Dark Matter *Models*

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Michigan Cosmology Summer School 2023

June 7th 2023

Outline

Lecture 1: evidence and model building

- Evidence for dark matter
- Dark matter model building
  - What we know about DM
  - Pre-requisites for a DM model
- Mass bounds
- Landscape of models
- MOND

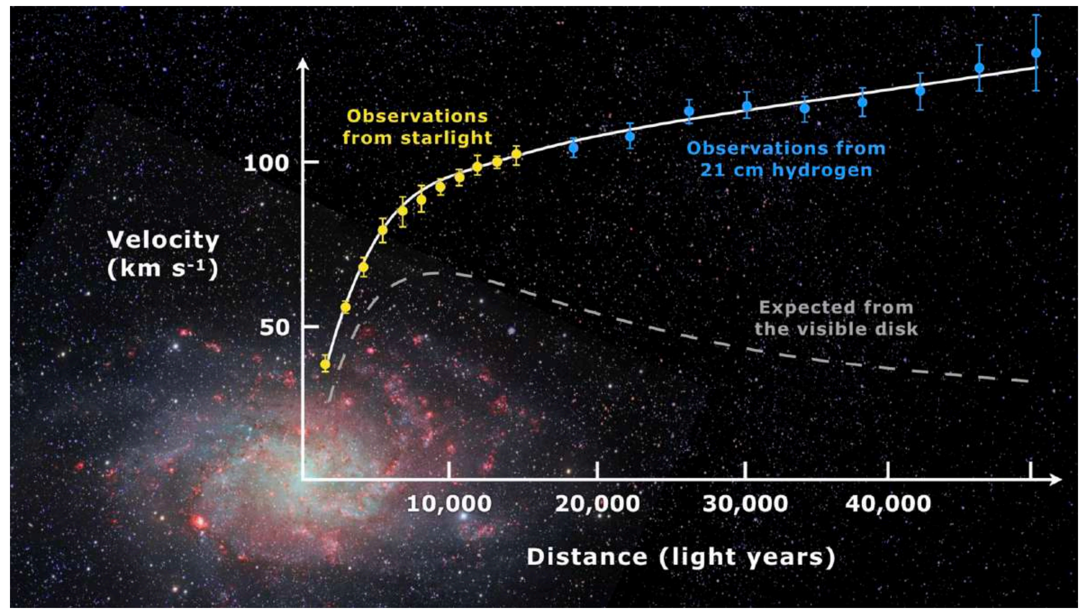
Lecture 2: DM models

- DM models
  - Particle DM: WIMPS
  - Macroscopic DM: MACHOS, Primordial BHs
  - Wave DM

Recap - lecture 1

Evidences for dark matter - properties

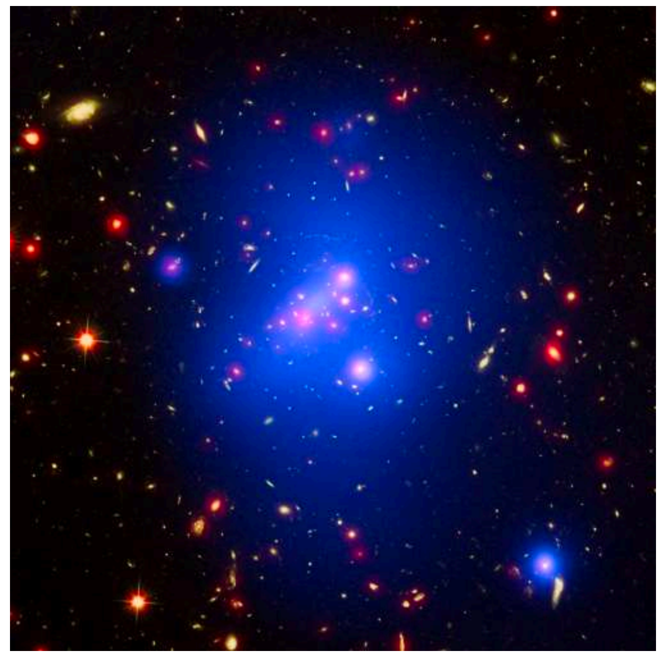
Galaxy rotation curves



Credit: Mario De Leo

- Mass fraction
- Distribution

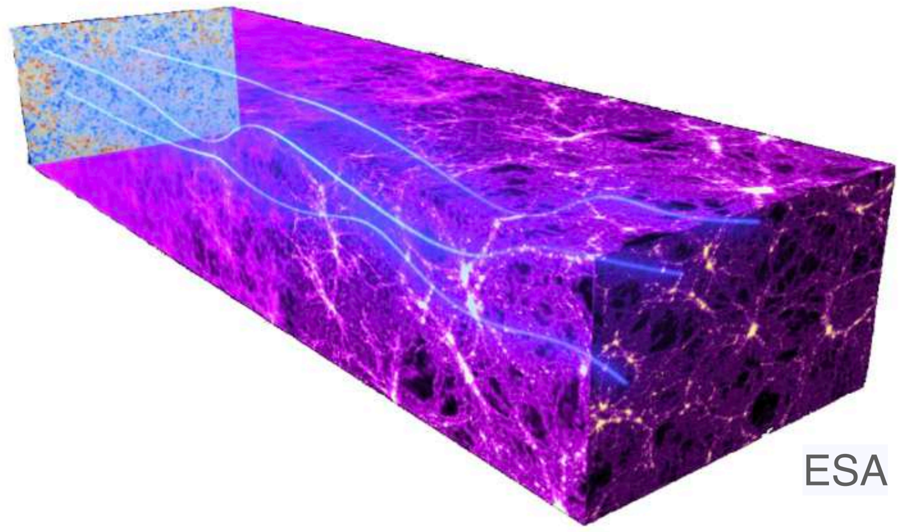
Clusters



CC BY 4.0

- Mass fraction
- Distribution

Lensing



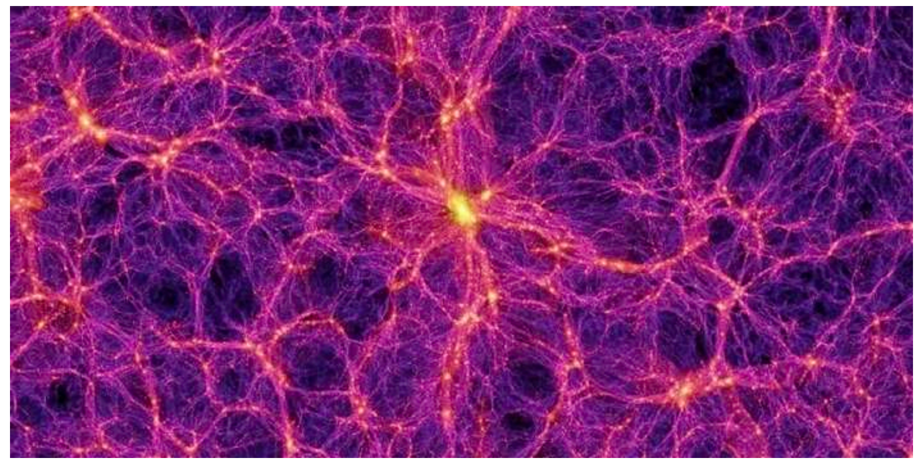
ESA

Strong lensing
- Mass fraction
- Distribution

Weak lensing
- Distribution
- Shape
- Structure

Micro lensing
- Mass fraction
- Smoothness

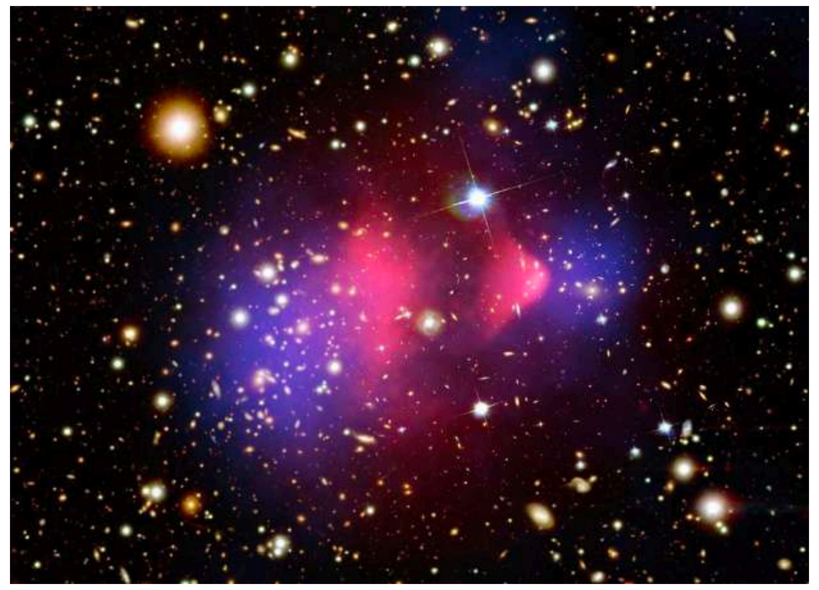
Large Scale Structure



Springel & others / Virgo Consortium

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

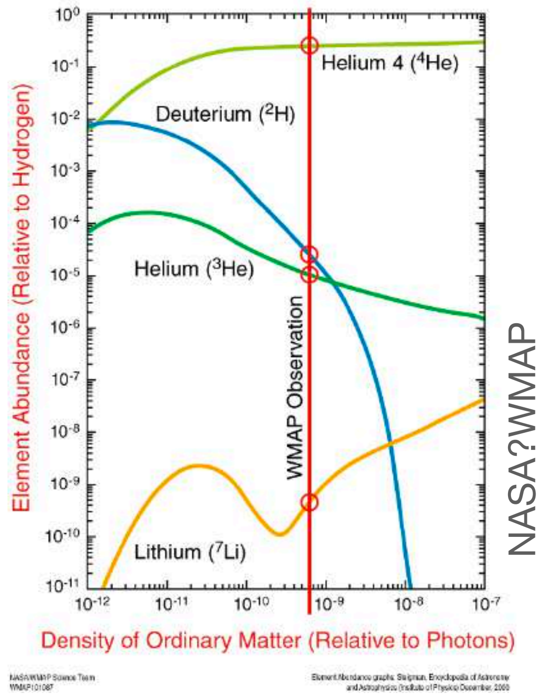
Cluster collision



NASA/CXC/CfA and NASA/STScI

- Distribution
- Separation from collisional matter
- Self-interaction

Big Bang Nucleosynthesis



NASA?WMAP

- Amount of baryons

Based on K. Mack

DM builder's guide

Pre-requisites for a dark matter candidate

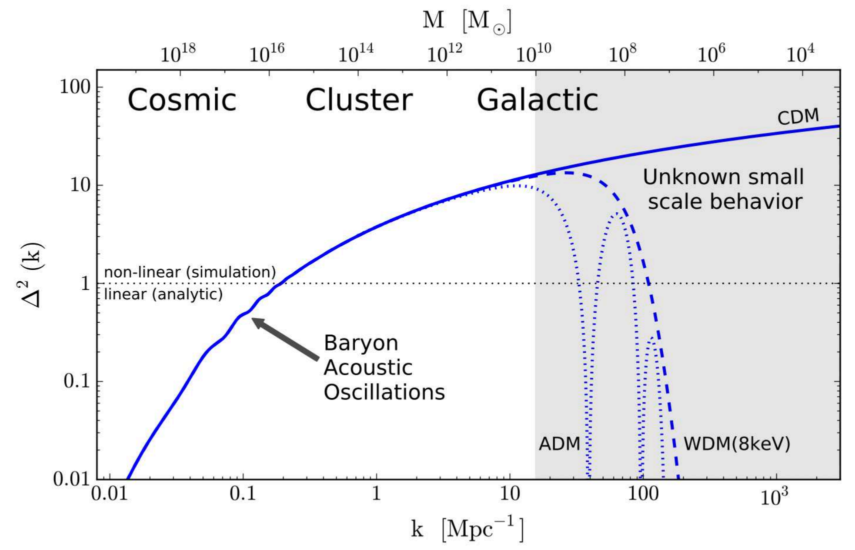
- Cold or warm Thermal candidate: $m_{dm} \geq \text{keV}$ Or produced cold by a non-thermal mechanism

  Has to be non-relativistic at BBN

- Reproduce large and small scale distribution

  Clusters like pressure-less fluid on large scales $k \lesssim 10\,\text{Mpc}^{-1}$

  Clustering on scales smaller than $k \gtrsim 10\,\text{Mpc}^{-1}$ highly unconstrained



- Non-interacting or weakly interacting (~~Dark, colissionless~~)

  Can have a small electromagnetic interaction. Bound < **milicharge**

  Can have a **self interaction**. Bounds: $\sigma/m_{dm} < 0.13\,\text{cm}^2/\text{g}\,,\ \sigma/m_{dm} < 0.35\,\text{cm}^2/\text{g}$

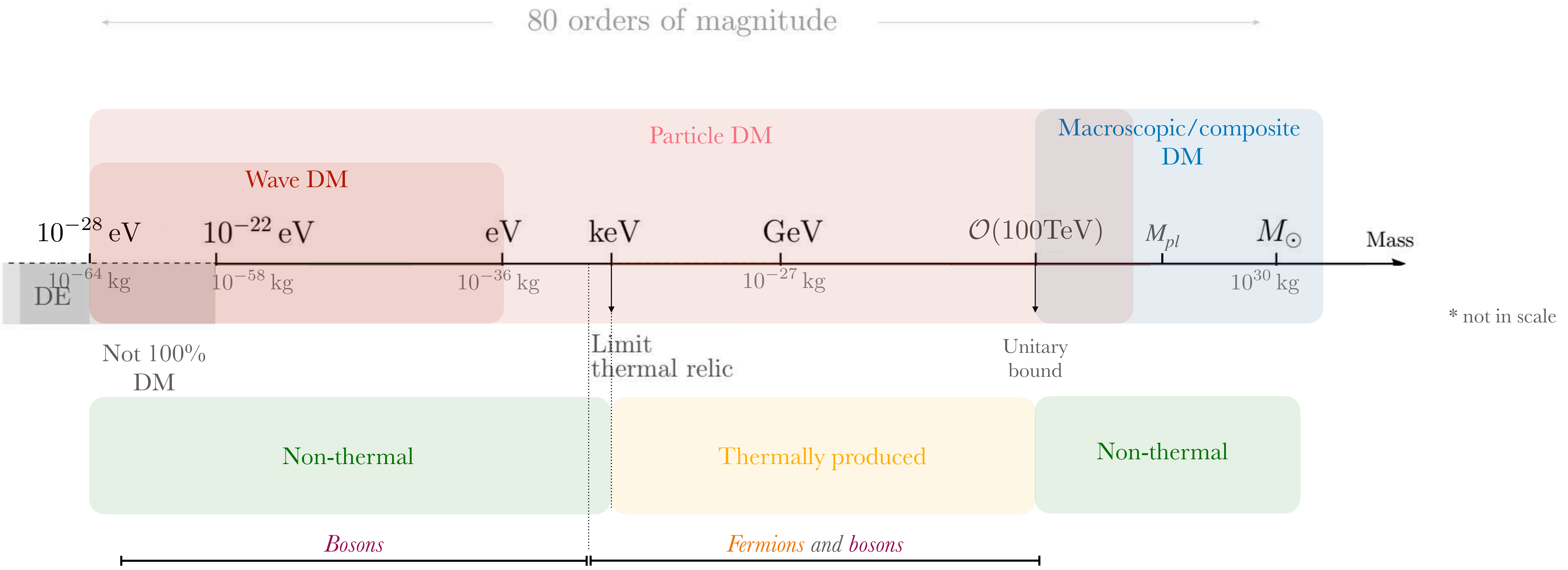
  Can interact via the ***weak force***

- Abundance $\Omega_m = 0.308 \pm 0.012$ (*Planck 2018*)

- Stable **If** it is a particle, it has to be stable with lifetime of DM should be much greater than the age of the universe

Mass scale of dark matter

We can use observations of LSS and galaxies to put bounds in the “particle" physics properties, like mass and spin, of the DM candidate



There are ways to evade some of these bounds!

Natural units ($c = 1$)
$1\,\text{kg} \to \sim 5 \times 10^{35}\,\text{eV}$
$1\,M_\odot \to \sim 10^{66}\,\text{eV}$

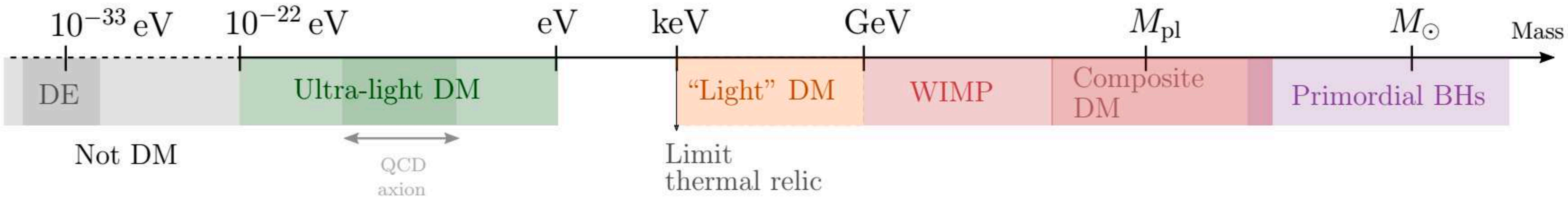
Landscape of dark matter models

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

State of the “art”

Mass scale of DM

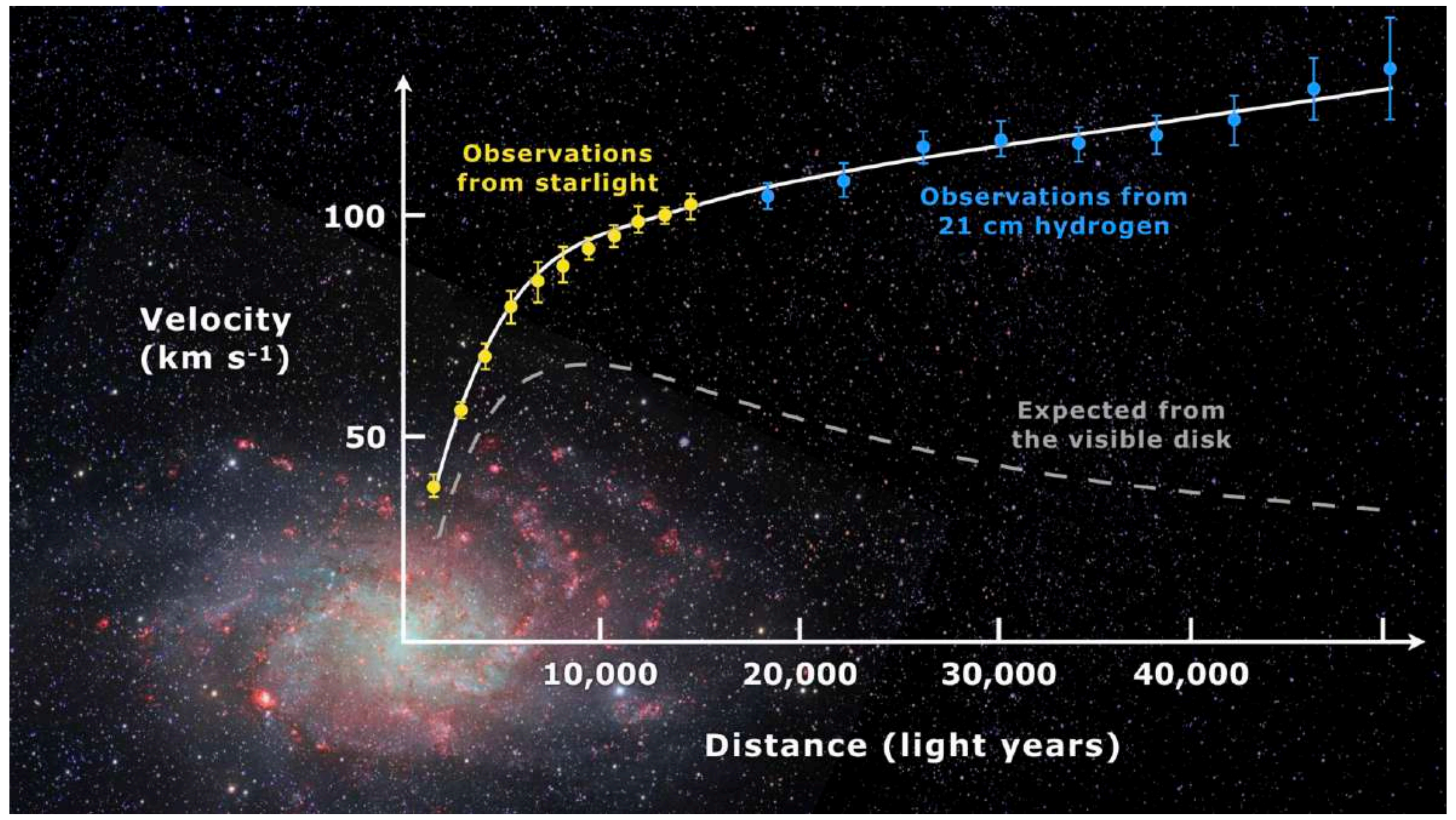
80 orders of magnitude



MOND

Milgrom, 1983.

Modified Newtonian Dynamics



Missing mass

$$v_c(r) = \sqrt{\frac{G_N M(r)}{r}}$$

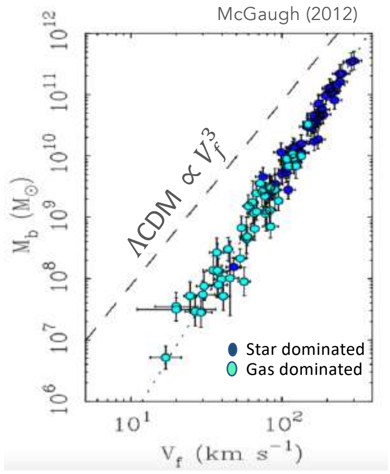
Empirical relation

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

$$a_N^b = \frac{G_N M_b}{r^2}$$

$$a_0 \simeq 1.2 \times 10^{-8}\,\mathrm{cm/s^2}$$

Curiosity: Baryons lead the dynamics!



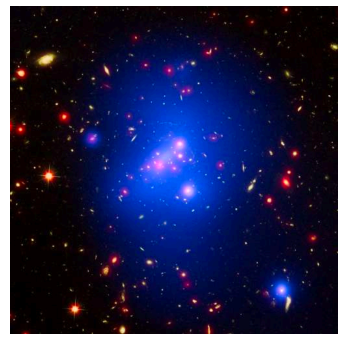
BTFR

Works really well to: (1) Fit galaxy rotation curves; (2) Explain the scaling relations

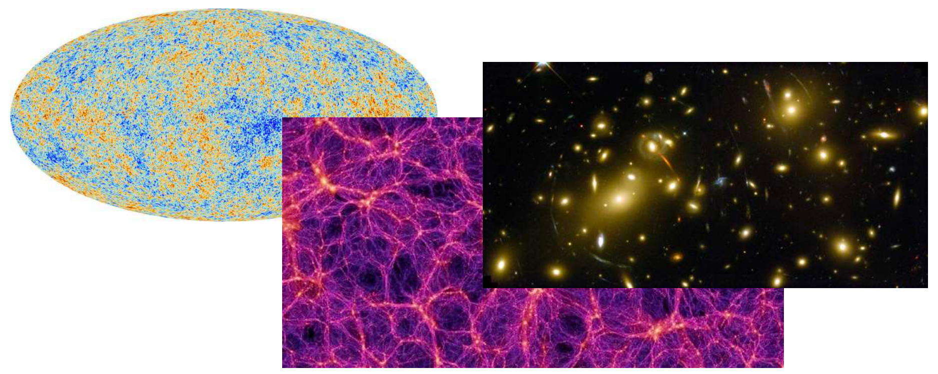
BUT: Modified theory of gravity

Milgrom, 1983.

~~MOND without DM~~



Clusters



Large scales

Relativistic extension: TeVeS, (BIMOND)

2020: "*A new relativistic theory for Modified Newtonian Dynamics*", C. Skordis, T. Zlosnik ⟶ Agreement with CMB

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  - Particle DM: WIMPS, WIMPzillas
  - Macroscopic DM: MACHOS, Primordial BHs
  - Wave DM

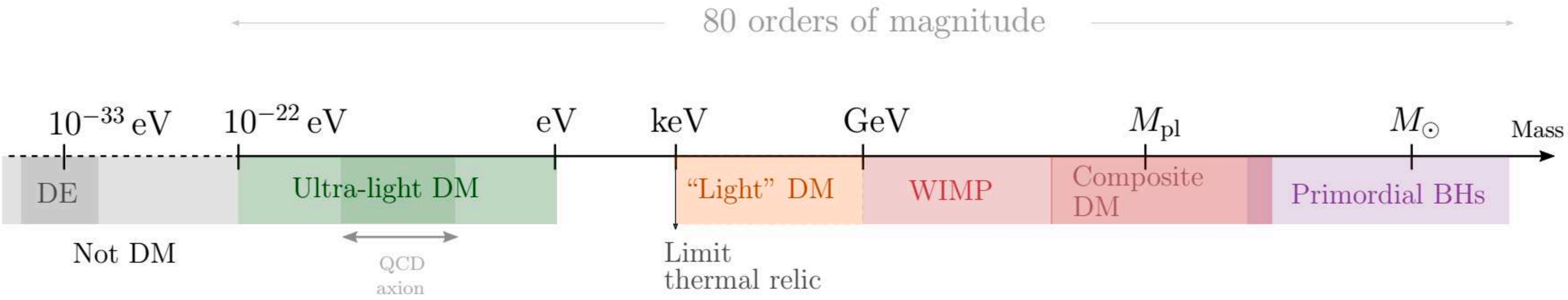
* Biased review of the DM models

Landscape of dark matter models

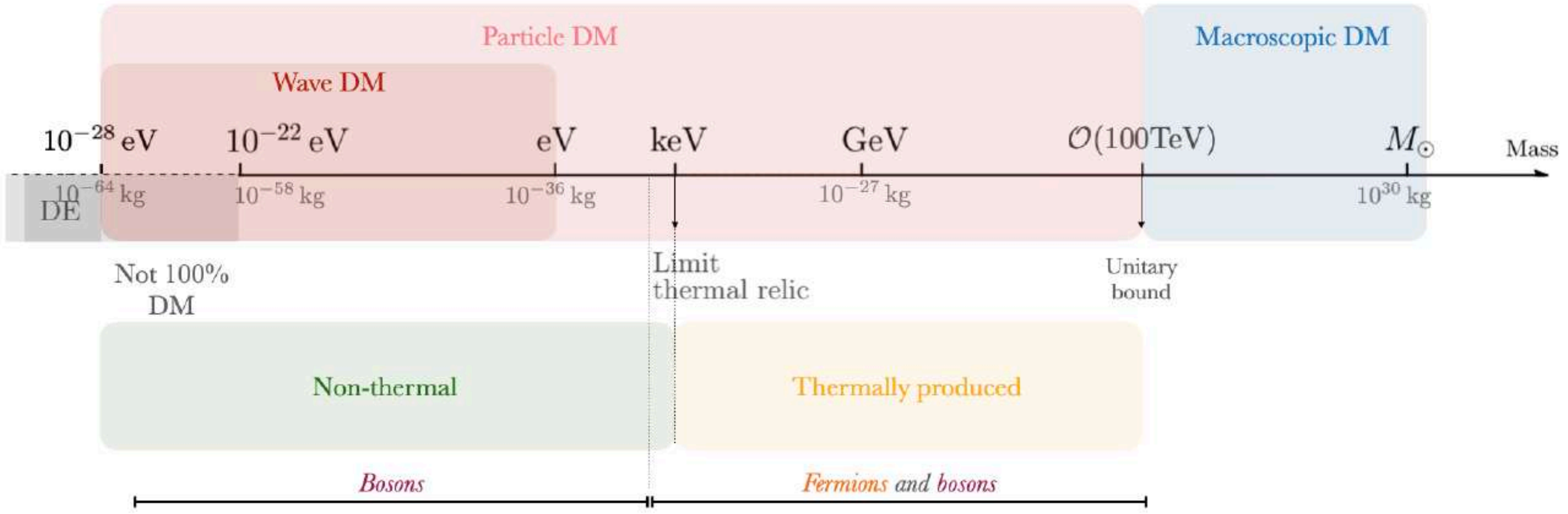
- What is DM? What is the nature of DM?

State of the "art"

Mass scale of DM



Particle DM



Particle DM
Macroscopic DM
Wave DM
10^{-28} eV
10^{-22} eV
eV
keV
GeV
$\mathcal{O}(100\text{TeV})$
$M_\odot$
Mass
10^{-64} kg
10^{-58} kg
10^{-36} kg
10^{-27} kg
10^{30} kg
DE
Not 100% DM
Limit thermal relic
Unitary bound
Non-thermal
Thermally produced
Bosons
Fermions and bosons

Landscape of dark matter models

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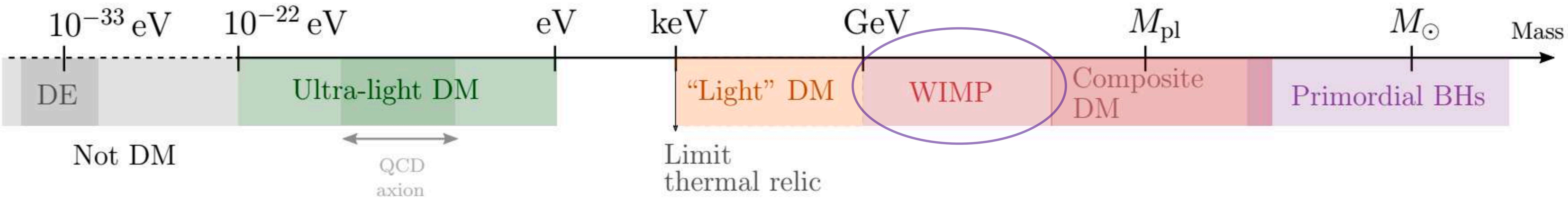
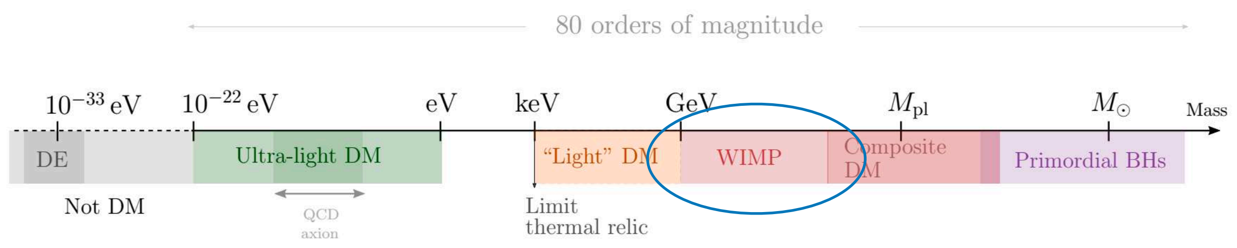


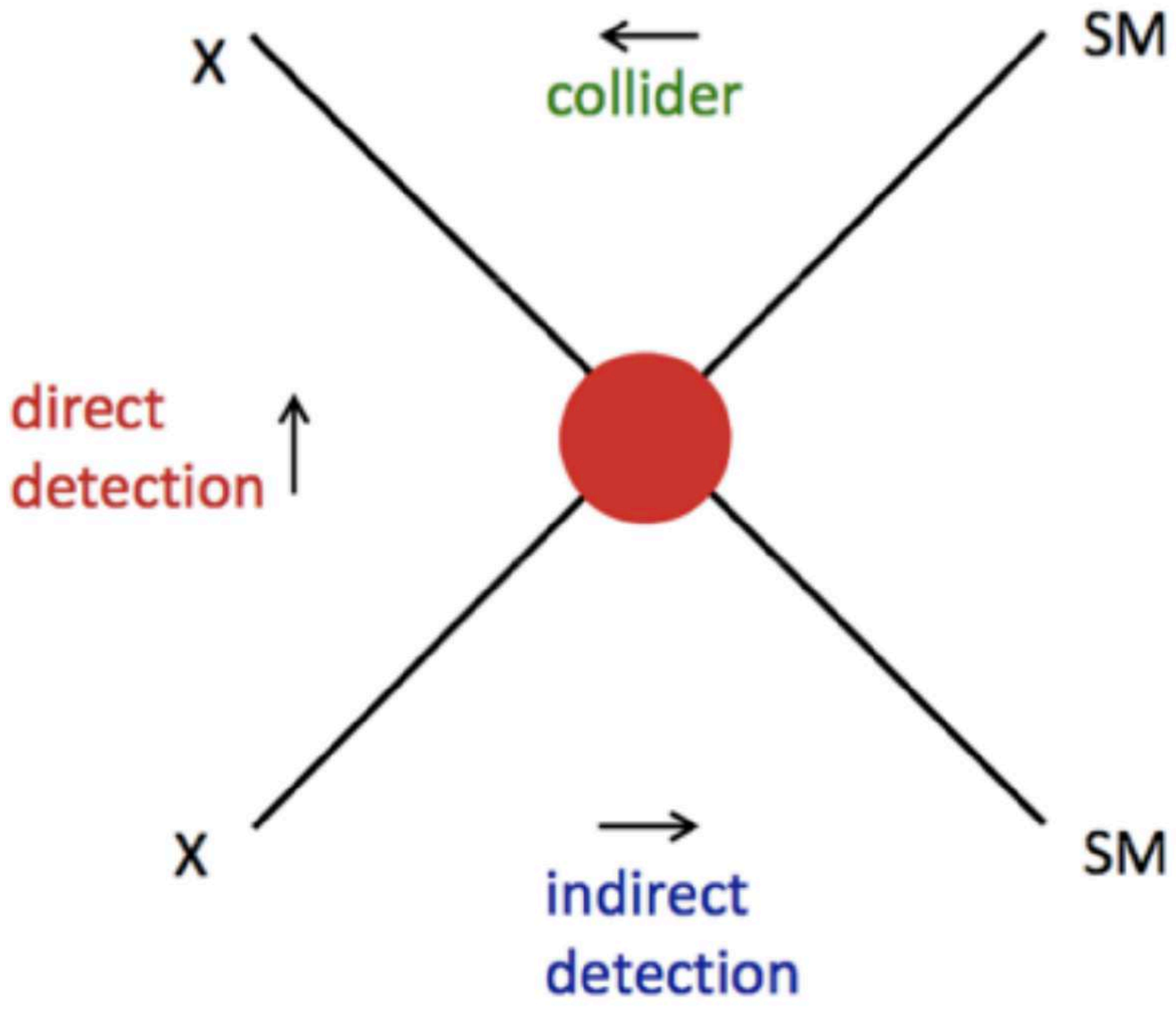
WIMPS

weakly interacting massive particles

WIMP - weakly interacting massive particle

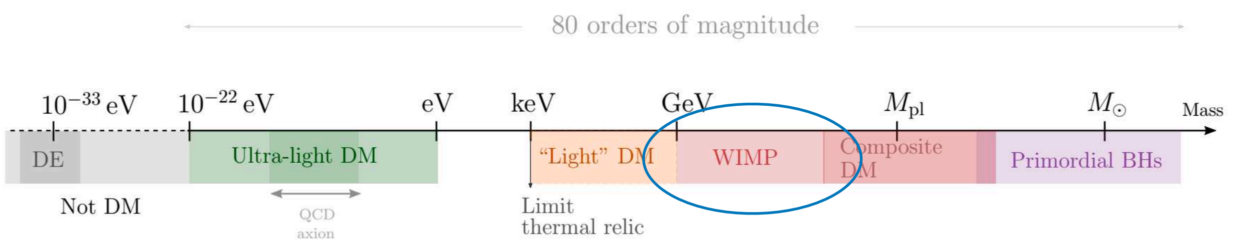


- Most accepted candidate
- (Beyond standard model) massive particle
- "WIMP miracle"
  - Thermally produced
  - m ~ weak scale → abundance of DM



Credito: F. Iocco

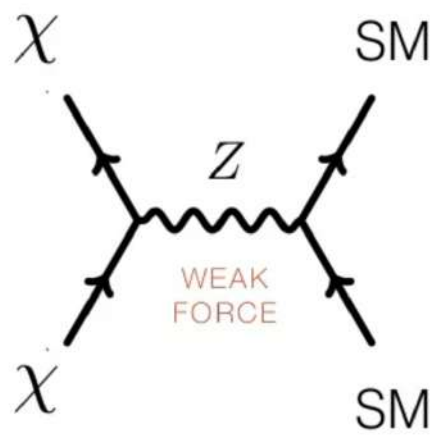
WIMP miracle



A thermal relic with cross-section ~weak interaction would freeze out with the ~ density of the obs. DM today

$$\Omega_\chi h^2 \simeq 0.1 \left(\frac{3 \times 10^{-9}\,\mathrm{GeV}^{-2}}{\langle \sigma v \rangle} \right)$$

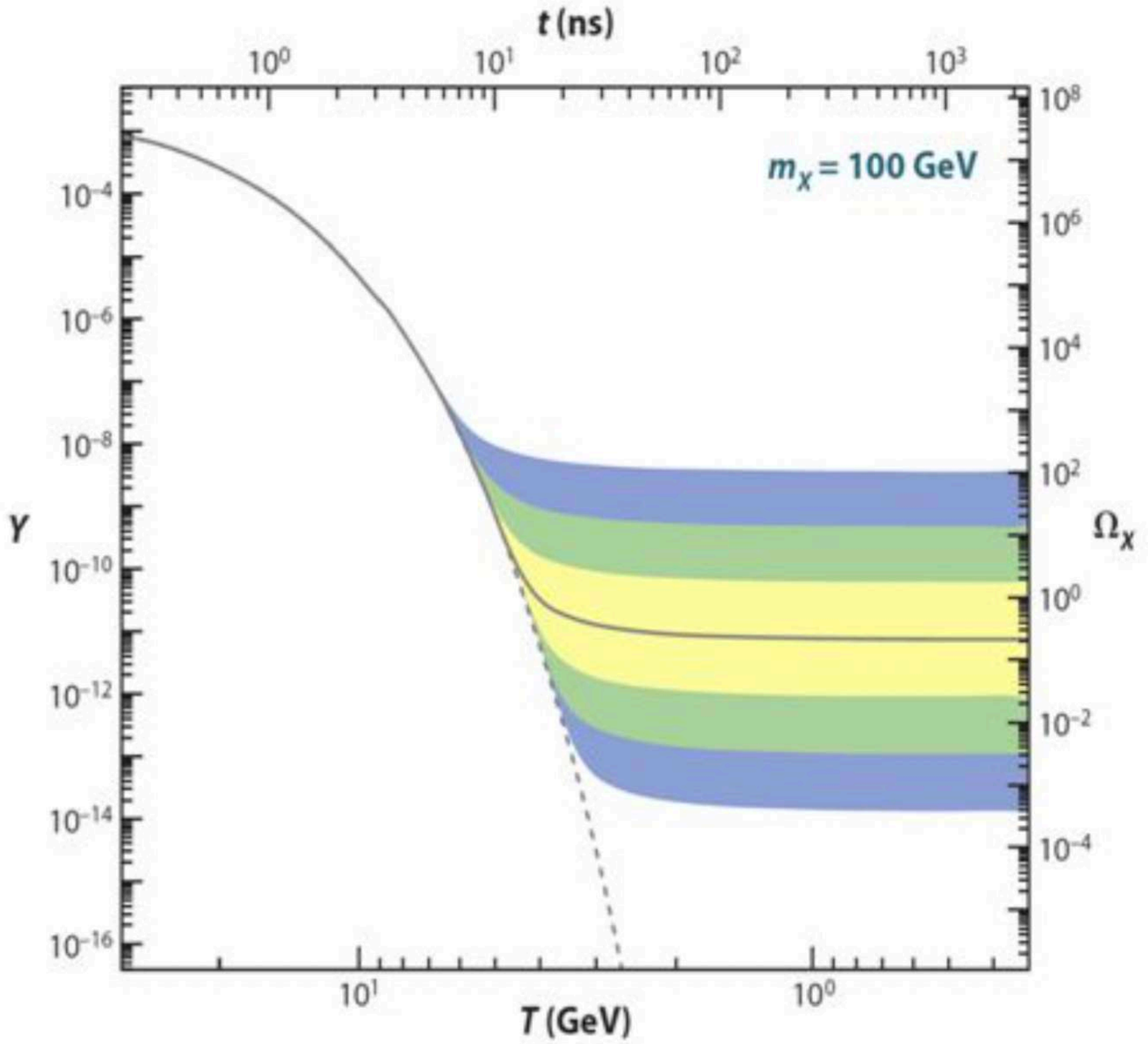
Annihilation cross-section



So we can have the correct abundance today:

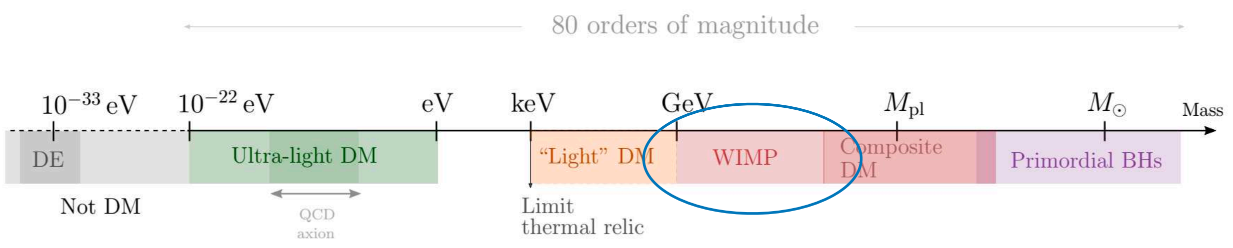
$$\langle \sigma v \rangle \simeq 3 \times 10^{-9}\,\mathrm{GeV}^{-2} \simeq G_F \times \frac{v_{wimp}}{c}$$

Expected cross-section for the weak interactions!

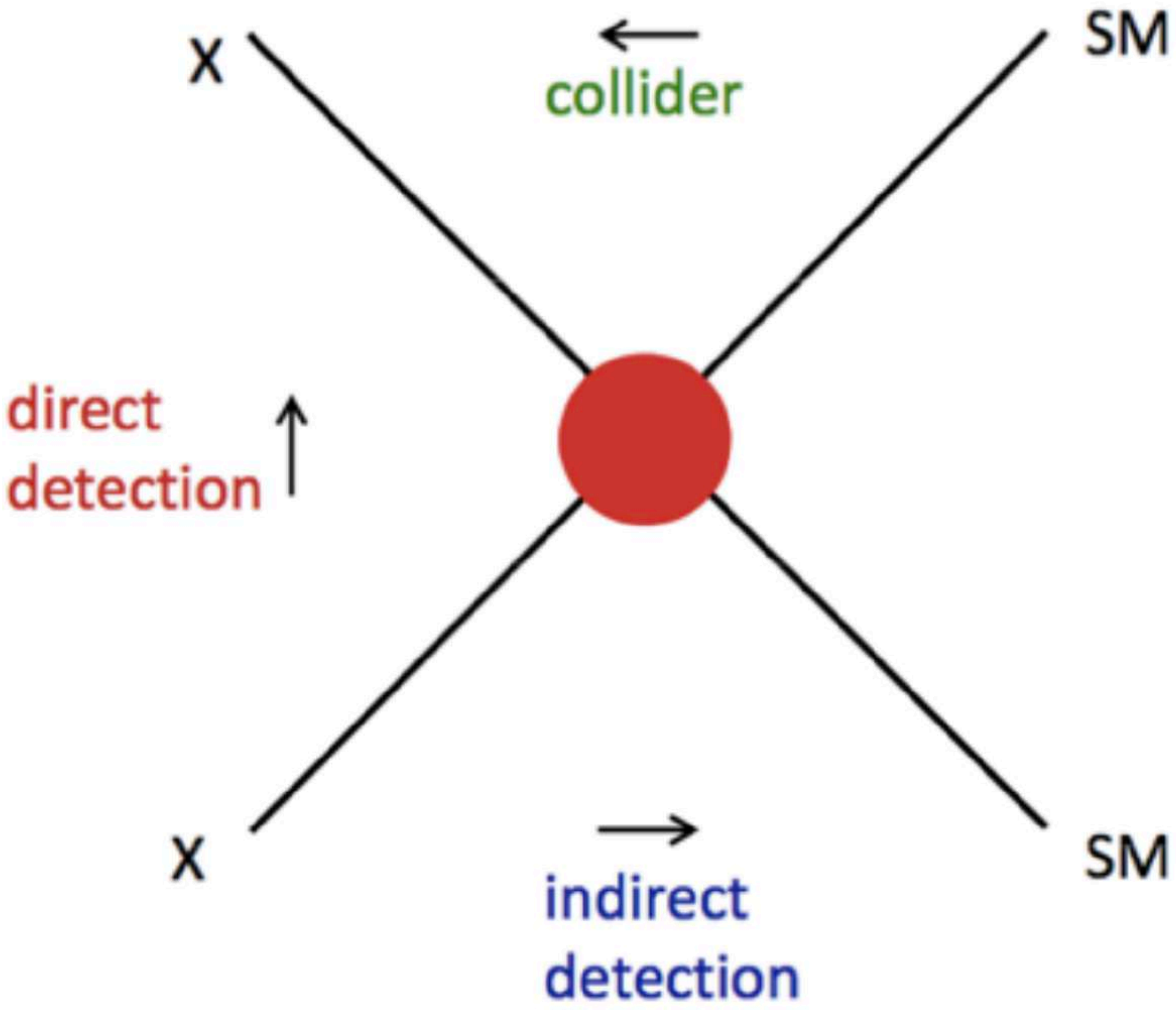


Therefore, if DM interacts through the weak force, we have the correct abundance of DM! Miracle!?

WIMP - weakly interacting massive particle



How can we measure it?

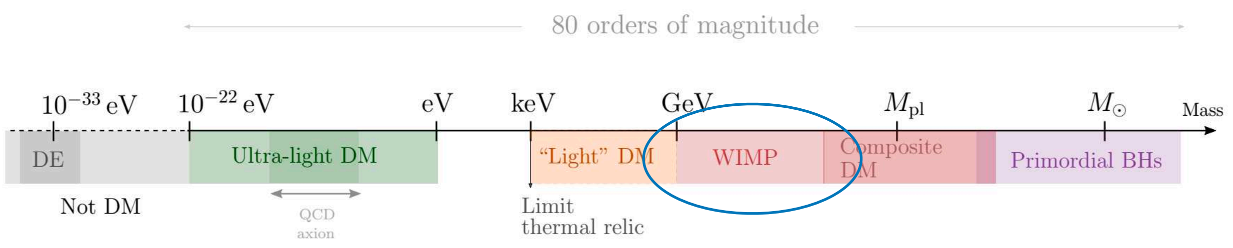


Credito: F. Iocco

+

Gravitationally
Cosmological and astrophysical searches

WIMP - weakly interacting massive particle



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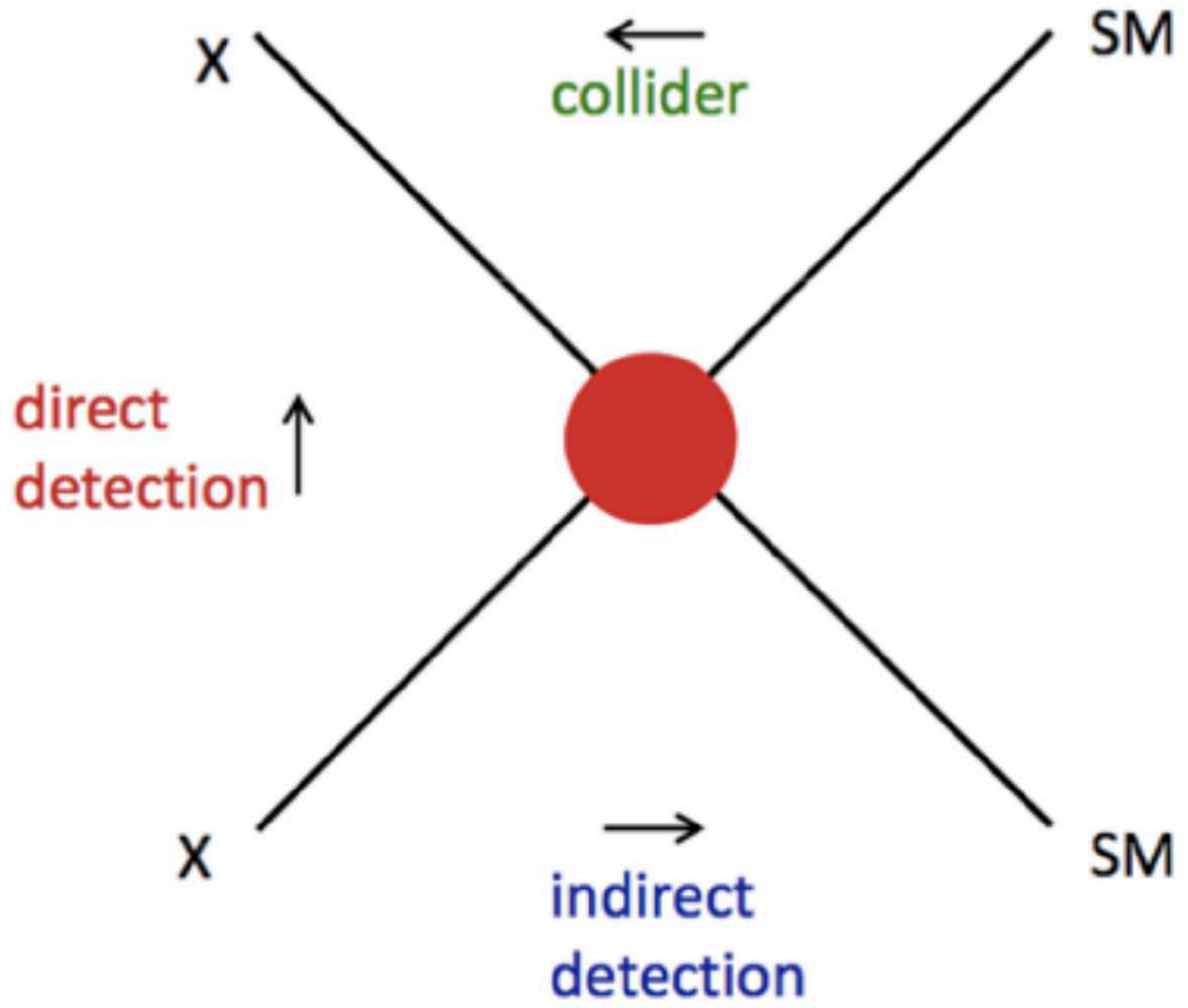


Credito: F. Iocco

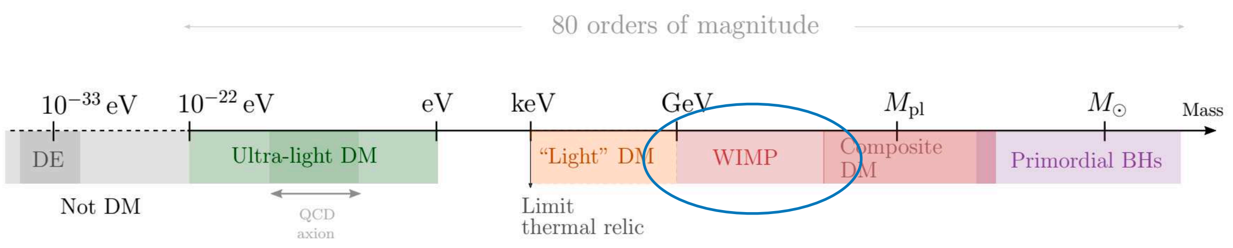
\+ Gravitationally
Cosmological and astrophysical searches

<u>Direct detection</u>:
- DM scattering against nuclei, recoil

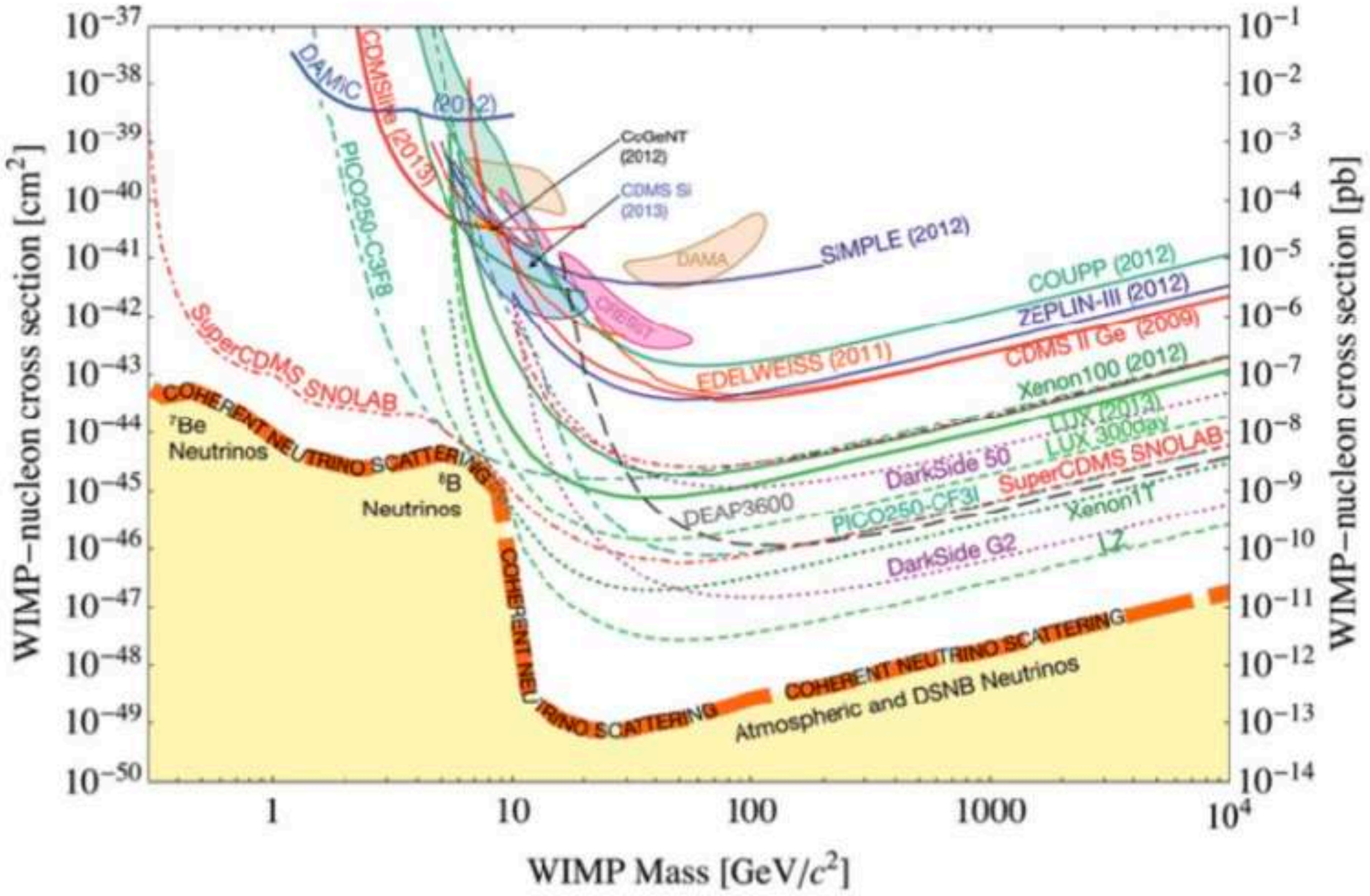
<u>Indirect detection</u>:
- Annihilation in astrophysical environment
- Observation of SM products of annihilation

<u>Production at collider</u> (LHC)

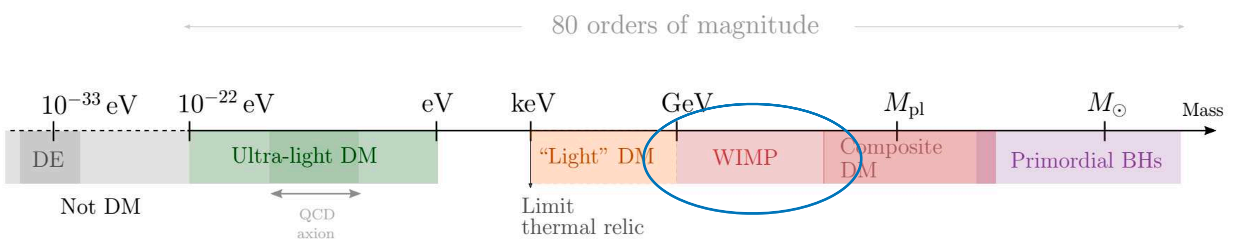
WIMP - weakly interacting massive particle



Bounds

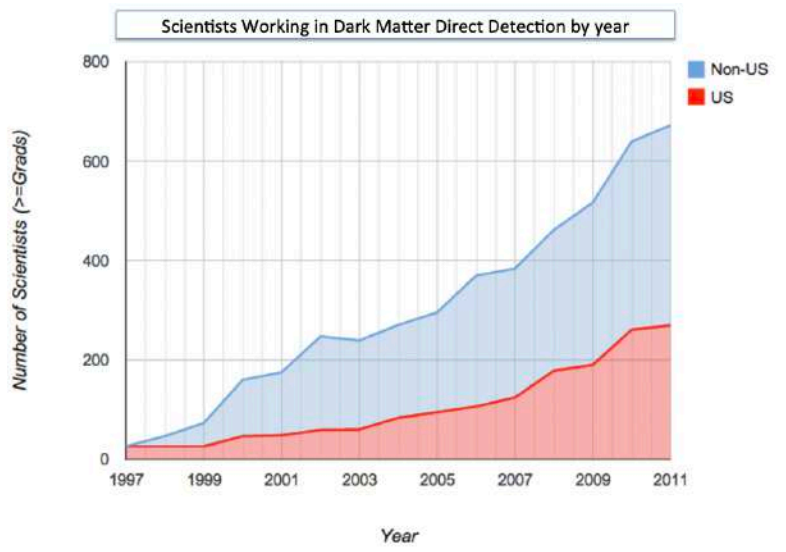


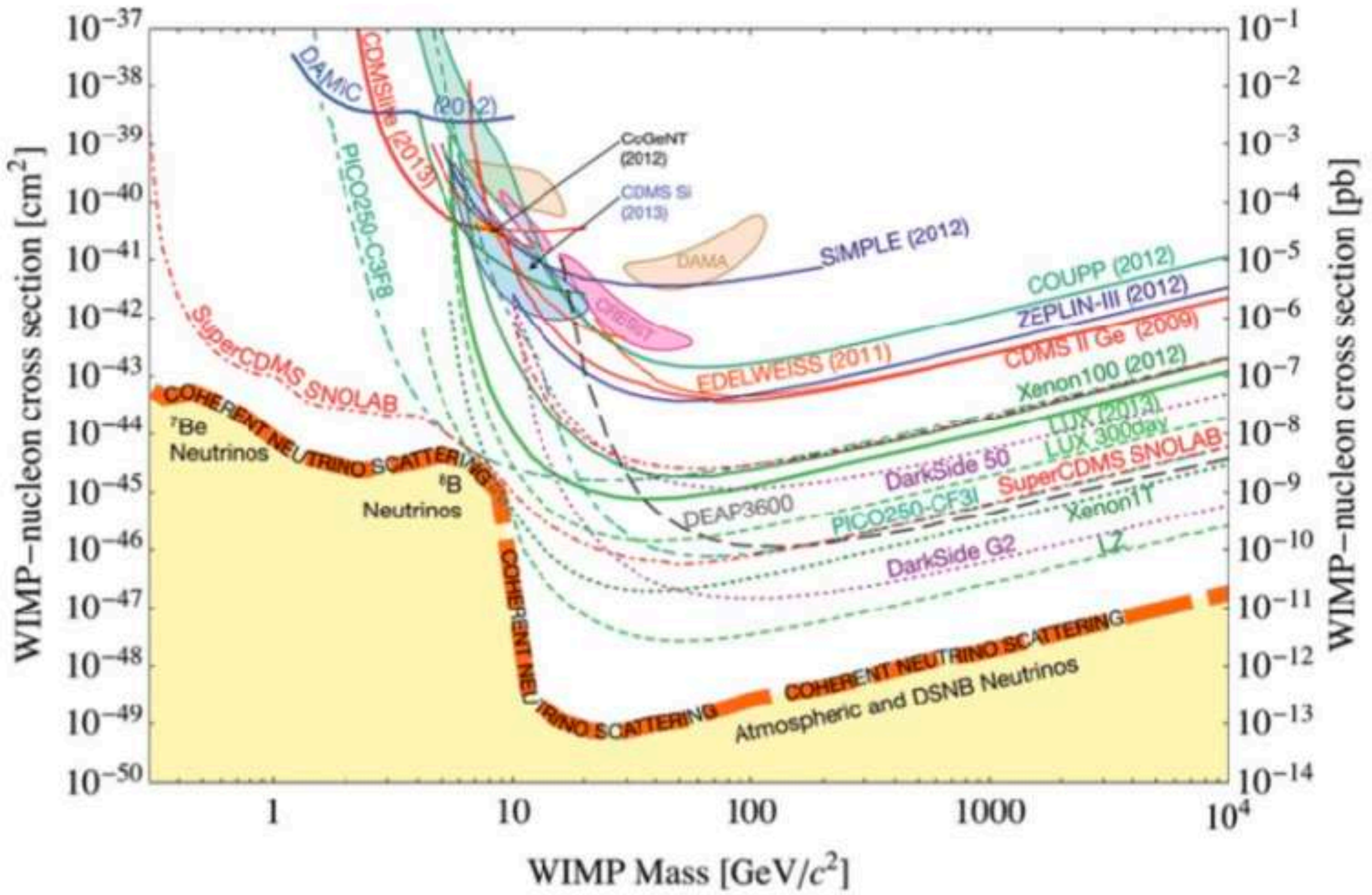
WIMP - weakly interacting massive particle



Bounds

Snowmass 2013



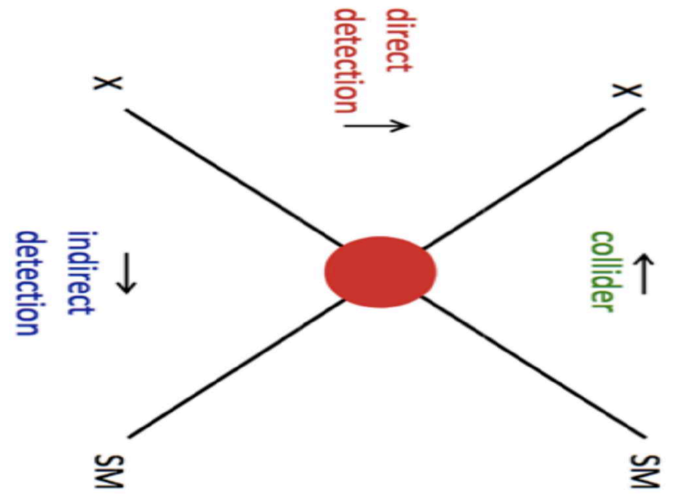


HUGE experimental effort for discovery/bound

Still not detected!

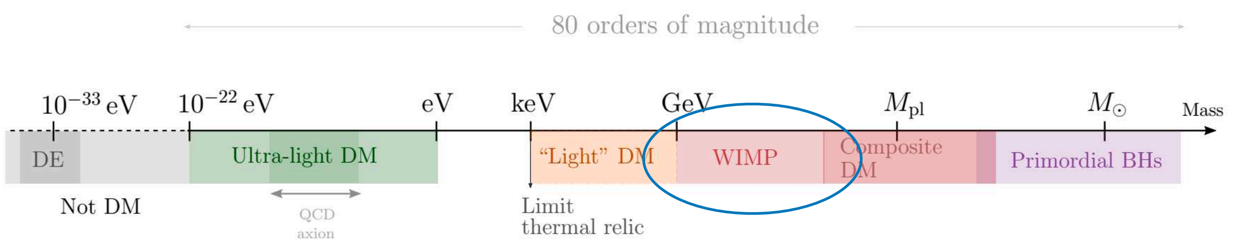
↓

Exclusion limits/bounds are of difficult interpretation for WIMPs



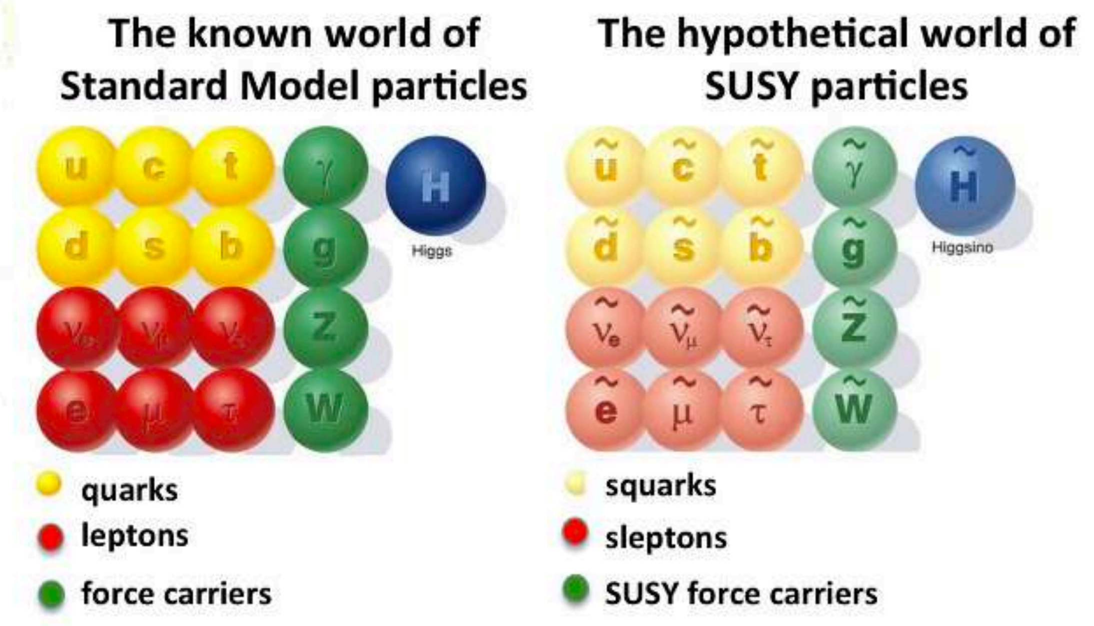
Supersymmetry

DM from supersymmetry

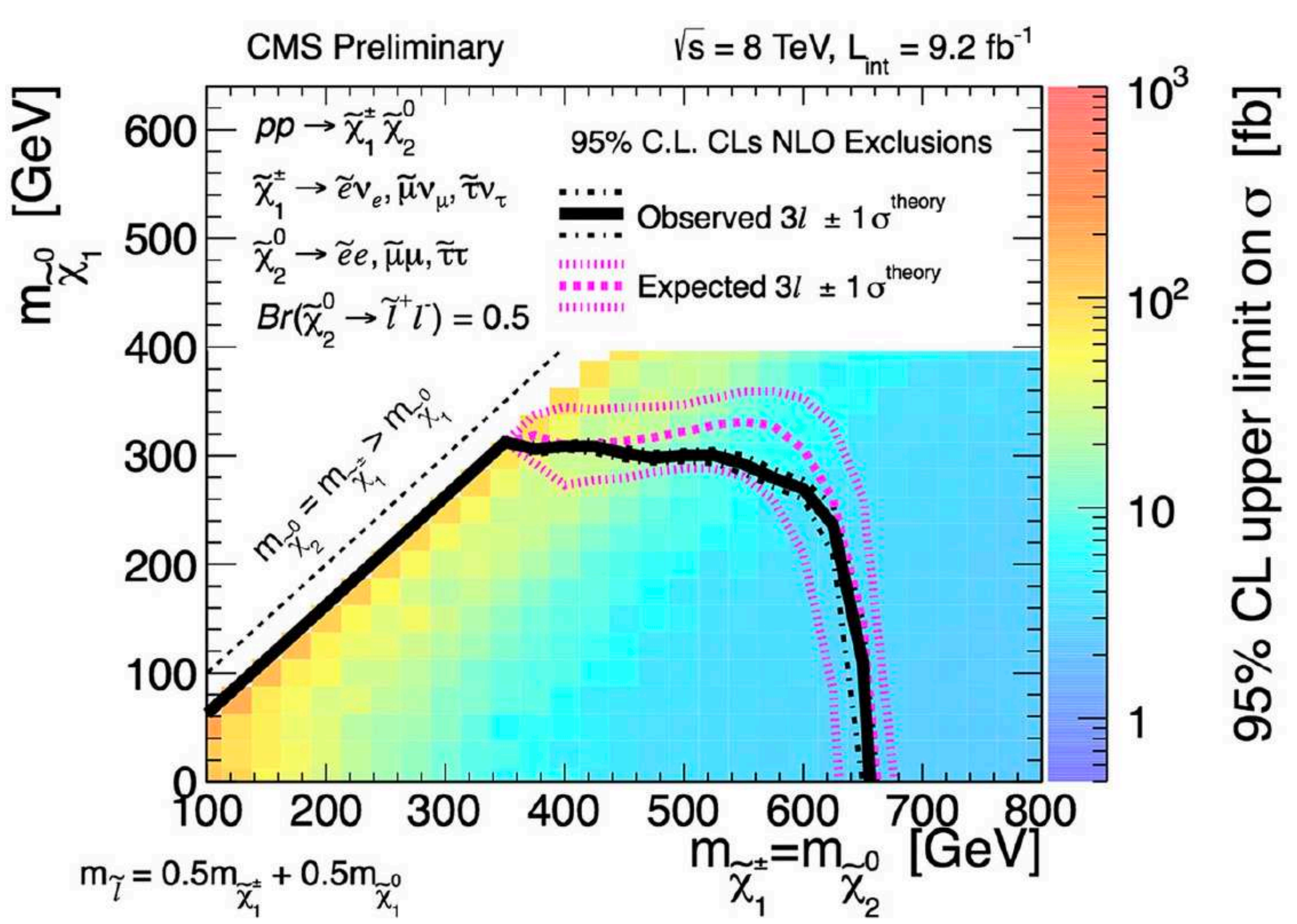


Lightest supersymmetric partner is stable

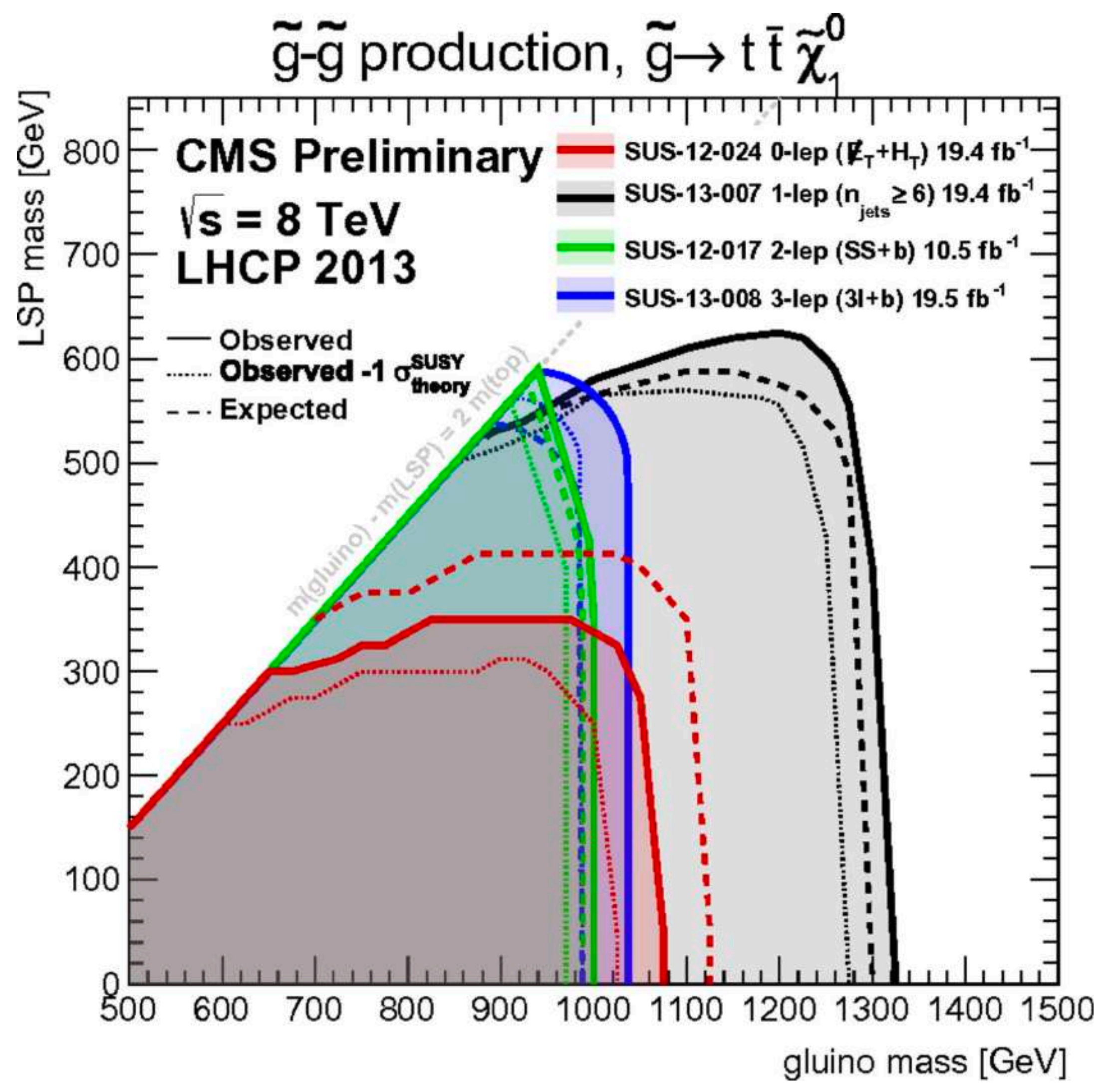
- Neutralino
- Gravitino
- Chargino
- Bino
- …



Search at colliders!

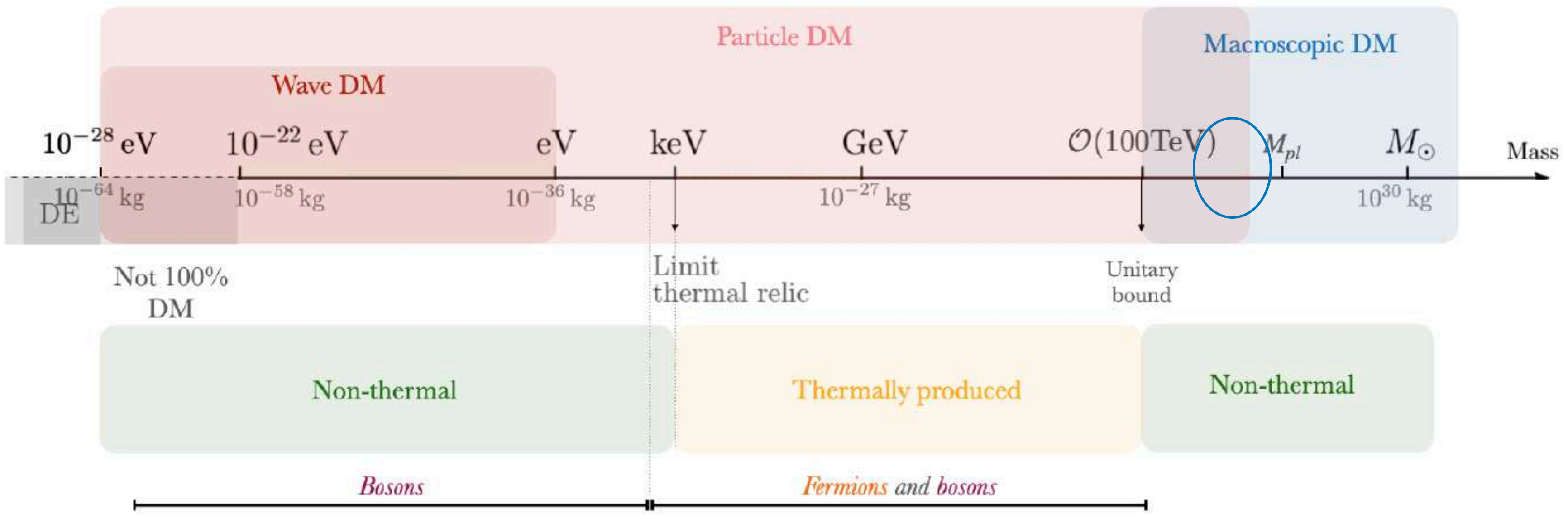


Neutralino and chargino



Gluino

WIMPzillas


Particle DM
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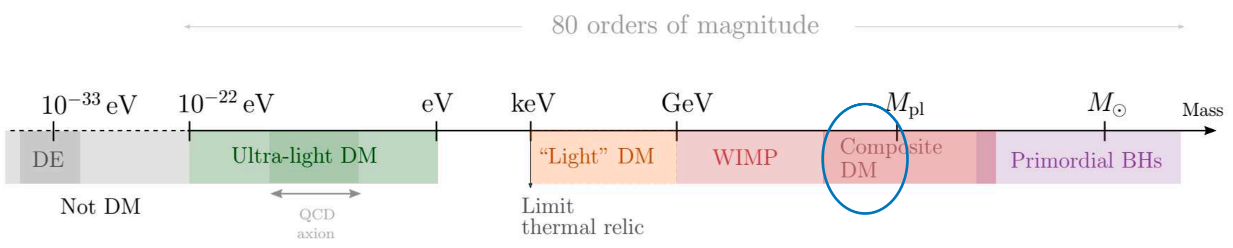
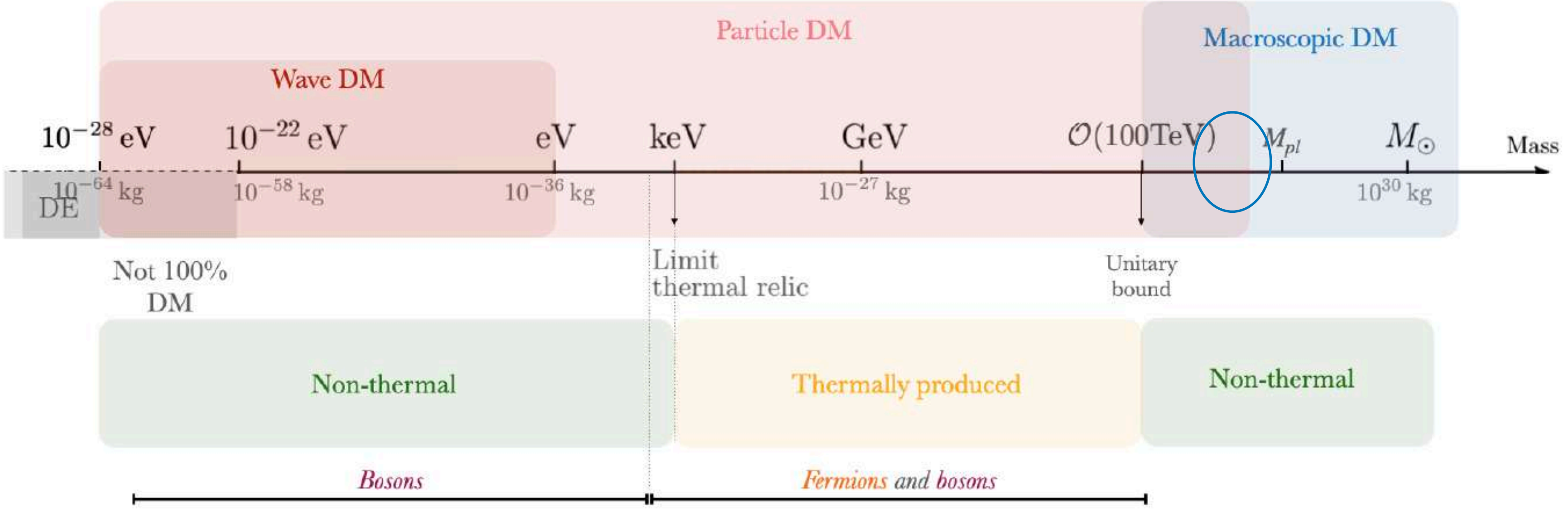
WIMPzillas



Not a lot of superheavy candidates between $\mathcal{O}(100)$ TeV – $\mathcal{O}(10^{40})$ eV

WIPMzillas: superheavy **particle**

Ref.: Kolb et al 1998



2 necessary conditions:

- Must be stable (Condition for being particle DM)
- Must not have been in equilibrium when it froze out (i.e., it is **not** a thermal relic), otherwise $\Omega_X h^2$ would be much larger than one
  - A sufficient condition for nonequilibrium is that the annihilation rate (per particle) must be smaller than the expansion rate: $n_X \sigma v < H$ (Condition for being non-thermal relic)

Produced non-thermally!!

(Not subjected to the unitary bound)

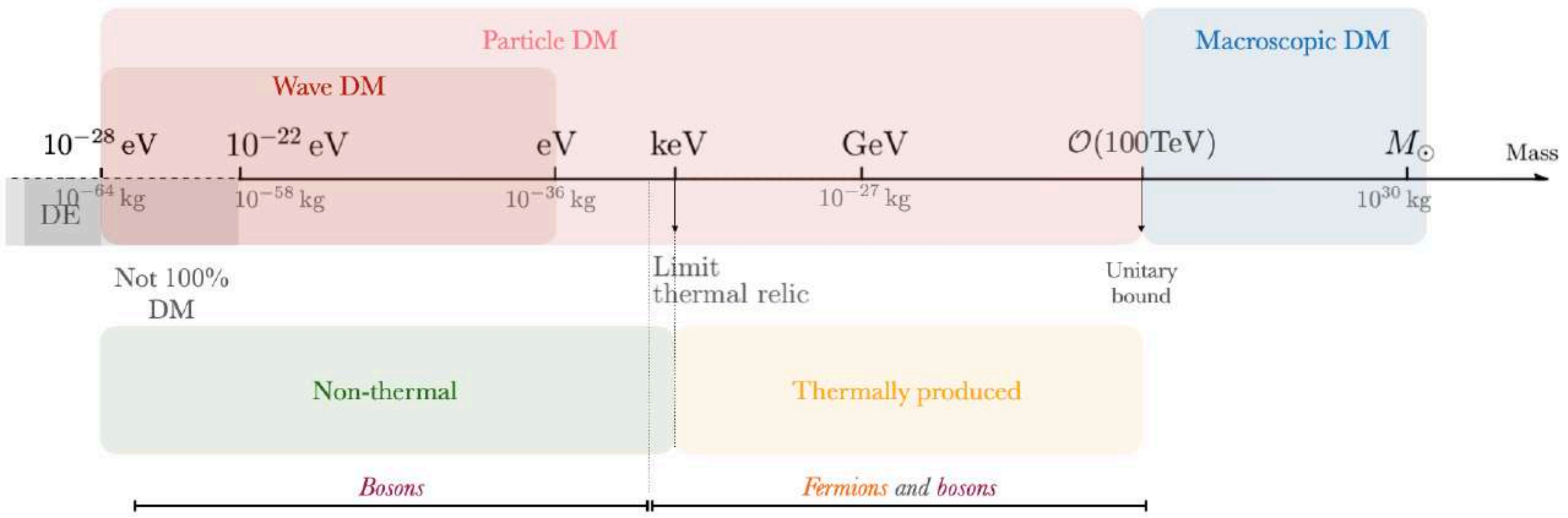
$\Rightarrow$ Produced during inflation - 10^9 GeV – 10^{16} GeV (GUT scale)

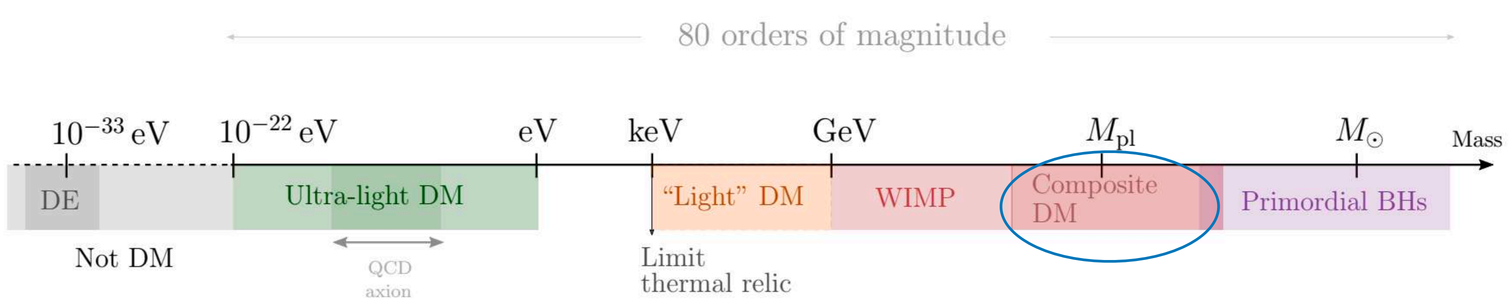
There are no experiments looking for WIMPzillas

(Size does matter)

$M_{pl} \sim 10^{19}$ GeV

Macroscopic/composite DM



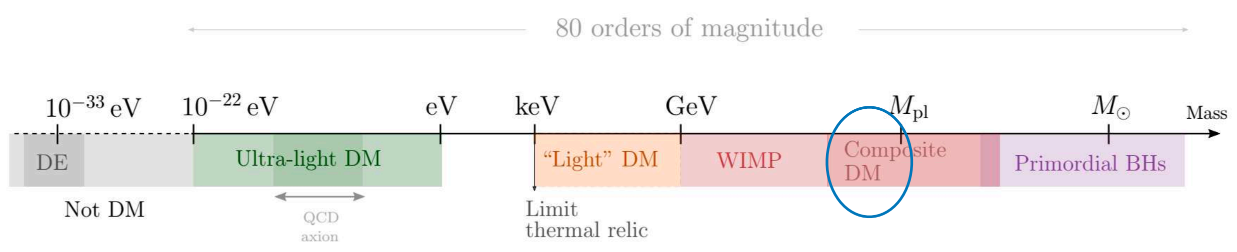


Composite DM

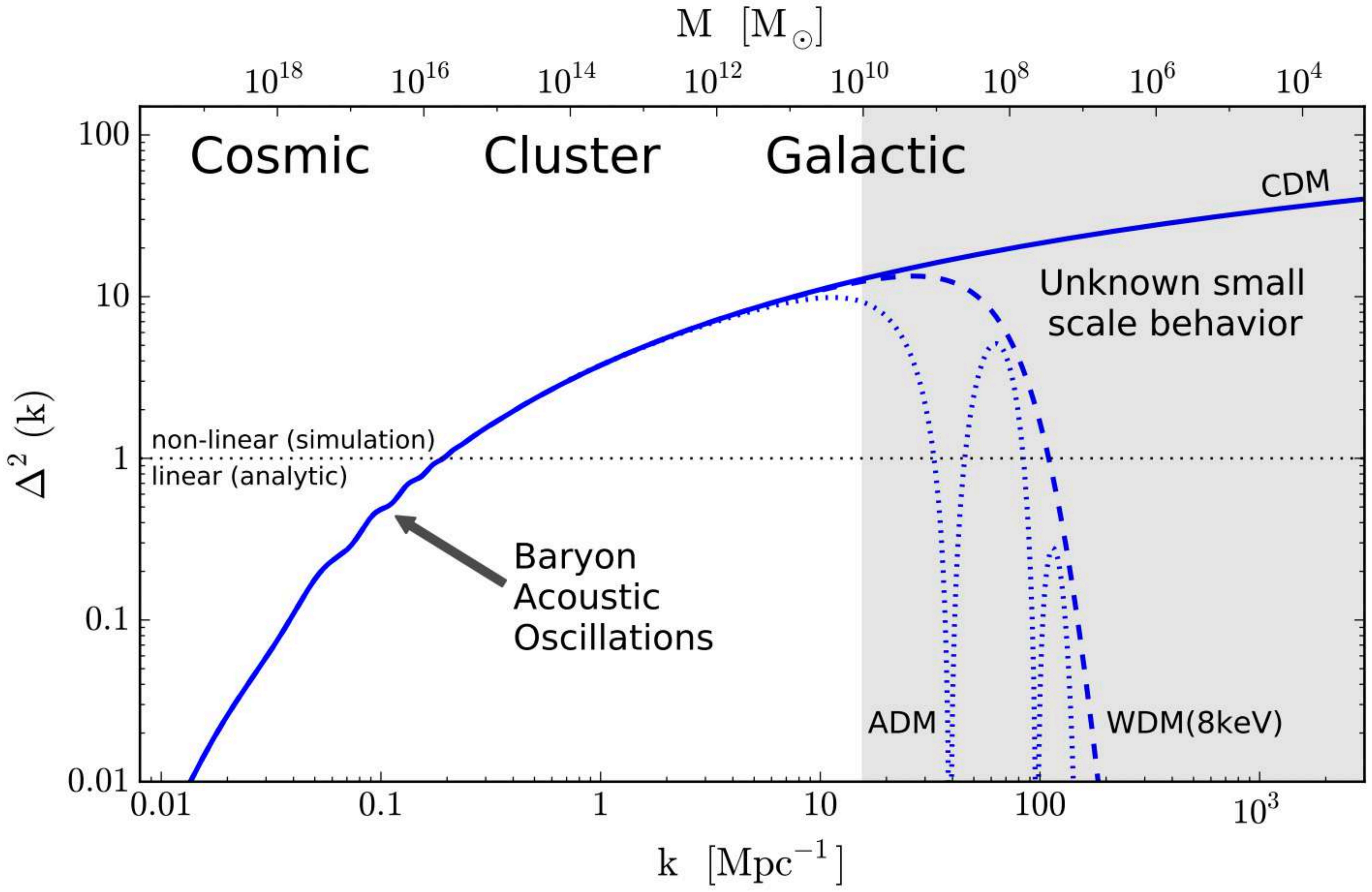
Dark atoms, (dark) glueballs, nuggets of baryons or other fermions …

(an entire "SM" dark sector)

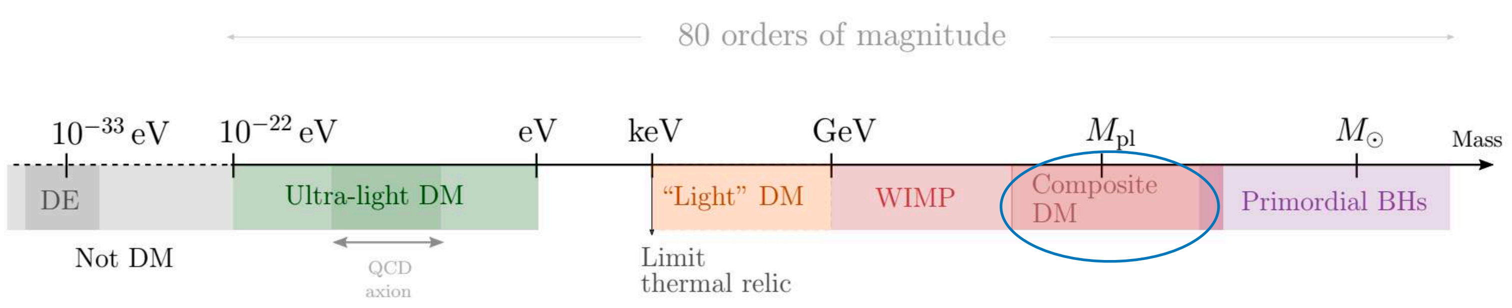
Atomic dark matter



Ref.: Kaplan et al 2009
Cyr-Racine et al 2012



Dark Acoustic Oscillations



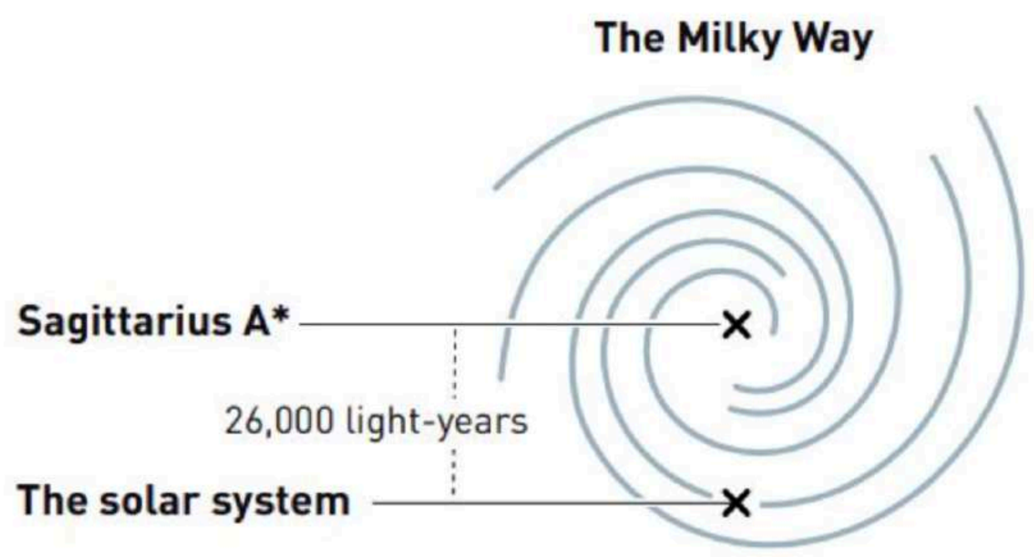
MACHOS

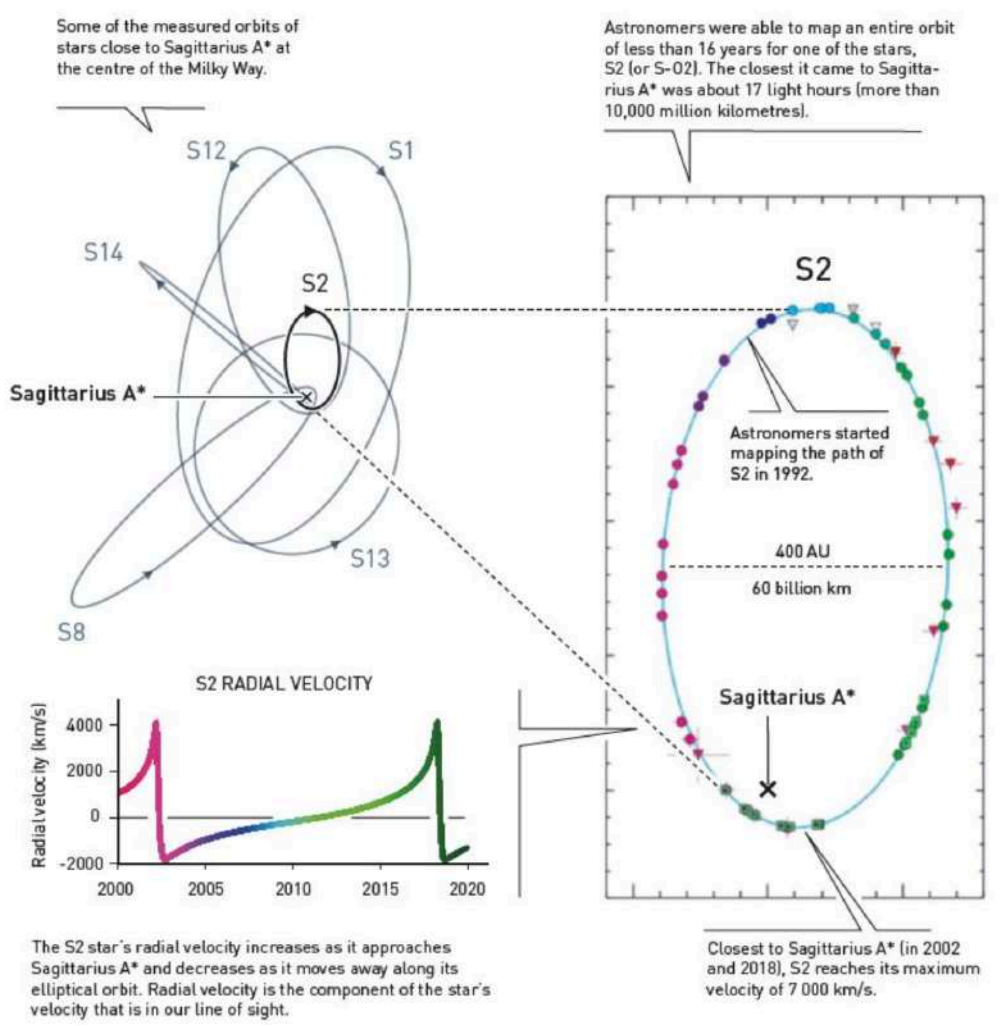
massive compact halo object

Primordial Black Holes

We know BHs exist!

Star motion

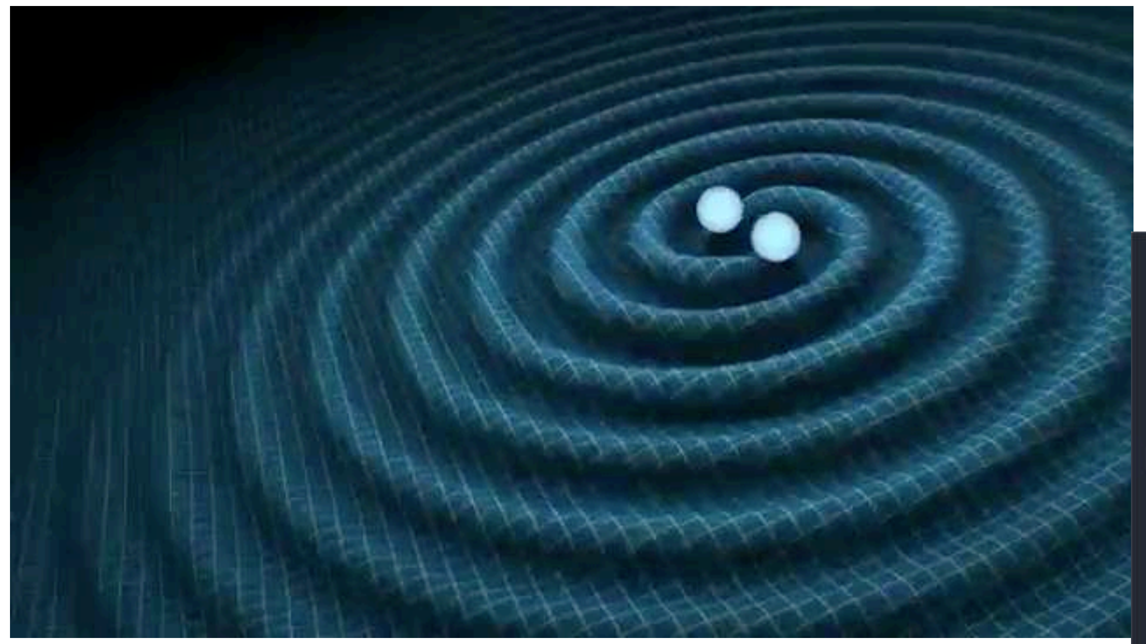




Crédito: Nobel Prize

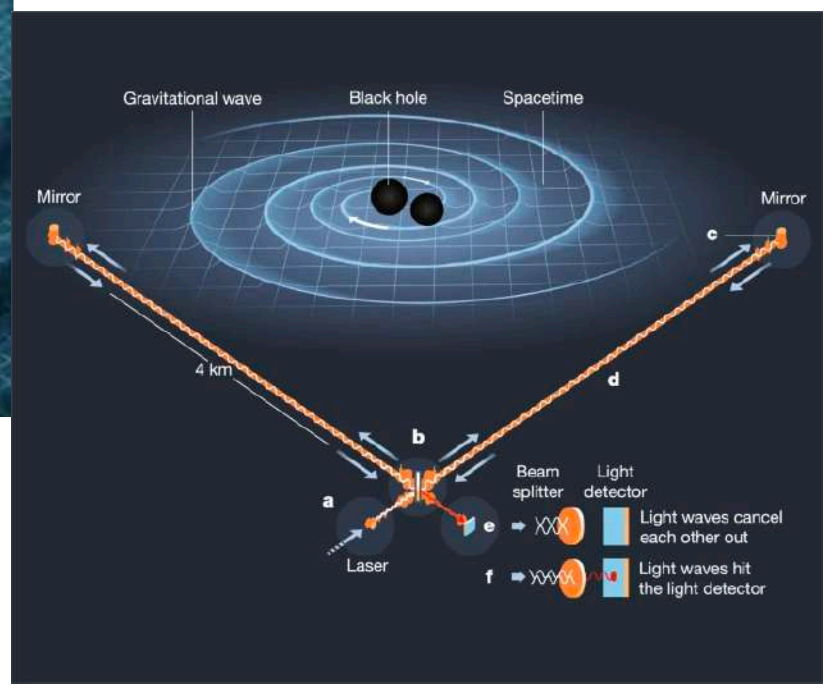
Nobel prize (2021)

Gravitational waves



Crédito: ABC Science

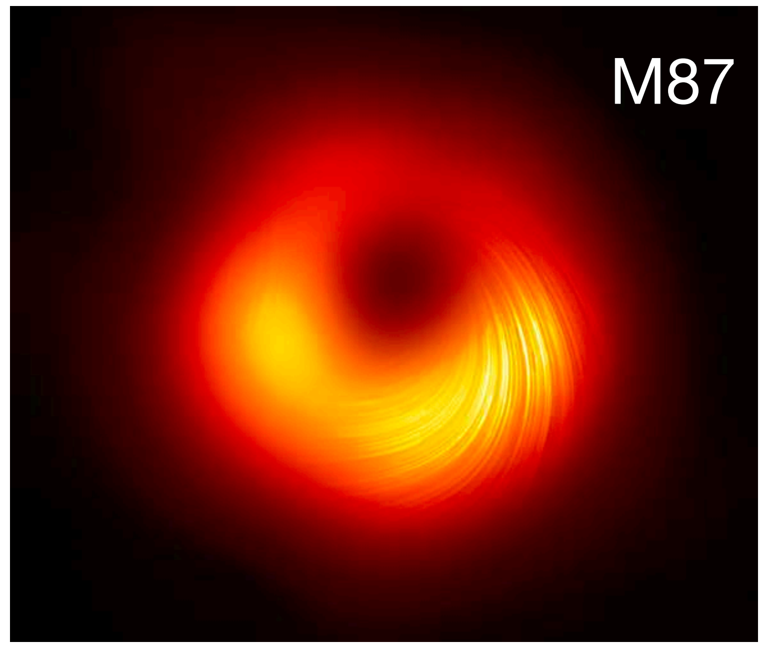
LIGO



Credito: ©Johan Jarnestad/The Royal Swedish Academy of Sciences.

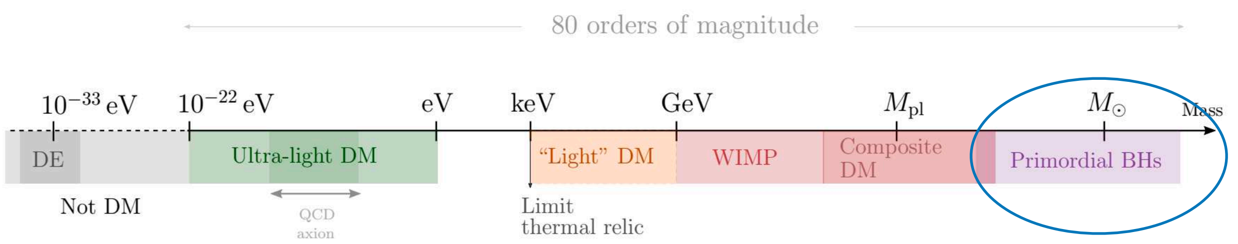
+ VIRGO + KAGRA

Event Horizon Telescope

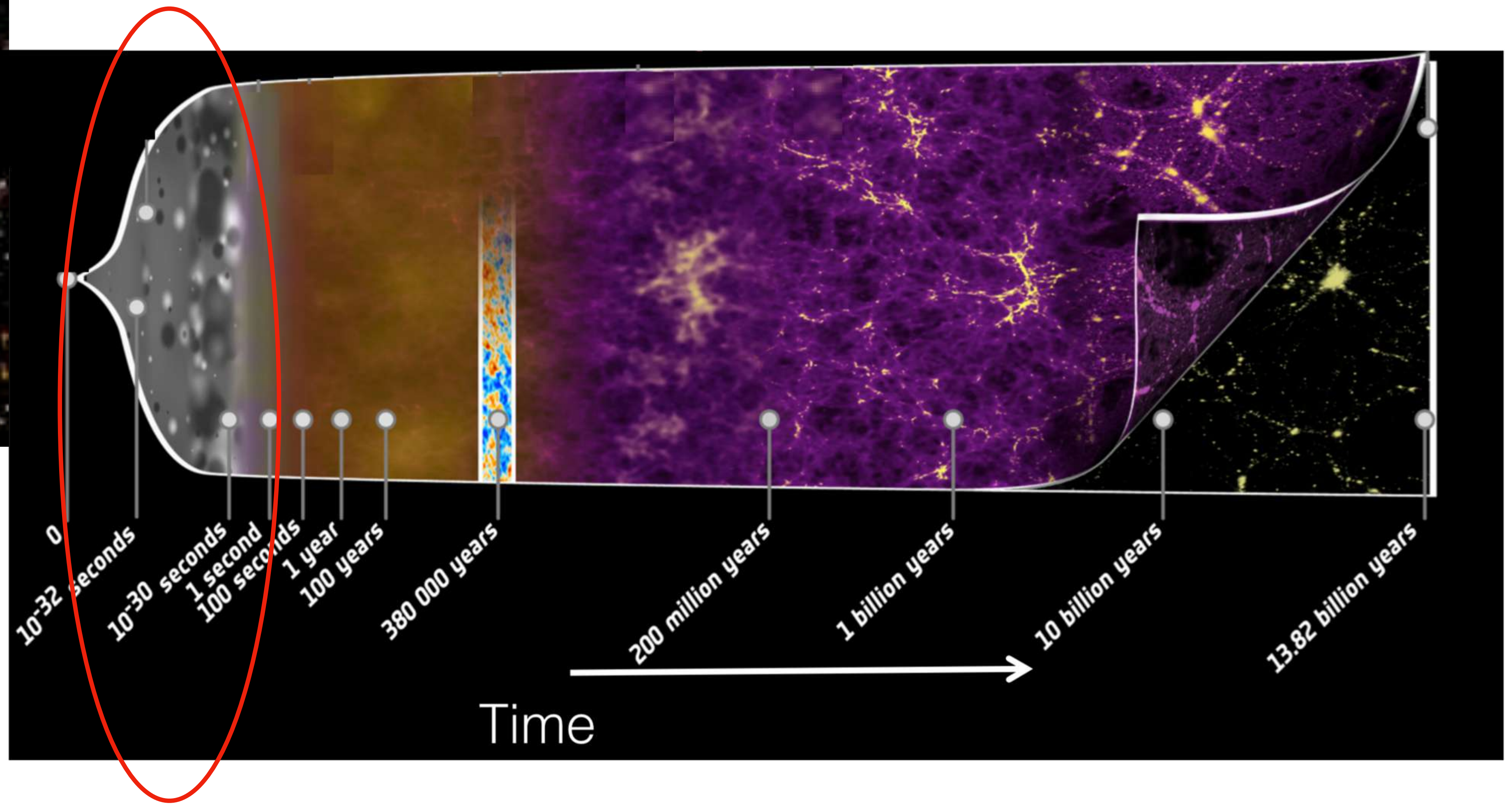


Crédito: ESO

Primordial Black Holes

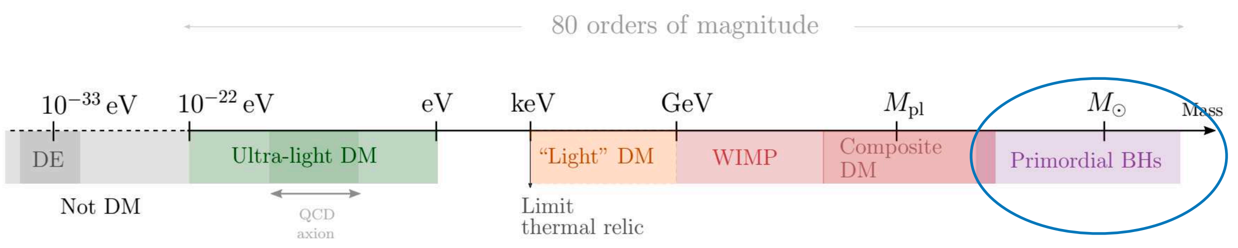


- BHS formed at early times
- BHs with mass $10^{-15}\, M_\odot \lesssim M_{\rm PBH} \lesssim \mathcal{O}(1)\, M_\odot$
- Can explain part or all of the DM



$M_\odot \sim 2 \times 10^{30}$ kg

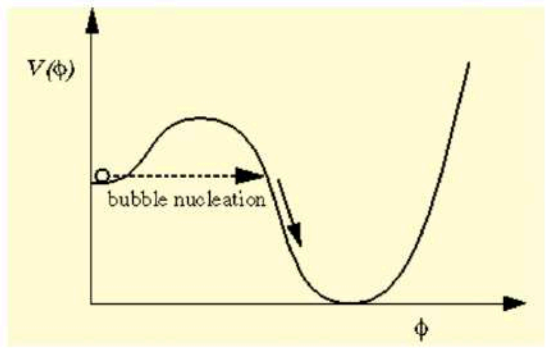
Primordial Black Holes



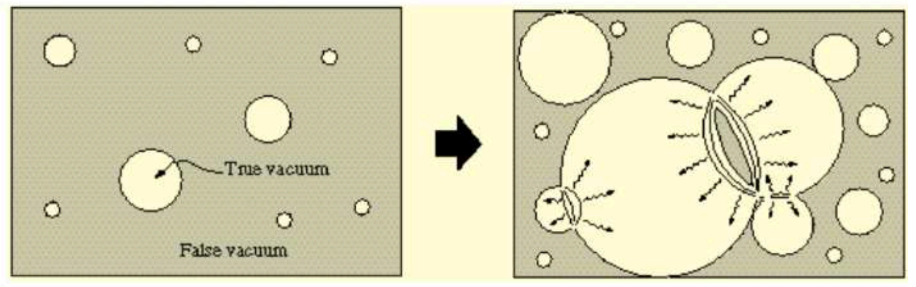
Formation mechanisms

- Bubble collision (Hawking et al, 1982)

  1st order phase transitions occur via the nucleation of bubbles



Bubbles



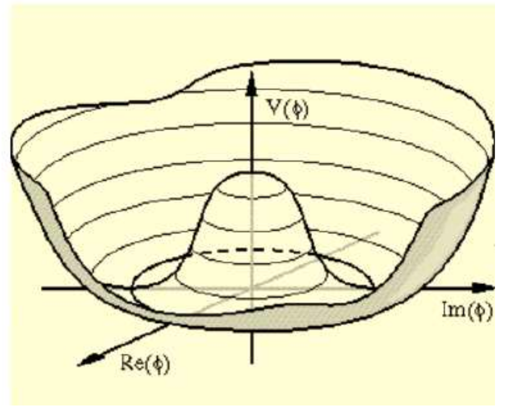
© Cambridge cosmology group

  PBHs can form when bubbles collide (but bubble formation rate must be fine tuned)

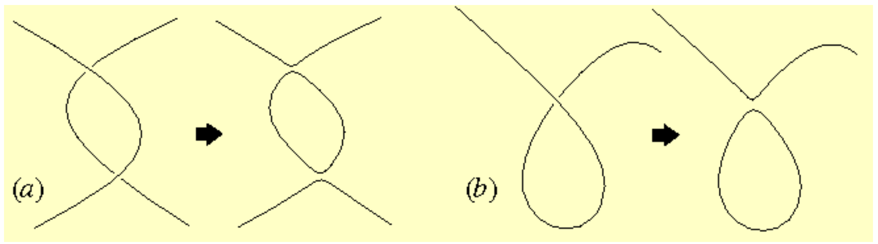
⇒ PBH mass ~ order horizon mass at phase transition.

- Cosmic string loops (Hawking 1987)

  Cosmic strings:1d topological defects formed during symmetry breaking phase transition



Loops



© Cambridge cosmology group

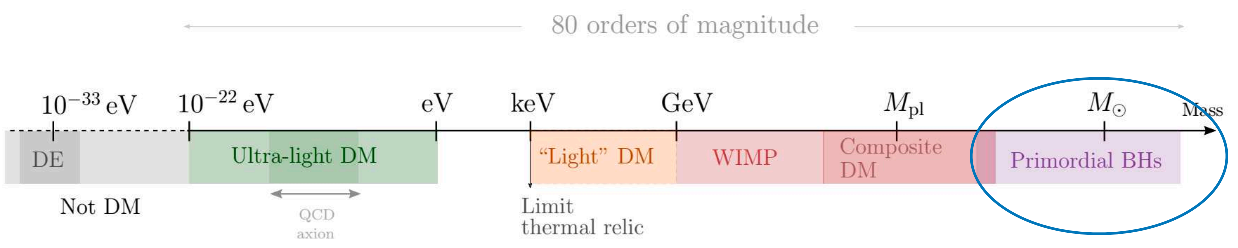
  Small probability that loop will get into configuration of size ~ Schwarzschild radius

⇒ hence collapse to from a PBH with mass of order the horizon mass at that time

- Collapse of density perturbations (Carr and Hawking 1974)

Based on Anne Green

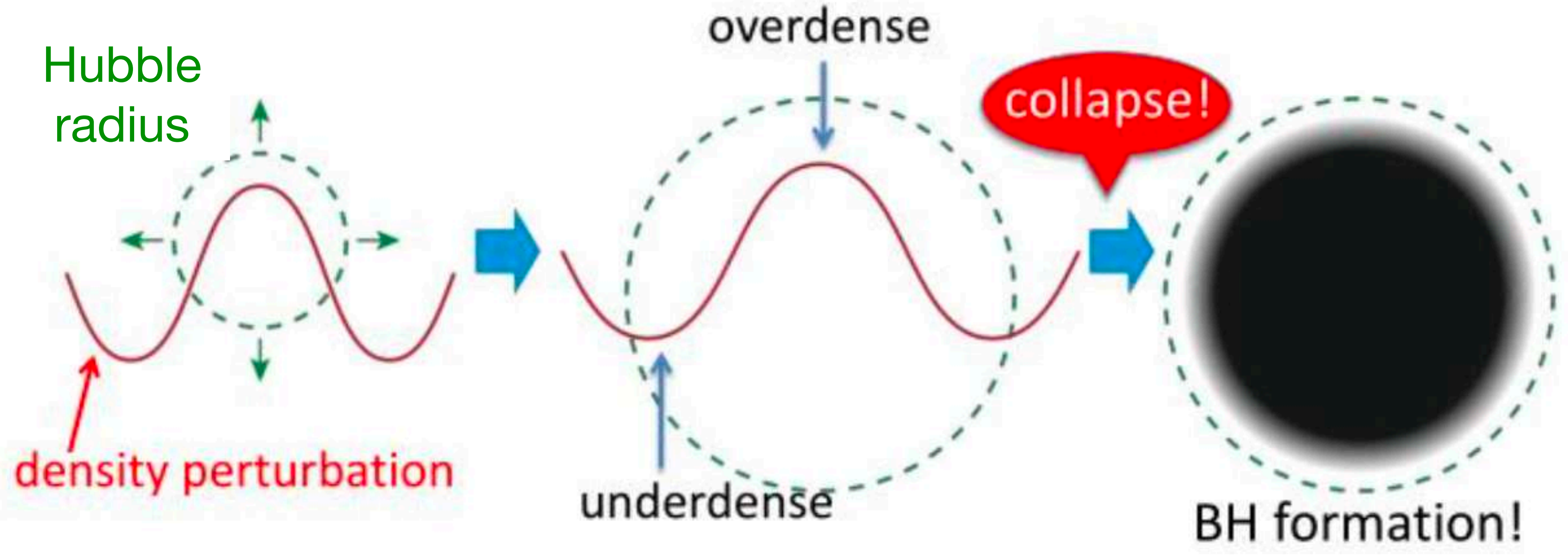
Primordial Black Holes



Formation mechanisms: collapse of large density perturbations (during radiation domination)

(0th order argument)

Typically requires $\delta \sim 1$



Kawasaki et al 2012

If a density perturbation is sufficiently large (at Hubble radius entry) it can collapse to form a PBH

Threshold for formation:

$$\delta_{hc} \geq \delta_c \sim w = \frac{P}{\rho} = \frac{1}{3}$$

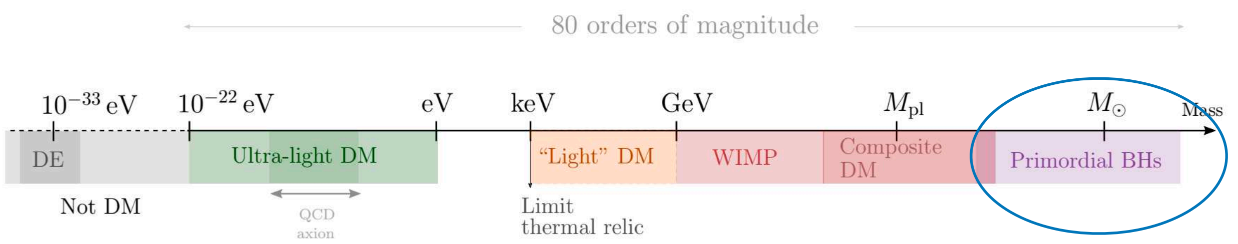
$\Rightarrow$ Form a PBH with $M_{\rm PBH} \sim M_{R_H}$

$$M_{R_H} = \frac{4\pi}{3}\rho(cH^{-1}) = \frac{c^3}{2GH} = \frac{tc^3}{G} \sim 10^{15}\,{\rm g}\left(\frac{t}{10^{-23}\,{\rm s}}\right) \sim M_\odot \left(\frac{t}{10^{-6}\,{\rm s}}\right) \sim M_{\rm PBH}$$

Mass contained in the Hubble radius

* Here not in natural units!!

Primordial Black Holes



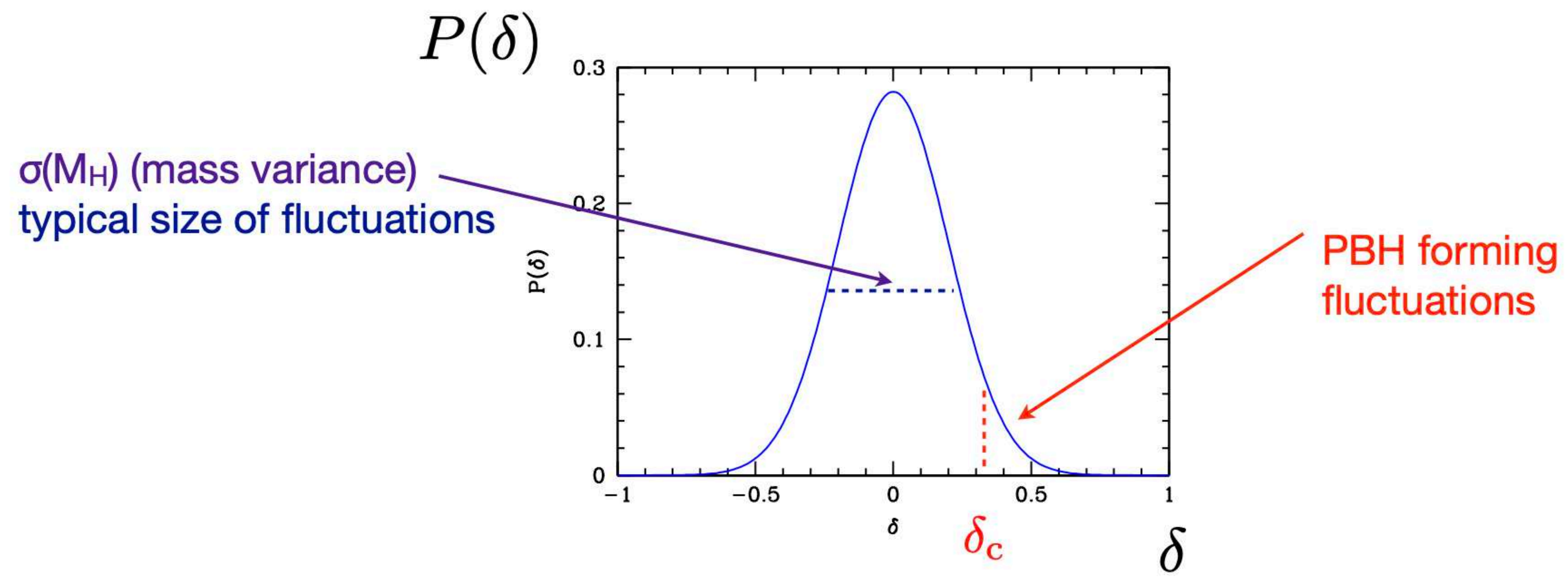
Initial PBH mass fraction: fraction of universe in regions dense enough to form PBHs

(0th order argument)

$$\beta(M) = \left(\frac{\rho_{\rm PBH}}{\rho_{tot}}\right)_i \sim \int_{\delta_c}^{\infty} P(\delta(M_{R_H}))d\delta(M_{R_H}) \sim \sigma(M_{R_H}) \exp\left(-\frac{\delta_c^2}{2\sigma^2(M_{R_H})}\right)$$

density contrast, smoothed on a scale R_H

Assuming Gaussian prob. distribution



Credit: Anne Green

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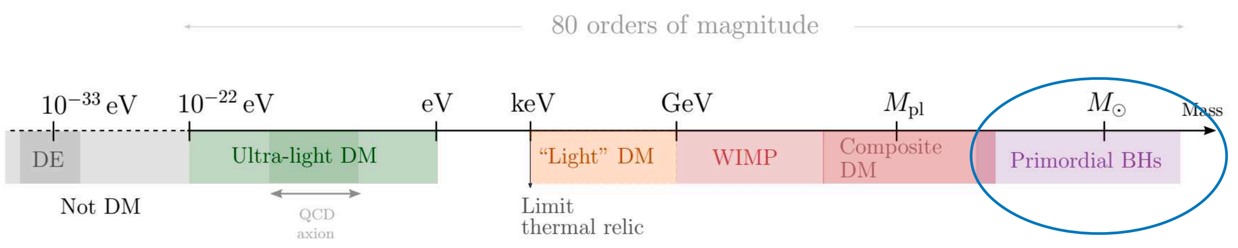
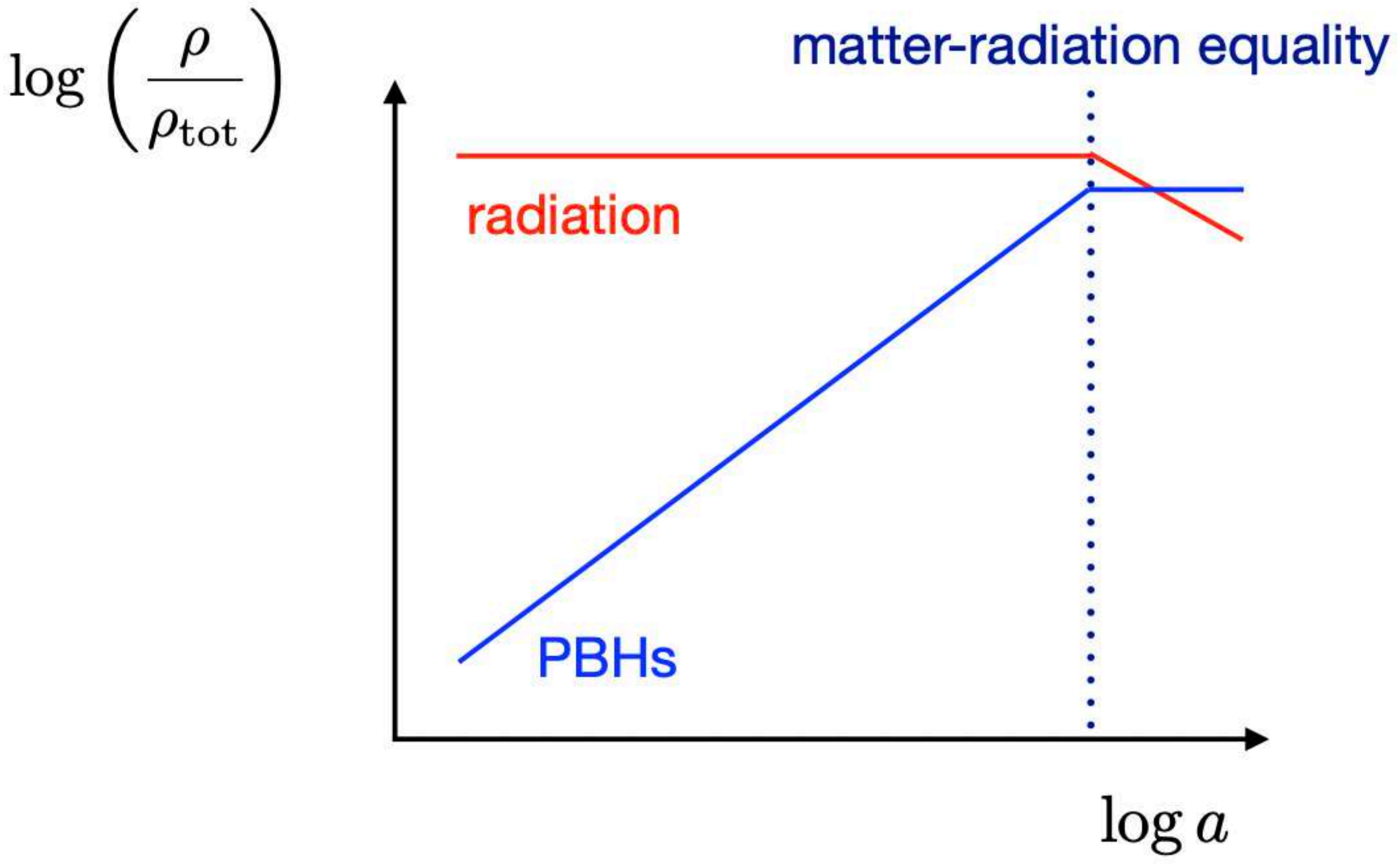
Primordial Black Holes



PBH abundance

Since PBHs are matter, during radiation domination the fraction of energy in PBHs grows

$$\frac{\rho_{\rm PBH}}{\rho_{rad}} \propto \frac{a^{-3}}{a^{-4}} \propto a$$

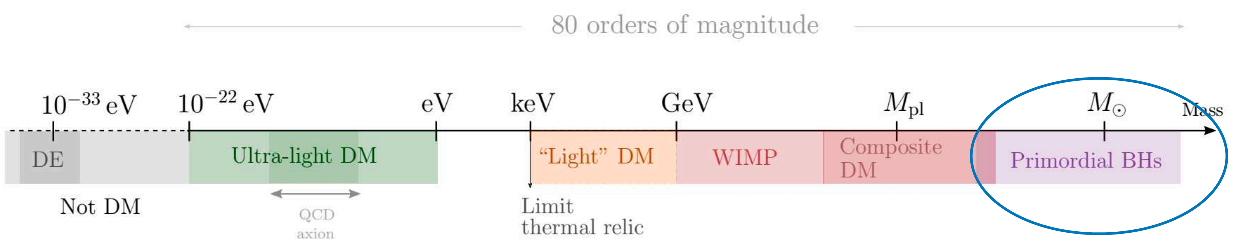


The PBH initial mass fraction, β, and **fraction of DM in form of** PBH are related by:

$$\beta(M) \sim 10^{-9} f_{\rm PBH} \left(\frac{M}{M_\odot}\right)^{1/2}$$

$\Rightarrow$ initial mass fraction must be small, but non-negligible.

Primordial Black Holes



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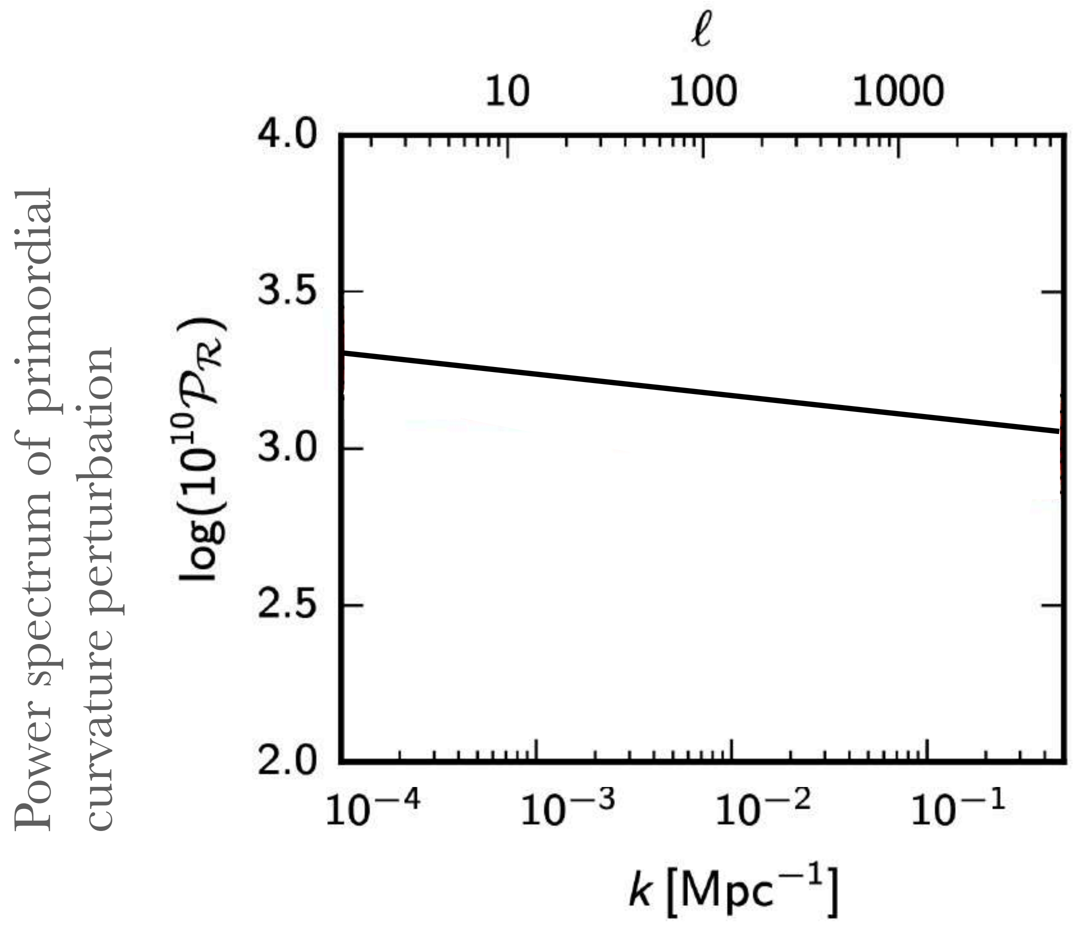
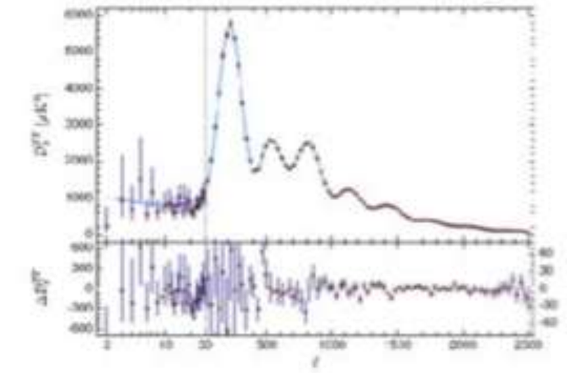
Initial perturbation:

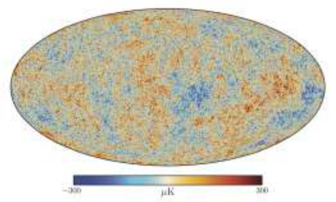
Can the (nearly) scale-invariant primordial pert from early times (same that is the seed to LSS) source PBH and give a sizeable initial fraction? NO!



$$\mathcal{P}_\mathcal{R} = A_S \left(\frac{k}{k_p}\right)^{n_s - 1}$$

From CMB: $\sigma(M_{R_H}) \sim 10^{-5}$



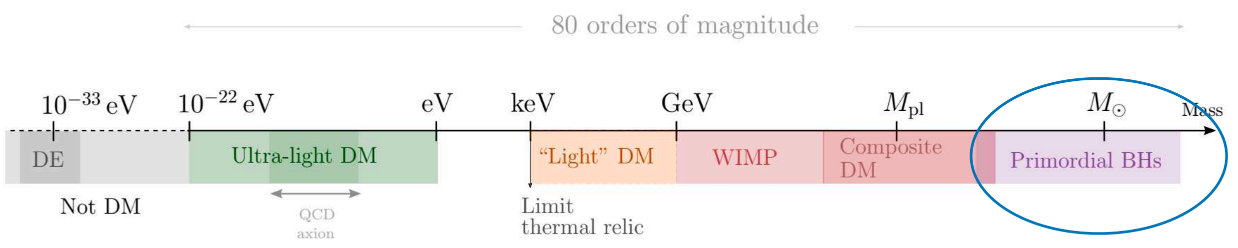


$$\beta(M) = \sigma(M_{R_H}) \exp\left(-\frac{\delta_c^2}{2\sigma^2 M_{R_H})}\right)$$

$$\sim \exp(10^{-10}) \ll 1$$

Negligible!

Primordial Black Holes



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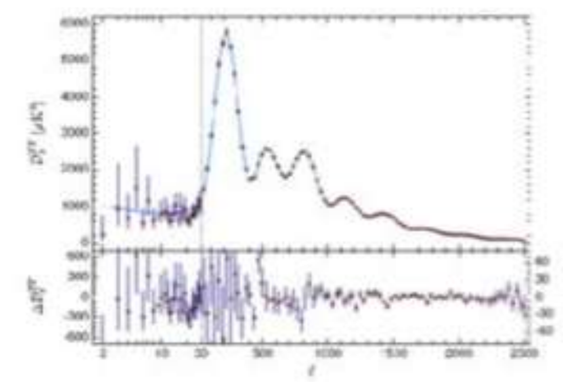
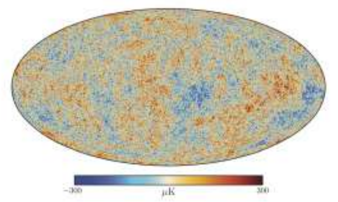
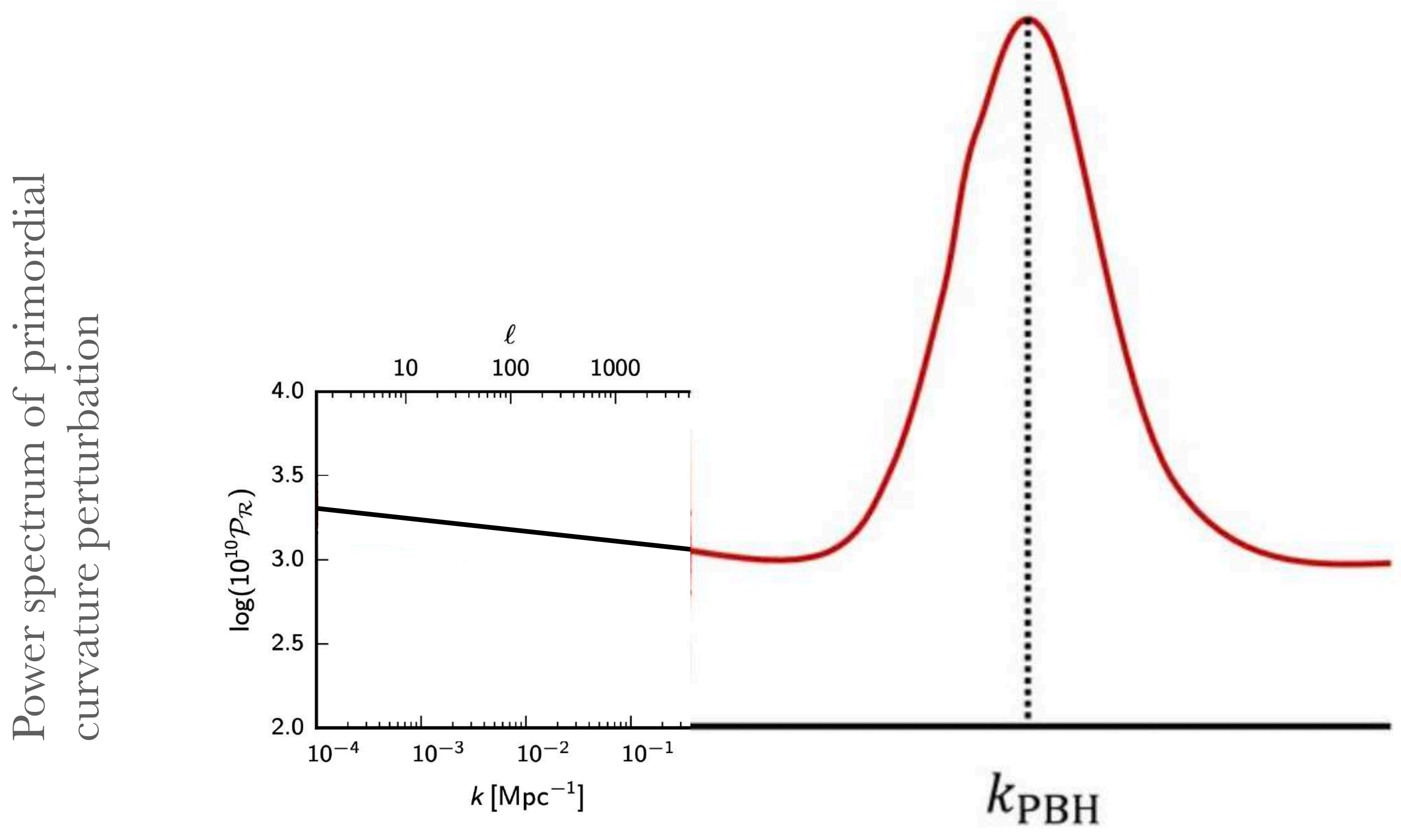






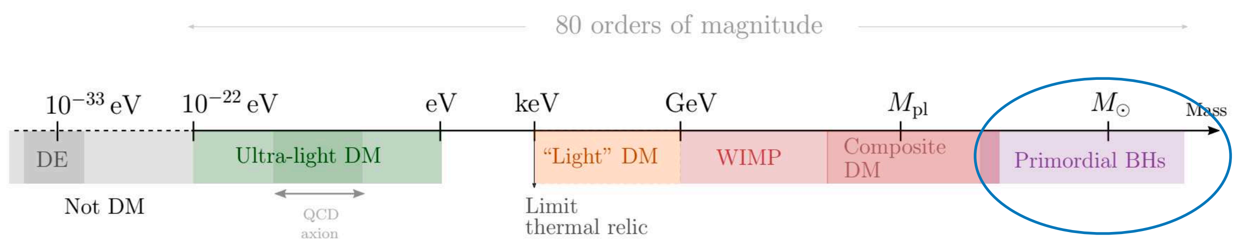
$$\beta(M) = \sigma(M_{R_H}) \exp\left(-\frac{\delta_c^2}{2\sigma^2 M_{R_H})}\right)$$

$$\sim \exp(-10^{10}) \ll 1$$

Negligible!

To form an interesting number of PBHs amplitude of primordial perturbations must be 2-3 orders of larger on small scales than on cosmological scales and fine-tuned.

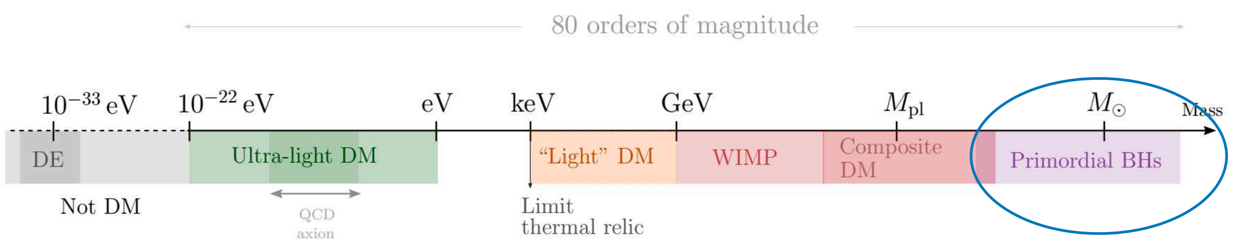
Primordial Black Holes

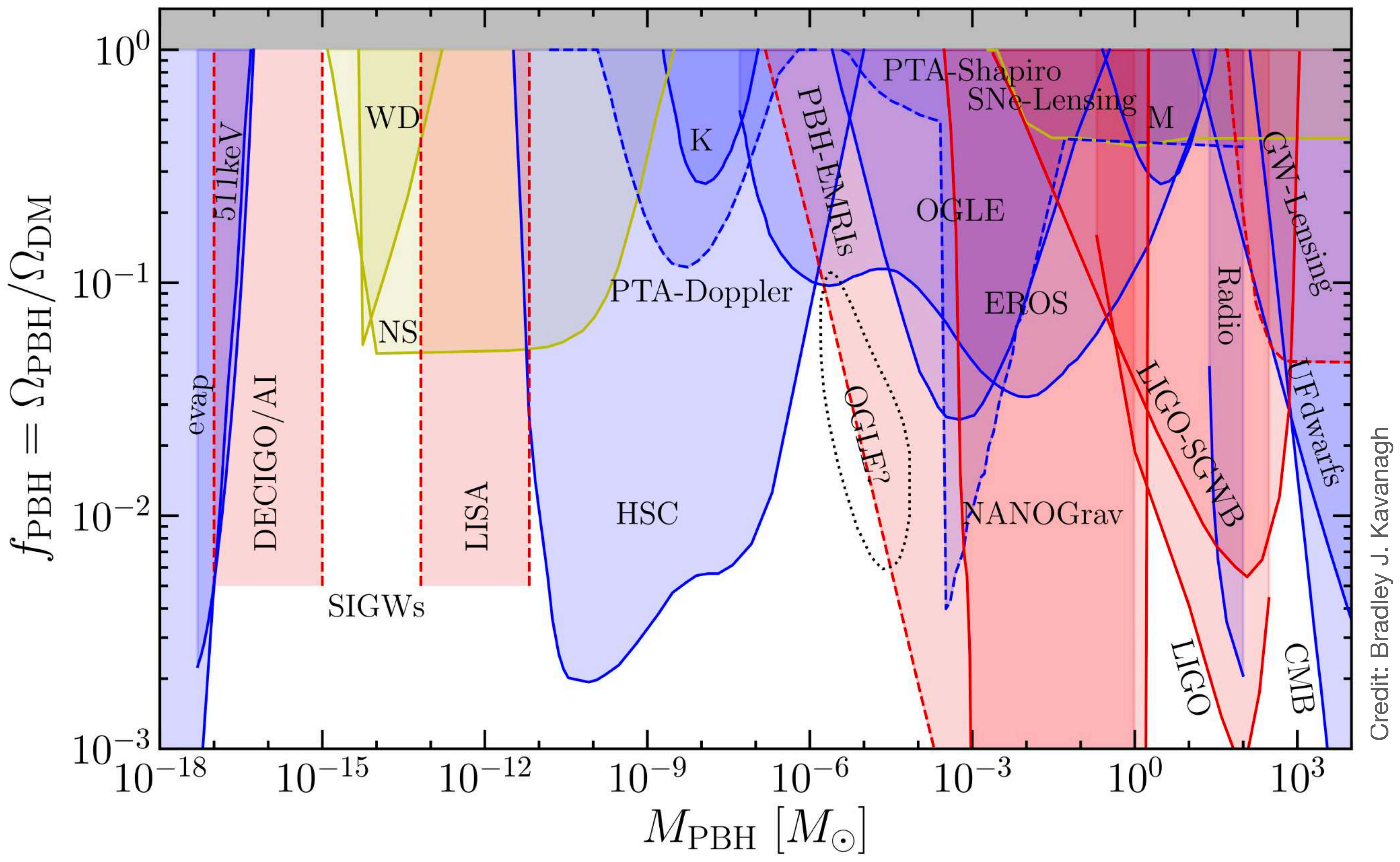


On cosmological scales PBH DM would behave like particle DM, however on galactic and smaller scales its granularity can have *observable consequences.*

Primordial Black Holes

Bounds

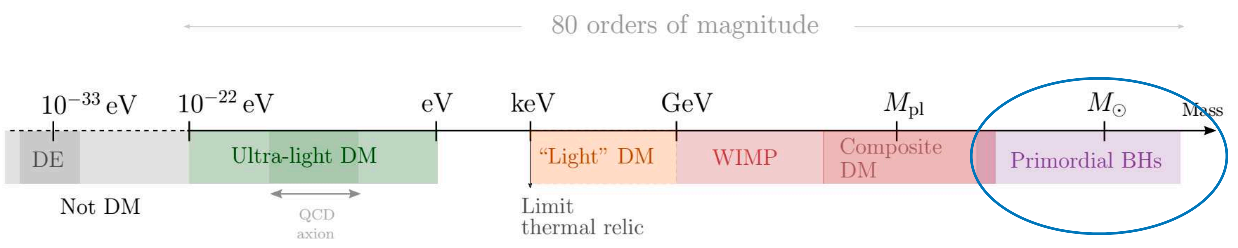


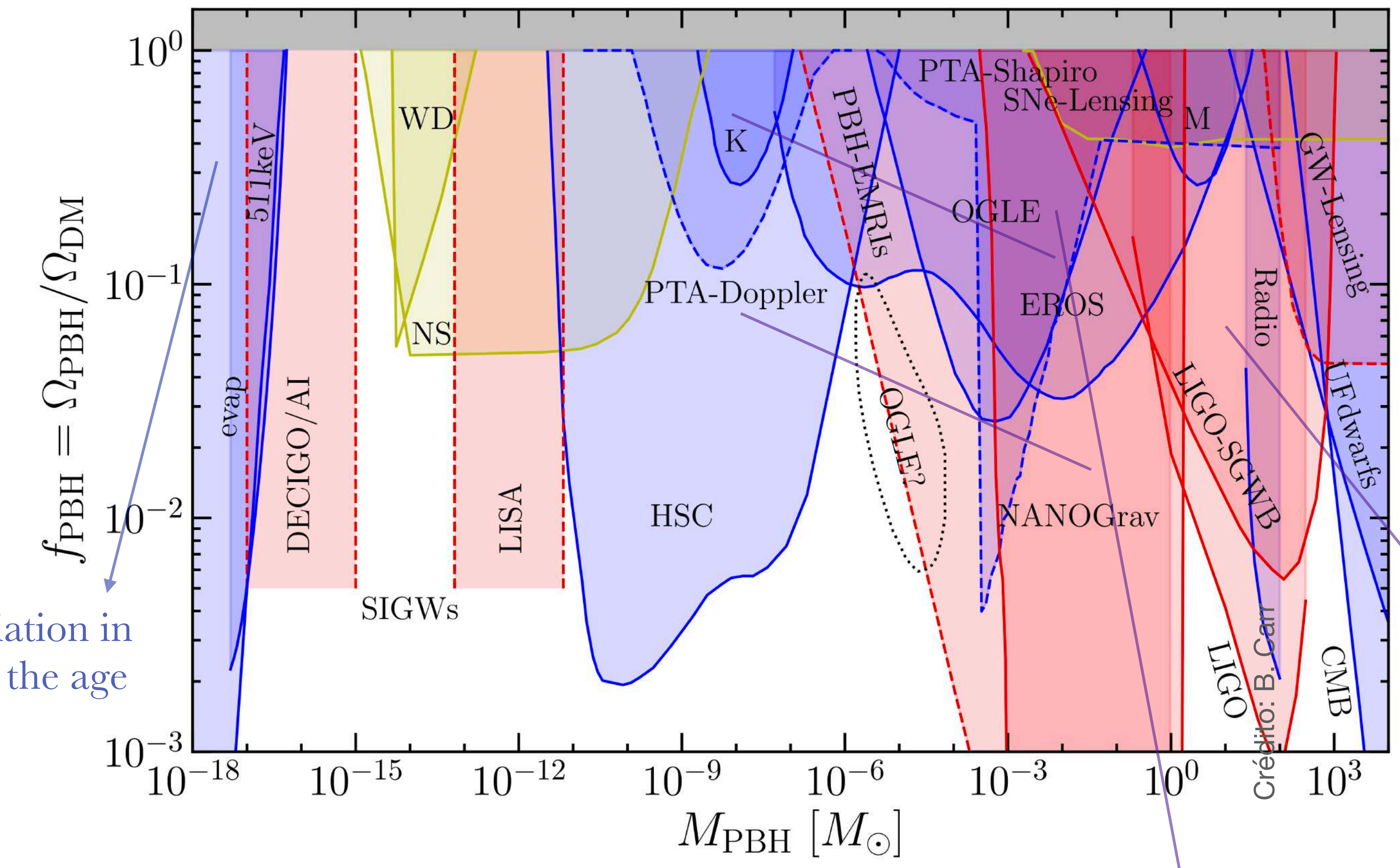


$M_\odot \sim 2 \times 10^{30}$ kg

Notebook to plot the PBH bounds: https://github.com/bradkav/PBHbounds

Primordial Black Holes





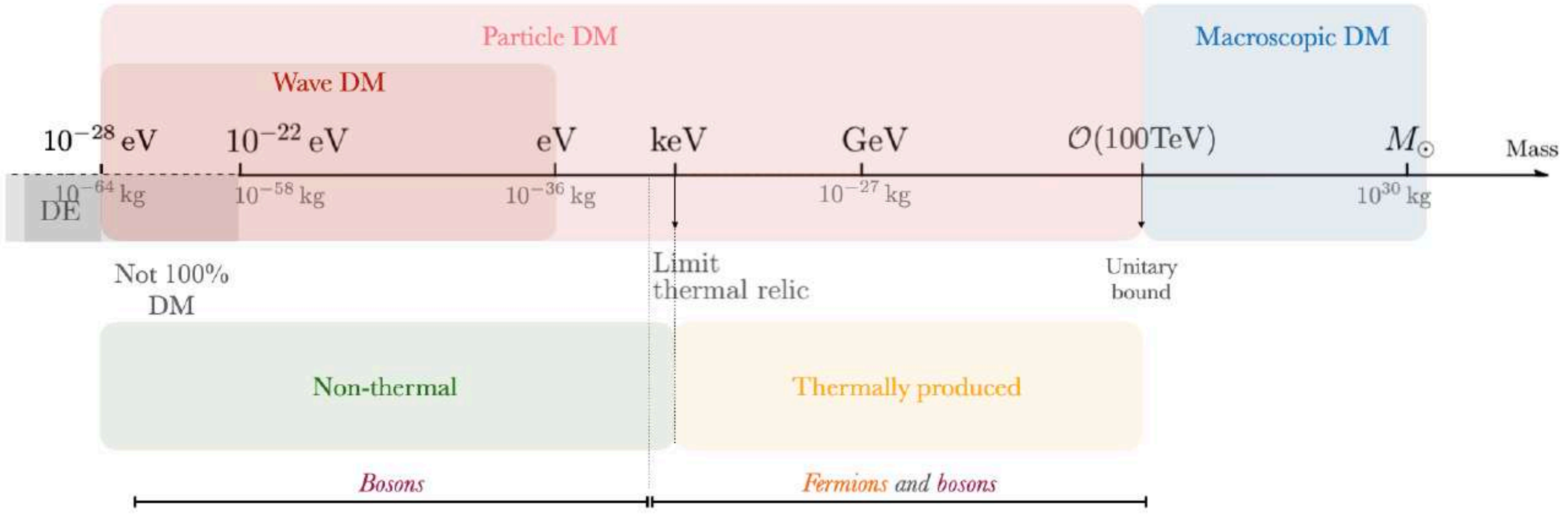
PBH evaporate, emits gamma radiation in scales or the order of smaller than the age of the universe

GW from LIGO

Direct searches via microlensingin our galaxy and M31,… (does not require that it is a BH - scalar bound system)

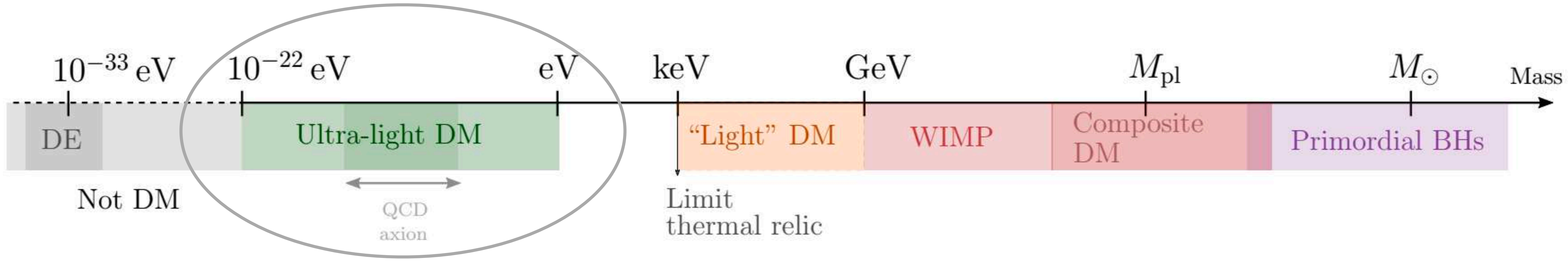
$M_\odot \sim 2 \times 10^{30}$ kg

Wave DM



Particle DM
Macroscopic DM
Wave DM
10^−28 eV
10^−22 eV
eV
keV
GeV
𝒪(100TeV)
M⊙
Mass
10^−64 kg
10^−58 kg
10^−36 kg
10^−27 kg
10^30 kg
DE
Not 100% DM
Limit thermal relic
Unitary bound
Non-thermal
Thermally produced
Bosons
Fermions and bosons

Ultra-light dark matter



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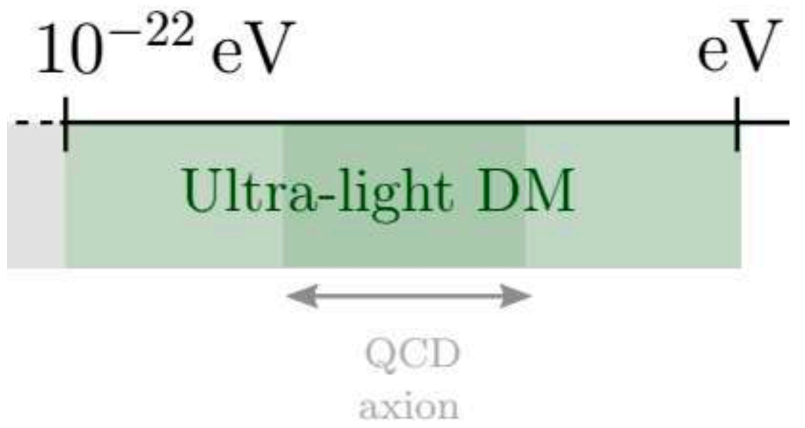
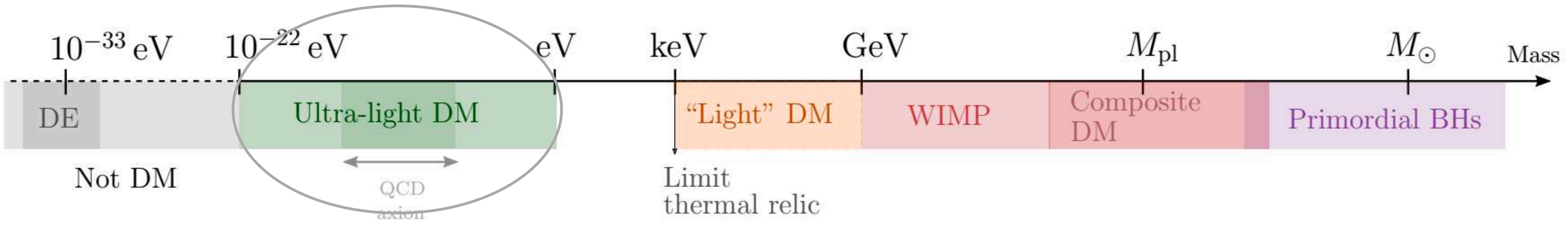
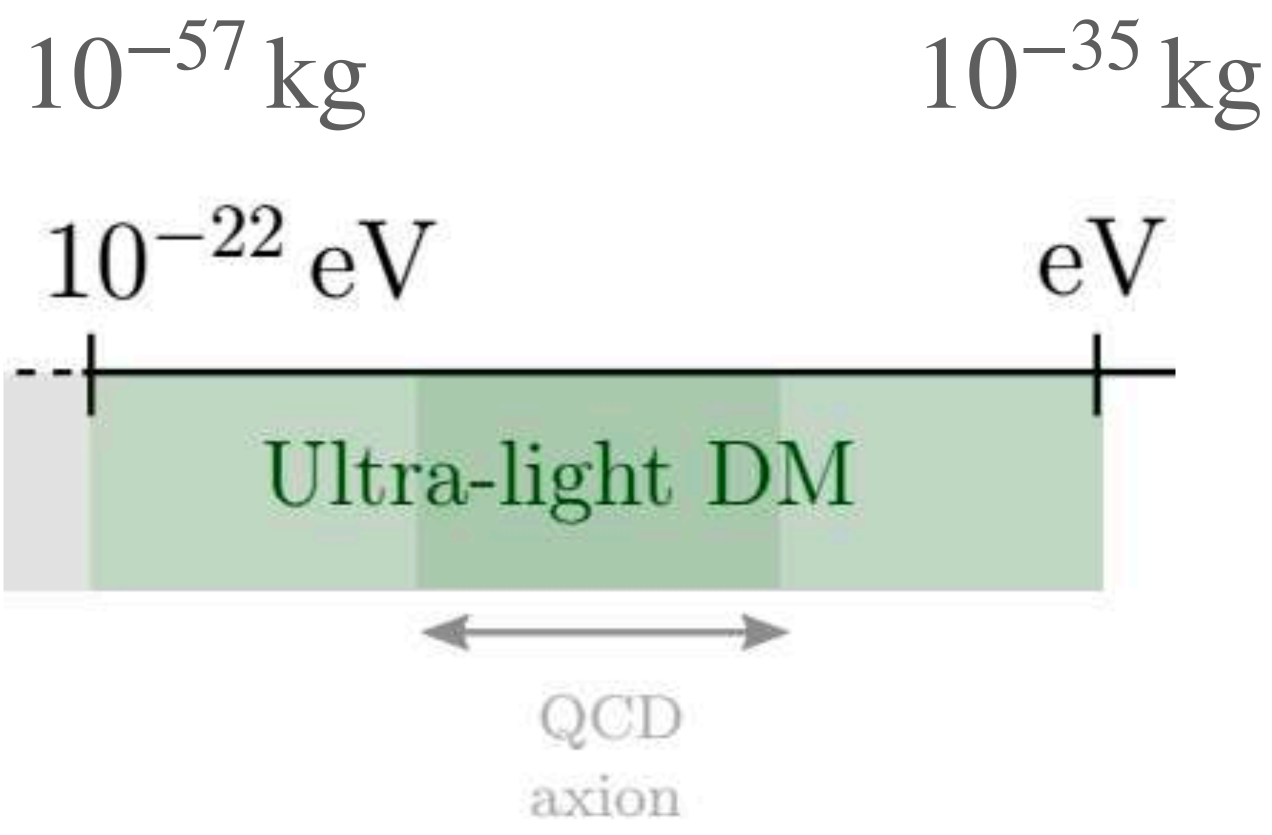


Ultra-light candidate, cold → Large $\lambda_{\mathrm{dB}} \sim 1/mv$

Lightest possible candidate for DM





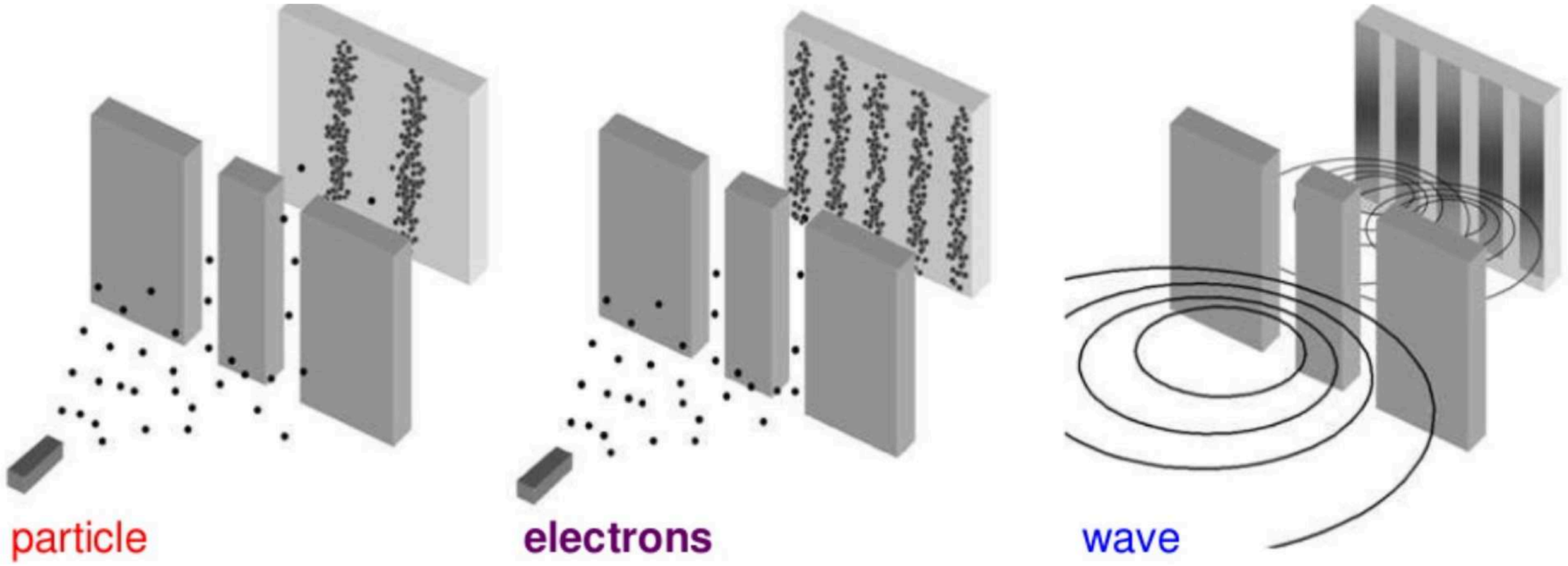
→ Bosons (scalar fields)

Non-thermally produced

Wave-Particle duality

All matter exhibits a wave behaviour

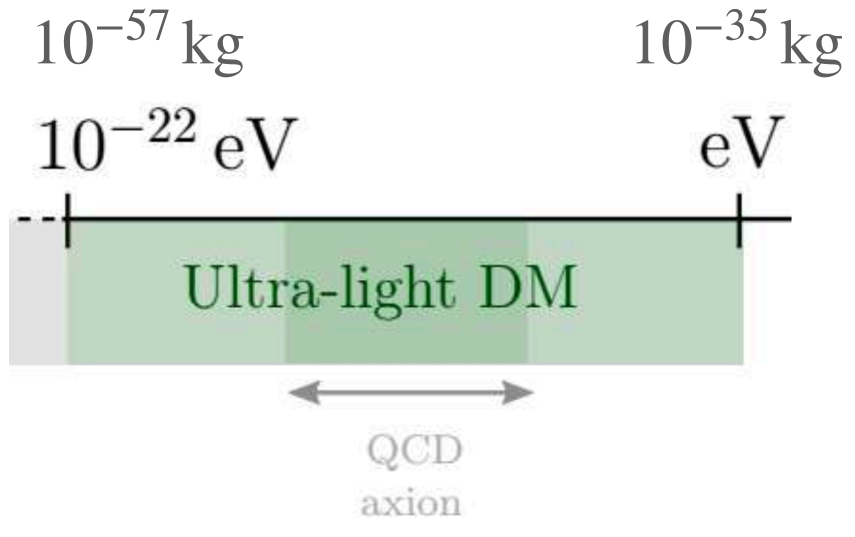
De Broglie 1924



$$\lambda_{dB} \sim \frac{1}{mv}$$

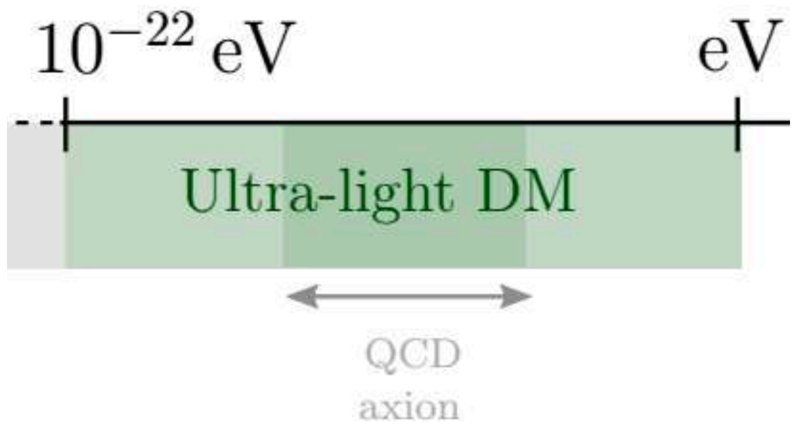
$$\lambda_{dB} \sim 1/\sqrt{2\pi m k_B T}$$

	Mass (kg)	Speed (m/s)	λ_{dB} (m)
Accelerated e-	9.1×10^{-31}	5.9×10^{6}	1.2×10^{-10}
Golf ball	0.045	220	4.8×10^{-30}



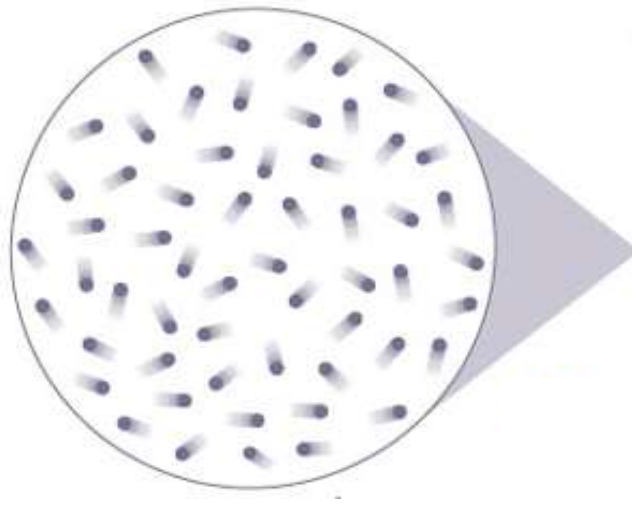
$$\lambda_{dB}^{ULDM} \sim \text{pc} - \text{kpc}$$

Ultra-light dark matter



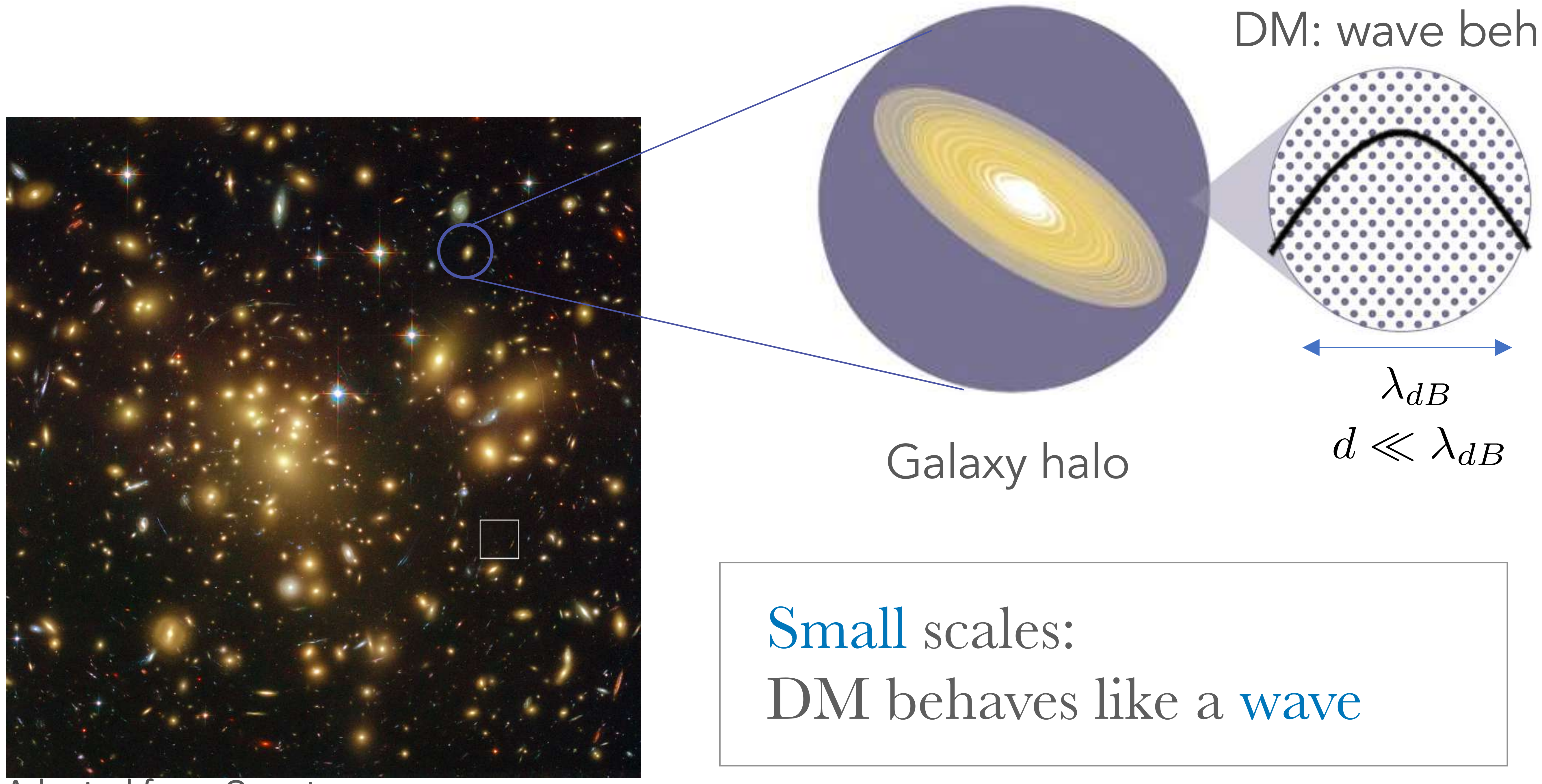
Ultra-light candidate $\longrightarrow$ Large $\lambda_{\mathrm{dB}} \sim 1/mv$

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



DM: particles

$d \gg \lambda_{dB}$



Adapted from Quanta

DM: wave behaviour

λ_{dB}

$d \ll \lambda_{dB}$

Galaxy halo

Small scales:
DM behaves like a wave

10^{-60} kg $\quad$ 10^{-35} kg

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

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

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

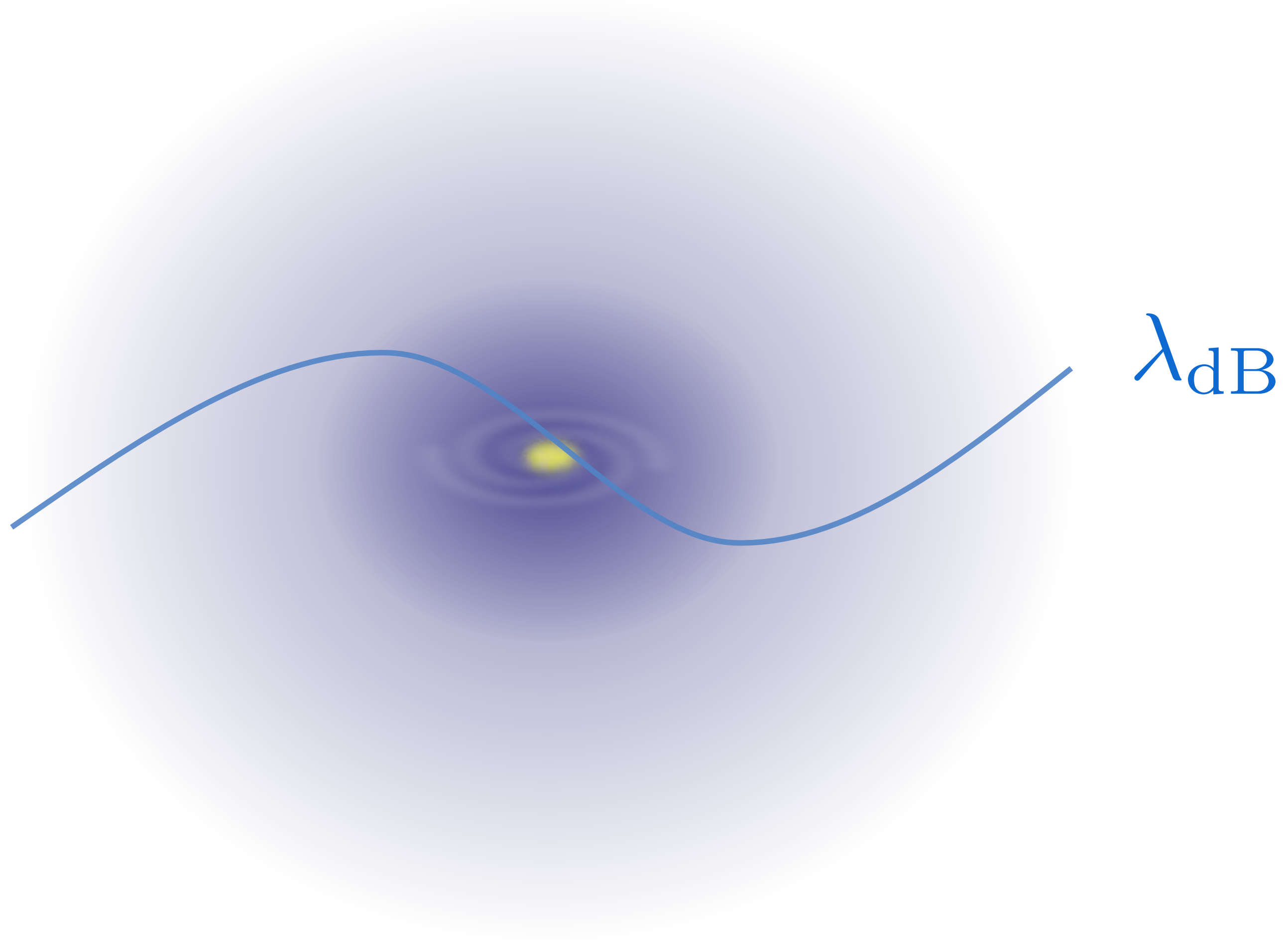
How light is ultra-light?

Behave as wave on galactic scales:

- λ_{dB} must be smaller than the halo

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

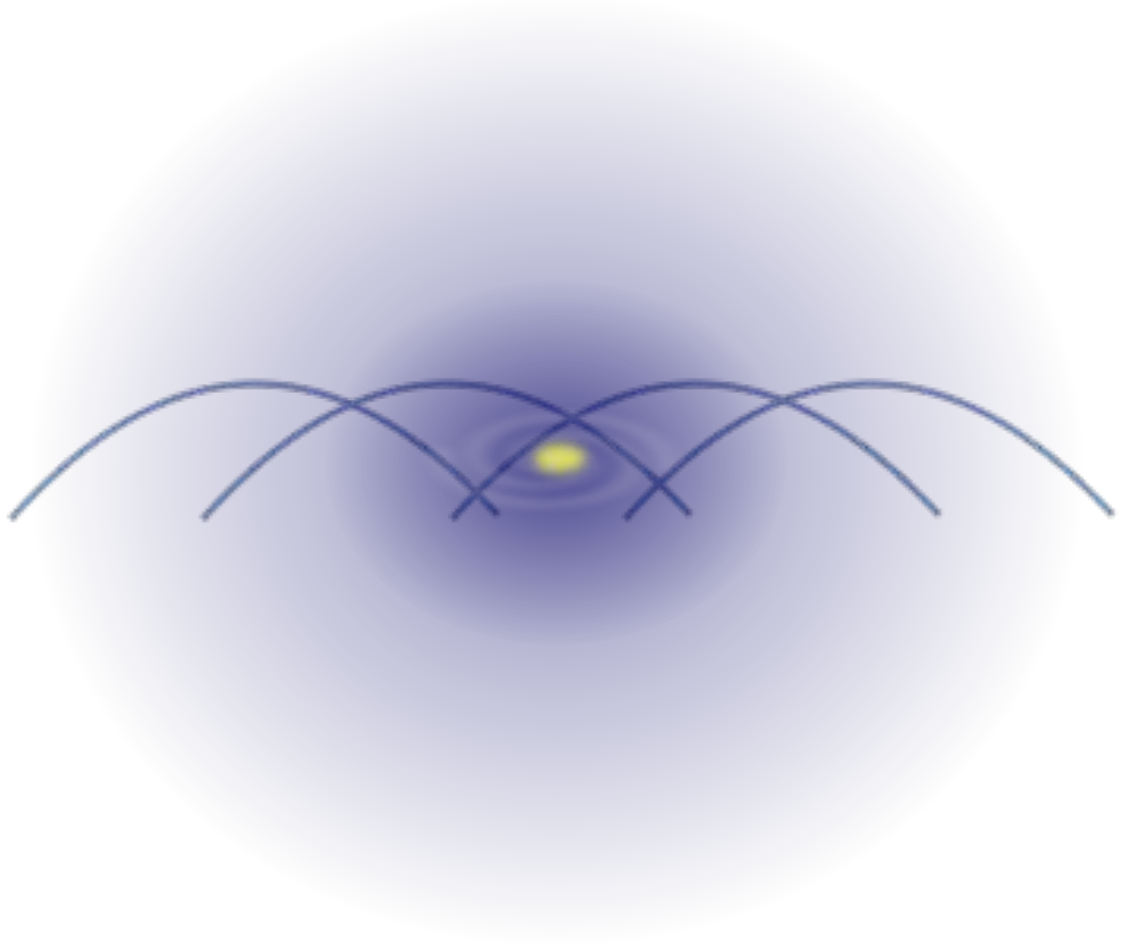
$$\implies \quad m \gtrsim 10^{-25}\,\mathrm{eV}$$



- λ_{dB} overlap to be of halo size

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

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



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

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

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

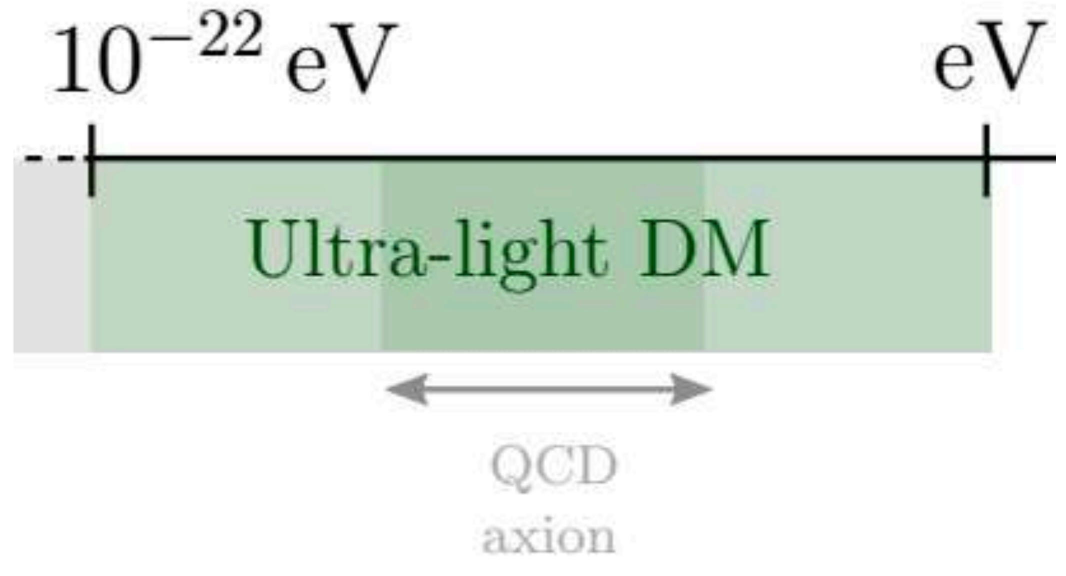
Motivation: particle physics

ULDM candidates

- Natural candidate for a light scalar field is a pseudo-Nambu Goldstone boson (breaking of an approximate symmetry)

Known PNGB: QCD axion → Candidate for DM

(Peccei and Quinn 1977; Weinberg 1978; Wilczek 1978)



Axion-like particles

Axions or Axion like particles (ALP)

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

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

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

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

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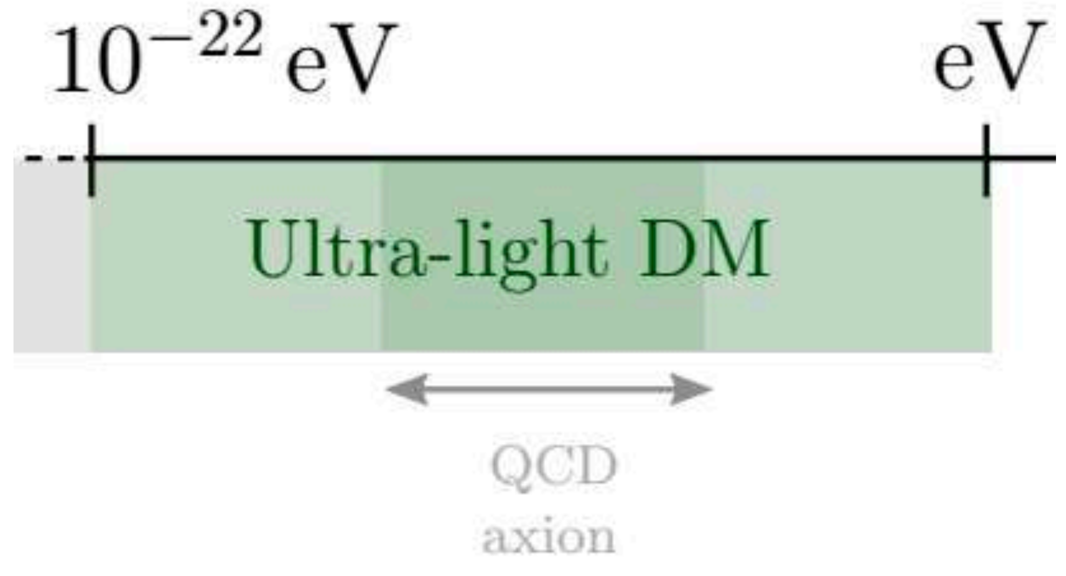

Axion-like particles or ultra-light axions:

- ALPs expected in string theory *(Arvanitaki et al., Svrcek, Witten)*
- Can generate PNGB that are ultra-light

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

Non-thermal mechanism (e.g. mis-alignement)

$$\Omega_{axion} \sim 0.15 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \theta_1^2$$

$$\Omega_{ALP} \sim 0.1 \left(\frac{f_a}{10^{17}\,\mathrm{GeV}}\right)^{2} \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)$$

L. Hui

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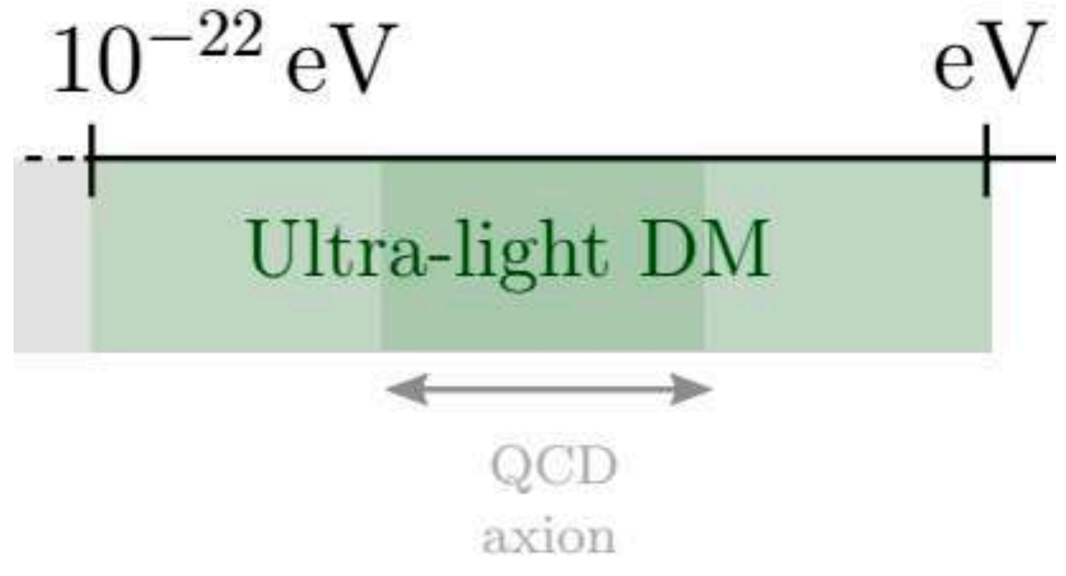

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Spin-0: Non-thermal mechanism (e.g. misalignement)

Vector FDM: challenging in the ultra-light regime
(e.g. from misalignment requires non-minimal couplings to Ricci scalar -> viol. of unitarity long. graviton-photon scattering; oscillating Higgs or oscillating misaligned axion - resonant production - choices for couplings for right abundance)
Spin 2 FDM: (e.g bigravity)

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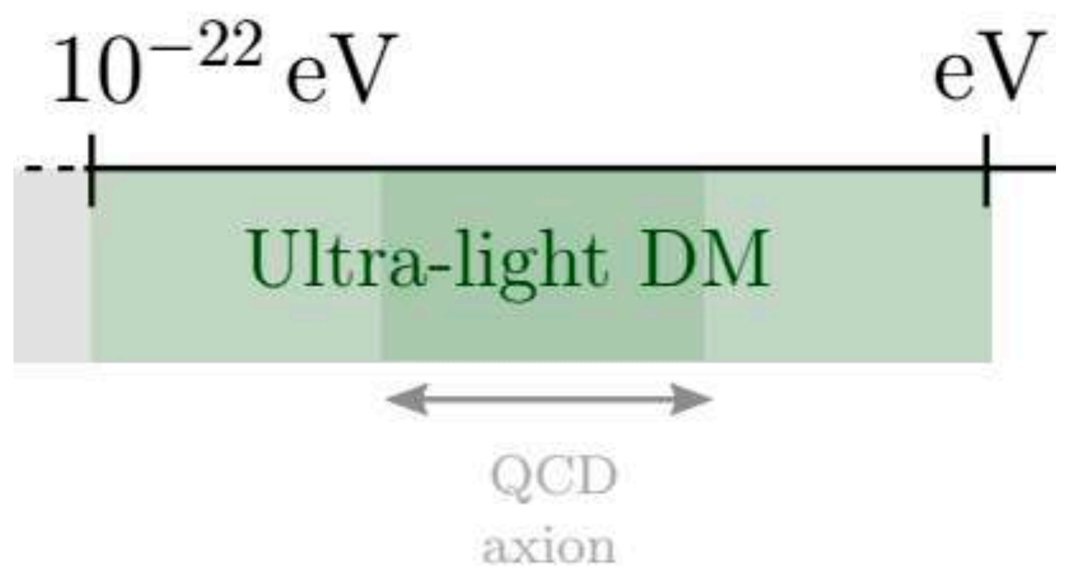

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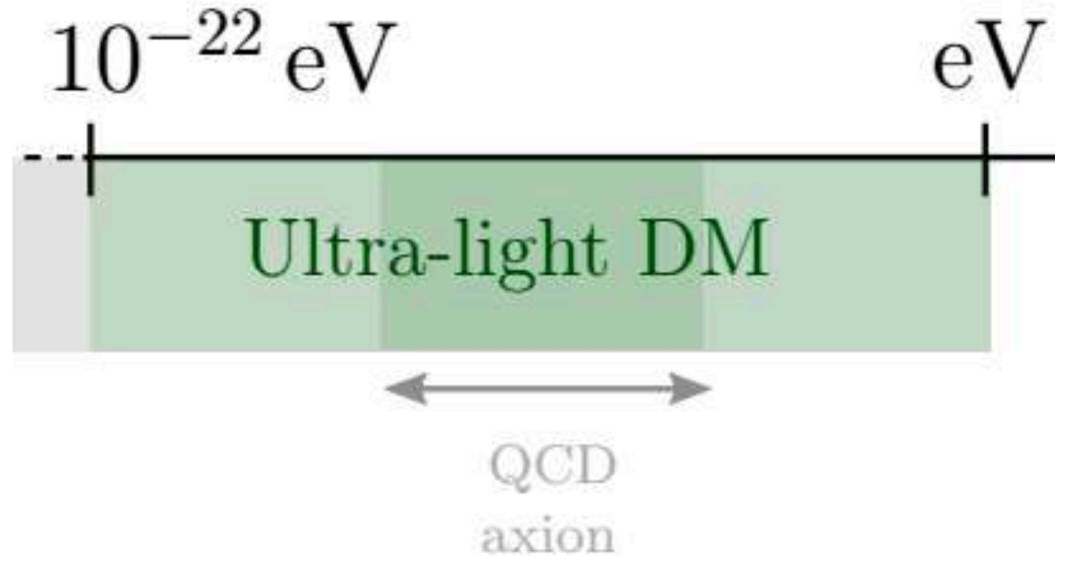
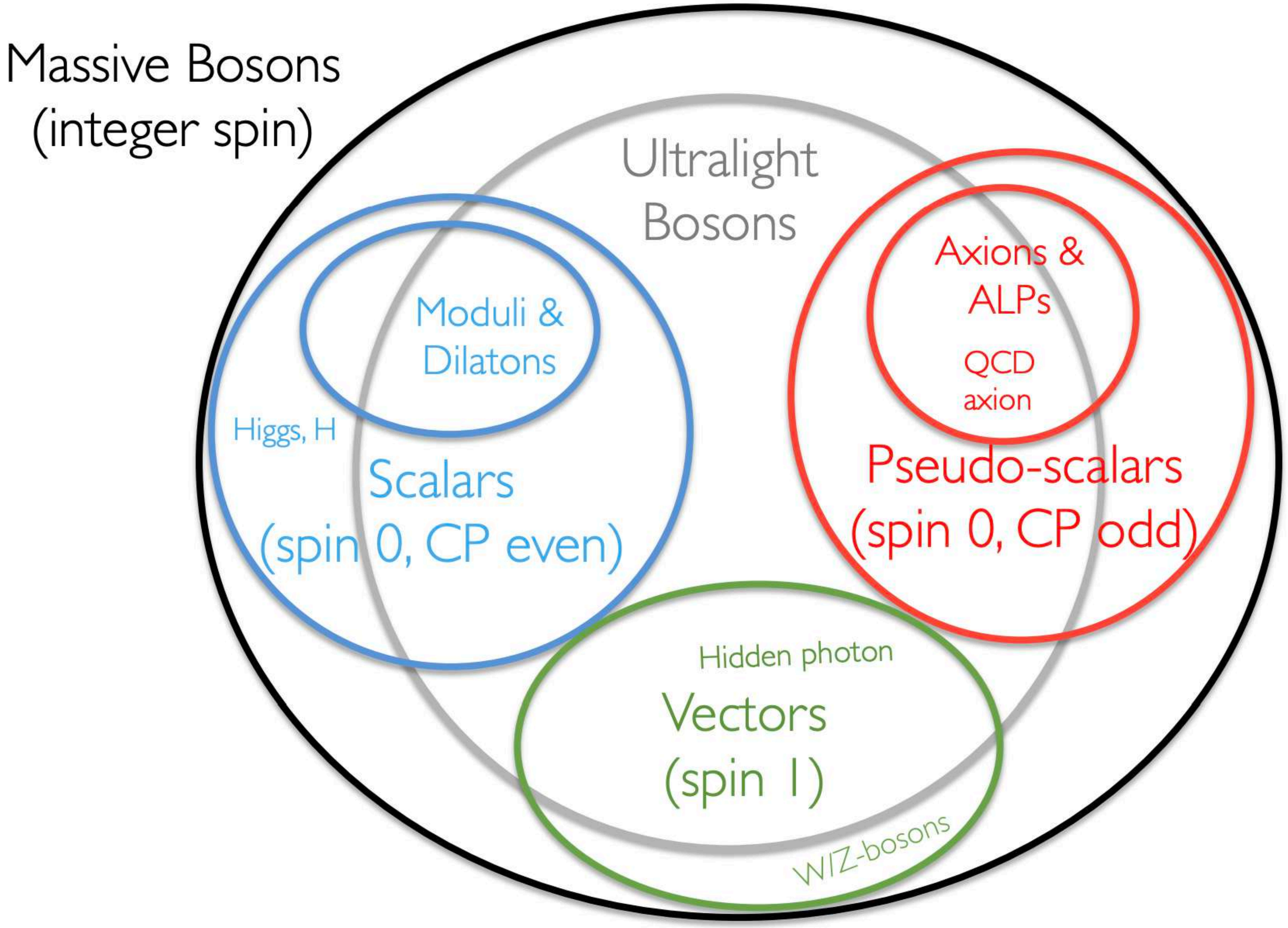
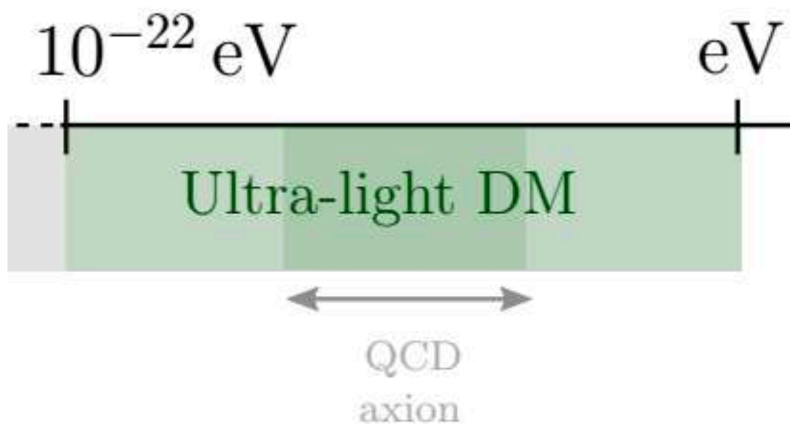


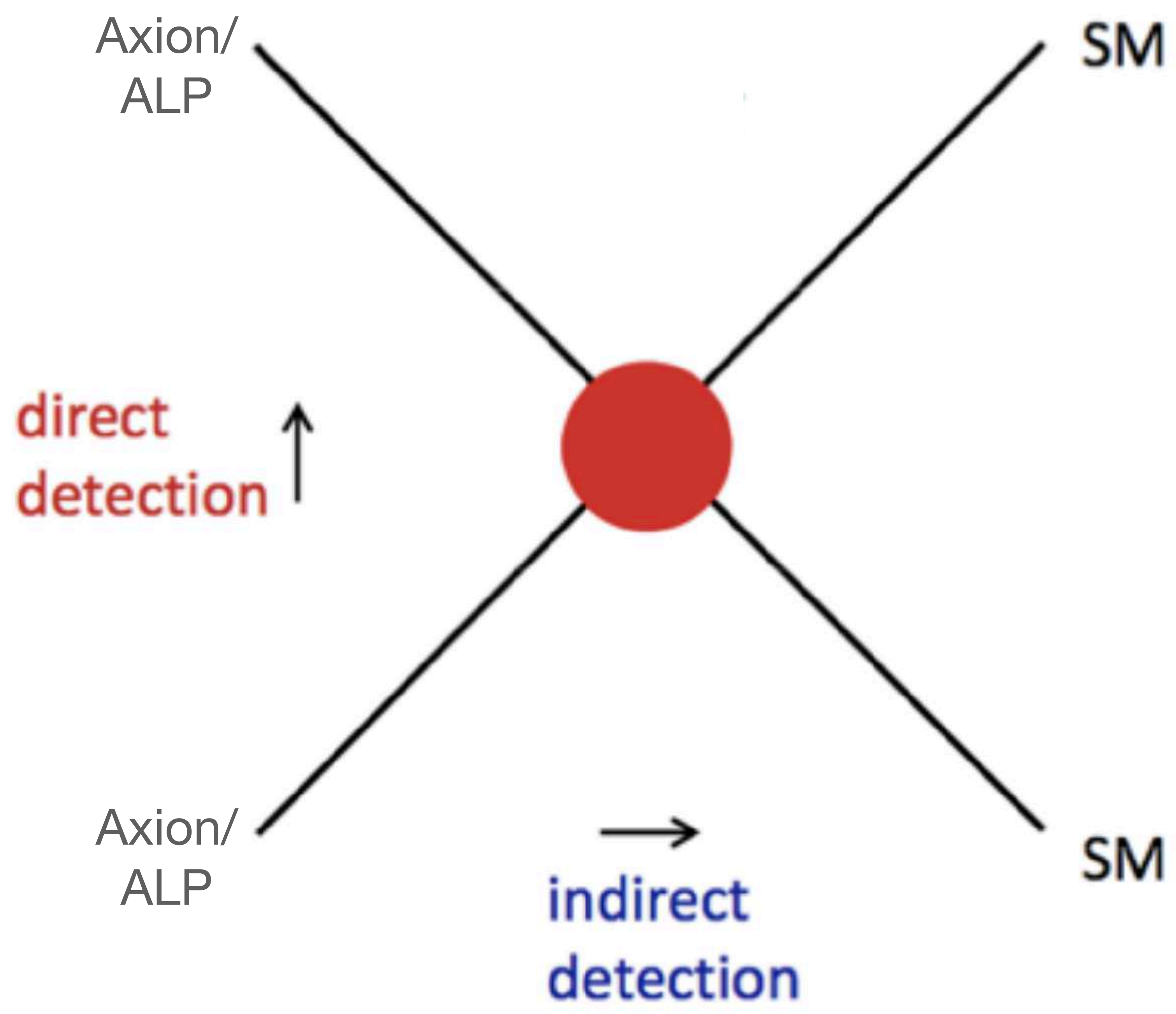
Many extensions of the Standard Model predict additional massive bosons



Ref.: Chadha-Day et al 2022

How to search for axions/ALPs?

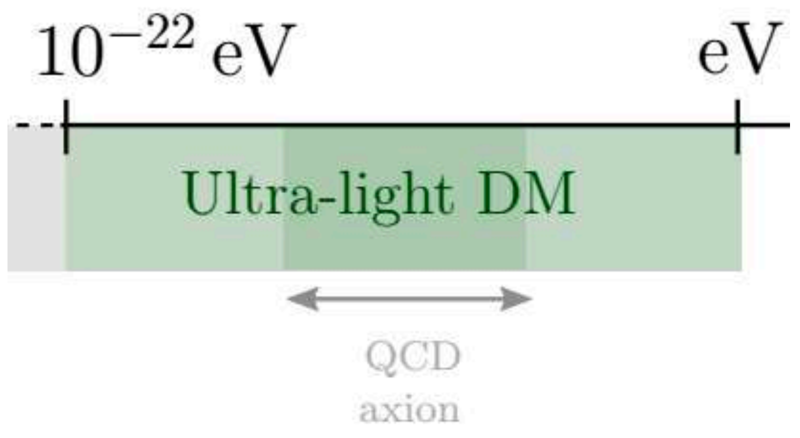




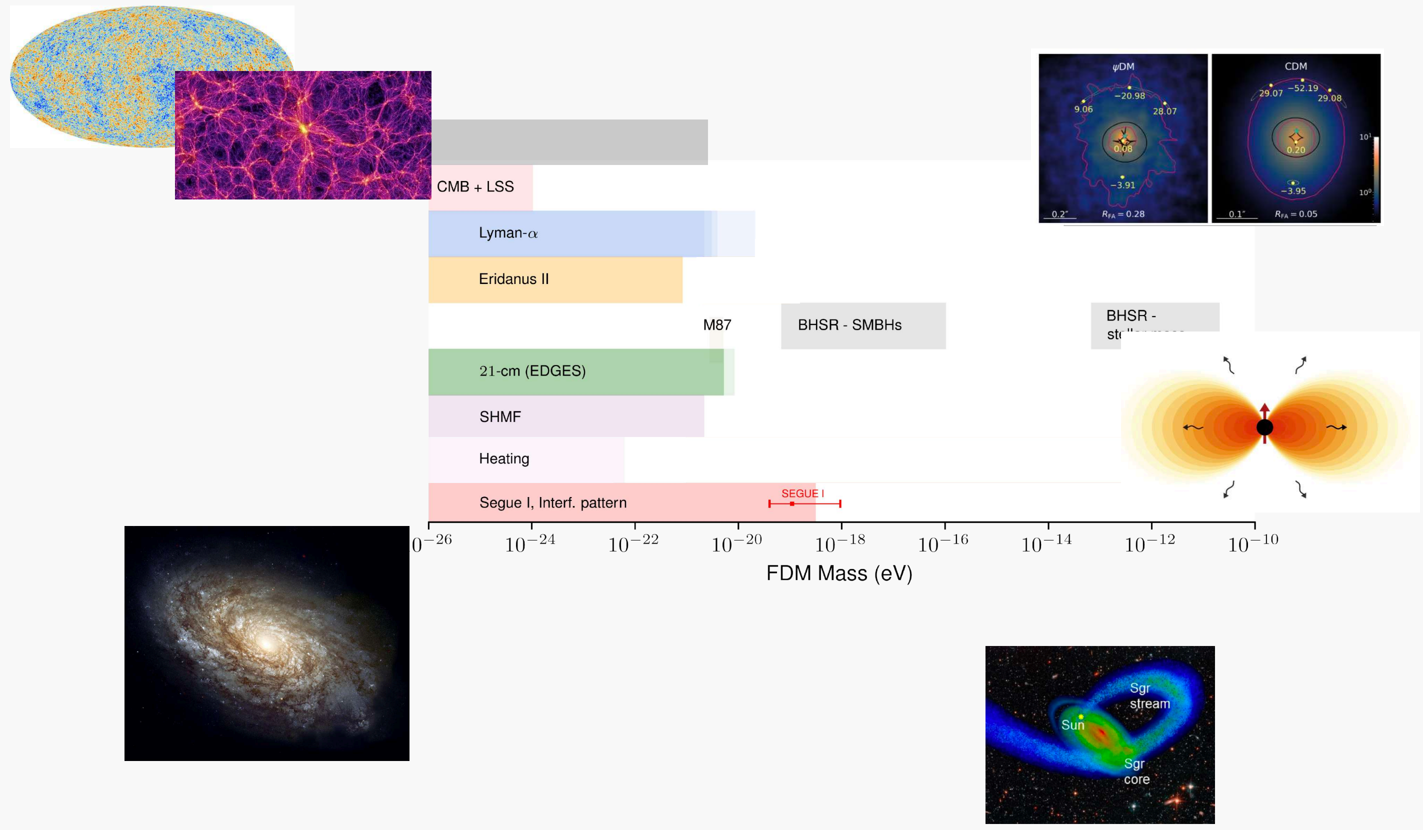
+

Gravitationally
Cosmological and astrophysical searches

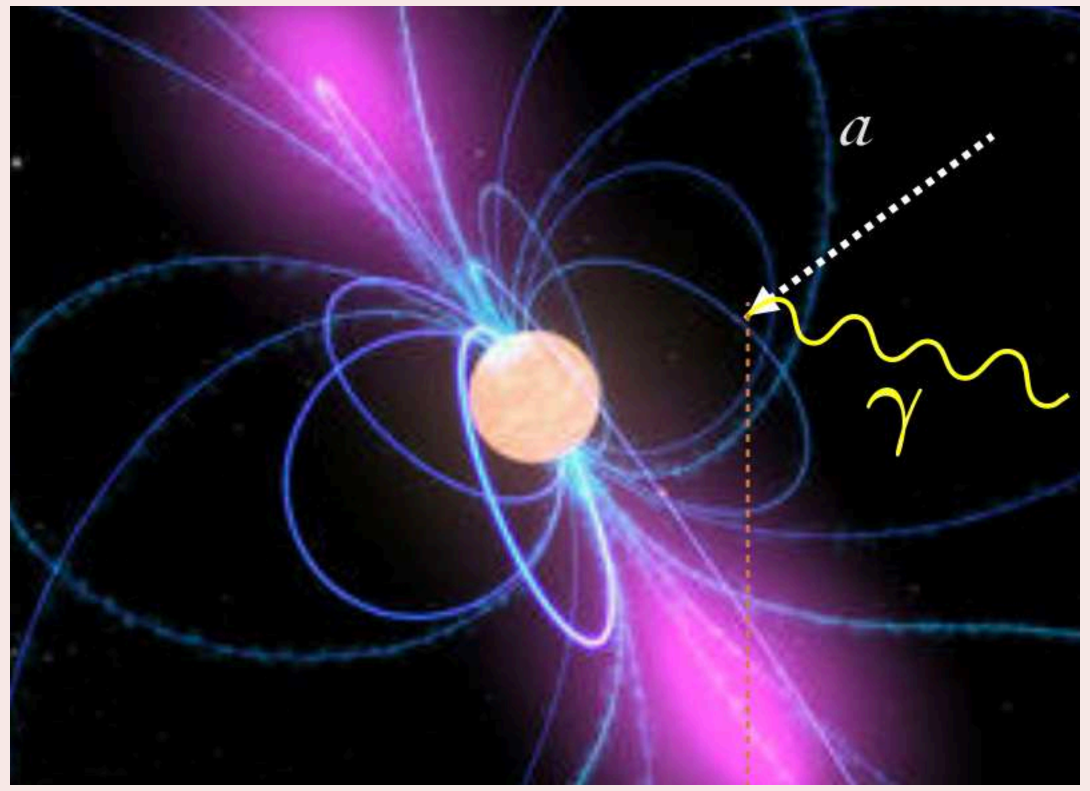
How to search for axions/ALPs?



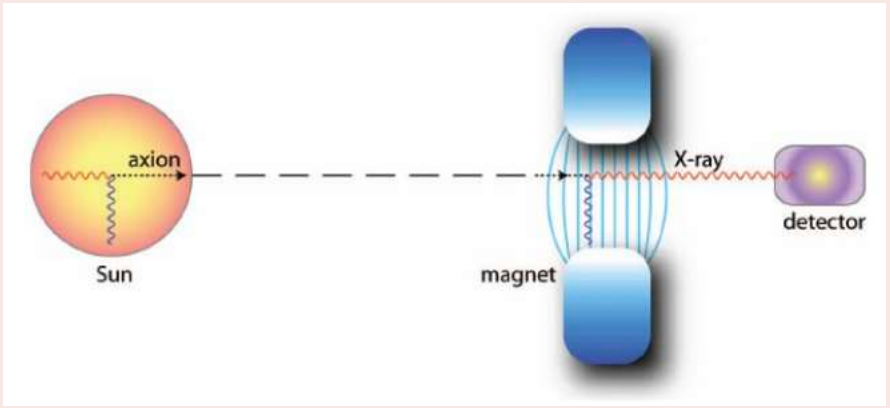
Cosmological and astrophysical searches

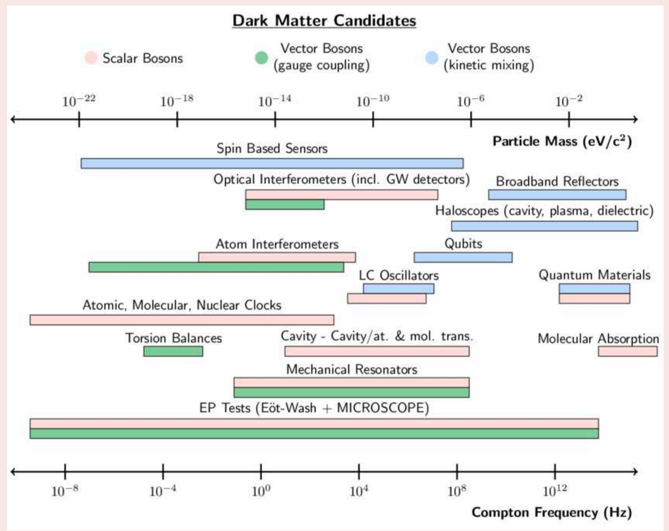


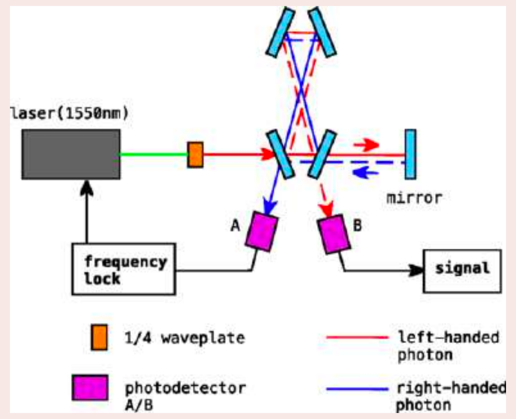
Indirect detection



"Direct detection" Axion/ALPs experiments

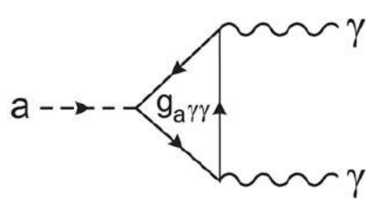


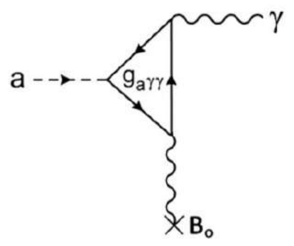




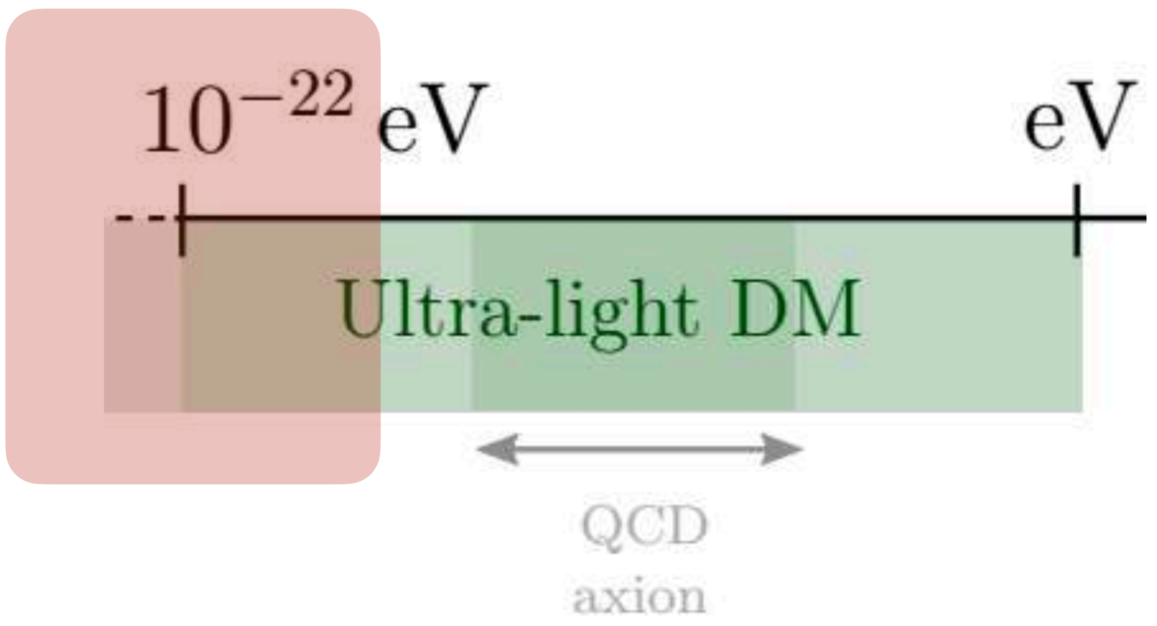
Gravitational

Interactions with the SM

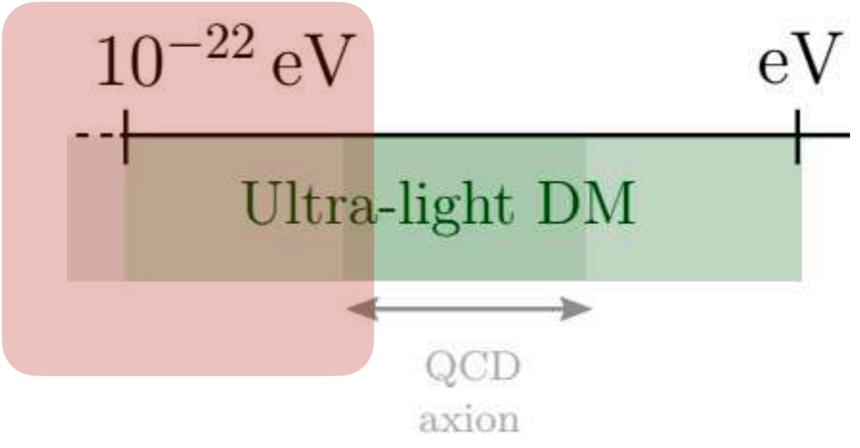




Cosmological signatures



Ultra-light Dark Matter -classes



3 classes:

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

Axion and ALP (axion like particles)

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

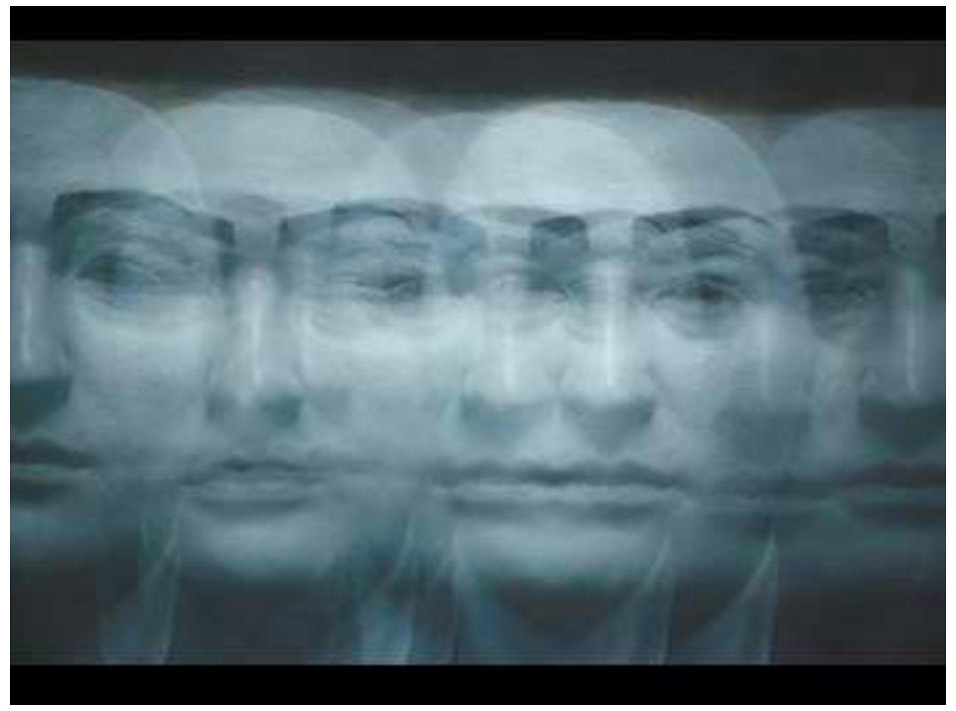
$$\mathcal{L} = P(X)$$

⟶ Connection with condensed matter and particle physics!

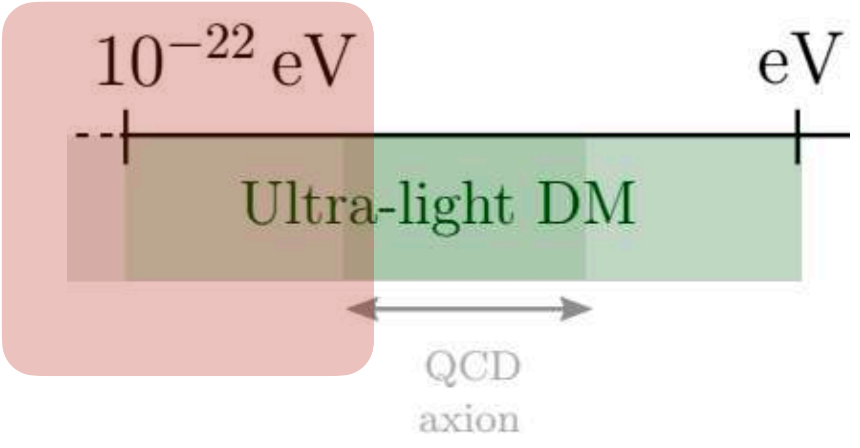
"Ultra-light dark matter", **E.Ferreira**, 2020. The Astronomy and Astrophysics Review.

Fuzzy dark matter

Self interacting fuzzy dark matter



Fuzzy dark matter



Fuzzy DM
(FDM)

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

m

Wave DM
Ultra-light axions

Self Interacting FDM
(SIFDM)

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

m g

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

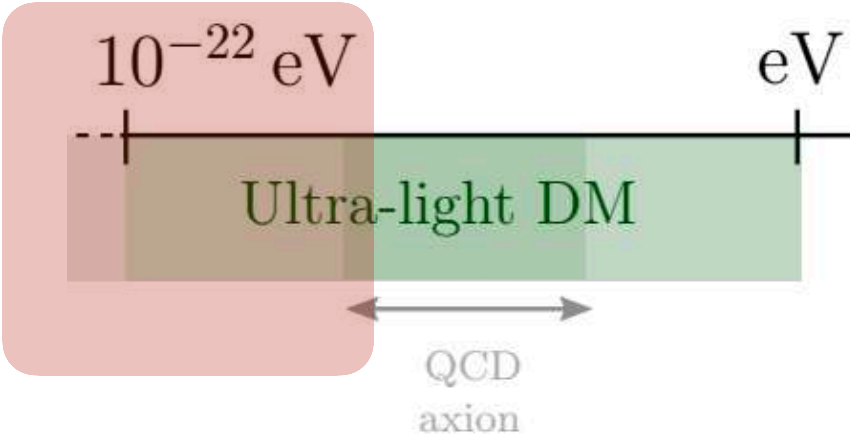
(Reviews: EF (2021), J. Niemeyer (2019), L. Hui (2021))

Idea:

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

address the small scale problems+ rich phenom.

Fuzzy dark matter



Fuzzy DM
(FDM)

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

m

Wave DM
Ultra-light axions

Focus in spin 0 particles here!

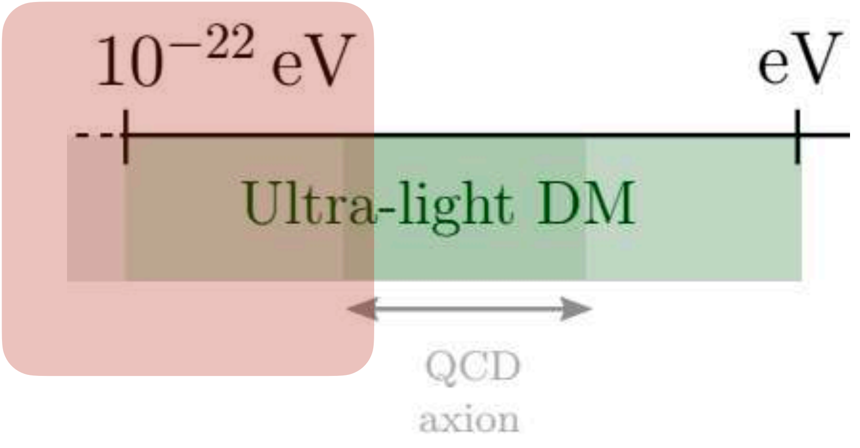
(Some of the grav. phenom. is carried for vectors, for example)

- Spin 0 - FDM
- Spin 1 - Vector FDM
- Higher spin FDM

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

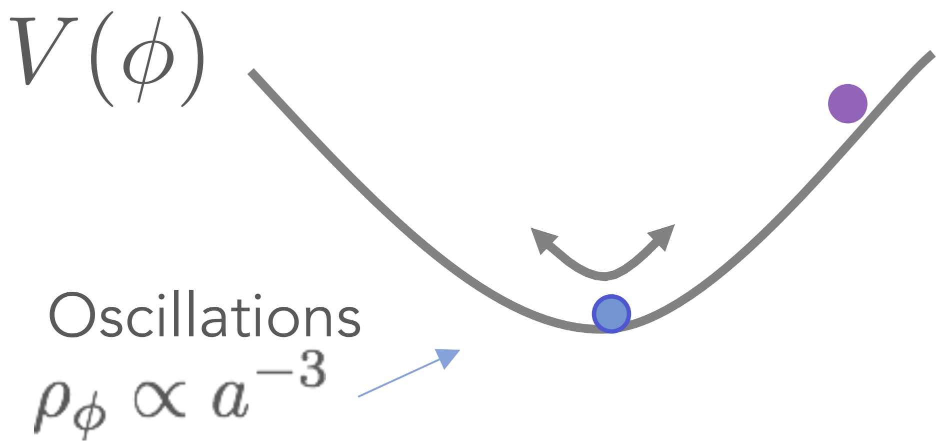
(Reviews: *EF (2021), J. Niemeyer (2019), L. Hui (2021)*)

Cosmological evolution

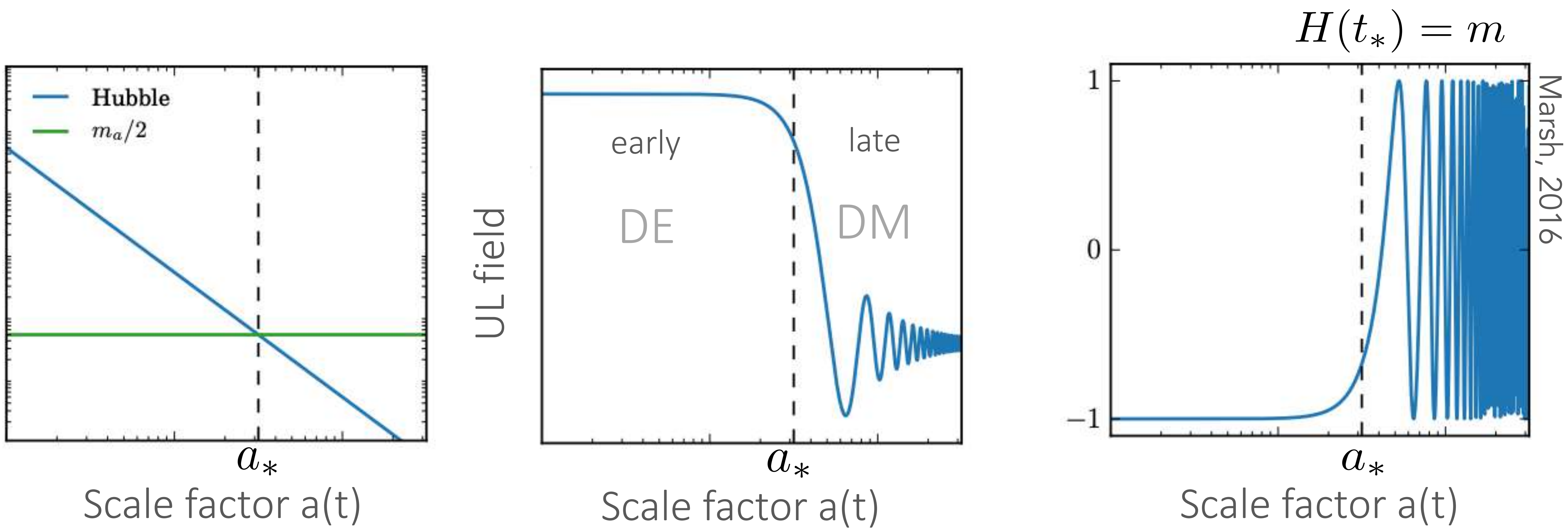


$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$$

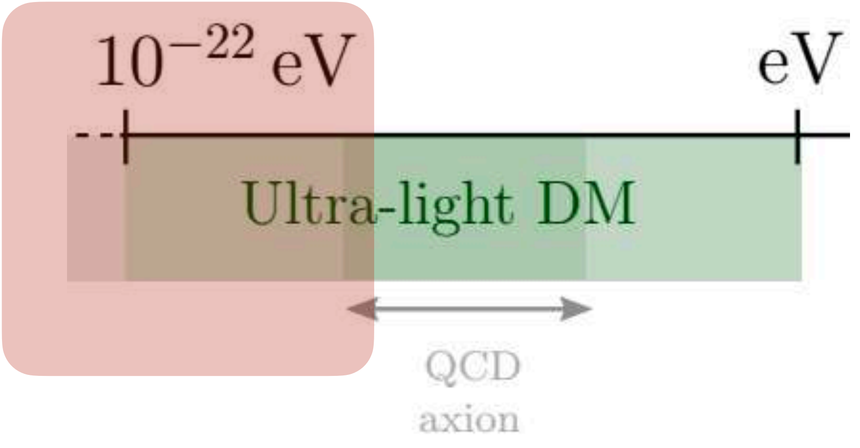
FDM



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



Structure formation - non-relativistic regime



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

Schrödinger-Poisson system : describe the FDM and the SIFDM

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

Schrödinger equation (Gross-Pitaevskii)

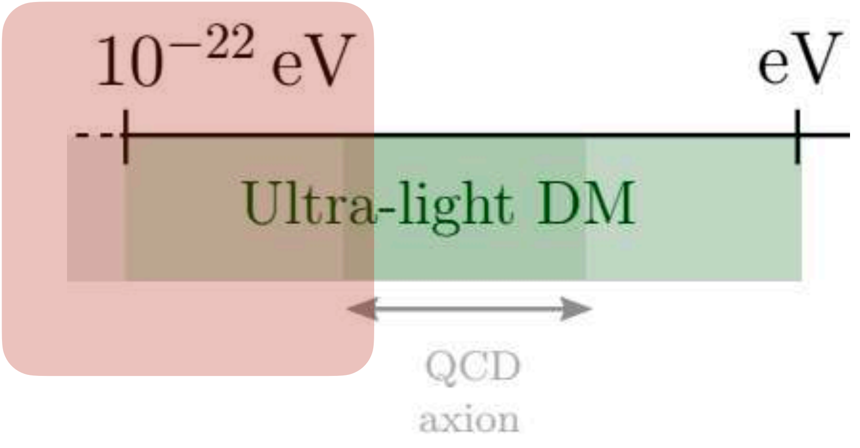
Poisson equation

$g = 0$ → FDM

$g \neq 0$ → SIFDM

Fundamentally different than CDM/WDM/SIDM!

Structure formation - non-relativistic regime



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Schrödinger equation (Gross-Pitaevskii)

Poisson equation

$g = 0 \rightarrow$ FDM

$g \neq 0 \rightarrow$ SIFDM

Fundamentally different than CDM/WDM/SIDM!

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

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

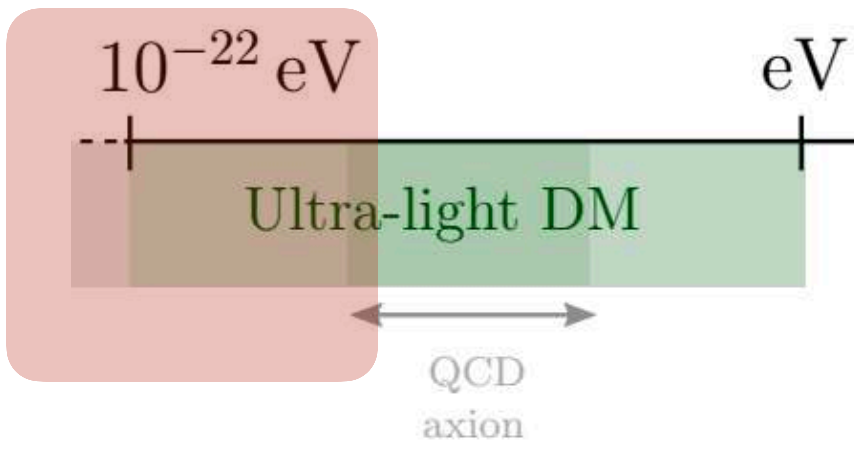
$$\dot{\mathbf{v}} + (\mathbf{v}\cdot\nabla)\mathbf{v} = -\frac{1}{m}\left(V_{grav} - P_{int} - \frac{1}{2m}\frac{\nabla^2\sqrt{\rho}}{\sqrt{\rho}}\right)$$

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

Quantum pressure

FLUID DESCRIPTION

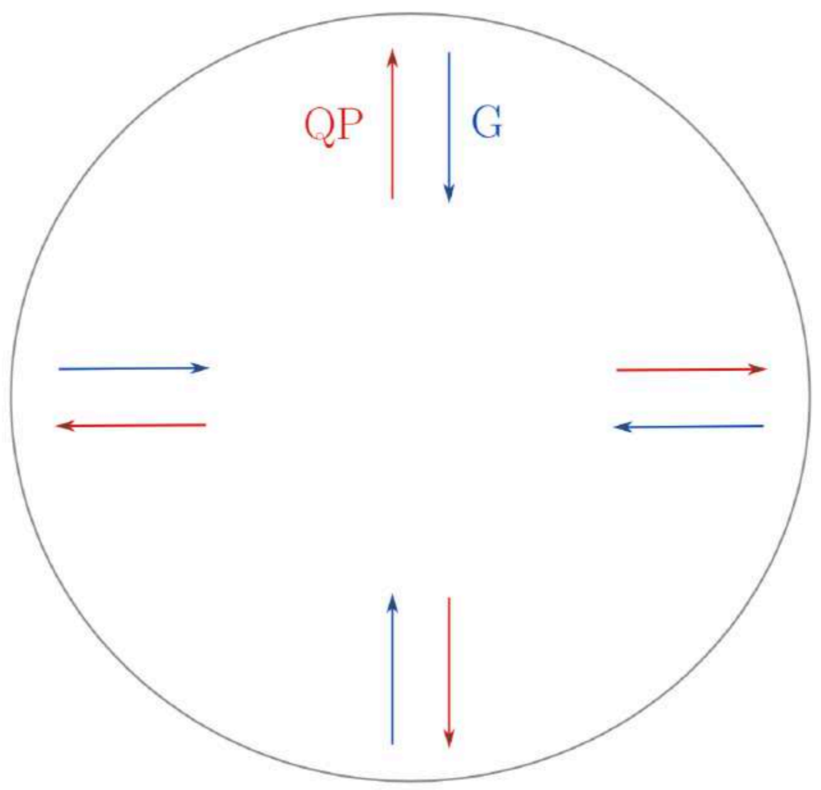
Structure formation - perturbation and stability



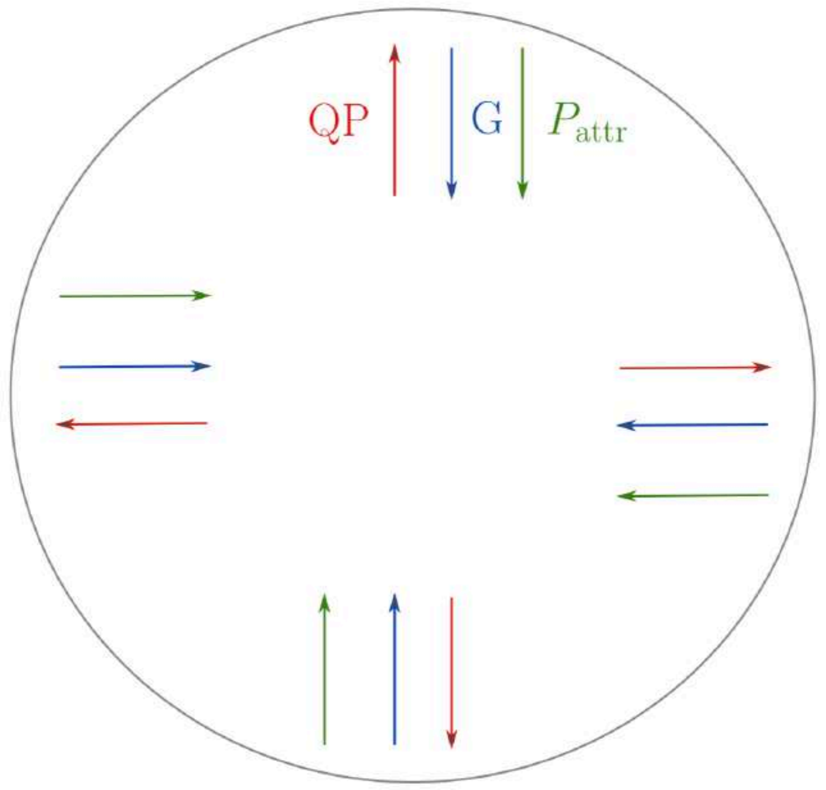
Competition between gravity and pressure (quantum pressure and interaction)

SIFDM

FDM

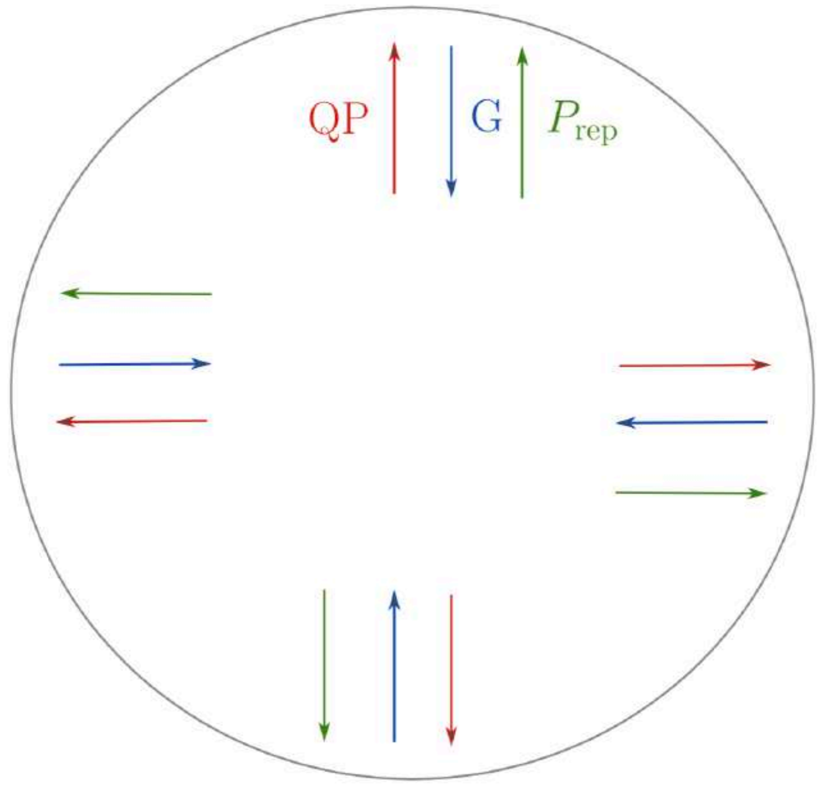


ATTRACTIVE



$g < 0$

REPULSIVE



$g > 0$

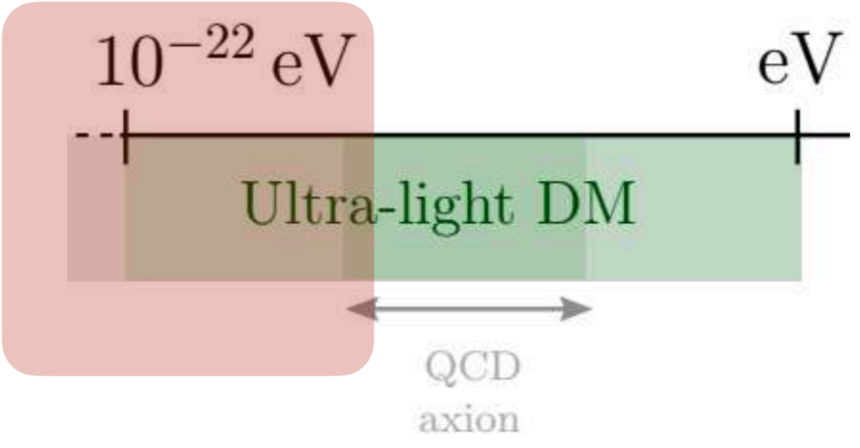
$$\dot{\rho} + \nabla \cdot (\rho\, \mathbf{v}) = 0$$

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

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

Quantum pressure

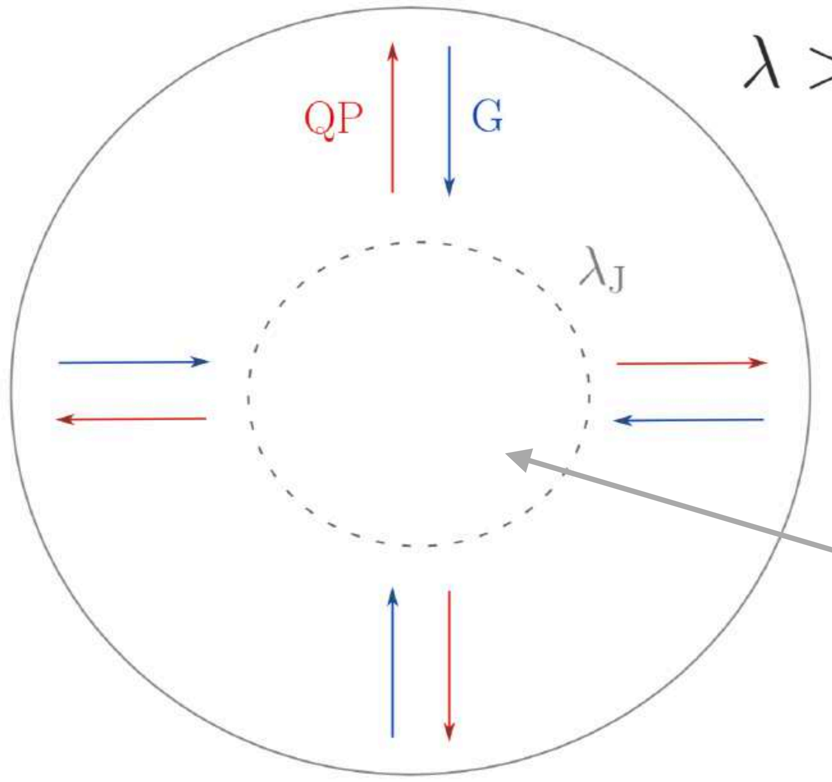
Structure formation - perturbation and stability



Finite clustering scale - no structure formation on small scales

SIFDM

FDM

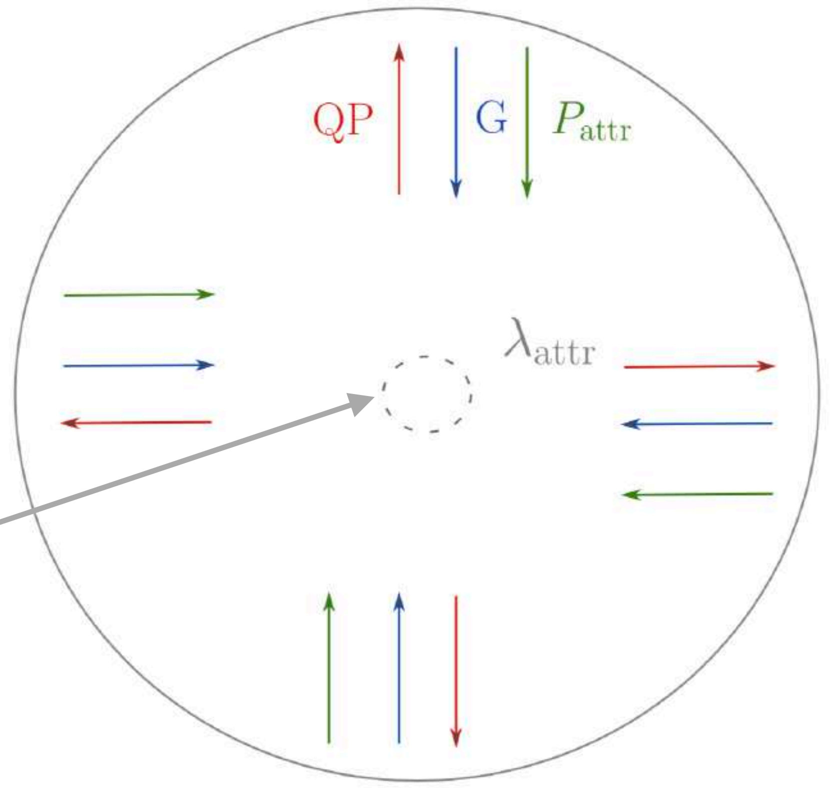


$\lambda > \lambda_J,\ \lambda_{attr},\ \lambda_{rep} \quad \longrightarrow \quad$ CDM

QP wins -
NO structure formation

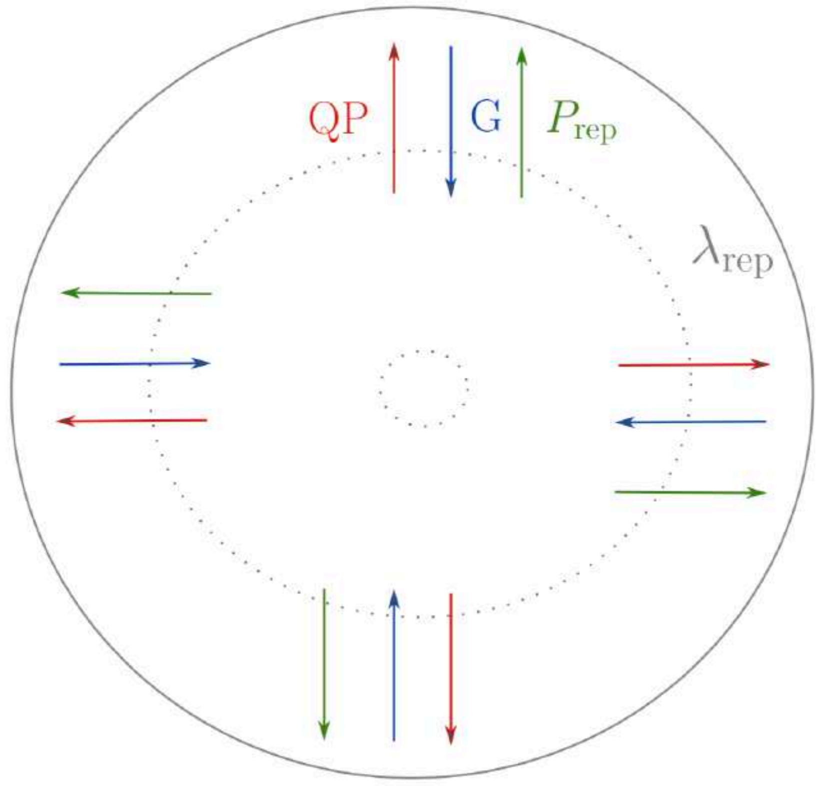
$\lambda < \lambda_J,\ \lambda_{attr},\ \lambda_{rep}$

ATTRACTIVE



$g < 0$

REPULSIVE



$g > 0$

Finite size coherent core – Bose stars

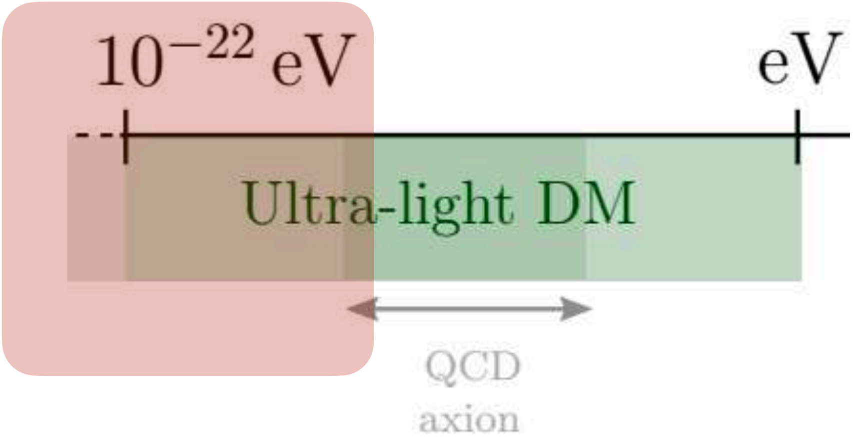
$$\lambda_J = 55 \left(\frac{m}{10^{-22}\,\mathrm{eV}} \right)^{-1/2} \left(\frac{\rho}{\bar{\rho}} \right)^{-1/4} (\Omega_m h)^{-1/4}\,\mathrm{kpc}$$

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

For attractive interactions can only form localized clumps (solitons)

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

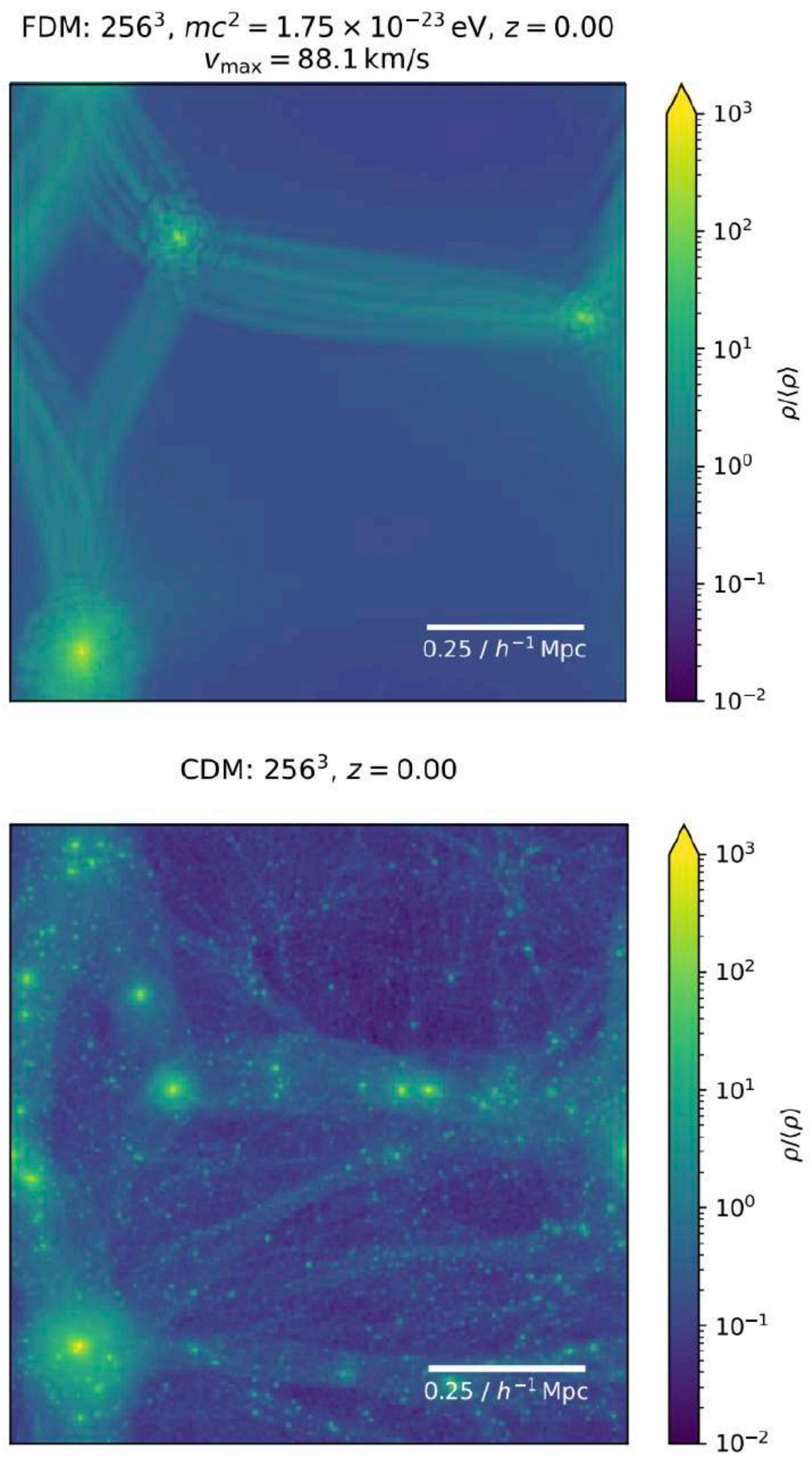
Phenomenology



RICH PHENOMENOLOGY ON SMALL SCALES

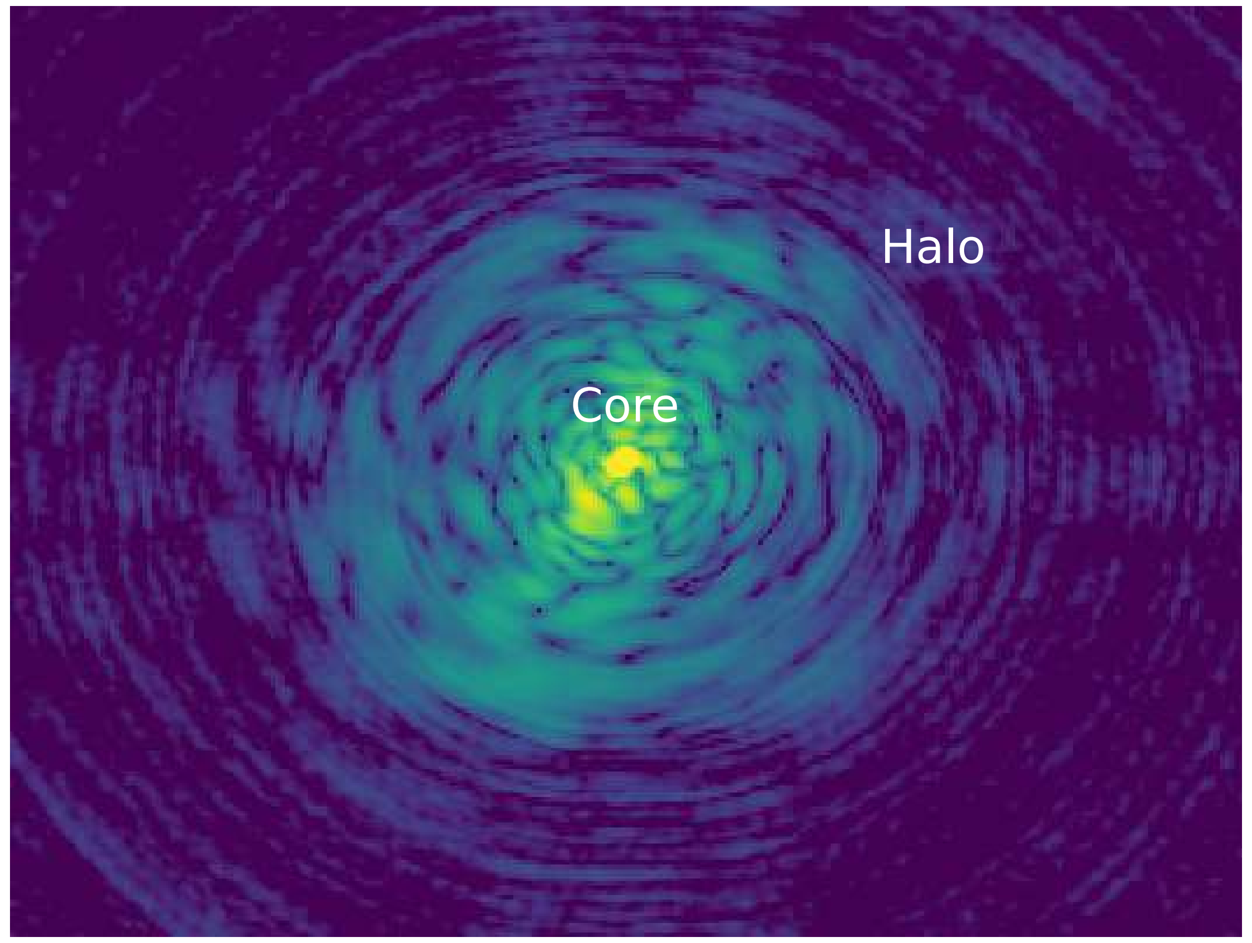
* Focus only in gravitational signatures

Suppression of small structures

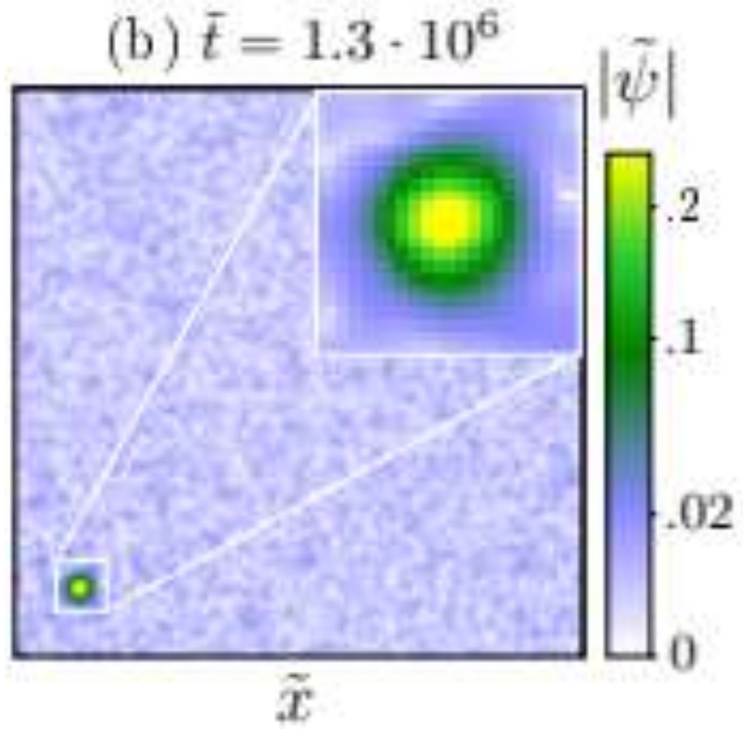


S. May et al. 2021

Formation of a solitonic core

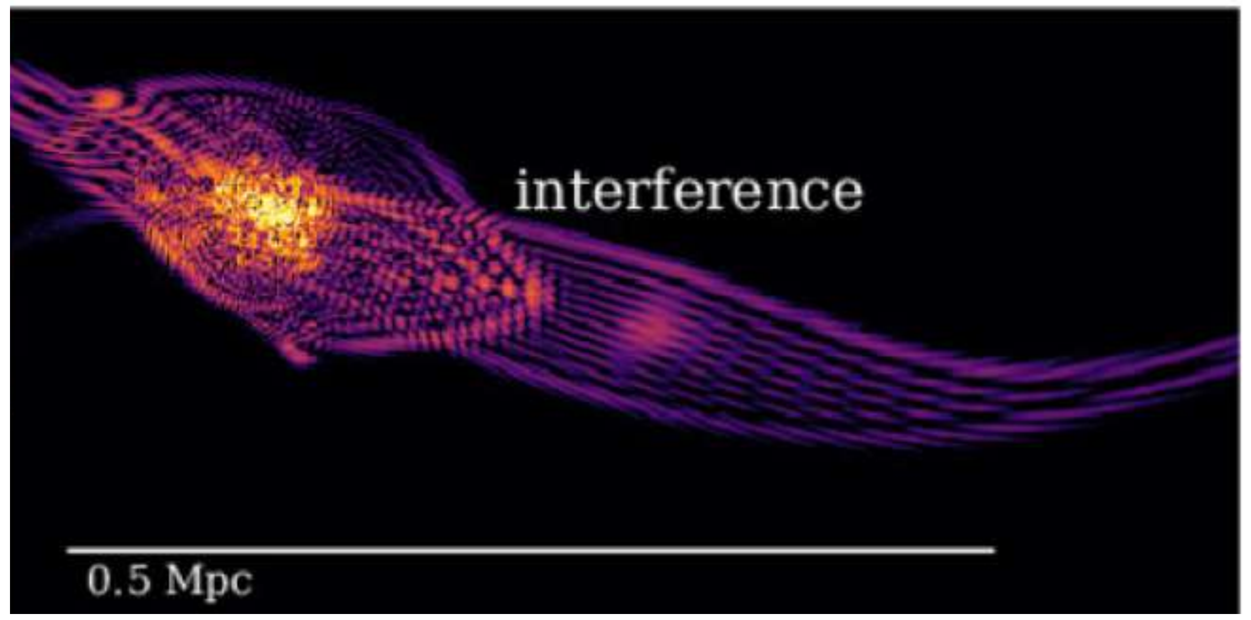


Dynamical effects



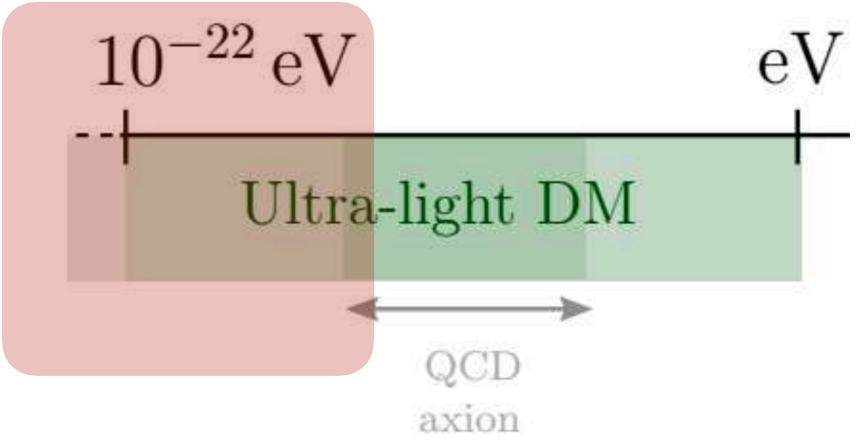
Levkov et al. 2018

Wave interference



Mocz et al. 2017

Phenomenology



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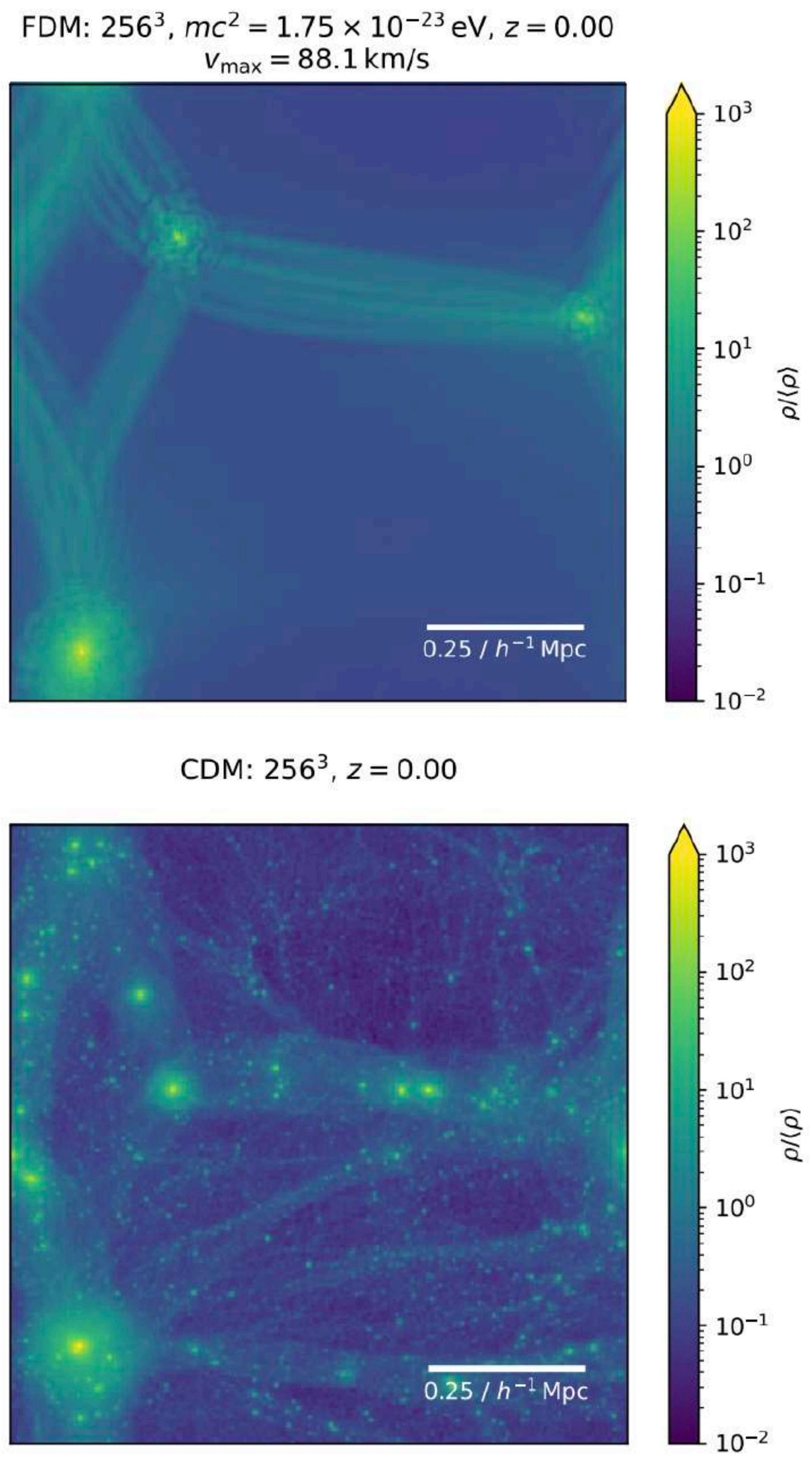

S. May et al. 2021

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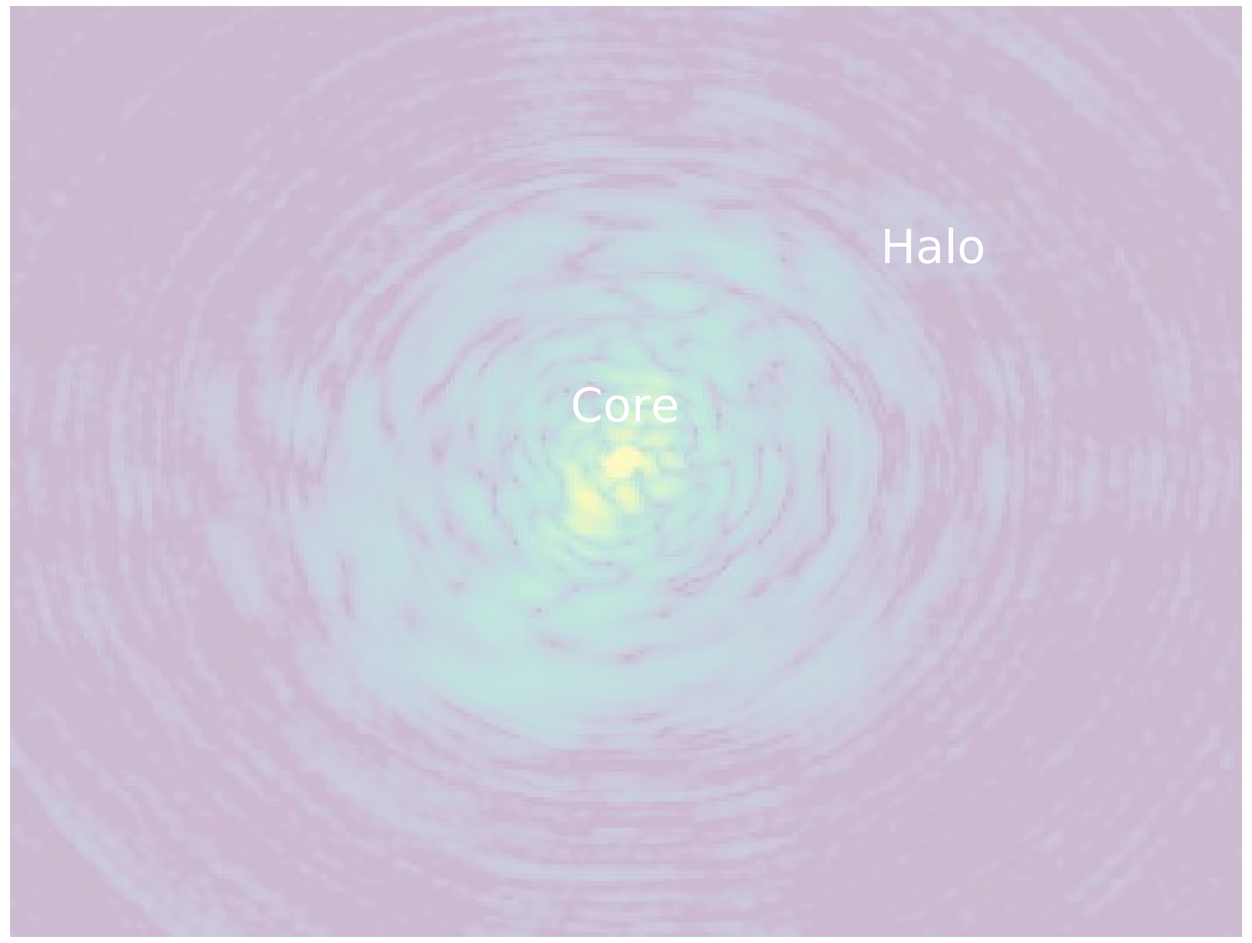
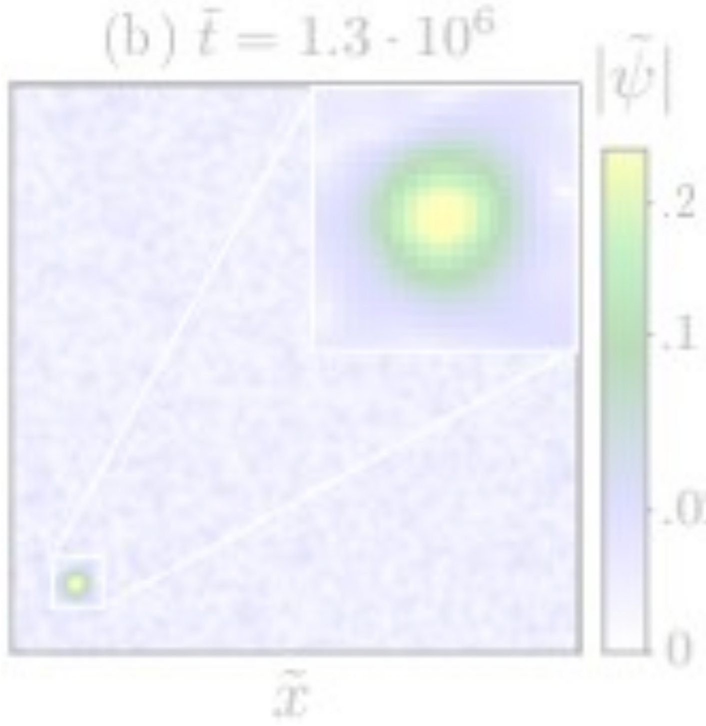


Dynamical effects



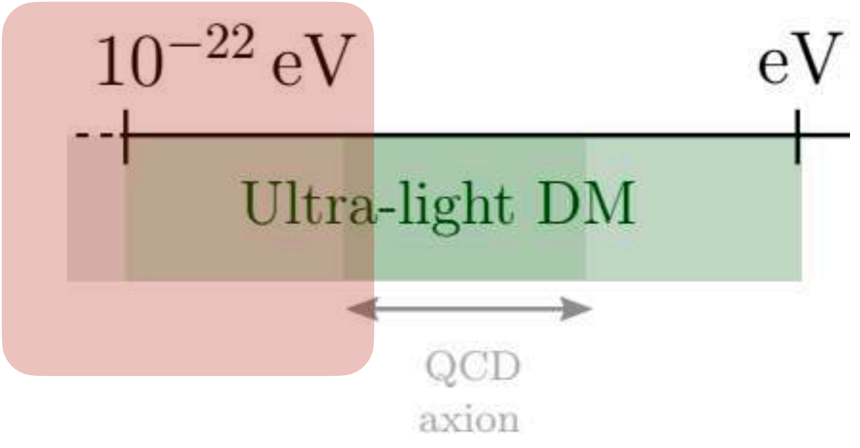
Levkov et al. 2018

Wave interference

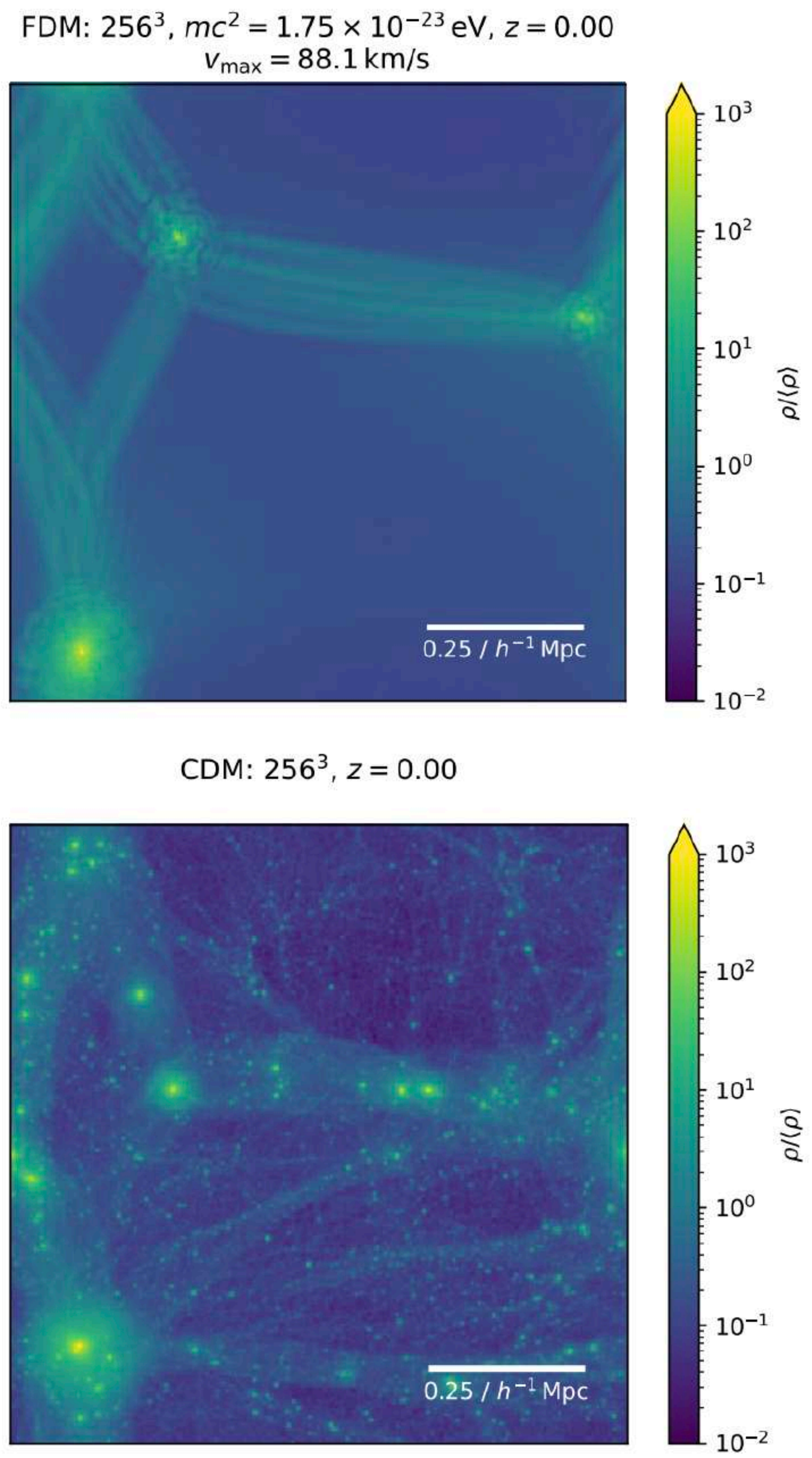
Mocz et al. 2017

Phenomenology

Suppression of small structures



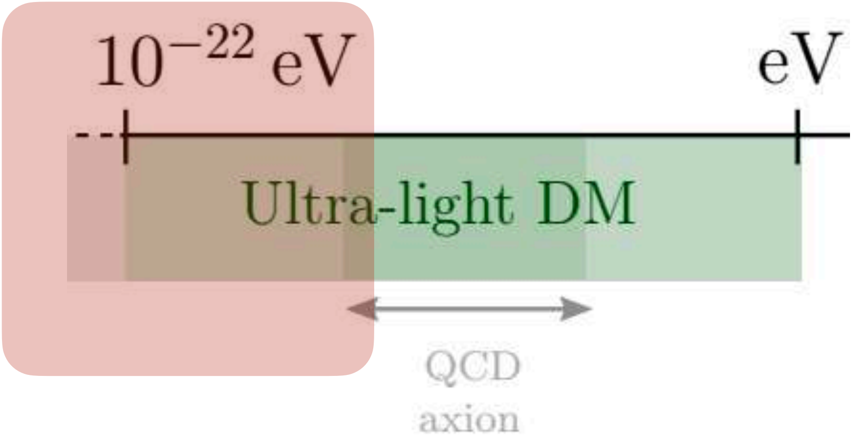
Finite Jeans length λ_J or $\lambda_{attr}, \lambda_{rep}$ → No small scale structure



S. May et al. 2021

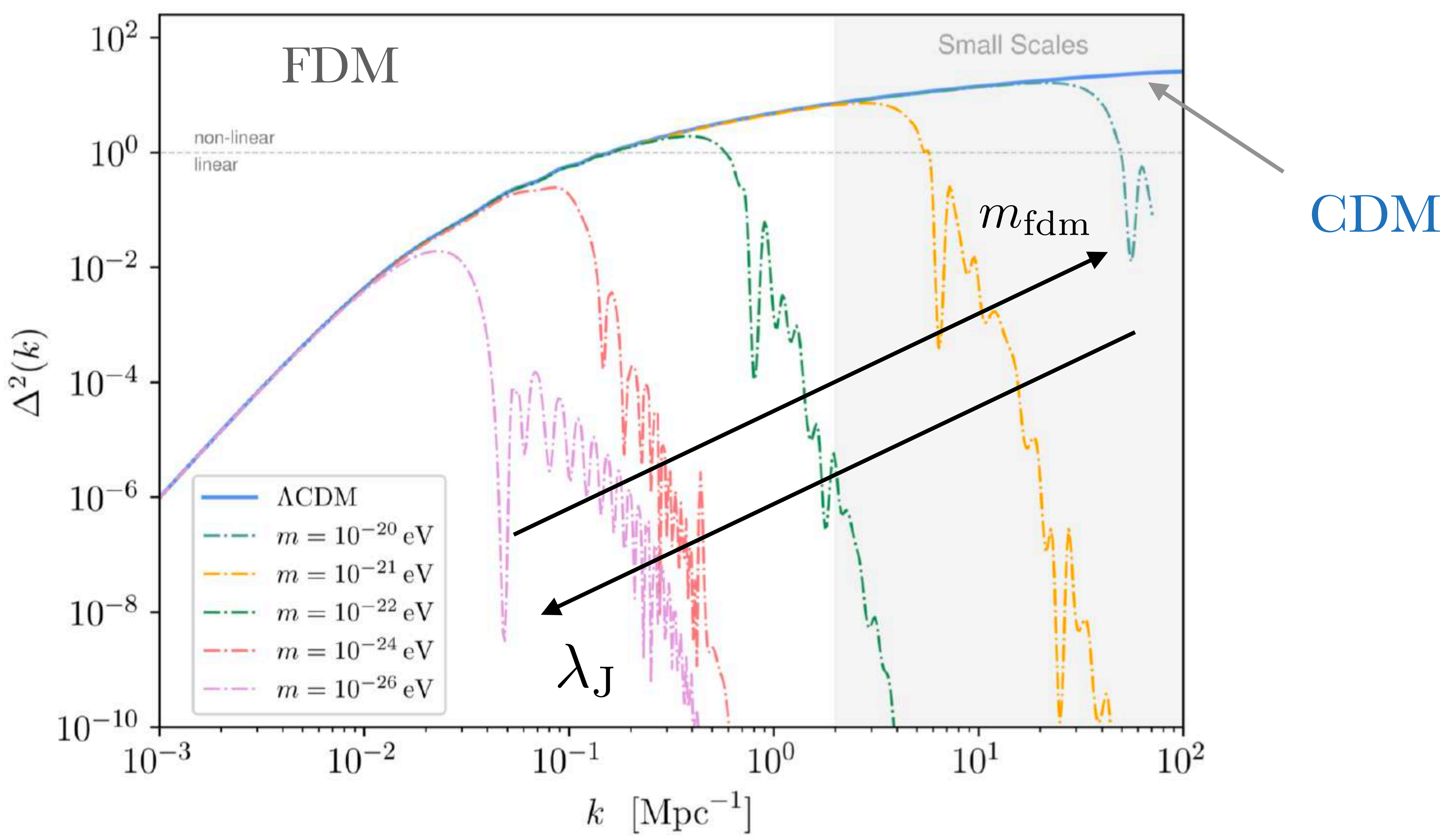
Phenomenology

Suppression of small structures

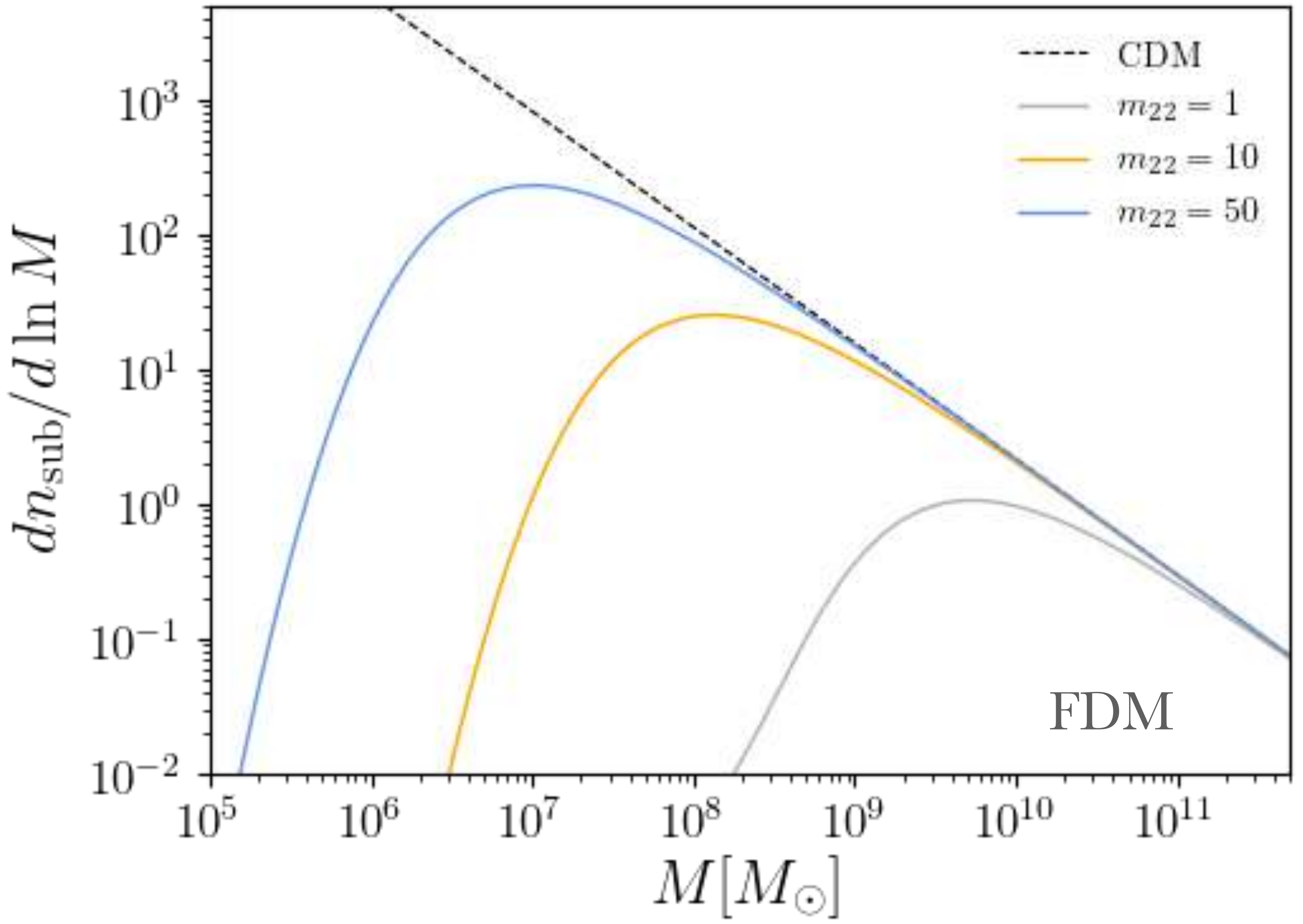


Finite Jeans length λ_J or λ_{attr}, λ_{rep} → Suppresses small scale structure

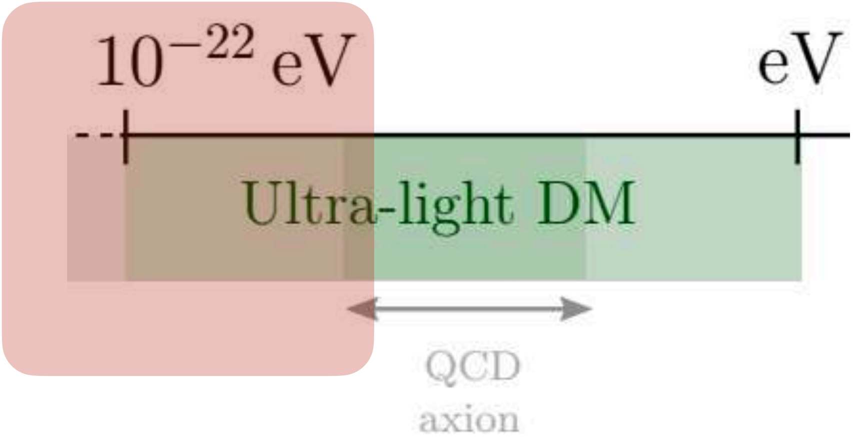
POWER SPECTRUM



(sub) HALO MASS FUNCTION

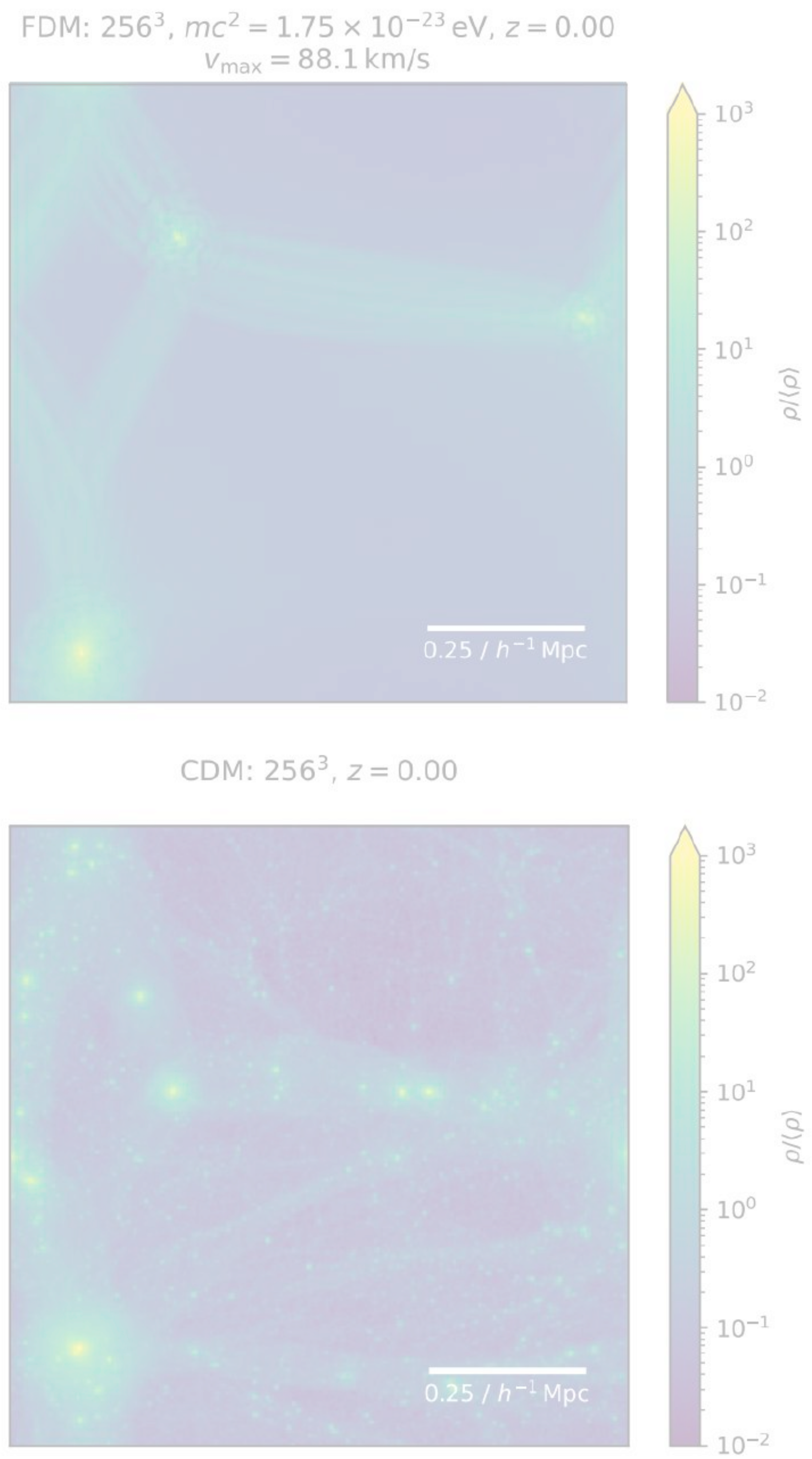


Phenomenology



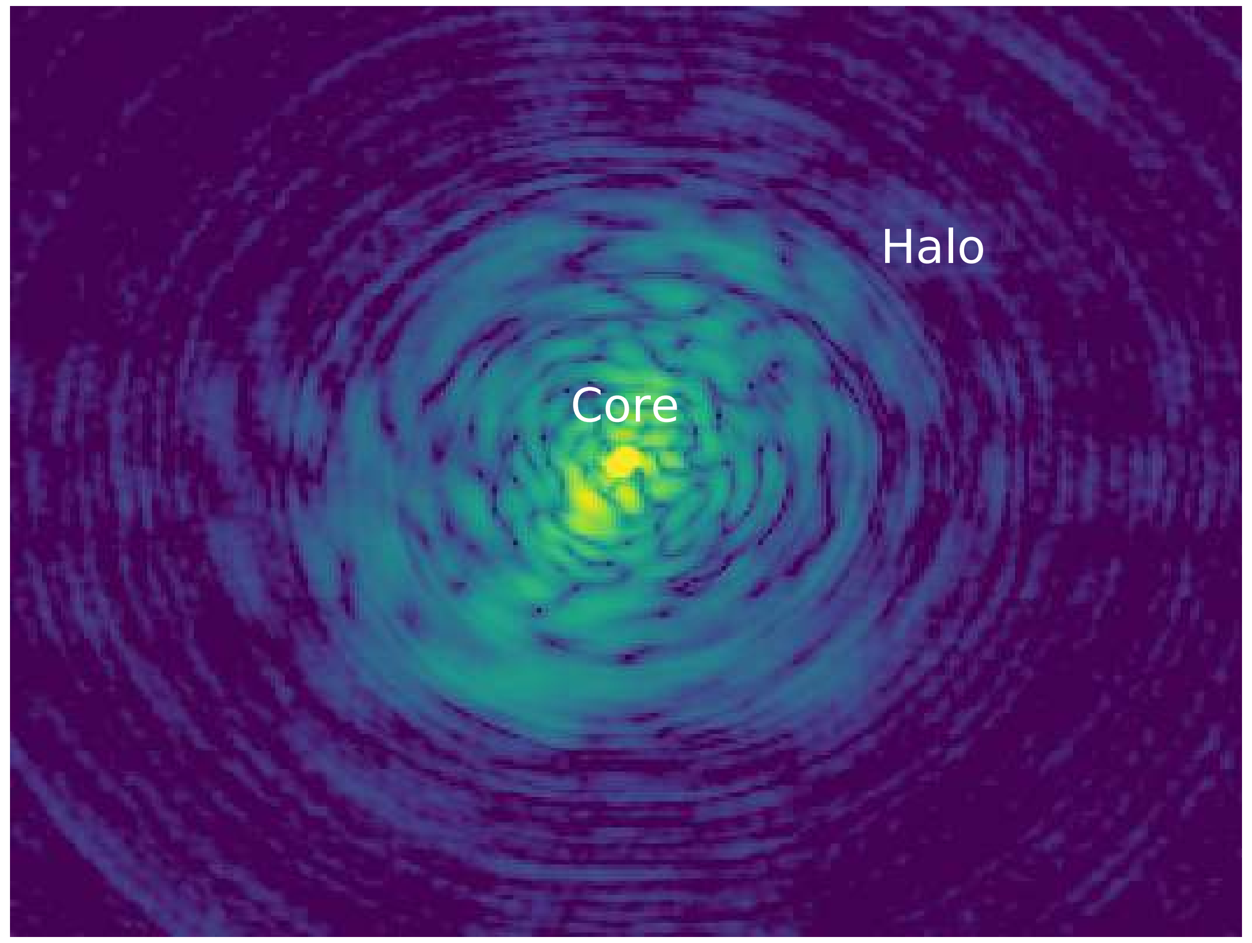
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

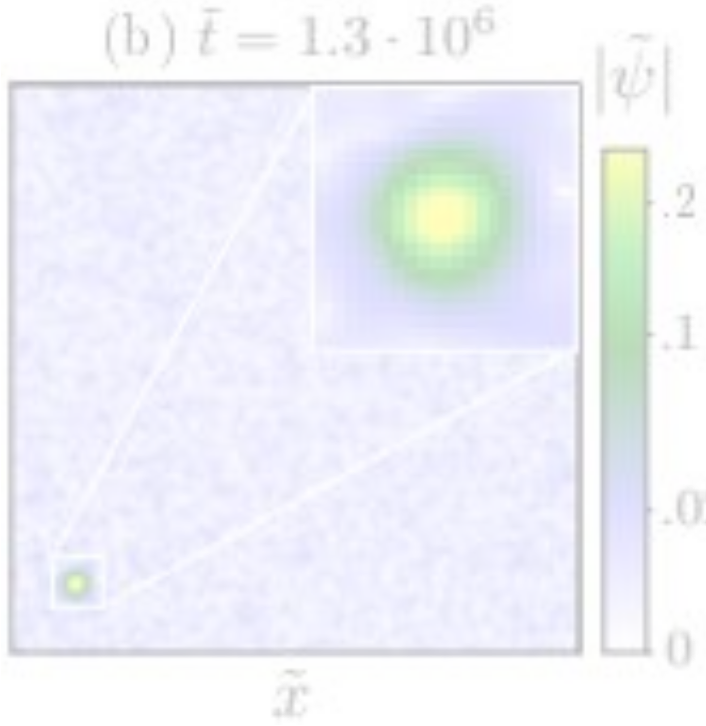


S. May et al. 2021

Formation of a solitonic core



Dynamical effects



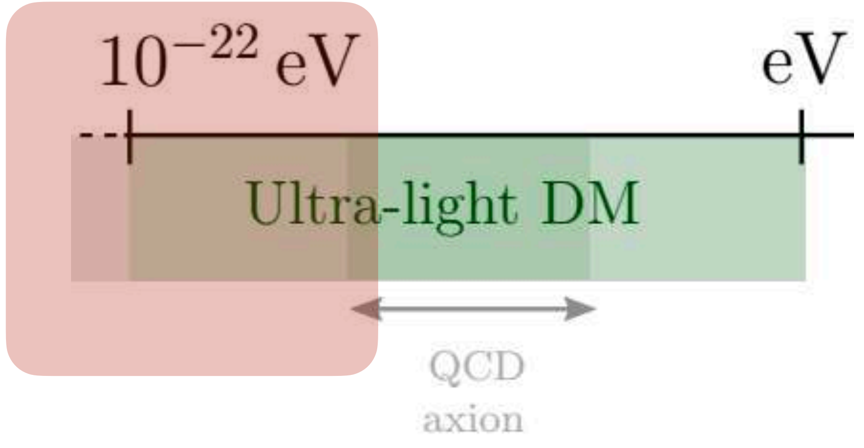
Levkov et al. 2018

Wave interference

Mocz et al. 2017

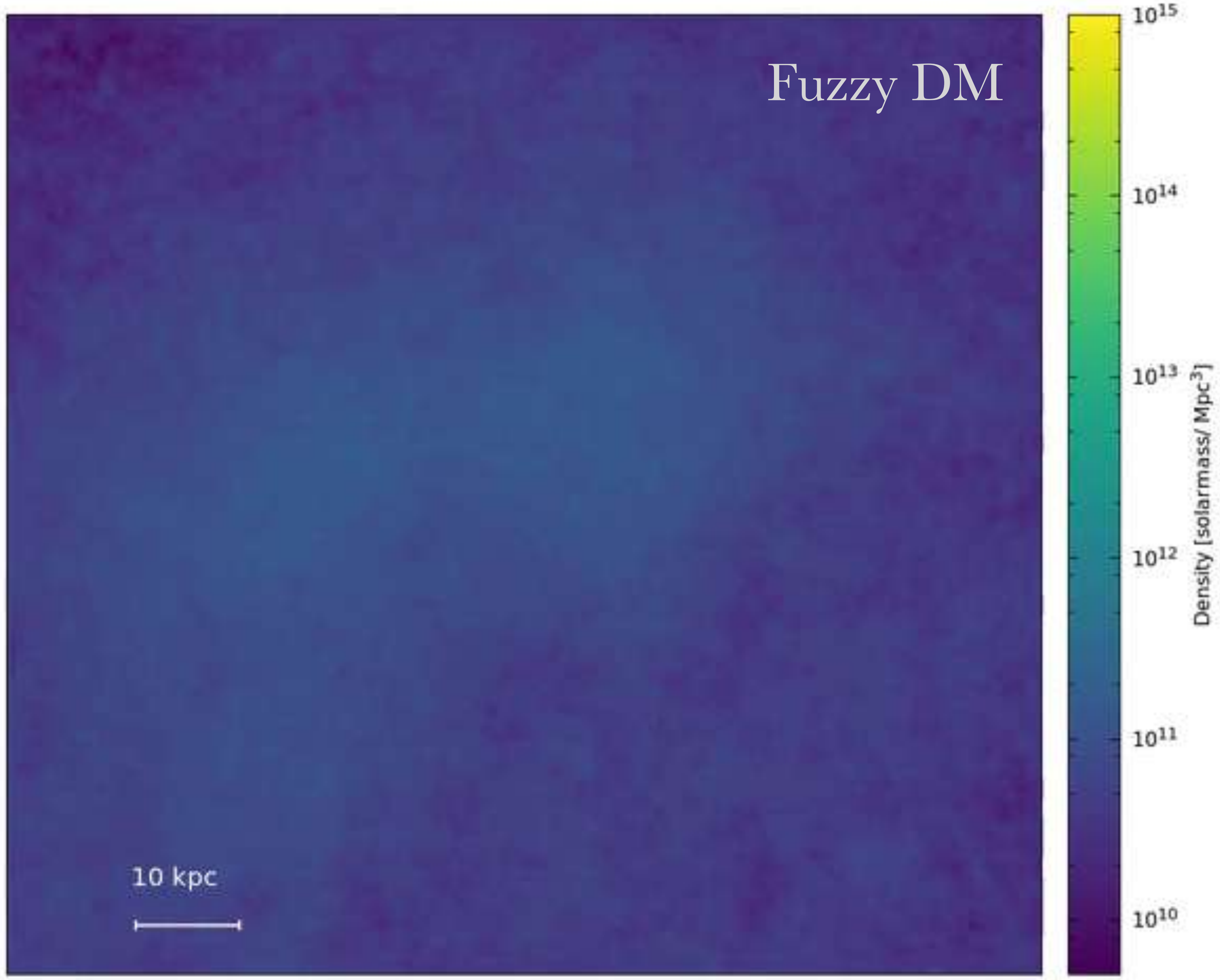
Phenomenology

Formation of cores

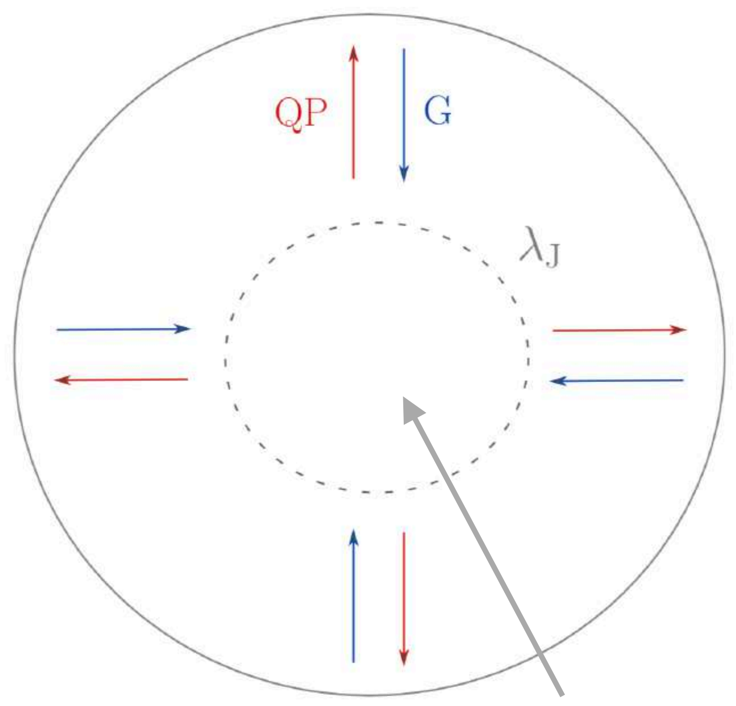


$m = 10^{-22}\,\mathrm{eV}$ $N = 512^3$ $L = 300\,\mathrm{kpc}$

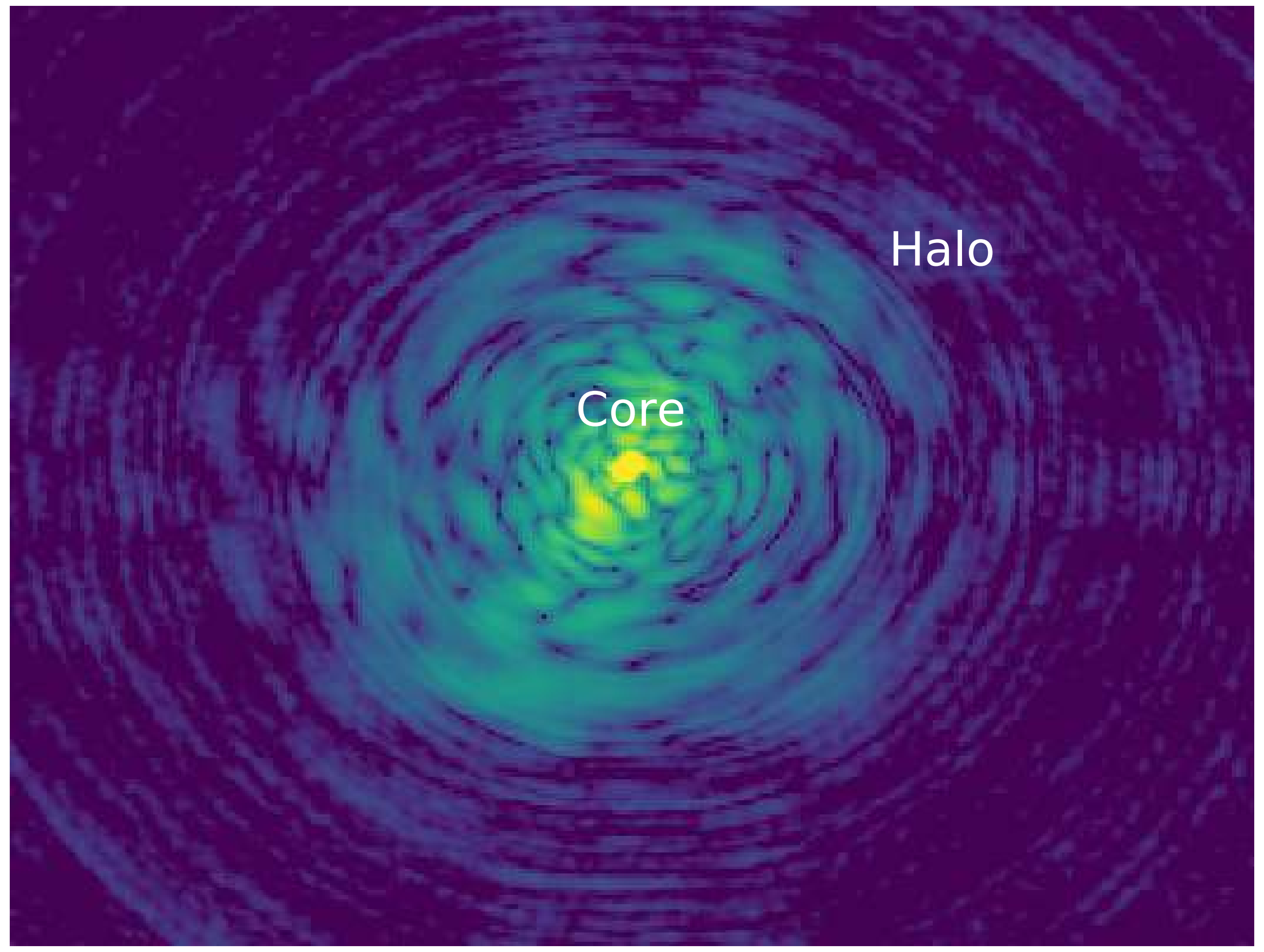
NON-LINEAR
evolution: need
simulations



Simulation by Jowett Chan

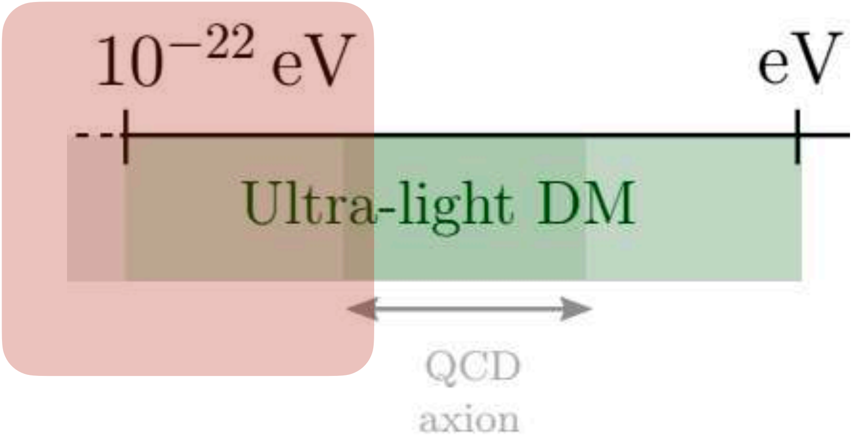


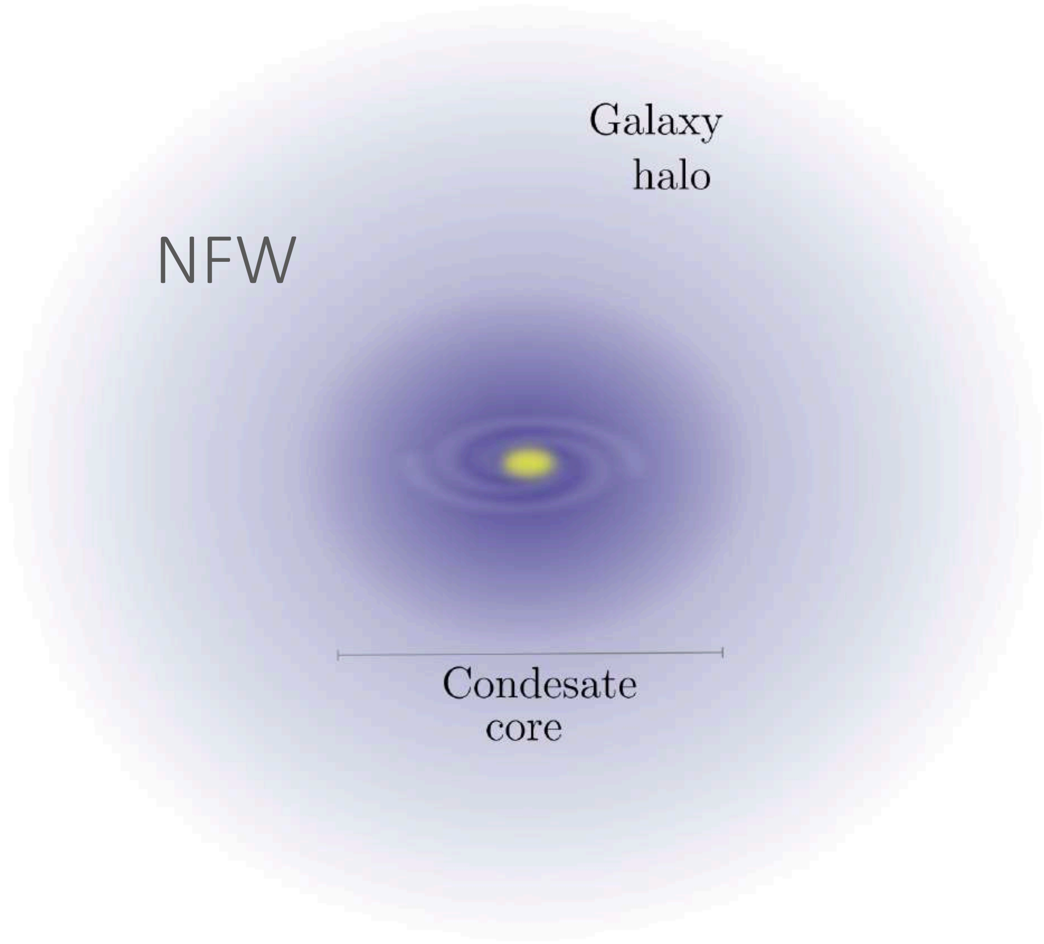
NO structure formation
Stable, oscillating solution



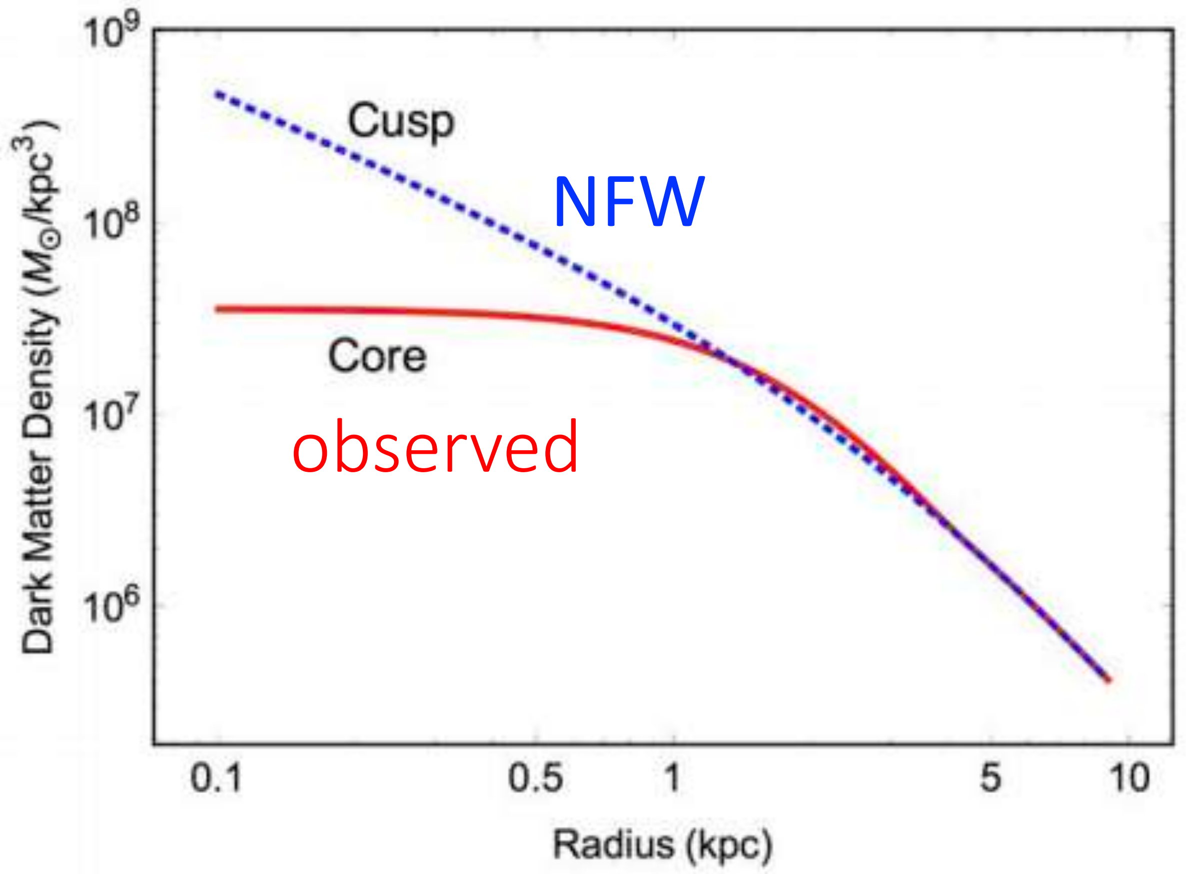
Phenomenology

Formation of cores





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



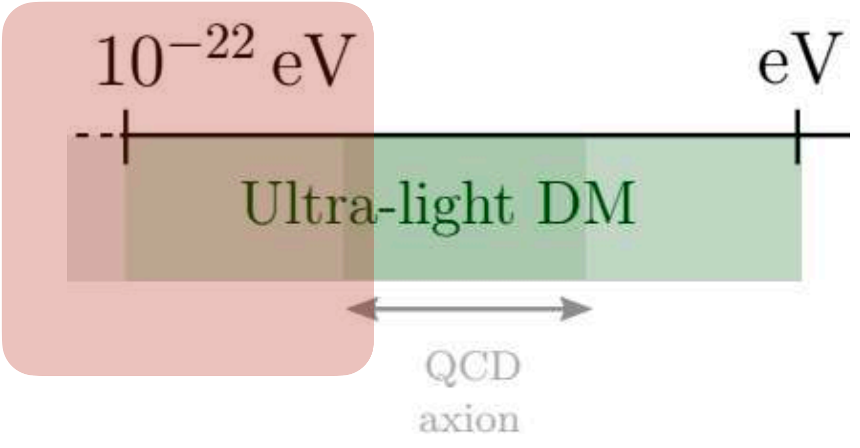
FDM From simulations Schive et al. 2014, fitting function: Stable core solution

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

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

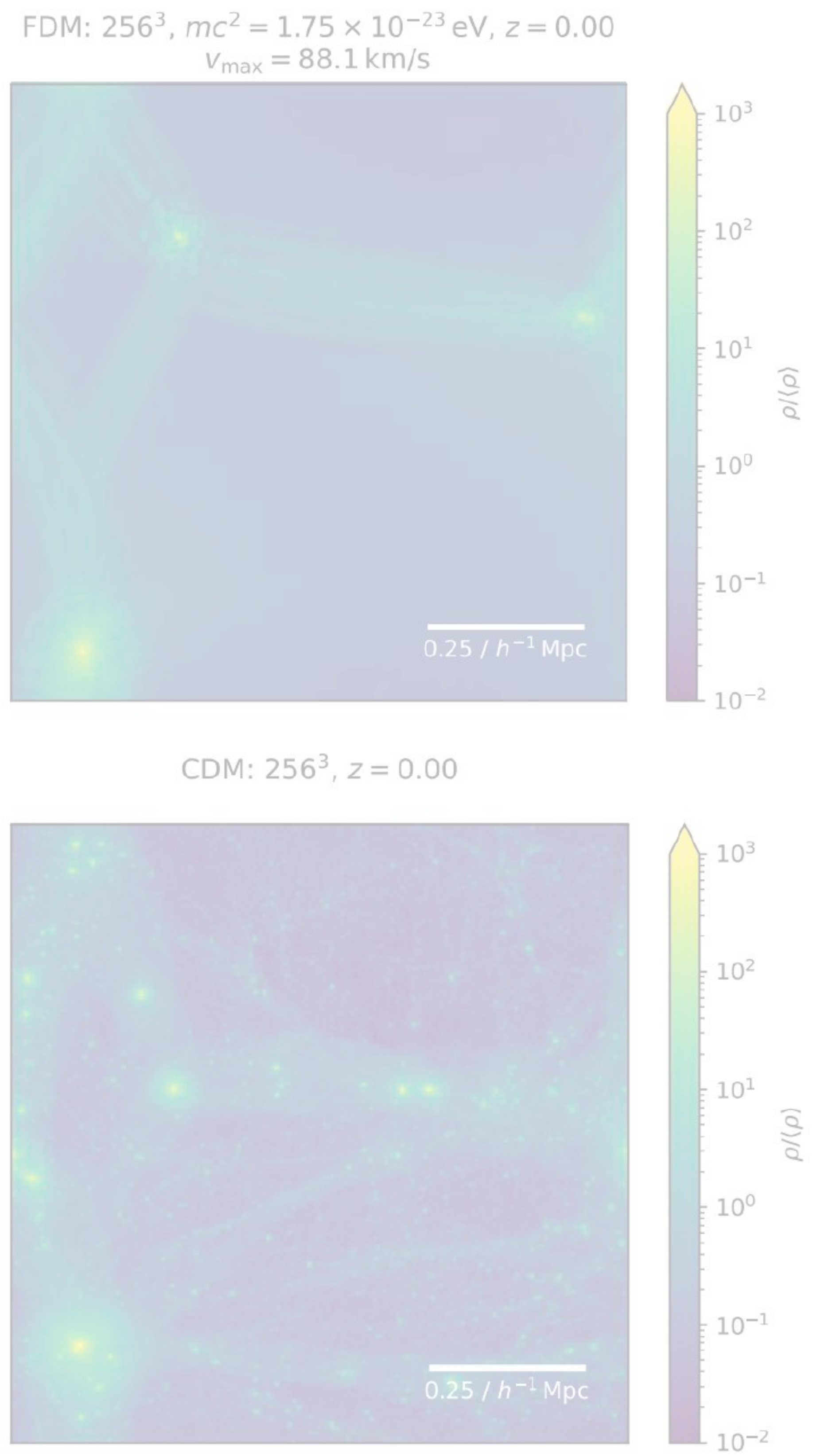
→ Relations used to compare with observations

Phenomenology



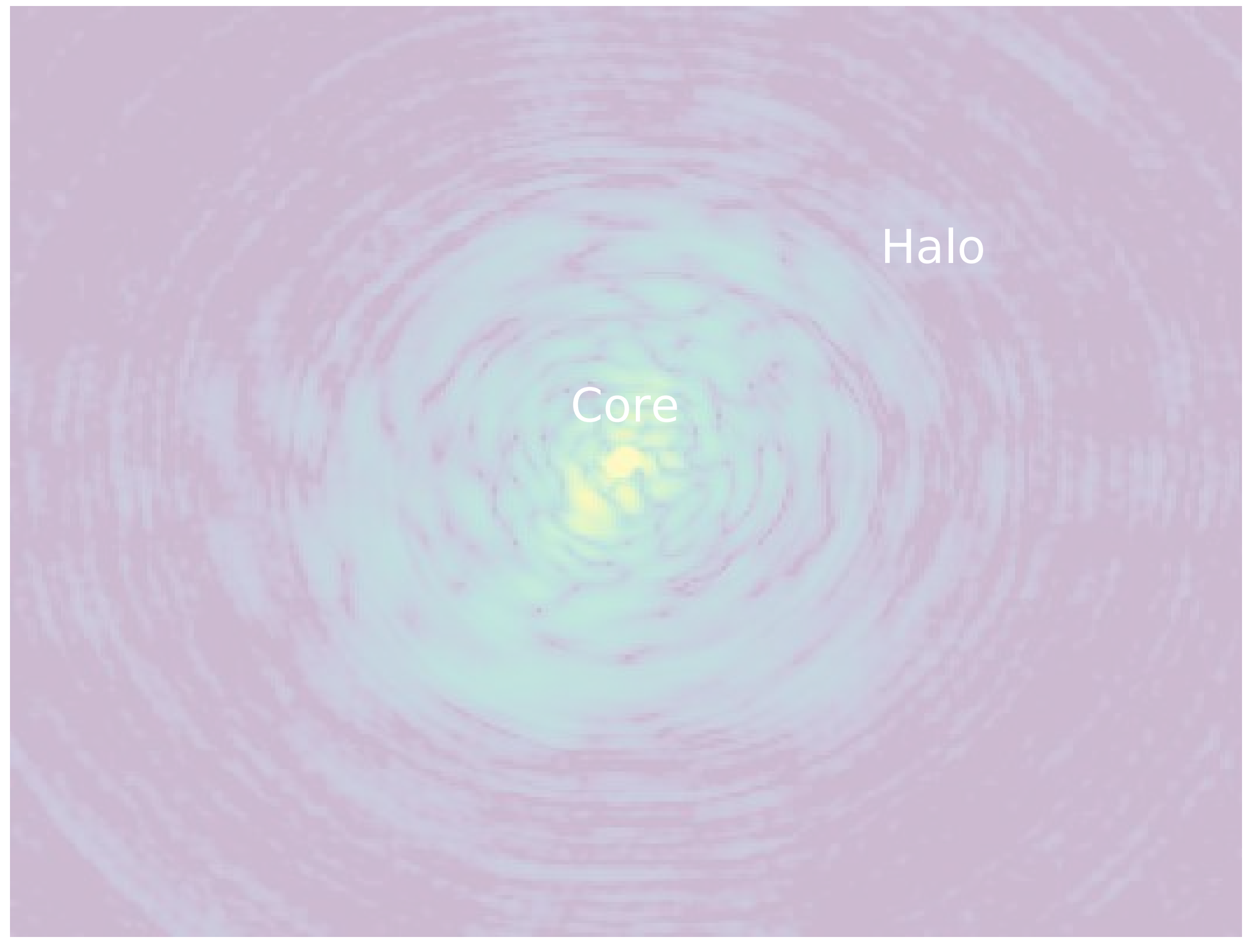
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

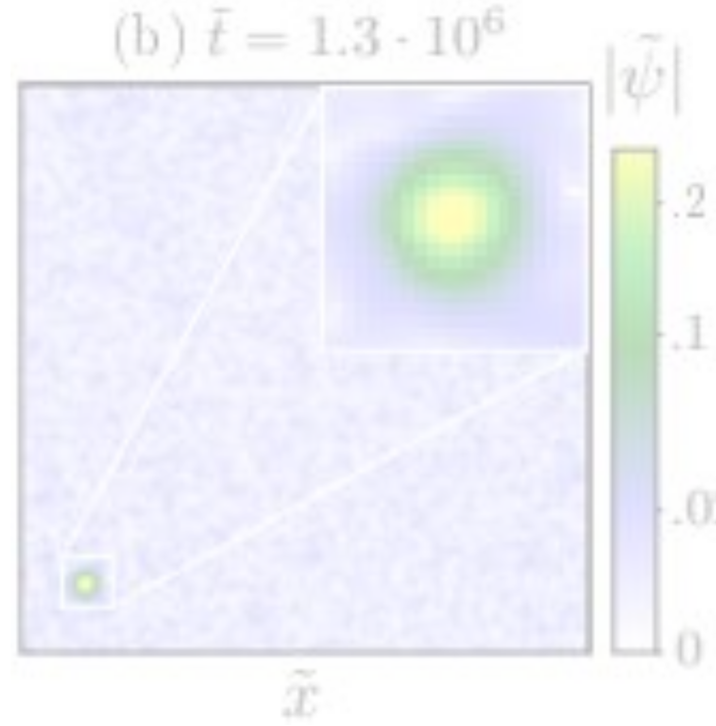


S. May et al. 2021

Formation of a solitonic core

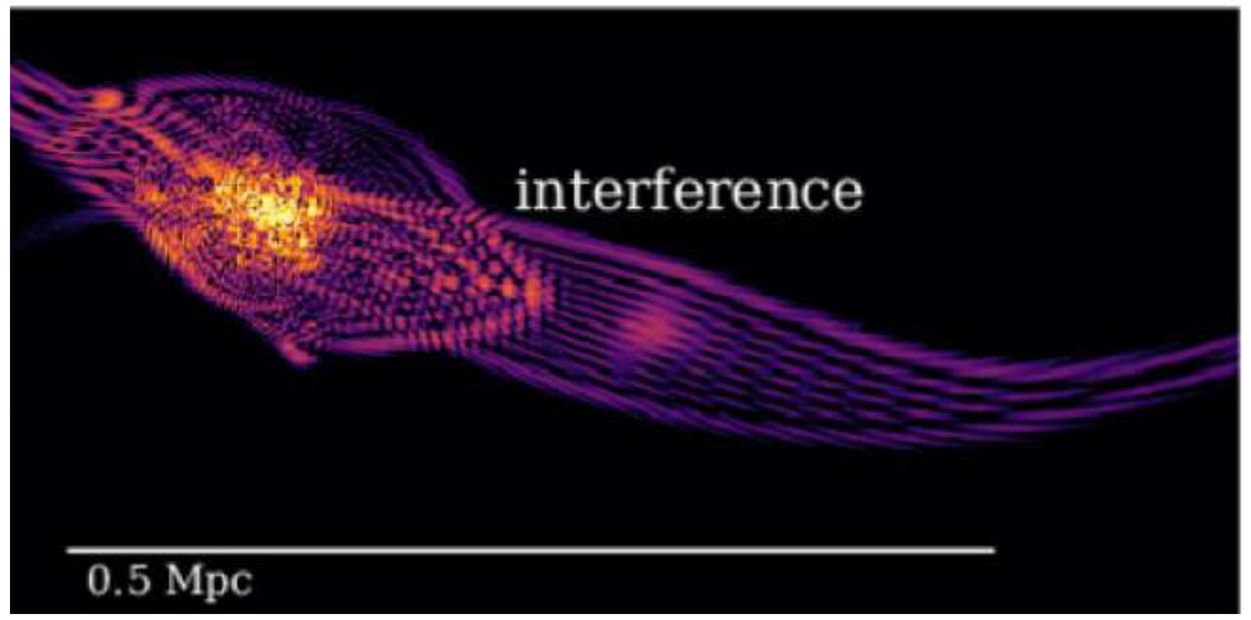


Dynamical effects



Levkov et al. 2018

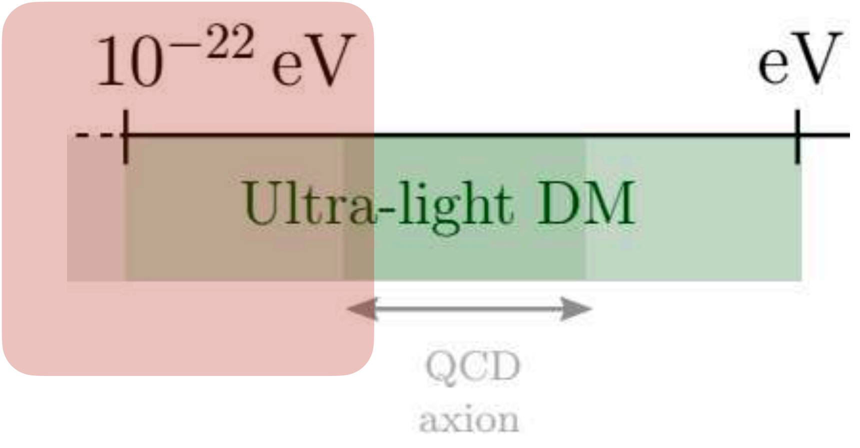
Wave interference

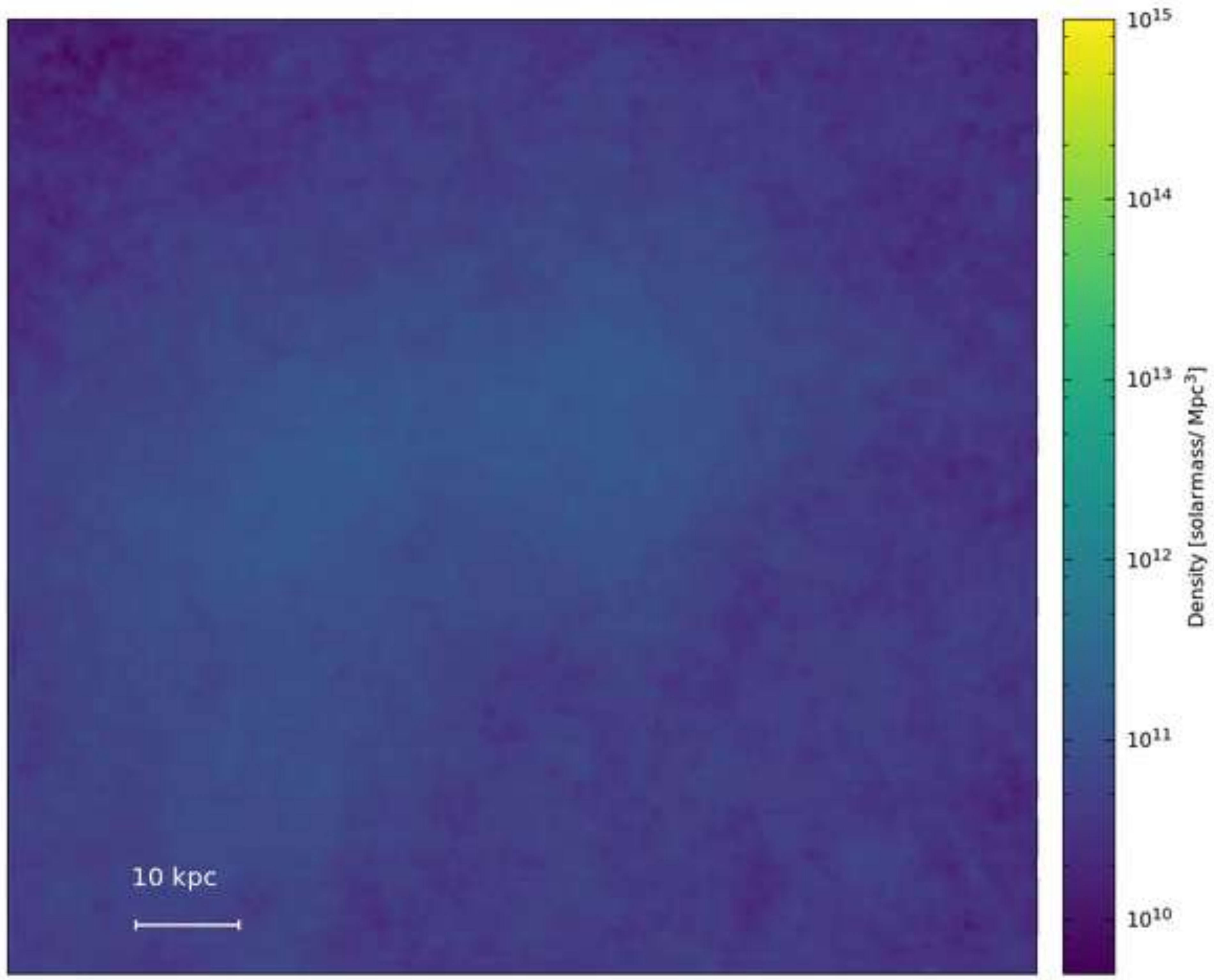


Mocz et al. 2017

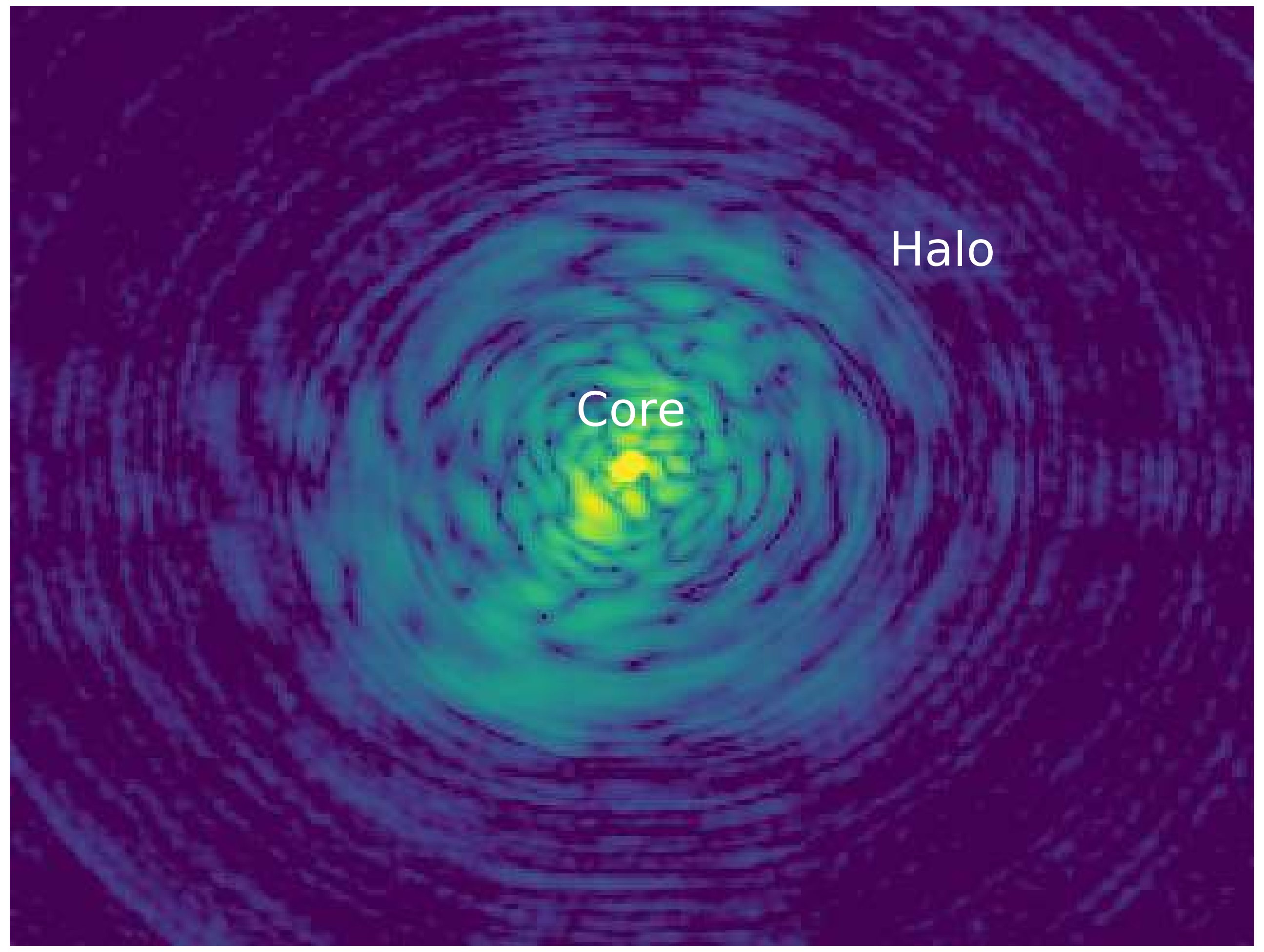
Phenomenology

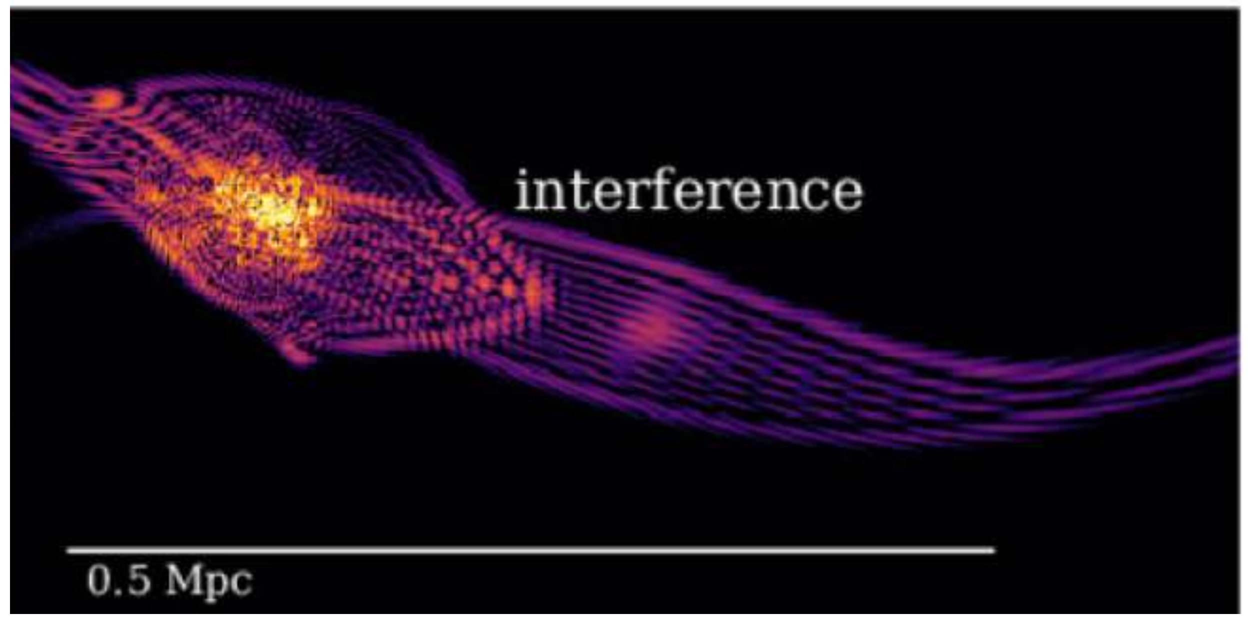
Wave interference: granules and vortices





Simulation by Jowett Chan





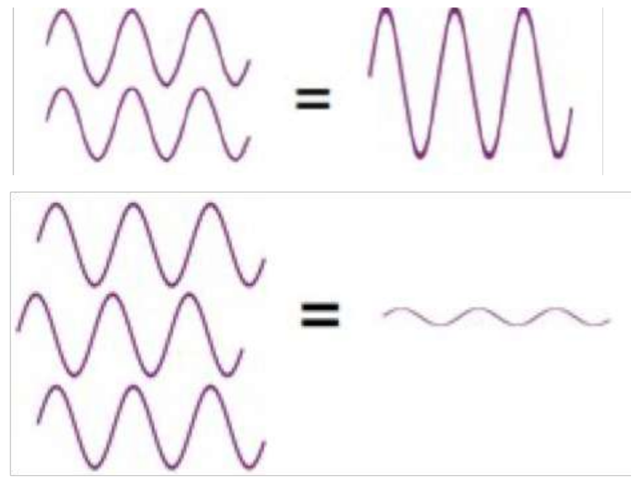
Mocz et al. 2017

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

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

Vector, higher spin or multicomponent FDM

Interference patterns

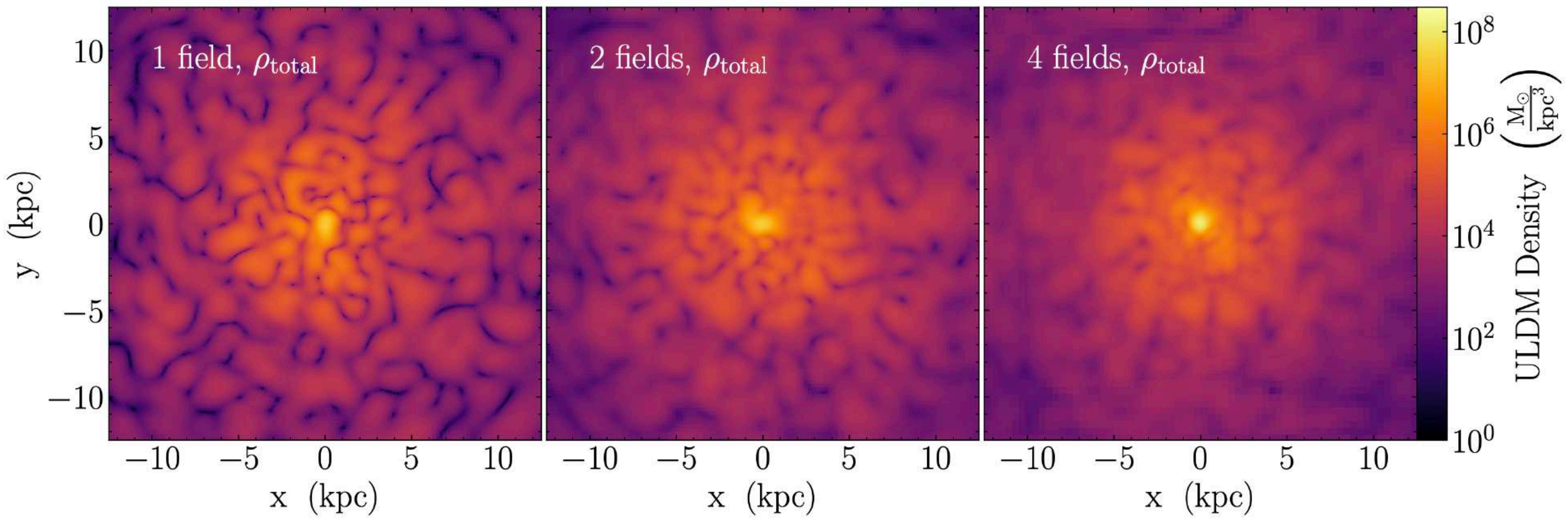


ULDM or ULA are a coherent wave - same frequency and constant phase difference

Multiple coherent waves

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)

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

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

Multicomponent FDM   Gonseca et al 2023

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)

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

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

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

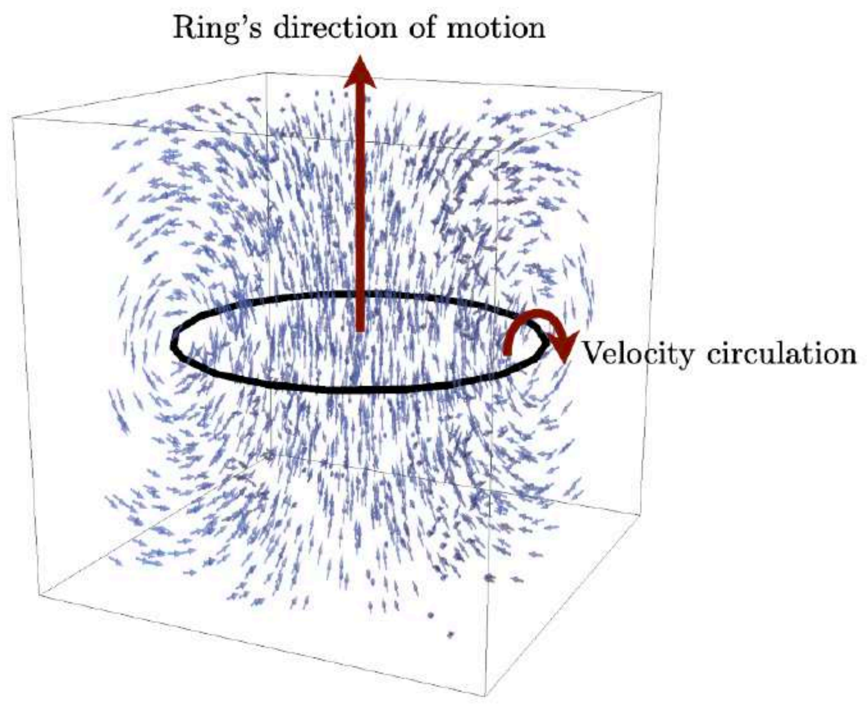
Vel. field is a gradient flow ⟶ irrotational fluid, no vorticity

Fuzzy DM

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

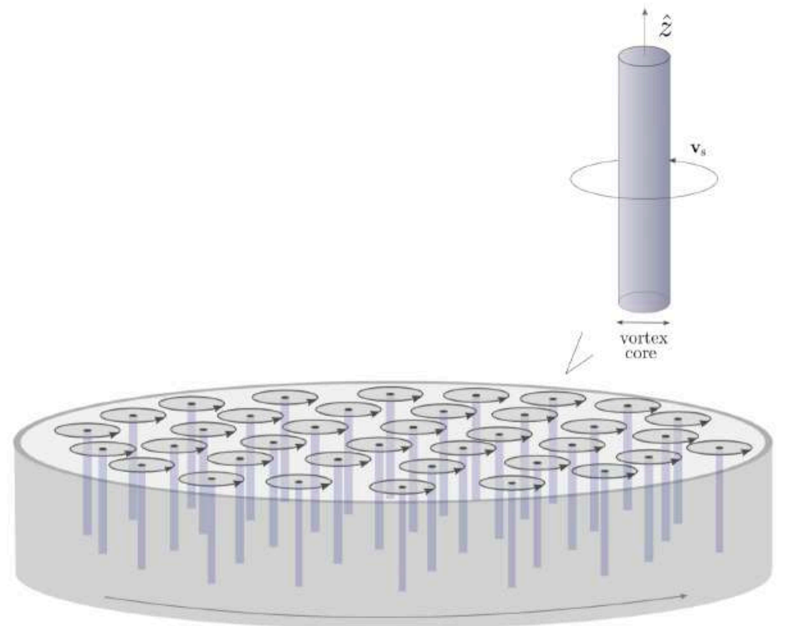
General defet in 3D

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



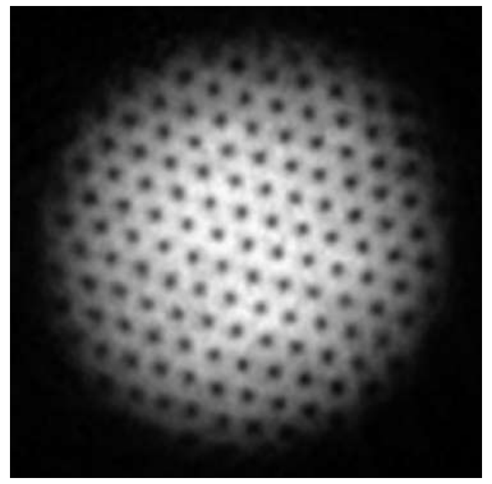
Self-interacting Fuzzy DM

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

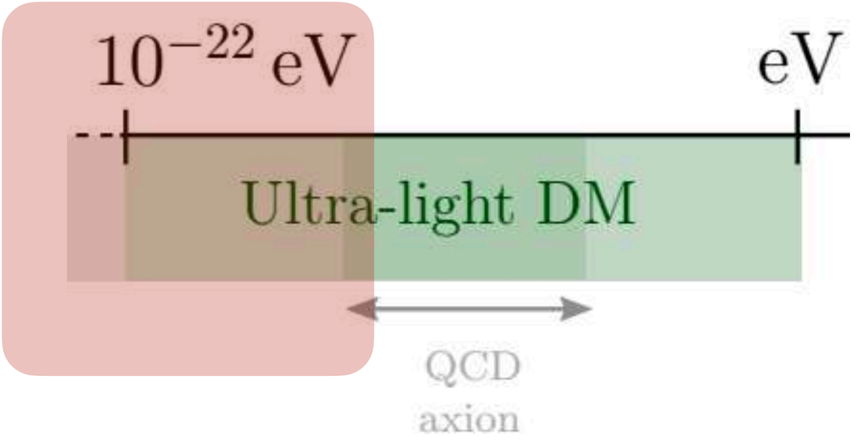


EF, 2020

© Martin Zwierlein.

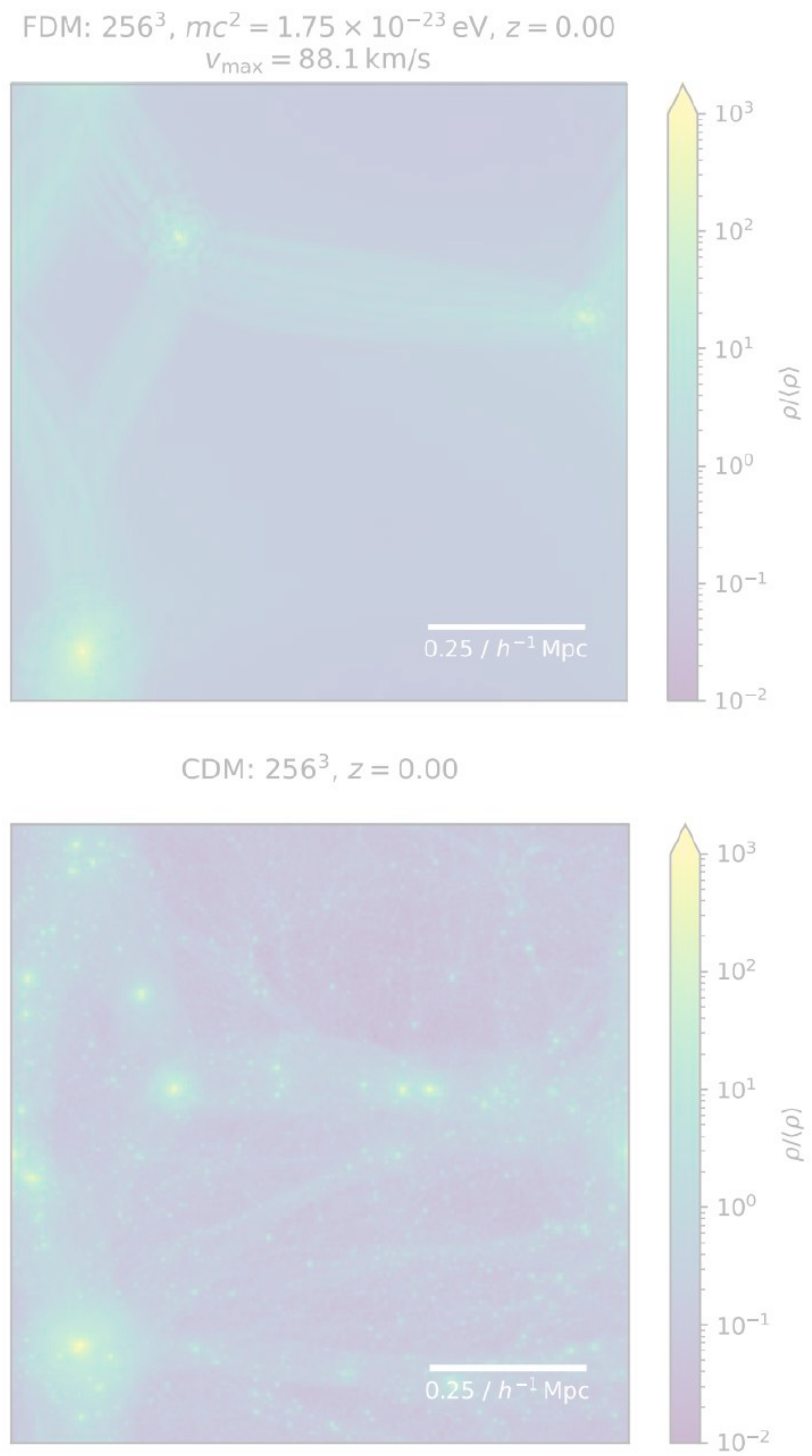


Phenomenology



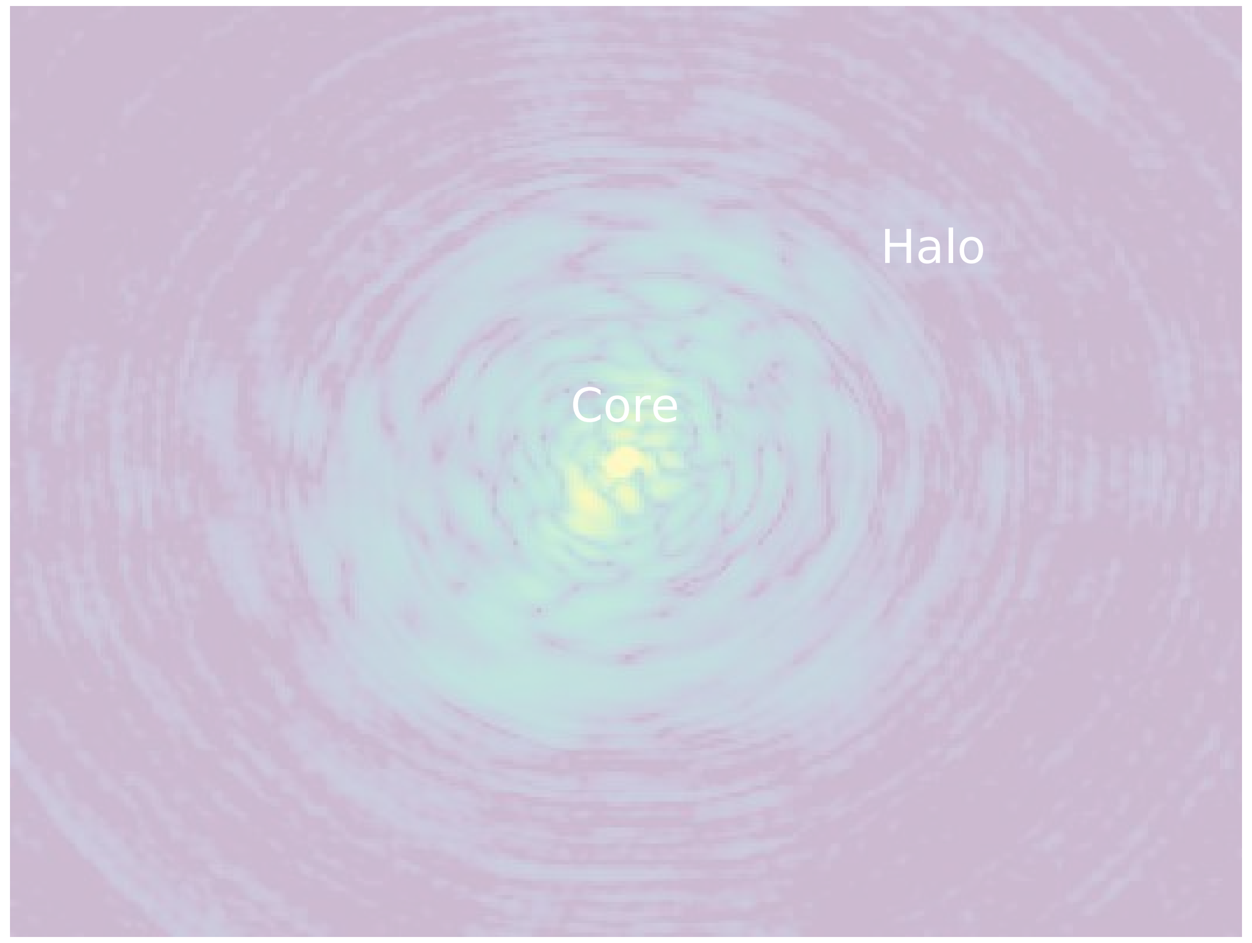
RICH PHENOMENOLOGY ON SMALL SCALES

Suppression of small structures

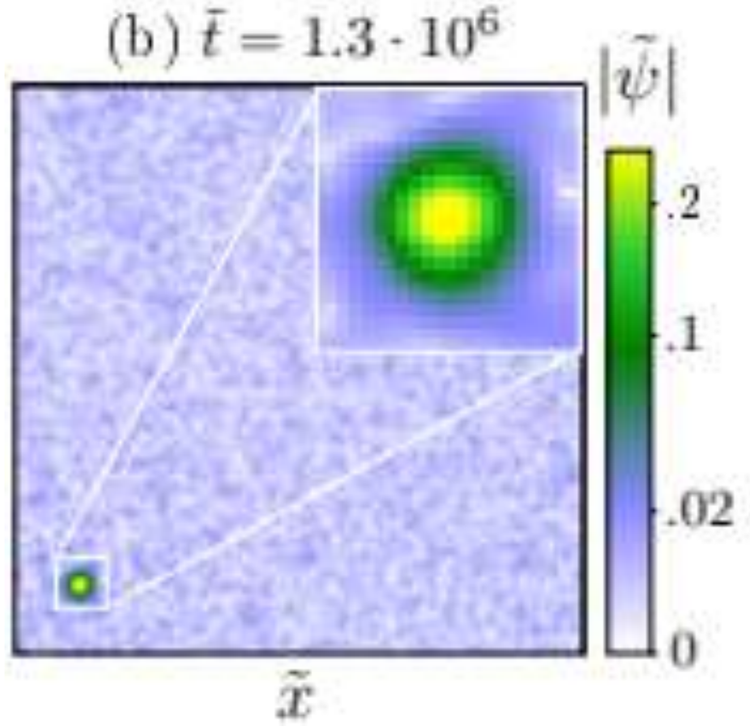


S. May et al. 2021

Formation of a solitonic core



Dynamical effects



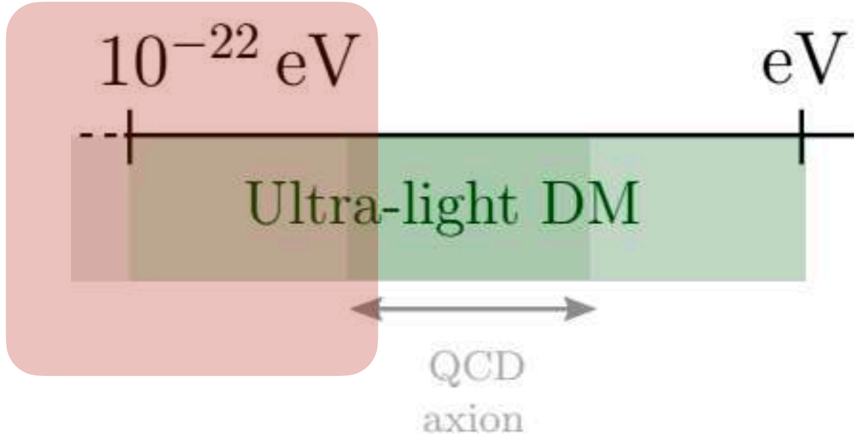
Levkov et al. 2018

Wave interference

Mocz et al. 2017

Phenomenology

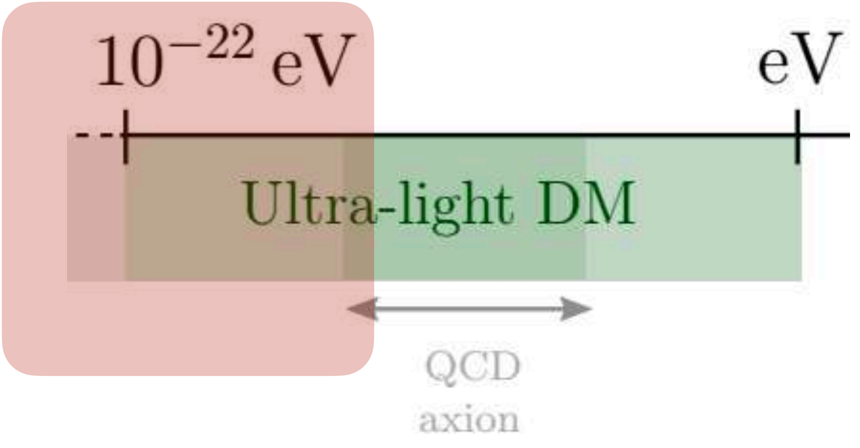
Dynamical effects



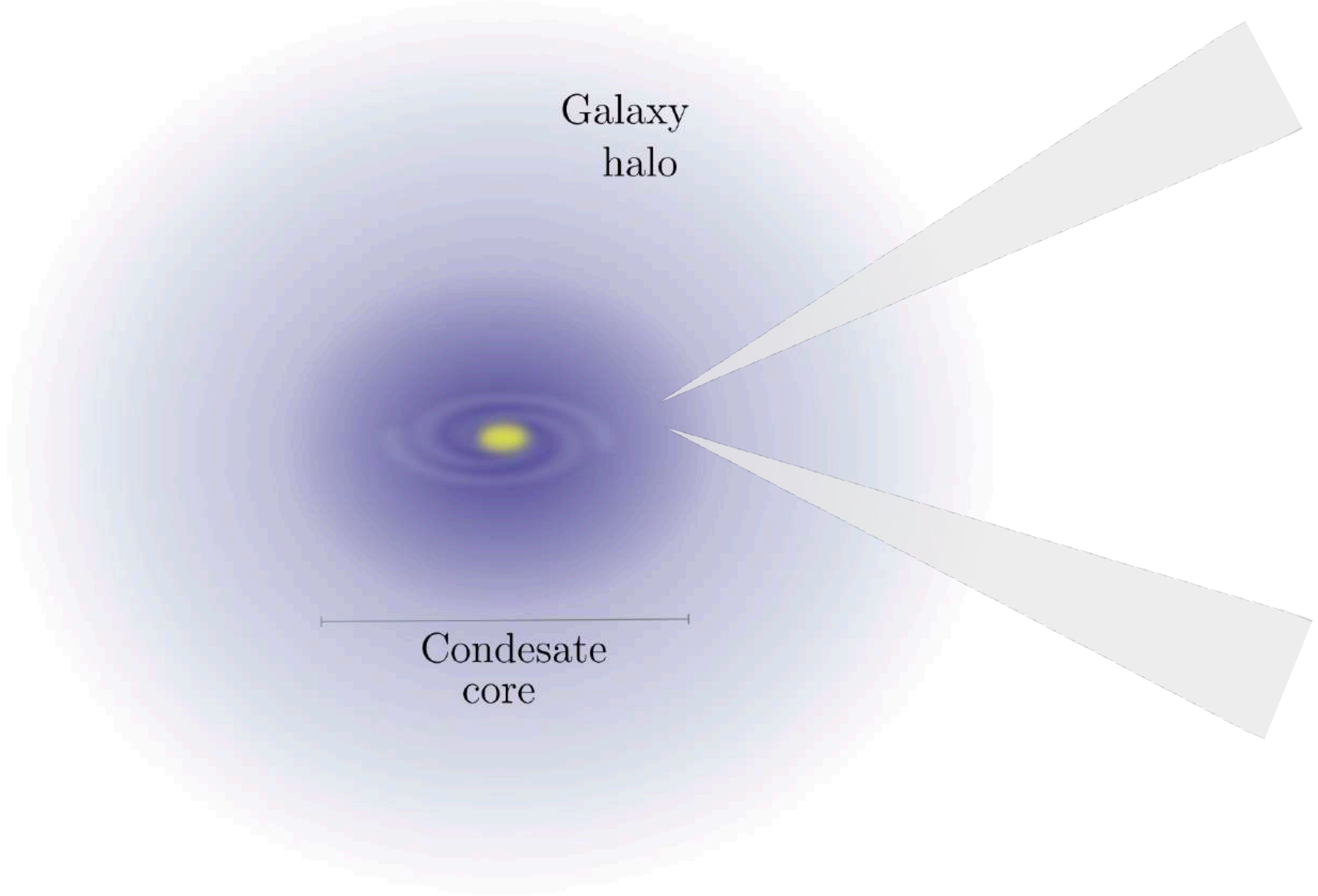
Relaxation, oscillation, friction, and heating

Phenomenology

Dynamical effects



Relaxation, oscillation, friction, and heating

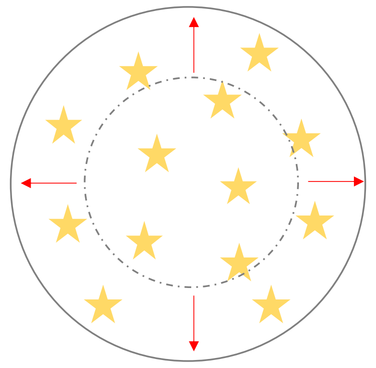


Heating

FDM granule

m_{eff}

System (star)
gains energy



Friction

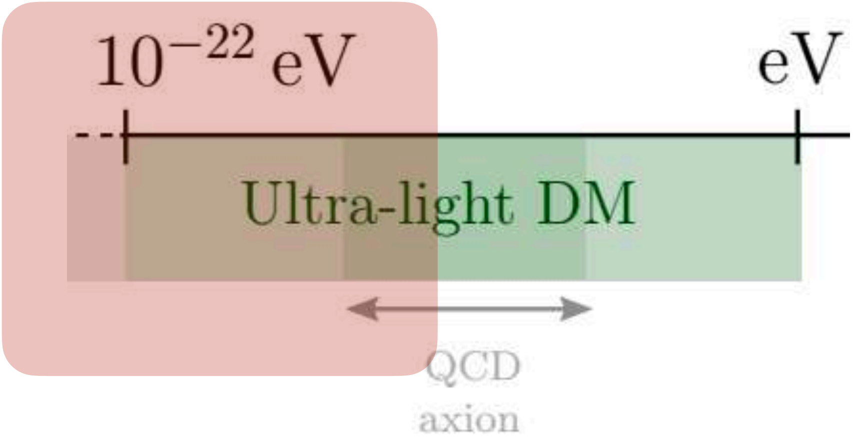
FDM granule

m_{eff}

Globular cluster

System (GC or BH)
loses energy

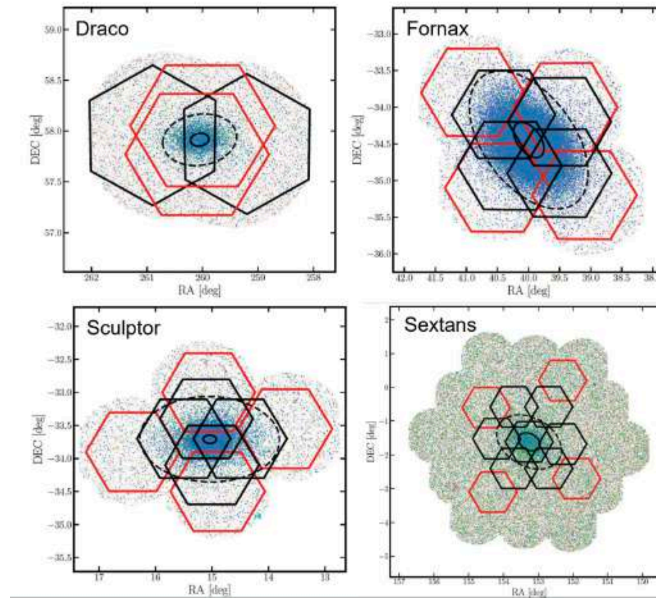
Observational implications and constraints



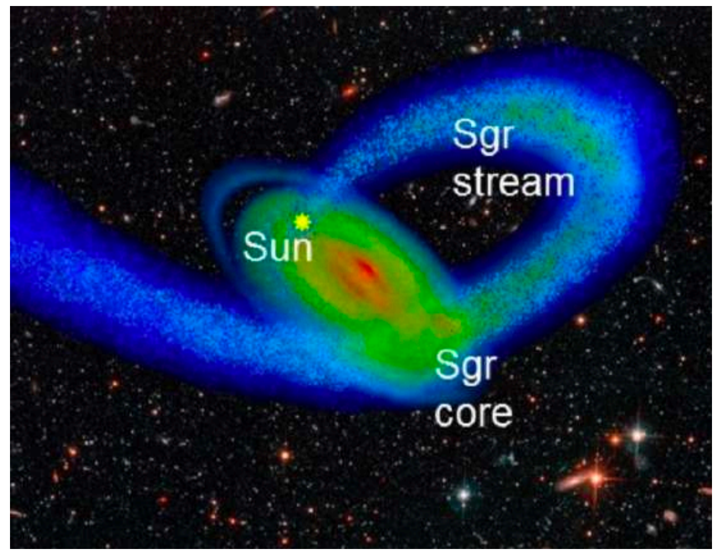
Galaxies

NASA and ESA

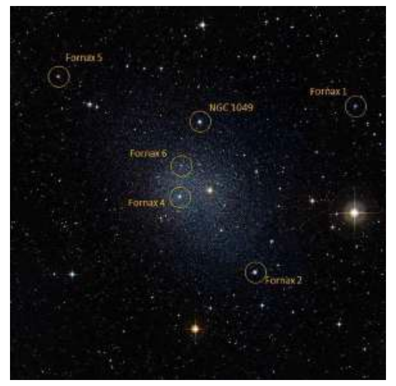
Dwarfs



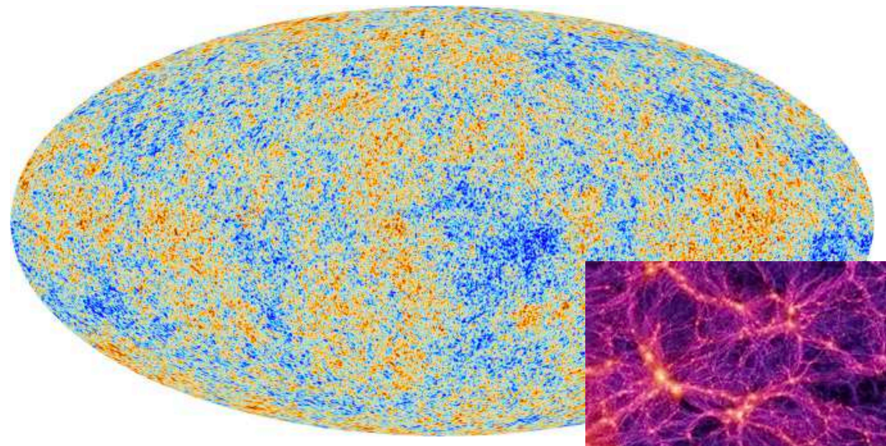
Stellar stream



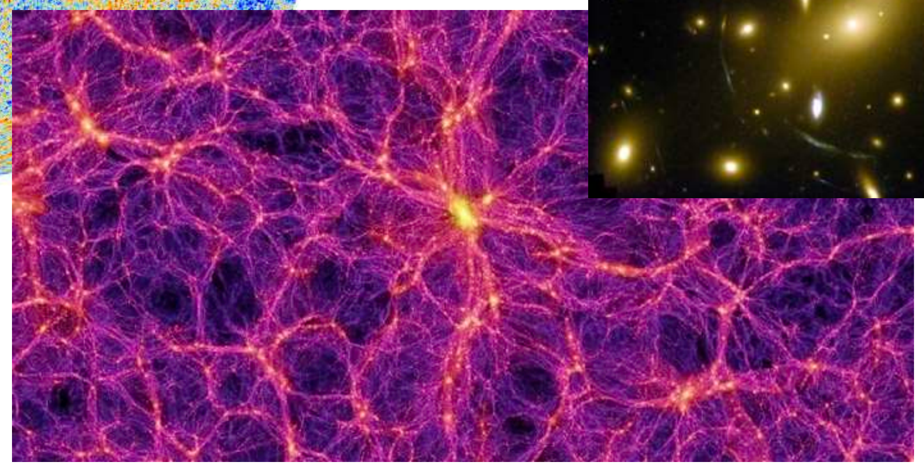
Globular clusters



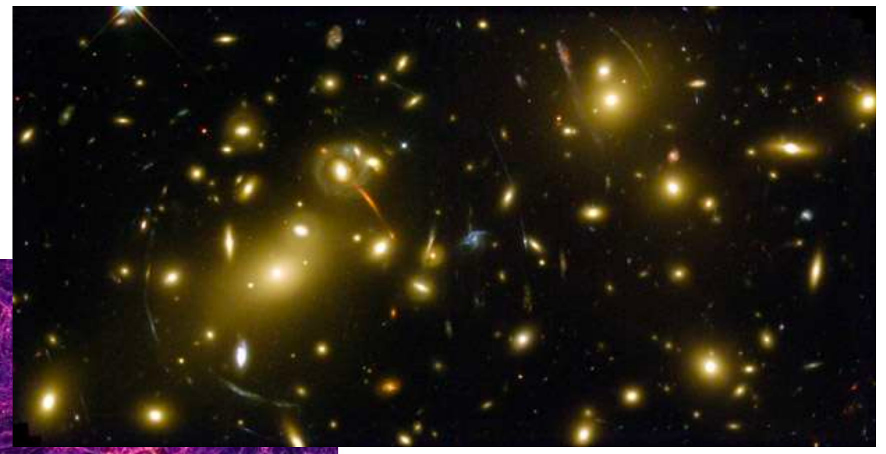
CMB+LSS



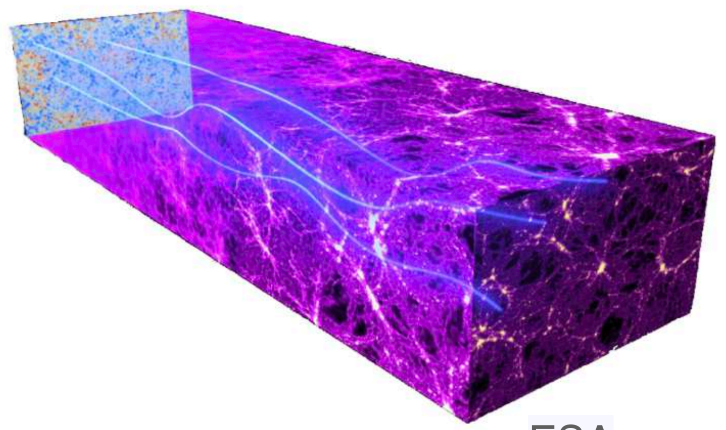
ESA and the Planck Collaboration



Springel & others / Virgo Consortium

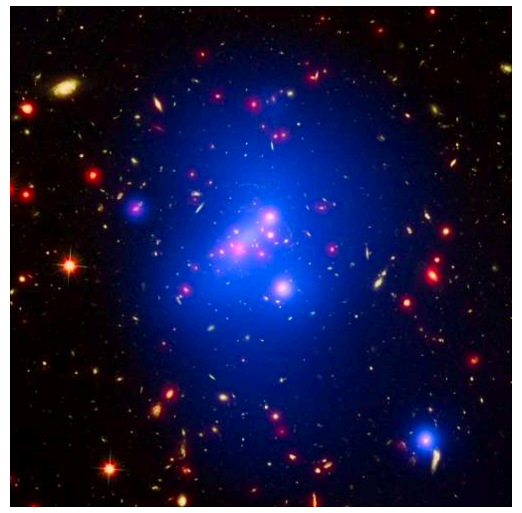


NASA and ESA



ESA

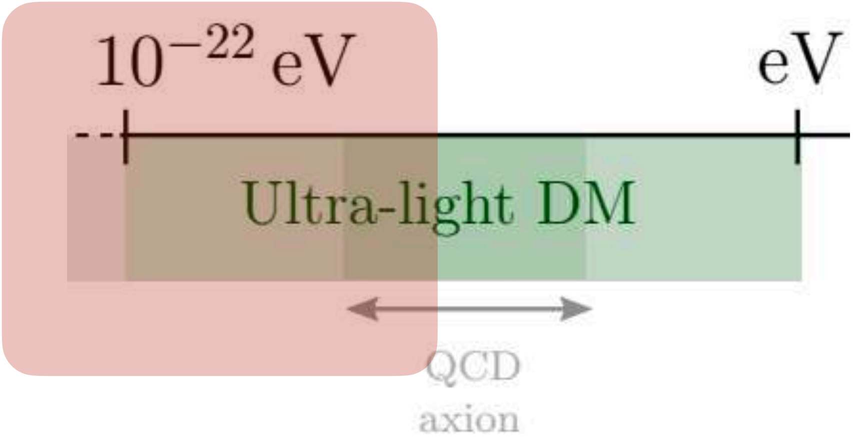
Clusters

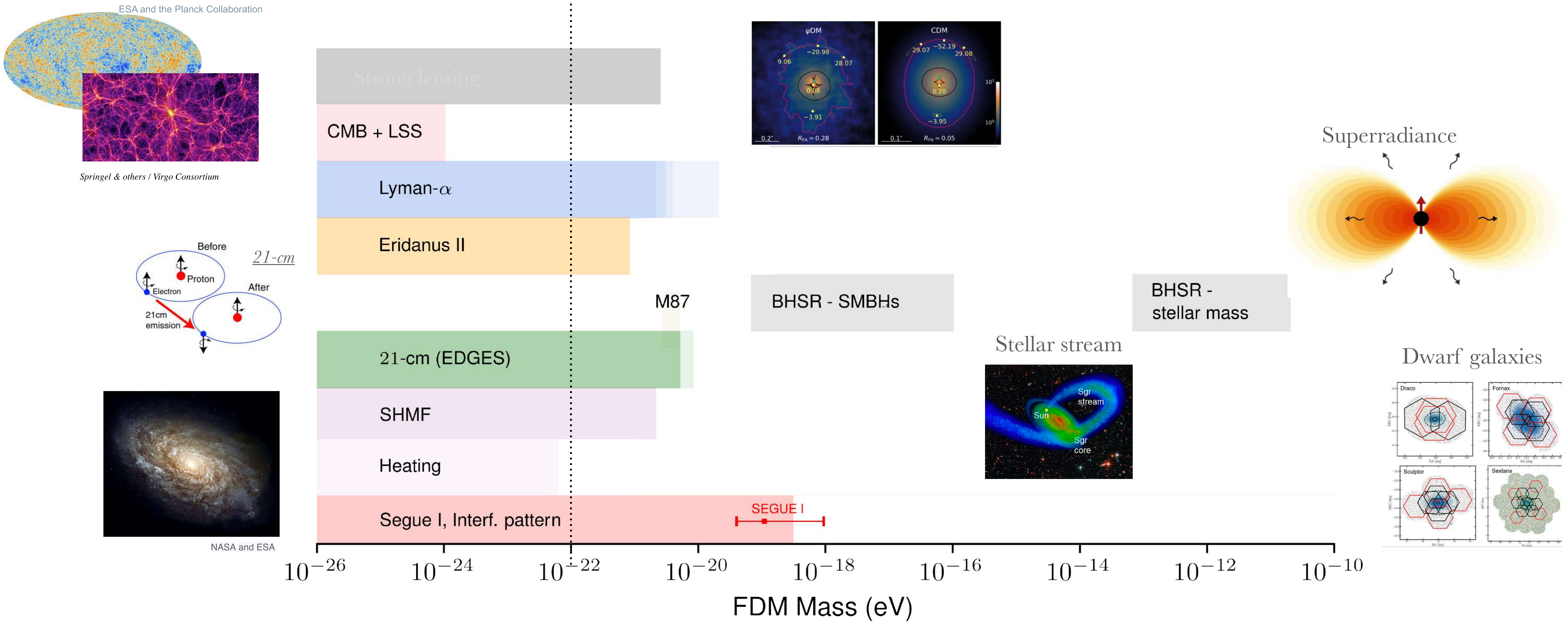


CC BY 4.0

Current status

Fuzzy Dark Matter - bounds on the mass

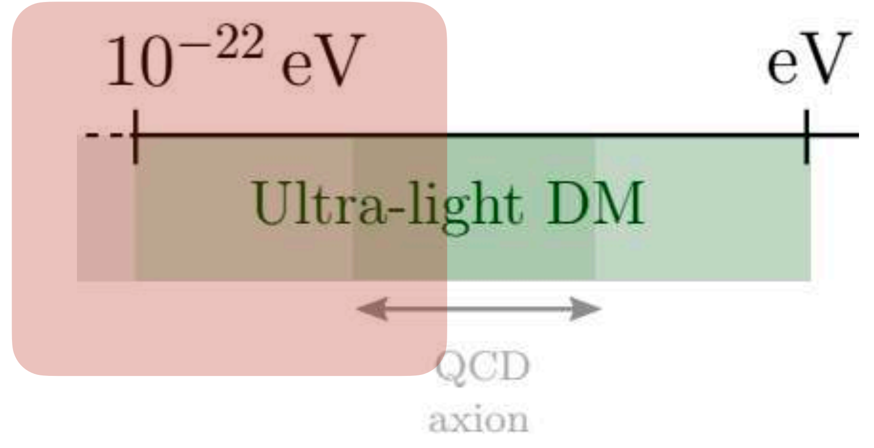


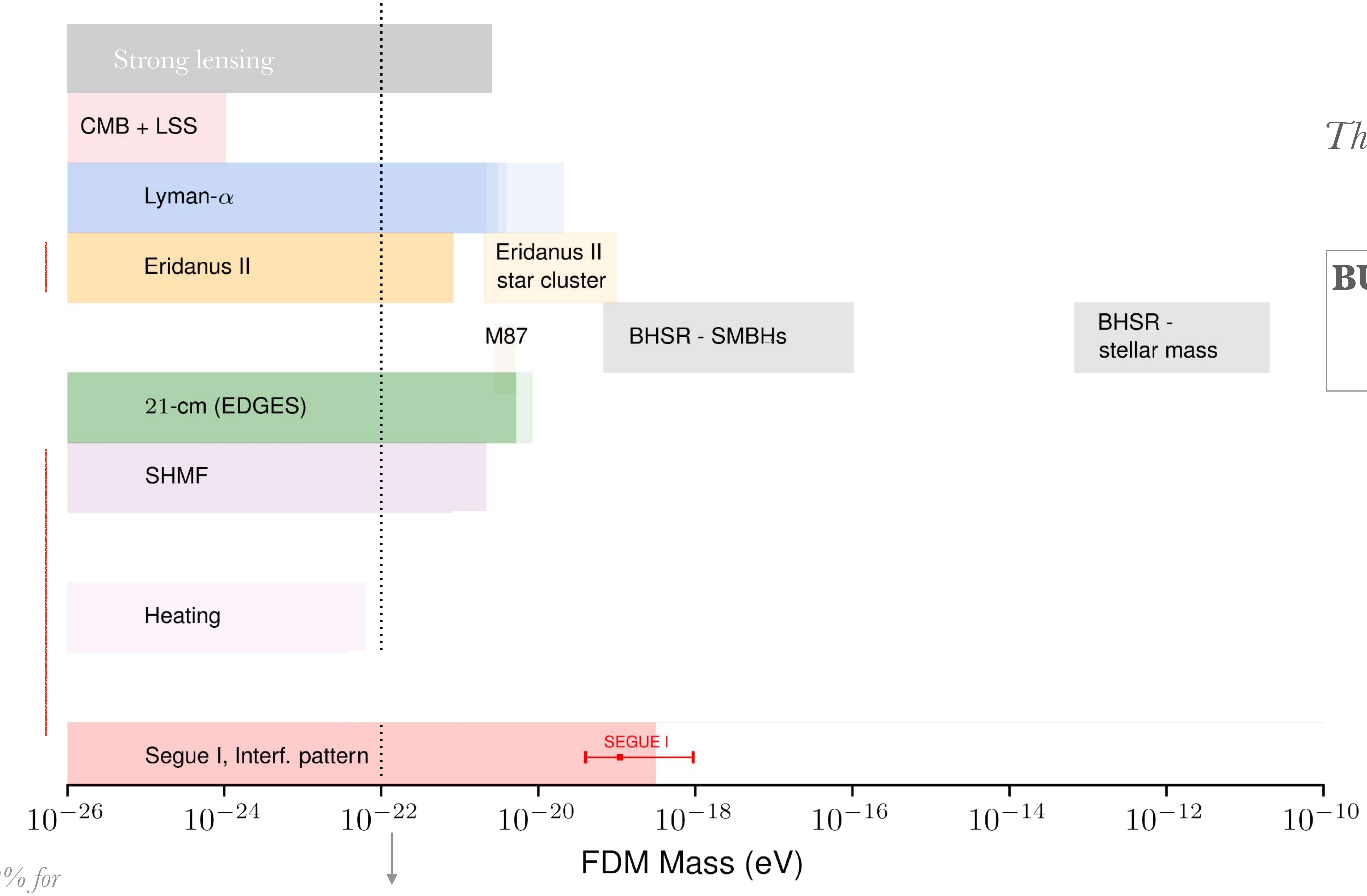


"Ultra-light dark matter", **E.F.**, 2020

Current status

Fuzzy Dark Matter - bounds on the mass





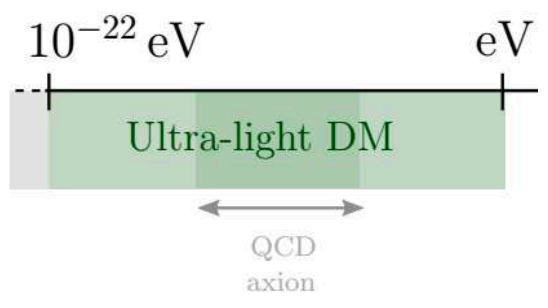
Sweet spot for solving small scale problems

Caner et al: FDM at most 10% for $10^{-21}\,\mathrm{eV} < m < 10^{-17}\,\mathrm{eV}$

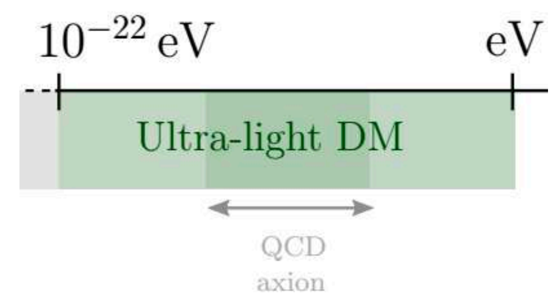
These models can be constrained

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

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



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

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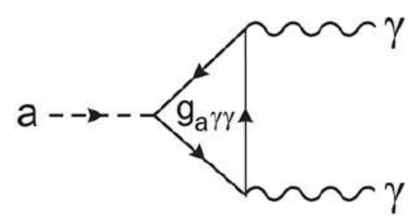
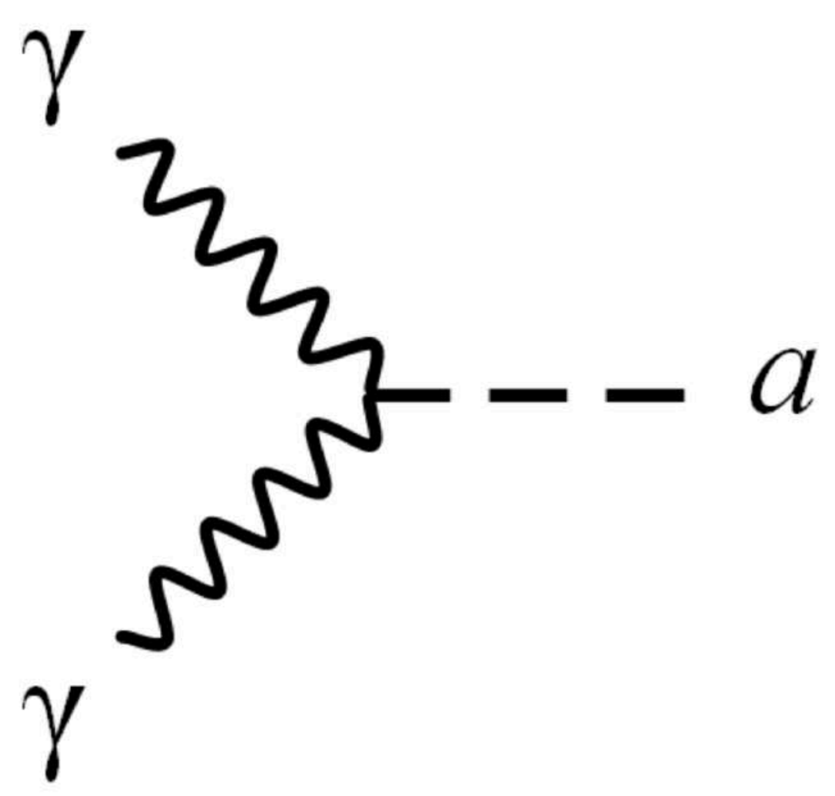
$$\mathbf{B} = \nabla \times \mathbf{A}$$

Axions and ALPs interact with the standard model particles

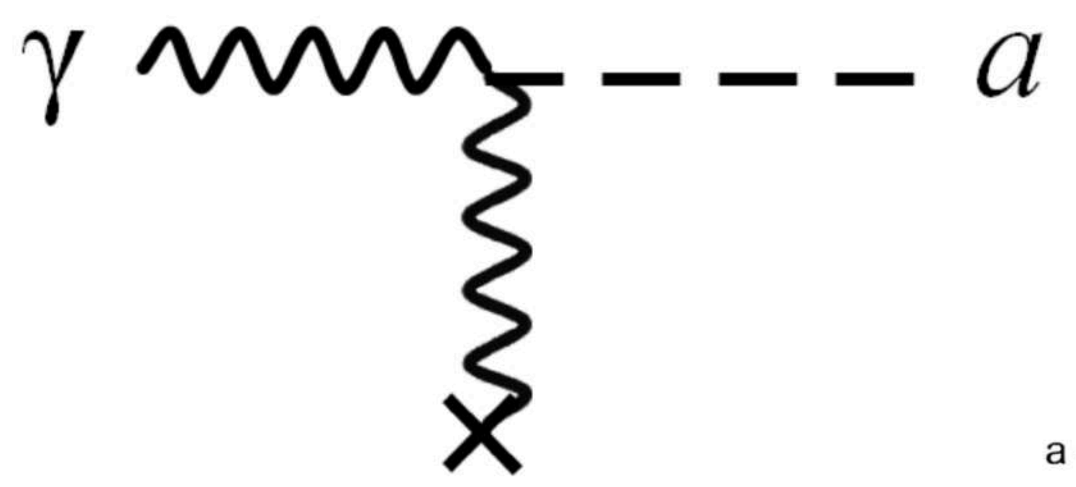
<u>Photon</u> - Axion electrodynamics

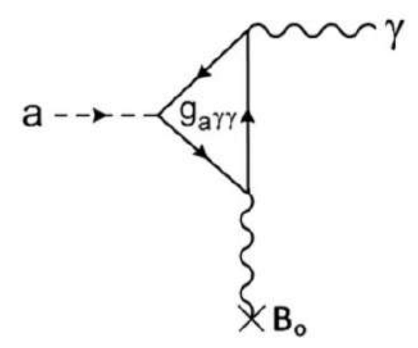
$$\mathcal{L}_{ALP} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}_{\mu\nu} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 + g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}\, a$$





Photon-photon-ALP vertex with coupling constant $g_{a\gamma\gamma}$





$\gamma \to a$ conversion in the external magnetic field $\mathbf{B}$ (Primakoff effect)

Other diagrams…

Axion and ALPs interaction with the SM

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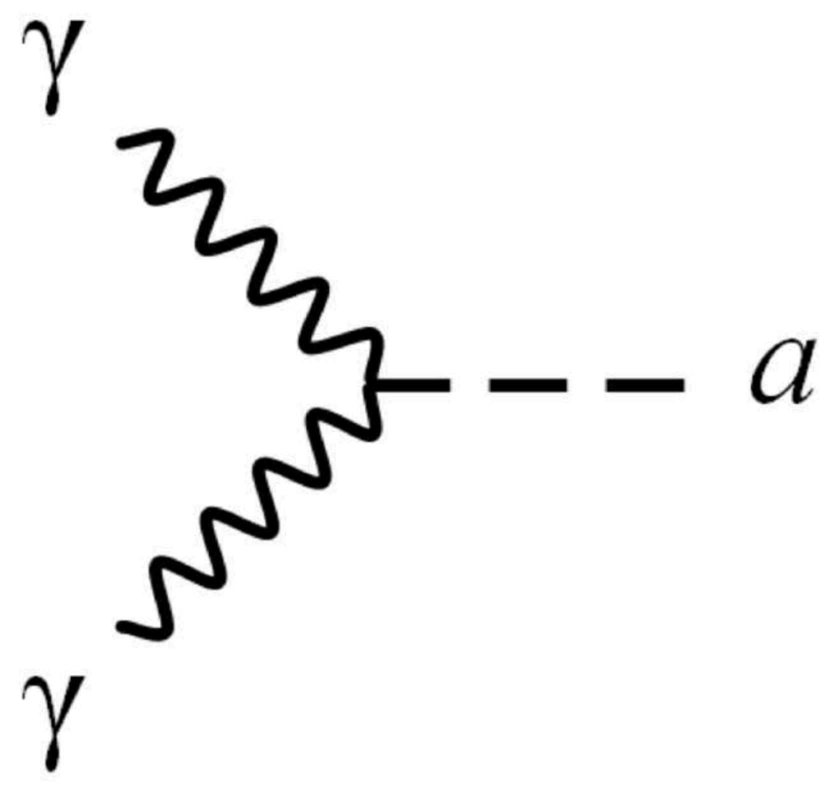
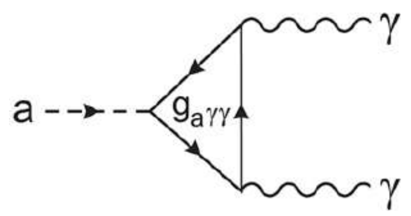
Axions and ALPs interact with the standard model particles

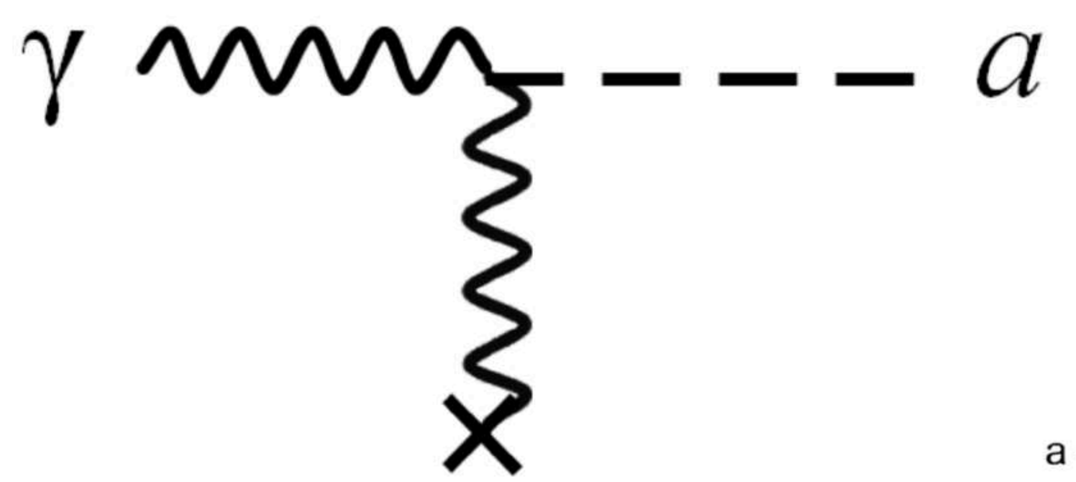
<u>Photon</u> - Axion electrodynamics

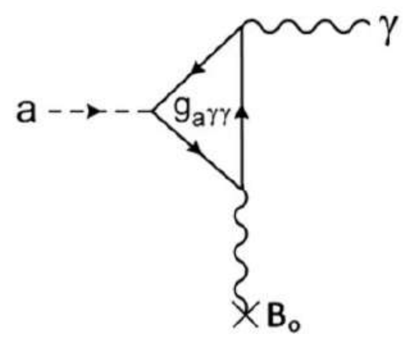
$$\mathcal{L}_{ALP} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}_{\mu\nu} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 + g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}\, a$$





Photon-photon-ALP vertex with coupling constant $g_{a\gamma\gamma}$





$\gamma \to a$ conversion in the external magnetic field $\mathbf{B}$
(Primakoff effect)

Other diagrams…

Axion and ALPs interaction with the SM

Axions and ALPs interact with the standard model particles

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$$\mathbf{B} = \nabla \times \mathbf{A}$$

Axion electrodynamics

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^\mu A_\mu - \frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a$$

- We can interpret axion as the source of an effective current:

$$\partial_\mu F^{\mu\nu} = J^\nu \underbrace{- g_{a\gamma}\widetilde{F}_{\mu\nu}\partial_\mu a}$$

$$J_a^\mu = g_{a\gamma}(-\mathbf{B}\cdot\nabla a,\ -\mathbf{E}\times\nabla a + \partial_t a\mathbf{B})$$

Maxwell's equations:

$$\nabla\cdot\mathbf{E} = \rho$$
$$\nabla\cdot\mathbf{B} = 0$$
$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$$
$$\nabla\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + \mathbf{J}$$

Extended Maxwell's equations:

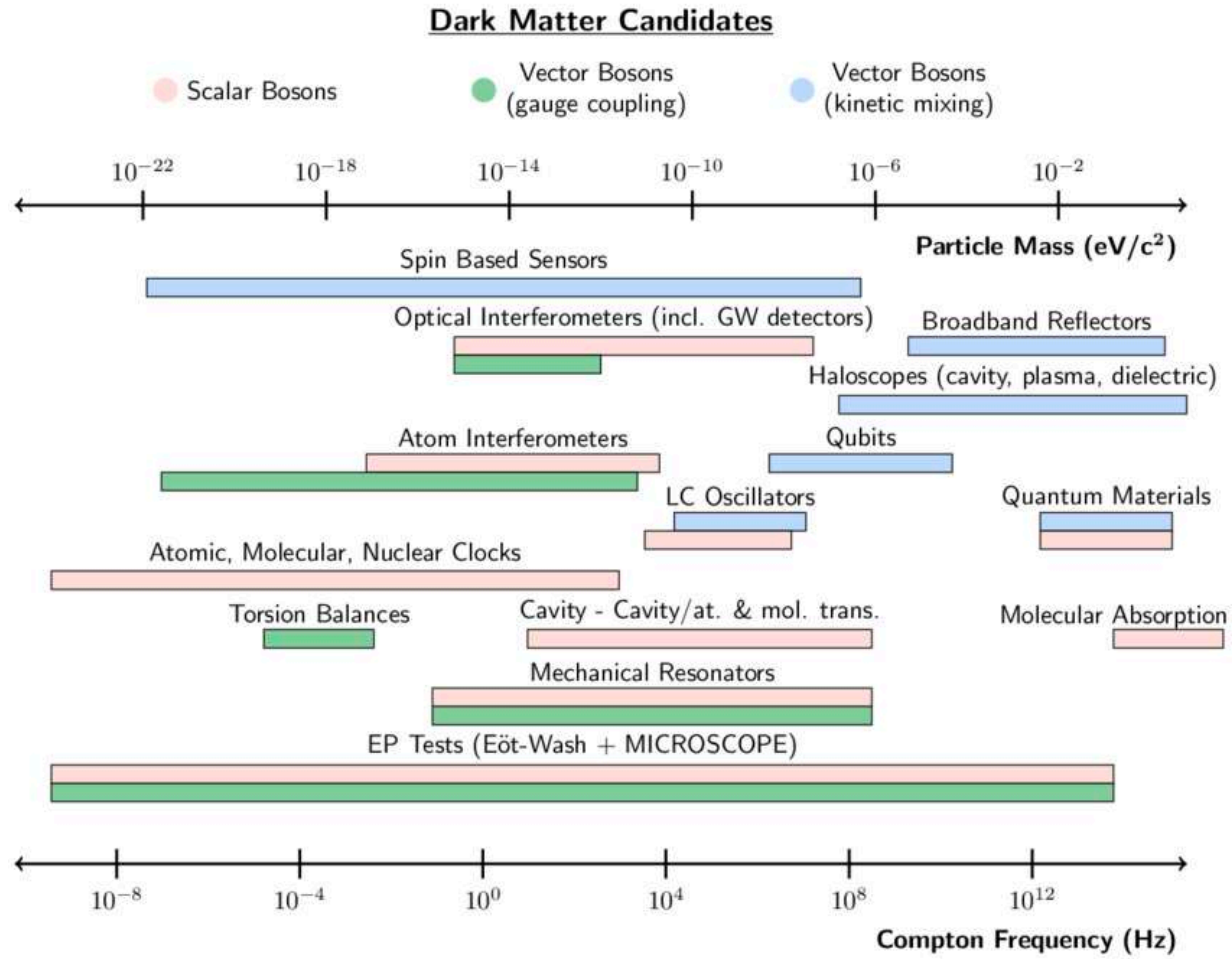
$$\nabla\cdot\mathbf{E} = \rho - g_{a\gamma}\,\mathbf{B}\cdot\nabla a$$
$$\nabla\cdot\mathbf{B} = 0$$
$$\nabla\times\mathbf{E} = -\frac{\partial\mathbf{B}}{\partial t}$$
$$\nabla\times\mathbf{B} = \frac{\partial\mathbf{E}}{\partial t} + \mathbf{J} - g_{a\gamma}\left(\mathbf{E}\times\nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right)$$

Adapted from: Cyaran O'Hare

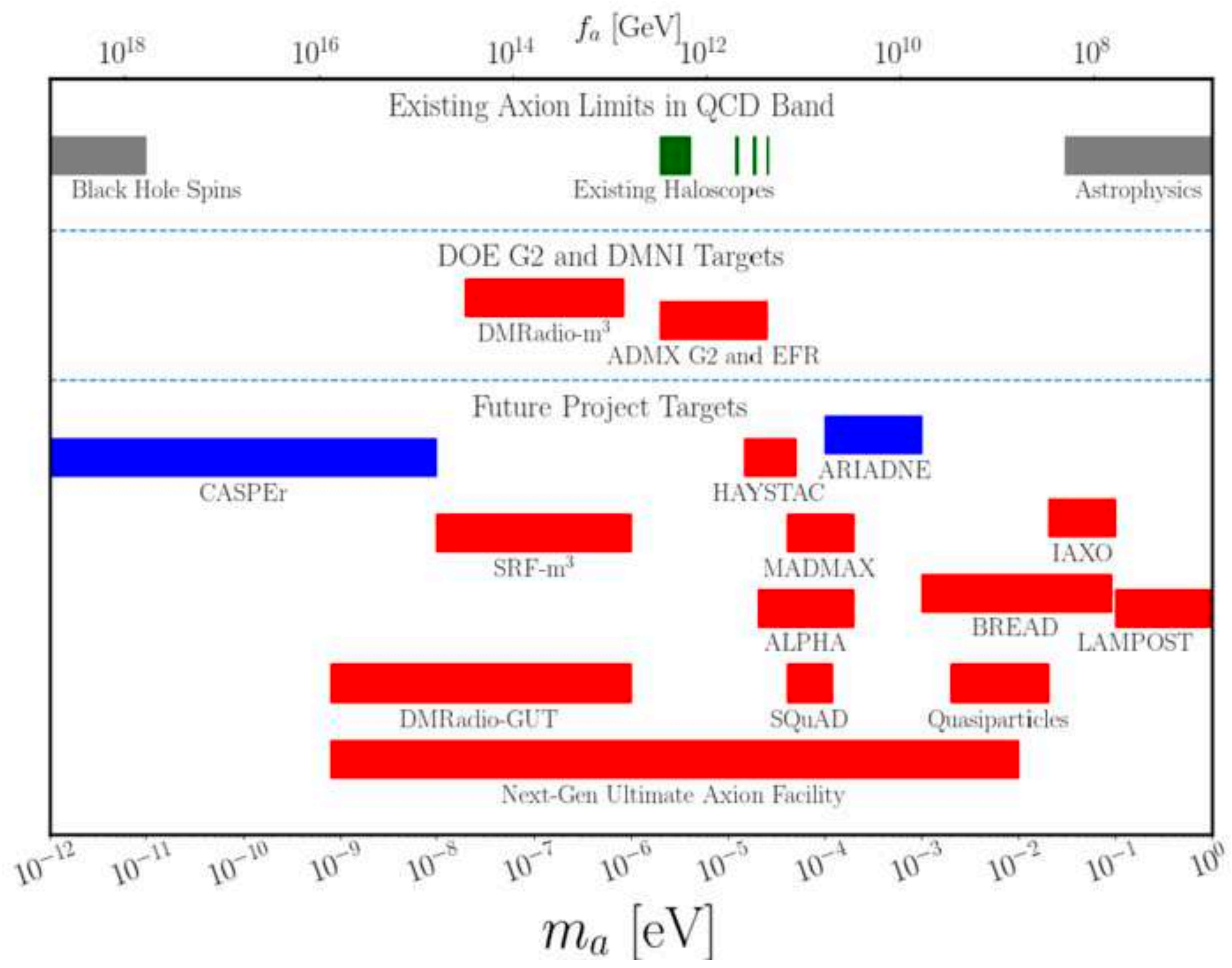
Axion and ALPs interaction with the SM

"Direct Detection": axion/ALPs experiments

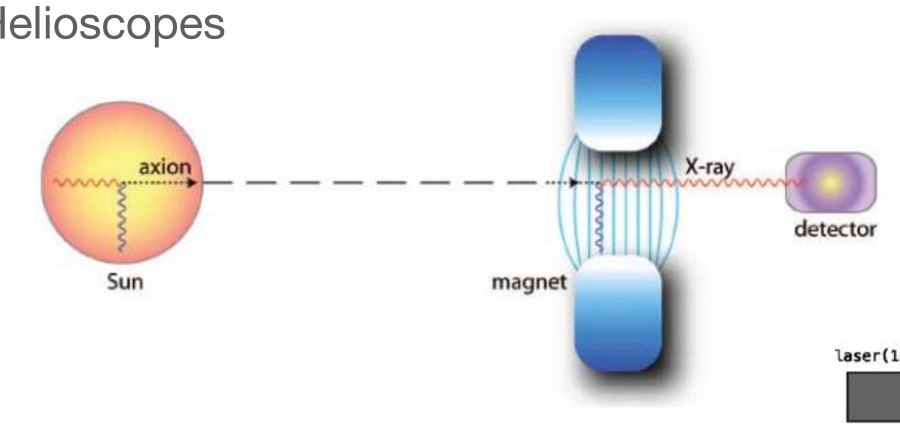
Overview of experimental techniques and the mass ranges they target

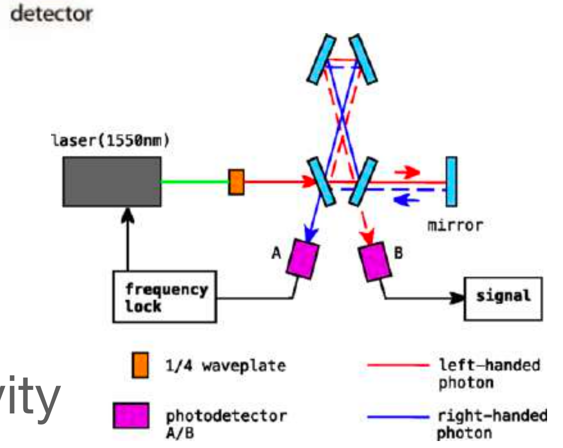


Experiments

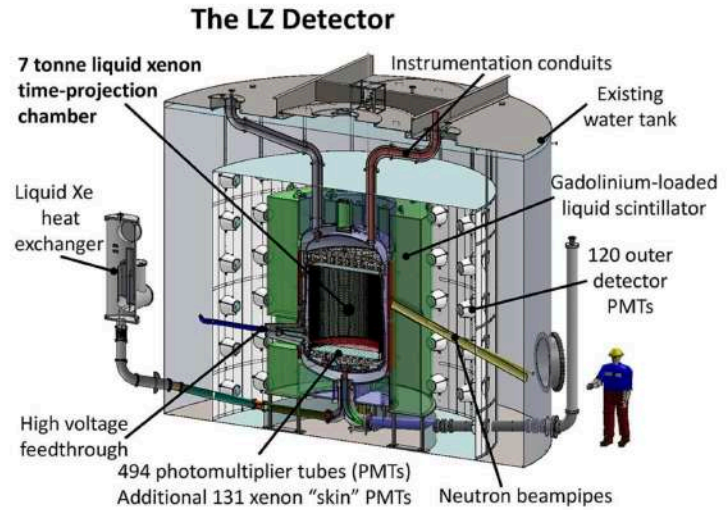


Helioscopes





Optical cavity

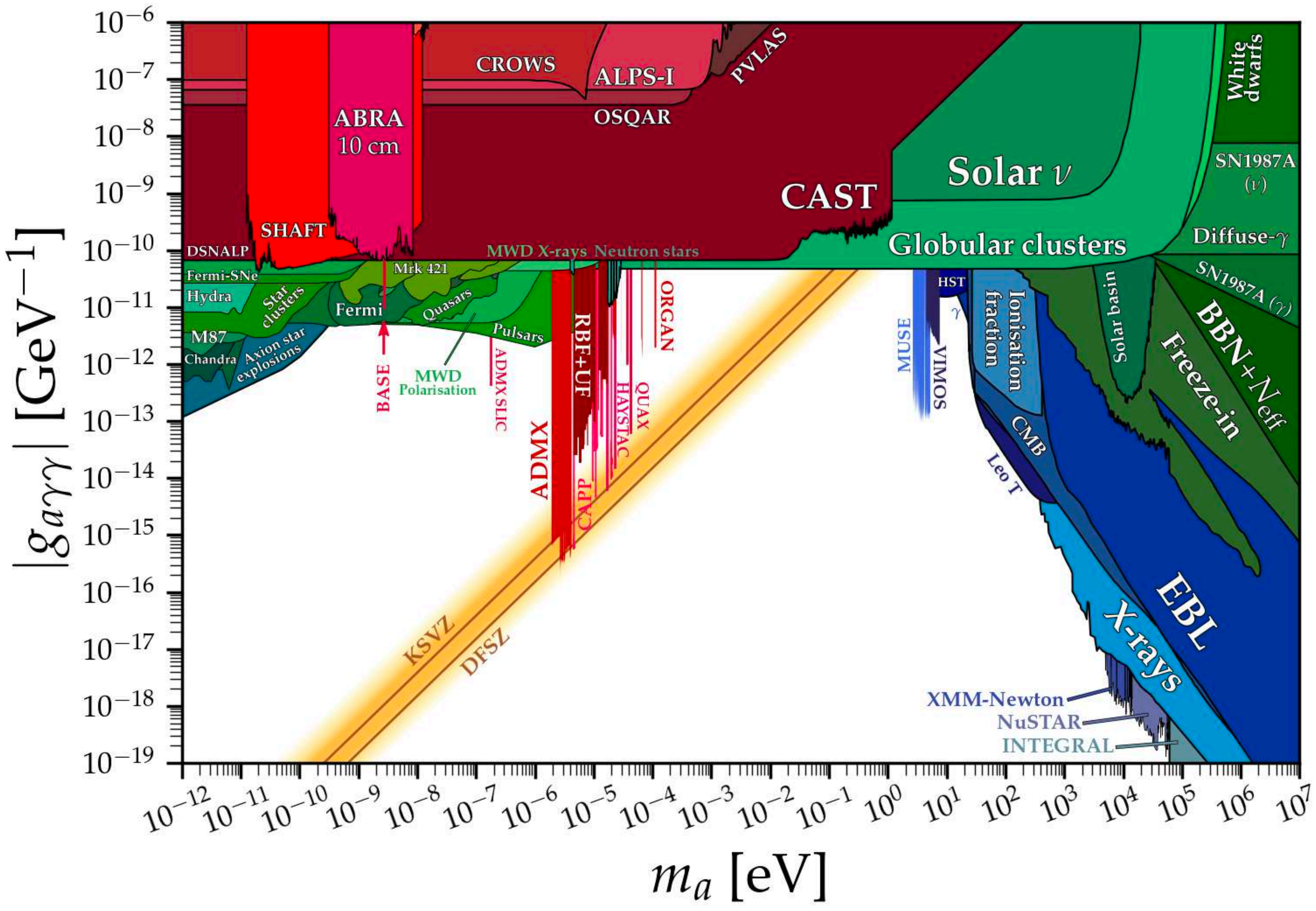


Ref. Jaeckel et al 2021

Axion and ALPs interaction with the SM

Bounds on Axion-photon coupling

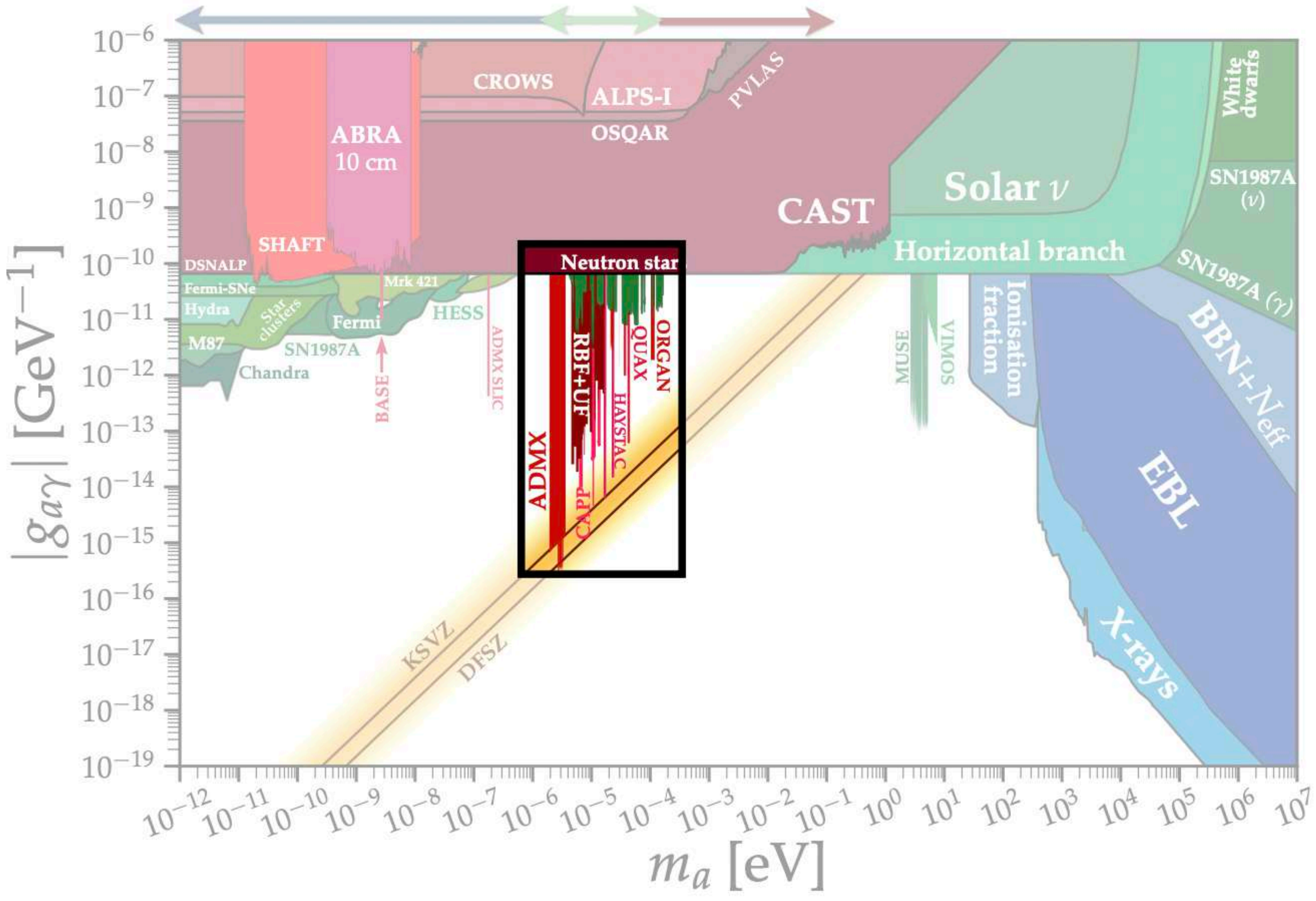
Includes direct and indirect detection



Website with up-to-date with axion/ALP bounds: https://cajohare.github.io/AxionLimits

Axion and ALPs interaction with the SM

Bounds on Axion-photon coupling



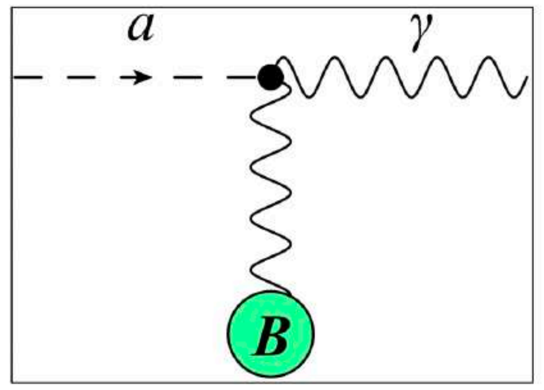
$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

Website with up-to-date with axion/ALP bounds: https://cajohare.github.io/AxionLimits

Axion and ALPs interaction with the SM

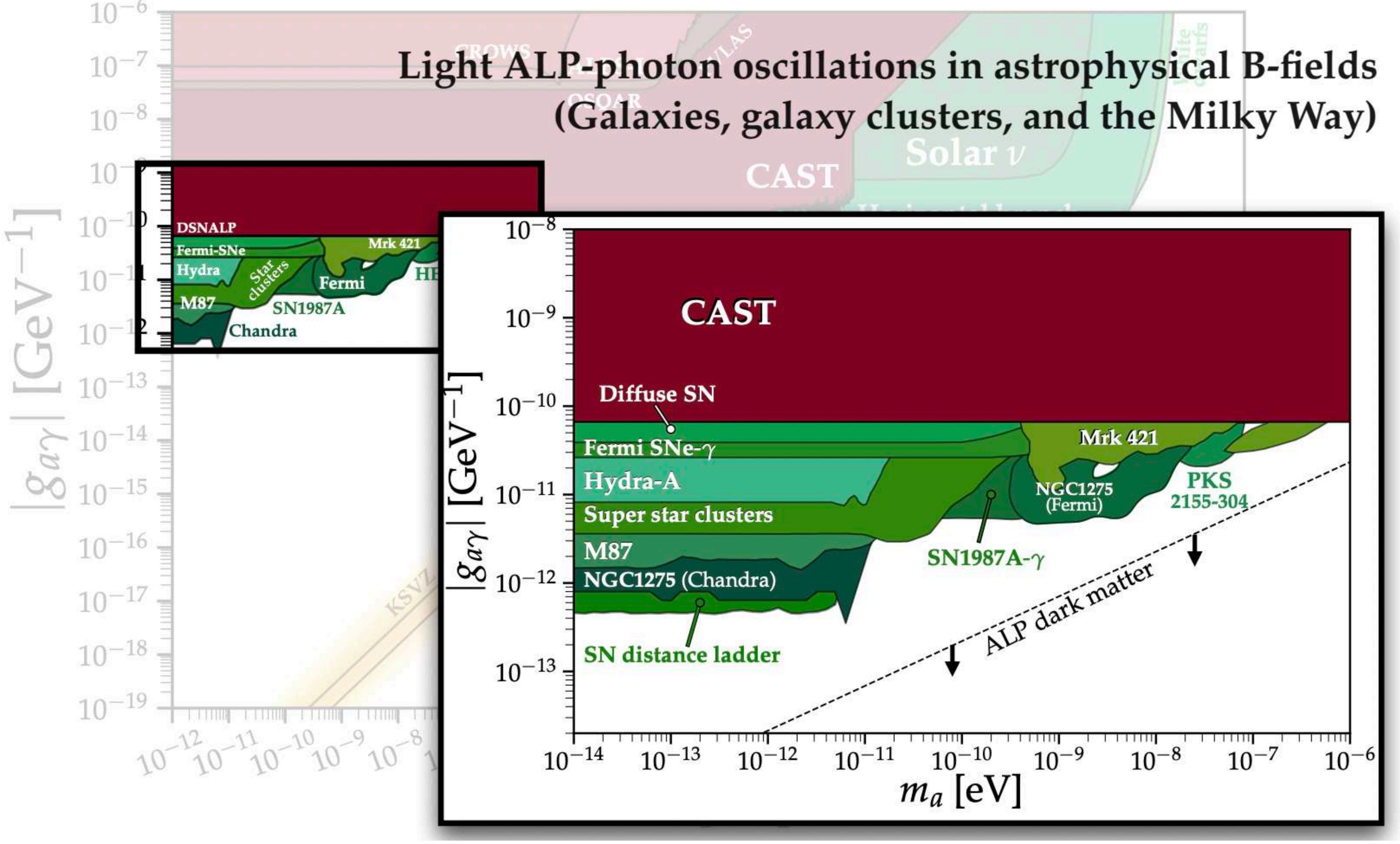
Indirect Detection

In astrophysical systems



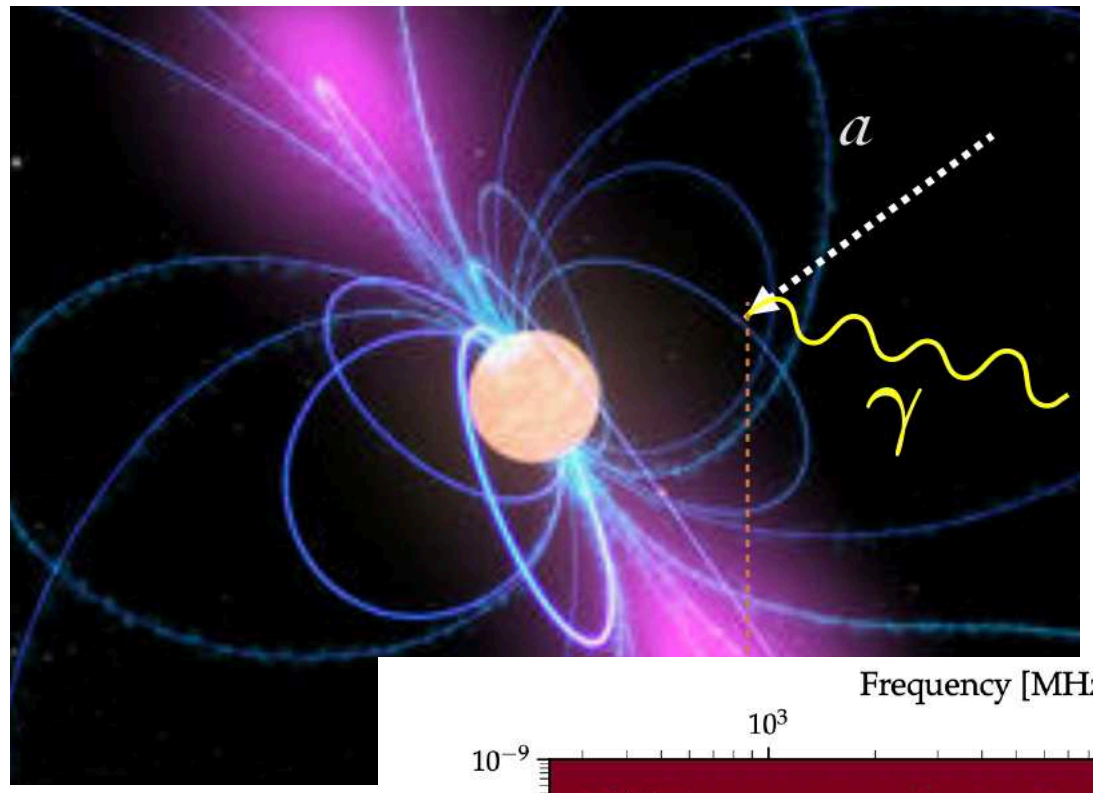
Axion-photon conversion (Primakoff effect)

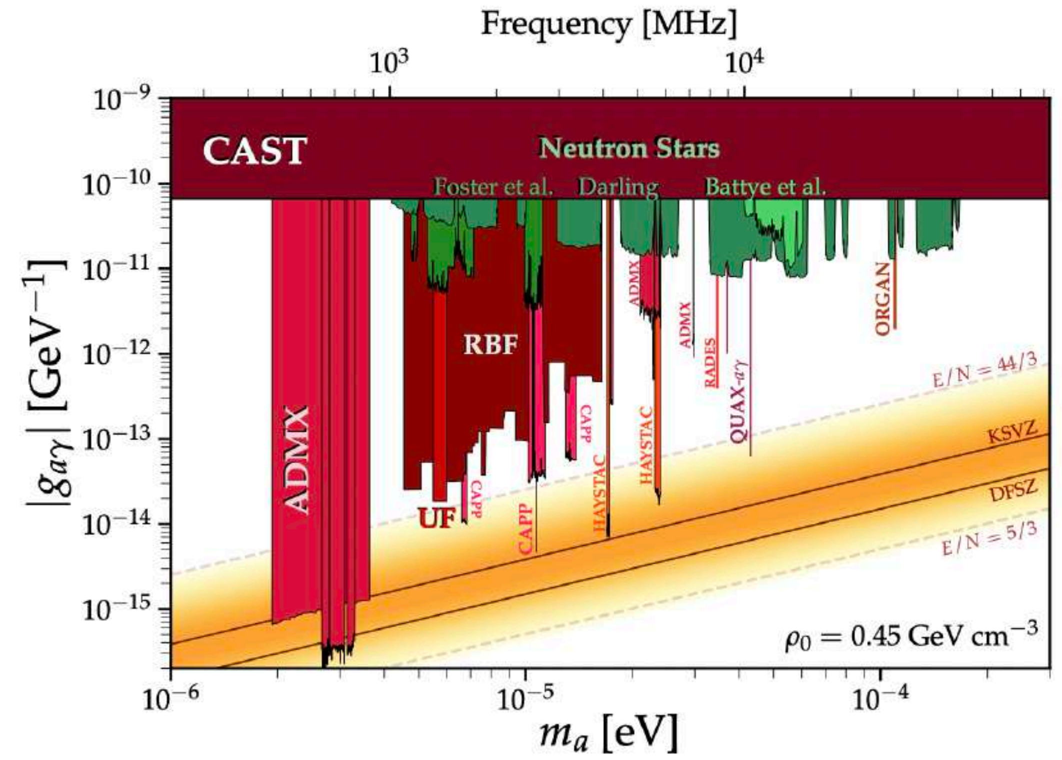
a : axion
γ : photon
B : magnetic field



+

DM axions in neutron star magnetospheres



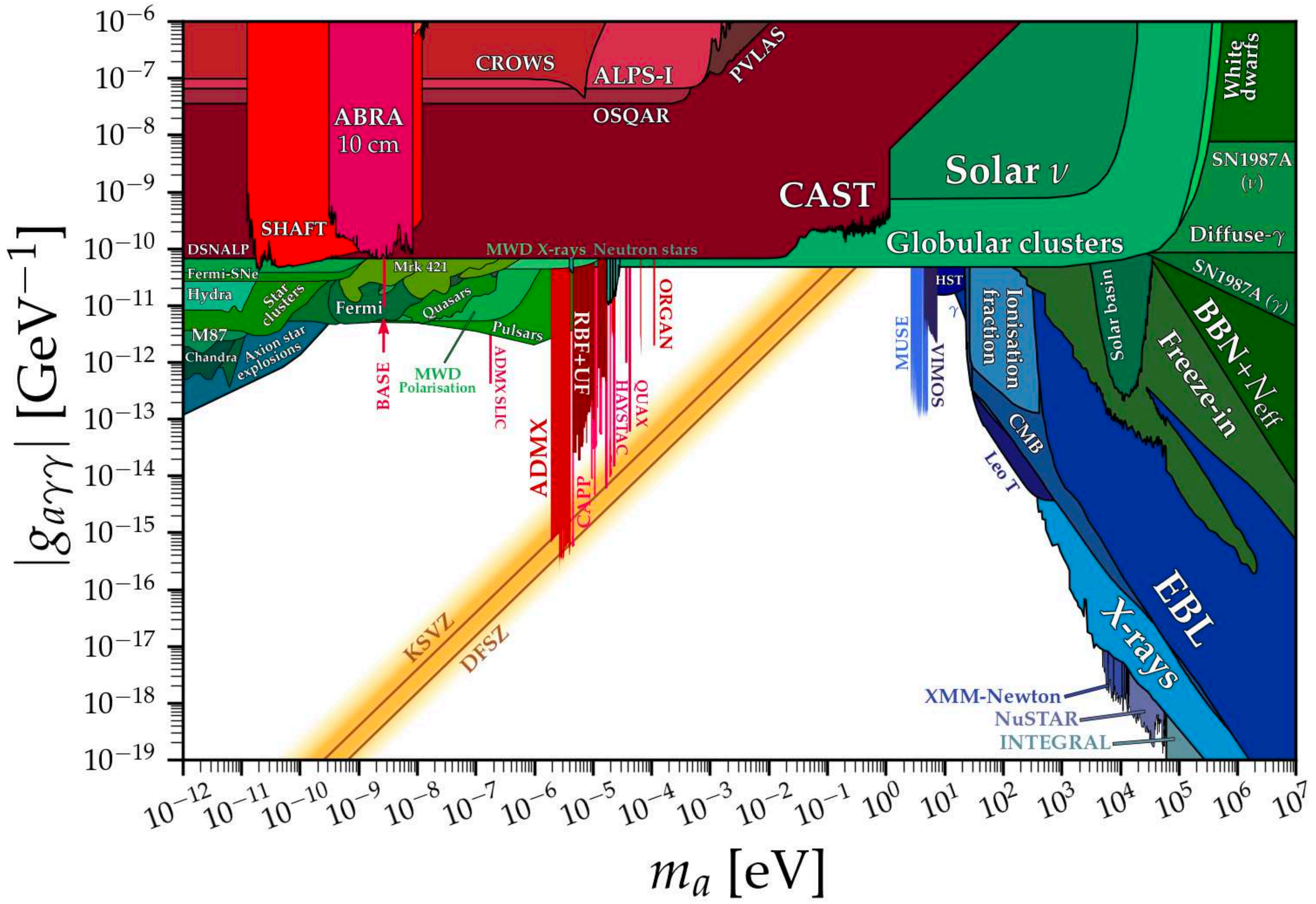


Axion and ALPs interaction with the SM

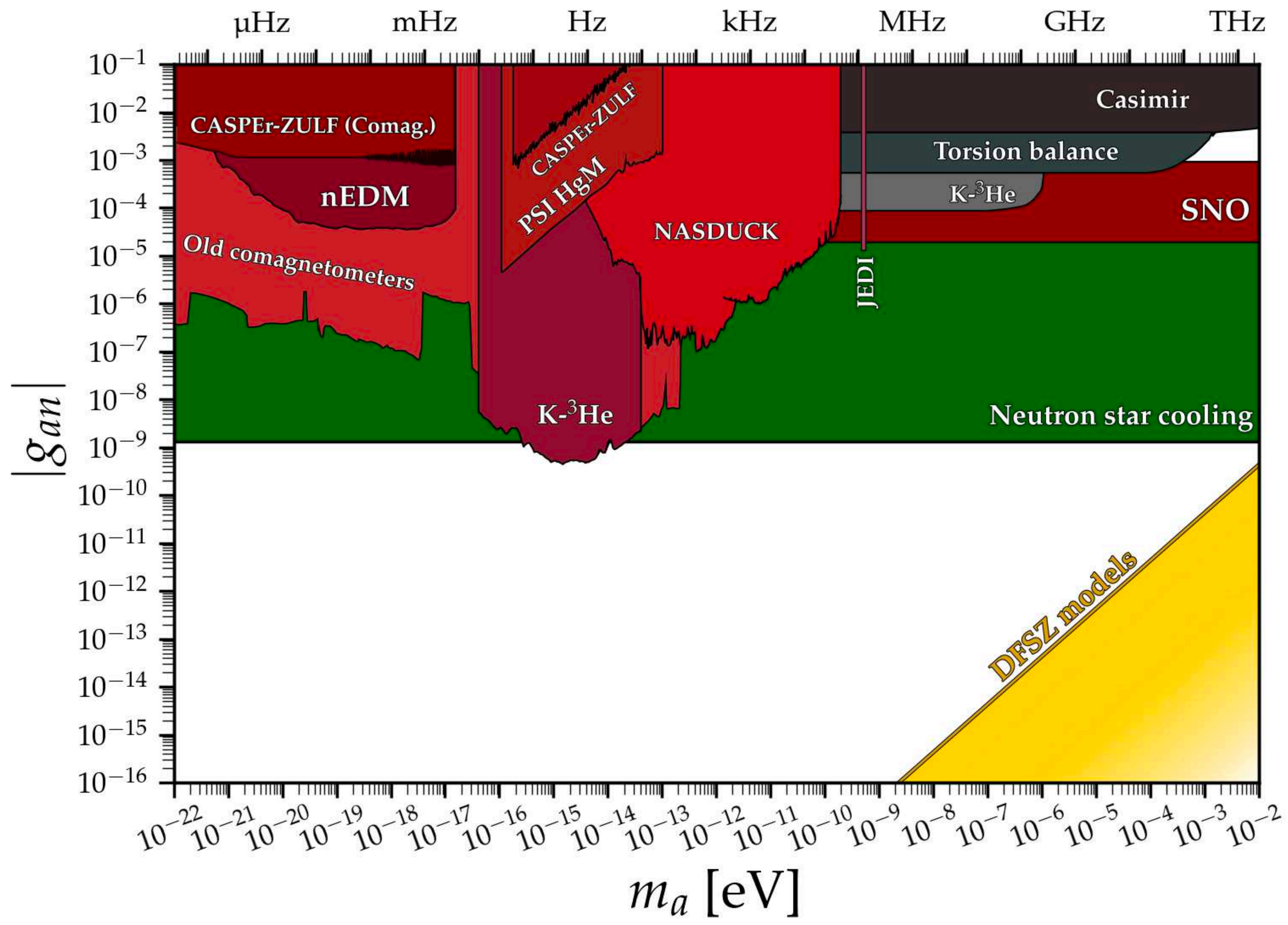
Bounds

Includes direct and indirect detection

Axion-electron coupling



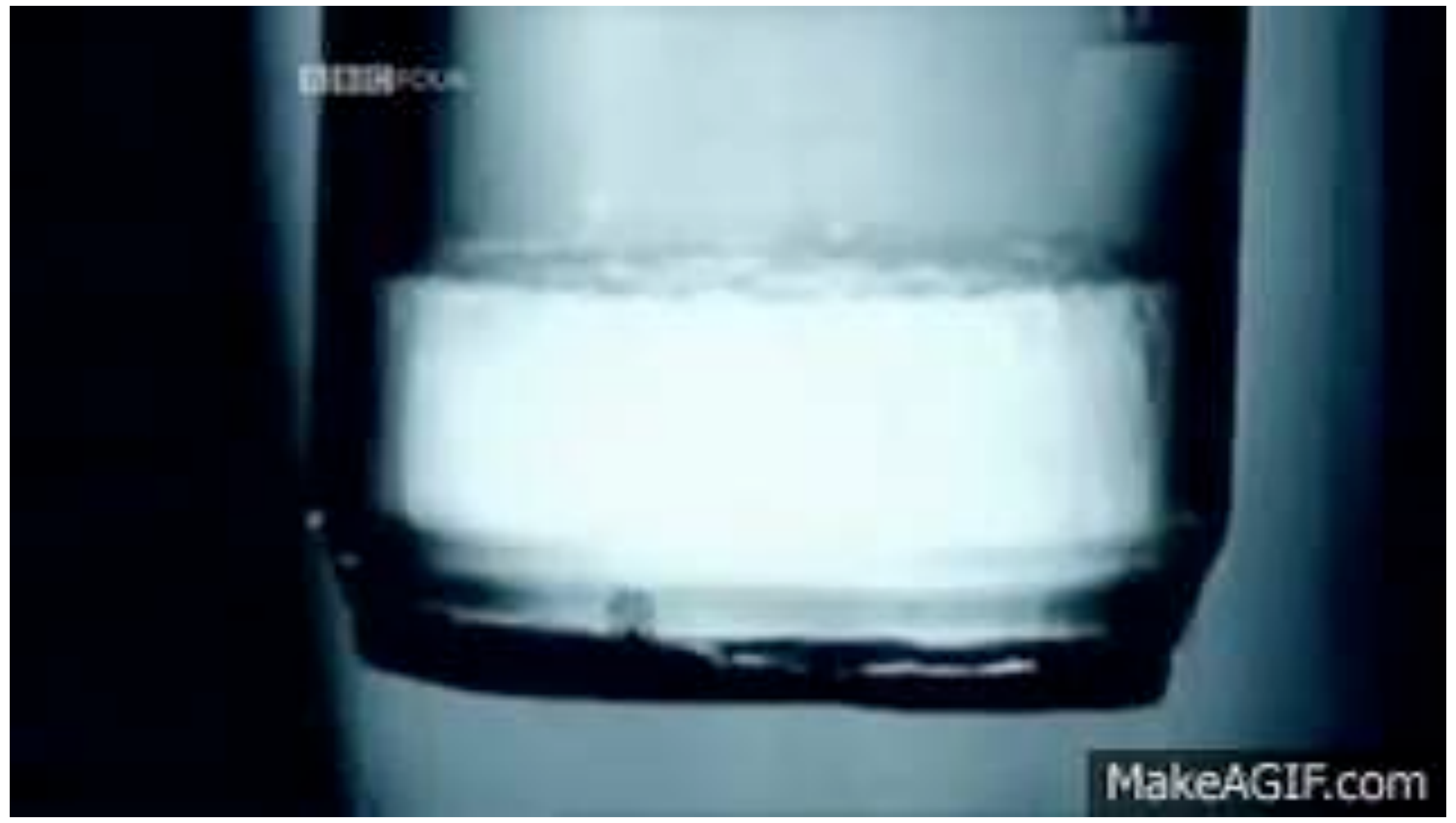
Axion-neutron coupling



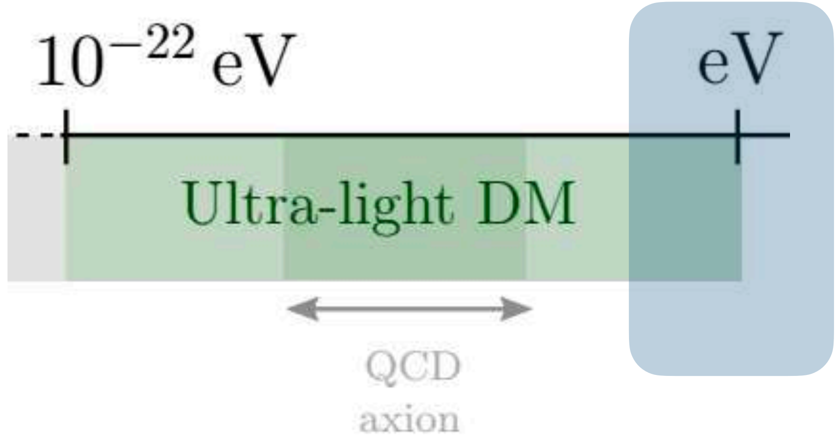
+ many more: axion-proton, dark photon, …

Website with up-to-date with axion/ALP bounds: https://cajohare.github.io/AxionLimits
(Includes notebooks)

Superfluid Dark Matter

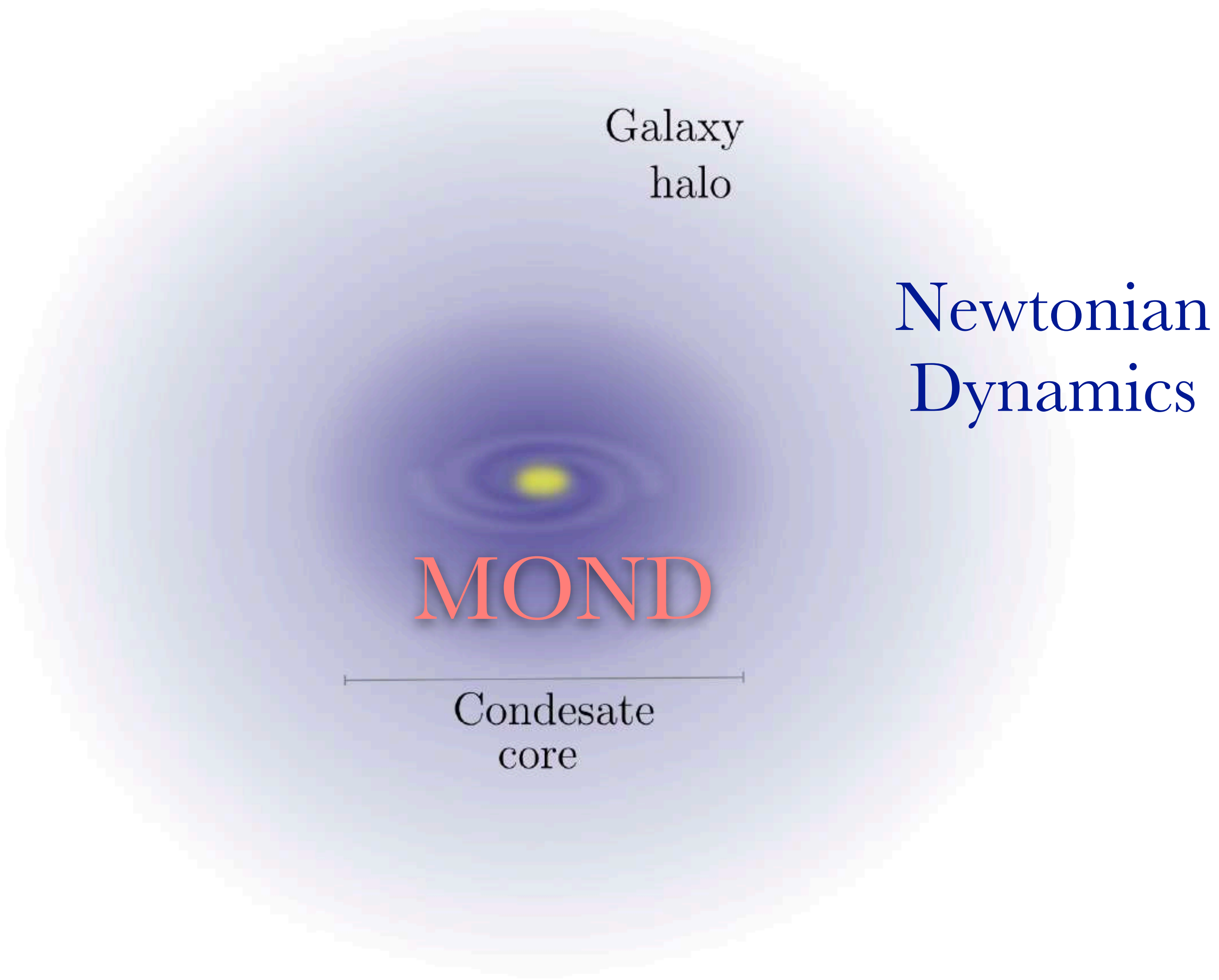


Superfluid Dark Matter



Lasha Berezhiani and Justin Khoury (2016)

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



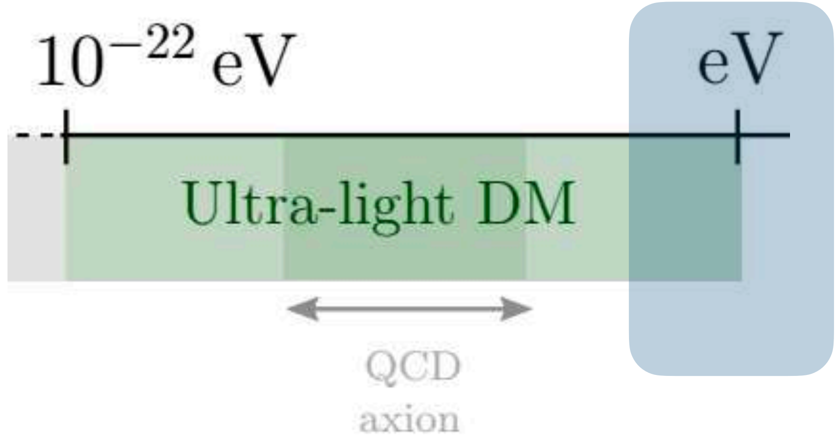
$$a = \begin{cases} a_N^b, & a_N^b \gg a_0. \\ \sqrt{a_N^b a_0}, & a_N^b \ll a_0. \end{cases}$$

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

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

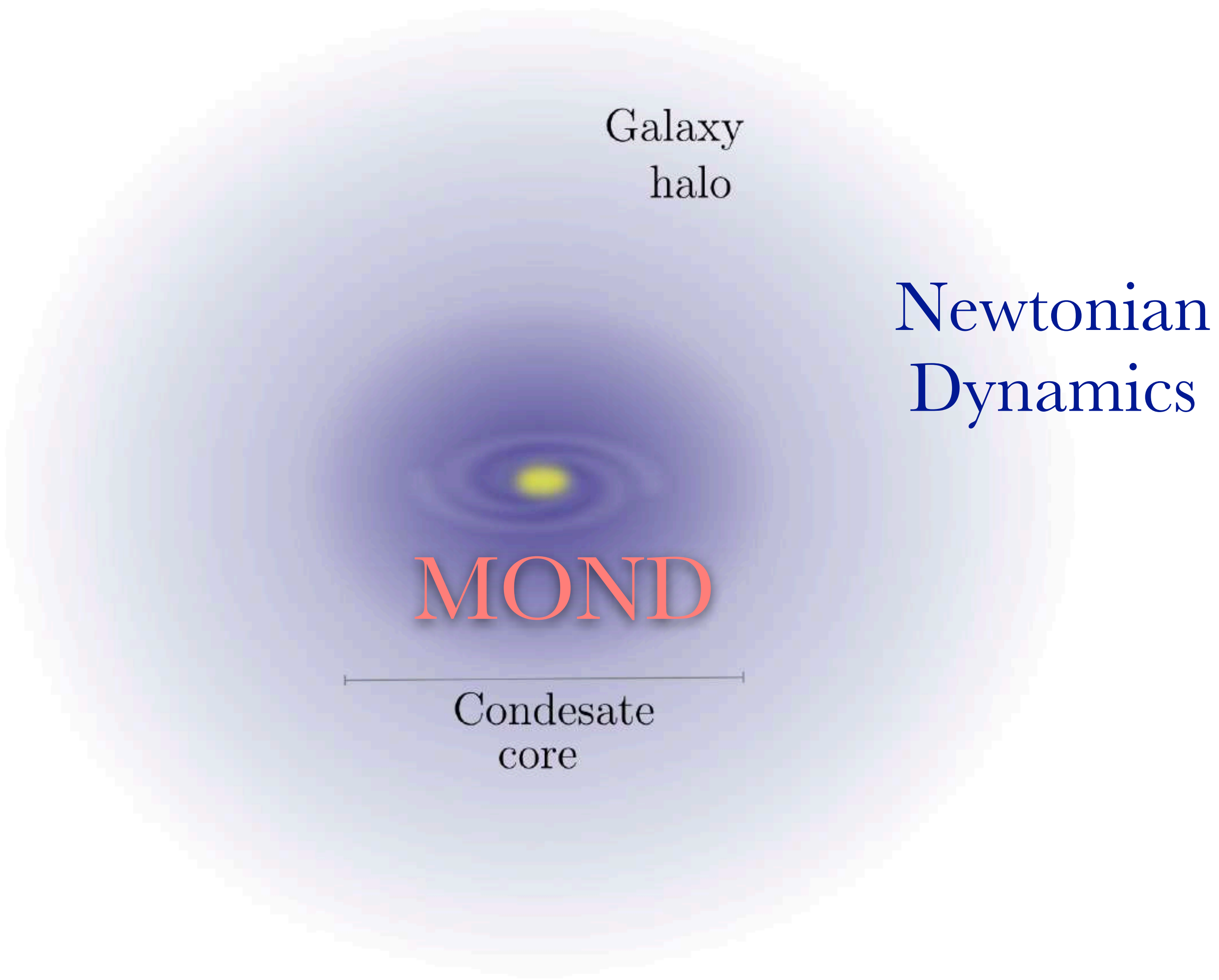
Suppresses small structures, dyn. effects, formation of cores

Superfluid Dark Matter



Lasha Berezhiani and Justin Khoury (2016)

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



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

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

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

Dark photon

New gauge dark sector - spin 1

Extend SM gauge group: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times U(1)'$

with vector X^μ

Below EW → $$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu} + \frac{m_X^2}{2}X_\mu X^\mu + j_\mu A^\mu$$

"Kinetic mixing"

$A^\mu \to A^\mu - \chi X^\mu$

$$\frac{m_X^2}{2}X_\mu X^\mu + j_\mu(A^\mu - \chi X^\mu)$$

→ X is massive force carrying vector,
→ SM Particles get dark millicharge ~ χe
→ Can also be coupled to other dark sector particles to create millicharged DM

$X^\mu \to X^\mu - \chi A^\mu$

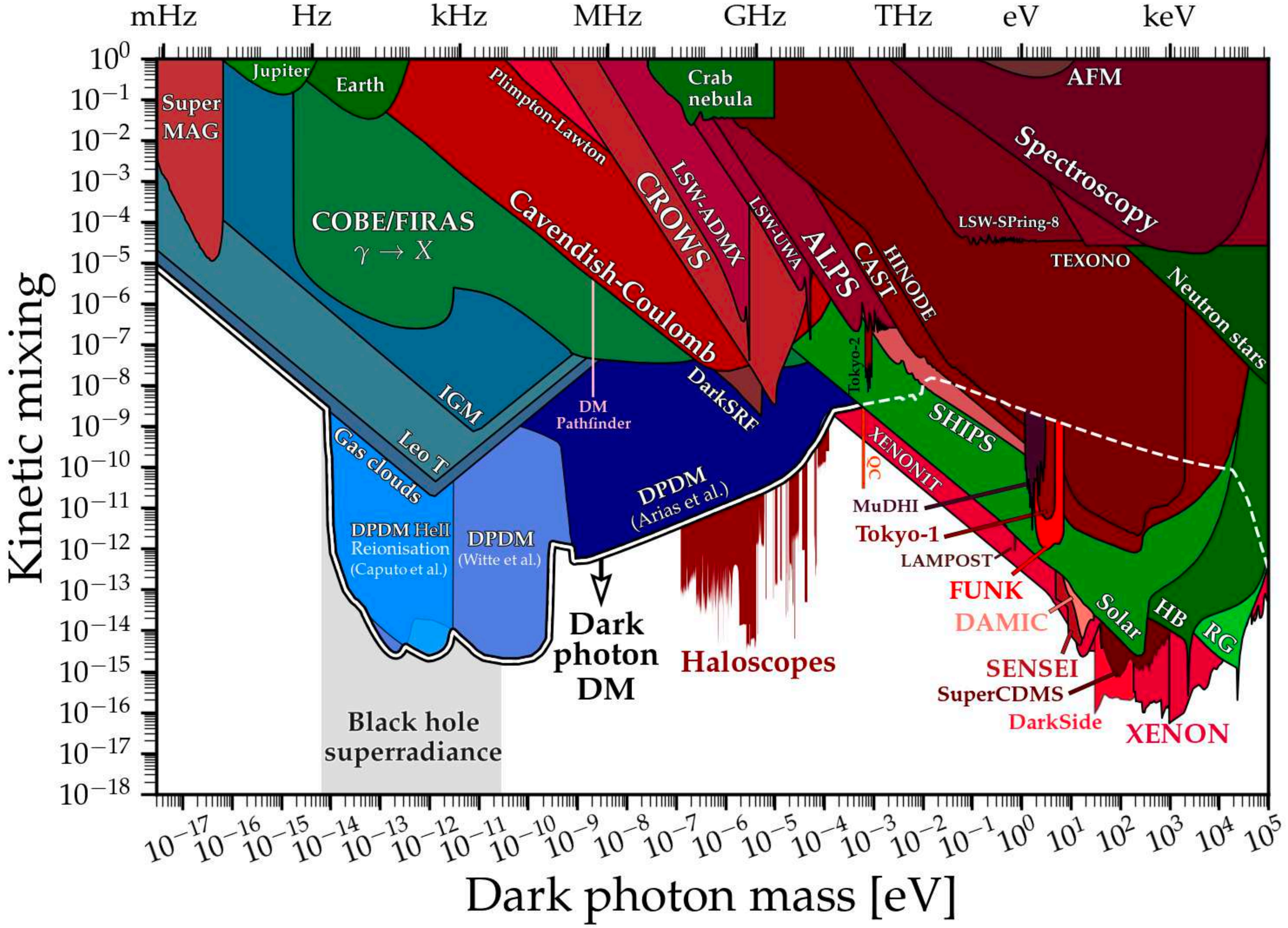
$$\frac{m_X^2}{2}(X_\mu X^\mu - 2\chi X_\mu A^\mu + \chi^2 A_\mu A^\mu) + j_\mu A^\mu$$

→ Non-diagonal mass term
→ SM photon-dark photon mixing

Adapted from: Cyaran O'Hare

Dark photon

New gauge dark sector - spin 1



Website with up-to-date with axion/ALP bounds: https://cajohare.github.io/AxionLimits
(Includes notebooks)

S8 *tension*

Ref.: K. Rogers et al 2023

Changes in the small scale paradigm can change the behaviour of DM in many scales, including cosmology

Ex.: Fuzzy DM

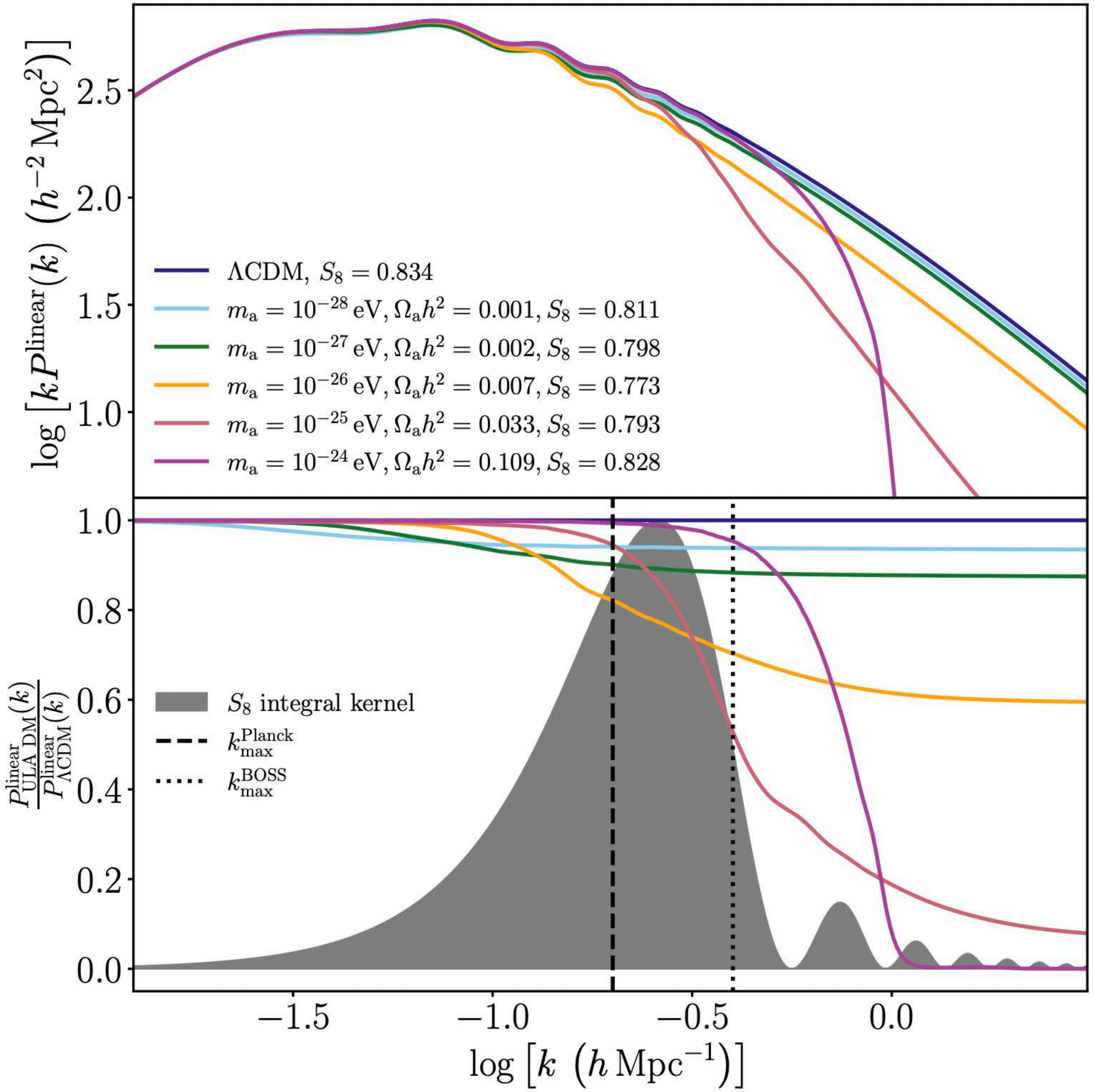
$$\sigma_8 = \int \mathrm{dln}k \, \frac{k^3}{2\pi} W^2(k) P^{\mathrm{linear}}(k)$$

$$S_8 = \sqrt{\frac{\Omega_\mathrm{m}}{0.3}} \sigma_8$$

The presence of ULAs can significantly lowers S8 for:

$$m_\mathrm{a} \in [10^{-27}, 10^{-25}] \, \mathrm{eV}$$

S8 is lowered because the Jeans scale today for $m_a = 10^{-25} - 10^{-26}\,\mathrm{eV}$ is about $\lambda_J = 4 - 12\, h^{-1}\,\mathrm{Mpc}$



S8 tension

Ref.: K. Rogers et al 2023

Ex.: Fuzzy DM

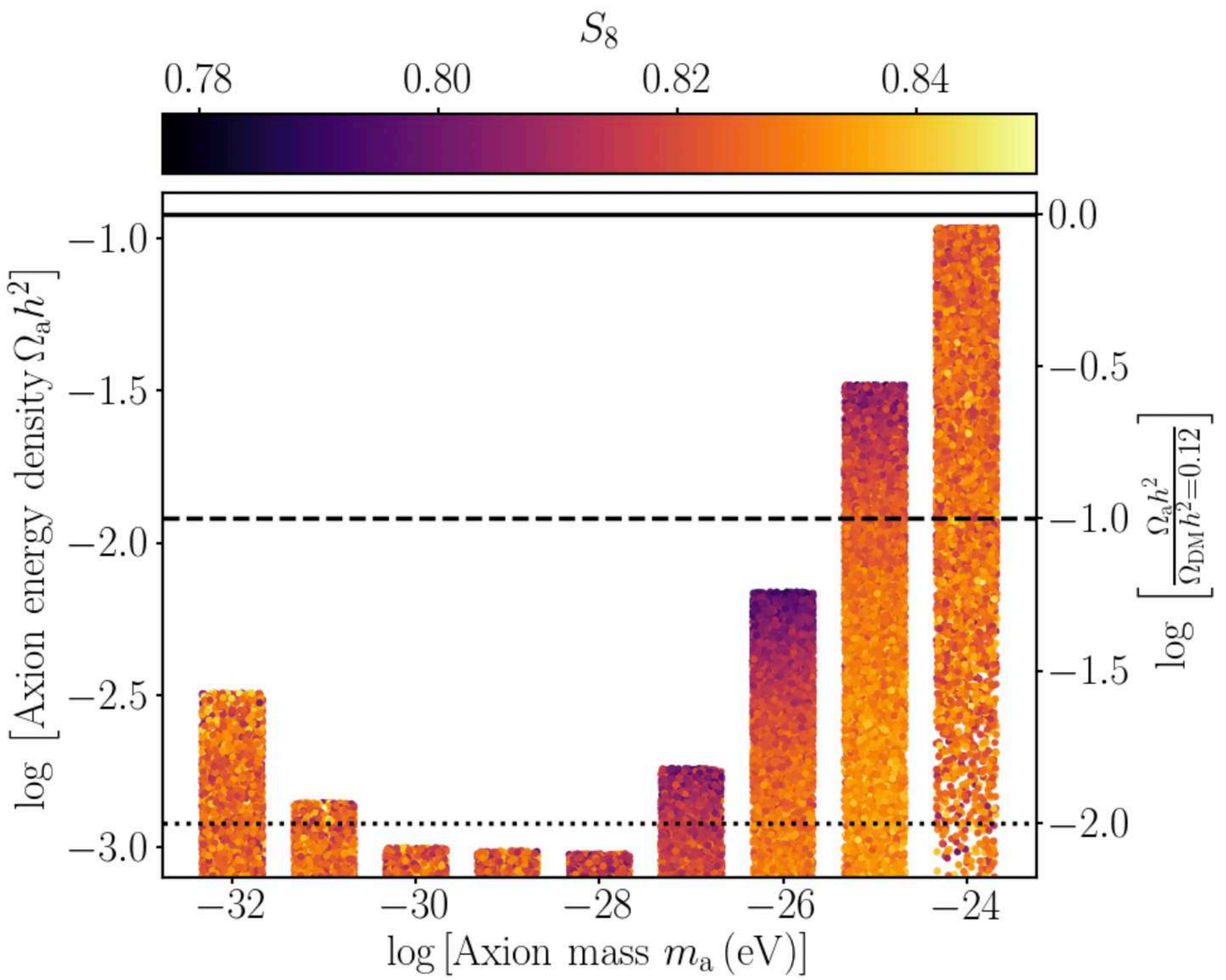
Planck + BOSS

The presence of ULAs with mass

$$10^{-28}\,\mathrm{eV} \leq m_a \leq 10^{-25}\,\mathrm{eV}$$

can improve consistency between CMB and galaxy clustering
(reduce the S8 discrepancy)

from 2.6σ to 1.7σ

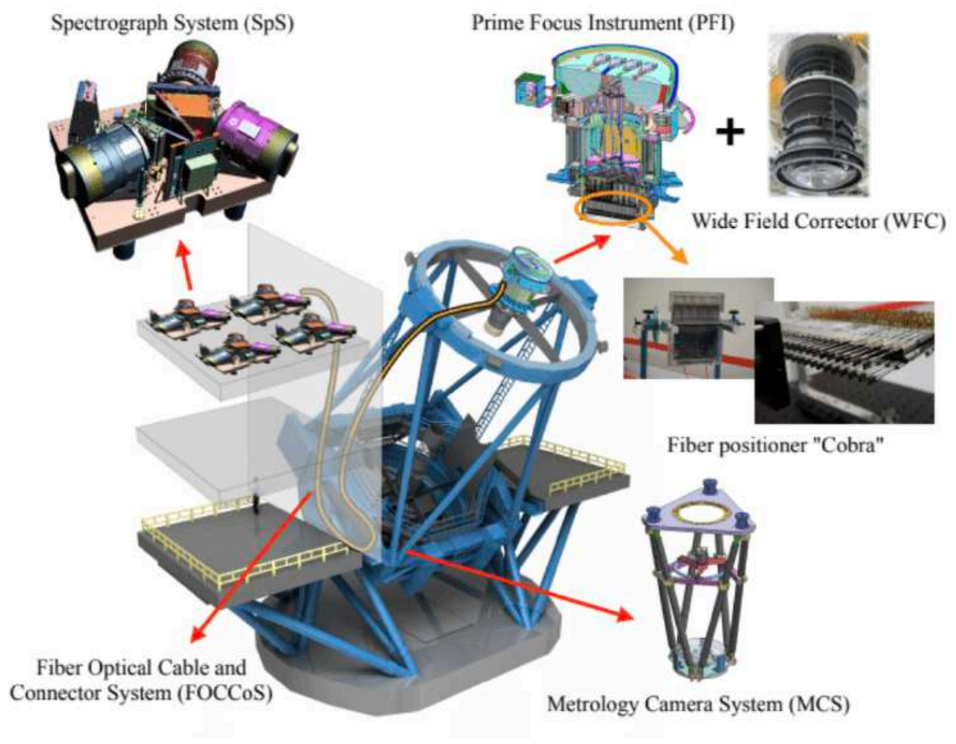


Ex.:
- H0 tension: Early dark energy - axion-like particle
- Model address H0 and S8 tensions: *"Chameleon EDE"*, Karwal et al 2021

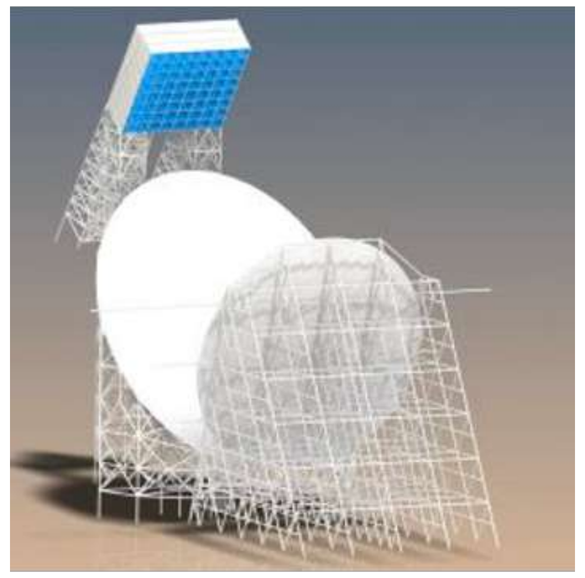
Future

Observations

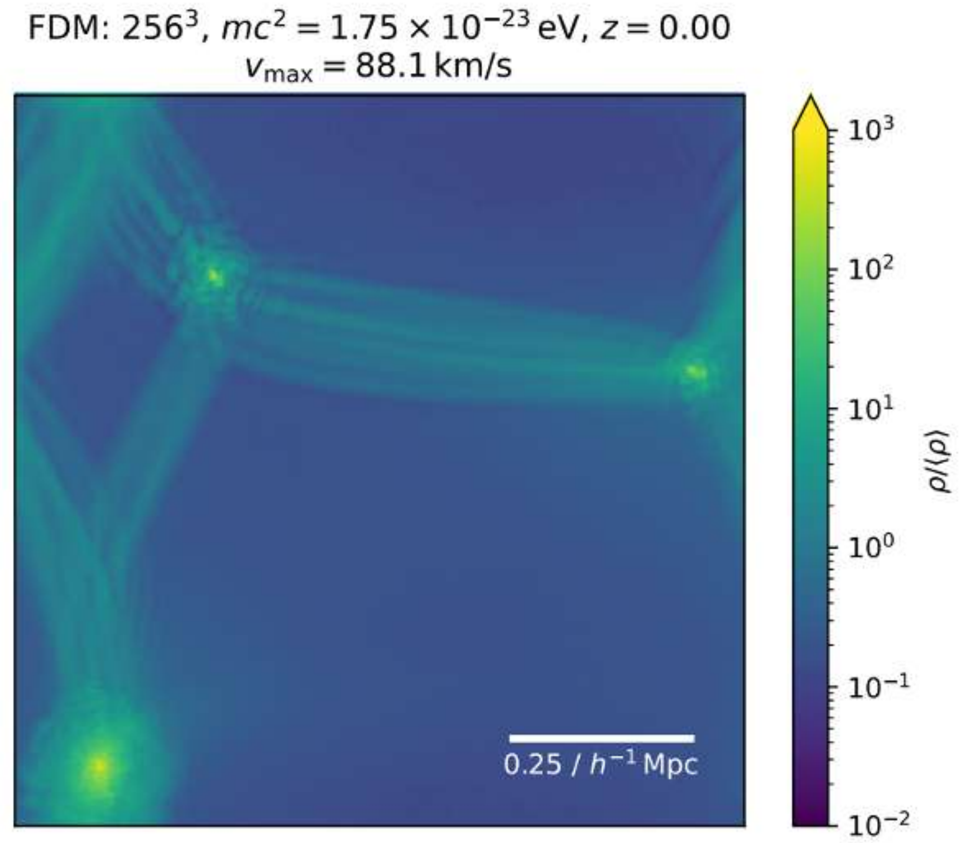
Prime Focus Specctrograph (PFS)



BINGO telescope



Simulations

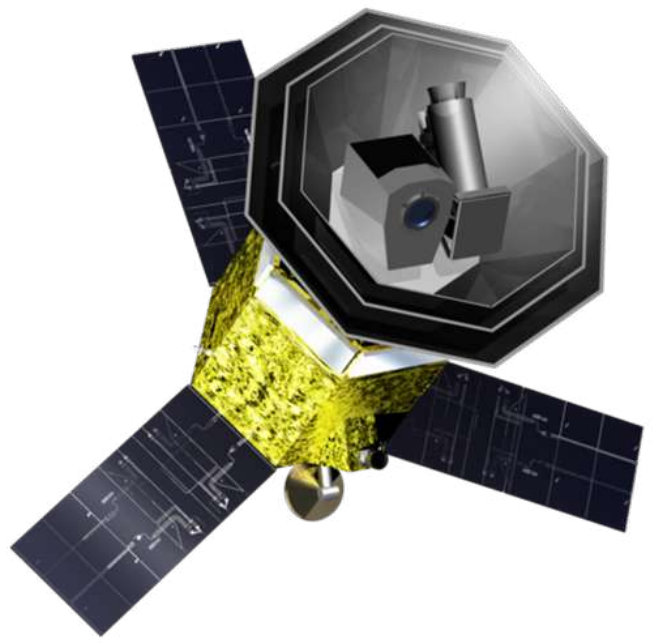


Vera Rubin observatory (LSST)

CMB-S4

CMB-S4
Next Generation CMB Experiment

LiteBIRD

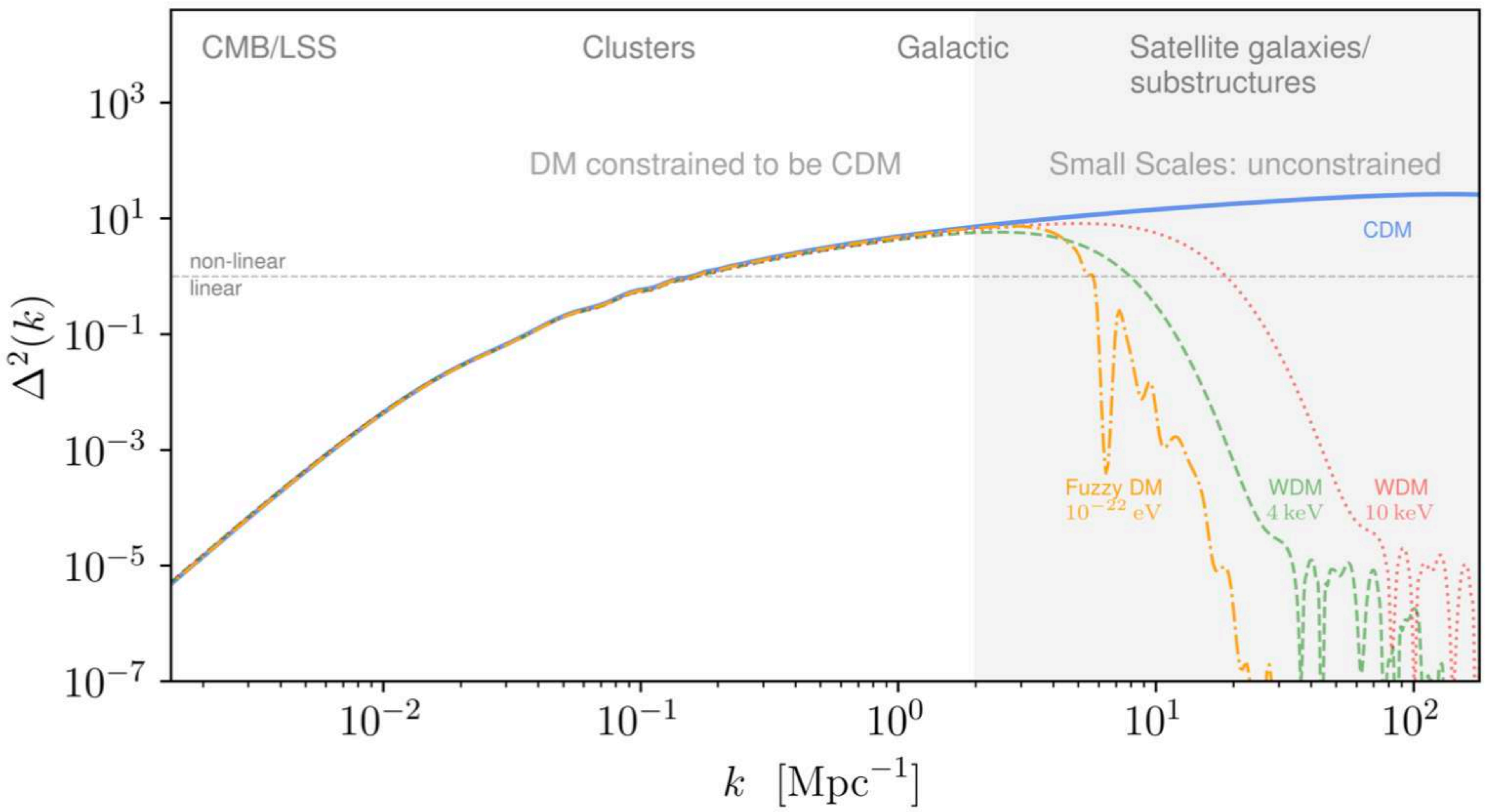


New probes

Sub-galactic power spectrum

New probes

Using gravitational probes, strong lensing and stellar streams, to describe substructures



Sub-galactic power spectrum

New probes

Using gravitational probes, strong lensing and stellar streams, to describe substructures

A. Diaz Rivero, et al. (2017); Diaz Rivero, et al. , (2018)

Bayer et al. (2018) ; Auger et al. 2009
FDM: *Kawai et al. (2021)*

Hezaveh et al. (2016) (projected mPS by using strong lensing)

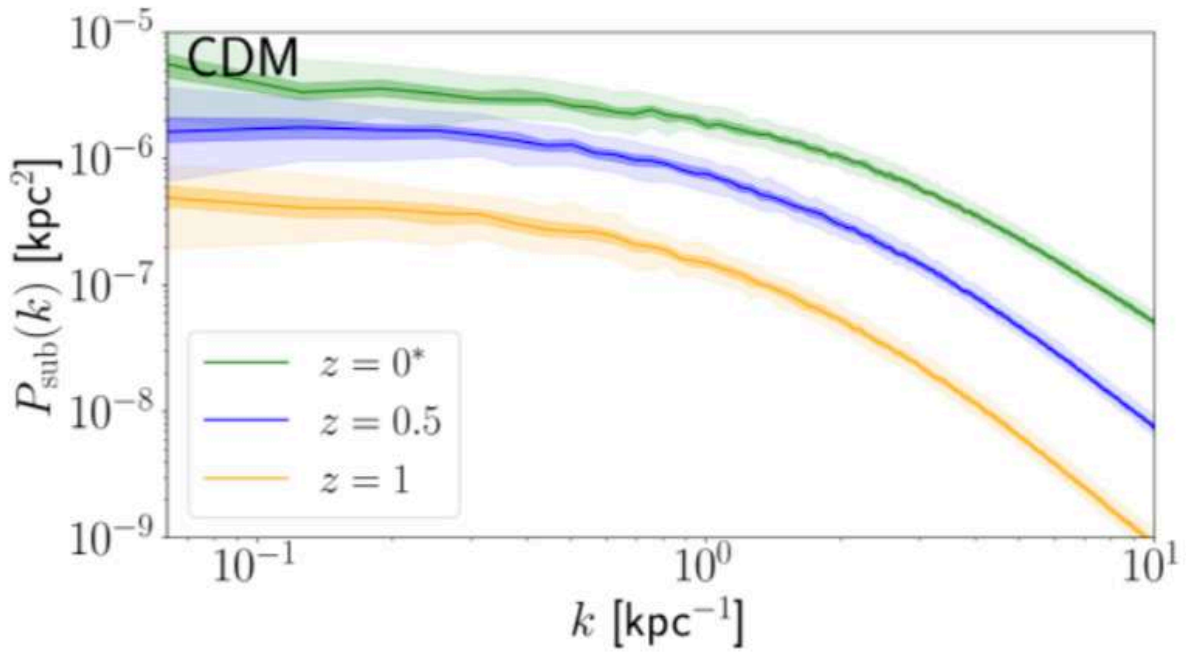
Substructure convergence power spectrum

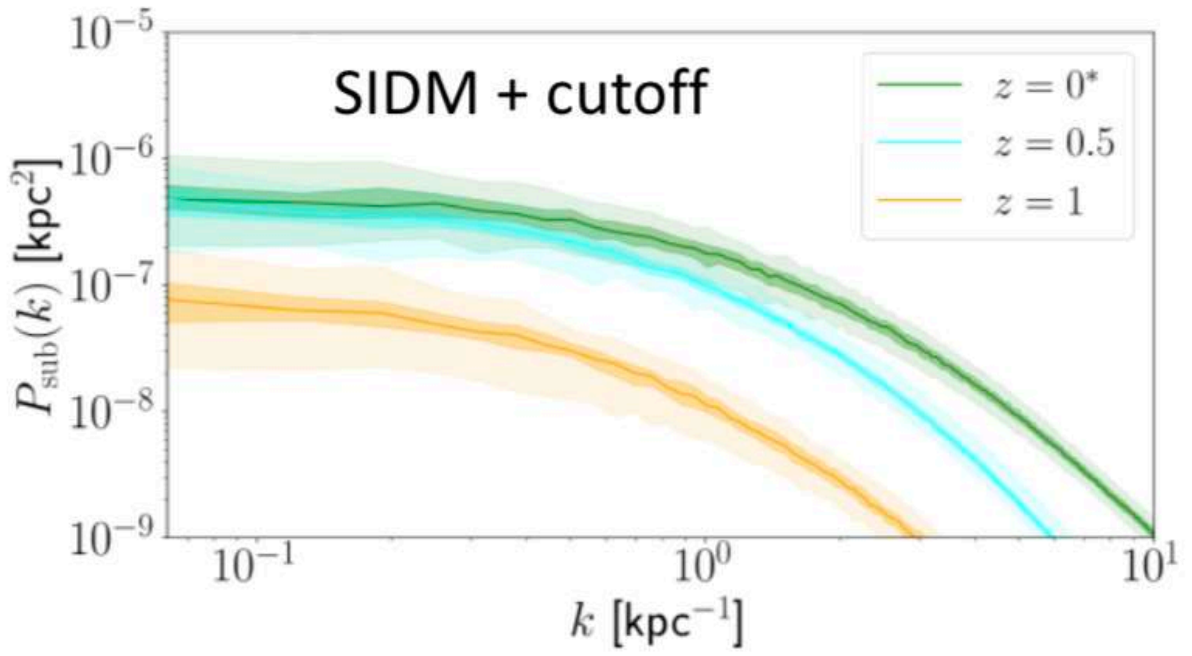
Develop a formalism to compute the substructure convergence power spectrum for different populations of dark matter subhalos.

Change of language: instead of talking about lensing perturbations in terms of individual subhalos, look at the correlation function of the projected density field.

(based on Dvorkin's slide)

$$P_{\rm sub}(k) = P_{\rm 1sh}(k) + P_{\rm 2sh}(k)$$





Sub-galactic power spectrum

New probes

Using gravitational probes, strong lensing and stellar streams, to describe substructures

Substructure convergence power spectrum

Sten Delos and Fabian Schmidt (2021)

Stellar streams: perturbed by passing substructure. Good gravitational probe, since given their low dynamical temperature and negligible self-interaction, it retains the memory of those encounters.

THIS WORK: Fully analytical understanding of the stream perturbations!

Power spectrum of a stream's stellar density is analytically related to that of the substructure background:

$$\boxed{P_*(k,t)} = \chi_*\left(k\sigma_0 t, \frac{D}{k\sigma_0^3}\right)\frac{k^2t^2}{3}P_{\Delta v}(k,t)$$

Stream power

Substructure power

$$P_{\Delta v}(k,t) = 16\pi^4 G^2\bar{\rho}^2 k^2 t \int_k^\infty \frac{\mathrm{d}q}{q}\frac{\boxed{\mathcal{P}(q)}}{q^6}\int \mathrm{d}^3\boldsymbol{u}\frac{f(\boldsymbol{u})}{u}\theta_H(qu - kv)$$

Previous:

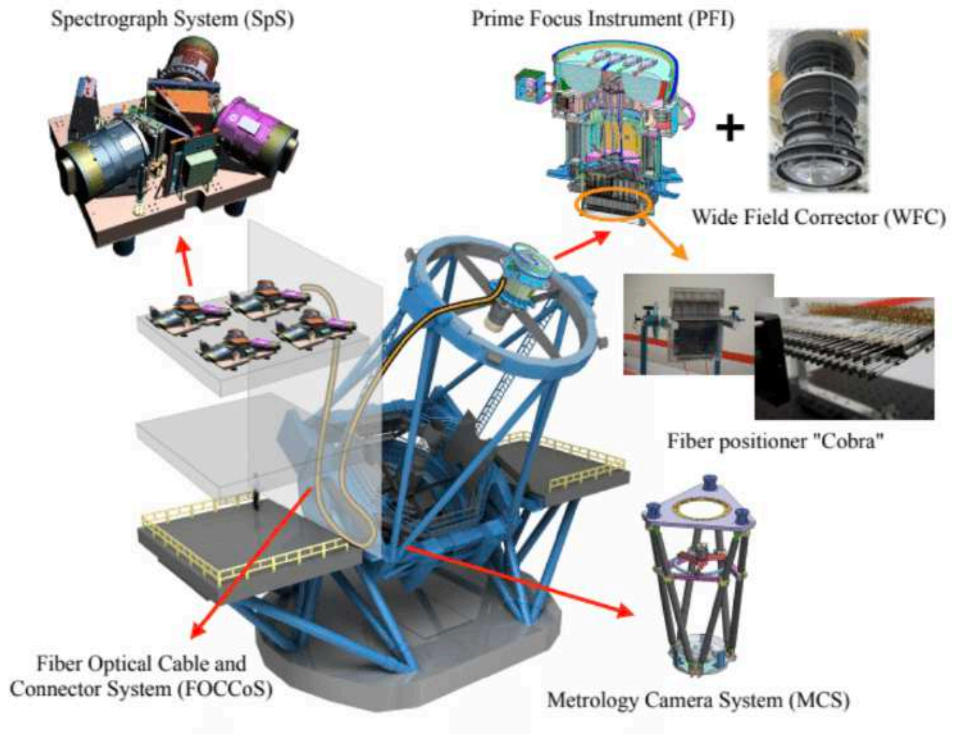
- Mostly numerical
- Perturbations ⟶ sub-halo mass function

Relates the stellar stream perturbation to the surrounding matter distribution, from dark and luminous substructure

Future

Observations

Prime Focus Specctrograph (PFS)



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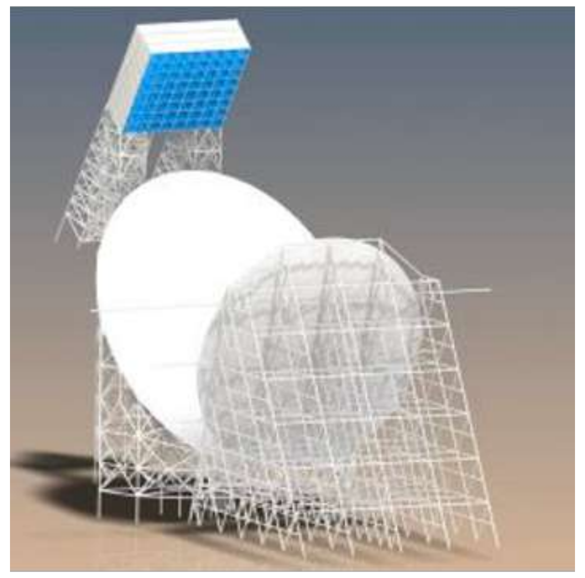
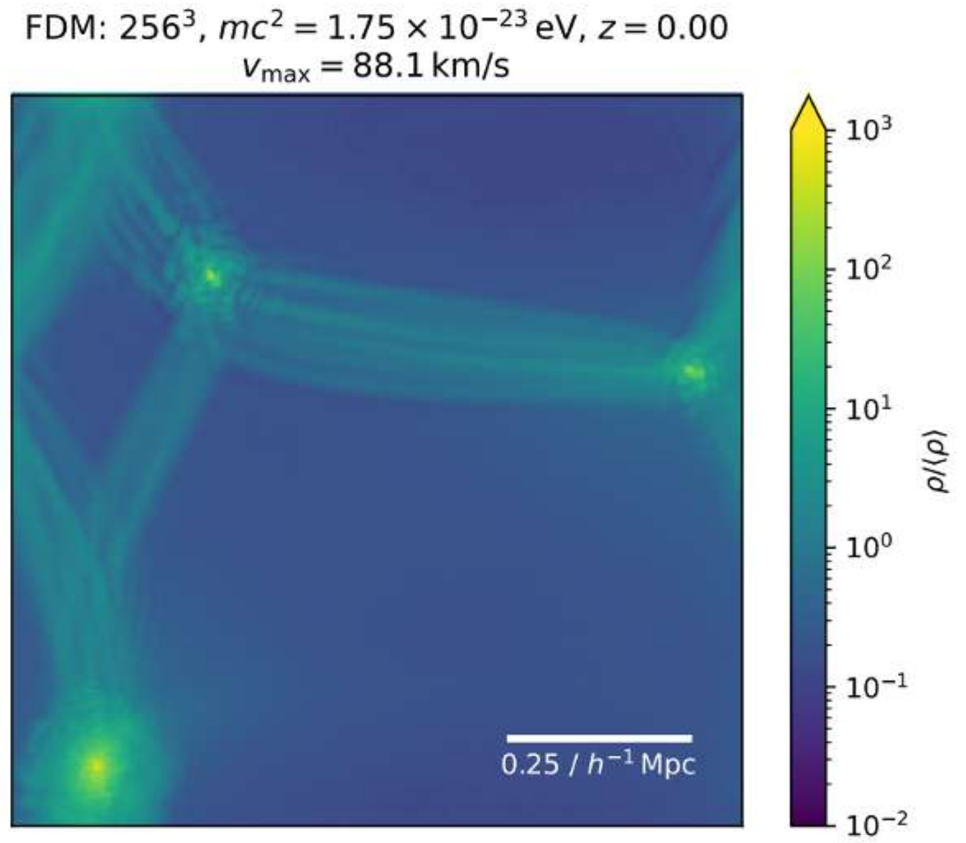


Simulations

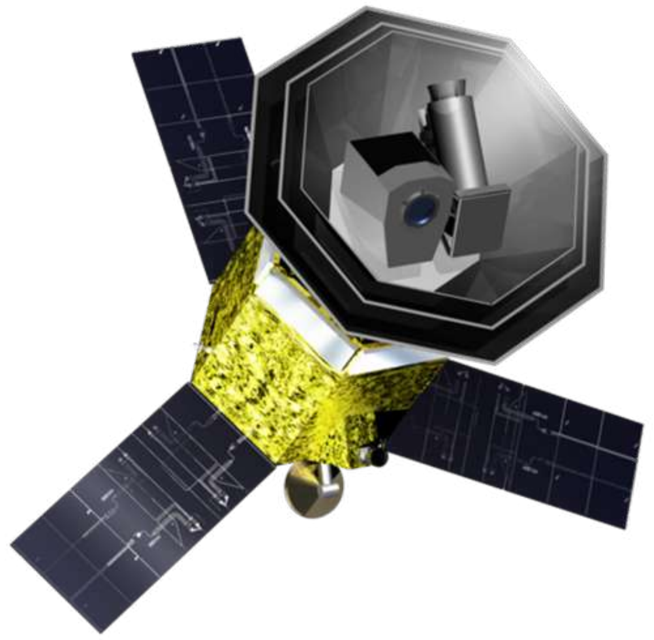


Vera Rubin observatory (LSST)

CMB-S4

CMB-S4
Next Generation CMB Experiment

LiteBIRD



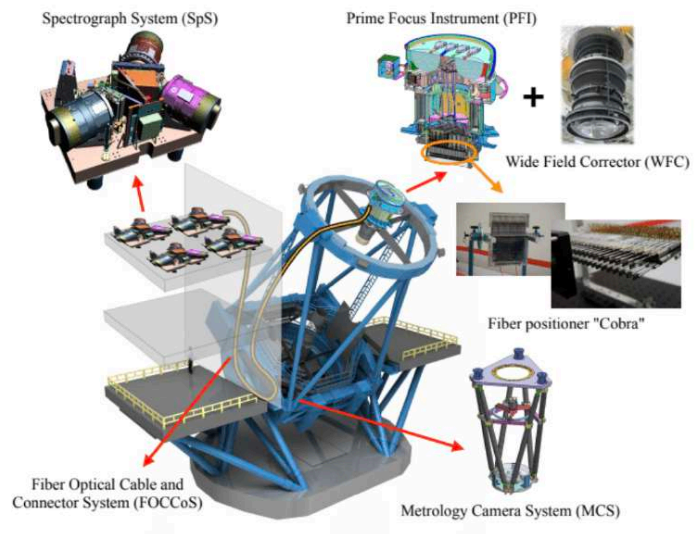
New probes

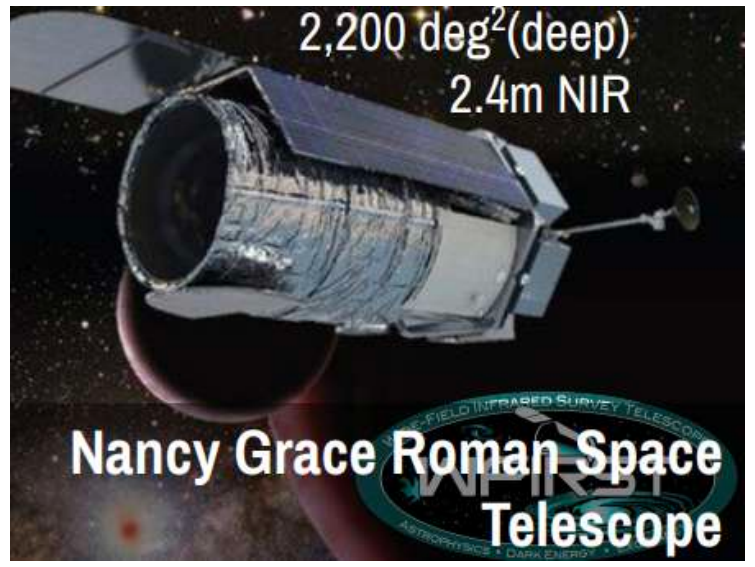
Future - signals in cosmology

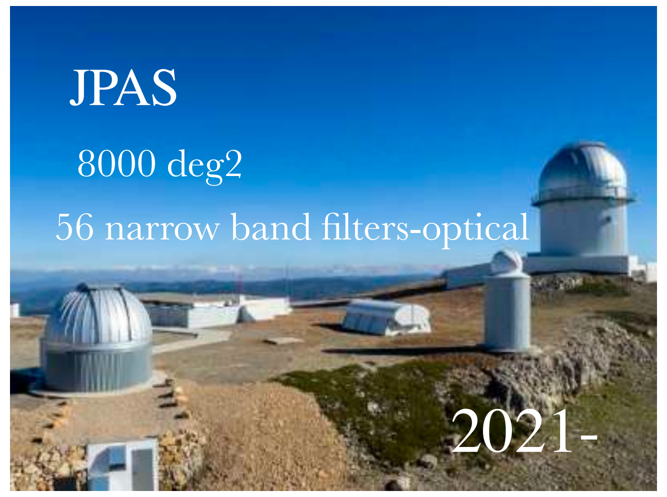
Observations

Photometric and spectroscopic surveys

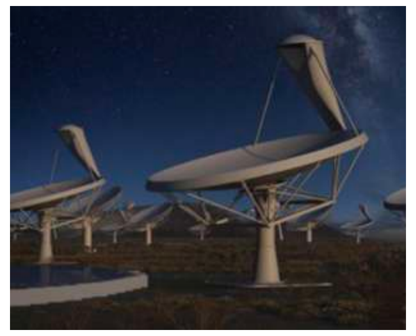
Prime Focus Spectrograph (PFS)







21cm



SKA SQUARE KILOMETRE ARRAY

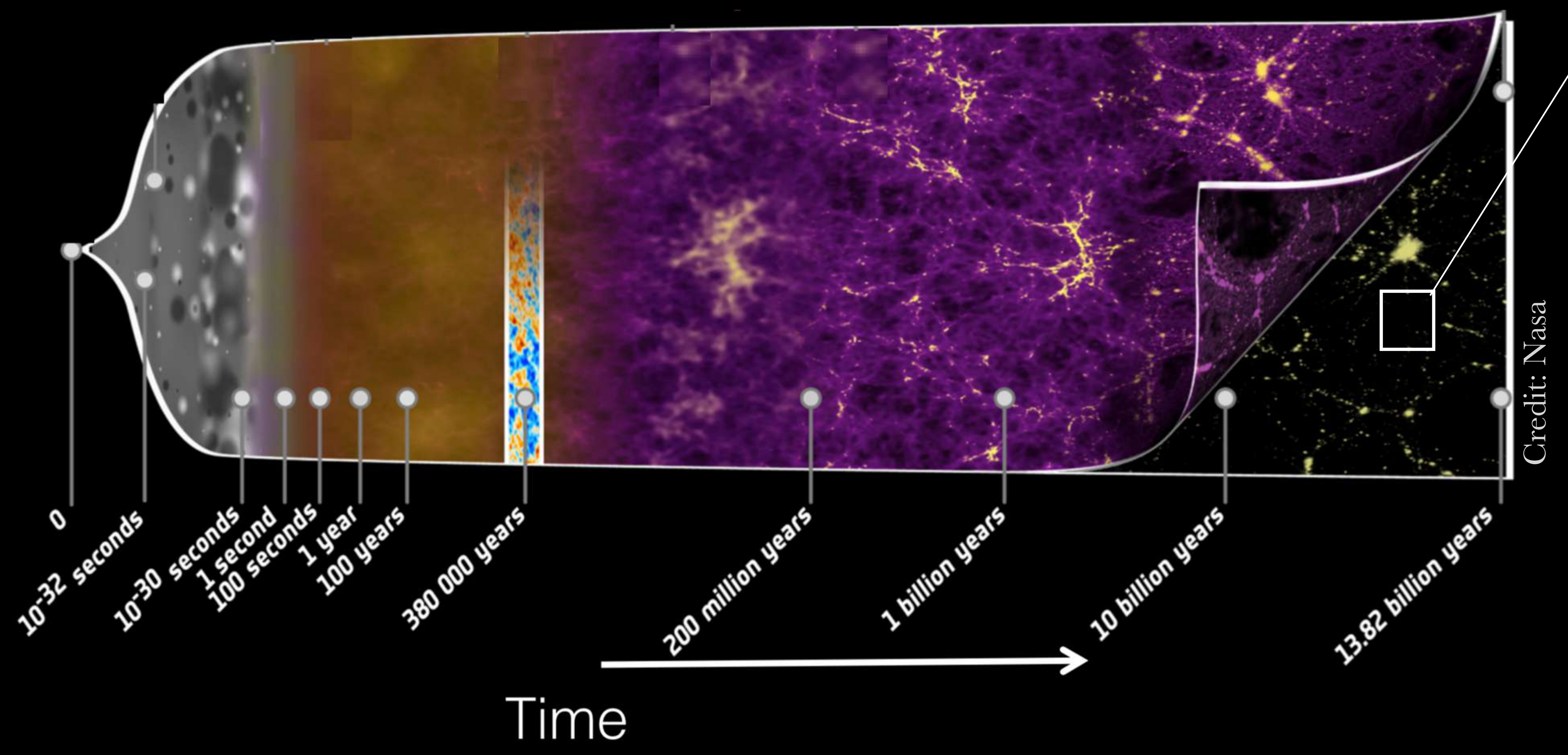
CMB

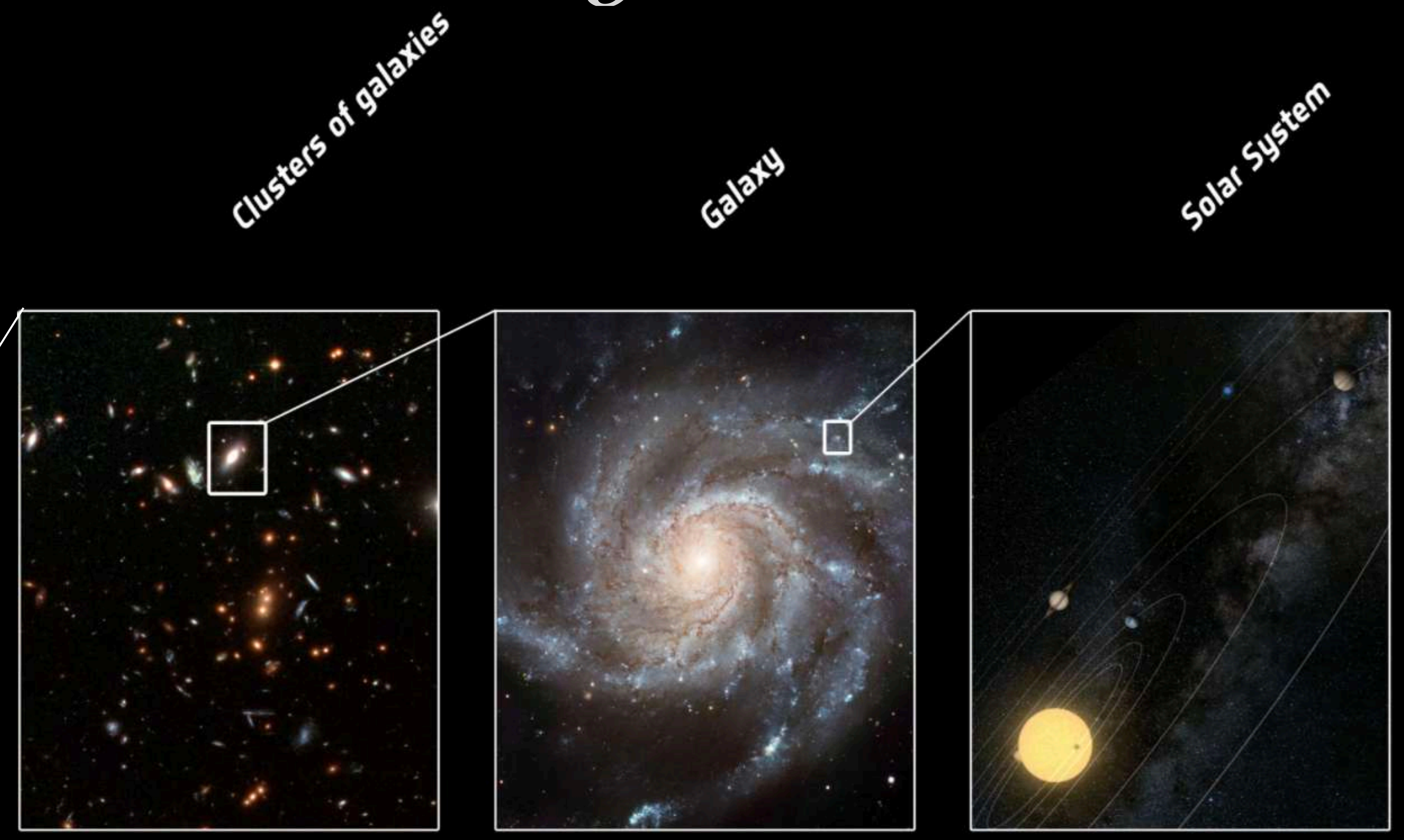
CMB-S4
Next Generation CMB Experiment

GWs

Modified from Jia Liu

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

Summary

DM builder's guide

What we learned from observations

- Cold or warm — Thermal candidate: $m_{dm} \geq \text{keV}$

  Or produced cold by a non-thermal mechanism

- Reproduce large and small scale distribution

  Clusters like CDM on large scales $k \lesssim 10\,\text{Mpc}^{-1}$

  Clustering on scales smaller than $k \gtrsim 10\,\text{Mpc}^{-1}$ highly unconstrained

- Non-interacting or weakly interacting

  Can have a small electromagnetic interaction. Bound < **milicharge**

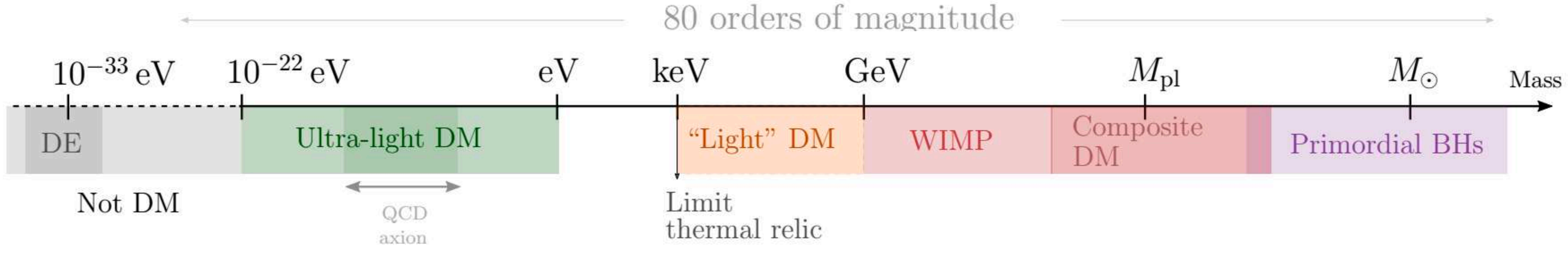
  Can have a small **self interaction**.

  Can interact via the ***weak force***

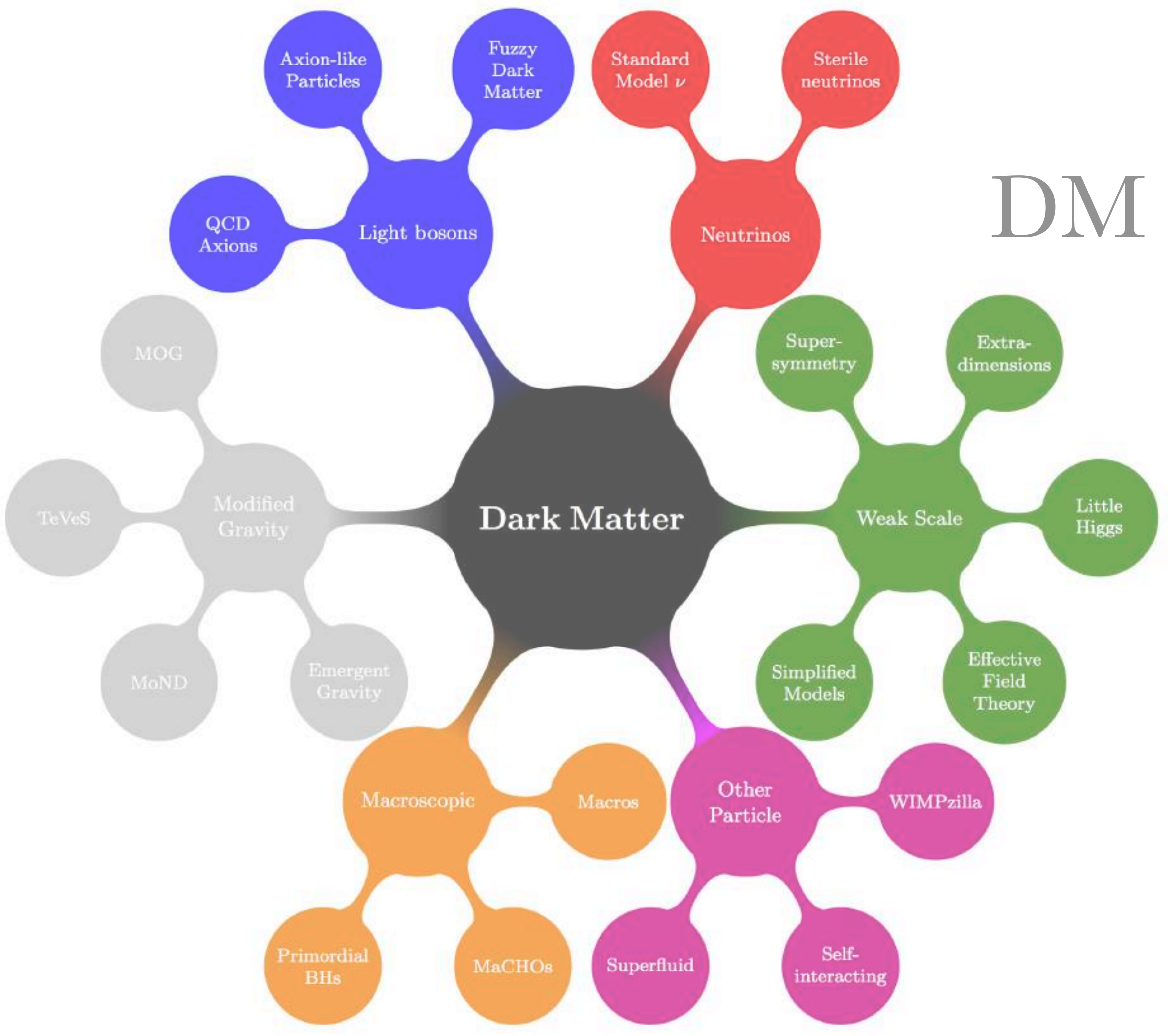
- Abundance $\Omega_m = 0.308 \pm 0.012$ *(Planck 2018)*

- Stable

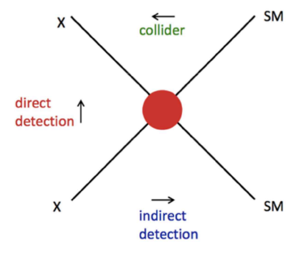
Mass scale of DM



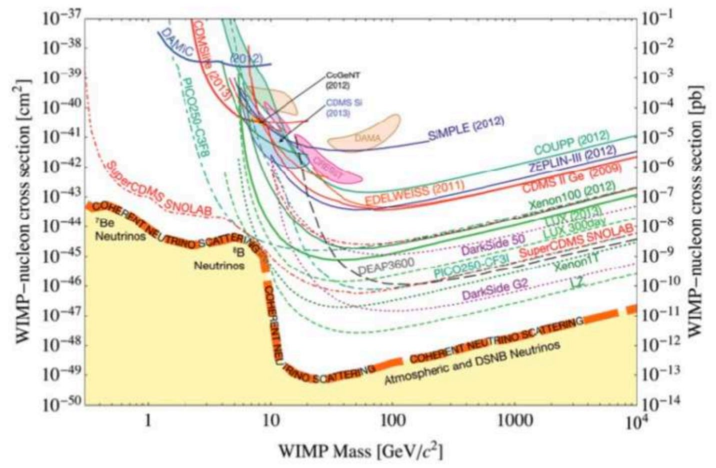
DM Landscape



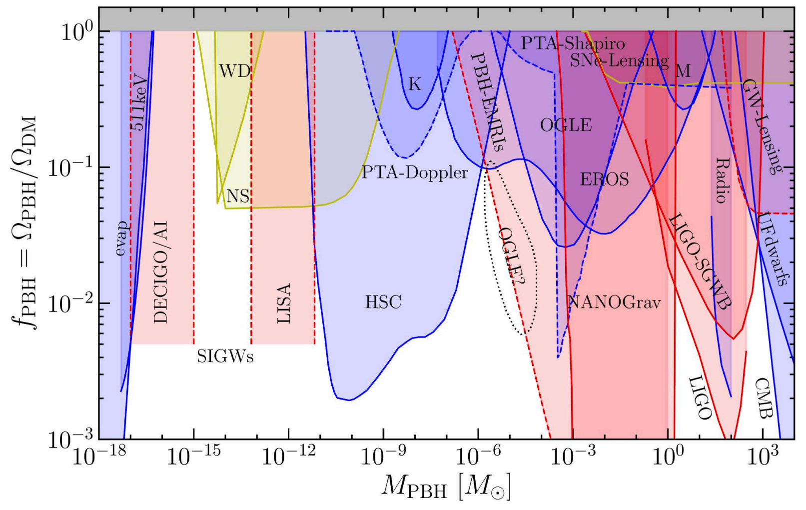
Search for DM



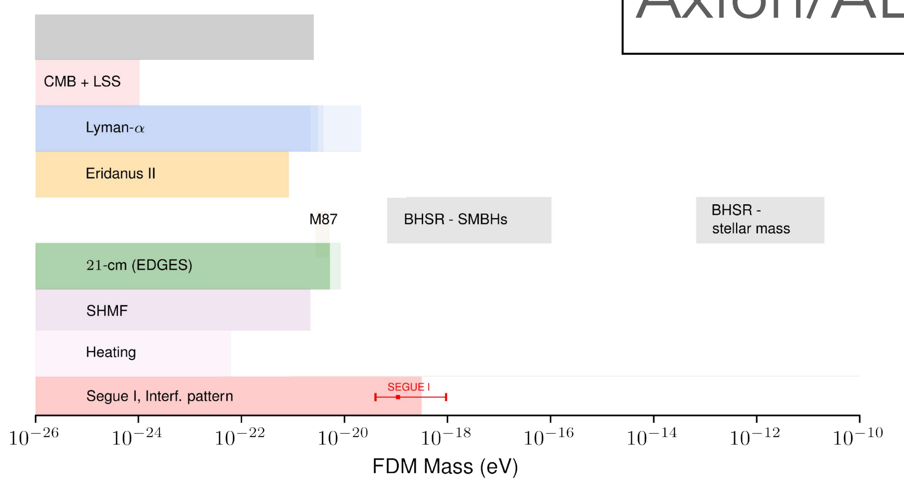
WIMPS

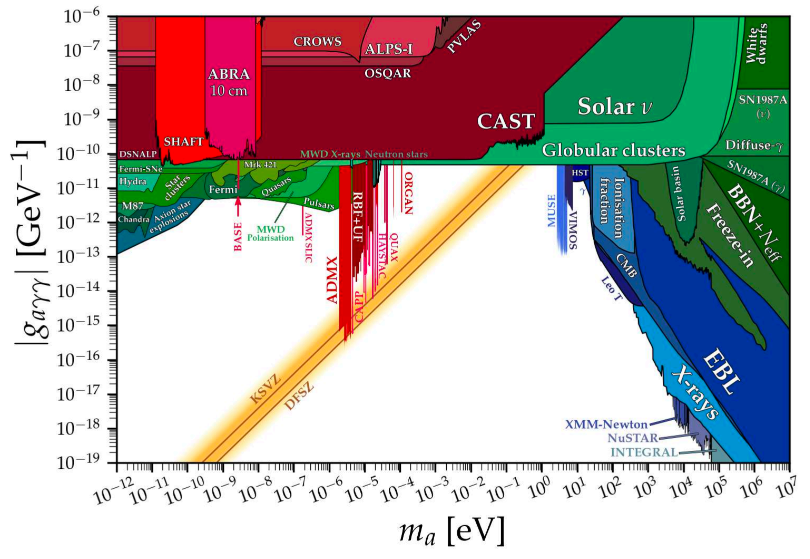


PBHs



Axion/ALP






Thank you very much!