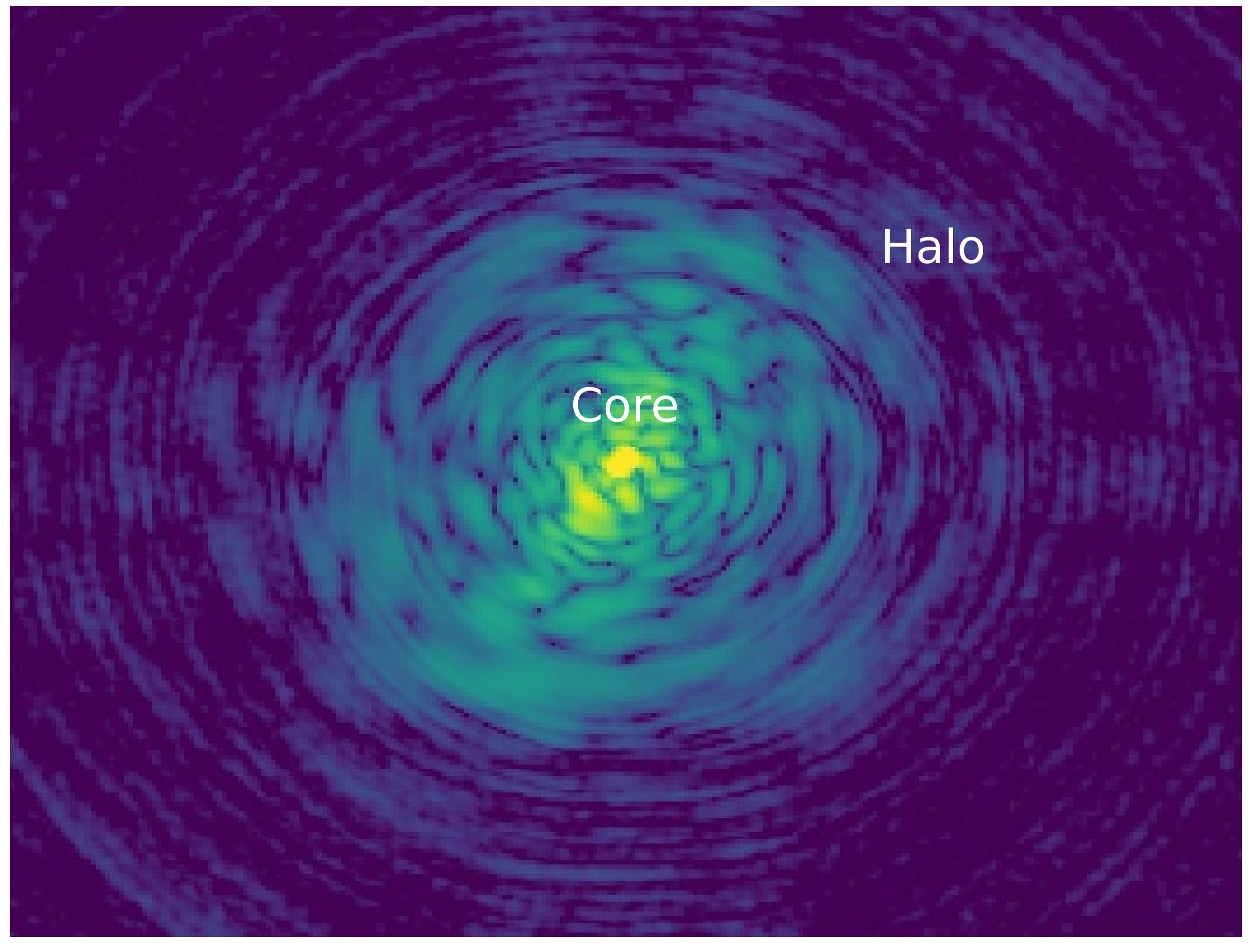
Suppression of small structures


FDM: 256^3, $mc^2 = 1.75 \times 10^{-23}$ eV, $z = 0.00$
$v_{\max} = 88.1$ km/s

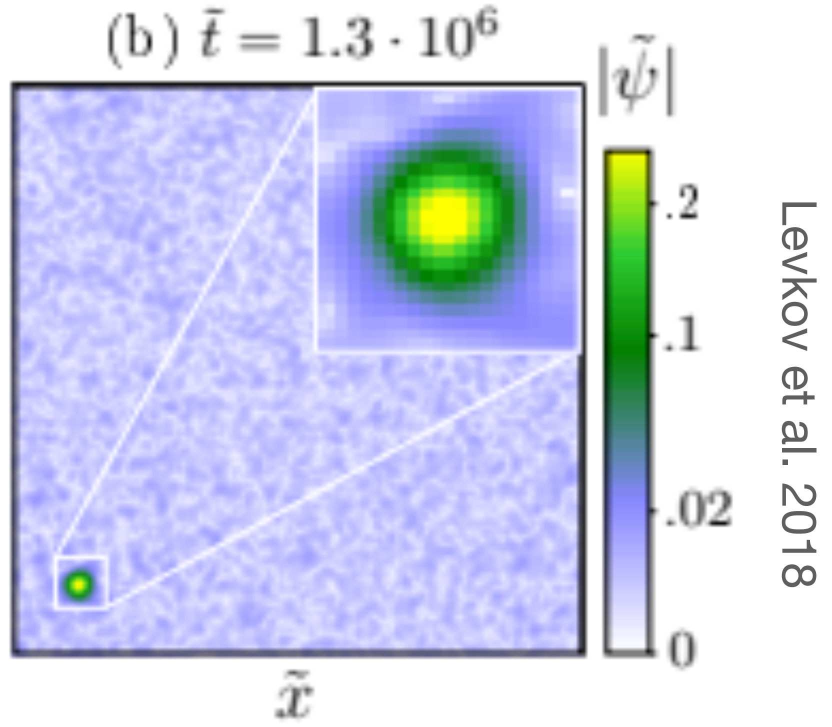
CDM: 256^3, $z = 0.00$

S. May et al. 2021

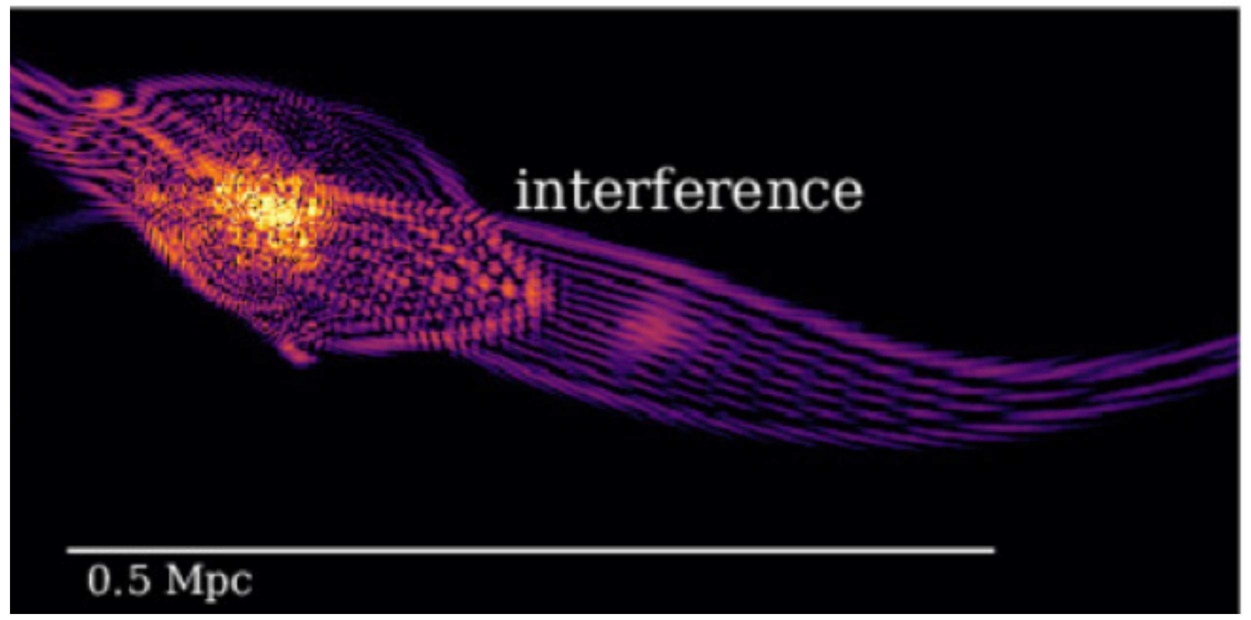
Formation of a solitonic core



Dynamical effects

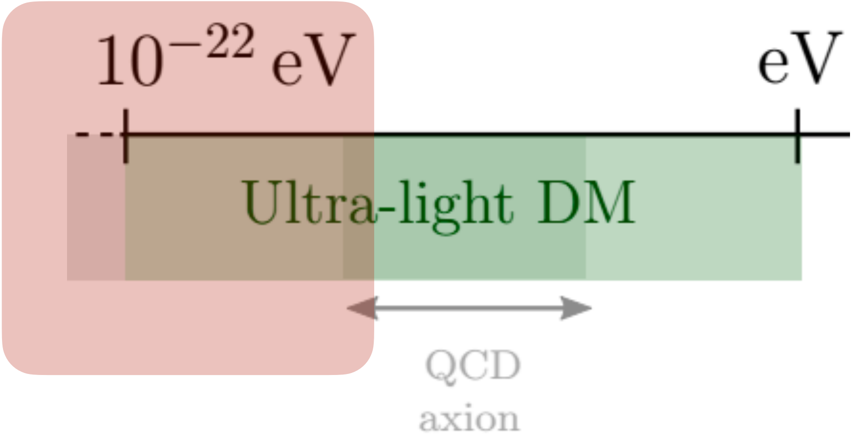


Wave interference



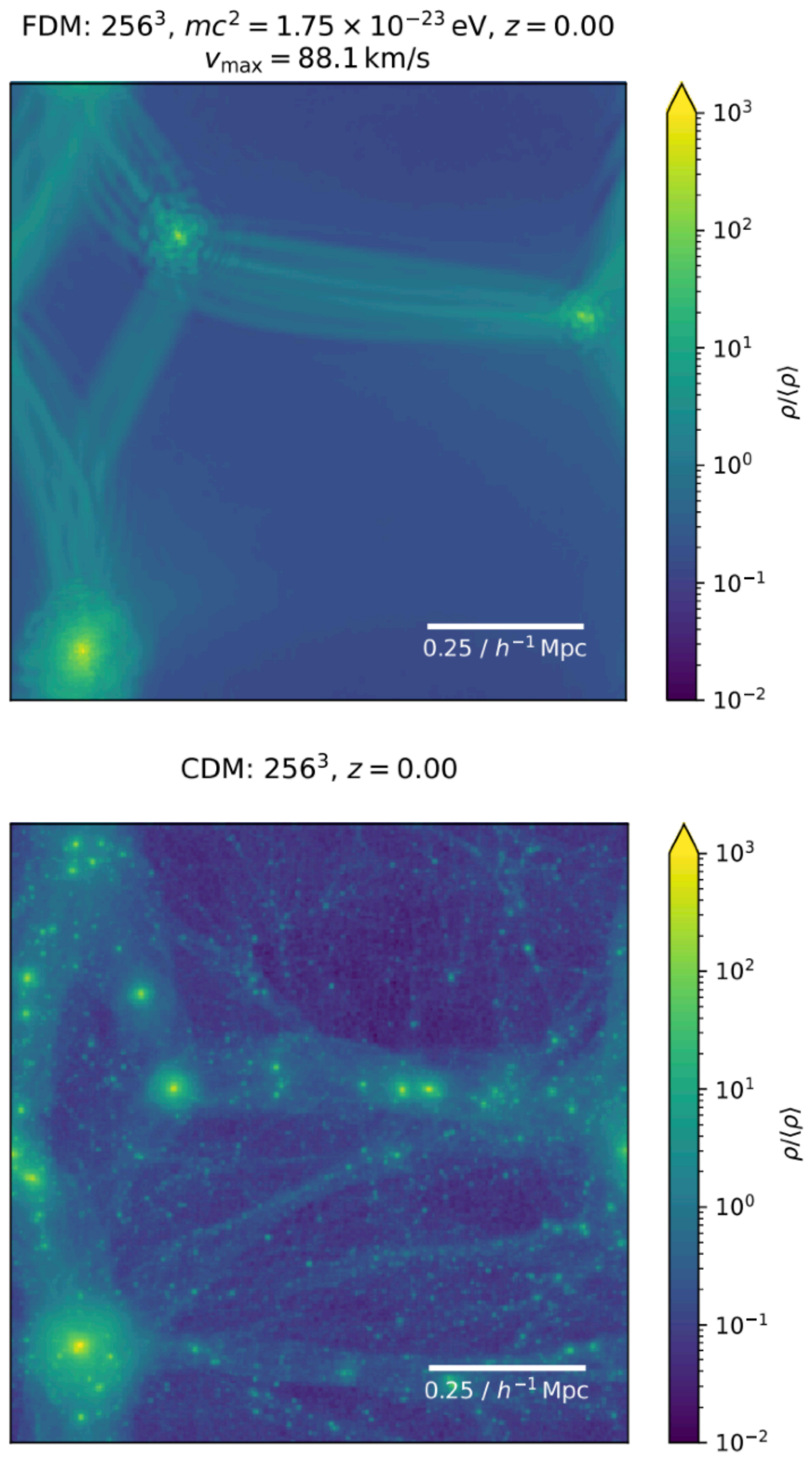
Mocz et al. 2017

Phenomenology



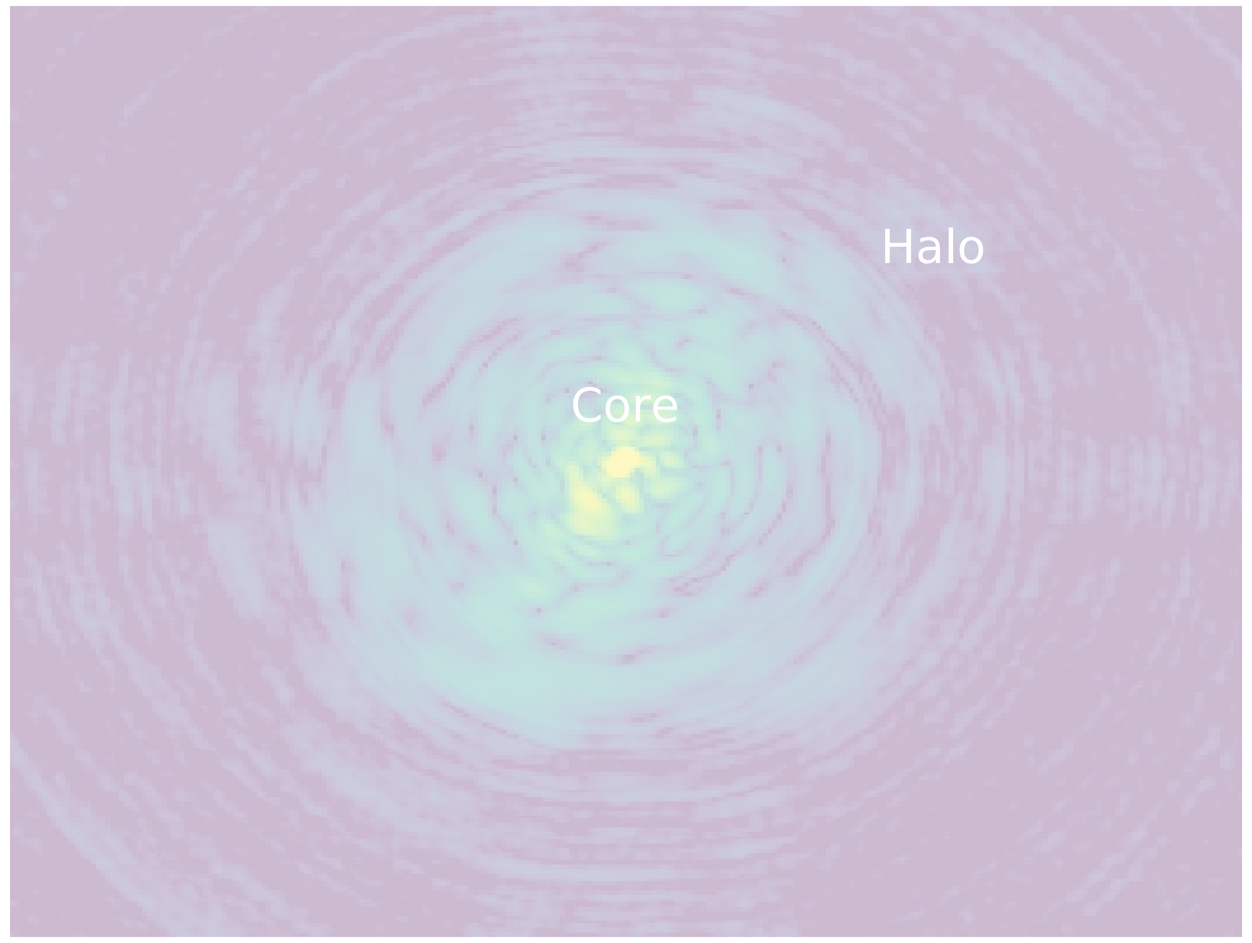
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

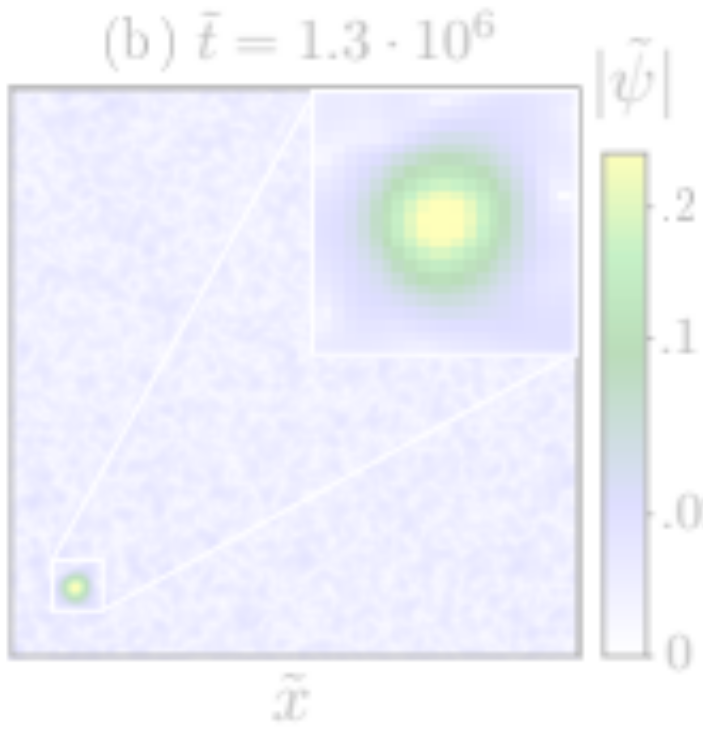


S. May et al. 2021

Formation of a solitonic core

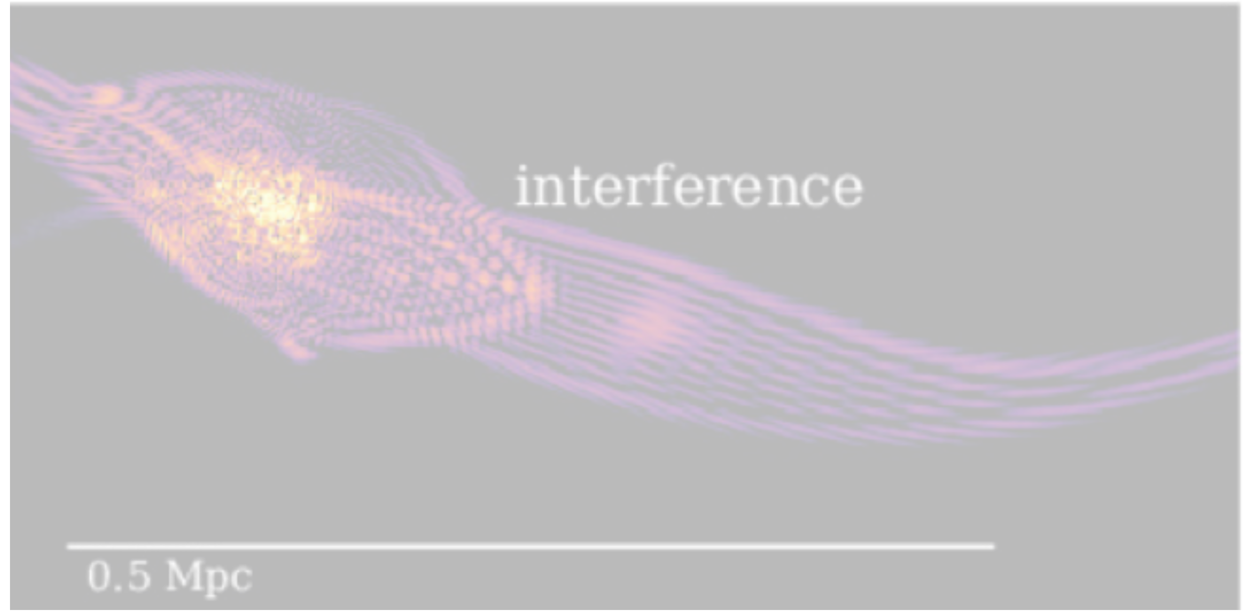


Dynamical effects



Levkov et al. 2018

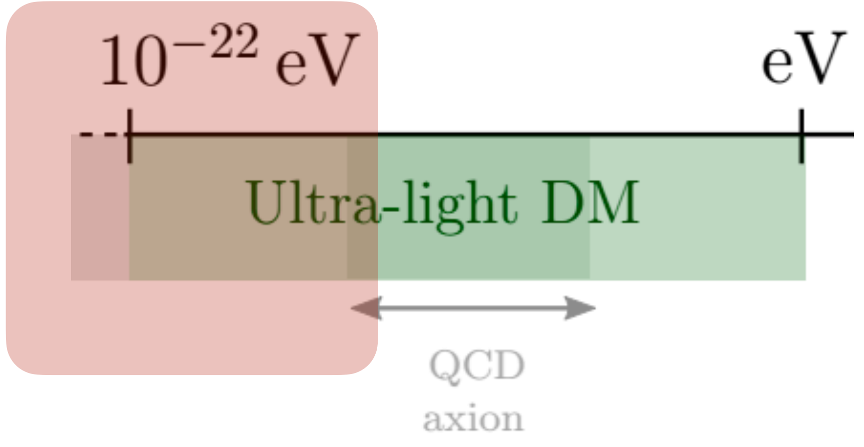
Wave interference



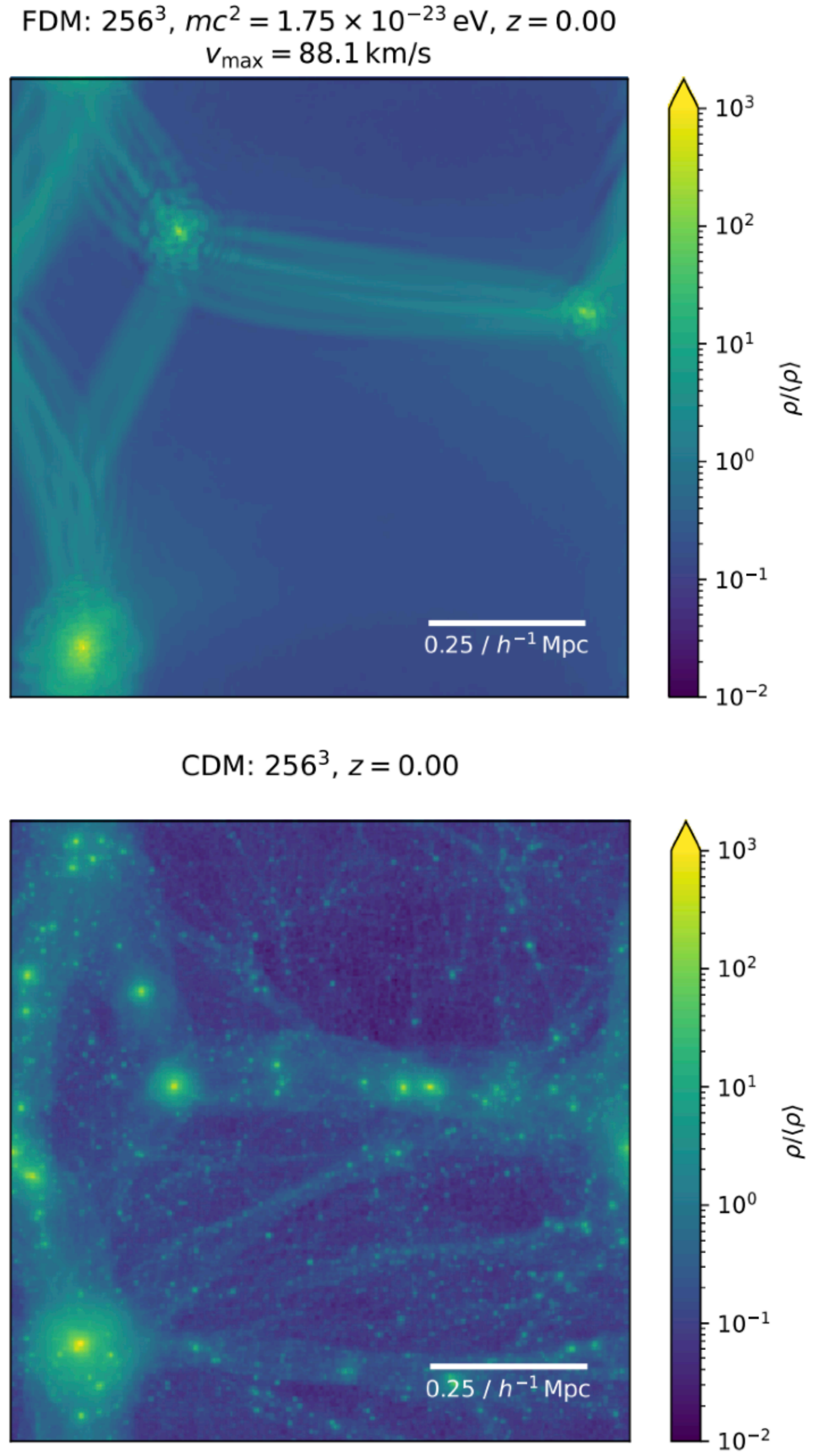
Mocz et al. 2017

Phenomenology

Suppression of small structures



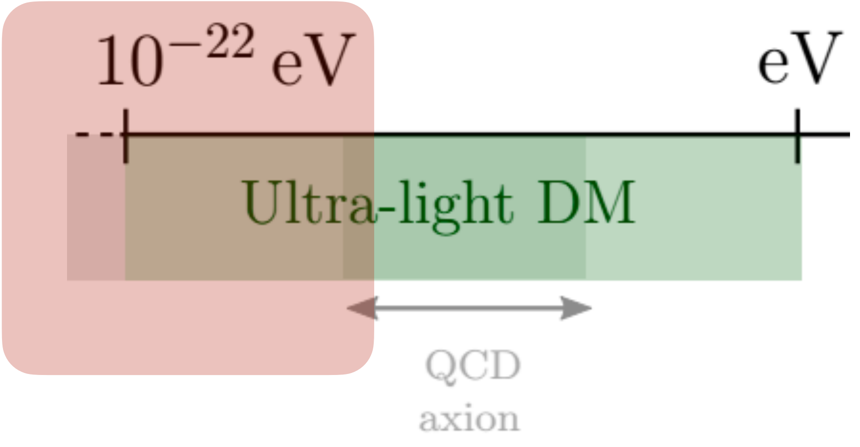
Finite Jeans length λ_J or $\lambda_{\text{attr}}, \lambda_{\text{rep}}$ → No small scale structure



S. May et al. 2021

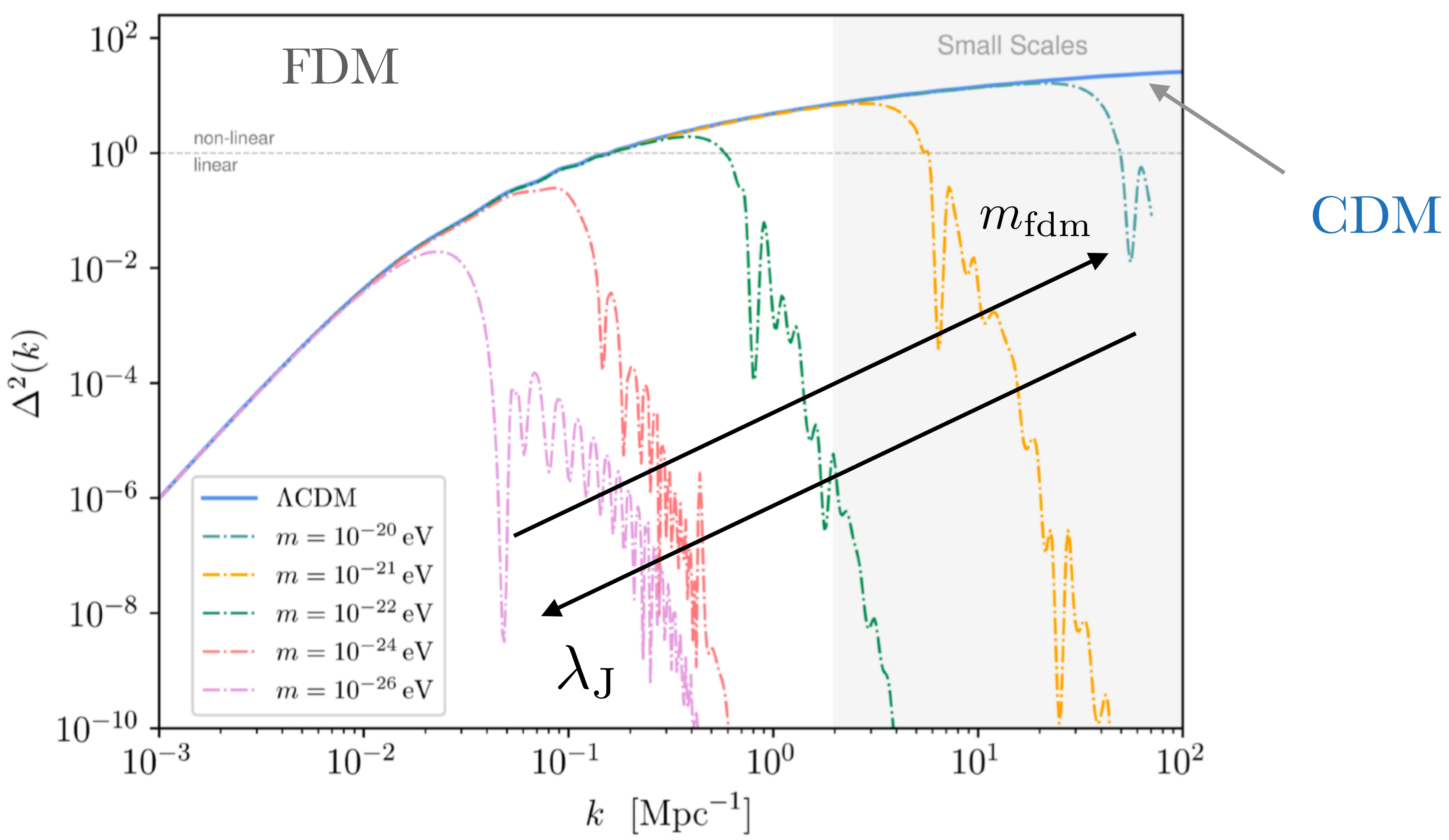
Phenomenology

Suppression of small structures

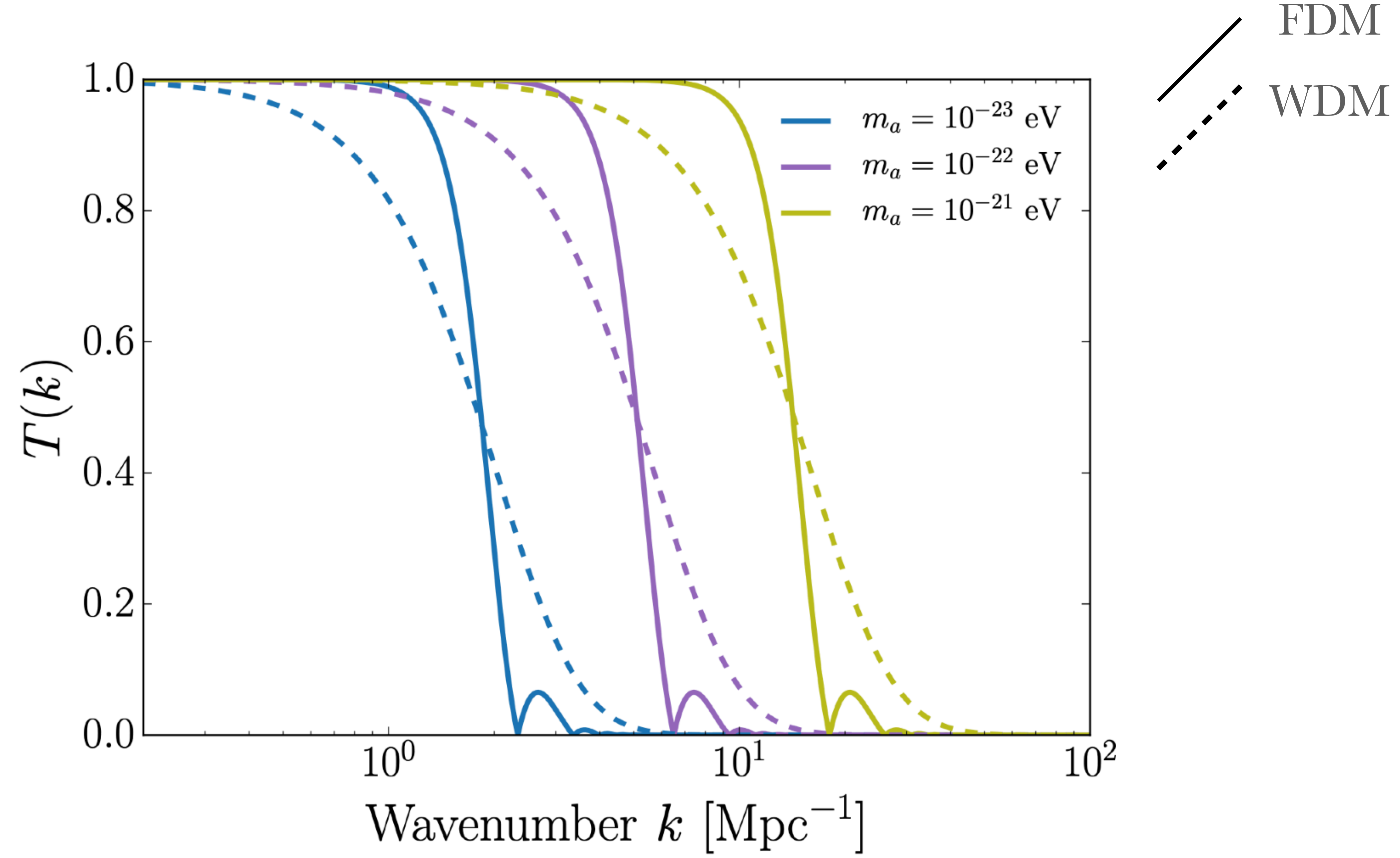


Finite Jeans length λ_J or $\lambda_{attr}, \lambda_{rep}$ → Suppresses small scale structure

POWER SPECTRUM



TRANSFER FUNCTION



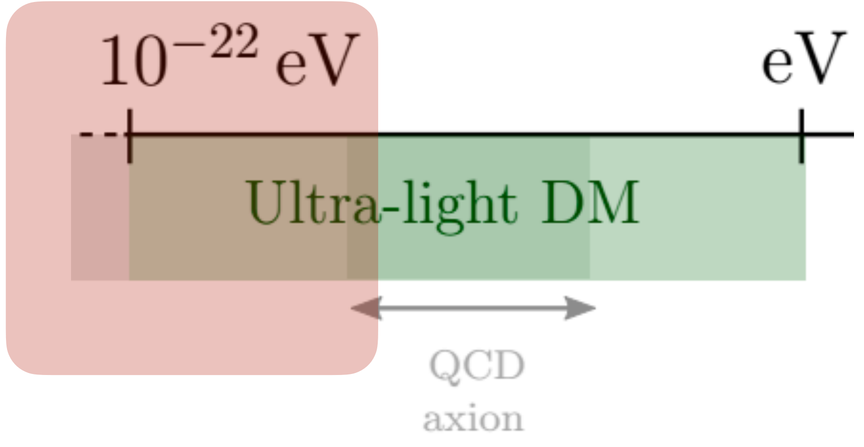
$$P_X(k,z) = T_X^2(k,z)\,P_{\Lambda CDM}(k)$$

$$\begin{cases} T_{WDM} = [1 + (\alpha k)^{2\mu}]^{-5/\mu} \\ T_{FDM} = \frac{\cos x_J^3(k)}{1+x_J^8(k)} \end{cases}$$

- Degenerate with WDM

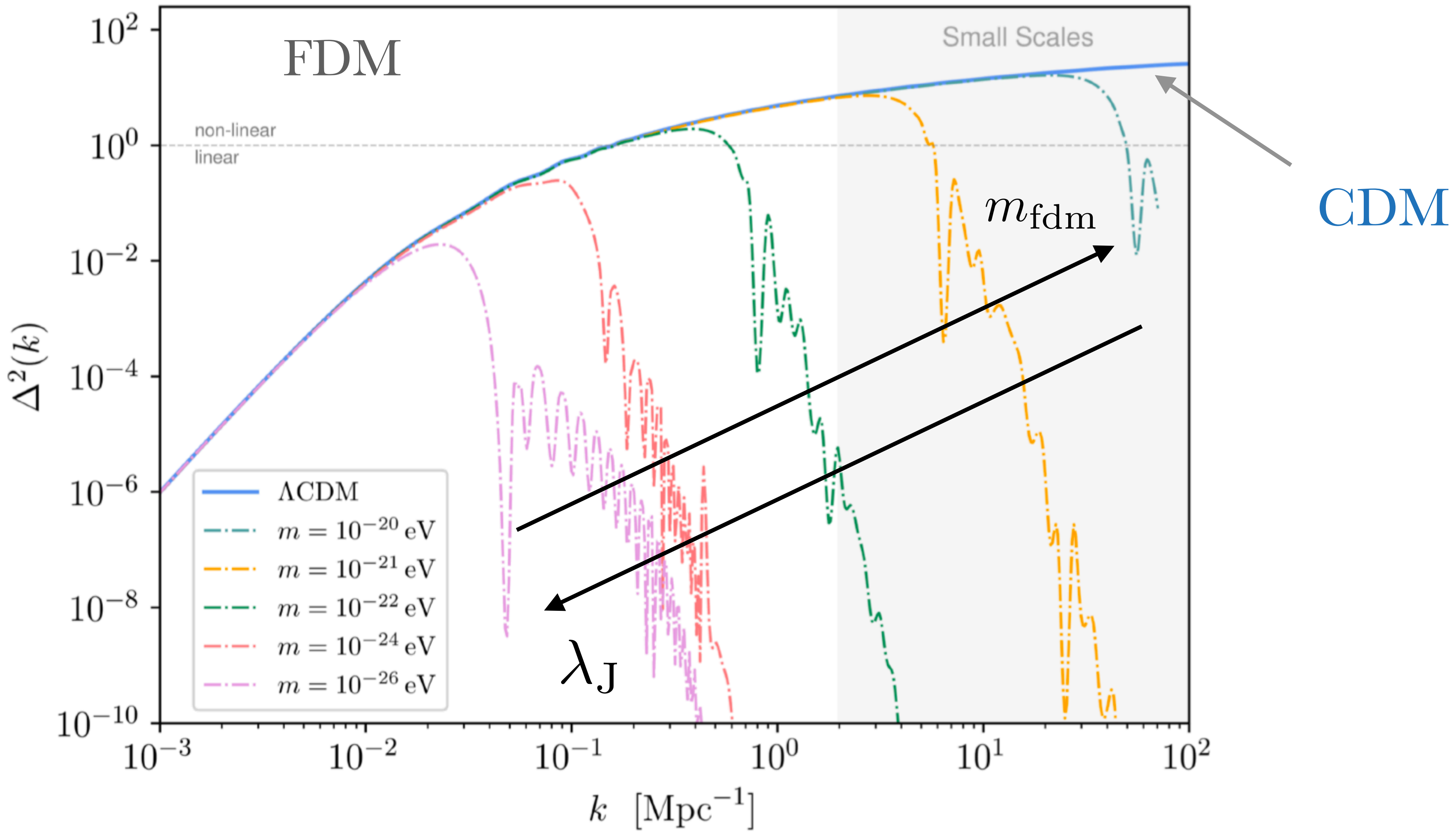
Phenomenology

Suppression of small structures

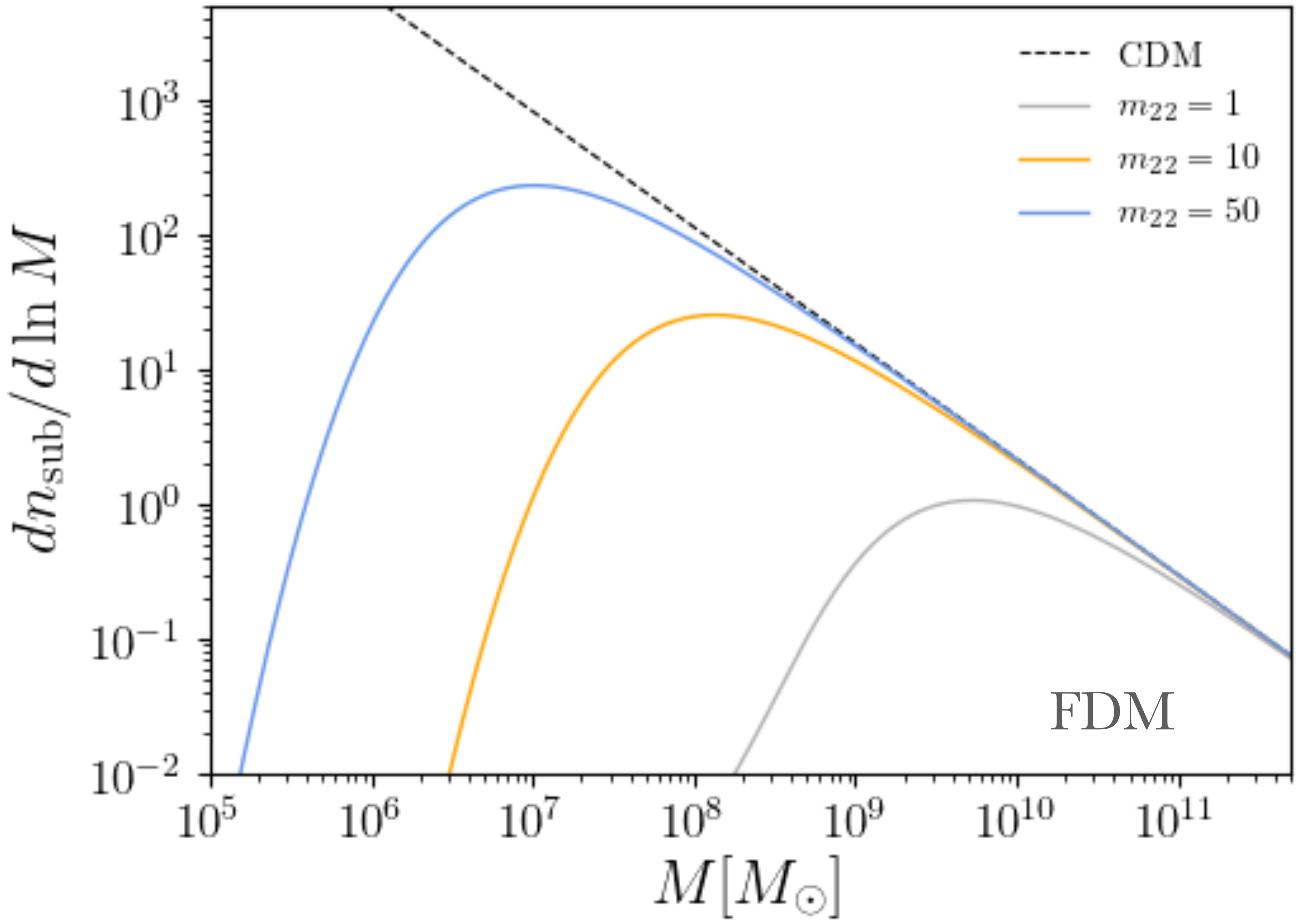


Finite Jeans length λ_J or $\lambda_{\rm attr}, \lambda_{\rm rep}$ $\longrightarrow$ Suppresses small scale structure

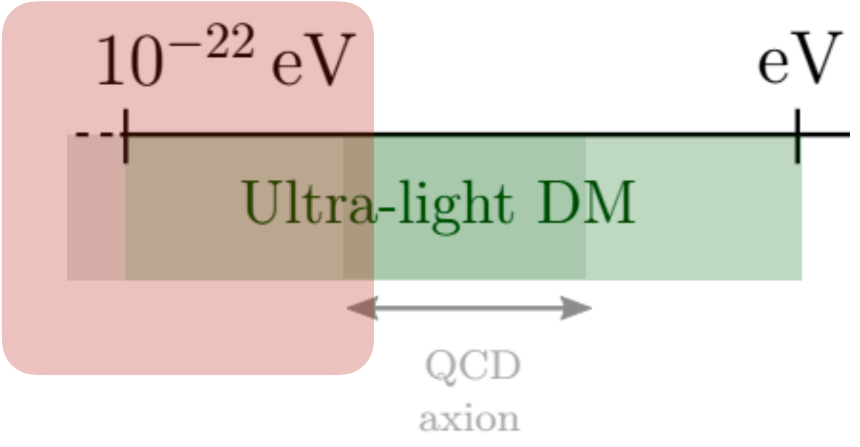
POWER SPECTRUM



(sub) HALO MASS FUNCTION

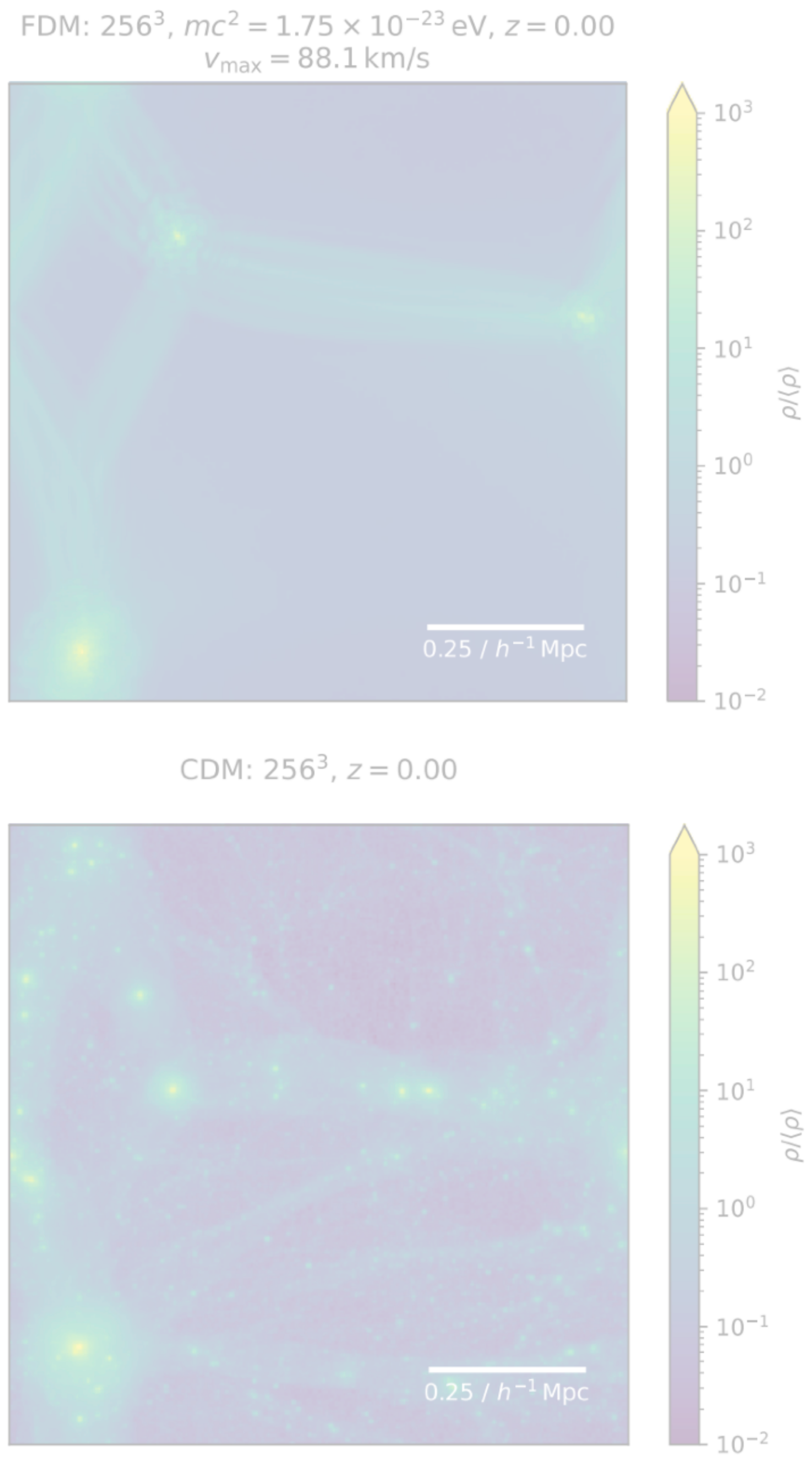


Phenomenology



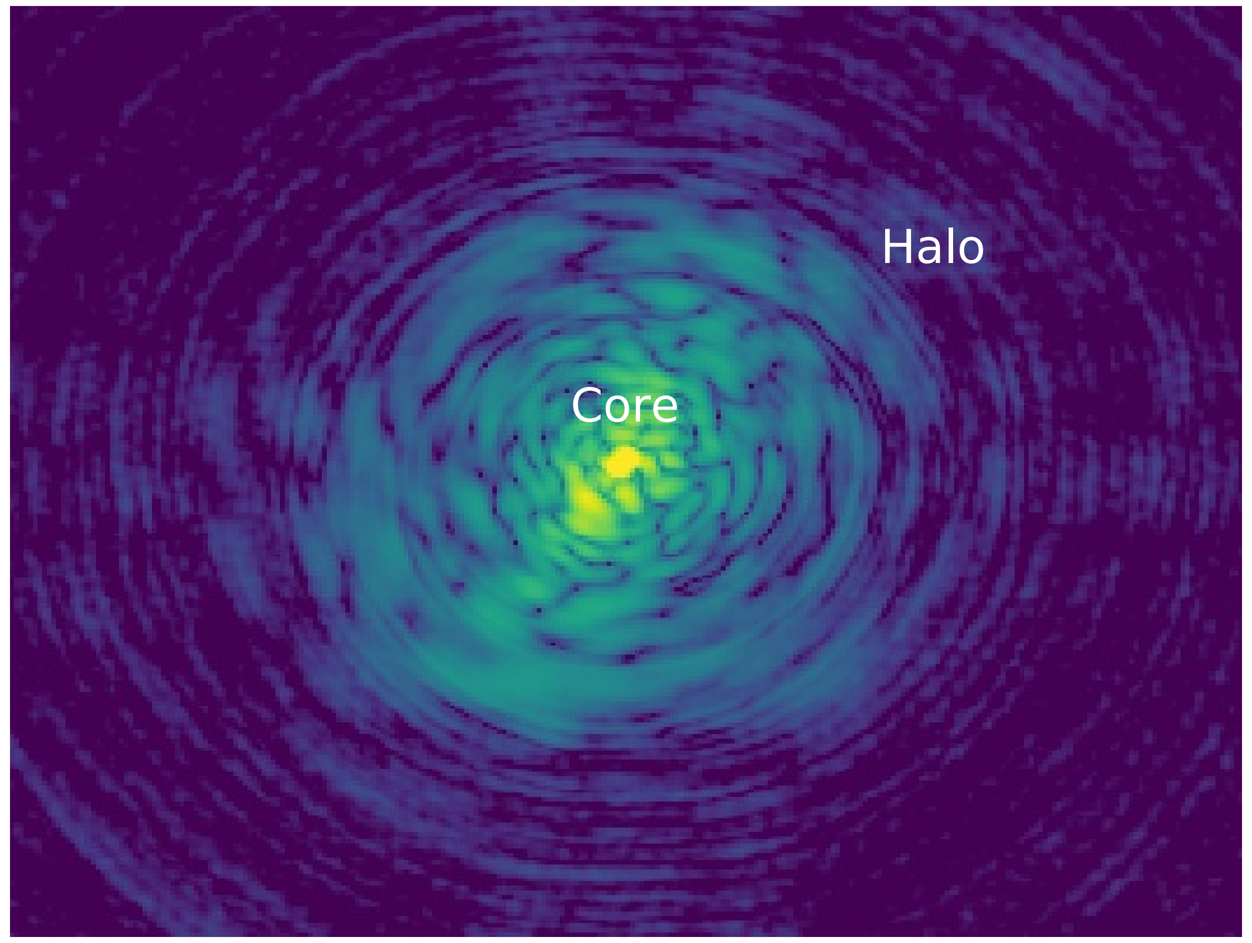
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

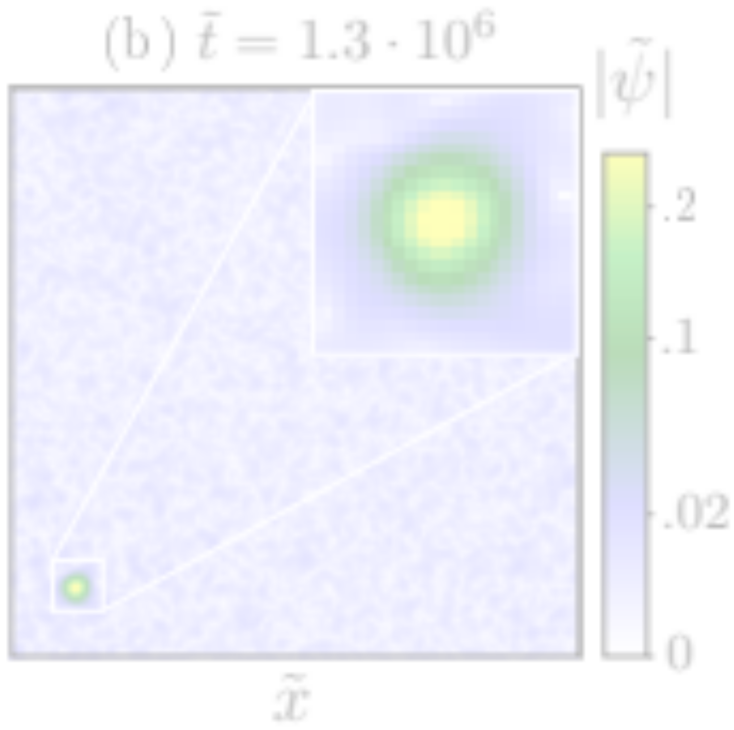


S. May et al. 2021

Formation of a solitonic core

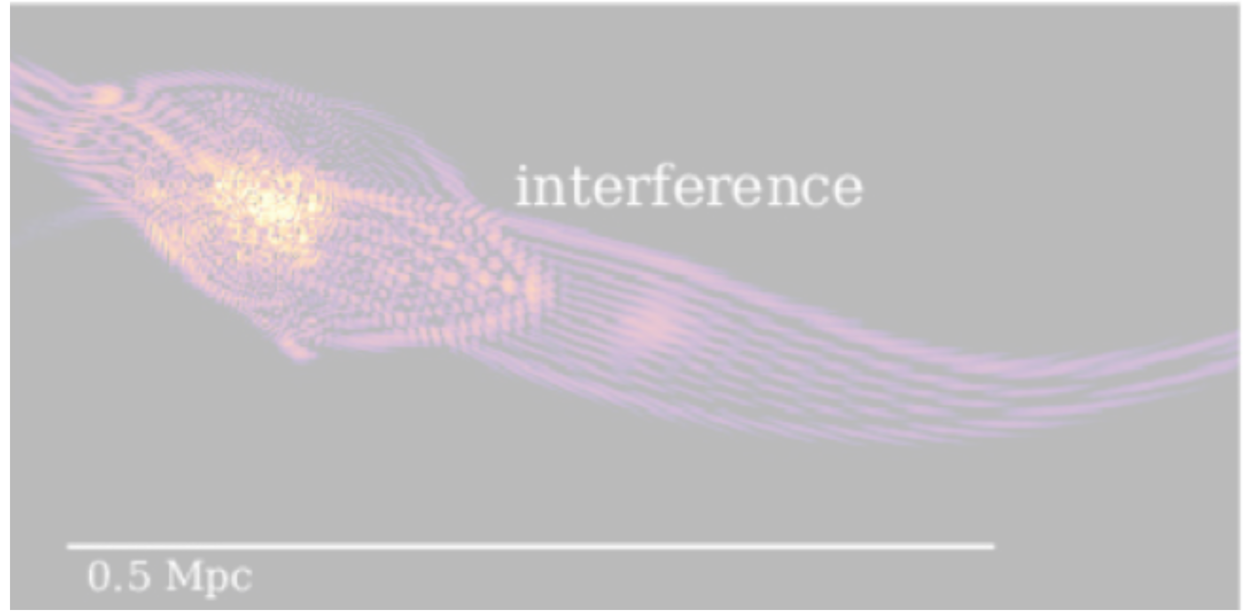


Dynamical effects



Levkov et al. 2018

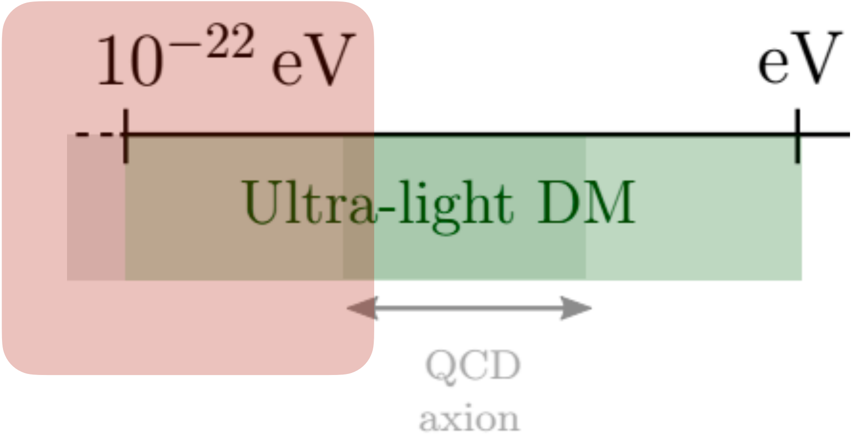
Wave interference



Mocz et al. 2017

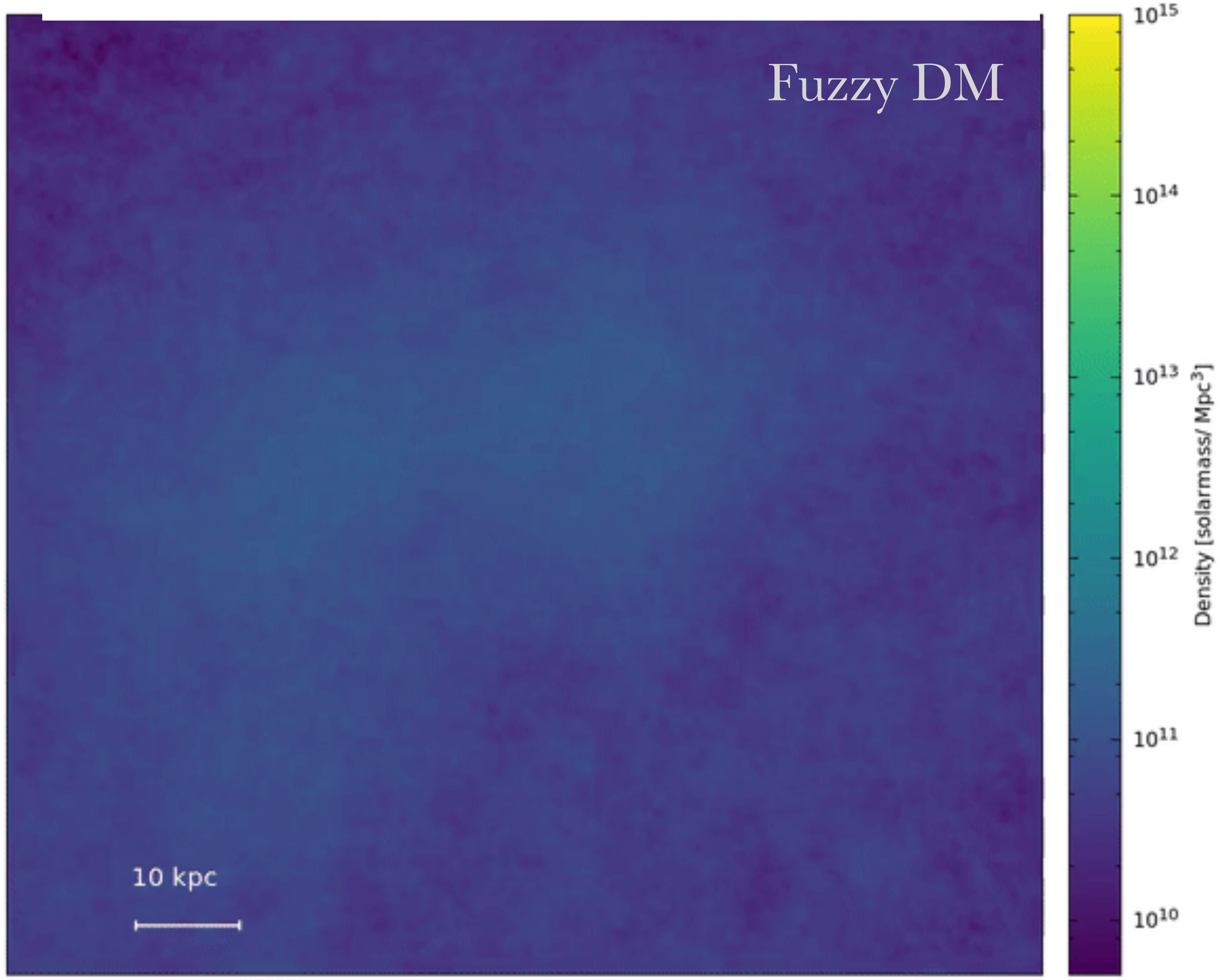
Phenomenology

Formation of cores

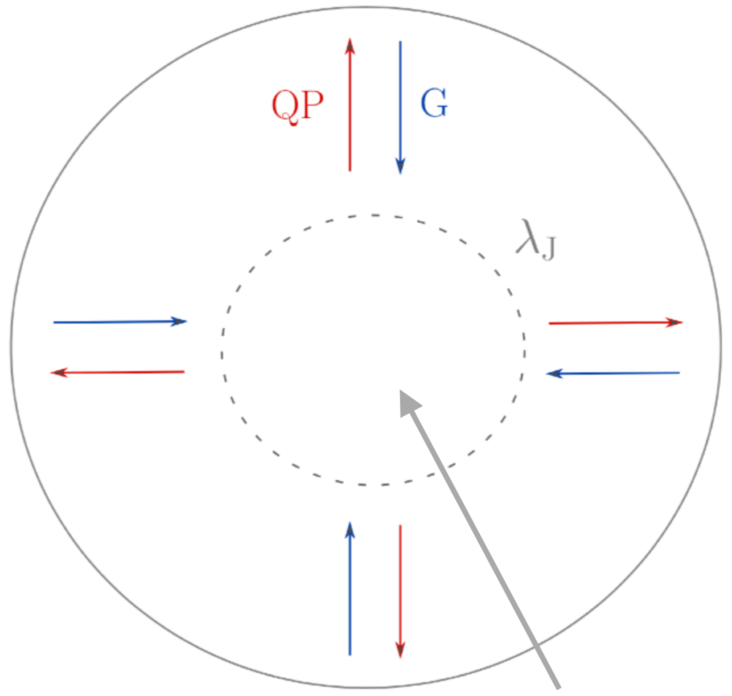


NON-LINEAR evolution: need simulations

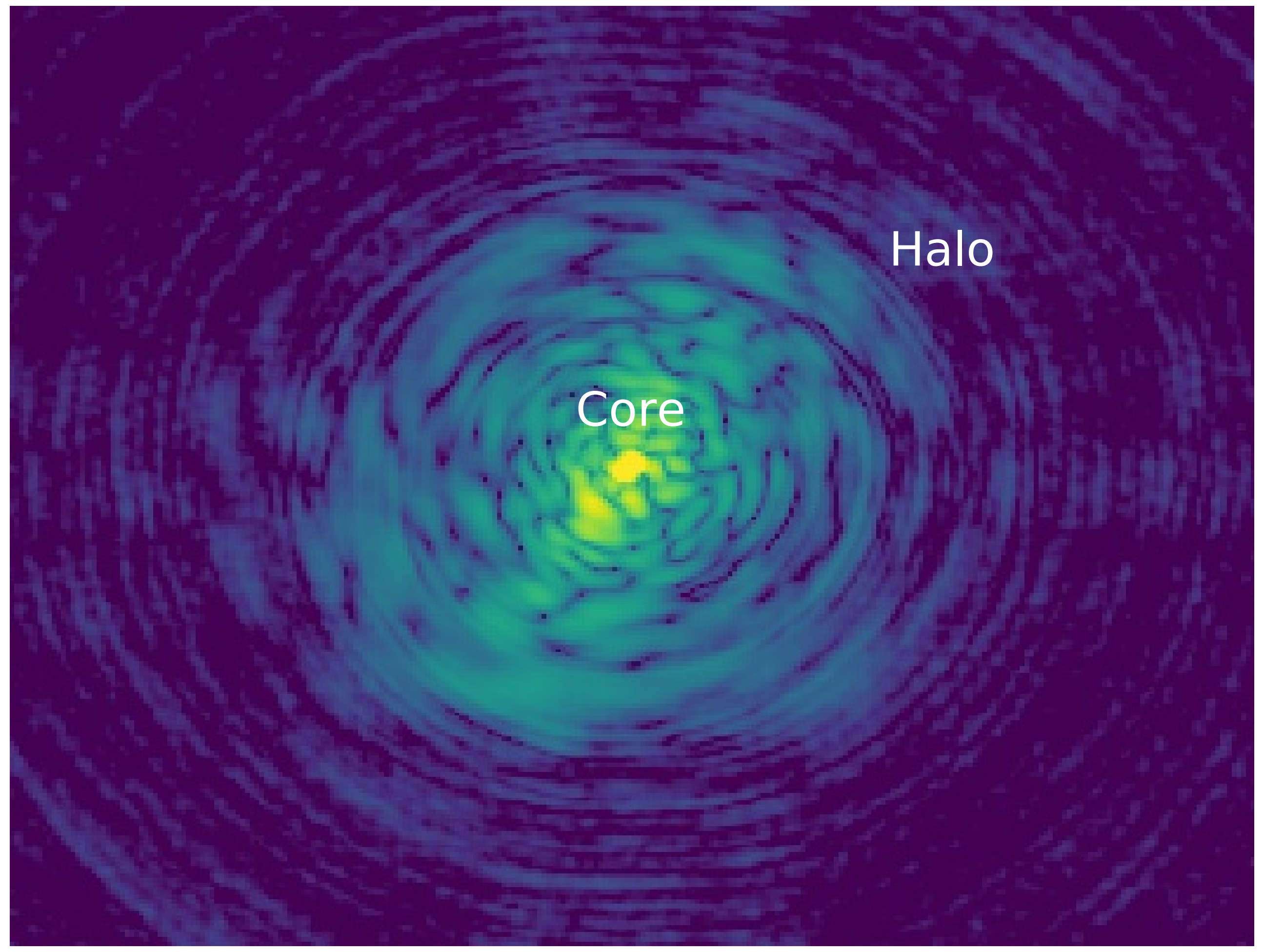
$$m = 10^{-22}\,\text{eV} \qquad N = 512^3 \qquad L = 300\,\text{kpc}$$



Simulation by Jowett Chan

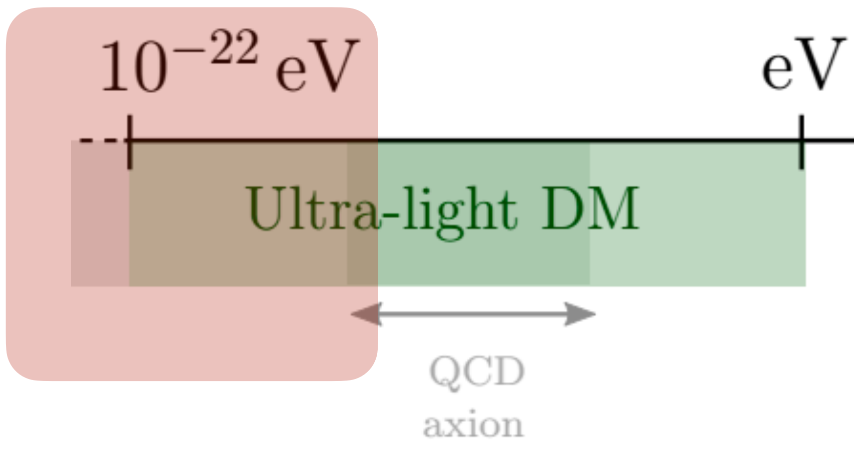


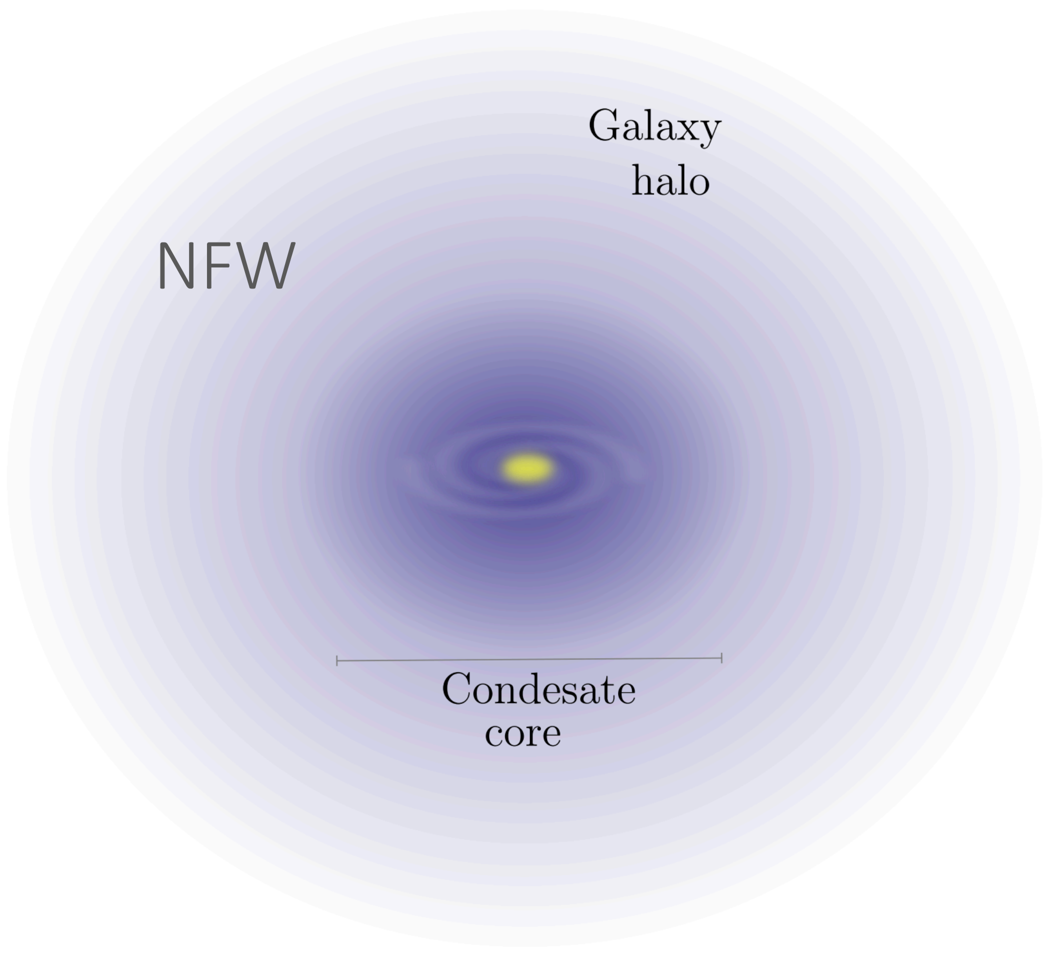
NO structure formation
Stable, oscillating solution



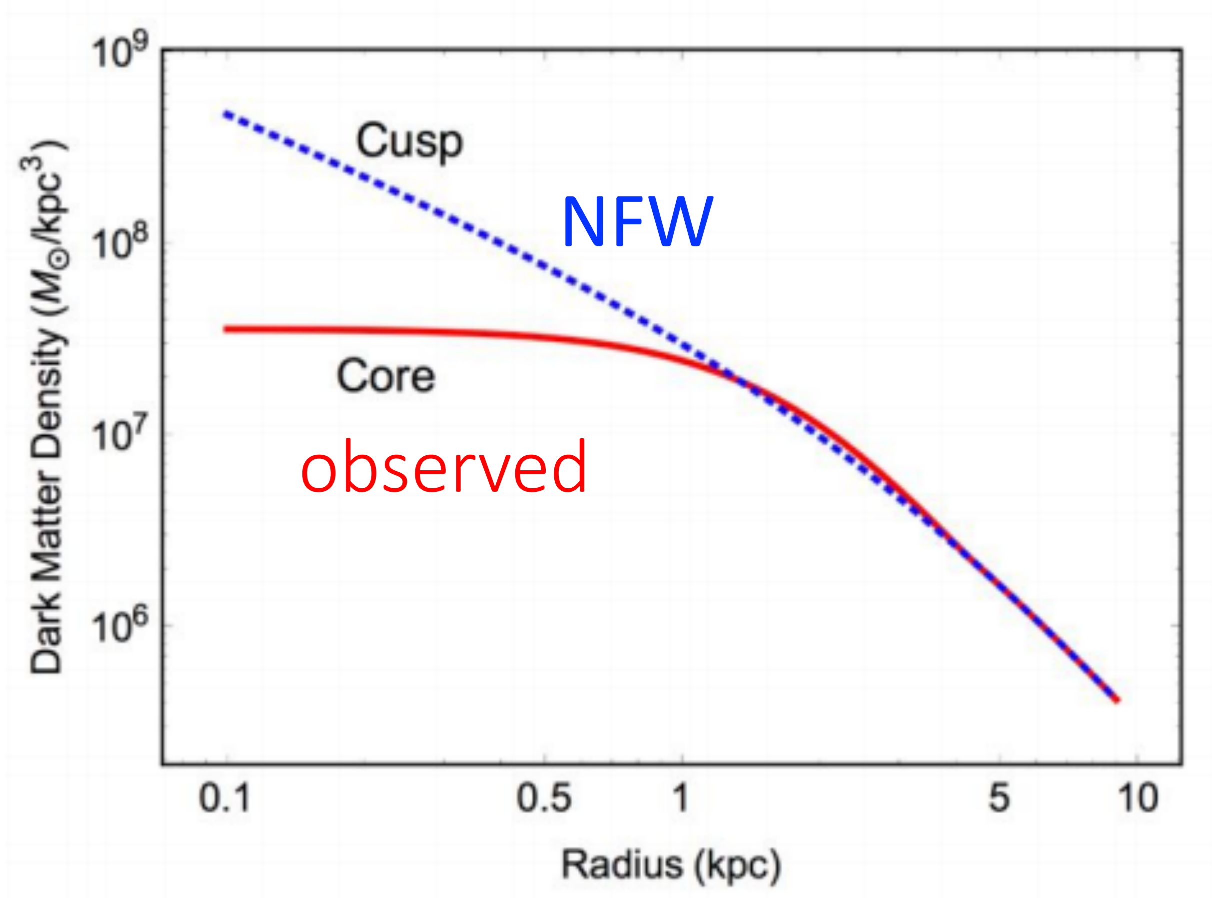
Phenomenology

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

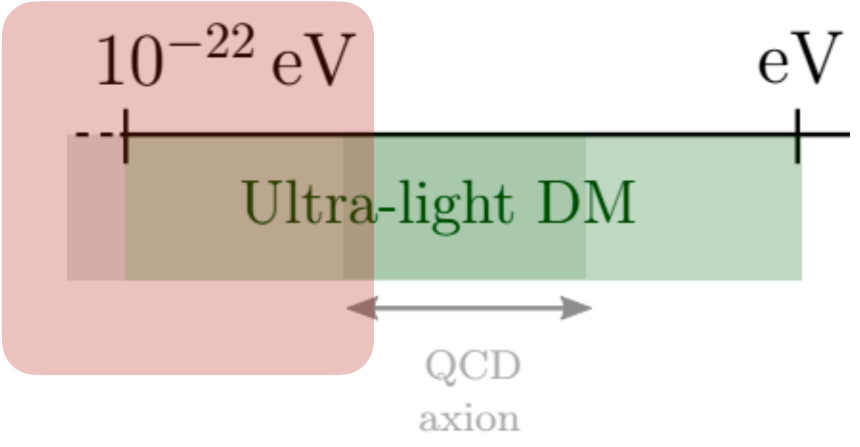
$$\rho_c \simeq \frac{1.9 \times 10^{-2}}{[1+0.091\,(r/R_{1/2,c})^2]^8} \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-2} \left(\frac{r_c}{\mathrm{kpc}}\right)^{-4} M_\odot\,\mathrm{pc}^{-3}\,,$$

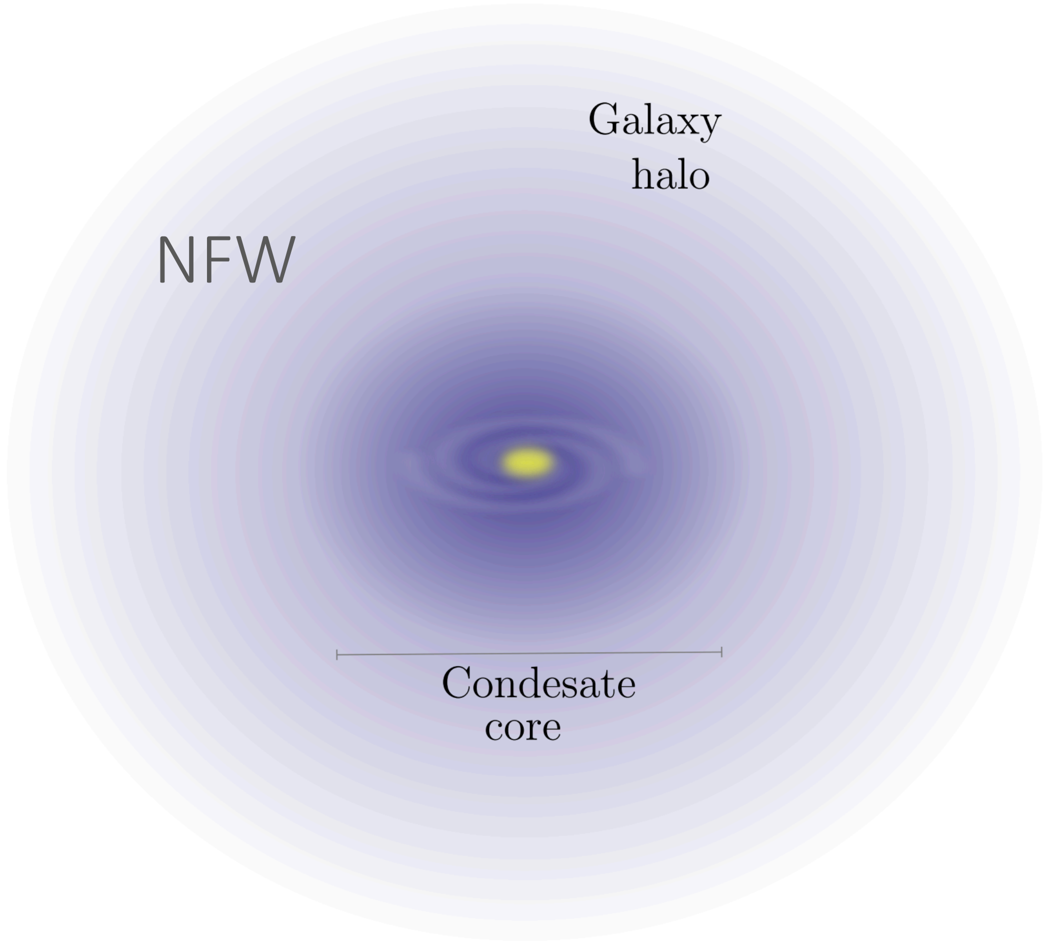
$$r_c \simeq 0.16 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1} \left(\frac{M}{10^{12}\,M_\odot}\right)^{-1/3} \mathrm{kpc}\,.$$

Relations used to compare with observations

Phenomenology

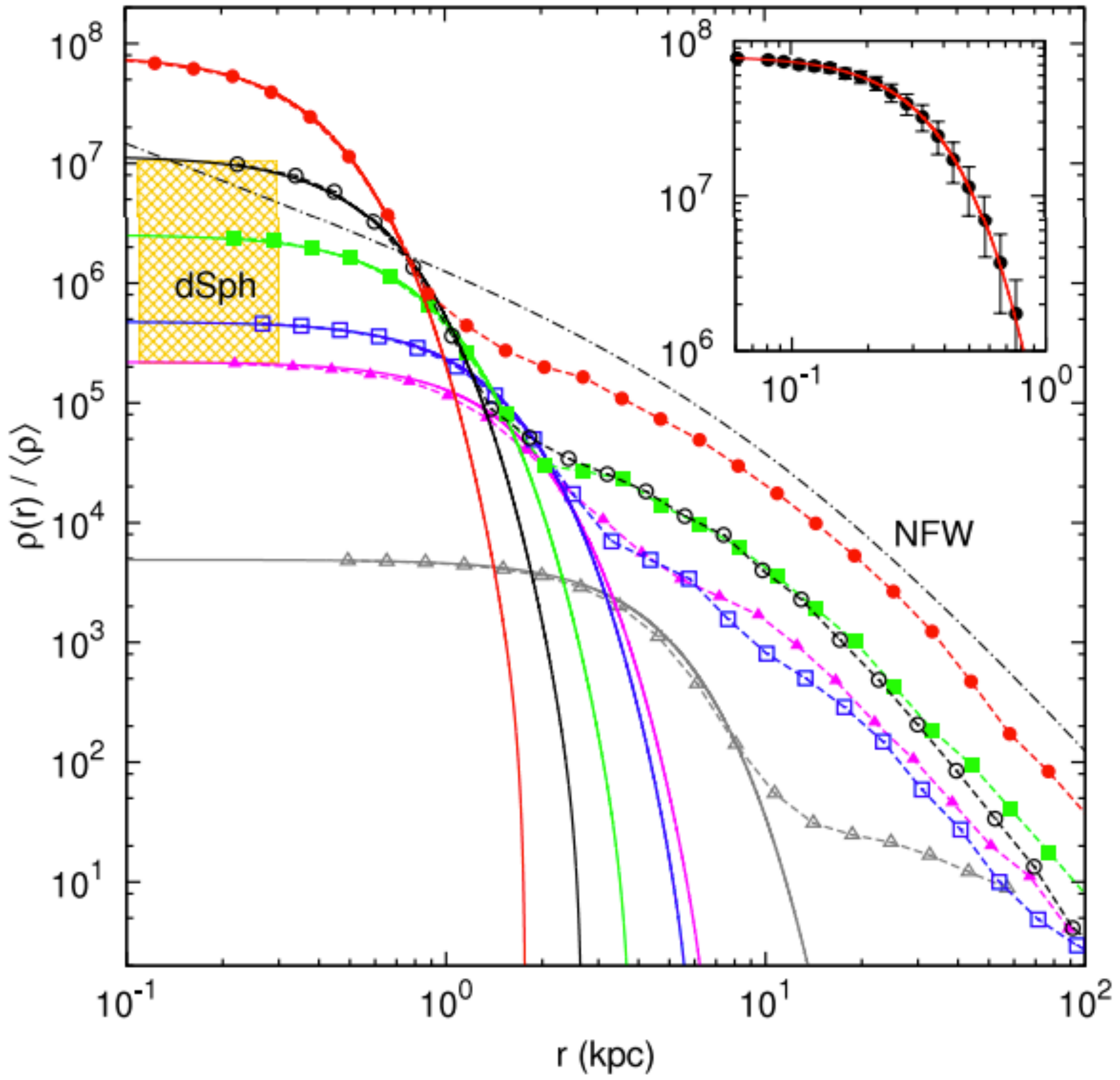
Formation of cores





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

Schive et al. 2014



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

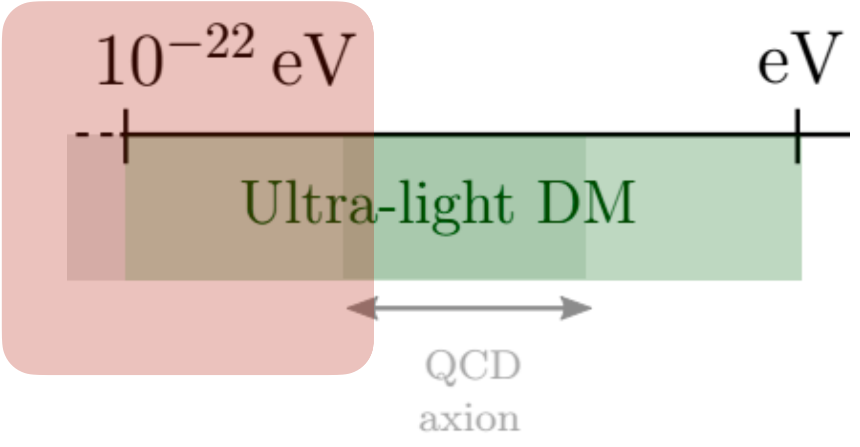
$$\rho_c \simeq \frac{1.9\times 10^{-2}}{[1+0.091\,(r/R_{1/2,c})^2]^8}\left(\frac{m}{10^{-22}\,\text{eV}}\right)^{-2}\left(\frac{r_c}{\text{kpc}}\right)^{-4} M_\odot\,\text{pc}^{-3}\,,$$

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

→

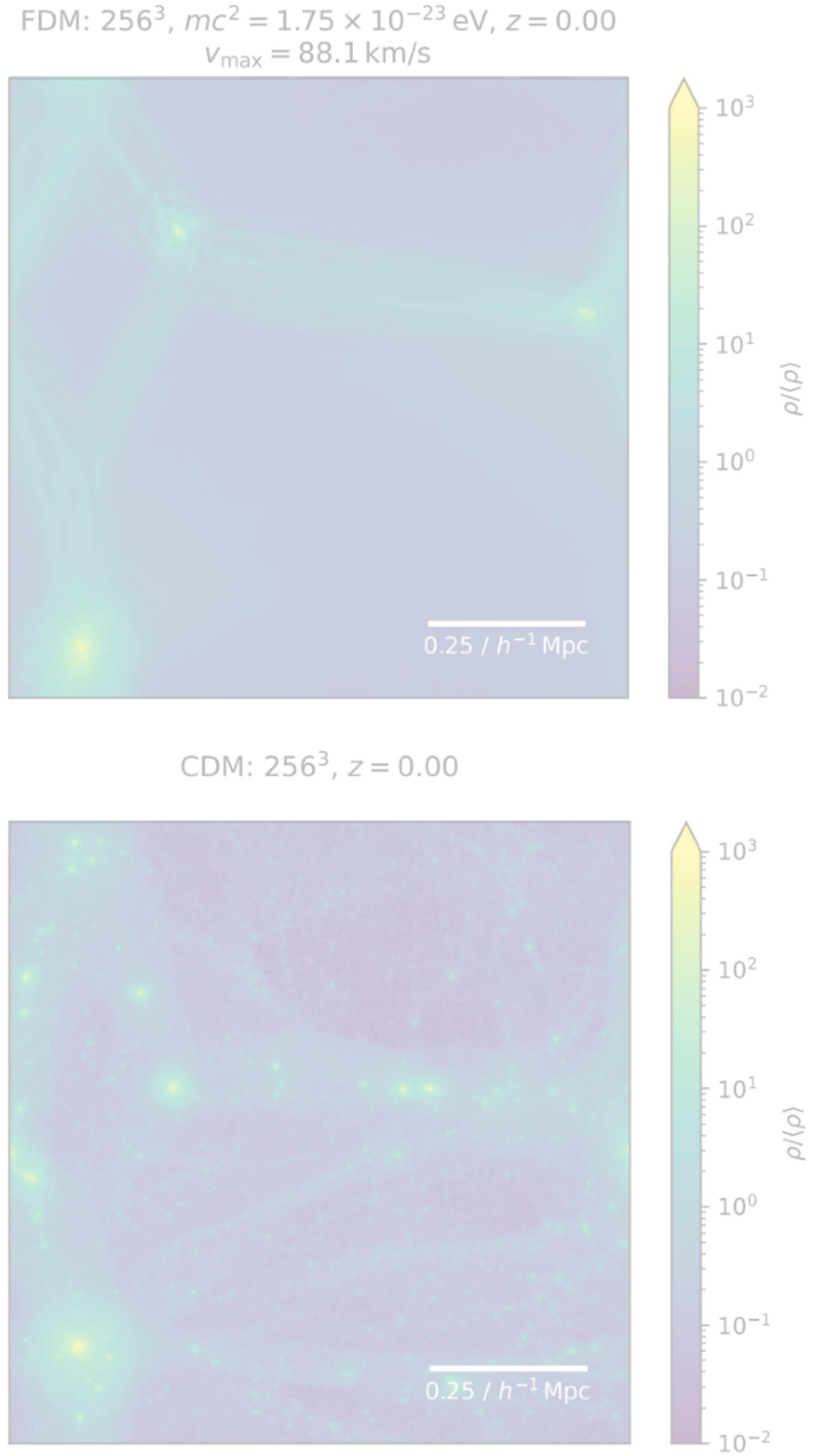
Relations used to compare
with observations

Phenomenology



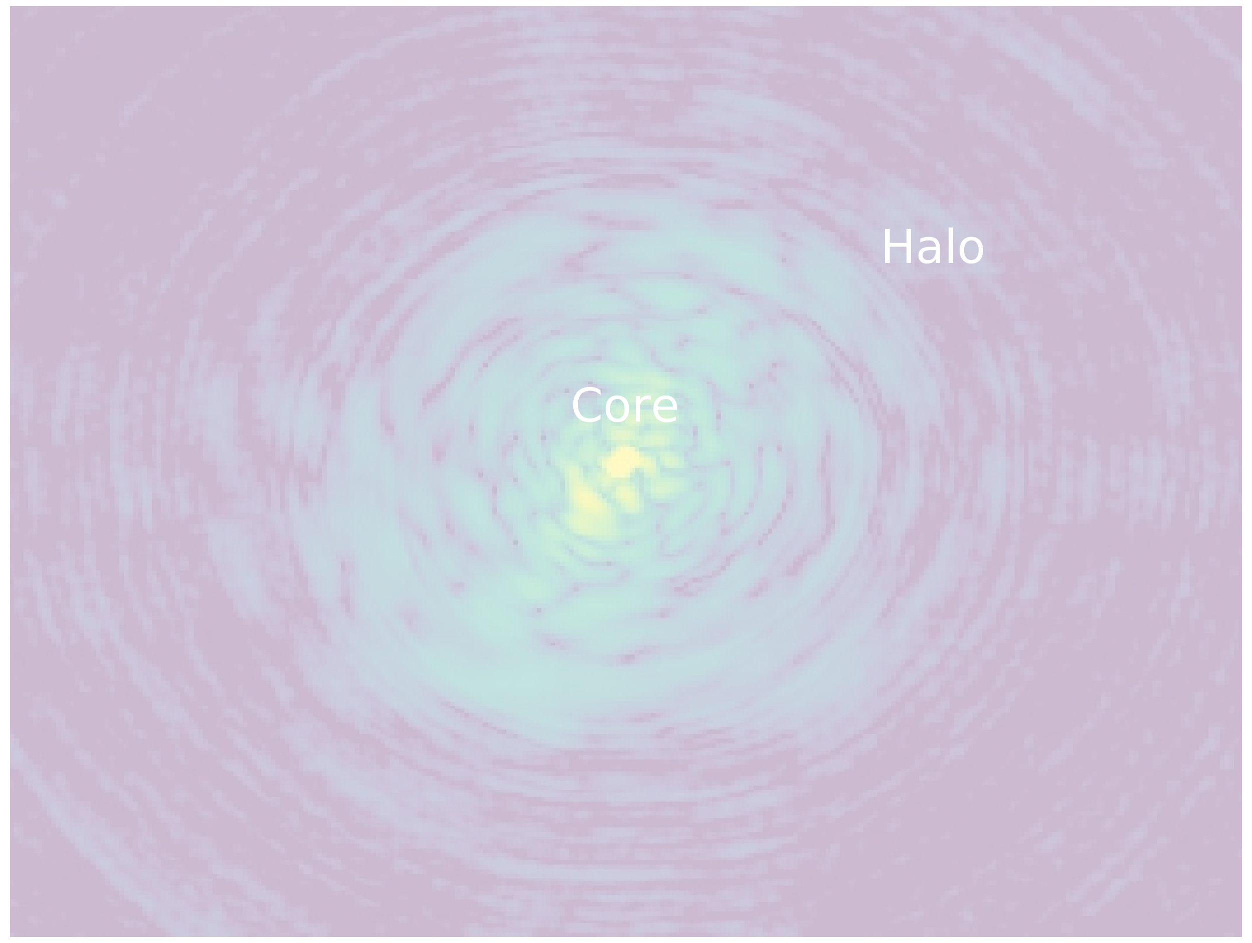
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

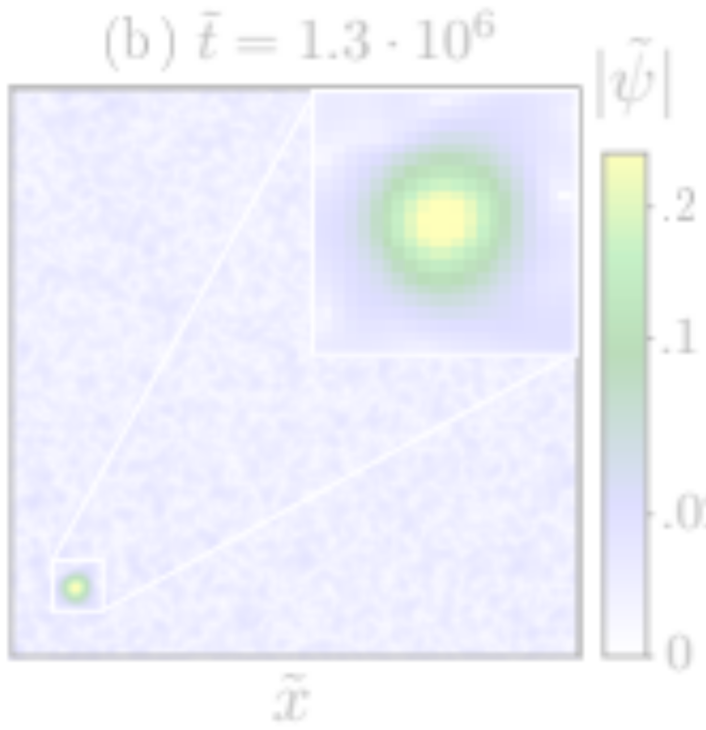


S. May et al. 2021

Formation of a solitonic core

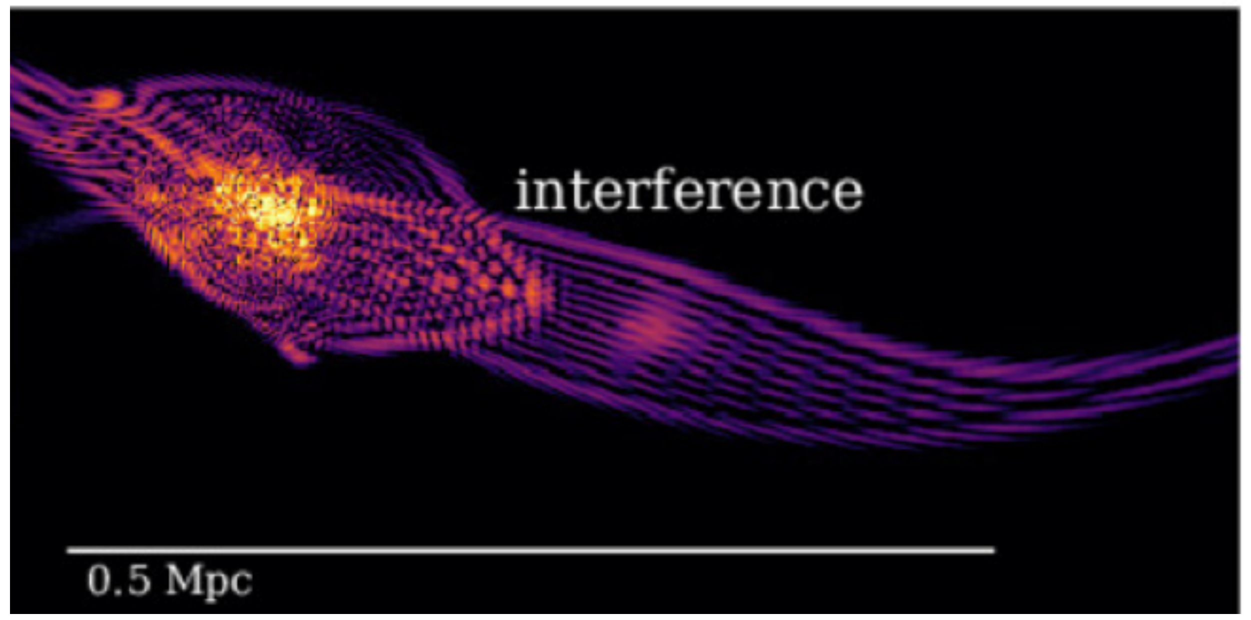


Dynamical effects



Levkov et al. 2018

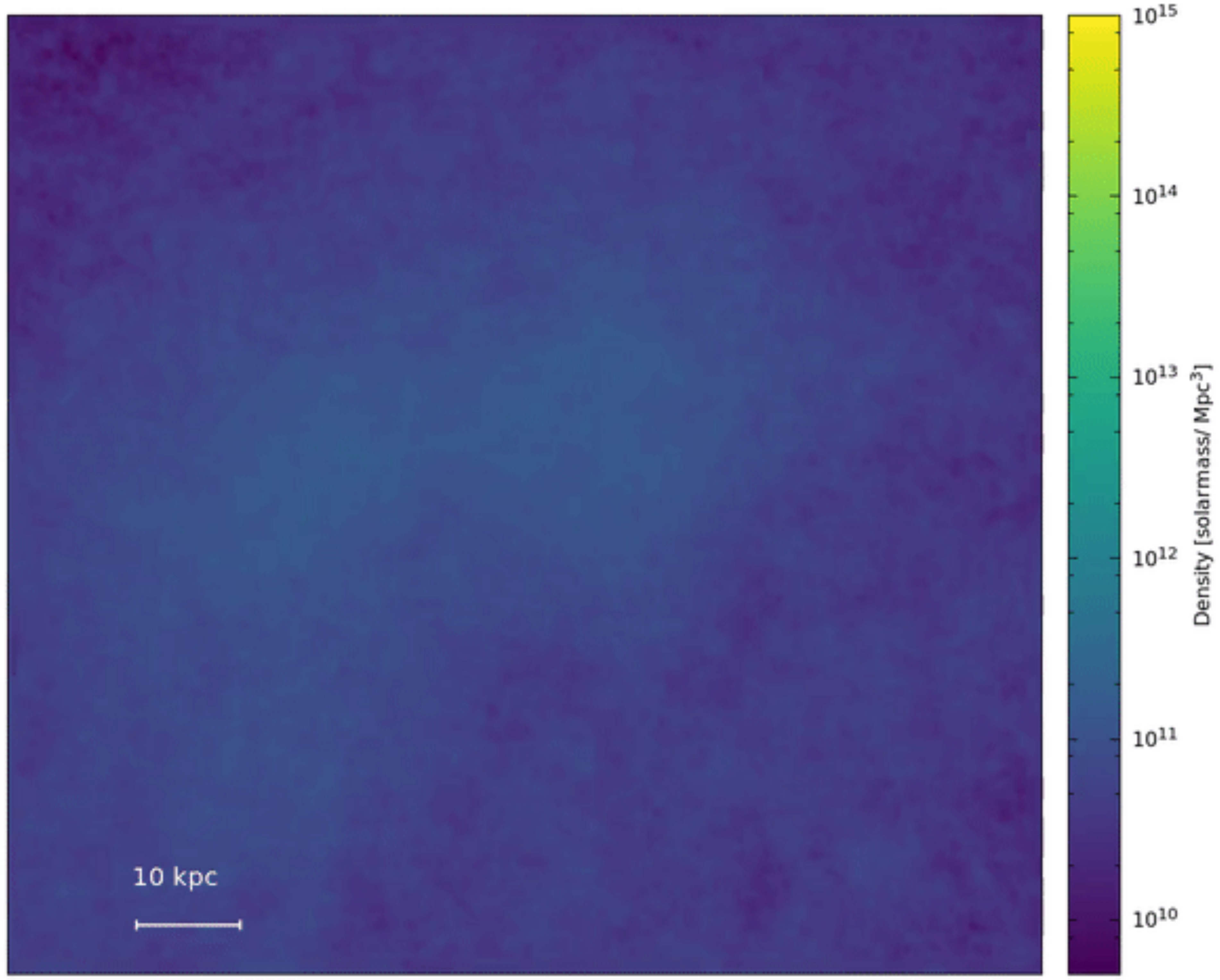
Wave interference



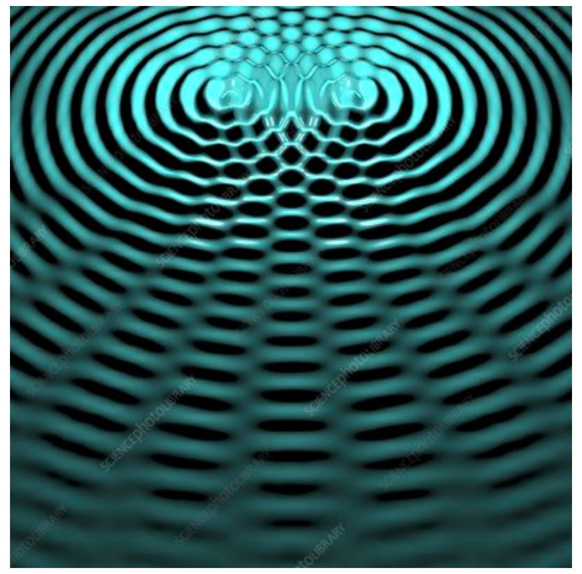
Mocz et al. 2017

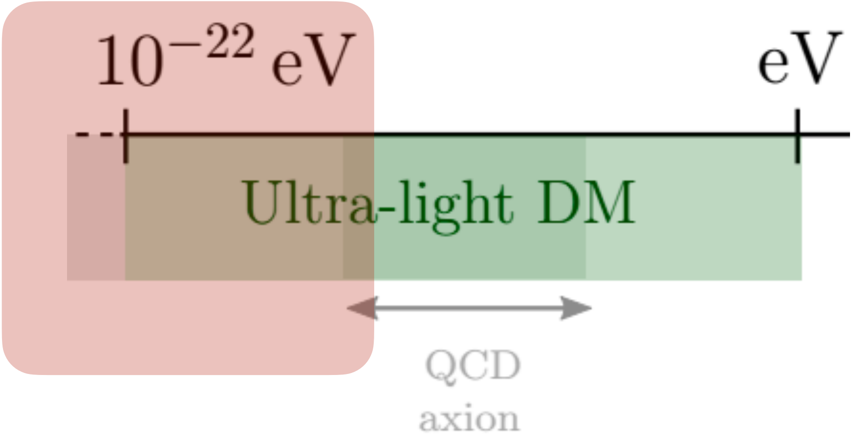
Phenomenology

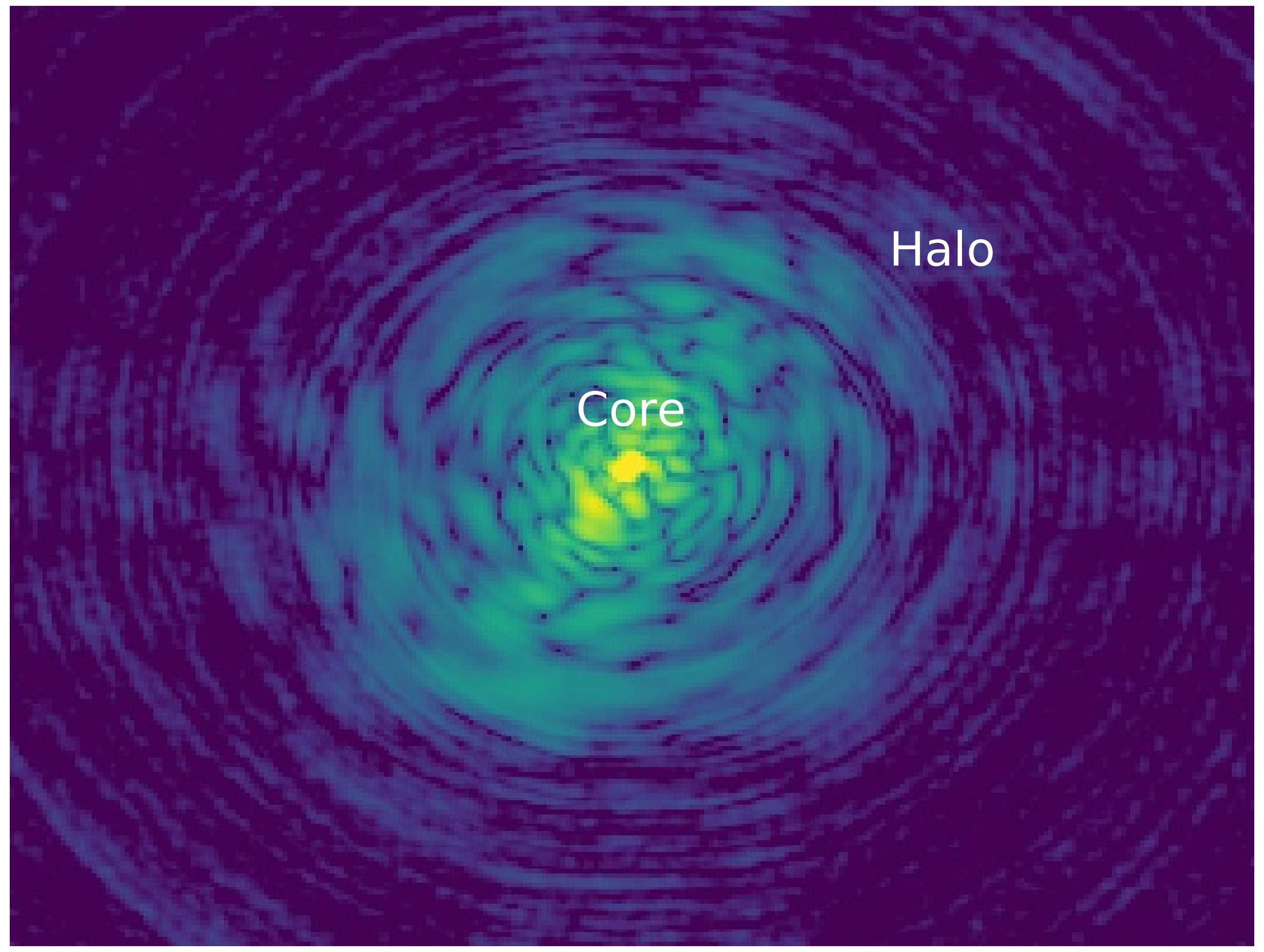
Wave interference: granules and vortices

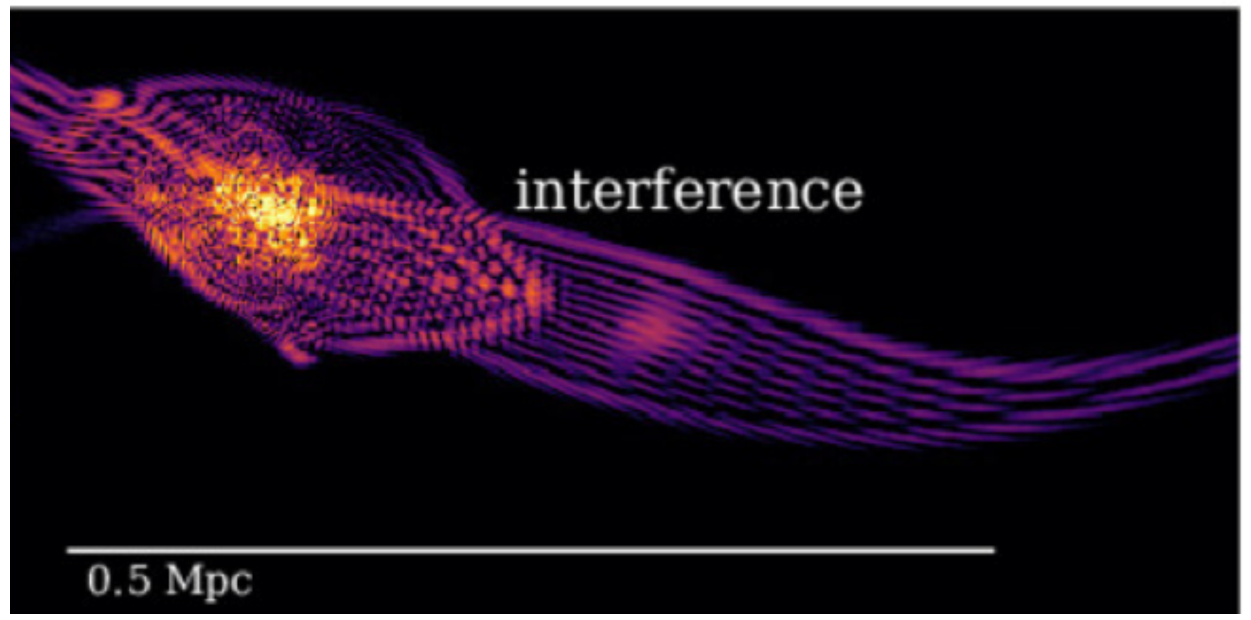


Simulation by Jowett Chan









Mocz et al. 2017

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

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

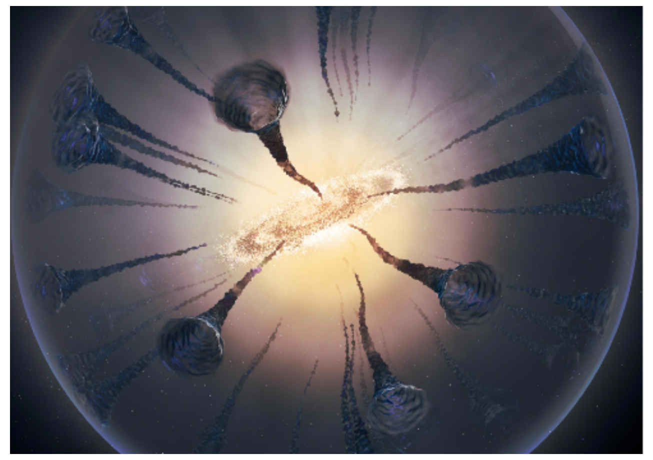
Phenomenology

Vortices

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

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

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



Quanta magazine

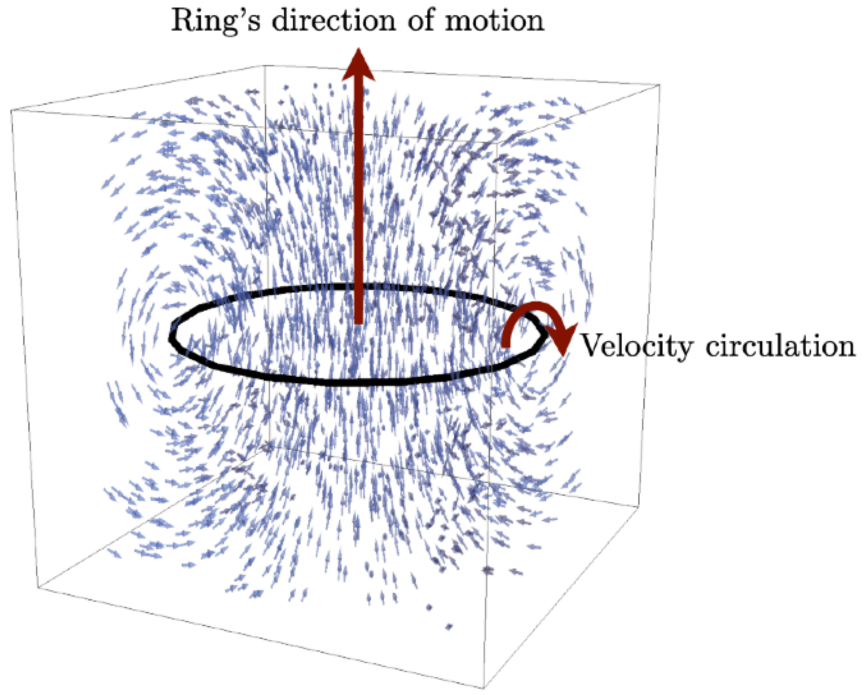
Two ways:
- regions where the density vanishes
- transfer of angular momentum (superfluids only)

Fuzzy DM

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

General defet in 3D

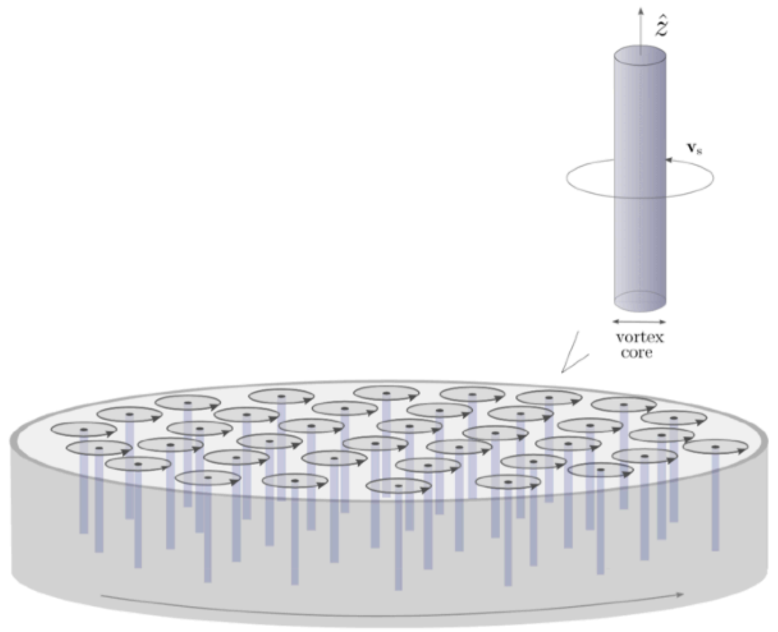
$$\mathcal{C} = \frac{1}{m}\oint_{\partial A} \mathrm{d}\theta = \frac{2\pi n}{m}$$



Hui et al 2020

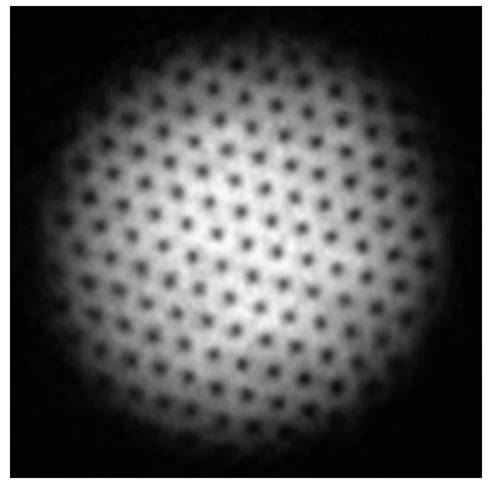
Self-interacting Fuzzy DM

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

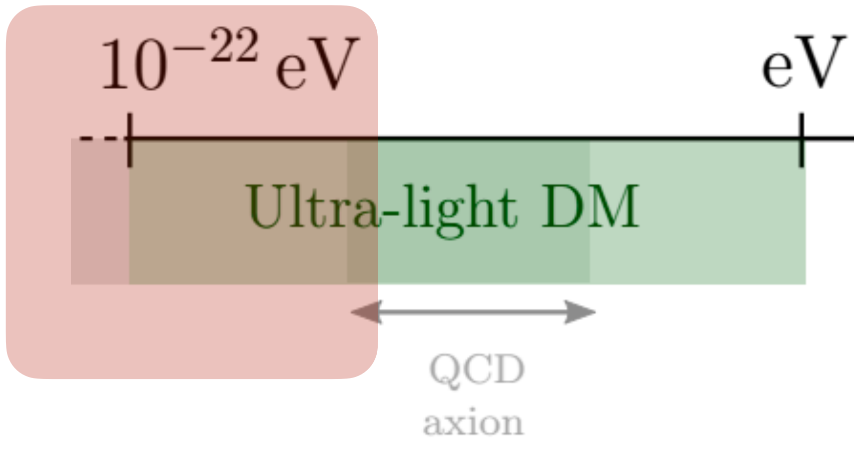


EF, 2020

© Martin Zwierlein.

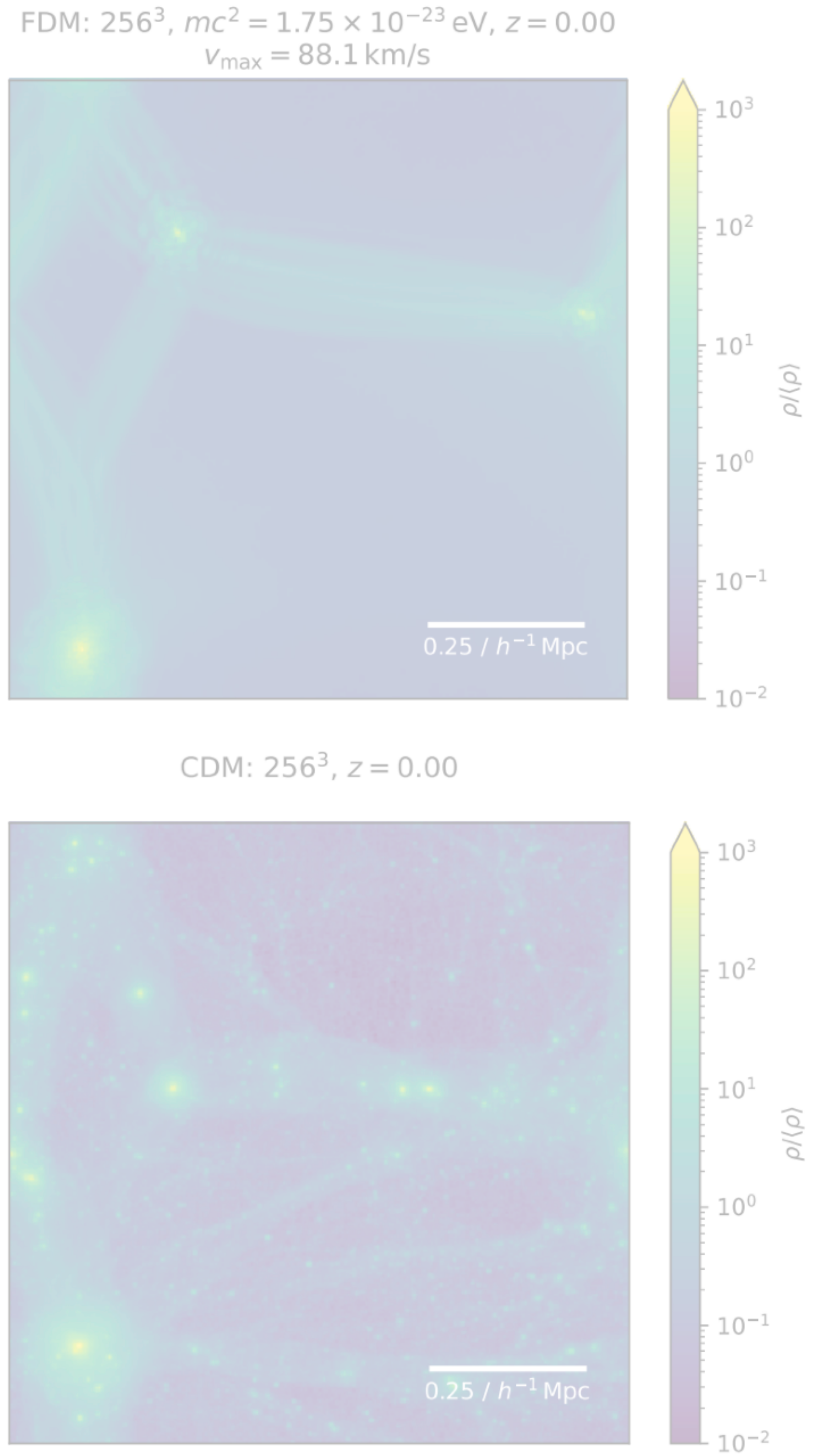


Phenomenology



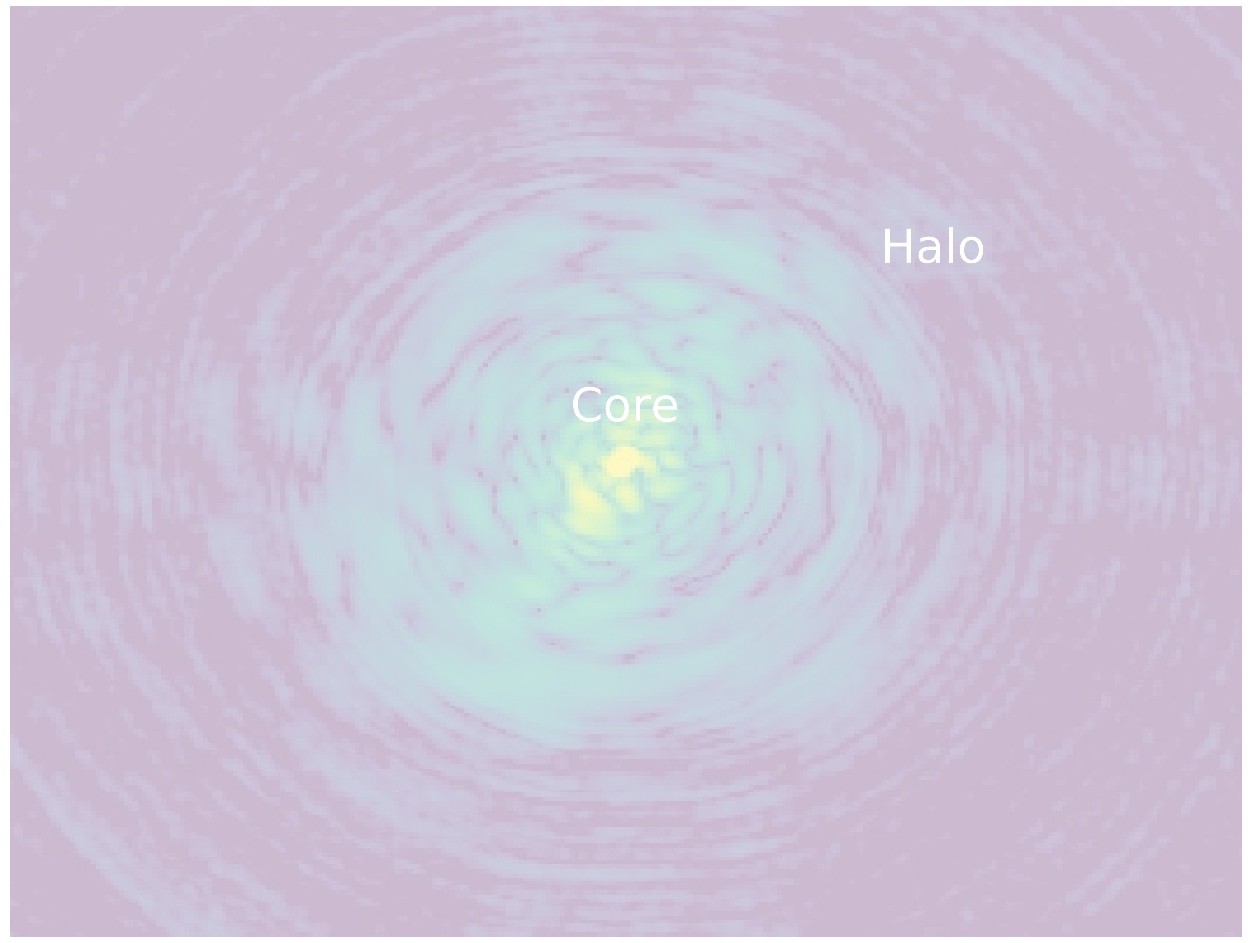
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

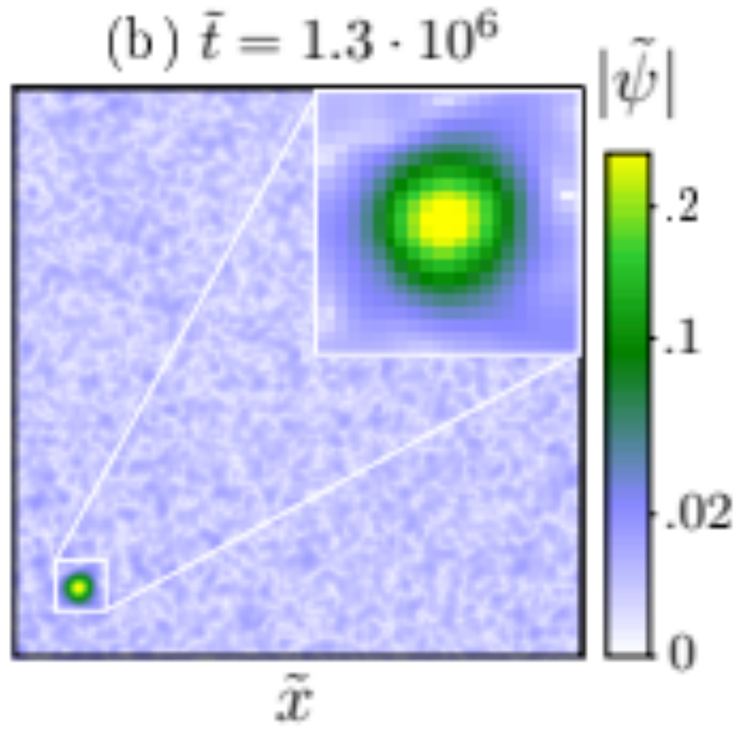


S. May et al. 2021

Formation of a solitonic core

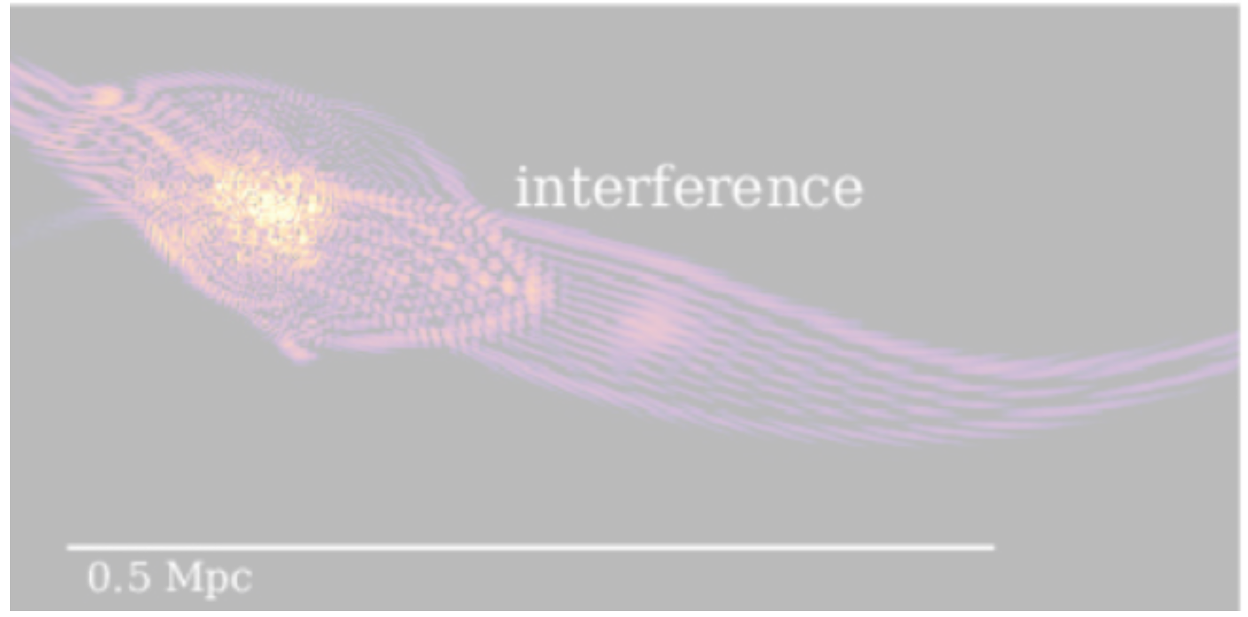


Dynamical effects



Levkov et al. 2018

Wave interference

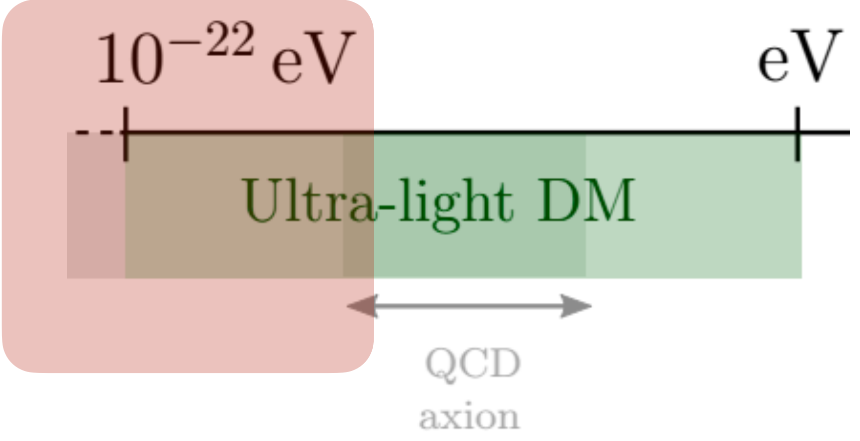


Mocz et al. 2017

Phenomenology

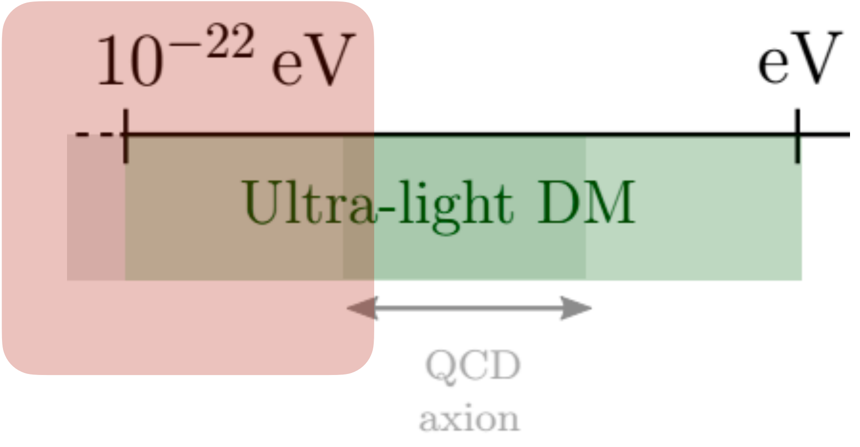
Dynamical effects

Relaxation, oscillation, friction, and heating

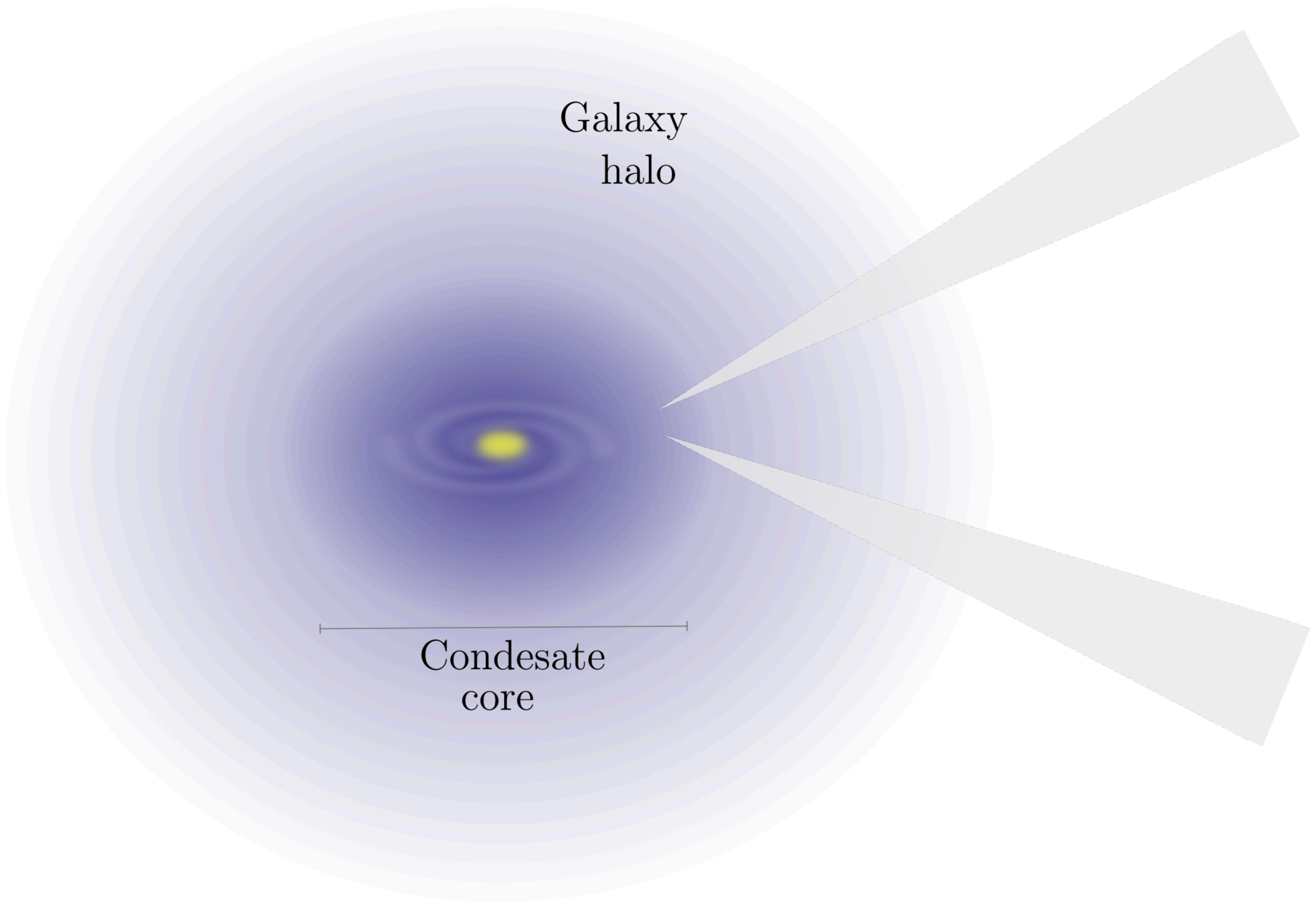


Phenomenology

Dynamical effects



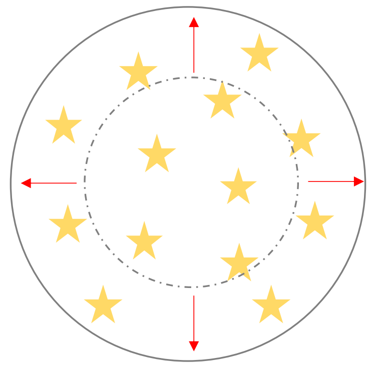
Relaxation, oscillation, friction, and heating



Heating

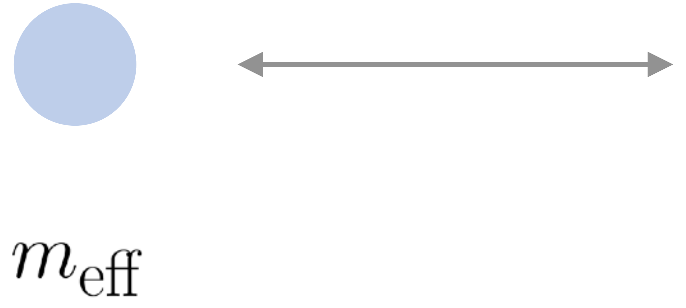
FDM granule

System (star) gains energy



Friction

FDM granule

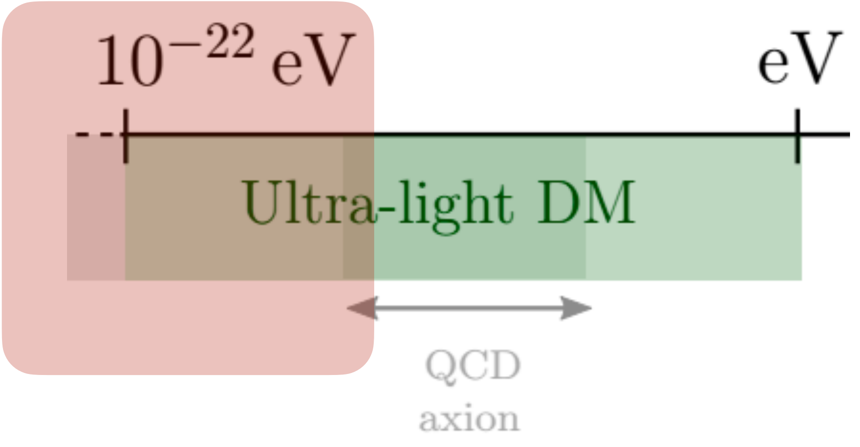


Globular cluster

System (GC or BH) loses energy

Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

→ Condensation

Formation of a BEC / superfluid

- Thermalization (and condensation) *seem* to happen inside the galaxy! Formation of a soliton (ground state) or Bose star in the interior of galaxies

A. Guth M. Hertzberg, C. Prescod-Weinstein (2014)

- Formation of a condensate and a core occur from gravitational interaction.

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

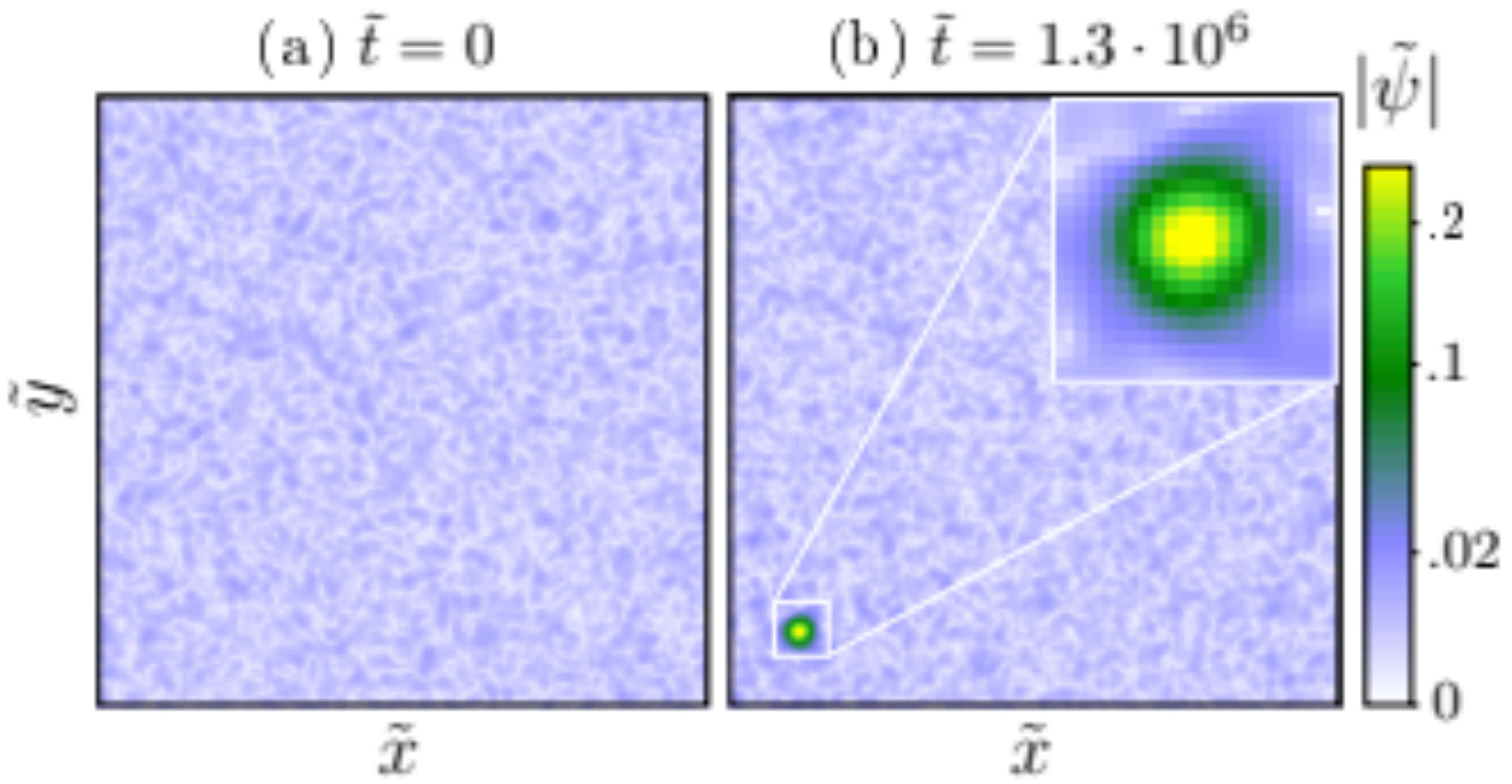
$$\tau_{\rm gr} \sim 10^6\,\mathrm{yr}\left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^3\left(\frac{v}{30\,\mathrm{km/s}}\right)^6\left(\frac{\rho}{0.1\,M_\odot/\mathrm{pc}^3}\right)^{-2}$$

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

Smaller than the age of the universe!

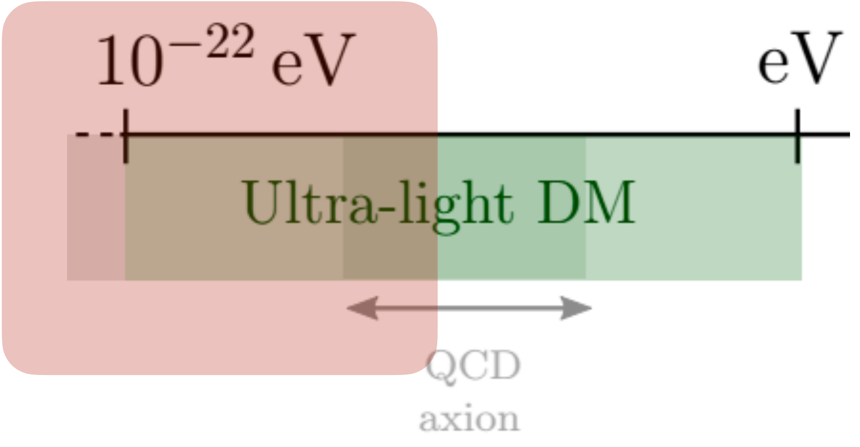
Open question!

Wave turbulence theory



Levkov et al. 2018, Kirpatrick et al. 2020

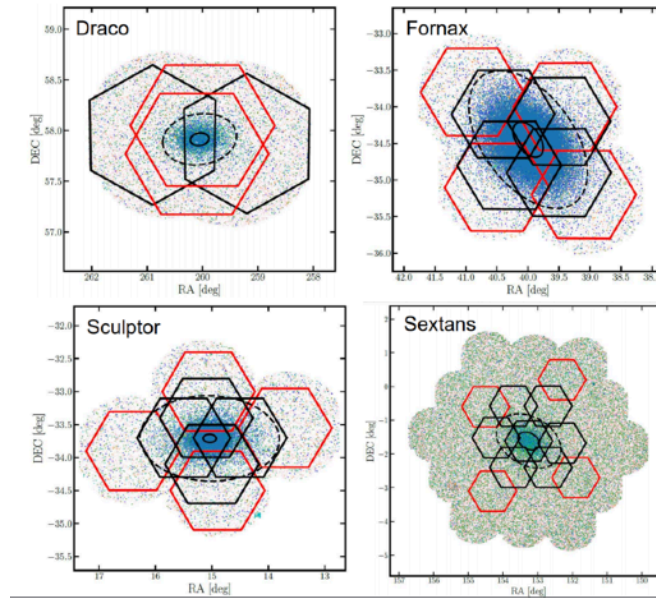
Observational implications and constraints



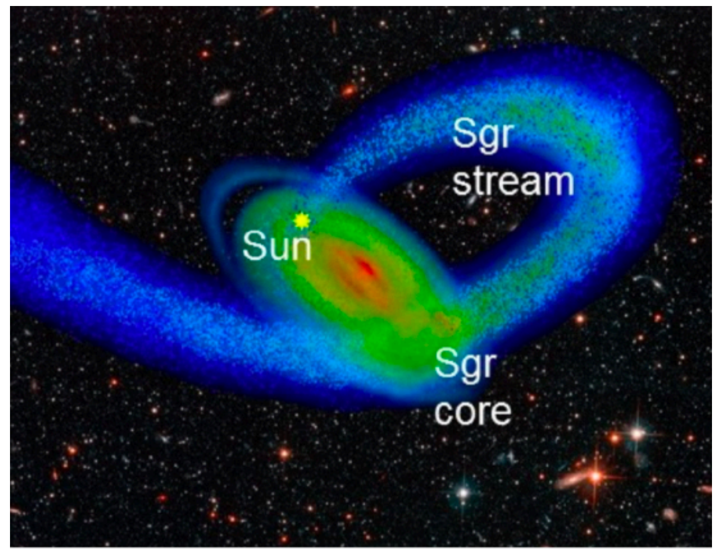
Galaxies

NASA and ESA

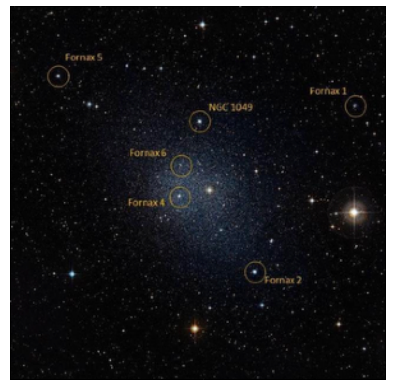
Dwarfs



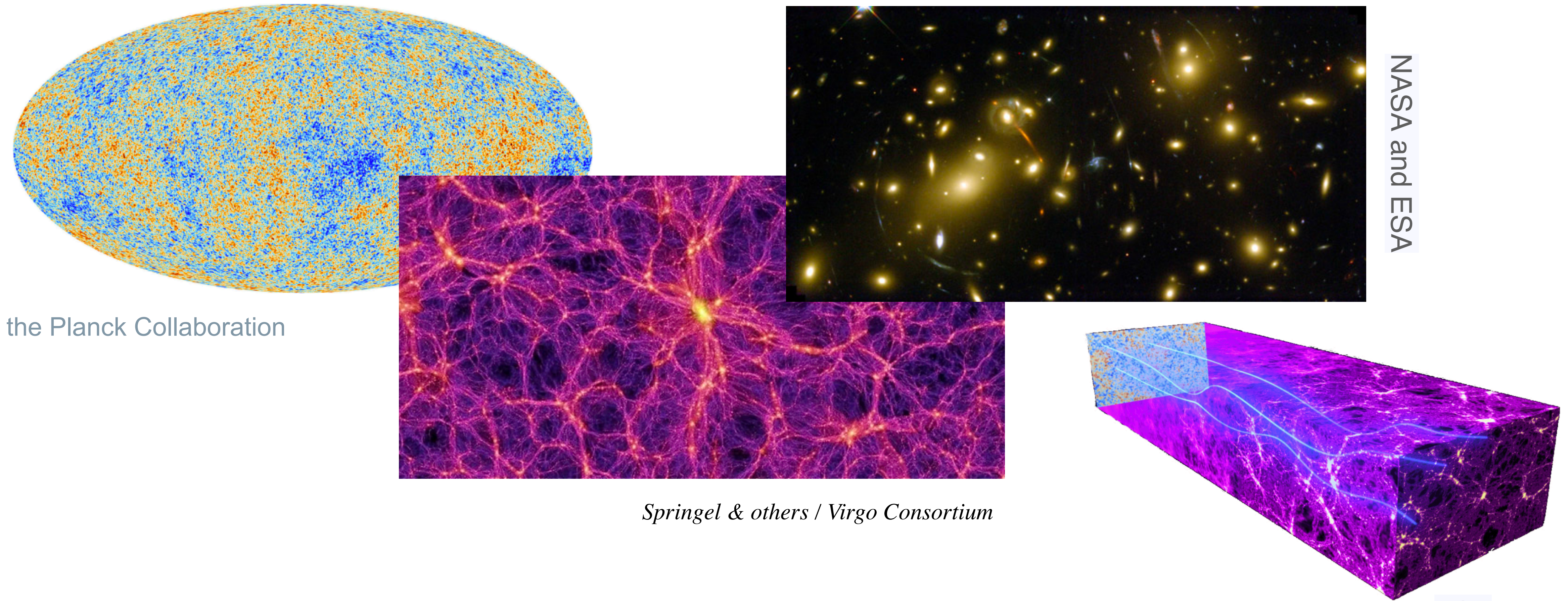
Stellar stream



Globular clusters



CMB+LSS



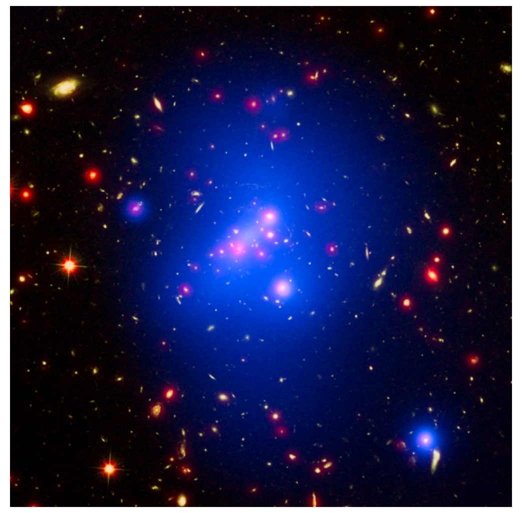
ESA and the Planck Collaboration

NASA and ESA

Springel & others / Virgo Consortium

ESA

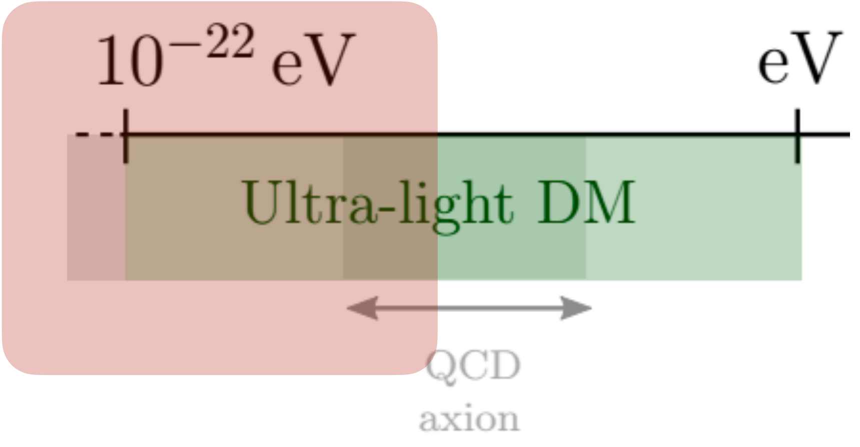
Clusters

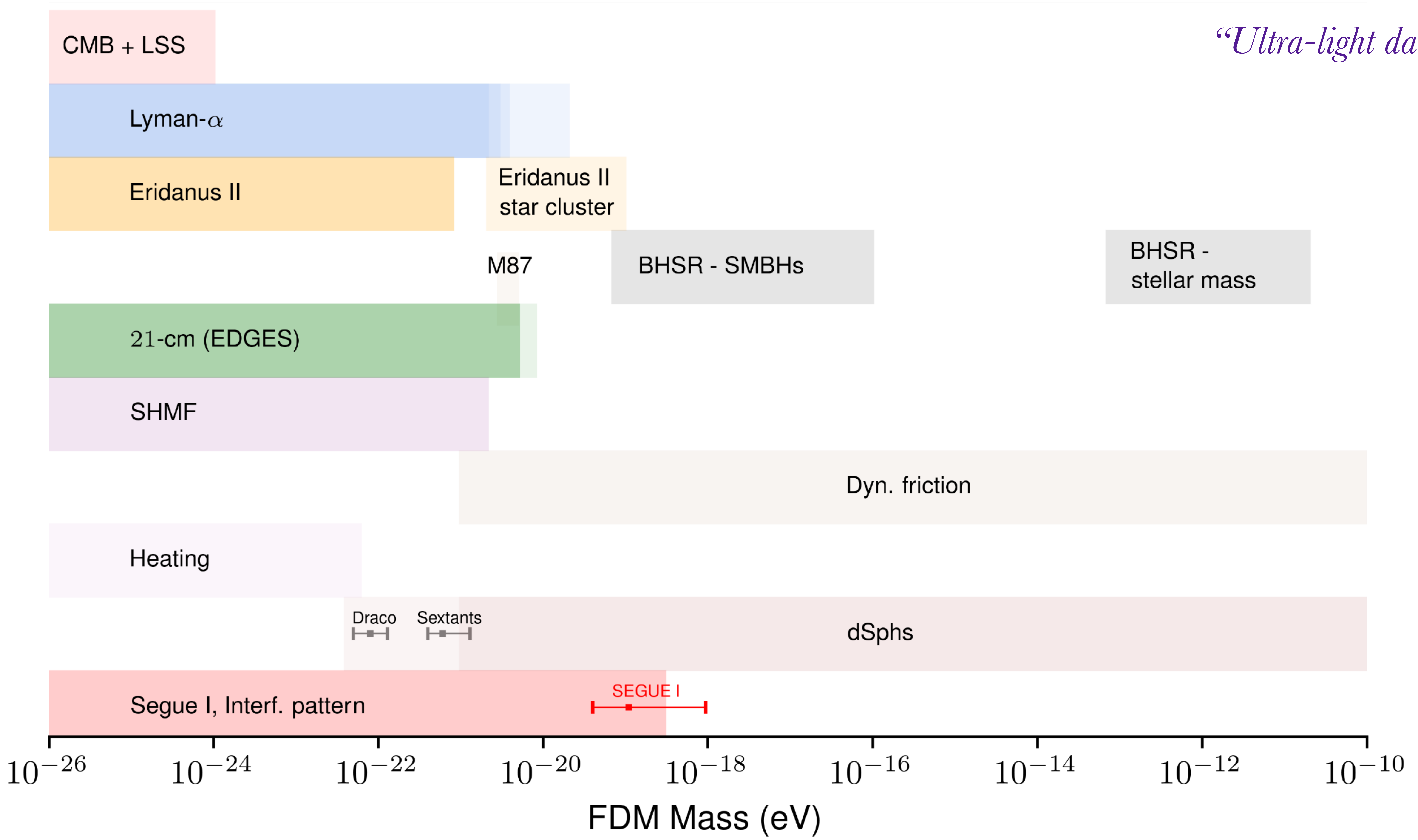


CC BY 4.0

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



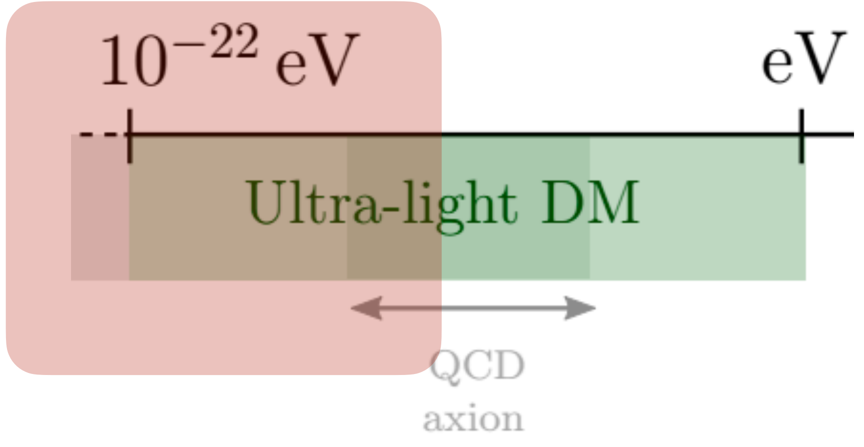


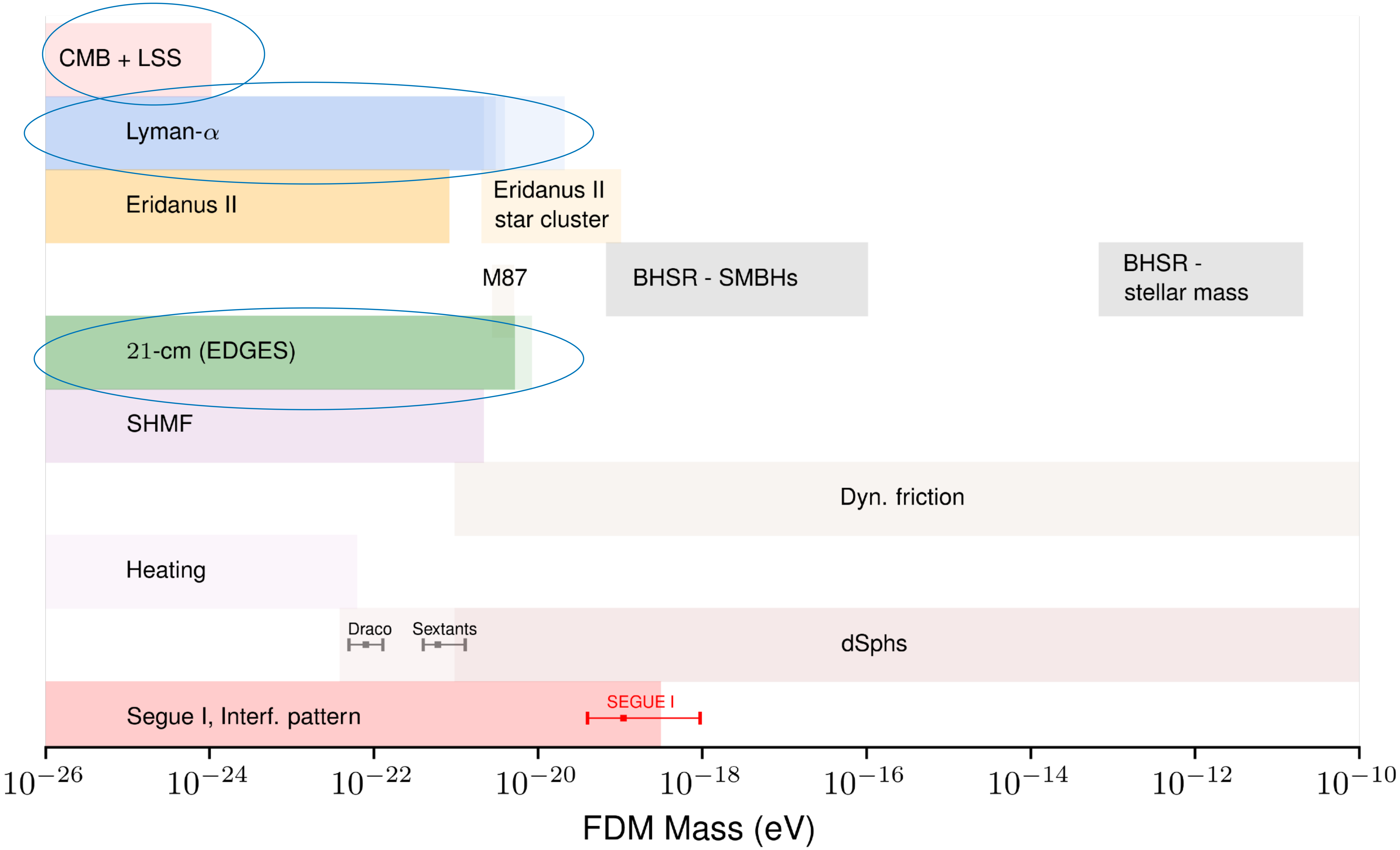
"Ultra-light dark matter", **E.F.**, 2020. The Astronomy and Astrophysics Review.

Bounds consider FDM is *all* DM

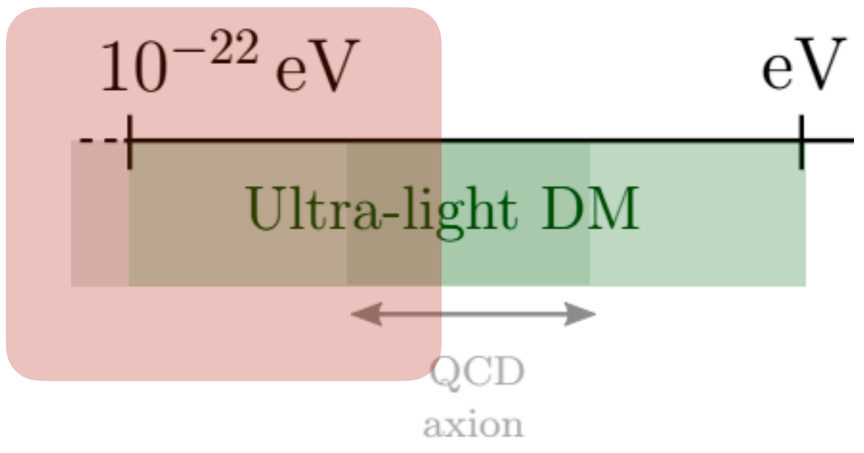
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass





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



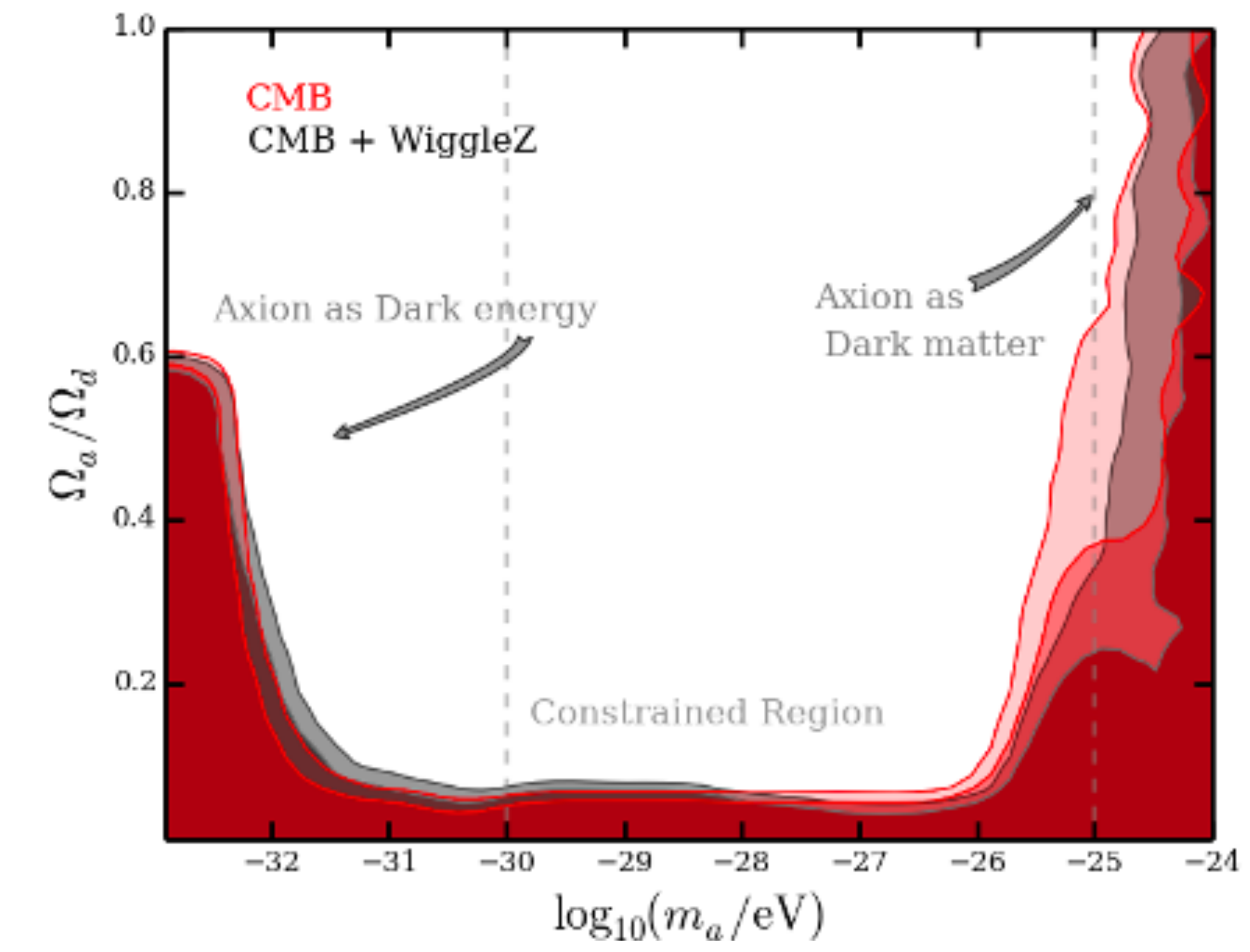
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

Suppression of small structures

CMB/LSS

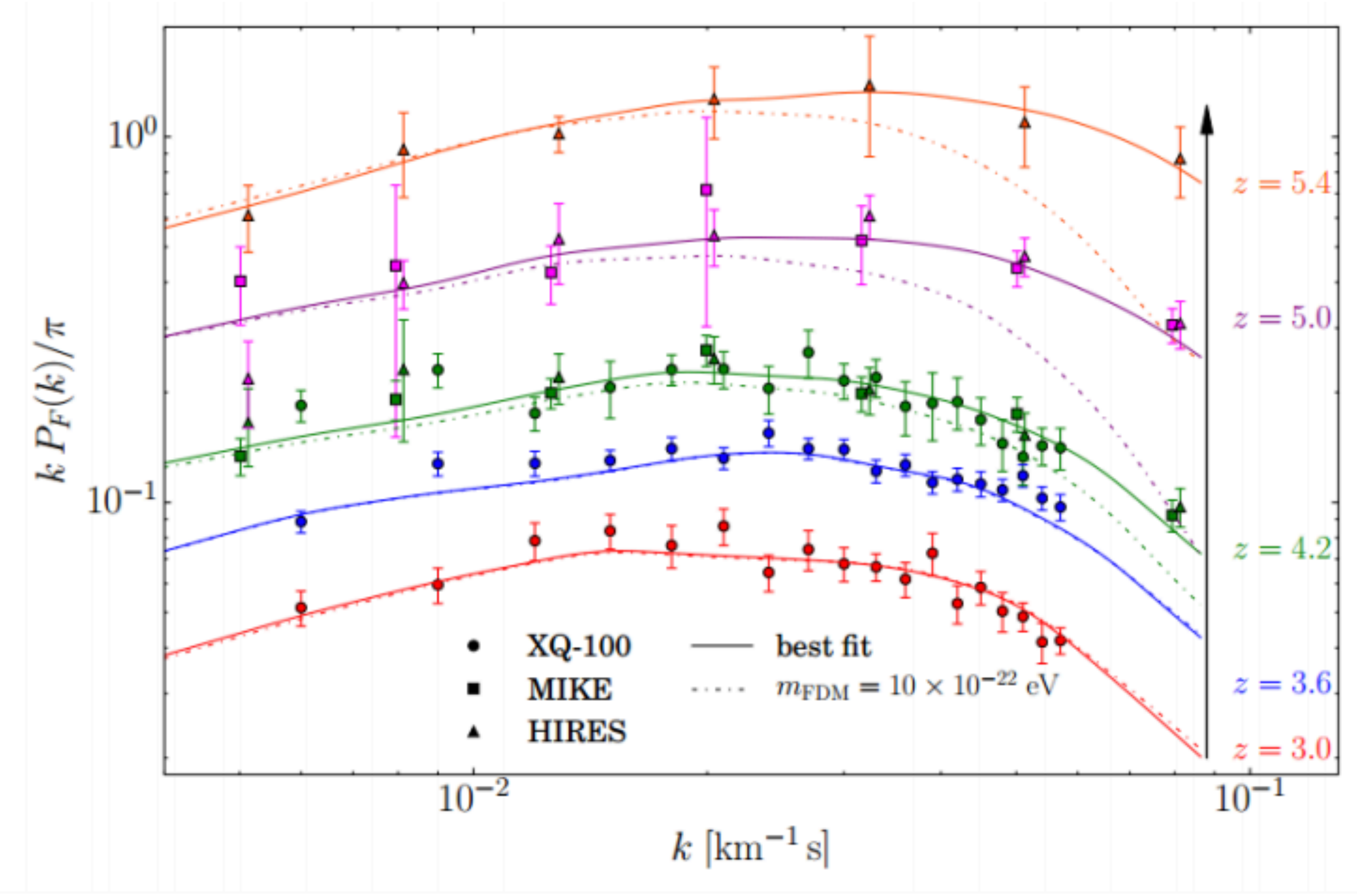
Hlozek et al, (2015, 2018)



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

Lyman alpha

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

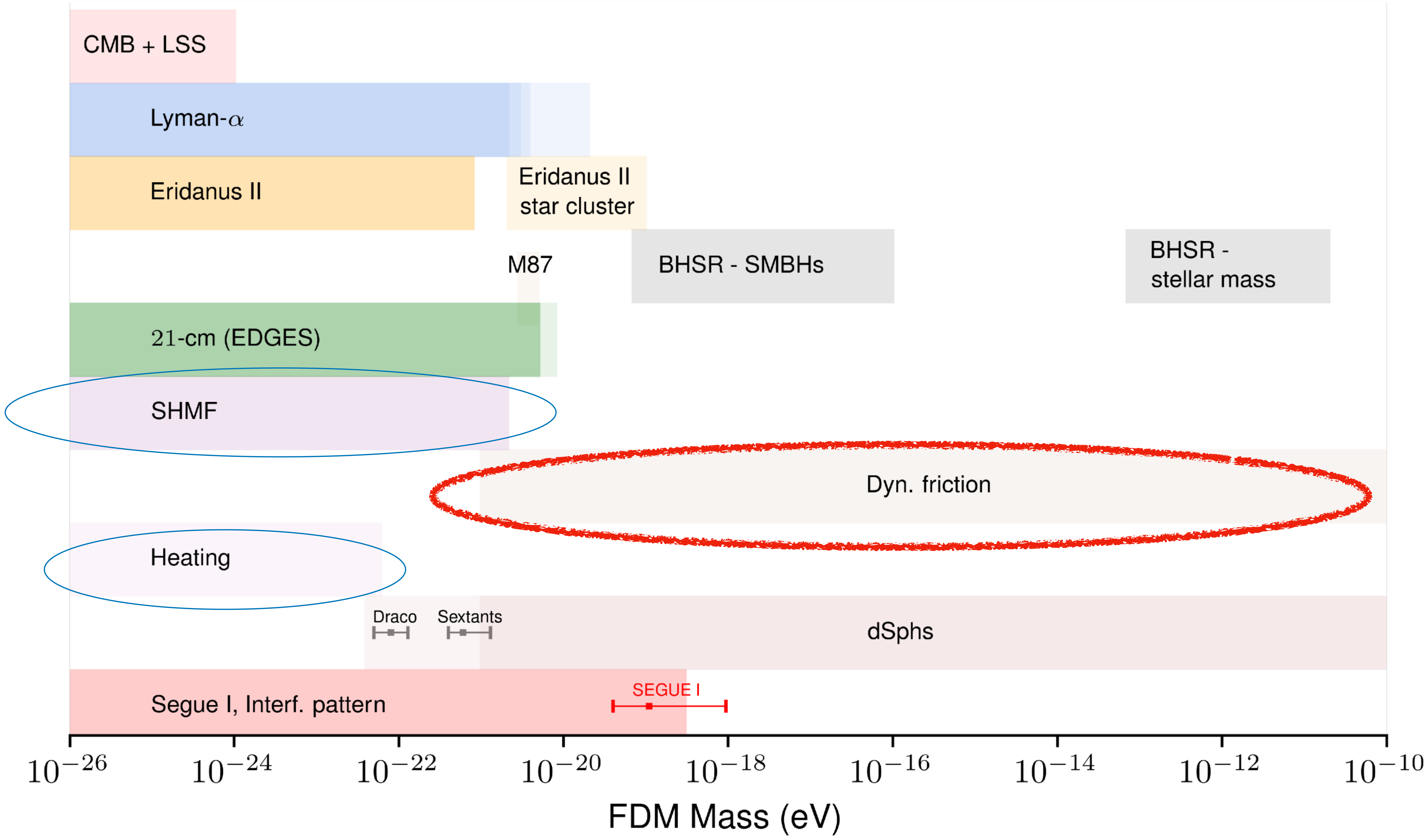


$$m \gtrsim 2 \times 10^{-20}\,\mathrm{eV}$$

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

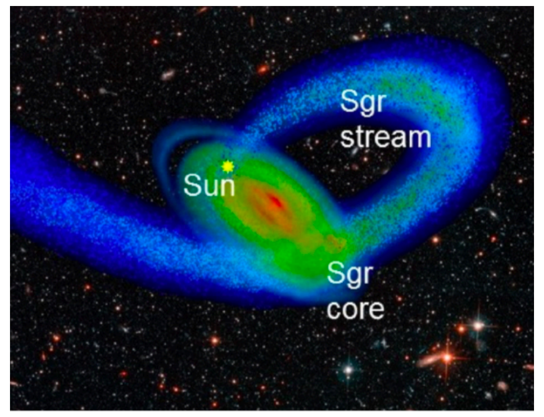
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



Suppression of small structures

Stellar streams



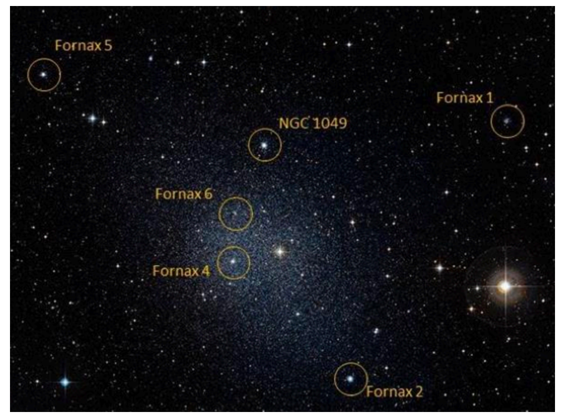
Schutz 2020: bound in the FDM SHMF using stellar streams and grav. lensing

Grav. lensing

Dynamical effects

Globular clusters

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



ESO/Digitized Sky Survey 2

Lancaster et al. 2020

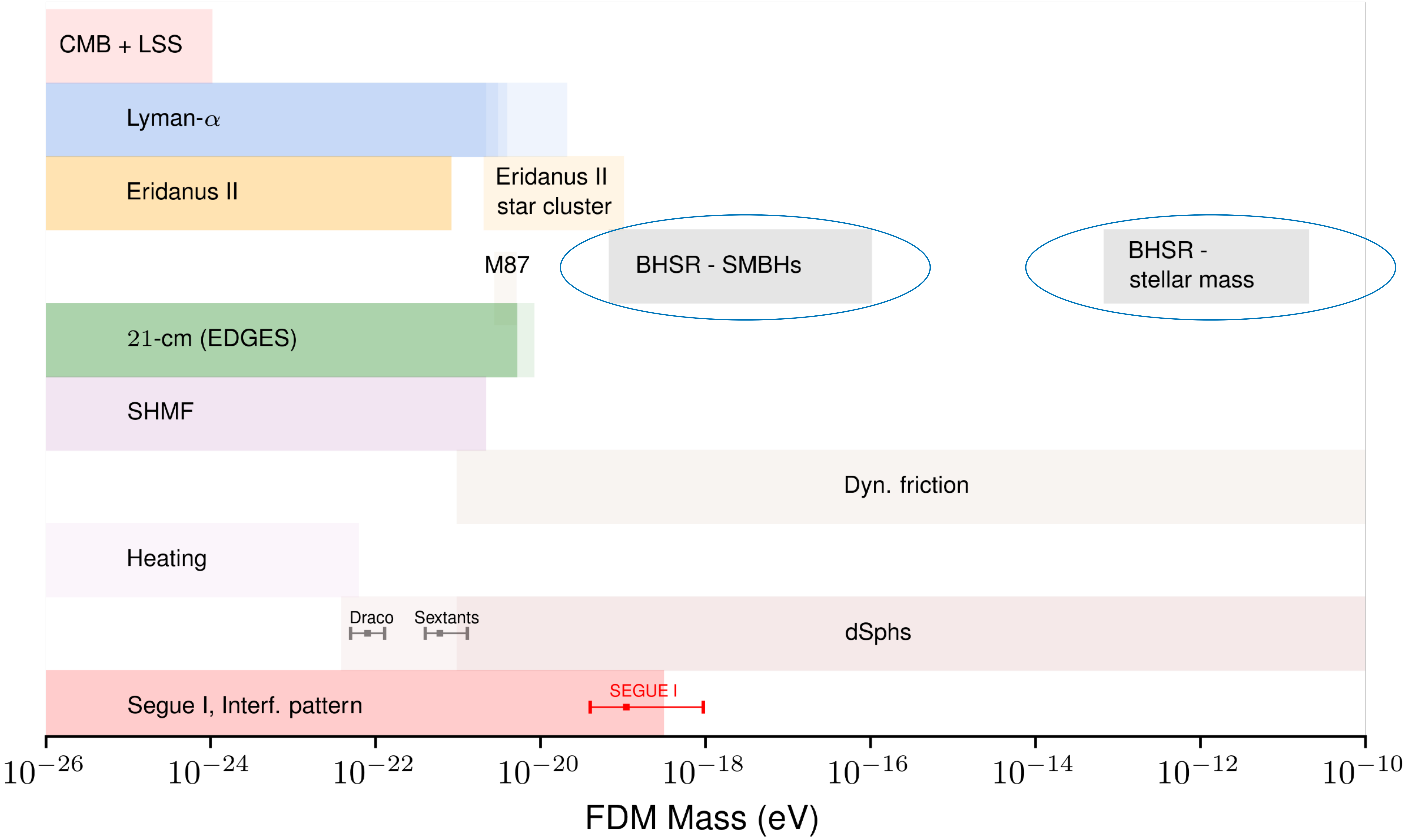
Heating of the MW disk

Church et al. 2019

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

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



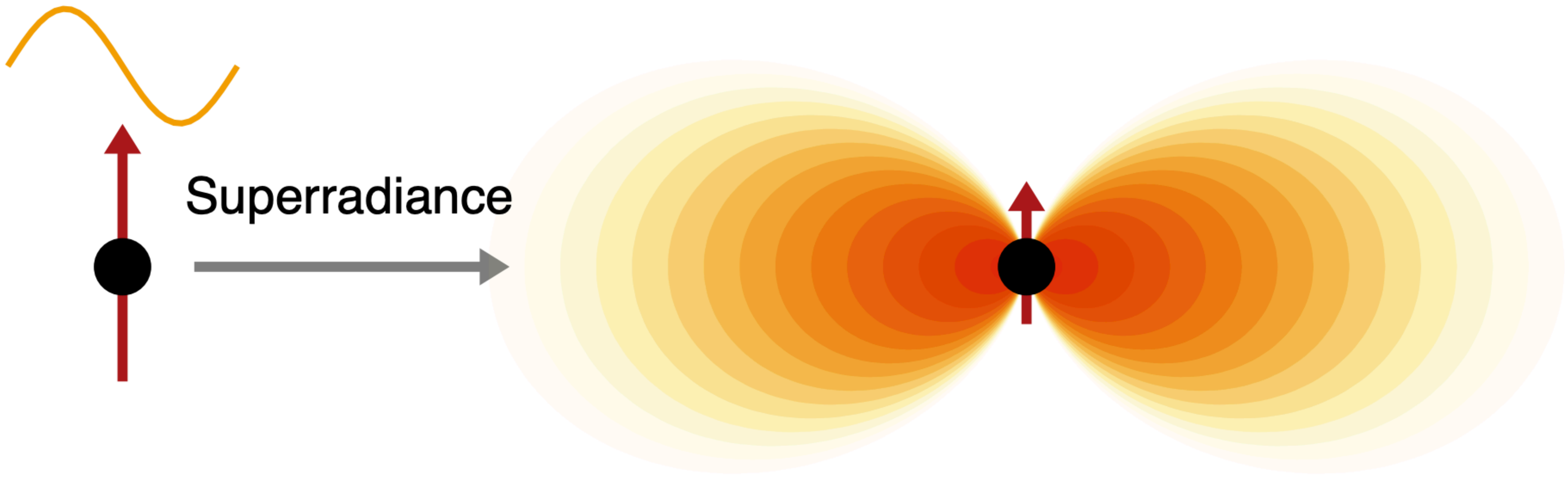
Black Hole Superradiance

Black Hole Superradiance

Zeldovich (1972) Starobinsky (1973) Arvanitaki et al. [0905.4720]

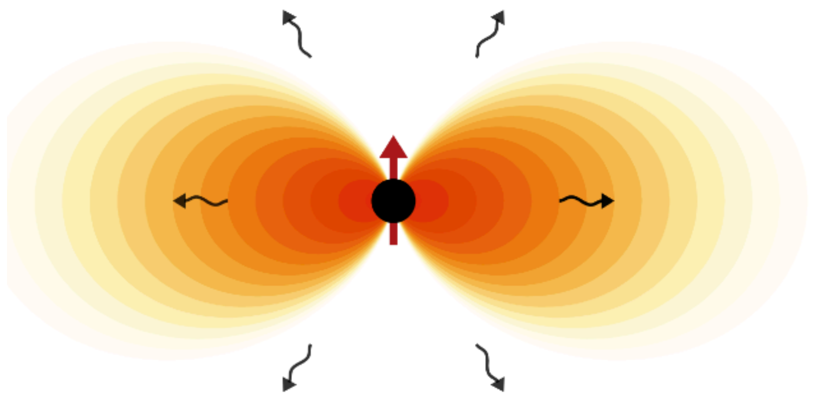
A cloud of ultra-light bosons (and vector fields) can be created around rotating black holes -
if the particle Compton wavelength is of the order of the size of the BH

Structure like a "gravitational atom"

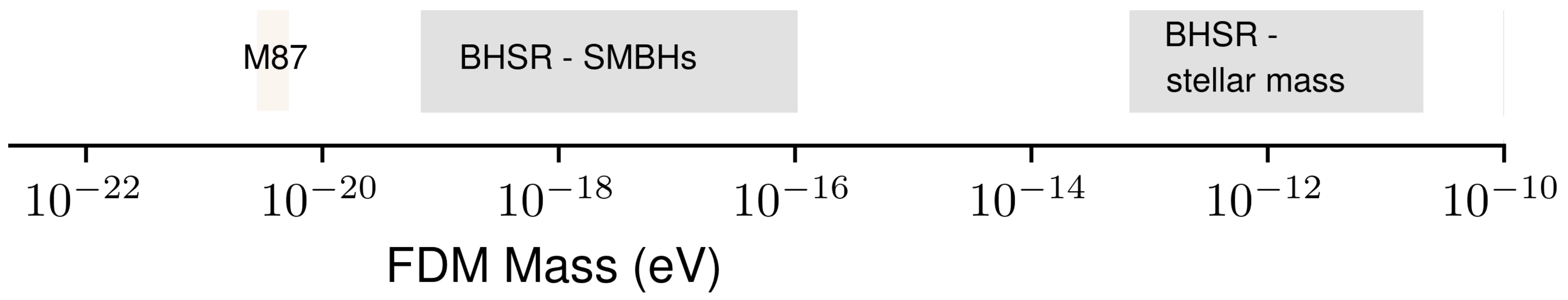


H. Chia et al, 2018

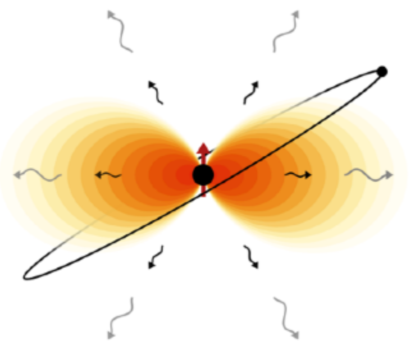
Emits gravitational waves



H. Chia et al, 2018



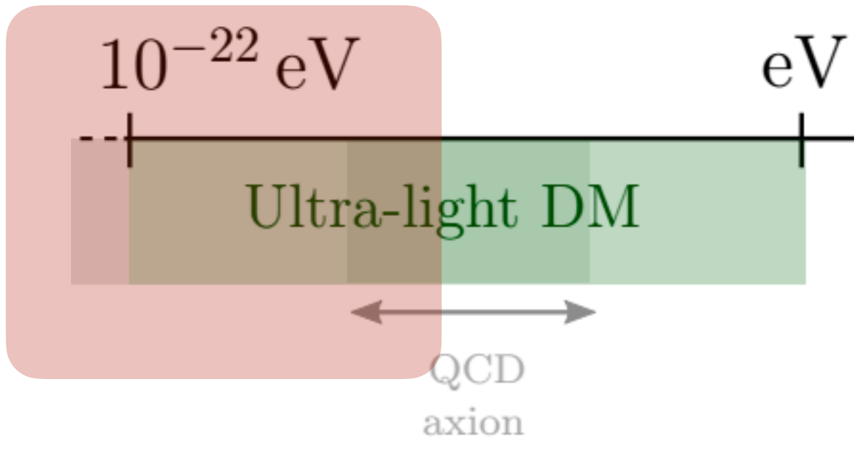
Dynamics can be altered by the presence of a companion - binary



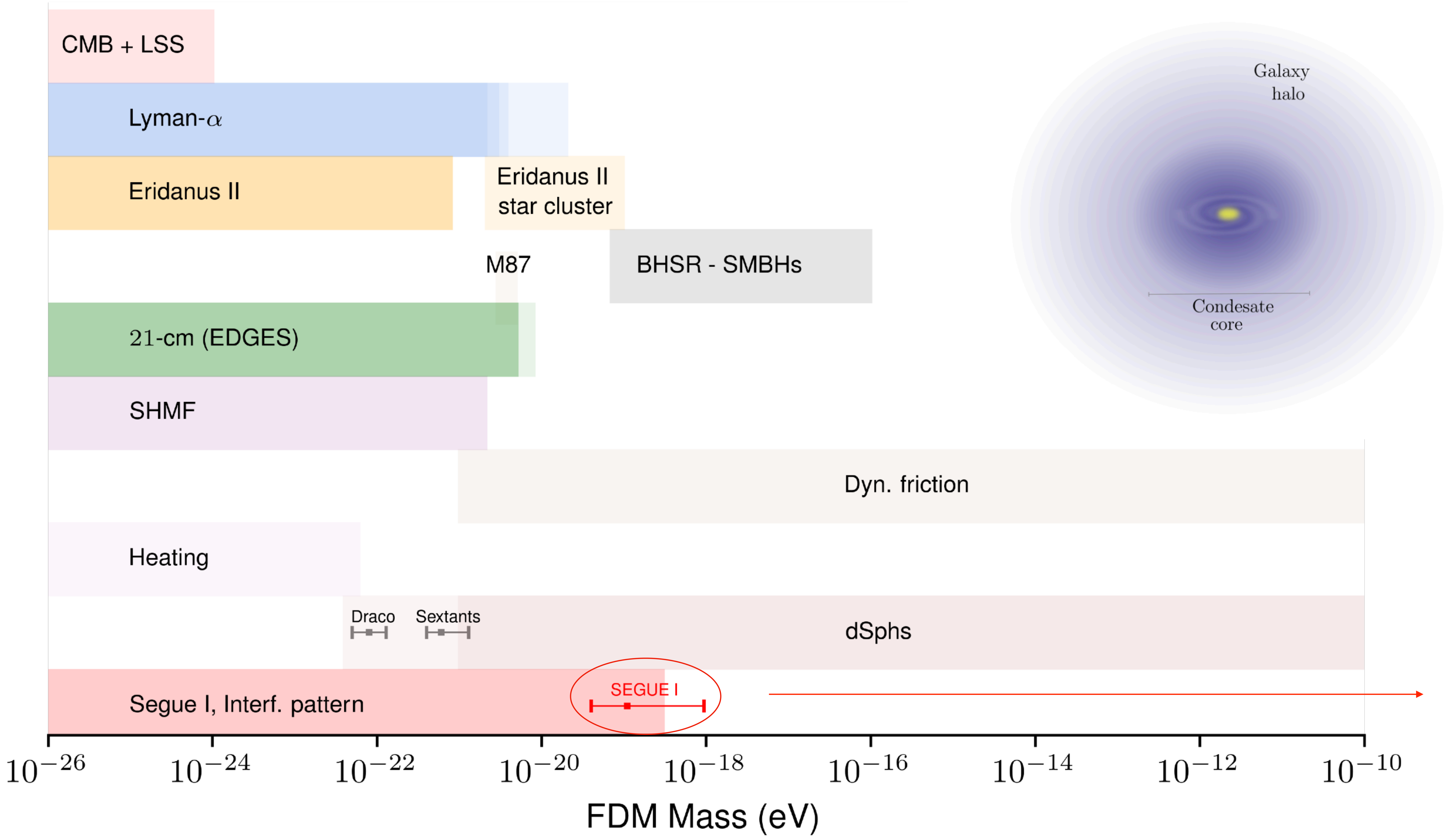
H. Chia et al, 2018

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



Presence of a core



DWARFS

Ultra faint dwarfs

FDM SIMULATIONS

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

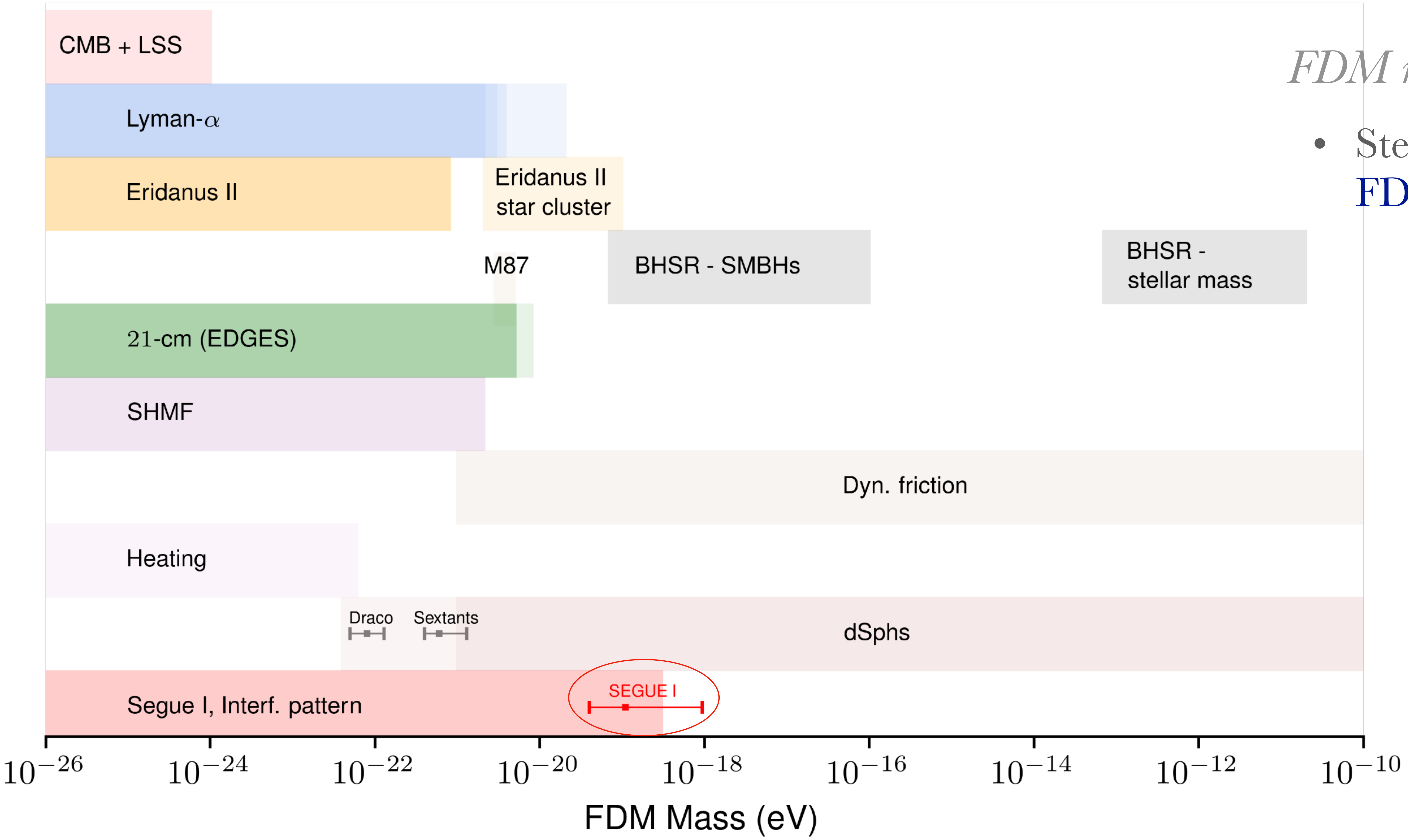
"Narrowing the mass range of Fuzzy Dark Matter with Ultra-faint Dwarfs", J. Chan, **E.F.**, K. Hayashi, 2021.

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass

Ultra faint dwarfs

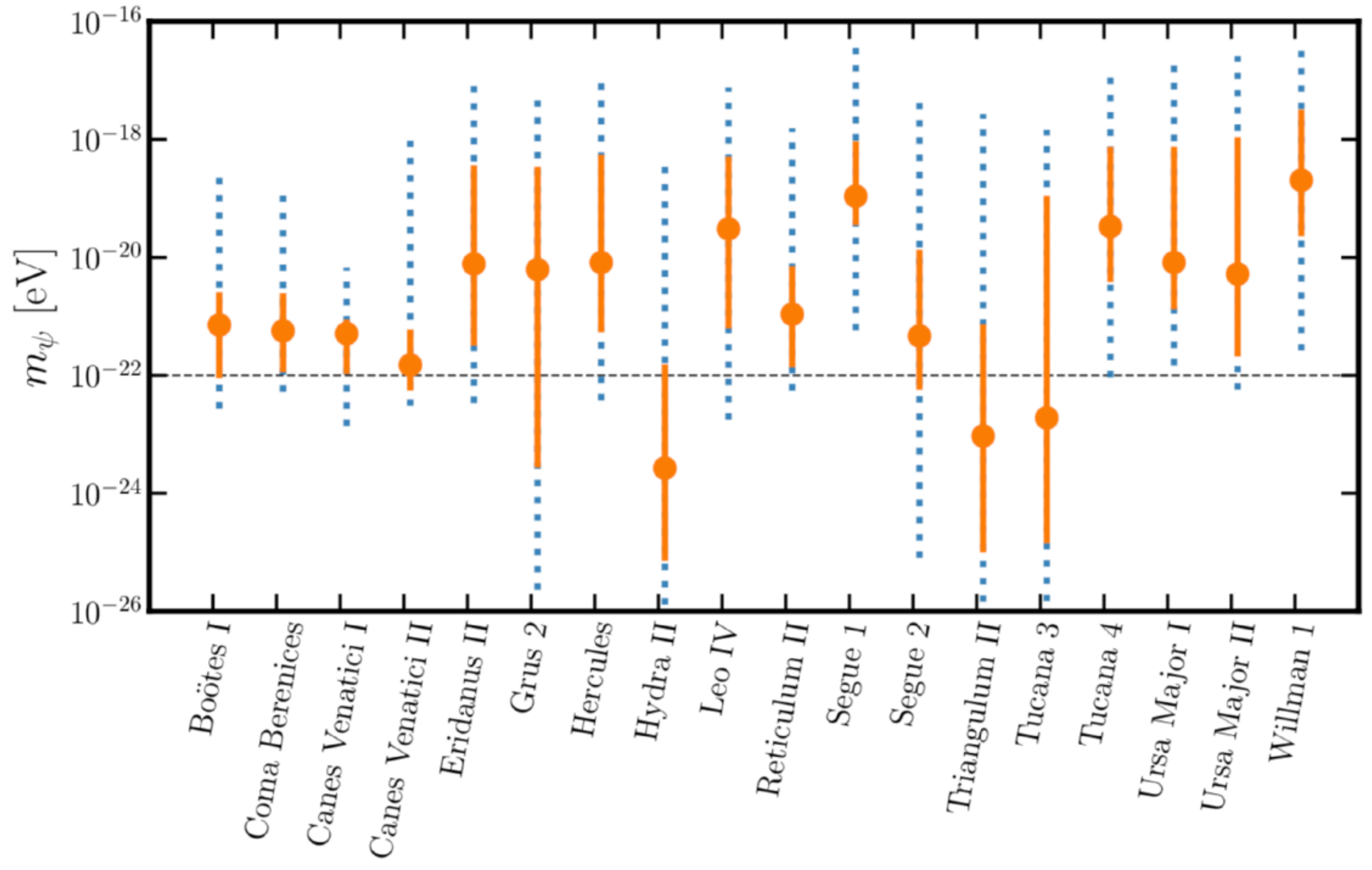
Hayashi, **E.F**,Chan, 2021.



FDM mass from Ultra-faint dwarfs

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

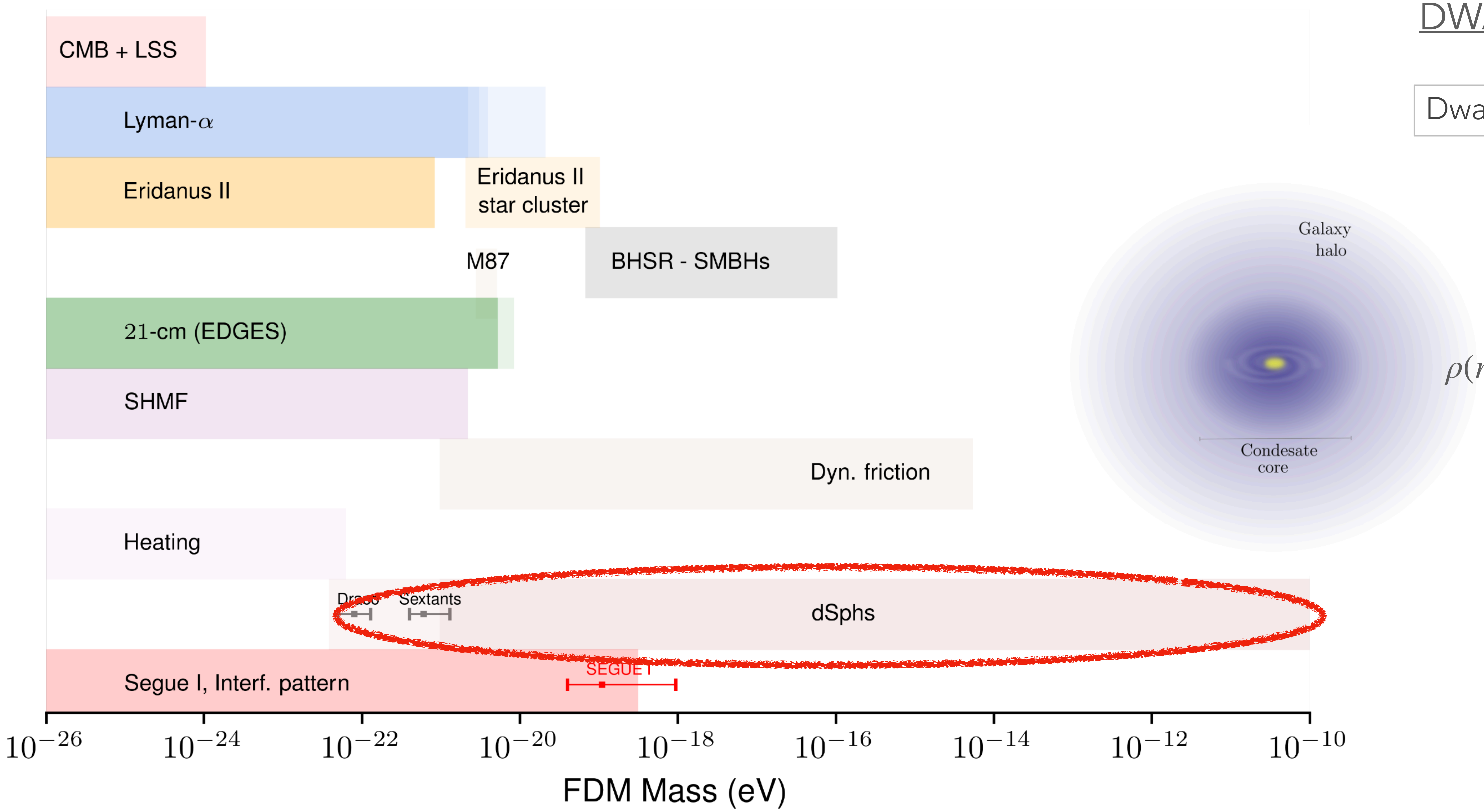
$$m_{\rm FDM}^{(Seg1)} = 1.1^{+8.3}_{-0.7}\times 10^{-19}\,\mathrm{eV}$$



Preference for higher mass

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



DWARFS

Dwarf Spheroidals (dSphs)

FDM SIMULATIONS

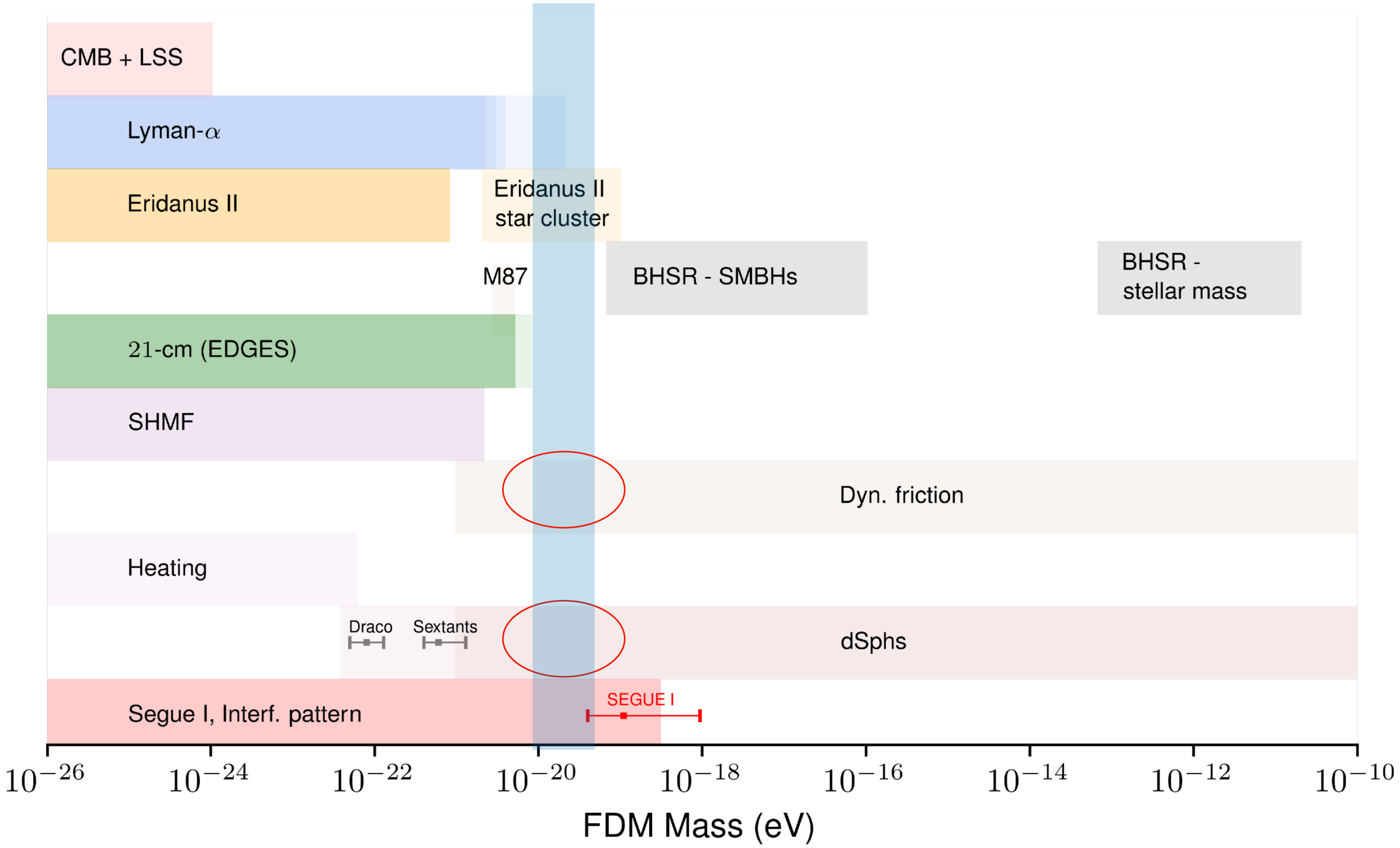
$$\rho(r) = \begin{cases} \rho_{\rm soliton} \simeq \dfrac{\rho_c}{\left[1+0.091(r/r_c)^2\right]^8}\,, & r<r_\epsilon \\ \rho_{\rm NFW} = \dfrac{\rho_s}{(r/r_s)(1+r/r_s)^2}\,, & r>r_\epsilon \end{cases}$$

Fornax - Sculptor

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

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

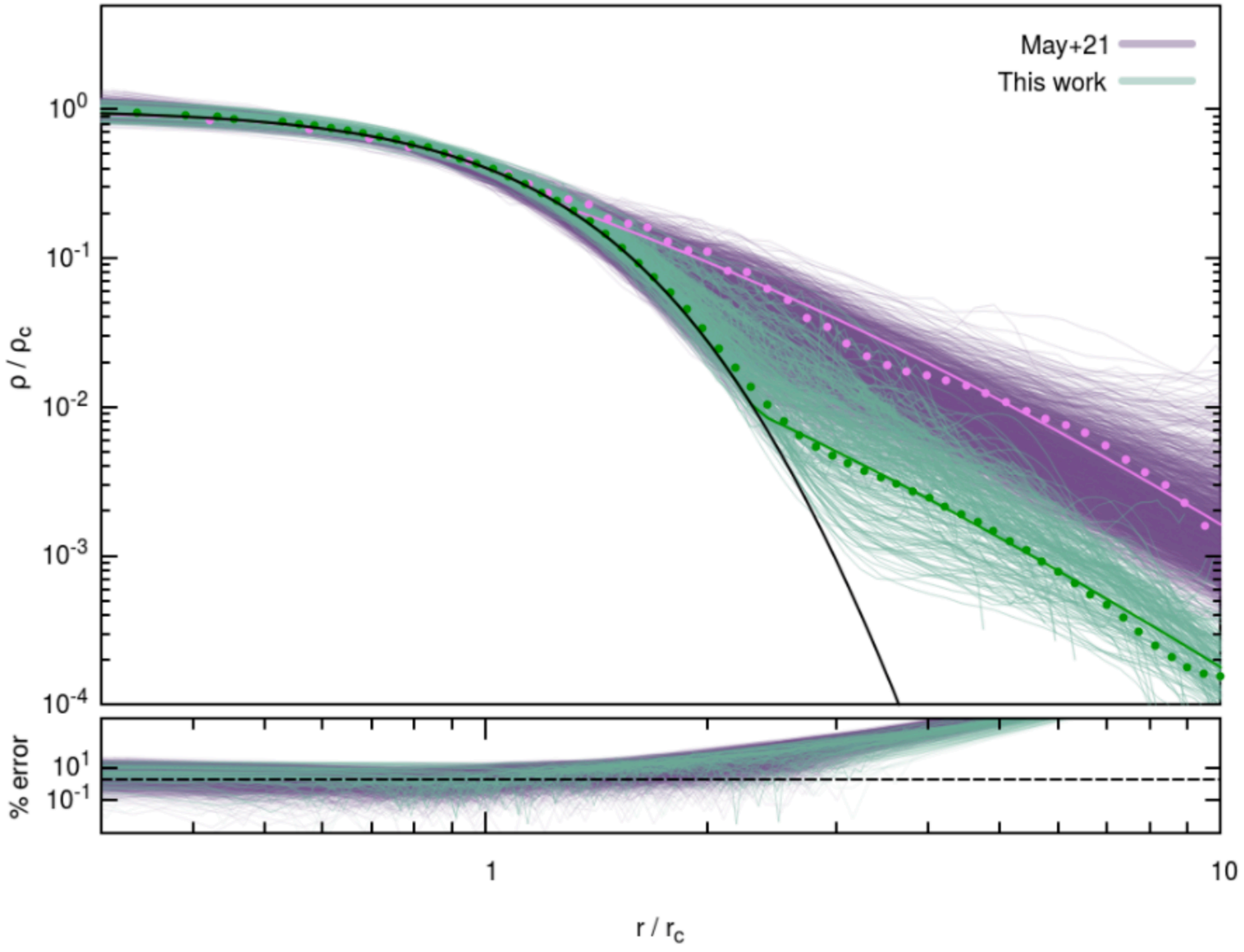
Possible reasons for this incompatibility:

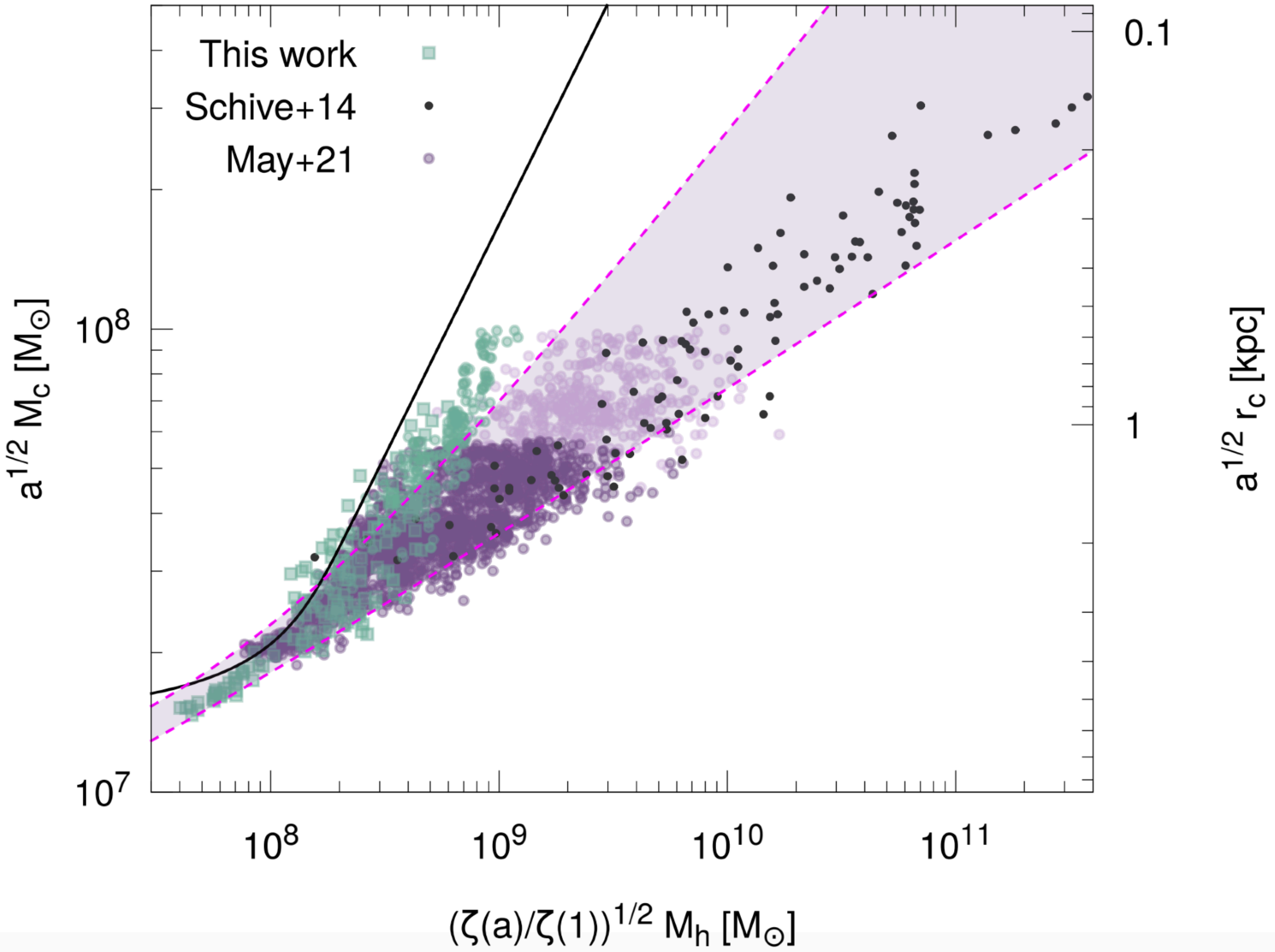
- *Influence of baryons:* baryonic processes can change the density structure of their halo - we are not probing the intrinsic DM profile.
- *Universality of the core profile*: FDM soliton profile might be too simplistic, could change for different systems (might also depend on baryons)
- *Core-mass 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, EF, S. May, K. Hayashi, M. Chiba 2021

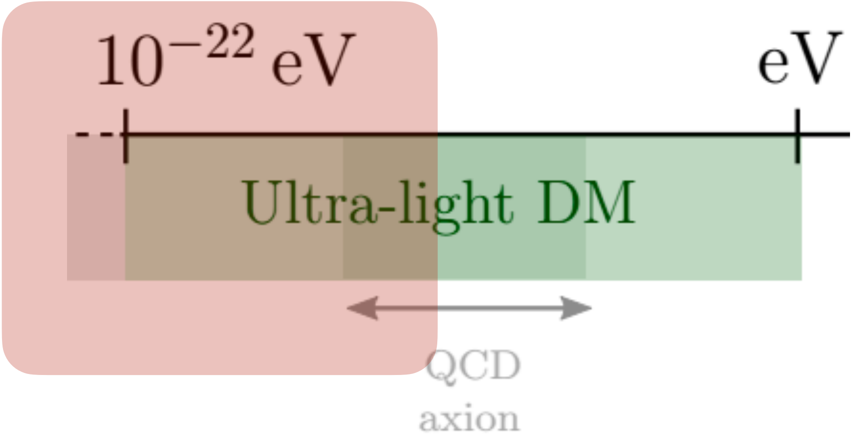


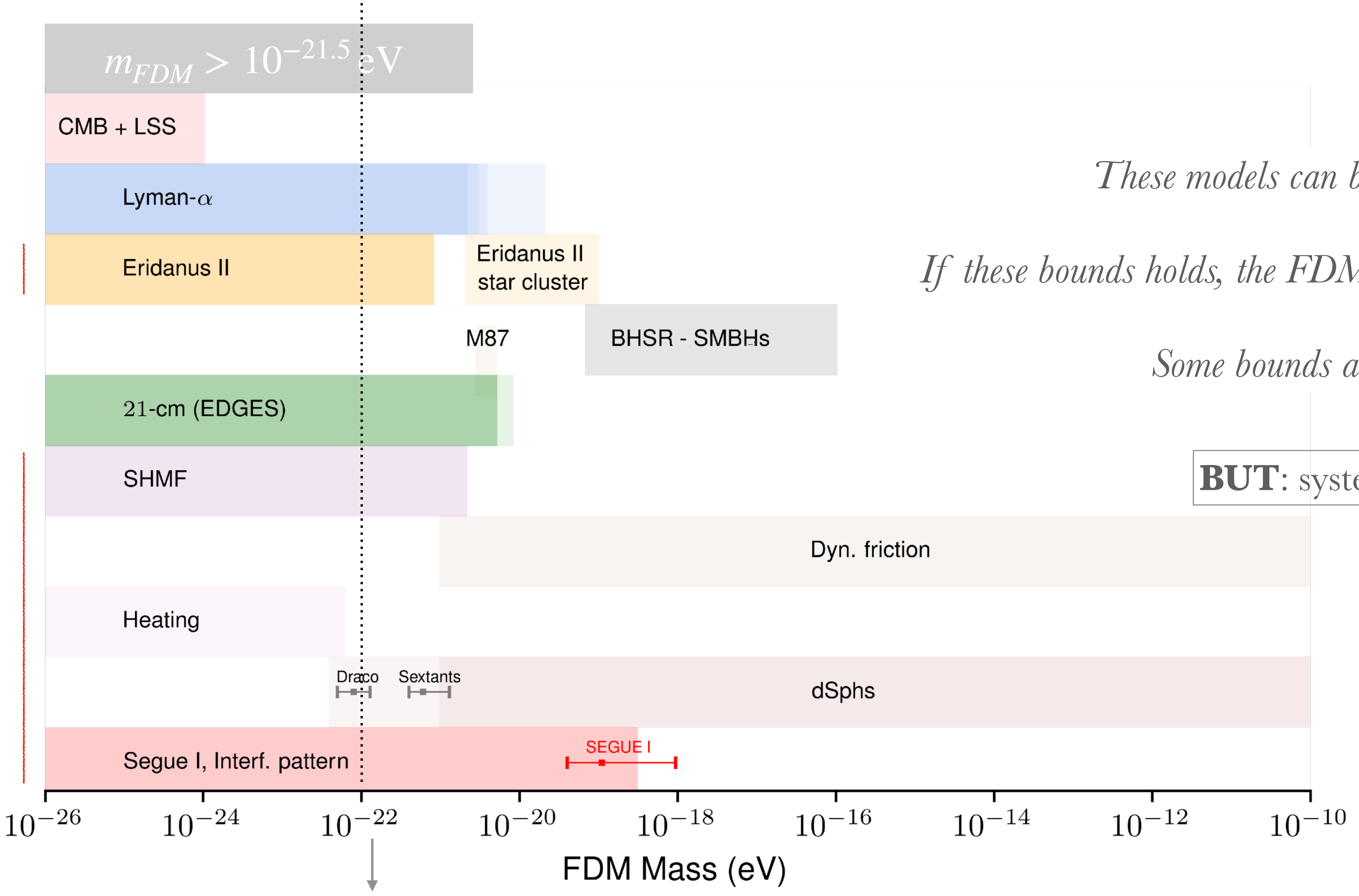


Steeper slope → Smaller core → Smaller mass

Current status

Fuzzy Dark Matter - bounds on the mass





Sweet spot for solving small scale problems

These models can be highly constrained

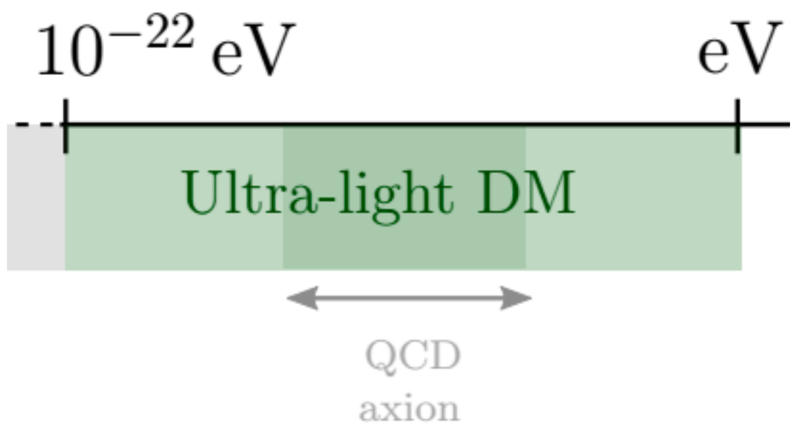
If these bounds holds, the FDM mass range is narrowing down

Some bounds are incompatible!

BUT: systematic effects!!

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

Current status



Bounds on the mass and other parameters

Self interacting FDM

m g

* Check: Lasha Berezhiani et al (2020)

DM Superfluid

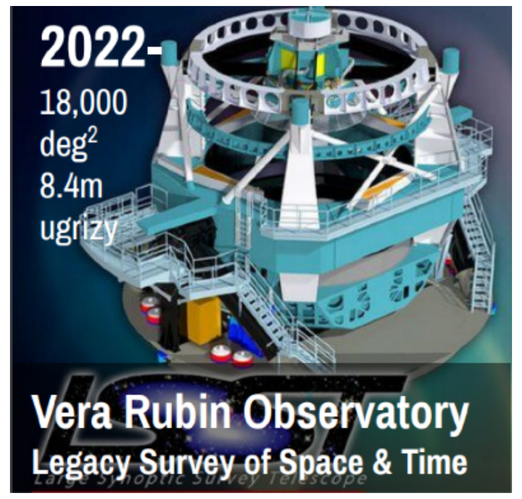
$$\mathcal{L} = P(X)$$

Still highly unconstrained

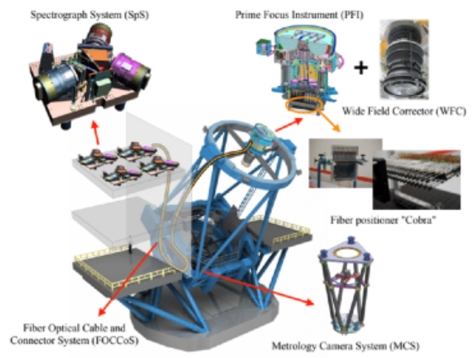
FUTURE

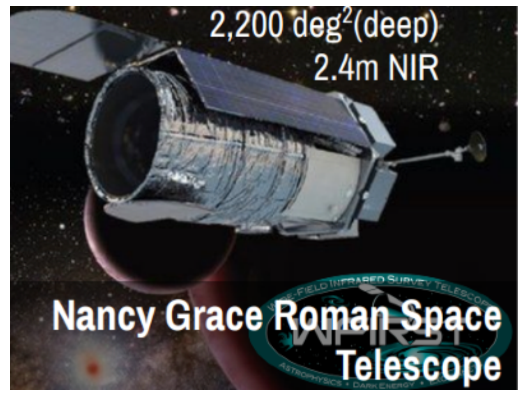
Observations

Photometric and spectroscopic surveys

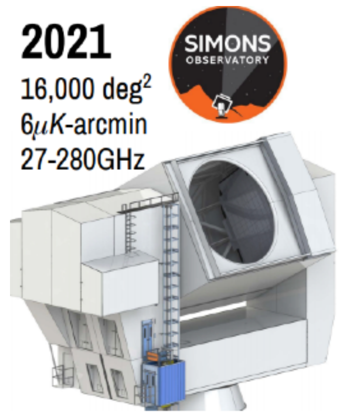


Prime Focus Spectrograph (PFS)





CMB

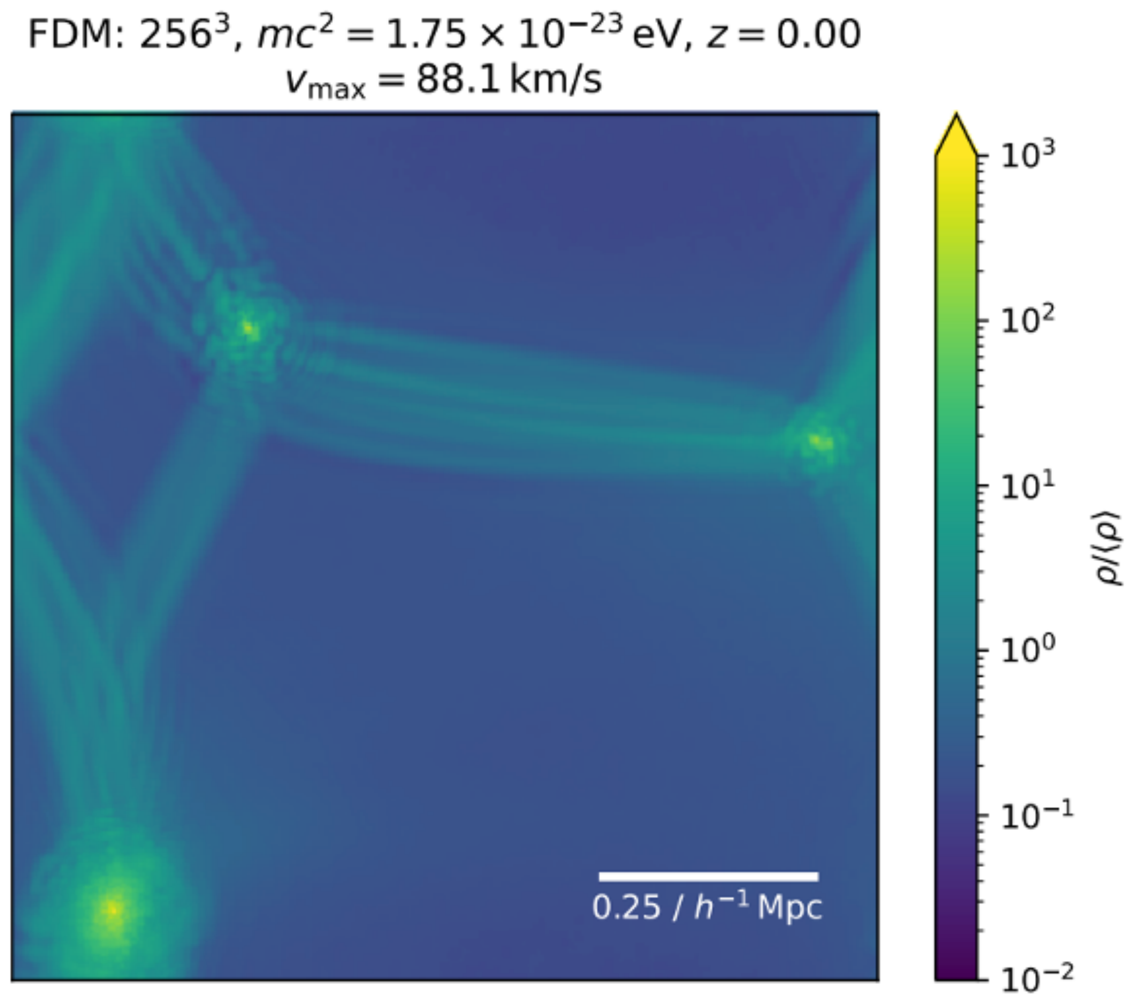


CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New observables

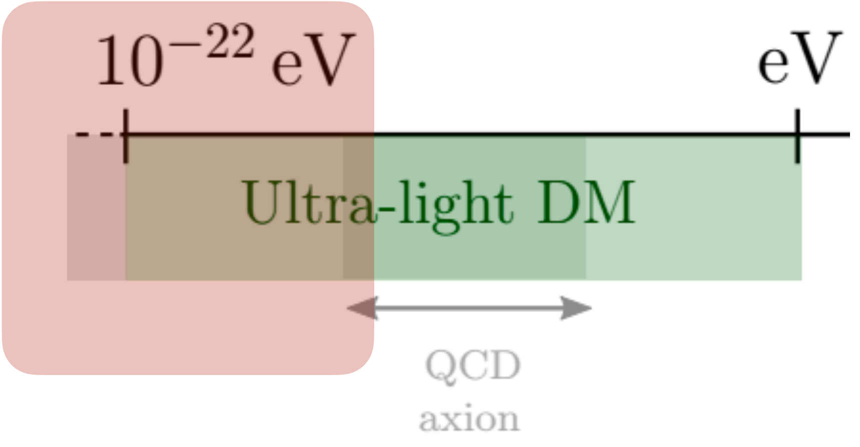
Ex.: - interference pattern
- vortices

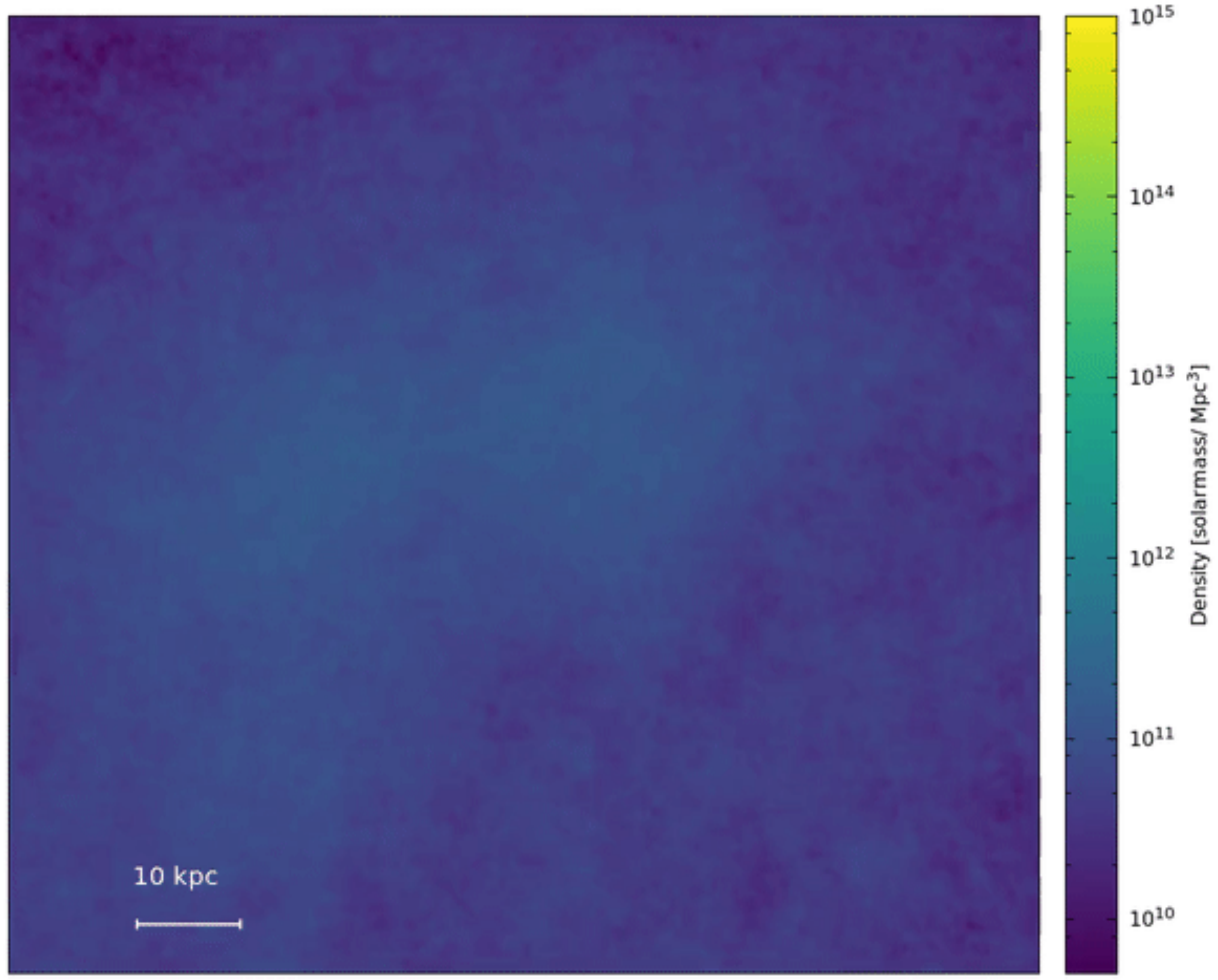
New probes

Modified from Jia Liu

New observables/new probes

Interference pattern





Simulation by Jowett Chan

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

Constructive interference: granules
Destructive interference

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

PROBES:
- Strong lensing
- Stellar streams
- Heating

ONGOING

In collaboration with Jowett Chan and Simon May

- Characterizing the interference patterns using full simulations
- Strong lensing *Devon Powel, Simona Vegetti, Simon White, John McKean*
- Stellar streams *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

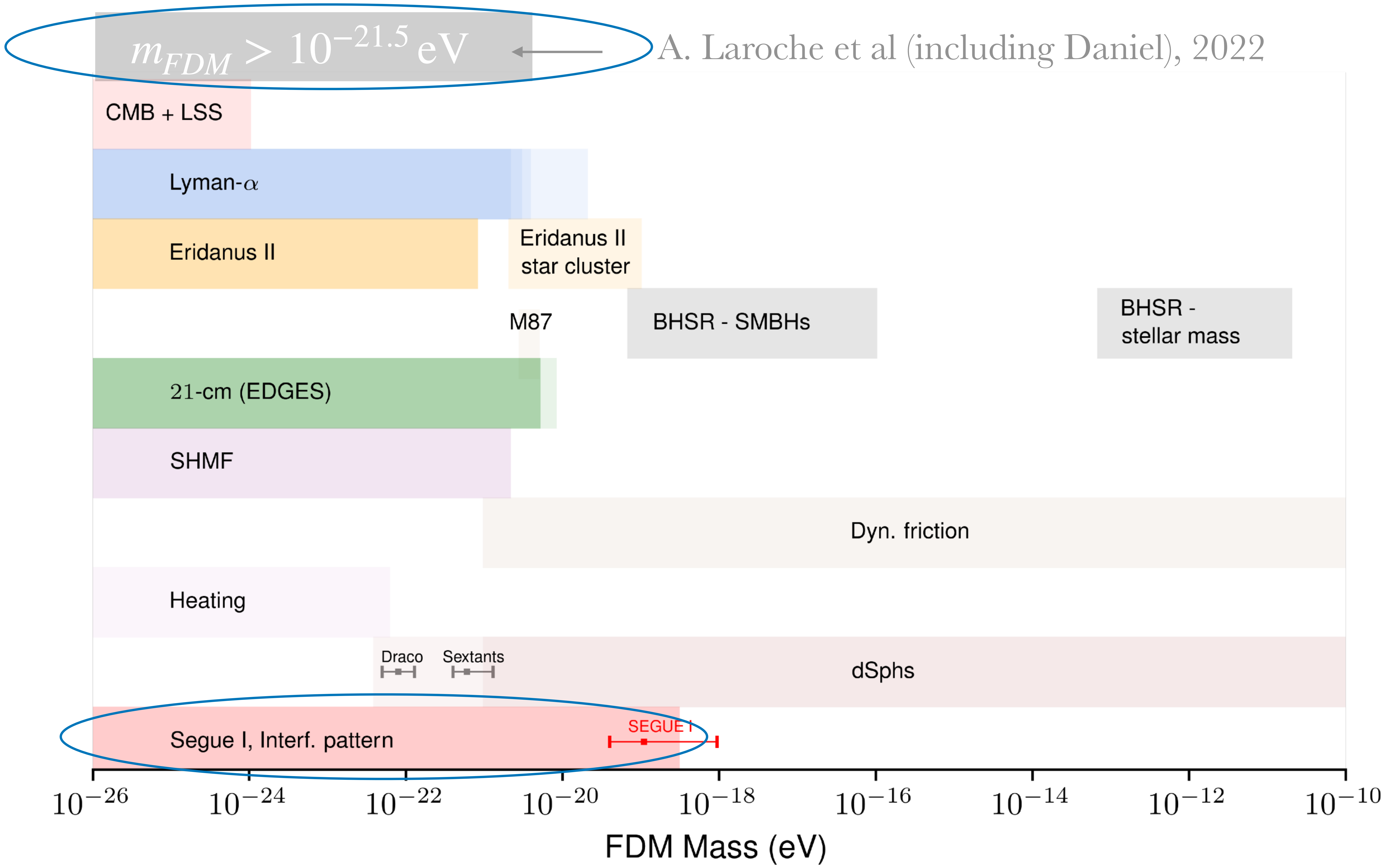
Sub-galactic power spectrum:
Hezaveh et al. (2016)

Sub-galactic power spectrum
Kawai, Oguri (2021)

Dwarfs
N. Dalal, A. Kravtsov, 2022

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



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

A. Laroche et al (including Daniel), 2022

<u>INTERFERENCE PATTERNS</u>

N. Dalal, A. Kravtsov, 2203.05750

$$m_{\rm FDM} > 1 \times 10^{-19} {\rm eV}$$

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

New observables/new probes

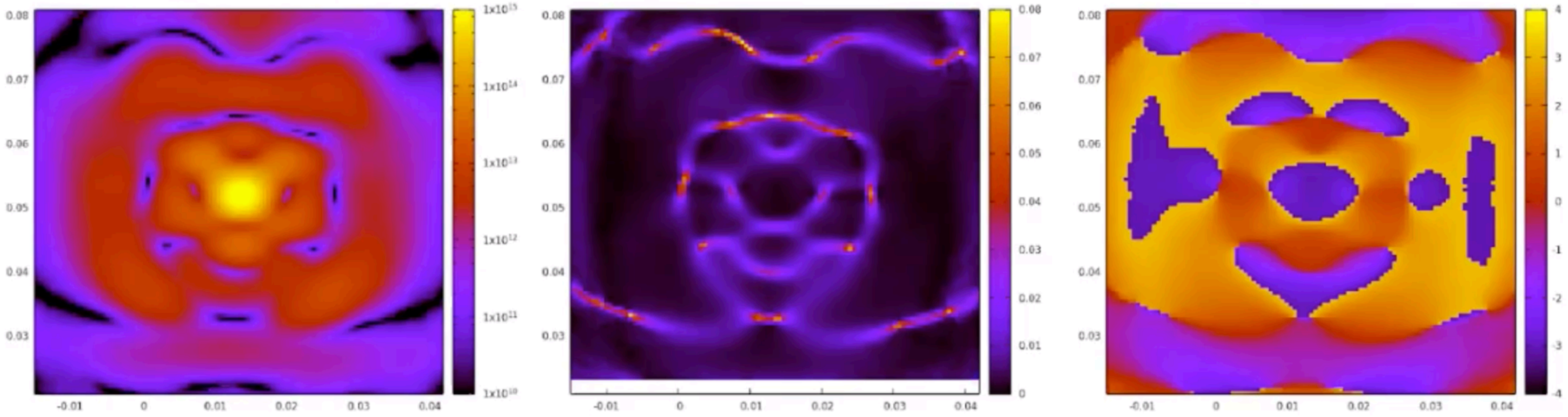
Ongoing: Vortices

PRELIMINARY

In collaboration with Jowett Chan

Fuzzy DM

Density | Vorticity | Phase

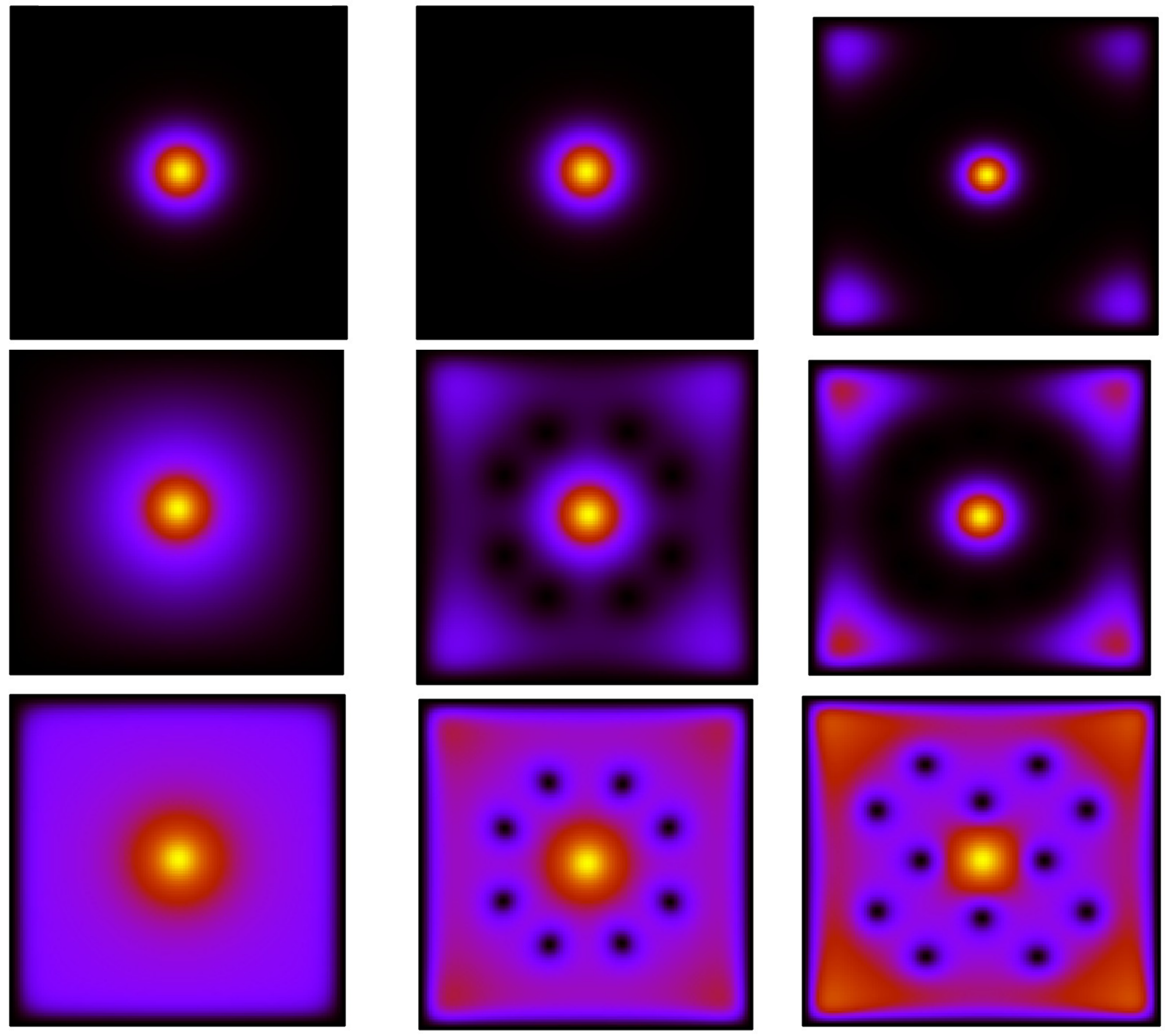


Vortice Ring?

Self-interacting Fuzzy DM

$\Omega[\ \mathrm{Myr}^{-1}]$: 0, 0.01, 0.04 — Ω increases →

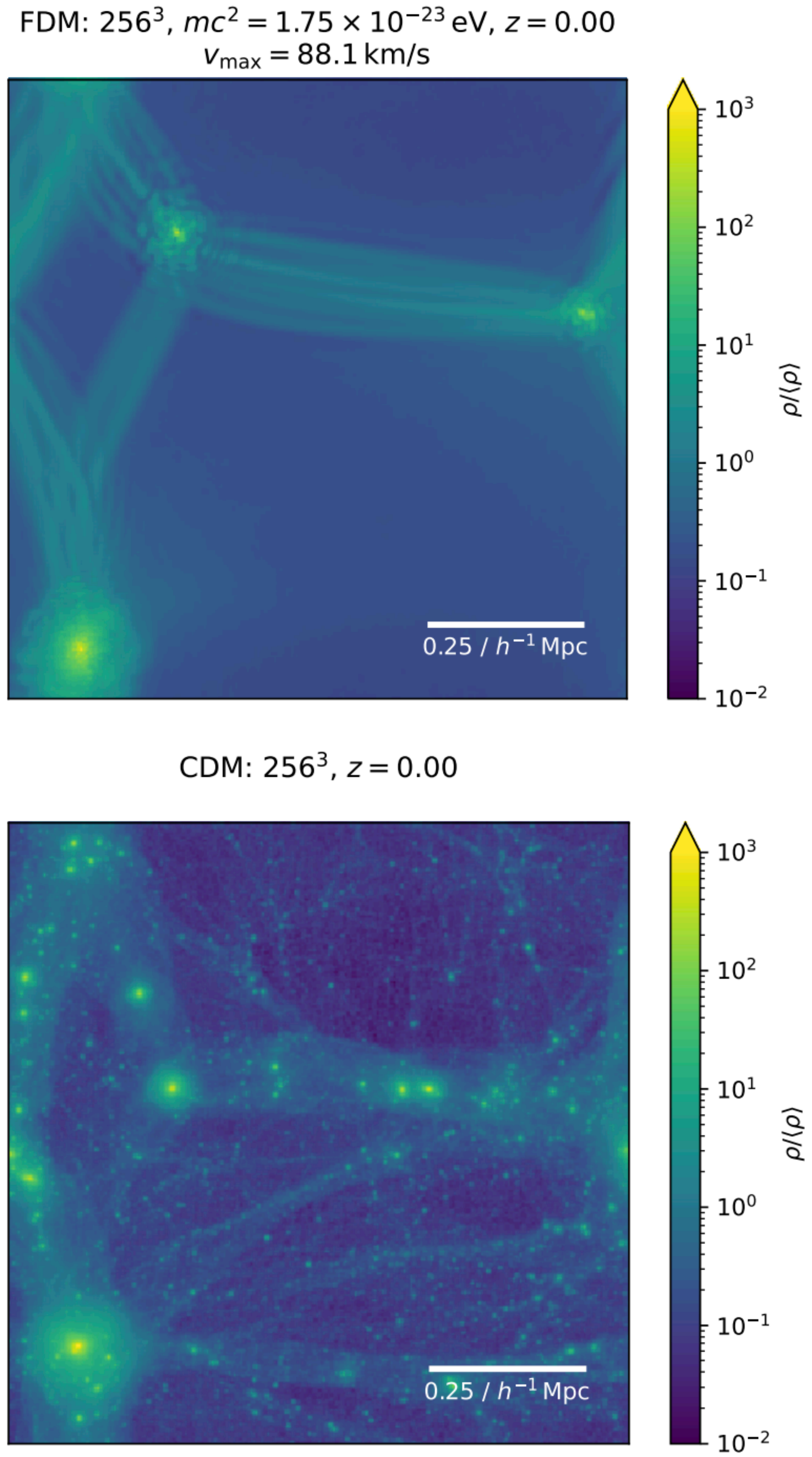
$g[\mathrm{eV\ cm}^3]$: 10^{-71}, 10^{-70}, 10^{-69} — g increases →



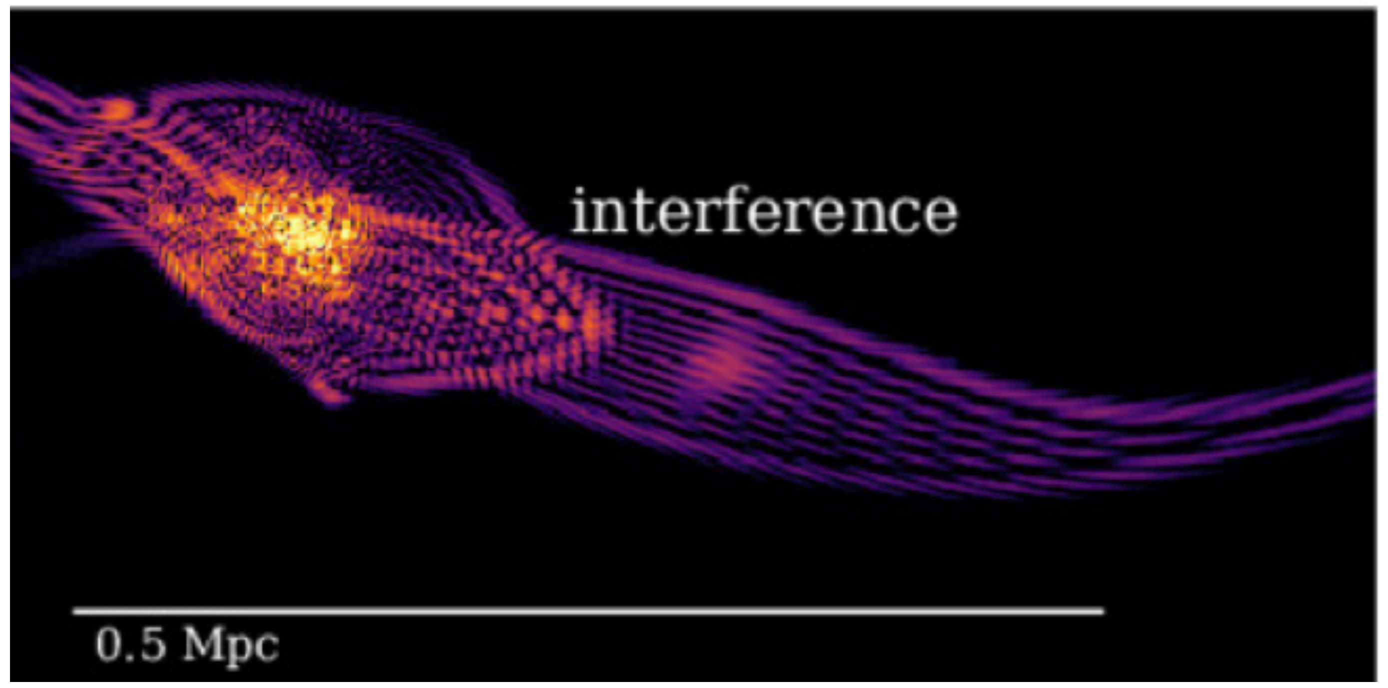
+ Improve theoretical understanding of these DM vortices *In collaboration with P. Bittar*

New observables/new probes

Filaments in FDM



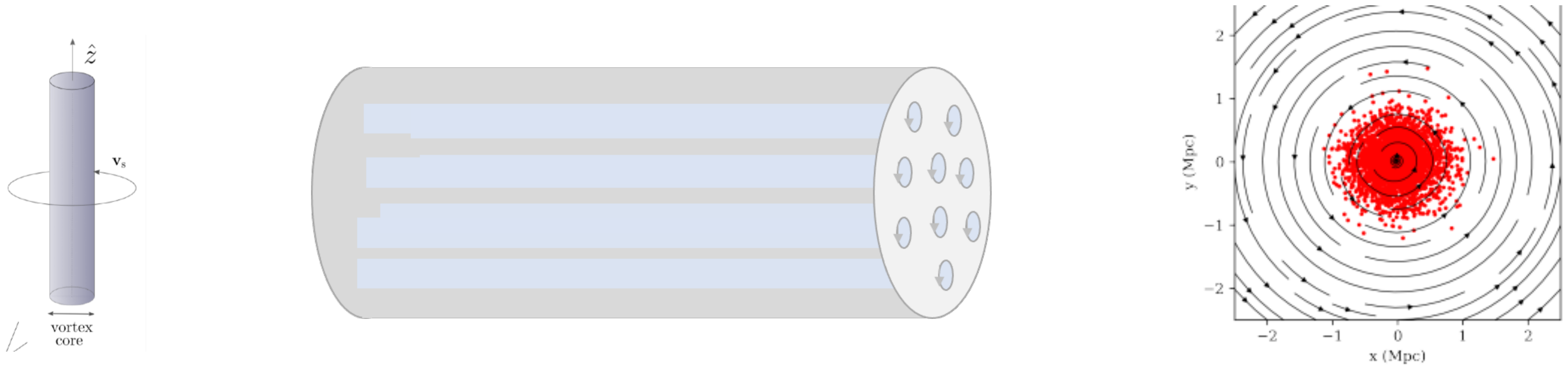
S. May et al. 2021



Mocz et al. 2017

Vortices in filaments

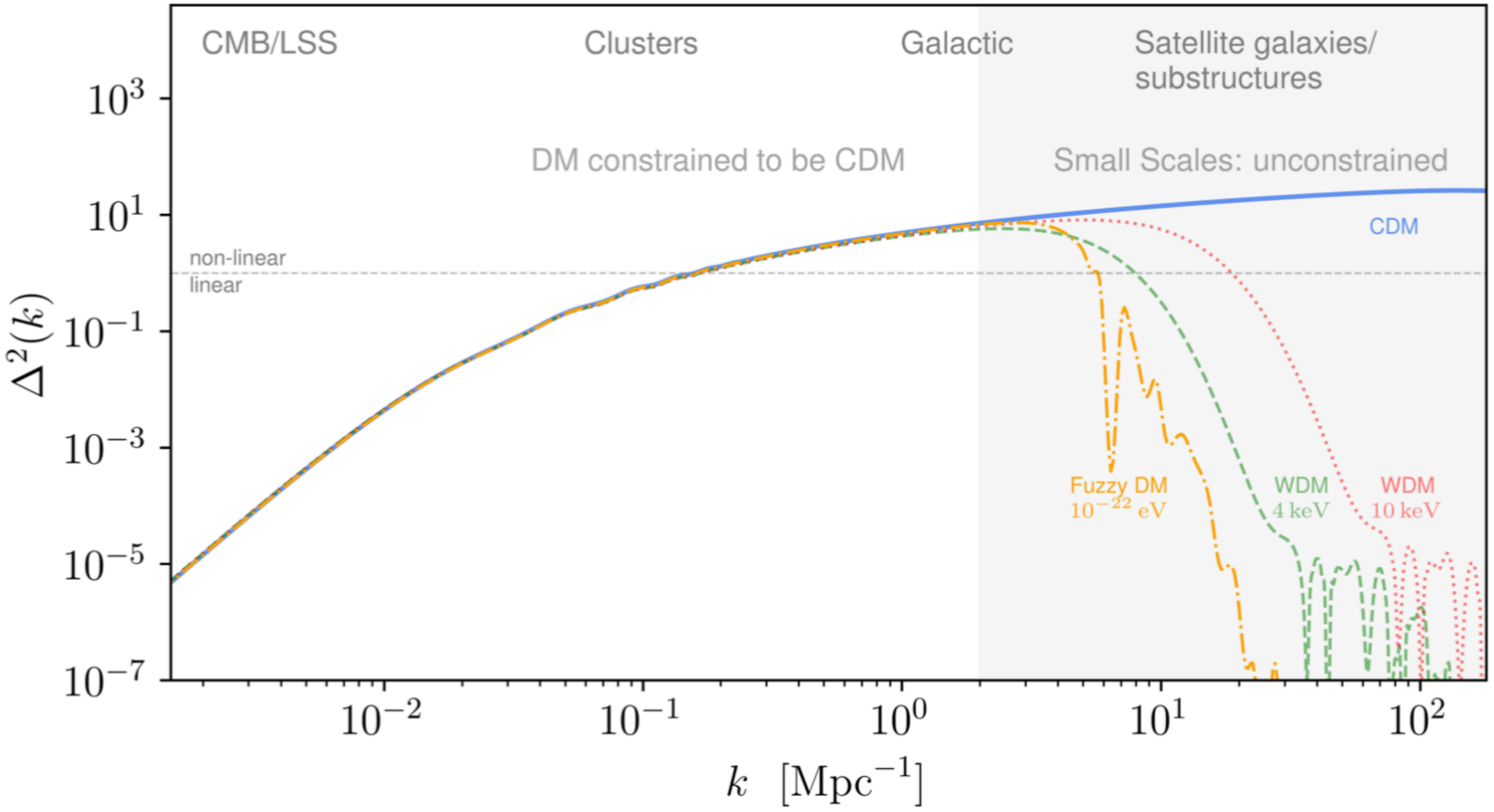
"Cosmic Filament Spin from Dark Matter Vortices" ,
S. Alexander, C. Capanelli, EF, and E. McDonough (2021)



Sub-galactic power spectrum

New probes

Using gravitational probes, strong lensing and stellar streams, to describe substructures



New probes

Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures

A. Diaz Rivero, et al. (2017); Diaz Rivero, et al. , (2018)

Substructure convergence power spectrum

Bayer et al. (2018) ; Auger et al. 2009
FDM: *Kawai et al. (2021)*

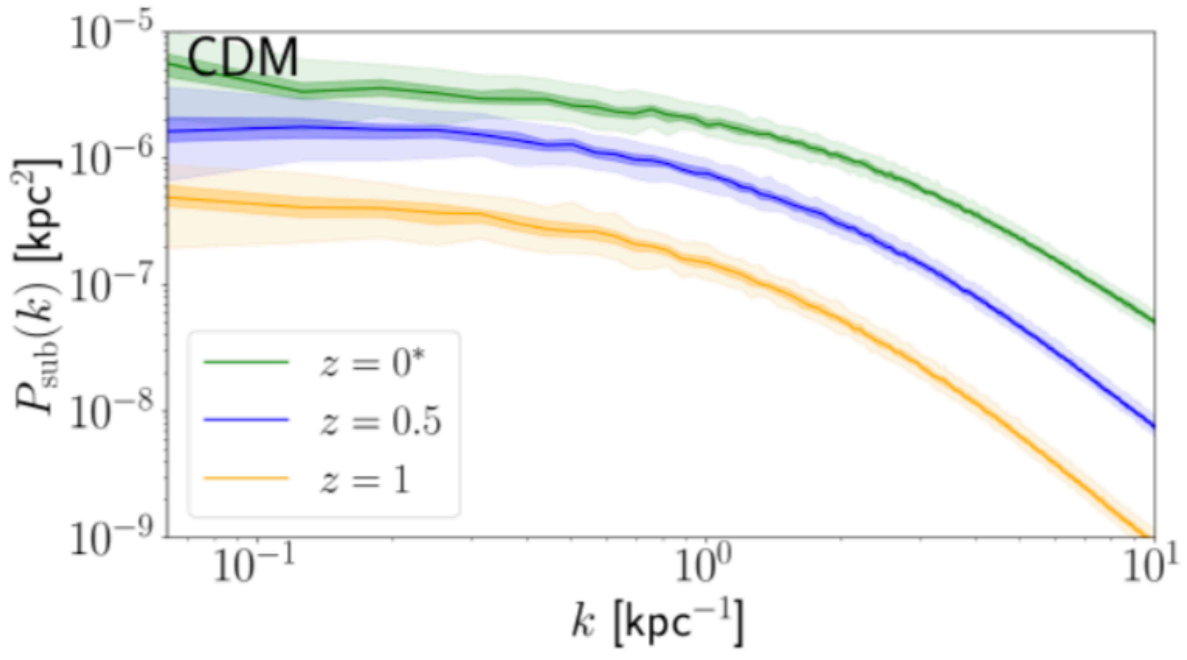
Develop a formalism to compute the substructure convergence power spectrum for different populations of dark matter subhalos.

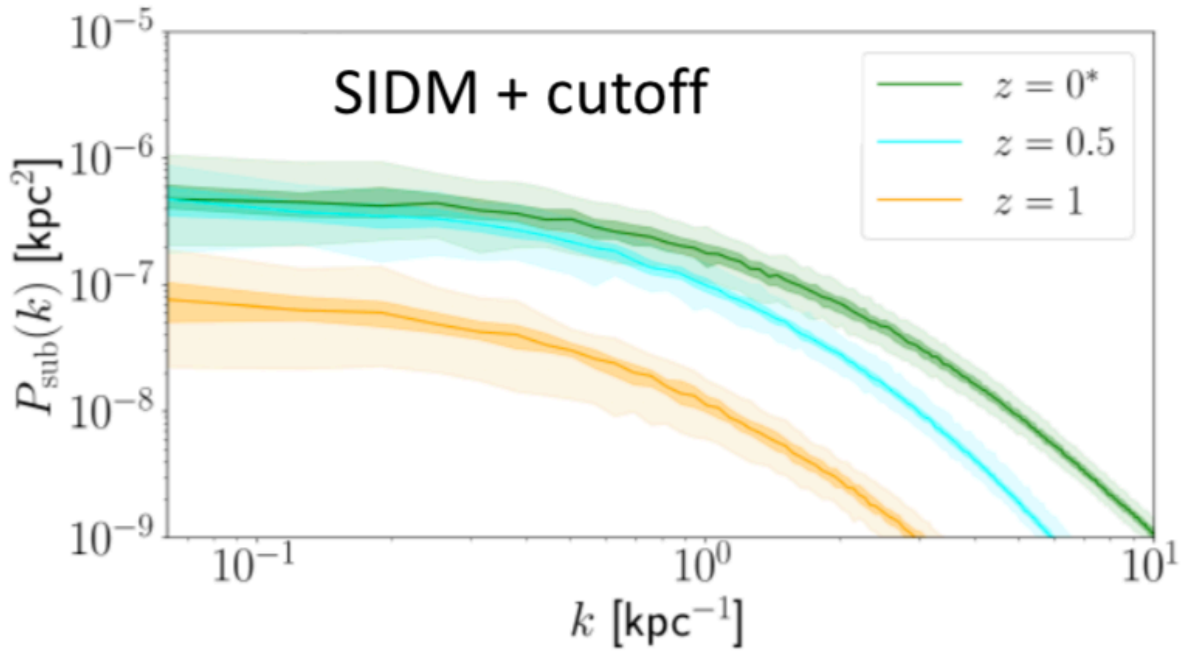
Hezaveh et al. (2016) (projected mPS by using strong lensing)

Change of language: instead of talking about lensing perturbations in terms of individual subhalos, look at the correlation function of the projected density field.

(based on Dvorkin's slide)

$$P_{\mathrm{sub}}(k) = P_{1\mathrm{sh}}(k) + P_{2\mathrm{sh}}(k)$$





New probes

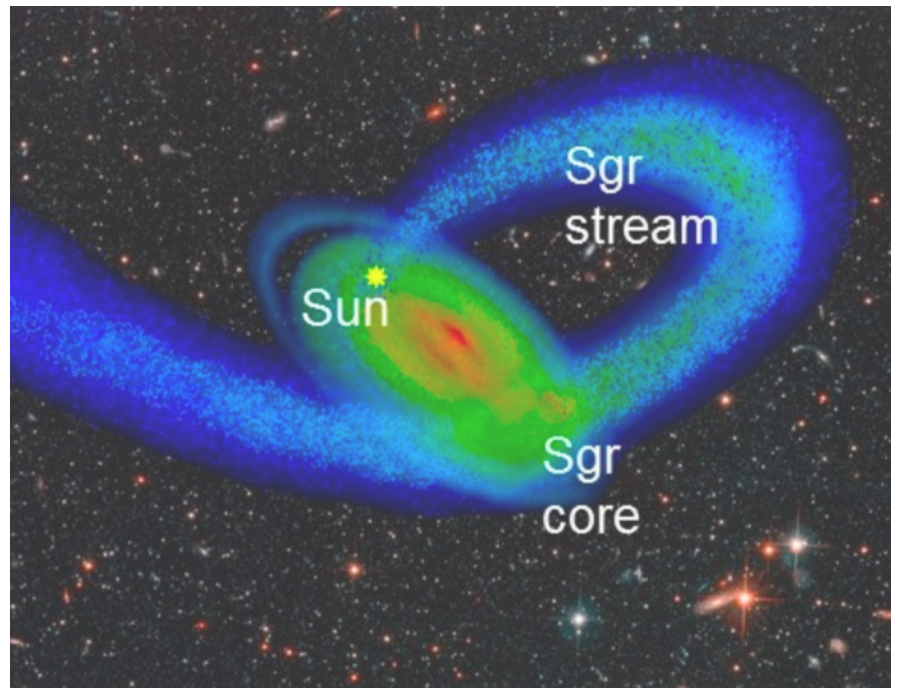
Sub-galactic power spectrum

Using gravitational probes, strong lensing and stellar streams, to describe substructures

Substructure convergence power spectrum

Sten Delos and Fabian Schmidt (2021)

Stellar streams: perturbed by passing substructure. Good gravitational probe, since given their low dynamical temperature and negligible self-interaction, it retains the memory of those encounters.



THIS WORK: Fully analytical understanding of the stream perturbations!

Power spectrum of a stream's stellar density is analytically related to that of the substructure background:

$$\underbrace{\boxed{P_*(k,t)}}_{\text{Stream power}} = \chi_*\left(k\sigma_0 t, \frac{D}{k\sigma_0^3}\right)\frac{k^2t^2}{3}P_{\Delta v}(k,t)$$

$$P_{\Delta v}(k,t) = 16\pi^4 G^2 \bar{\rho}^2 k^2 t \int_k^\infty \frac{\mathrm{d}q}{q}\frac{\overbrace{\boxed{\mathcal{P}(q)}}^{\text{Substructure power}}}{q^6}\int \mathrm{d}^3\boldsymbol{u}\frac{f(\boldsymbol{u})}{u}\theta_H(qu - kv)$$

Previous:
- Mostly numerical
- Perturbations ⟶ sub-halo mass function

Relates the stellar stream perturbation to the surrounding matter distribution, from dark and luminous substructure

Simulations of ULDM

Very challenging!

Might be interesting to the C02 (simulation) group!

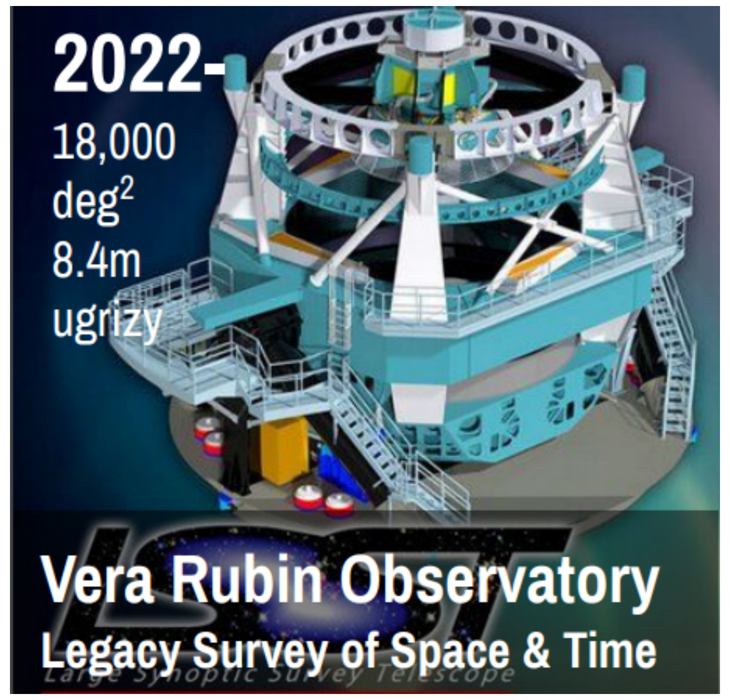
- Hybrid simulations: large scales (hydro) + small sales (SP-sims) ←
- Zoom-in ← Jowett Chan
- Soliton mergers
    - Soliton oscillations
- Adding baryons

(See works from S. May & V. Springel, L. Hui, Veelmat, Niemeyer & Schwabe, Schive, Chiueh & Broadhurst, Mocz et al., …)

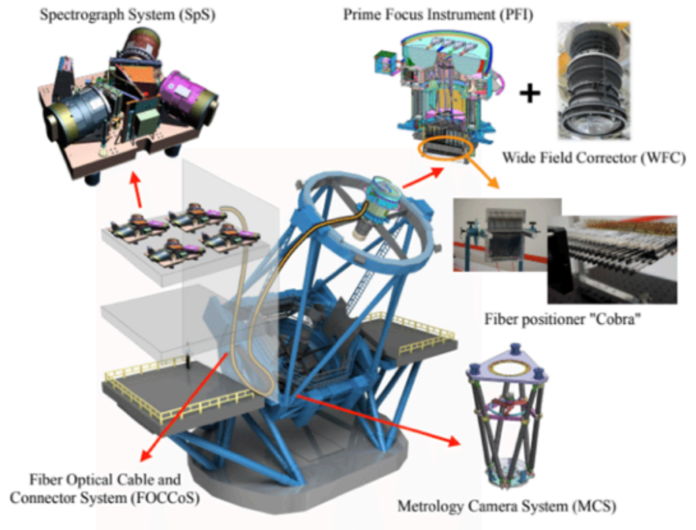
Future - signals in cosmology

Observations

Photometric and spectroscopic surveys

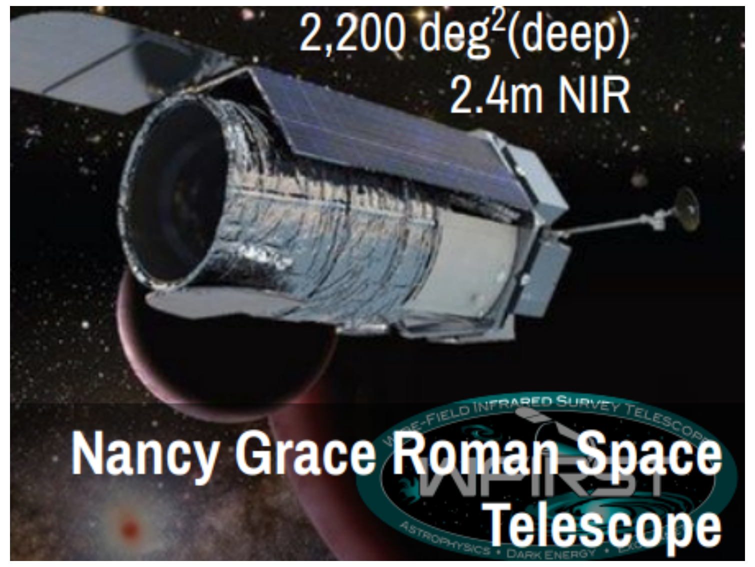

2022-
18,000 deg^2
8.4m
ugrizy
Vera Rubin Observatory
Legacy Survey of Space & Time

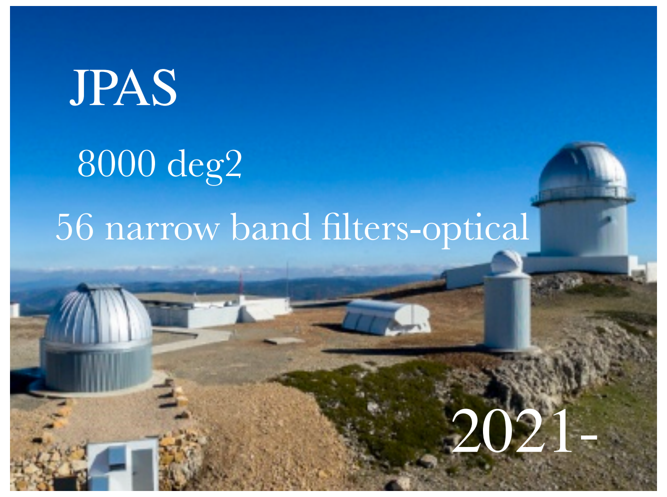
Prime Focus Spectrograph (PFS)




2022-
15,000 deg^2
1.2m Optical/NIR

Euclid Mission


2,200 deg^2(deep)
2.4m NIR
Nancy Grace Roman Space Telescope


JPAS
8000 deg2
56 narrow band filters-optical
2021-

GWs

21cm


CHIME


BINGO
2022

SKA
SQUARE KILOMETRE ARRAY


HIRAX

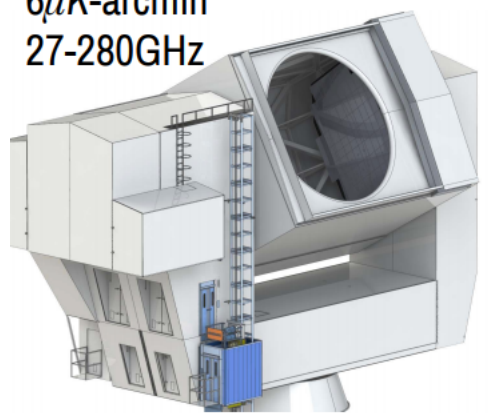
CMB


LiteBIRD

Full sky
$100\mu K$-arcmin
40-402GHz

2021
16,000 deg^2
$6\mu K$-arcmin
27-280GHz

SIMONS OBSERVATORY



CMB-S4
Next Generation CMB Experiment

Modified from Jia Liu

PFS (Prime Focus Spectrograph)

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

PFS: spectroscopy part of *SuMIRe project*

DM with PFS ⟶ synergy between science goals

Galaxy archeology

- Nature of DM (dSphs)
- Structure of MW dark halo
- Streams
- Stellar kinematics and chemical abundances – MW & M31

Cosmology

- Power spectrum
- HSC+PFS
- Linear growth (RSD)

Galaxy evolution

- 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

PFS - Galactic Archaeology

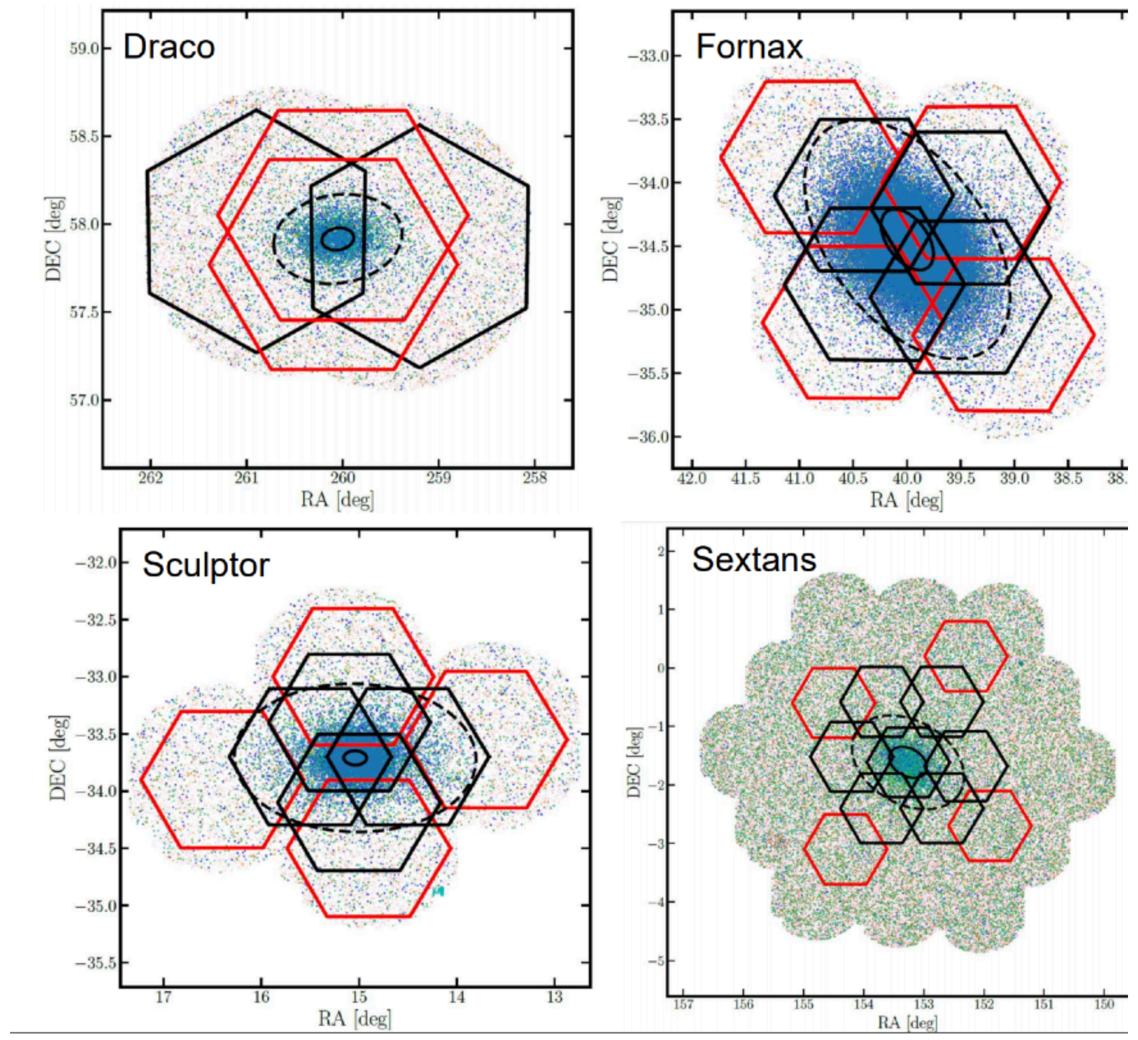
B02 group (Subaru spectroscopy)

TESTING ULTRA LIGHT DM/DM with PFS

Galaxy archeology

- Nature of DM (dSphs)
- Structure of MW dark halo
- Streams
- Stellar kinematics and chemical abundances – MW & M31

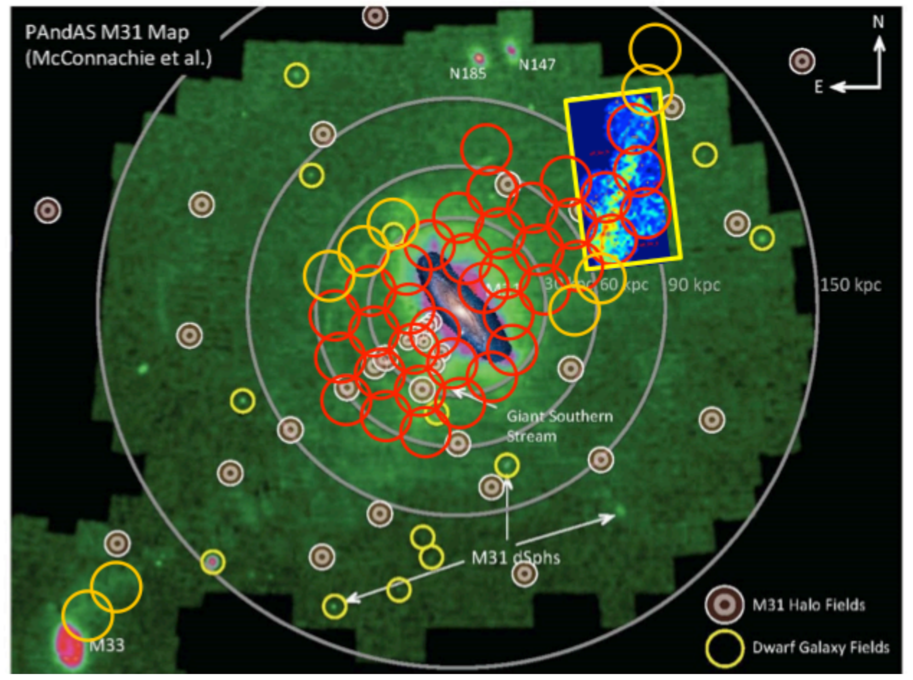
Wide & deep survey of MW dwarf galaxies w. Subaru/PFS

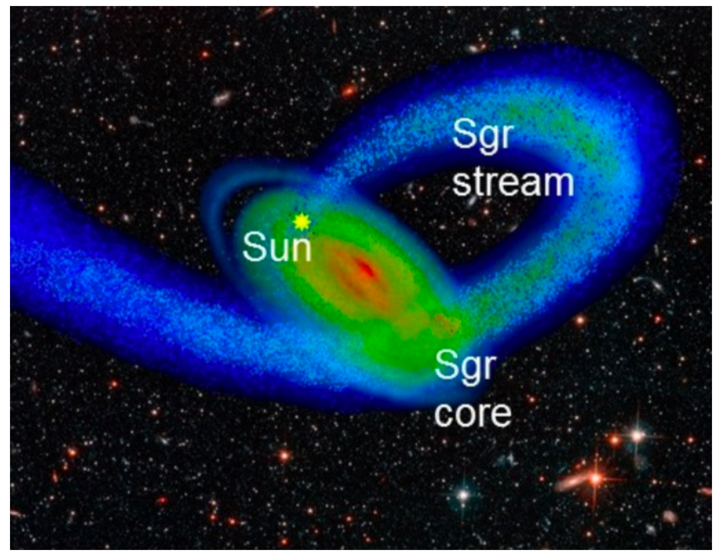


dSphs

Stelar streams

M31





MW outer disk

Dwarf galaxies:

(1) Sample sizes in excess of 1000 stars per dSph,

(2) Wide-area coverage well suited for dSphs,

(3) Velocity precision much smaller than the velocity dispersion of a dSph,

(4) Abundance measurements

(5) Synergy with Subaru/HSC pre-imaging.

GA ⟶ potential to put unprecedented constraints on ULDM.

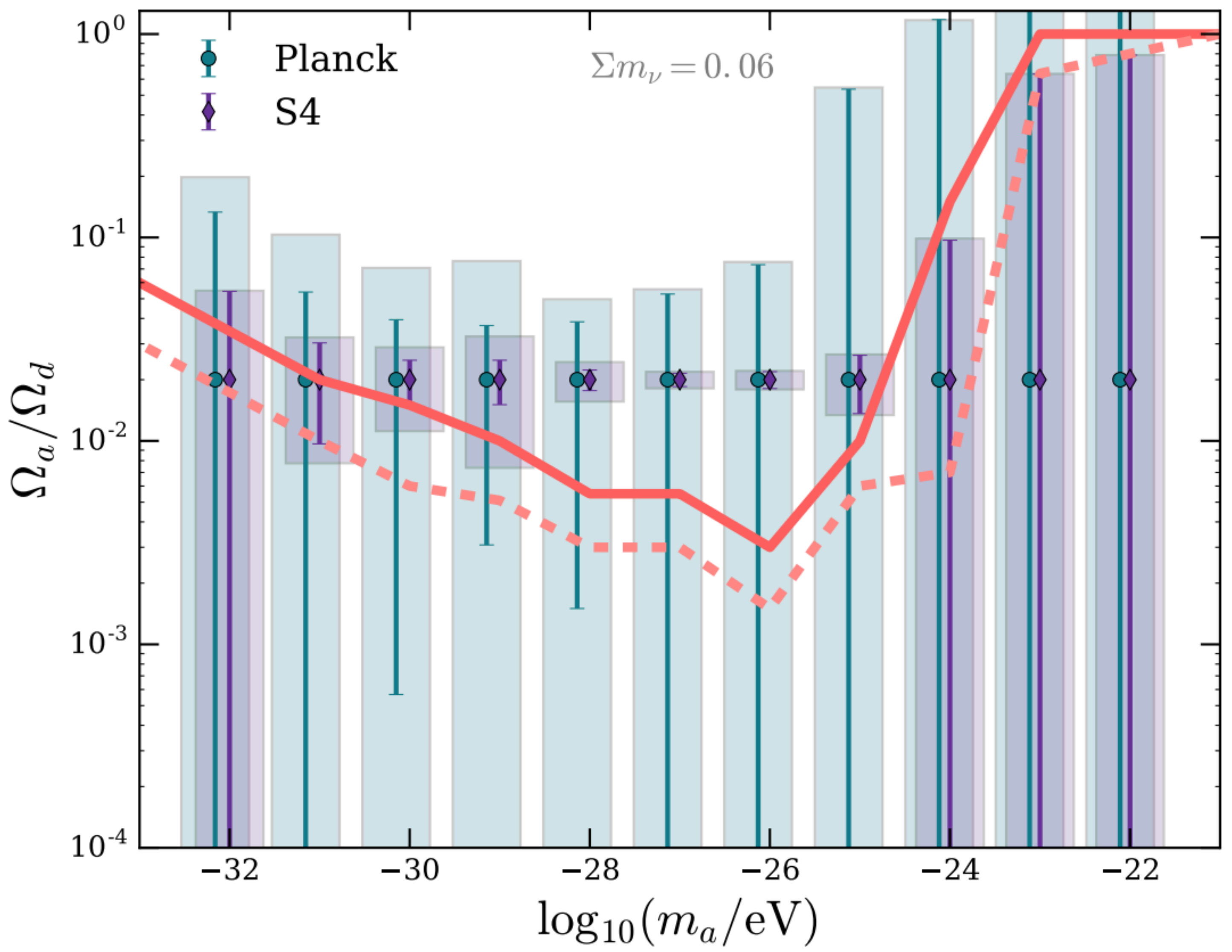
SSP proposal

Future - *Cosmic Microwave Background*

TESTING ULTRA LIGHT DM CMB

CMB - S4

Constraints on Ω_a/Ω_d



Hlozek et al., 2016

Significantly improve constraints on the composition of the dark sector!

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

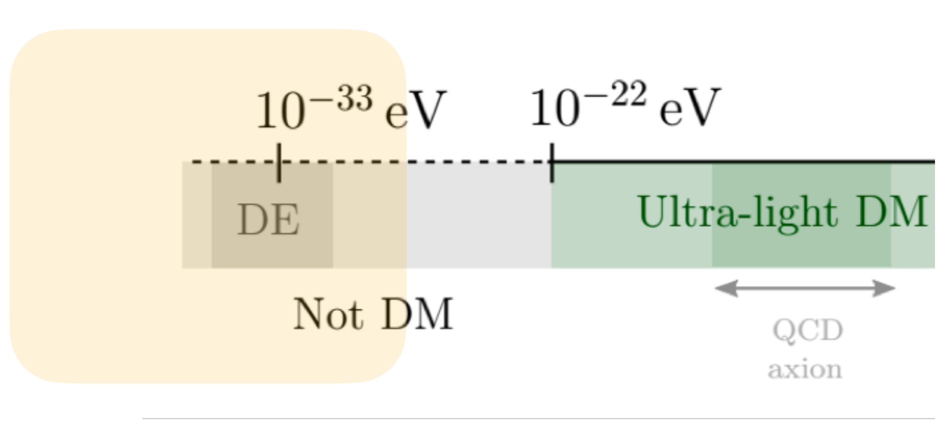
Constraint the ULDM mass

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

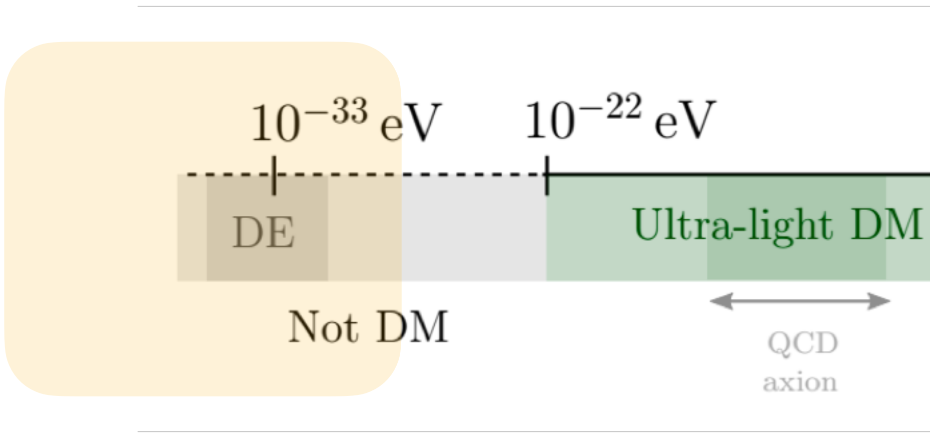
- *LiteBIRD*
- *Advances ACTPol*
- *CMB-S4*

Cosmic Birefringence

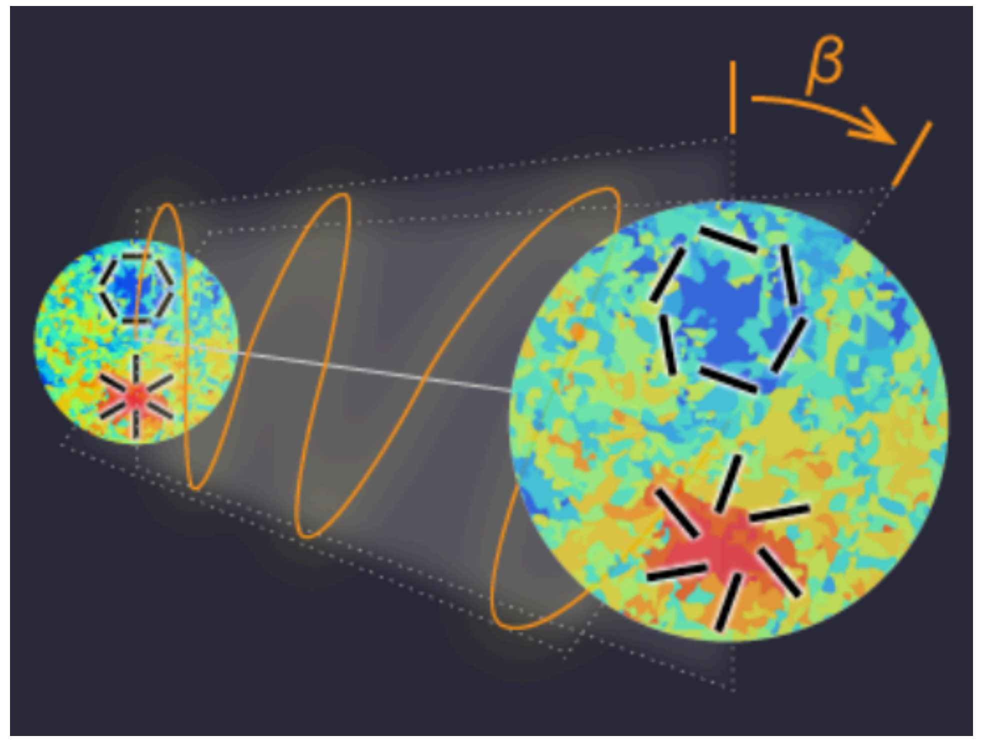
CMB and light DM groups' talks!



ALP as dark energy



Cosmic Birefringence from axions



Minami/Komatsu

Parity-violating physics in polarisation of the cosmic microwave background

↓

Rotation of the CMB polarization plane

Minami , Komatsu 2020

Could be cause by an ultra-light axion that behaves like dark energy

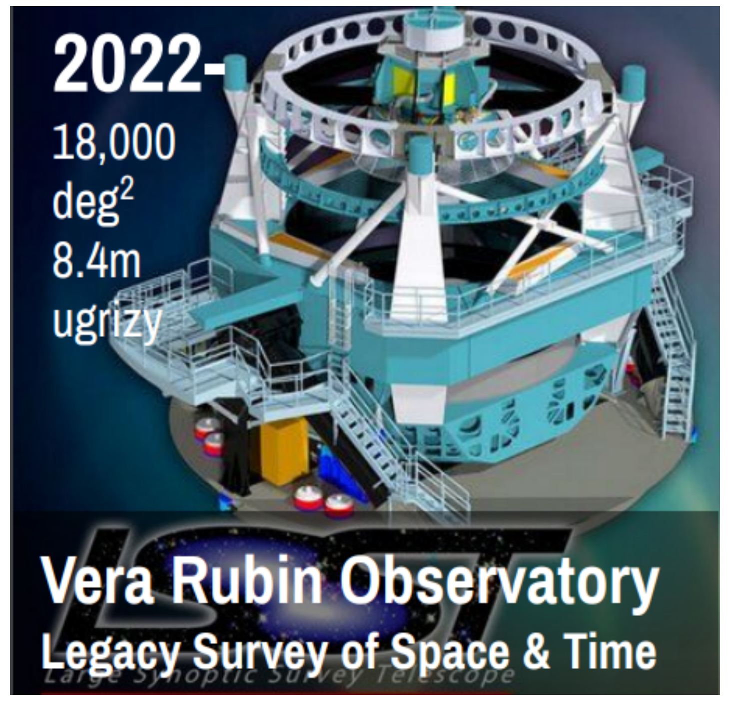
- Develop models with such axion
- Study their predictions
- Forecasts for LiteBIIRD

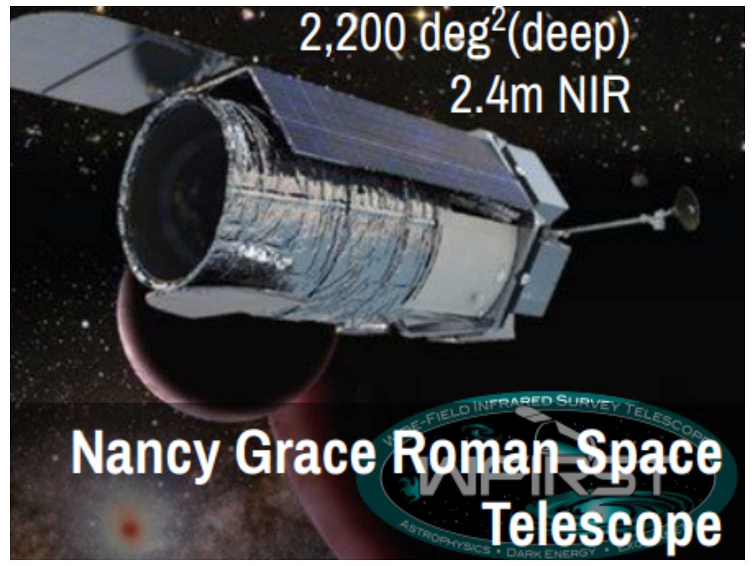
LiteBIRD can possibly constraint this effect

LSS probes

PFS in coordination with:

- Vera C. Rubin Legacy Survey of Space and Time (LSST)
- Atacama Large Millimeter/submillimeter Array (ALMA)
- Nancy Grace Roman Space Telescope (WFIRST)
- *Gaia*
- …





Much stronger statistical constraints on dark matter models!

And many more creative ideas!

Summary

Ultra-Light Dark Matter

Well motivated DM models

Rich and distinct phenomenology on small scales

Testable prediction

Small Scales

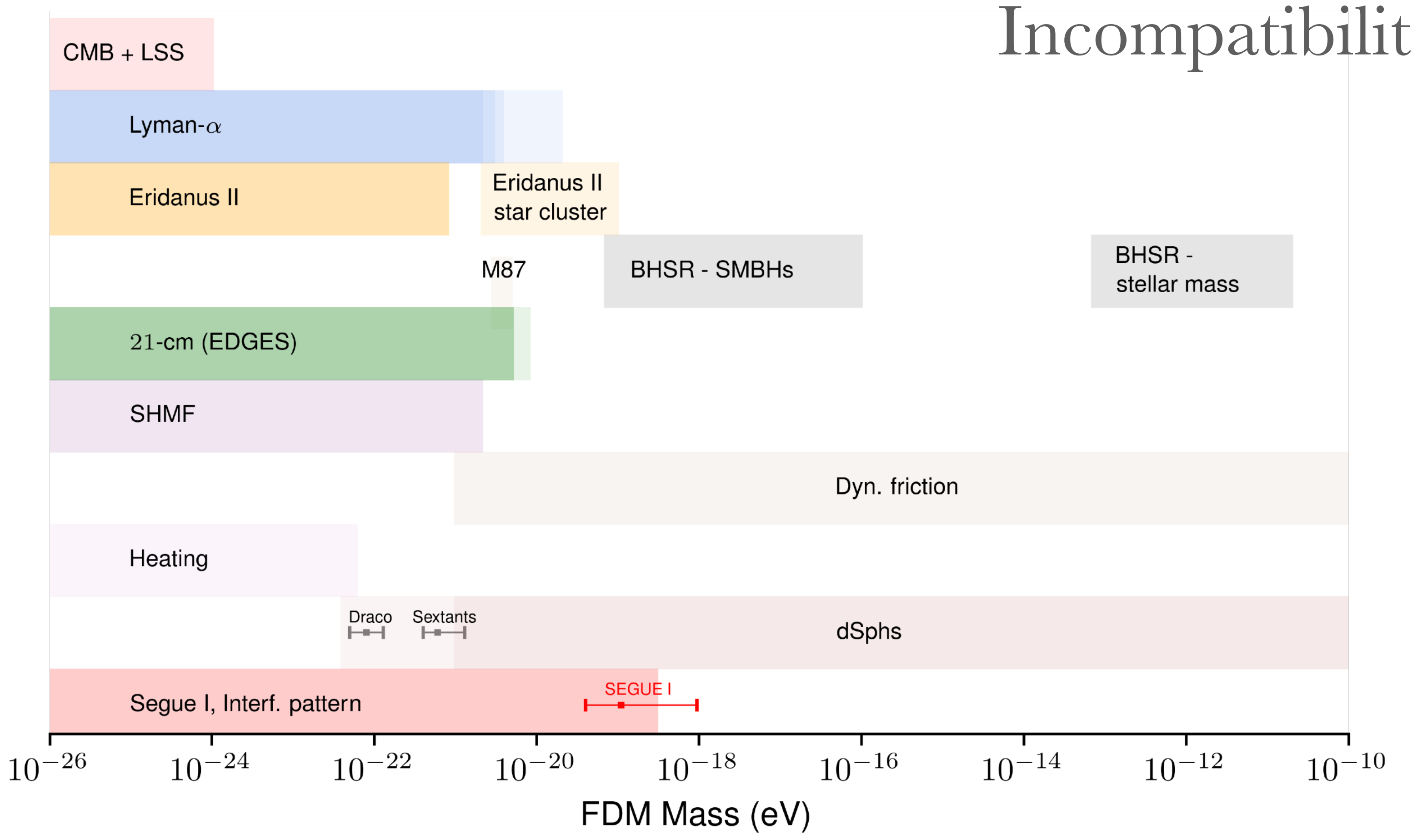
Opportunity to probe the microphysics, particle physics properties of DM

Small scales provide strong constraints in these models

FDM mass being narrowed down

Incompatibility between dwarf bounds

Current status



Incompatibilities!

Future

Observations: PFS

PFS-GA

CMB

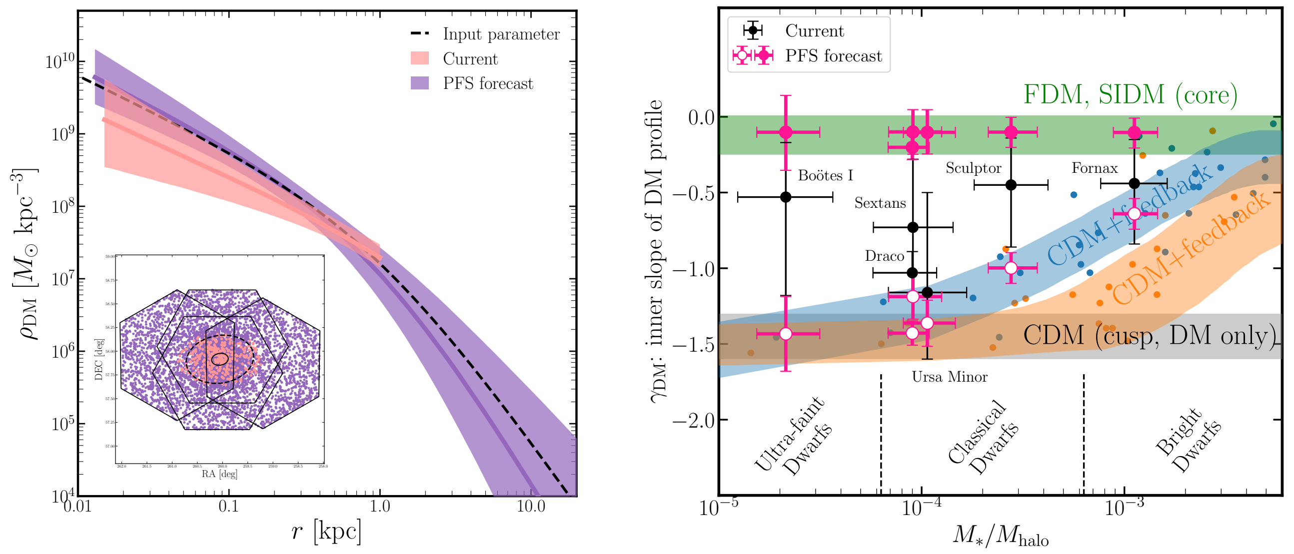
LSS

Small scales

Simulations: cosmological

New observables: interference patterns and vortices

New probes



Thank you very much!