Dark matter & axion detection

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Interest:
Astrophysical methods to study Fundamental Physics

→ Fundamental interactions

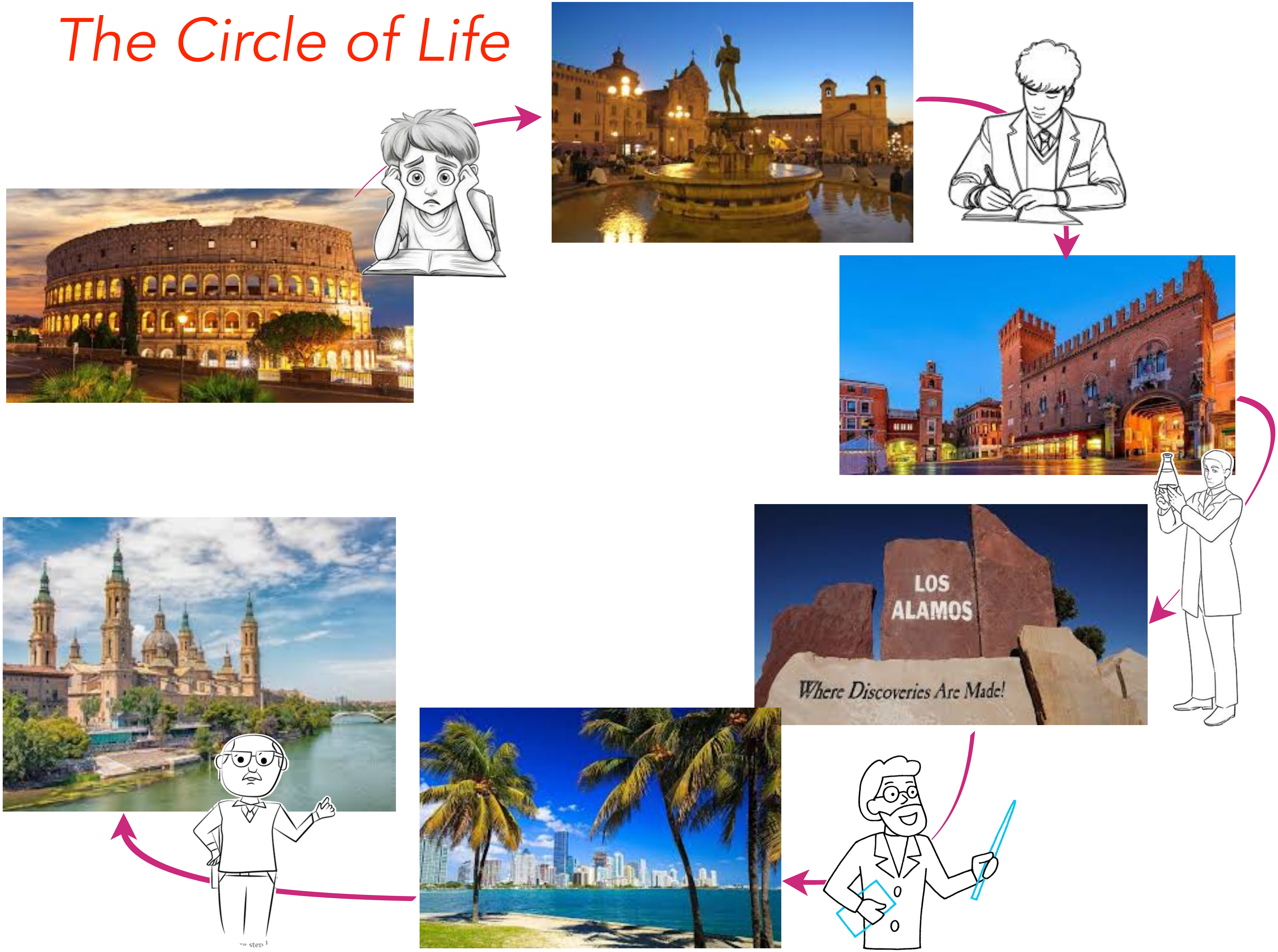
→ New particles

→ Particle Physics beyond the Standard Model (SM)

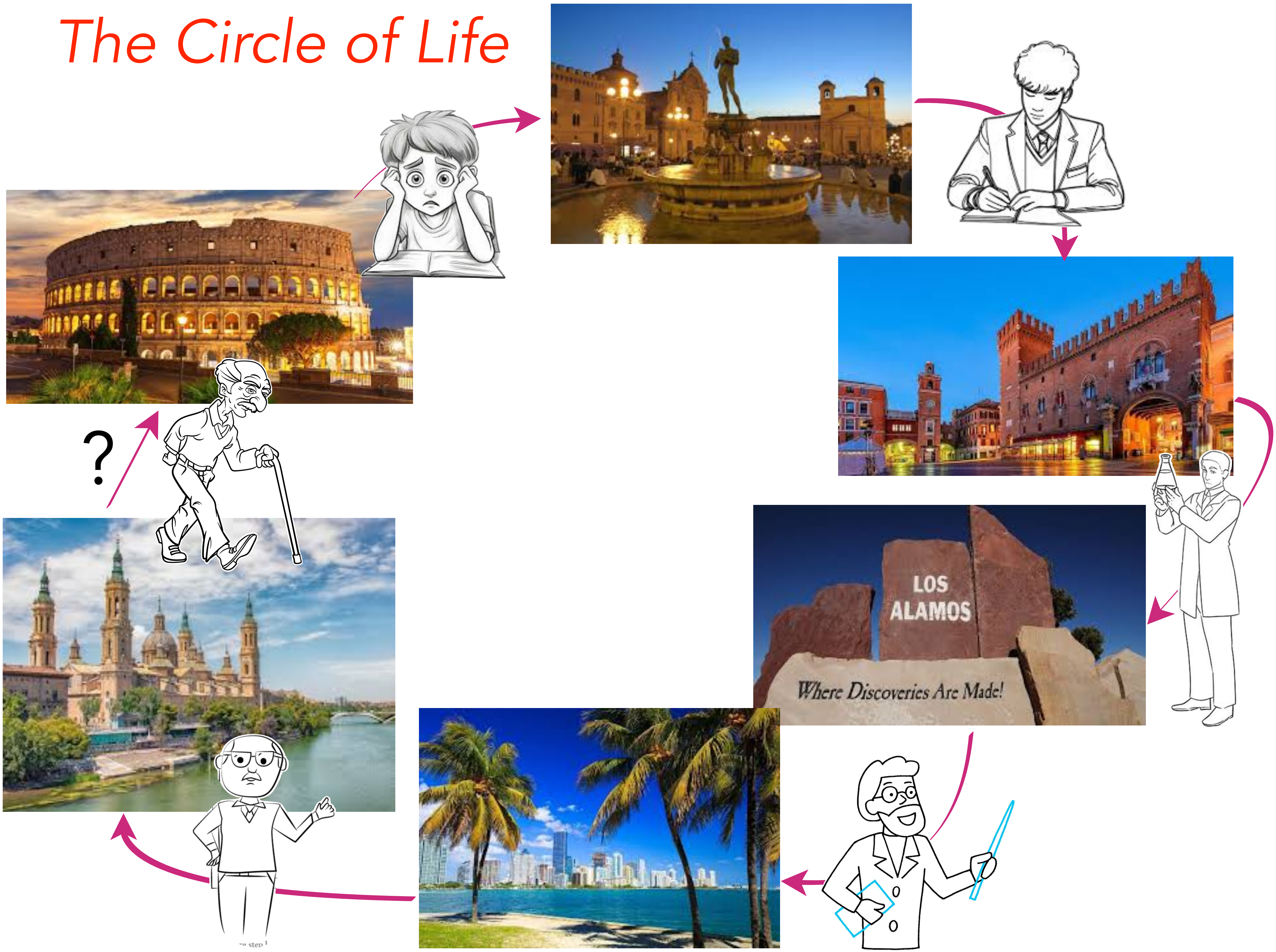
Be ready to Travel

Universidad de Zaragoza (Spain)

The Circle of Life



The Circle of Life



Summary

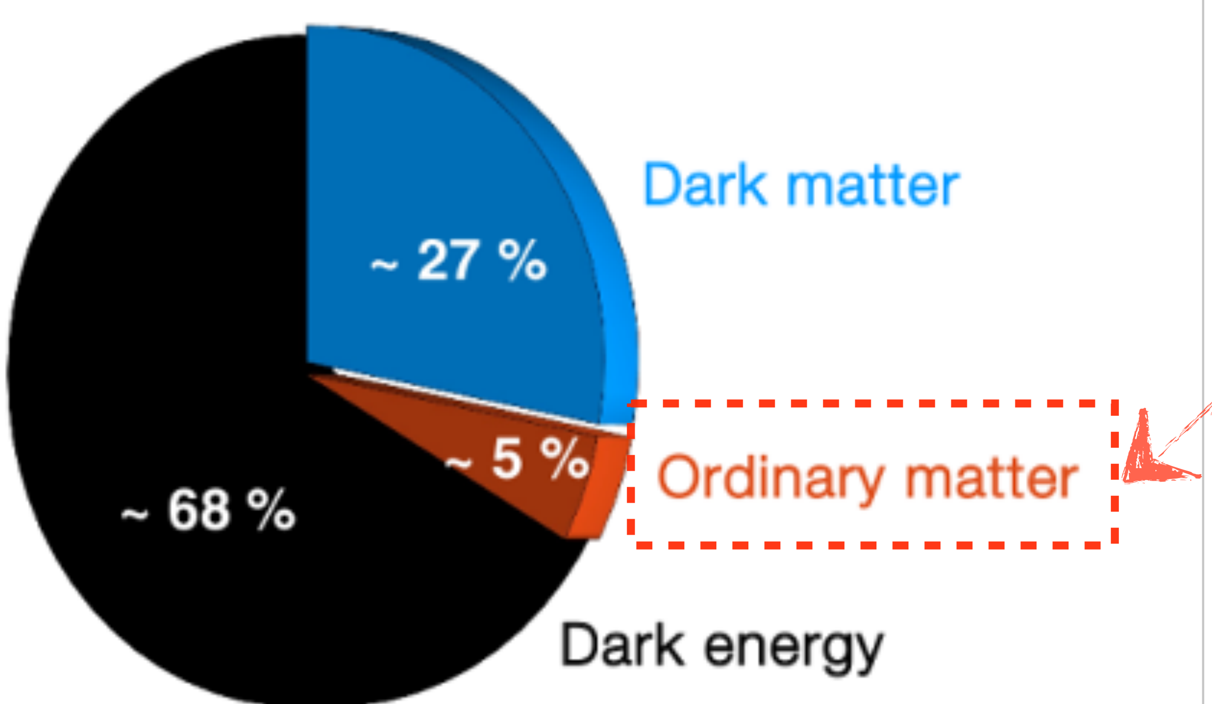
- *Dark Matter*
- *Axions as a fundamental QCD ingredient*
- *The search for axions*

Disclaimer: *Far from complete. Please contact me if you want to get more info or want to know about groups involved in some of this research*

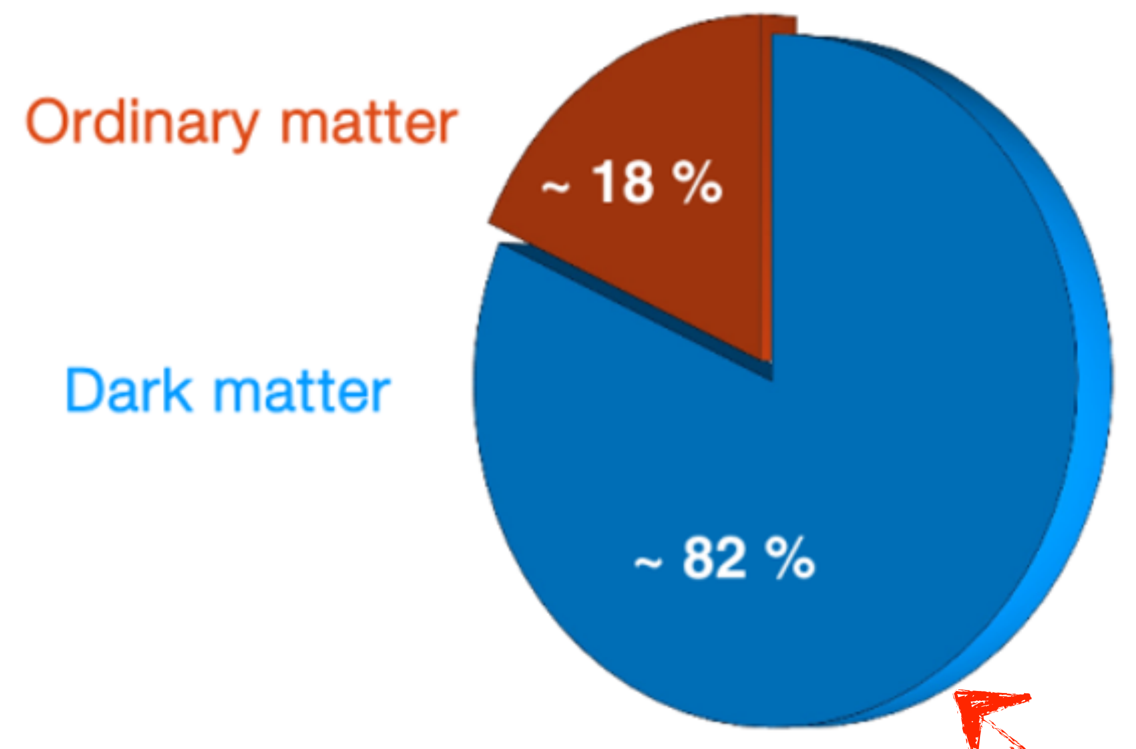
Part 1: Dark Matter

The Dark Matter problem

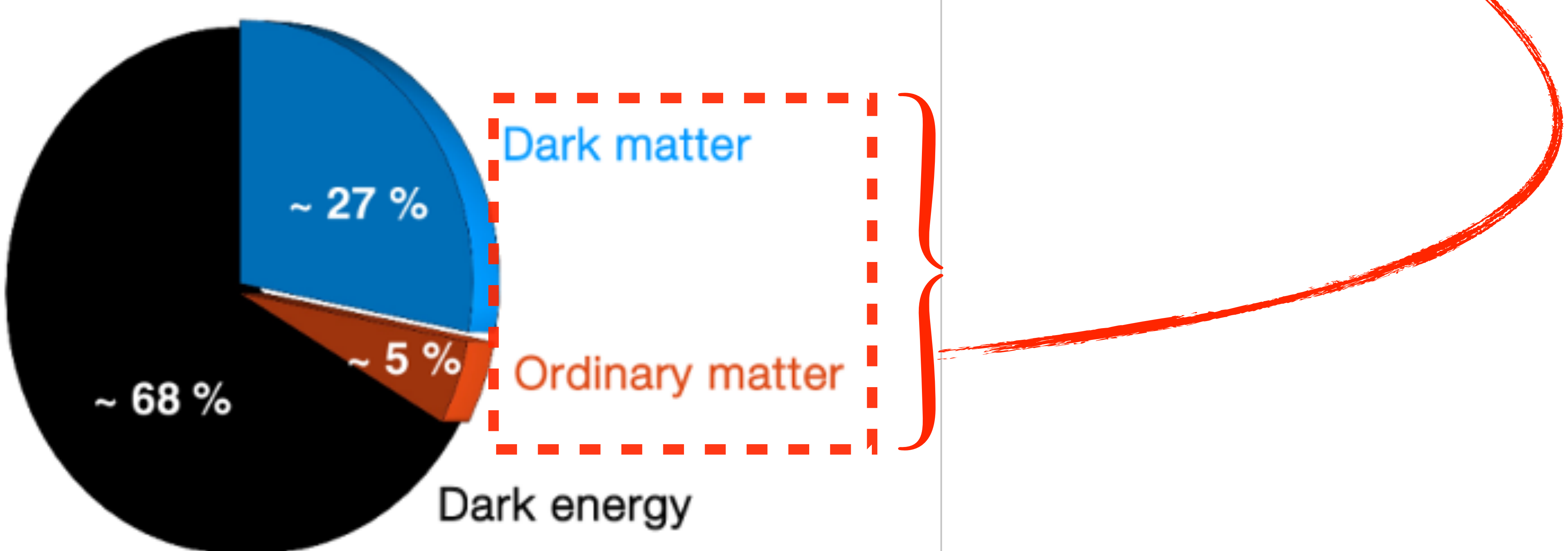
What we understand about the universe



The Dark Matter problem



Most of the matter is dark



Dark Matter?

- **Lord Kelvin** discussed in the appendix of a book based on a series of lectures given in 1884 the hypothesis of “dark bodies”. In discussing Kelvin’s work, in 1906 **Henri Poincaré** used the French term [matière obscure] ("dark matter")

- Dutch astronomer **Jacobus Kapteyn** suggest the existence of dark matter using stellar velocities in 1922

- **Oort** found that the mass in the galactic plane must be greater than what was observed, but this measurement was later determined to be incorrect

- In 1933, Swiss astrophysicist **Fritz Zwicky** applied the virial theorem to the Coma Cluster and obtained evidence of unseen mass he called dunkle Materie ('dark matter'). Zwicky estimated its mass based on the motions of galaxies near its edge and compared that to an estimate based on its brightness and number of galaxies.

- One of the observations that served as evidence for the existence of galactic halos of dark matter were those of **Vera Rubin** and **Kent Ford** about the shape of galaxy rotation curves (1970s).

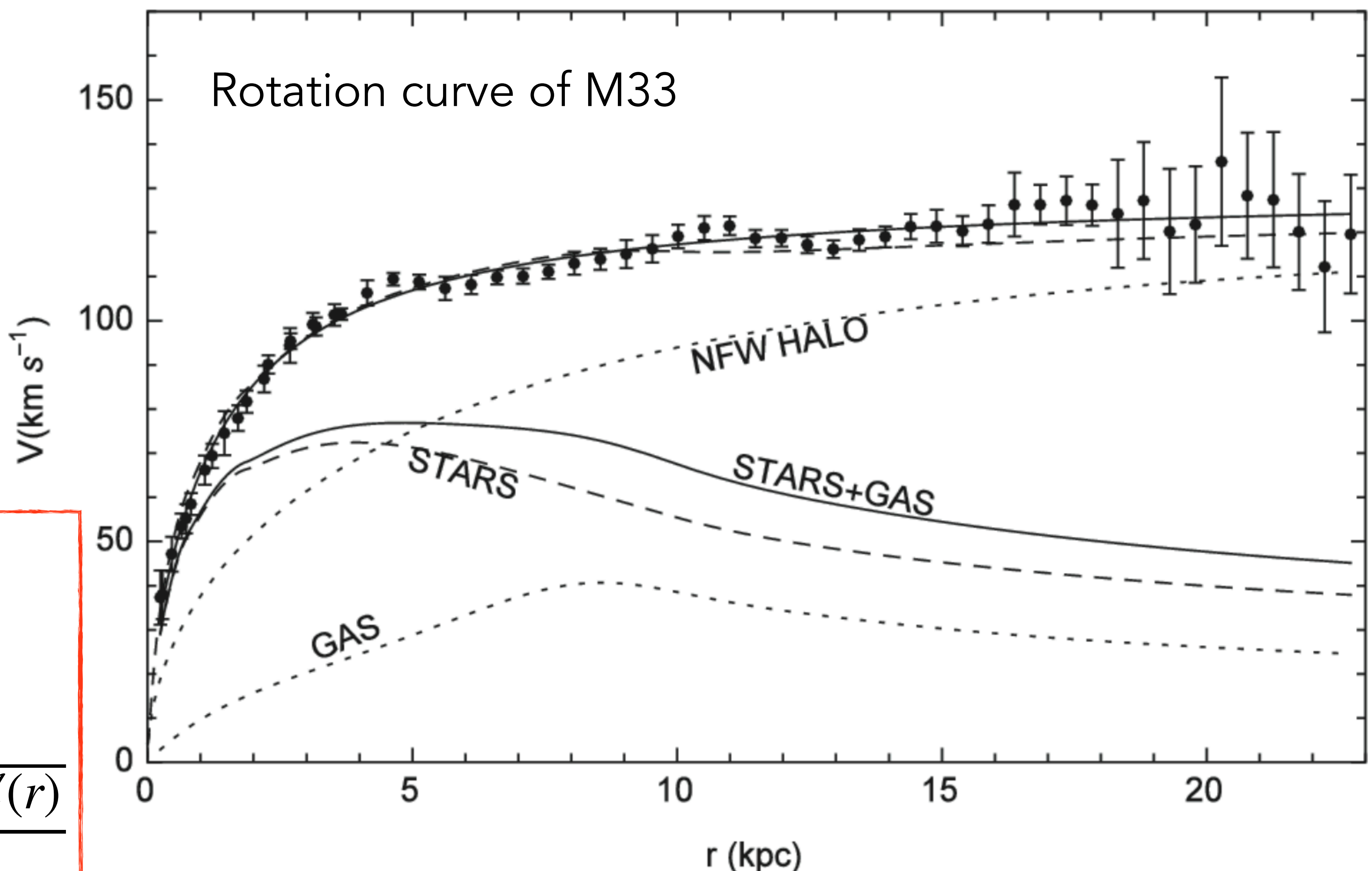
Rotation curves of spiral galaxies

Measuring the Doppler shift of atomic lines in spiral galaxies → circular velocity of stars as a function of their distance from the galactic center

rotation curve.

$$m\frac{v_{\rm circ}^2(r)}{r} = \frac{Gm\mathscr{M}(r)}{r^2}$$

$$\Rightarrow \quad v_{\rm circ}(r) = \sqrt{\frac{G\mathscr{M}(r)}{r}}$$



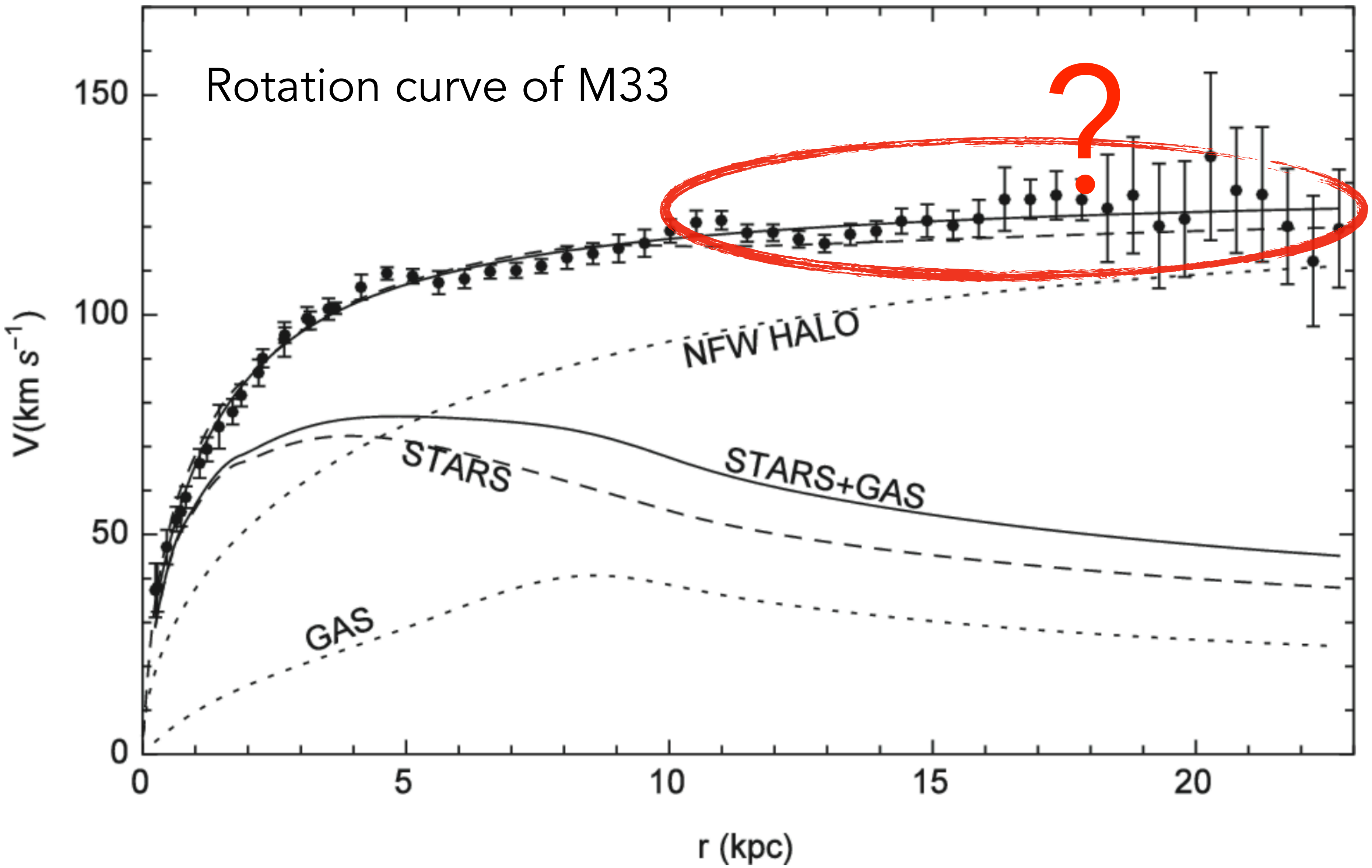
Yu: 2024 TASI Lectures: A Dark Matter Primer

Rotation curves of spiral galaxies

Measuring the Doppler shift of atomic lines in spiral galaxies → circular velocity of stars as a function of their distance from the galactic center

Rubin and Ford in 1970: first precise measurement of the rotation curve of the Andromeda galaxy (M31)

They determined the curve to be rather flat out to~22 kpc



Yu: 2024 TASI Lectures: A Dark Matter Primer

X-rays probe of DM in Galaxy Clusters

Hydrostatic equilibrium for a gas in a galaxy cluster

$$\frac{1}{\rho_{\rm gas}(r)}\frac{dP_{\rm gas}}{dr} = -\frac{d\phi}{dr} = -\frac{GM(r)}{r^2}$$

Ideal gas:

$$P_{\rm gas} = \frac{\rho_{\rm gas} k T_{\rm gas}}{\mu m_p},$$

($\mu \approx 0.6$ = mean molecular weight of an admixture of $\sim 75\,\%$ H and $\sim 25\,\%$ He)

Density and temperature can be measured from the intensity and the spectrum of the X-ray emission, thereby allowing to reconstruct the total cluster mass as well as its profile using raw HE equation

The results confirm that the gas constitutes only a portion of the total mass of the galaxy cluster

DM halos around galaxies

The existence of massive DM halos around galaxies can also be proven via galaxy-galaxy lensing

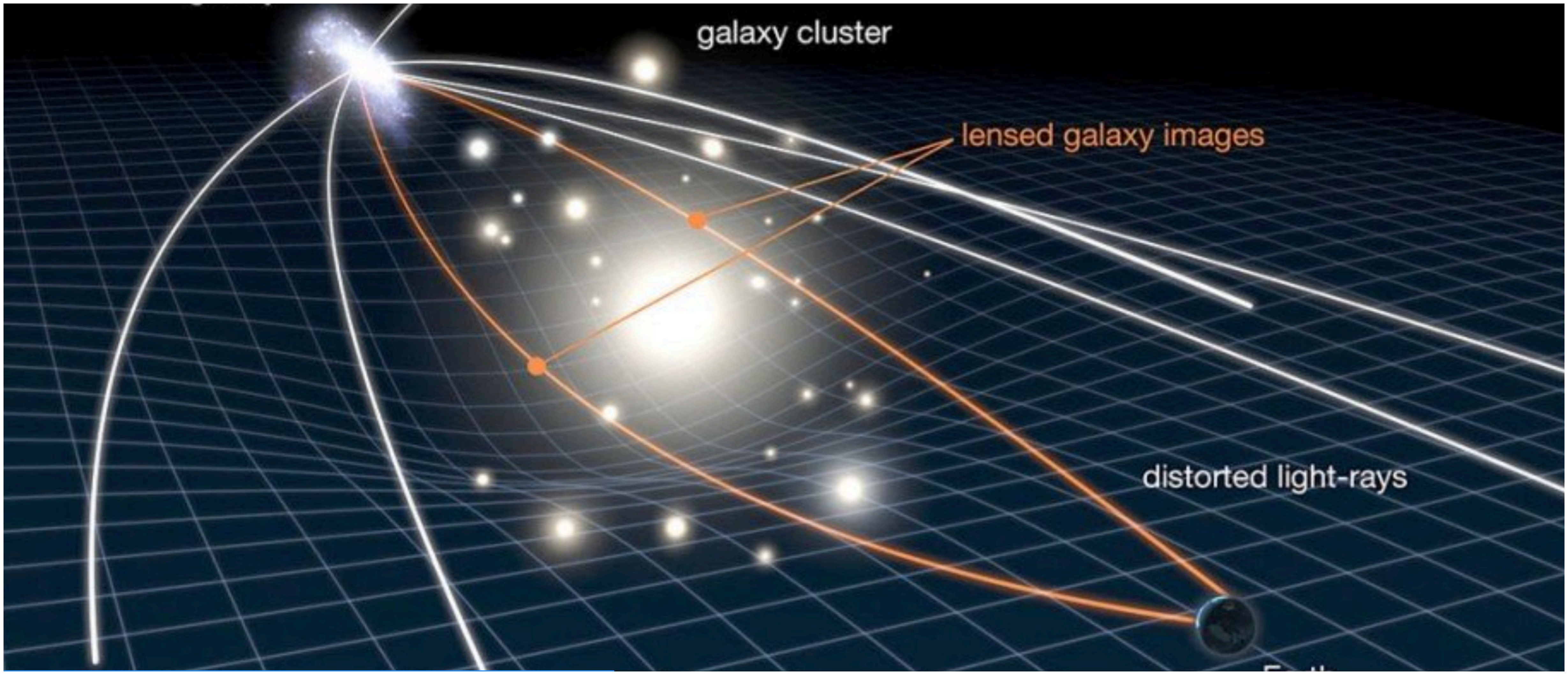


Figure credit Bodo Schwabe

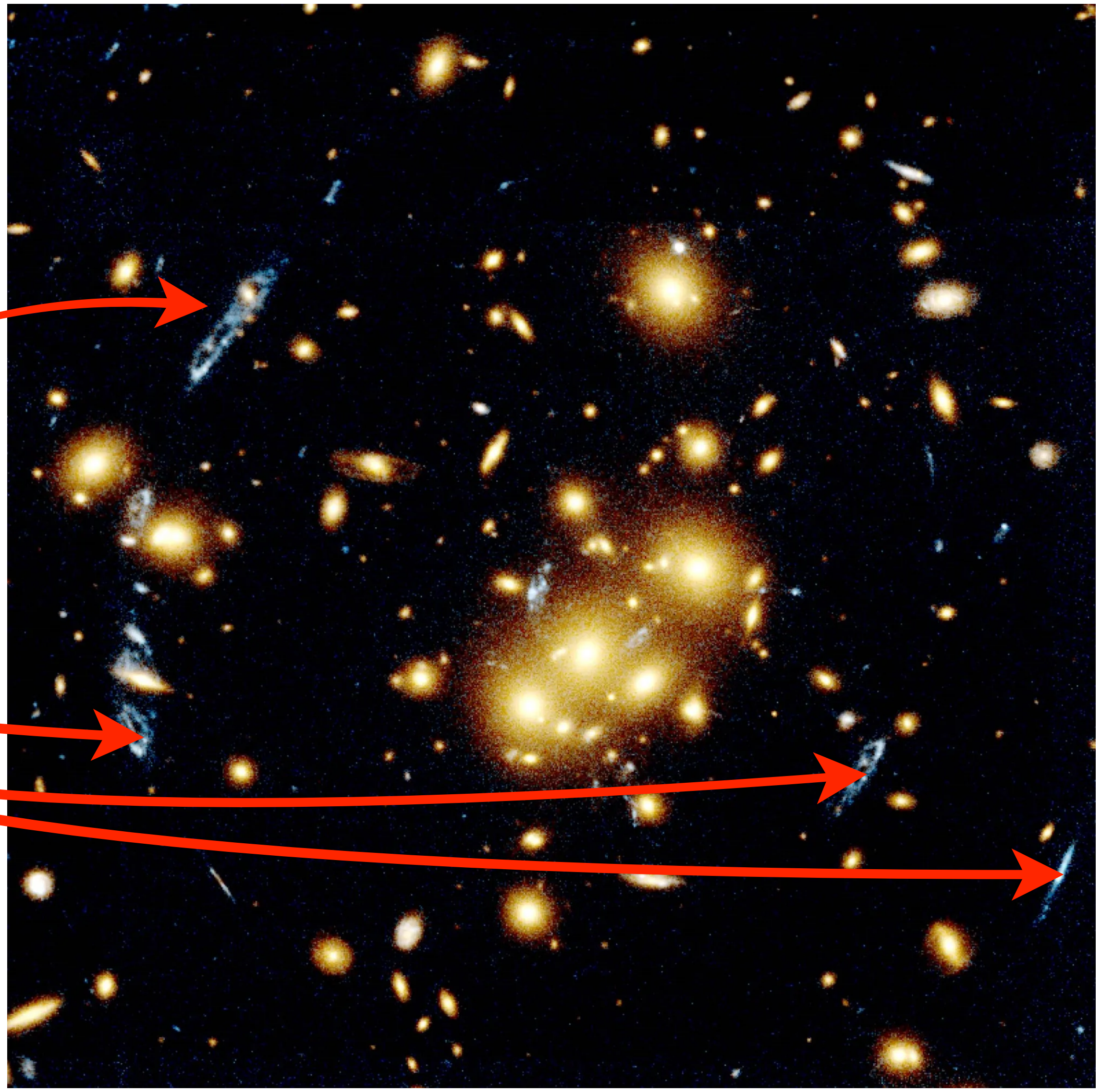
DM halos around galaxies

The existence of massive DM halos around galaxies can also be proven via galaxy-galaxy lensing

This is the distortion of the images of background galaxies induced by the gravitational lensing effect of the foreground galaxies.

Lensed images of the same galaxy

In the case in figure the lens is the galaxy cluster 0024+1654



Hubble image. Source: science.nasa.gov

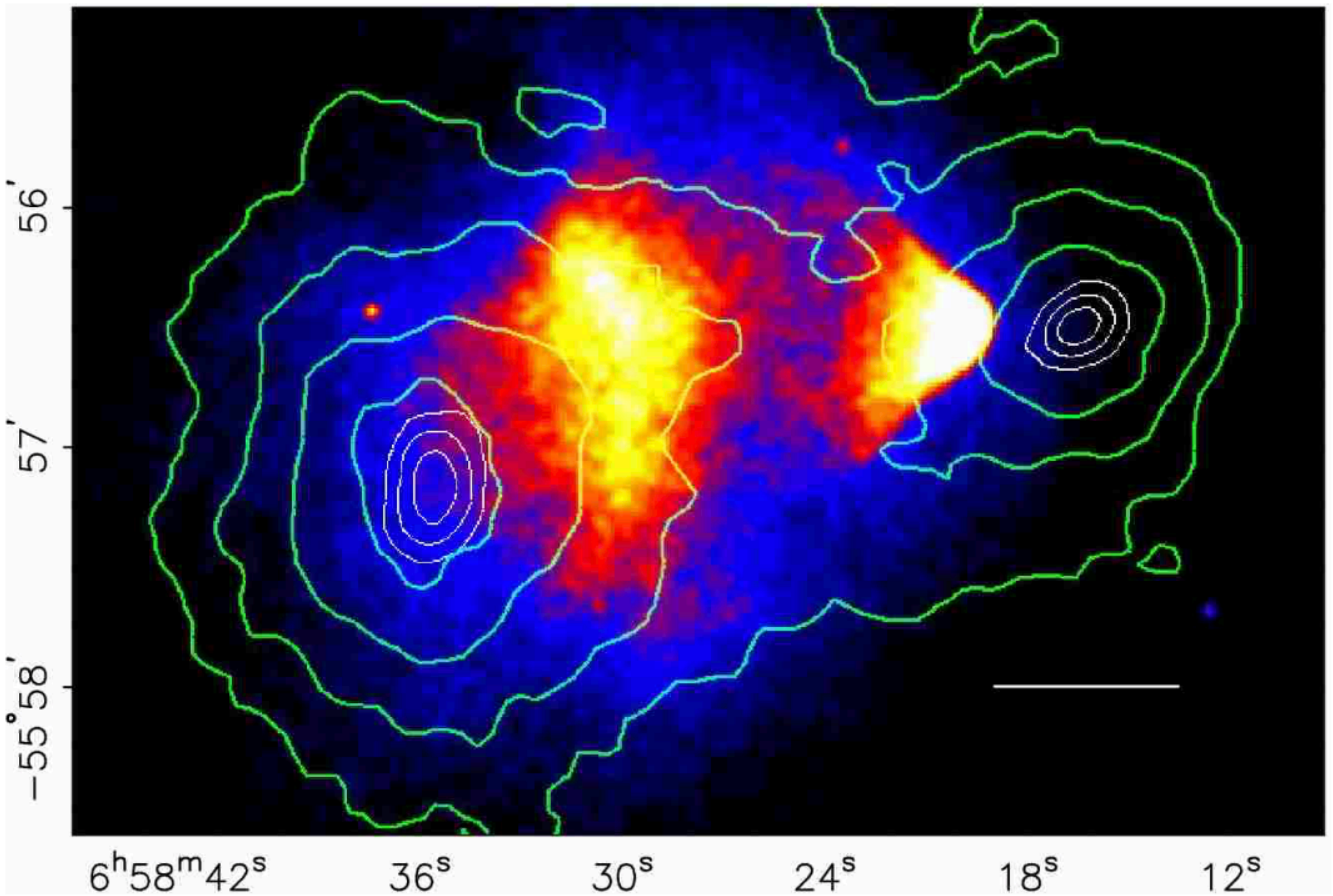
The Bullet Cluster

One of the most remarkable empirical evidence of DM

System consists of two colliding galaxy clusters.

Lensing allows to map the total mass (including DM) while X-ray observations can map the hot baryon gas.

Evidently, the majority of the mass is not impacted by the collision, while the baryonic gas is slowed down.

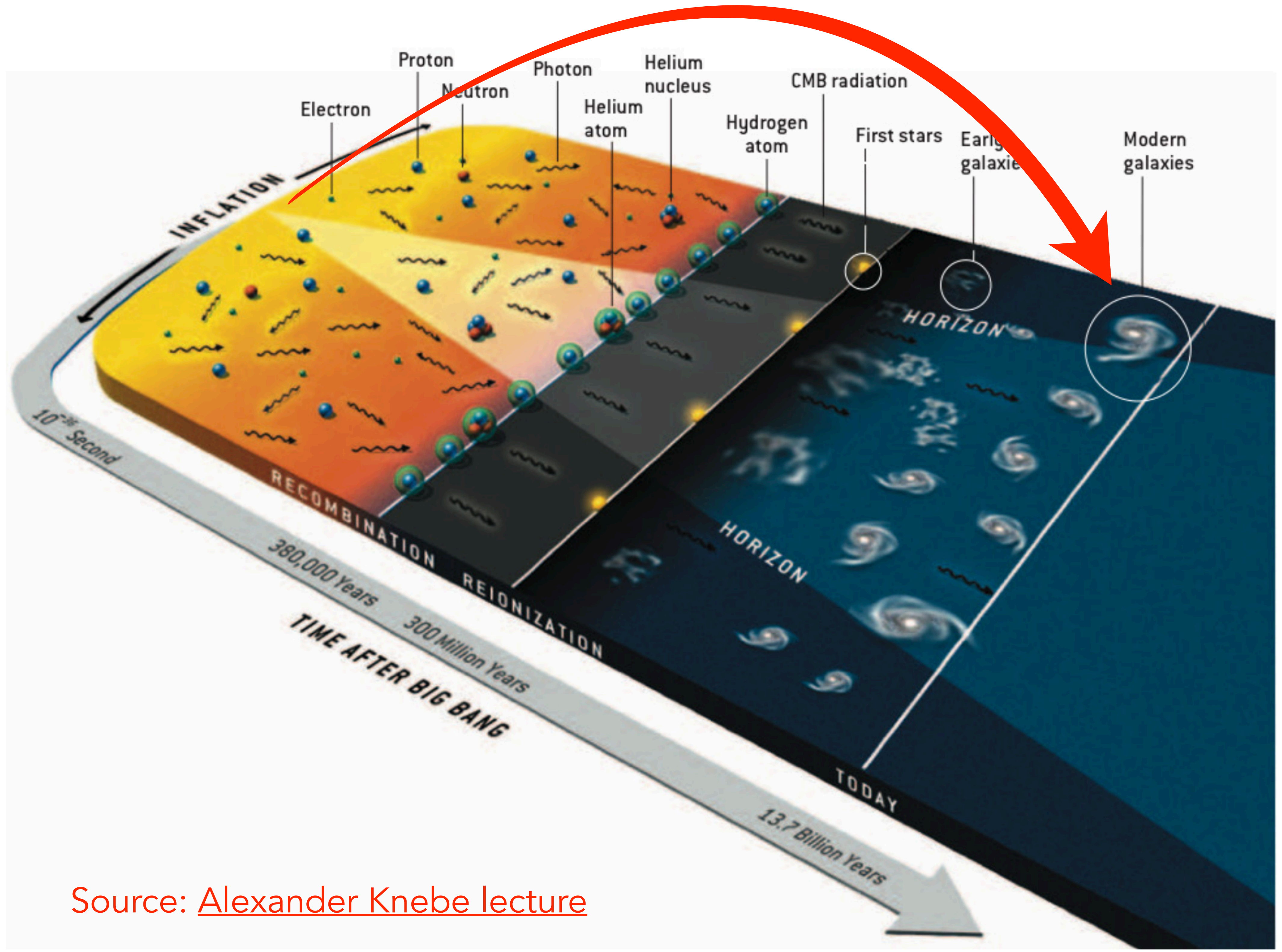


Mass in green contours and hot gas in color scale. Fig. from the original study: D. Clowe et al. (2006)

⇒ Strong constraints on DM self-interaction

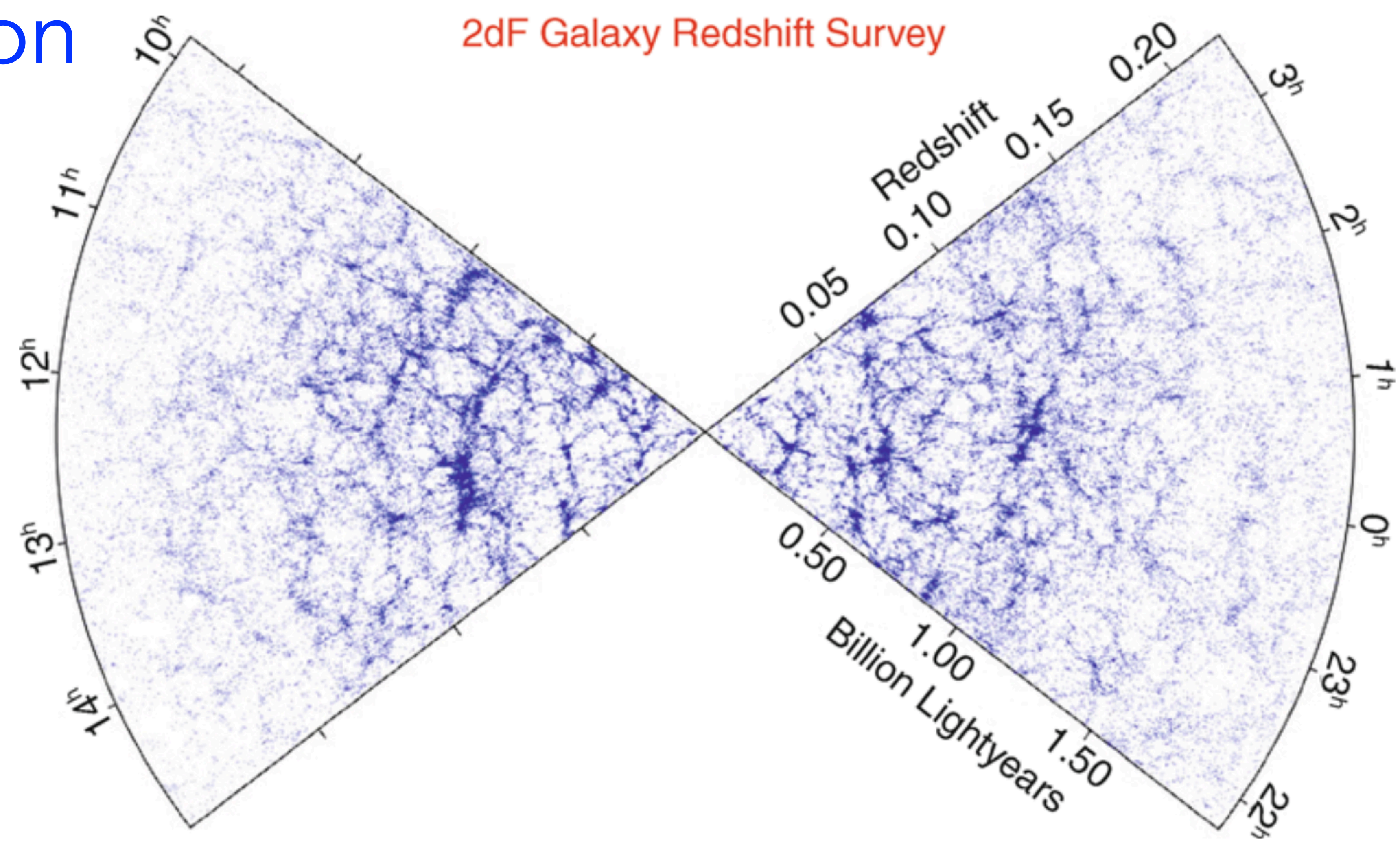
One of the most detailed maps of the bullet cluster (include JWST observations) in
→ S. Cha et al. (2025) arXiv:2503.21870

Galaxy Formation



Source: Alexander Knebe lecture

Galaxy distribution



two-degree-Field Galaxy Redshift Survey

The universe is homogenous at scales above $\sim 100h^{-1}\mathrm{Mpc}$.

On smaller scales, galaxies form clusters which are themselves not distributed uniformly, but their positions are correlated, grouped together in superclusters.

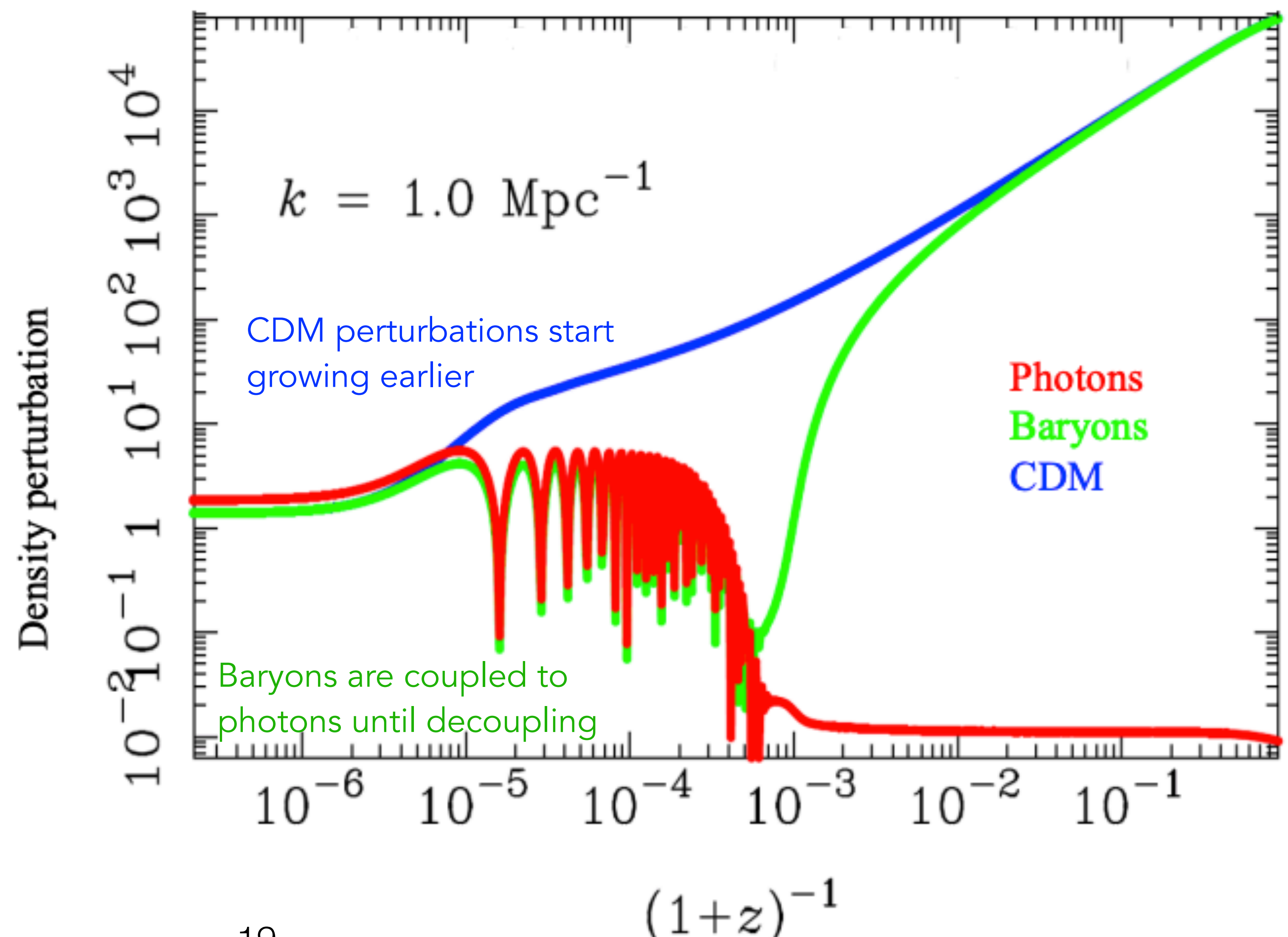
The Inhomogeneous Universe and DM

For structures to collapse, gravity should dominate over pressure.

For baryons this can happen only after decoupling, $z \approx 1100$. For DM it can happen earlier, at $z_{eq} \approx 3300$

After decoupling, baryons are are pressure-less matter. At last they feel only gravity, so they fall into the existing CDM potential wells and start to grow, chasing the blue curve (DM)

Present day inhomogeneity observations require DM.



The Inhomogeneous Universe and DM

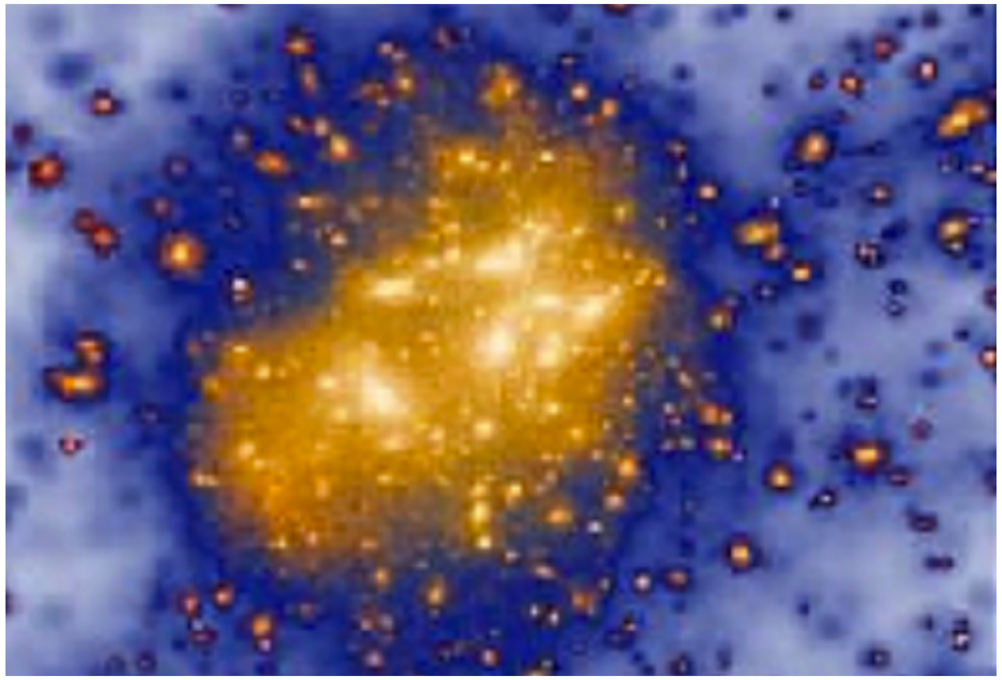
DM tends to be roughly spherically distributed in gravitationally bound systems. Normal baryonic matter then collapses in the gravitational well, during which it dissipates energy and cools down, resulting in the spinning disks exhibited by many galaxies

N-body simulations suggest the **Navarro-Frenk-White (NFW)** profile of individual halos

$$\rho_{\rm NFW}(r) = \rho_s \frac{r_s}{r}\left(1 + \frac{r}{r_s}\right)^{-2}$$

with $d\ln\rho/d\ln r$ changing from -3 to -1 around r_S

DM halos are **not necessarily spherical**! In addition, simulations reveal the presence of numerous **smaller sub-halos orbiting within and around main halos**.



DM density near the sun.

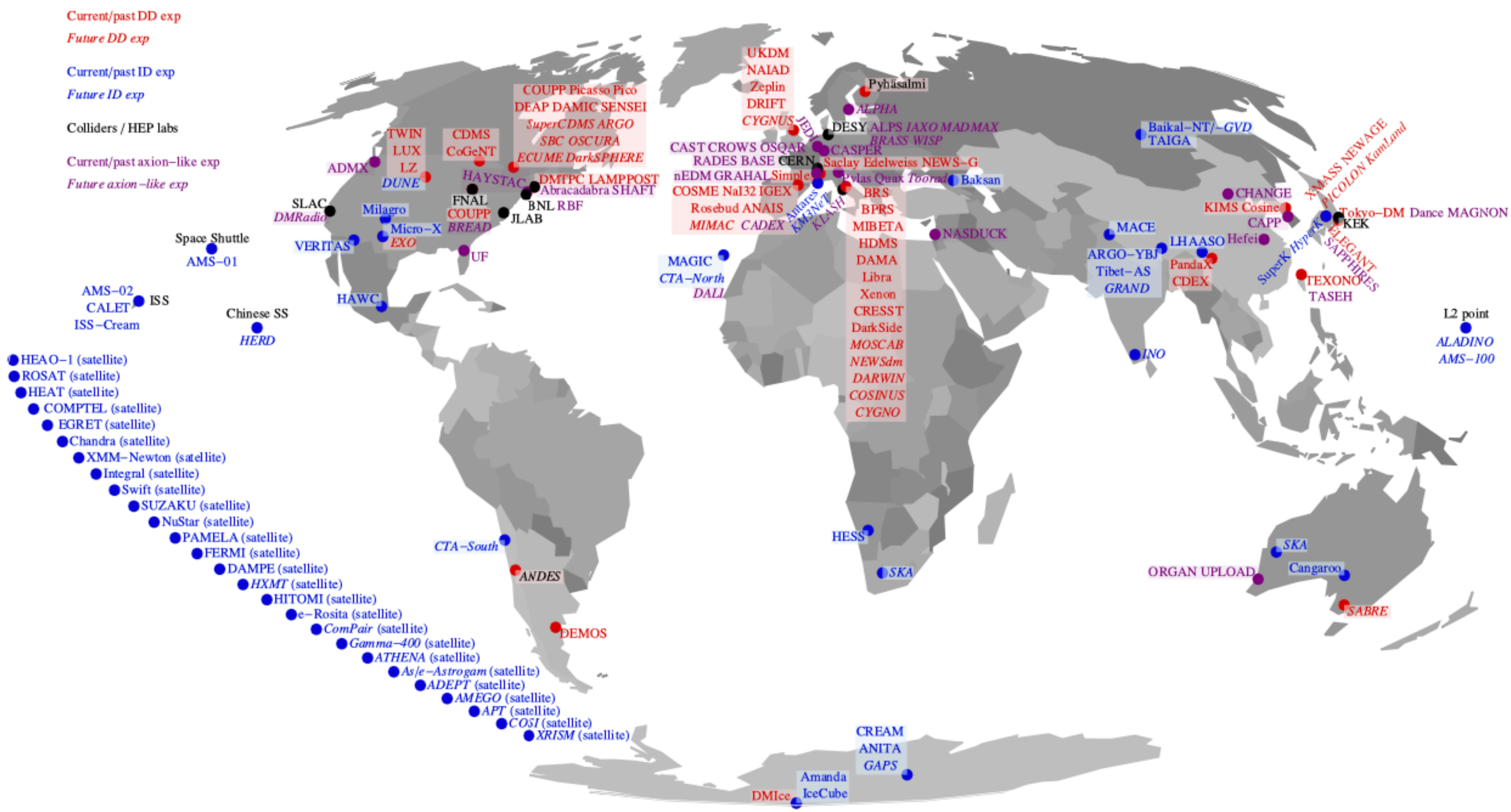
Current studies point to

$$\rho_\odot \approx 0.40 \mathrm{GeV/cm}^3$$
$$\approx 0.0106 M_\odot/\mathrm{pc}^3$$

That is considerably less than the estimated total matter density in a averaged over a neighborhood of a few 100 pc around the location of the Sun

Authors	Date	$\rho_\odot$ in GeV/cm^3	Notes
Turner	1986	0.28	'uncertainty of about a factor of 2'
Flores	1988	$0.3 \leftrightarrow 0.43$	
Kuijken & Gilmore	1991	$0.42\ (\pm 20\%)$	
Widrow et al.	2008	0.304 ± 0.053	
Catena & Ullio	2009	0.385 ± 0.027	Einasto
		0.389 ± 0.025	NFW
Weber & de Boer	2009	$0.2 \leftrightarrow 0.4$	
Salucci et al.	2010	$0.43 \pm 0.11 \pm 0.10$	
McMillan	2011	0.40 ± 0.04	
Garbari et al.	2011	$0.11^{+0.34}_{-0.27}$	isothermal stellar tracers
		$1.25^{+0.30}_{-0.34}$	non-isothermal stellar tracers
Iocco, Pato & Bertone	2011	$0.2 \rightarrow 0.56$	
Bovy & Tremaine	2012	0.3 ± 0.1	
Zhang et al.	2012	0.28 ± 0.08	
Piffl et al.	2014	$0.59\ (\pm 15\%)$	
Pato, Iocco & Bertone	2015	0.420 ± 0.025	
McKee et al.	2015	0.49 ± 0.13	
McMillan	2016	0.40 ± 0.04	
Sivertsson et al.	2017	$0.46^{+0.07}_{-0.09}$	
Buch et al.	2018	0.608 ± 0.380	result depends on chosen tracers
Eilers et al.	2018	0.30 ± 0.03	
Evans et al.	2018	0.55 ± 0.17	
Karukes et al.	2019	$0.43 \pm 0.02 \pm 0.01$	stat and sys errors
Cautun et al.	2020	0.33 ± 0.02	
Sofue	2020	0.359 ± 0.017	own determination
		0.39 ± 0.09	average of recent results
Salomon et al.	2020	$0.42 \leftrightarrow 0.53$	
Hattori et al.	2020	0.342 ± 0.007	
Benito, Iocco & Cuoco	2021	$0.4 \leftrightarrow 0.7$	inferred 2σ range
Lim, Putney, Buckley, Shih	2023	0.446 ± 0.054	
Staudt et al.	2024	0.42 ± 0.06	from simulations

Dark Matter Hunting



Alternative to DM

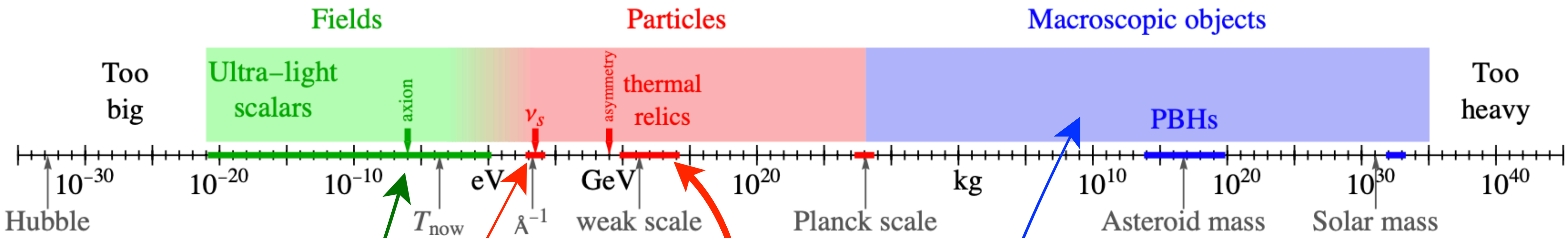
- The evidence for DM is, at the moment, purely gravitational.

- Could just that mean that we don't have an adequate theory of gravity to describe very large scales?

- Modified gravity theories like **MOND** (Modified Newtonian Dynamics) have progressed a lot but still fail to provide a simple model valid on all scales.

What is Dark Matter?

See → M. Cirelli, A. Strumia and J. Zupan (2024)



Axions

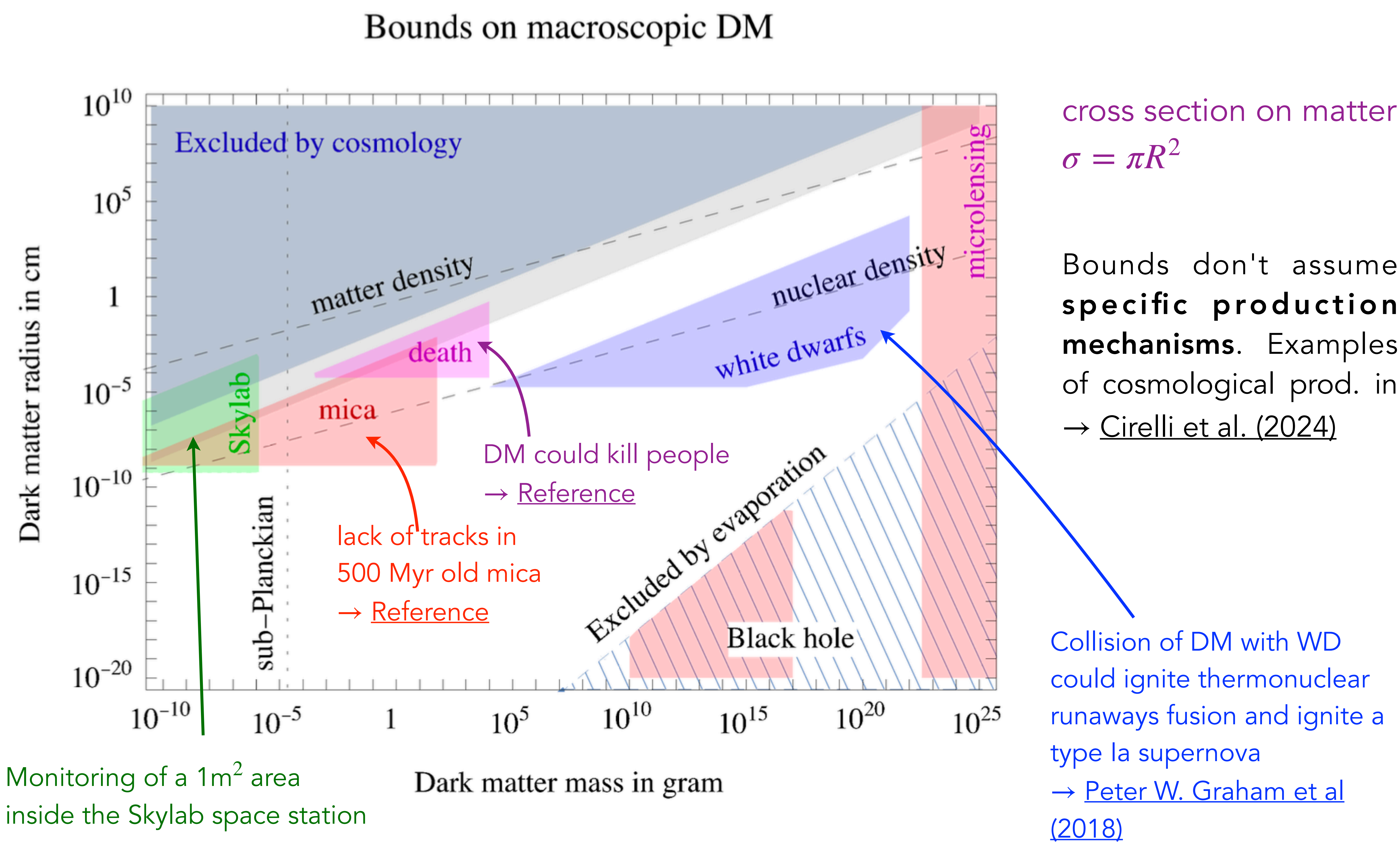
Sterile neutrinos

WIMPs

MACHOs,
Primordial Black Holes

Macroscopic DM

See → Jacobs, Starkman, Lynn (2015) and → M. Cirelli, A. Strumia and J. Zupan (2024)



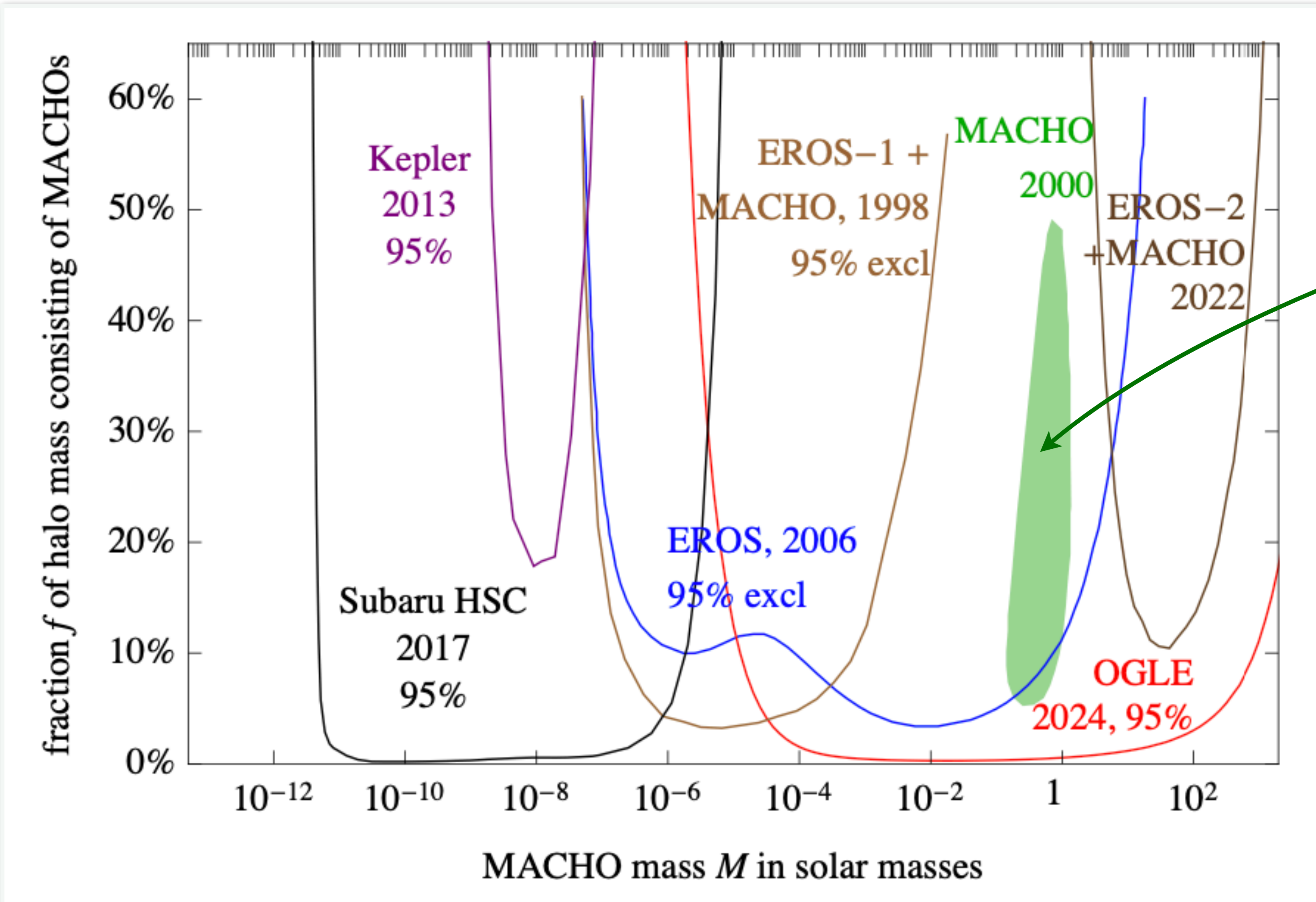
cross section on matter

$\sigma = \pi R^2$

Bounds don't assume **specific production mechanisms**. Examples of cosmological prod. in → Cirelli et al. (2024)

MACHOs

MACHOs = Massive Astrophysical Compact Halo Objects



MACHOs hint (Unconfirmed by later survey)

Baryonic MACHOs can be only a small fraction of DM (because of BBN constraints)

Primordial Black Holes

Astrophysical objects that consist of baryonic matter but have been created before the BBN are not subject to the BBN constraints since the material that they are made of gets subtracted from the baryonic budget very early on.

This is the case of PBH

The formation of PBH is not trivial. We should assure that there is gravitational collapse during radiation dominated era. So, the over density must be efficiently boosted to large values.

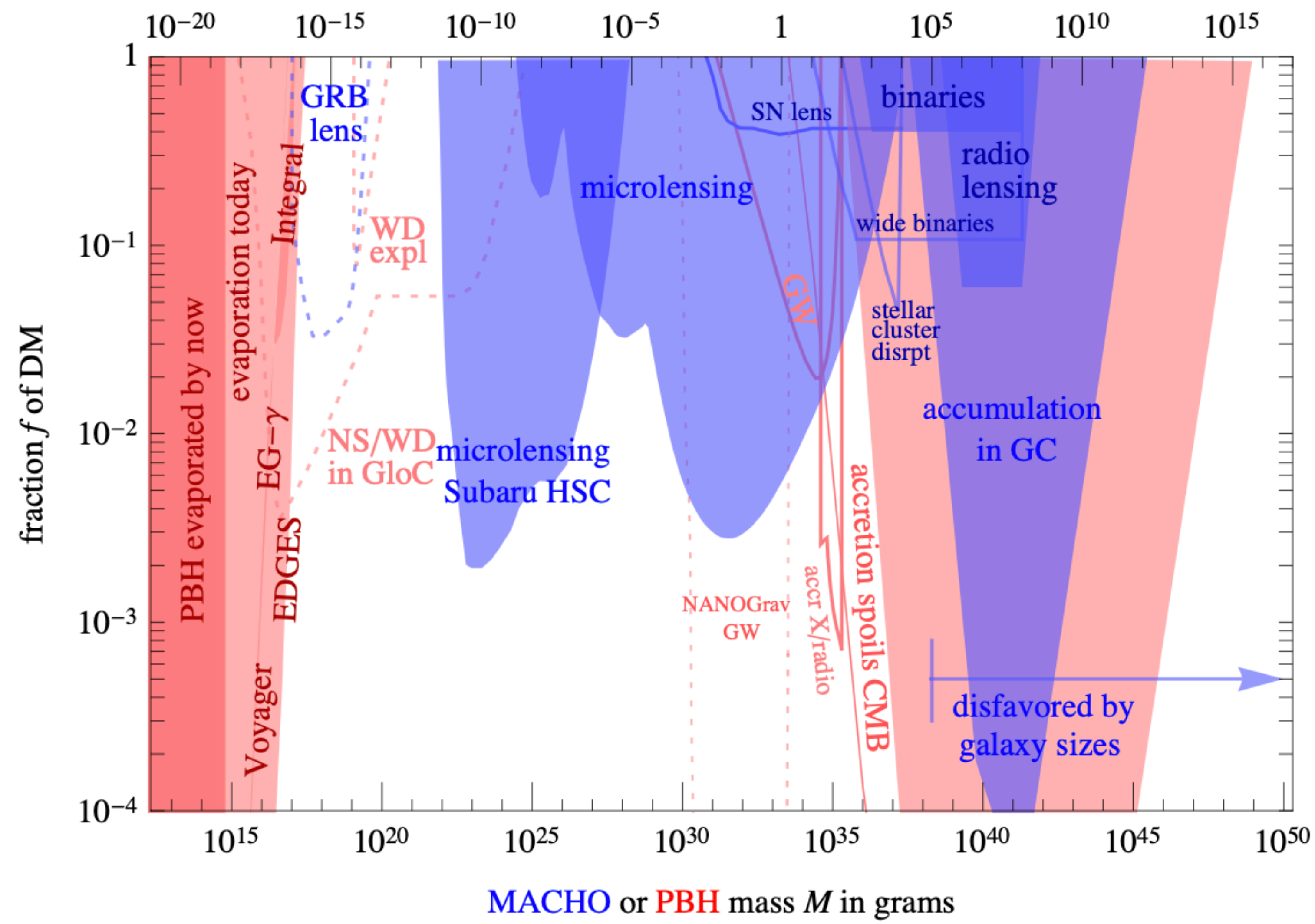
Key check: → The PBH should not have evaporated by now.

Primordial Black Holes

Searched through a series of methods:

- Gravitational microlensing,
- Compact-binary GWs,
- Hawking-radiation bursts (not seen by gamma ray telescopes), et.

PBH bounds in red



Recent and controversial bounds are shown as dashed lines

Details in → B. Kavanagh PBHbounds (Github)

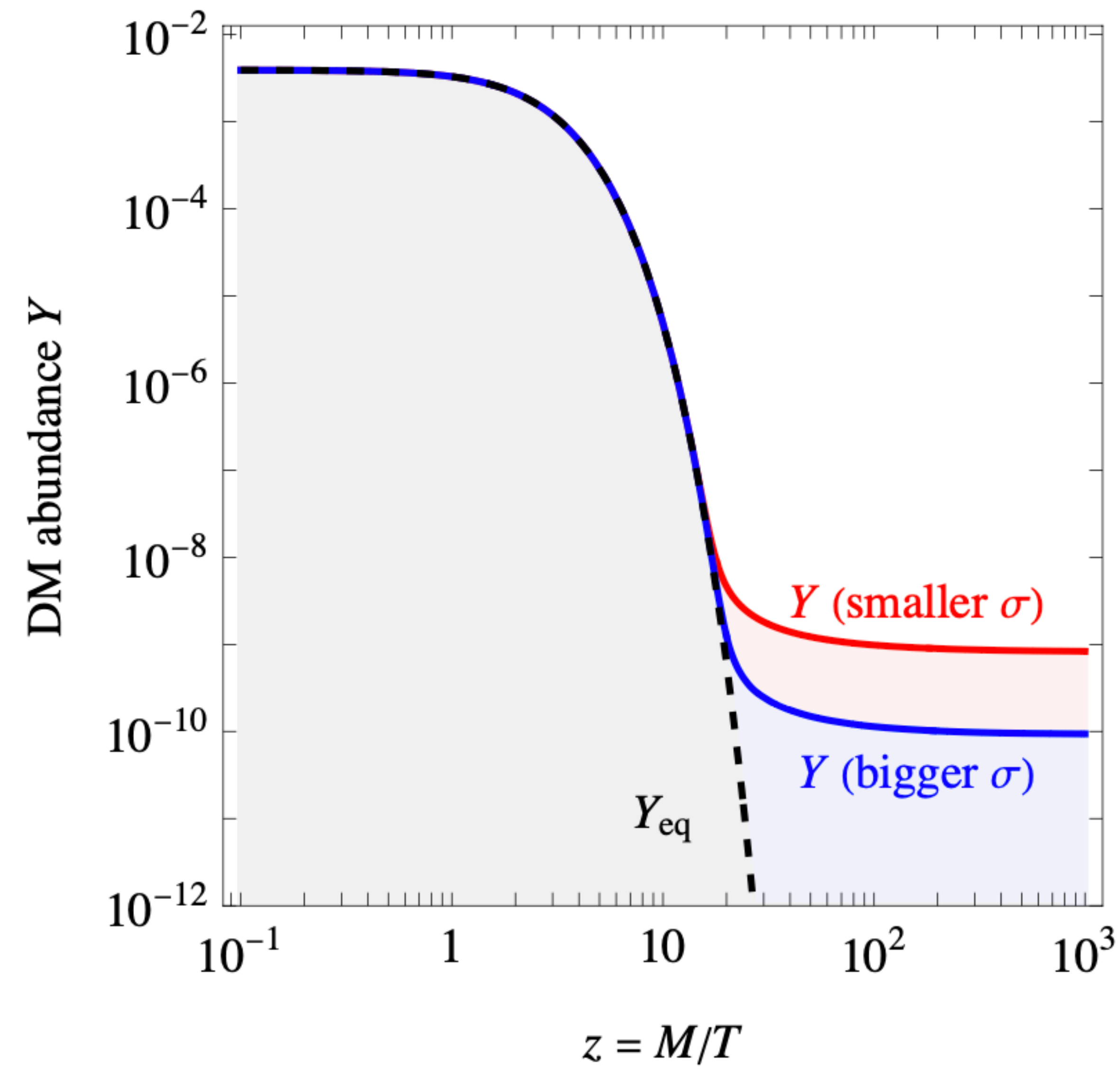
Weakly Interacting Massive Particles (WIMPs)

The evolution of the **WIMP** number density n is governed by the Boltzmann equation

$$\frac{dn}{dt} + 3Hn = -\langle\sigma v\rangle\left(n^2 - \left(n_{eq}\right)^2\right)$$

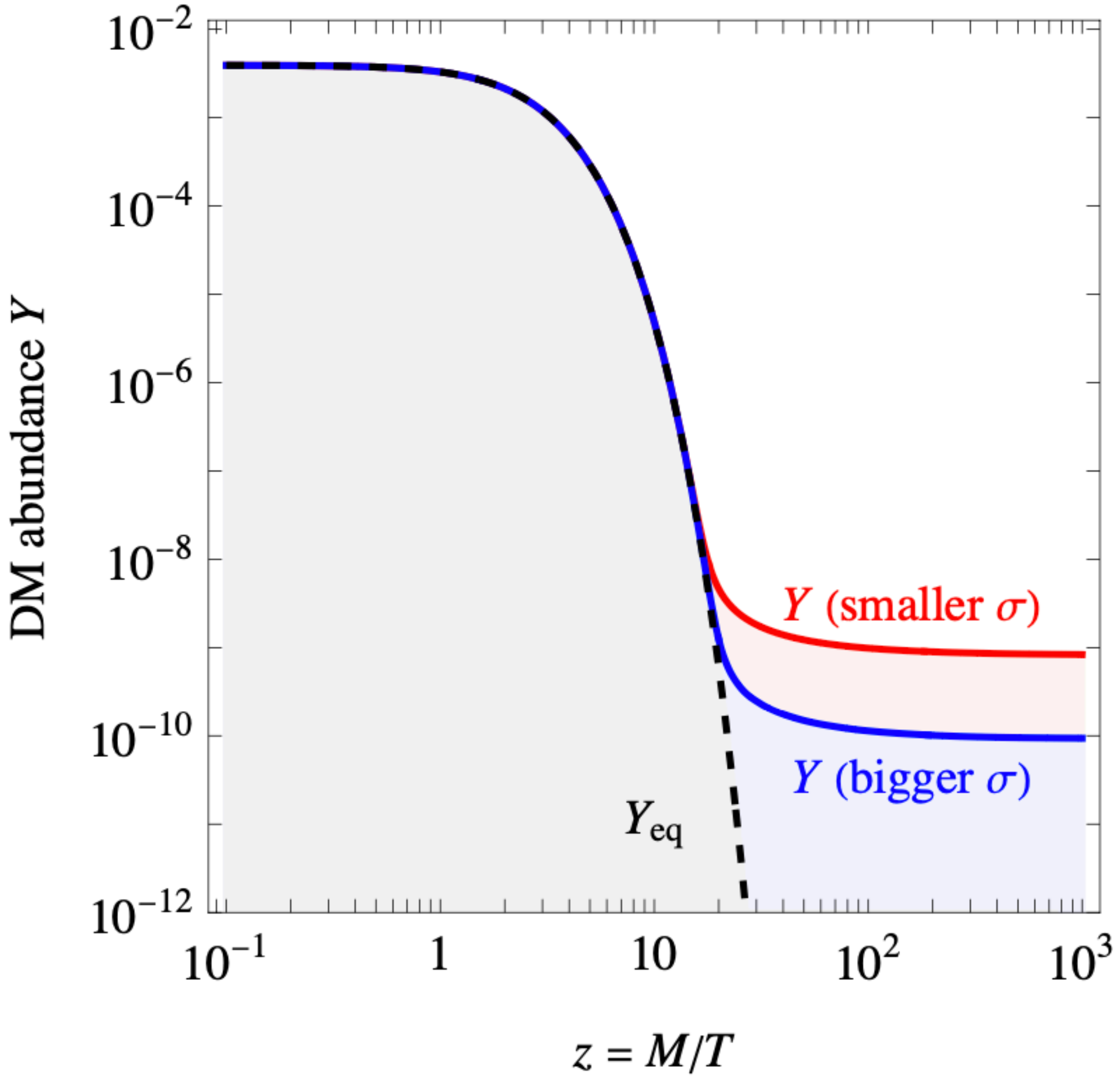
Freeze out when the interaction rate falls below the Hubble rate

$$\Gamma = n_{eq}\langle\sigma v\rangle \lesssim H$$



The WIMP Miracle

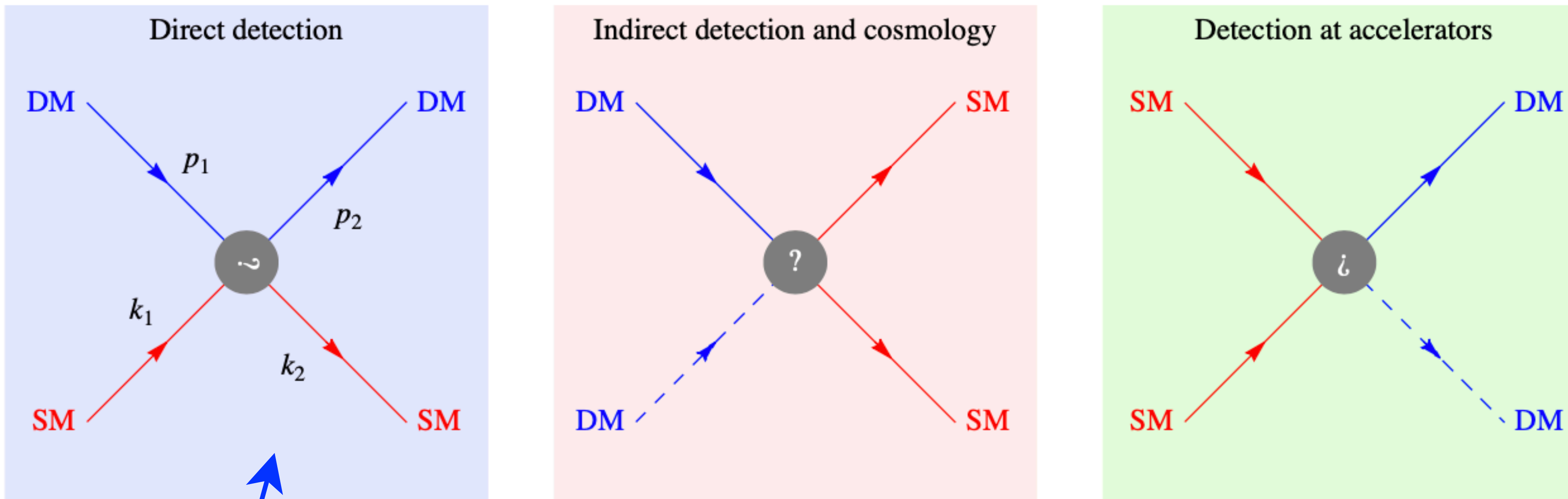
The precise numerical result for the special value σv, which reproduces the cosmological DM abundance turns out to ***miraculously* correspond to a typical weak annihilation cross section**.



Hunting WIMPs

Could also happen in astrophysical environment but with tiny rates

→ fig 4.6 of M. Cirelli, A. Strumia and J. Zupan (2024)

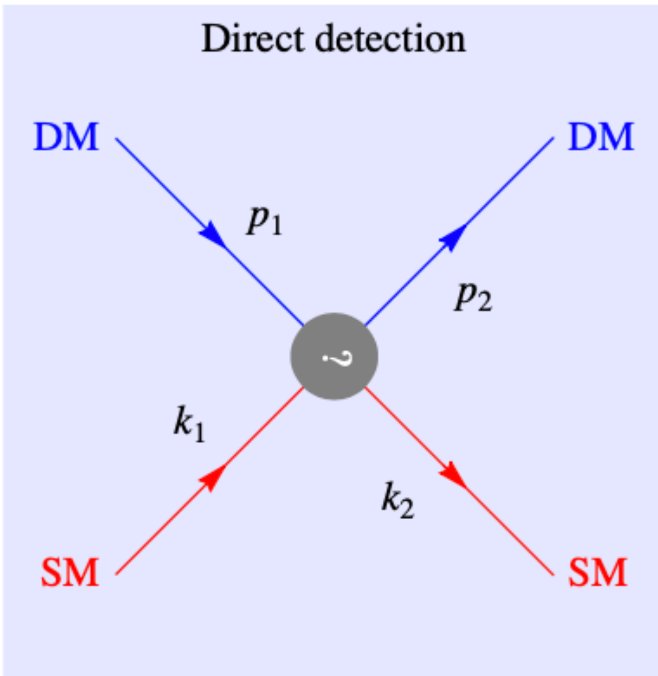


Recoil events in nuclei or electrons in a highly shielded and closely monitored underground detector

DM annihilations/decays in astrophysical environments, by searching for signatures in cosmic rays, photons or neutrinos arriving at Earth.

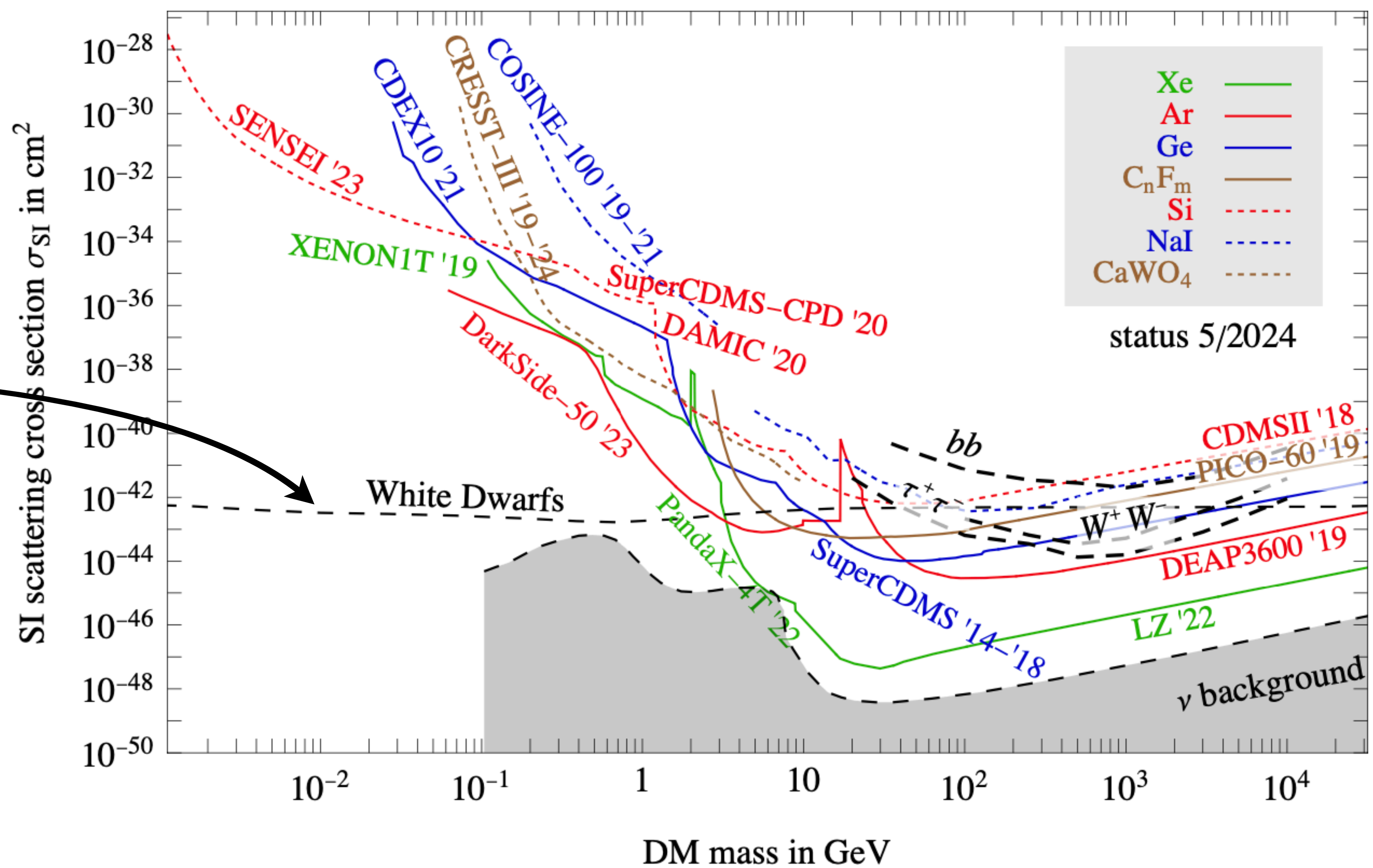
Production of DM in a controlled environment (e.g., pp collisions at LHC, e^+e^- collisions at lower energy machines or in beam dump experiments). Presence of DM deduced via missing energy.

Hunting WIMPs



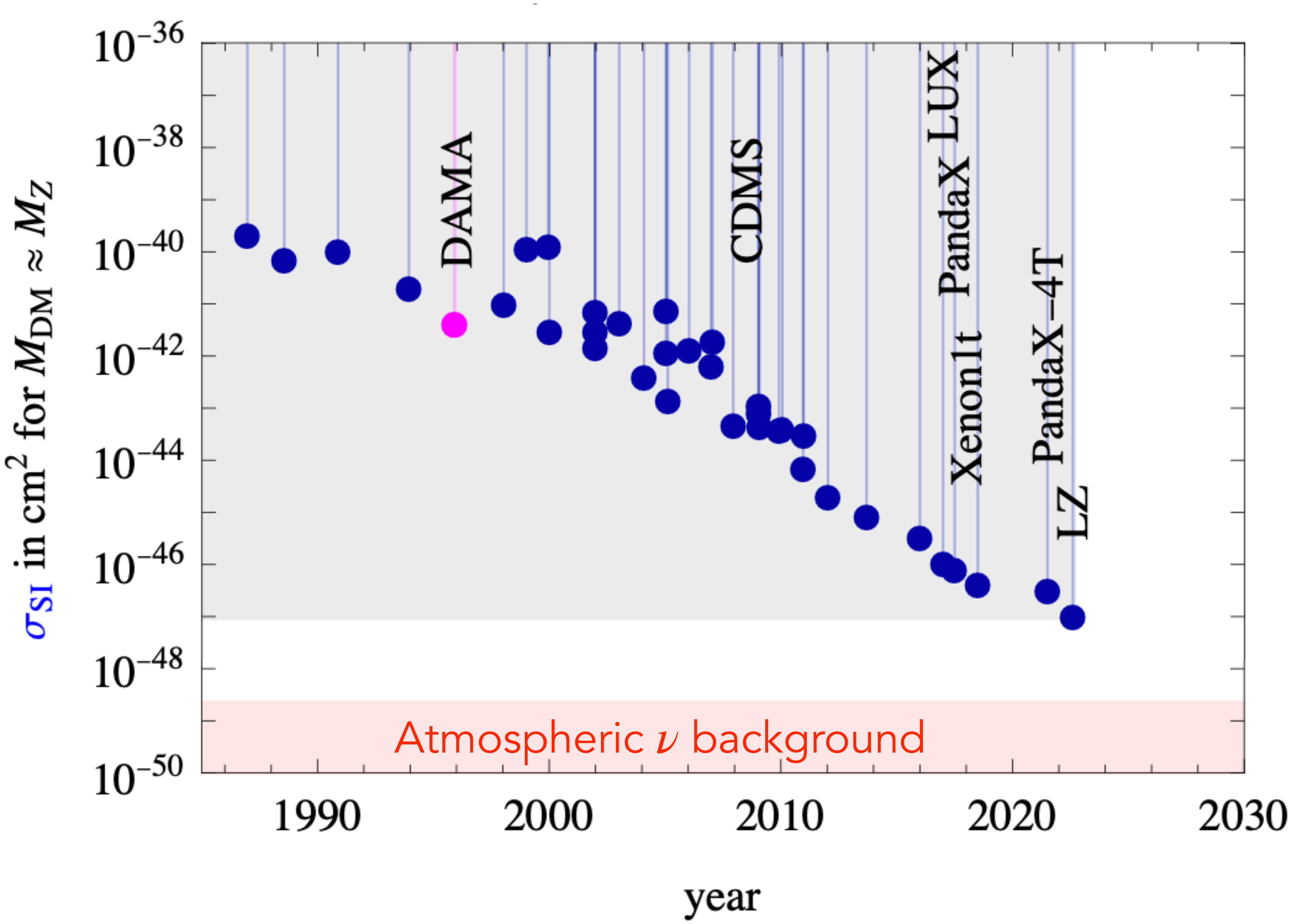
WIMPs can be detected through the tiny recoil energy produced when a WIMP collides with an atomic nucleus in a detector buried underground to shield from background noise

Latest estimates in →
F. Calore et al. (2025)



Incomplete sample of experimental searches. For more see, e.g., → M. Cirelli, A. Strumia and J. Zupan (2024)

Hunting WIMPs



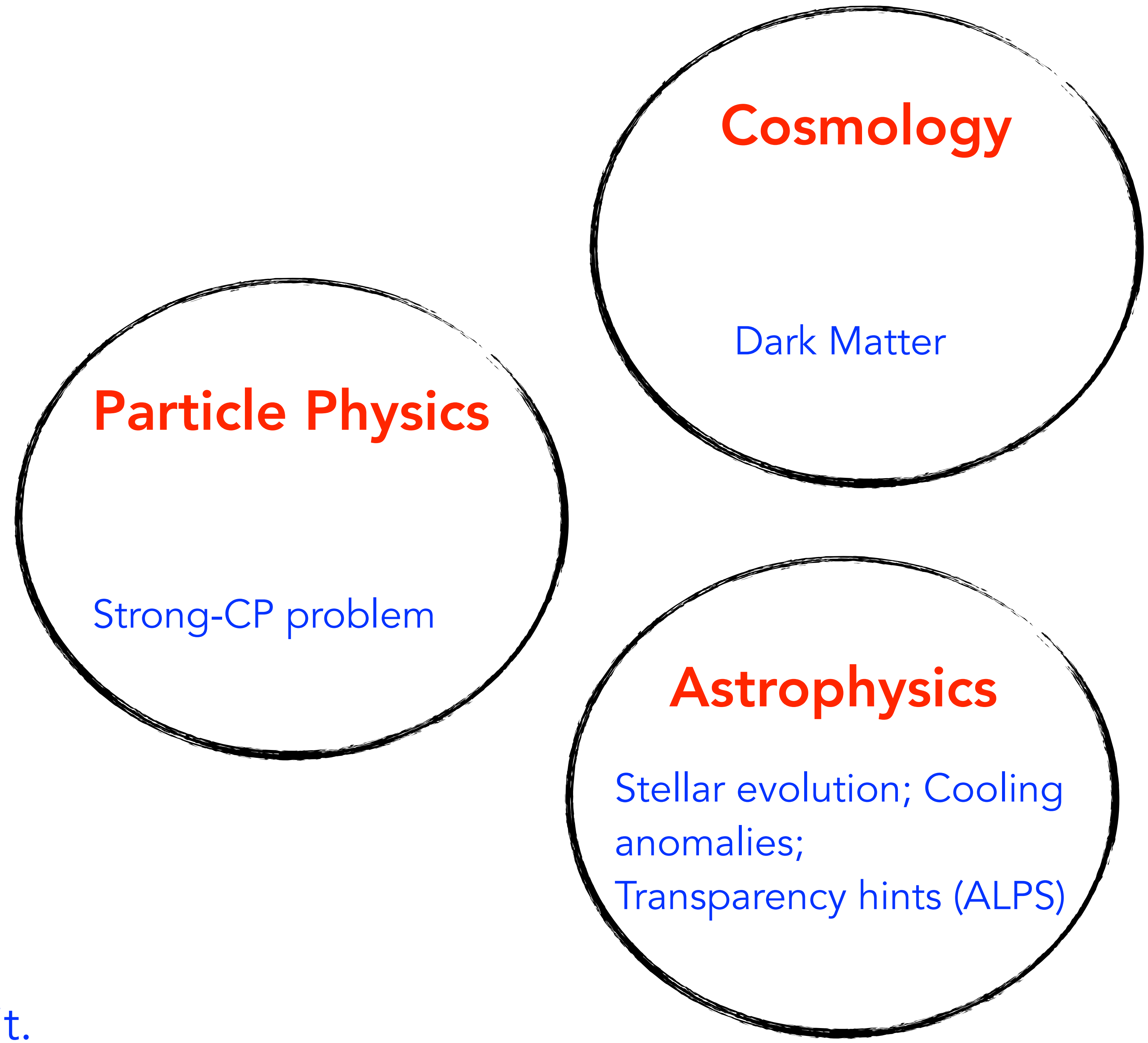
→ [M. Cirelli, A. Strumia and J. Zupan (2024)]

Direct detection bounds for spin-independent DM–nucleon scattering, assuming DM mass at around the Z boson mass.

Part 2: Axions

Axions

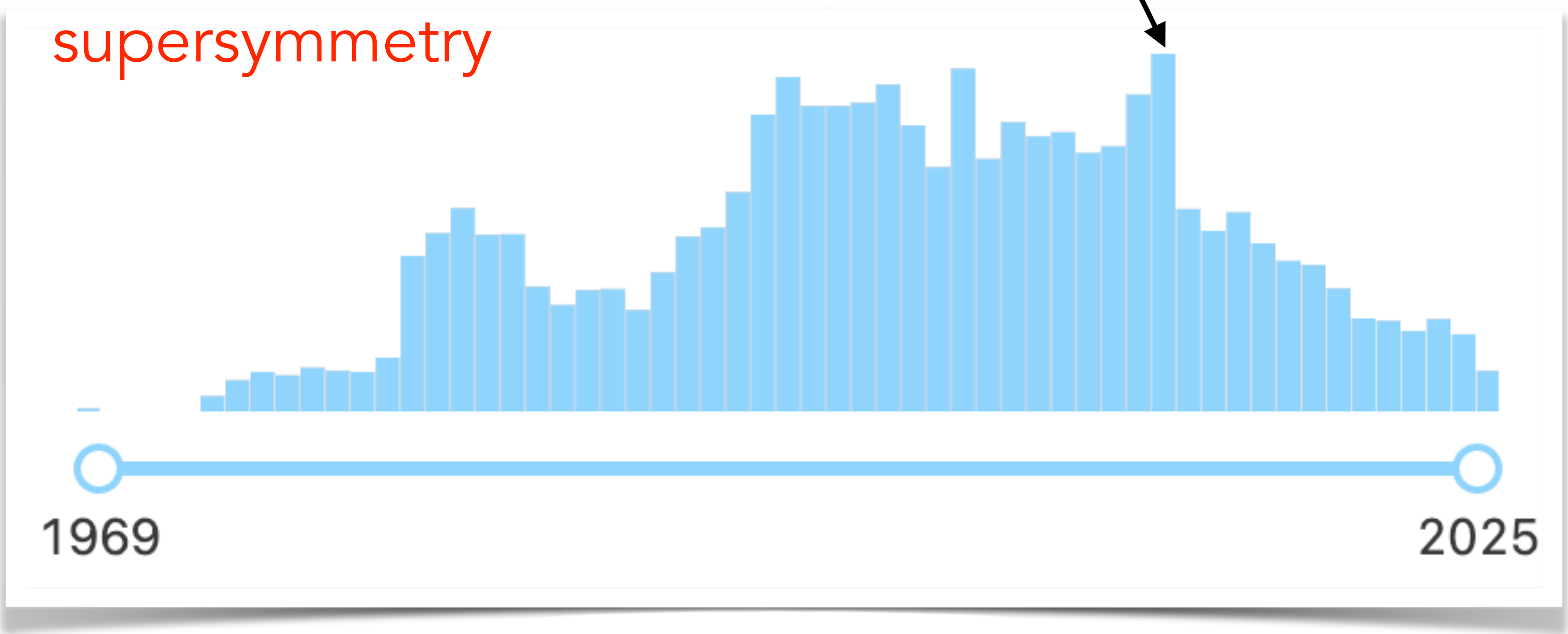
Axions are among the most studied DM candidates



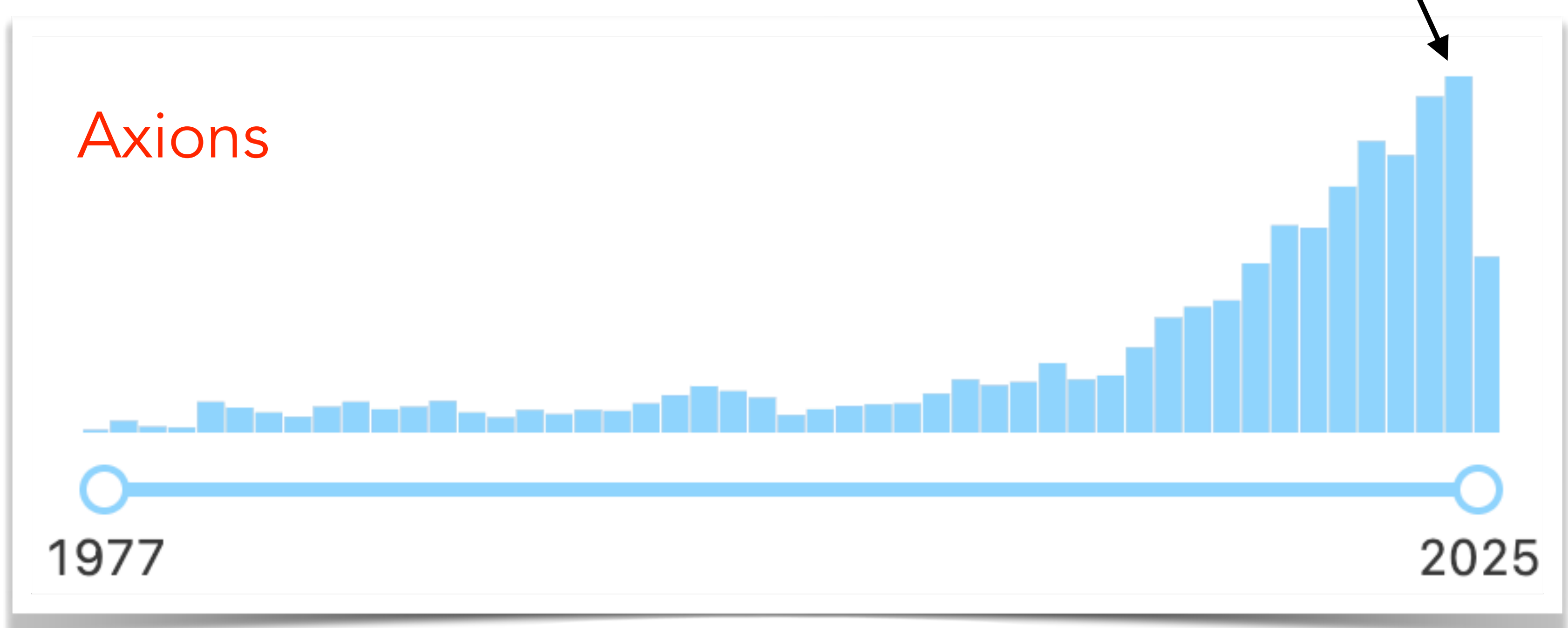
World-wide effort to detect it.

Axions

428 articles (2012)



432 articles (2024)



The θ-term

QCD Lagrangian

$$L = -\frac{1}{4}G^2 + \bar{q}(i\gamma^\mu D_\mu - m_q)q + \theta\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$$

θ-term: Violates CP

Gluon kinetic term

Quark kinetic and mass term, plus quark gluon interactions

The $\theta\frac{\alpha_s}{8\pi}G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$ term is a total derivative. However, there are configurations which contribute to the action integral. These are called **instantons** $\Rightarrow$ this term cannot be thrown away and has phenomenological consequences.

One consequence is to give mass to the η' meson. In fact, all the terms which explicitly break the symmetry (so, both mass term and anomaly term) contribute to the mass of the Goldstone boson.

For the math inclined, beautiful relation with topology. See, e.g., Coleman, Aspects of Symmetry

The θ-term

See, e.g., Schwartz, Ch. 30.5.2

It is hard to calculate the η' mass. One method is lattice.

Veneziano and Witten (1979) showed that the η' mass is related to the topological susceptibility $\chi_t \equiv \left\langle \left(G\tilde{G}\right) \left(G\tilde{G}\right) \right\rangle$ as

$$\chi_t = \frac{f_\pi^2}{12}\left(m_\eta^2 + m_{\eta'}^2 - 2m_K^2\right)$$

→ if $G\tilde{G}$ had no effect then $\chi_T = 0$ and the η' mass would be small. In particular, in the chiral limit m_η, $m_K \to 0$ one would find also $m_{\eta'} = 0$.

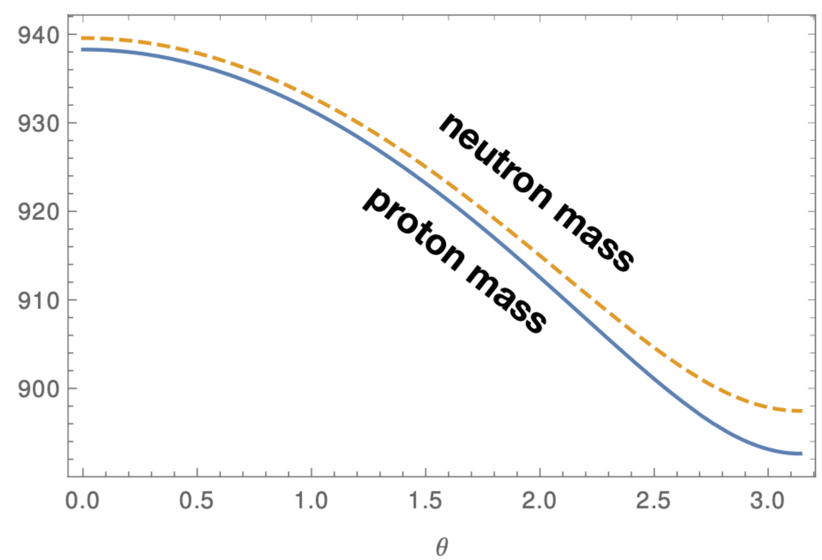
→ The experimental evidence that η' is not a Goldstone boson (it is "heavy") suggests that the instantons do play a role in QCD.

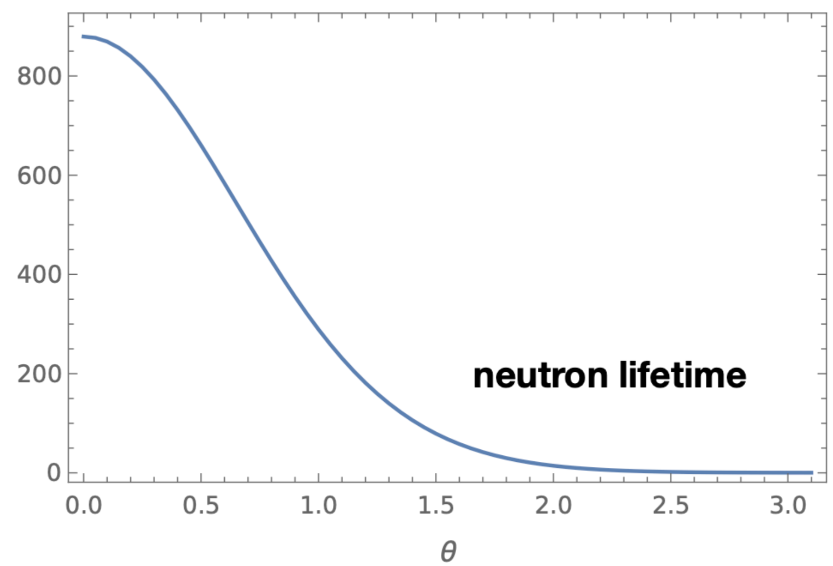
The θ-term

- The vacuum energy depends on θ
  It is minimized for $\theta = 0$

- The nucleon masses depend on θ
  $\Rightarrow$ the neutron lifetime $\Rightarrow$ nucleosynthesis depends on theta.

$$m_n - m_p \simeq \left(1.29 + 0.21\,\theta^2 + \mathcal{O}(\theta^4)\right)\,\mathrm{MeV}$$





C. Vafa, E. Witten, Phys. Rev. Lett. 53 (1984) 535

- L. Ubaldi, Phys. Rev. D81 (2010) 025011
- M. Dine, L. Stephenson Haskins, L. Ubaldi, D. Xu,JHEP 05 (2018) 171

- Lee, Meißner, Olive, Shifman, Vonk, Phys.Rev.Res. 2 (2020) 3, 033392 (2020)

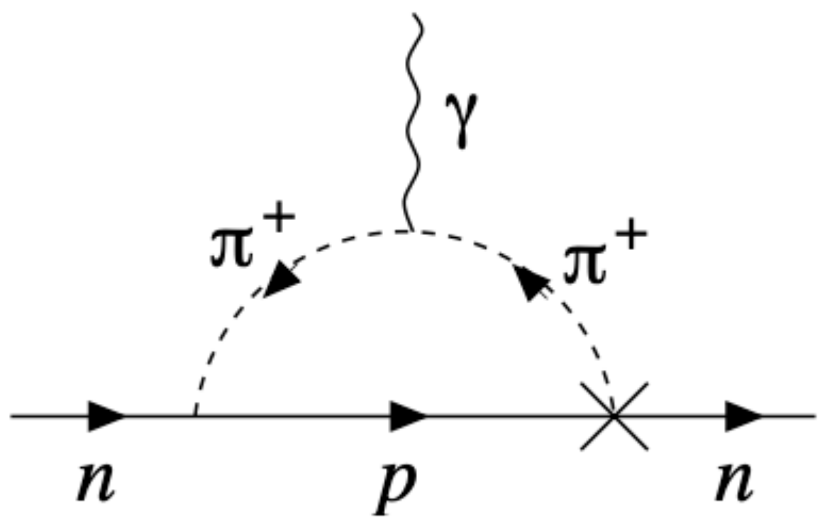
See Nick Houston talk at
→ Axions beyond boundaries, GGI-2023

The θ-term and Strong CP

The θ-term generates a neutron EDM

M. Pospelov, A. Ritz (2020)

$\rightarrow \quad d_n \approx 2.4(1.0) \times 10^{-16}\, \theta\, e \cdot \mathrm{cm}$



This gives the strongest constraint

See PhD dissertation by Drew Backhouse, University of Oxford (2021), arXiv:2108.04285, for a pedagogical introduction

The latest experimental search found

$$\left| d_n^{\mathrm{exp}} \right| < 1.8 \cdot 10^{-26} e \ \mathrm{cm} \quad (90\,\%\ \mathrm{CL}) \quad \Rightarrow \quad \theta \lesssim 10^{-10}$$

Strong CP Problem

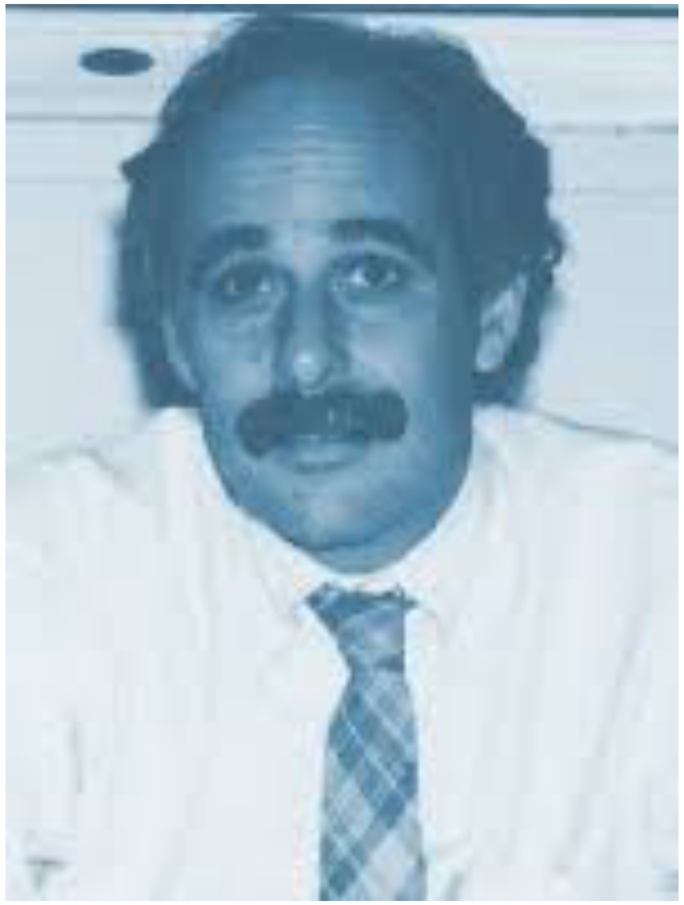
Abel et al., Phys.Rev.Lett. 124 (2020) 8, 081803

Peccei-Quinn Solution

Peccei and Quinn solution:

→ θ is dynamical → Settles to 0 (Vafa-Witten theorem)

Peccei, Quinn (1977)



Very similar to the $m_u = 0$ solution.
However, the new axial symmetry is added *by hand*

The Axion

$$L = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \bar{q}\,(i\gamma^\mu D_\mu - \bar{q}M)\,q - \theta\frac{1}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{f_a}\frac{g_s^2}{32\pi^2}G\tilde{G} + \ldots$$

$$\theta \to \theta + a/f_a$$

Axion

Note the need for a new energy scale, f_a, from a pure dimensional argument.

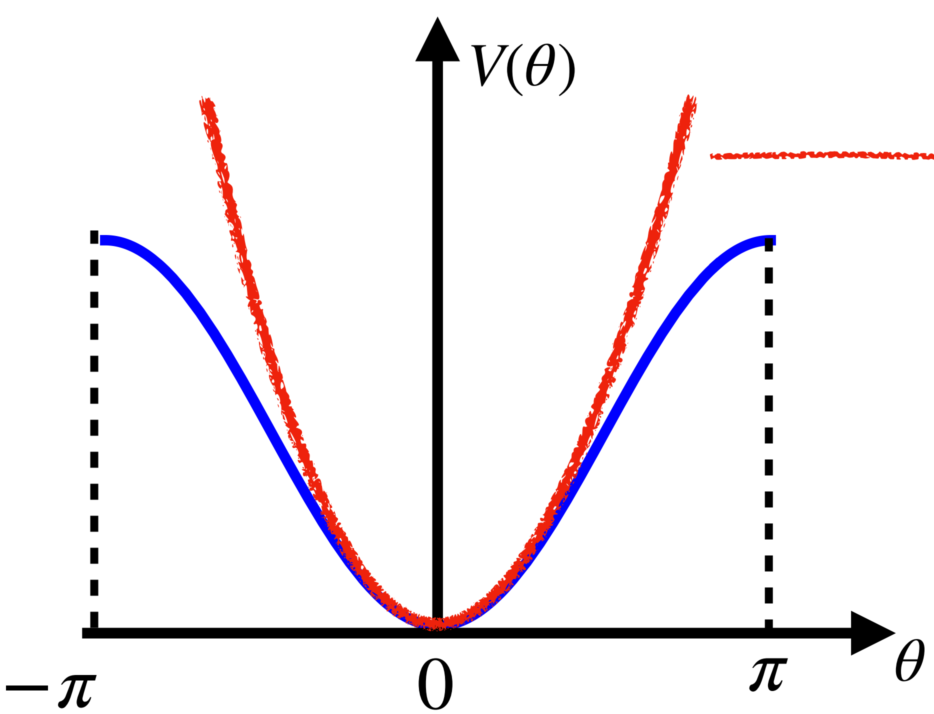
This is related (but not necessarily equal to) the scale at which $U(1)_{PQ}$ is spontaneously broken.

S. Weinberg Phys. Rev. Lett. 40 (1978) 223-226;

F. Wilczek Phys. Rev. Lett. 40 (1978) 279–282

Some facts about QCD Axions

1- The axion potential can be calculated in QCD



$$m_a \simeq 5.7 \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mu\mathrm{eV}$$

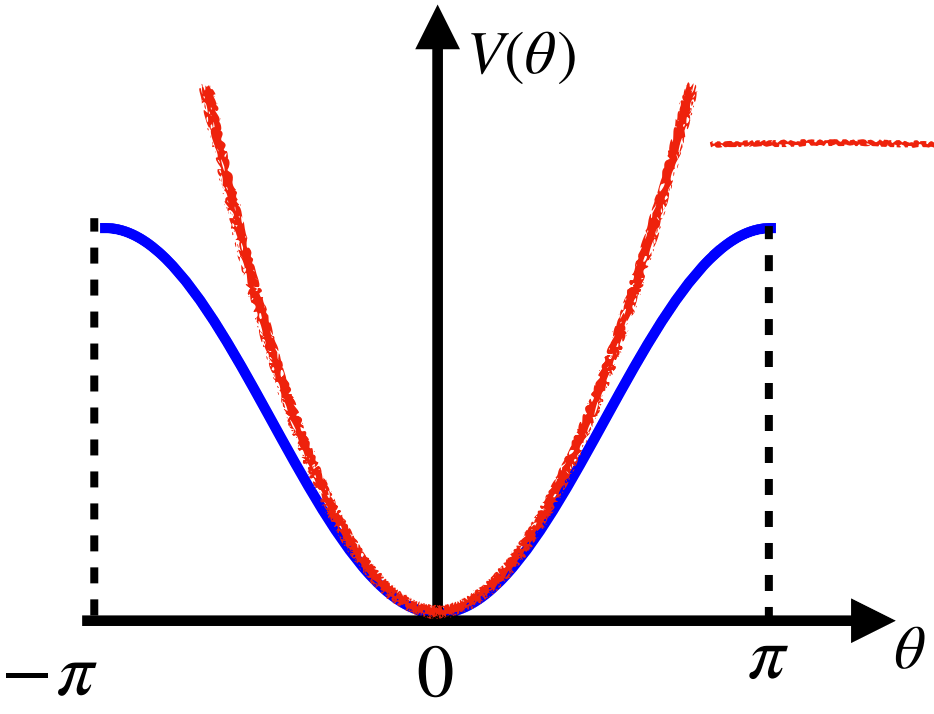
Grilli di Cortona et al., JHEP 1601 (2016)

Axions can get mass only from terms that break explicitly the PQ symmetry. The only thing that does that is the anomaly. So, the axion mass can only come from $G\tilde{G}$.

Not surprisingly, the resulting mass term is related to the topological susceptibility χ_T, just like in the case of the η'.

Some facts about QCD Axions

1- The axion potential can be calculated in QCD



$$m_a \simeq 5.7 \left(\frac{10^{12}\,\mathrm{GeV}}{f_a} \right) \mu\mathrm{eV}$$

Relaxing the $m_a - f_a$ relation requires substantial changes to QCD, for example the addition of a new QCD sector. This is all theoretically possible. However, here we will disregard this possibility for now. See sec. 6.6.2 of L. Di Luzio, M.G., Nardi, Visinelli, Phys.Rept. 870 (2020) for some options.

Grilli di Cortona et al., JHEP 1601 (2016)

Some facts about QCD Axions

1- The axion potential can be calculated in QCD

2- The axion couplings are model dependent.

There are 2 sources for the axion couplings:

- The model independent $aG\tilde{G}$ coupling; it generates couplings to quarks and photons. Not to electrons (at tree level)

- Model dependent contributions from the specific UV completion

Some facts about QCD Axions

1- The axion potential can be calculated in QCD

2- The axion couplings are model dependent.

$$L_{int} = C_{af} \frac{\partial_\mu a}{2f_a} \bar{f}\gamma_5\gamma_\mu f + \frac{1}{4} C_{a\gamma} \frac{\alpha}{2\pi f_a} aF\tilde{F}$$

Photons

Fermions (electrons, nucleons)

Spin-density coupling with matter

Two photon coupling of the form $a\mathbf{E}\cdot\mathbf{B}$, from electromagnetic anomaly

Some facts about QCD Axions

1- The axion potential can be calculated in QCD

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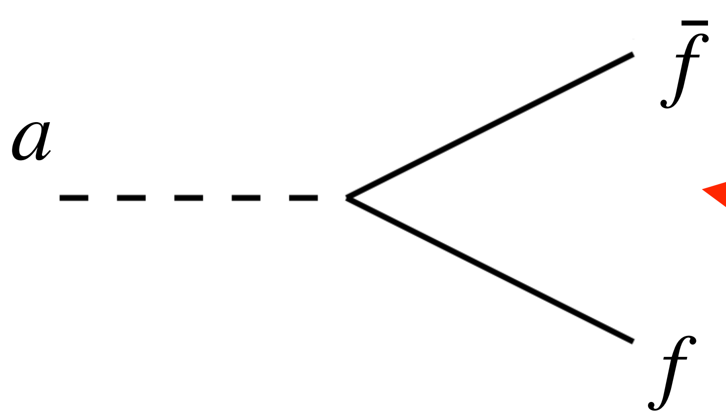
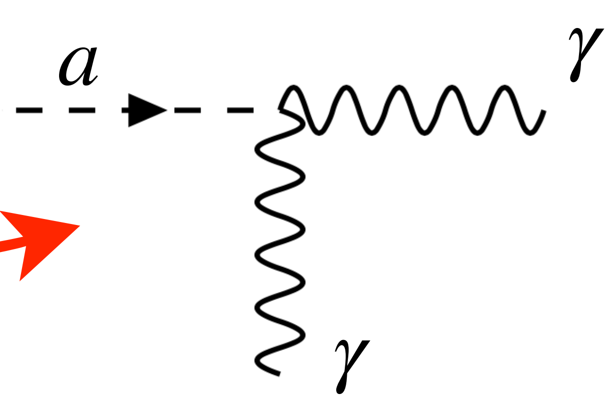
$$L_{int} = C_{af}\,\frac{\partial_\mu a}{2f_a}\,\bar{f}\gamma_5\gamma_\mu f + \frac{1}{4}\,C_{a\gamma}\,\frac{\alpha}{2\pi f_a}\,aF\tilde{F}$$





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f_a suppression (Remember $m_a \propto 1/f_a$)

In general: light ↔ weakly coupled

Some facts about QCD Axions

1- The axion potential can be calculated in QCD

2- The axion couplings are model dependent.

$$L_{int} = C_{af} \frac{\partial_\mu a}{2 f_a} \bar{f} \gamma_5 \gamma_\mu f + \frac{1}{4} C_{a\gamma} \frac{\alpha}{2\pi f_a} a F \tilde{F}$$

QCD contribution to the couplings can be substantially changed according to the particular UV completion…

… in principle, the coupling to fermions can be significantly reduced: $C_{af} \to 0$.

However, difficult for C_{aN}

- Di Luzio, Mescia, Nardi, Panci, Ziegler, Phys.Rev.Lett. 120 (2018)
- M. Badziak, K. Harigaya, arXiv:2301.09647 (2023);
- F. Takahashi, W. Yin, arXiv:2301.10757 (2023)

Some facts about QCD Axions

1- The axion potential can be calculated in QCD

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$$L_{int} = C_{af} \frac{\partial_\mu a}{2f_a} \bar{f}\gamma_5\gamma_\mu f + \frac{1}{4} C_{a\gamma} \frac{\alpha}{2\pi f_a} aF\tilde{F}$$

$$C_{a\gamma} = \frac{E}{N} - \frac{2}{3}\frac{4m_d + m_u}{m_u + m_d} = \frac{E}{N} - 1.92(4)$$

Model dependent contribution

Model independent contribution

… The coupling to photons is also model dependent and can (in principle) be tuned to $C_{a\gamma} \ll 1$

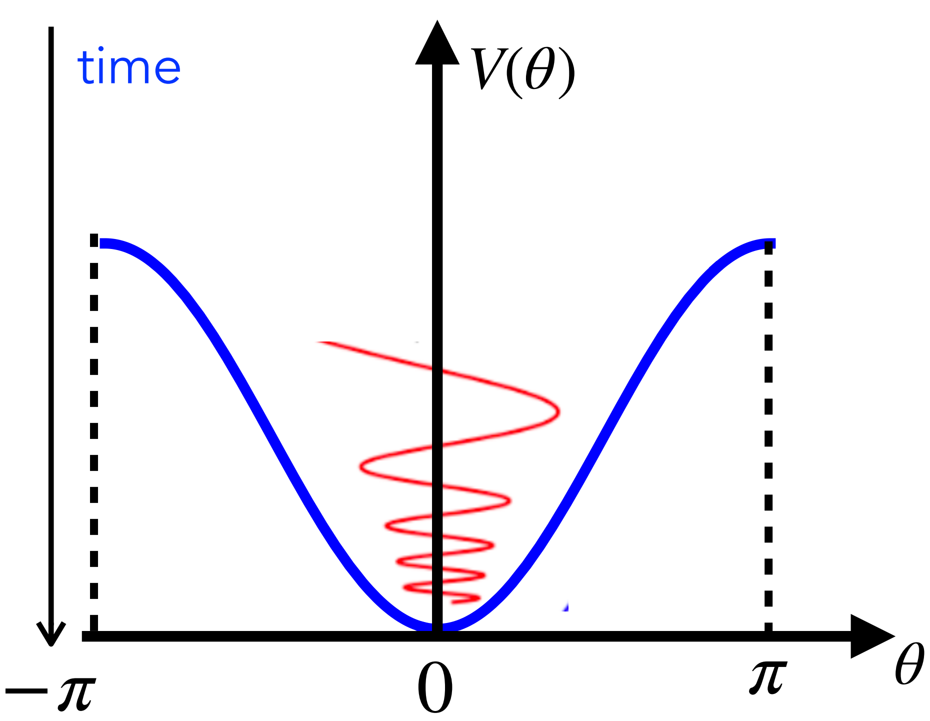
Some facts about QCD Axions

1- The axion potential can be calculated in QCD

2- The axion couplings are model dependent.

3- Axions contribute to Dark Matter .

- Preskill, Wise and Wilczek (1983)
- Abbott and Sikivie (1983)
- Dine and Fischler (1983)

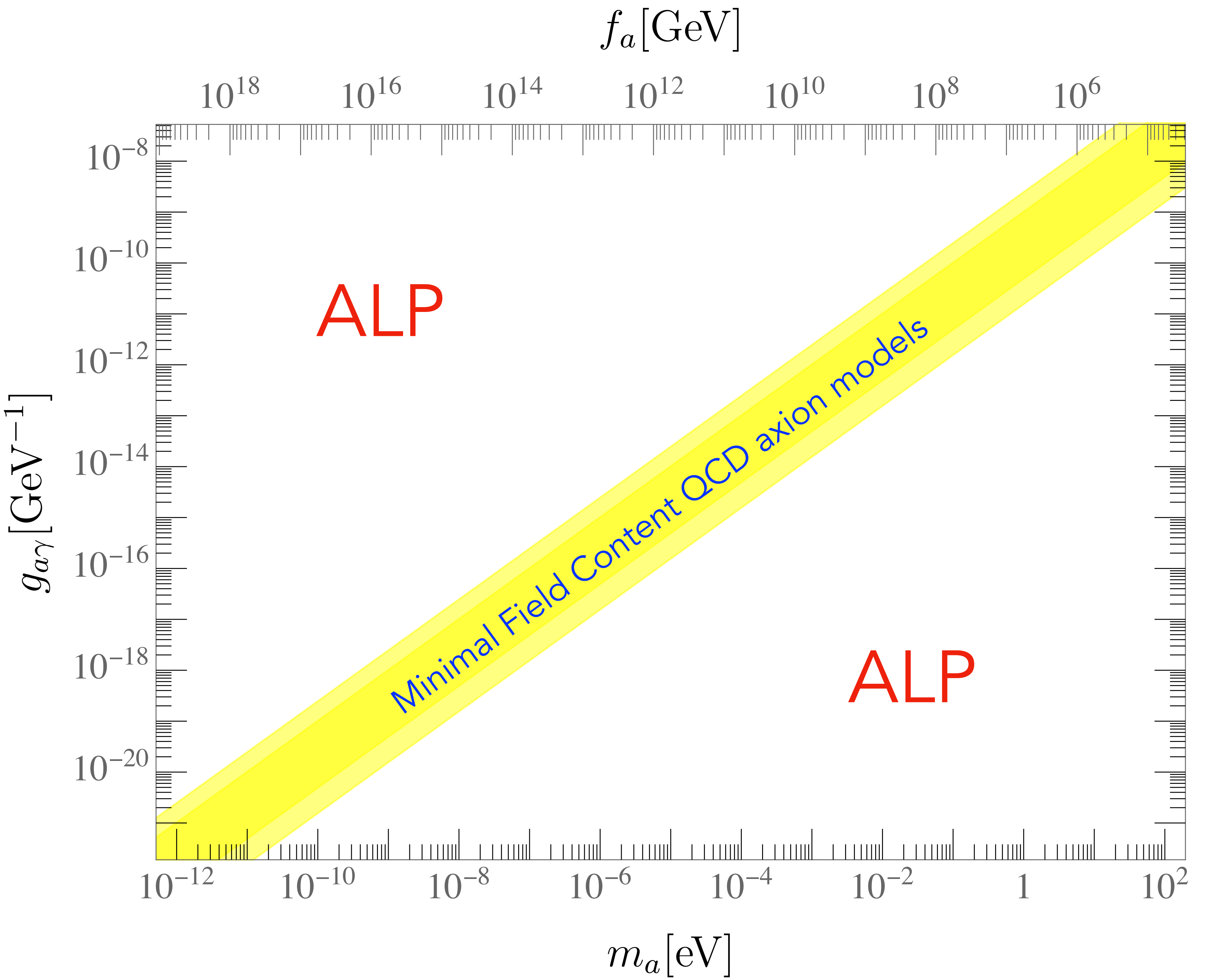


The PQ solution is dynamical, not instantaneous

The universe has a finite age

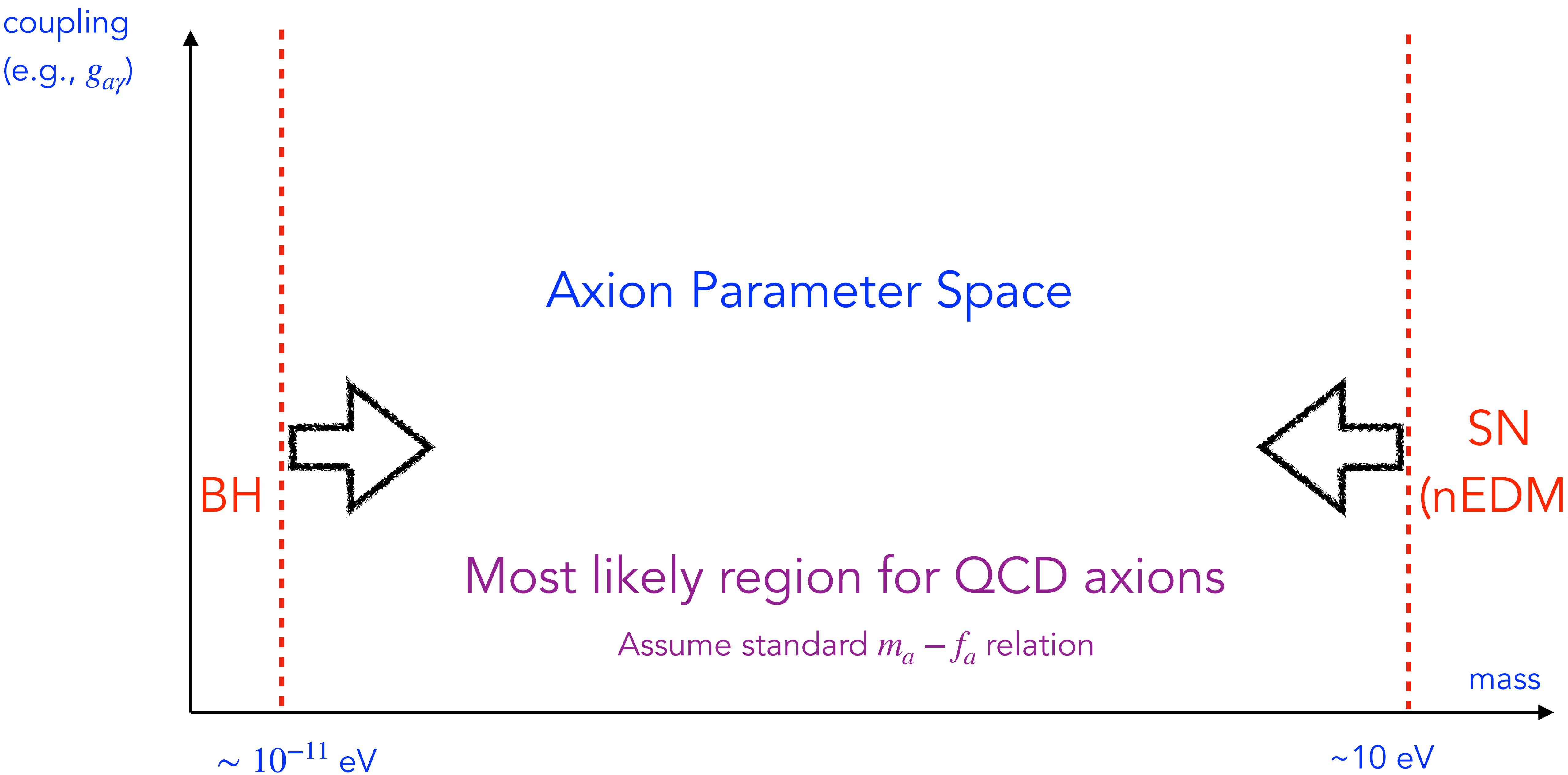
The axion field is still oscillating today around the CP-conserving minimum of the potential
→ Axion is CDM

The axion/ALP parameter space



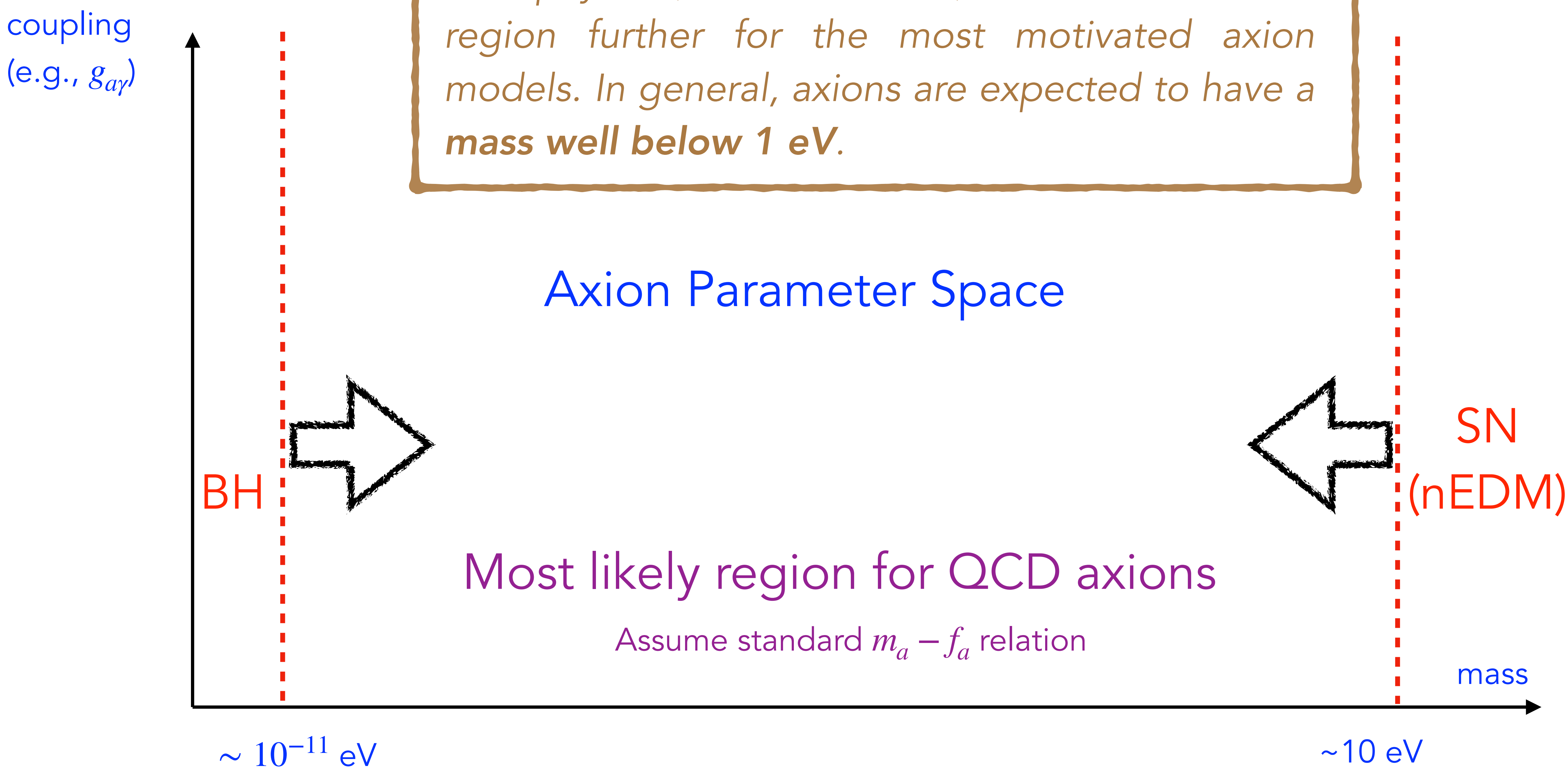
ALP =
Axion-Like
Partilce

The axion mass



The axion mass

Astrophysics (stellar evolution) constrains the mass region further for the most motivated axion models. In general, axions are expected to have a ***mass well below 1 eV****.*



Part 3: Axion Sources and Detection

Natural Axion/ALP sources

Cosmological

- Realignment, Topological Defects — Non-thermal: CDM — $E_a \simeq m_a$
- Thermal — HDM

Astrophysical

- Stellar
  - Thermal — $E_a \sim T_{core}$, keV or 100 MeV (SN)
  - Nuclear — $E_a \sim$ keV, MeV
  - Resonant $\gamma + B \to a + B$ — $E_a \sim \omega_{pl}$ (eV in the sun)
- Galactic/ Extra-Galactic
  - Diffuse SN background — $\sim$100 MeV
  - Conversion of photons in B_{ext} — High to very high energy

Natural Axion/ALP sources

Cosmological
- Realignment
- Topological Defects
- Thermal

Direct: Haloscopes

Indirect: cosmological probes, telescopes ($a \to \gamma\gamma$), …

Astrophysical
- Stellar
  - Thermal
  - Nuclear
  - Resonant $\gamma + B \to a + B$

  Direct: Helioscopes → Sun, SN(?)

  Indirect: NuSTAR/Fermi ($a + B \to \gamma$)
- Galactic/ Extra-Galactic
  - Diffuse SN background — Fermi: Indirect ($a + B \to \gamma$)
  - Conversion of photons in B_{ext} — Indirect ($a + B \to \gamma$) Chandra, NuSTAR,Fermi…

Axions as Dark Matter

- In spite of being light, axions — and Axion Like Particles (ALPs) — can be CDM, thanks to non-thermal production mechanisms.

Very light DM behaves like waves.
Requires specific technologies. Extremely fruitful research field.

"Discovery of dark matter waves would provide a glimpse into the earliest moments in the origin of the universe and the laws of nature at ultrahigh energies, beyond what can be probed in colliders"

→ Kolb et al., https://doi.org/10.2172/1659757, 2018

Axions as Dark Matter

For an observed DM density of $\rho \sim 0.2 - 0.56\,\mathrm{GeV/cm^3}$

Axion number density

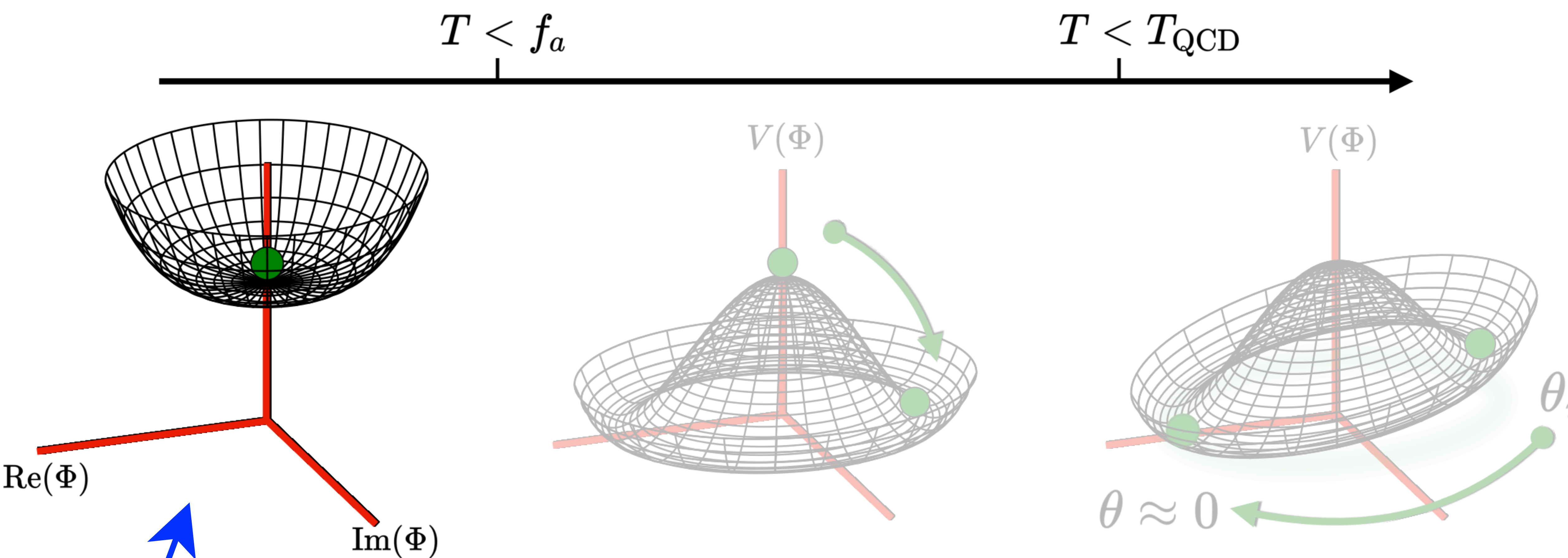
$$n_a \sim \rho_a/m_a \sim 4 \times 10^{13} \left(\frac{10\mu\mathrm{eV}}{m_a}\right) \text{ axions } /\mathrm{cm}^3$$

Axion DB wavelength ($v \sim 10^{-3}$): $\lambda_{\mathrm{dB}} = \frac{h}{p} = \frac{h}{mv} \simeq 120\,\mathrm{m}\left(\frac{10\mu\mathrm{eV}}{m_a}\right)$

So, the axion occupation number= number of axions in a reduced de Broglie volume, is $\sim 10^3$ for $m_a \sim 1$ eV.

→ Very large. Axion DM behaves like waves.

Axion Dark matter

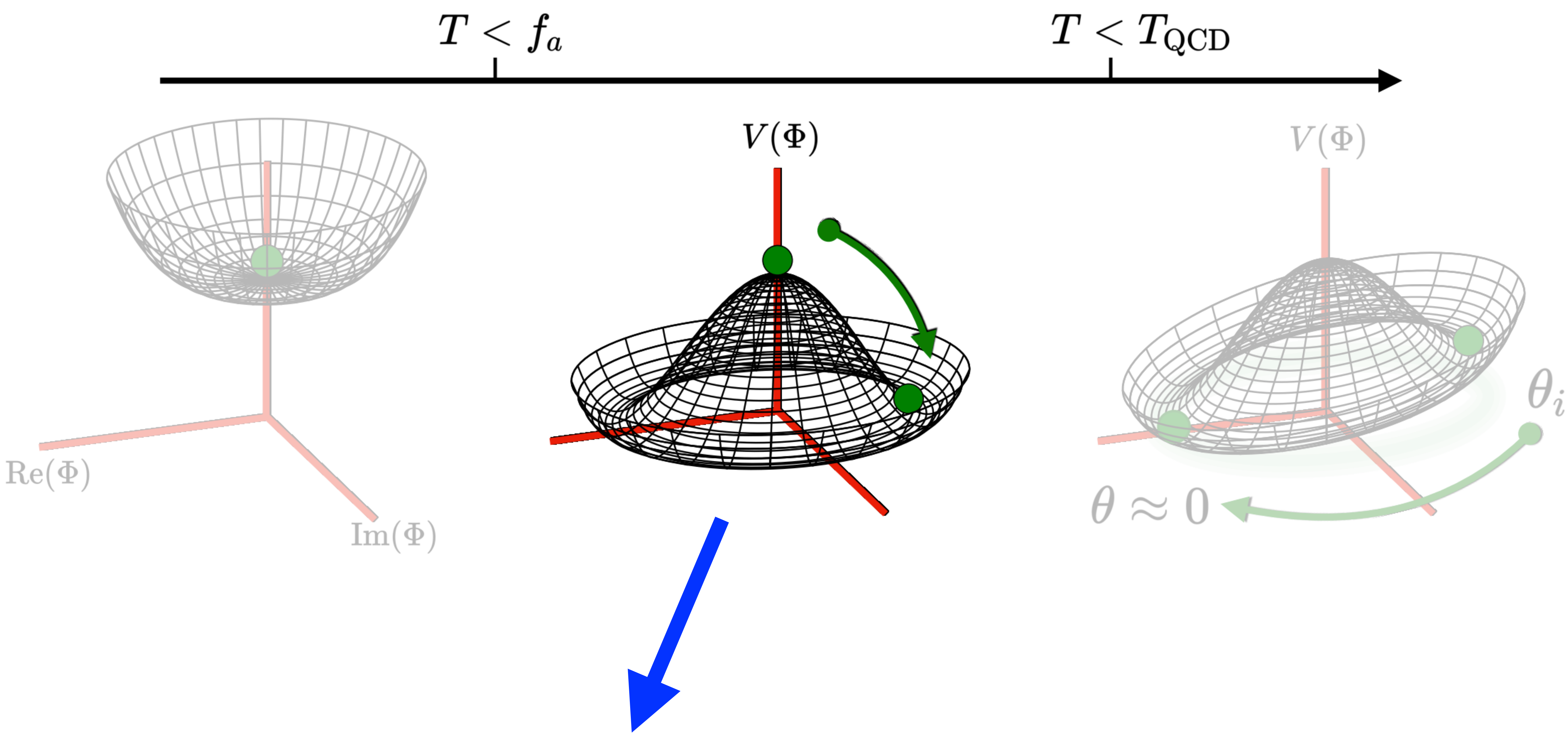


See C. O'Hare, Axion cosmology COST (2023) Training School

The axion emerges from the phase of the scalar field

$$\phi = \frac{1}{\sqrt{2}} \left(v_a + \rho \right) e^{ia/v_a}$$

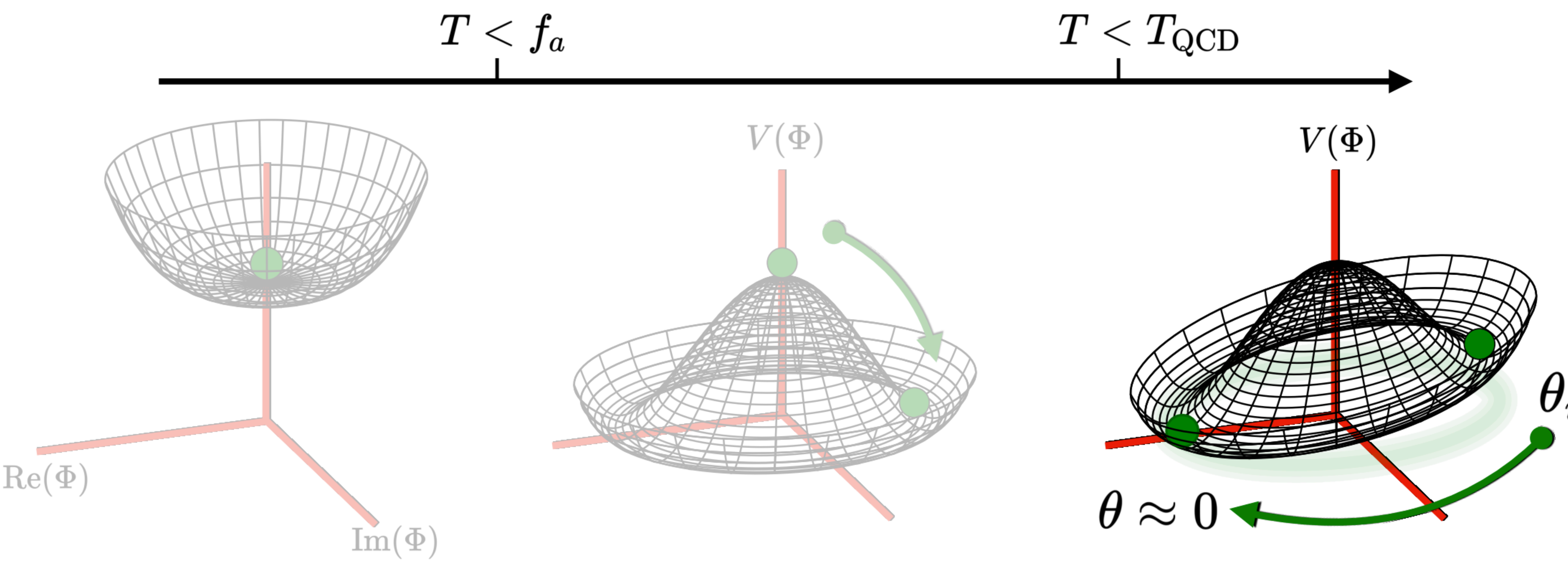
Axion Dark matter



At low enough temperature the PQ symmetry is spontaneously broken.

→ the θ angle is randomly selected. The **axion** is the massless d.o.f. in the flat direction of the potential

Axion Dark matter

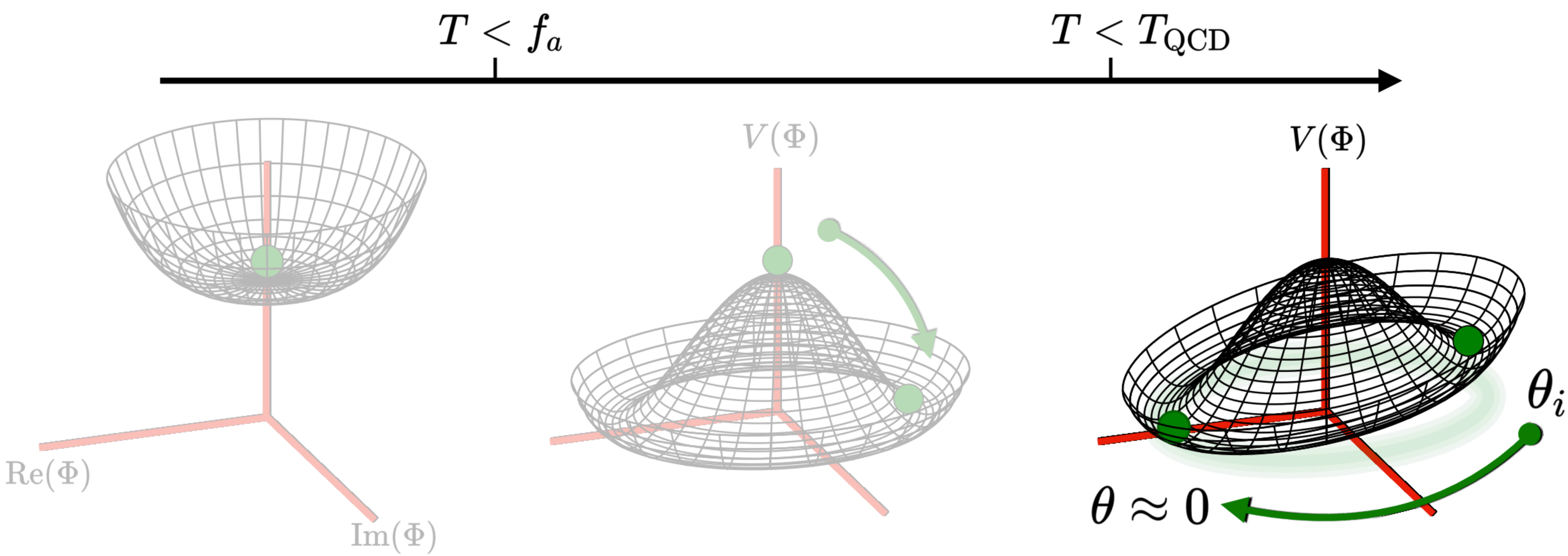


Around the QCD transition ($T \approx 1$ GeV), axions acquire a mass

$$m_a(T)^2 = \begin{cases} m_a^2 \left(\dfrac{T}{T_{\rm QCD}}\right)^{-n} & \text{for } T > T_{\rm QCD} \\ m_a^2 & \text{for } T < T_{\rm QCD} \end{cases}$$

with $T_{\rm QCD} \approx 150\,\mathrm{MeV}$ and $n \approx 8$.

Axion Dark matter



So, we have an axion field, which evolves according to the

→ Equation of motion

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

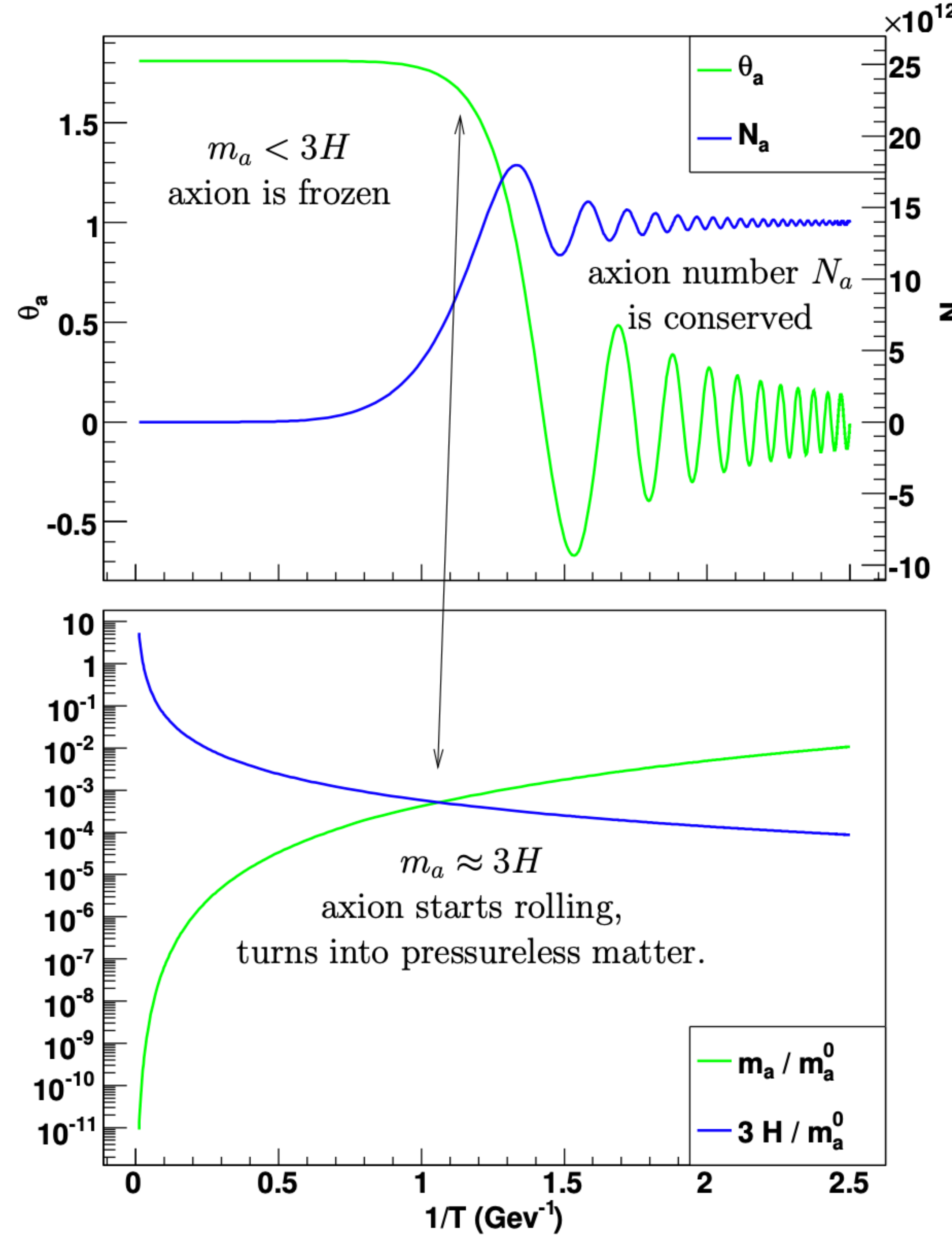
Axion Dark matter

→ Equation of motion

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

Numerical solution

See Olivier Wantz, E.P.S. Shellard



Axion Dark Matter: Some Considerations

For a spatially uniform real field $a(t)$ with potential $V = \frac{1}{2}m_a^2 a^2$,

$$\rho = \frac{1}{2}\dot{a}^2 + \frac{1}{2}m_a^2 a^2, \quad P = \frac{1}{2}\dot{a}^2 - \frac{1}{2}m_a^2 a^2, \quad w \equiv \frac{P}{\rho}.$$

If $m_a \gg H$, the friction can be ignored and the axion oscillates approximately as

$$a(t) = A(t)\cos\left(m_a t + \theta\right)$$

Thus,

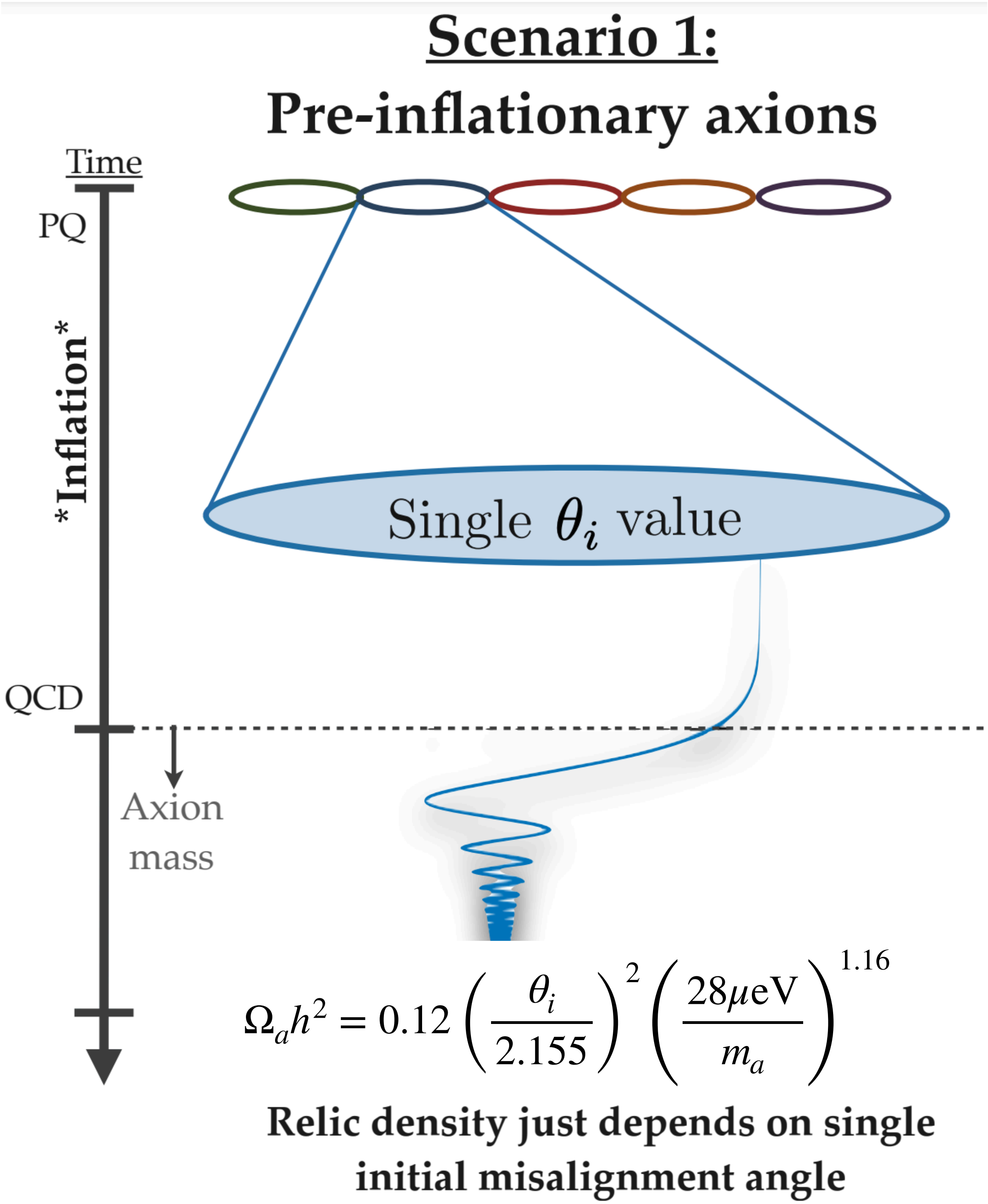
$$\Rightarrow \left\langle \dot{a}^2 \right\rangle = m_a^2 A^2 \left\langle \sin^2 \right\rangle = \frac{1}{2}m_a^2 A^2, \quad \left\langle a^2 \right\rangle = \frac{1}{2}A^2$$

$$\Rightarrow \langle P \rangle = \frac{1}{2}\left\langle \dot{a}^2 - m_a^2 a^2 \right\rangle = 0, \quad \langle \rho \rangle = \frac{1}{2}m_a^2 A^2.$$

⇒ Cold dark matter!

$$\Omega_a h^2 = 0.12\left(\frac{\theta_i}{2.155}\right)^2\left(\frac{28\mu\text{eV}}{m_a}\right)^{1.16}$$

Axion Dark matter: Pre-inflationary scenario



Calculable axion abundance
but unknown initial conditions

Figure Credits: C. O'Hare (2021)
https://cajohare.files.wordpress.com/2021/10/axions.pdf

Axion Dark matter: Post-inflationary scenario

Predictable initial angle.

Axion abundance depends also on production from topological defects

Estimating contribution from topological defects is very difficult. Numerical simulations still make very different predictions.

Important numerical advances thanks to Adaptive Mesh Refinement

M. Buschmann et al., *Nature Commun.* 13 (2022) 1, 1049.

Still controversial. More work required.

- M. Gorghetto, E. Hardy, arXiv:2212.13263
- O'Hare, Pierobon, Redondo, Wong, Phys.Rev.D 105 (2022)
- M. Gorghetto, E. Hardy, G. Villadoro, SciPost Phys. 10, 050 (2021)

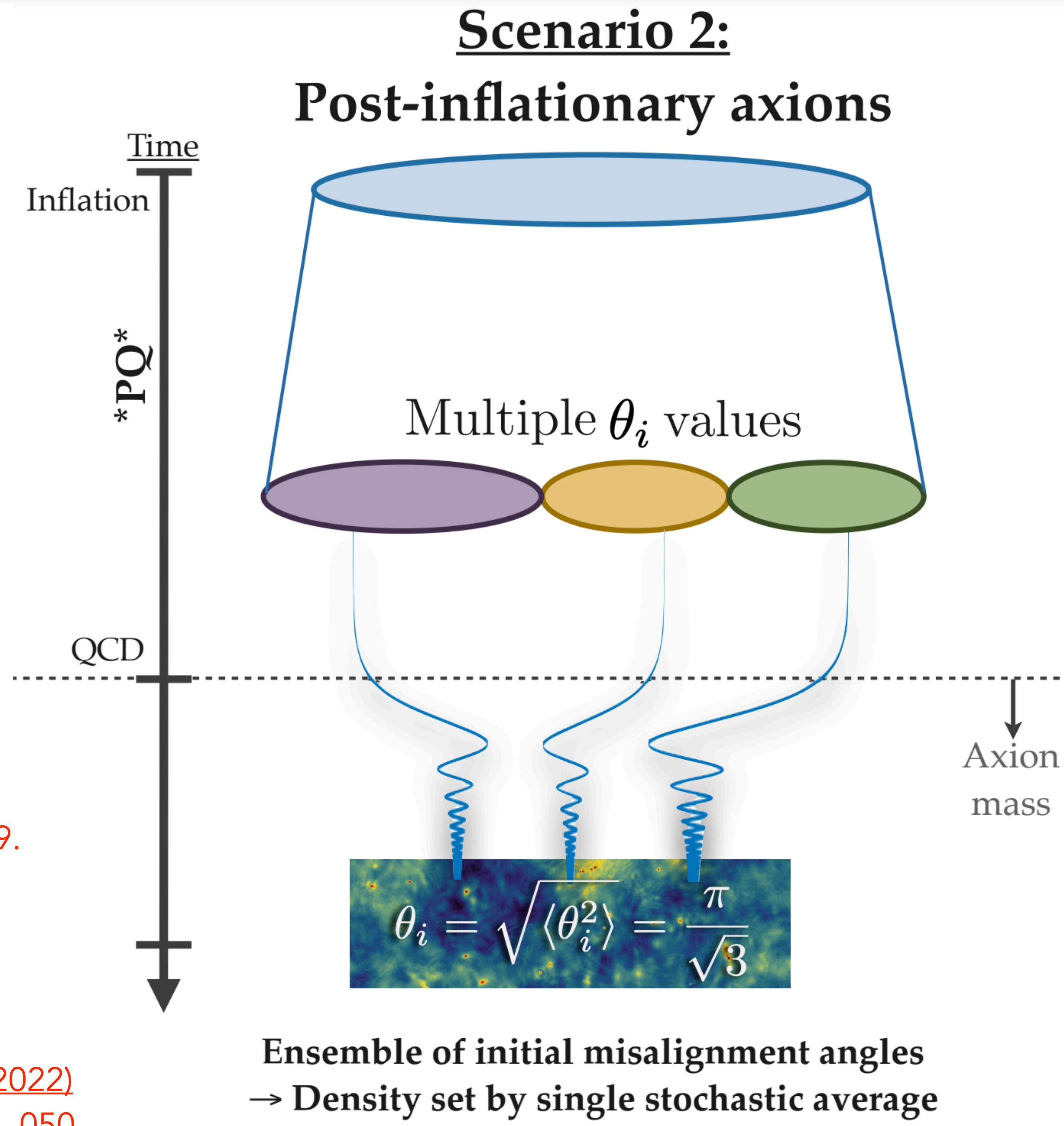
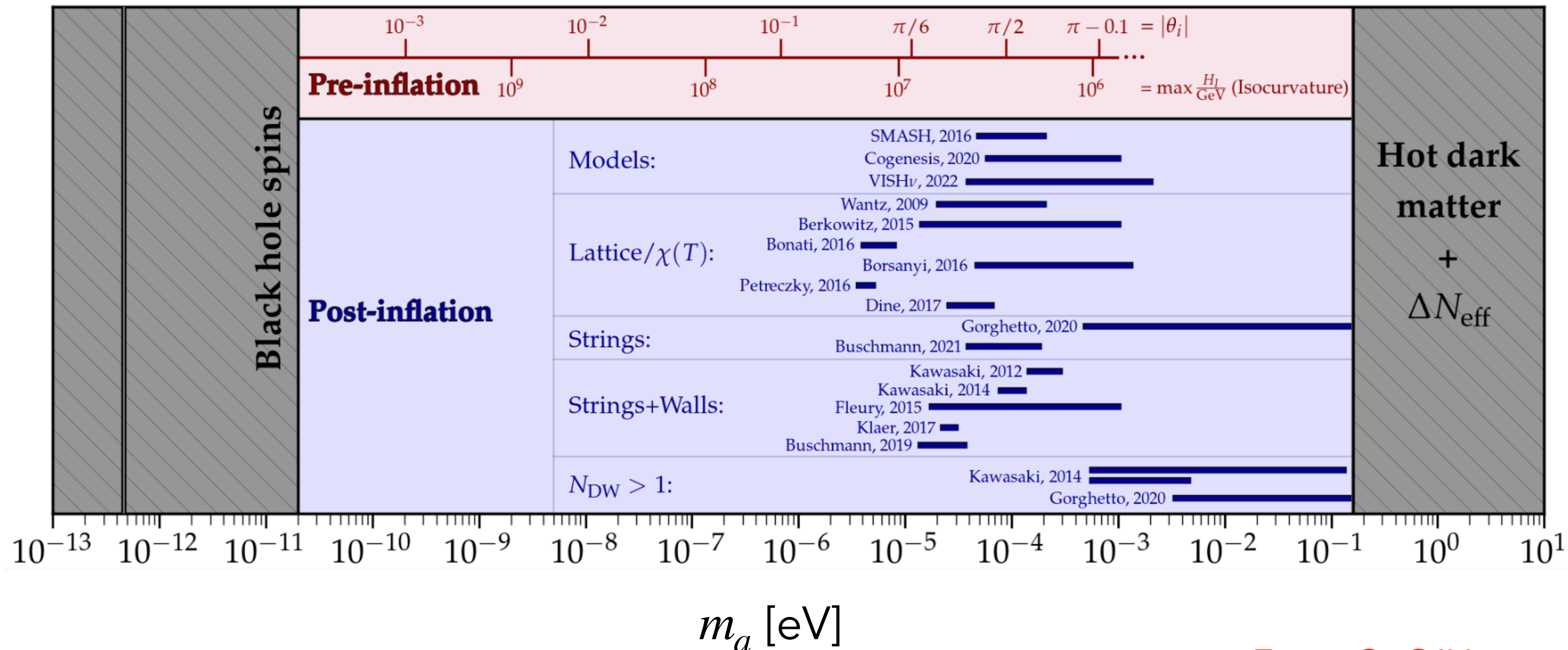


Figure Credits: C. O'Hare (2021)
https://cajohare.files.wordpress.com/2021/10/axions.pdf

Dark Matter Mass Predictions



From C. O'Hare

Predictions in post-inflation point at $m_a \gtrsim \mu\mathrm{eV}$

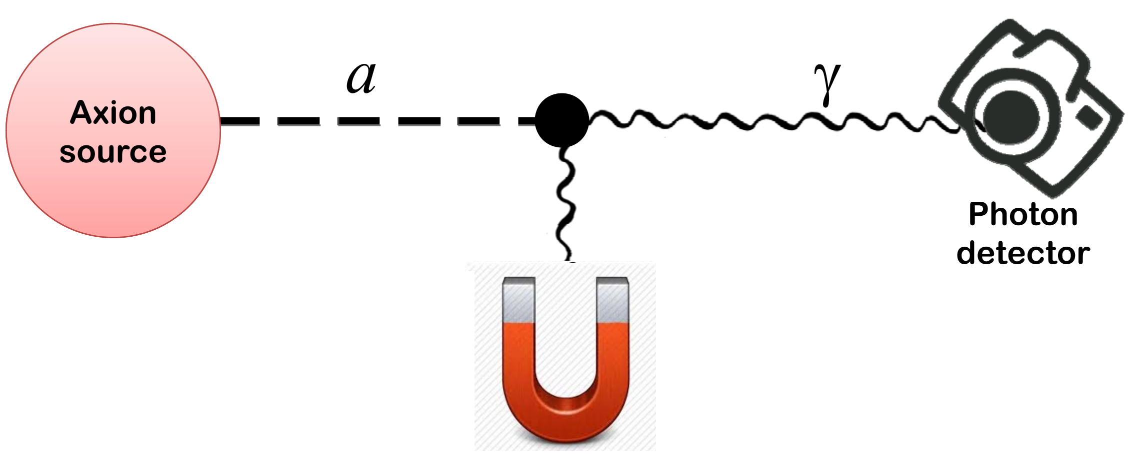
Hunting down the elusive axions

Our focus: $m_a \lesssim 1\text{eV}$.

Specific experimental challenges, and combination of specific know-hows

→ **cross-disciplinary technology transfer:**
E.g.,high-field magnets, super-conduction, RF techniques, X-ray optics, low background detection, low radioactivity techniques, quantum sensors, atomic physics, etc.

Most (but not all) detection strategies make use of the axion-photon coupling $g_{a\gamma}$
$a\,\vec{E}\cdot\vec{B}$



Sikivie (1983)

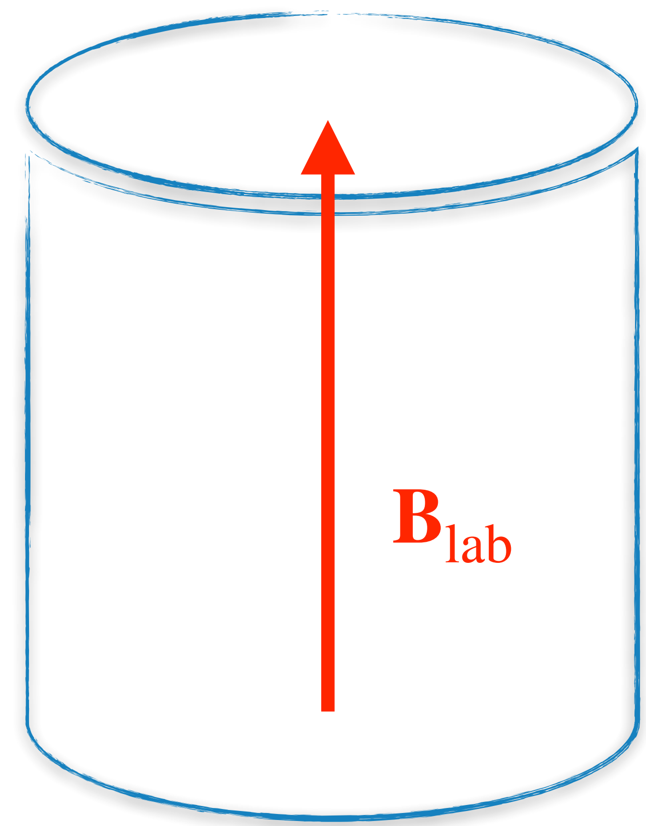
The Cavity Haloscope

Ideal, cylindrical cavity, with perfectly metallic surfaces

Standing EM waves in a cavity

$$\begin{aligned} \varepsilon \nabla \cdot \mathbf{E} &= \rho_o, \\ \nabla \cdot \mathbf{B} &= 0, \\ \nabla \times \mathbf{E} + \dot{\mathbf{B}} &= 0, \\ \mu^{-1} \nabla \times \mathbf{B} - \varepsilon \dot{\mathbf{E}} &= \mathbf{J}_o. \end{aligned}$$

Sources



Two kinds of modes TE_{nmp} and TM_{nmp}

Symbol	Meaning	Allowed values
m	azimuthal order (number of field variations in ϕ)	$0, 1, 2, \ldots$
n	radial order (n-th root of Bessel or its derivative)	$1, 2, \ldots$
p	axial order (number of half-wavelengths along z)	$0, 1, 2, \ldots$

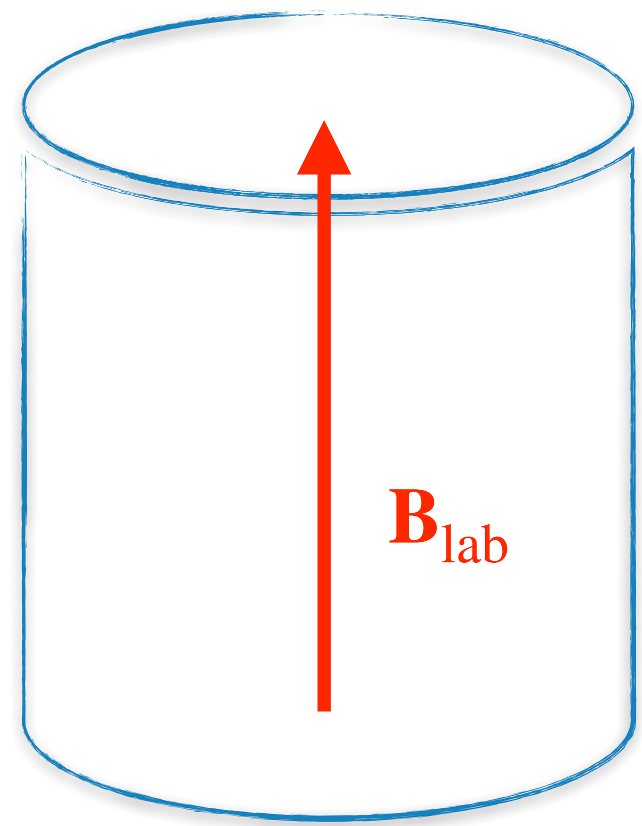
The Cavity Haloscope

Add axions + Uniform $\mathbf{B}_{\text{Lab}}$ $\quad L_{a\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} \propto a\,\mathbf{B}\cdot\mathbf{E}$

Standing EM waves in a cavity

$$\begin{aligned}
\varepsilon\nabla\cdot\mathbf{E} &= \rho_o + \rho_a, \\
\nabla\cdot\mathbf{B} &= 0, \\
\nabla\times\mathbf{E} + \dot{\mathbf{B}} &= 0, \\
\mu^{-1}\nabla\times\mathbf{B} - \varepsilon\dot{\mathbf{E}} &= \mathbf{J}_o + \mathbf{J}_a\,.
\end{aligned}$$

Sources



$$\rho_a = g_{a\gamma\gamma}\nabla a\cdot\mathbf{B}_0$$

$$\mathbf{J}_a = -\,g_{a\gamma\gamma}(\dot{a}\mathbf{B} + (\nabla a)\times\mathbf{E})$$

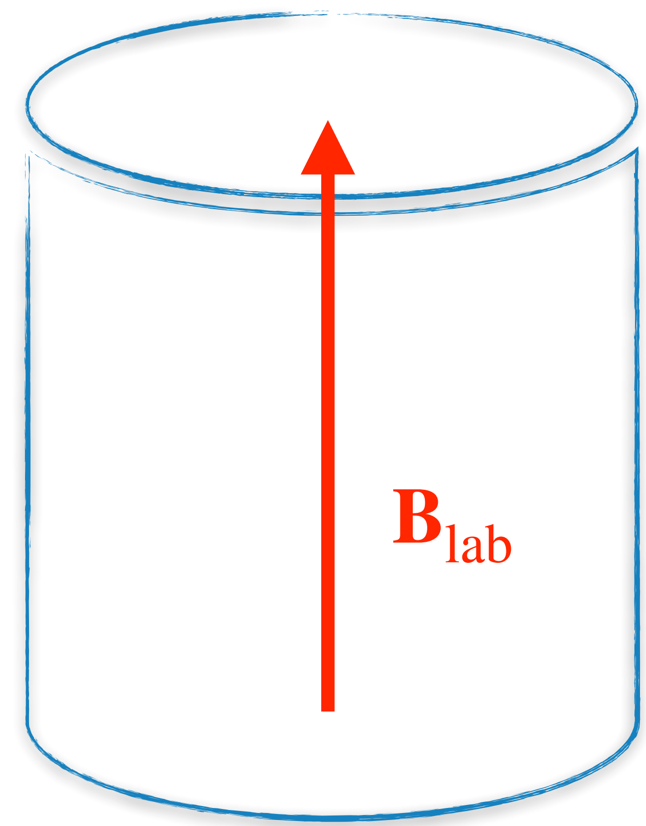
The Cavity Haloscope

Add axions + Uniform $\mathbf{B}_{\text{Lab}}$ $\quad L_{a\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} \propto a\,\mathbf{B}\cdot\mathbf{E}$

Standing EM waves in a cavity

$$\begin{aligned} \varepsilon\nabla\cdot\mathbf{E} &= \cancel{\rho_o} + \rho_a, \\ \nabla\cdot\mathbf{B} &= 0, \\ \nabla\times\mathbf{E} + \dot{\mathbf{B}} &= 0, \\ \mu^{-1}\nabla\times\mathbf{B} - \varepsilon\dot{\mathbf{E}} &= \cancel{\mathbf{J}_o} + \mathbf{J}_a\,. \end{aligned}$$

Sources



$$\rho_a = g_{a\gamma\gamma}\cancel{\nabla}a\cdot\mathbf{B}_0$$

Uniform background of CDM axions

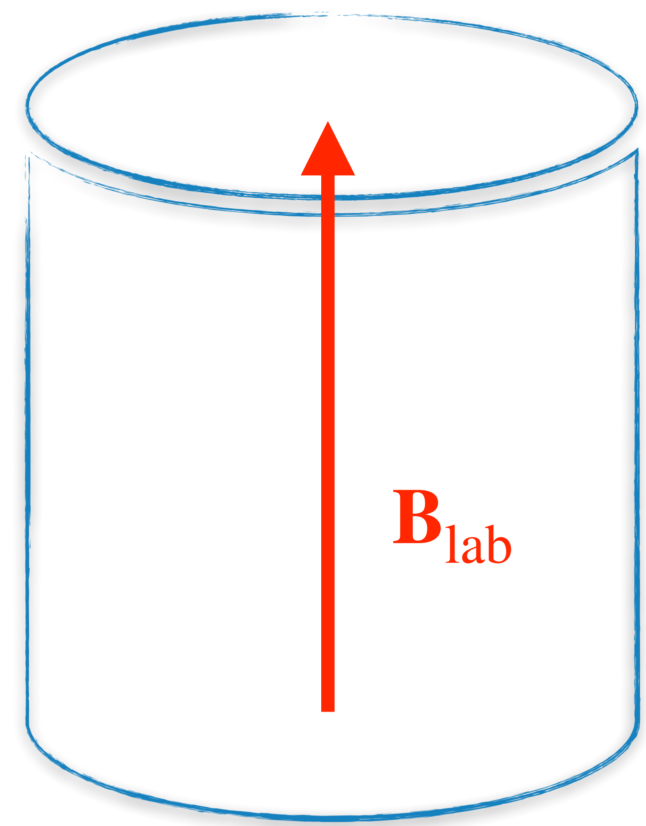
$$\mathbf{J}_a = -g_{a\gamma\gamma}(\dot{a}\mathbf{B} + (\cancel{\nabla a})\times\mathbf{E})$$

The Cavity Haloscope

Standing EM waves in a cavity

$$L_{a\gamma} \propto a\,\mathbf{B} \cdot \mathbf{E}$$

$\approx \mathbf{B}_{\rm lab}$ Cavity mode $\mathbf{E}_{\rm cav}$



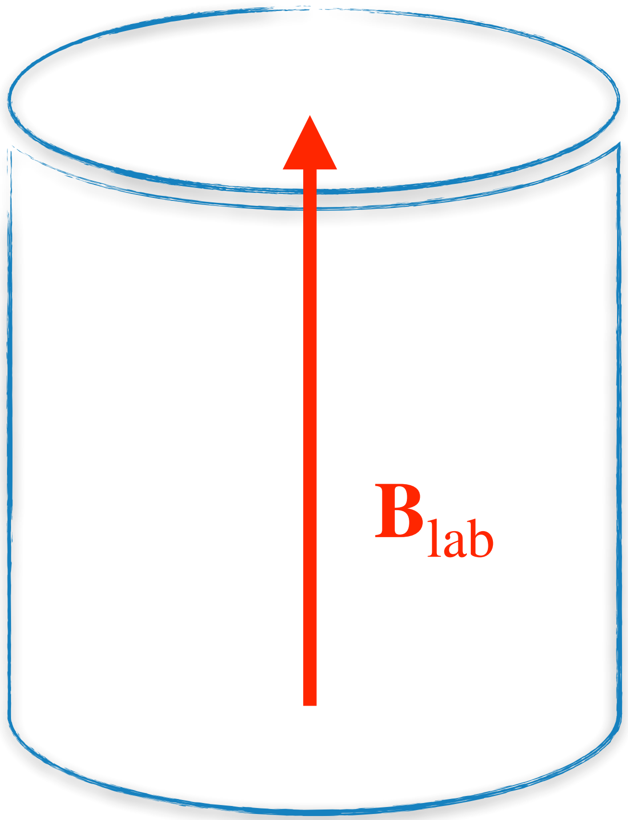
Only TM_{nmp} modes → lowest mode TM_{010}.

The Cavity Haloscope

Example: Ideal cylindrical cavity

Frequency of the TM_{010} mode:

$$f \approx \frac{2.4\, c}{2\pi r}$$

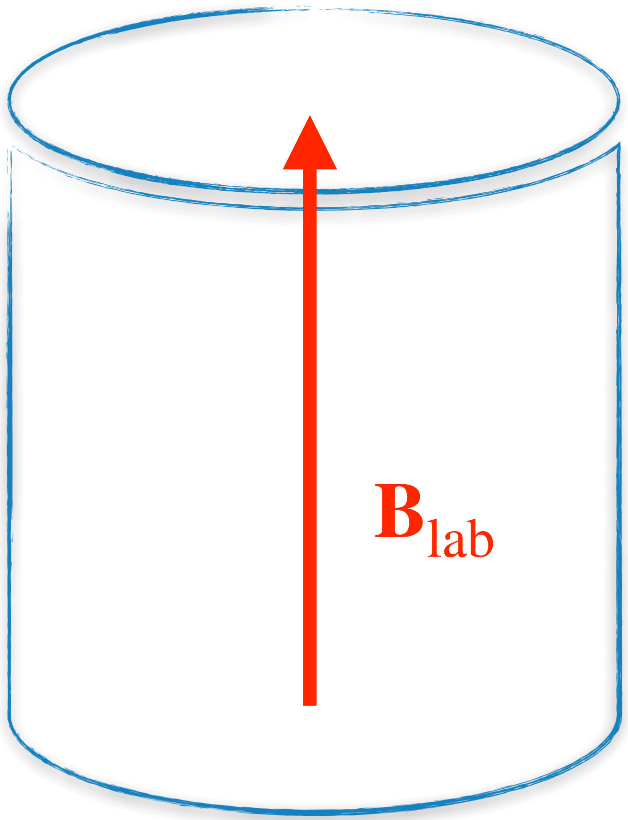


The axion frequency ($\approx m_a$) should be tuned with the cavity size r

The Cavity Haloscope: Power Generation

The power is proportional to

$$\int_V \mathbf{J} \cdot \mathbf{E}_{\rm cav}\, dV, \quad \text{with} \quad \mathbf{J} \propto g_{a\gamma}\, \dot{a}\, \mathbf{B}_{\rm lab}$$

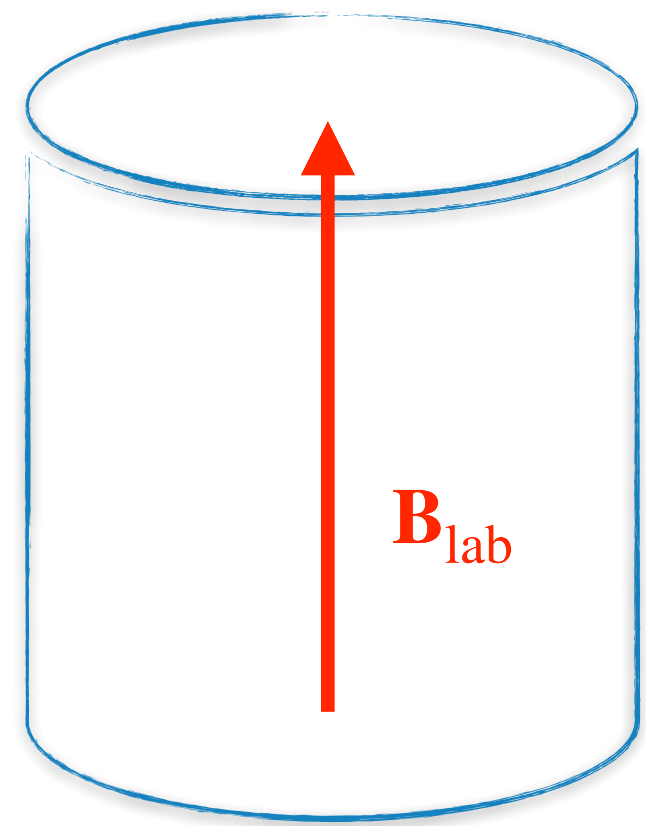


Large $\mathbf{B}_{\rm lab}$ and large volume increase the power.

The Cavity Haloscope: Power Generation

The power is proportional to

$$\int_V \mathbf{J} \cdot \mathbf{E}_{\rm cav}\, dV, \quad \text{with} \quad \mathbf{J} \propto g_{a\gamma}\, \dot{a}\, \mathbf{B}_{\rm lab}$$



In performing the integral →

$$g_{a\gamma} \int_V \underbrace{(\partial_t a)}\, \mathbf{B}_{\rm lab}(\mathbf{r}) \cdot \mathbf{E}_{\rm cav}(\mathbf{r})\, dV$$

Make sure that a is roughly constant within the cavity, otherwise there will be self-canceling terms.

$$|\mathbf{k}_a|\, L \ll 1 \quad \Longleftrightarrow \quad L \ll \lambda_{\rm dB} = \frac{2\pi}{m_a v}$$

The Cavity Haloscope: Fourier Analysis

1- Expand e.m. field in cavity eigenmodes: $\mathbf{A}(\mathbf{x}, t) = \sum_\alpha \mathbf{e}_\alpha(\mathbf{x})\psi_\alpha(t)$

2- Plug in Maxwell eq and use orthogonality conditions of $\mathbf{e}_\alpha$

$$\rightarrow \quad \ddot{\psi}_\beta + \omega_\beta^2 \psi_\beta + \gamma_\beta \dot{\psi}_\beta = - g_{a\gamma} \int_V d^3x \mathbf{B}_{\text{lab}}(\mathbf{x}) \cdot \mathbf{e}_\beta(\mathbf{x}) \partial_t a(t)$$

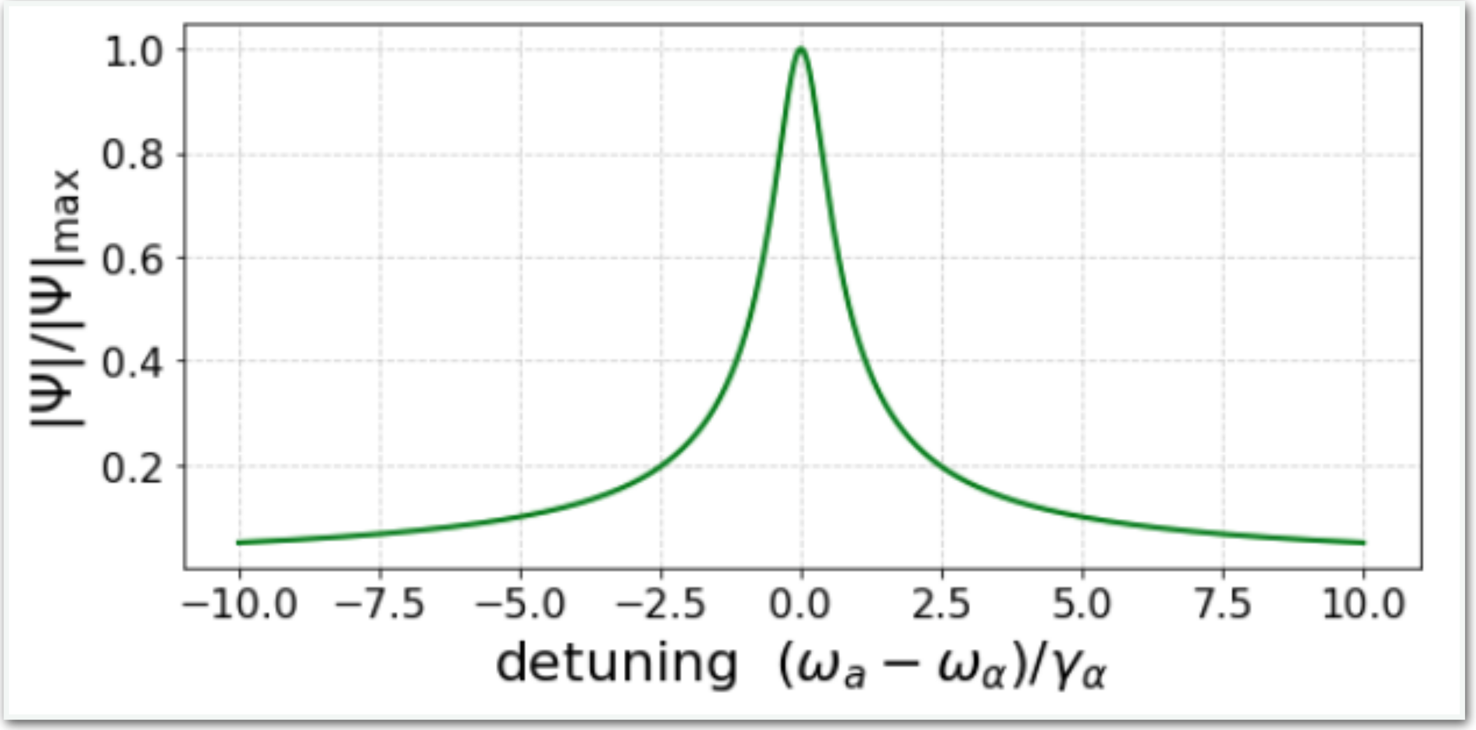
Added *by hand* to account for energy losses

For $\gamma = 0$ and no axions, each mode behaves just like an harmonic oscillator, with never ending oscillations.

The Cavity Haloscope: Fourier Analysis

3- Write axion field as:

$$a(t) = \mathrm{Re}\left(Ae^{-i\omega_a t}\right)$$



4- Go back to the amplitude equation

$$\ddot{\psi}_\beta + \omega_\beta^2 \psi_\beta = -\, g_{a\gamma} \int_V d^3x \mathbf{B}_{\mathrm{lab}}(\mathbf{x}) \cdot \mathbf{e}_\beta(\mathbf{x}) \partial_t a(t) - \gamma_\beta \dot{\psi}_\beta$$

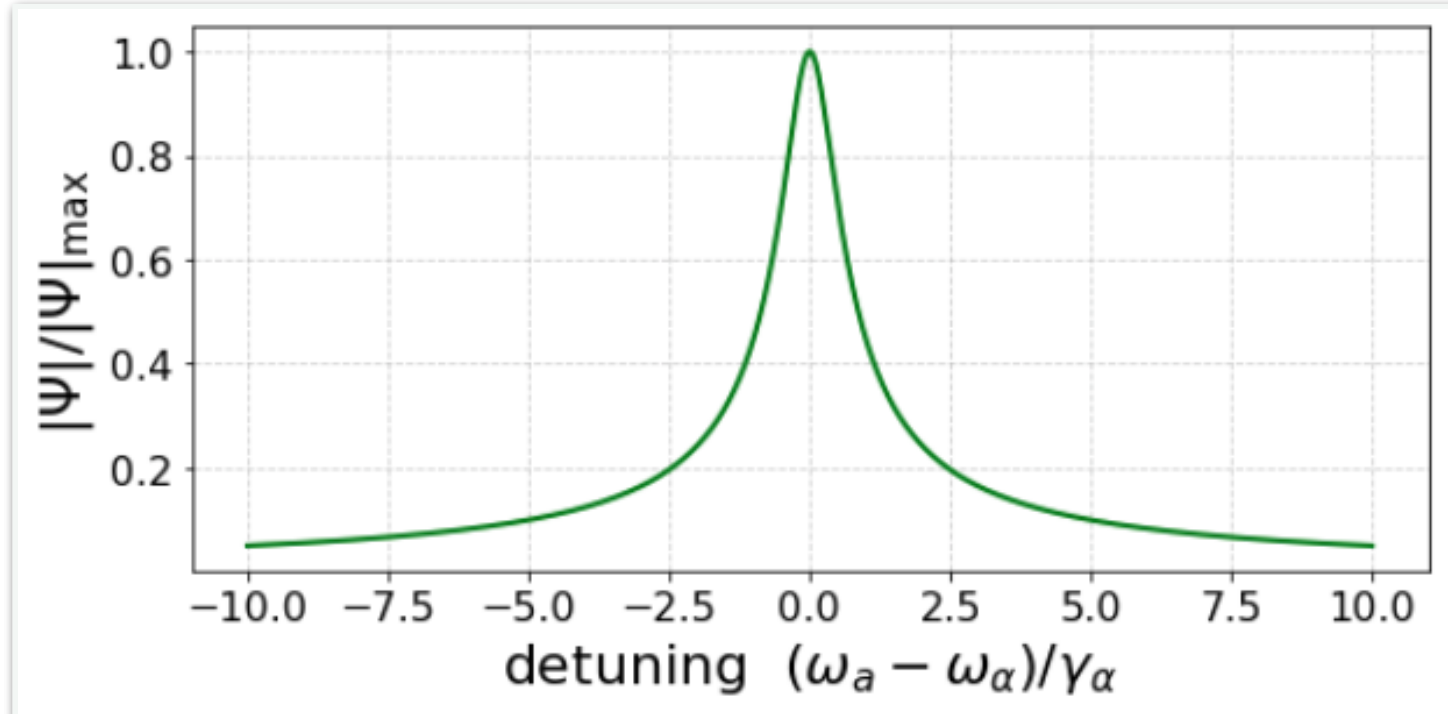
and solve for the mode amplitude

$$\psi_\alpha(t) = g_{a\gamma\gamma}\, \omega_\alpha \left(\int_V d^3x \mathbf{B}_{\mathrm{lab}} \cdot \mathbf{e}_\alpha \right) \mathrm{Re}\left[\frac{i a_0\, e^{-i\omega_a t}}{\omega_\alpha^2 - \omega_a^2 - i\gamma_\alpha \omega_a} \right]$$

The Cavity Haloscope: Fourier Analysis

Resonance!

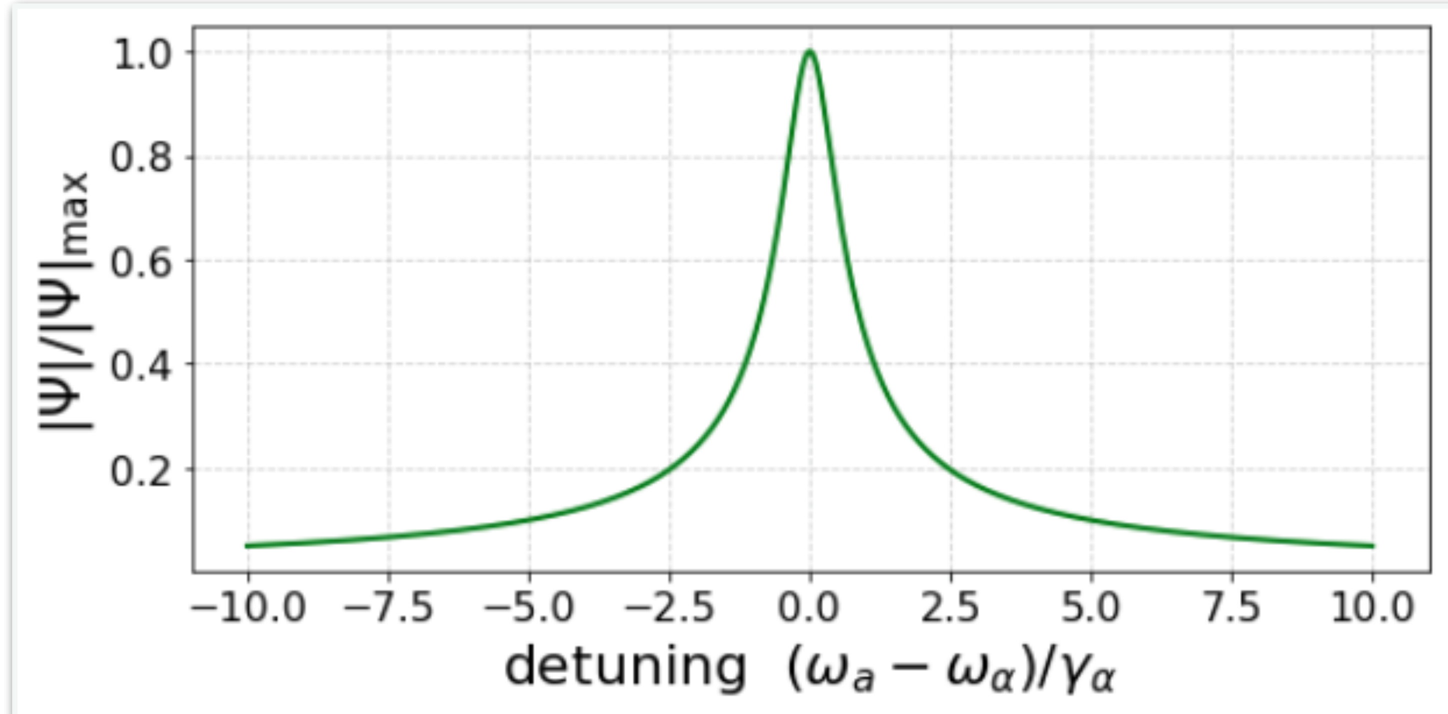
Strong signal when the axion frequency matches the mode frequency



Detailed calculation in Sikivie (2020): Invisible Axion Search Methods

The Cavity Haloscope: Power Signal

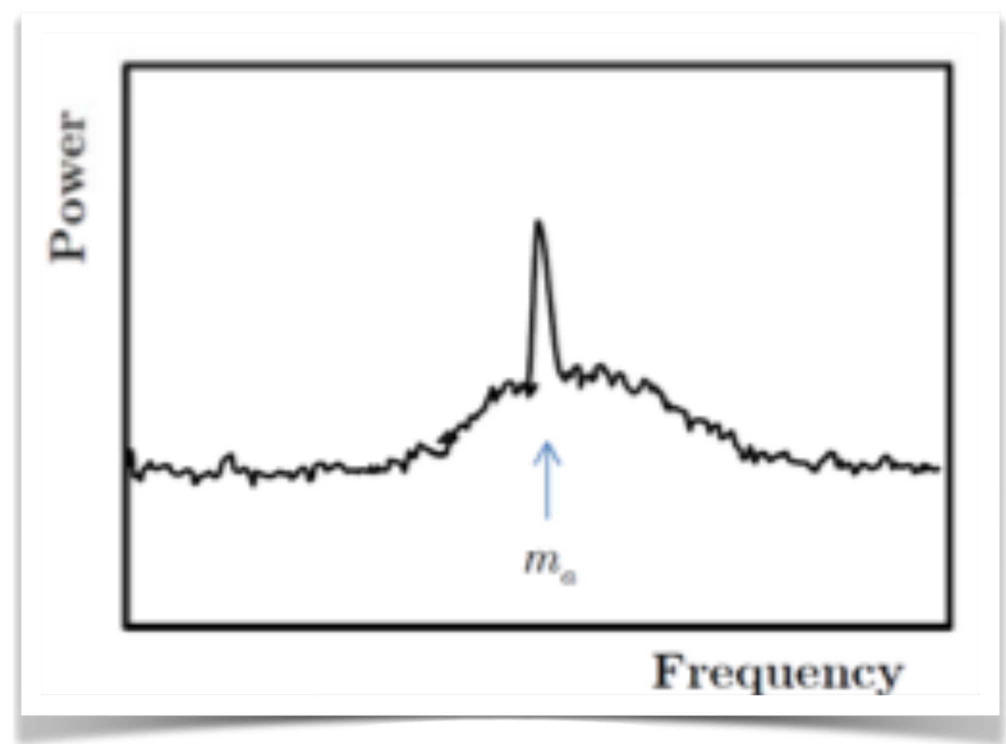
The power can be calculated in the usual way, as average energy over time.



In the limit $\omega_a \simeq \omega_\alpha$

the expression is simplified significantly

$$P_\alpha = g_{a\gamma}^2 \rho_a B_{\text{lab}}^2 V C_\alpha \frac{Q_\alpha}{m_a}$$



Very slow scanning of mass region

The Cavity Haloscope: Noise

Practically:
→ **thermal noise** attributed to the blackbody radiation by the physical temperature of the cavity
→ noise added by the RF readout chain

D. Kim et al. JCAP 03 (2020) 066

$$\mathrm{SNR} \equiv \frac{P_{\mathrm{signal}}}{\delta P_{\mathrm{noise}}}$$

Dicke's radiometer equation

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{P_s}{T_{\mathrm{sys}}}\sqrt{\frac{\Delta t}{\Delta \nu}}$$

Wish list:

- long scanning time
- narrow band
- low T_{sys}

The Cavity Haloscope: Noise

Practically:
→ **thermal noise** attributed to the blackbody radiation by the physical temperature of the cavity
→ noise added by the RF readout chain

D. Kim et al. JCAP 03 (2020) 066

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Dicke's radiometer equation

$$\frac{\mathrm{S}}{\mathrm{N}} = \frac{P_s}{T_{\mathrm{sys}}}\sqrt{\frac{\Delta t}{\Delta \nu}}$$

This is what controls the scanning time!

$$T_{\mathrm{sys}} = T_{\mathrm{phy}} + T_{\mathrm{add}}$$

System noise

Physical temperature

Amplifier

Wish list:
- long scanning time
- narrow band
- low T_{sys}

The Cavity Haloscope: Noise

Modern approaches include

- low-temperature refrigerators
- Quantum Sensing to increase the S/N and reduce the scanning time

Recent ERC grant awarded to explore quantum technology in axion cavity detection

DarkQuantum

European Research Council

Established by the European Commission

Cavity Experiments

Micro eV mass range:

Most experience.

- ADMX: proven sensitivity to few μeV

High Mass:

Difficult: higher masses requires smaller volume → lower sensitivity. Possible solutions:

- lower noise
- matching more cavities or new multicavity designs
- More powerful magnets
- Dielectric Haloscopes
- …

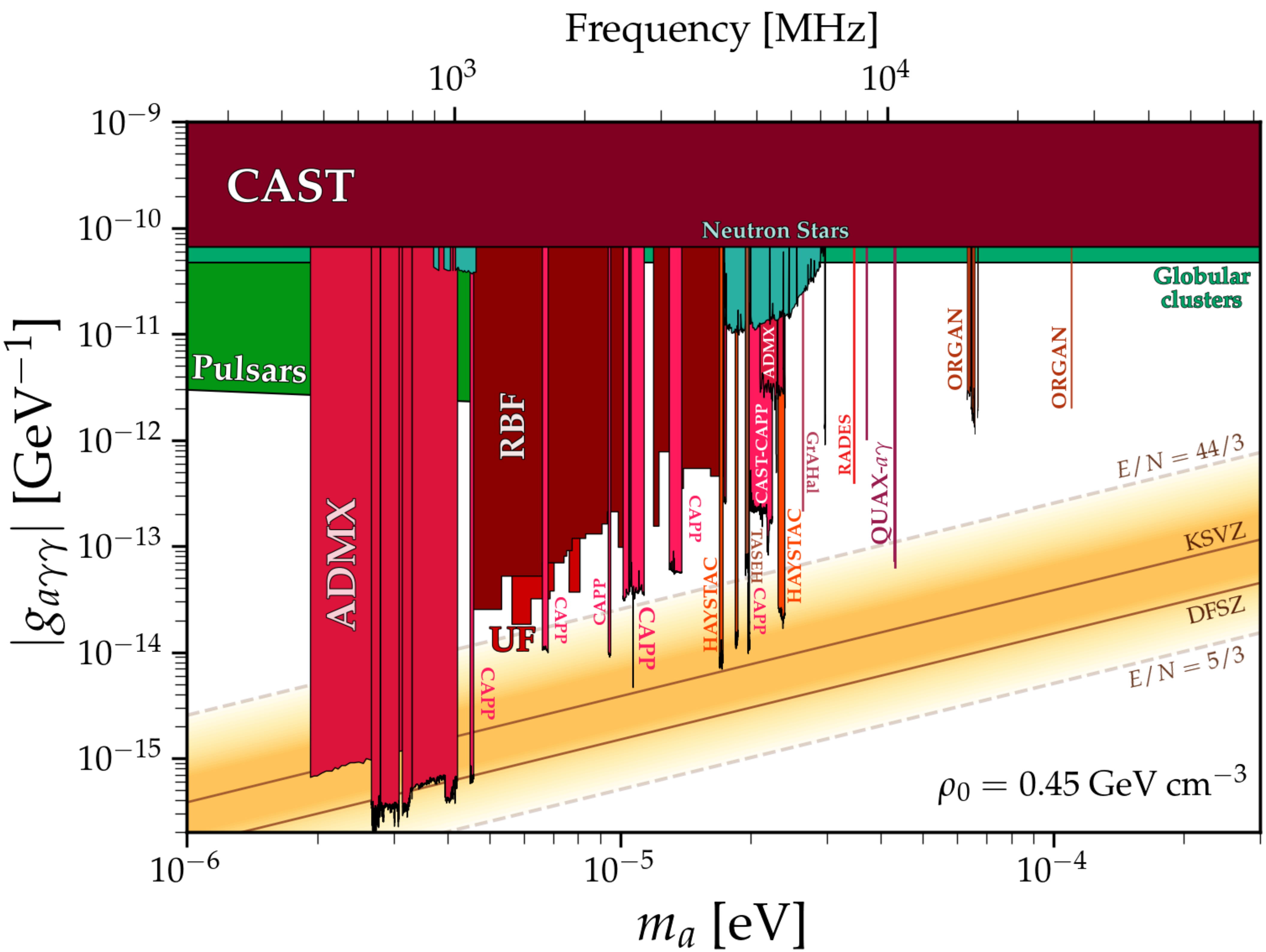
Many projects: HAYSTAC, CAPP, MADMAX,

Low Mass:

Technologically simpler. However, expensive. Needs large magnets

- FLASH (concept)
- BabyIAXO (to be built)
- IAXO

Cavity Experiments



Haloscopes

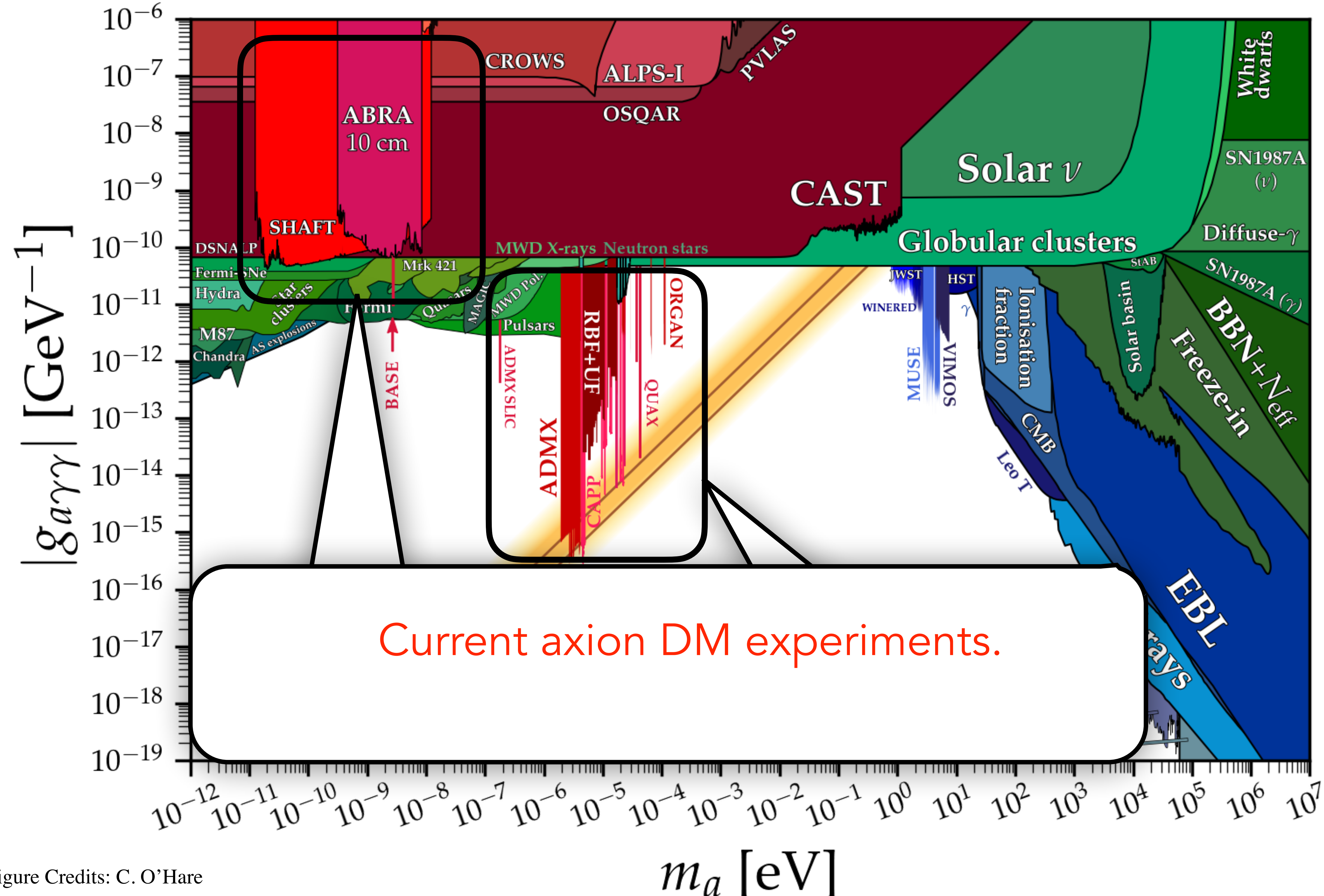


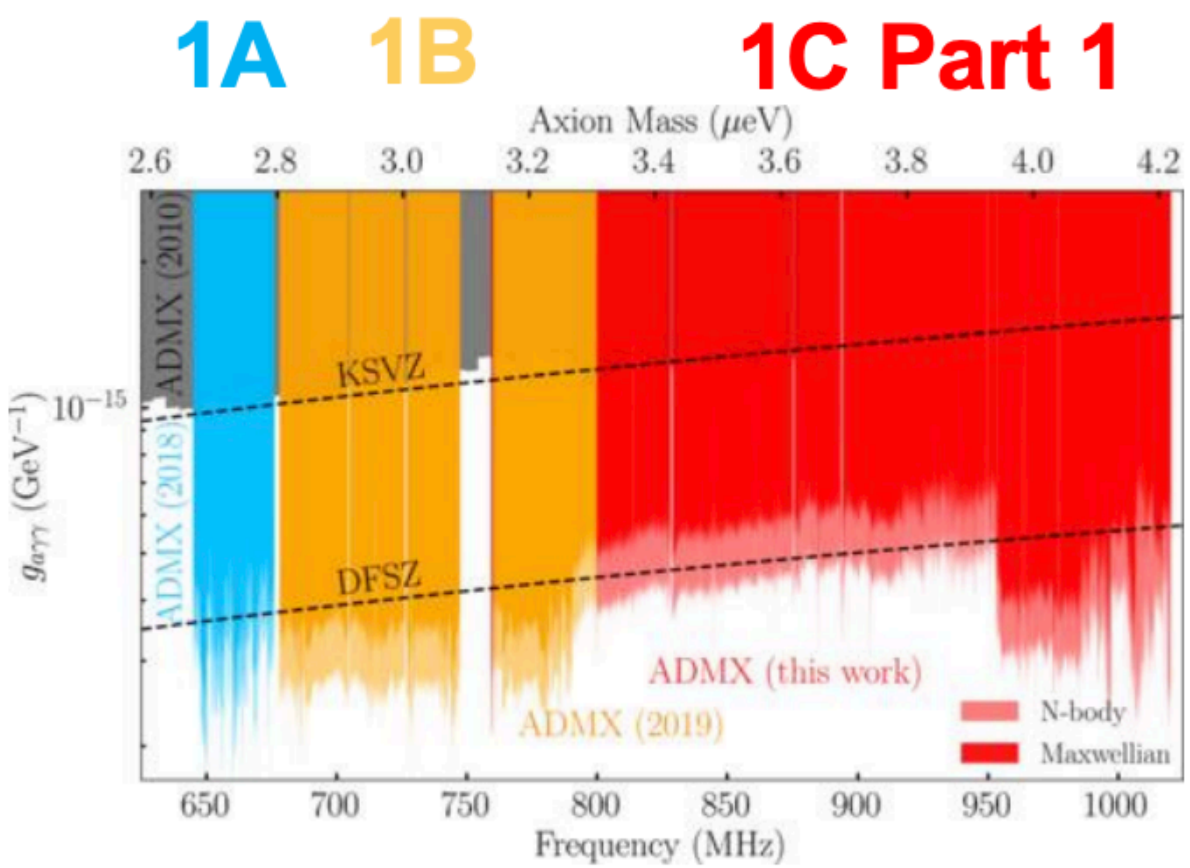
Figure Credits: C. O'Hare
https://cajohare.github.io/AxionLimits/

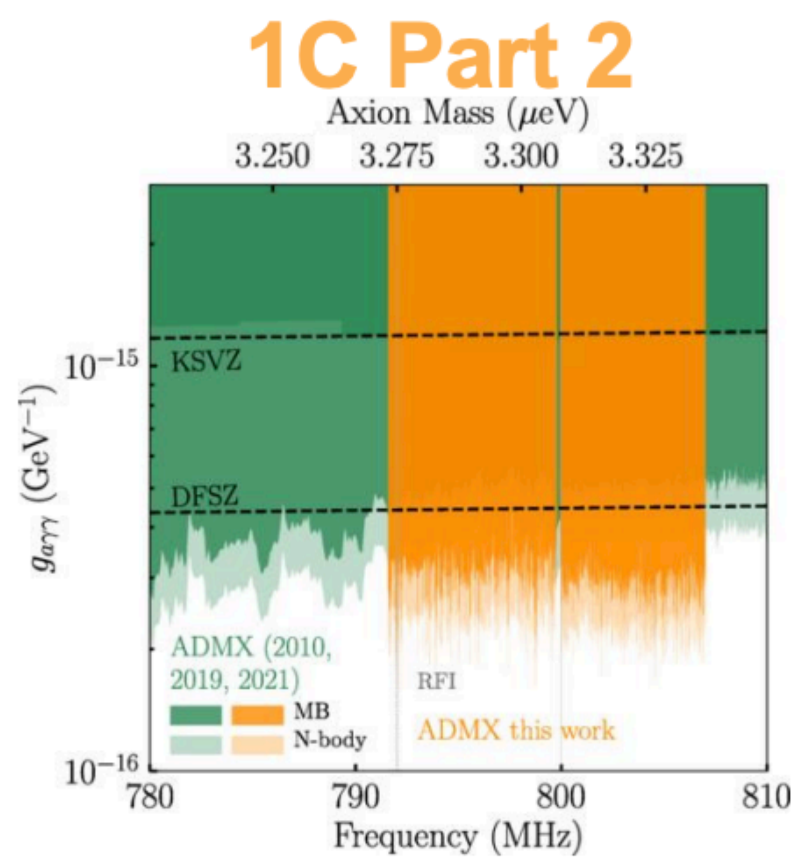
Cavity Searches

Micro eV mass range:

Most experience.

- ADMX: proven sensitivity to few μeV





Run 1 segmented into four parts A-D

- A: 645-680MHz (2017)
- B: 680-790MHz (2018)
- C: 790-1025MHz (2020+2022)
- D: 1.0-1.4GHz, in 2 parts (to be completed in 2025)

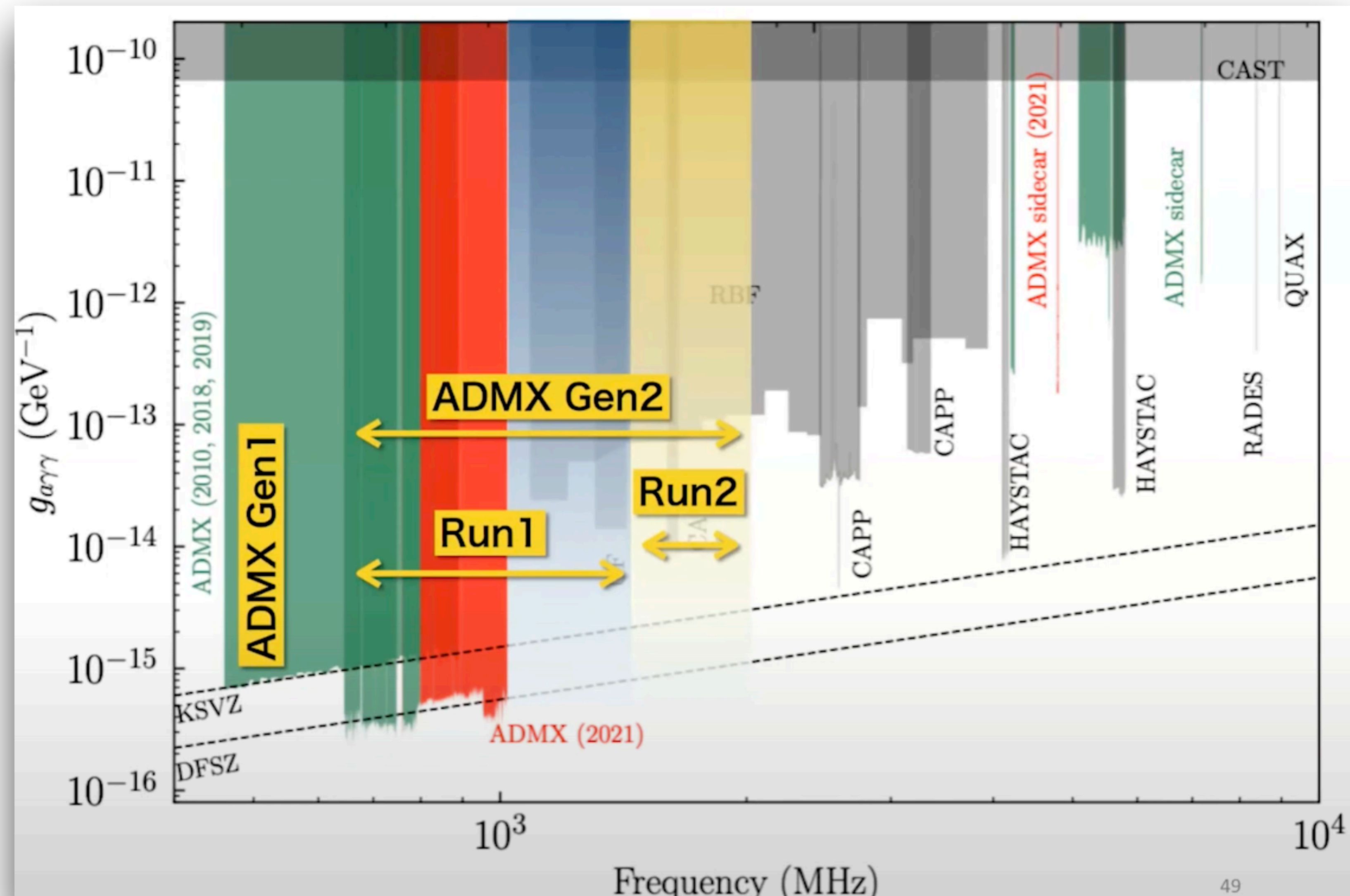
See → Erik Lentz @ UCLA Dark Matter Meeting, 2025

Cavity Searches

Micro eV mass range:

Most experience.

- ADMX: proven sensitivity to few μeV



Future:

Move to multicavity designs

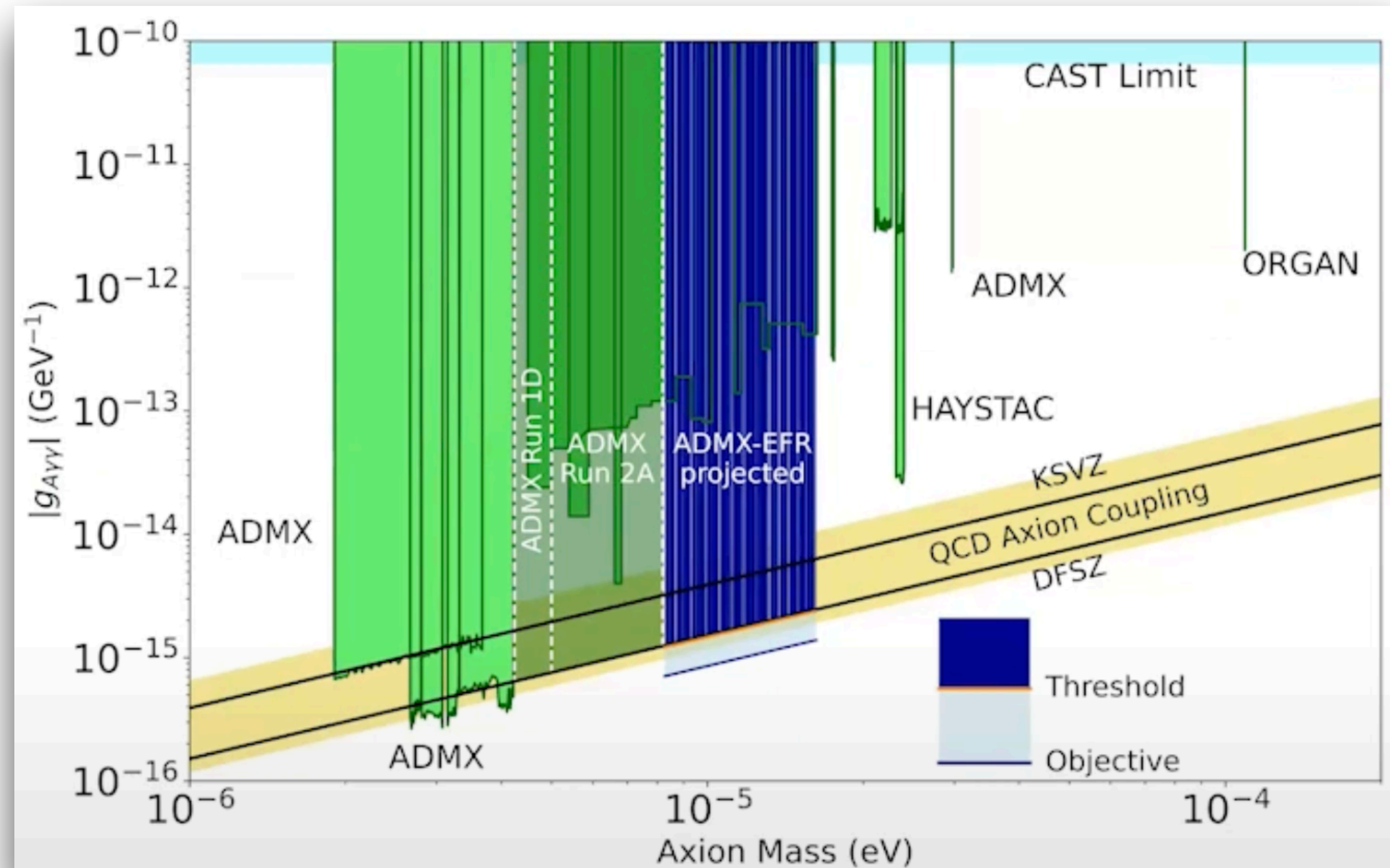
Set to begin upgrade for Run 2 in 2026-7

→ Erik Lentz @ UCLA Dark Matter Meeting, 2025

Gray Rybka @ GGI 2023

Cavity Searches

Micro eV mass range:
Most experience.
- ADMX: proven sensitivity to few μeV



Gray Rybka @ GGI 2023

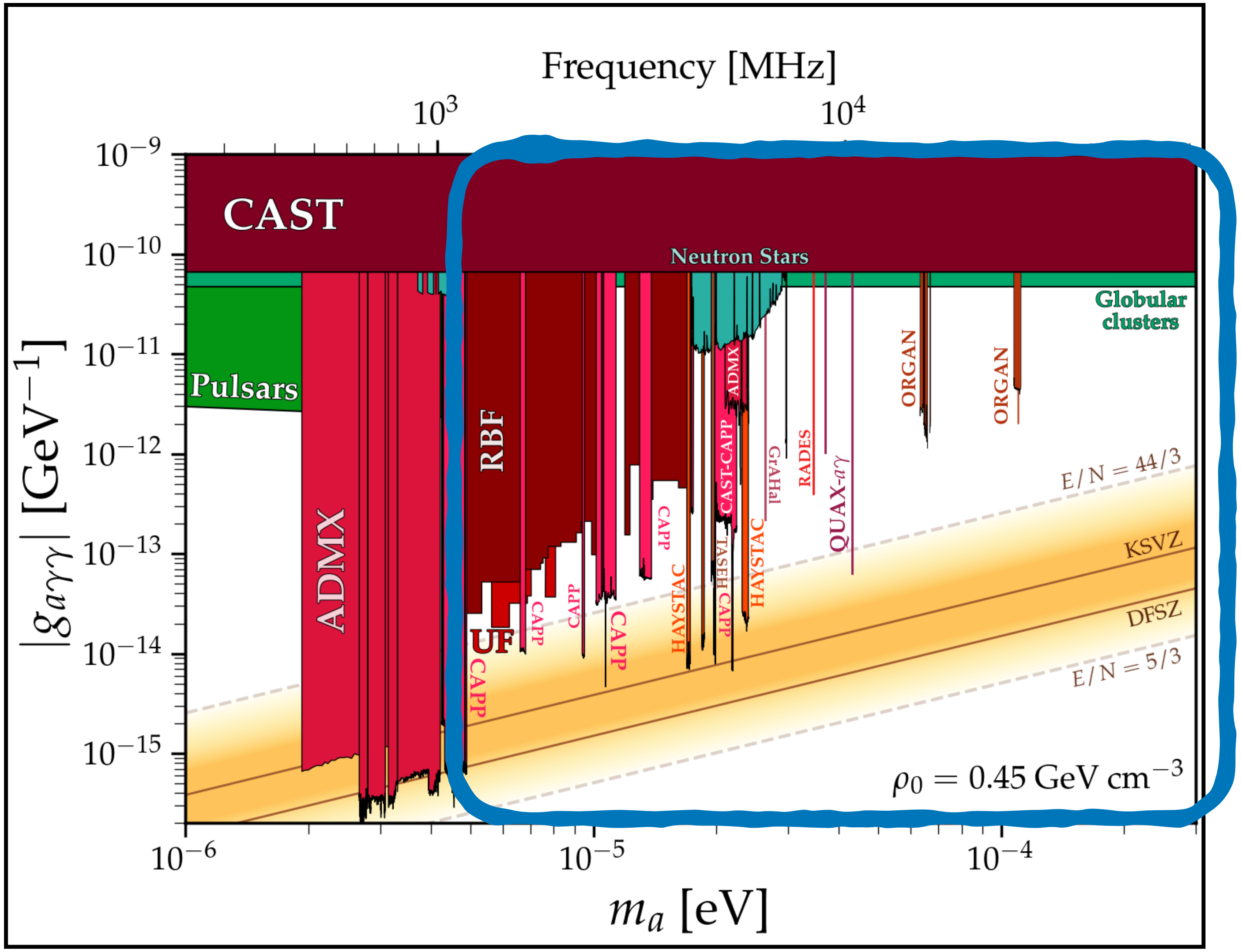
Future:

ADMX - EFR
(Extended Frequency Reach:
2 -4GHz)

However: "*Feb. 2025: EFR was selected to not continue as a DMNI project*"
Erik Lentz @ UCLA Dark Matter Meeting, 2025

Cavity Searches

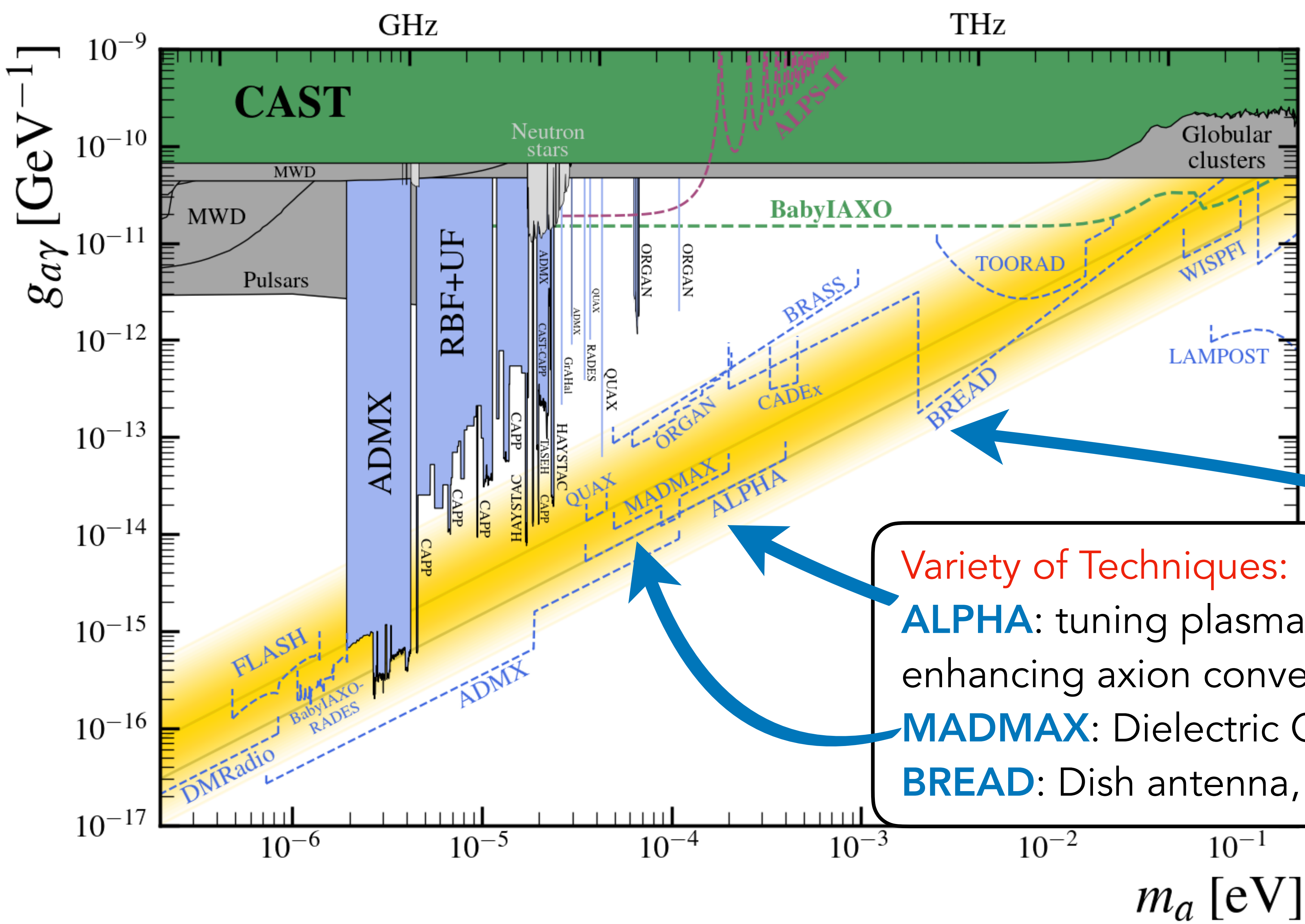
High mass:
HAYSTAC, CAPP, MADMAX, QUAX, ORGAN etc.



- Significant advances from CAPP
- CAPP, QUAX, HAYSTAC touch the QCD band
- Experimental application of quantum technologies for axion searches by HAYSTAC [Nature 590 238 (2021)]: double the scanning rate for axions

Cavity Searches

Many proposals to probe the higher mass region



Variety of Techniques:

ALPHA: tuning plasma frequency and enhancing axion conversions

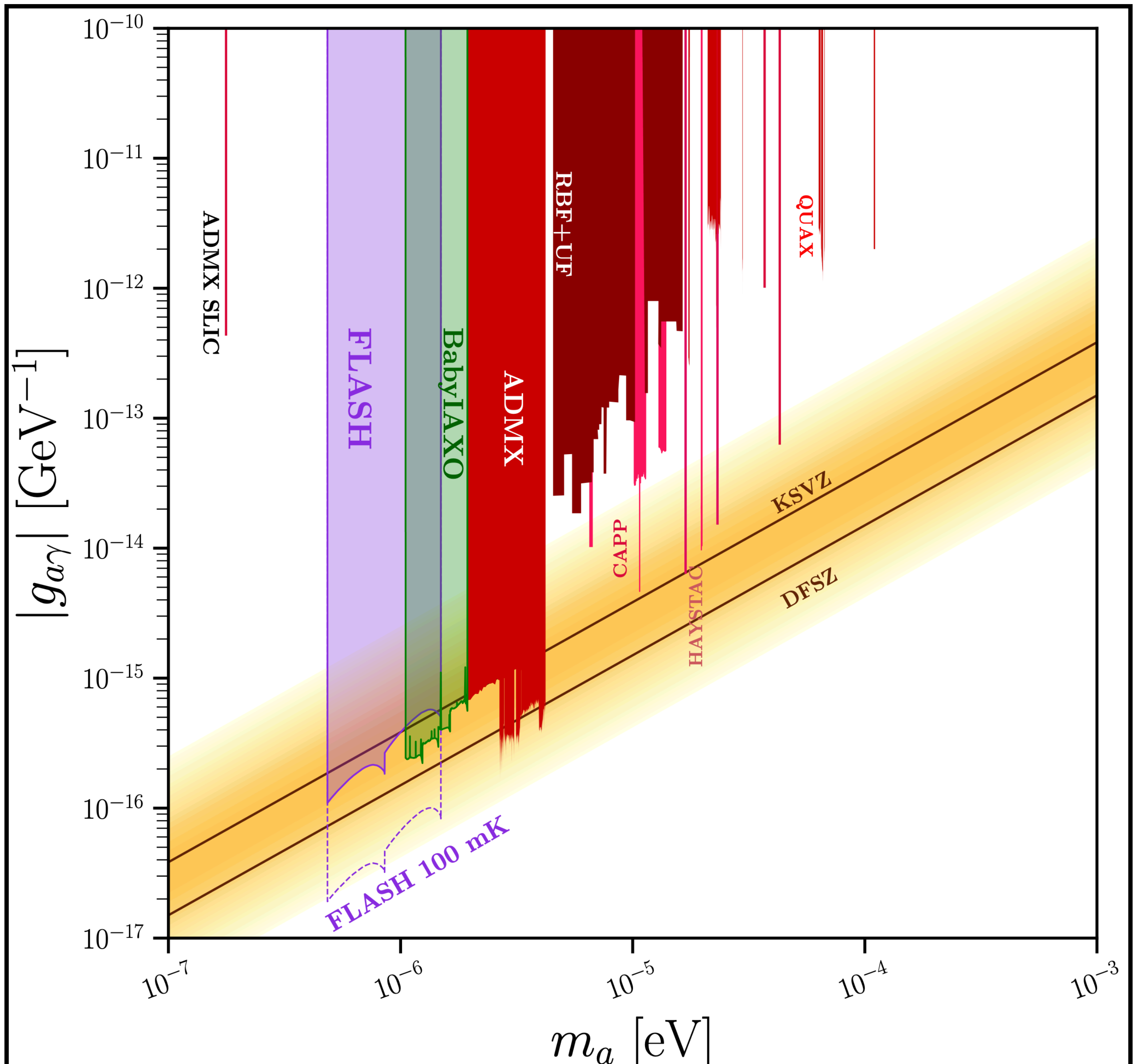
MADMAX: Dielectric Cavities

BREAD: Dish antenna, broadband

From FIP white paper (2022)

Cavity Searches

Low mass:
FLASH and BabyIAXO (RADES)



FLASH and BabyIAXO will cover the region left of ADMX.

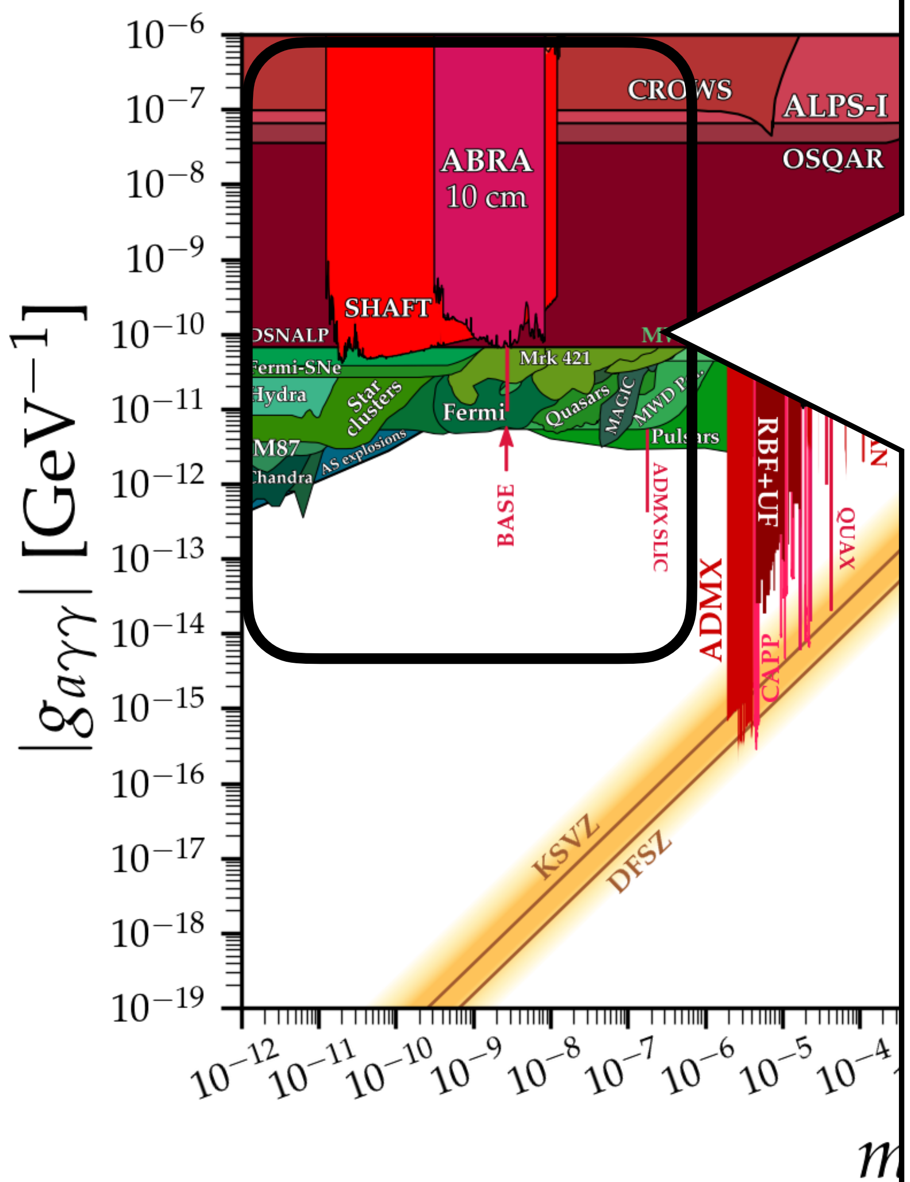
Preparing for TDR

Expected to reach the QCD band.

Jan 19th 2024: FINUDA cooled down to 4K and energized with a current of 2706 A, generating a magnetic field of 1.05 T

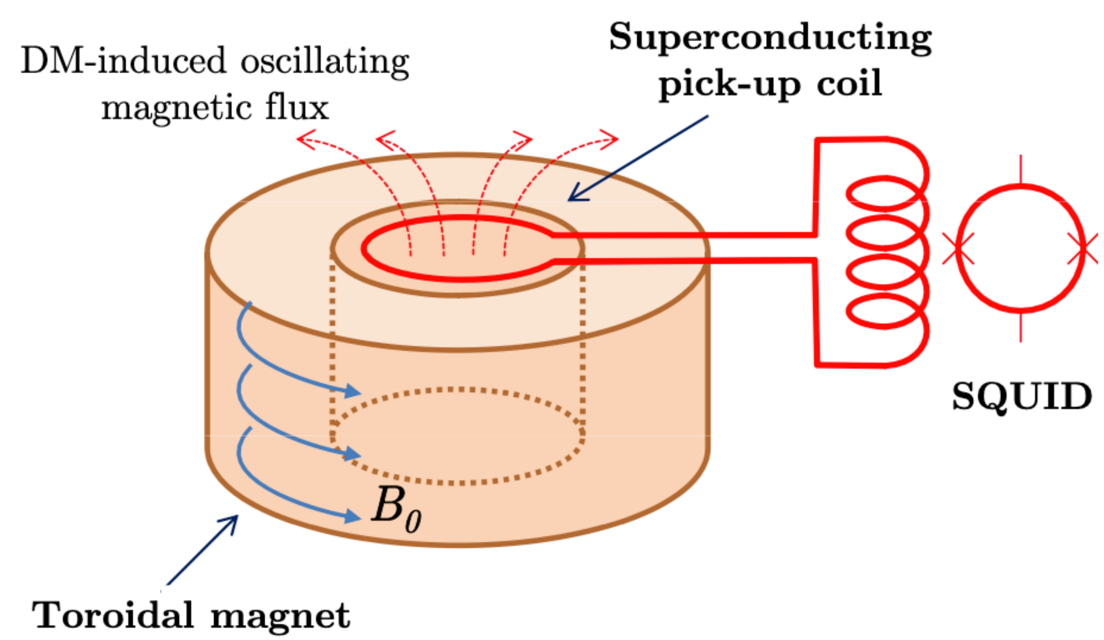
Very Low Mass Haloscopes

Very Low mass:
ABRA, SHAFT, ADMX SLIC



Very low mass: other techniques:
ADMX SLIC → LC circuit,

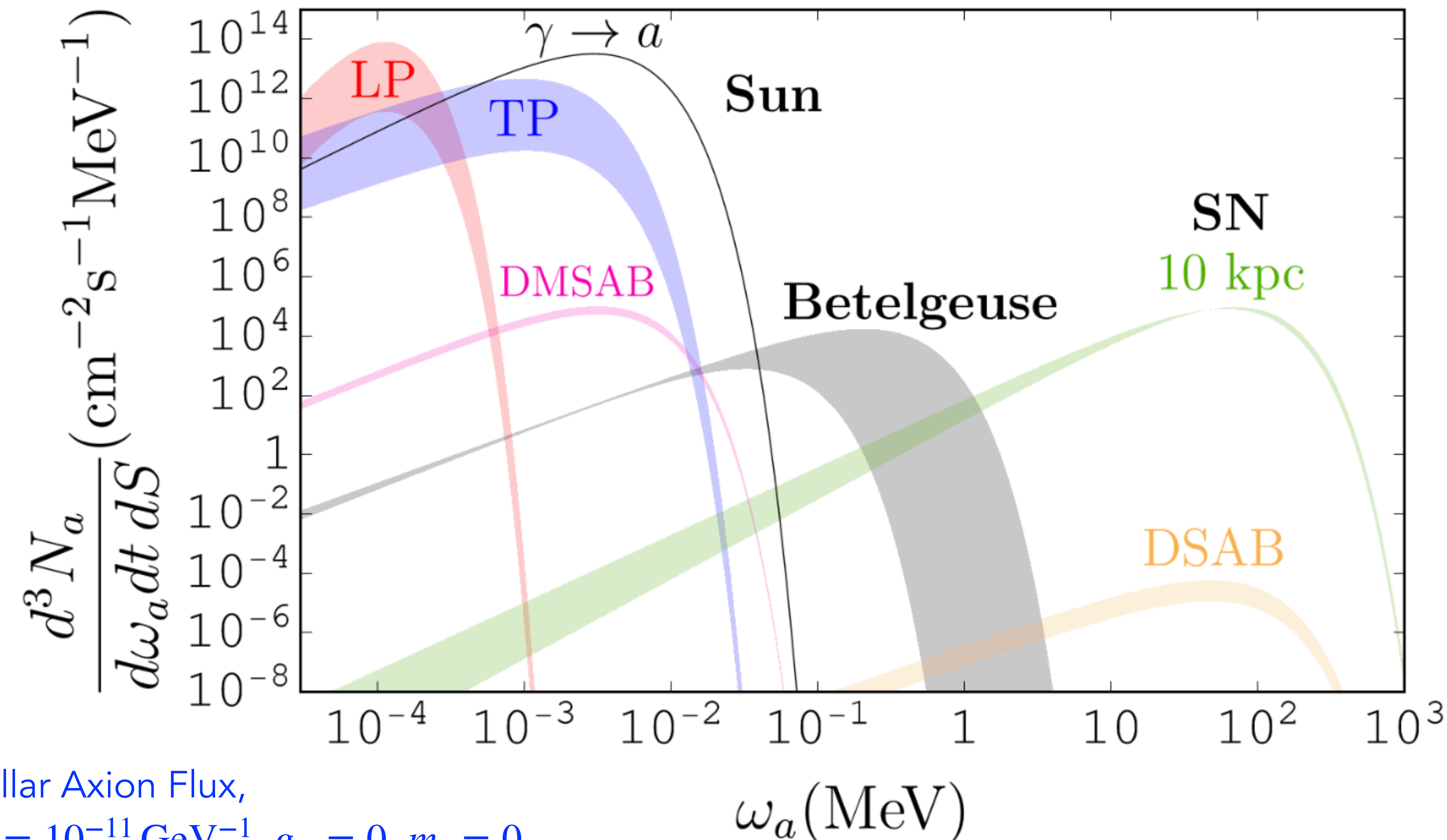
ABRA (to become DM radio) → toroidal magnet configuration



The ALP DM field excites an oscillating E_a field along the field lines of a static toroidal field B_e.

The oscillating E_a induces an oscillating B_e field along the symmetric axis read by a pickup coil connected to a SQUID.

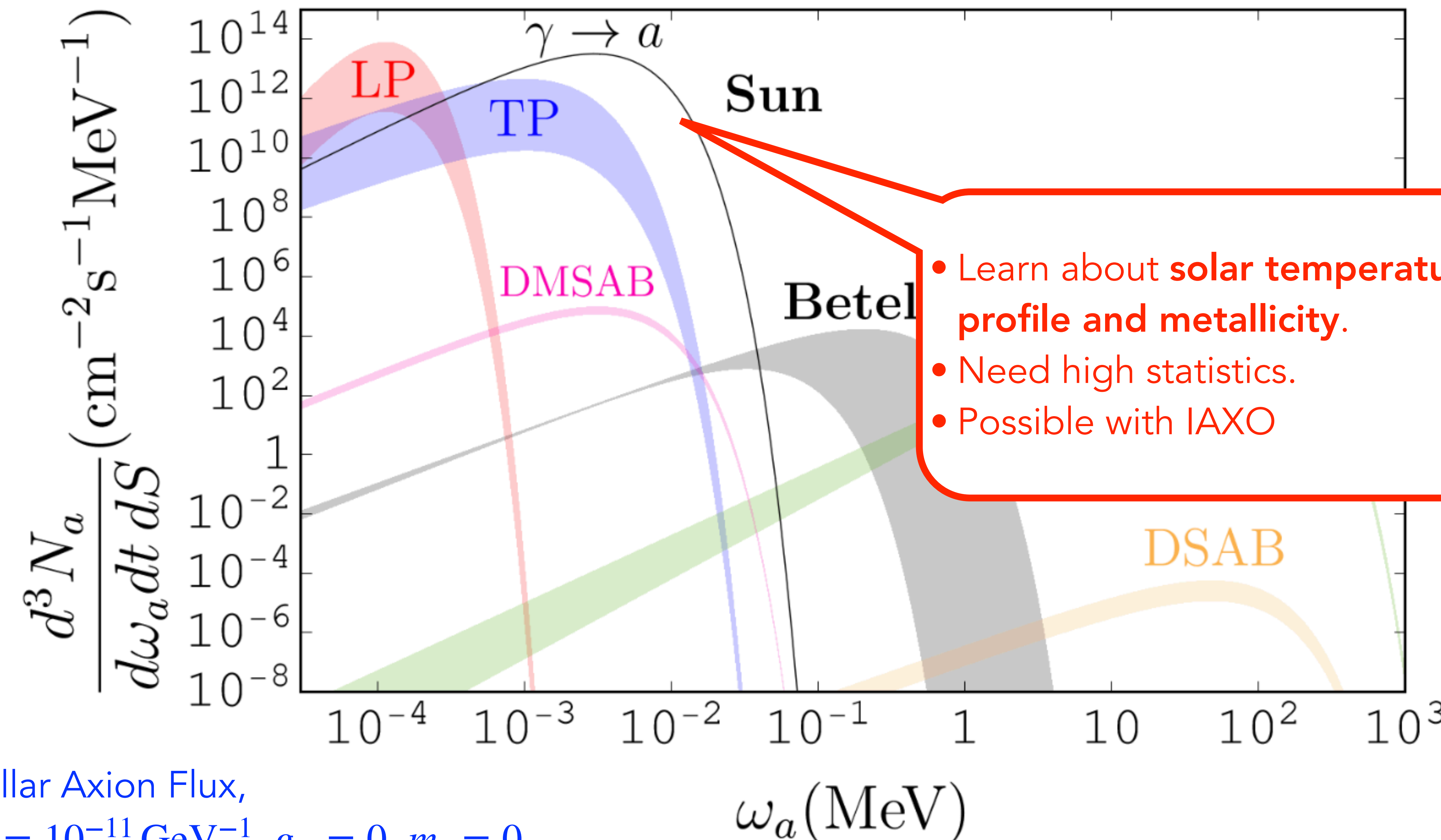
Opportunities: Axion Telescopes?



Stellar Axion Flux,
$g_{a\gamma} = 10^{-11}\,\mathrm{GeV}^{-1}$, $g_{ai} = 0$, $m_a = 0$

→ *P. Carenza, M.G., J. Isern, A. Mirizzi, O. Straniero, Phys.Rept. 1117 (2025) 1-102*

Opportunities: Axion Telescopes?



- Learn about **solar temperature profile and metallicity**.
- Need high statistics.
- Possible with IAXO

Stellar Axion Flux,
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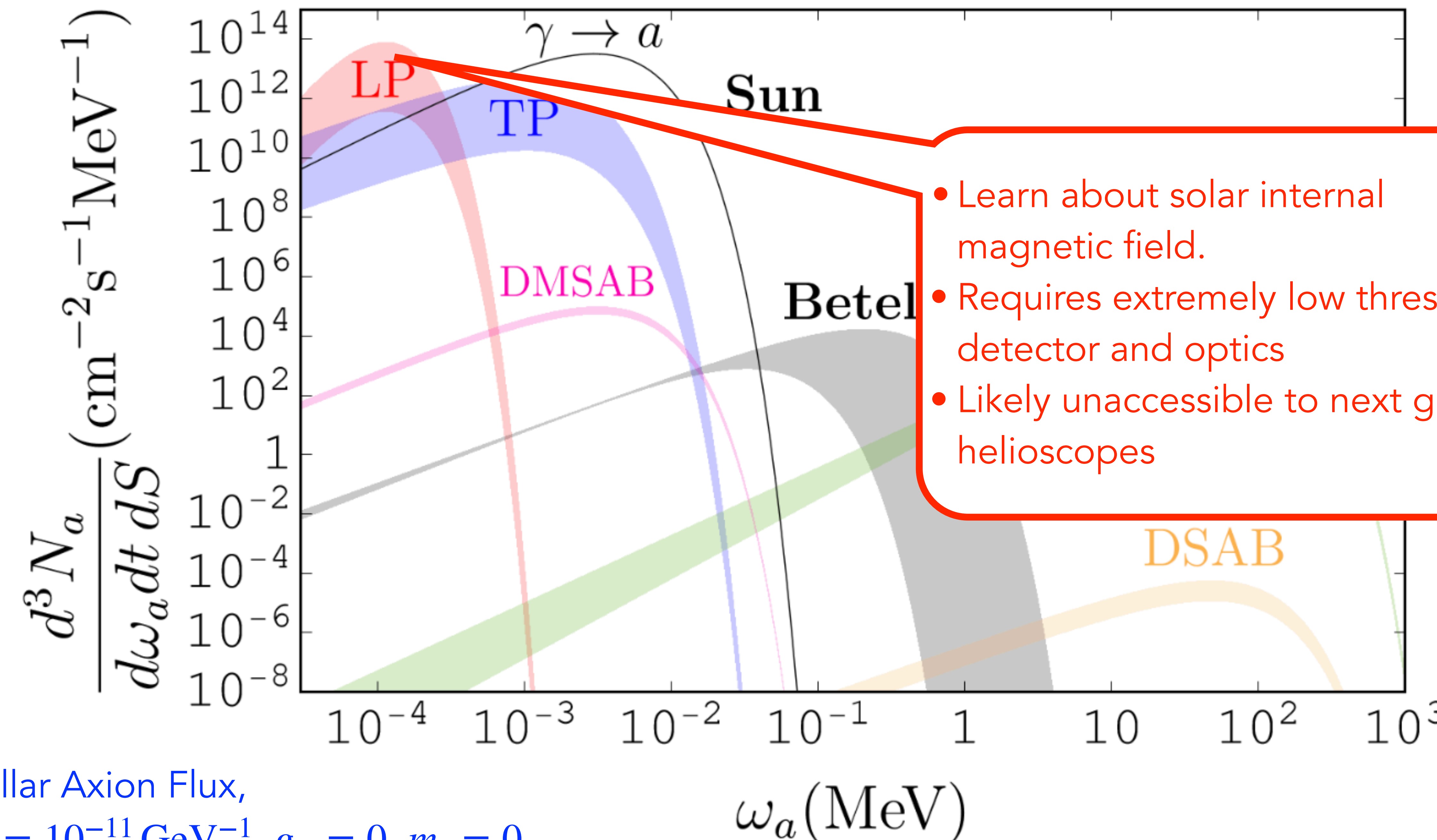
Opportunities: Axion Telescopes?



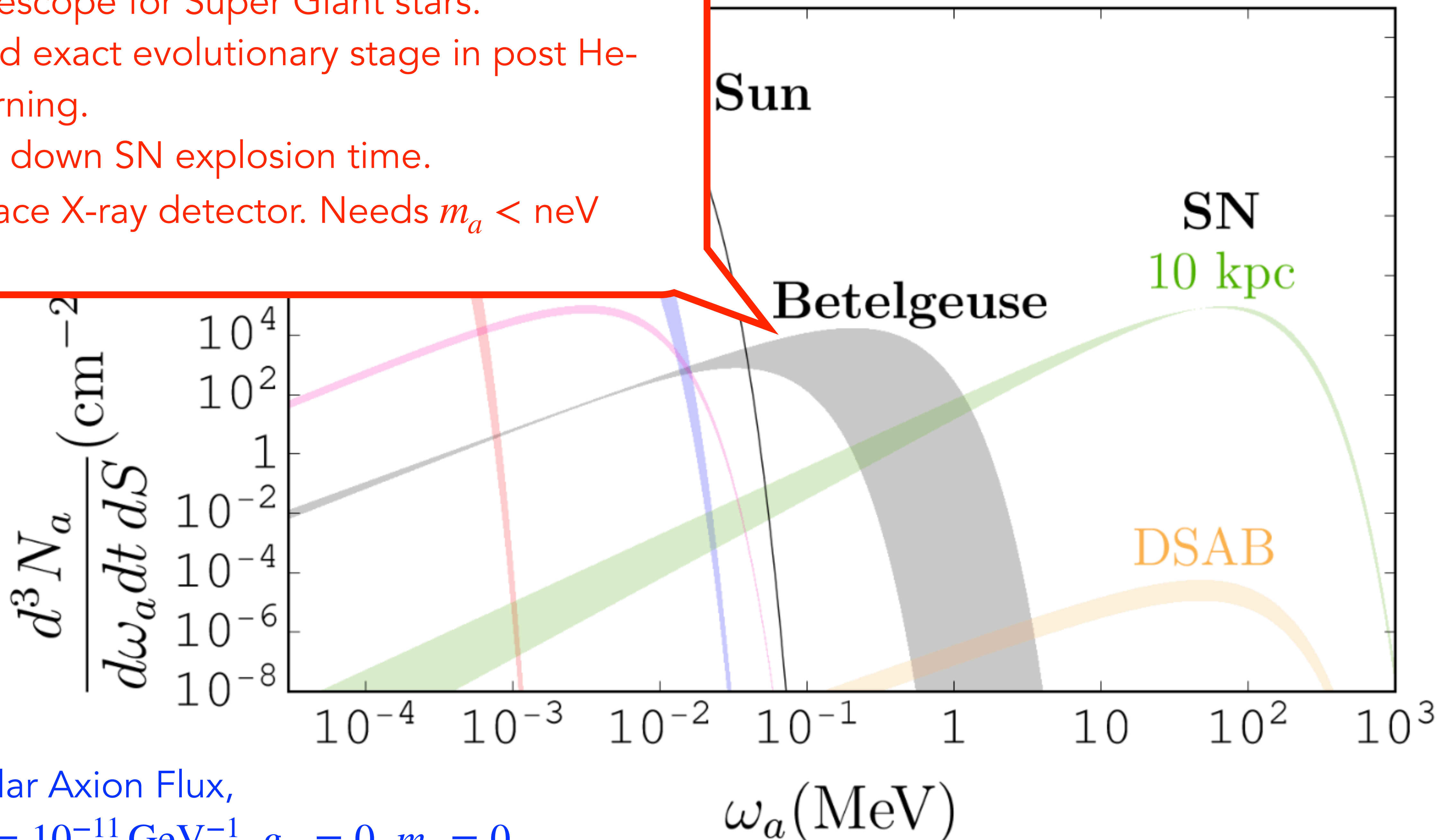
- Learn about solar internal magnetic field.
- Requires extremely low threshold detector and optics
- Likely unaccessible to next gen helioscopes

Stellar Axion Flux,
$g_{a\gamma} = 10^{-11}\,\mathrm{GeV}^{-1}$, $g_{ai} = 0$, $m_a = 0$

→ *P. Carenza, M.G., J. Isern, A. Mirizzi, O. Straniero, Phys.Rept. 1117 (2025) 1-102*

Opportunities: Axion Telescopes?

- Telescope for Super Giant stars.
- Find exact evolutionary stage in post He-burning.
- Pin down SN explosion time.
- Space X-ray detector. Needs $m_a <$ neV



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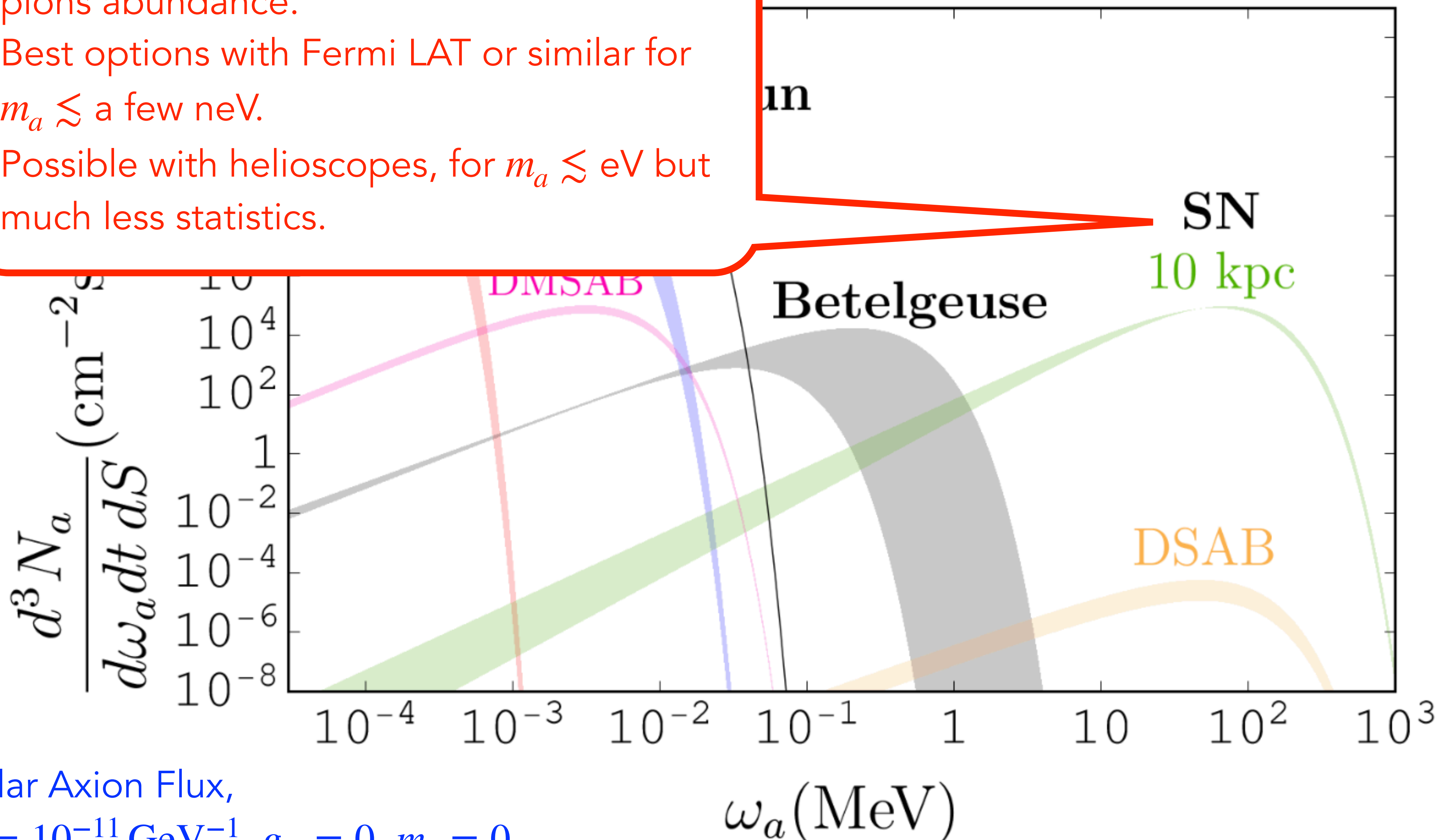
→ *P. Carenza, M.G., J. Isern, A. Mirizzi, O. Straniero, Phys.Rept. 1117 (2025) 1-102*

Opportunities: Axion Telescopes?

- Could reveal temperature, density and pions abundance.
- Best options with Fermi LAT or similar for $m_a \lesssim$ a few neV.
- Possible with helioscopes, for $m_a \lesssim$ eV but much less statistics.



Stellar Axion Flux,
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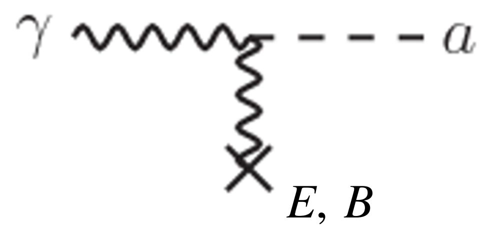
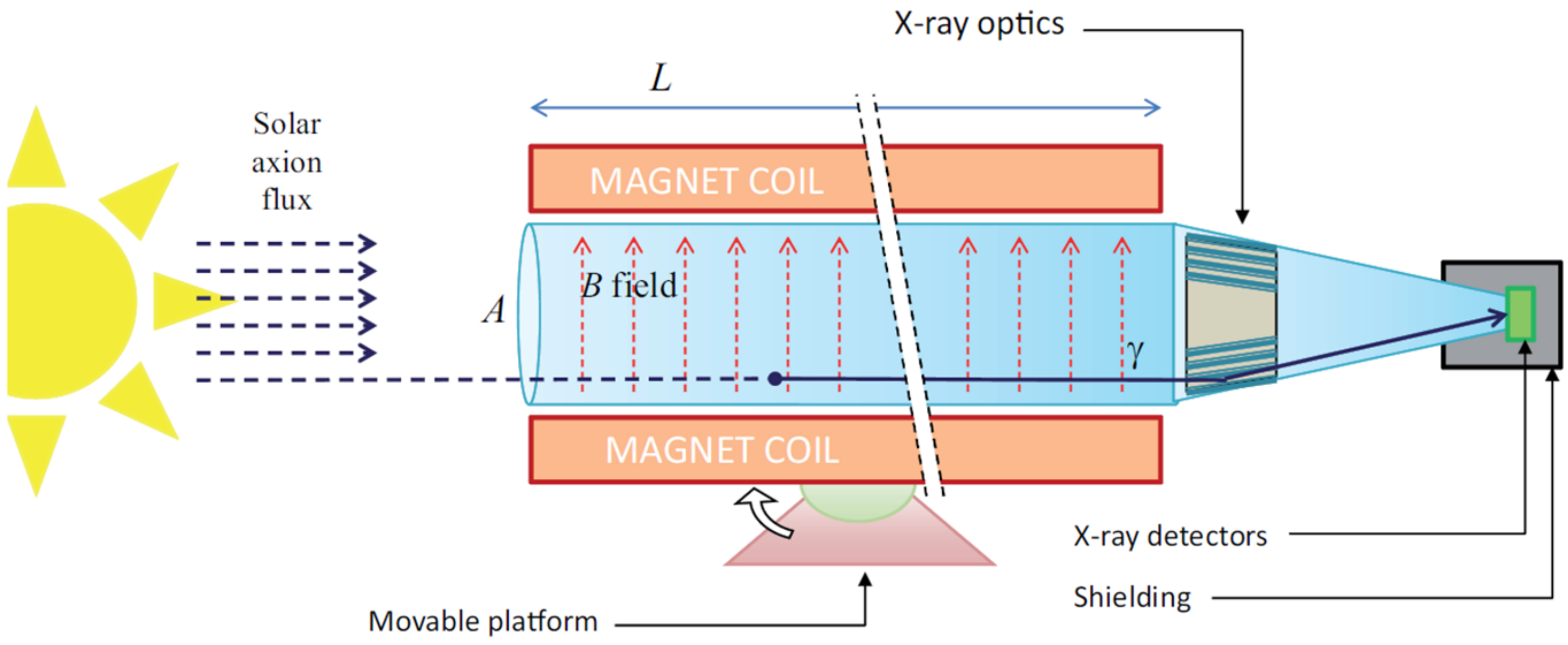
→ *P. Carenza, M.G., J. Isern, A. Mirizzi, O. Straniero, Phys.Rept. 1117 (2025) 1-102*

Solar Axions

Coupling	Process	Energy
$g_{a\gamma}$	Primakoff (E) Primakoff (B) 	$\sim (3-4)\,\mathrm{keV}$ $\sim (10-200)\,\mathrm{eV}$ (LP) $\lesssim 1\,\mathrm{keV}$ (TP)
g_{ae}	ABC e.g., $e + Z_e \rightarrow Ze + e + a$	$\sim 1\,\mathrm{keV}$
g_{aN}	nuclear reactions $p + d \rightarrow {}^{3}\mathrm{He} + a$ Nuclear de-excitation $^{57}\mathrm{Fe}^{*} \rightarrow {}^{57}\mathrm{Fe} + a$ $^{7}\mathrm{Li}^{*} \rightarrow {}^{7}\mathrm{Li} + a$ $^{83}\mathrm{Kr}^{*} \rightarrow {}^{83}\mathrm{Kr} + a$	$5.5\,\mathrm{MeV}$ $14.4\,\mathrm{keV}$ $0.478\,\mathrm{MeV}$ $9.4\,\mathrm{keV}$

Hunting Solar Axions: Sikivie Helioscope

P. Sikivie PRL 51:1415 (1983)



Rescalable: increasing collecting area, length, and B.

Sensitivity

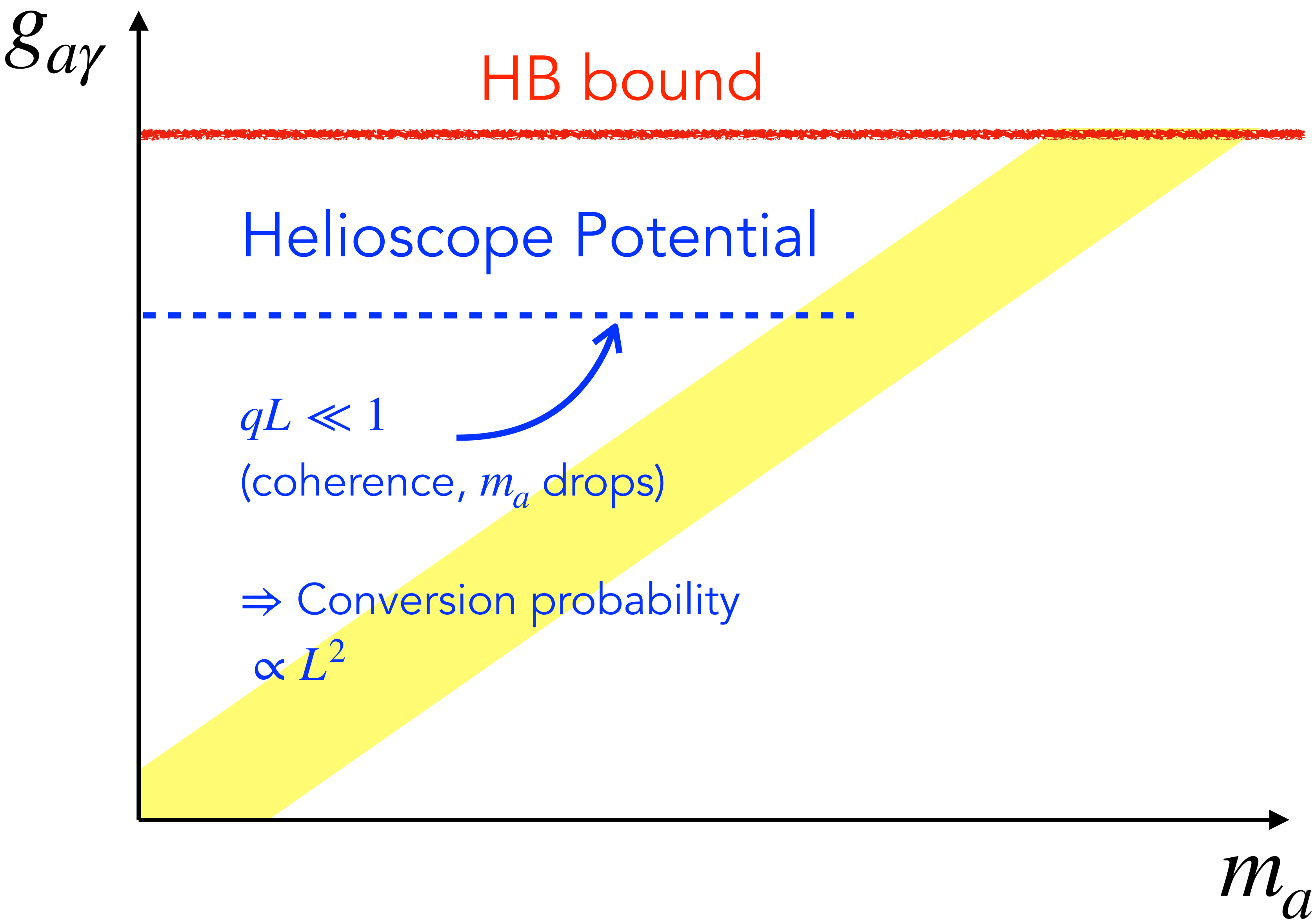
$$P_{a\gamma} = \left(\frac{g_{a\gamma} B L}{2}\right)^2 \frac{\sin^2(qL/2)}{(qL/2)^2}$$

B= magnetic field

L= magnet length

q= momentum transfer

$$q \simeq \frac{m_a^2 - m_\gamma^2}{2\omega}$$



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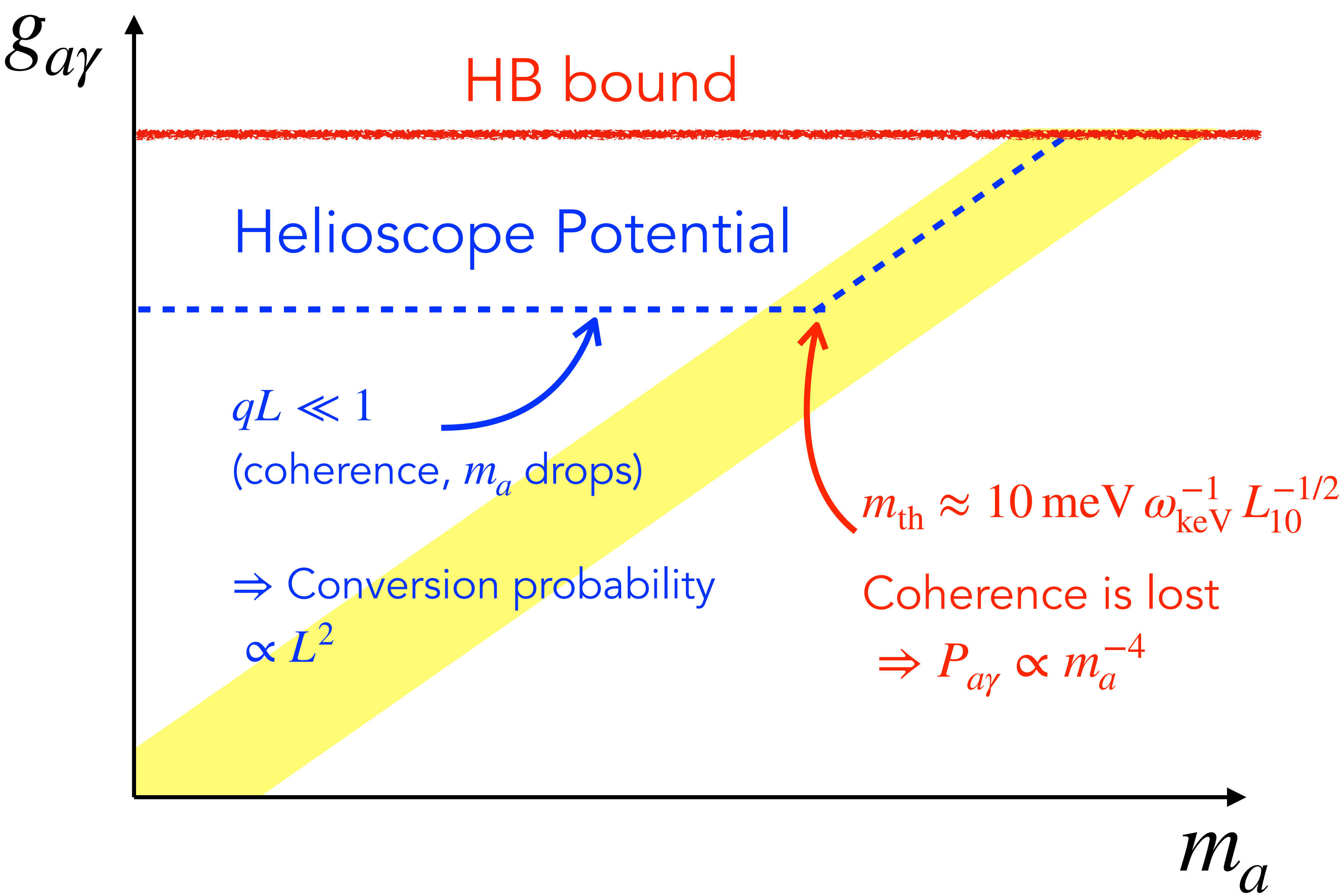

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$$P_{a\gamma} = \left(\frac{g_{a\gamma}BL}{2}\right)^2 \frac{\sin^2(qL/2)}{(qL/2)^2}$$

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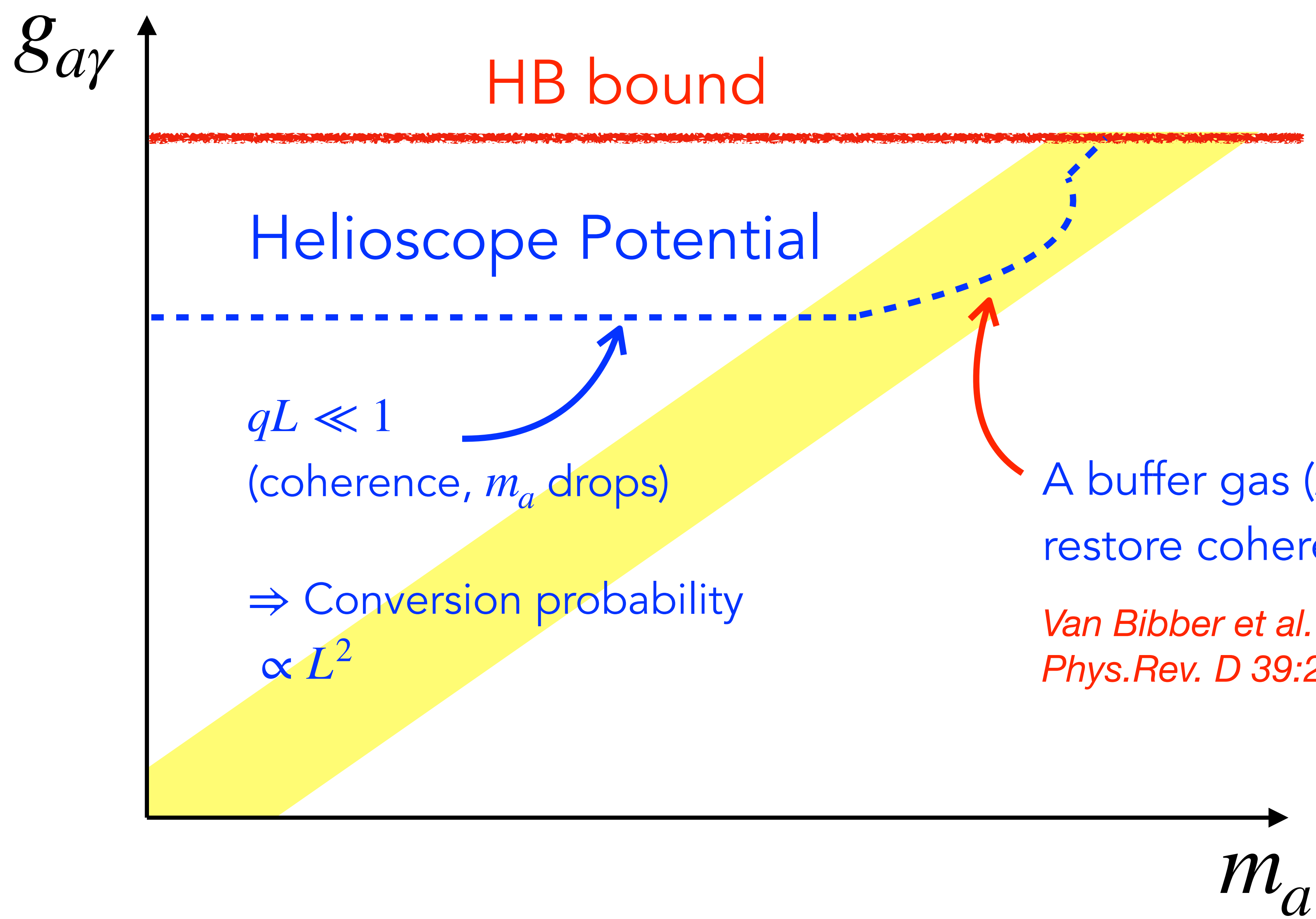


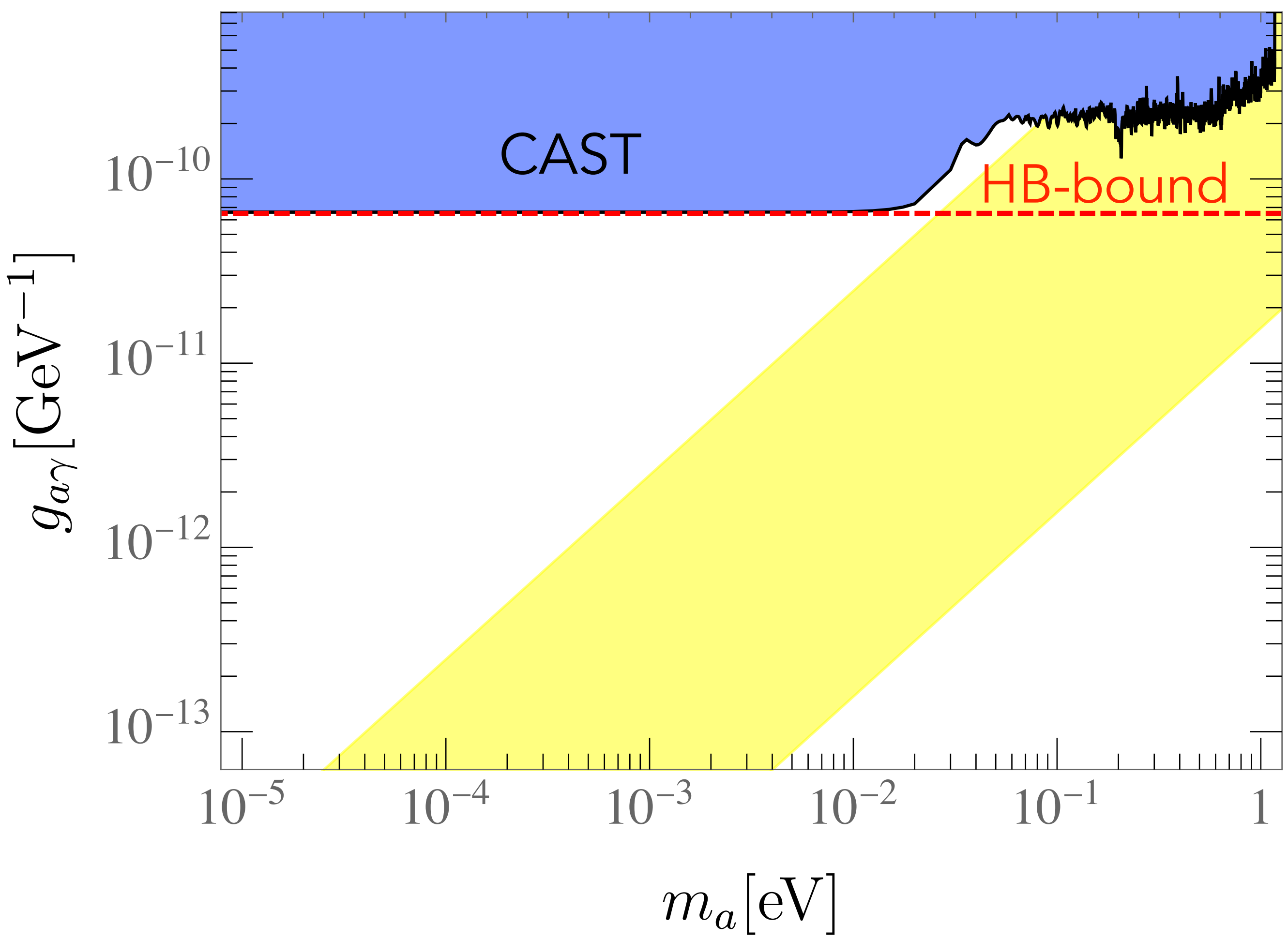
A buffer gas ($m_\gamma \simeq m_a$) can restore coherence

Van Bibber et al.
Phys.Rev. D 39:2089 (1989)

The CERN Axion Solar Telescope (CAST)

Reached the HB bound for the first time

V. Anastassopoulos, et al., Nature Phys. 13 (2017)



Decommissioned LHC test magnet,
B=9T, D=43 mm, L= 9.3 m

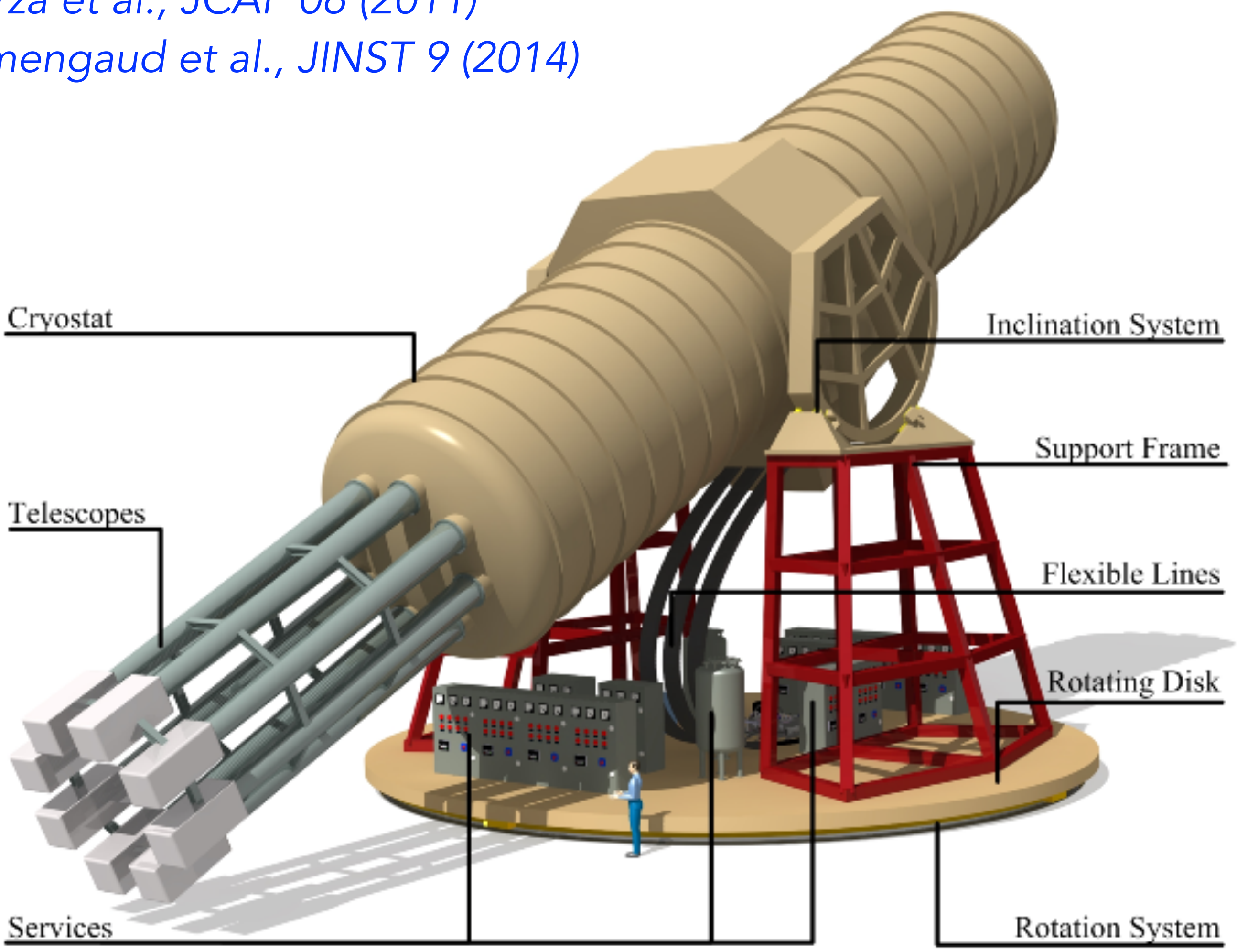
~2 h tracking/day

X-ray optics

The International AXion Observatory

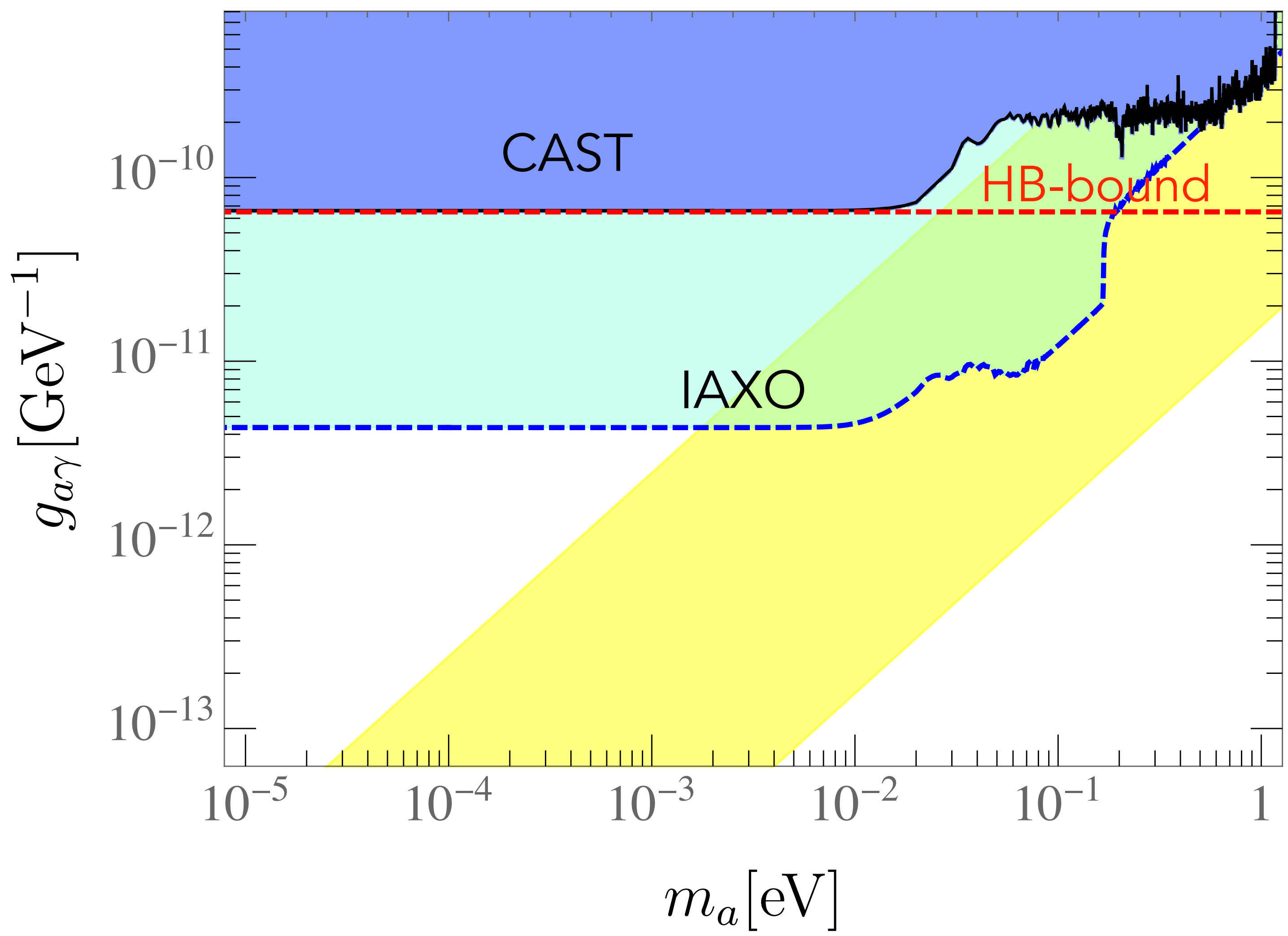
- Large toroidal 8-coil magnet L = ~20 m
- 8 bores: 60 cm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services

Irastorza et al., JCAP 06 (2011)
E. Armengaud et al., JINST 9 (2014)



IAXO will consist of a superconducting toroid magnet with eight custom x-ray telescopes that focus the reconverted photons onto ultra-low background detectors.

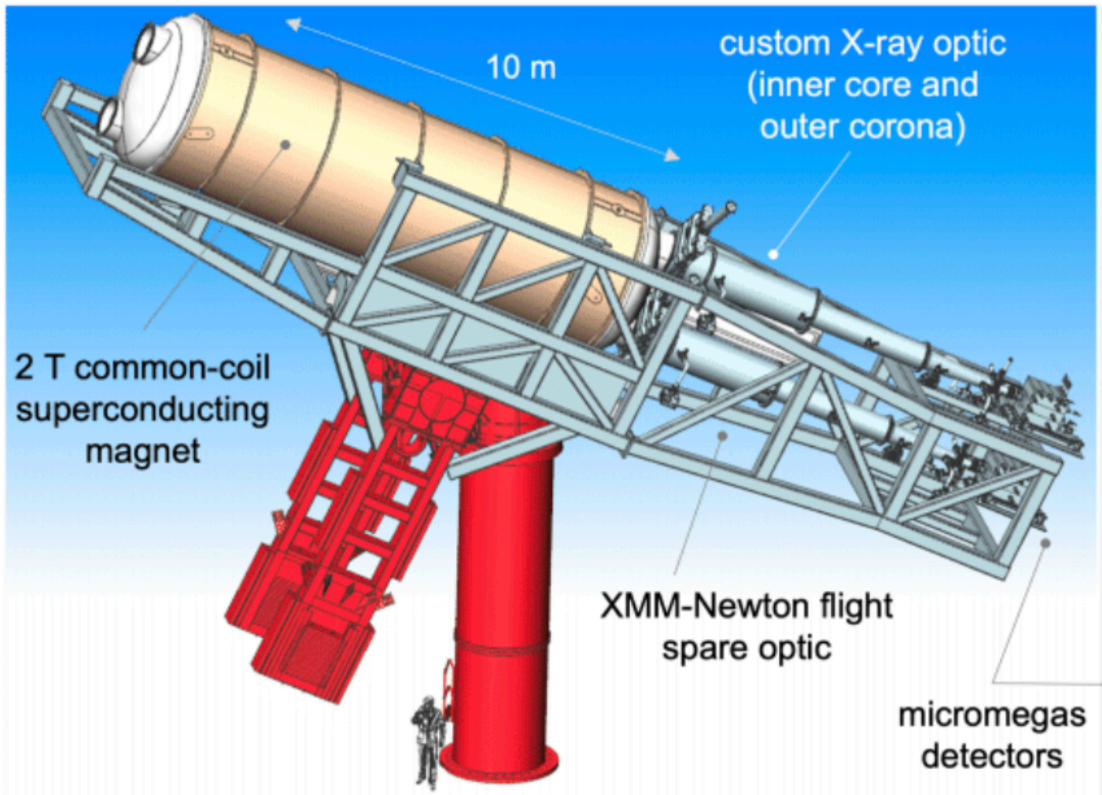
The International AXion Observatory

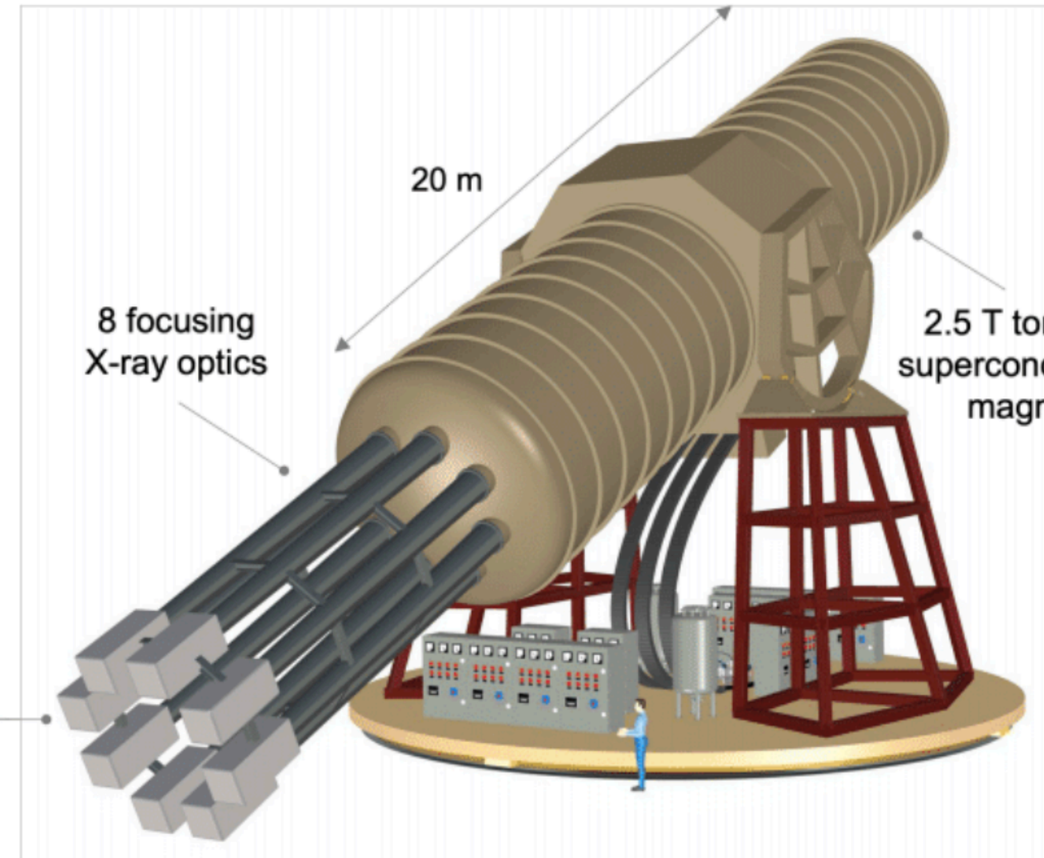


Strong potential to probe the high (>meV) mass region (stellar window)

Physics potential of the International Axion Observatory (IAXO) JCAP 1906 (2019) 047

BabyIAXO





- Prototype: Intermediate experimental stage before IAXO
- Test & improve all systems. Risk mitigation for full IAXO.
- Physics: expected relevant physics outcome (~100 x CAST FOM)

erc **2017 ERC advanced grant** by I. Irastorza to support the development

DESY PRC endorsed BabyIAXO in

Other detection strategies for solar axions

Helioscopes based on Axioelectric effect: LUX, XENON1T, …

Large underground DM detectors.
Axioelectric = axion analog to the photoelectric (pe) effect

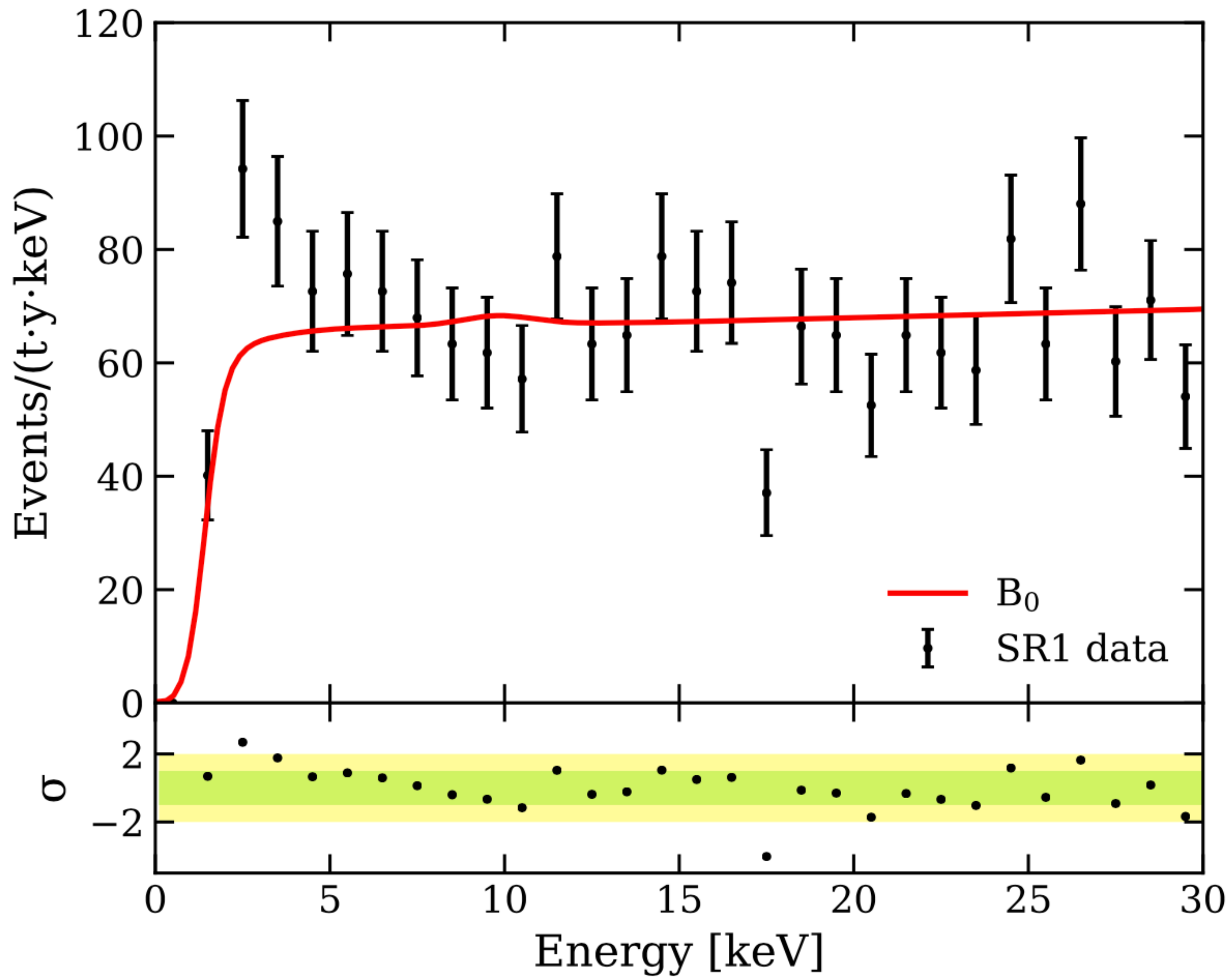
$$\sigma_{\rm ae} = \sigma_{\rm pe} \frac{g_{\rm ae}^2}{\beta} \frac{3E_{\rm a}^2}{16\pi\alpha m_{\rm e}^2}\left(1 - \frac{\beta^{2/3}}{3}\right)$$

Low energy suppression $(E_a/m_e)^2$

However, they can reach higher masses

Excess Electronic Recoil Events in XENON1T

Solar axions?



Stimulated a lot of interesting work on the low energy frontier

E.g., axions with $g_{ae} \sim 3 \times 10^{-12}$

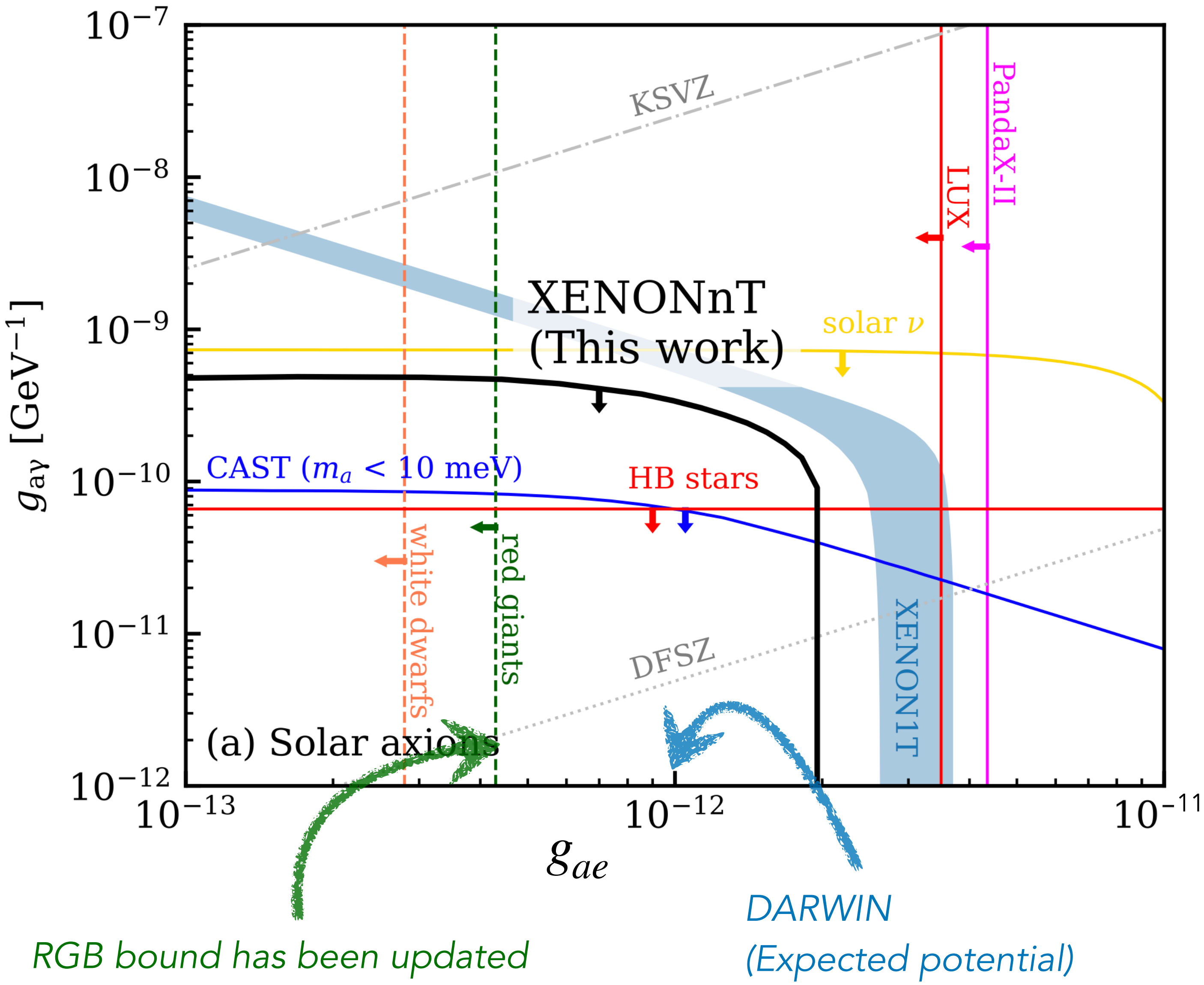
The value is very large and in tension with stellar evolution

(see talk by O. Straniero)

E. Aprile et al., PHYSICAL REVIEW D 102, 072004 (2020)

New results: XENONnT

Solar axions?

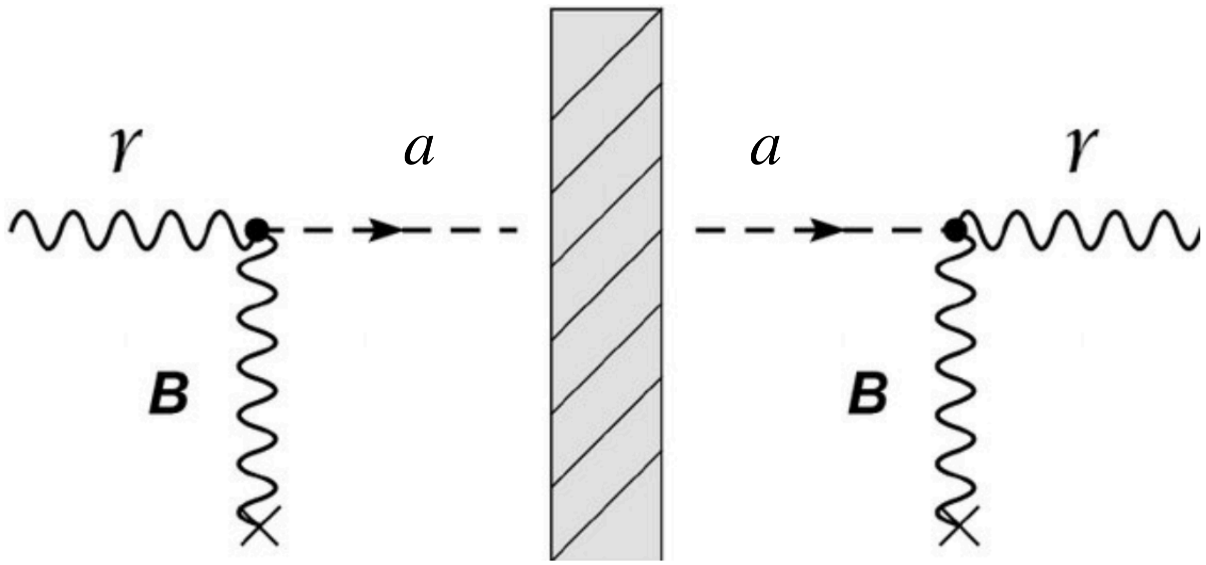


Hint conclusively dismissed by the first science run of the XENONnT dark matter experiment (Jul 22, 2022), which confirmed the origin as decays from trace amounts of tritium

$$g_{ae} \lesssim 2 \times 10^{-12}$$

E. Aprile et al., e-Print: 2207.11330 [hep-ex] (2022)

Light Shining Through a Wall



Everything is under control. However, signal suppressed as $g_{a\gamma}^4$

Relativisti axions:

$$P_{a\gamma} = \left(\frac{g_{a\gamma}BL}{2}\right)^2 \frac{\sin^2(qL/2)}{(qL/2)^2}$$

B= magnetic field

L= magnet length

q = momentum transfered

$$q \simeq \frac{m_a^2 - m_\gamma^2}{2\omega}$$

Lost of coherence for $qL \gtrsim 1$

Light Shining Through a Wall

→ **ALPS** @ DESY and the **OSQAR** @ CERN are active LSW experiments.
Use powerful accelerator dipole magnets, from HERA (ALPS) and LHC (OSQAR).
In both cases the sensitivity drops above $m_a \sim 10^{-4}$ eV .

→ **CROWS** experiment @ CERN

Uses a different wavelength: microwaves!

Large scale MW LSW studied and proposed in the literature → **STAX**
LSW at X-rays also explored in the past (not large power)

→ Next Gen: **JURIA**. Concept being discussed at the Physics Beyond Colliders (PBC) group at CERN

- L ~ 1km, B ~13T, P~2.5 MW,... Very challenging parameters...
- Physics case to be settled (it may depend if positive signal in other exps)

Relativisti axions:

$$P_{a\gamma} = \left(\frac{g_{a\gamma}BL}{2}\right)^2 \frac{\sin^2(qL/2)}{(qL/2)^2}$$

B= magnetic field
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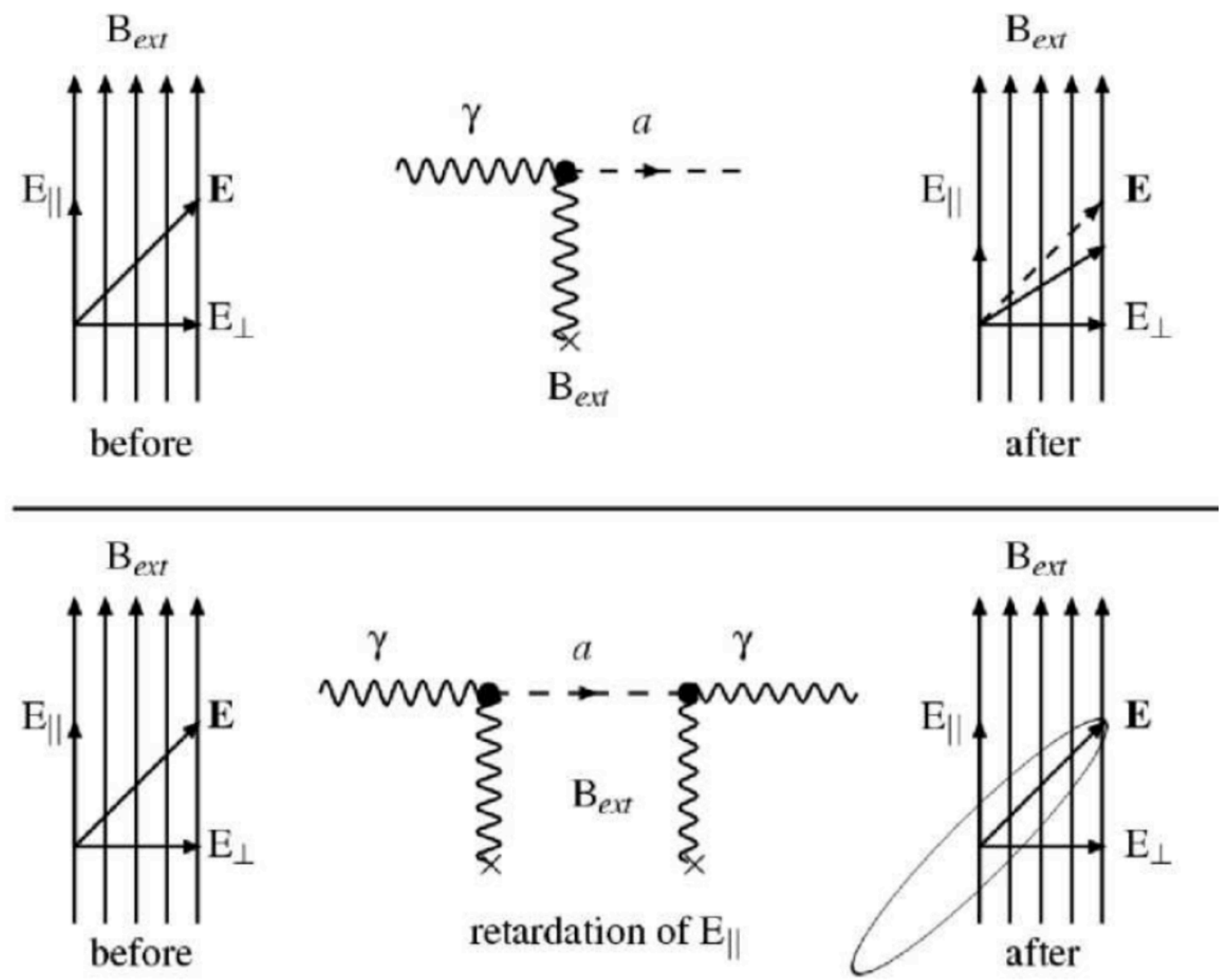
Lost of coherence for $qL \gtrsim 1$

Polarization experiments



Dichroism:

Production of real particles

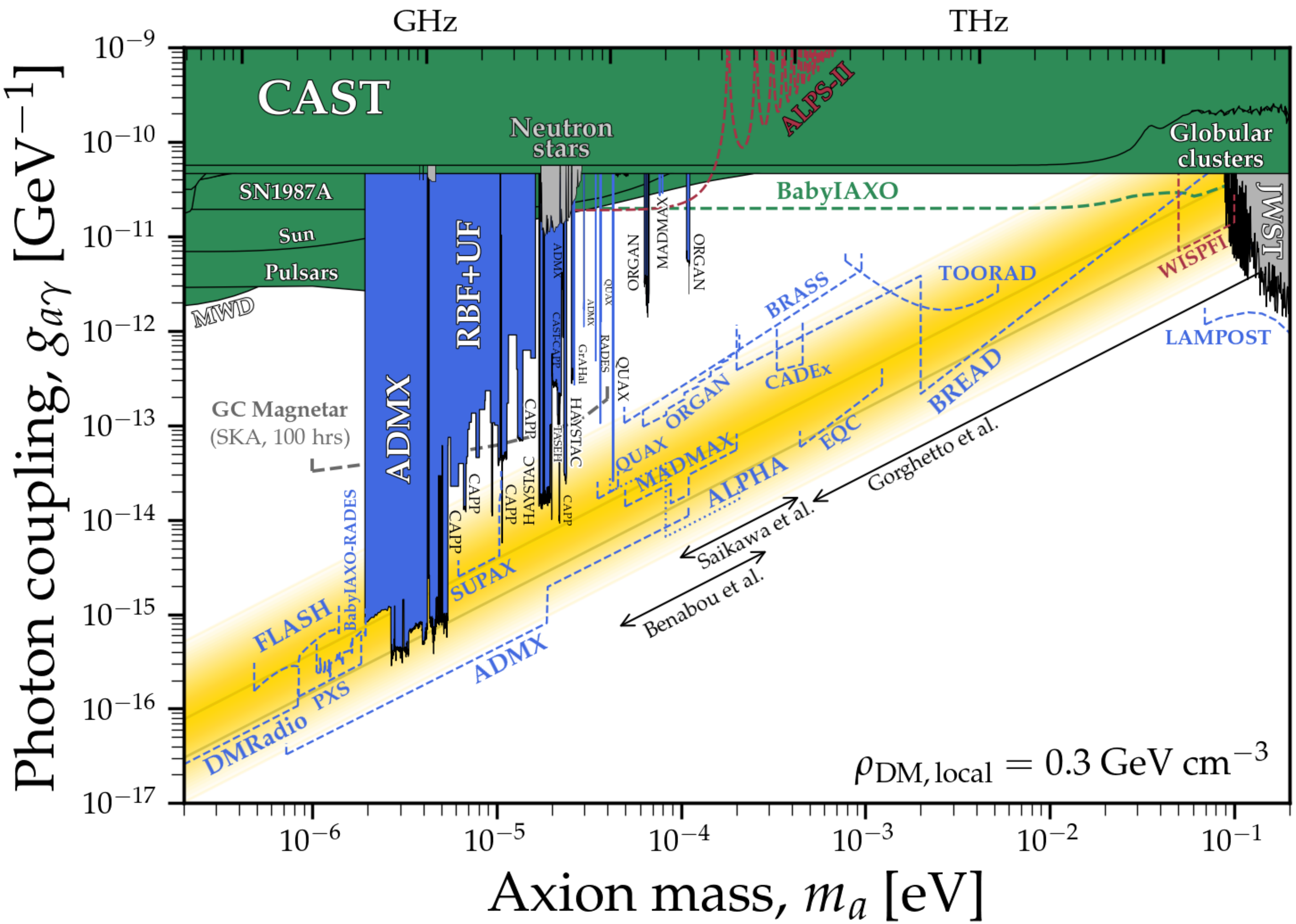
Ellipticity:

Production of massive virtual particles

PVLAS experiment: study QED vacuum birefringence (standard effect), but also sensitivity to ALPs:

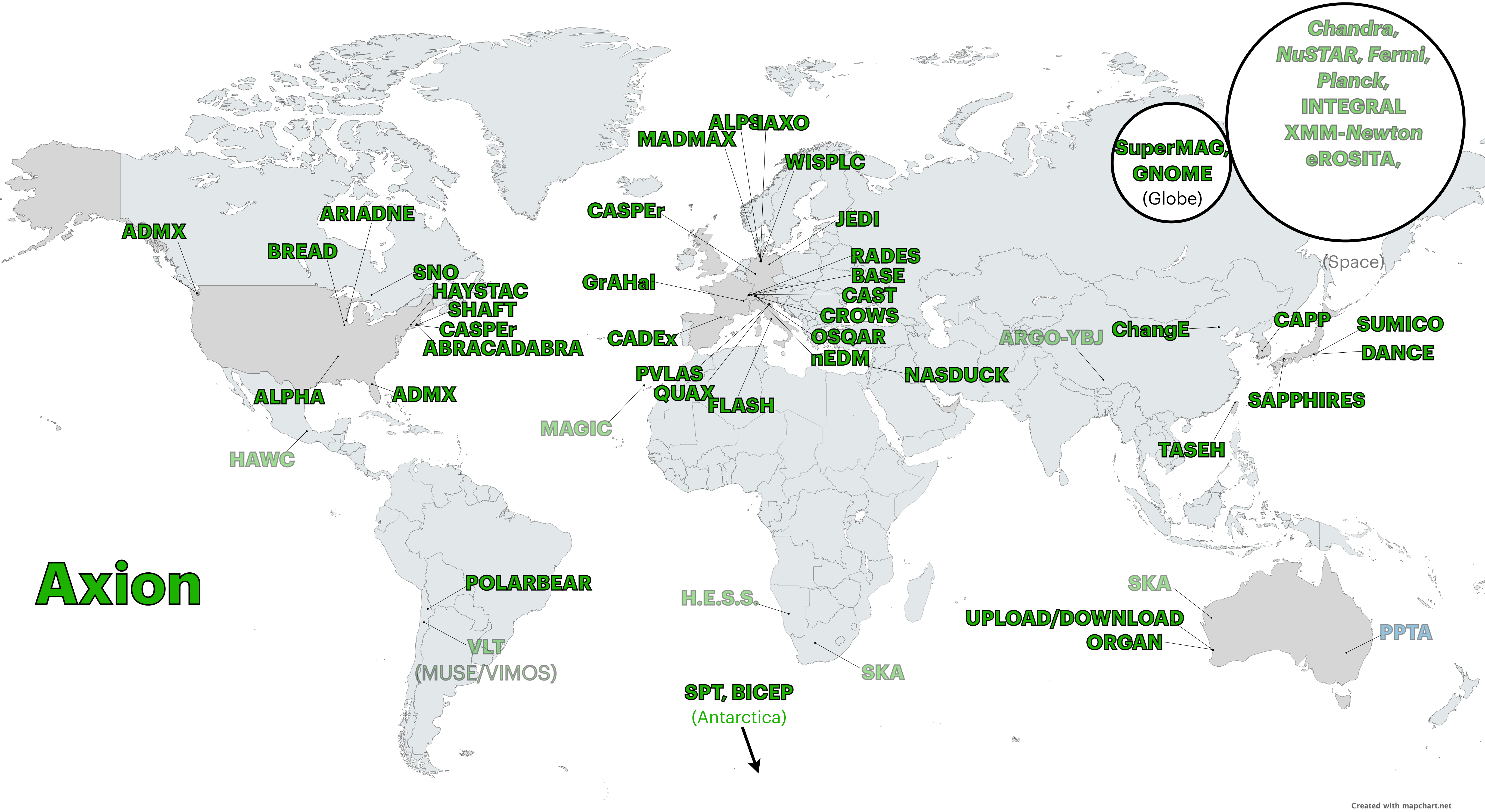
Future project under discussion at PBC: VMB@CERN

Future Perspectives



From O'Hare AxionLimits

Axions Around the World



Conclusions and Comments

- A lot of research on Dark Matter and specifically on Axions

- Important progress in last years in the attempts to detect axions in all fronts:
  - ✓ Huge progress with cavity haloscopes + several new proposals
  - ✓ Major LSW experiment starting (ALPS II)
  - ✓ Major new Helioscope proposal under progress (IAXO)
  - ✓ Several innovative ideas

- Most interesting parameter space accessible to Next Gen Experiments
  → a groundbreaking discovery is possible

- Axions with couplings at the current thresholds would excellent astrophysical messengers.

To know more about Axions

- A soft and enjoyable introduction is the article by David J. E. Marsh: *Axions for amateurs* arXiv:2308.16003

- More technical: L. Di Luzio, M.G., E. Nardi, L. Visinelli, *The landscape of QCD axion models*, Phys.Rept. 870 (2020)

- Especially good for theory:
  - Villadoro Lectures GGI 2015, GGI 2023
  - Anson Hook, TASI Lectures, arXiv:1812.02669

- For astrophysics:
  - P. Carenza, M.G., A. Mirizzi, J. Isern, O. Straniero, *Axion astrophysics*, Phys.Rept. 1117 (2025)
  - A. Caputo and G. Raffelt, Astrophysical Axion Bounds: The 2024 Edition, PoS COSMICWISPers (2024) 041

- For experiments: I. Irastorza, J. Redondo, *New experimental approaches in the search for axion-like particles*, Prog.Part.Nucl.Phys. 102 (2018)

… and in general, on Dark Matter

- Very recent, interesting and comprehensive review
  → M. Cirelli, A. Strumia and J. Zupan (2024)

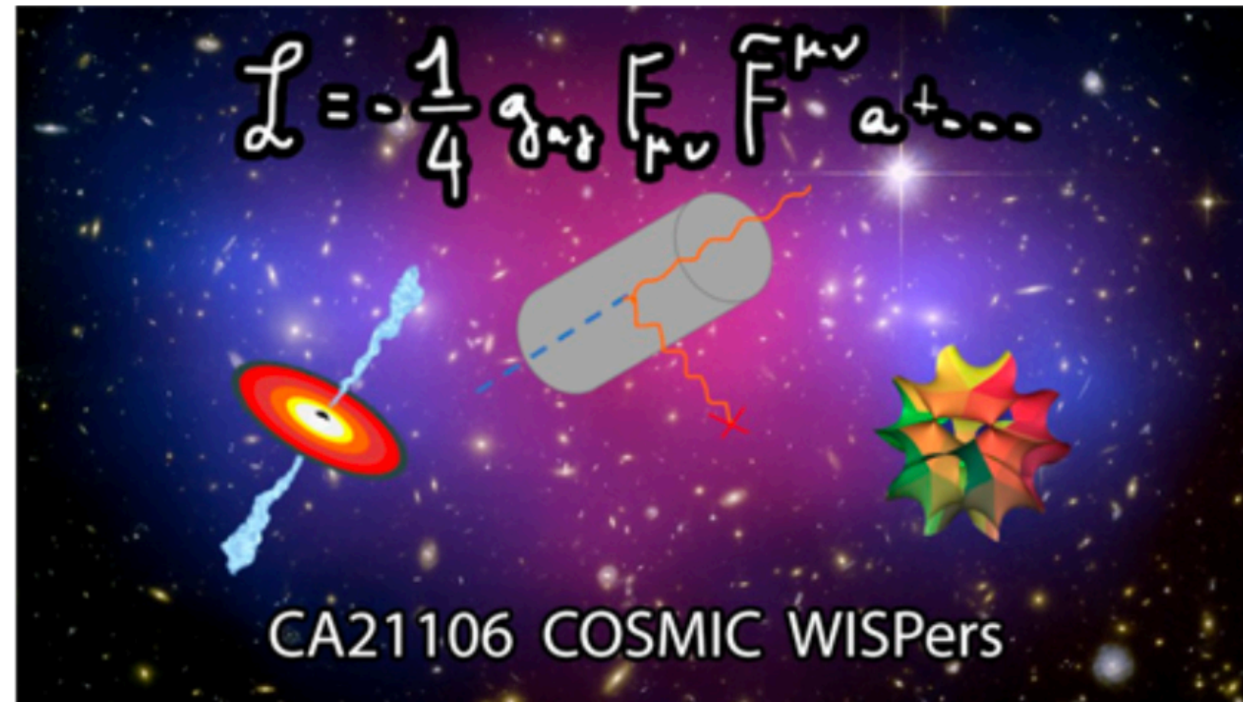
- Also interesting the very recent short review Bozorgnia et al.
  → Dark Matter Candidates and Searches

- For Axion Cosmology, See C. O'Hare, Axion cosmology
  COST (2023) Training School

- There is a Long evidence for Dark Matter.
  See → A History of Dark Matter, by G. Bertone and D. Hooper (2018)

Cosmic WISPers in the Dark Universe

Join our network and working groups
→ COST CA21106



COSMIC
WISPERS
CA21106