Constraining ultra-light dark matter *with small scales observations*

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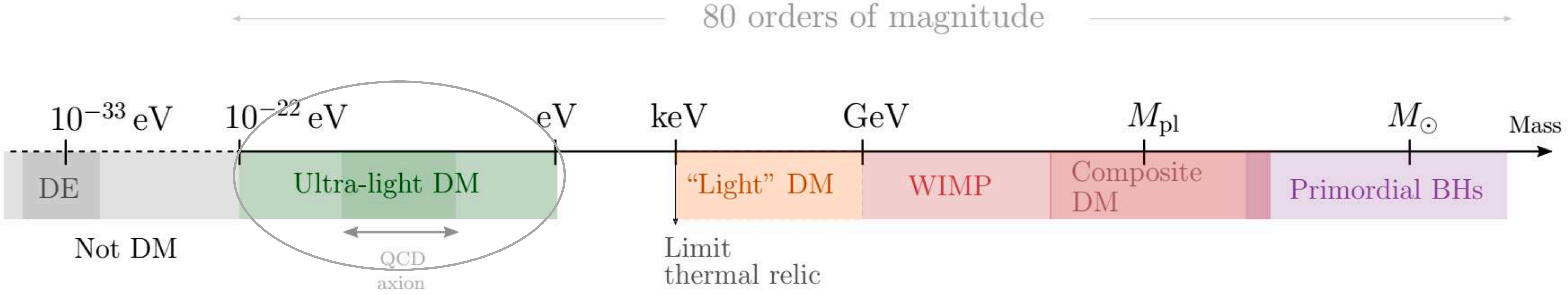
Kavli IPMU & University of Sao Paulo

"What is dark matter? --Comprehensive study of the huge discovery space in dark matter" Symposium,
March 30 2022

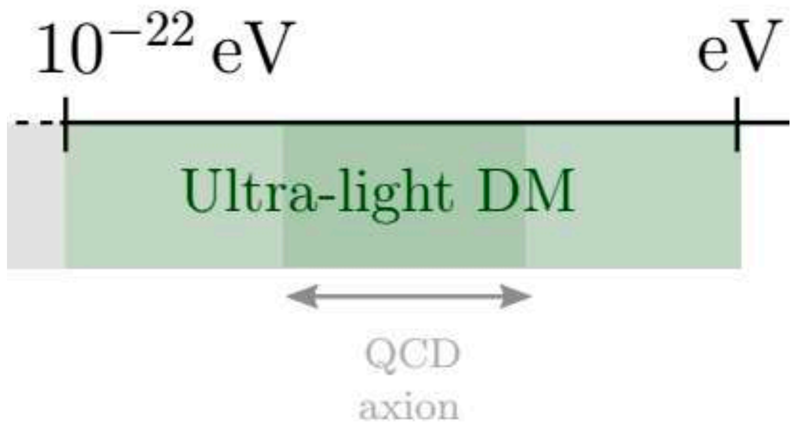
Status of the "art"

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

Mass scale of DM

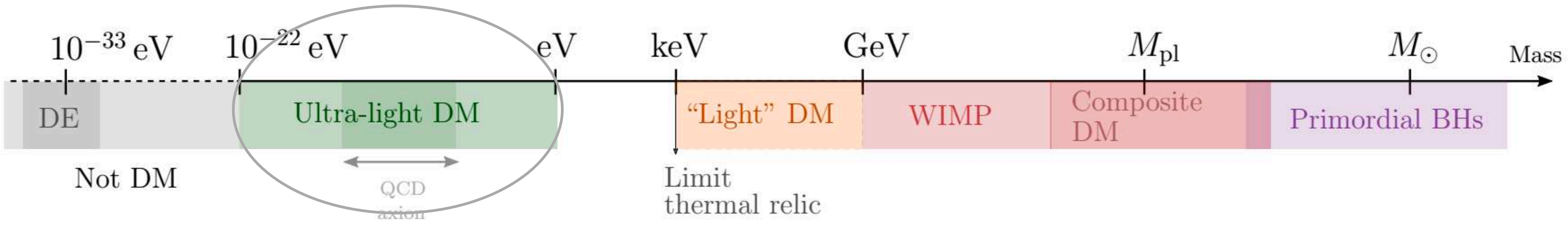


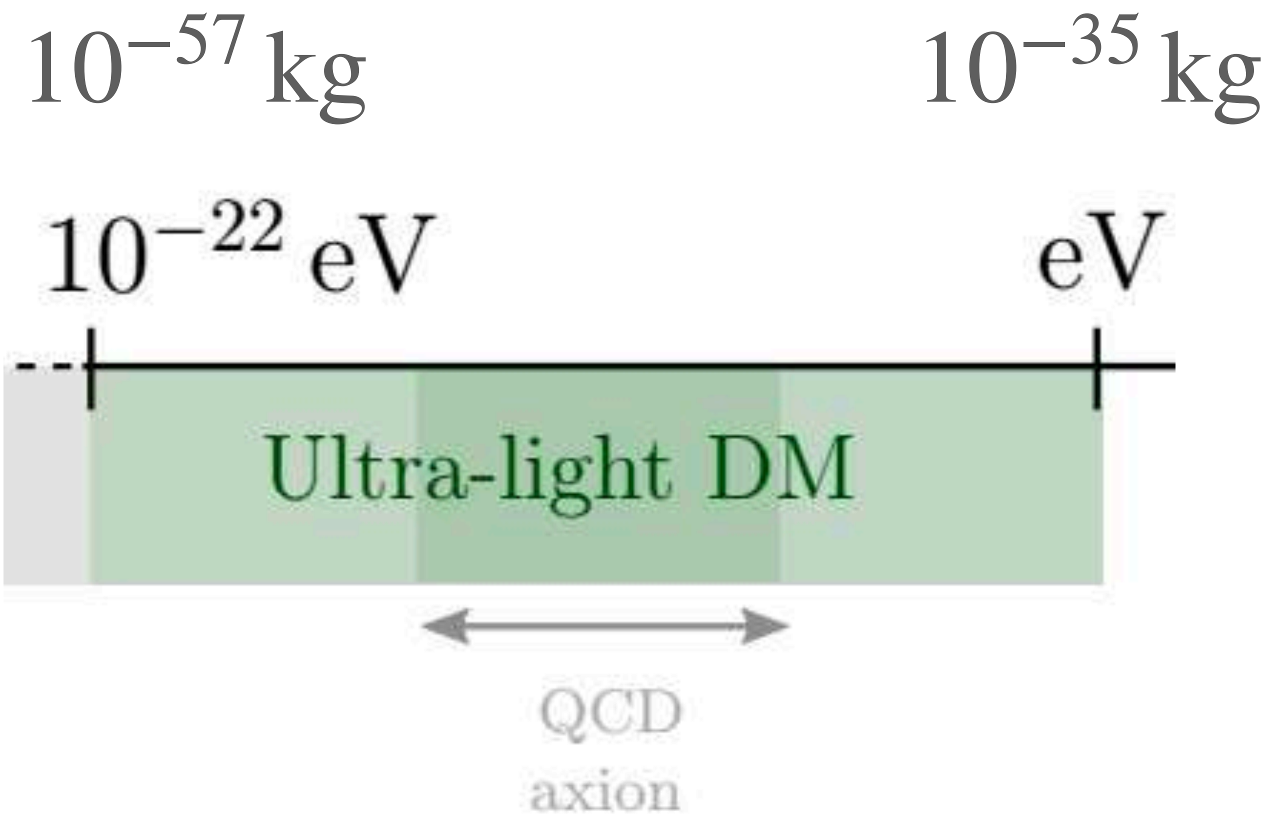
Ultra-light Dark Matter



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

Lightest possible candidate for DM

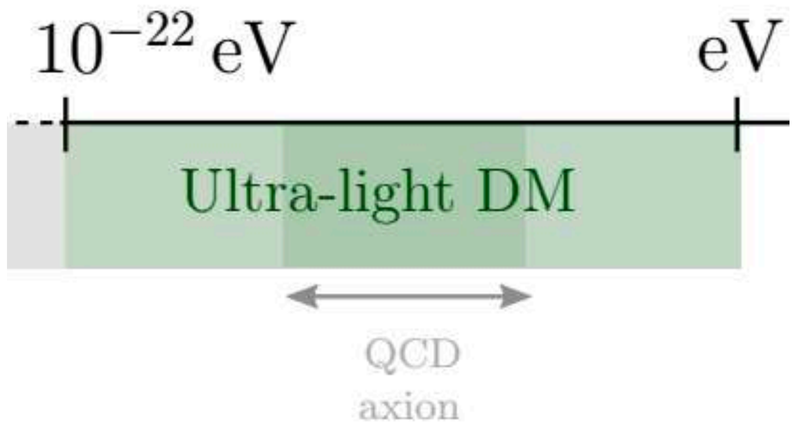




→ Bosons

Non-thermally produced

Ultra-light Dark Matter



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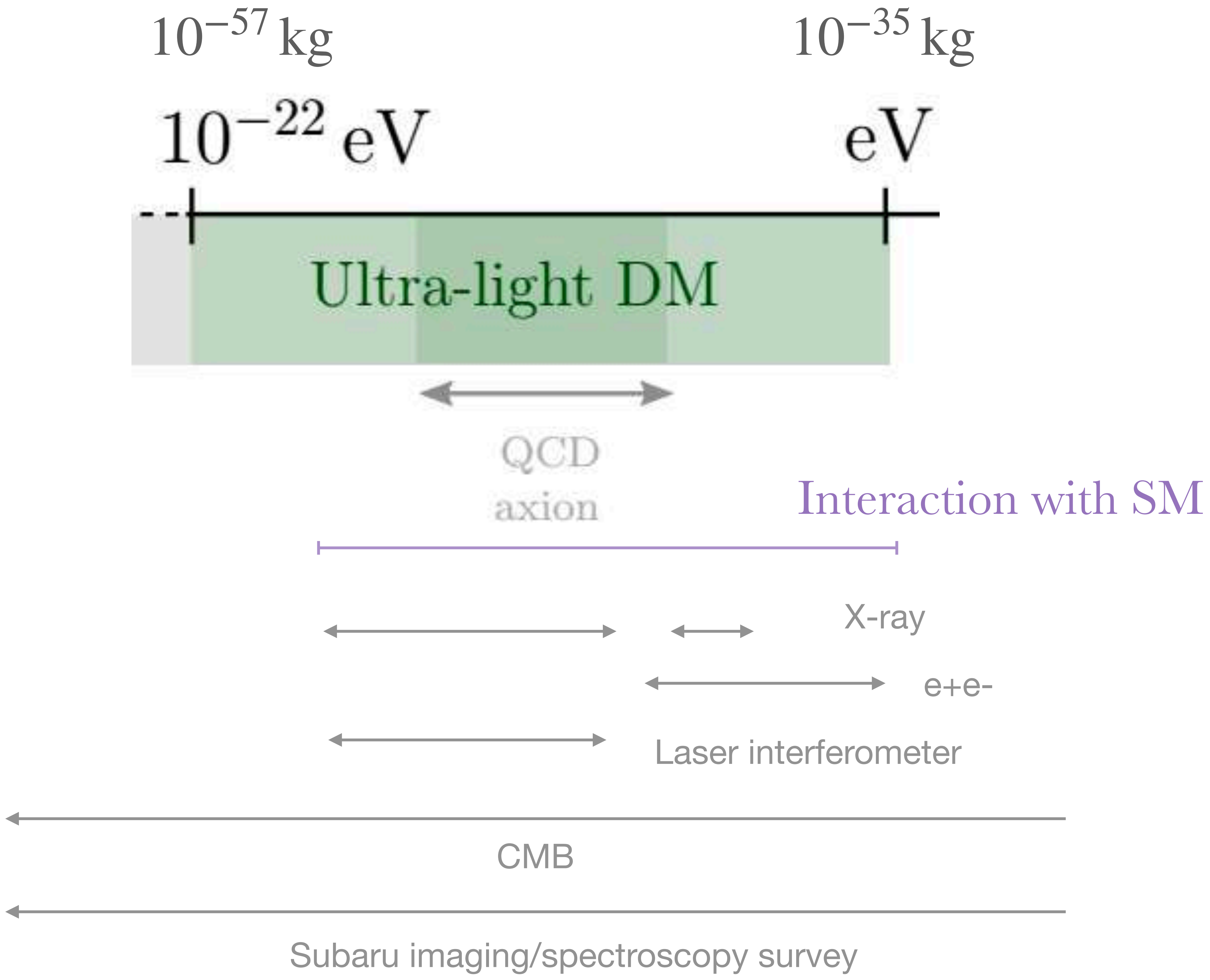
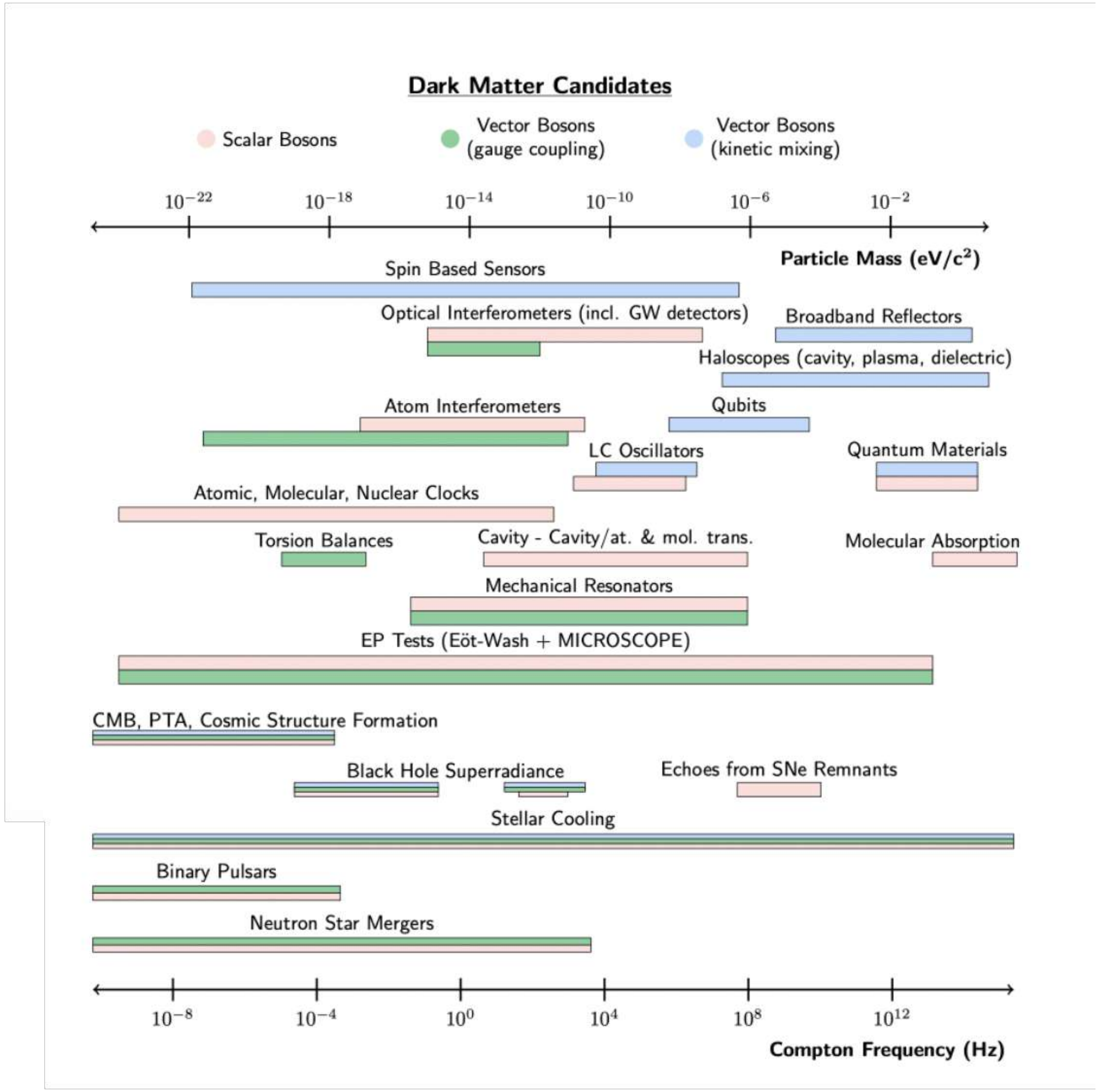
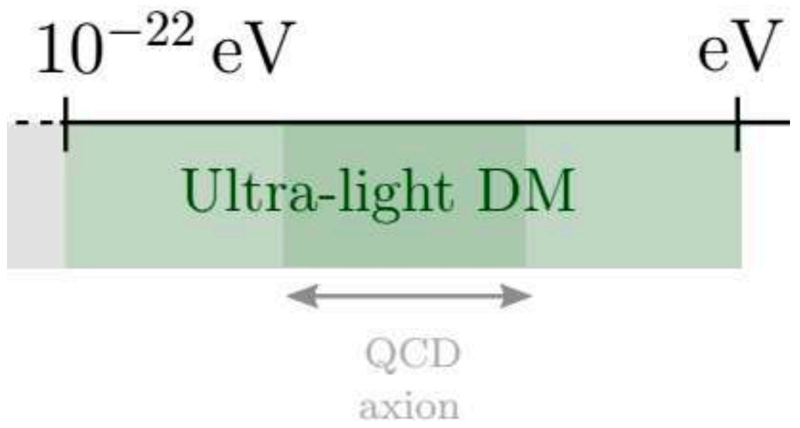


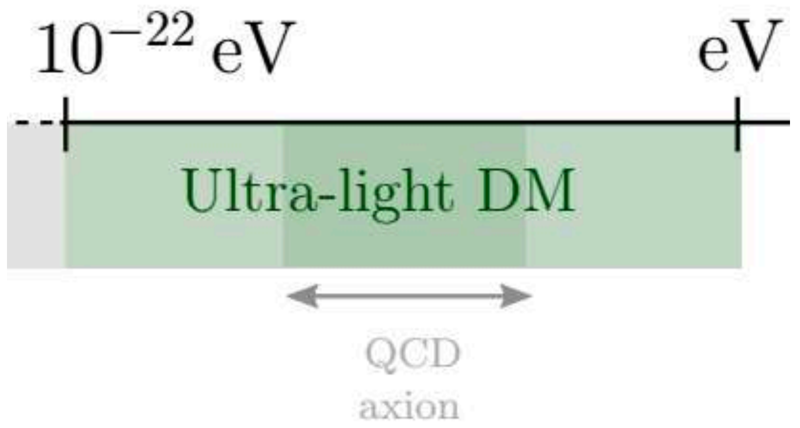
Ultra-light Dark Matter





Adapted from "Snowmass 2021 White Paper New Horizons: Scalar and Vector Ultralight Dark Matter", 2203.14915

Ultra-light Dark Matter



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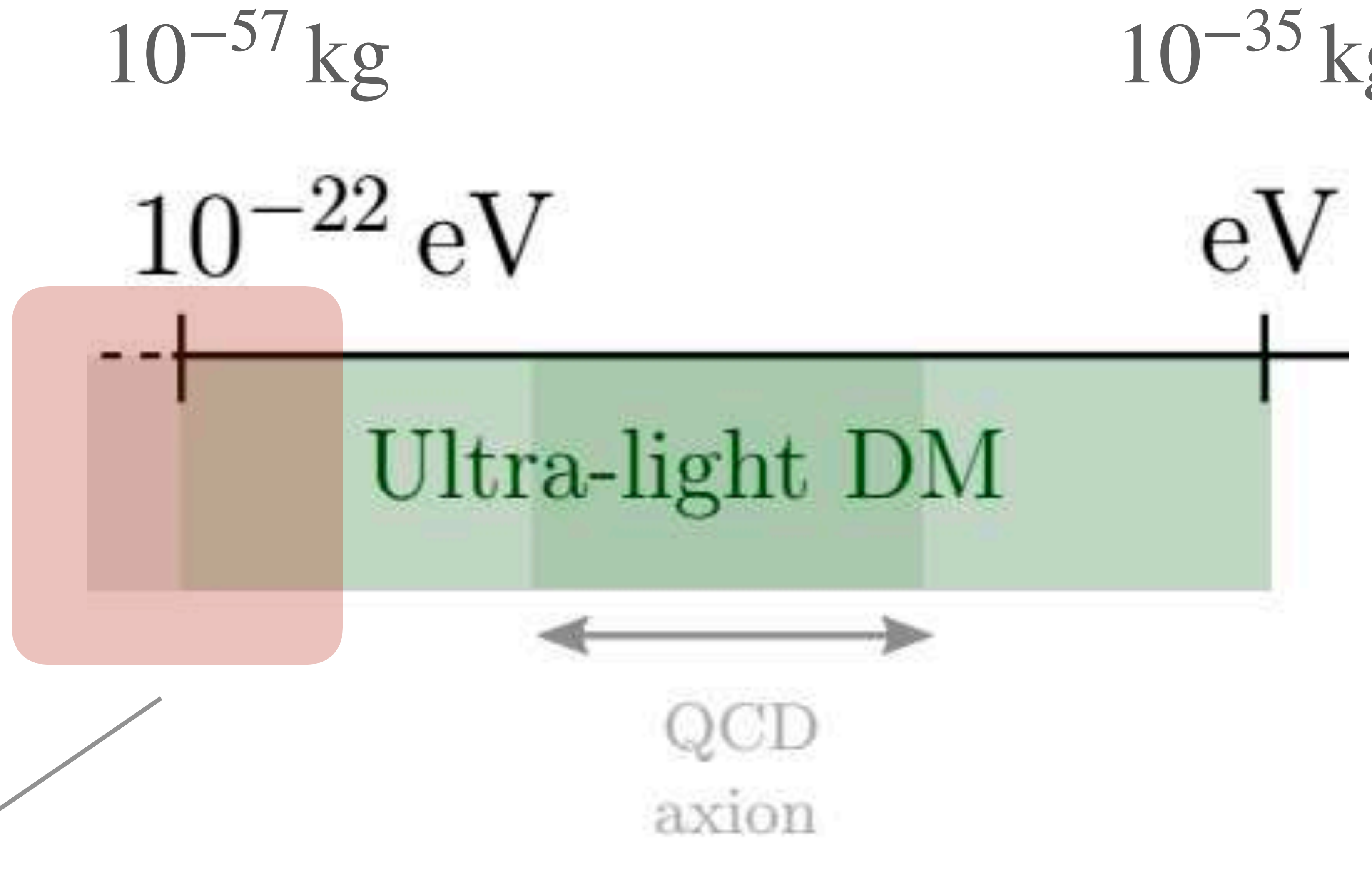
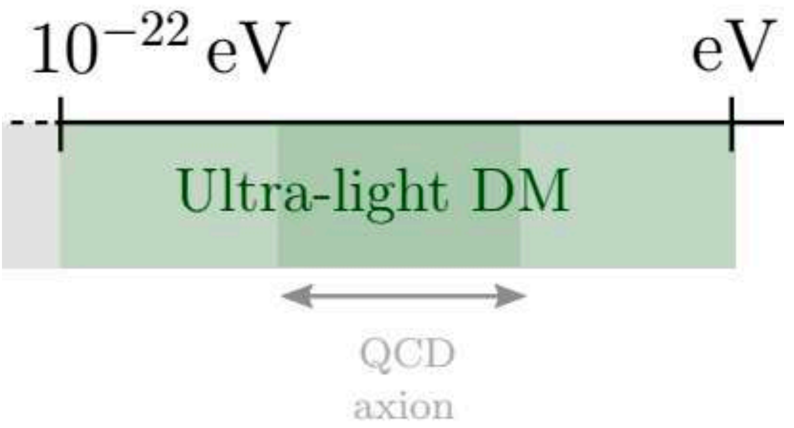


$$10^{-24}\,\mathrm{eV} \lesssim m_{\rm fdm} \lesssim 10^{-18}\,\mathrm{eV}$$

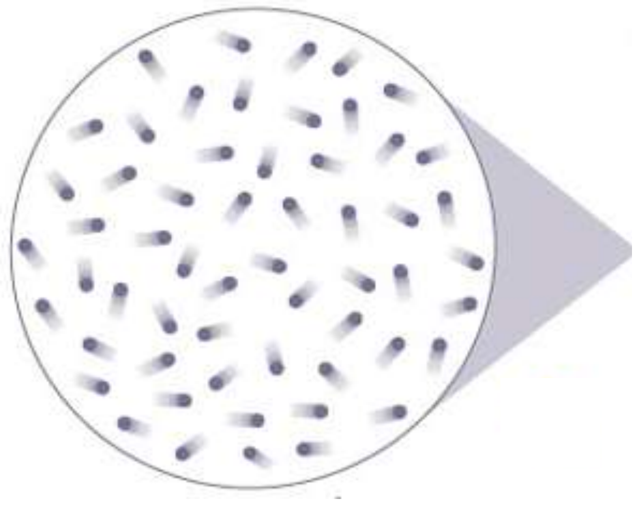
Ultra-light Dark Matter

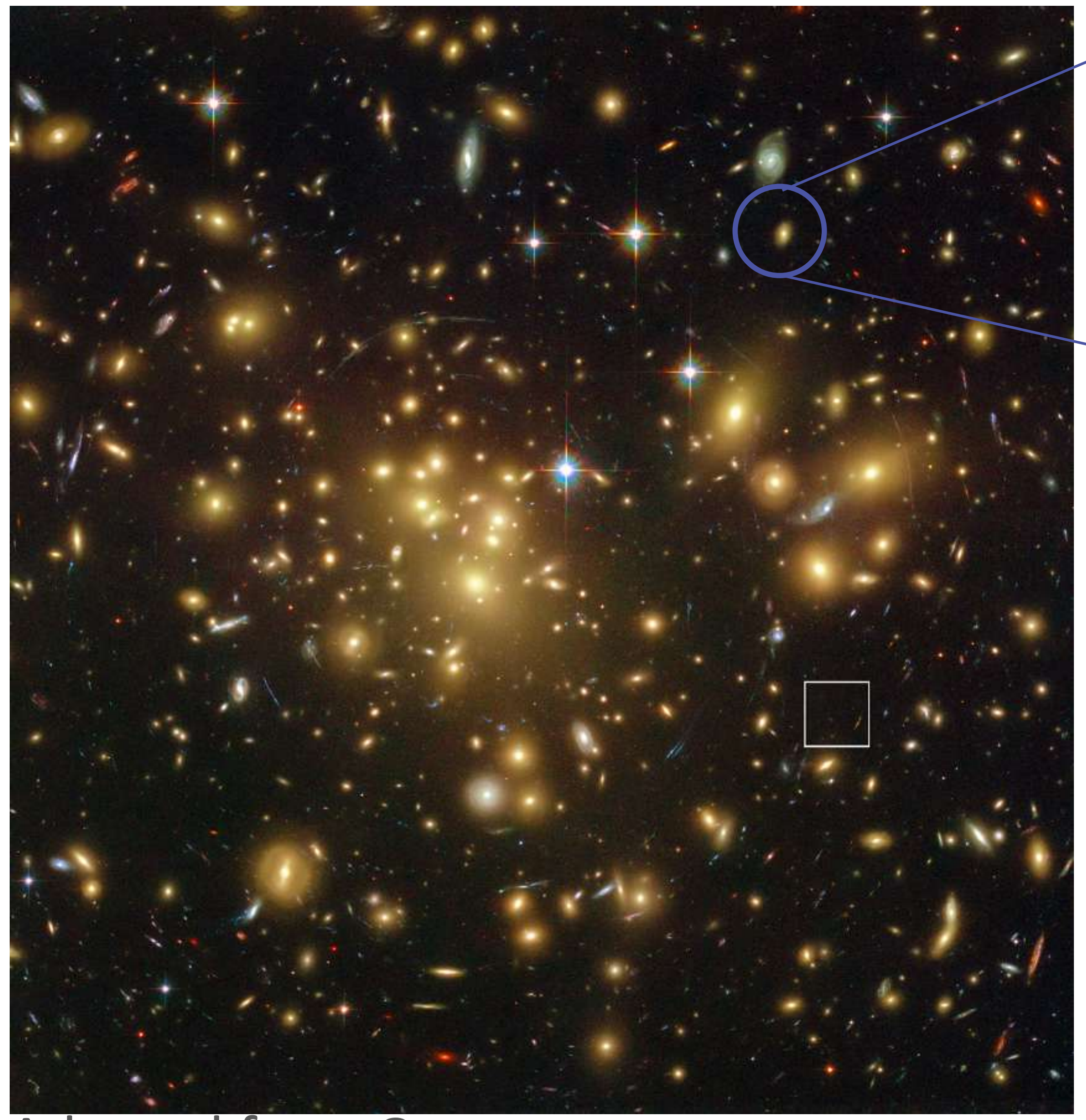


Ultra-light candidate ⟶ Large $\lambda_{\rm dB} \sim 1/mv$

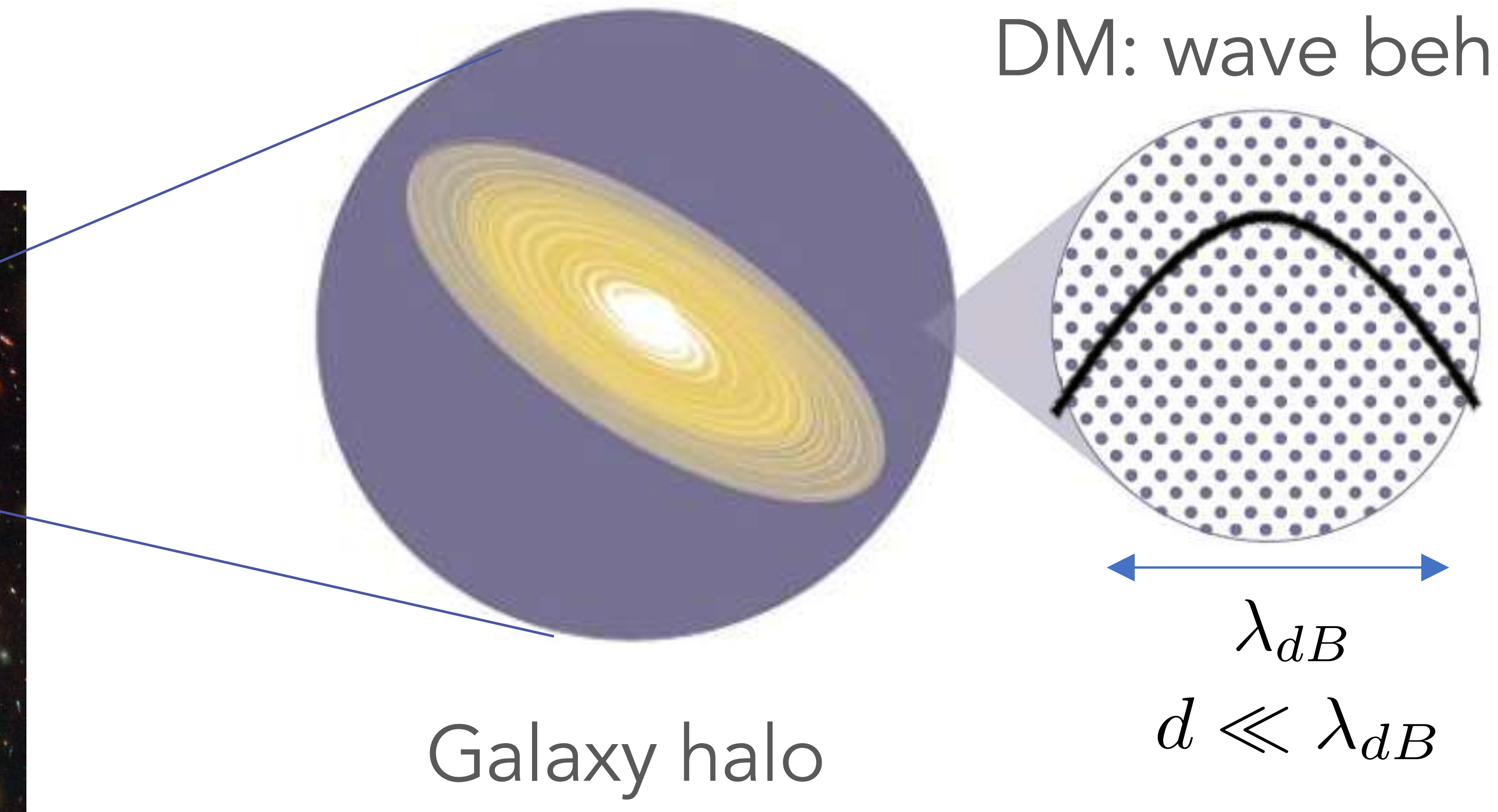
Lightest possible candidate for DM

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





Adapted from Quanta



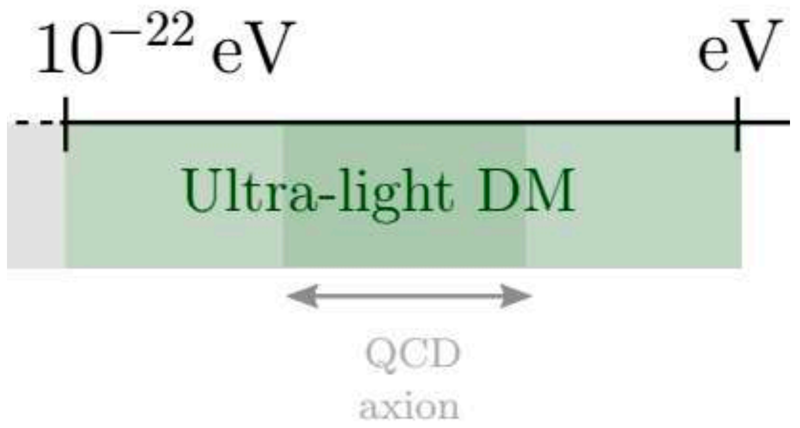
Small scales:
DM behaves like a wave

10^{-60} kg　　10^{-35} kg

$$10^{-22}\,\text{eV} \lesssim m \lesssim \text{eV}$$

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

Ultra-light Dark Matter



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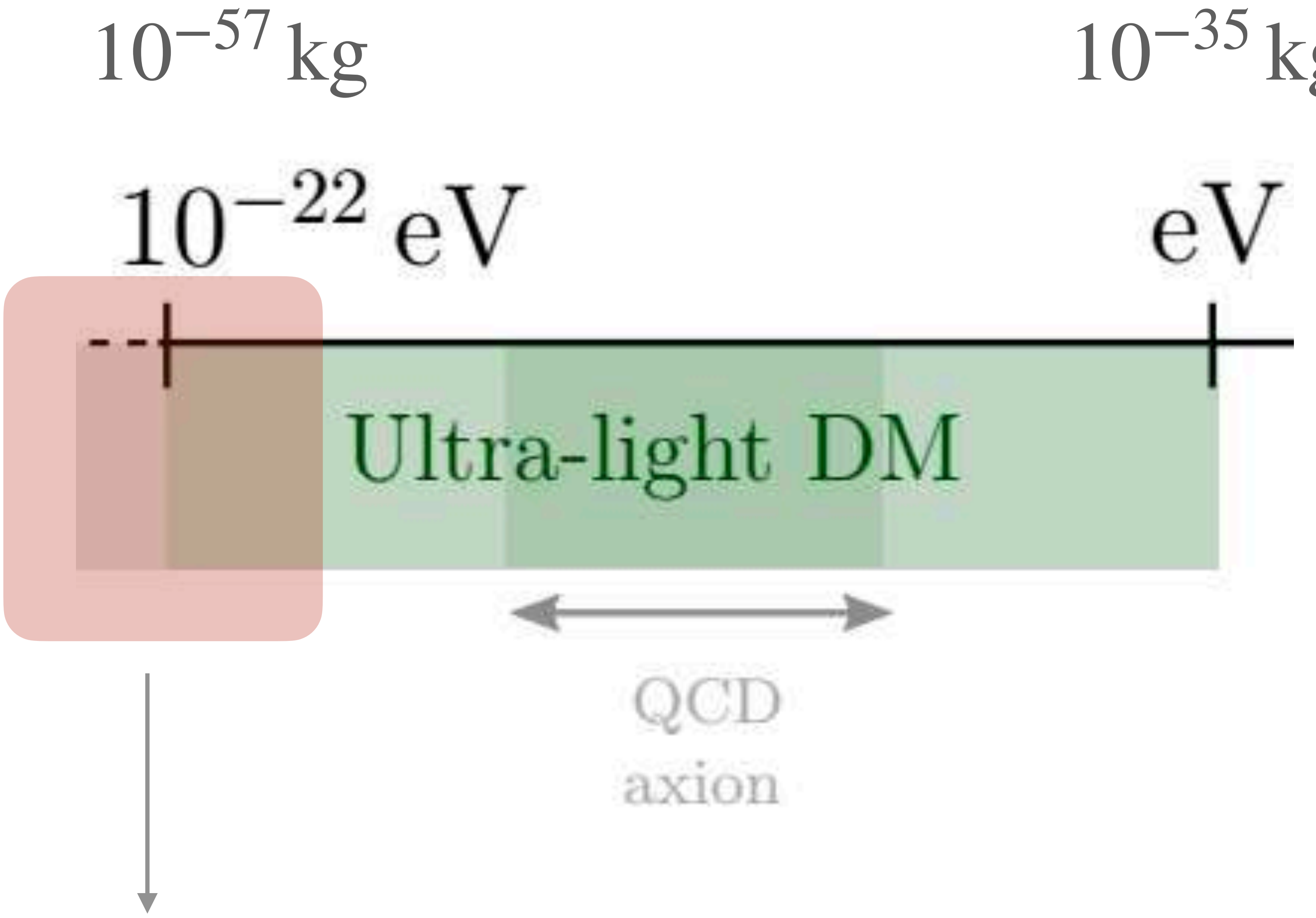
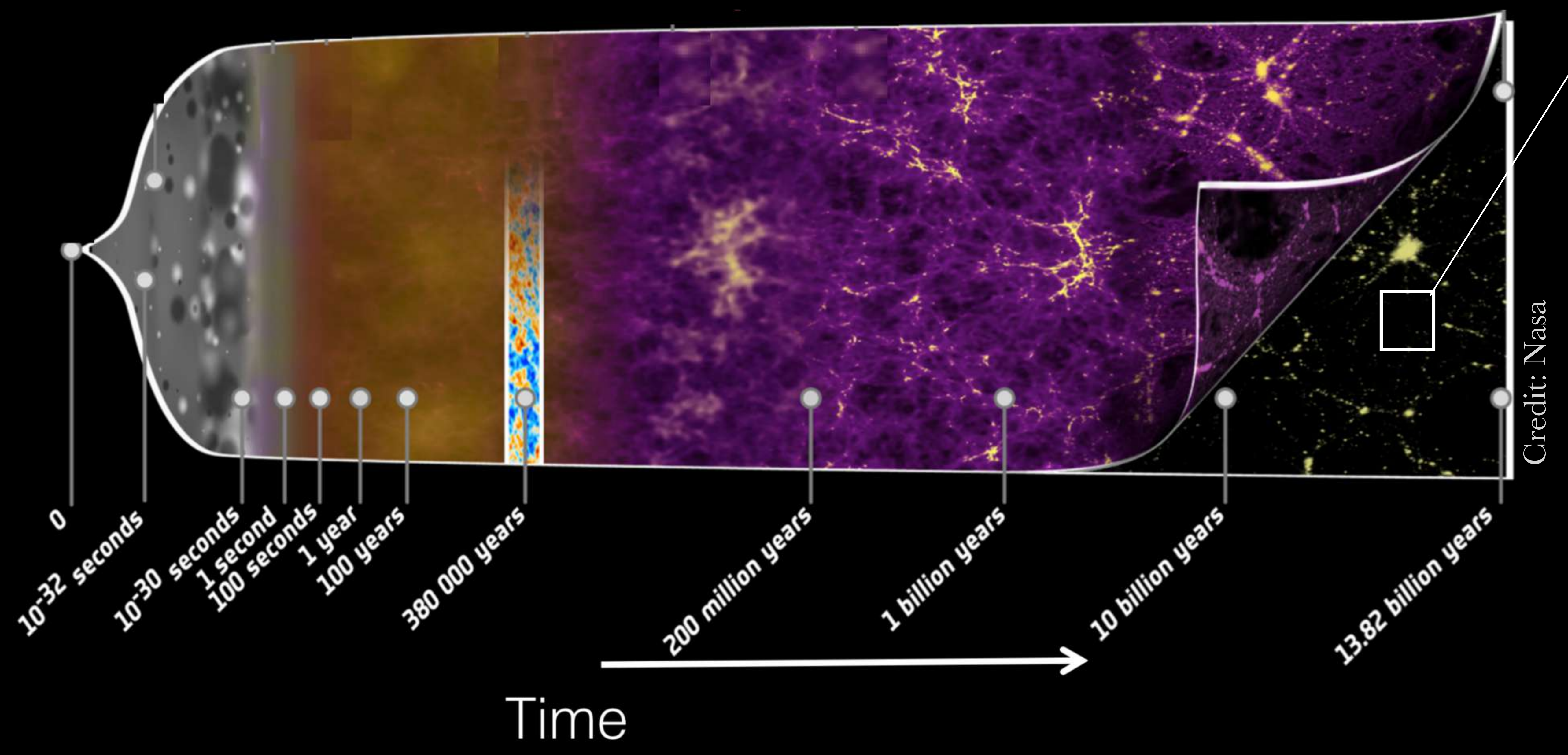
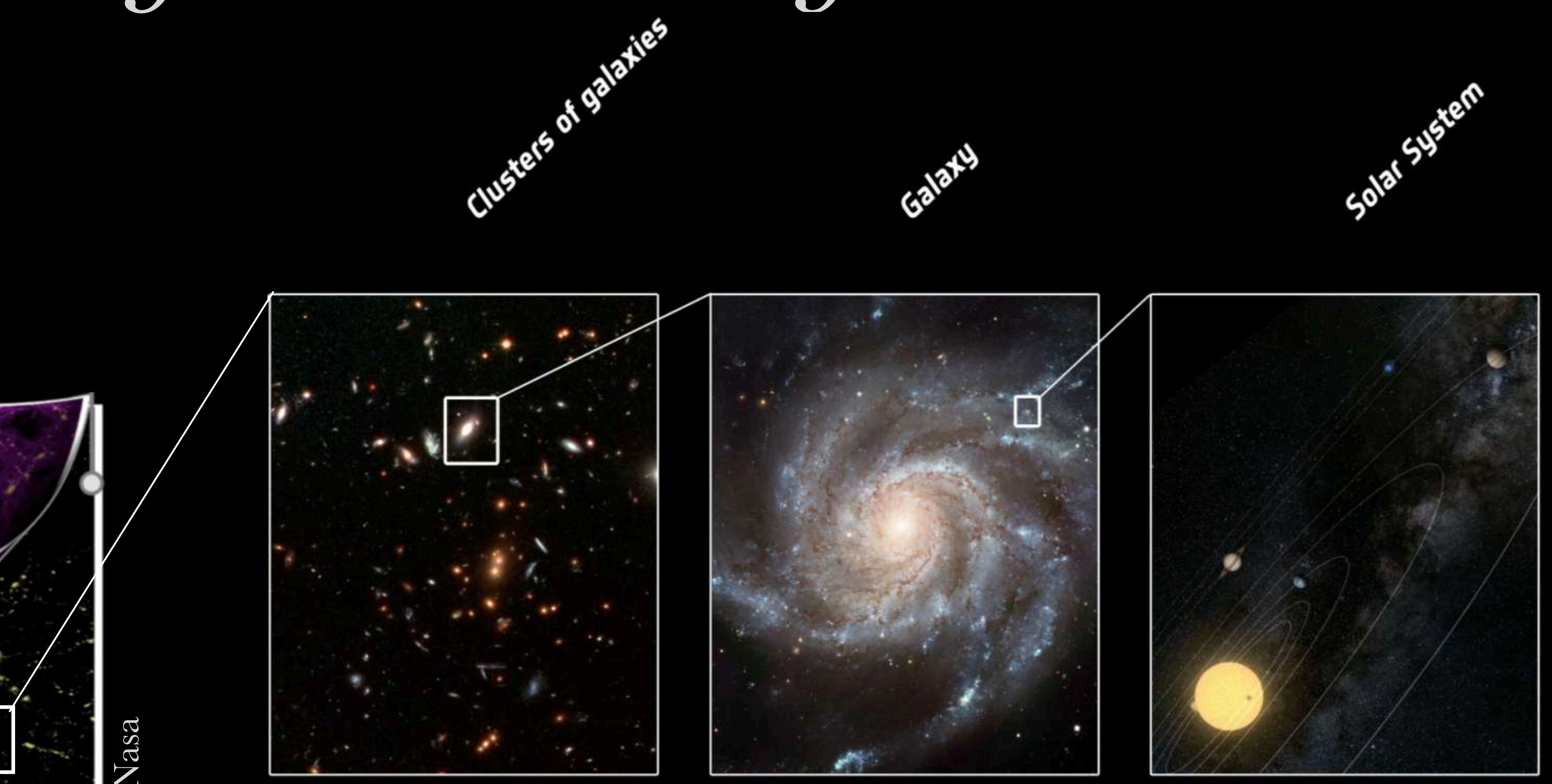


Gravitational probes

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

Small scales can offer some hints of the nature of DM



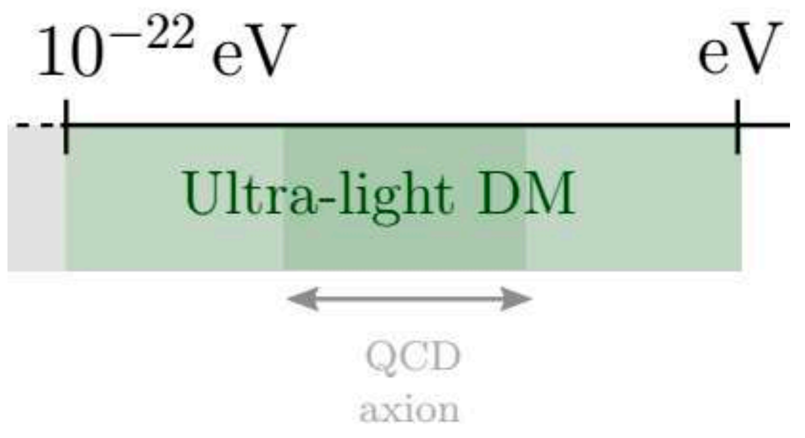


Small Scales

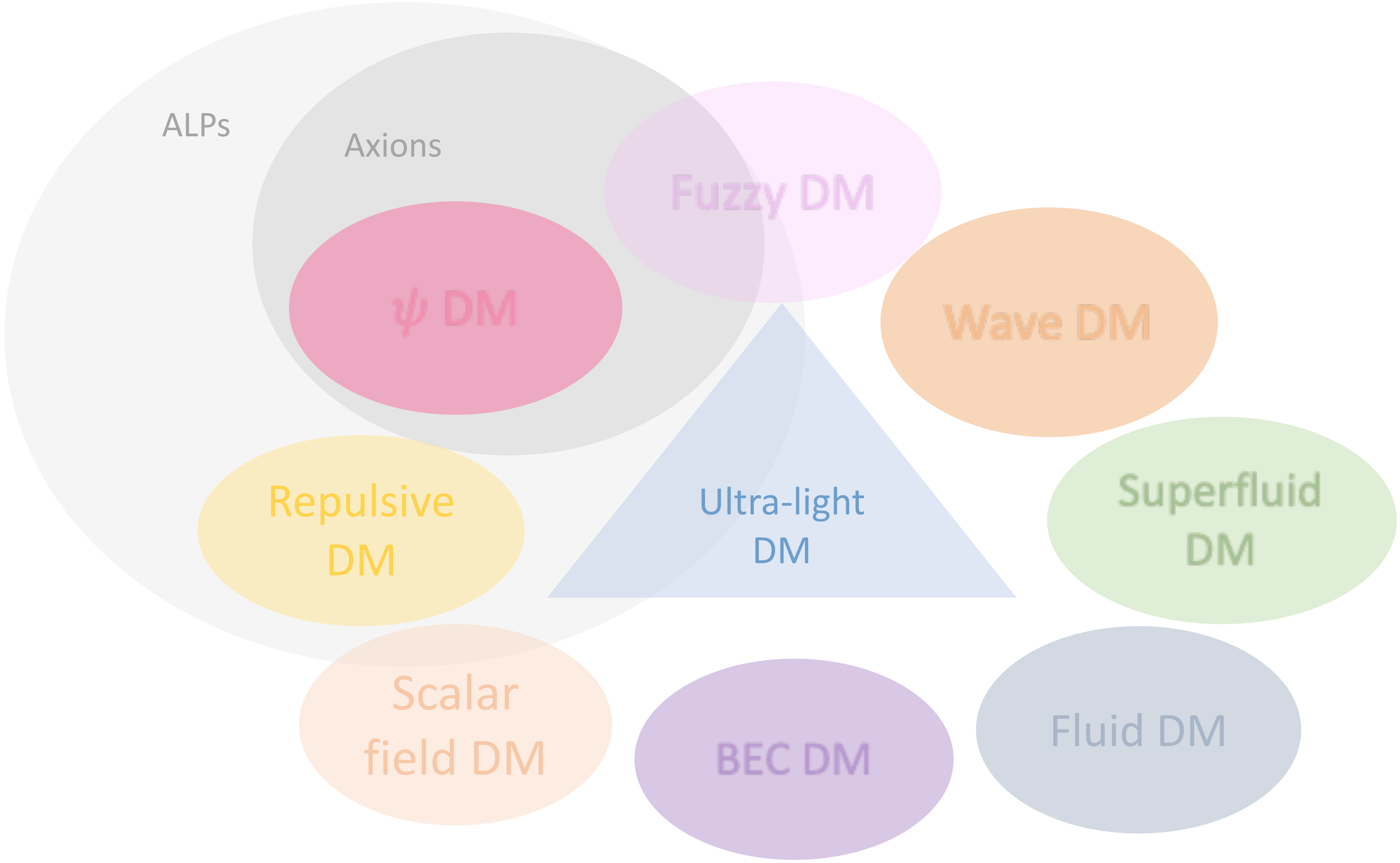
Opportunity to probe the nature of DM!

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

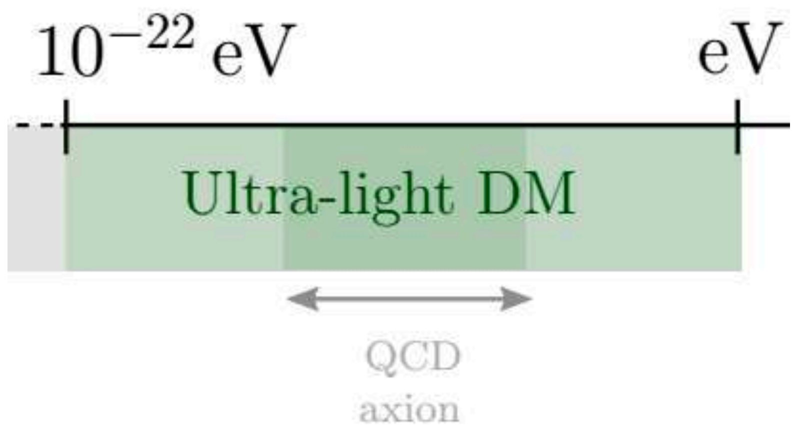
Ultra-light Dark Matter - models



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	- Presence of (weakly) self-interaction	- Forms a superfluid in galaxies - MOND behaviour interior of galaxies
DOFs	m	m g	

Axion and ALP (axion like particles)

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

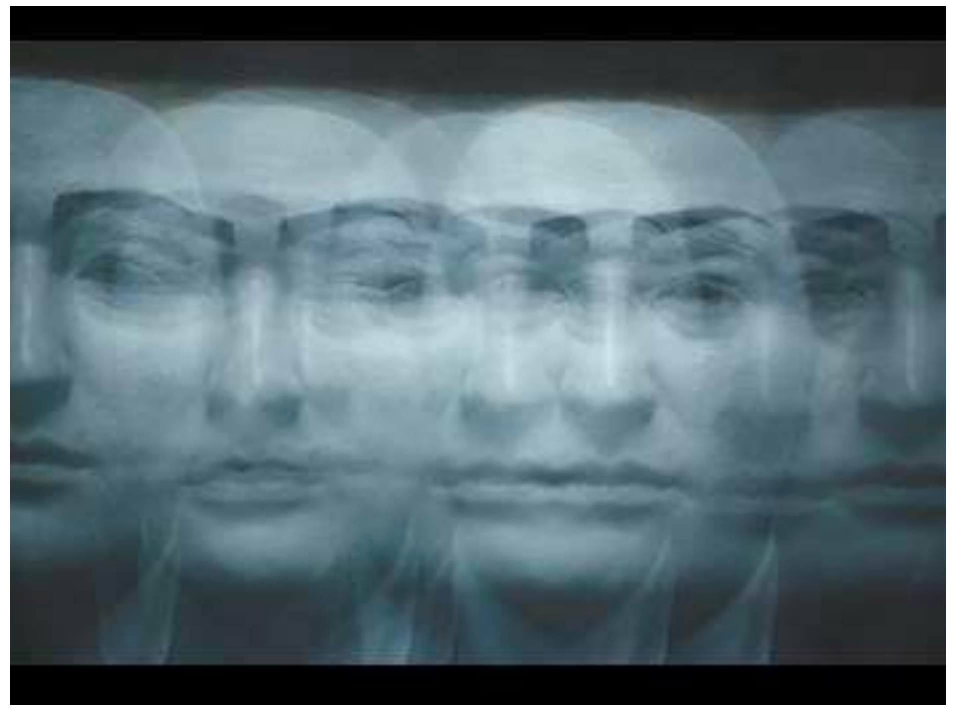
$$\mathcal{L} = P(X)$$

⟶ Formation mechanism: see Satoshi Shirai's talk!

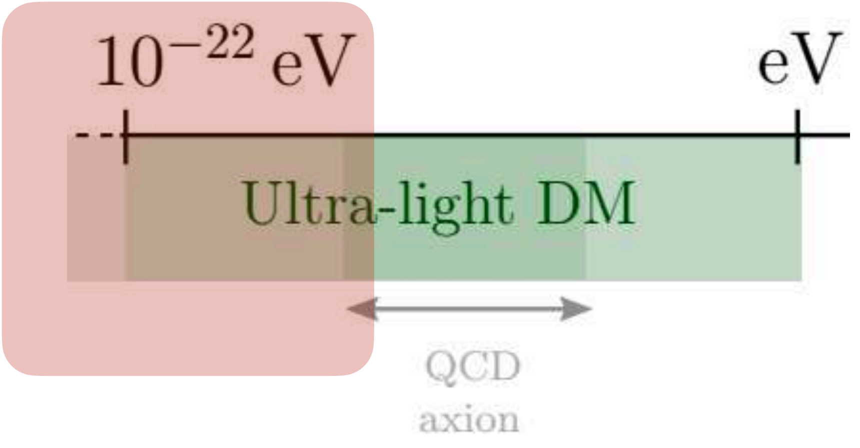
"Ultra-light dark matter", **E.Ferreira**, 2020. The Astronomy and Astrophysics Review.

Fuzzy dark matter

Self interacting fuzzy dark matter



Fuzzy dark matter



Fuzzy DM
(FDM)

- Gravitationally bounded ultra-light scalar field model

m

Wave DM
Ultra-light axions

Focus in spin 0 particles here!

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

Vector DM: Tomohiro Fugita's talk!

Idea:

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

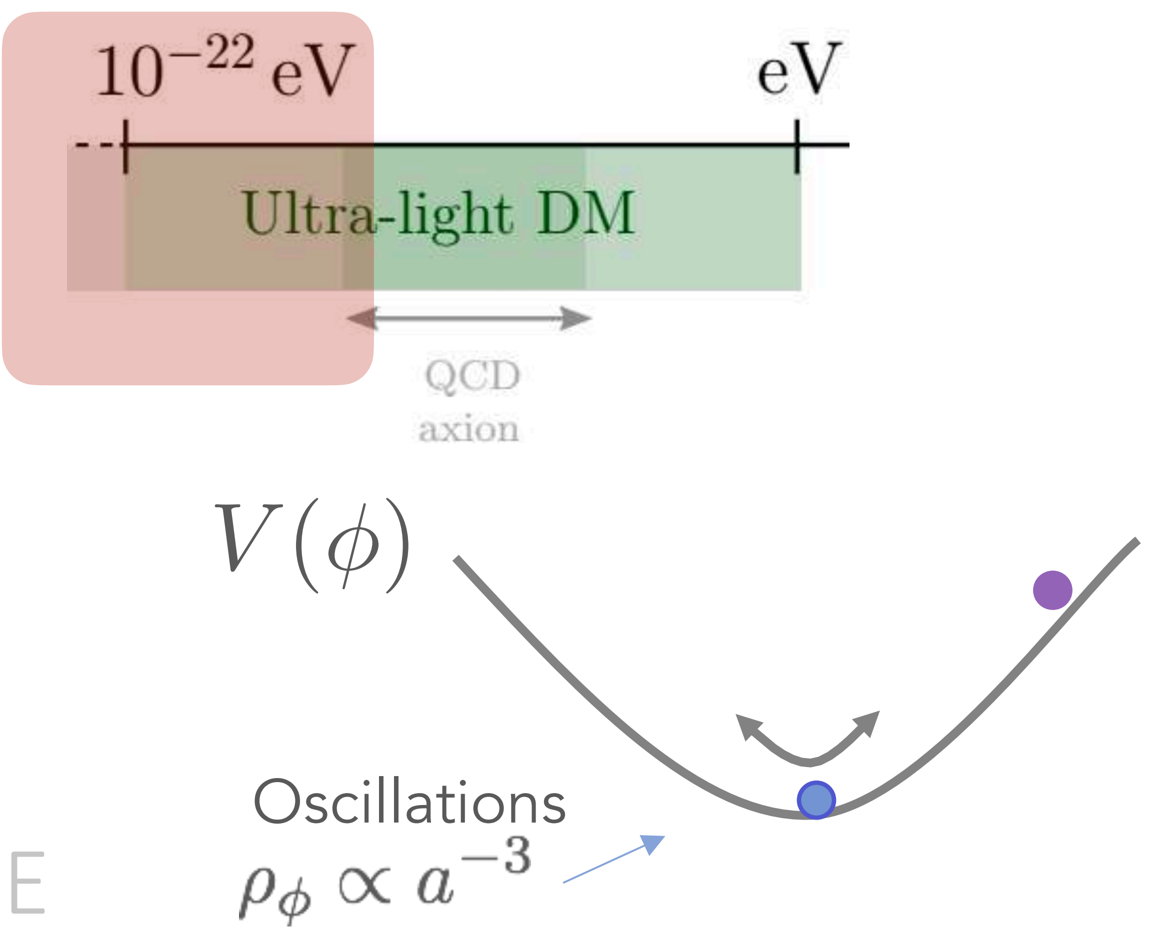
address the small scale problems+ rich phenom.

Formation mechanism: see Satoshi Shirai's talk!

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

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

Cosmological evolution

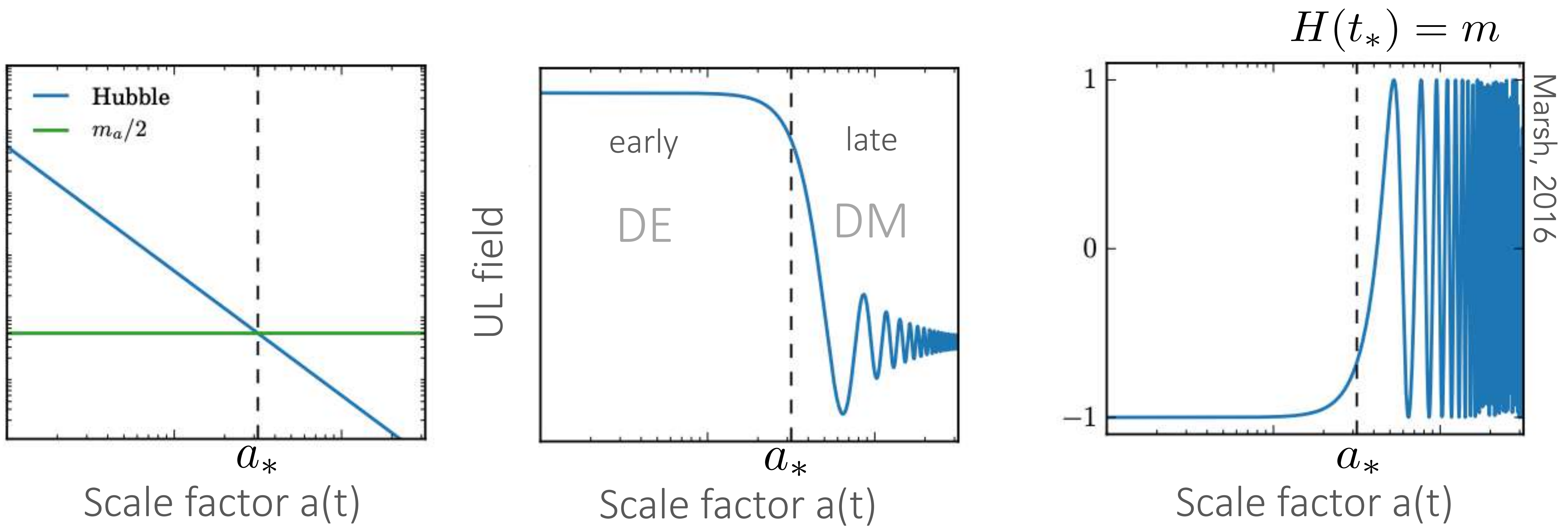


$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

FDM

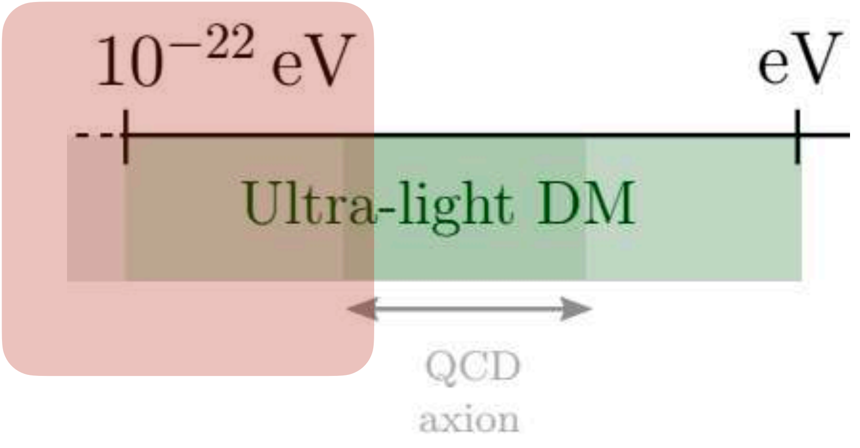
$$\begin{cases} H \gg m \implies \phi_{\text{early}} = \phi(t_i) \longrightarrow \omega = -1 & \text{DE} \\ H \ll m \implies \phi_{\text{late}} \propto e^{imt} \longrightarrow \langle \omega \rangle = 0 & \text{DM} \end{cases}$$

$$V(\phi) = \Lambda_a^4 \left[1 - \cos(\phi/f_a)\right] \to \frac{1}{2}m^2\phi^2 + \frac{g}{4}\phi^4$$



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

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

Schrödinger equation (Gross-Pitaevskii)

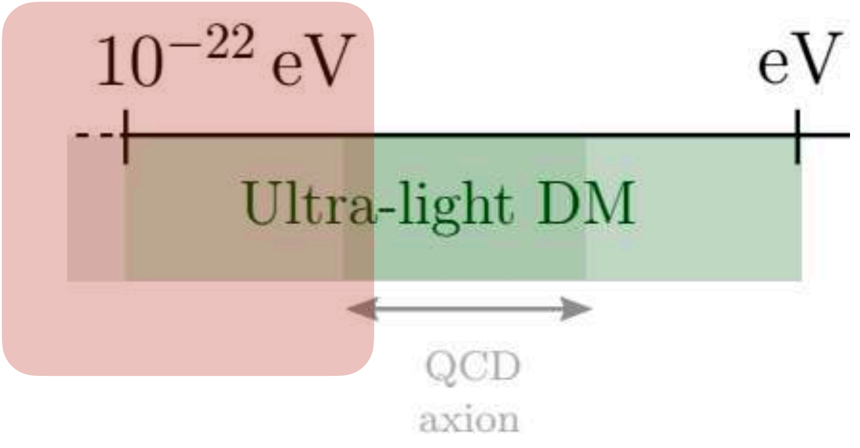
Poisson equation

$g = 0$ → FDM

$g \neq 0$ → SIFDM

Fundamentally different than CDM/WDM/SIDM!

Structure formation - non-relativistic regime



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Poisson equation

$g = 0 \rightarrow$ FDM

$g \neq 0 \rightarrow$ SIFDM

Fundamentally different than CDM/WDM/SIDM!

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

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

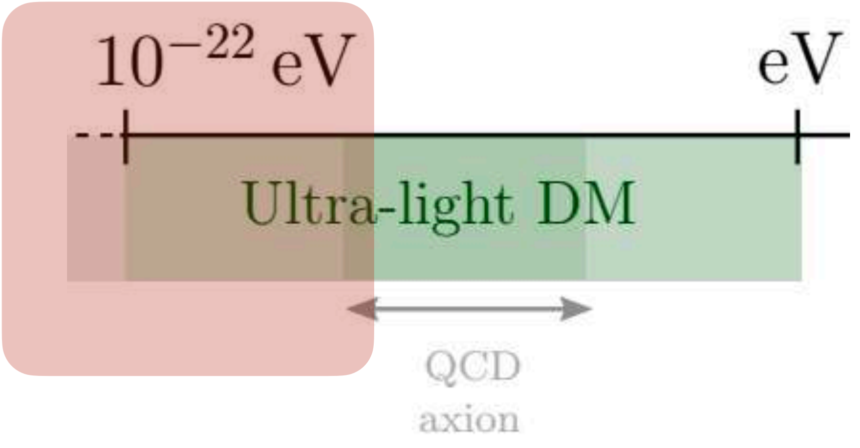
$$\dot{\mathbf{v}} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - P_{int} - \frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

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

Quantum pressure

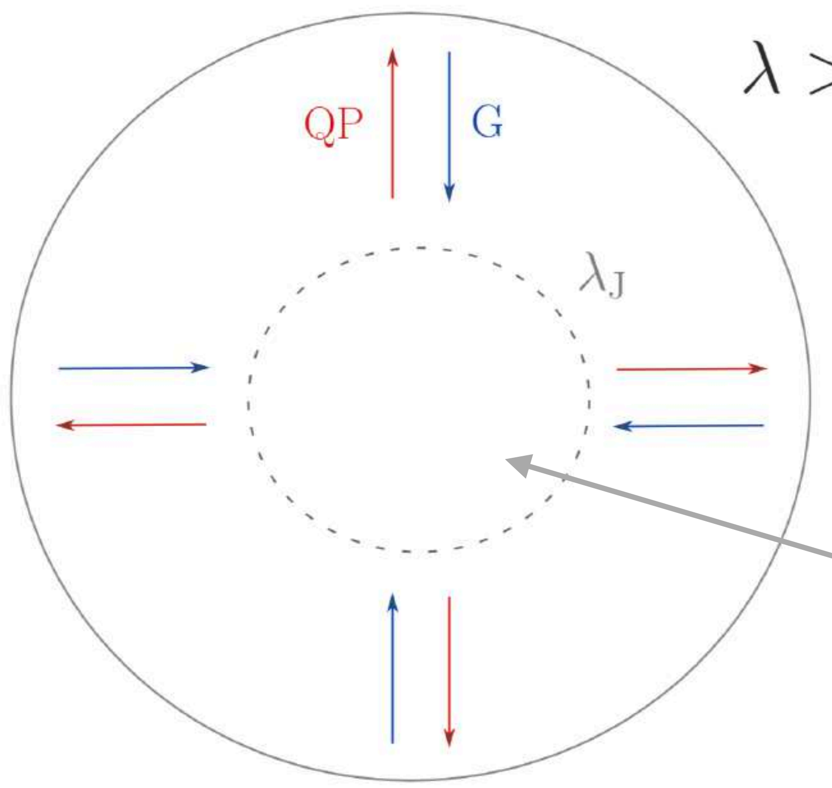
FLUID DESCRIPTION

Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

FDM



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

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

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

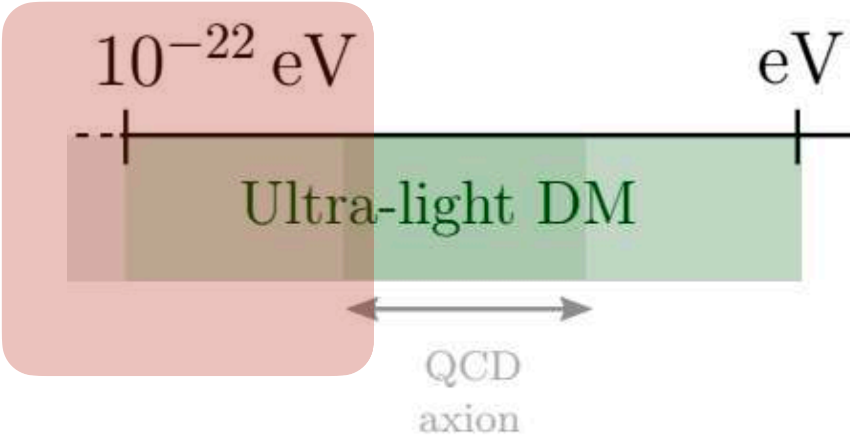
$$\dot{\rho} + \nabla\cdot(\rho\,\mathbf{v}) = 0$$

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

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

Quantum pressure

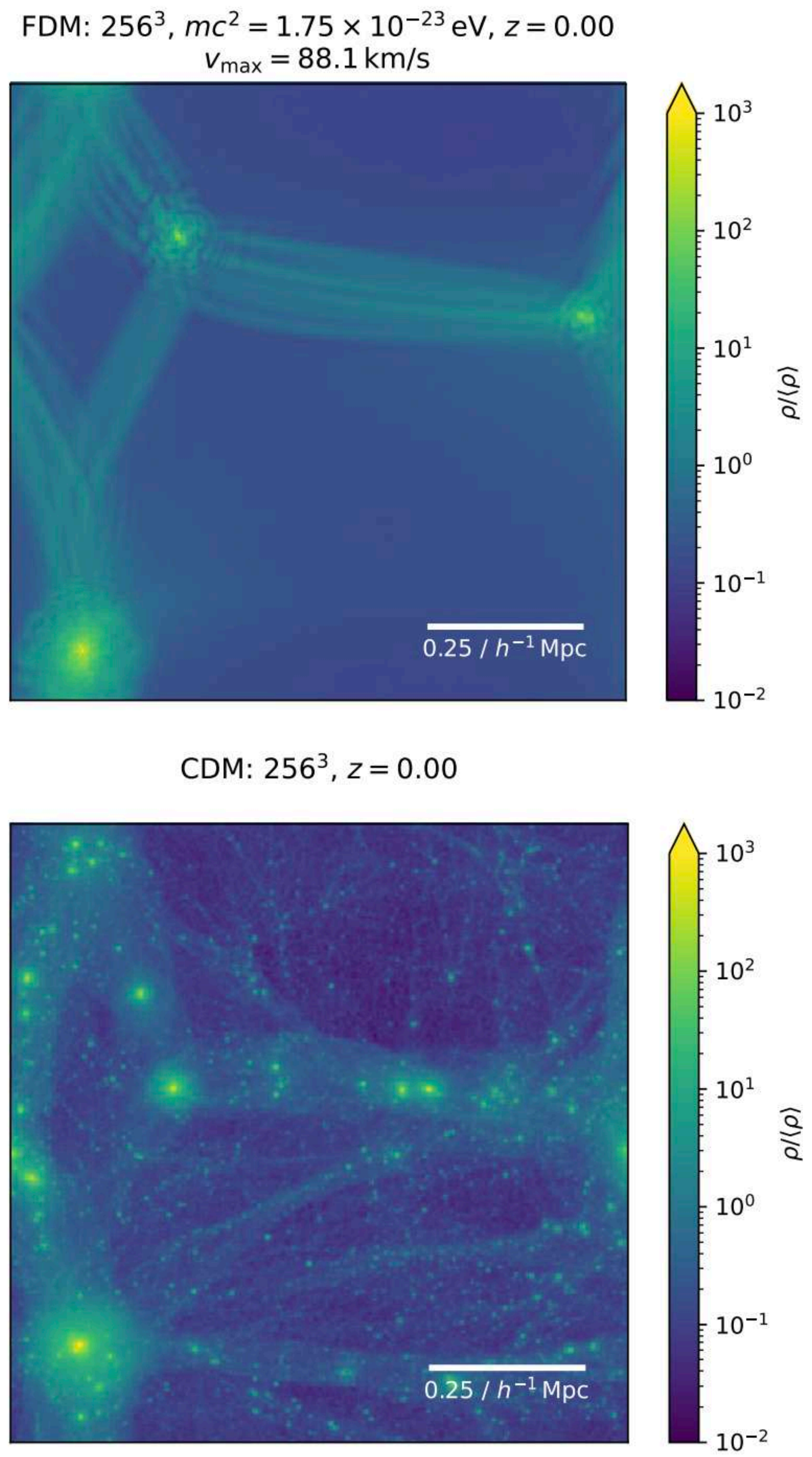
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

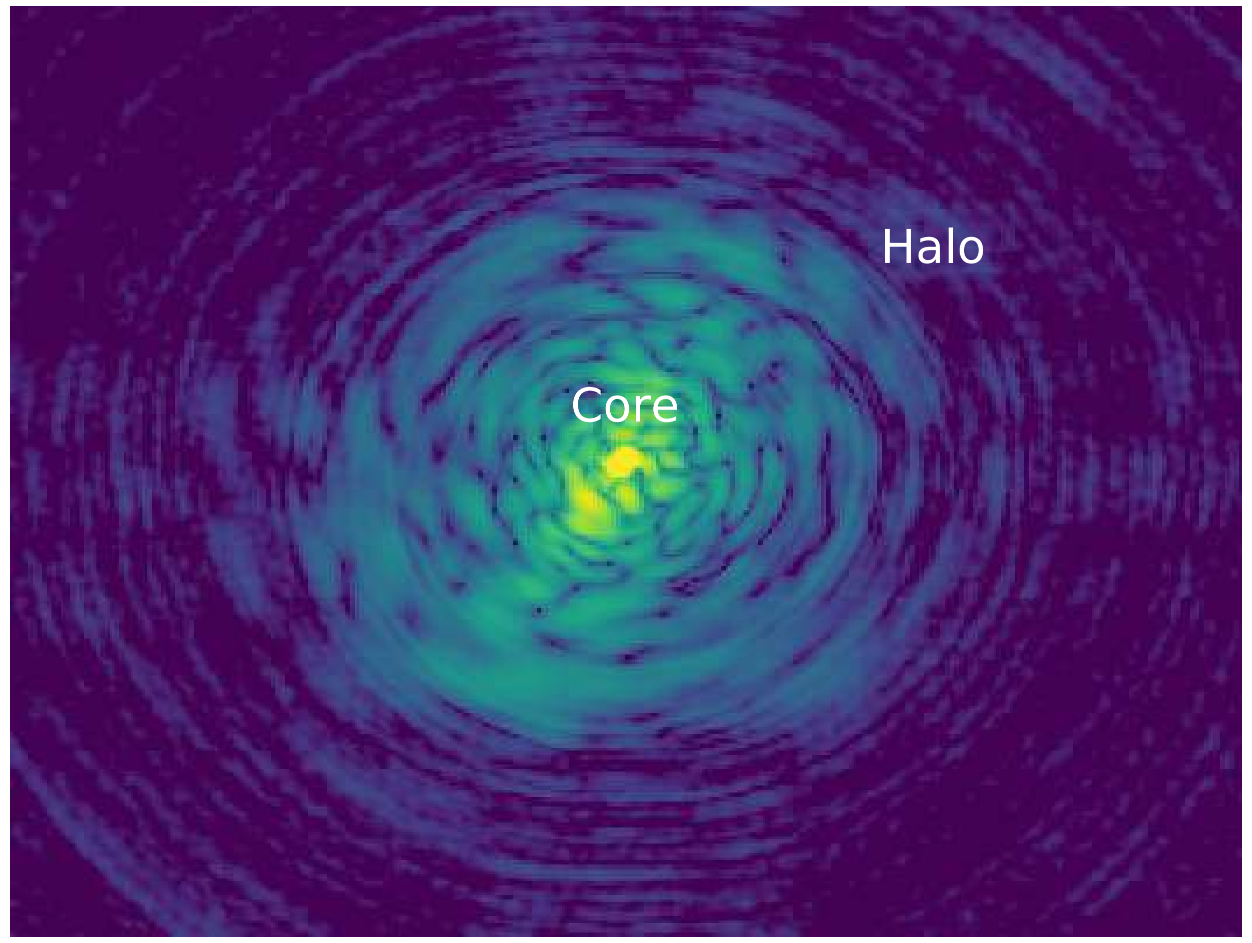
* Focus only in gravitational signatures

Suppression of small structures

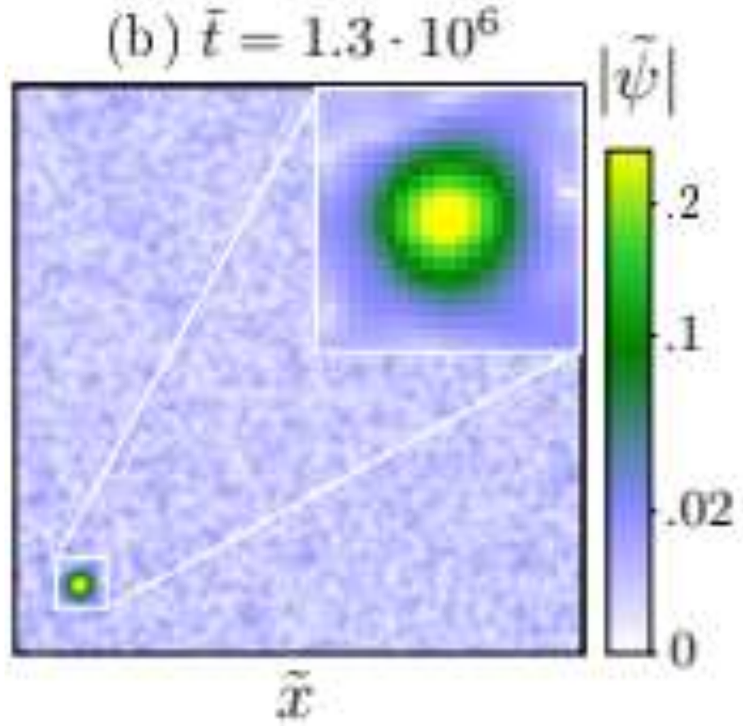


S. May et al. 2021

Formation of a solitonic core

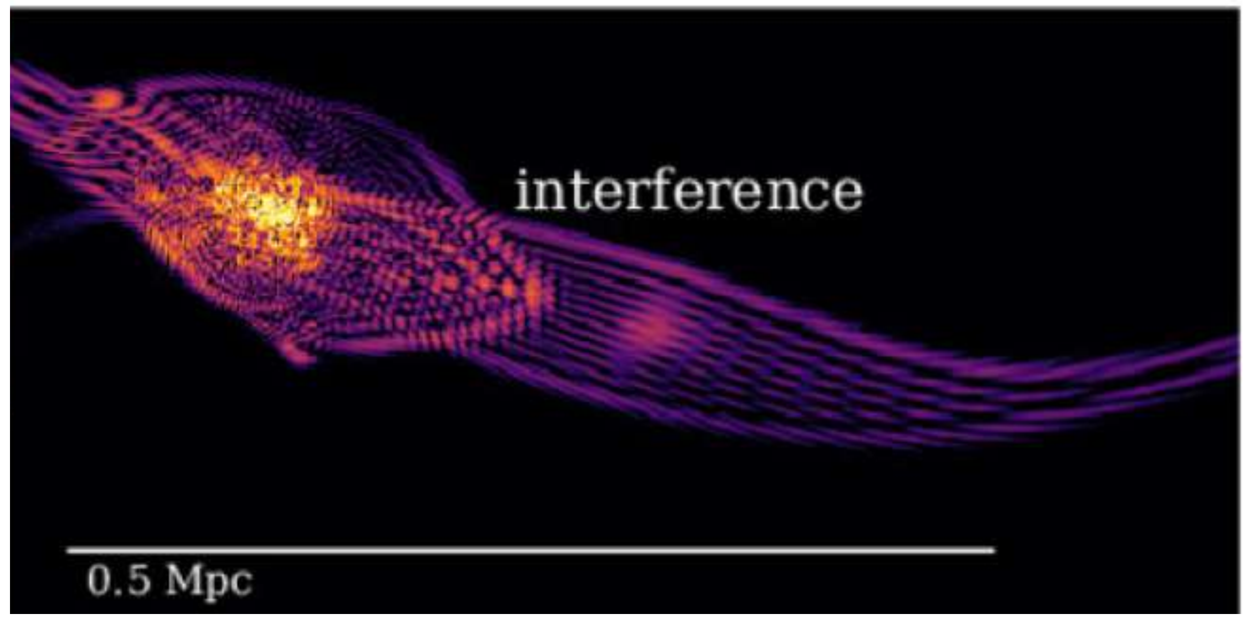


Dynamical effects



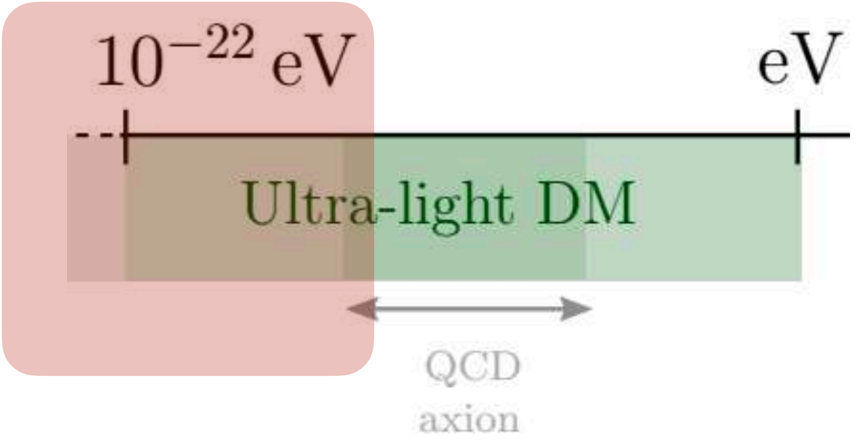
Levkov et al. 2018

Wave interference



Mocz et al. 2017

Phenomenology



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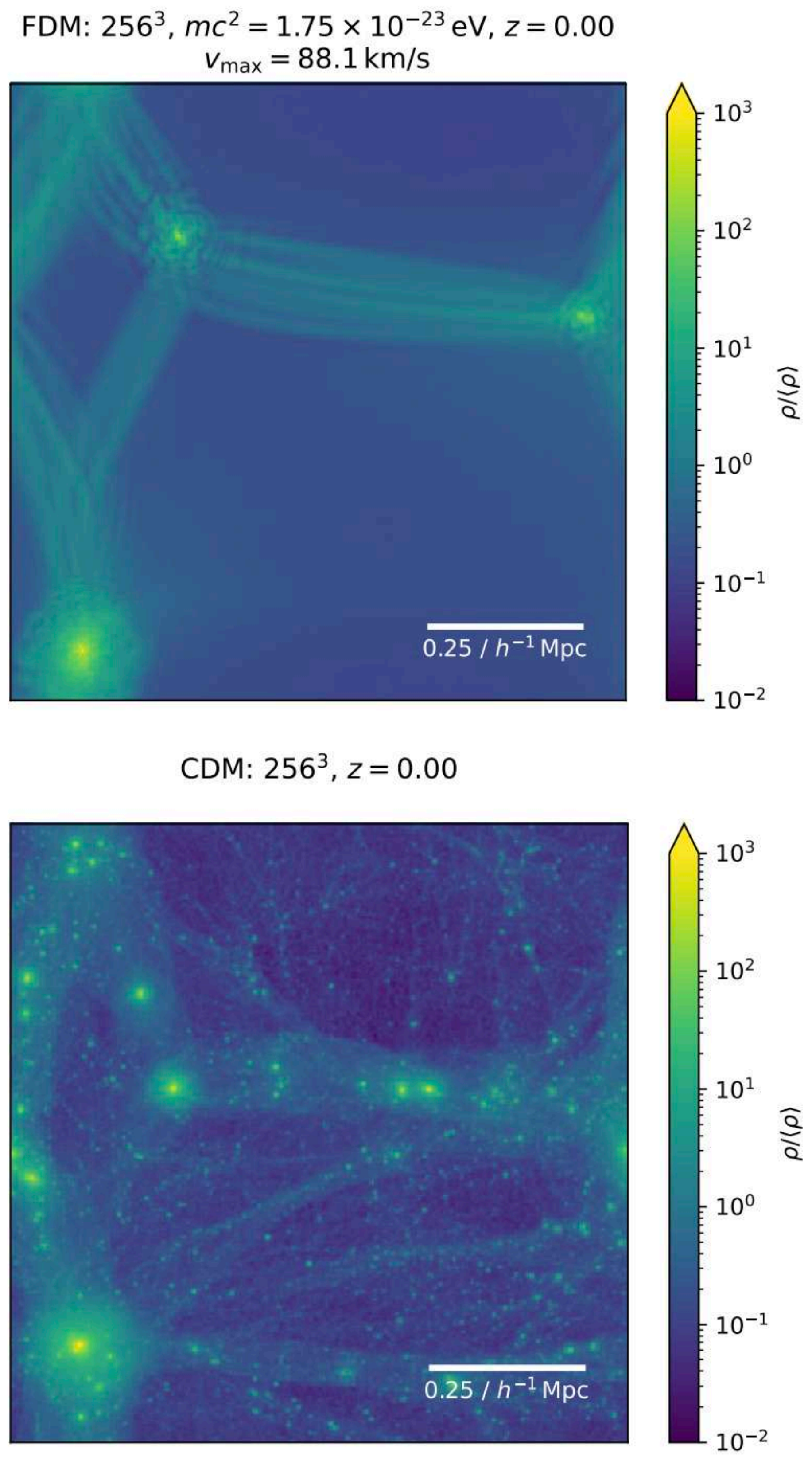

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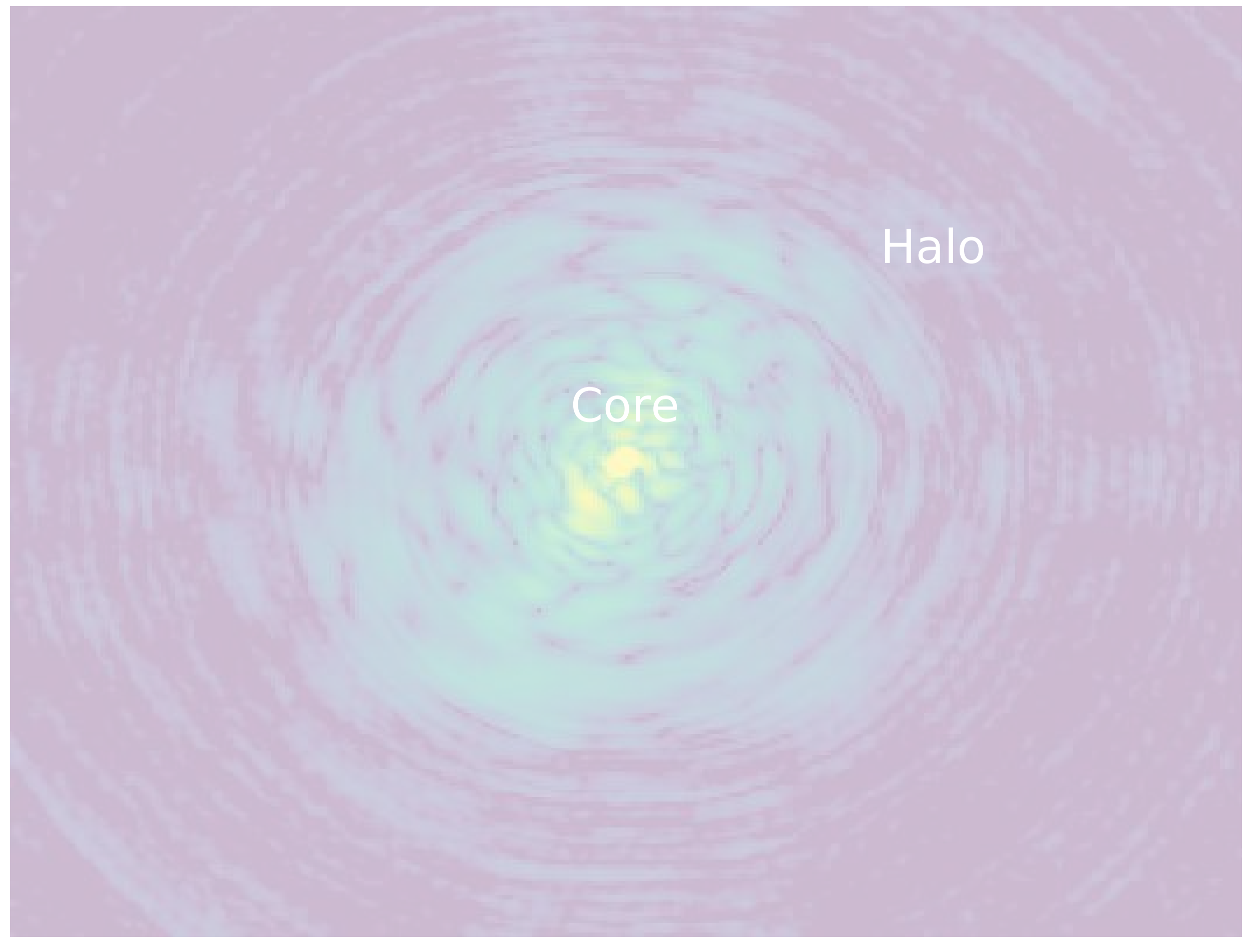

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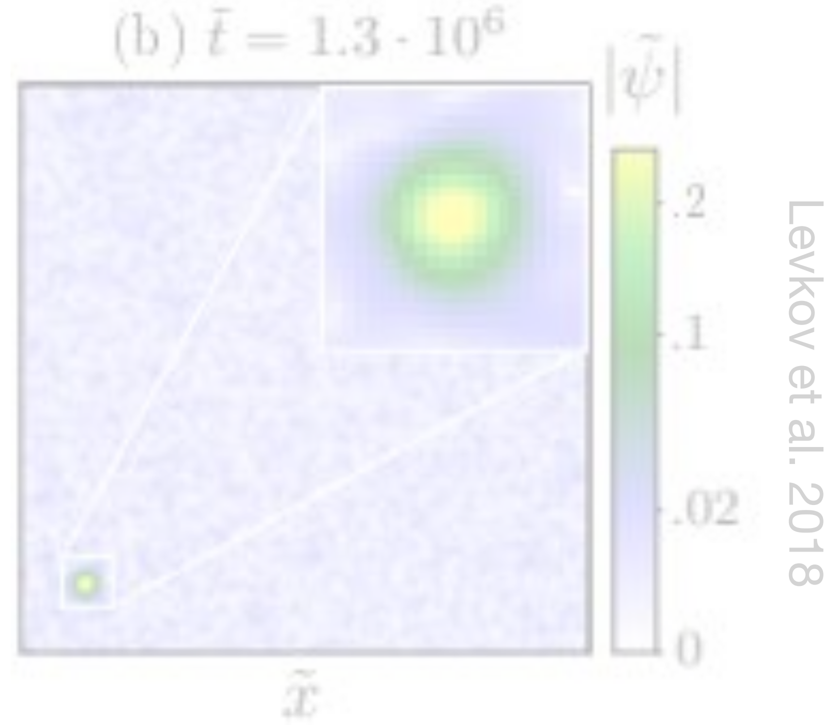

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Phenomenology

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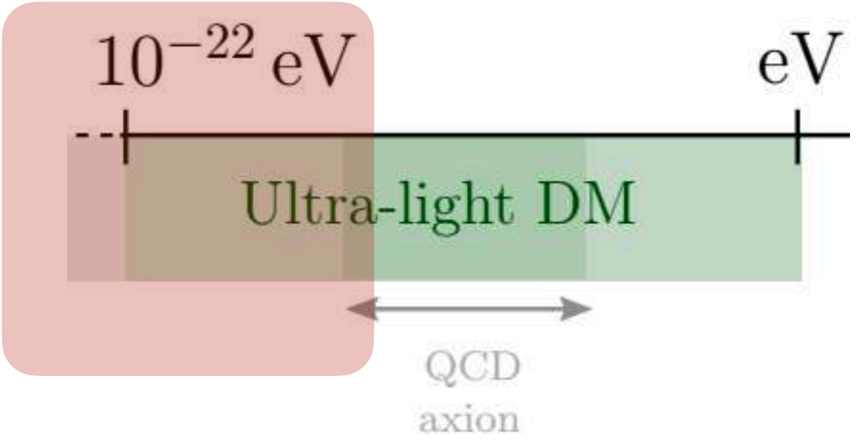
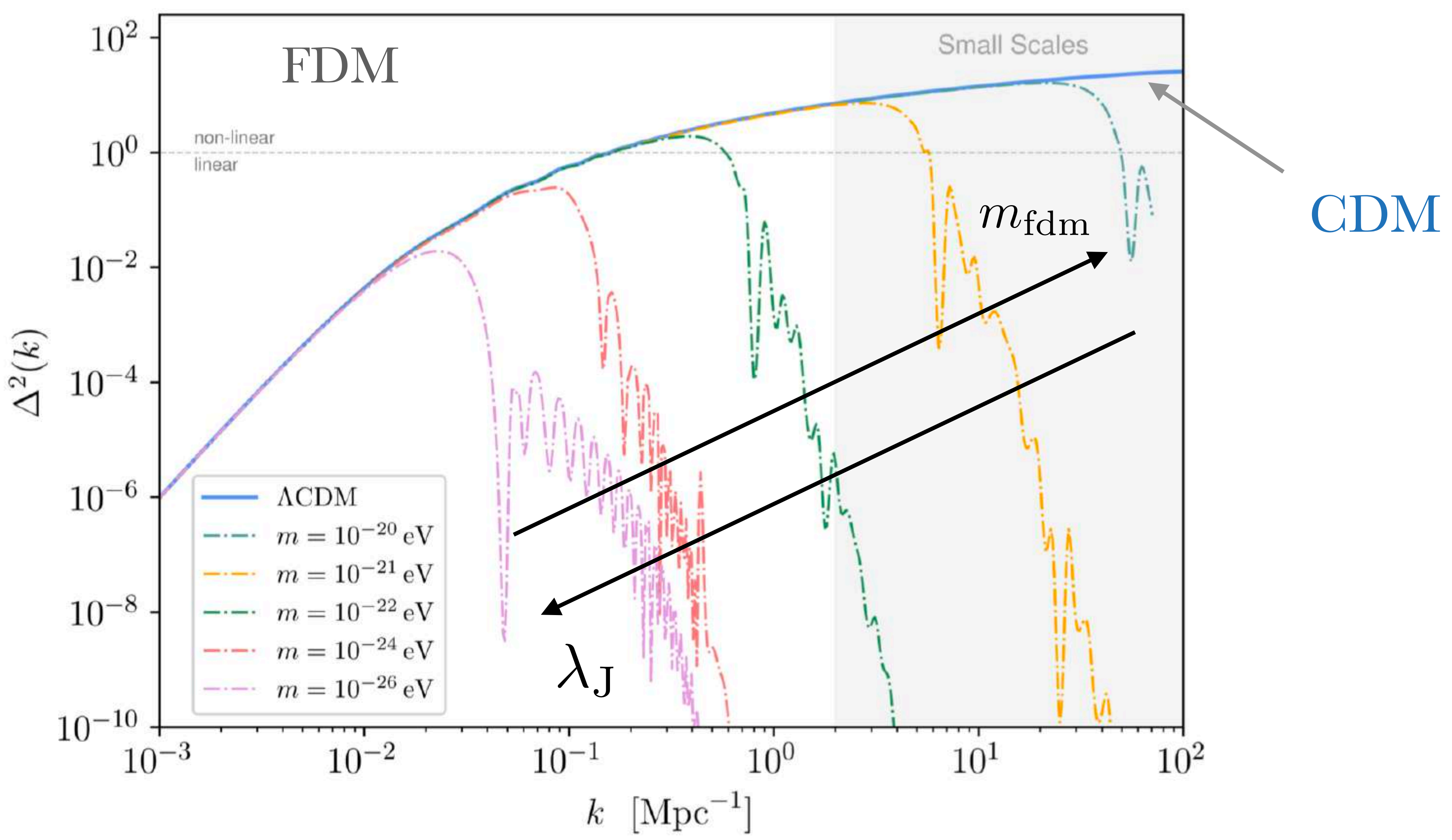
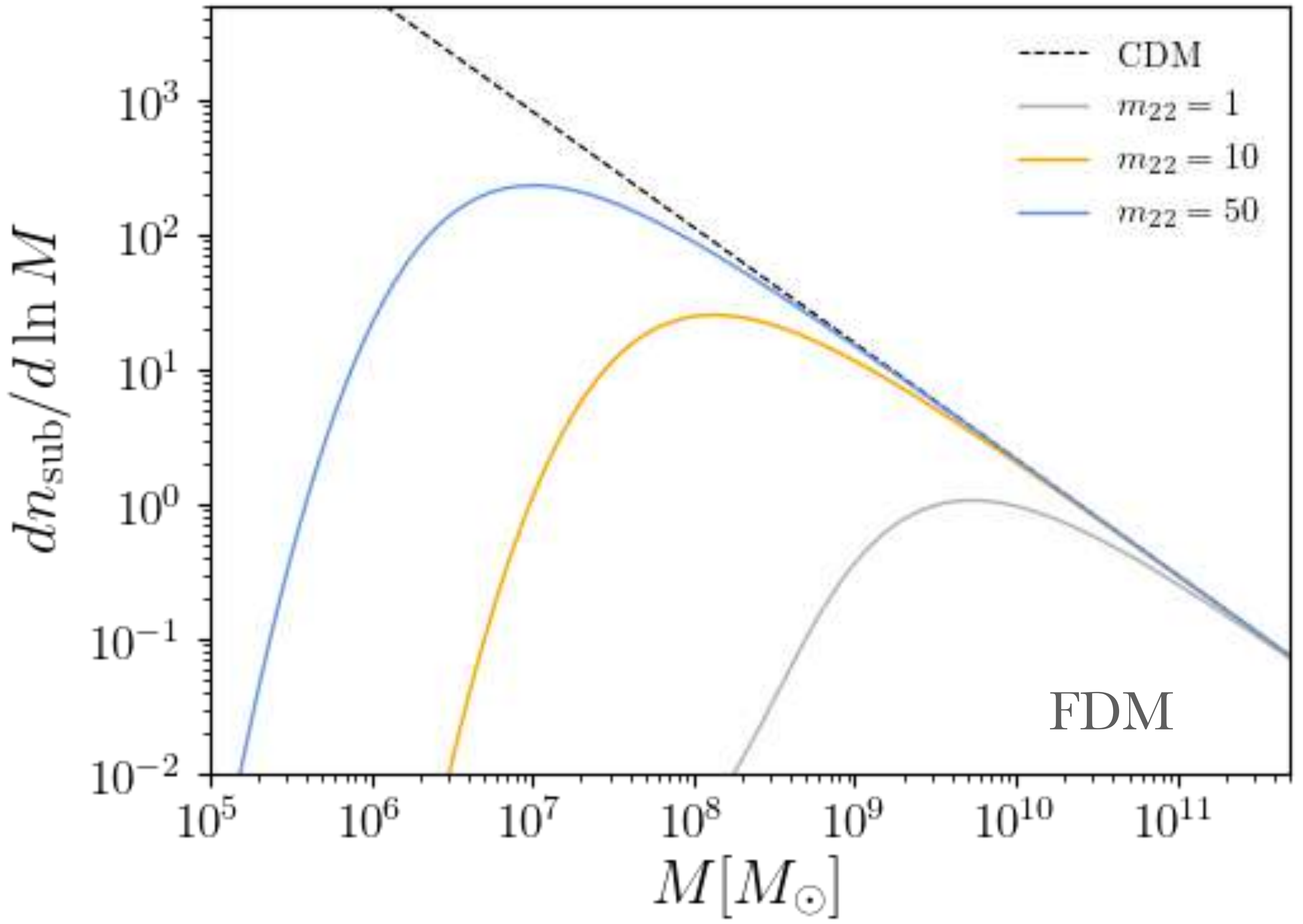


Finite Jeans length λ_J or $\lambda_{attr}, \lambda_{rep}$ → Suppresses small scale structure

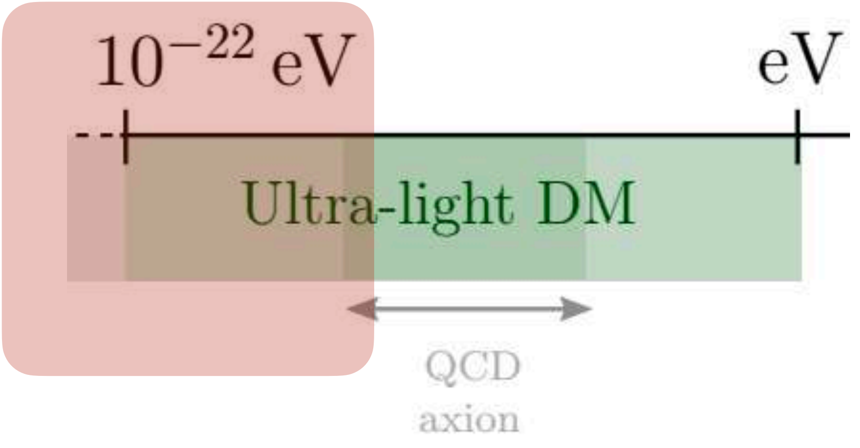
POWER SPECTRUM



(sub) HALO MASS FUNCTION



Phenomenology



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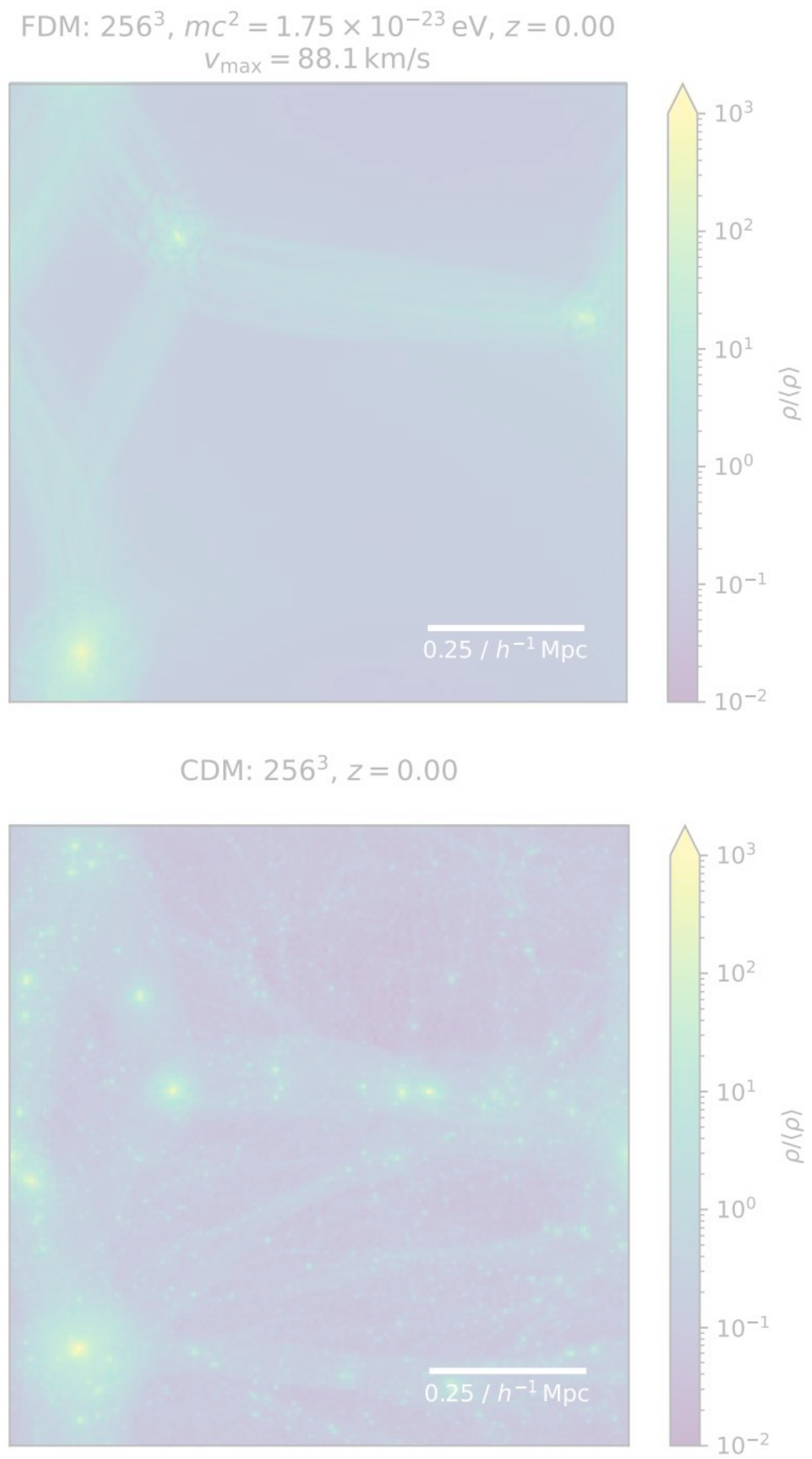

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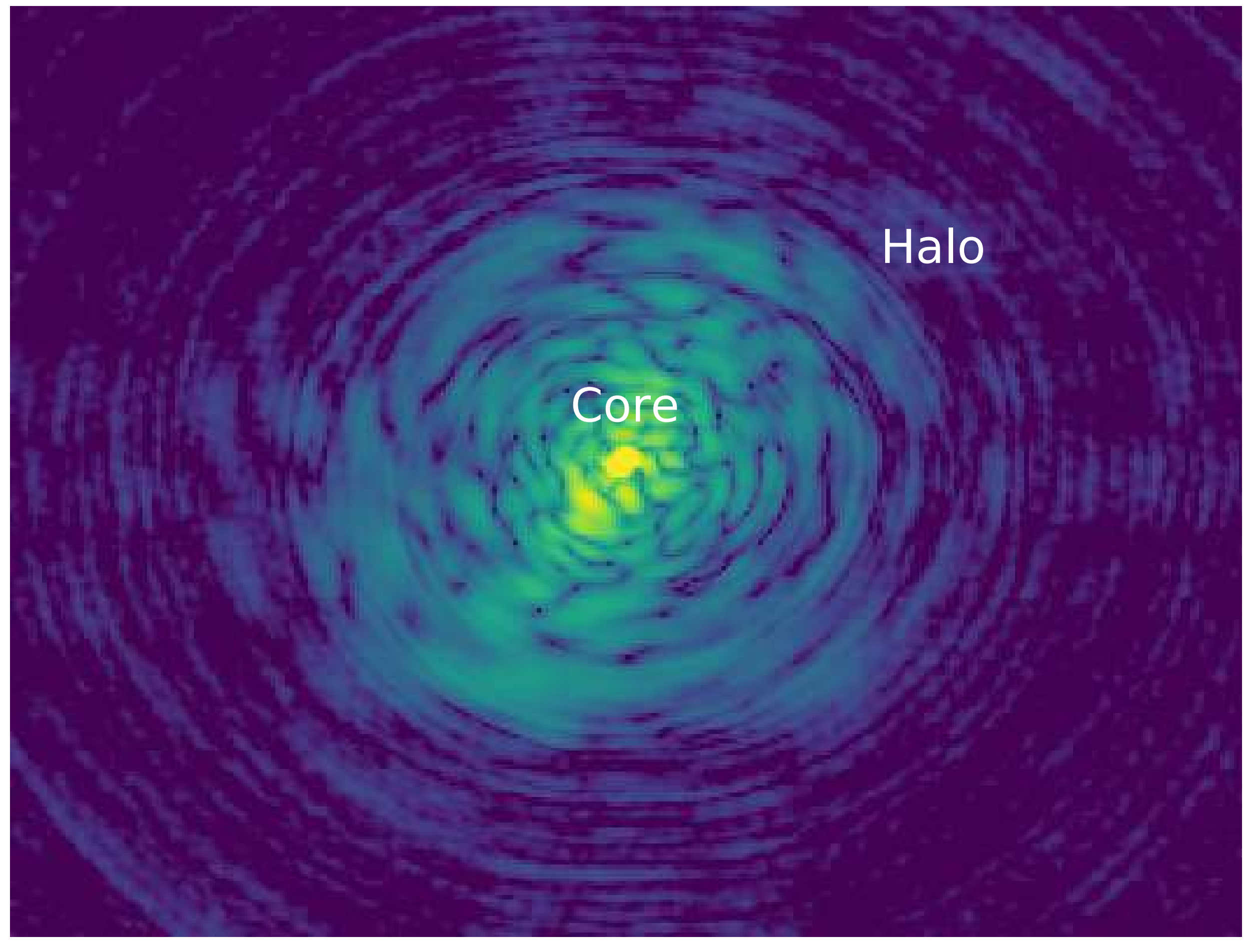

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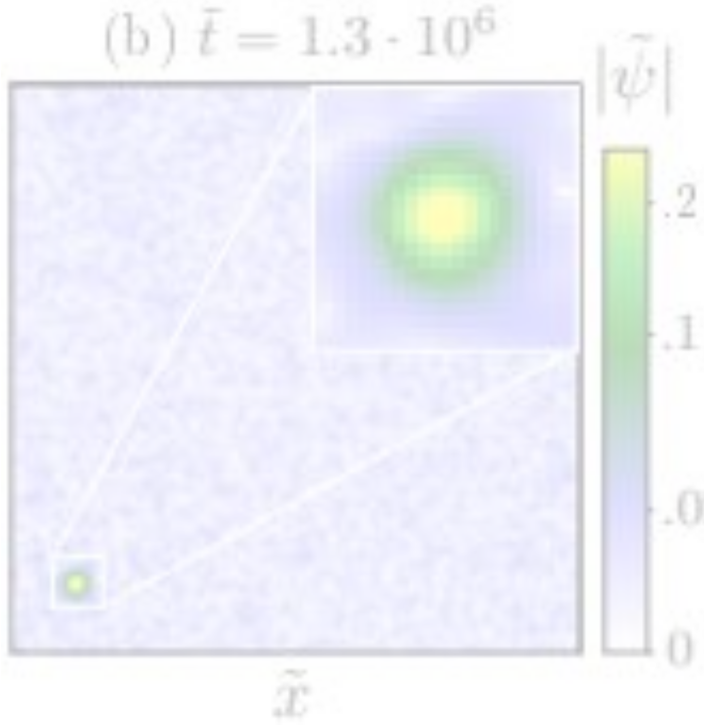


Levkov et al. 2018

Wave interference

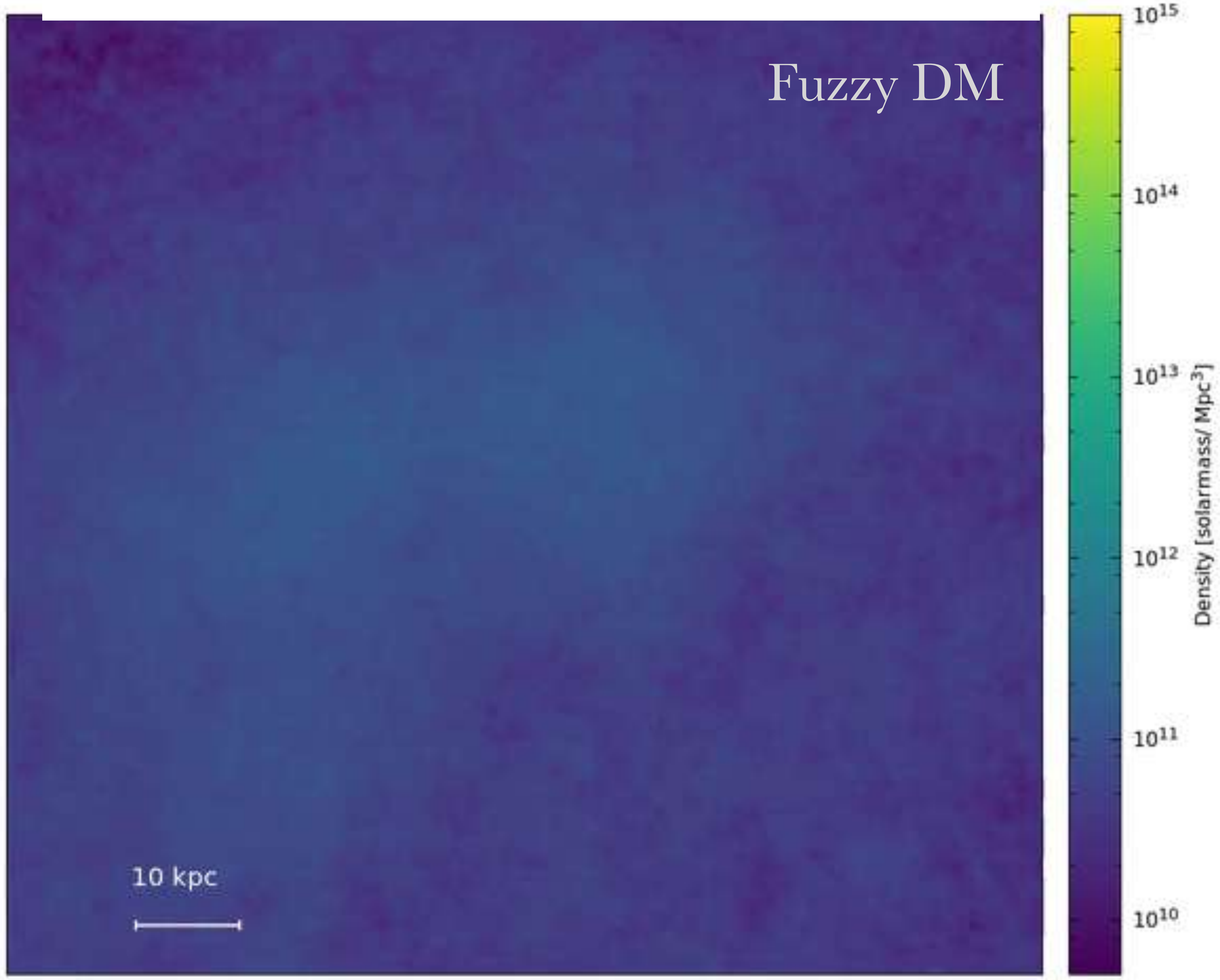
Mocz et al. 2017

Phenomenology

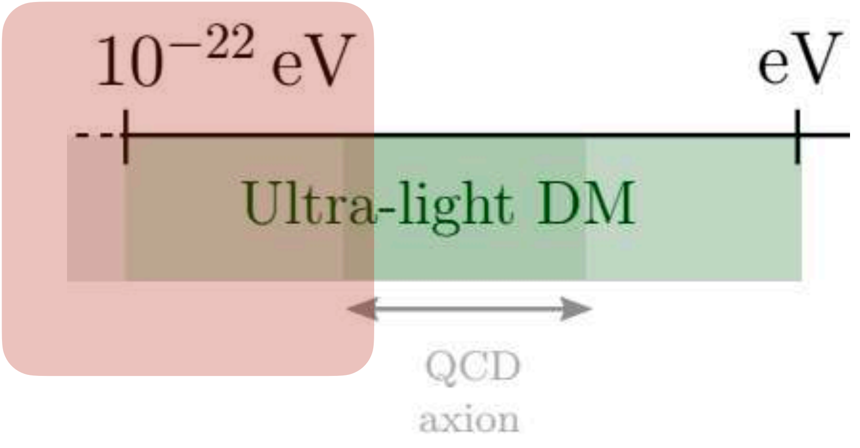
Formation of cores

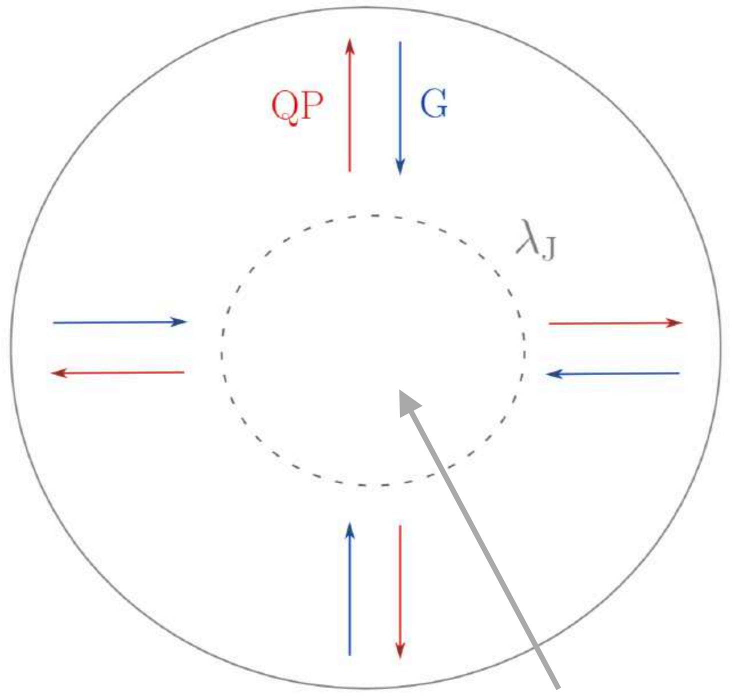
$m = 10^{-22}\,\mathrm{eV}$ $N = 512^3$ $L = 300\,\mathrm{kpc}$

NON-LINEAR evolution: need simulations

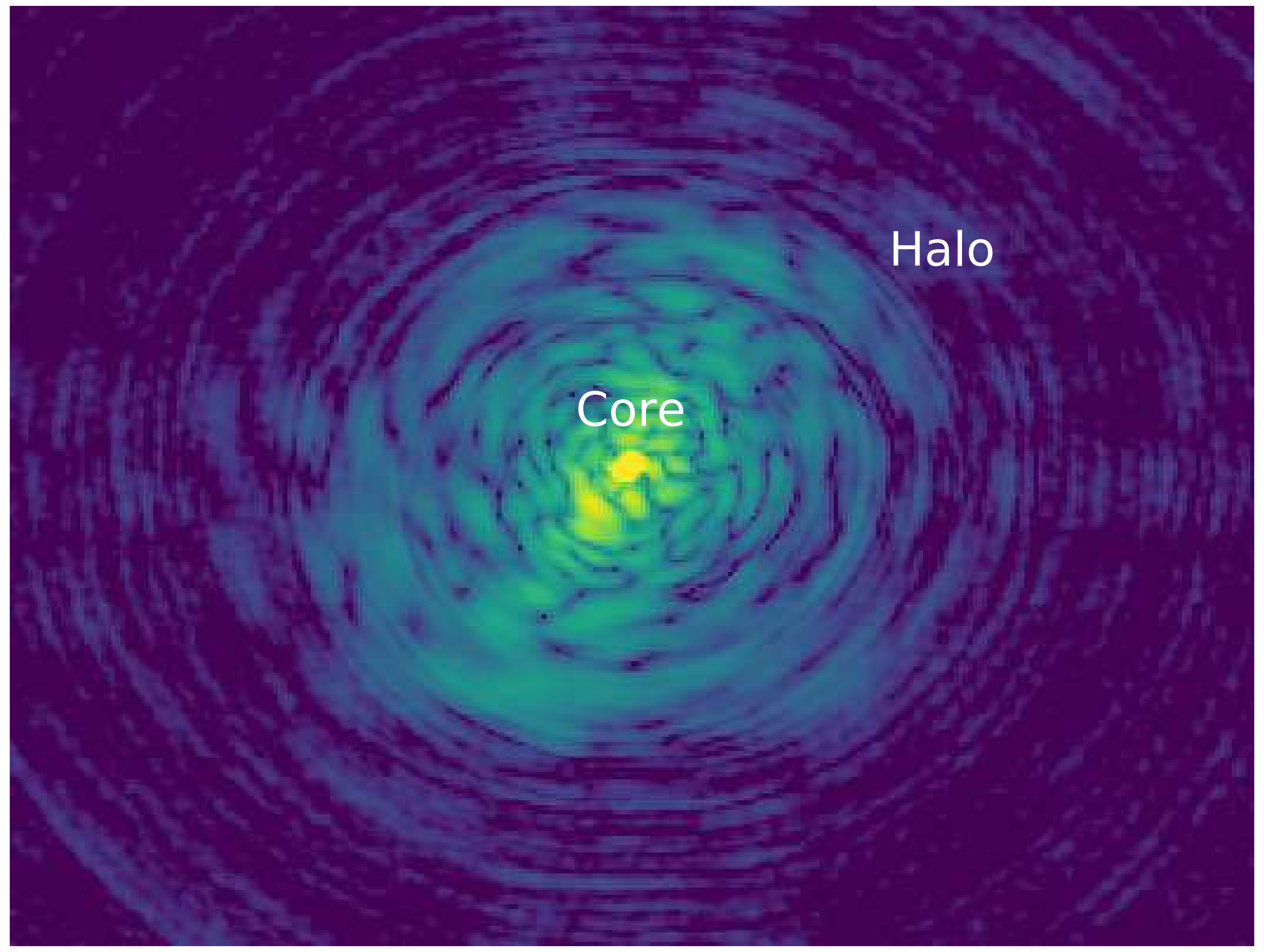


Simulation by Jowett Chan



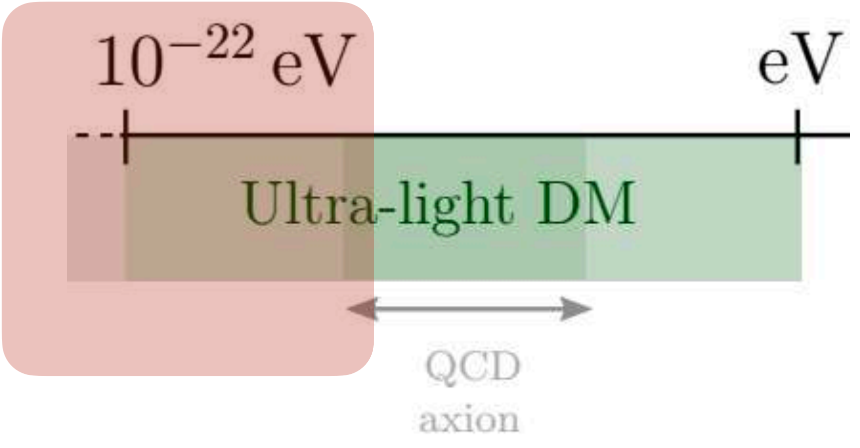


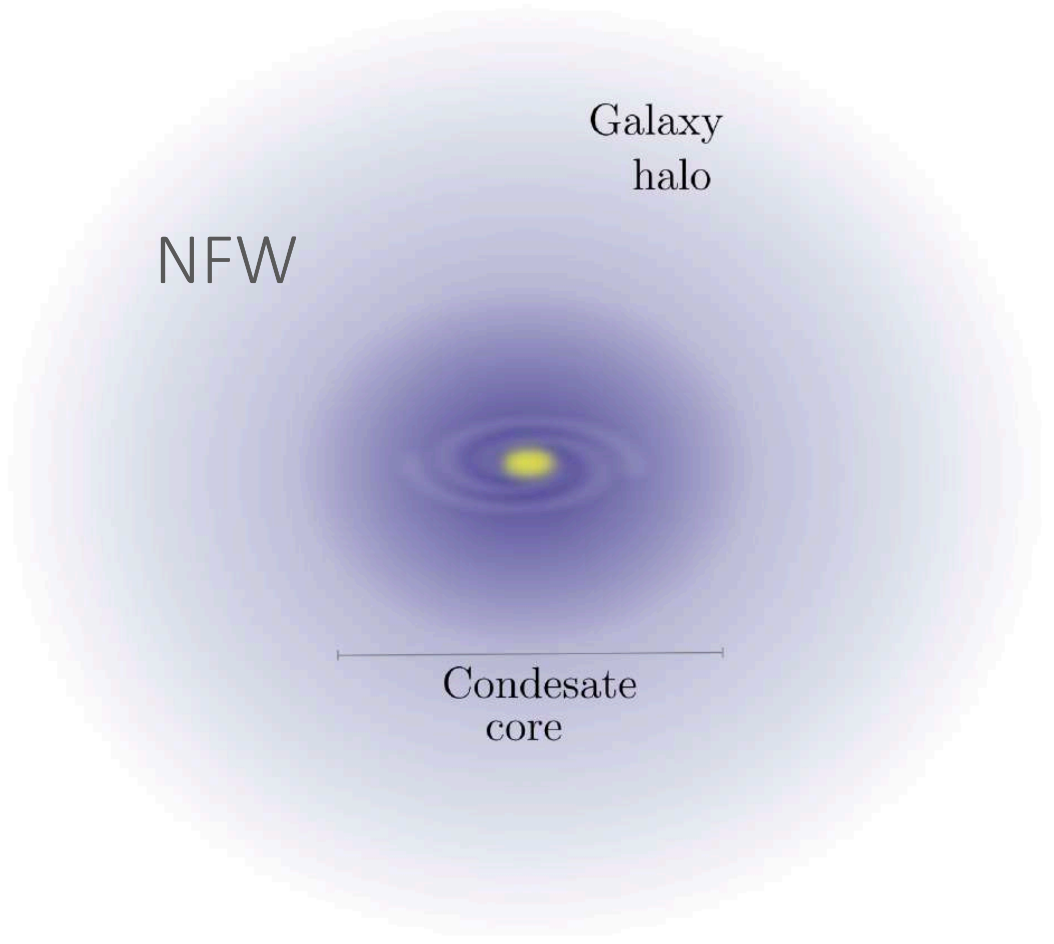
NO structure formation
Stable, oscillating solution



Phenomenology

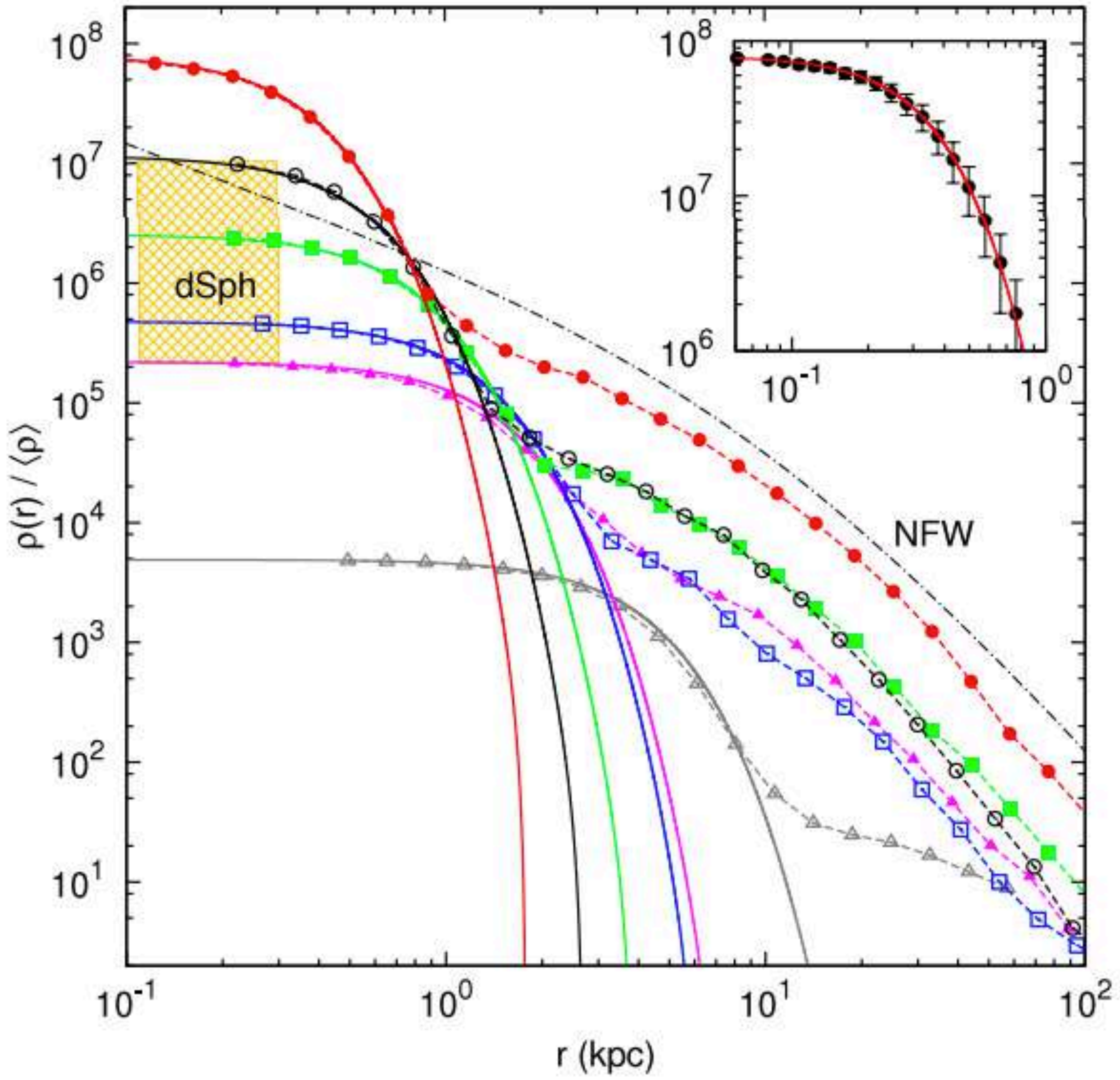
Formation of cores





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

Schive et al. 2014



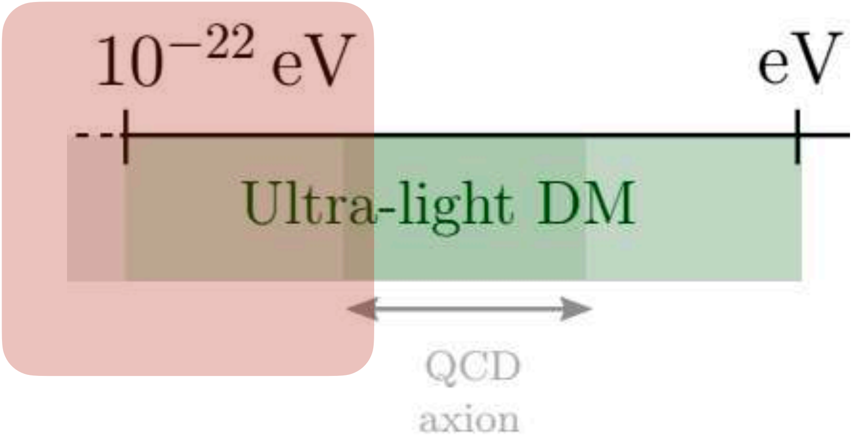
FDM From simulations Schive et al. 2014, fitting function: Stable core solution

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

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

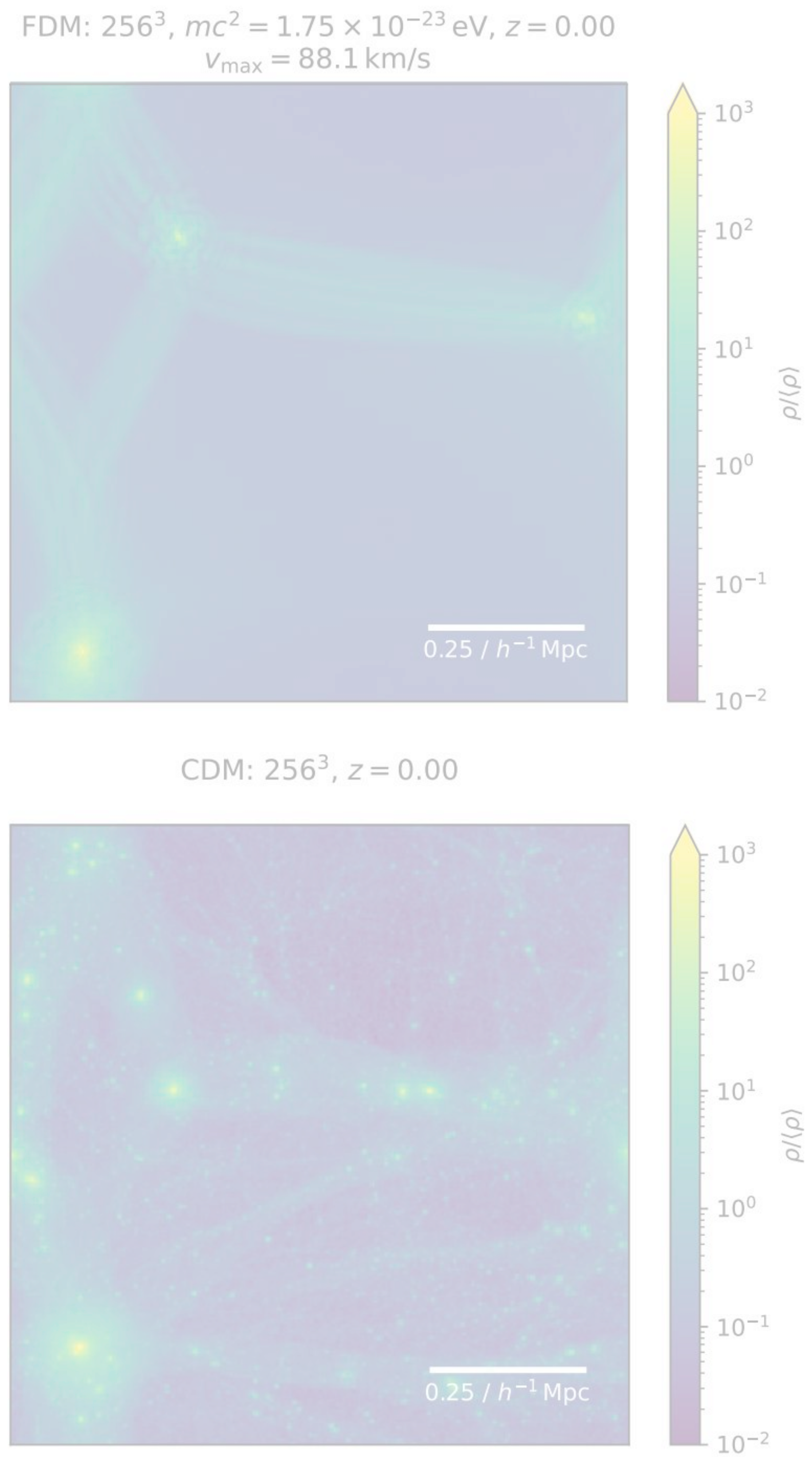
→ Relations used to compare with observations

Phenomenology



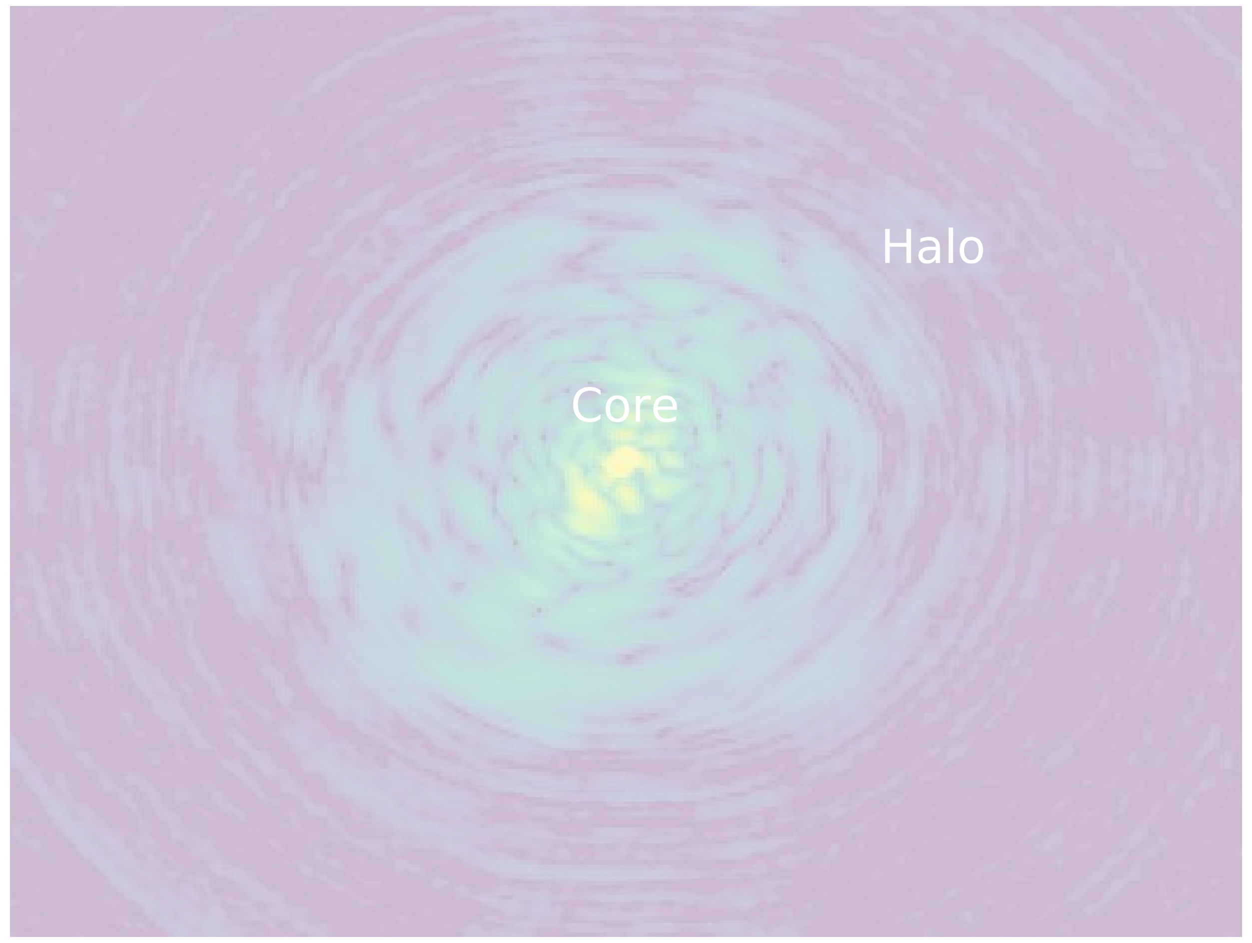
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

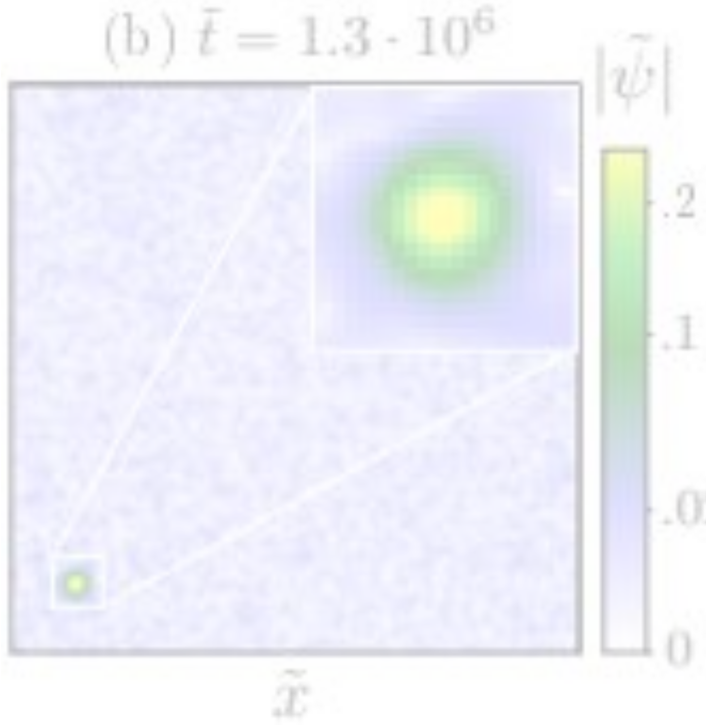


S. May et al. 2021

Formation of a solitonic core

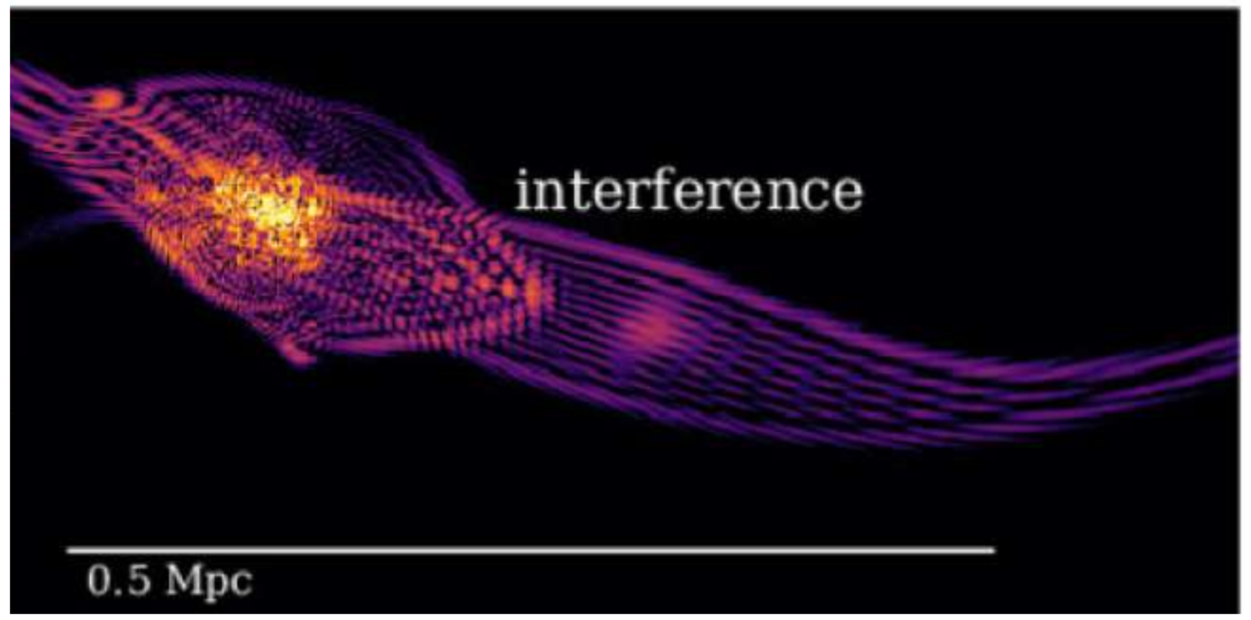


Dynamical effects



Levkov et al. 2018

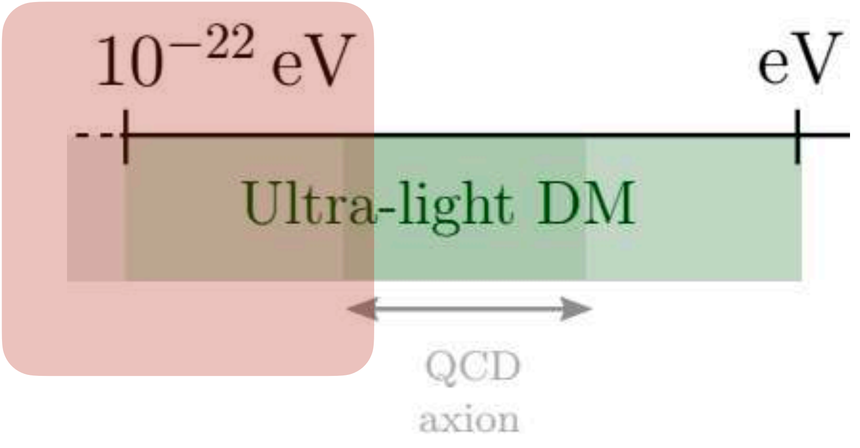
Wave interference

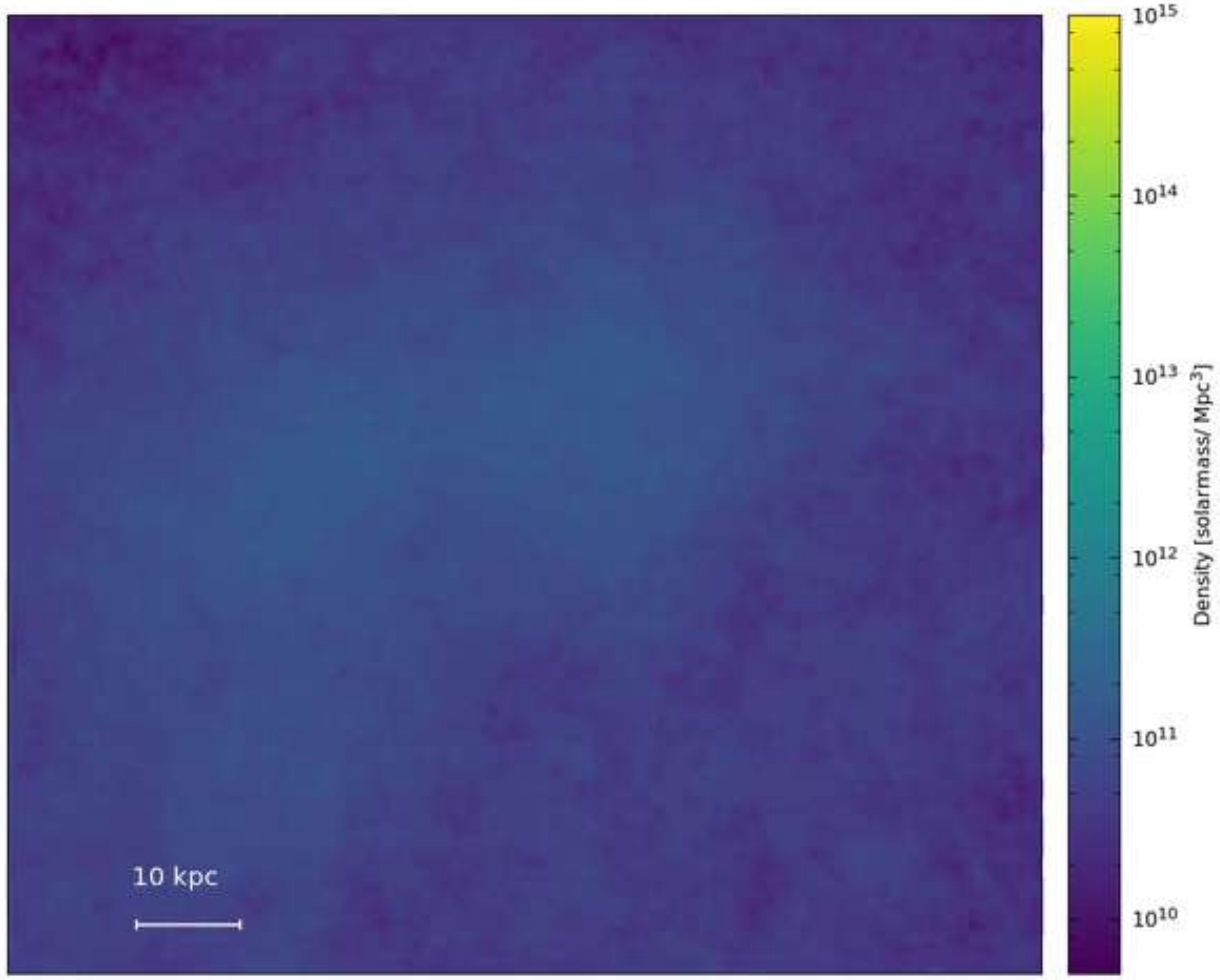


Mocz et al. 2017

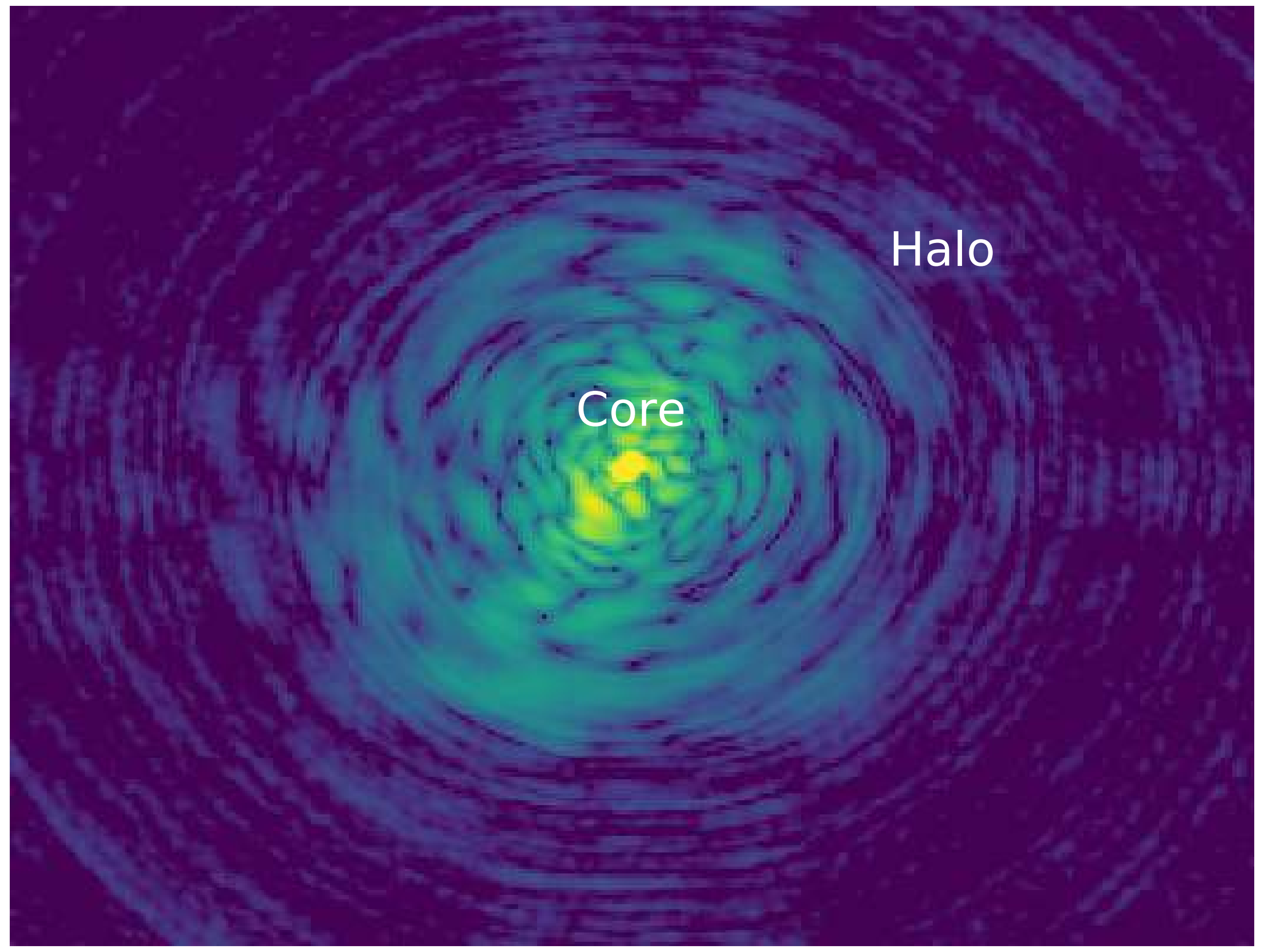
Phenomenology

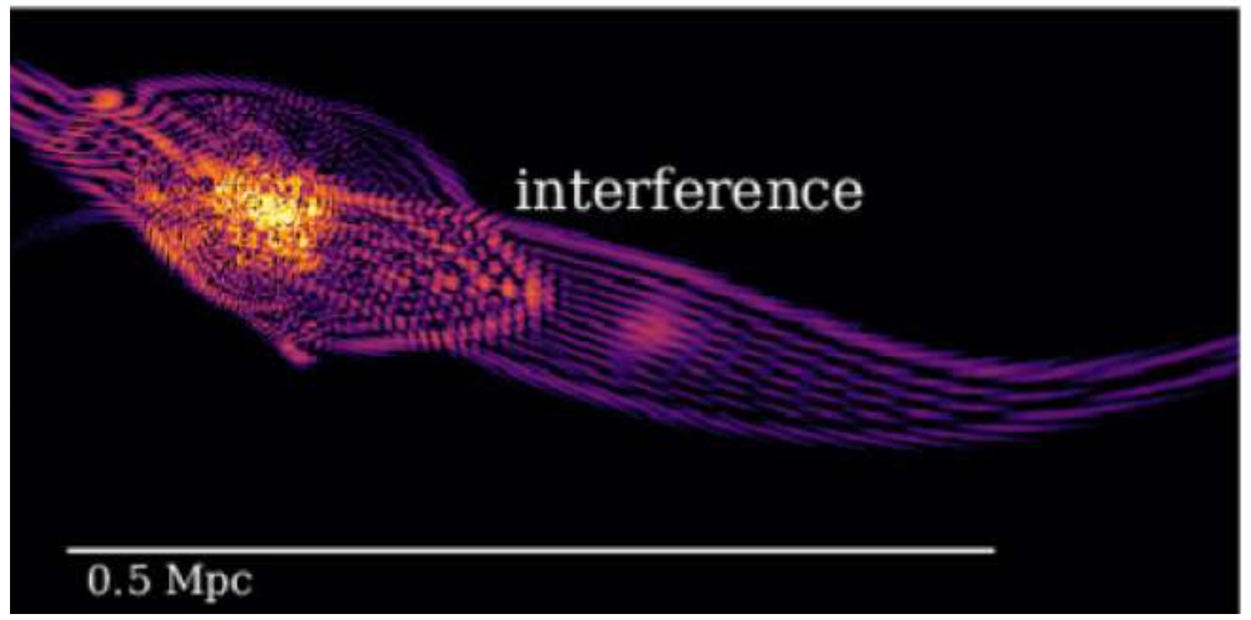
Wave interference: granules and vortices





Simulation by Jowett Chan





Mocz et al. 2017

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

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

Hard to observe!

Phenomenology

Vortices

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

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

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

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

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

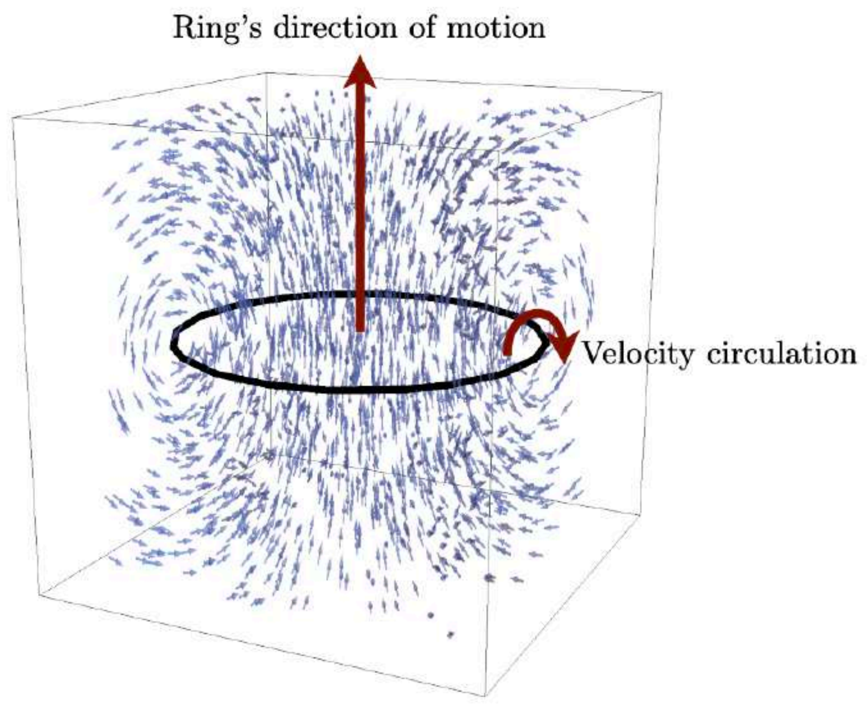
Vel. field is a gradient flow ⟶ irrotational fluid, no vorticity

Fuzzy DM

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

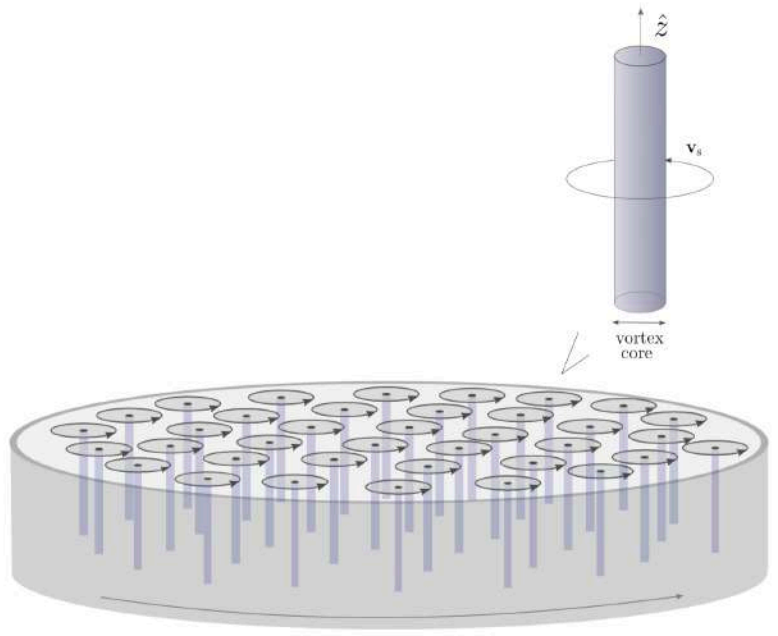
General defet in 3D

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



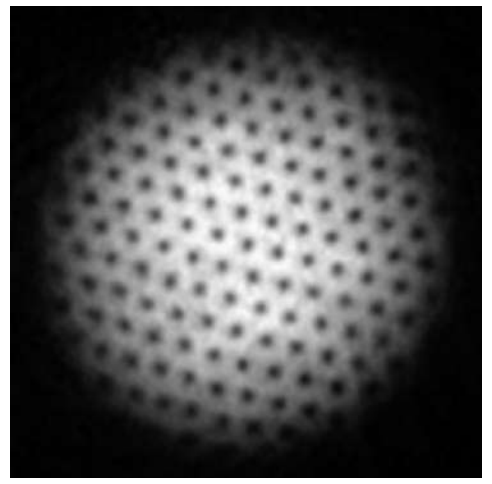
Self-interacting Fuzzy DM

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

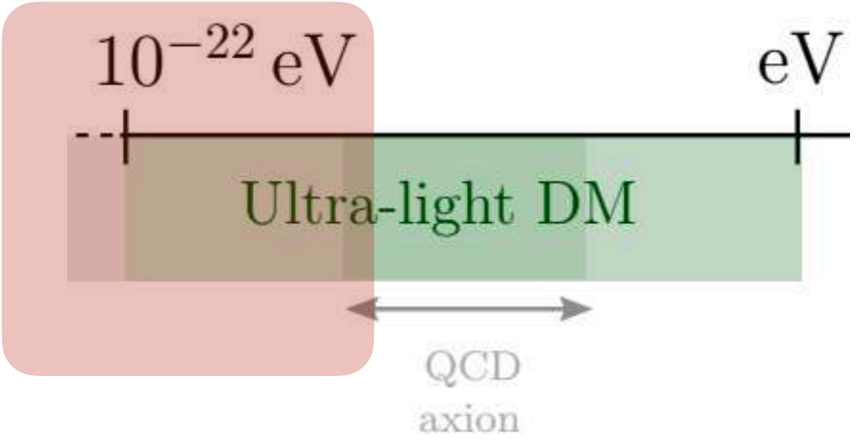


EF, 2020

© Martin Zwierlein.



Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

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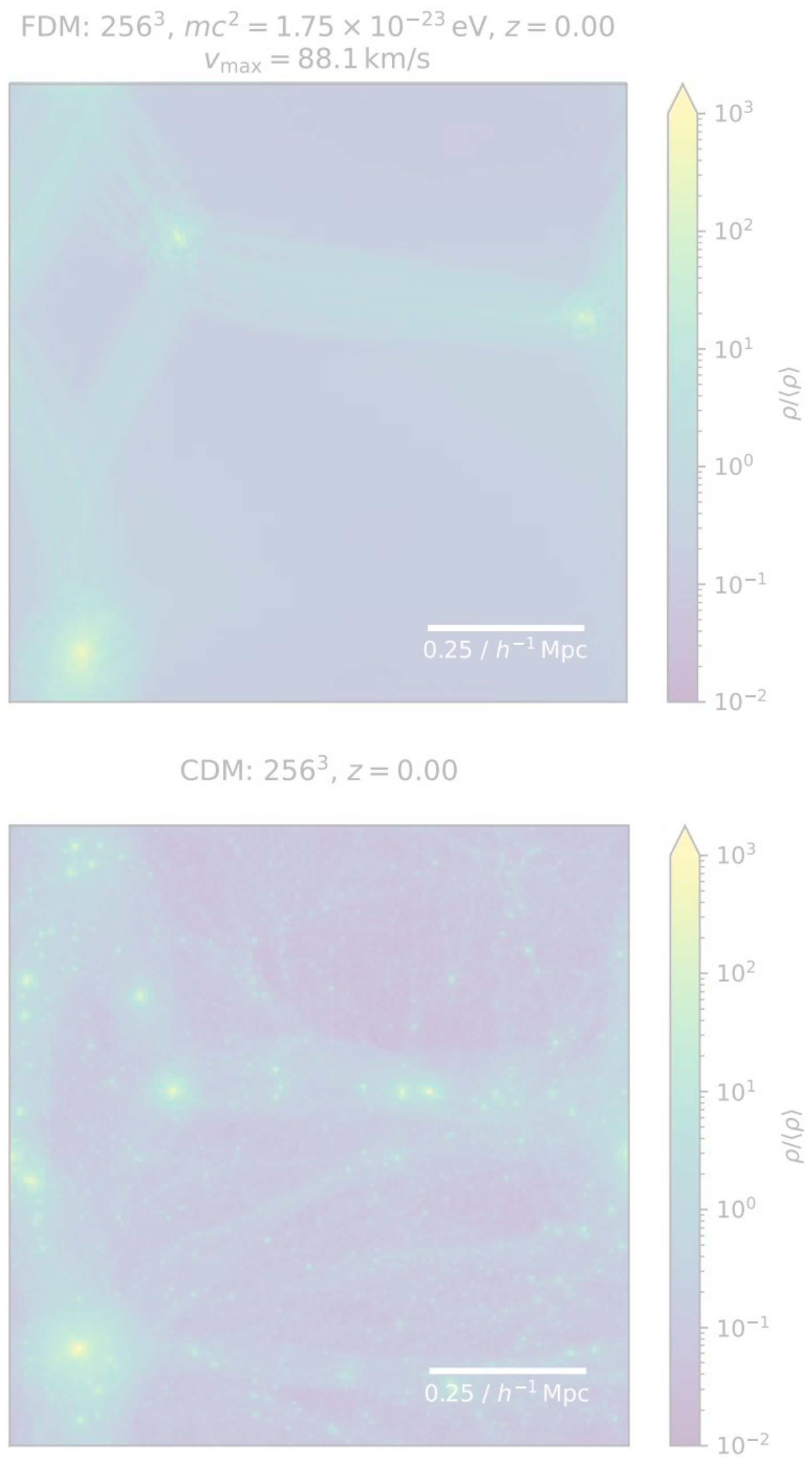

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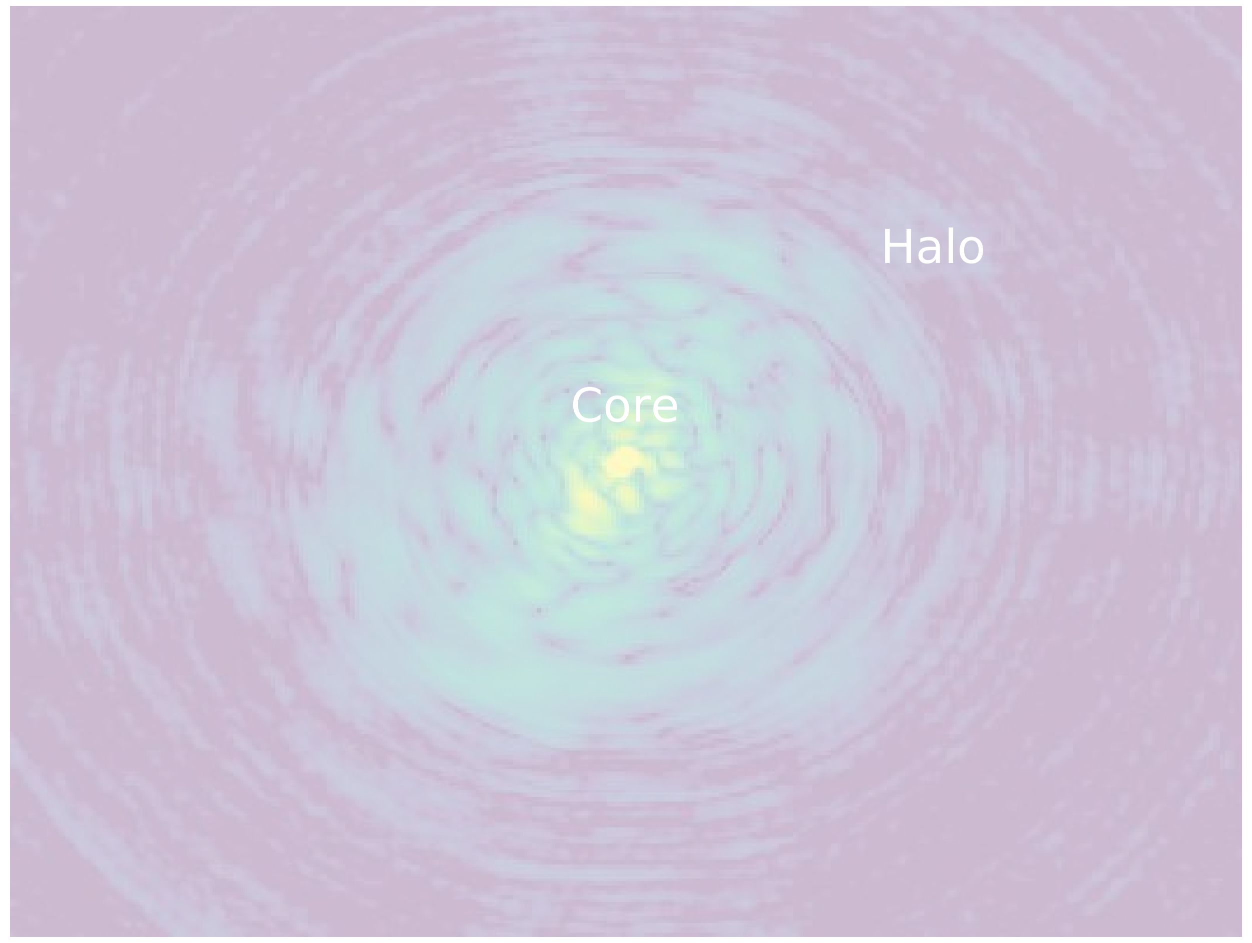
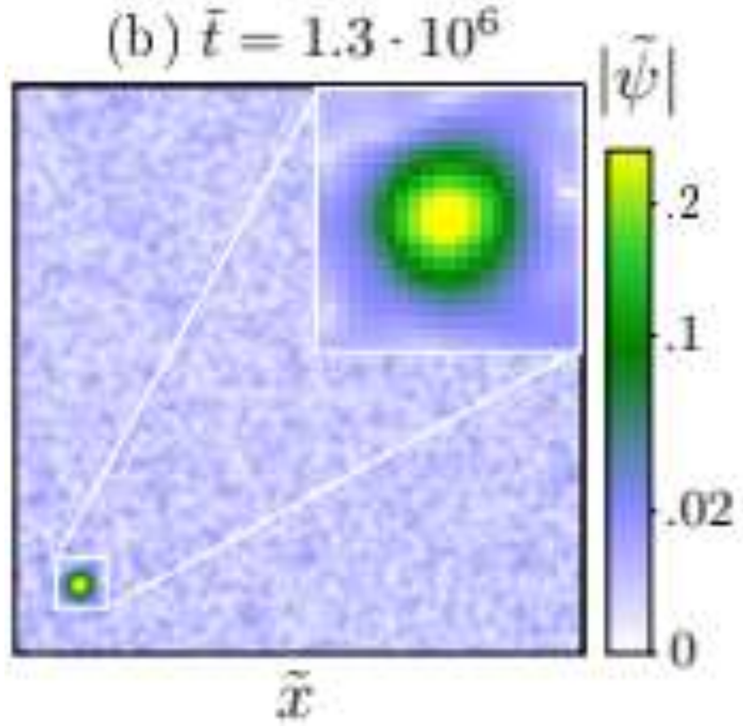


Dynamical effects



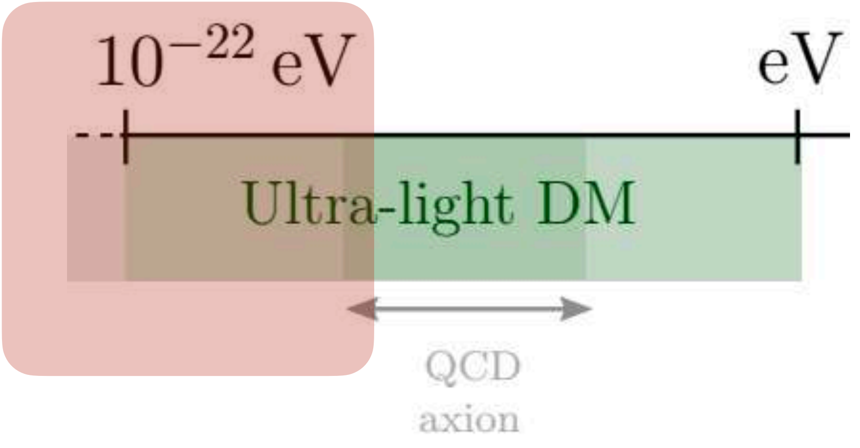
Levkov et al. 2018

Wave interference

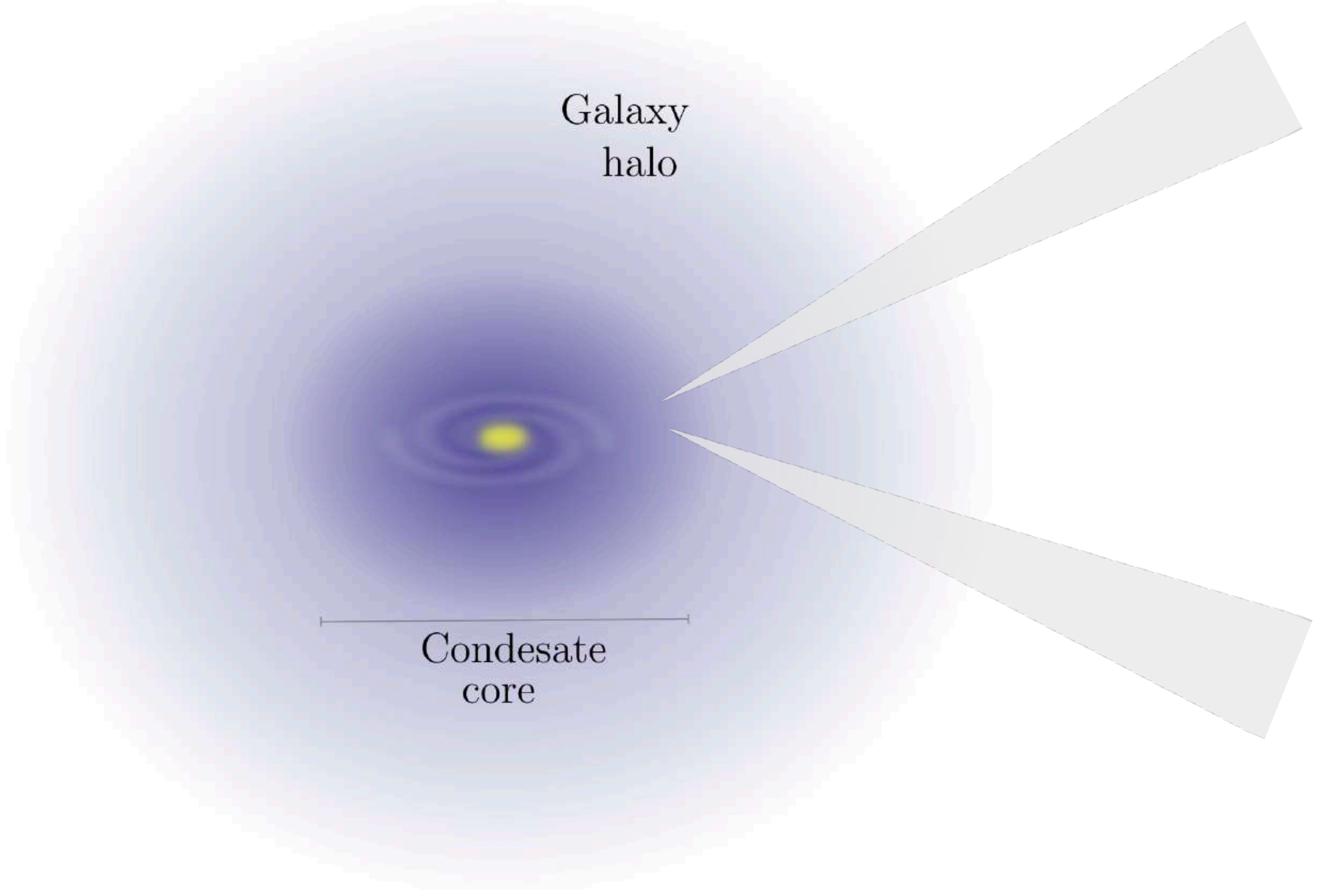
Mocz et al. 2017

Phenomenology

Dynamical effects



Relaxation, oscillation, <u>friction, and heating</u>

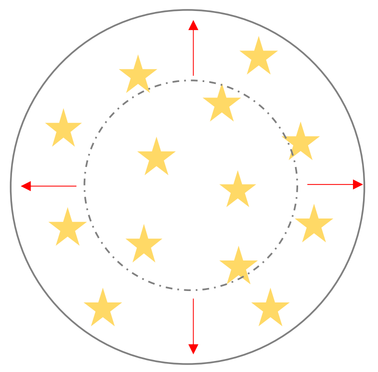


Heating

FDM granule

m_{eff}

System (star) gains energy



Friction

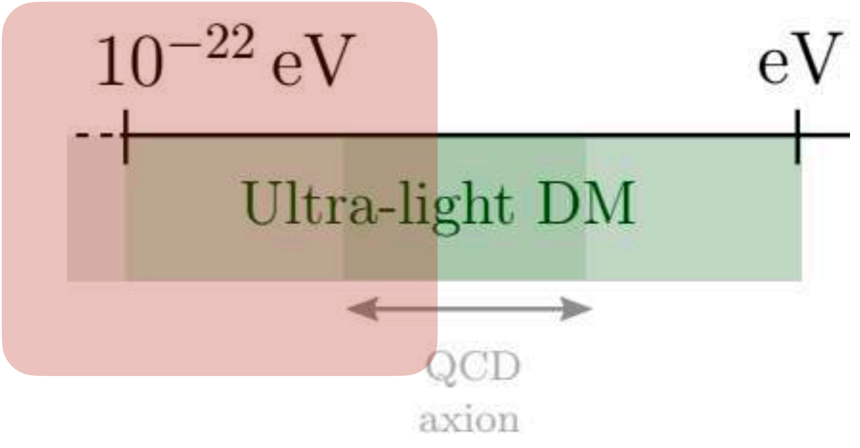
FDM granule

m_{eff}

Globular cluster

System (GC or BH) loses energy

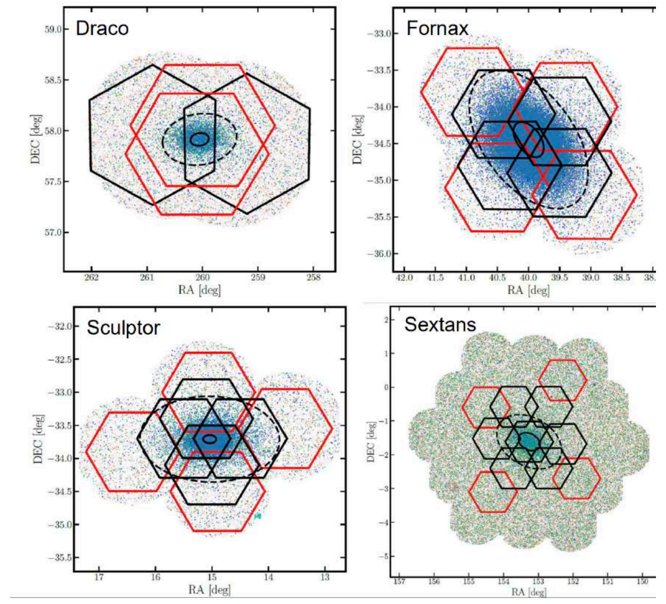
Observational implications and constraints



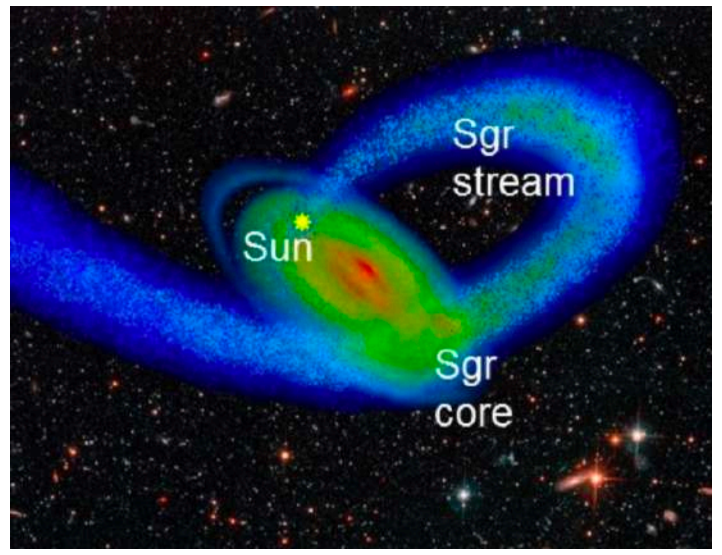
Galaxies

NASA and ESA

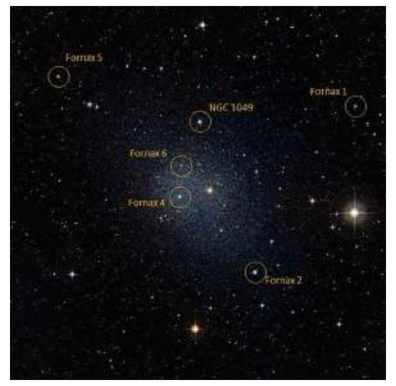
Dwarfs



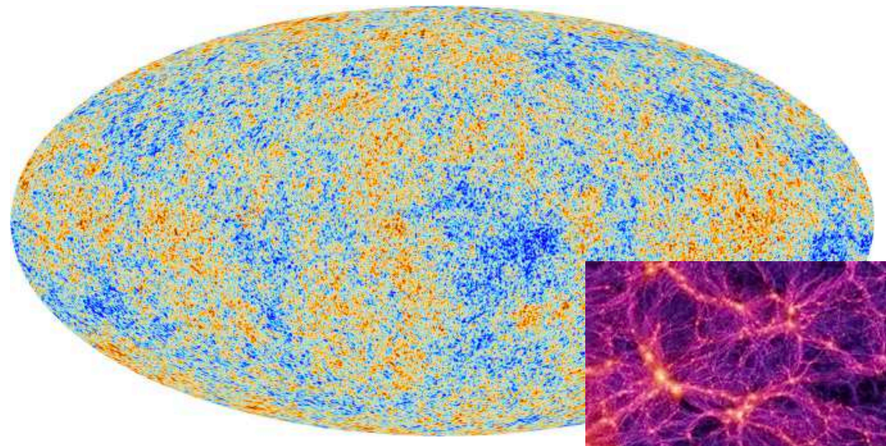
Stellar stream



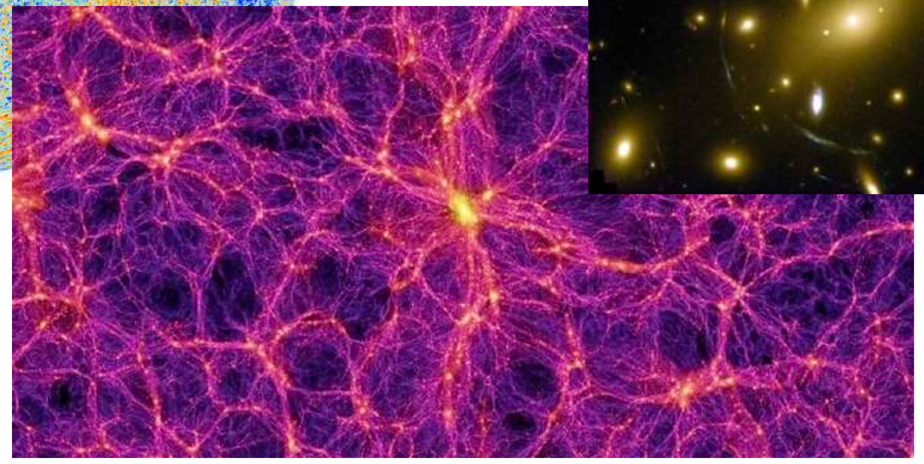
Globular clusters



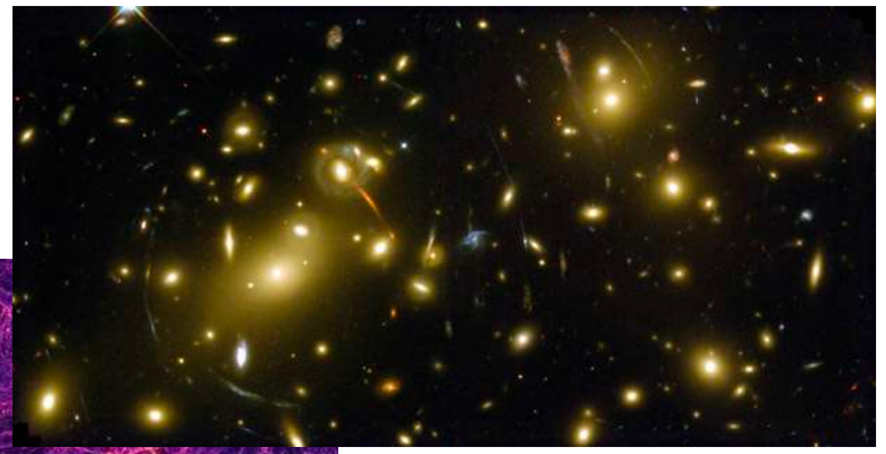
CMB+LSS



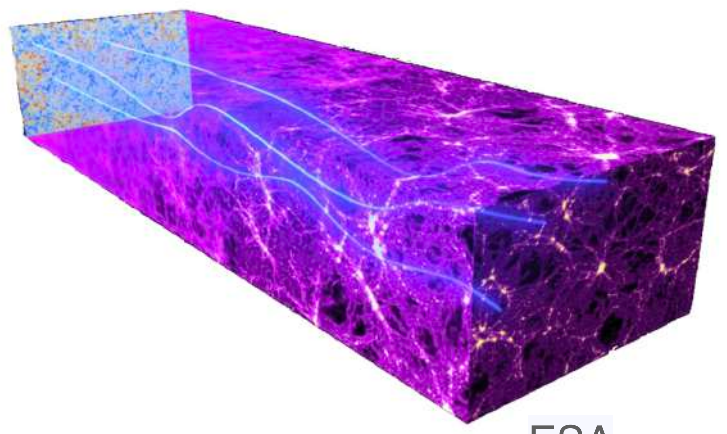
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

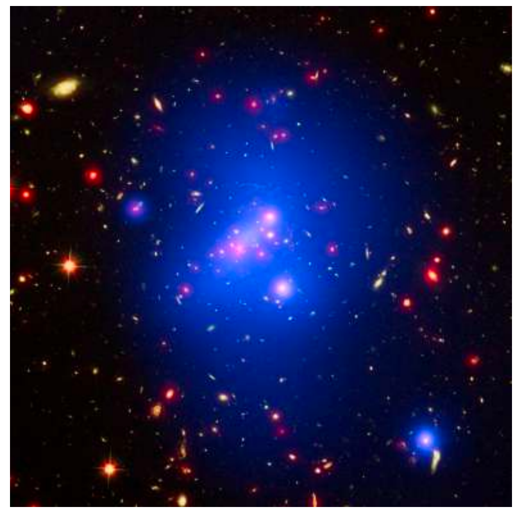


NASA and ESA



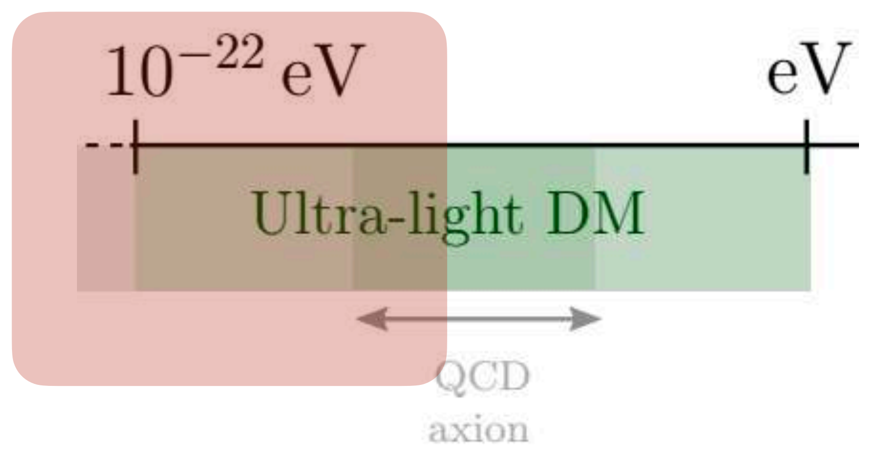
ESA

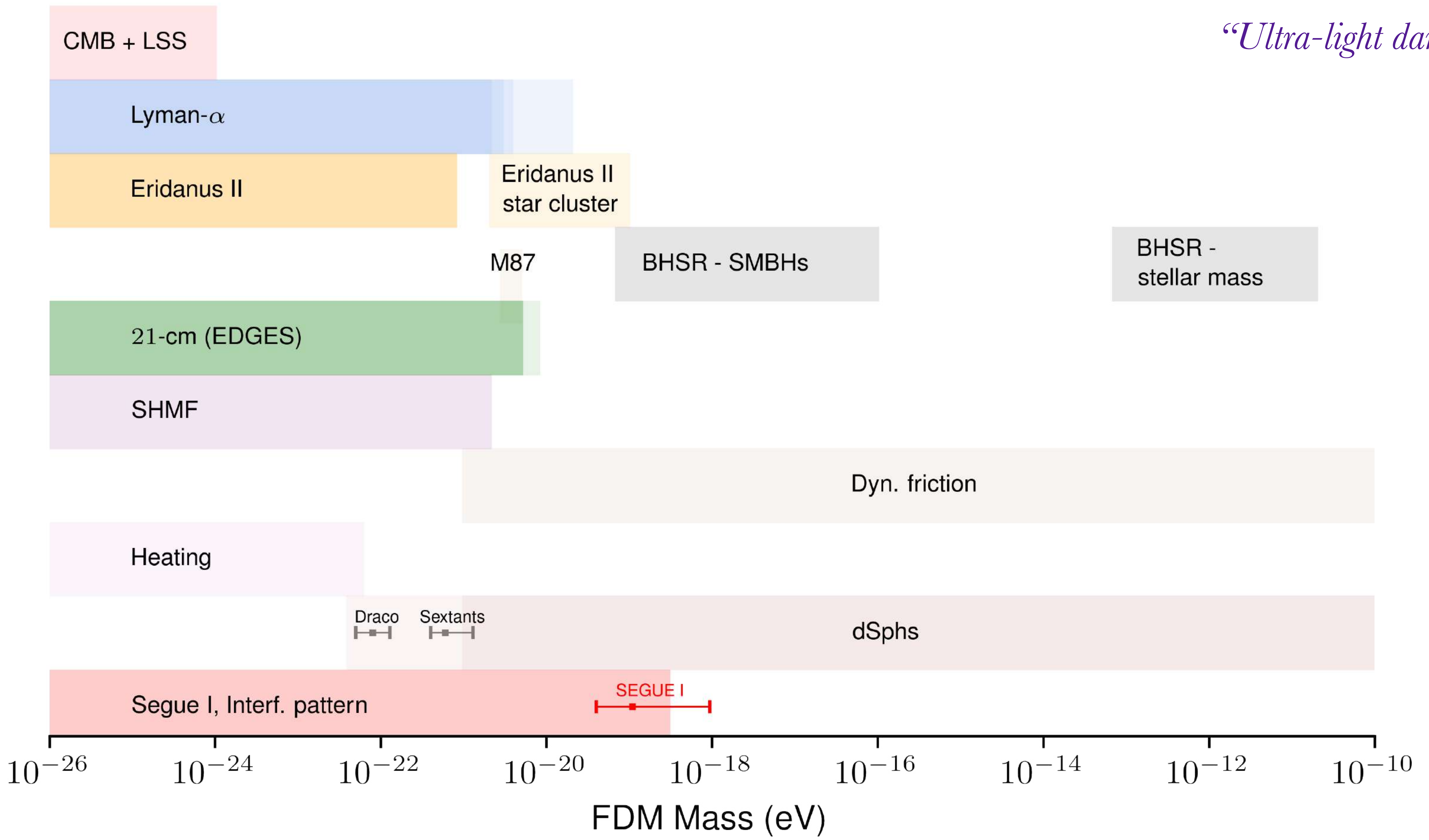
Clusters



Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



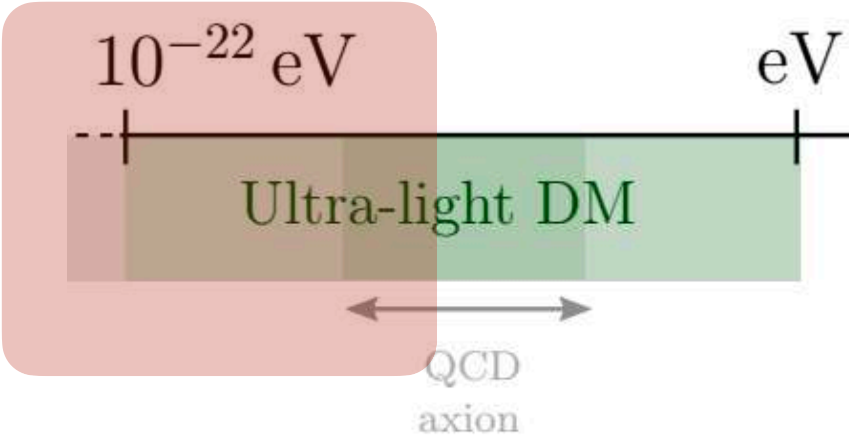


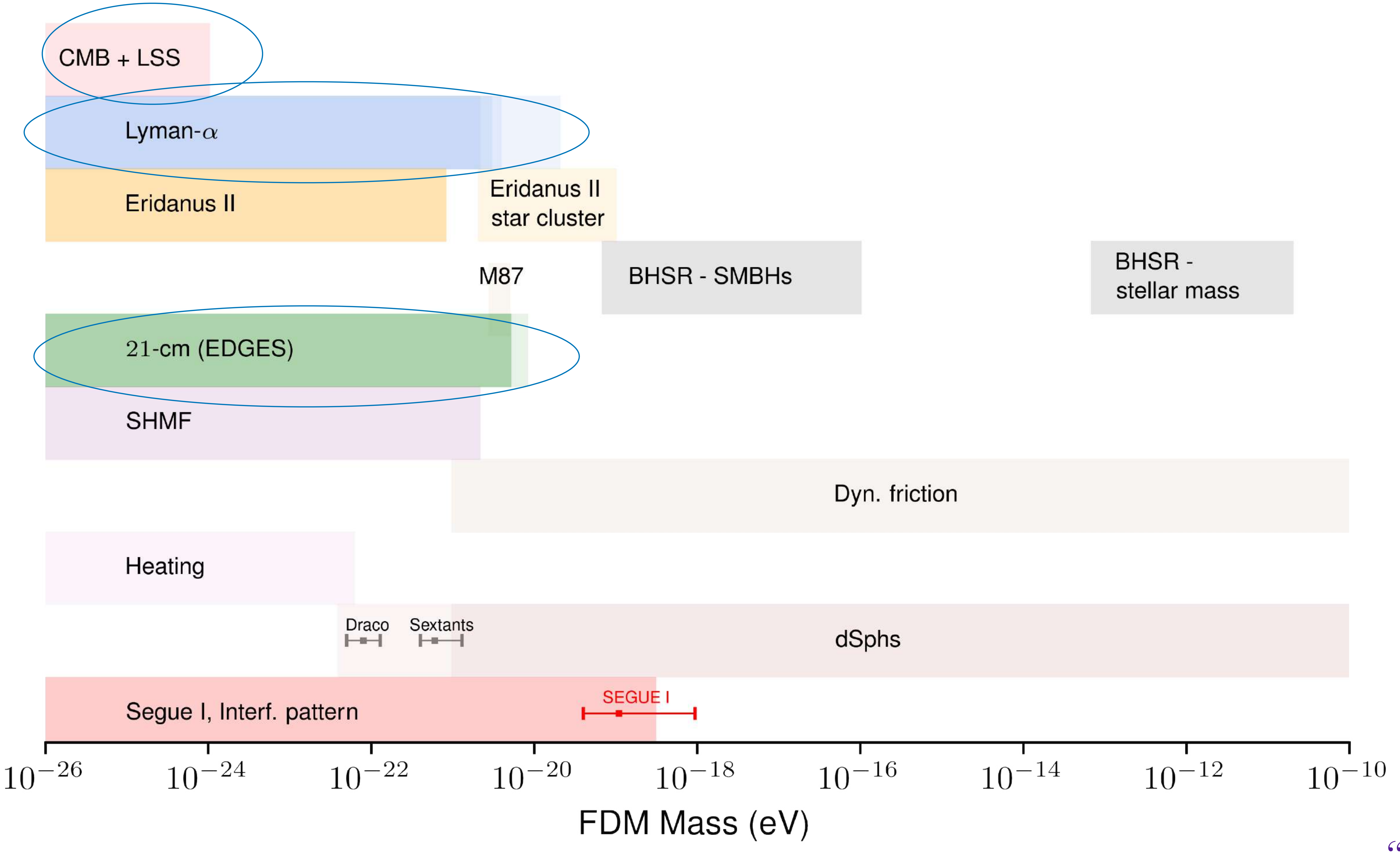
"Ultra-light dark matter", **E.F.**, 2020. The Astronomy and Astrophysics Review.

Bounds consider FDM is *all* DM

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass





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

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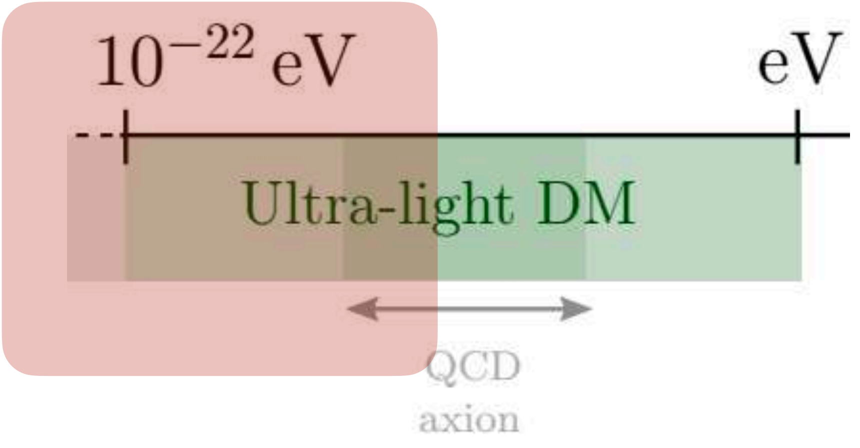
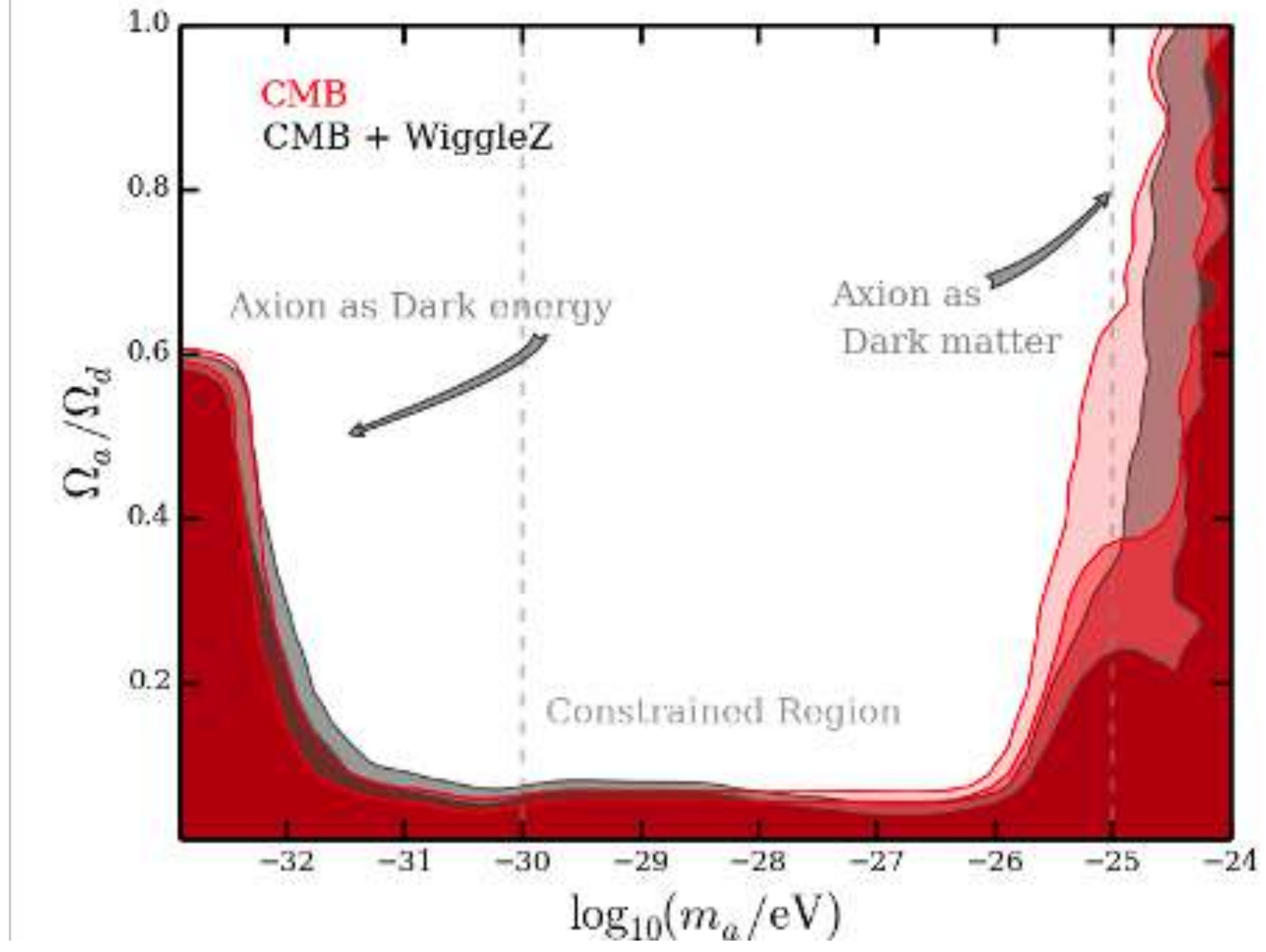


Suppression of small structures

CMB/LSS

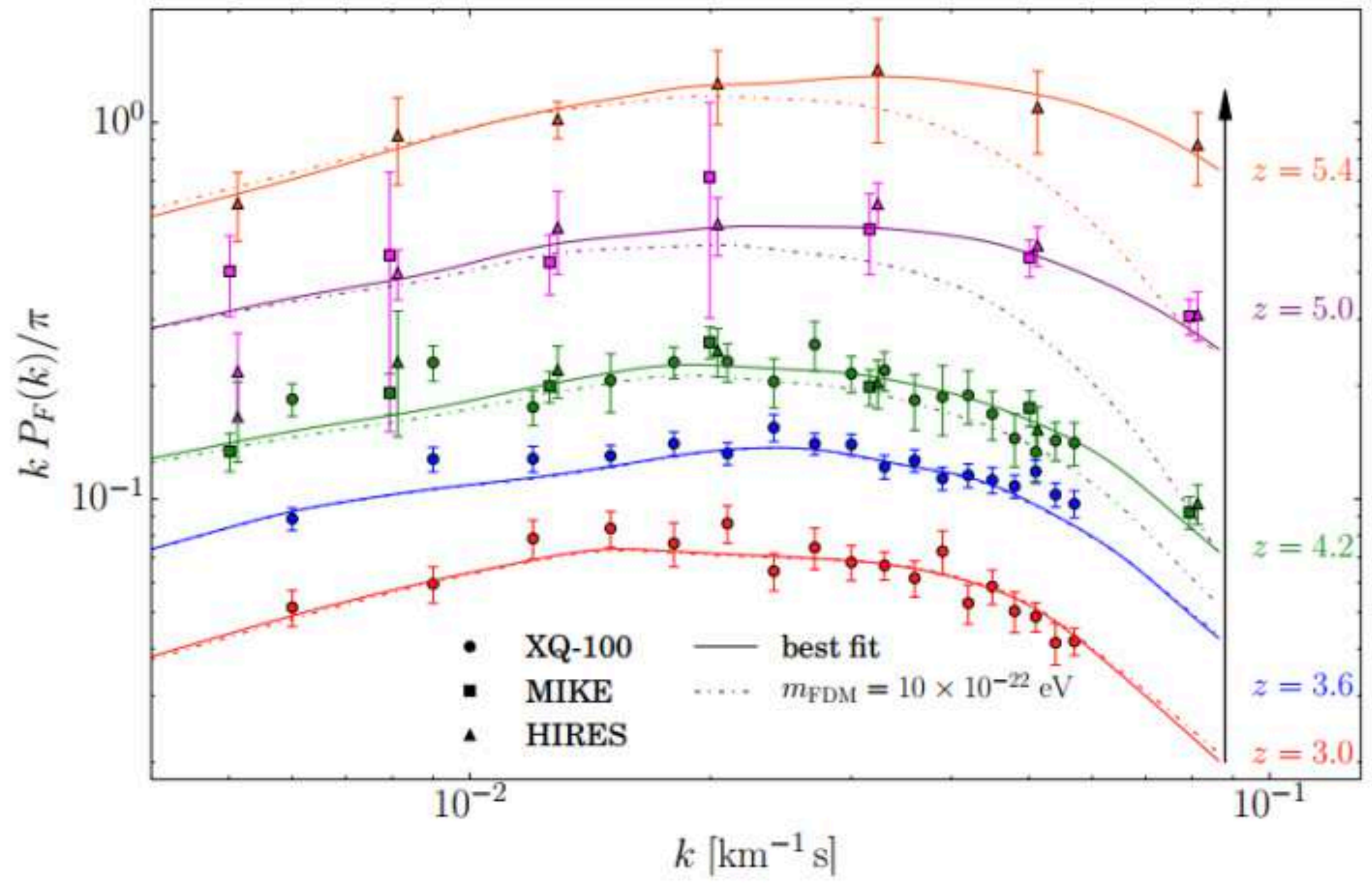
Hlozek et al, (2015, 2018)



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

Lyman alpha

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

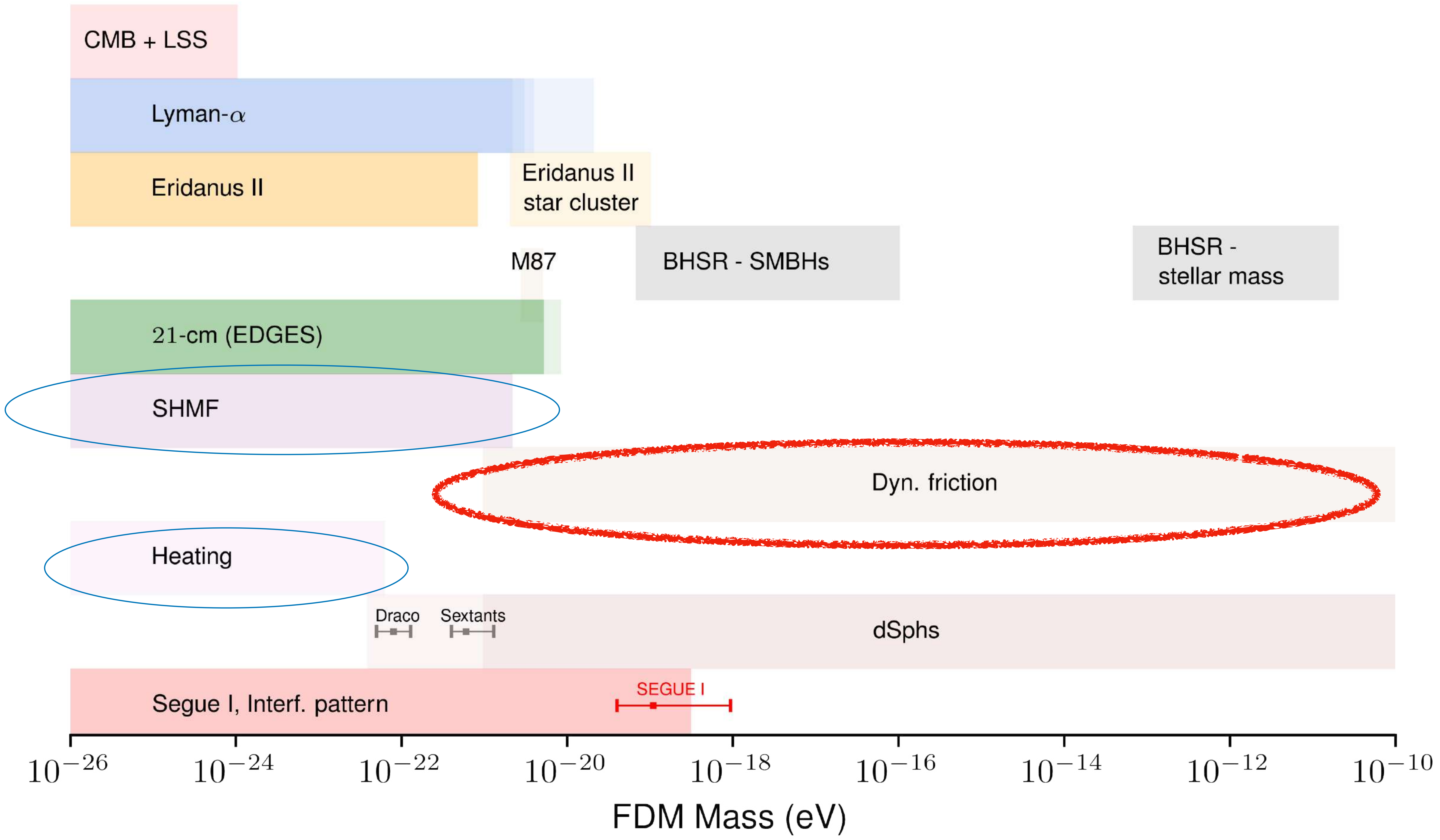


$$m \gtrsim 2 \times 10^{-20}\,\mathrm{eV}$$

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

Observational implications and constraints

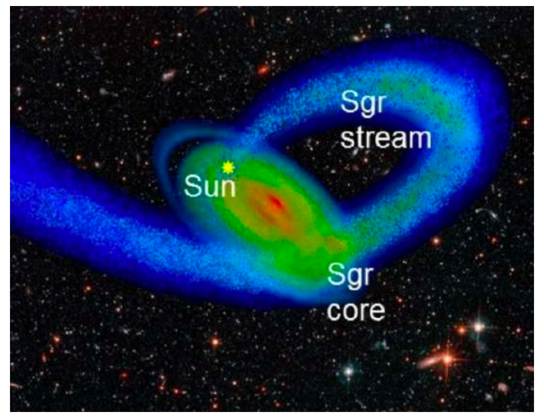
Fuzzy Dark Matter - bounds on the mass



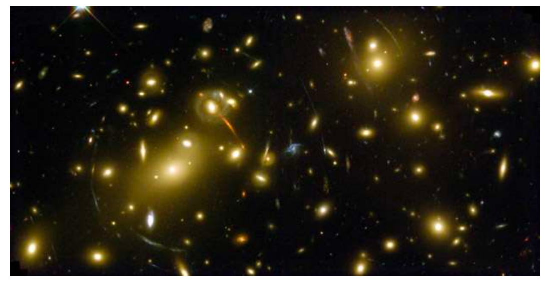
Suppression of small structures

Stellar streams

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



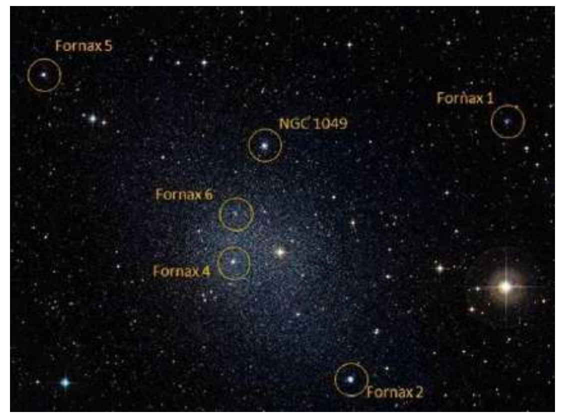
Grav. lensing



Dynamical effects

Globular clusters

$m < 10^{-21}$ eV



ESO/Digitized Sky Survey 2

Lancaster et al. 2020

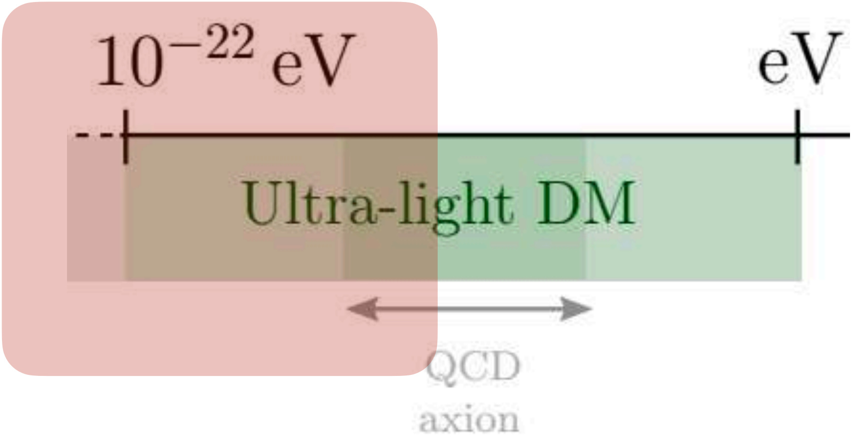
Heating of the MW disk

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

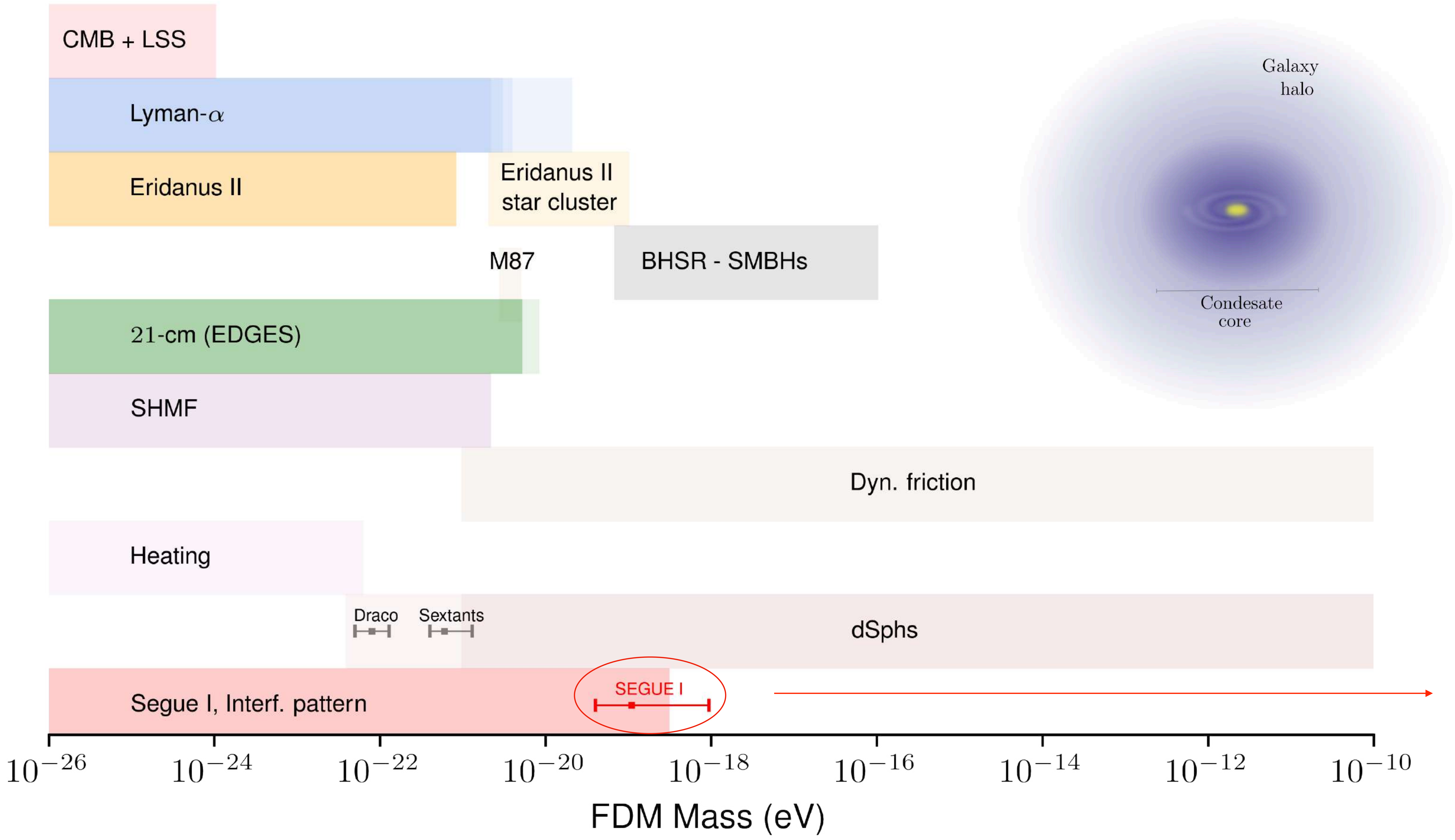
Church et al. 2019

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



Presence of a core



FDM SIMULATIONS

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

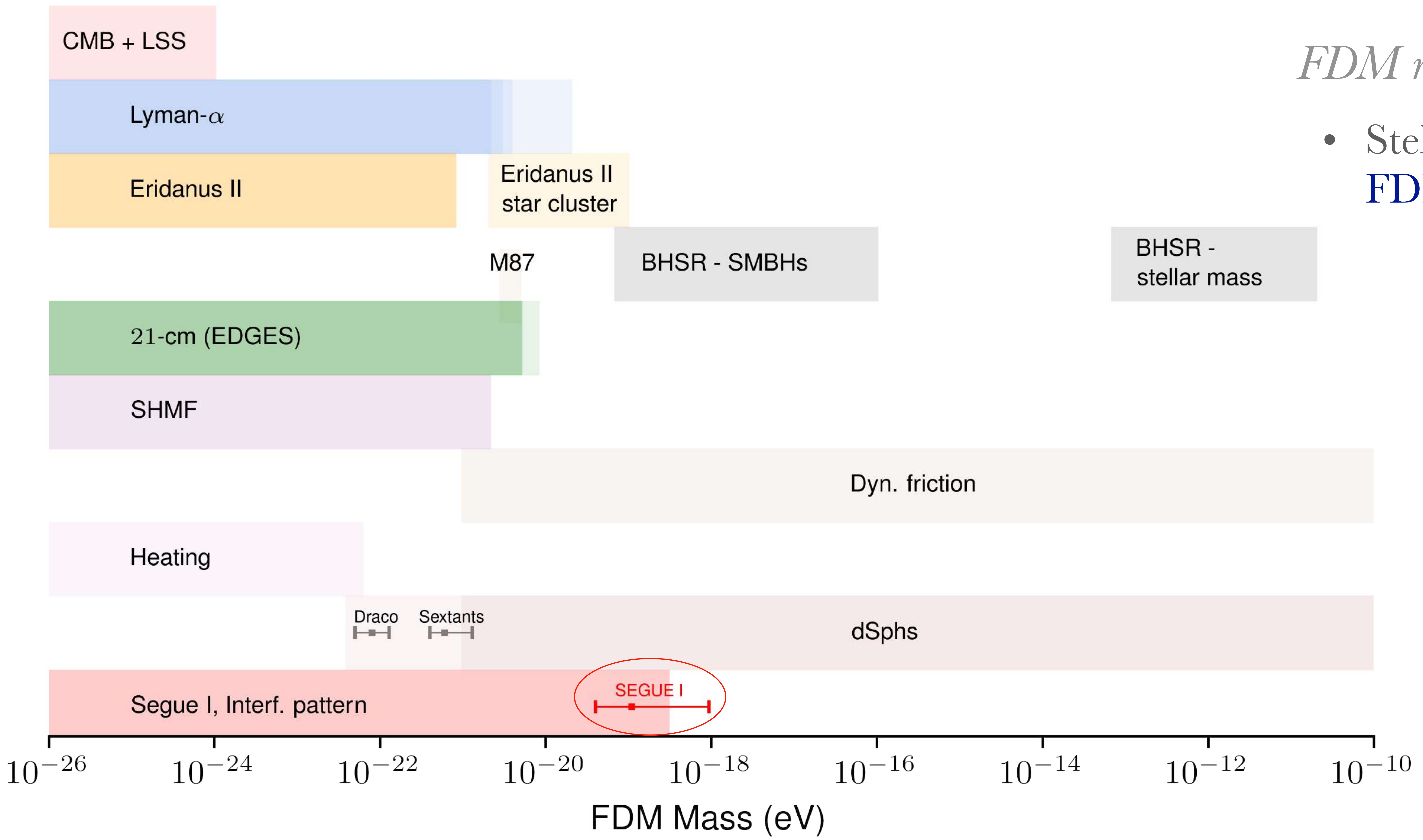
Jeans analysis like presented by Shunichi Horigome and Kohei Hayashi (and Shinichiro Ando)

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

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass

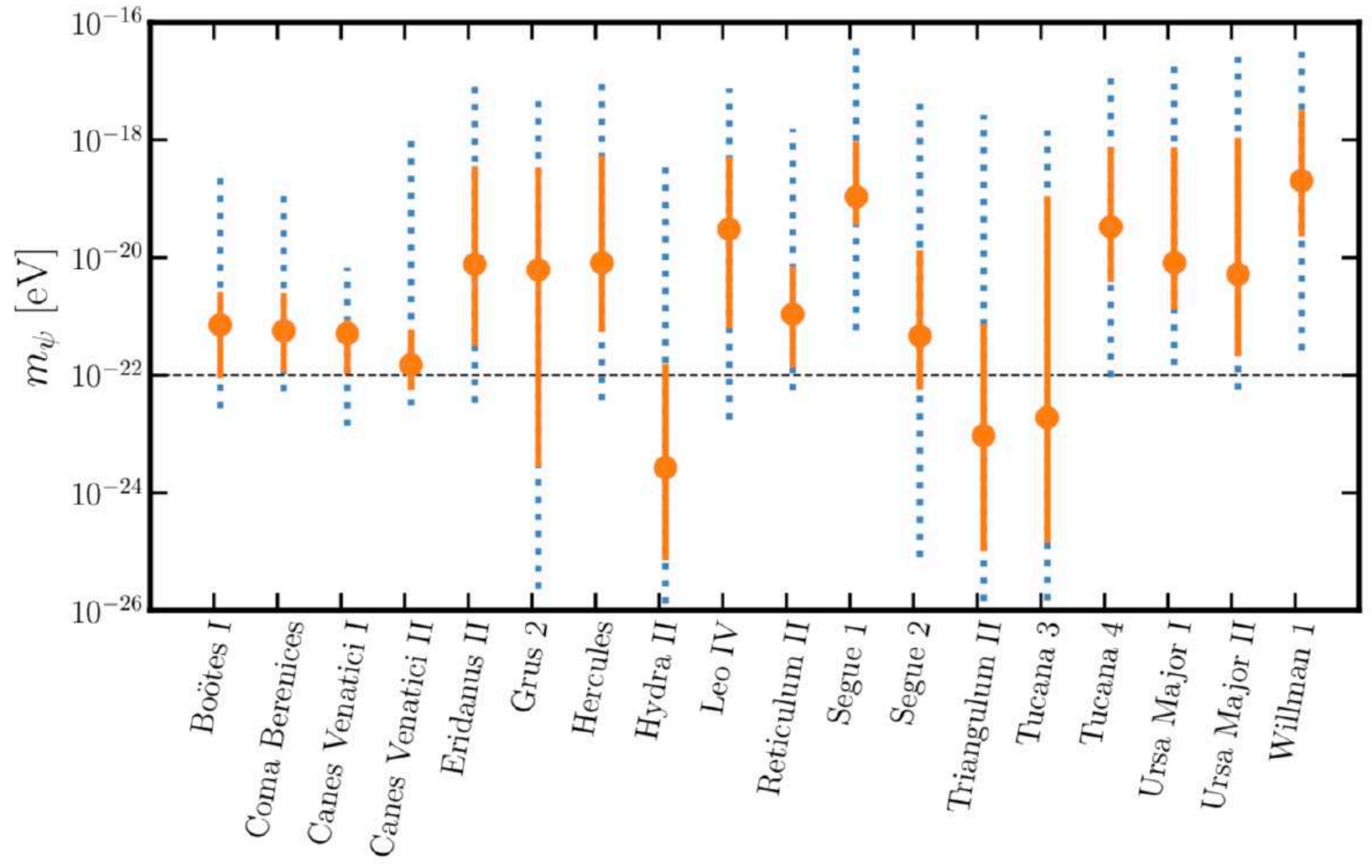
Hayashi, **E.F**,Chan, 2021.



FDM mass from Ultra-faint dwarfs

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

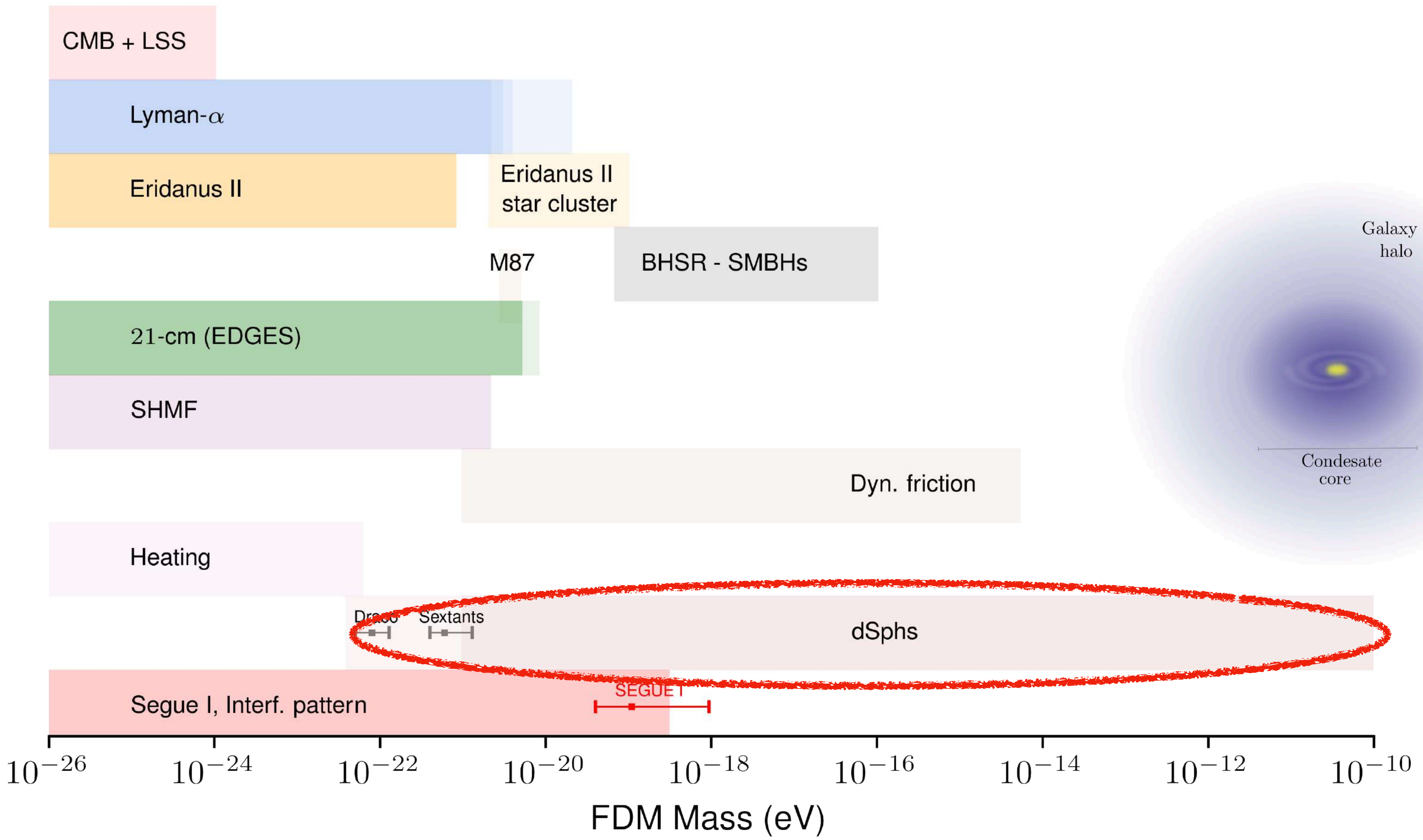
$$m_{\rm FDM}^{(Seg1)} = 1.1^{+8.3}_{-0.7} \times 10^{-19}\,\text{eV}$$



Preference for higher mass

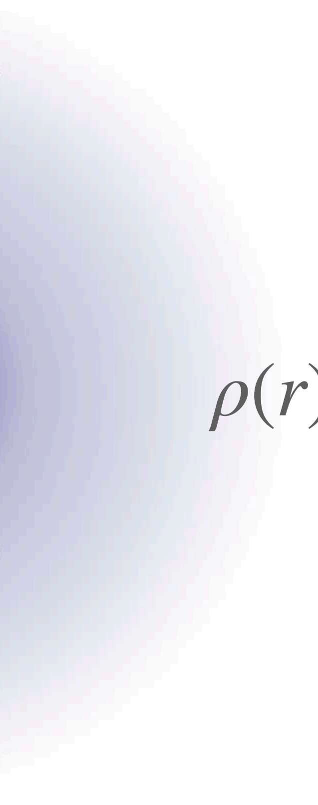
Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



DWARFS

Dwarf Spheroidals (dSphs)



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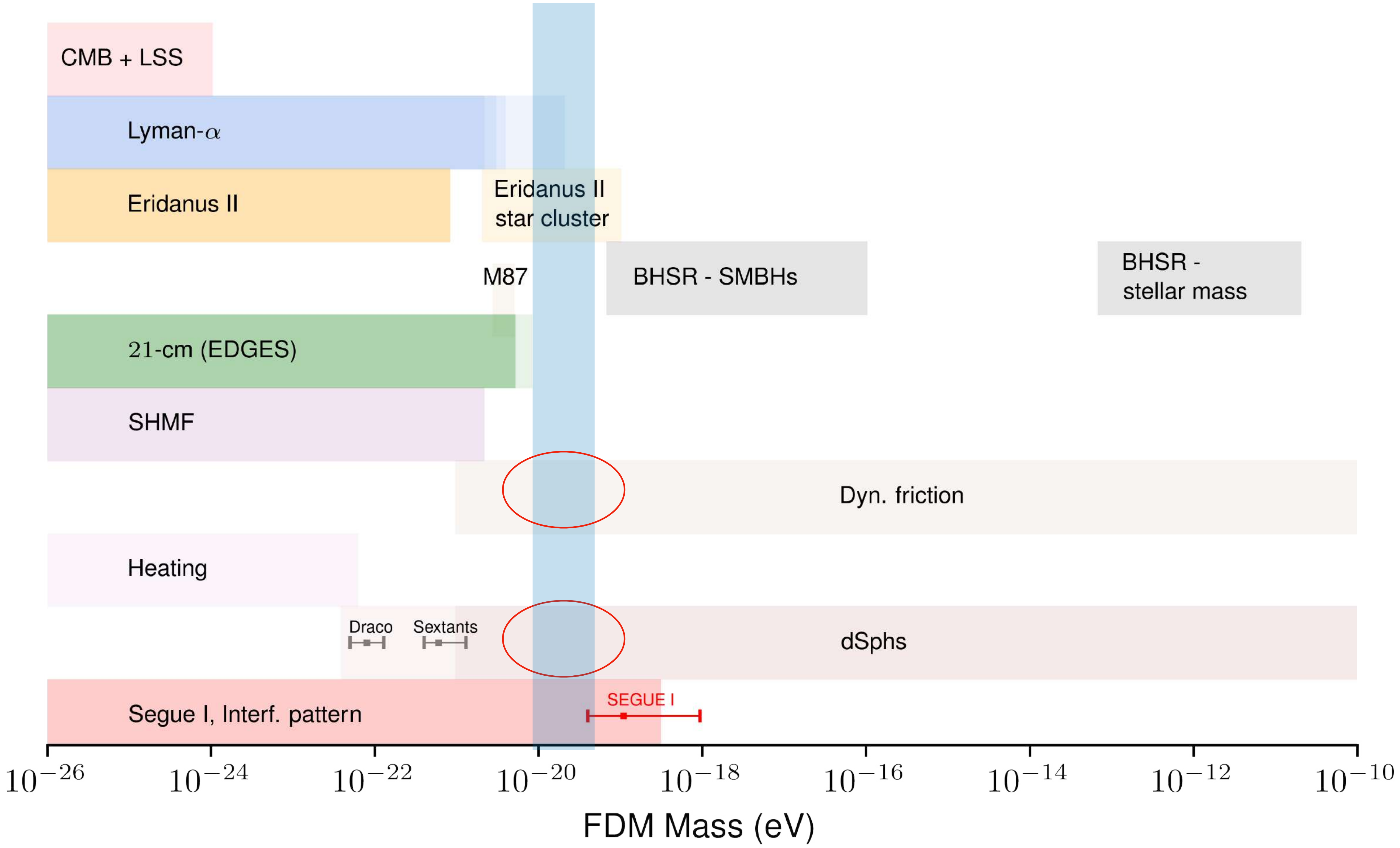
Fornax - Sculptor

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

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

Constraints on the mass



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

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

Possible reasons for this incompatibility:

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

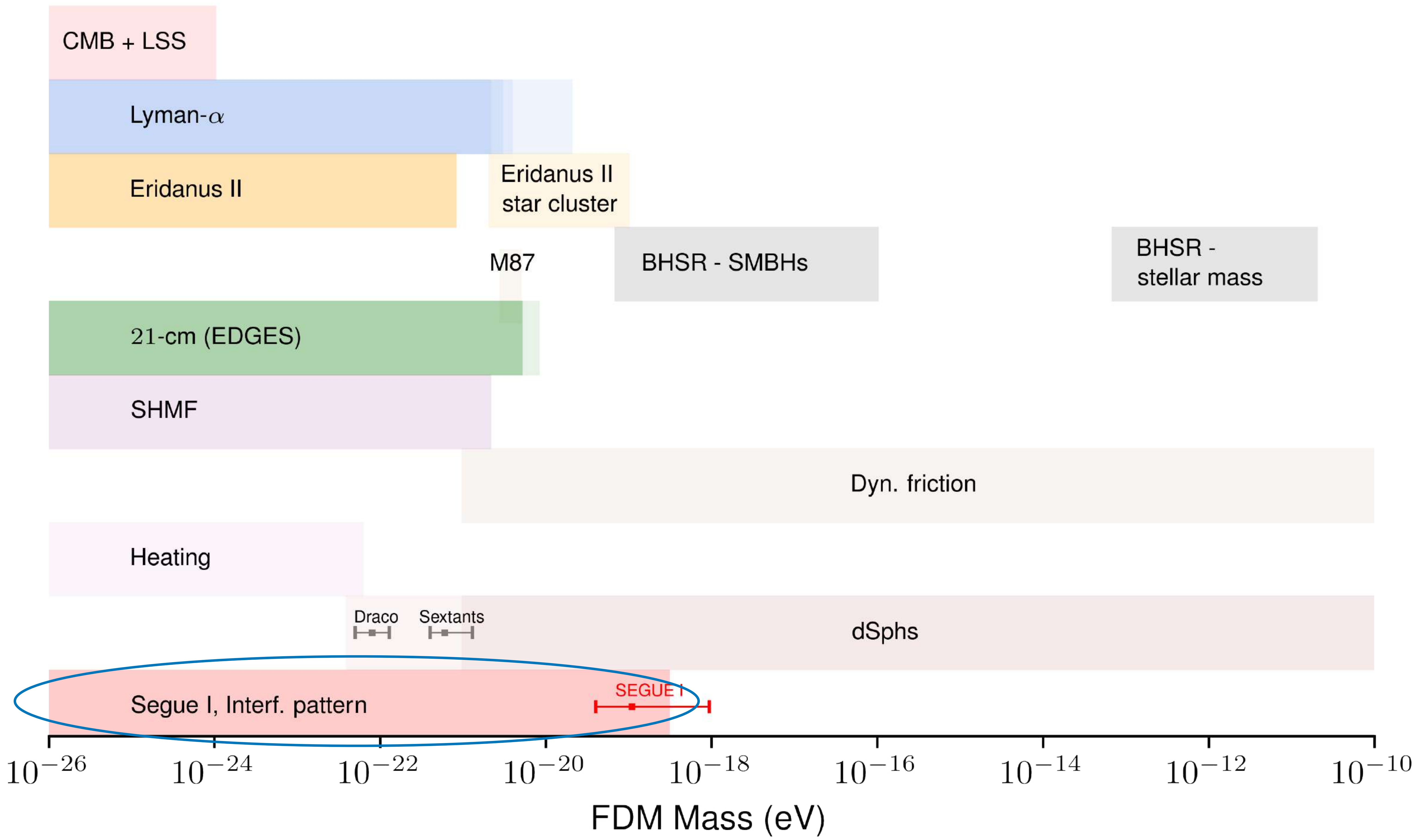
Jowett Chan's and Masashi Chiba's talks!

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

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

Shinichiro Ando's presentation



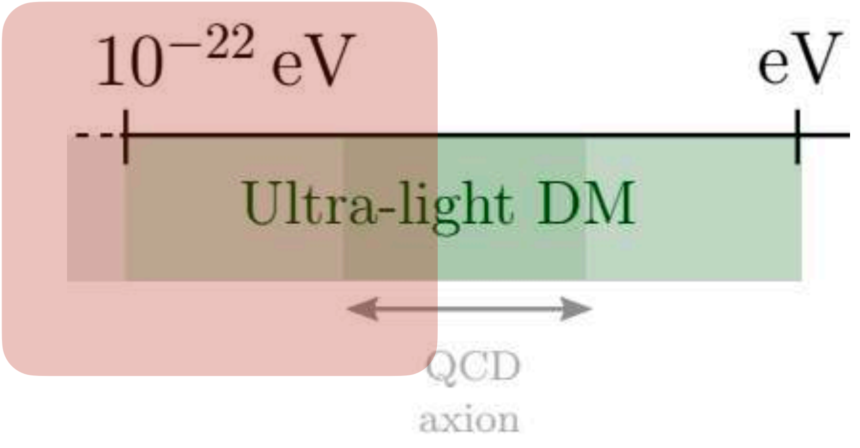
INTERFERENCE PATTERNS

N. Dalal, A. Kravtsov, 2203.05750

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

Current status

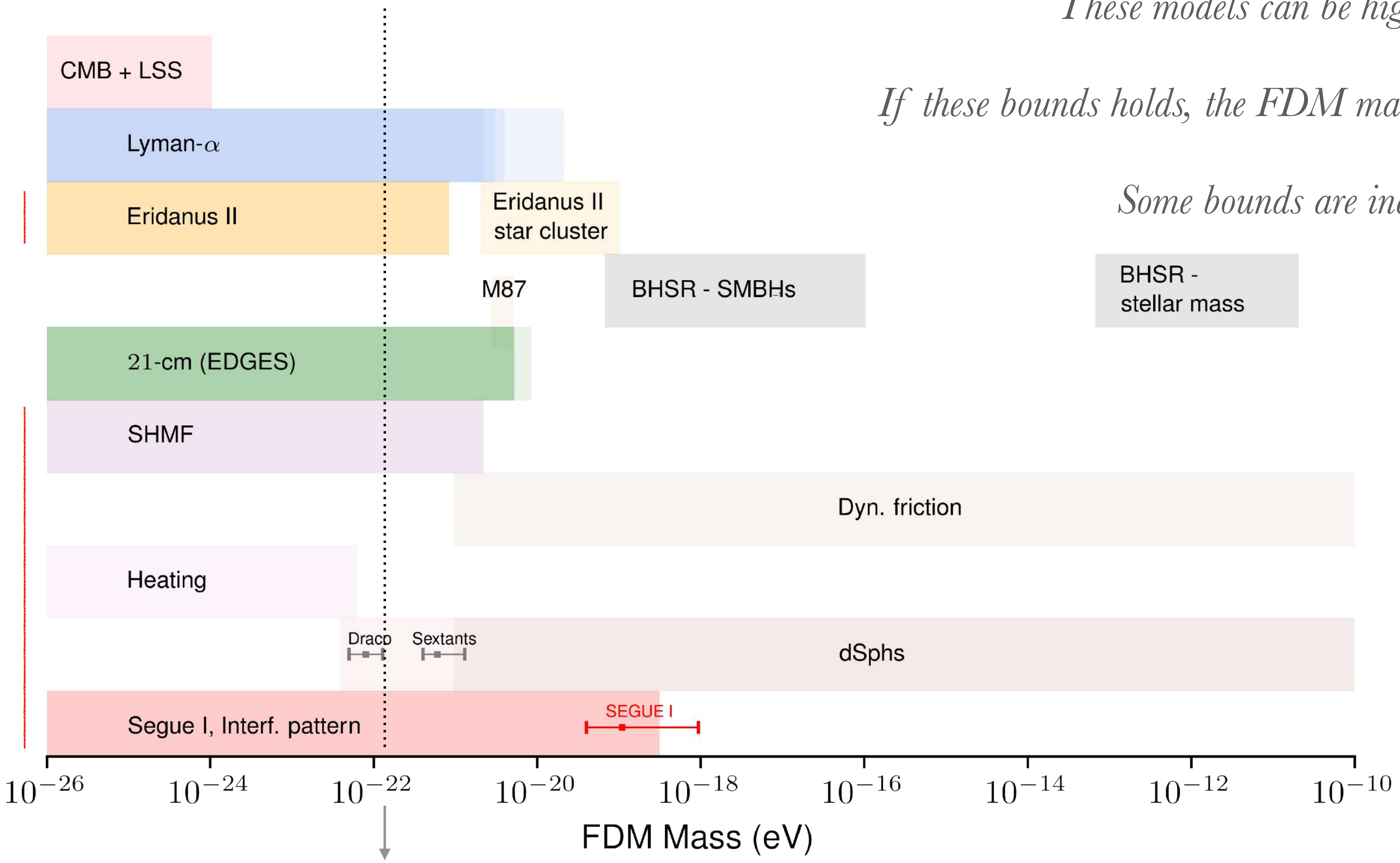
Fuzzy Dark Matter - bounds on the mass



These models can be highly constrained

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

Some bounds are incompatible!



Sweet spot for solving small scale problems

BUT: systematic effects!!

Need:

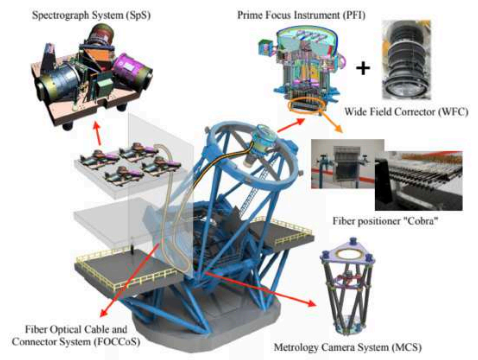
- Observations
- Improve sims
- New observables
- New probes

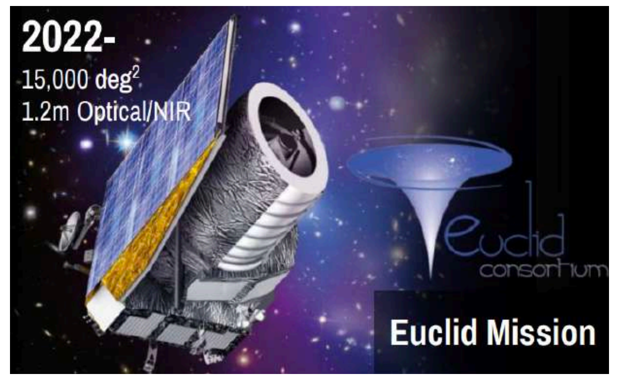
FUTURE

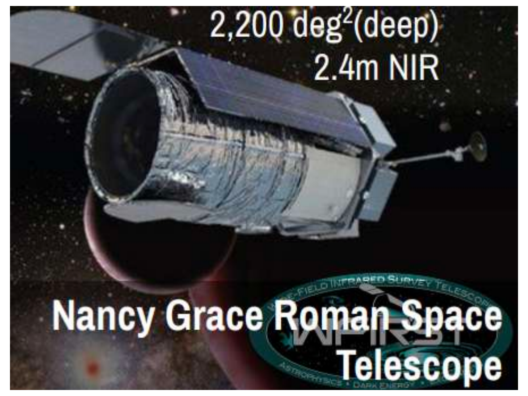
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)







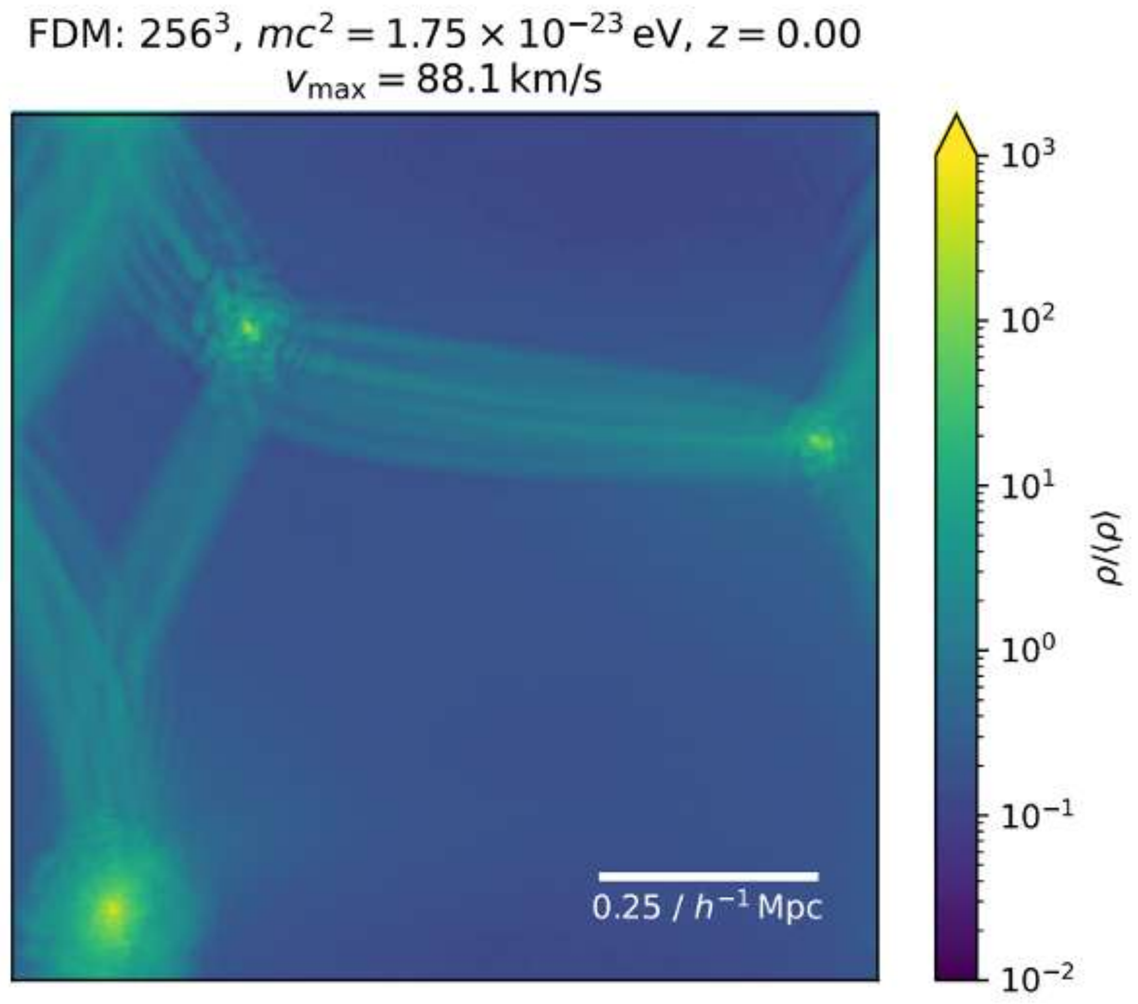
CMB

CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New observables

Ex.: - interference pattern
- vortices

New probes

Sub-galactic power spectrum

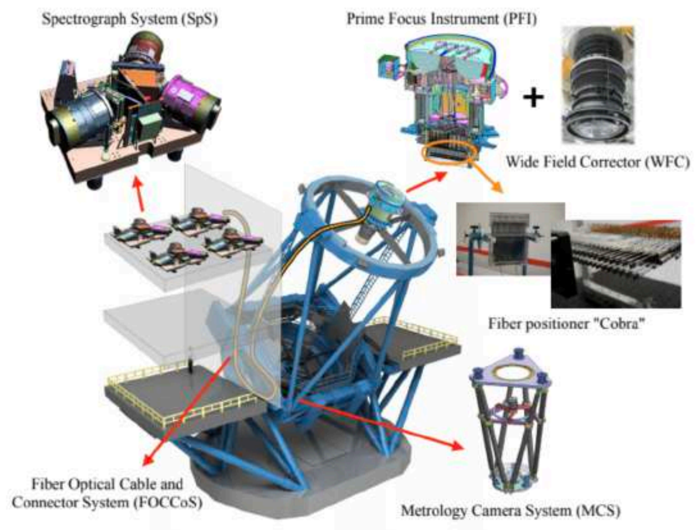
Modified from Jia Liu

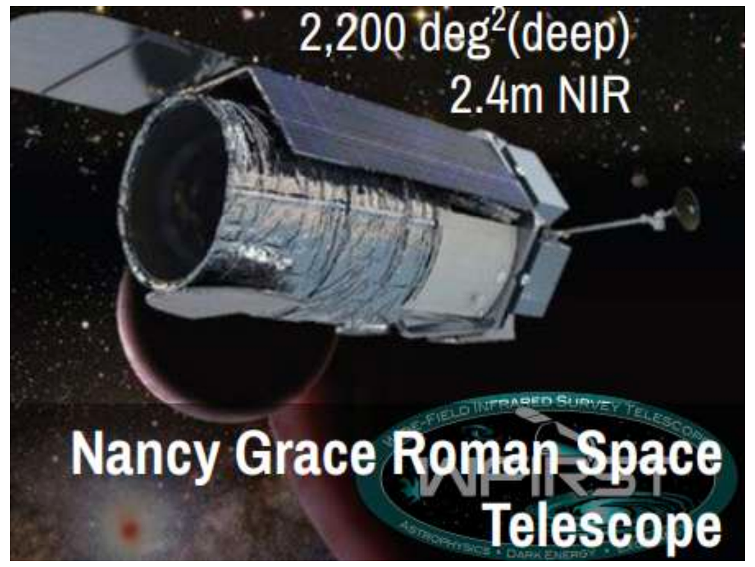
Future - signals in cosmology

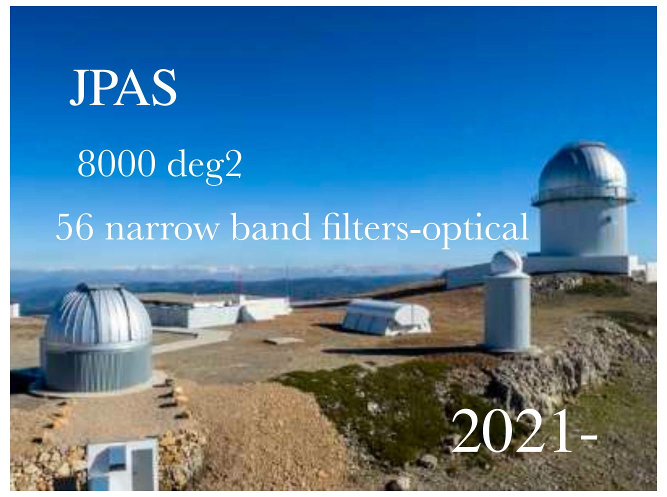
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)

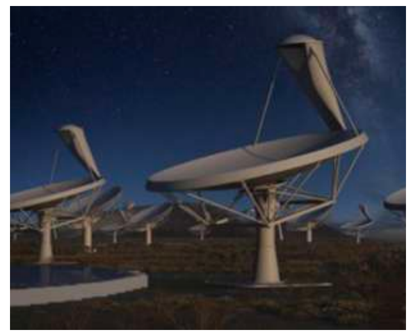






GWs

21cm



SKA
SQUARE KILOMETRE ARRAY

CMB

2021
16,000 deg^2
6μK-arcmin
27-280GHz

SIMONS OBSERVATORY

CMB-S4
Next Generation CMB Experiment

Modified from Jia Liu

PFS (Prime Focus Spectrograph)

B02 group (Subaru spectroscopy)

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

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

PFS - Galactic Archaeology

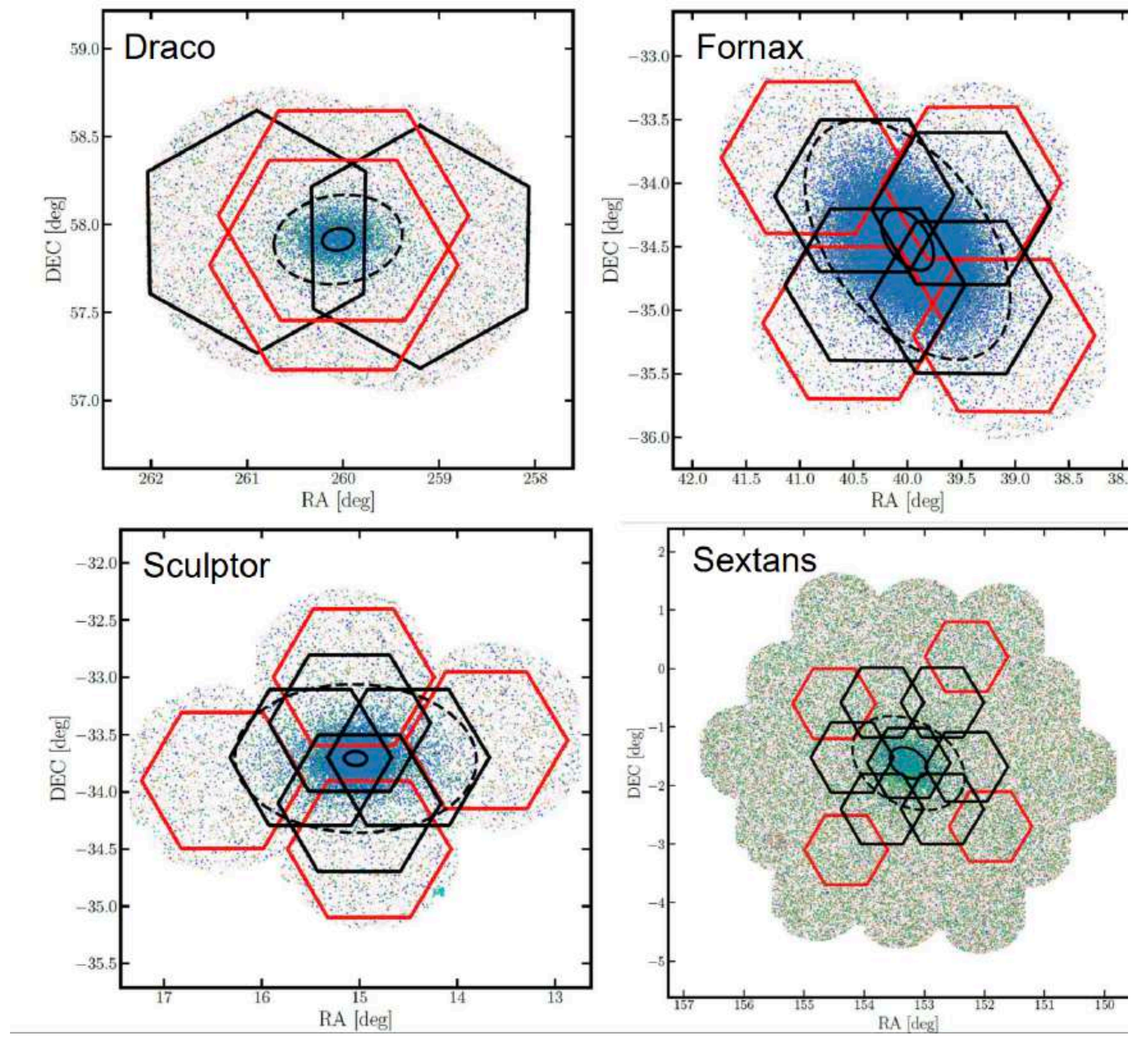
B02 group (Subaru spectroscopy)

TESTING ULTRA LIGHT DM/DM with PFS

Galaxy archeology

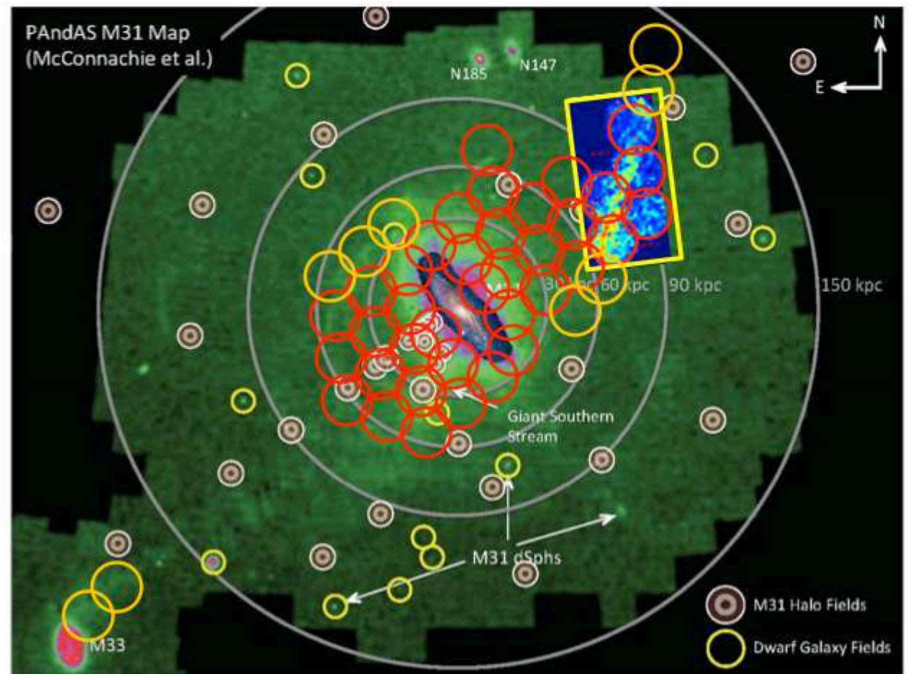
- Nature of DM (dSphs)
- Structure of MW dark halo
- Streams
- Stellar kinematics and chemical abundances – MW & M31

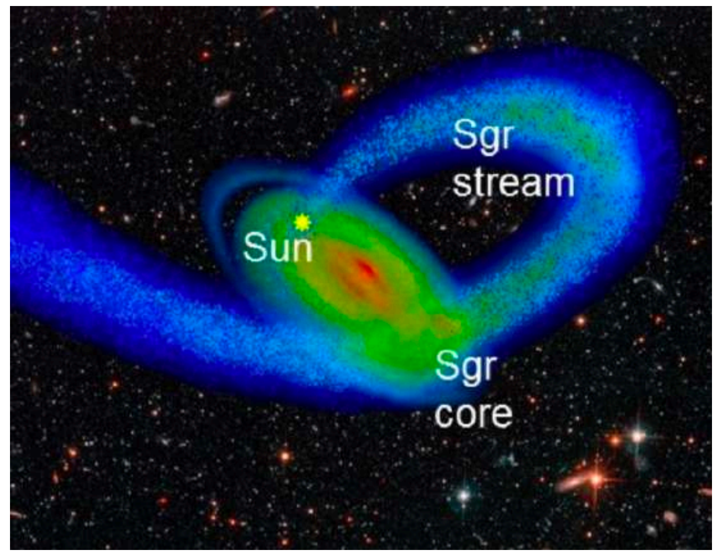
Wide & deep survey of MW dwarf galaxies w. Subaru/PFS



dSphs

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

PFS - Galactic Archaeology

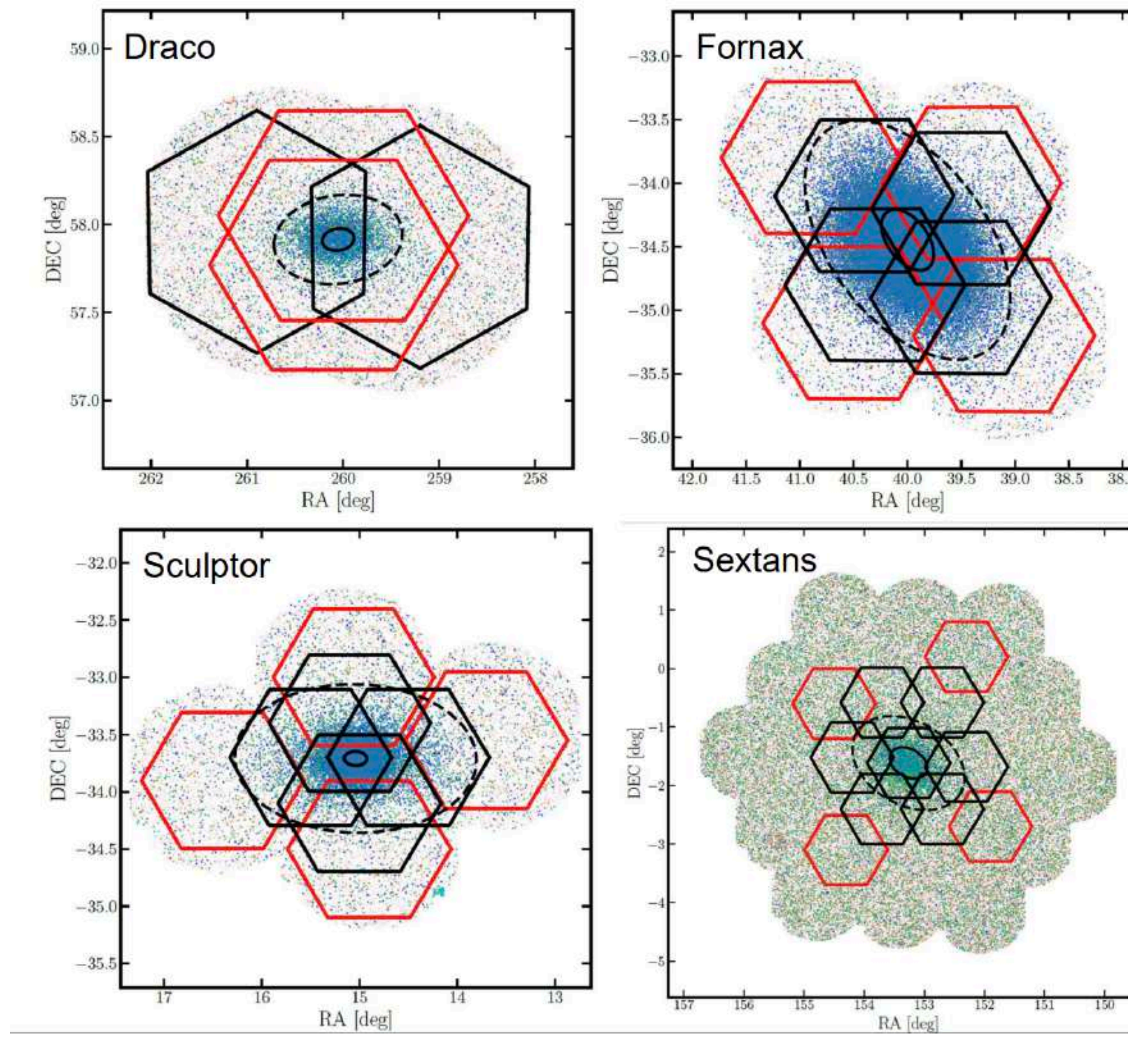
B02 group (Subaru spectroscopy)

TESTING ULTRA LIGHT DM/DM with PFS

Galaxy archeology

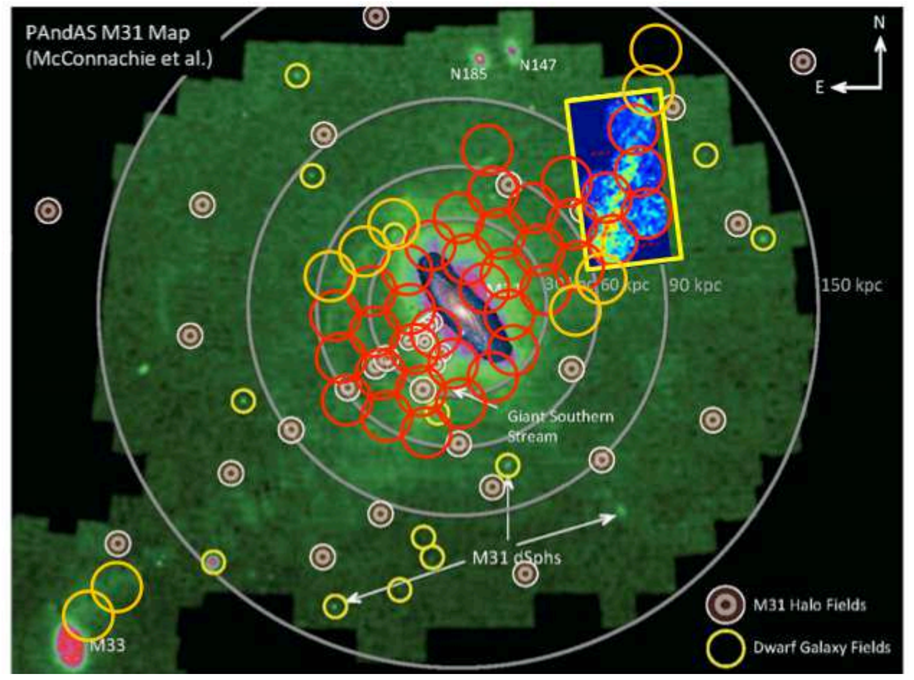
- Nature of DM (dSphs)
- Structure of MW dark halo
- Streams
- Stellar kinematics and chemical abundances – MW & M31

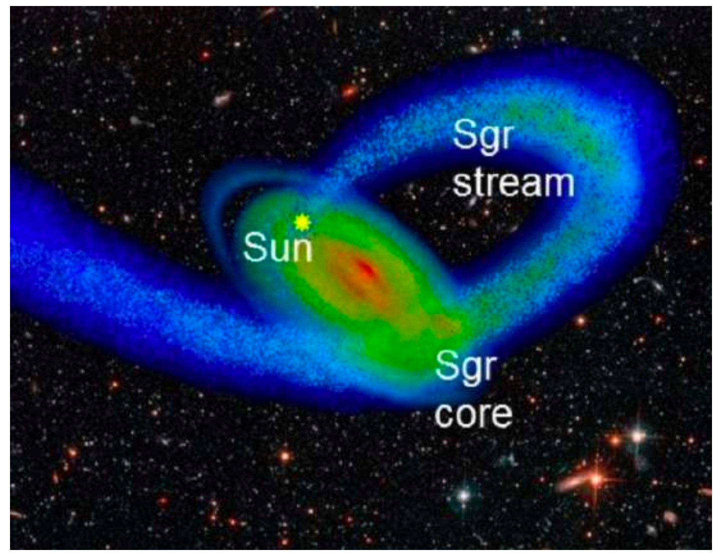
Wide & deep survey of MW dwarf galaxies w. Subaru/PFS



dSphs

M31





MW outer disk

<u>Dwarf galaxies</u>:

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

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

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

(4) Abundance measurements

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

<u>Stelar streams</u>

GA ⟶ potential to put unprecedented constraints on ULDM.

SSP proposal

PFS - *Galactic Archaeology*

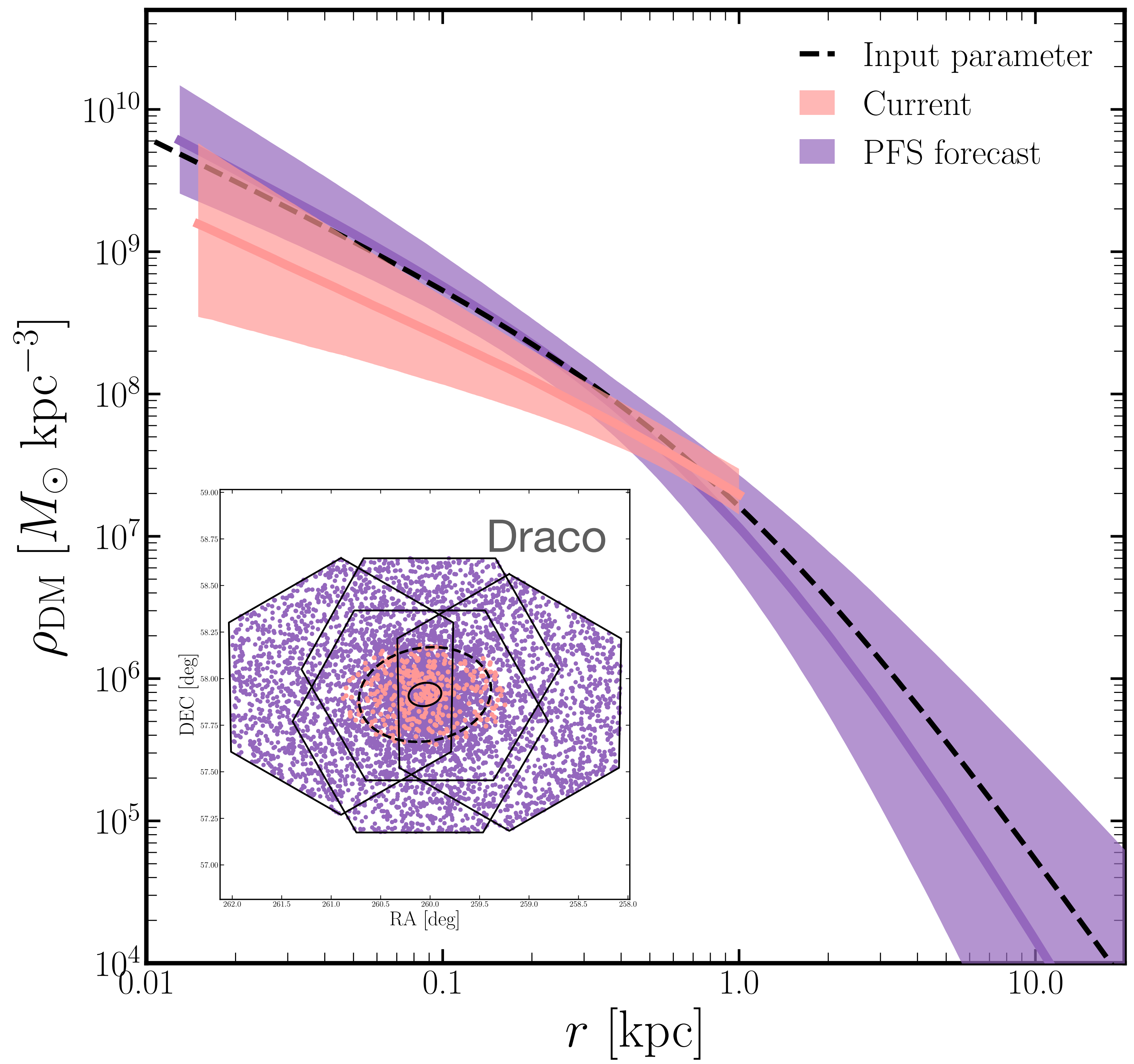
B02 group (Subaru spectroscopy)

DM searches with PFS-GA

Leader: Kohei Hayashi

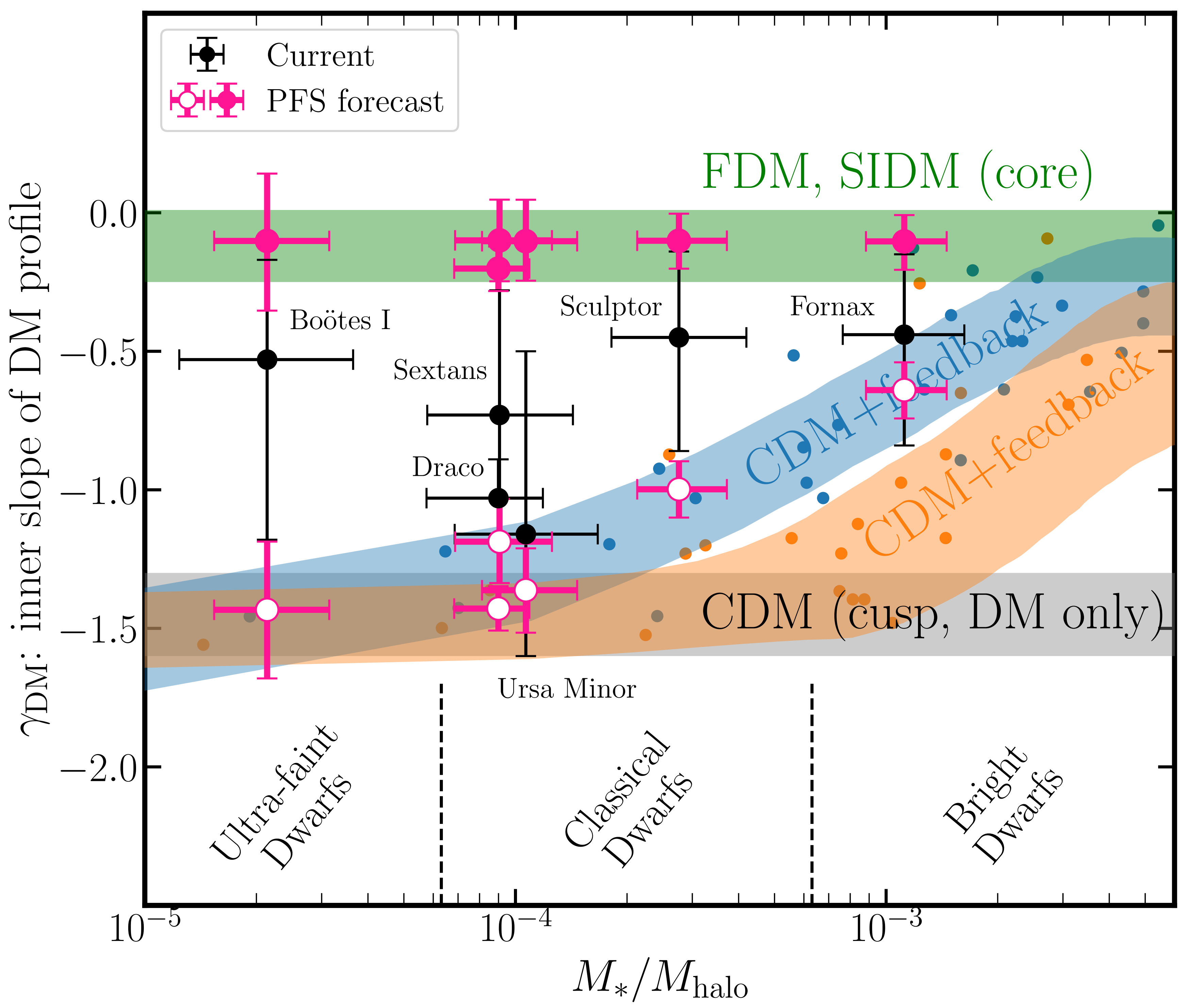
Figures by Kohei Hayashi

Dark matter density profile



"Current" (N = 500) and "PFS forecast" (N = 5, 000 stars) samples

Inner dark-matter density profile slope derived for PFS-GA selected sample of dSphs vs. their stellar-to-halo mass ratio



Adapted from Kohei Hayashi, Masashi Chiba, Tomoaki Ishiyama, ApJ (2022)

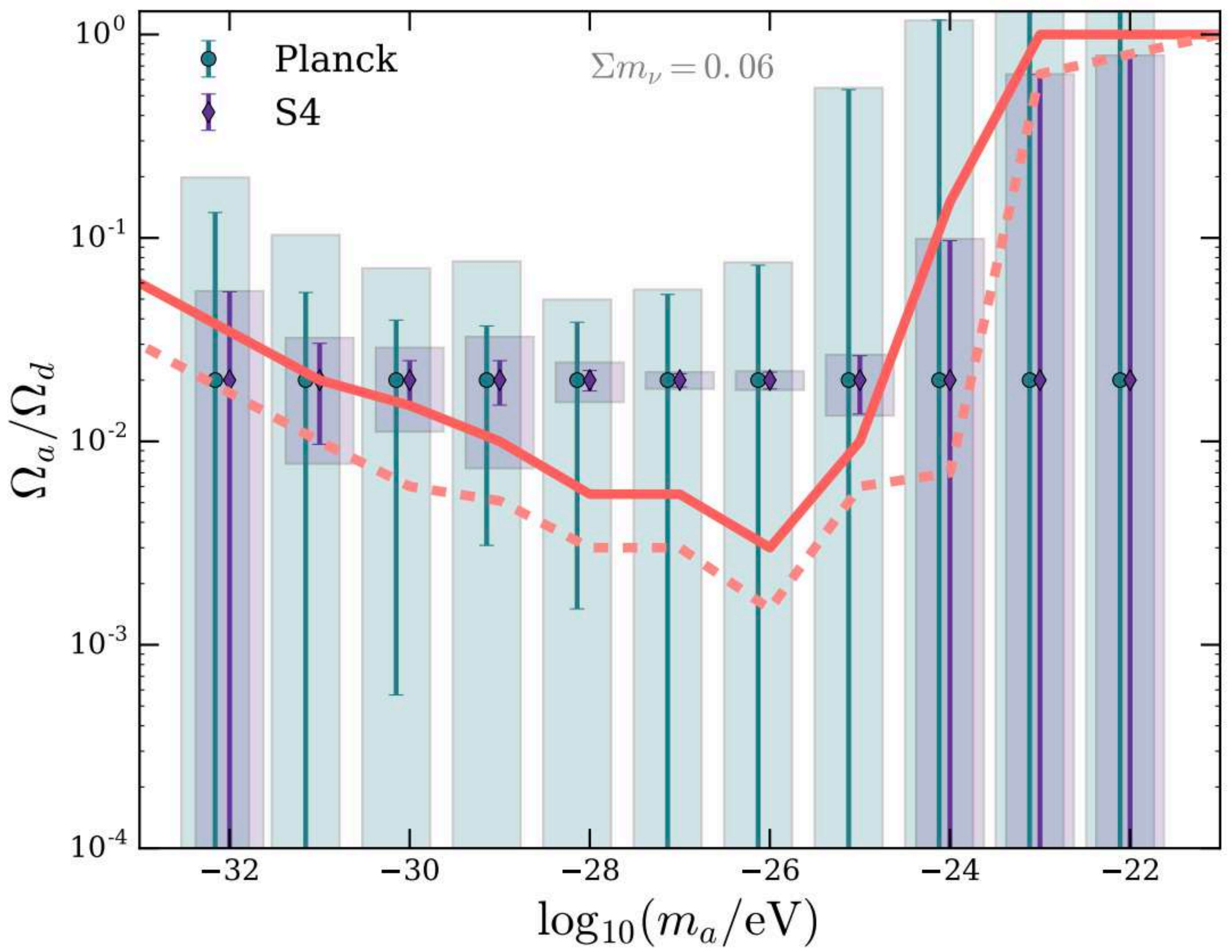
Future - *Cosmic Microwave Background*

CMB working group

TESTING ULTRA LIGHT DM CMB

CMB - S4

Constraints on Ω_a/Ω_d



Hlozek et al., 2016

Significantly improve constraints on the composition of the dark sector!

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

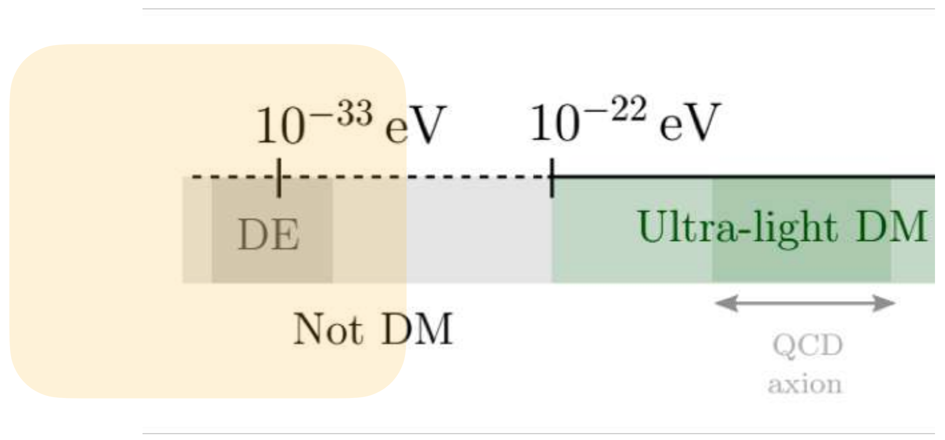
Constraint the ULDM mass

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

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

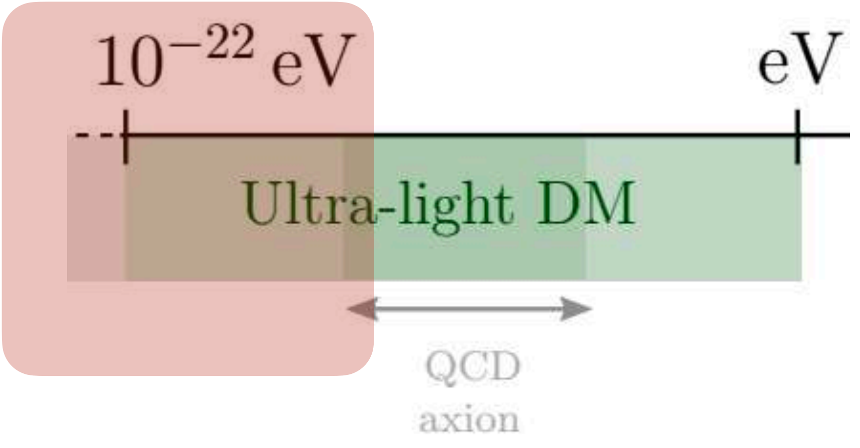
Cosmic Birefringence

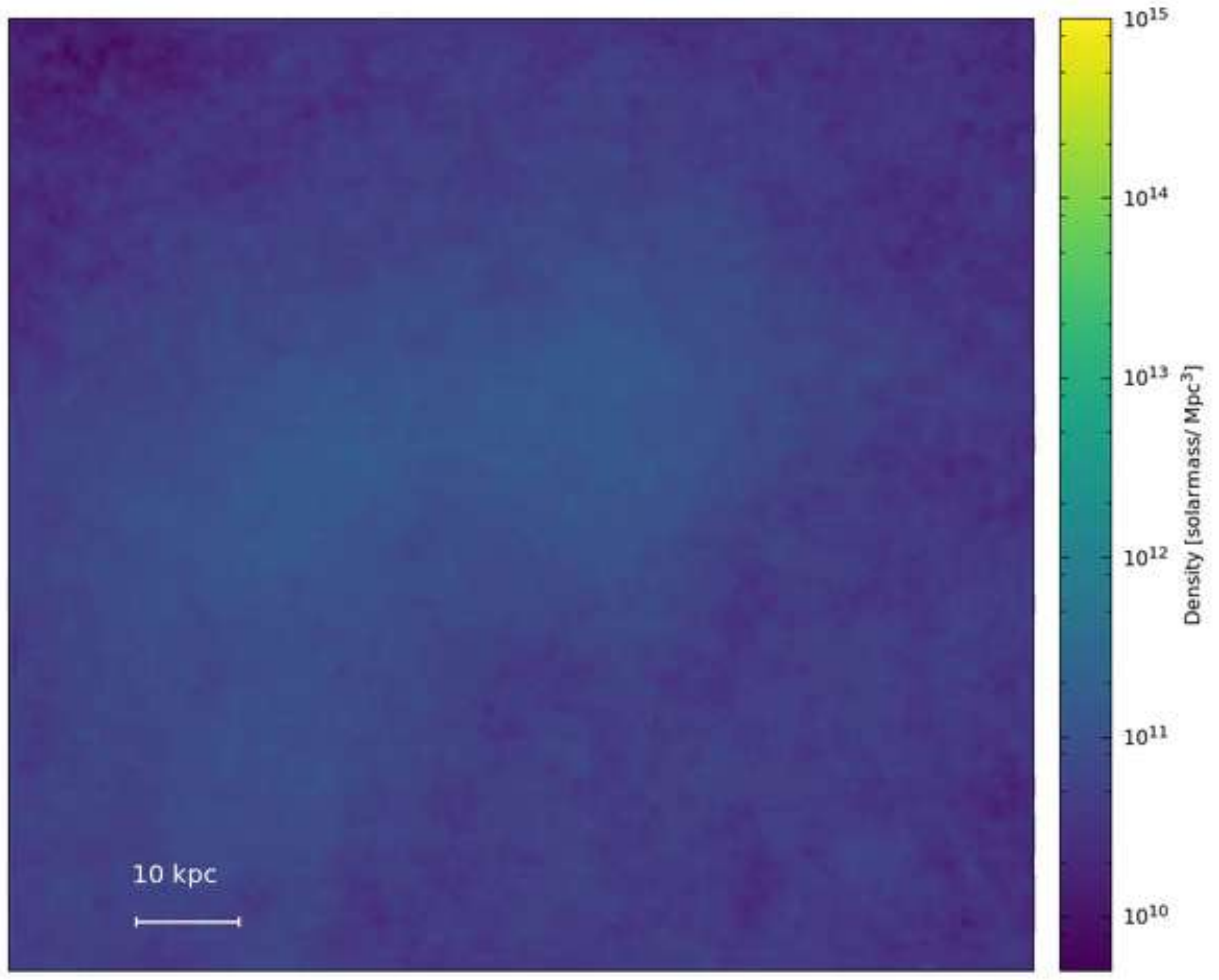
CMB and light DM groups' talks!



New probes

Interference pattern





Simulation by Jowett Chan

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

Constructive interference: granules
Destructive interference

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

ONGOING — *In collaboration with Jowett Chan and Simon May*

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

Previous studies:

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

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

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

Sub-galactic power spectrum
Kawai, Oguri (2021) — *M. Oguri's talk!*

Dwarfs
N. Dalal, A. Kravtsov, 2022


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

New probes

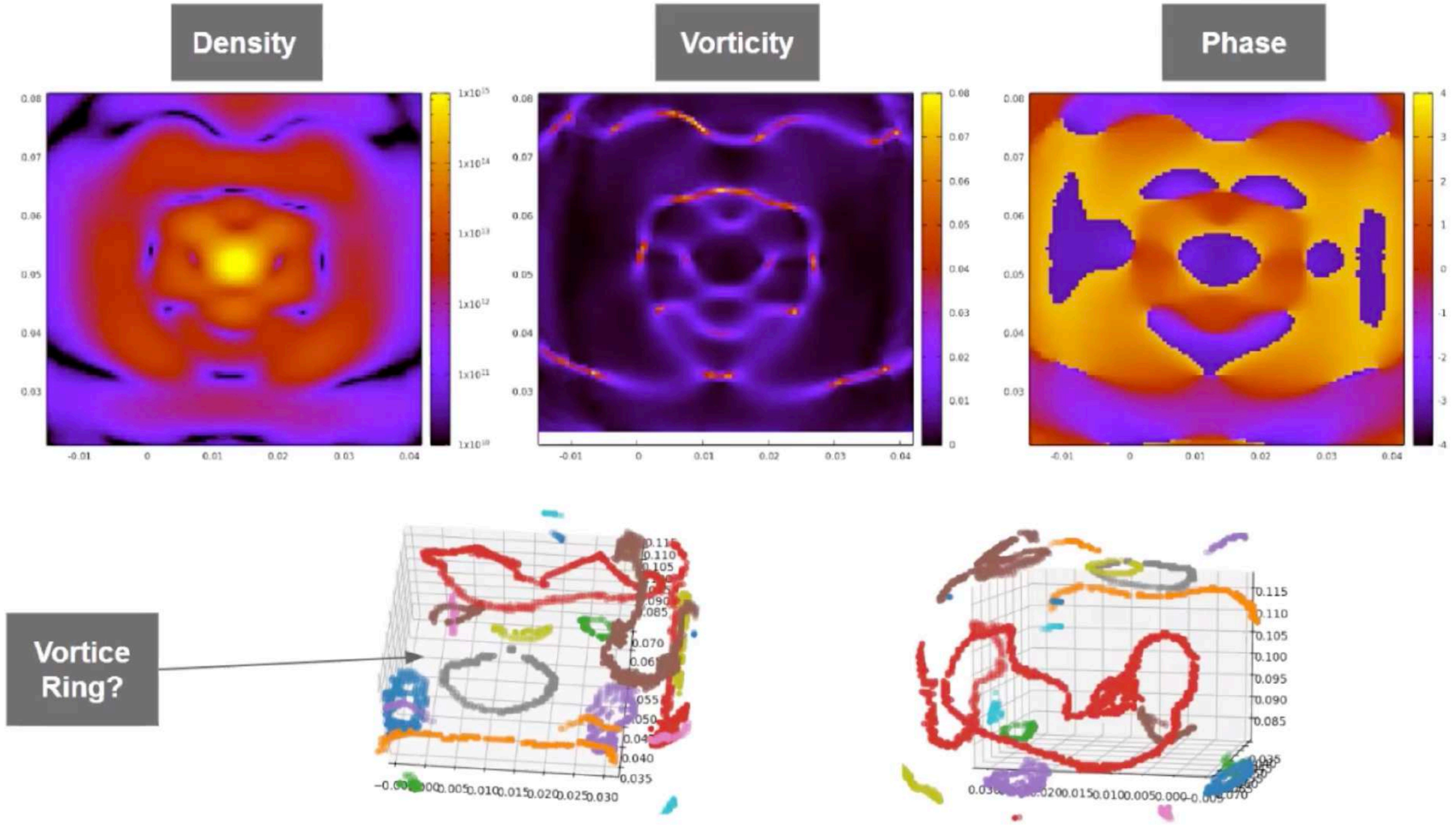
Ongoing: *Vortices*

PRELIMINARY

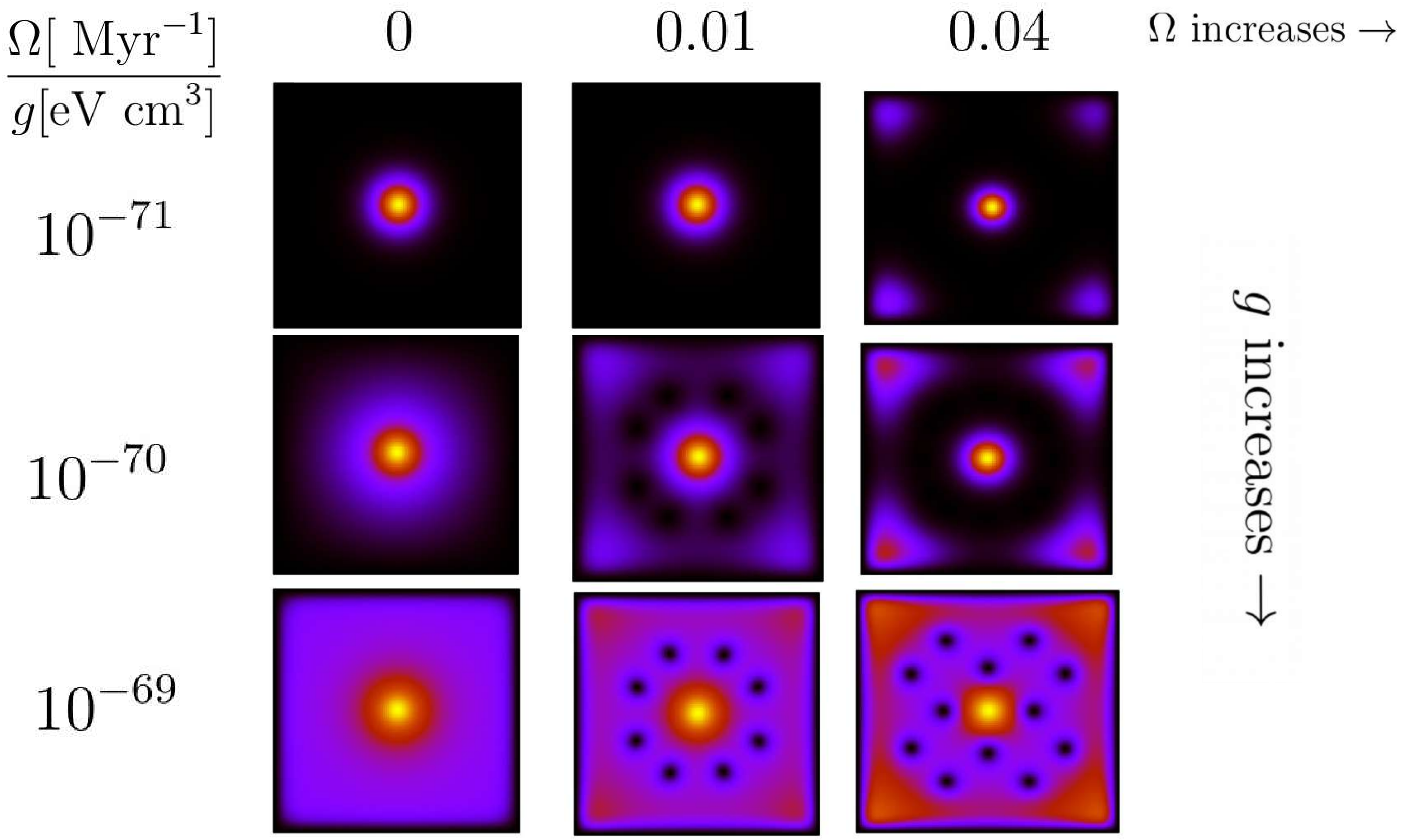
In collaboration with Jowett Chan
(some aspects with Noam Libeskind and S. May)

Might be interesting to the C02 (simulation) group!

Fuzzy DM



Self-interacting Fuzzy DM



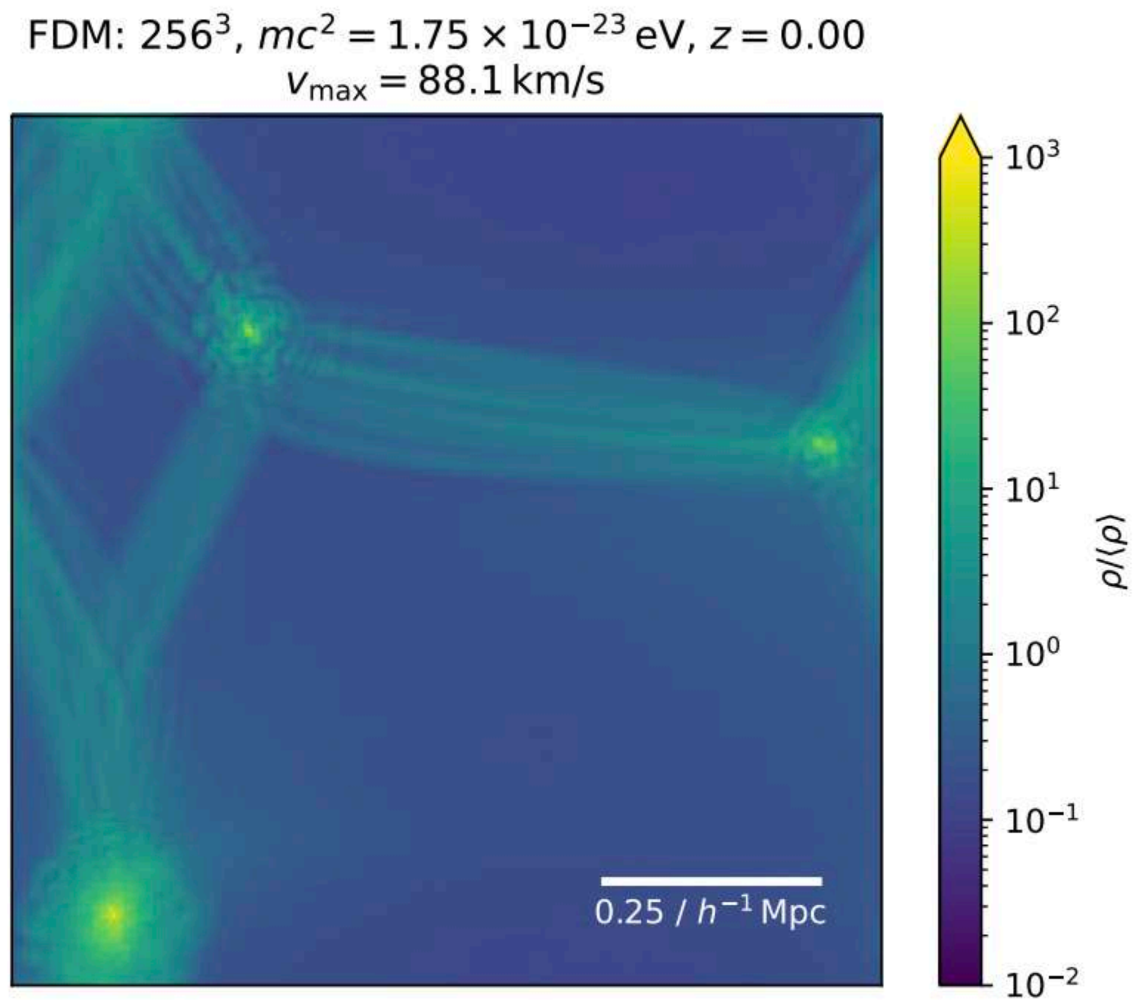
\+ Improve theoretical understanding of these DM vortices

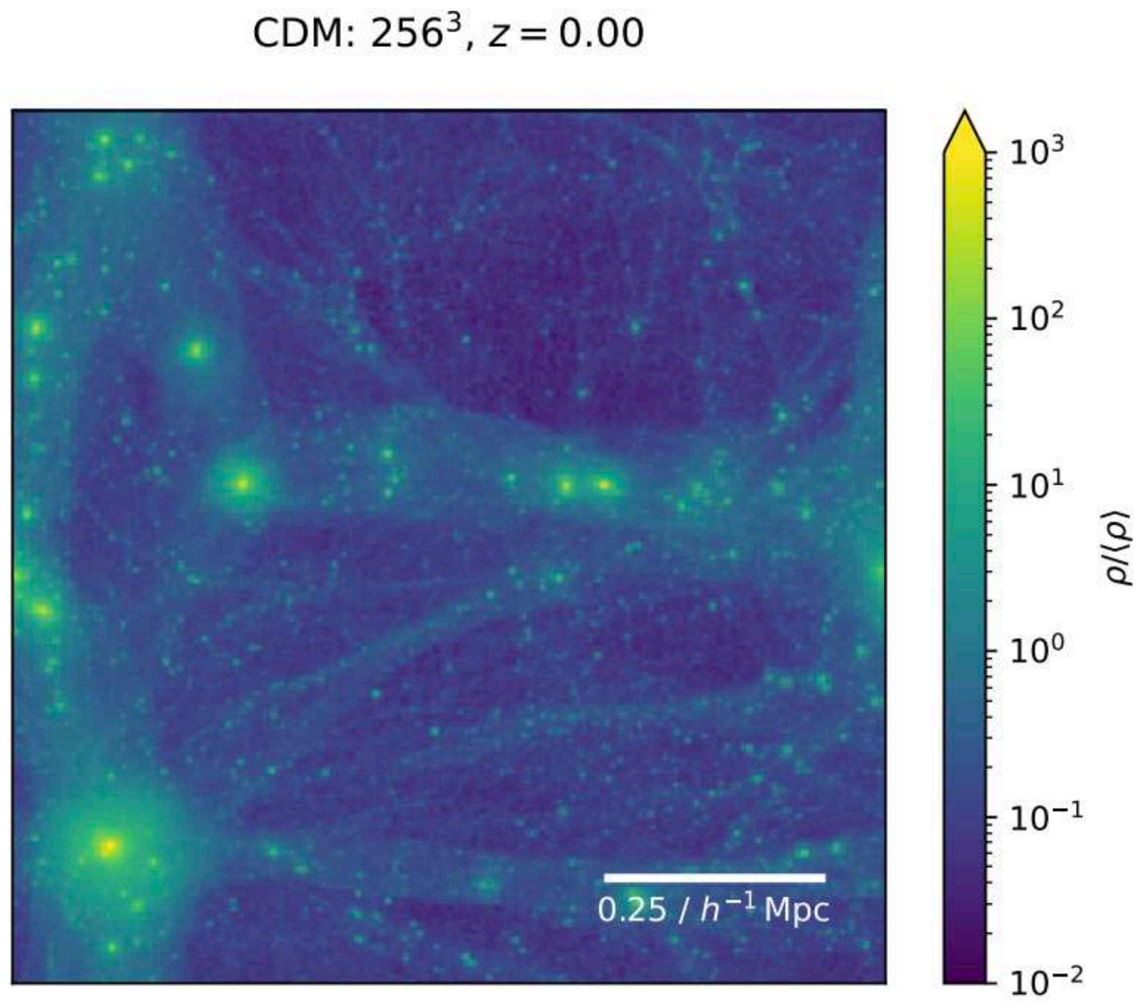
In collaboration with P. Bittar

Might be interesting to the A01 (light DM) group!

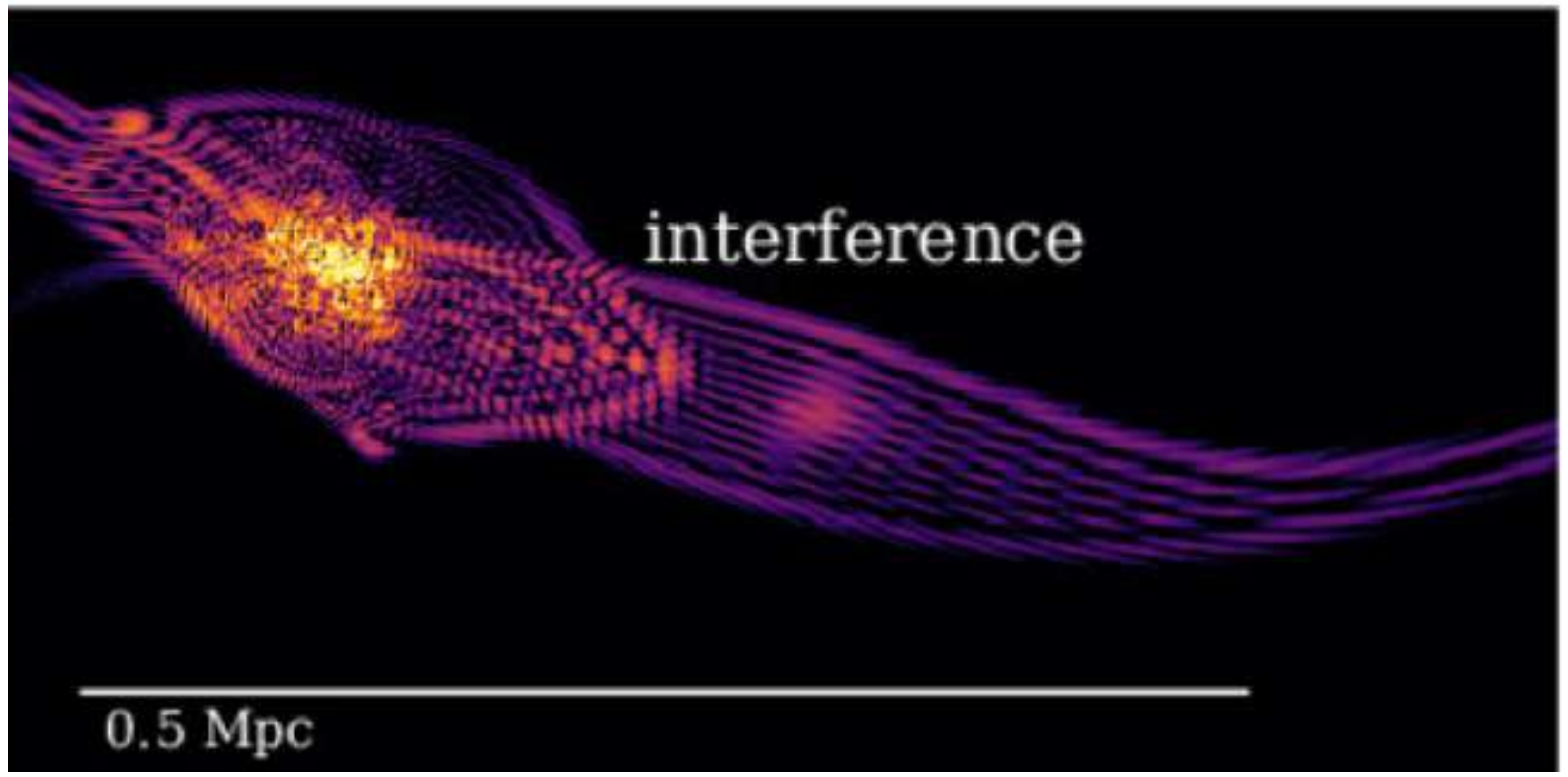
New probes

Filaments in FDM





S. May et al. 2021



Mocz et al. 2017

Vortices in filaments

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

Simulations of ULDM

Very challenging!

Might be interesting to the C02 (simulation) group!

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

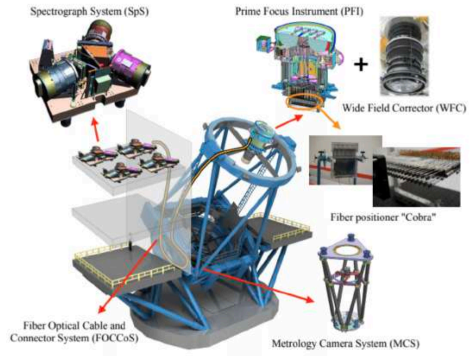
(See works from S. May & V. Springel, L. Hui, Veelmat, Niemeyer & Schwabe, Schive, Chiueh & Broadhurst, Mocz et al., …)

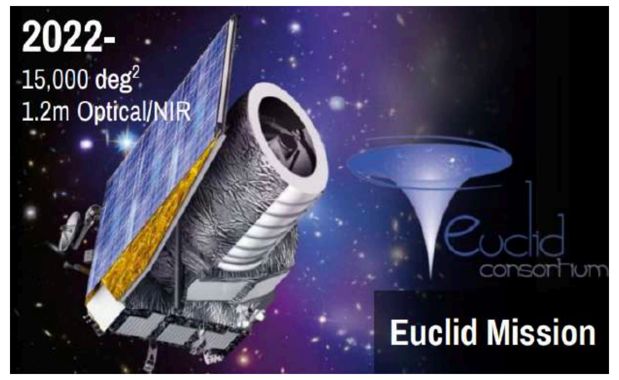
Future - signals in cosmology

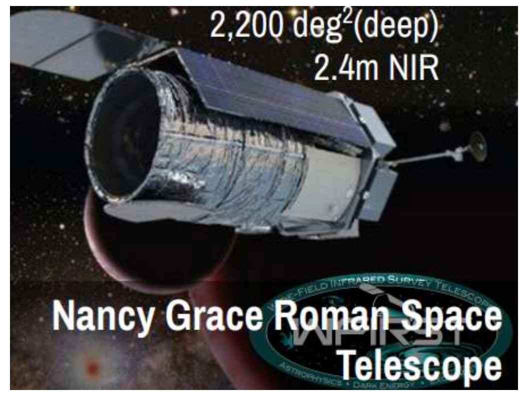
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)







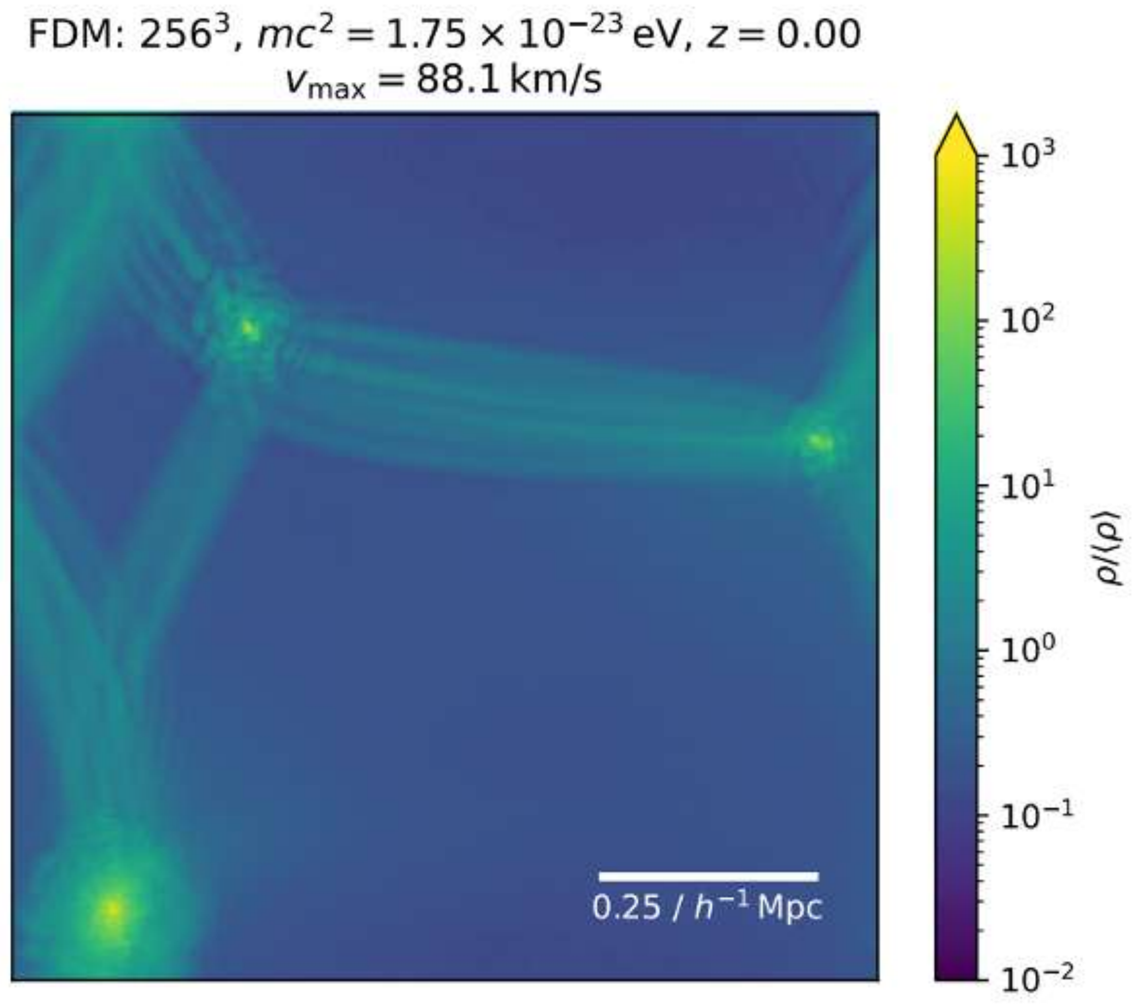
CMB

CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New probes

Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Modified from Jia Liu

Summary

Ultra-Light Dark Matter

Well motivated DM models

Rich and distinct phenomenology on small scales

Testable prediction

Small Scales

Opportunity to probe the microphysics, particle physics properties of DM

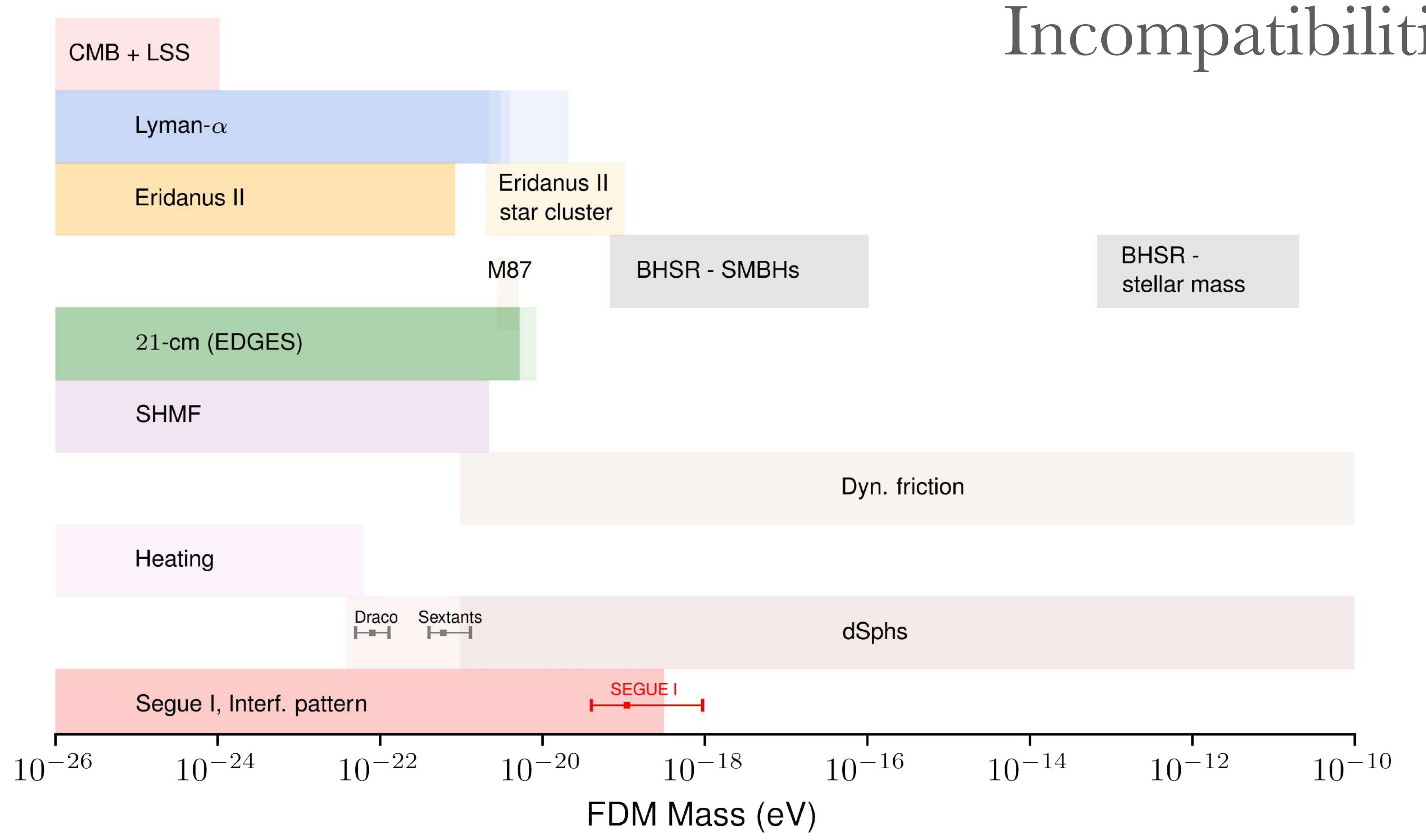
Small scales provide strong constraints in these models

FDM mass being narrowed down

Incompatibility between dwarf bounds

Current status

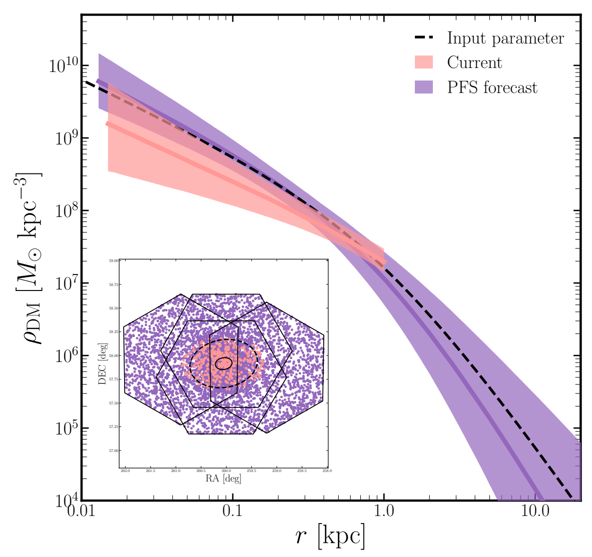
Incompatibilities!

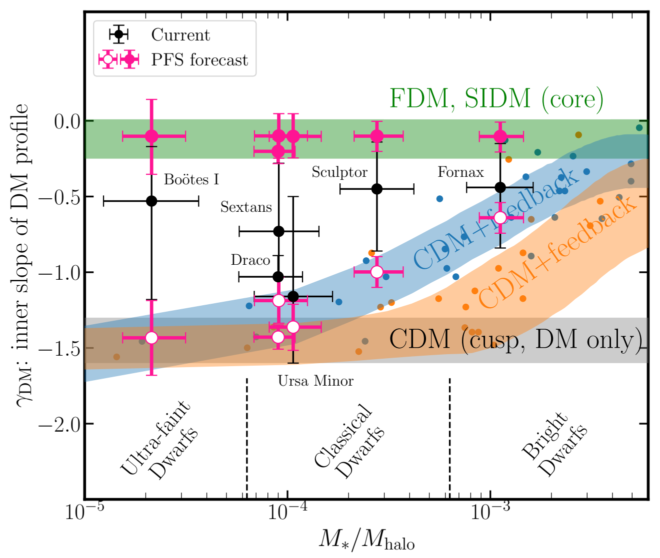


Future

Observations: PFS

PFS-GA





Simulations: cosmological

New observables: interference patterns and vortices

New probes


Thank you very much!

Extra slides

Ultra-light Dark Matter

FDM mass from Ultra-faint dwarfs

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

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

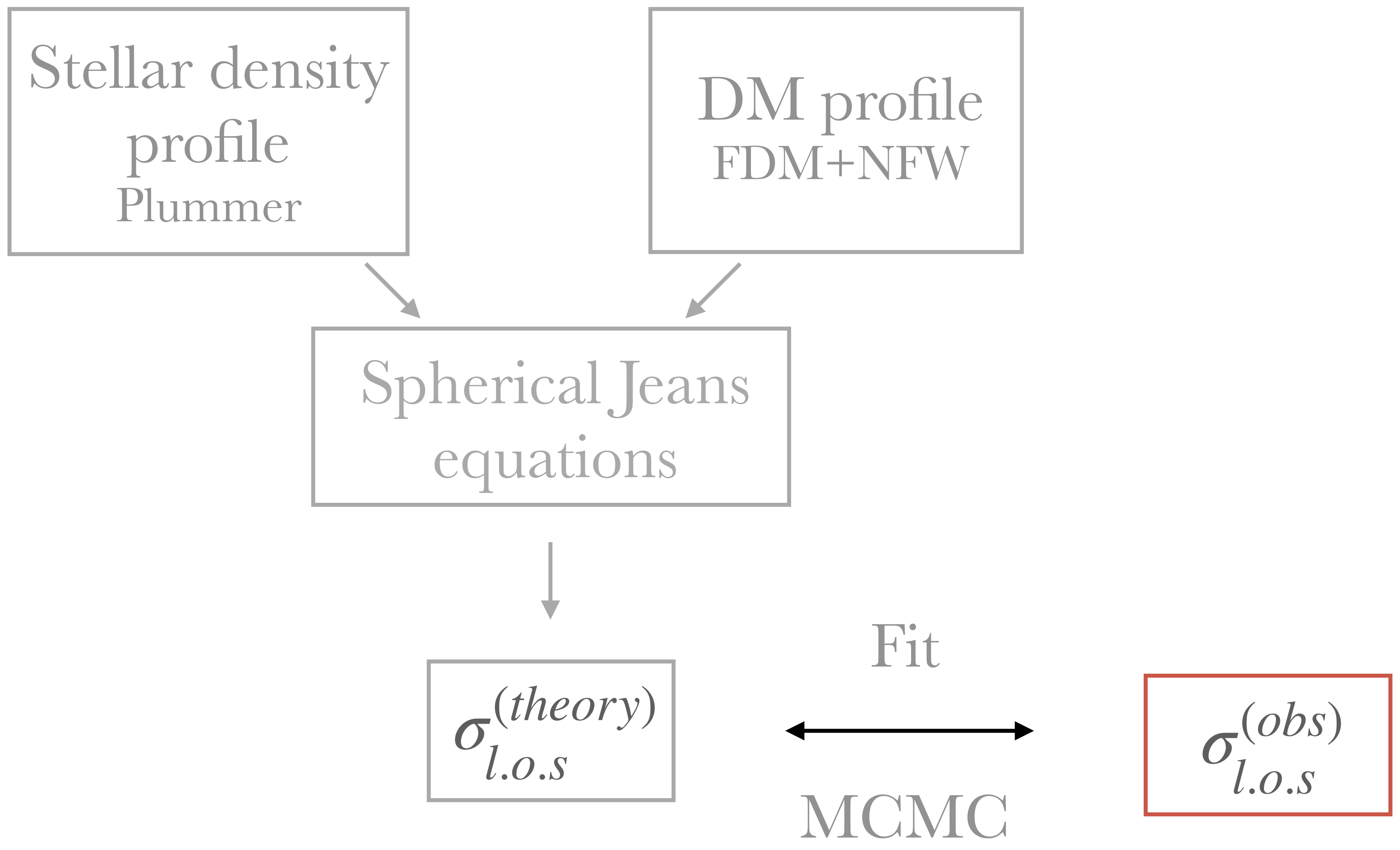
FDM SIMULATIONS

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

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

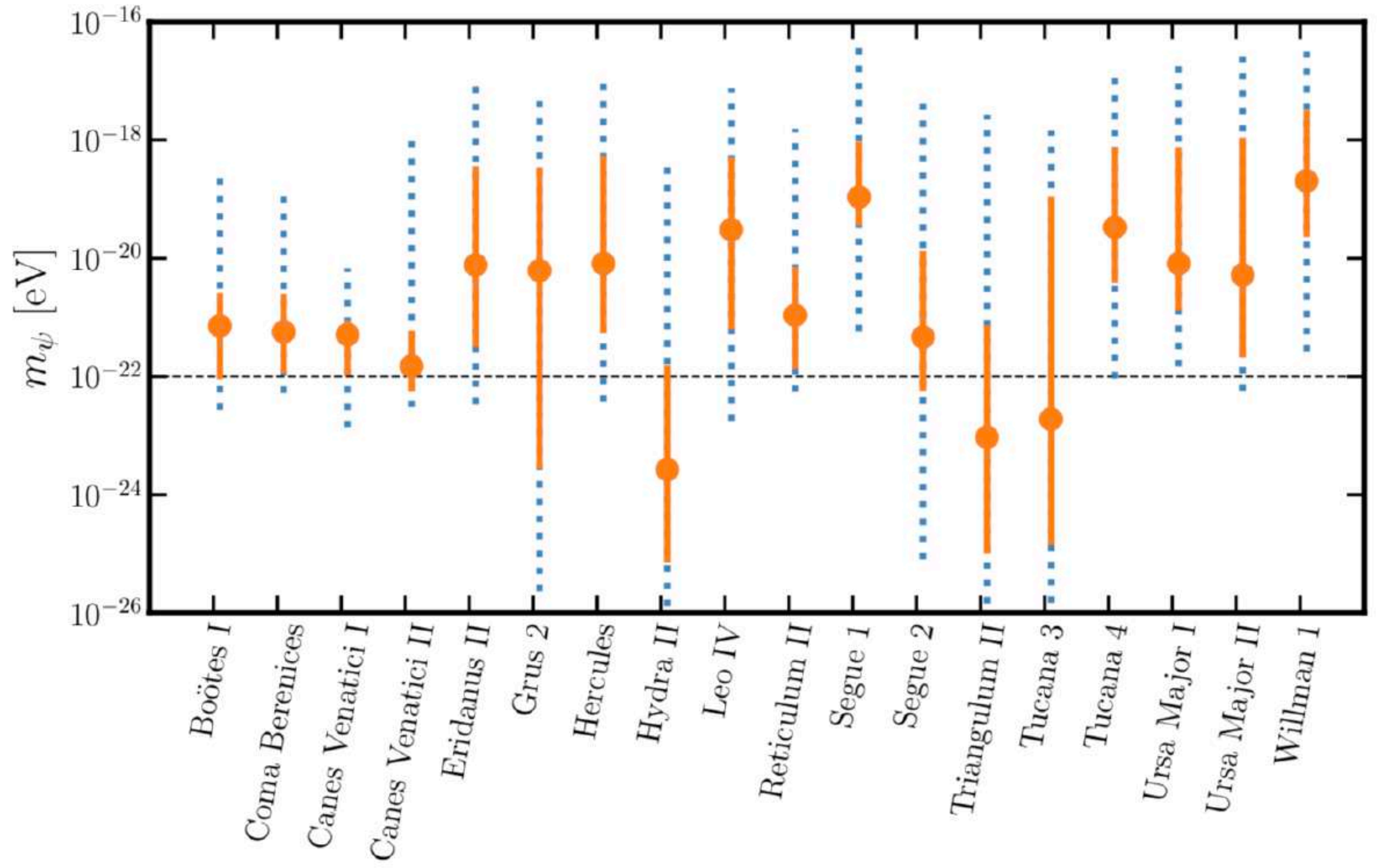
$$\rho_c(r) = 1.9 \times 10^{12} \left(\frac{m}{10^{-23}\,{\rm eV}}\right)^{-2} \left(\frac{r_c}{\rm pc}\right)^{-4} [M_\odot\,{\rm pc}]$$

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



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



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

FDM simulation

Spectral technique to solve the SP system

$$i\hbar\partial_t\psi_c(t,\mathbf{x}) = -\frac{\hbar^2}{2m\,a(t)^2}\nabla_c^2\psi_c(t,\mathbf{x}) + \frac{m}{a(t)}\Phi_c\,\psi_c(t,\mathbf{x})$$

$$\nabla_c^2\Phi_c(t,\mathbf{x}) = 4\pi G m\left(|\psi_c(t,\mathbf{x})|^2 - \langle|\psi_c|^2\rangle(t)\right)$$

Time evolution of the wave function

$$\Psi(\boldsymbol{x}, t+\Delta t) = T\exp\left[-\frac{\mathrm{i}\Delta t}{\hbar}\int \mathrm{d}t'\left(-\frac{\hbar^2}{2m}\nabla^2 + mV(\boldsymbol{x}, t')\right)\right]\Psi(\boldsymbol{x}, t)$$

Small Δt:

$$\Psi(\boldsymbol{x}, t+\Delta t) = \exp\left(\frac{\mathrm{i}\hbar\Delta t}{2m}\nabla^2 - \frac{\mathrm{i}m\Delta t}{2\hbar}V(\boldsymbol{x}, t+\Delta t) - \frac{\mathrm{i}m\Delta t}{2\hbar}V(\boldsymbol{x}, t)\right)\Psi(\boldsymbol{x}, t),$$

Split into 3 operations (Baker-Campbell-Haussdorff formula)

$$\Psi(\boldsymbol{x}, t+\Delta t) = \exp\left(-\frac{\mathrm{i}m\Delta t}{2\hbar}V(\boldsymbol{x}, t+\Delta t)\right)\exp\left(\frac{\mathrm{i}\hbar\Delta t}{2m}\nabla^2\right)\exp\left(-\frac{\mathrm{i}m\Delta t}{2\hbar}V(\boldsymbol{x}, t)\right)\Psi(\boldsymbol{x}, t)$$

Operator Splitting Spectral Method

$$\psi_c^{n+1} \approx \underbrace{e^{i\Phi_c\,\Delta t/2}}_{3^{\mathrm{rd}}}\,\underbrace{\mathcal{F}^{-1}\left[e^{ik^2\Delta t}\right.}_{2^{\mathrm{nd}}}\,\underbrace{\left.\mathcal{F}^{-1}\left[e^{i\Phi_c\,\Delta t/2}\,\psi_c^n\right]\right]}_{1^{\mathrm{st}}}$$

$$\Delta t \sim \Delta x^2$$

Timestep criteria

FDM simulation

Spectral technique to solve the SP system

$$i\hbar\partial_t\psi_c(t,\mathbf{x}) = -\frac{\hbar^2}{2m\,a(t)^2}\nabla_c^2\psi_c(t,\mathbf{x}) + \frac{m}{a(t)}\Phi_c\,\psi_c(t,\mathbf{x})$$

$$\nabla_c^2\Phi_c(t,\mathbf{x}) = 4\pi G m\left(|\psi_c(t,\mathbf{x})|^2 - \langle|\psi_c|^2\rangle(t)\right)$$

Operator Splitting Spectral Method

$$\psi_c^{n+1} \approx \underbrace{e^{i\Phi_c\,\Delta t/2}}_{3^{\text{rd}}}\,\underbrace{\mathcal{F}^{-1}\left[e^{ik^2\Delta t}\right.}_{2^{\text{nd}}}\,\underbrace{\mathcal{F}^{-1}\left[e^{i\Phi_c\,\Delta t/2}\,\psi_c^n\right]}_{1^{\text{st}}}\left.\right]$$

$$\Delta t \sim \Delta x^2$$

Timestep criteria

FDM simulation

The fields ψ and Φ are discretised on a uniform Cartesian mesh with N^3 grid points - allow numerical computations using Fast Fourier transform. It follows the operations:

- Calculate the potential

- $$\psi_c \leftarrow e^{-i\frac{m}{\hbar}\frac{1}{a}\frac{\Delta t}{2}\Phi_c}\psi_c \qquad \text{(kick)} \qquad (20a)$$
- $$\psi_c \leftarrow \mathrm{FFT}^{-1}\left(e^{-i\frac{\hbar}{m}\frac{1}{a^2}\frac{\Delta t}{2}k^2}\,\mathrm{FFT}(\psi_c)\right) \qquad \text{(drift)} \qquad (20b)$$
- $$\Phi_c \leftarrow \mathrm{FFT}^{-1}\left(-\frac{1}{k^2}\,\mathrm{FFT}\left(4\pi G m\left(|\psi_c|^2 - \langle|\psi_c|^2\rangle\right)\right)\right) \qquad \text{(update potential)} \qquad (20c)$$
- $$\psi_c \leftarrow e^{-i\frac{m}{\hbar}\frac{1}{a}\frac{\Delta t}{2}\Phi_c}\psi_c \qquad \text{(kick)} \qquad (20d)$$
- Go to step (20a) (20e)

Schrödinger-Poisson system

$$i\hbar\partial_t\psi_c(t,\mathbf{x}) = -\frac{\hbar^2}{2m\,a(t)^2}\nabla_c^2\psi_c(t,\mathbf{x}) + \frac{m}{a(t)}\Phi_c\,\psi_c(t,\mathbf{x})$$
$$\nabla_c^2\Phi_c(t,\mathbf{x}) = 4\pi G m\left(|\psi_c(t,\mathbf{x})|^2 - \langle|\psi_c|^2\rangle(t)\right)$$

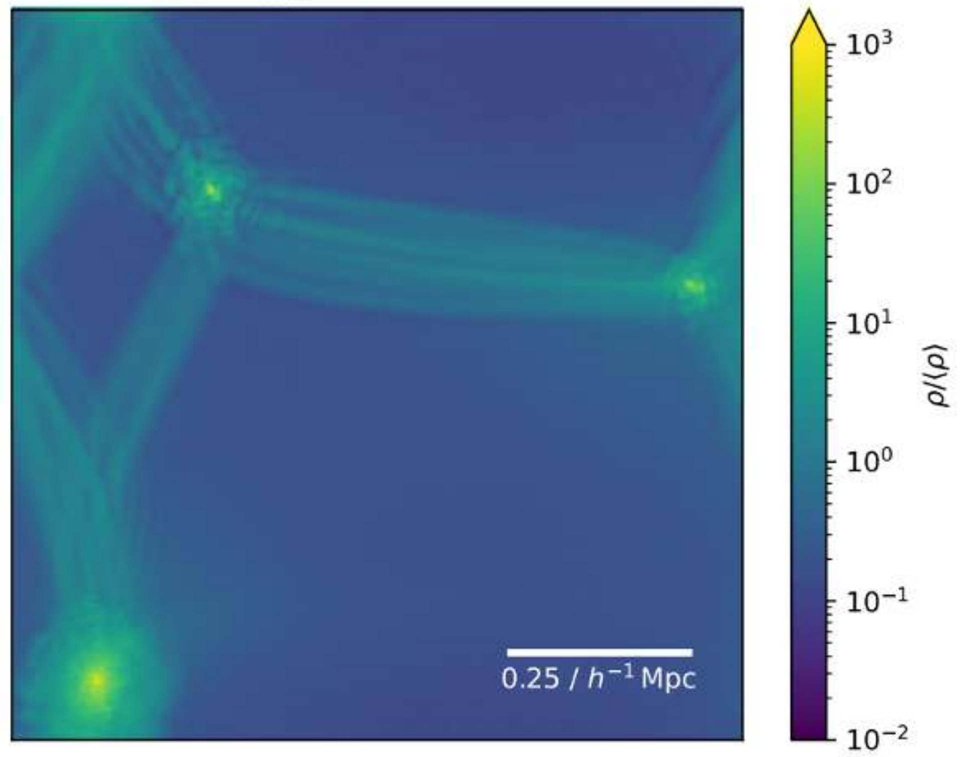
May et al. 2020
Steps (20a) to (20e) implemented as a module in the AREPO code

Jowett
Own implementation

FDM simulation

May et al 2020: Box size and resolution

Largest three-dimensional cosmological simulations of FDM structure formation to low redshifts



Type	Res. el.	$L\,/\,h^{-1}$ Mpc	mc^2 / eV	Resolution
FDM	8640^3	10	7×10^{-23}	$1.16\,h^{-1}$ kpc
FDM	4320^3	10	$(3.5, 7) \times 10^{-23}$	$2.31\,h^{-1}$ kpc
FDM	3072^3	10	$(3.5, 7) \times 10^{-23}$	$3.26\,h^{-1}$ kpc
FDM	2048^3	10	$(3.5, 7) \times 10^{-23}$	$4.88\,h^{-1}$ kpc
FDM	4320^3	5	7×10^{-23}	$1.16\,h^{-1}$ kpc
FDM	3072^3	5	$(3.5, 7) \times 10^{-23}$	$1.63\,h^{-1}$ kpc
FDM	2048^3	5	$(3.5, 7) \times 10^{-23}$	$2.44\,h^{-1}$ kpc
FDM	1024^3	5	$(3.5, 7) \times 10^{-23}$	$4.88\,h^{-1}$ kpc
CDM	2048^3	10	—	$9.69 \times 10^3\,h^{-1}\,M_\odot$
CDM	1024^3	10	—	$7.75 \times 10^4\,h^{-1}\,M_\odot$
CDM	512^3	10	—	$6.20 \times 10^5\,h^{-1}\,M_\odot$
CDM	1024^3	5	—	$9.69 \times 10^3\,h^{-1}\,M_\odot$
CDM	512^3	5	—	$7.75 \times 10^4\,h^{-1}\,M_\odot$

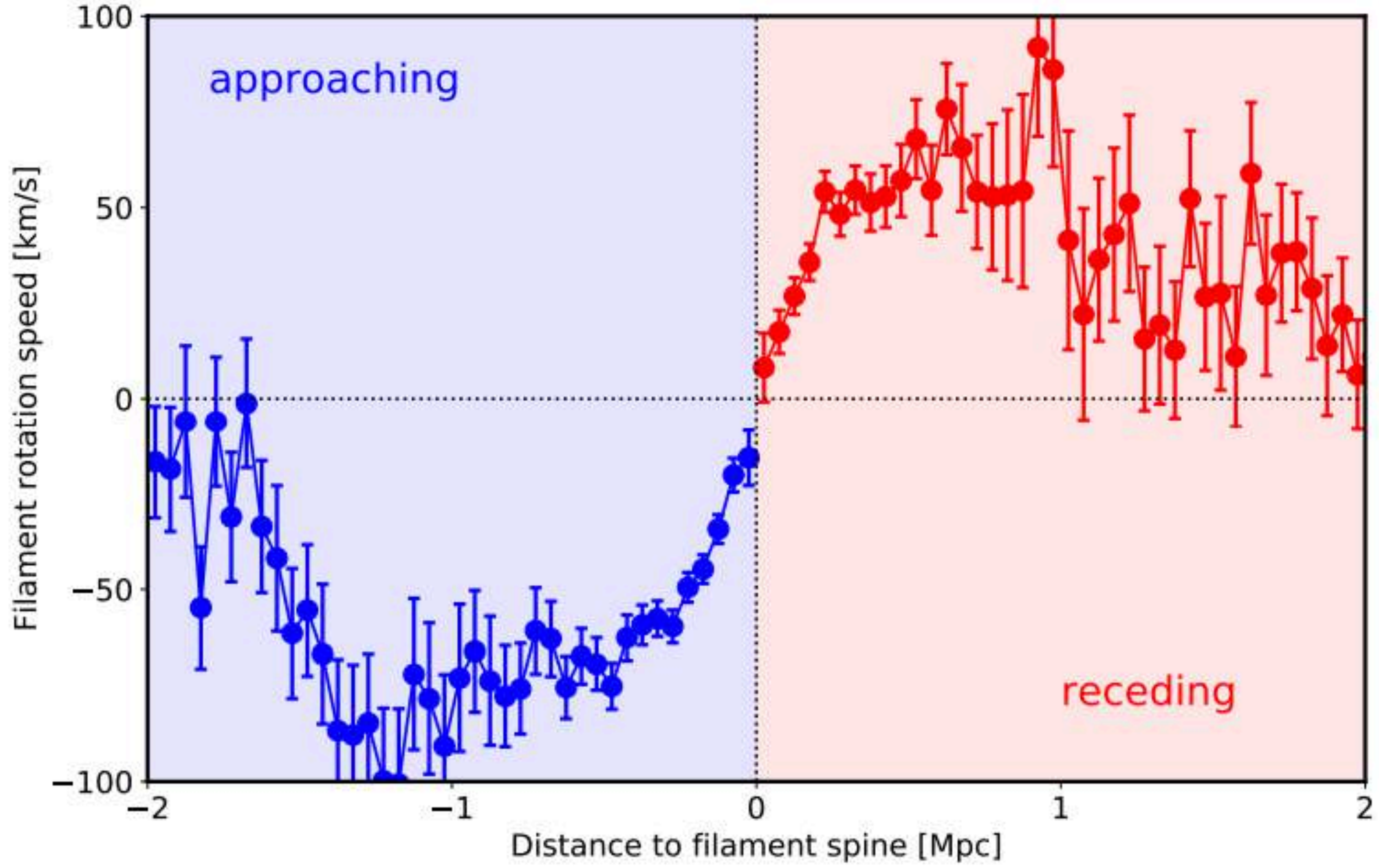
Table 1. List of performed simulations with important characteristics. The lengths given for the box sizes and resolutions are comoving.

Simulations: $\{\Omega_m = 0.3,\ \Omega_b = 0,\ \Omega_\Lambda = 0.7,\ H_0 = 70\,\mathrm{km\,s^{-1}}(h = 0.7),\ \sigma_8 = 0.9\}$

IC: $z = 127$

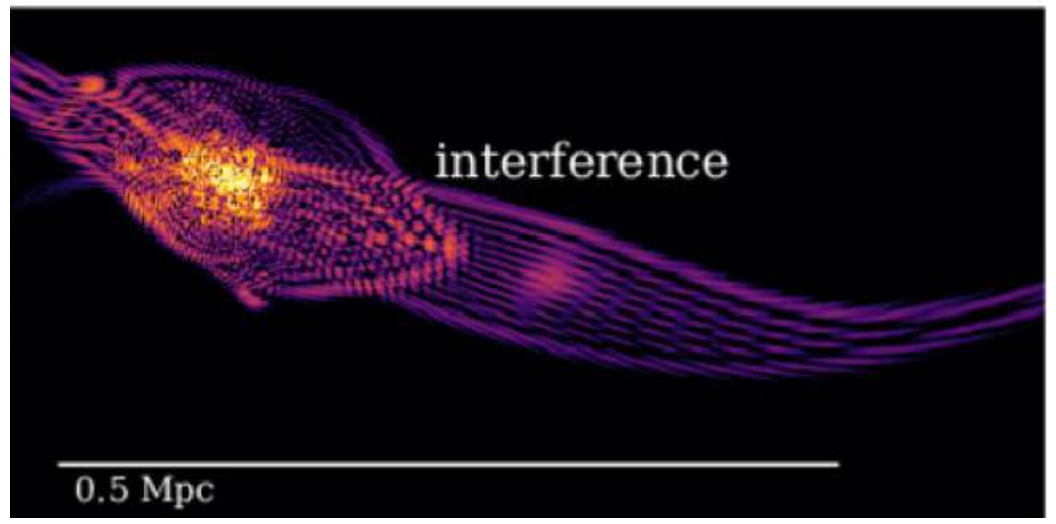
Rotation of filaments: vortices

Peng Wang, Noam I. Libeskind, Elmo Tempel, Xi Kang, Quan Guo, "*Possible observational evidence that cosmic filaments spin*", Nature Astronomy (2021)



- Stacking thousands of filaments and examining the velocity of galaxies perpendicular to the filament's axis (via their red and blue shift)
- Found that filaments display motion consistent with rotation ⟶ largest objects known to have angular momentum

Rotation of filaments: vortices

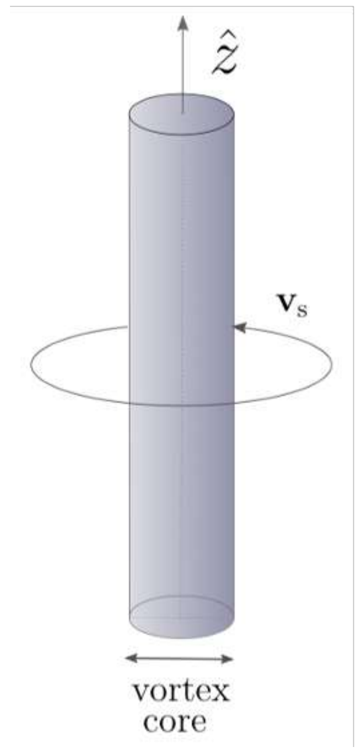


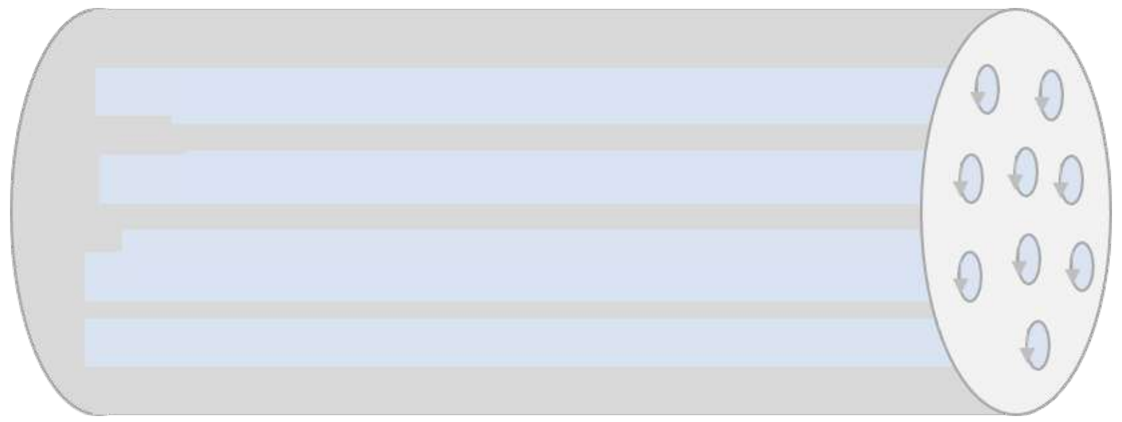
Mocz et al. 2017

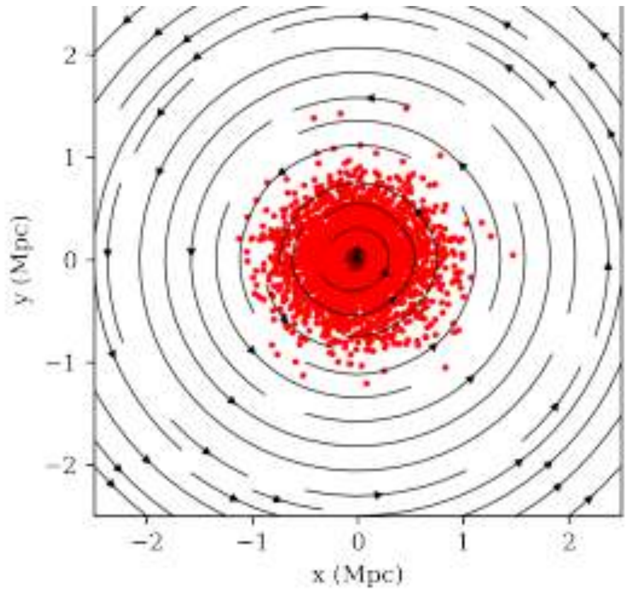
- Not clear that we can get spinning cosmic filaments in LCDM
  - Seems to be difficult to theoretically explain the acquisition of angular momentum on megaparsec scales
  - Some simulations seem to be finding spinning cosmic filaments

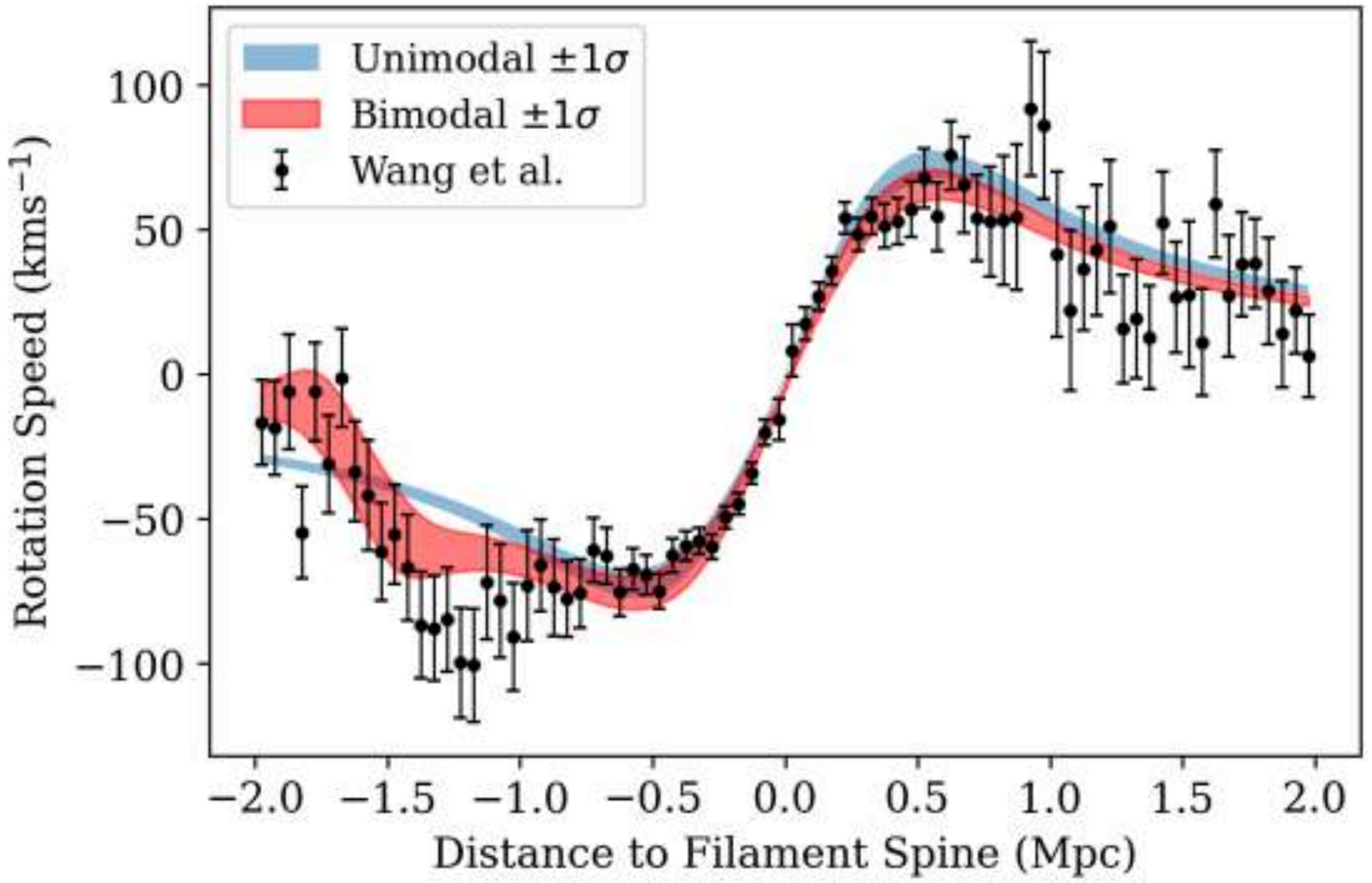
"Cosmic Filament Spin from Dark Matter Vortices" , Stephon Alexander, Christian Capanelli, Elisa G. M. Ferreira, and Evan McDonough (2021)

- Suggest that a collection of (dark) vortices enclosed in a cylindrical volume aligned with the axis of a filament are able to generate rotations at the Mpc scale and reproduce the result of Wang et al (2021)







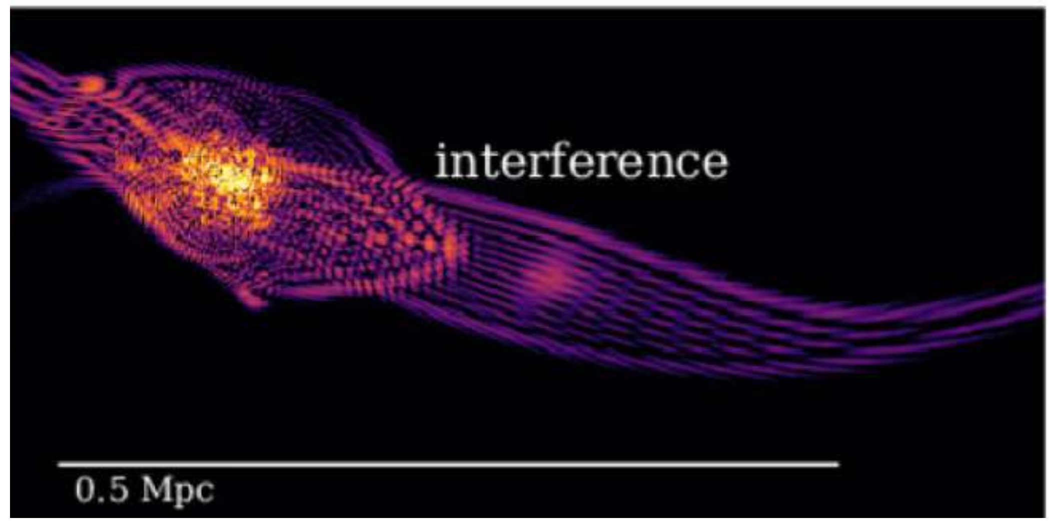


$$R = 0.51^{+0.02}_{0.02}\,\mathrm{Mpc}$$

$$\frac{N_V}{m} = 2.9^{+0.2}_{-0.2}\,\mathrm{eV}^{-1}$$

Independent on the formation mechanism of these vortices!

Rotation of filaments: vortices



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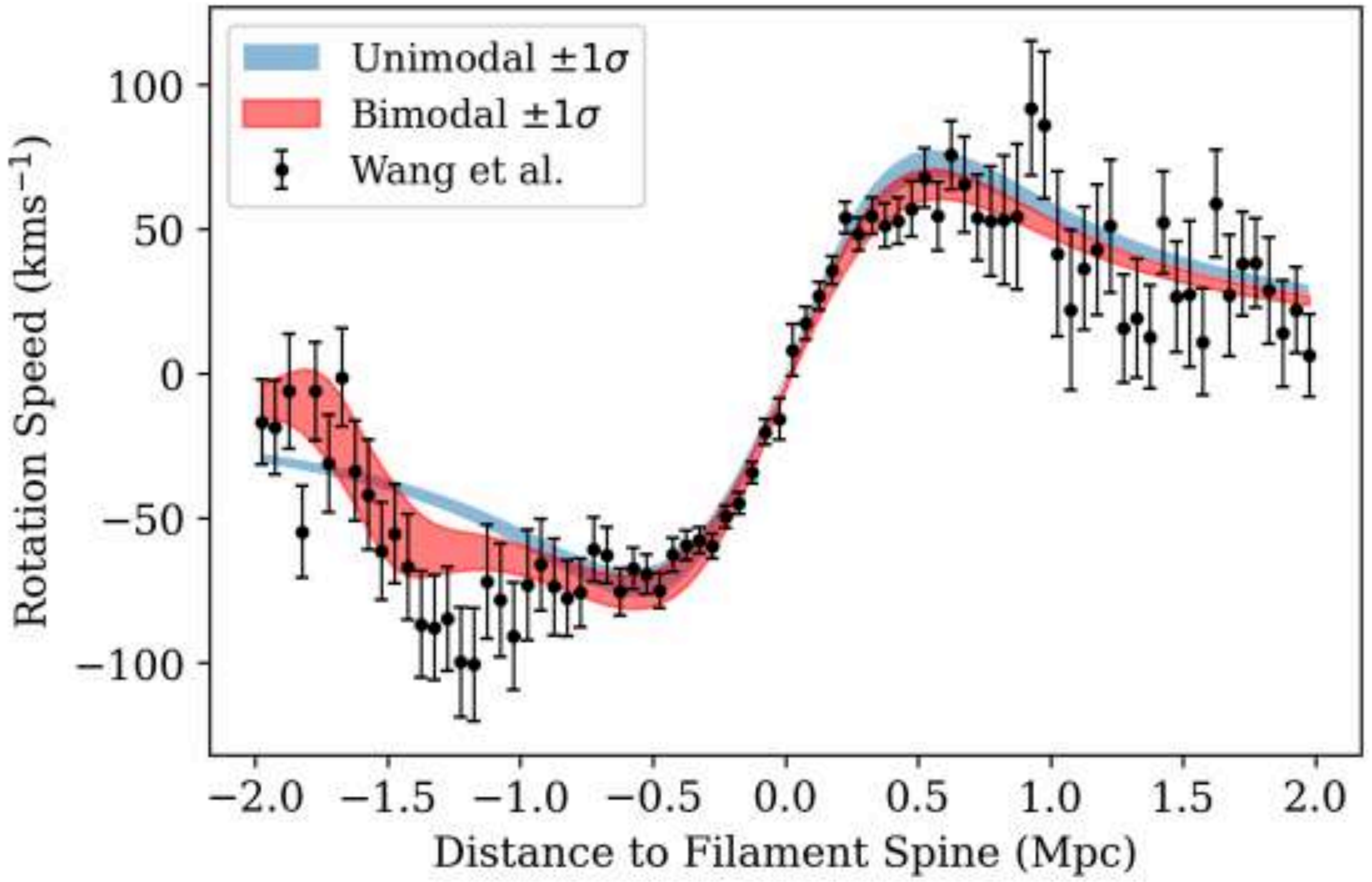
"Cosmic Filament Spin from Dark Matter Vortices" , Stephon Alexander, Christian Capanelli, Elisa G. M. Ferreira, and Evan McDonough (2021)

- Suggest that a collection of (dark) vortices enclosed in a cylindrical volume aligned with the axis of a filament are able to generate rotations at the Mpc scale and reproduce the result of Wang et al (2021)



$$R = 0.51^{+0.02}_{0.02}\,\mathrm{Mpc}$$

$$\frac{N_V}{m} = 2.9^{+0.2}_{-0.2}\,\mathrm{eV}^{-1}$$

For example, for a $m \sim 10^{-22}\mathrm{eV} \longrightarrow N_V \sim 3000$

Possible formation mechanisms:

- in regions where the density vanishes (*Hui et al 2020, Lague et al 2020*)
- Transfer of angular momentum (*Berezhiani, 2015*)

Compatible with those!

* In CDM - formation of vortices