Narrowing the mass range of Ultra-light Dark Matter

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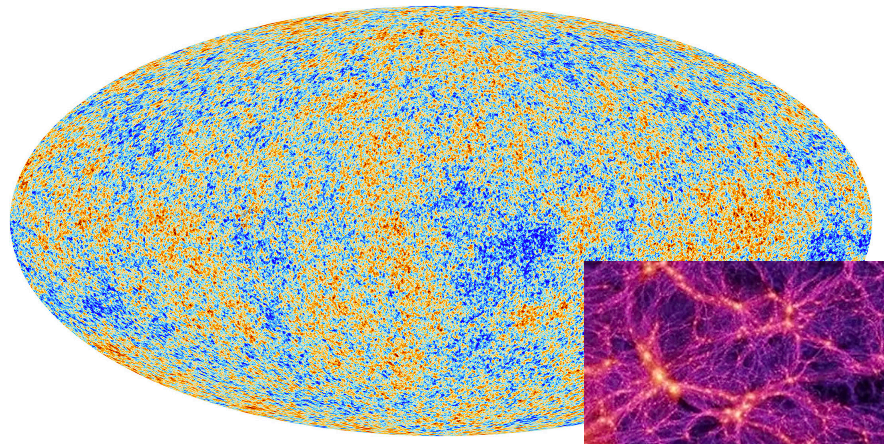
Evidences for dark matter

We can observe its effects in

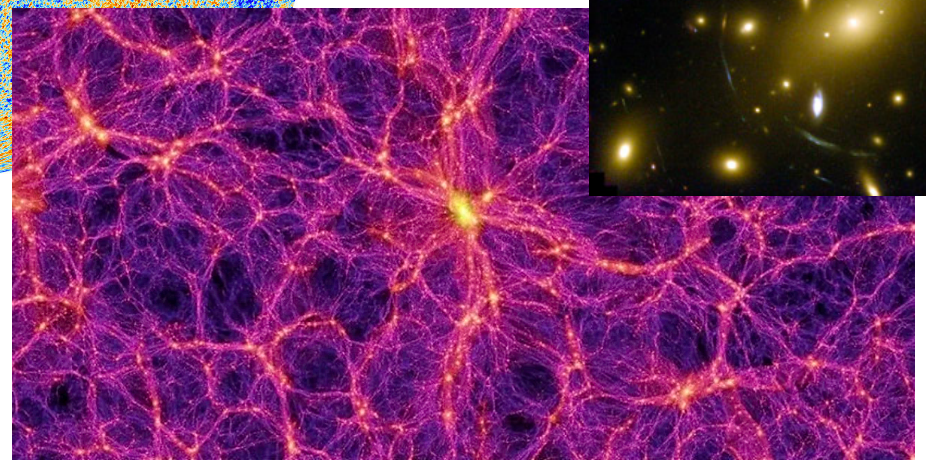
Galaxies

NASA and ESA

CMB+LSS



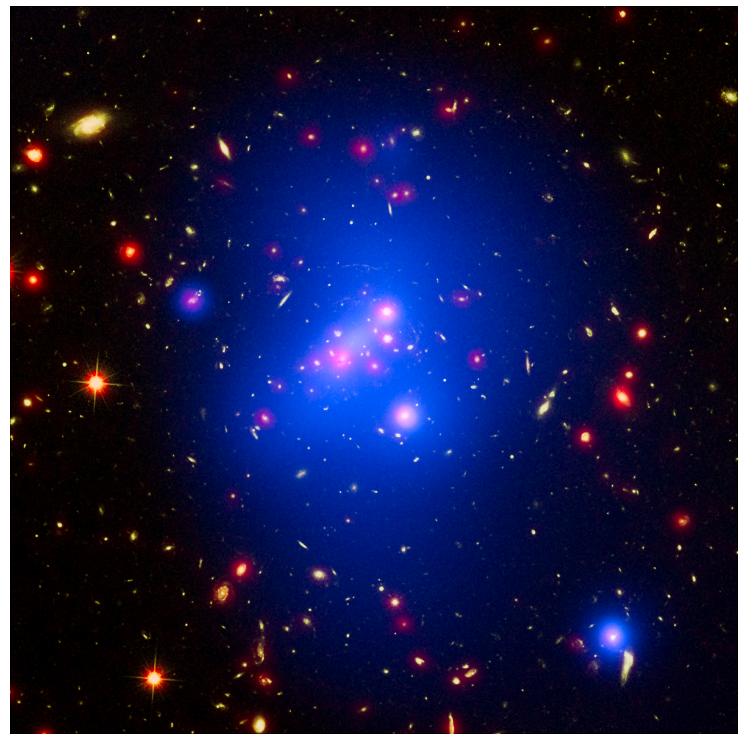
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

NASA and ESA

Clusters



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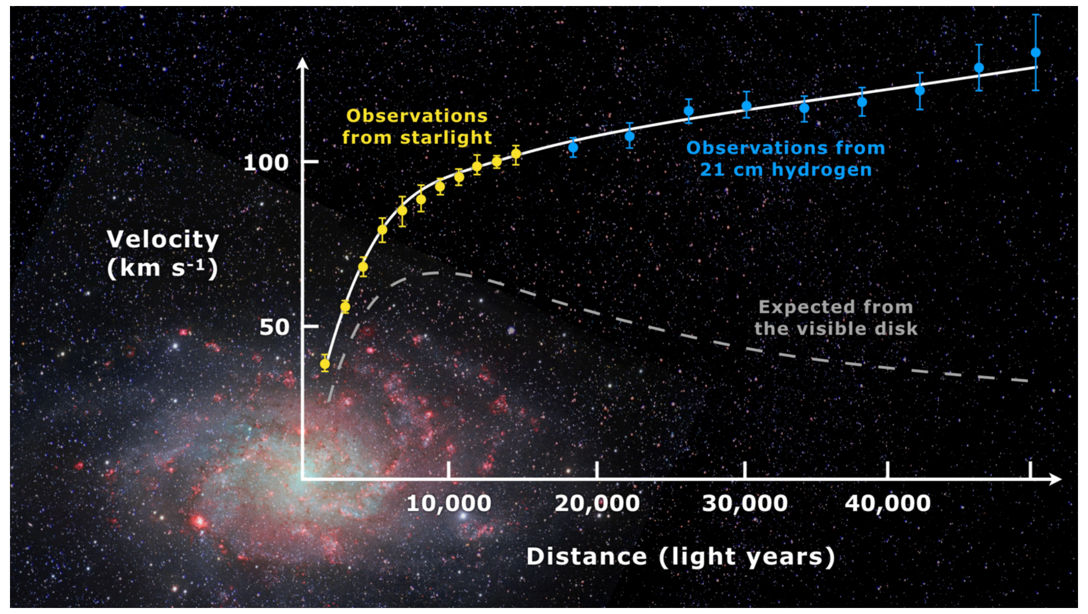
Huge amount of evidence
From all scales

Evidences for dark matter

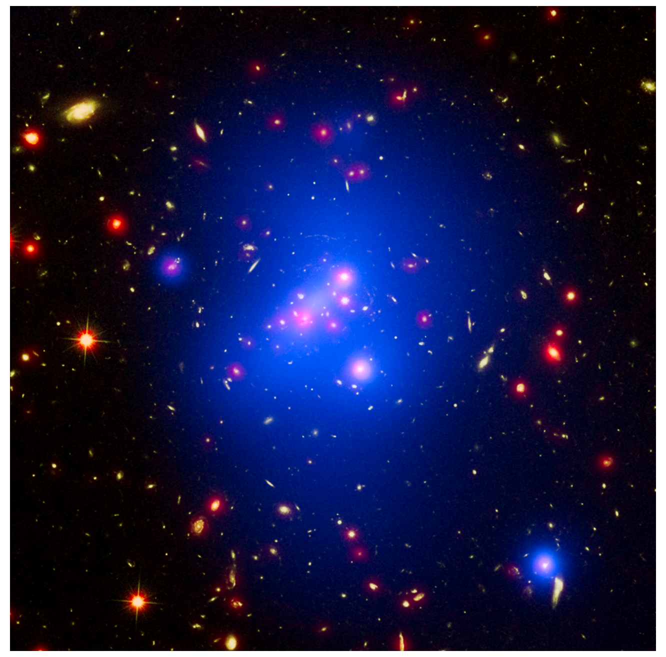
Galaxy rotation curves



Credit: Mario De Leo

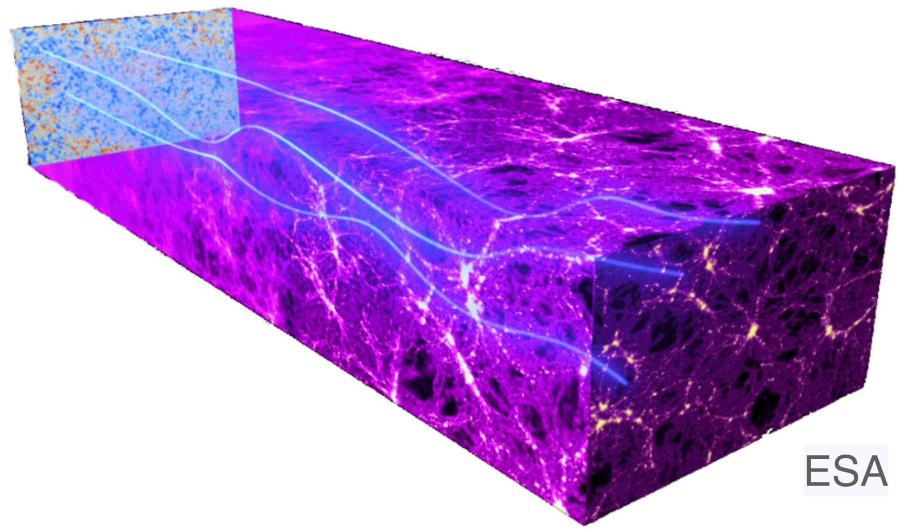
- Mass fraction
- Distribution

Clusters



- Mass fraction
- Distribution

Lensing



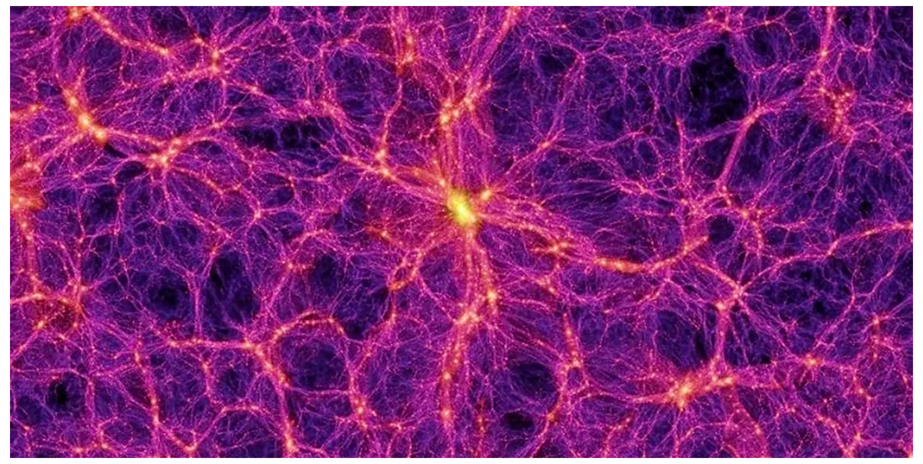
ESA

Strong lensing
- Mass fraction
- Distribution

Weak lensing
- Distribution
- Shape
- Structure

Micro lensing
- Mass fraction
- Smoothness

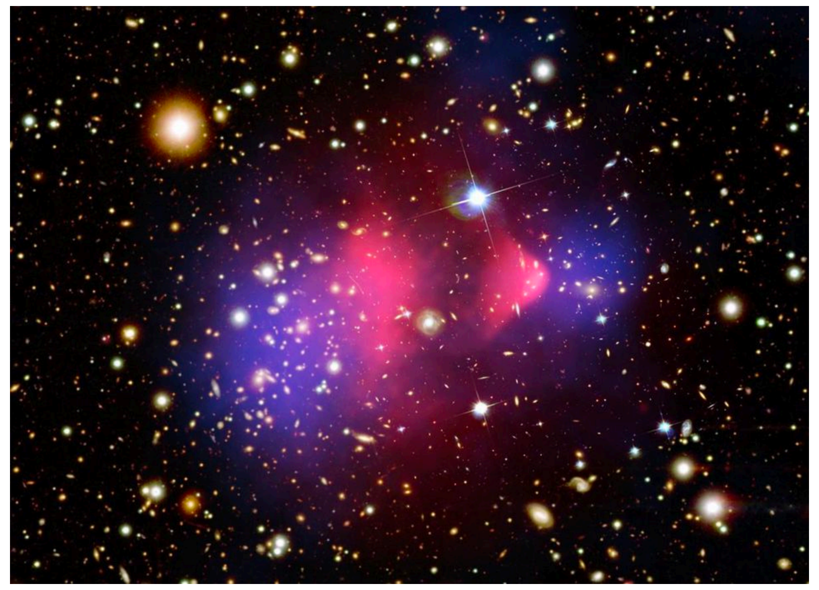
Large Scale Structure



Springel & others / Virgo Consortium

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

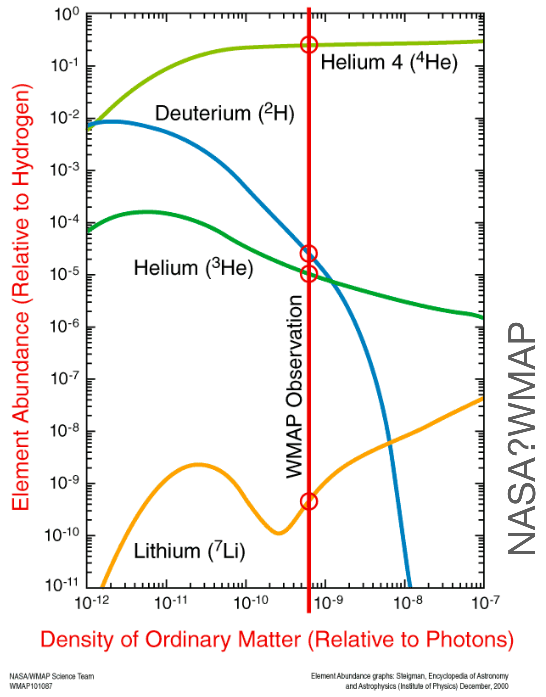
Cluster collision



NASA/CXC/CfA and NASA/STScI

- Distribution
- Separation from collisional matter
- Self-interaction

Big Bang Nucleosynthesis



NASA?WMAP

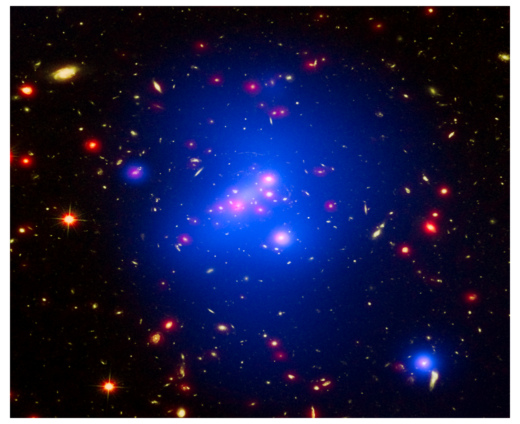
- Amount of baryons

Based on K. Mack

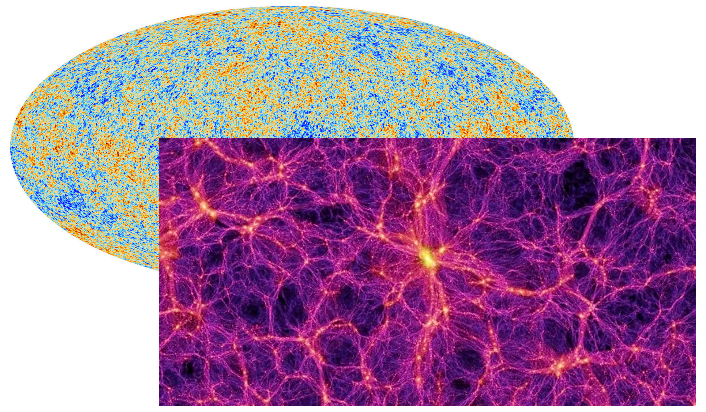
What we know about dark matter

Galaxies

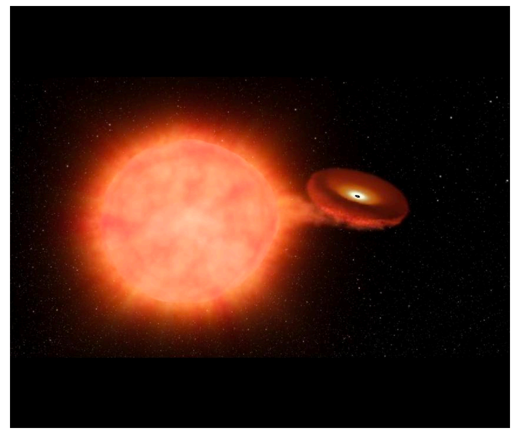
Clusters



Large scales

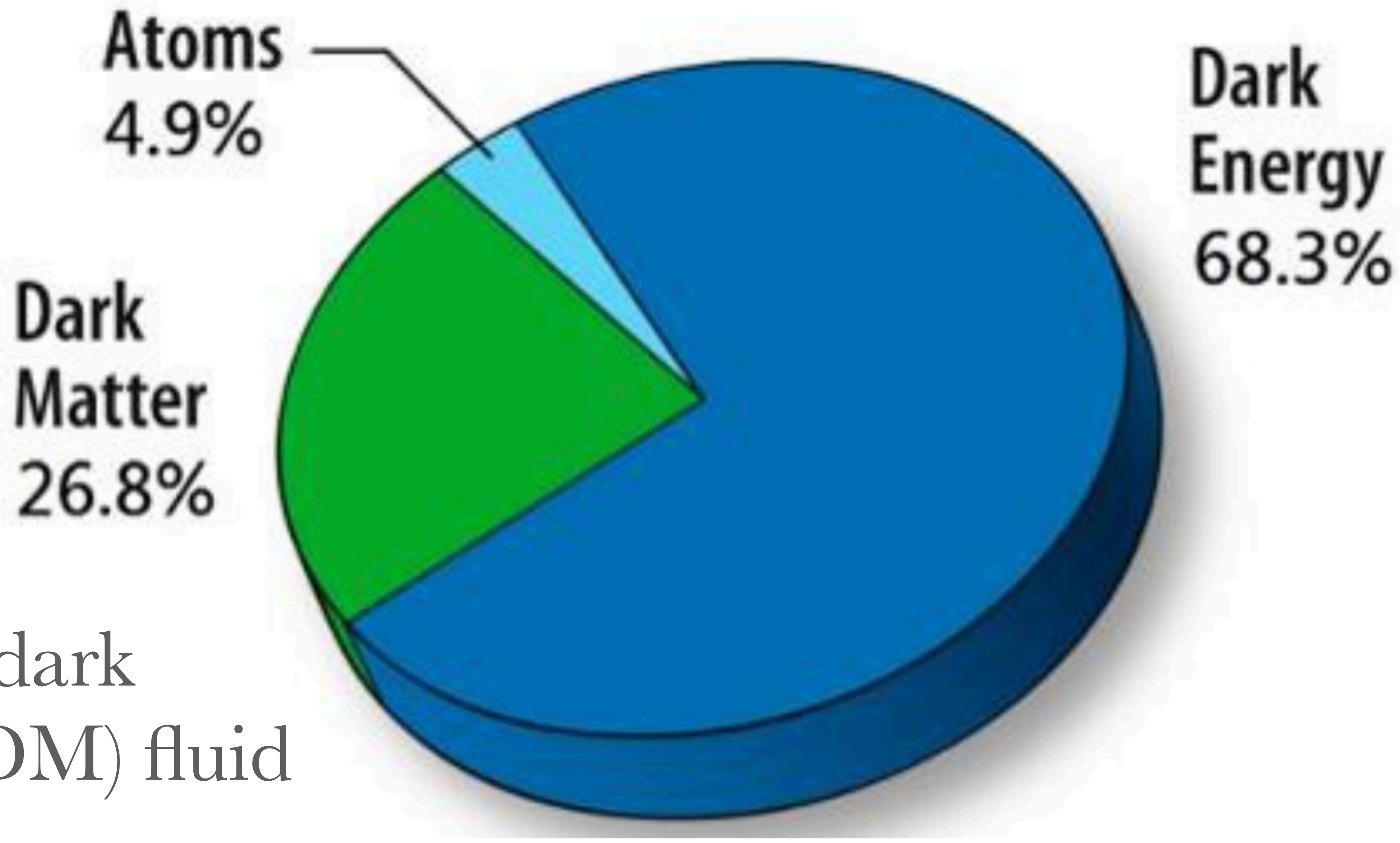


Sn Ia



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 (transparent)~~ → Non-gravitational interaction? Milicharged DM
- ~~Collisionless~~ → How small sefl-interaction? SIDM

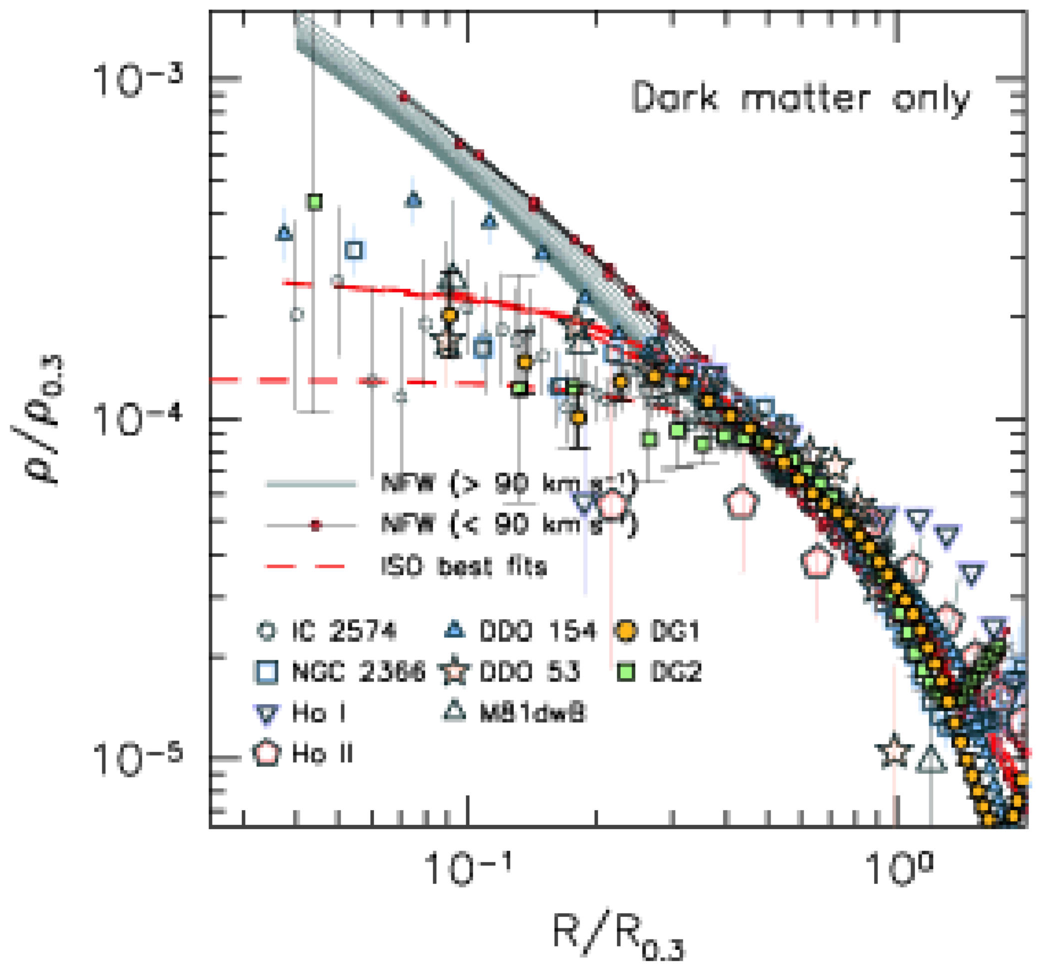
Although still behaves like CDM on large scales

Small scale behavior: still weakly constrained and small scale challenges

Small scale challenges

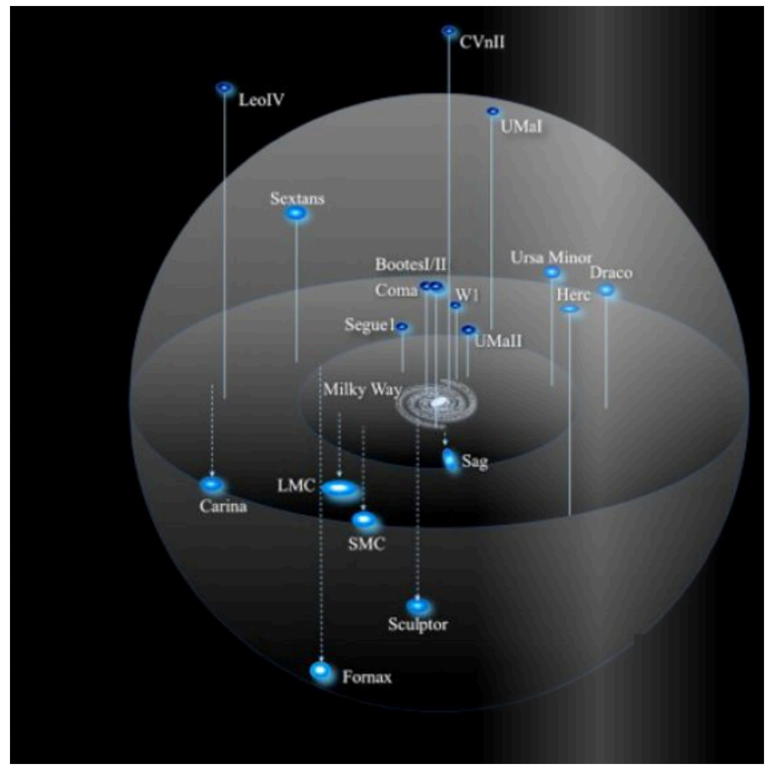
Cusp-core

Density



THINGS (HI Near Galaxy Survey)/LITTLE THINGS

Radius



Bullock, Baylon-Kolchin

Missing satellites

Incompatibility between the # of satellites predicted by simulations using LCDM and the # of observed satellites

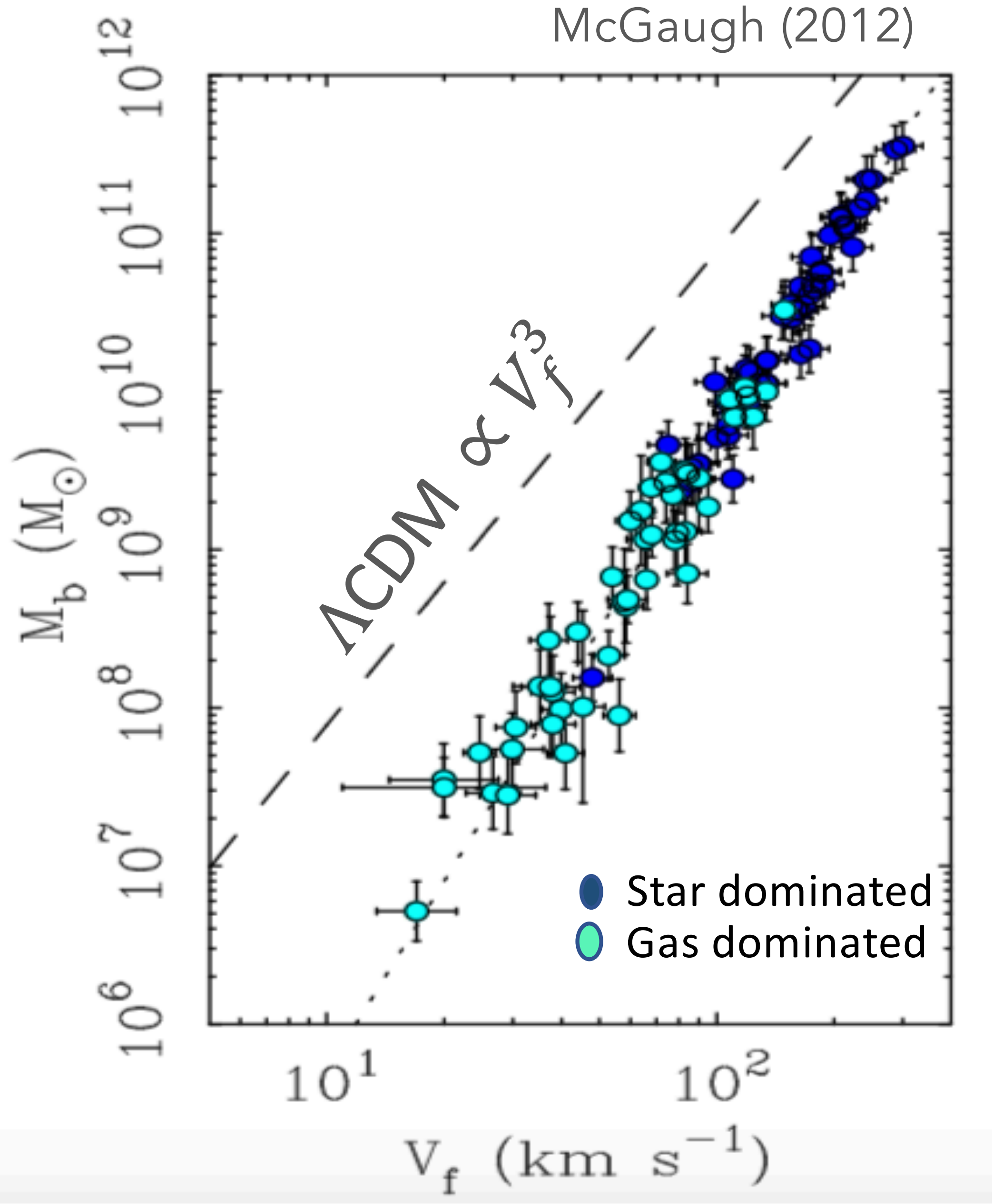
Regularity/diversity of rotation curves

- Baryonic Tully-Fisher relation (BTFR)

  Remarkably tight scaling relations between dynamical and baryonic properties.

McGaugh (2012)

Baryonic mass



Circular velocity

$$a_0 \simeq \frac{1}{6} H_0 \simeq 1.2 \times 10^{-8}\ \mathrm{cm/s^2} = 2.7 \times 10^{-34}\ \mathrm{eV}\,.$$

Dark matter- Large scales: CDM

Small scales:

• **Feedback:** Within ΛCDM

- Star formation
- Stellar evolution
- Sn rates
- BH and AGN feedback
- Stellar feedback
- …

Questions:

- Can it solve all these?
- ≠ simulations, ≠ parametrizations
- Enough feedback?
- Explains tight scaling relation?

• **MOND:**

Modified Newtonian Dynamics

Empirical relation

$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

Curiosity: Baryons drive the dynamics!

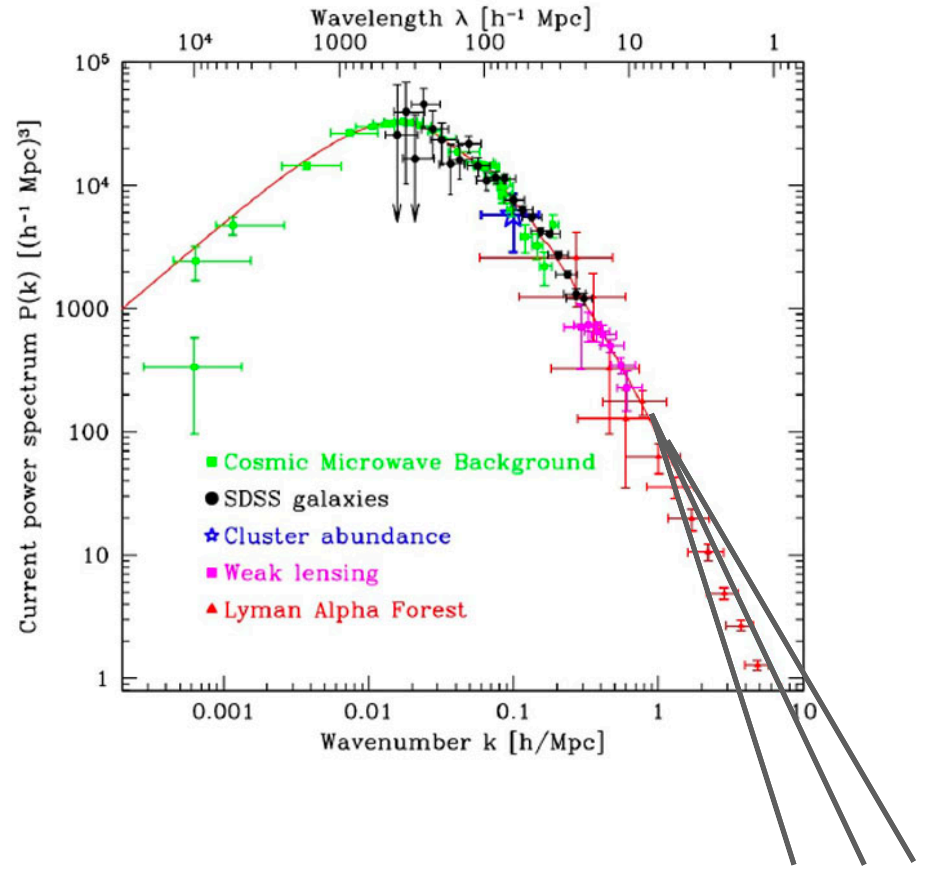
Works extremely well for: (1) rotation curves; (2) scaling relations

BUT: ~~MOND without DM~~

Problems explaining large scales

• **Modify dark matter:**

DM with different properties on small scales

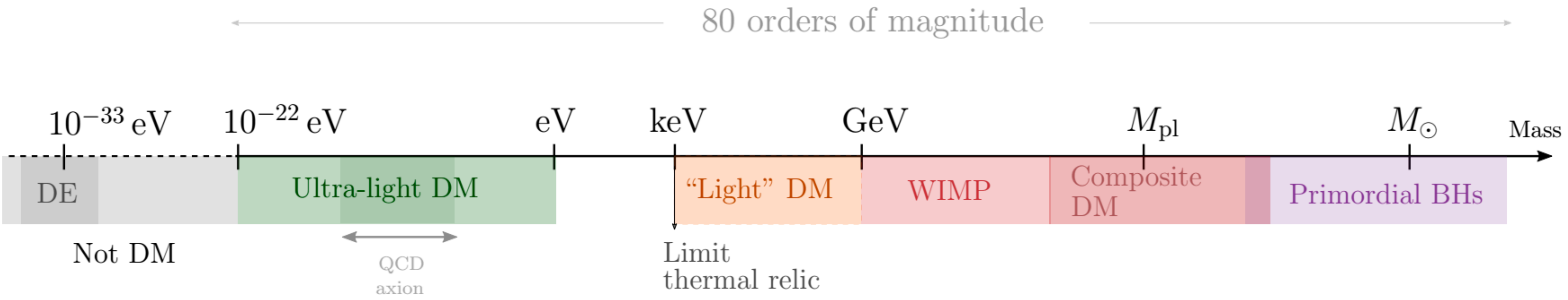


What we don't know

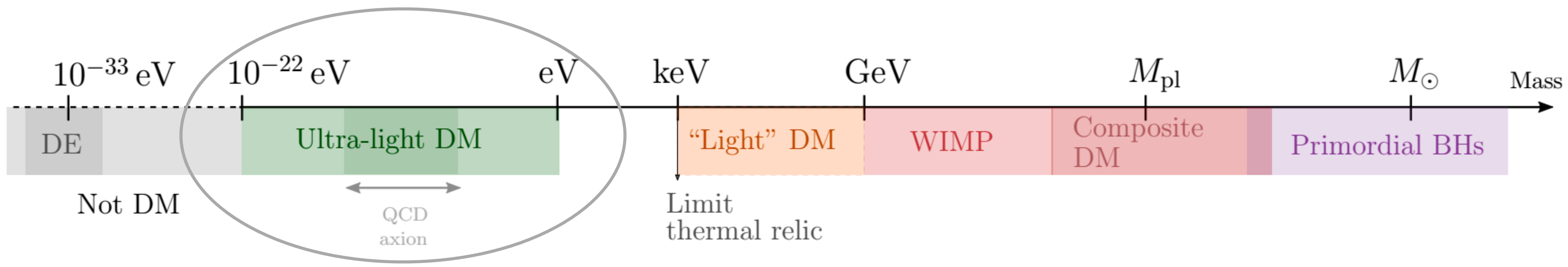
- What is DM? What is the nature of DM?

State of the "art"

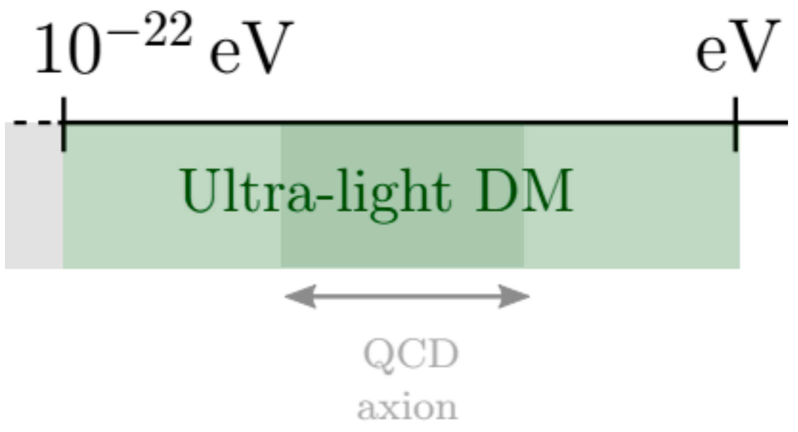
Mass scale of DM



Ultra-light dark matter

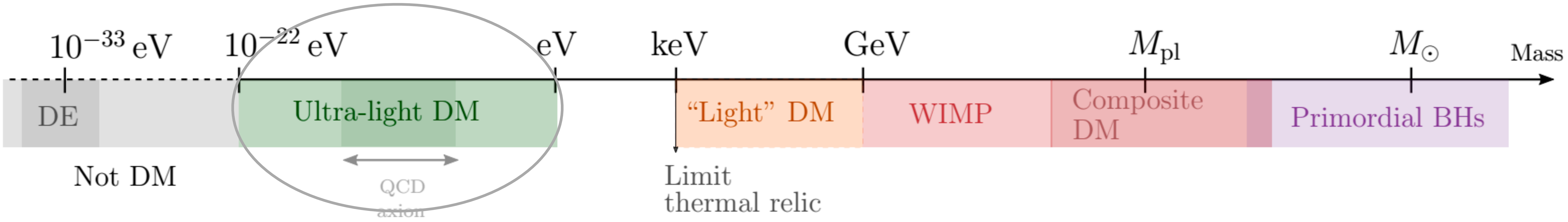


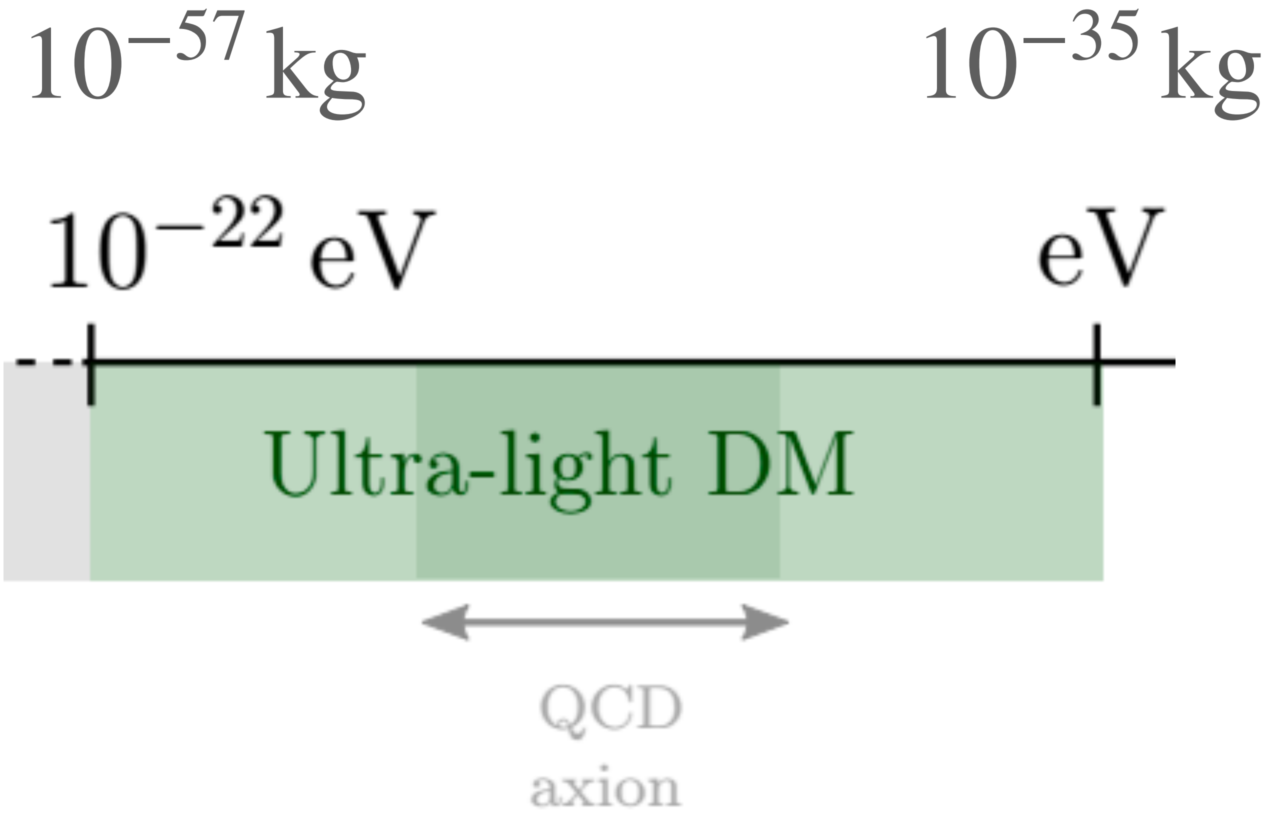
Ultra-light Dark Matter



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

Lightest possible candidate for DM

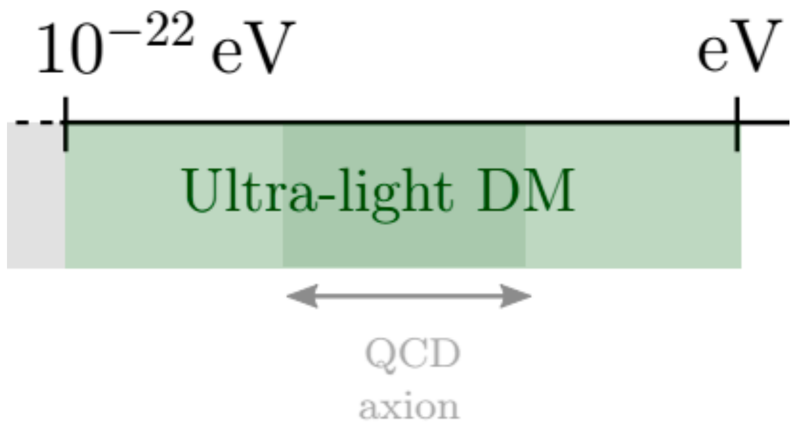




→ Bosons (scalar fields)

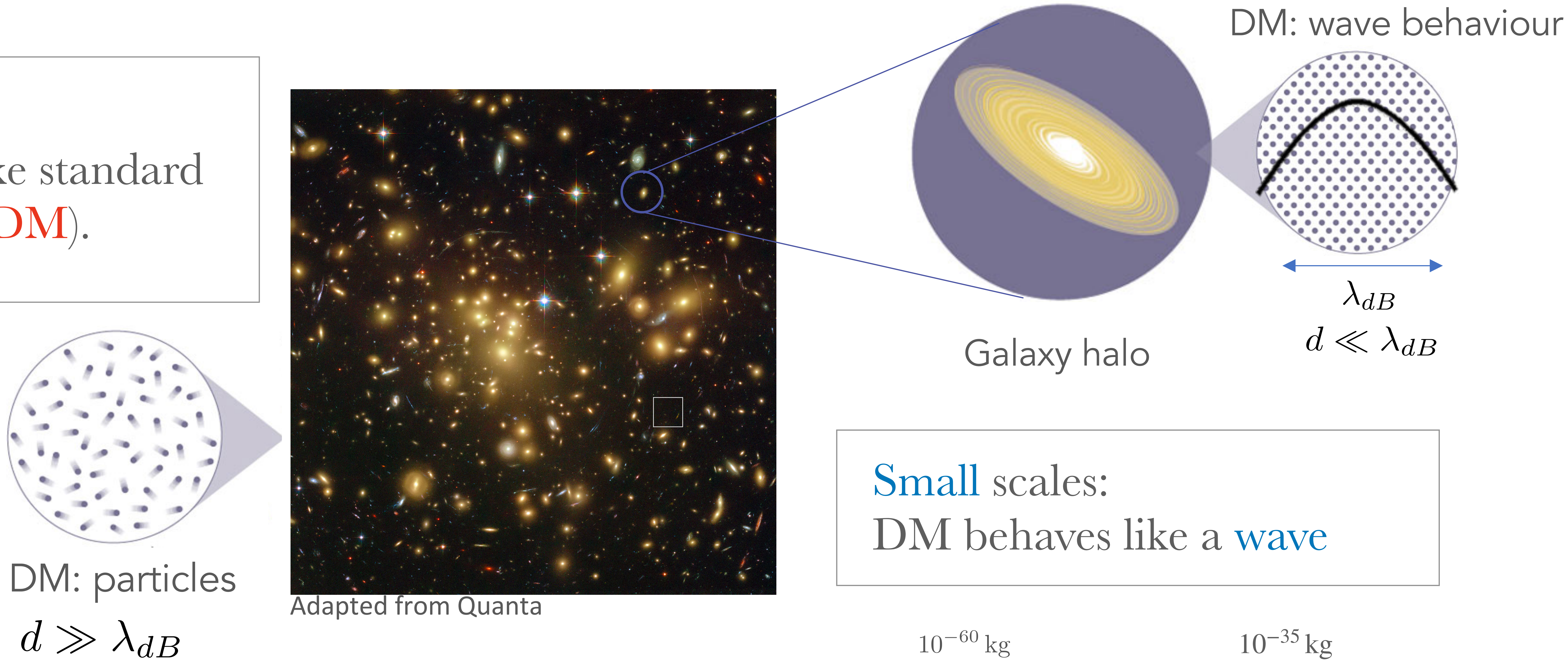
Non-thermally produced

Ultra-light Dark Matter



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

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

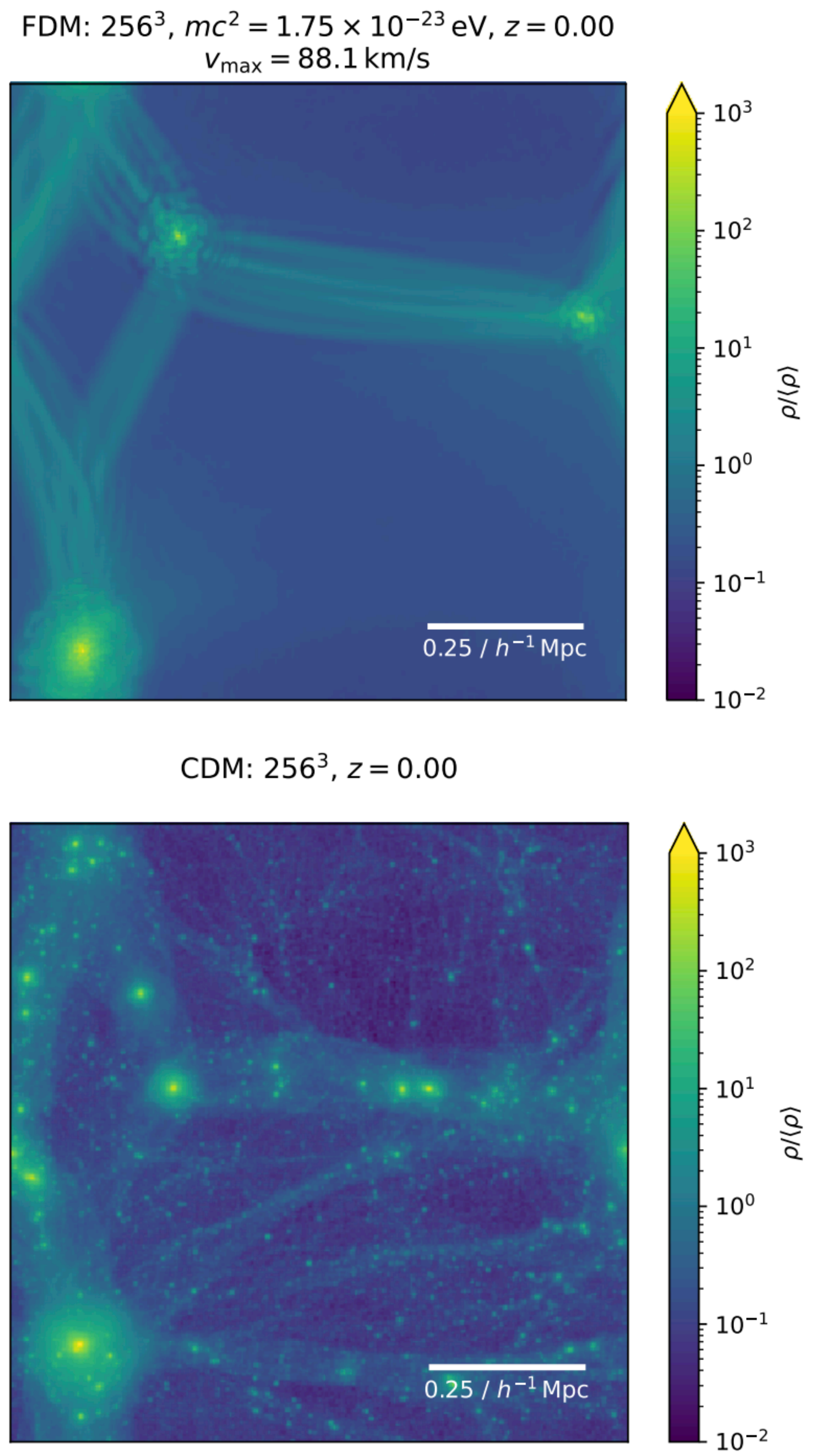
$$10^{-25}\,\text{eV} \lesssim m \lesssim \text{eV}$$

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

Phenomenology

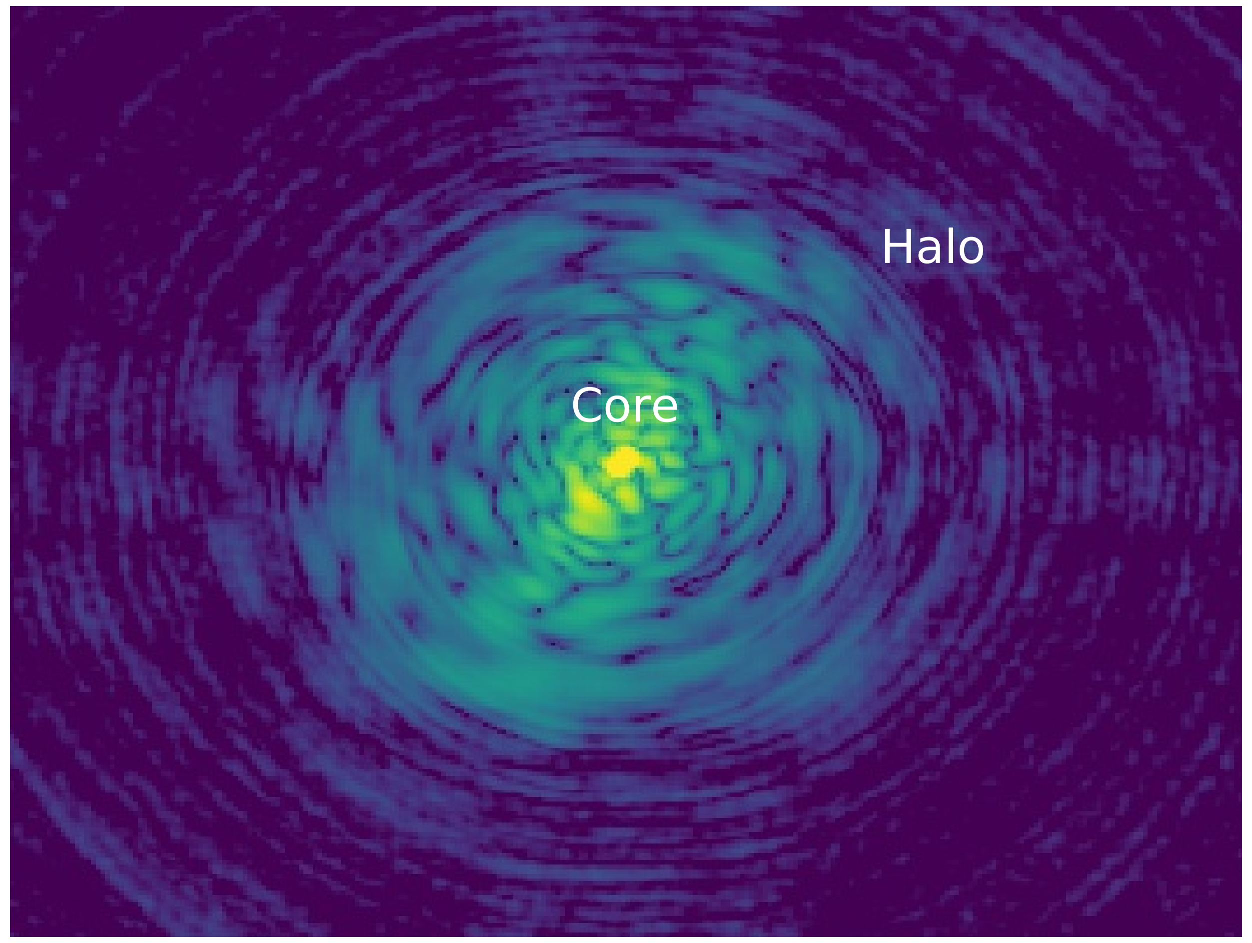
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

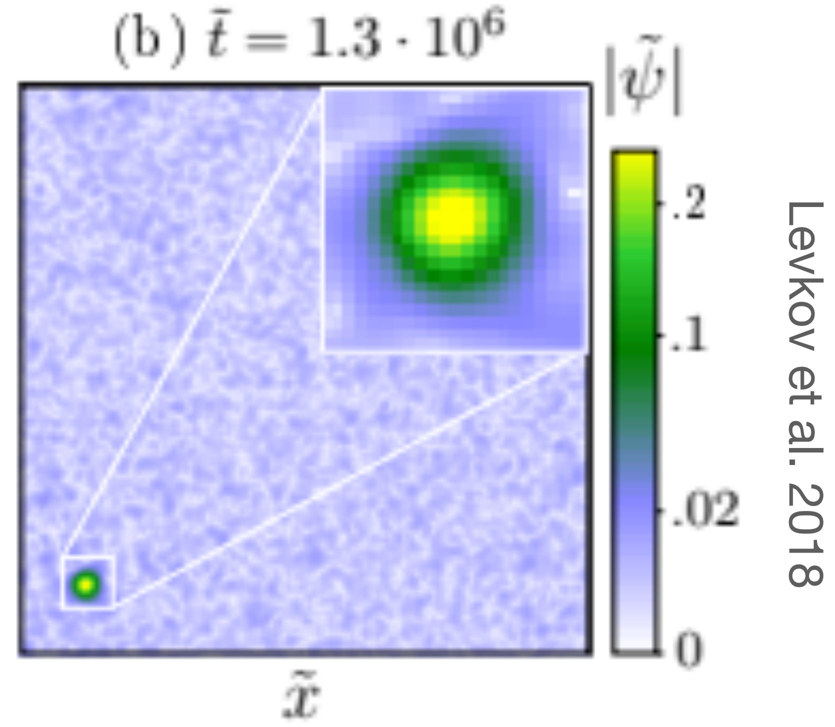


S. May et al. 2021

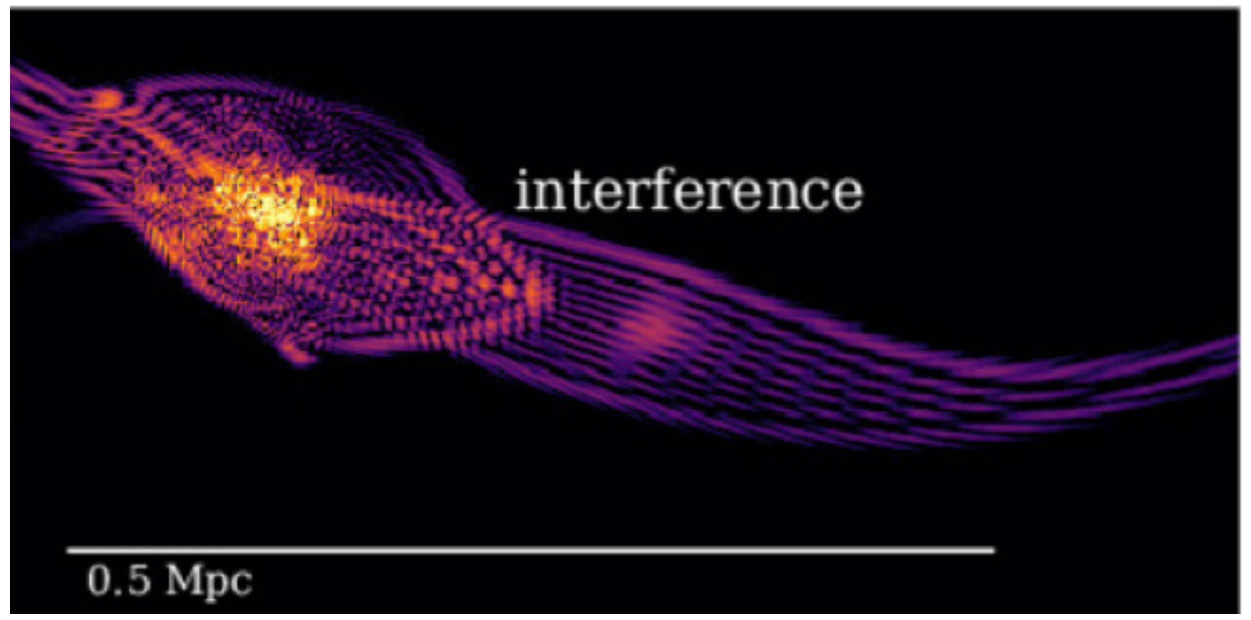
Formation of a solitonic core



Dynamical effects

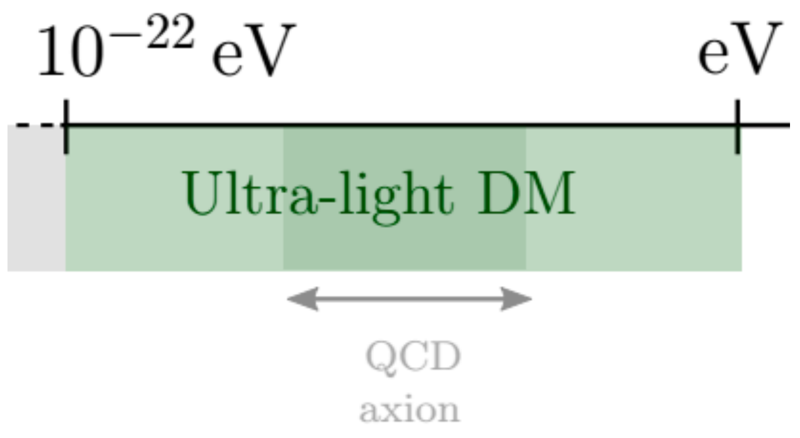


Wave interference

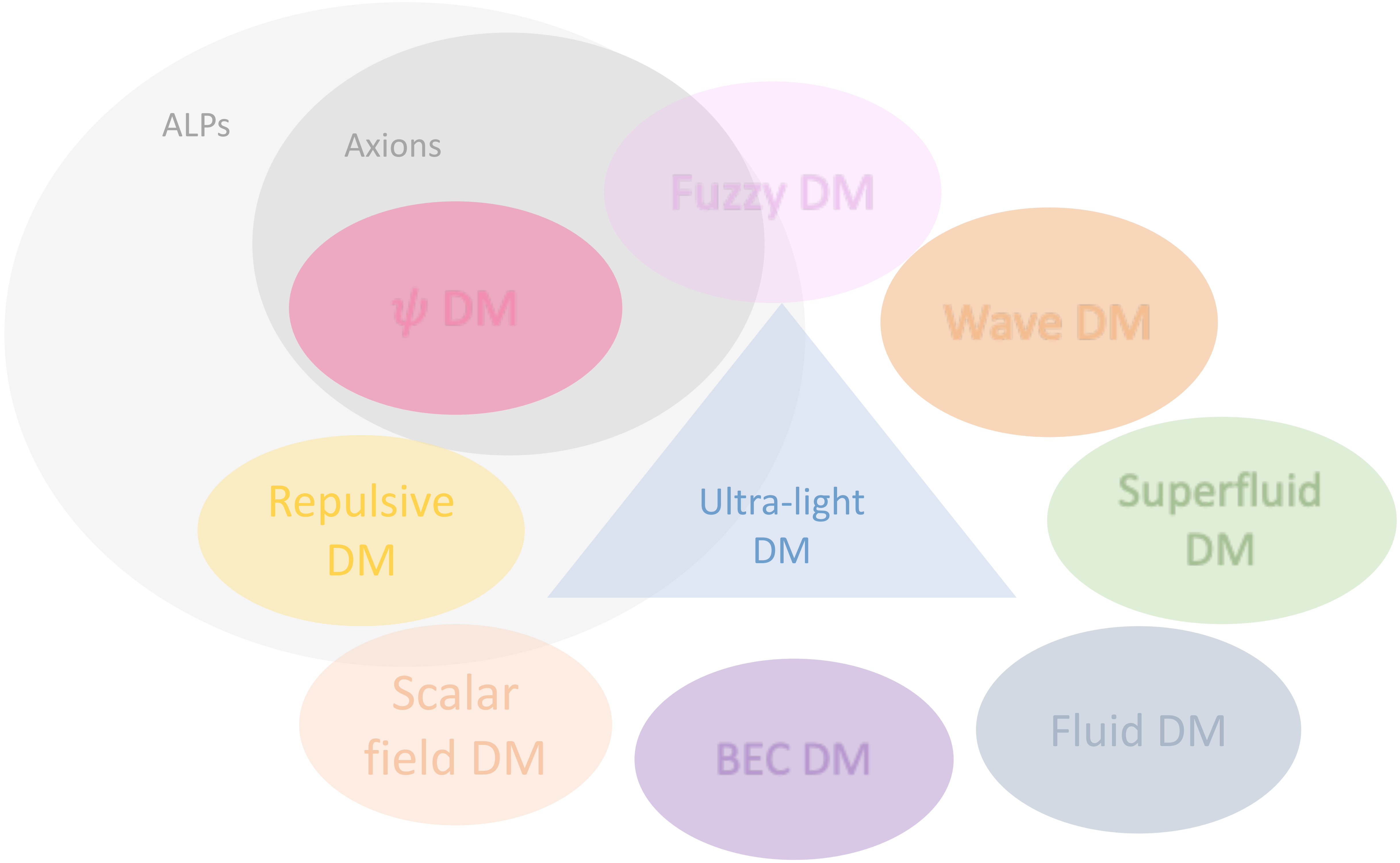


Mocz et al. 2017

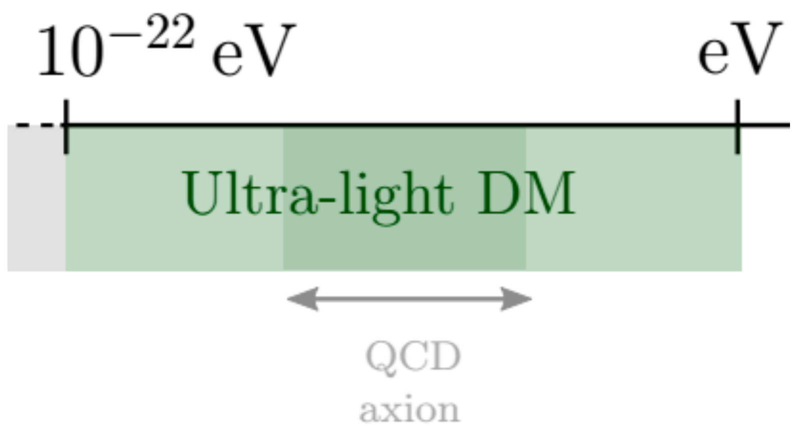
Ultra-light Dark Matter - models



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

Axion and ALP (axion like particles)

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

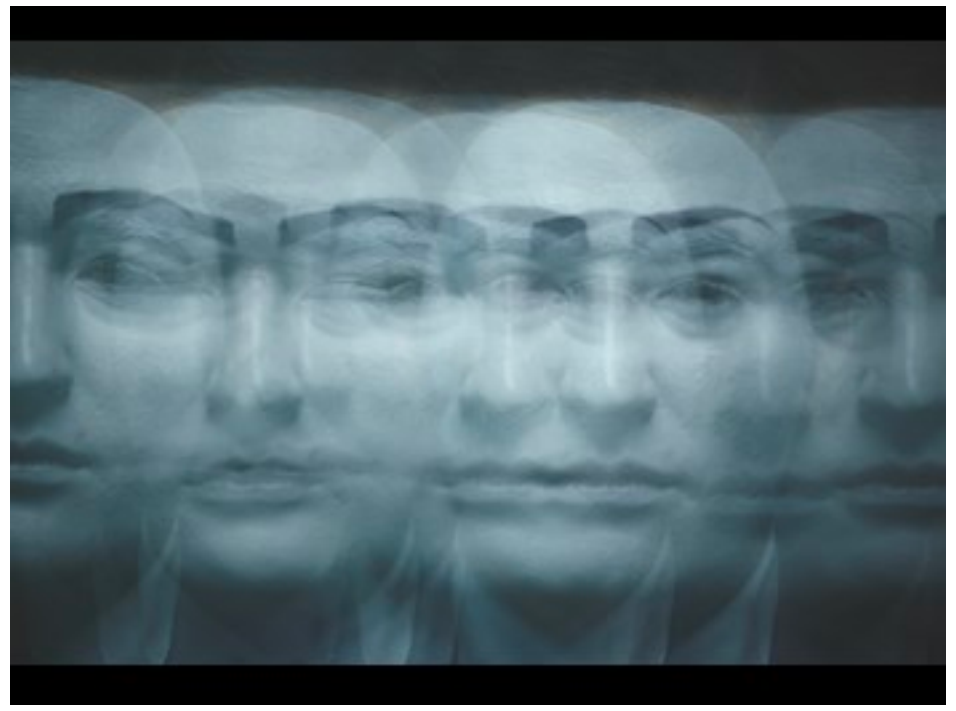
$$\mathcal{L} = P(X)$$

⟶ Connection with condensed matter and particle physics!

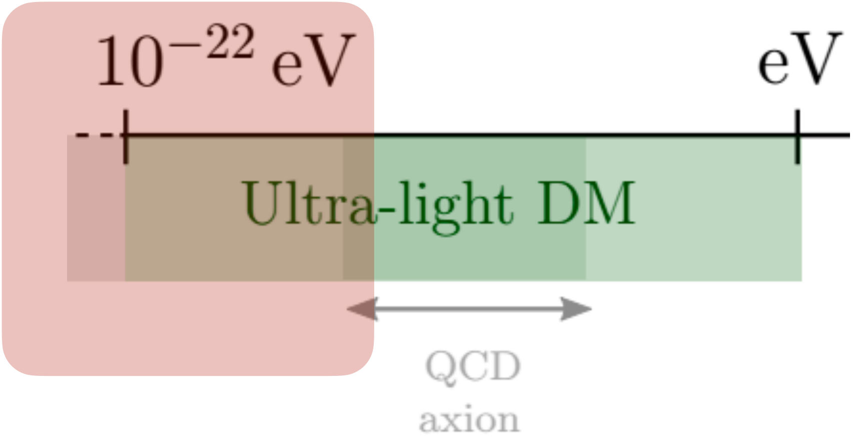
"Ultra-light dark matter", **E.Ferreira**, 2020. The Astronomy and Astrophysics Review.

Fuzzy dark matter

Self interacting fuzzy dark matter



Fuzzy DM and self-interacting FDM



Fuzzy DM (FDM)

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

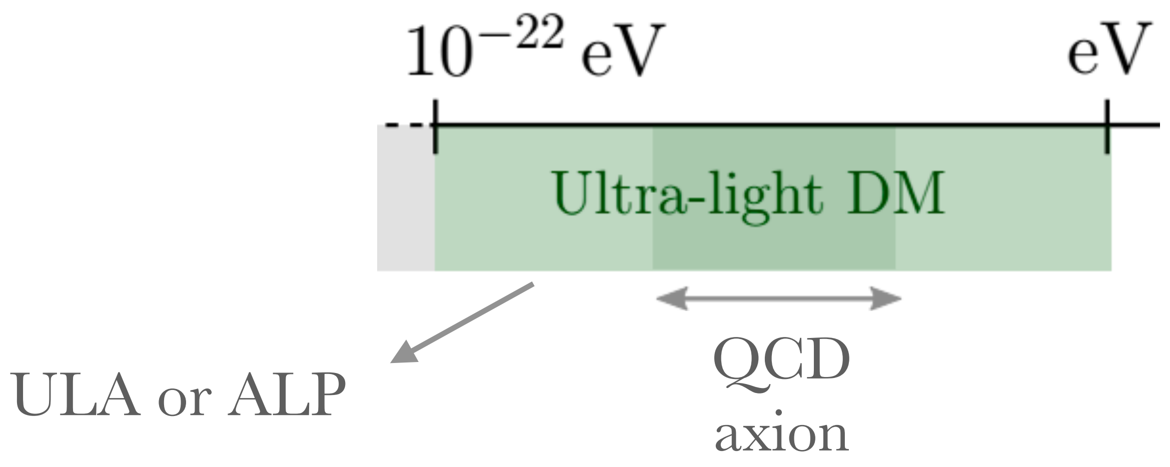
m

Self Interacting FDM (SIFDM)

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

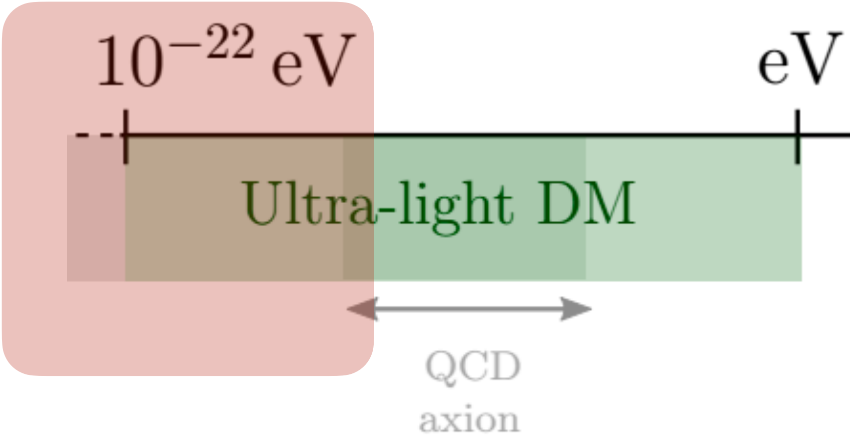
m g

Candidates: Ultra-light scalar particles, axion and ALP (axion like particles) or ultra-light axions



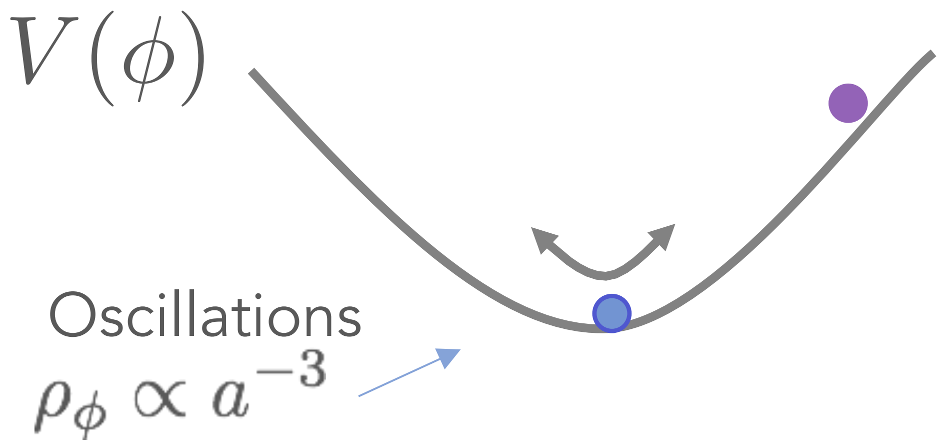
Axions/ALPs
- Motivation from particle physics
- Axions/ALPs behave like DM: one of the leading candidates for DM

Cosmological evolution



Boson/ Scalar field in a cosmological (FRW) background

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



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

<u>Axions or Axion like particles (ALP)</u>

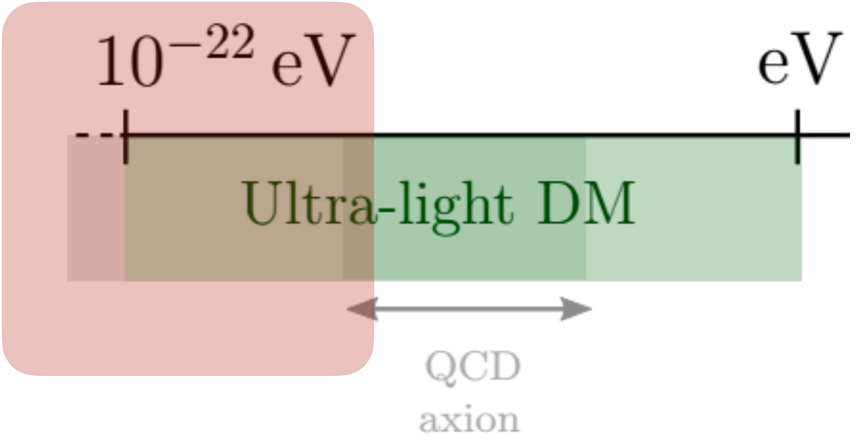
Axions and ALPs are pseudo Nambu Goldstone bosons from the spontaneous symmetry breaking of a $U_{PQ}(1)$ (U(1)) symmetry, and are described by the complex field: $\Psi = v\, e^{i\phi/f_a}$

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

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

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

Cosmological evolution

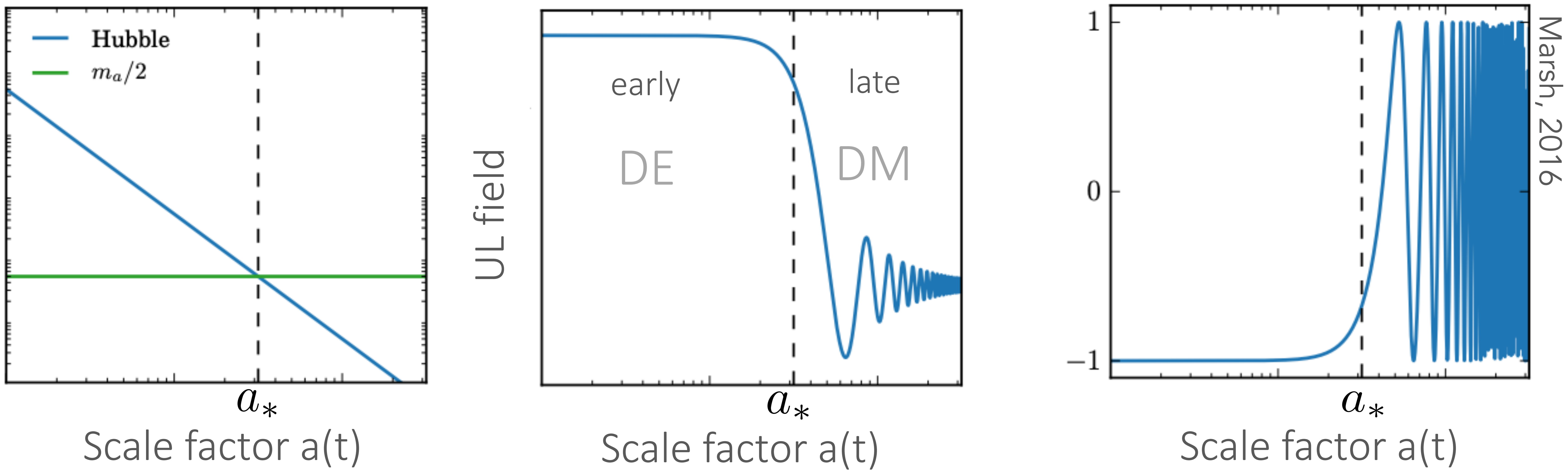


$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

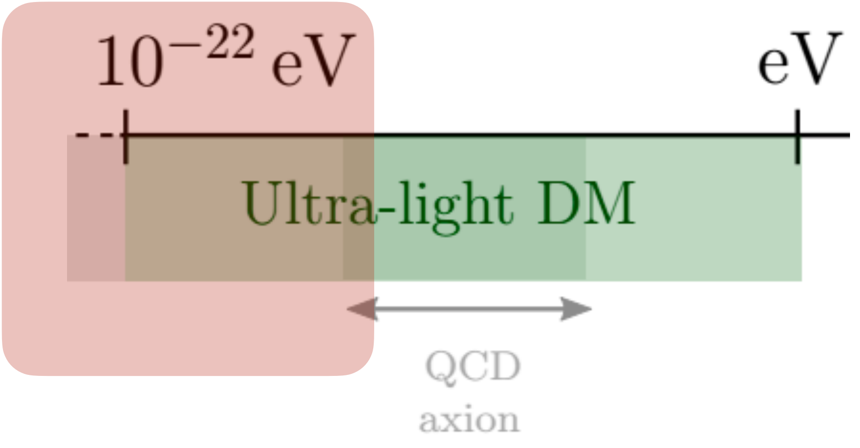
FDM

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

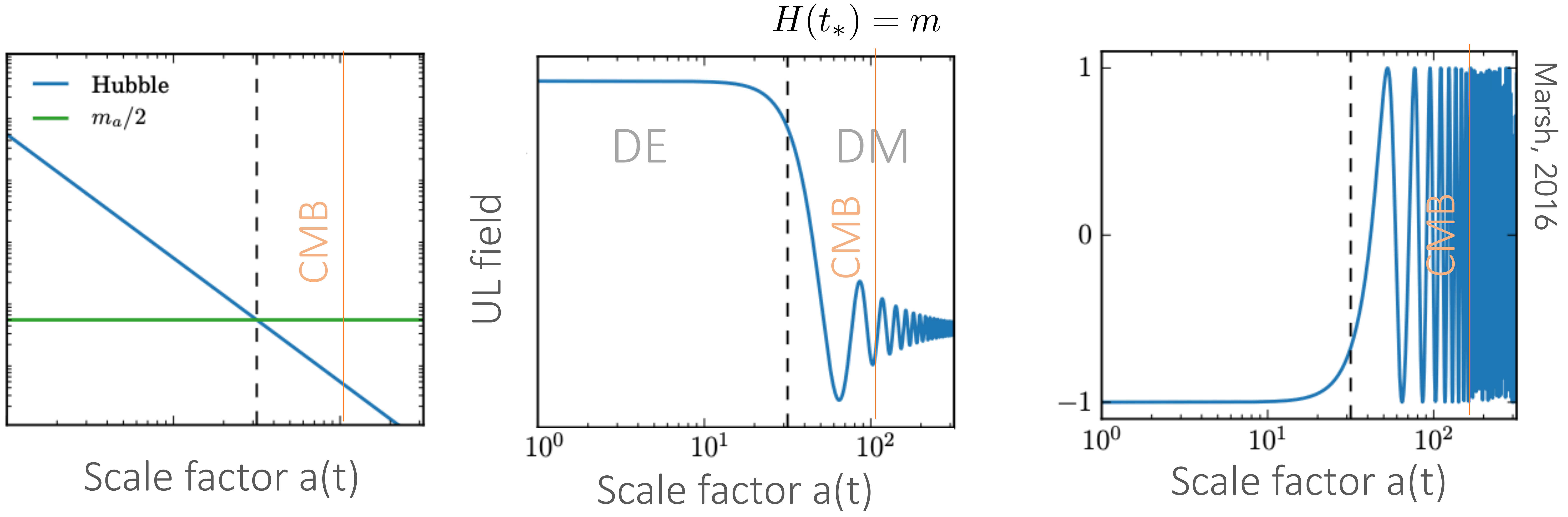
$H(t_*) = m$



Cosmological evolution

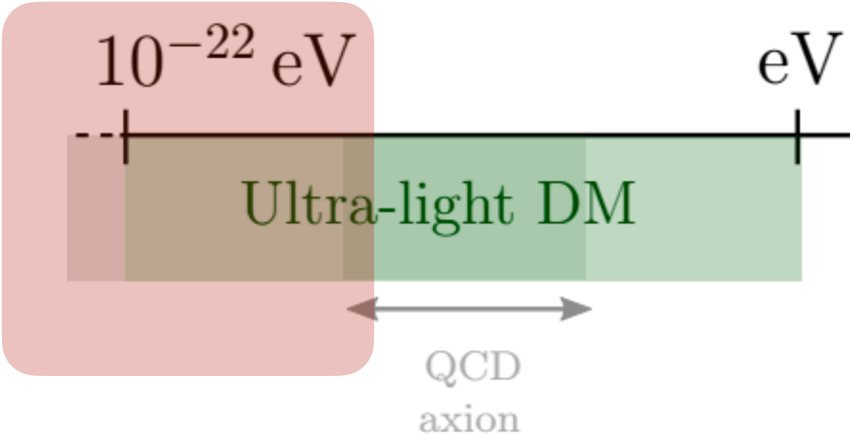


In order to behave like DM: start oscillating before matter-radiation equality



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

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)

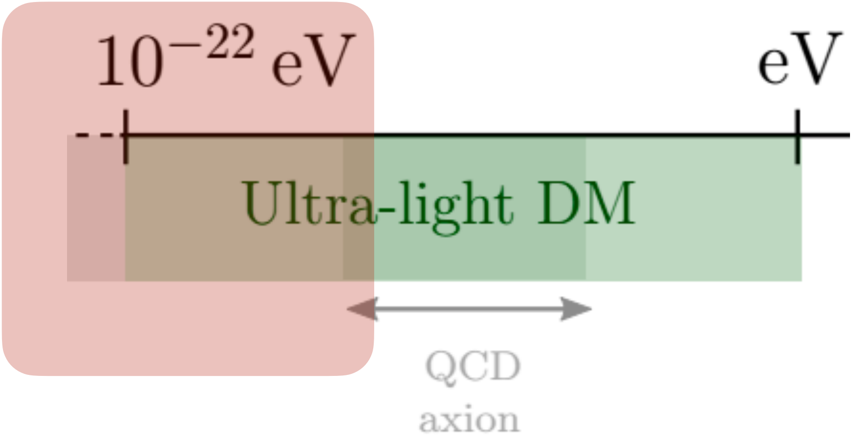
Poisson equation

$g = 0$ → FDM

$g \neq 0$ → SIFDM

Fundamentally different than CDM/WDM/SIDM!

Structure formation - non-relativistic regime



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

$g = 0 \longrightarrow$ FDM

$g \neq 0 \longrightarrow$ SIFDM

Fundamentally different than CDM/WDM/SIDM!

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

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

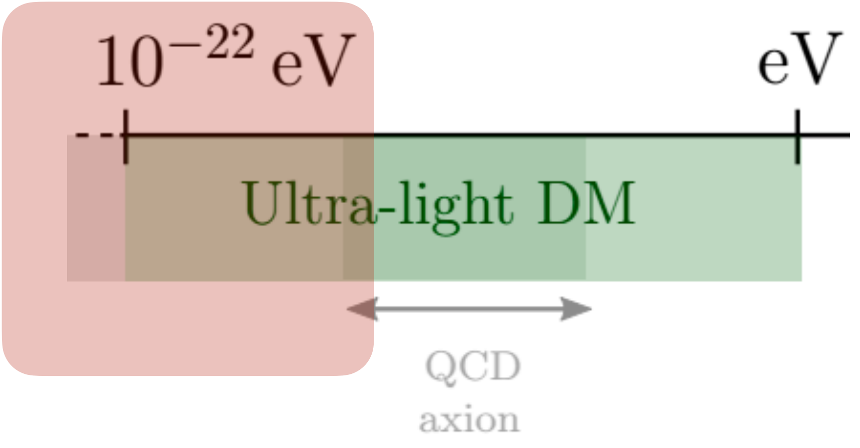
$$\dot{\mathbf{v}} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - P_{int} - \frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

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

Quantum pressure

FLUID DESCRIPTION

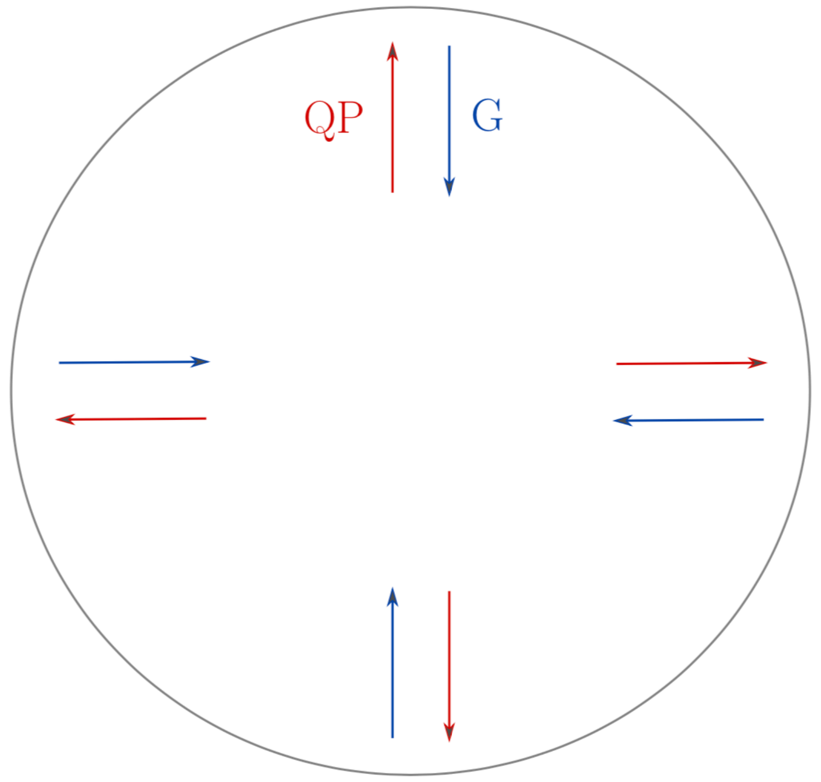
Structure formation - perturbation and stability



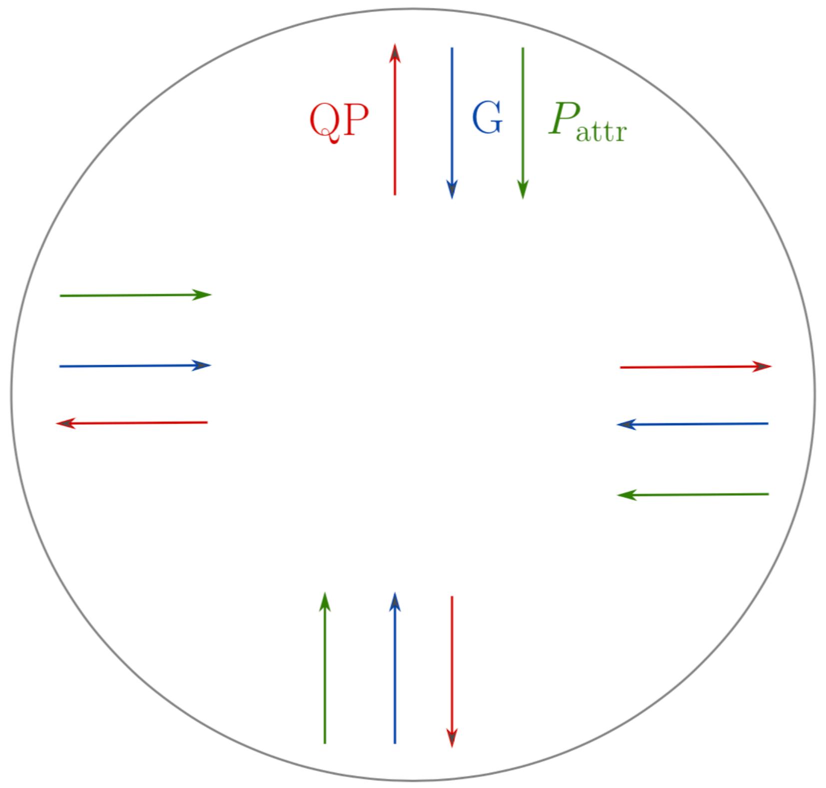
Competition between gravity and pressure (quantum pressure and interaction)

SIFDM

FDM

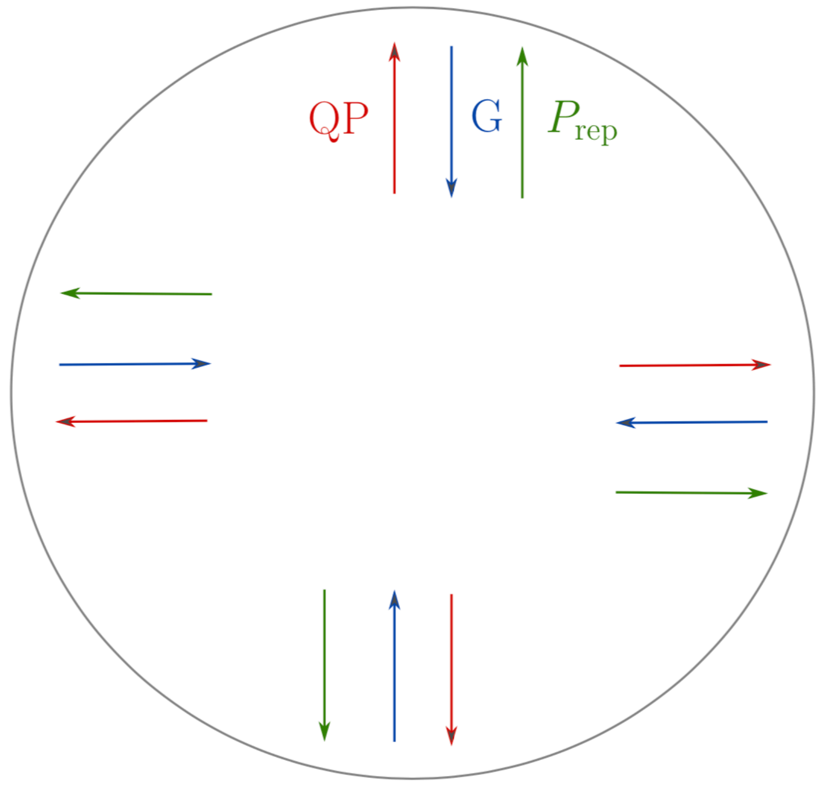


ATTRACTIVE



$g < 0$

REPULSIVE



$g > 0$

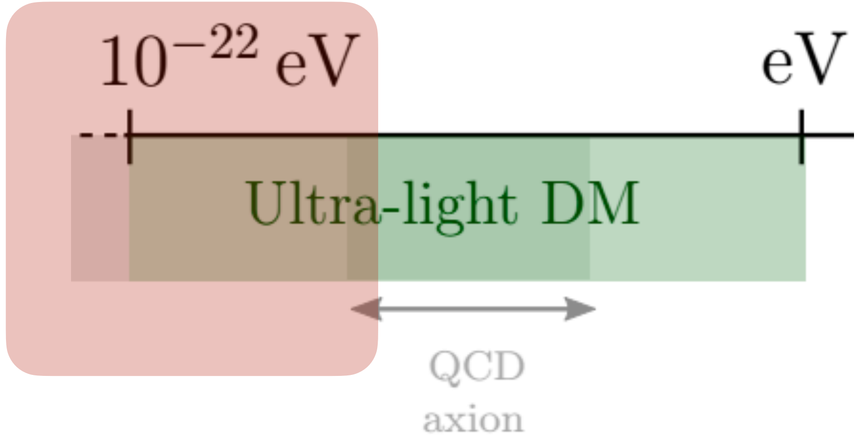
$$\dot{\rho} + \nabla \cdot (\rho\, \mathbf{v}) = 0$$

$$P_{\rm int} = \frac{g}{2m^2}\rho^2$$

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

Quantum pressure

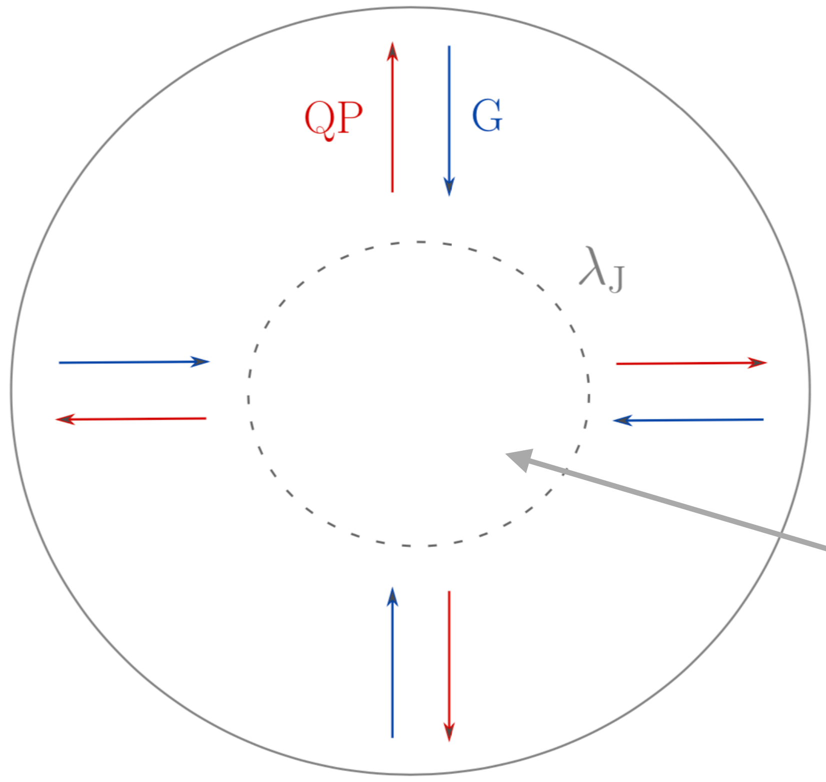
Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

SIFDM

FDM



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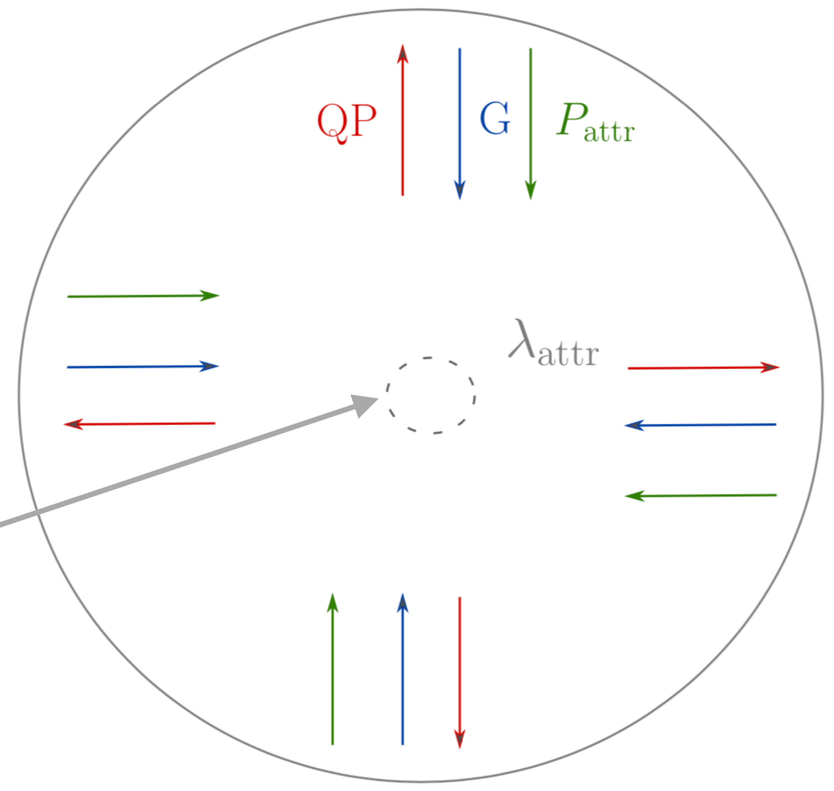
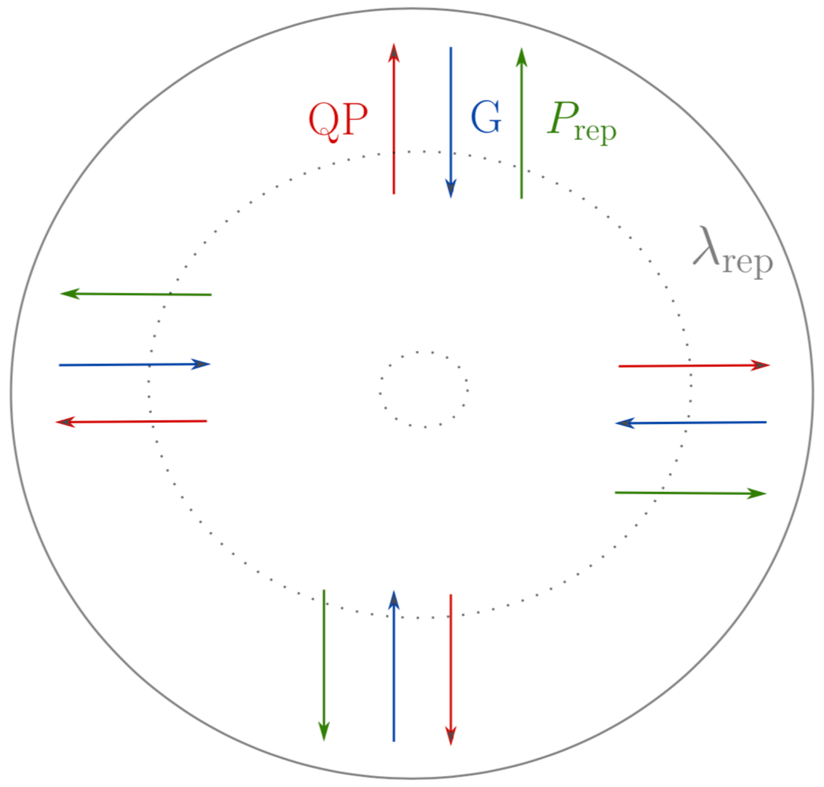


$g < 0$

REPULSIVE



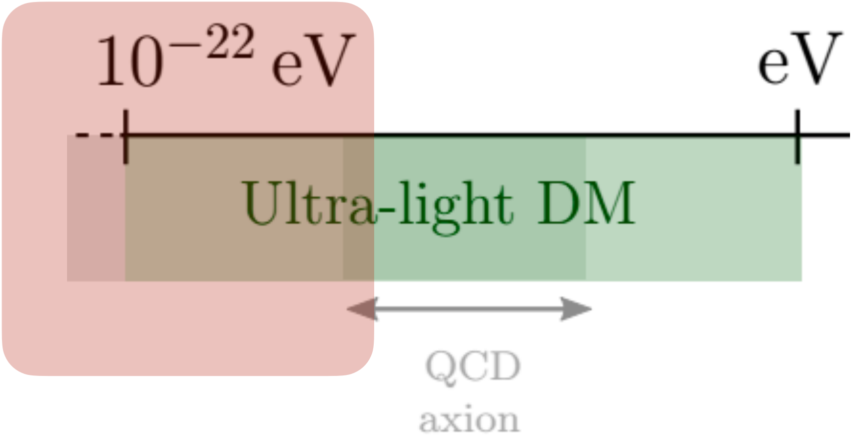
$g > 0$

QP wins -
Stable solution
NO structure formation

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

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

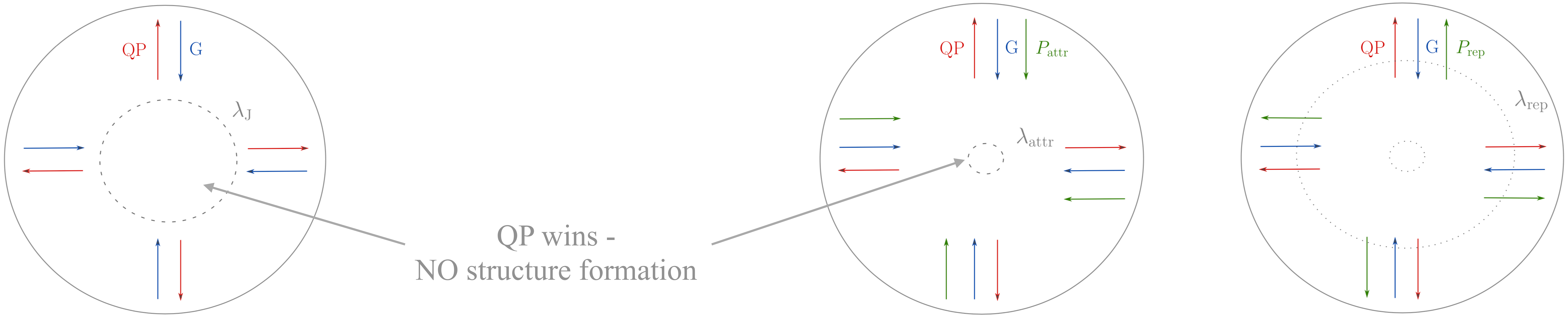
Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

SIFDM

FDM | ATTRACTIVE | REPULSIVE



$g < 0$ $\quad$ $g > 0$

Finite size coherent core – Bose stars

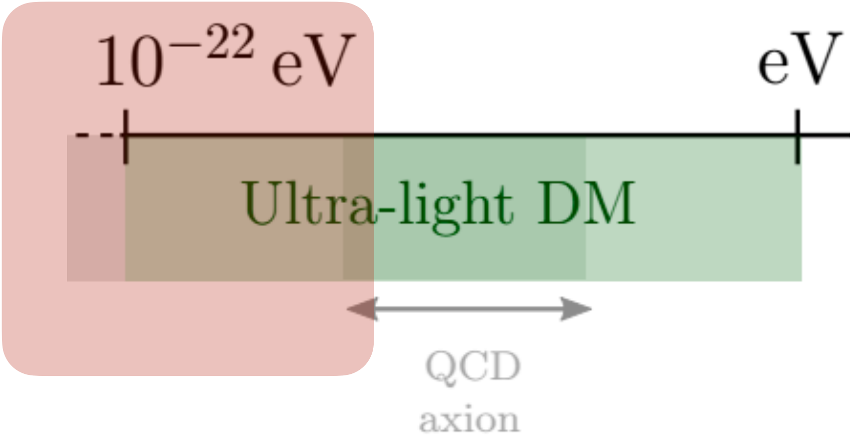
$$\lambda_J = 55 \left(\frac{m}{10^{-22}\,\text{eV}}\right)^{-1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{-1/4} (\Omega_m h)^{-1/4}\,\text{kpc}$$

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

For attractive interactions can only form localized clumps (solitons)

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

Structure formation - perturbation and stability



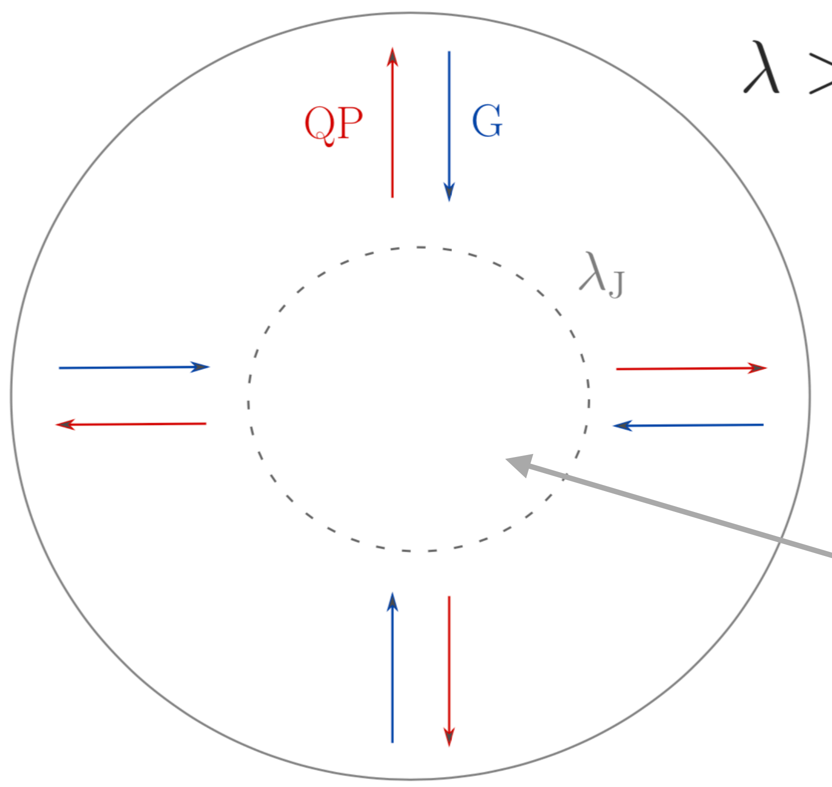
Finite clustering scale - no structure formation on small scales

SIFDM

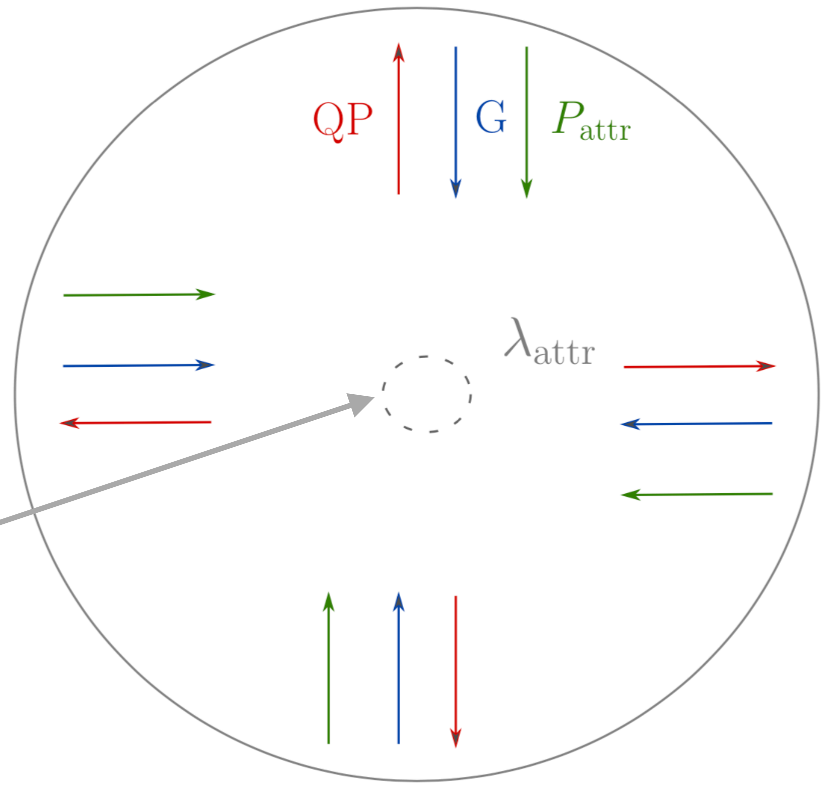
FDM

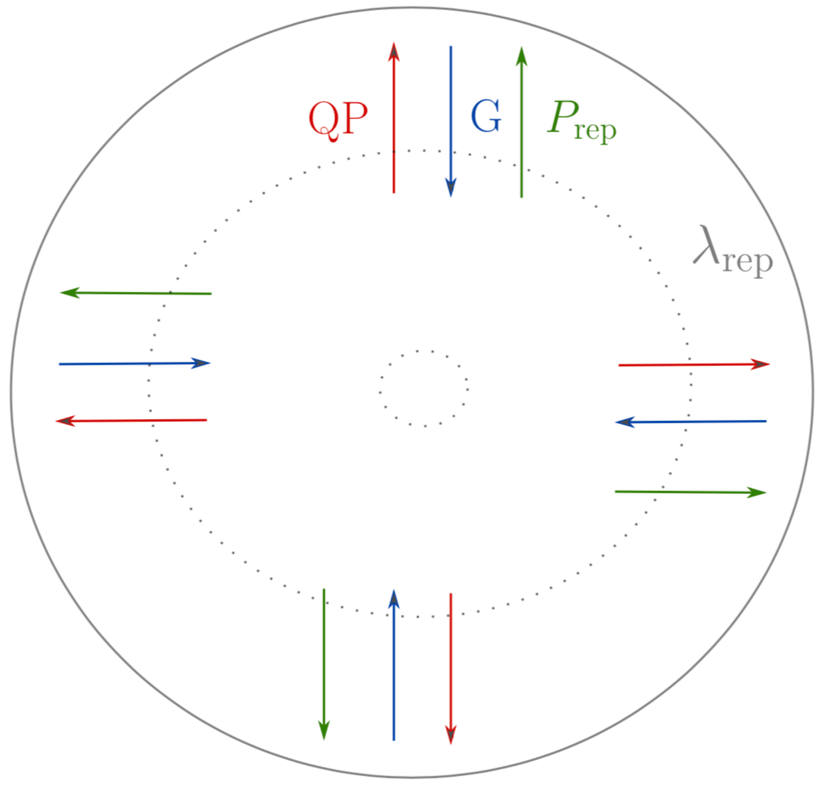
ATTRACTIVE

REPULSIVE



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





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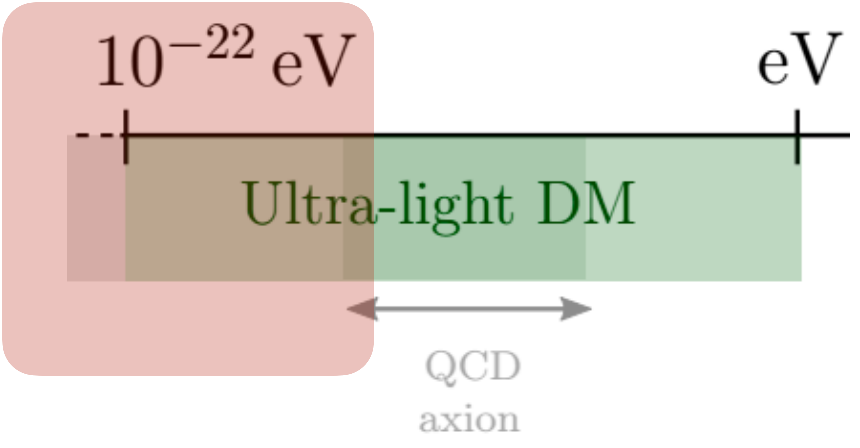
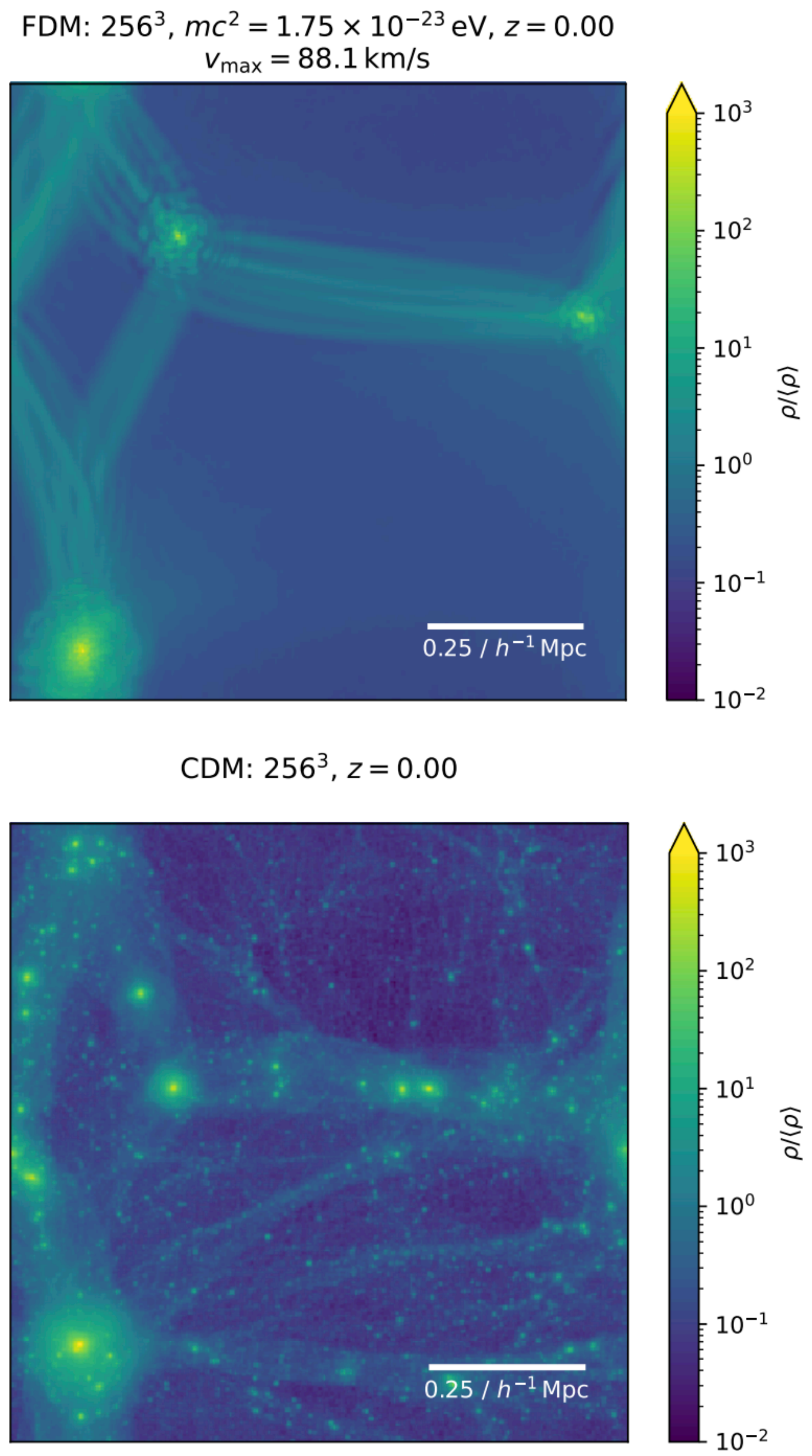
Phenomenology



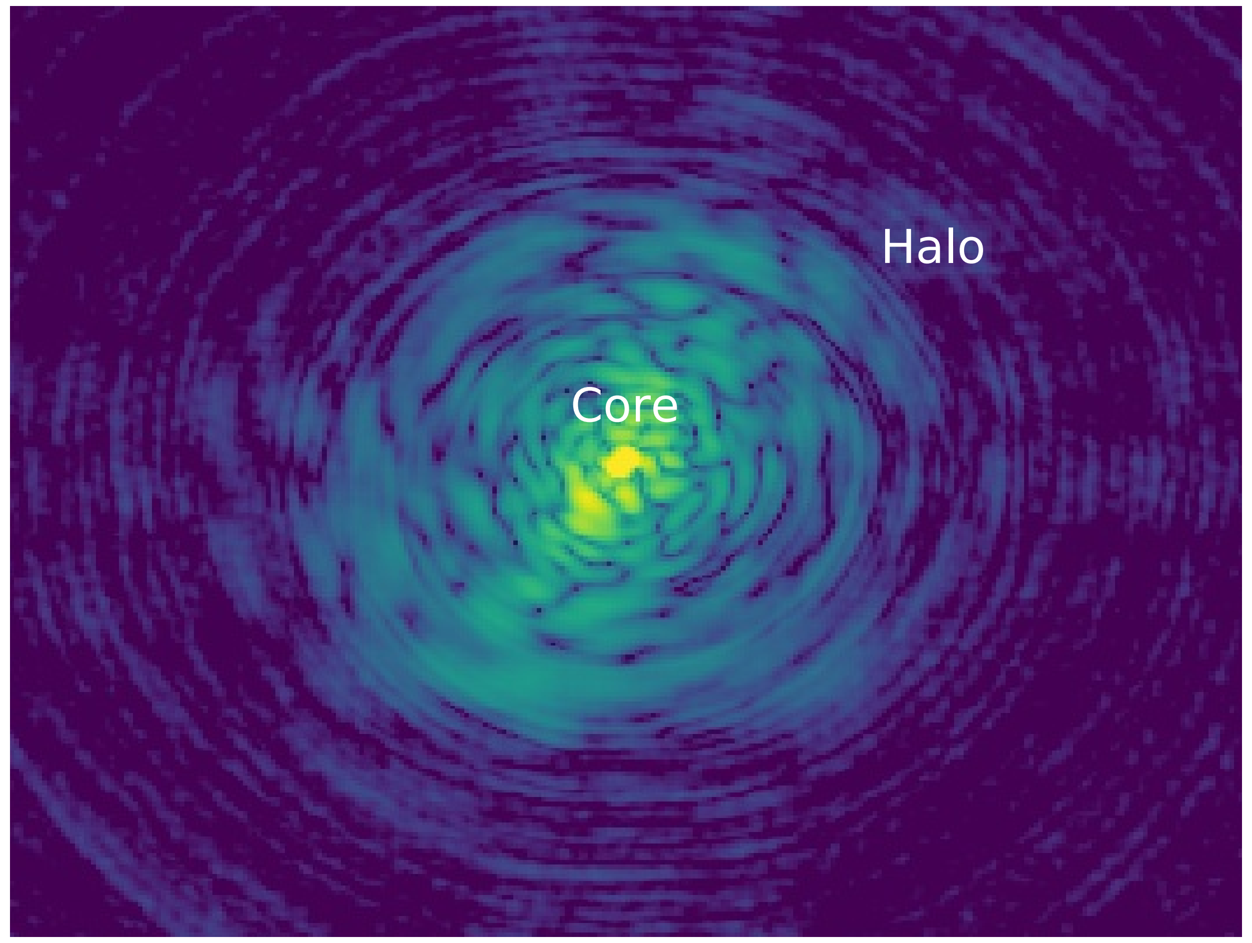
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

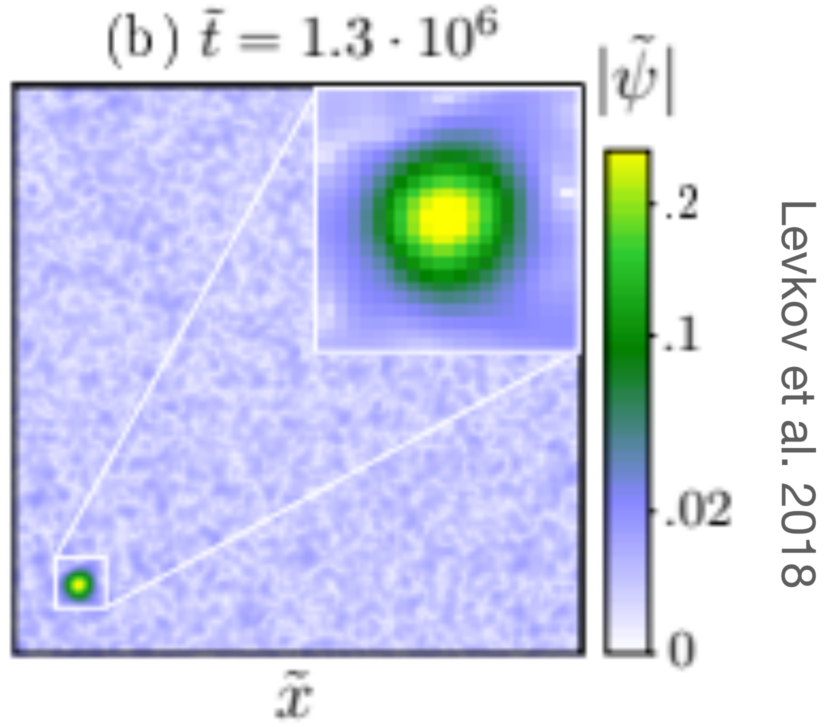


S. May et al. 2021

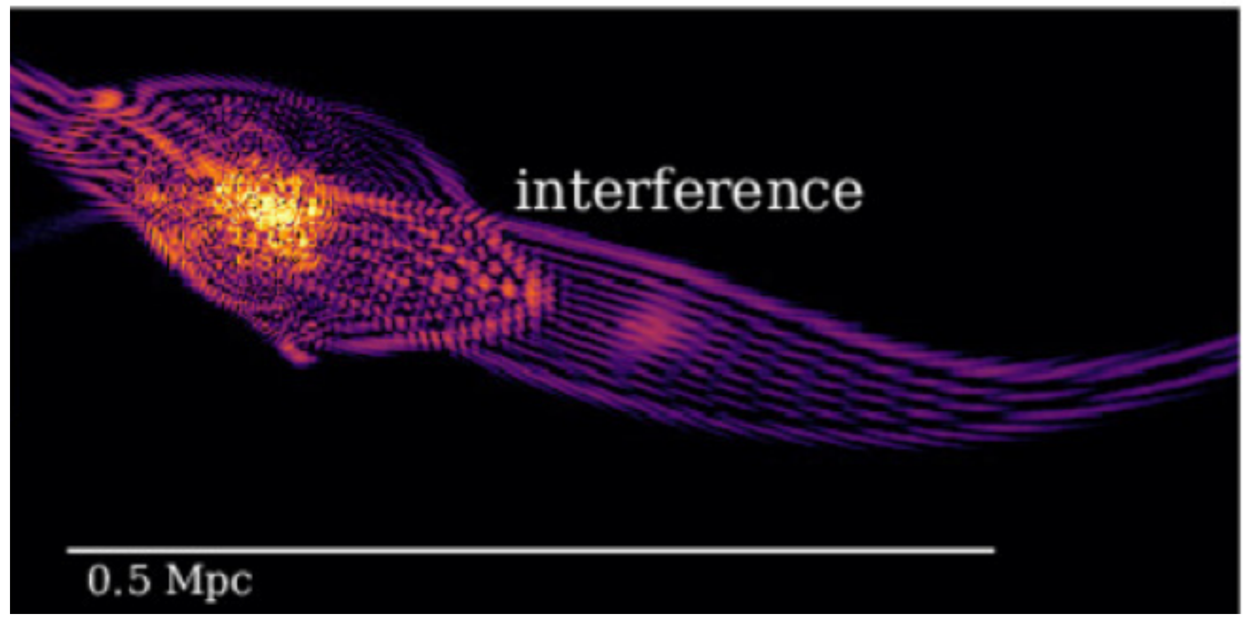
Formation of a solitonic core



Dynamical effects

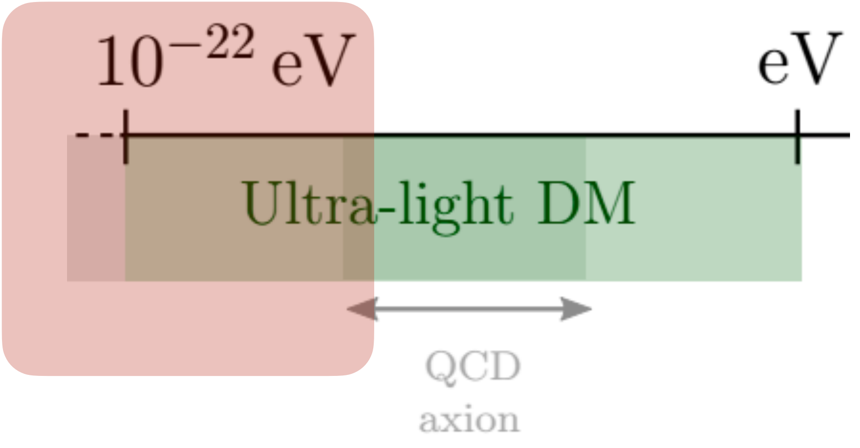


Wave interference



Mocz et al. 2017

Phenomenology



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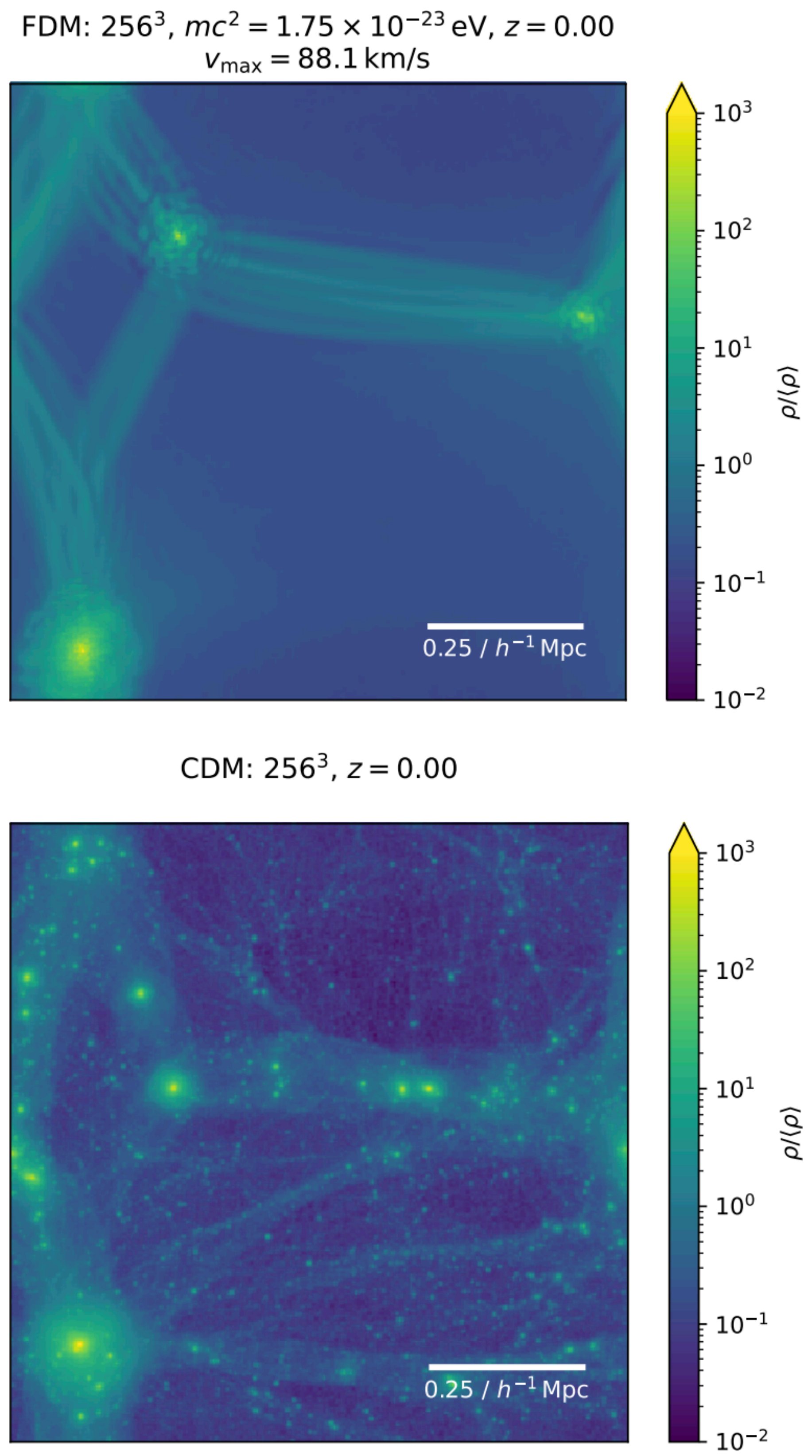

S. May et al. 2021

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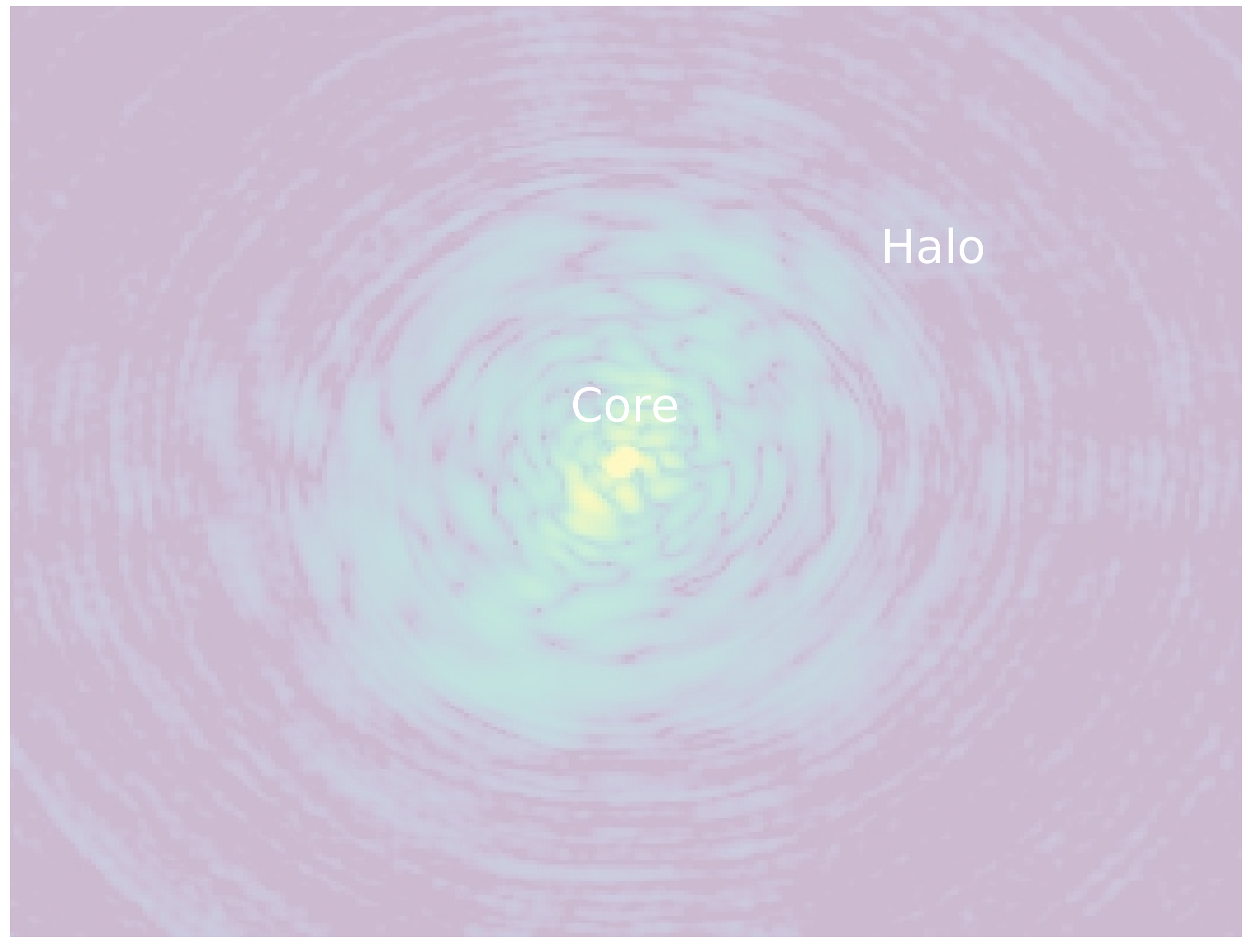

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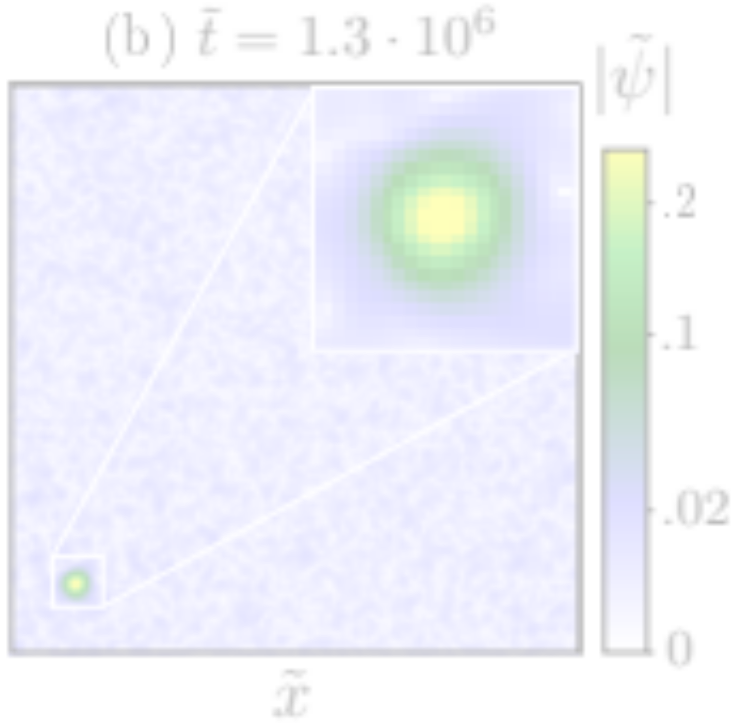
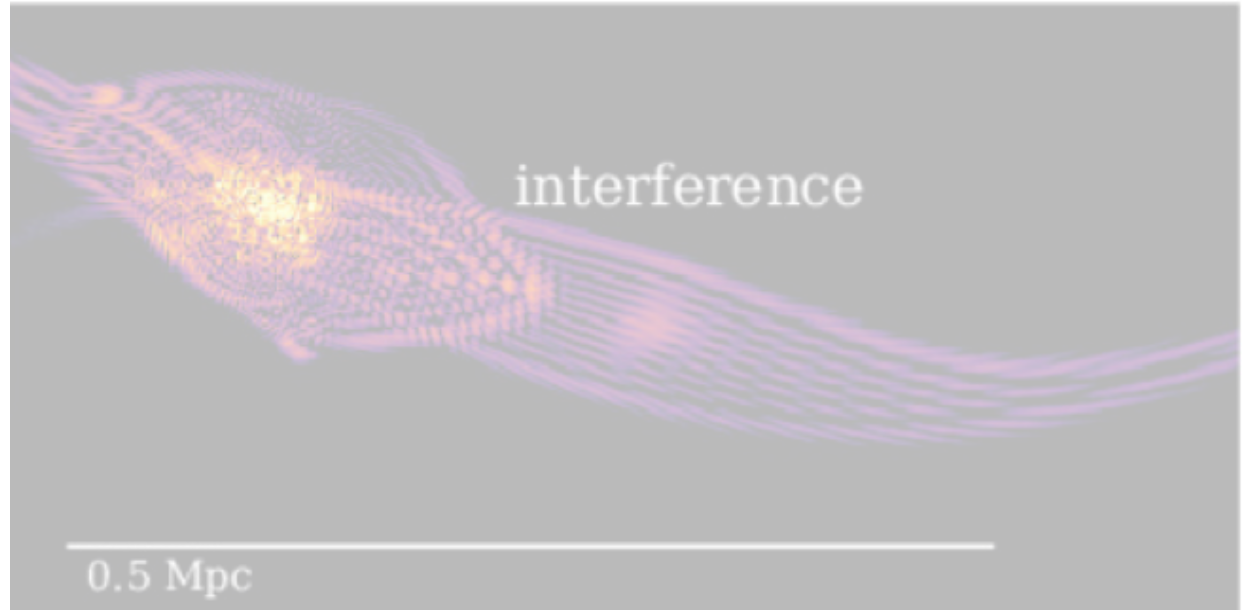


Levkov et al. 2018

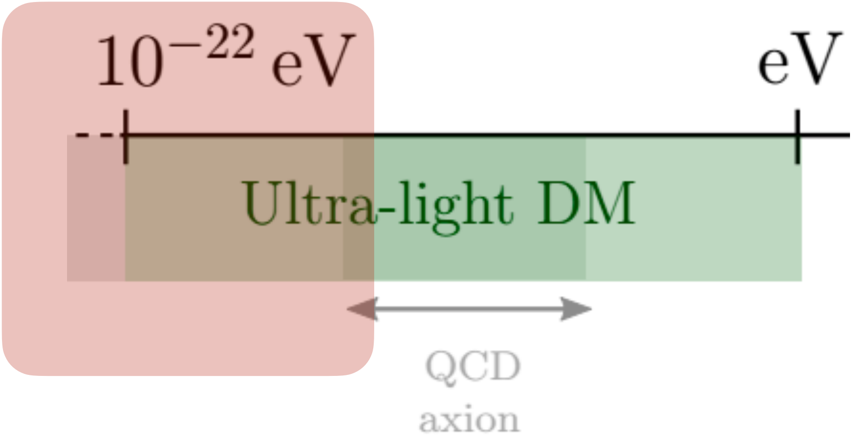
Wave interference



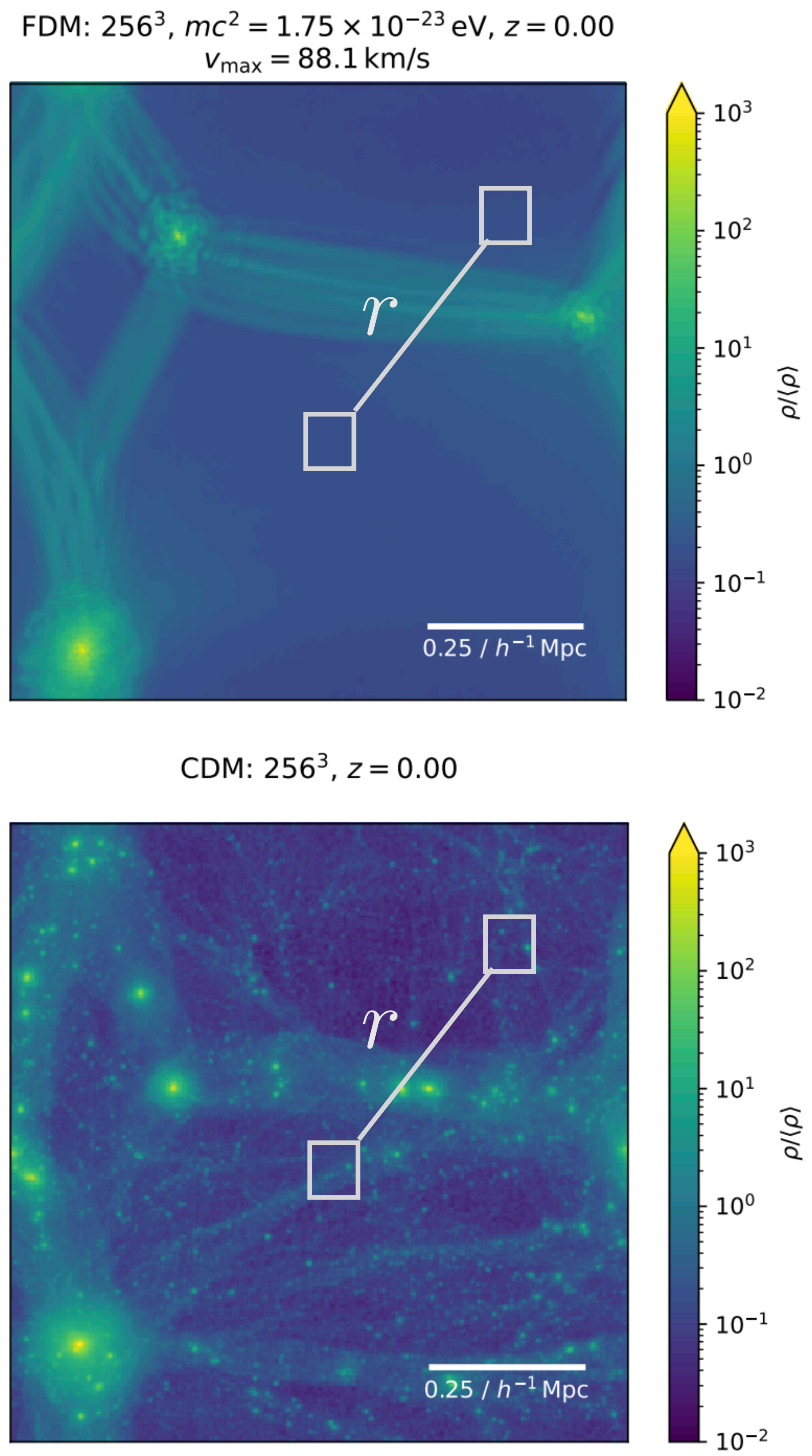
Mocz et al. 2017

Phenomenology

Suppression of small structures



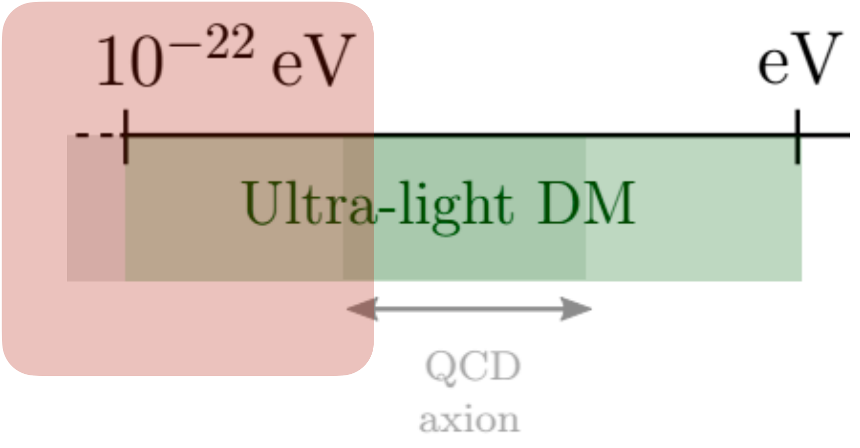
Finite Jeans length λ_J or λ_{attr} , λ_{rep} ⟶ No small scale structure



S. May et al. 2021

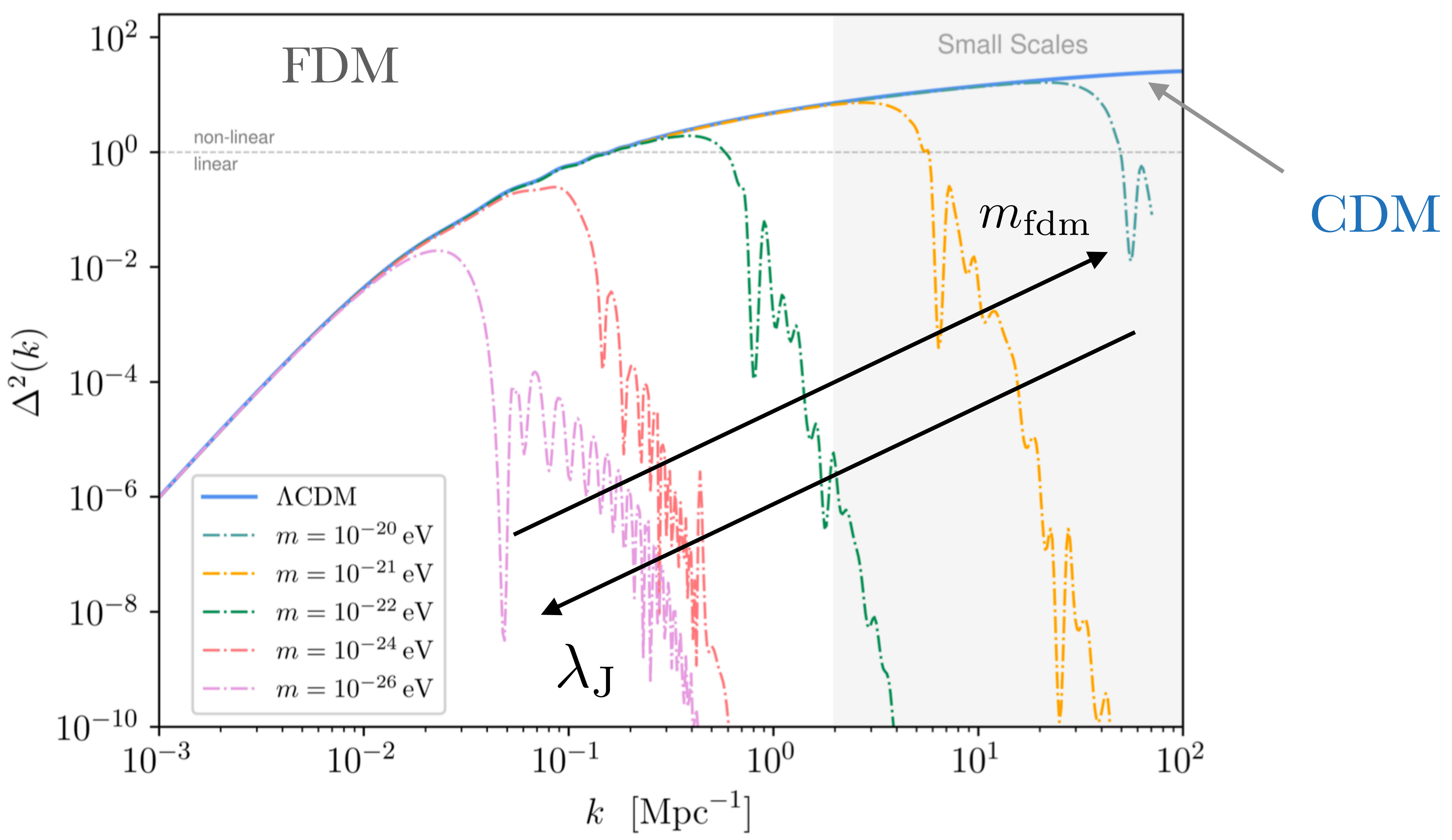
Phenomenology

Suppression of small structures

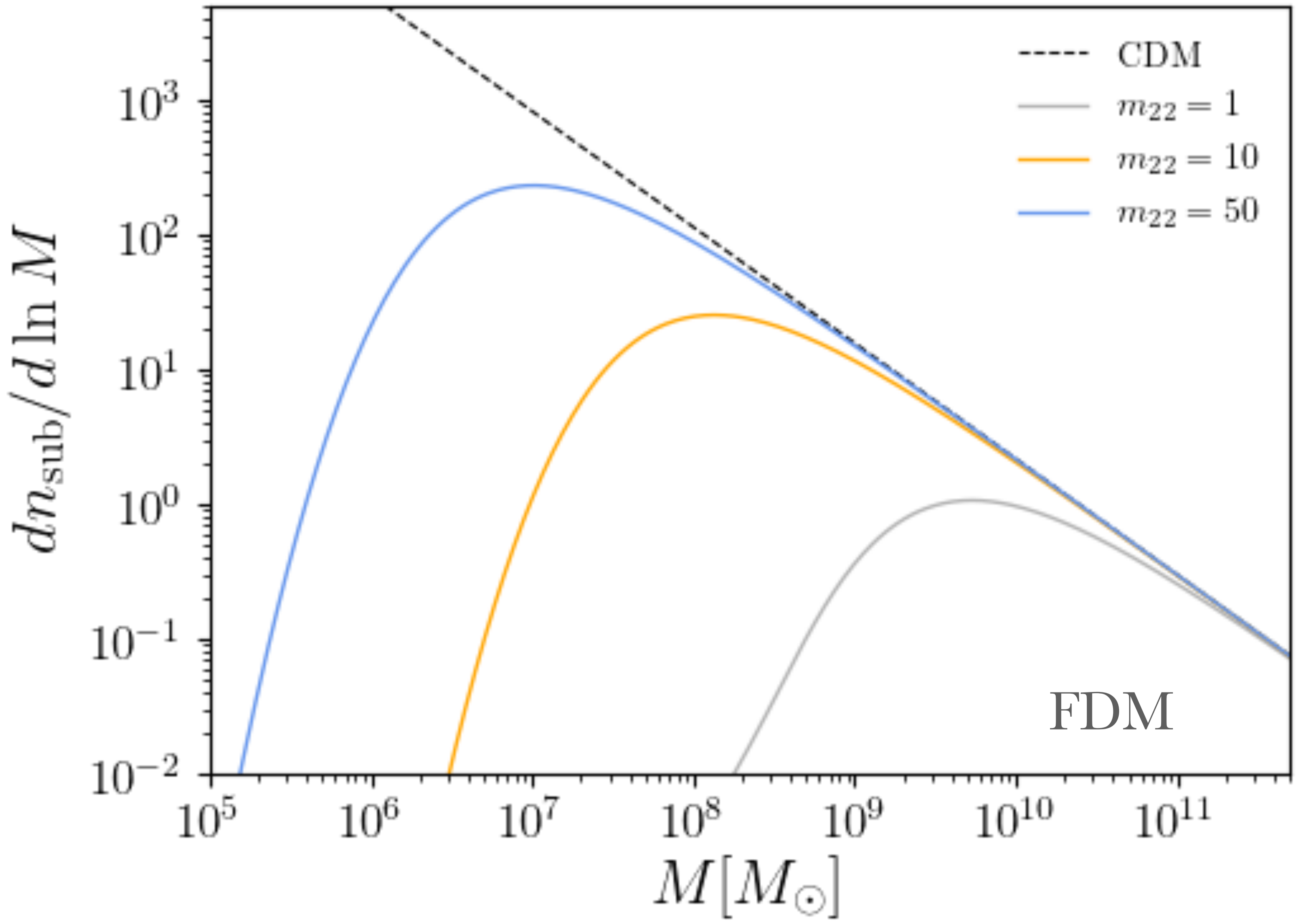


Finite Jeans length λ_J or $\lambda_{attr}, \lambda_{rep}$ → Suppresses small scale structure

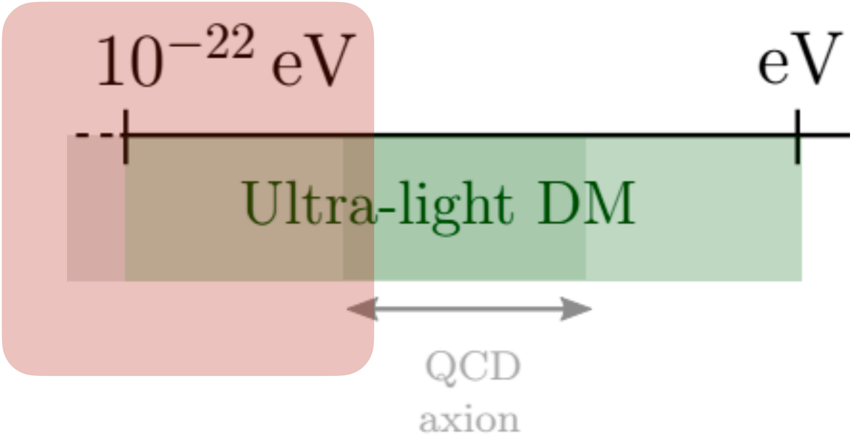
POWER SPECTRUM



(sub) HALO MASS FUNCTION



Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

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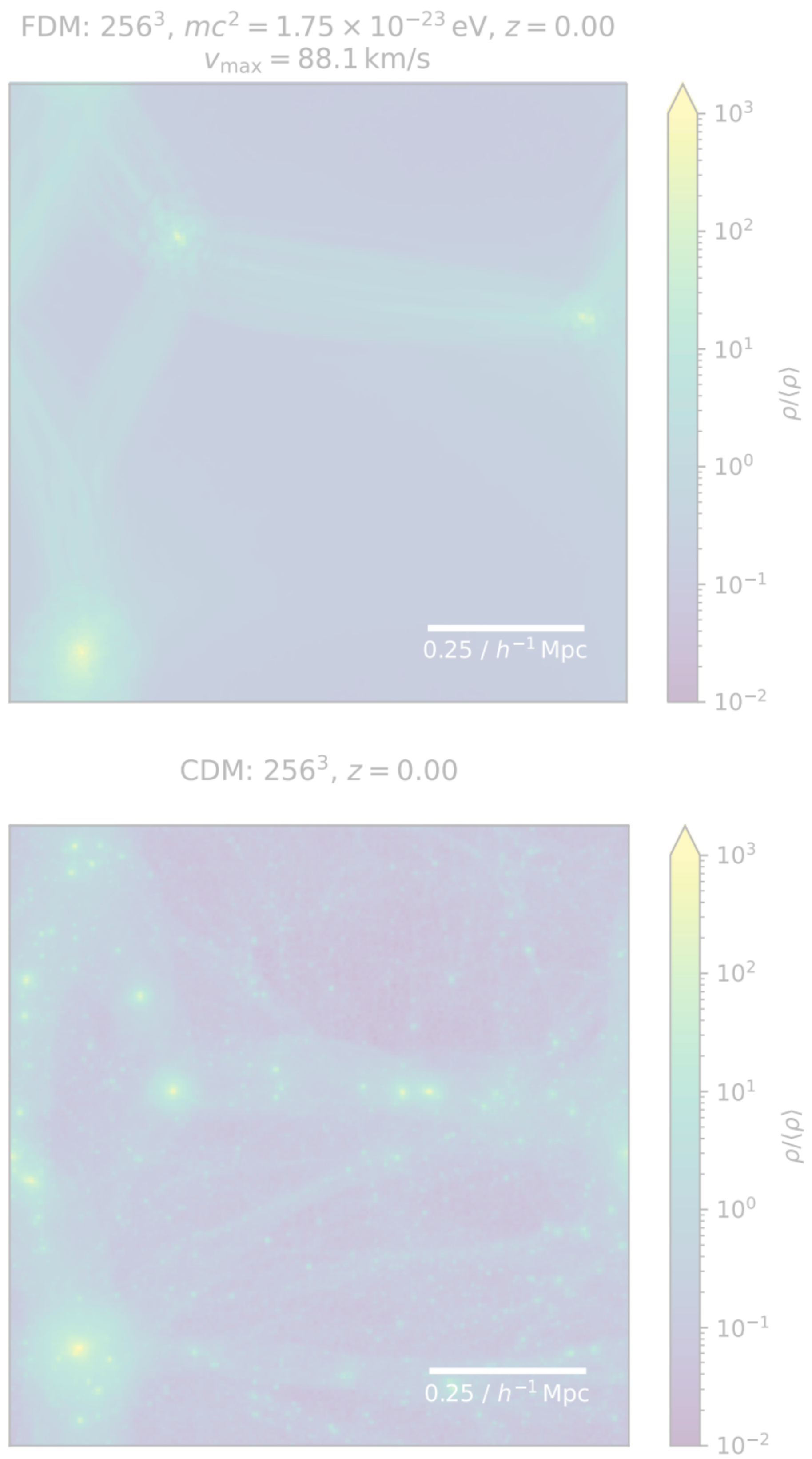
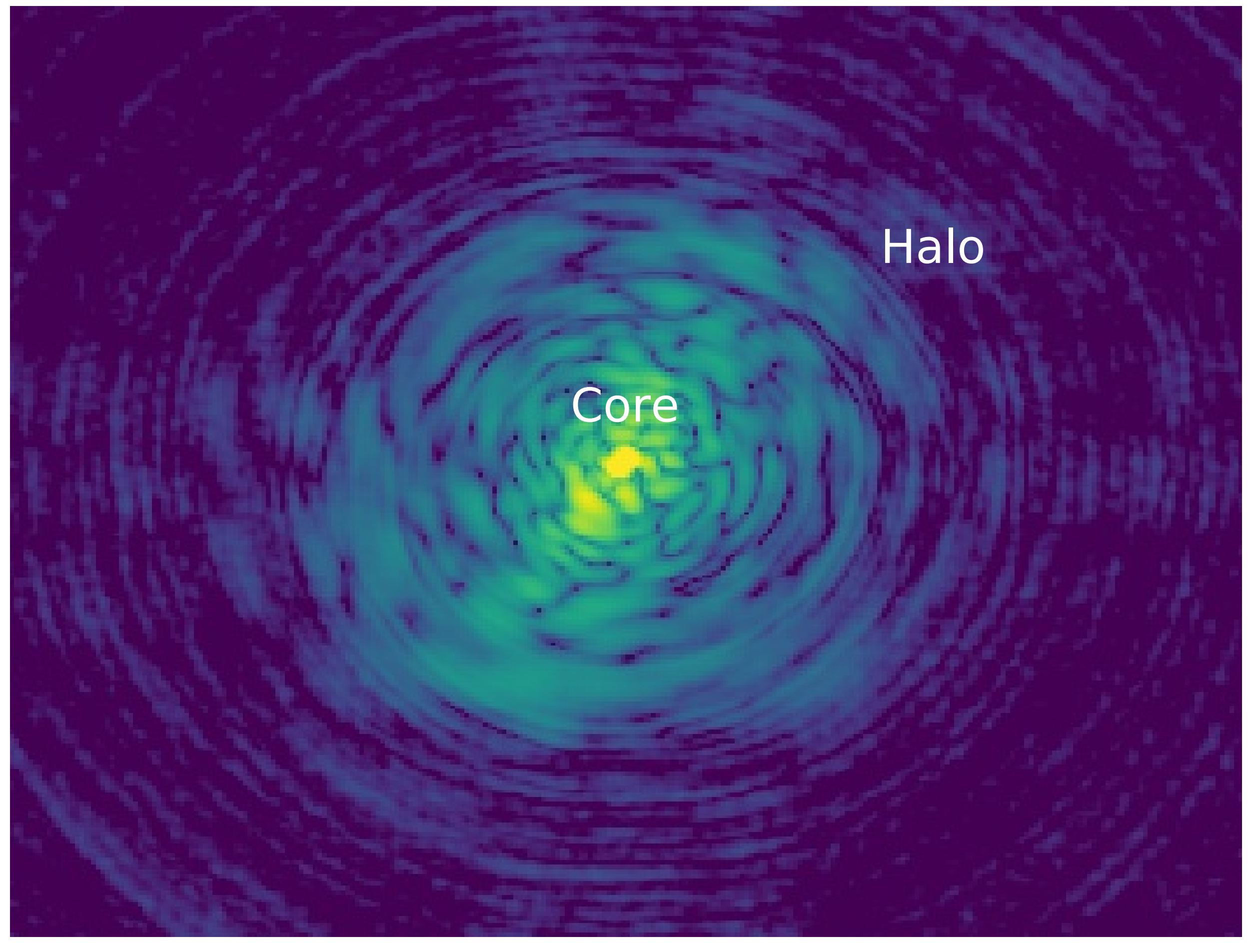


S. May et al. 2021

Formation of a solitonic core



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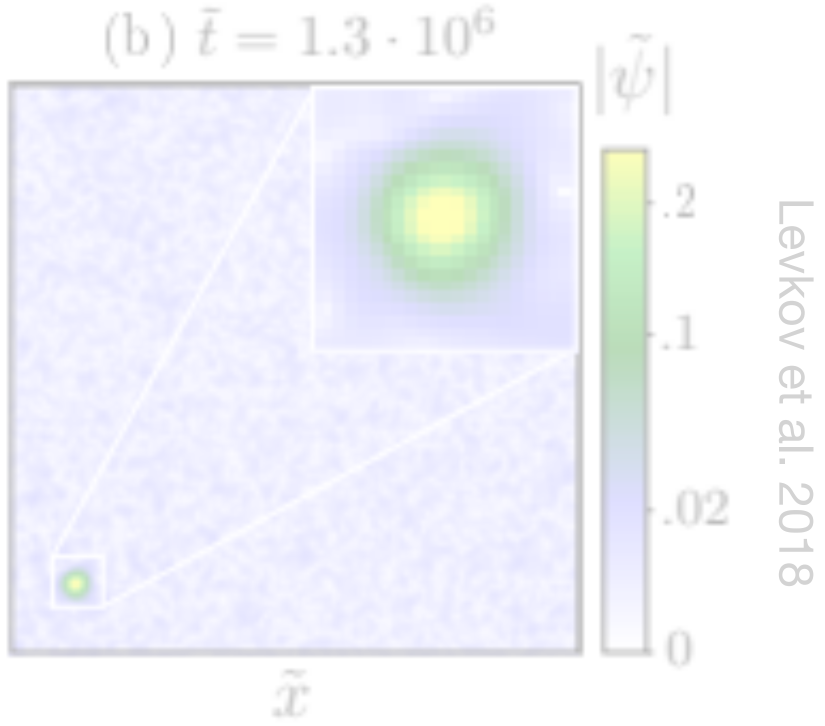

Levkov et al. 2018

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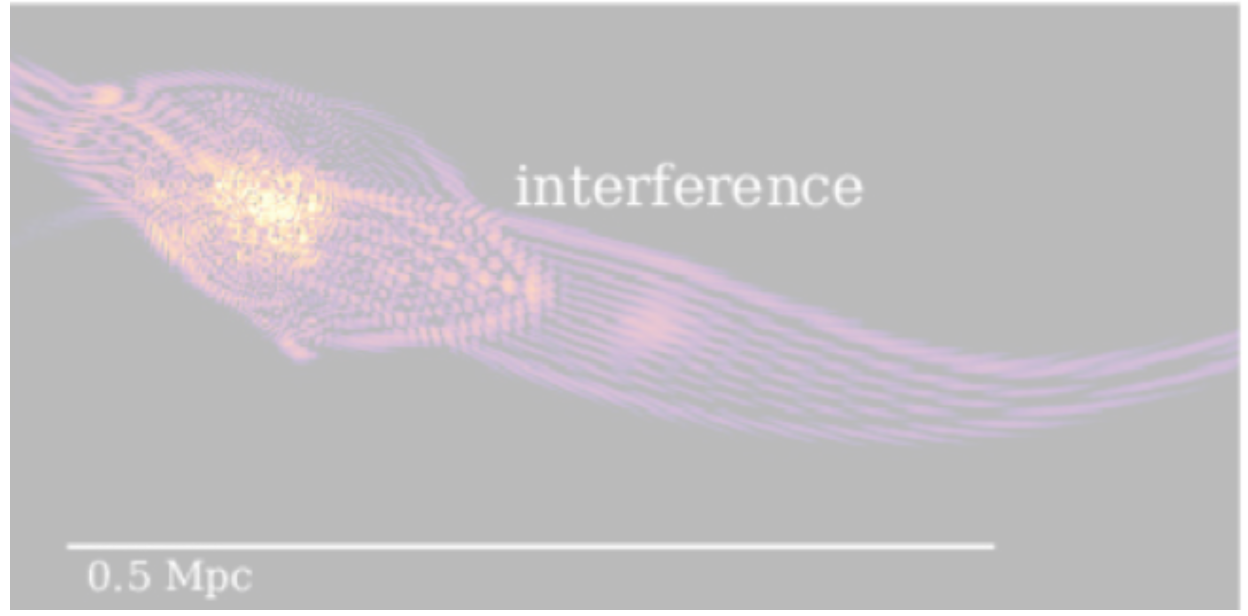
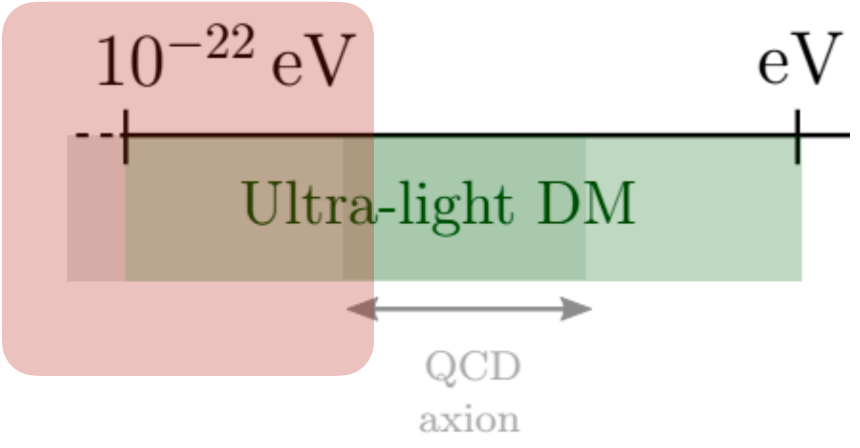


Mocz et al. 2017

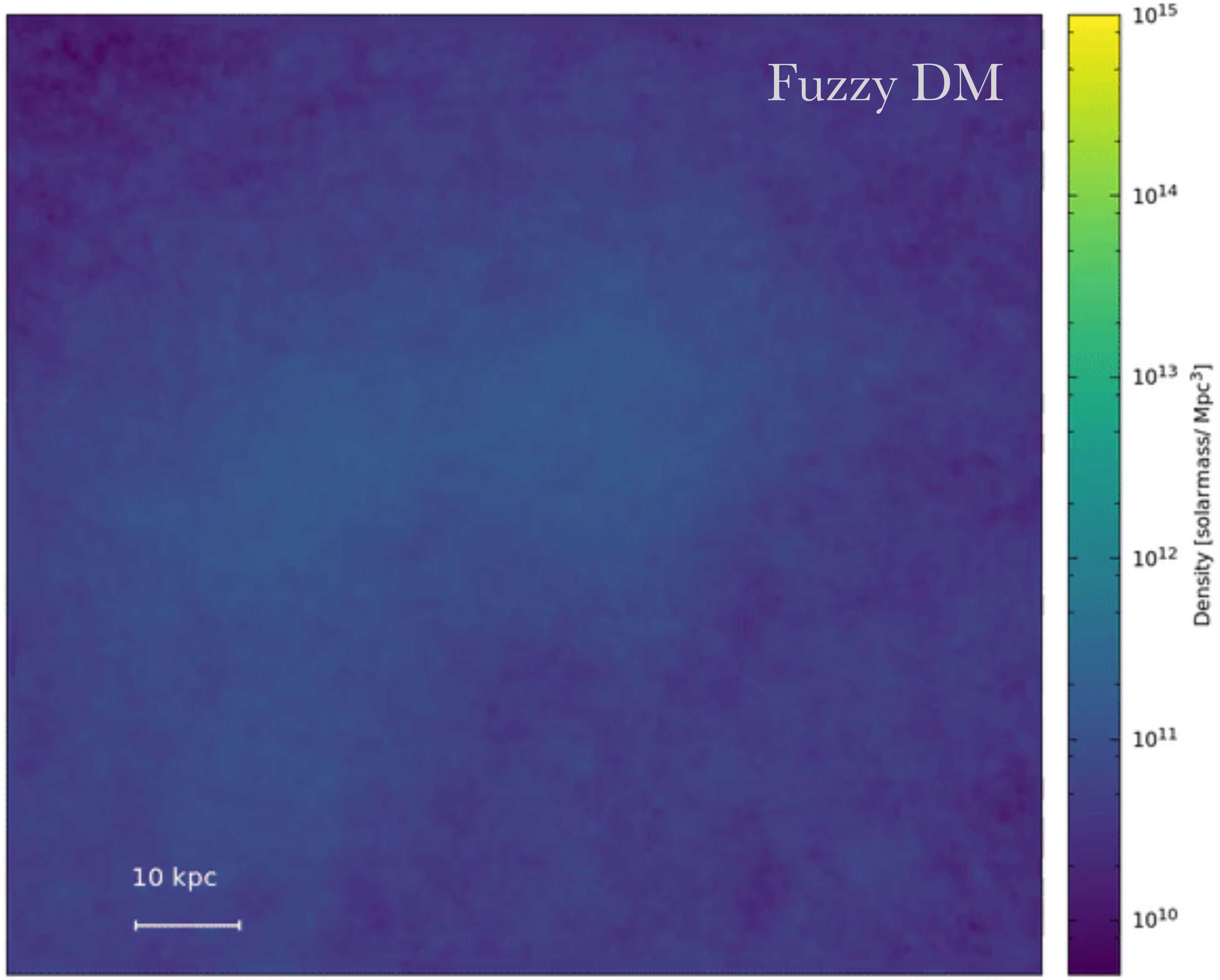
Phenomenology

Formation of cores

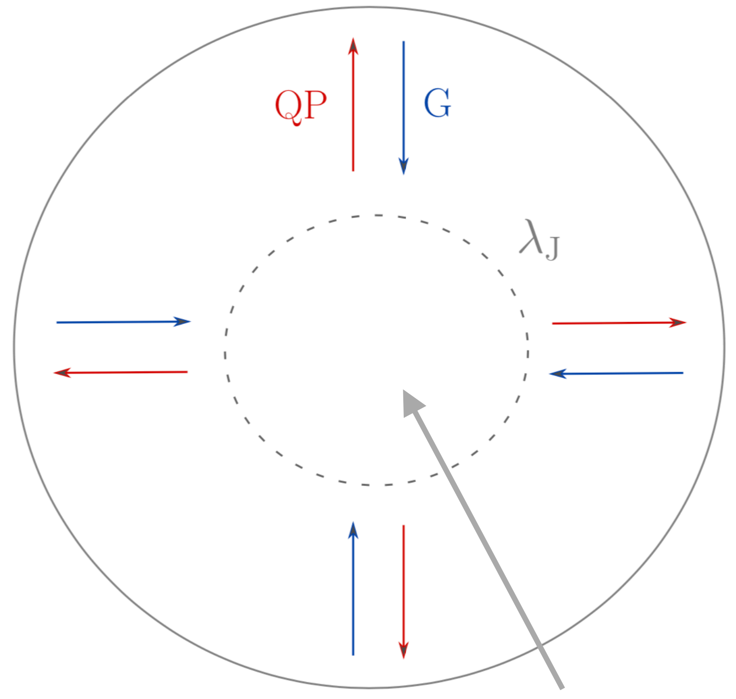


$m = 10^{-22}\,\mathrm{eV}$ $N = 512^3$ $L = 300\,\mathrm{kpc}$

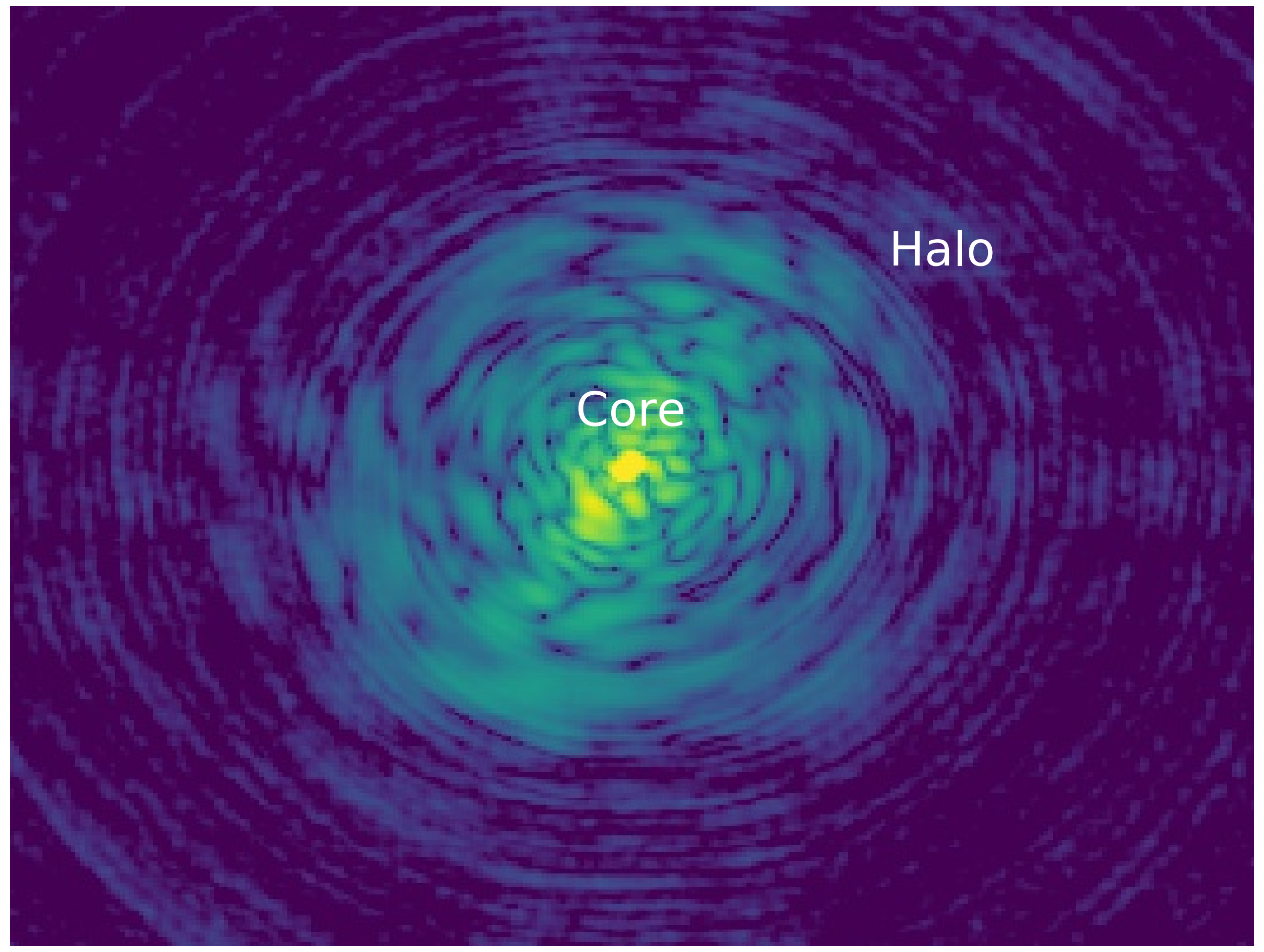
NON-LINEAR evolution: need simulations



Simulation by Jowett Chan



NO structure formation
Stable, oscillating solution



Phenomenology

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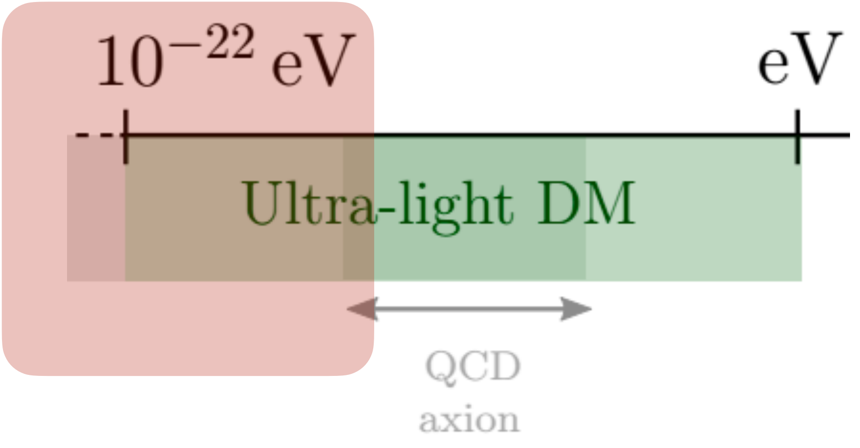
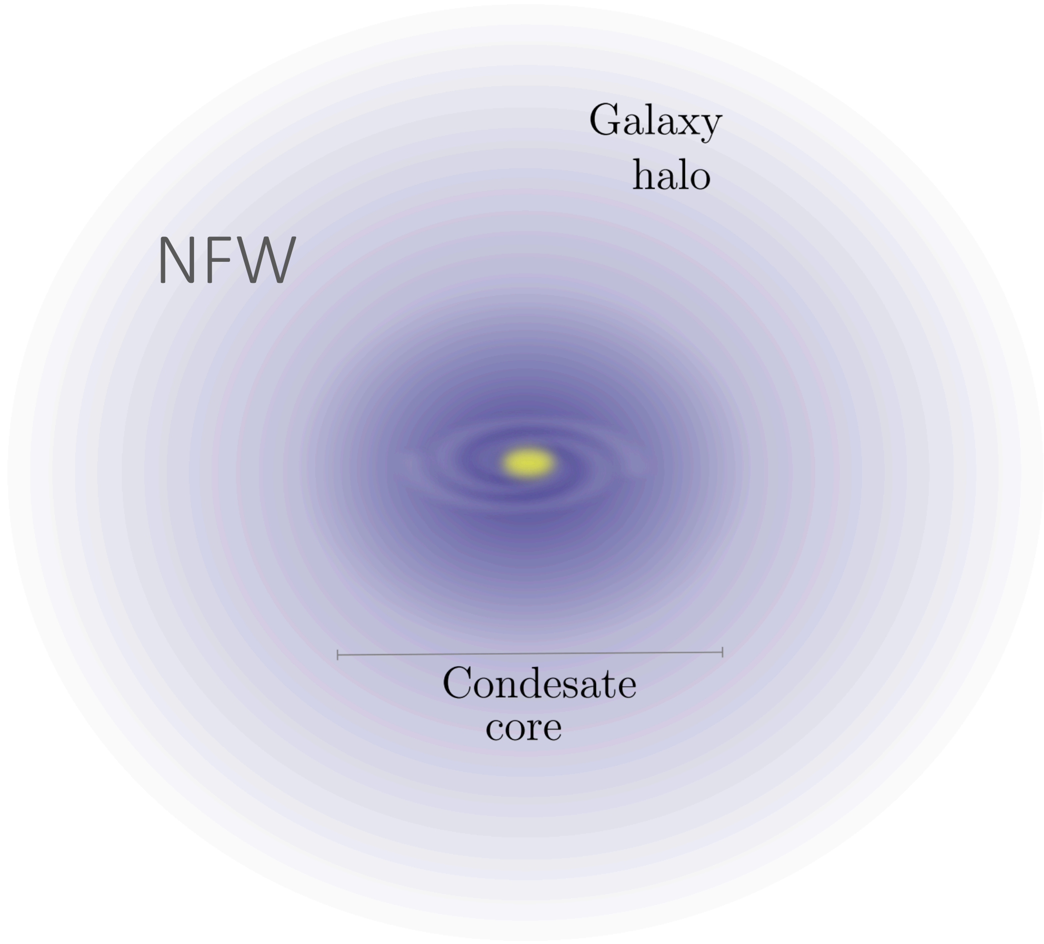
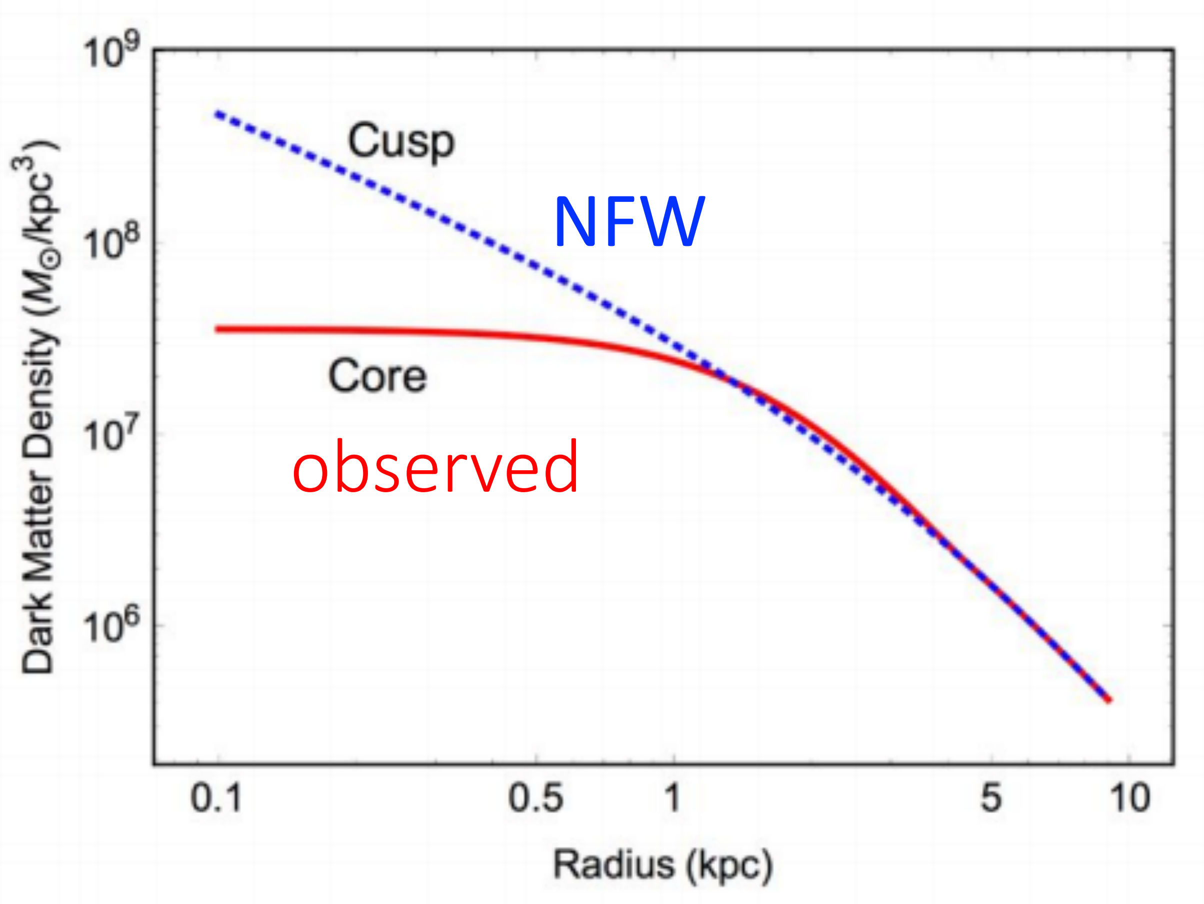




$$\rho(r) \simeq \begin{cases} \rho_c & \text{for } r \leq r_c \\ \rho_{\rm NFW} & \text{for } r \geq r_c \end{cases}$$

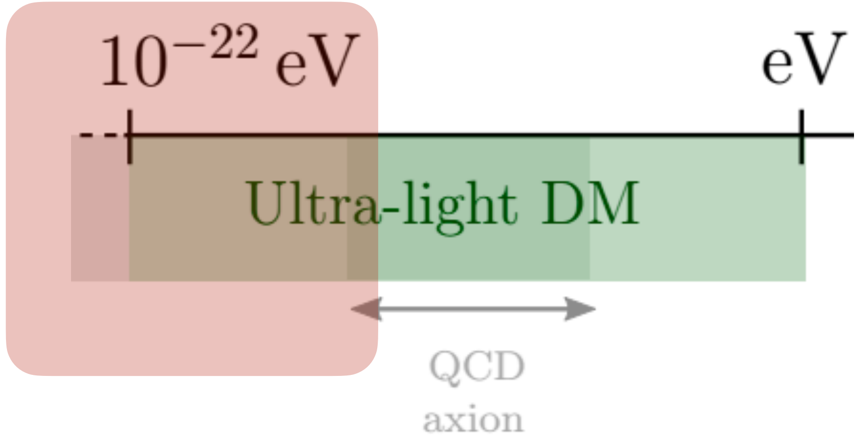


FDM — From simulations Schive et al. 2014, fitting function: Stable core solution

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

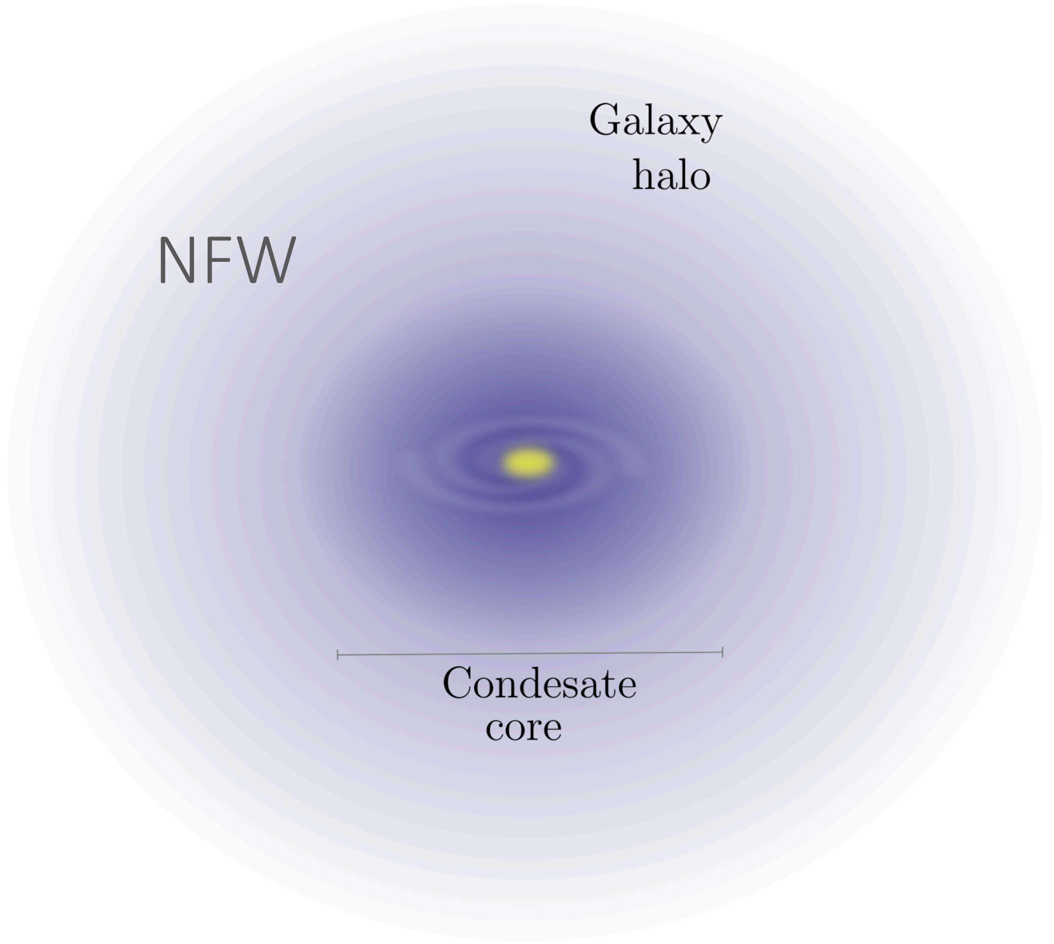
$$r_c \simeq 0.16\left(\frac{m}{10^{-22}\,{\rm eV}}\right)^{-1}\left(\frac{M}{10^{12}\,M_\odot}\right)^{-1/3}{\rm kpc}\,.$$

→ Relations used to compare with observations



Phenomenology

Formation of cores



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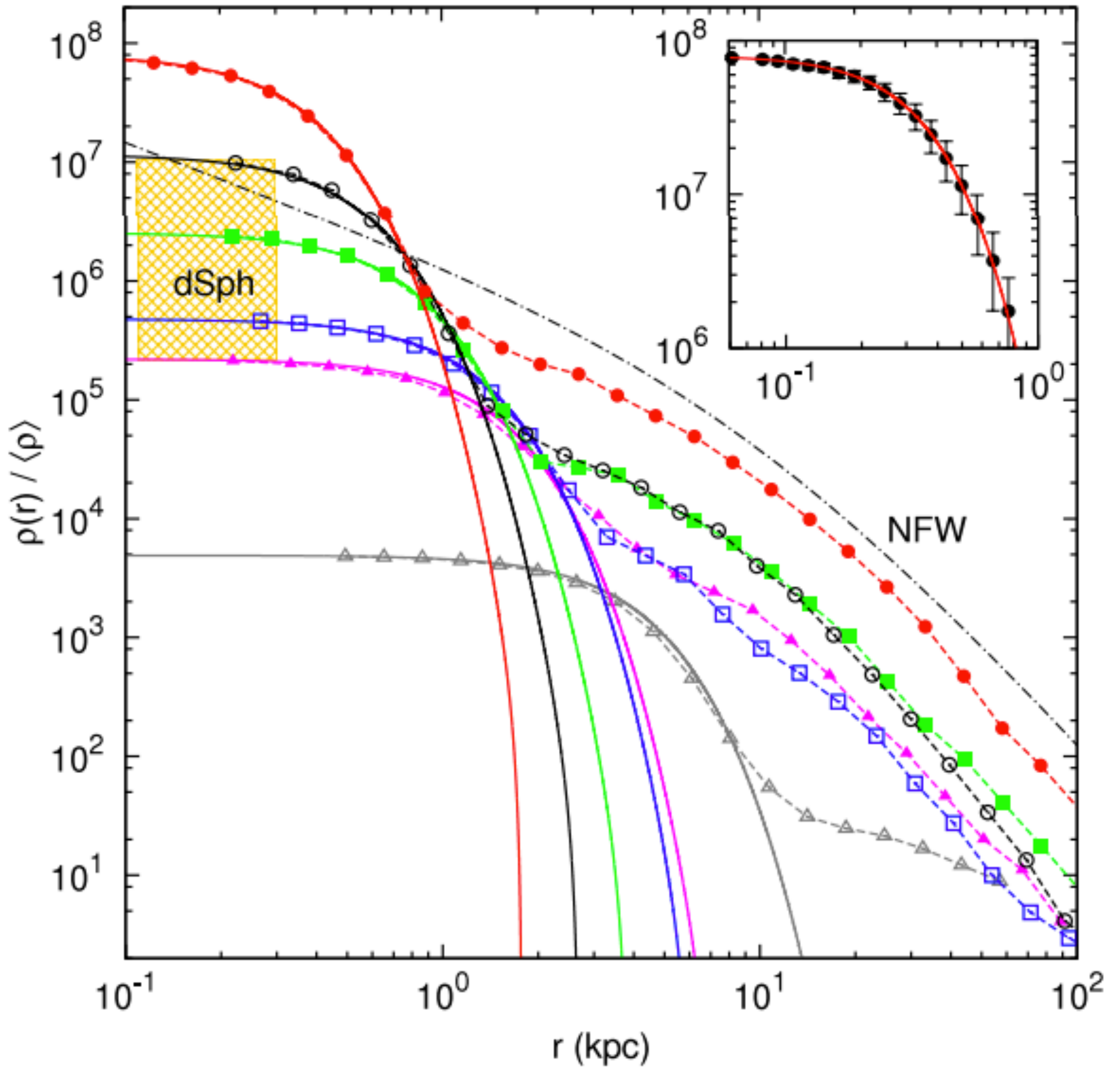
Schive et al. 2014



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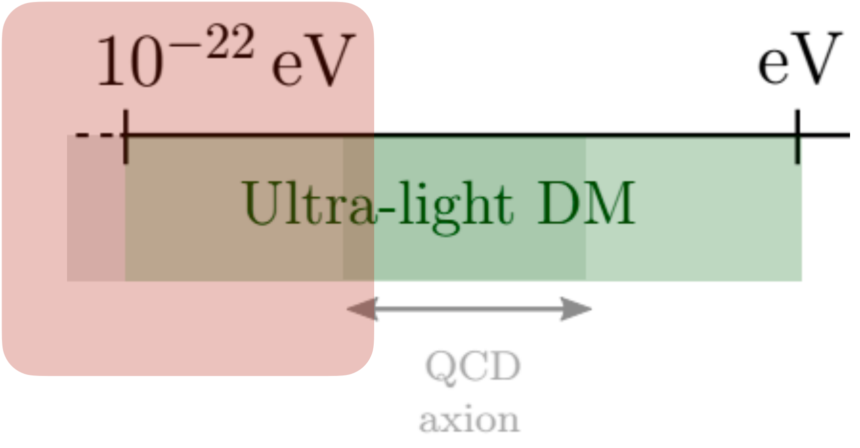
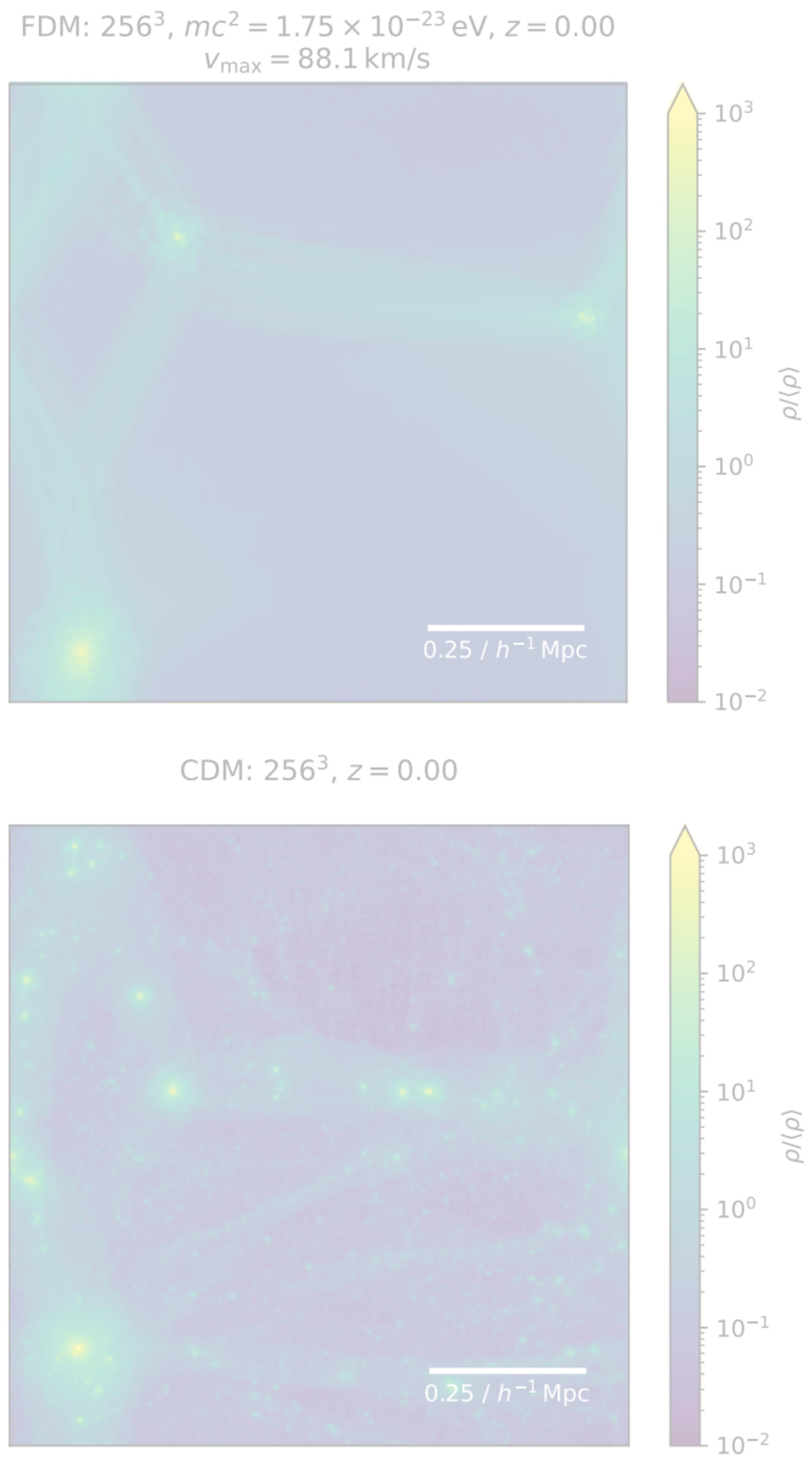
Relations used to compare with observations

Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures



S. May et al. 2021

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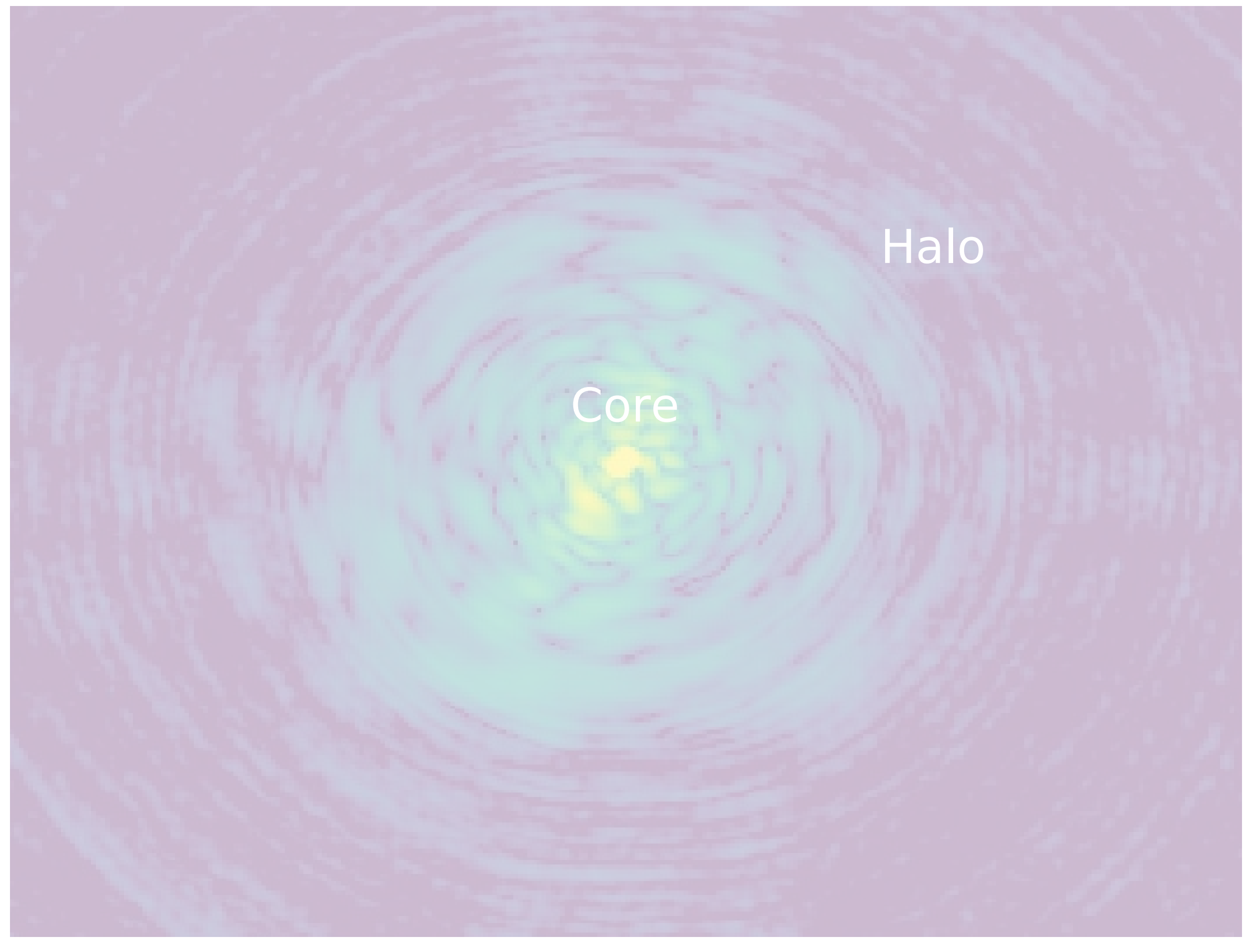
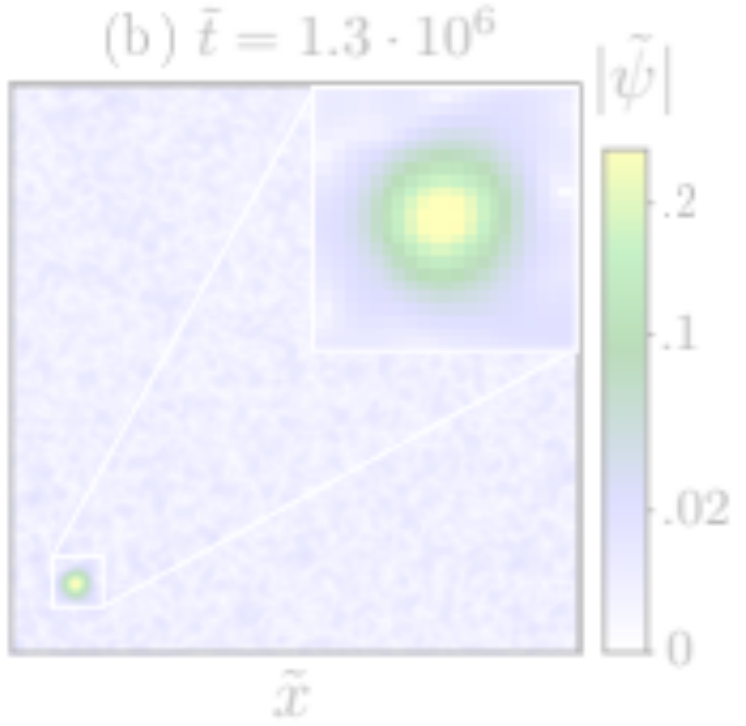
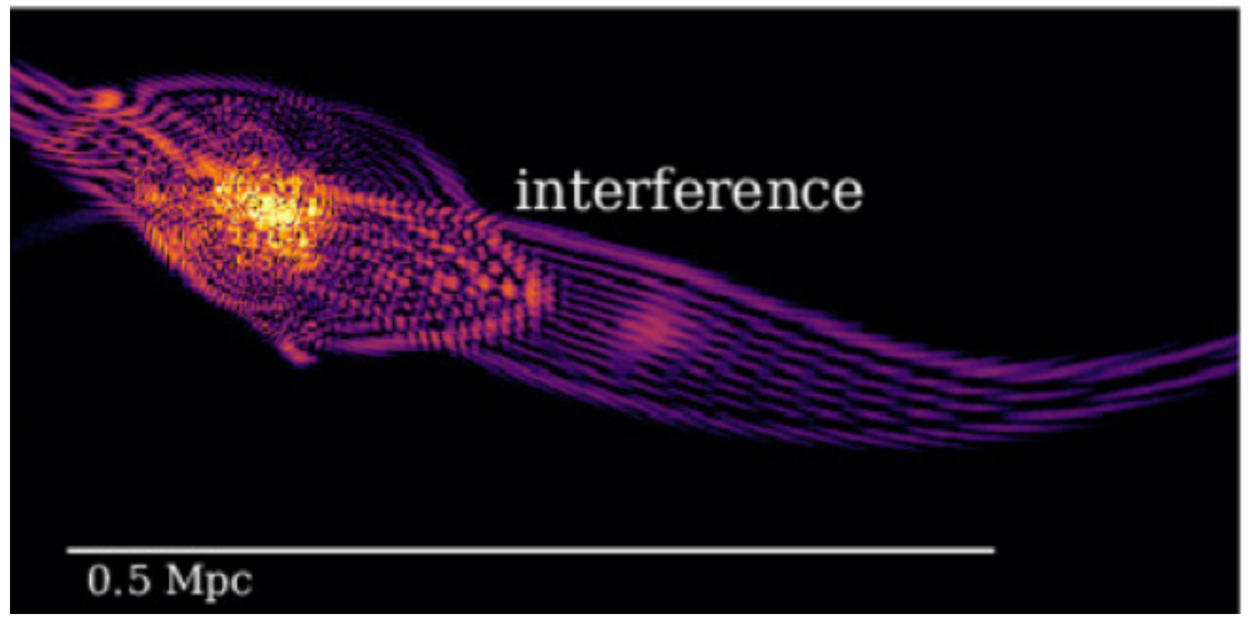


Dynamical effects



Levkov et al. 2018

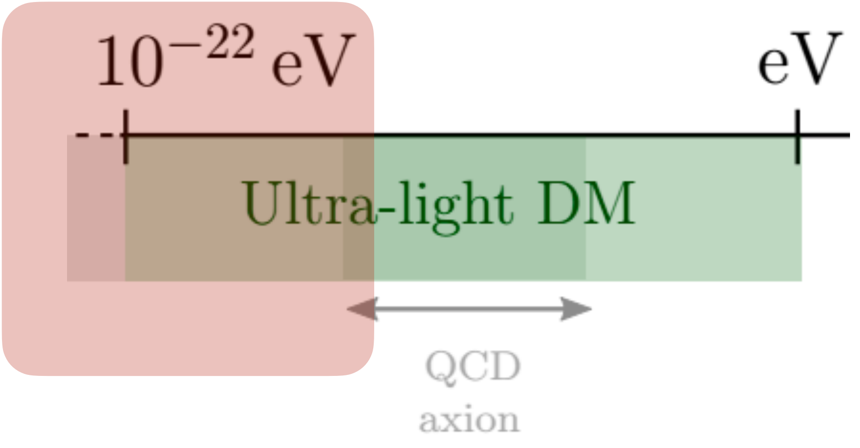
Wave interference

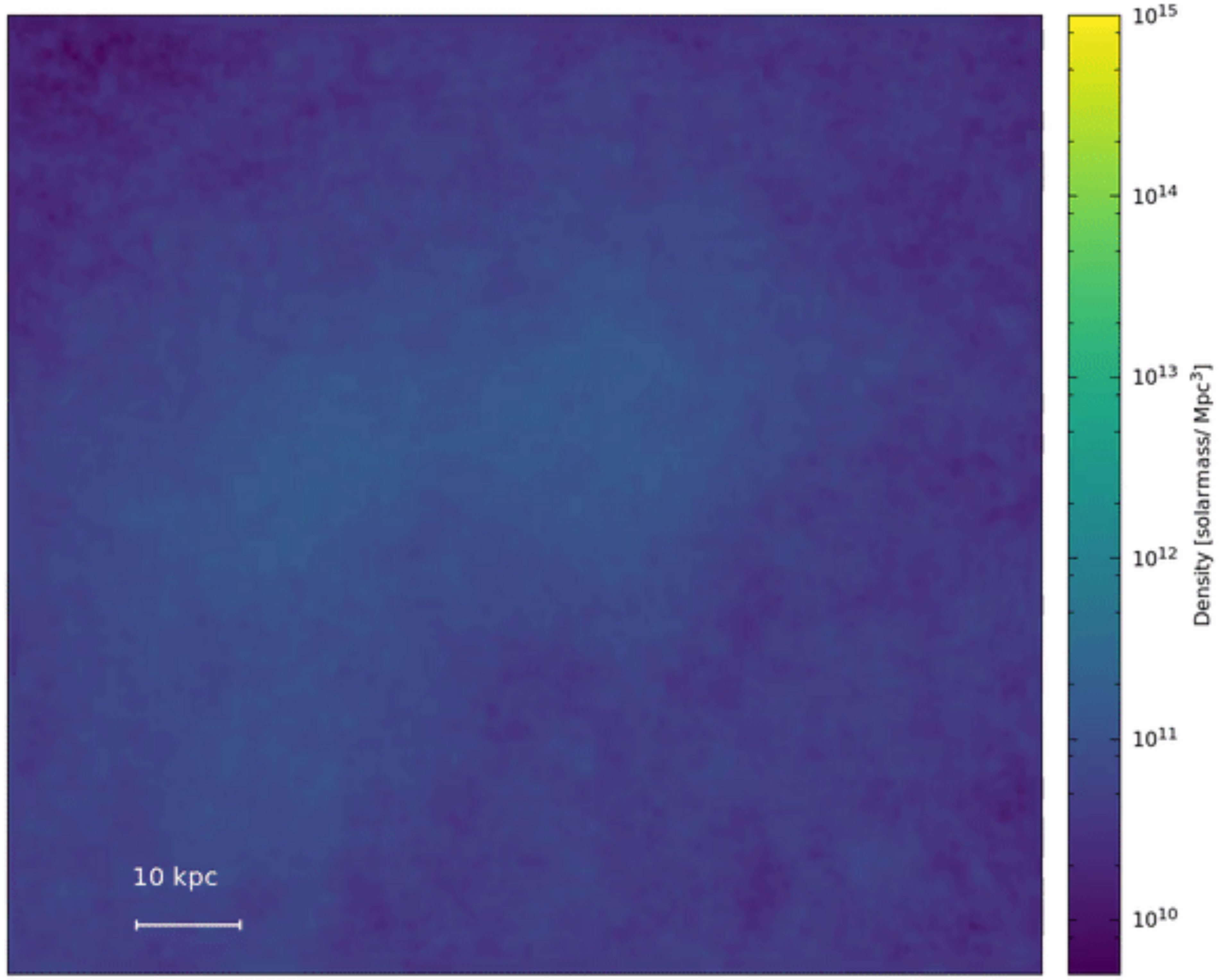


Mocz et al. 2017

Phenomenology

Wave interference: granules and vortices





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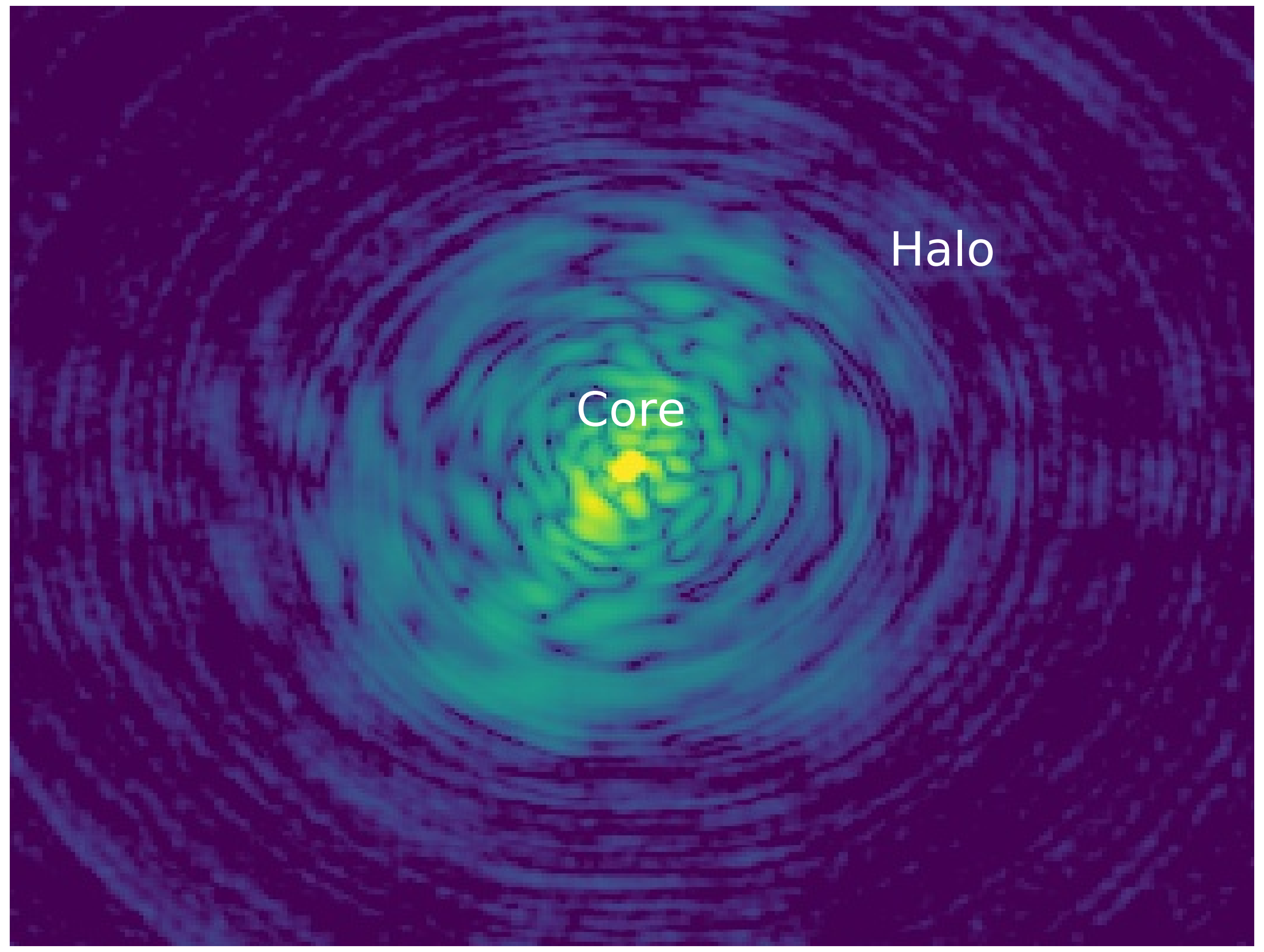
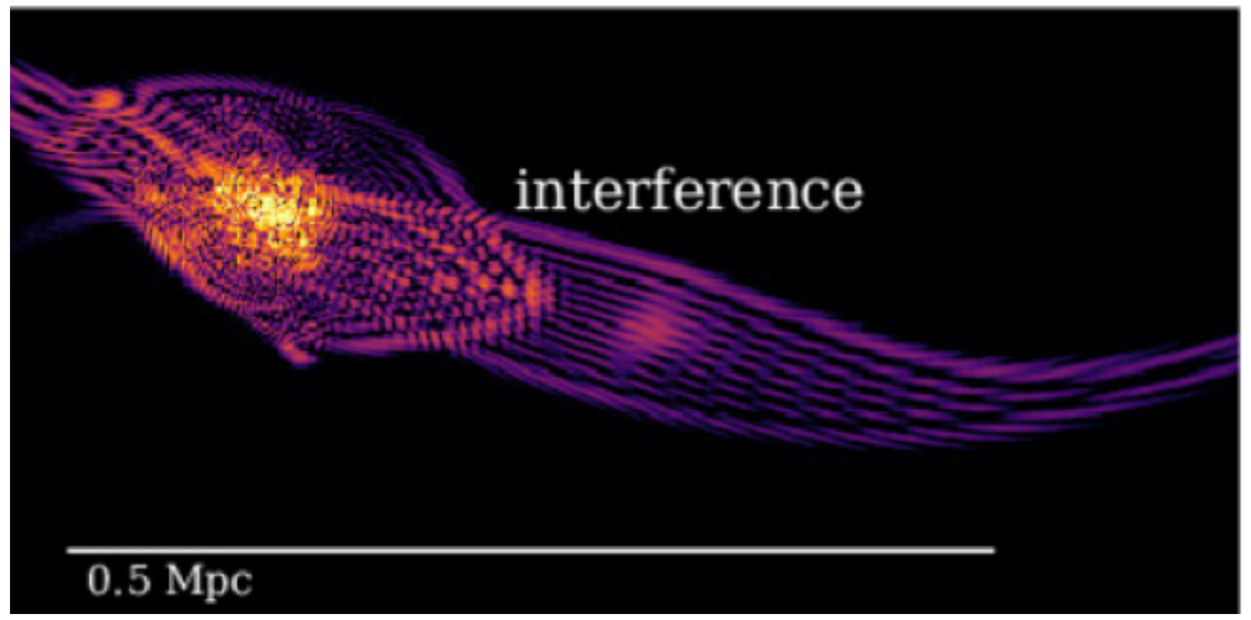




Mocz et al. 2017

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

$\longrightarrow \sim \lambda_{dB}$

Hard to observe!

Phenomenology

Vortices

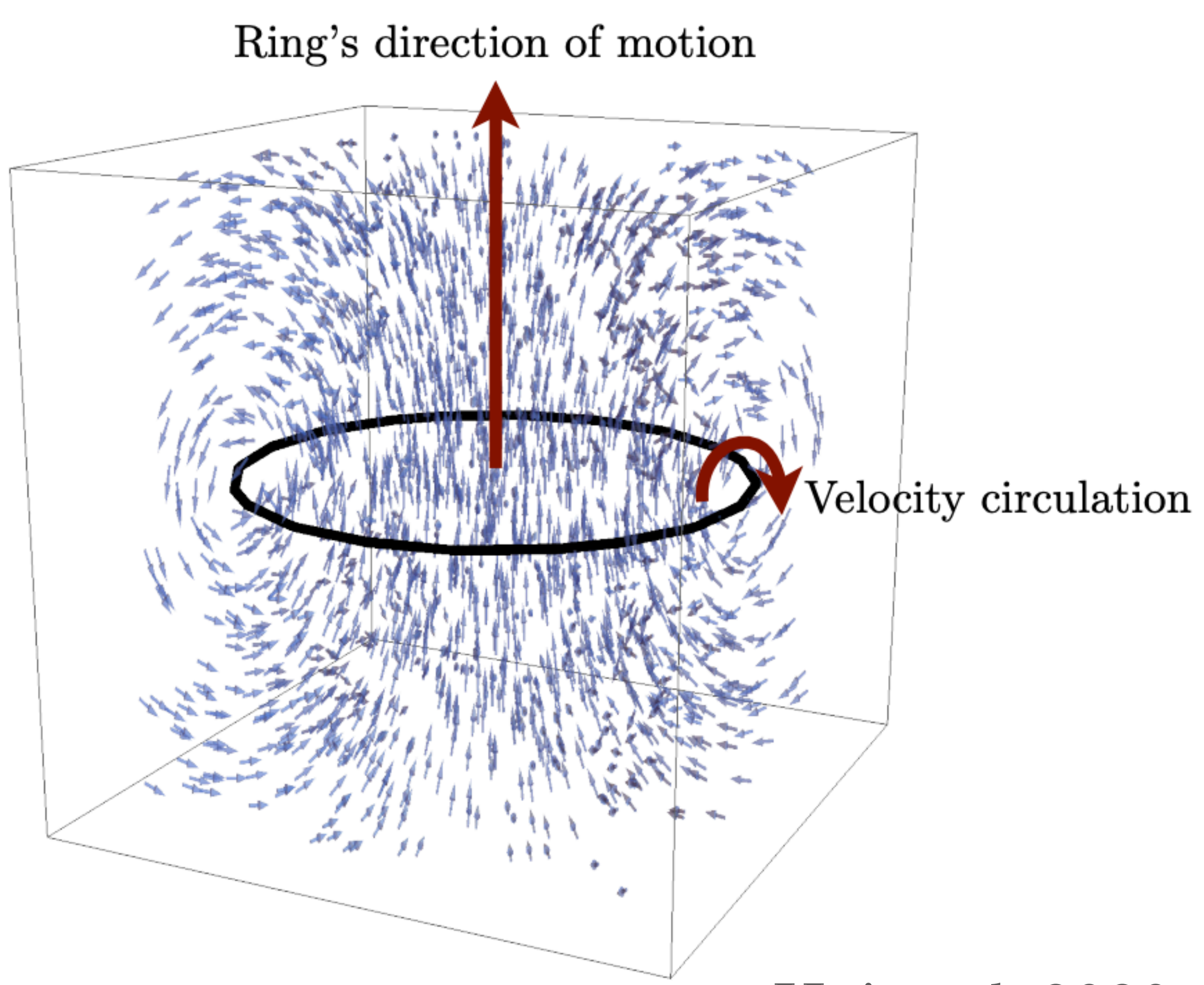
Vortices are sites where the fluid velocity has a non-vanishing curl

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

Phenomenology

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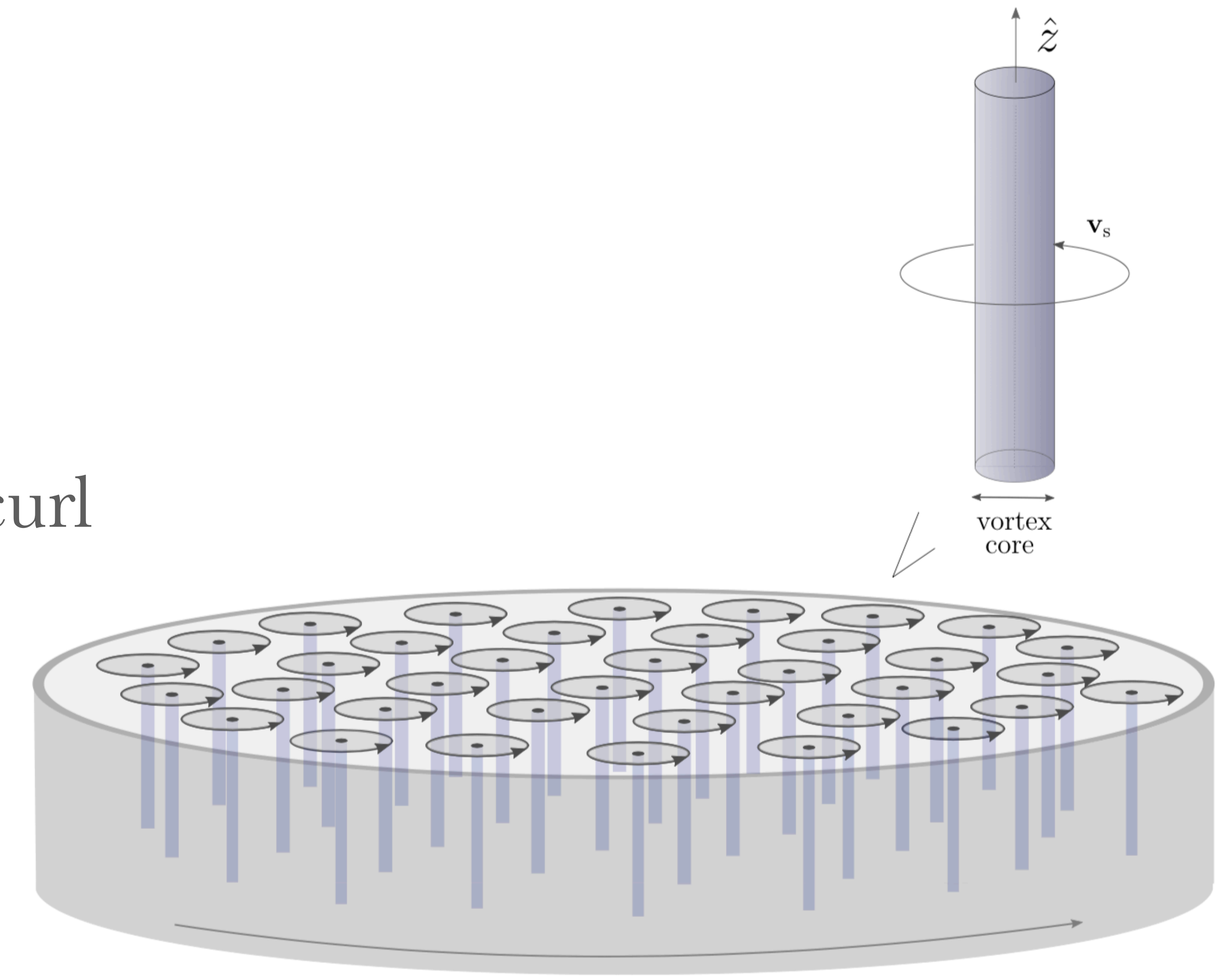
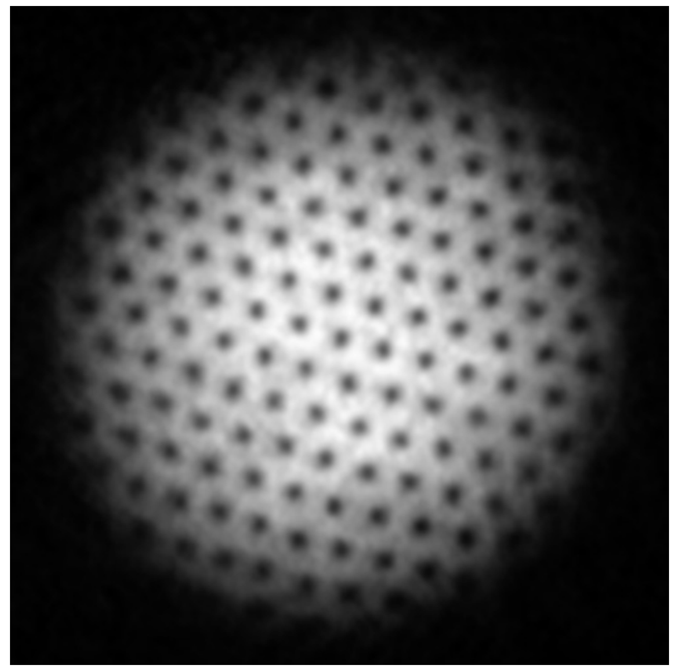


EF, 2020

© Martin Zwierlein.



Self-interacting Fuzzy DM

Observational signature of superfluidity

Reveals *quantum mechanical* nature of superfluid

Superfluid cannot rotate uniformly.

If the superfluid rotates faster than the critical vel.:

$$\omega_{cr} \sim \frac{1}{mR^2} \sim 10^{-41}\text{s}^{-1}$$

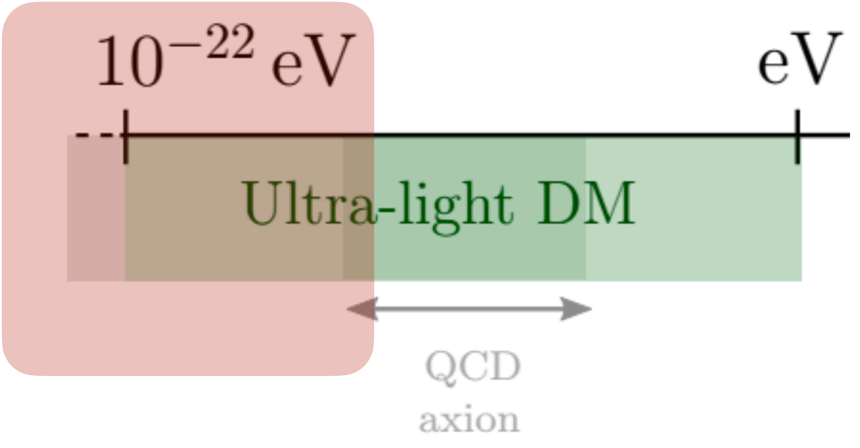
$$>$$

$$\omega \sim \lambda\sqrt{G_N \rho_{halo}} \sim 10^{-18}\lambda\text{s}^{-1}$$

Formation of vortices!

Vortices: smoking gun for superfluid DM

Phenomenology



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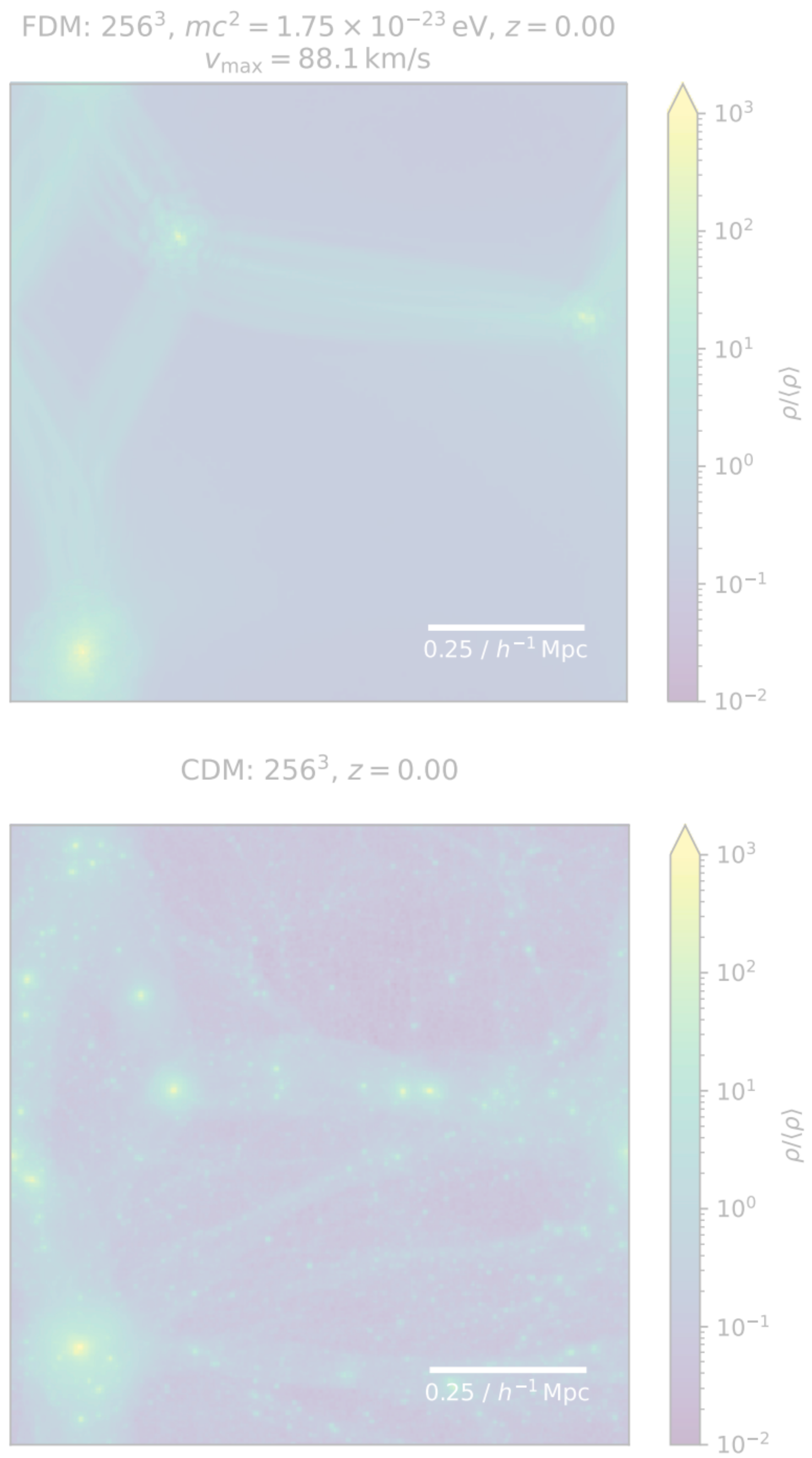

S. May et al. 2021

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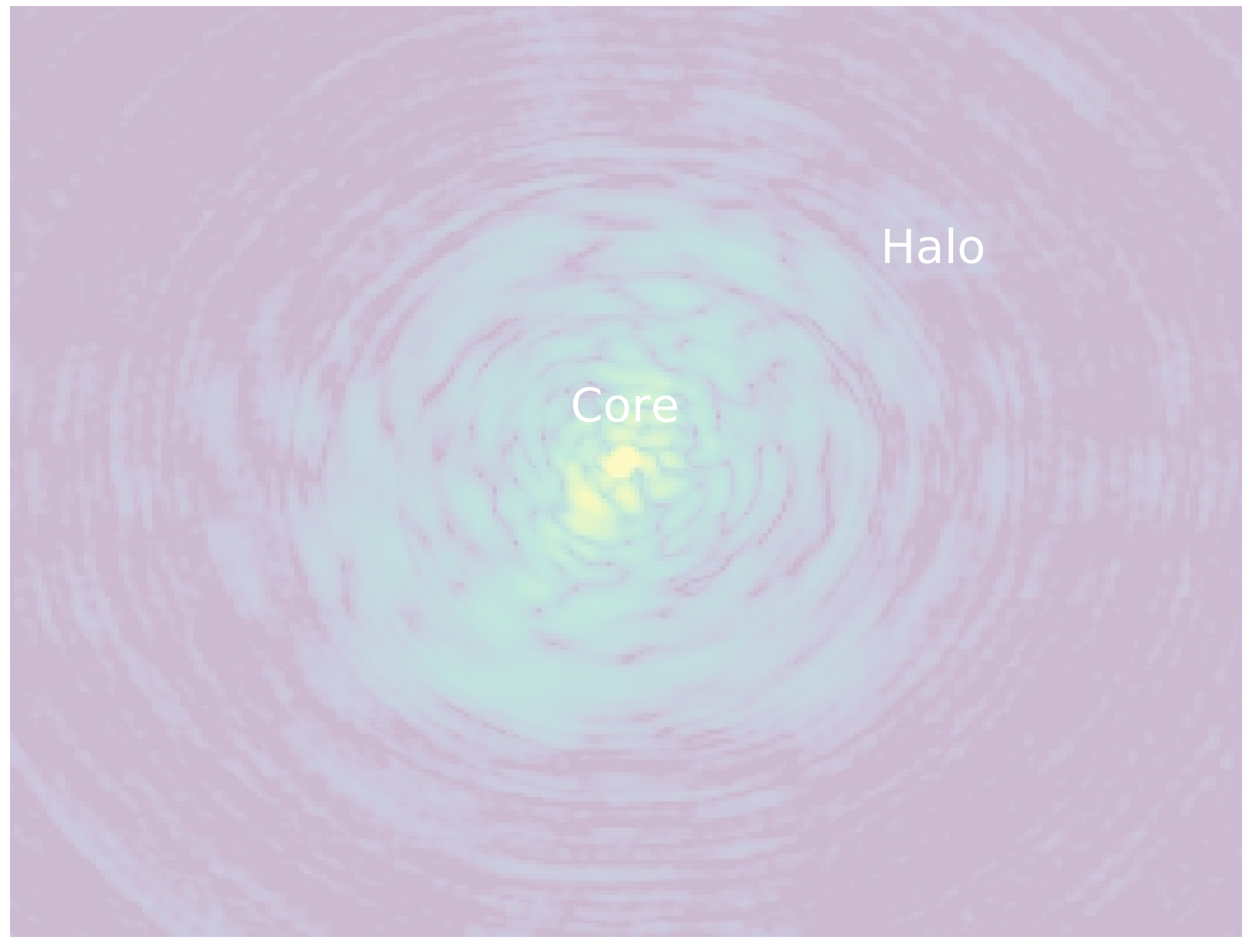
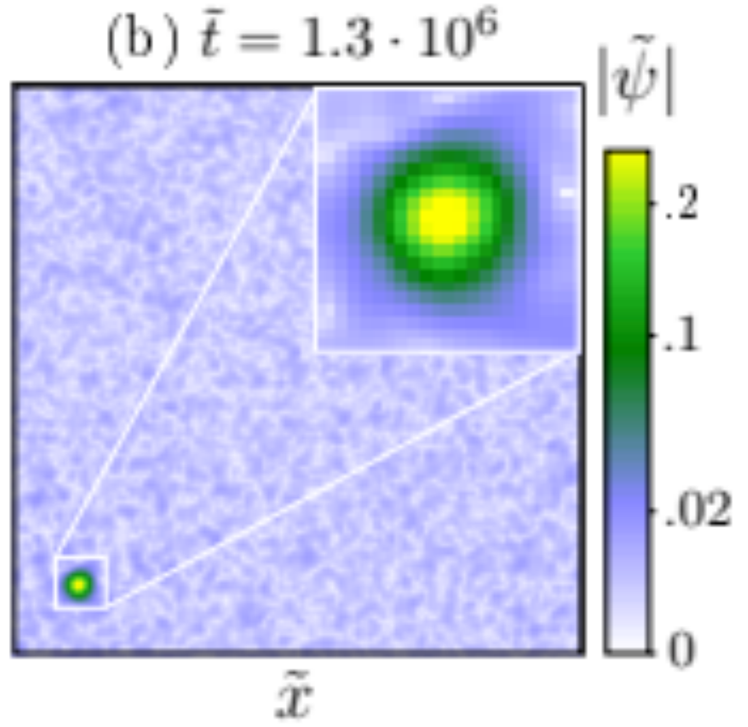
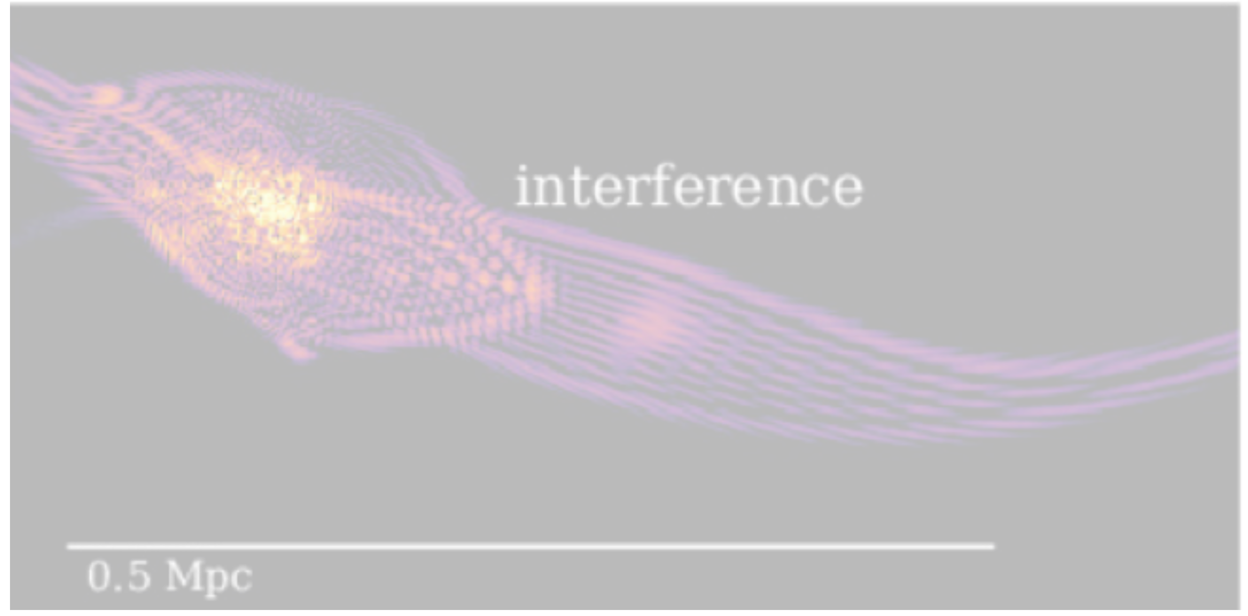


Dynamical effects



Levkov et al. 2018

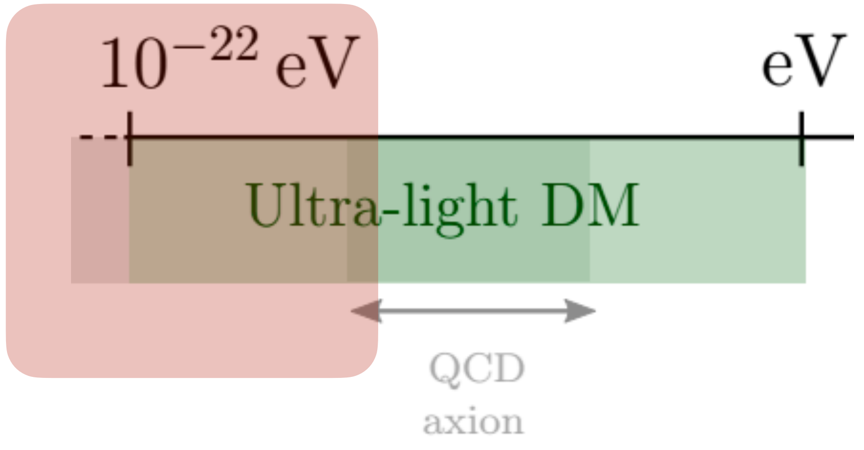
Wave interference



Mocz et al. 2017

Phenomenology

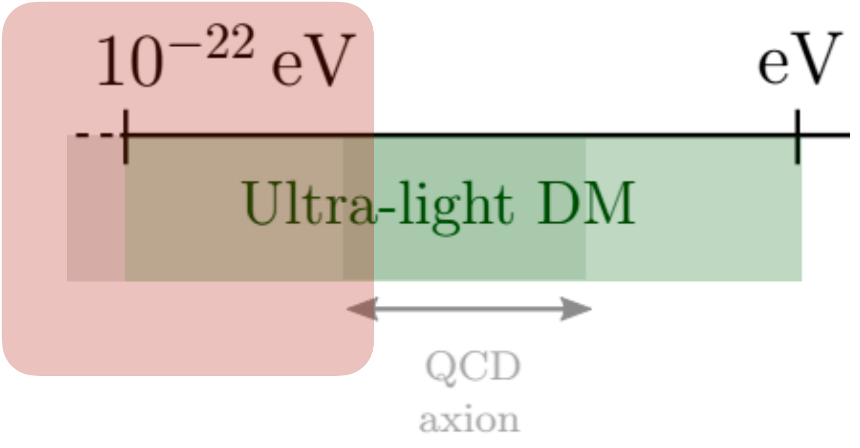
Dynamical effects



Relaxation, oscillation, friction, and heating

Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

Formation of a BEC / superfluid

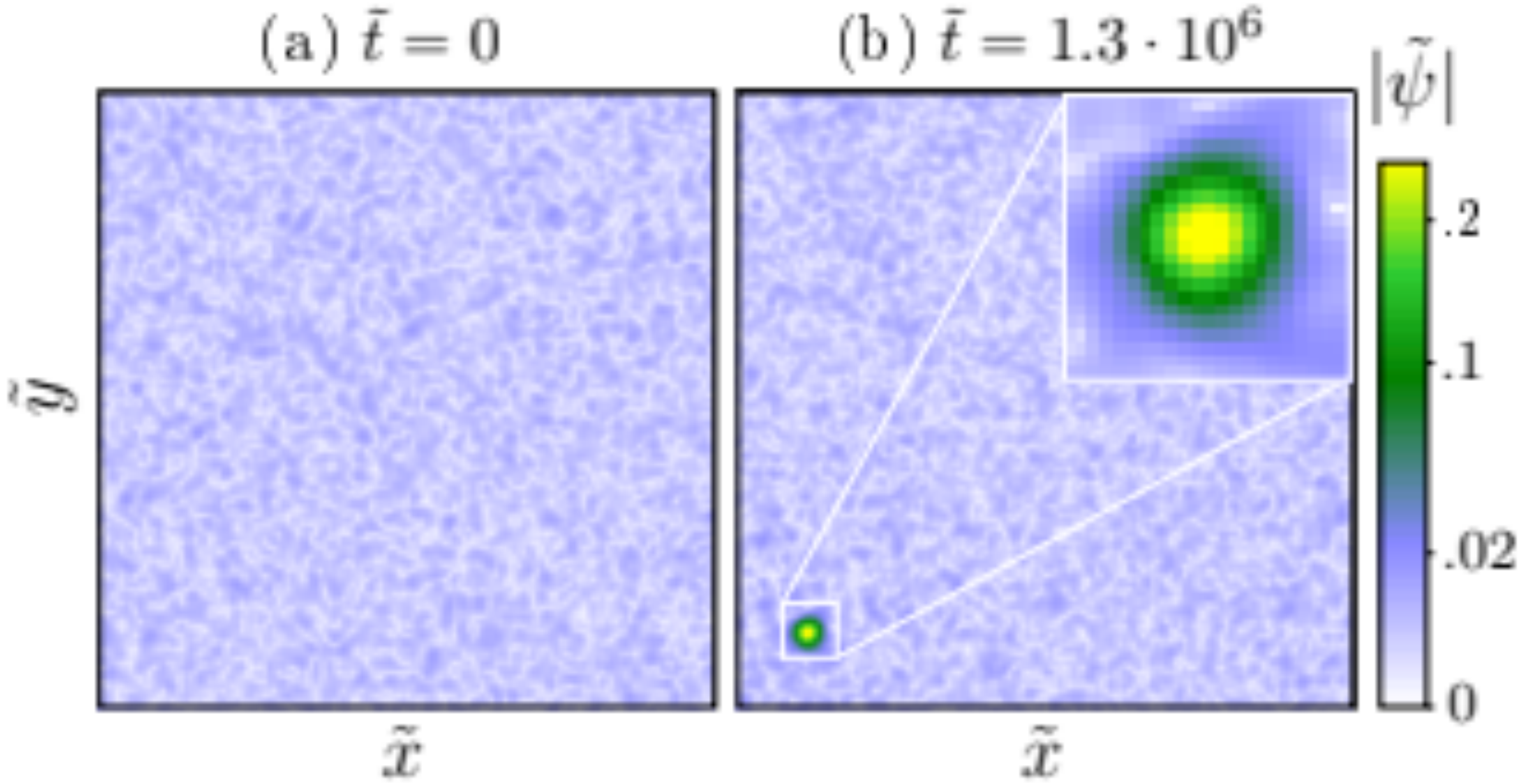
Formation of a condensate and a core occur from gravitational interaction.

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

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

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

Smaller than the age of the universe!

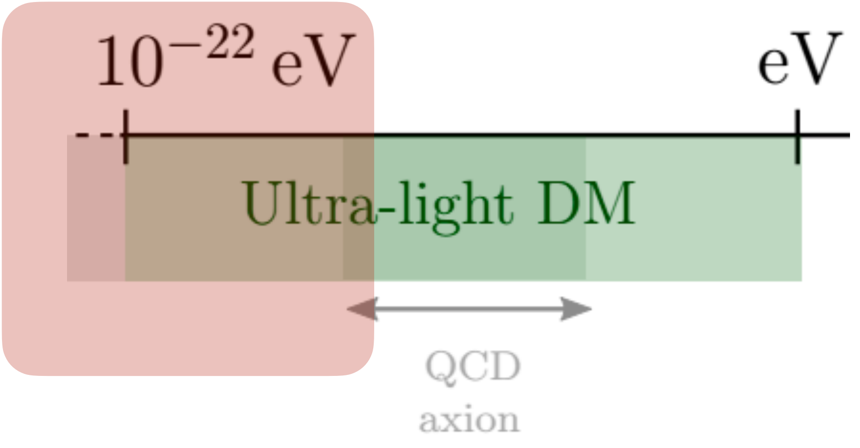


Levkov et al. 2018, Kirpatrick et al. 2020

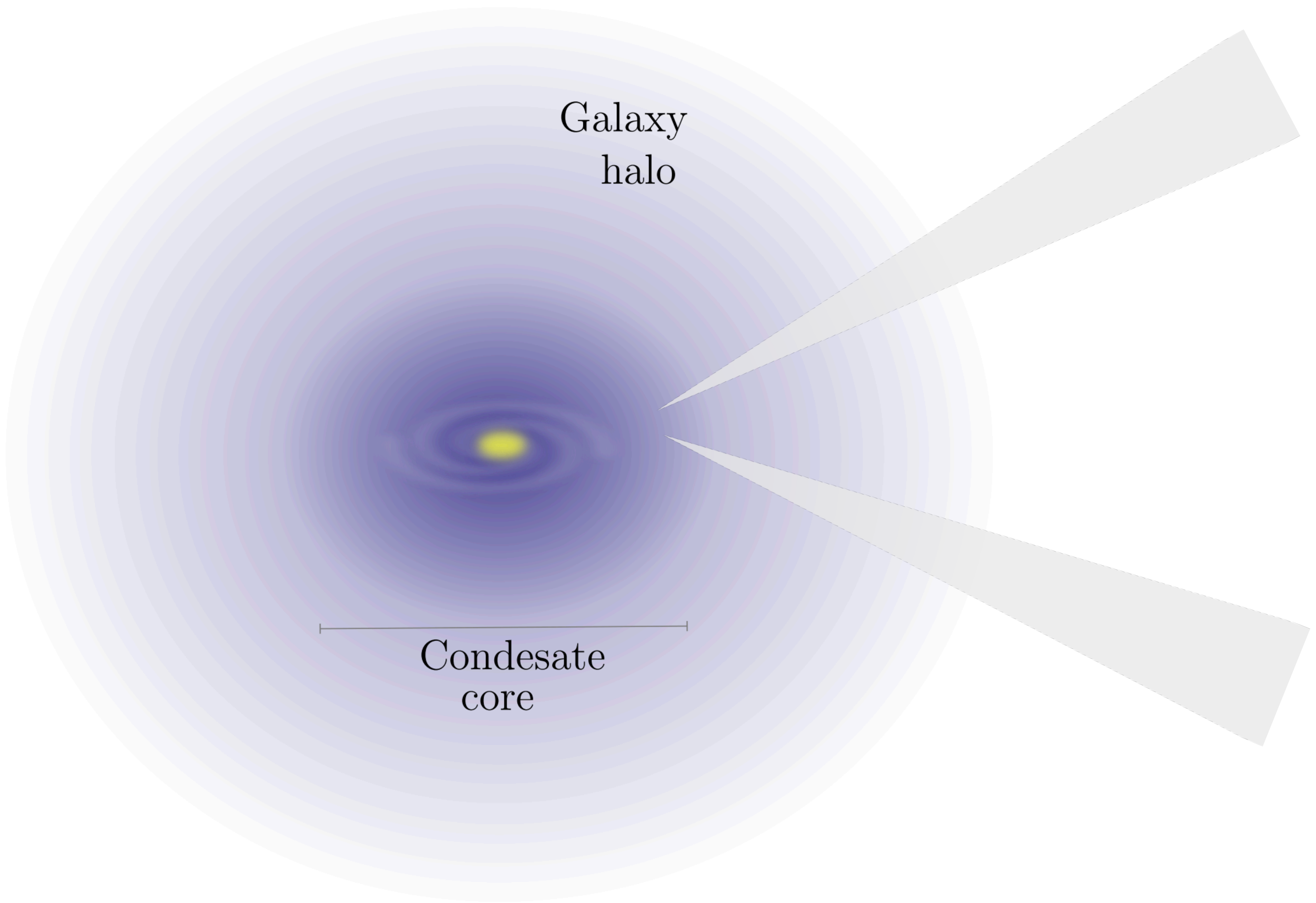
Thermalization and condensation *seem* to happen inside the galaxy!
Formation of a soliton (ground state) or Bose star in the interior of galaxies

Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

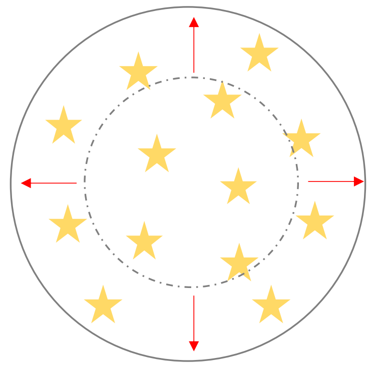


Heating

FDM granule

$m_{\rm eff}$

System (star)
gains energy



Friction

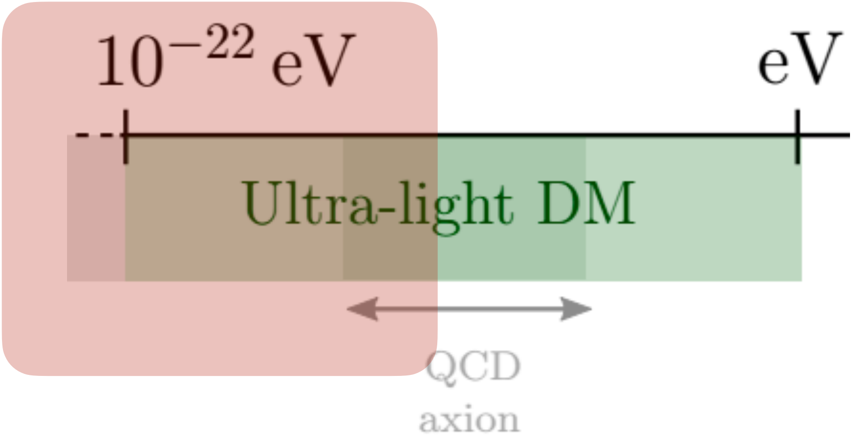
FDM granule

$m_{\rm eff}$

Globular cluster

System (GC or BH)
loses energy

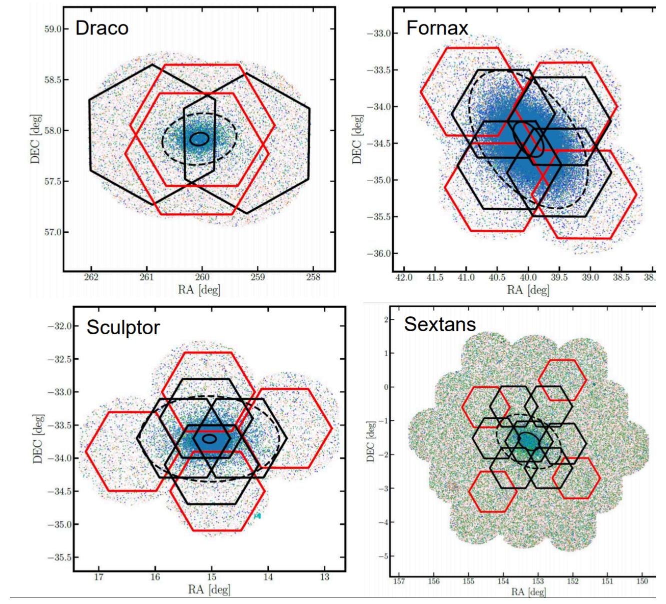
Observational implications and constraints



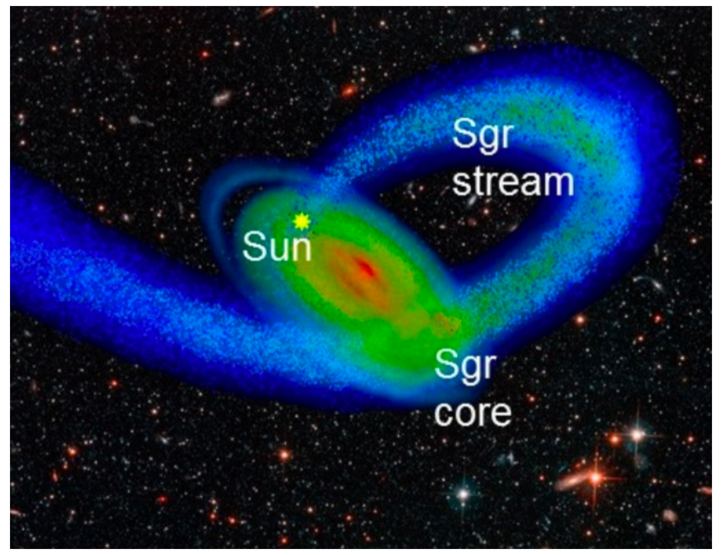
Galaxies

NASA and ESA

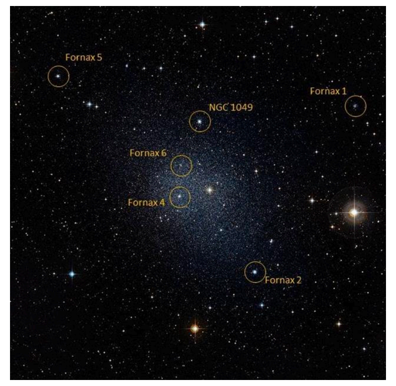
Dwarfs



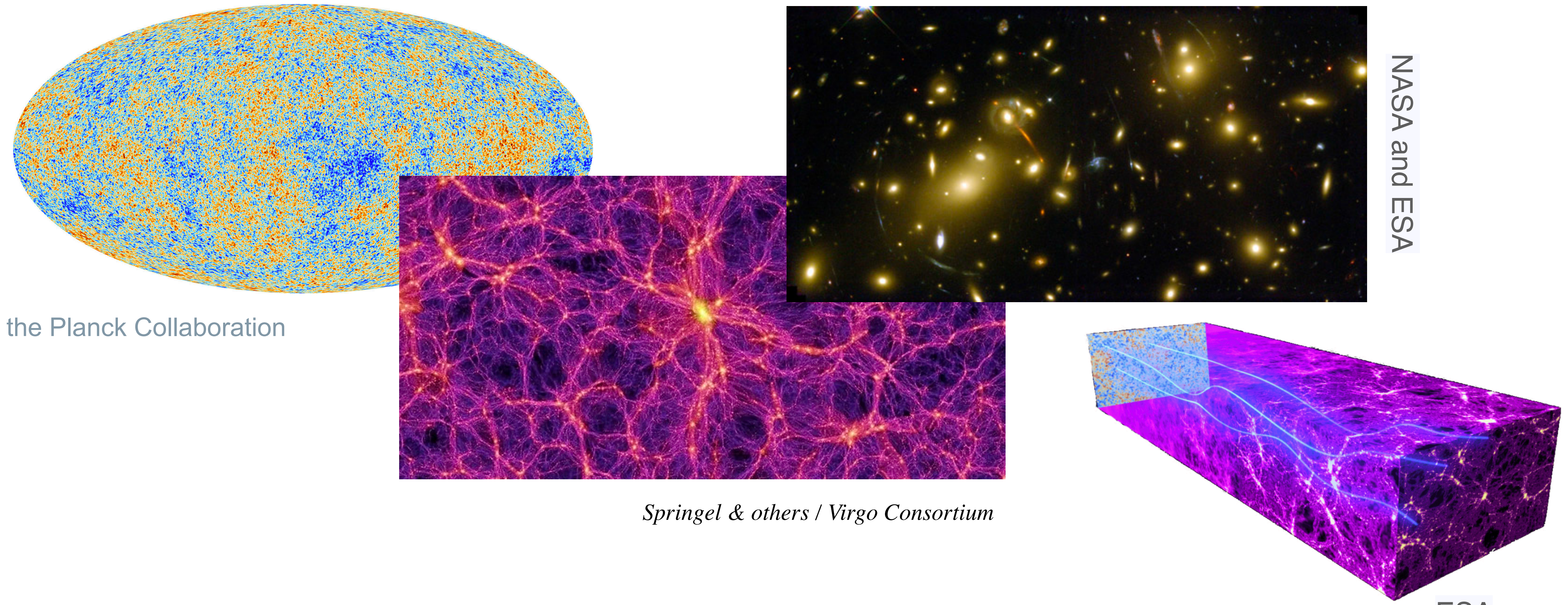
Stellar stream



Globular clusters



CMB+LSS



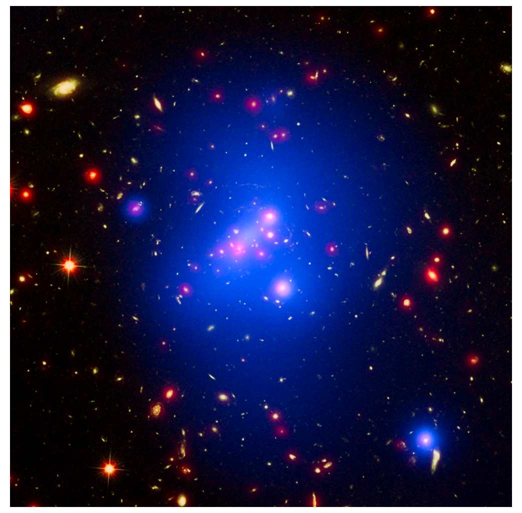
ESA and the Planck Collaboration

Springel & others / Virgo Consortium

NASA and ESA

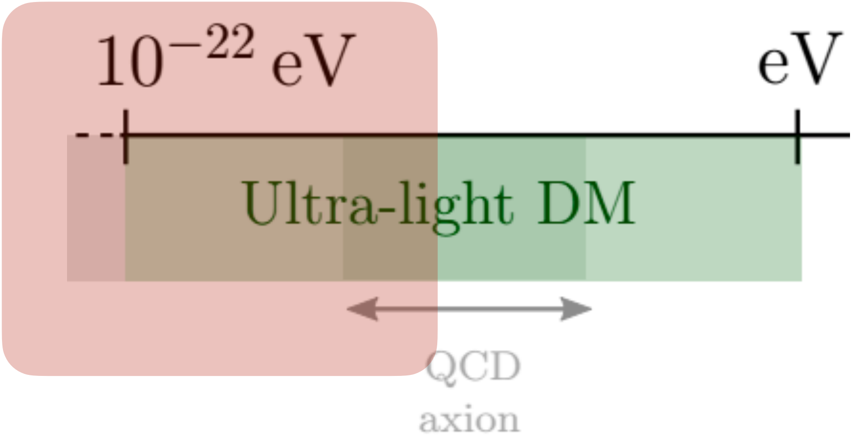
ESA

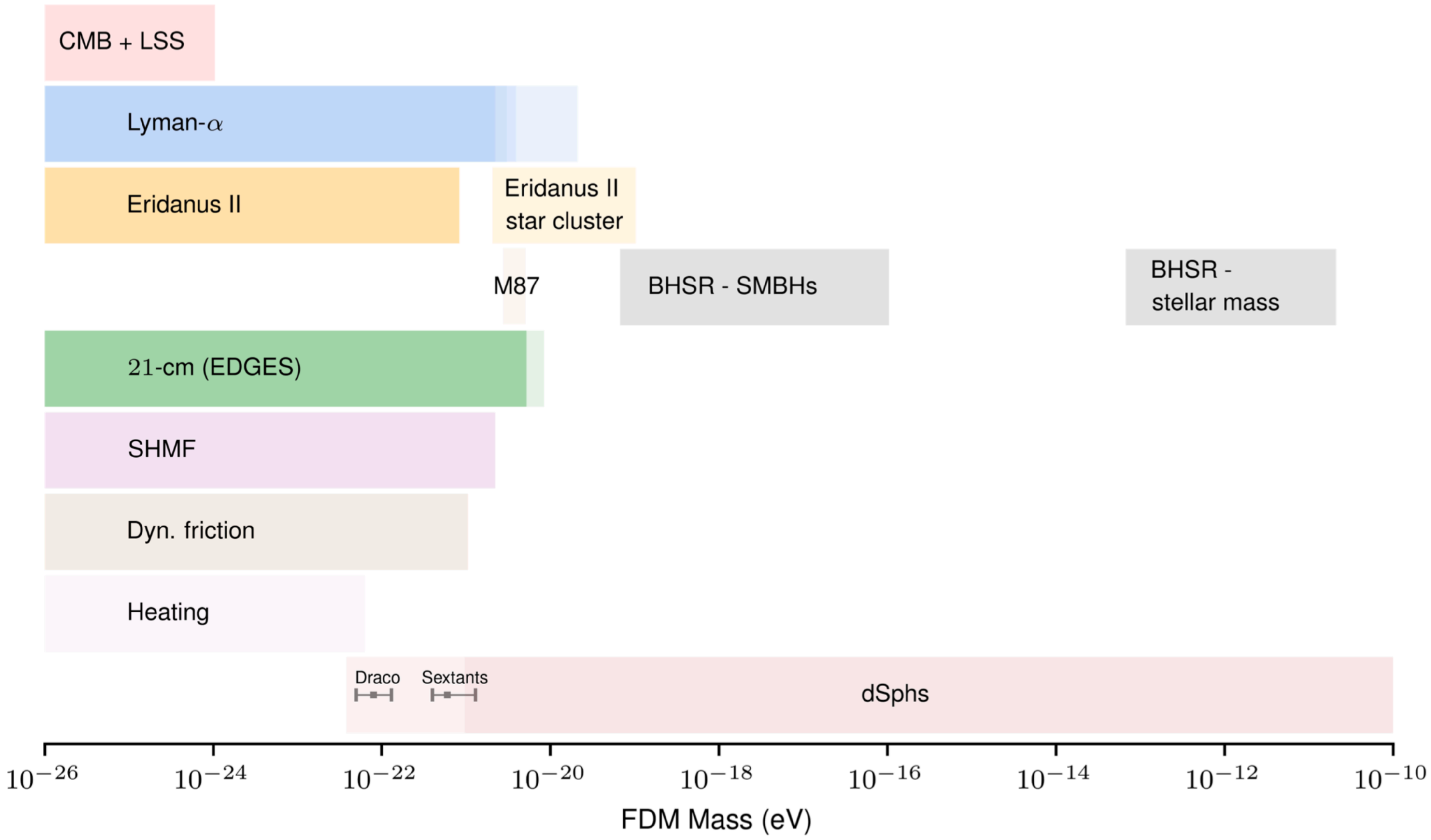
Clusters



Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

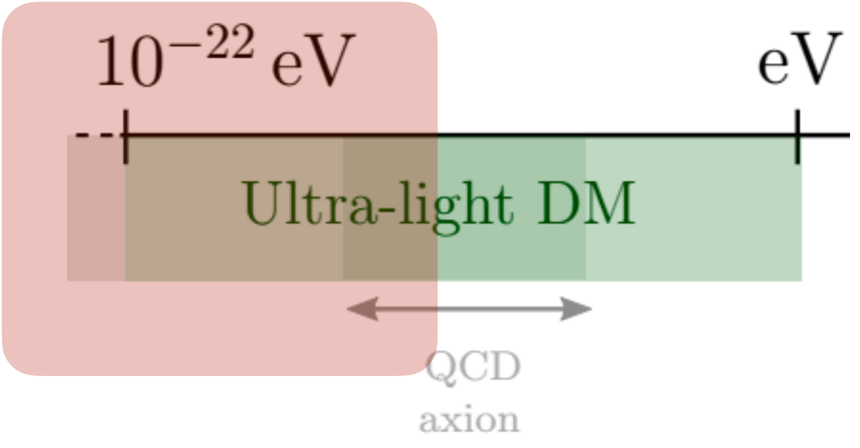


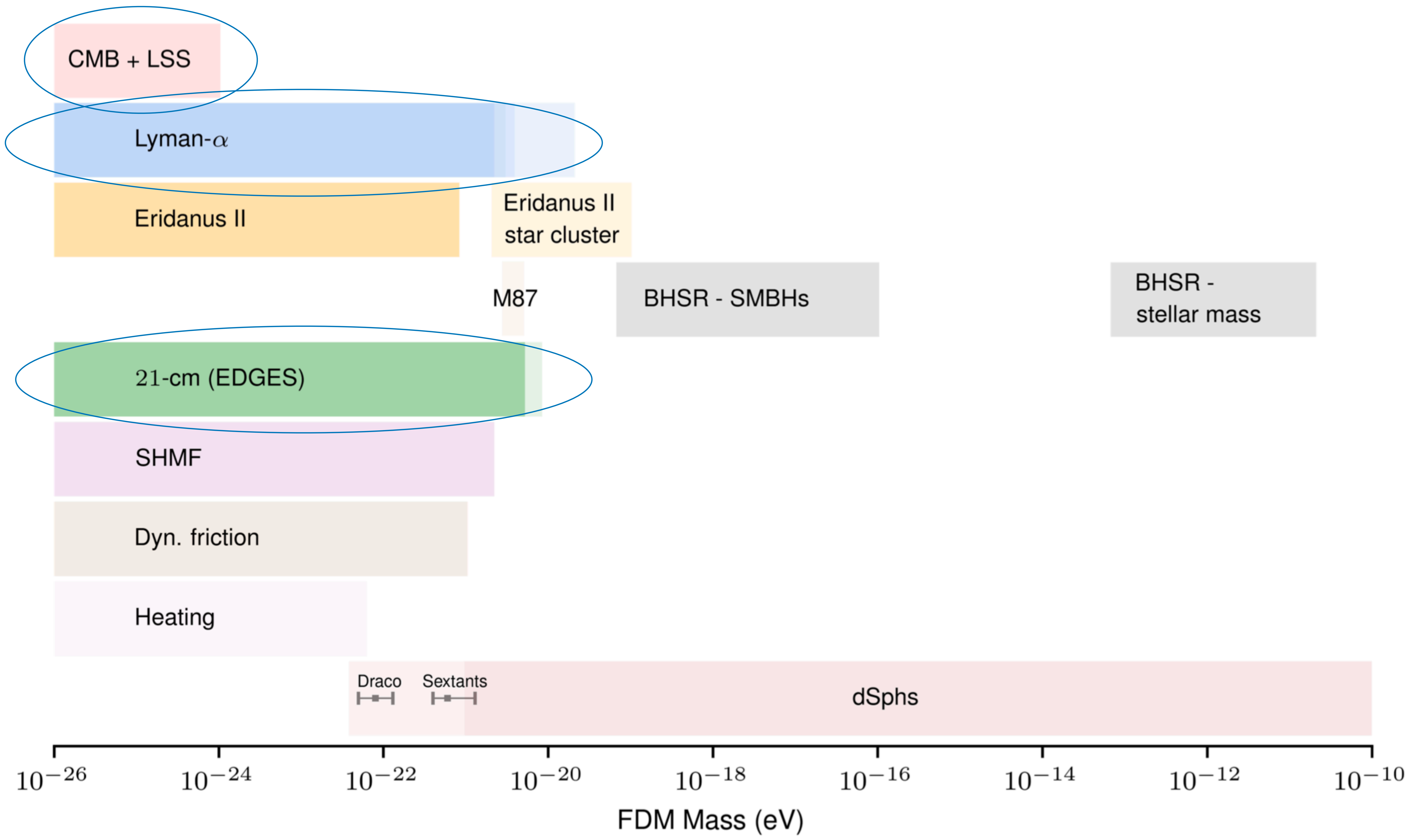


"Ultra-light dark matter", **E.F.**, 2020. The Astronomy and Astrophysics Review.

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

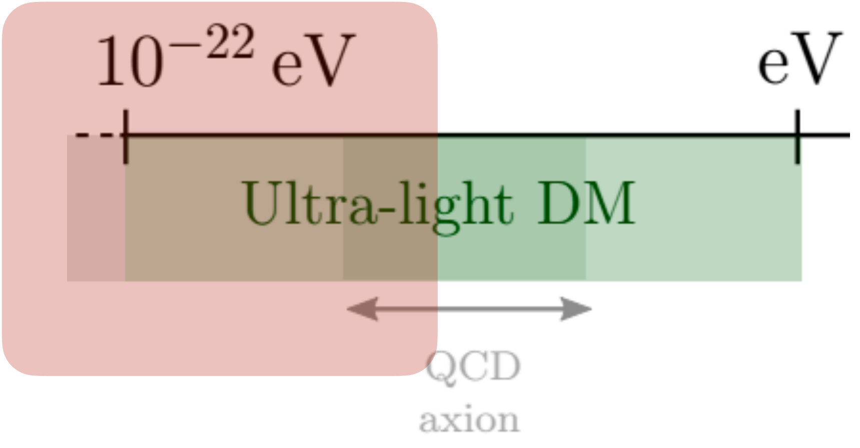




"Ultra-light dark matter", **E.F.**, 2020

Observational implications and constraints

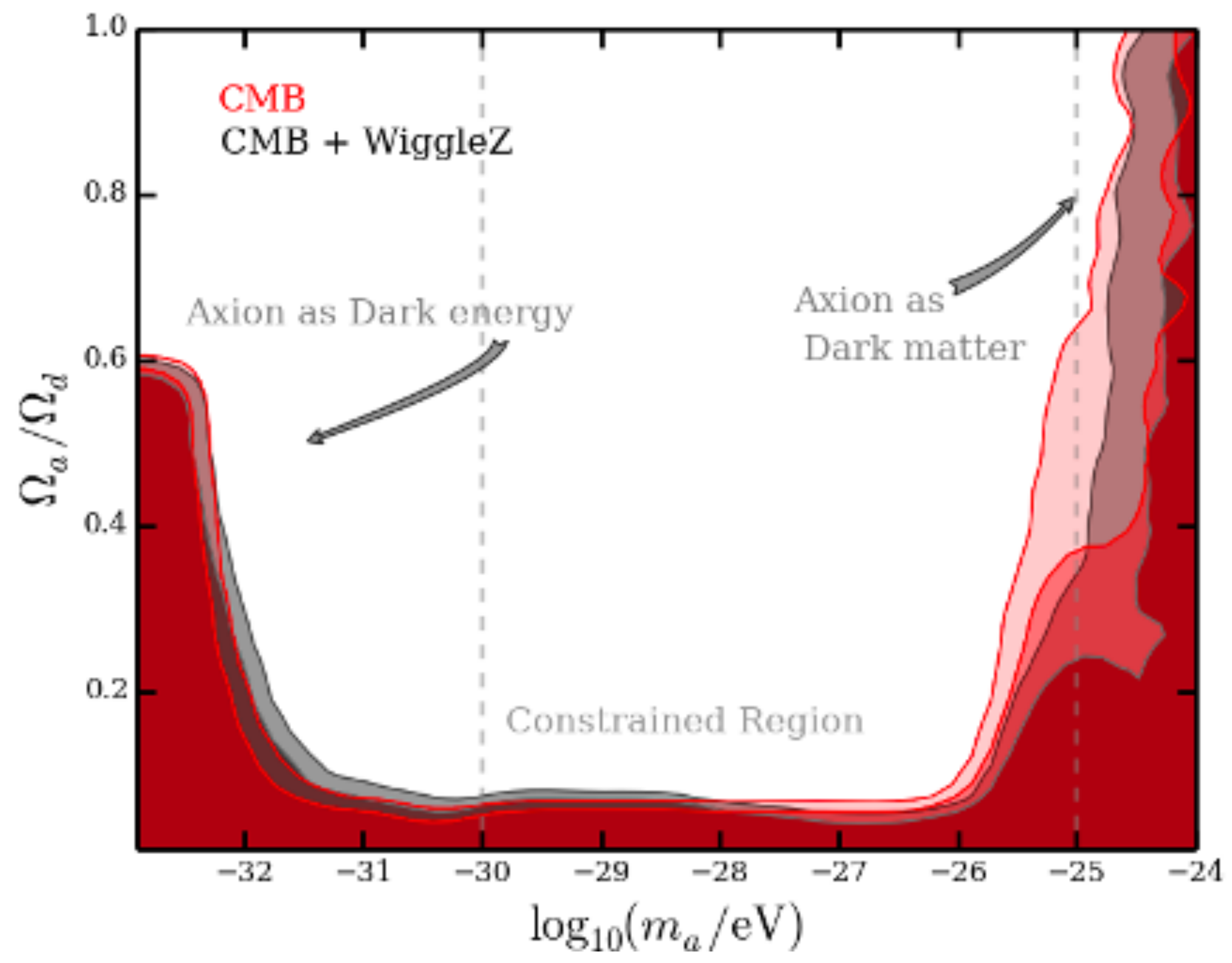
Fuzzy Dark Matter - bounds on the mass



Suppression of small structures

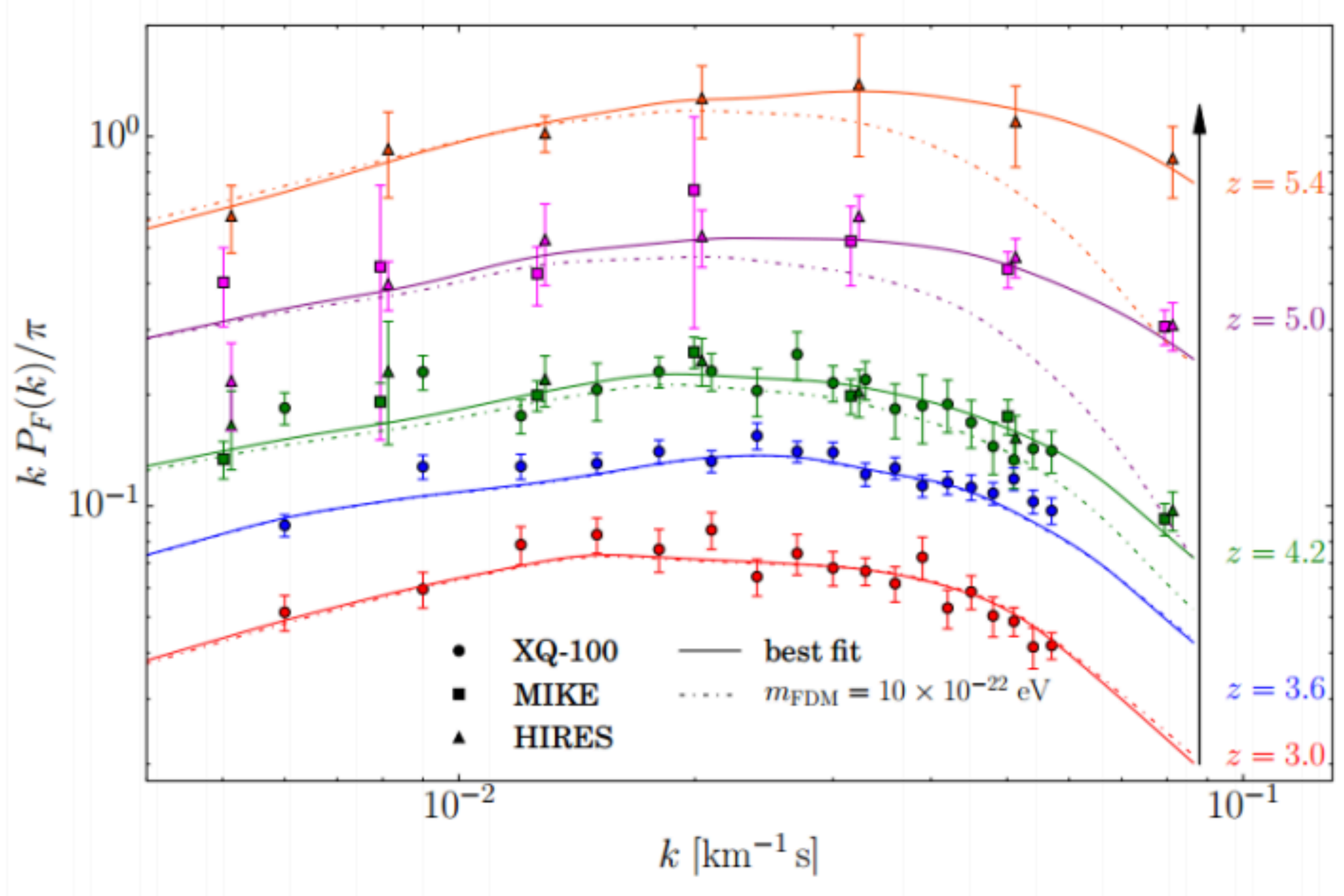
CMB/LSS	Lyman alpha	Global 21 cm

Hlozek et al, (2015, 2018)



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

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



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

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

Suppressed small scale structure

↓

Postpone Ly-α coupling, heating, reionization H

↓

Smaller 21-cm global signal

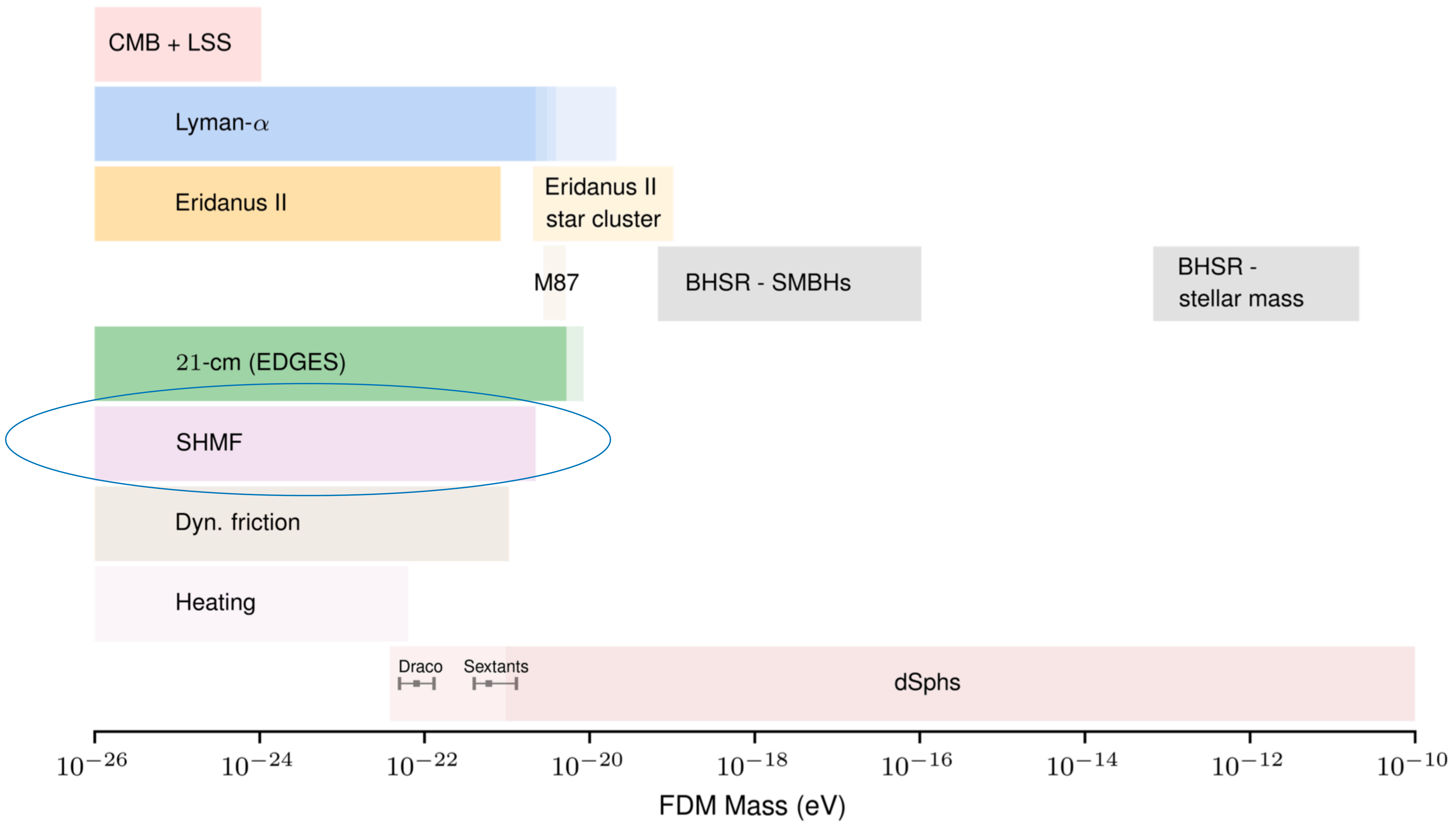
$m \gtrsim 6 \times 10^{-22}$ eV

EDGES global 21 cm signal

Olof Nebrin et al.(2019)

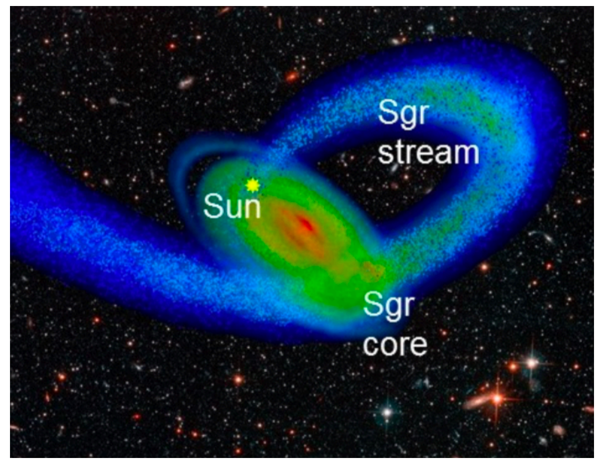
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



Suppression of small structures

Stellar streams



- DM properties encoded in variations density in stellar streams
- Opportunity to probe nature of DM
- GD-1 : compatible with CDM

Ibata et al. (2020): at this stage, hard to disentangle DM signal.

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

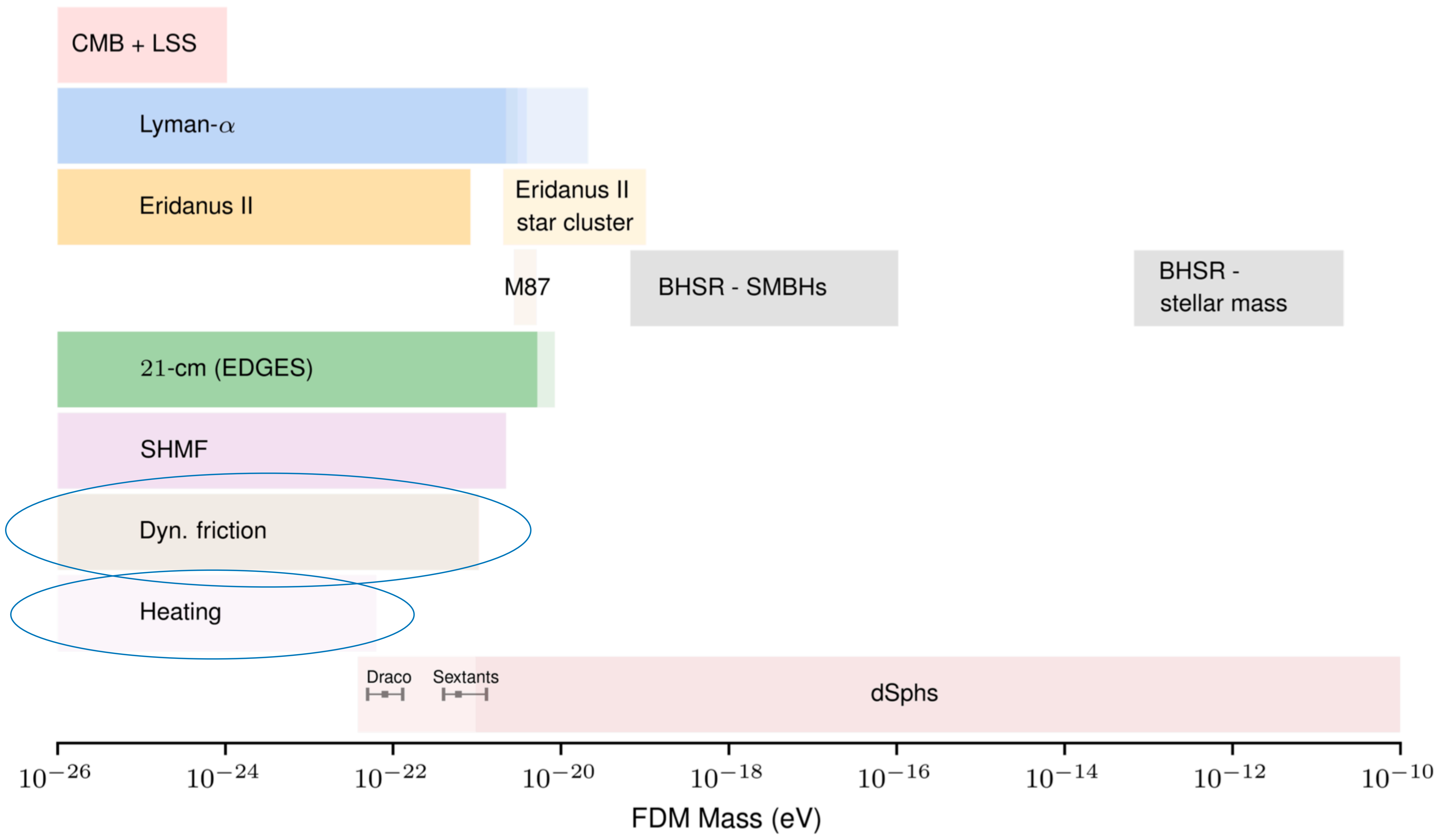
Future: PFS, LSST

Grav. lensing

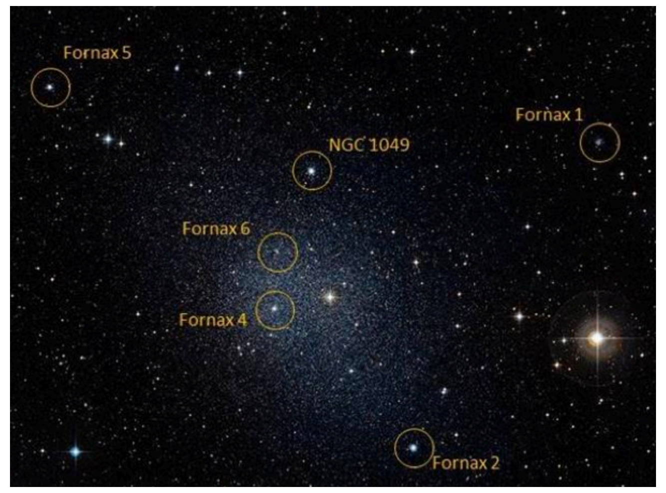
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

Dynamical effects



ESO/Digitized Sky Survey 2



Globular clusters

Fornax: globular clusters should have merged with Fornax due to dynamical friction.

Can explain these glob. Clusters

Lancaster et al. 2020

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

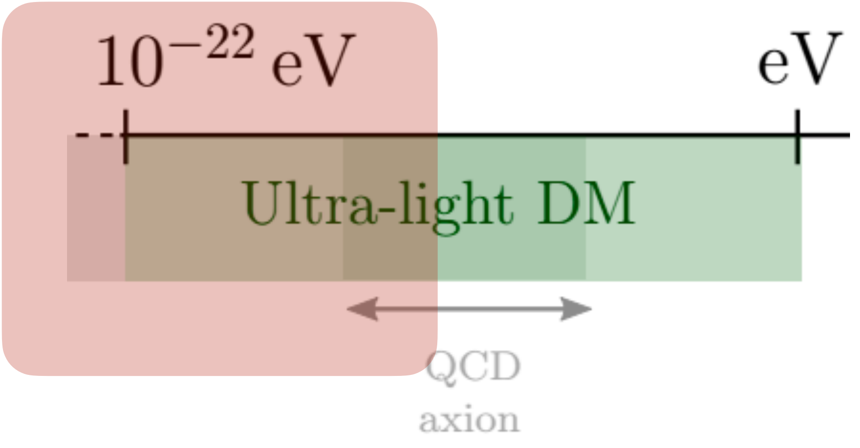
Heating of the MW disk

Church et al. 2019

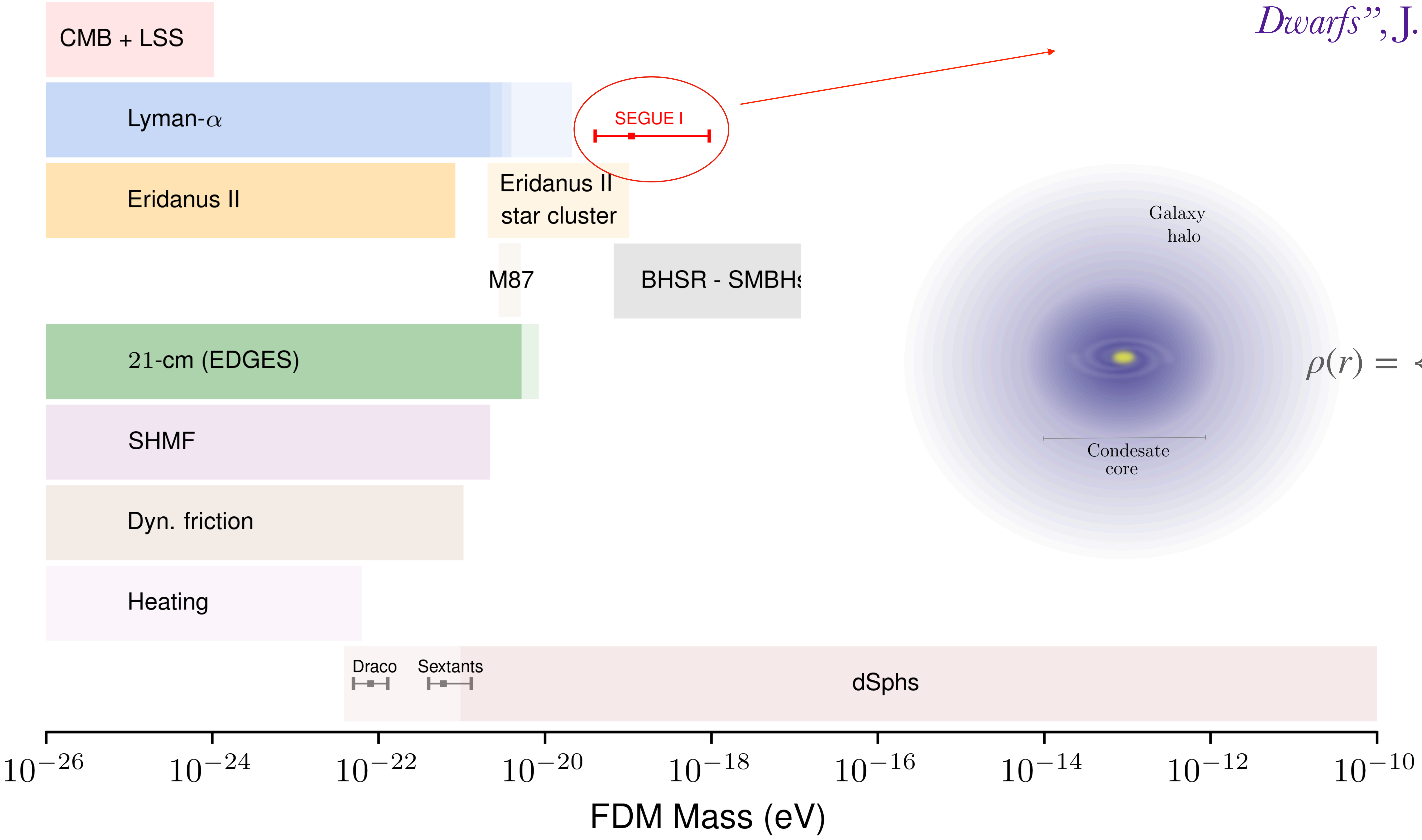
$$m > 0.6 \times 10^{-22}\,\mathrm{eV}$$

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



Presence of a core



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

FDM SIMULATIONS

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

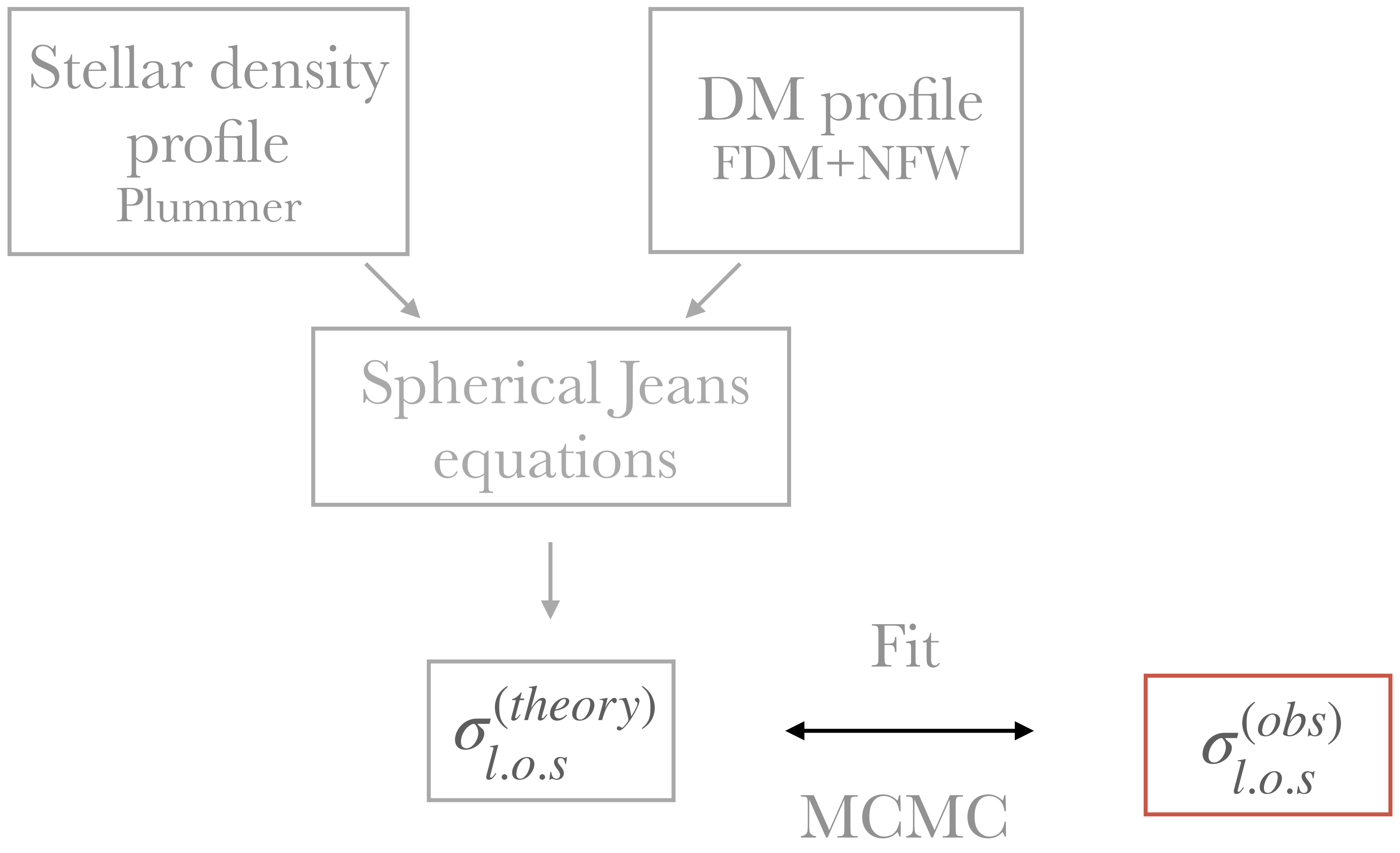
Ultra-light Dark Matter

FDM mass from Ultra-faint dwarfs

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

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

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



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

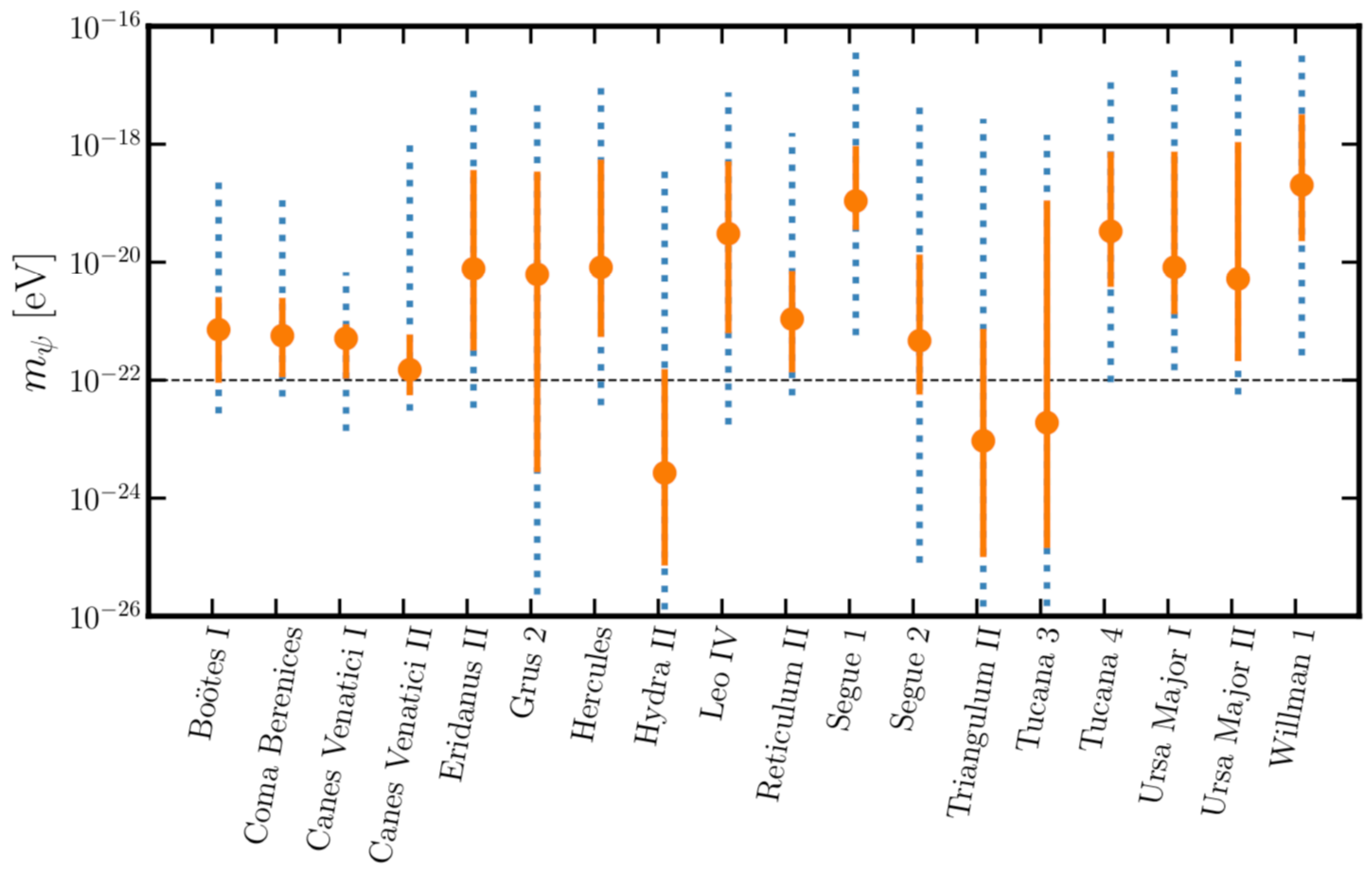
Velocity anisotropy

FDM SIMULATIONS

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

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

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

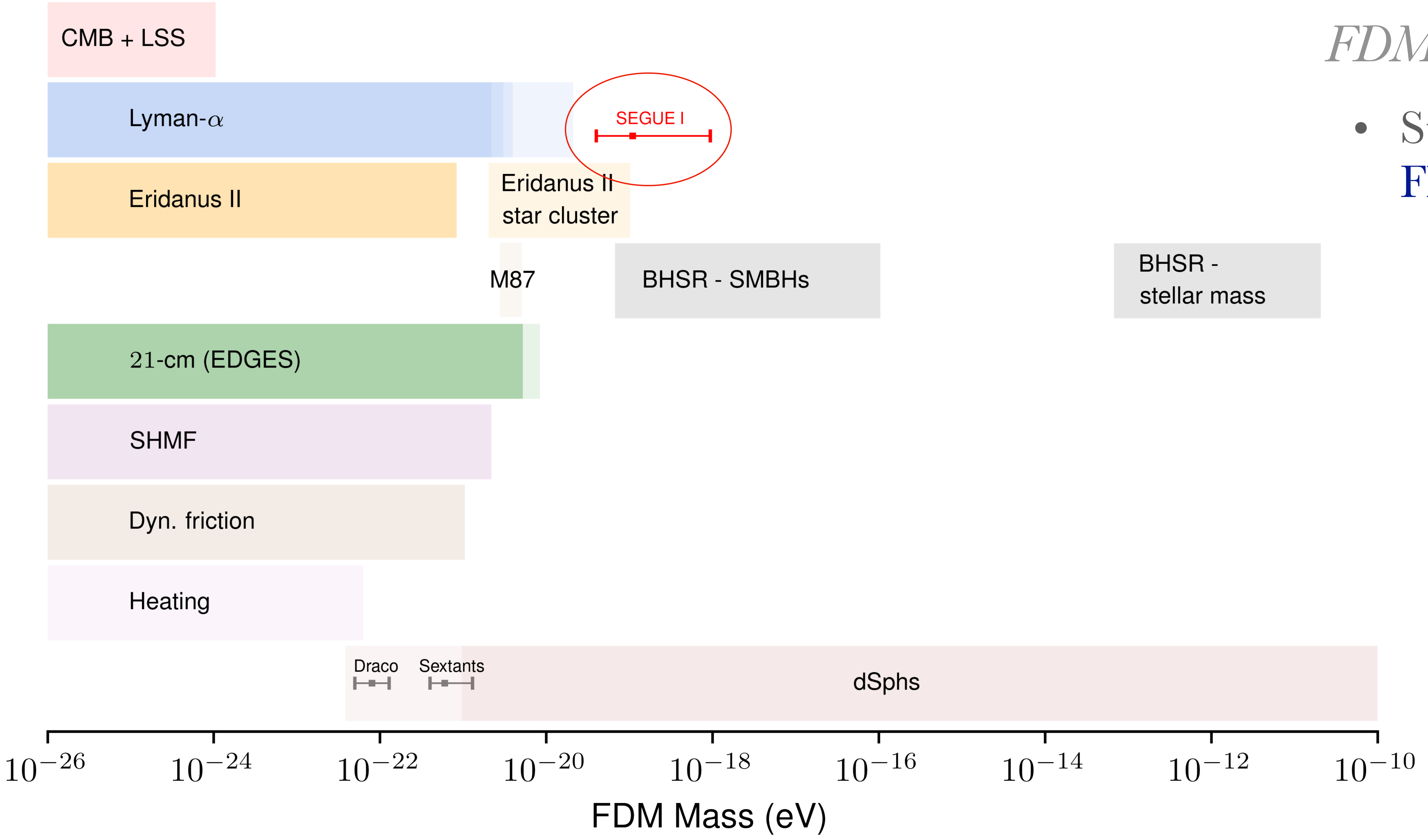


Strongest constraint on $m_{\rm FDM}$ to date!

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass

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

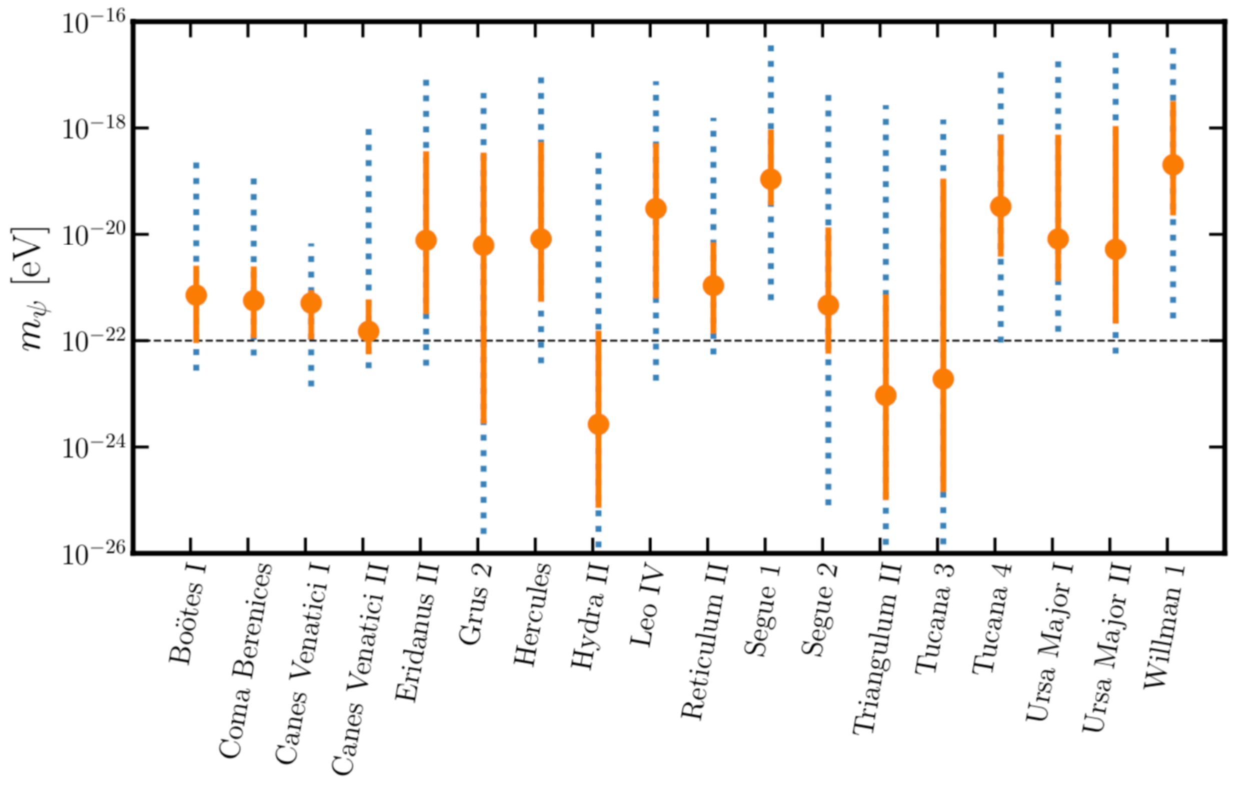


FDM mass from Ultra-faint dwarfs

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

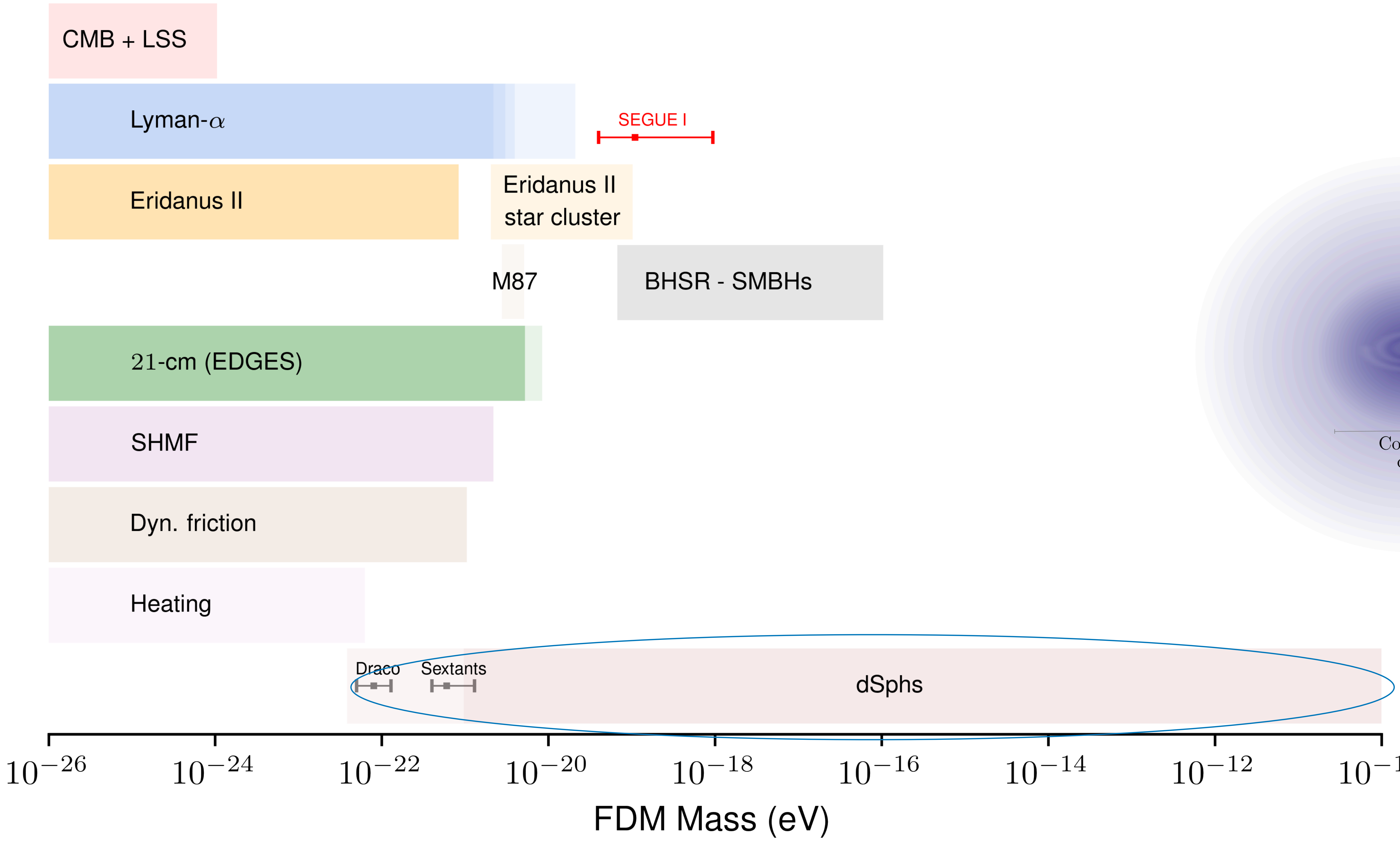
$$m_{\rm FDM}^{(Seg1)} = 1.1^{+8.3}_{-0.7} \times 10^{-19}\,\text{eV}$$

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



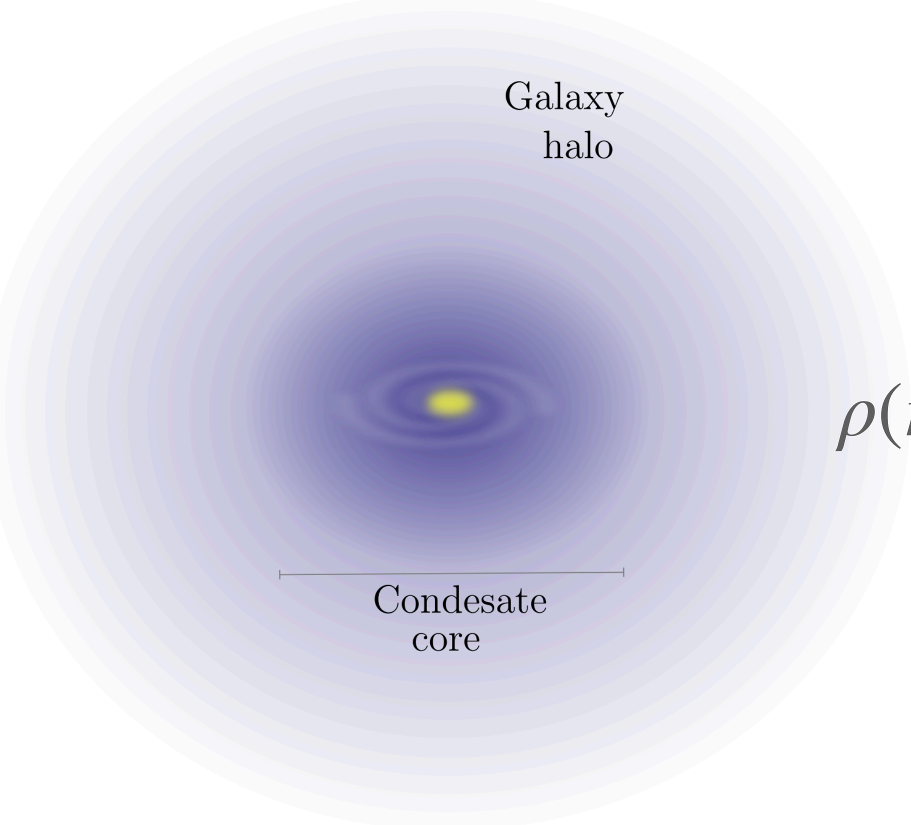
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



DWARFS

Dwarf Spheroidals (dSphs)



FDM SIMULATIONS

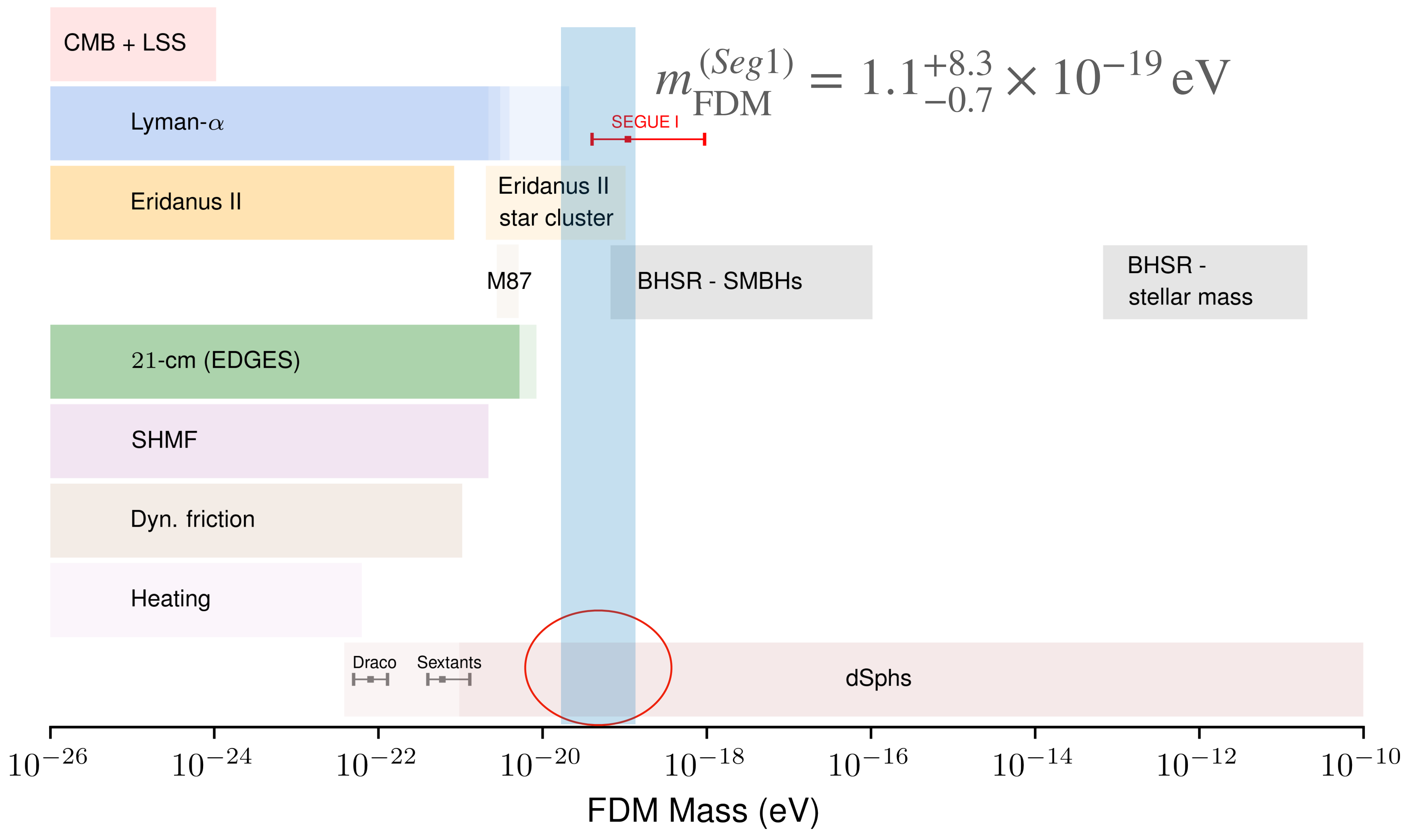
$$\rho(r) = \begin{cases} \rho_{\text{soliton}} \simeq \dfrac{\rho_c}{\left[1 + 0.091(r/r_c)^2\right]^8}, & r < r_\epsilon \\ \rho_{\text{NFW}} = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, & r > r_\epsilon \end{cases}$$

Fornax - Sculptor

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

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

Constraints on the mass



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. $\neq$ relation in $\neq$ simulations
- *Challenge for the FDM model*

Safarzadeh and Spergel 2019; Hayashi, EF, Chan 2021

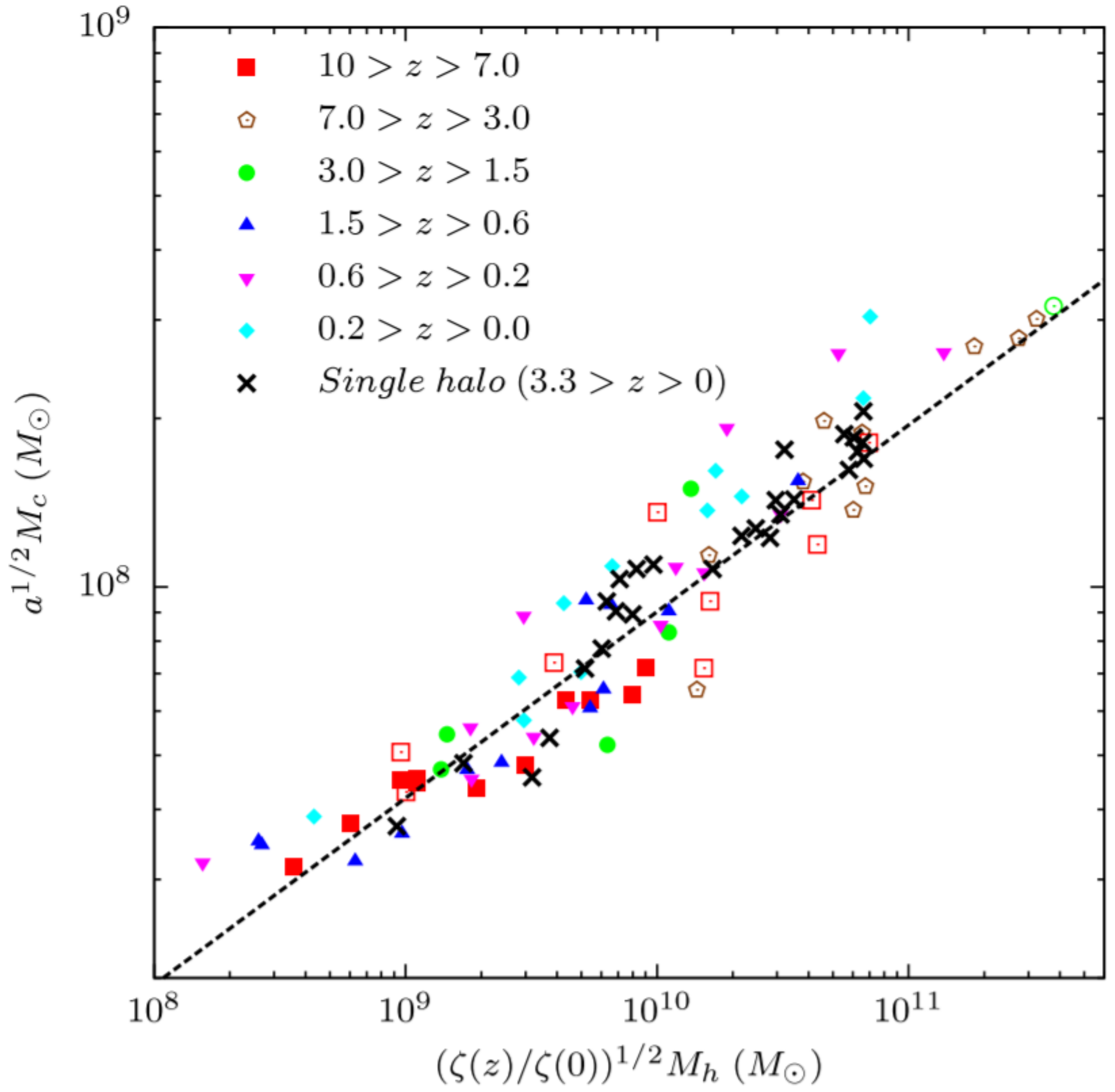
FDM - *Core-halo mass relation*

Ongoing

We want to study how the core relates to the halo mass

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

$\xrightarrow{?}$ M_h



Schive et al. 2014

Schive et al 2014

$$M_c \propto M_h^{1/3}$$

Velocity dispersion tracing

$$\sigma_c \sim \sigma_h$$

Mocz et al 2017

$$M_c \propto M_h^{5/9}$$

Energy tracing

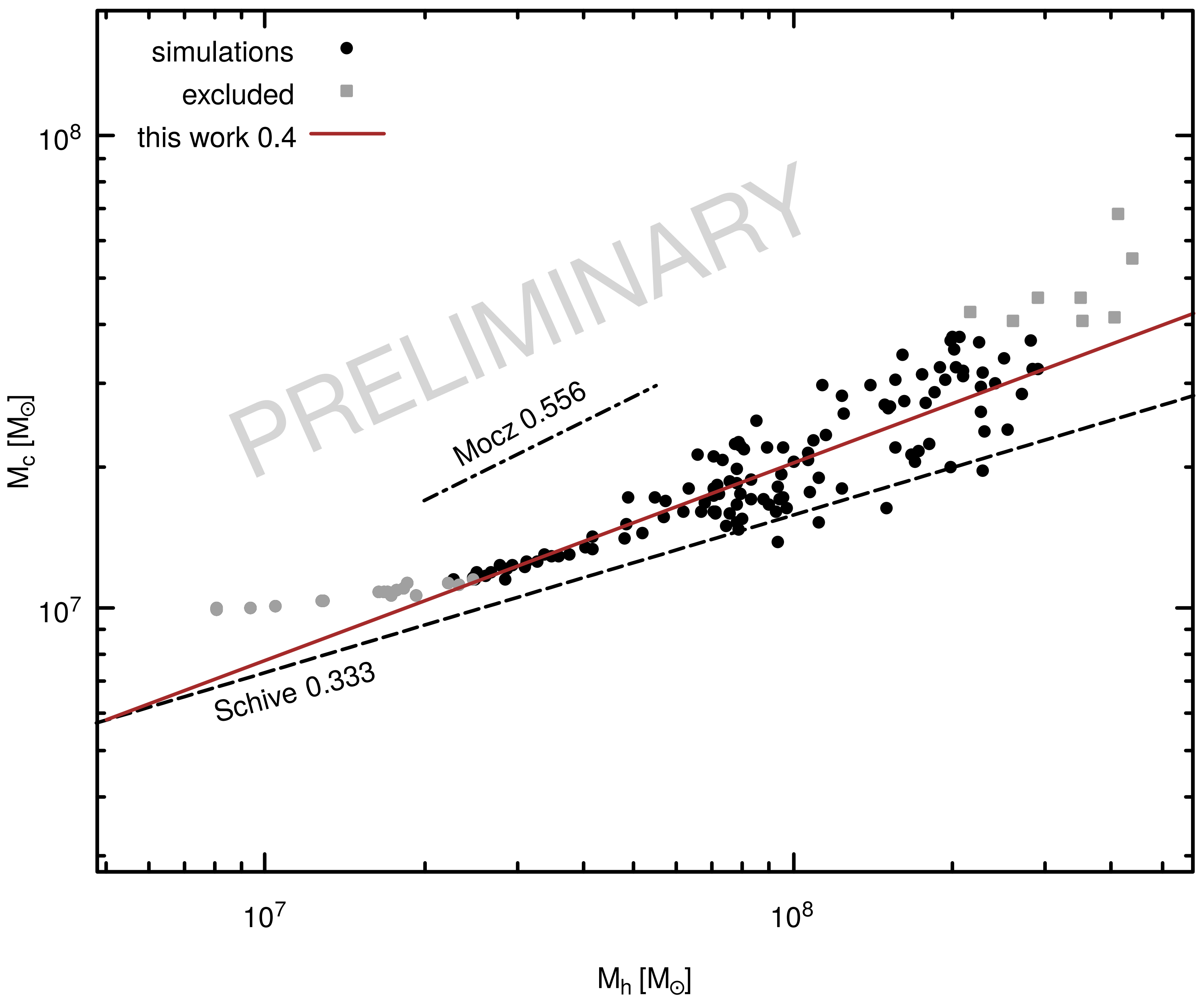
$$M_c\,\sigma_c^2 \sim M_h\,\sigma_h^2$$

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

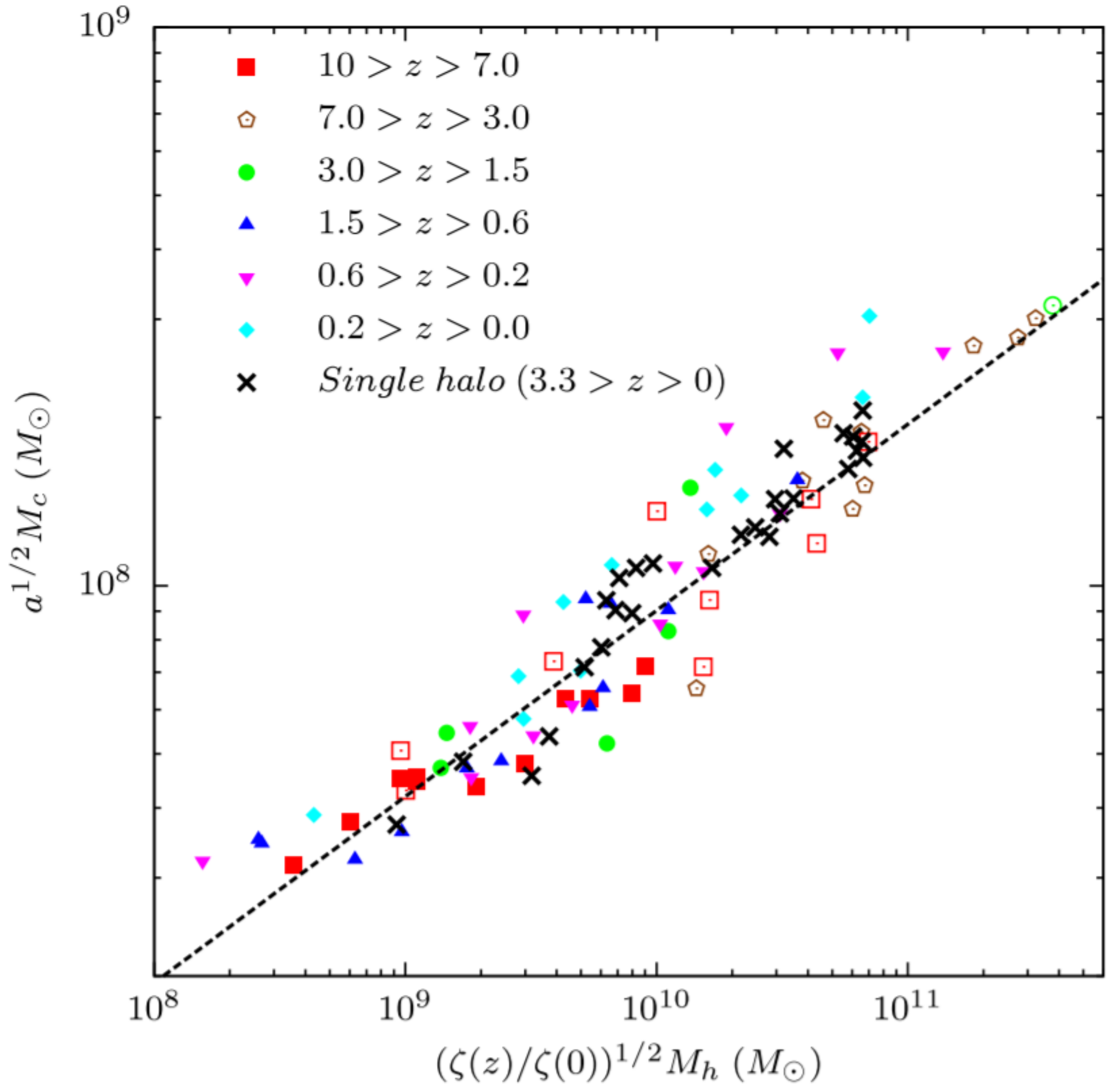
= Schive (Velmatt et al 2018)   ≠ Schive (Nori et al 2020, Nima et al 2020)

FDM - Core-halo mass relation

Ongoing



Schive et al. 2014



UFD → dSphs

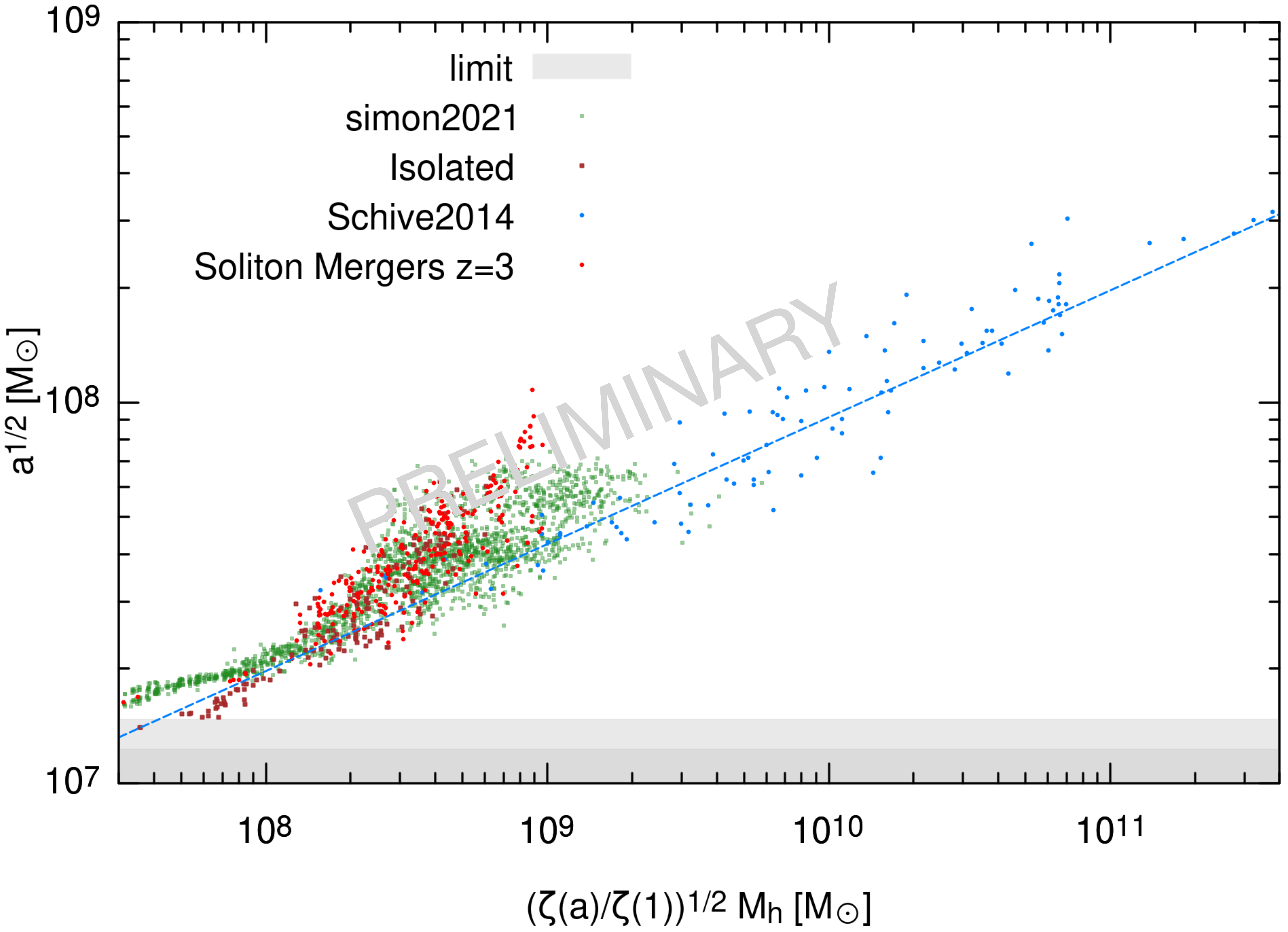
Can change the inferred FDM mass!

Steeper slope → Smaller core → Smaller mass (?)

FDM - Core-halo mass relation

Ongoing

In collaboration with Jowett Chan

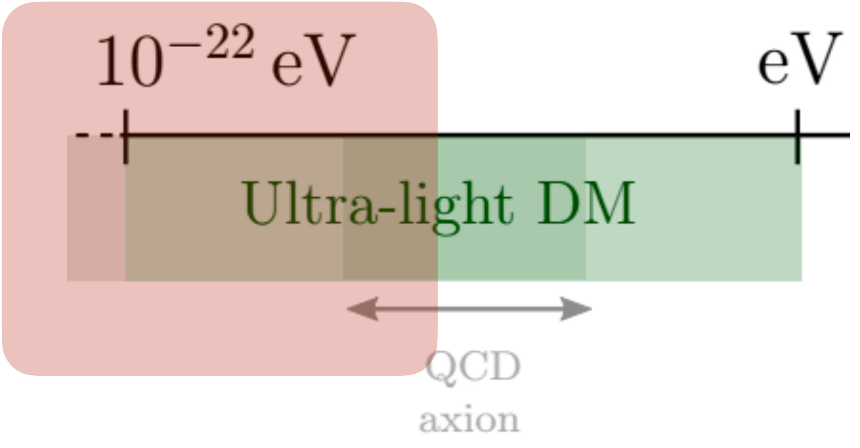


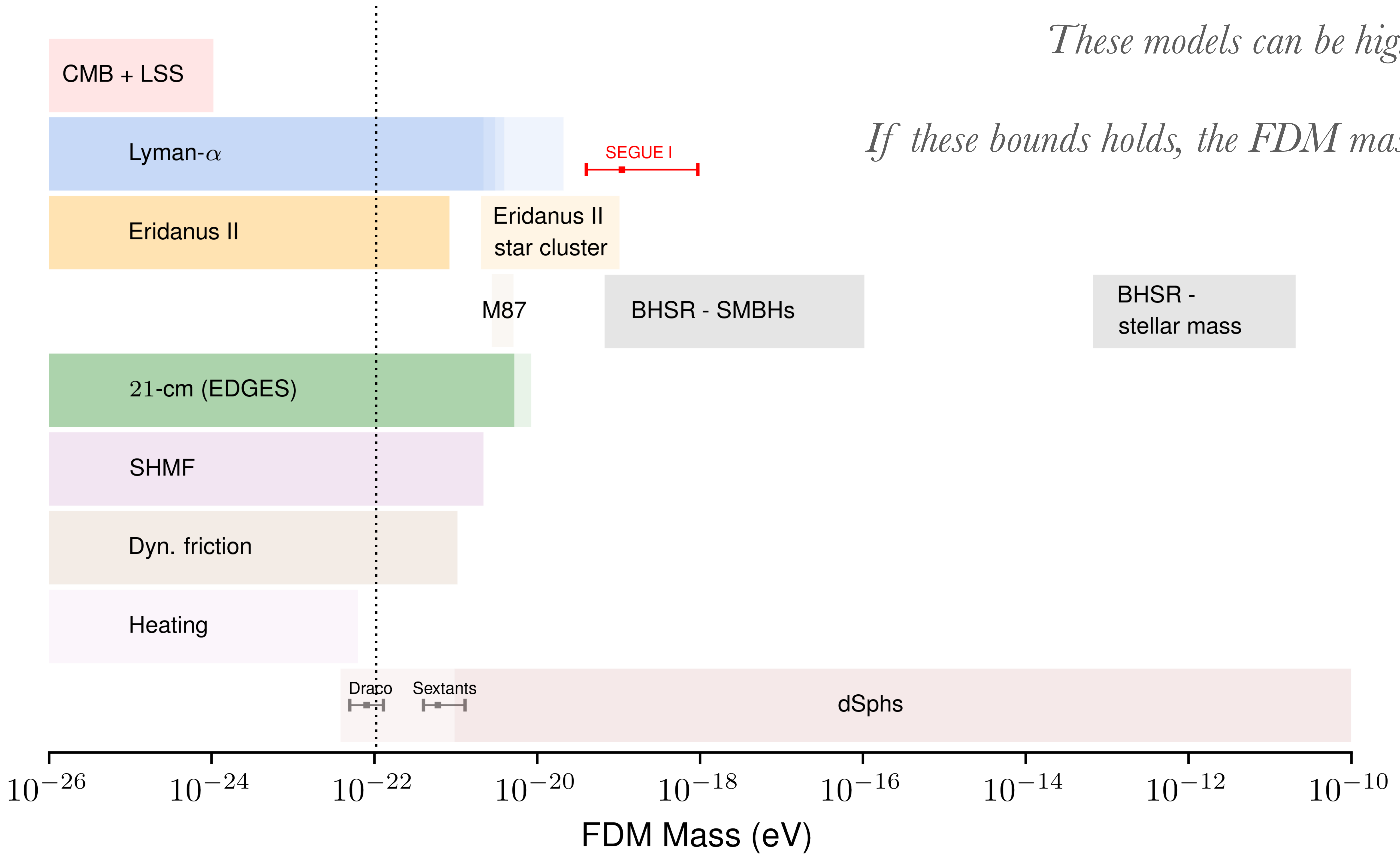
Schive et al: $M_c \propto M_h^{1/3}$

Mocz: steeper

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass





These models can be highly constrained

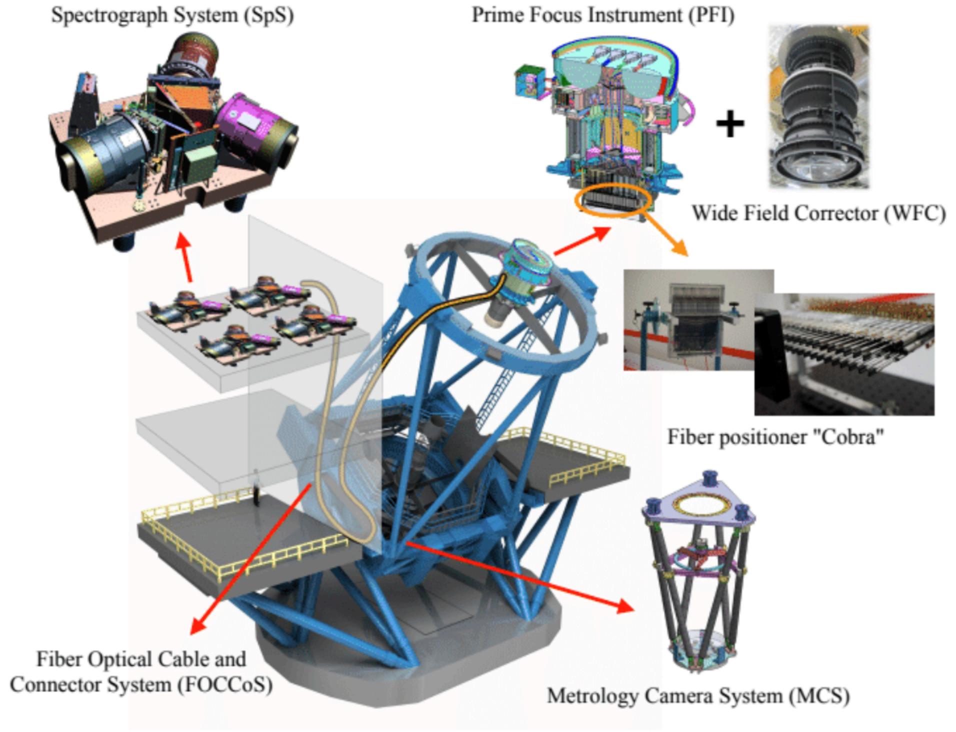
If these bounds holds, the FDM mass range is narrowing down

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

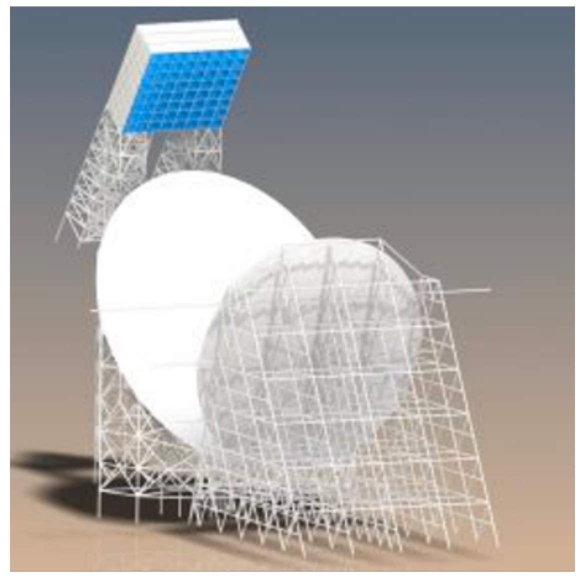
Future

Observations

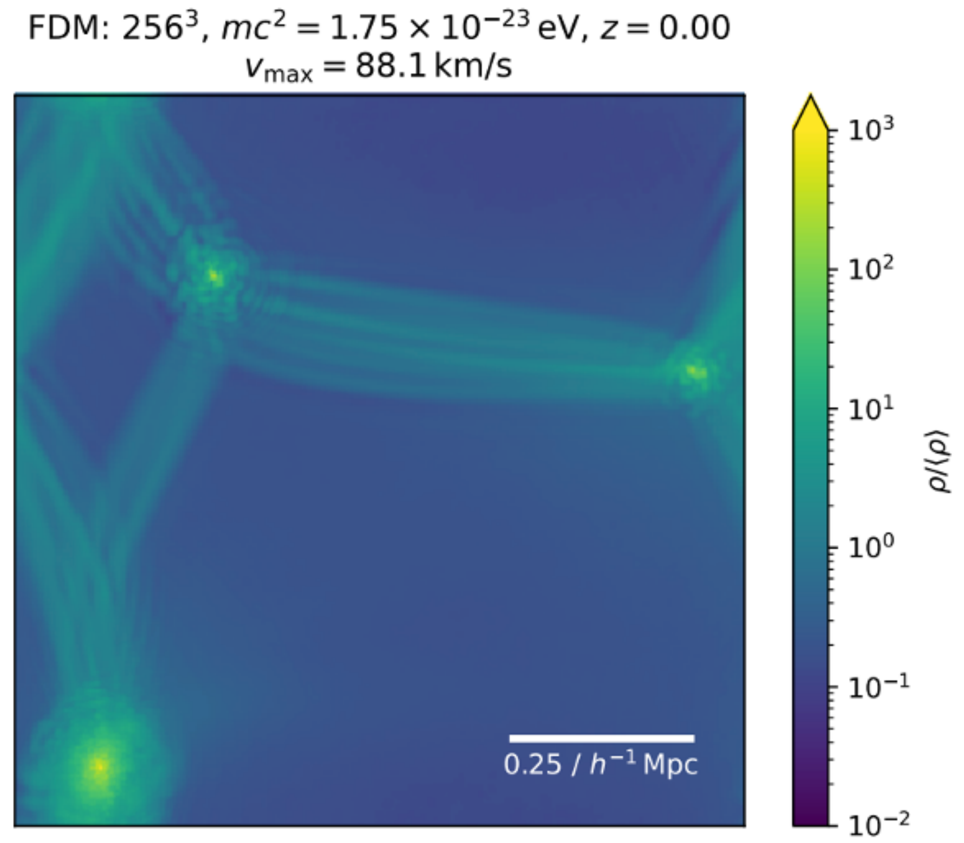
Prime Focus Specctrograph (PFS)



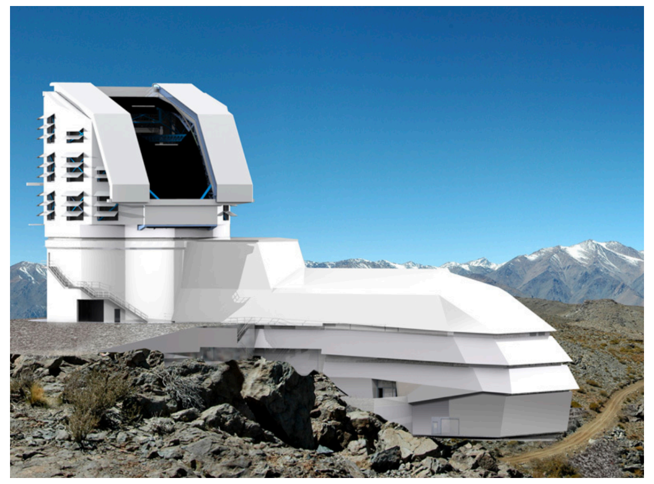
BINGO telescope



Simulations



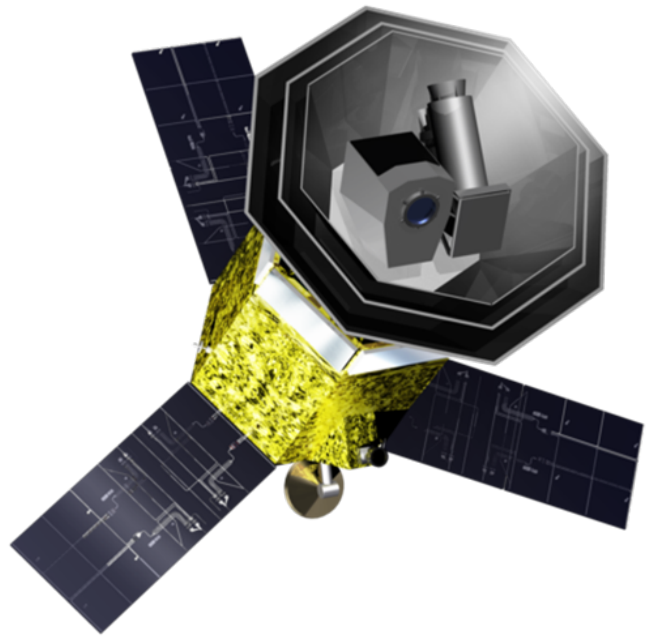
Vera Rubin observatory (LSST)



CMB-S4

CMB-S4
Next Generation CMB Experiment

LiteBIRD



New probes

PFS (Prime Focus Spectrograph)

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

GOAL

PFS: spectroscopy part of *SuMIRe project*

DM with PFS ⟶ *synergy between science goals*

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

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

PFS (Prime Focus Spectrograph)

Ongoing

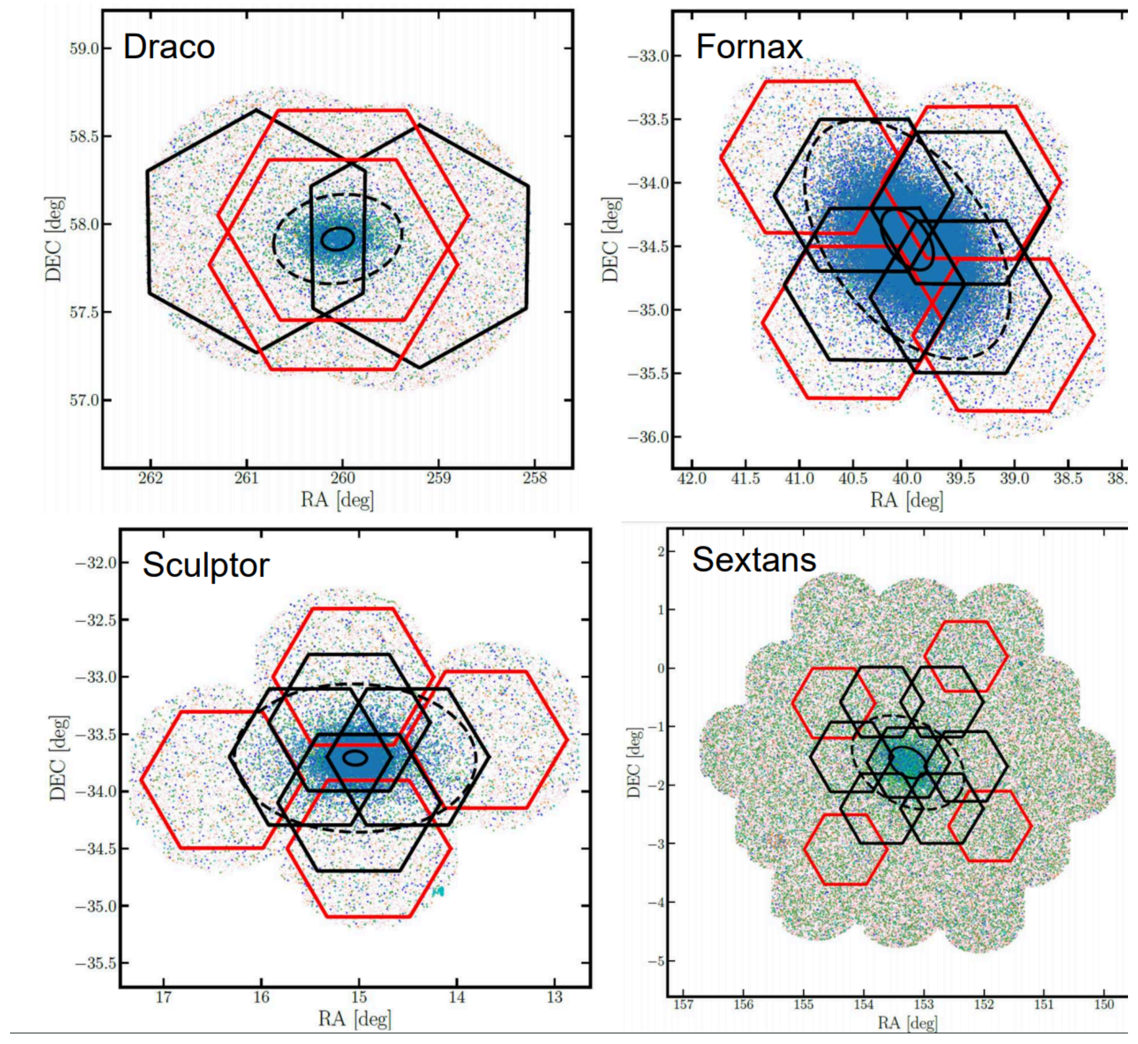
TESTING ULTRA LIGHT DM/DM with PFS

GOAL

Galaxy archeology

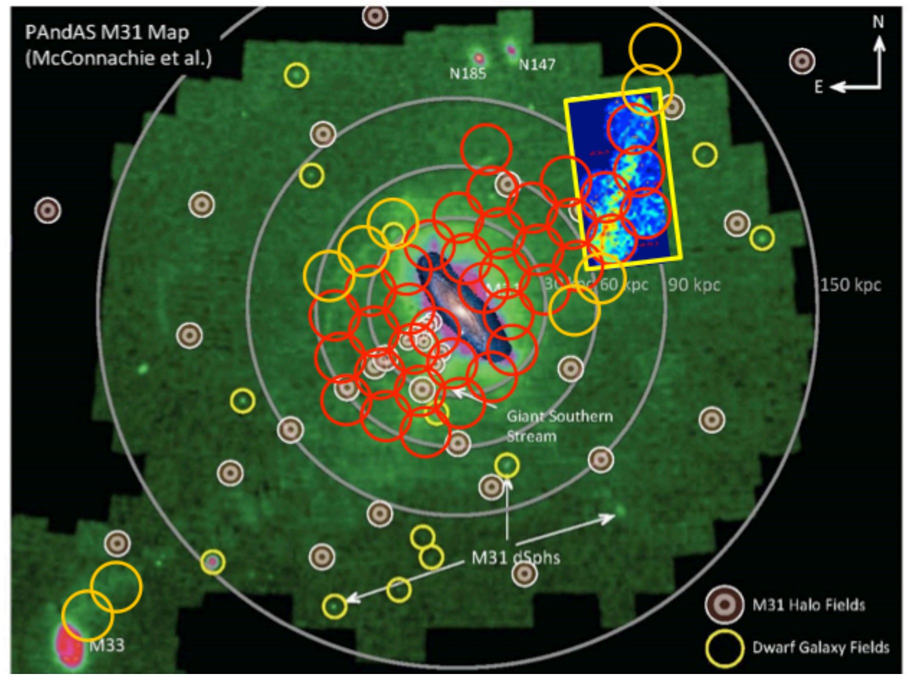
- Nature of DM (dSphs)
- Structure of MW dark halo
- Streams
- Stellar kinematics and chemical abundances – MW & M31

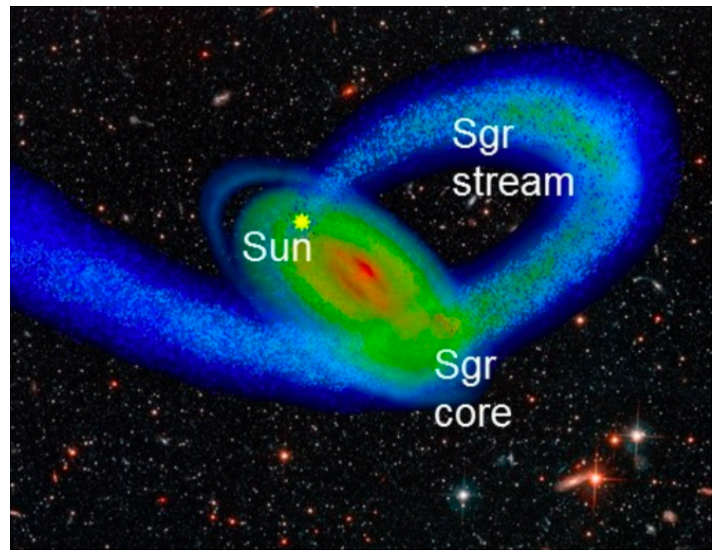
Wide & deep survey of MW dwarf galaxies w. Subaru/PFS



dSphs

M31





MW outer disk

- MW dwarf satellites - DM halo profile and [Fe/H] & [α/Fe] over largest areas ⟶ Unique & high impact
- M31 halo - DM subhalos, chemo-dynamics with spectroscopic [Fe/H] and [α/Fe]
- MW halo/streams/disks - Chemo-dynamics of the MW outer disks, halo dynamics, constraints on the Galactic potential ⟶ Unique: beyond reach of *Gaia* and VLT

GA ⟶ potential to put unprecedented constraints on ULDM. Potential for discovery!

PFS (Prime Focus Spectrograph)

GOAL

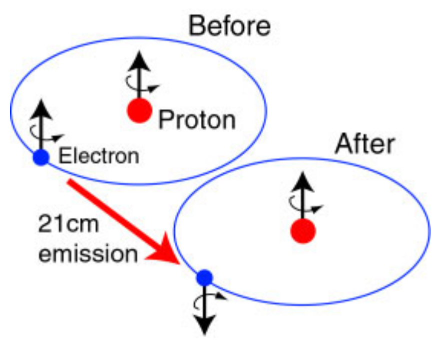
DM Science with PFS

DM with PFS ⟶ synergy between science goals

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

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

Use PFS GA, GE and cosmology to constrain the properties of DM.



21-cm

Future - BINGO *telescope*

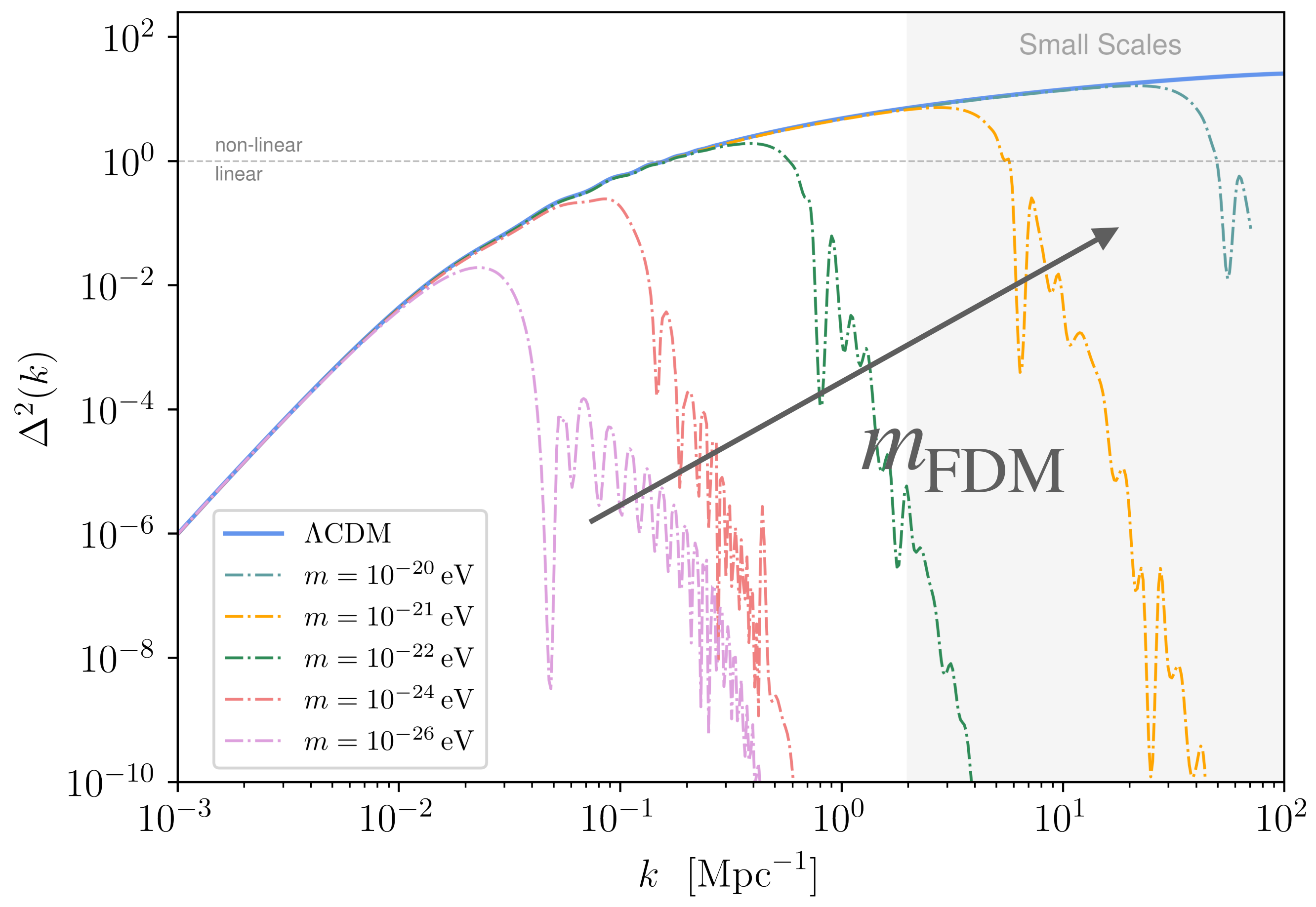
TESTING ULTRA LIGHT DM w/ 21-cm (BINGO)

Ongoing

Ultra-light DM (FDM) with 21-cm intensity mapping

- Intensity mapping (IM) - 3D tomographic map: great potential as a future cosmological probe
- Complementary to forest probes
- Capacity to probe power spectrum for *smaller scales*

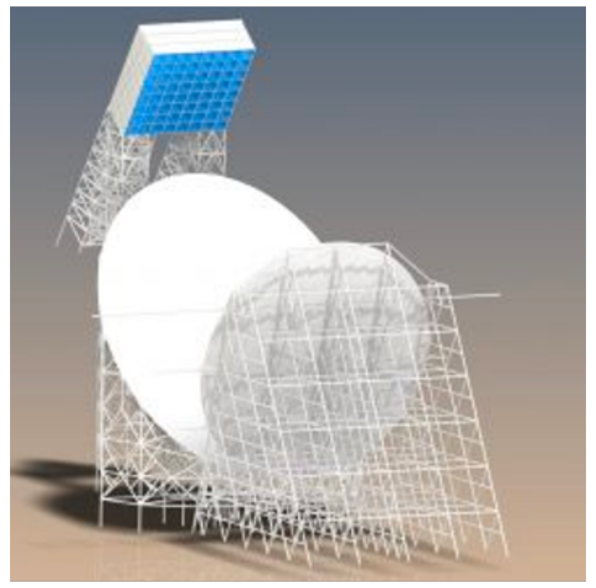
With 21-cm we can probe: m Ω_a/Ω_t



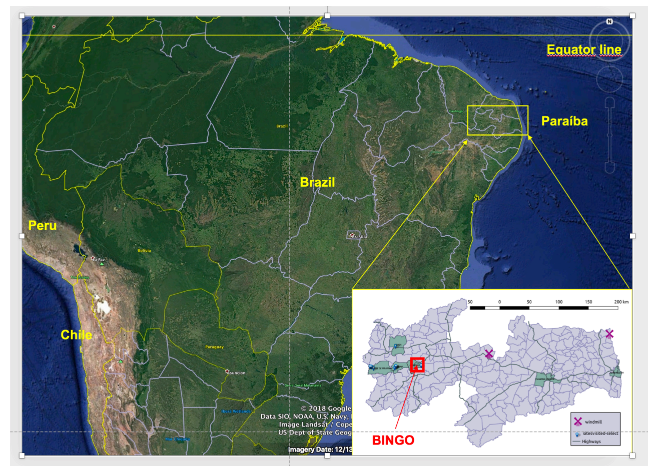
- Suppression of PS
- Increase in b_{HI}

BINGO (BAO In Neutral Gas Observations)

Intensity mapping - BAO



- Dish diameter: 40m
- Area : 15 x 200deg^2 – drift scan
- Frequency range: 960 - 1260MHz
- Redshift range: 0.12 - 0.48



- Main goals: DE, FRBs
- Constraints on DM

Observation start: end of 2022

FORECAST $\sigma(\Omega_a/\Omega_T)_{bingo} = 0.2$

Bauer et al 2020

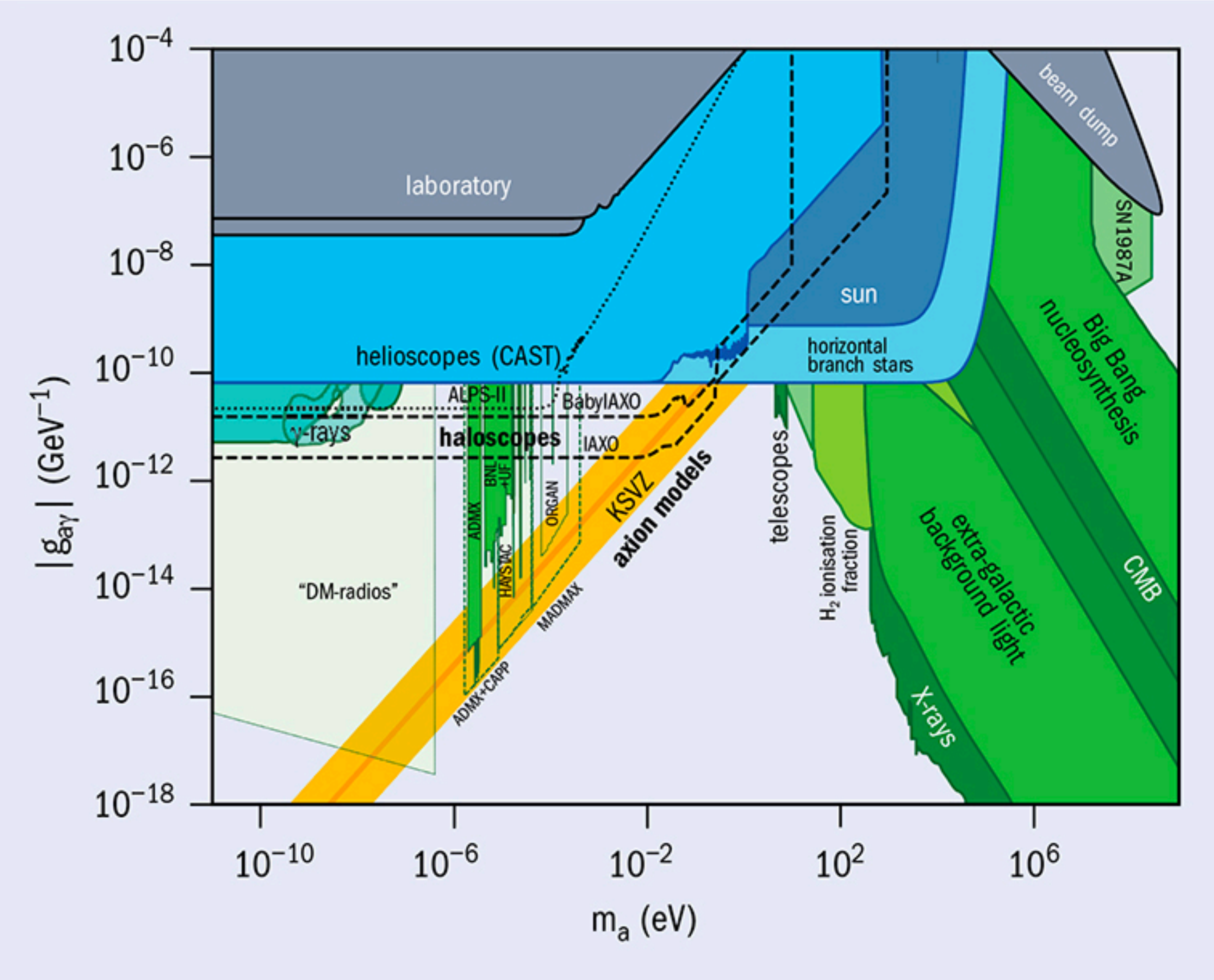
Carucci et al 2018

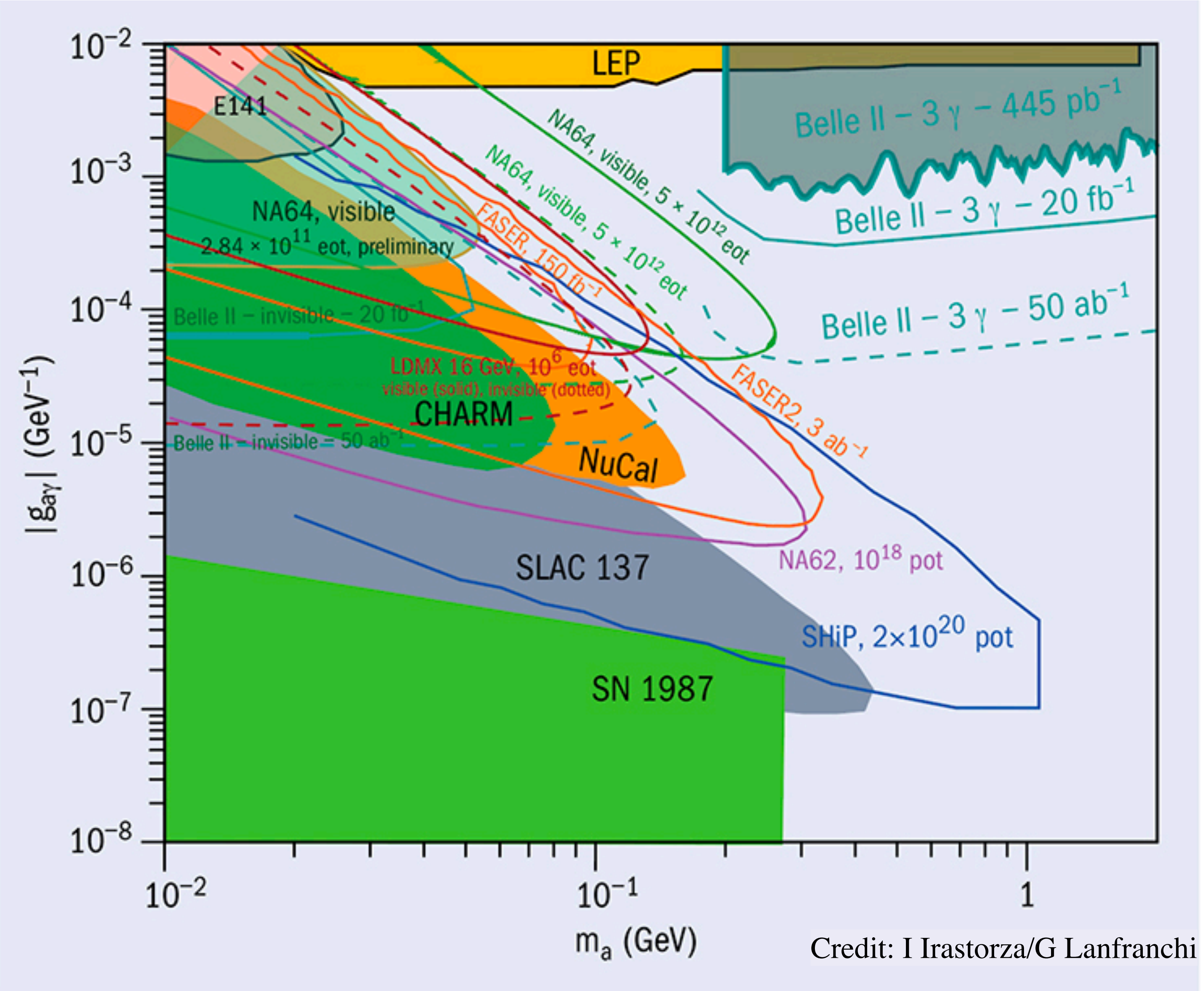
"The BINGO project I", Abdalla, **E.F.**, et al, 2021

+*The BINGO project II - VII, including E.F.*

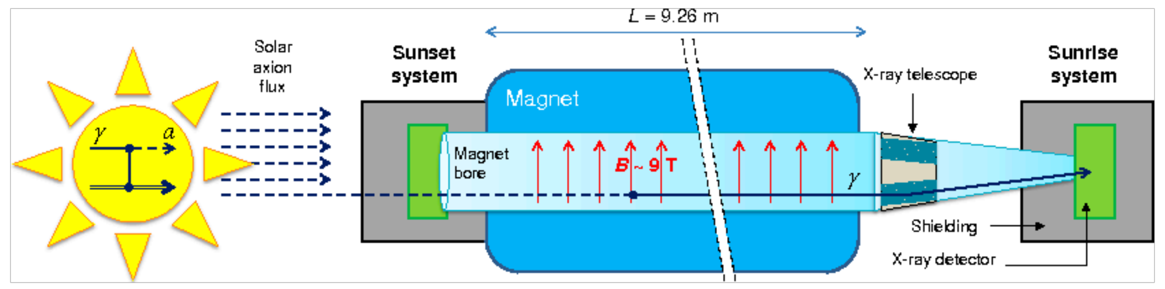
Axion - direct and indirect detection

Axion ou ALP interacts with photons



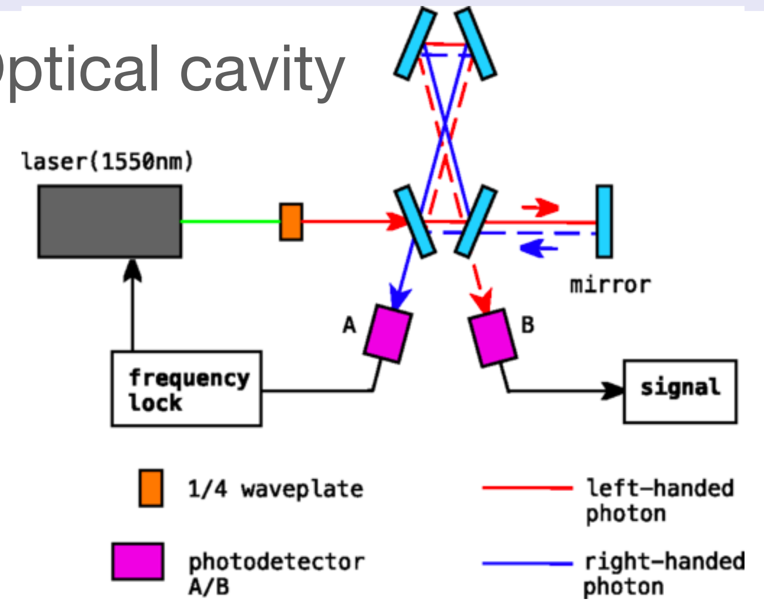


Credit: I Irastorza/G Lanfranchi



CAST

Optical cavity

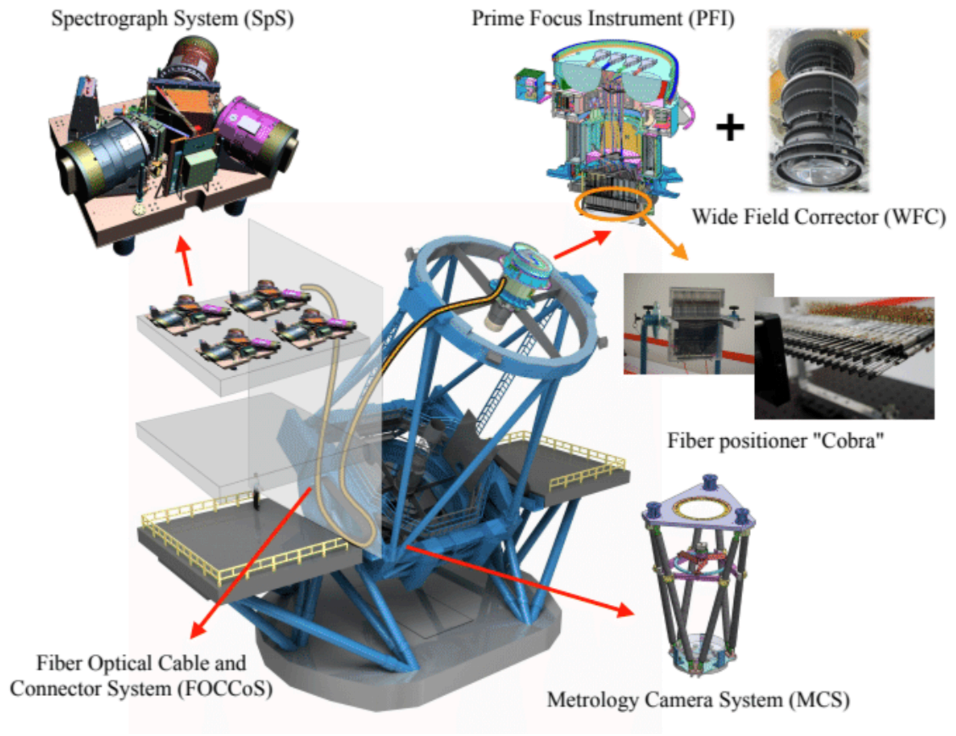


Obata et al 2018

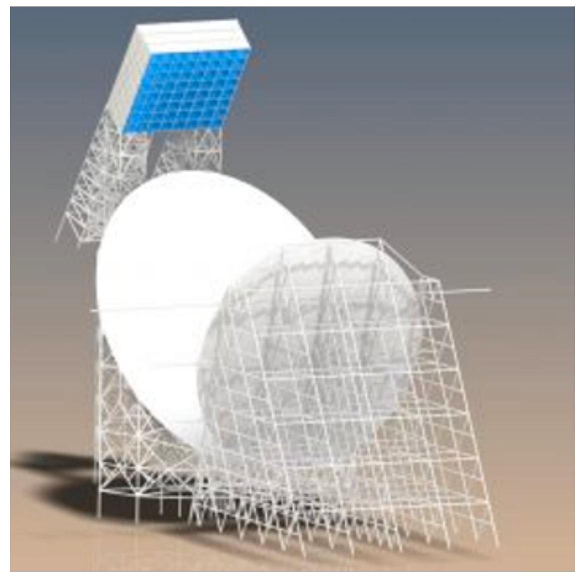
Future

Observations

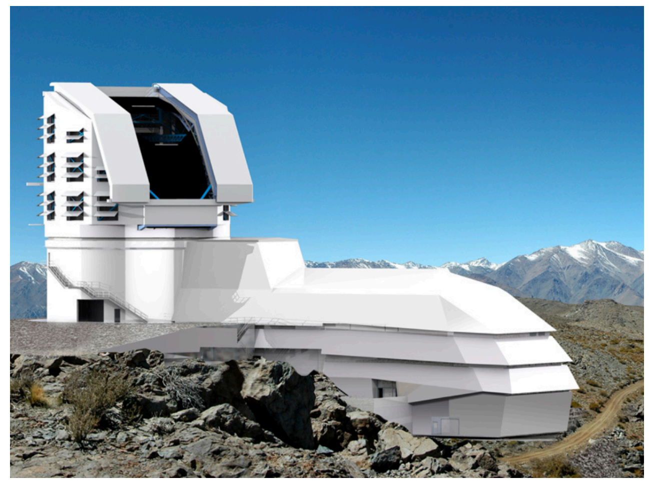
Prime Focus Specctrograph (PFS)



BINGO telescope



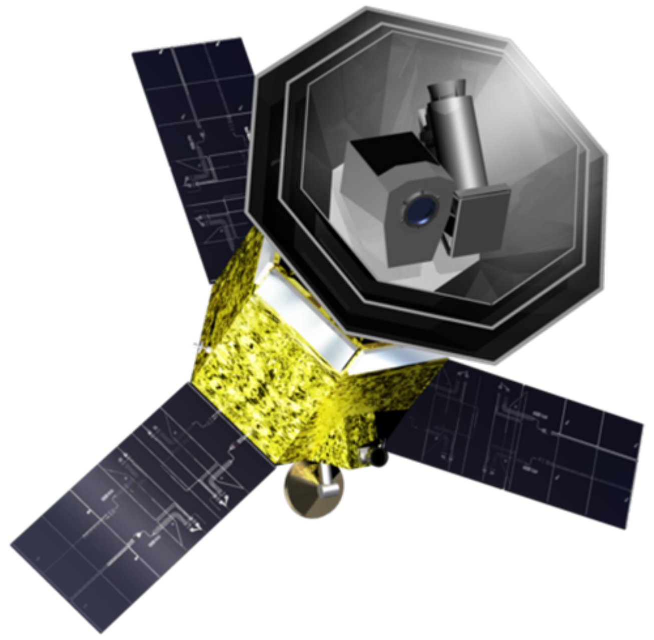
Vera Rubin observatory (LSST)



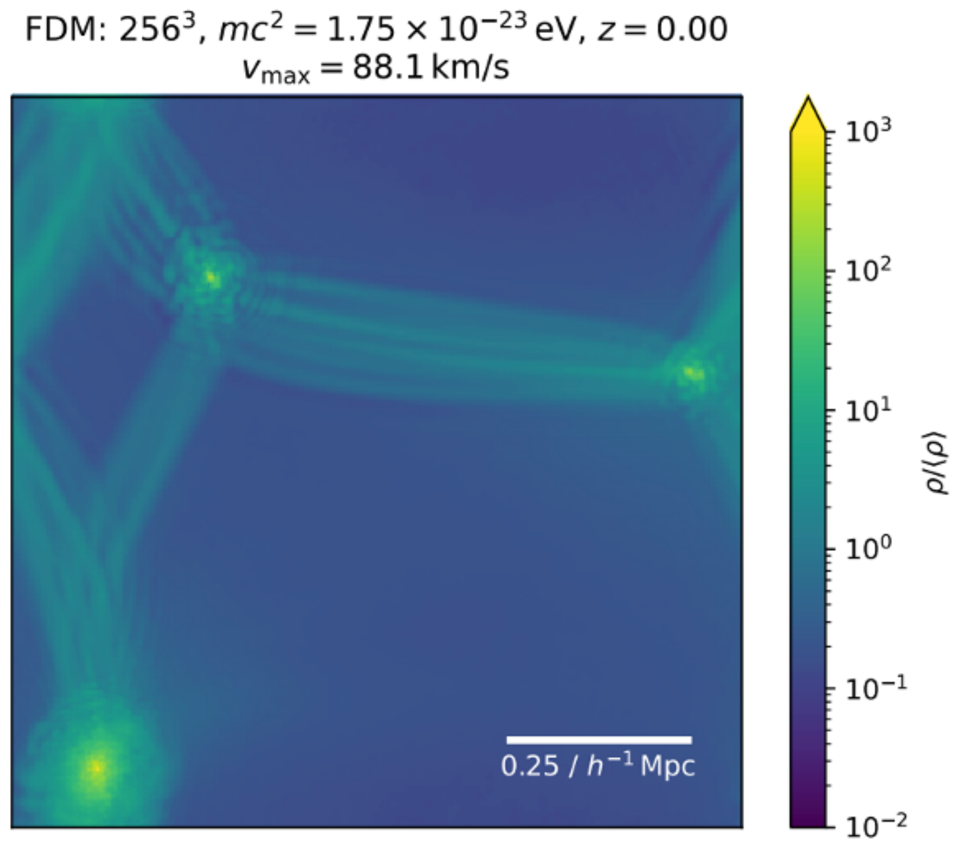
CMB-S4

CMB-S4
Next Generation CMB Experiment

LiteBIRD



Simulations



New probes

Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Superfluid Dark Matter

Ultra-light fields as Dark Energy

Summary

Ultra-Light Dark Matter

Well motivated DM models
Rich and distinct phenomenology on small scales
Testable prediction
One of the leading candidate for DM

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

Core-halo mass relation

Requires further investigation
Aa different relation could change the mass bounds
Simulations - relation not universal ? Large spreading?

Vortices

Vortices might exist in our simulations.
Need to improve their identification


Muito obrigada!