Lecture 2: ULDM

Constraints

Elisa G. M. Ferreira

Kavli IPMU

3rd Training School COST Action *“Cosmic WISPers"*
September 19, 2025

Axions in Japan

Nov 10 – 14, 2025
Kavli IPMU
Asia/Tokyo timezone

Invited speakers

- Andrey Kravtsov
- Atsushi Nishizawa
- Chanda Prescod-Weinstein
- Cora Uhlemann
- Francesca Chadha-Day
- Ippei Obata
- Jens Niemeyer
- Keir Rogers
- Masahiro Kawasaki
- Mustafa Amin
- Neal Dalal
- Philip Mocz
- Richard Easther
- Simona Vegetti
- Tomohiro Fujita
- Vera Gluscevic
- Yuko Urakawa
- Yuta Michimura

Website: https://indico.ipmu.jp/event/467/

Dark matter and black holes

Dec 1 – 5, 2025
Kavli IPMU
Asia/Tokyo timezone

Enter your search term

Speaker List

Invited speaker list (alphabetical order; as of 24/March/2024):

- **George Fuller** - UCSD
- **Shunsaku Horiuchi** - Institute of Science Tokyo
- **Tesla Jeltema** - UCSC
- **Kazunori Kohri** - NAOJ
- **Sachiko Kuroyanagi** - IFT, Madrid
- **Yifan Lu** - UCLA
- **Shigeki Matsumoto** - Kavli IPMU
- **Lucio Mayer** - University of Zurich
- **Smadar Naoz** - UCLA
- **Stefano Profumo** - UCSC
- **Surjeet Rajendran** - JHU
- **John Silverman** - Kavli IPMU
- **Masahiro Takada** - Kavli IPMU
- **Jonathan Tan** - Chalmers University, Virginia

Website: https://indico.ipmu.jp/event/464/

Registration open!!!

Outline

Lecture 1: Cosm. Signatures

Part I:

- Evidences of DM
- DM model building
- DM models

Part II:

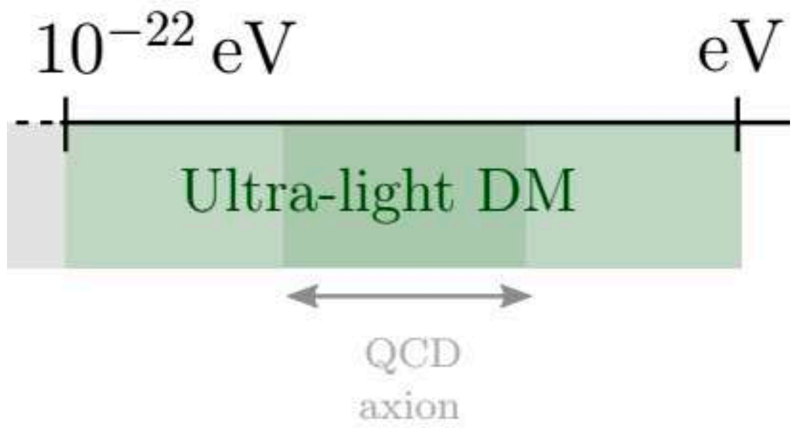
- ULDM definition
- ULDM models
- ULDM dynamics
- Observational signatures

Lecture 2: ULDM bounds

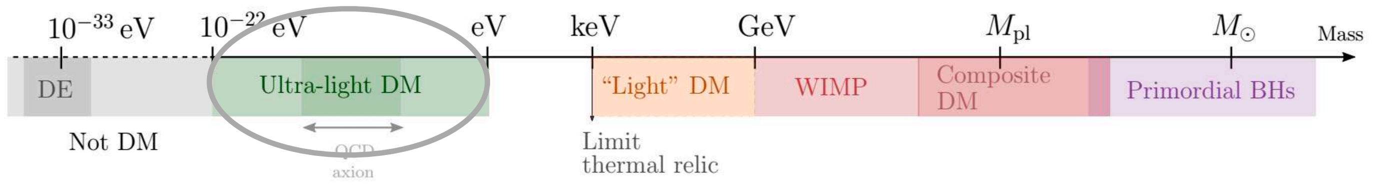
- ULDM gravitational bounds
    - Current bounds
- Interaction of ULDM with SM
    - Birefringence
- Next steps: multifield, self interacting ULDM
- DM Superfluid

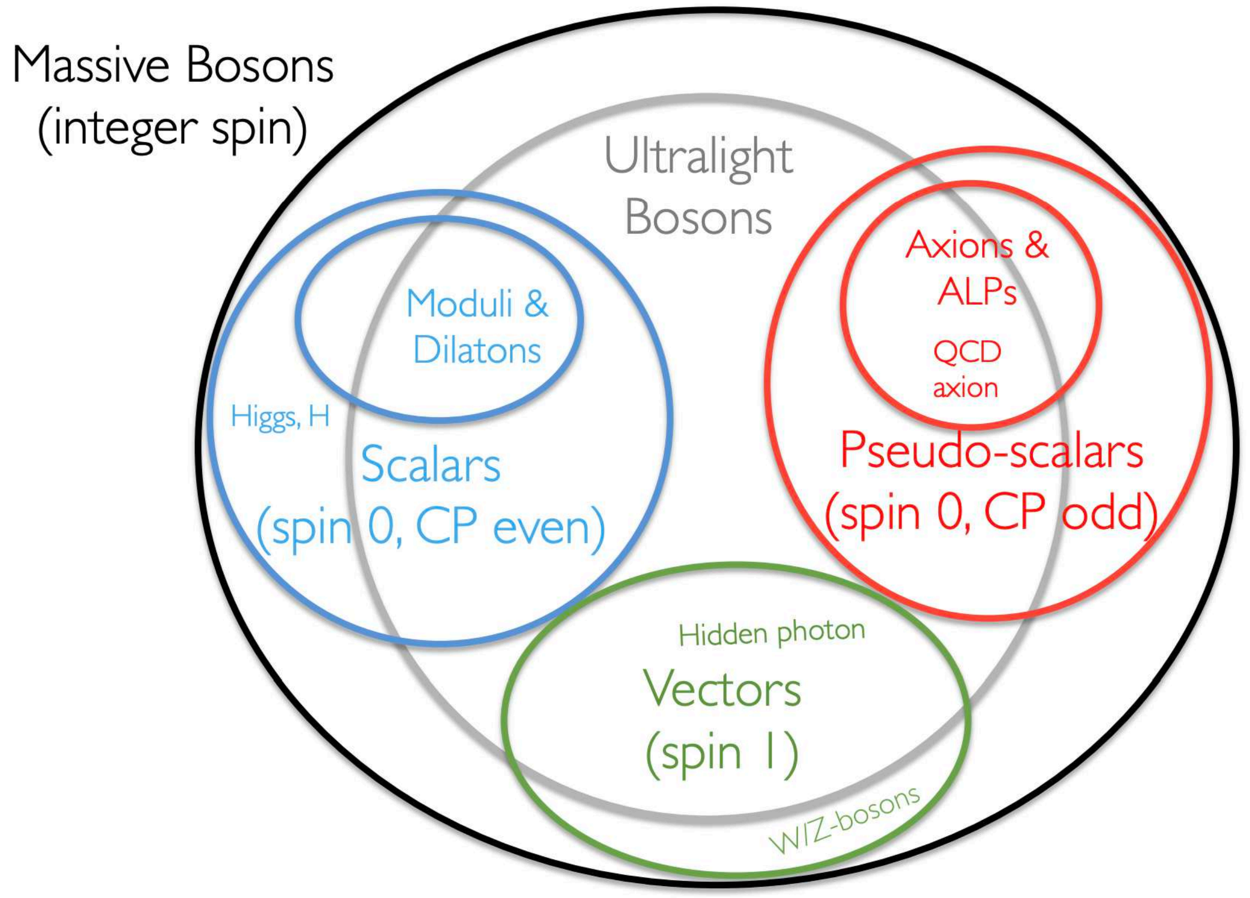
Recap: lecture 1

Ultra-light dark matter



Definition





Evolution

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

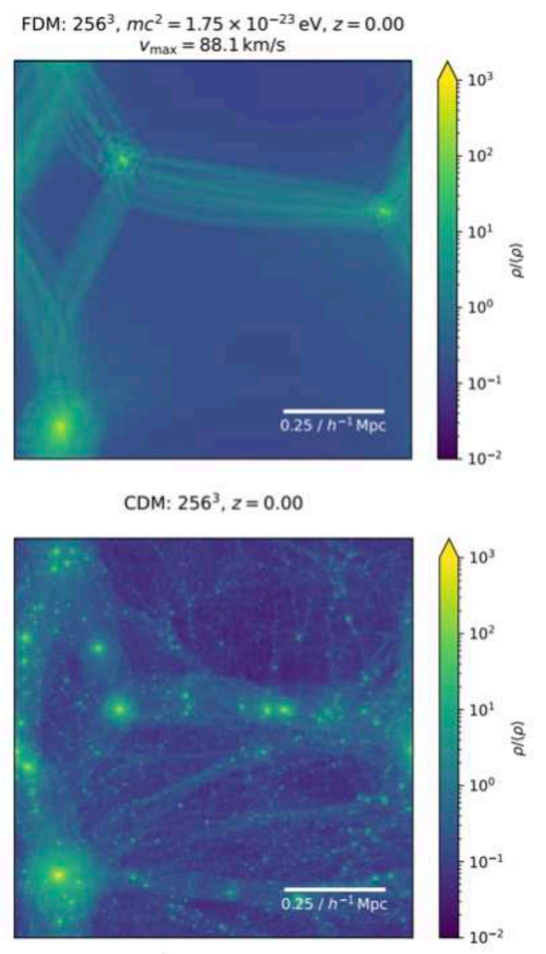
Schrödinger equation (Gross-Pitaevskii)

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

Poisson equation

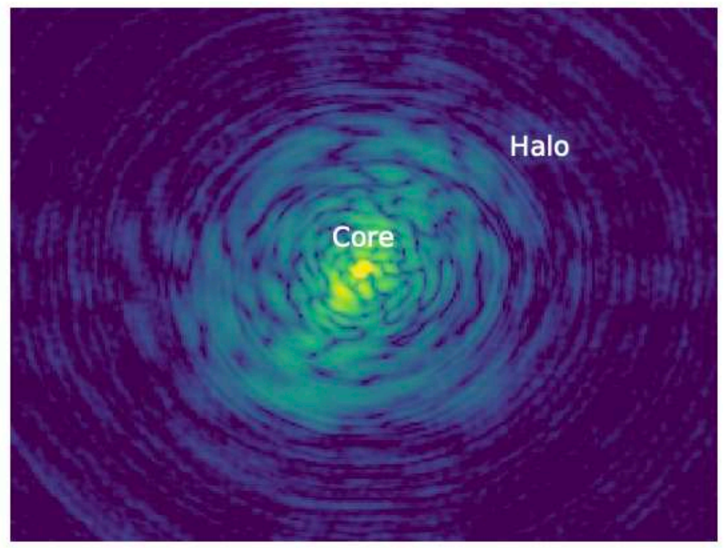
Phenomenology

Suppression of small structures

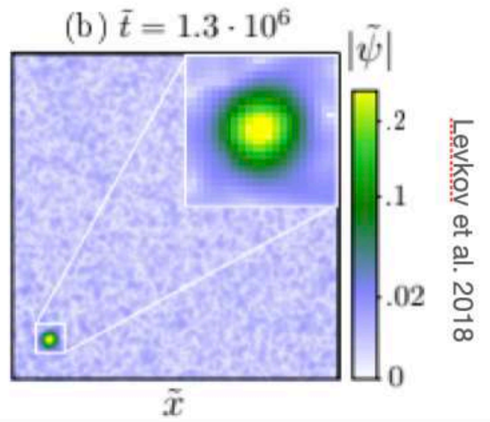


S. May et al. 2021

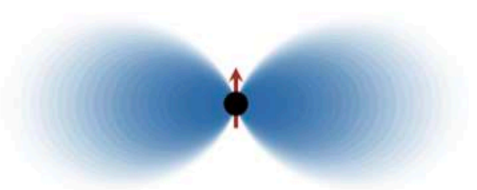
Formation of a solitonic core



Dynamical effects

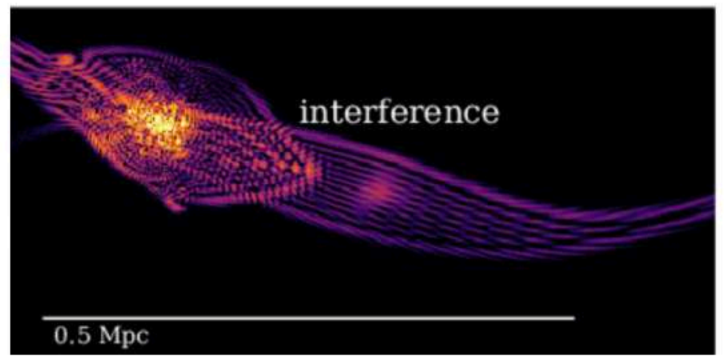


Axion clouds



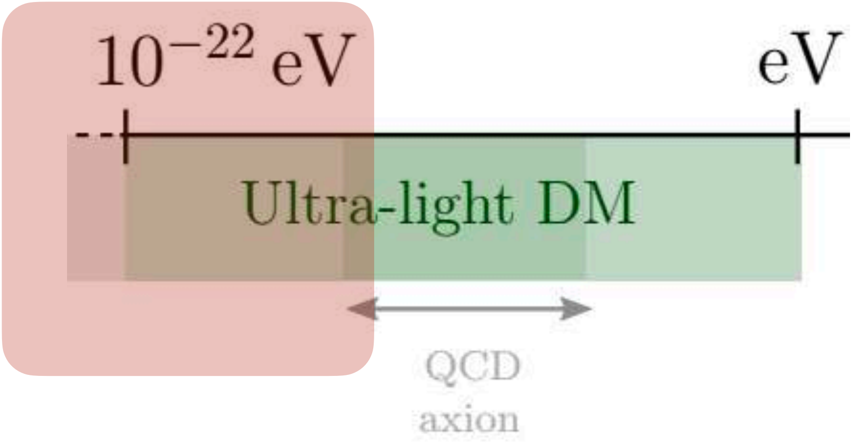
Baumann et al. 2019

Wave interference



Mocz et al. 2017

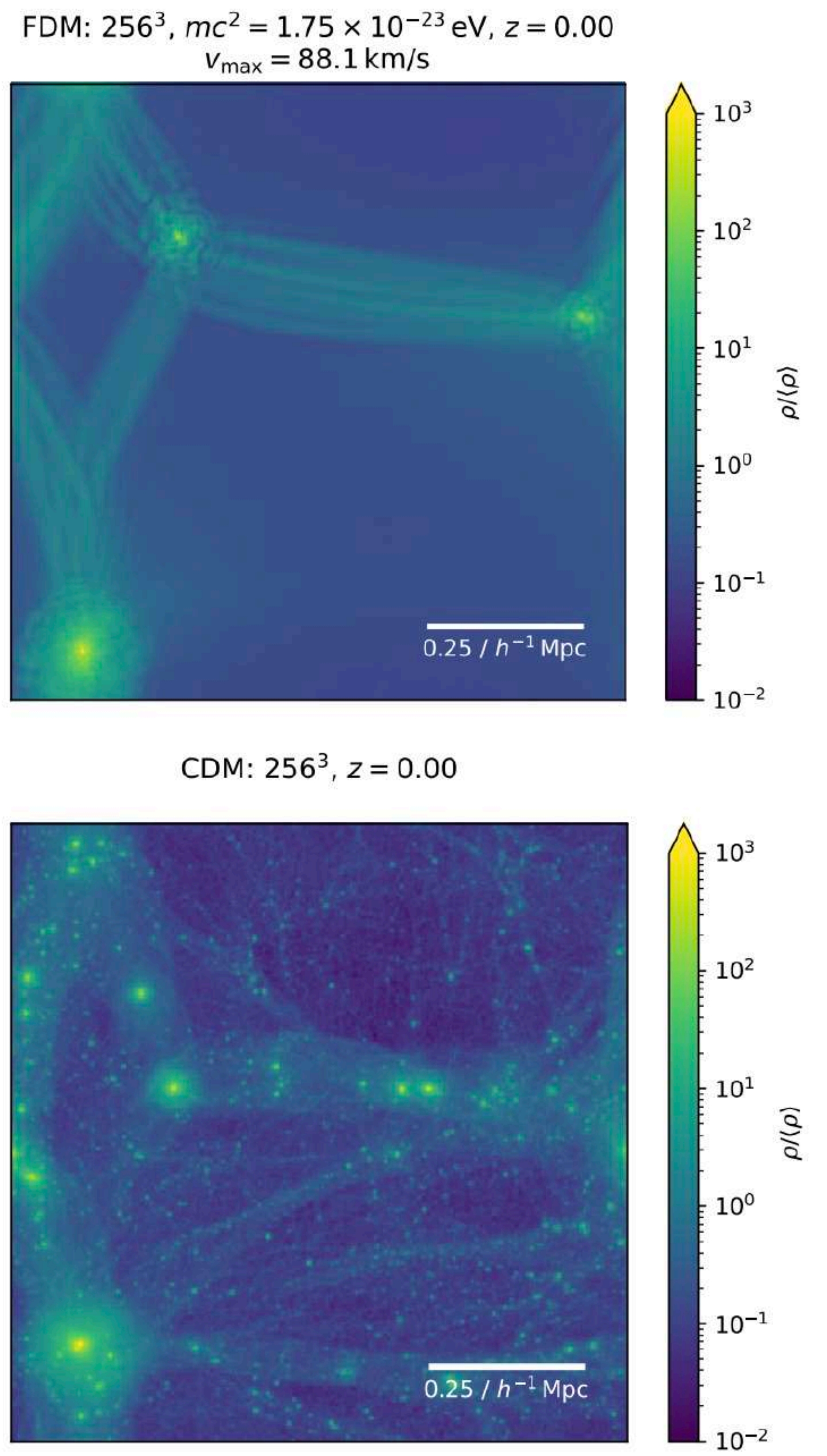
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

* Focus only in gravitational signatures

Suppression of small structures



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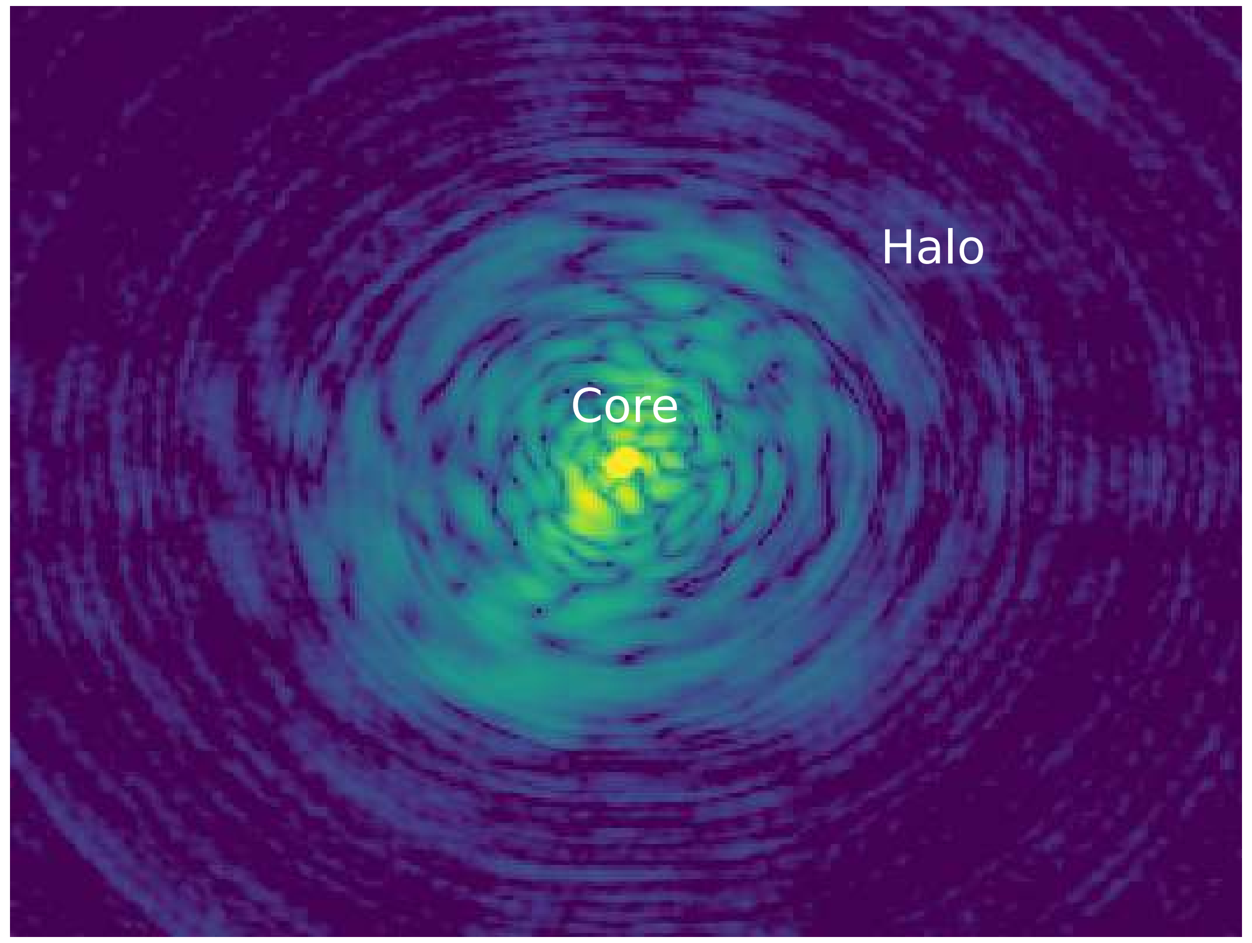

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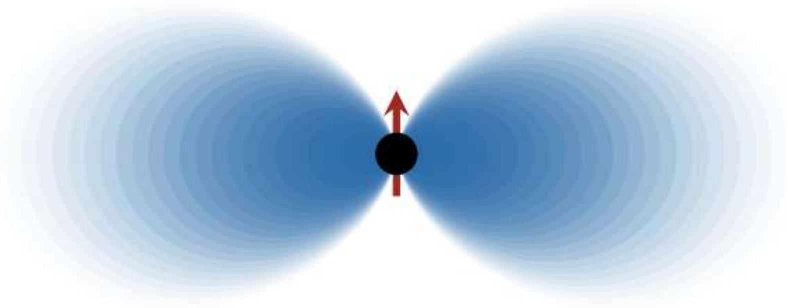

Baumann et al. 2019

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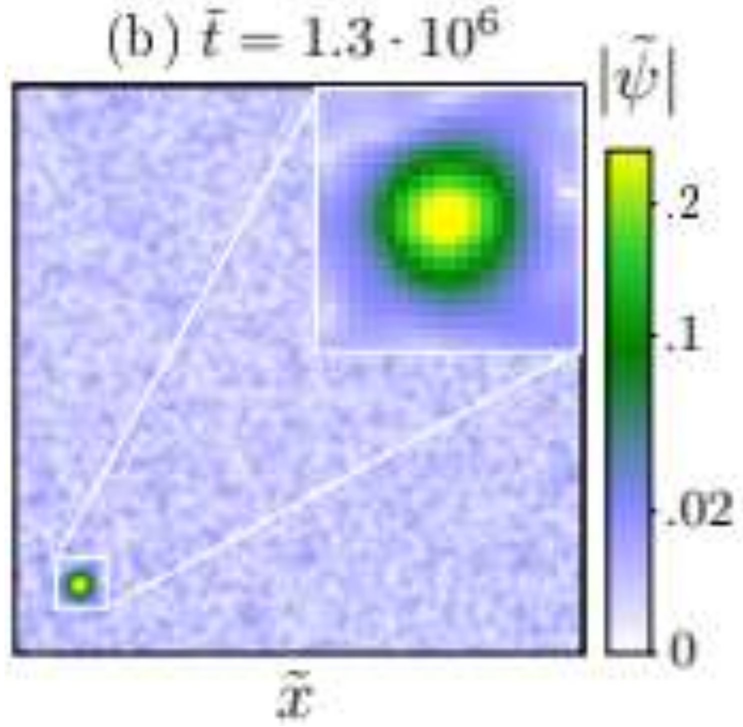
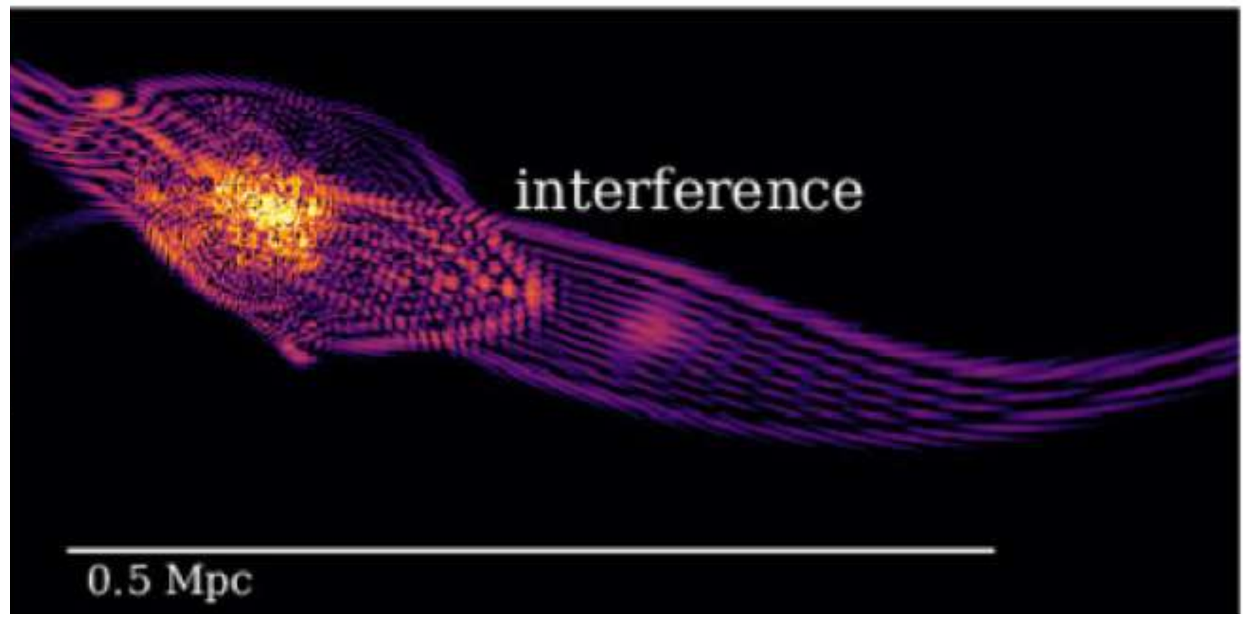


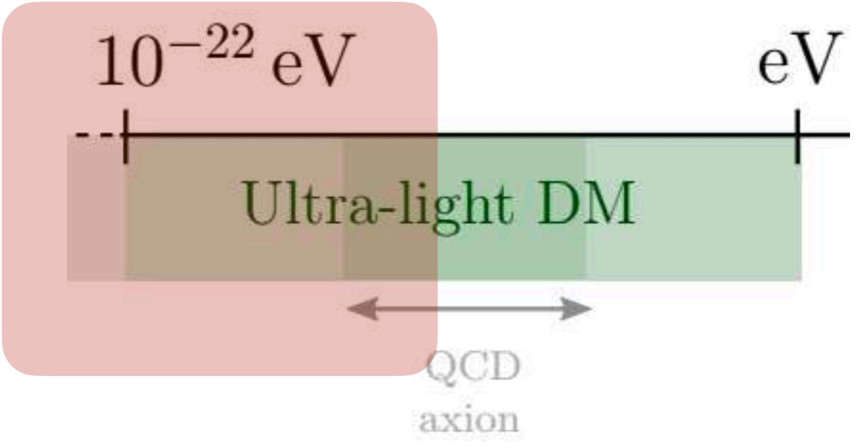
Levkov et al. 2018

Wave interference



Mocz et al. 2017

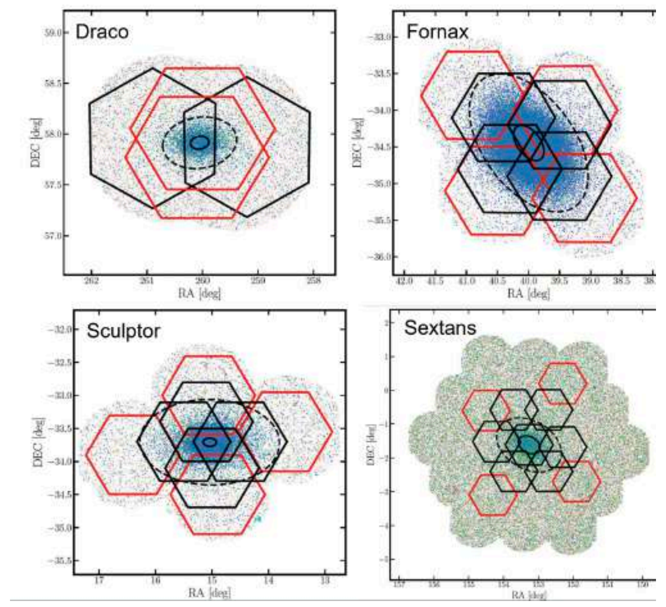
Observational implications and constraints



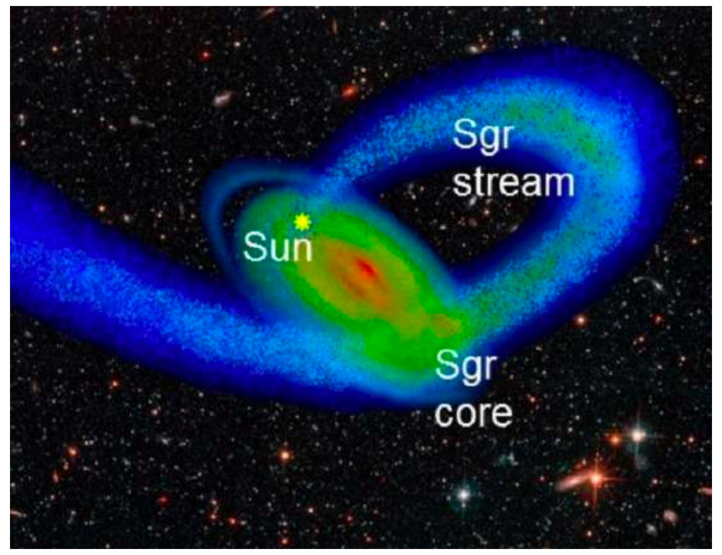
Galaxies

NASA and ESA

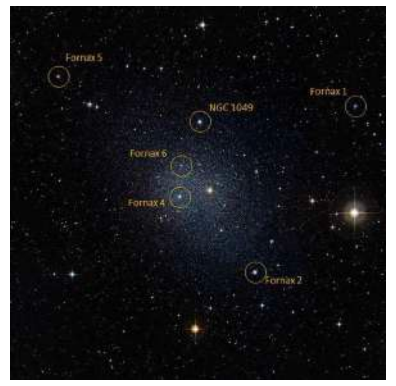
Dwarfs



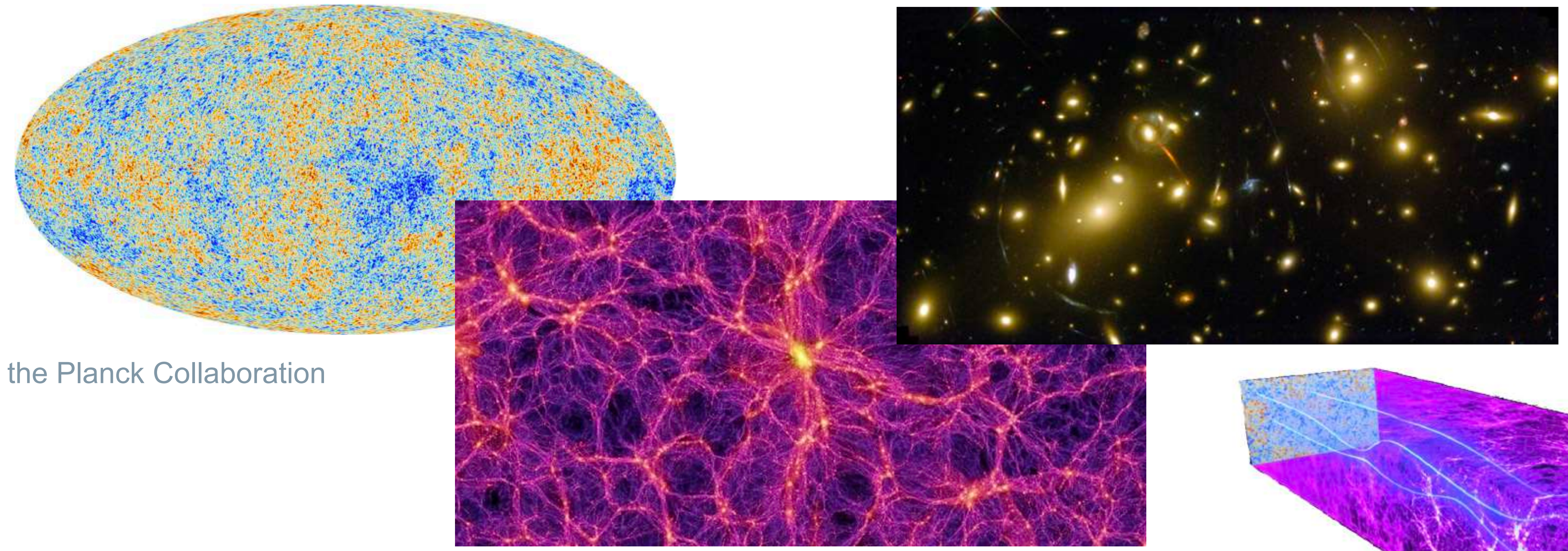
Stellar stream



Globular clusters



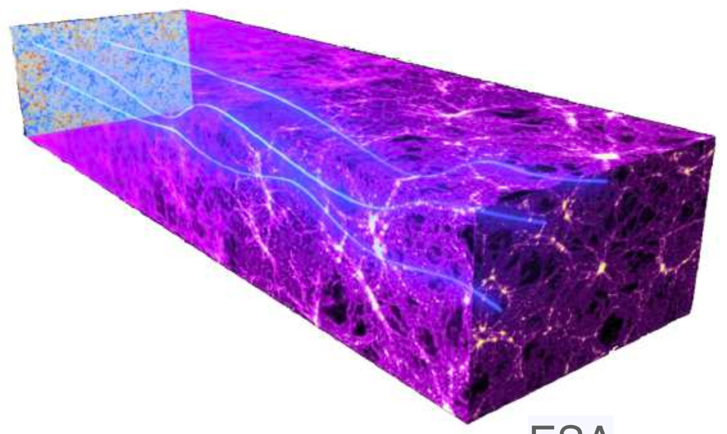
CMB+LSS



ESA and the Planck Collaboration

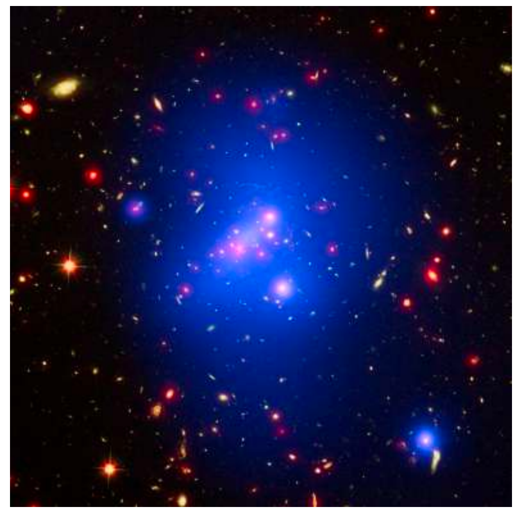
NASA and ESA

Springel & others / Virgo Consortium



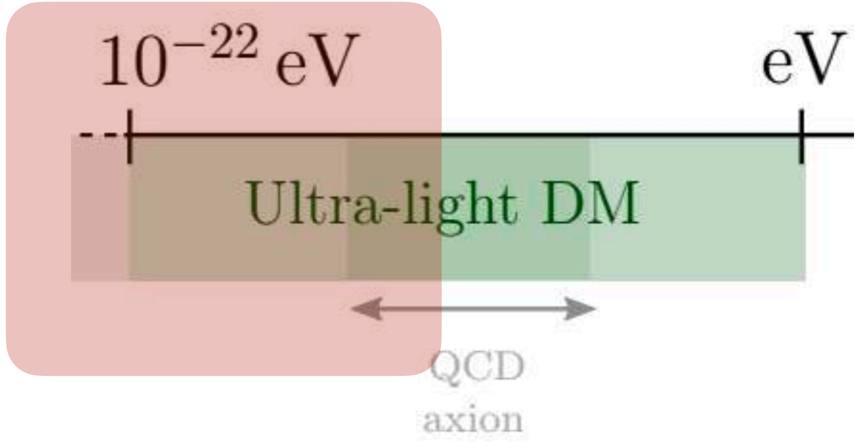
ESA

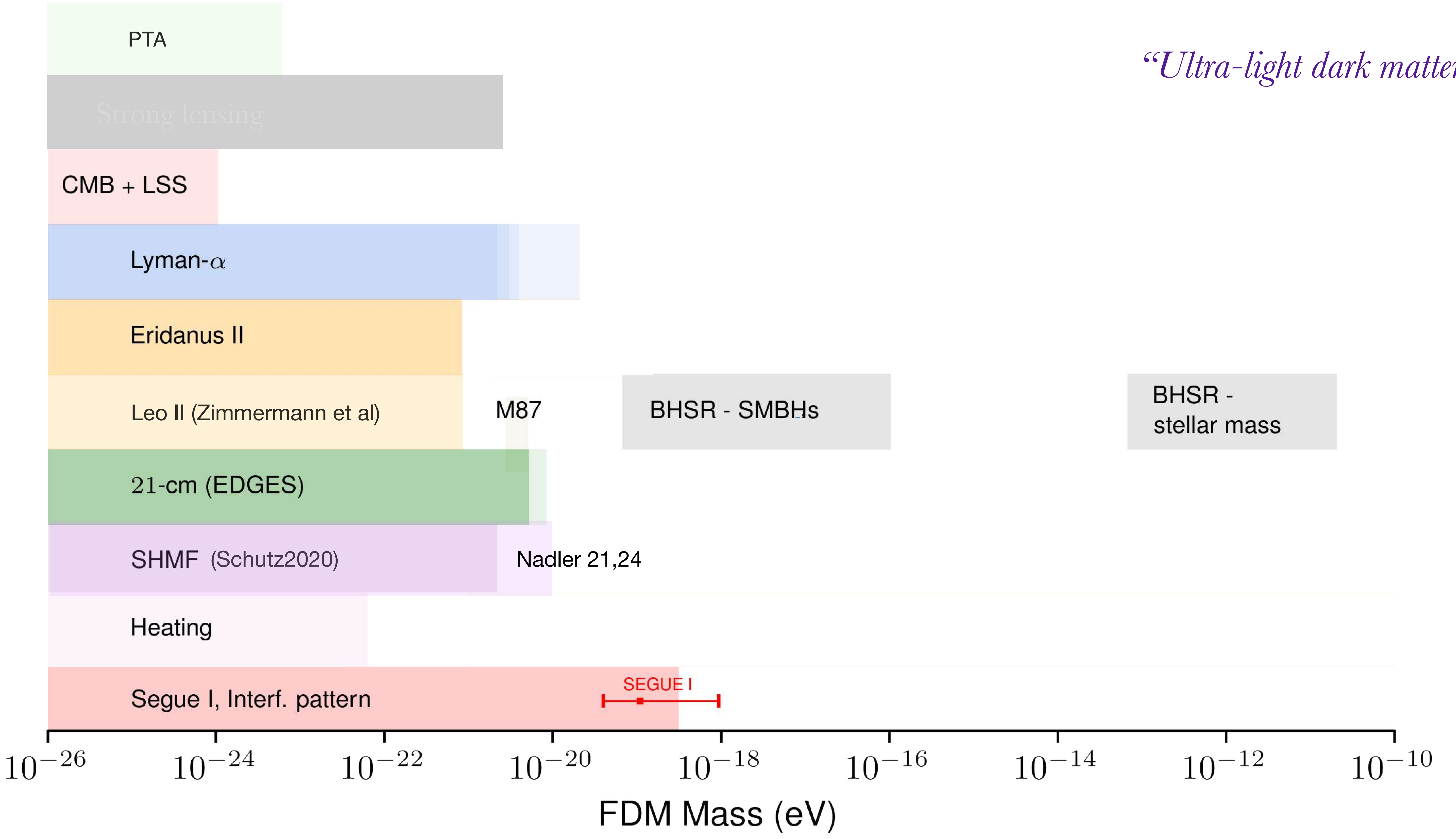
Clusters



Observational implications and constraints

Fuzzy Dark Matter - *bounds on the mass*



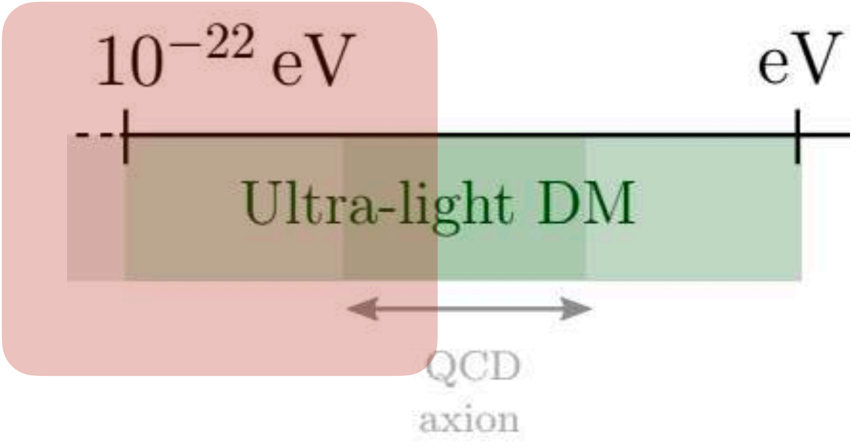


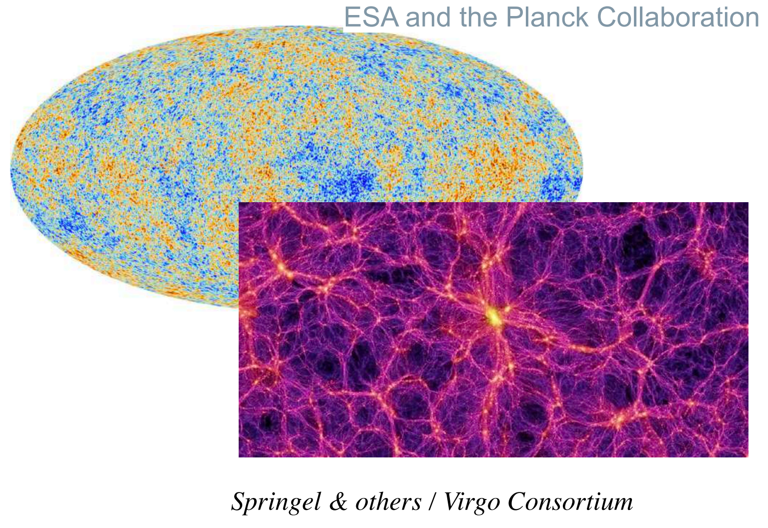
"Ultra-light dark matter", **E.F.**, 2020. The Astronomy and Astrophysics Review.

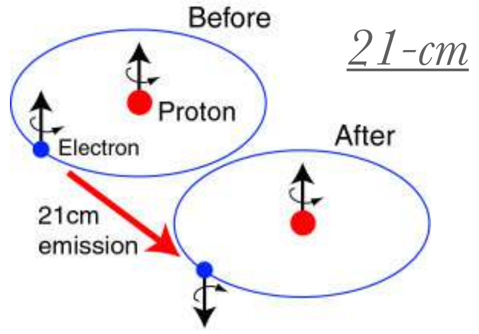
Bounds consider FDM is *all* DM

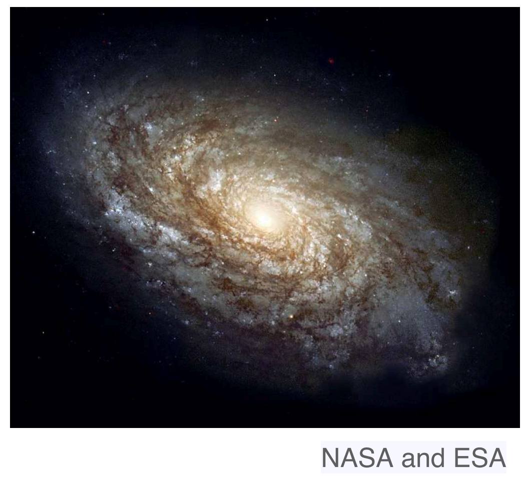
Current status

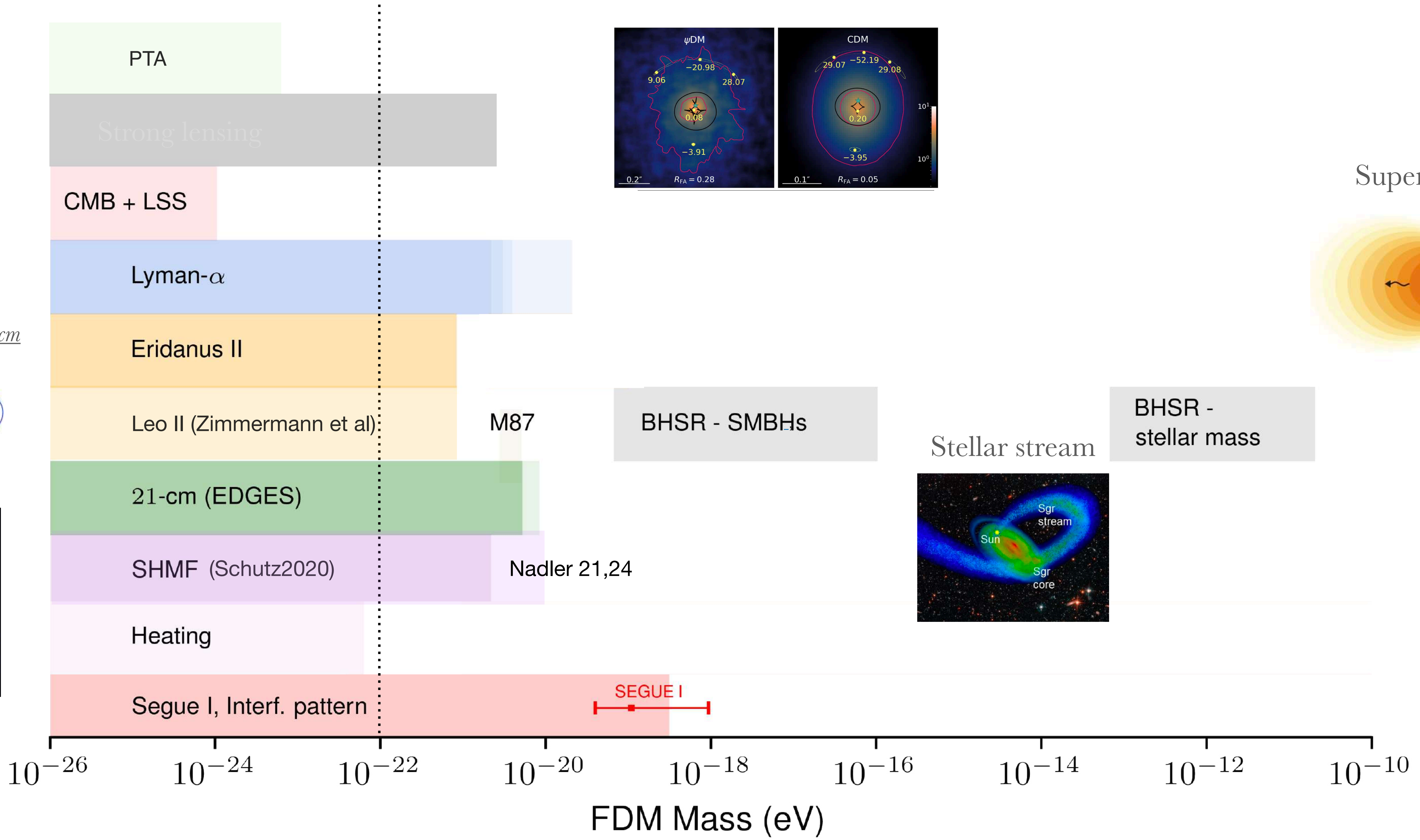
Fuzzy Dark Matter - bounds on the mass

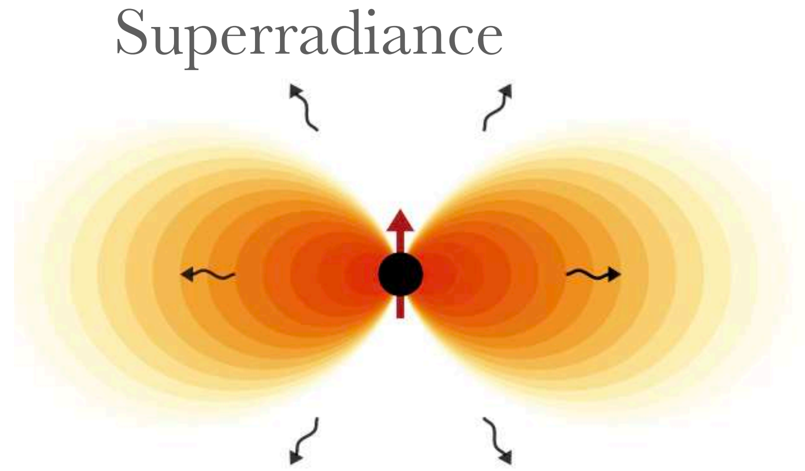


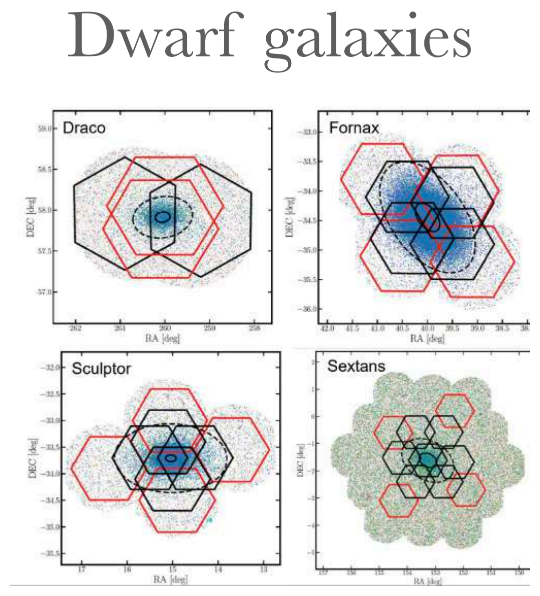












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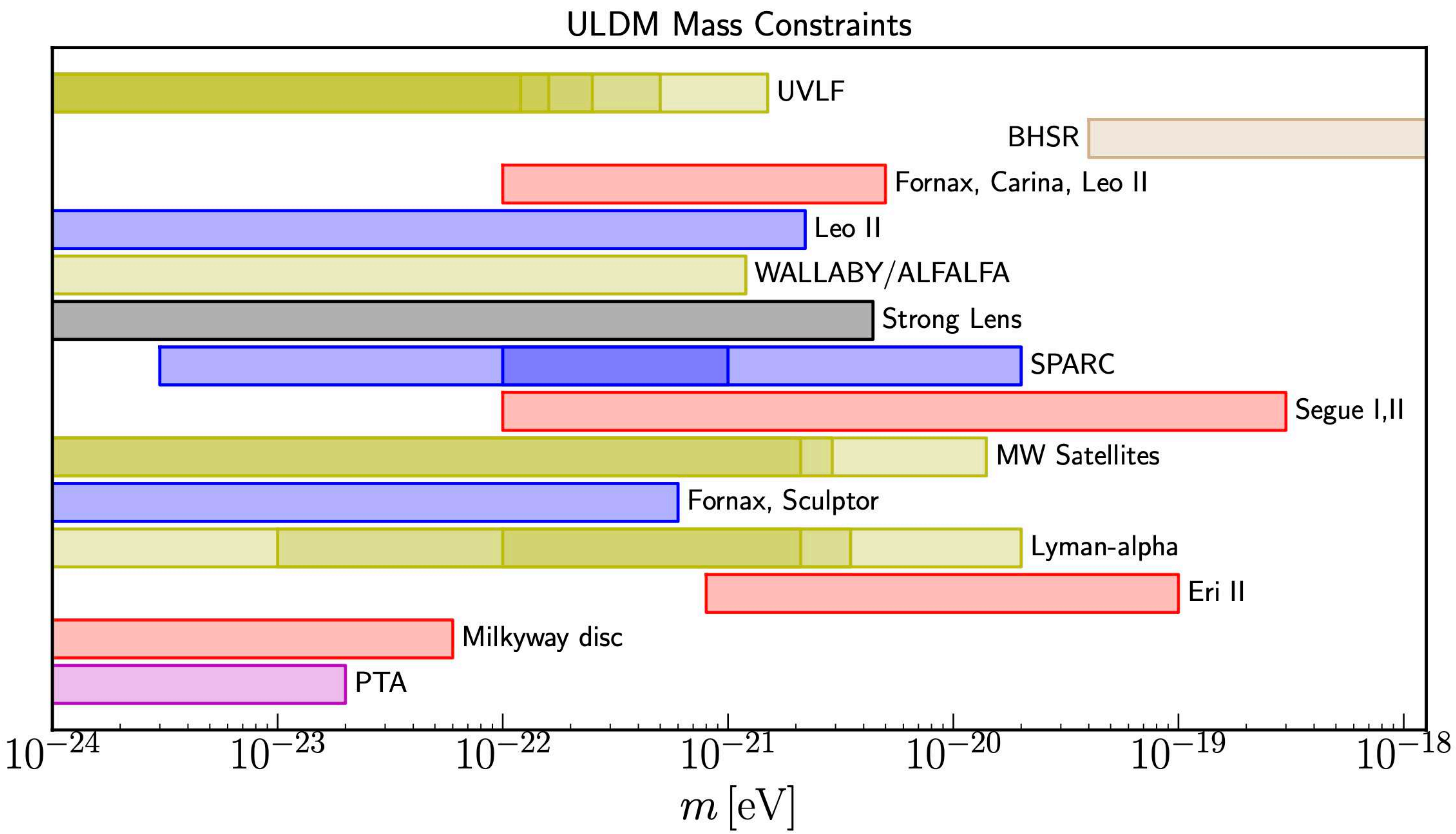
Current status

Fuzzy Dark Matter - bounds on the mass

Review: Eberhardt, EF, 2025



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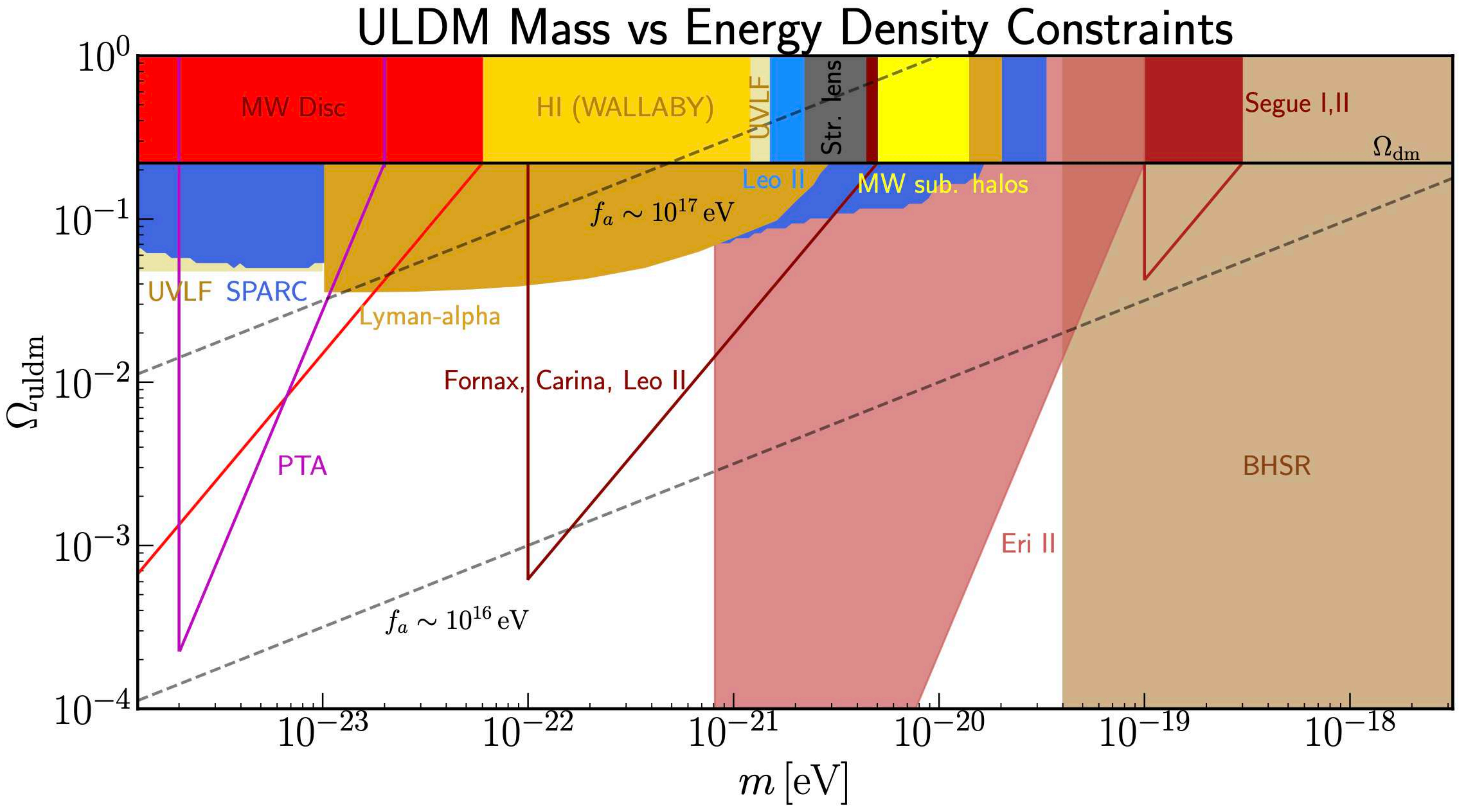
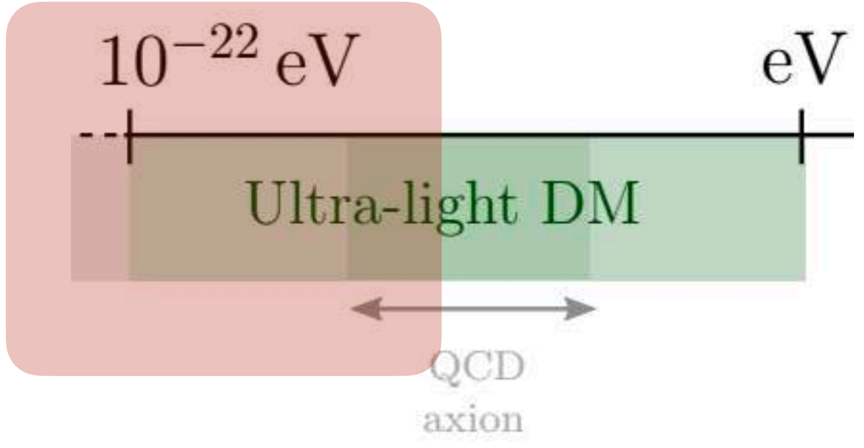
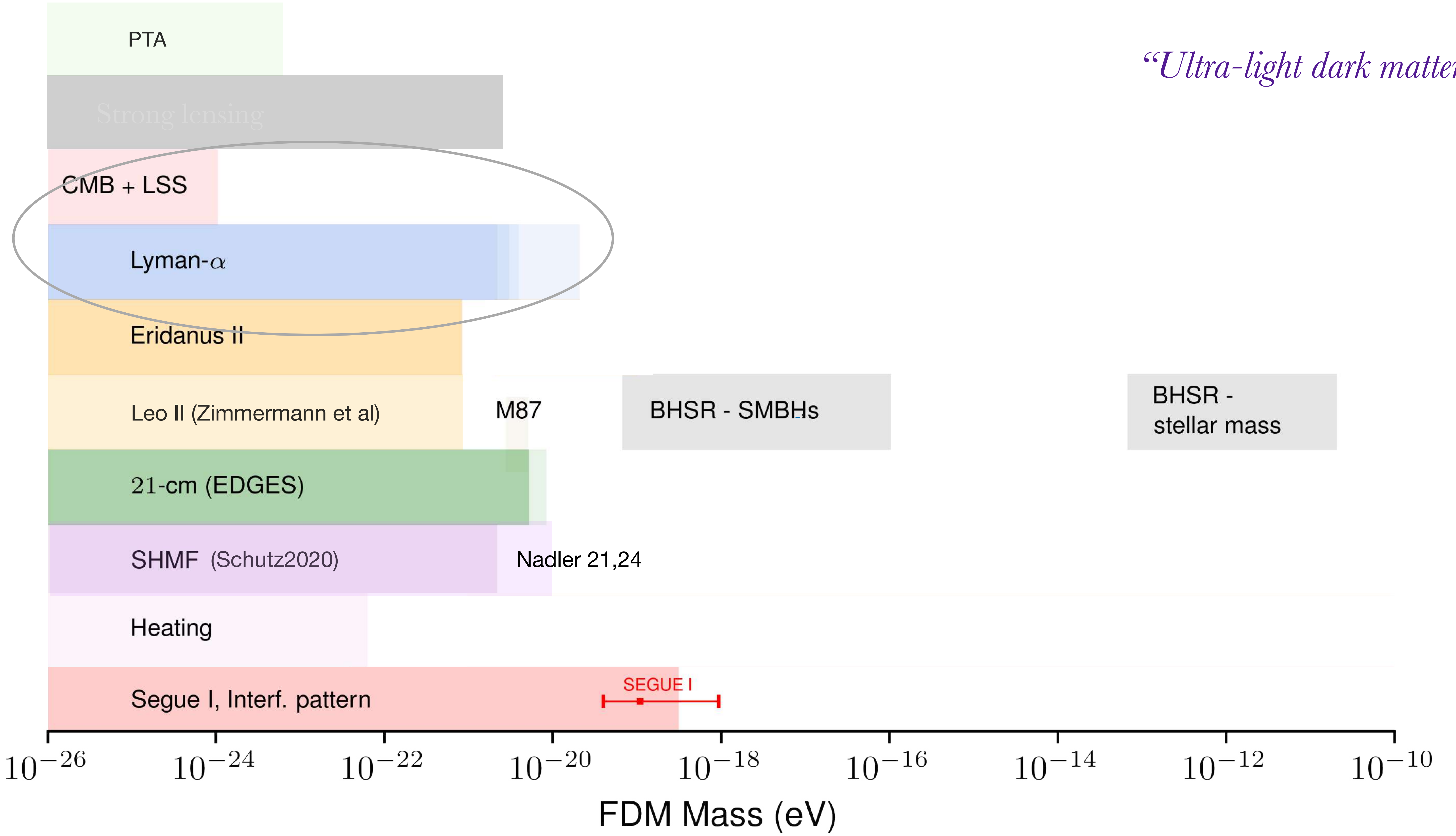


Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass





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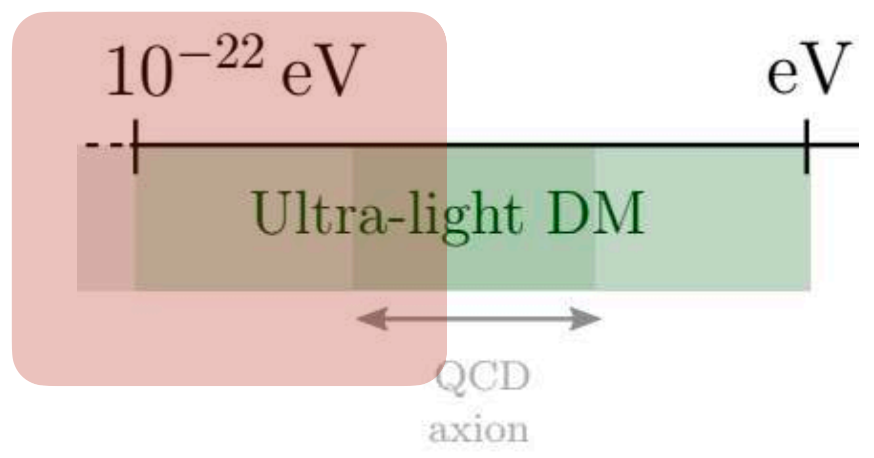
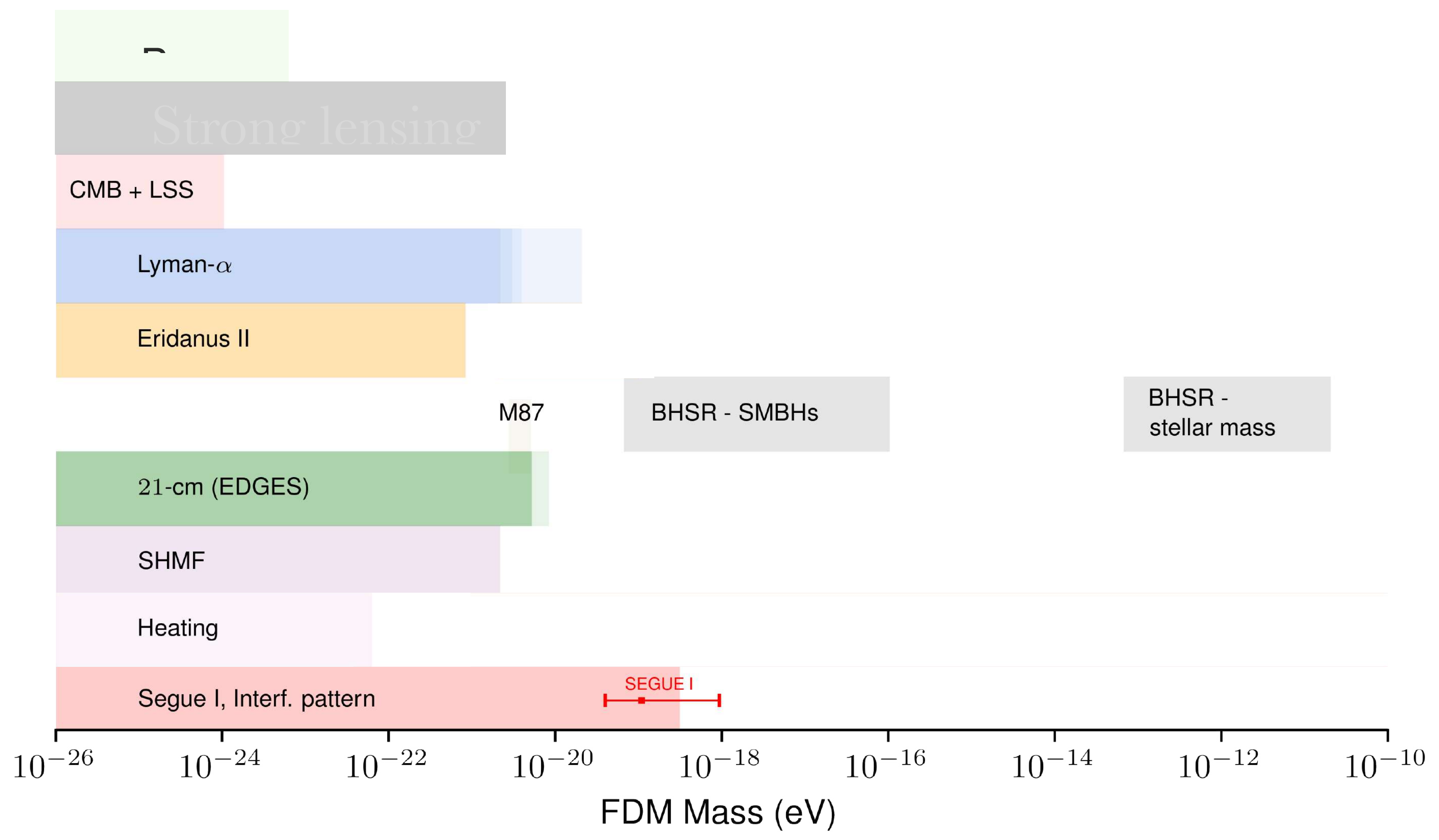


Observational implications and constraints

CMB and LSS

The most precise measurements

Measure evolution and suppression of the power spectrum

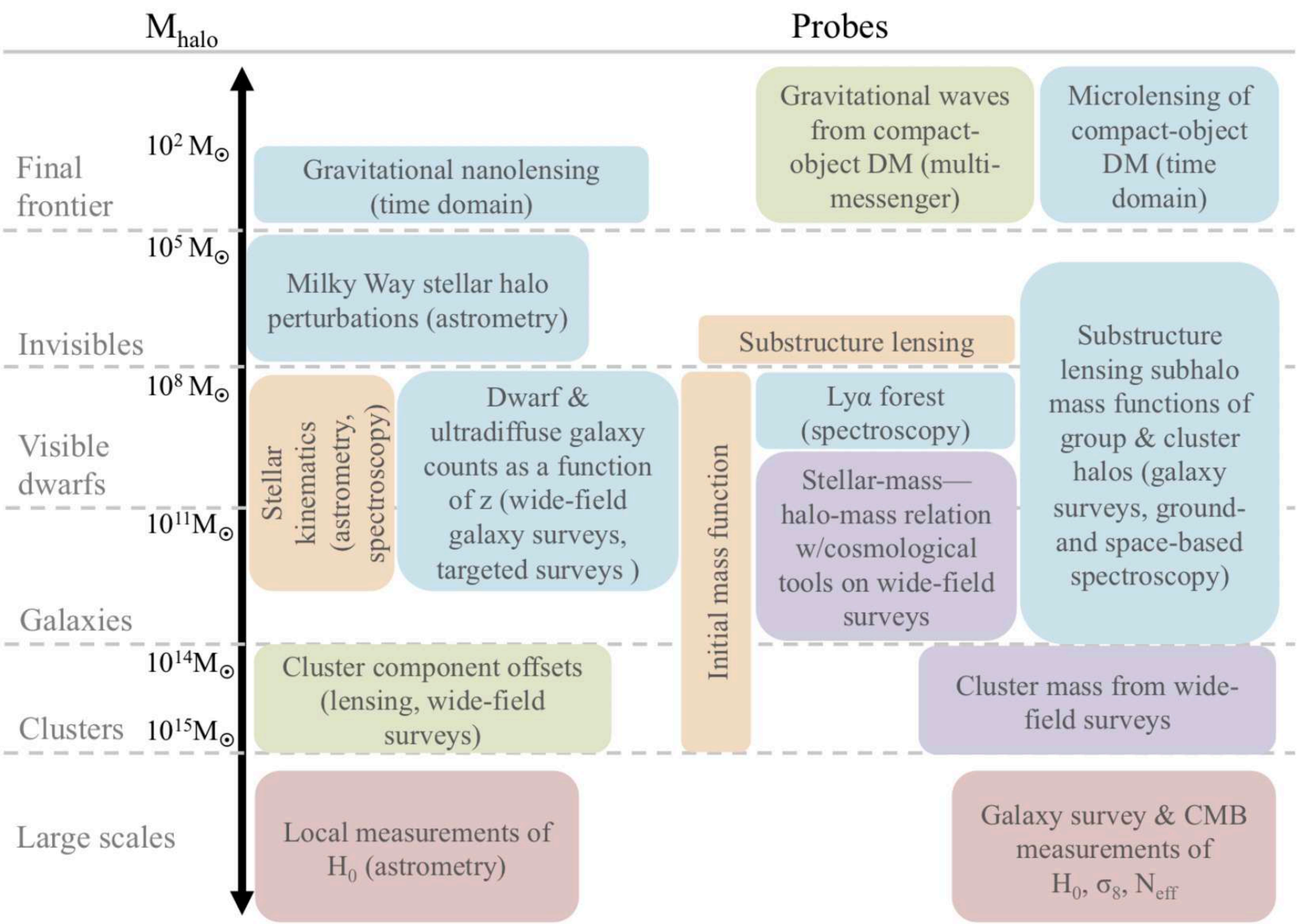


interlude

Cosmological and astrophysical ***probes*** *of dark matter*

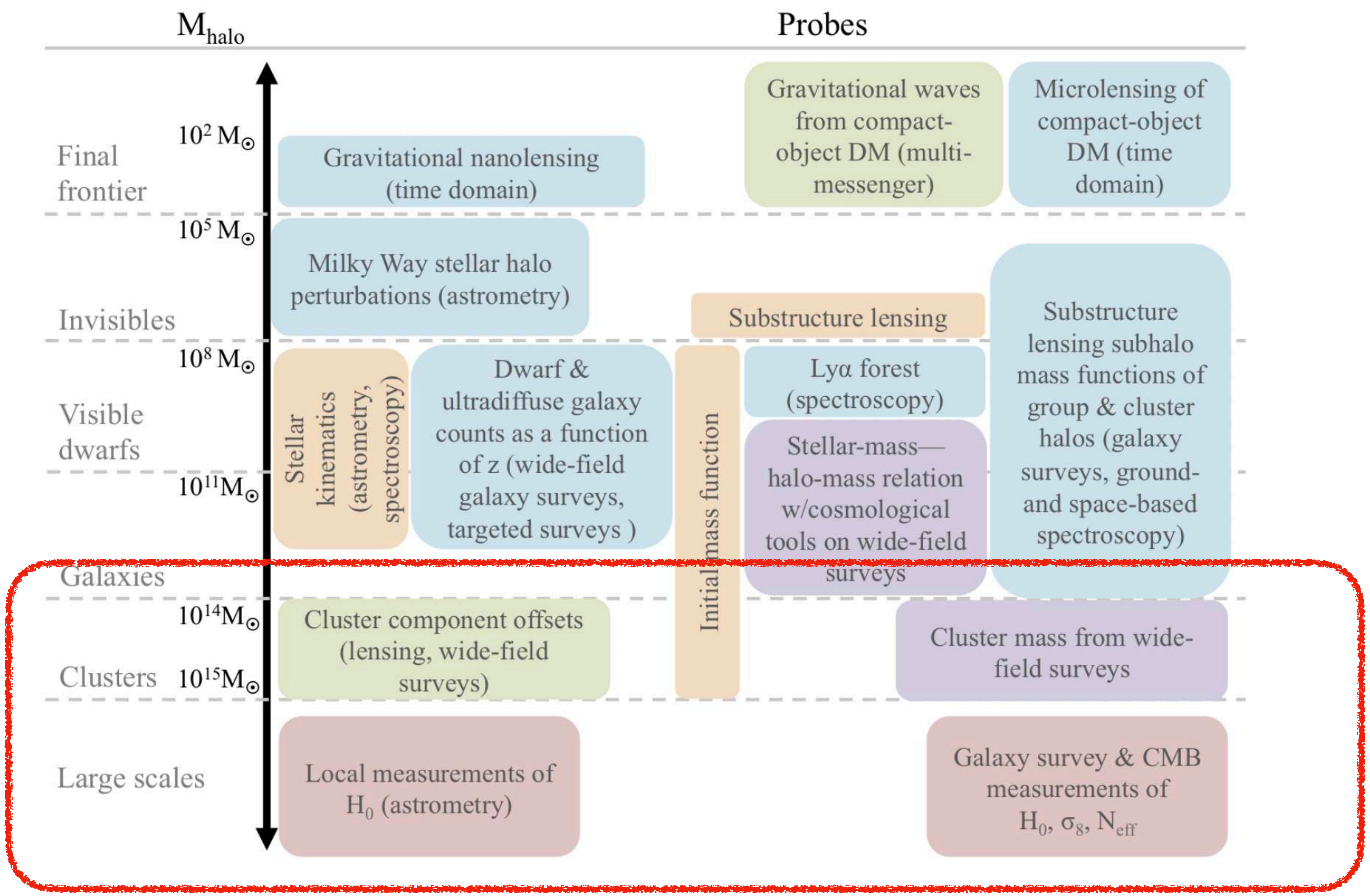
Good reference:
"Gravitational probes of dark matter physics", Matthew R. Buckley , Annika H. G. Peter, 2017

Cosmological and astrophysical ***probes*** *of dark matter*



Buckleya et al 2017

*Cosmological and astrophysical **probes** of dark matter*



Planck

SDSS
DES
HSC
KIDS
…

CMB and LSS

Highly constrained

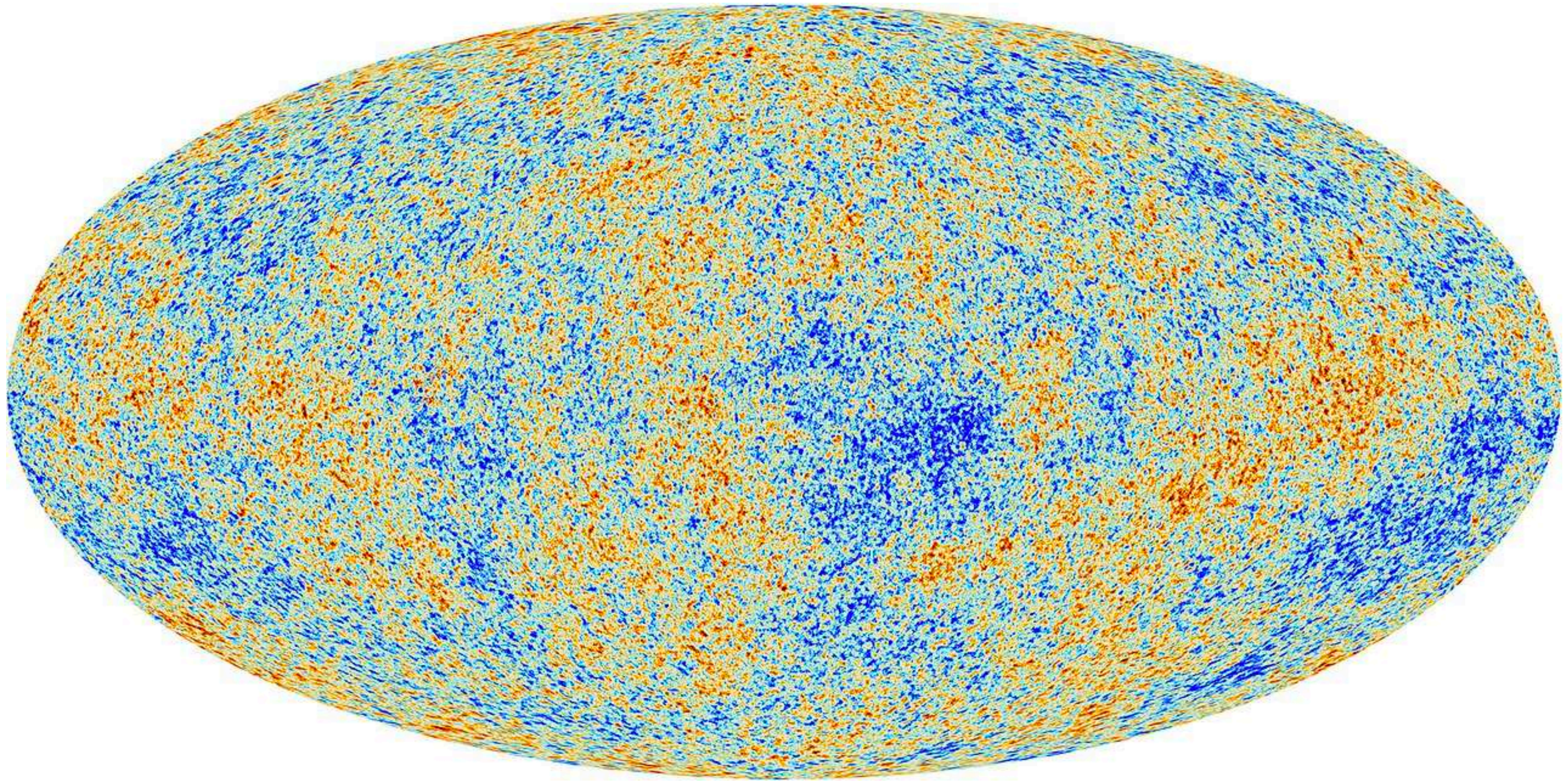
Precise measurements

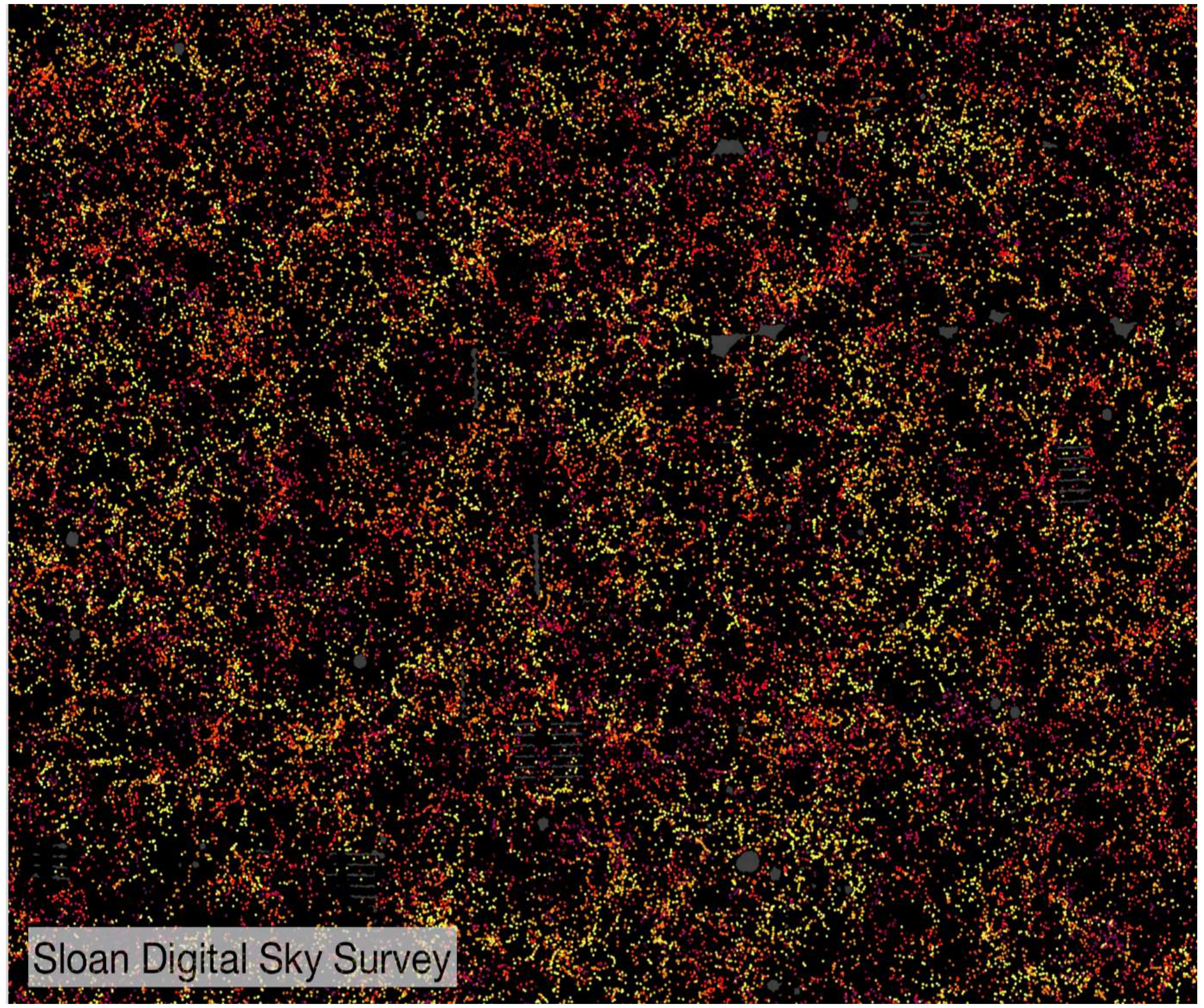
Buckleya et al 2017

Cosmological and astrophysical ***probes*** *of dark matter*

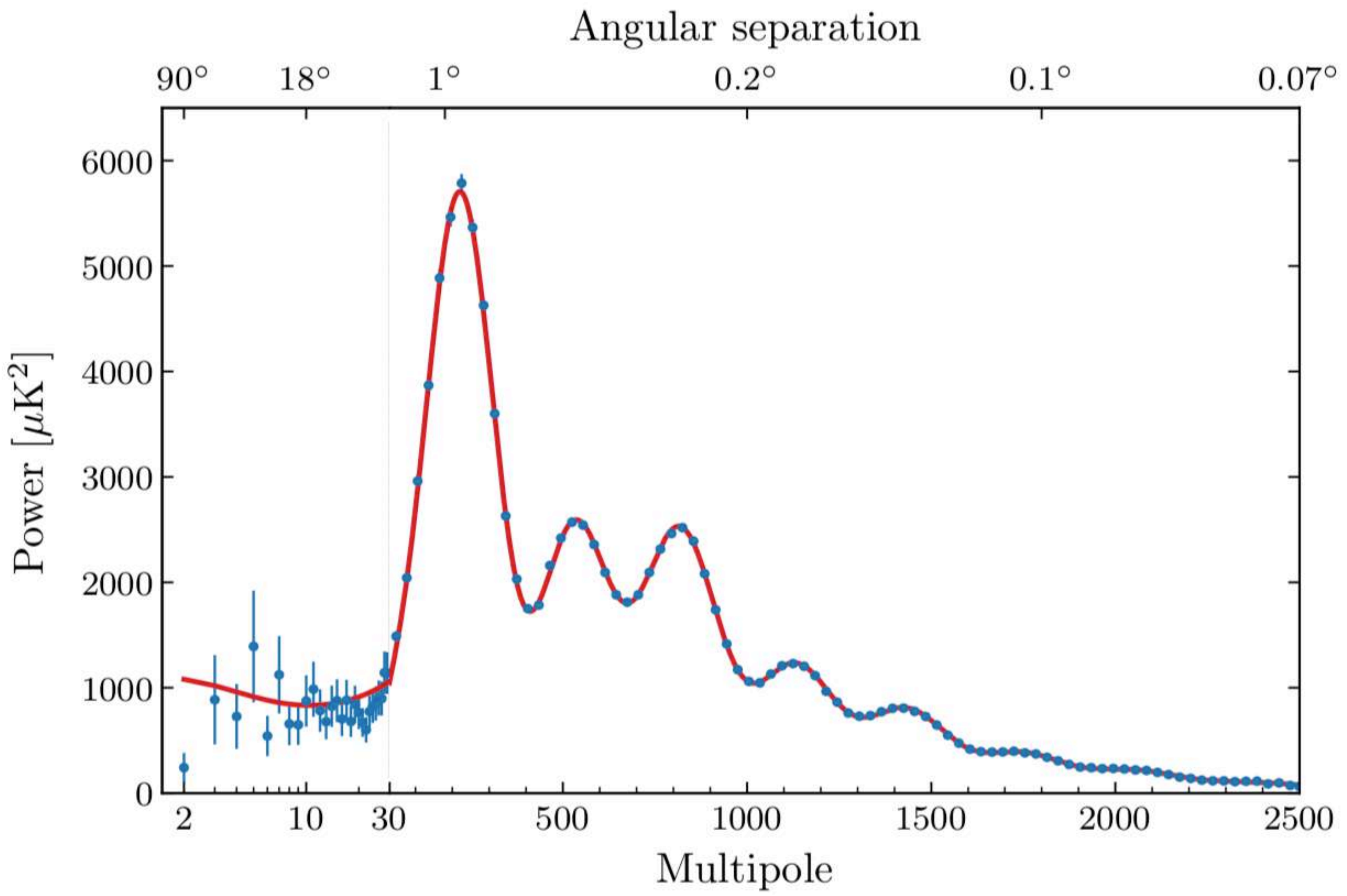
CMB and LSS

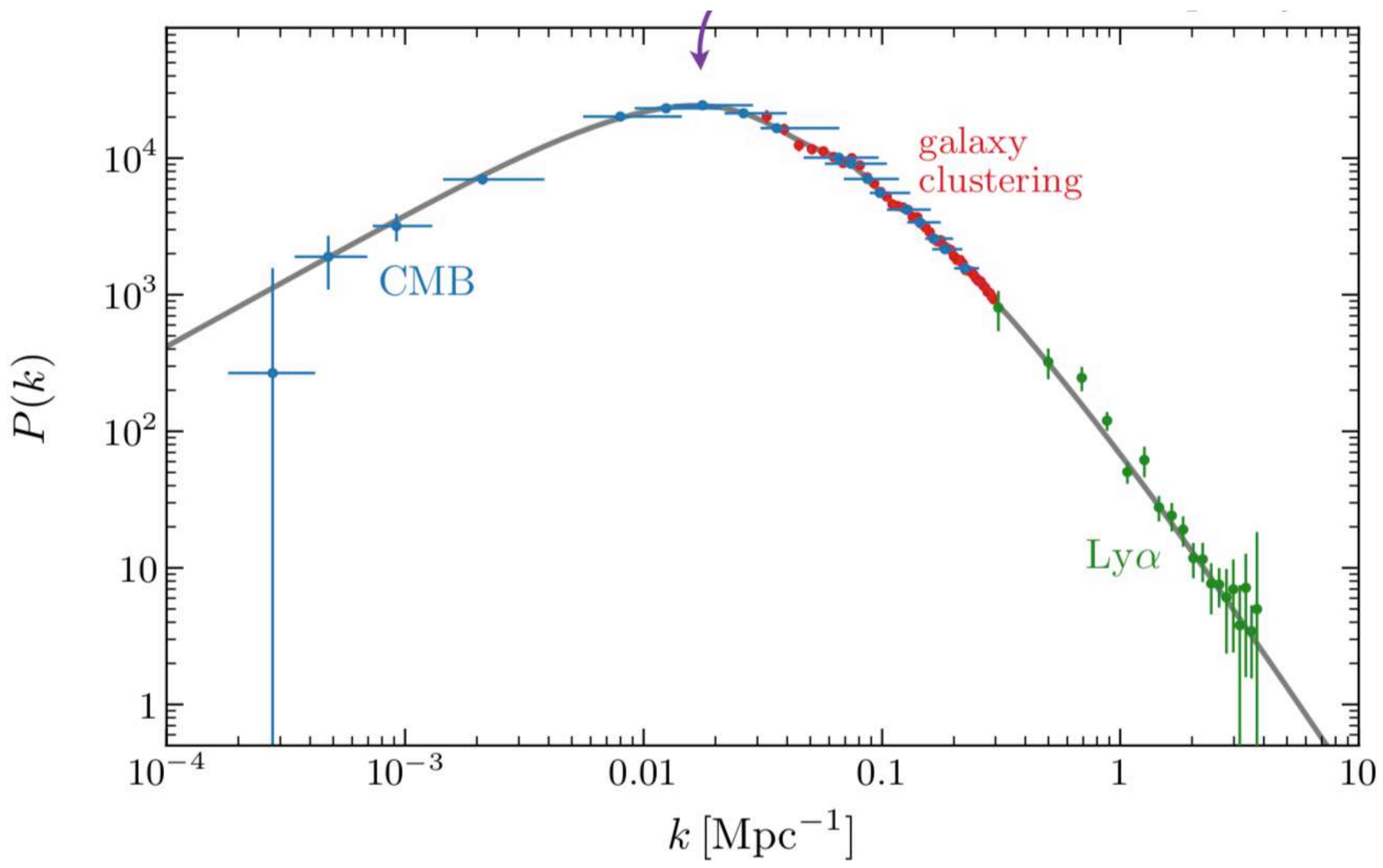
Large scale structure





Large scale structure





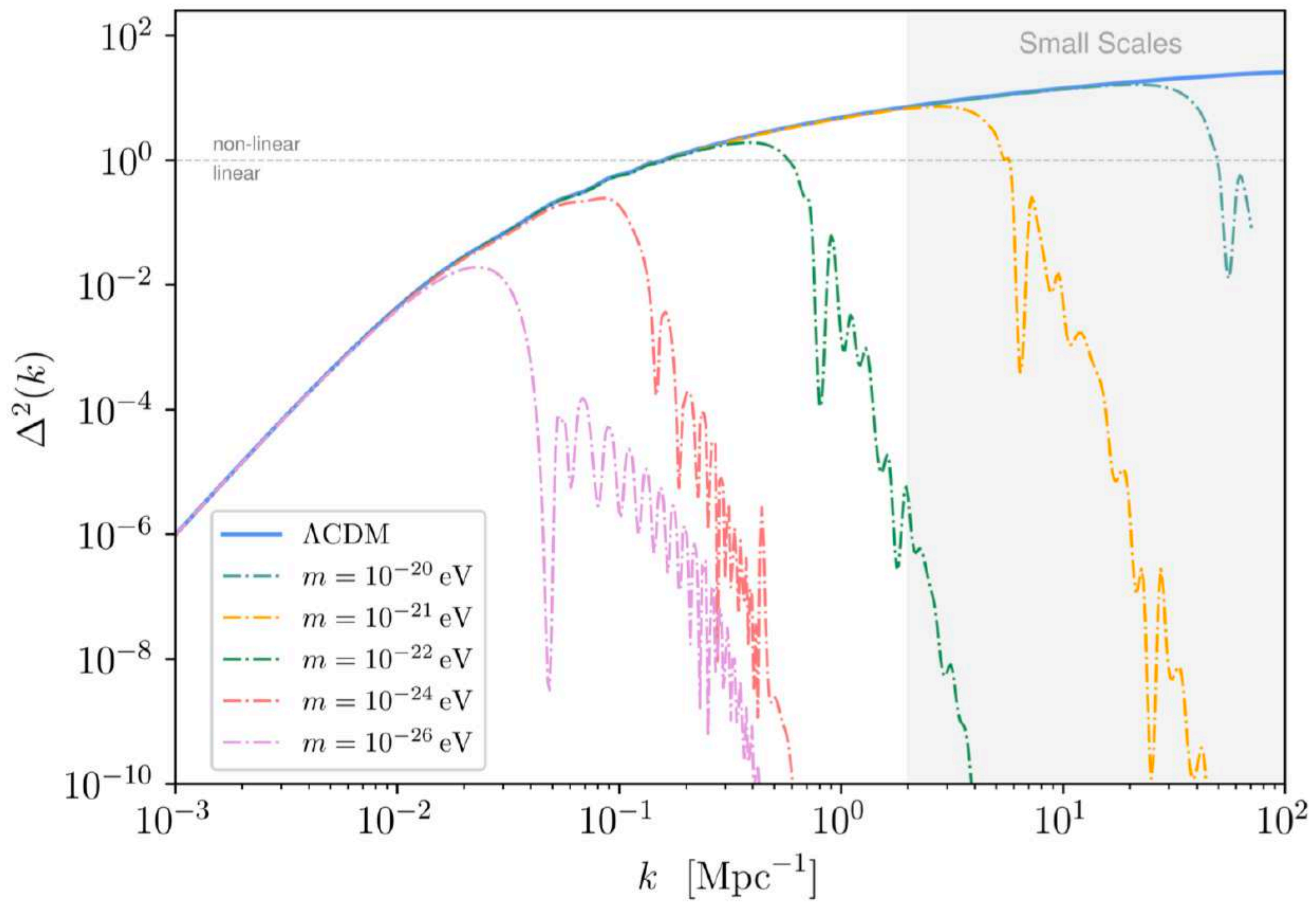
$$\Omega_m = 0.308 \pm 0.012$$

(Planck 2018)

Cosmological and astrophysical ***probes*** *of dark matter*

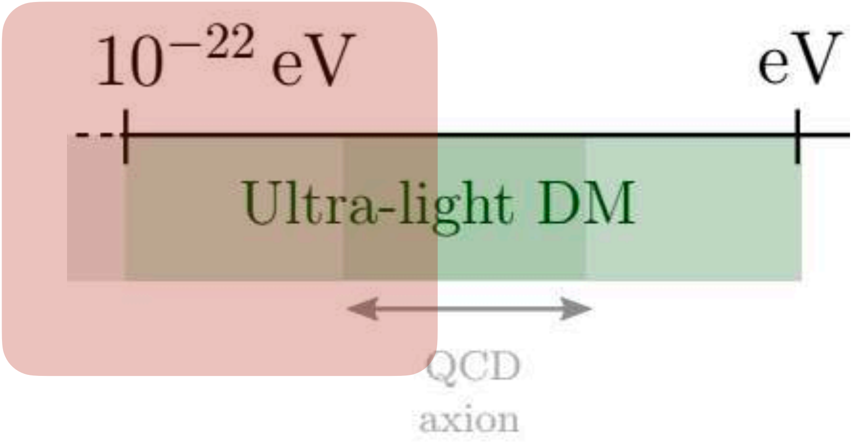
CMB and LSS

Depends on the amount of CDM - a cold fluid
Evolution
Damping/suppression
…



Observational implications and constraints

Fuzzy Dark Matter - bounds on the mass

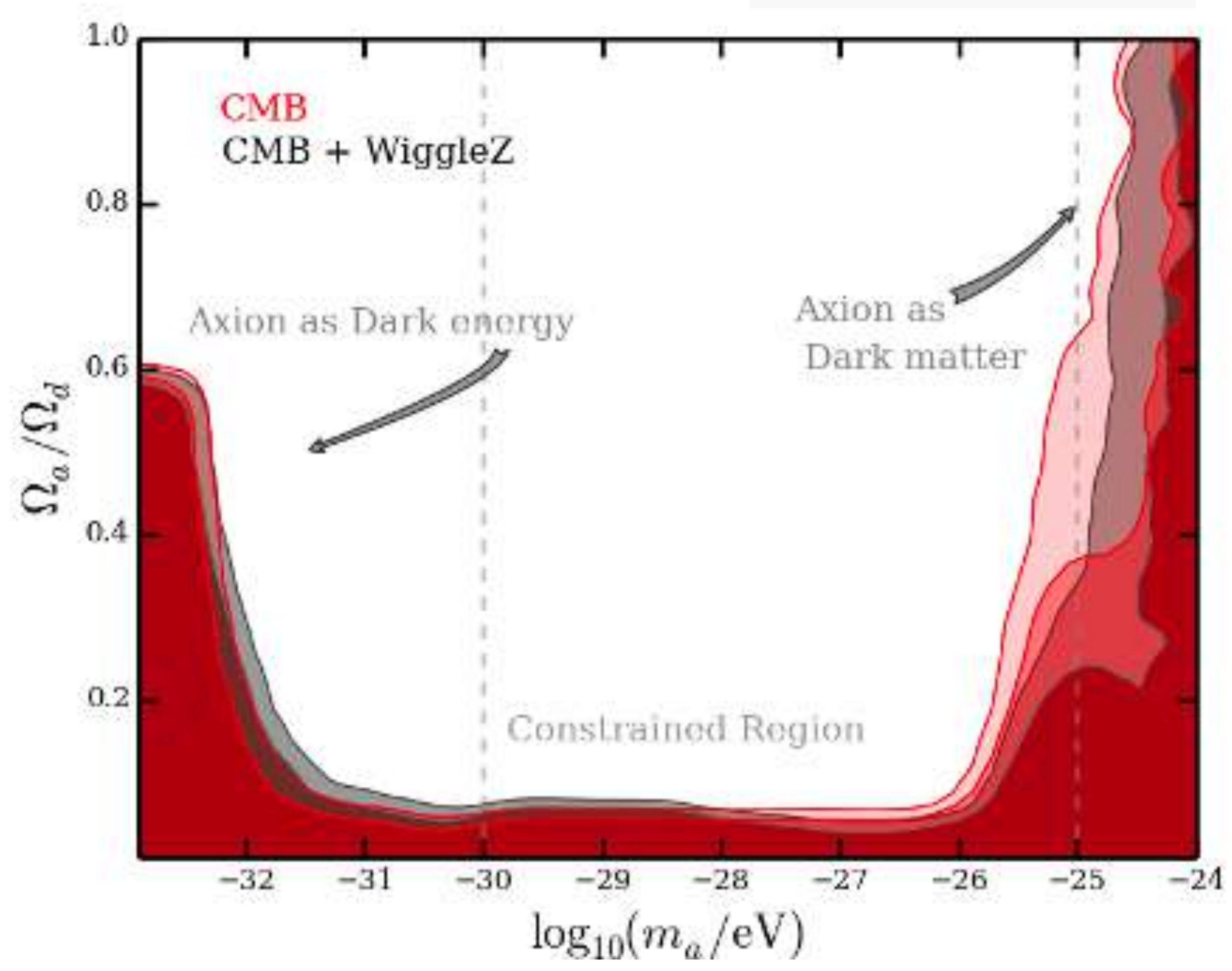


Suppression of small structures + evolution

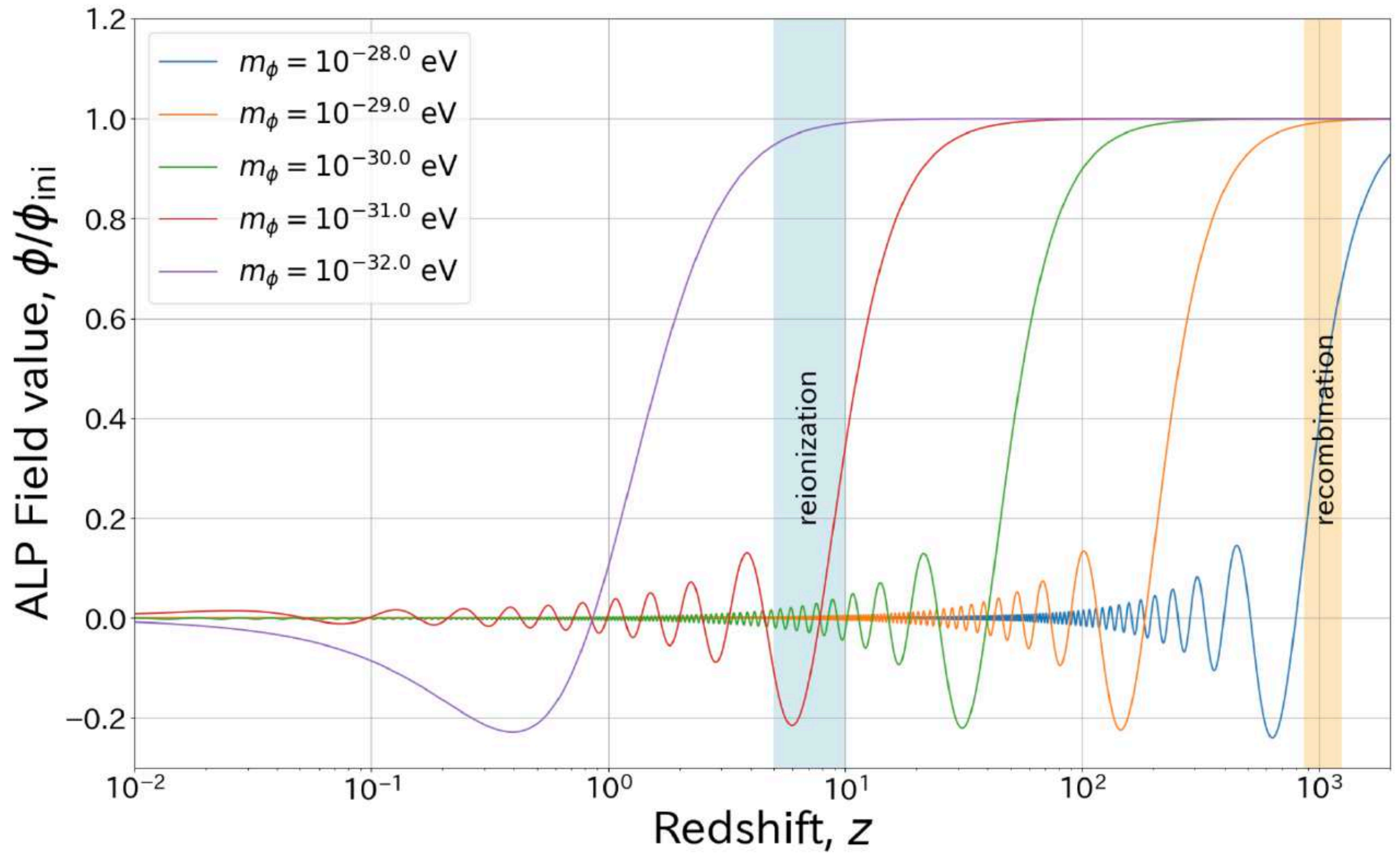
Extremely light dark matter and axion DE

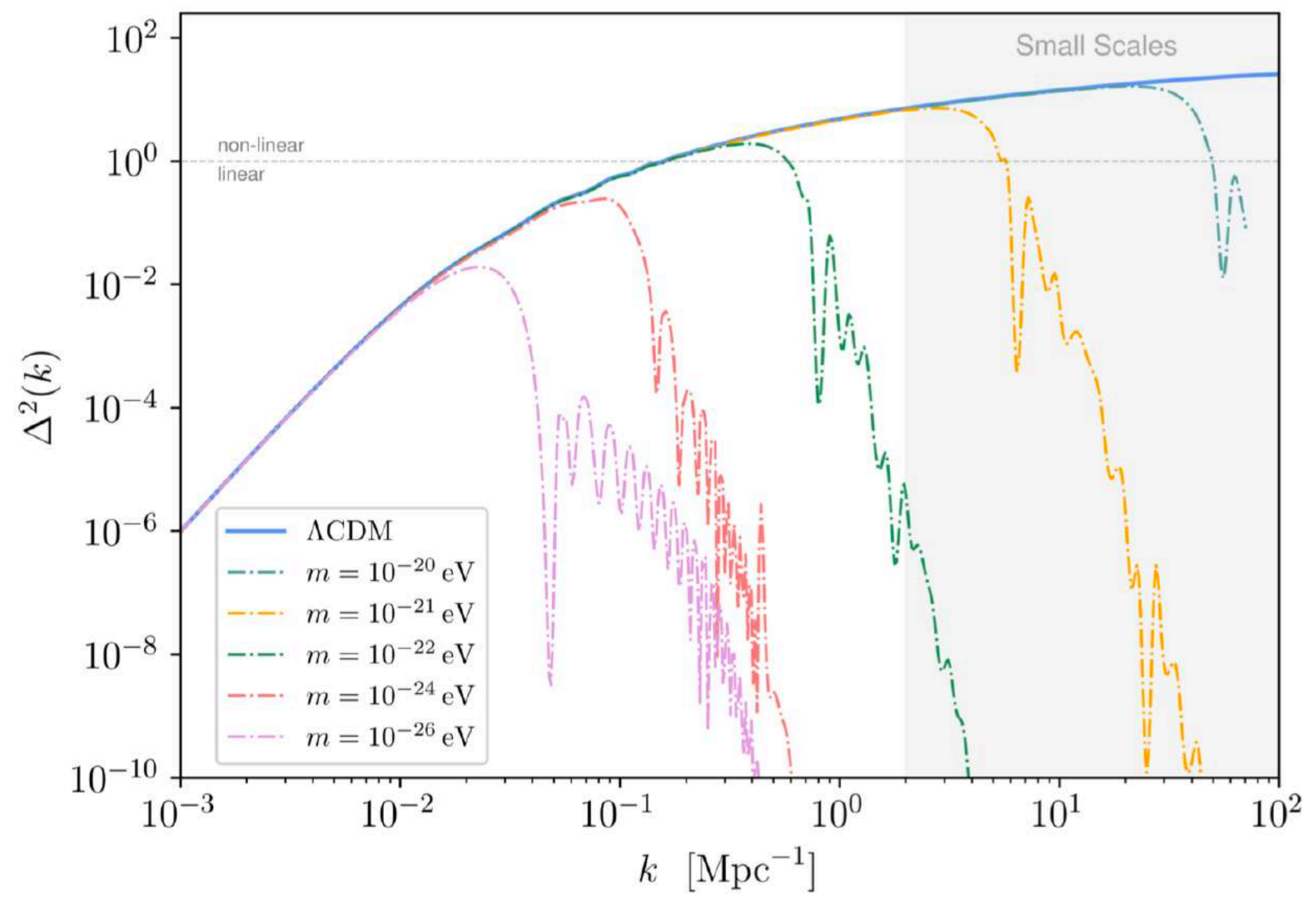
CMB/LSS

Hlozek et al, (2015, 2018)



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



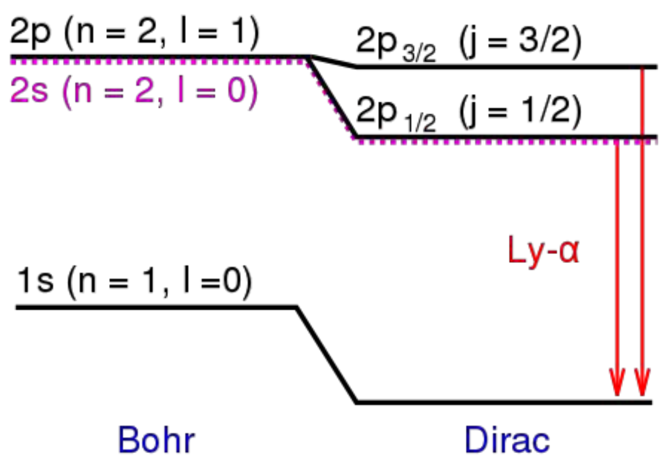


Atacama Cosmology Telescope (ACT) Data Release 6 (DR6) (2025) improved over these bounds

Cosmological and astrophysical ***probes*** *of dark matter*

Lyman α

Spectral line of hydrogen



Tobix10

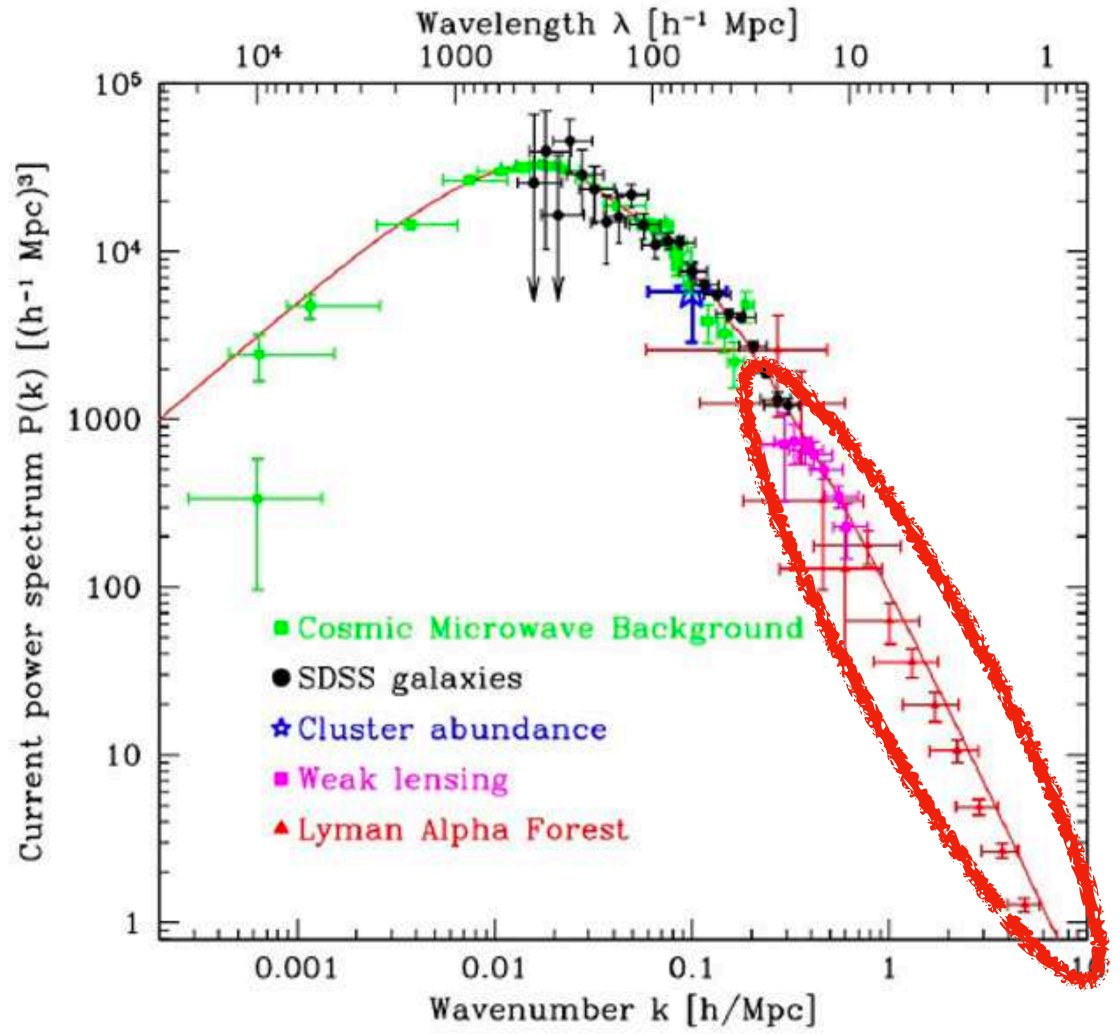
Lyman-alpha forest is a series of absorption lines in the spectra of distant galaxies and quasars arising from the Lyman-alpha electron transition of the neutral hydrogen atom

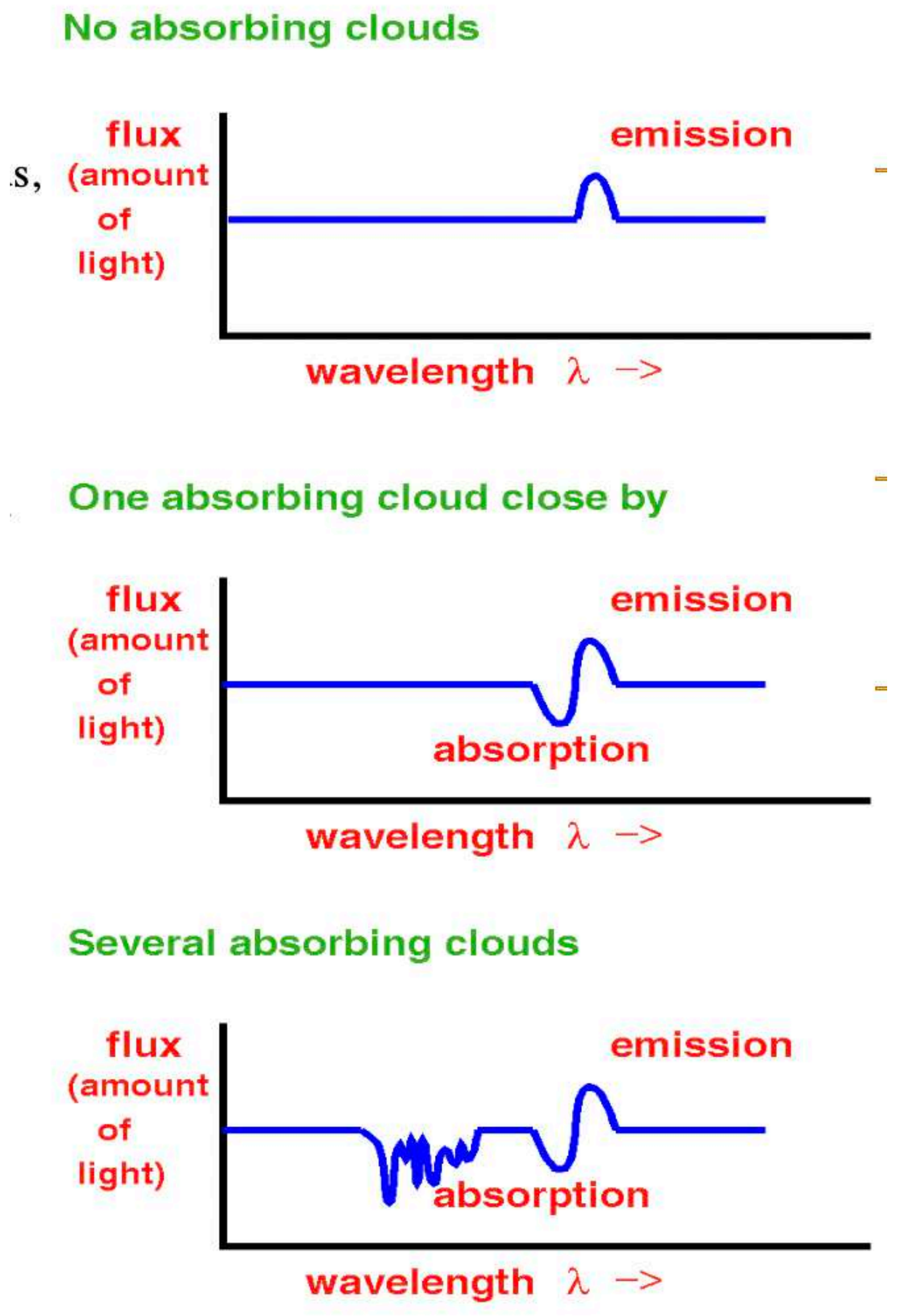
Armengaud

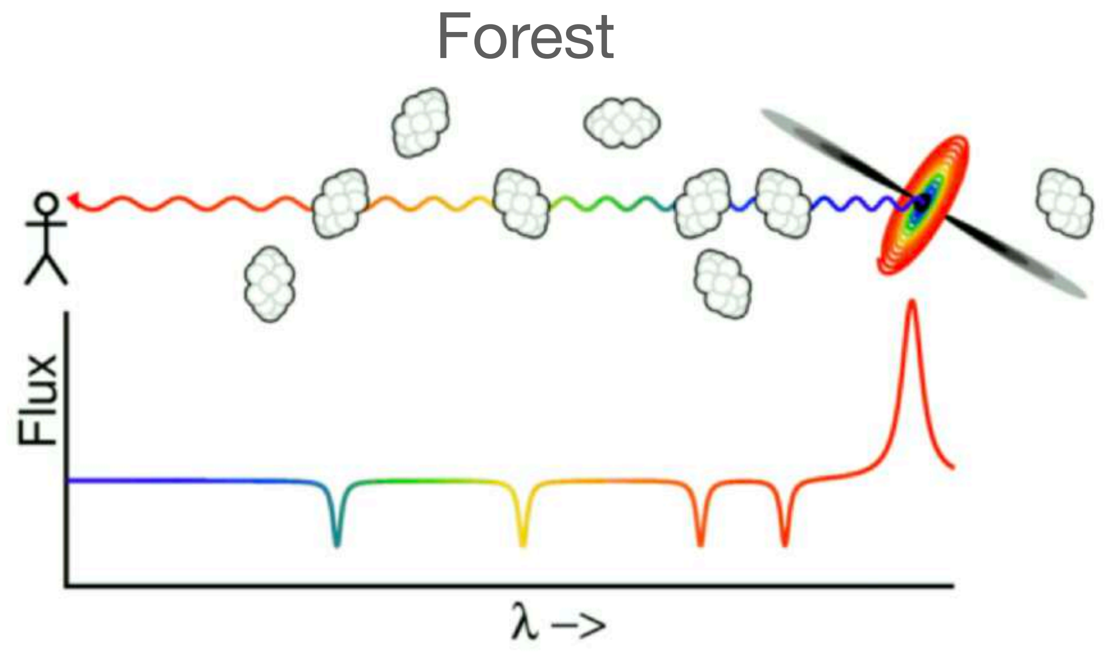
$$\delta(\lambda) = \frac{f(\lambda)}{C_q(\lambda)\bar{f}(z)} - 1$$

$P_{1D}(k) = <(FFT(\delta))^2>$

related to 3D matter P(k)







Lyα forest: series of absorption lines

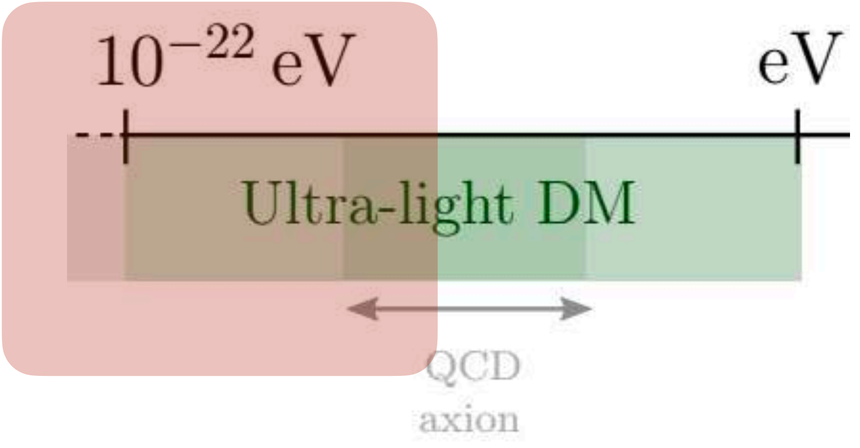
Advantage: provide PS on intermediary scales

It probes the matter power spectrum in the mildly nonlinear regime over a large range of redshifts ($z = 2 - 6$) down to small scales ($1 - 80\ h^{-1}$ Mpc)

Challenges:

- Modelling/simulating of DM on NL scales
- Modelling/simulating Lyα
  - Reionization

Observational implications and constraints

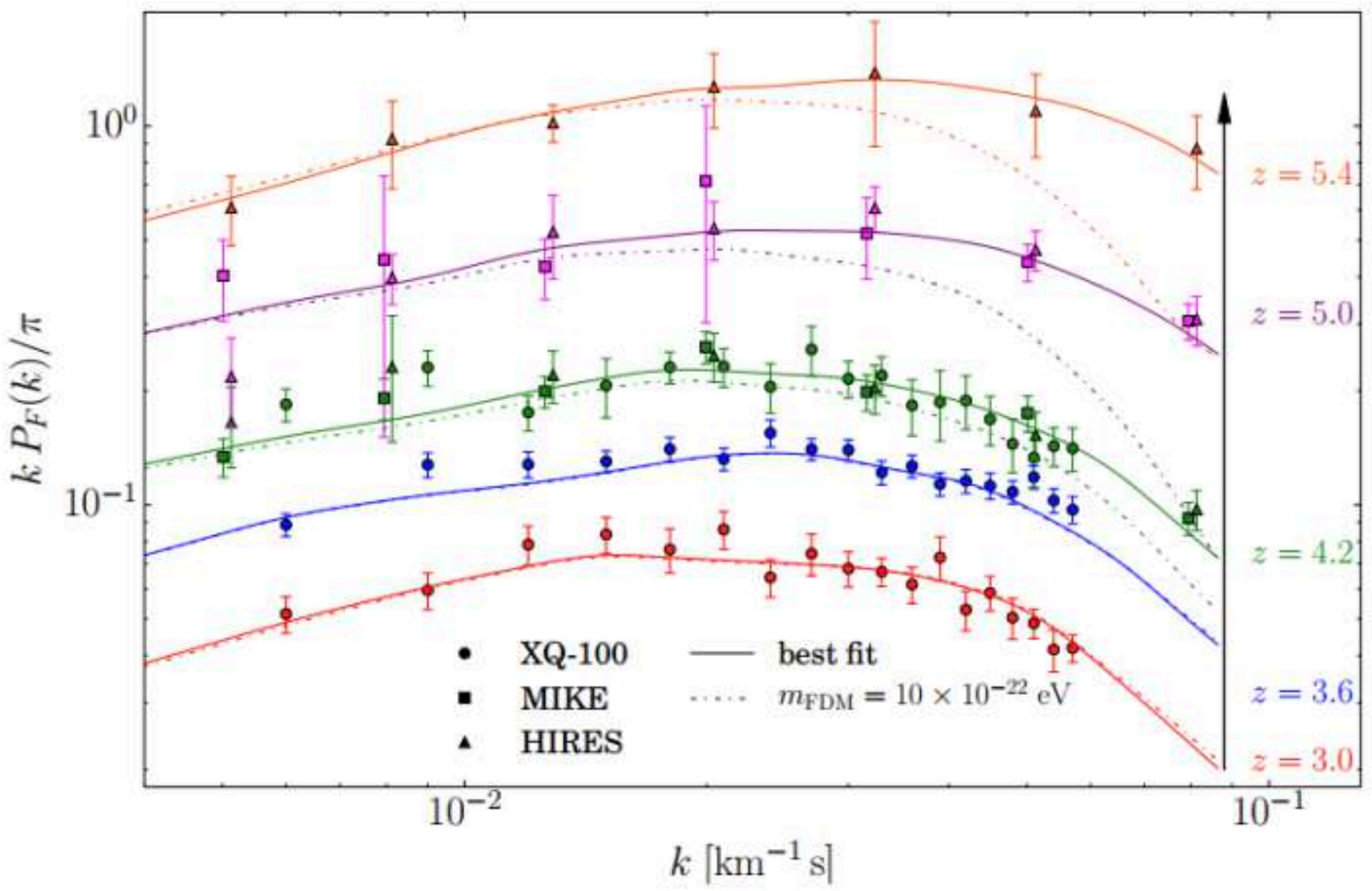


Fuzzy Dark Matter - bounds on the mass

Suppression of small structures + evolution

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.

One of the strongest bounds on ULDM!

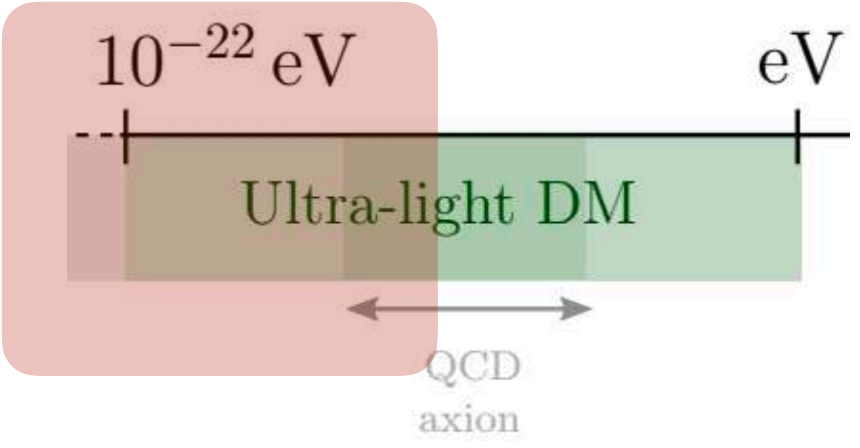
Constraints depends on:

- IGM modelling - simplifying assumptions
- Trusts on IC sims

(Work in progress) with Simon May

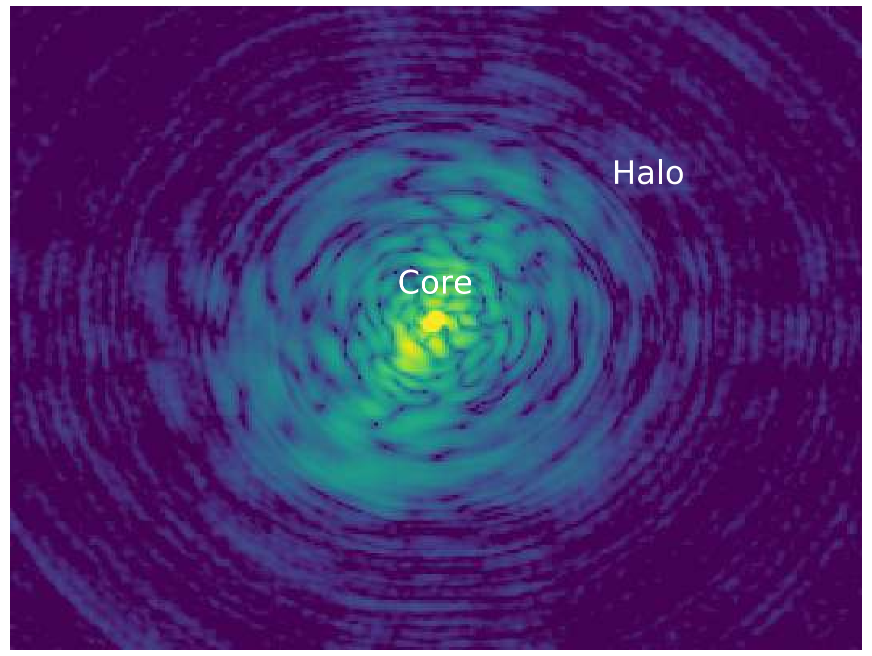
New cosmological fuzzy dark matter simulations including baryons, using the IllustrisTNG galaxy formation model

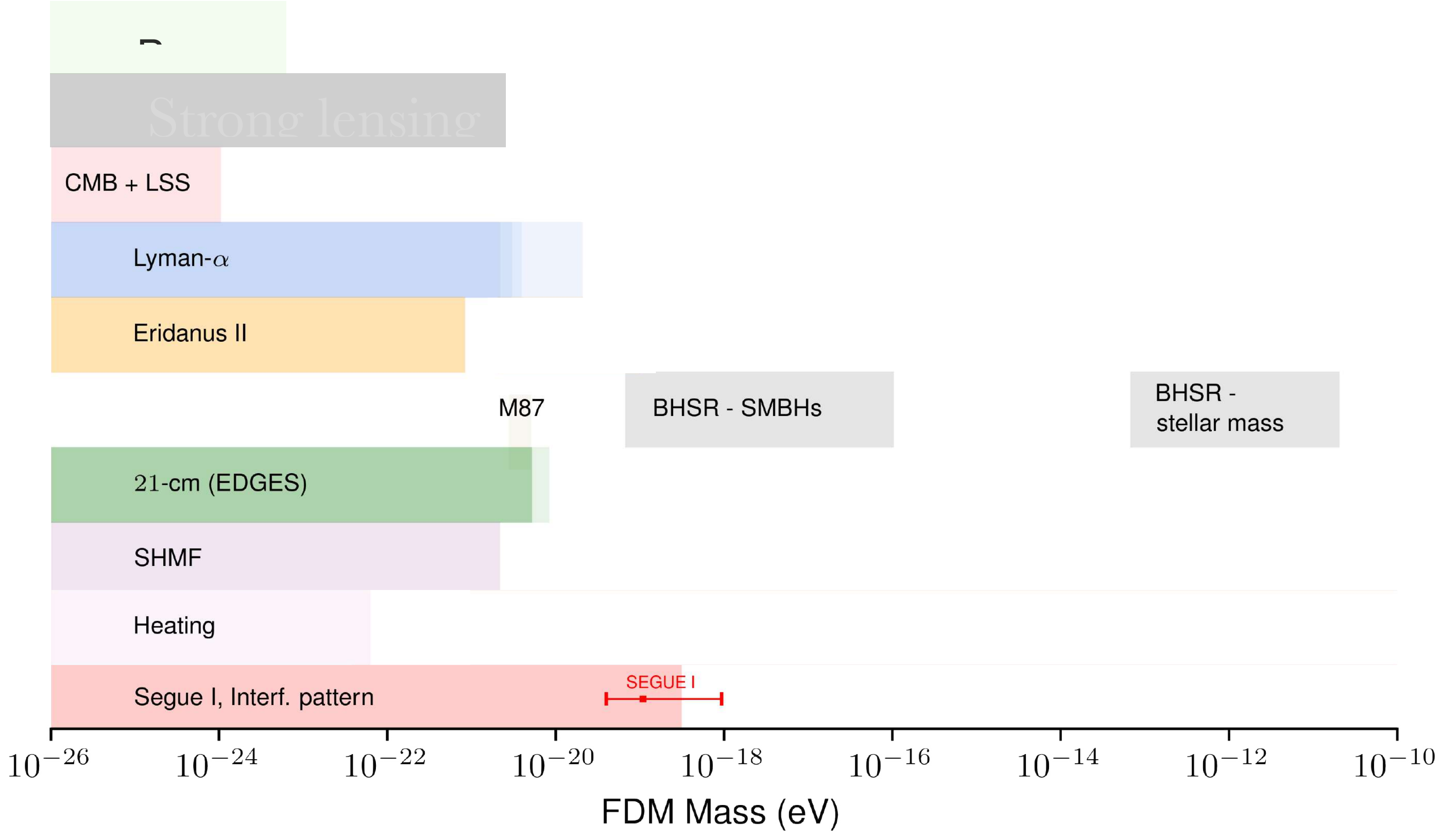
Revise these bounds + study the evolution of IGM as a way of constraining FDM.
IGM properties not so influenced by feedback
Filaments and interference patterns important here!



Observational implications and constraints

Core in the interior of galaxies





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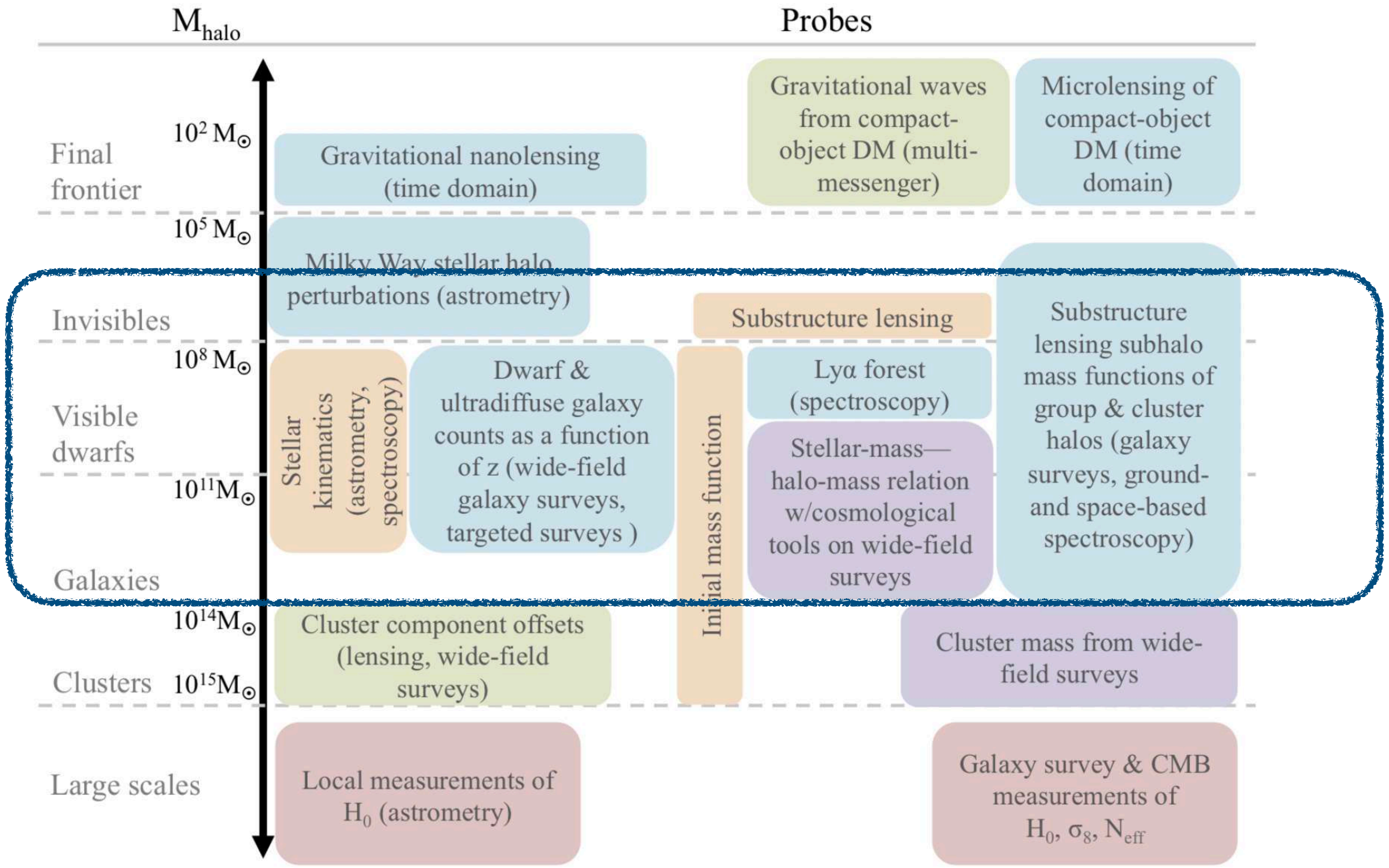
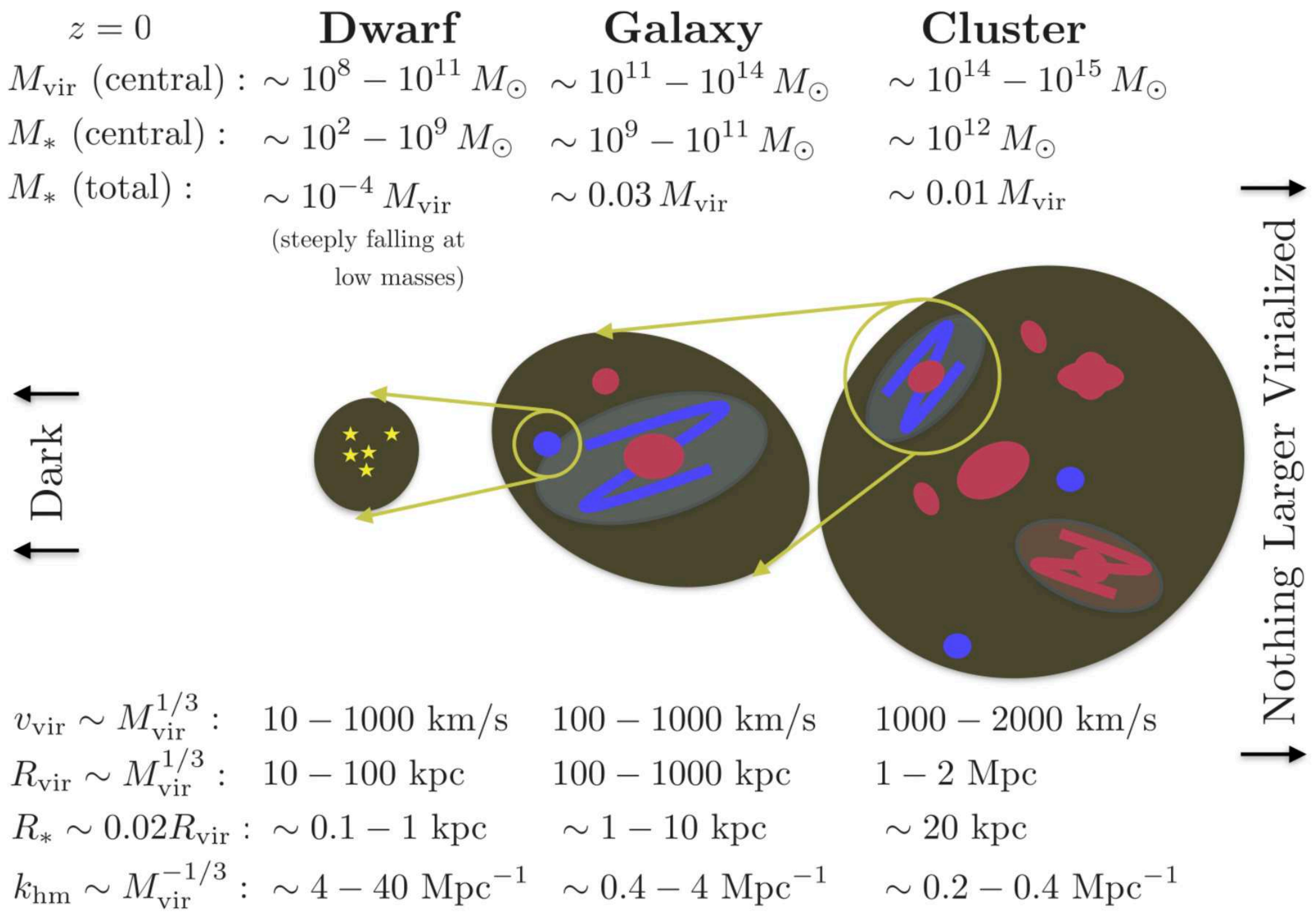


Currently being measured

Precision improving

Buckleya et al 2017

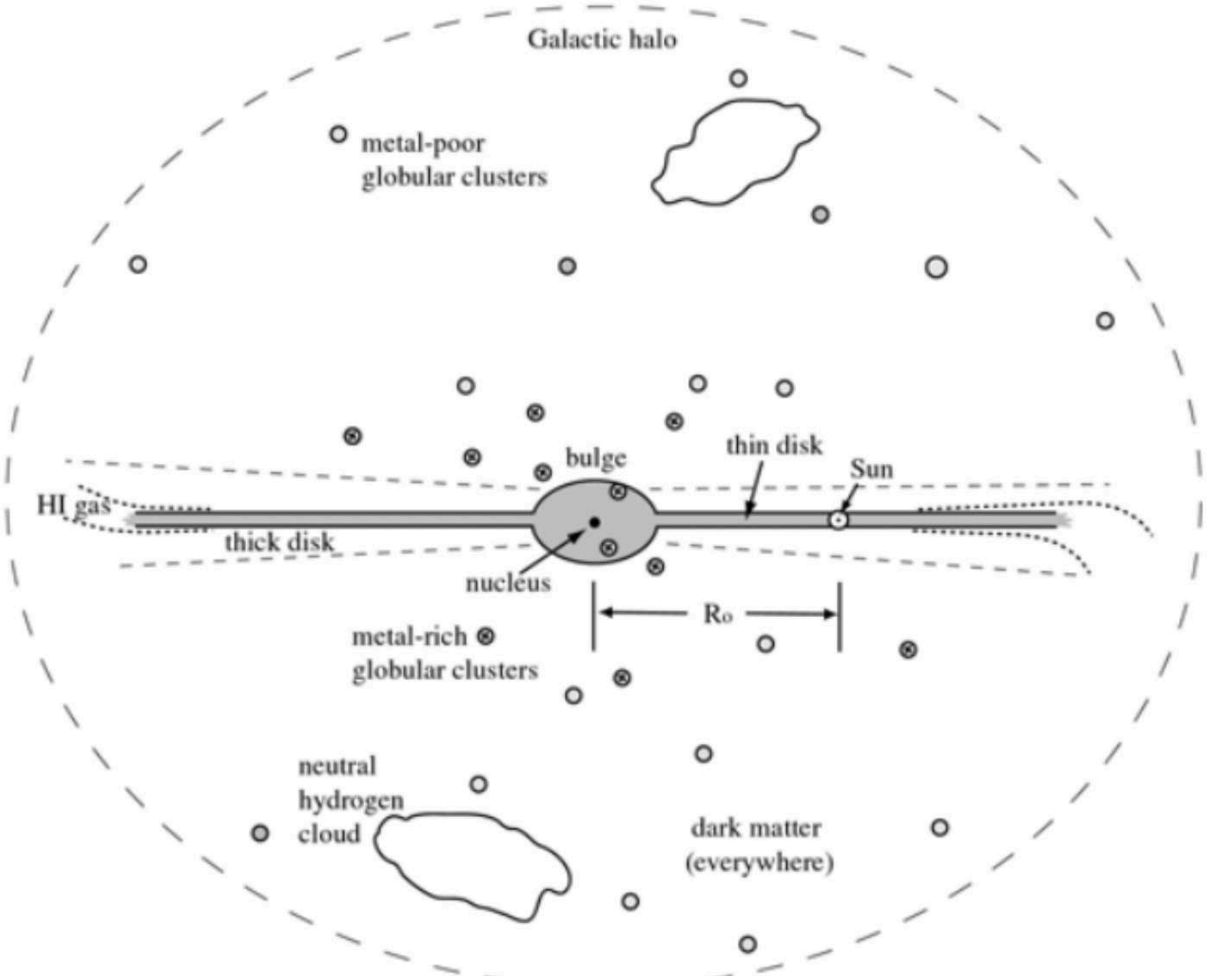
Cosmological and astrophysical ***probes*** *of dark matter*



Buckleya et al 2017

Cosmological and astrophysical ***probes*** *of dark matter*

Galaxies



A schematic side view of the Milky Way

Sparke & Gallagher

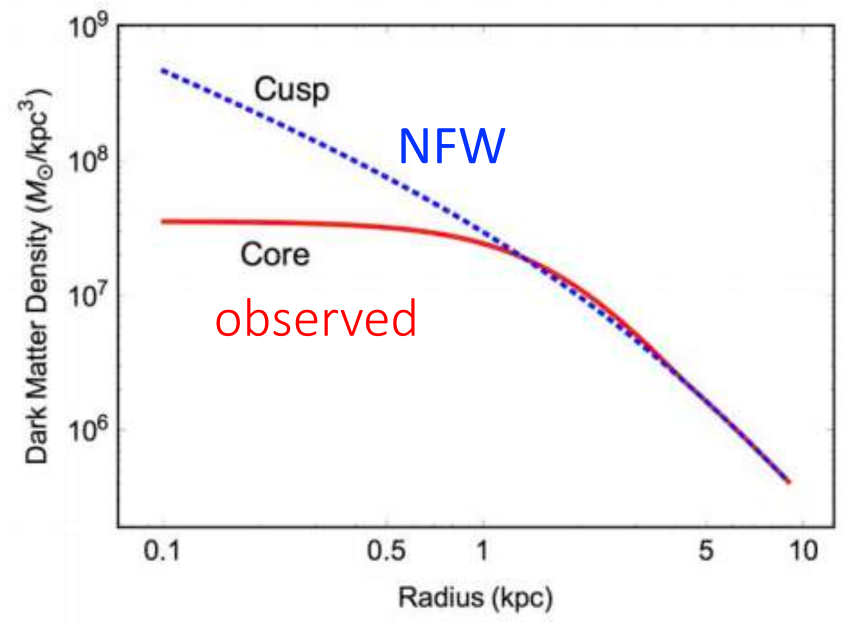
Cosmological and astrophysical ***probes*** *of dark matter*

Galaxies/dwarf galaxies

Local Milky Way observables and stellar streams

- Density profile
  - MW gravitational profile
  - Dwarfs density profile

- Vertical dynamics
- Velocity dispersion
- Dynamical effect
  - Heating
  - Dynamical friction
- Counting small galaxies
- Stellar stream *(More later)*
- …



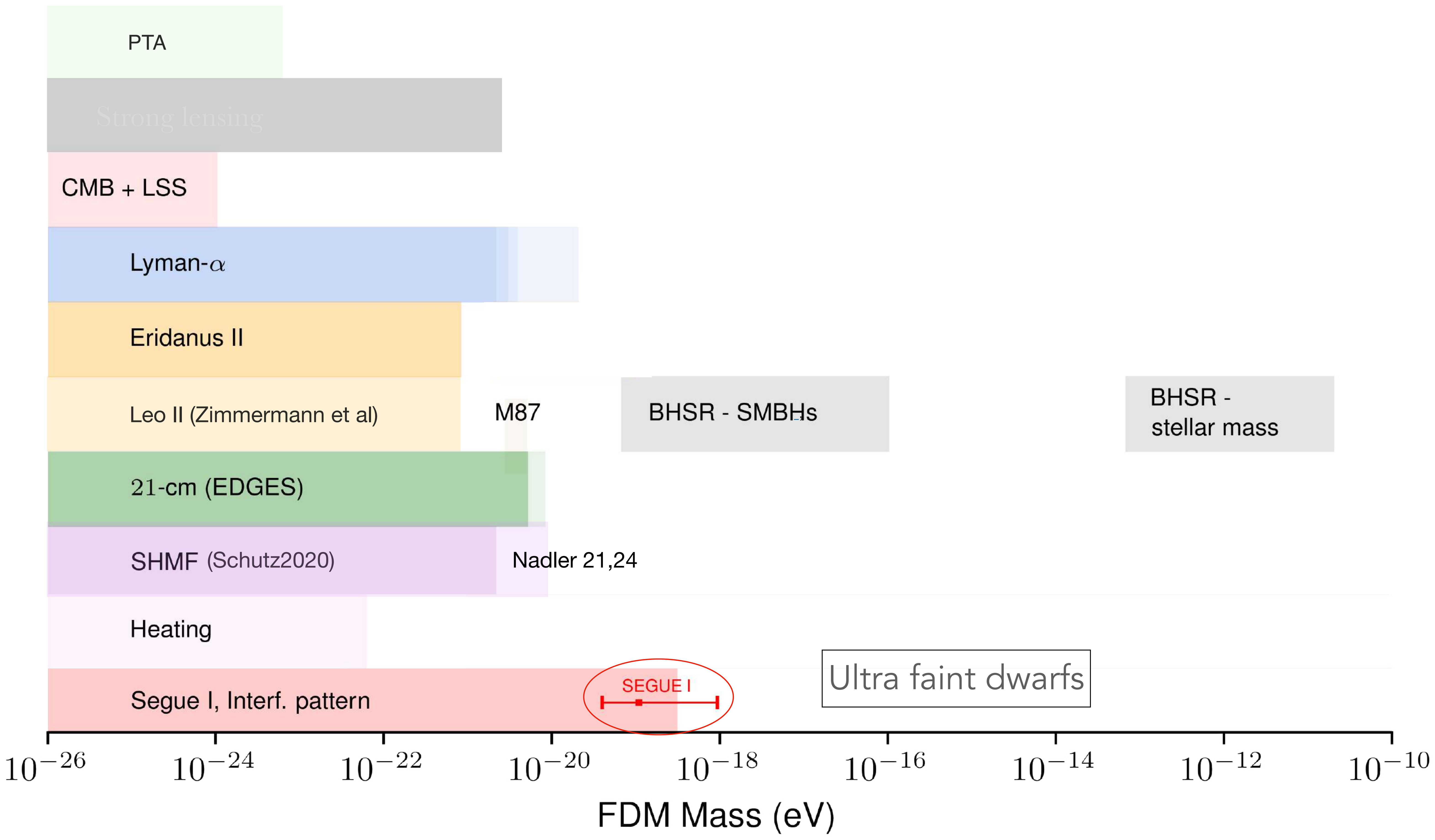
Gravitational lensing

(More later)

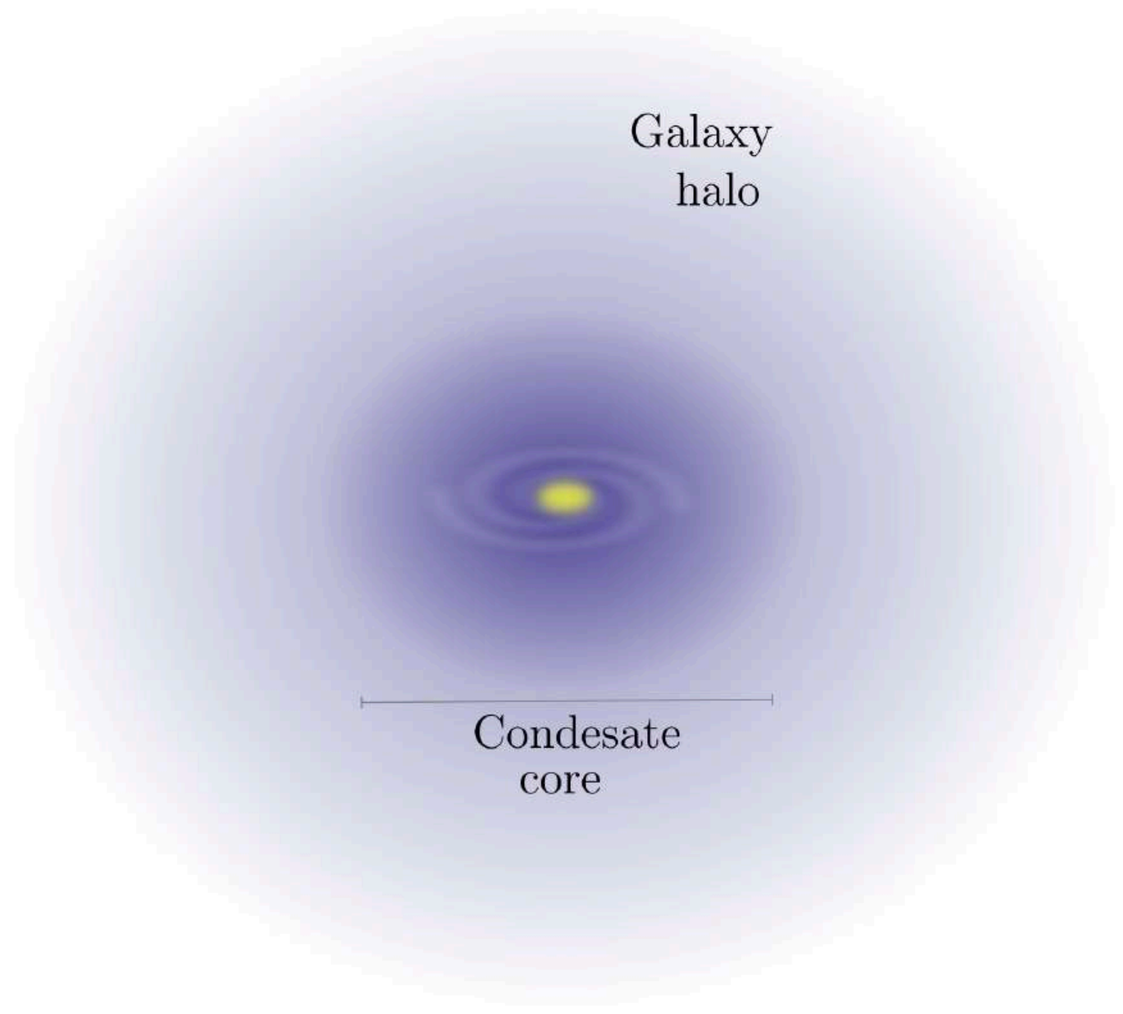
Observational implications and constraints

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.

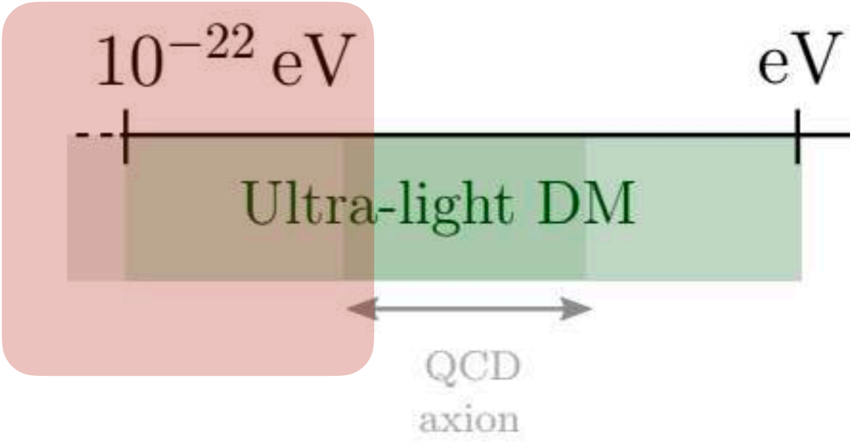


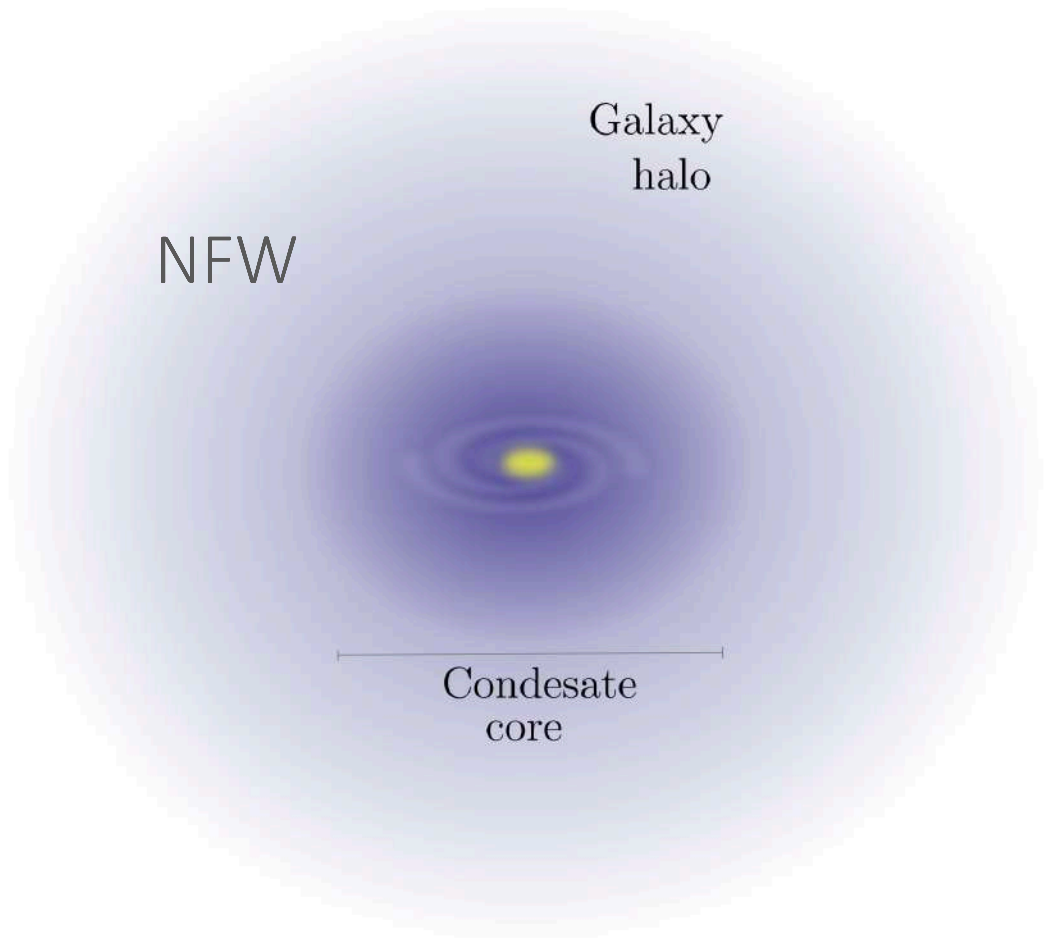
Presence of a core



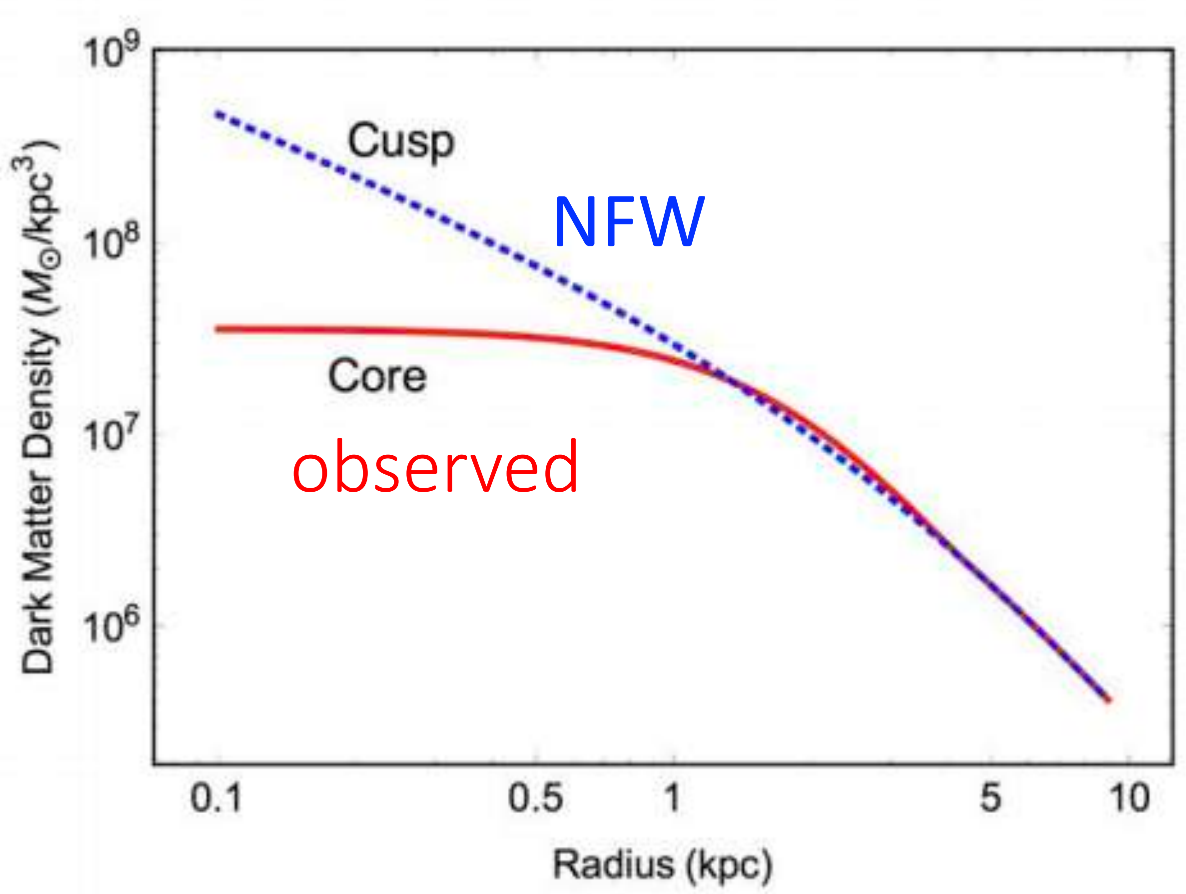
Phenomenology

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 in *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

FDM mass from Ultra-faint dwarfs

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

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

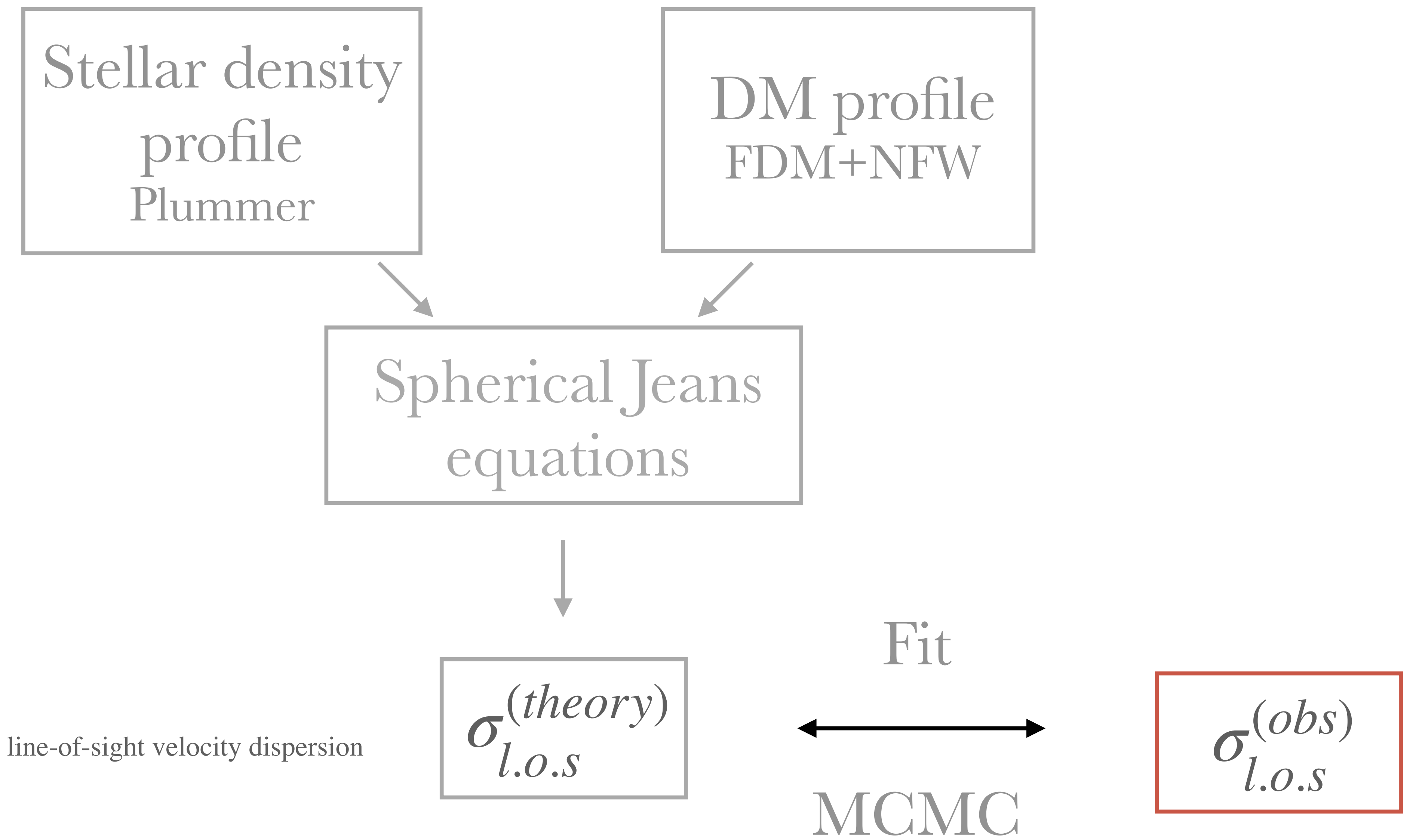
Stellar kinematic data from 18 UFDs to fit the FDM profile:

FDM SIMULATIONS

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

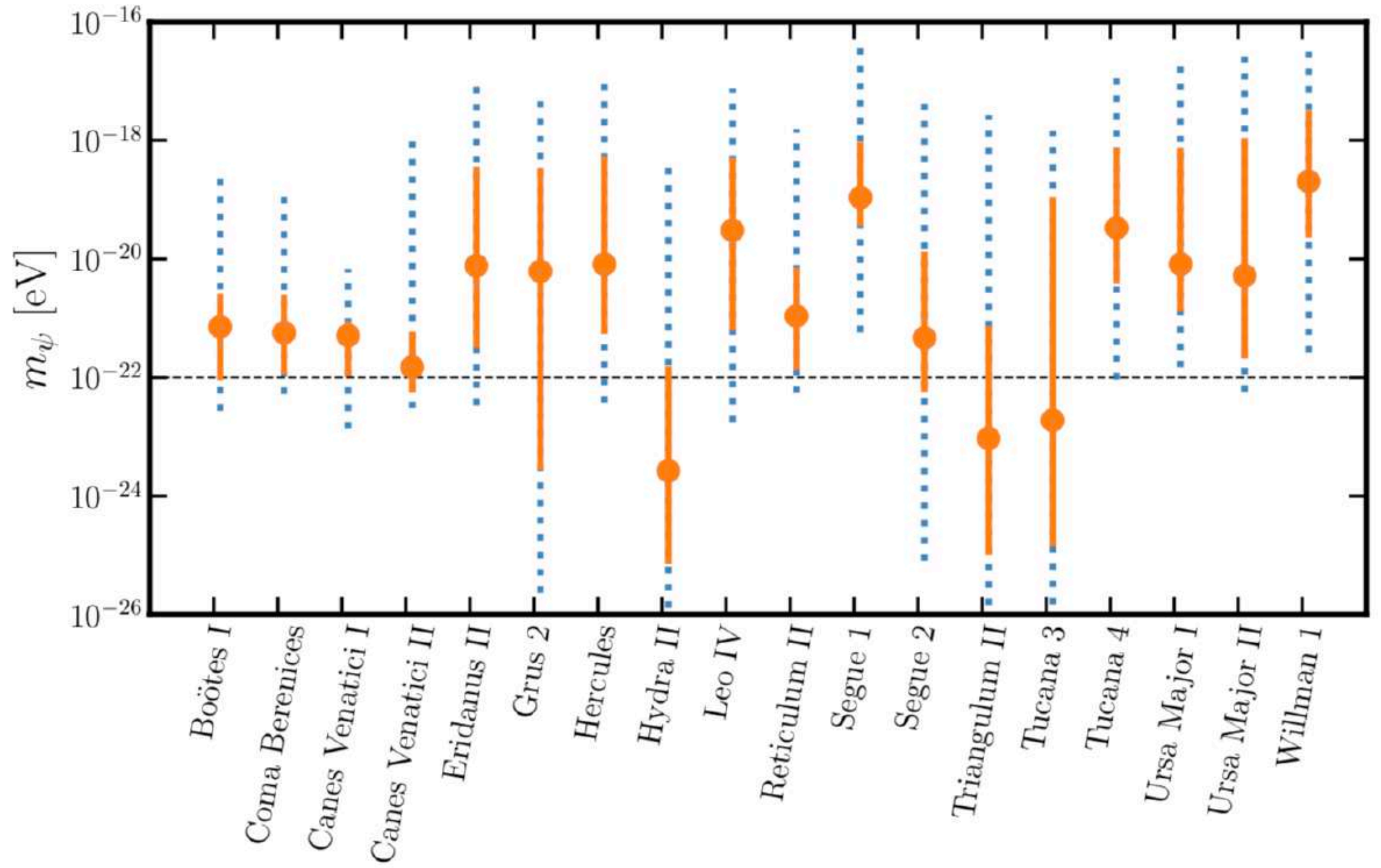
$$\rho_c(r) = 1.9 \times 10^{12} \left(\frac{m}{10^{-23}\,{\rm eV}}\right)^{-2} \left(\frac{r_c}{\rm pc}\right)^{-4} [M_\odot\,{\rm pc}]$$

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



Parameter space (10): $\{m, M_{\rm halo}, r_\epsilon, r_s, r_\beta, \beta_0, \beta_\infty, \eta, r_h, v_{sys}\}$

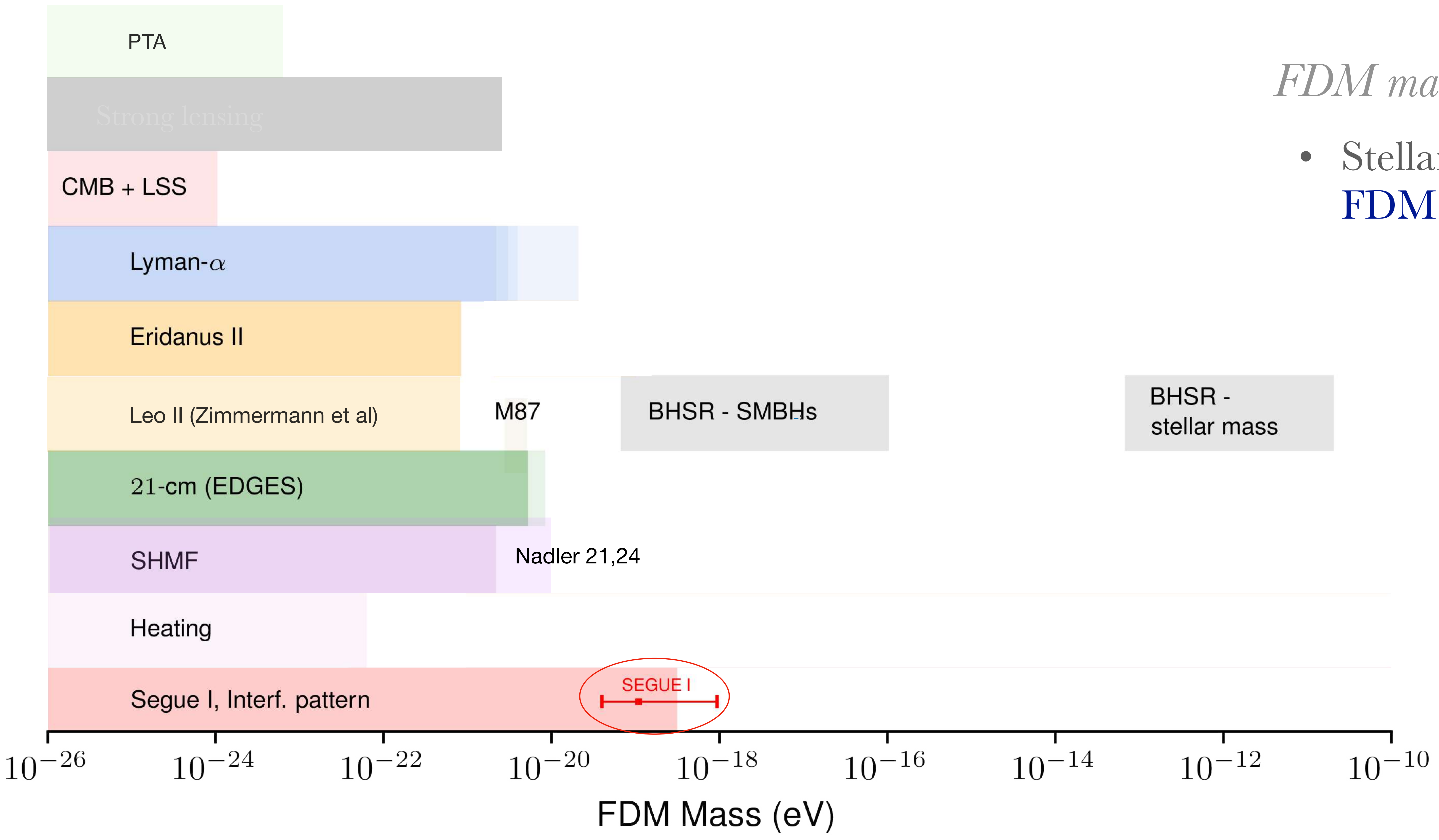
Stellar velocity anisotropy



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

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass



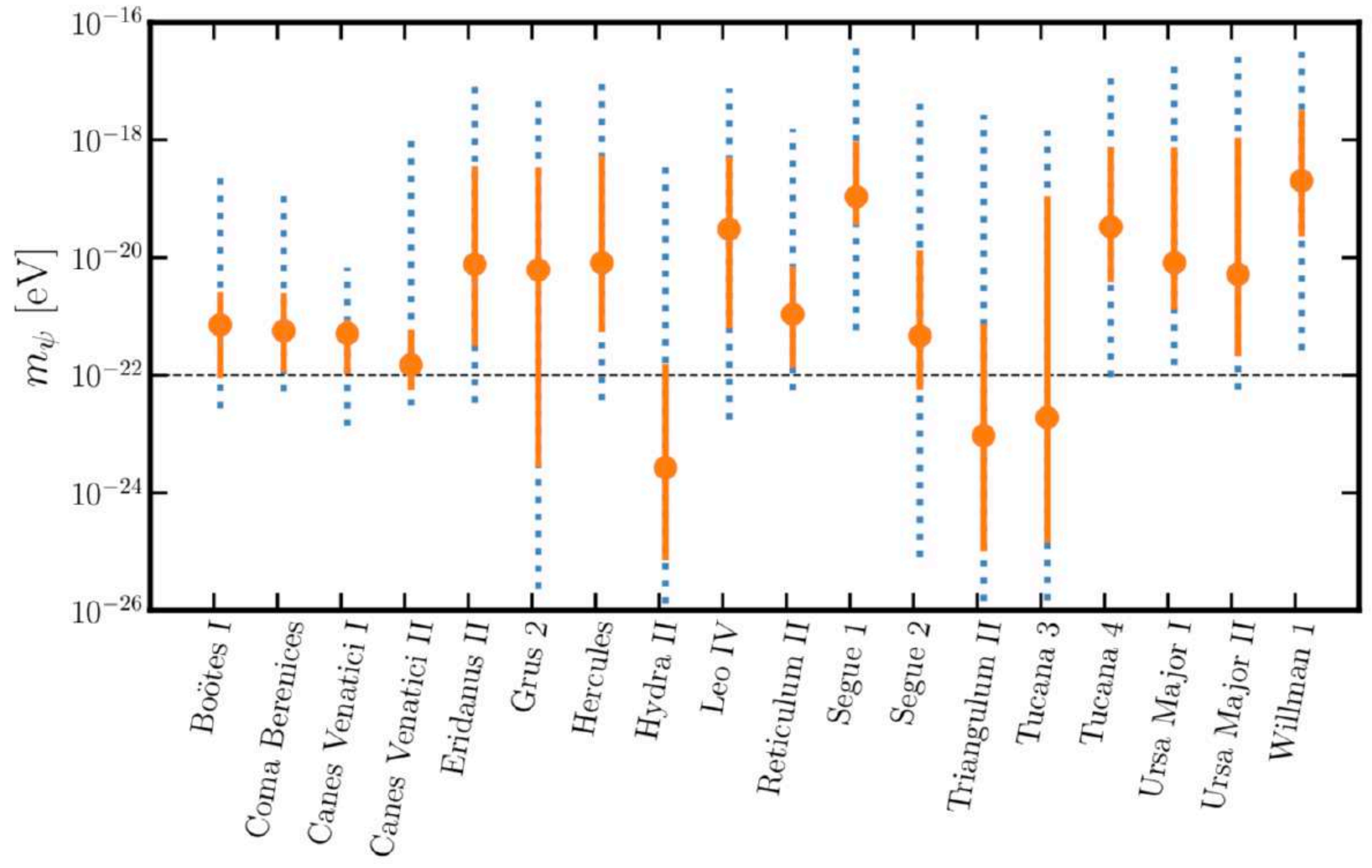
Ultra faint dwarfs

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

FDM mass from Ultra-faint dwarfs

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

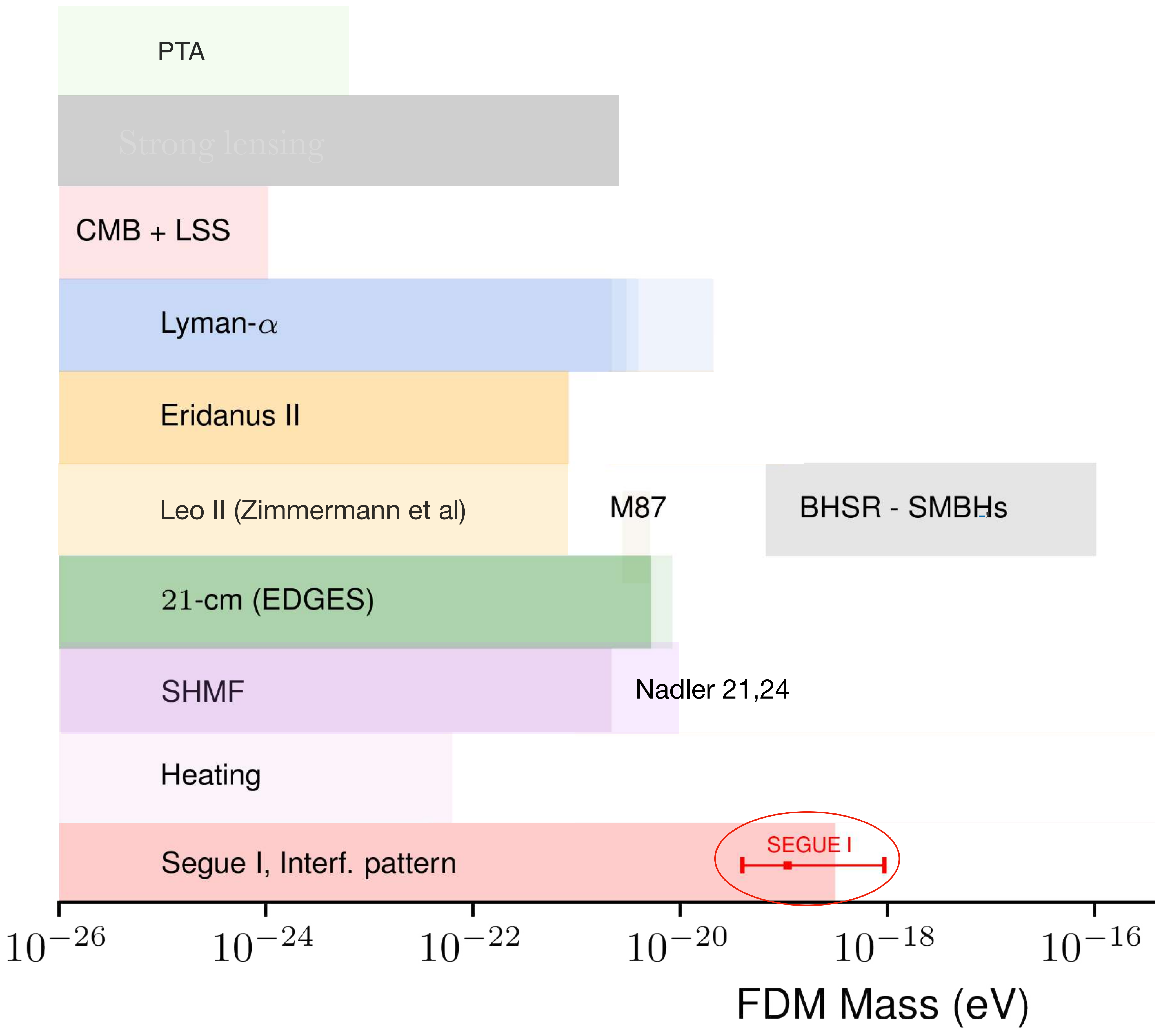
$$m_{\rm FDM}^{(Seg1)} = 1.1^{+8.3}_{-0.7} \times 10^{-19}\,{\rm eV}$$



Preference for higher mass

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass



Ultra faint dwarfs

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

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

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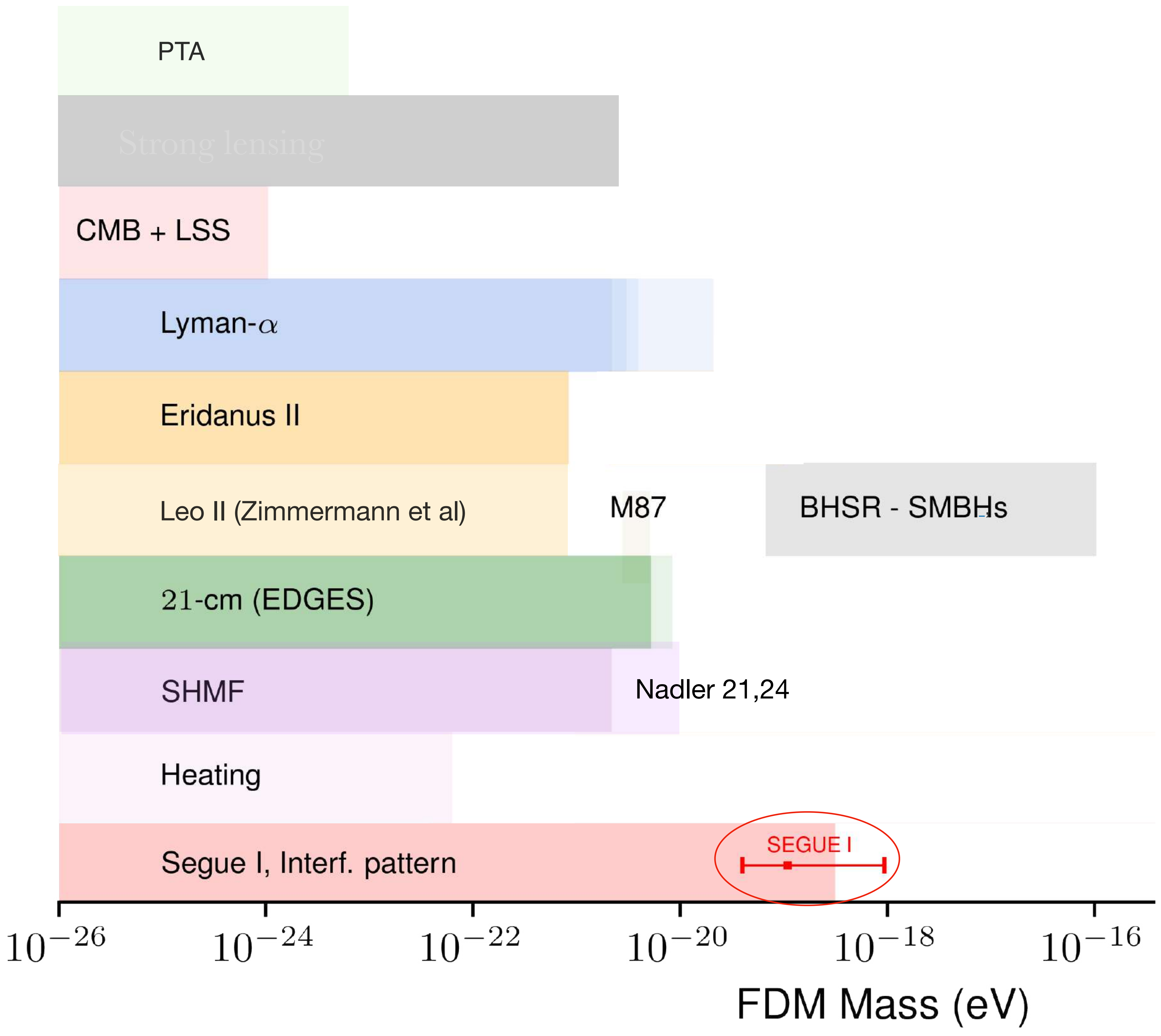
Important:

- Bayesian analysis - reason for a constraint
- 'Bad' assumption
- Systematic effects !

Ultra-light Dark Matter

Fuzzy Dark Matter - bounds on the mass



Ultra faint dwarfs

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

FDM mass from Ultra-faint dwarfs

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

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

Important:

- Bayesian analysis - reason for a constraint
- 'Bad' assumption
- Systematic effects !

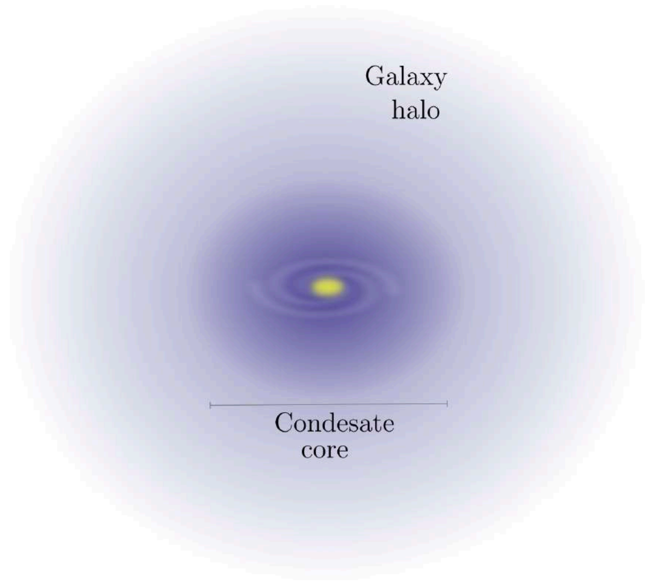
FDM - Core-halo mass relation

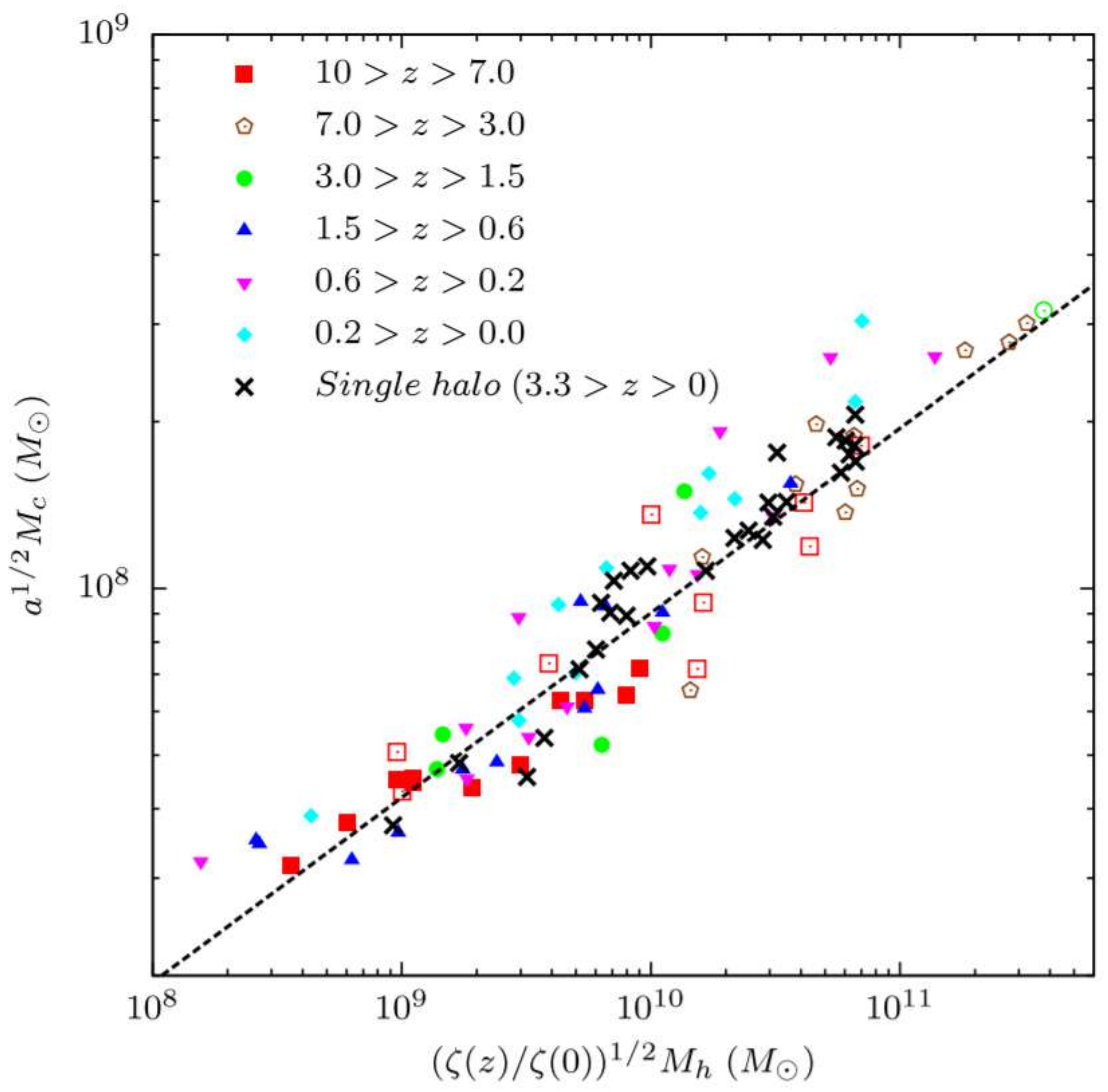
J. Chan et al. 2021

We want to study how the core relates to the halo mass - might be one part this puzzle

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

$\xrightarrow{?}$ M_h





Schive et al. 2014

Schive et al 2014

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

Velocity dispersion tracing

$$\sigma_c \sim \sigma_h$$

Mocz et al 2017

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

Energy tracing

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

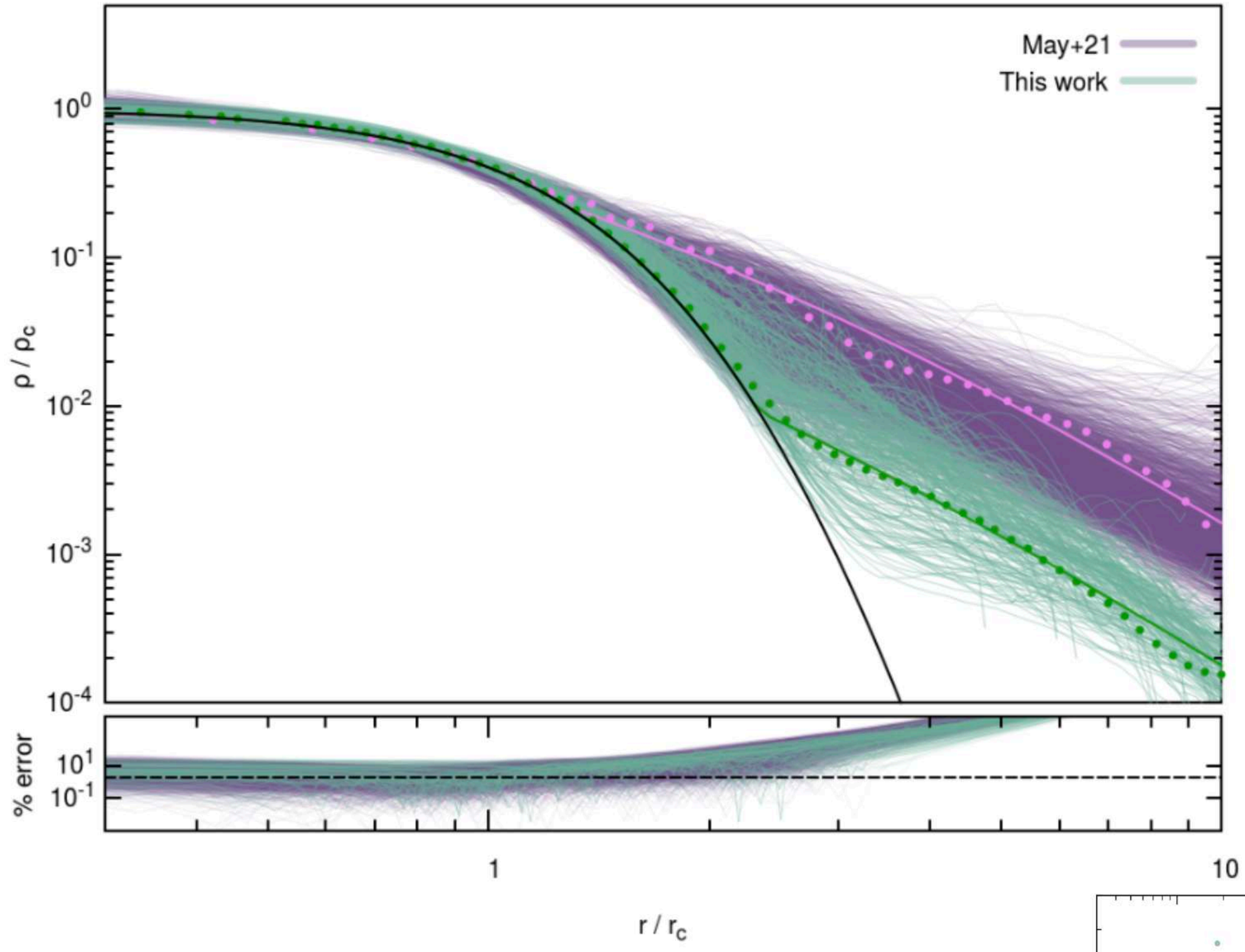
Velmatt et al 2018, Nori et al 2020, Nima et al 2020

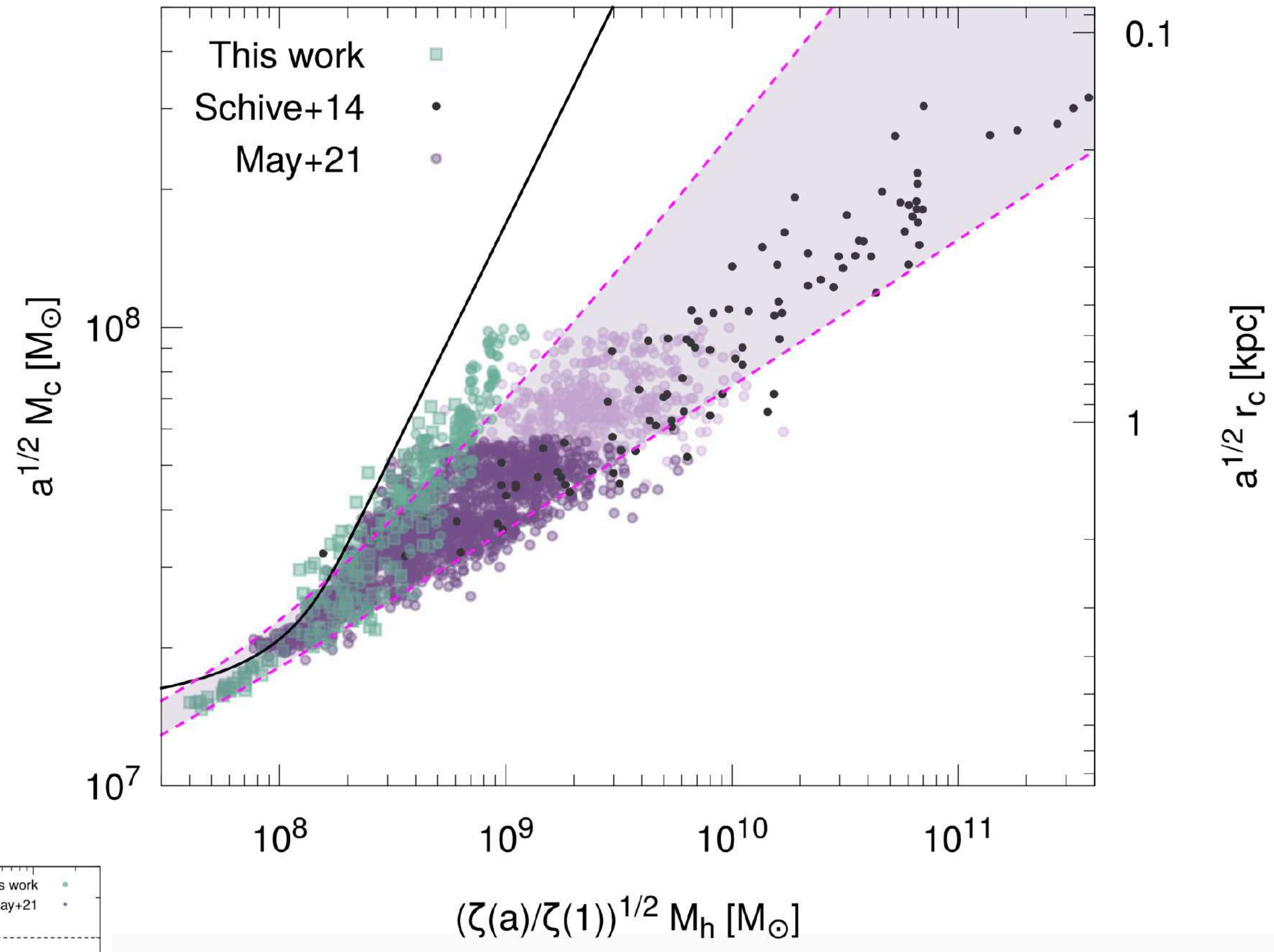
= Schive (Velmatt et al 2018)

≠ Schive (Nori et al 2020, Nima et al 2020)

FDM - Core-halo mass relation

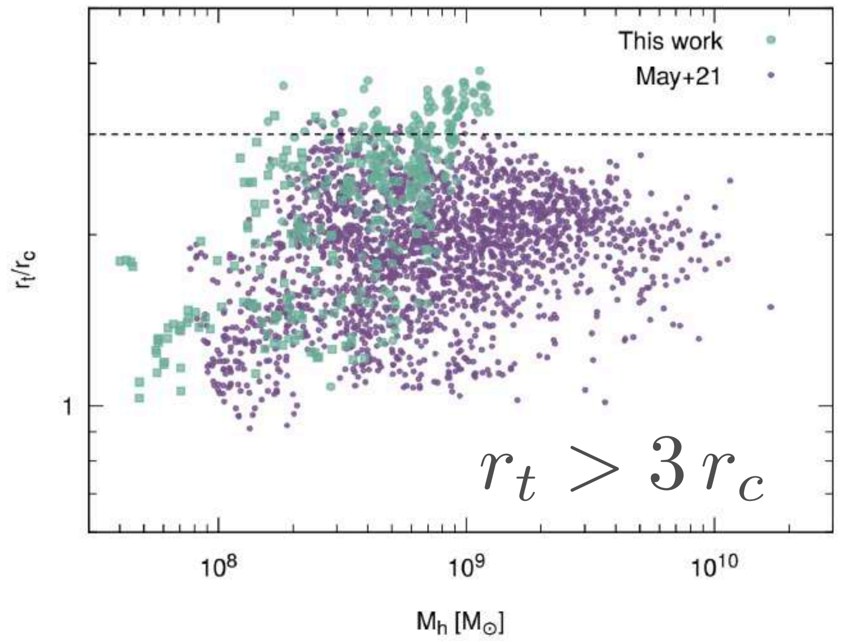
J. Chan, EF, S. May, K. Hayashi, M. Chiba 2021





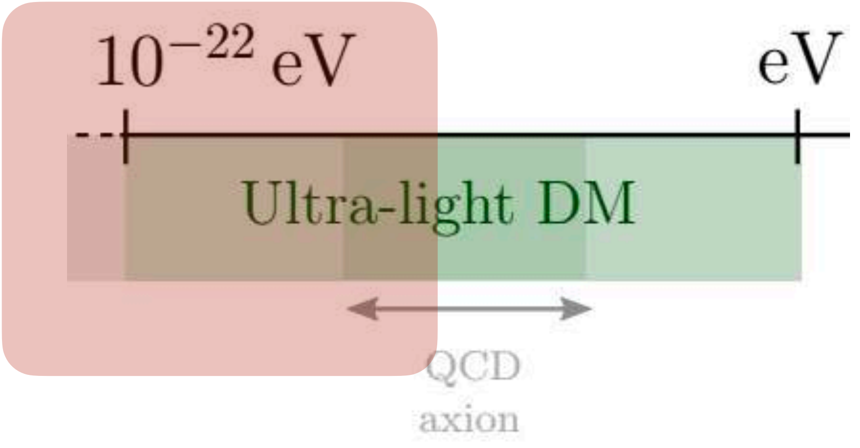
Well fitted by:

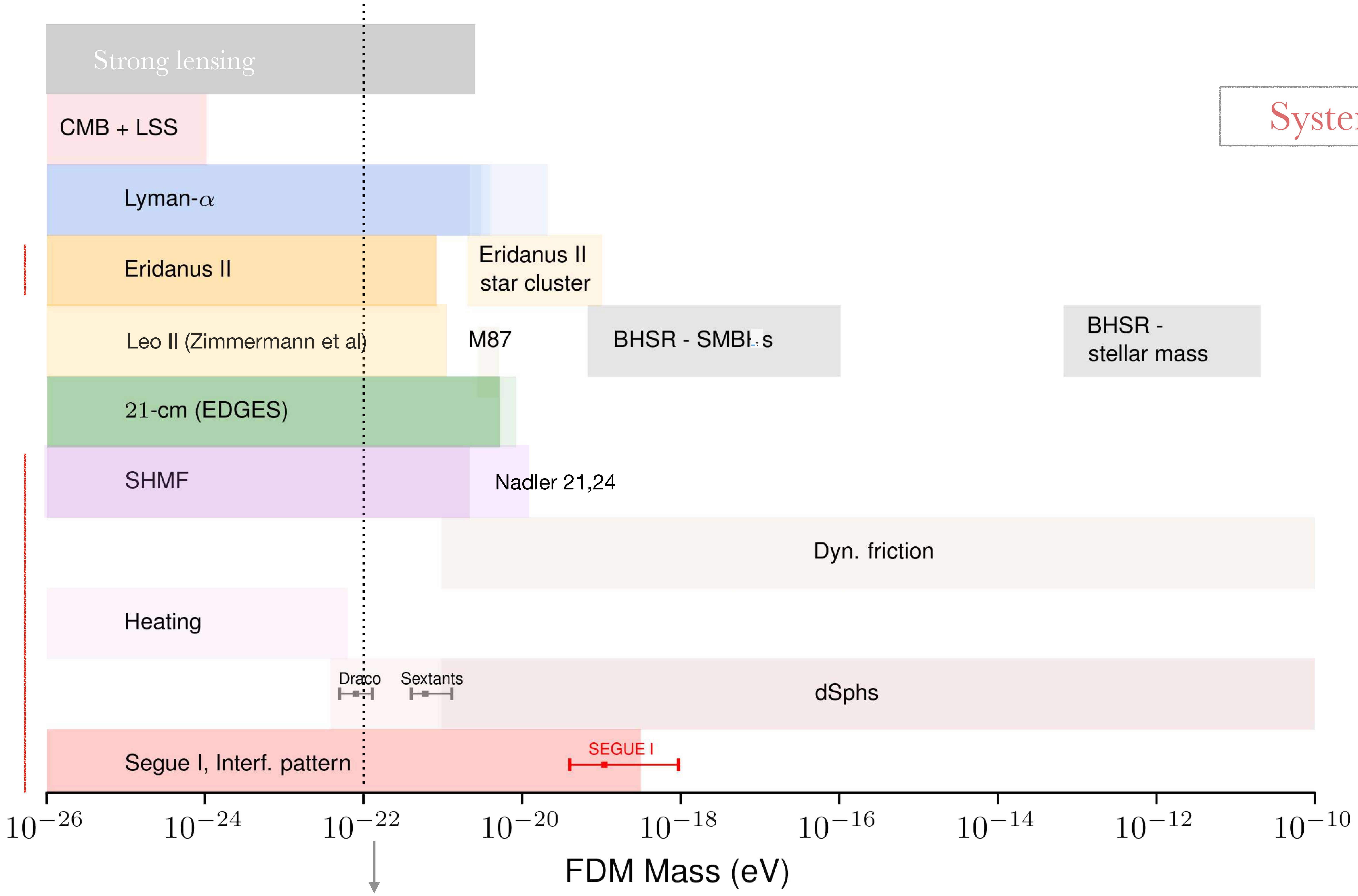
$$\rho(r) = \begin{cases} \rho_{\rm soliton} \simeq \dfrac{\rho_c}{\left[1 + 0.091(r/r_c)^2\right]^8}, & r < r_\epsilon \\ \rho_{\rm NFW} = \dfrac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, & r > r_\epsilon \end{cases}$$



Current status

Fuzzy Dark Matter - bounds on the mass





Sweet spot for solving small scale problems

Systematics everywhere!

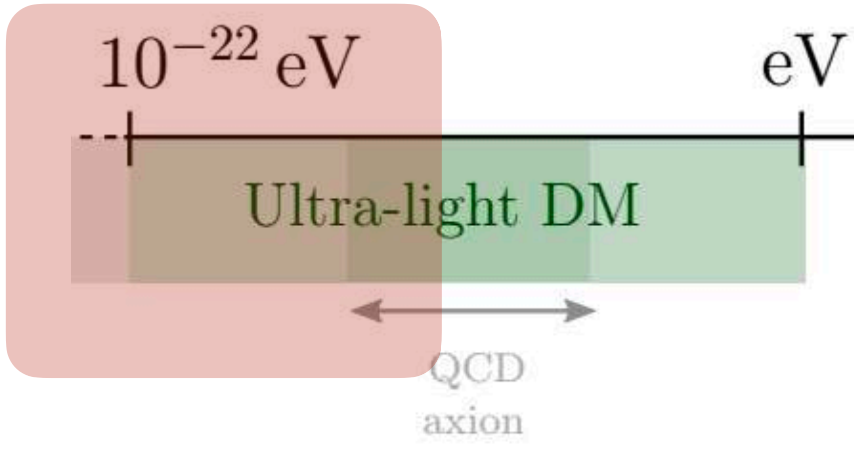
BUT: - systematic effects!!
- dynamics of FDM not fully understood.

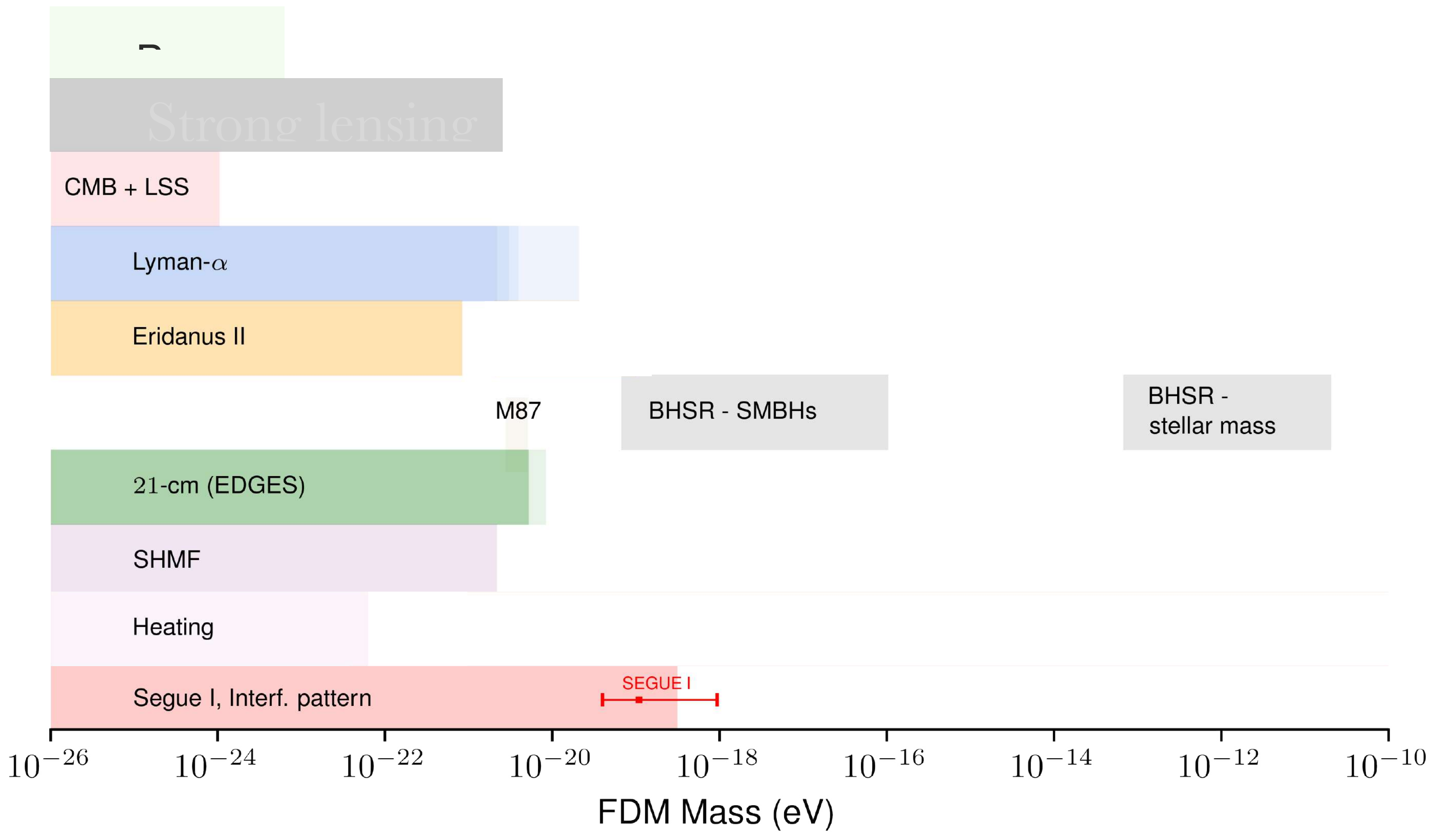
Need:
- Observations
- Improve sims
- New observables
- New probes

It is not because a bound is here that is correct!

Observational implications and constraints

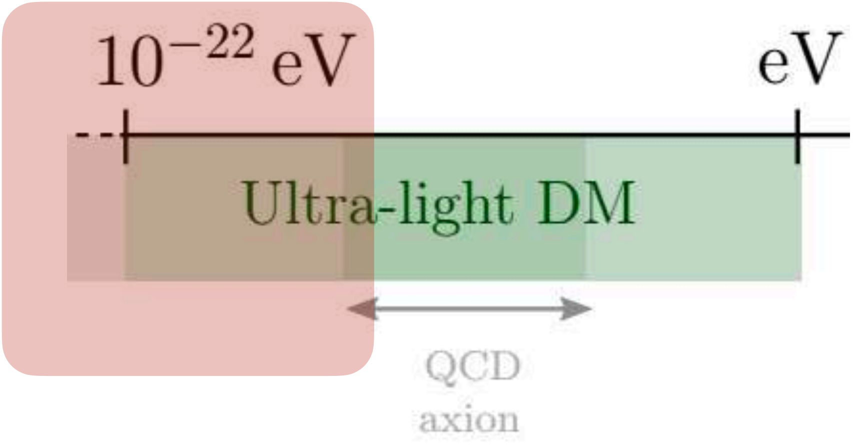
Interference patterns





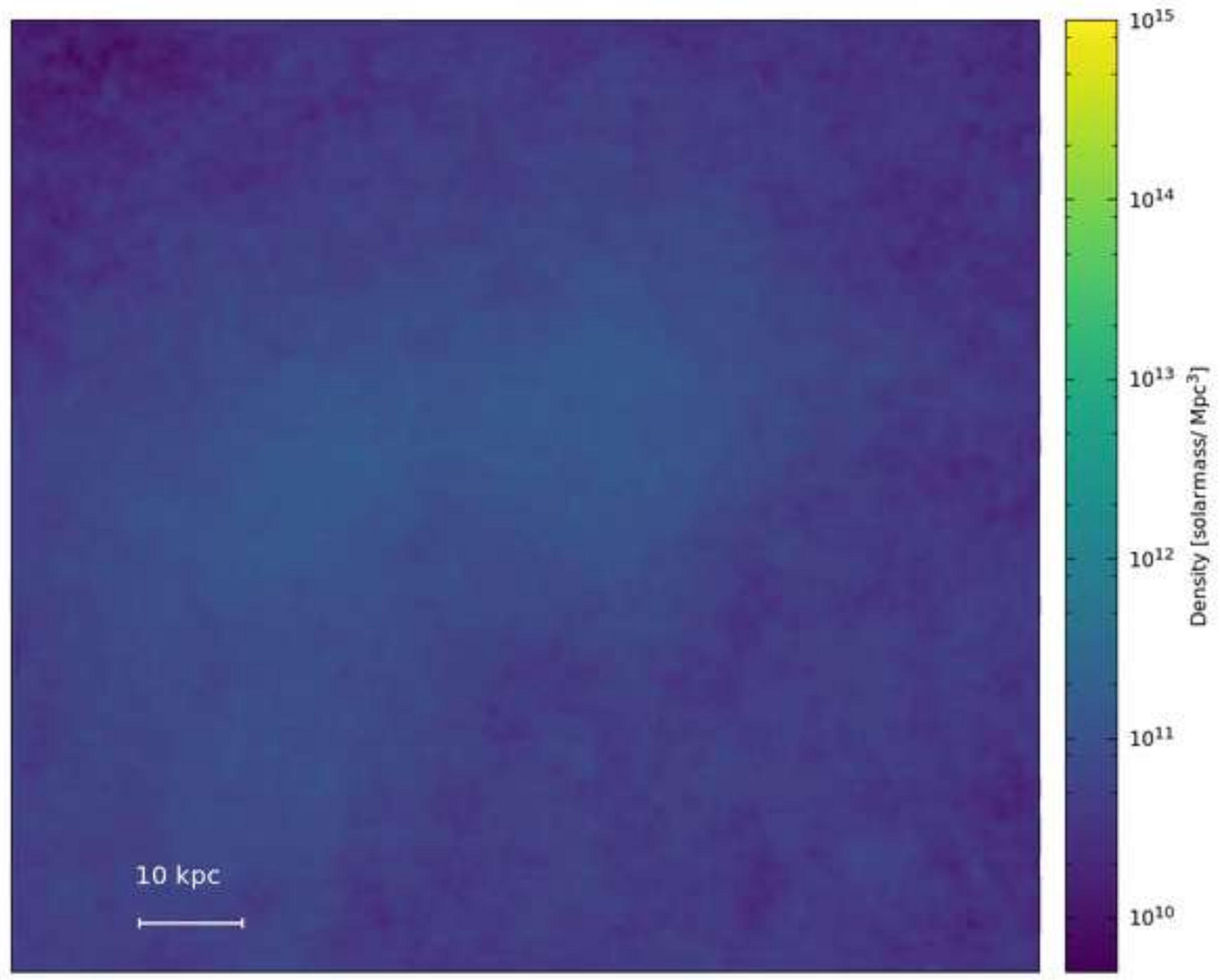
FDM constraints 2.0

Interference pattern



PROBES:

- Strong lensing
- Stellar streams
- Heating
- Dynamical friction



Simulation by Jowett Chan

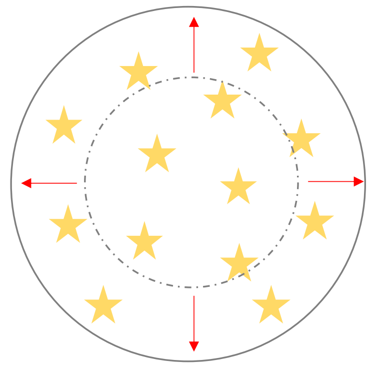
$\mathcal{O}(1)$ fluctuations in density $\longrightarrow\ \sim \lambda_{\rm dB}$

Heating

FDM granule

$m_{\rm eff}$

System (star) gains energy



Friction

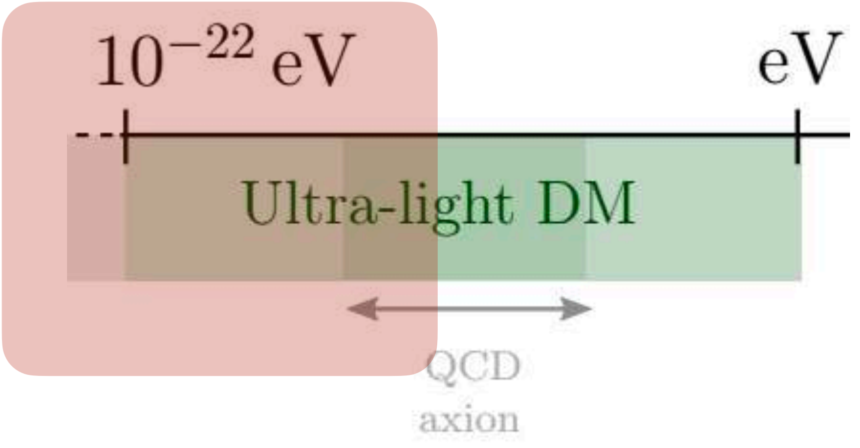
FDM granule

$m_{\rm eff}$

Globular cluster

System (GC or BH) loses energy

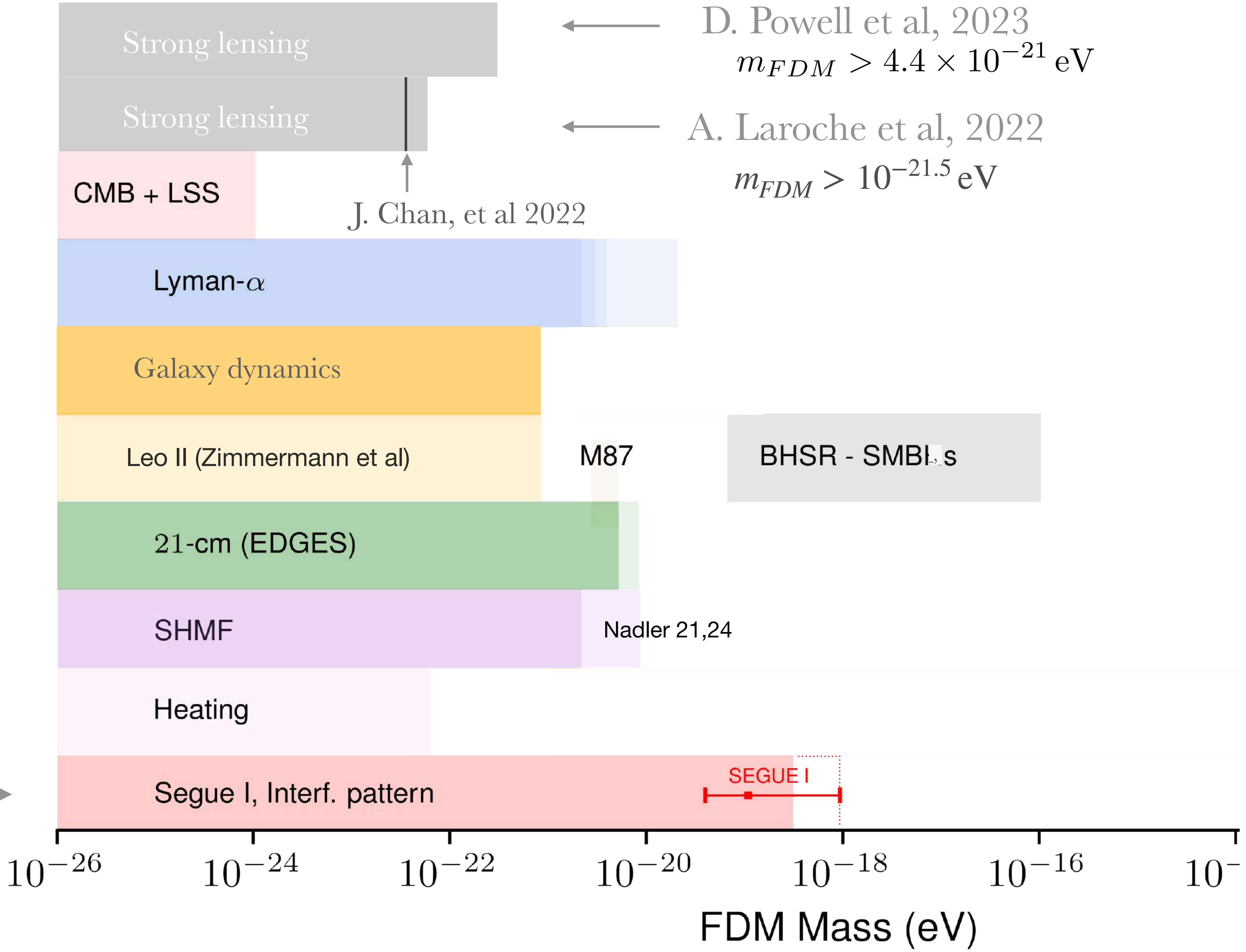
Interference patterns - granules



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

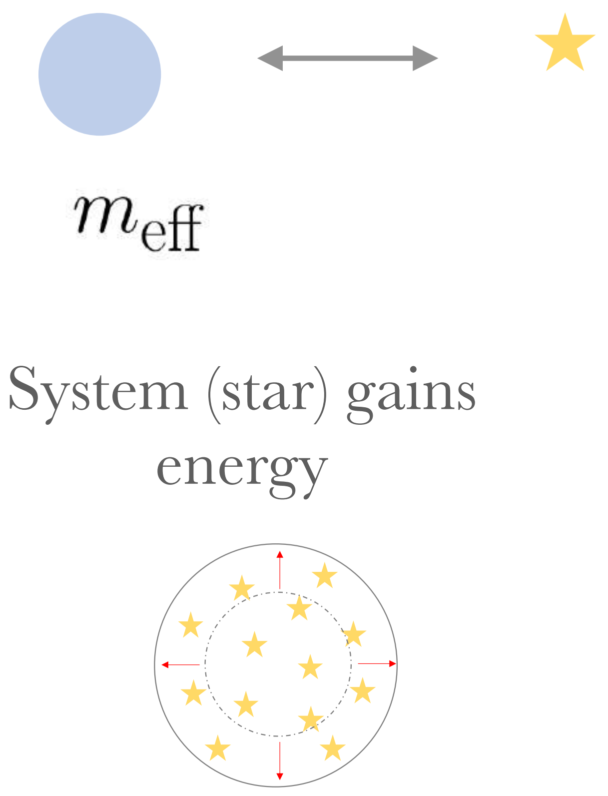


Stellar heating

Dalal et al, 2022
$m_{FDM} > 3 \times 10^{-19}$ eV

Heating

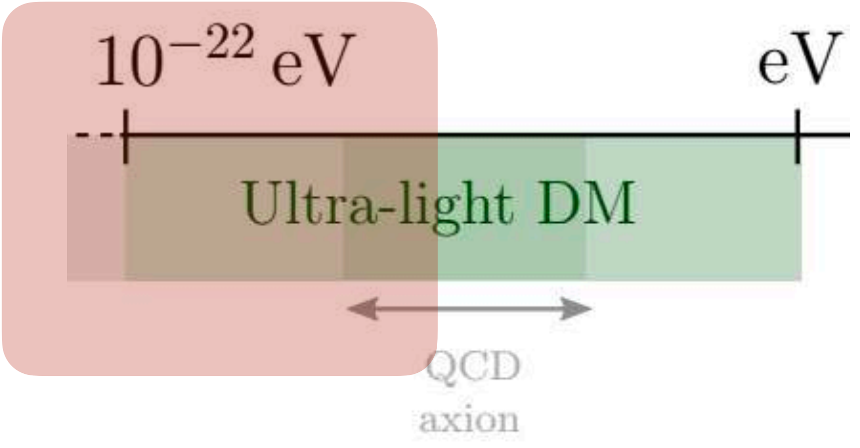
FDM granule



System (star) gains energy

See Peter Graham talk

Interference patterns - granules



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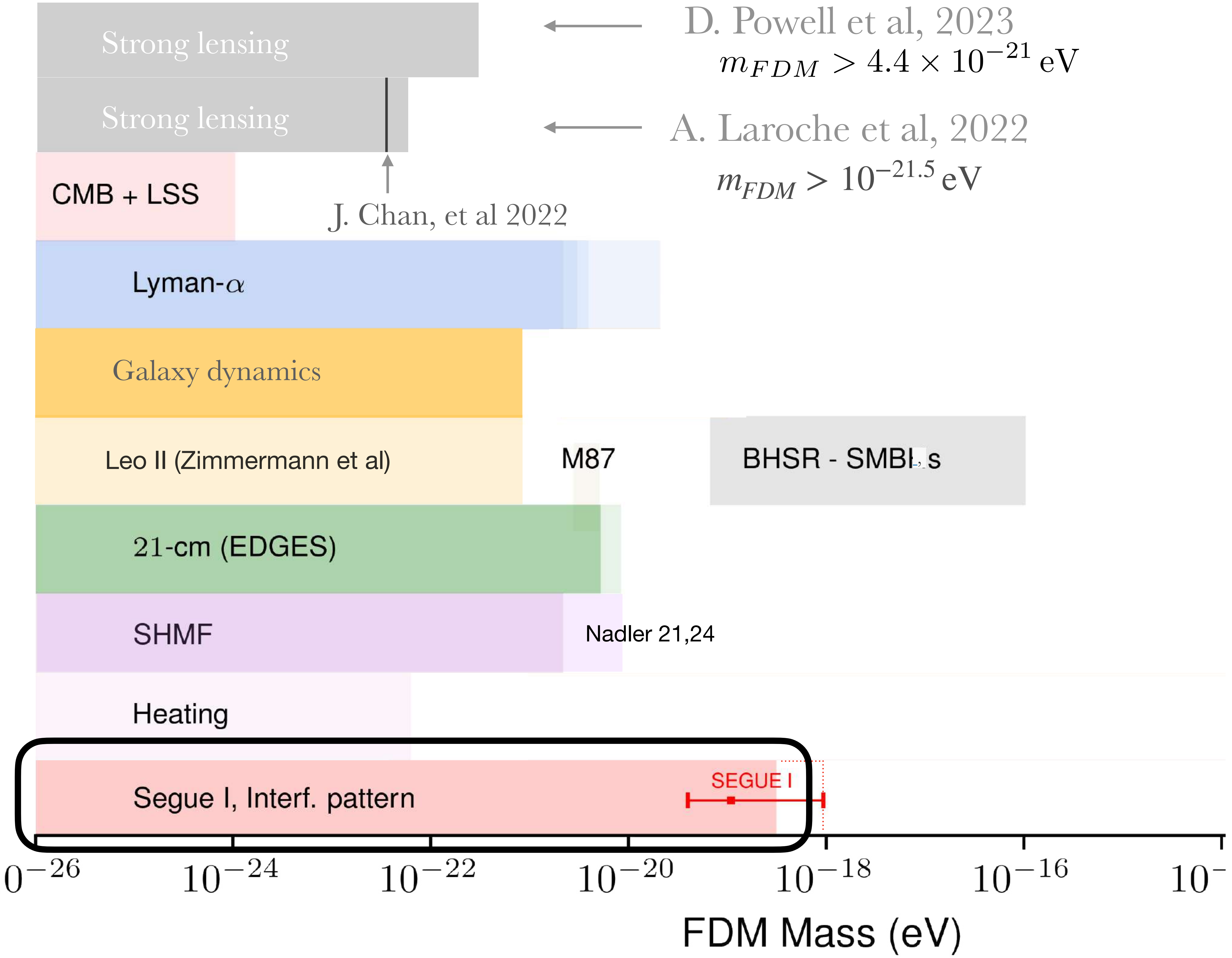

Stellar heating

Dalal et al, 2022
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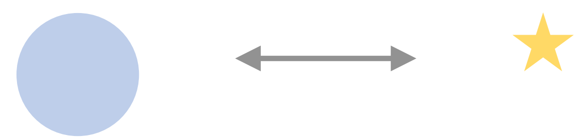
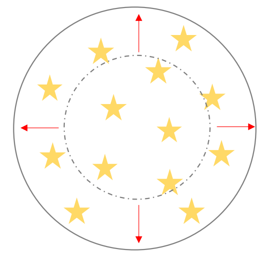
Heating

FDM granule



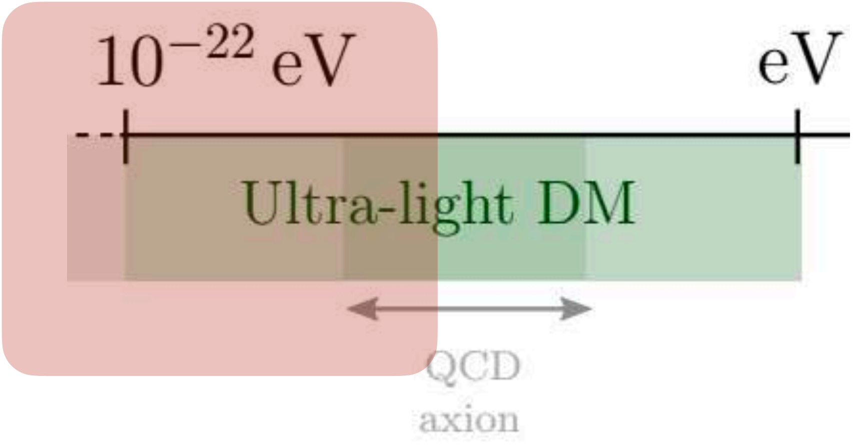
$m_{\rm eff}$

System (star) gains energy



See Peter Graham talk

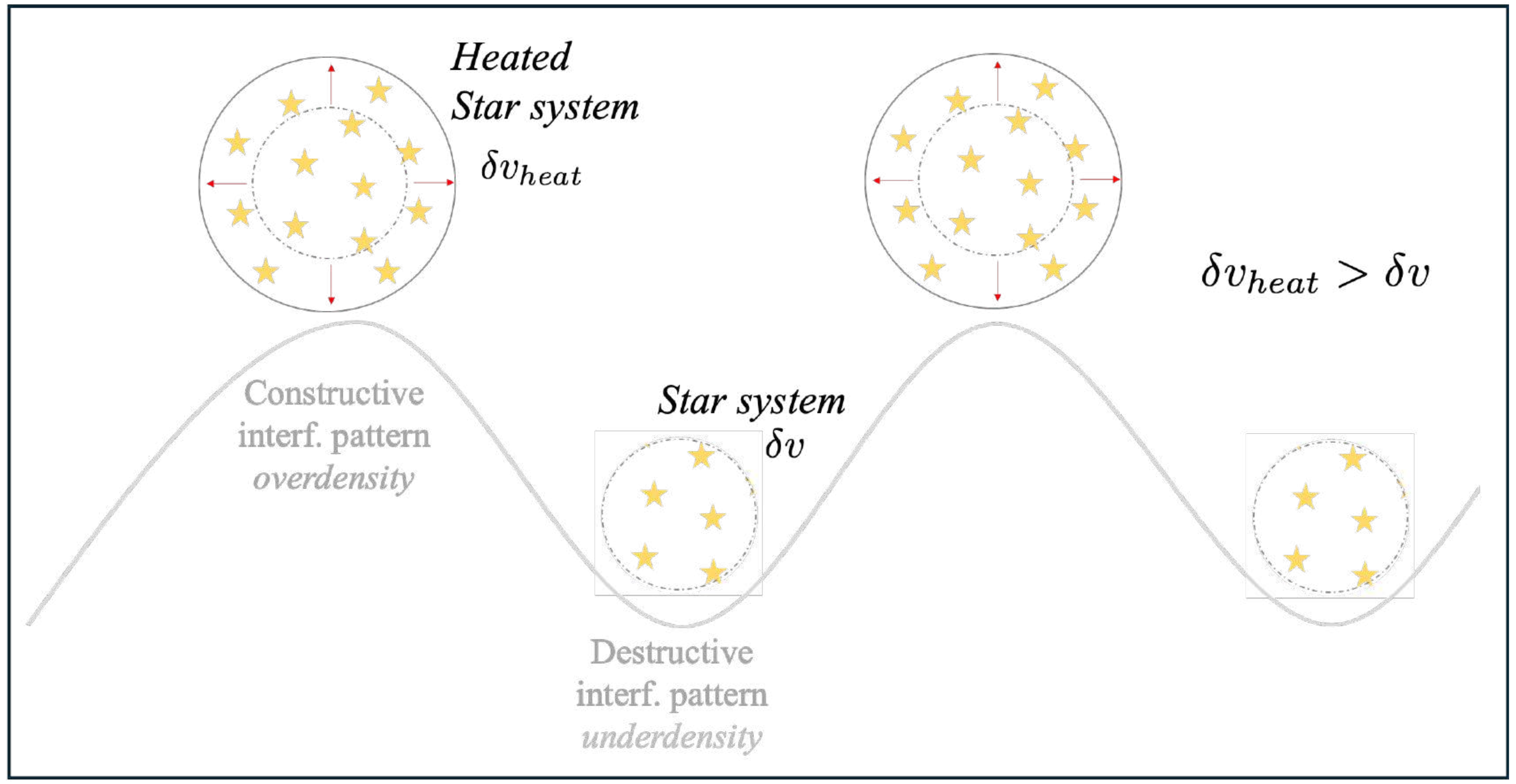
Stellar heating - ultra-faint dwarfs



Dalal et al 2022

- Study stellar heating on UFD due to the presence of granules
- Track the half-light radius and stellar dispersion
- Compared with observations of Segue I and II

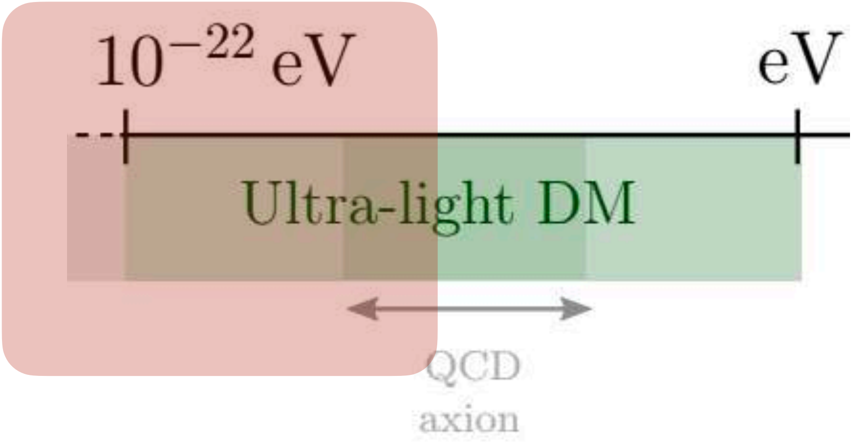
$$m > 3 \times 10^{-19}\,\mathrm{eV}$$



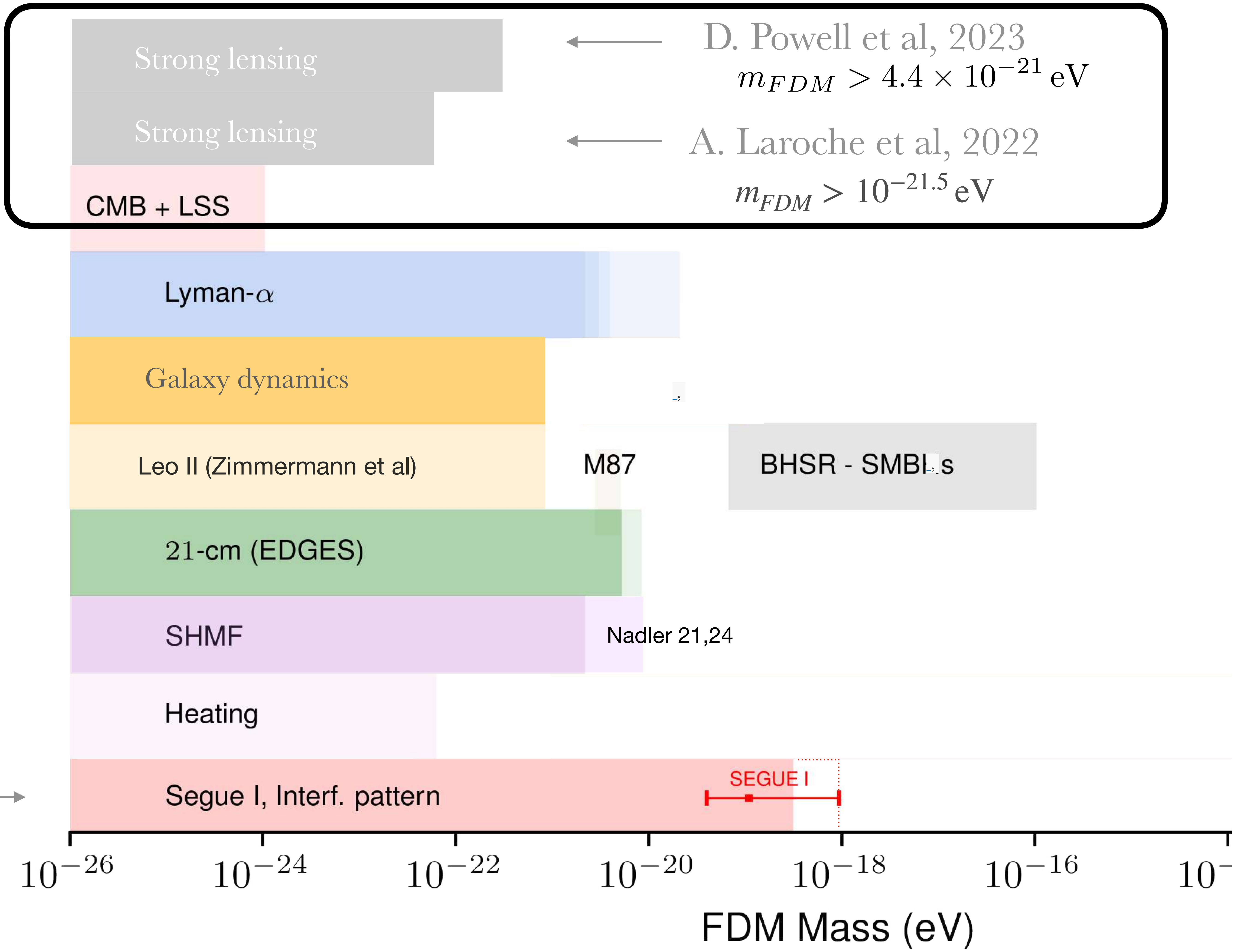
Details:

- Soliton excluded (authors claim conservative bounds)
- Tidally stripped halo? Alters the granules

Interference patterns - granules



Strong lensing

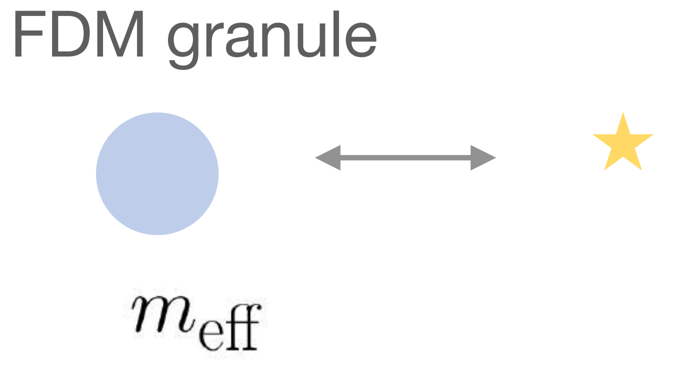


Stellar heating

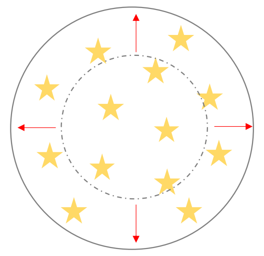
Dalal et al, 2022

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

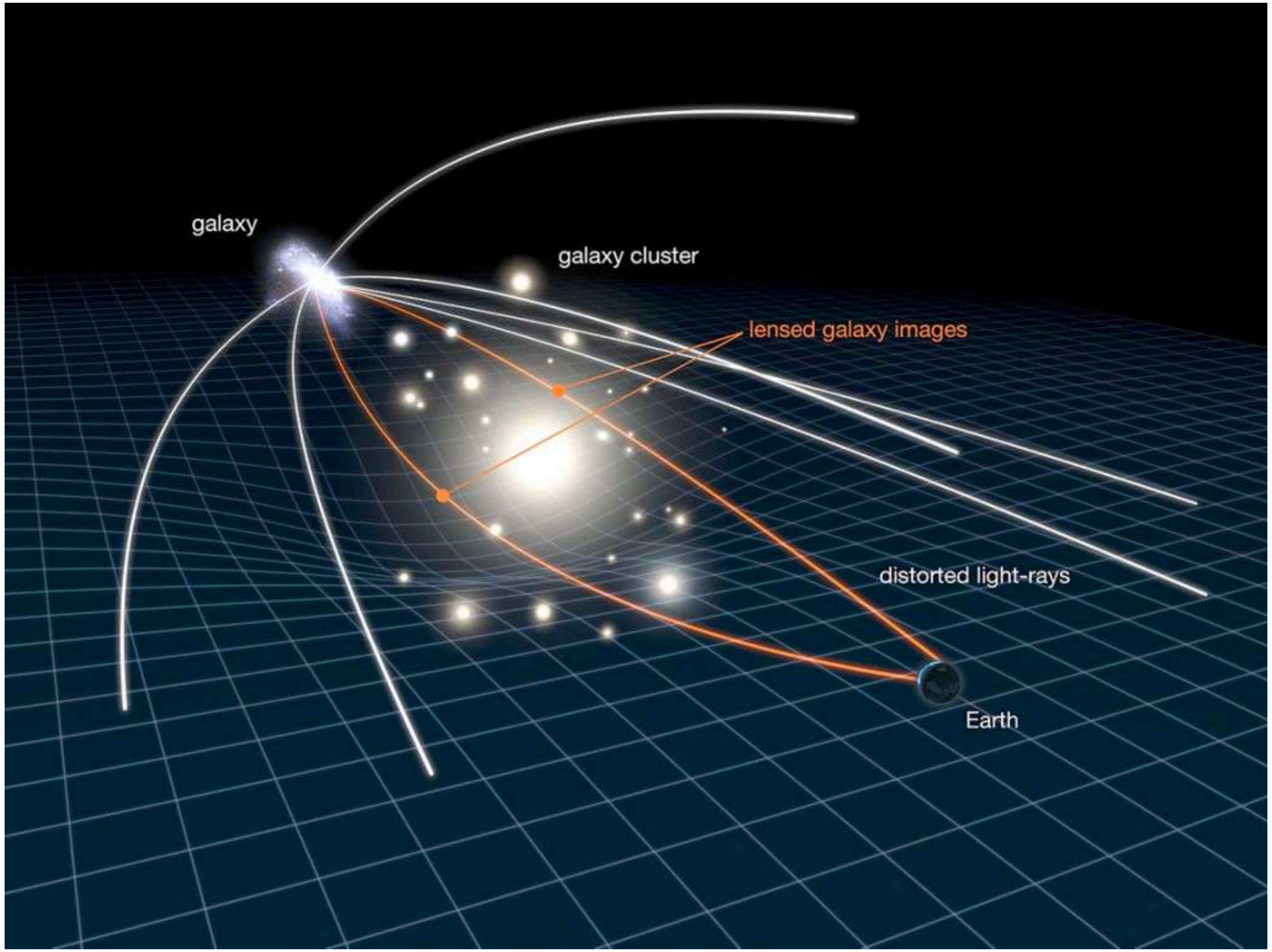
Heating



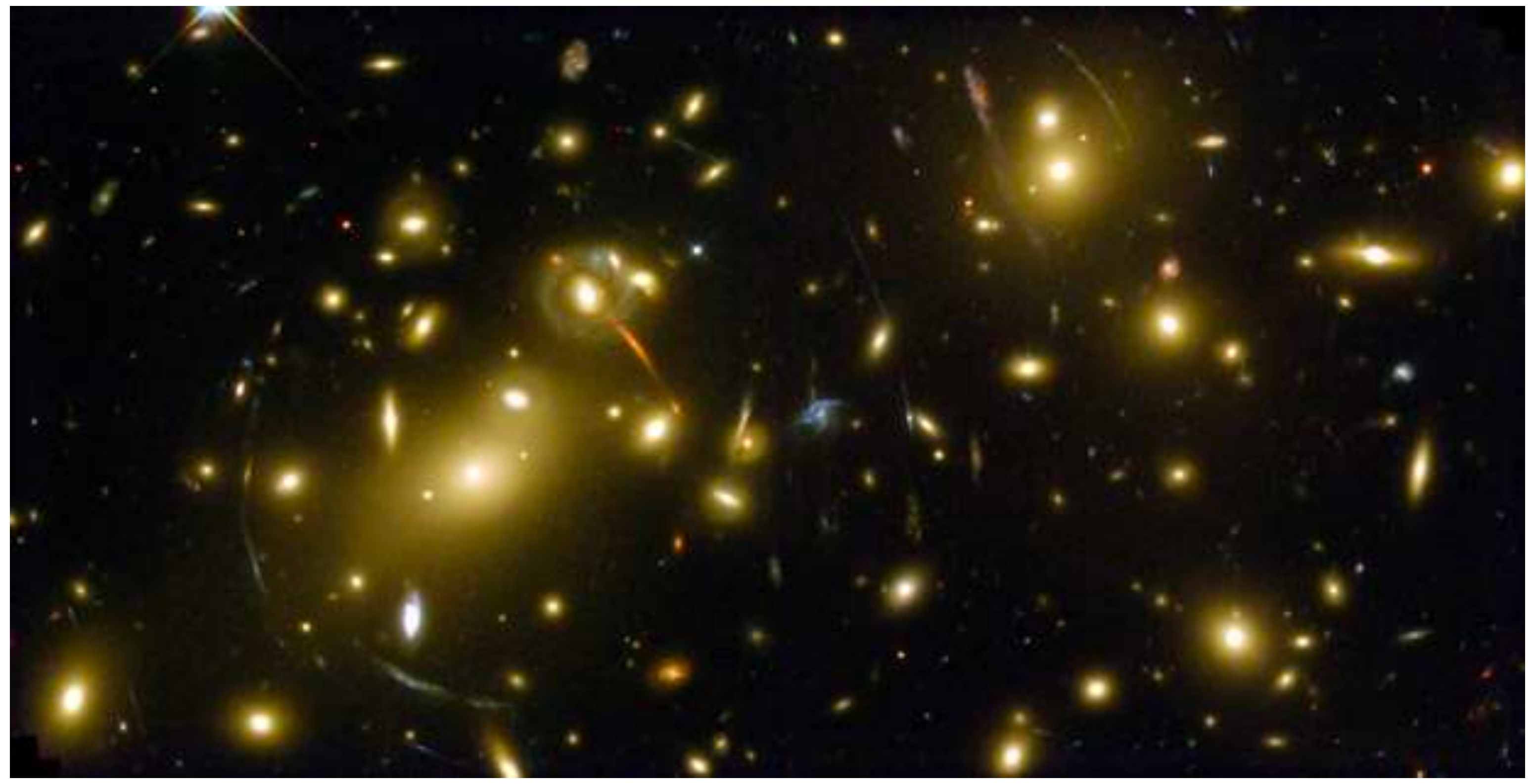
System (star) gains energy



Gravitational lensing



mage: NASA/ESA



NASA and ESA

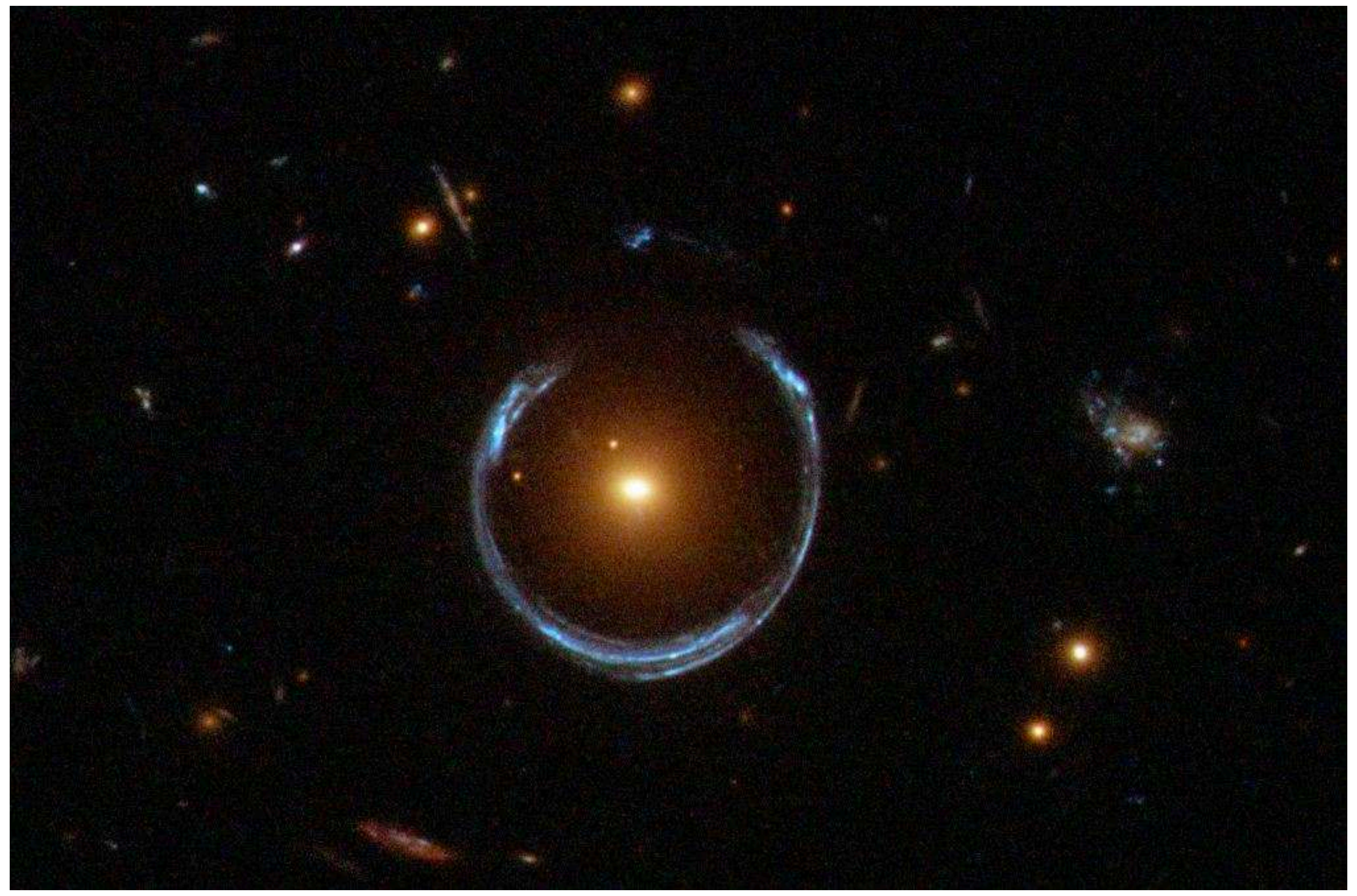
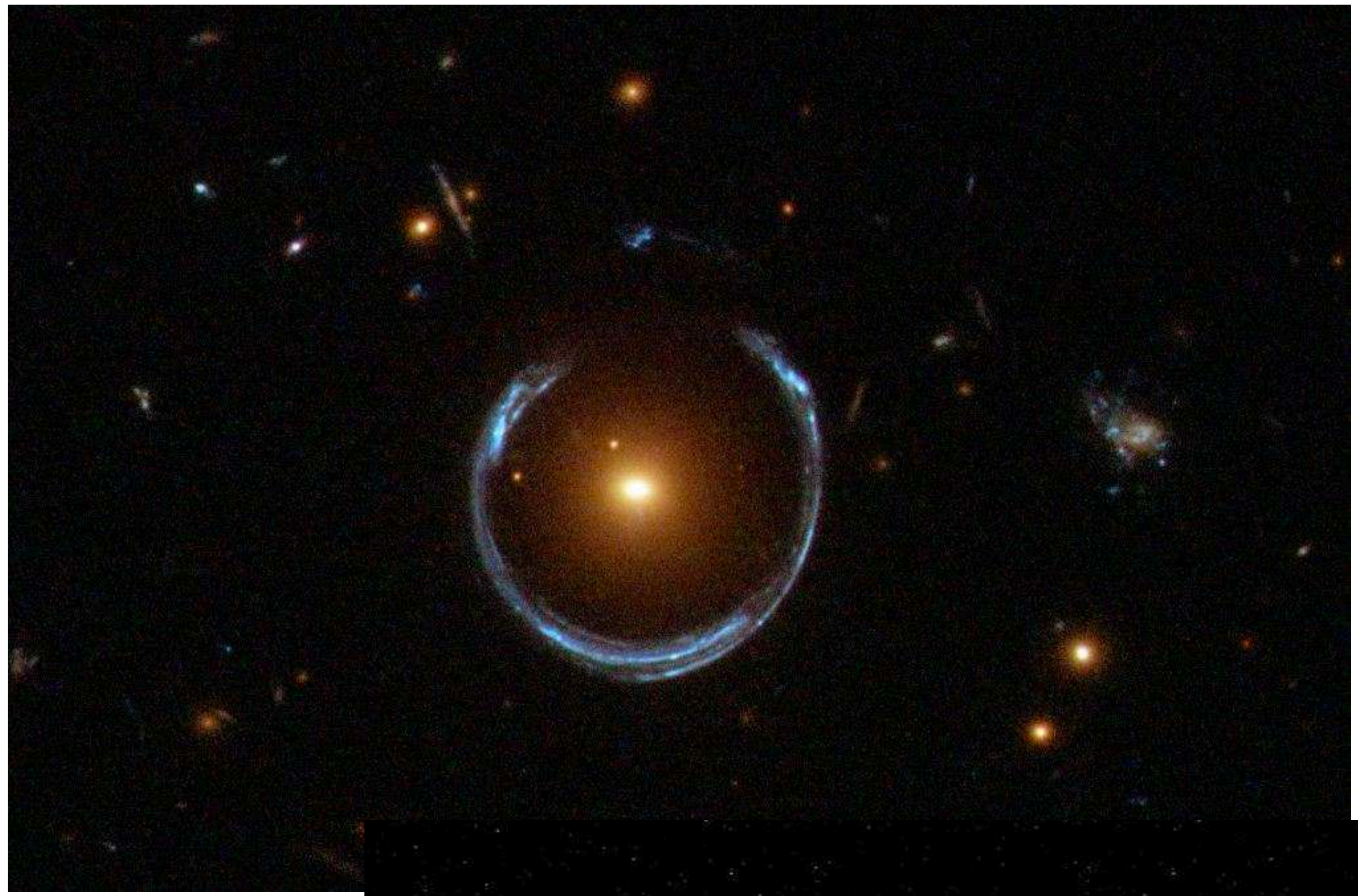
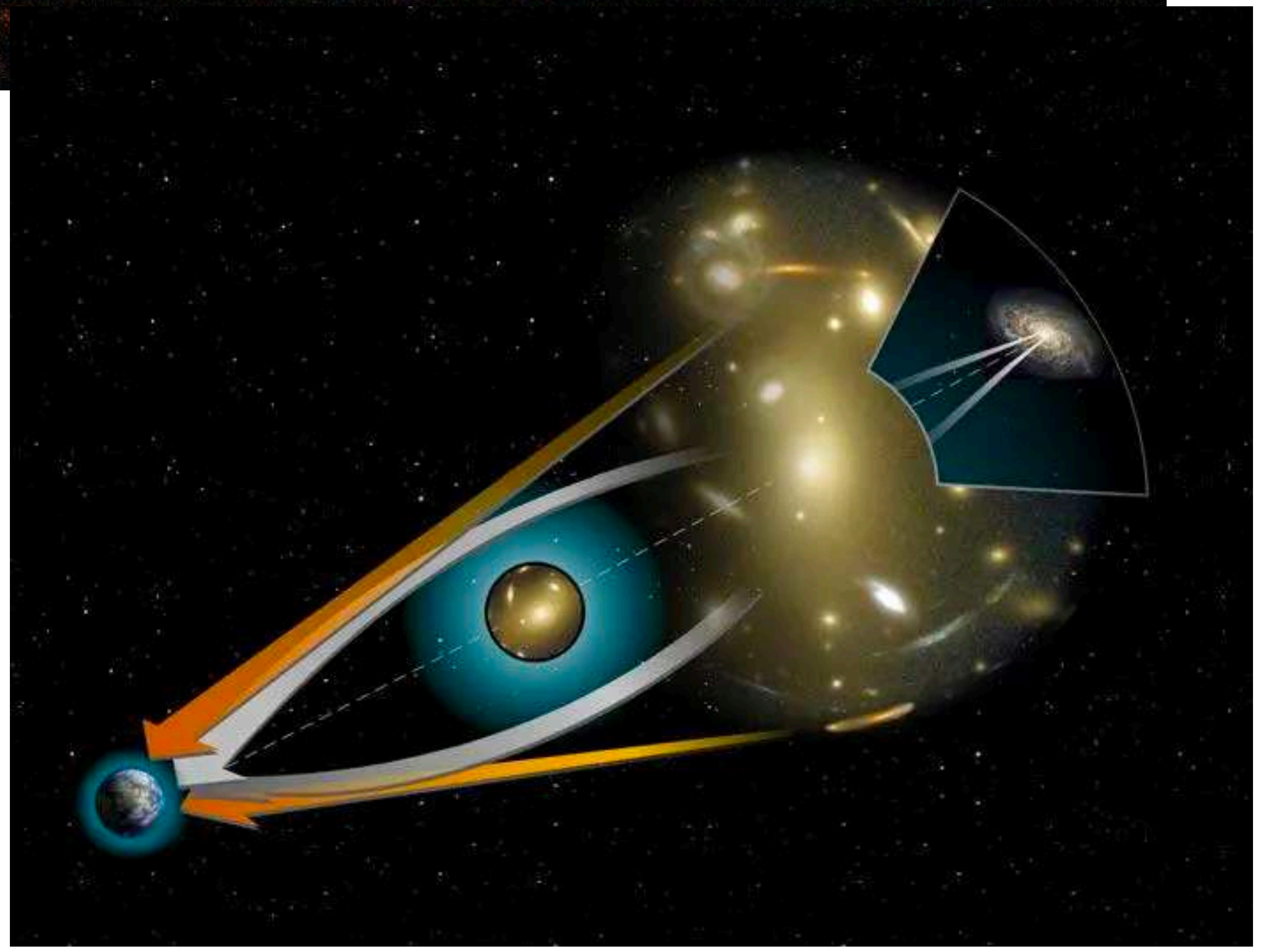


Image: © ESA/Hubble/NASA)

Strong lensing

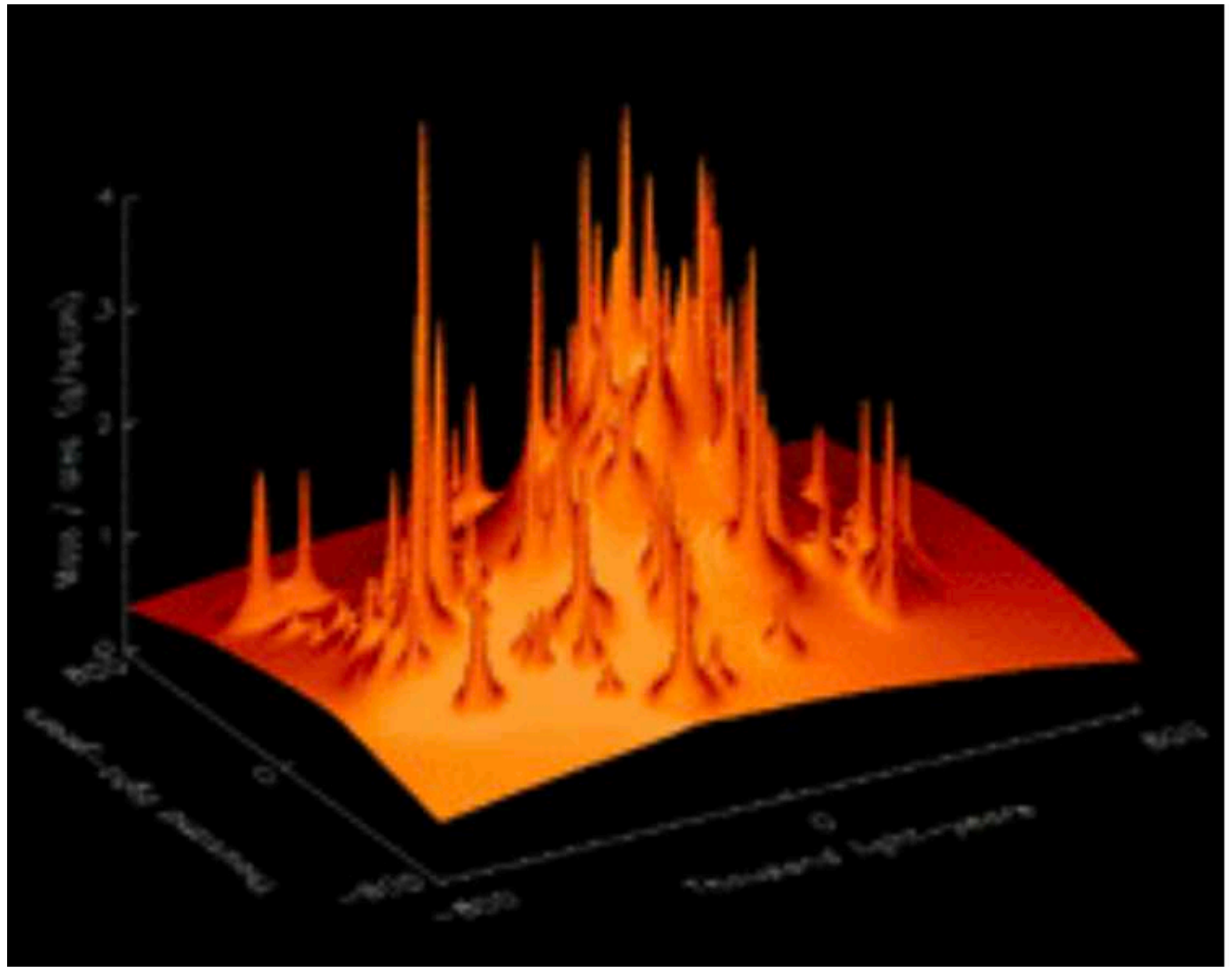
Image: © ESA/Hubble/NASA)





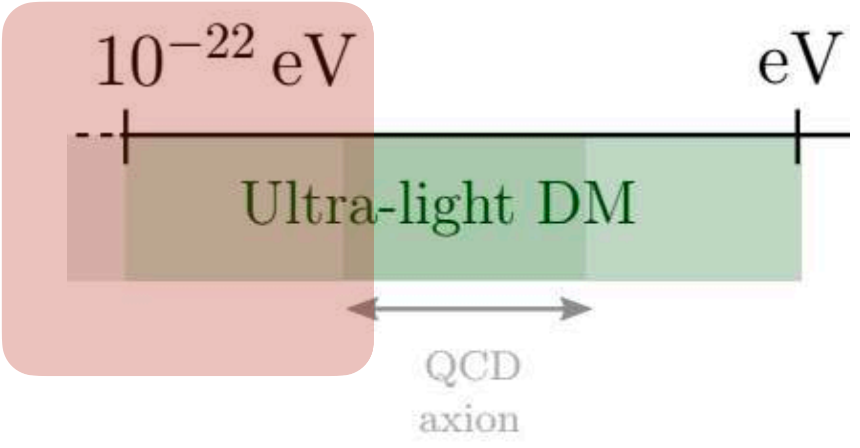
NASA / STSCI

Tyson, Kochanski & Dell'Antonio



- Reconstruct the gravitational potential (total enclosed mass) of the lens
- Total mass on small scales

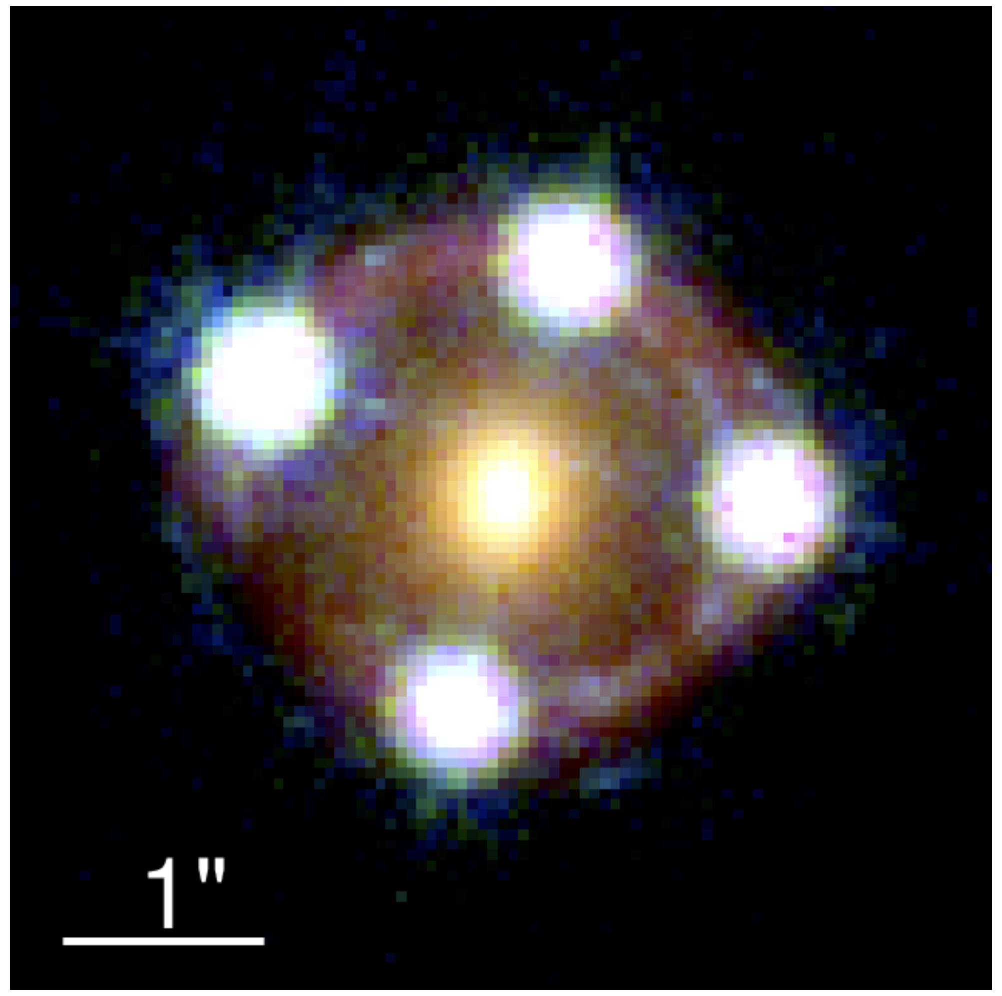
Strong lensing



Strong lensing: sensitive to the mass distribution of the total matter in the lens system

<u>Flux anomaly</u>

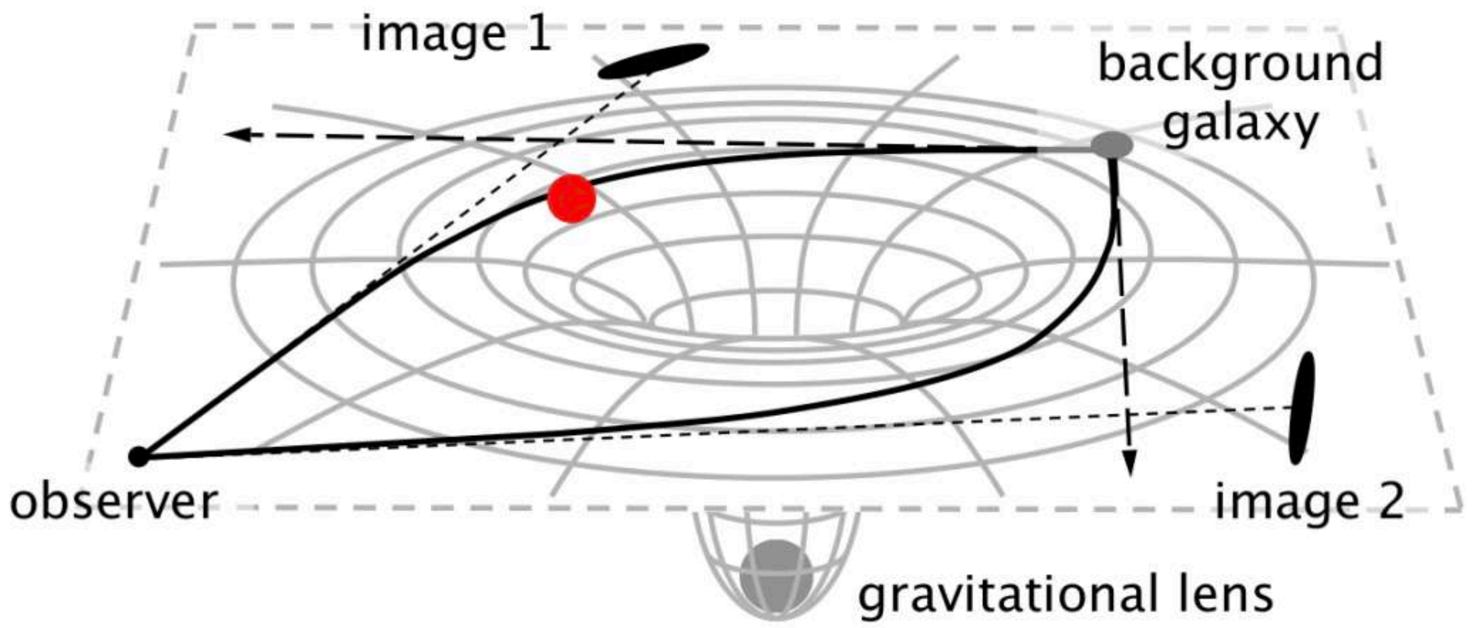
Unresolved strong lensed system

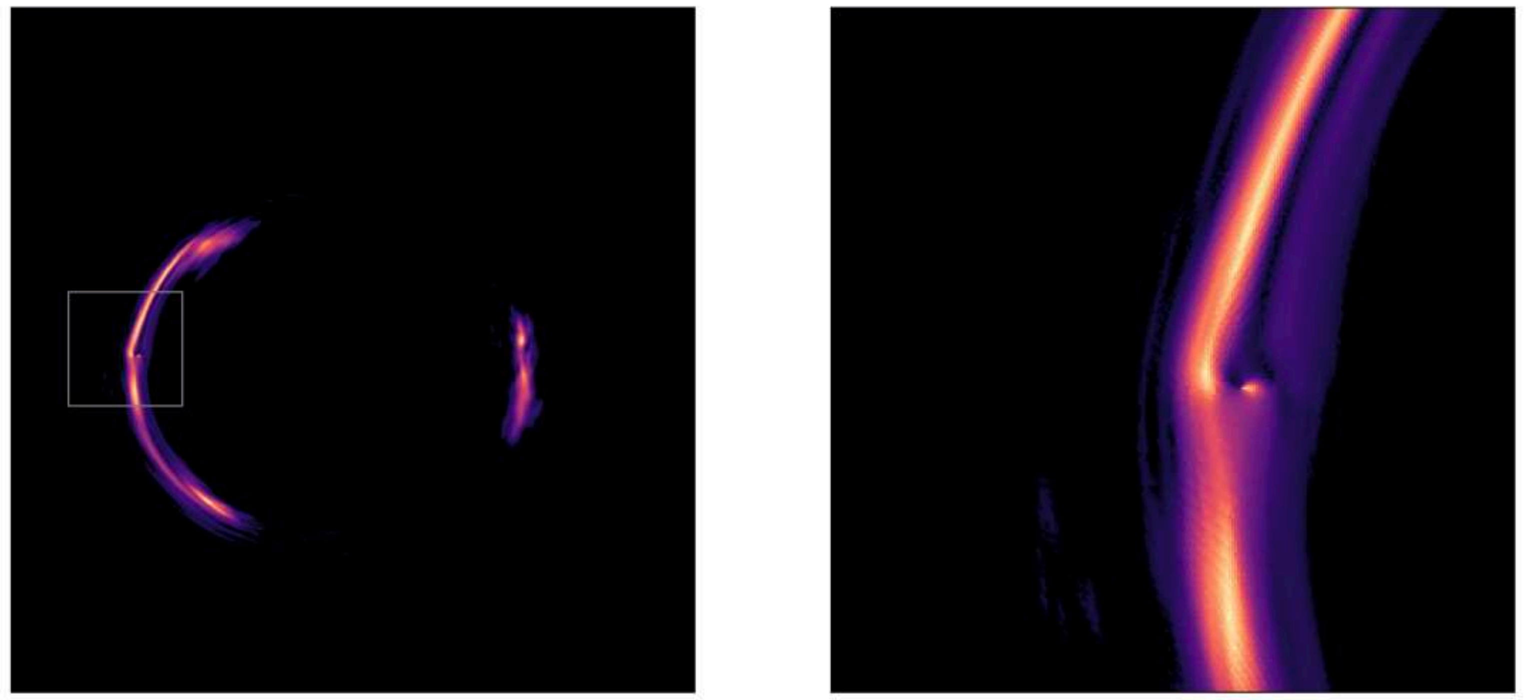


Any asymmetry in the structure in the lens, can break the symmetry that yielded the flux ratio predictions

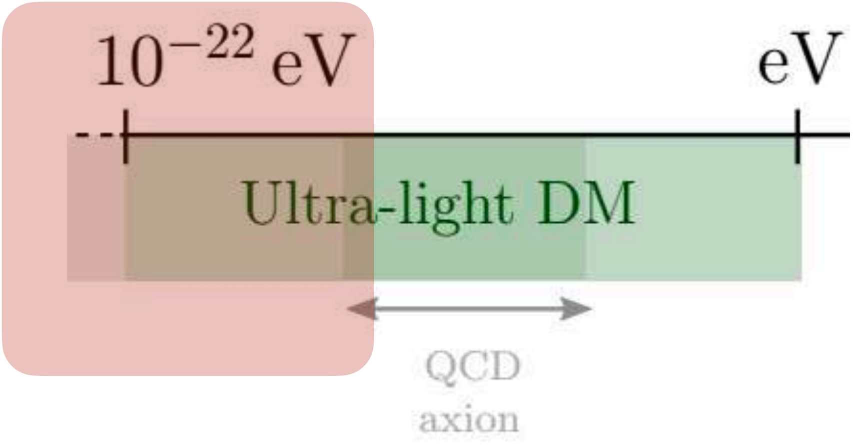
<u>Resolved imaging</u>

Resolved strong lensing from galaxy surface brightness

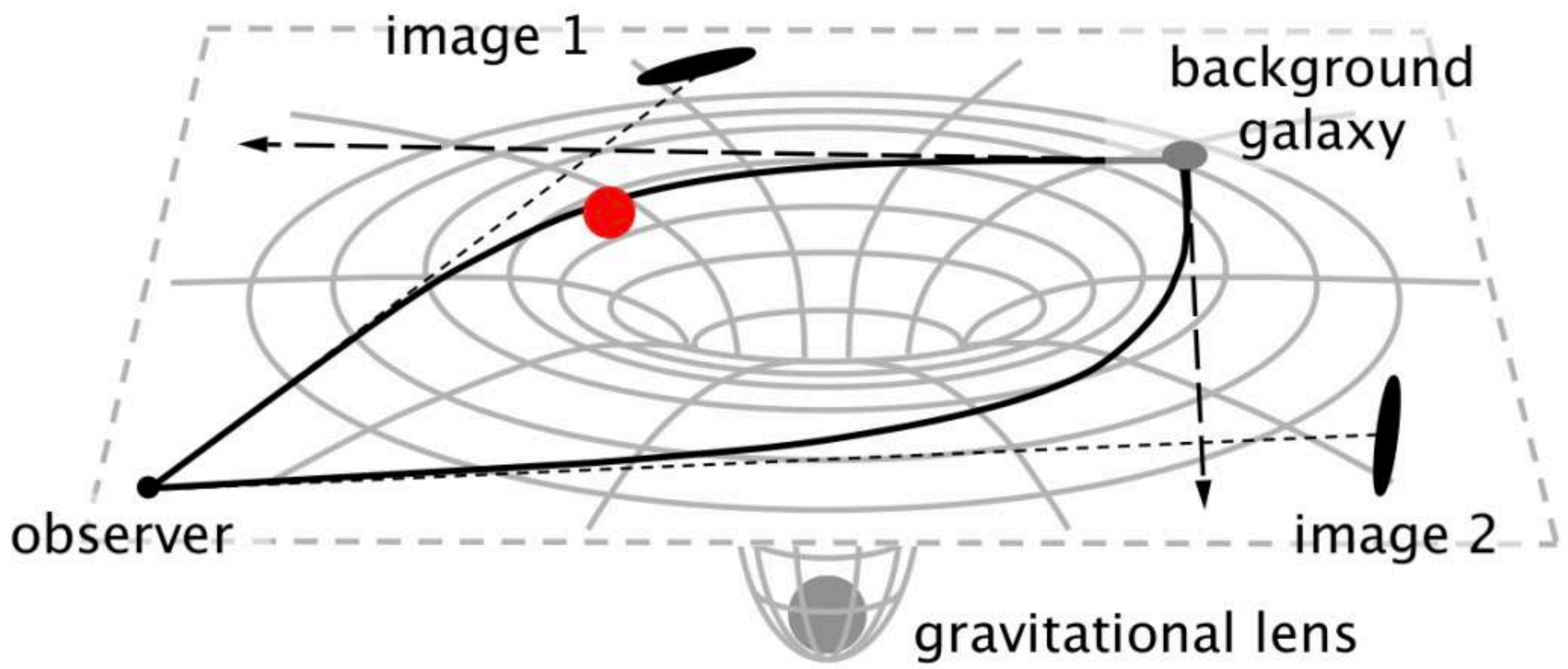


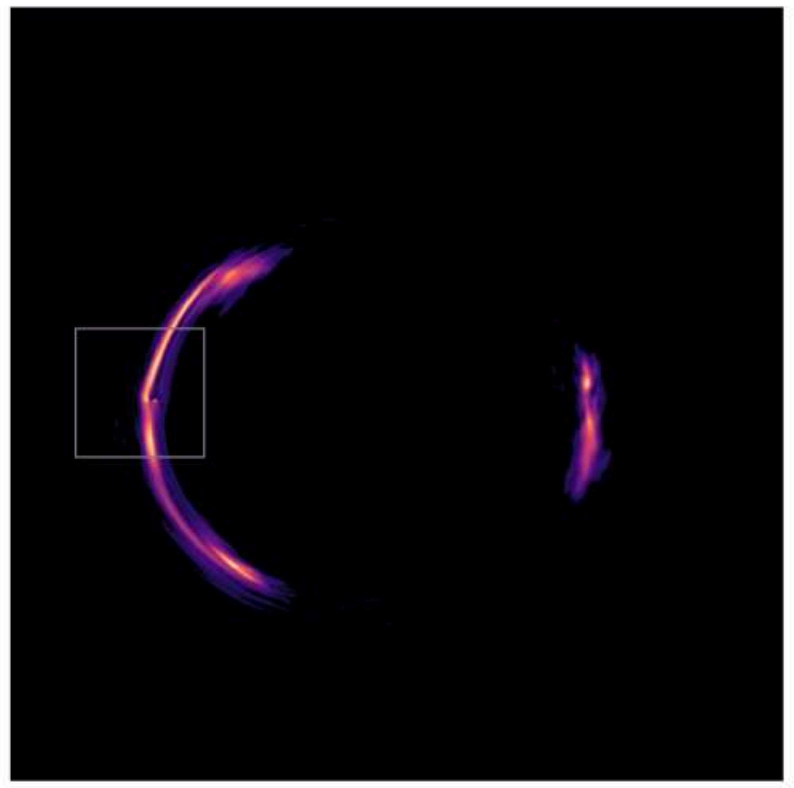


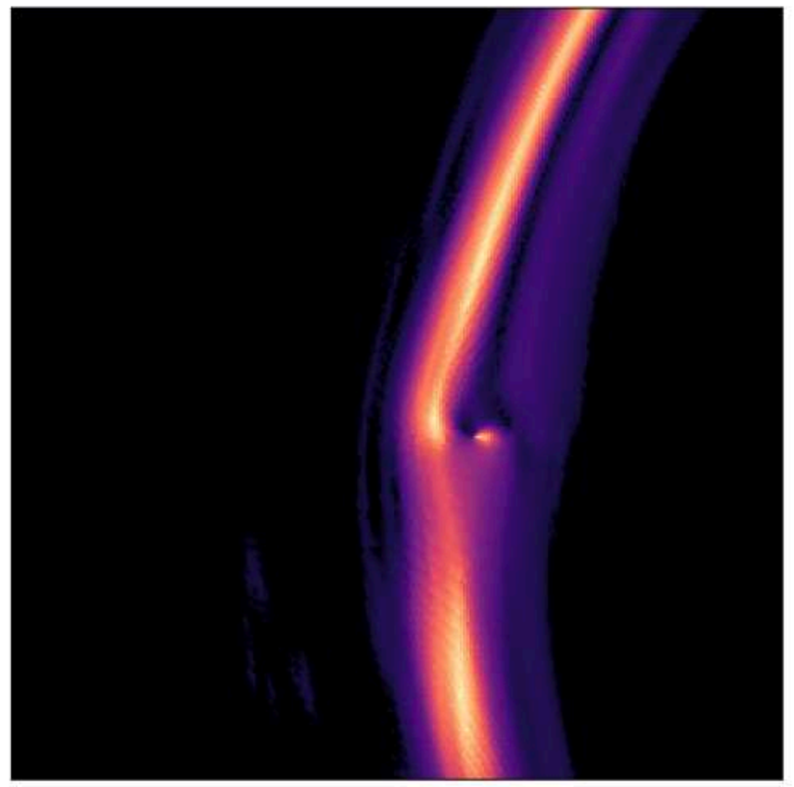
Strong lensing



Low mass perturber with lensing

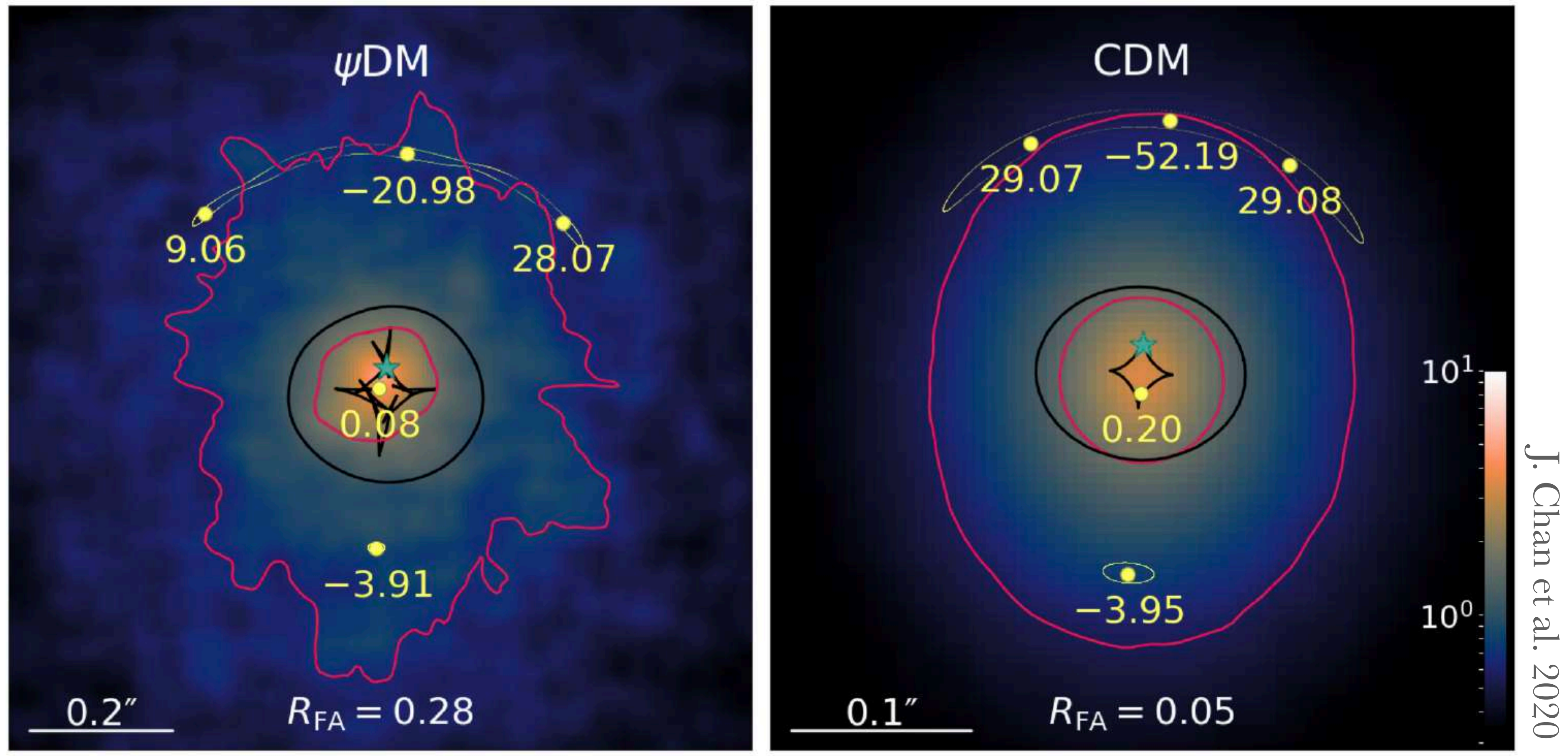






Presence of granules

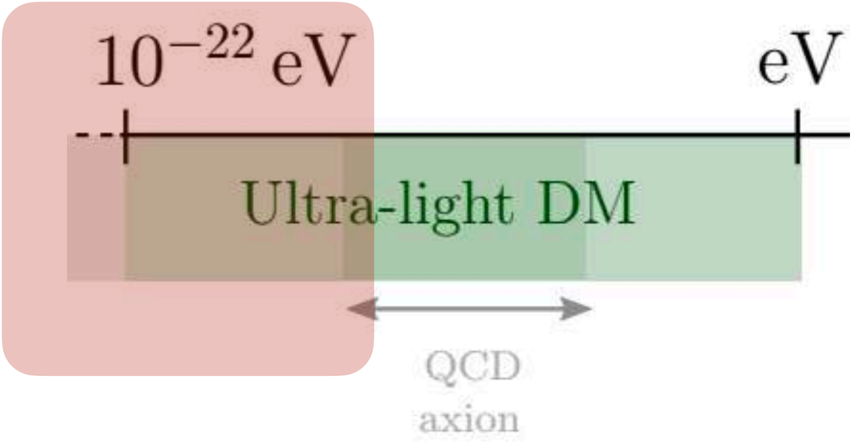
Surface densities overlaid with sources and quad images for fuzzy and smooth lenses



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

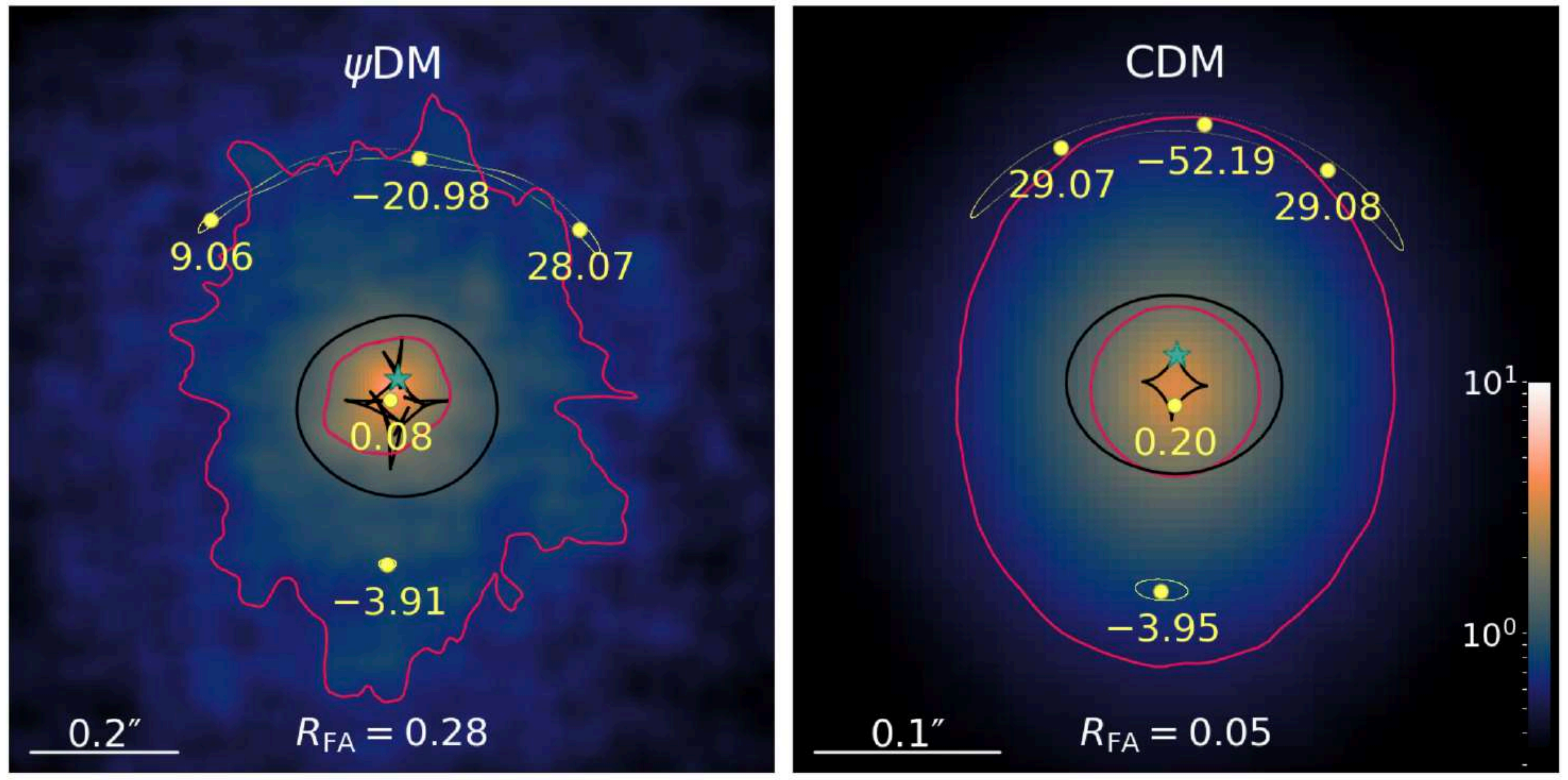
Previous works:
J. Chan, H.Schive, S.g Wong, T. Chiueh, T. Broadhurst, 2020
A. Laroche, Daniel Gilman, X. Li, J. Bovy, X. Du, 2022

Strong lensing



Presence of granules

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



J. Chan et al. 2020

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Laroche et al

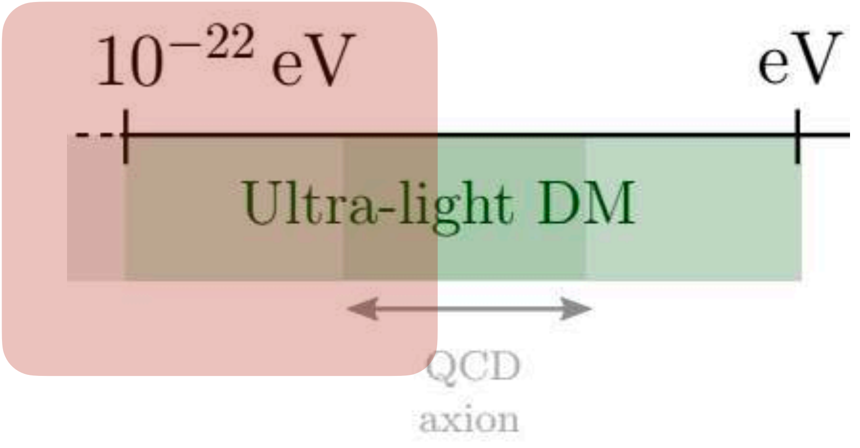
- 11 quadruply imaged quasars
- granularity arising from FDM can significantly affect flux ratios

$$m_{FDM} > 10^{-21.5}\,\text{eV}$$

Chan et al

- 11 quadruply imaged quasars
- quadruply lensed system HS 0810+2554
- successfully reproduce both the positions and fluxes of the observed images, including anomalies that CDM models fail to explain

Interference patterns - granules



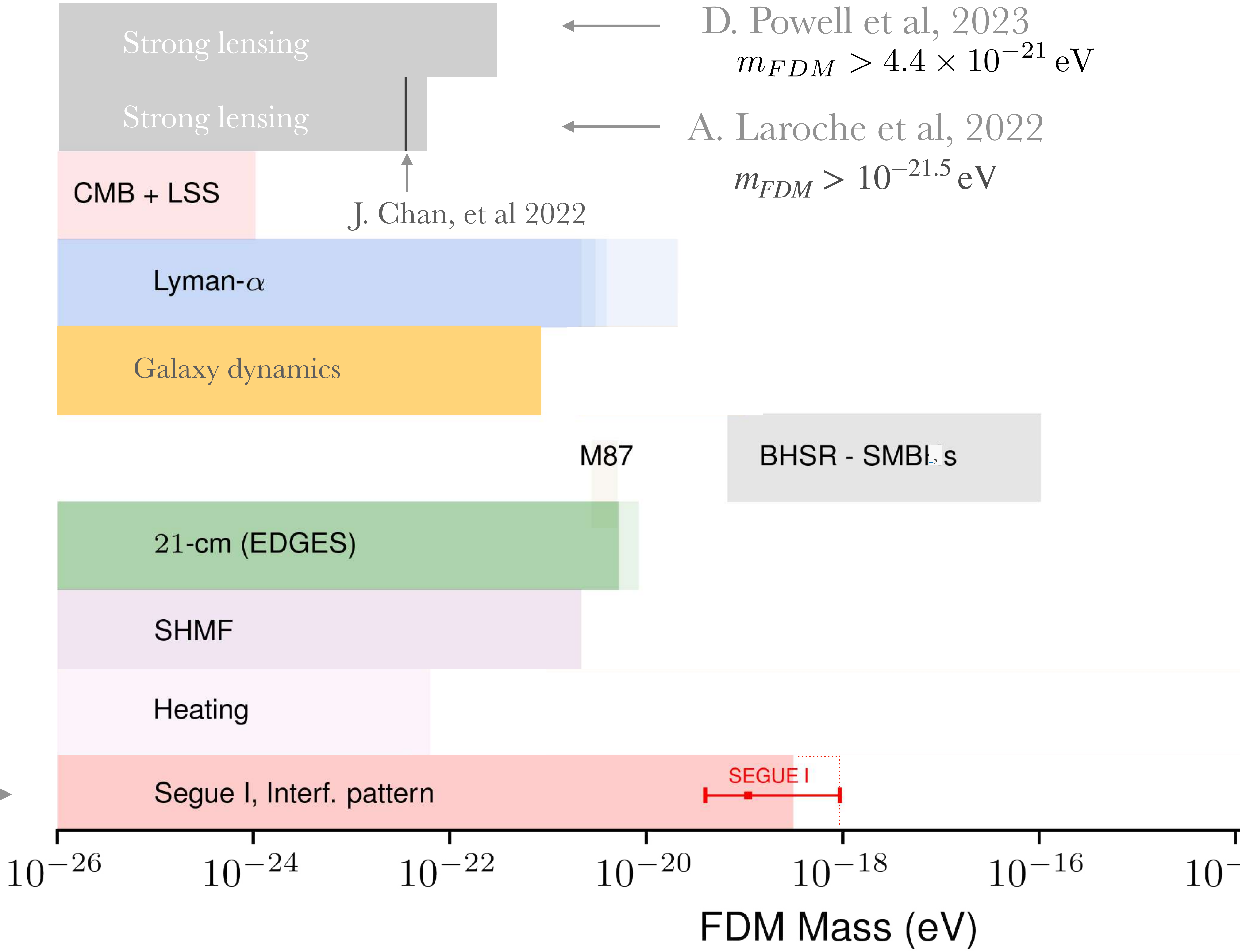
Strong lensing

D. Powell et al, 2023

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

A. Laroche et al, 2022

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



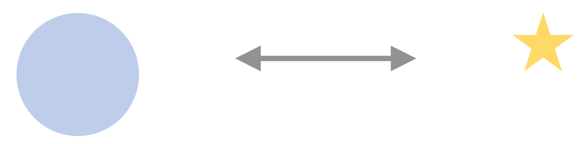
Stellar heating

Dalal et al, 2022

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

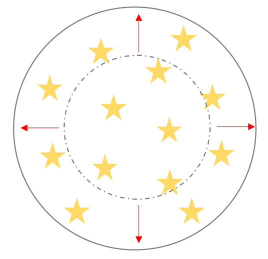
Heating

FDM granule



$m_{\rm eff}$

System (star) gains energy

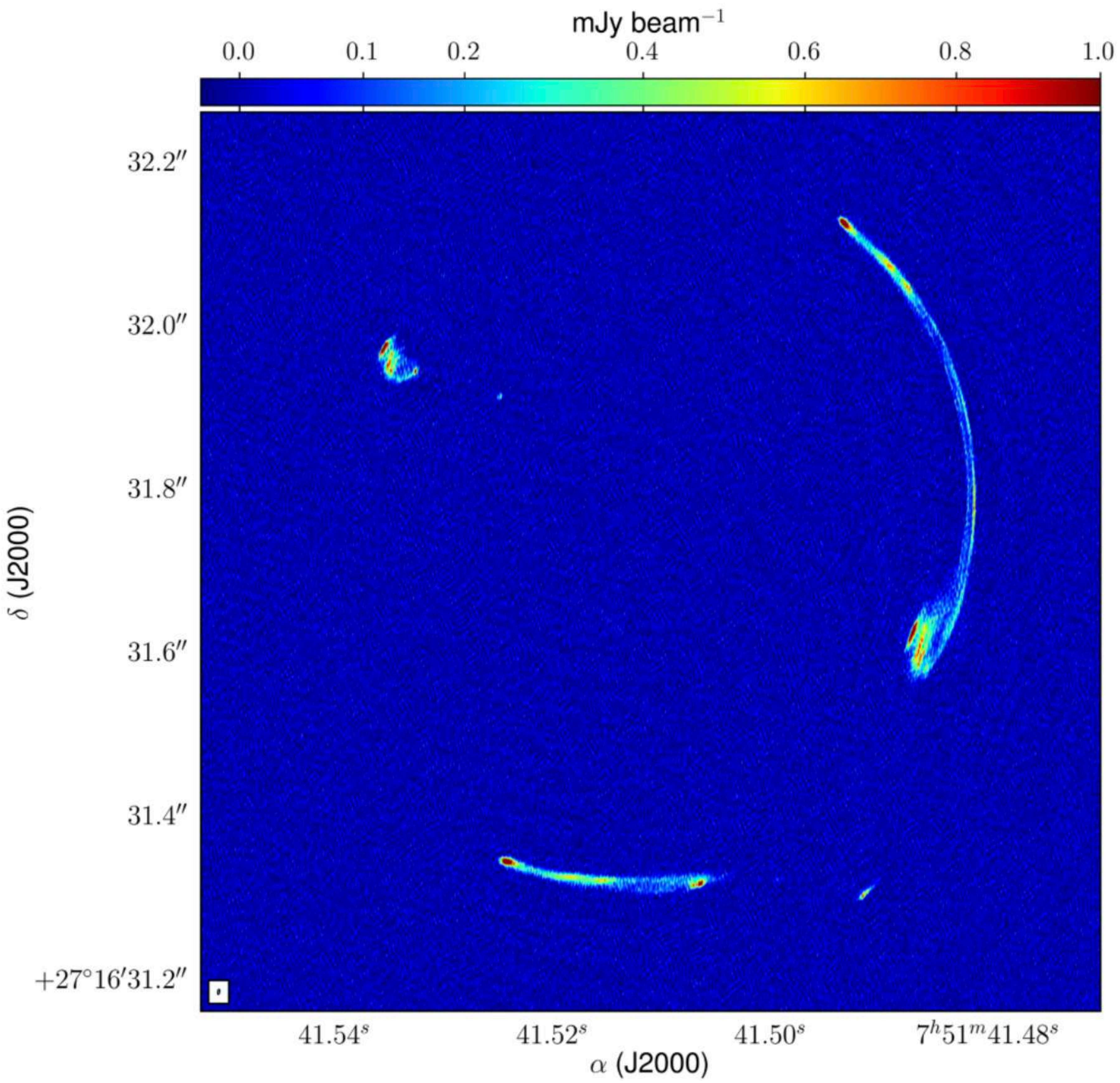


See Peter Graham talk

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



- 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

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

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

Strong lensing

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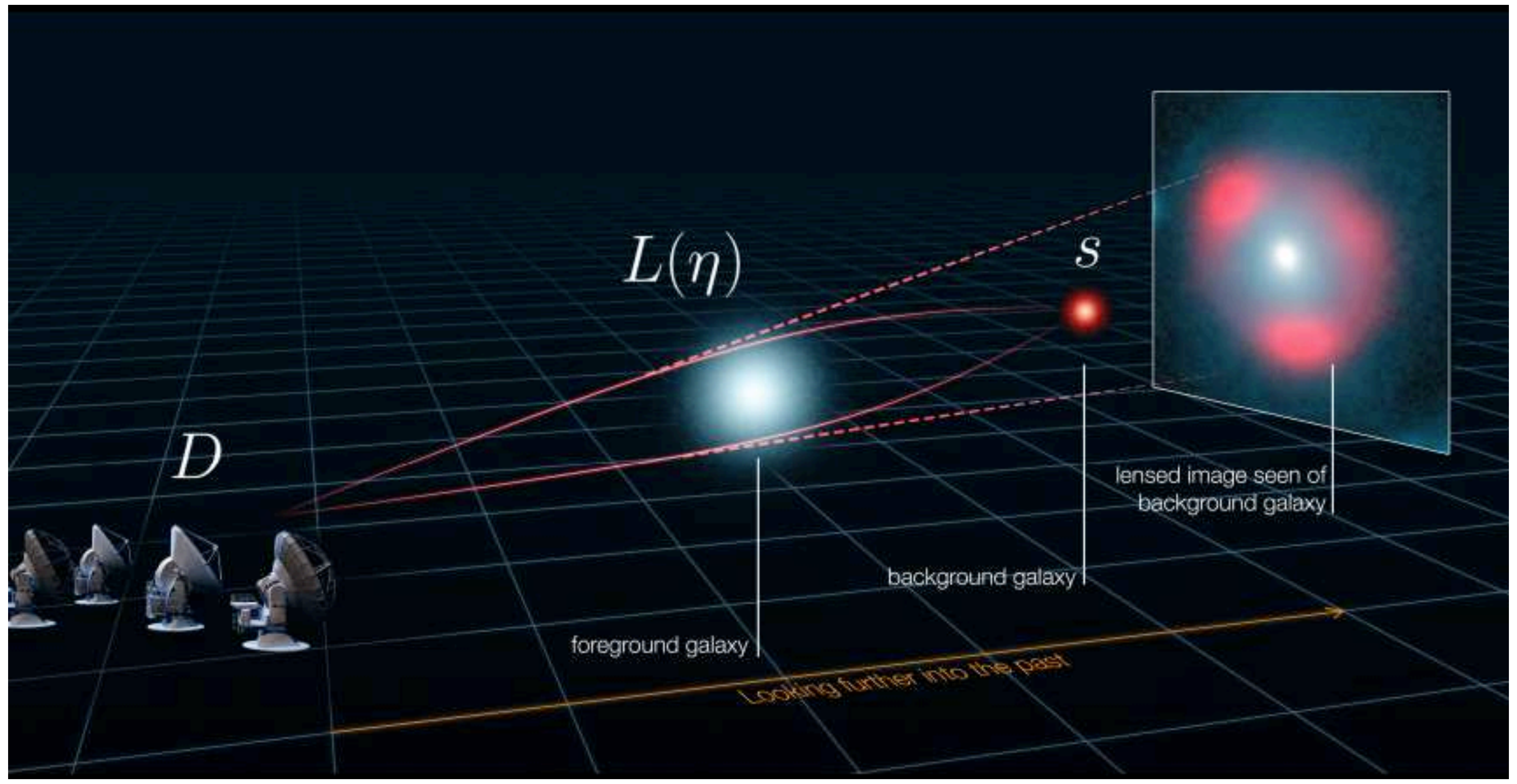
Forward modelling



Instrumental response

source

$$\mathbf{m} = \mathbf{D}\,\mathbf{L}(\delta\psi, \eta)\,\mathbf{s}$$

Lens operator

Smooth lens model

Potential perturbations

$$\delta\psi(m_{fdm}, f_{dm}, \sigma_v)$$

Smooth lensing model: from Powell et al 2022

FDM granules:

Model by Chan et al 2020: statistics of spatially-varying surface mass density fluctuations, given the density profile of the dark matter, as well as some basic assumptions on the behavior of scalar fields in a potential well

$\delta\psi(m_{fdm}, f_{dm}, \sigma_v)$ - is the perturbation of the lensing potential - fluctuations in the projected surface mass density written as perturbations in the lensing convergence due to the presence of the granules:

$$\langle \delta\kappa^2 \rangle = \frac{\lambda_{db}}{2\sqrt{\pi}\Sigma_c^2} \int_{los} \rho_{DM}^2 \, dl$$

We wish to infer a posterior distribution on the dark matter particle mass $\mathcal{P}(m_{fdm})$

We compute likelihoods for 10^4 sample FDM lens realizations with m_{fdm} drawn from the log-uniform prior range $\log(m_{fdm}/\mathrm{eV}) \in [-21.5, -19.0]$.

Free parameters: $\{m, f_{\mathrm{DM}, \sigma_v, \eta}, \lambda_s\}$

Strong lensing

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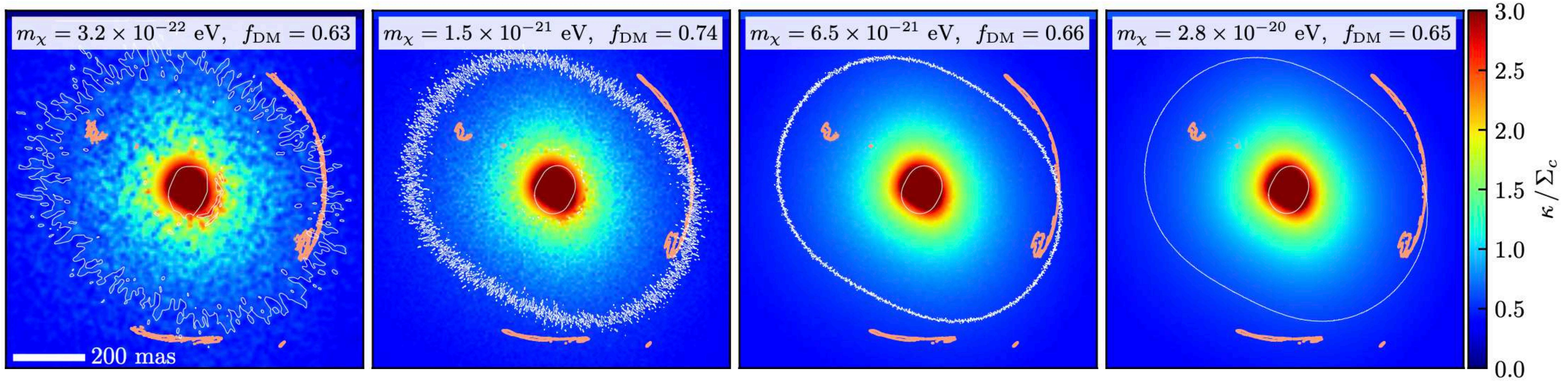
Example convergence maps with corresponding MAP surface mass density maps (κ, in units of the critical density Σc) reconstruction for 4 random realizations of MG J0751+2716 in an FDM cosmology - the model lensed images in orange contours



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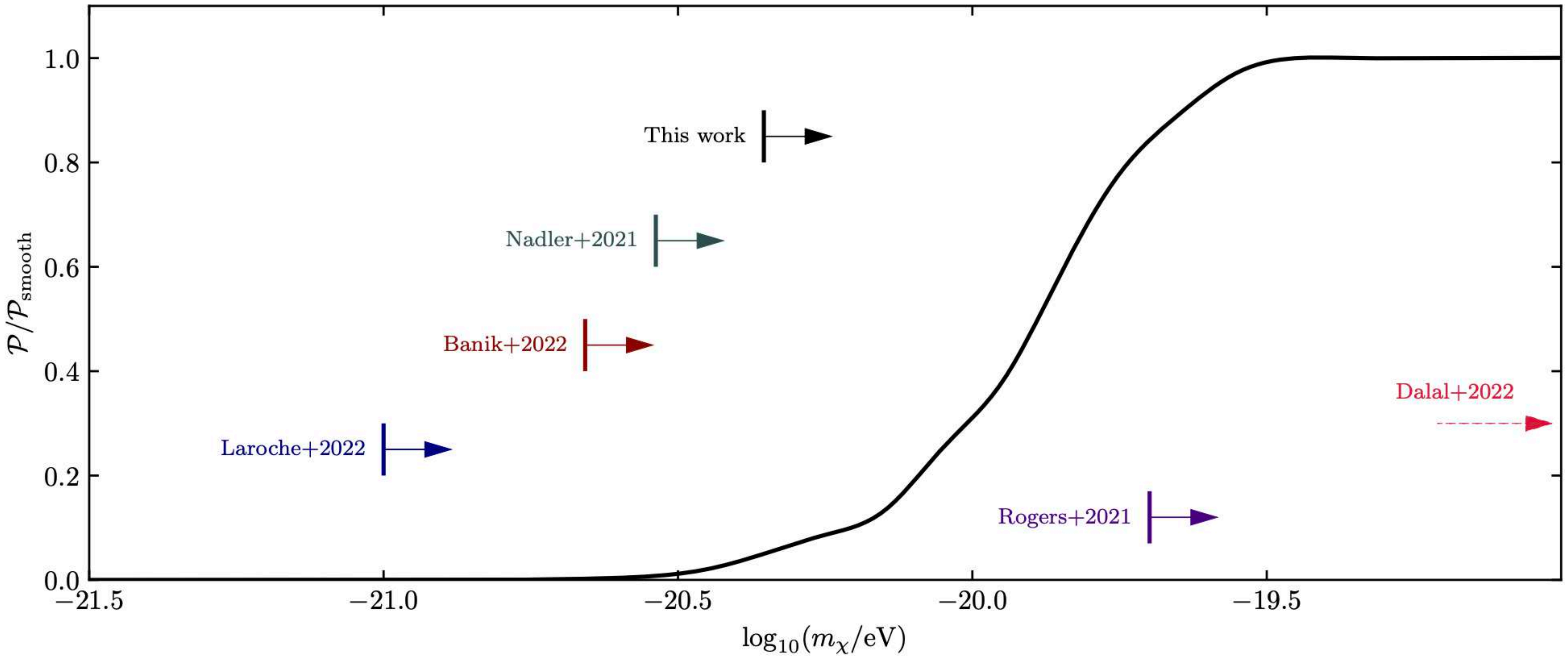
Results quoted in terms of posterior odds ratio (POR) between FDM with a particle mass m_{fdm} and the smooth model, $\mathscr{P}/\mathscr{P}$smooth



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

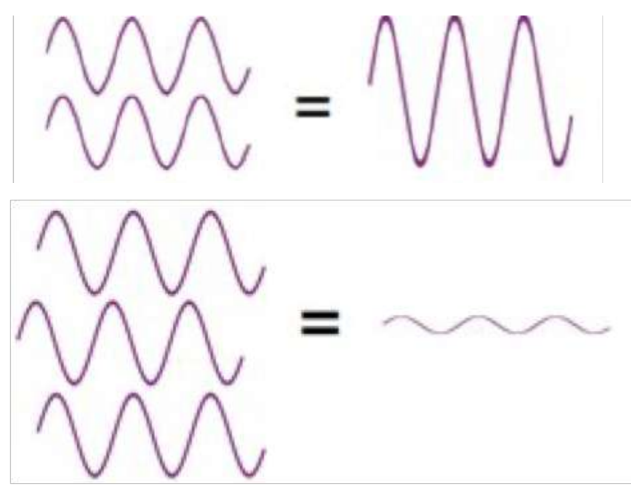
$m_{\rm vdm} > 1.4 \times 10^{-21}$ eV

Spin-2 FDM

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

Vector, higher spin or multicomponent FDM

Interference patterns

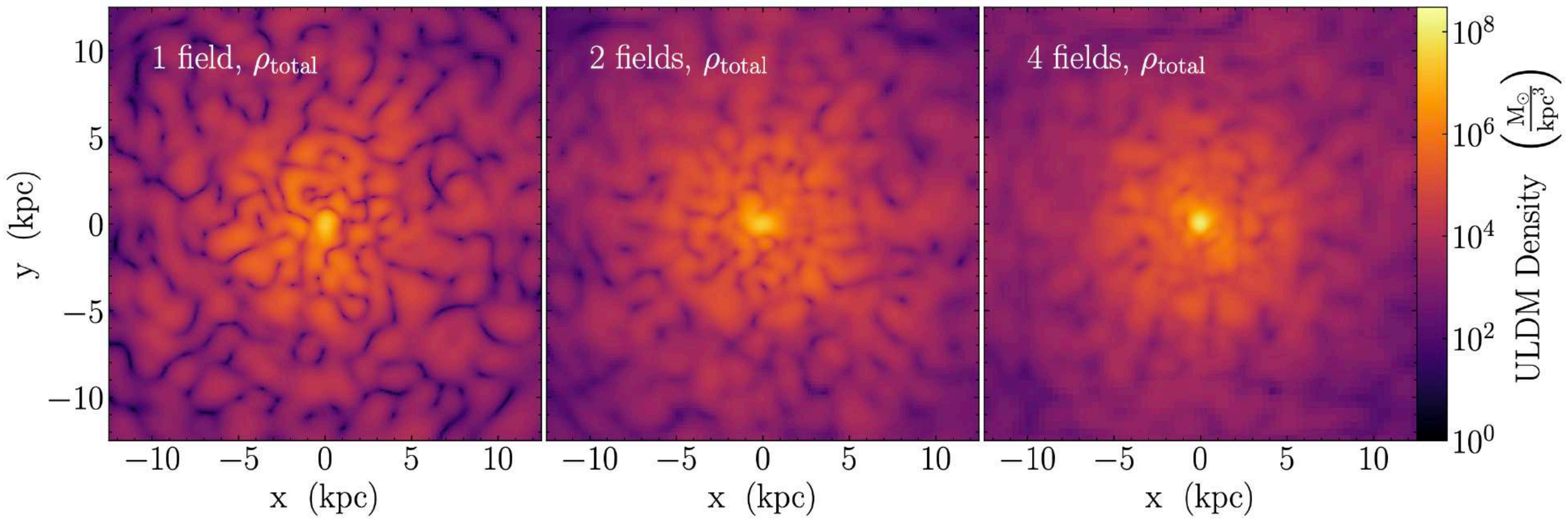


ULDM or ULA are a coherent wave - same frequency and constant phase difference

Multiple coherent waves

Gonseca et al 2023

For ULDM:



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)

Expectation for lensing:

$$\langle \delta\kappa^2 \rangle = \frac{\lambda_{dB}}{2\sqrt{\pi}\,\Sigma_c^2}\int \rho_{\rm DM}^2\, dl$$

$$m_{nfdm,s} = \frac{m_{fdm}}{N} = \frac{m_{fdm}}{2s+1}$$

Detailed simulations and analysis in the future!

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

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

Multicomponent FDM   Gonseca et al 2023

Strong lensing

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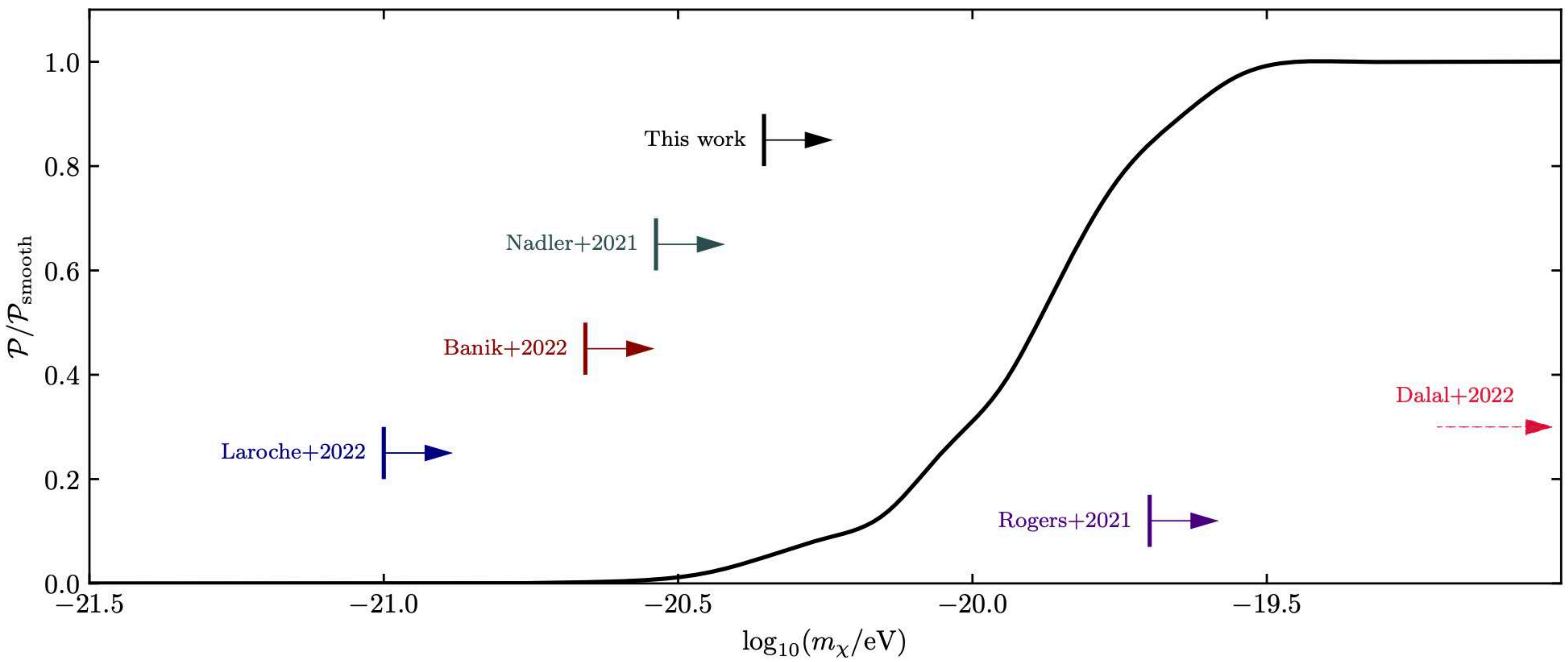

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OR 3 same mass FDM

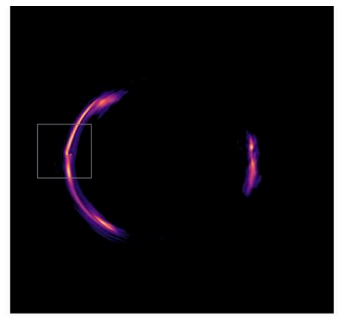
$m_{\rm vdm} > 1.4 \times 10^{-21}$ eV

Spin-2 FDM

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

Milli-arcsecond angular resolution of VLBI, competitive constraints on dark matter models can be inferred using a single strong gravitational lens observation

Gravitational effects can give tell us about particle properties of DM (mass, spin, self-interaction, …)



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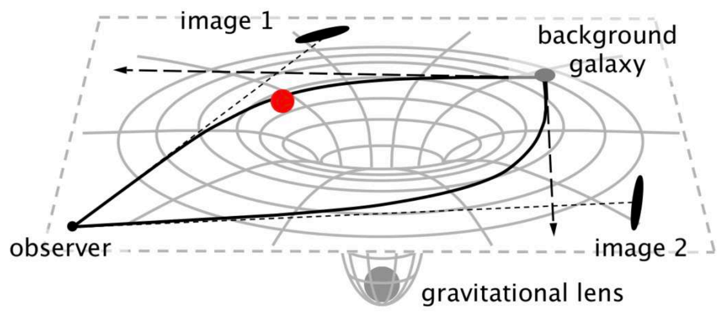
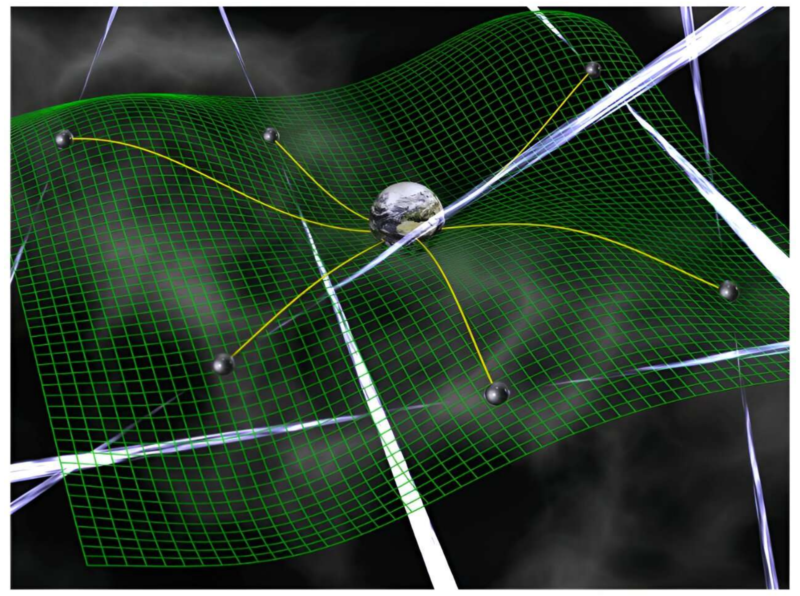


axion-photon coupling

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

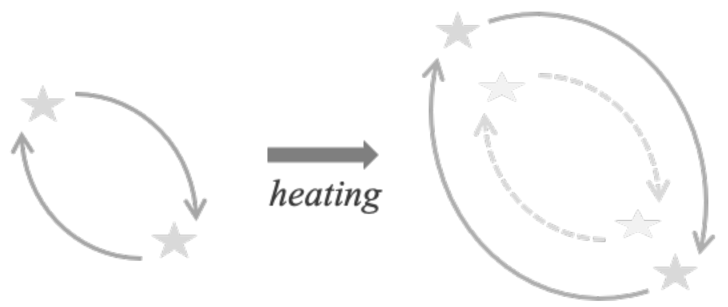
Pulsar Timing Array



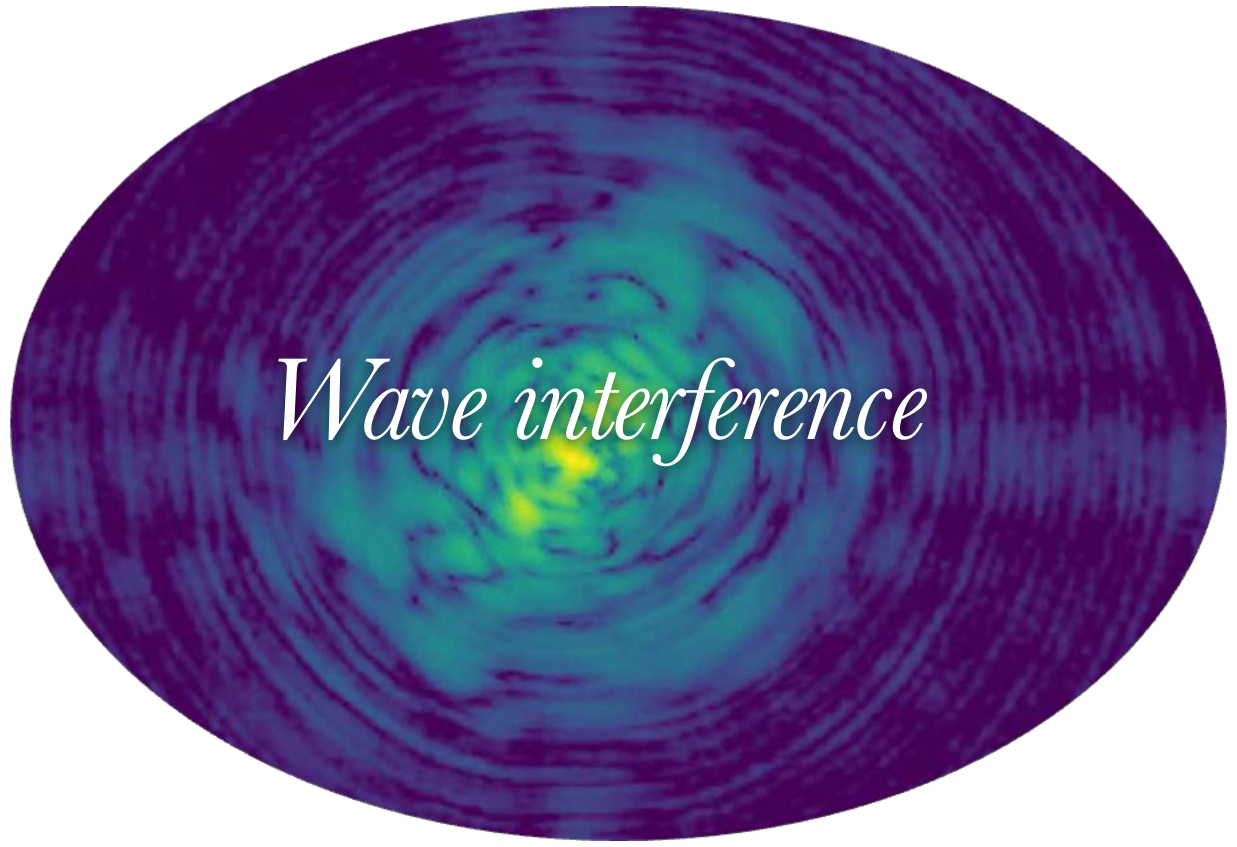
Artistic representation of the Pulsar Timing Array concept. Credit: David Champion / MPIfR

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

Binary stars

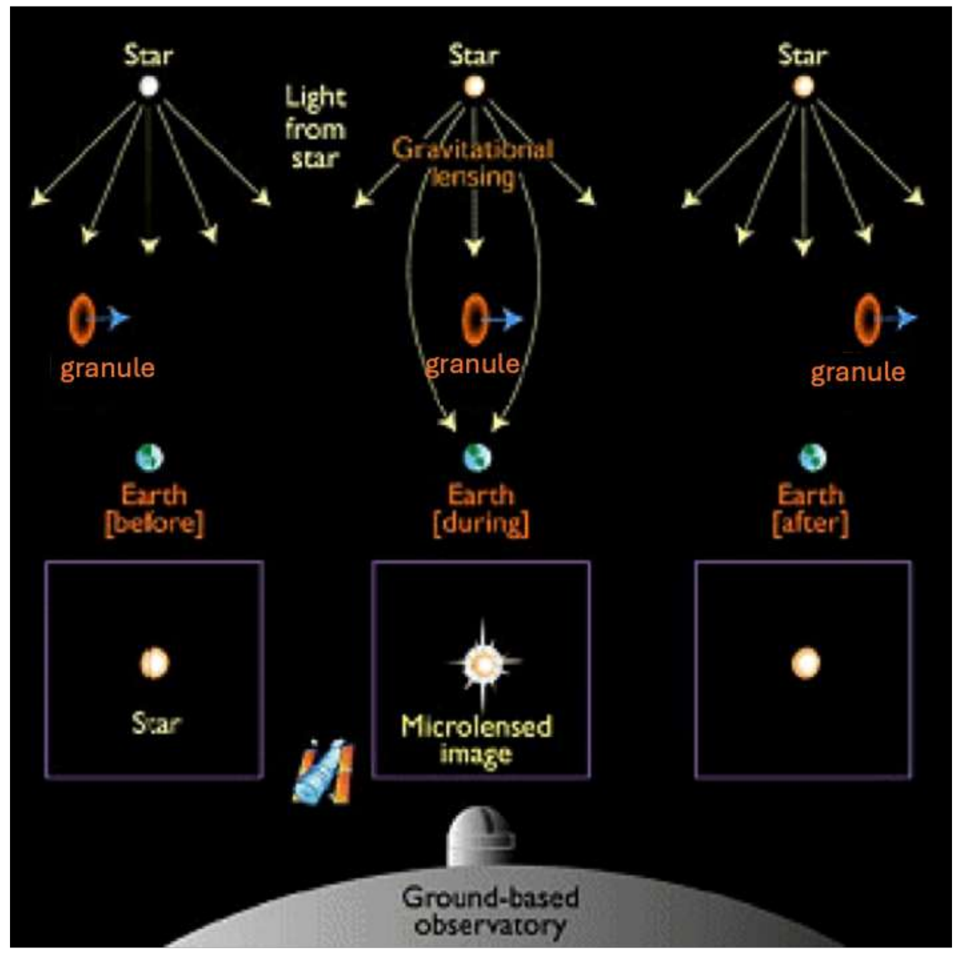


$m \sim 10^{-[16-10]}$ eV



Mass, spin (# particles), fraction self interaction

Stochastic lensing

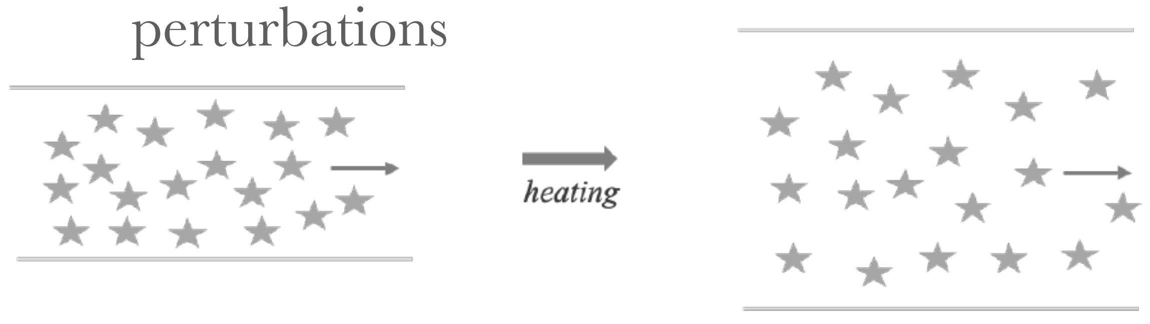


Modified from: https://i.astro.tsinghua.edu.cn/~smao/contents/microlens.html

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

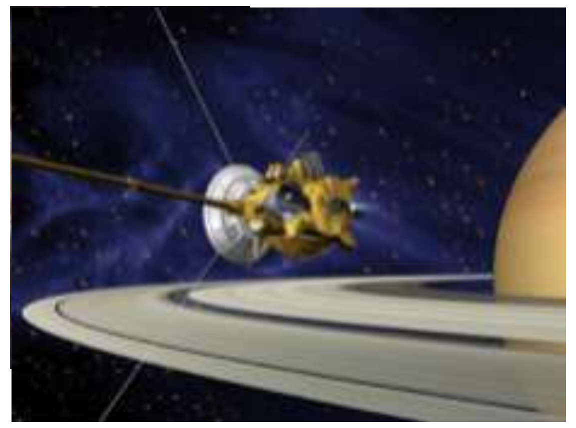
Stellar streams

Heating + coherent perturbations



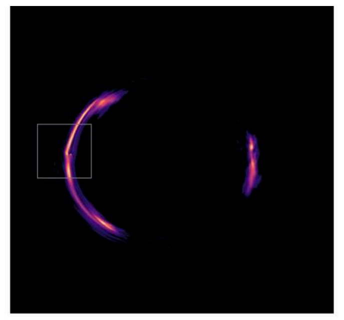
$m \sim 10^{-[23-18]}$ eV

Solar system

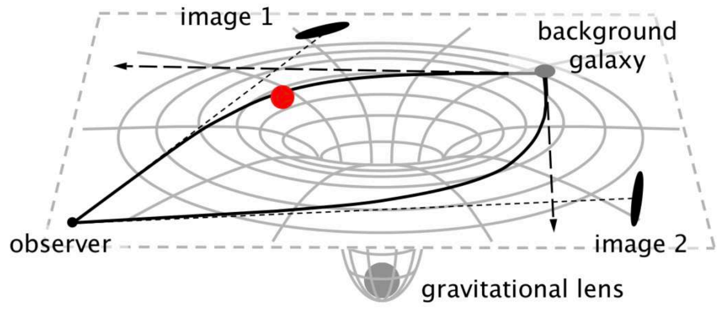


$m \sim 10^{-[16-10]}$ eV

axion-photon coupling



Strong lensing

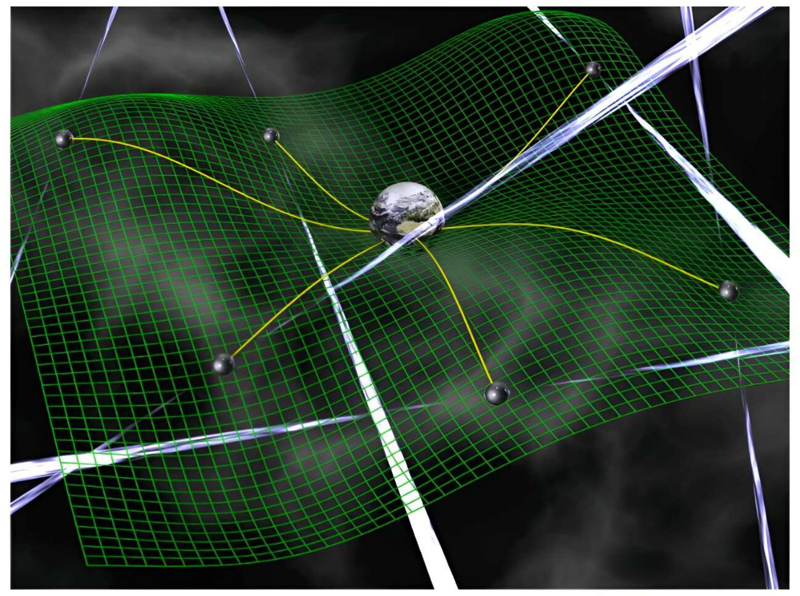


axion-photon coupling

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

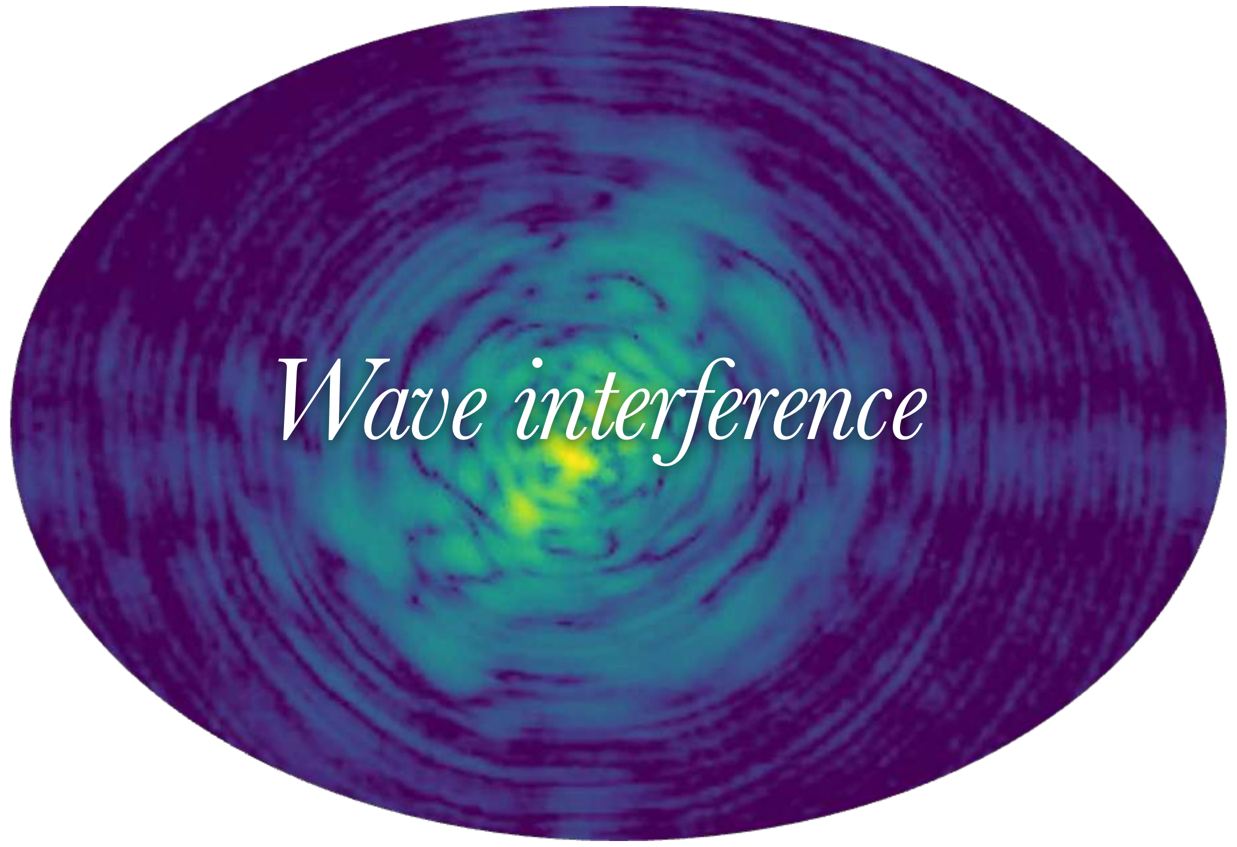
(Work in progress)

Pulsar Timing Array



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

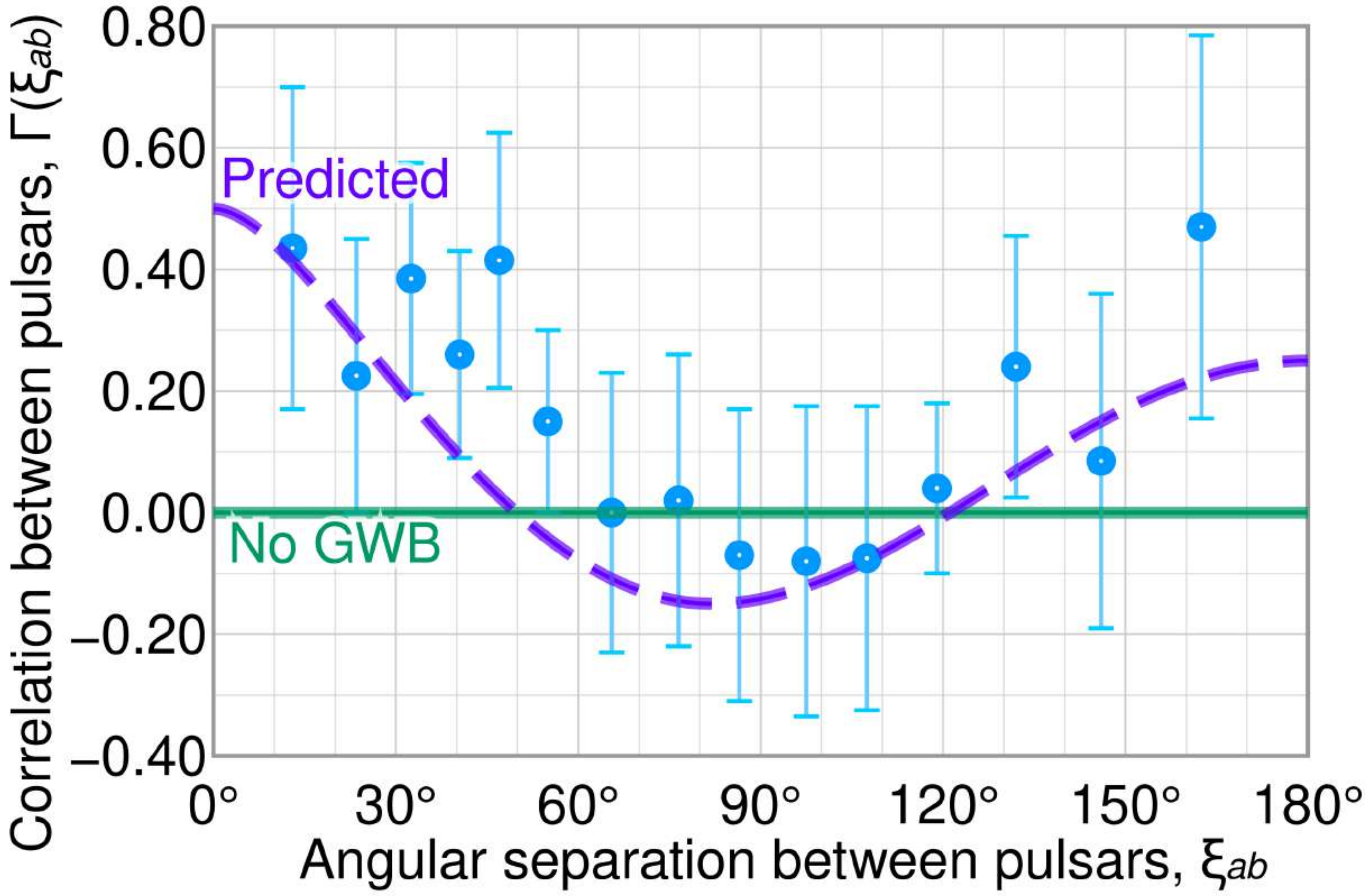
$m \sim 10^{-[22-17]}$ eV



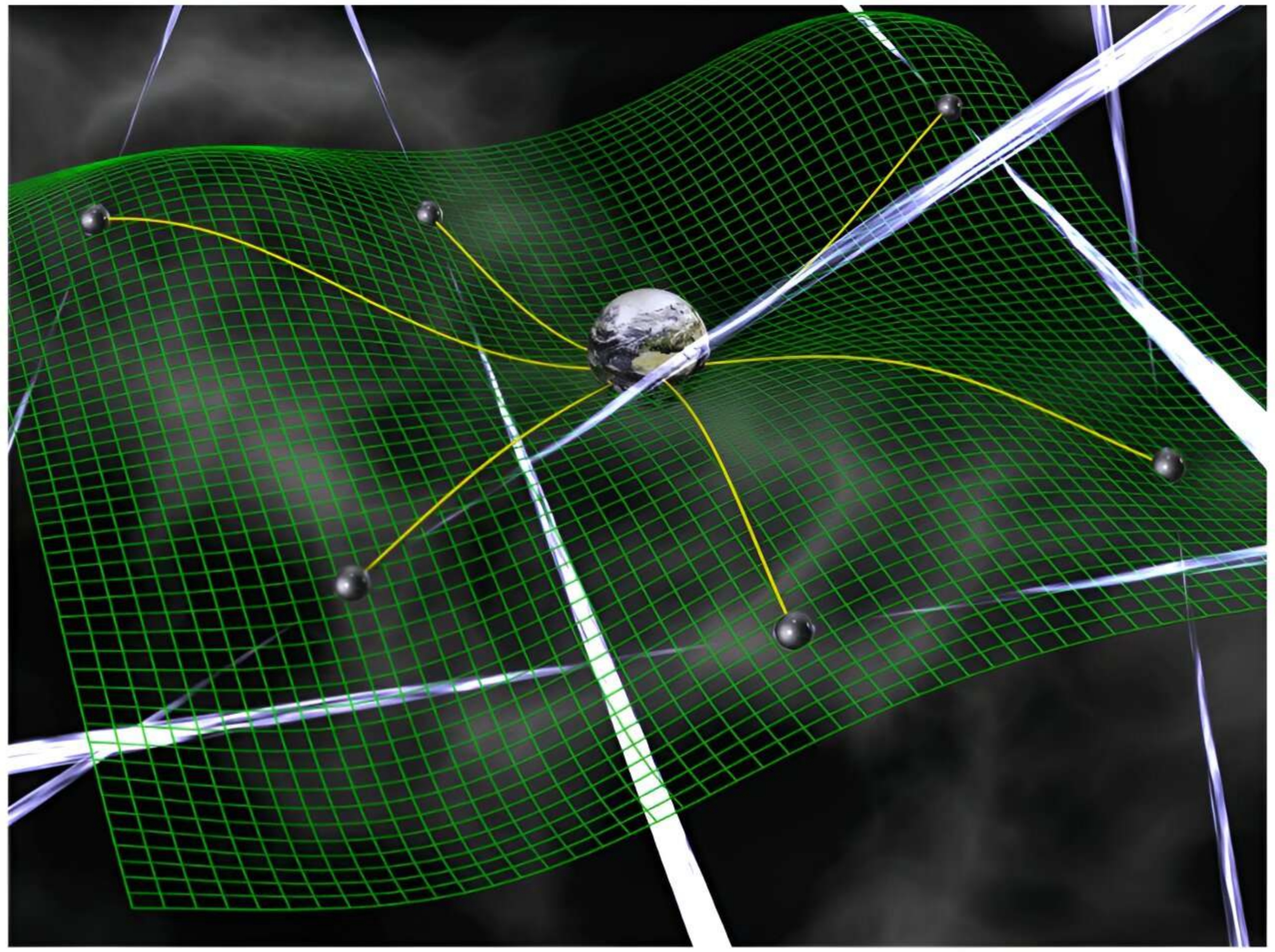
Mass, spin (# particles), fraction self interaction

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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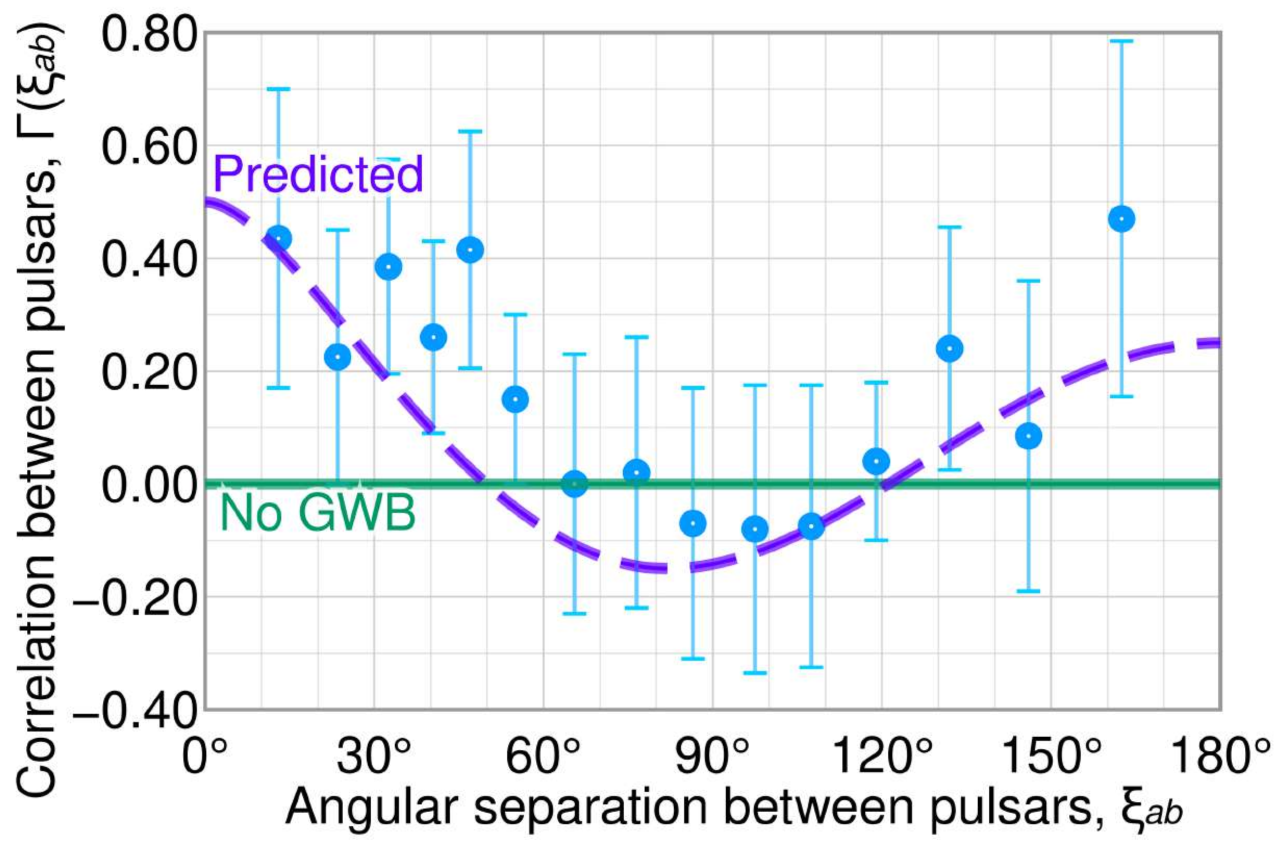
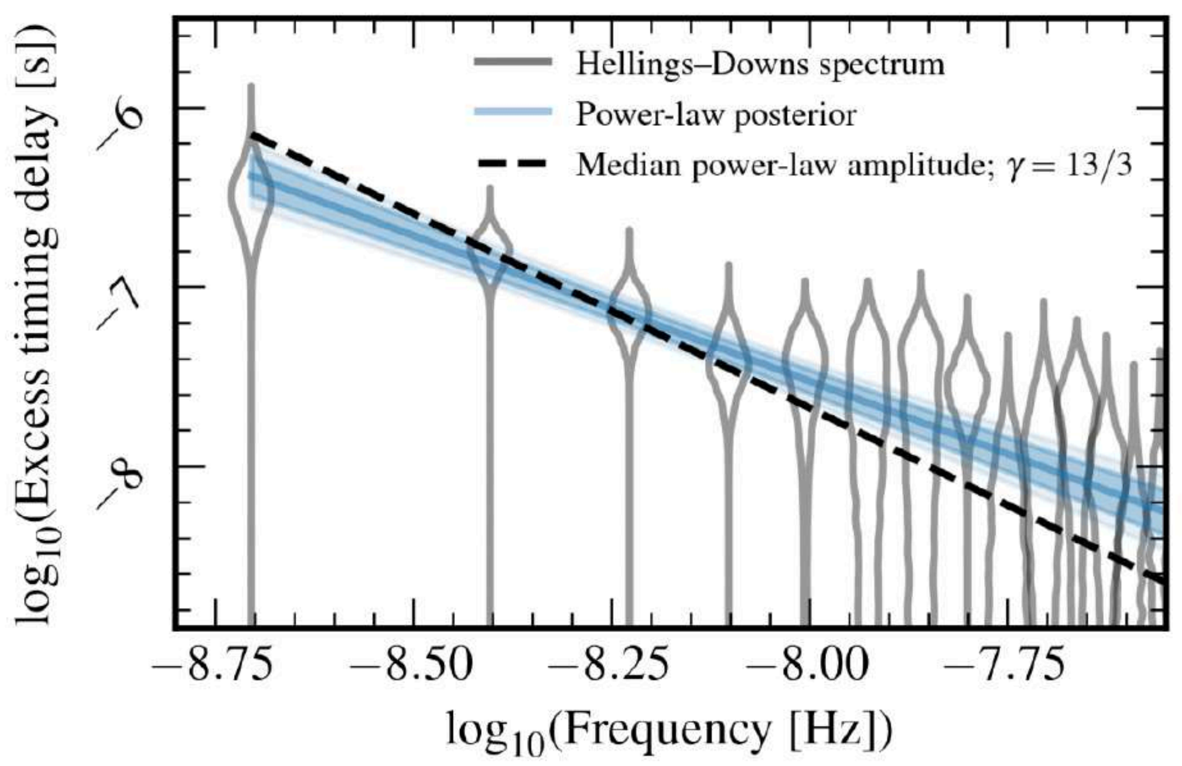




Possibility of being a **Gravitational Wave Background** signal caused by:

- Ensemble of binary supermassive black-holes
- New physics

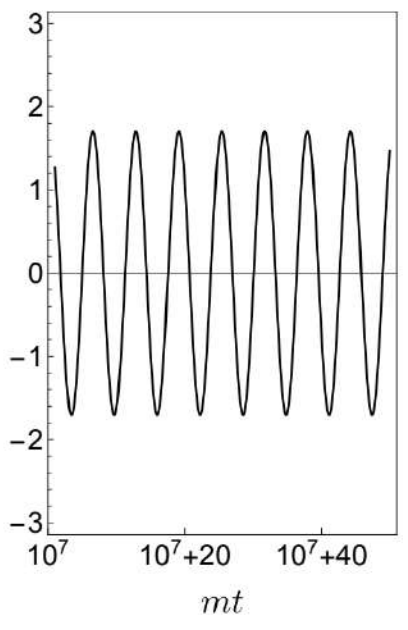
Pulsar Timing array

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

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

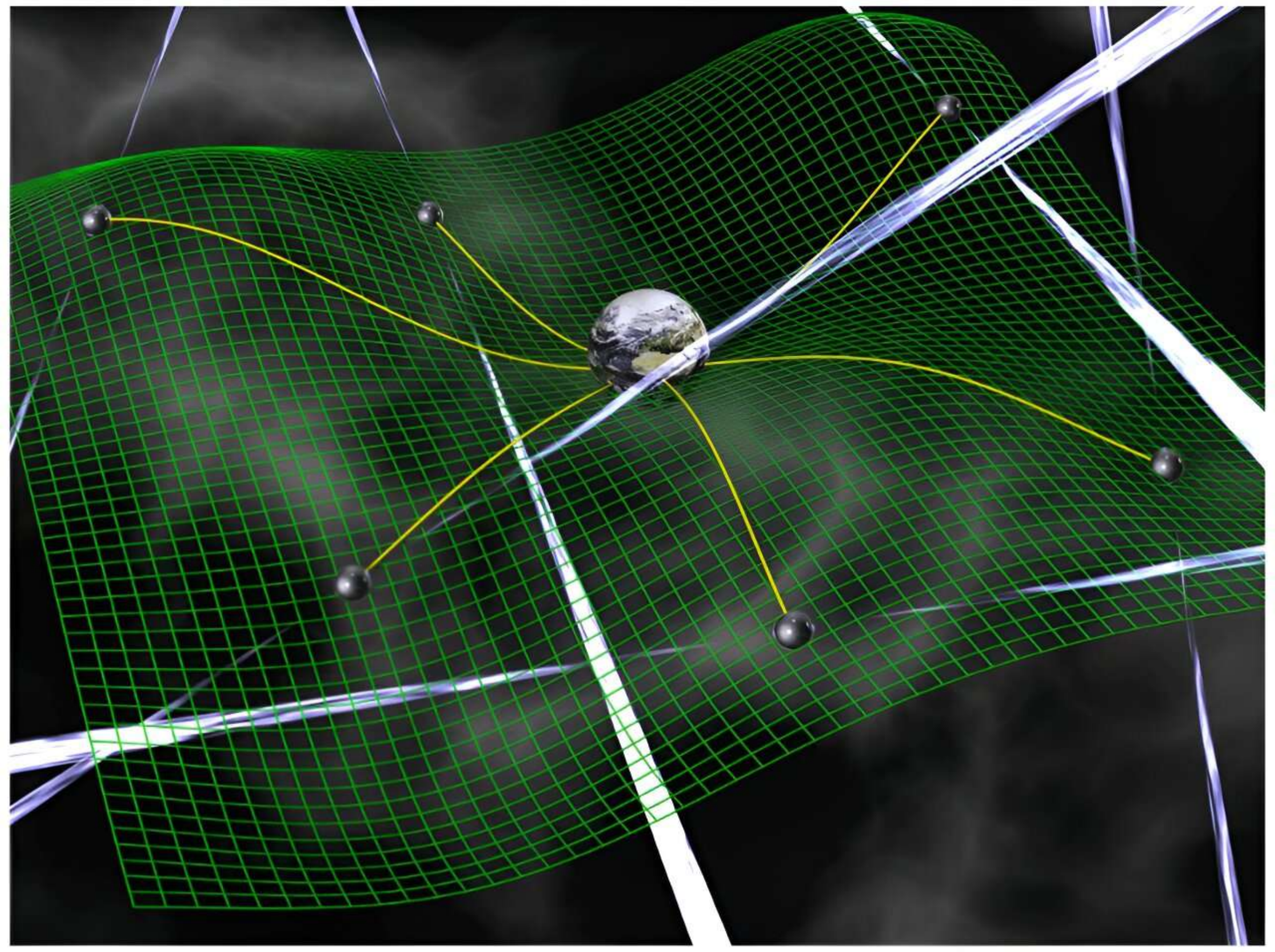
Clemente Smarra *et al.* (European Pulsar Timing Array), Phys. Rev. Lett. **131**, 171001

Ultra-light DM: Coherent wave oscillation of ULDM



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

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

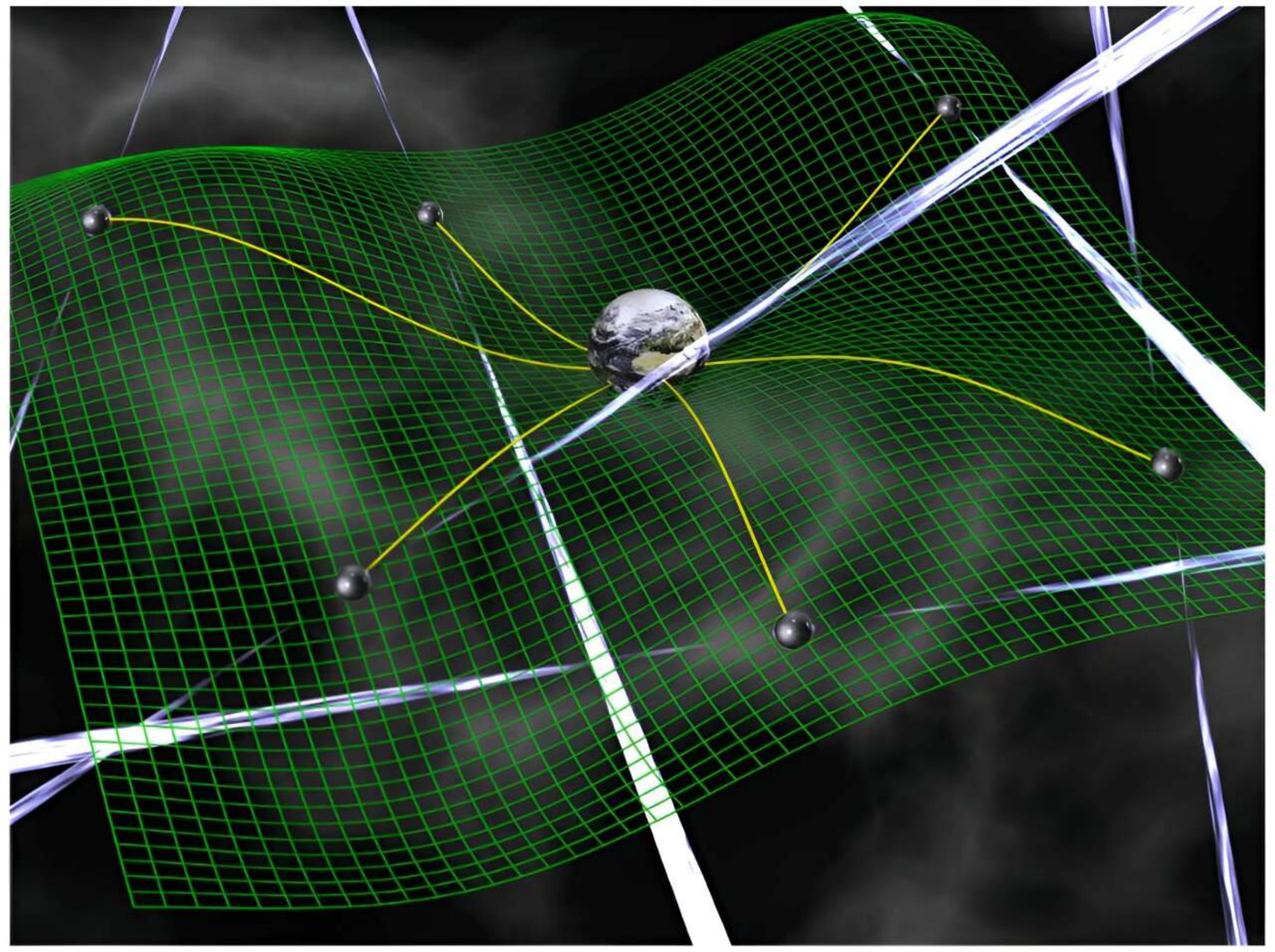
Sources an oscillating gravitational potential. Solving the 00 and ii components of Einstein's equations at first order:

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

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

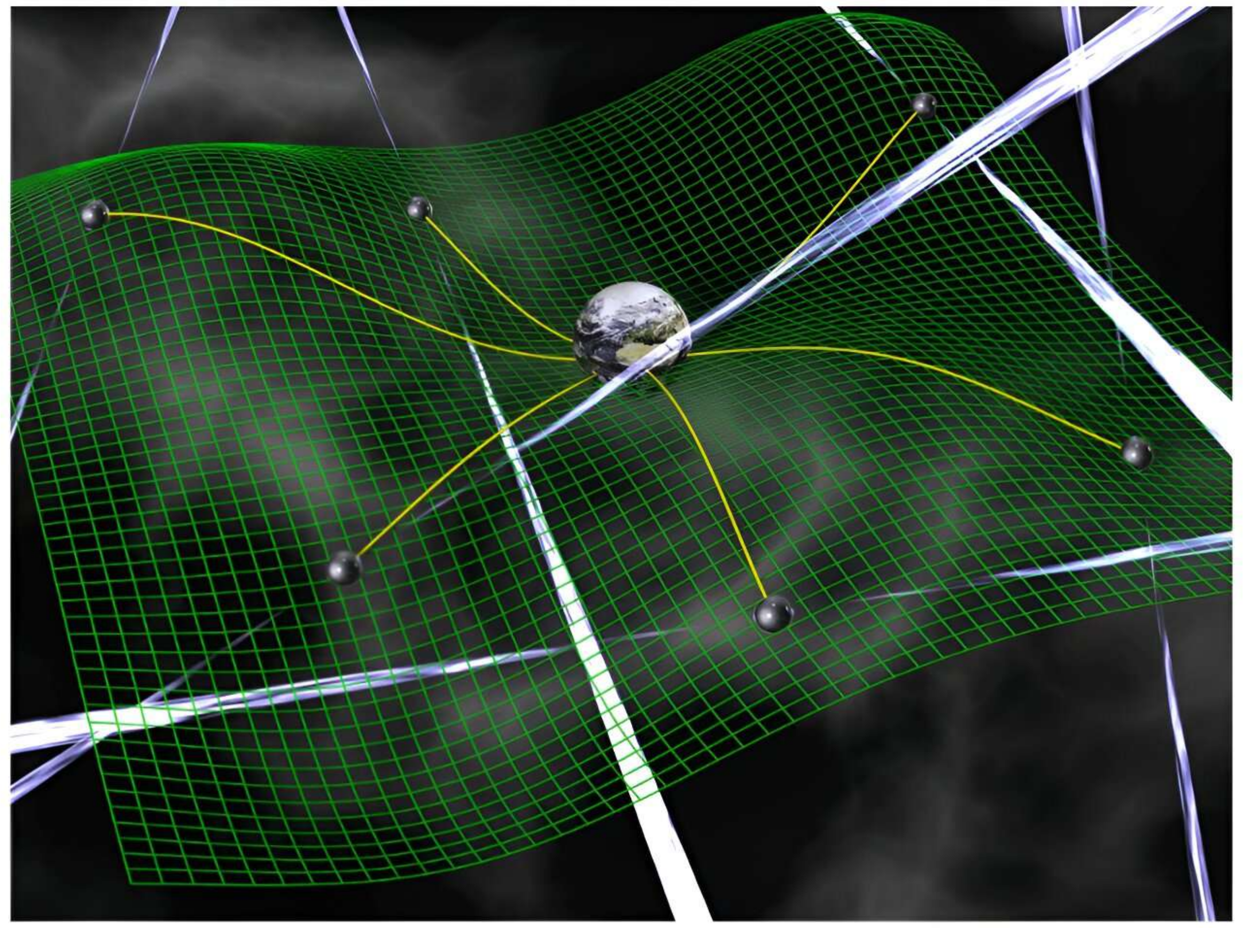
$$\delta t_{gw} = \frac{h_c}{\omega} \sin\left(\frac{\omega D(1 - \cos(\theta))}{2}\right) (1 + \cos\theta) \sin(2\psi)$$

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



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

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Pulsar-Earth distance is O(kpc)

ULDM coherent length:

$$l_c \sim 0.4 \left(\frac{10^{-22}\,\mathrm{eV}}{m} \right)$$

bellow which only coherent oscillation matters

They identify 3 regimes:

- *Uncorrelated*: $l_c <$ average inter-pulsar and pulsar-Earth separation → $m > 10^{-23}\,\mathrm{eV}$
- *Pulsar-correlated*: average inter-pulsar and pulsar-Earth separation but $l_c <$ galaxy central region → $\hat{\phi}_E = \hat{\phi}_P$ but $\hat{\phi}$ free parameter → $m < 10^{-24}\,\mathrm{eV}$ $(m \sim 10^{-24}\,\mathrm{eV})$
- *Correlated*: $l_c >$ average inter-pulsar and pulsar-Earth separation + encloses the typical galaxy central region → $\hat{\phi}_E = \hat{\phi}_P$ and rotation curves samples the same coherence patch, and thus measure the local DM abundance → $2 \times 10^{-24}\,\mathrm{eV} \lesssim m \lesssim 5 \times 10^{-23}\,\mathrm{eV}$

Pulsar Timing array

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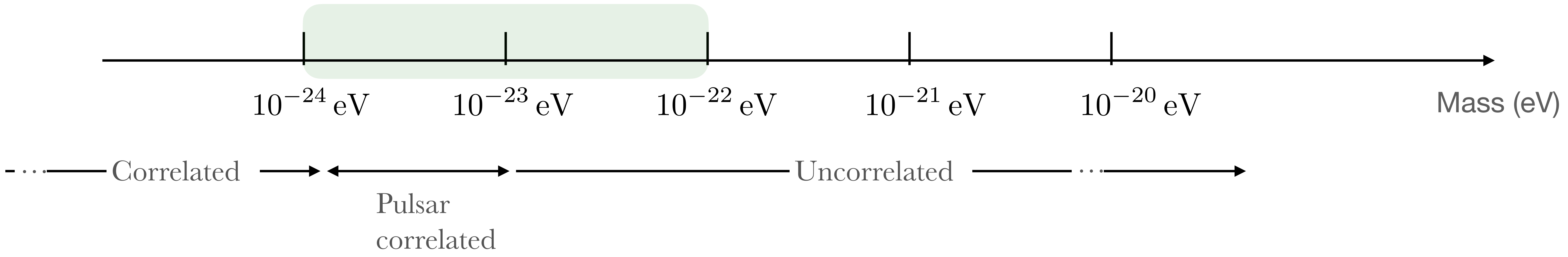
$$\delta t_{dm} = \frac{\Phi(\vec{x})}{2m}\left[\hat{\phi}_E^2 \sin(2m + \alpha_E) - \hat{\phi}_P^2 \sin(2m + \alpha_P)\right]$$

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

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

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



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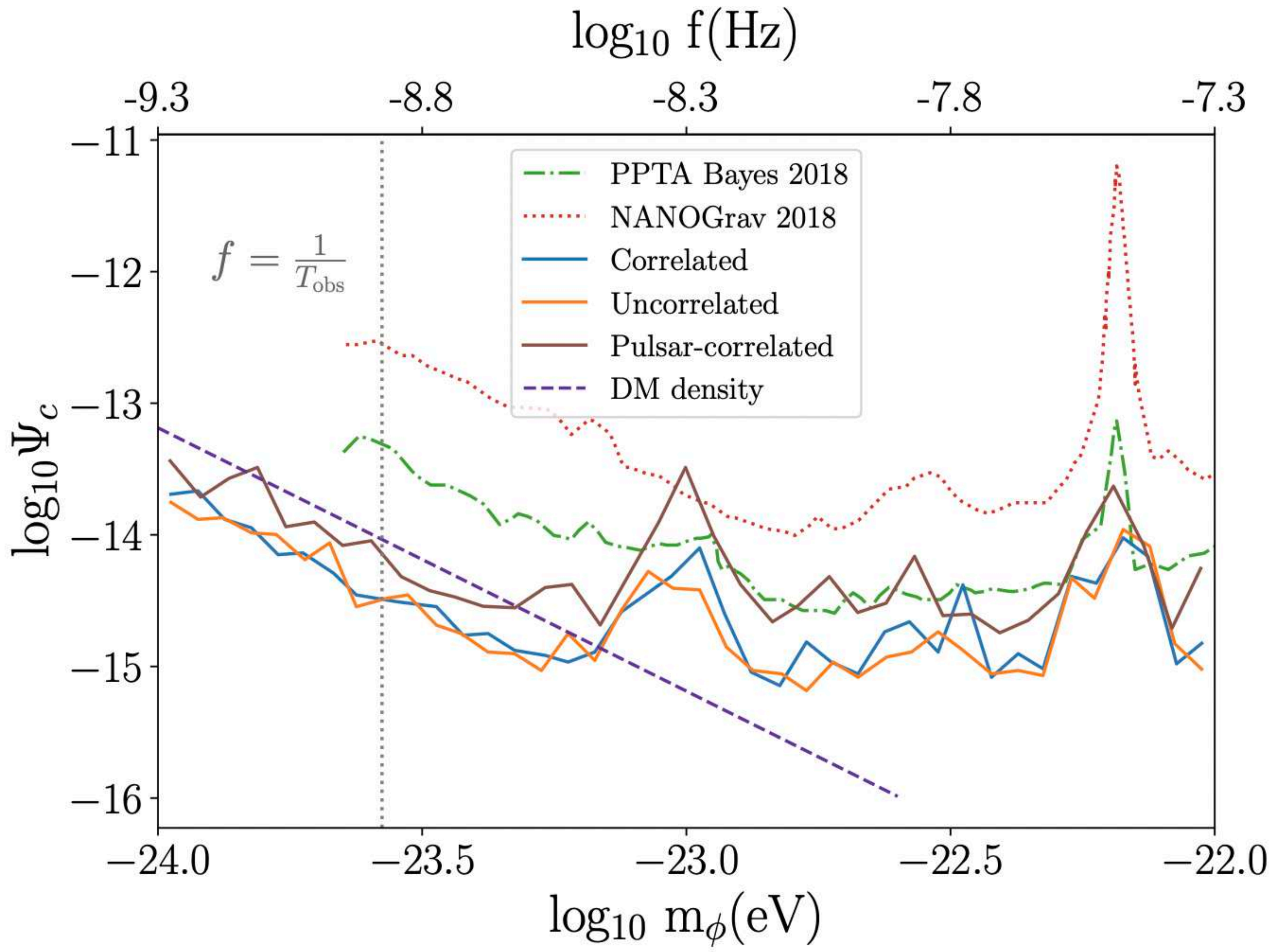

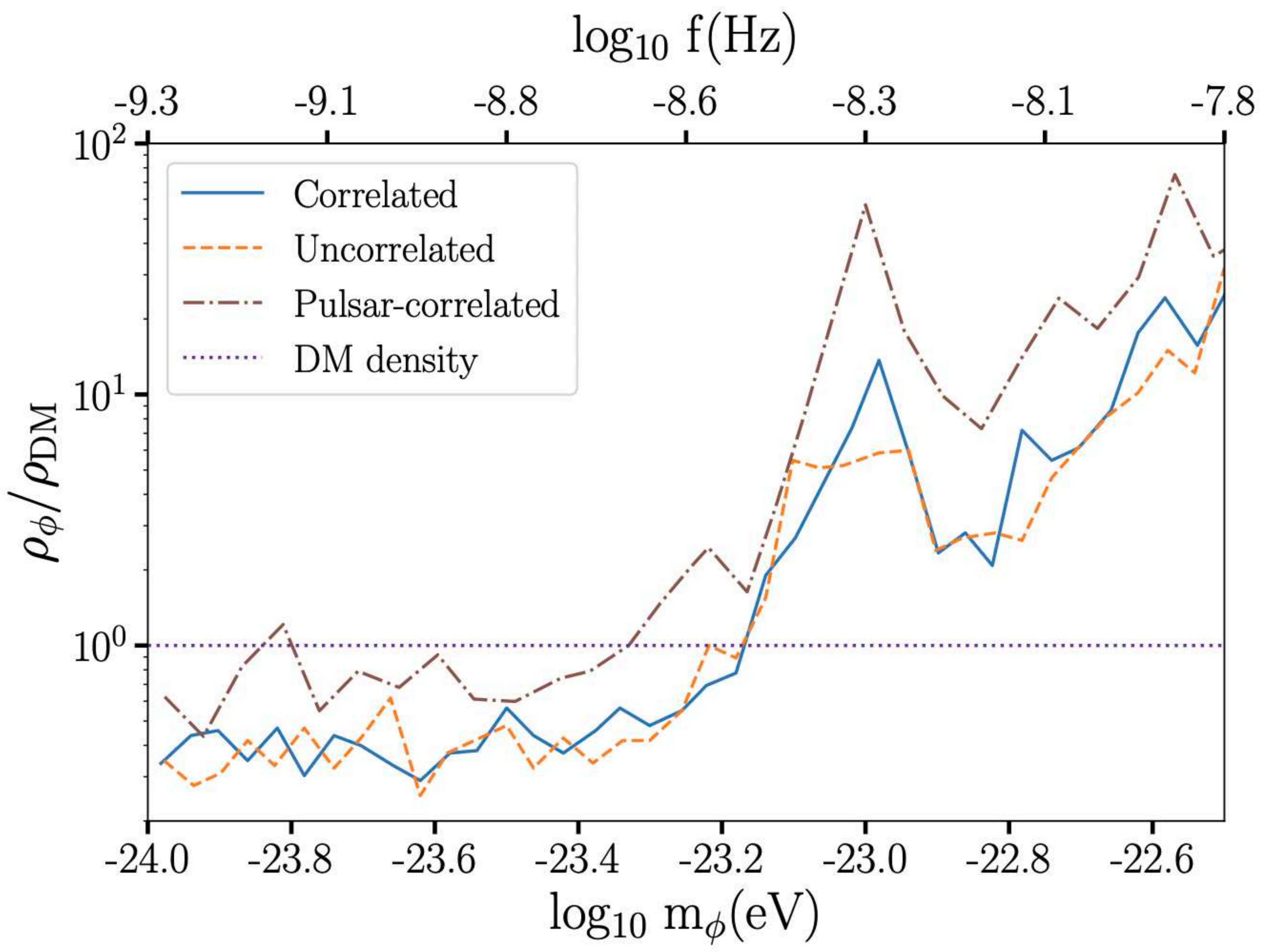

$-24.0 < \log_{10}\,(m_\phi/\mathrm{eV}) < -23.7 \longrightarrow f_\phi \lesssim 30 - 40\,\%$

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

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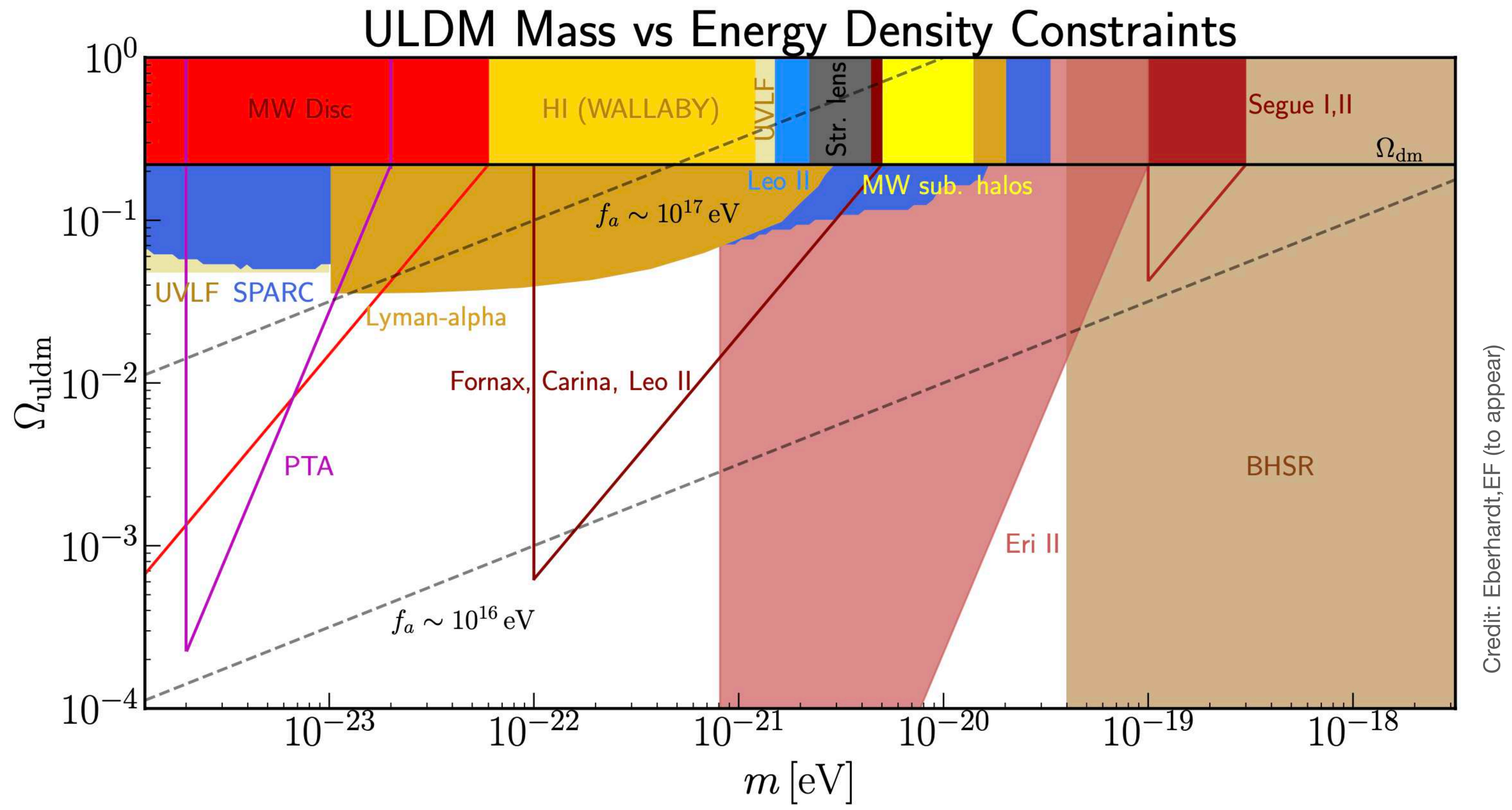

$$-24.0 < \log_{10}\,(m_\phi/\mathrm{eV}) < -23.7 \longrightarrow f_\phi \lesssim 30-40\,\%$$

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

* Notice they did not show that ULDM describes what was measured, the Hellings-Downs curve

Pulsar Timing array

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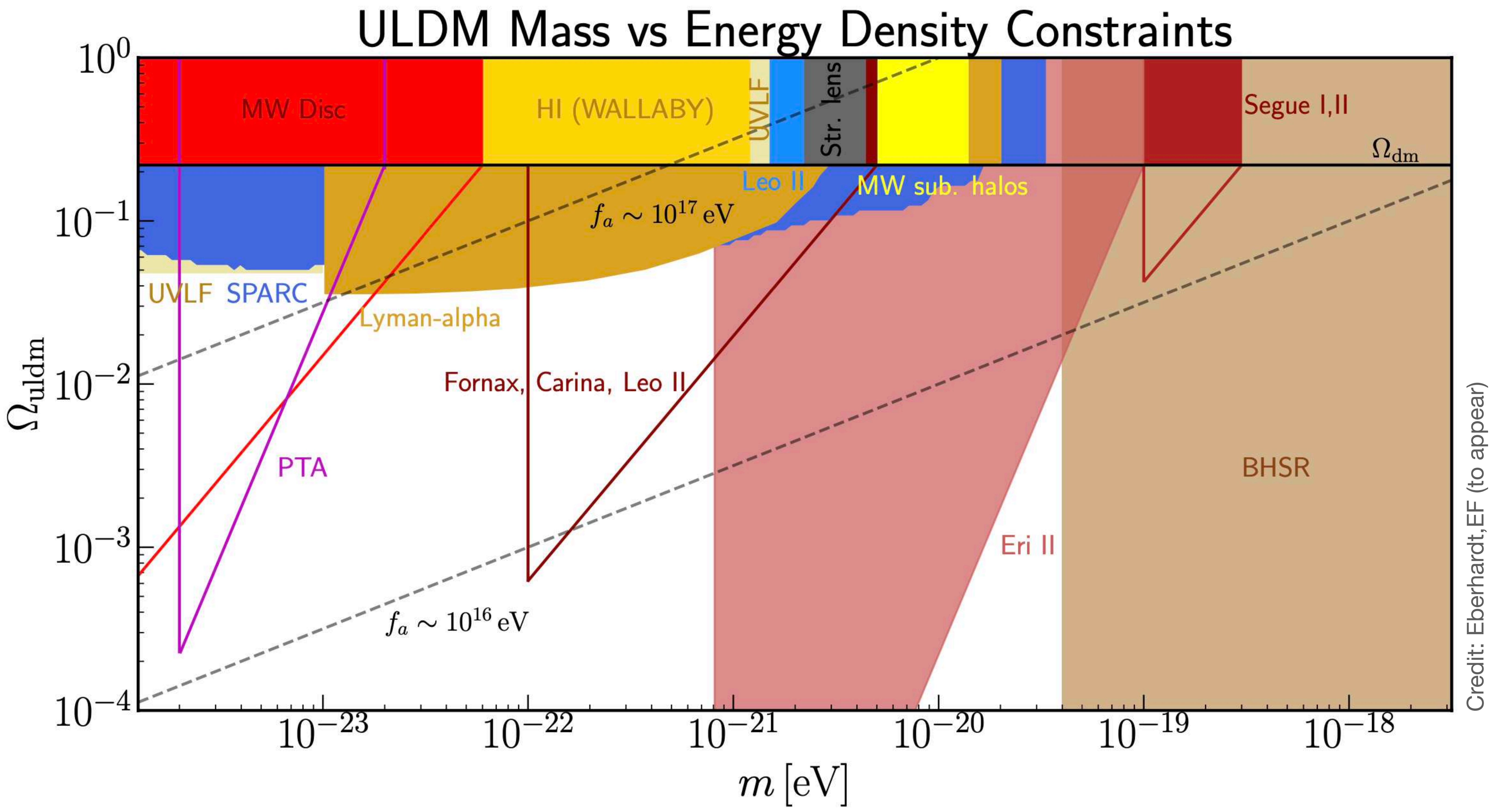

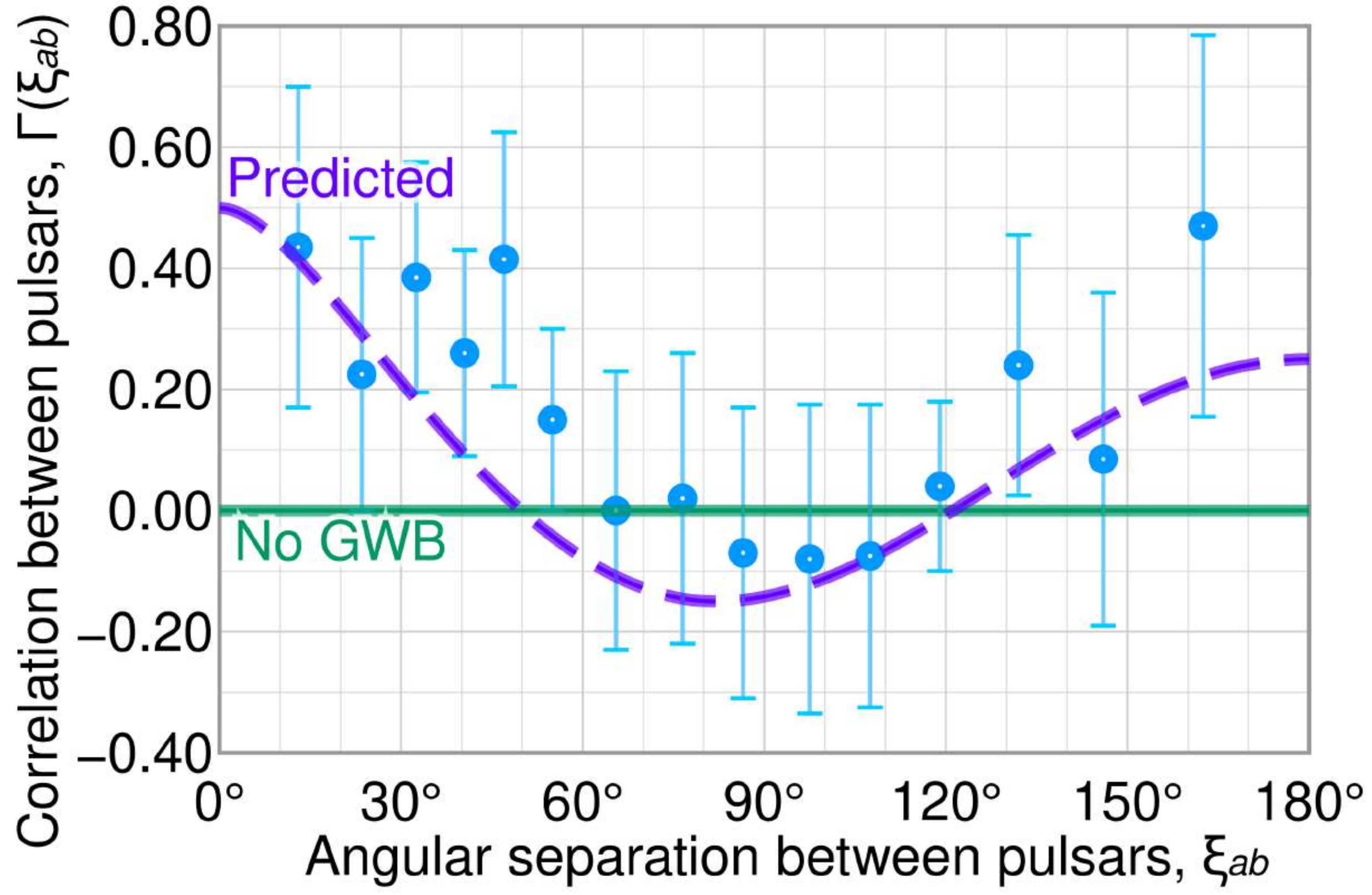

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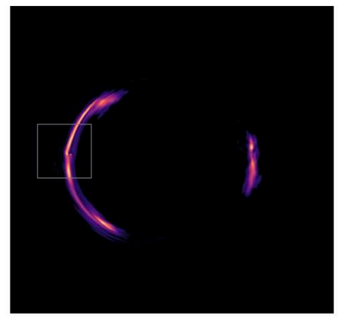
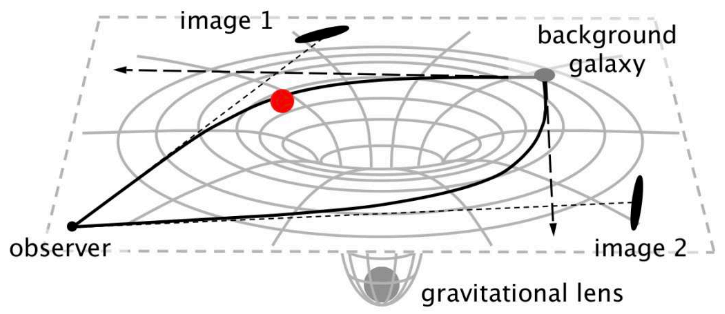


Strong lensing

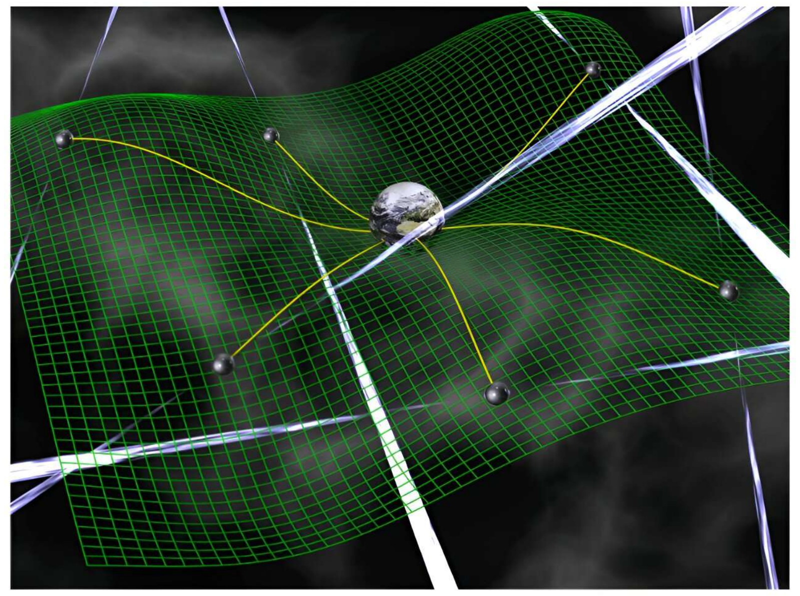


axion-photon coupling

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

(Work in progress)

Pulsar Timing Array



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

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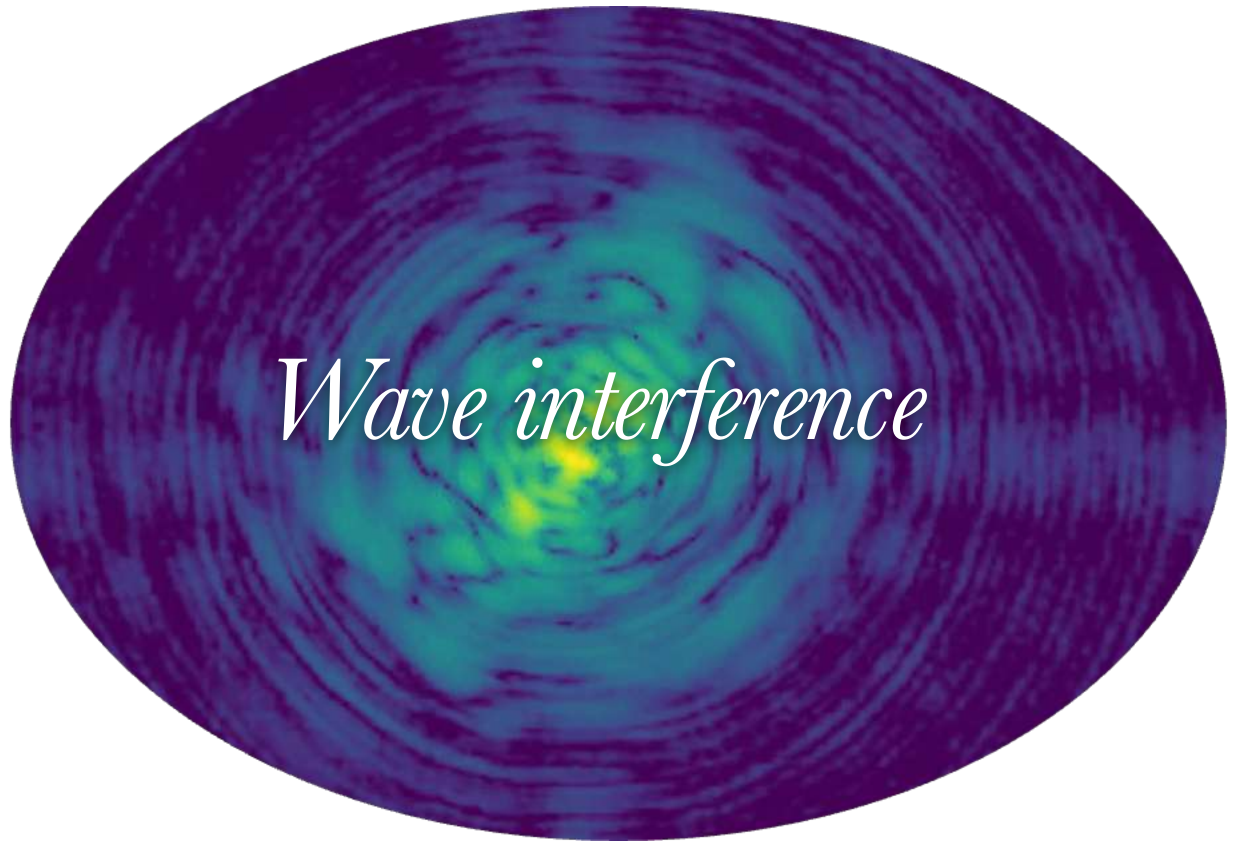
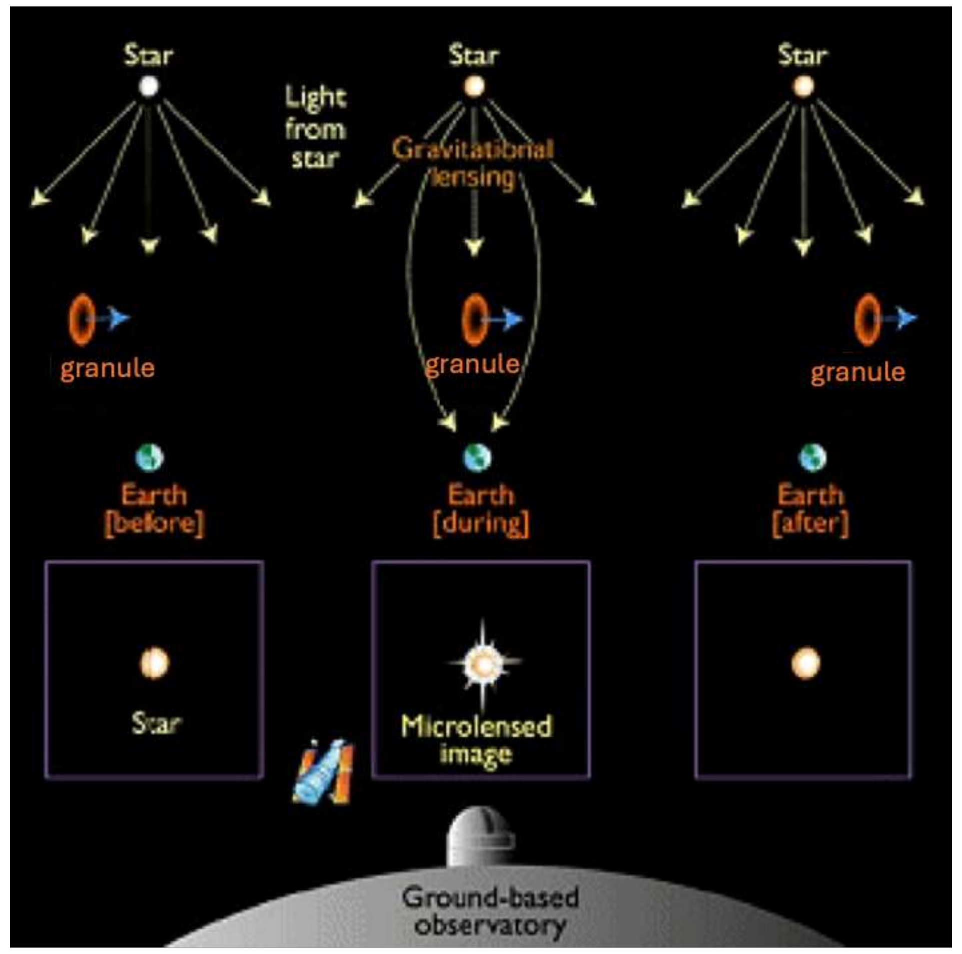


Mass, spin (# particles), fraction self interaction

Microlensing



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

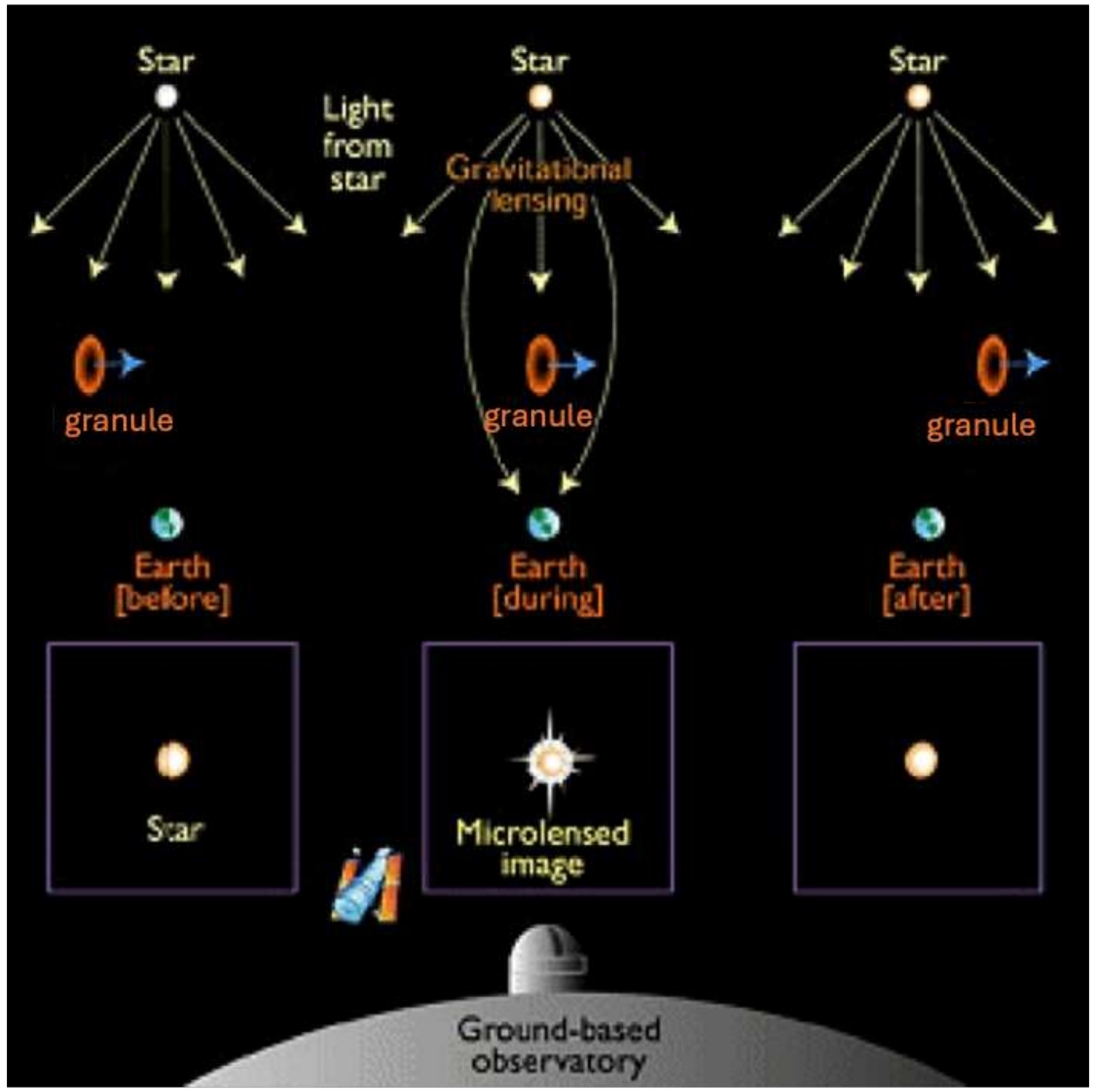
$m \sim 10^{-[23-18]}$ eV

Stochastic lensing

(Work in progress)

In collaboration with Andrew Eberhardt, Wentao Lui, Yin Li and Shurui Lin

Microlensing



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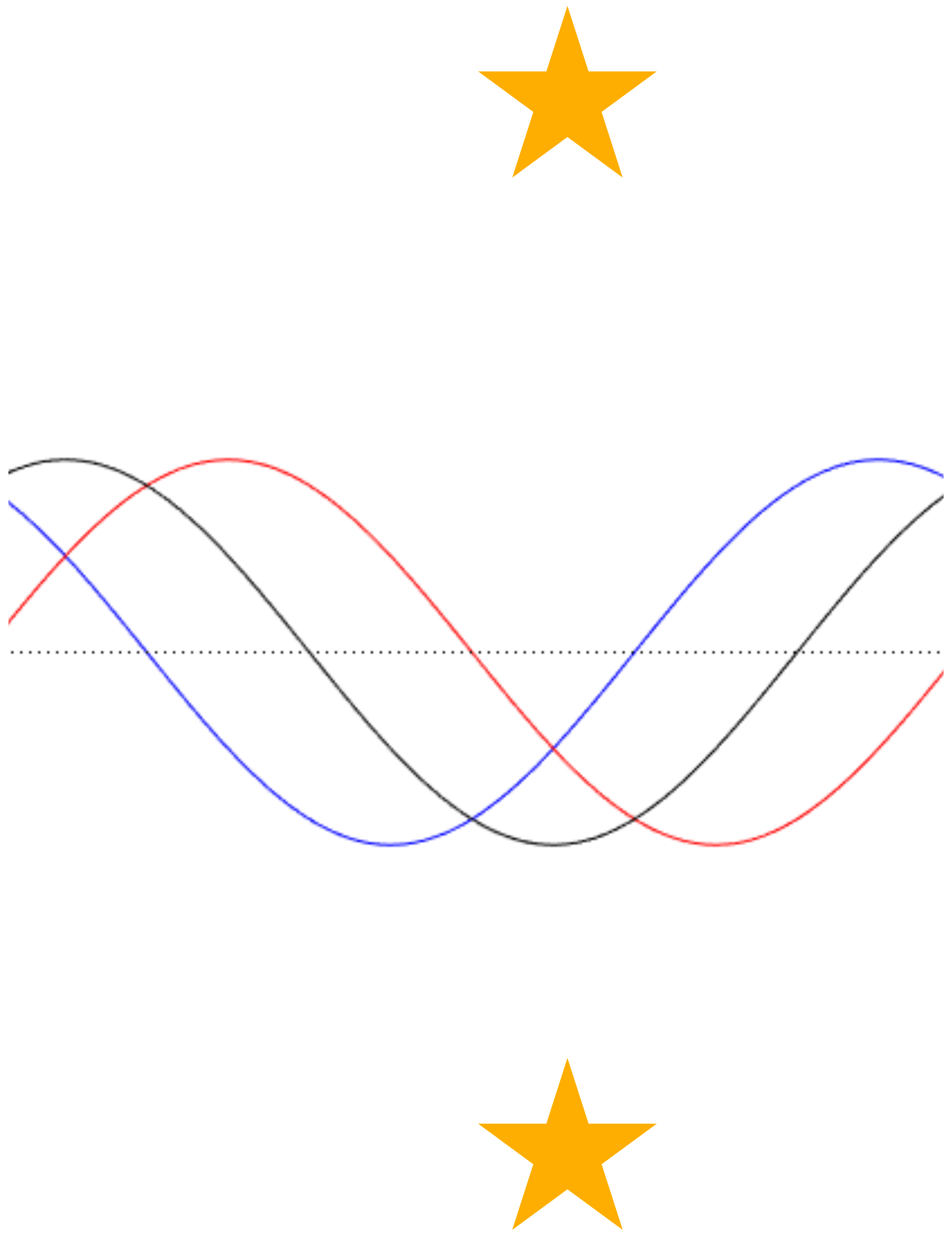


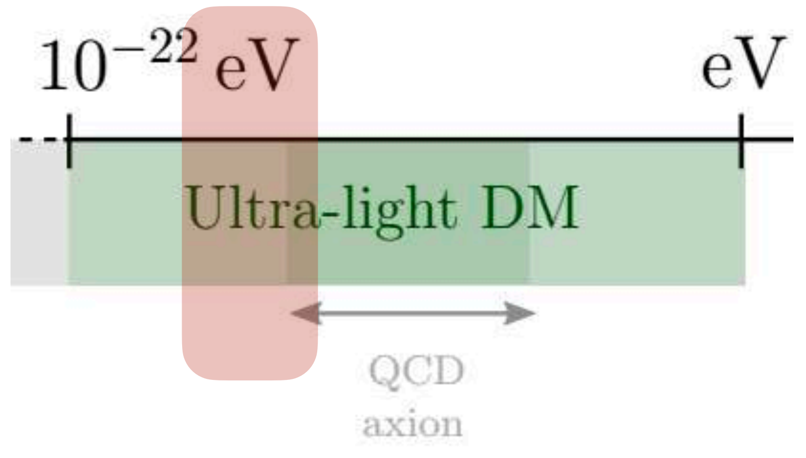
Stochastic *lensing*

Andrew Eberhardt, Wentao Lui, Yin Li
and Shurui Lin, 2025

ULDM

$$\lambda_{\rm db} = \hbar/m\sigma \sim 6\times 10^{-6}\left(\frac{10^{-17}\,{\rm eV}}{m}\right)\left(\frac{200\,{\rm km/s}}{\sigma}\right)\,{\rm kpc}\,.$$

$$\tau_{\rm db} = 2\pi\hbar/m\sigma^2 \sim 30\left(\frac{10^{-17}\,{\rm eV}}{m}\right)\left(\frac{200\,{\rm km/s}}{\sigma}\right)^2\,{\rm yrs}\,,$$



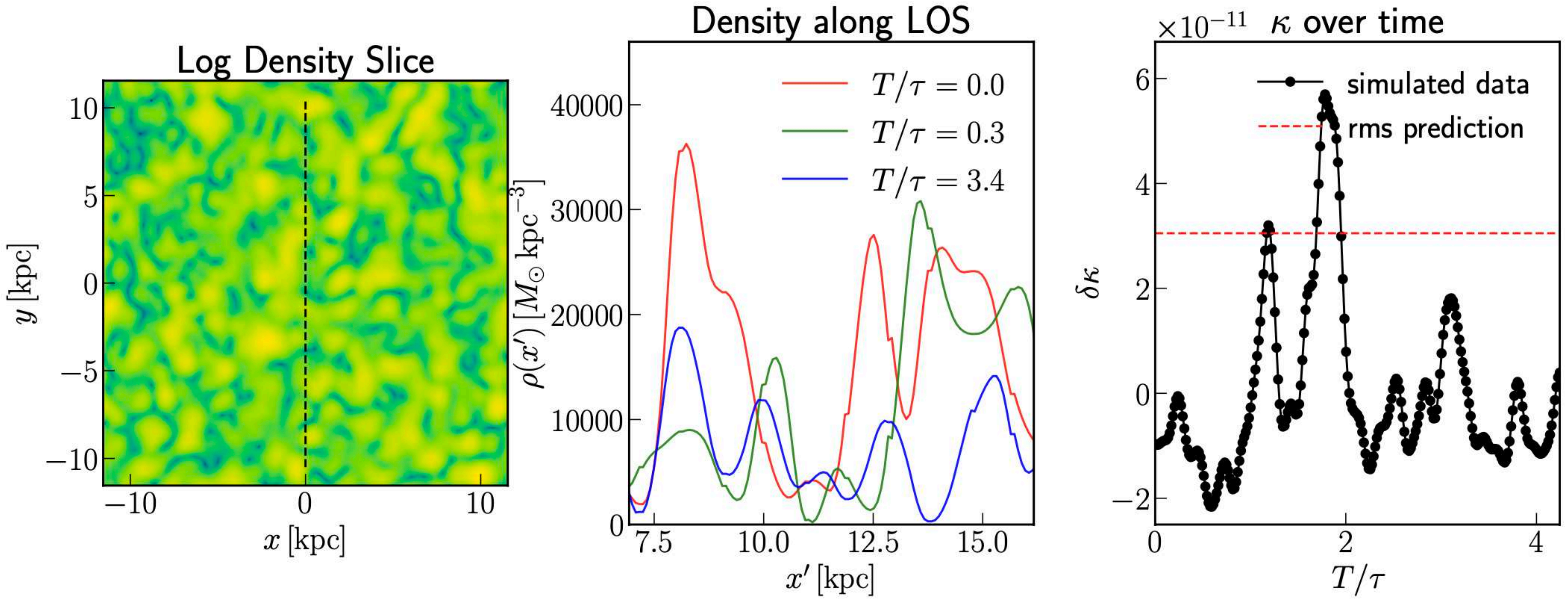
Lensing

Lensing convergence:

observer at the origin and source a distance D away along the line of sight

$$\delta\kappa_{\rm gr} = \frac{4\pi G}{c^2}\int_0^D dx\,\frac{x(D-x)}{D}\,\delta\rho(x)$$

$\rho - \rho_{sm}$



We approximate the dark matter granules as a Gaussian random field with correlation length equal to the de Broglie wavelength, $\lambda = \hbar/m\sigma$, and expectation and variance given

$$\langle\delta\rho\rangle = 0 \text{ and } \langle\delta\rho^2\rangle = \rho_{sm}^2$$

$$\delta\kappa_{\rm rms}^{\rm gr} \sim 3\times 10^{-12}\left(\frac{m}{10^{-17}\,{\rm eV}}\right)^{-1/2}\left(\frac{\sigma}{200\,{\rm km/s}}\right)^{-1/2}\left(\frac{\rho}{10^7\,{\rm M_\odot/kpc^3}}\right)\left(\frac{D}{\rm kpc}\right)^{3/4}$$

Stochastic lensing

Andrew Eberhardt, Wentao Lui, Yin Li
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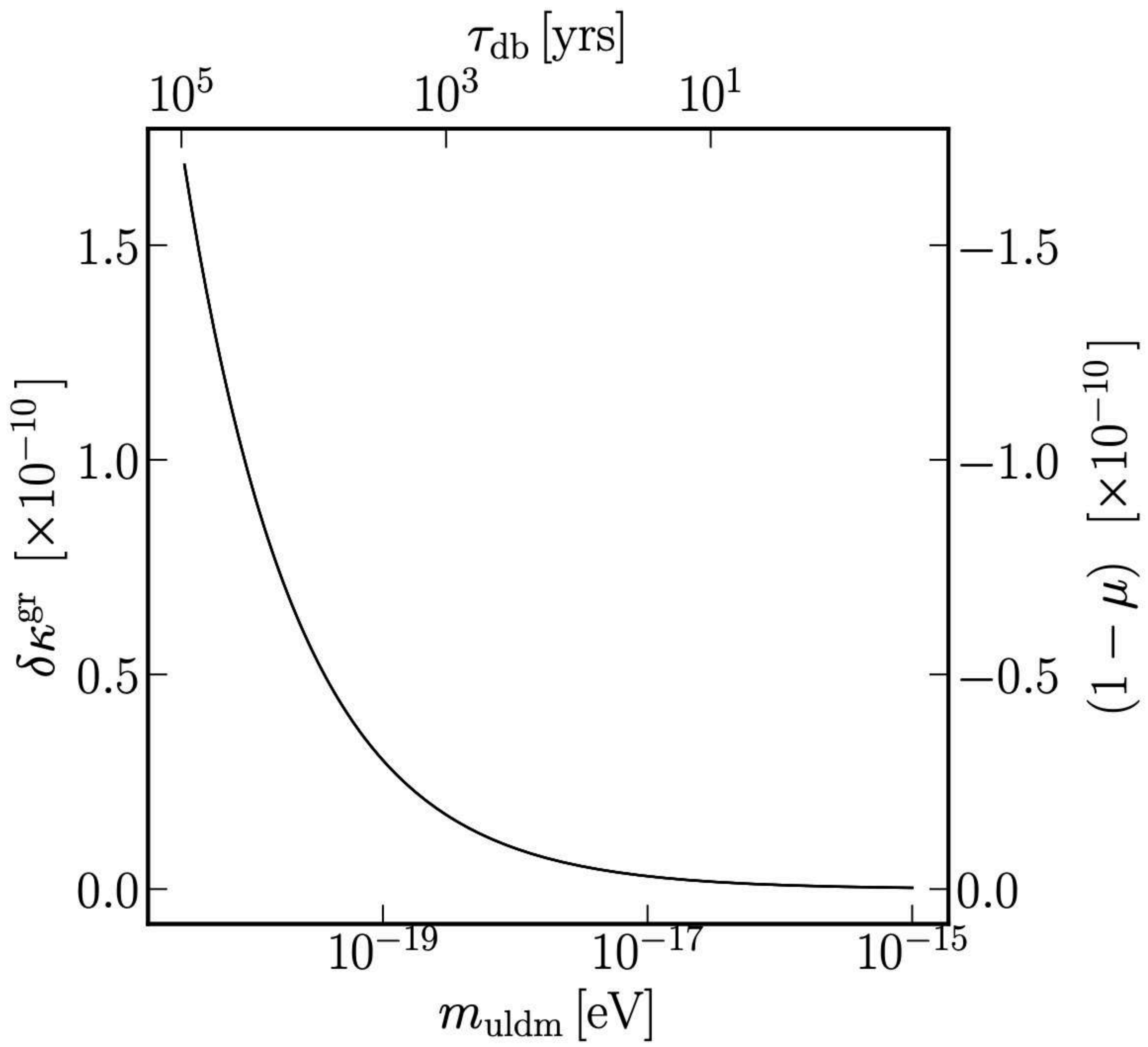

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Andrew Eberhardt, Wentao Lui, Yin Li and Shurui Lin, 2025

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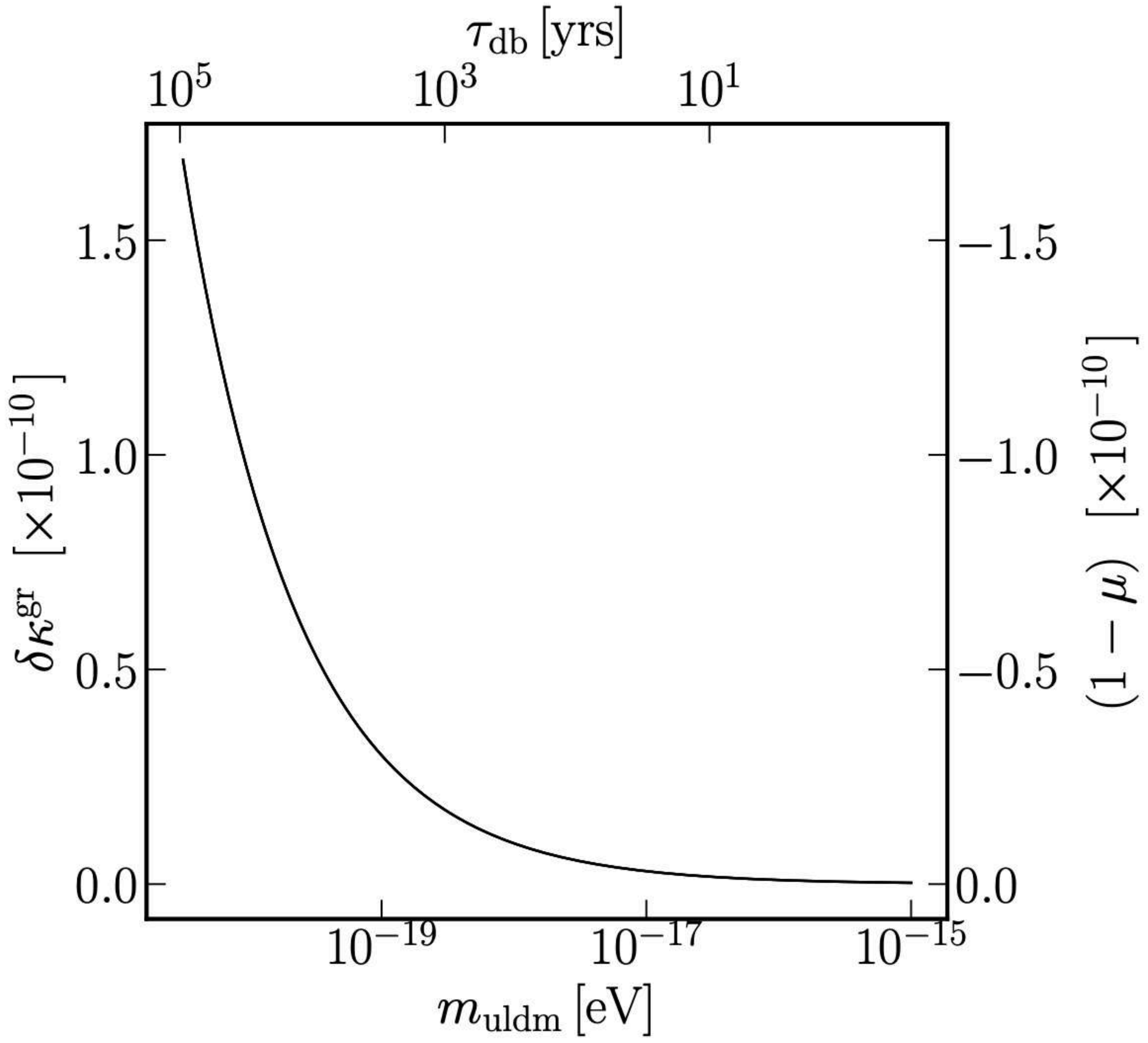


Observational effect

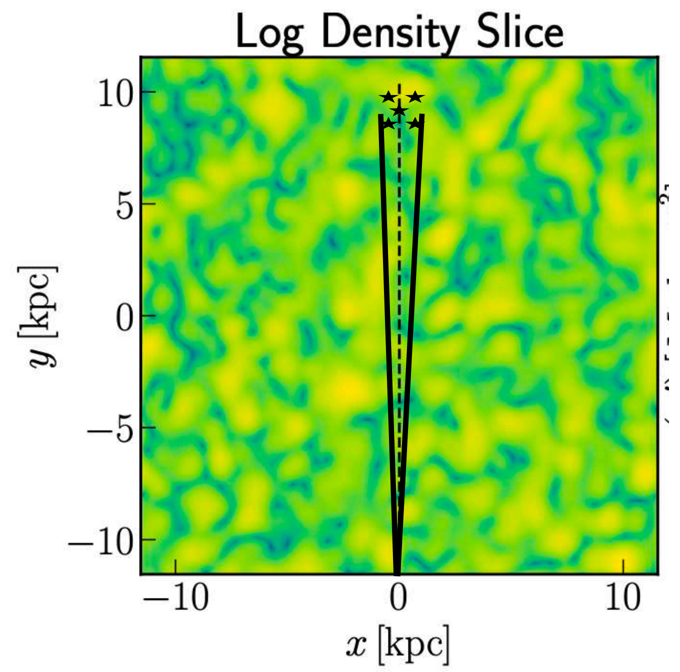
Every source in the galaxy will flicker with a period given by the mass

$$\tau_{\rm db} = 2\pi\hbar/m\sigma^2 \sim 30\left(\frac{10^{-17}\,{\rm eV}}{m}\right)\left(\frac{200\,{\rm km/s}}{\sigma}\right)^2\,{\rm yrs}\,,$$

Objects to use?

Ex.: globular cluster, star, …

(Work in progress)
FRB diffraction
W/ Ue-li Pen

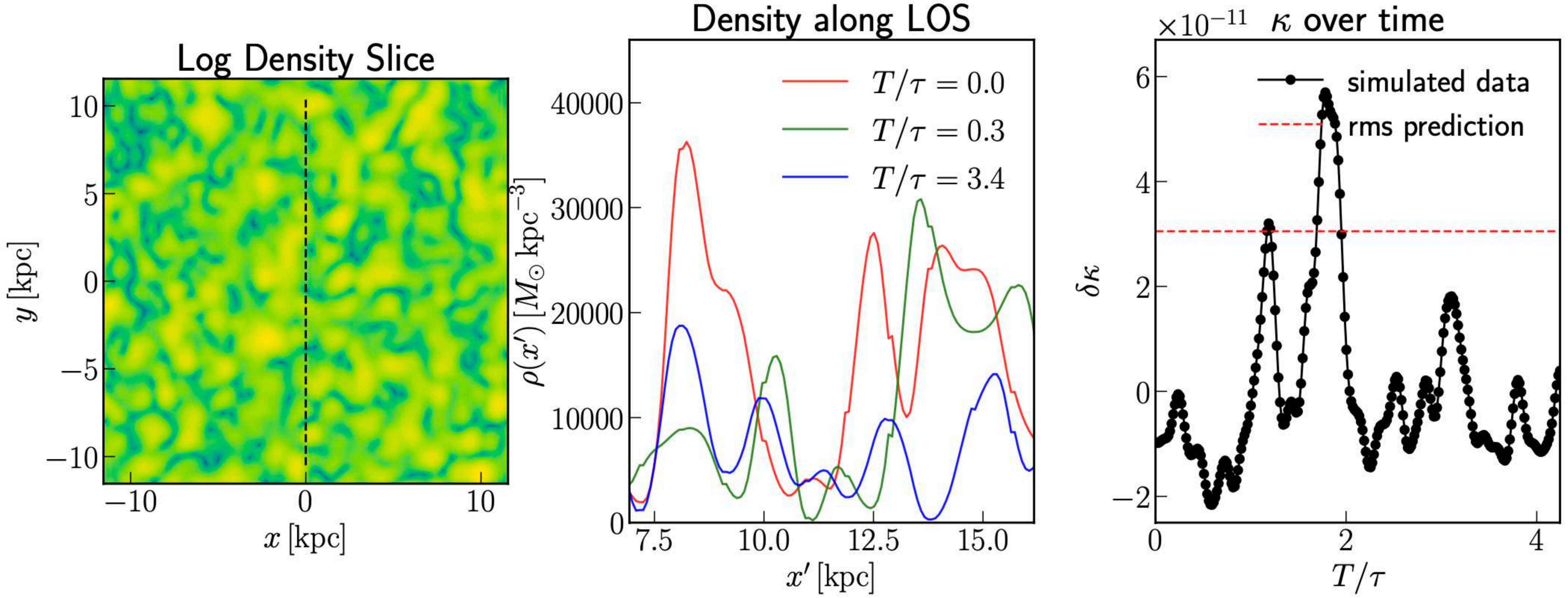


Stochastic lensing

Andrew Eberhardt, Wentao Lui, Yin Li and Shurui Lin, 2025

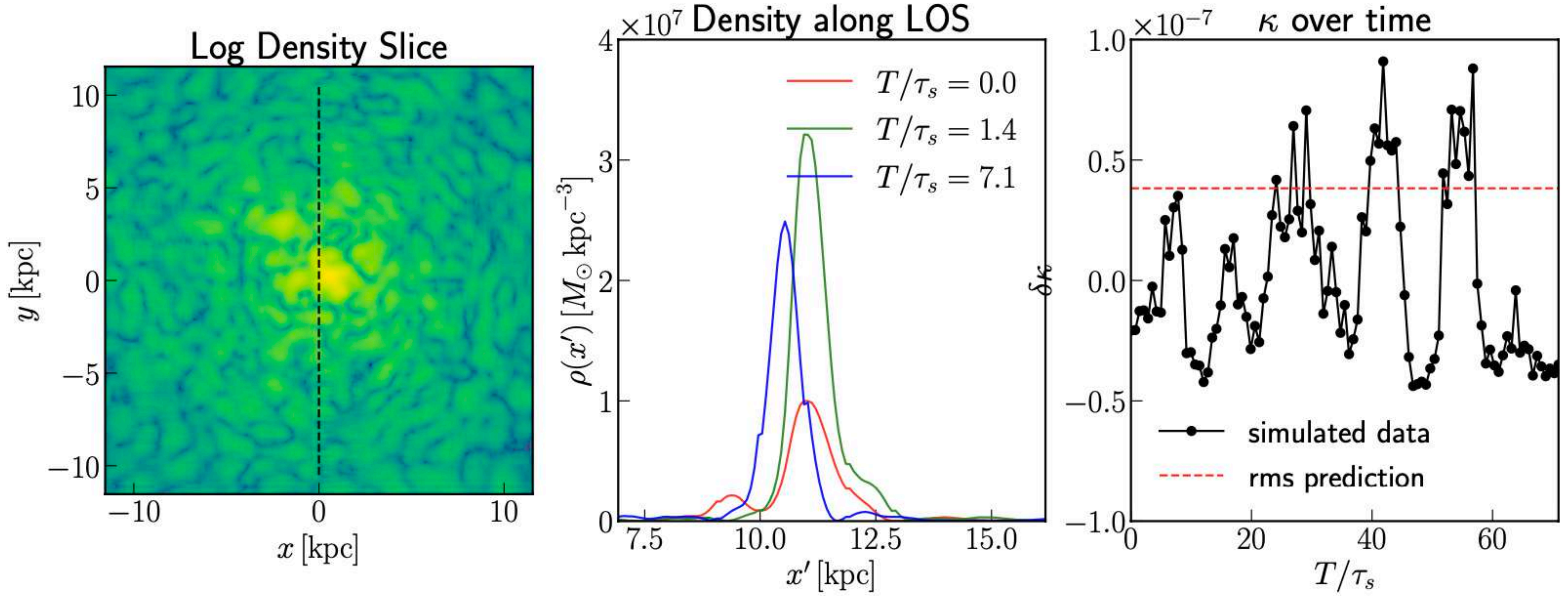
Granules $\sim \mathcal{O}(10^{-17})\,\mathrm{eV}$

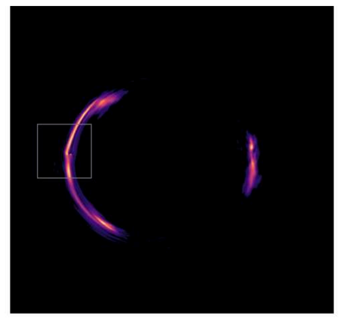
$$\delta\kappa^{\mathrm{gr}}_{\mathrm{rms}} \sim 3\times 10^{-12}\left(\frac{m}{10^{-17}\,\mathrm{eV}}\right)^{-1/2}\left(\frac{\sigma}{200\,\mathrm{km/s}}\right)^{-1/2}\times\left(\frac{\rho}{10^{7}\,\mathrm{M_\odot/kpc^3}}\right)\left(\frac{D}{\mathrm{kpc}}\right)^{3/4}$$



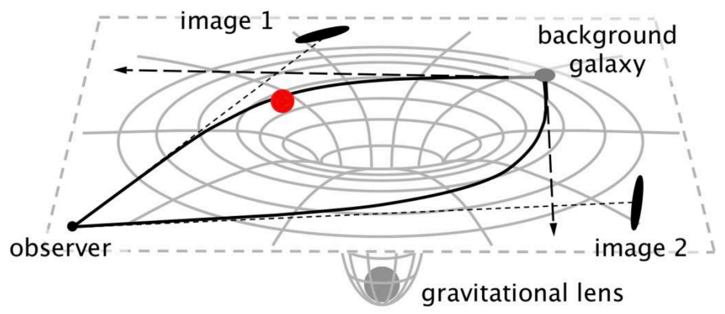
Soliton oscillation $\sim \mathcal{O}(10^{-23} - 10^{-22})\,\mathrm{eV}$

$$\kappa^{\mathrm{s}}_{\mathrm{rms}} \sim 10^{-8}\left(\frac{m}{10^{-23}\,\mathrm{eV}}\right)^{-2}\left(\frac{r_c}{\mathrm{kpc}}\right)^{-3}\left(\frac{D_s(D-D_s)/D}{\mathrm{kpc}}\right)$$





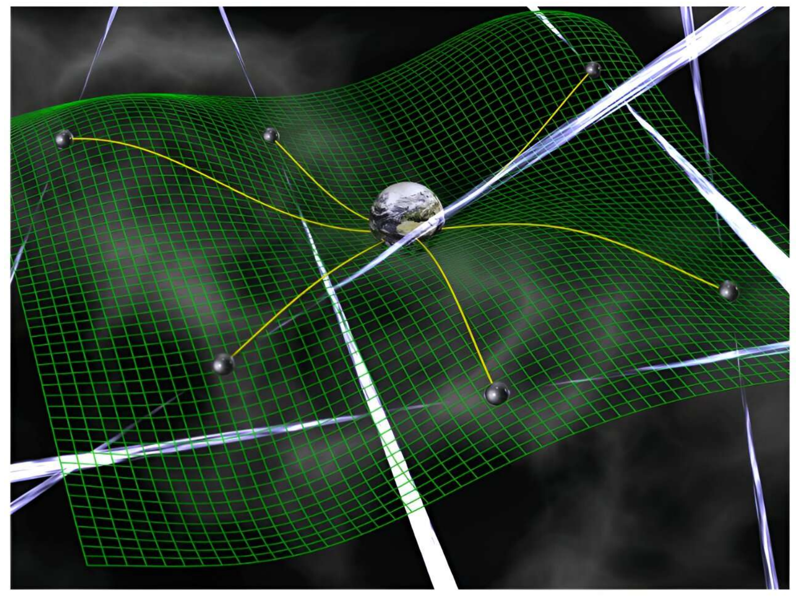
Strong lensing



axion-photon coupling

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

Pulsar Timing Array



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

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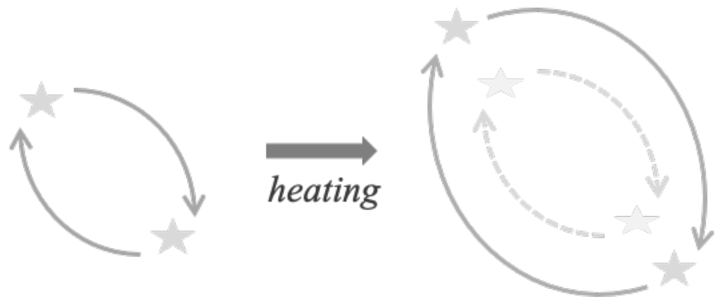
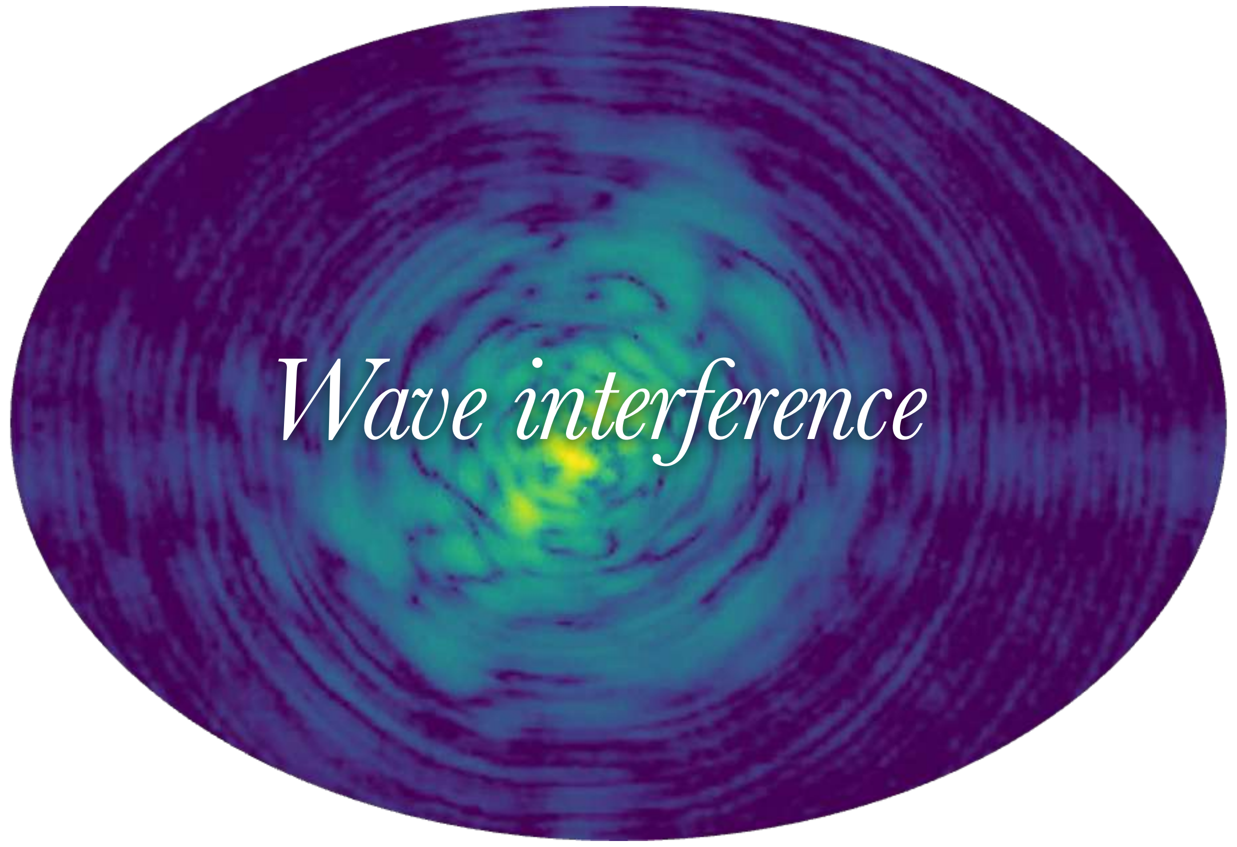
Binary stars



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



Mass, spin (# particles), fraction self interaction

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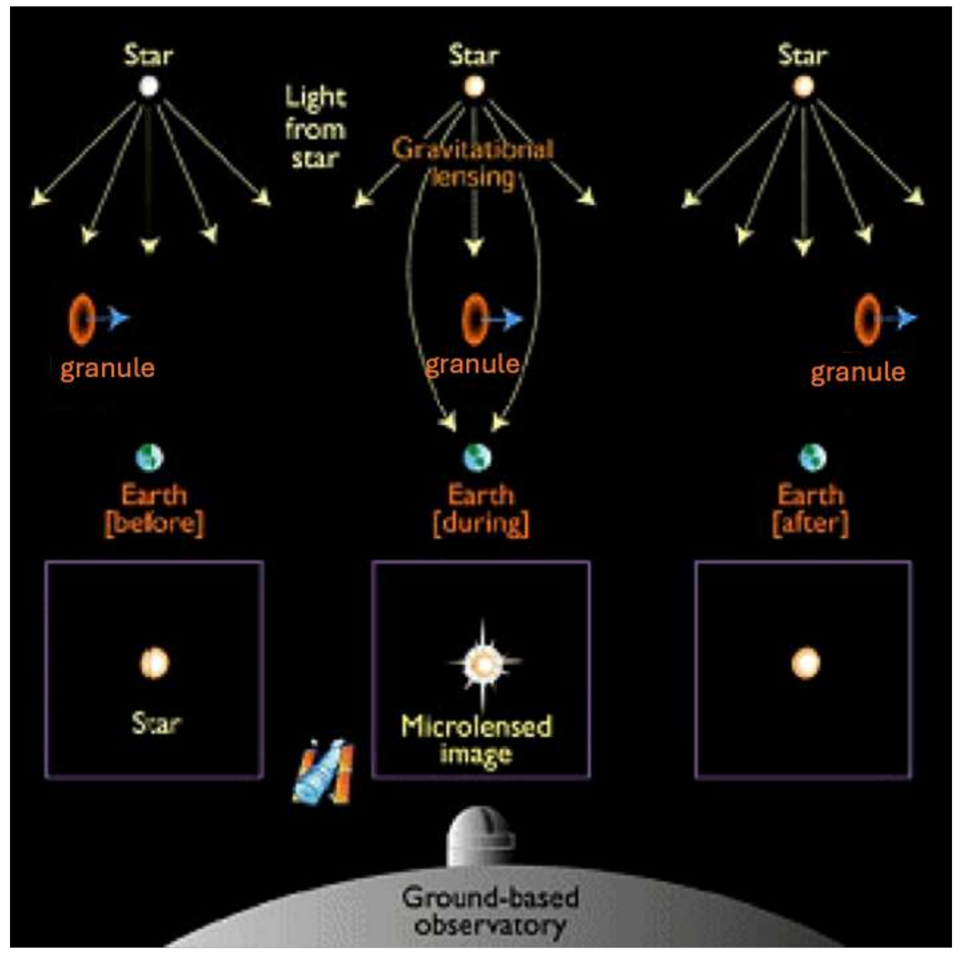

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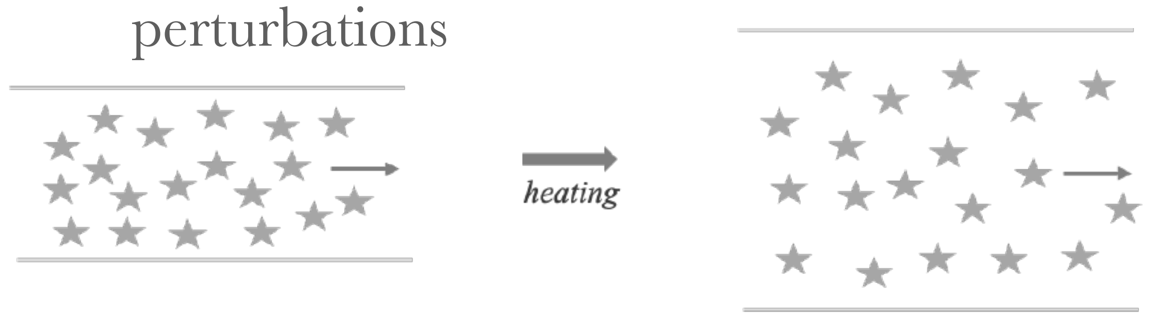
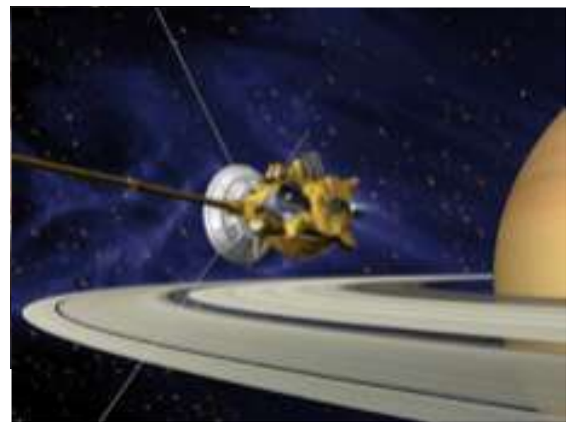
Stellar streams

Heating + coherent perturbations



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

Solar system



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

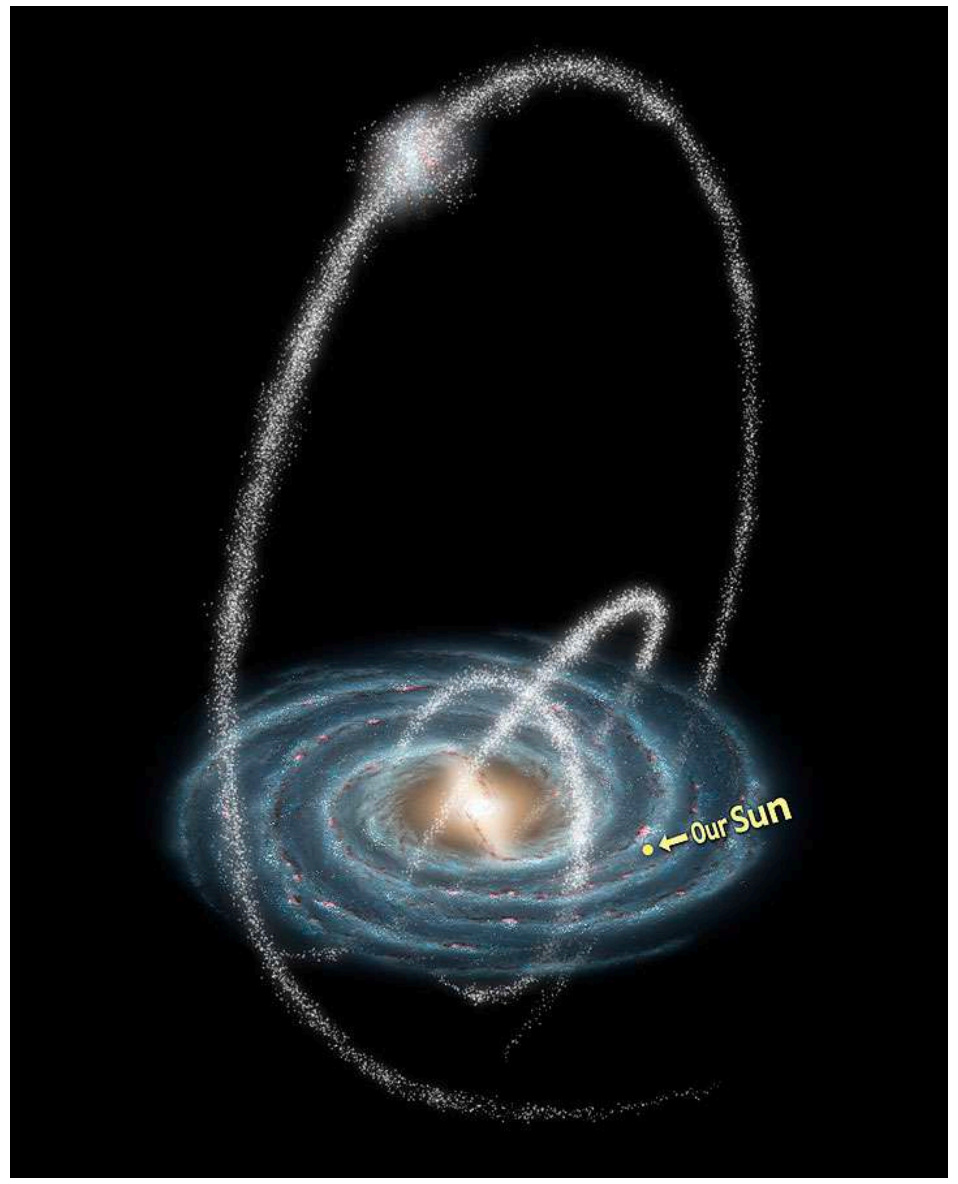
axion-photon coupling

Stellar streams

Stellar streams are a stream of stars orbiting a galaxy which are remnants of a tidally disrupted globular clusters or dwarf galaxies, that was torn apart by a more massive system.

These streams are usually thin and very long, extending to dozens of kpc across the 3-dimensions of the halo, and wrap around the disrupting galaxy.

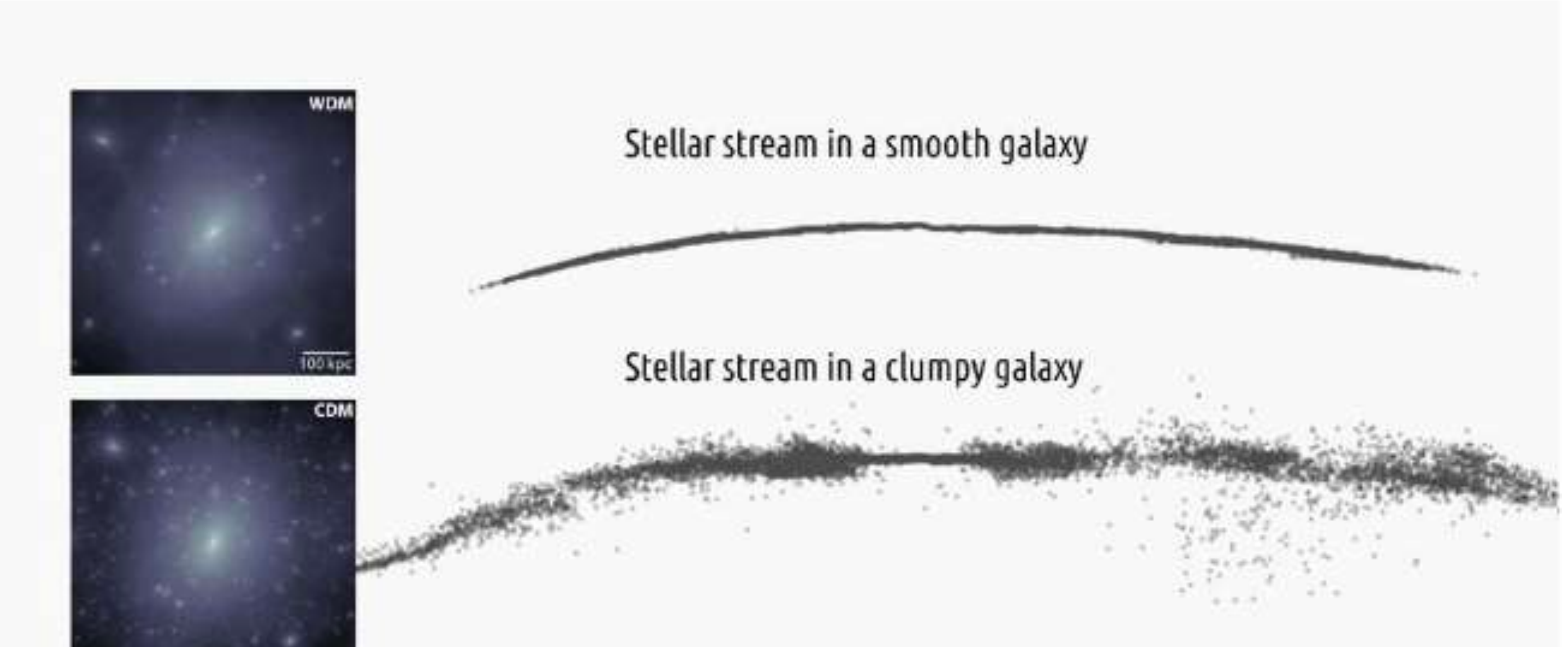
Streams are good dynamical probes since they are initially cold and very sensitive to the gravitational potential



NASA

⟶ Substructures present in the halo when encounter the streams disturb it causing:

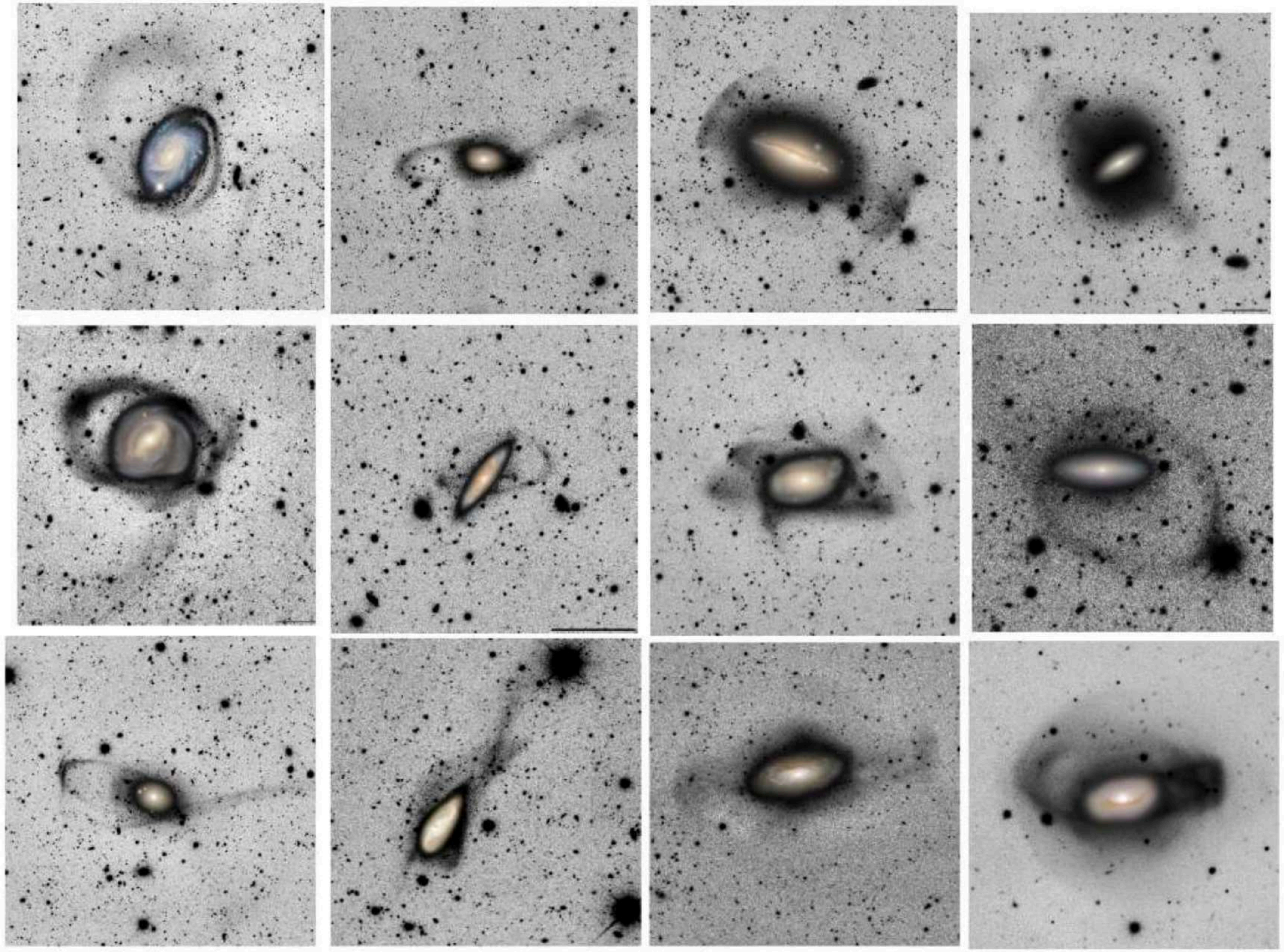
- Dynamical heating: which are changes in the velocities in the stream,
- Disturbances in the morphology of the stream: formation of gaps which are underdensities caused by the sub-halos encountered



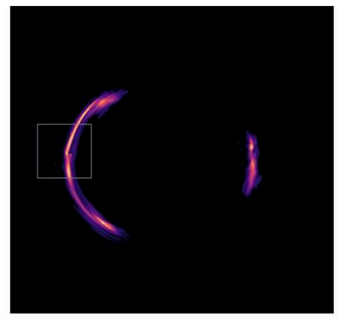
Bonaca et al. (2014)

It is estimated that we can observe gaps in streams cause by substructures with mas as low as $M \sim 10^5 - 10^6\, M_\odot$ (Erkal and Belokurov 2015; Erkal et al. 2016; Bovy et al. 2017)

Stellar streams



Martinez-Delgado et al. 2021;arXiv:2104.06071



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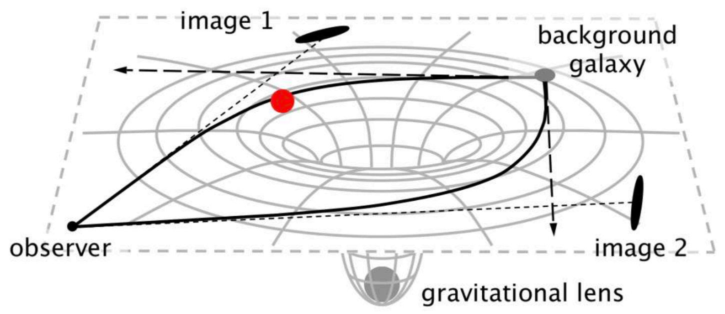

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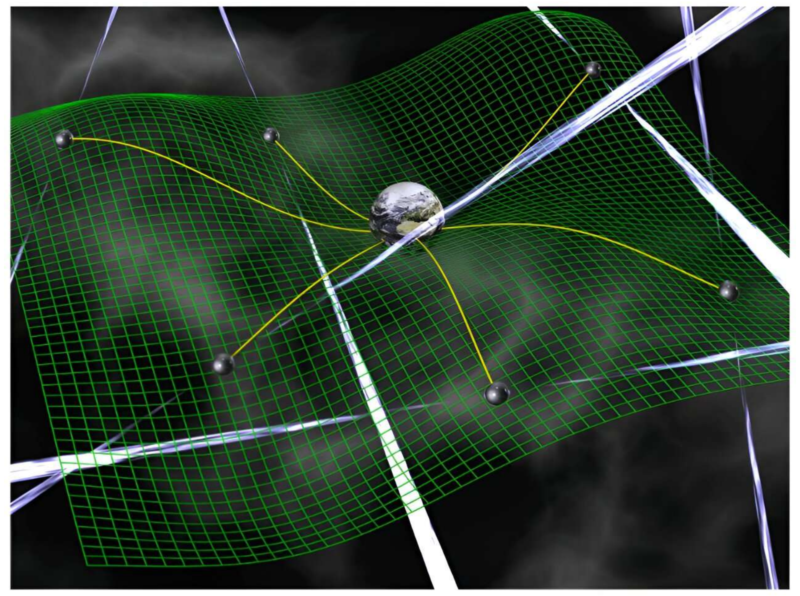
Pulsar Timing Array



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

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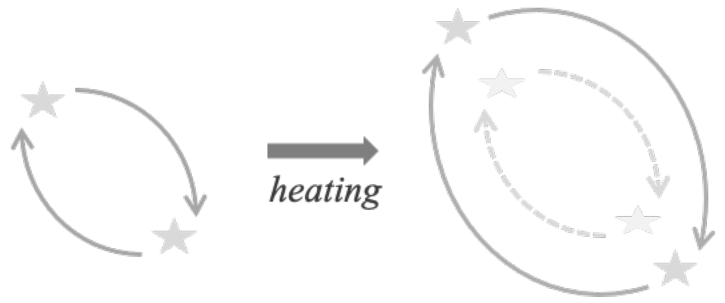

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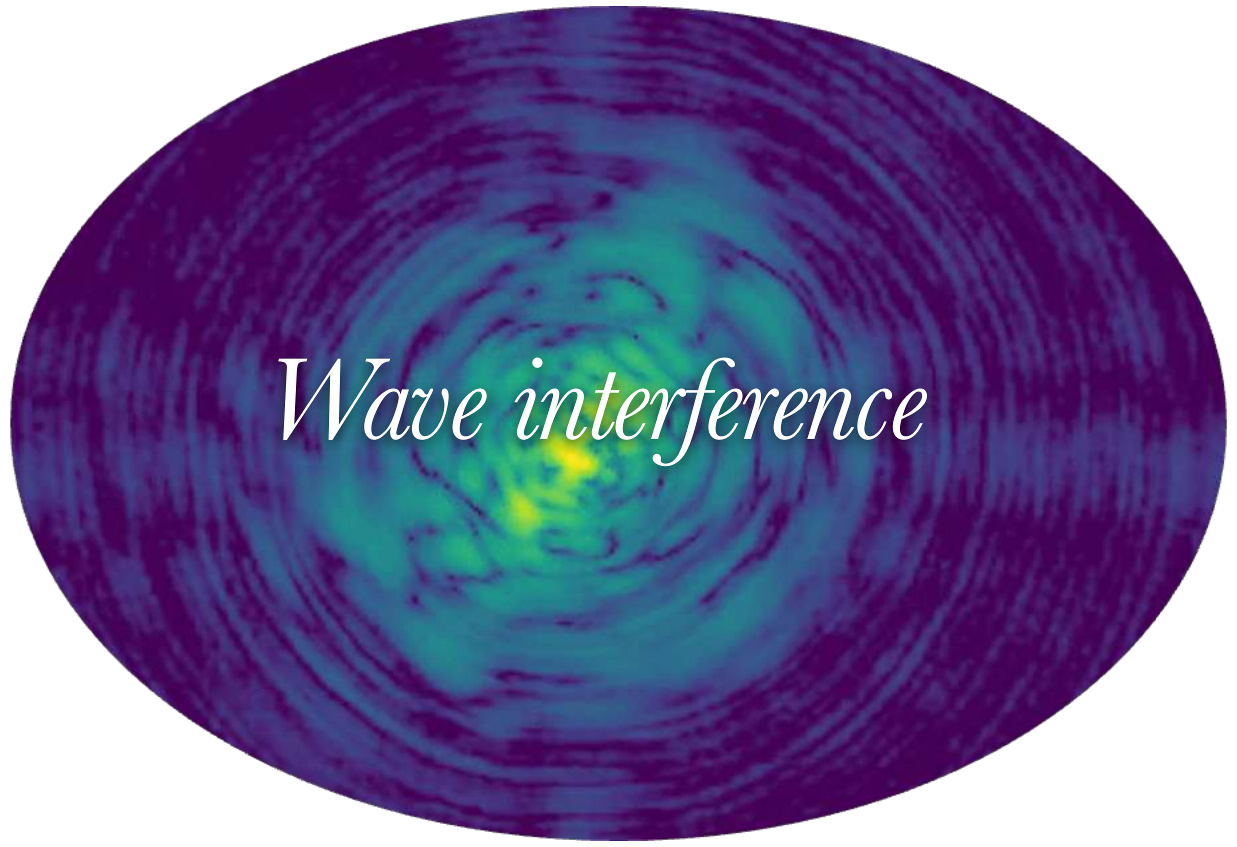
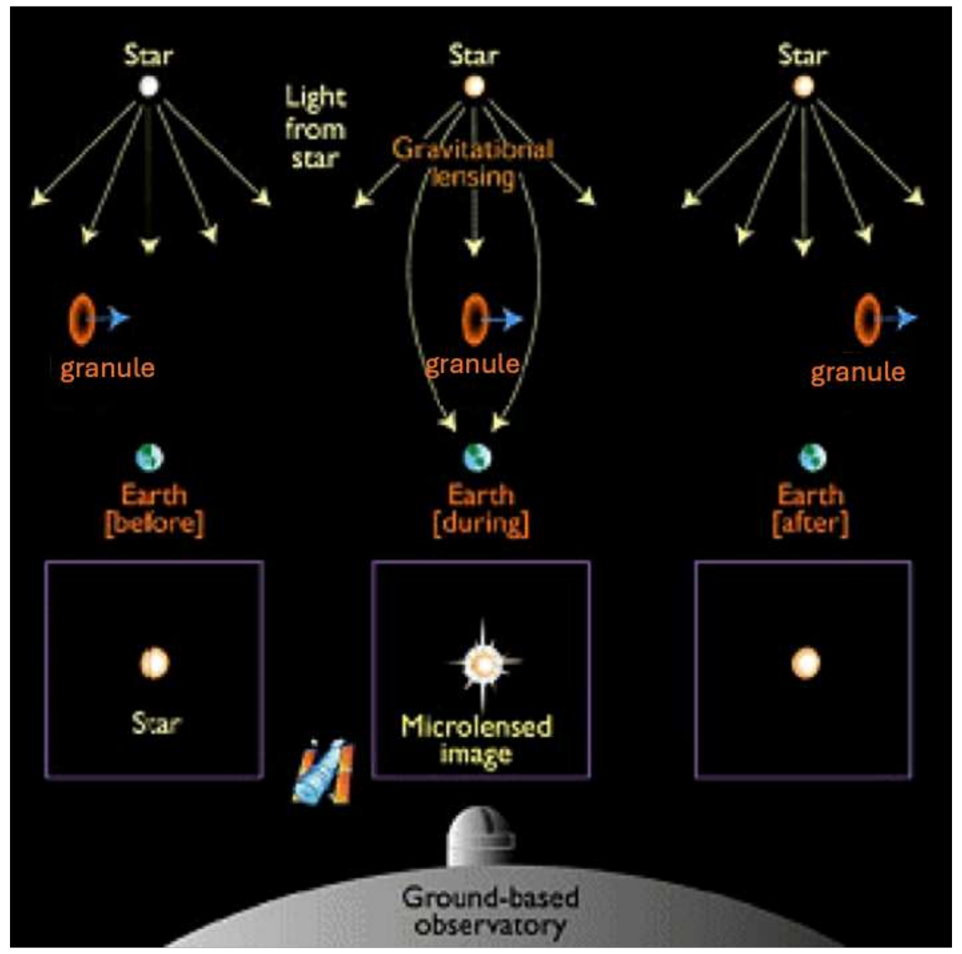


Mass, spin (# particles), fraction self interaction

Stochastic lensing



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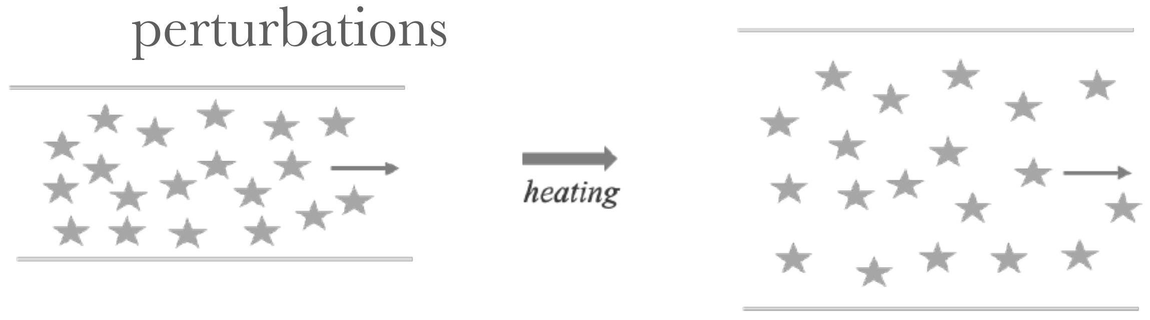
Stellar streams

Heating + coherent perturbations



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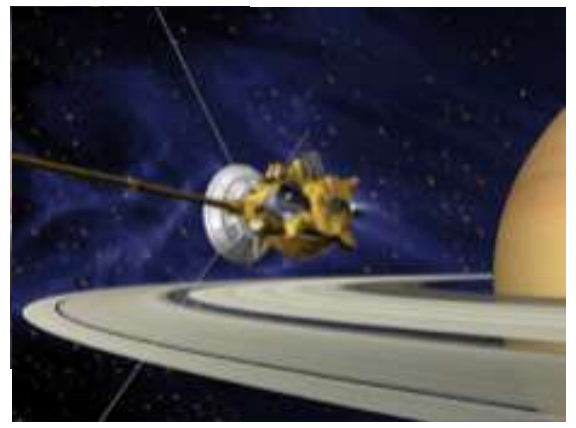
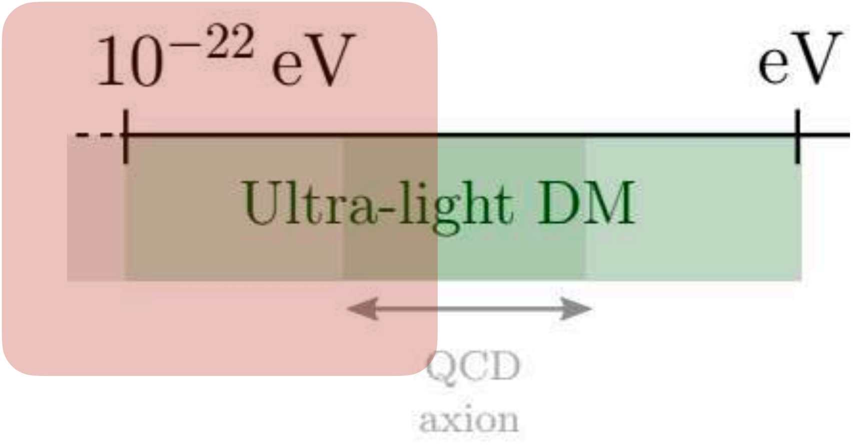
Solar system



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

axion-photon coupling

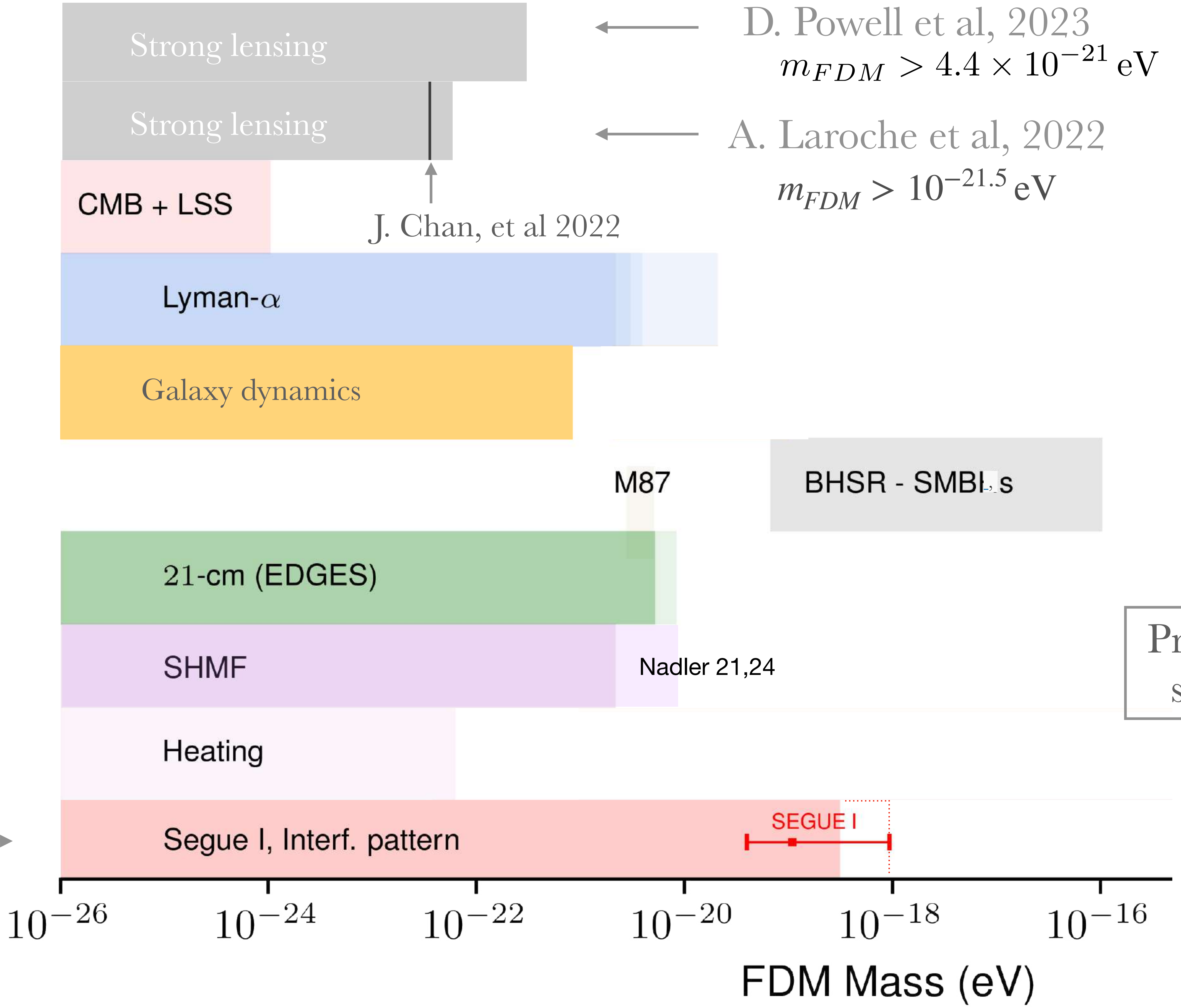
Interference patterns - granules



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



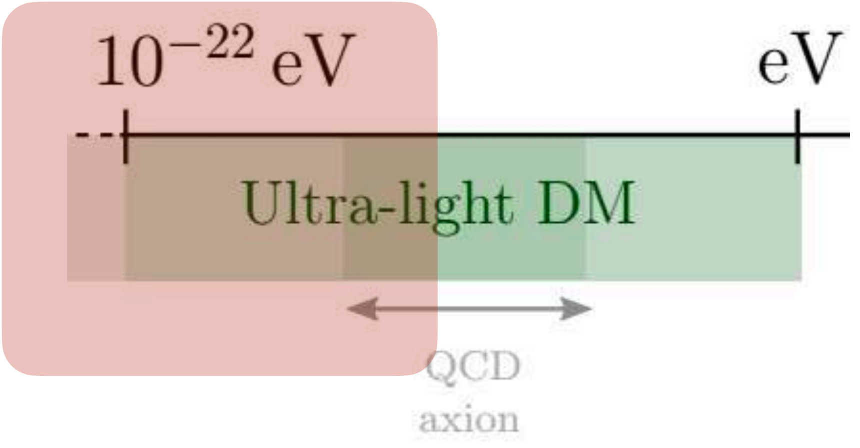
Probing the fuzziness on smaller and smaller scales (larger masses) - still wave behavior!

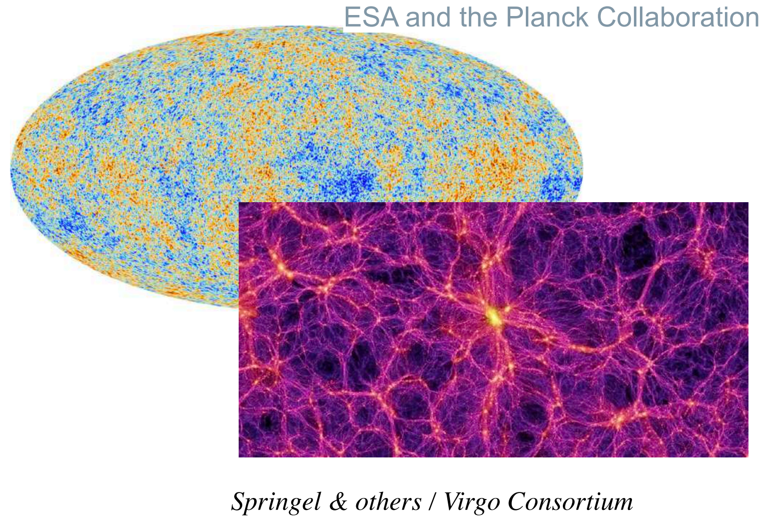
Stellar heating

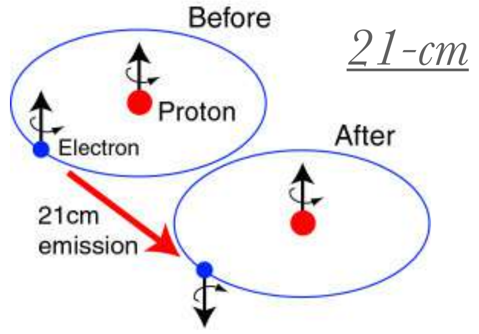
Dalal et al, 2022
$m_{FDM} > 3 \times 10^{-19}$ eV

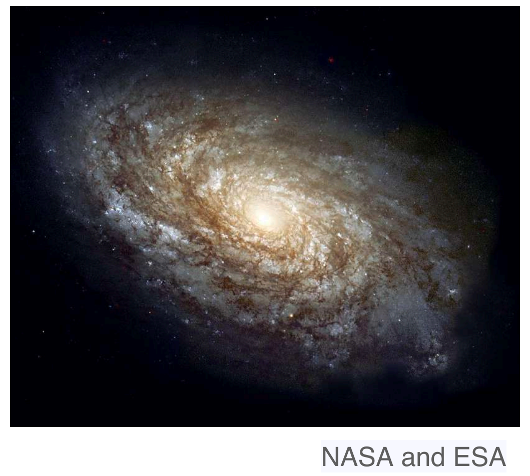
Current status

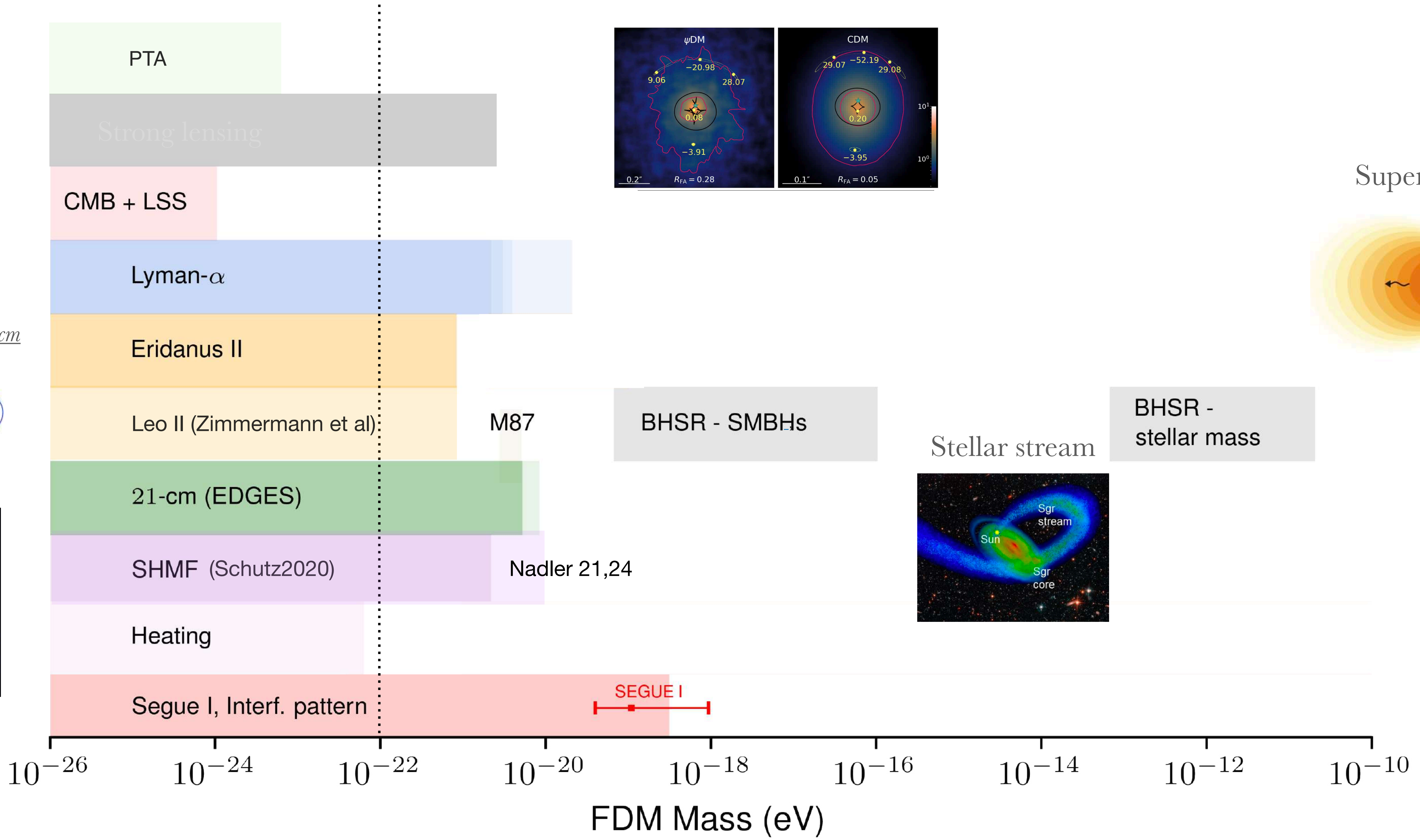
Fuzzy Dark Matter - bounds on the mass

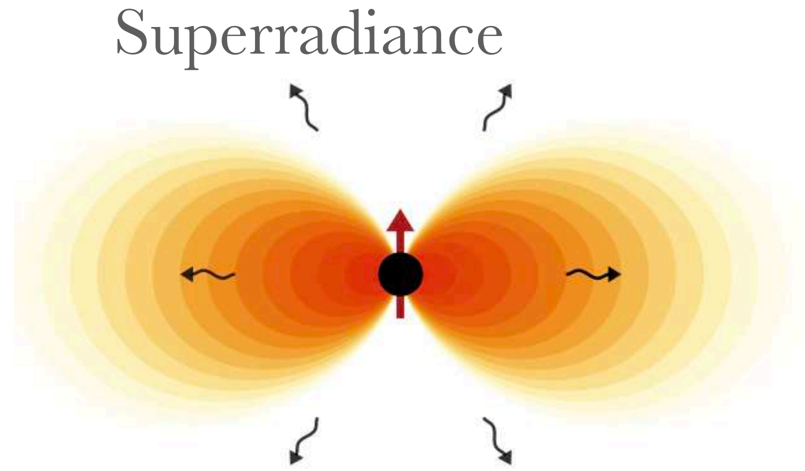


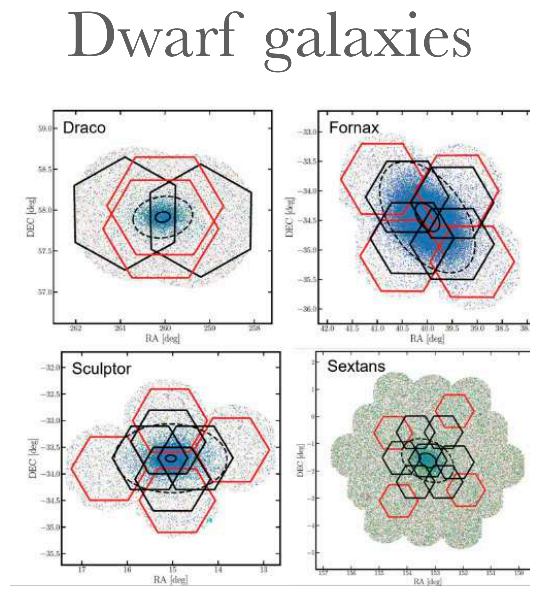










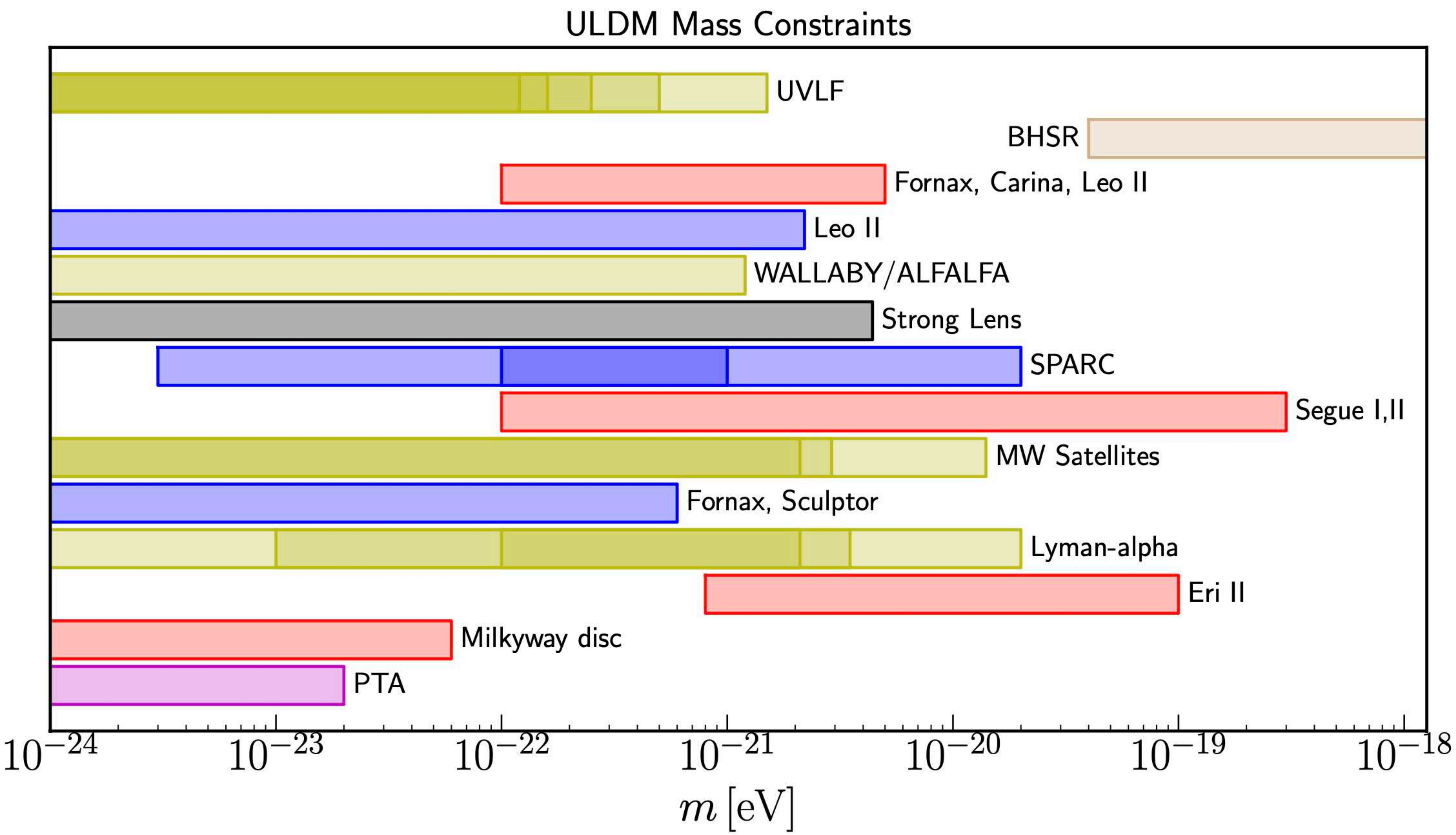


"Ultra-light dark matter", **E.F.**, 2020

Current status

Fuzzy Dark Matter - bounds on the mass

Review: Eberhardt, EF (to appear)



Bounds depend on assumptions, simplifications, simulations, …
And can be conservative or best case scenario.
Systematic effects!
Careful when interpreting them!

Current status

Fuzzy Dark Matter - bounds on the mass

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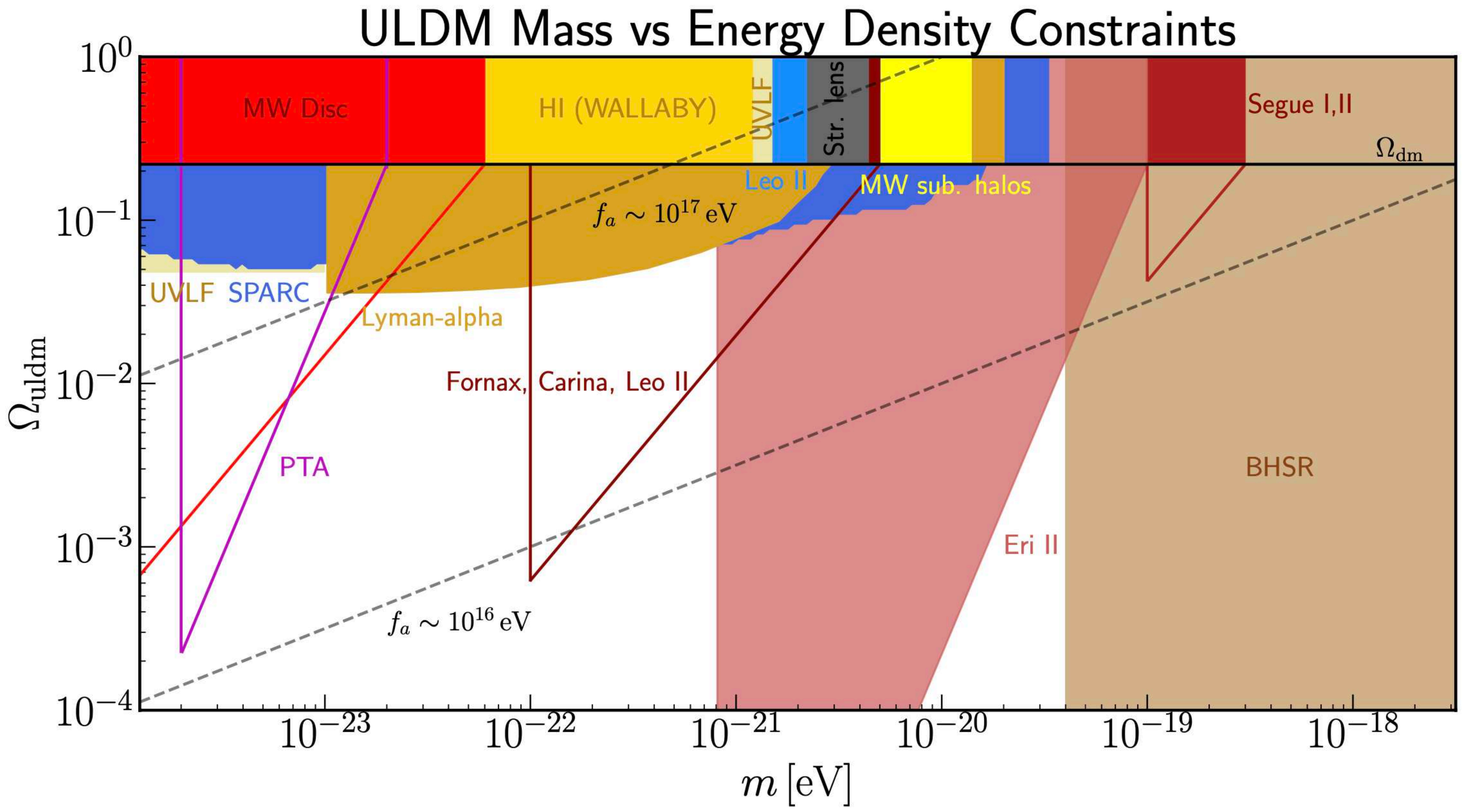


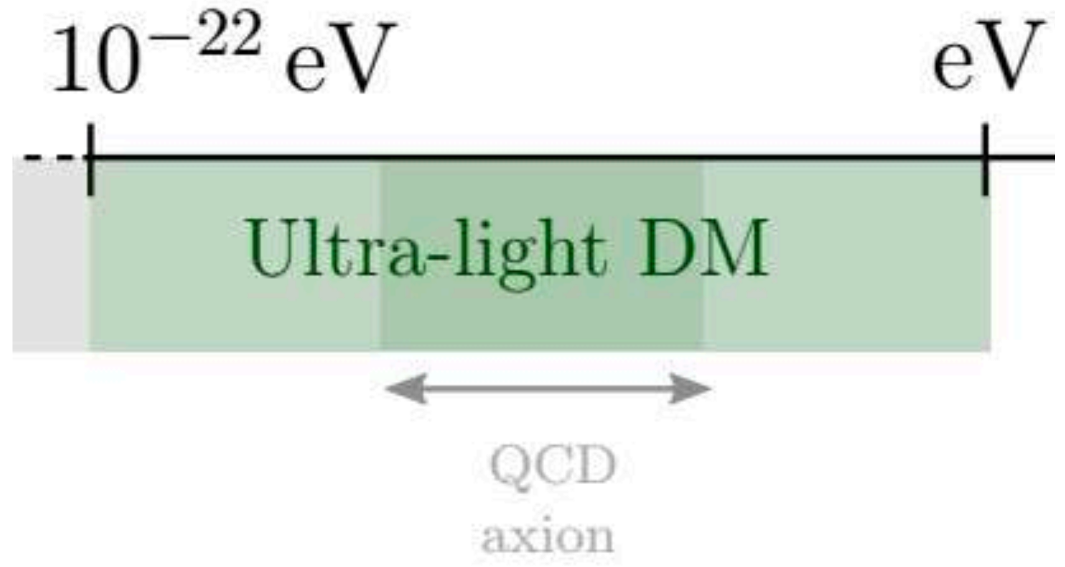
Much more:

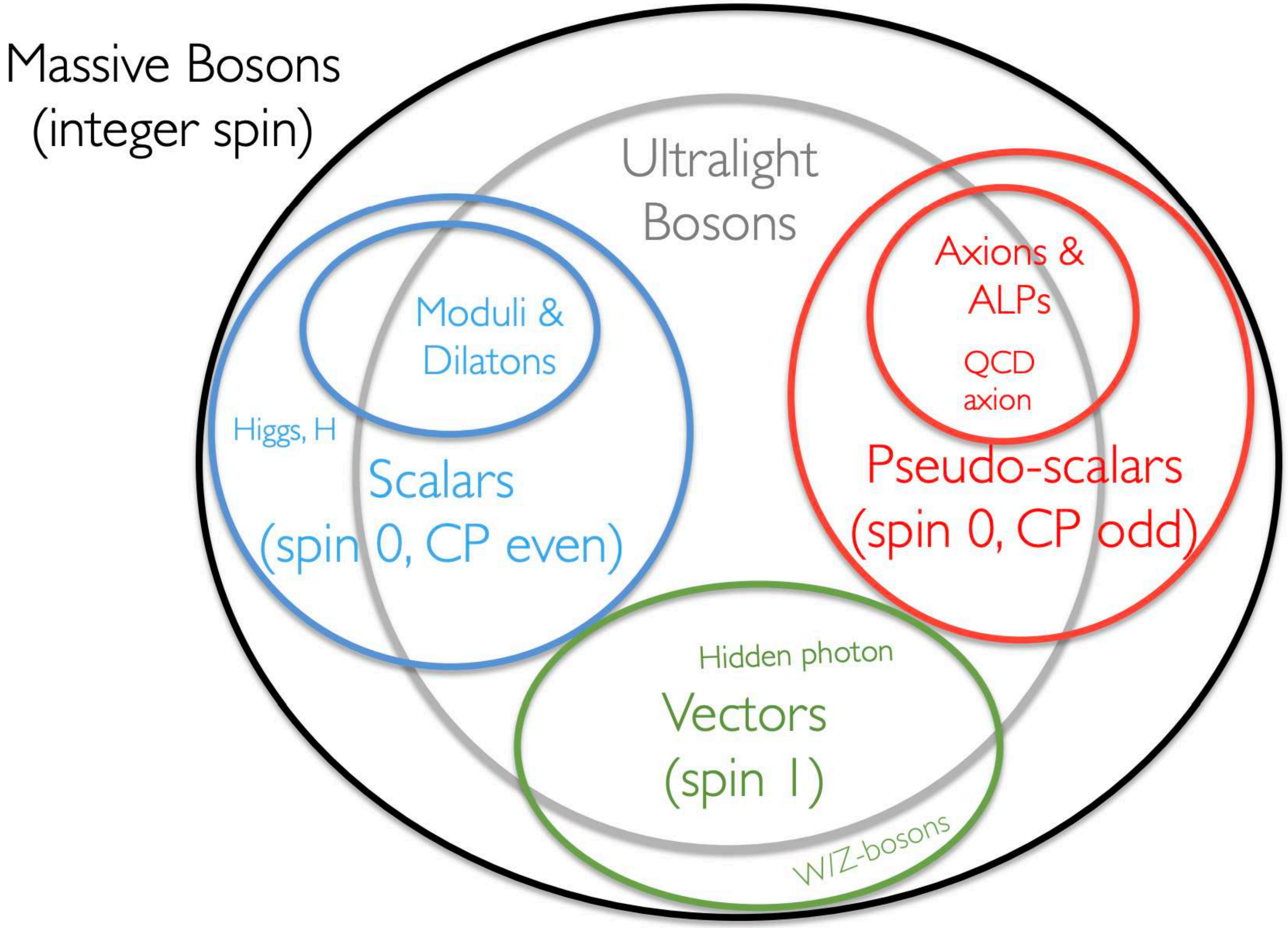
- ULDM not 100%
- Multiple axions
- Add self-interaction
- Couplings
- Spin

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

ULDM candidates

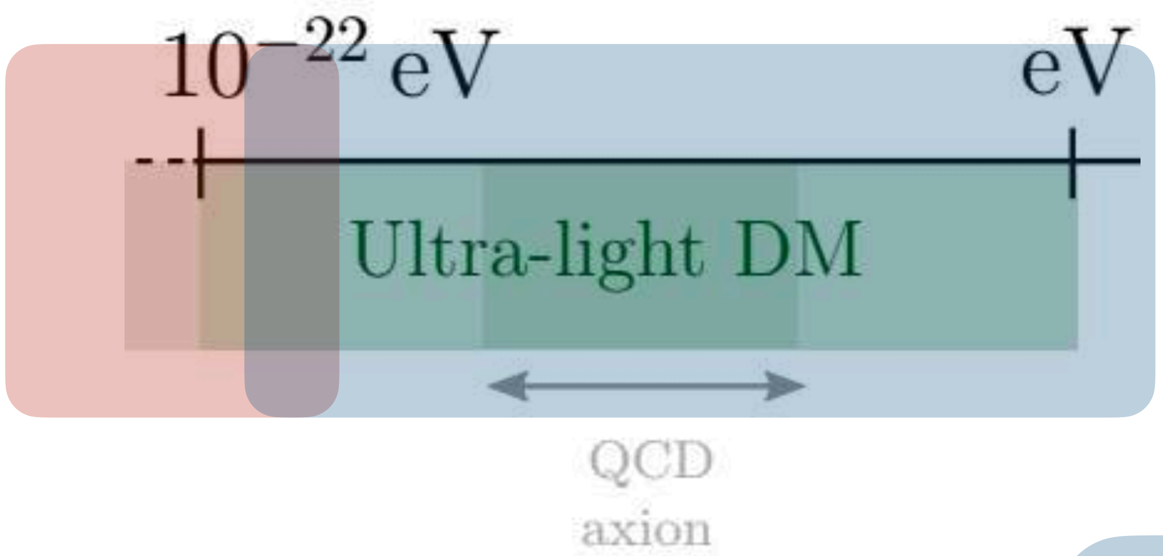
Many extensions of the Standard Model predict additional massive bosons





Ref.: Chadha-Day et al 2022

How to search for ULDM?

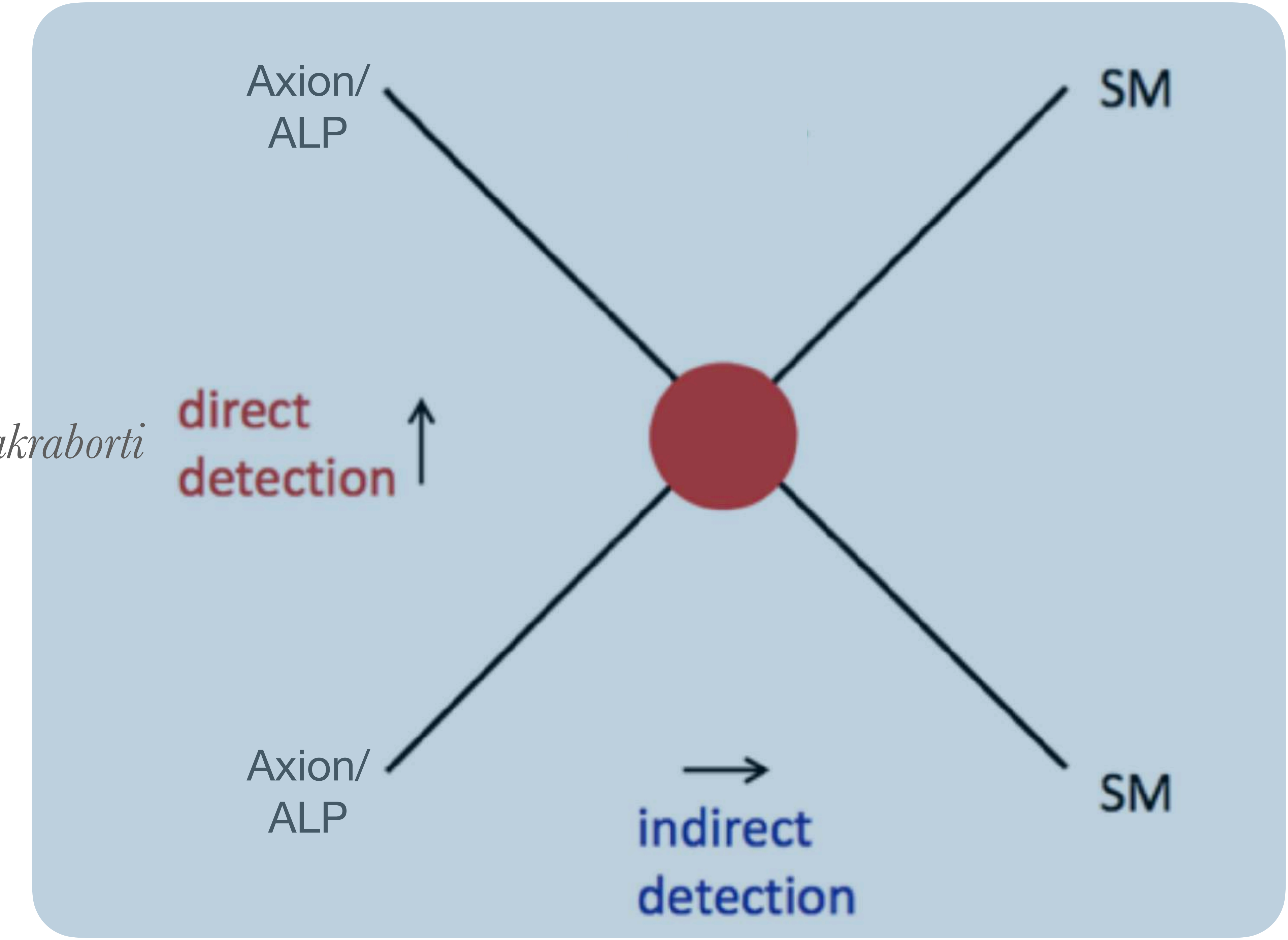


Gravitationally
Cosmological and astrophysical searches

Talk by

Sreemanti Chakraborti

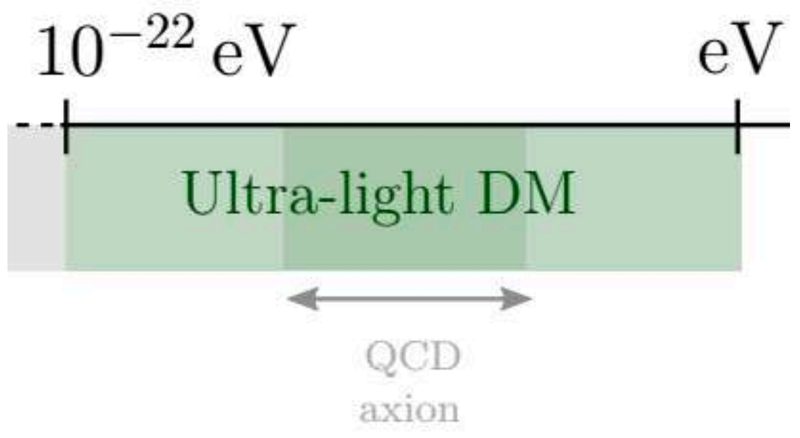
+



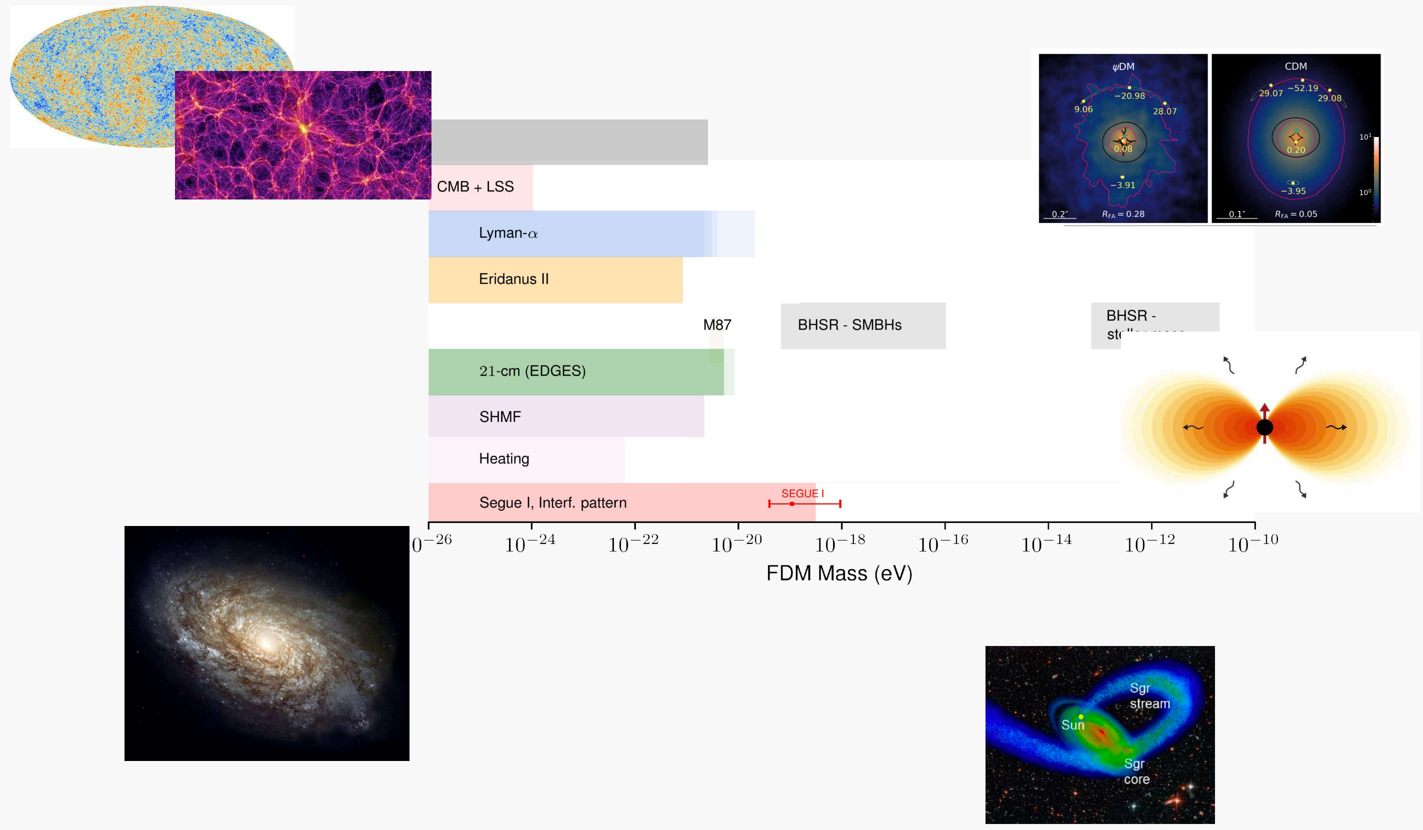
Talk by

Jamie McDonald

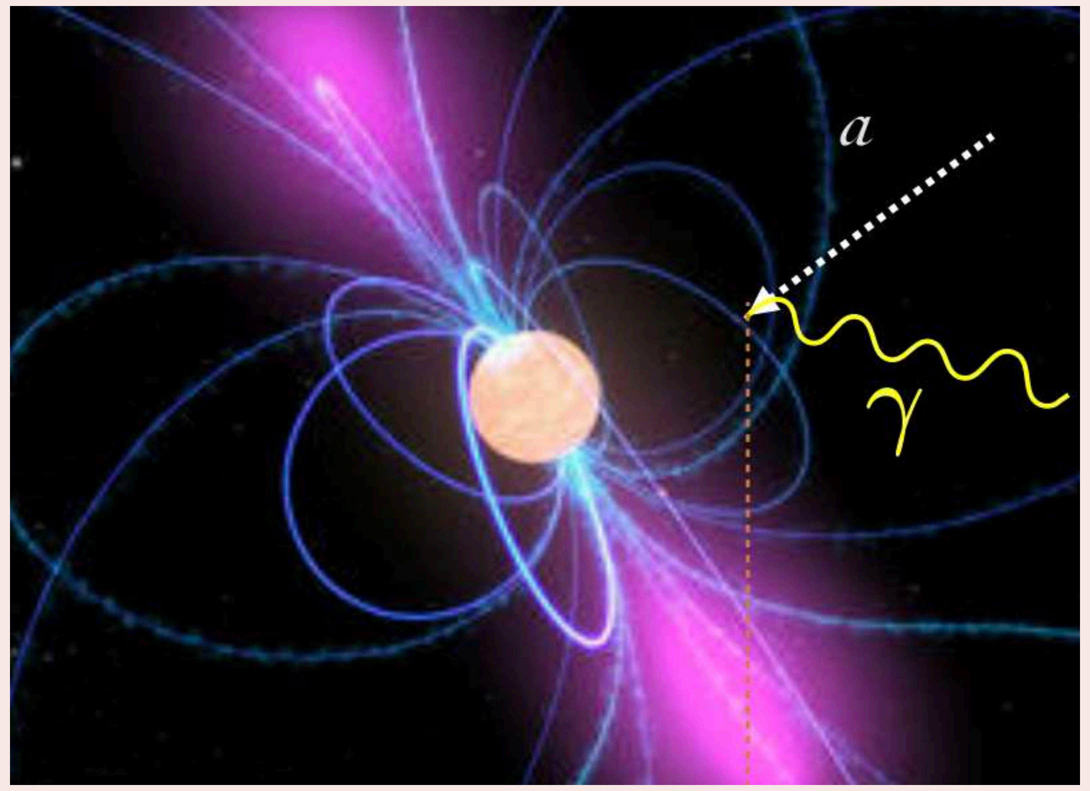
How to search for axions/ALPs?



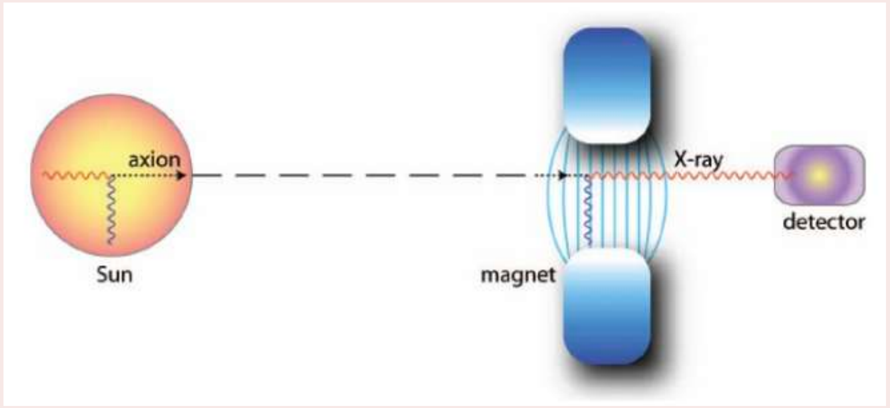
Cosmological and astrophysical searches

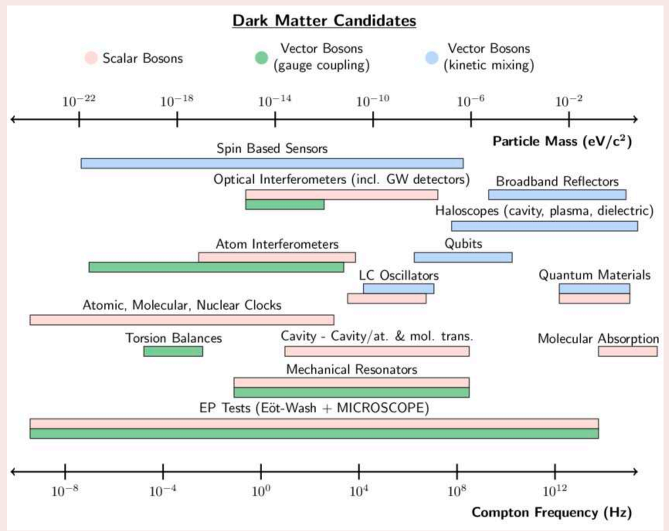


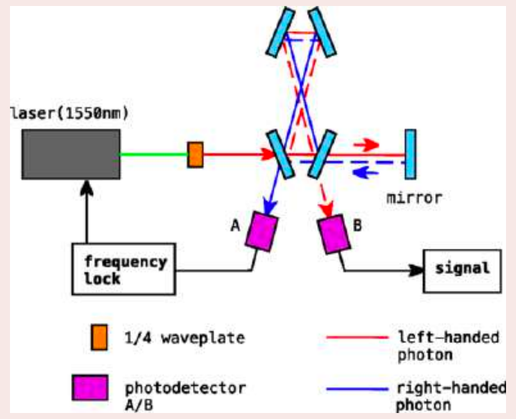
Indirect detection



"Direct detection" Axion/ALPs experiments

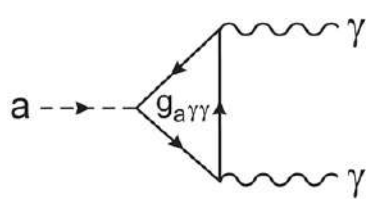


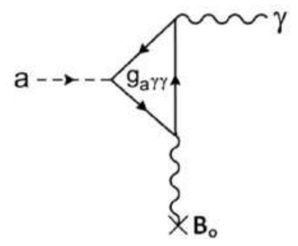


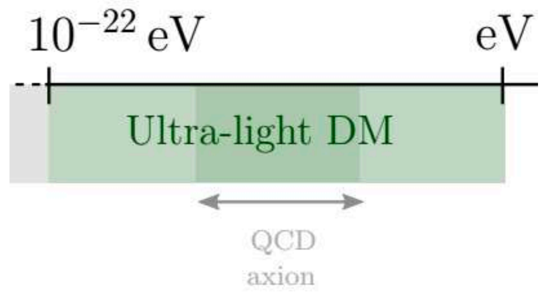


Gravitational

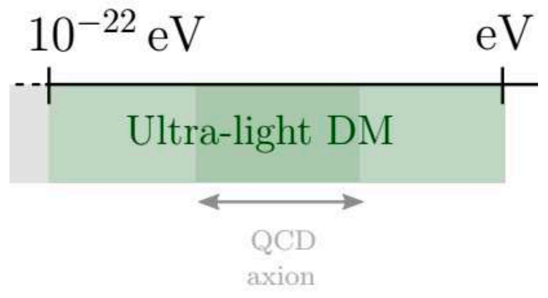
Interactions with the SM







Axion and ALPs interaction with the SM



Axion and ALPs interaction with the SM

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$
$$\widetilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$$
$$\mathbf{E} = -\nabla A_0 - \dot{\mathbf{A}}$$
$$\mathbf{B} = \nabla \times \mathbf{A}$$

Axions and ALPs interact with the standard model particles

Minimal definition: New light pseudoscalar, with coupling to photons and/or derivative couplings to fermions

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \frac{1}{2}m_a^2 a^2 - \frac{g_{a\gamma}}{4} a F_{\mu\nu}\widetilde{F}^{\mu\nu} + \partial_\mu a \sum_\psi \frac{g_{a\psi}}{2m_\psi}\left(\bar{\psi}\gamma^\mu\gamma^5\psi\right)$$

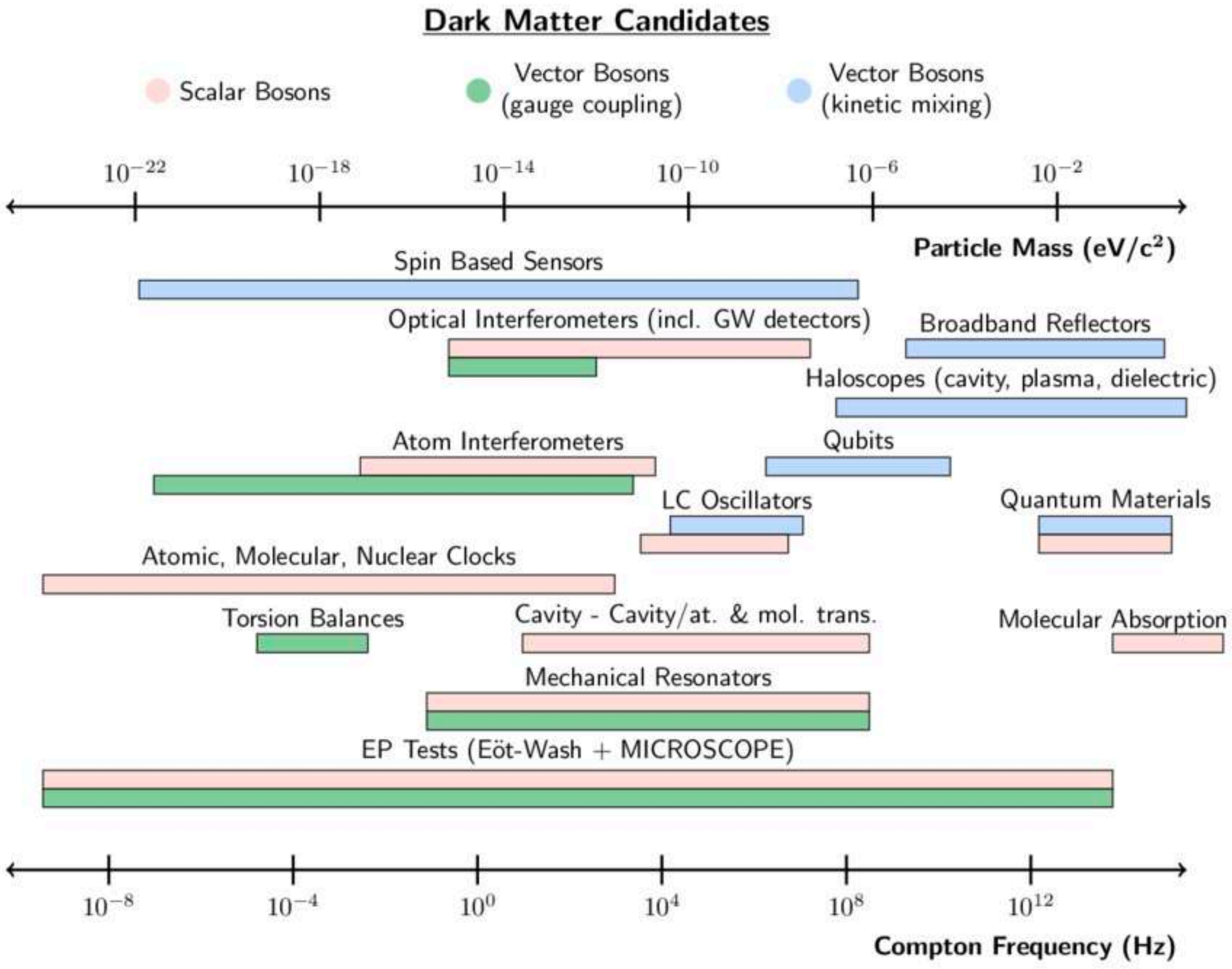
Not considering here

+ a few model-dependent assumptions

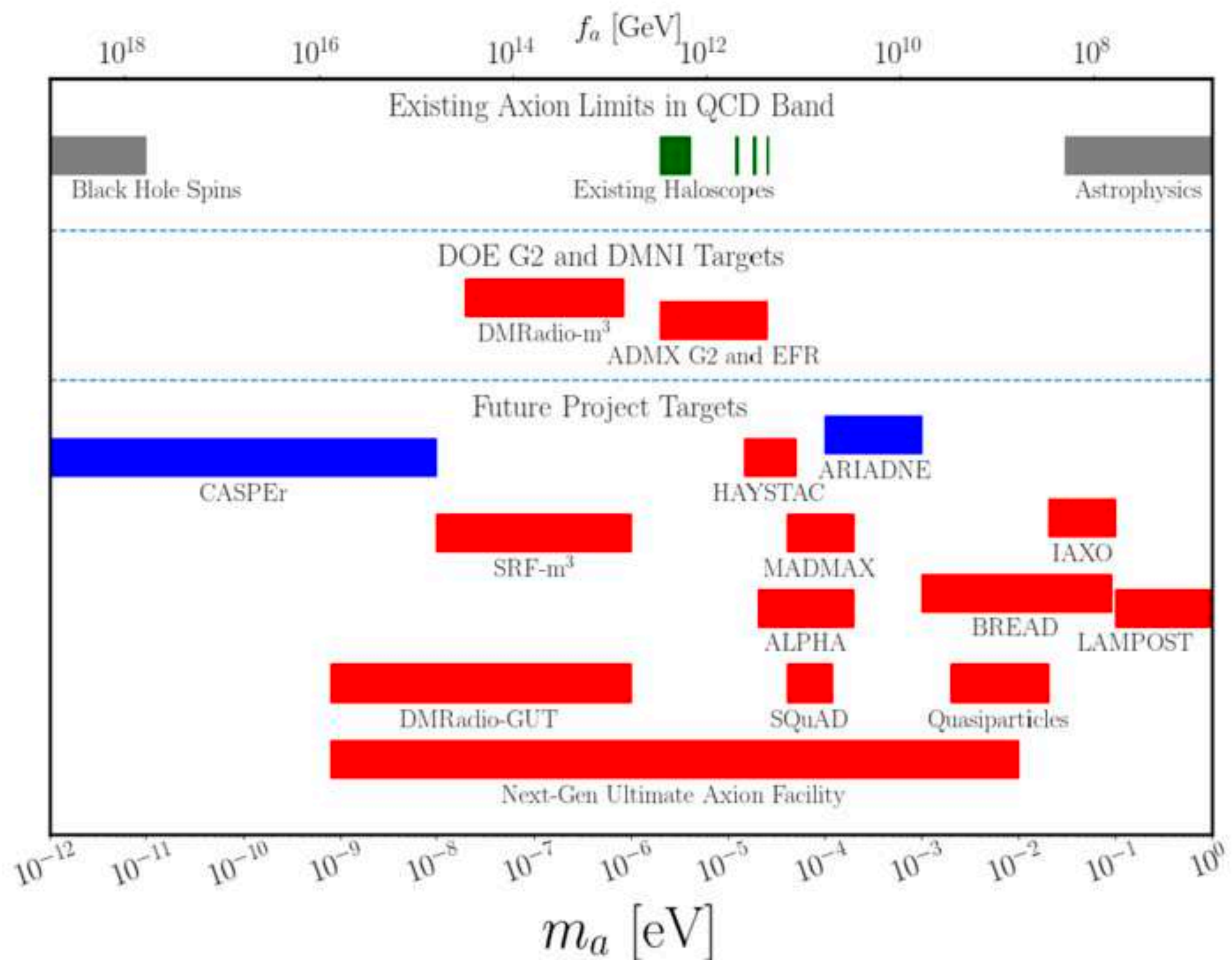
Axion and ALPs interaction with the SM

"Direct Detection”: axion/ALPs experiments

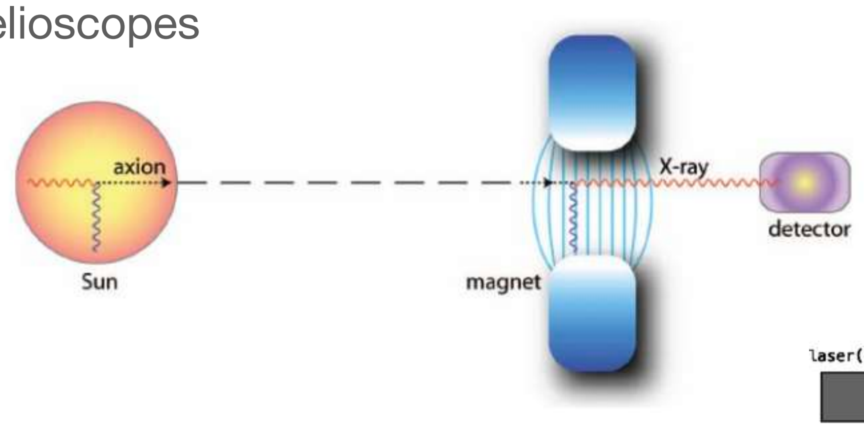
Overview of experimental techniques and the mass ranges they target

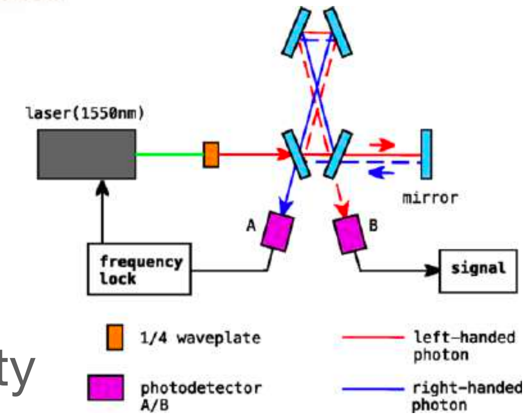


Experiments

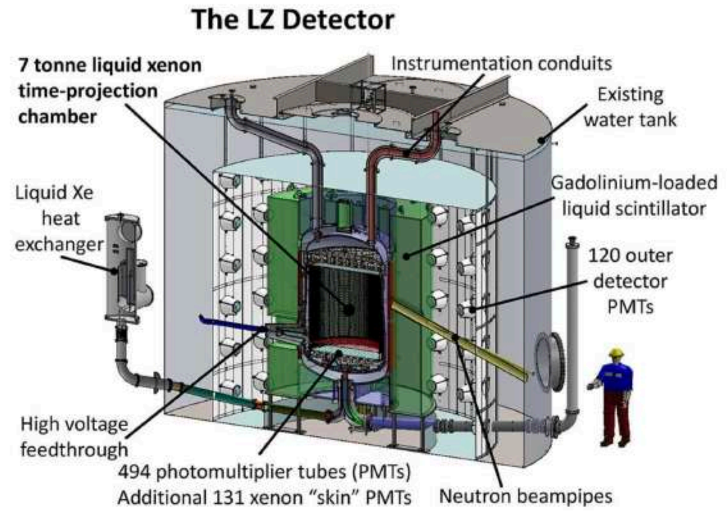


Helioscopes





Optical cavity

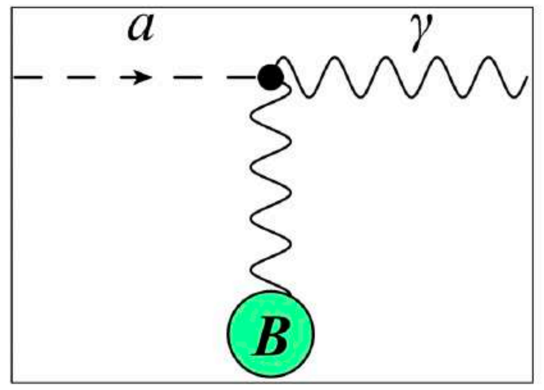


Ref. Jaeckel et al 2021

Axion and ALPs interaction with the SM

Indirect Detection

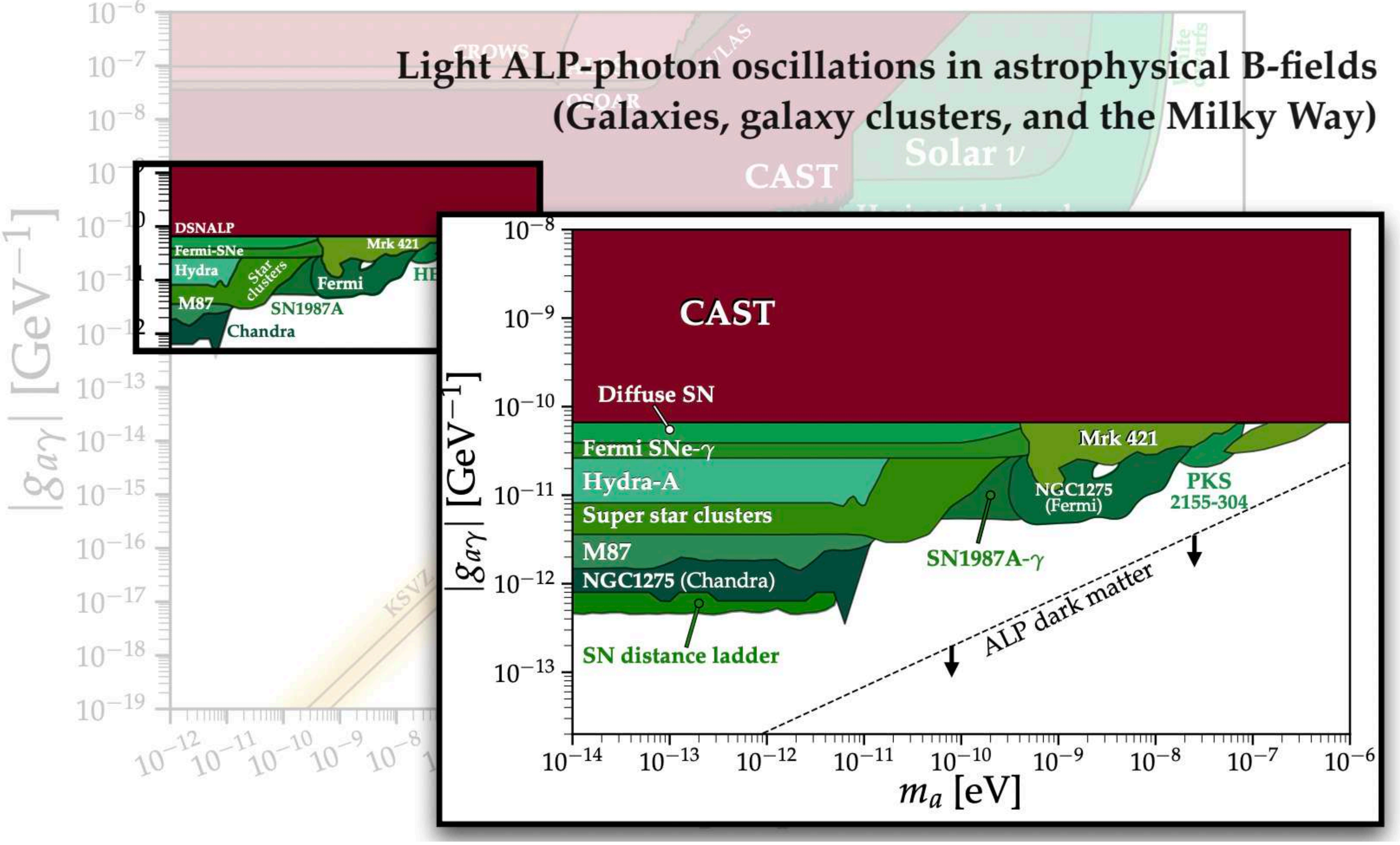
In astrophysical systems



Axion-photon conversion (Primakoff effect)

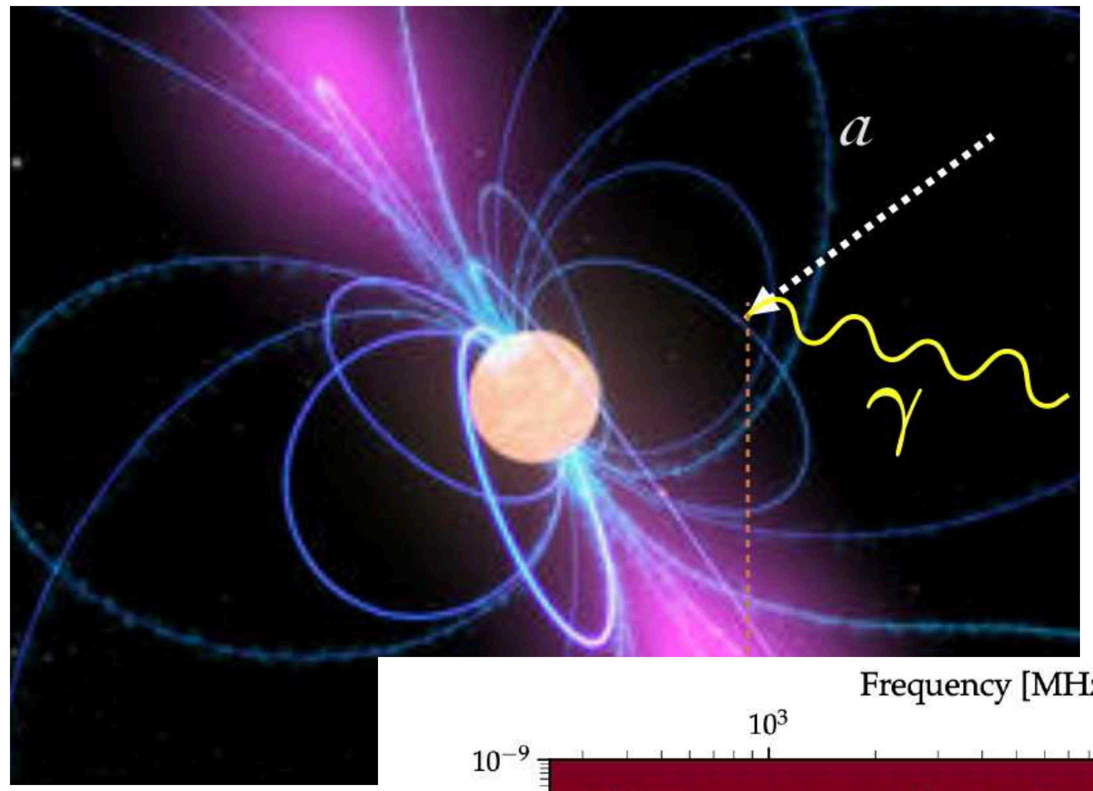
a : axion
γ : photon
B : magnetic field

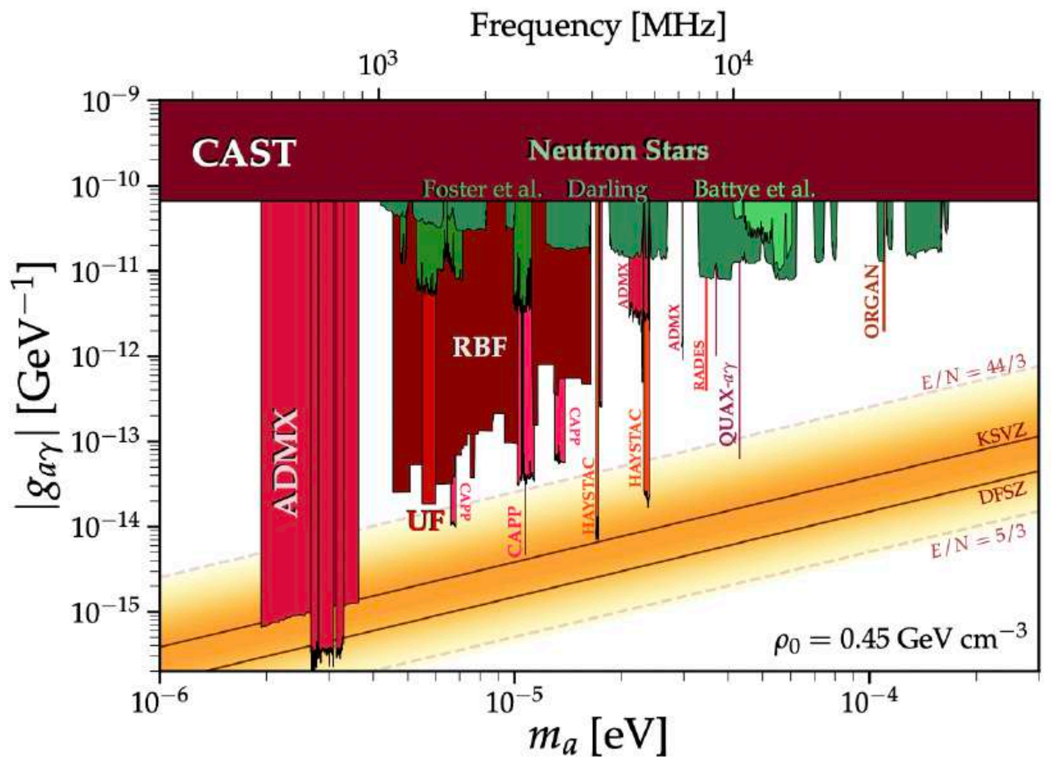
Light ALP-photon oscillations in astrophysical B-fields (Galaxies, galaxy clusters, and the Milky Way)

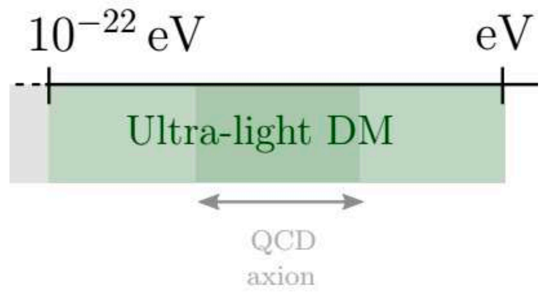


+

DM axions in neutron star magnetospheres



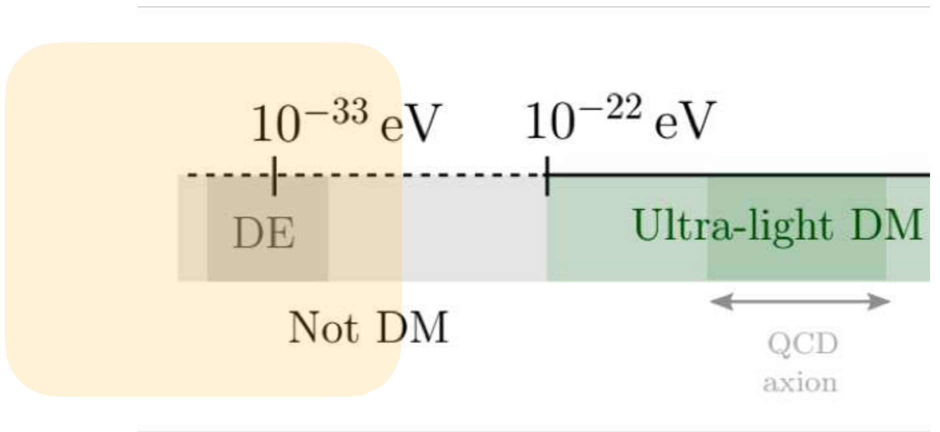




Axion and ALPs interaction with the SM

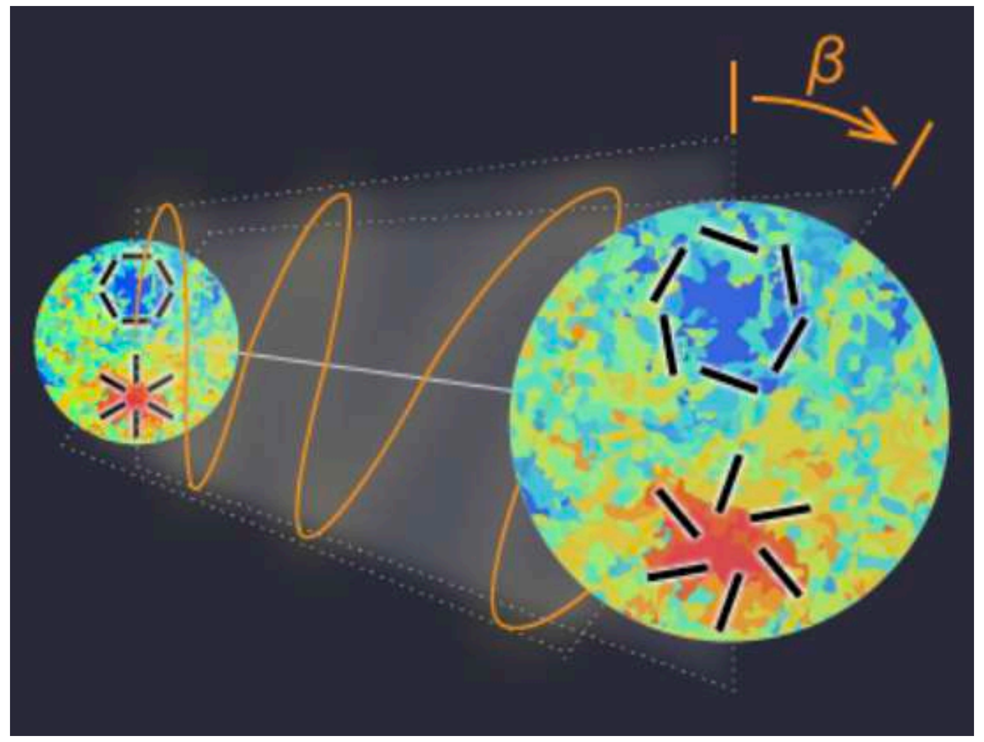
Birefringence

Cosmic birefringence



Cosmic Birefringence from axions

Minami/Komatsu



Rotation of the CMB polarization plane

↓

Parity-violating physics in the universe

Minami , Komatsu 2020

Eskilt et al 2022

$$\beta = 0.342^\circ \,{}^{+0.094^\circ}_{-0.091^\circ} \longrightarrow 3.6\sigma \text{ significance}$$

Another hint:
4-pt correlation function (BOSS)
Found parity violation! (?)

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

(Or strings, axion string loops, …)

Cosmic birefringence

Cosmic Birefringence from axions

For example:

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

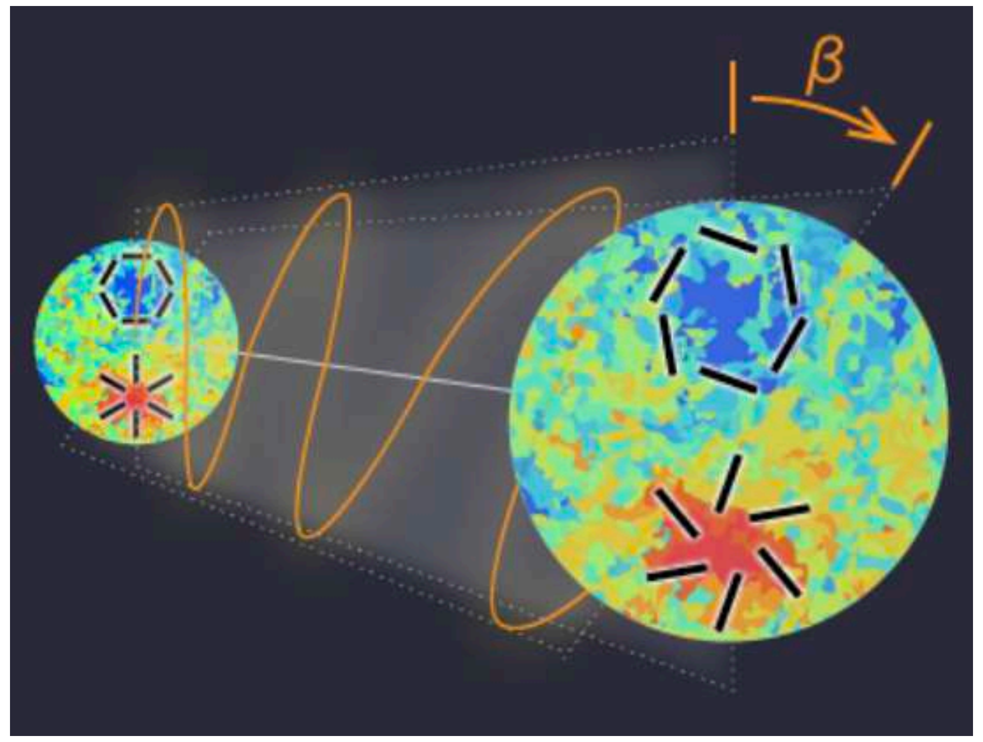
$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{4}g_{\phi\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Plane of polarisation of linearly polarised light is rotated with respect to the plane at emission and the amount of rotation β or $\Delta\theta_a$ depends on **m** and **g**

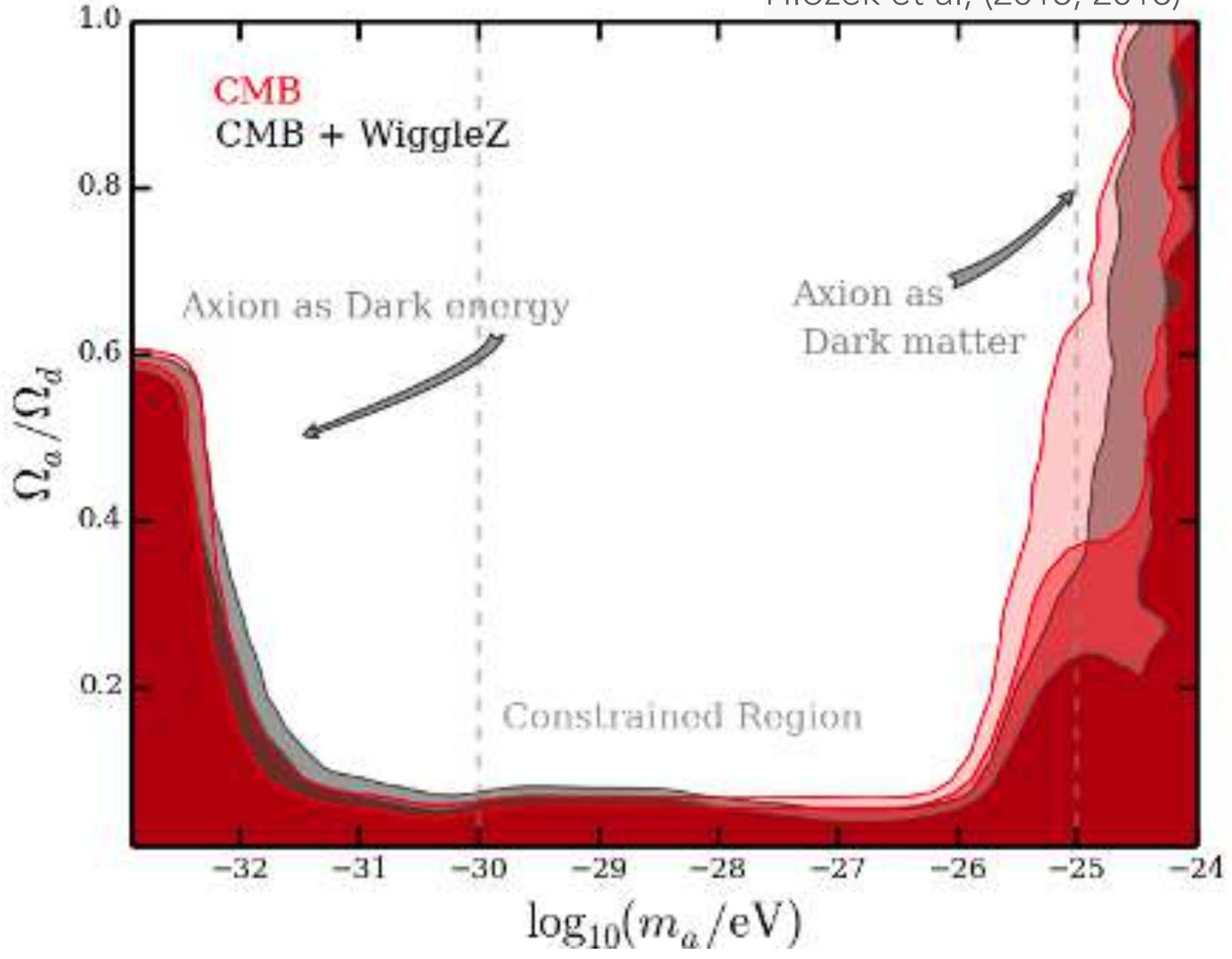
$$10^{-32}\,\mathrm{eV} < m < 10^{-22}\,\mathrm{eV}$$

Nakatsuka, et al 2022

Minami/Komatsu



Hlozek et al, (2015, 2018)



Constraining Ultralight Axion DM in Light of Cosmic Birefringence

D. Zhang, EF, I. Obata, T. Namikawa,
2408.08063

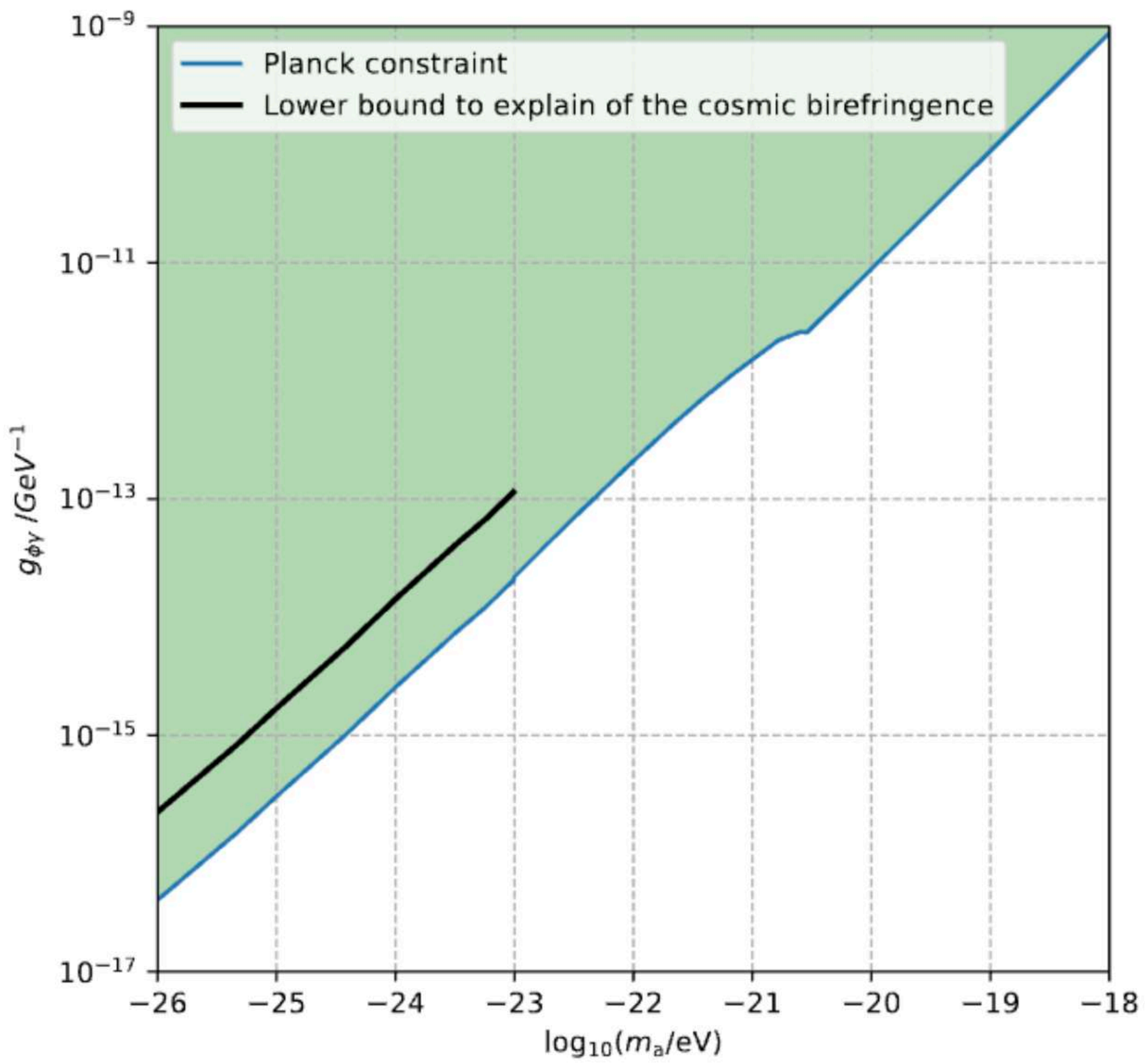
Goal: understand the **real possible** range of masses that can explain isotropic cosmic birefringence

We calculate the capability of axions to account for cosmic birefringence in the long-neglected mass range 10^{-26} eV to 10^{-23} eV

↓

Stringently excluded by the washout effect in the CMB polarization

⇒ ALPs with $m \gtrsim 10^{-26}$ eV fails to explain the isotropic birefringence when considering its late-time non-linear evolution ALPs, strongly narrowing down the mass range of ALPs as an explanation for birefringence.



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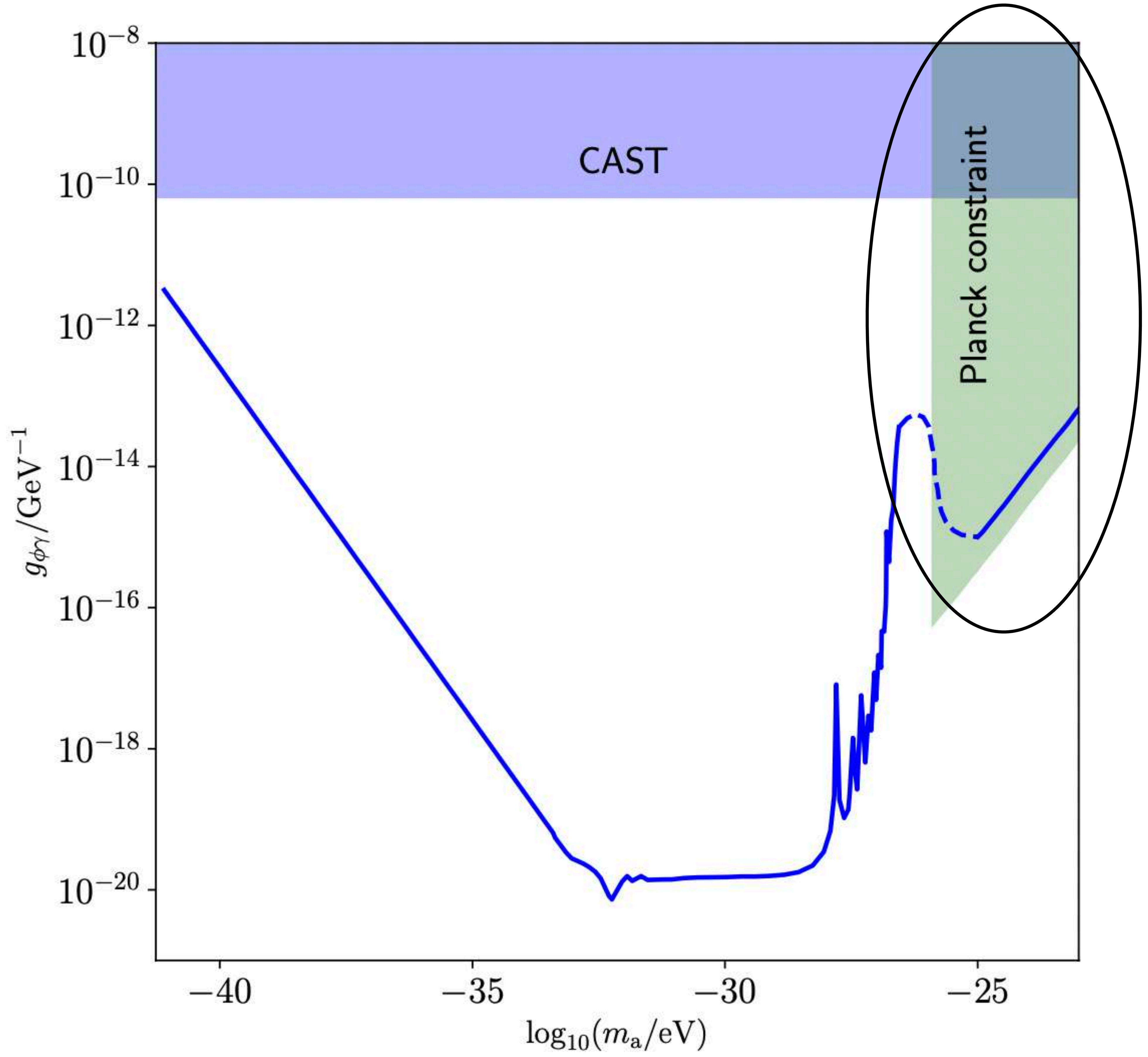
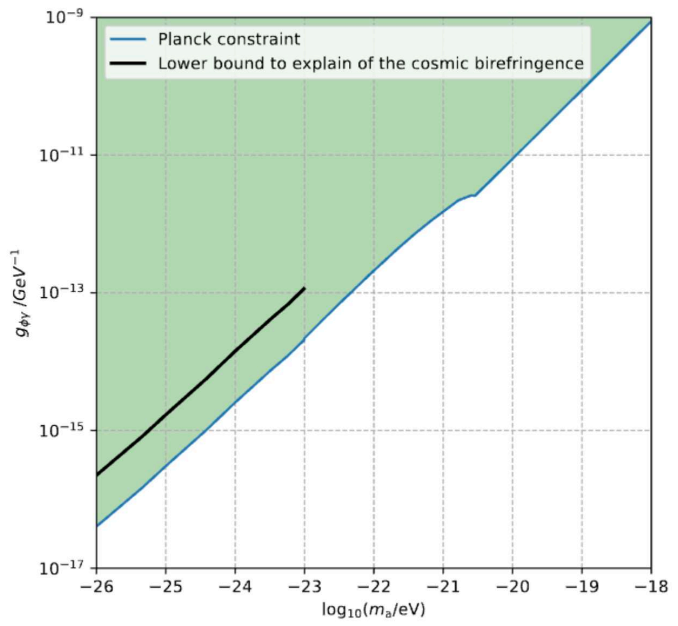




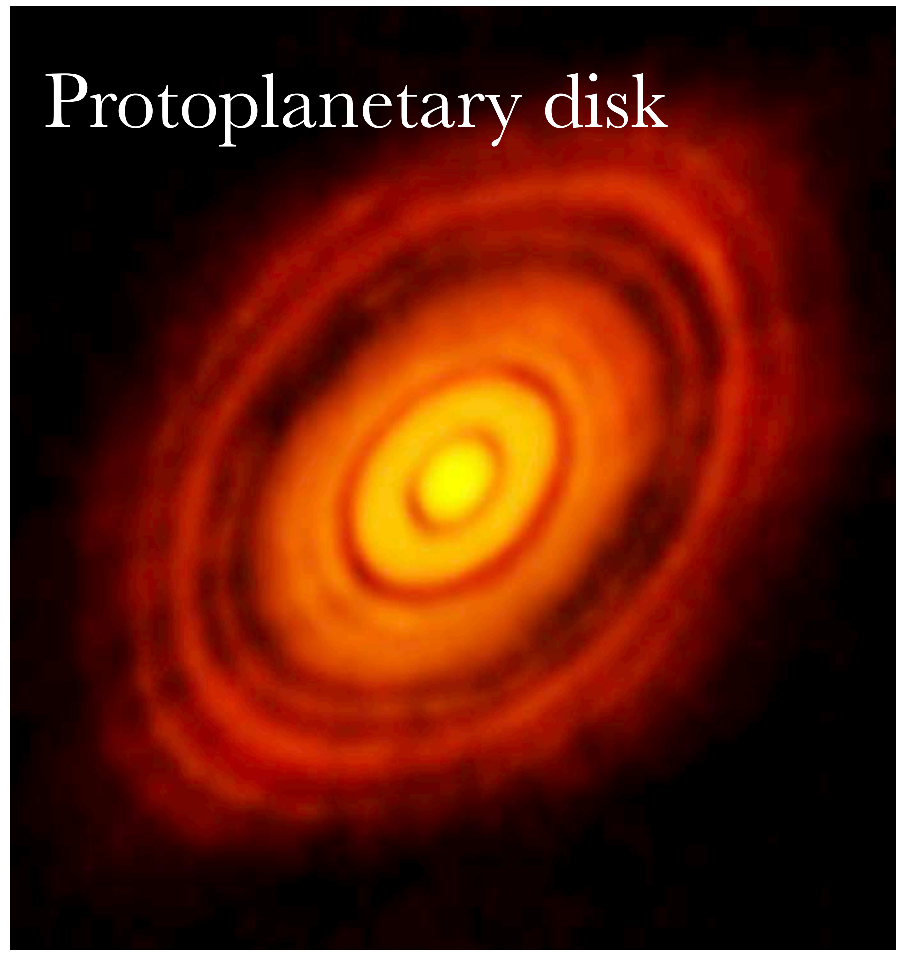
Mass range that explains birefringence

$$10^{-32}\,\mathrm{eV} \lesssim m \lesssim 10^{-26}\,\mathrm{eV}$$

Measuring birefringence with strong lensing

ALP induced birefringence is achromatic and $\Delta\theta_a$ can be measured through observations of suitable linearly polarised astrophysical systems

E.g.



mage credit: ALMA

mage credit: NASA/ESA/CSA/Joseph Olmsted (STScI)

Measuring birefringence with strong lensing

ALP induced birefringence is achromatic and $\Delta\theta_a$ can be measured through observations of suitable linearly polarised astrophysical systems

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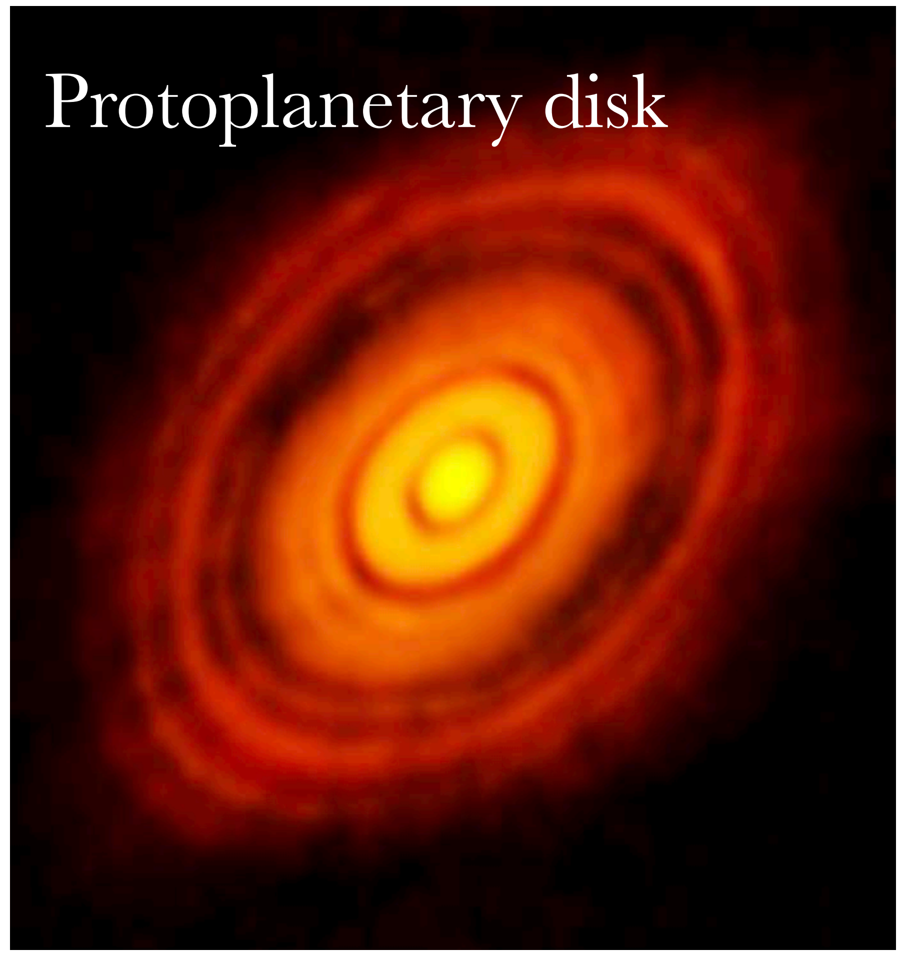


mage credit: ALMA

Intrinsic polarization?

Calibration: instrumental offset and sensitivity?

mage credit: NASA/ESA/CSA/Joseph Olmsted (STScI)

Fujita et al. 2018

Measuring birefringence with strong lensing

Basu et al 2020

ALP induced birefringence is achromatic and $\Delta\theta_a$ can be measured through observations of suitable linearly polarised astrophysical systems

Since the birefringence induced by the interaction of photons with ALP field is achromatic

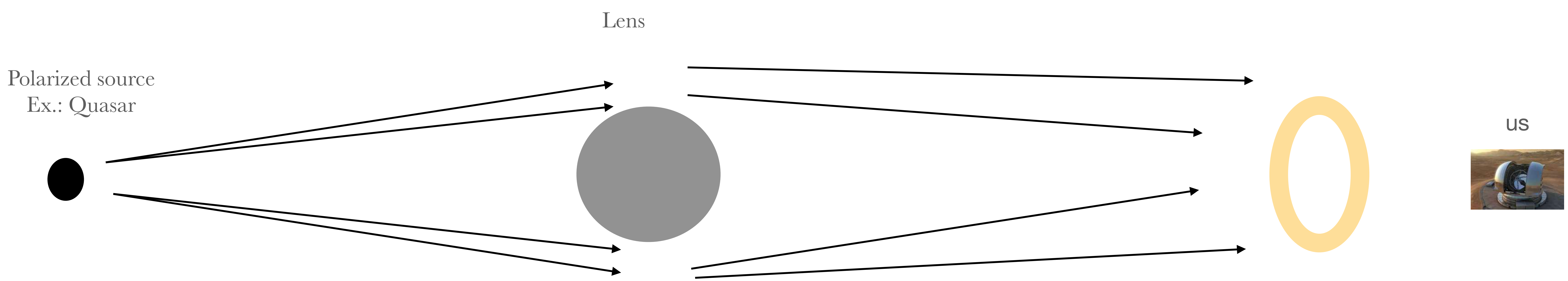
$$\theta_0 = \theta_{\mathrm{p.source}} + \Delta\theta + \delta\theta_{\mathrm{cal}}$$

Strong lensing overcomes problem of having to know the intrinsic source angle and offset angle due to improper calibration

Multiple images from lensing allow for performing differential polarisation angle measurements which alleviates instrumental offsets and does not rely on modelling the intrinsic astrophysics of the system

Measuring birefringence with strong lensing

Basu et al 2020

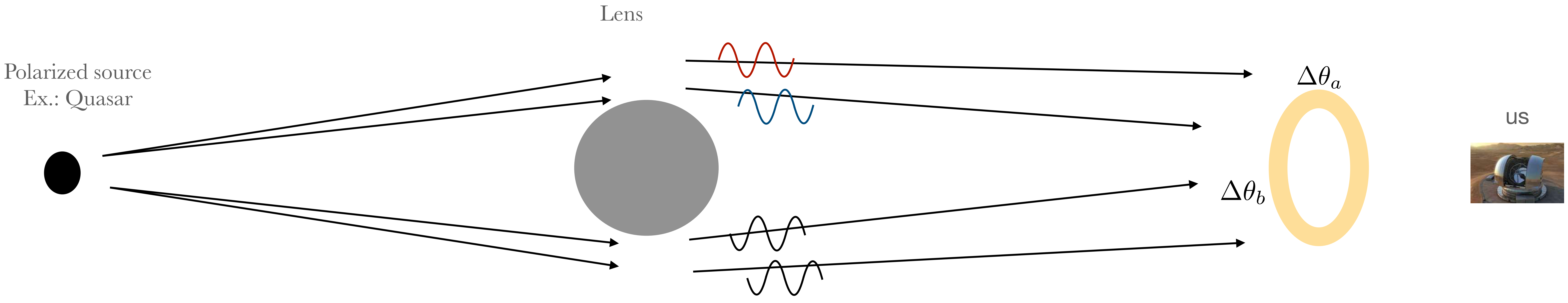


Measuring birefringence with strong lensing

Basu et al 2020

The time-separated images encode the time variation of the oscillating ALP field at the emitting source

The polarisation plane of each lensed images undergo different amount of birefringence - comparing the polarisation angle of lensed images provide information on $\Delta\theta_a$



$$\theta_0 = \theta_{\rm p.source} + \boxed{\Delta\theta} + \delta\theta_{\rm cal}$$

$$\Delta\,\theta_{\rm a} = \frac{1}{2}\,g_{a\gamma}\,\left[a(t_{\rm obs}, x^i_{\rm obs}) - a(t_{\rm em}, x^i_{\rm em})\right]$$

$$\Delta\,\theta_{\rm a,lens} = \theta_{0,\rm A} - \theta_{0,\rm B} = \Delta\,\theta_{\rm a,A} - \Delta\,\theta_{\rm a,B}$$

Strong lensing with polarised sources as a powerful new probe of ultra-light ALPs via birefringence

Axion being DM or not!

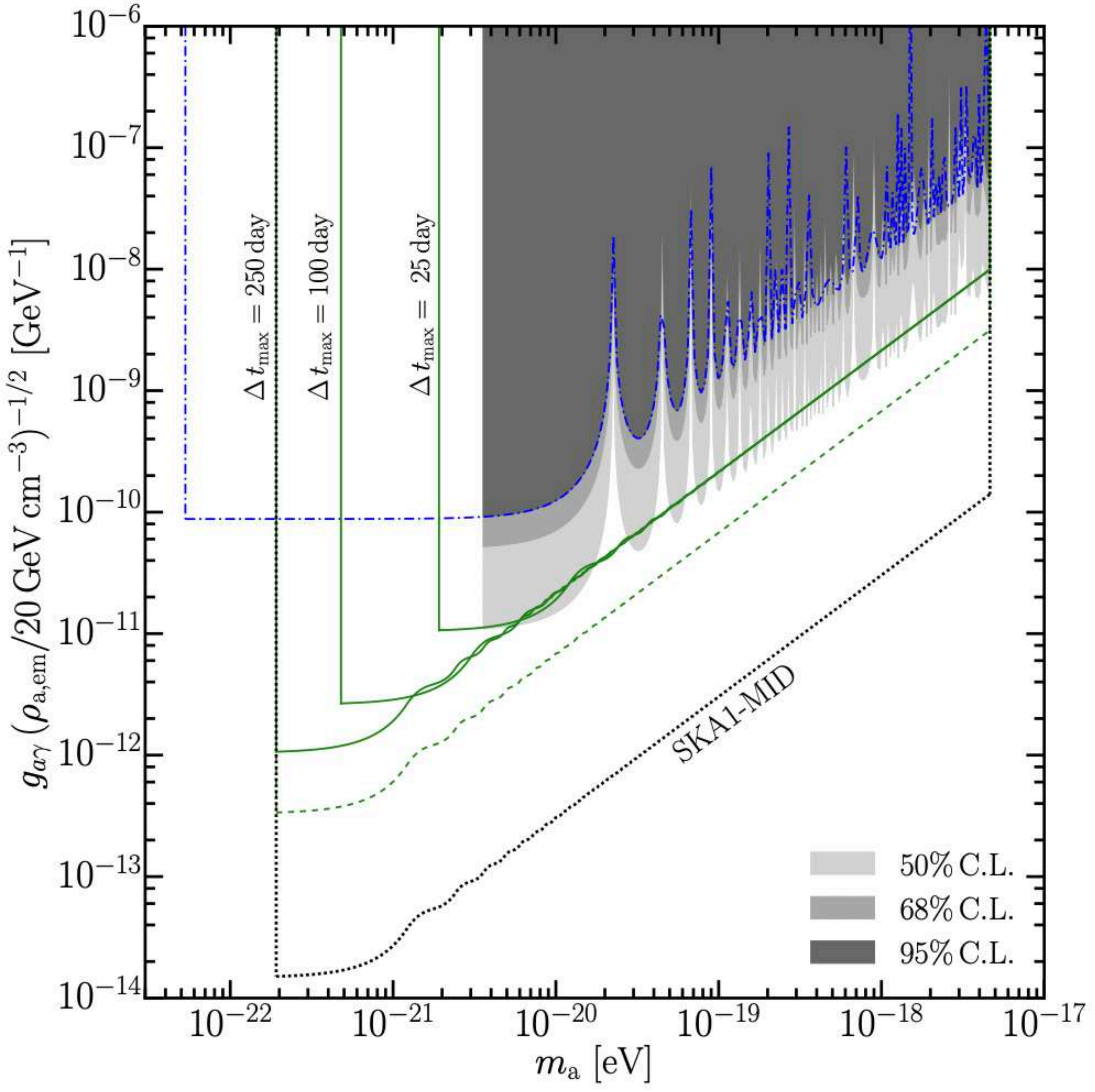
Measuring birefringence with strong lensing

Basu et al 2020

Gray: bounds obtained from CLASS B1152+199

Blue: in 5 years

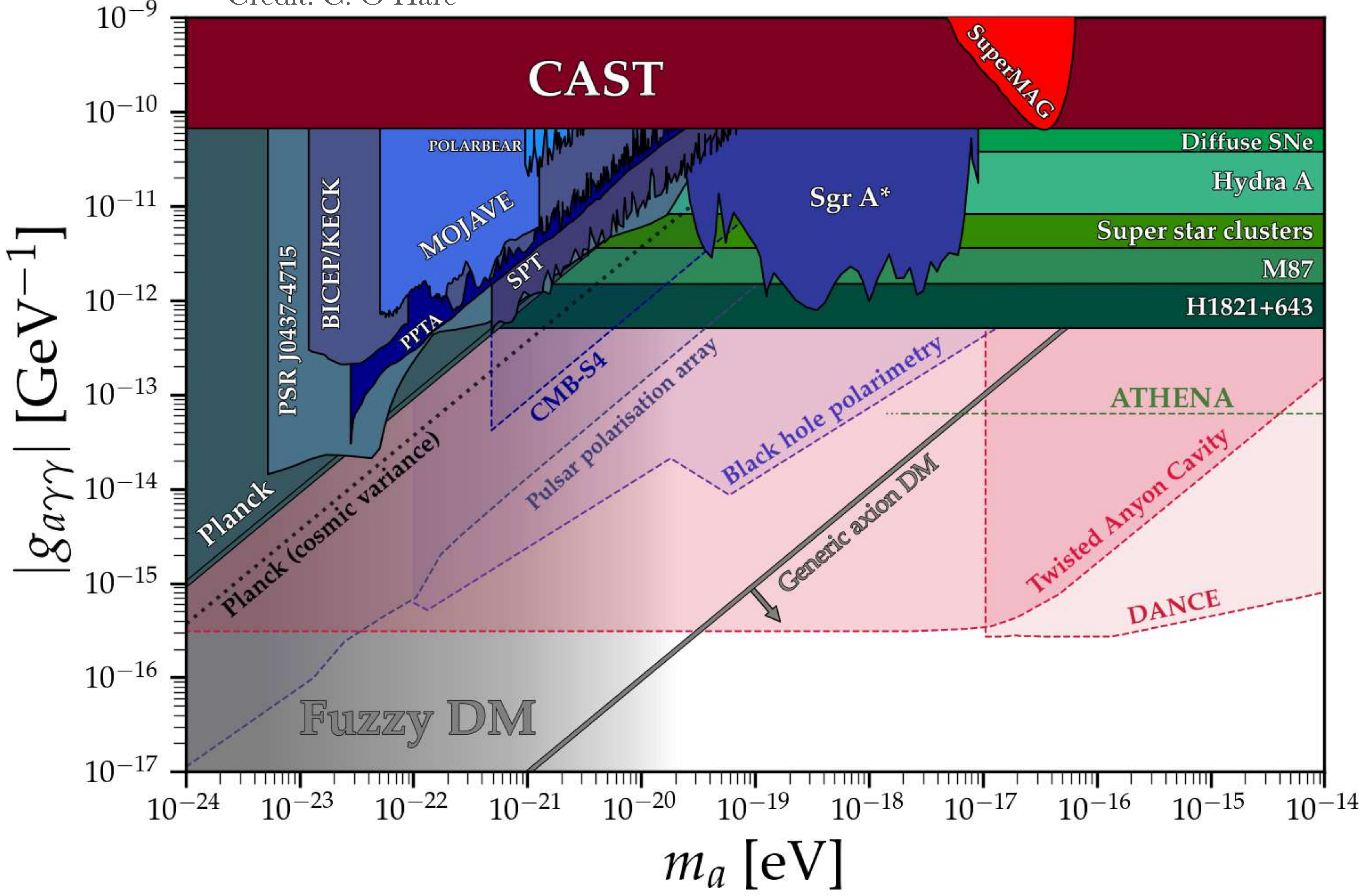
Green: if sample of 100 and 1000 gravitational lens system

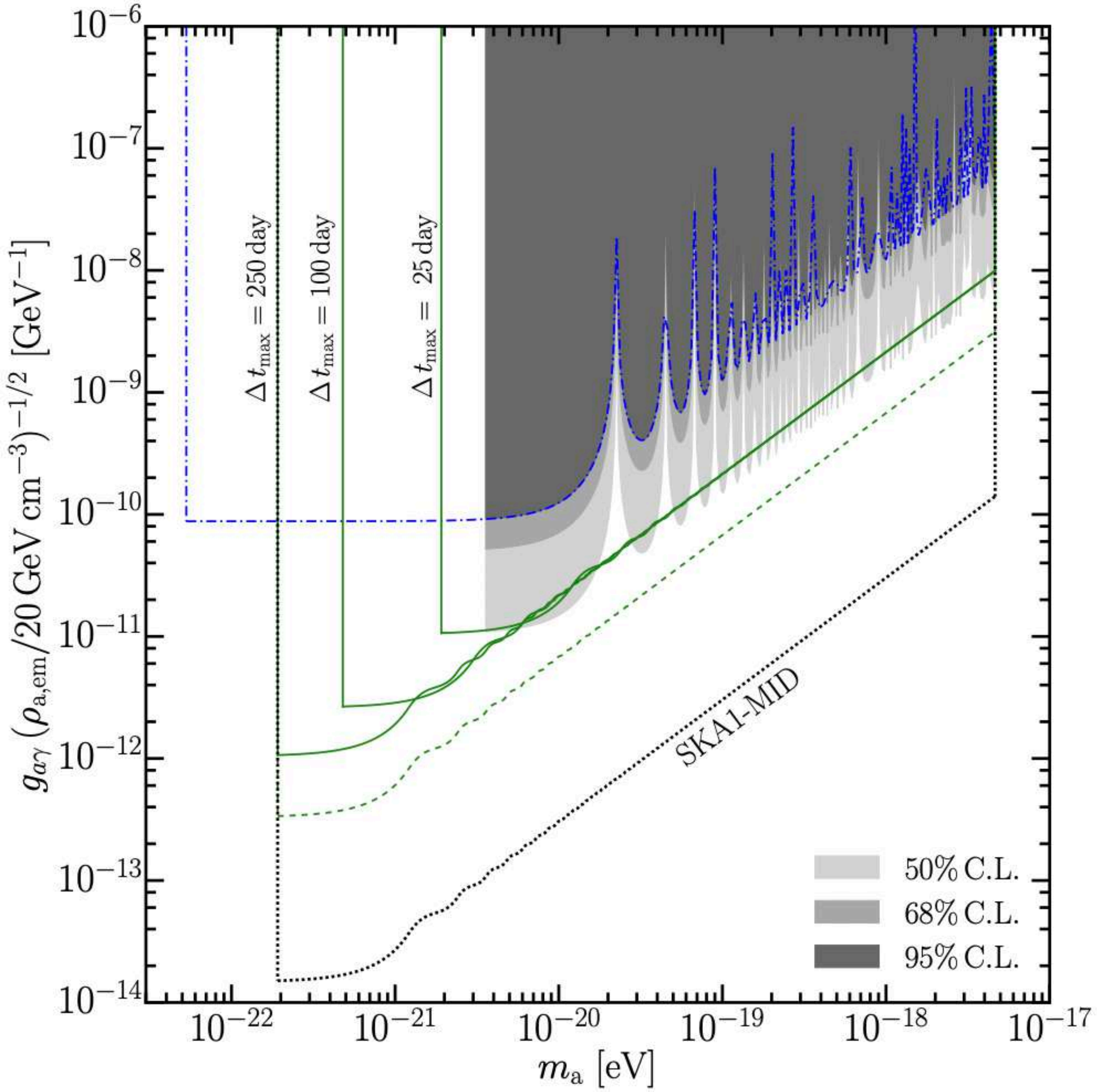


Measuring birefringence with strong lensing

Basu et al 2020

Credit: C. O'Hare





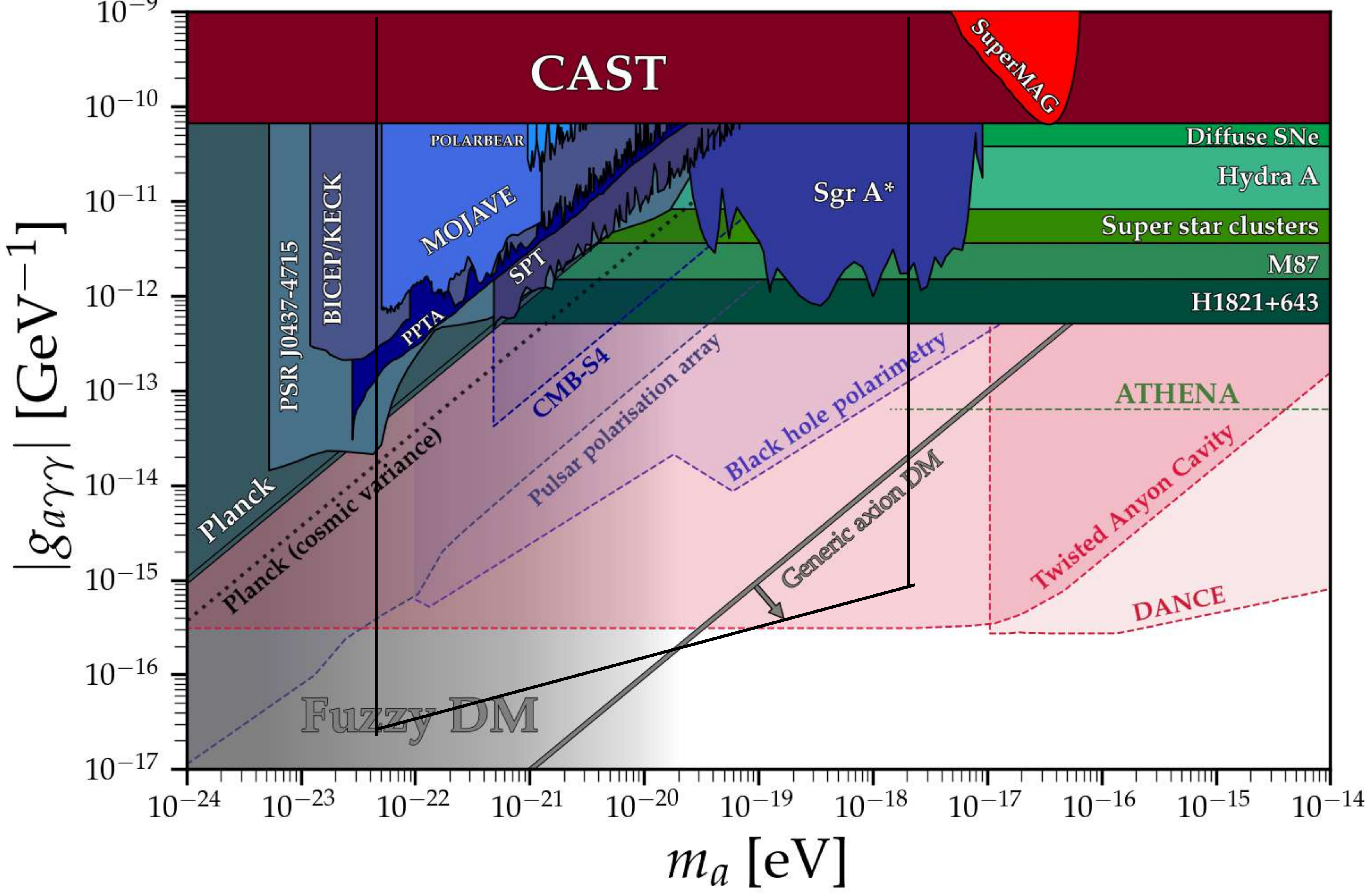
(Work in progress)

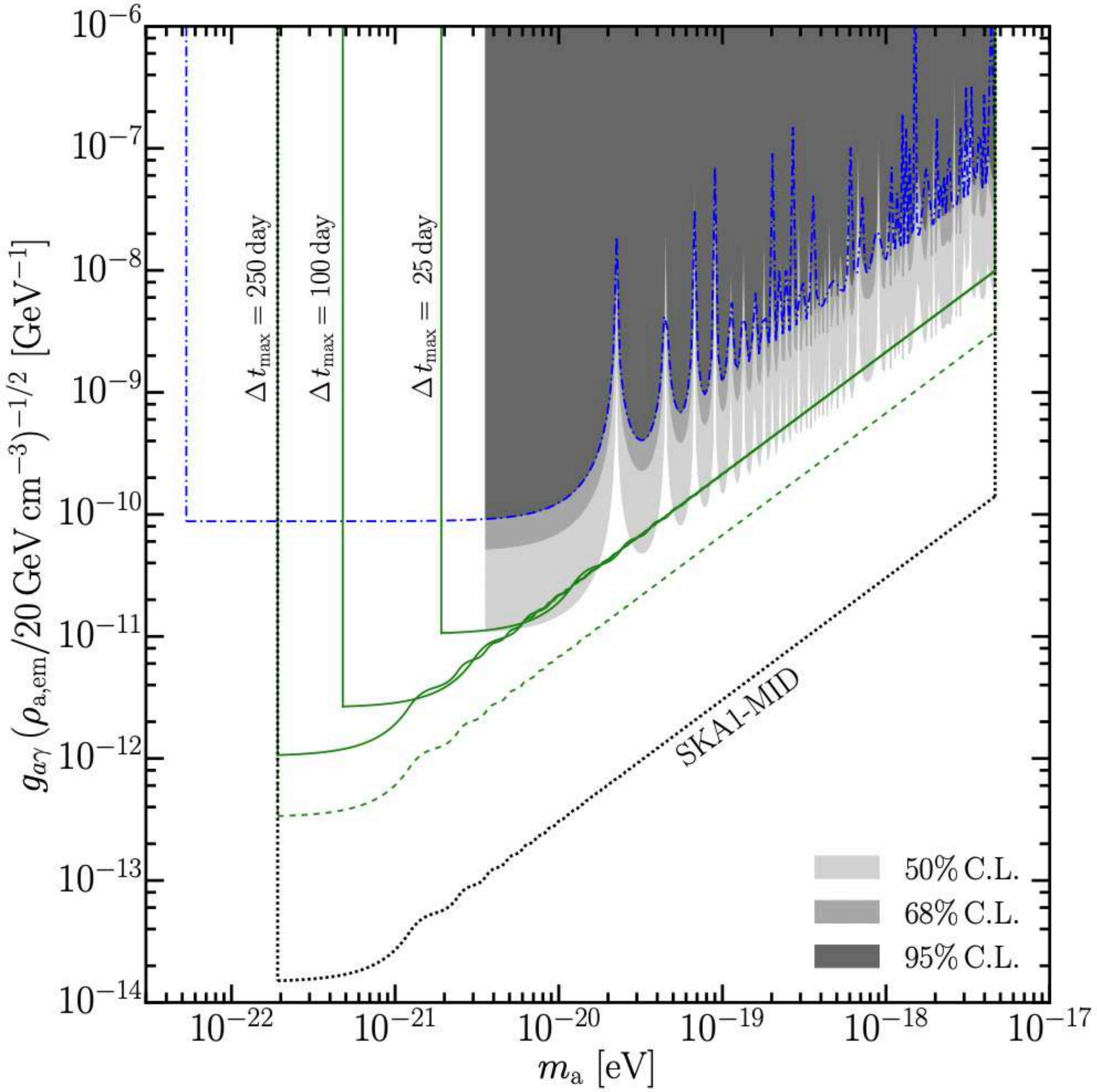
In collaboration with Simona Vegetti and Devon Powell

Measuring birefringence with strong lensing

Basu et al 2020

Credit: C. O'Hare



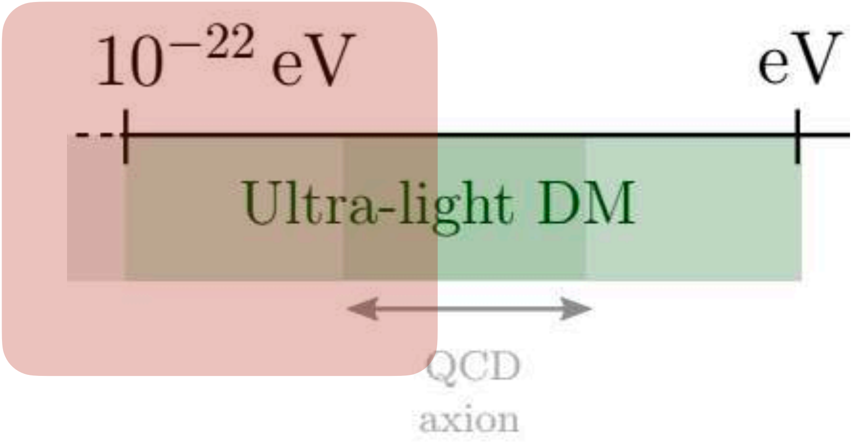


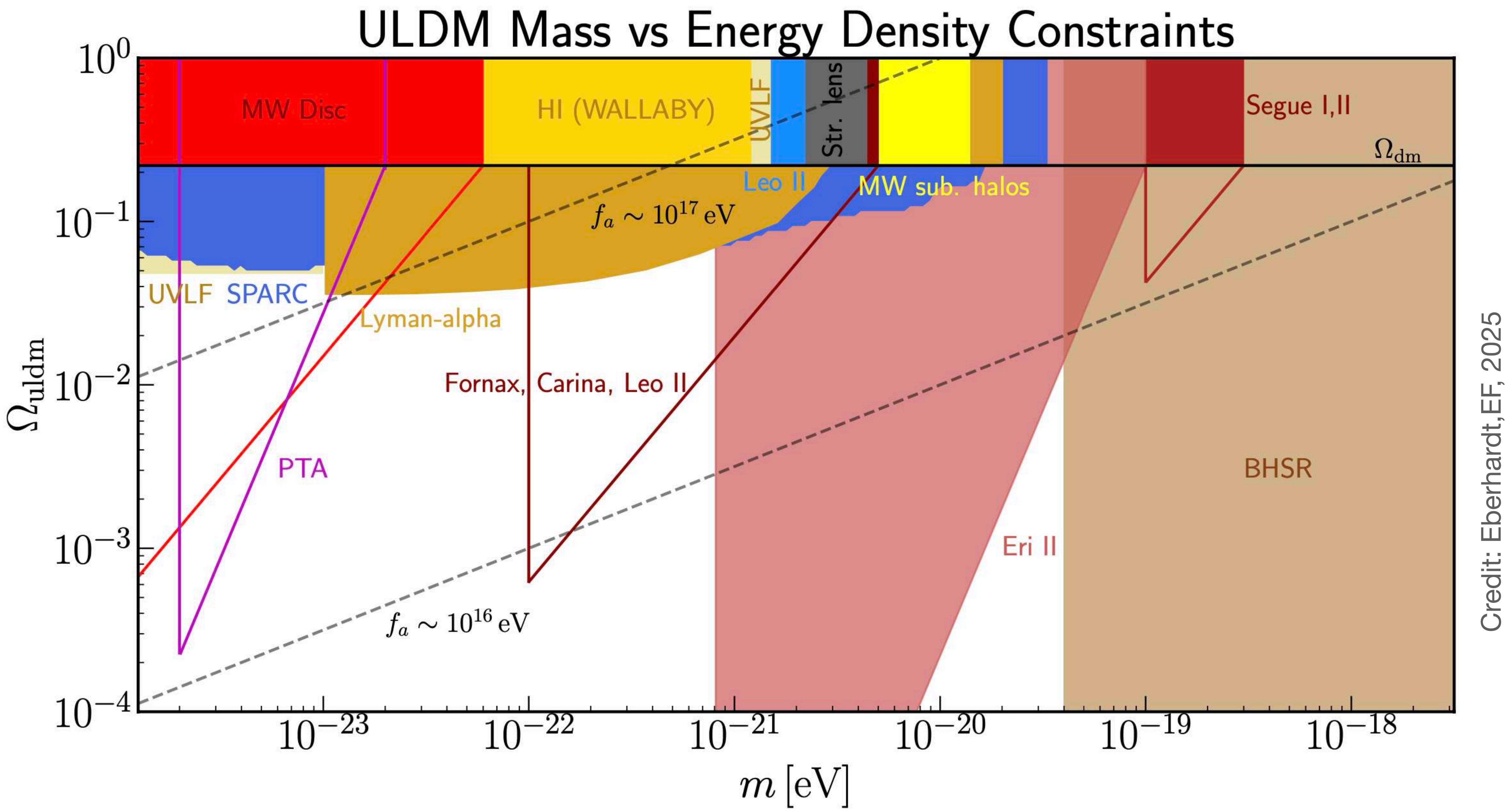
(Work in progress)

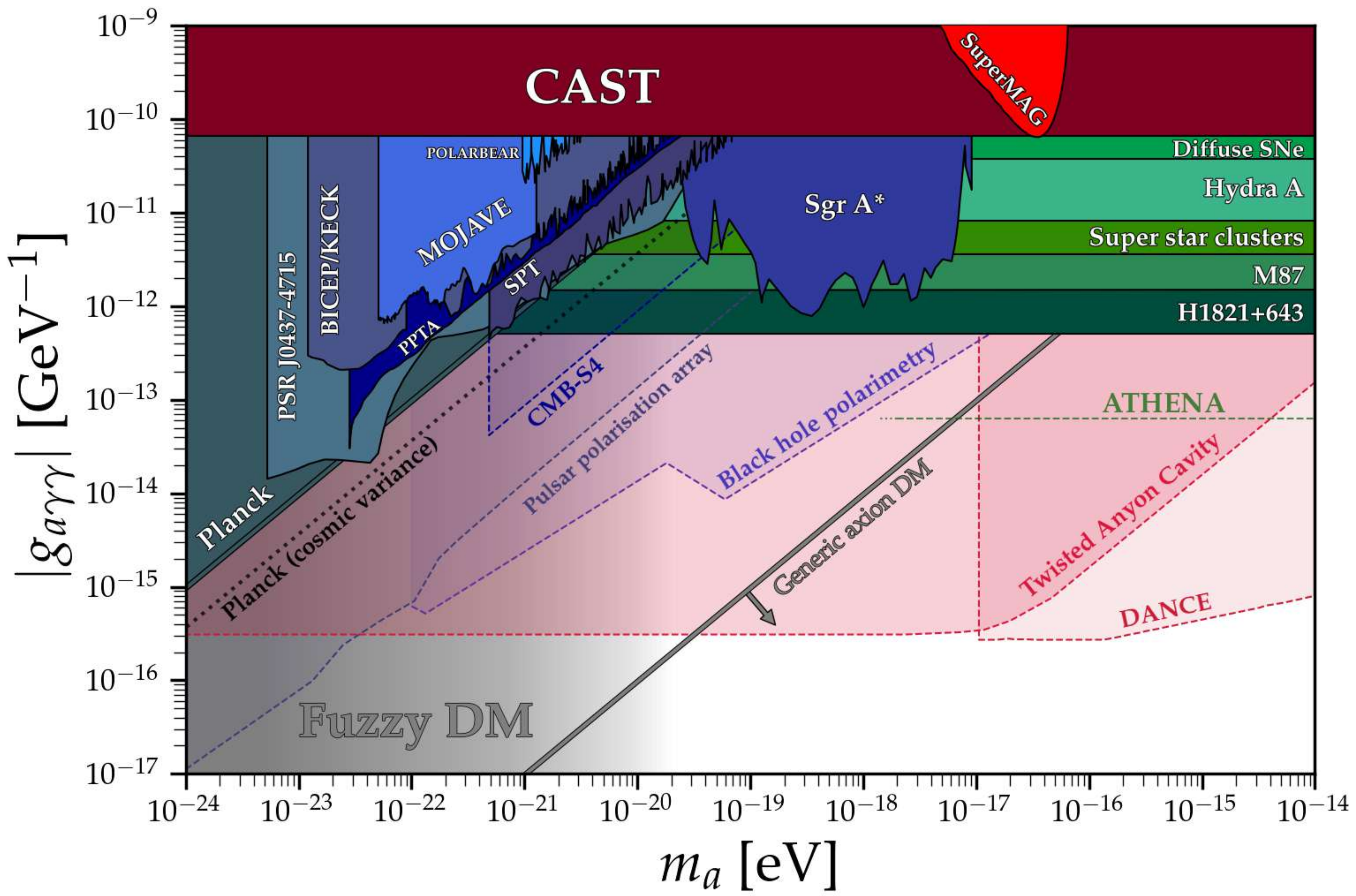
In collaboration with Simona Vegetti and Devon Powell

Current status

Fuzzy Dark Matter - bounds on the mass



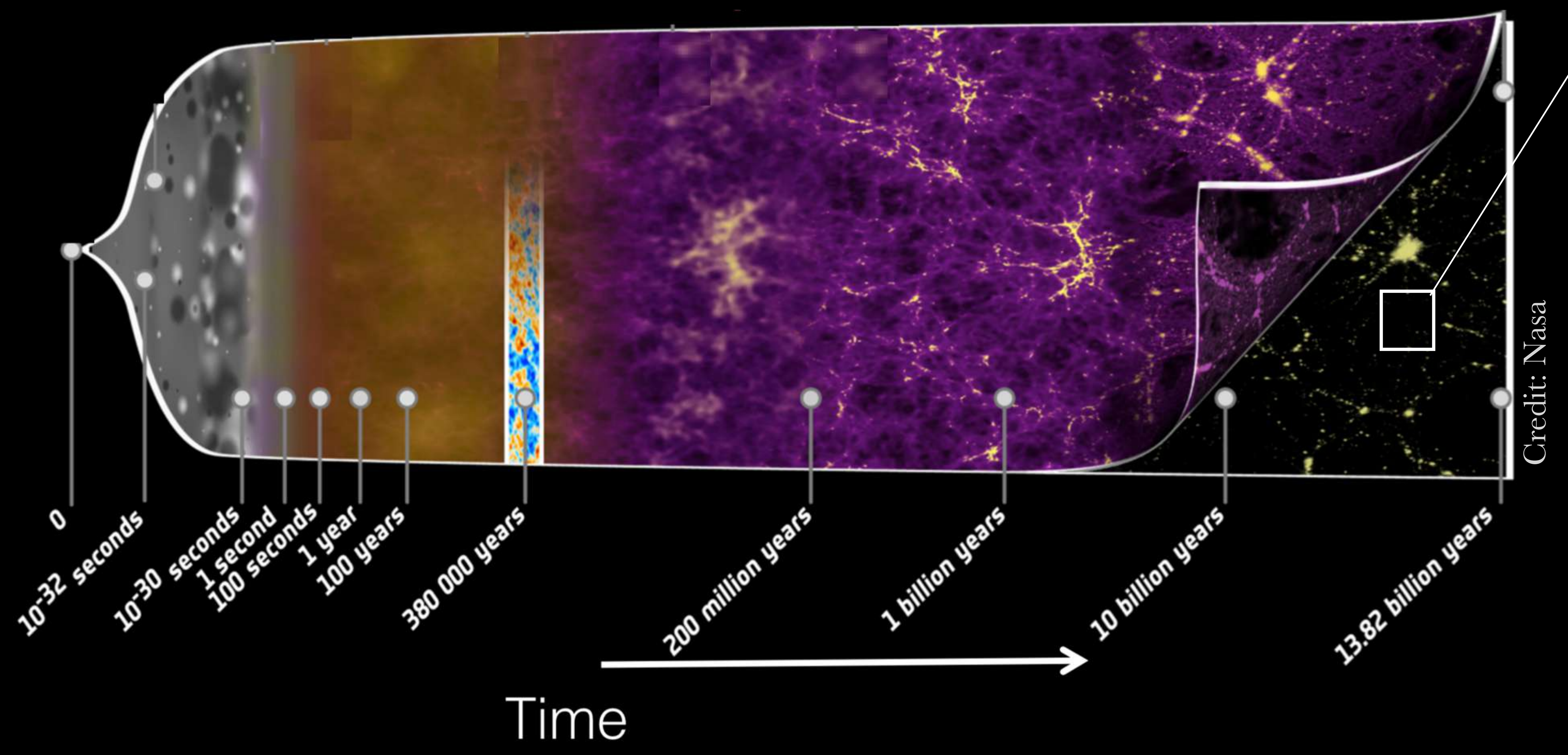


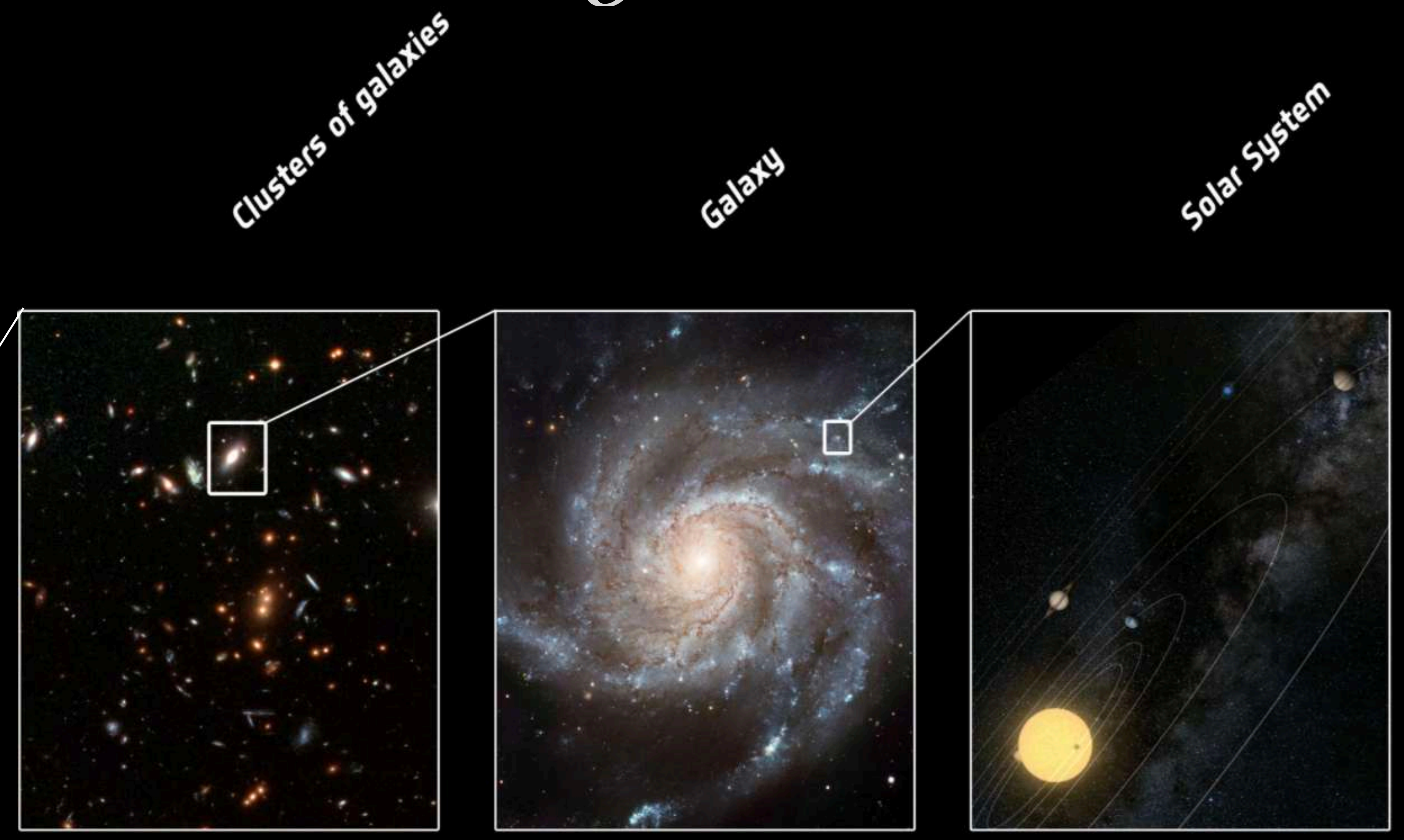


The search for dark matter (ULDM) is a multi-probe/multi-scale endeavour…

exciting times for axion dark matter

Small scales can offer some hints of the nature of DM



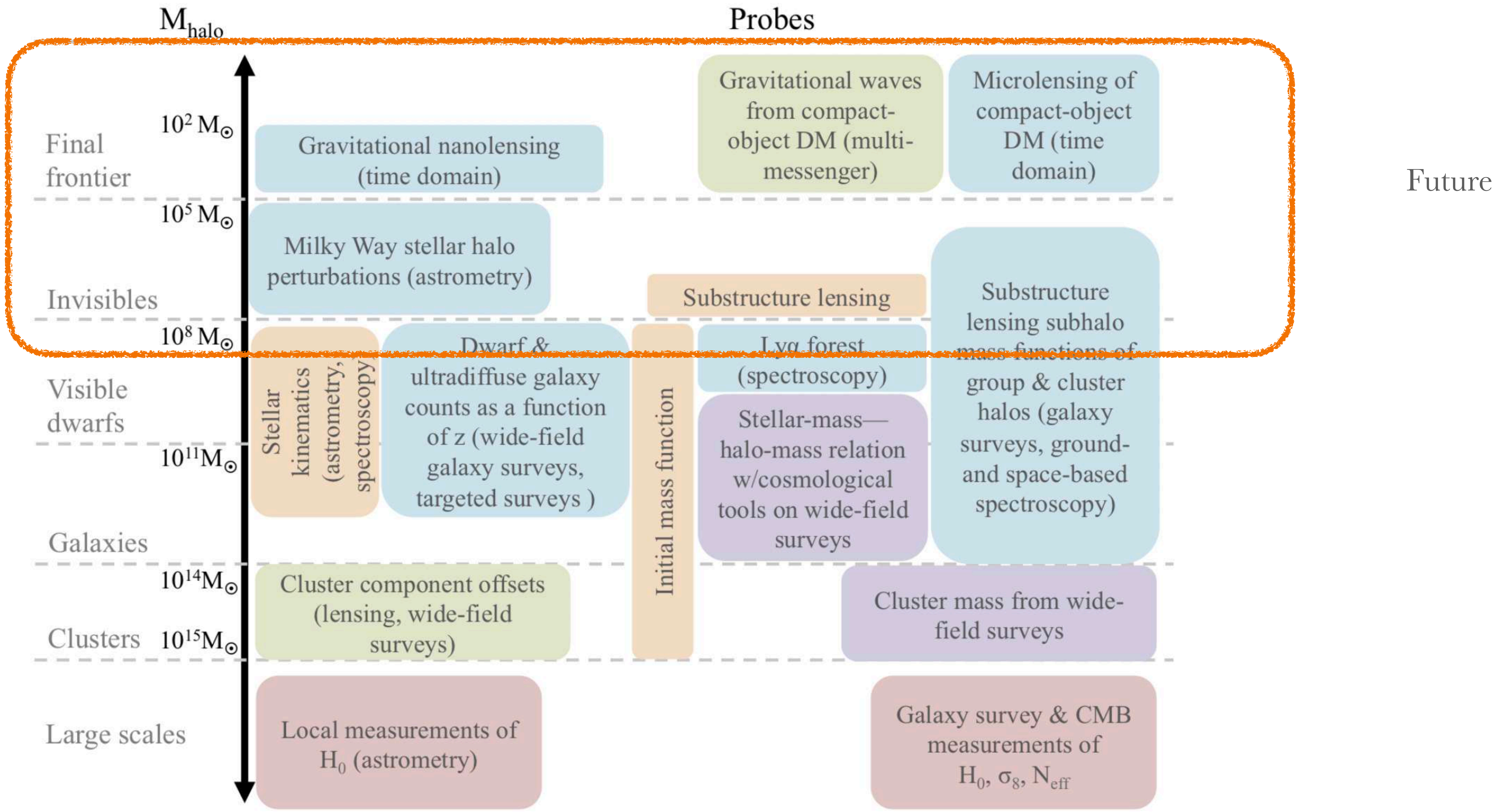


Small Scales

Opportunity to probe the nature of DM!

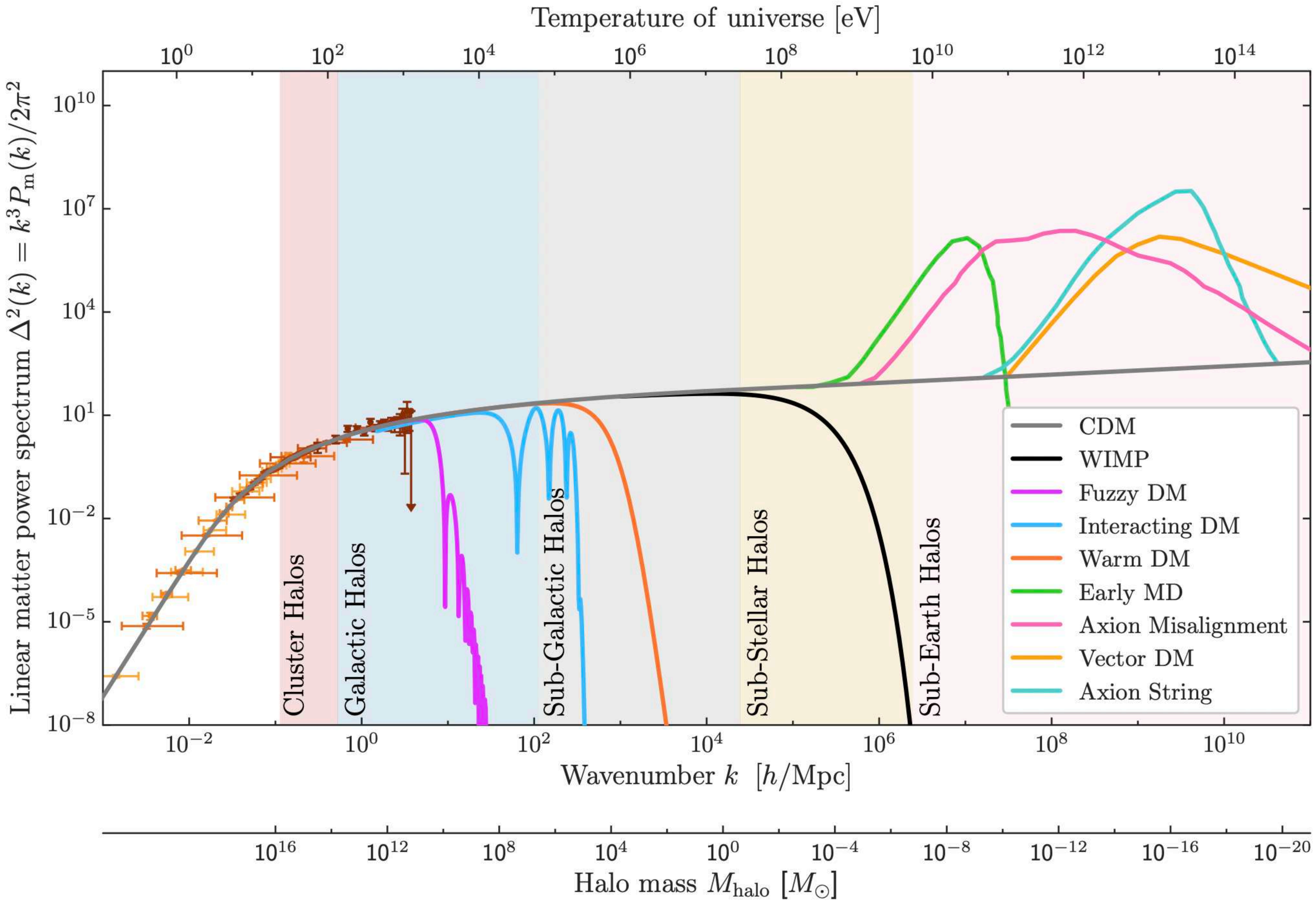
Astrophysical Observables → DM Distribution → Nature of DM Microphysics Particle physics

*Cosmological and astrophysical **probes** of dark matter*



Buckleya et al 2017

Small scales can offer some hints of the nature of DM



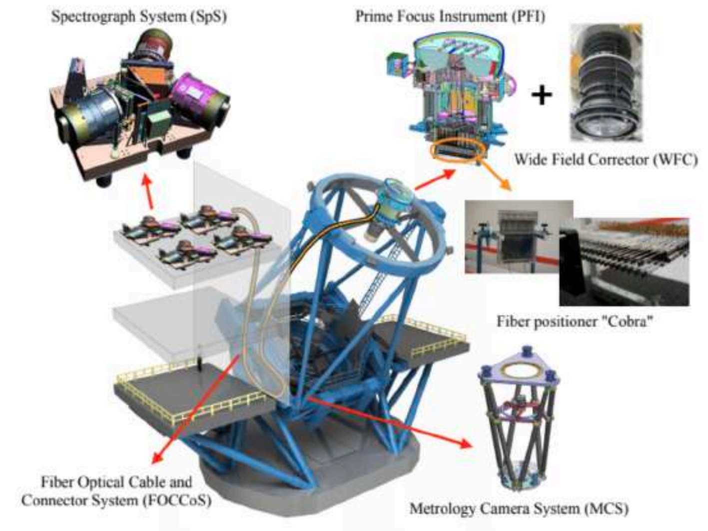
Improving these bounds

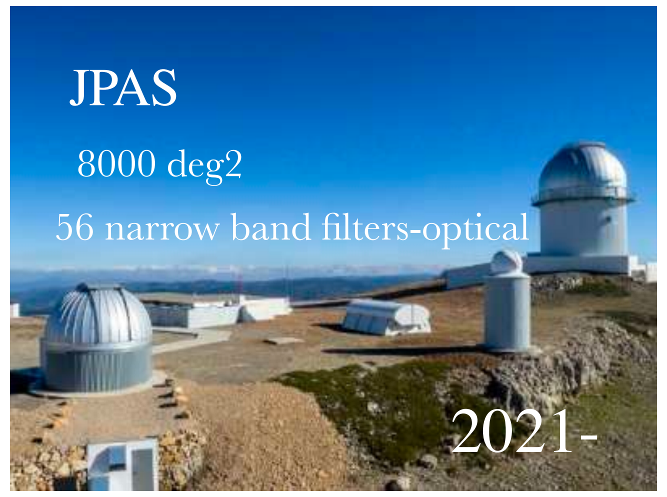
Observations

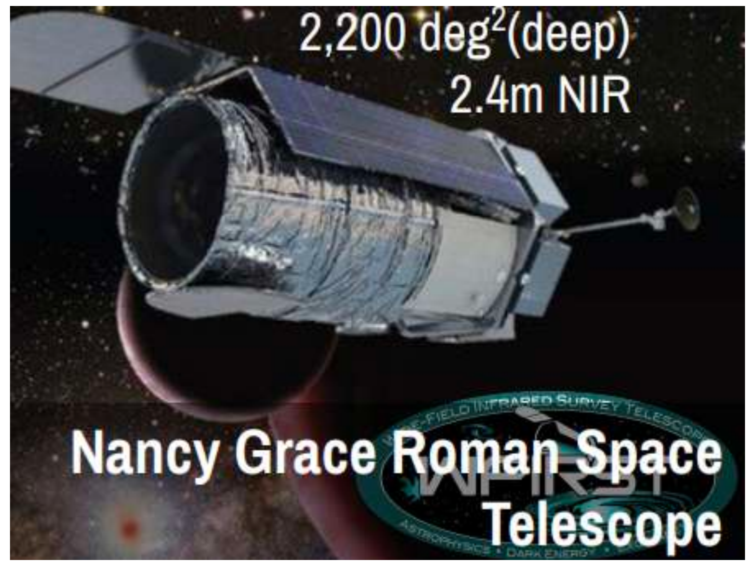
Photometric and spectroscopic surveys

DESI

Prime Focus Spectrograph (PFS)





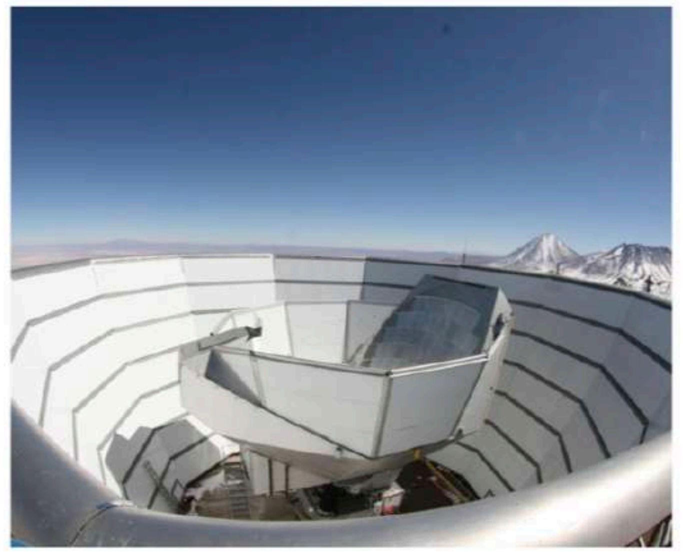


21cm

GWs

CMB

ACT



SPT

CMB-S4
Next Generation CMB Experiment

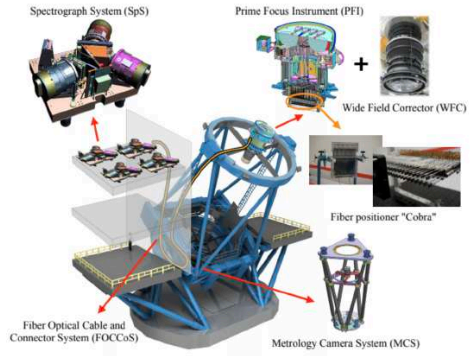
Modified from Jia Liu

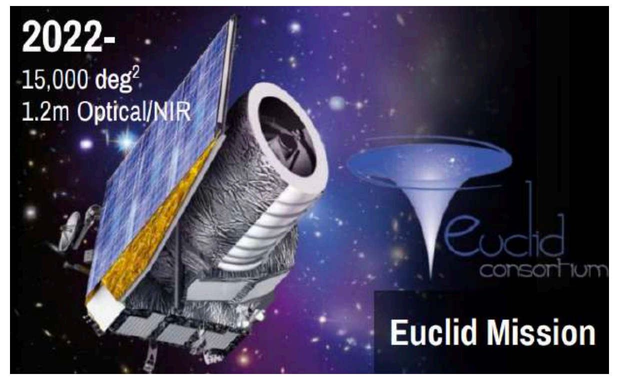
Improving these bounds

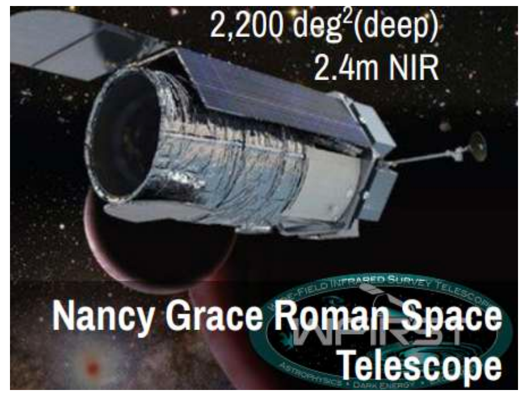
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)







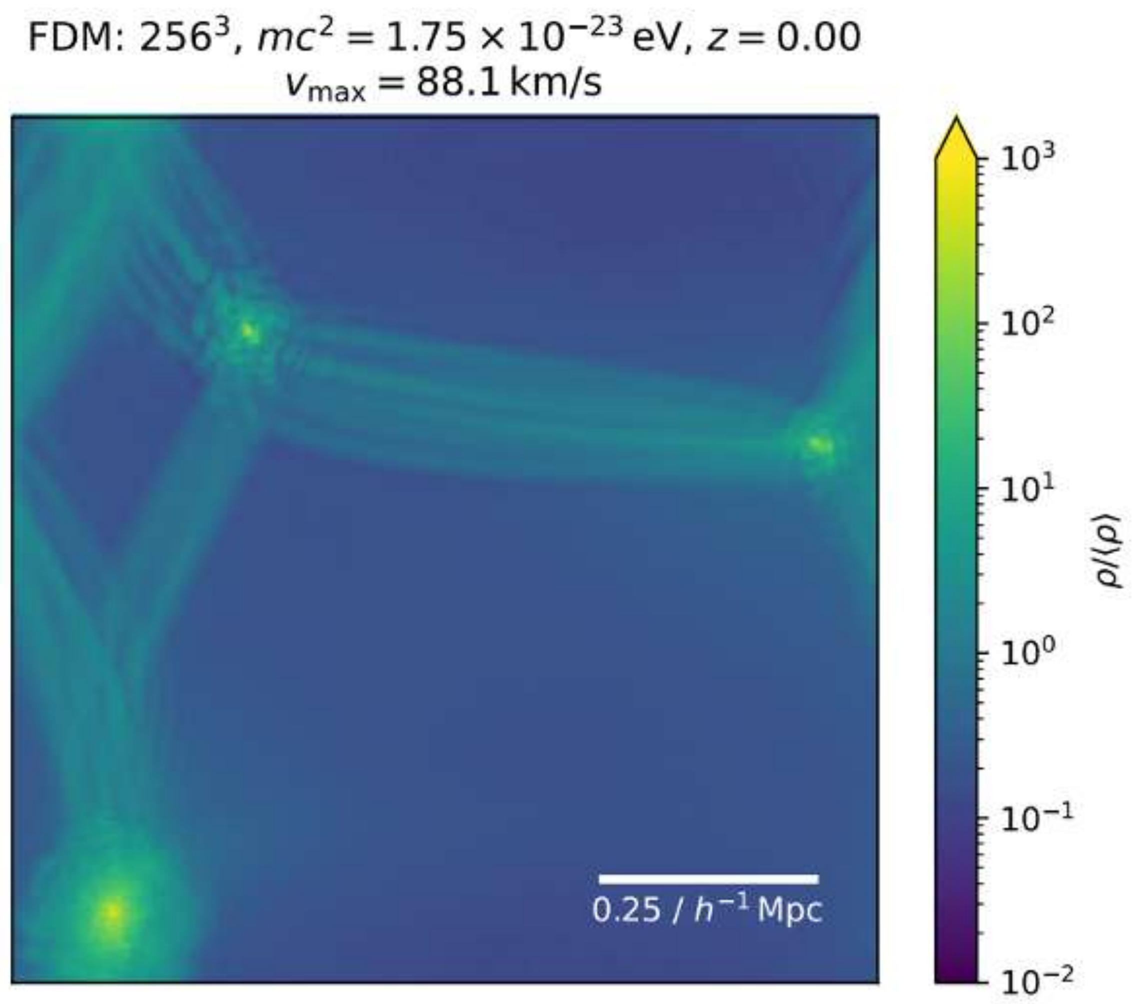
CMB

CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New observables

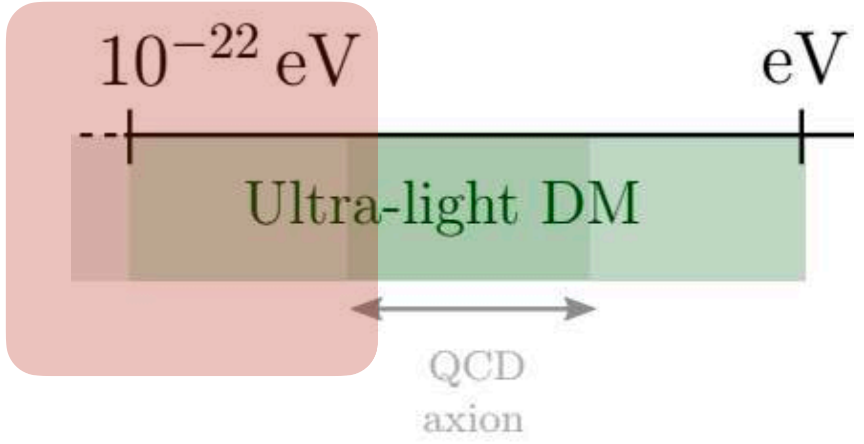
New probes

Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Modified from Jia Liu

Open questions - FDM



<u>Open questions</u>:

-Condensation?

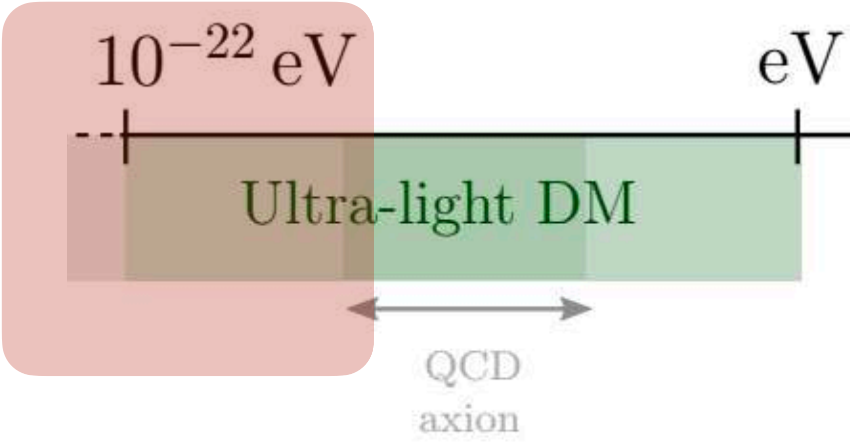
-Quantum mechanical?

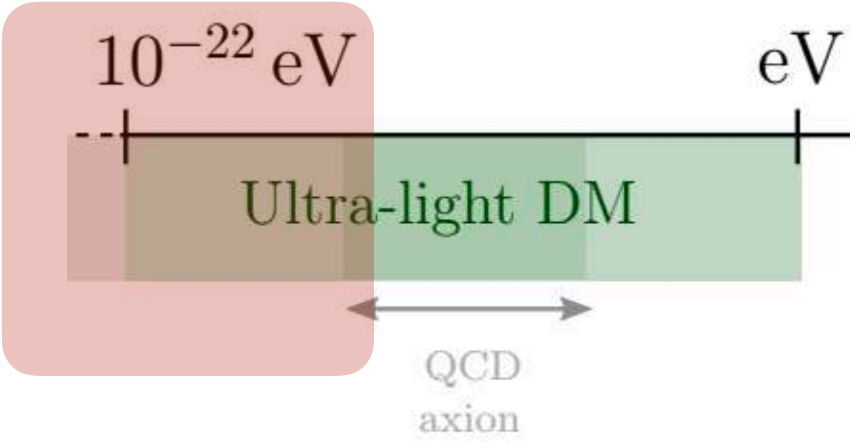
-Vortice description

-Baryons influence

-…

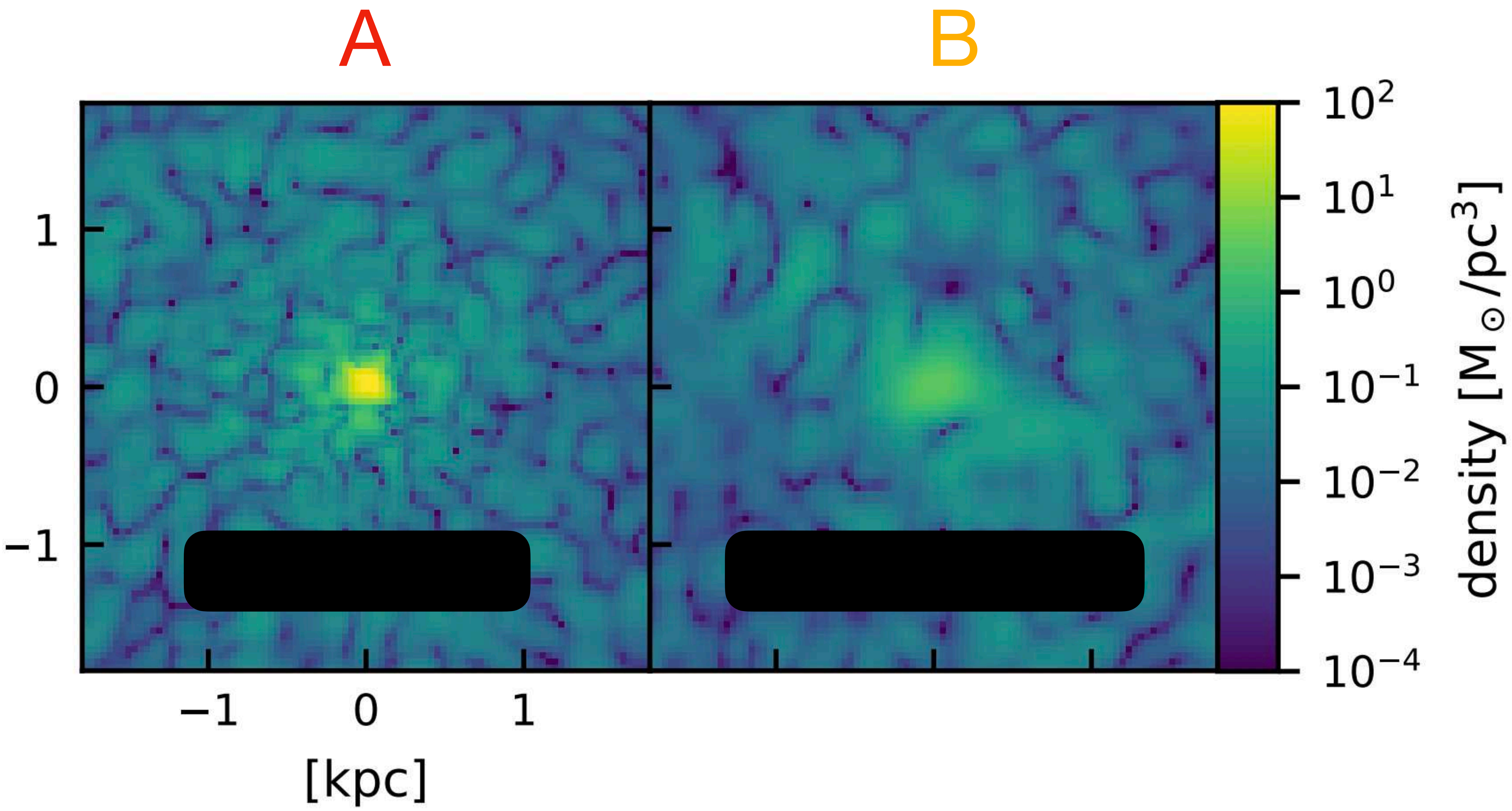
Role of baryons



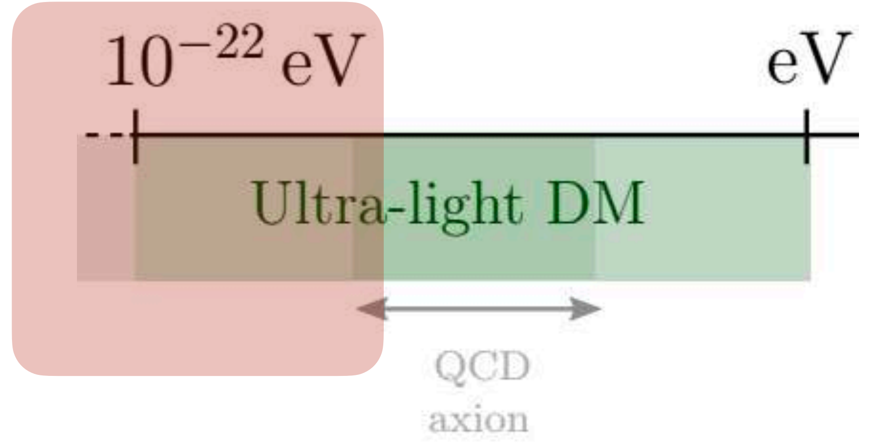


Role of baryons

From those two images, which one do you think has the influence of baryons?

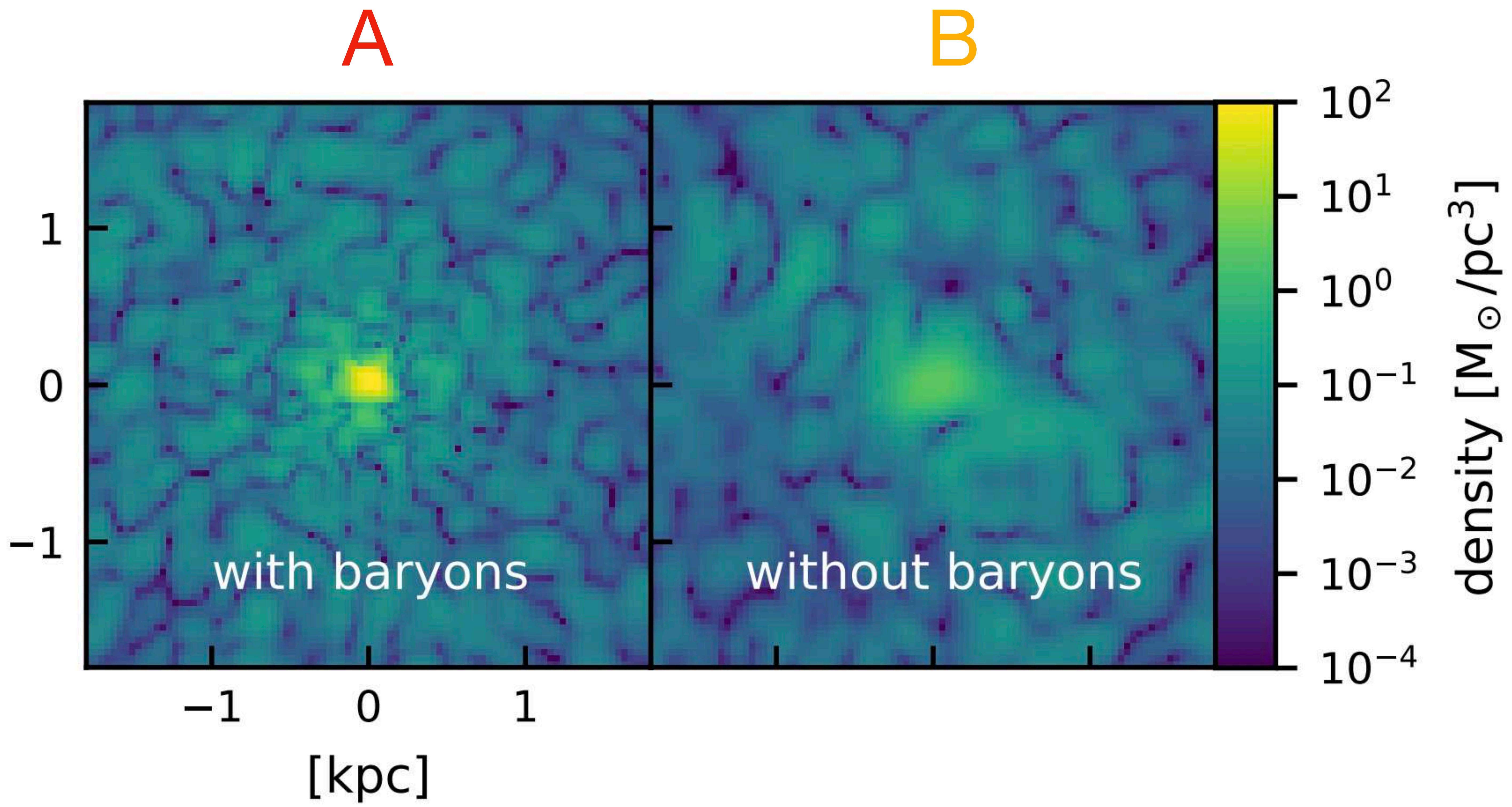


Veltmaat et al 2020



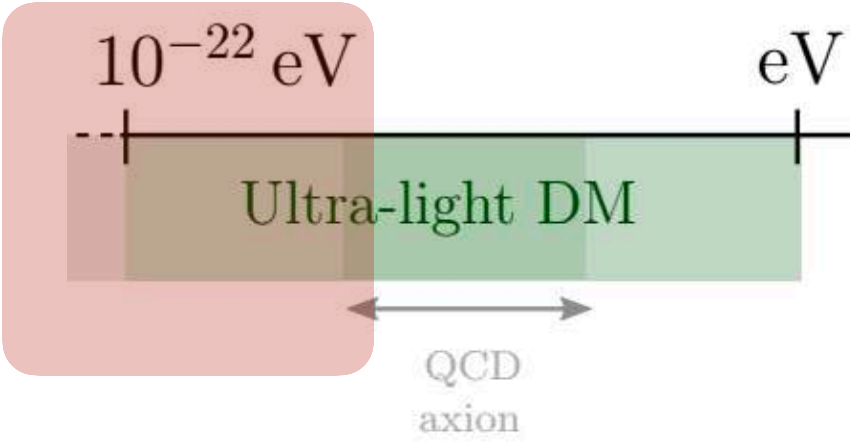
Role of baryons

From those two images, which one do you think has the influence of baryons?



Veltmaat et al 2020

Role of baryons



How baryons influence the behavior of ULDM?

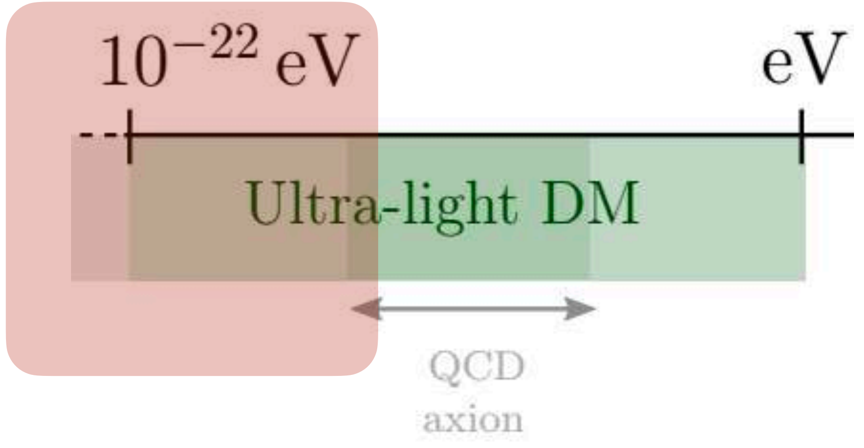
A) Enhance the small scale structures

C) Suppress small scale structure

B) Eject matter from galaxies

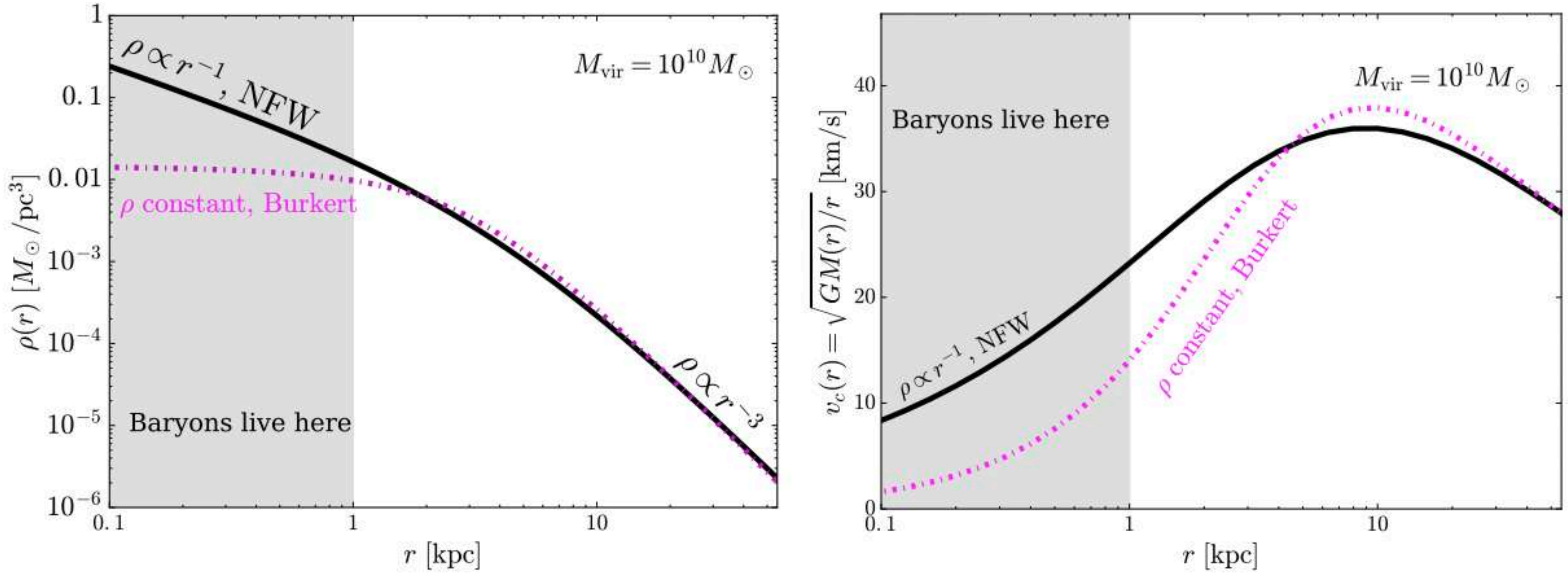
D) All of the above

Role of baryons

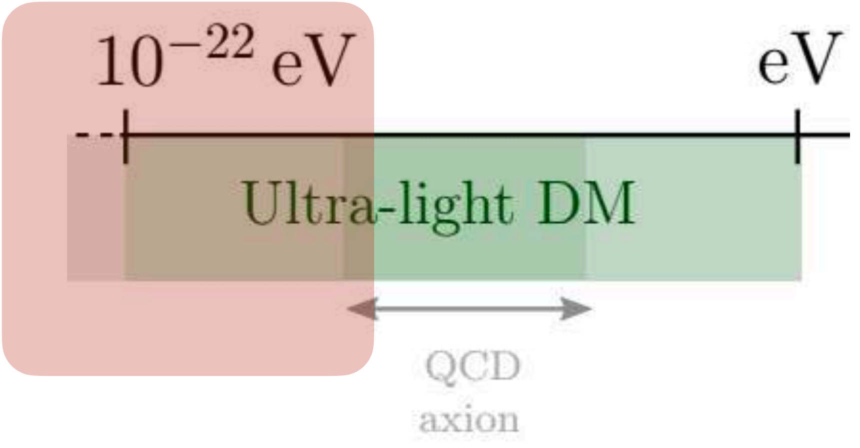


Core

Baryonic feedback

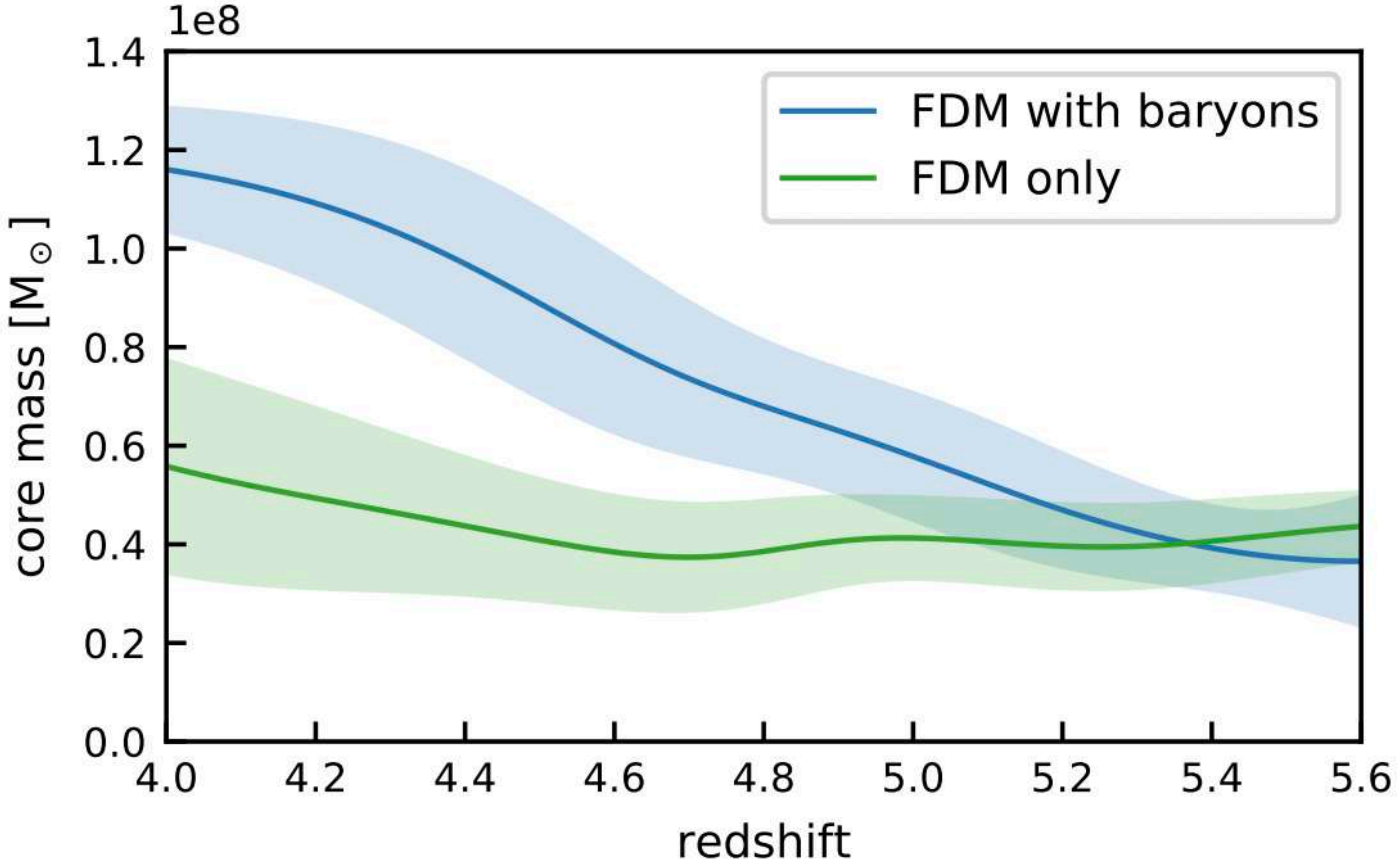


Role of *baryons*

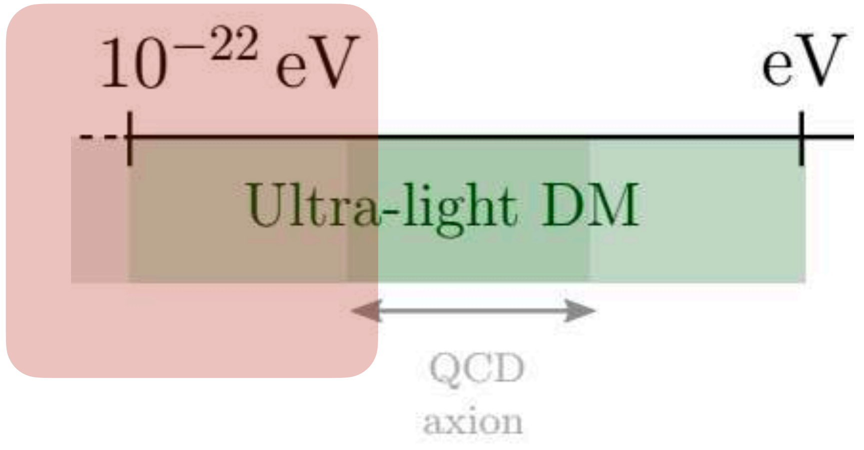


Core

Adding baryons: increase in the gravitational potential in the interior of the halo

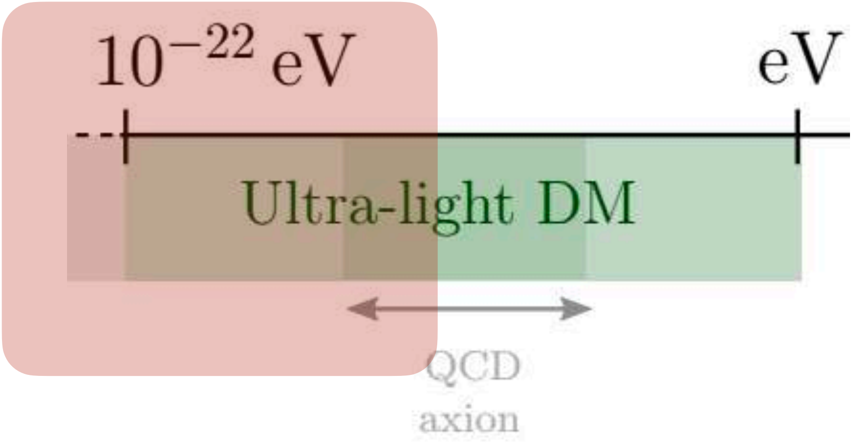


More massive and larger core than without baryons



Role of *baryons*

Interference pattern

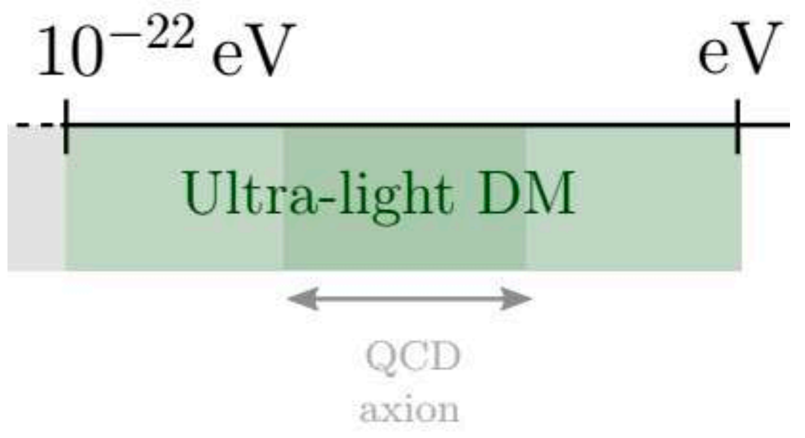


Extensions of the model

Beyond FDM

Adding self-interactions

Bounds on the mass and other parameters



Self interacting FDM

m g

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

DM Superfluid

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

Still highly unconstrained

* Check: Lasha Berezhiani et al (2020)

Multiple ULDM fields

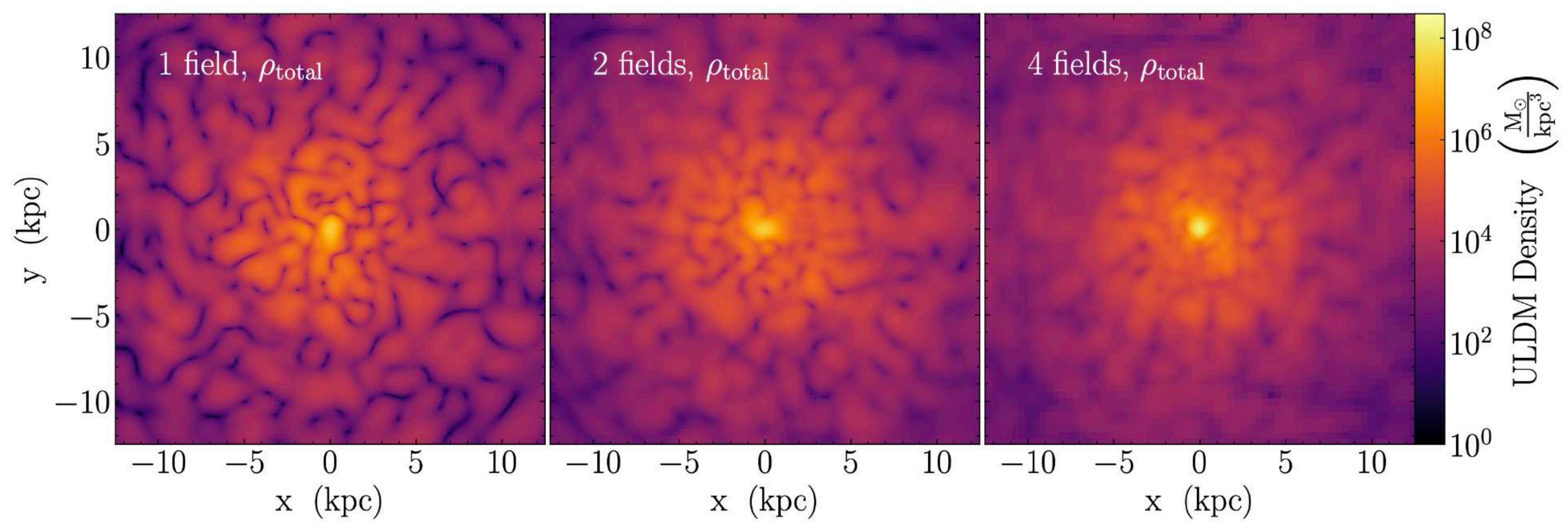
A natural extension of the standard single field FDM is to have more than one field.

The presence of more than one light field is predicted in many beyond SM and string theory models (e.g. axiverse)

These multiple fields can have **self-interaction** or not, and can be **coupled** with each other or not.

Interference pattern

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)

Multiple ULDM fields

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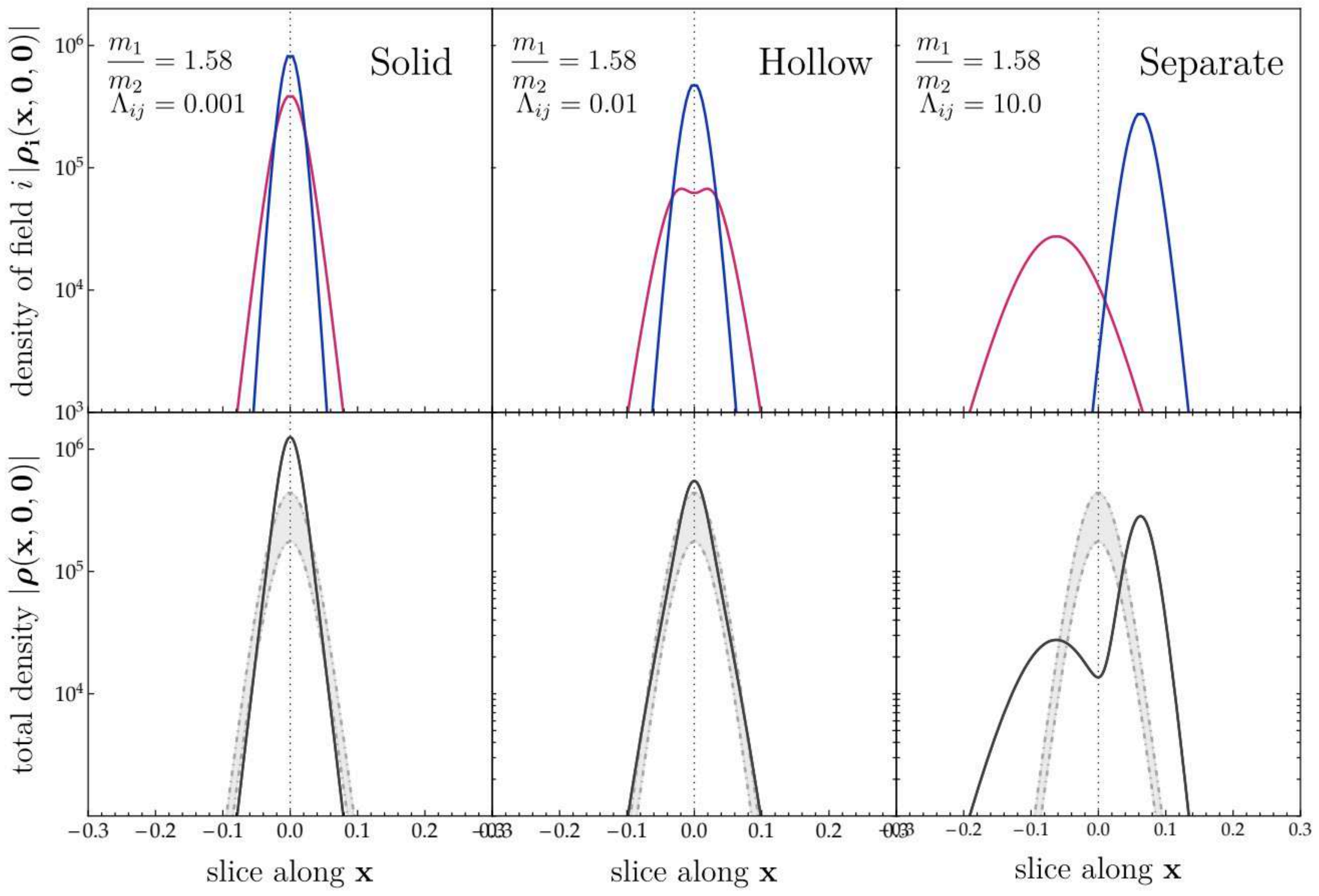
These multiple fields can have **self-interaction** or not, and can be **coupled** with each other or not.

<u>Soliton</u>

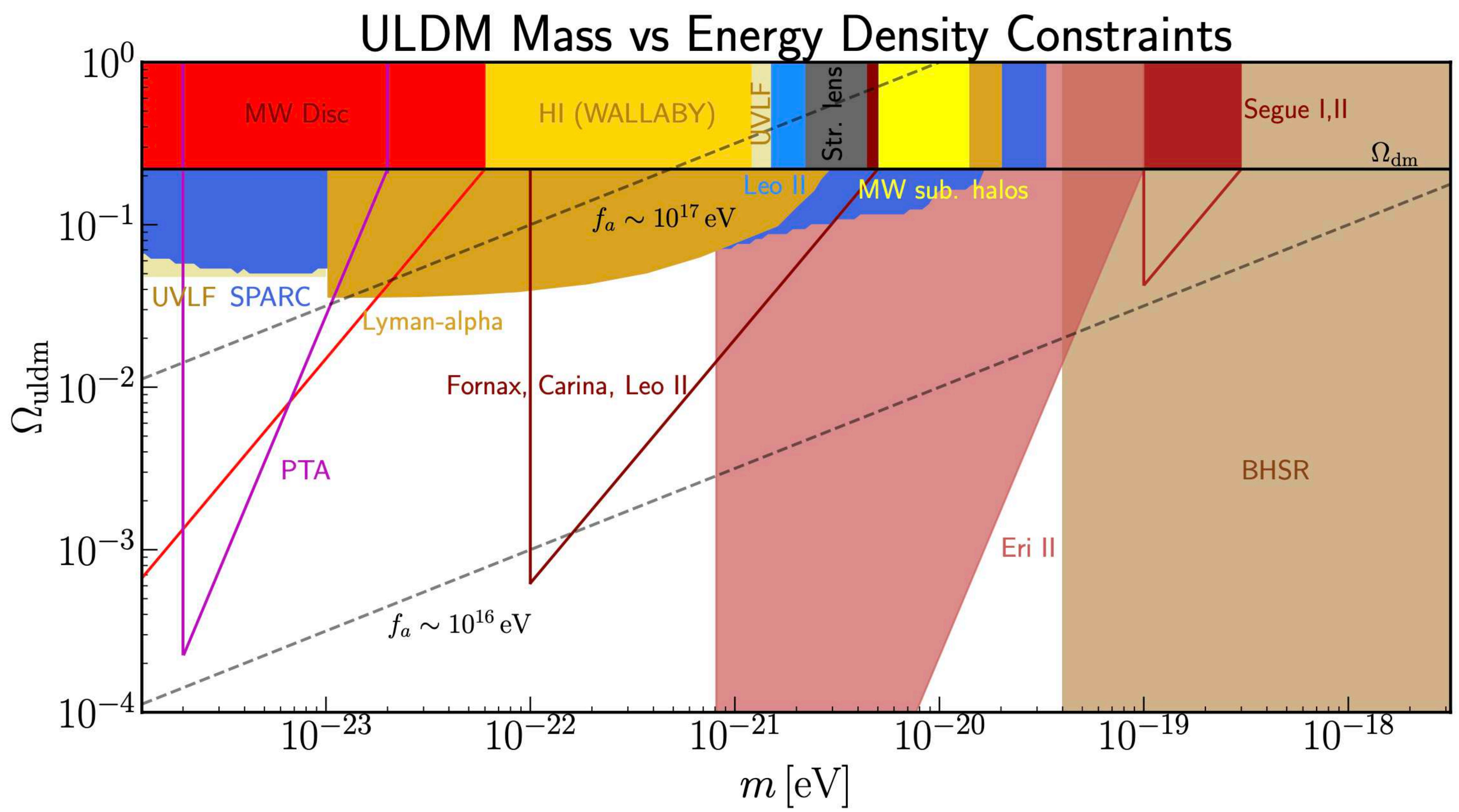


Mirasola et al 2024

See also: Capaneli, EF, McDonough 2025

Mixed CDM + ULDM

Another natural extension of the standard single field FDM is to consider that FDM is responsible for a fraction of the dark sector.

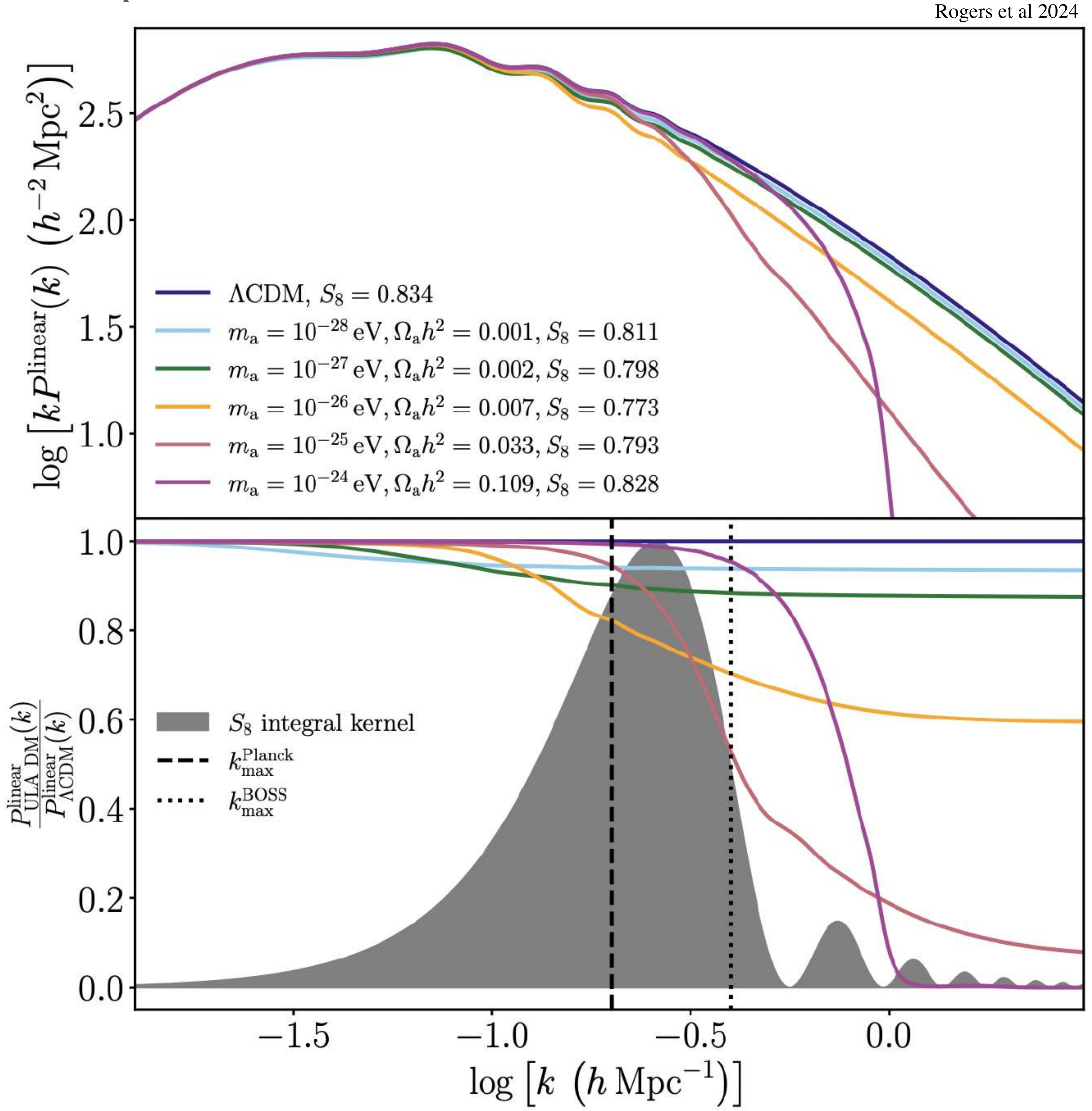


Mixed CDM + ULDM

Another natural extension of the standard single field FDM is to consider that FDM is responsible for a fraction of the dark sector.

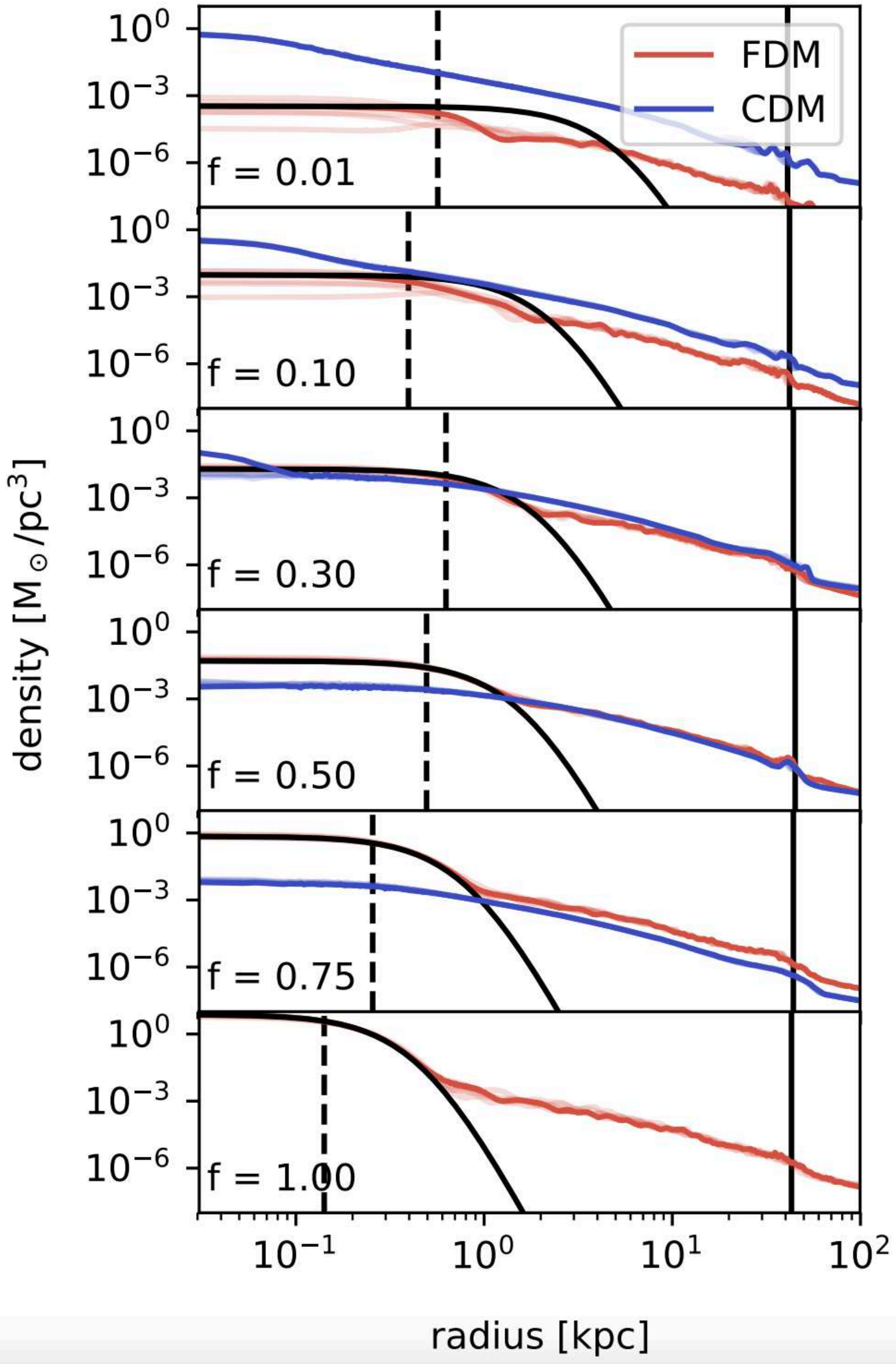
Power spectrum

Rogers et al 2024



Halo simulations

Schwabe et al 2020

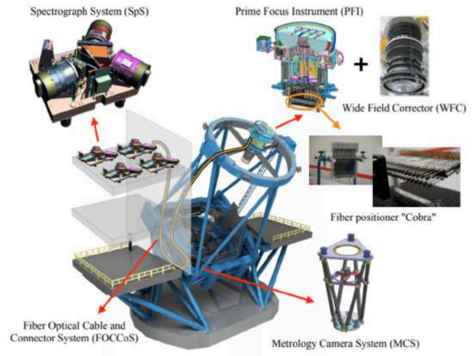


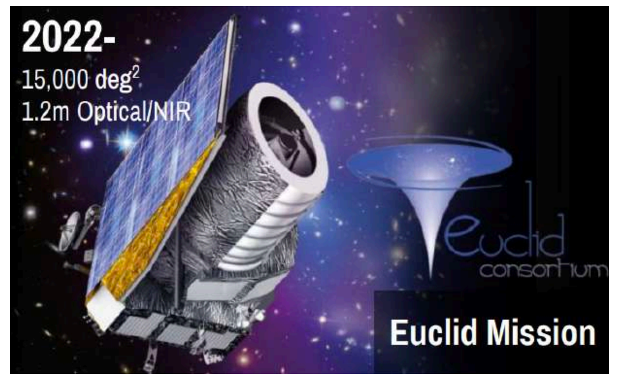
Future - signals in cosmology

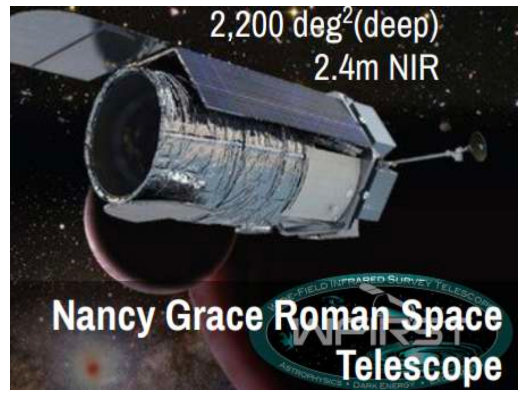
Observations

Photometric and spectroscopic surveys

Prime Focus Spectrograph (PFS)







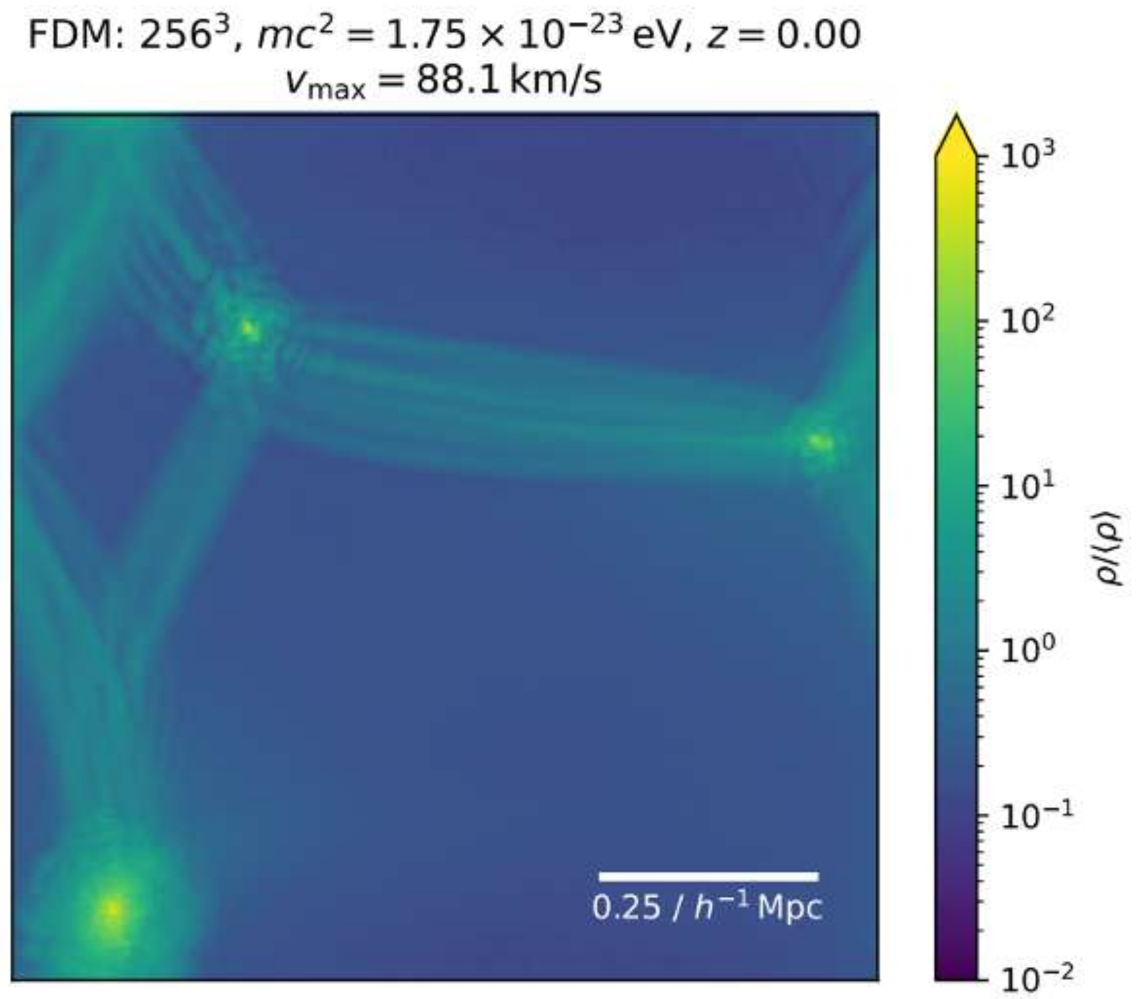
CMB

CMB-S4
Next Generation CMB Experiment

21cm

SKA
SQUARE KILOMETRE ARRAY

Simulations



New observables

New probes

Substructures
- strong lensing
- stellar streams

Small scale information from PS
- substructure convergence PS

Modified from Jia Liu

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)

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

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

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

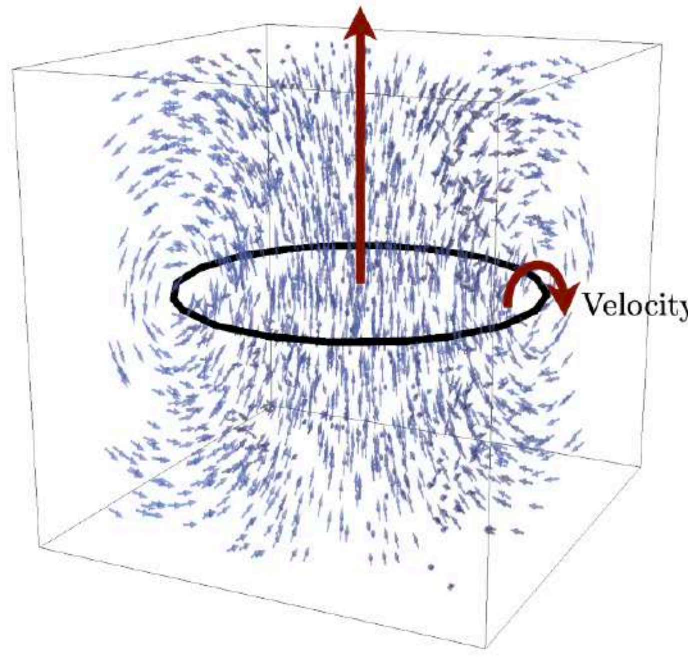
Vel. field is a gradient flow $\longrightarrow$ irrotational fluid, no vorticity

Fuzzy DM

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

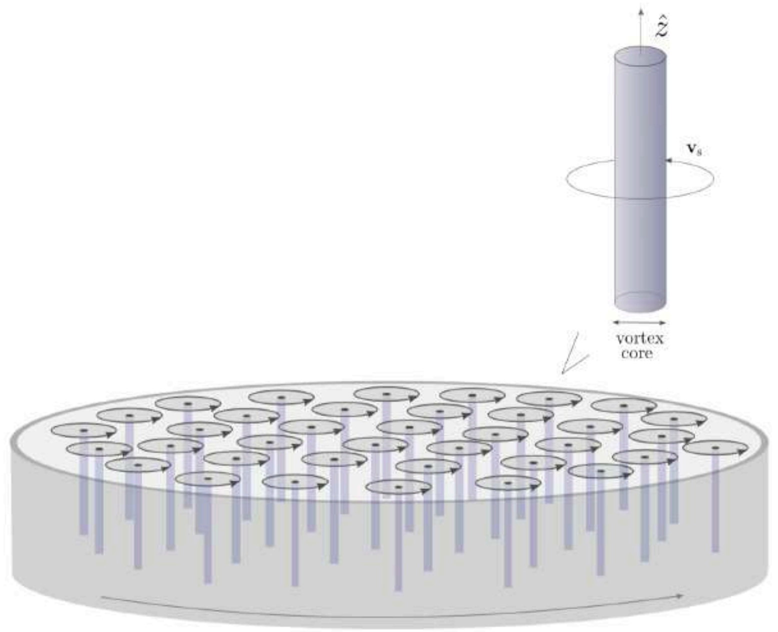
General defet in 3D

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



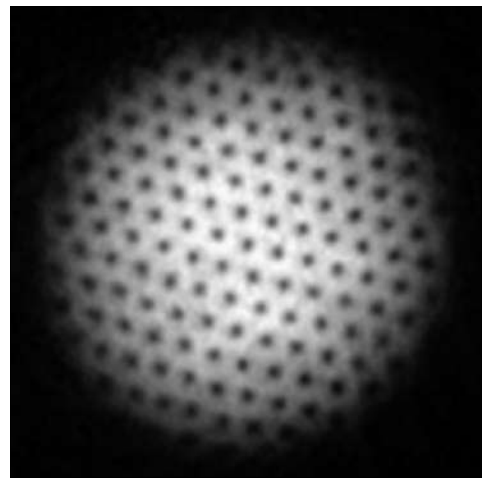
Self-interacting Fuzzy DM

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



EF, 2020

© Martin Zwierlein.




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

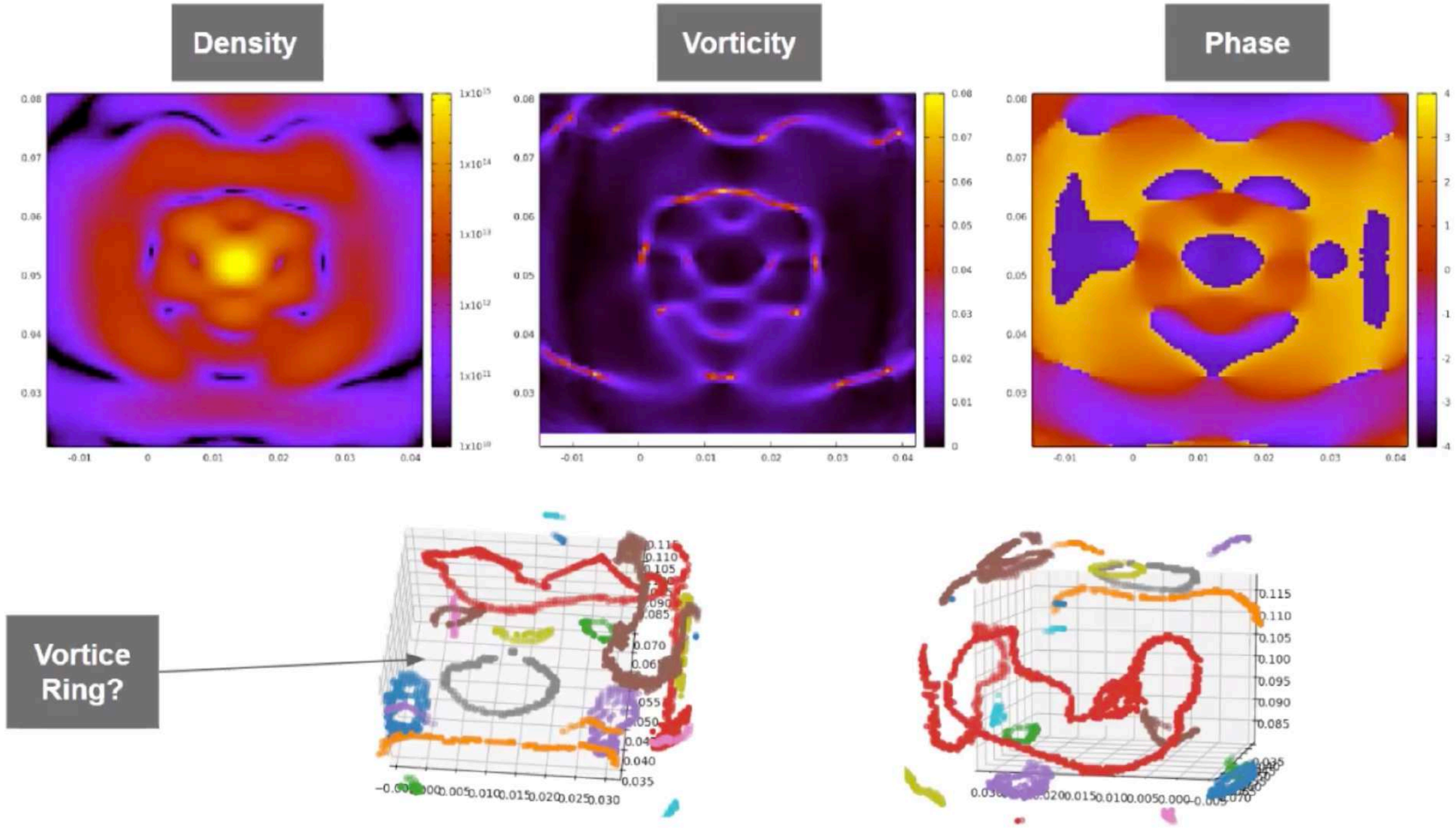
New observables

Vortices

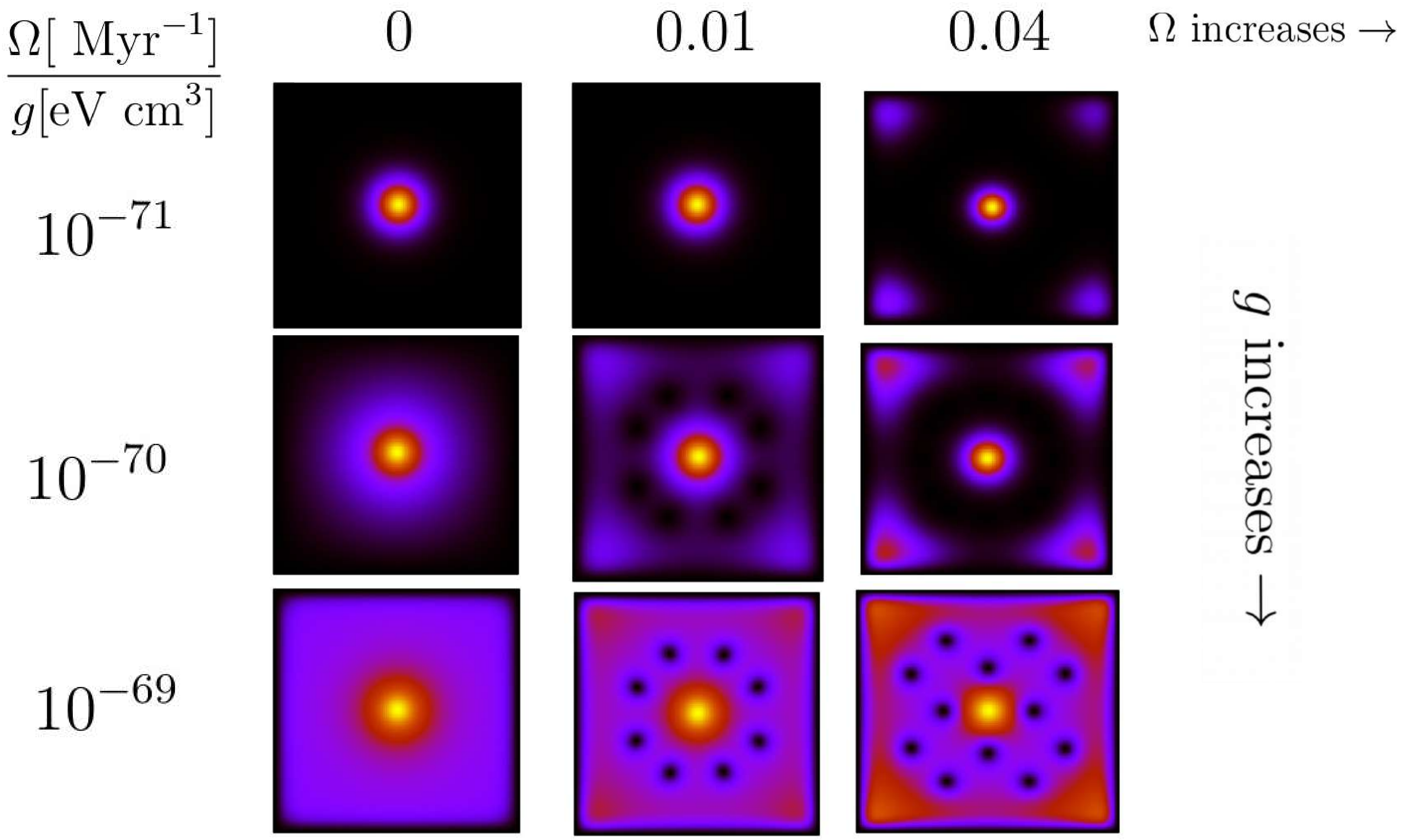
PRELIMINARY

In collaboration with Jowett Chan

Fuzzy DM



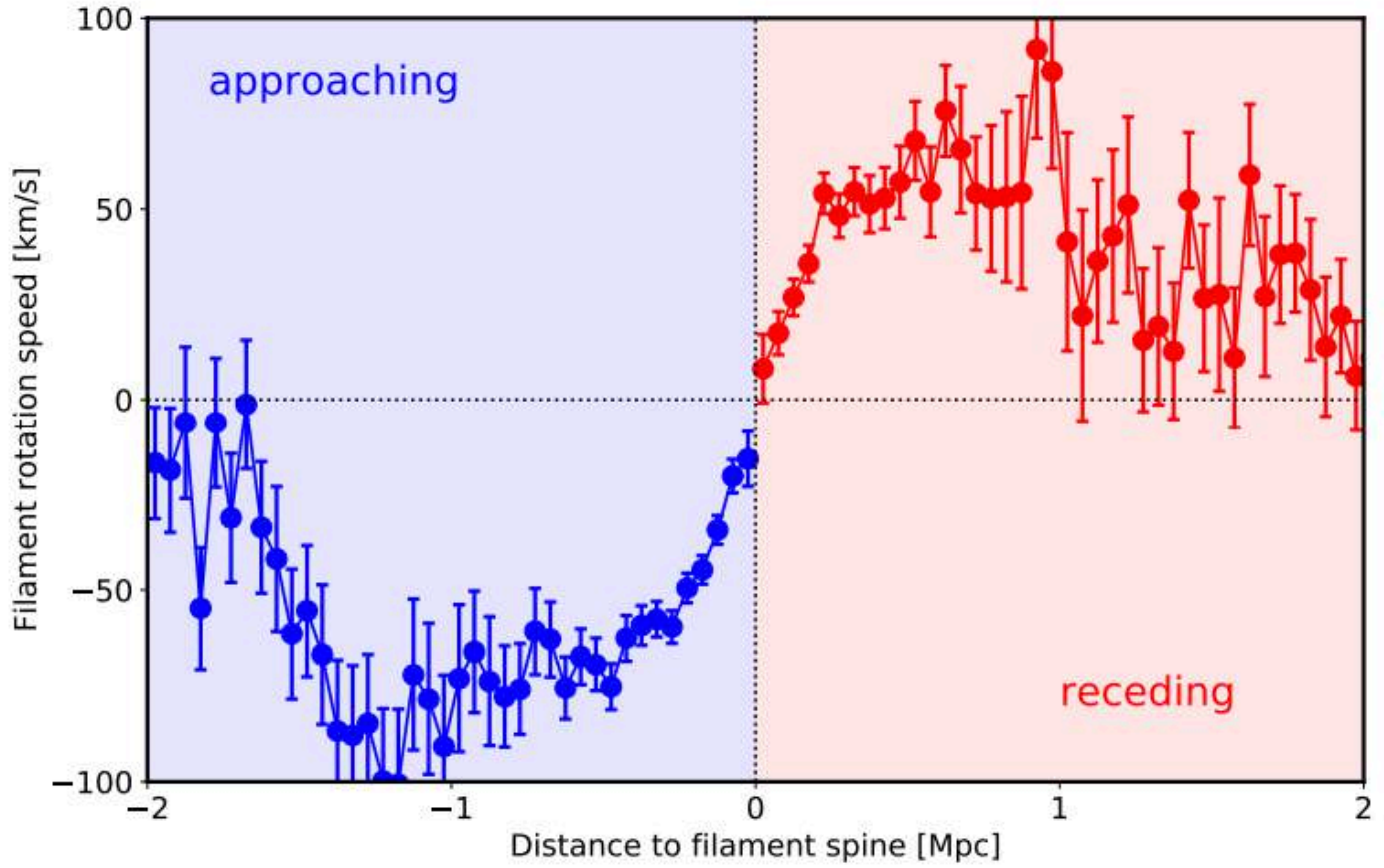
Self-interacting Fuzzy DM



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

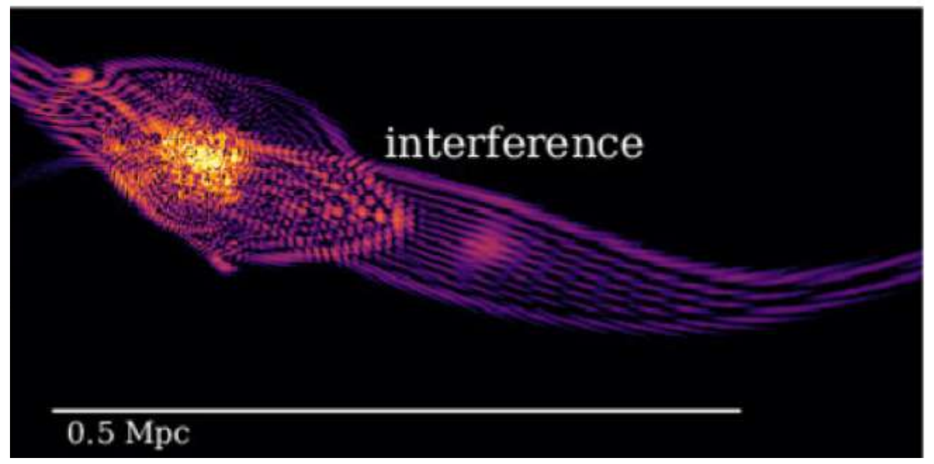
Rotation of filaments: vortices

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

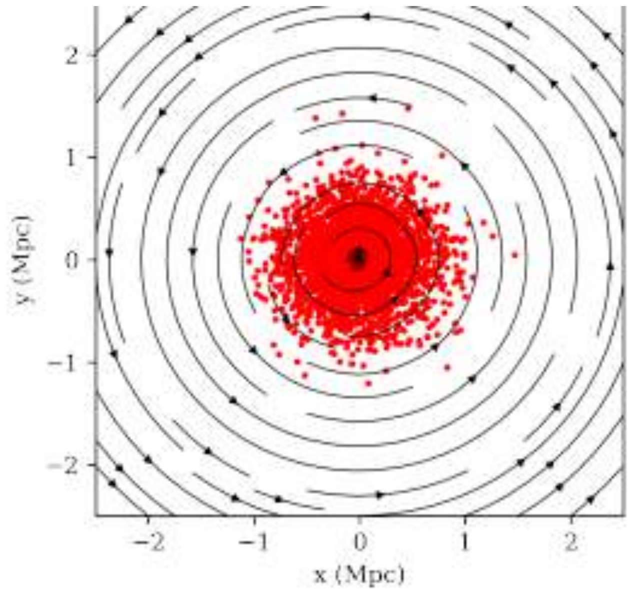


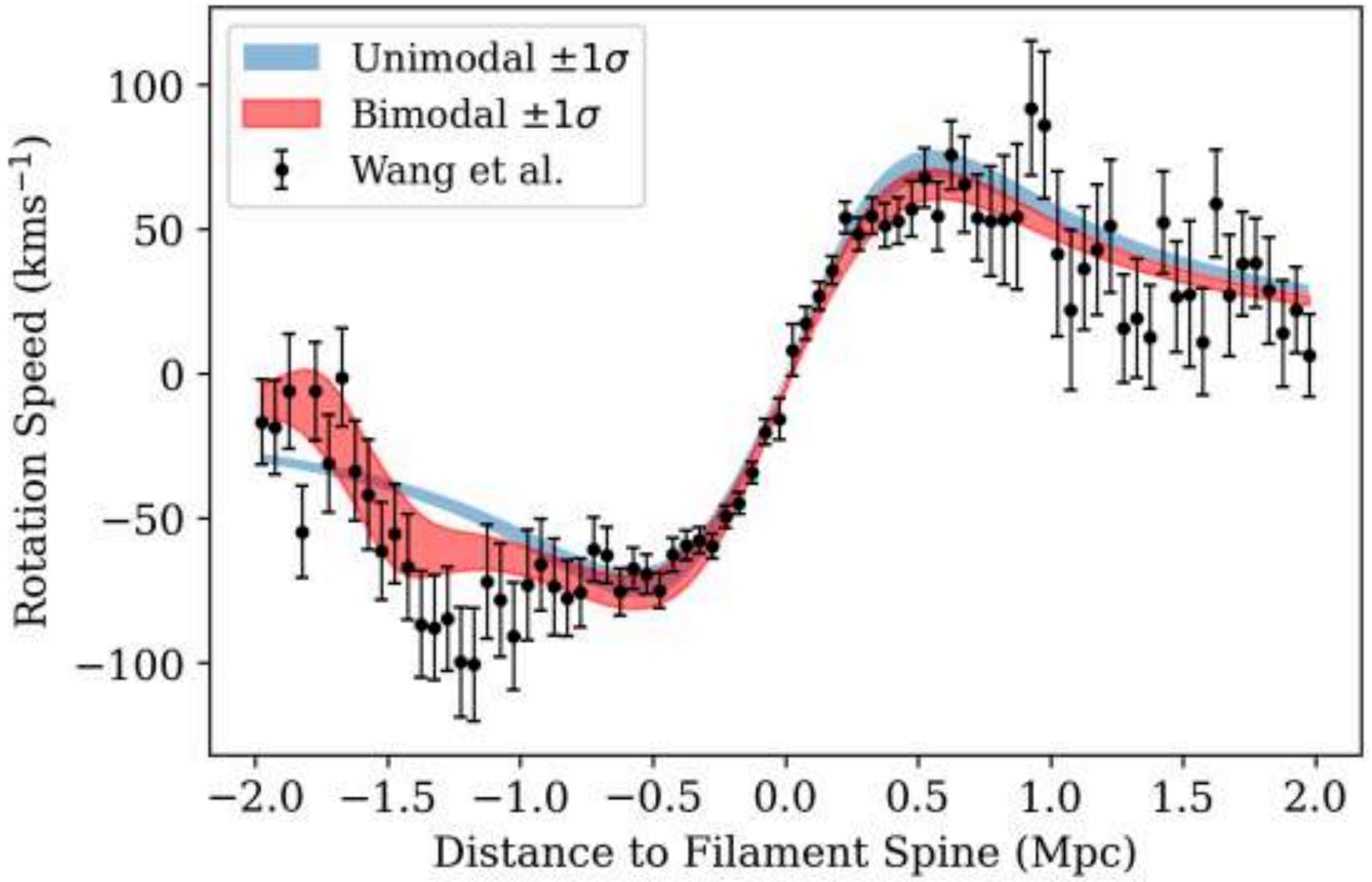
Mocz et al. 2017

- 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

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

- Suggest that a collection of (ULDM) 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)





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

$$\frac{N_V}{m} = 2.9^{+0.2}_{-0.2} \times 10^{25}\ \mathrm{eV}^{-1}.$$

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

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

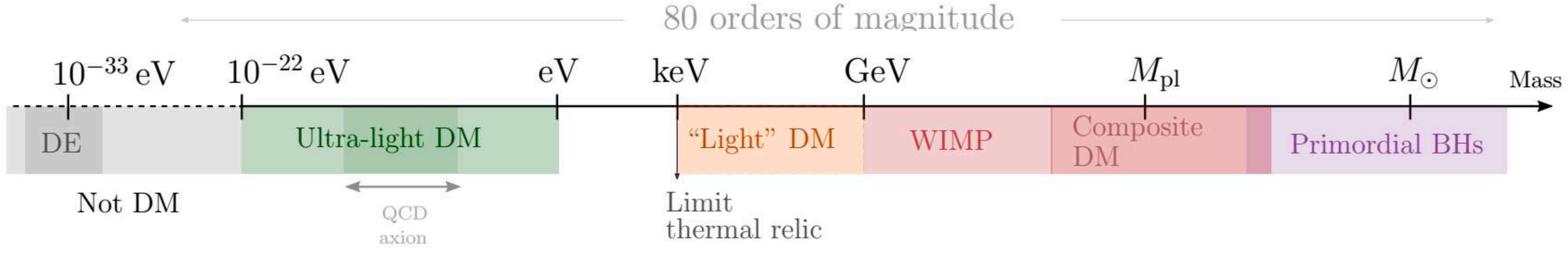
Summary

DM builder's guide

What we learned from observations

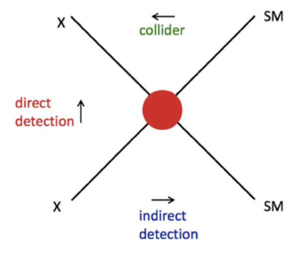
- **Cold or warm** Thermal candidate: $m_{dm} \geq \mathrm{keV}$
  Or produced cold by a non-thermal mechanism
- **Reproduce large and small scale distribution**
  Clusters like CDM on large scales $k \lesssim 10\,\mathrm{Mpc}^{-1}$
  Clustering on scales smaller than $k \gtrsim 10\,\mathrm{Mpc}^{-1}$ highly unconstrained
- **Non-interacting or weakly interacting**
  Can have a small electromagnetic interaction. Bound < **milicharge**
  Can have a small **self interaction**.
  Can interact via the ***weak force***
- **Abundance** $\Omega_m = 0.308 \pm 0.012$ *(Planck 2018)*
- **Stable**

Mass scale of DM

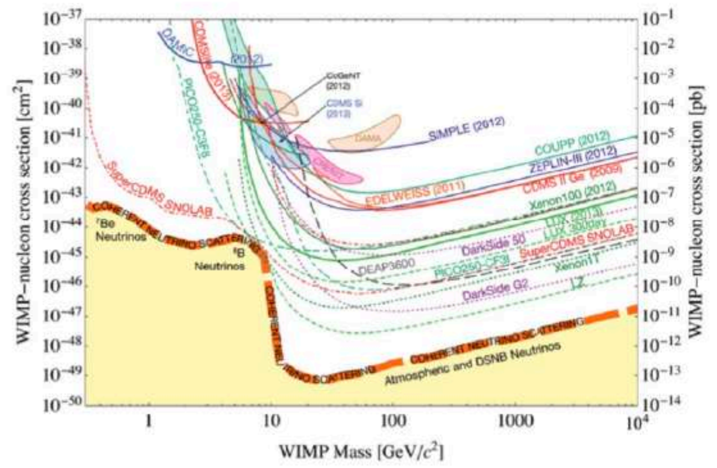


DM Landscape

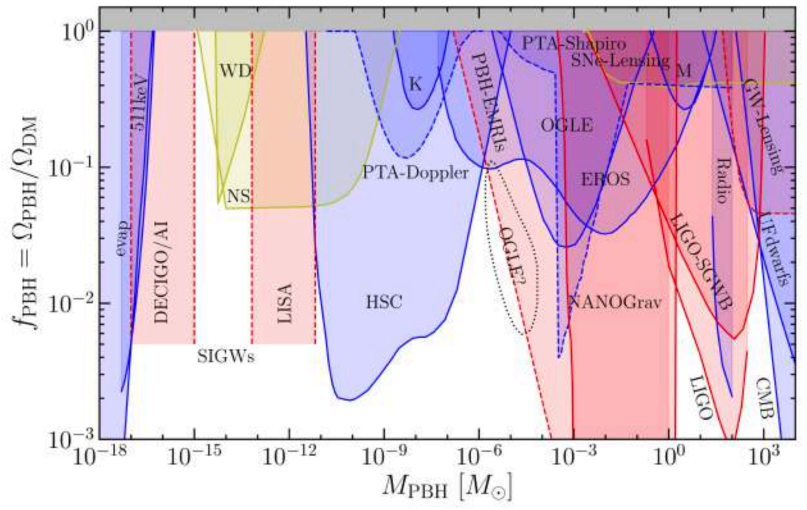
Search for DM



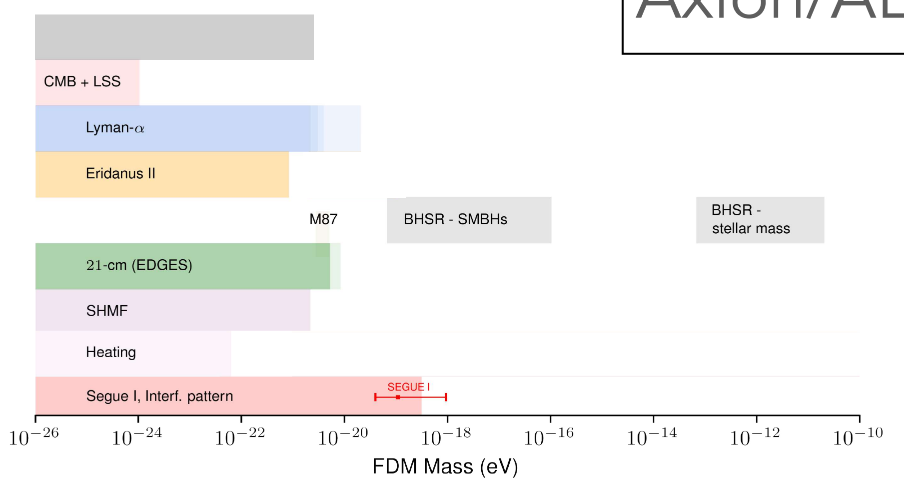
WIMPS

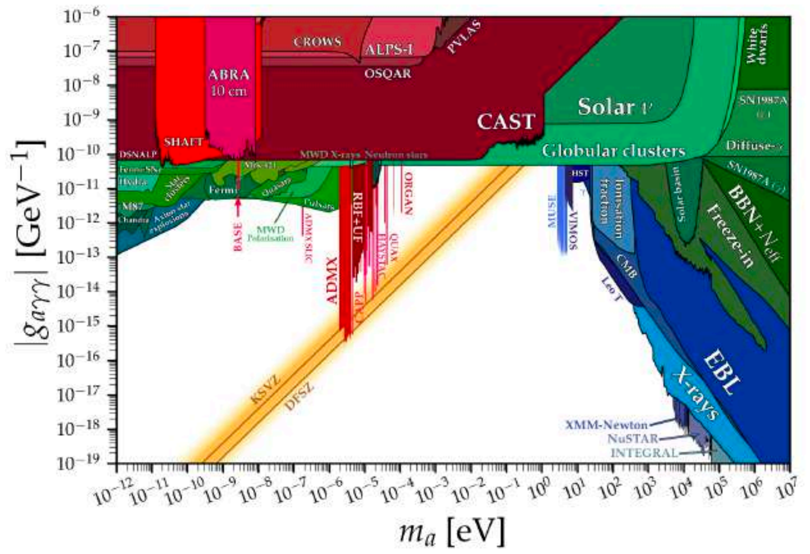


PBHs



Axion/ALP






Thank you very much!