Ultra-light dark matter: the light and fuzzy side of our universe

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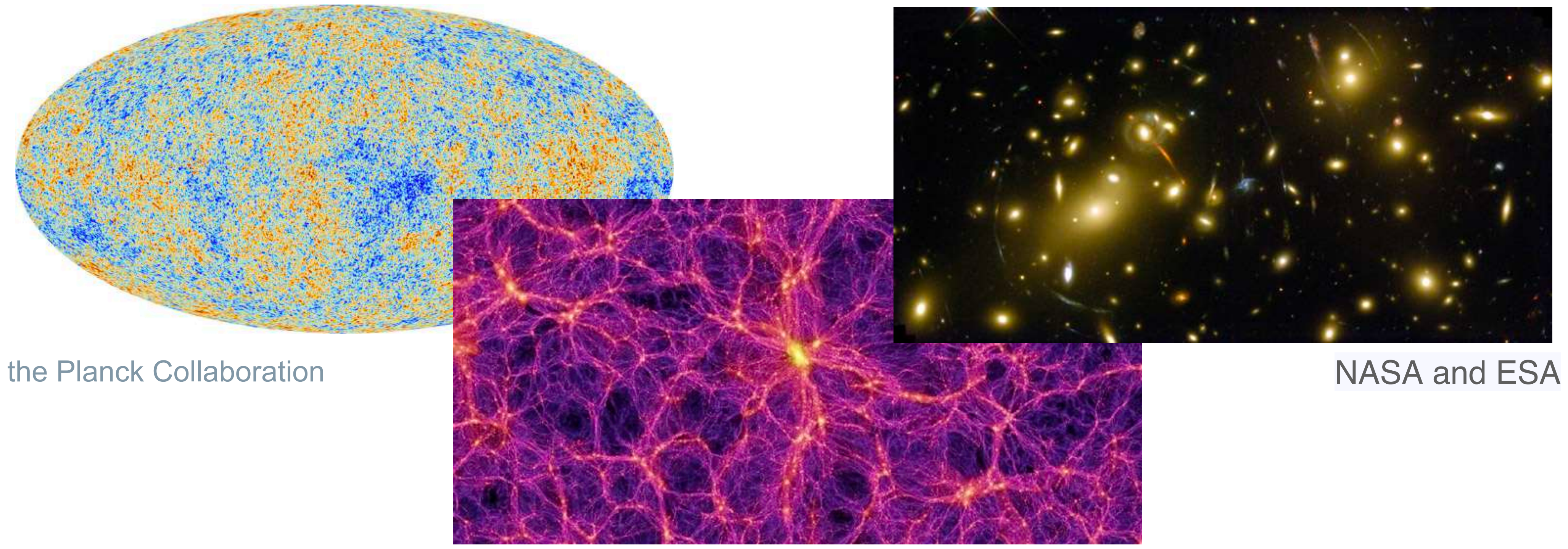
Evidences for dark matter

We can observe its effects in

Galaxies

NASA and ESA

CMB+LSS

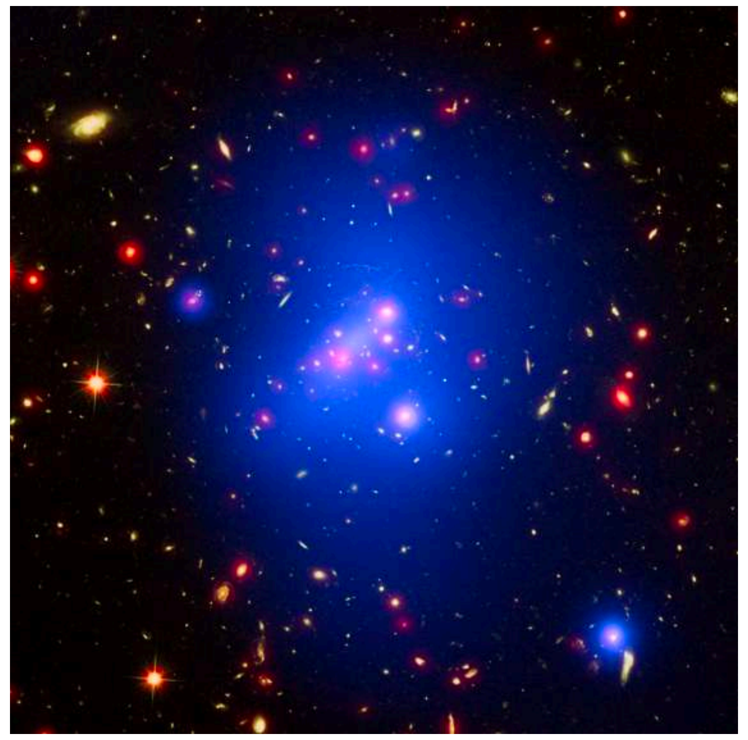


ESA and the Planck Collaboration

NASA and ESA

Springel & others / Virgo Consortium

Clusters

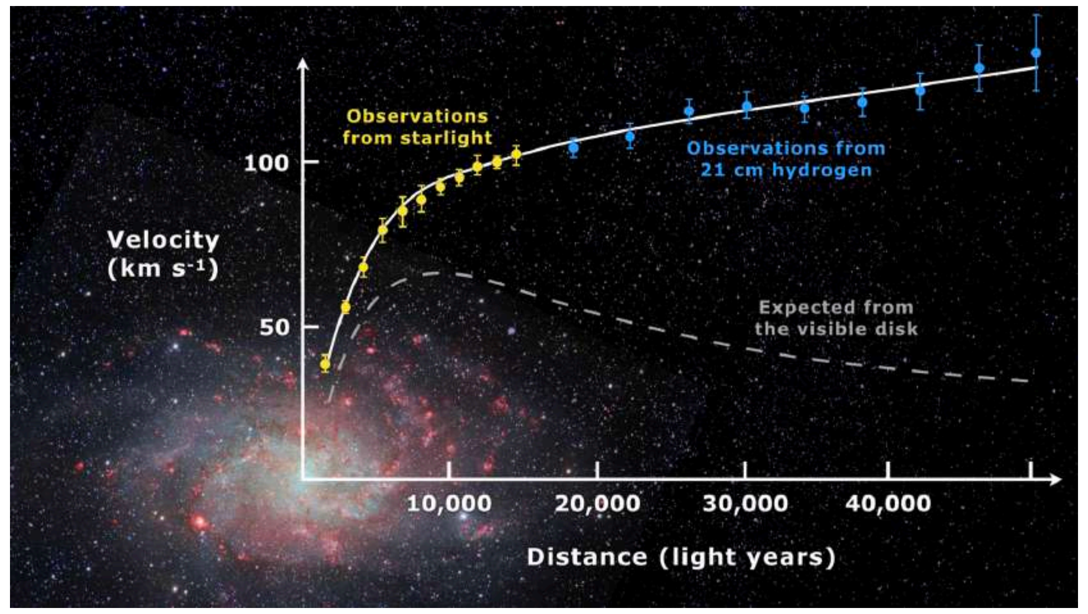


CC BY 4.0

Huge amount of evidence
From all scales

Evidences for dark matter

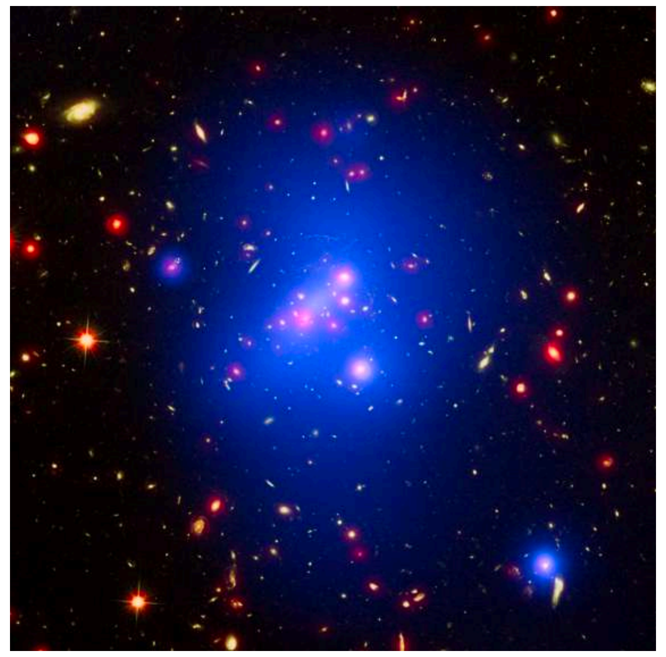
Galaxy rotation curves



Credit: Mario De Leo

- Mass fraction
- Distribution

Clusters



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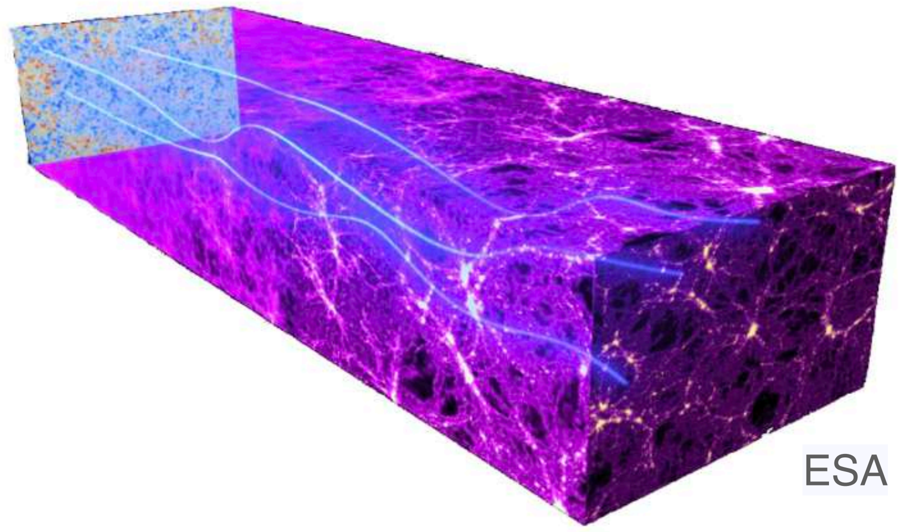
- Mass fraction
- Distribution

Lensing



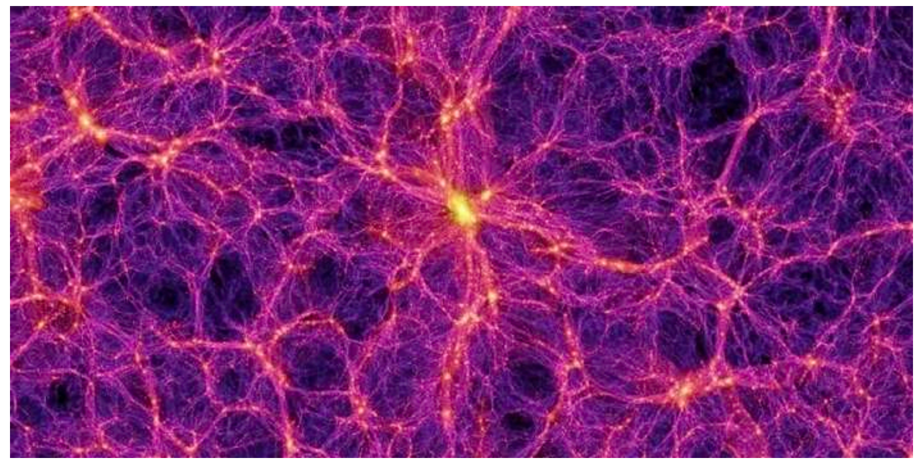
ESA

Strong lensing
- Mass fraction
- Distribution

Weak lensing
- Distribution
- Shape
- Structure

Micro lensing
- Mass fraction
- Smoothness

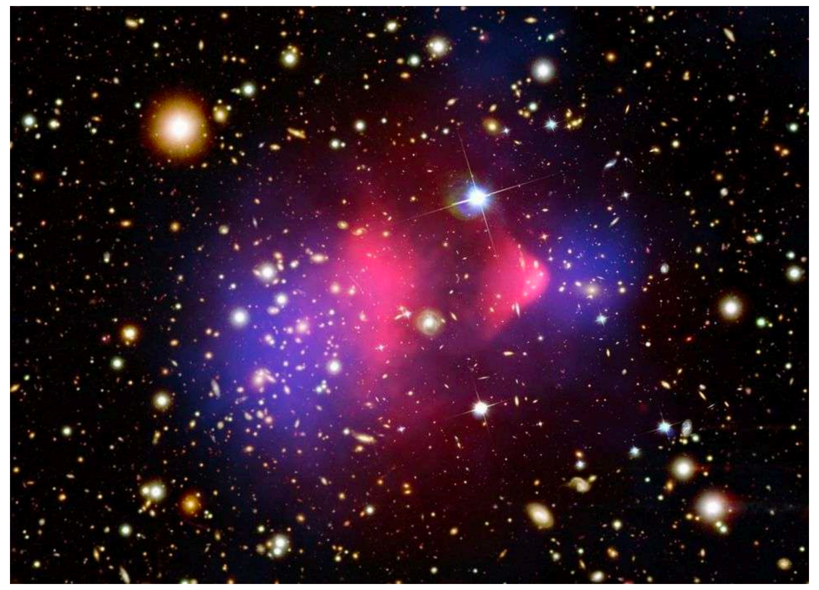
Large Scale Structure



Springel & others / Virgo Consortium

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

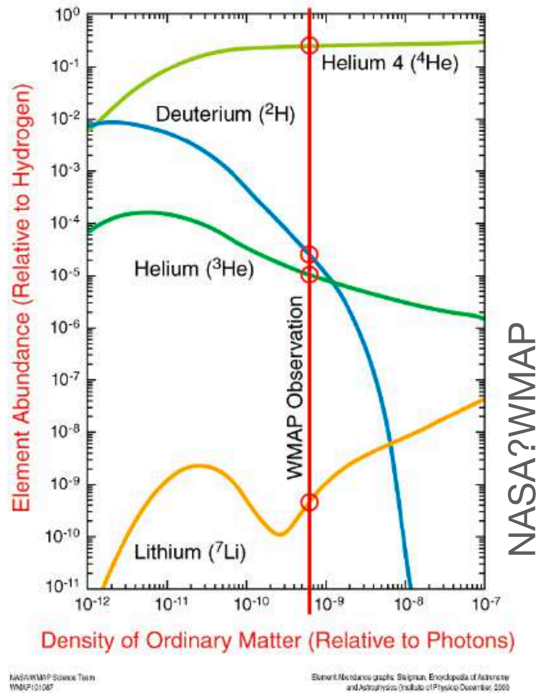
Cluster collision



NASA/CXC/CfA and NASA/STScI

- Distribution
- Separation from collisional matter
- Self-interaction

Big Bang Nucleosynthesis



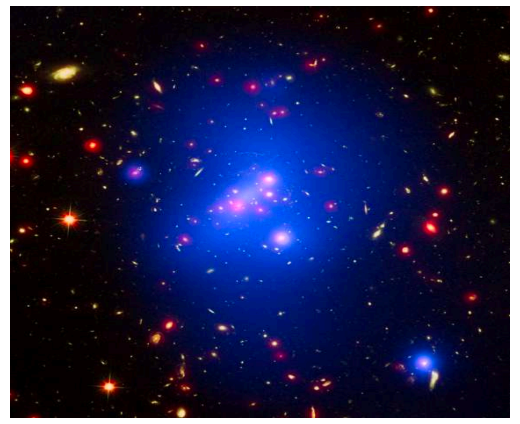
NASA?WMAP

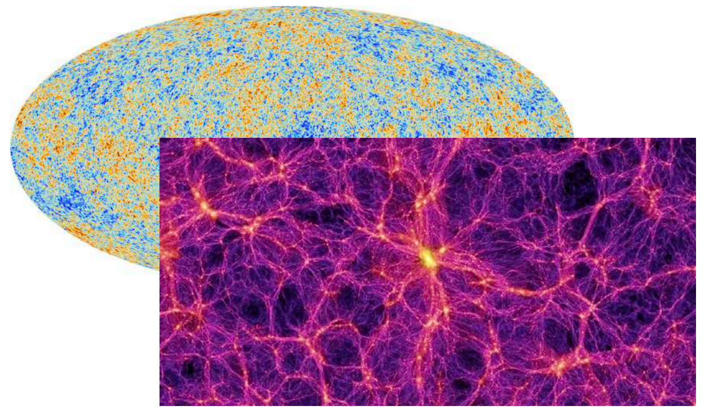
- Amount of baryons

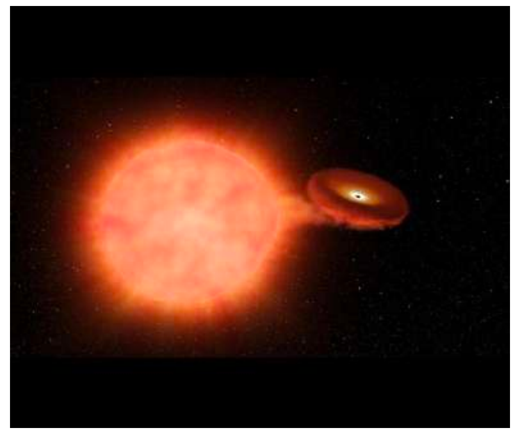
Based on K. Mack

What we know about dark matter


Galaxies

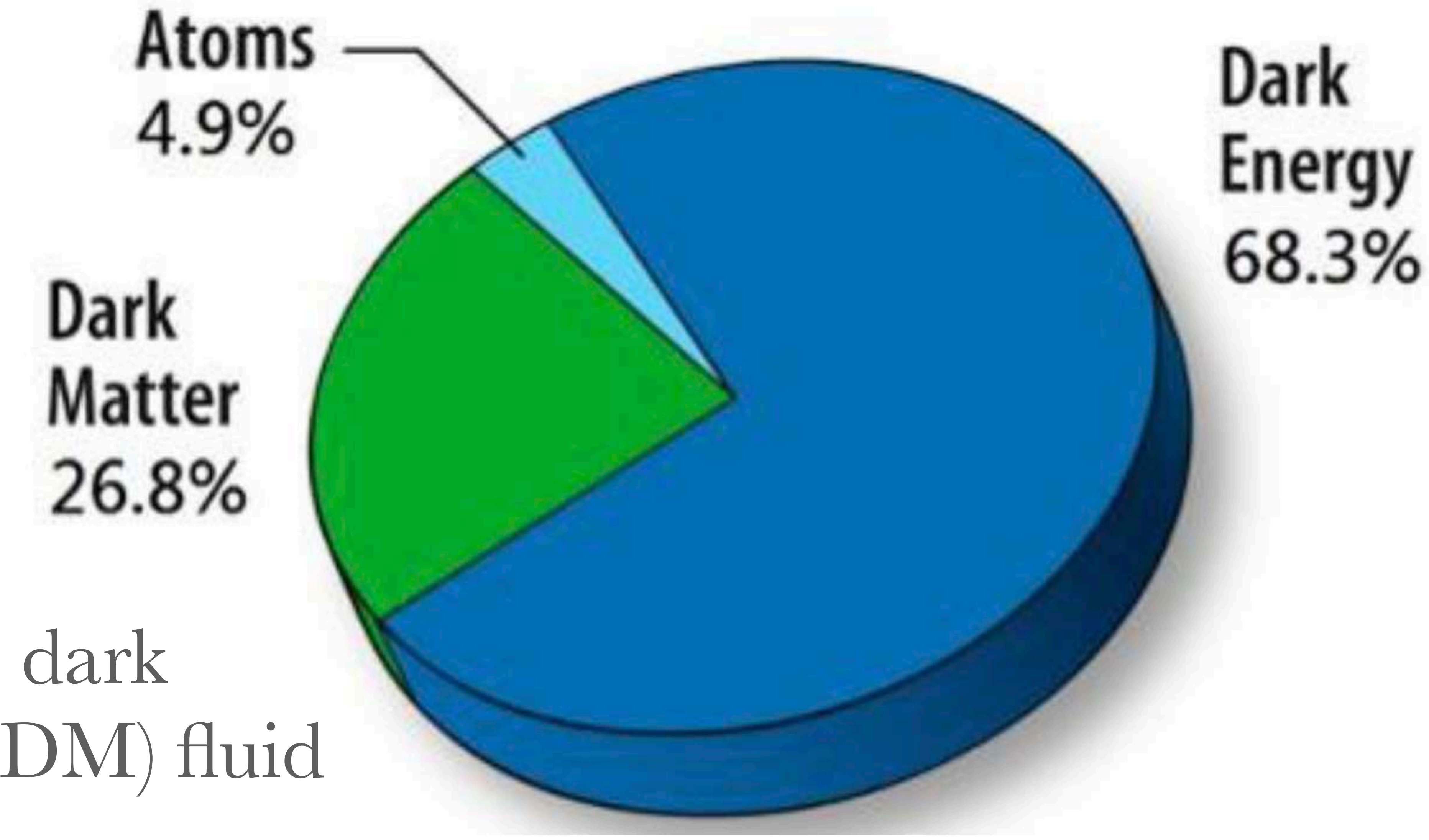

Clusters


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

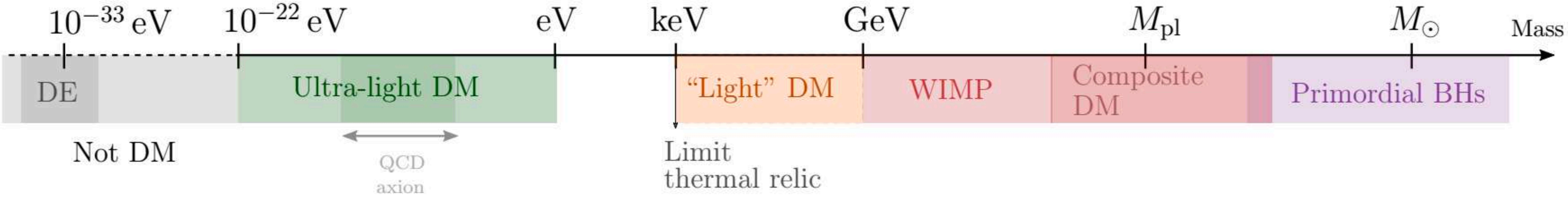
What we don’t know

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

State of the “art"

Mass scale of DM

80 orders of magnitude



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

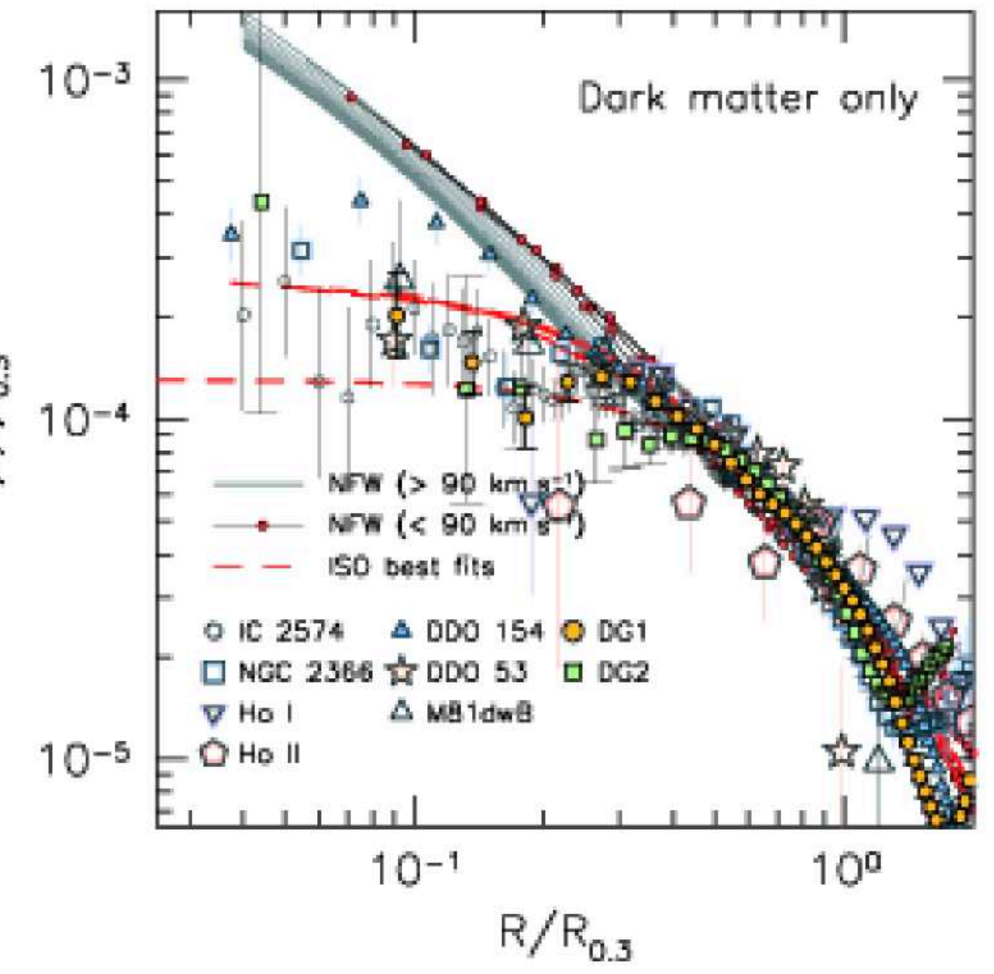
Although still behaves like CDM on large scales

Small scale behavior: still weakly constrained and small scale challenges

Small scale challenges

Cusp-core

Density



Radius

THINGS (HI Near Galaxy Survey)/LITTLE THINGS

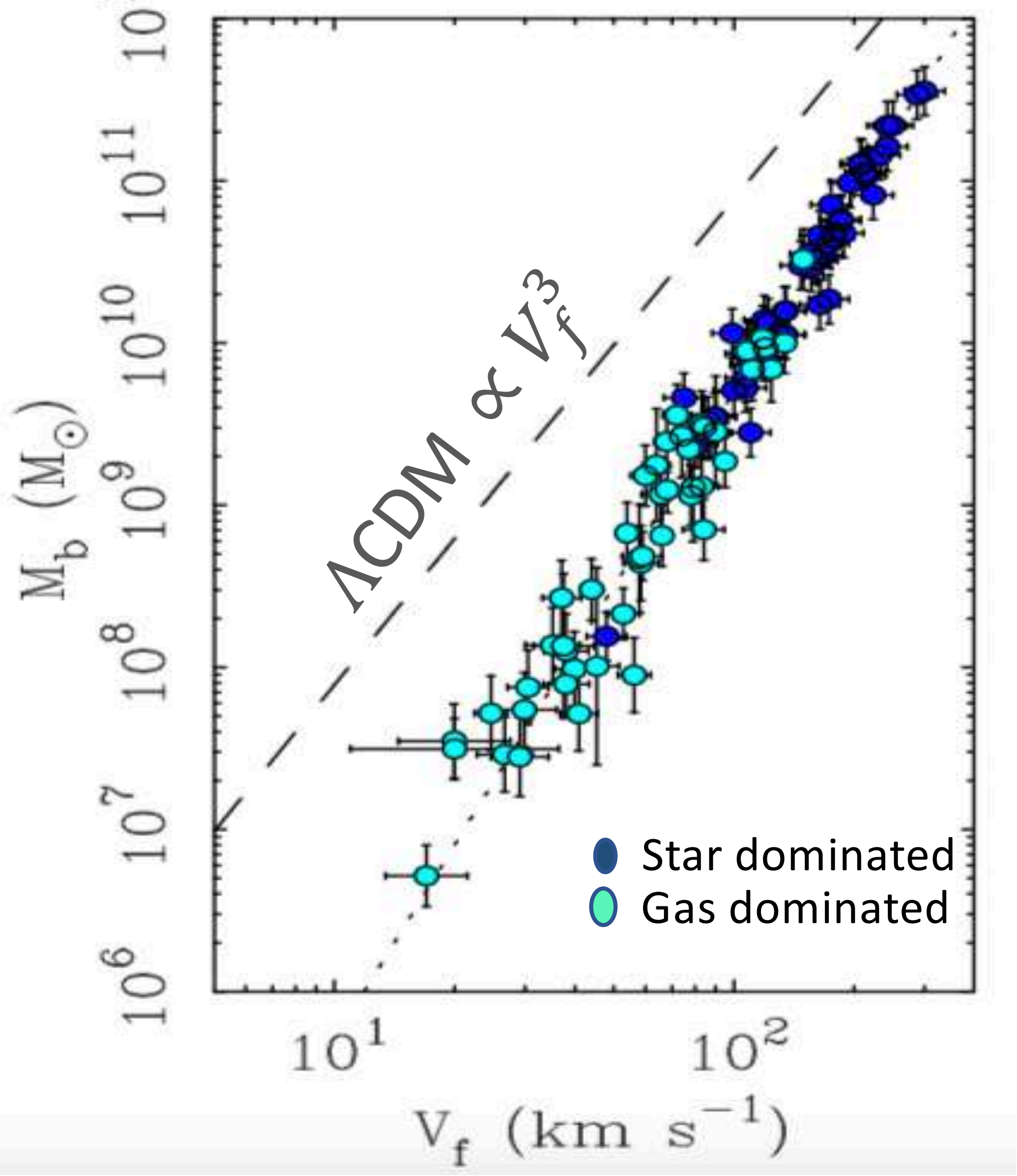
Regularity/diversity of rotation curves

- Baryonic Tully-Fisher relation (BTFR)

Remarkably tight scaling relations between dynamical and baryonic properties.

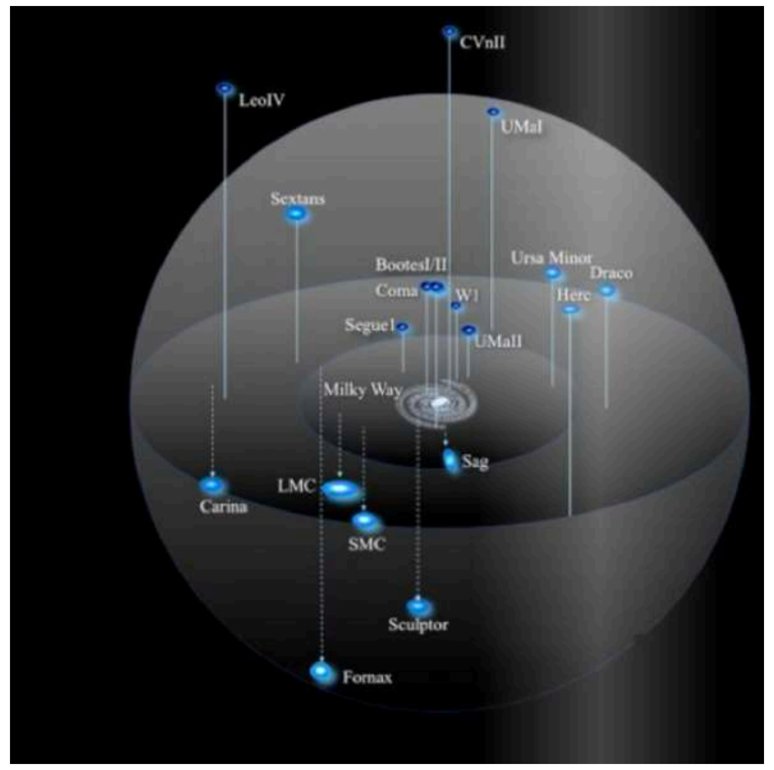
McGaugh (2012)

Baryonic mass



Circular velocity

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



Bullock, Baylon-Kolchin

Missing satellites

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

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

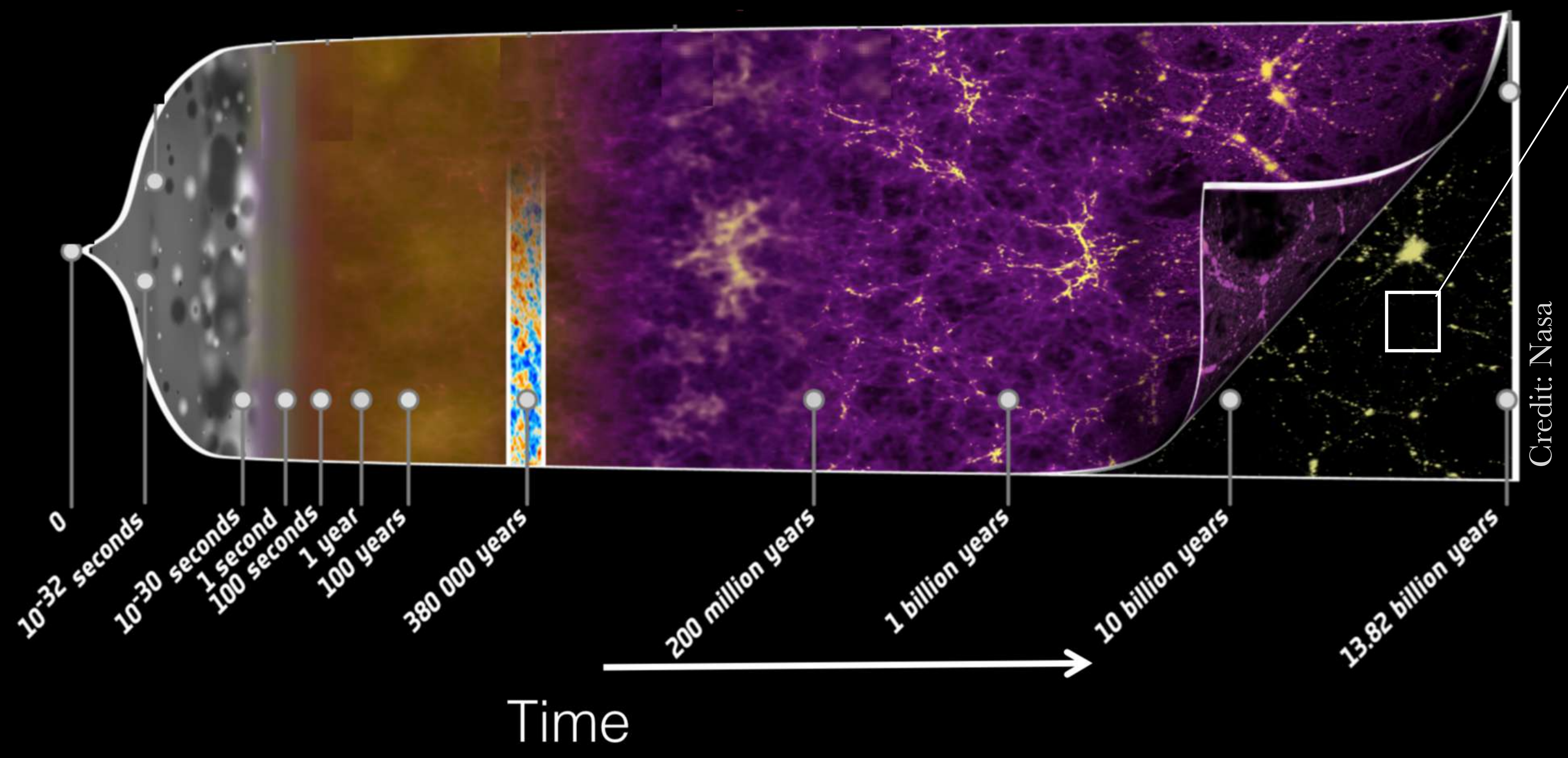
BUT: ~~MOND without DM~~

Problems explaining large scales

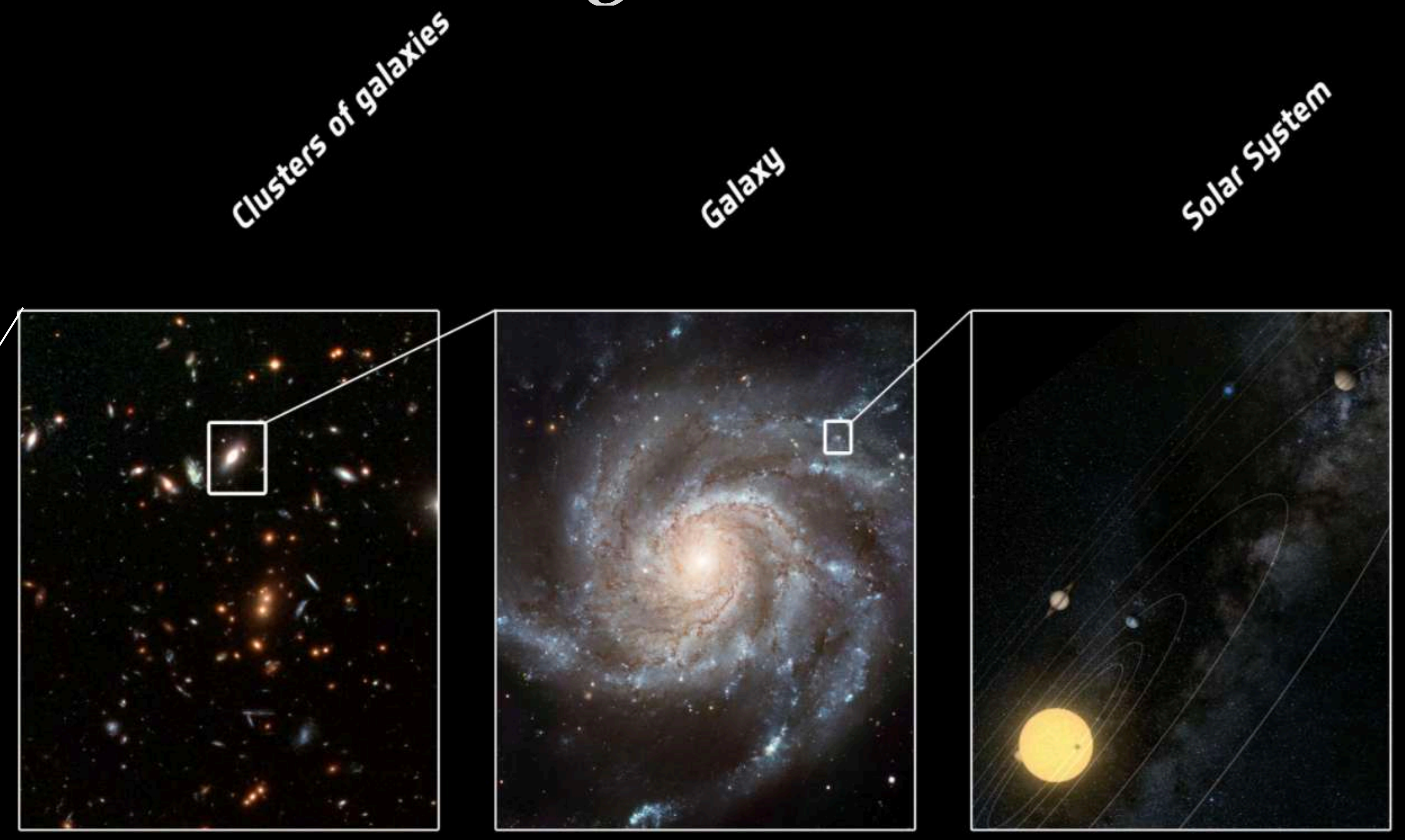
• Modify dark matter:

DM with different properties on small scales

Small scales can offer some hints of the nature of DM



Credit: Nasa

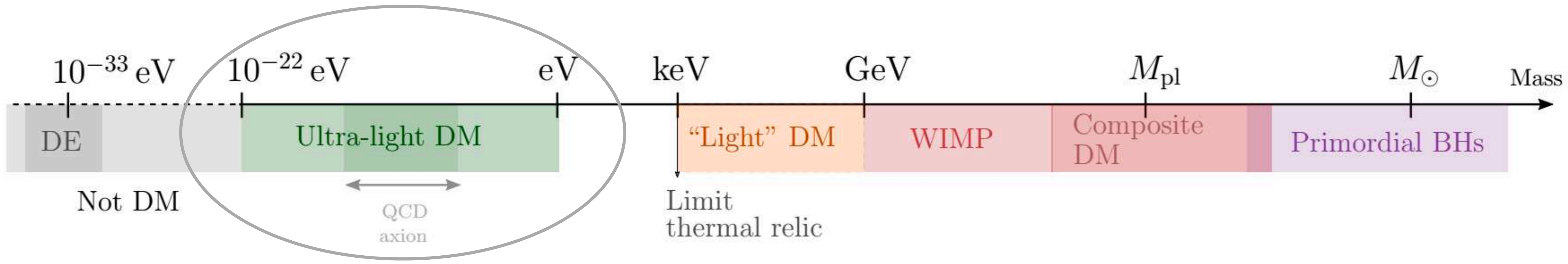


Small Scales

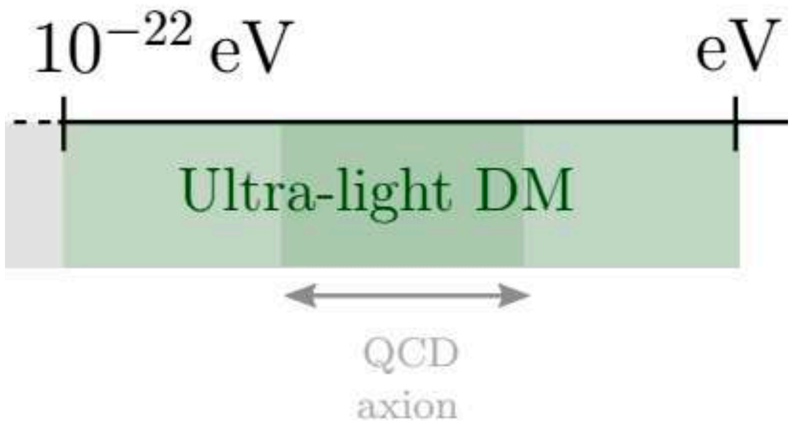
Opportunity to probe the nature of DM!

Astrophysical Observables → DM Distribution → Nature of DM Microphysics Particle physics

Ultra-light dark matter

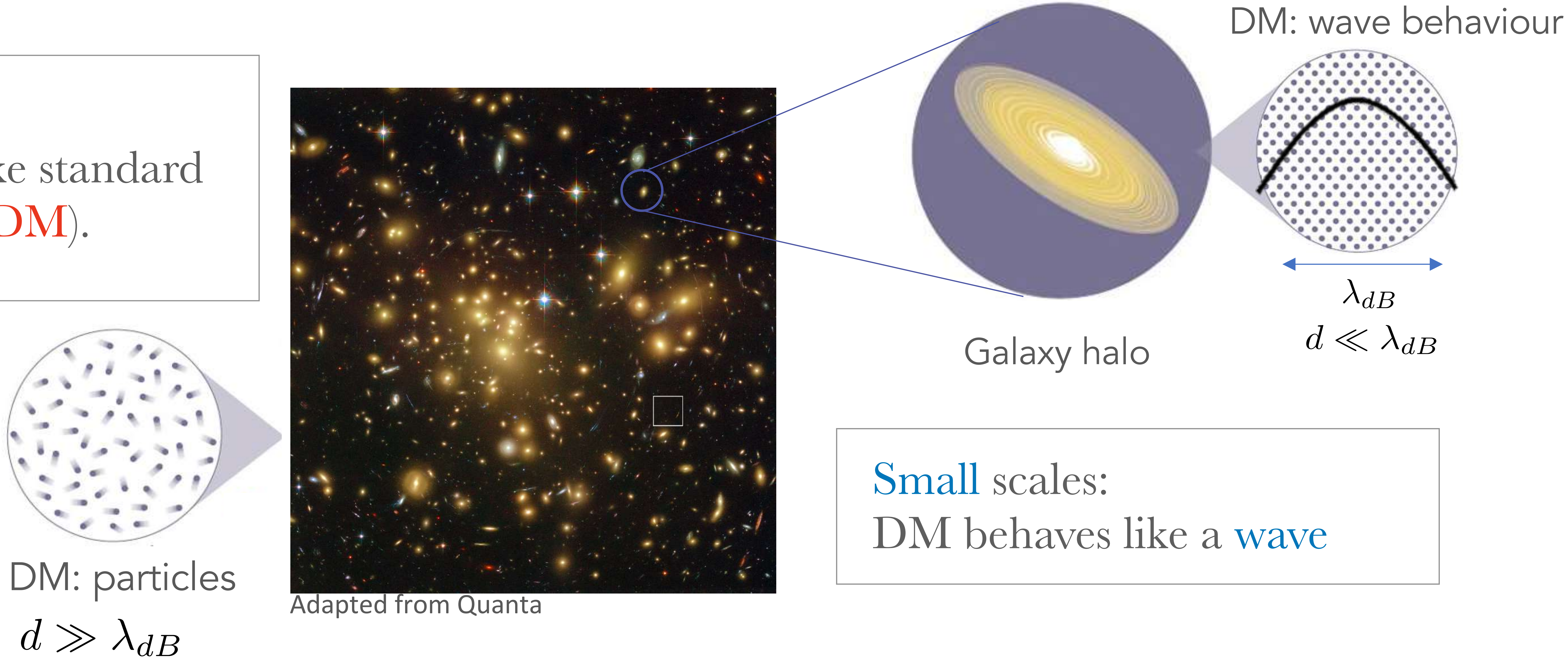


Ultra-light Dark Matter



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

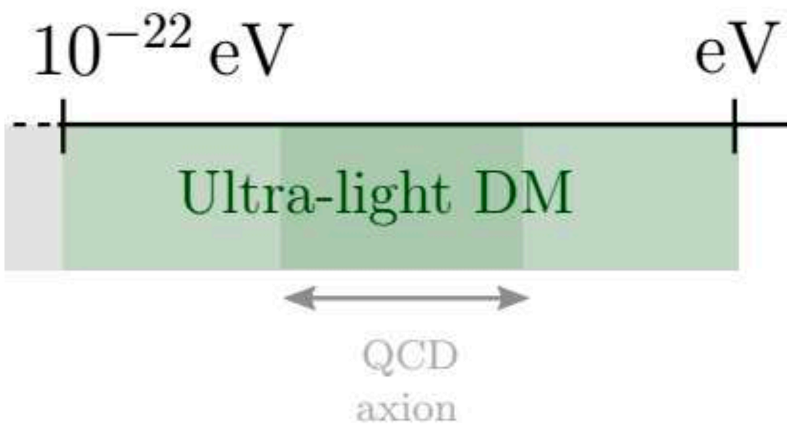
Large scales:
DM behaves like standard particle DM (CDM).



Adapted from Quanta

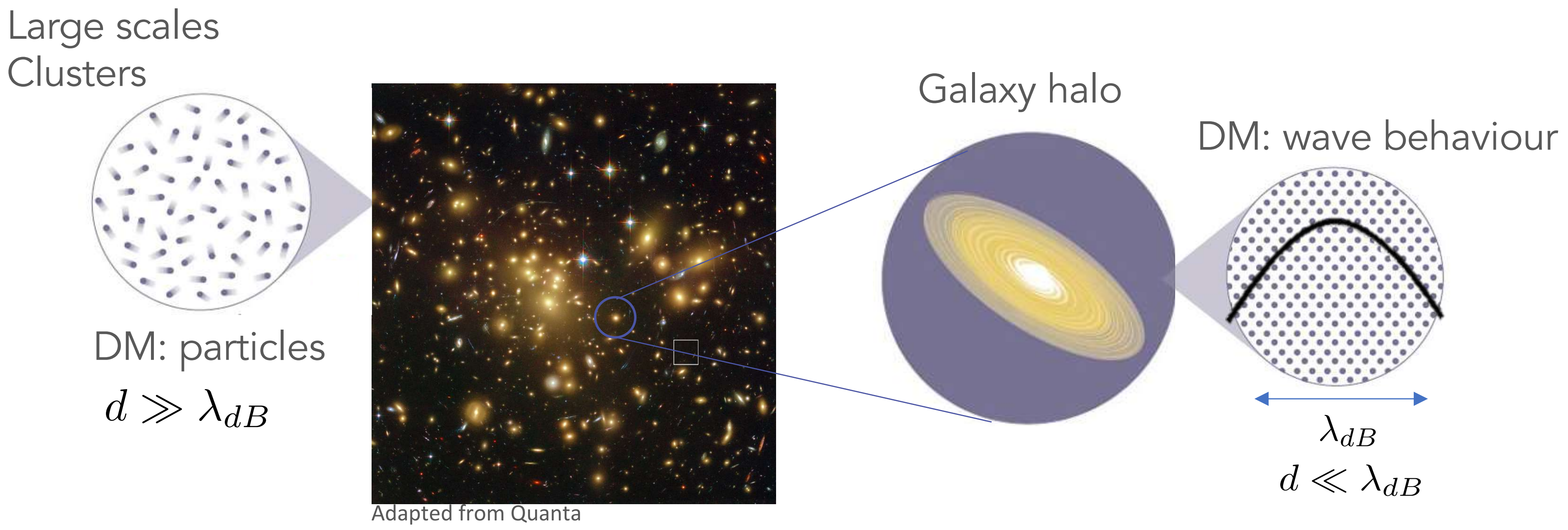
Small scales:
DM behaves like a wave

Strengths of the ULDM



- Particle physics/HEP/condensed matter motivation

    Candidates: Axions, ALPs, UL particles, …



Adapted from Quanta

- Might address small scales problems

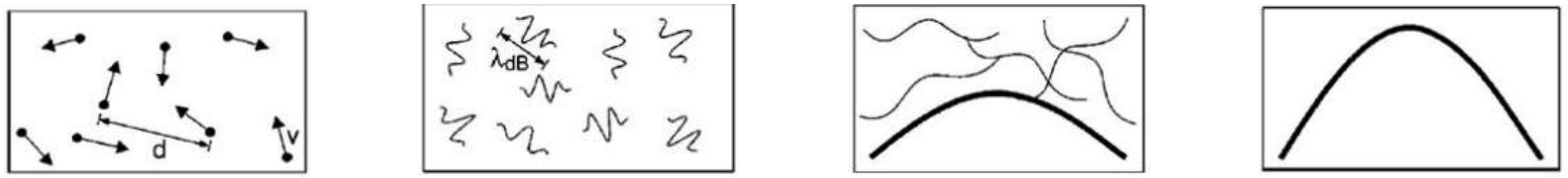
- **Rich phenomenology on small scales:**

    - Wave nature manifest on galactic scales

    - Forms a Bose-Einstein condensate or superfluid interior of galaxies

→ Allows to probe the internal properties of the ULDM

Bose Einstein Condensate



High temperature
Thermal velocities

Low temperature
$\lambda_B \sim T^{-1/2}$
"wave packets"

$T = T_c$
BEC
"matter wave overlap"
$d \sim \lambda_{dB}$

$T = 0$
Pure BEC
"giant matter wave"

- Bose Einstein condensate (BEC): macroscopic occupation of the ground state
- At low temperatures, each particle wave function overlap - single wave function describes the entire fluid.

Superfluid

- Appears at low T after the superfluid condenses into a BEC.
- Effective dynamics: fluid flows without friction

Description

Mean field approximation:
Large N, dilute

$$\hat{\Psi}(\mathbf{r},t) = \psi(\mathbf{r},t) + \delta\hat{\Psi}(\mathbf{r},t)$$

with $\psi(\mathbf{r},t) = \langle\hat{\Psi}(\mathbf{r},t)\rangle$

Fixed $n_0 = |\psi(\mathbf{r},t)|^2$

classical field "wavefunction of the condensate"

small perturbation: describes depletion of the condensate

Credit: Peking University

$$\boxed{i\partial_t\psi(\mathbf{r},t) = \left(-\frac{\nabla^2}{2m} + V_{trap}(\mathbf{r}) + U_0|\psi(\mathbf{r},t)|^2\right)\psi(\mathbf{r},t)}$$

Non-linear Schrödinger equation - Gross-Pitaevskii equation

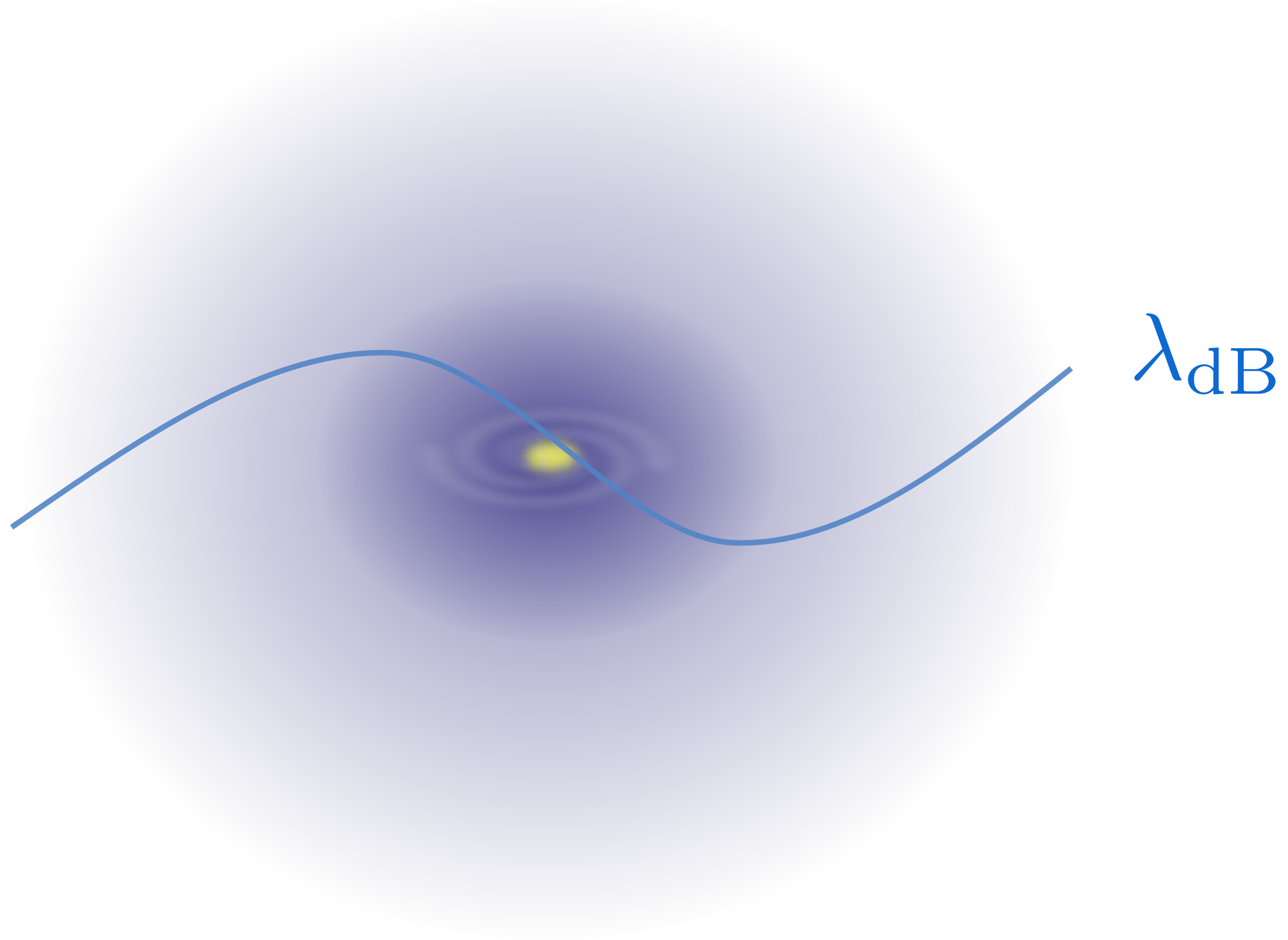
How light is ultra-light?

Behave as wave on galactic scales:

- λ_{dB} must be smaller than the halo

$$\lambda_{\mathrm{dB}} < R_{\mathrm{halo}}$$

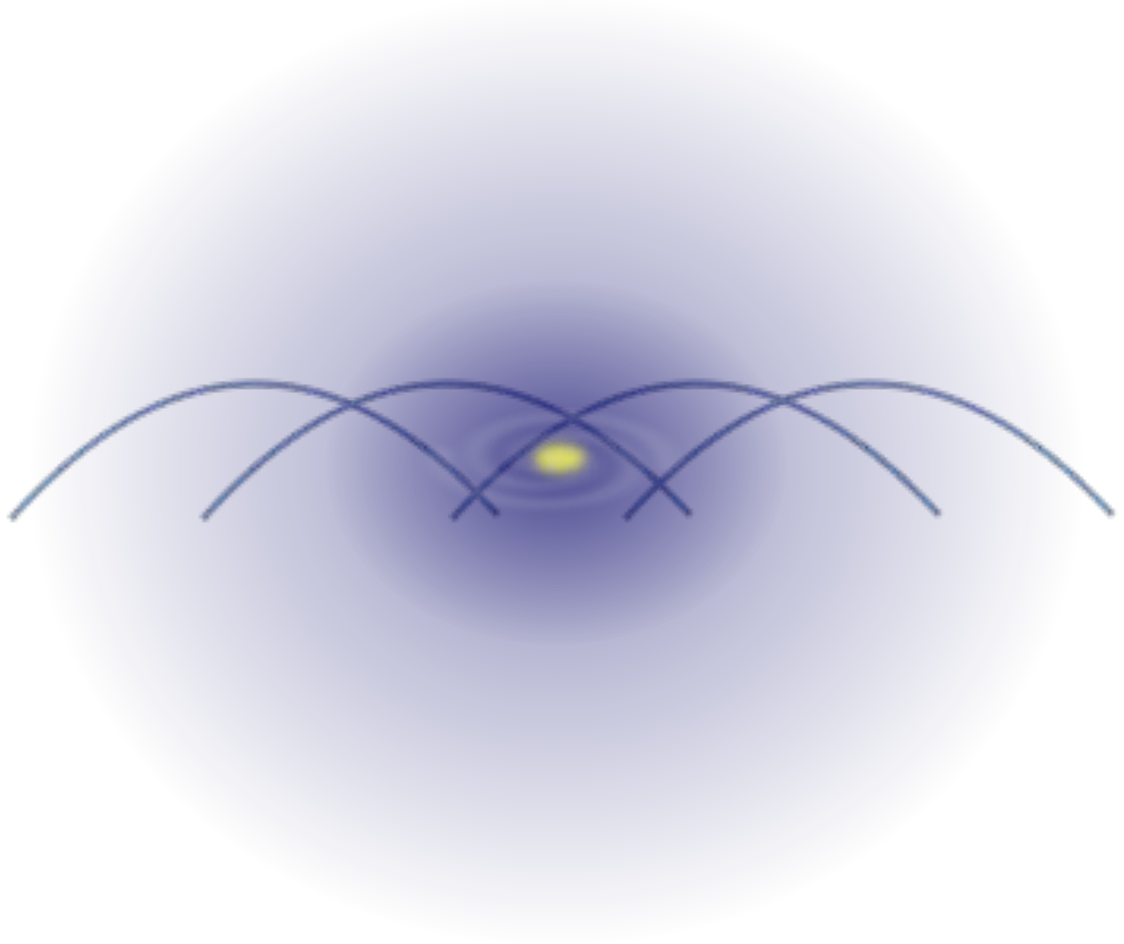
$$\implies \quad m \gtrsim 10^{-25}\,\mathrm{eV}$$



- λ_{dB} overlap to be of halo size

$$\lambda_b \sim \frac{1}{mv} \geq d \sim \left(\frac{m}{\rho_{vir}}\right)^{\frac{1}{3}}$$

$$\implies \quad m \leq 2\mathrm{eV}$$



$10^{-60}\,\mathrm{kg}$ $10^{-35}\,\mathrm{kg}$

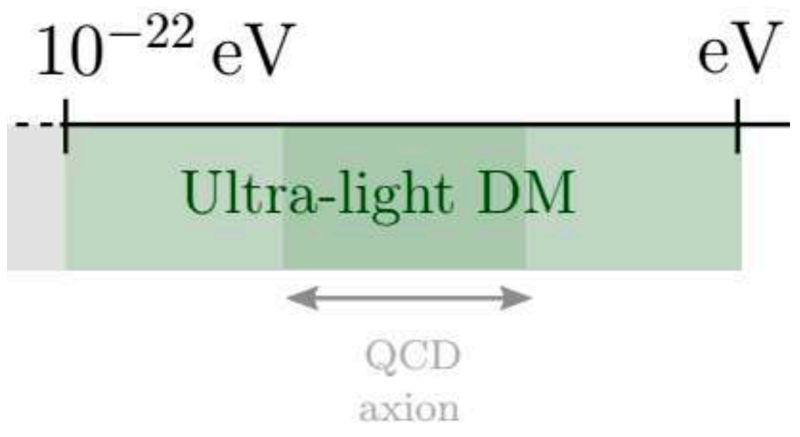
$$\boxed{10^{-25}\,\mathrm{eV} \lesssim m \lesssim \mathrm{eV}}$$

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

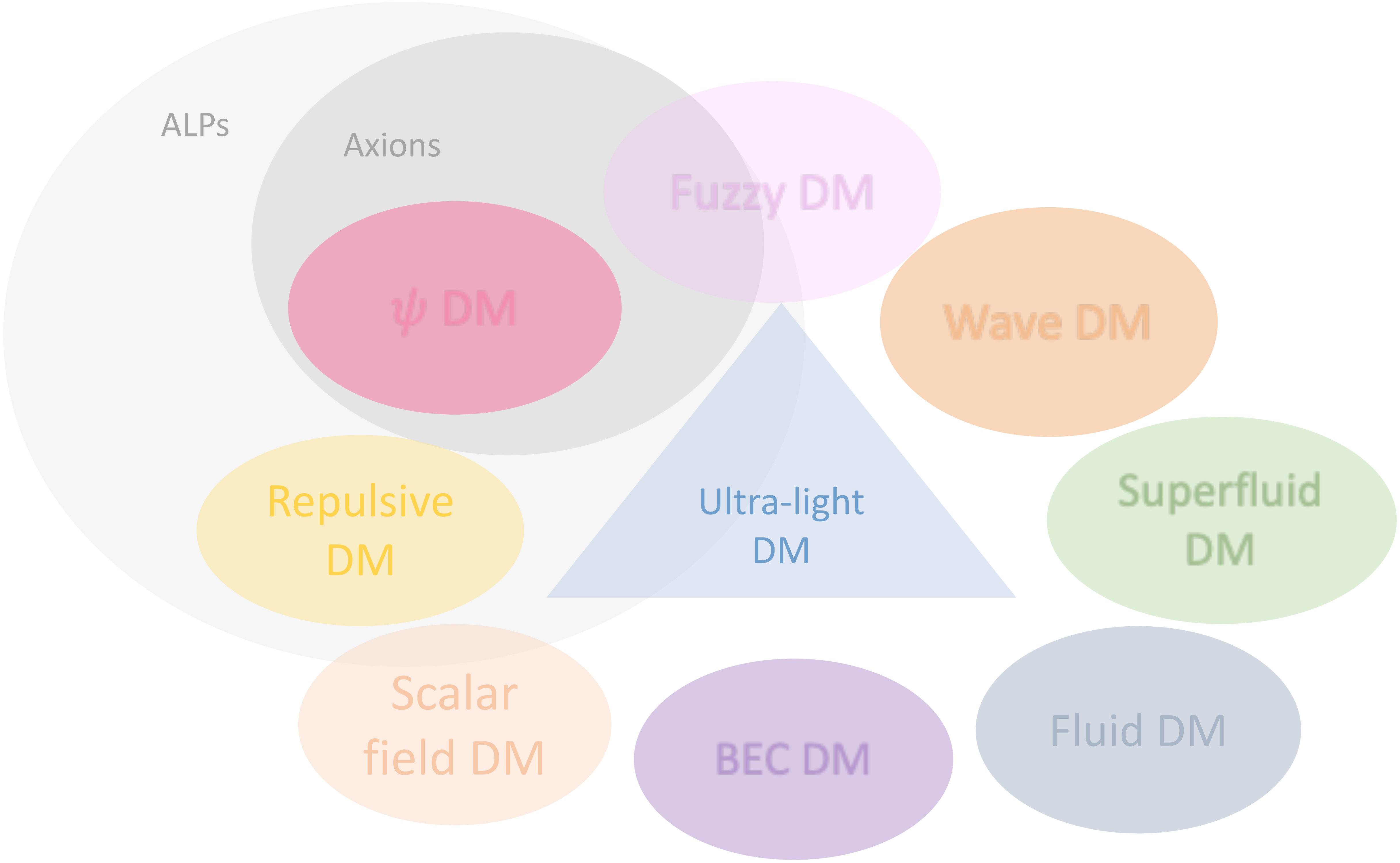
"Ultra-light dark matter", **EF**, 2020.

$\mathrm{pc} \simeq 3 \times 10^{16}\,\mathrm{m}$

Ultra-light Dark Matter - models



There are many ULDM models in the literature
However, each of these models presents a different dynamics on small scales - different phenomenology



ALPs

Axions

Fuzzy DM

ψ DM

Wave DM

Repulsive DM

Ultra-light DM

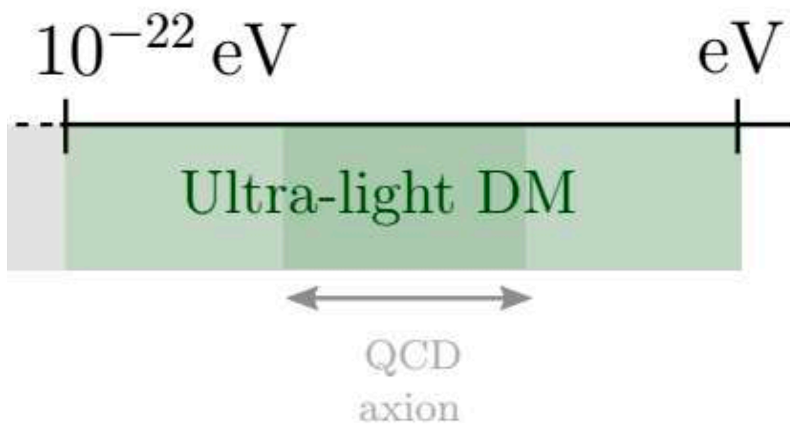
Superfluid DM

Scalar field DM

BEC DM

Fluid DM

Ultra-light Dark Matter -classes



3 classes:

Fuzzy DM
(FDM)

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

DOFs m

Self Interacting FDM
(SIFDM)

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

m g

DM Superfluid

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

Axion and ALP (axion like particles)

⟶ Connection with condensed matter and particle physics!

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

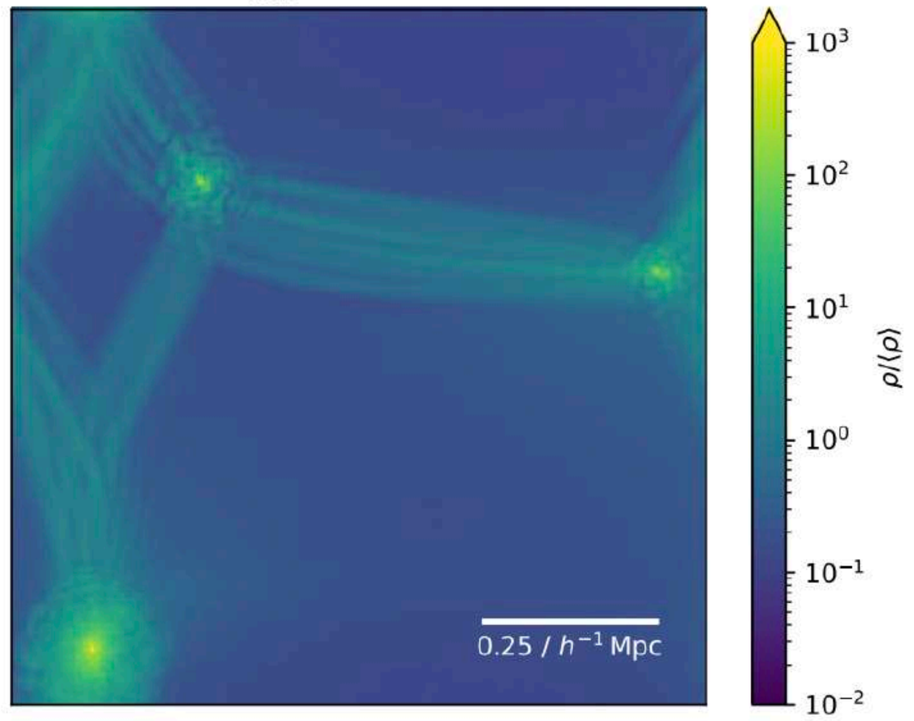
Phenomenology

"Ultra-light dark matter", **E.Ferreira**, 2020. Review.

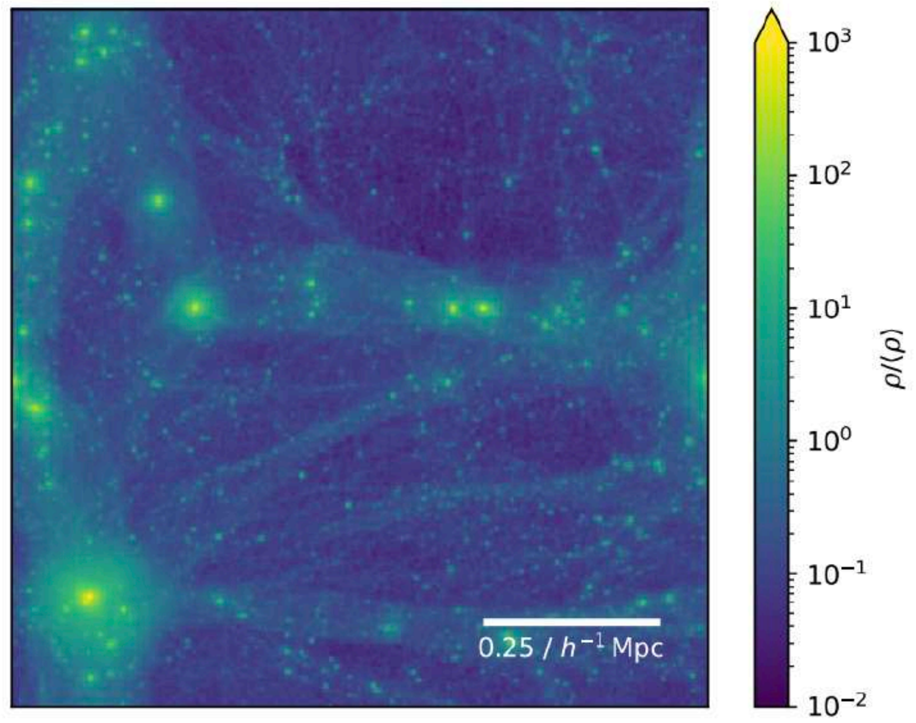
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

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

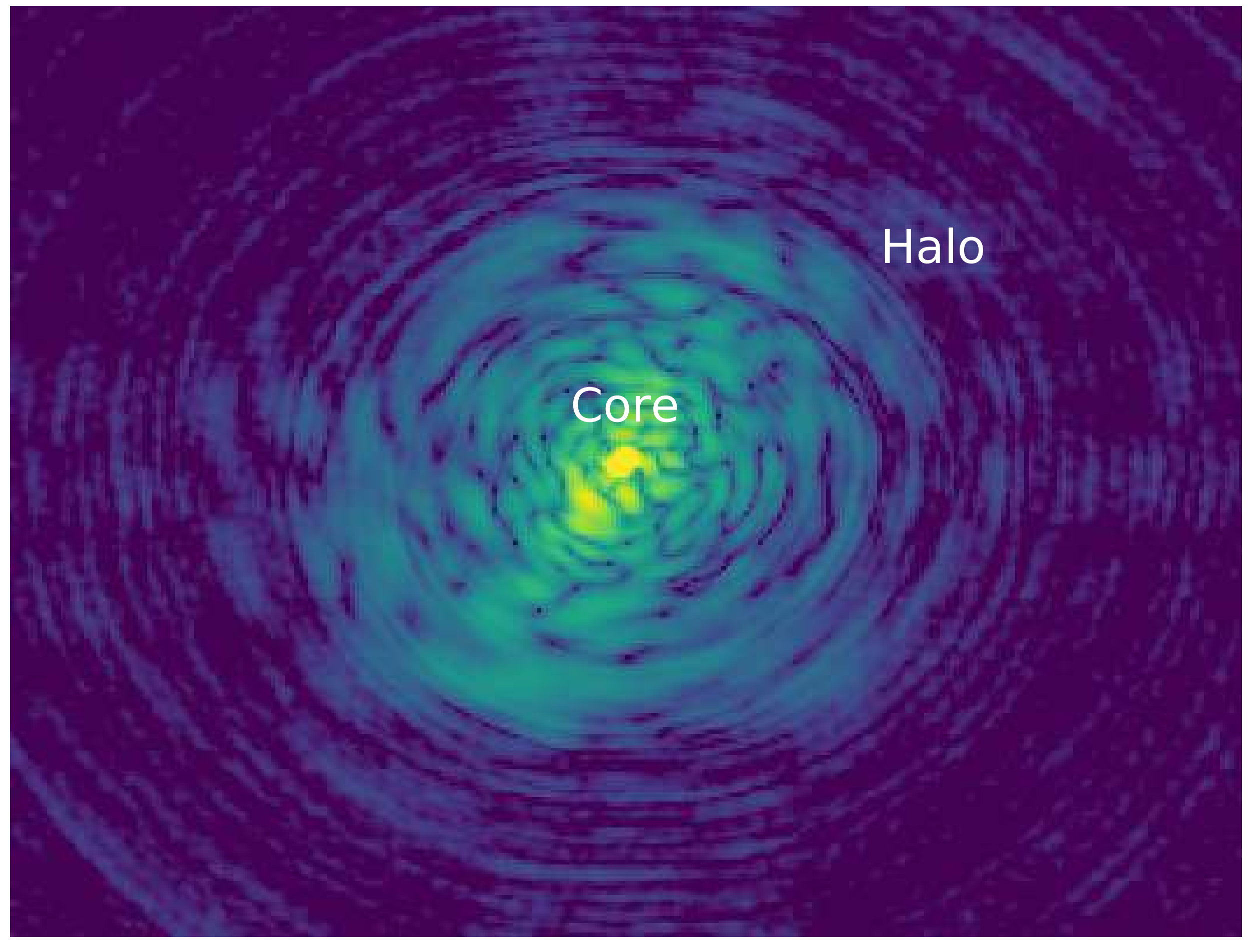


CDM: 256^3, $z = 0.00$

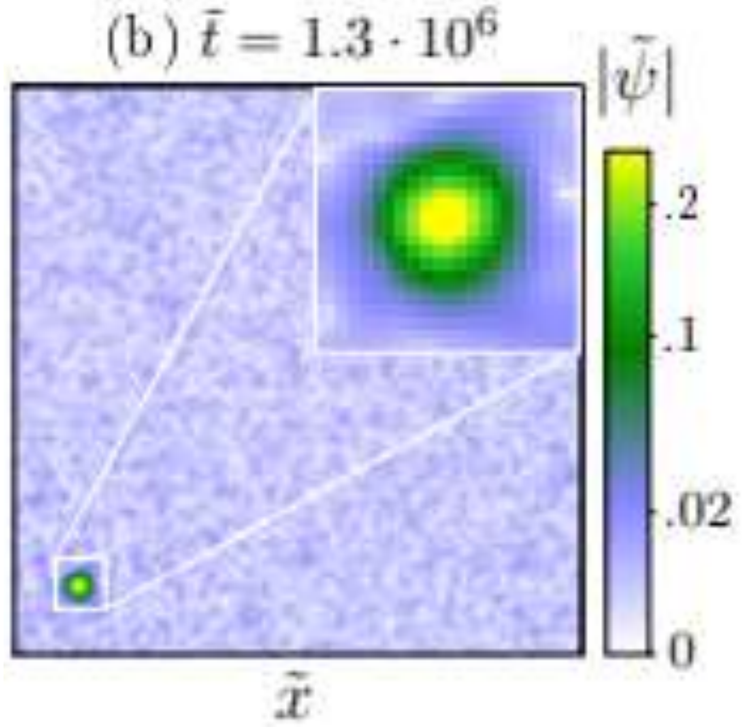


S. May et al. 2021

Formation of a solitonic core

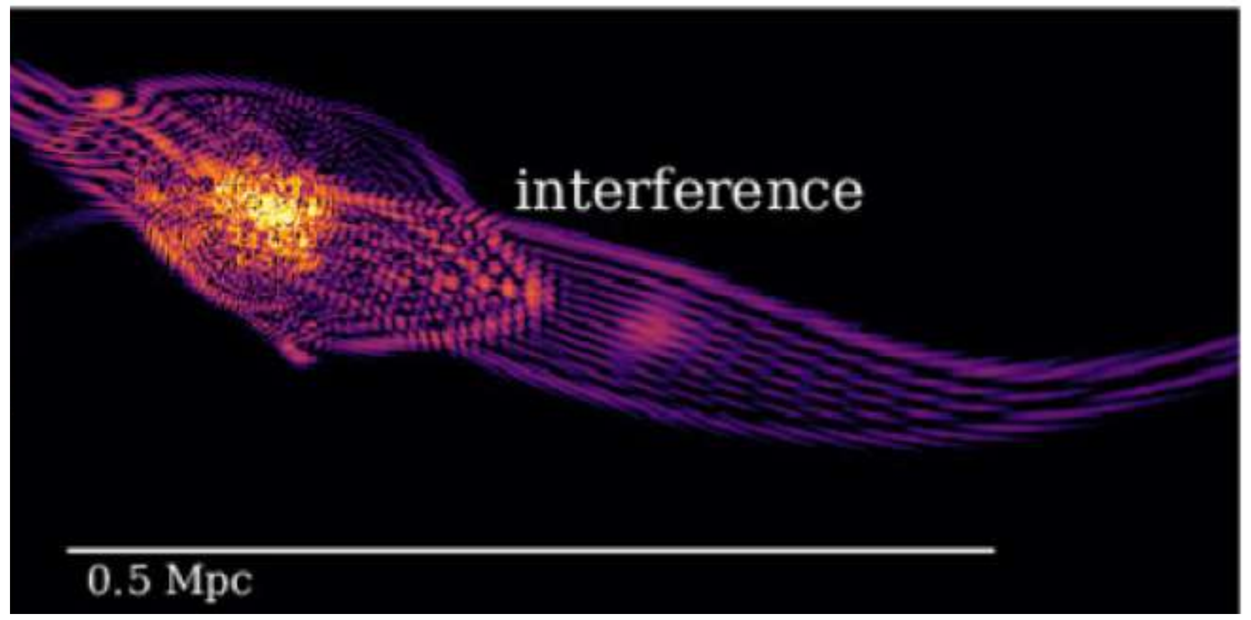


Dynamical effects



Levkov et al. 2018

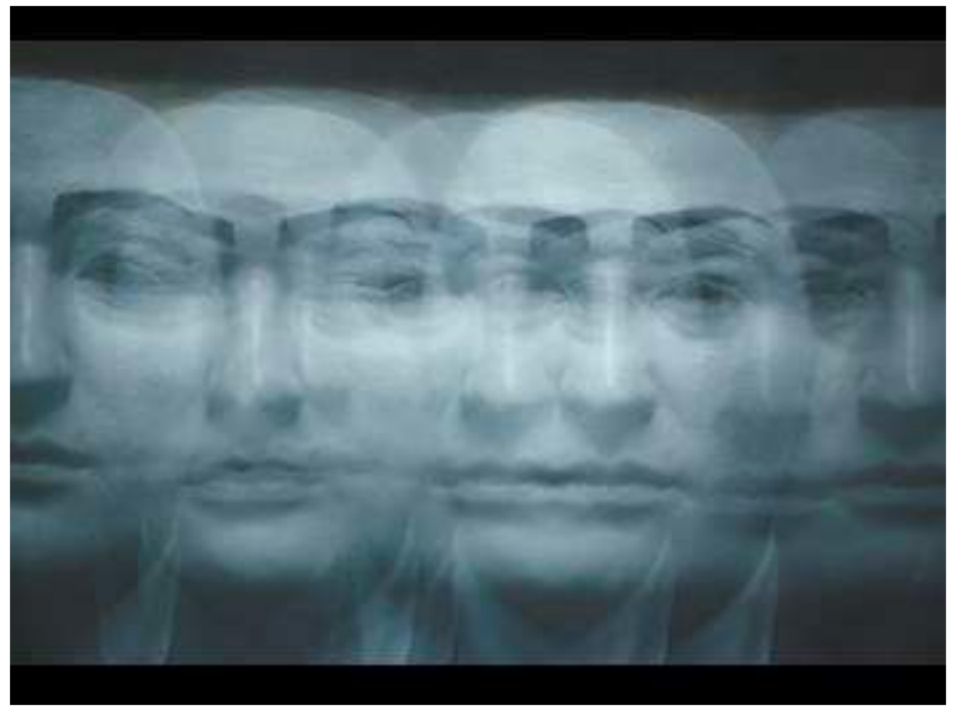
Wave interference



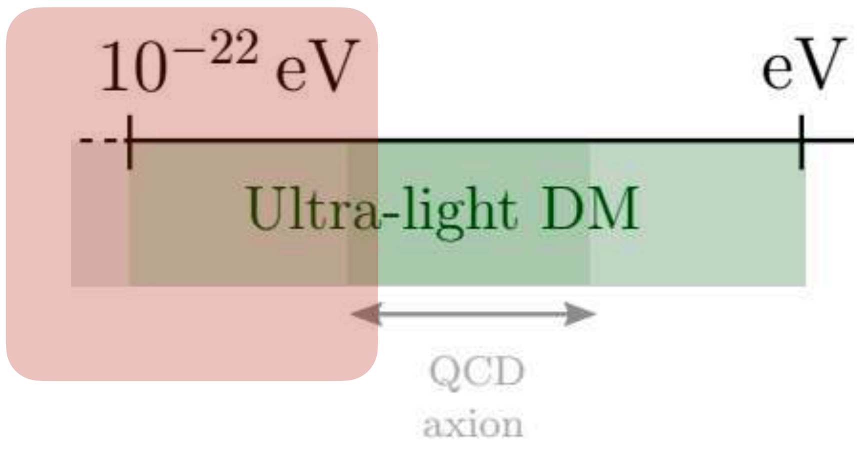
Mocz et al. 2017

Fuzzy dark matter

Self interacting fuzzy dark matter



Fuzzy DM and self-interacting FDM



Fuzzy DM
(FDM)

- Gravitationally bounded ultra-light scalar field model
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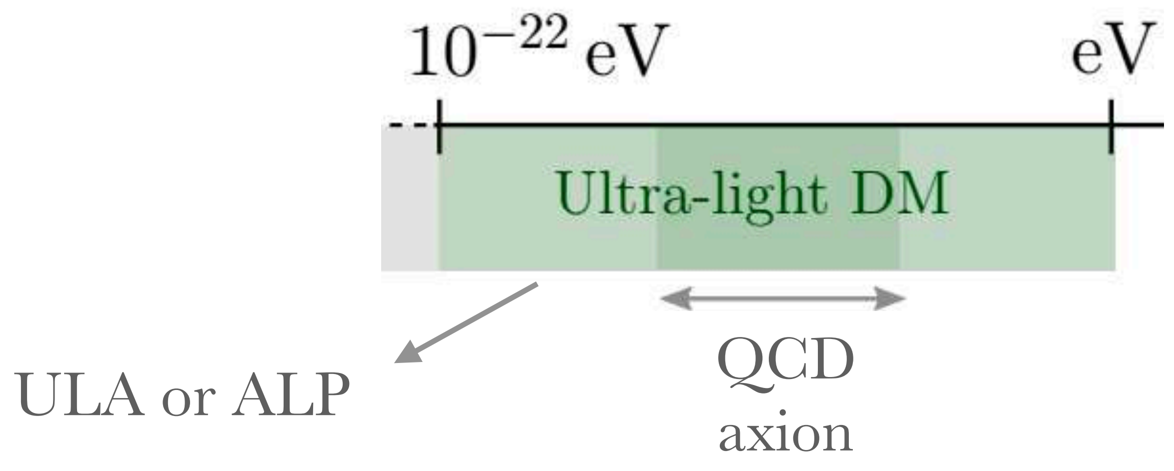
m

Self Interacting FDM
(SIFDM)

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

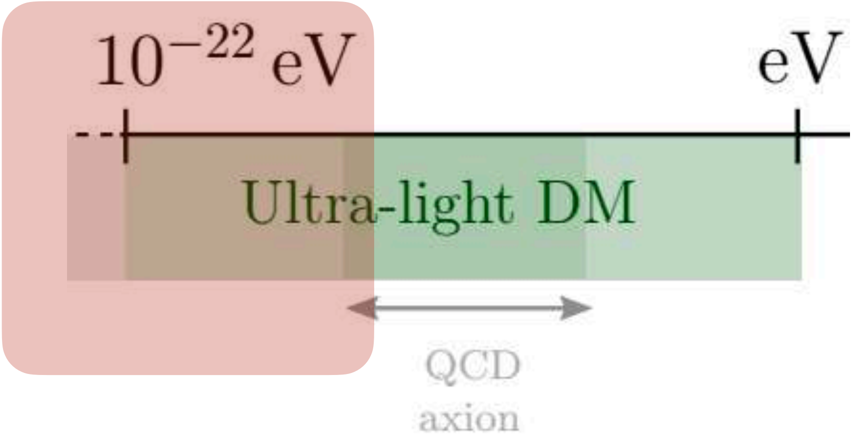
m g

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



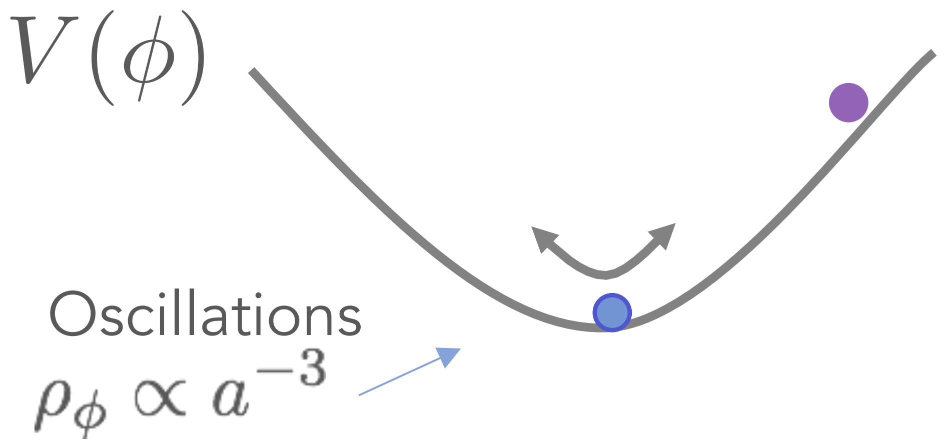
Axions/ALPs
- Motivation from particle physics
- Axions/ALPs behave like DM: one of the leading candidates for DM

Cosmological evolution



Boson/ Scalar field in a cosmological (FRW) background

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



Axions or Axion like particles (ALP)

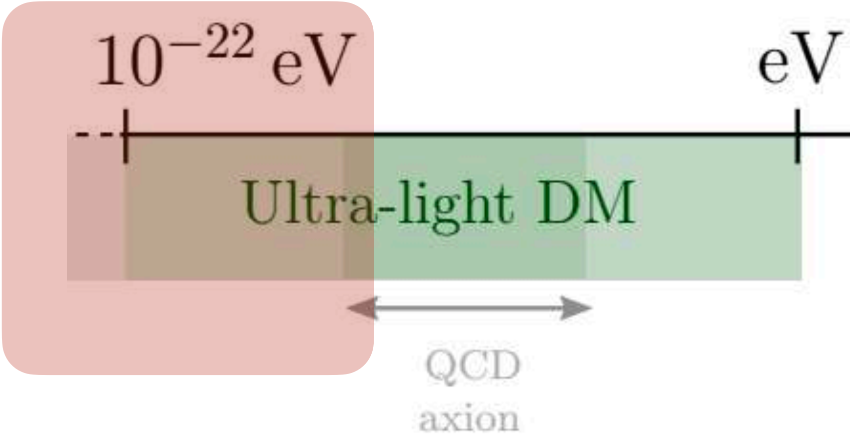
Axions and ALPs are pseudo Nambu Goldstone bosons from the spontaneous symmetry breaking of a U$_{\text{PQ}}$(1) (U(1)) symmetry, and are described by the complex field: $\Psi = v\,e^{i\phi/f_a}$

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

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

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

Structure formation - non-relativistic regime



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

<u>Schrödinger-Poisson system</u> : 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)

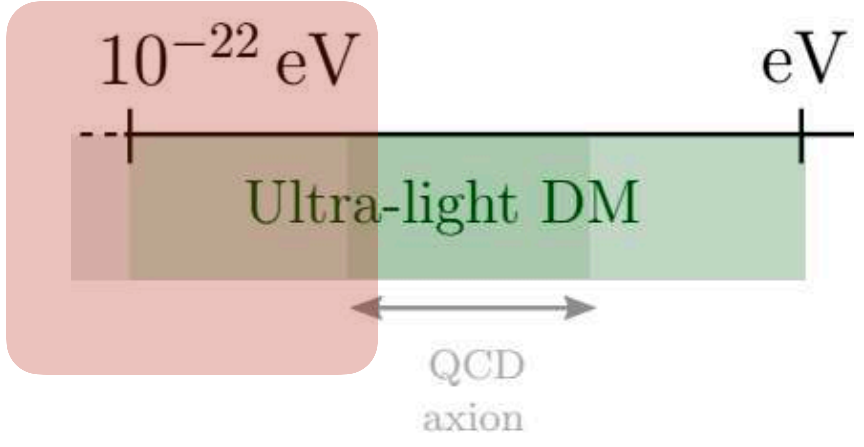
Poisson equation

$g = 0 \longrightarrow$ FDM

$g \neq 0 \longrightarrow$ SIFDM

Fundamentally different than
CDM/WDM/SIDM!

Structure formation - non-relativistic regime



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Schrödinger equation
(Gross-Pitaevskii)

Poisson equation

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$g \neq 0 \longrightarrow$ SIFDM

Fundamentally different than
CDM/WDM/SIDM!

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

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

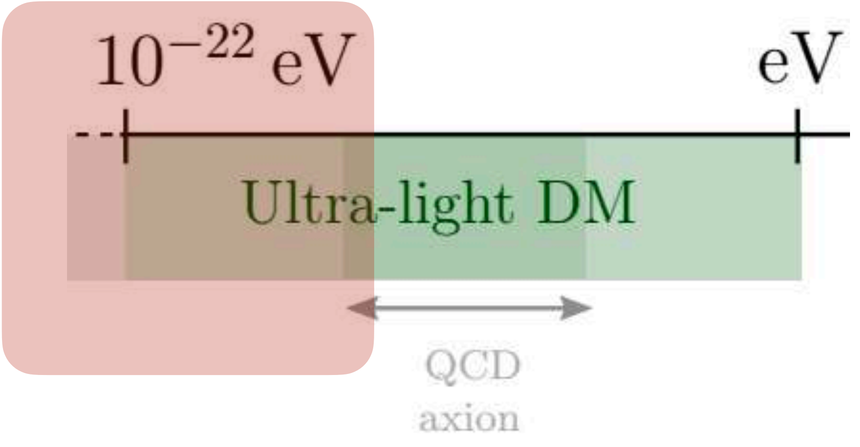
$$\dot{\rho} + \nabla\cdot(\rho\,\mathbf{v}) = 0$$

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

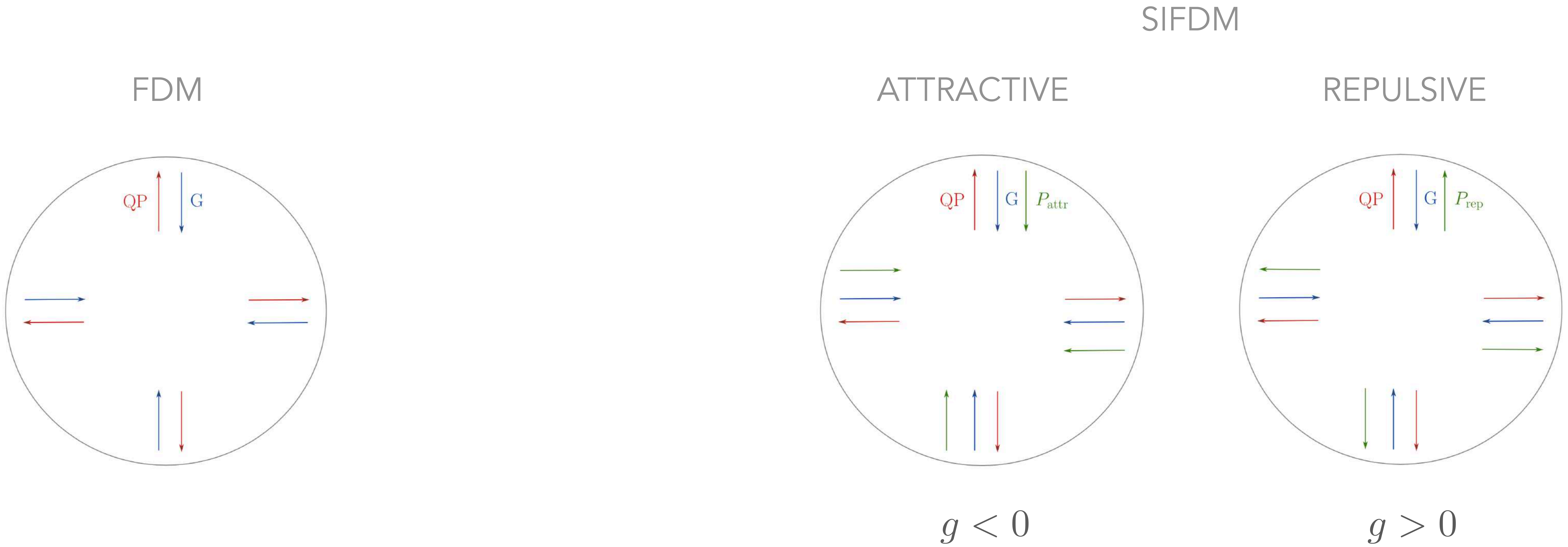
Quantum pressure

FLUID
DESCRIPTION

Structure formation - perturbation and stability



Competition between gravity and pressure (quantum pressure and interaction)



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

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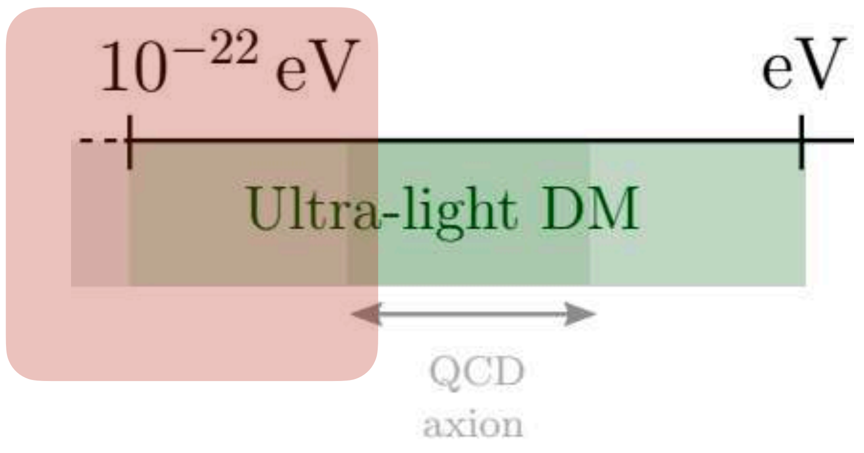
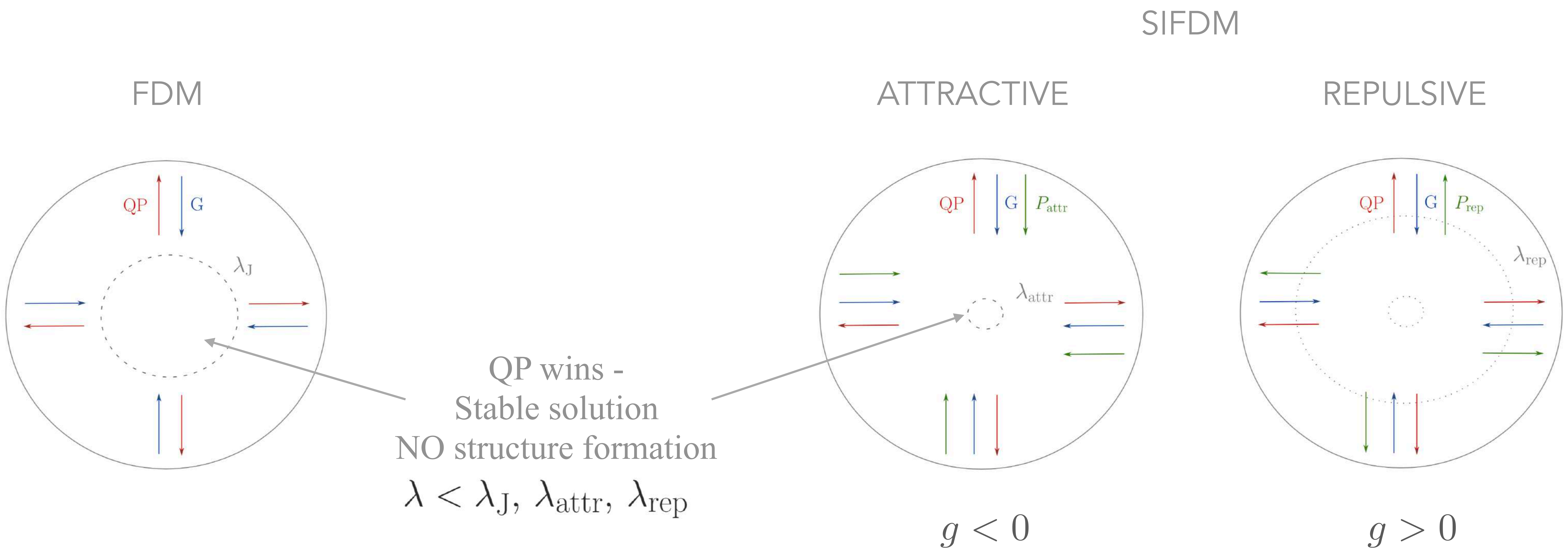
Quantum pressure

Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales



QP wins -
Stable solution
NO structure formation

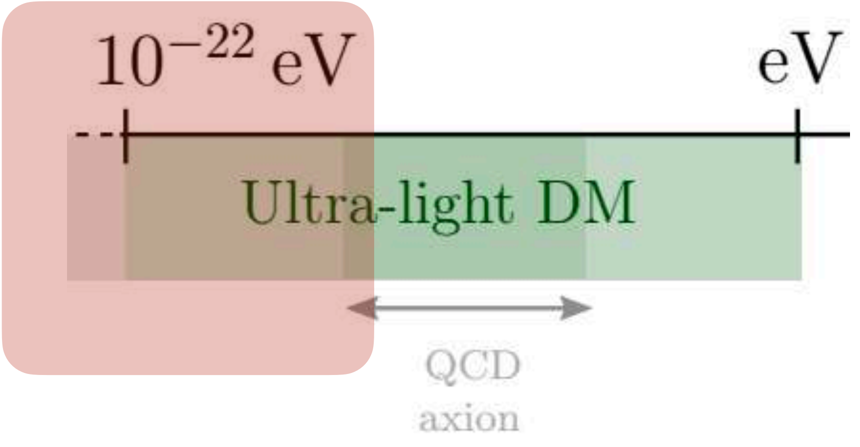
$\lambda < \lambda_J, \lambda_{\mathrm{attr}}, \lambda_{\mathrm{rep}}$

$g < 0$

$g > 0$

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

Structure formation - perturbation and stability



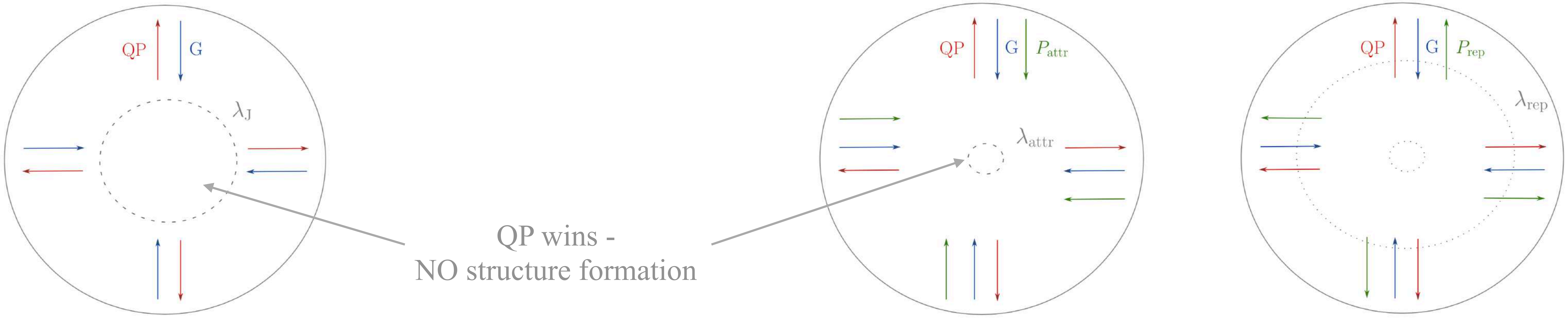
Finite clustering scale - no structure formation on small scales

SIFDM

FDM

ATTRACTIVE

REPULSIVE



QP wins -
NO structure formation

$g < 0$

$g > 0$

Finite size coherent core – Bose stars

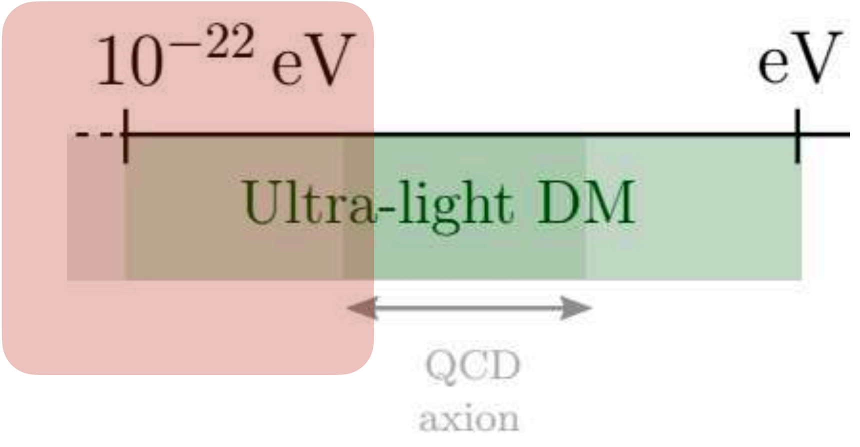
$$\lambda_J = 55 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1/2} \left(\frac{\rho}{\bar{\rho}}\right)^{-1/4} (\Omega_m h)^{-1/4}\,\mathrm{kpc}$$

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

For attractive interactions can only form localized clumps (solitons)

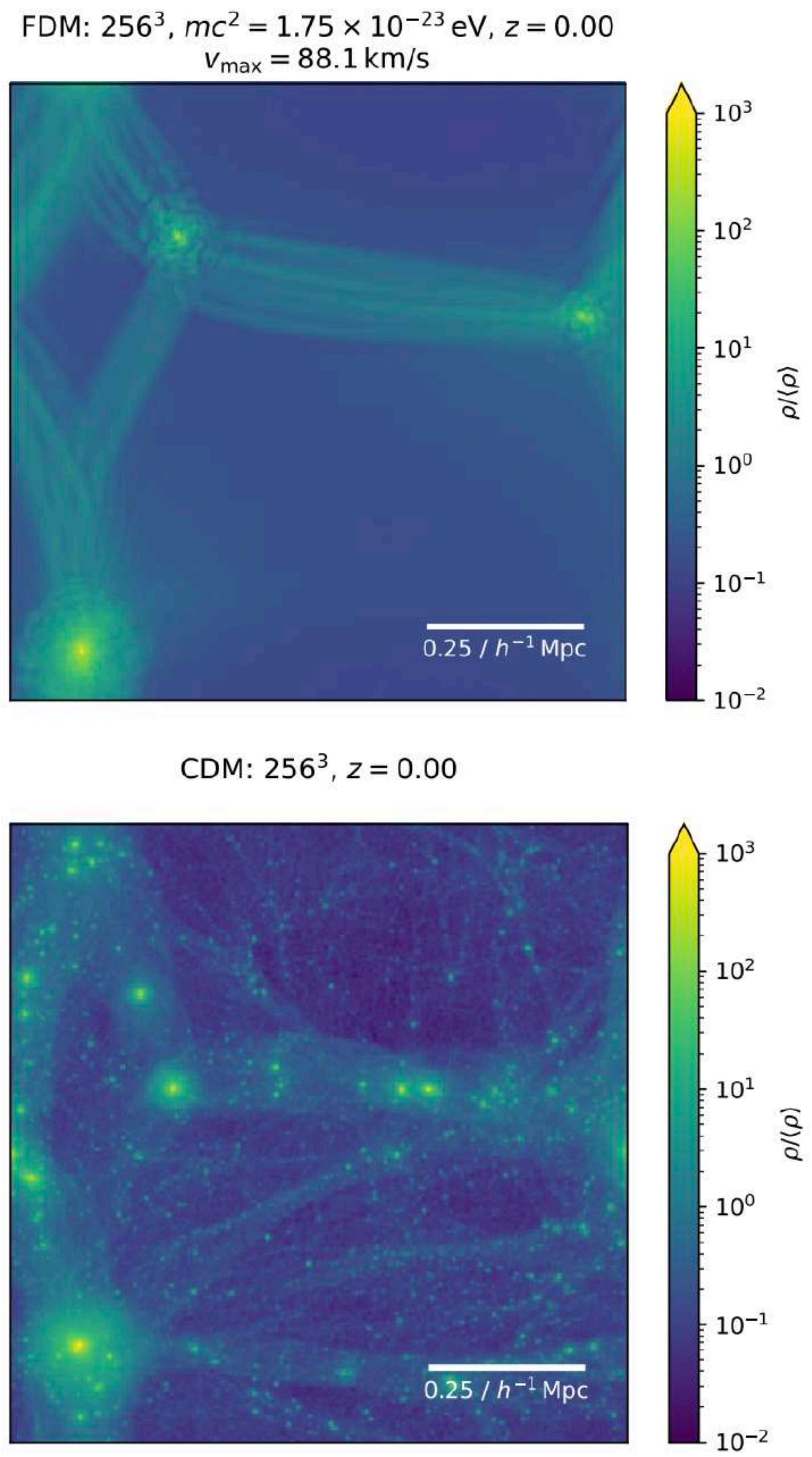
QCD axion: $m \sim 10^{-5}\,\mathrm{eV}$ $\lambda_a \sim -10^{-48}$ $\longrightarrow$ $l_{soliton} \sim 10^{-5}\,\mathrm{kpc}$

Phenomenology



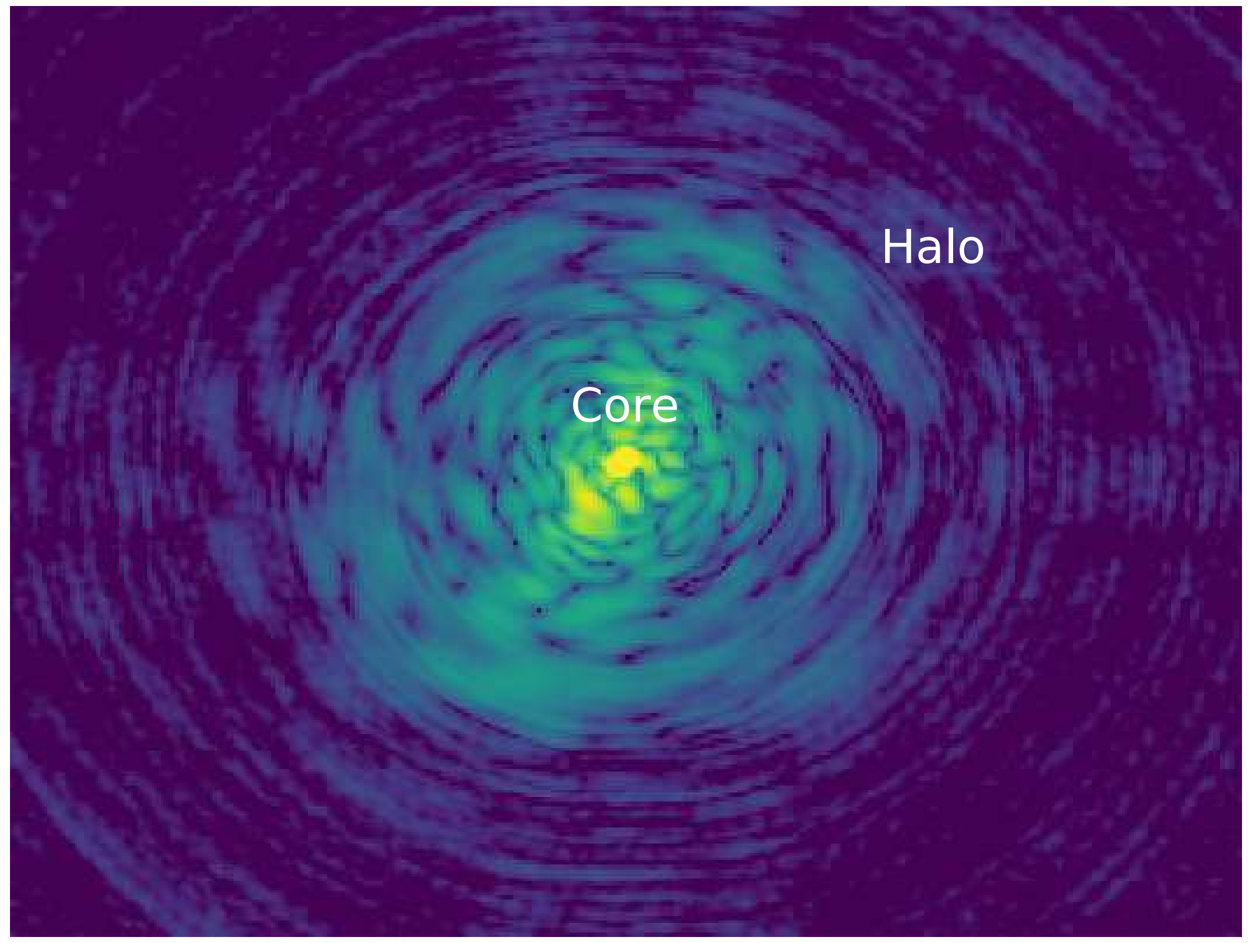
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

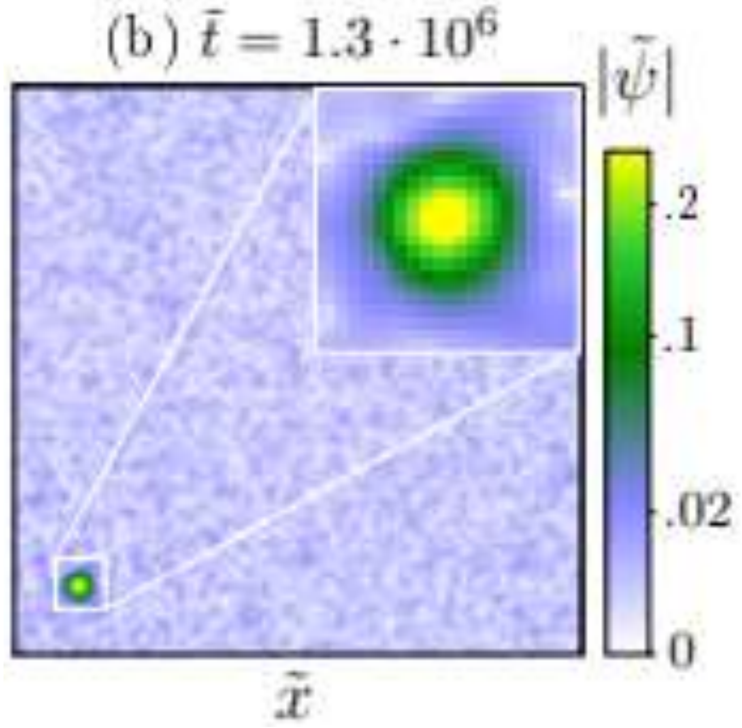


S. May et al. 2021

Formation of a solitonic core

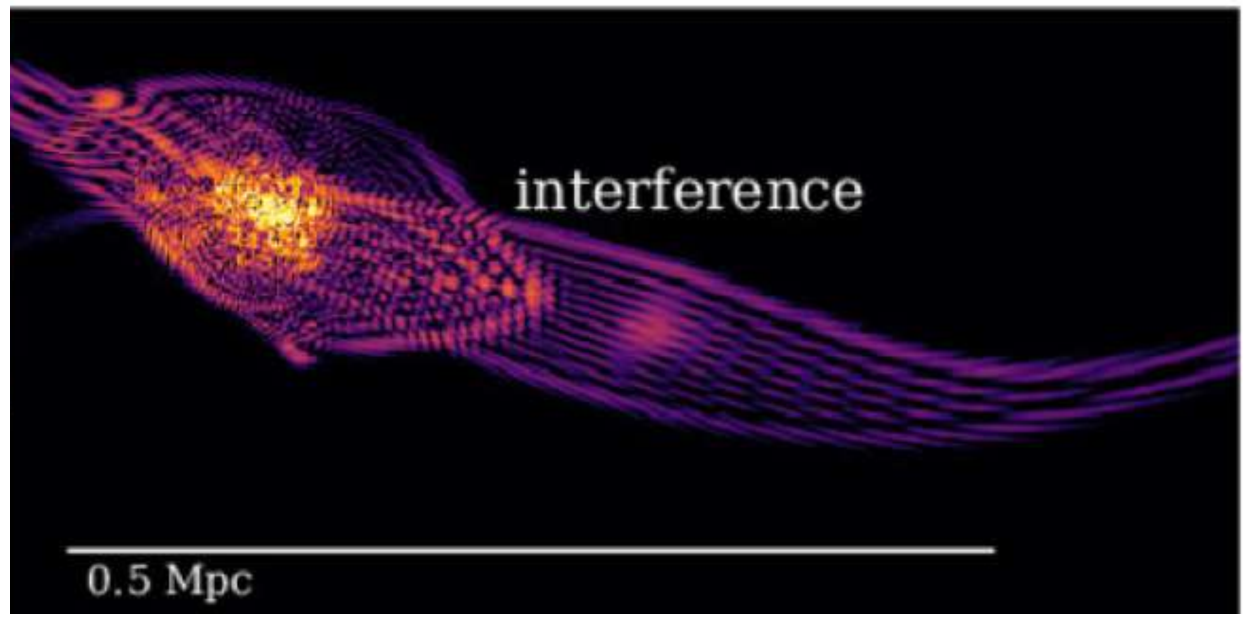


Dynamical effects



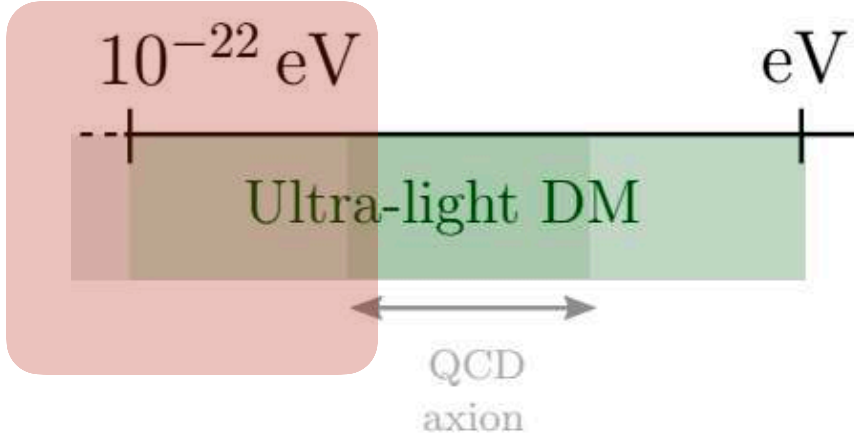
Levkov et al. 2018

Wave interference



Mocz et al. 2017

Phenomenology



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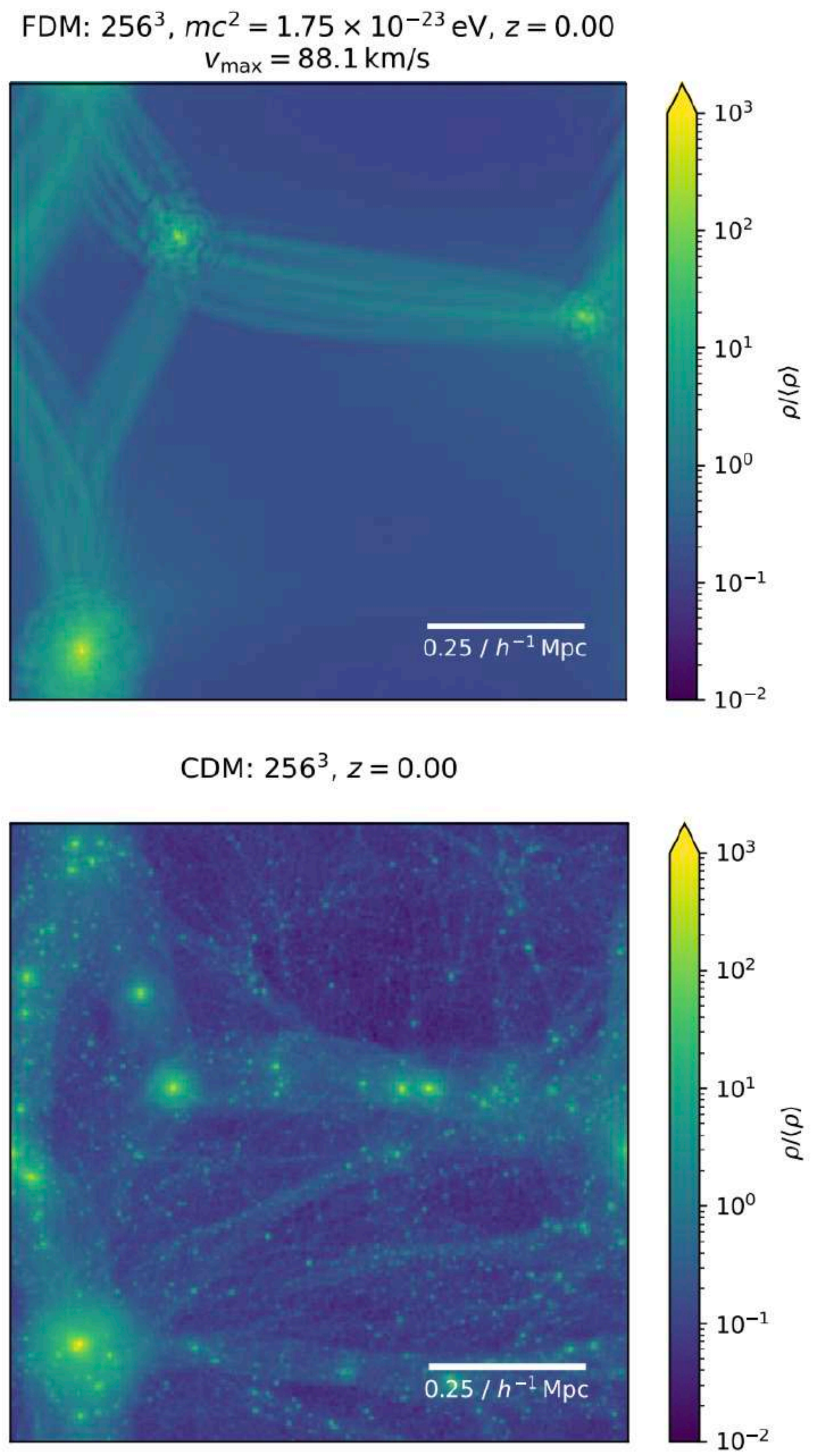
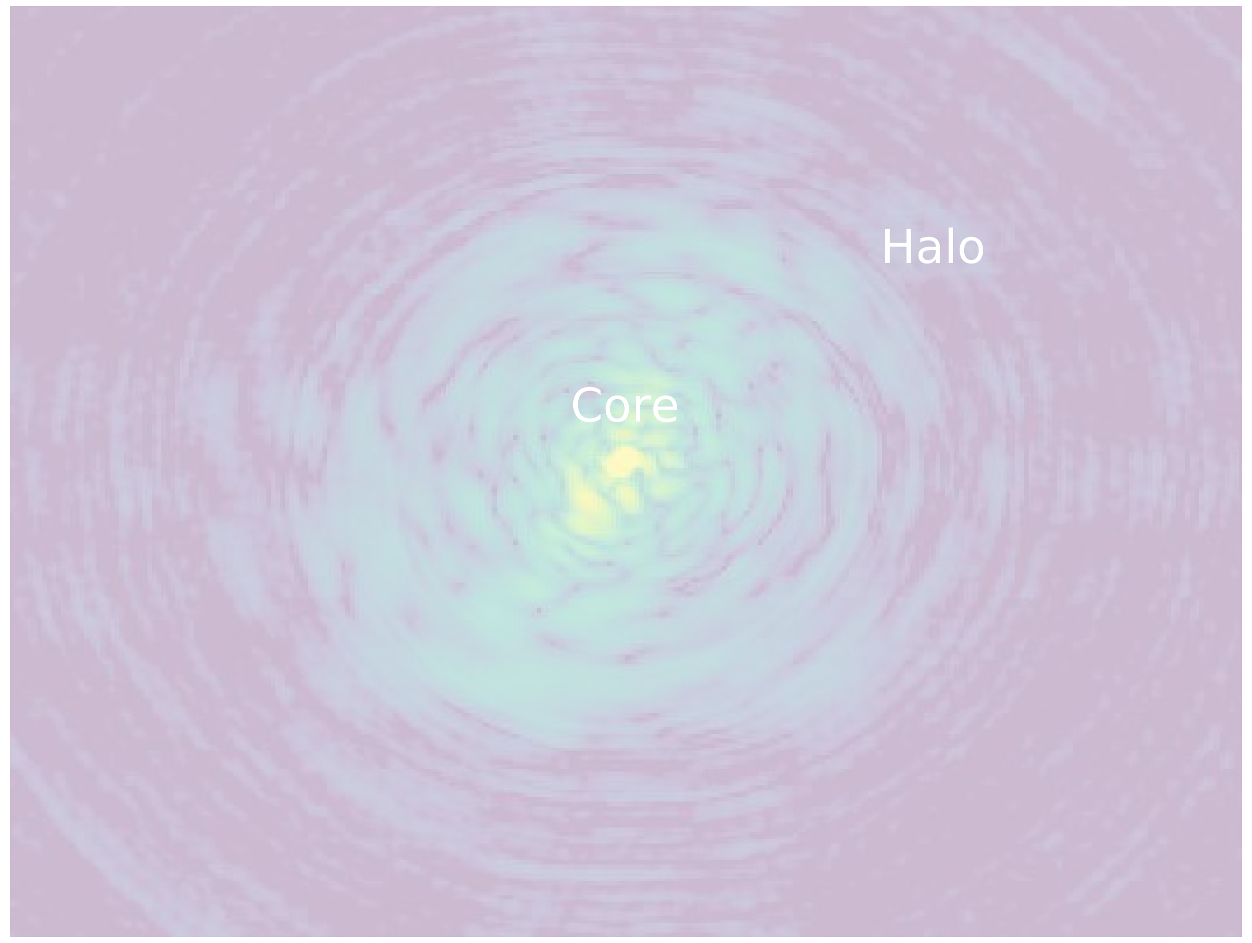


S. May et al. 2021

Formation of a solitonic core



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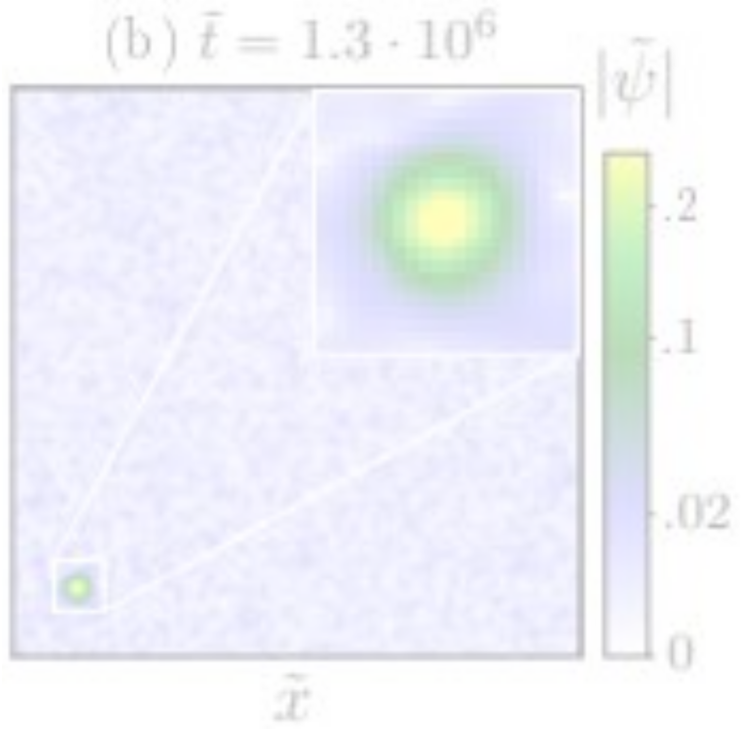

Levkov et al. 2018

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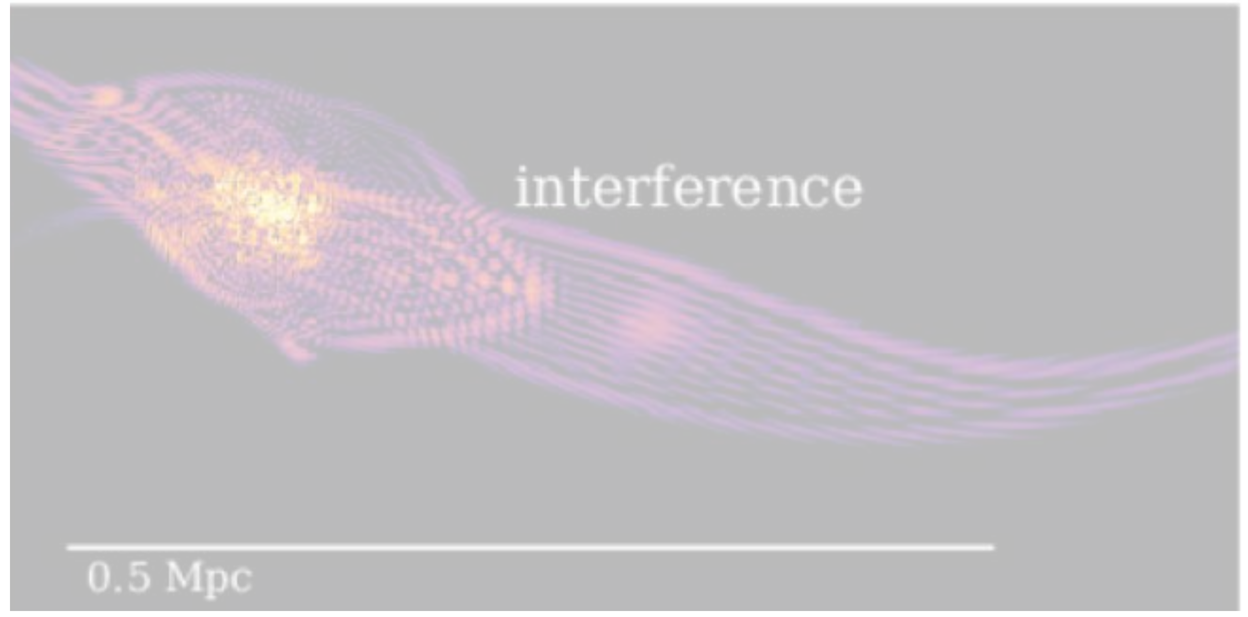
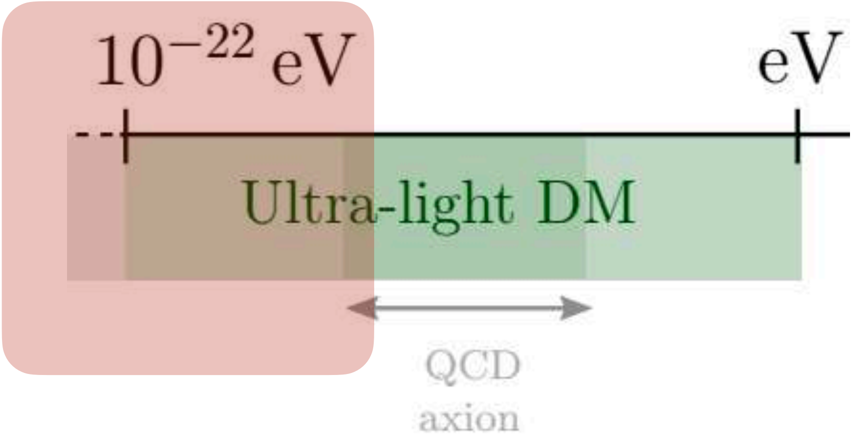


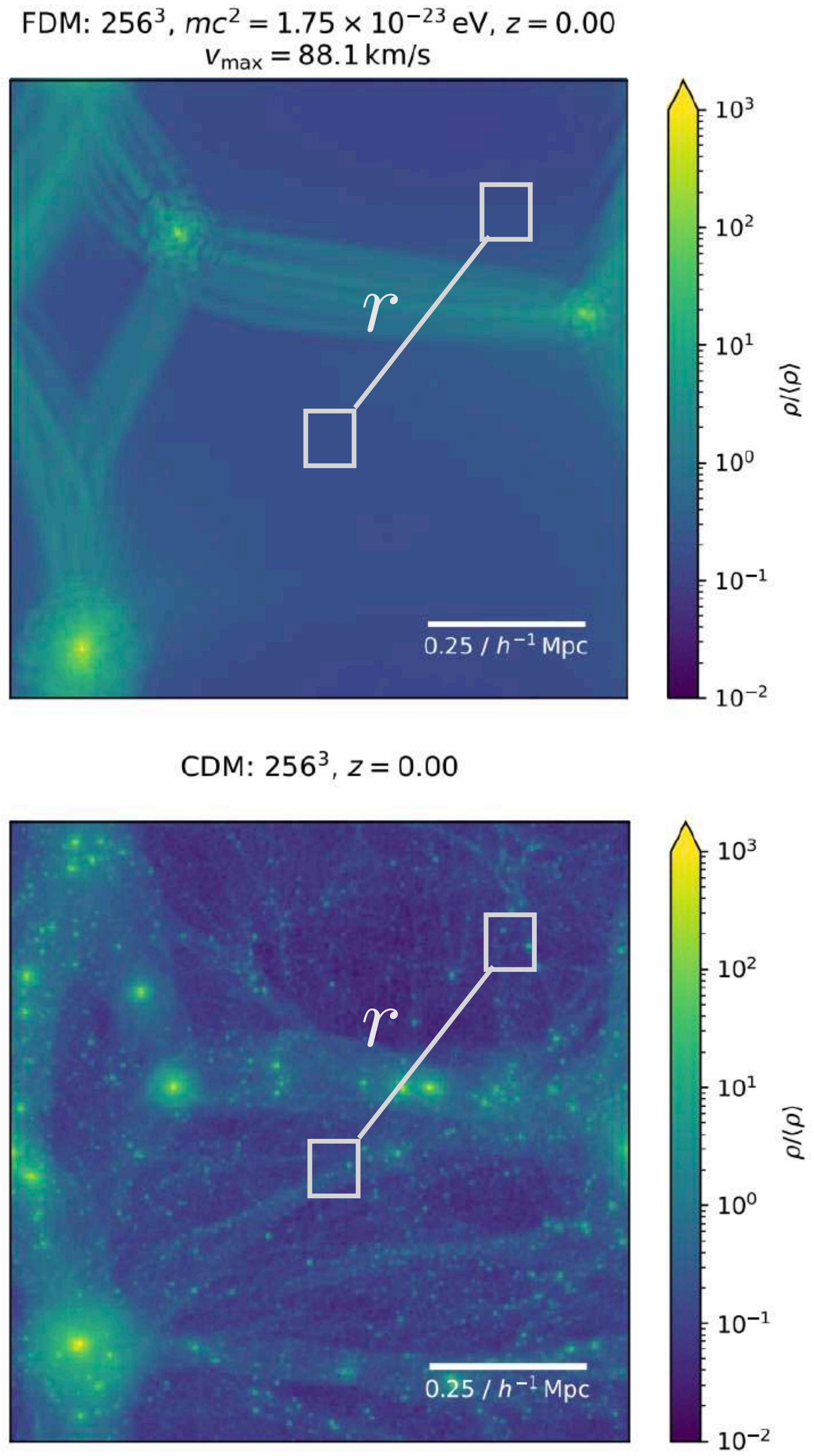
Mocz et al. 2017

Phenomenology

Suppression of small structures



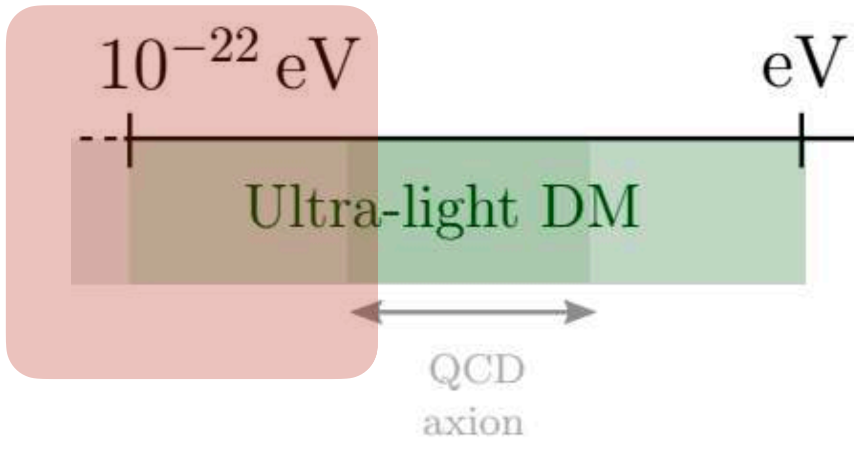
Finite Jeans length λ_J or $\lambda_{\text{attr}}, \lambda_{\text{rep}}$ → No small scale structure



S. May et al. 2021

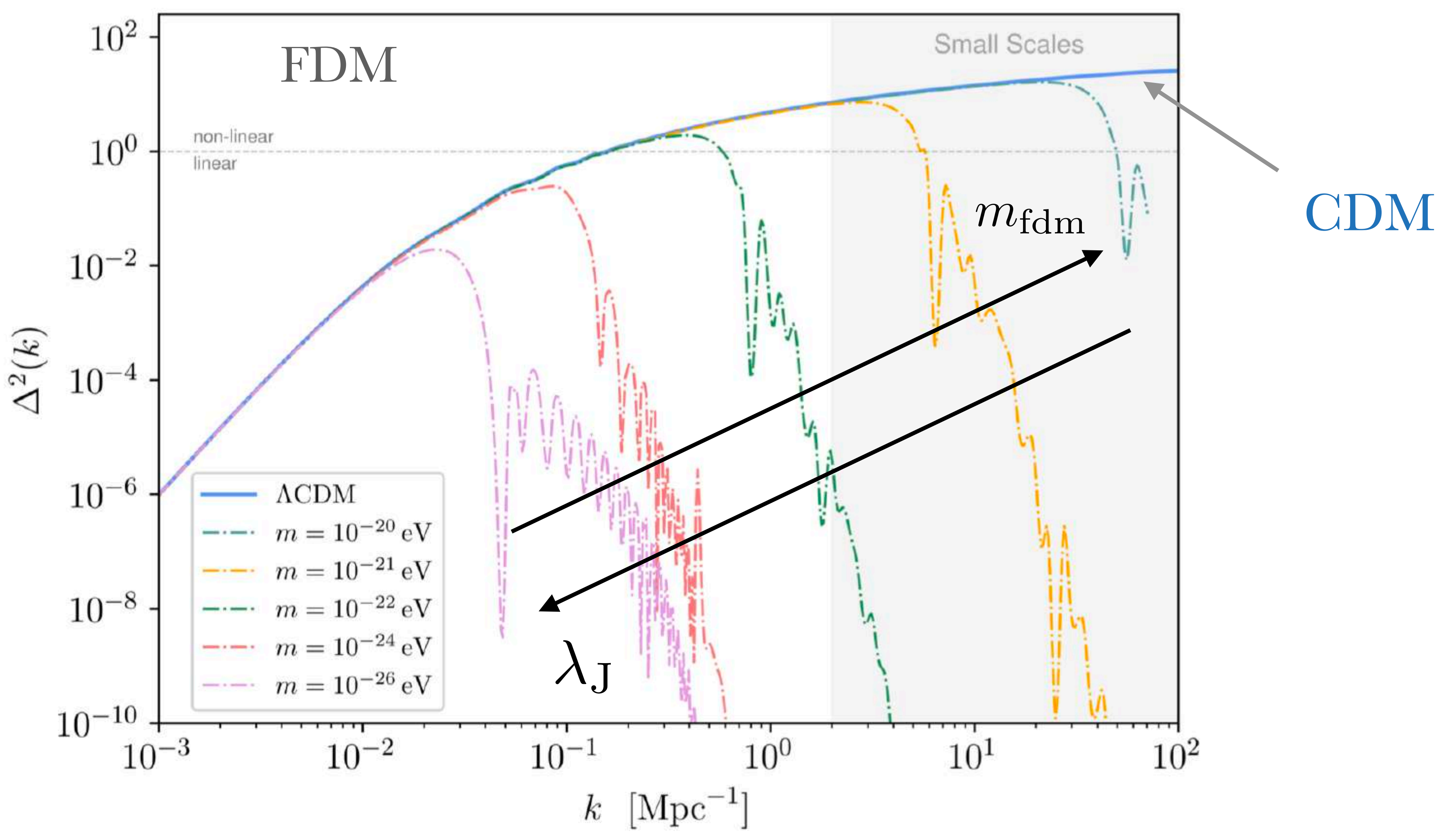
Phenomenology

Suppression of small structures

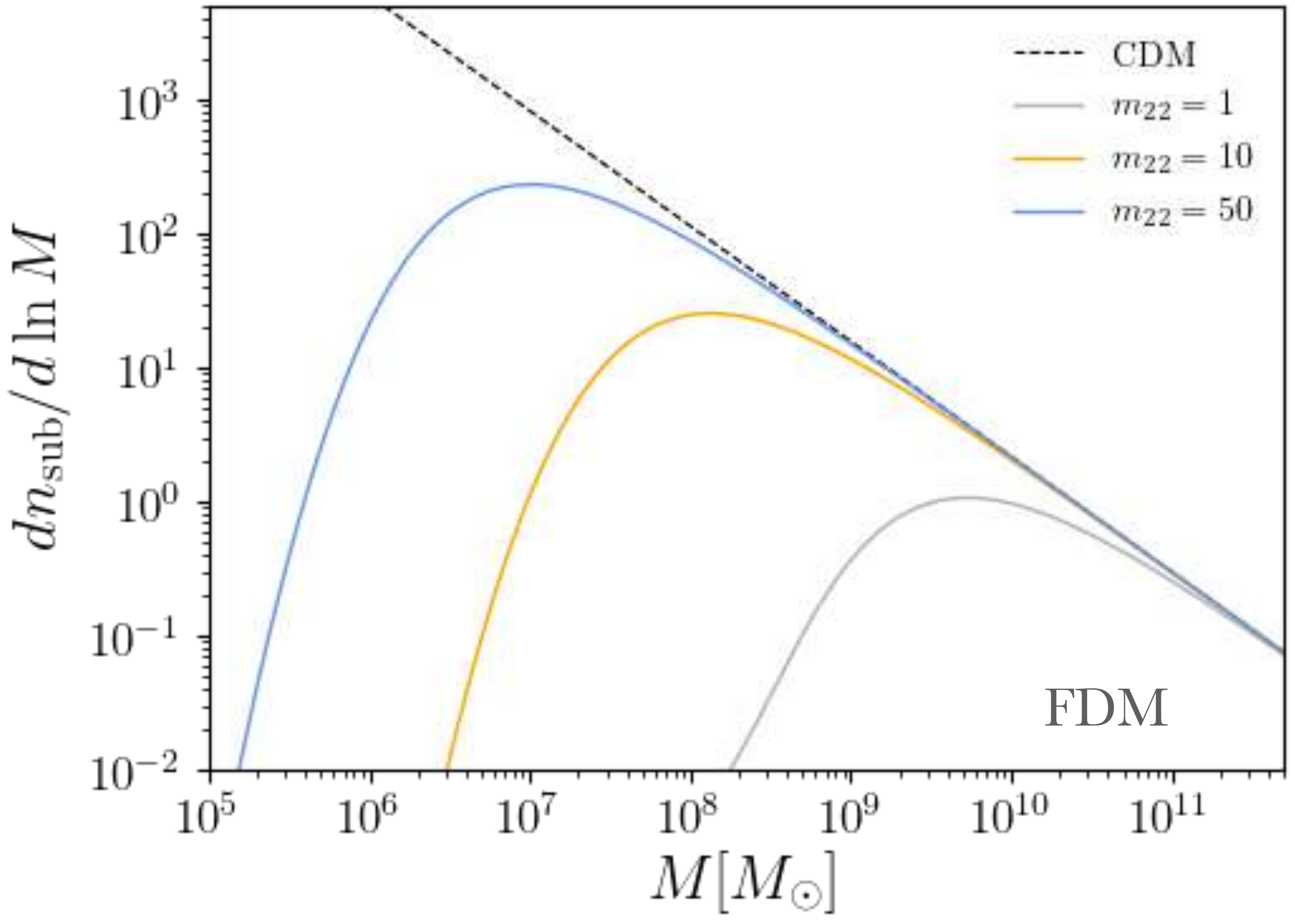


Finite Jeans length λ_J or $\lambda_{\text{attr}}, \lambda_{\text{rep}}$ → Suppresses small scale structure

POWER SPECTRUM

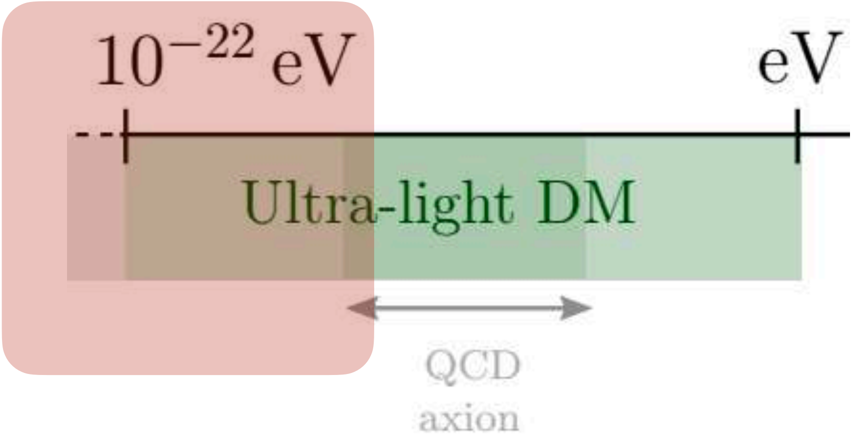


(sub) HALO MASS FUNCTION



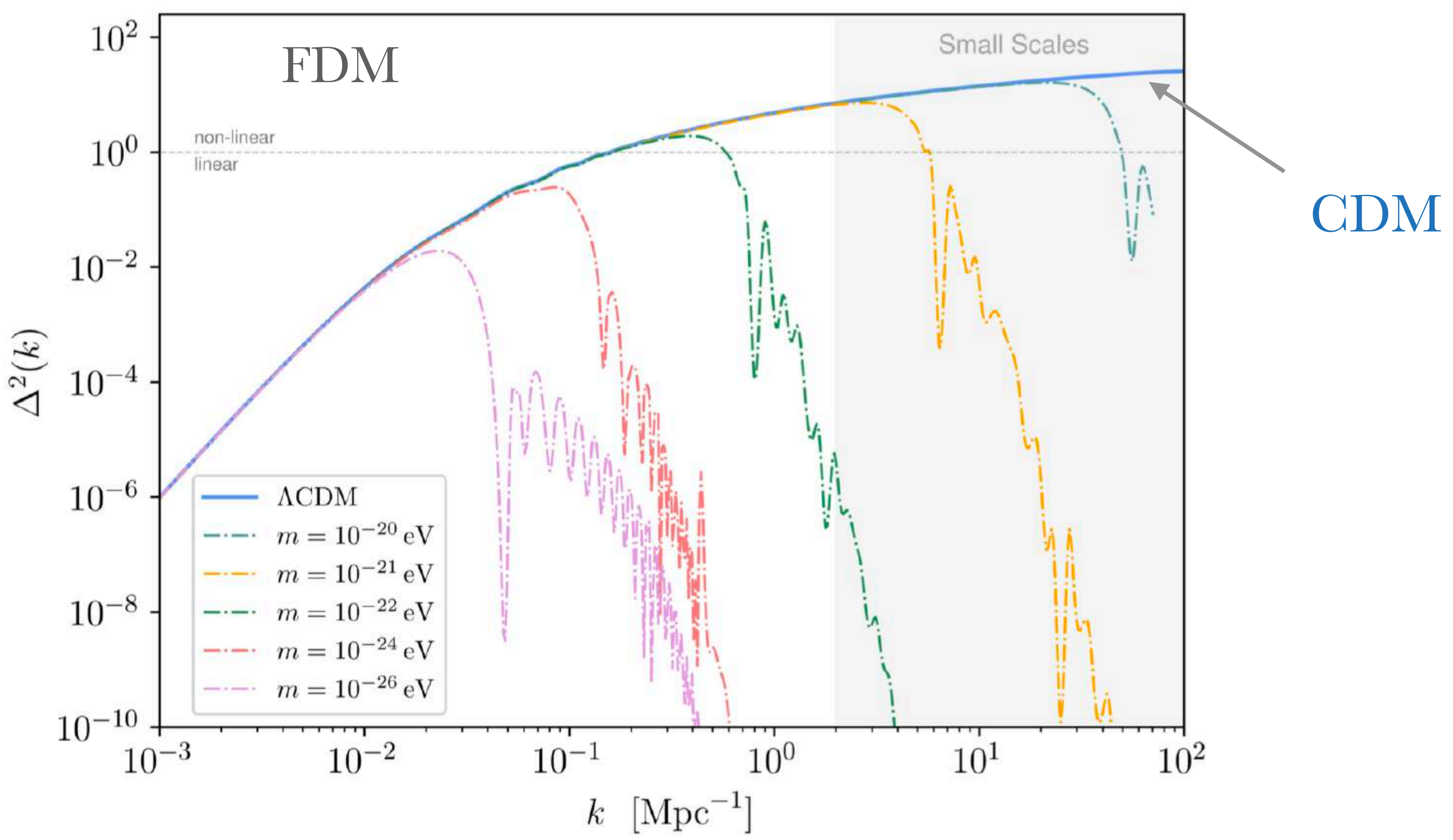
Phenomenology

Suppression of small structures



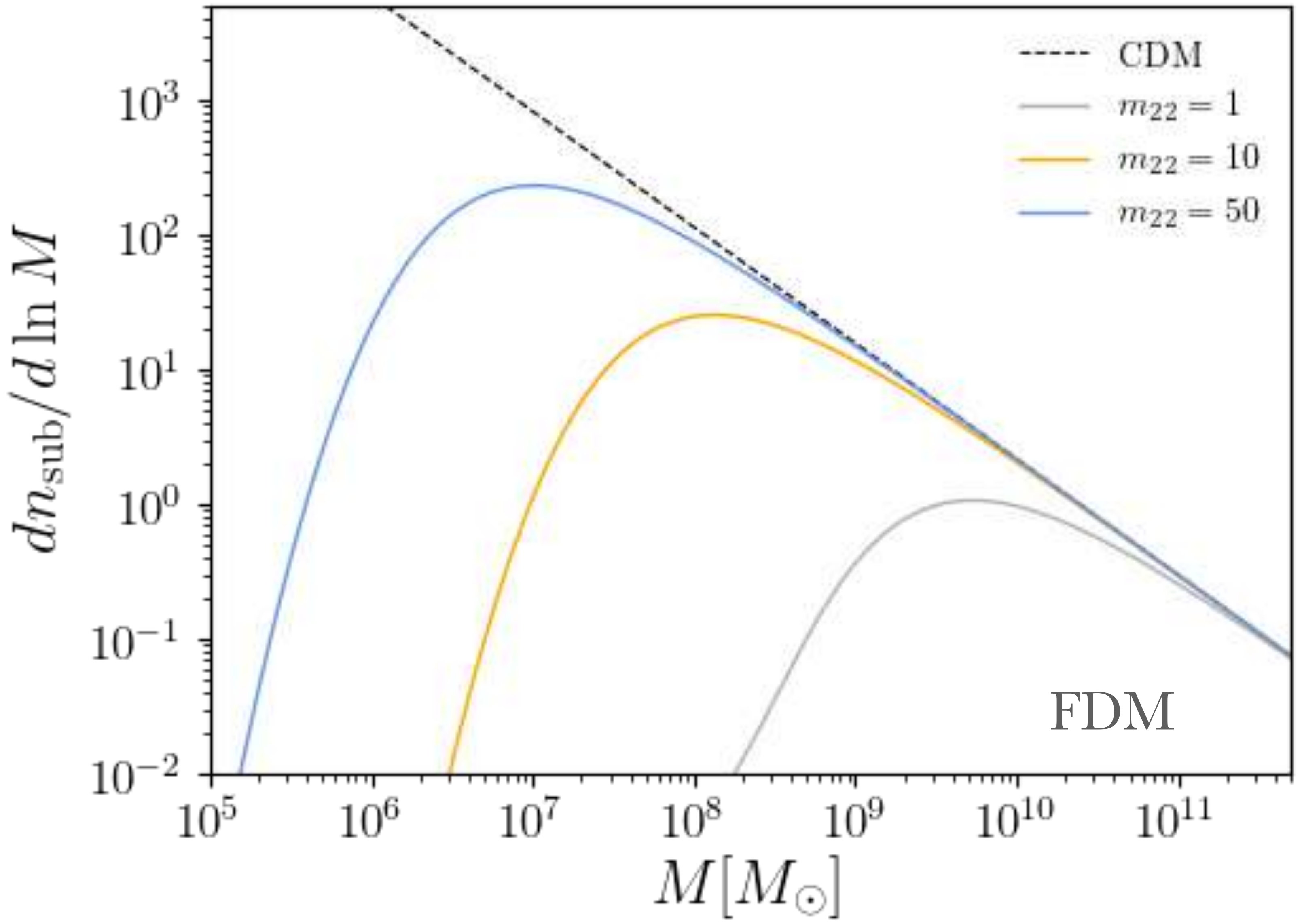
Finite Jeans length λ_J or $\lambda_{\rm attr}$, $\lambda_{\rm rep}$ → Suppresses small scale structure

POWER SPECTRUM



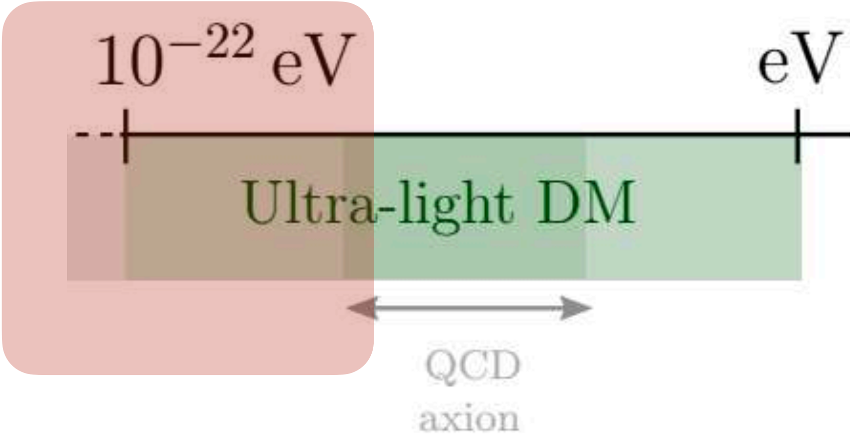
CDM

(sub) HALO MASS FUNCTION



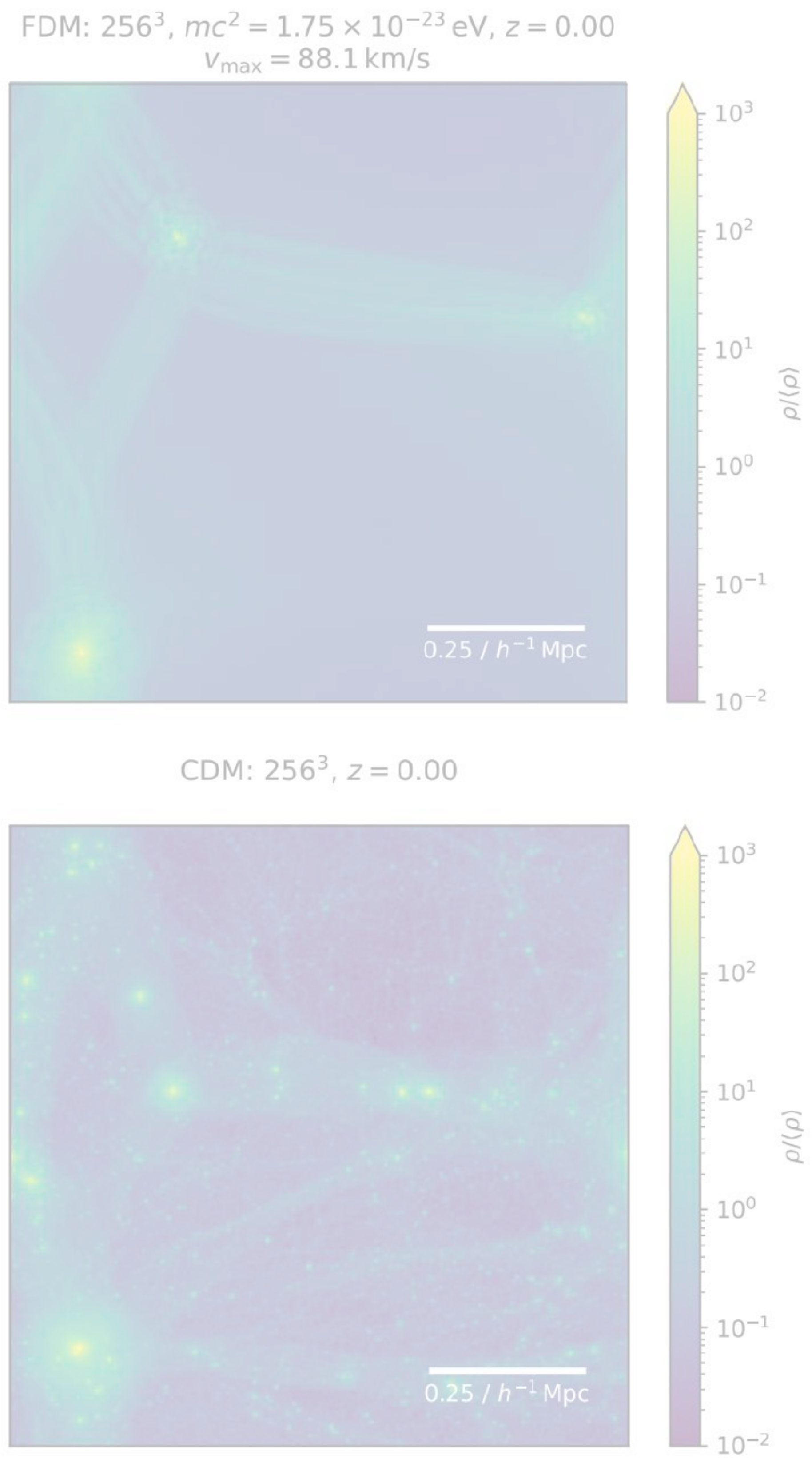
Ongoing: Modifying Boltzmann codes (*CLASS*) for the SIFDM case.

Phenomenology



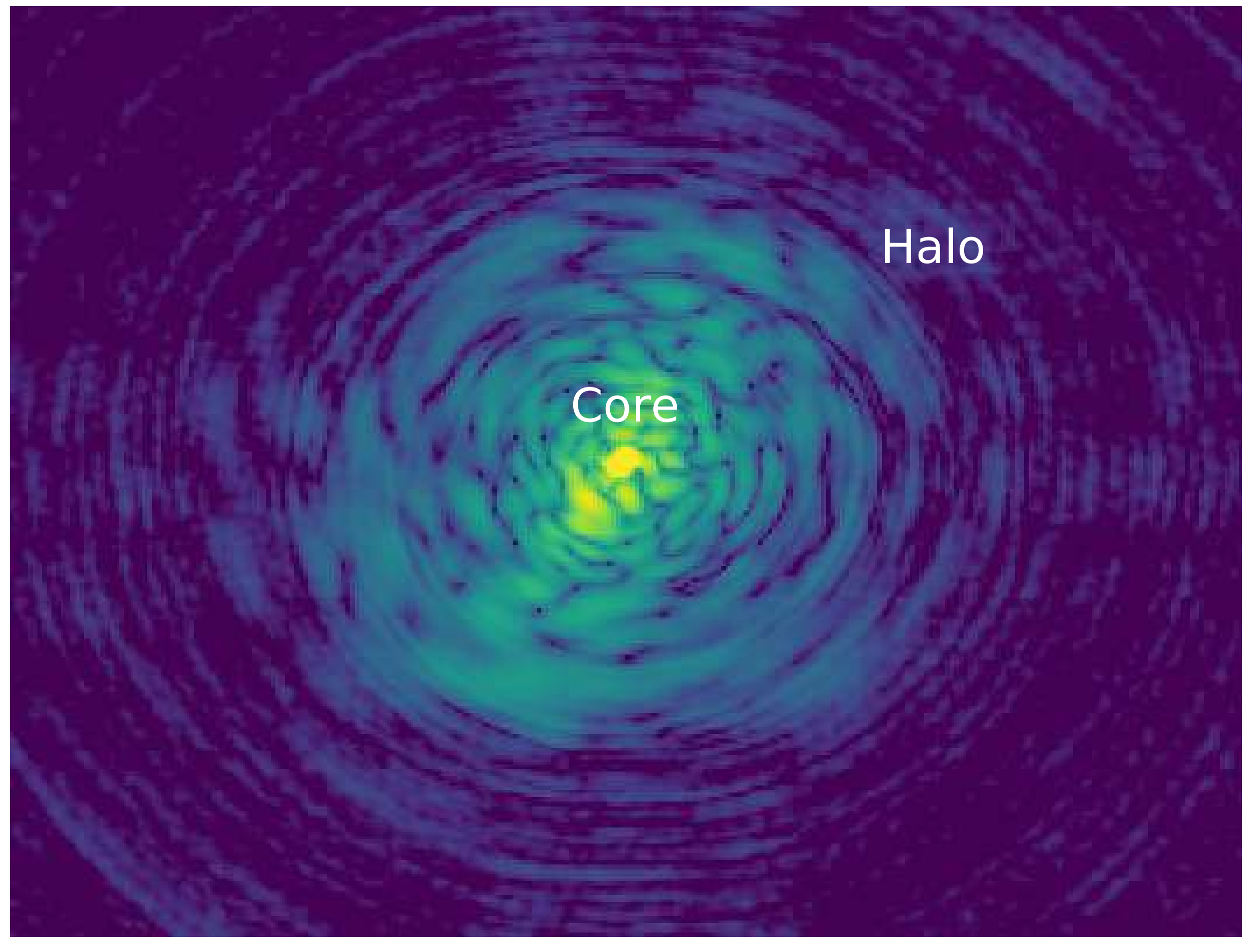
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

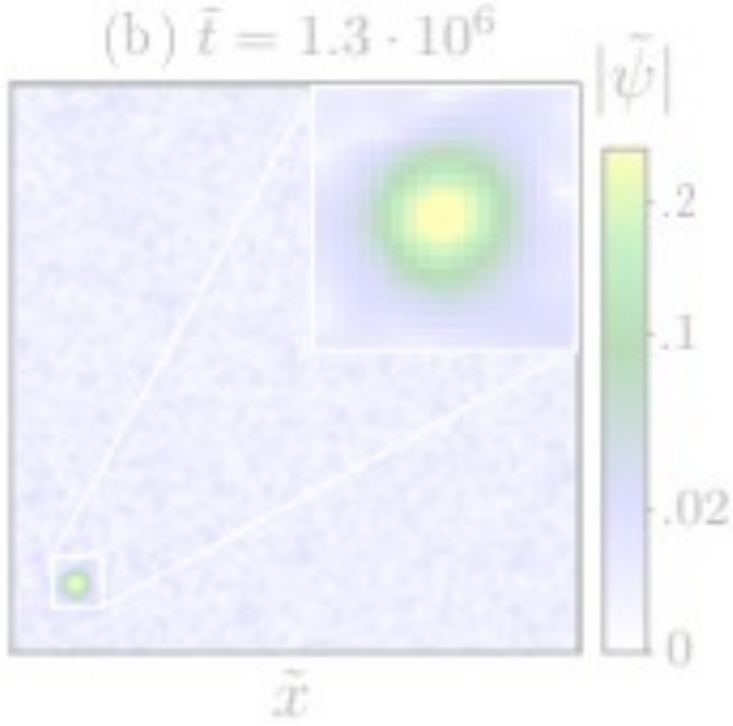


S. May et al. 2021

Formation of a solitonic core



Dynamical effects



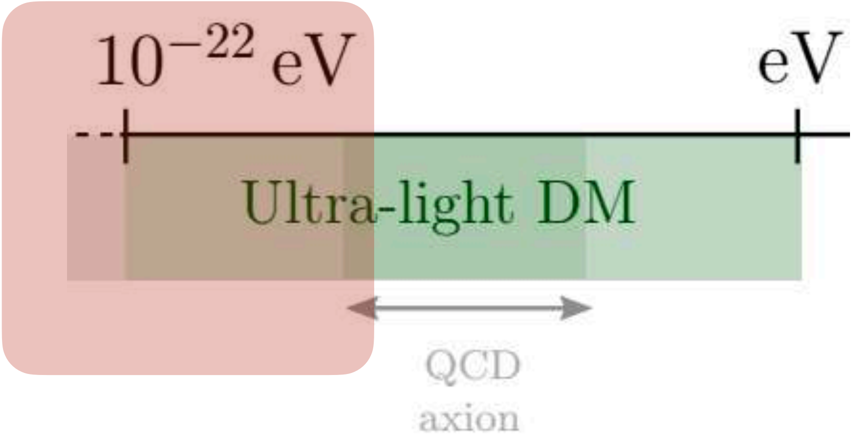
Levkov et al. 2018

Wave interference

Mocz et al. 2017

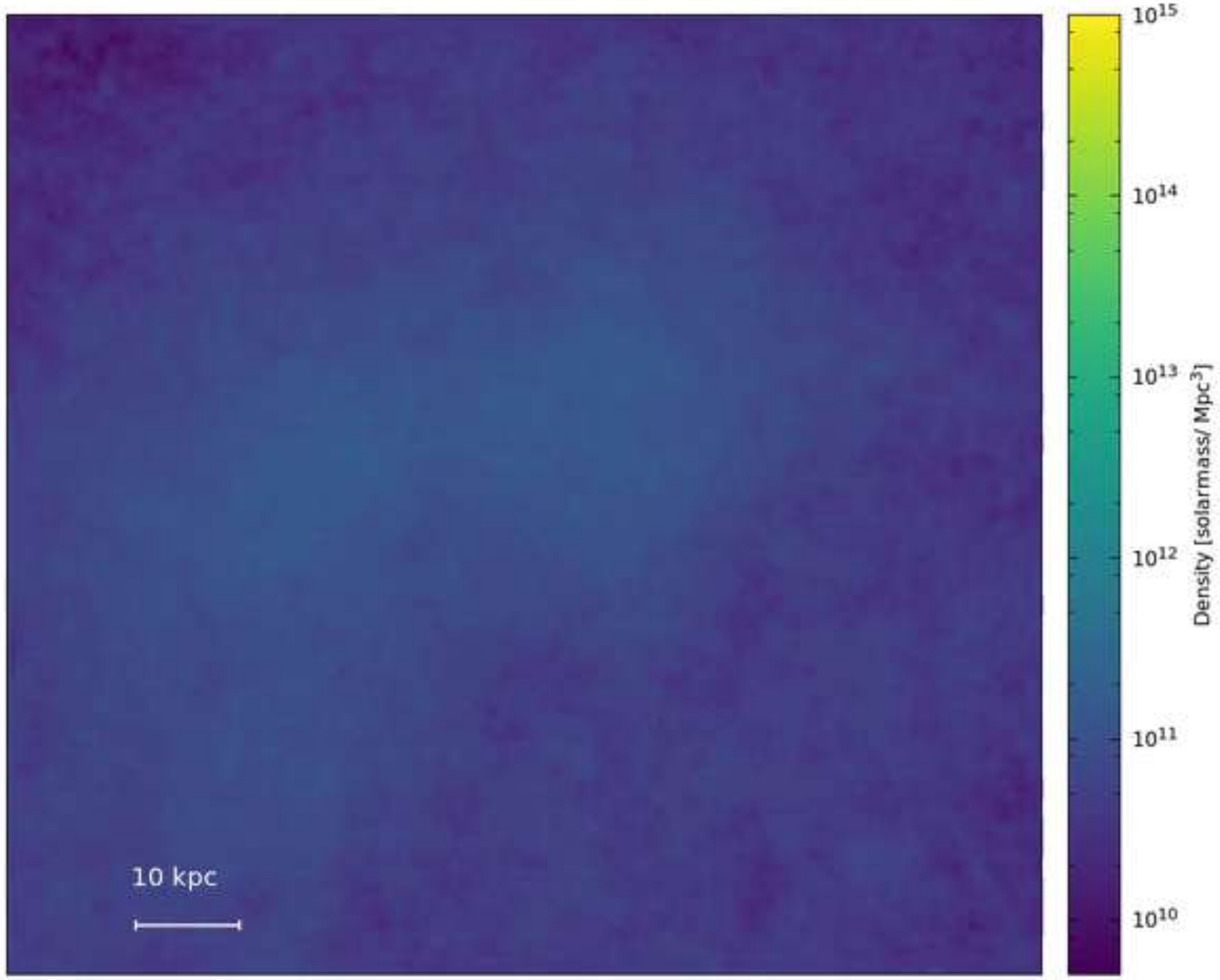
Phenomenology

Formation of cores

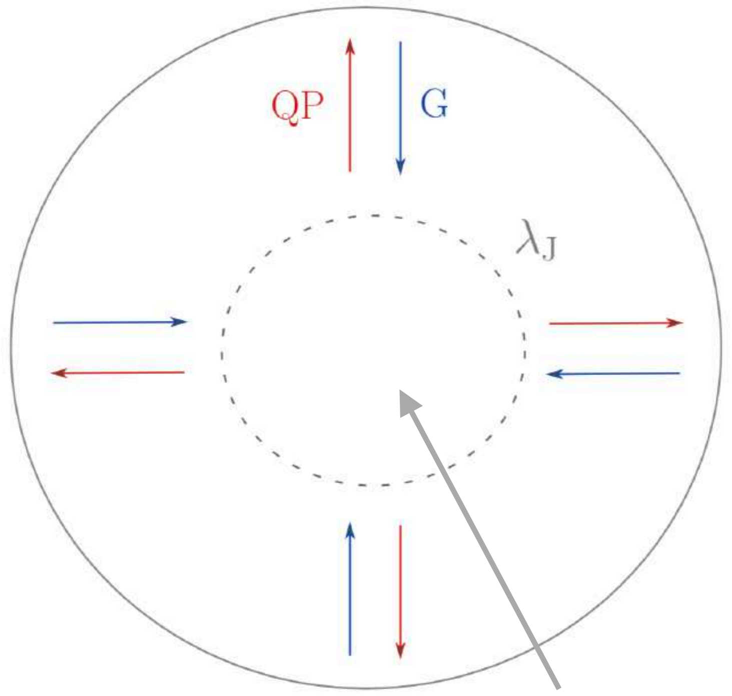


NON-LINEAR evolution: need simulations

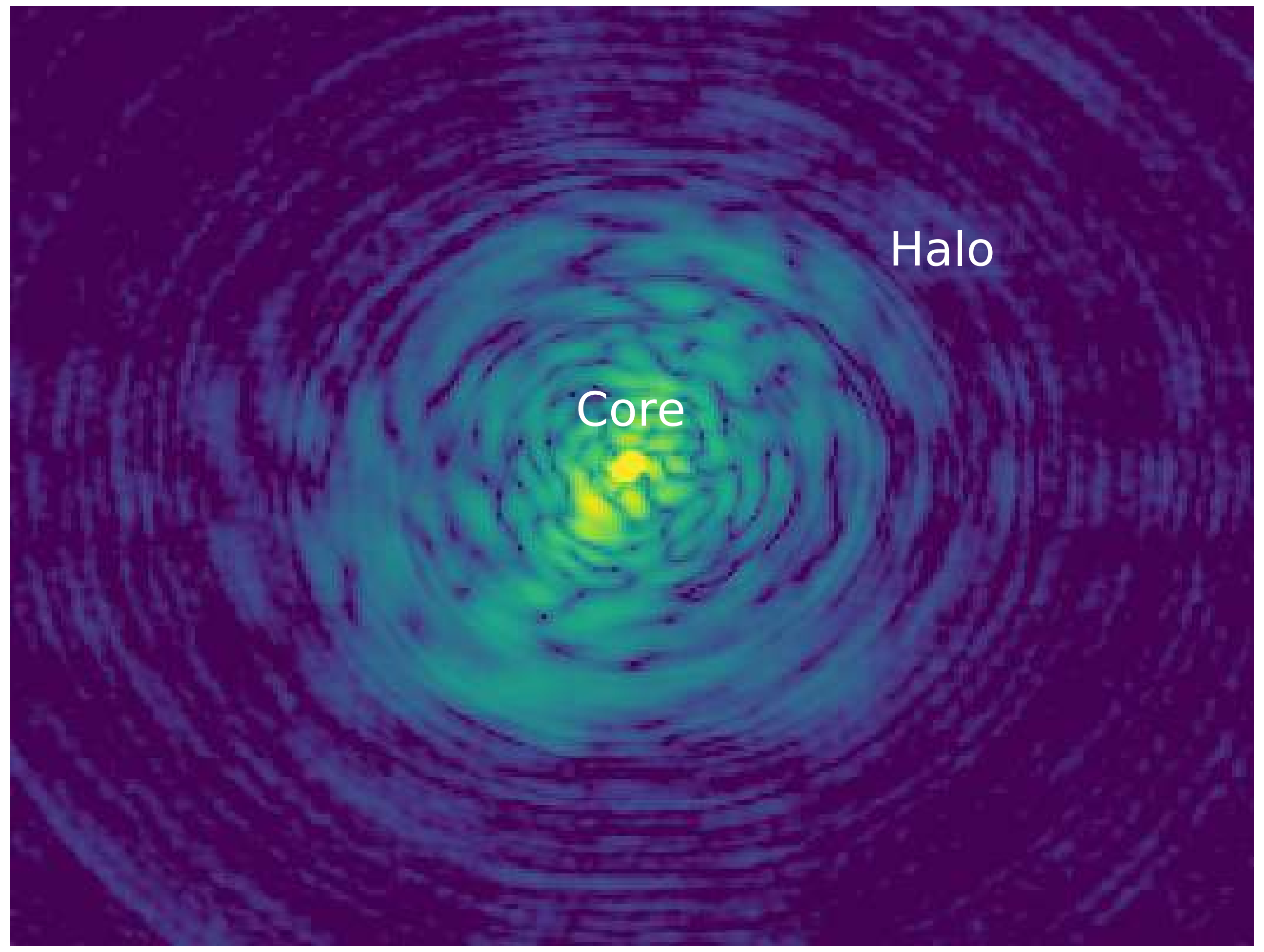
$m = 10^{-22}\,\mathrm{eV}$ $N = 512^3$ $L = 300\,\mathrm{kpc}$



Simulation by Jowett Chan

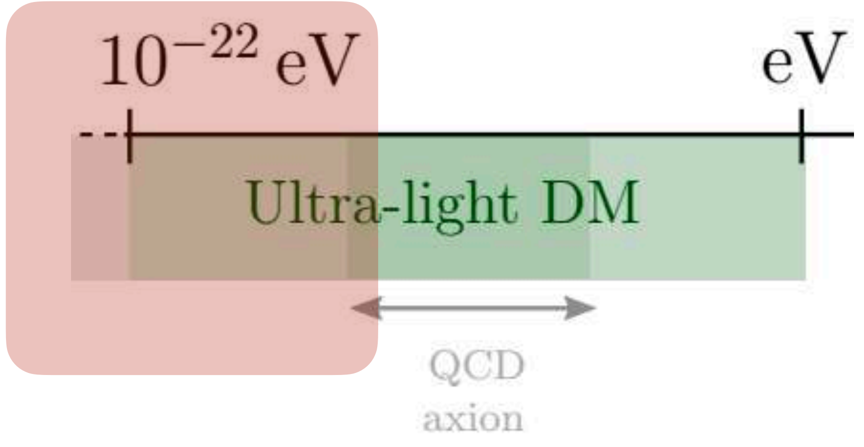


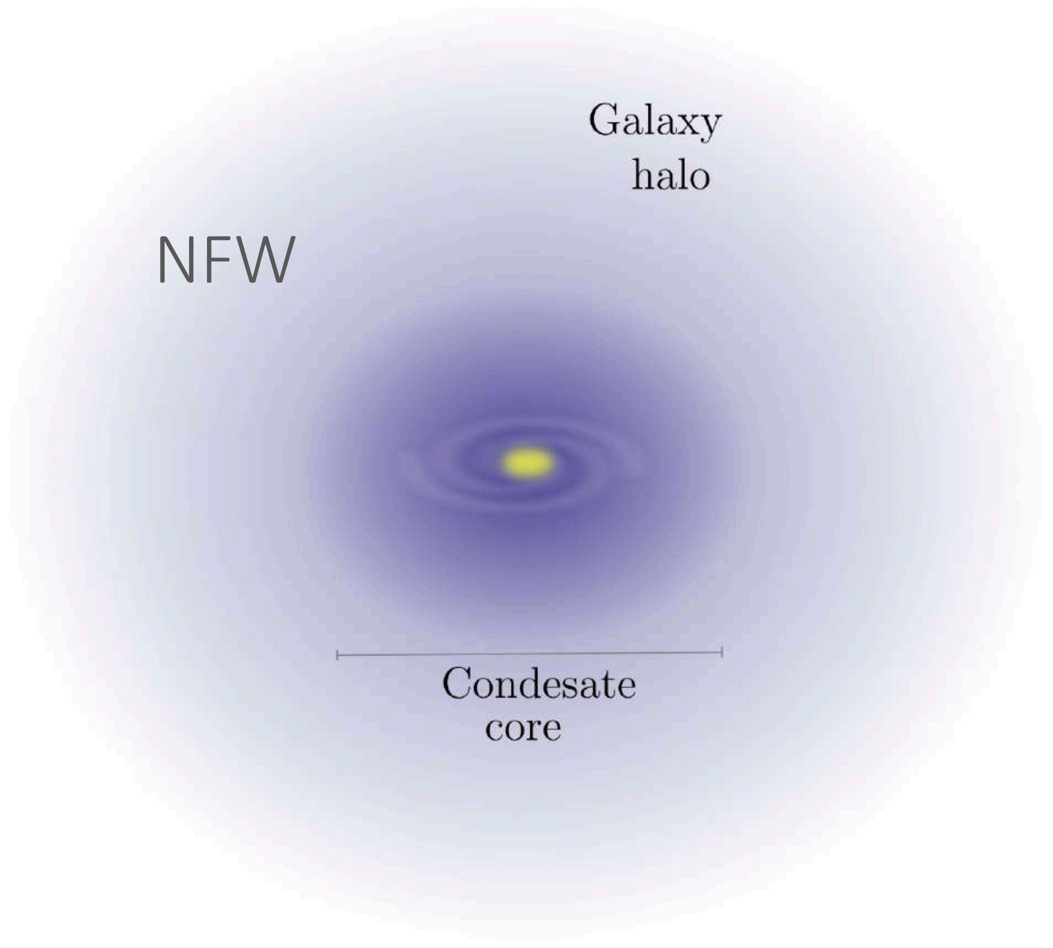
NO structure formation
Stable, oscillating solution



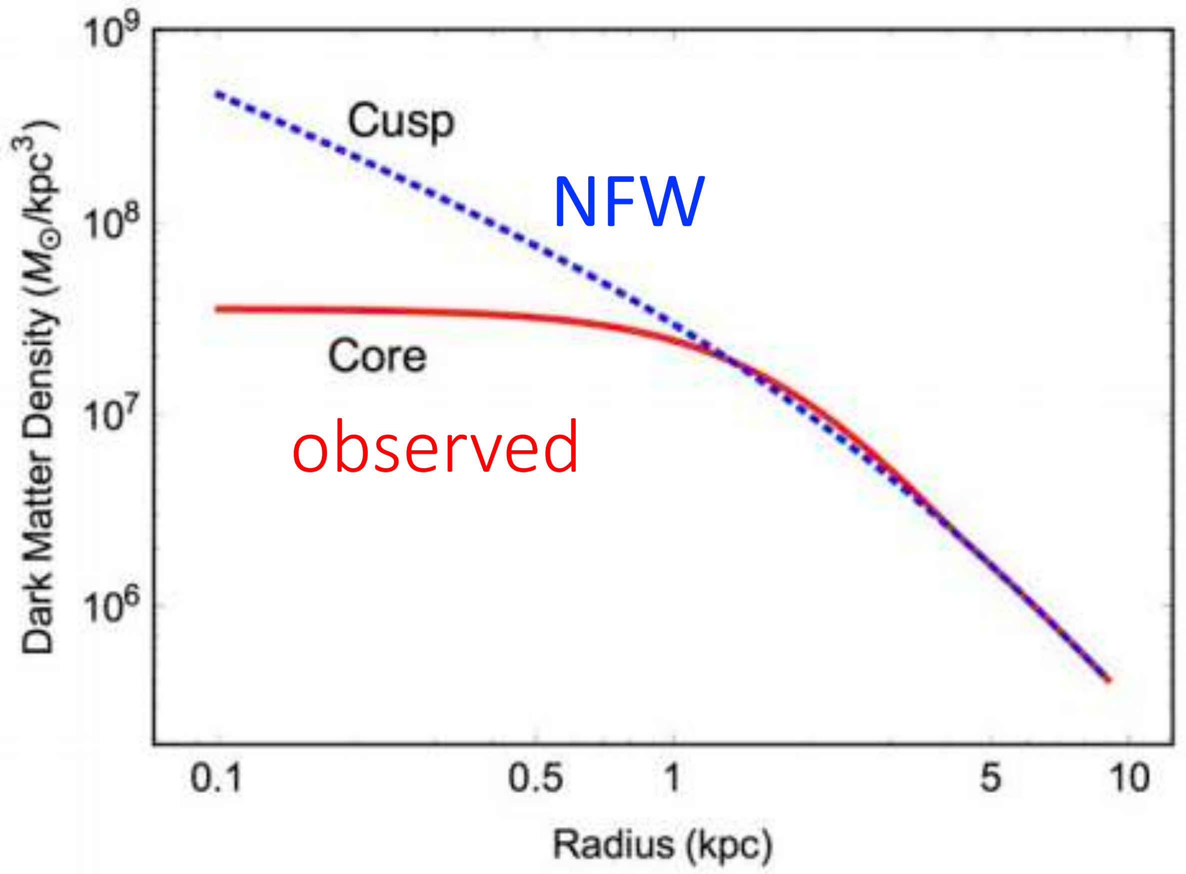
Phenomenology

Formation of cores





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



FDM From simulations Schive et a. 2014, fitting function:

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

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

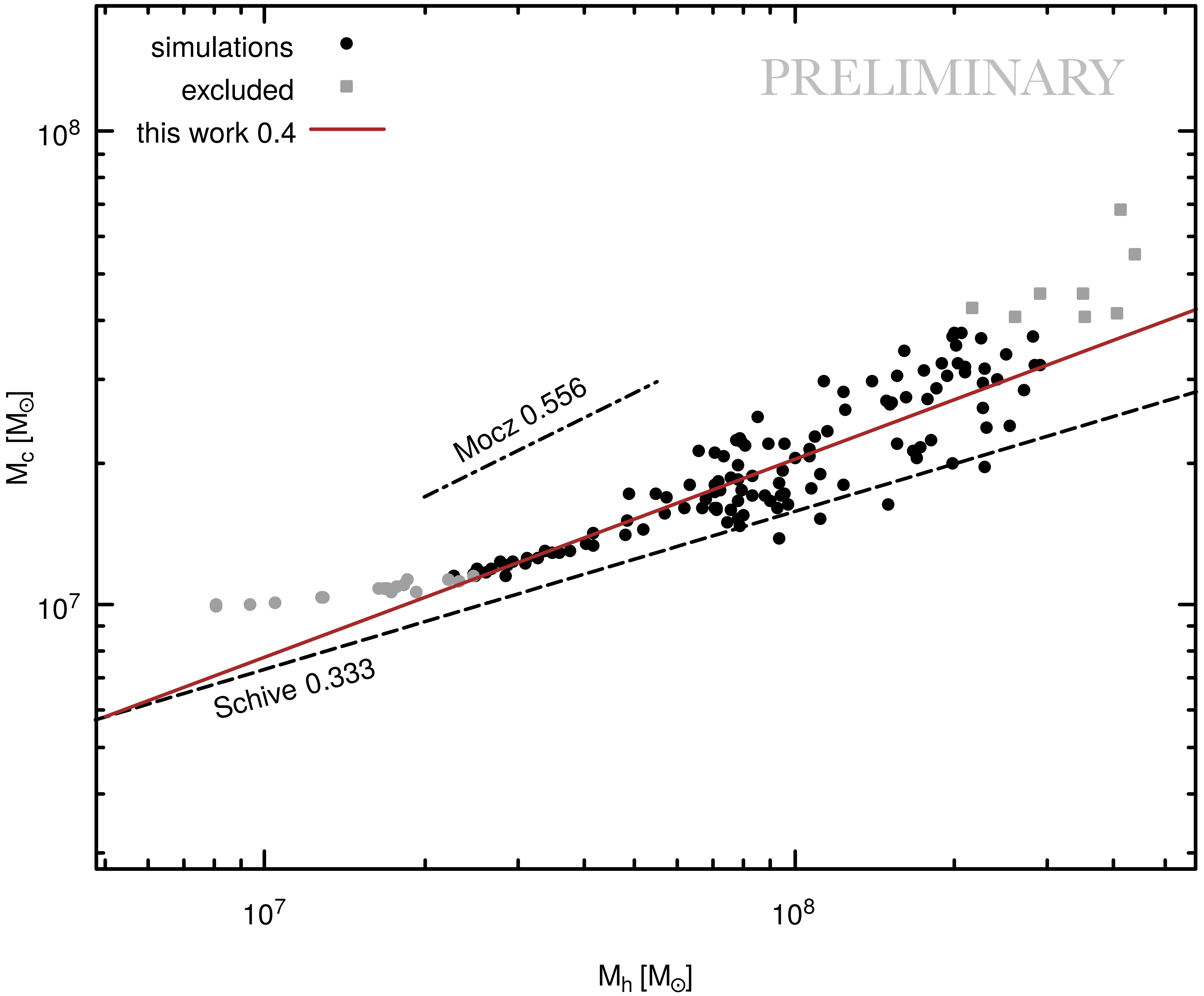
→ Relations used to compare with observations

Ongoing: *Core - halo relation*

Simulation of the FDM model: solving the *Schrödinger-Poisson equations* using a splitting spectral method

In collaboration with Jowett Chan

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



GOAL

Test the $M_c \times M_{\mathrm{halo}}$ relation

Different relation than the literature

Can change predictions of m!

Ongoing: Simulation of the SIFDM

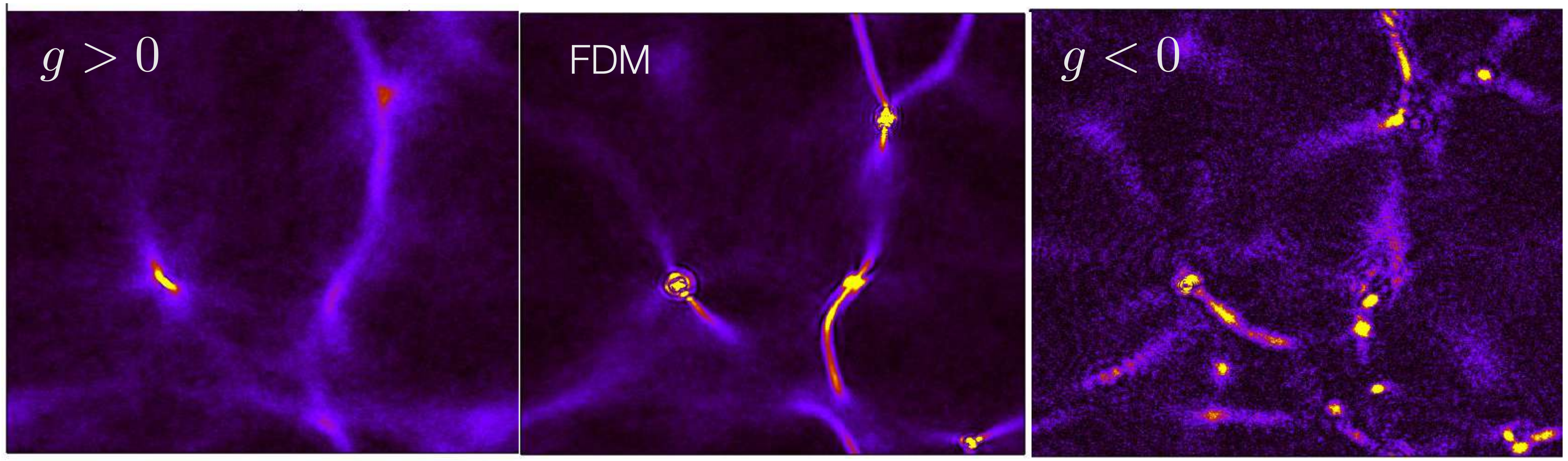
In collaboration with Jowett Chan

SIFDM can present very different phenomenology - very few simulations of this class

Solving the *Schrödinger-Poisson equations* using a splitting spectral method

L = 1 Mpc/h
N = 980^3
z_i = 50
timestep = 1000

PRELIMINARY



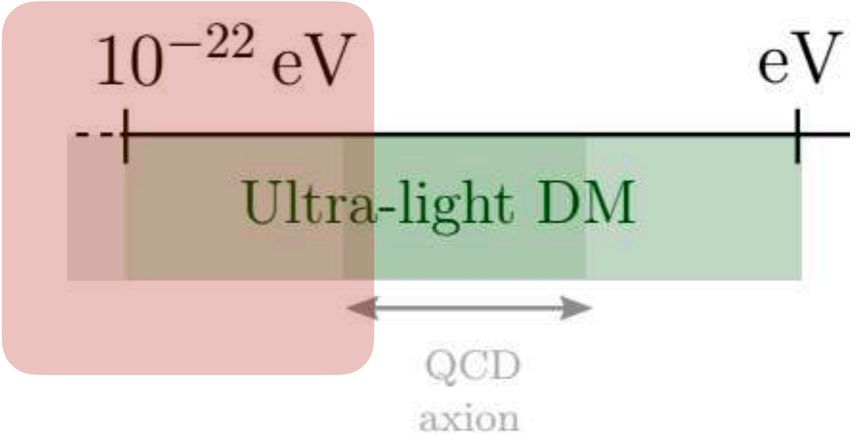
m = 1e-22 eV
a_s = 2e-74 cm

m = 1e-22 eV
a_s = 0 cm

m = 1e-22 eV
a_s = - 2e-74 cm

Other simulations with SIFDM: Amin et al. 2019,
Hartman et al. 2019 (2 fluid – Madelung), Glennon et al 2020 (PySIUltraLight).

Phenomenology


10^{-22} eV

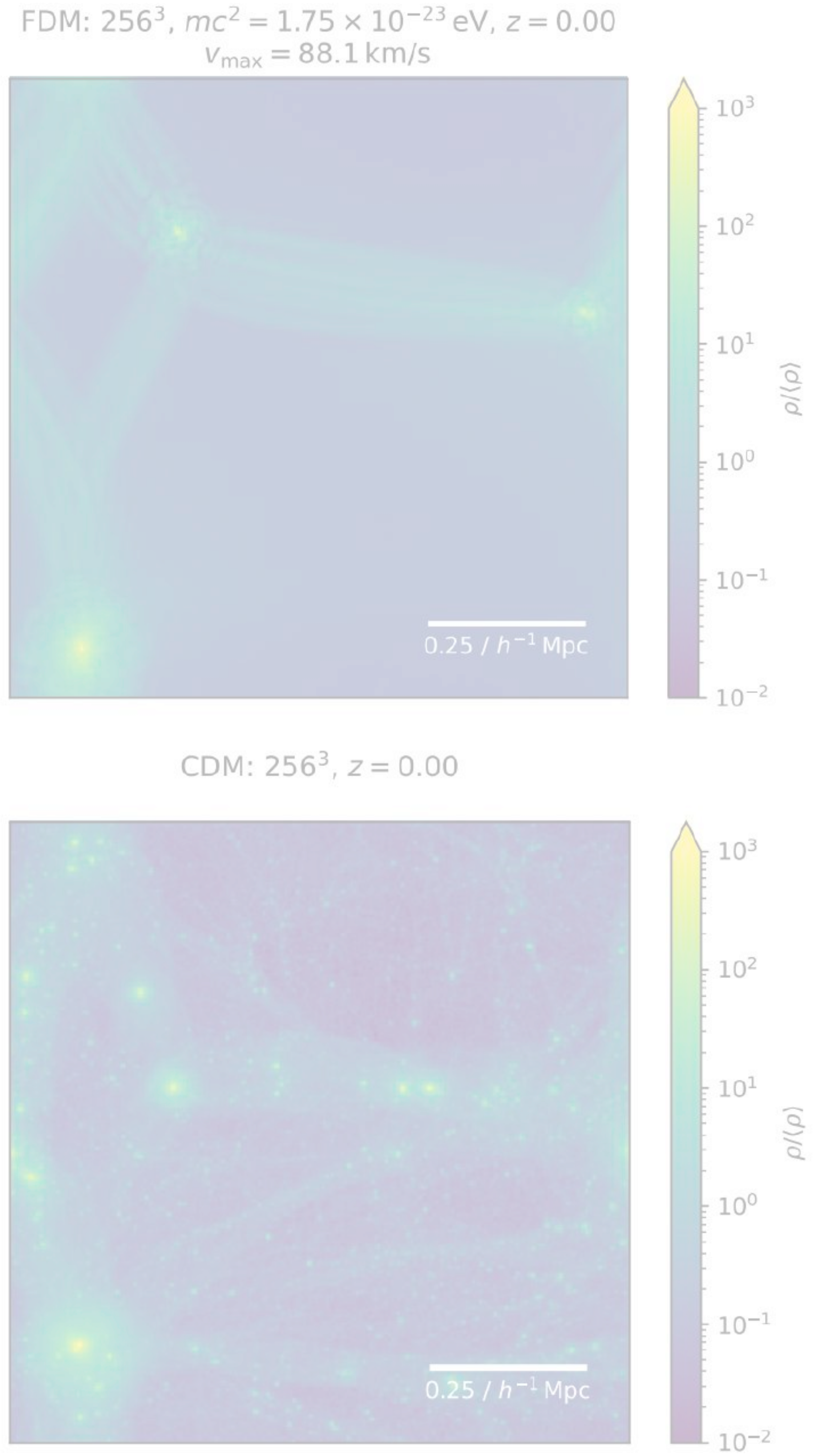
eV

Ultra-light DM

QCD axion

RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures



S. May et al. 2021

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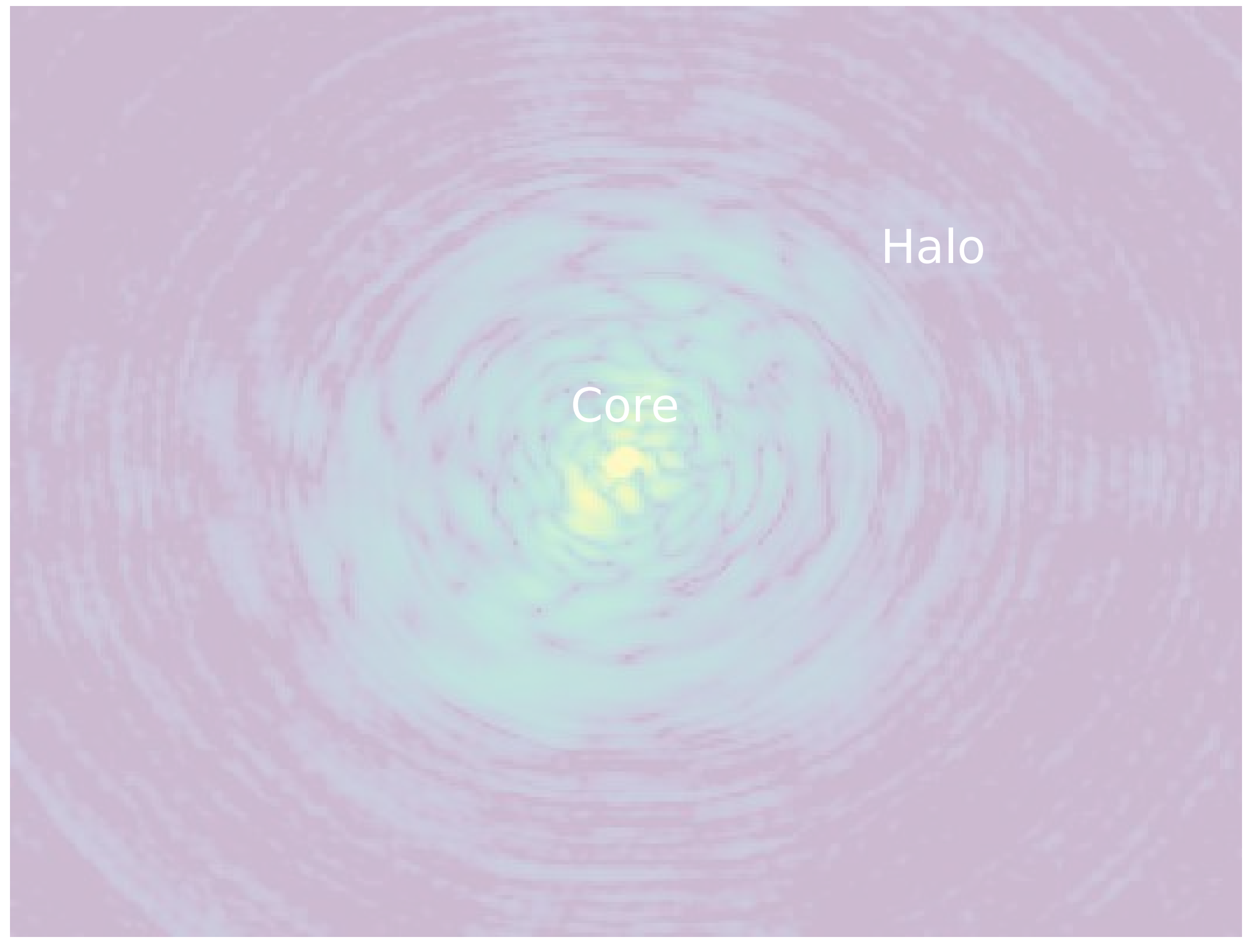
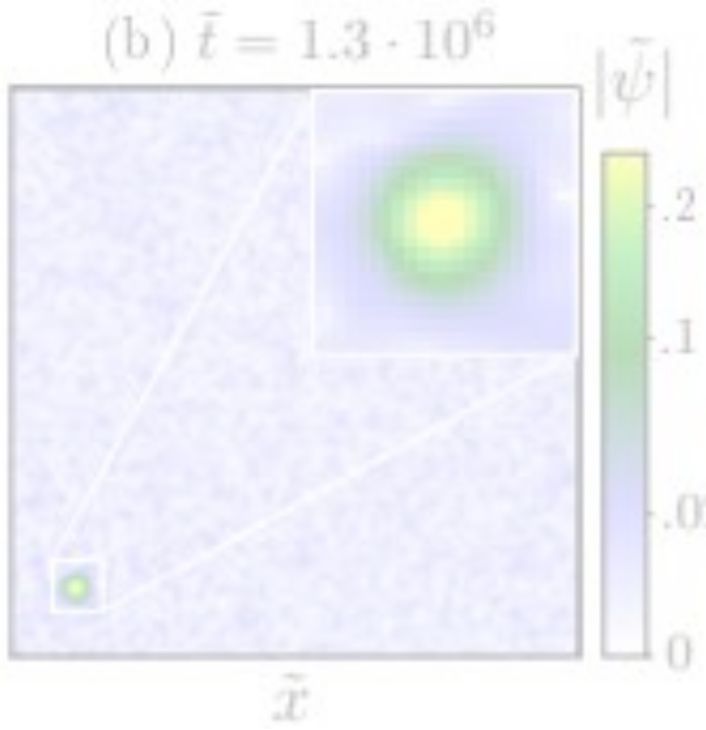
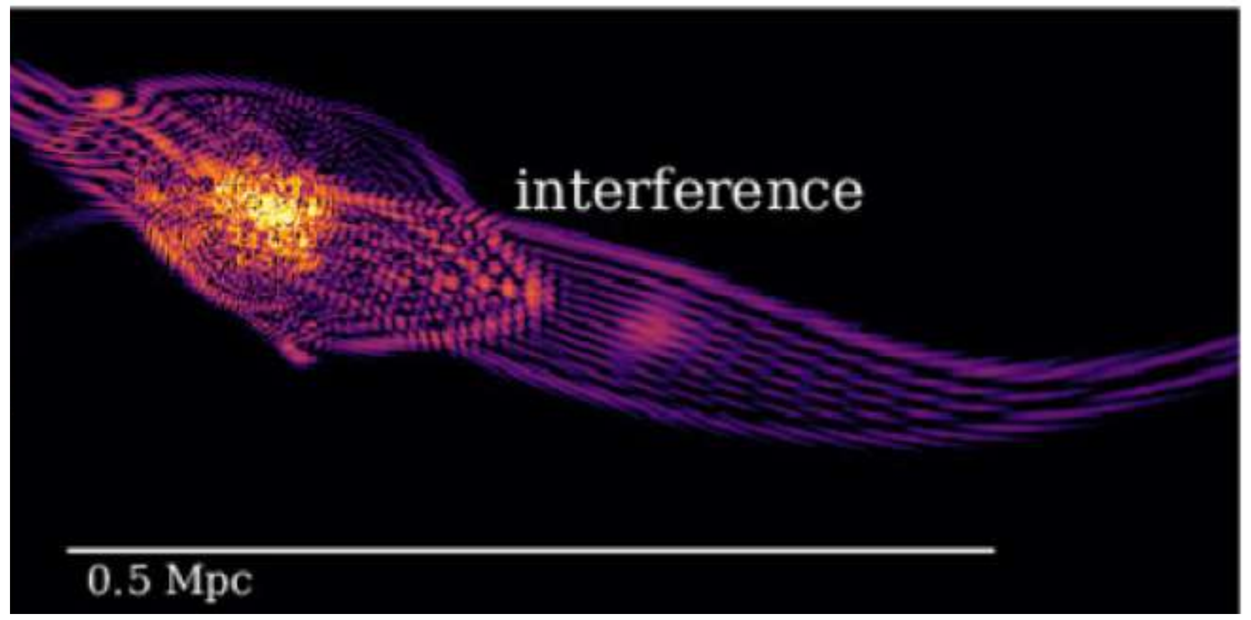


Dynamical effects



Levkov et al. 2018

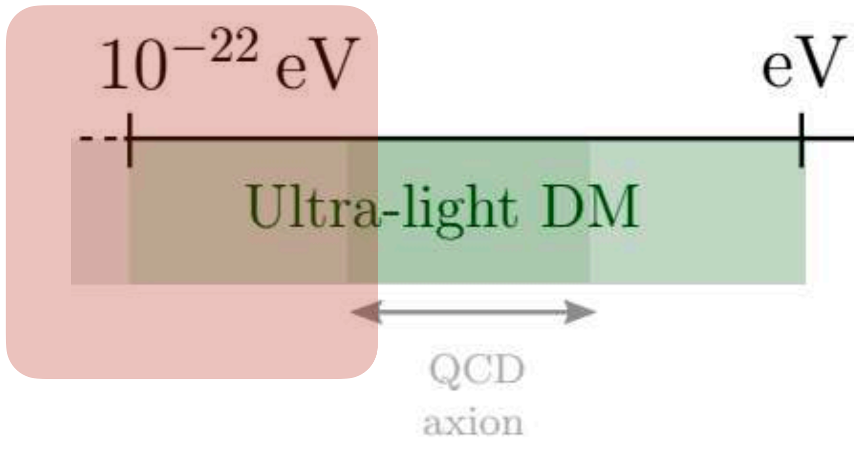
Wave interference

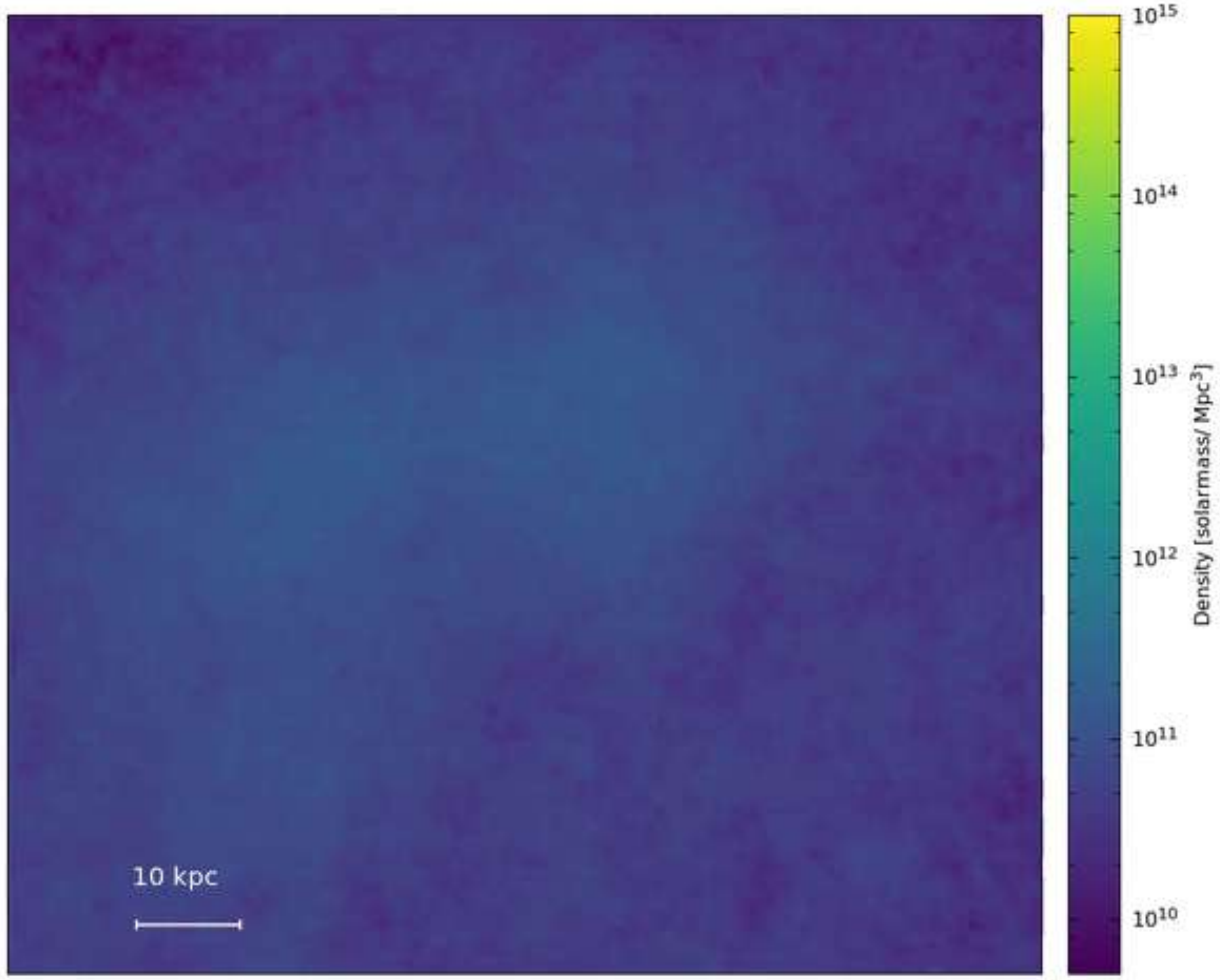


Mocz et al. 2017

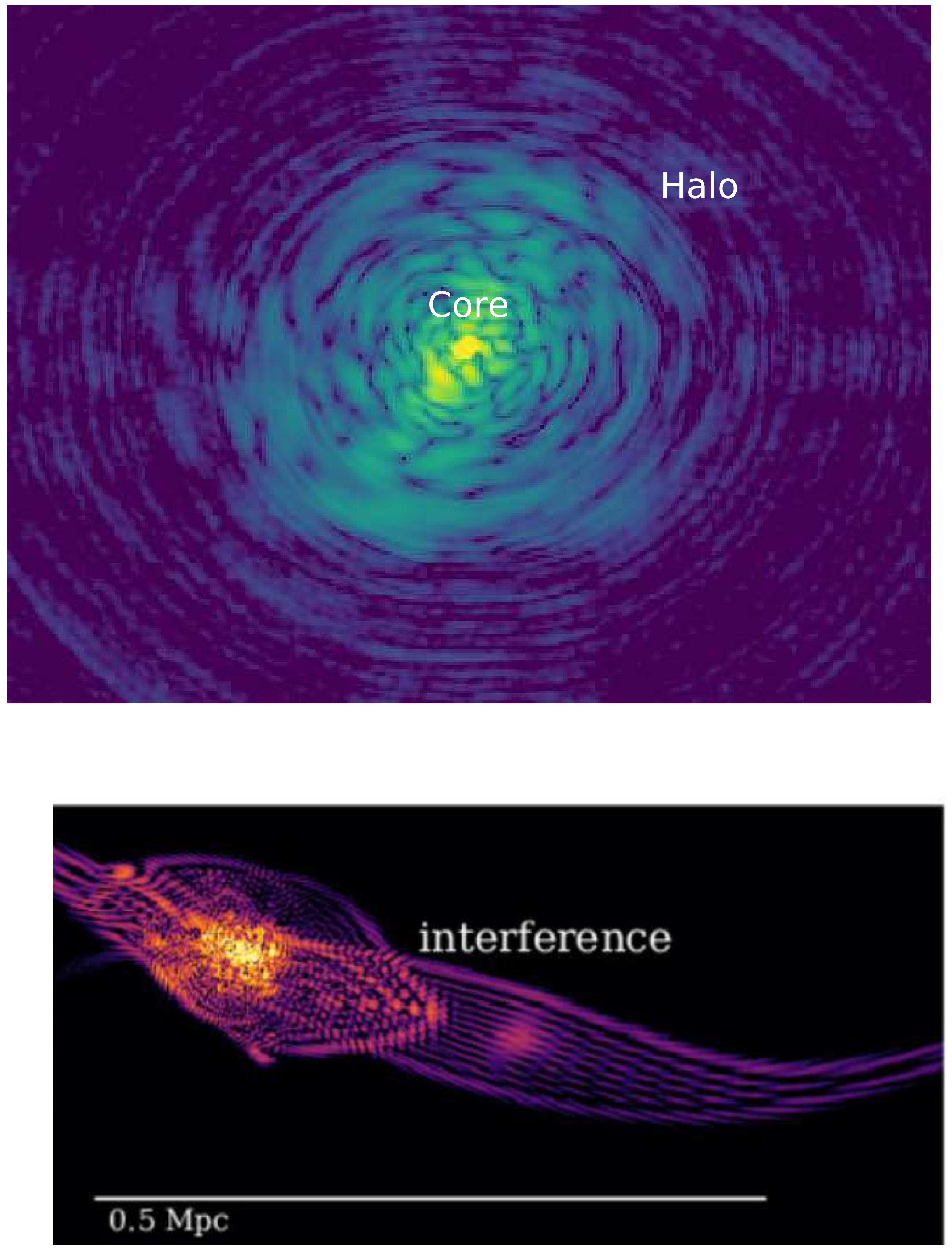
Phenomenology

Wave interference: granules and vortices





Simulation by Jowett Chan



Mocz et al. 2017

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

Destructive interference

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

Phenomenology

Vortices

Observational signature of superfluidity

Reveals *quantum mechanical* nature of superfluid

Superfluid cannot rotate uniformly.

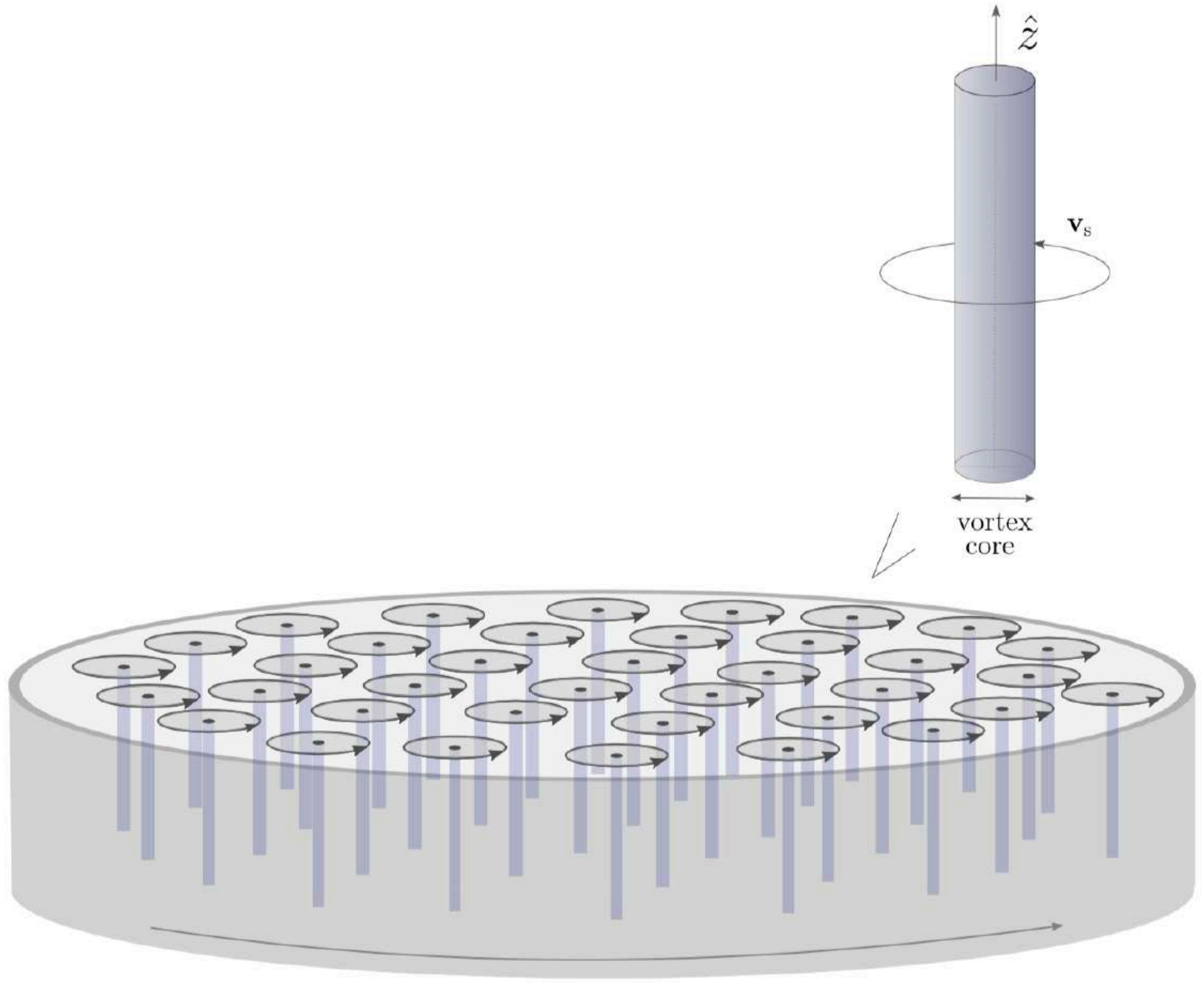
If the superfluid rotates faster than the critical vel.:

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

$$>$$

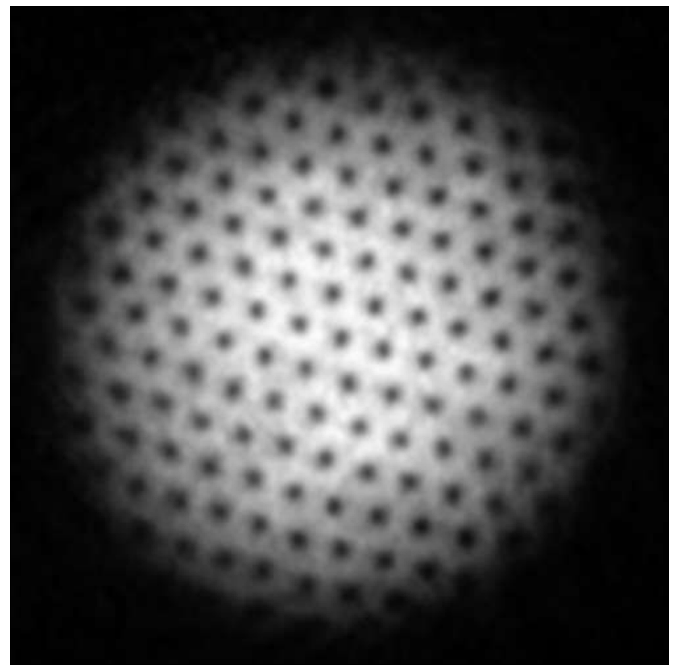
$$\omega \sim \lambda\sqrt{G_N \rho_{halo}} \sim 10^{-18}\lambda\mathrm{s}^{-1}$$

Formation of vortices!



EF, 2020

© Martin Zwierlein.



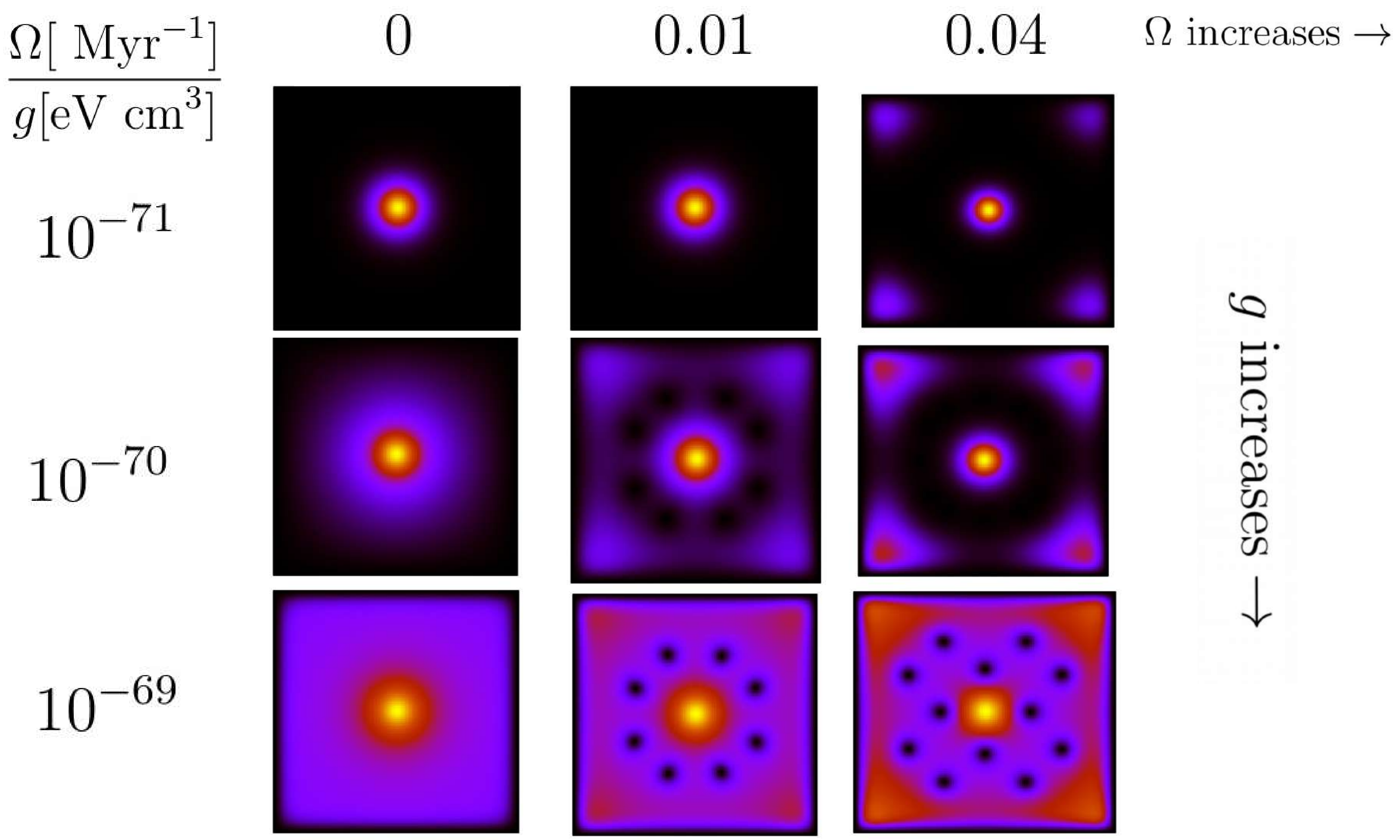
Vortices: smoking gun for superfluid DM

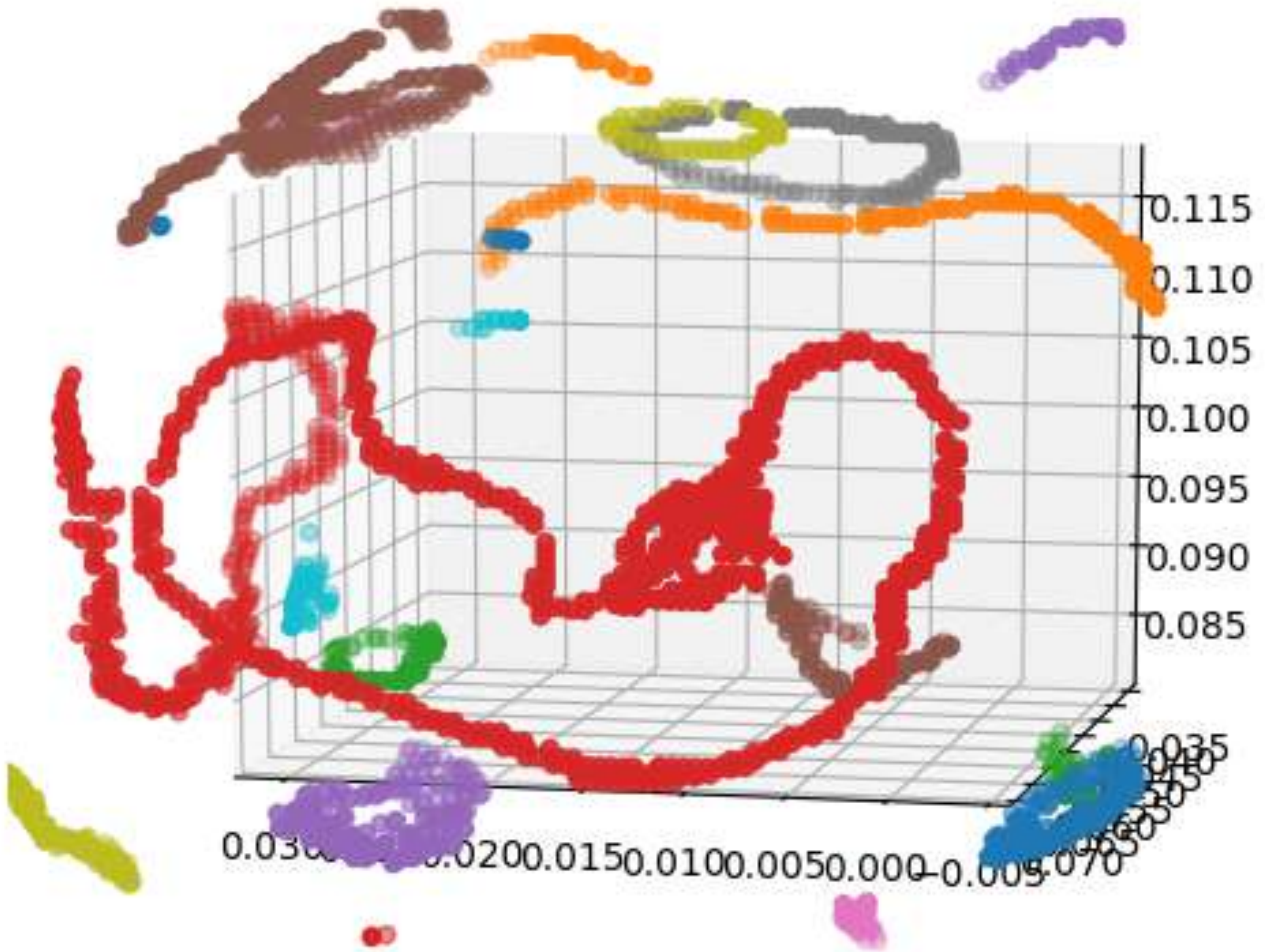
What is the predicted size and abundance of vortices in the halo?
Are they observable?

Ongoing: *Vortices in SIFDM*

In collaboration with Jowett Chan

PRELIMINARY

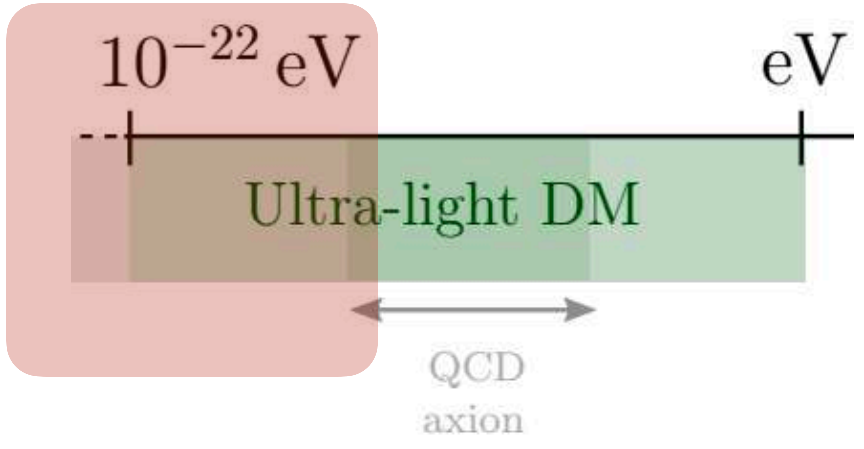




$$i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{g}{8m^2}|\psi|^2 - m\Phi\right)\psi$$

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

Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

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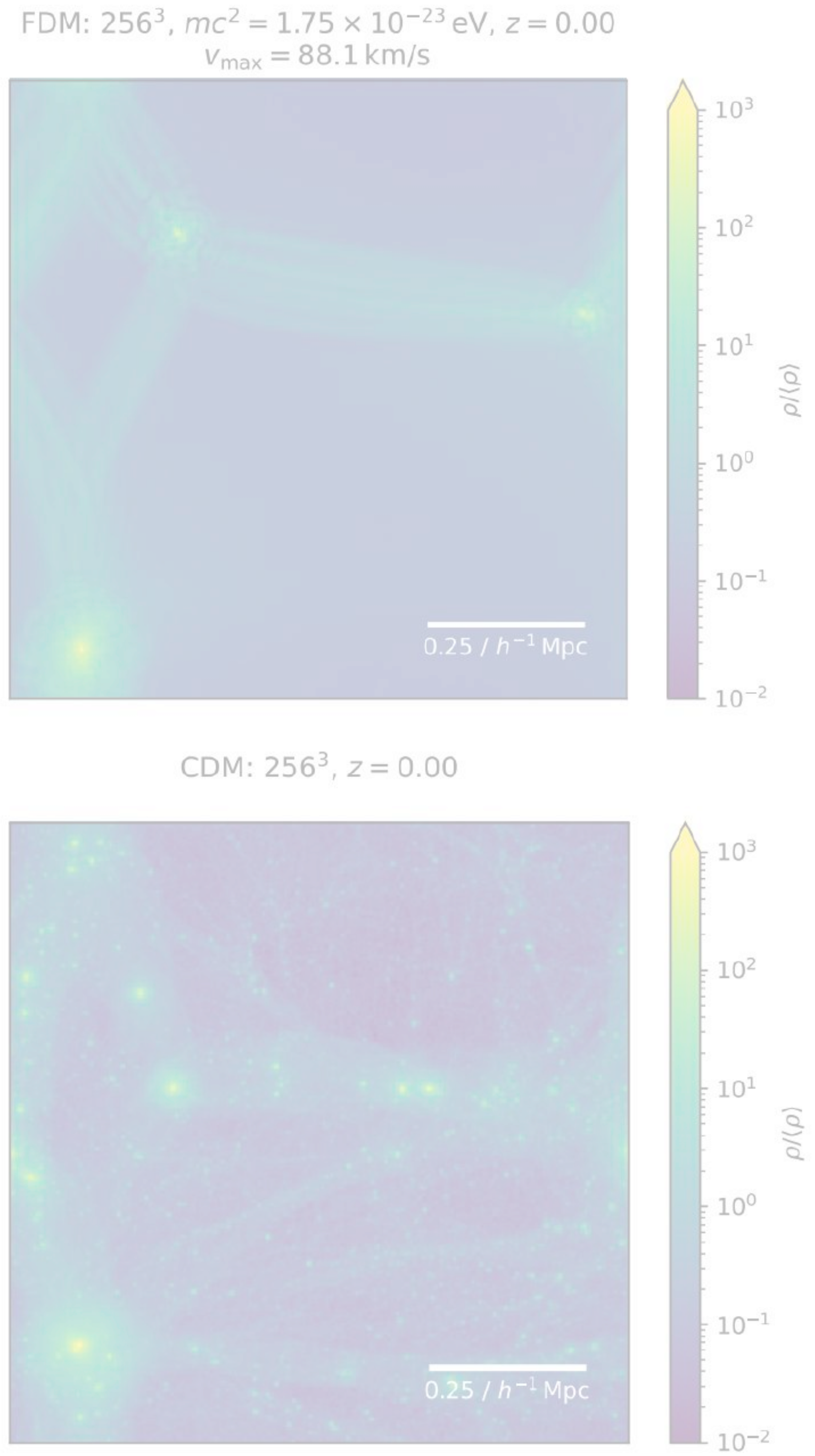

S. May et al. 2021

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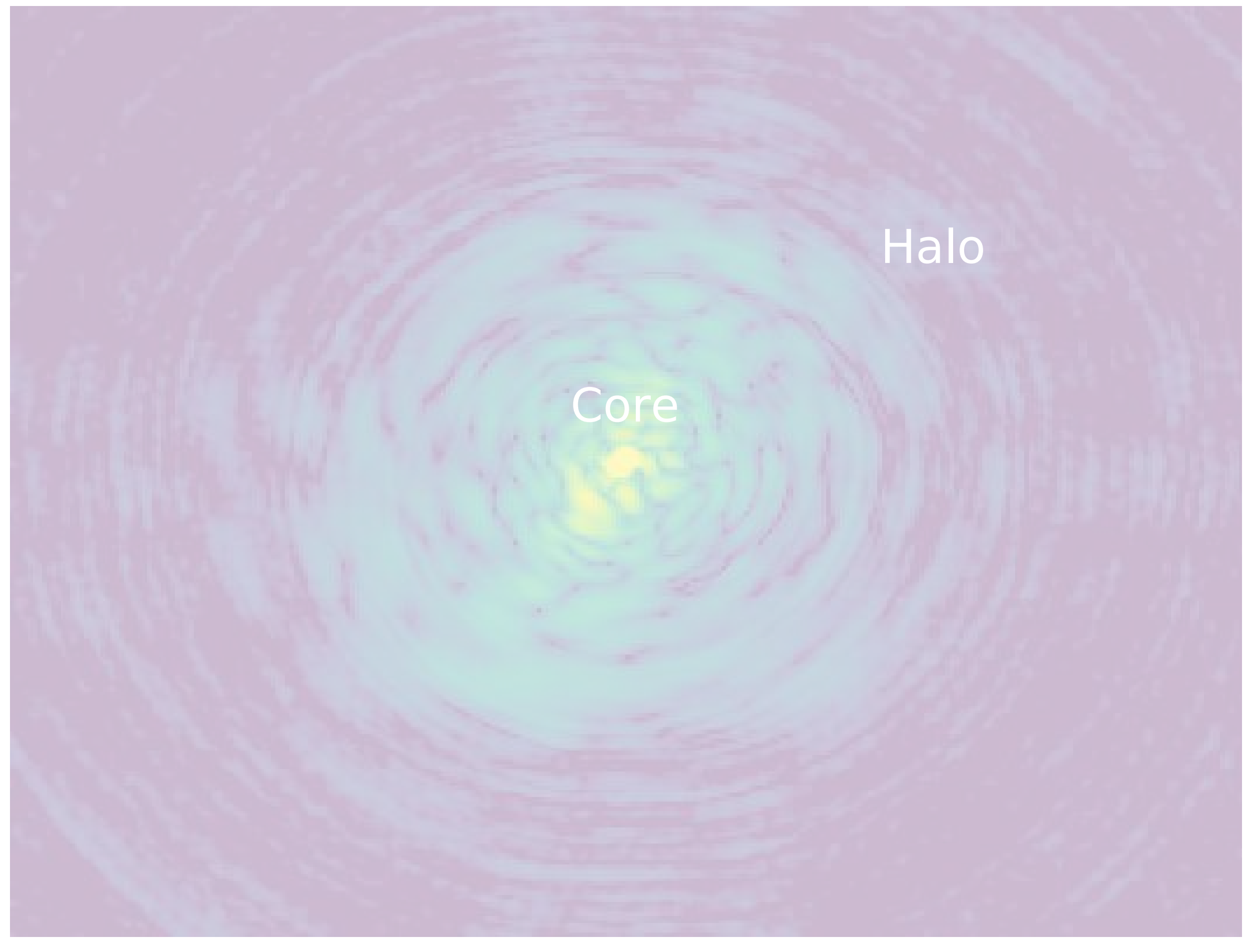
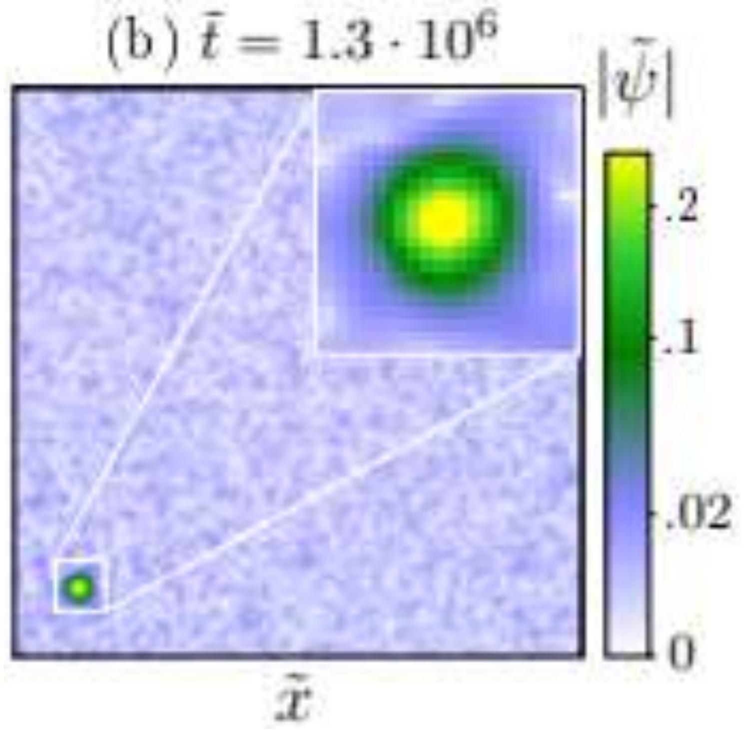


Dynamical effects



Levkov et al. 2018

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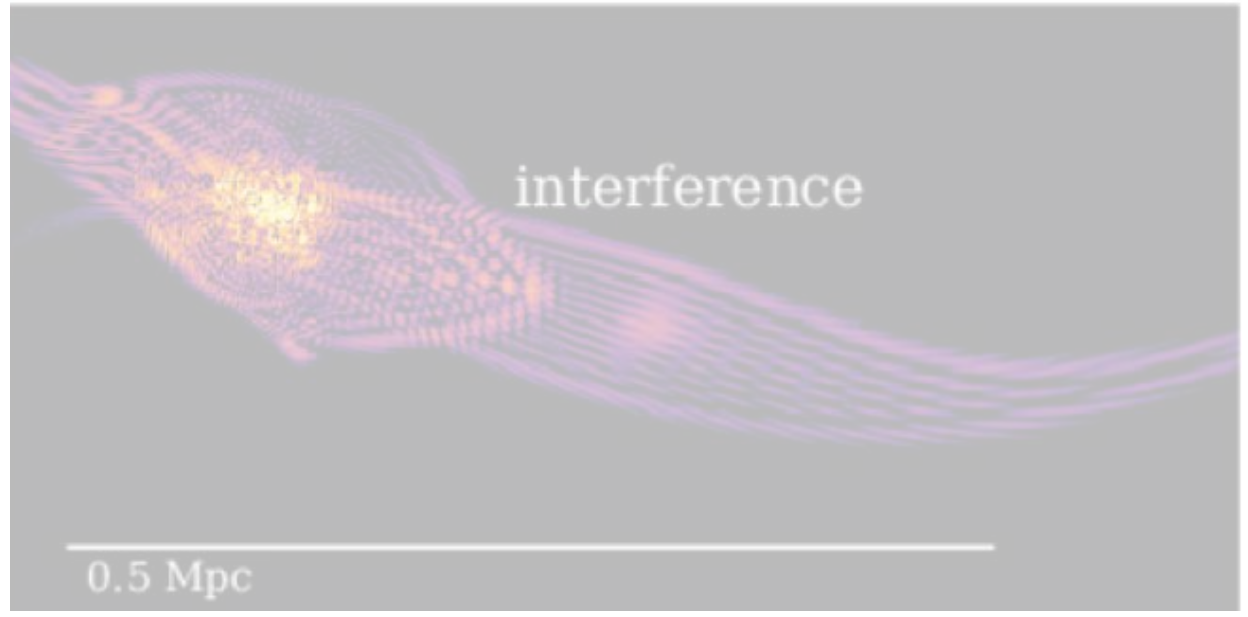
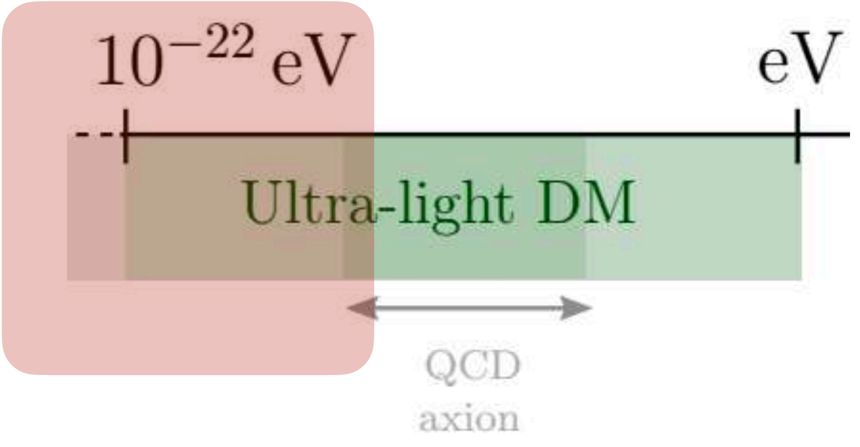


Mocz et al. 2017

Phenomenology

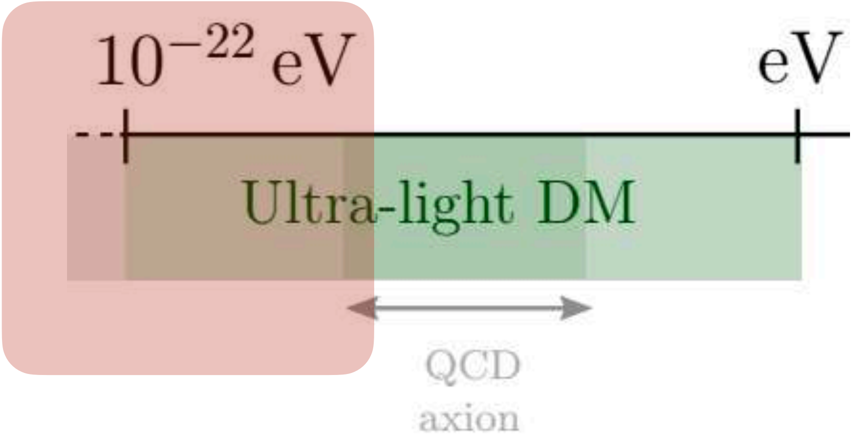
Dynamical effects

Relaxation, oscillation, friction, and heating



Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

Formation of a BEC / superfluid

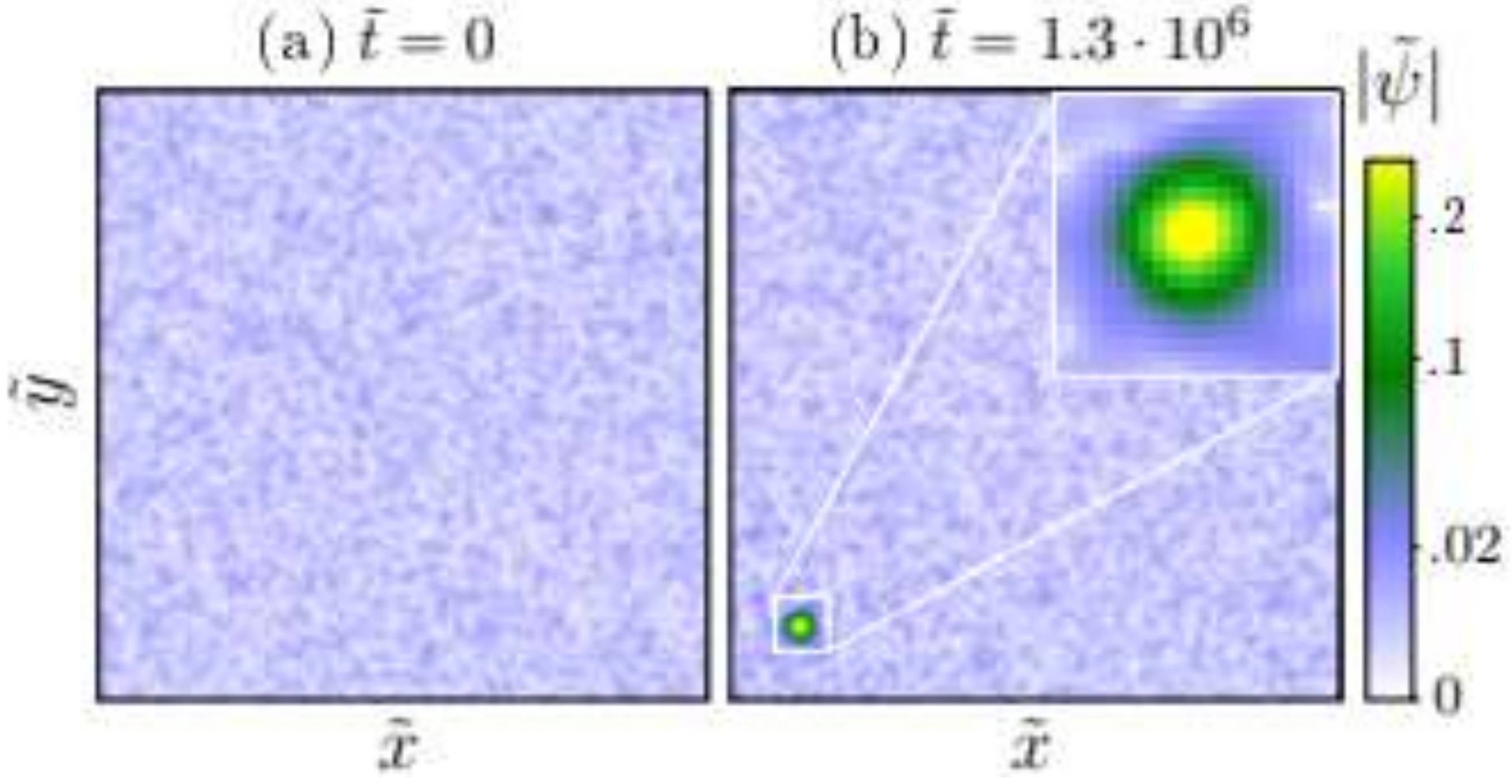
Formation of a condensate and a core occur from gravitational interaction.

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

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

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

Smaller than the age of the universe!

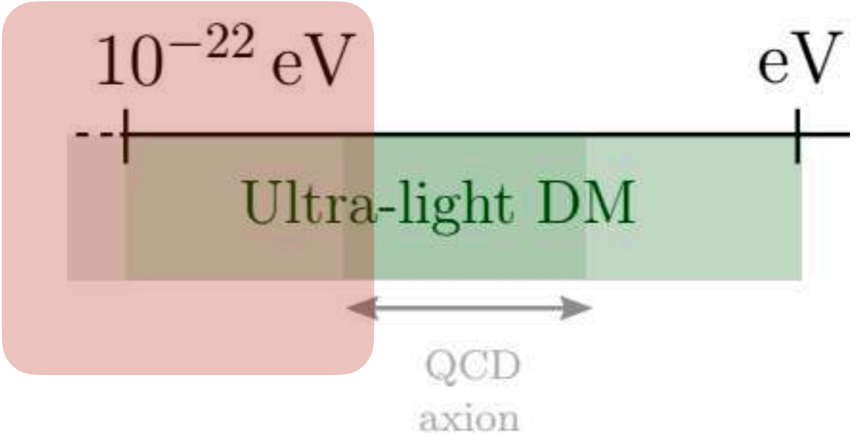


Levkov et al. 2018, Kirpatrick et al. 2020

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



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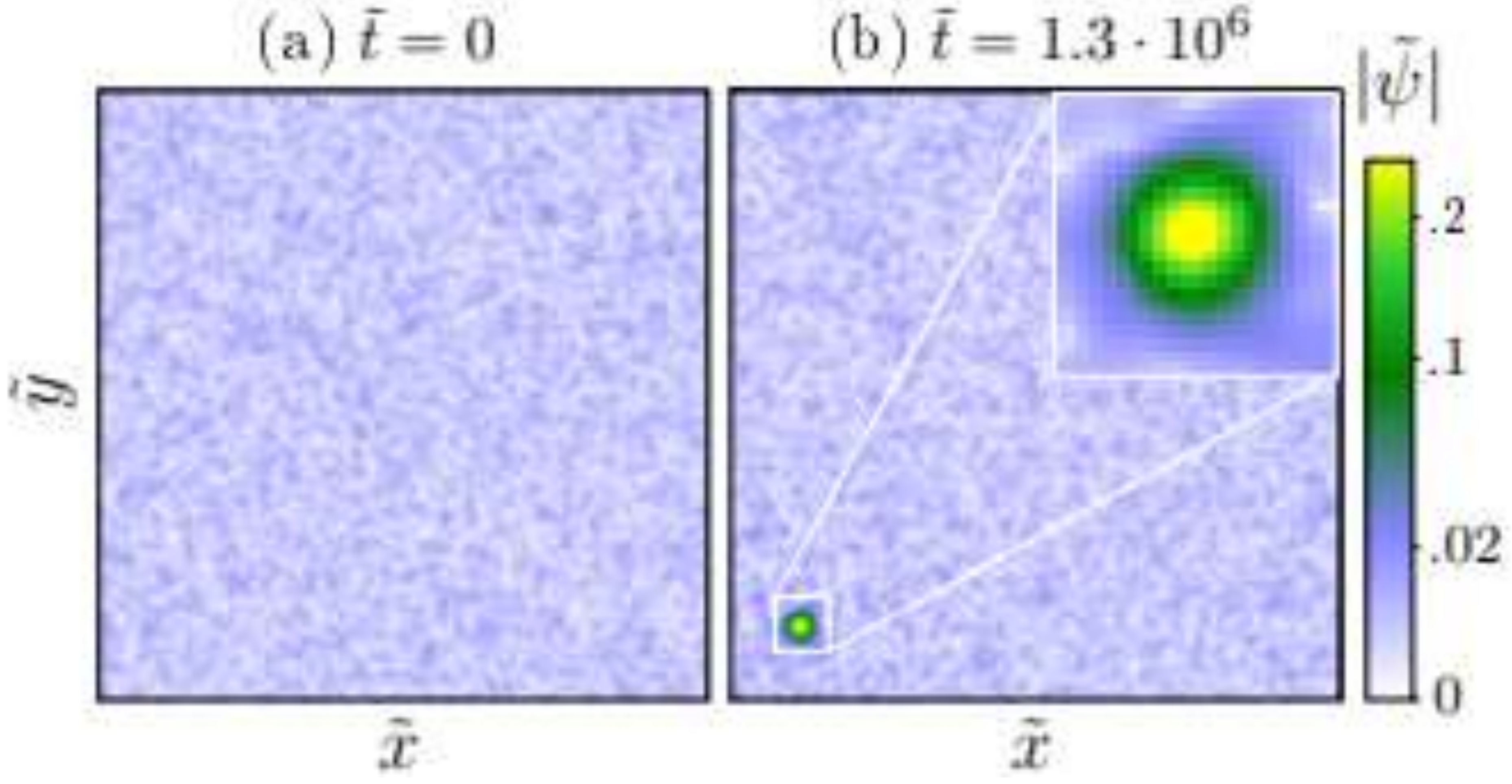
Formation of a condensate and a core occur from gravitational interaction.

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

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

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

Smaller than the age of the universe!

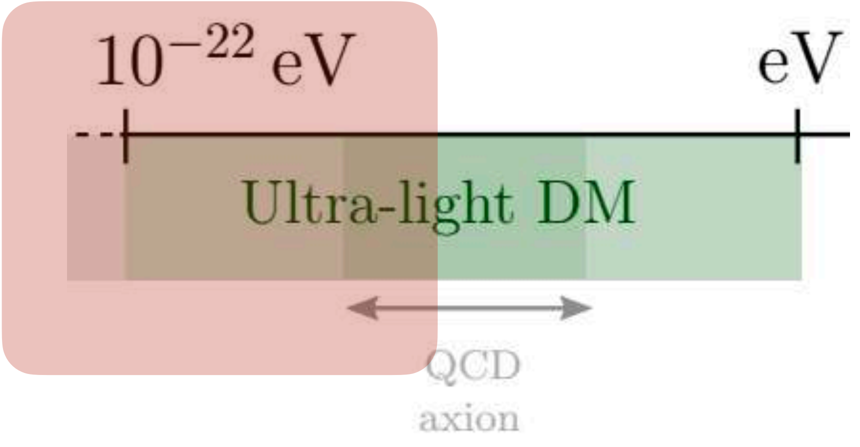


Levkov et al. 2018, Kirpatrick et al. 2020

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

BUT: Analogous system to a condensate used.
Condensation happens?
Open question!
GOAL

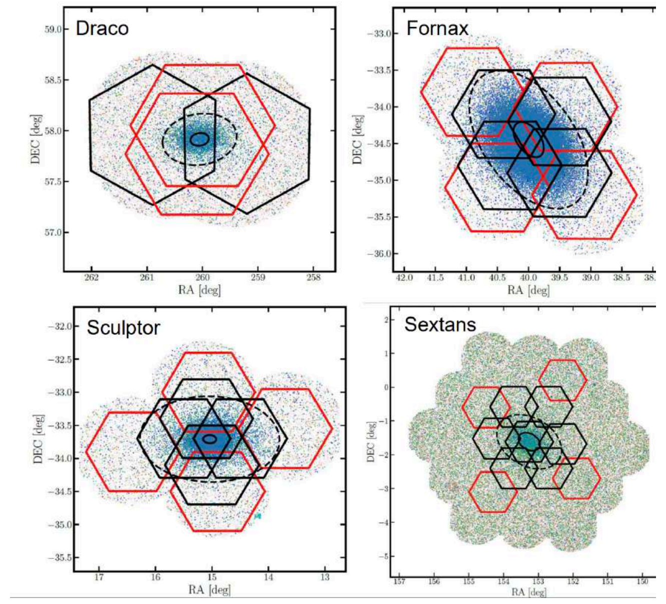
Observational implications and constraints



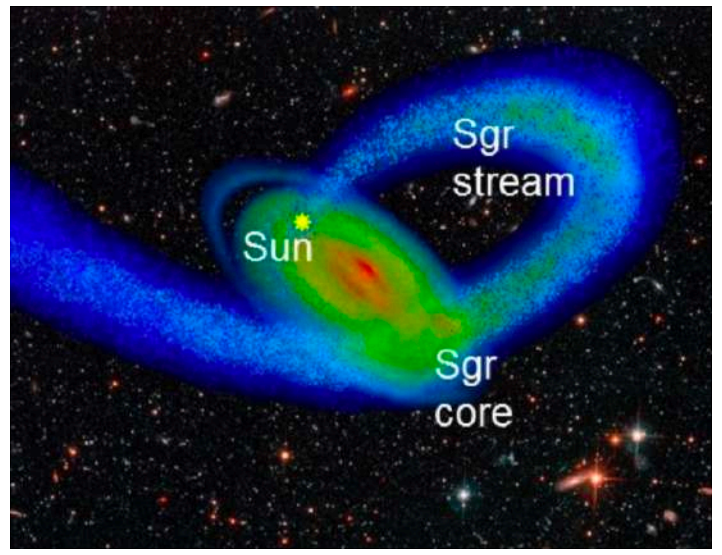
Galaxies

NASA and ESA

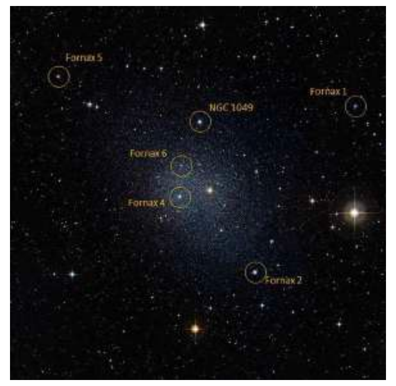
Dwarfs



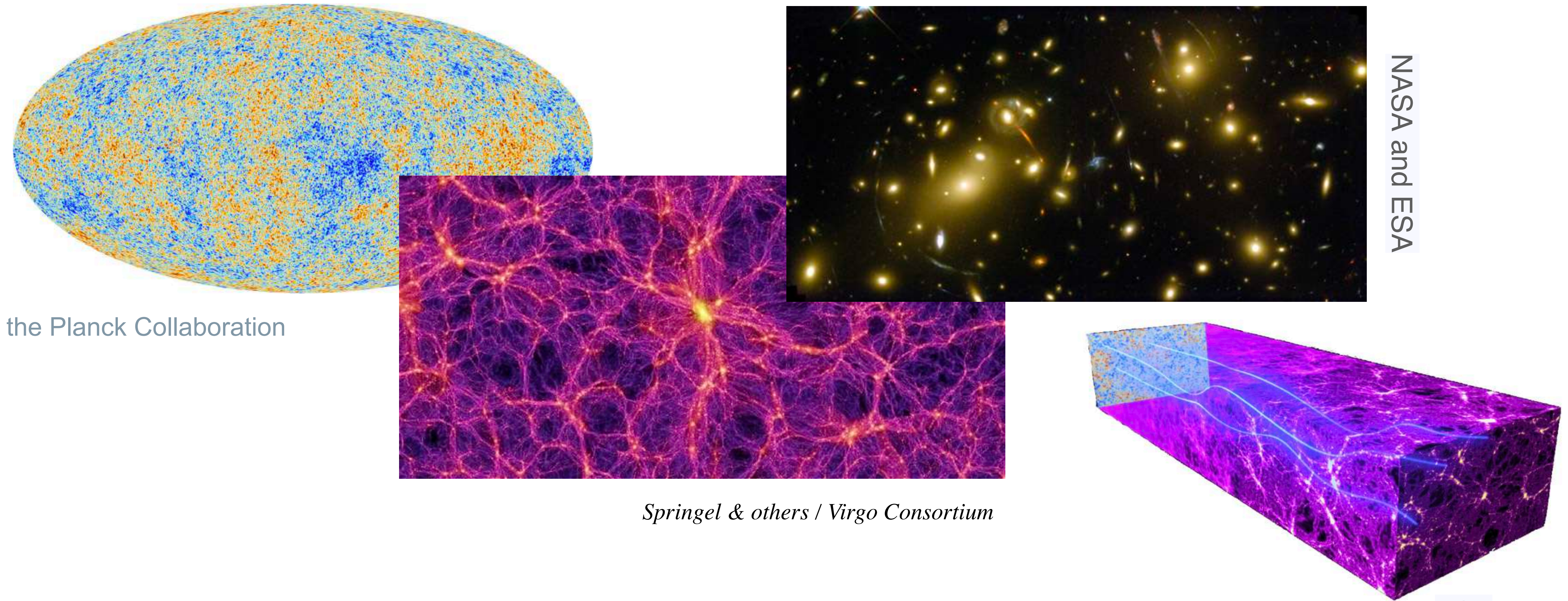
Stellar stream



Globular clusters



CMB+LSS



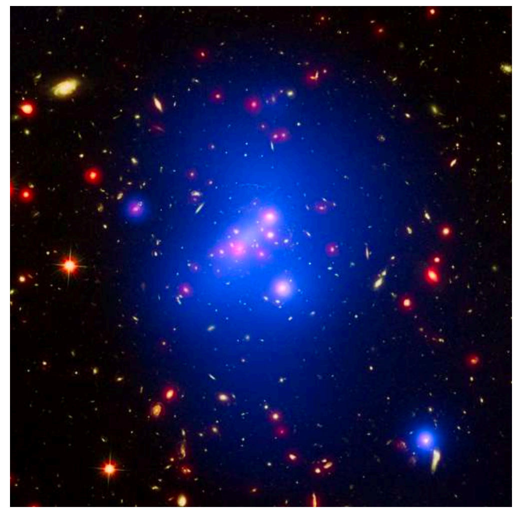
ESA and the Planck Collaboration

NASA and ESA

Springel & others / Virgo Consortium

ESA

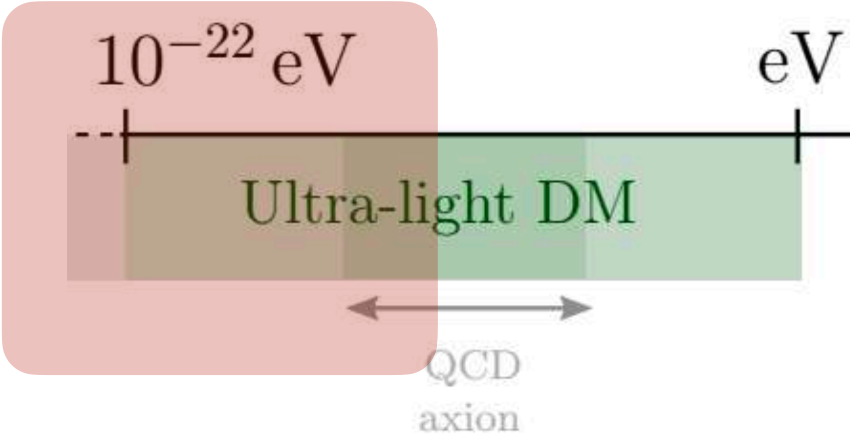
Clusters

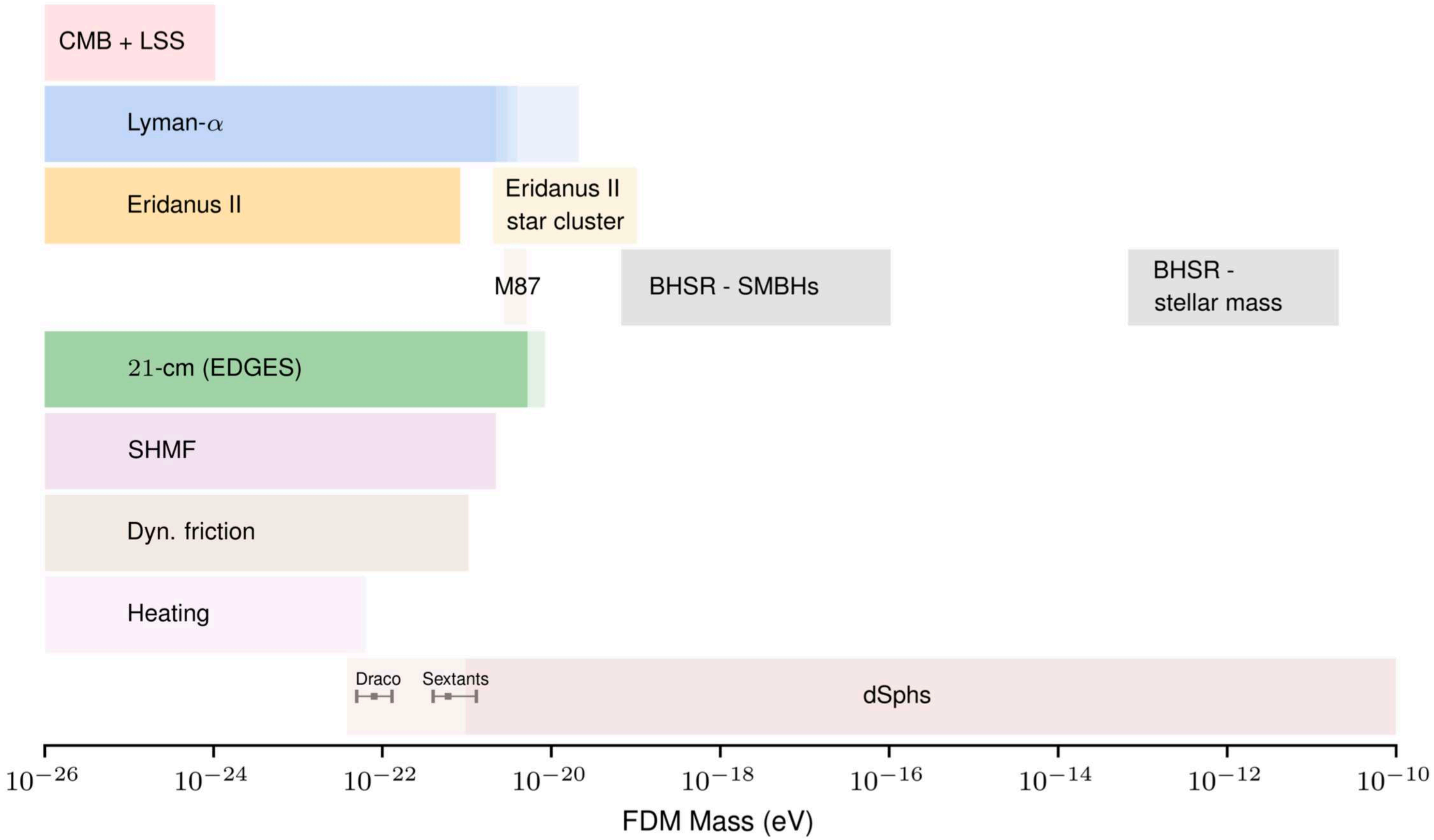


CC BY 4.0

Observational implications and constraints

Fuzzy dark matter - bounds on the mass

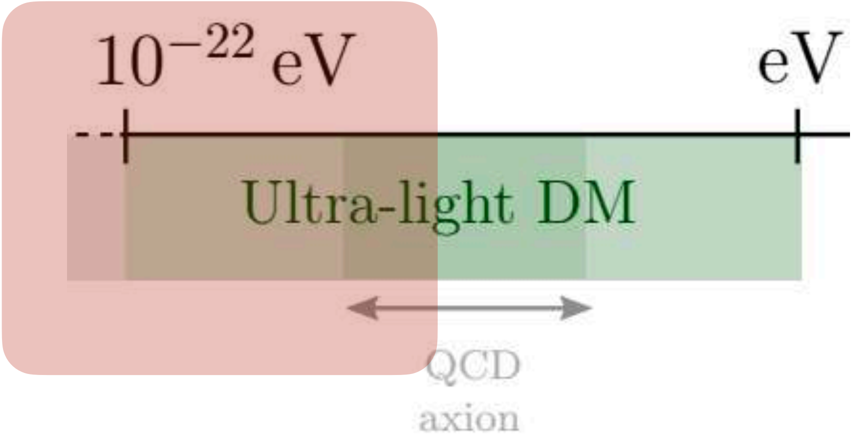


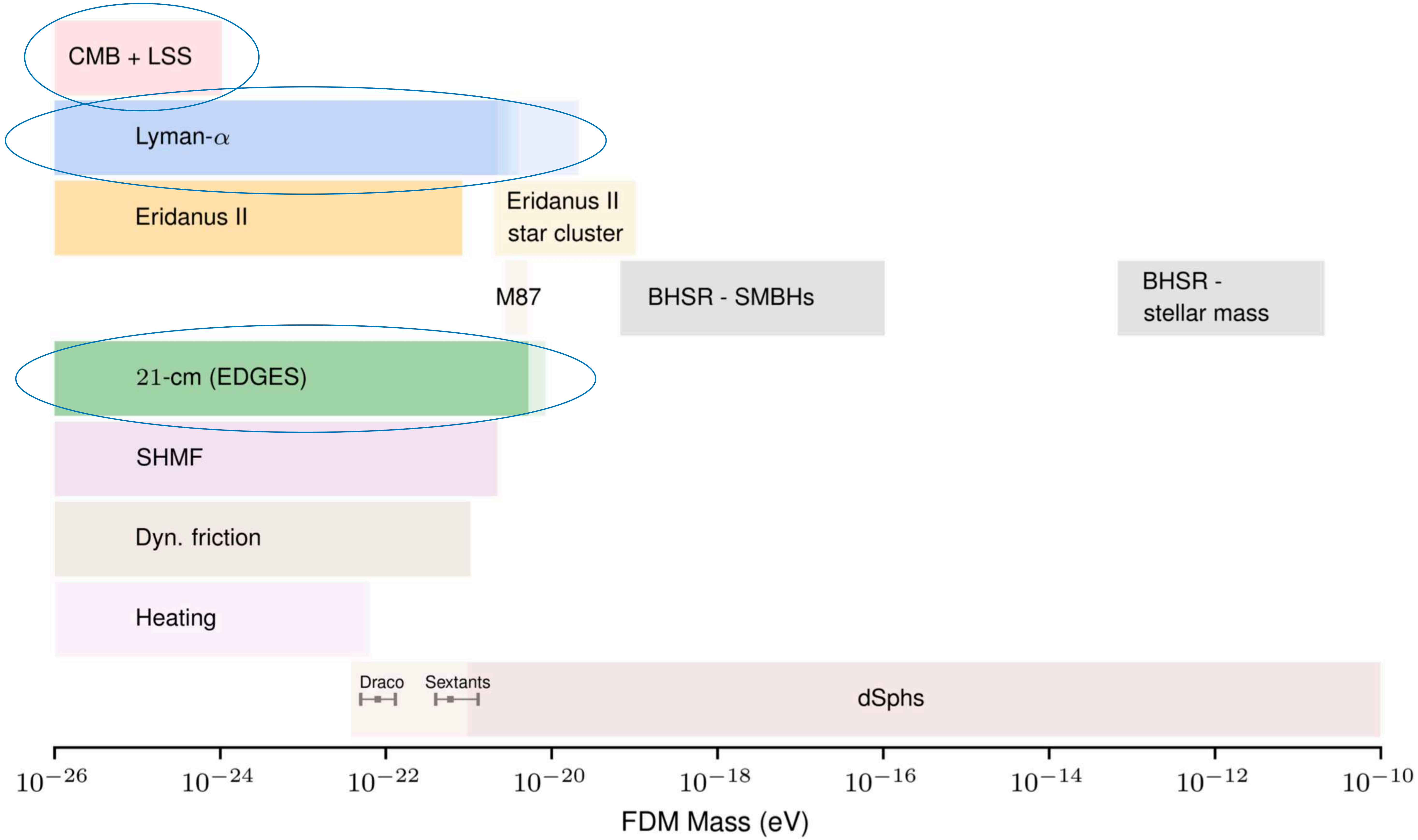


"Ultra-light dark matter", **E.F.**, 2020. The Astronomy and Astrophysics Review.

Observational implications and constraints

Fuzzy dark matter - bounds on the mass





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

Observational implications and constraints

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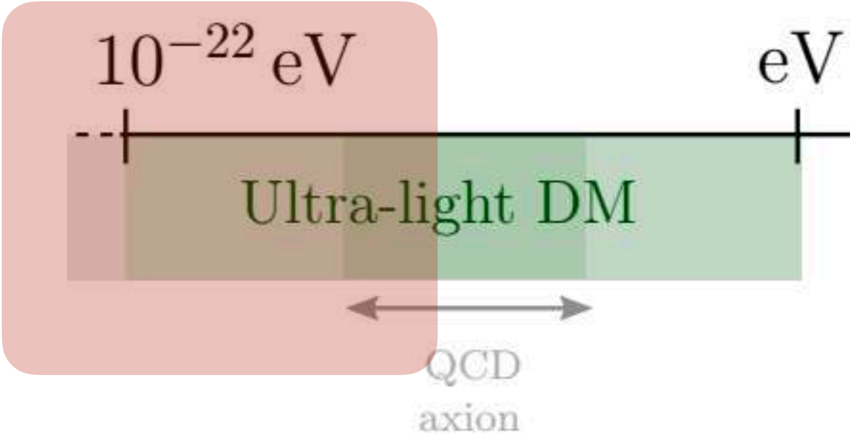
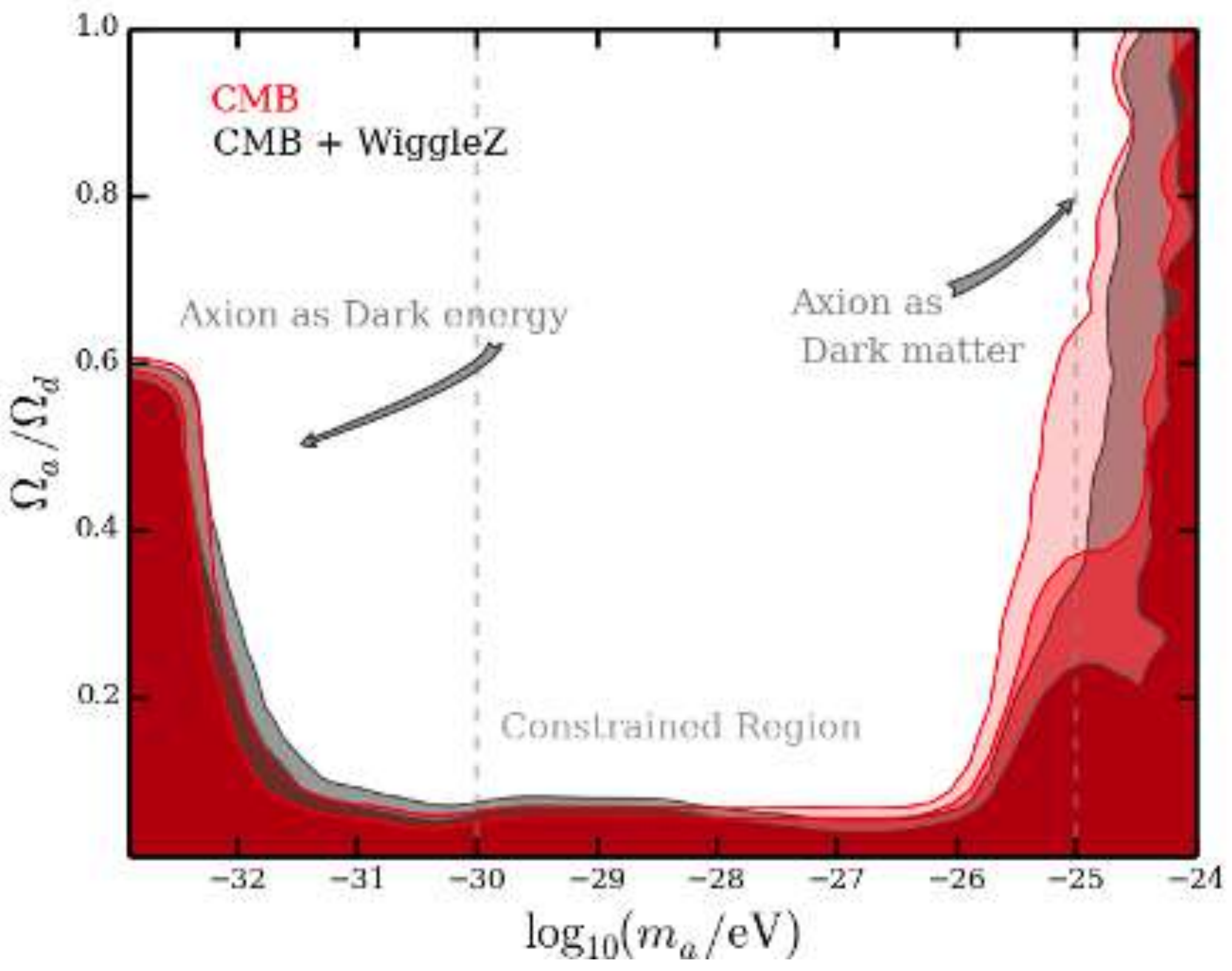


CMB/LSS

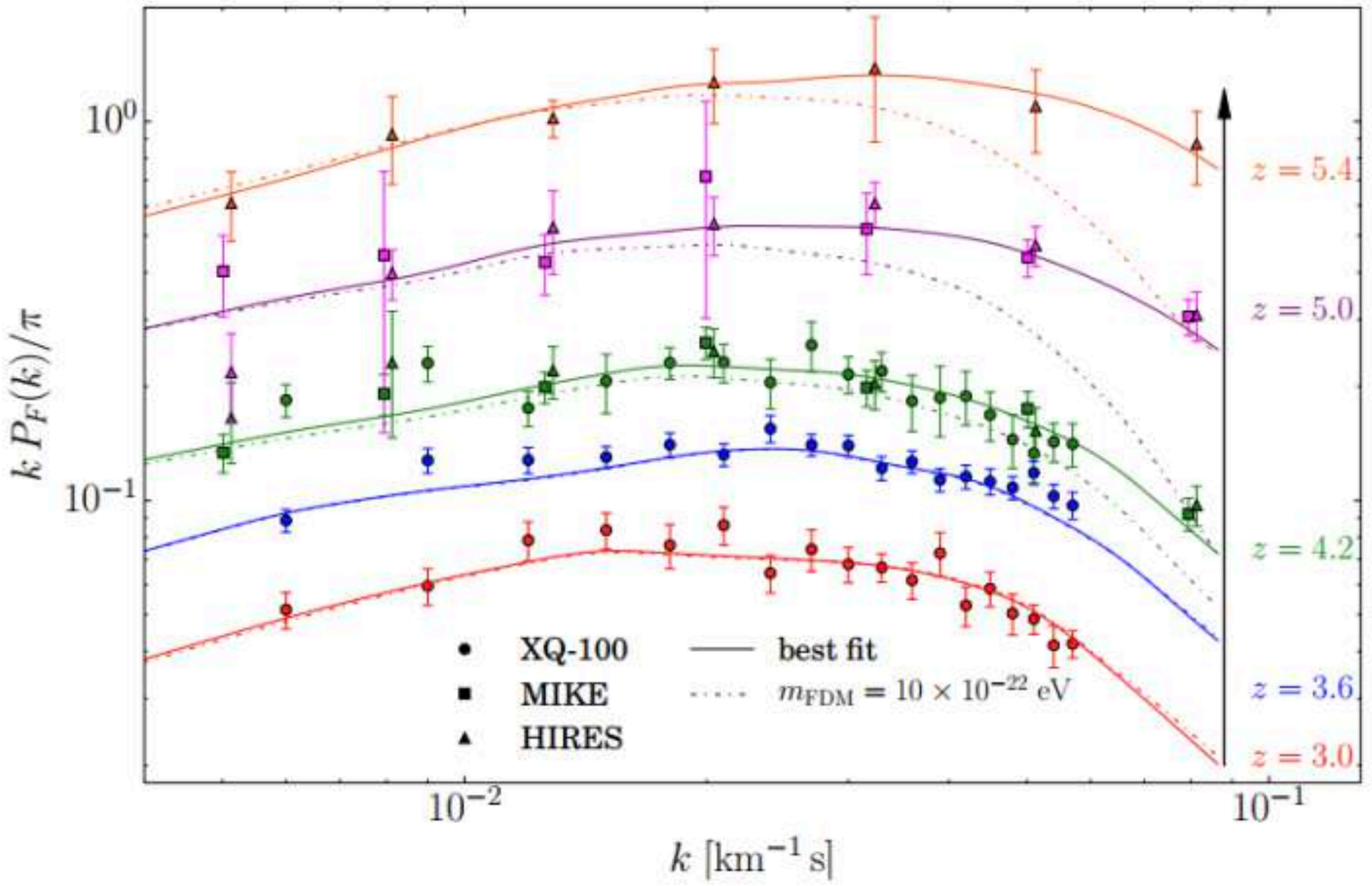
Hlozek et al, (2015, 2018)



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

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.

Global 21 cm

Suppressed small scale structure

↓

Postpone Ly-α coupling, heating, reionization H

↓

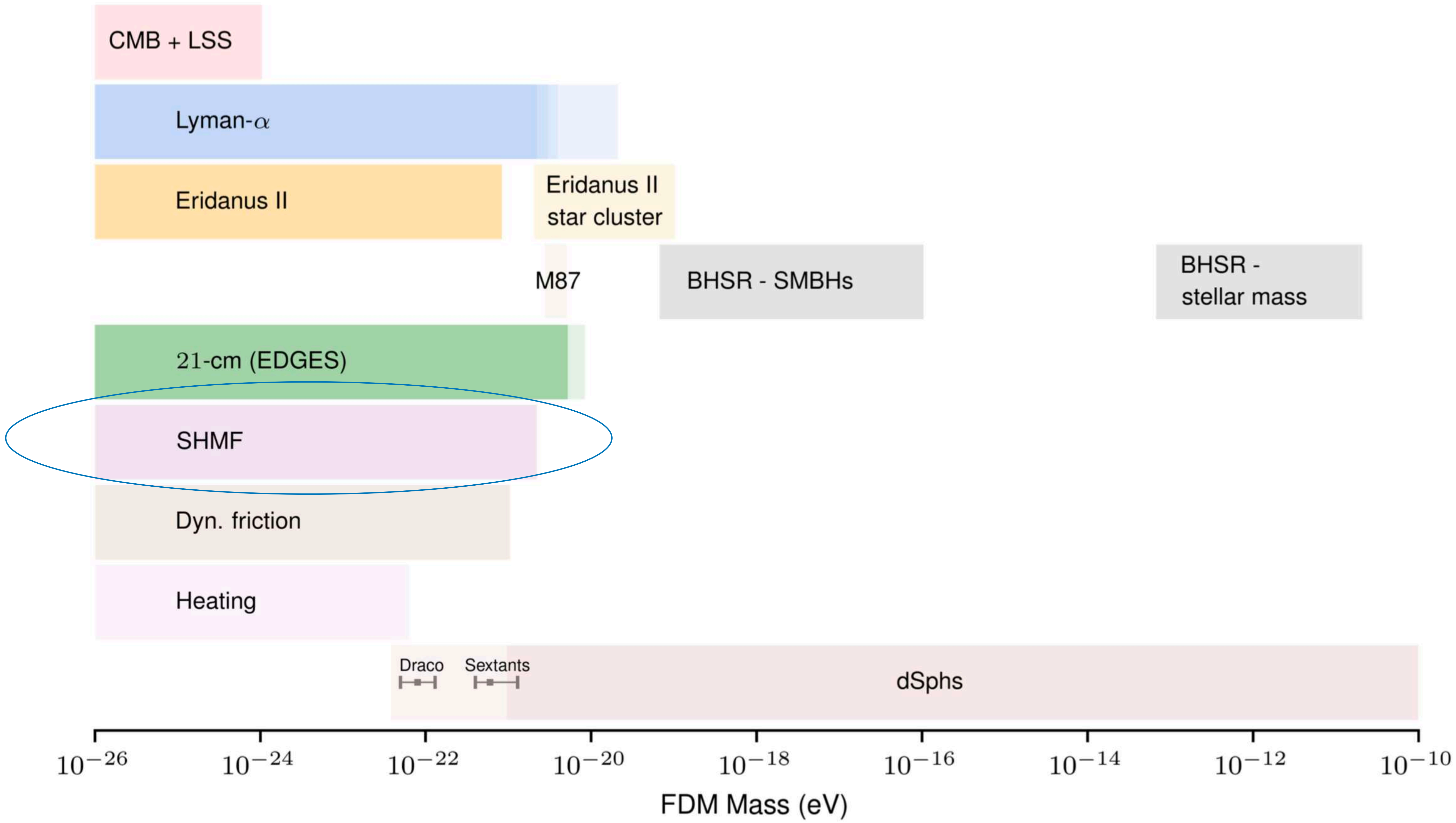
Smaller 21-cm global signal

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

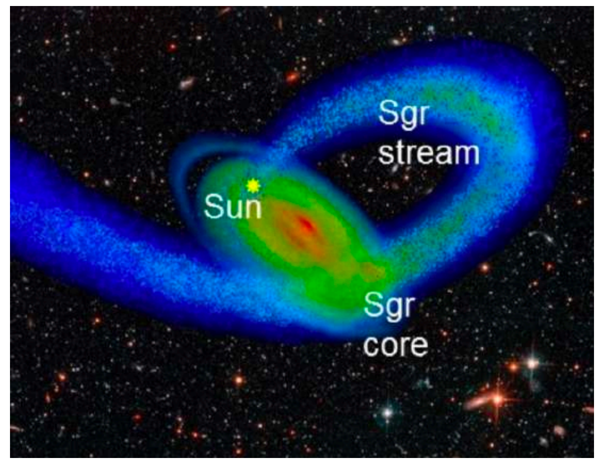
EDGES global 21 cm signal
Olof Nebrin et al.(2019)

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



Stellar streams



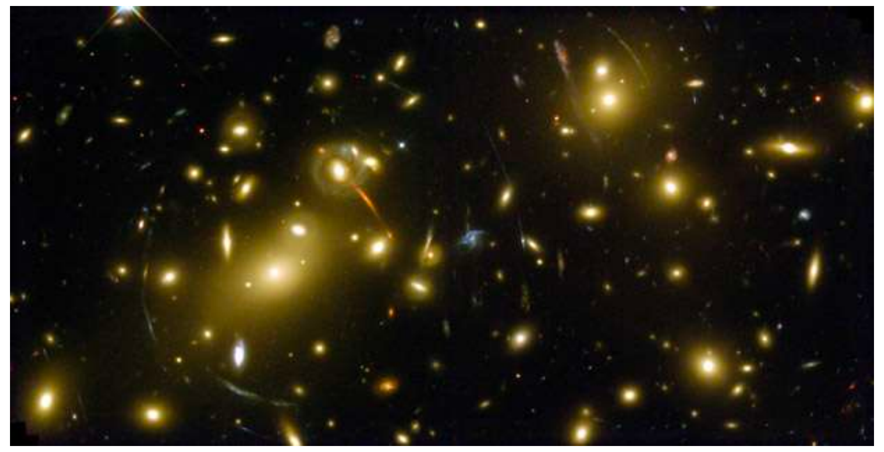
- DM properties encoded in variations density in stellar streams
- Opportunity to probe nature of DM
- GD-1 : compatible with CDM

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

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

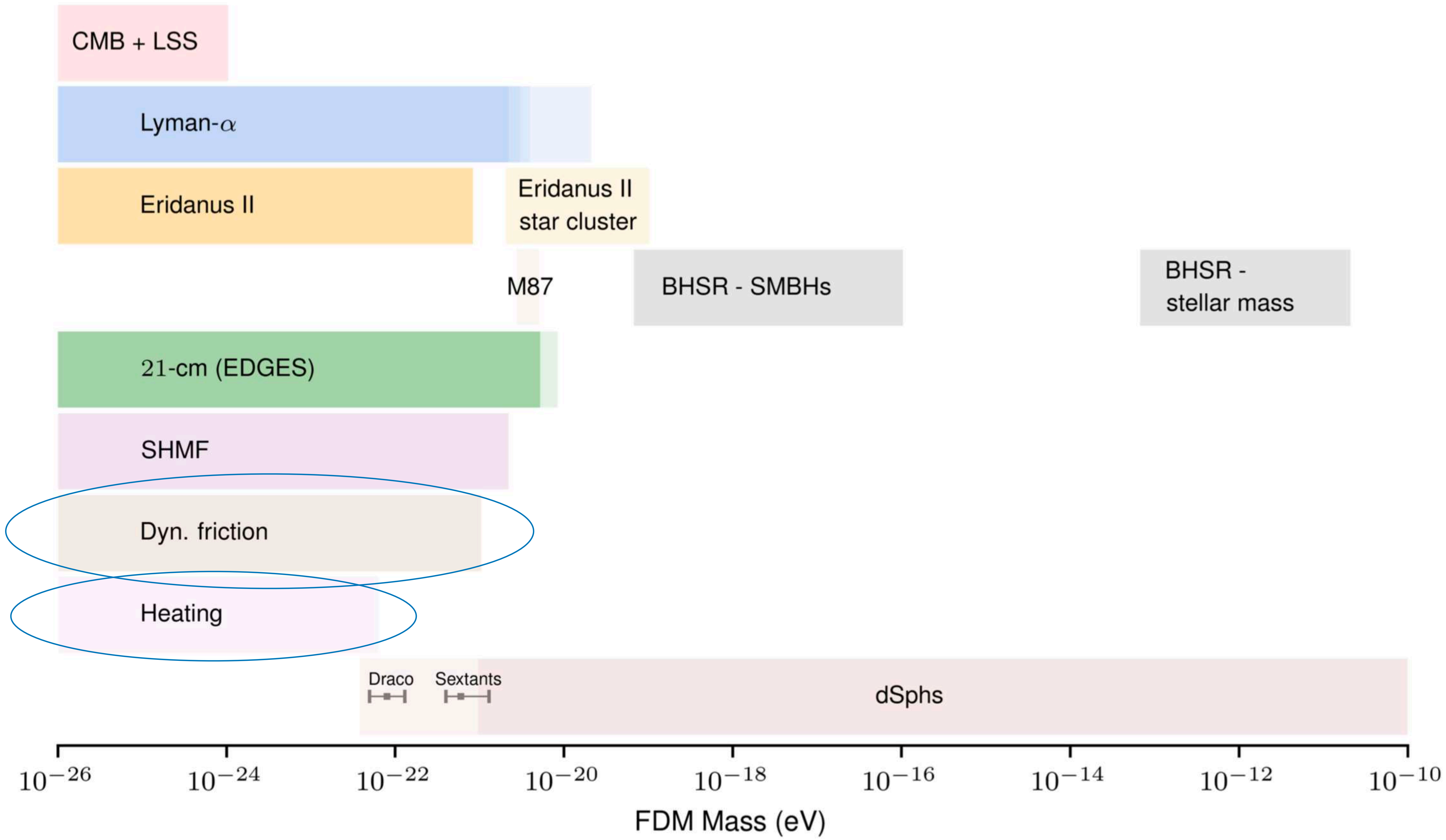
Future: PFS, LSST

Grav. lensing



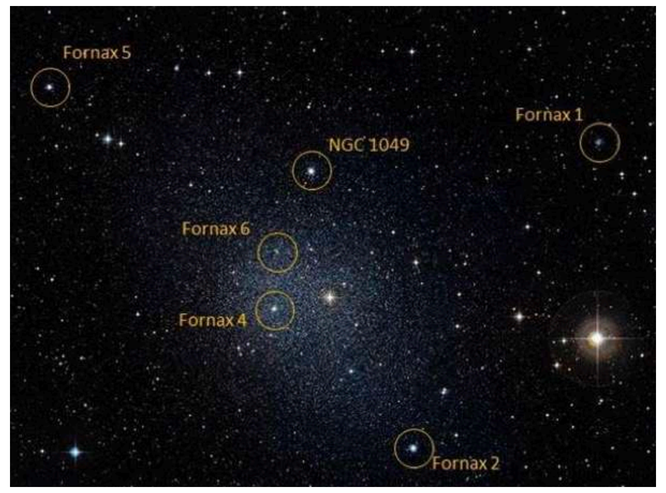
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



Globular clusters

ESO/Digitized Sky Survey 2



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

Can explain these glob. Clusters

Lancaster et al. 2020

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

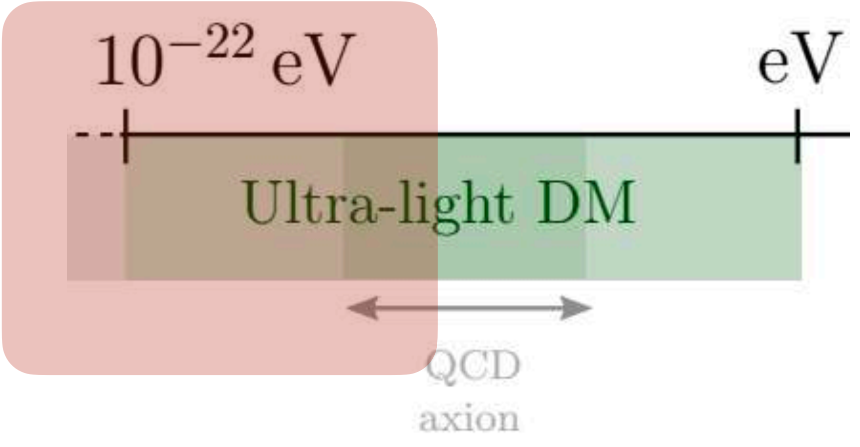
Heating of the MW disk

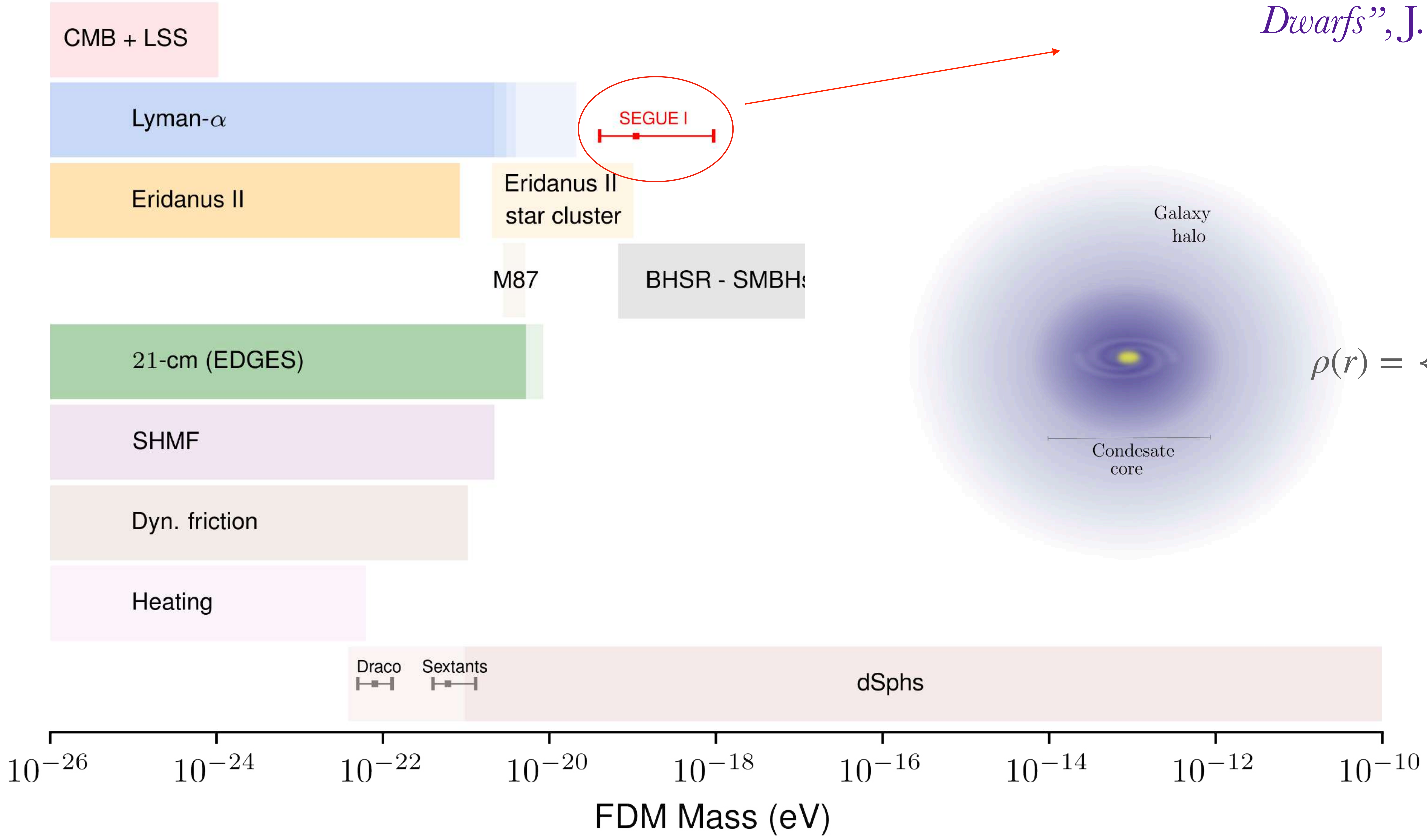
Church et al. 2019

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

Observational implications and constraints

Fuzzy dark matter - bounds on the mass





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

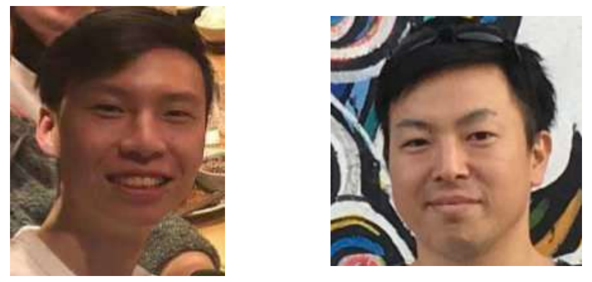
FDM SIMULATIONS

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

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

Constraints on the mass

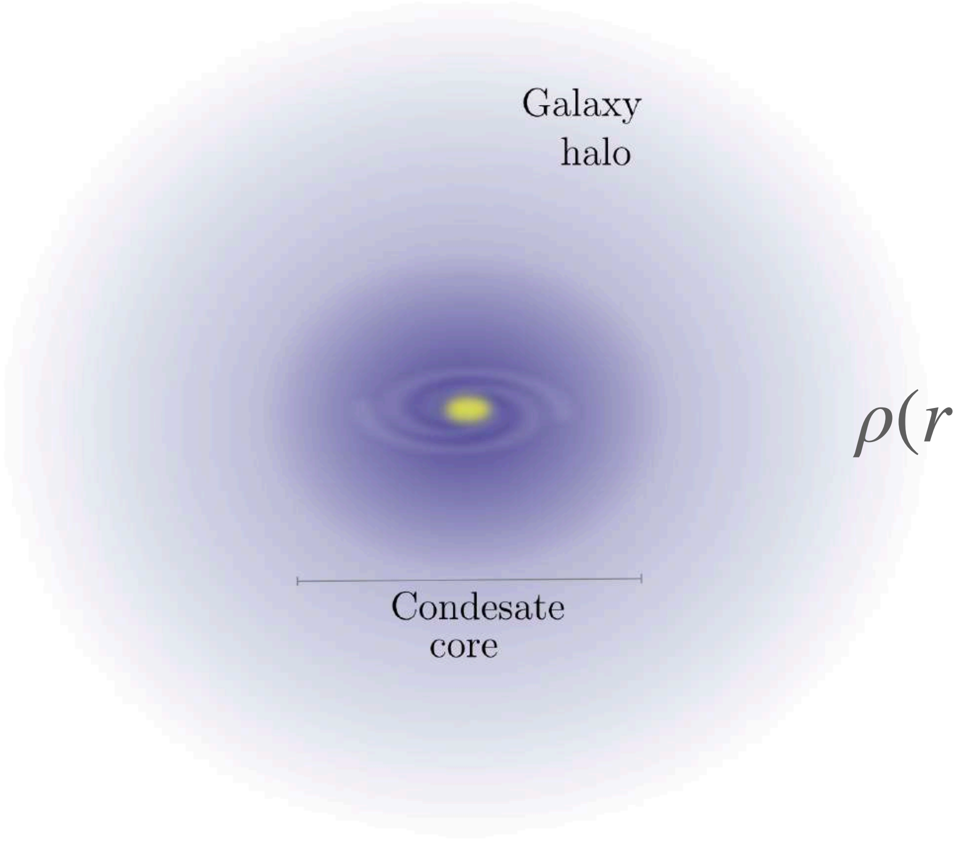
FDM mass from Ultra-faint dwarfs



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

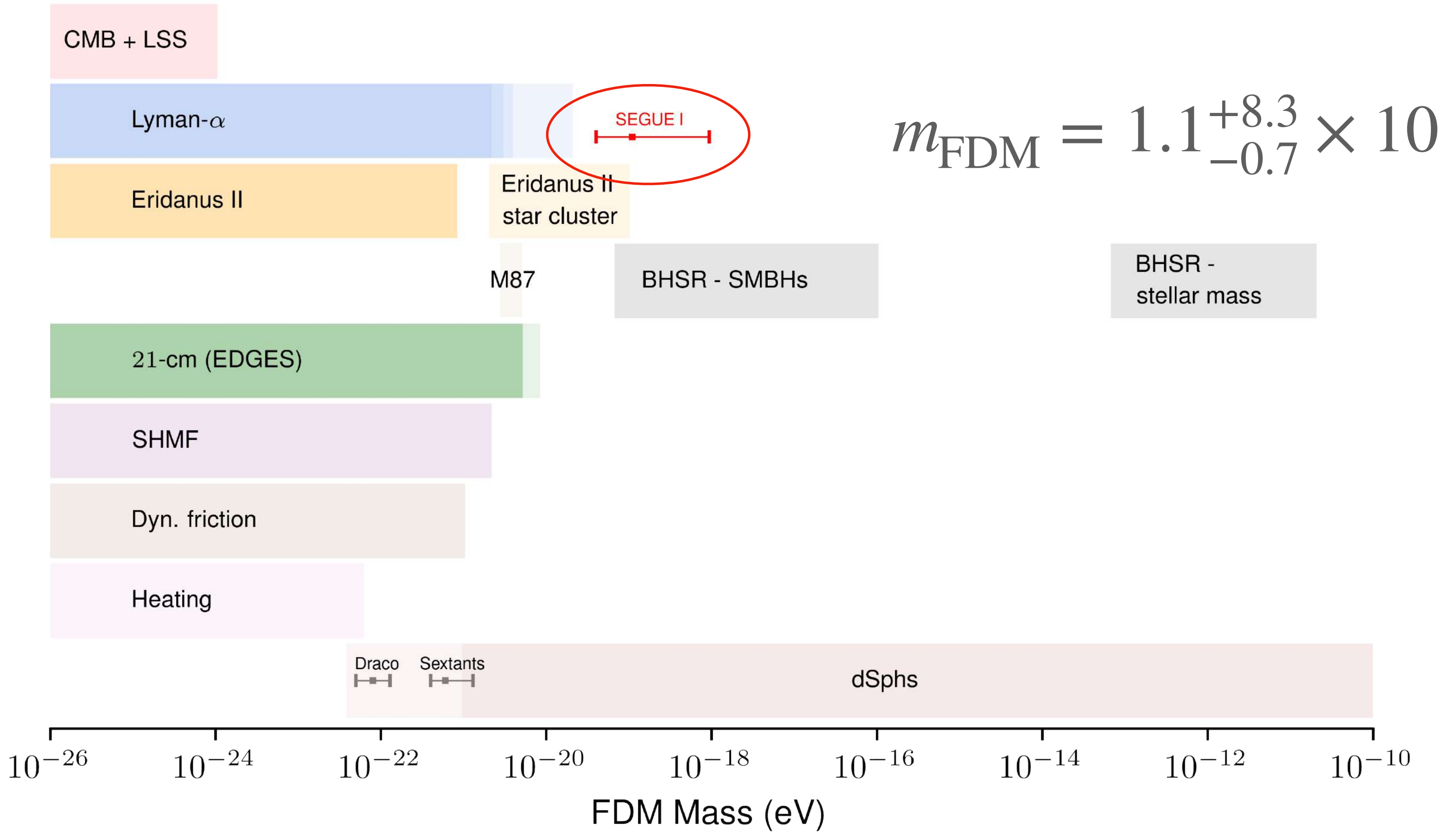
Ultra-faint dwarfs (UFD): ideal laboratory to study DM

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

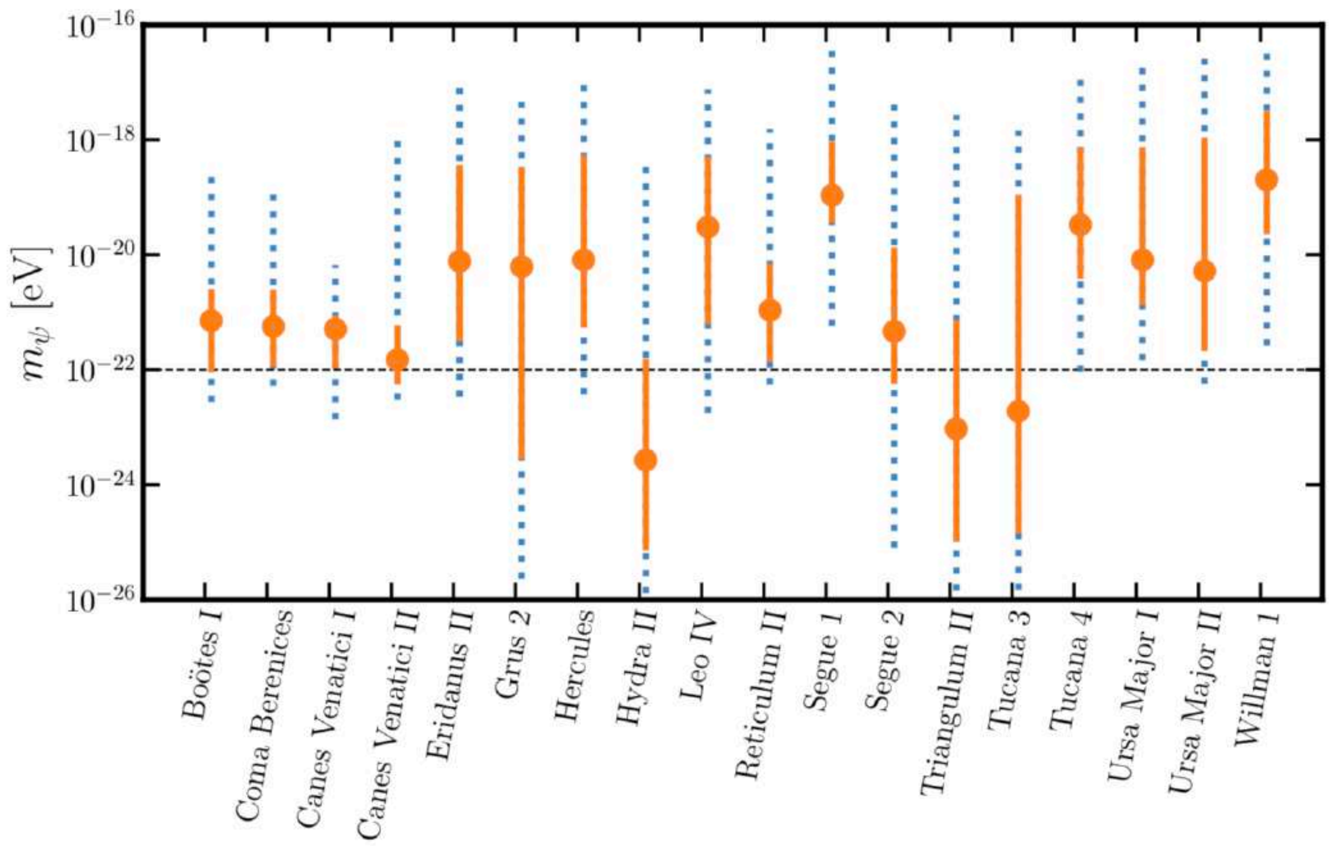


FDM SIMULATIONS

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



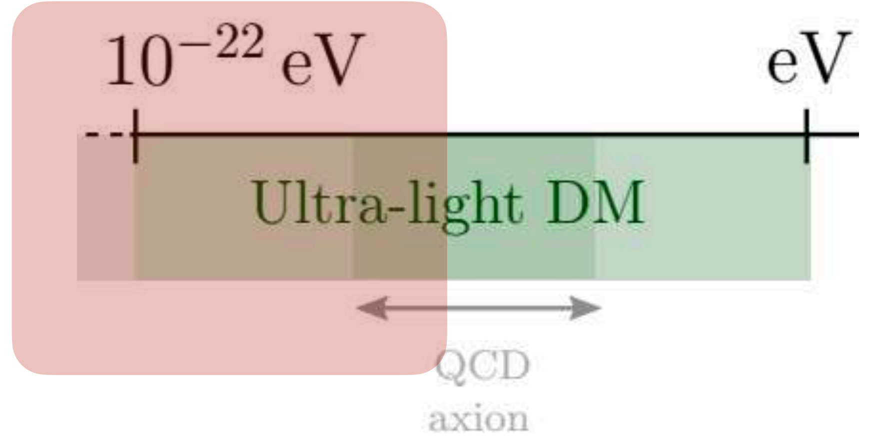
$$m_{\rm FDM} = 1.1^{+8.3}_{-0.7} \times 10^{-19}\,{\rm eV}$$

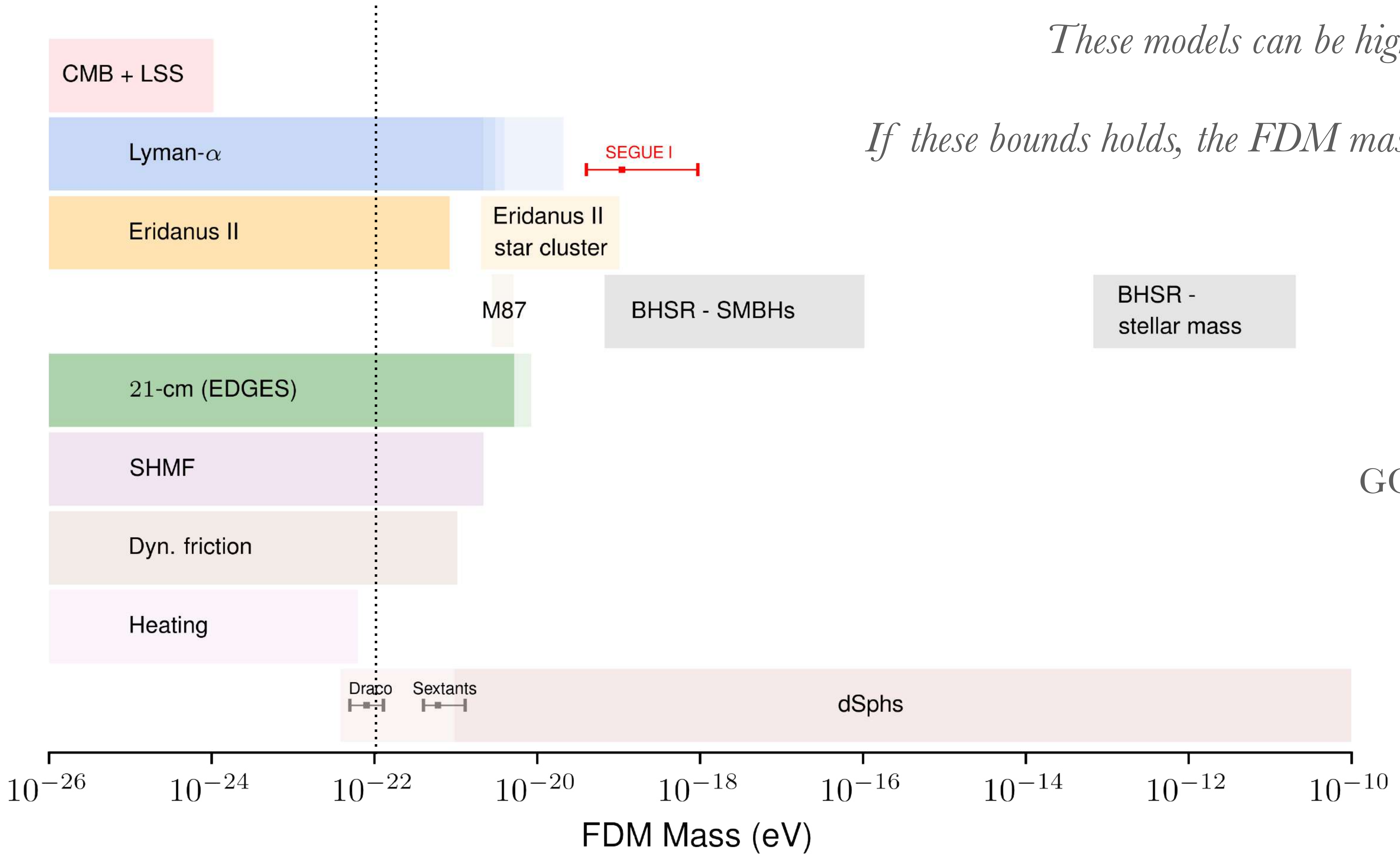


Strongest constraint on $m_{\rm FDM}$ to date!

Observational implications and constraints

Fuzzy dark matter - bounds on the mass





These models can be highly constrained

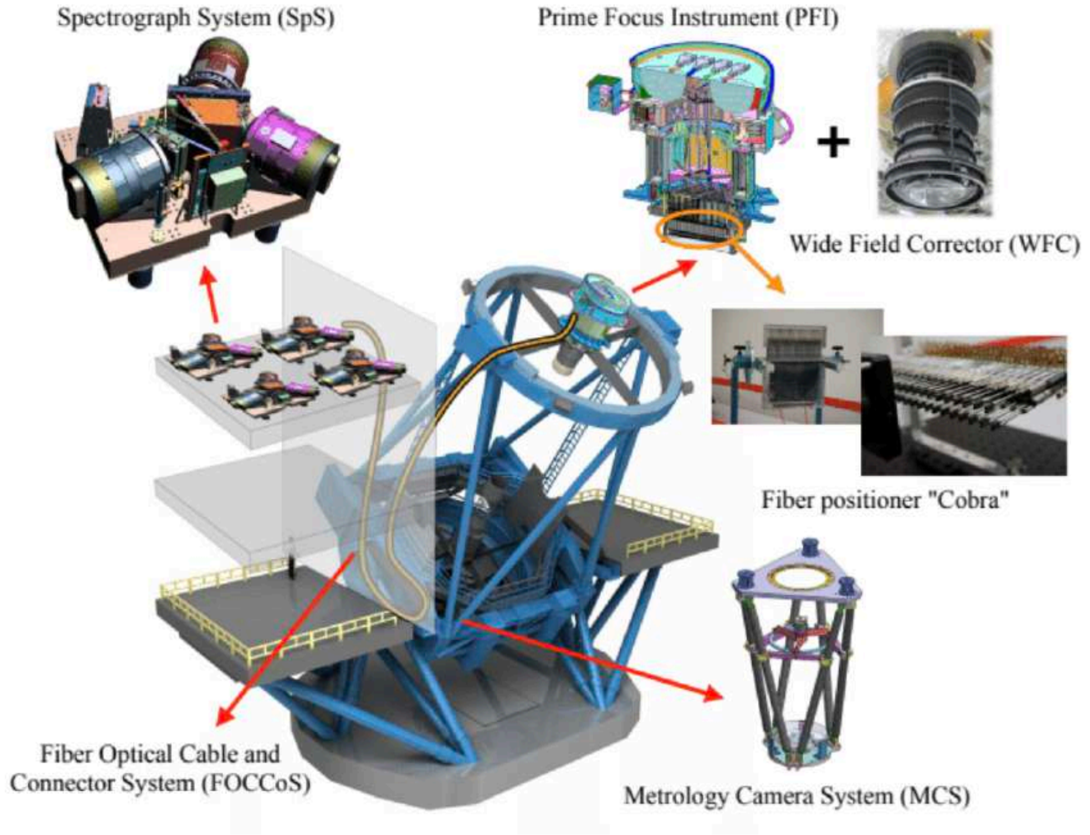
If these bounds holds, the FDM mass range is narrowing down

GOAL: Constraints for SIFDM

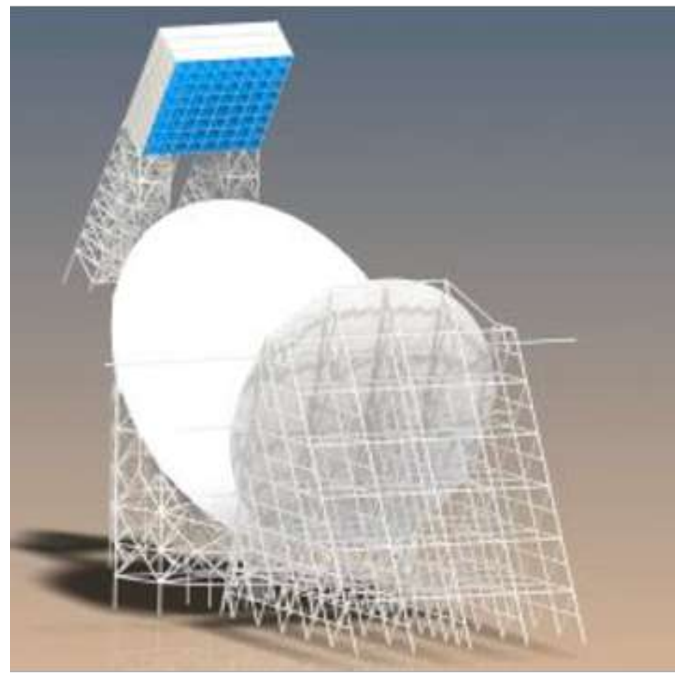
"Ultra-light dark matter", **E.F.**, 2020

Future

Prime Focus Specctrograph (PFS)



BINGO telescope

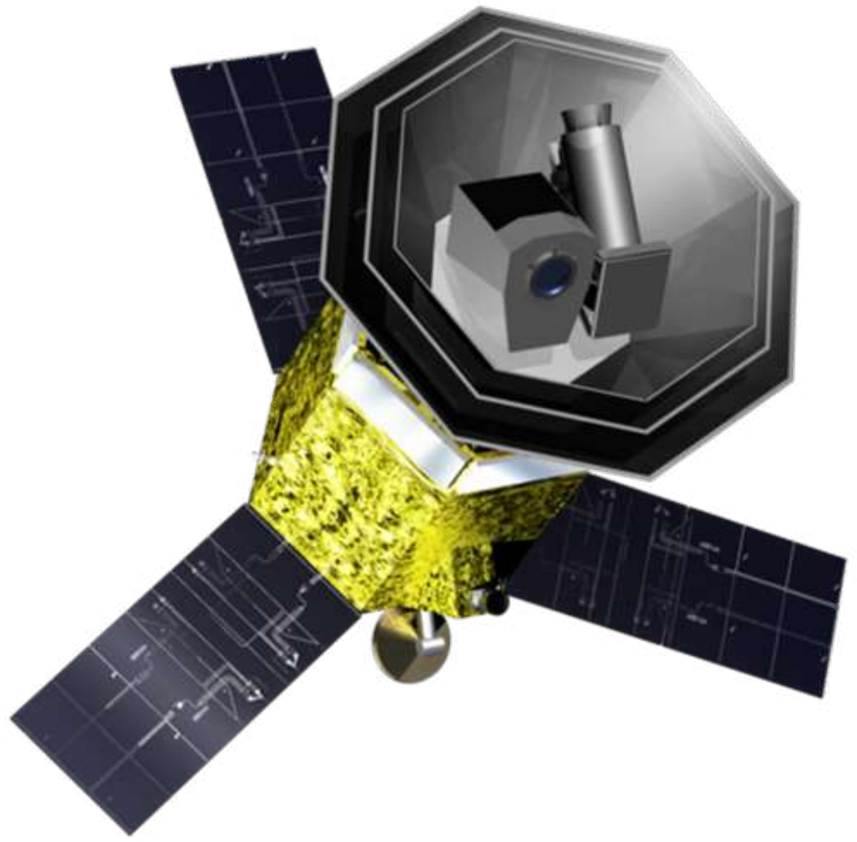


Vera Rubin observatory (LSST)

CMB-S4

CMB-S4
Next Generation CMB Experiment

LiteBIRD



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

- 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 (Prime Focus Spectrograph)

Ongoing

TESTING ULTRA LIGHT DM/DM with PFS

GOAL

Galaxy archeology

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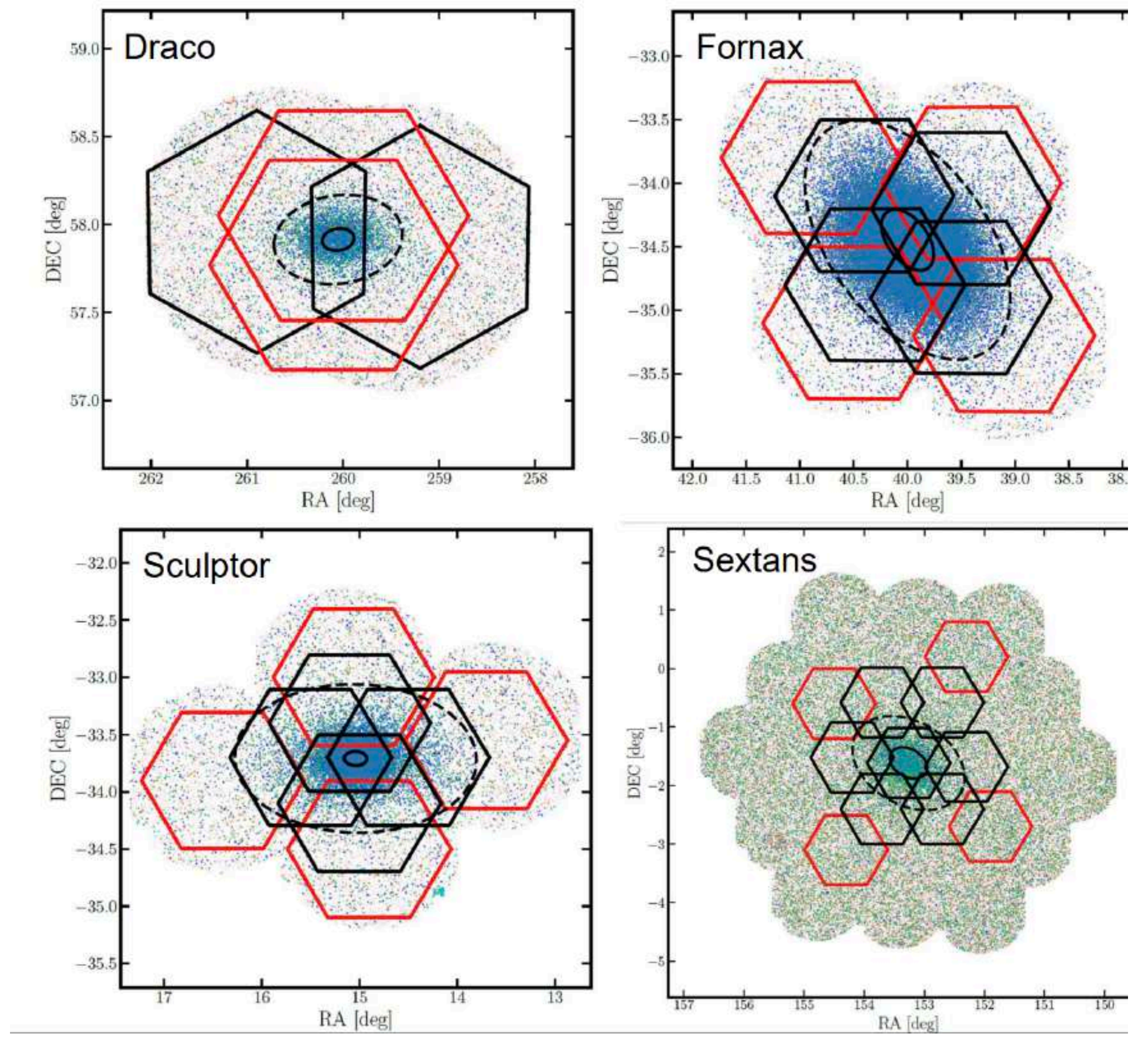
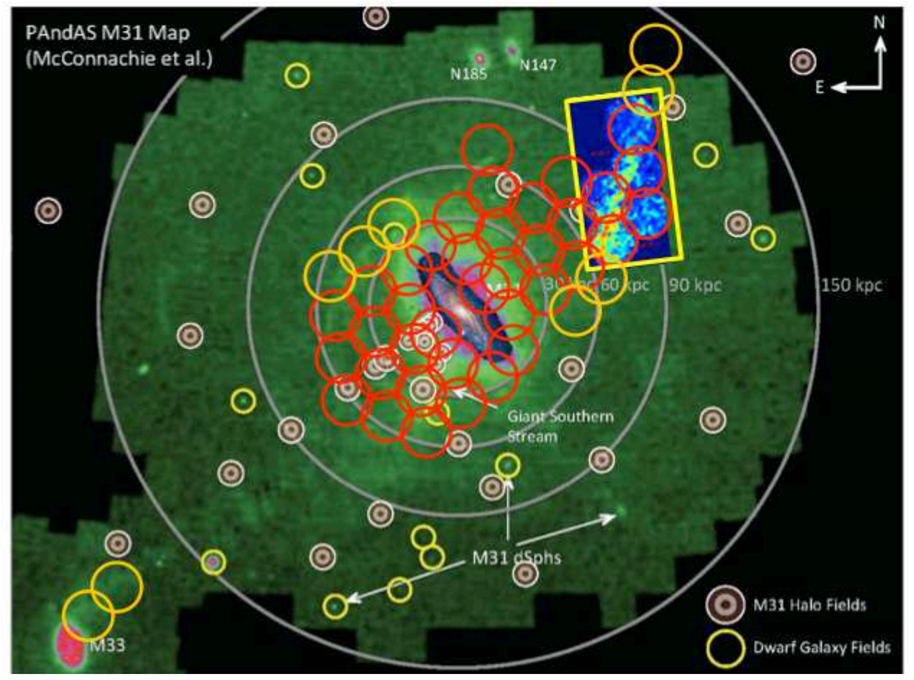
- Stellar kinematics and chemical abundances – MW & M31

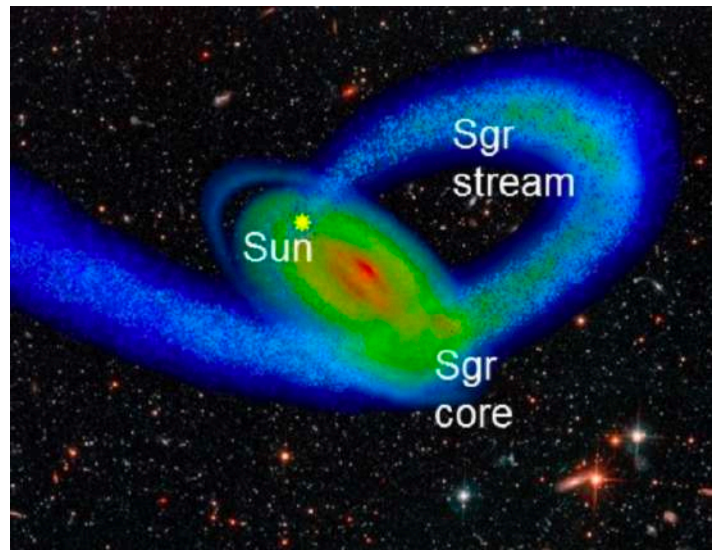
Wide & deep survey of MW dwarf galaxies w. Subaru/PFS



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

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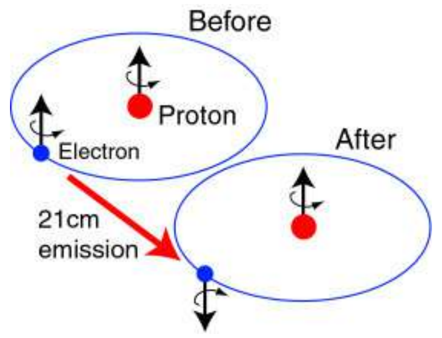
- Tomography of gas and DM

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

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

Future - BINGO *telescope*



21-cm

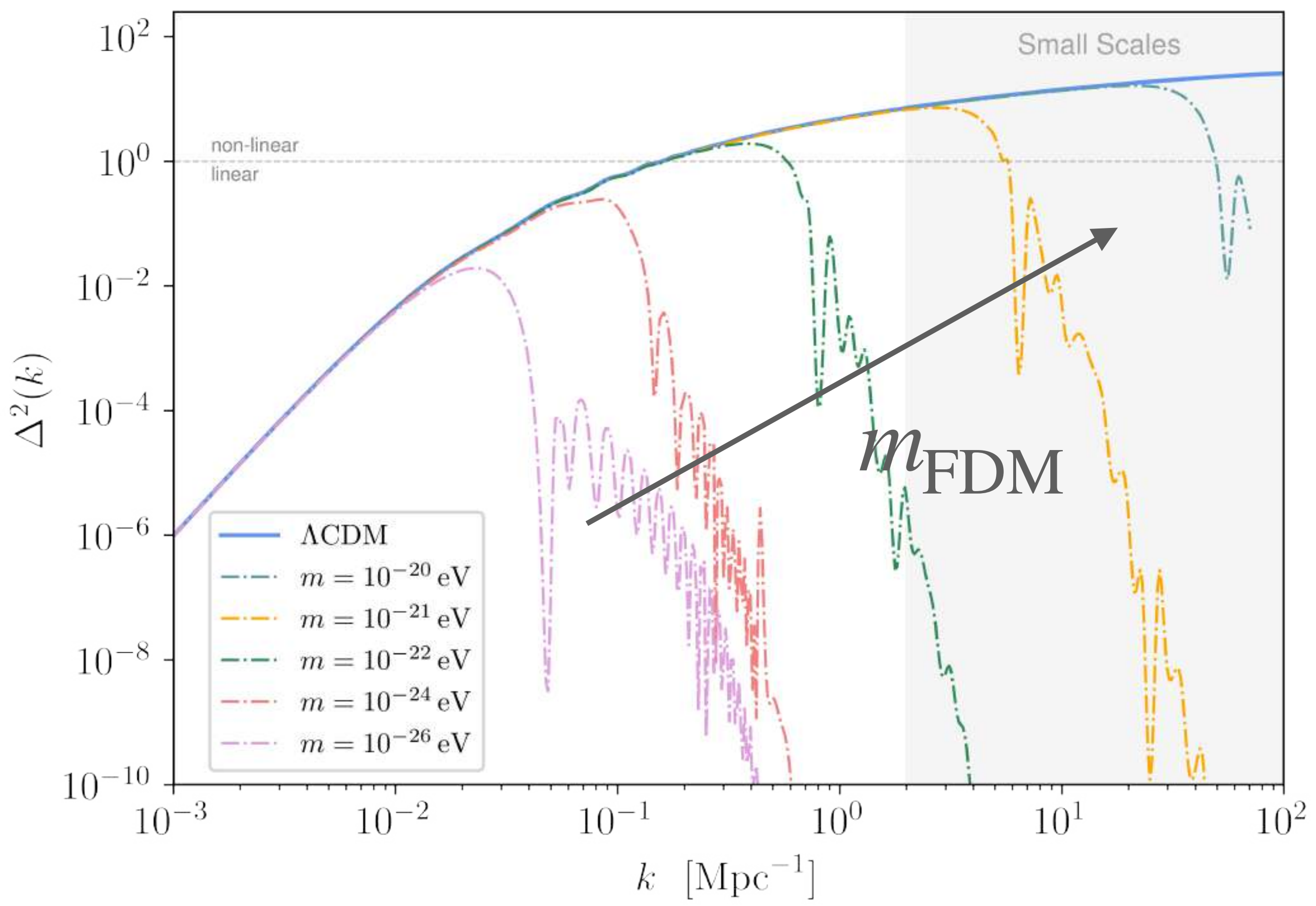
TESTING ULTRA LIGHT DM w/ 21-cm (BINGO)

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

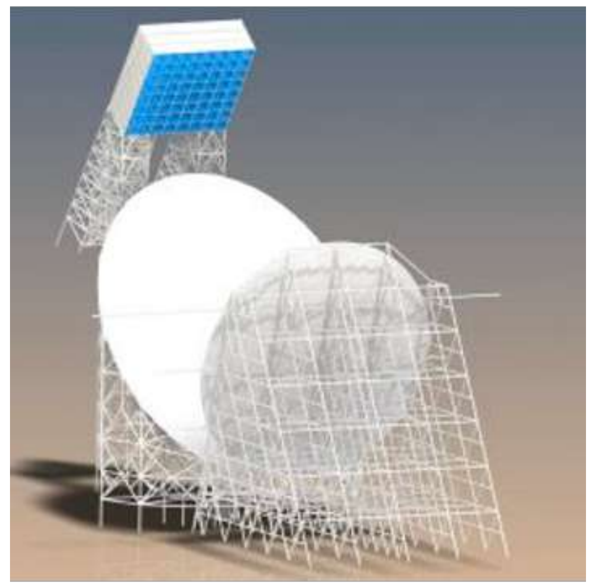


- Suppression of PS
- Increase in b_{HI}

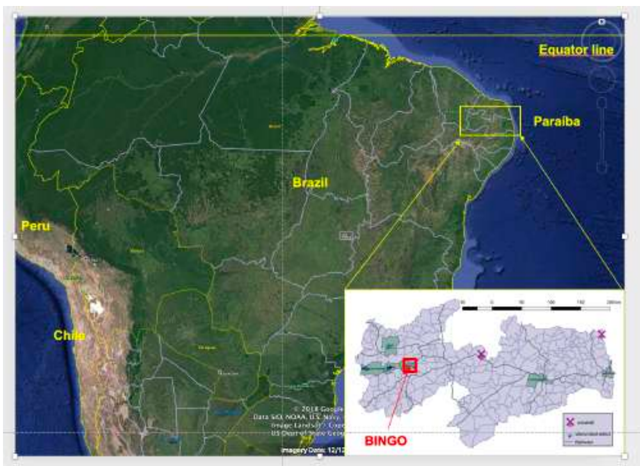
BINGO (BAO In Neutral Gas Observations)

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.*

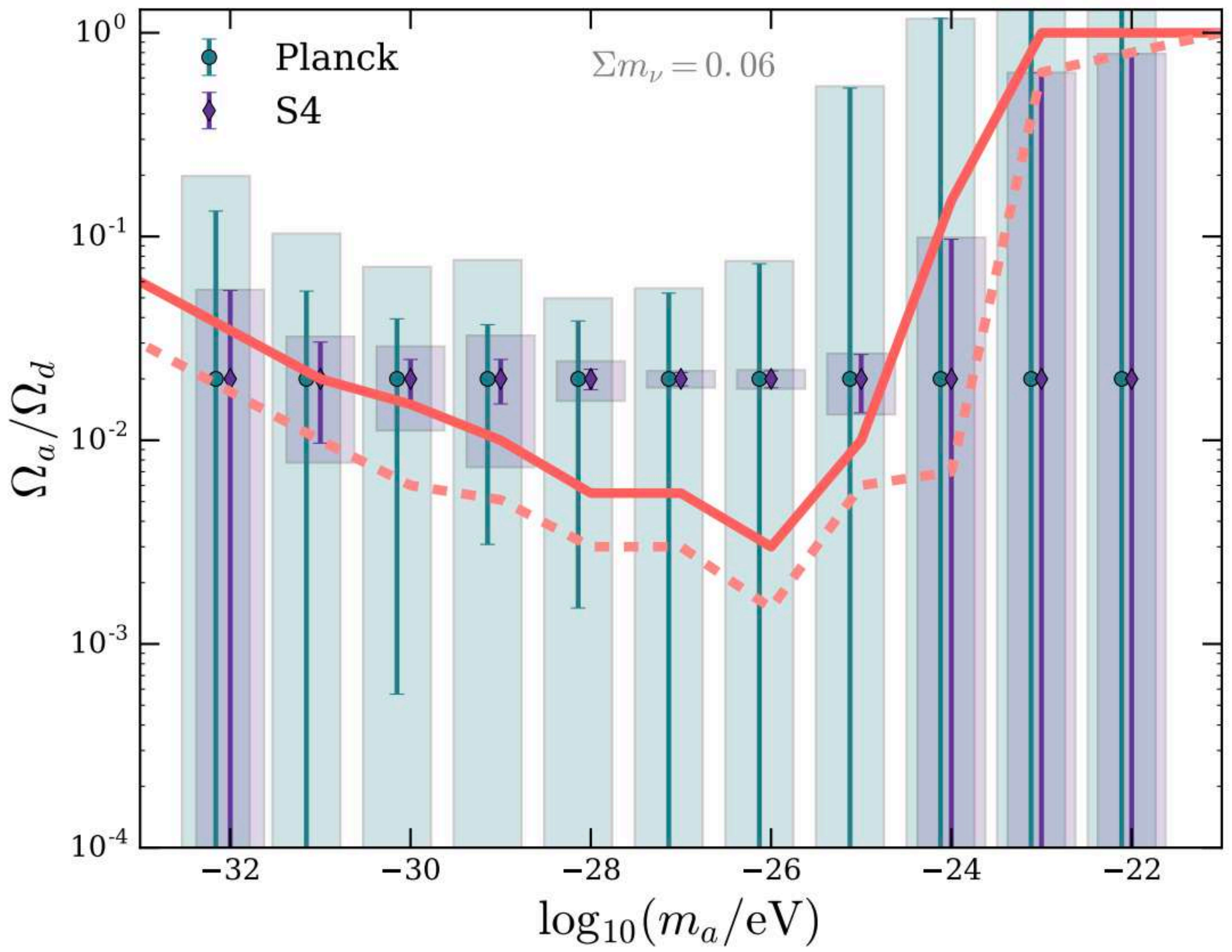
Future - Cosmic Microwave Background

TESTING ULTRA LIGHT DM CMB

GOAL

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* $\tau(r_{\rm rec})$

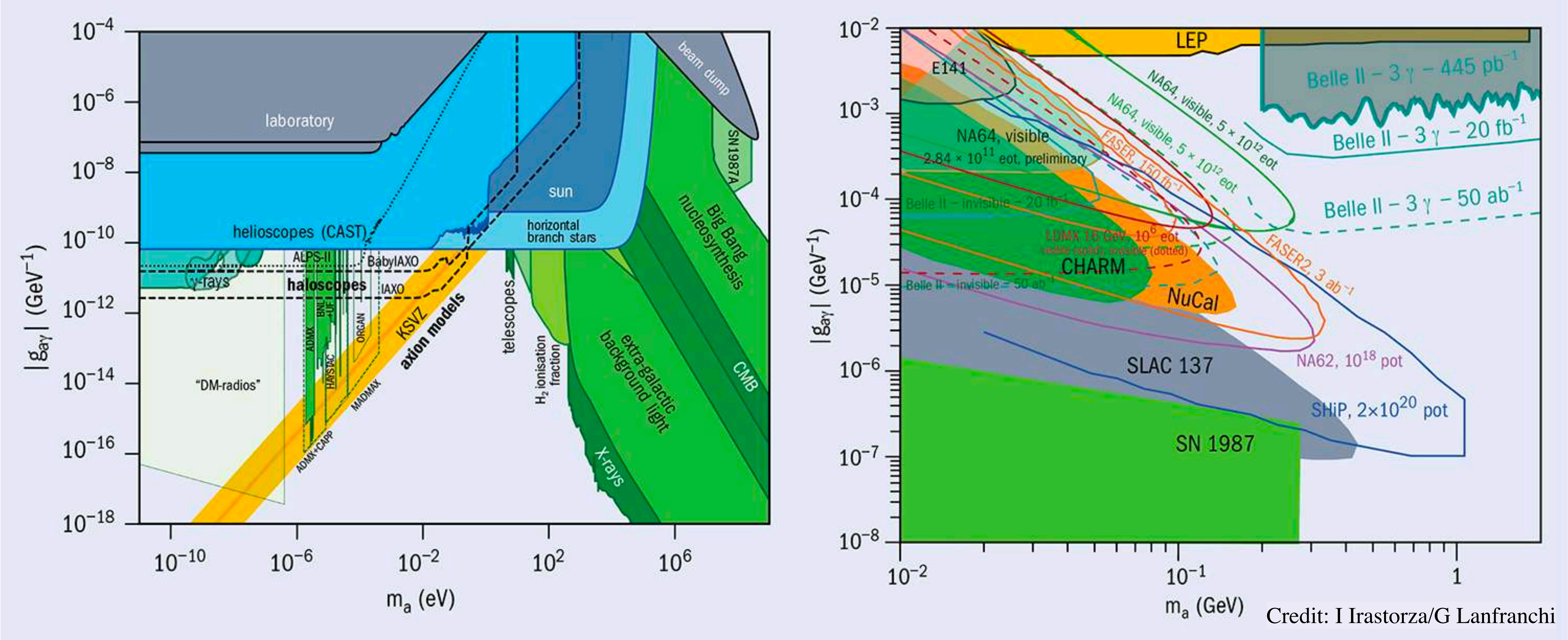
Constraint the ULDM mass

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

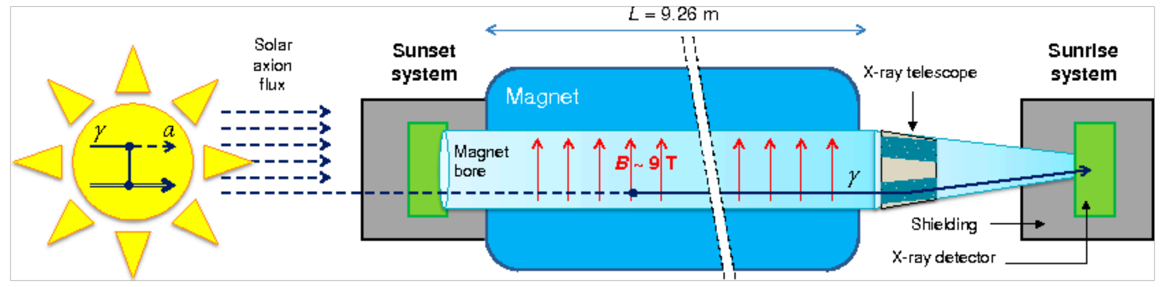
- *LiteBIRD*
- *Advances ACTPol*
- *CMB-S4*

Axion - direct and indirect detection

Axion ou ALP interacts with photons

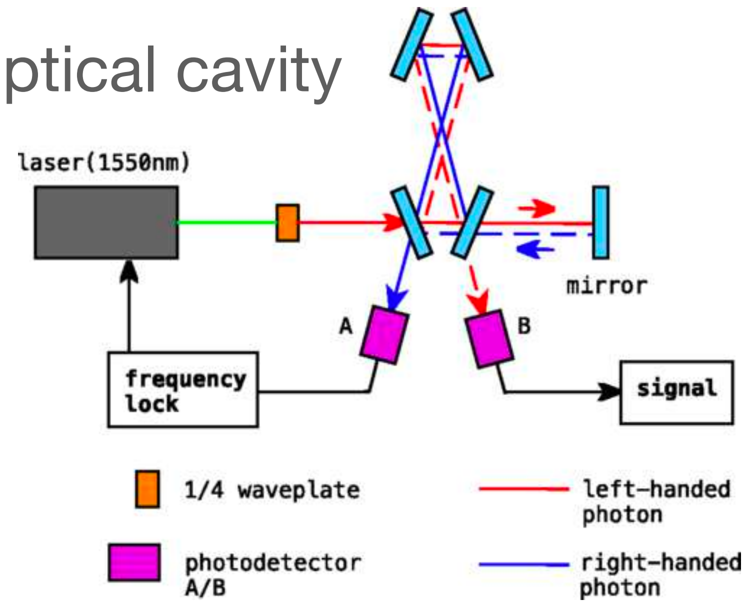


Credit: I Irastorza/G Lanfranchi



CAST

Optical cavity



Obata et al 2018

Axion ou ALP interacts with neutrinos

Shao-Feng Ge, Hitoshi Murayama, 2019

Abhish Dev et al, 2020

Effects of oscillations of the axions can be probed in neutrino oscillation experiments

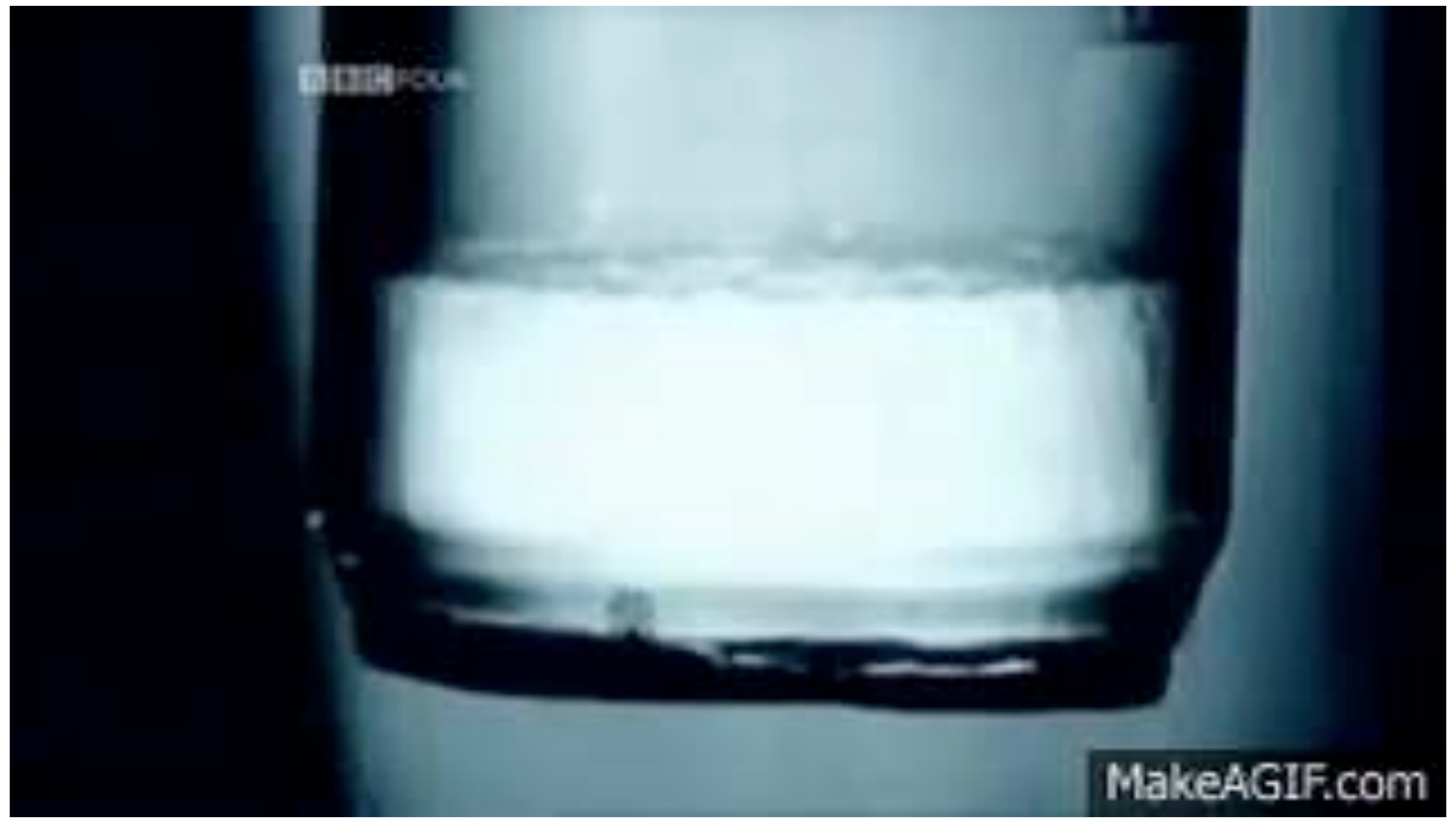
- time variation os neutrino signal
- Oscillation prob. distorted
- …

Super-Kamiokande?
(Hyper-K)

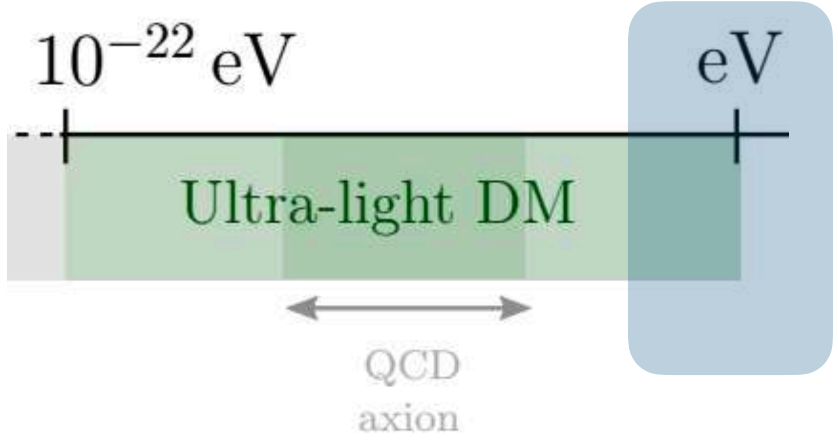
This effect can also be seen in:

- CMB
- BBN
- Astrophysical neutrinos and Sn 1987A

Superfluid Dark Matter

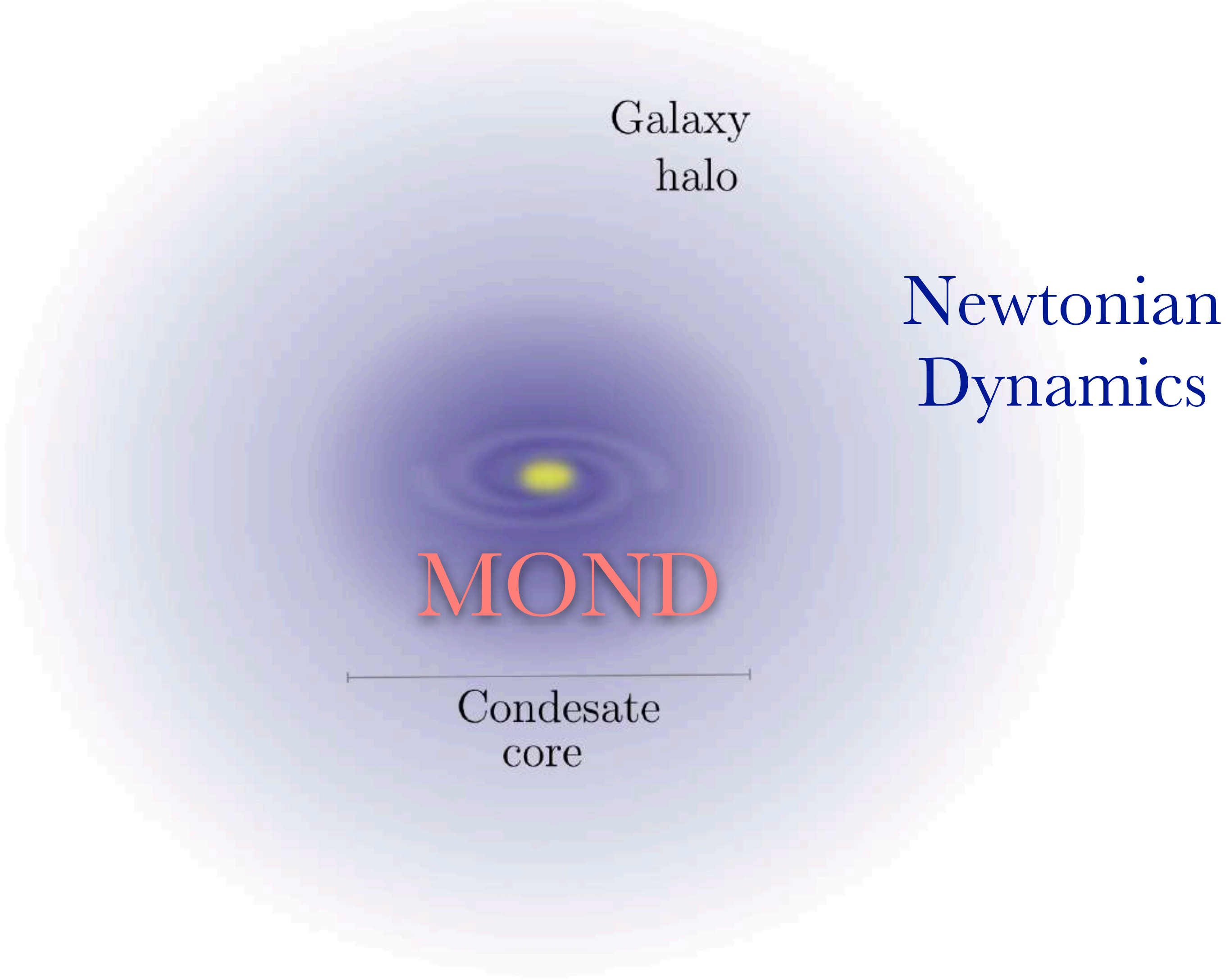


Superfluid Dark Matter



Lasha Berezhiani and Justin Khoury (2016)

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



Galactic scales:
DM forms a superfluid
⟶ emergent MOND dynamics in galaxies

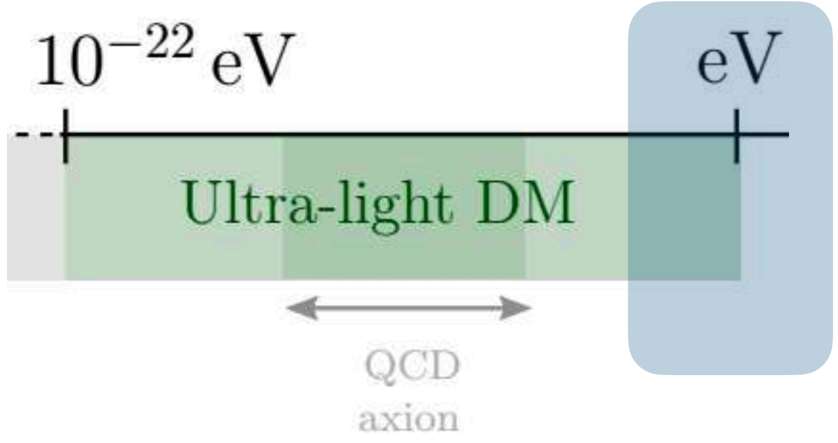
$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

Similar phenomenology than the FDM & SIFDM + explains the rotations curves and scaling relations

Suppresses small structures, dyn. effects, formation of cores

Superfluid Dark Matter

How to construct - MOND from phonons

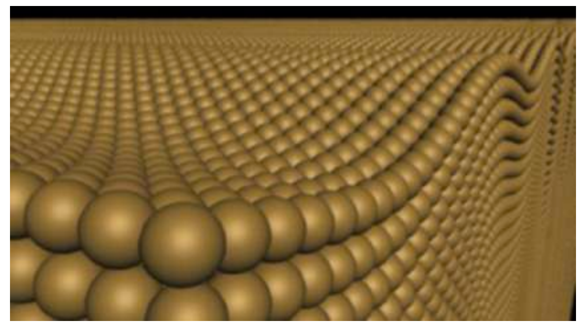


Lasha Berezhiani and Justin Khoury (2016)

EFT of superfluids $\mathcal{L} = P(X)$ $X = \dot{\theta} - m\Phi - \frac{(\vec{\nabla}\theta)^2}{2m}$

Different phenomena $P(X) \propto \left(\dot{\theta}/m\right)^n$

$n = 2:$	$P \sim \rho^2$	BEC
$n = 3/2:$	$P \sim \rho^3$	"MOND"
$n = 5/2:$	$P \sim \rho^{5/3}$	Unitary Fermi gas



Crystal Lens

$$\Psi = (v + \rho)e^{i(\mu t + \theta)}$$

Low energy: only θ excited - phonon
Nambu Goldstone boson

To describe non-relativistic MOND, it is imposed that:

$$P(X) = \frac{2\Lambda\,(2m)^{3/2}}{3} X\sqrt{|X|}$$

⟶ Leads to an equation of state $P \sim \rho^3$ required to describe MOND

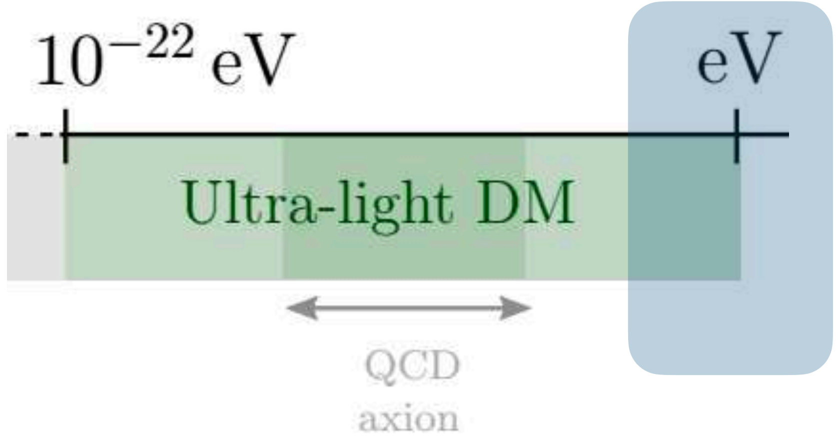
To mediate the MONDian force, couple phonons to baryons:

$$\mathcal{L}_{int} \sim \frac{\Lambda}{M_{pl}}\theta\rho_b$$

Softly breaks shift symmetry

$$\Lambda = \sqrt{a_0 M_{pl}} \sim 0.8\,\mathrm{meV}$$

Superfluid Dark Matter



- Newtonian limit: $|\vec{\nabla}\Phi| > 3\,a_0$

$$\Longrightarrow \quad \boxed{\vec{\nabla}^2\Phi = \frac{\rho_s + \rho_b}{2M_{pl}^2}}$$

- MOND limit: $|\vec{\nabla}\Phi| < 3\,a_0$

$$\Longrightarrow \quad \boxed{\vec{\nabla}\cdot\left(\frac{|\vec{\nabla}\Phi|}{a_0}\vec{\nabla}\Phi\right) = \frac{\rho_s + \rho_b}{2M_{pl}^2}}$$

Only DM

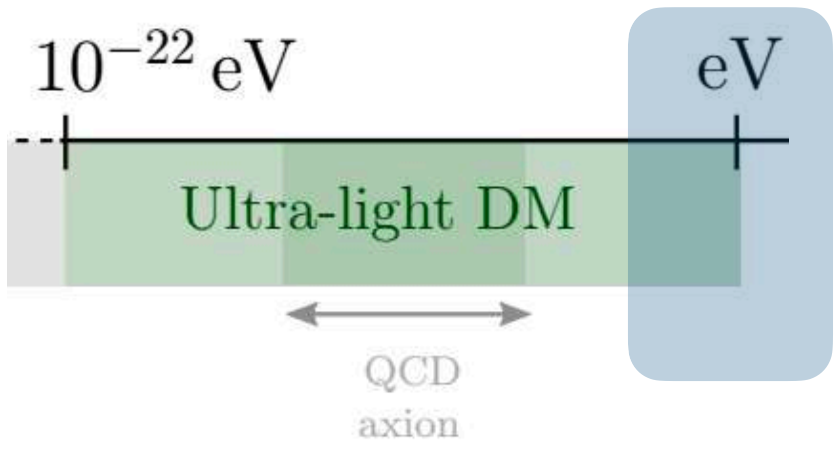
Mostly DM

”MOND”

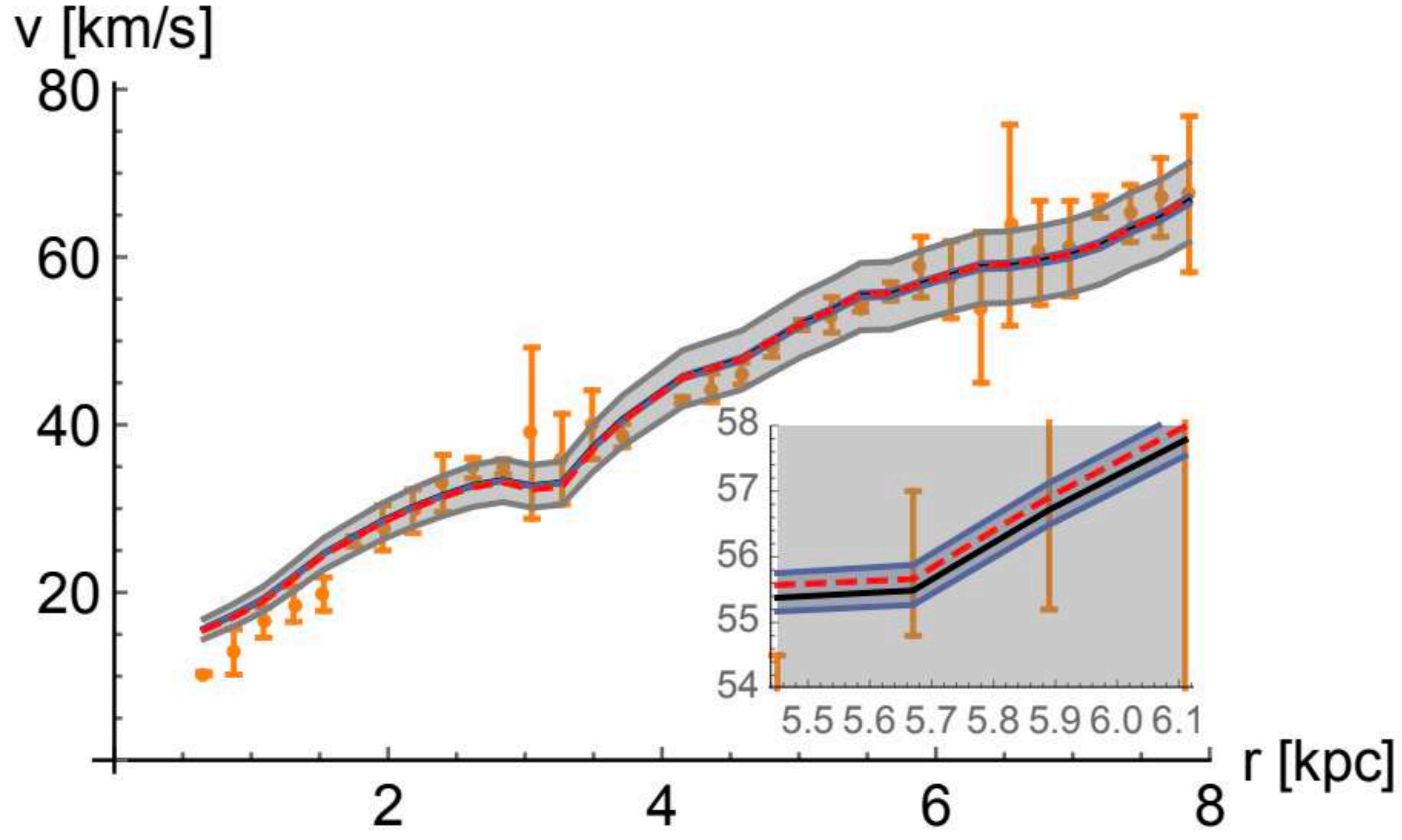
No MOND

Superfluid Dark Matter

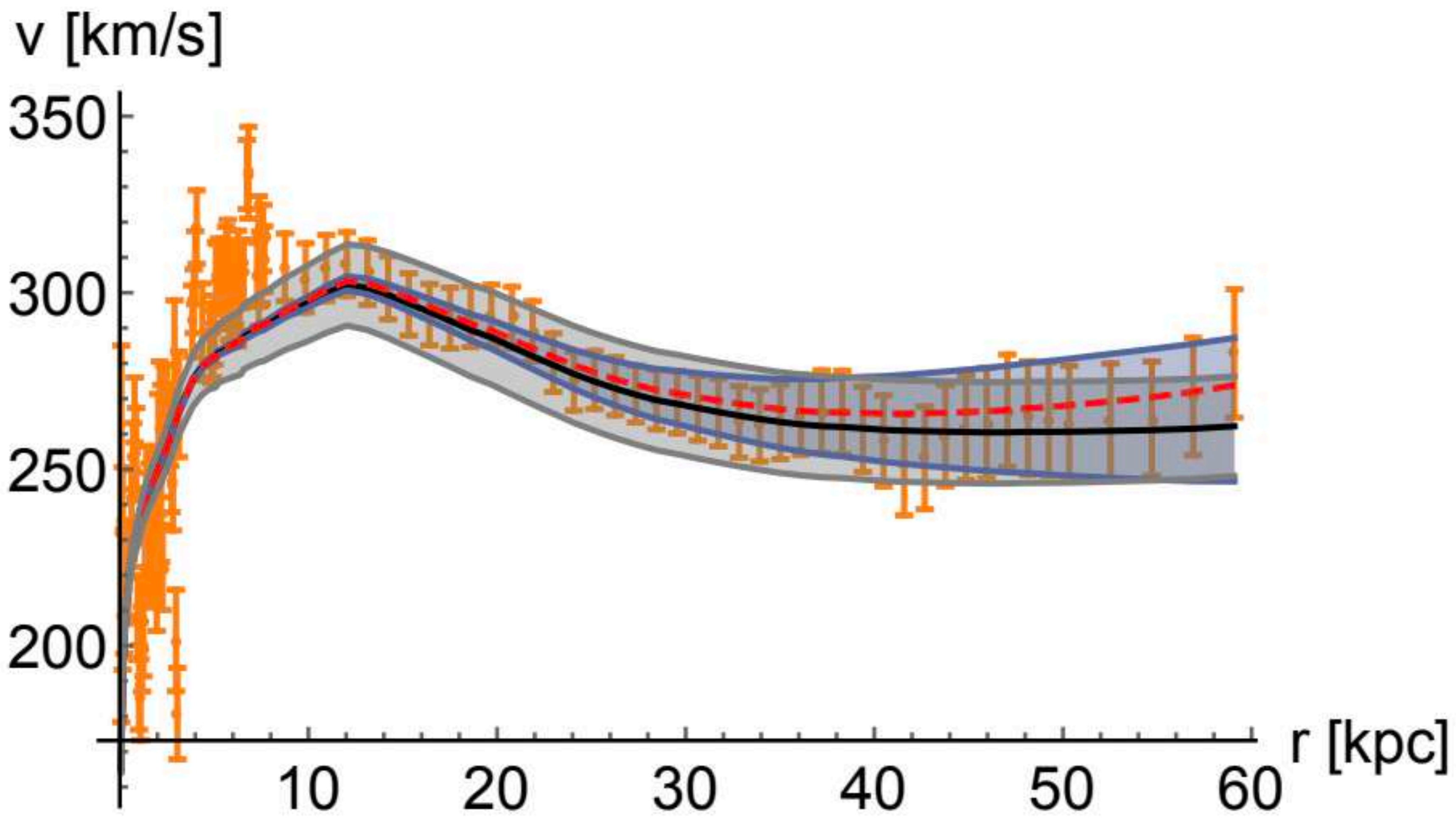
Rotation curves



Low surface brightness



High surface brightness



Superfluid core:

$$R_{halo} = 57\,\mathrm{kpc}$$

$$R_{Sf} = 40\,\mathrm{kpc}$$

58% of the total mass of the halo

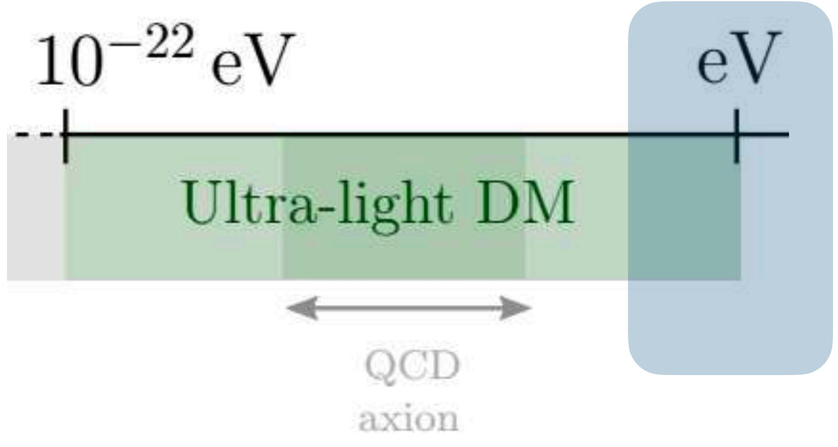
$$R_{halo} = 445\,\mathrm{kpc}$$

$$R_{Sf} = 79\,\mathrm{kpc}$$

25% of the total mass of the halo

Superfluid Dark Matter

Observational consequences



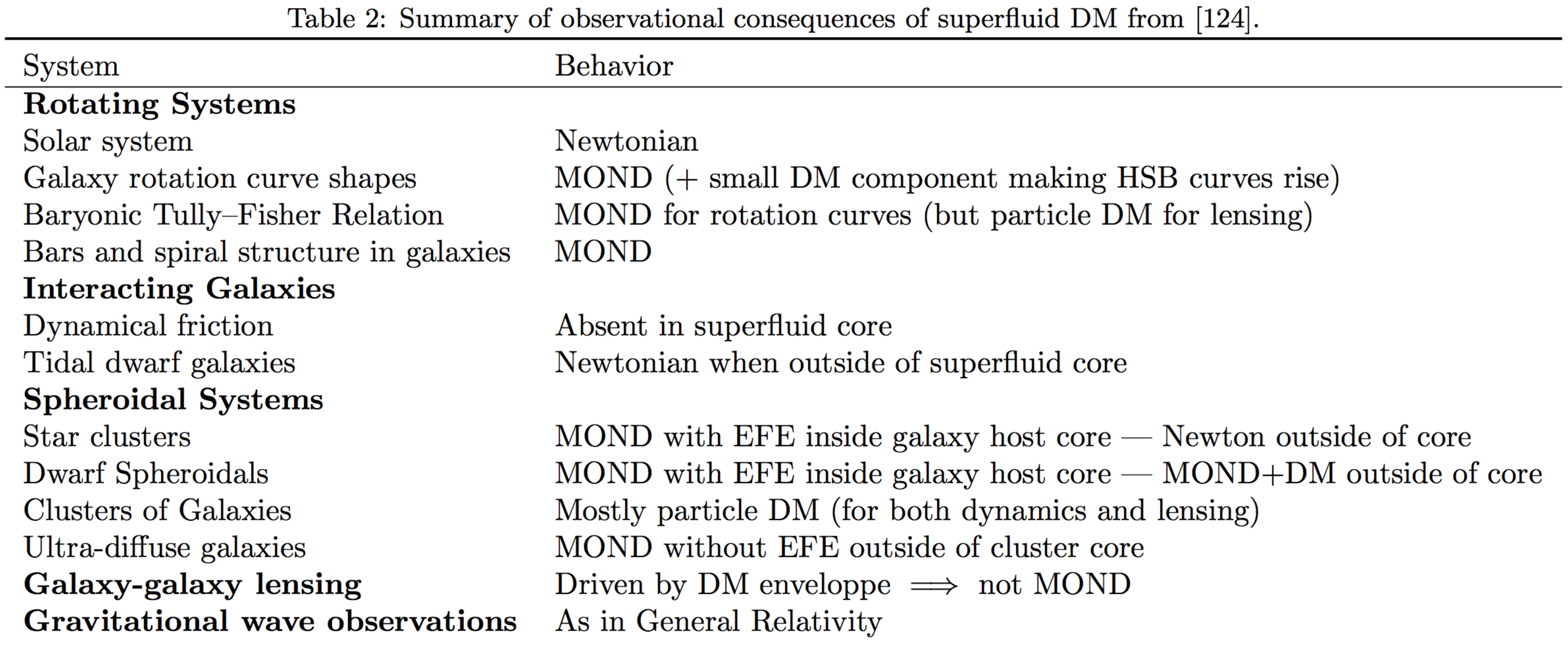


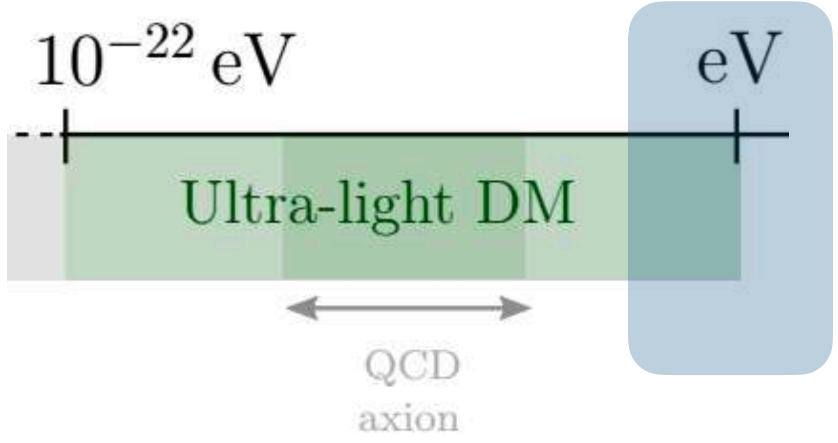
Table 2: Summary of observational consequences of superfluid DM from [124].

System	Behavior
Rotating Systems	
Solar system	Newtonian
Galaxy rotation curve shapes	MOND (+ small DM component making HSB curves rise)
Baryonic Tully–Fisher Relation	MOND for rotation curves (but particle DM for lensing)
Bars and spiral structure in galaxies	MOND
Interacting Galaxies	
Dynamical friction	Absent in superfluid core
Tidal dwarf galaxies	Newtonian when outside of superfluid core
Spheroidal Systems	
Star clusters	MOND with EFE inside galaxy host core — Newton outside of core
Dwarf Spheroidals	MOND with EFE inside galaxy host core — MOND+DM outside of core
Clusters of Galaxies	Mostly particle DM (for both dynamics and lensing)
Ultra-diffuse galaxies	MOND without EFE outside of cluster core
Galaxy-galaxy lensing	Driven by DM enveloppe $\Longrightarrow$ not MOND
Gravitational wave observations	As in General Relativity

Berezhiani et al. 2018)

Superfluid Dark Matter

Dynamical Friction



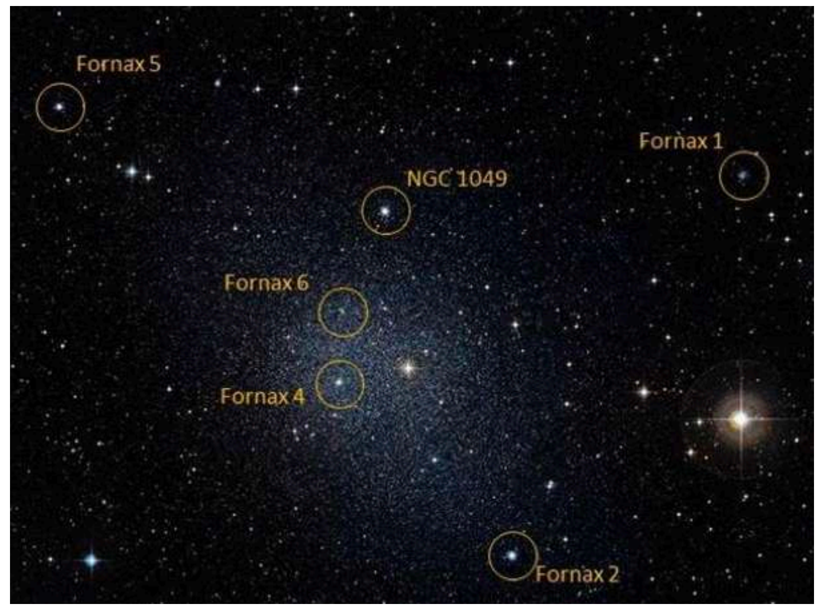
Inner region of galaxy:
Superfluid core

→

Superfluid flows without friction

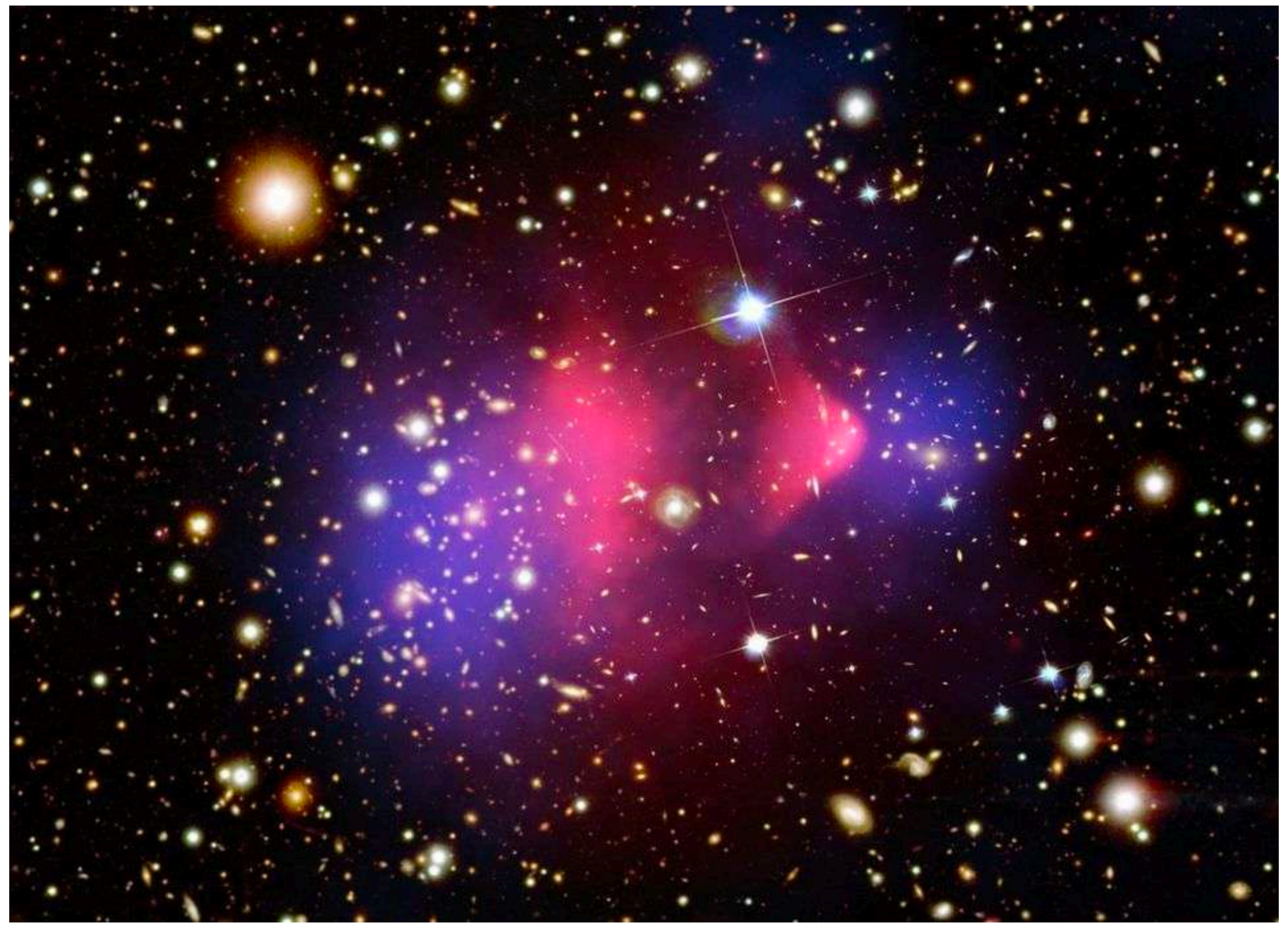
BUT: what about the Bullet Cluster?

- Fornax: globular cluster should have merged with Fornax due to dynamical friction.
  Superfluid → no friction
  Can explain these glob. Clusters



ESO/Digitized Sky Survey 2

Complete analysis in: B. Elder et al., JCAP 1910 (2019) no.10, 074

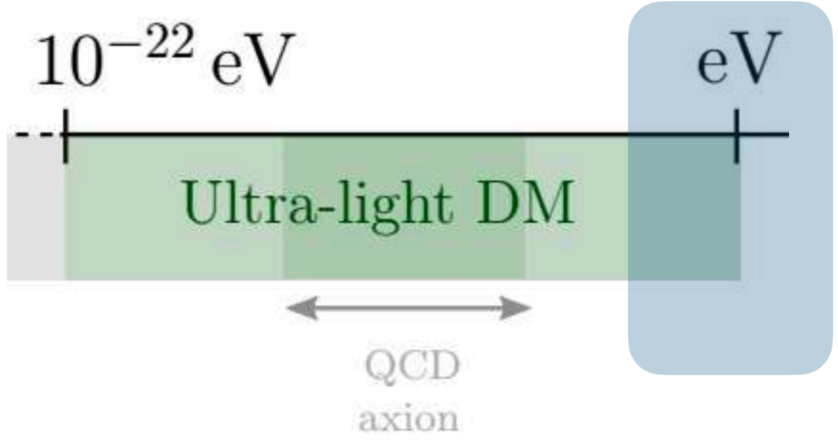


Composite Credit: X-ray: NASA/CXC/CfA/ M.Markevitch et al.;
Lensing Map: NASA/STScl; ESO WFI; Magellan/U.Arizona/ D.Clowe et al.
Optical: NASA/STScl; Magellan/U.Arizona/D.Clowe et al.;

Large cluster subsonic and small cluster supersonic (Sf core)
Bullet cluster as expected!

Landa criteria for superfluid
$v < v_c$

Superfluid Dark Matter



Superfluid DM model presents a very interesting behaviour in galaxies, being able to reproduce MOND from DM

- Presents only a phenomenological non-relativistic description
- Need to develop cosmology
- Does not present many constraints yet.

Presents opportunities of theoretical and observational advances!

Ultra-light fields as Dark Energy

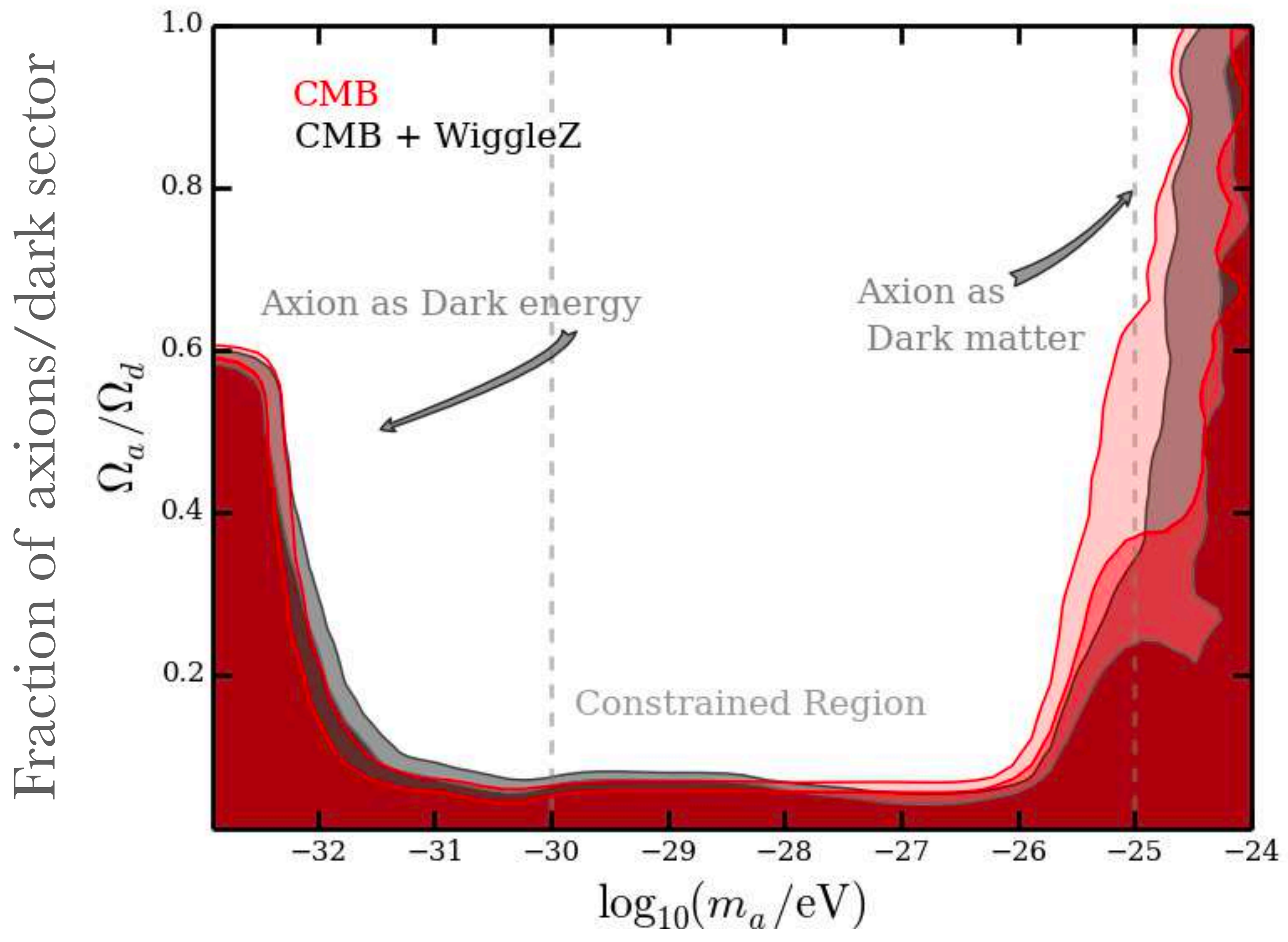
Ultra-light fields as Dark Energy

Fuzzy Dark Matter

Behave as dark energy with $w \sim -1$ for

$$m_{\mathrm{fdm}} < 10^{-32}\,\mathrm{eV}$$

Hlozek et al, 2015; Jiangang Kang et al. (2019)



Ultra-light fields as Dark Energy

Unified superfluid dark sector

"Unified superfluid dark sector", EF, G. Franzmann, J. Khoury, R. Brandenberger, 2018

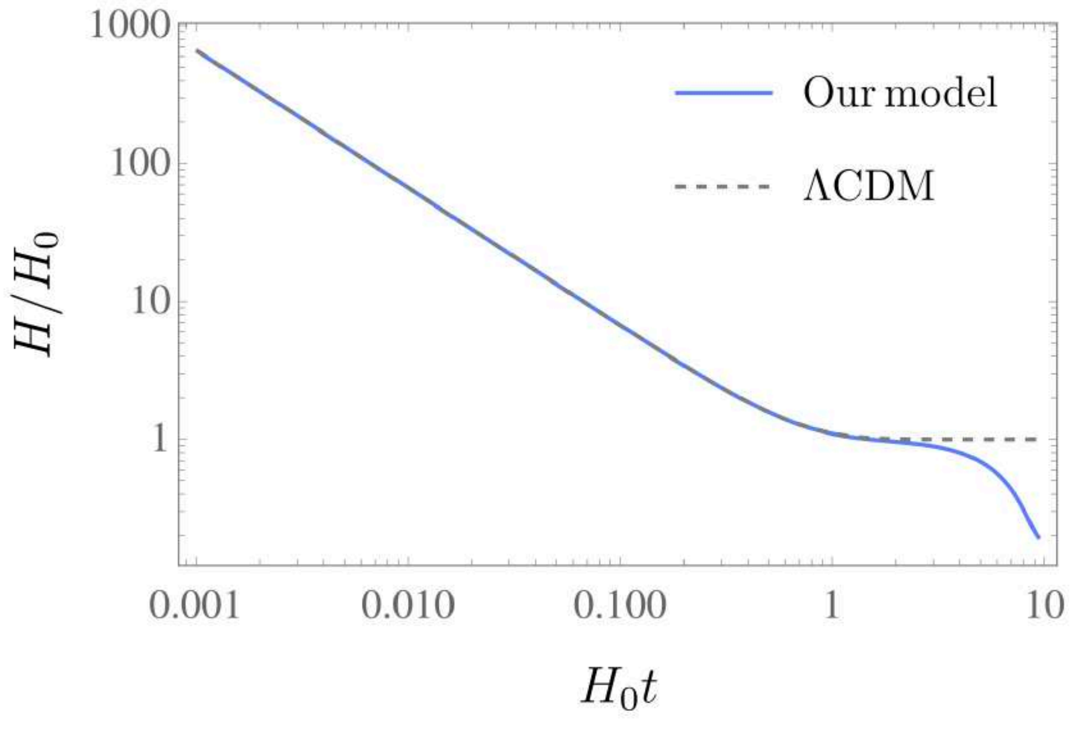
- DM superfluid with two interacting distinguishable states.
- Phonons: propagate with different phases for each species

  ⟶ Potential for the $(\theta_1 - \theta_2)$
- Prediction for clustering

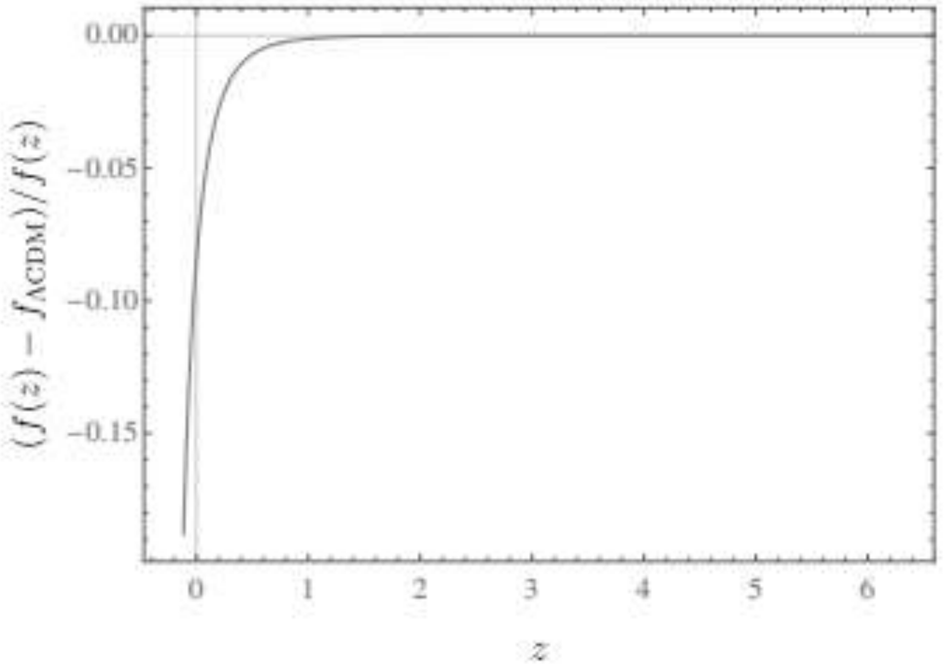
Unified framework
w/ DM alone!

$$\mathscr{L} = \underbrace{P(X_1) + P(X_2)}_{\textit{Dark matter}} - \underbrace{M^4\left[1 + \cos(\theta_1 - \theta_2)/f\right]}_{\textit{Potential - dark energy}}$$

Background evolution



Clustering:
growth factor

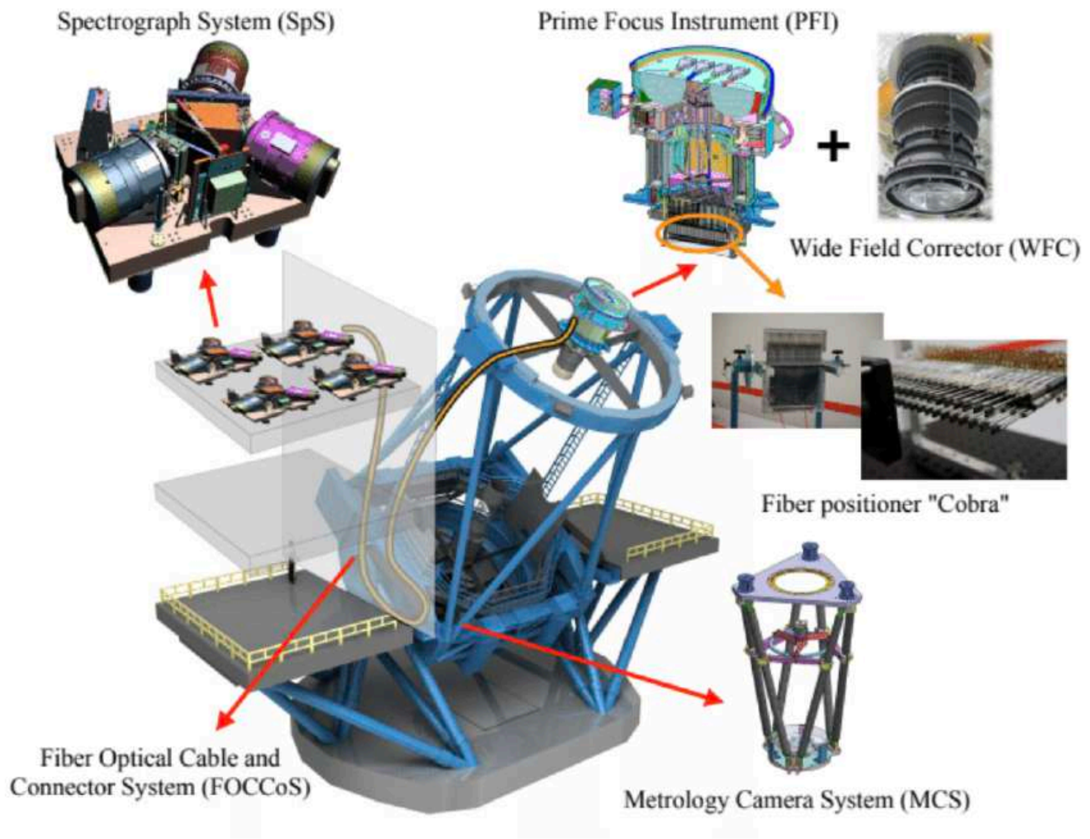


- Acceleration from interactions (no dark energy)
- Use condensed matter methods in cosmology – effective change of the dynamics, no change in the fundamental theory.

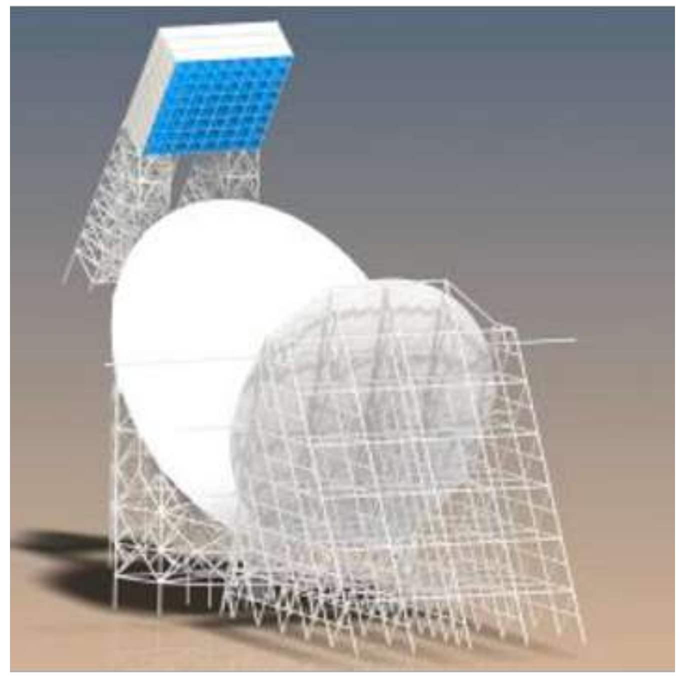
Future

Search for DE - main goal of many of these experiemnts

Prime Focus Specctrograph (PFS)



BINGO telescope

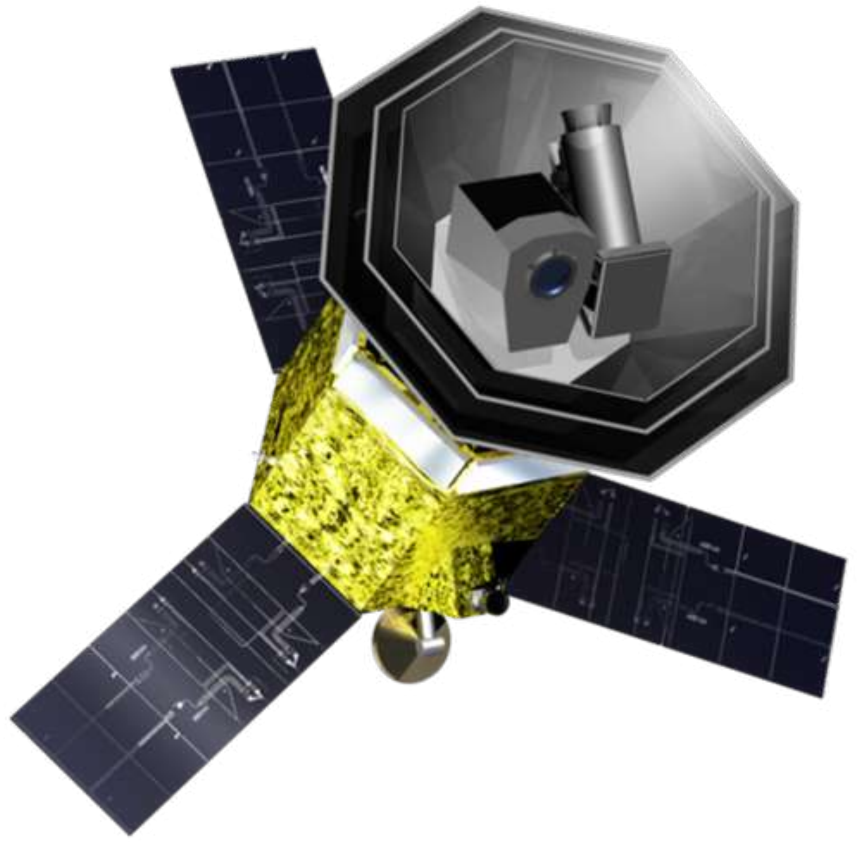


Vera Rubin observatory (LSST)

CMB-S4

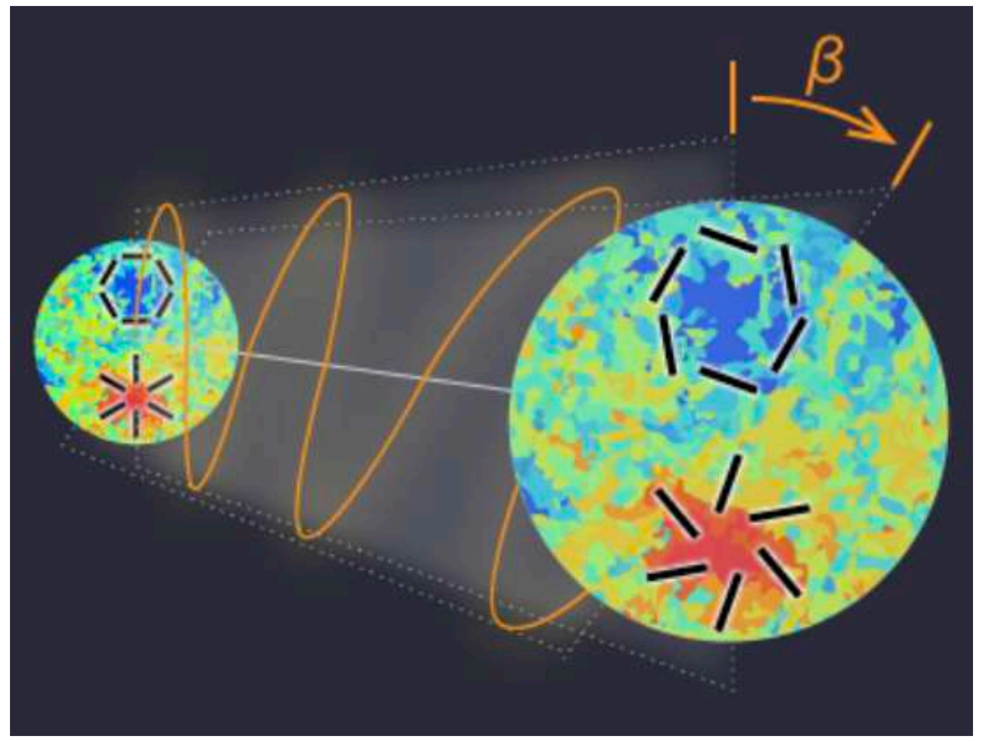
CMB-S4
Next Generation CMB Experiment

LiteBIRD



Future - *Cosmic Microwave Background*

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

LiteBIRD can possibly constraint this effect

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

Future Directions

Future Directions

Exciting times for the study of ULDM - new simulations, new probes and observations

We have only scratched the surface of the study of these models and their constraints:

Observations: testing ULDM/ axions

PFS (Prime Focus Spectrograph)

21cm with BINGO

Constraining ALPs with LiteBIRD

Numerical Simulations

Ultra-light Dark Matter

Predictions, improving and developing models

Ultra-Light field as Dark Energy

Potential for discovery (highly constrain) these models in the near future!

Future Directions

Open questions

Exciting times for the study of ULDM - new simulations, new probes and observations

We have only scratched the surface of the study of these models and their constraints:

Self-Interacting FDM

- Observable signatures?
- Simulations?

Dark Matter superfluid

- Relativistic completion?
- Microphysics description?
- Cosmology?
- Mass?

Condensation

- BEC or a Superfluid formed in galaxies?
- Break of classicality?

Core vs halo relation

- Observable signatures?
- Simulations?
- Mergers?

Vortices

- Prediction - simulations?
- Observable? How can be probed?

New models

- New well motivated models? (vector ULDM)
- New microphysics description?

Future Directions

Exciting times for the study of ULDM - new simulations, new probes and observations

We have only scratched the surface of the study of these models and their constraints:

Ultra-light Dark Matter

Observations: testing ULDM/axions

PFS (Prime Focus Spectrograph)

21cm with BINGO

Constraining ALPs with LiteBIRD

Numerical Simulations

Necessary to compare these models with observations

- SIFDM and DM Sf
- NEW observable: vortices and its predictions
- Zoom-in simulations - halo mass vs core relation

Predictions, improving and developing models

Open questions

Ultra-Light field as Dark Energy

ALPs and UL fields role in the dark sector

- Unified DM superfluid: completion and test

Potential for discovery (highly constrain) these models in the near future!

Also happy to talk about my work on other topics in cosmology

DARK ENERGY

- "Constraining interacting dark energy with CMB and BAO future surveys", L. Santos, Wen Zhao,, EF, J. Quintin, (2017).
- "Testing the Interaction between Dark Energy and Dark Matter with Planck Data", A. Costa, X. Xu, B. Wang, EF, E. Abdalla, 2014.
- "Evidence for interacting dark energy from BOSS", EF, J. Quintin, A. Costa, E. Abdalla, B. Wang, 2017.

EARLY UNIVERSE

- *"Covariant c-flation"*, R. , R. Cuzinatto, **EF**, G. Franzmann, 2019.
- *"Dynamics of Cosmological Perturbations and Reheating in the Anamorphic Universe"*, L. Graef, W. Hipolito-Ricaldi, **EF**, R,Brandenberger, 2017
- *"Particle Production in Ekpyrotic Scenarios"*, W. Hipolito-Ricaldi, **EF**, R. Brandenberger, L. Graef, 2017.
- *"Curvature Perturbations in a Cosmology with a Space-Like Singularity"*, **EF**, R. Brandenberger, 2016.
- *"Fluctuations in a cosmology with a spacelike singularity and their gauge theory dual description"*, R. Bradenberger, **EF**, et al., 2016.
- *"A new model of axion monodromy inflation and its cosmological implications"*, Yi-Fu Cai, F. Chen, **EF**, J. Quintin, 2016.
- *"Searching for Features of a String Inspired Inflationary Model with Cosmological Observations"*, Yi-Fu Cai, **EF**, B. Hu, J. Quintin, 2015.
- *"Resonance of Entropy Perturbations in Massless Preheating"*, H. Moghaddam, R. Brandenberger, Yi-Fu Cai, **EF**, 2015.
- *"The Trans-Planckian Problem in the Healthy Extension of Horava-Lifshitz Gravity"*, **EF**, R. Brandenberger, 2014.

BINGO

- *“The Bingo project I: Baryon Acoustic Oscillations from Integrated Neutral Gas Observations”*, E. Abdalla, **EF**, et al., 2021.
- *“The Bingo project II: Instrument”*, C. Wuensche, et al. (including **EF**), 2021.
- *“The Bingo project III: Optics”*, F. Abdalla, et al. (including **EF**), 2021.
- *“The Bingo project IV: Simulations for Mission Performance Assessment”*, V. Liccardo, et al. (including **EF**), 2021.
- *“The Bingo project V: Component Separation and Bispectrum Analysis”*, K. Fornazier, et al. (including **EF**), 2021.
- *“The Bingo project VI: Halo Occupation Distribution and Mock Building”*, J. Zhang, et al. (including **EF**), 2021.
- *“The Bingo project VII: Forecast”*, A. Costa, R. Landim, **EF**, et al., 2021.

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

Dark Energy

Axion like particles and ultra-light fields can have an important role in the dark sector

Future

PFS will be exquisite to to measure the properties of DM

21cm - complementary probe, power on small scales (BINGO telescope)

Simulations necessary for testing ULDM models with observations

New observables, new well motivated models

Thank you!

どうもありがとうございました