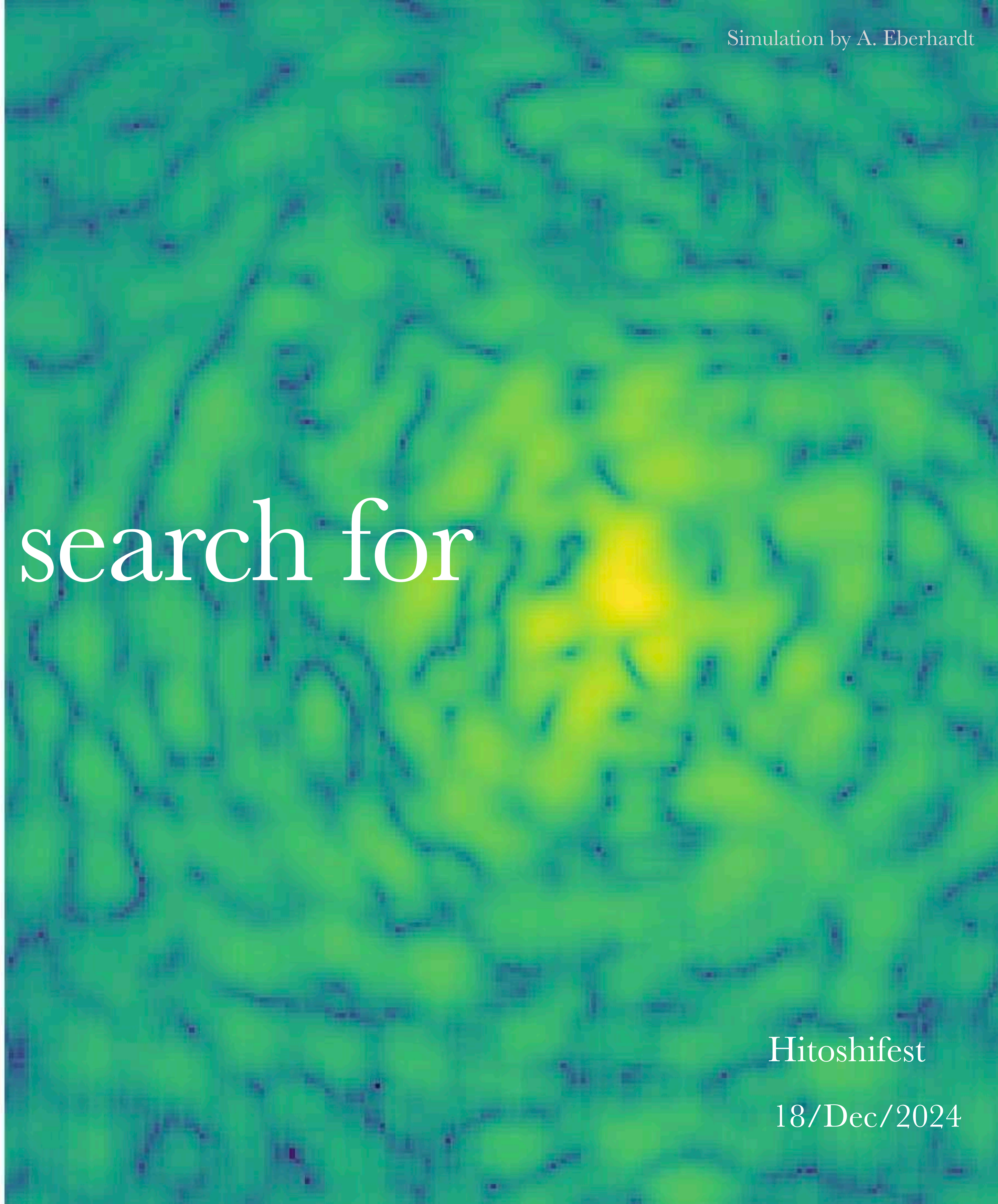
Continuing Hitoshi's search for axions in the universe



Simulation by A. Eberhardt

Elisa G. M. Ferreira

Kavli IPMU

Hitoshifest

18/Dec/2024

Congratulations, Hitoshi!

Thank you Hitoshi!

KAVLI IPMU

I am very grateful for you to have founded this amazing institute, the perfect environment for researchers!

Congratulations, Hitoshi!

Hitoshi's papers one of the reasons I work on dark matter and why I came to KAVLI IPMU

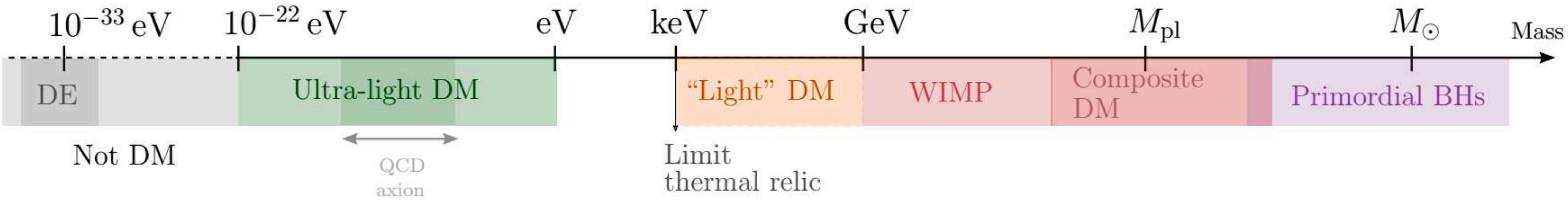
What is dark matter?

- What is the nature of DM?

State of the “art"

Mass scale of DM

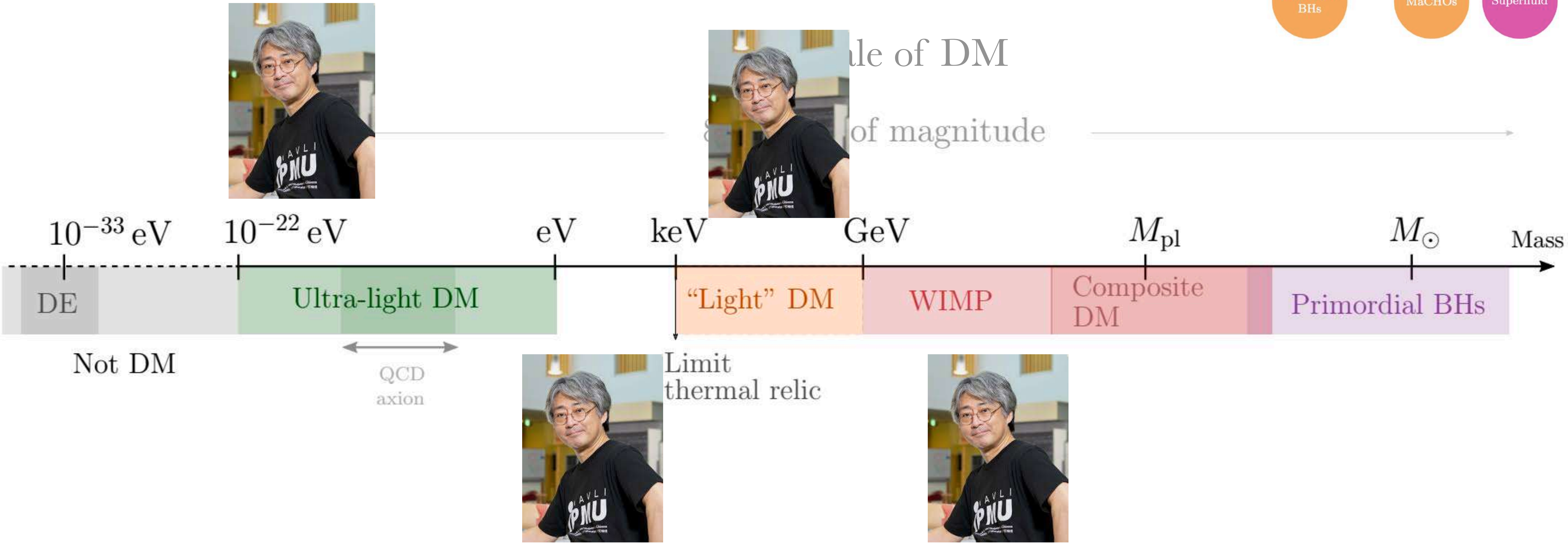
80 orders of magnitude



What is dark matter?

- What is the nature of DM?

State of the “art"



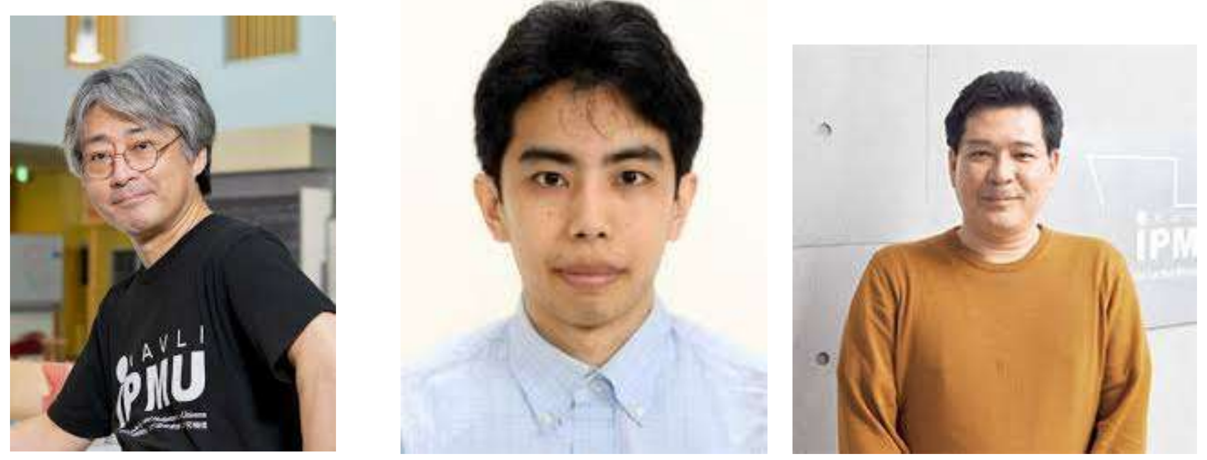
Dark matter

@ KAVLI IPMU

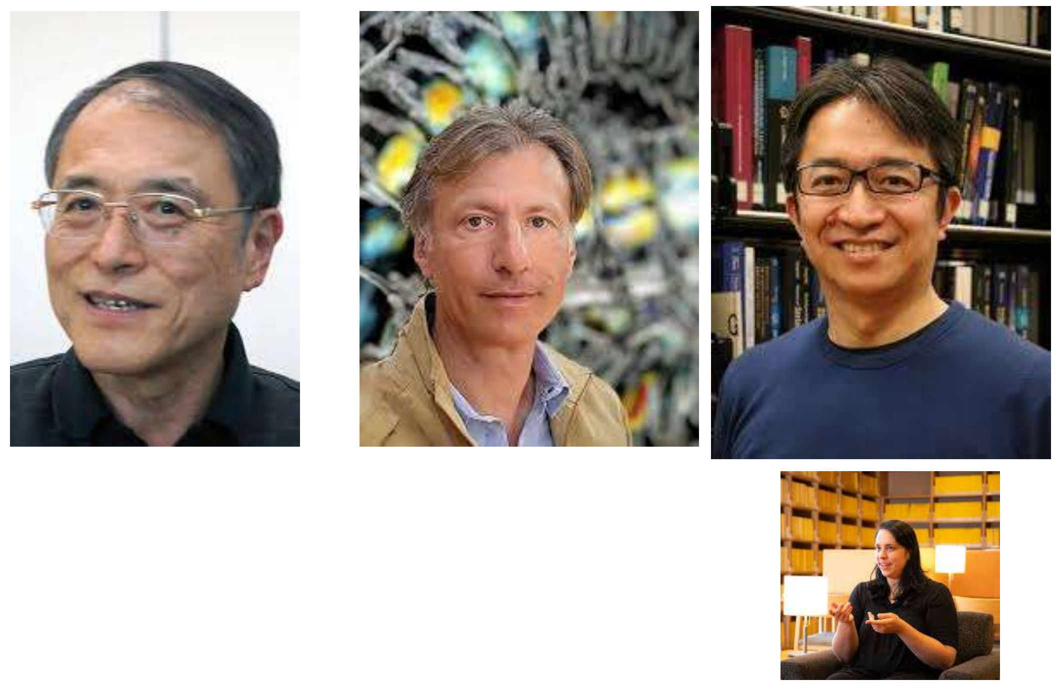
The search for dark matter @ KAVLI IPMU

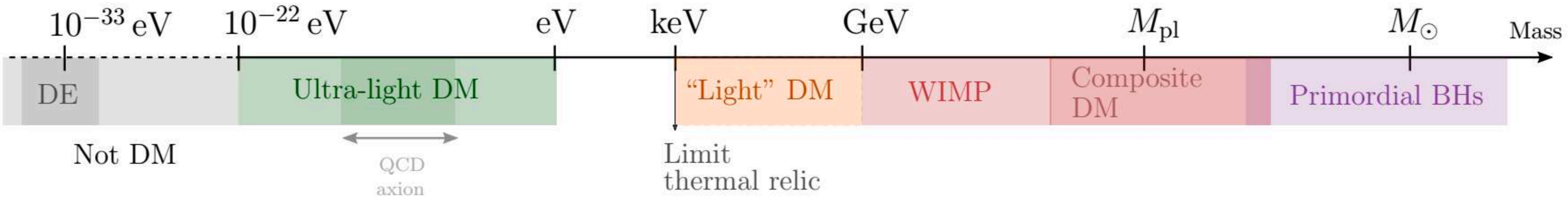
DM science is very strong at IPMU.
We work on this entire range of DM candidates…
one of Hitoshi legacy!

Heavy DM



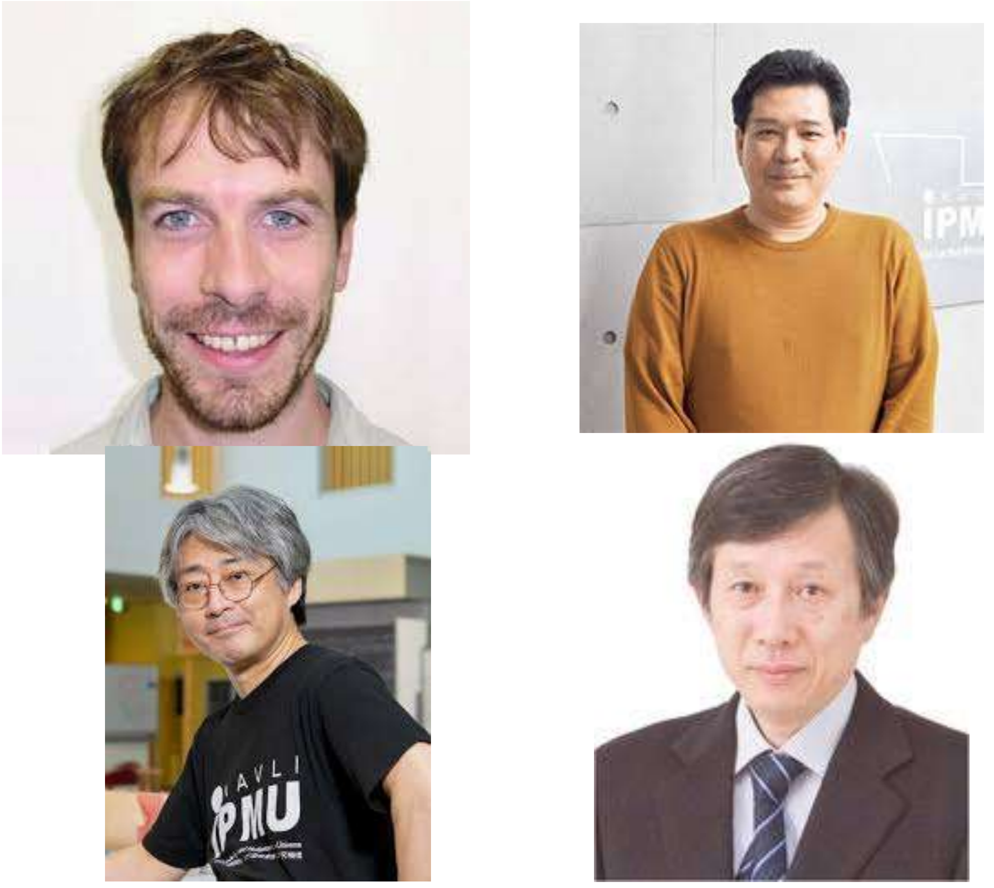
Primordial BHs





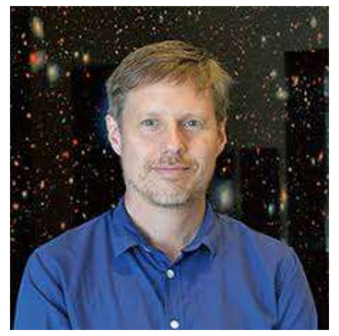
Ultra-light DM

Light DM



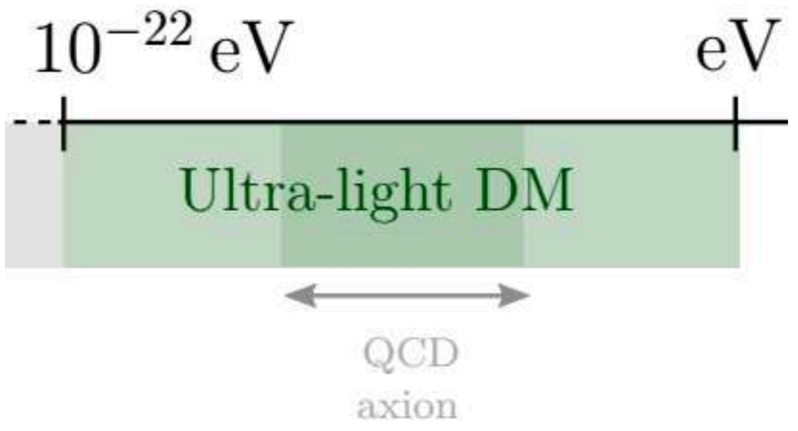
COSI

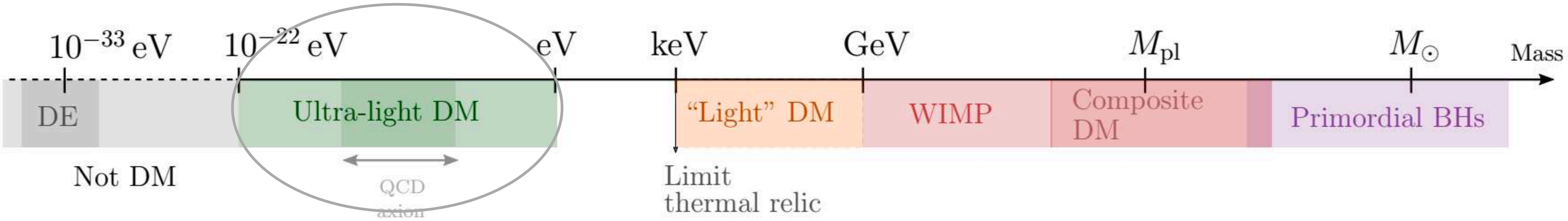
DM at high z

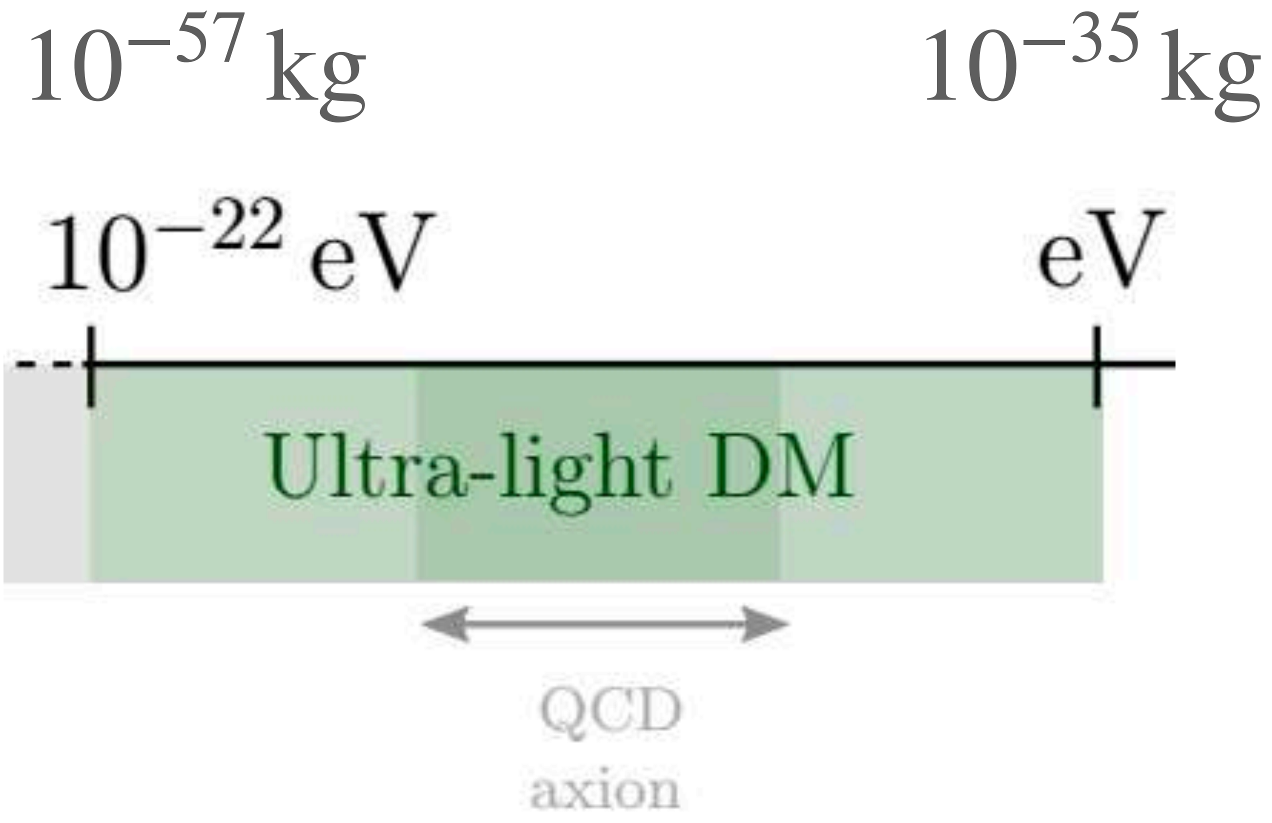


Grav. probe DM

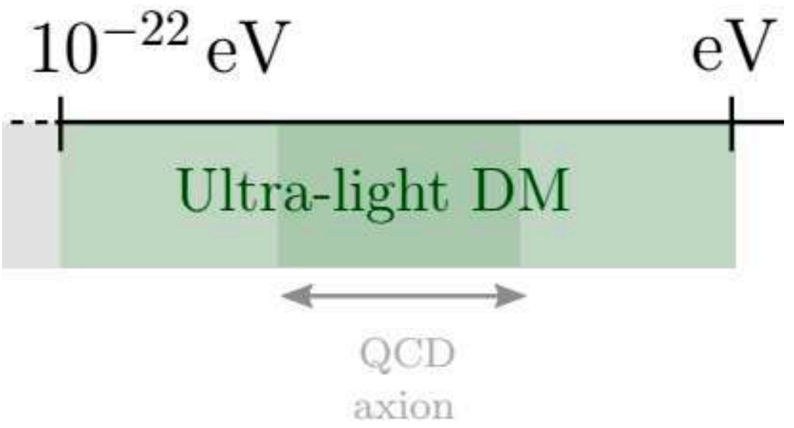
Axion/ALP Dark Matter

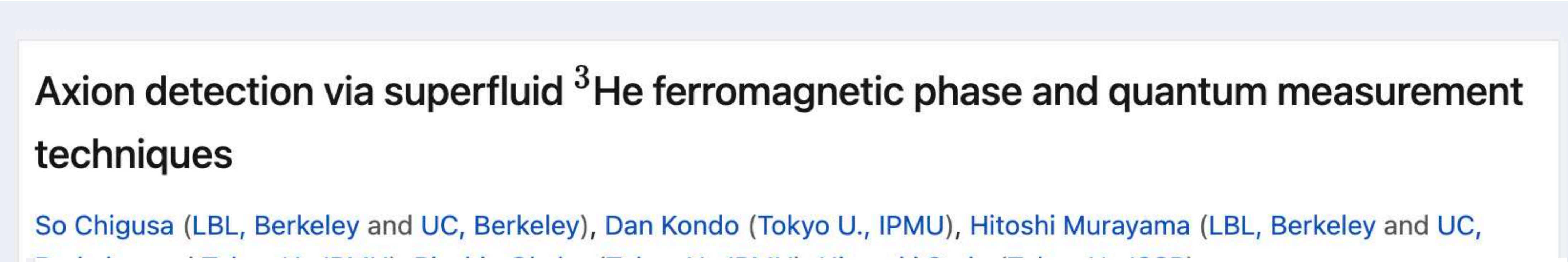






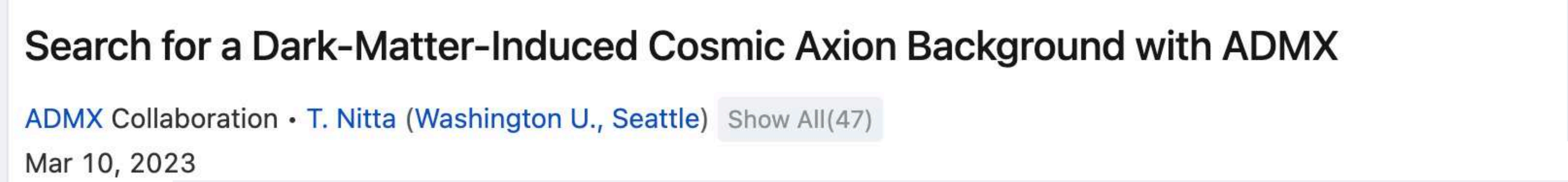
Axion/ALP Dark Matter





Axion detection via superfluid ^{3}He ferromagnetic phase and quantum measurement techniques

So Chigusa (LBL, Berkeley and UC, Berkeley), Dan Kondo (Tokyo U., IPMU), Hitoshi Murayama (LBL, Berkeley and UC,

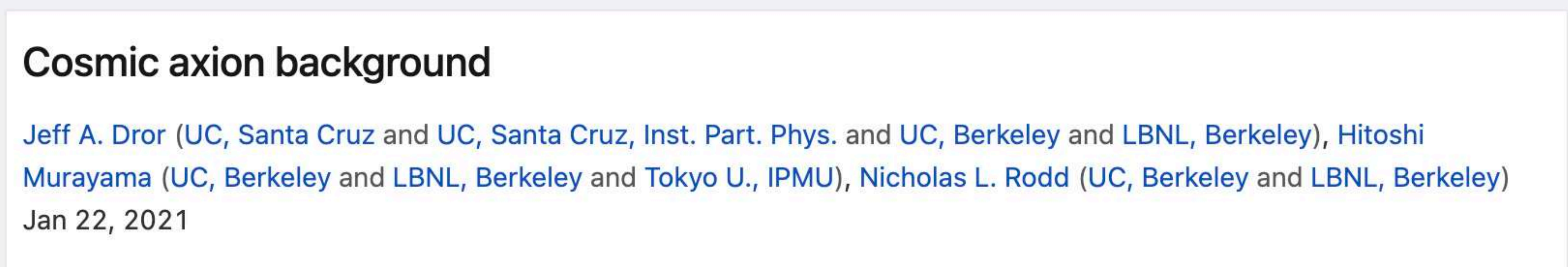


Search for a Dark-Matter-Induced Cosmic Axion Background with ADMX

ADMX Collaboration • T. Nitta (Washington U., Seattle) Show All(47)

Mar 10, 2023

7 pages



Cosmic axion background

Jeff A. Dror (UC, Santa Cruz and UC, Santa Cruz, Inst. Part. Phys. and UC, Berkeley and LBNL, Berkeley), Hitoshi Murayama (UC, Berkeley and LBNL, Berkeley and Tokyo U., IPMU), Nicholas L. Rodd (UC, Berkeley and LBNL, Berkeley)

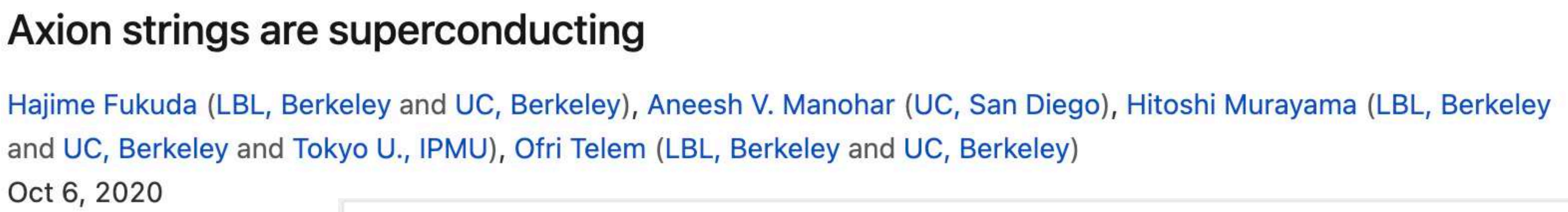
Jan 22, 2021

Axion detection via superfluid ^{3}He ferromagnetic phase and quantum measurement techniques

So Chigusa (LBL, Berkeley and UC, Berkeley), Dan Kondo (Tokyo U., IPMU), Hitoshi Murayama (LBL, Berkeley and UC, Berkeley and Tokyo U., IPMU), Risshin Okabe (Tokyo U., IPMU), Hiroy

Sep 17, 2023

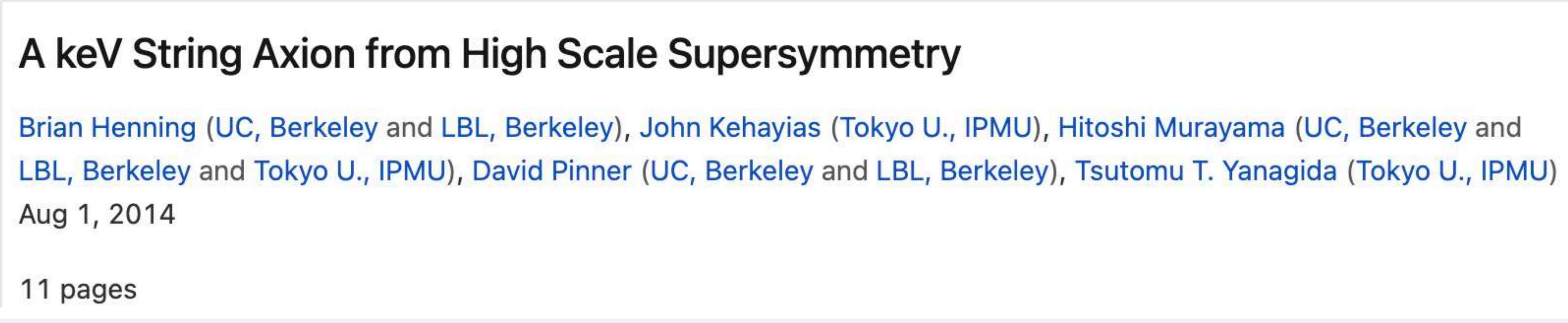
41 pages



Axion strings are superconducting

Hajime Fukuda (LBL, Berkeley and UC, Berkeley), Aneesh V. Manohar (UC, San Diego), Hitoshi Murayama (LBL, Berkeley and UC, Berkeley and Tokyo U., IPMU), Ofri Telem (LBL, Berkeley and UC, Berkeley)

Oct 6, 2020



A keV String Axion from High Scale Supersymmetry

Brian Henning (UC, Berkeley and LBL, Berkeley), John Kehayias (Tokyo U., IPMU), Hitoshi Murayama (UC, Berkeley and LBL, Berkeley and Tokyo U., IPMU), David Pinner (UC, Berkeley and LBL, Berkeley), Tsutomu T. Yanagida (Tokyo U., IPMU)

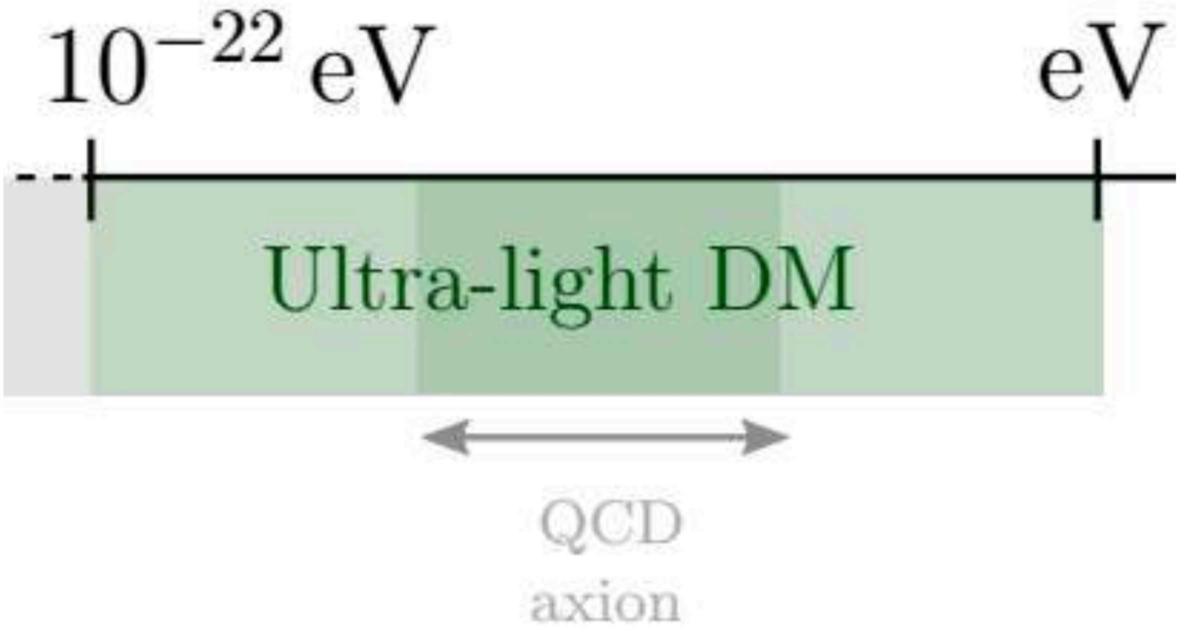
Aug 1, 2014

11 pages

Quark mass uncertainties revive Kim-Shifman-Vainshtein-Zakharov axion dark matter

Matthew R. Buckley (UC, Berkeley and LBL, Berkeley), Hitoshi Murayama (UC, Berkeley and LBL, Berkeley)

May 2007



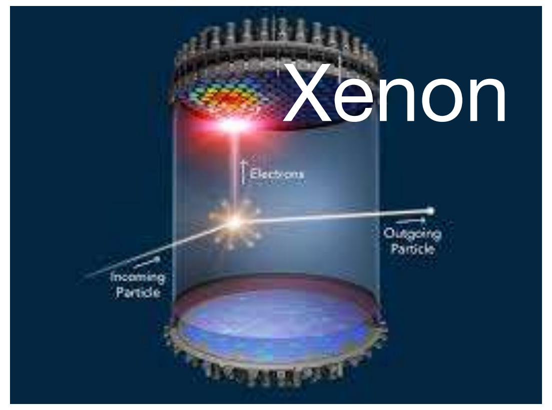
How to detect dark matter

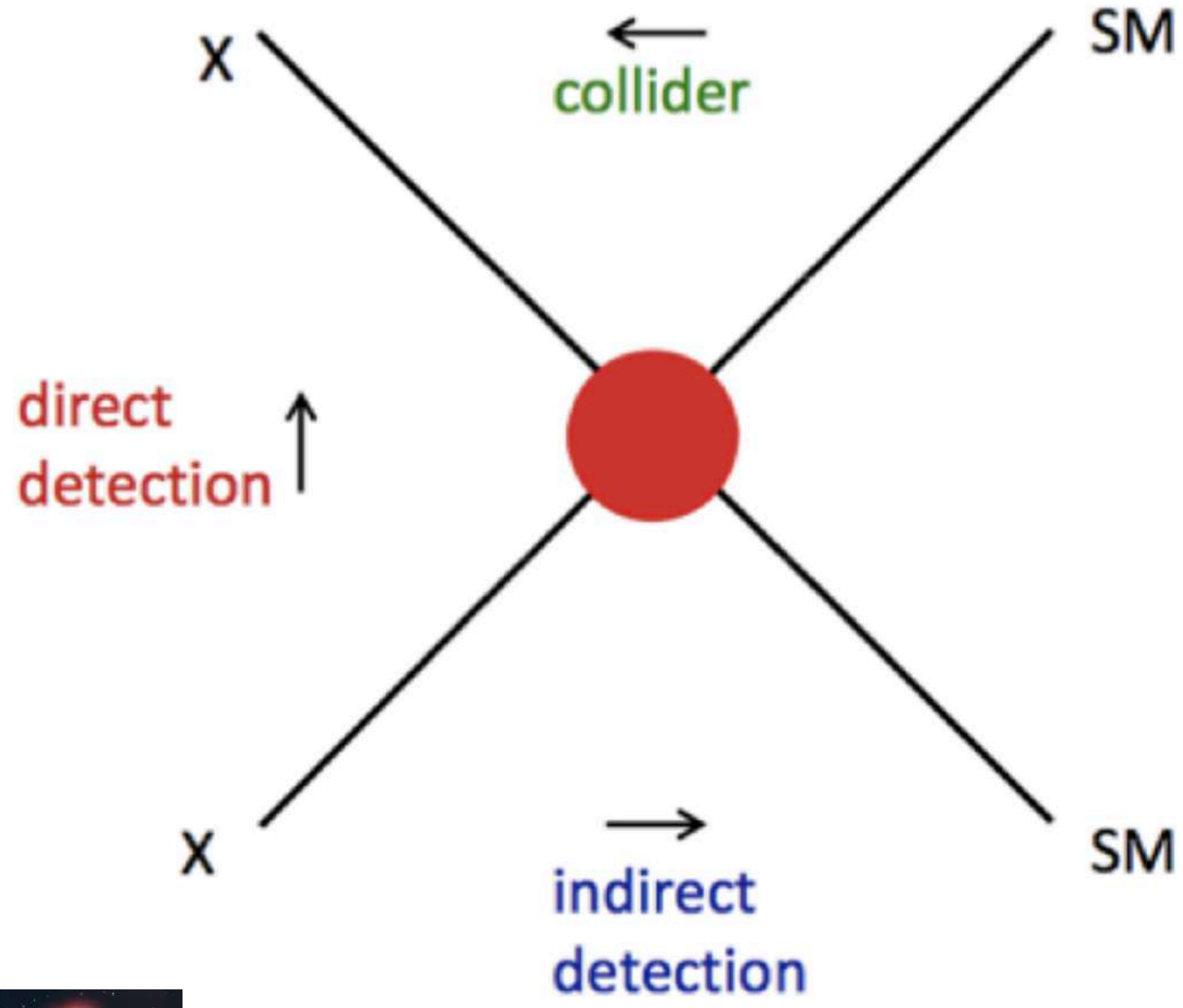
All of these experiments have KAVLI IPMU involvement or leadership

Interaction with the SM

Talks by Lindley Winslow, Kai Martens and Risshin Okabe

Muon colliders



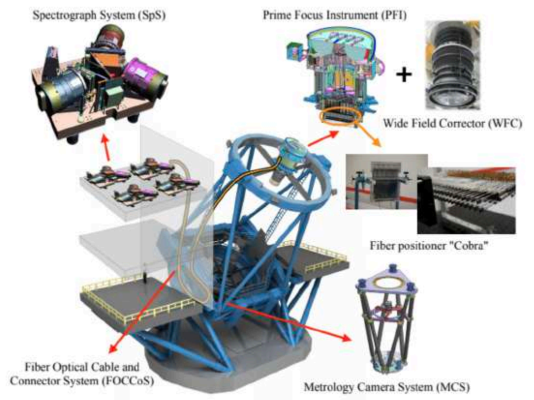


+

Gravitationally
Cosmological and astrophysical searches

Hyper Suprime-Cam (HSC)

Prime Focus Spectrograph (PFS)

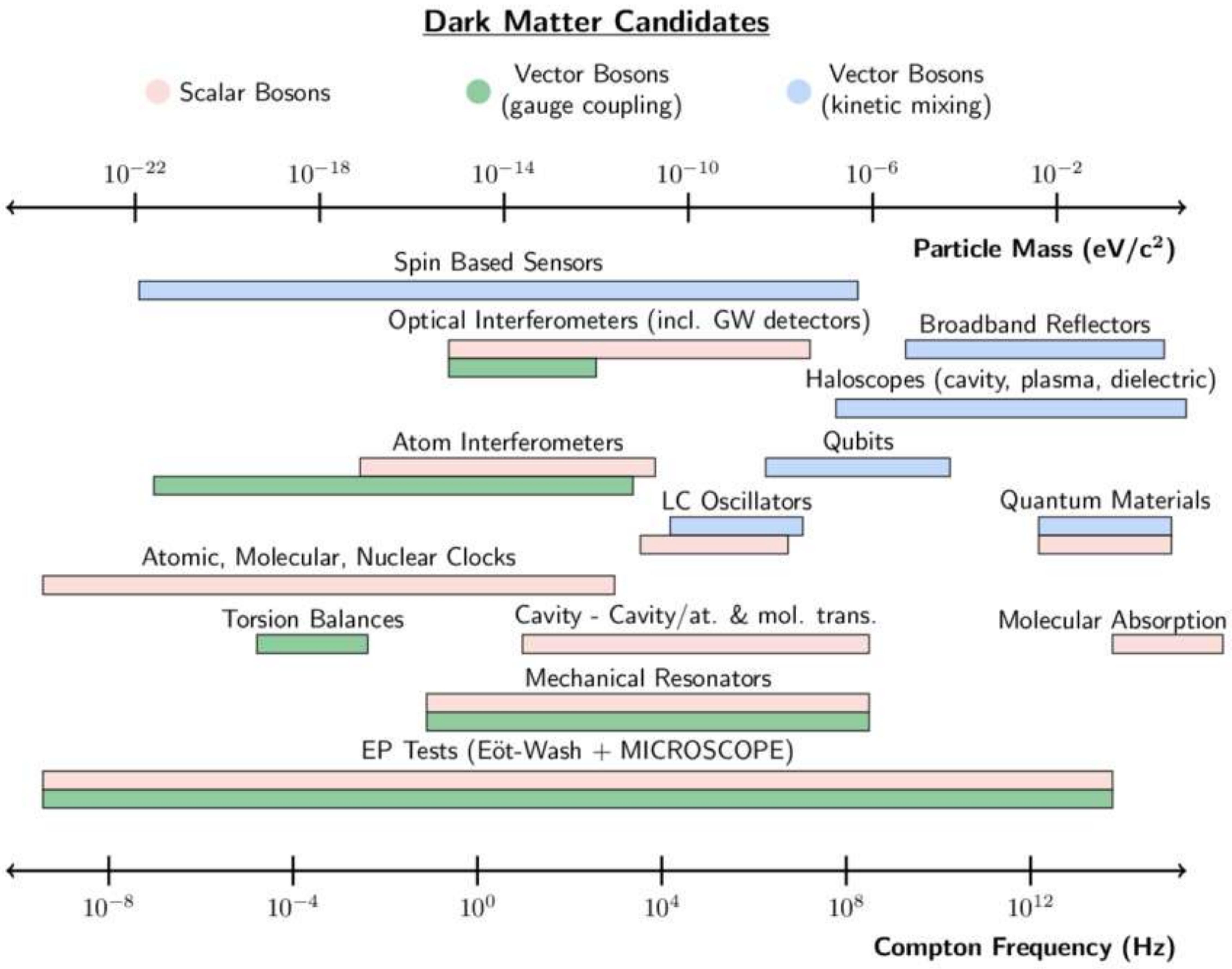


JWST

* not a complete list

How to detect axion/ALP dark matter

Interaction with the SM



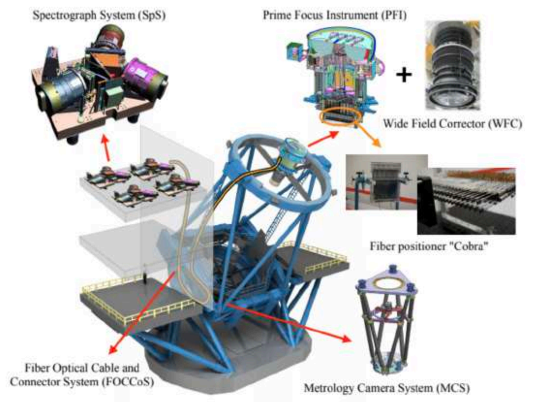
Talks by Lindley Winslow and Risshin Okabe

+

Gravitationally Cosmological and astrophysical searches

Hyper Suprime-Cam (HSC)

Prime Focus Spectrograph (PFS)

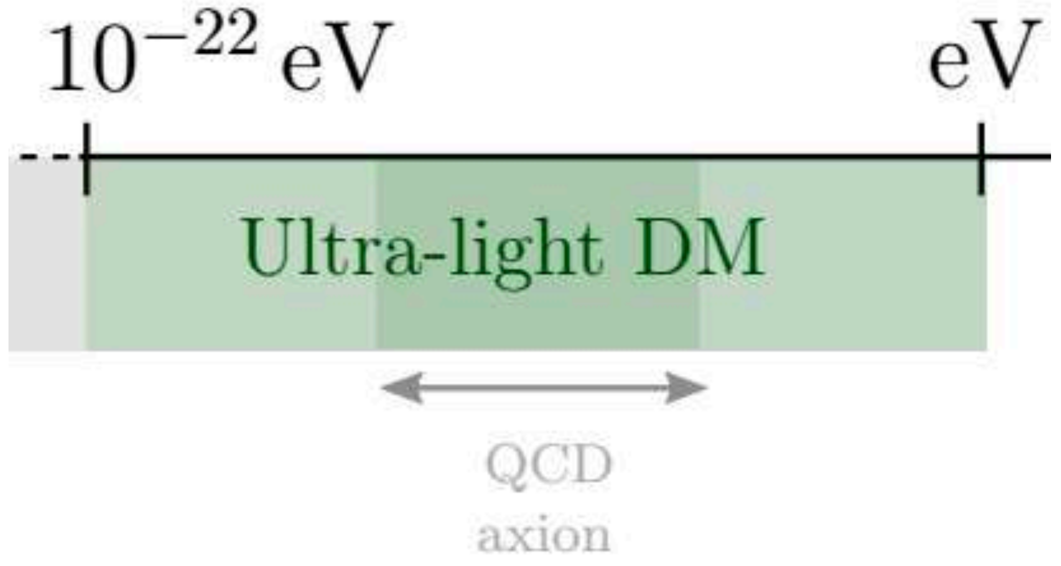


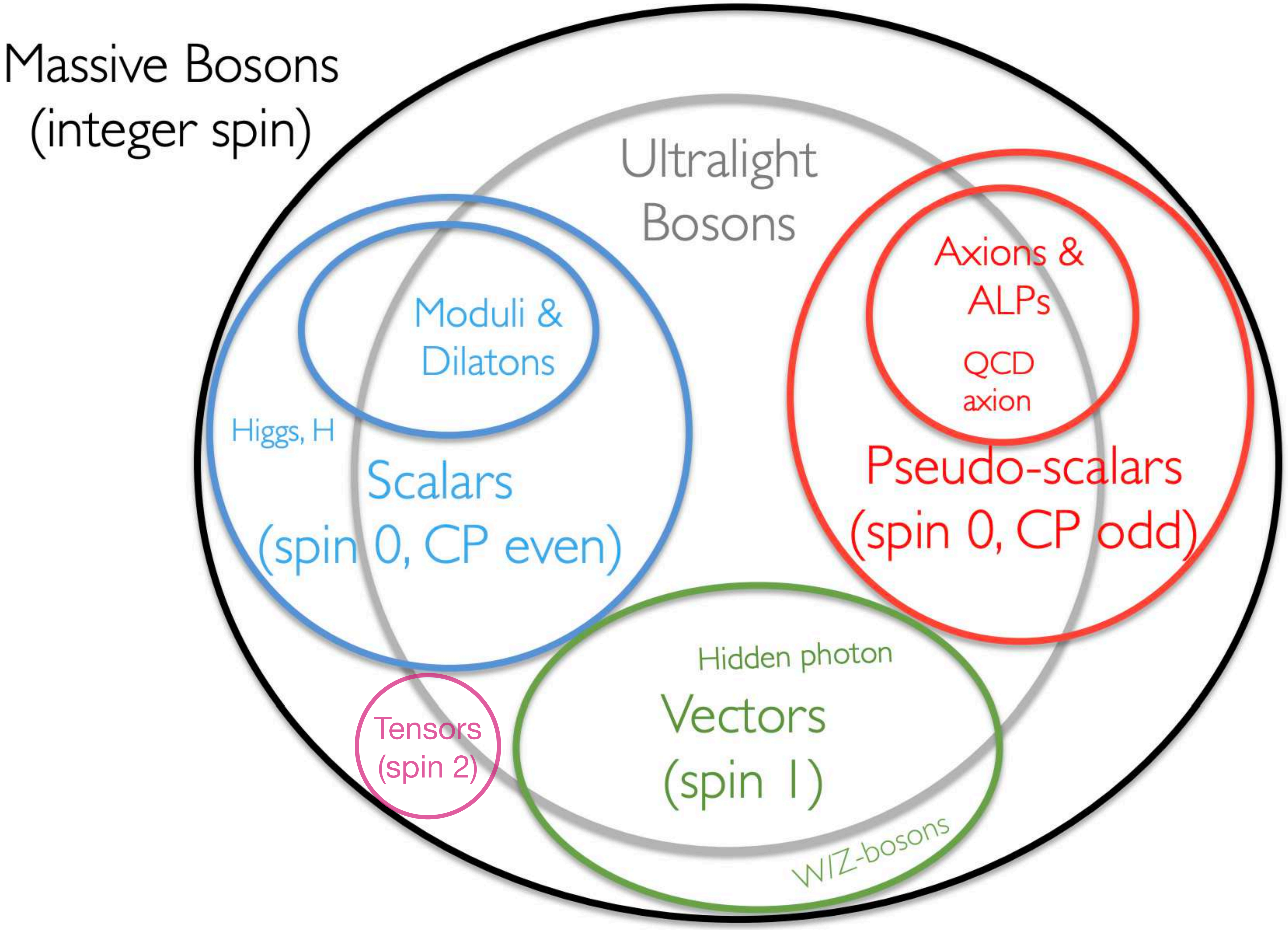
JWST

* not a complete list

Ultra-light Dark Matter

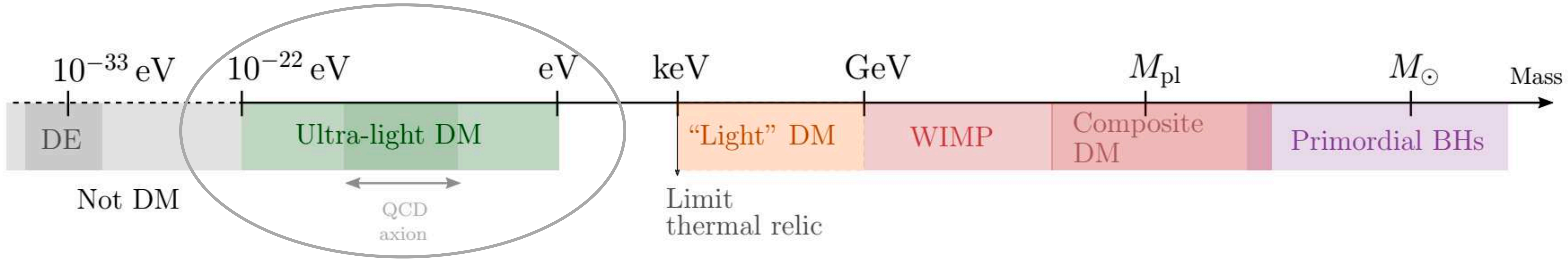
Since we are interested in the gravitational signatures…





Ref.: Modified from Chadha-Day et al 2022

Ultra-light dark matter



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

Andrew
Eberhardt

Qiuyue
Liang

Ippei
Obata

Shun'ichi
Horigome

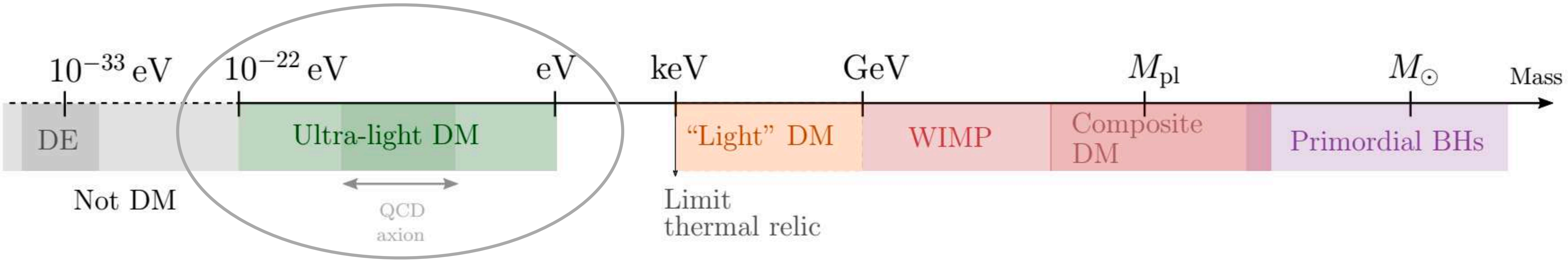
Dongdong
Zhang

Dan
Kondo

Margot
Imbach

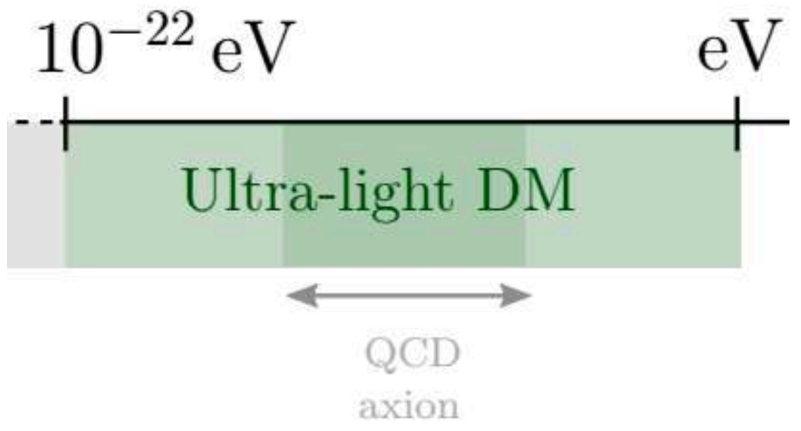
Fernanda
Matos

Ultra-light dark matter



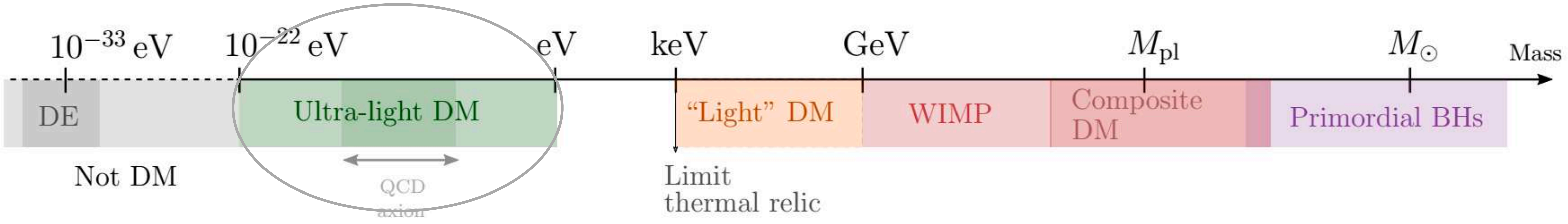
"Ultra-light dark matter", **E.Ferreira**, 2020. The Astronomy and Astrophysics Review.

Ultra-light Dark Matter

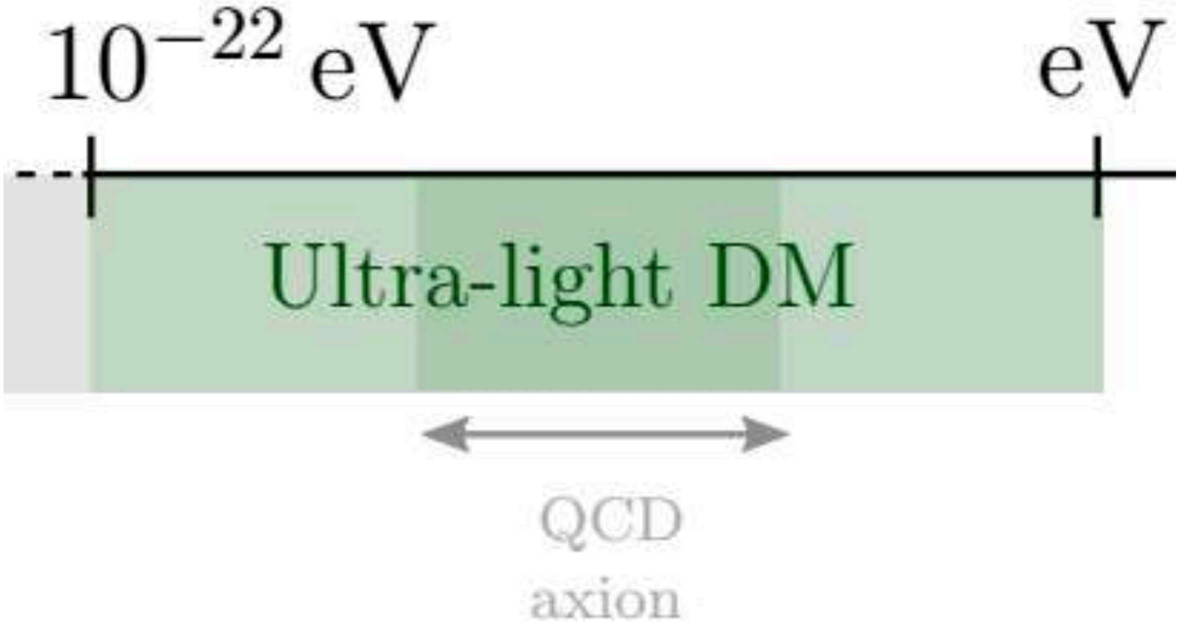


Ultra-light candidate, cold → Large $\lambda_{\mathrm{dB}} \sim 1/mv$

Lightest possible candidate for DM



10^{-57} kg 10^{-35} kg

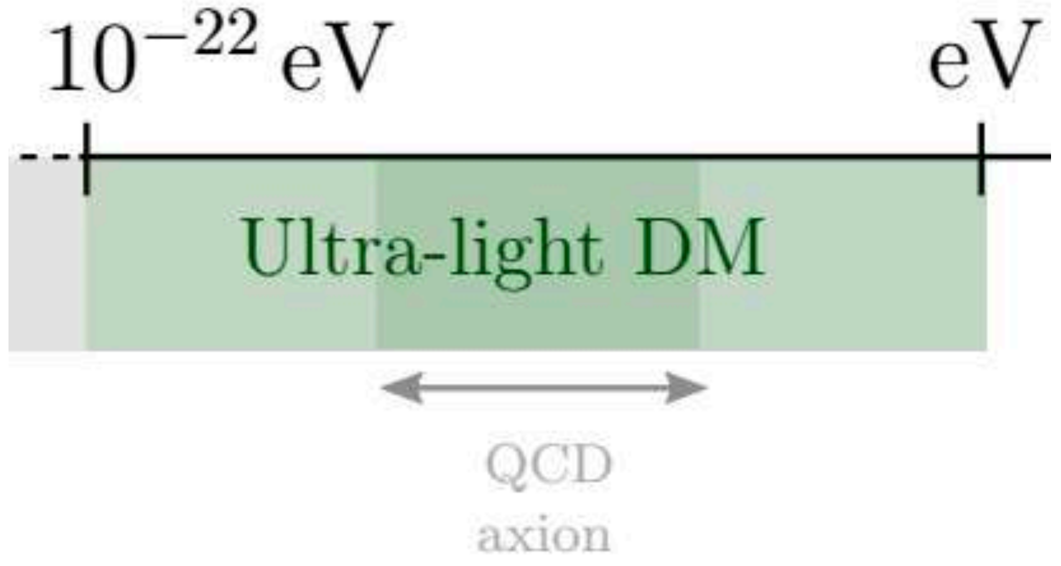


→ Bosons

Non-thermally produced

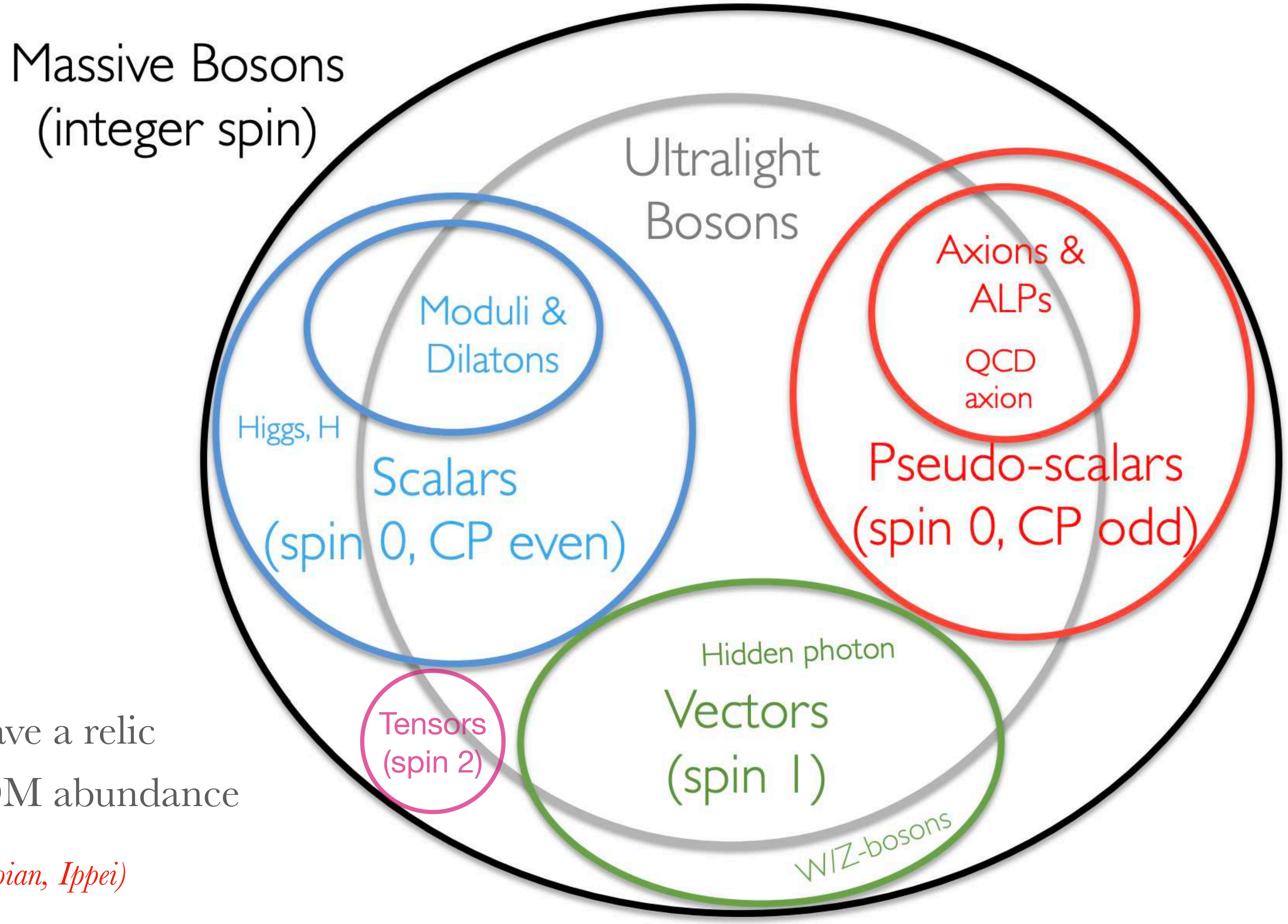
Motivation: particle physics

ULDM candidates



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

Many extensions of the Standard Model predict additional massive bosons



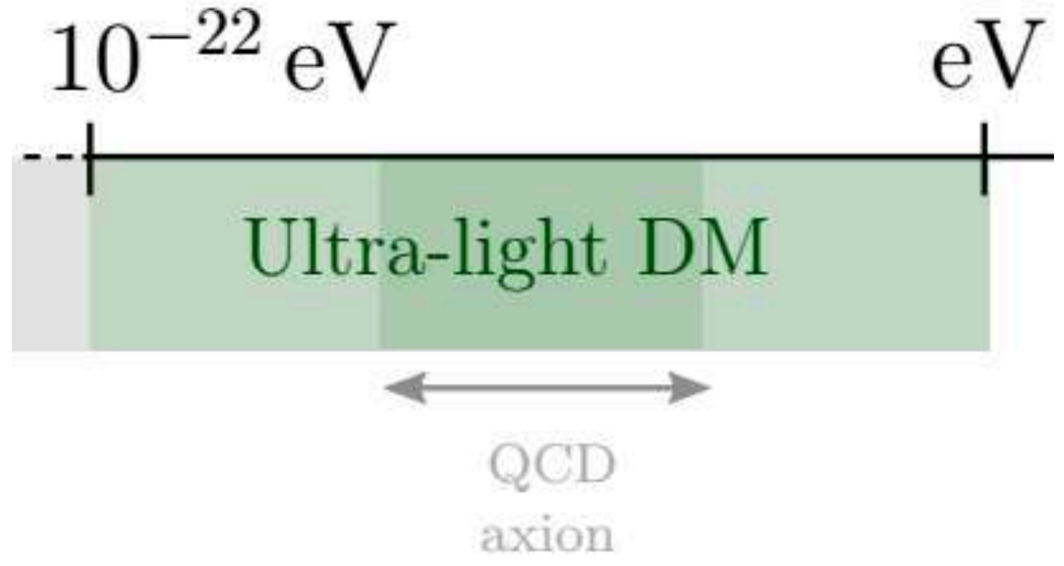
- Formation mechanism: needs to have a relic abundance that gives the correct DM abundance

A lot of research in this at IPMU! (e.g. Kaloian, Ippei)

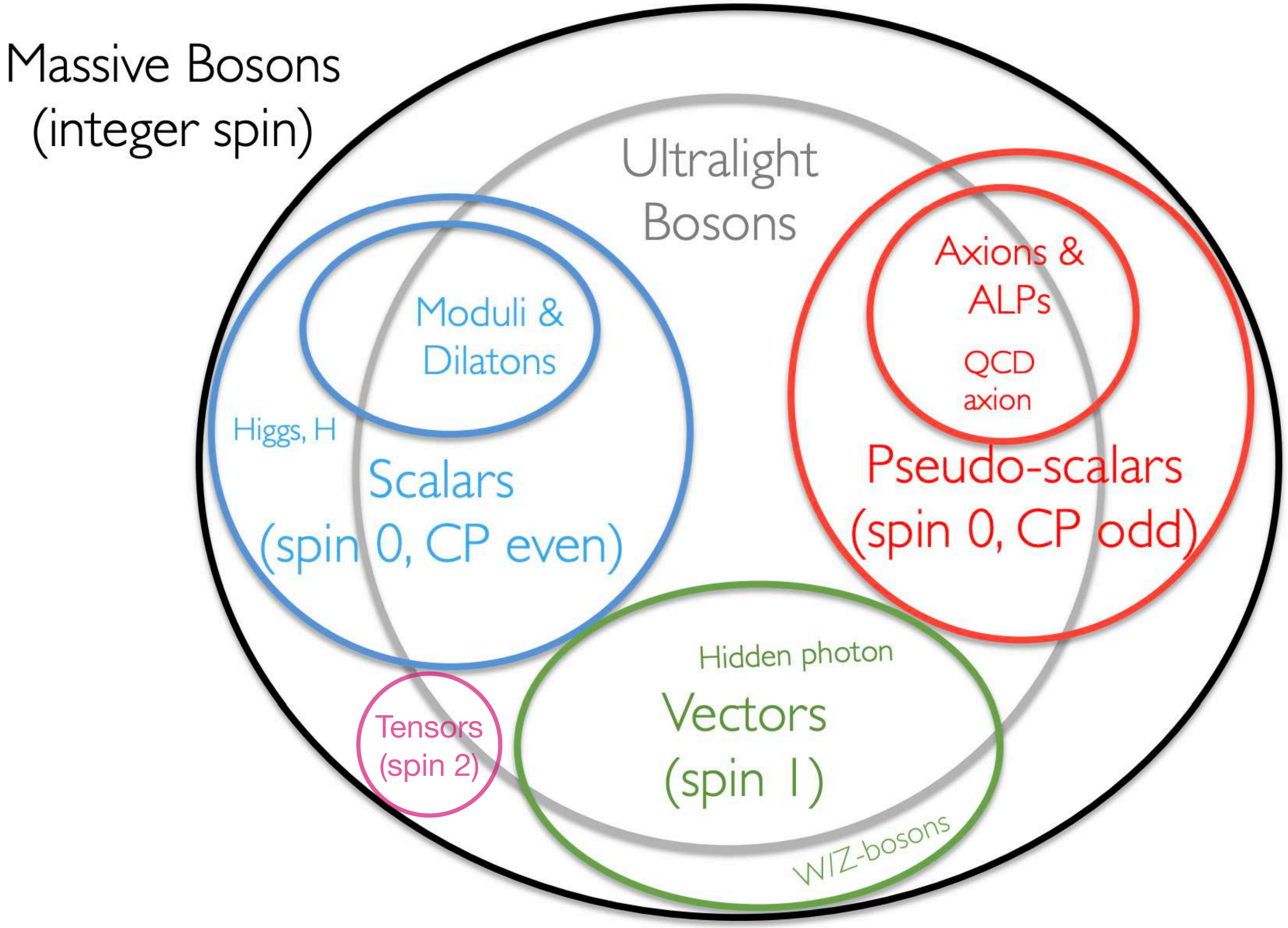
Ref.: Modified from Chadha-Day et al 2022

Motivation: particle physics

ULDM candidates



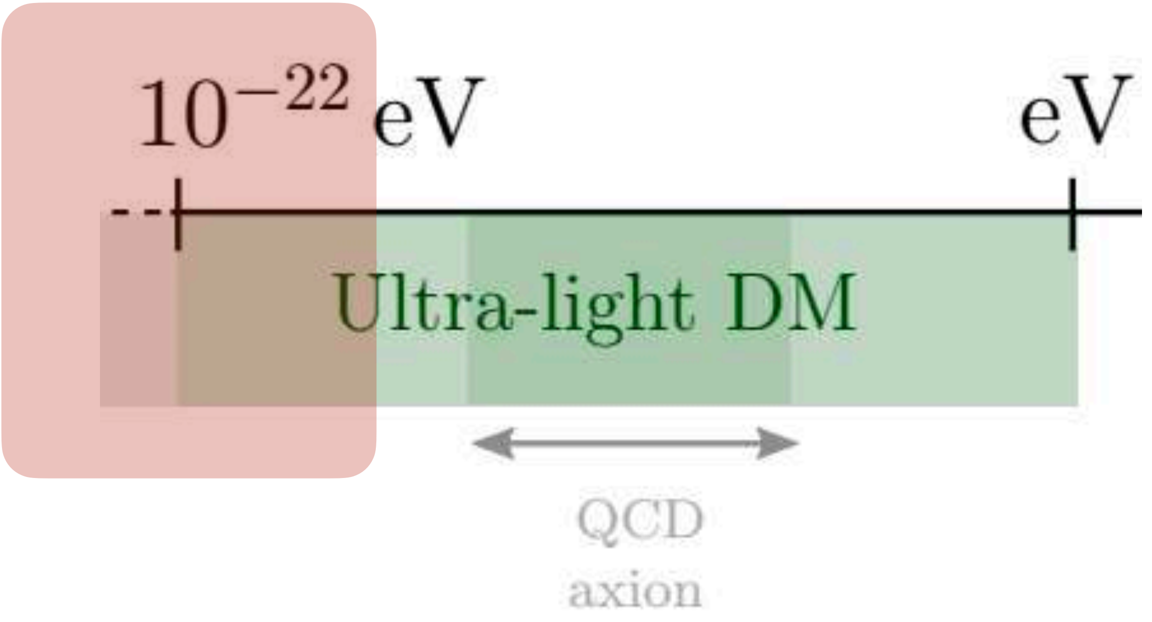
Many extensions of the Standard Model predict additional massive bosons



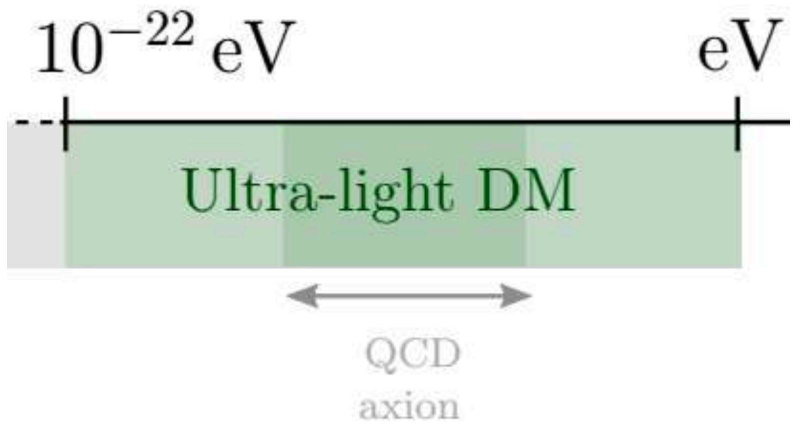
For most of this talk:
Gravitational signatures!

Ref.: Modified from Chadha-Day et al 2022

Cosmological signatures



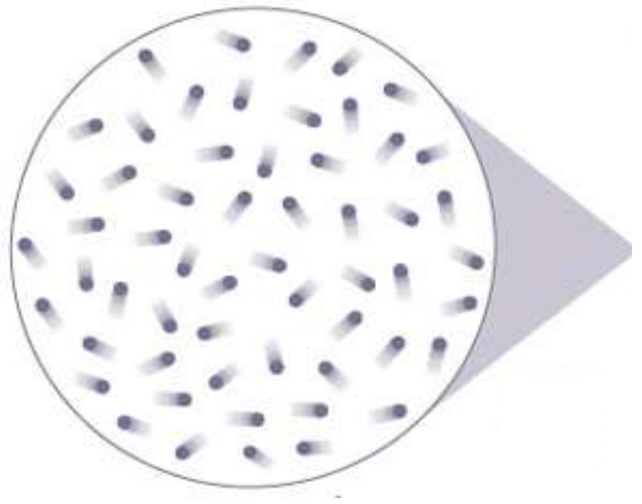
Ultra-light Dark Matter



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

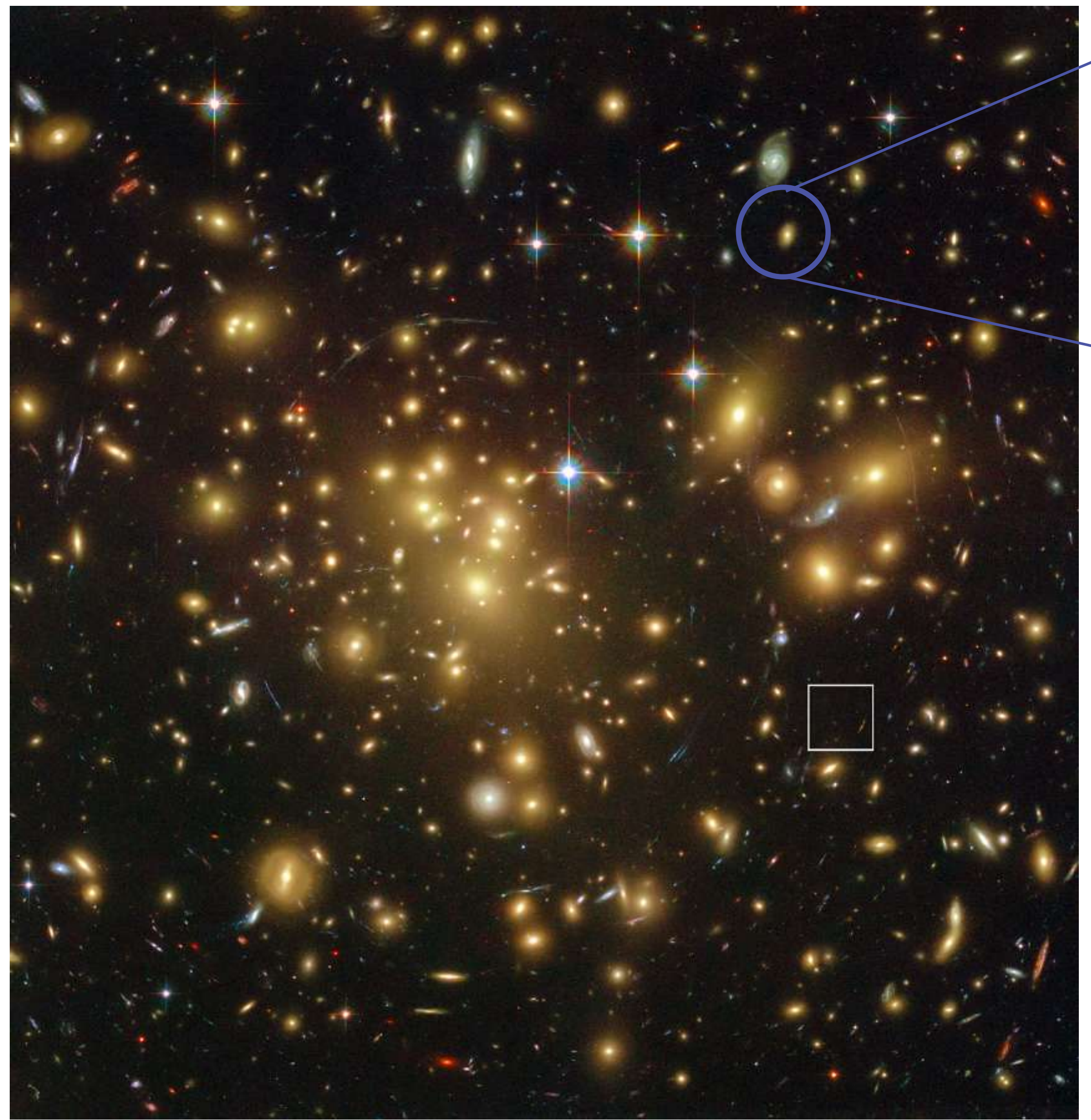
Lightest possible candidate for DM

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

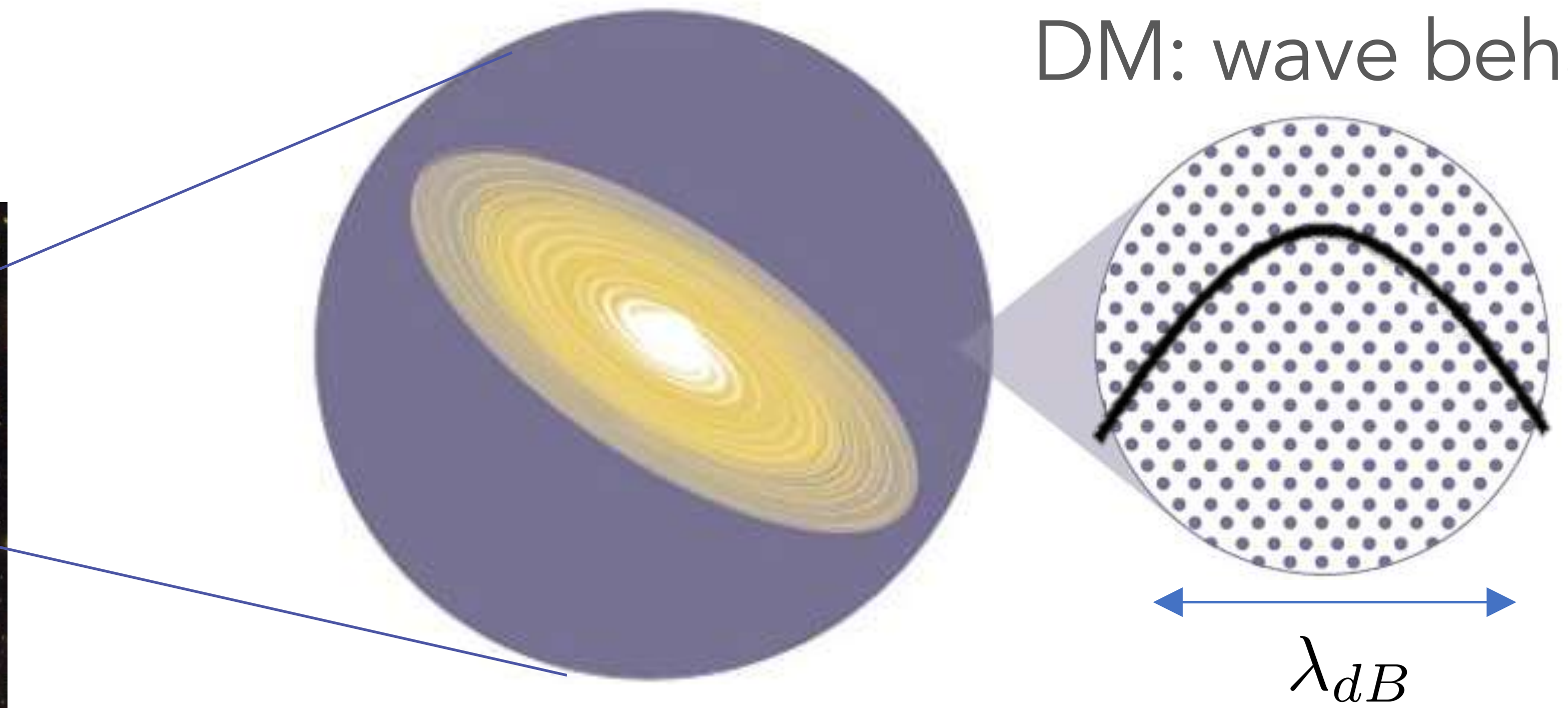


DM: particles

$d \gg \lambda_{dB}$



Adapted from Quanta



DM: wave behaviour

λ_{dB}

Galaxy halo

$d \ll \lambda_{dB}$

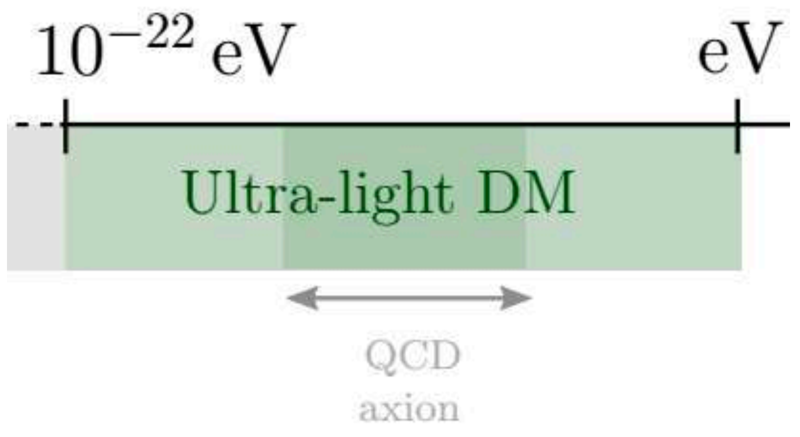
Small scales:
DM behaves like a wave

10^{-60} kg 10^{-35} kg

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

$\lambda_{dB}^{ULDM} \sim$ pc – kpc

Ultra-light Dark Matter -classes



3 classes:

Fuzzy DM
(FDM)

- Gravitationally bounded ultra-light scalar field model

DOFs m

Self Interacting FDM
(SIFDM)

- Presence of (weakly) self-interaction

m g

DM Superfluid

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

Axion and ALP (axion like particles)

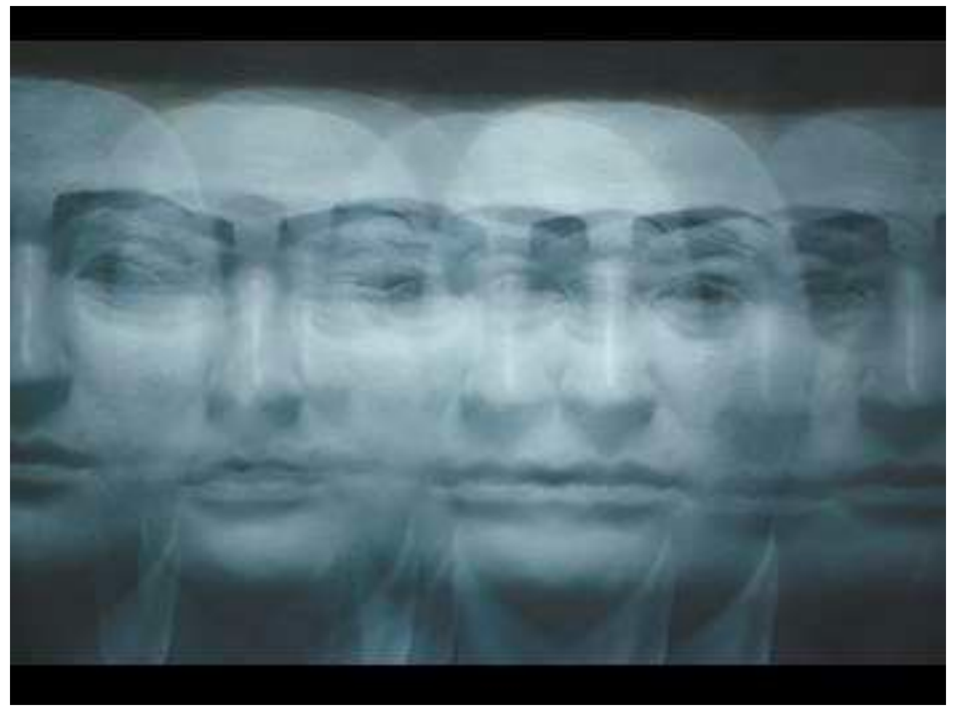
$$i\dot{\psi} = \left(-\frac{1}{2m}\nabla^2 + \frac{g}{8m^2}|\psi|^2 - m\Phi\right)\psi$$

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

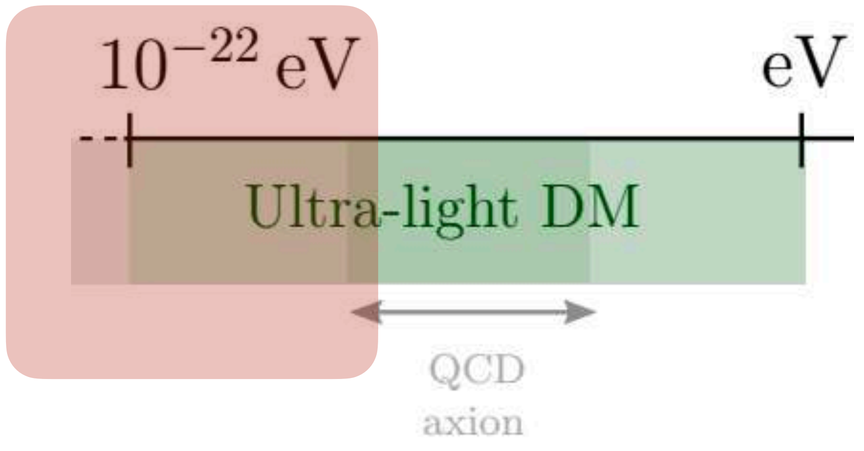
⟶ Connection with condensed matter and particle physics!

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

Fuzzy dark matter



Fuzzy Dark Matter



Fuzzy DM
(FDM)

- Gravitationally bounded ultra-light scalar field model

m

Wave DM
Ultra-light axions

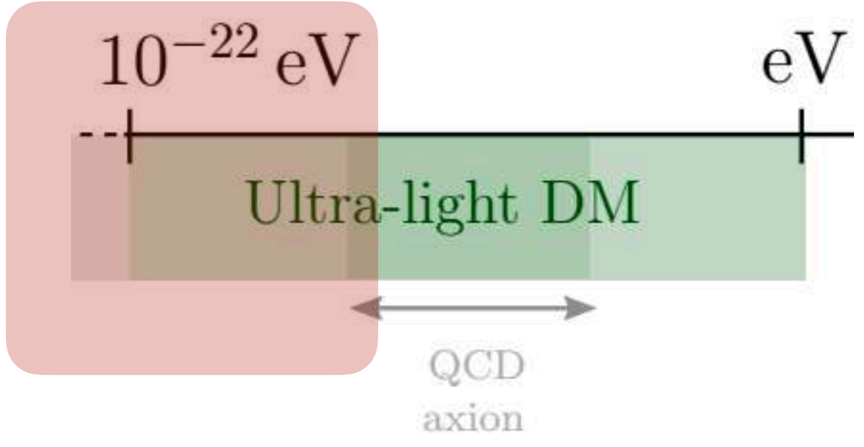
Focus *more* on spin 0 particles here!

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

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

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

Structure formation - non-relativistic regime



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

Schrödinger-Poisson system : describe the FDM and the SIFDM

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

Schrödinger equation (Gross-Pitaevskii)

Poisson equation

$g = 0$ → FDM

$g \neq 0$ → SIFDM

Fundamentally different than CDM/WDM/SIDM!

FLUID DESCRIPTION

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

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

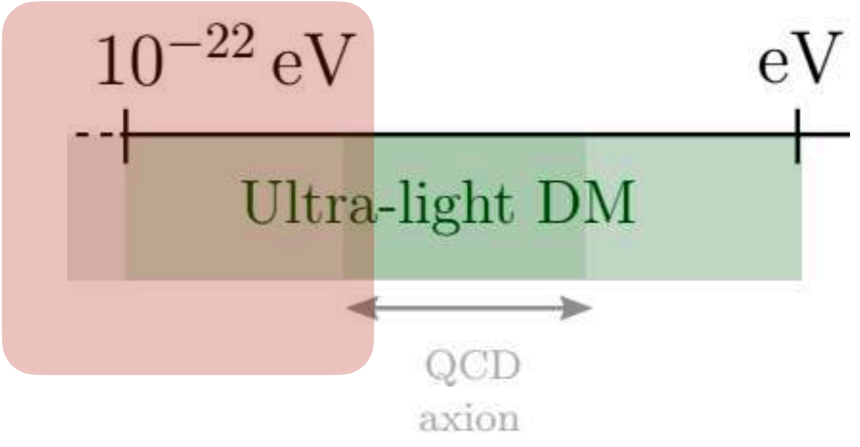
$$\dot{\mathbf{v}} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - P_{int} - \boxed{\frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}}\right)$$

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

Quantum pressure

Finite Jeans length - Suppresses structure formation on small scales

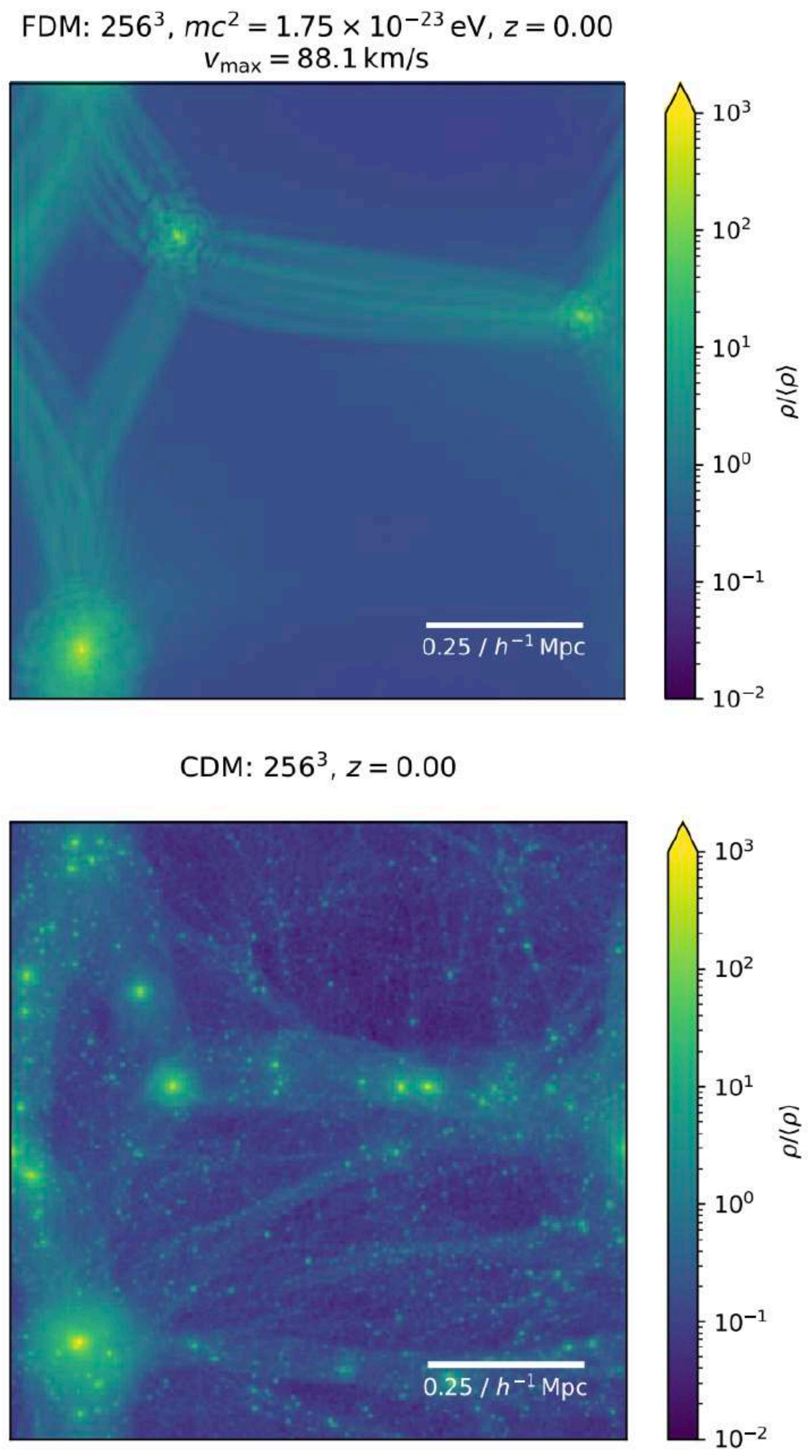
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

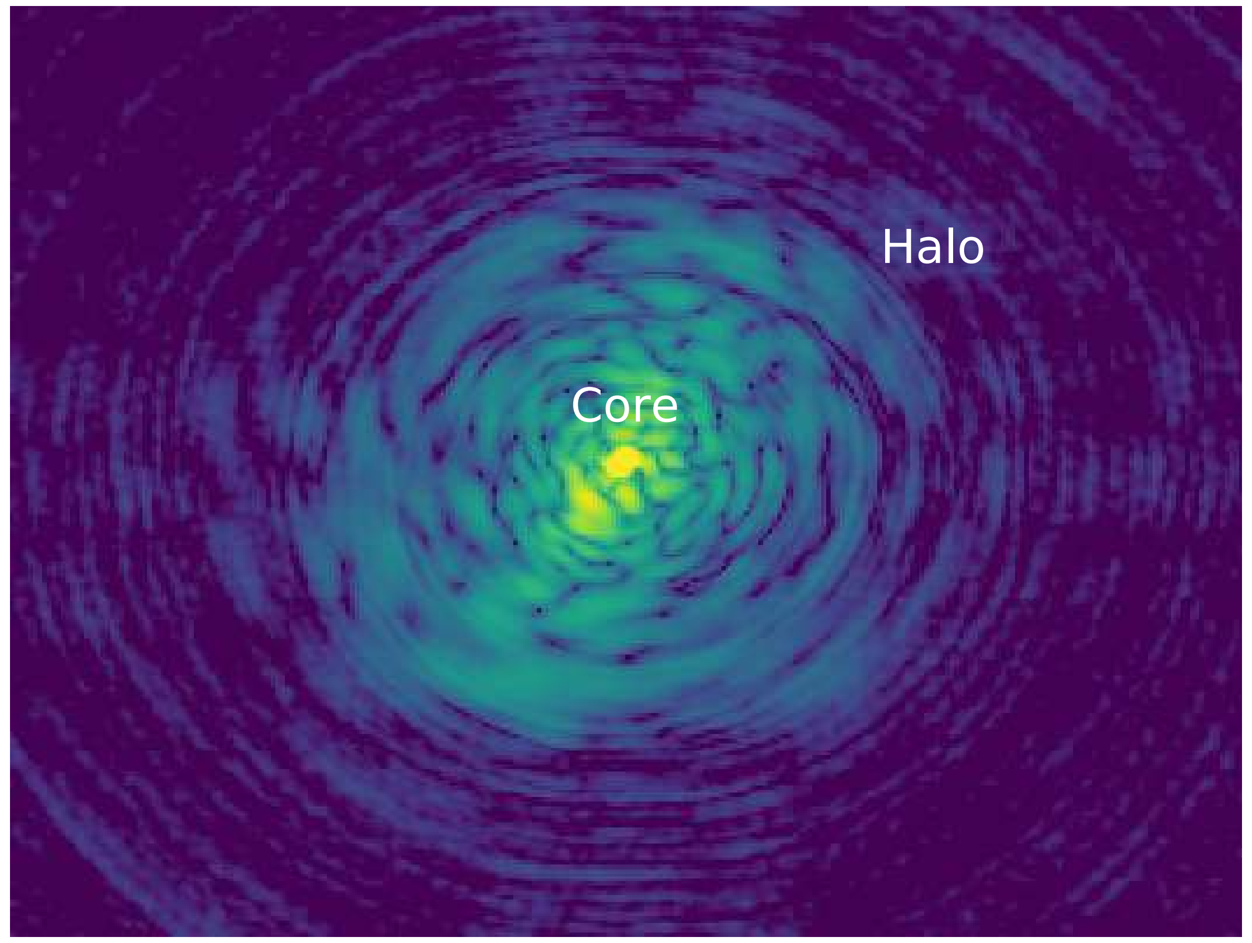
* Focus only in gravitational signatures

Suppression of small structures

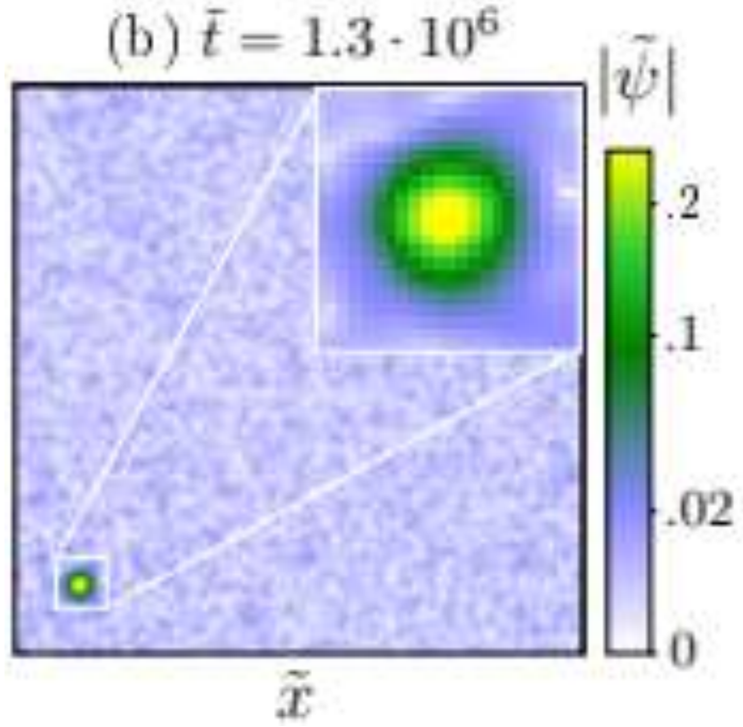


S. May et al. 2021

Formation of a solitonic core

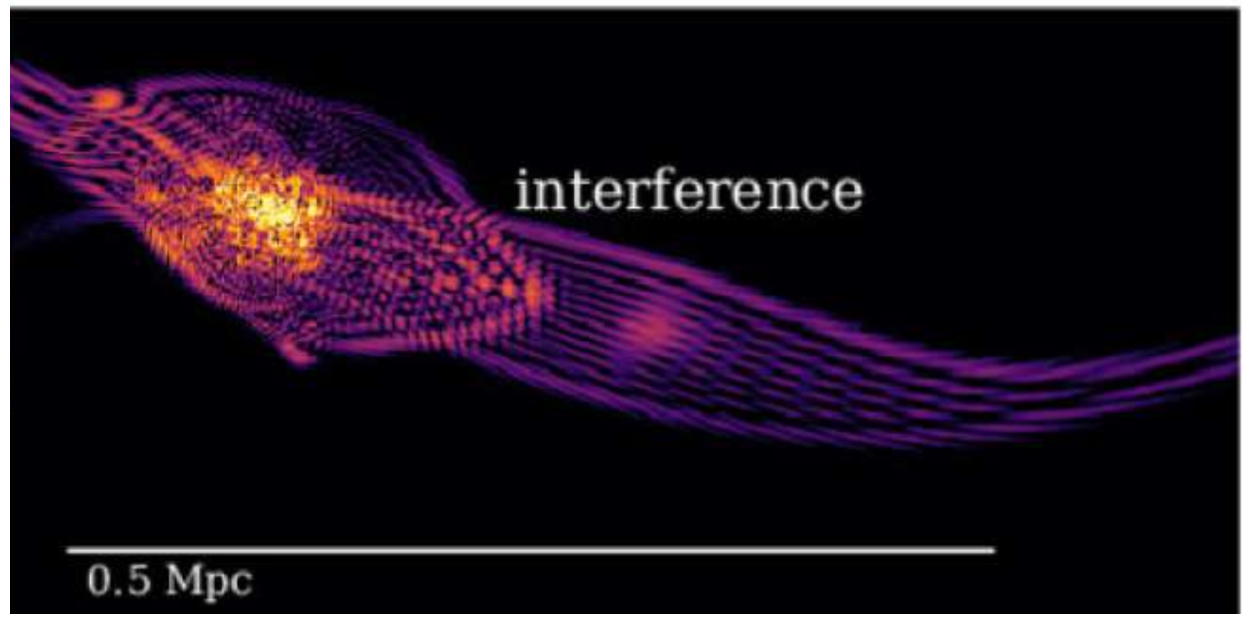


Dynamical effects



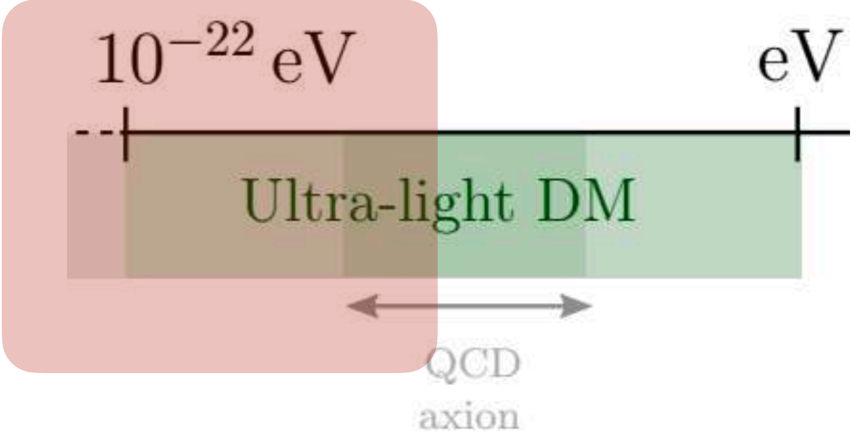
Levkov et al. 2018

Wave interference



Mocz et al. 2017

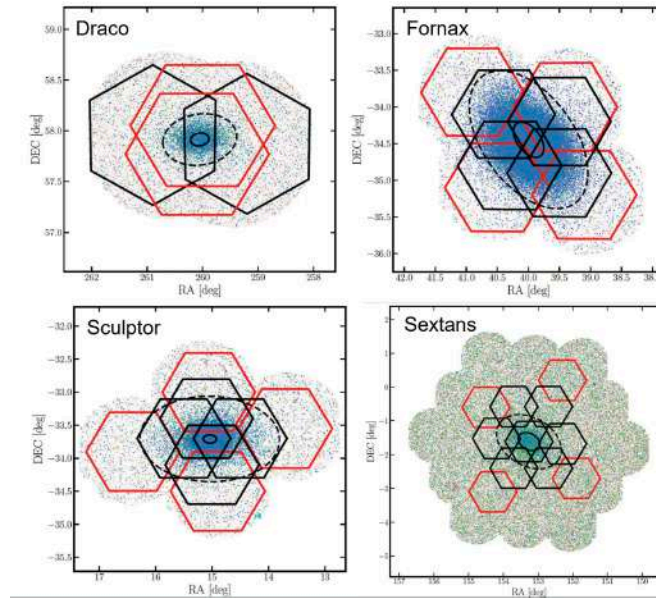
Observational implications and constraints



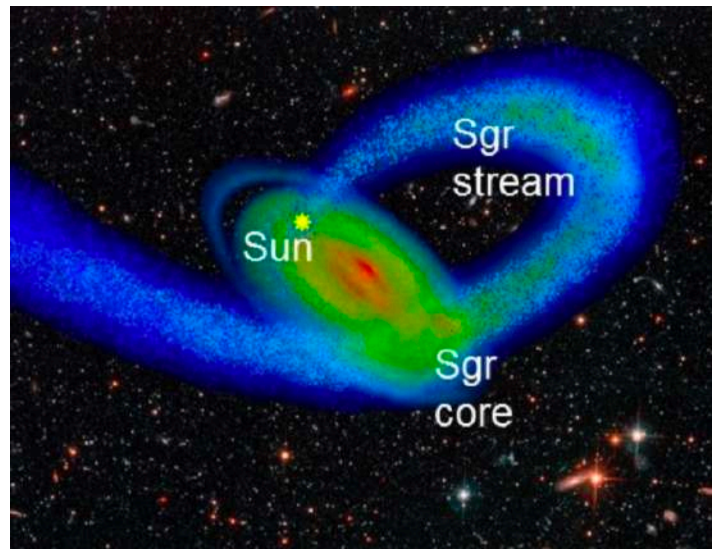
Galaxies

NASA and ESA

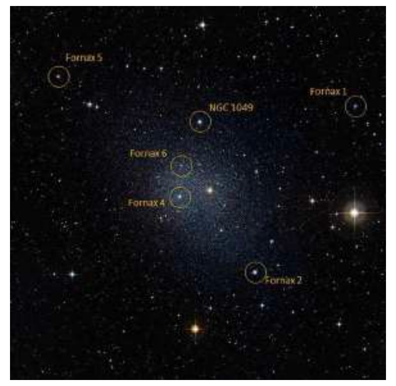
Dwarfs



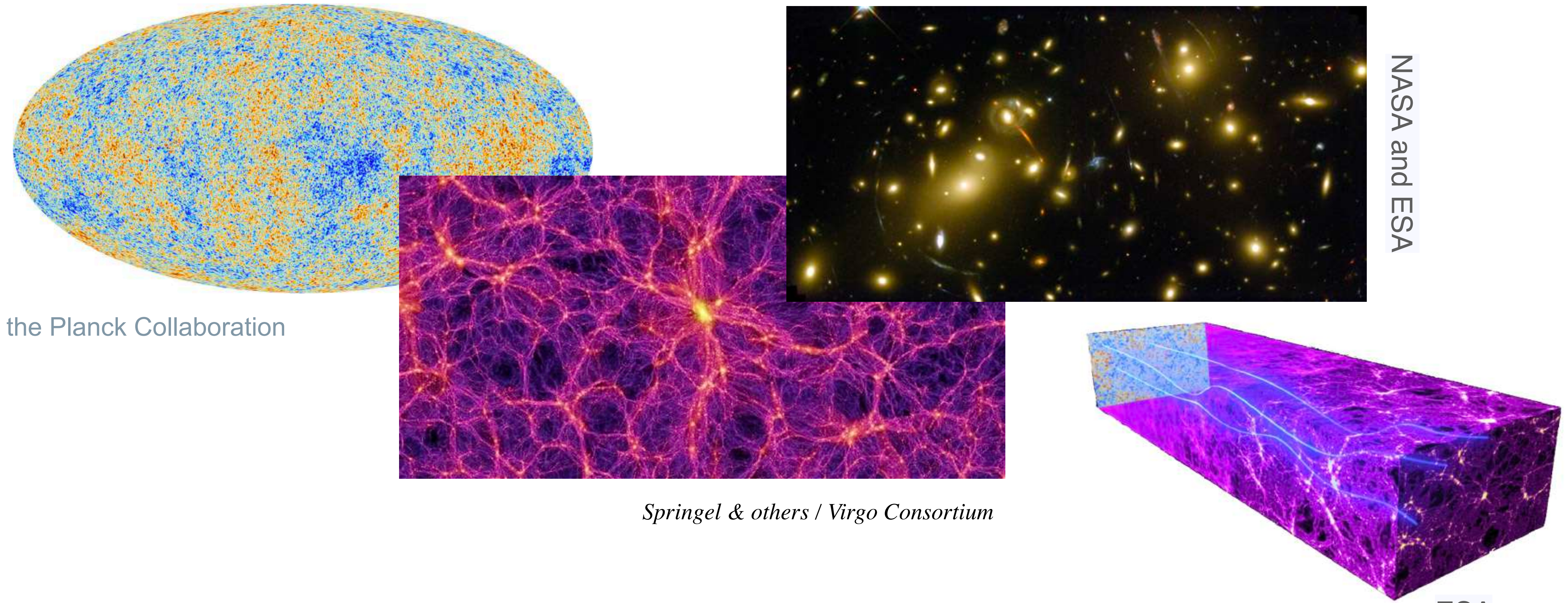
Stellar stream



Globular clusters



CMB+LSS



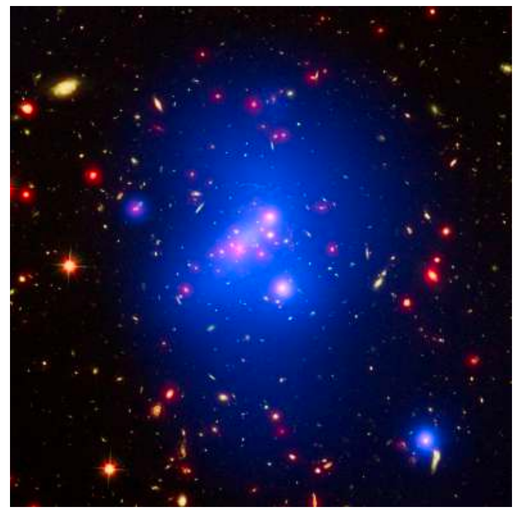
ESA and the Planck Collaboration

NASA and ESA

Springel & others / Virgo Consortium

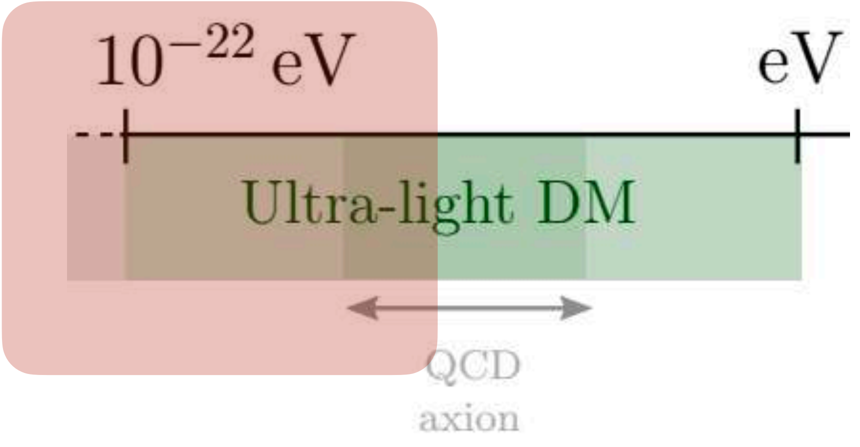
ESA

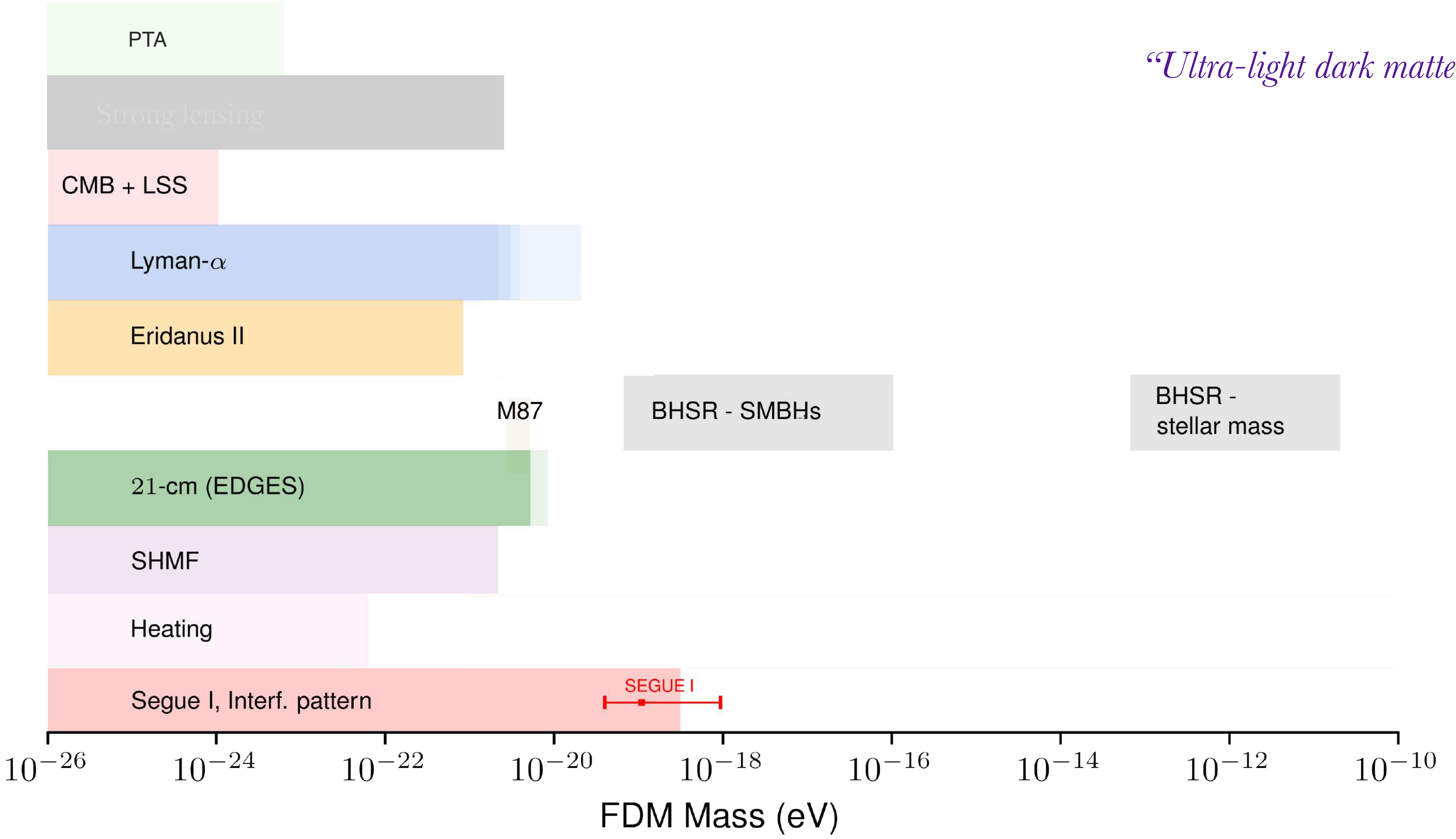
Clusters



Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



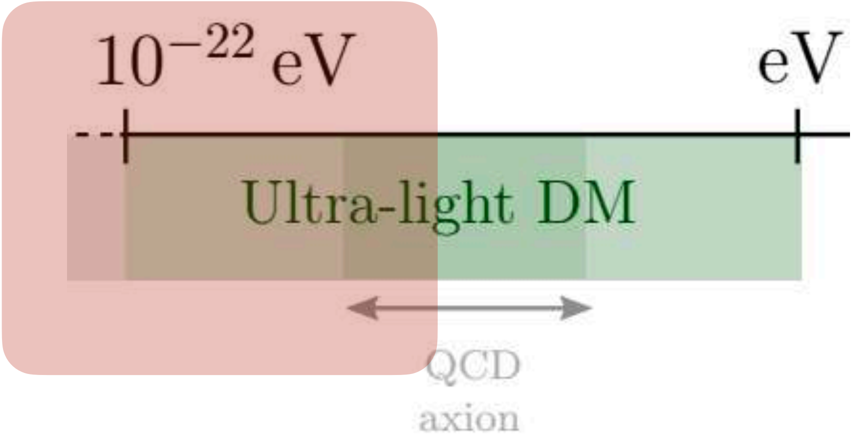


"Ultra-light dark matter", **E.F.**, 2020. The Astronomy and Astrophysics Review.

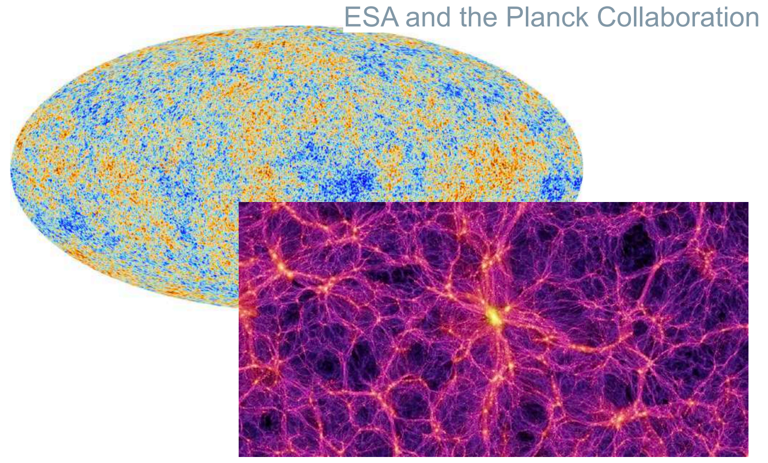
Bounds consider FDM is *all* DM

Current status

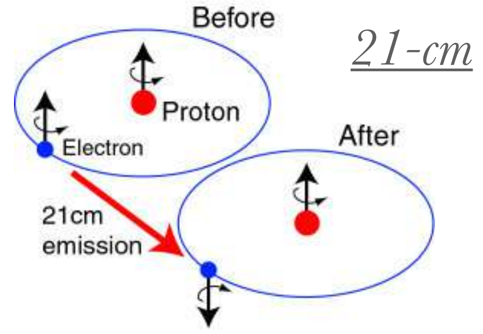
Fuzzy Dark Matter - bounds on the mass



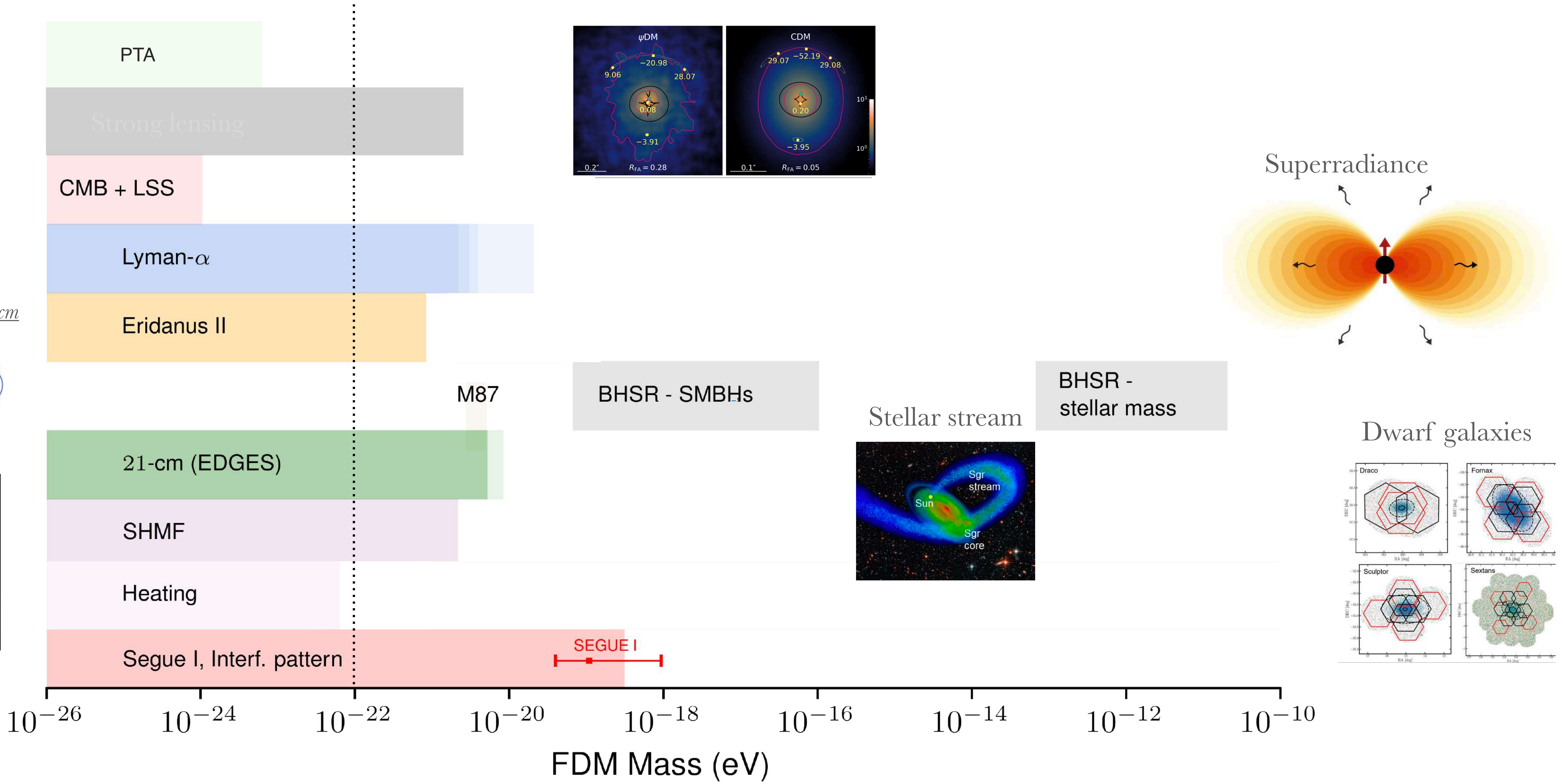
ESA and the Planck Collaboration



Springel & others / Virgo Consortium



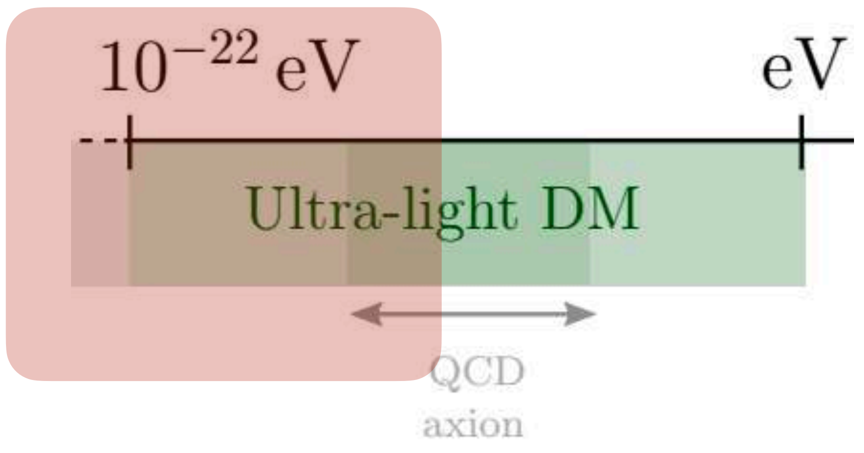
NASA and ESA

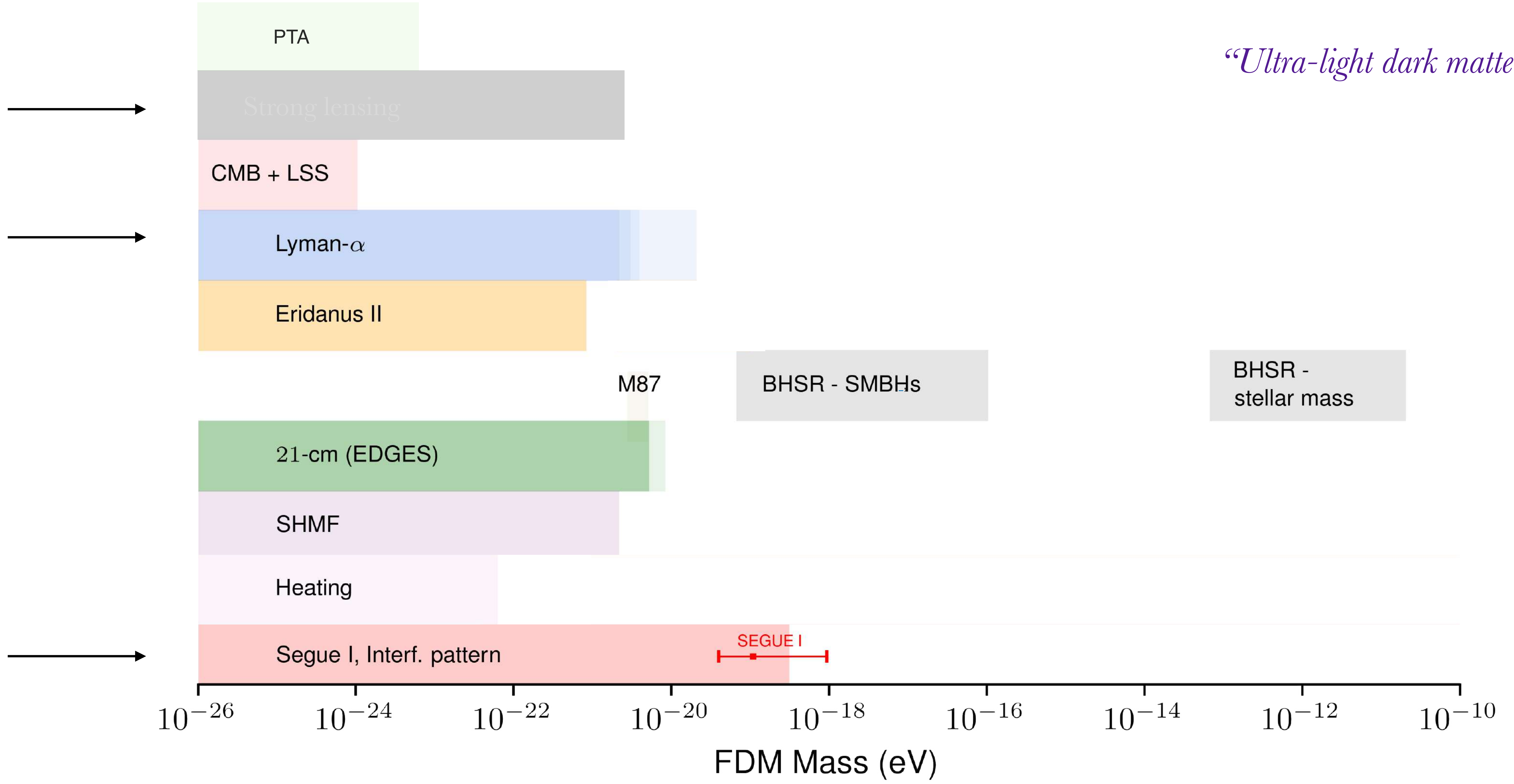


“Ultra-light dark matter”, **E.F.**, 2020

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass





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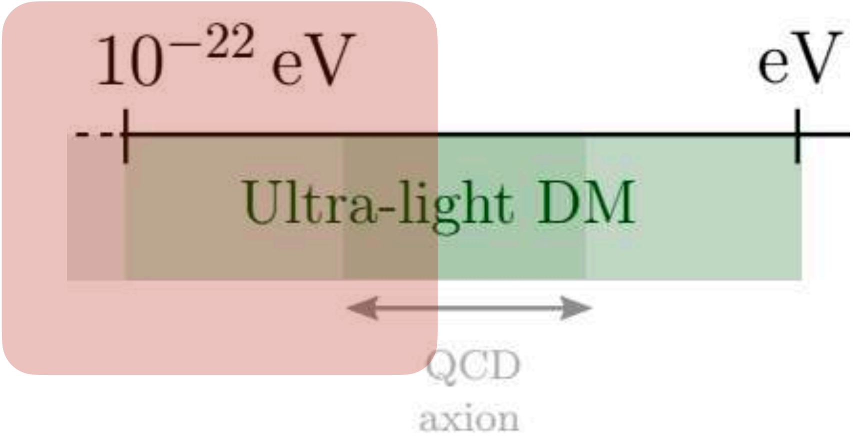
Bounds consider FDM is *all* DM

Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass



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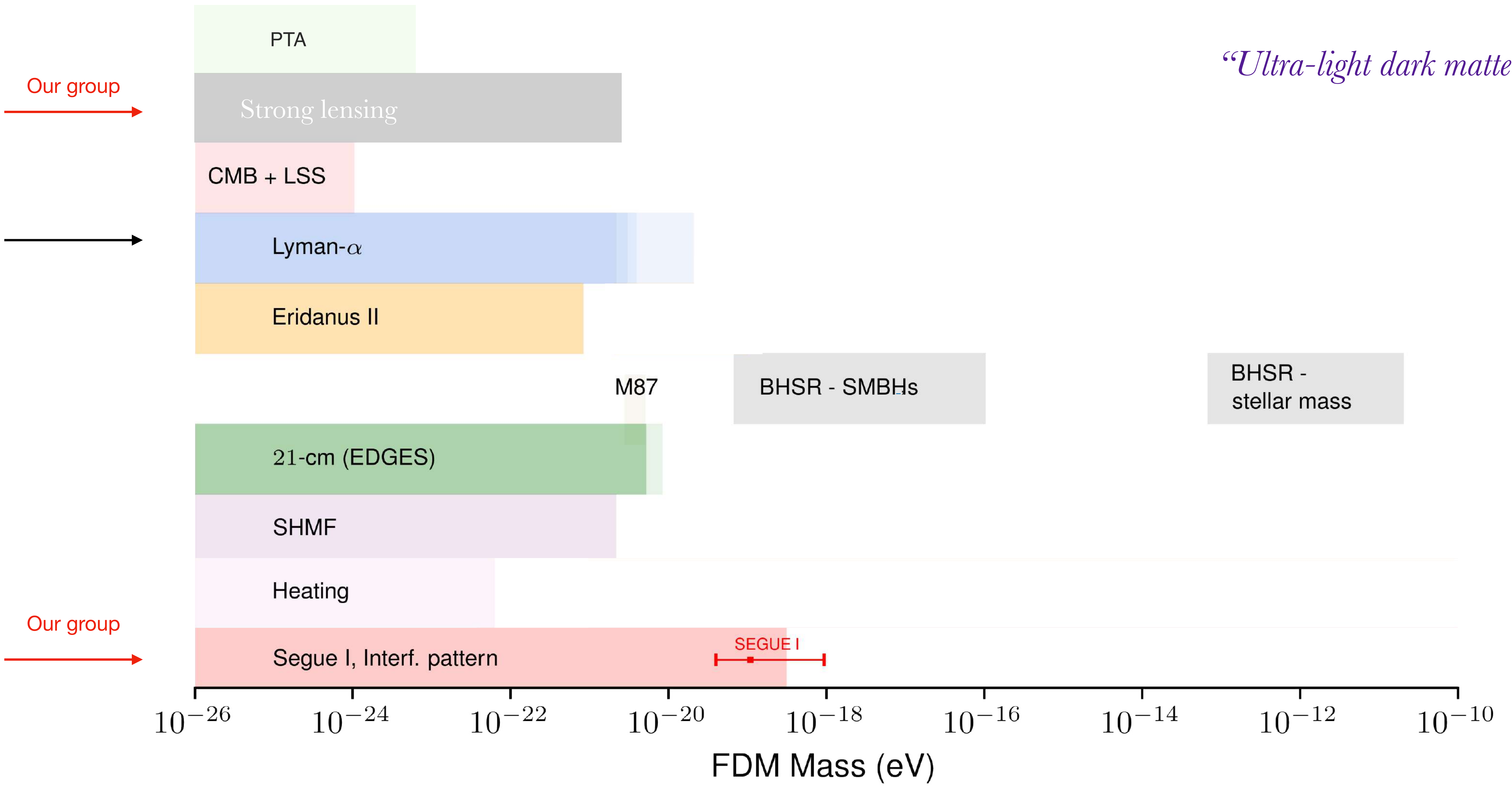


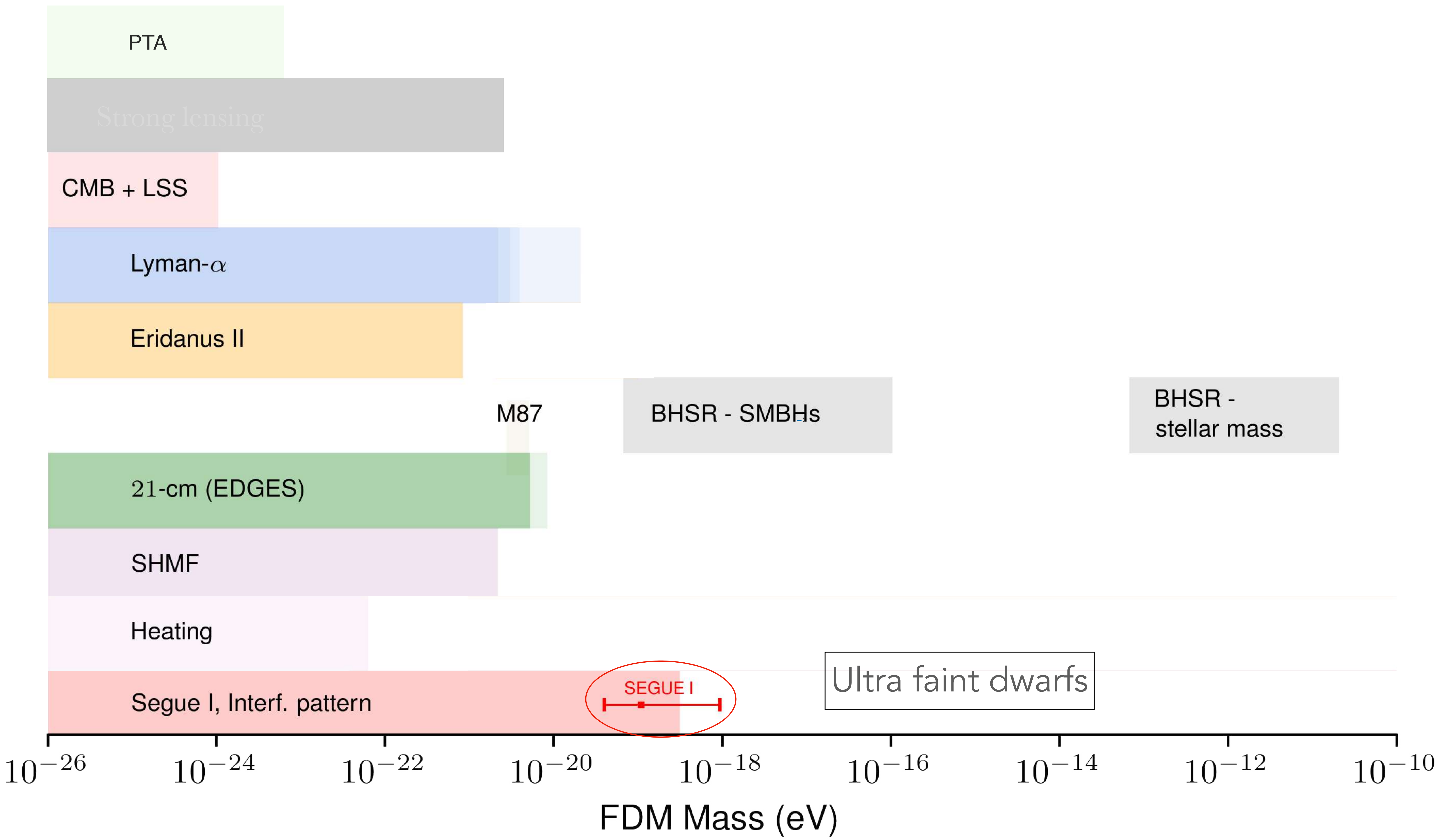
Bounds consider FDM is *all* DM

Our group has some of the strongest bounds on these models!

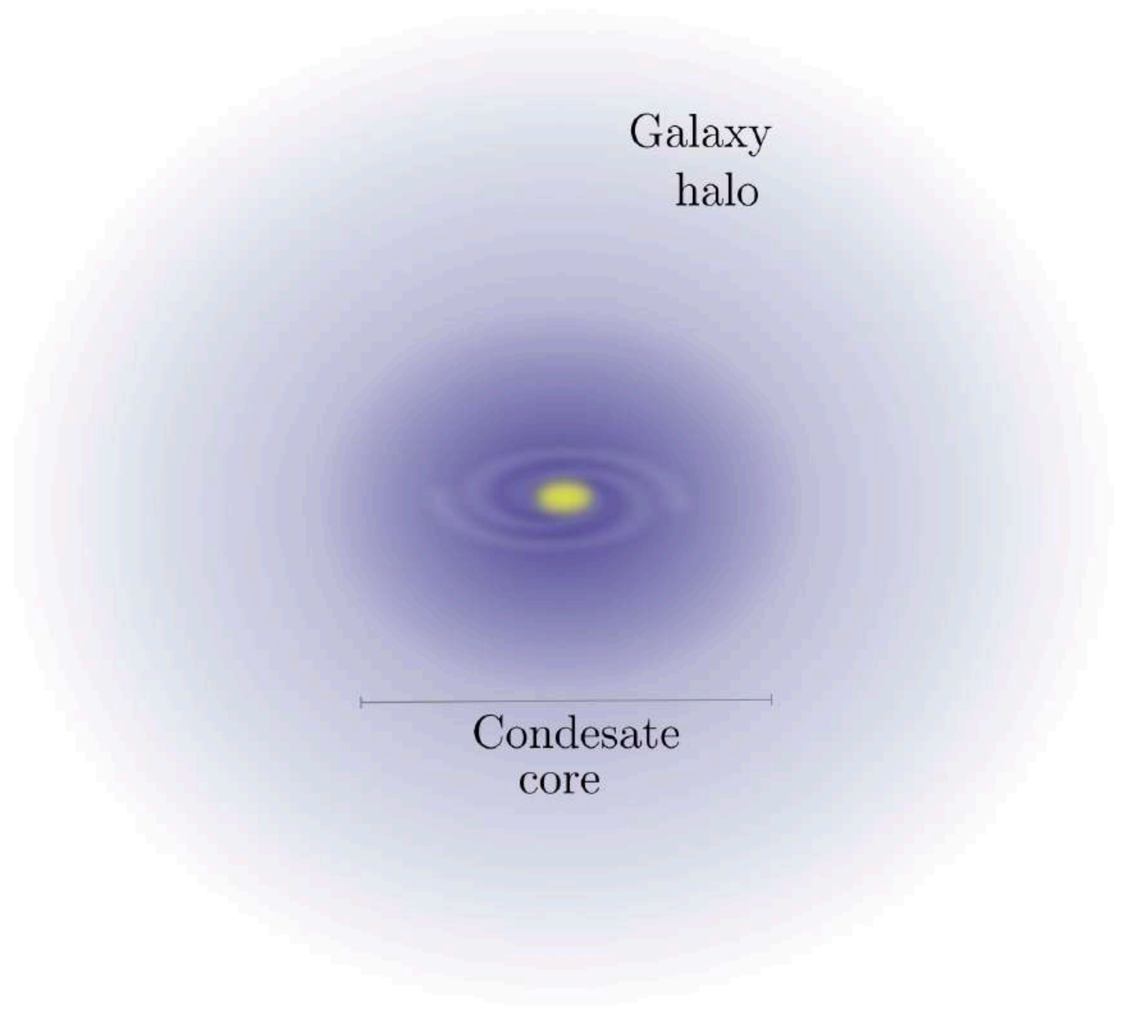
Observational implications and constraints

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.

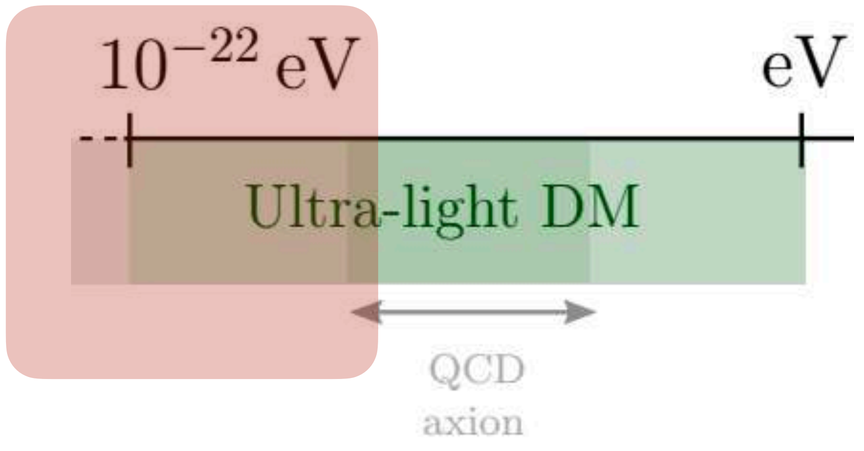


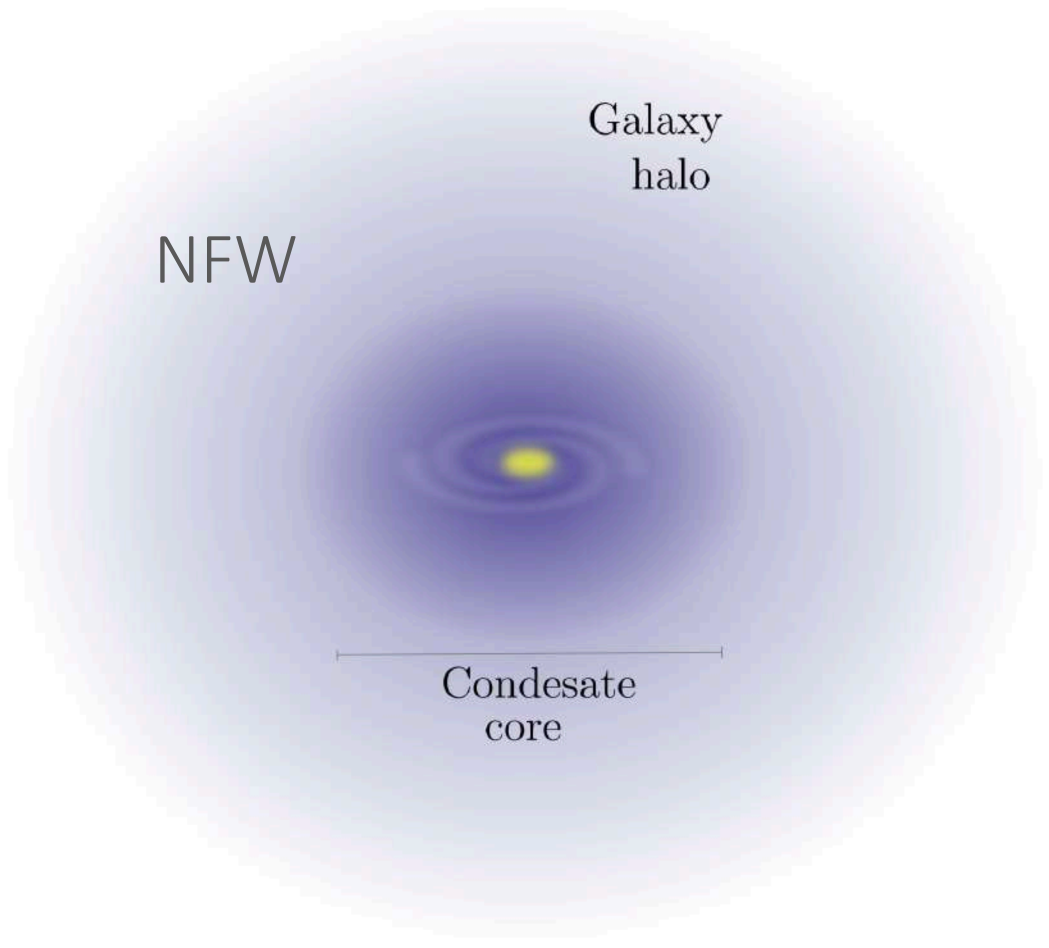
Presence of a core



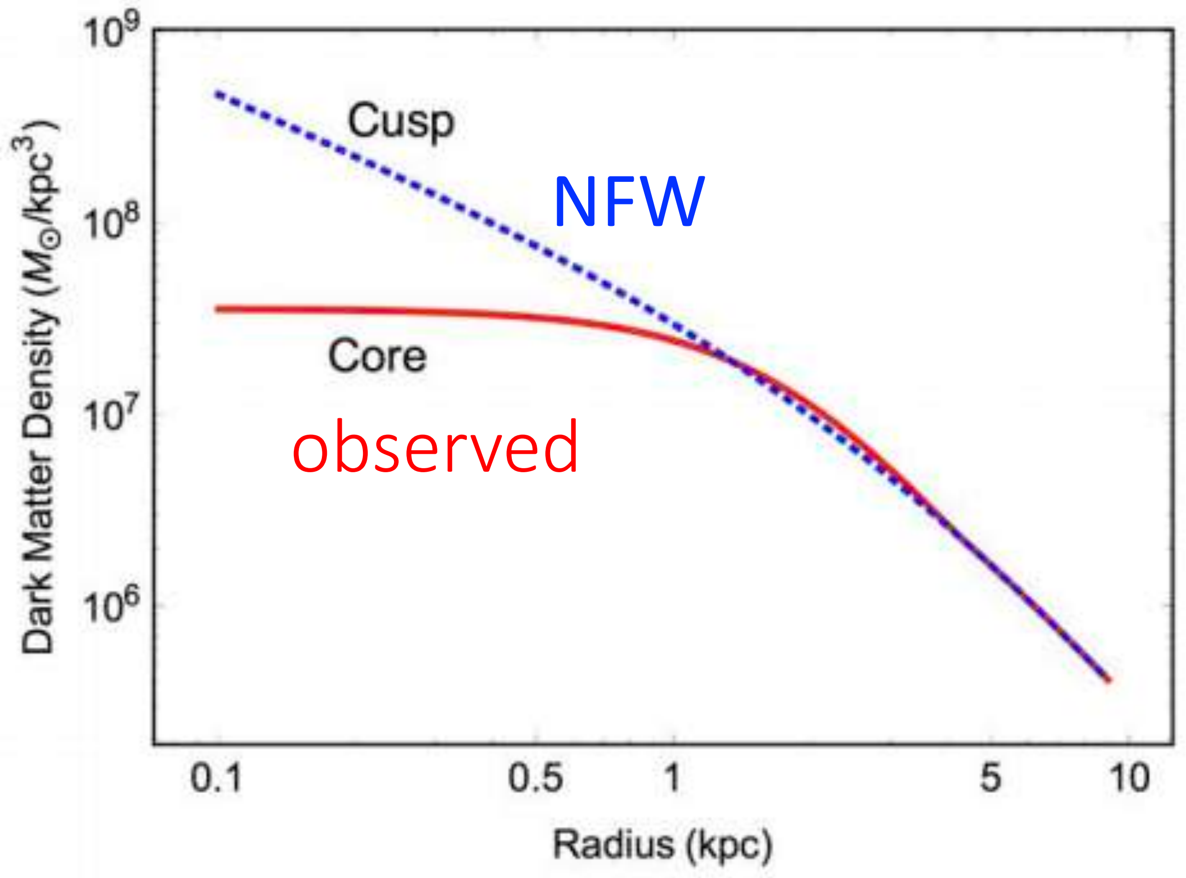
Phenomenology

Formation of cores





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



FDM

From simulations Schive et al. 2014, fitting function:

Updated by our group (*Chan, EF et al 2021*)

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

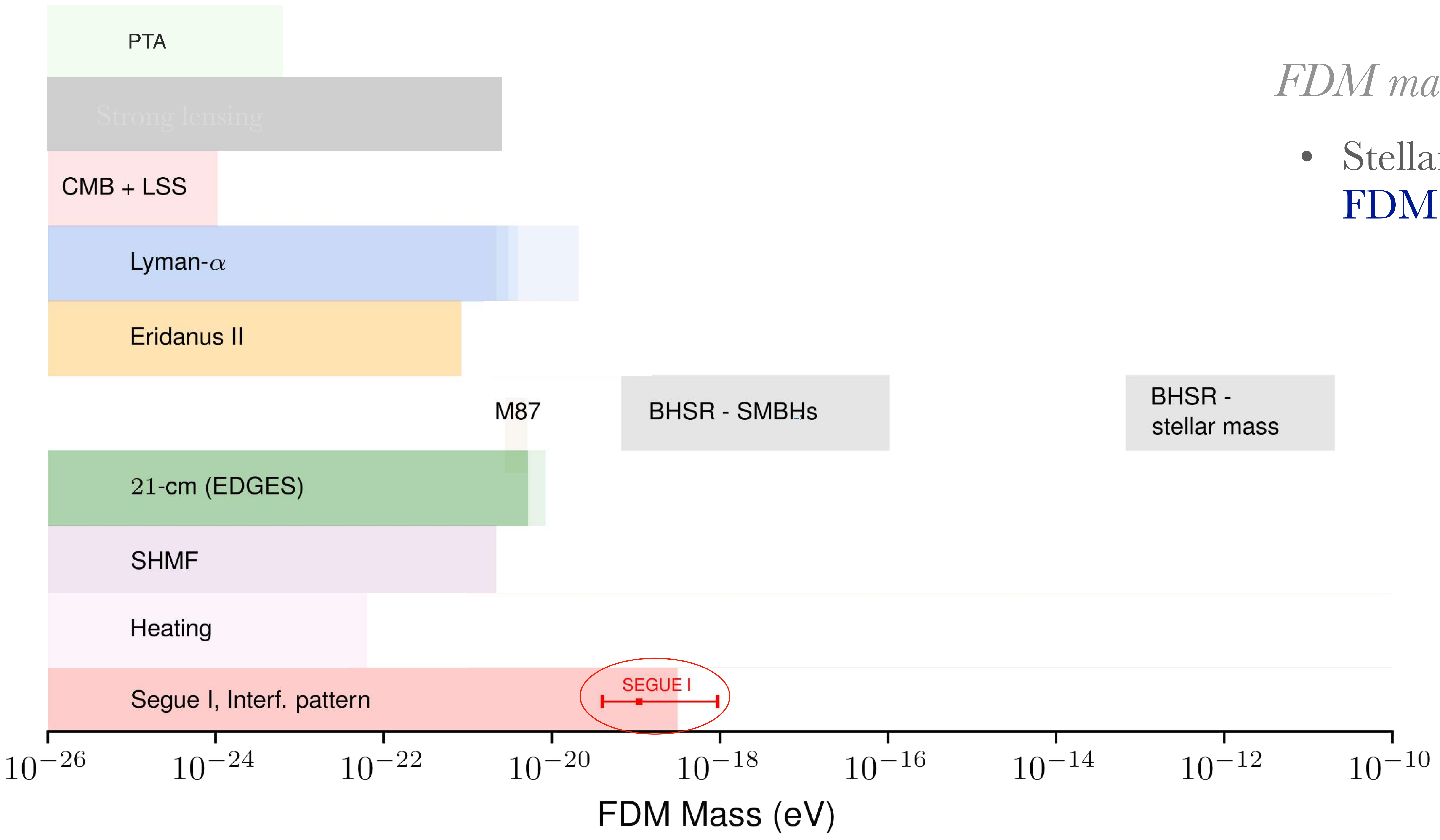
$$r_c \simeq 0.16\left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1}\left(\frac{M}{10^{12}\,M_\odot}\right)^{-1/3}\mathrm{kpc}\,.$$

→

Relations used to compare
with observations

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass



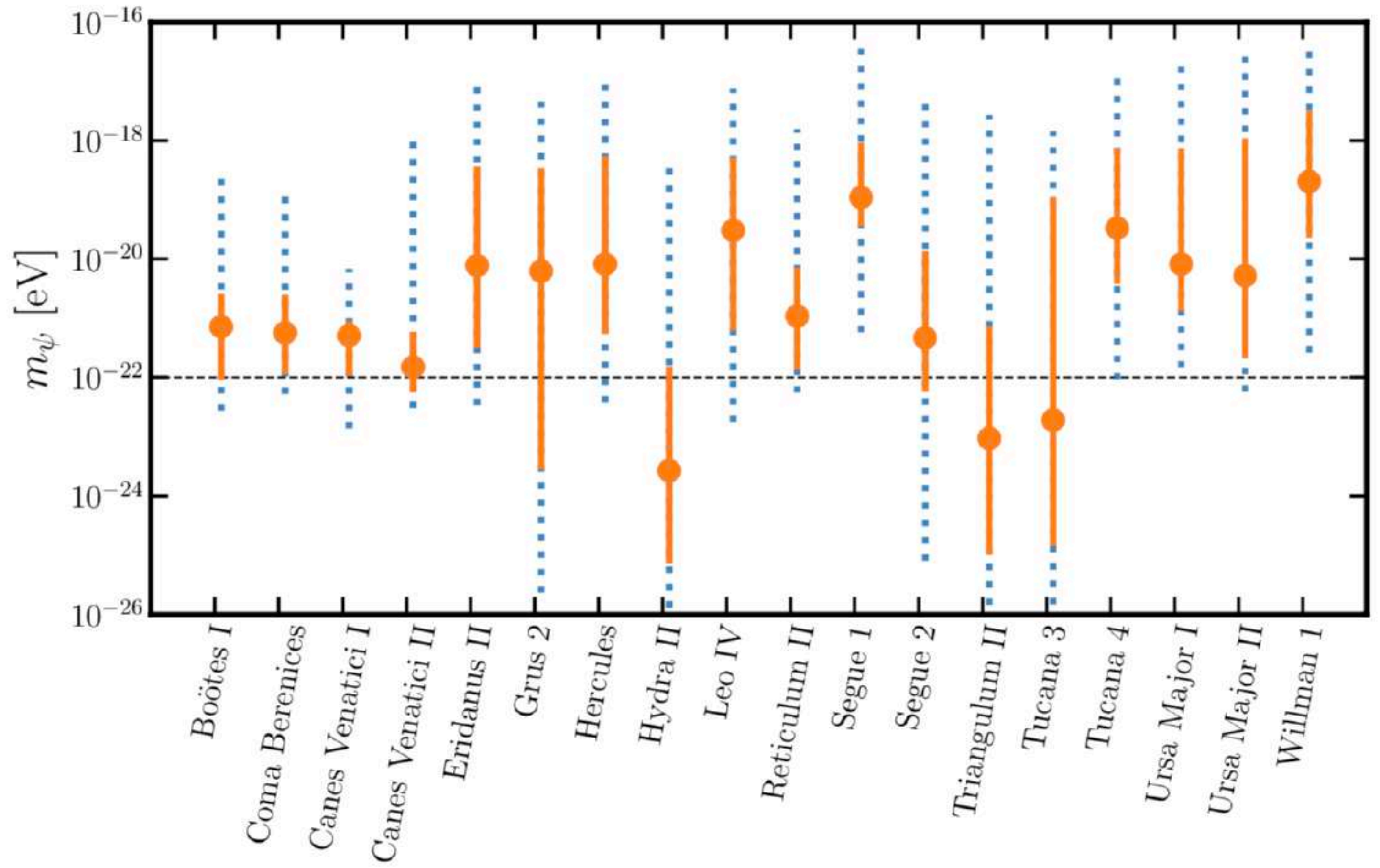
Ultra faint dwarfs

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

FDM mass from Ultra-faint dwarfs

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

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



Preference for higher mass

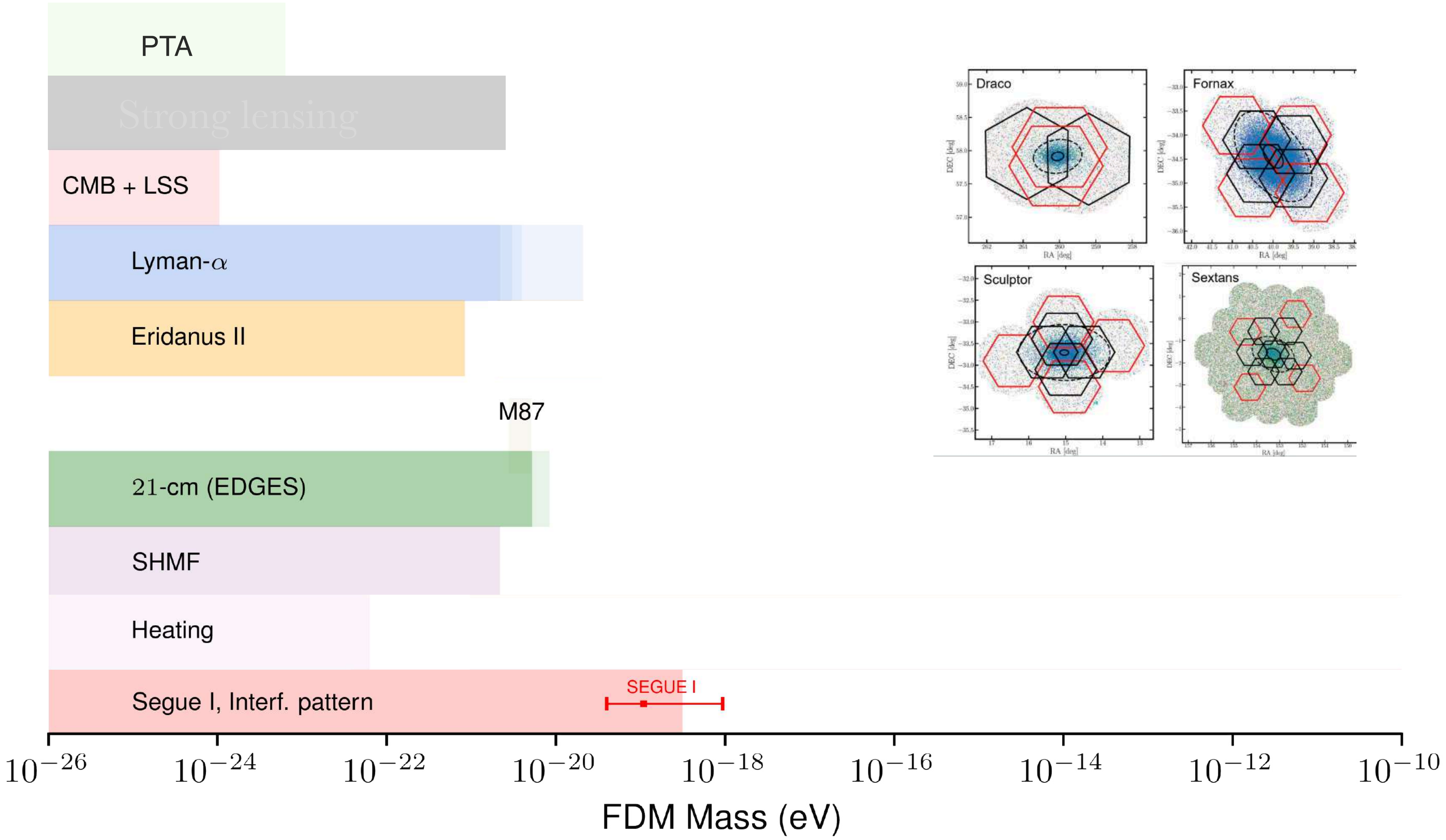
Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass

(Work in progress)


Shun'ichi Horigome


Shin'ichiro Ando



FDM mass from Ultra-faint dwarfs

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

- Repeat the previous analysis with:

  - Improved modelling of FDM based on previous work and simulation from our group

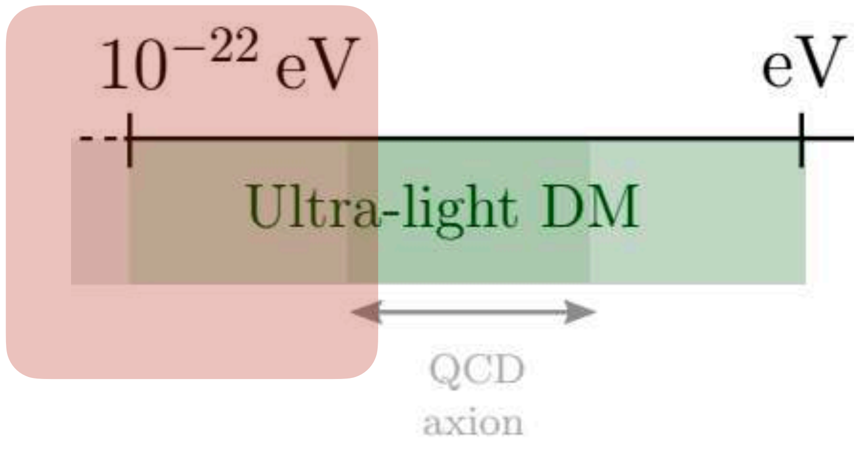
  - Using **environmental effects** to put informed priors for Bayesian analysis the dwarfs quantities - SASHIMI

↓

Result: more conservative and improved bounds
Lessons for **PFS** analysis!

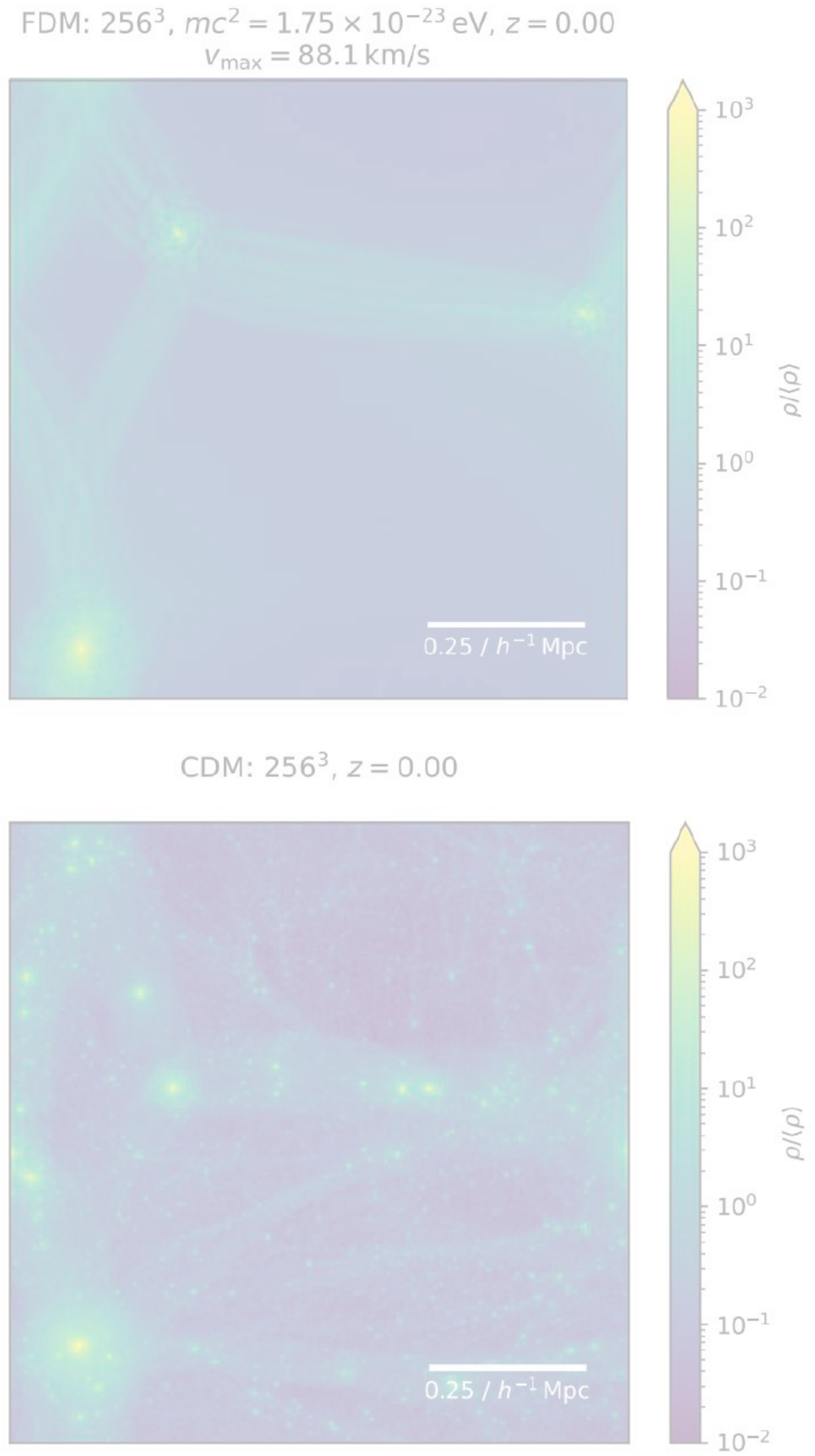
Preparation for PFS!

Phenomenology



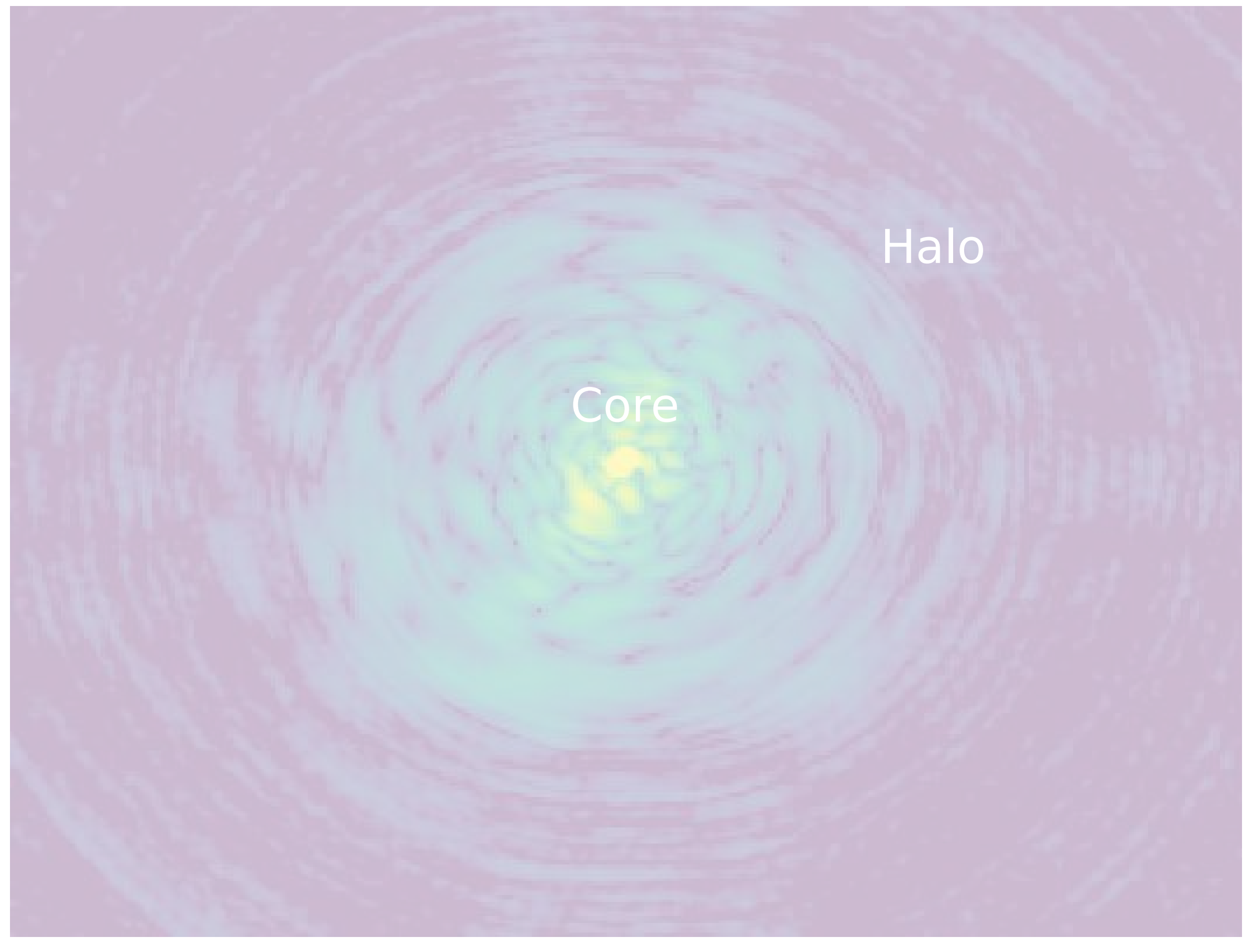
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

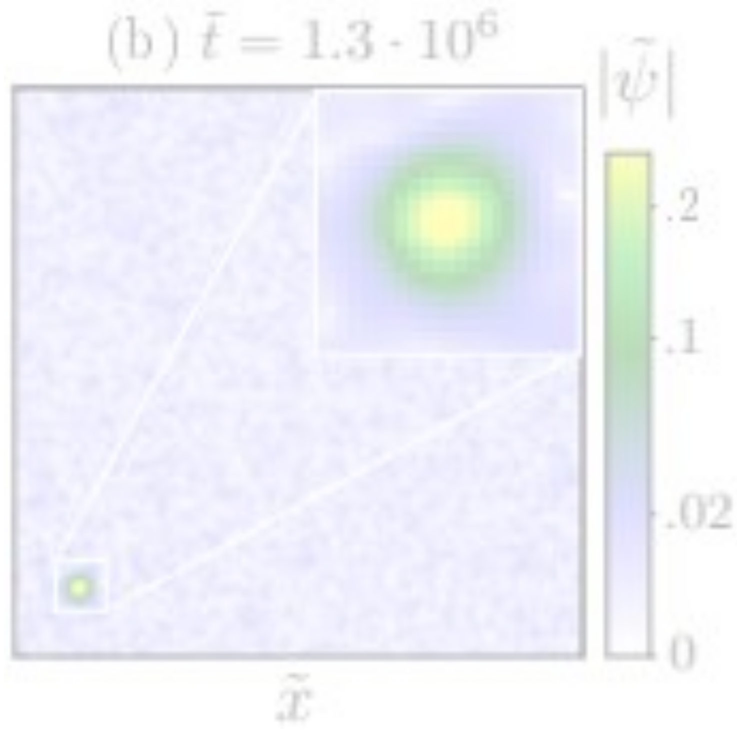


S. May et al. 2021

Formation of a solitonic core

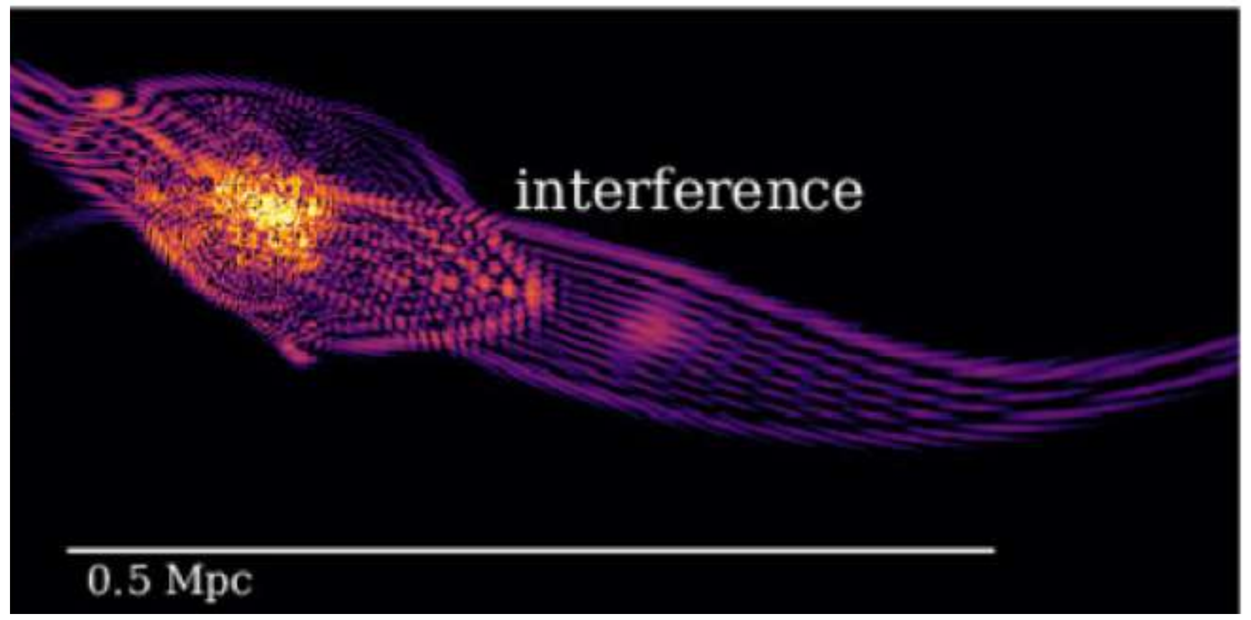


Dynamical effects



Levkov et al. 2018

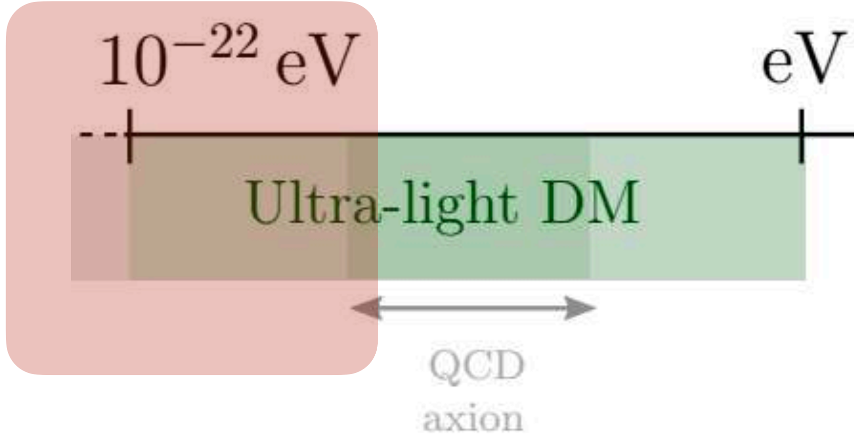
Wave interference

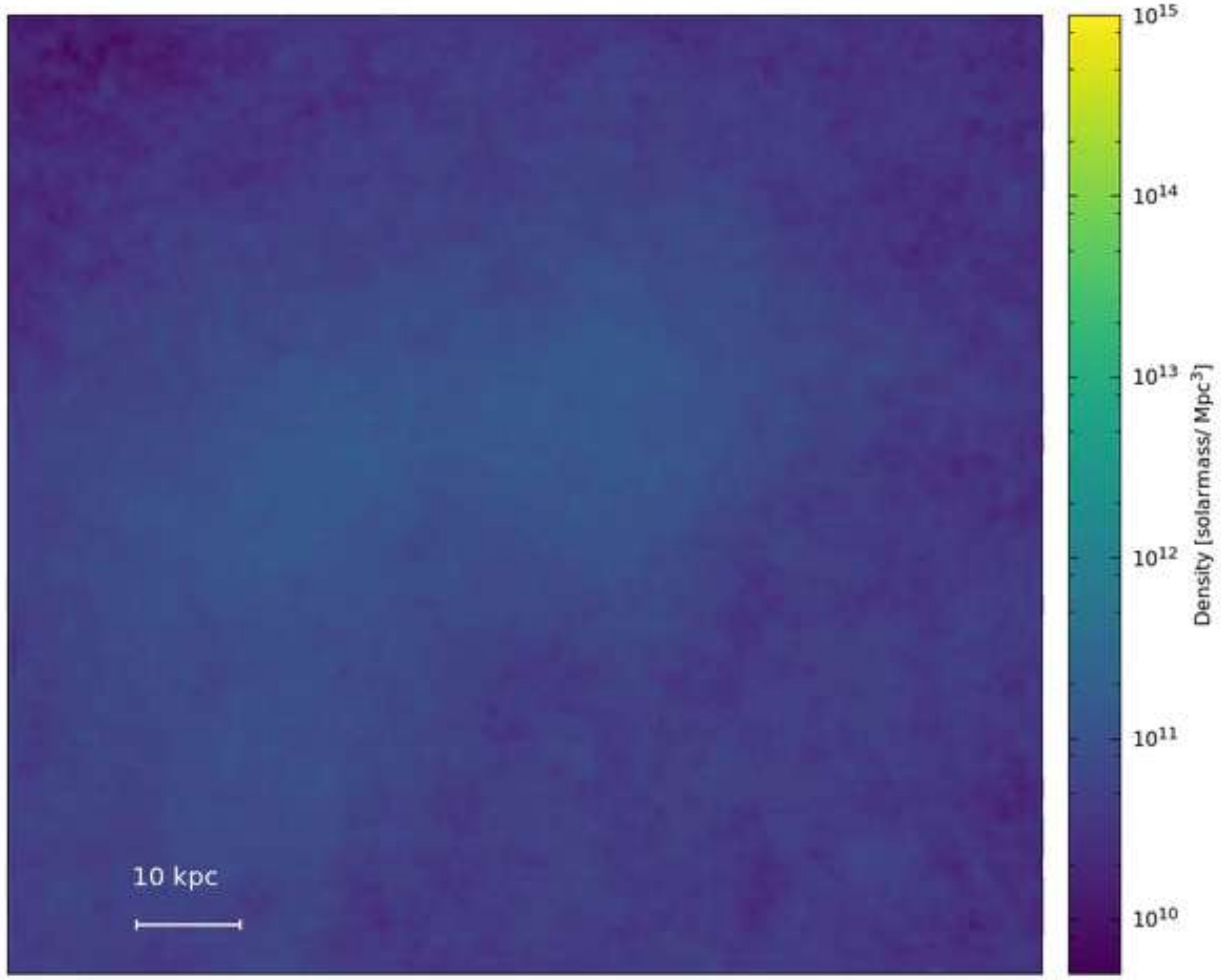


Mocz et al. 2017

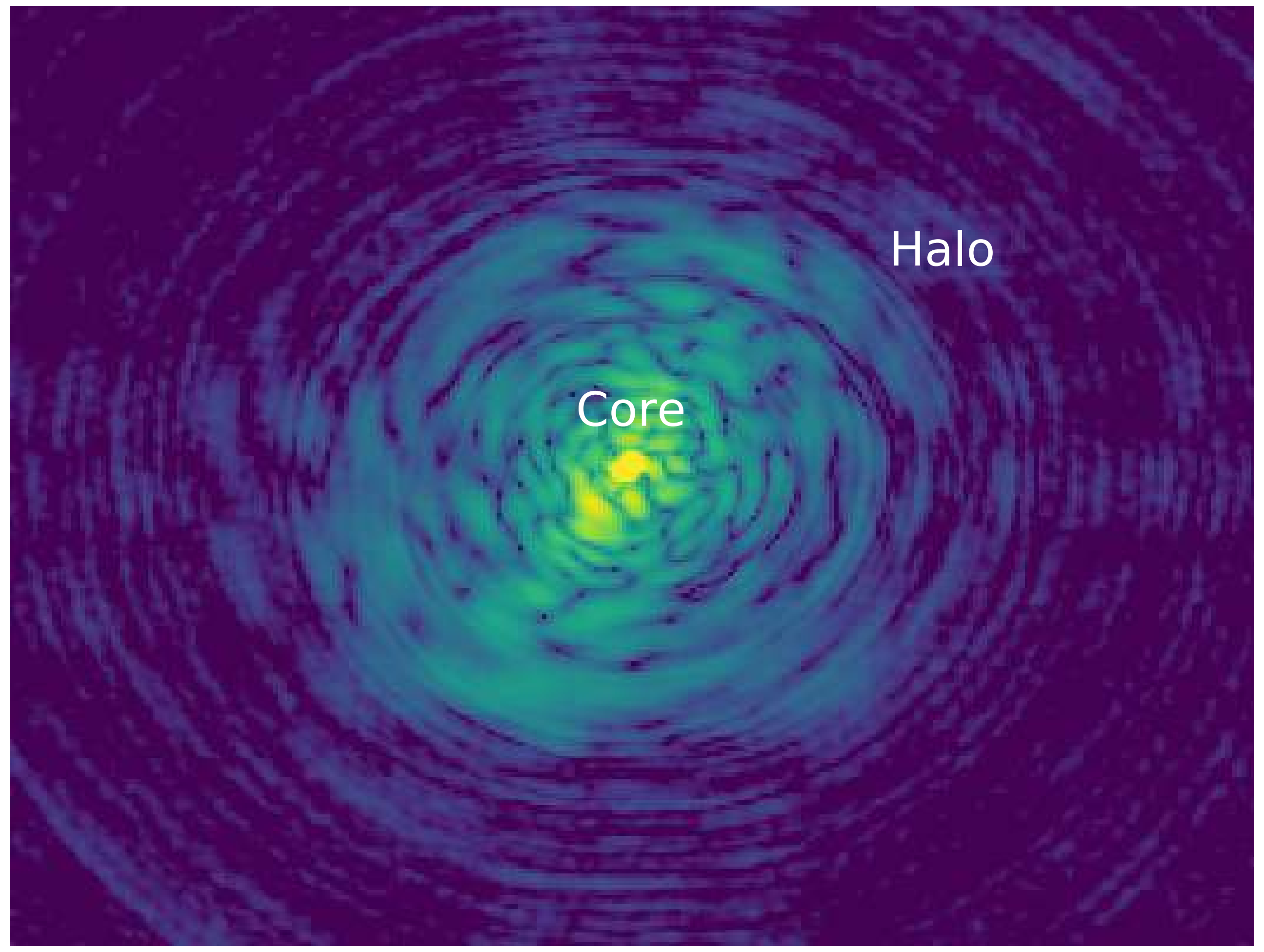
Phenomenology

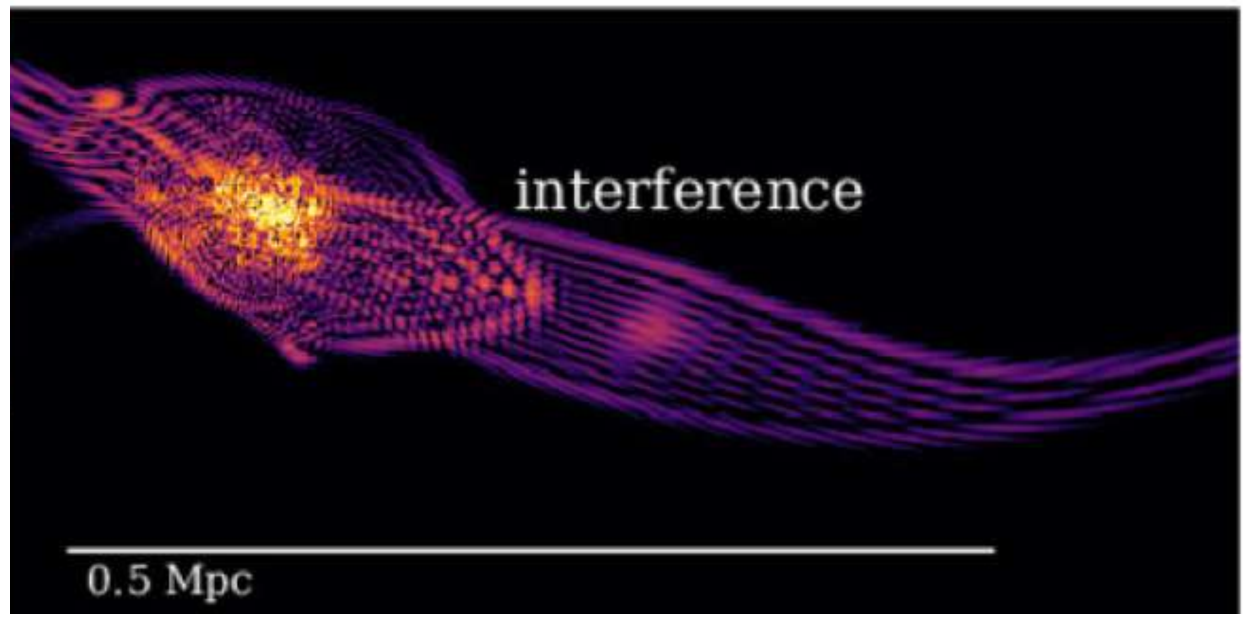
Wave interference: granules and vortices





Simulation by Jowett Chan





Mocz et al. 2017

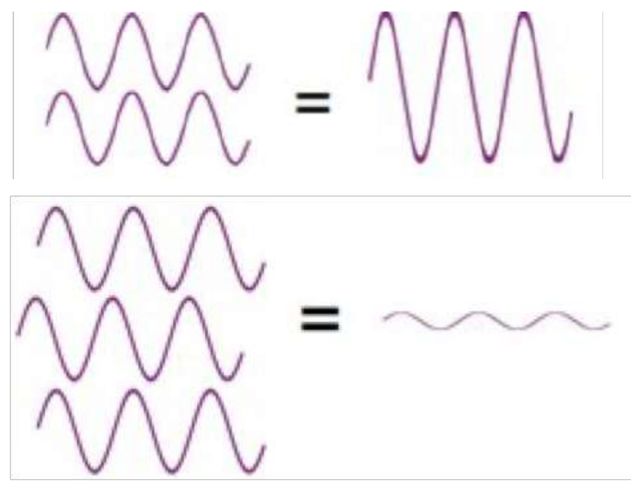
Order one fluctuations in density $\longrightarrow$ Constructive interference: granules

Destructive interference

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

Vector, higher spin or multicomponent FDM

Interference patterns

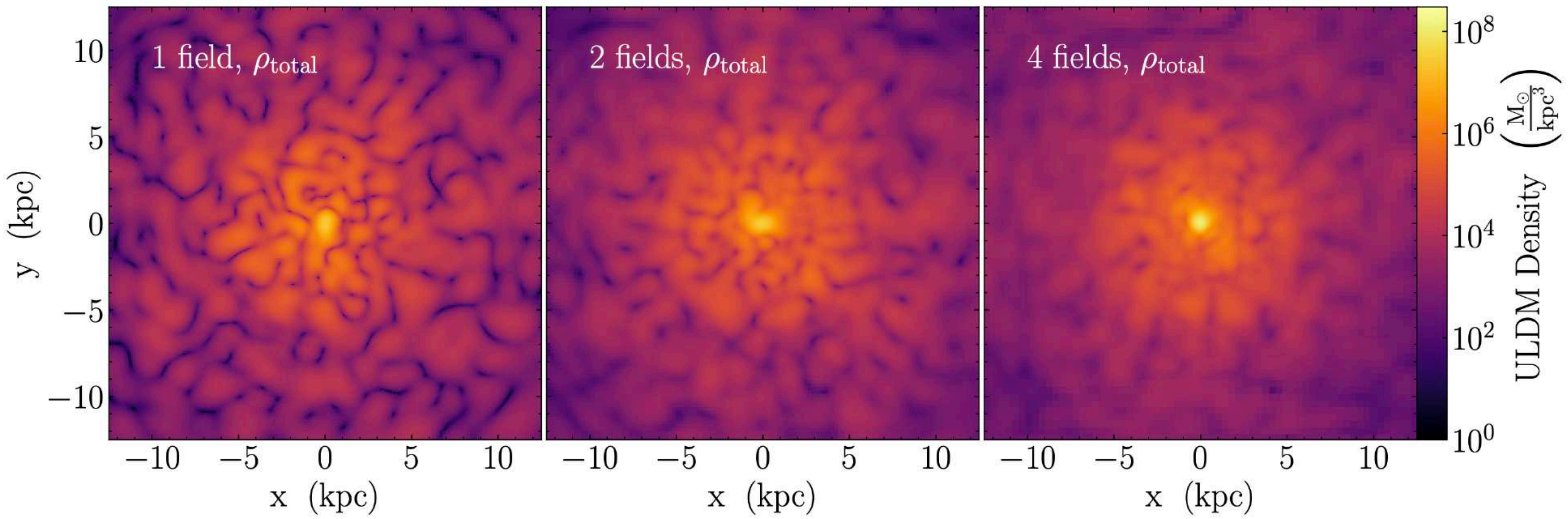


ULDM or ULA are a coherent wave - same frequency and constant phase difference

Multiple coherent waves

For ULDM:

Gonseca et al 2023



Multiple FDM or VFDM (or higher spin s FDM) *attenuates* the granule amplitude by

$$\frac{[\delta\rho/\rho]_{\rm nfdm,s}}{[\delta\rho/\rho]_{\rm fdm}} \propto \frac{1}{\sqrt{(2s+1)}} = \frac{1}{\sqrt{N}}$$

(Amin et al 2022)

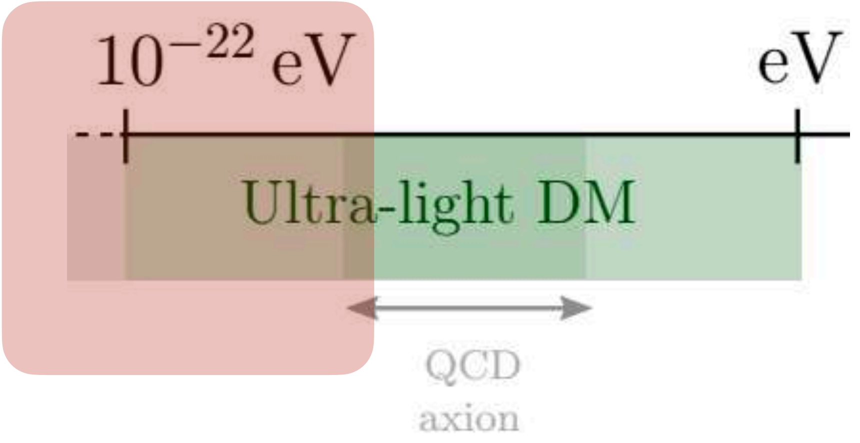
Vector (and higher-spin) FDM Amin et al 2022

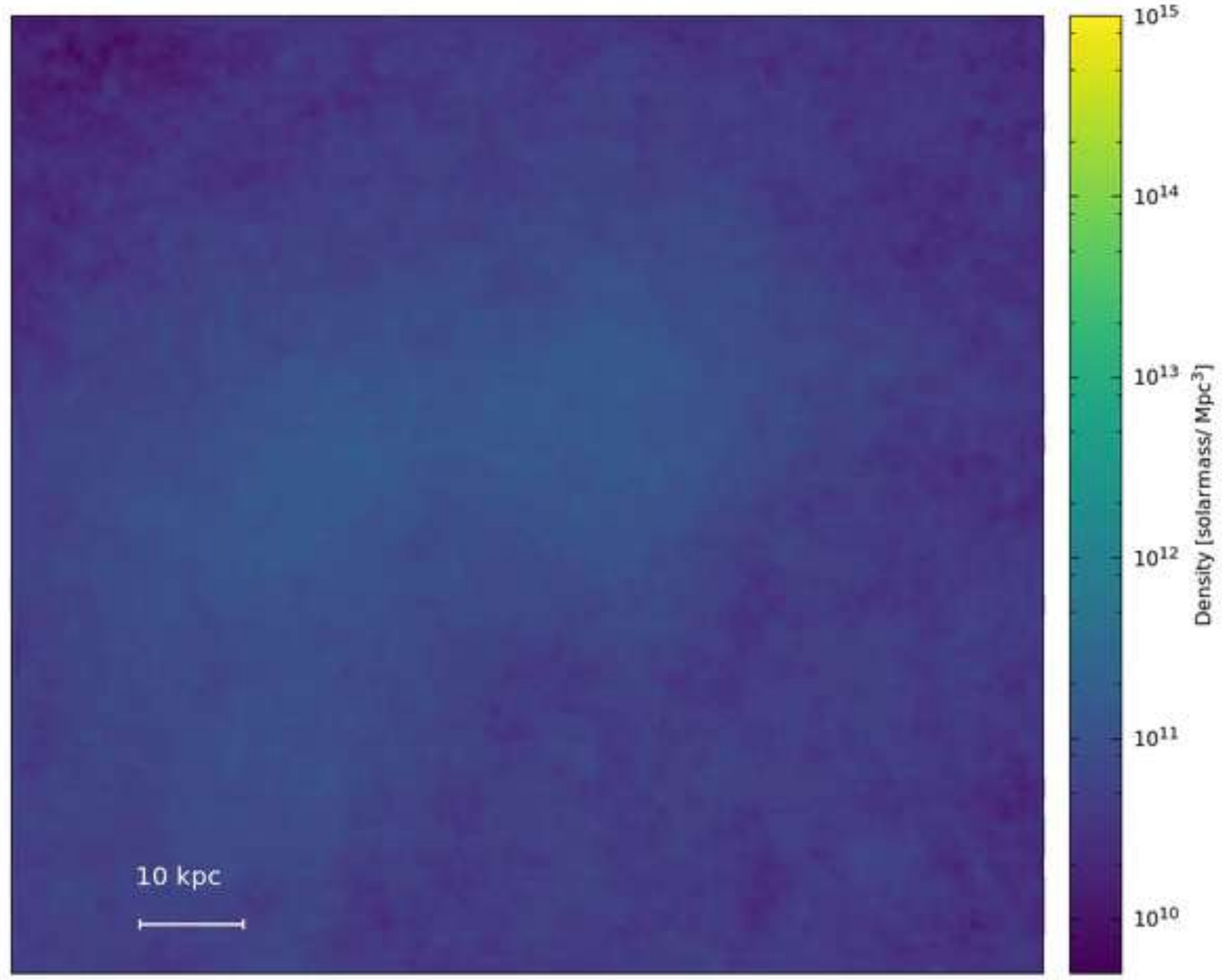
(Vector FDM = 3 x same mass FDM (spin 0))

Multicomponent FDM Gonseca et al 2023

FDM constraints 2.0

Interference pattern





Best probe for ULDM

PROBES:
- Strong lensing
- Stellar streams
- Heating

$\mathscr{O}(1)$ fluctuations in density $\longrightarrow$ $\sim \lambda_{\mathrm{dB}}$

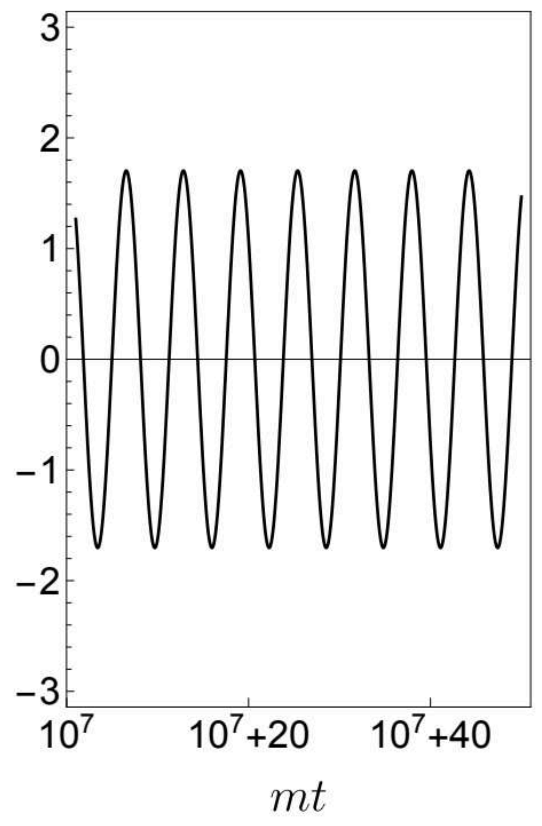
Modeling a granular halo

Coherent wave oscillation of ULDM

$$\phi(t,\vec{x}) = m^{-1}\sqrt{2\rho(t,\vec{x})}\ \cos[mt + \theta]$$

Fixed freq.

Constant phase



Modeling a granular halo

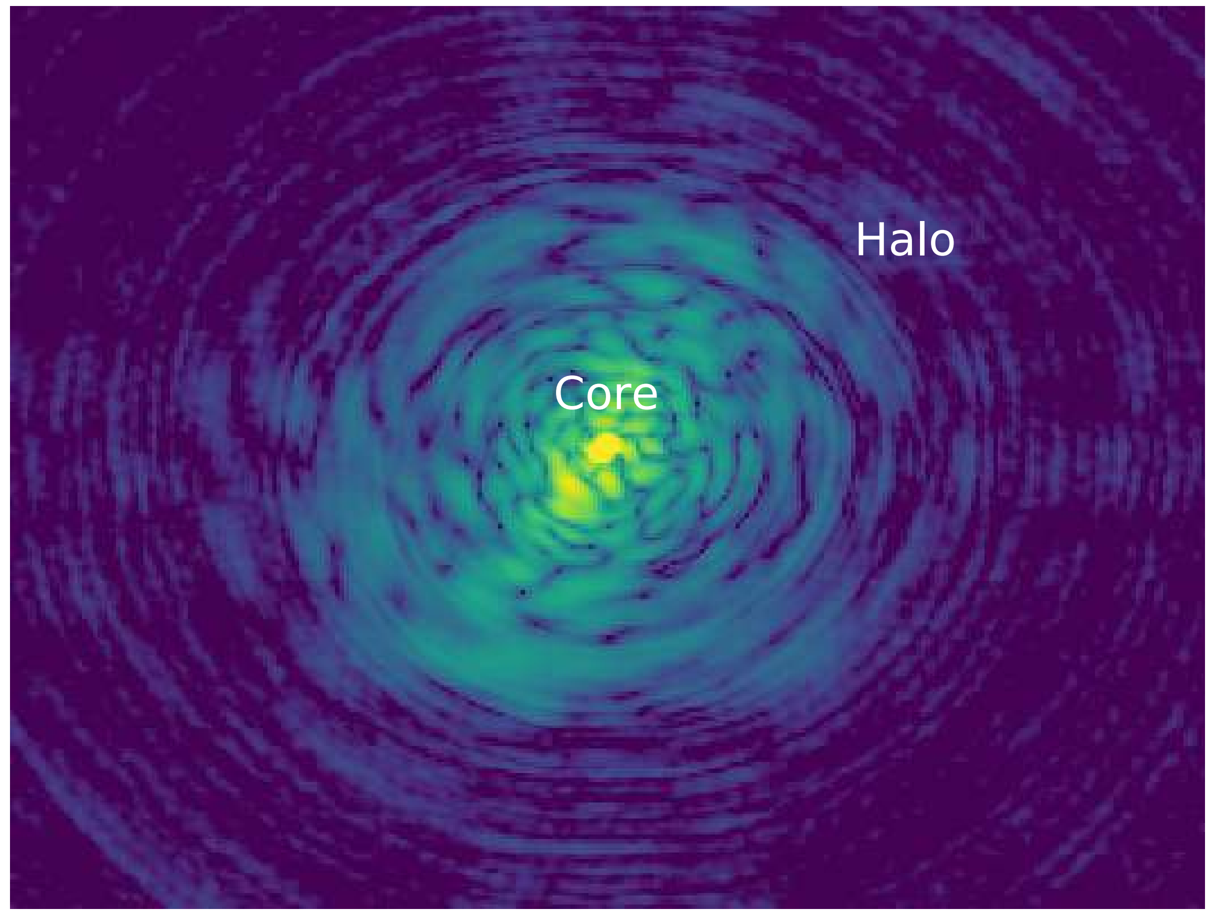
Coherent wave oscillation of ULDM

$$\phi(t,\vec{x}) = m^{-1}\sqrt{2\rho(t,\vec{x})}\,\cos[mt+\theta]$$

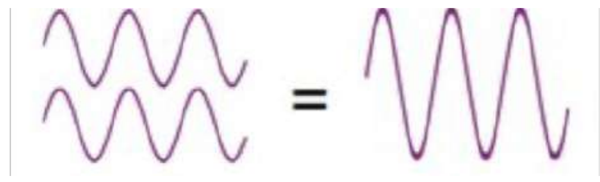
Fixed freq.

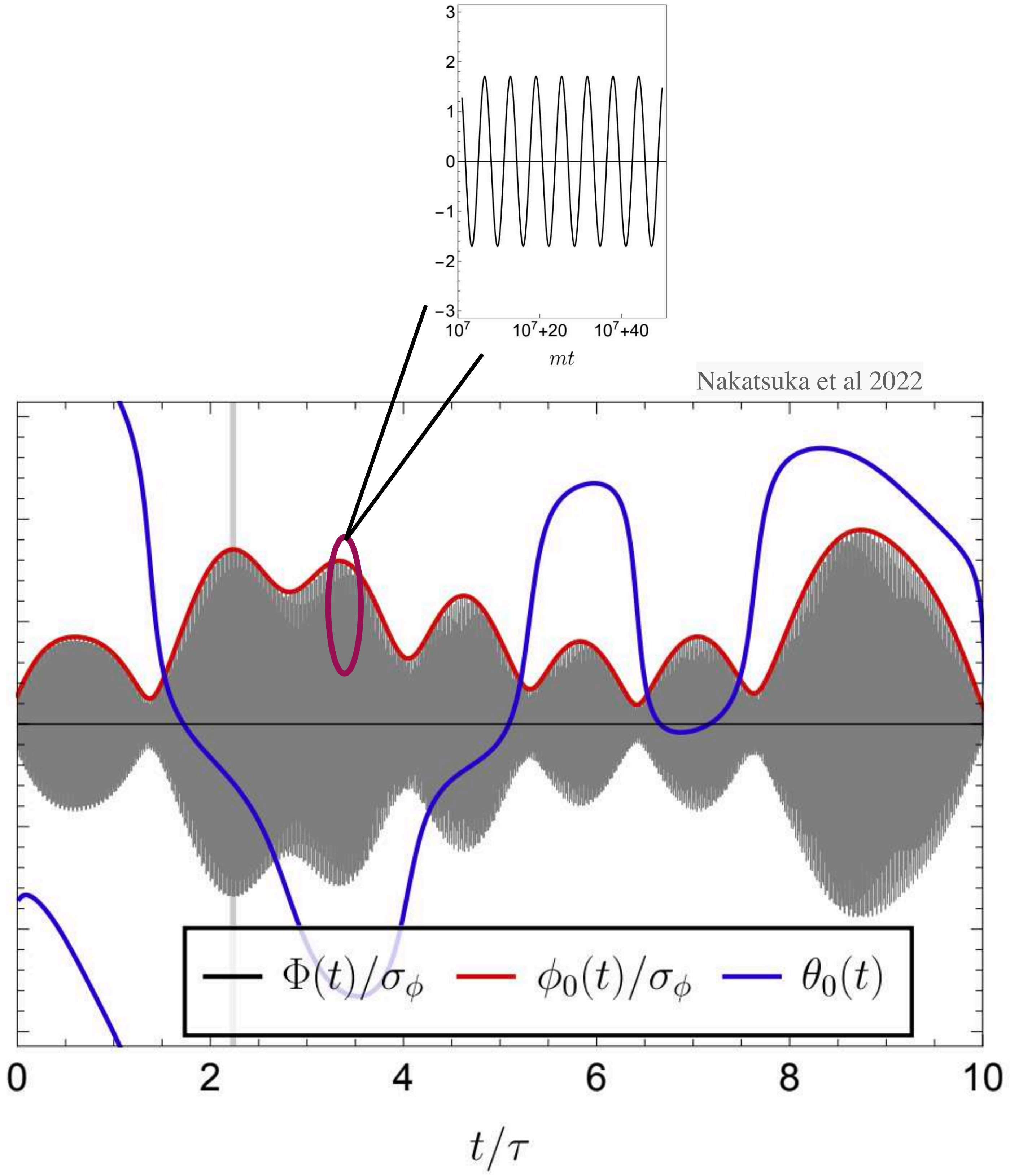
Constant phase

But, the halo in these models is like this:



Superposition of plane waves





Nakatsuka et al 2022

Modeling a granular halo

Full SP simulations can describe perfectly this interference pattern (while fluid ones *cannot* describe it)

OR

We can adopt simpler descriptions of the galactic halo to describe this effect.

1) A simple model of a galactic halo, consider a superposition of plane waves:

Randomly distributed

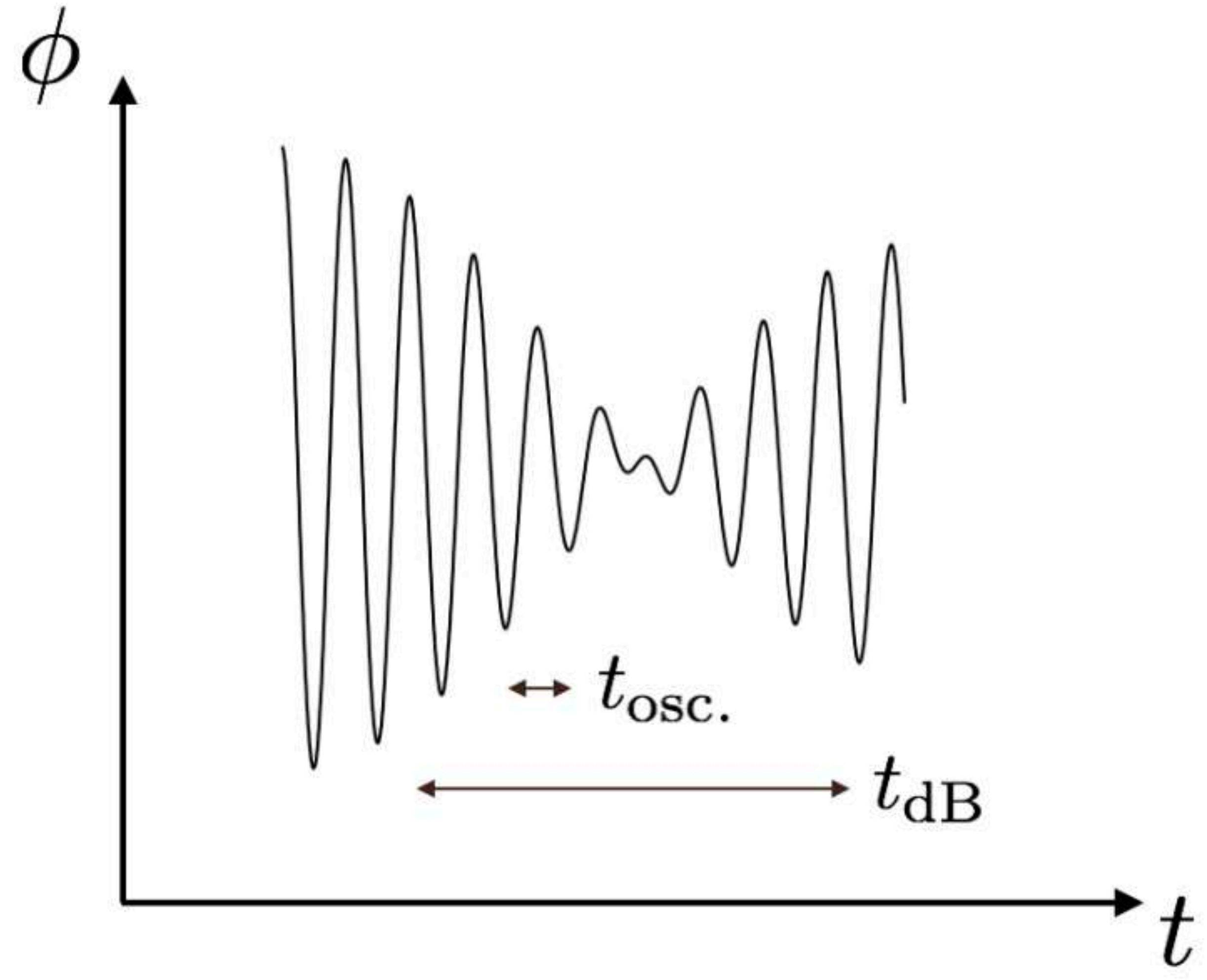
$$\psi(t,\vec{x}) = \sum_{\vec{k}} A_{\vec{k}} e^{iB_{\vec{k}}} e^{i\vec{k}\cdot\vec{x} - i\omega_k t}$$

Wave interference produces de-Broglie-scale, order unity density fluctuations which vary on time scale of t_{dB}

This collection of plane waves can also be represented like this:

$$\phi(t,\vec{x}) = A(\vec{x})\cos(m\,t + \alpha(\vec{x}))$$

describes the interference patterns



$$t_{\rm osc.} = 2\pi/m$$

$$t_{\rm dB} = 2\pi/(mv^2)$$
$$= 1.9 \times 10^6\,{\rm yr}\left(\frac{10^{-22}\,{\rm eV}}{m}\right)\left(\frac{250\,{\rm km/s}}{v}\right)^2$$

Modeling a granular halo

Full SP simulations can describe perfectly this interference pattern (while fluid ones *cannot* describe it)

OR

We can adopt simpler descriptions of the galactic halo to describe this effect.

1) A simple model of a galactic halo, consider a superposition of plane waves:

2) A more realistic model would superimpose eigenstates of a desired gravitational potential (Lin et al. 2018, Li et al. 2021)

Perform an eigenmode decomposition of the halo wavefunction, where the eigenmodes are for a fixed gravitational potential
→ ω_k is the energy of each eigenmode (labeled abstractly by k), with $e^{i\vec{k}\cdot\vec{x}}$ replaced by the corresponding eigenfunction.

Energy eigenvalue

$$\psi(r,\theta,\phi,t) = \sum_{n,l,m} A_{nlm} F_{nlm}(r,\theta,\phi) e^{-iE_{nl}t/\hbar}$$

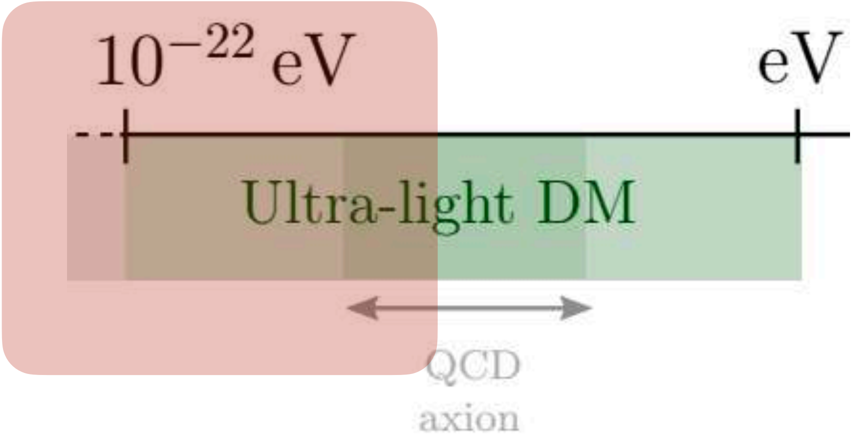
Spherical harmonics

$$F_{nlm}(r,\theta,\phi) = R_{nl}(r) Y_l^m(\theta,\phi) \longrightarrow$$

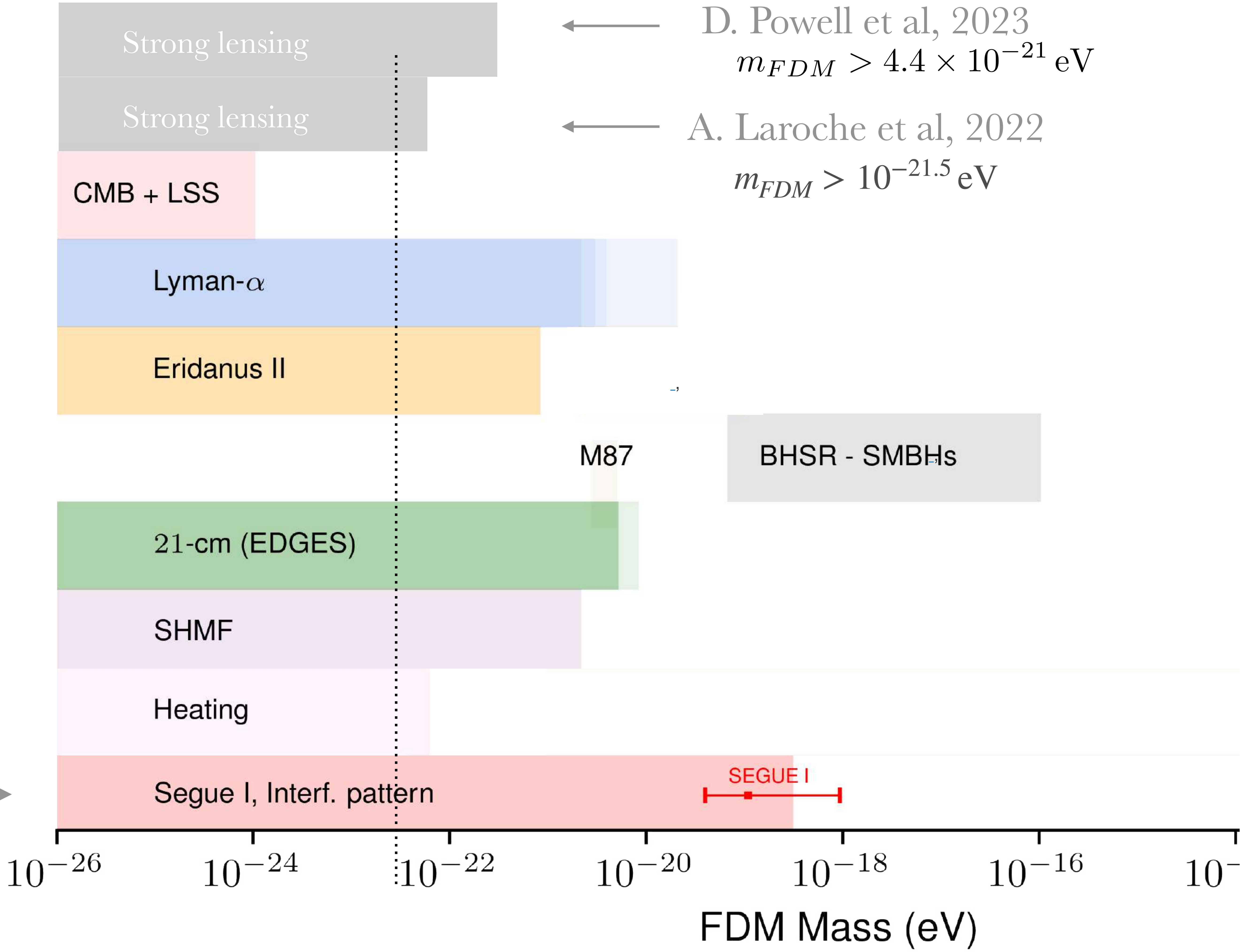
Radial eigenfunction

energy eigenmodes of the gravitational potential of the virialized halo

Interference patterns - granules



Constraints 2.0



Strong lensing

D. Powell et al, 2023

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

A. Laroche et al, 2022

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

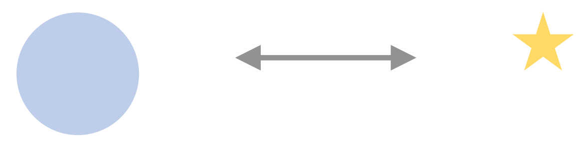
Stellar heating

Dalal et al, 2022

$m_{FDM} > 3 \times 10^{-19}$ eV

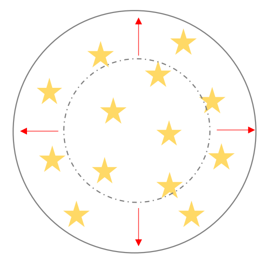
Heating

FDM granule

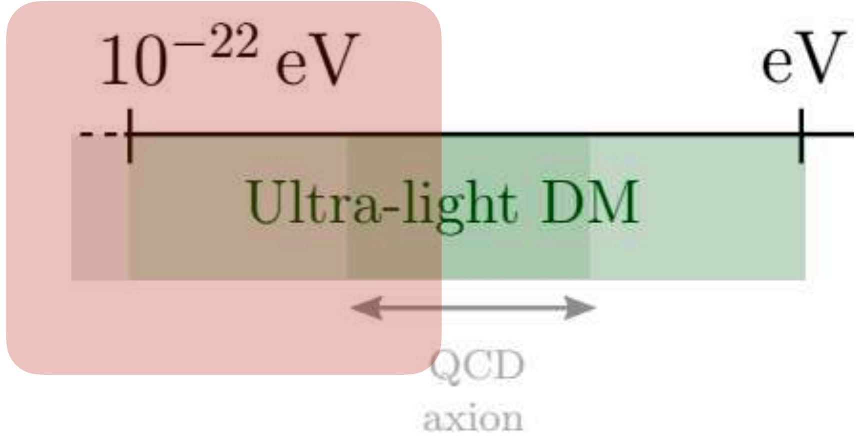


$m_{\rm eff}$

System (star) gains energy



Interference patterns - granules



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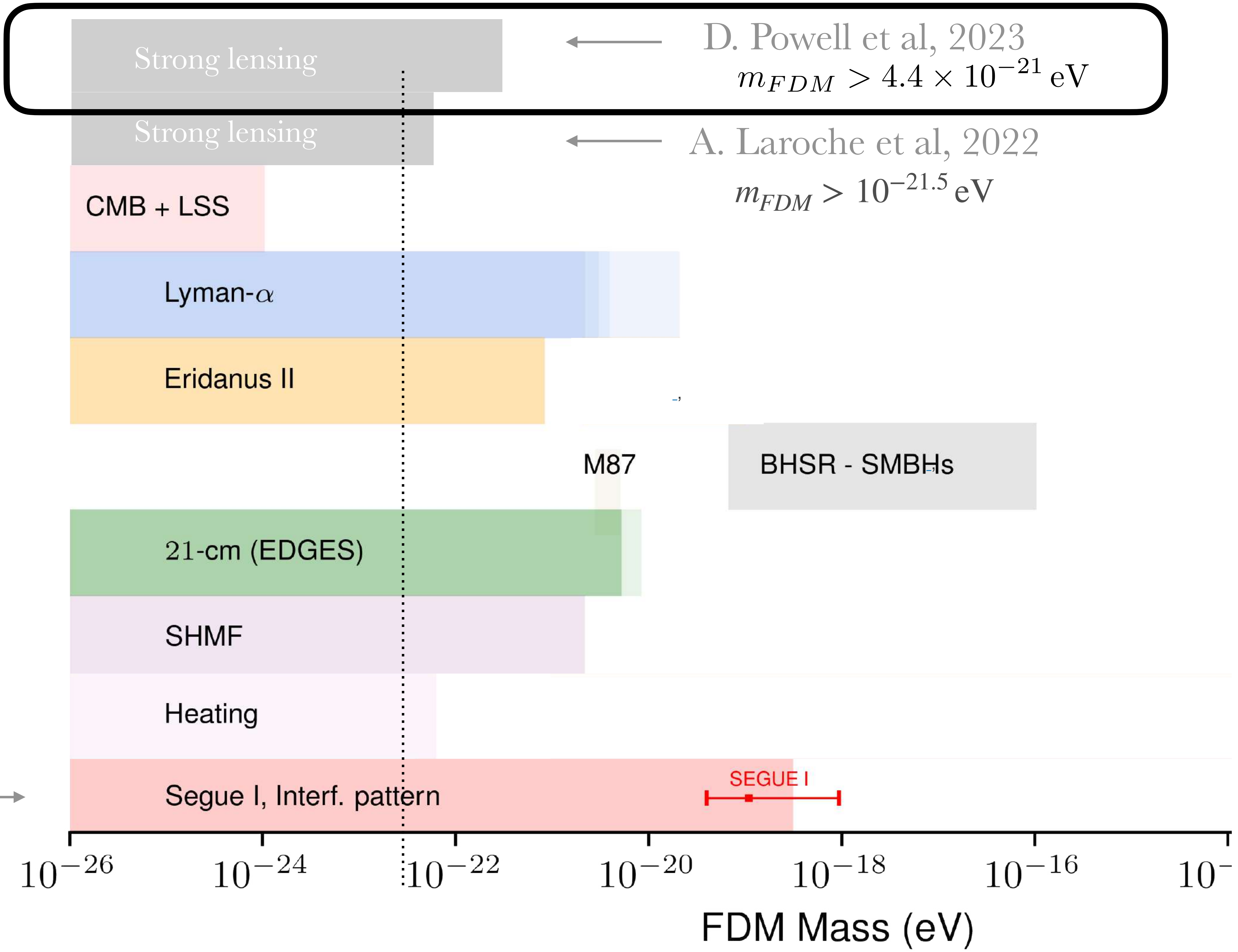

Stellar heating

Dalal et al, 2022
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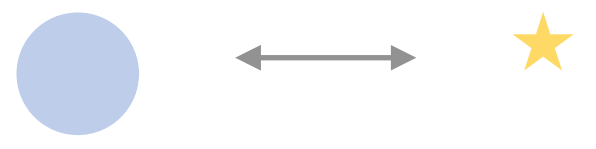
Heating

FDM granule



$m_{\rm eff}$

System (star) gains
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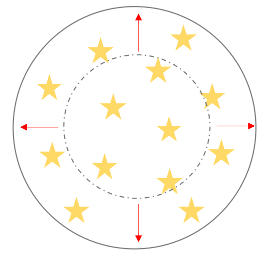
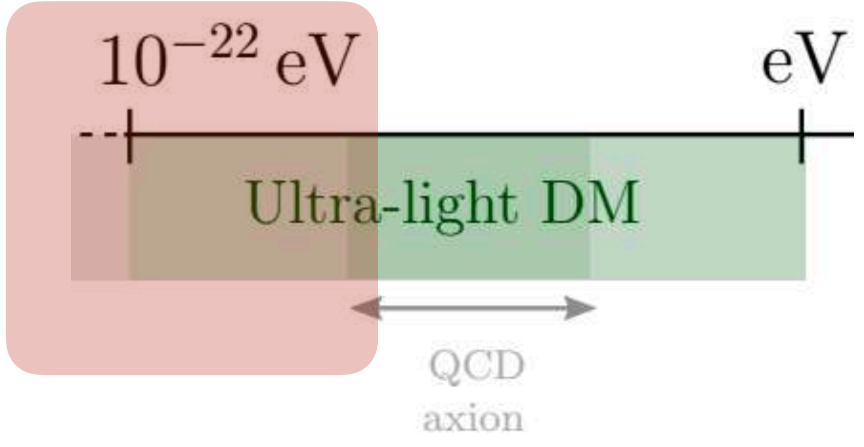
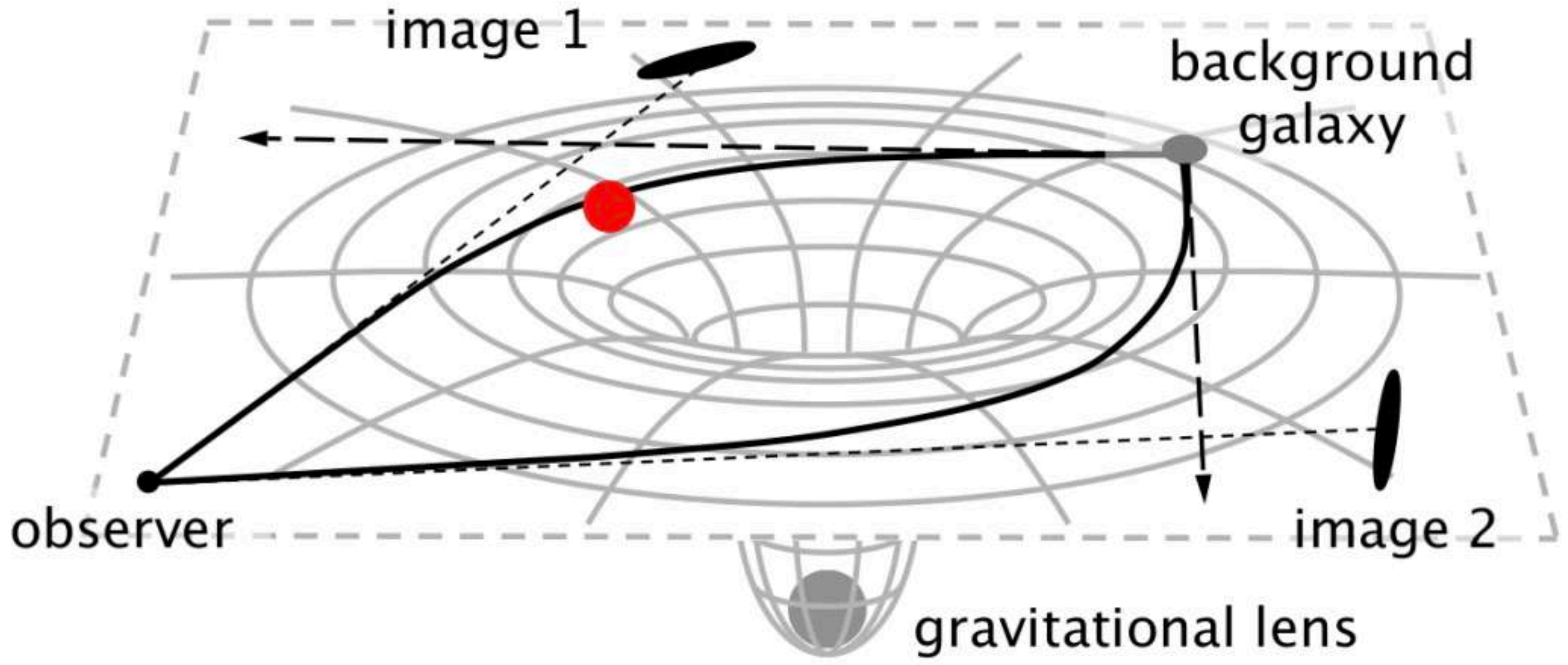
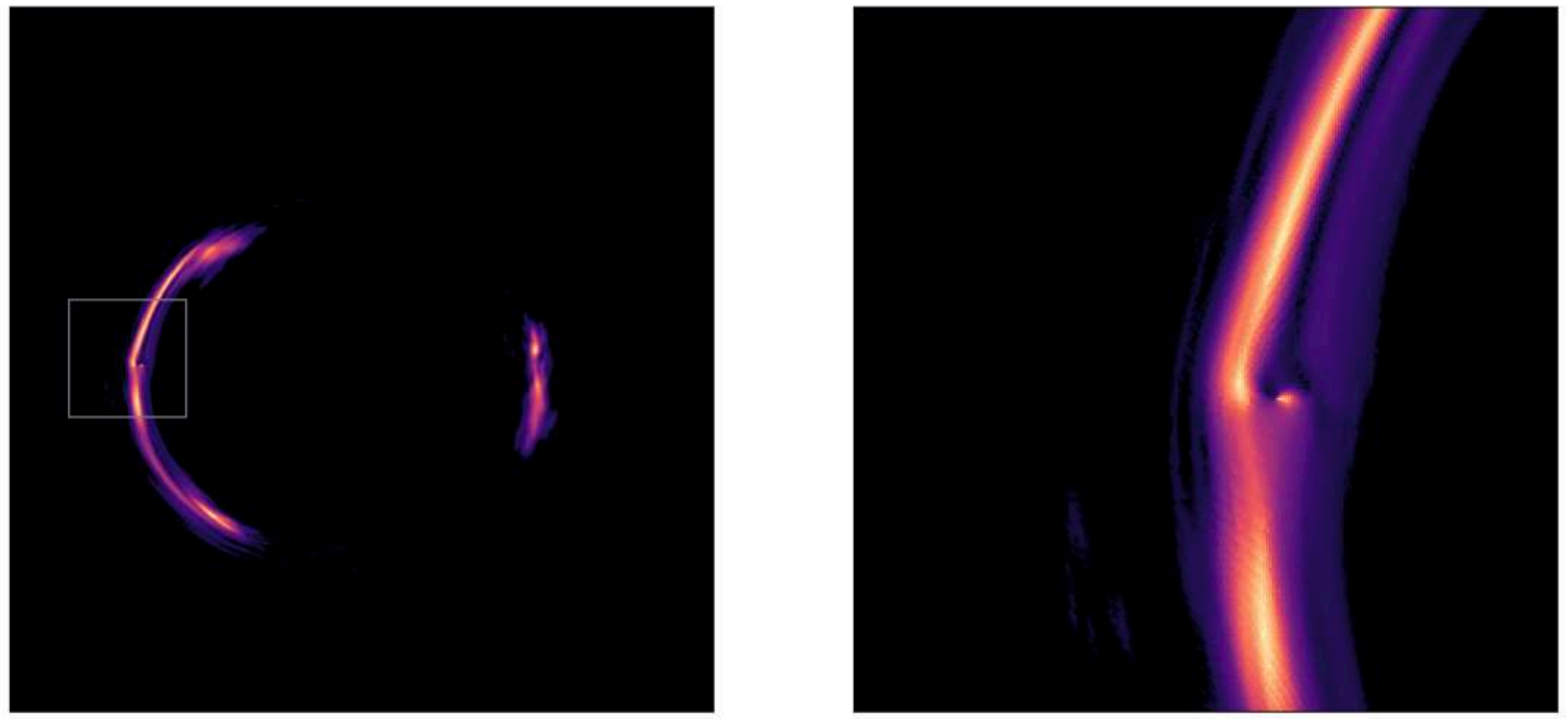


Strong lensing



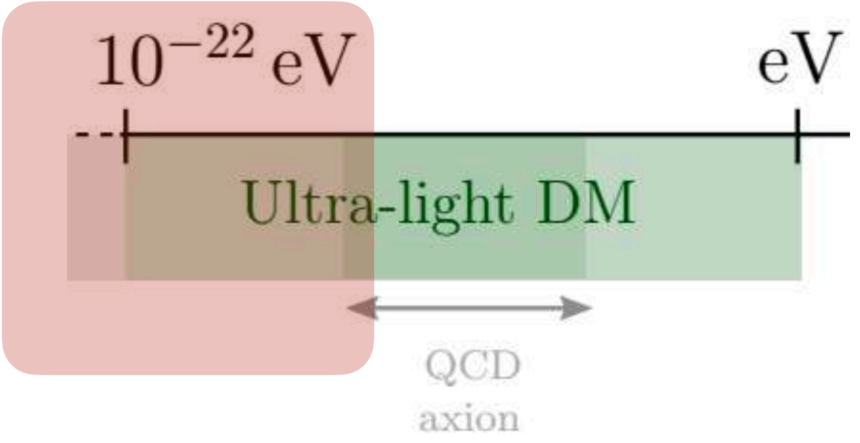
Low mass perturber with lensing



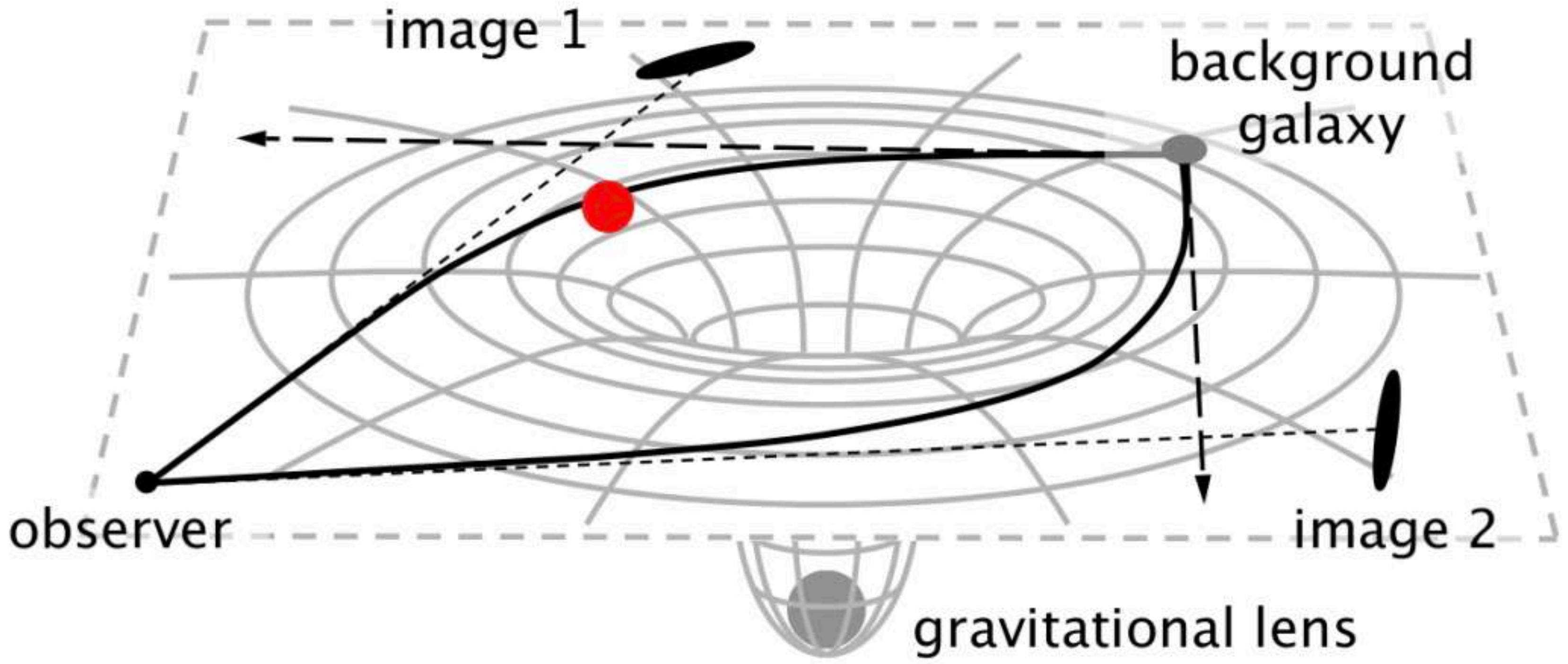


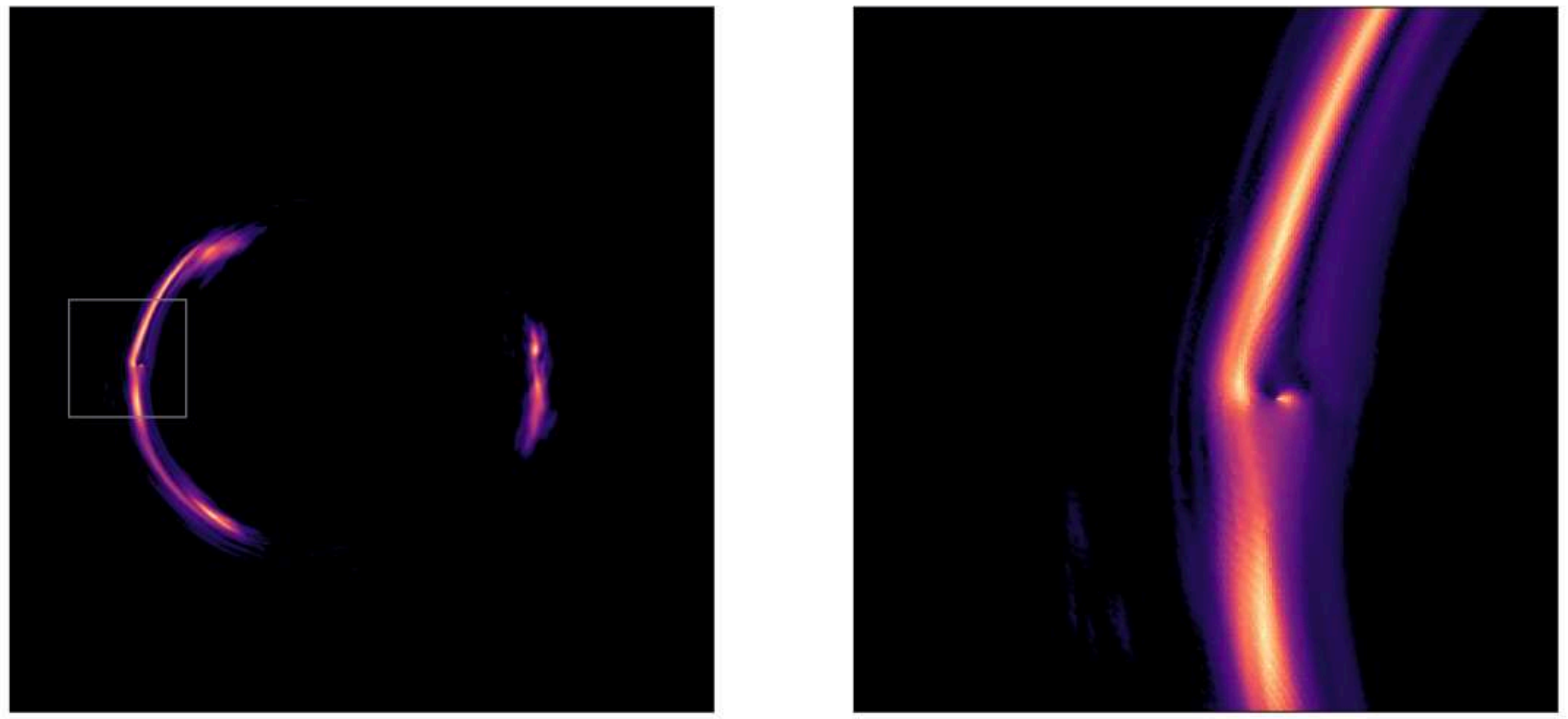
- Strong lensing: powerful probe of substructure
- Sensitivity is limited by angular angular resolution
- Roughly speaking, the resolution must be better than the scale radius of the perturber

Strong lensing



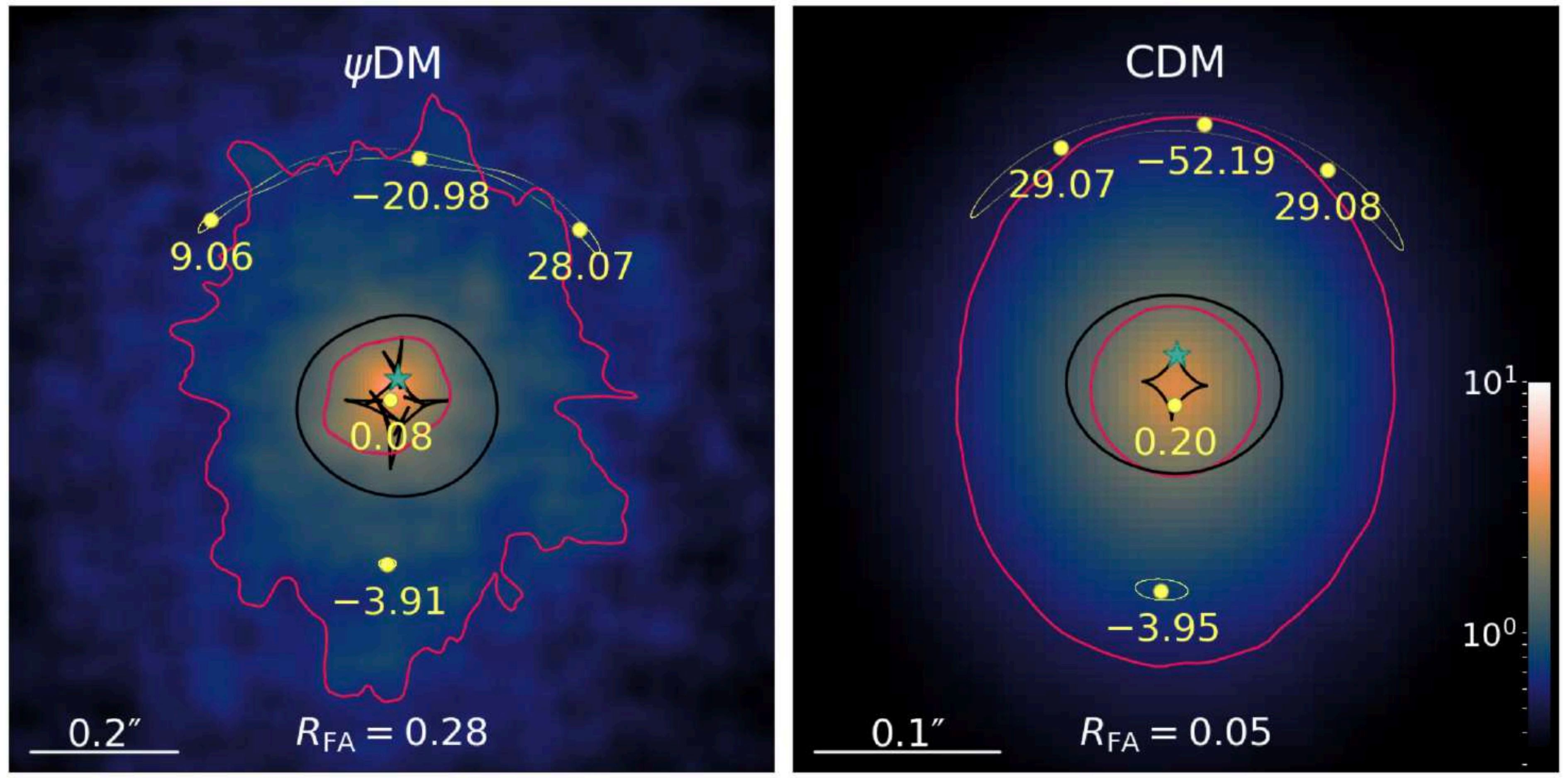
Low mass perturber with lensing





Presence of granules

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



J. Chan et al. 2020

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

Previous works:

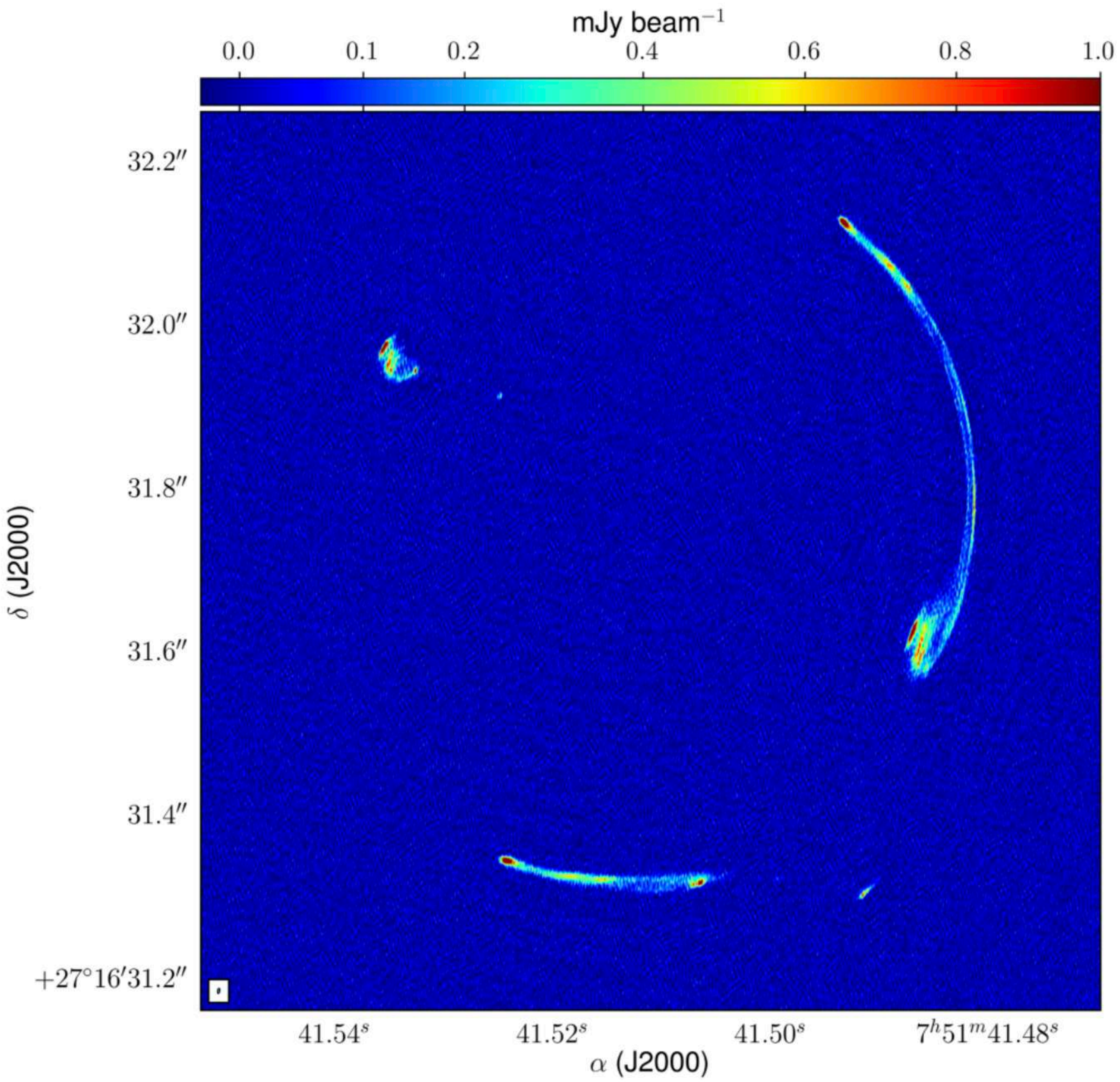
J. Chan, H.Schive, S.g Wong, T. Chiueh, T. Broadhurst, 2020

A. Laroche, Daniel Gilman, X. Li, J. Bovy, X. Du, 2022

Strong lensing

A lensed radio jet at milli-arcsecond resolution II: Constraints on fuzzy dark matter from an extended gravitational arc
D. Powell, S. Vegetti, J.P. McKean, S. White, EF, S. May, C. Spingola

MG J0751+2716



Data taken at 1.6 GHz using global very long baseline interferometry (VLBI) with an angular resolution, measured as the full width at half maximum (FWHM) of the main lobe of the dirty beam response, of 5.5×1.8 mas^2

- Lensed radio jet, observed with global VLBI
- First image of a lensed radio jet!
- Source structure allows us to "image" the lens surface density
- Extended lensed radio arcs and the milli-arcsecond resolution provide direct sensitivity to the presence of FDM granules in the halo of the lens galaxy

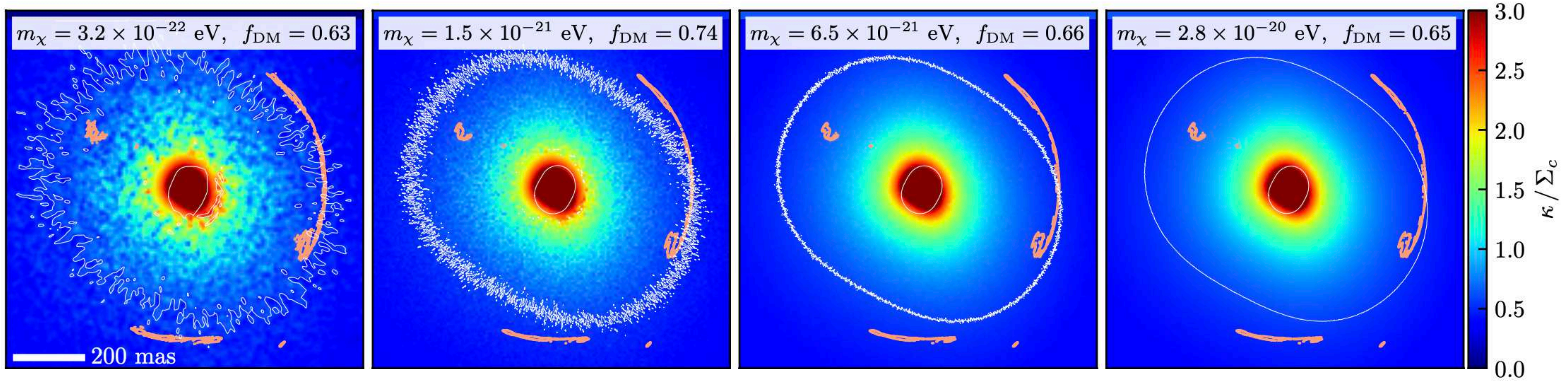
Bayesian approach to jointly inferring the lens mass model and source surface brightness distribution

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

Strong *lensing*

A lensed radio jet at milli-arcsecond resolution II: Constraints on fuzzy dark matter from an extended gravitational arc
D. Powell, S. Vegetti, J.P. McKean, S. White, EF, S. May, C. Spingola

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



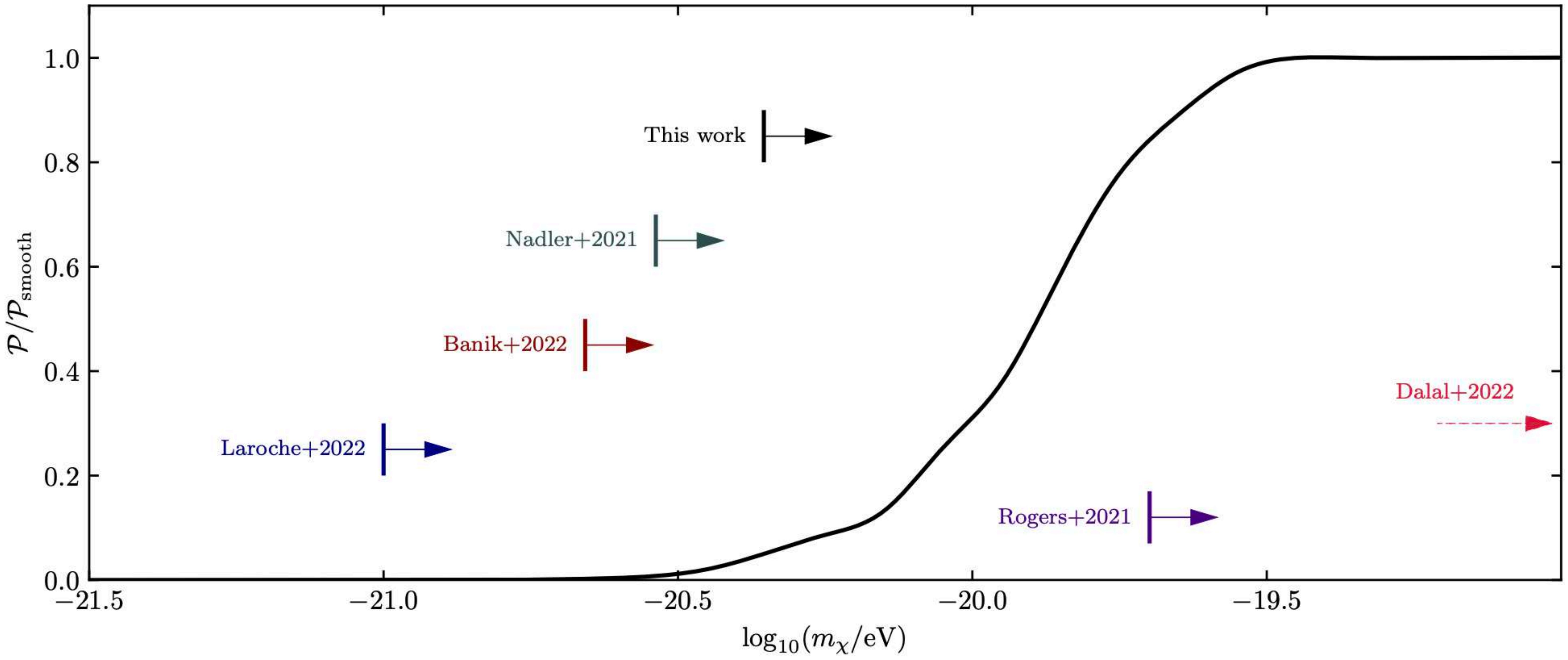
The lensing effect of the FDM granules is apparent: The critical curves wiggle back and forth across the lensed arcs, which would require the presence of multiple images of the same region of the source along the arc.

Strong *lensing*

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

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

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



Fuzzy dark matter
(Single spin-0 particle)

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

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

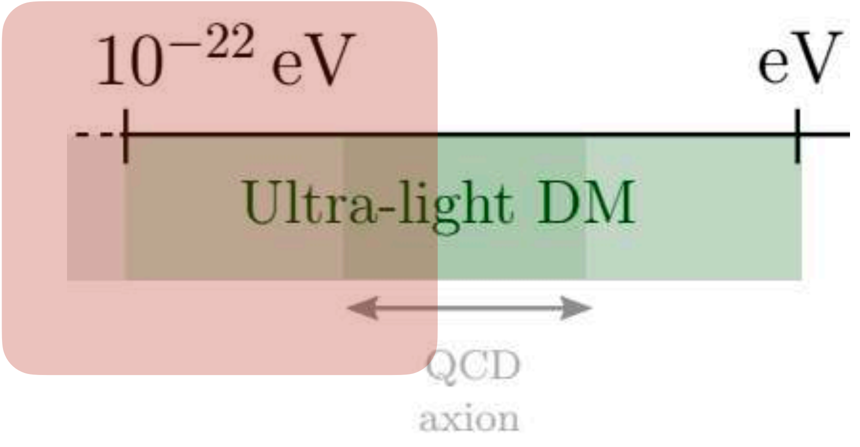
$m_{\rm vdm} > 1.4 \times 10^{-21}$ eV

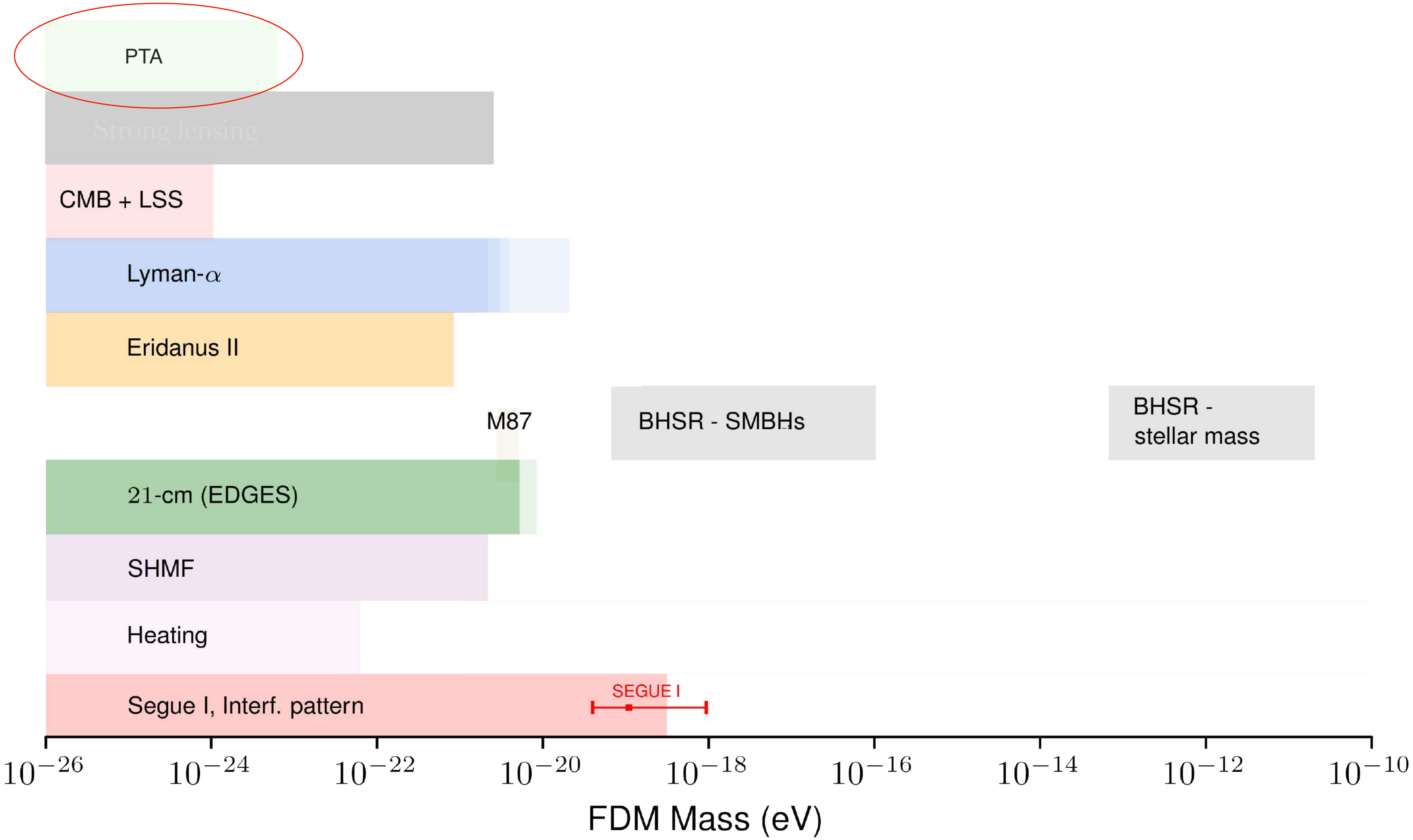
Spin-2 FDM

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

Current status

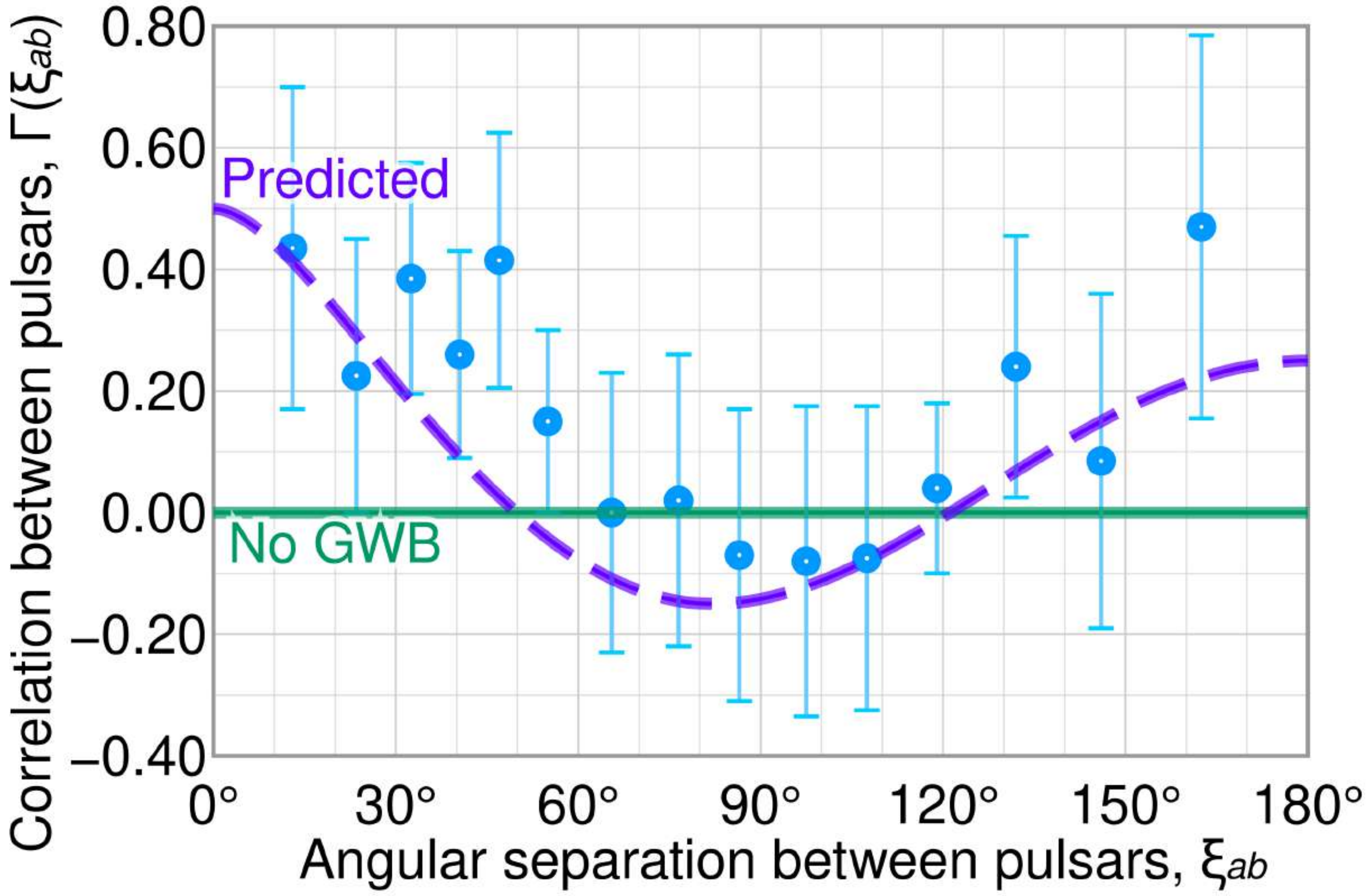
Fuzzy Dark Matter - bounds on the mass



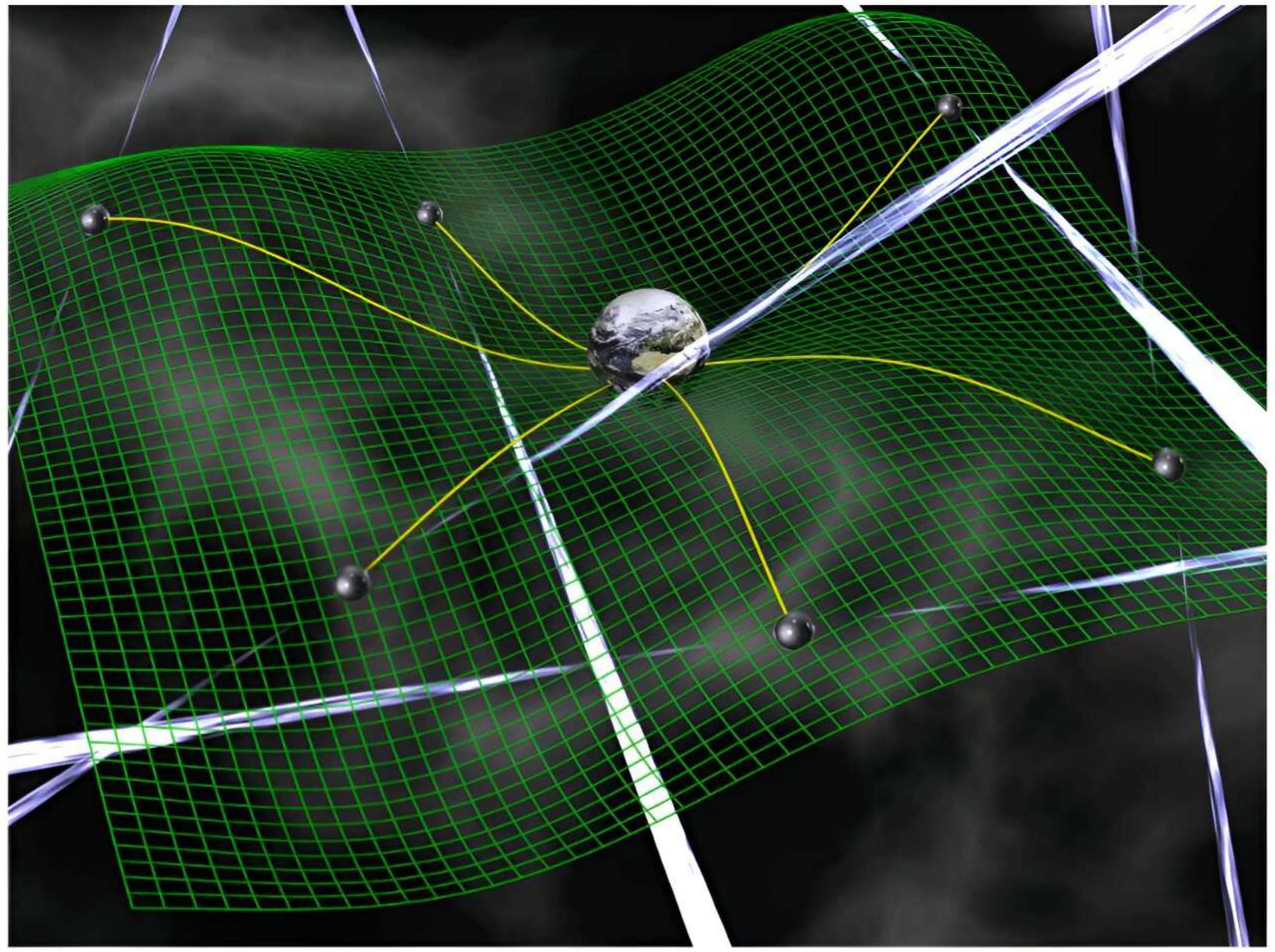


Pulsar Timing array

NANOGrav, EPTA, PPTA, and InPTA announced that they found evidence for a gravitational wave background



EPTA - 3σ
CPTA - 4.6σ



Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

Hellings-Downs curve refers to the wave-like shape predicted to appear in a plot of timing residual correlations versus the angle of separation between pairs of pulsars

Pulsar Timing array

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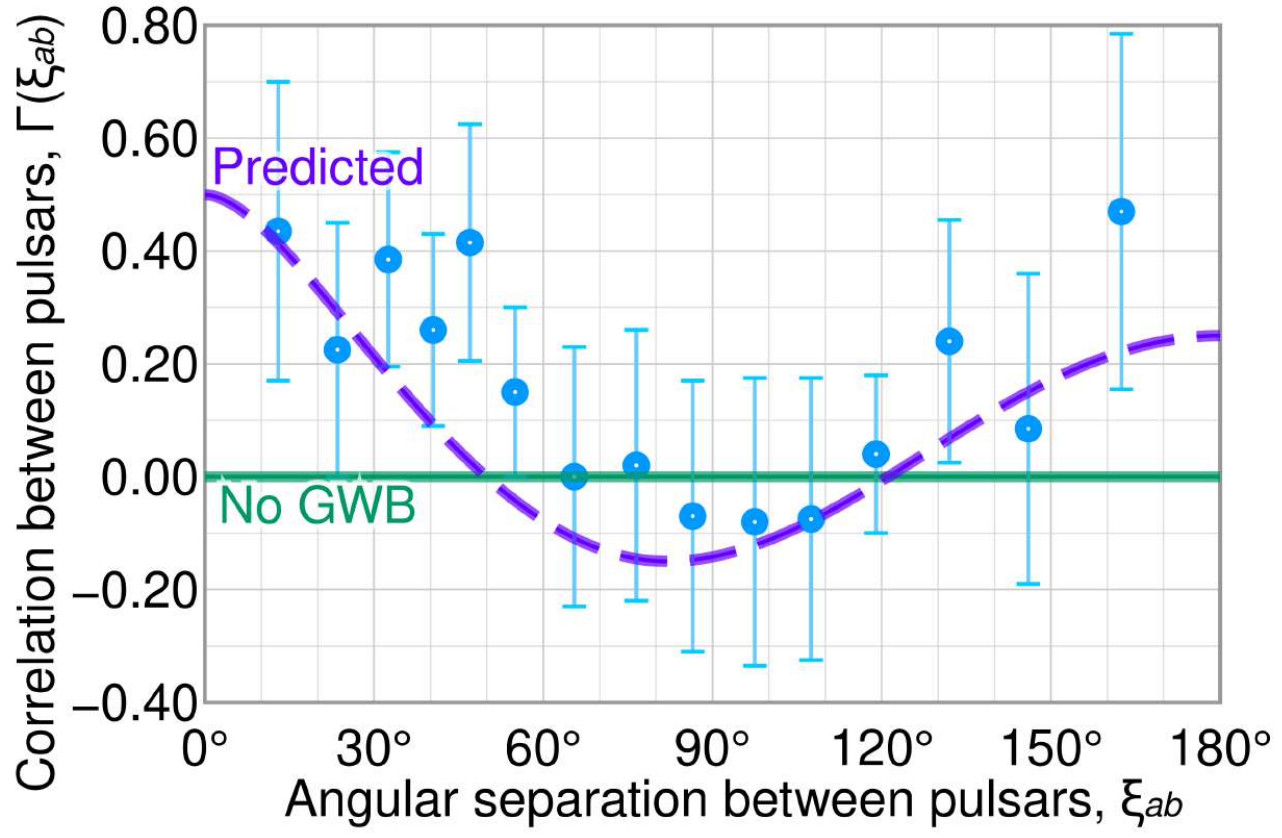
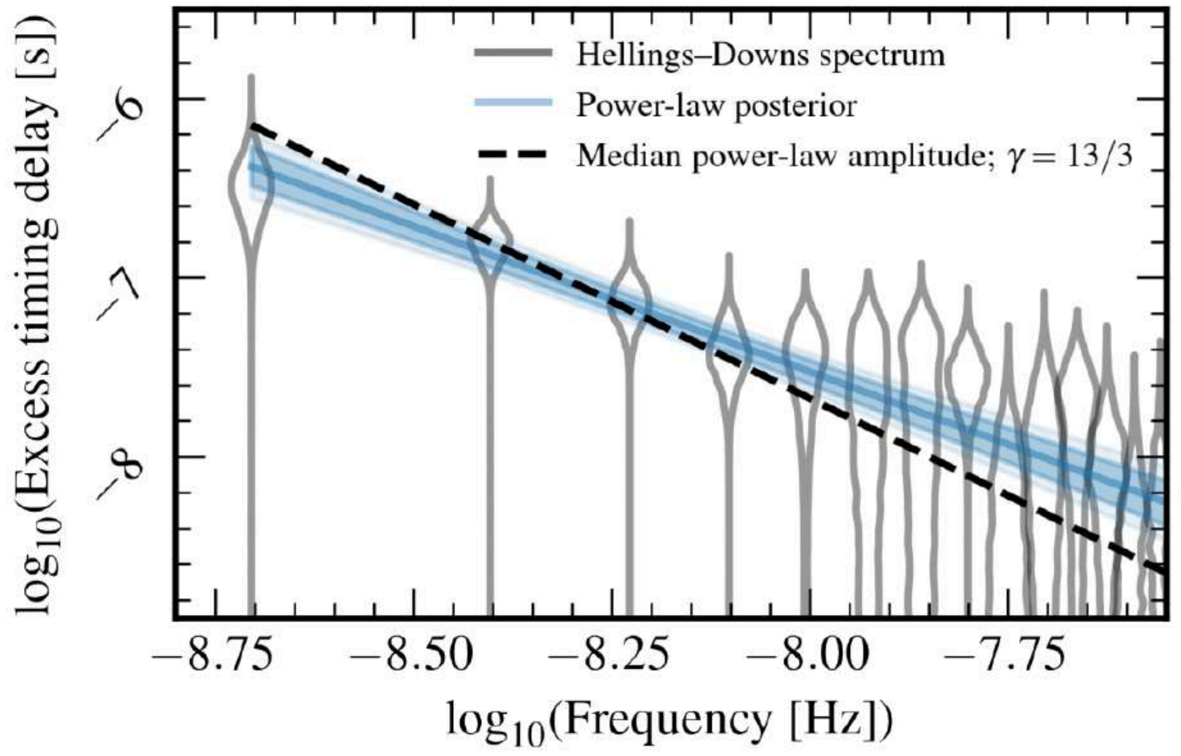




Possibility of being a **Gravitational Wave Background** signal caused by:

- Ensemble of binary supermassive black-holes

- New physics

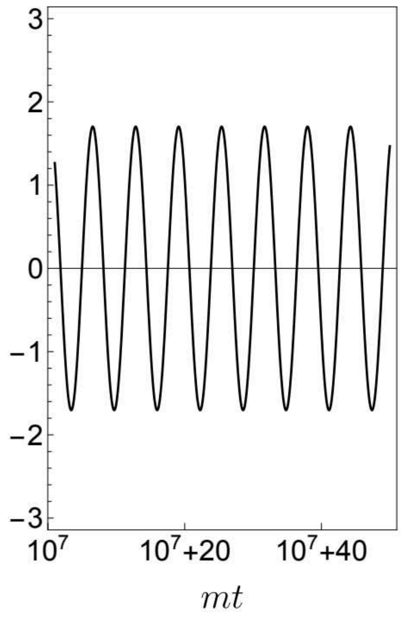
Pulsar Timing array

The presence of ULDM induces an oscillating gravitational potential that affects the light travel time of radio pulses emitted by pulsars.
PTAs can be used to test the presence of ULDM particles in the MW ⟶ how ULDM affects the SGWB in PTA system

Ultra-light DM: Coherent wave oscillation of ULDM

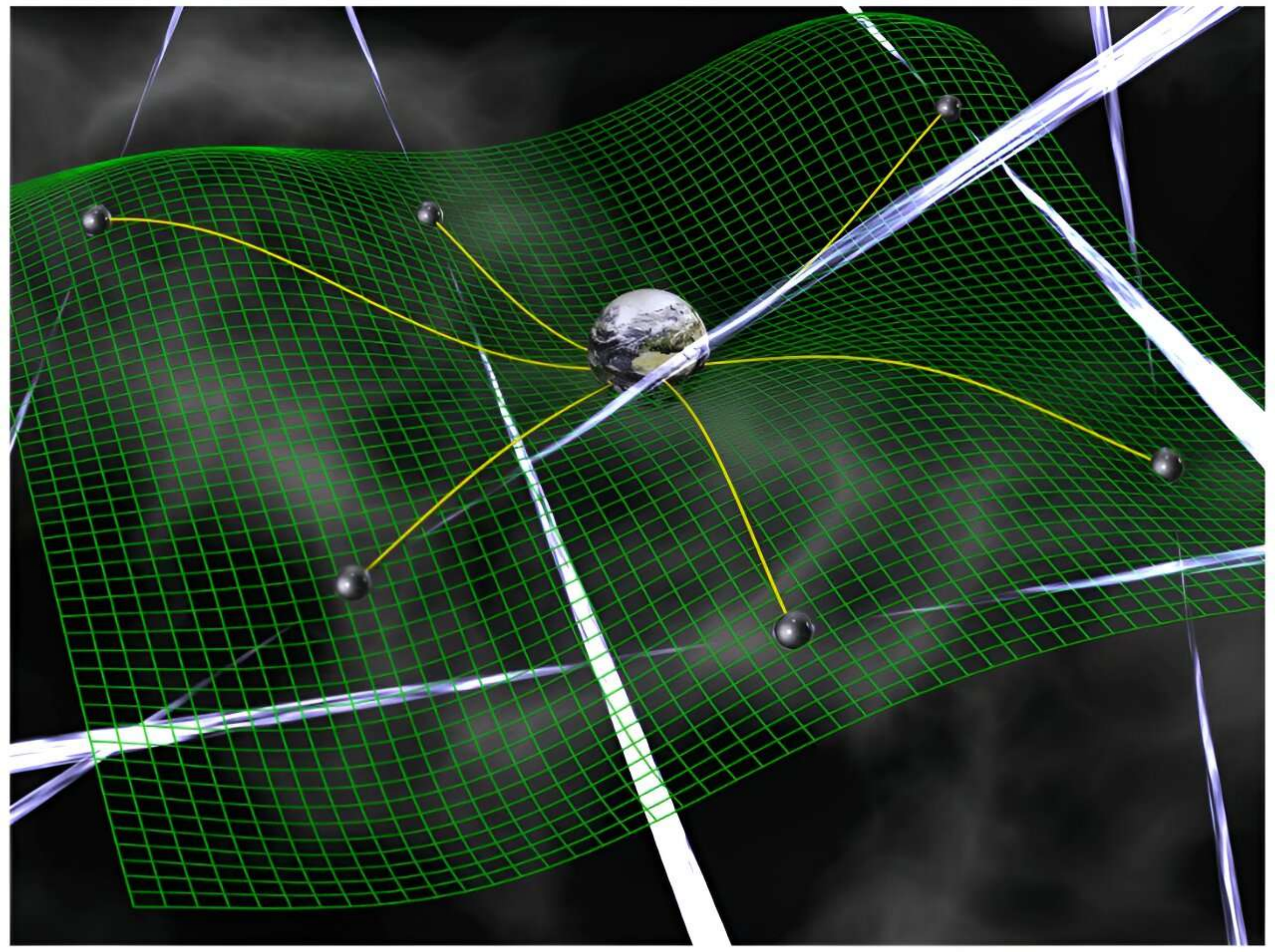
"Second Data Release from the European Pulsar Timing Array: Challenging the Ultralight Dark Matter Paradigm"

Clemente Smarra *et al.* (European Pulsar Timing Array), Phys. Rev. Lett. **131**, 171001



$$\phi(t,\vec{x}) = m^{-1}\sqrt{2\rho(t,\vec{x})}\cos[mt+\theta(t,\vec{x})]$$

Sources an oscillating gravitational potential



Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

Khmelnitsky & Rubakov (2014)

Pulsar Timing array

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$$\phi(t,\vec{x}) = m^{-1}\sqrt{2\rho(t,\vec{x})}\cos[mt+\theta(t,\vec{x})]$$

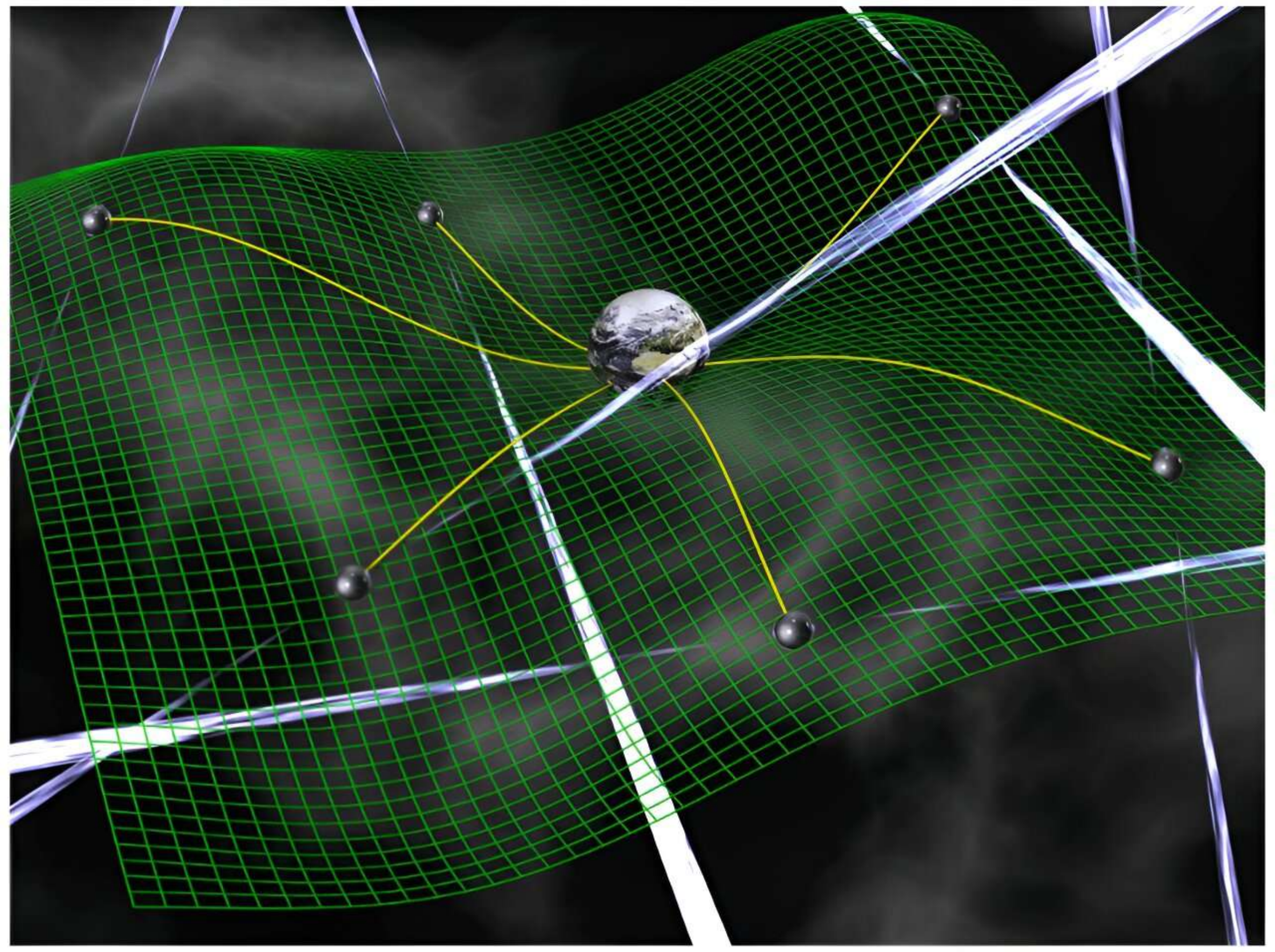
Sources an oscillating gravitational potential. Solving the 00 and ii components of Einstein's equations at first order:

1) 00: constant that obeys Poisson eq. $\nabla^2\Phi = 4\pi G(m|\psi|^2 - \bar{\rho})$

2) Trace part if ij: oscillating part obeying: $-\ddot{\Phi} \sim 4\pi G P$

with $P = (\dot{\phi}^2 - m^2\phi^2)/2$ oscillating with frequency $2m$

$\Rightarrow$ Φ oscillates with frequency $2m$ (and amplitude $\pi G\rho/m^2$)



Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

In the Milky Way: the constant part of Φ is of the order 10^{-6}; the oscillating part is $\sim 10^{-12}$

Khmelnitsky & Rubakov (2014)

Pulsar Timing array

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Coherent wave oscillation of ULDM: Φ oscillates with frequency $2m$ (and amplitude $\pi G\rho/m^2$)

$$\Phi(t,\vec{x}) \simeq \Phi_0(\vec{x}) + \Phi_c(\vec{x})\cos(\omega t + 2\alpha(\vec{x})) + \Phi_s(\vec{x})\sin(\omega t + 2\alpha(\vec{x}))$$

From Poisson eq.: $\Phi_0 \sim G\rho_{dm}/k^2$

Oscillating part: $\Phi_c(\vec{x}) = (1/2)\pi G A(\vec{x})^2 = \pi\frac{G\rho_d m(\vec{x})}{m^2}$

(smaller Φ_0 by a factor of $k^2/m^2 = v^2$)

This oscillation induces a **time-dependent frequency shift and a time delay for any propagating signal**. This is a displacement in the time on arrival (TOAs) of radio pulses emitted by pulsars

$$\delta t_{dm}(t) = -\int_0^t \frac{\Omega(t) - \Omega_0}{\Omega_0}\,dt'$$

$$\simeq \frac{2\Phi_c}{\omega}\sin\left(\frac{\omega D}{2} + \alpha(\vec{x} - \alpha(\vec{x}_p)\right)$$

$\Omega(t)$	pulse arrival frequency at the detector at the moment t
Ω_0	frequency in the absence of this oscillation - coincides with the pulse emission frequency at the pulsar

This expression depends on the distance to the pulsar and the scalar field phase α at the locations of the pulsar and the detector.

Pulsar Timing array

Comparing with GWs

ULDM

$$\delta t_{dm} \simeq \frac{2\Phi_c}{\omega} \sin\left(\frac{\omega D}{2} + \alpha(\vec{x} - \alpha(\vec{x}_p)\right)$$

Root mean square values of the time residuals, averaged over the distance to the pulsar:

$$\sqrt{\langle \delta t_{dm}^2 \rangle} = \sqrt{2}\frac{\Phi_c}{\omega}$$

ULDM has same effect on the pulsar timing measurements as GWB with characteristic strain:

$$h_c = 2\sqrt{3}\Phi_c = 2 \times 10^{-15} \left(\frac{\rho_{dm}}{0.3\mathrm{GeV/cm}}\right) \left(\frac{10^{-23}\,\mathrm{eV}}{m}\right)^2$$

At frequency

$$f \equiv 2\pi\omega = 5 \times 10^{-9}\mathrm{Hz} \left(\frac{m}{10^{-23}\,\mathrm{eV}}\right)$$

GWs

For a single monochromatic gravitation wave with frequency ω and characteristic strain h_c the amplitude of the timing residual

Polarization angle of GW

$$\delta t_{gw} = \frac{h_c}{\omega} \sin\left(\frac{\omega D(1 - \cos(\theta))}{2}\right) (1 + \cos\theta) \sin(2\psi)$$

Direction to the source

RMS: averaged over D ($\omega D \ll 1$), θ and ψ:

$$\sqrt{\langle \delta t_{gw}^2 \rangle} = \frac{1}{\sqrt{3}} \frac{h_c}{\omega}$$

Pulsar Timing array

Comparing with GWs

<u>ULDM</u>

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At frequency

$$f \equiv 2\pi\omega = 5 \times 10^{-9}\mathrm{Hz} \left(\frac{m}{10^{-23}\,\mathrm{eV}} \right)$$

➡

<u>EPTA</u>: for the ULDM coherent oscillation, the PTA frequency coverage corresponds to

$$m \sim 10^{-24} - 10^{-22}\,\mathrm{eV}$$

Pulsar Timing *array*

"Second Data Release from the European Pulsar Timing Array: Challenging the Ultralight Dark Matter Paradigm"

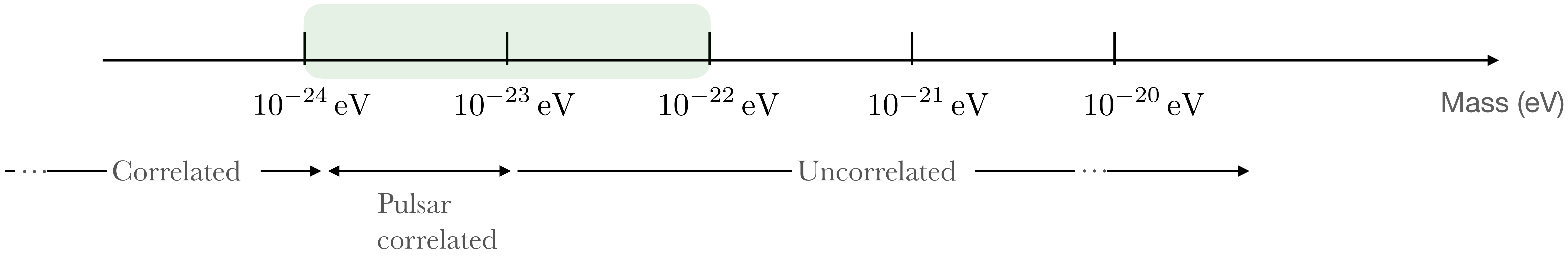
Clemente Smarra *et al.* (European Pulsar Timing Array), Phys. Rev. Lett. **131**, 171001

$$\delta t_{dm} = \frac{\Phi(\vec{x})}{2m}\left[\hat{\phi}_E^2 \sin(2m + \alpha_E) - \hat{\phi}_P^2 \sin(2m + \alpha_P)\right]$$

$$\Phi(\vec{x}) \sim 6.52 \times 10^{-18} \left(\frac{10^{-22}\,\mathrm{eV}}{m}\right)^2 \left(\frac{\rho_\phi}{0.4\,\mathrm{GeV/cm}^3}\right)$$

$$\alpha_P \equiv 2\alpha(\vec{x}_p) - 2md_p/c;$$
$$\alpha_E \equiv 2\alpha(\vec{x}_E)$$

$\hat{\phi}(\vec{x})$ accounts for the interference pattern in the proximity of $\vec{x}$



Correlated

Pulsar correlated

Uncorrelated

Pulsar Timing *array*

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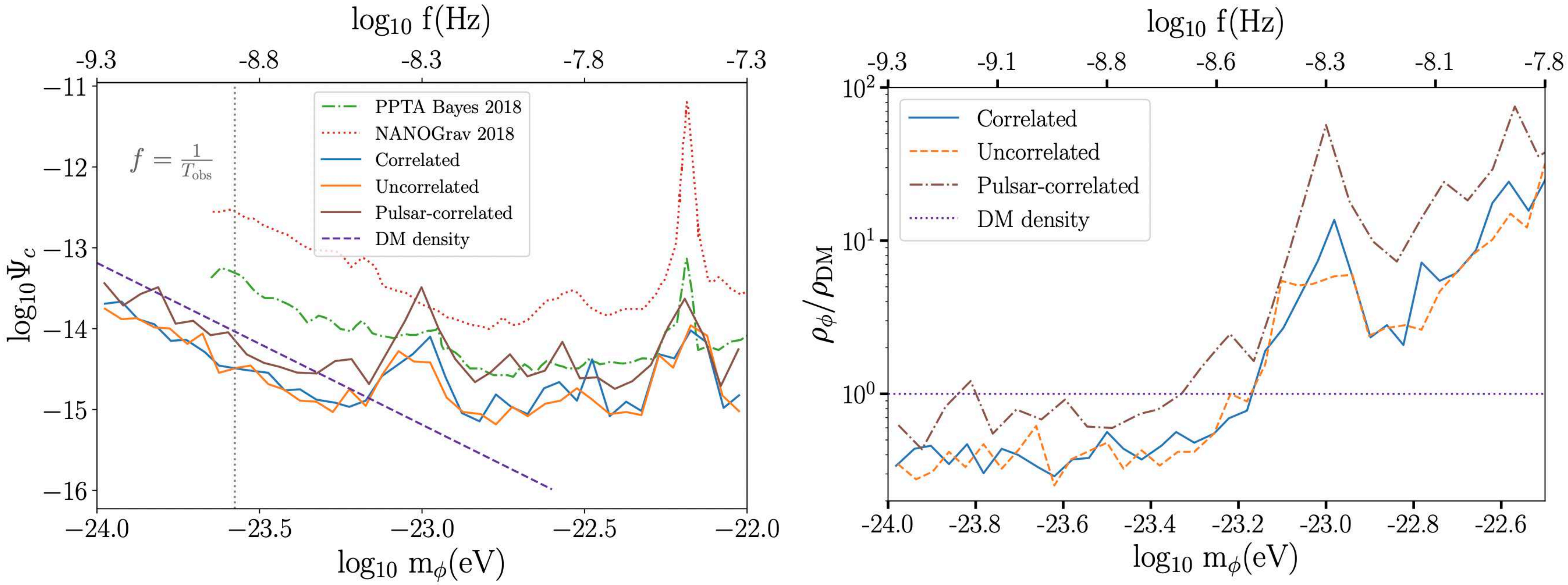

$$-24.0 < \log_{10}\,(m_\phi/\mathrm{eV}) < -23.7 \longrightarrow f_\phi \lesssim 30 - 40\,\%$$

$$-23.7 < \log_{10}\,(m_\phi/\mathrm{eV}) < -23.3 \longrightarrow \text{up to } f_\phi \sim 70\,\%$$

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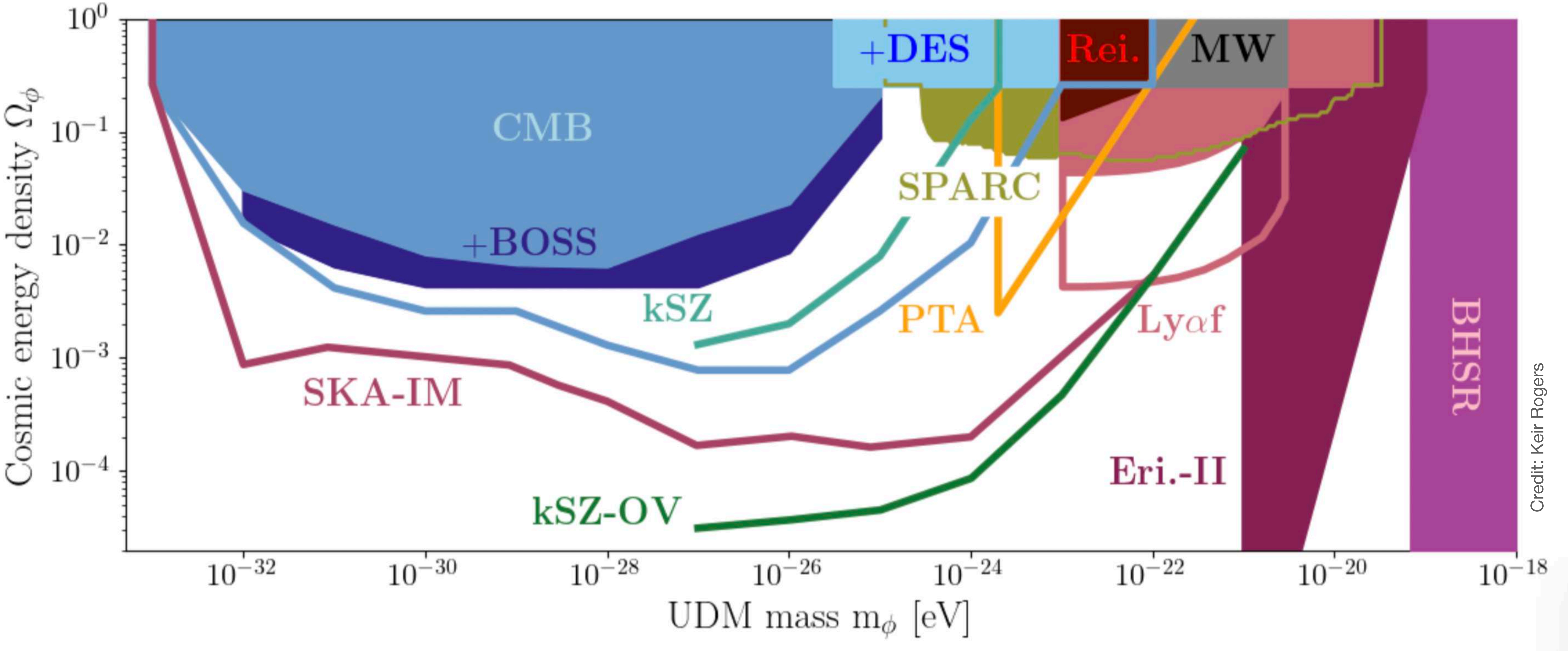

Credit: Keir Rogers

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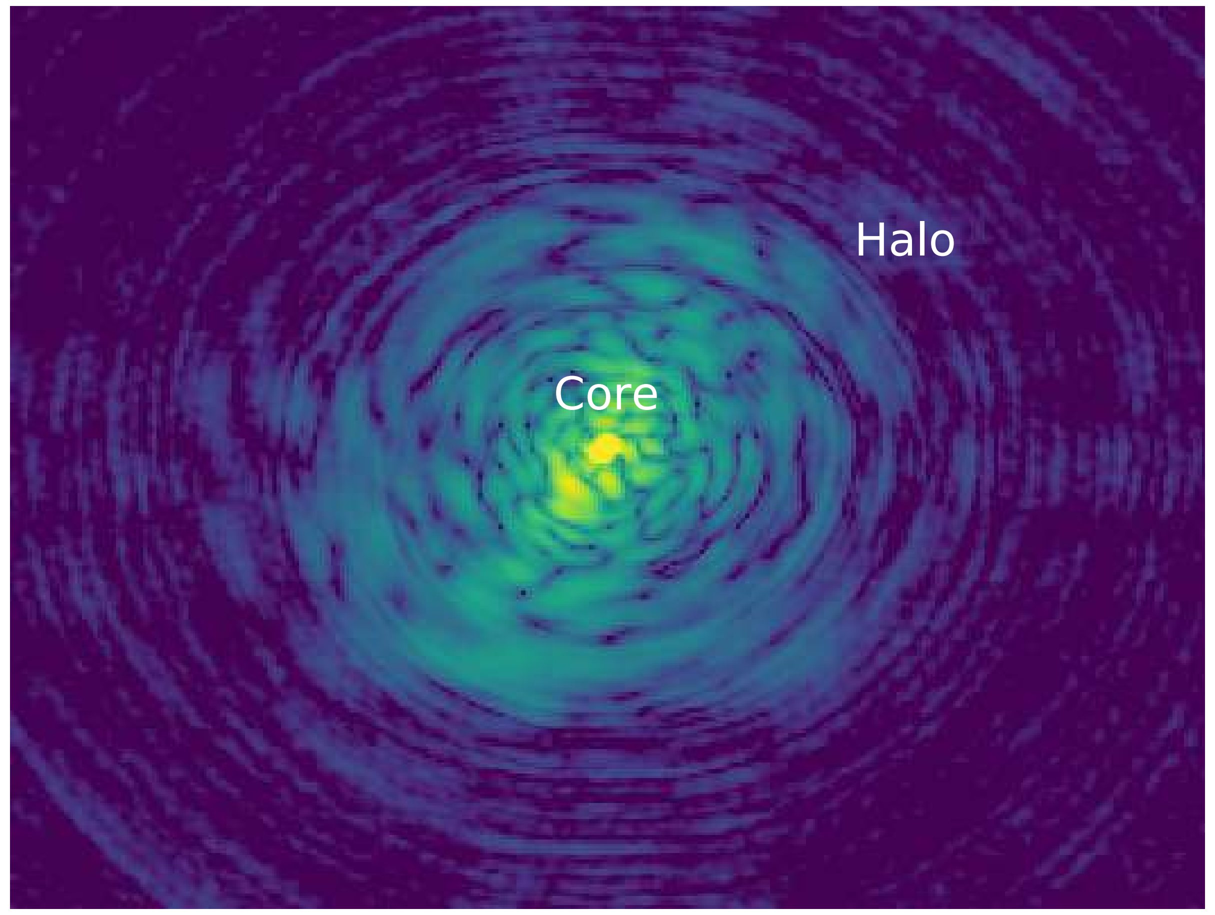
de Broglie scale time delays

(Work in progress)

In collaboration with Andrew Eberhardt and Qiuyue Liang

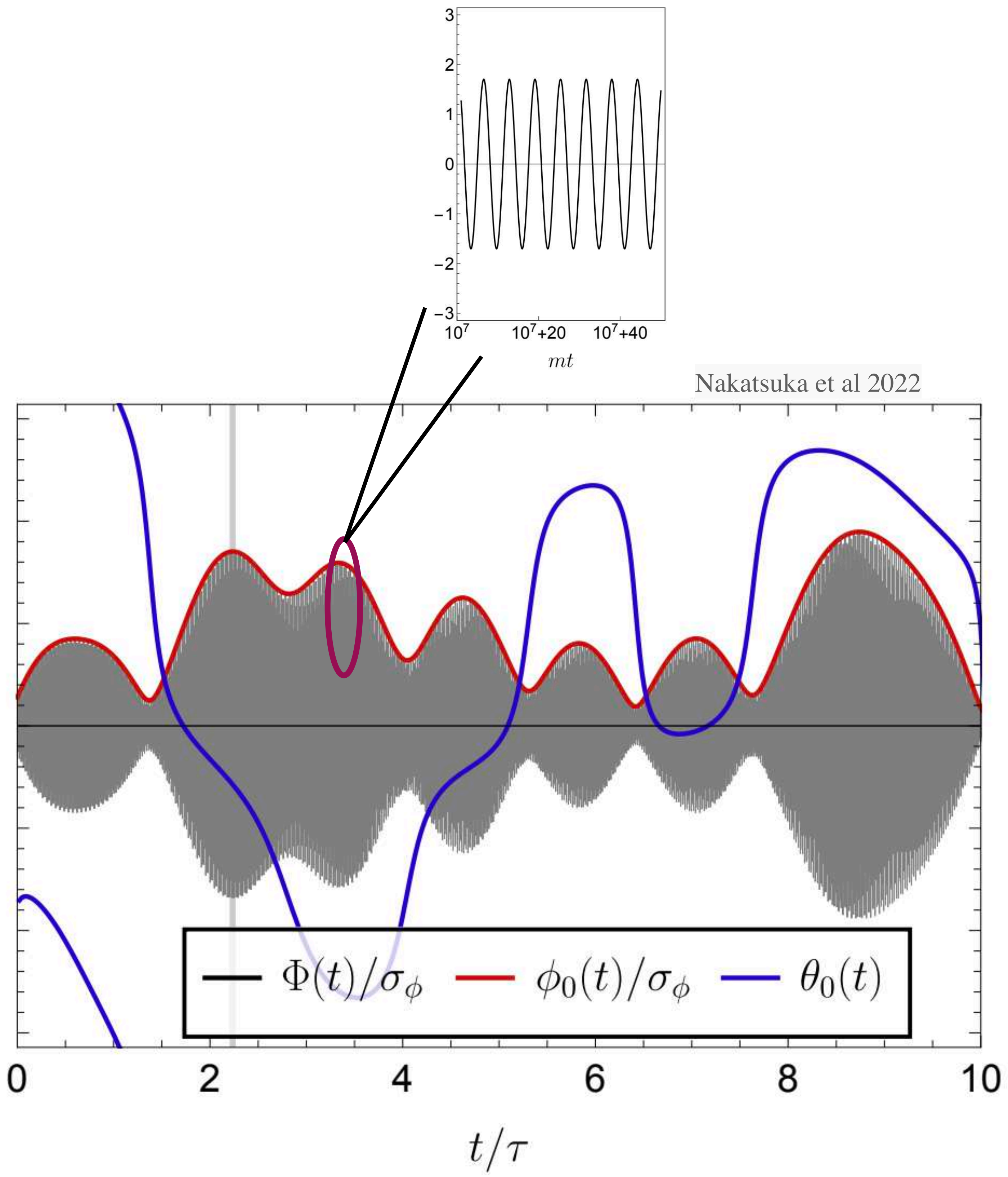
Our analysis: Considering the interference pattern



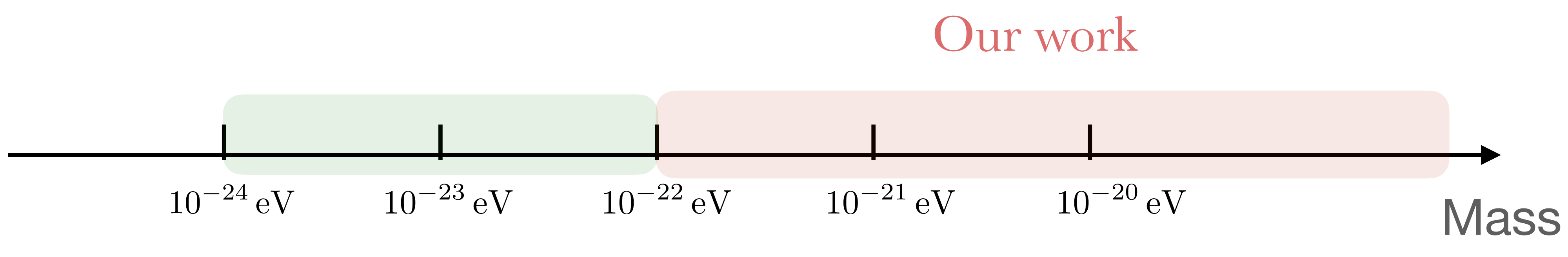
~~$\phi(t,\vec{x}) = m^{-1}\sqrt{2\rho(t,\vec{x})}\cos[mt+\theta(t,\vec{x})]$~~

Random phase halo model: as a simple model of a galactic halo, consider a superposition of plane waves:

$$\phi(t,\vec{x}) = \sum_{i}^{N} \frac{\phi(0)}{\sqrt{N}} \cos\left(mt + \frac{m}{2}v_i^2 t - m\vec{v}_i\cdot\vec{x} + \theta_i\right)$$



Nakatsuka et al 2022



Our work

de Broglie scale time delays

Pulsar Timing array

(Work in progress)

In collaboration with Andrew Eberhardt and Qiuyue Liang

<u>Our analysis</u>: Considering the interference pattern

$$\tau_{coh} = \frac{2\pi}{\Delta E \phi} \sim 10^6\, T_{osc}$$

$$\boxed{m\,t \ll \tau_{coh}}$$

Correlated

$$\Phi(t) \sim \cos(mt)$$

+

Large granules:

Ex.: $m \sim 10^{-22}$ eV, granules of 1/10 of kpc

Angular correlation of PTA signal within a granular size would be enhanced due to the superposition.

$$\boxed{m\,t = t_{propagating} \sim \tau_{coh}}$$

$$t_{propagating} \sim 3000\,\text{yrs}$$

➡

$$3000\,\text{yrs} \sim 10^6/m$$

$$m \sim 4.38 \times 10^{-20}\text{eV}$$

Pulse would go through many granules during the propagation.

$$\boxed{m\,t = t_{obs} \sim \tau_{coh}}$$

$$t_{obs} \sim 10\,\text{yrs}$$

➡

$$30\,\text{yrs} \sim 10^6/m$$

$$m \sim 1.3 \times 10^{-17}\text{eV}$$

de Broglie scale time delays

de Broglie scale time delays in pulsar networks for ultralight dark matter
Andrew Eberhardt, Qiuyue Liang, EF, 2411.18051

$m \gtrsim 10^{-17}\,\mathrm{eV}$ granules fluctuate on timescales similar to observational timescales

de Broglie scale time delays

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Andrew Eberhardt, Qiuyue Liang, EF, 2411.18051

Time delays:

$$\delta t_{dm}(t) = -\int_0^t \frac{\Omega(t') - \Omega_0}{\Omega_0}\, dt'$$

$$\Delta\Omega = \underbrace{\Delta\Omega^{\rm osc}_{\rm sh} + \Delta\Omega_{\rm sh}}_{\text{Shapiro time delay}} + \underbrace{\Delta\Omega^{\rm osc}_{\rm gr} + \Delta\Omega_{\rm gr}}_{\text{Gravitational redshift}}$$

Gravitational redshift

$$\frac{\Delta\Omega_{gr}}{\Omega_0} = \Phi_P - \Phi_E$$

↓

The frequency change comes from the time variation of this path

$$\frac{\Delta\Omega_{\rm gr}}{\Omega_0} = \frac{\partial_t \ell}{1 - \partial_t \ell}$$

Shapiro time delay

The travel time as an integral along the path from the pulsar to Earth

$$\ell = \int d\ell' \left(1 + 2\Phi(\ell')\right)$$

→

$$\delta t_{\rm sh} = \int_p^e \frac{dl}{c} 2\Phi(l)$$

de Broglie scale time delays

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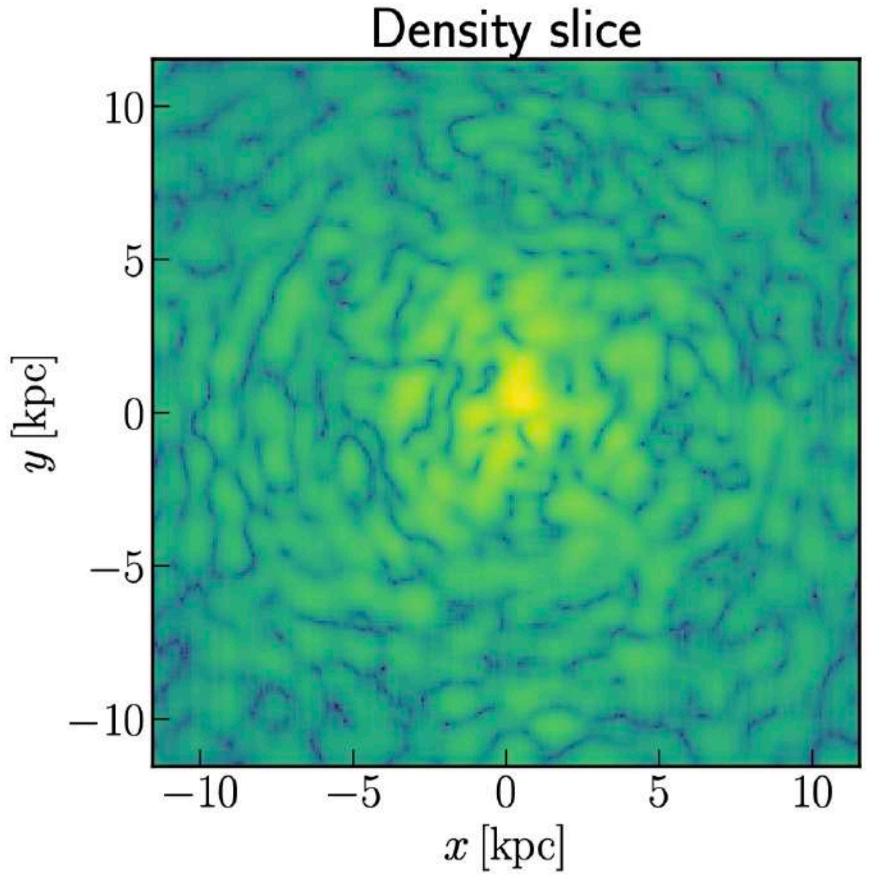
We simulate arrays of mock pulsars in a fluctuating granular density field

$$\delta t^{\rm sh}_{\rm rms} \sim 5\times 10^{-2}\left(\frac{10^{-17}\,\mathrm{eV}}{m}\right)^{7/3}\left(\frac{200\,\mathrm{km/s}}{\sigma}\right)^{7/3}\left(\frac{\rho}{10^{7}\,\mathrm{M}_\odot/\mathrm{kpc}^3}\right)\left(\frac{D}{\mathrm{kpc}}\right)^{2/3}\ \mathrm{ns}\,,$$

$$\delta t^{\rm z}_{\rm rms} \sim 4\times 10^{-4}\left(\frac{10^{-17}\,\mathrm{eV}}{m}\right)^{3/2}\left(\frac{200\,\mathrm{km/s}}{\sigma}\right)^{4}\left(\frac{\rho}{10^{7}\,\mathrm{M}_\odot/\mathrm{kpc}^3}\right)\left(\frac{T}{30\,\mathrm{yrs}}\right)^{3/2}\ \mathrm{ns}\,,$$



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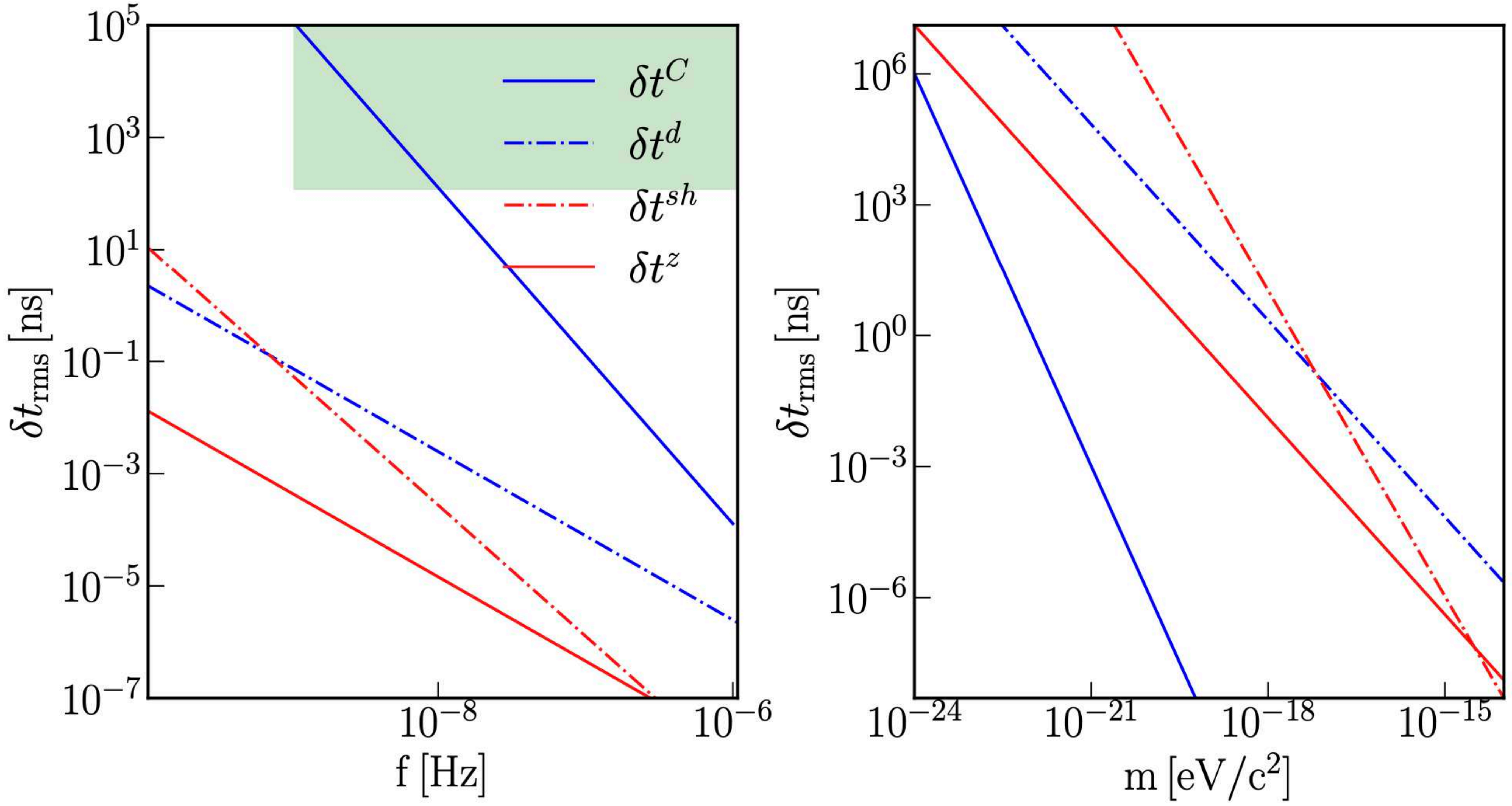
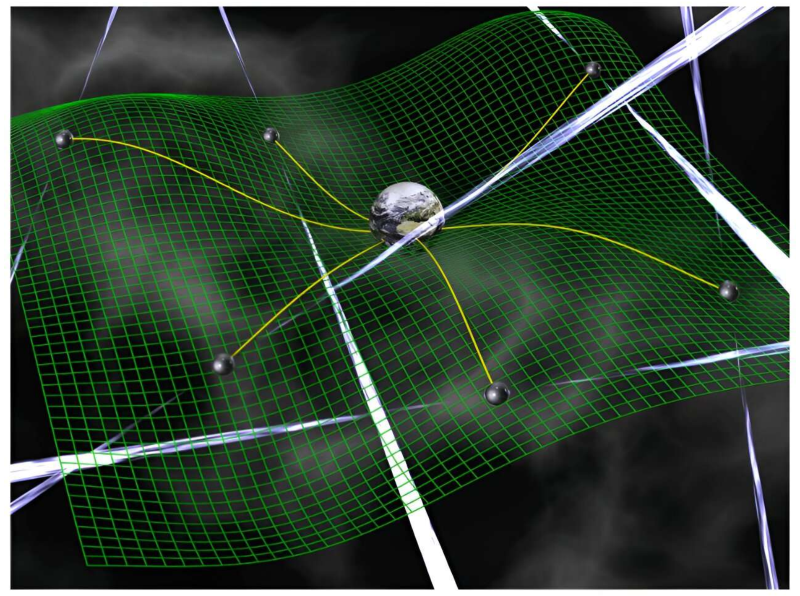


- Not the dominant effect for pulsar timing experiments
- dB scale effects on observable timescales could potentially provide sensitivity to mass scales higher than those probed thus far by small-scale structure
- Current largest limitation appears to be the longest de Broglie time to which experiments are sensitive
- Experiments with longer runtimes or somehow sensitive to **longer time scales** would substantially improve the signal from the effects studied here

The left edge of the shaded regions in green corresponds to when the relevant timescale (dB time for dB scale effects or Compton time for Compton scale effects) is 30 yrs

Pulsar Timing array


Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

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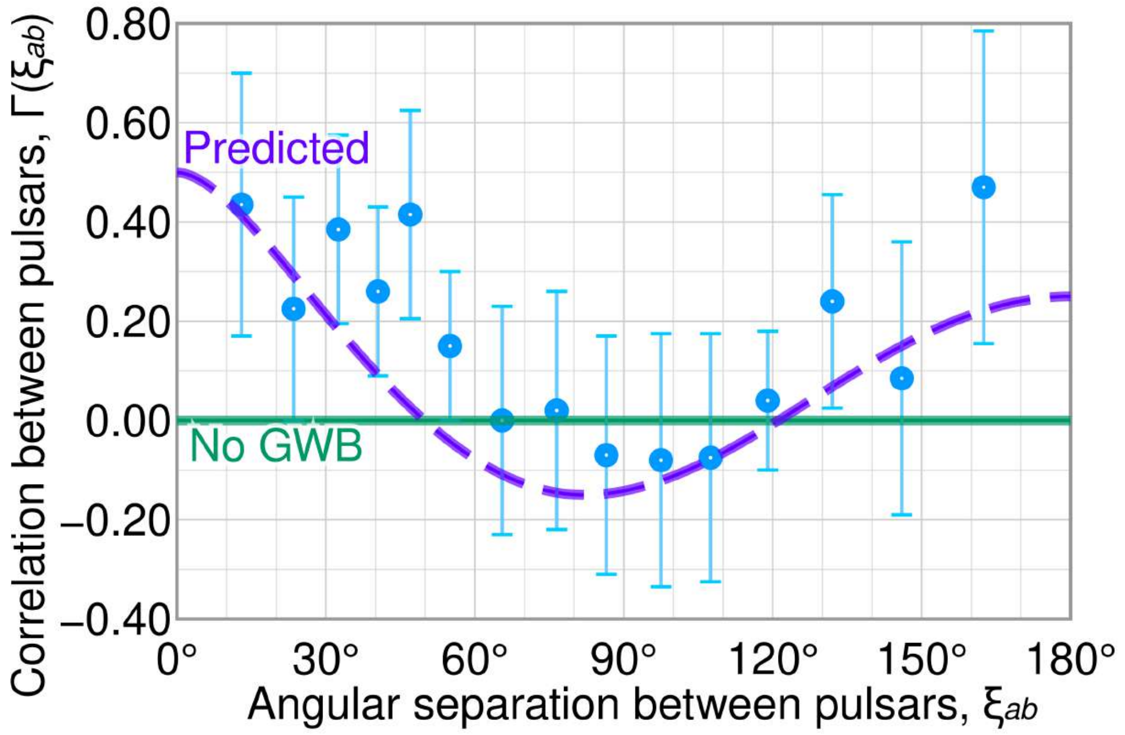

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- New physics

The presence of ULDM induces an oscillating gravitational potential that affects the light travel time of radio pulses emitted by pulsars.
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EPTA, Smarra et al 2024

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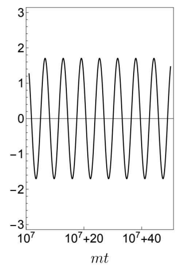
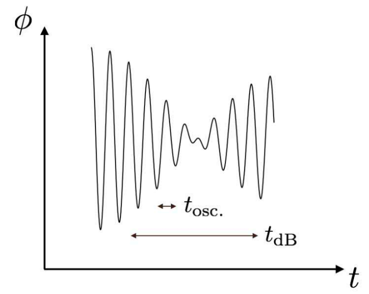
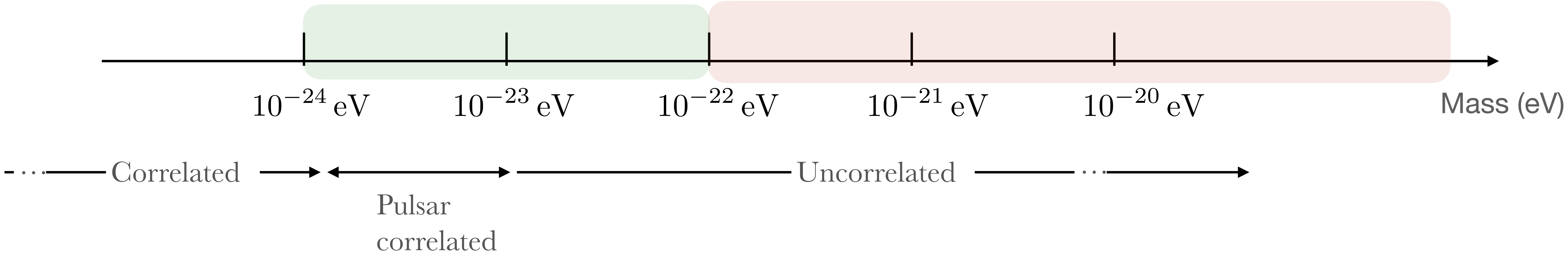




Our work



10^{-24} eV 10^{-23} eV 10^{-22} eV 10^{-21} eV 10^{-20} eV Mass (eV)

Correlated

Pulsar correlated

Uncorrelated

Pulsar Timing array

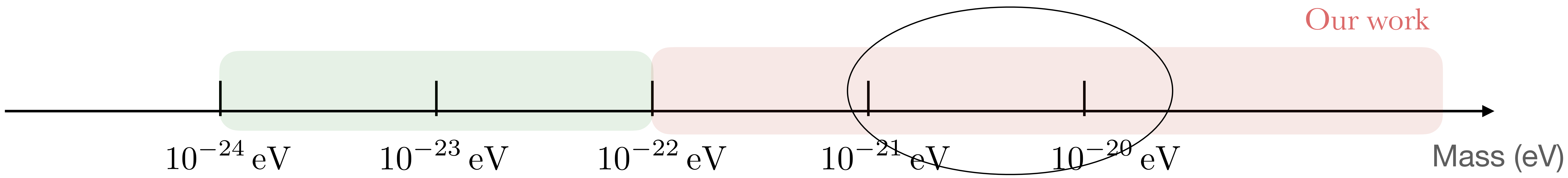
(Work in progress)

In collaboration with Andrew Eberhardt and Qiuyue Liang

The presence of ULDM induces an oscillating gravitational potential that affects the light travel time of radio pulses emitted by pulsars.

PTAs can be used to test the presence of ULDM particles in the MW ⟶ how ULDM affects the SGWB in PTA system

Considering the interference pattern



de Broglie scale time delays

Pulse would go through many granules during the propagation.

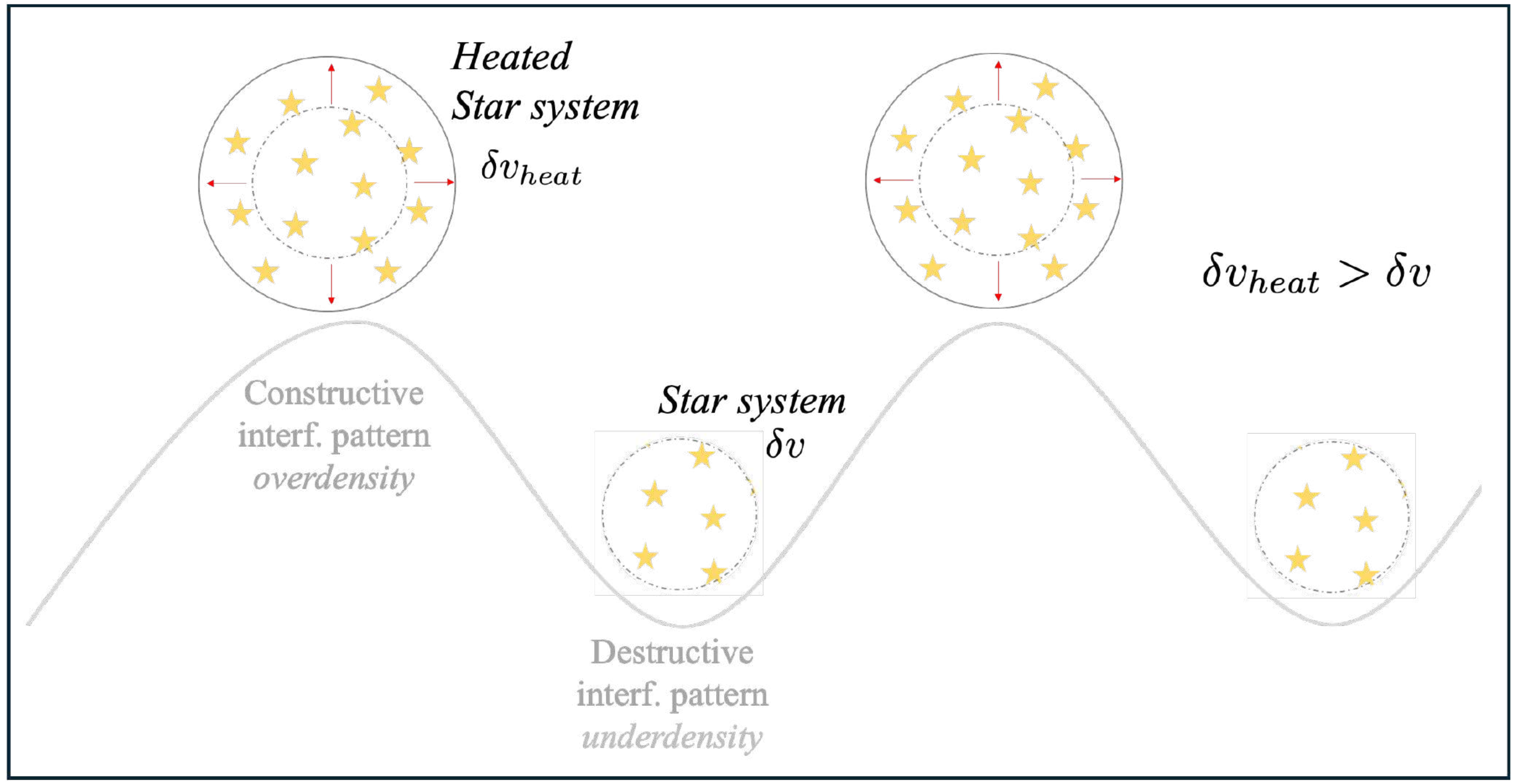
Angular correlation

Binary stars - as a probe of ULDM

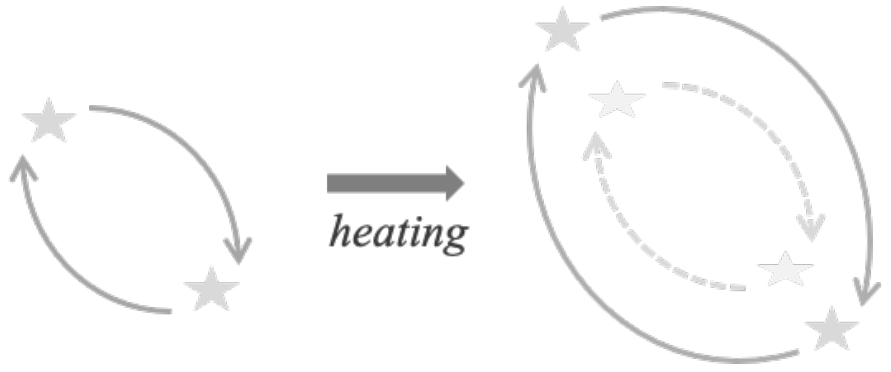
(Work in progress)

In collaboration with Andrew Eberhardt, Margot Imbach and Naoki Yoshida

Stellar heating



Binary stars

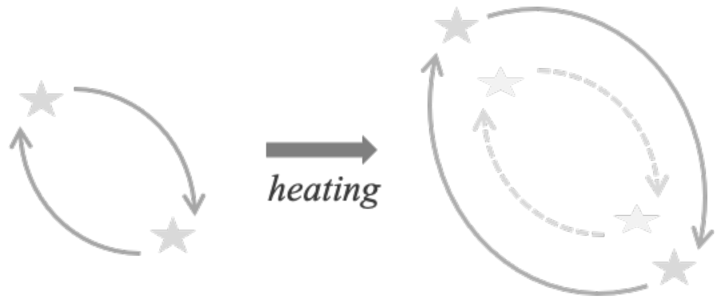


$$m \sim 10^{-[16-10]}\,\mathrm{eV}$$

Preparation for PFS!

Stellar heating

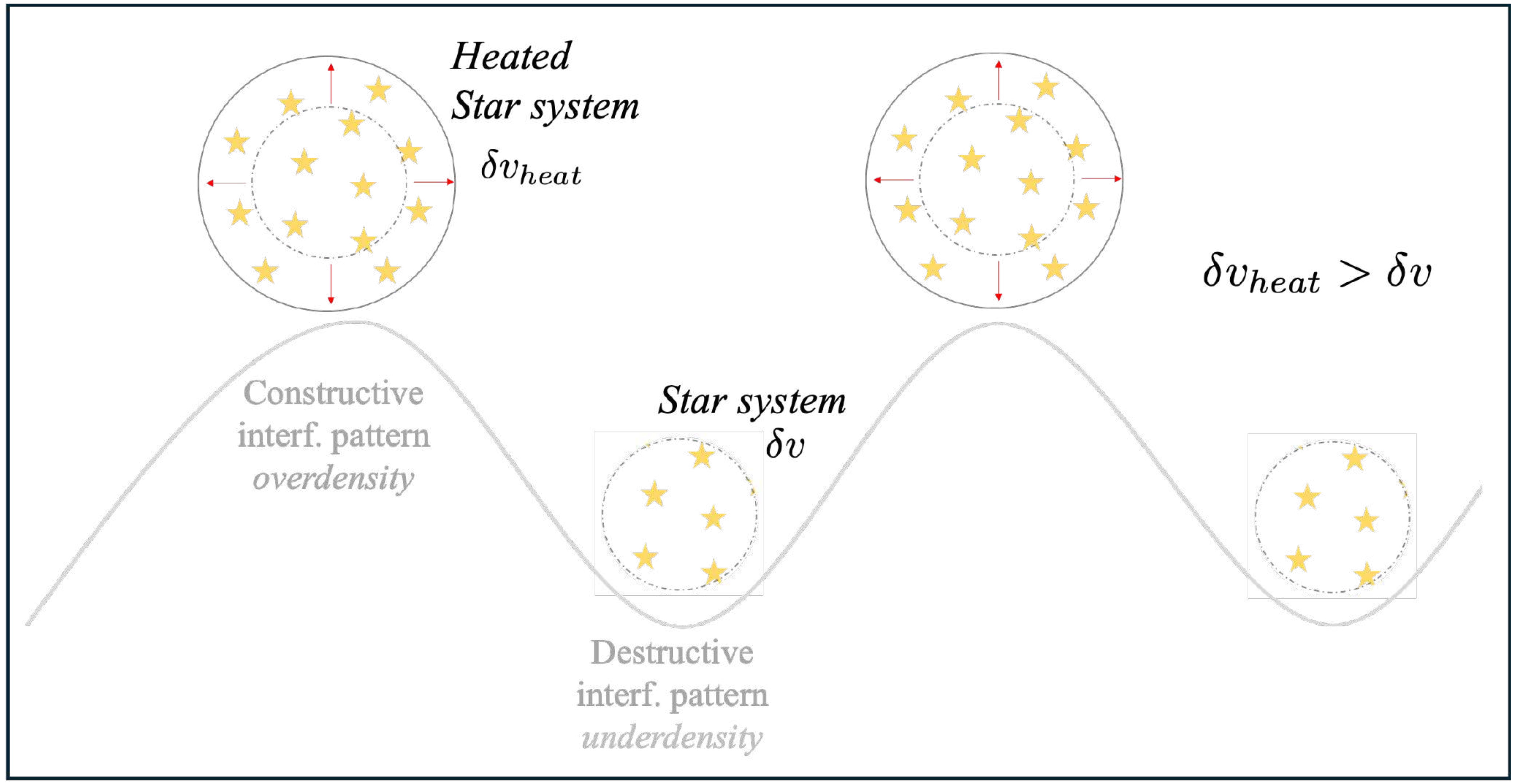
Binary stars



$m \sim 10^{-[16-10]}$ eV

Stellar streams

$m \sim 10^{-[23-18]}$ eV

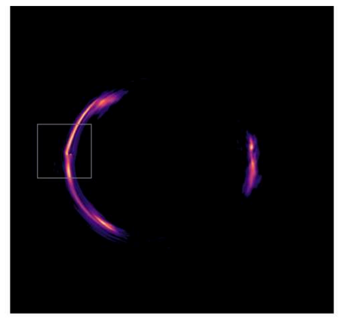


(Work in progress)

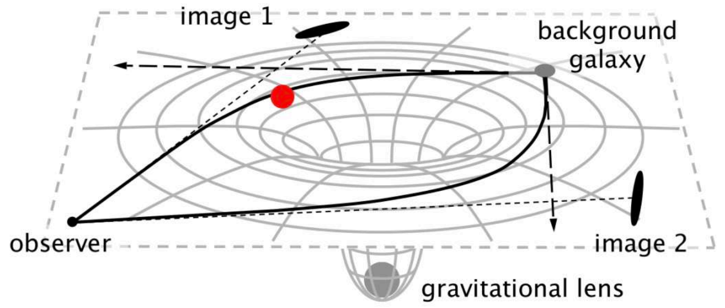
In collaboration with Andrew Eberhardt,
and Fabian Schmidt

Preparation for PFS!

The search for dark matter (ULDM) is a multi-probe/multi-scale endeavour…

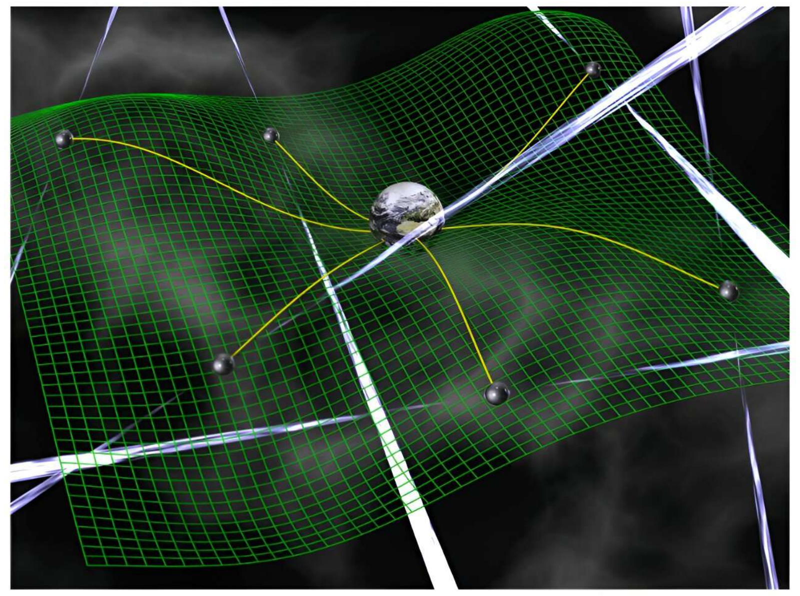


Strong lensing



$m \sim 10^{-[22-17]}\,\mathrm{eV}$

Pulsar Timing Array

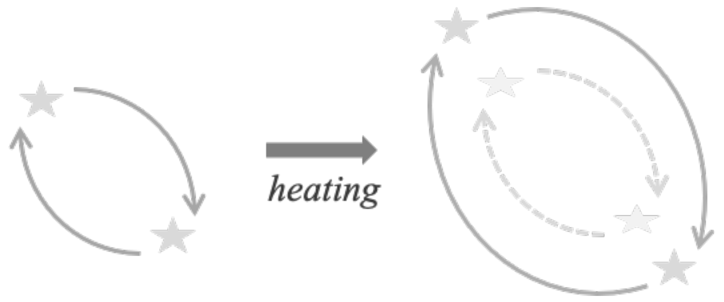


Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

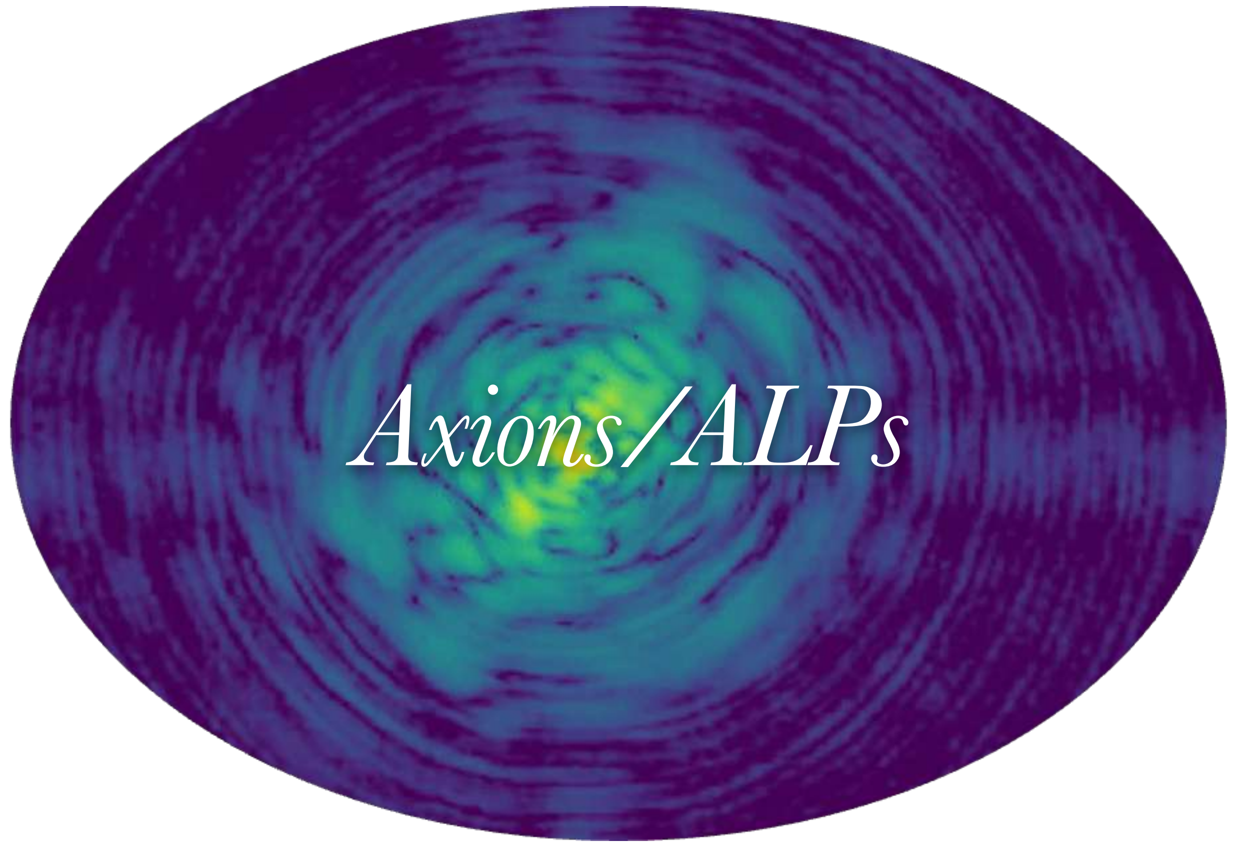
$m \sim 10^{-[22-17]}\,\mathrm{eV}$

(Work in progress)

Binary stars



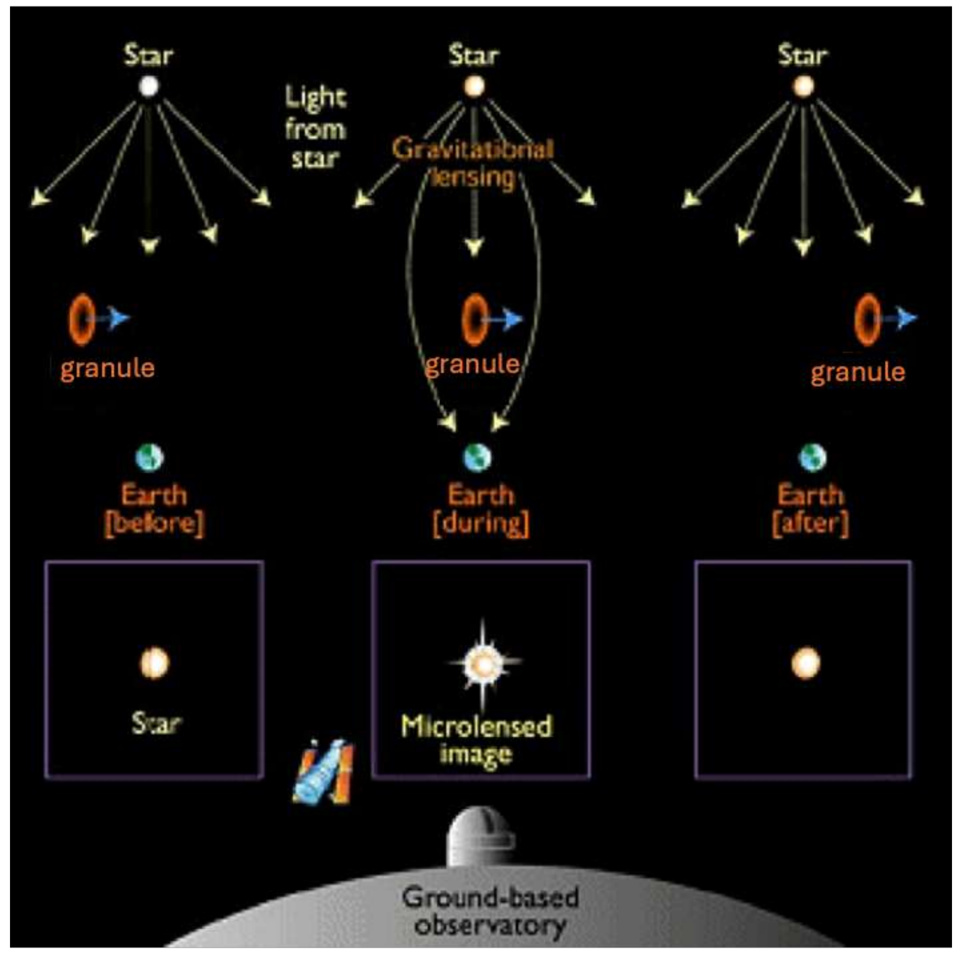
$m \sim 10^{-[16-10]}\,\mathrm{eV}$



Axions/ALPs

Mass, spin (# particles), fraction self interaction axion-photon coupling

Microlensing



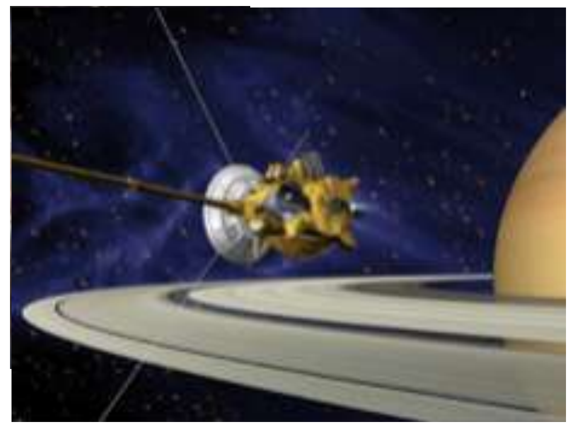
Modified from: https://i.astro.tsinghua.edu.cn/~smao/contents/microlens.html

$m \sim 10^{-[23-18]}\,\mathrm{eV}$

Stellar streams

$m \sim 10^{-[23-18]}\,\mathrm{eV}$

Solar system



$m \sim 10^{-[16-10]}\,\mathrm{eV}$

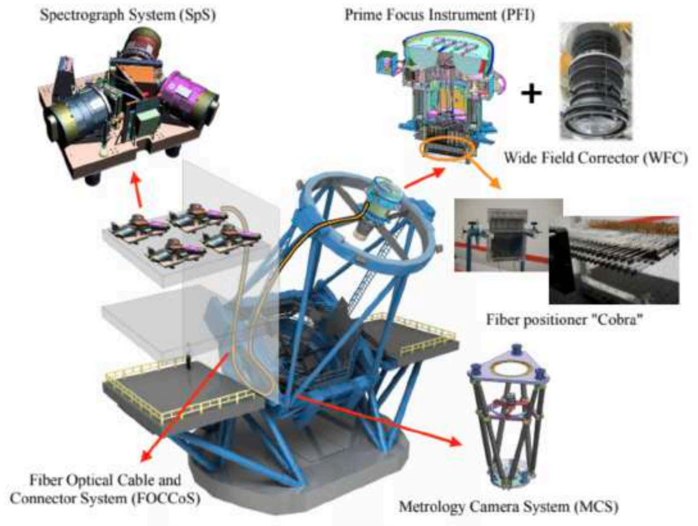
axion-photon coupling

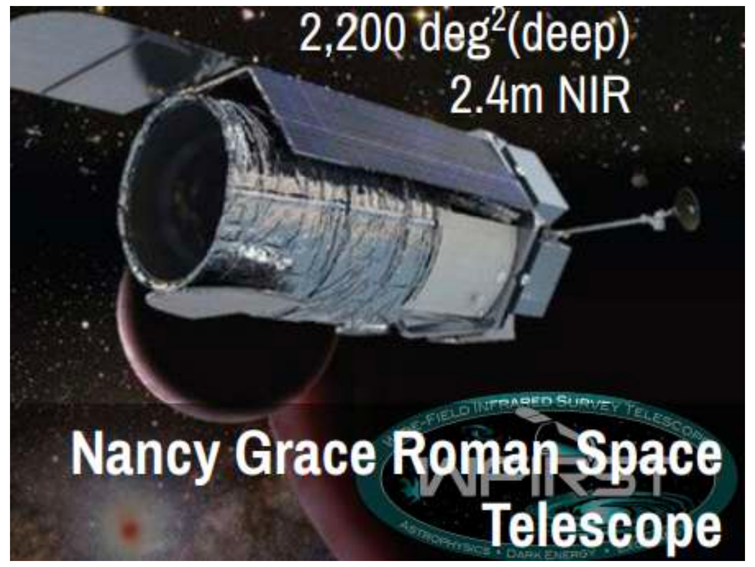
Improving these bounds

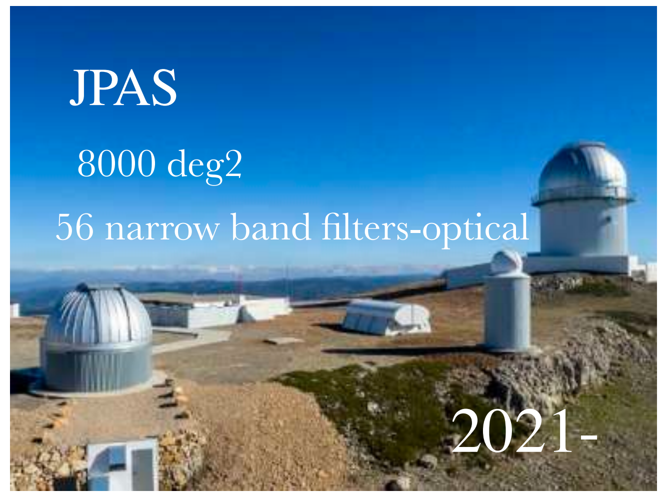
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)

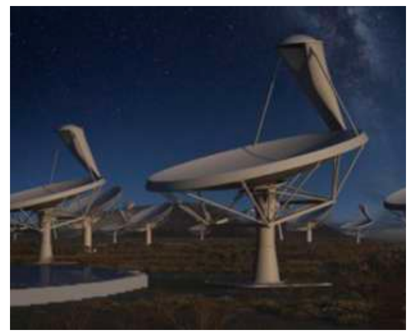






GWs

21cm



SKA
SQUARE KILOMETRE ARRAY

CMB

CMB-S4
Next Generation CMB Experiment

+ direct detection experiments

Modified from Jia Liu

PFS (Prime Focus Spectrograph)

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

PFS: spectroscopy part of *SuMIRe project*

DM with PFS ⟶ *synergy between science goals*

Galaxy archeology

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

Cosmology

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

Galaxy evolution

- Small-scale tests of structure growth
- Halo-galaxy connection M_*/M_{200}
- Physics of cosmic reionization via LAEs & 21cm studies
- Tomography of gas and DM

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

DM with PFS

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- Science with dwarf galaxies
  Core:
  - Presence of a core or not (slope)
  - Size of the core

FDM

  - Profile

SIDM

    - Inner density
    - Transition radius

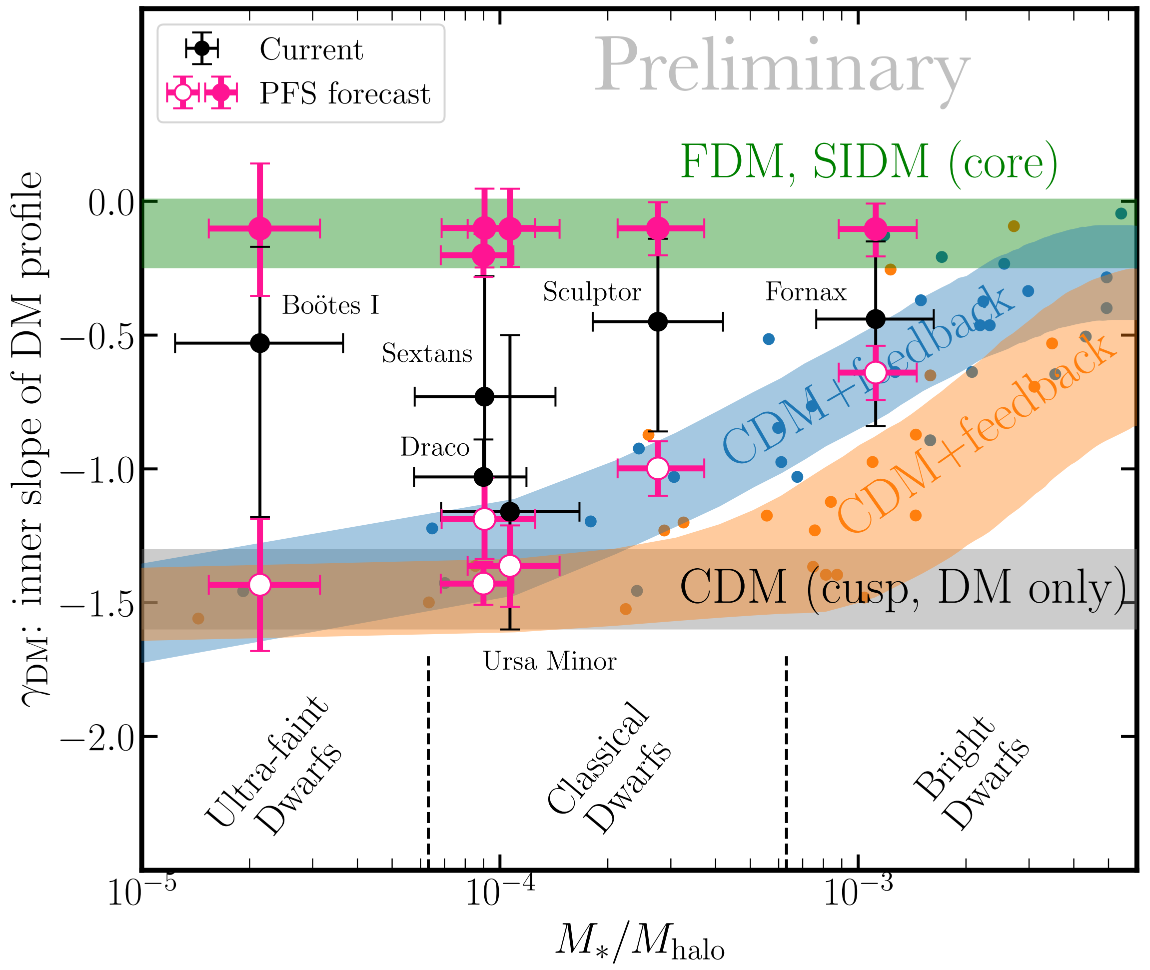
ULA

  - Abundance data to understand the role of baryons in each system
- *Beyond the core*
  - Granules: heating of stars (dwarfs)
    - Angular momentum

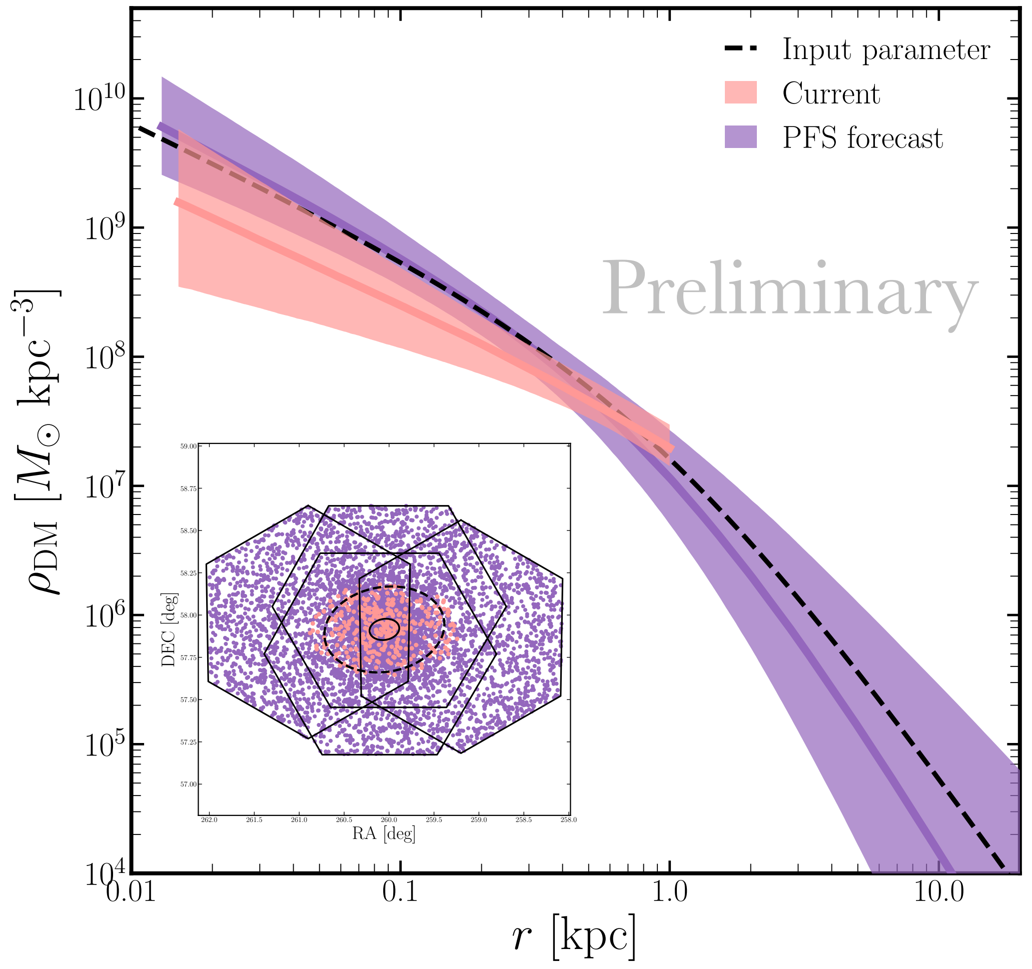
FDM

  - Stellar streams
  - Binary stars

…



Figures by Kohei Hayashi



DM with PFS

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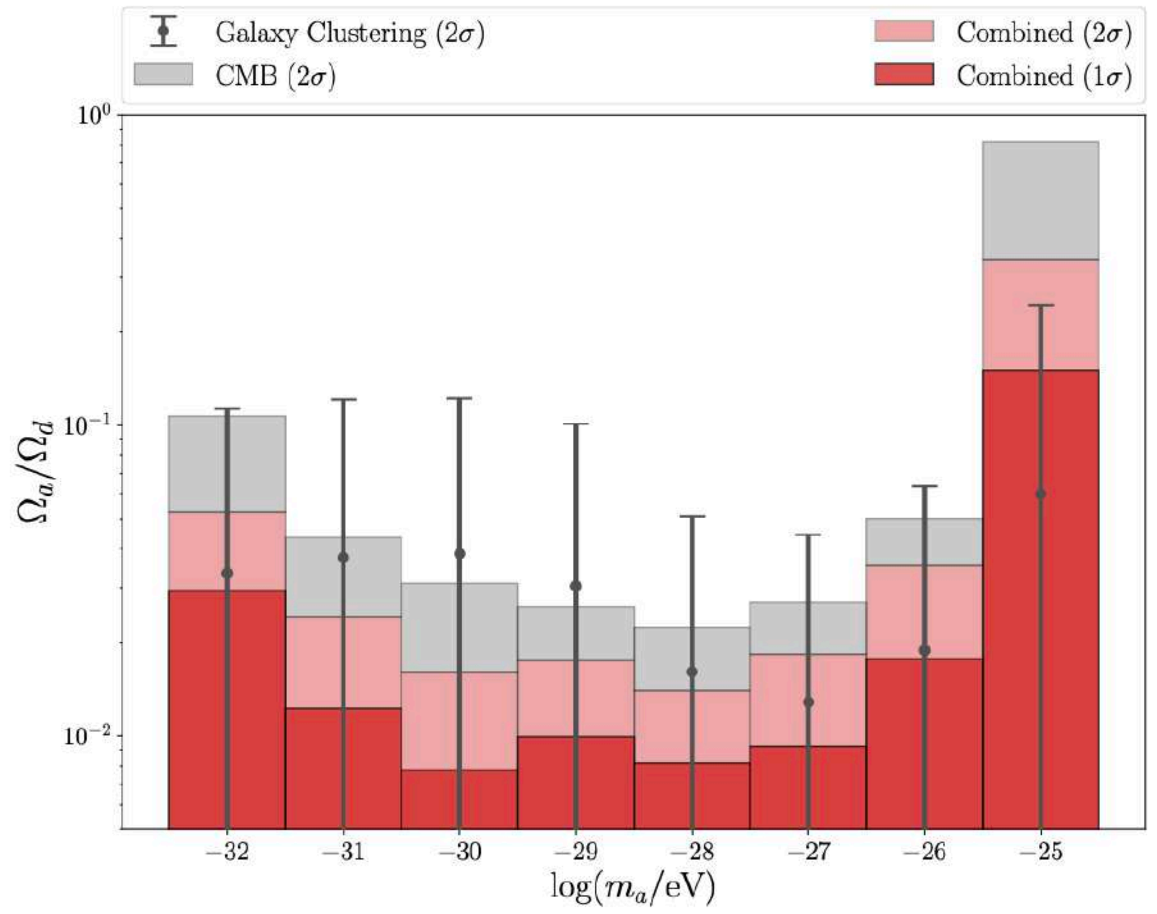
  - Binary stars …

Fraction of axions in the dark sector: $10^{-32}\,\mathrm{eV} < m < 10^{-25}\,\mathrm{eV}$



Lague et al 2021

ULA

FDM

WDM

SIDM

The small-scale Ly-α forest power spectrum

Halo mass function

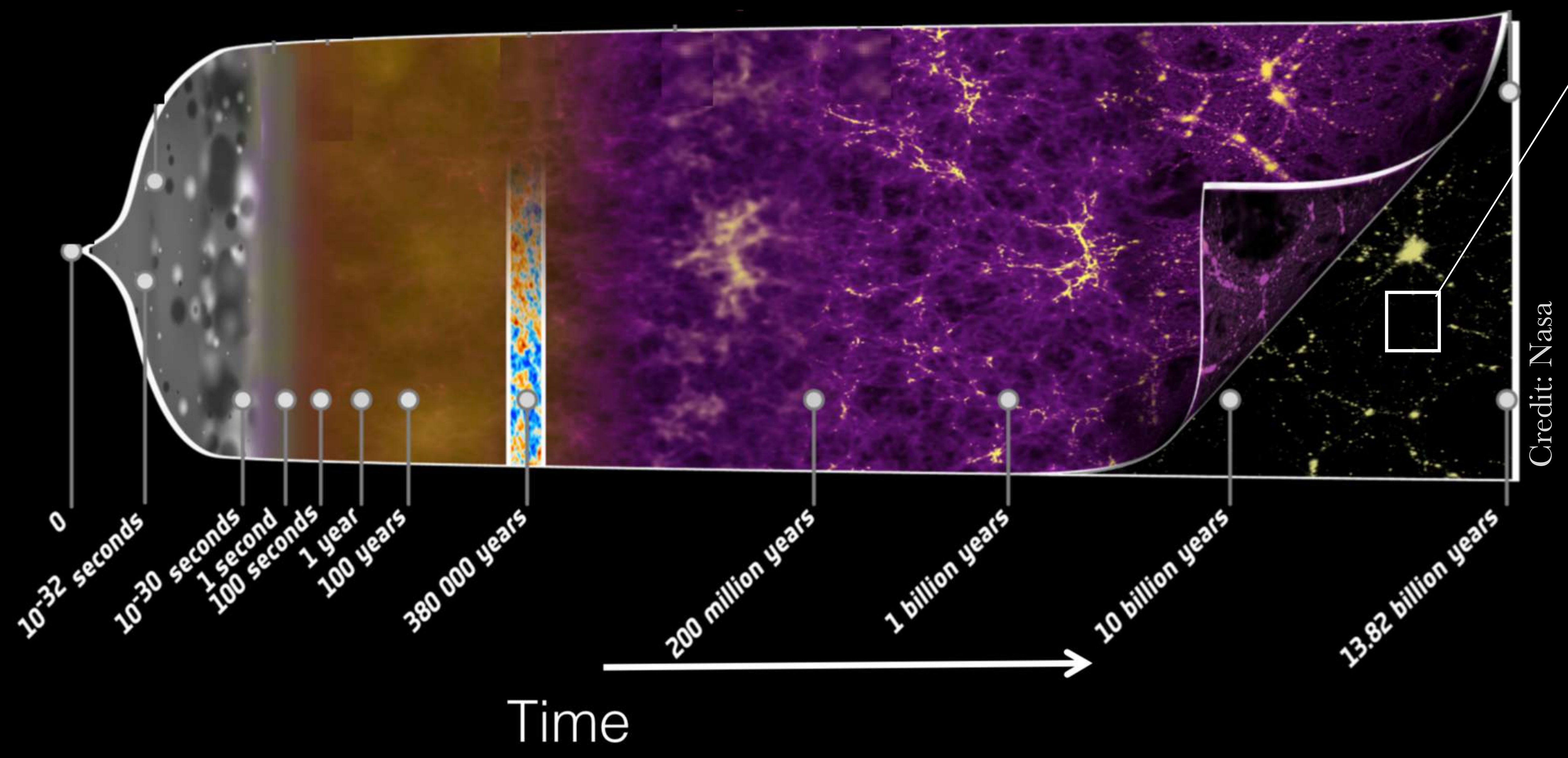
Constraints on the *optical depth:*

Constraint the ULDM mass

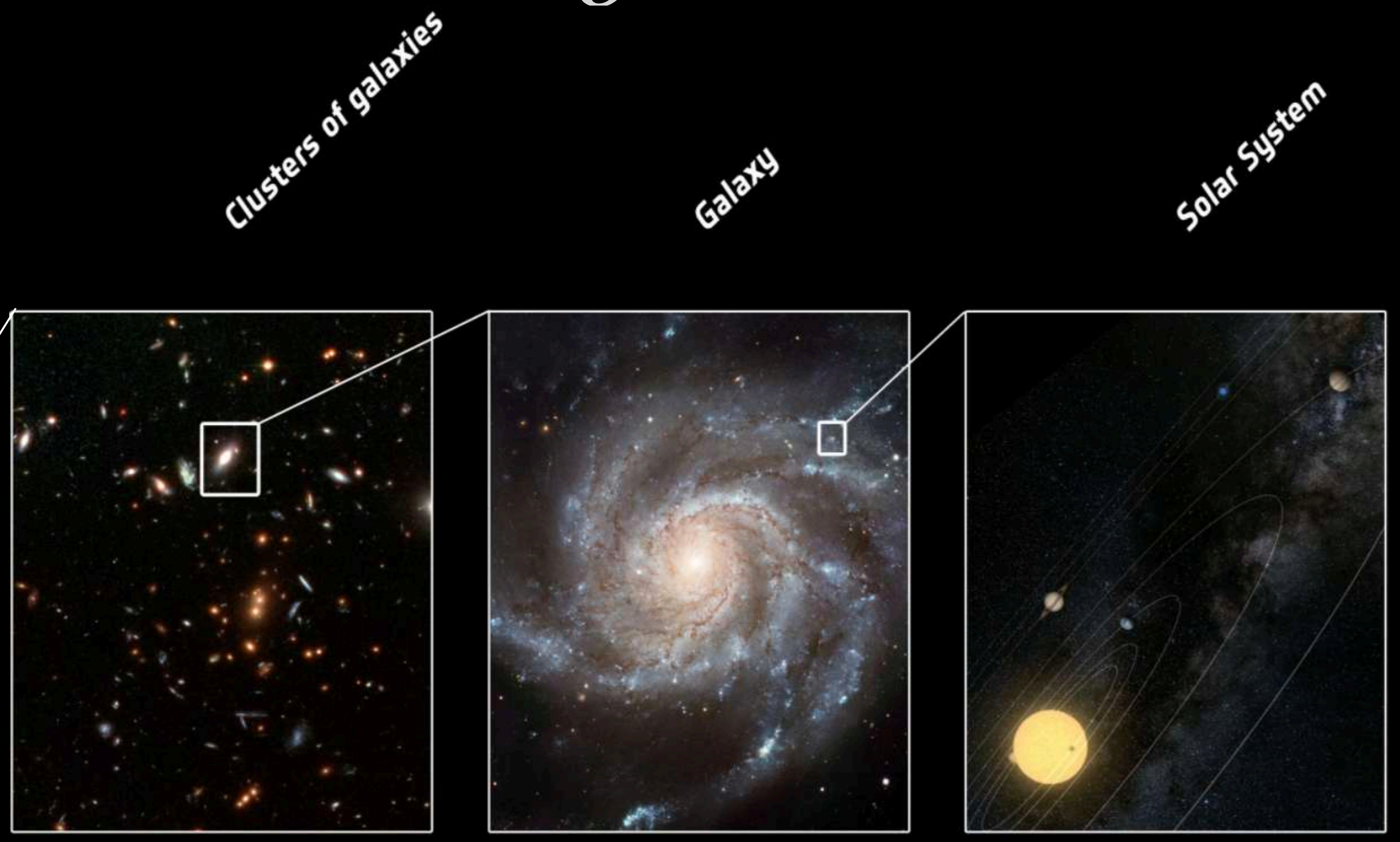
Kinematic Sunyaev–Zel'dovich effect: sensitive to the duration of the reionization

Properties of DM

Small scales can offer some hints of the nature of DM



Credit: Nasa

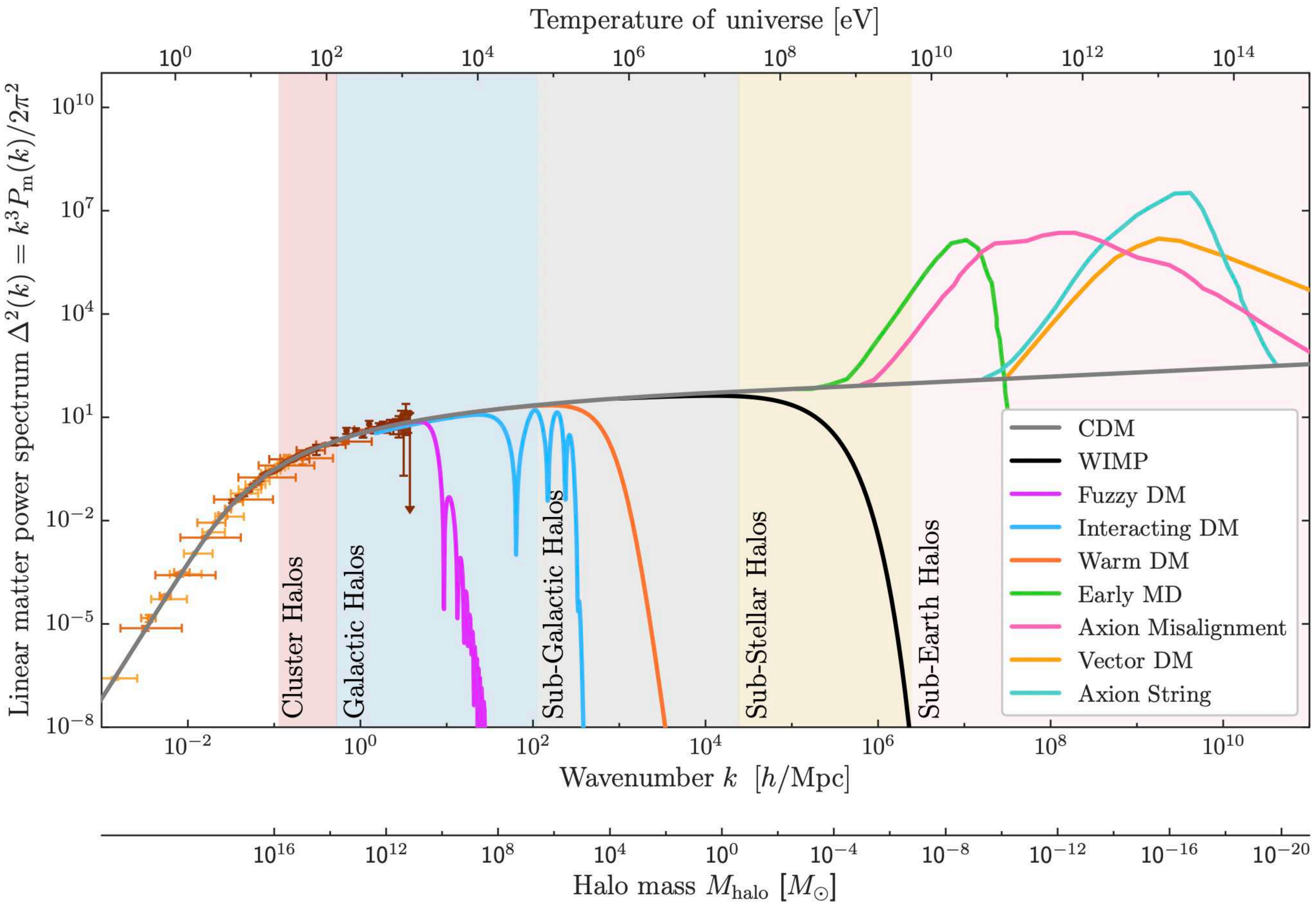


Small Scales

Opportunity to probe the nature of DM!

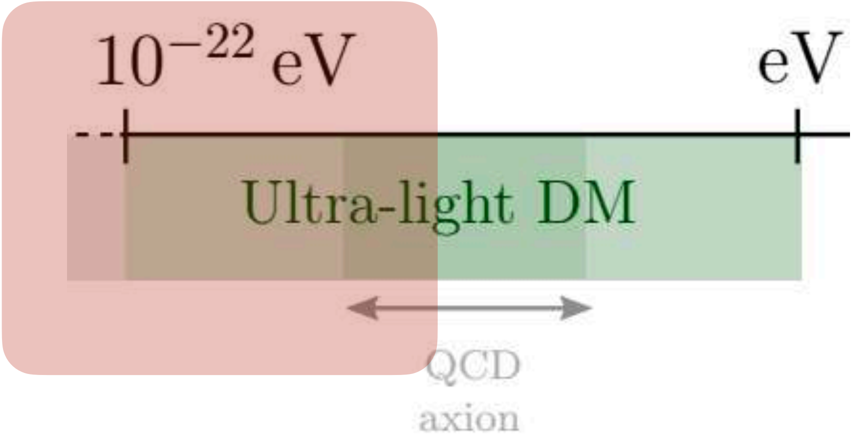
Astrophysical Observables → DM Distribution → Nature of DM Microphysics Particle physics

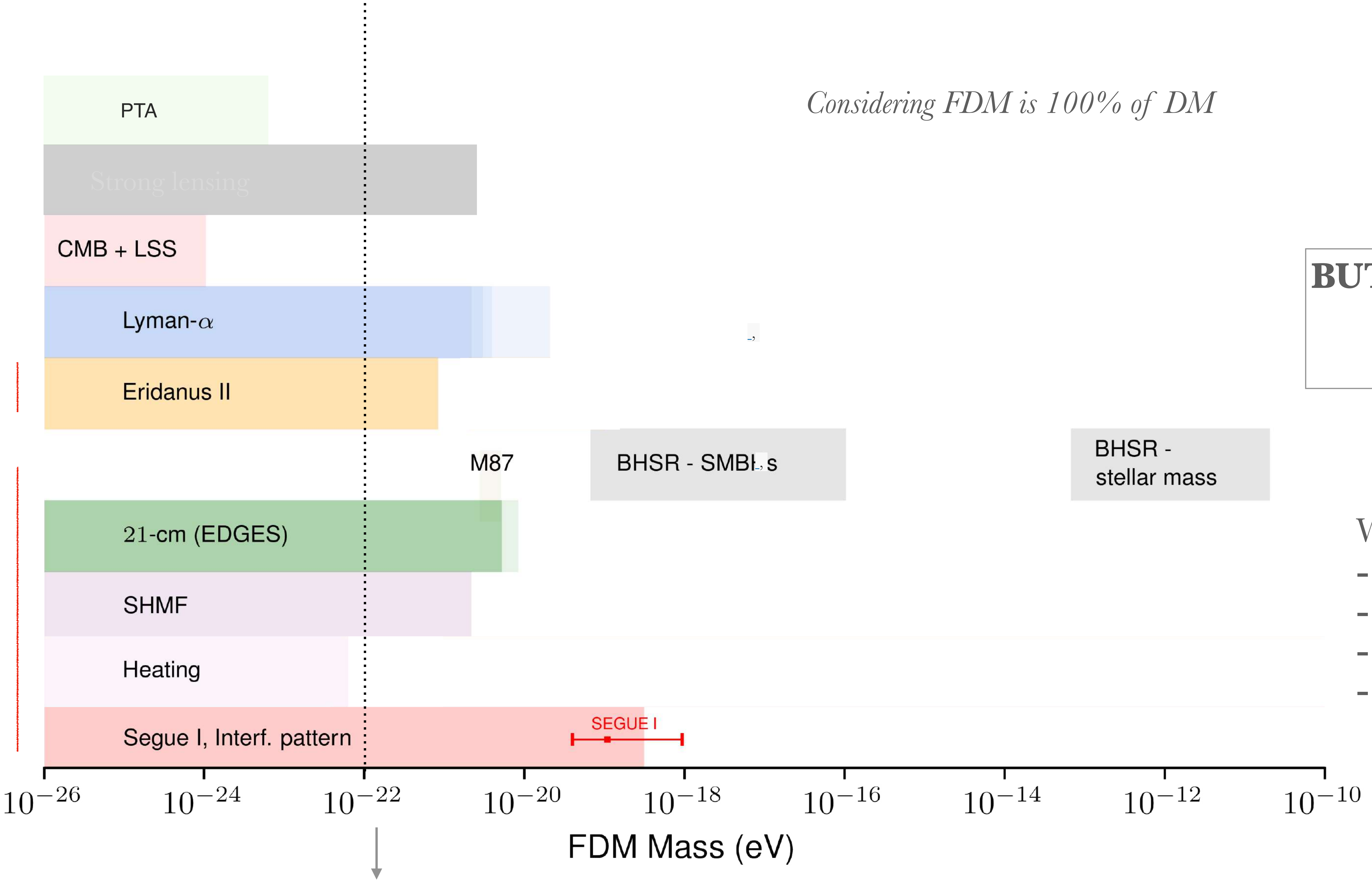
Small scales can offer some hints of the nature of DM



Current status

Fuzzy Dark Matter - bounds on the mass





Considering FDM is 100% of DM

Sweet spot for solving small scale problems

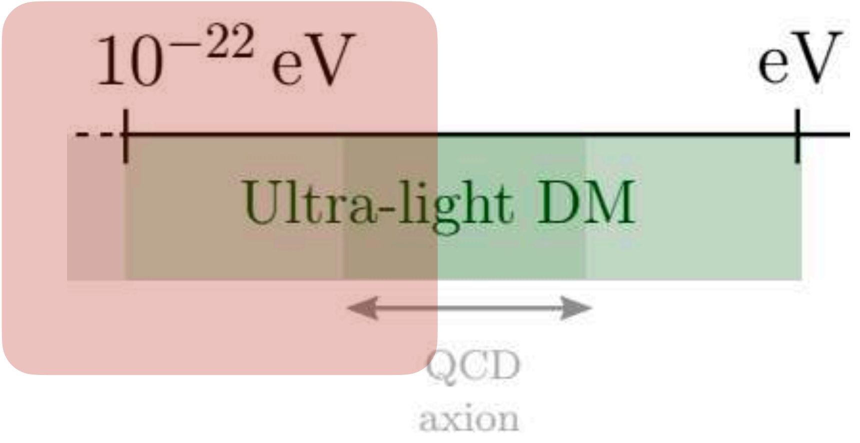
BUT: - systematic effects!!
- dynamics of FDM not fully understood.

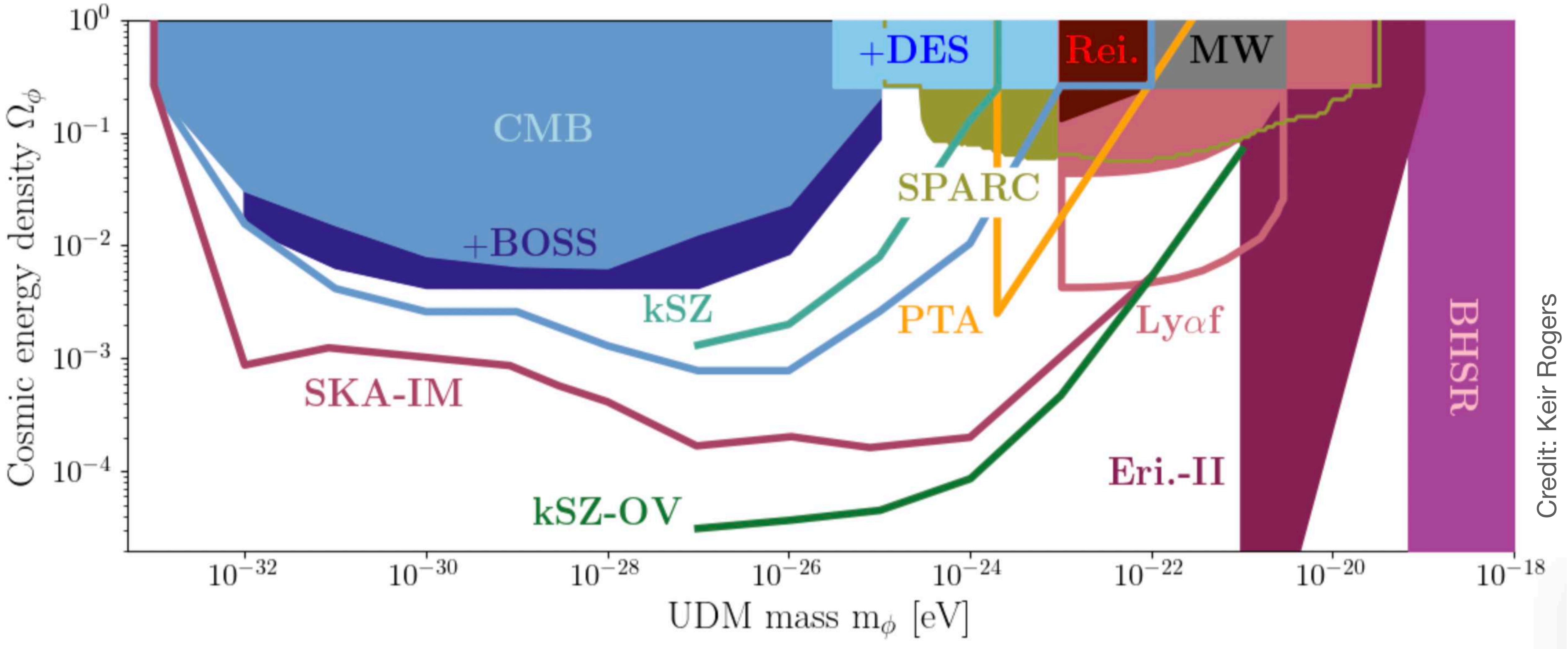
What if:
- DM not 100%
- Mixed CDM+ULDM
- More than one field - axiverse
- …

These bounds would change!

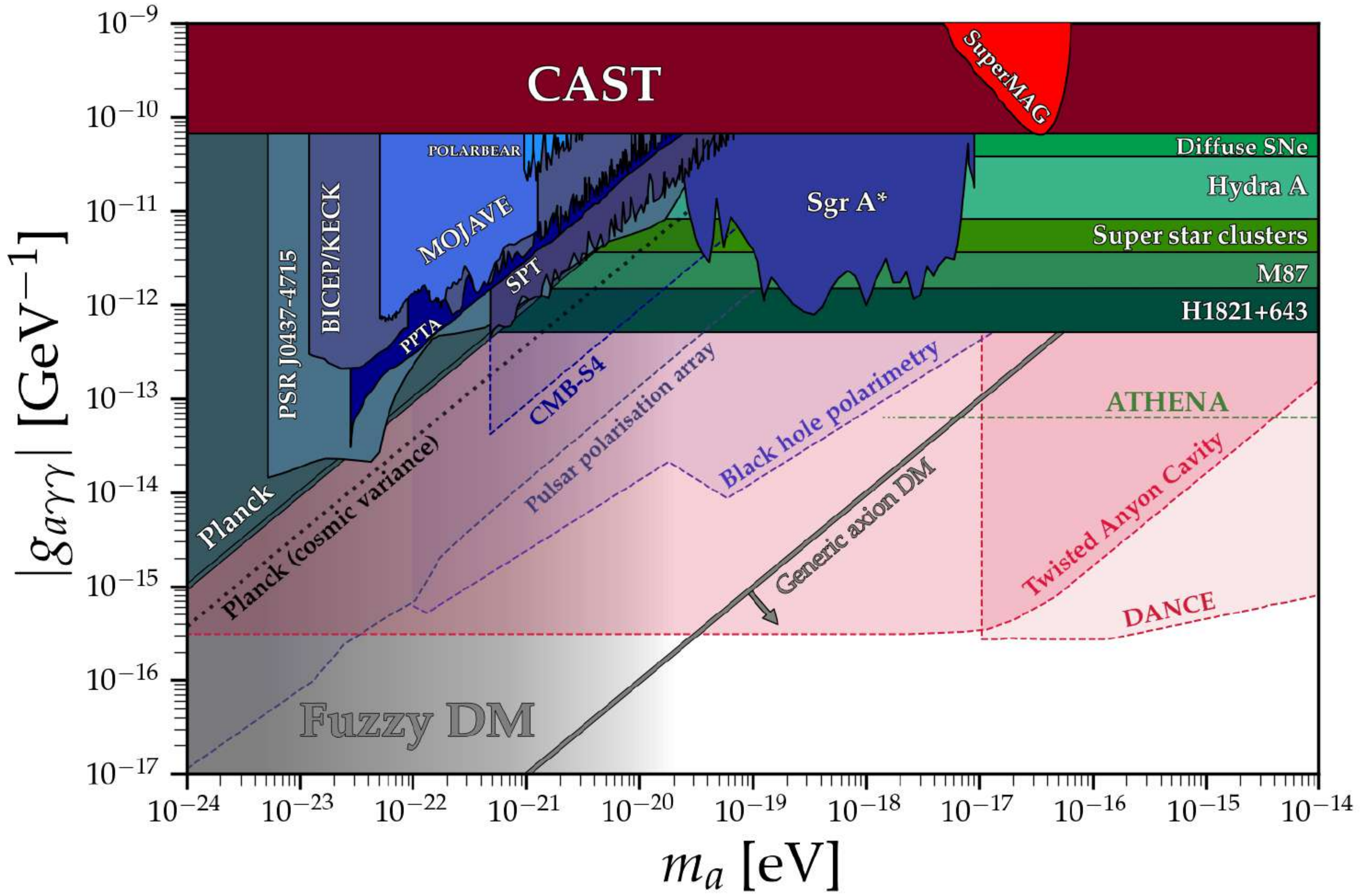
Current status

Fuzzy Dark Matter - bounds on the mass





Credit: Keir Rogers



The search for dark matter (ULDM) is a multi-probe/multi-scale endeavour…

exciting times for axion dark matter

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exciting times for axion dark matter

Congratulations, Hitoshi!