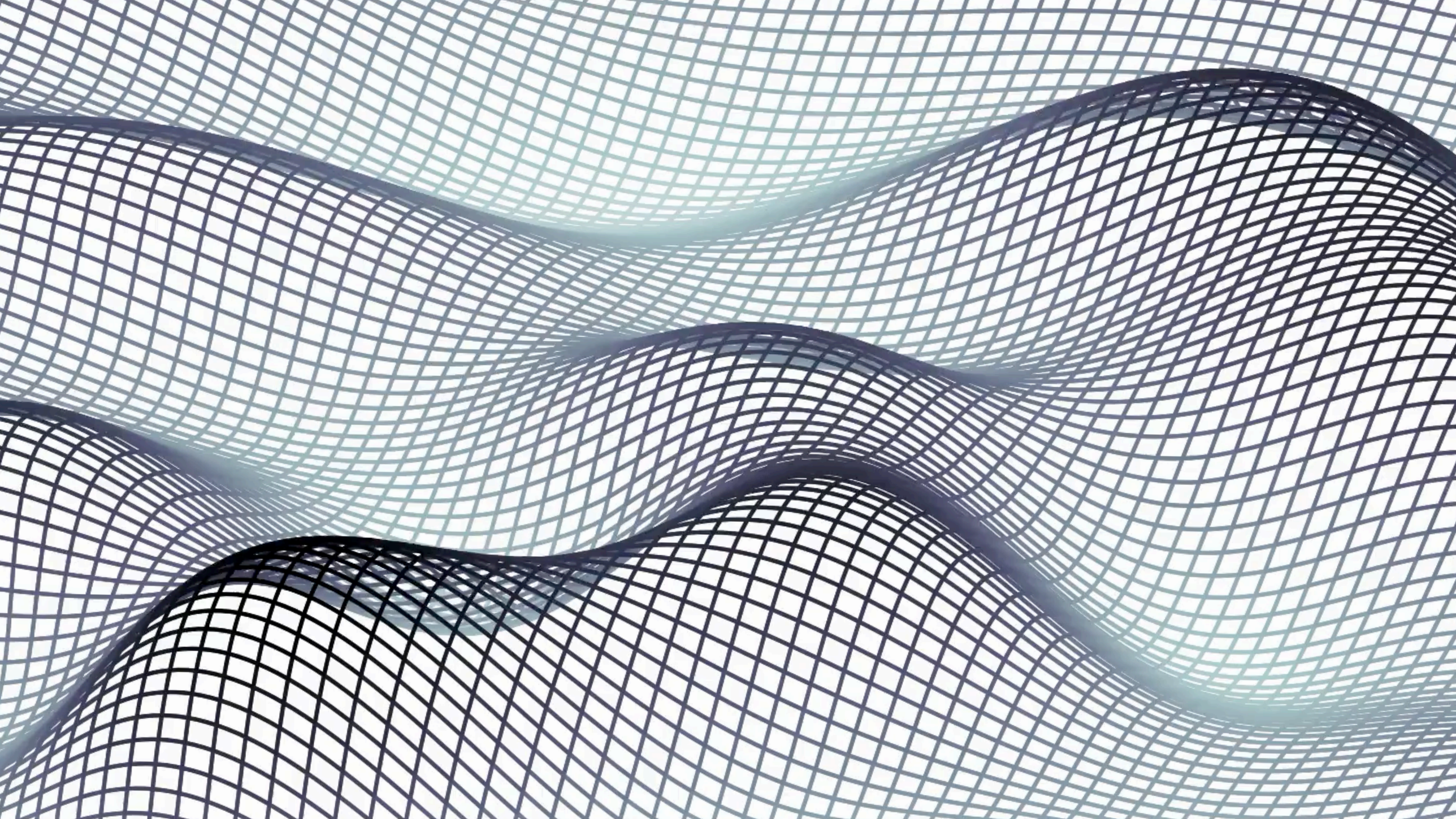
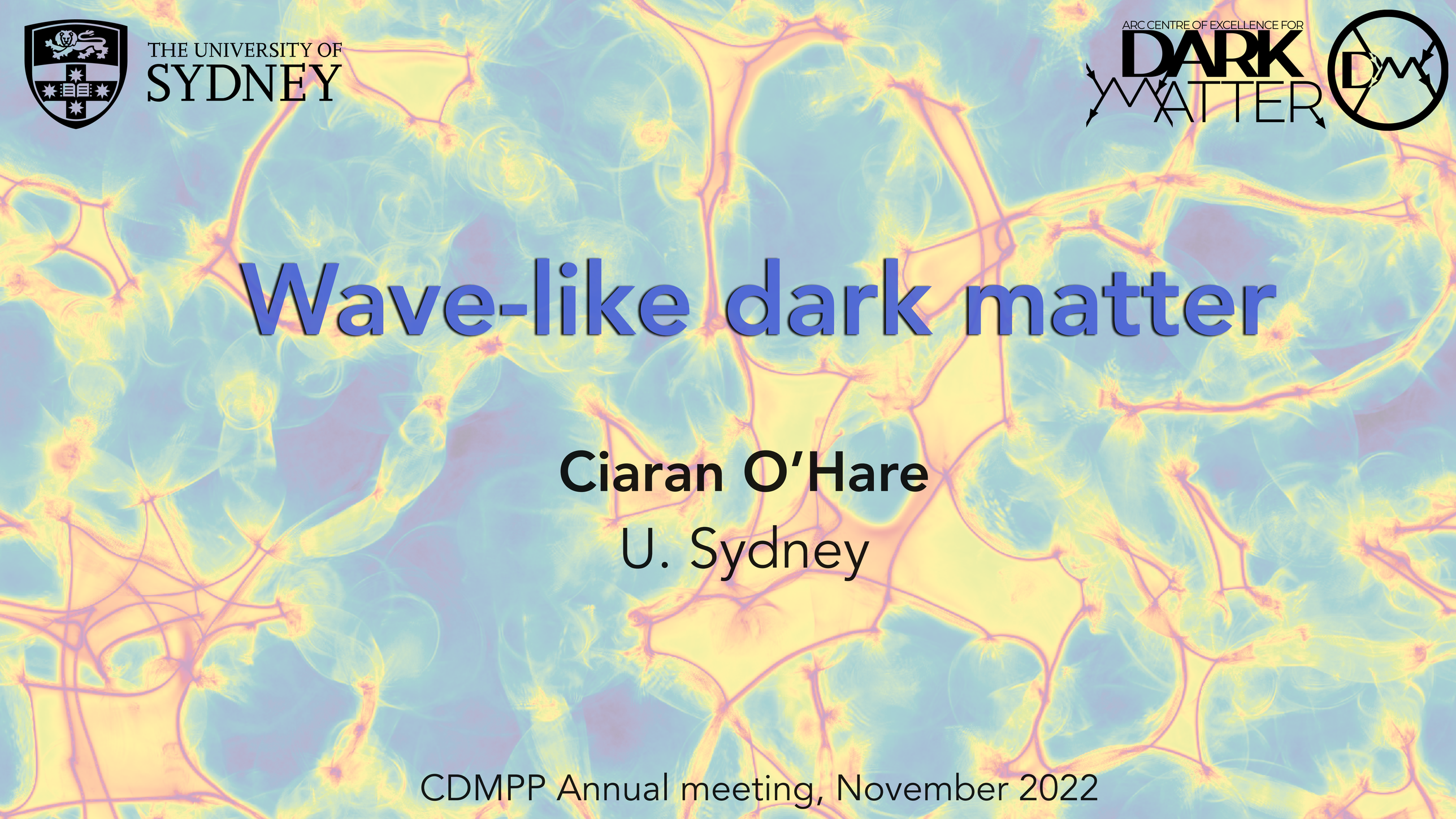


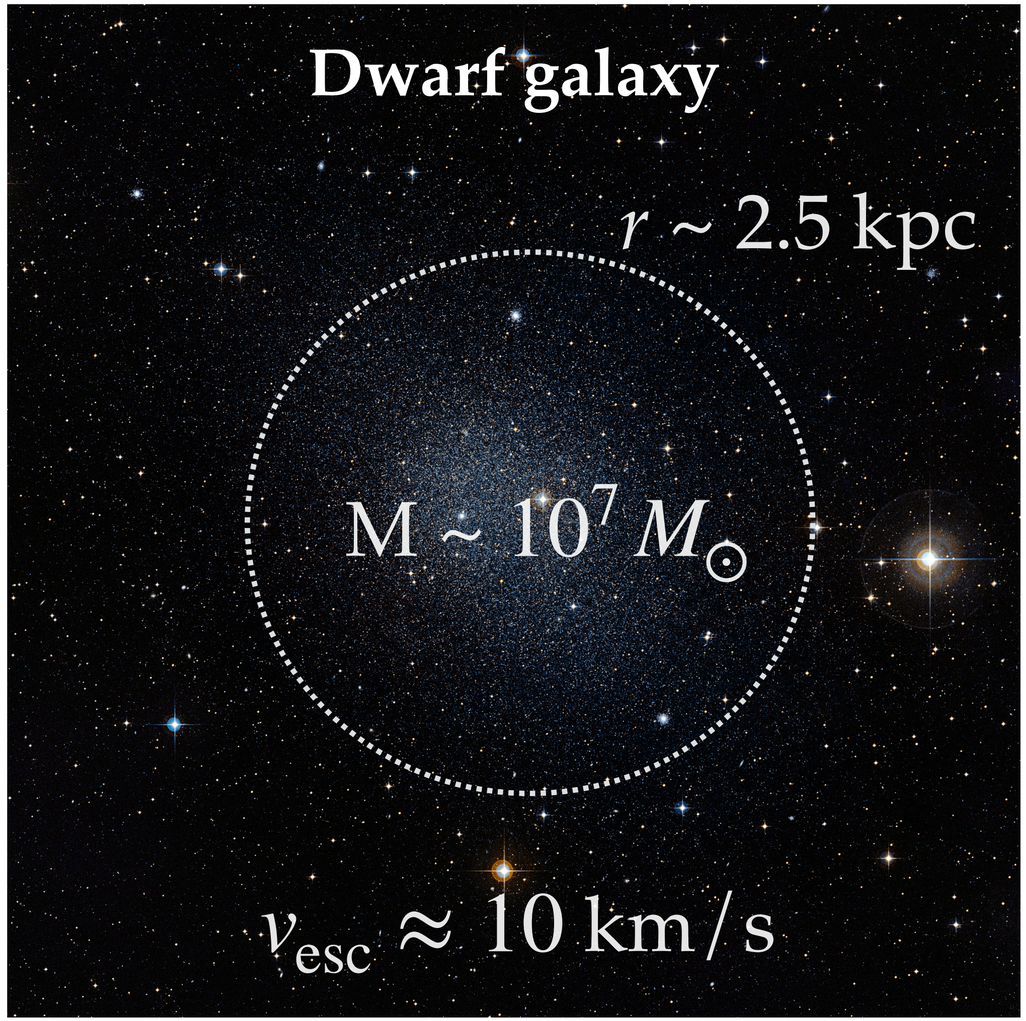


Wave-like dark matter

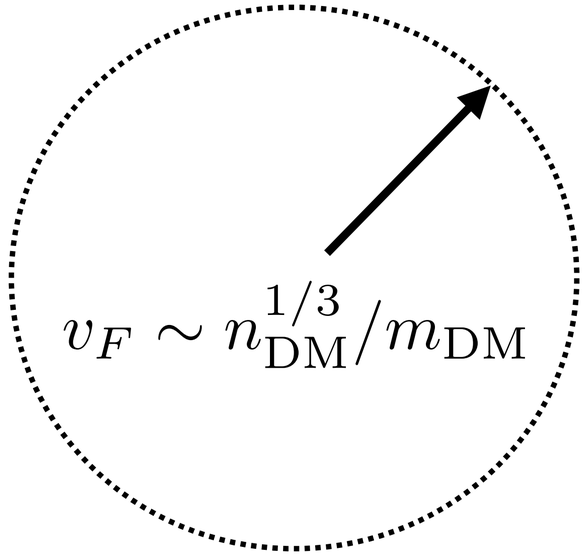
Ciaran O'Hare
U. Sydney

CDMPP Annual meeting, November 2022

How light can dark matter be if it is made of fermions?



Sphere of degenerate fermions



$$v_F < v_{\rm esc}$$

$$\Rightarrow m_\chi \gtrsim 100 \text{ eV}$$

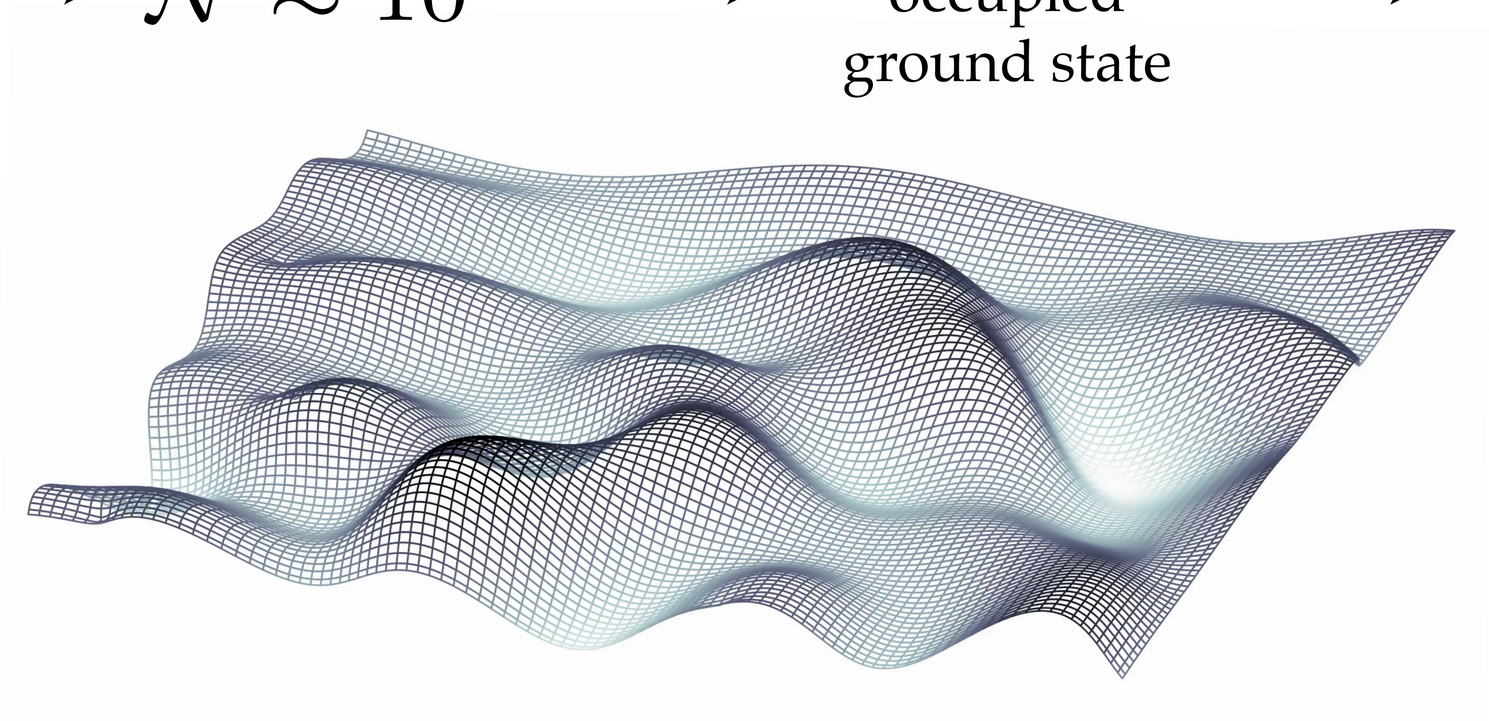
"Tremaine-Gunn bound": Pauli exclusion principle prevents you from cramming fermions lighter than ~100 eV into dark matter halos

Bosonic “wave-like” dark matter

Occupation number:

$$\mathcal{N} \approx (\rho_{\rm DM}/m) \times \lambda_{\rm dB}^3$$

$m = 1\ \mu$eV $\longrightarrow$ $\mathcal{N} \approx 10^{32}$ $\longrightarrow$ Macroscopically occupied ground state $\longrightarrow$ Classical field



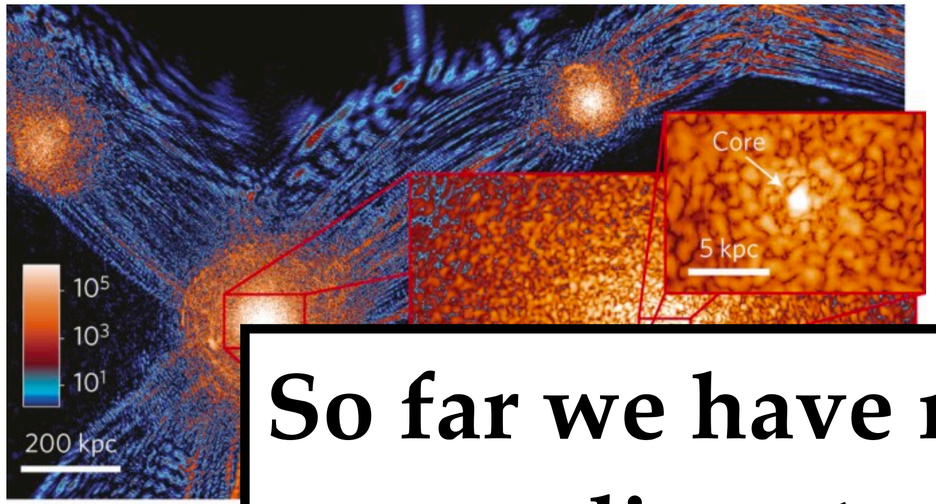
Wave-like dark matter mass range

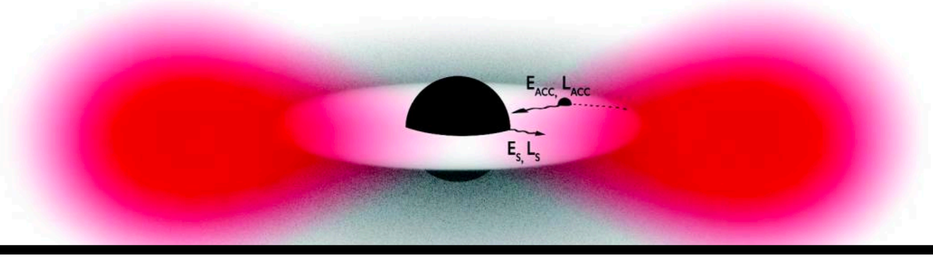
yeV zeV aeV feV peV neV μeV meV eV

Particle DM

"Fuzzy dark matter"
Wave-like effects on scales $\lambda_{dB} \gtrsim$ pc

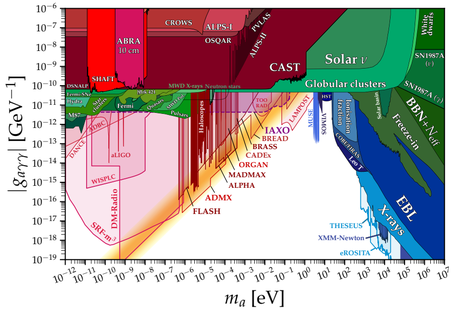
"Black hole superradiance"
Build up of boson cloud around BHs sucks their spins away

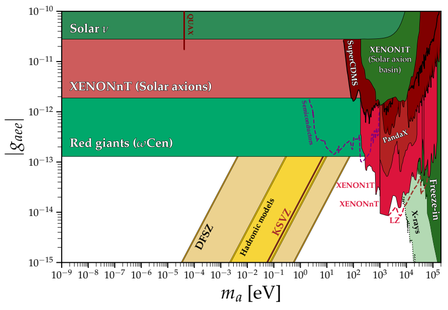


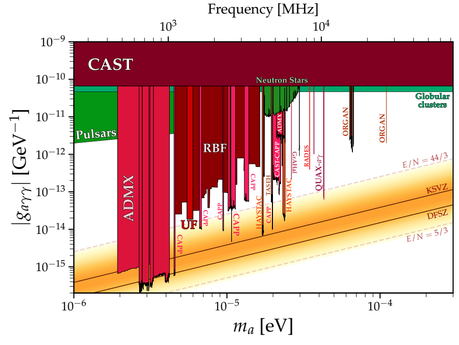


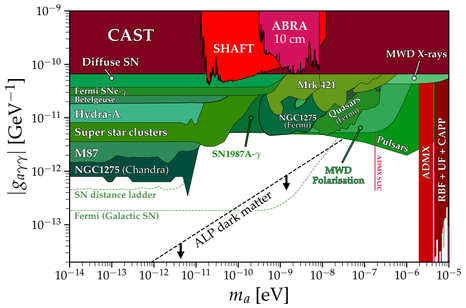
So far we have not assumed anything about any couplings to the SM other than via gravity.

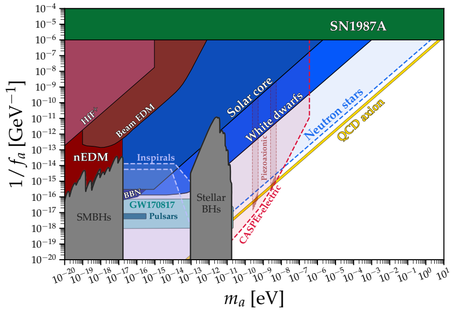
What can it couple to?

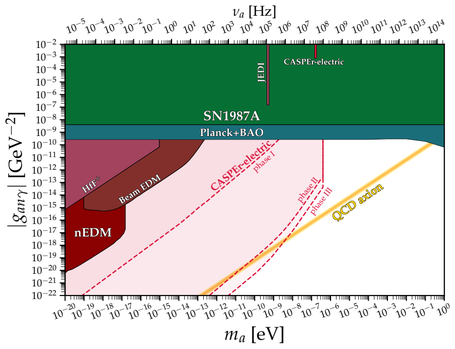


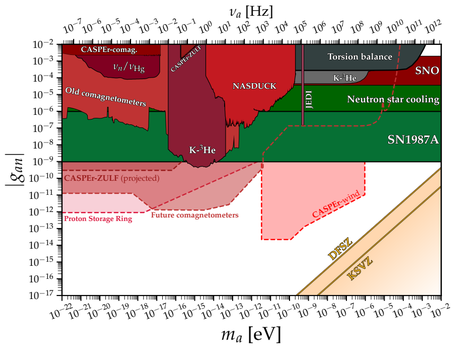


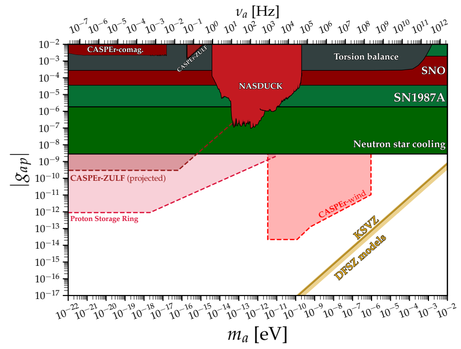


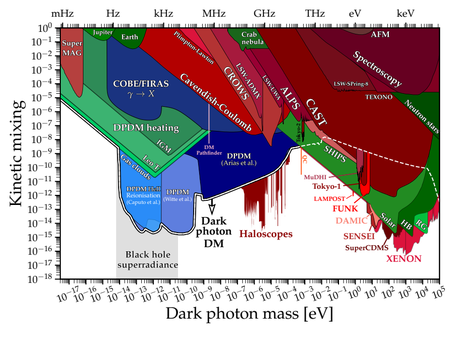


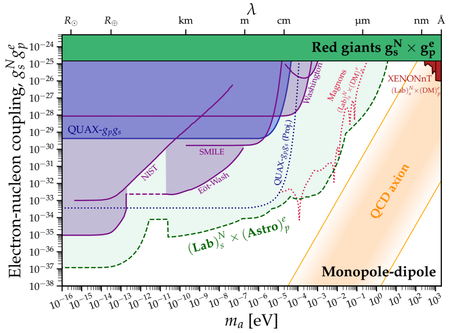


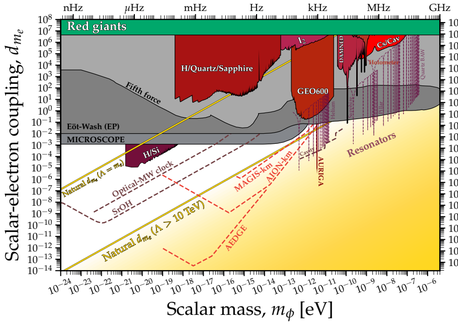


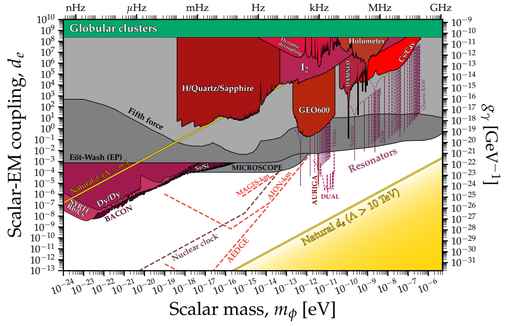


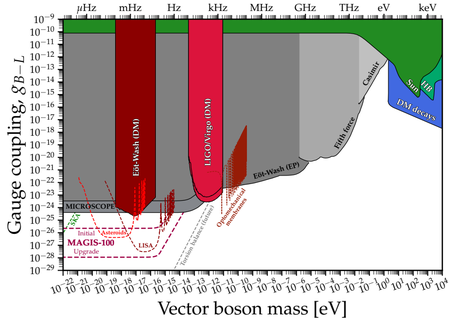


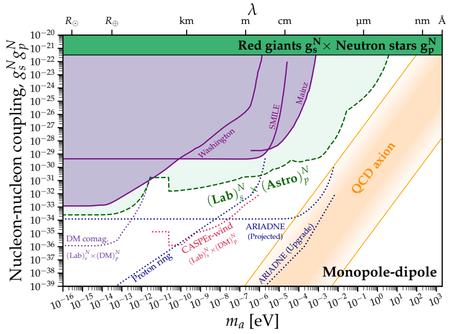


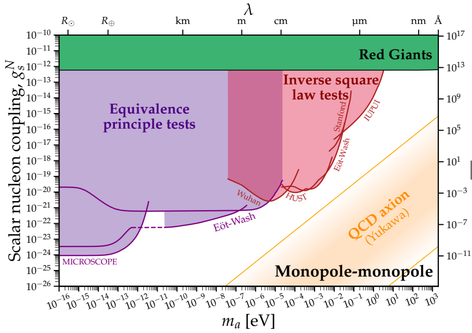






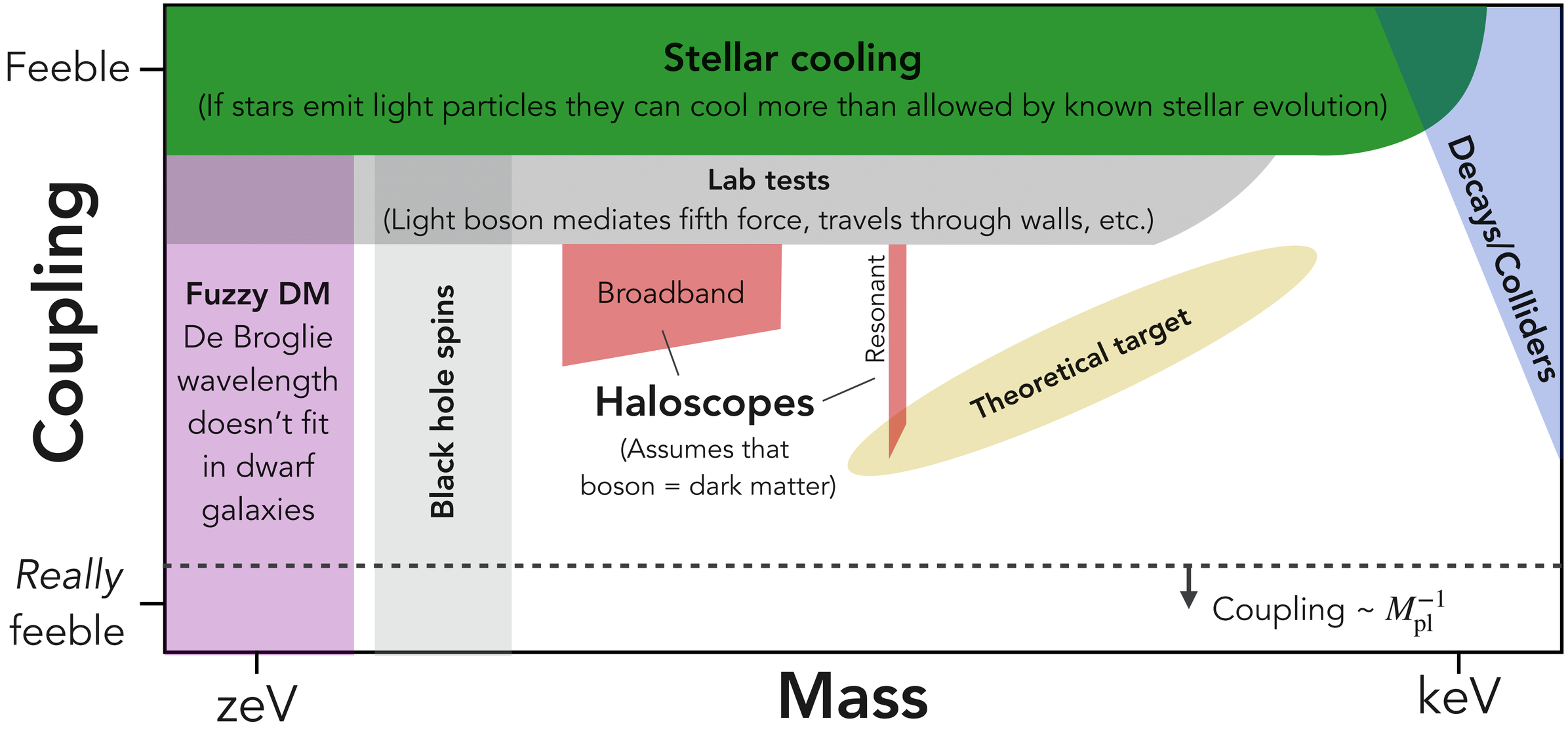






For more, see cajohare.github.io/AxionLimits/ → Now lists results from ~300 publications!

Schematic of a parameter space for an ultralight boson



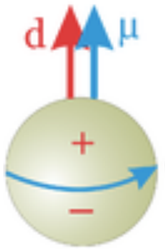
Wave-like dark matter experiments

- Axion
- Dark photon
- Scalar/Vector

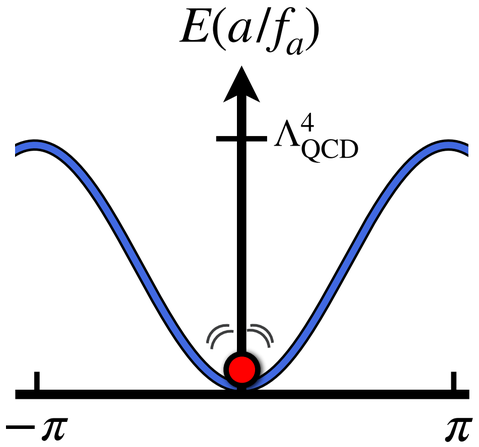
The axion

The "**QCD axion**" is the explanation for why the neutron doesn't have an EDM

$d \propto$ some angle



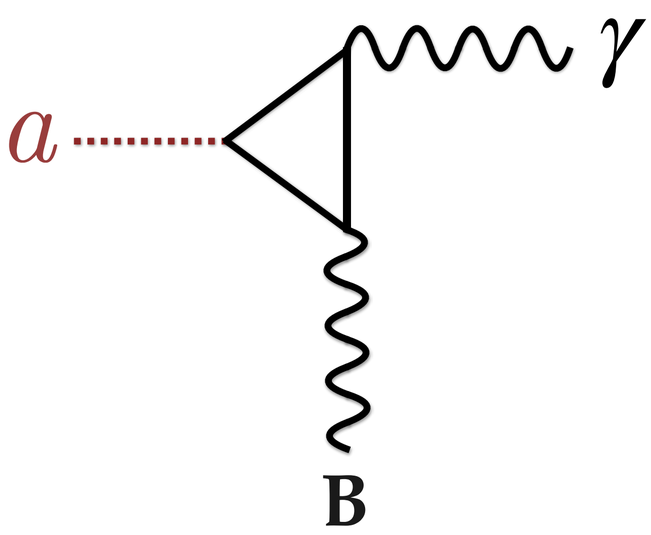
Some angle → New field



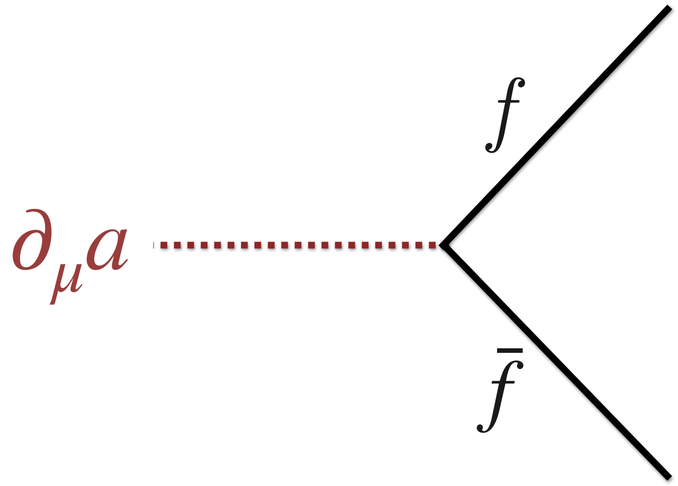
→ Tiny mass related to the energy scale f_a at which axion is created as a pseudo-Goldstone boson

$$m_a \simeq \frac{\Lambda^2_{\rm QCD}}{f_a} \simeq 6\,{\rm meV}\left(\frac{10^9 {\rm GeV}}{f_a}\right)$$

Axion-photon



Axion-fermion



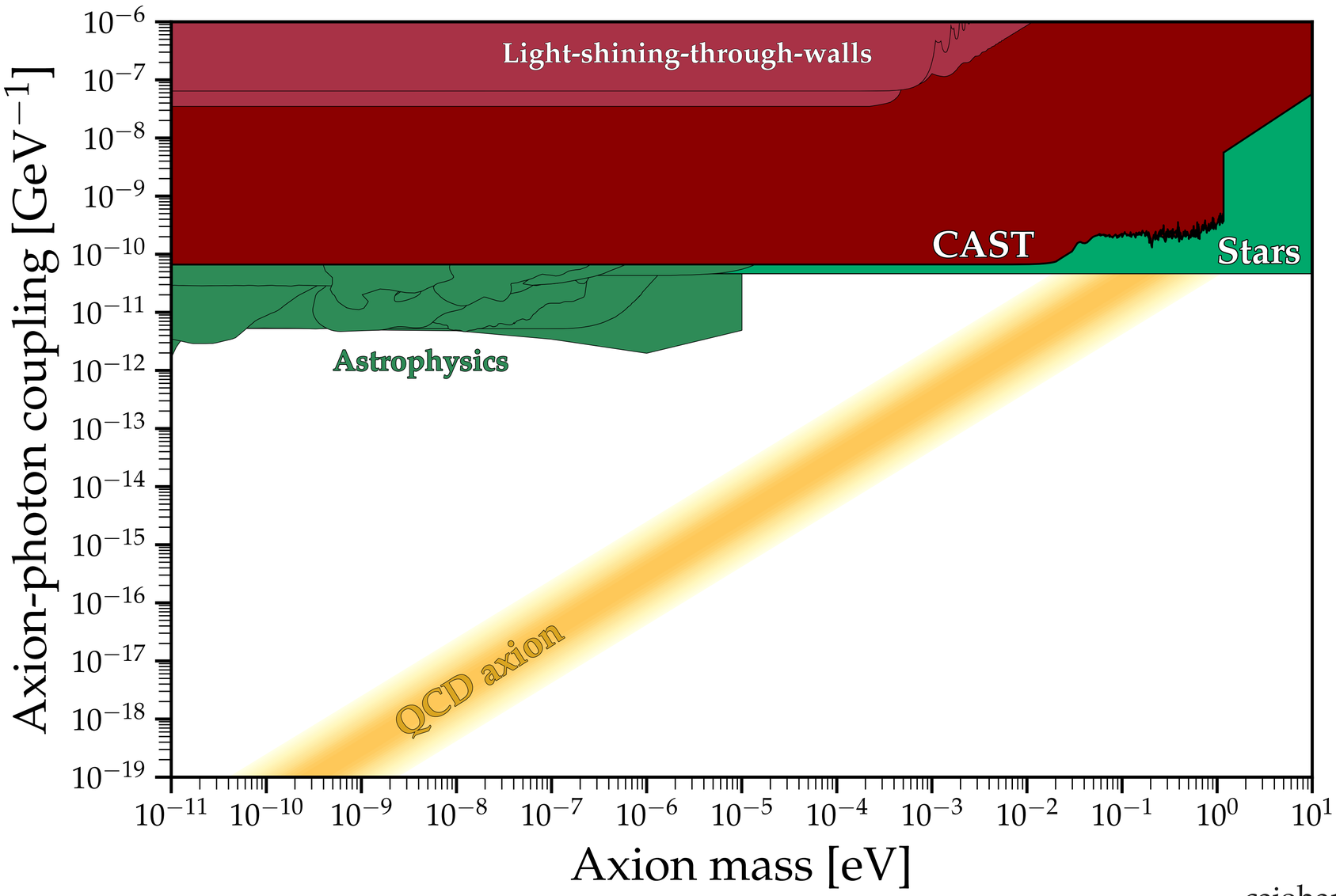
All couplings suppressed by high energy scale: $g \sim f_a^{-1}$

Small couplings ⇒ **dark matter**

Small couplings *and* small mass ⇒ ***wave-like* dark matter**

Constraints on an the existence of an axion coupled to the photon

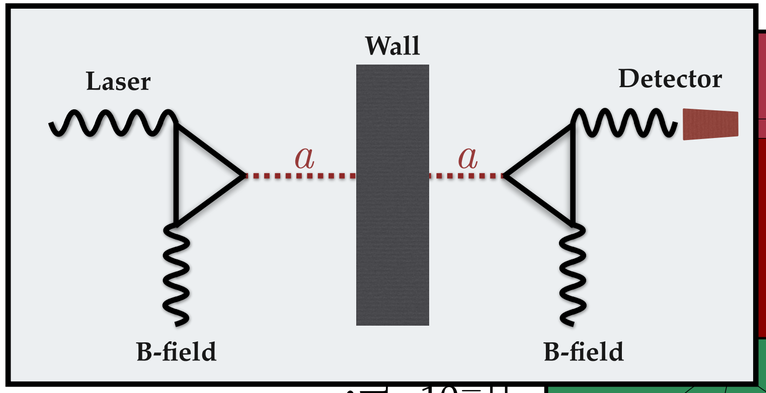
(Nothing assumed about dark matter)



cajohare.github.io/AxionLimits/

Constraints on an the existence of an axion coupled to the photon

(Nothing assumed about dark matter)

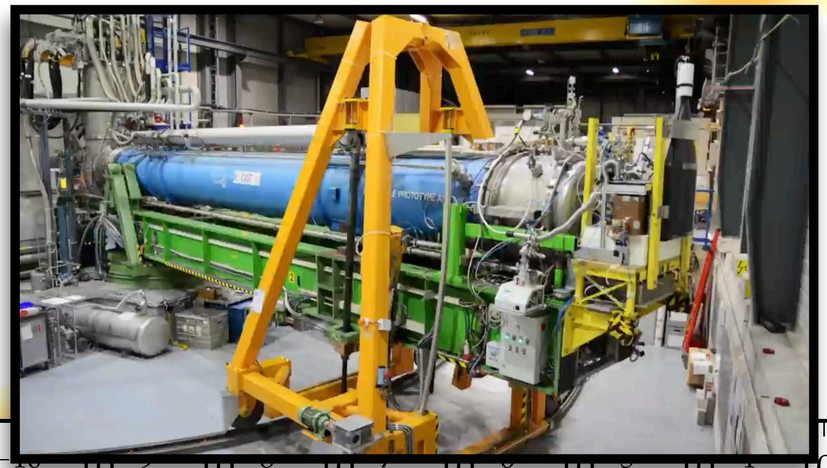


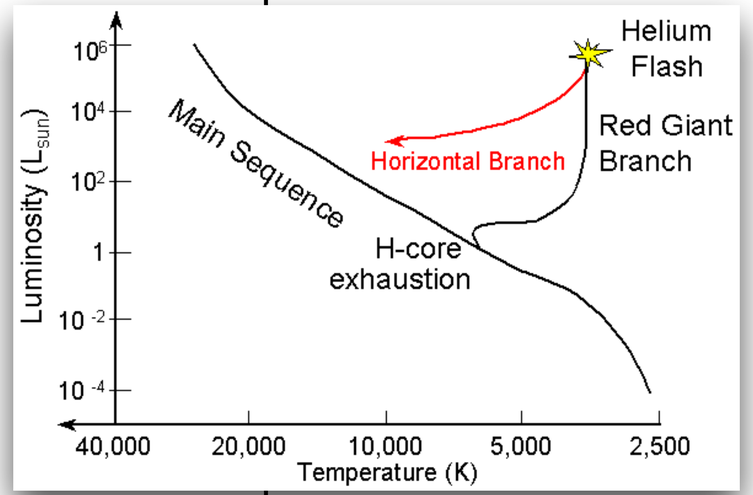
Light-shining-through-walls

CAST

Stars

Astrophysics





Axion-photon coupli

10^{-11} 10^{-12} 10^{-13} 10^{-14} 10^{-15} 10^{-16} 10^{-17} 10^{-18} 10^{-19}

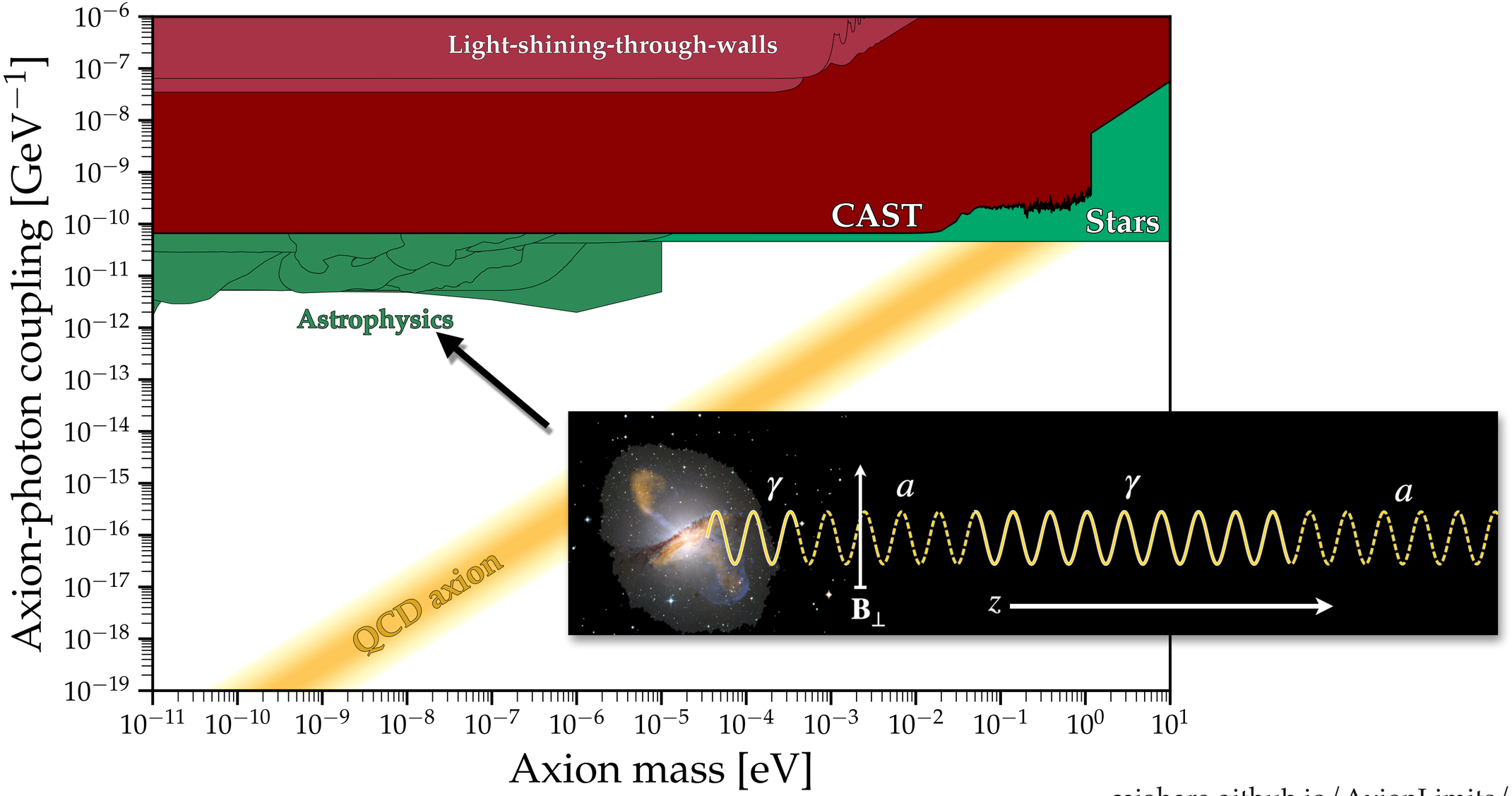
10^{-11} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}

Axion mass [eV]

cajohare.github.io/AxionLimits/

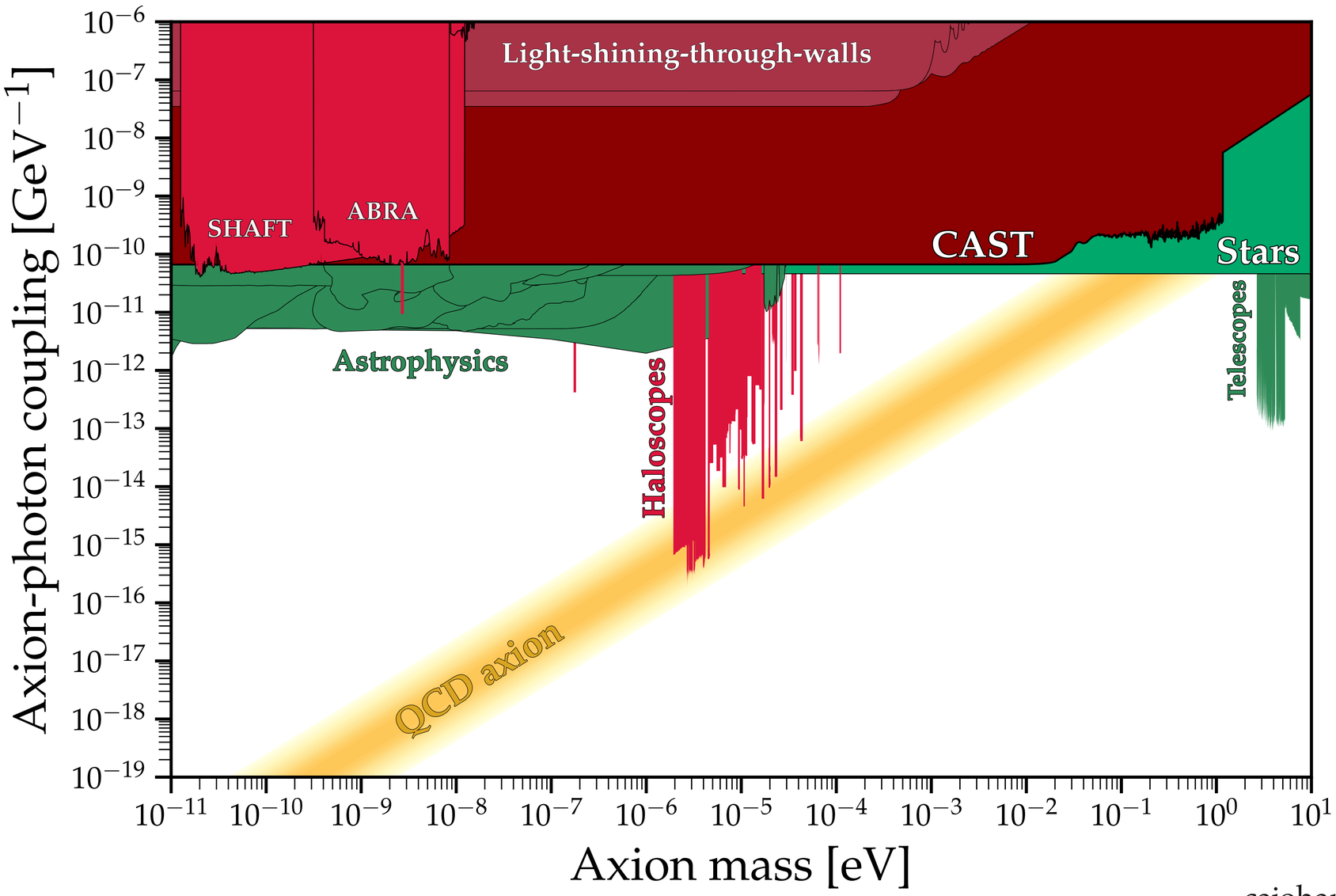
Constraints on an the existence of an axion coupled to the photon

(Nothing assumed about dark matter)



cajohare.github.io/AxionLimits/

Searches that *do* assume axions are dark matter

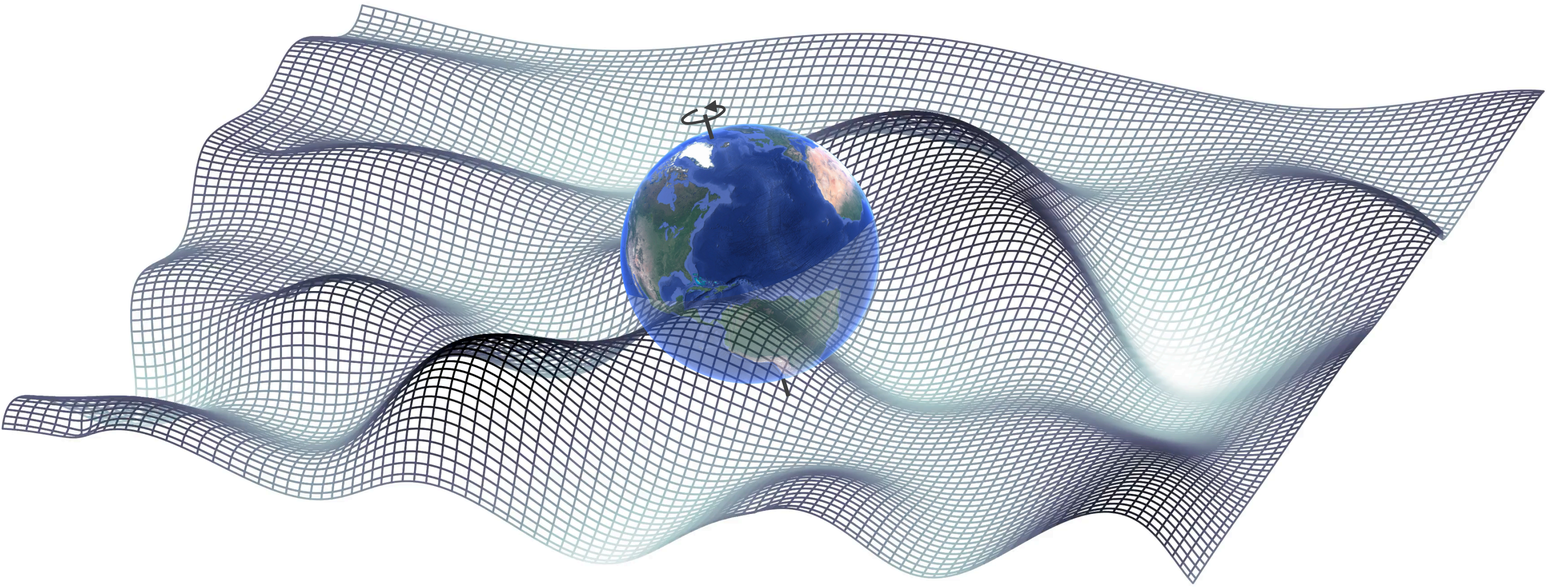


cajohare.github.io/AxionLimits/

Direct detection

To calculate *any* experimental signal of dark matter we need to know

1. How much dark matter there is around the Earth, ρ
2. How fast it's moving, v



For wave-like dark matter these correspond to:

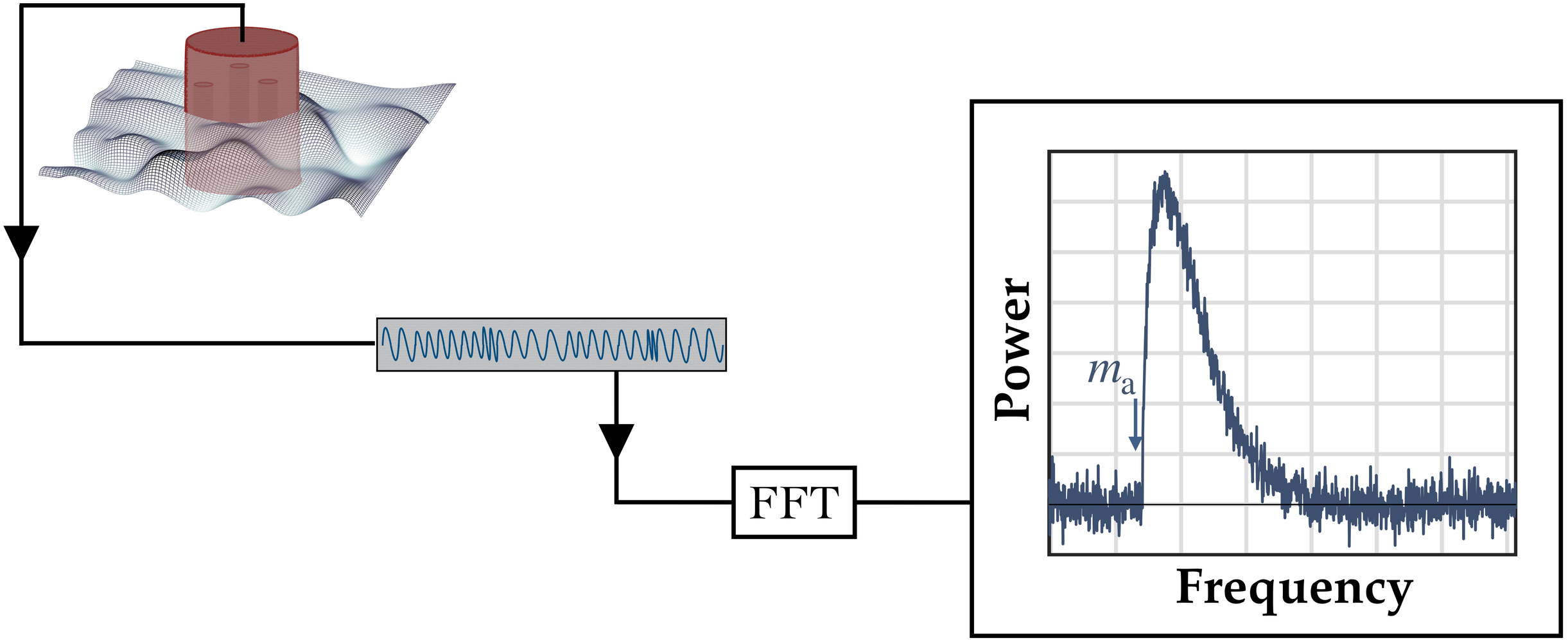
Amplitude: $A = \dfrac{\sqrt{2\rho_a}}{m_a}$

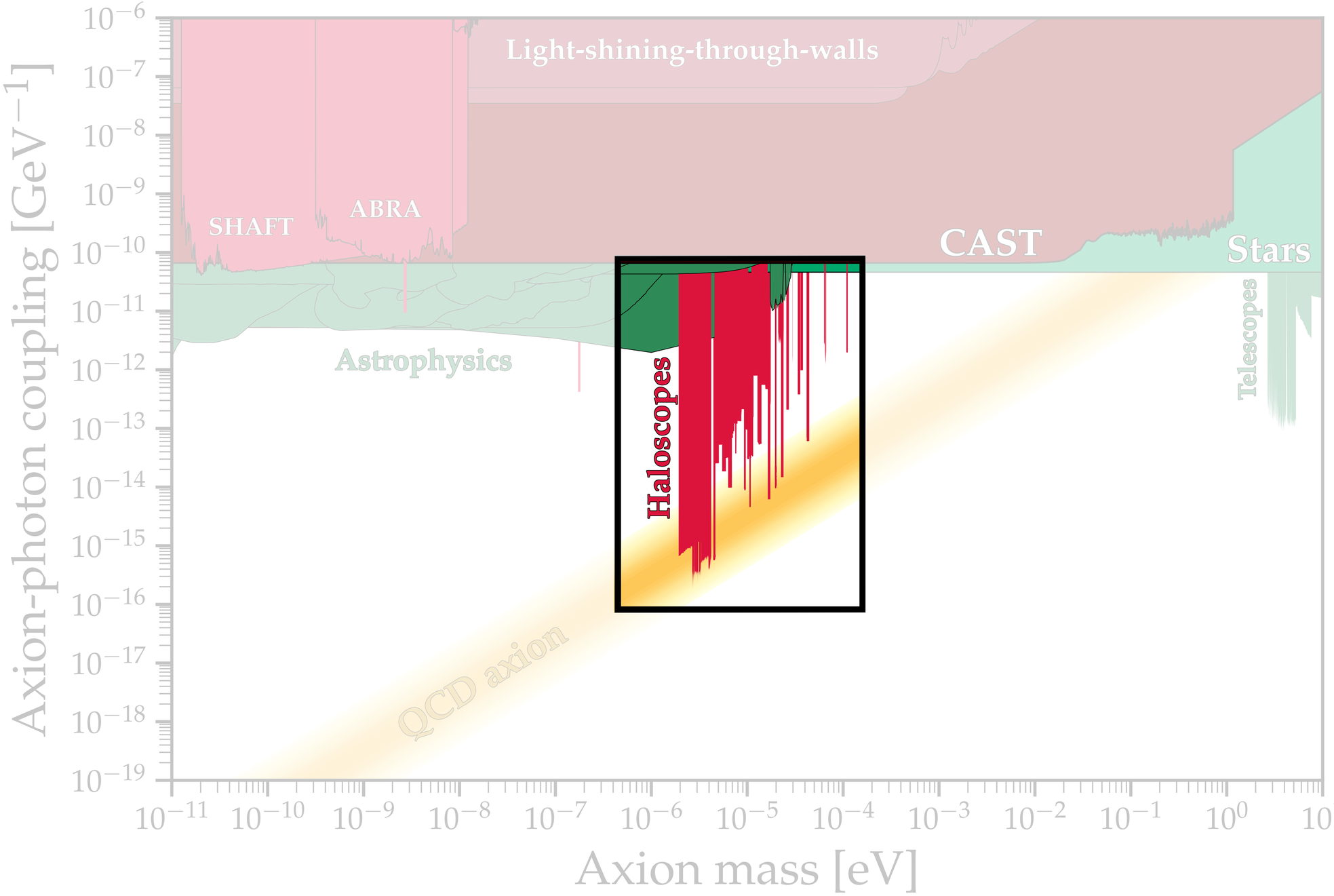
Frequency: $\omega = m_a + \dfrac{1}{2} m_a v^2$

$$\approx m_a(1 + 10^{-6})$$

Wave-like dark matter “lineshape”

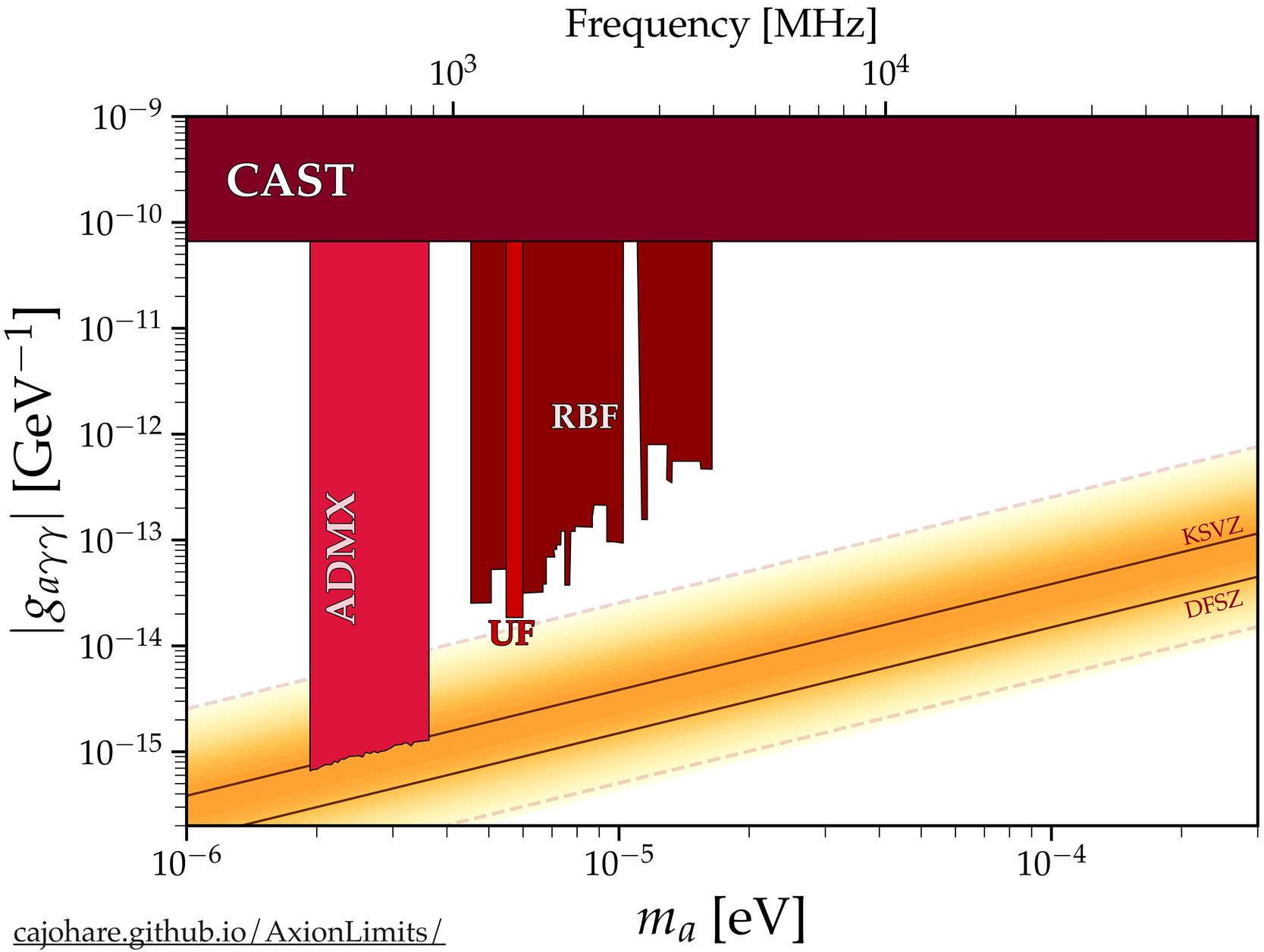
Oscillations are coherent for 10^6 cycles, but most haloscopes observe over much longer timescales



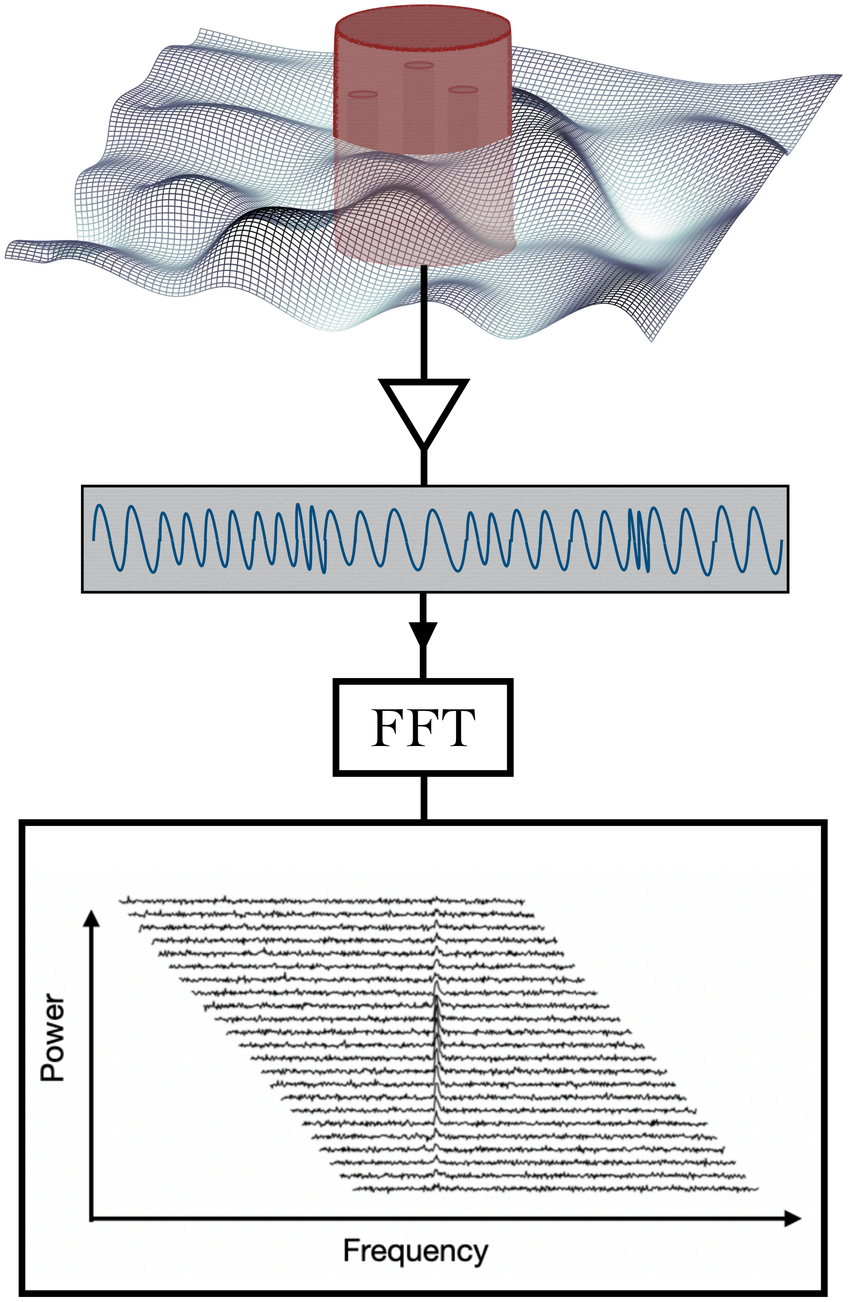


cajohare.github.io/AxionLimits/

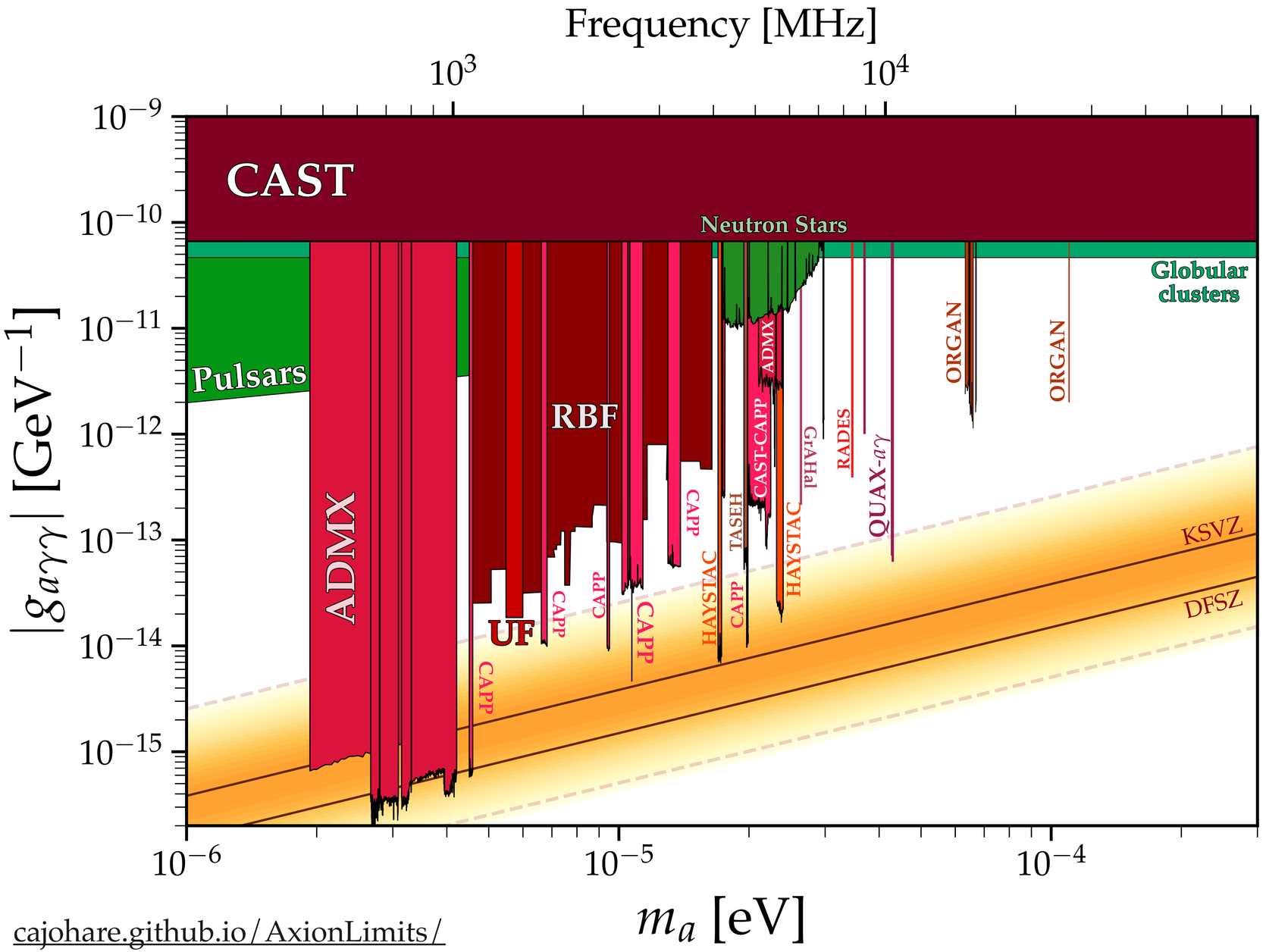
Axion haloscopes



cajohare.github.io/AxionLimits/

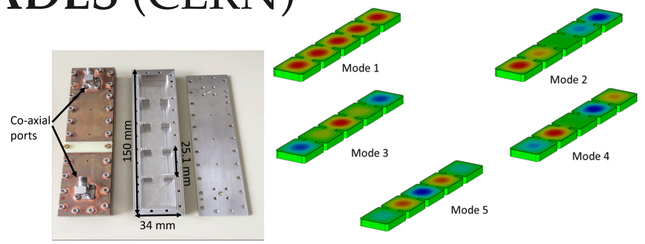


Axion haloscopes

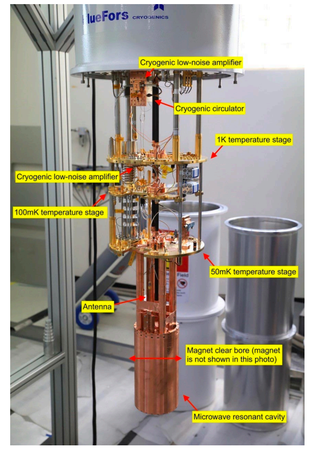


cajohare.github.io/AxionLimits/

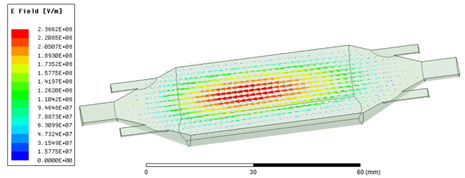
RADES (CERN)



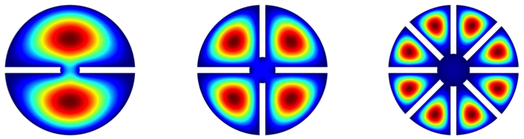
ORGAN (UWA)



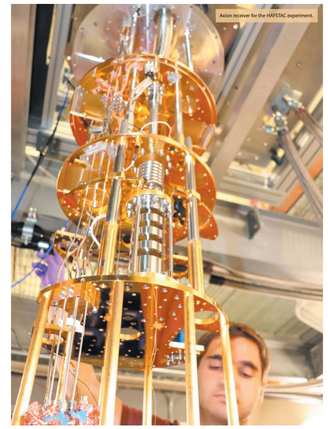
QUAX (Legnaro)



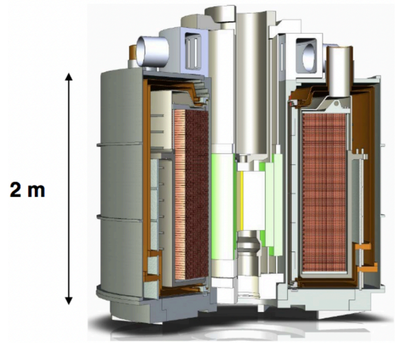
CAPP (IBS)

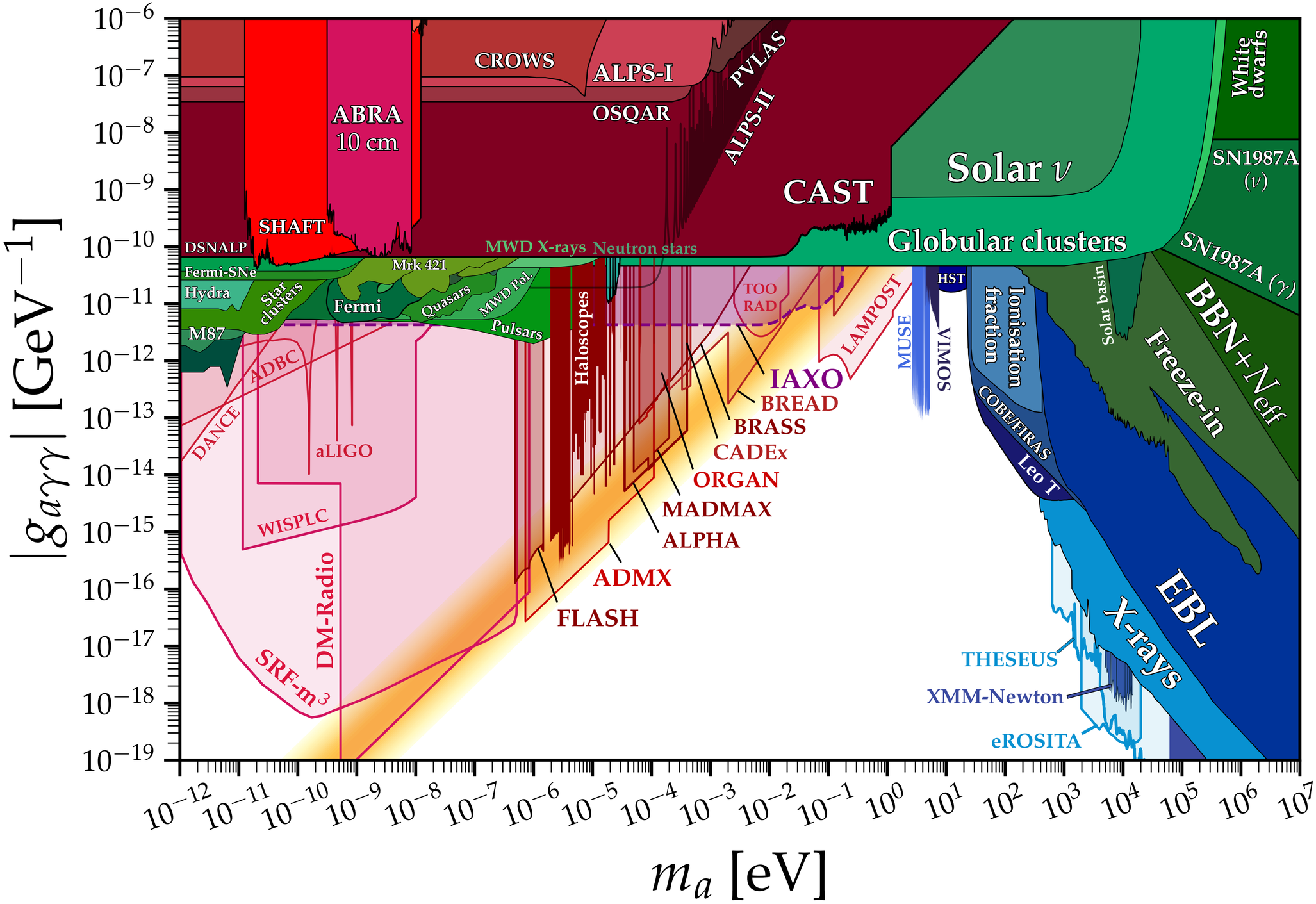


HAYSTAC (Yale)



GrAHal (Grenoble)

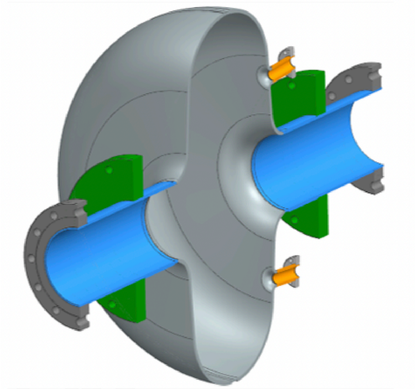




cajohare.gith

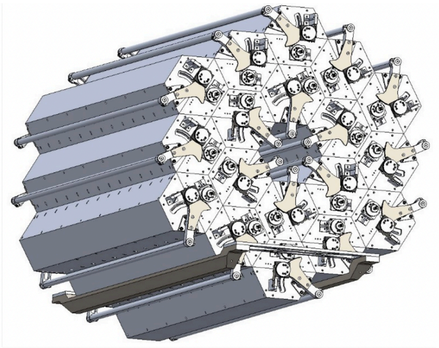
Dark-SRF

2207.11346



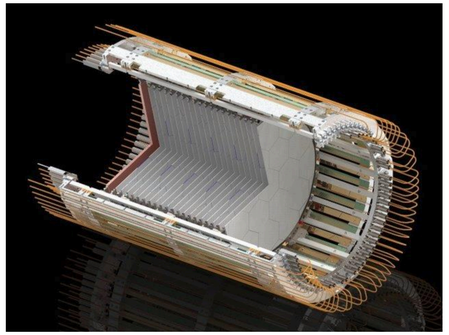
ADMX-EFR

2203.14923



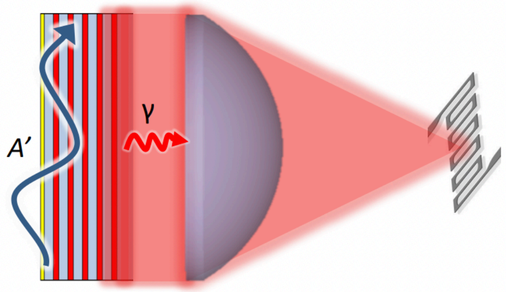
MADMAX

2003.10894



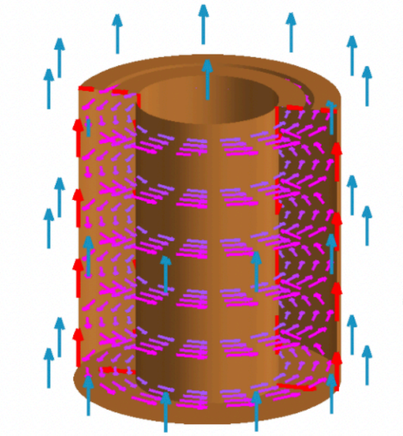
LAMPOST

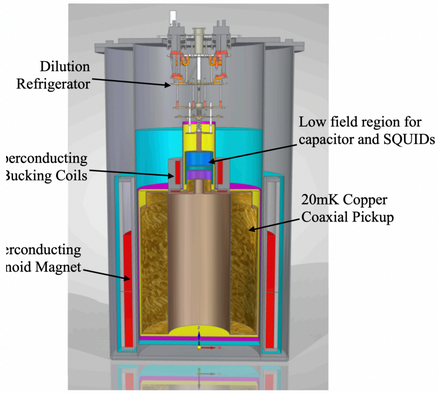
2110.01582



MHz GHz THz

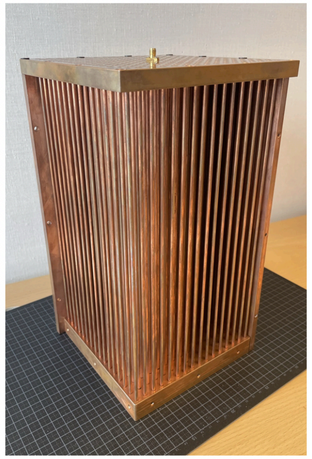
neV μeV meV





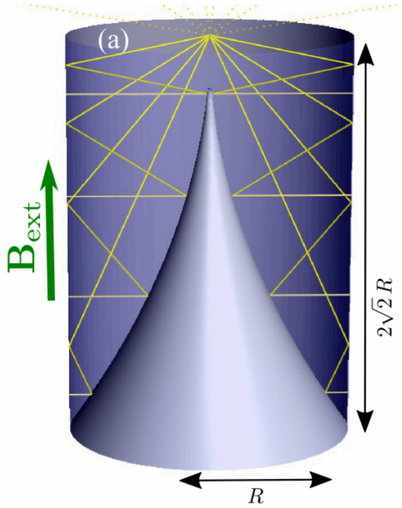
DM-Radio

2204.13781



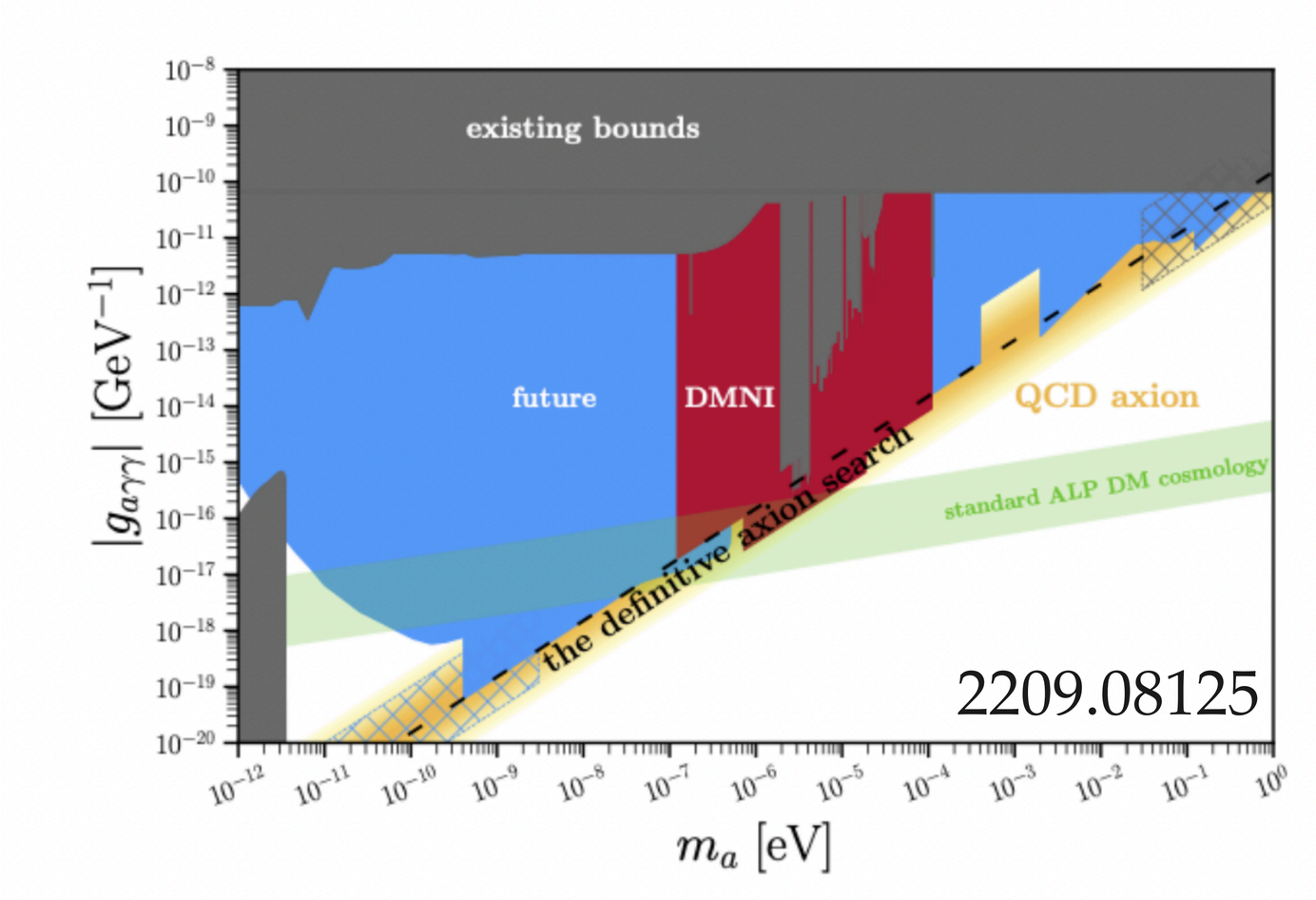
ALPHA

2210.00017



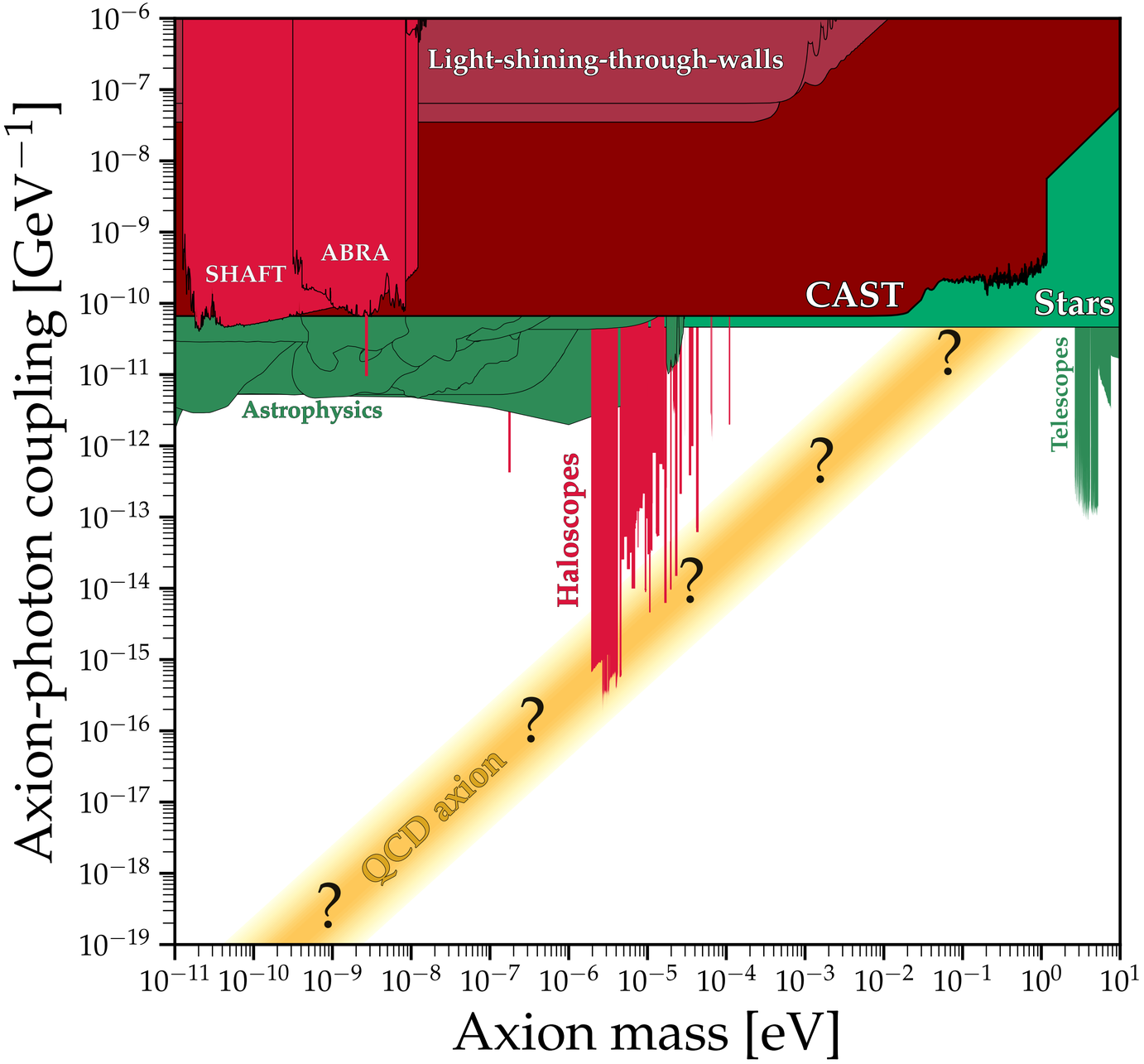
BREAD

2111.12103



Dark matter new initiative (DMNI) Snowmass ’21

US putting $ into
→ ADMX-EFR (high mass)
→ DM-Radio m^3 (low mass)



Biggest challenge right now is clearly that we don't know the axion mass

→ Too much space to cover

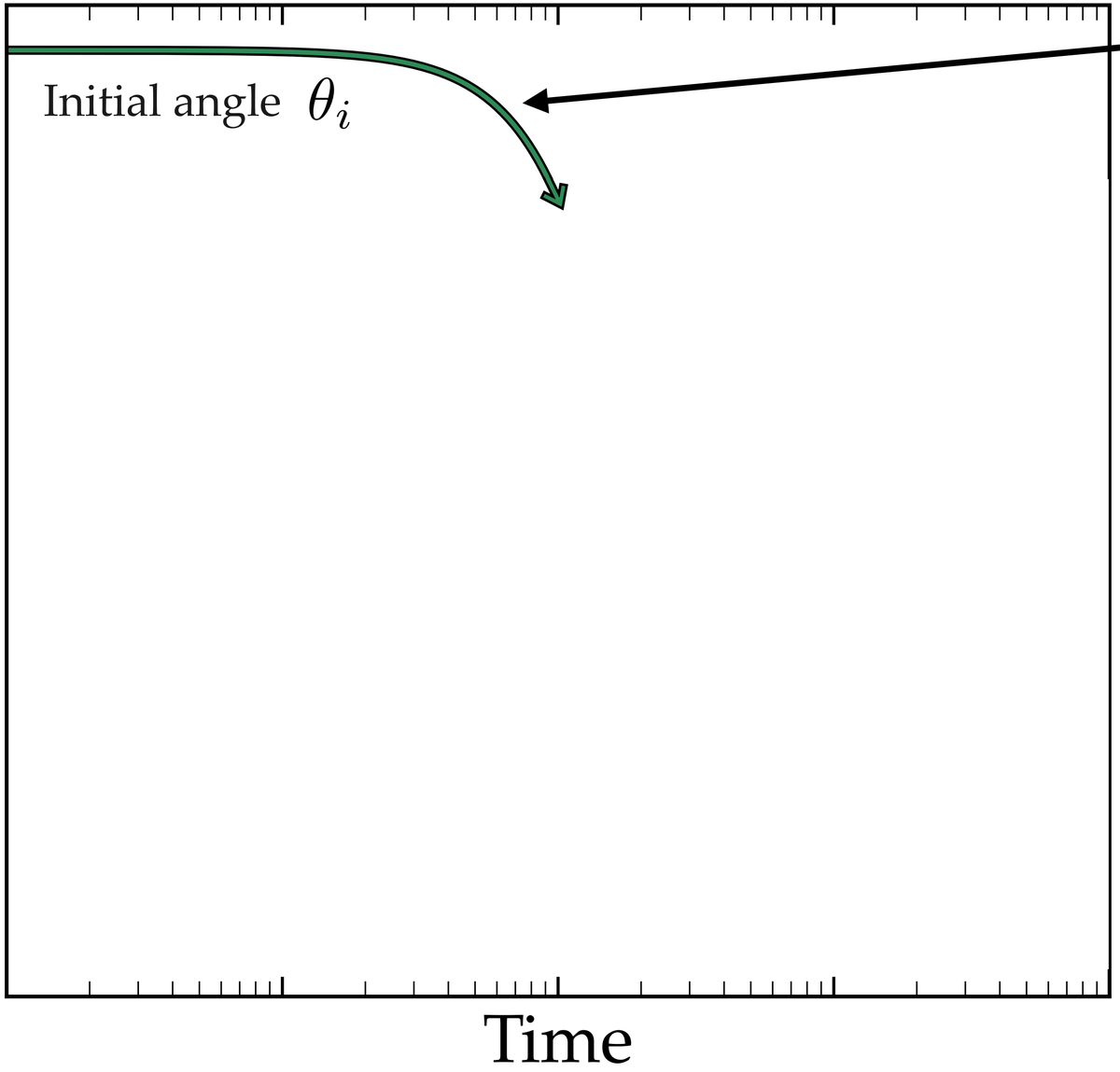
Sensitivity:

$$g_{a\gamma} \propto T^{-1/4}$$

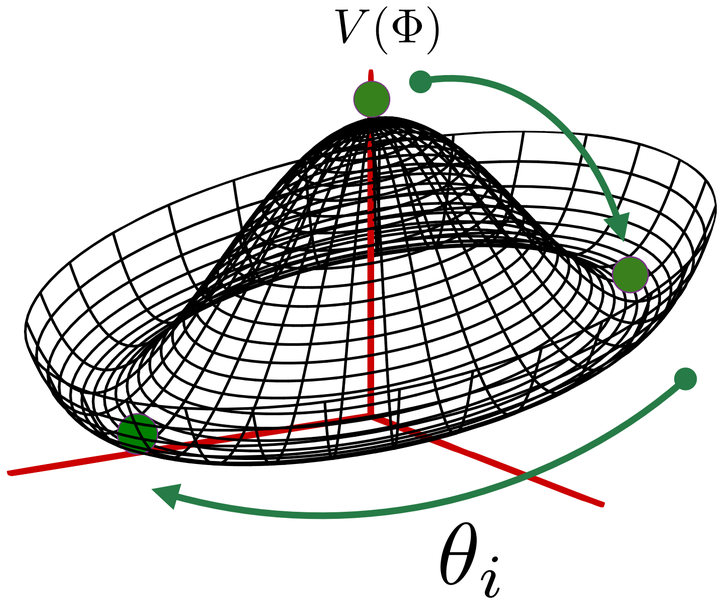
However, if we knew the correct mass, the axion could be found tomorrow

cajohare.github.io/AxionLimits/

Axion cosmology: the misalignment mechanism

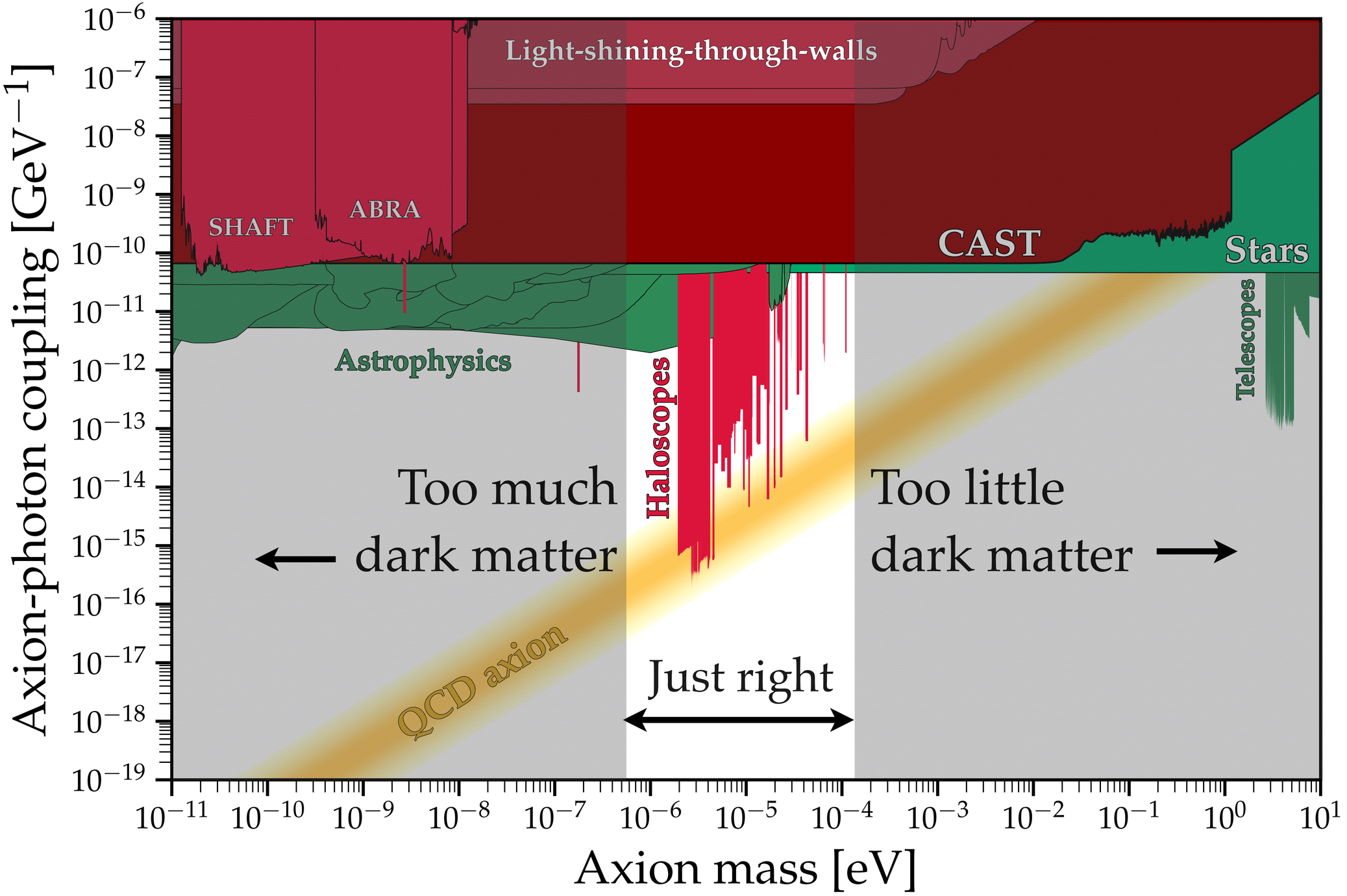


Axion is the phase of a complex scalar field governed by a tilted wine-bottle potential.



Axion field rolls down from some angle and becomes a damped harmonic oscillator

Amount of DM $\propto \theta_i^2$

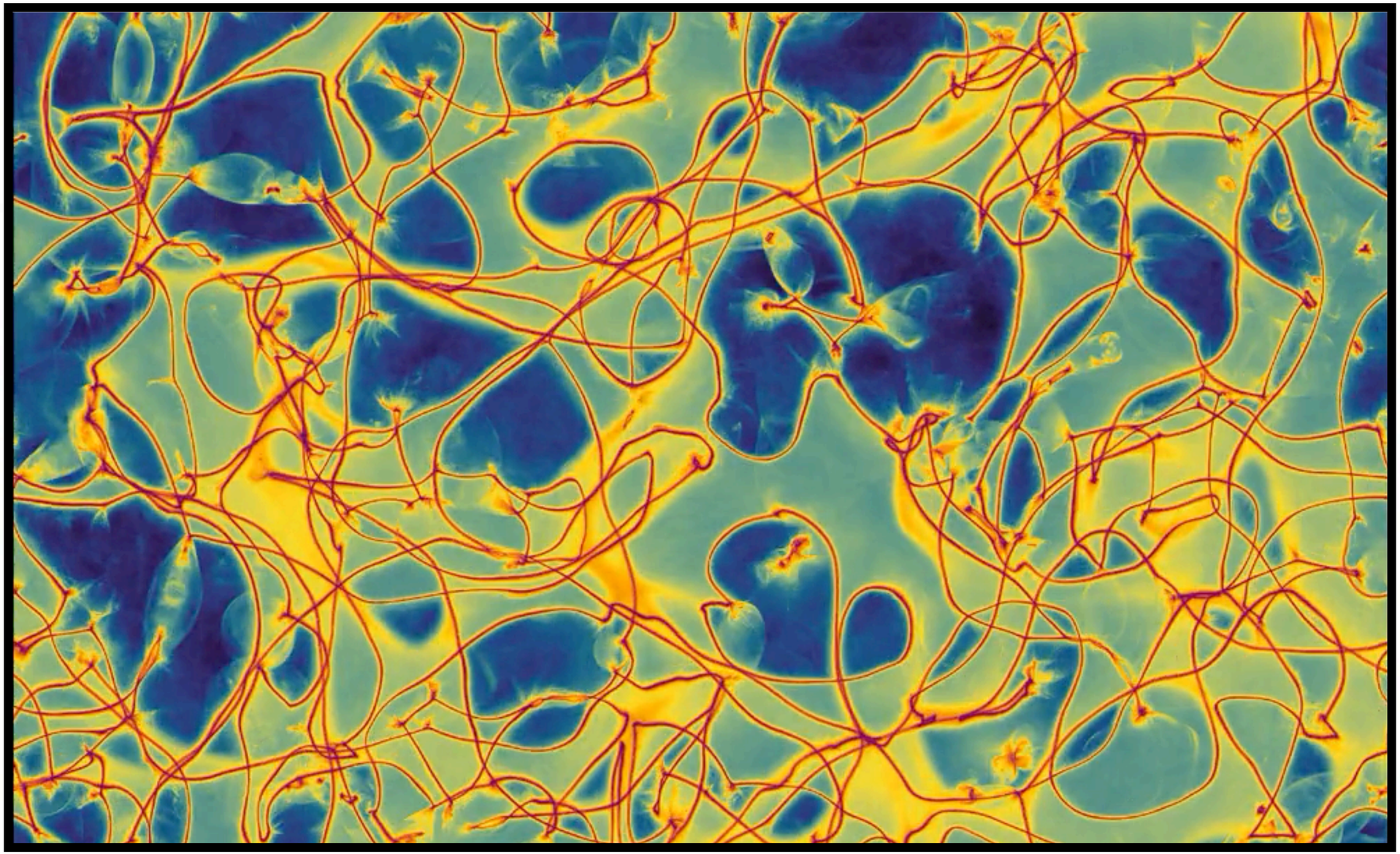

Light-shining-through-walls
SHAFT
ABRA
CAST
Stars
Astrophysics
Telescopes
Haloscopes
Too much
dark matter
Too little
dark matter
QCD axion
Just right
Axion-photon coupling [GeV^{-1}]
Axion mass [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}

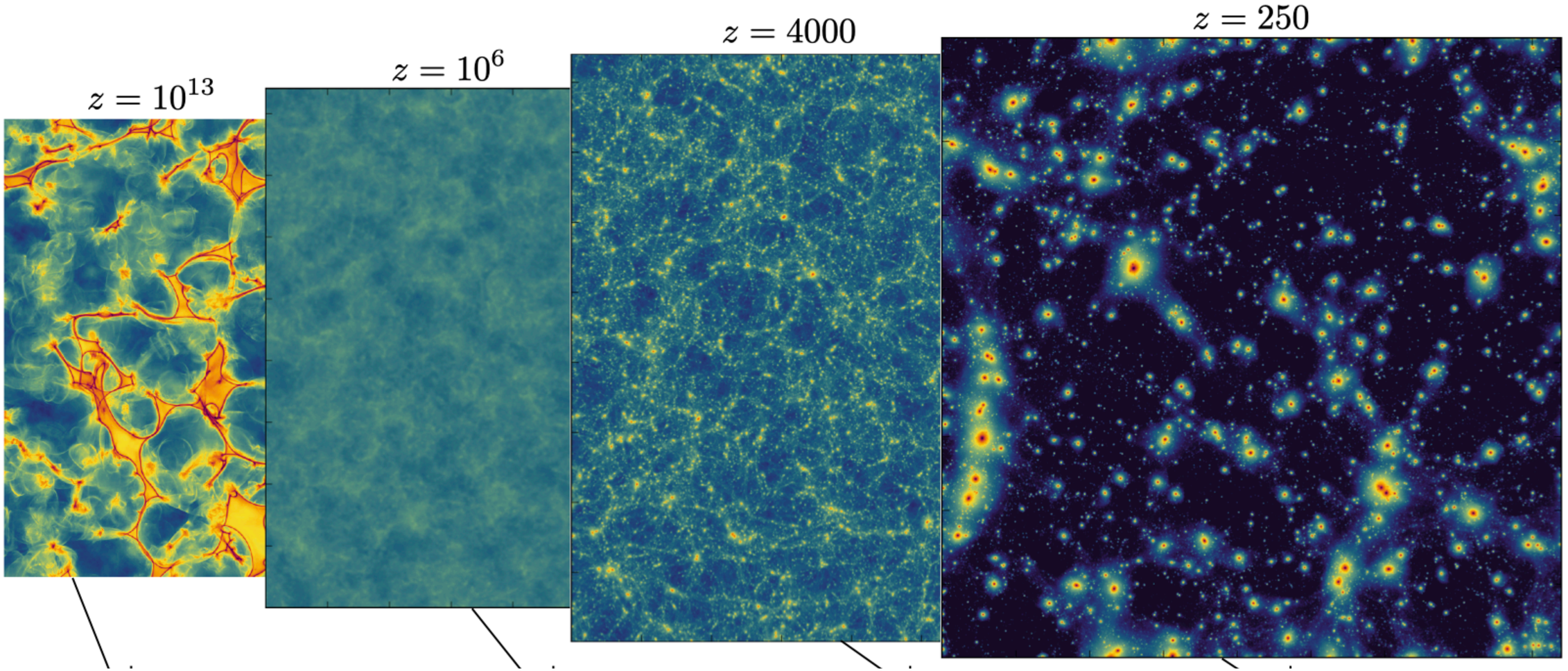
We should be able to do better than this.
But there are two big problems…

Pre-inflation: calculation is easy… but there is a free parameter θ_i that we have no a priori knowledge of

Post-inflation: no free parameters… but things get complicated

Topological defects in the axion field in the post-inflationary scenario





Topological defects produce relativistic axions

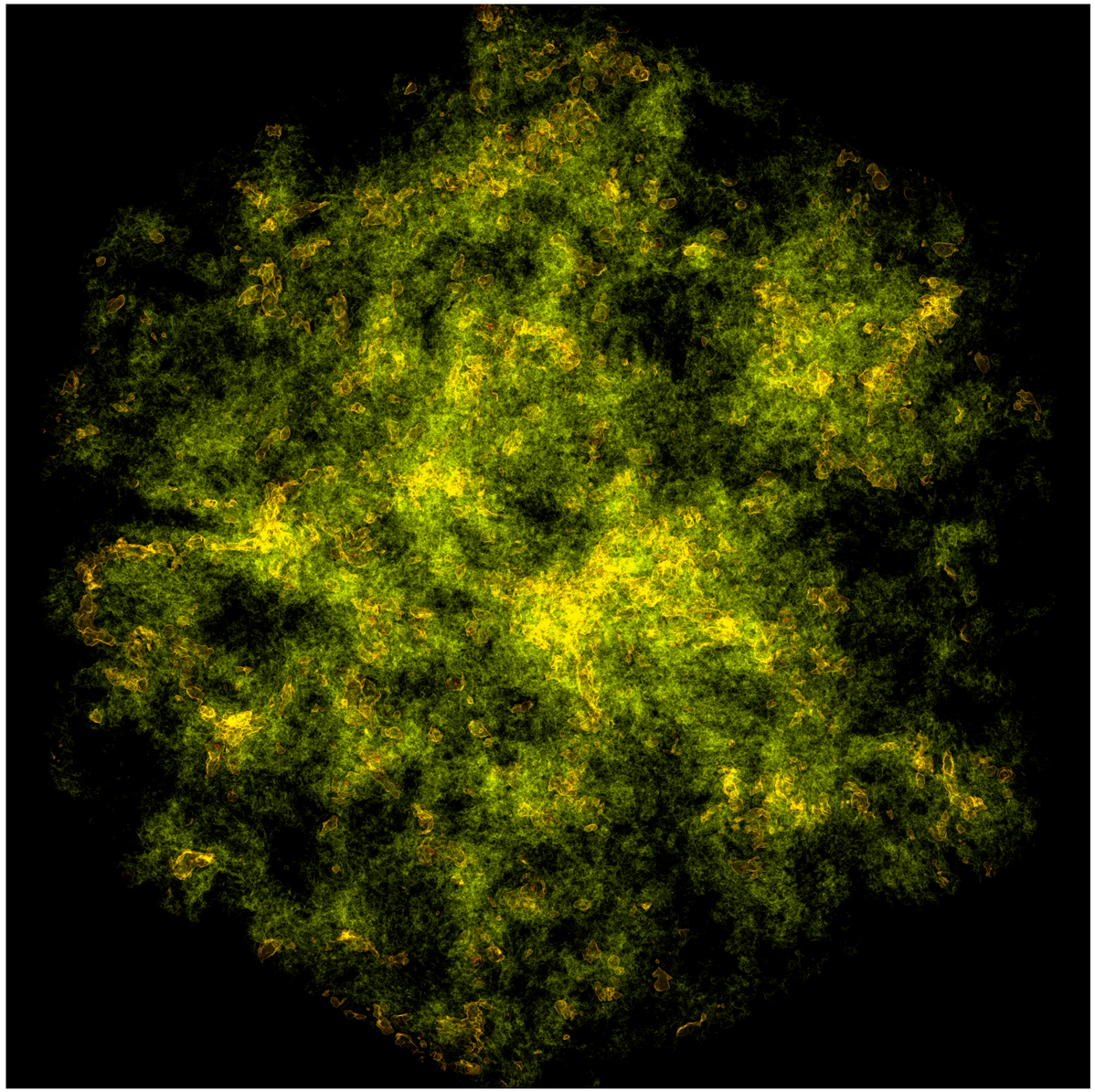
Axions free-stream until non-relativistic

Ultra-small scale structures collapse

Axion miniclusters form

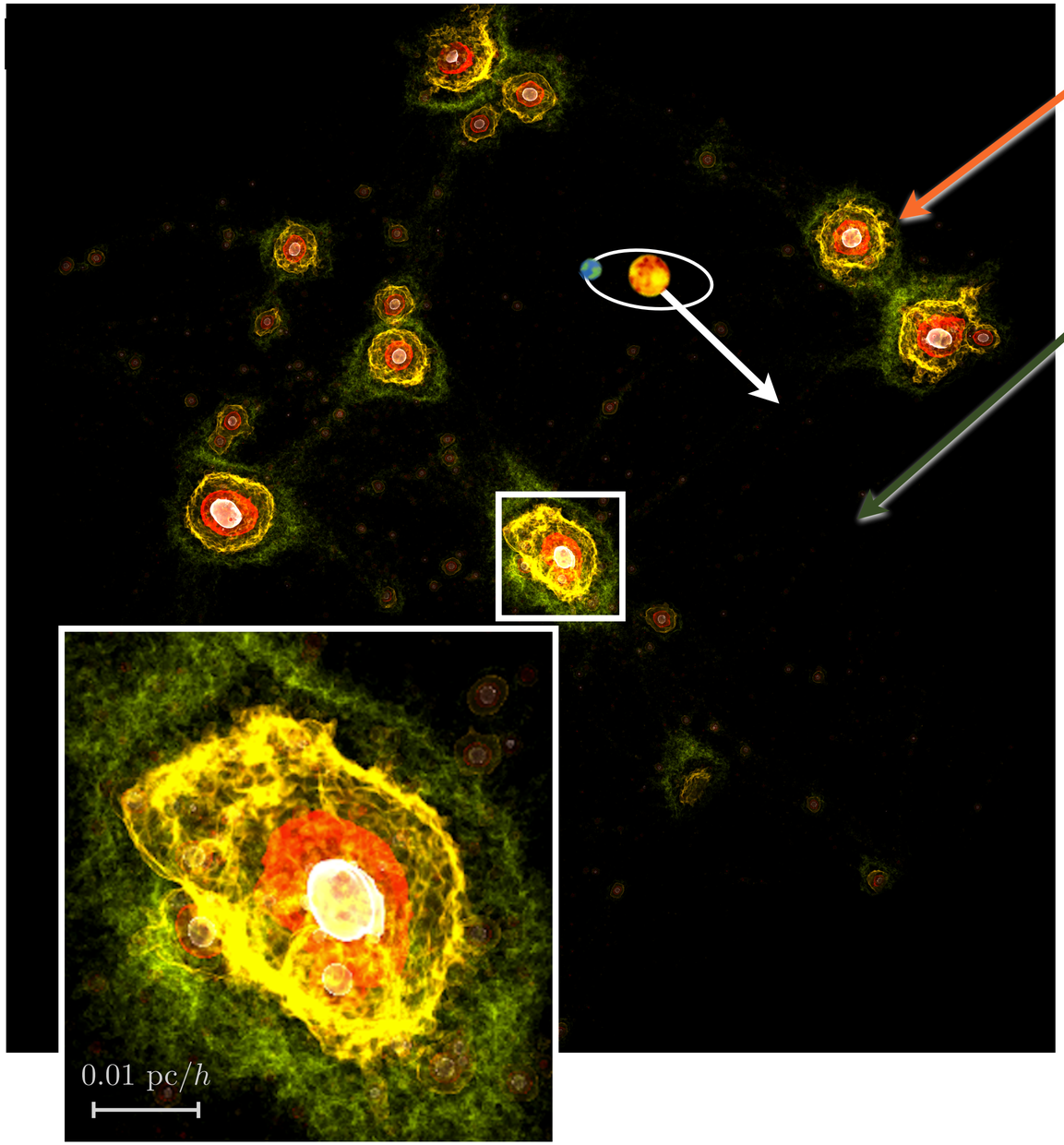
Gravitational collapse of inhomogeneities left over after QCD phase transition leads to the formation of ~AU sized clumps of axions with masses $M \in [10^{-15}, 10^{-9}]\ M_\odot$

→ **axion miniclusters**



Eggemeier, O'Hare, Pierobon, Redondo, Wong [in prep.]

Eggemeier, O'Hare, Pierobon, Redondo, Wong [in prep.]



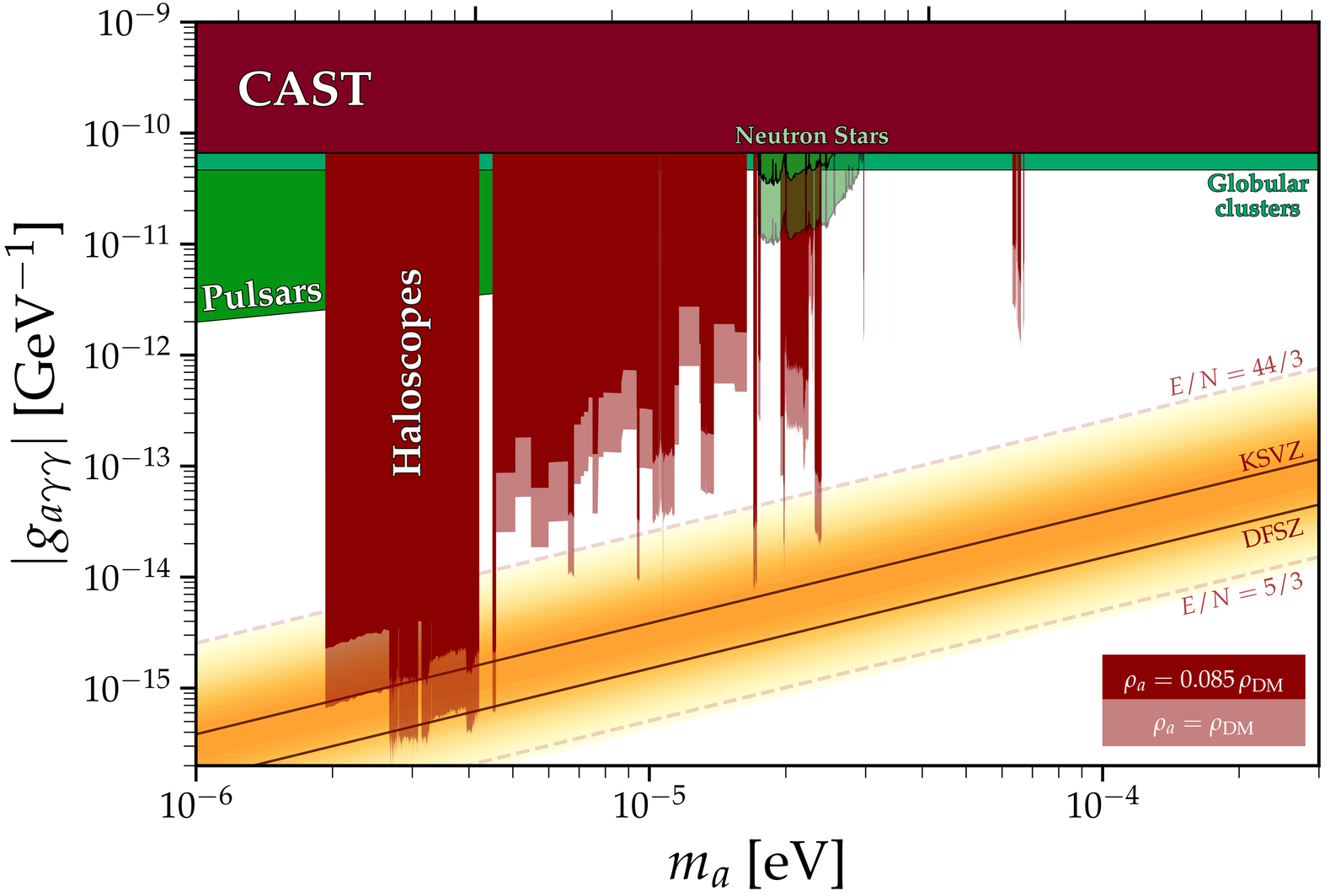
Miniclusters

"Minivoids"

Miniclusters contain >80% of the axions but make up <1% of the volume

We travel at about 0.2 mpc per year through the galaxy so are much more likely to be in the ***minivoids*** than the miniclusters

Implications for haloscopes



Typical density in the minivoids is ~0.085 of the mean density of dark matter

→ Not a nice conclusion, but it could have been much worse!

Eggemeier, O'Hare, Pierobon, Redondo, Wong [in prep.]

Enough axions

Vector wave-dark matter:
Dark photons

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

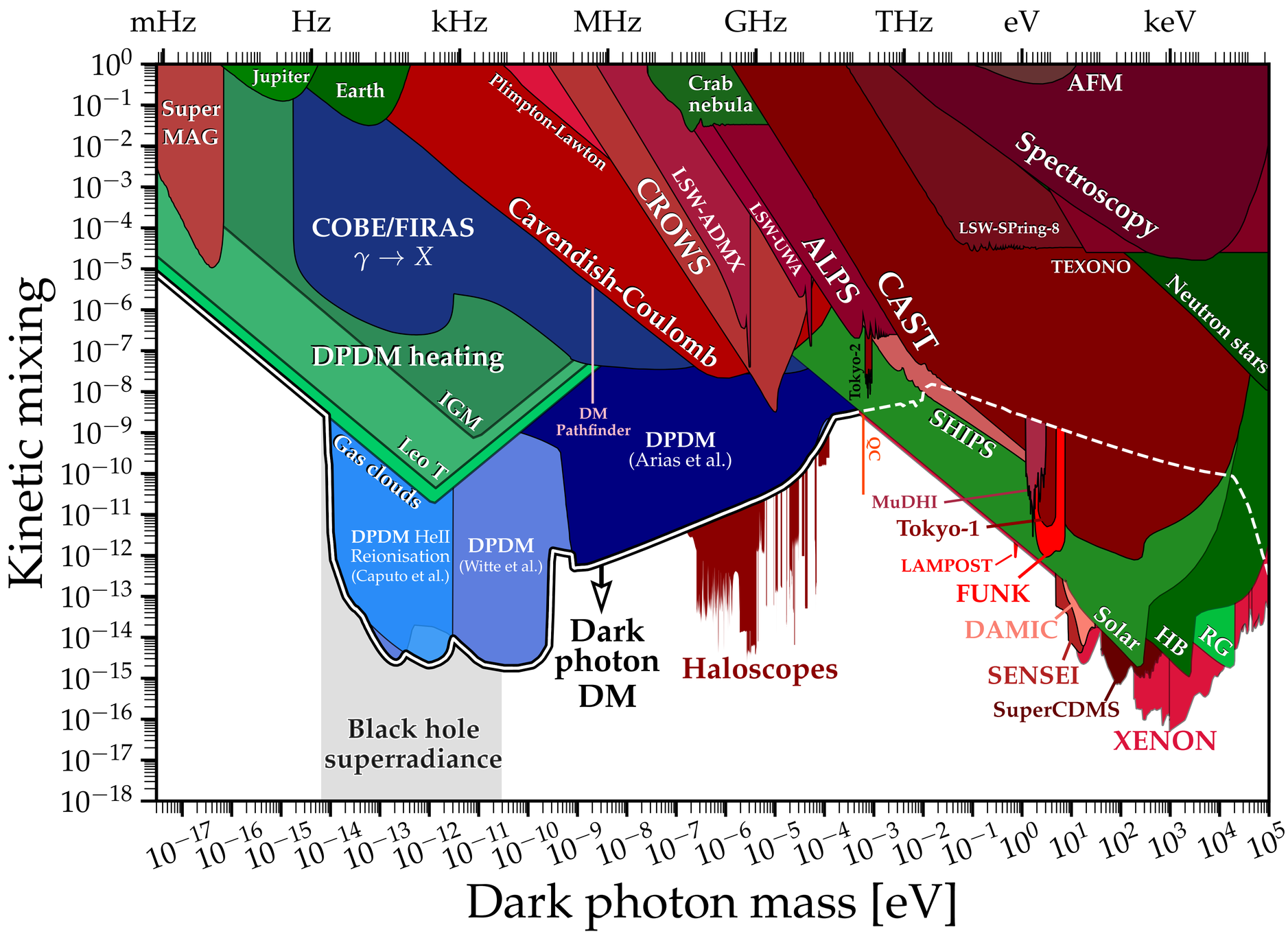
with some gauge boson X^μ

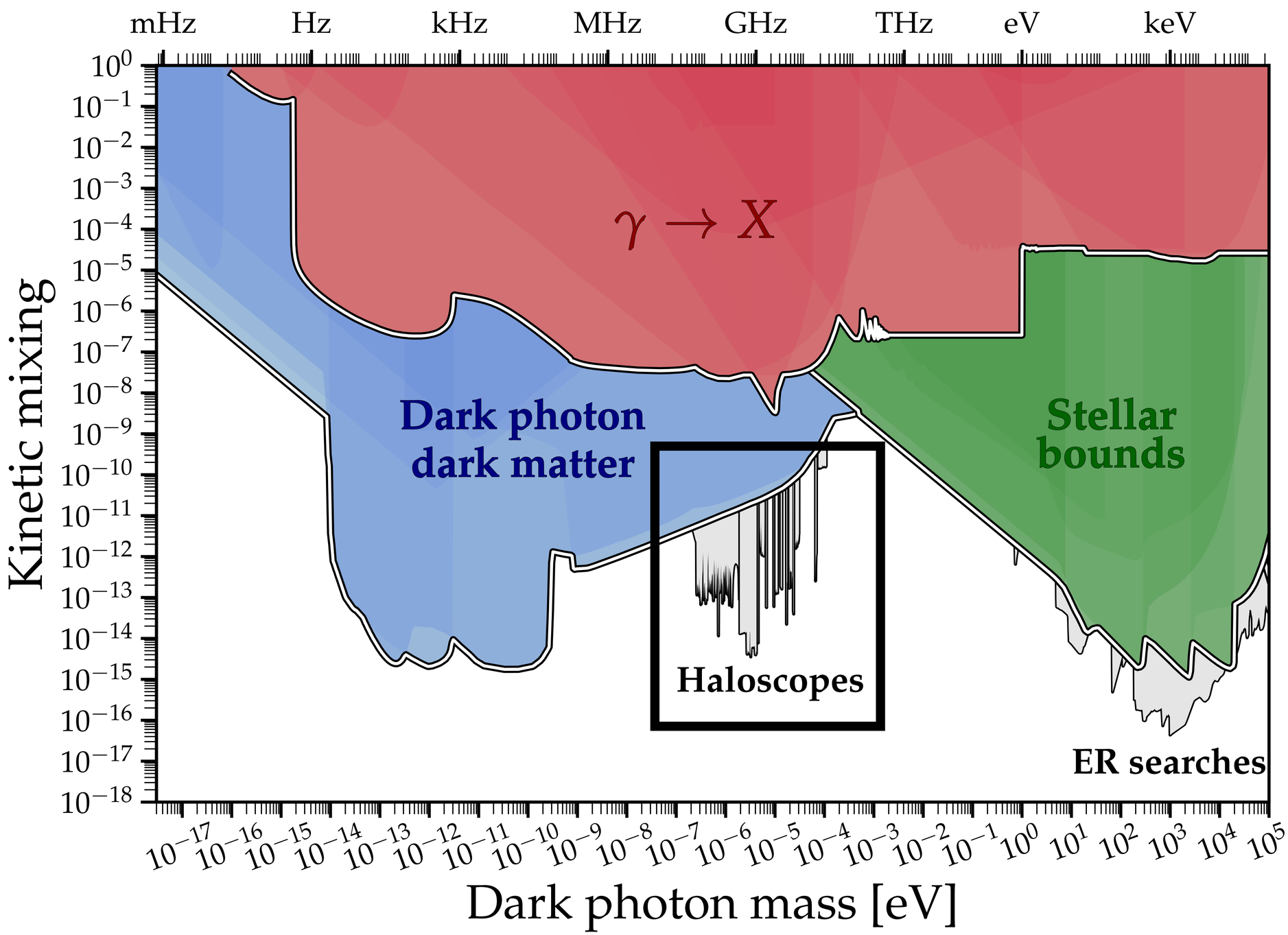
Below EW $\rightarrow$ $\mathcal{L} \supset -\frac{\chi}{2} F_{\mu\nu} X^{\mu\nu}$

"Kinetic mixing" with SM photon quantified by χ

Need a mass-generation mechanism, but that's it

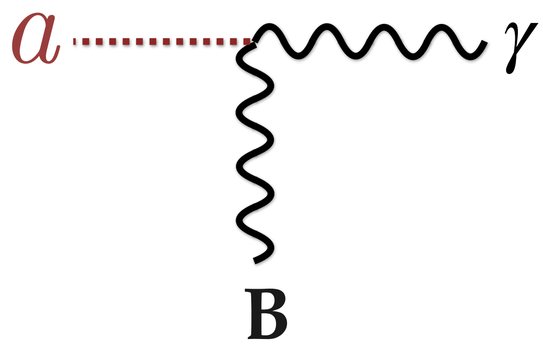
$\rightarrow$ Very minimal model. Can be a mediator to a dark sector coupled via millicharge, or a wave-like DM candidate in and of itself


mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Kinetic mixing
Dark photon mass [eV]
Super MAG
Jupiter
Earth
Plimpton-Lawton
Crab nebula
AFM
Spectroscopy
LSW-SPring-8
TEXONO
Neutron stars
COBE/FIRAS
$\gamma \to X$
Cavendish-Coulomb
CROWS
LSW-ADMX
LSW-UWA
ALPS
CAST
Tokyo-2
DPDM heating
IGM
Leo T
Gas clouds
DM Pathfinder
DPDM (Arias et al.)
SHIPS
3σ
MuDHI
Tokyo-1
LAMPOST
FUNK
DAMIC
Solar
HB
RG
SENSEI
SuperCDMS
XENON
DPDM HeII Reionisation (Caputo et al.)
DPDM (Witte et al.)
Dark photon DM
Haloscopes
Black hole superradiance


mHz
Hz
kHz
MHz
GHz
THz
eV
keV
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
Kinetic mixing
$\gamma \to X$
Dark photon
dark matter
Stellar
bounds
Haloscopes
ER searches
10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
Dark photon mass [eV]

Dark photon electrodynamics versus Axion electrodynamics

Axions source an effective current in a similar way, but only in the presence of an applied B-field, meaning DPs can searched for with exactly the same techniques
→ **no B-field required!**



$$P_{\mathrm{DP}} = \kappa \mathcal{G} V Q \rho_{\mathrm{DM}} \chi^2 m_X$$

$$P_{\mathrm{axion}} = \kappa \mathcal{G} V Q \rho_{\mathrm{DM}} \frac{g_{a\gamma}^2 B^2}{m_a}$$

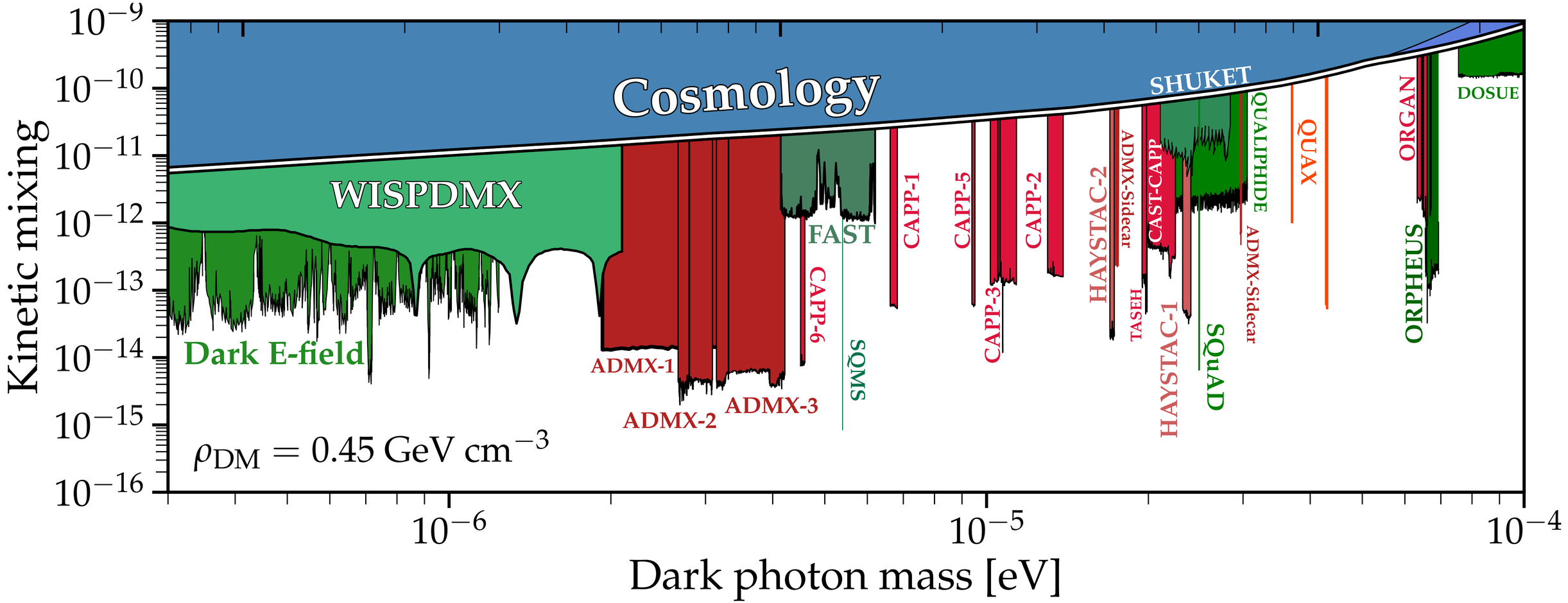
DP limit

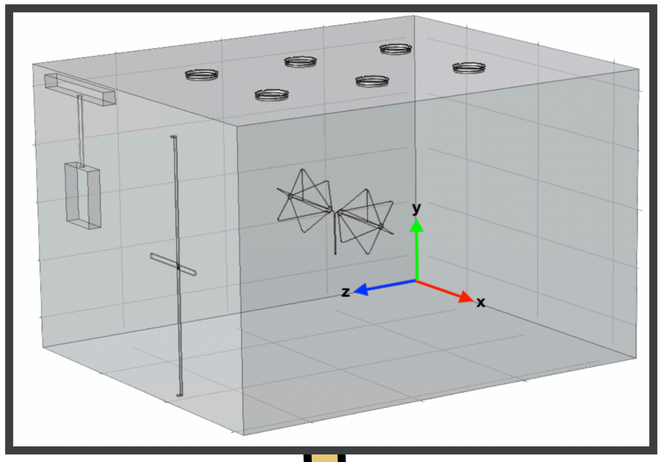
$$\chi m_X \leftrightarrow g_{a\gamma} B$$

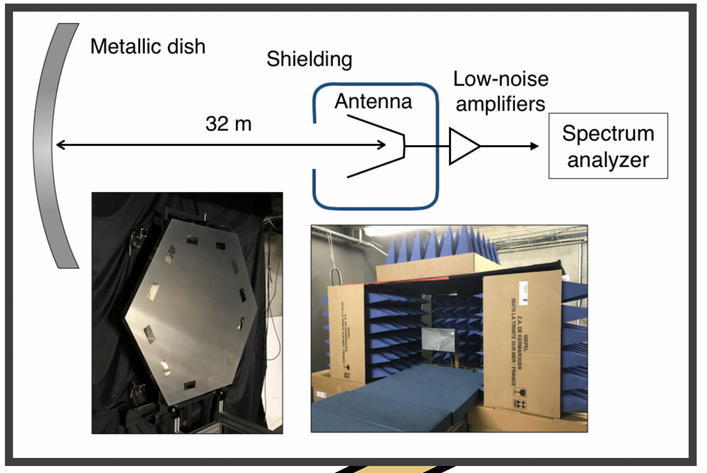
Axion limit

Green = dedicated DP searches

Red = recasted axion searches







Kinetic mixing

10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}

Cosmology

SHUKET

WISPDMX

Dark E-field

FAST

SQMS

ADMX-1
ADMX-2
ADMX-3

CAPP-6
CAPP-1
CAPP-5
CAPP-3
CAPP-2

HAYSTAC-2
ADMX-Sidecar
TASEH
CAST-CAPP
HAYSTAC-1
SQuAD
QUALIPHIDE
ADMX-Sidecar
QUAX
ORGAN
ORPHEUS
DOSUE

$\rho_{\rm DM} = 0.45\,{\rm GeV\,cm^{-3}}$

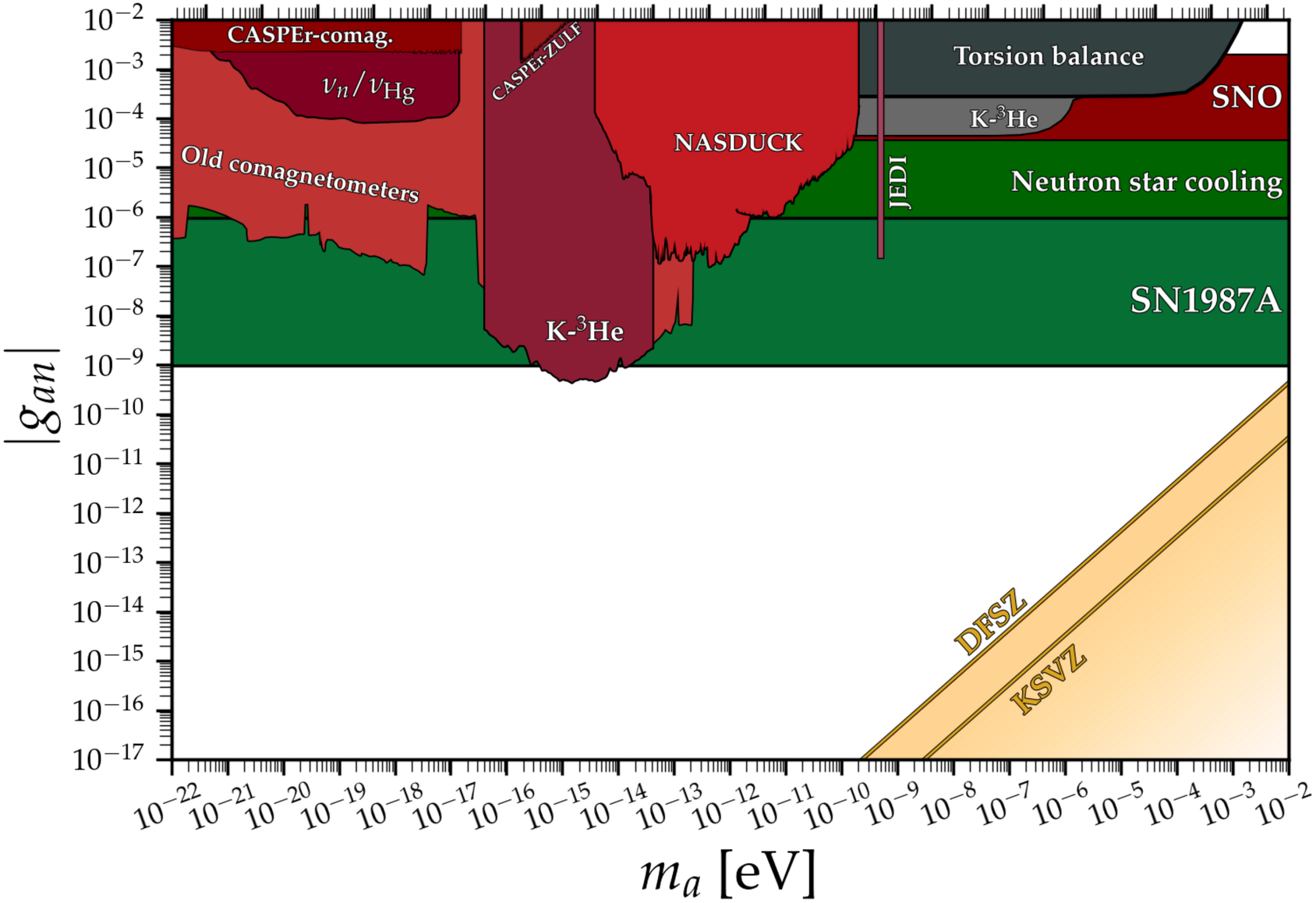
10^{-6}
10^{-5}
10^{-4}

Dark photon mass [eV]

Enough photons

Back to axions… fermion couplings, e.g. neutron

→ Hard to beat astrophysical bounds



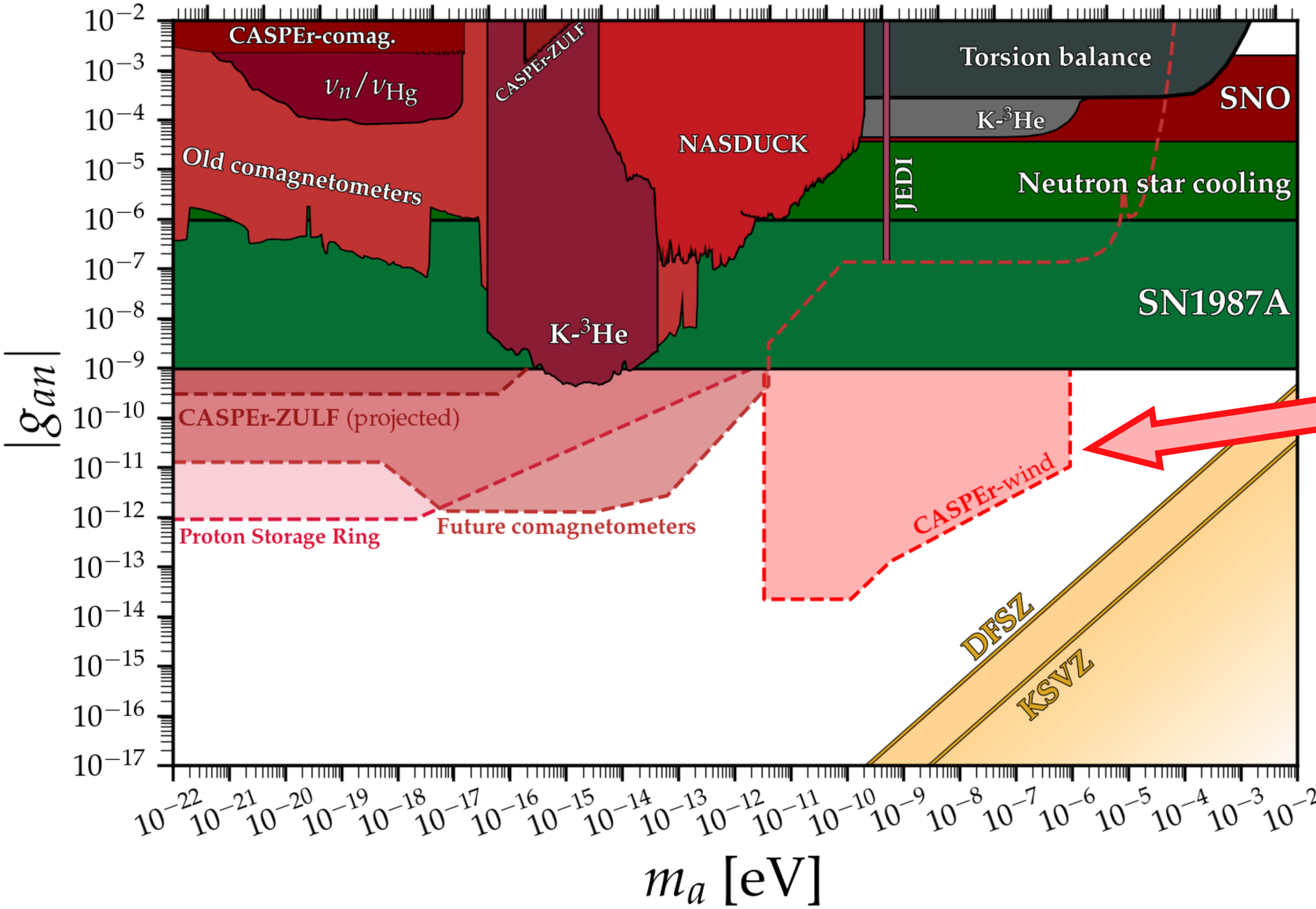
Why?

$$\mathcal{L} = -\frac{g_{an}}{2m_n}\partial_\mu a\,\underbrace{\bar{n}\gamma^5\gamma^\mu n}_{\text{Spin-dependent}}$$

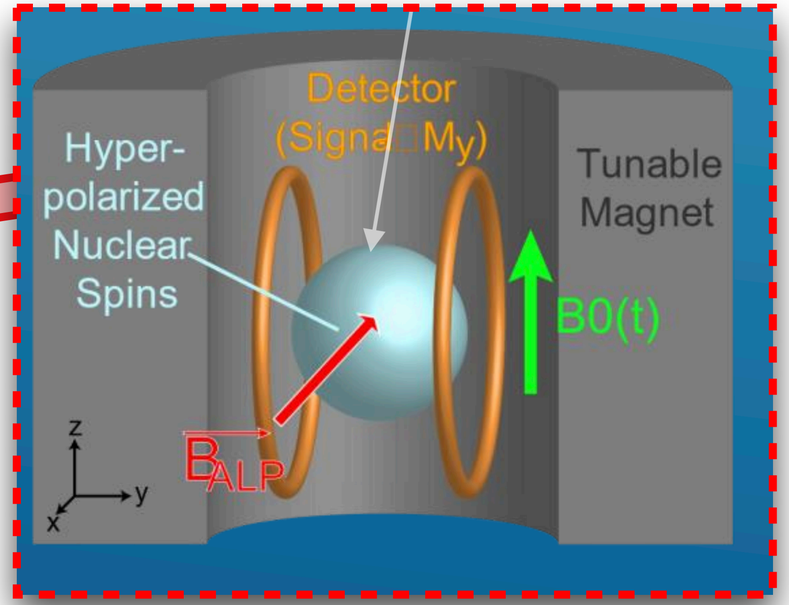
Hard to get large-enough samples of spin-polarised materials to compete with a star

Back to axions… fermion couplings, e.g. neutron

→ Hard to beat astrophysical bounds

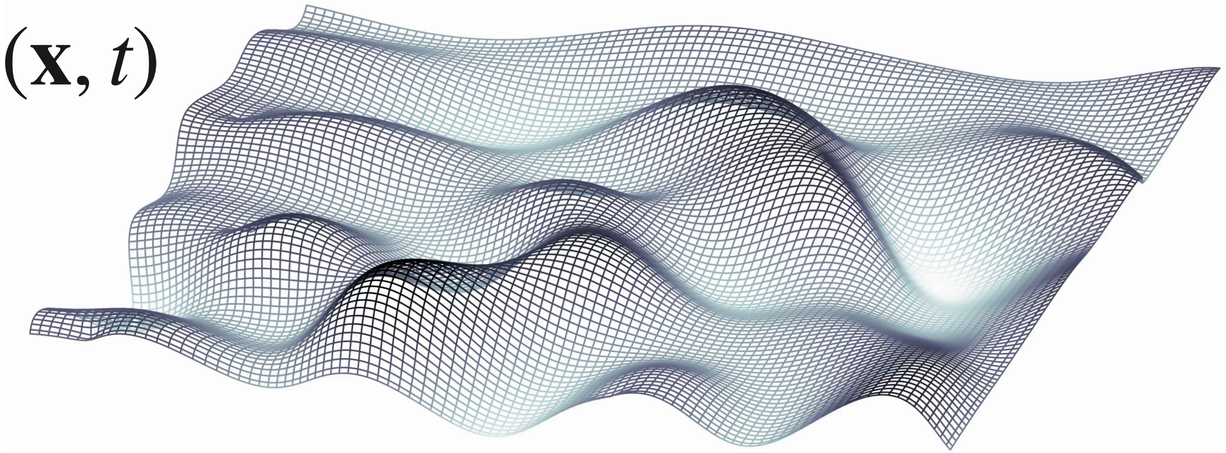


CASPEr-wind



An easier path… Scalar dark matter

$\phi(\mathbf{x}, t)$



$$\mathcal{L} = \cdots + \frac{1}{4} g_\gamma \phi(\mathbf{x}, t) F_{\mu\nu} F^{\mu\nu} - g_\psi \phi(\mathbf{x}, t) \bar{\psi} \psi$$

Interaction looks like a mass term

→ e.g. time-varying electron mass

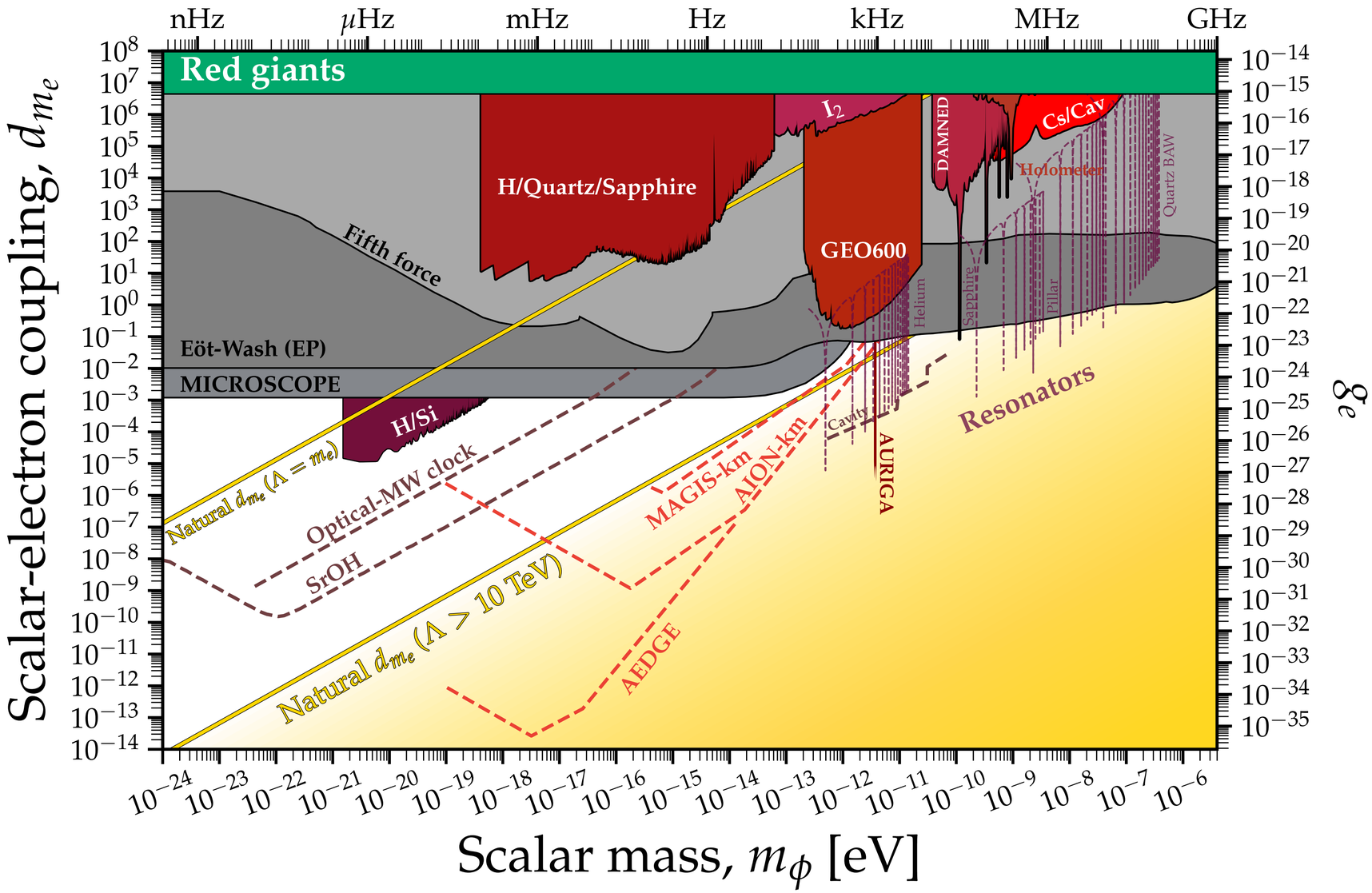
Scalar dark matter constraints

Two problems:

→ hard to beat laboratory fifth-force constraints

→ A "natural" theory with a UV cutoff at $\Lambda_{\rm Nat}$ must have:

$$g_e \lesssim \frac{4\pi m_\phi}{\Lambda_{\rm Nat}}$$

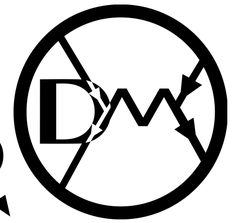


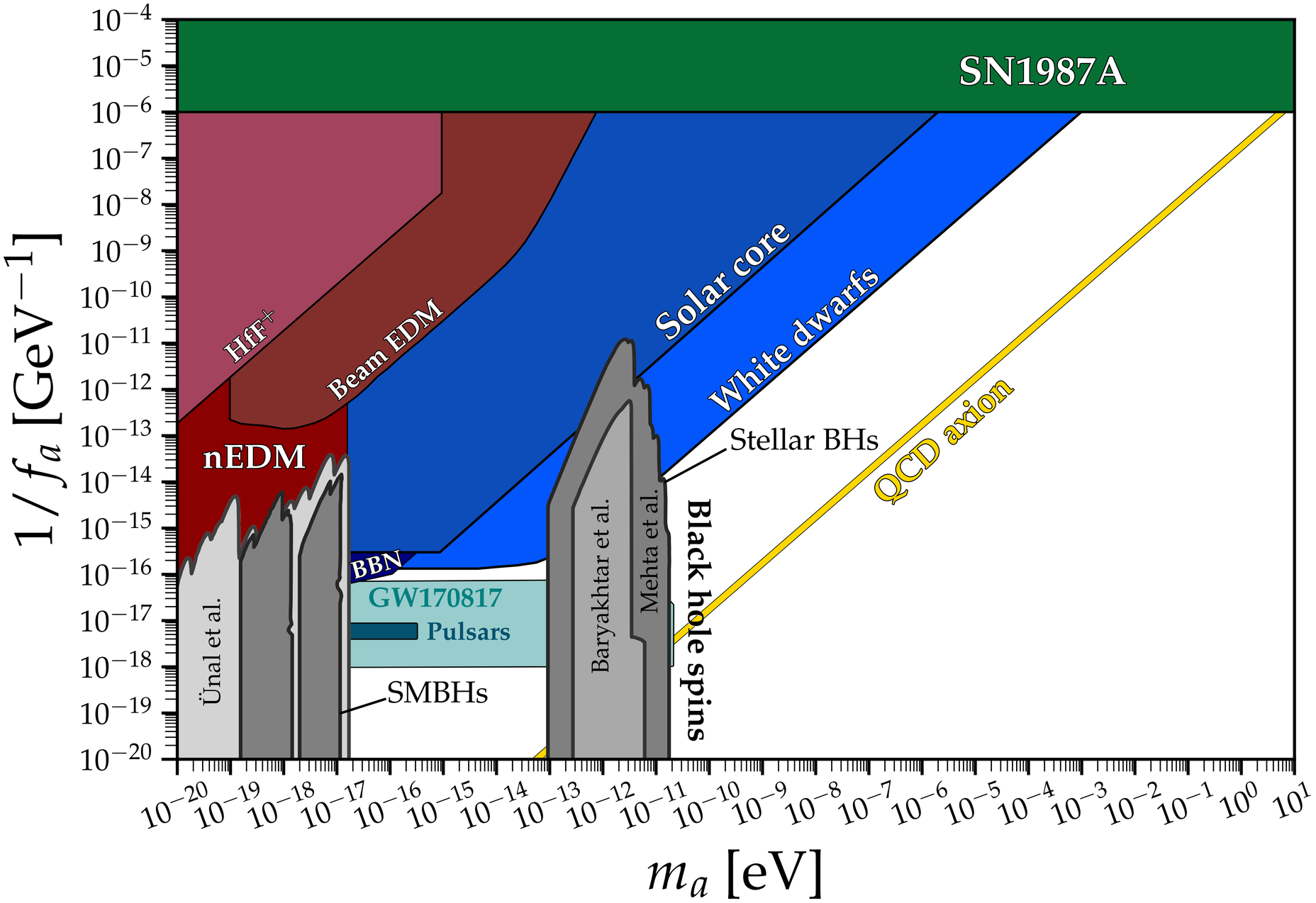
Summary

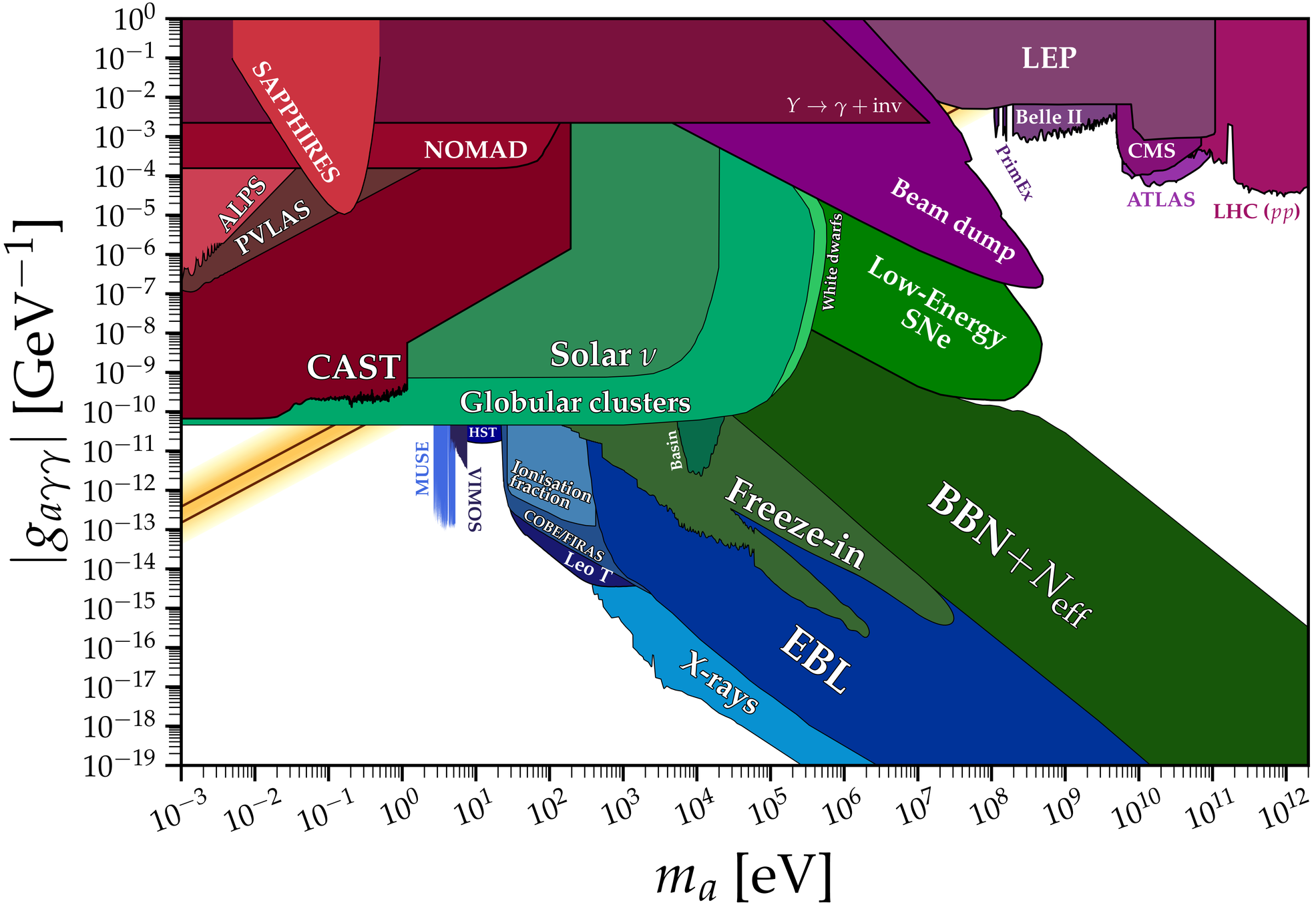
- Wave

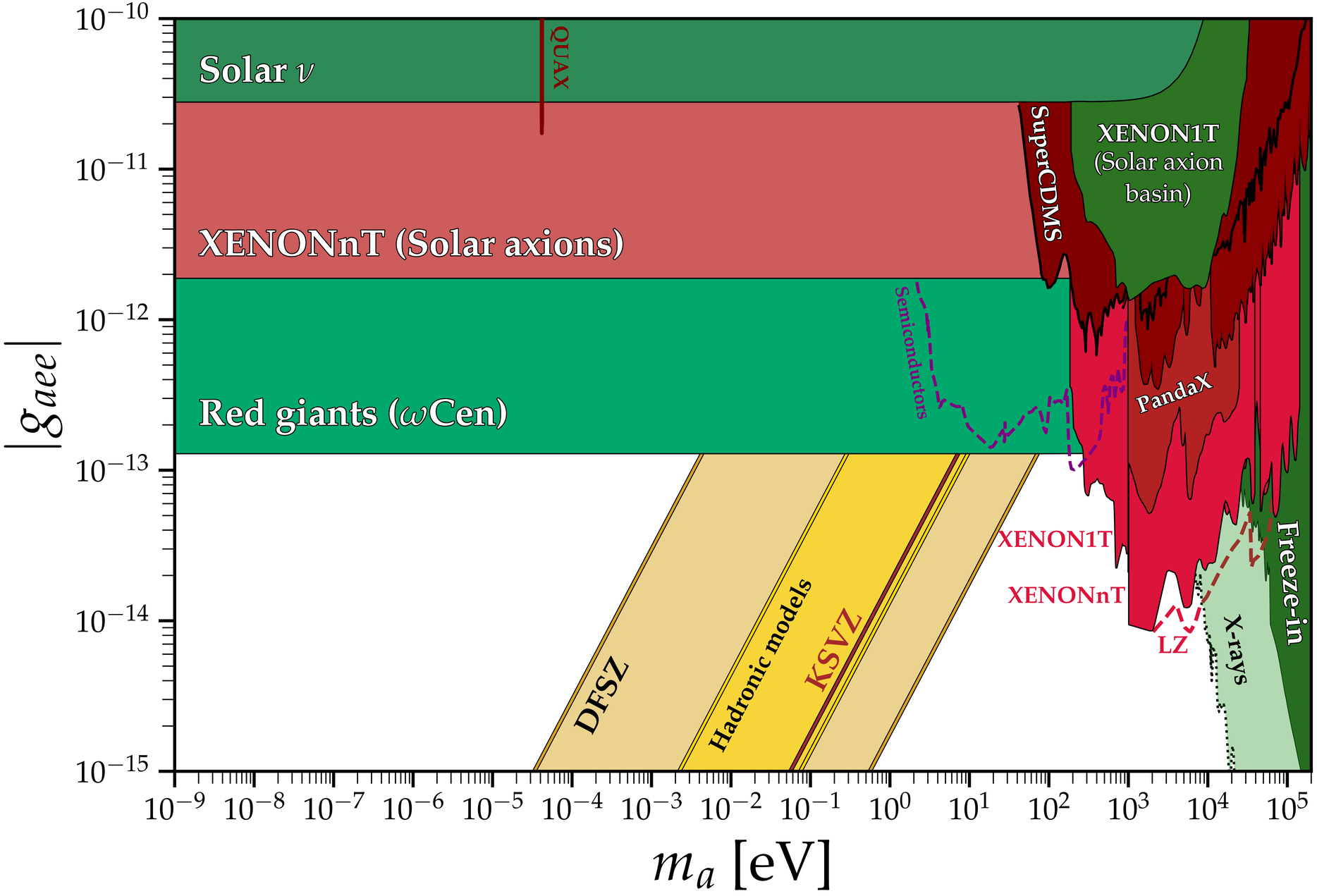
THE UNIVERSITY OF SYDNEY

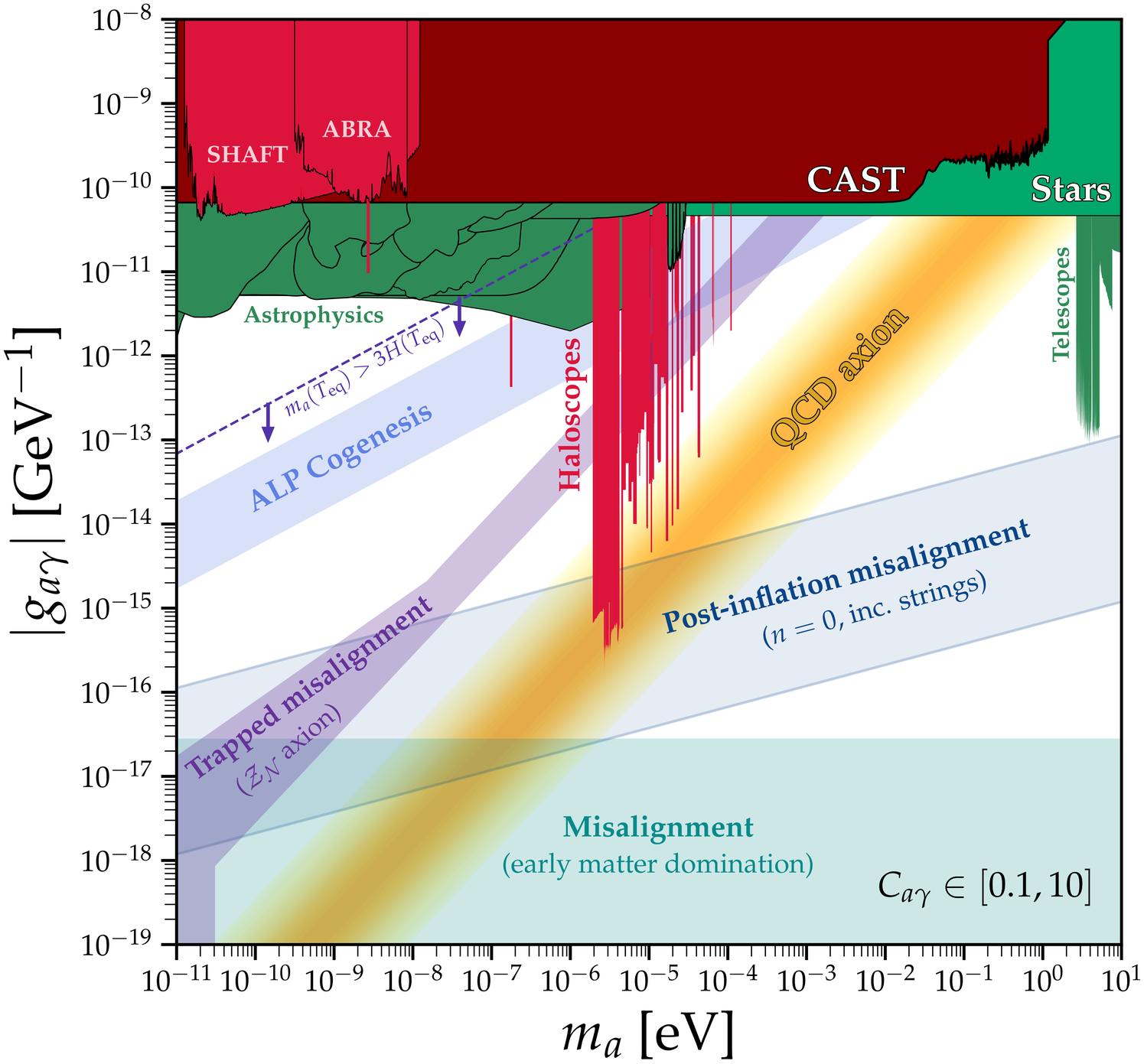
ARC CENTRE OF EXCELLENCE FOR DARK MATTER

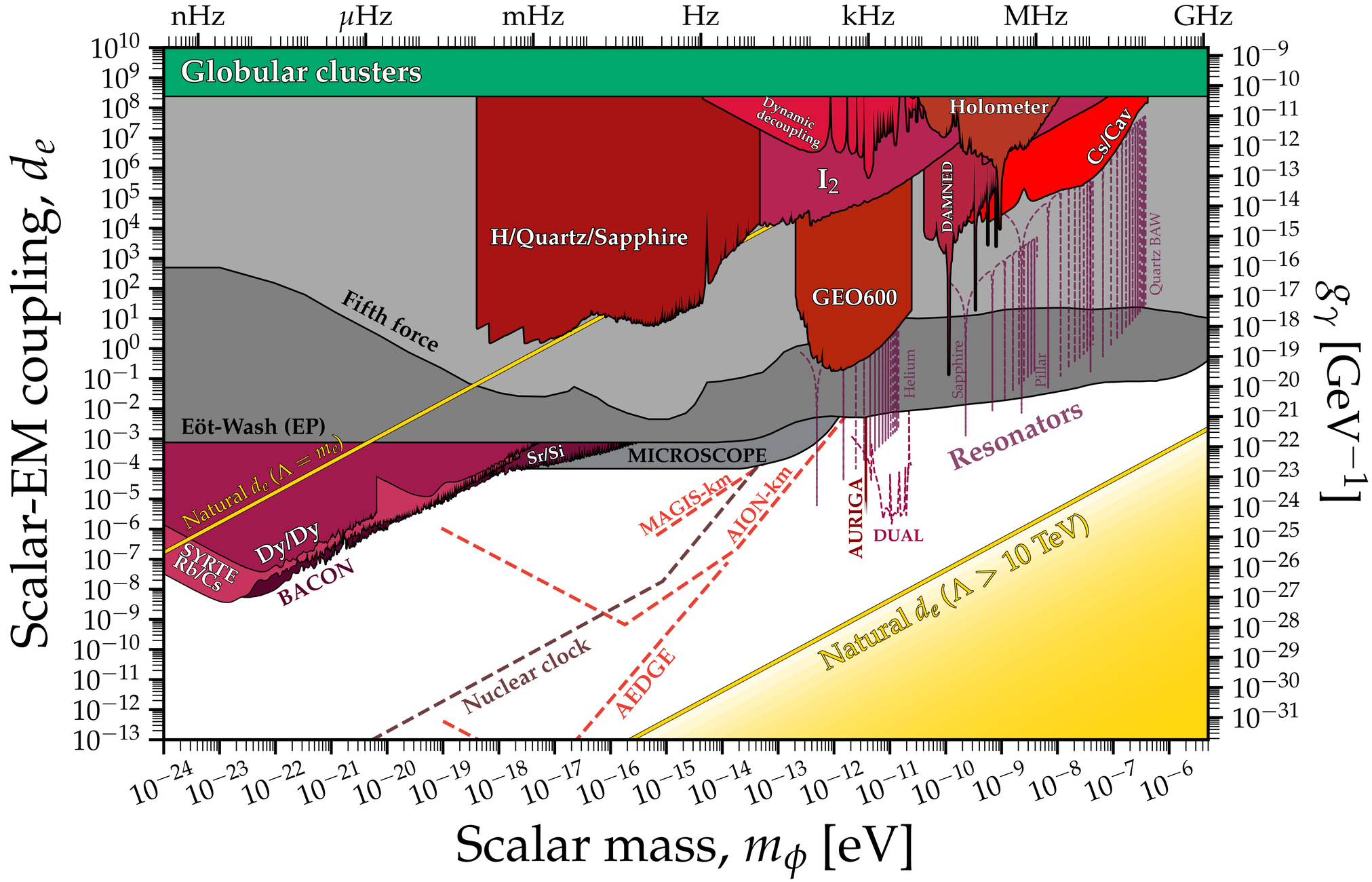


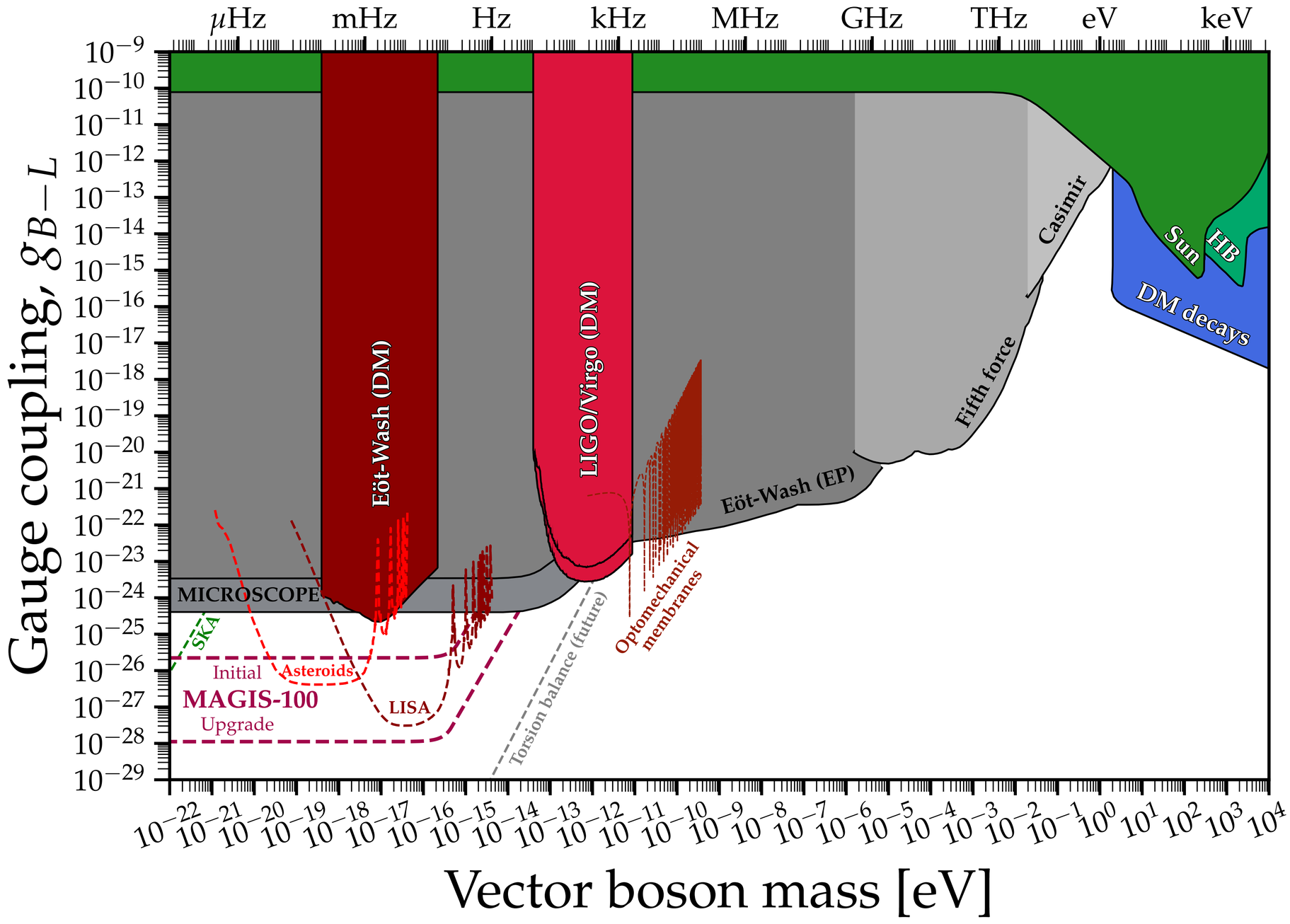

SN1987A
HfF+
Beam EDM
nEDM
Solar core
White dwarfs
Stellar BHs
QCD axion
BBN
GW170817
Pulsars
SMBHs
Ünal et al.
Baryakhtar et al.
Mehta et al.
Black hole spins
$1/f_a$ [GeV^{-1}]
m_a [eV]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-20} 10^{-19} 10^{-18} 10^{-17} 10^{-16} 10^{-15} 10^{-14} 10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}


LEP
$\Upsilon \to \gamma + \text{inv}$
Belle II
PrimEx
CMS
ATLAS
LHC (pp)
SAPPHIRES
NOMAD
ALPS
PVLAS
Beam dump
White dwarfs
Low-Energy SNe
CAST
Solar ν
Globular clusters
HST
MUSE
VINOS
Ionisation fraction
Basin
COBE/FIRAS
Leo T
Freeze-in
BBN+N_{eff}
EBL
X-rays
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]


Solar ν
QUAX
XENONnT (Solar axions)
SuperCDMS
XENON1T
(Solar axion
basin)
Red giants (ωCen)
Semiconductors
PandaX
XENON1T
XENONnT
LZ
X-rays
Freeze-in
DFSZ
Hadronic models
KSVZ
$|g_{aee}|$
m_a [eV]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}


SHAFT
ABRA
CAST
Stars
Astrophysics
Telescopes
$m_a(T_{\rm eq}) > 3H(T_{\rm eq})$
ALP Cogenesis
Haloscopes
QCD axion
Post-inflation misalignment
($n = 0$, inc. strings)
Trapped misalignment
(Z_N axion)
Misalignment
(early matter domination)
$C_{a\gamma} \in [0.1, 10]$
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}

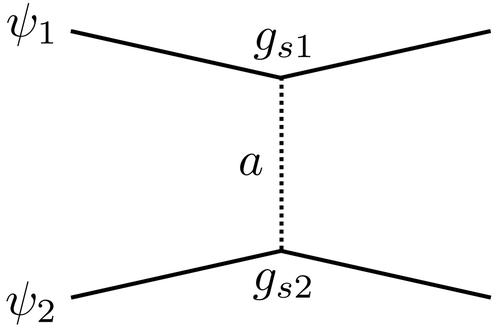

nHz
μHz
mHz
Hz
kHz
MHz
GHz
Globular clusters
Holometer
Dynamic decoupling
I2
Cs/Cav
DAMNED
H/Quartz/Sapphire
GEO600
Quartz BAW
Fifth force
Helium
Sapphire
Pillar
Eöt-Wash (EP)
Sr/Si
MICROSCOPE
Natural de (Λ = me)
Resonators
MAGIS-km
AION-km
AURIGA
DUAL
Dy/Dy
SYRTE Rb/Cs
BACON
Nuclear clock
AEDGE
Natural de (Λ > 10 TeV)
Scalar-EM coupling, de
gγ [GeV−1]
Scalar mass, mϕ [eV]


μHz
mHz
Hz
kHz
MHz
GHz
THz
eV
keV
Gauge coupling, g_{B-L}
Vector boson mass [eV]
Eöt-Wash (DM)
LIGO/Virgo (DM)
Casimir
Sun
HB
DM decays
Fifth force
Eöt-Wash (EP)
MICROSCOPE
SKA
Initial
Asteroids
MAGIS-100
Upgrade
LISA
Torsion balance (future)
Optomechanical membranes

Pure laboratory tests of axion-fermion fifth forces

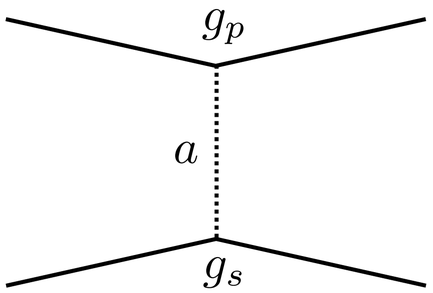
Key point: any SM or BSM CP-violation (could be e.g. size of Jarlskog invariant of CKM matrix) could shift axion vev and generate **CP-violating** axion-fermion couplings in addition to the **CP-conserving** ones

$$\mathcal{L} \supset -a \sum_{\psi} g_p^{\psi} \left(i\bar{\psi}\gamma^5\psi \right) - a \sum_{\psi} g_s^{\psi} (\bar{\psi}\psi)$$



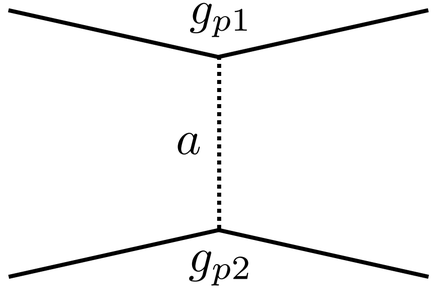
Monopole-monopole (Spin independent)

→ e.g. tests of inverse square law/WEP



Monopole-dipole (Spin dependent)

→ Spin-mass forces e.g. ARIADNE/QUAX



Dipole-dipole (Spin dependent)

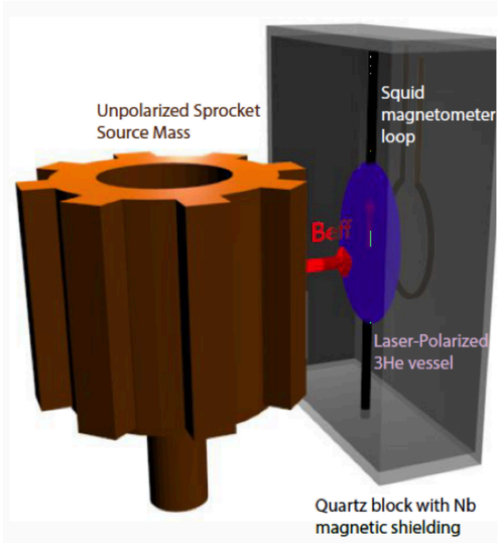
→ Forces between spin-polarised samples

Monopole-dipole searches

Conceptually similar, spin an unpolarised source mass near to a spin-polarised target

ARIADNE

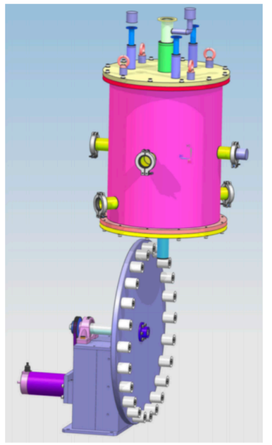
Constrains: g_p g_s (nucleon-nucleon)



QUAX

Constrains: g_p g_s (electron-nucleon)

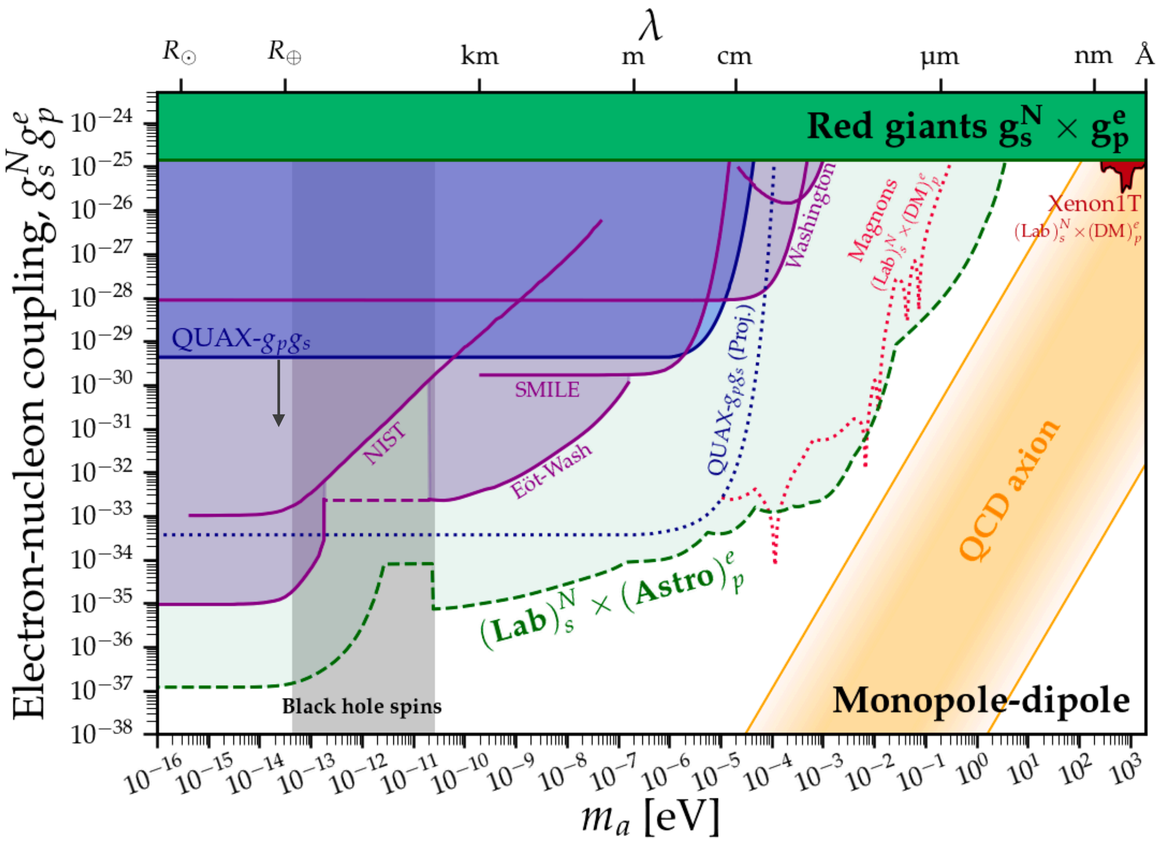
(Latest QUAX result **2011.07100)**



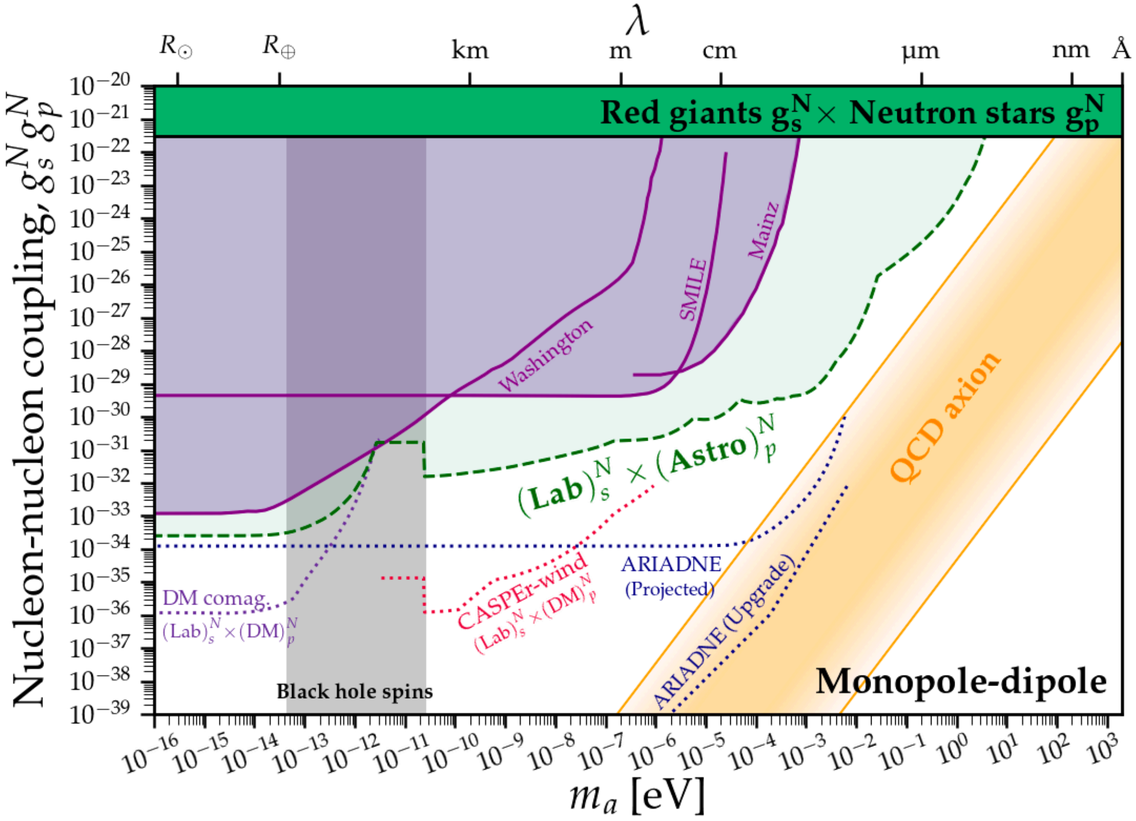
Challenge: stellar bounds tightly constrain g_p, and spin independent fifth force tests easily constrain g_s: so Astro x Lab bound on these coupling combos are very strong

Pure laboratory tests for monopole-dipole axion-mediated forces

Electron-nucleon coupling



Nucleon-nucleon coupling



Hard to beat the astrophysical bounds, but **ARIADNE** projects that it will

O'Hare & Vitagliano [2010.03889]

CP violation and the neutron electric dipole moment

Theory: Vacuum structure of QCD (instantons) generates a term

$$\mathcal{L}_{\rm QCD} = \ldots - \frac{\alpha_s}{8\pi}\theta_{\rm QCD} G_{\mu\nu a}\widetilde{G}^{\mu\nu}_a$$

Some angle, not fixed by theory, so presumably $\mathcal{O}(1)$

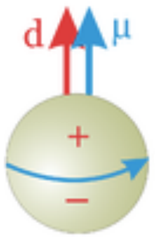
Experiment: $\theta_{\rm QCD}$ observable but bundled with phase from quark masses

$$\bar{\theta} = \theta_{\rm QCD} + \theta_q$$

Where it sets the electric dipole moment of the neutron

$$d_n = (2.4 \pm 1.0)\bar{\theta} \times 10^{-3}\, e\,\text{fm}$$

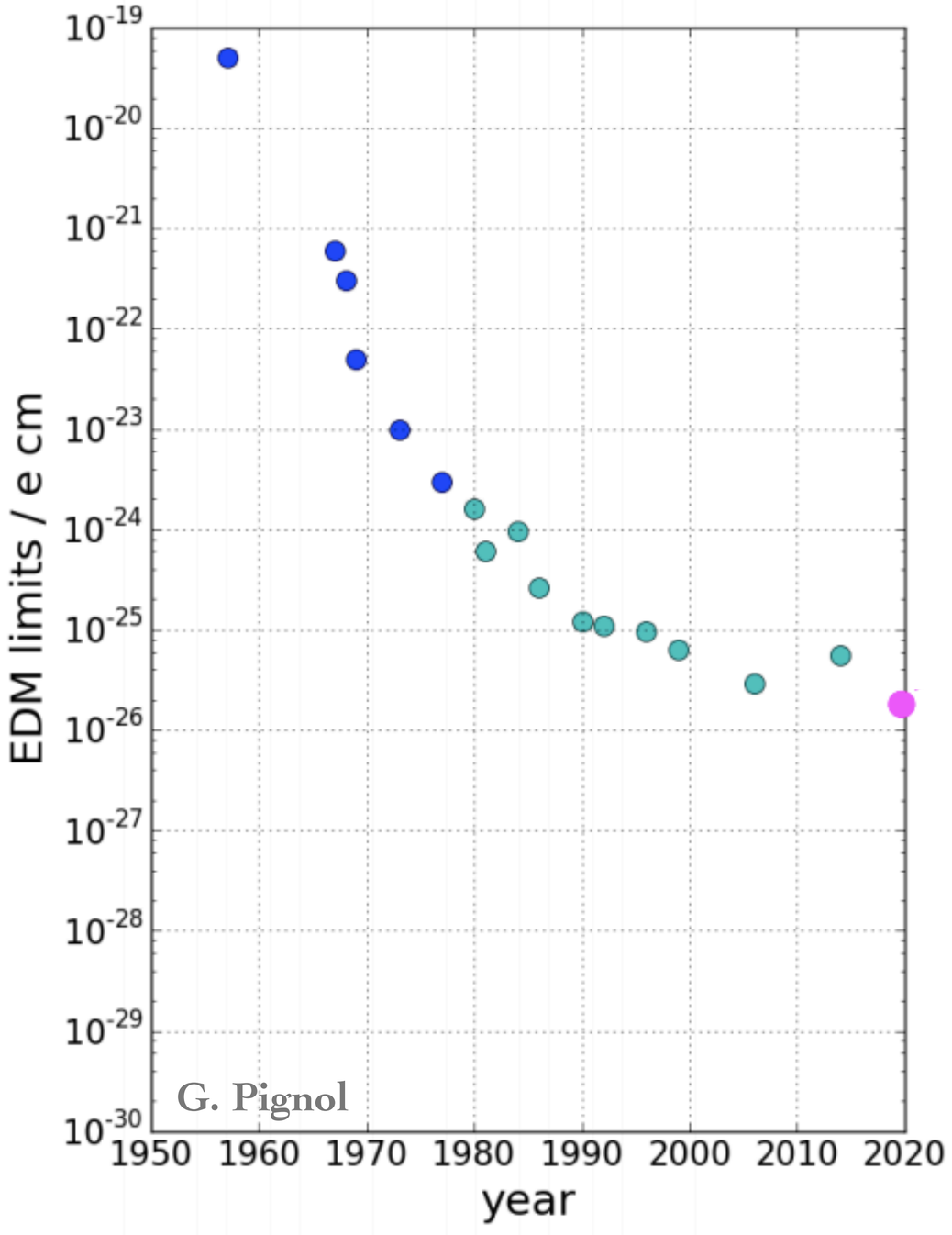
Put some spin-polarised neutrons in E, B fields → Measure spin precession frequencies → Calculate neutron EDM → Measure Fundamental parameter of SM



$$\nu_\pm = 2|\mu_n B \pm d_n E|$$

$$d_n$$

$$\theta_{\rm QCD}$$



What do they see?

Recent measurement [2001.11966]

$$|d_n| < 1.8 \times 10^{-26}\, e\,\mathrm{cm} \quad (90\%\ \mathrm{CL})$$

$$\Rightarrow \theta \lesssim 10^{-10}$$

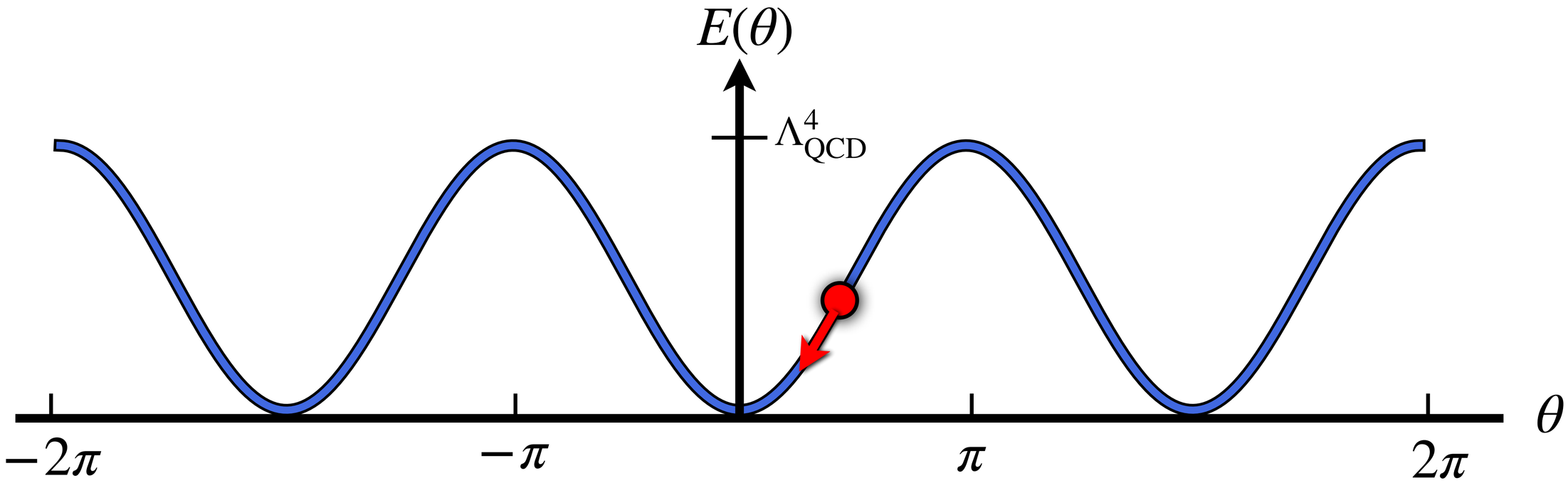
Conclusion: The strong interaction seems to be conserving CP when it generically shouldn't
→ **The strong CP problem**

↓

The real problem: why are two completely unrelated numbers cancelling each other < ppb?

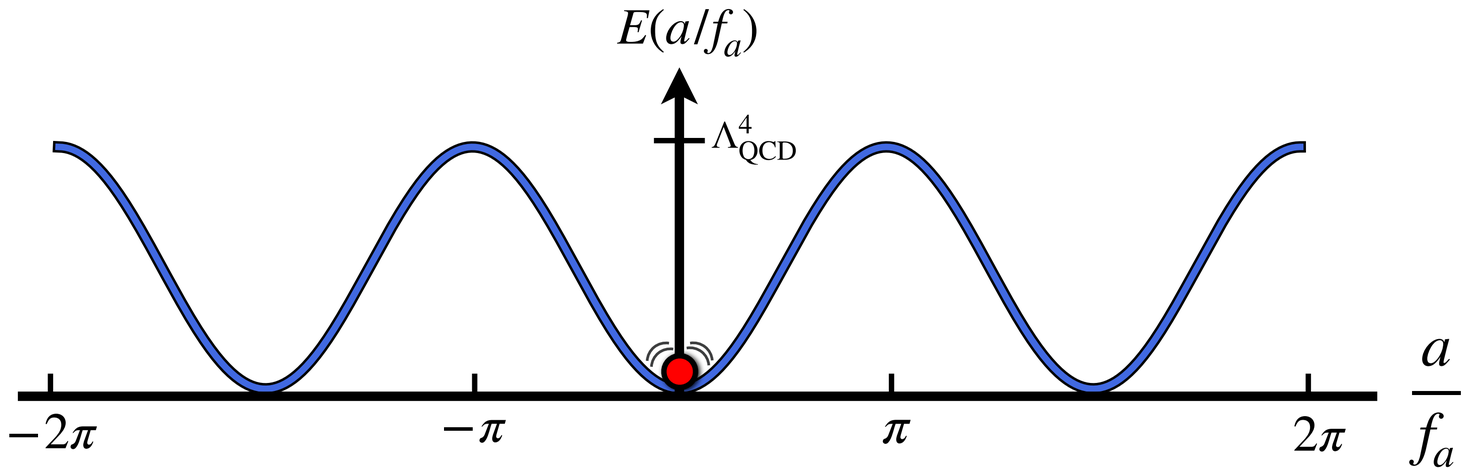
The solution, a la Peccei-Quinn

QCD vacuum energy density already has a minimum at $\theta = 0$ (Vafa-Witten theorem). However θ is just a parameter, there is no mechanism to cause it to want to minimise energy



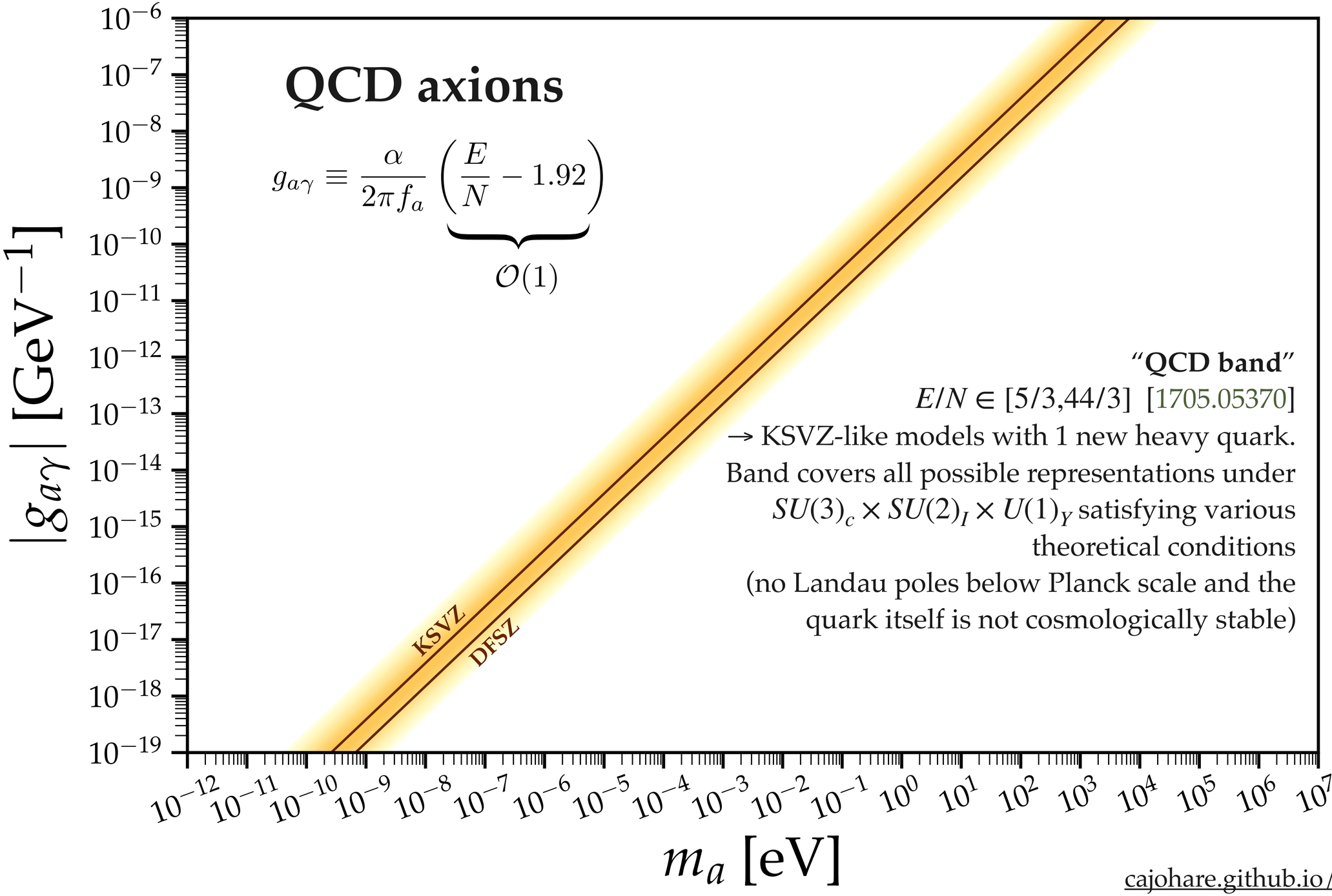
PQ mechanism: what if there was?

The axion

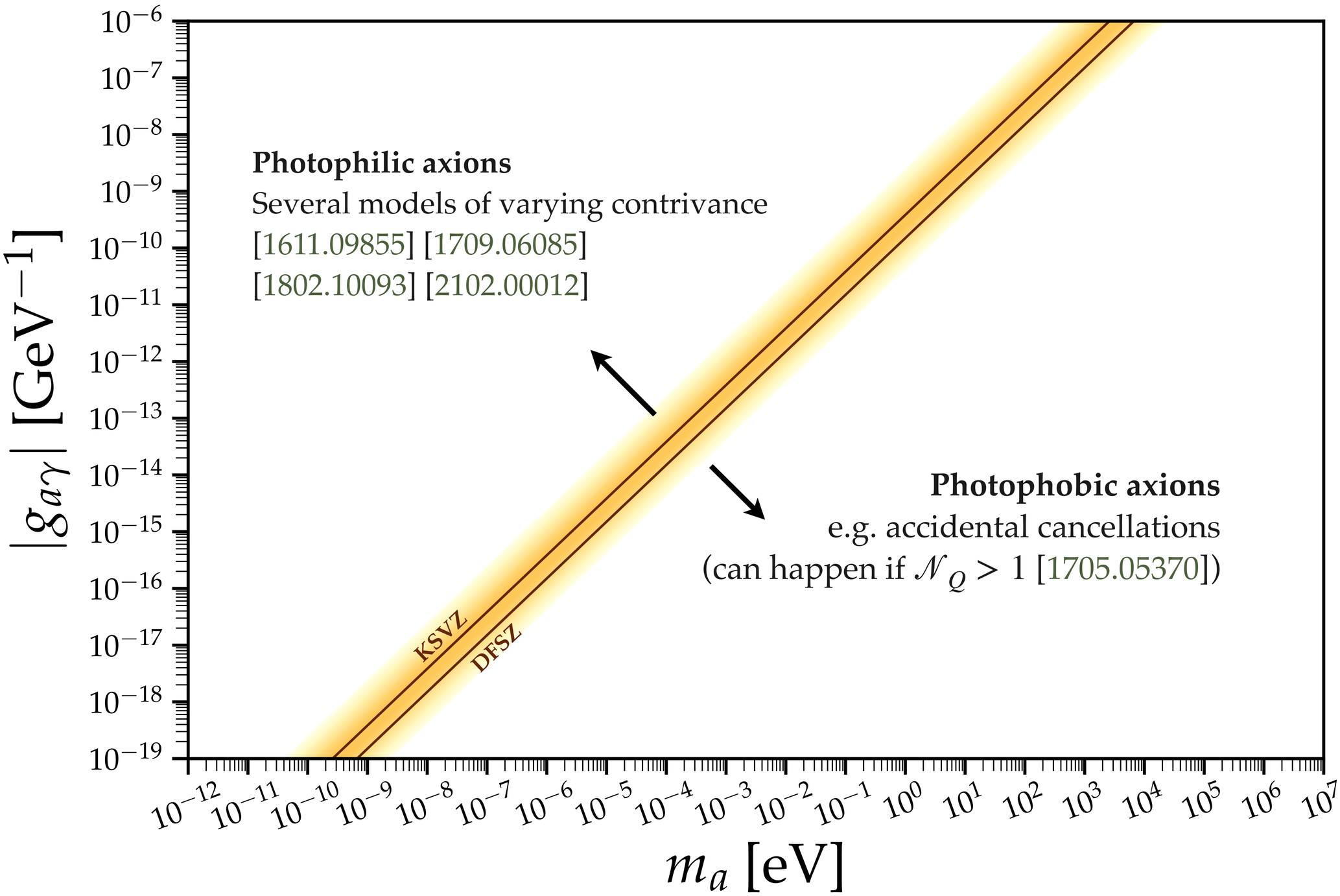


- Introduce field, a, that couples to gluons $\propto (a/f_a)\, G\tilde{G}$. It will have a shift symmetry that can be used to cancel off any unwanted CP violation while VW theorem ensures $\langle a \rangle = 0$
- QCD vacuum implies a potential for the axion and thus a small mass

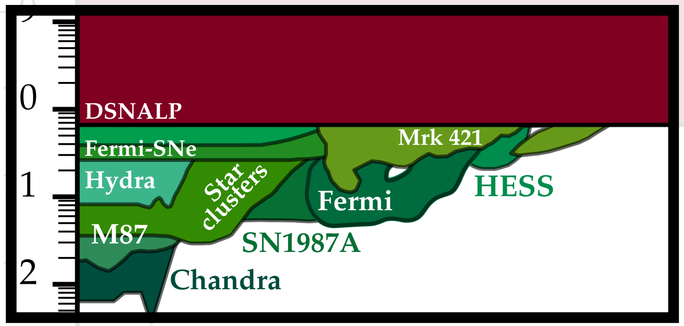
$$V(a) \approx \Lambda^4_{\rm QCD}\left[1 - \cos\left(\bar{\theta} + \frac{a}{f_a}\right)\right] \longrightarrow m_a \simeq \frac{\Lambda^2_{\rm QCD}}{f_a} \simeq 6\,{\rm meV}\left(\frac{10^9 {\rm GeV}}{f_a}\right)$$

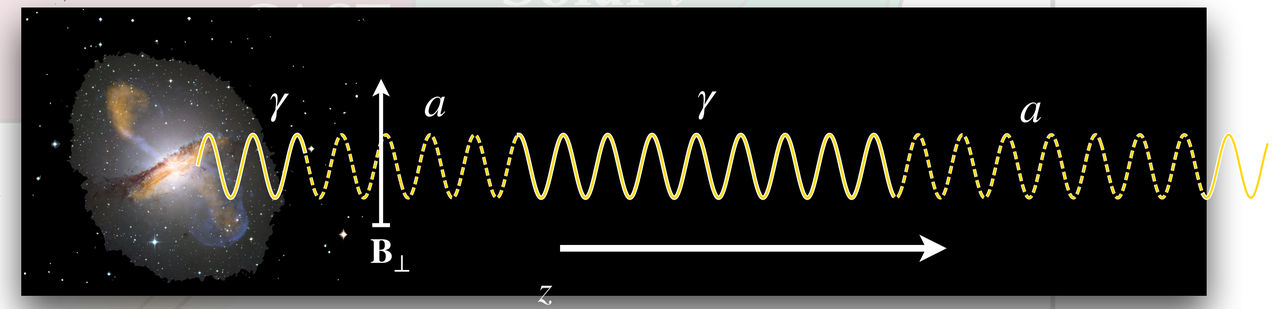


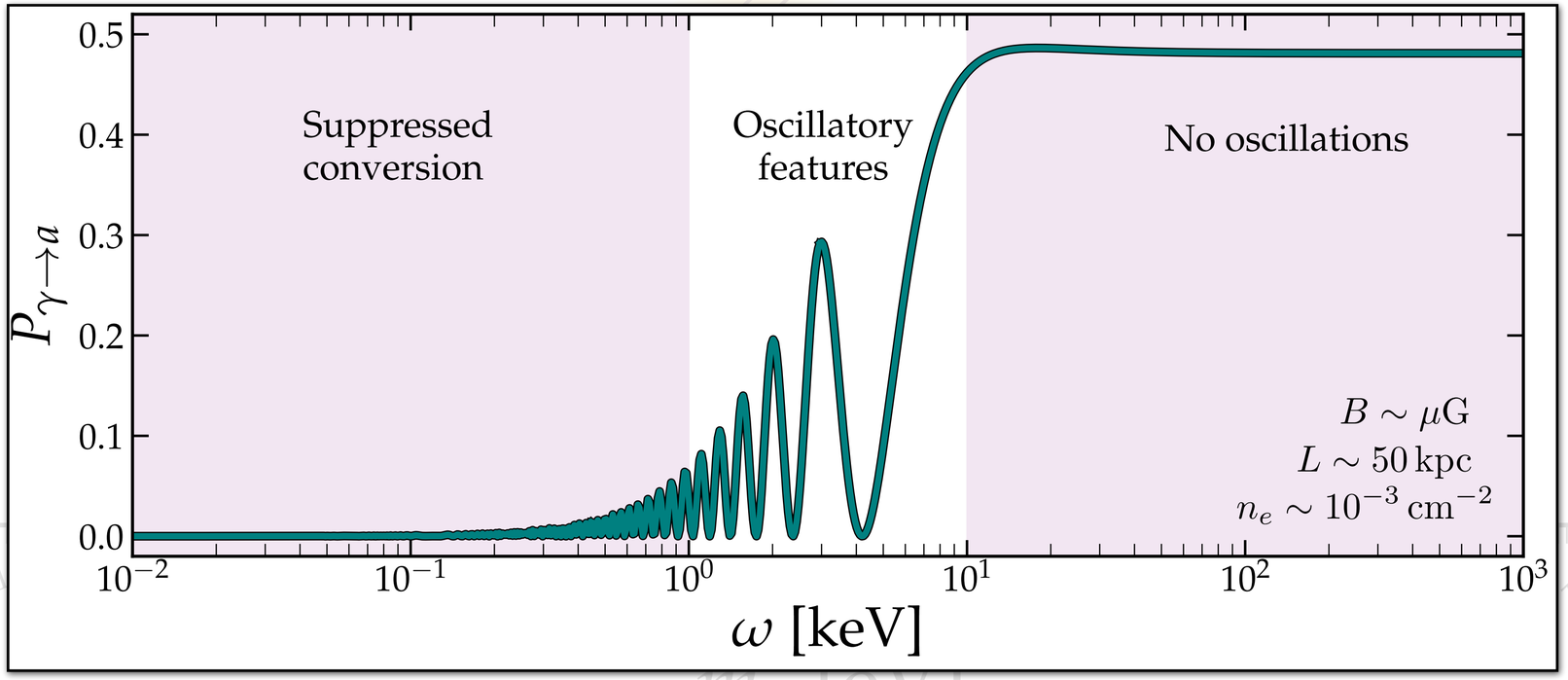
cajohare.github.io/AxionLimits/


$|g_{a\gamma}|$ [GeV^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
Photophilic axions
Several models of varying contrivance
[1611.09855] [1709.06085]
[1802.10093] [2102.00012]
KSVZ
DFSZ
Photophobic axions
e.g. accidental cancellations
(can happen if $\mathcal{N}_Q > 1$ [1705.05370])
10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
m_a [eV]

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





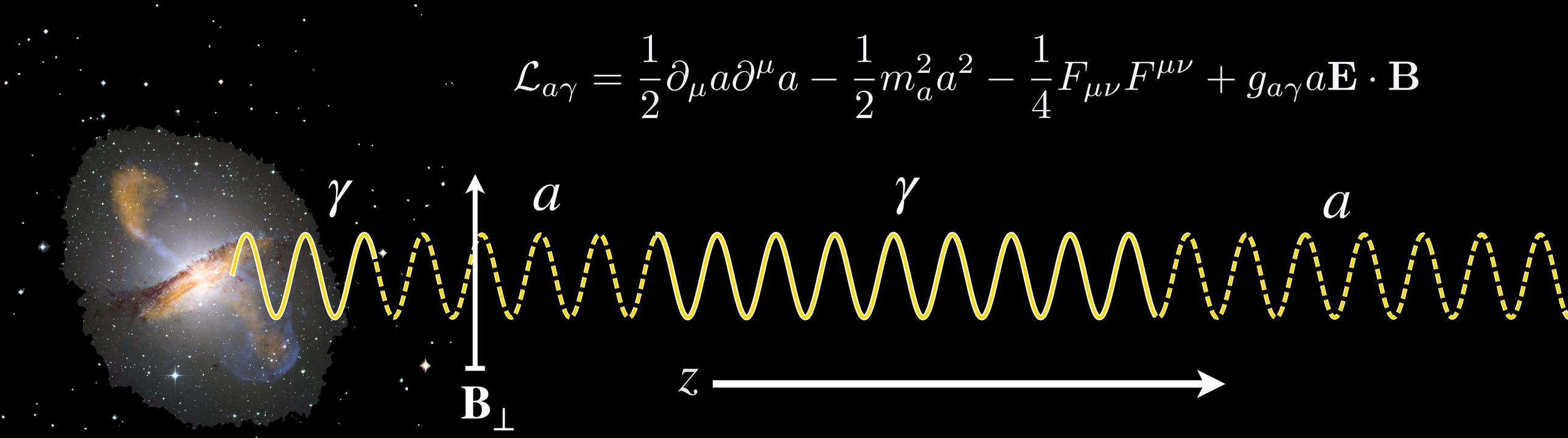


cajohare.github.io/AxionLimits/

Photon-axion mixing in a B-field

Raffelt & Stodolsky 1988
(https://inspirehep.net/literature/253874)

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

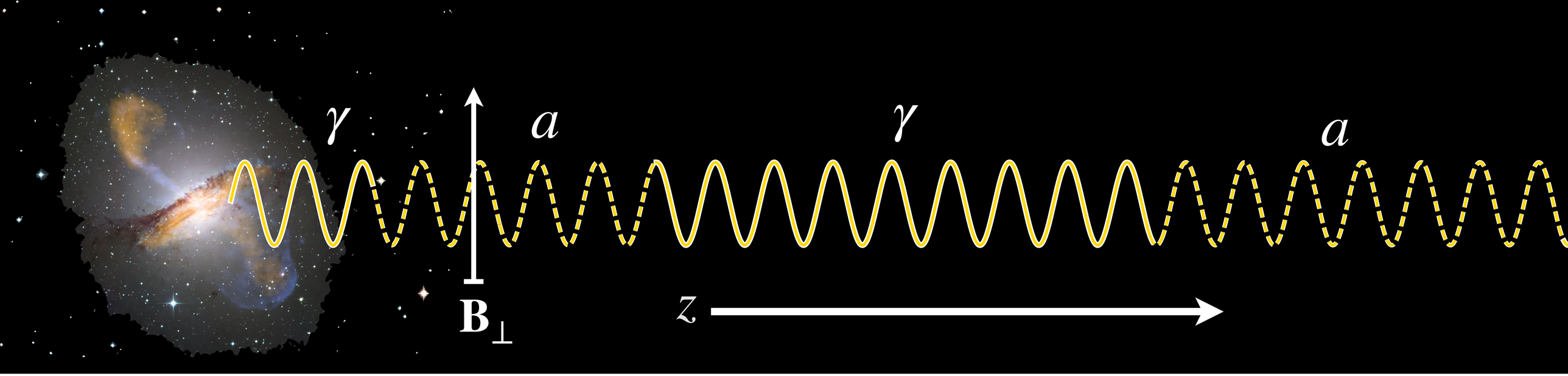


Linearised wave equation for photon-axion mixing

$$\left(\omega + \begin{pmatrix} \Delta_{\rm pl} & 0 & 0 \\ 0 & \Delta_{\rm pl} & \Delta_{\gamma a} \\ 0 & \Delta_{\gamma a} & \Delta_a \end{pmatrix} - i\partial_z\right)\begin{pmatrix} |A_\perp\rangle \\ |A_\parallel\rangle \\ |a\rangle \end{pmatrix} = 0$$

$$\Delta_{\gamma a} = \frac{g_{a\gamma}B_\perp}{2} \qquad \Delta_a = -\frac{m_a^2}{2\omega} \qquad \Delta_{\rm pl} = -\frac{\omega_{\rm pl}^2}{2\omega}$$

Mixing element | Axion mass element | Photon mass element



Axion only mixes with $A_{\parallel}$ so rotate into new basis and solve like neutrino oscillations:

$$\begin{pmatrix} |A'_{\parallel}\rangle \\ |a'\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} |A_{\parallel}\rangle \\ |a\rangle \end{pmatrix}$$

Probability for photon to convert to axion after travelling distance z:

$$|\langle\gamma(0) \mid a(L)\rangle|^2 = P_{a\to\gamma} = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos(2\theta)}\right)$$

Where,

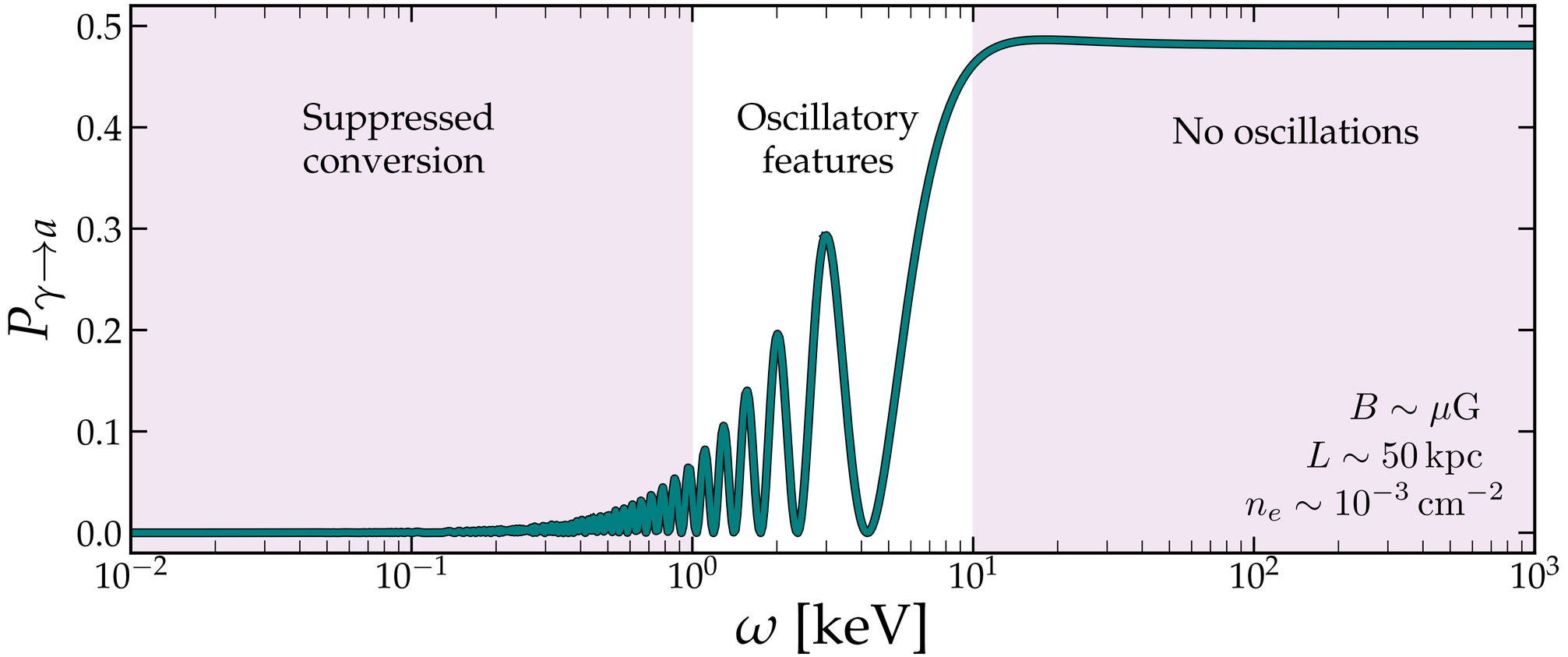
$$\theta = \frac{1}{2}\arctan\left(\frac{2\Delta_{\gamma a}}{\Delta_{\rm pl} - \Delta_a}\right) \qquad \Delta = \frac{|m_a^2 - \omega_{\rm pl}^2|L}{4\omega}$$

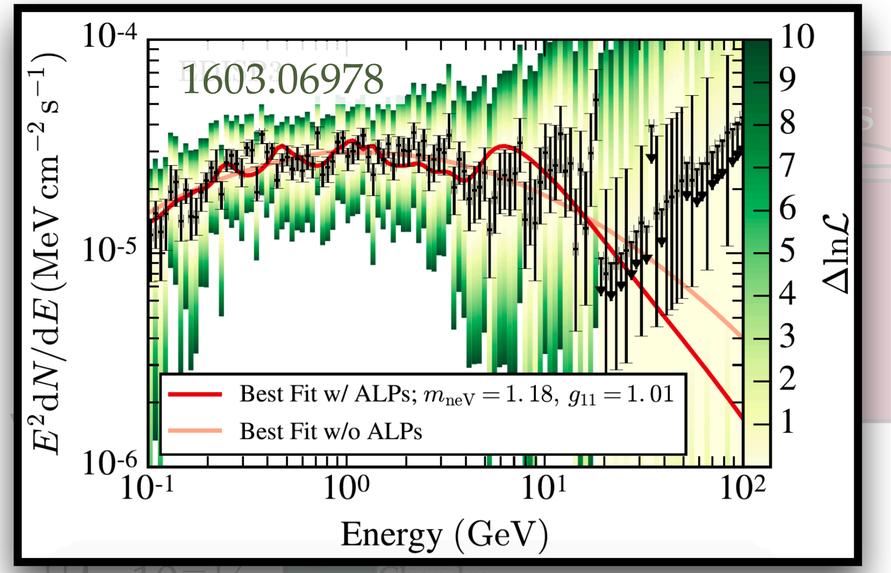
Photon-axion conversion probability

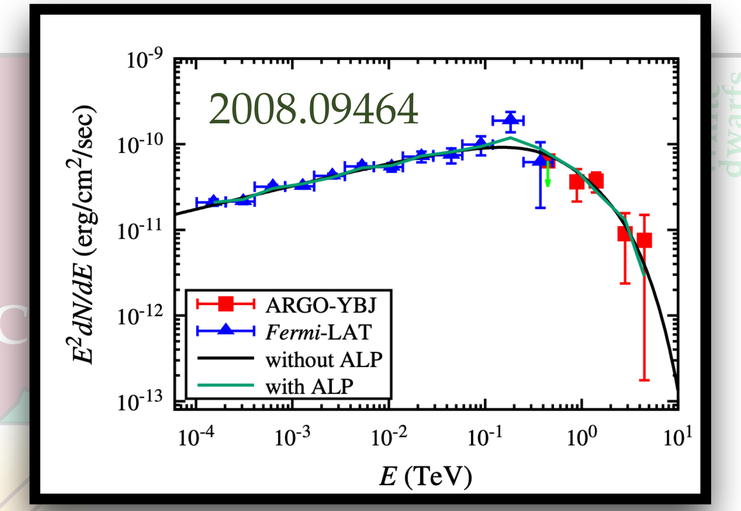
For very light axions, m_a is negligible compared to $\omega_{\rm pl}$

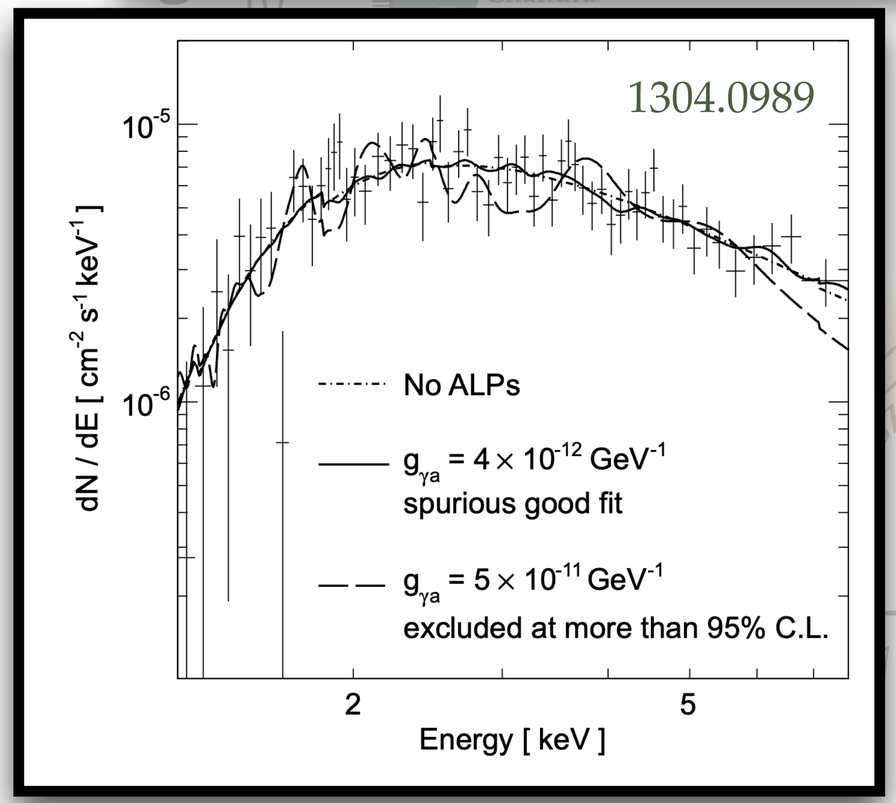
$\rightarrow$ $m_a \lesssim 10^{-12}$ eV for typical astrophysical plasmas $n_e = 10^{-3}$ cm^{-3}

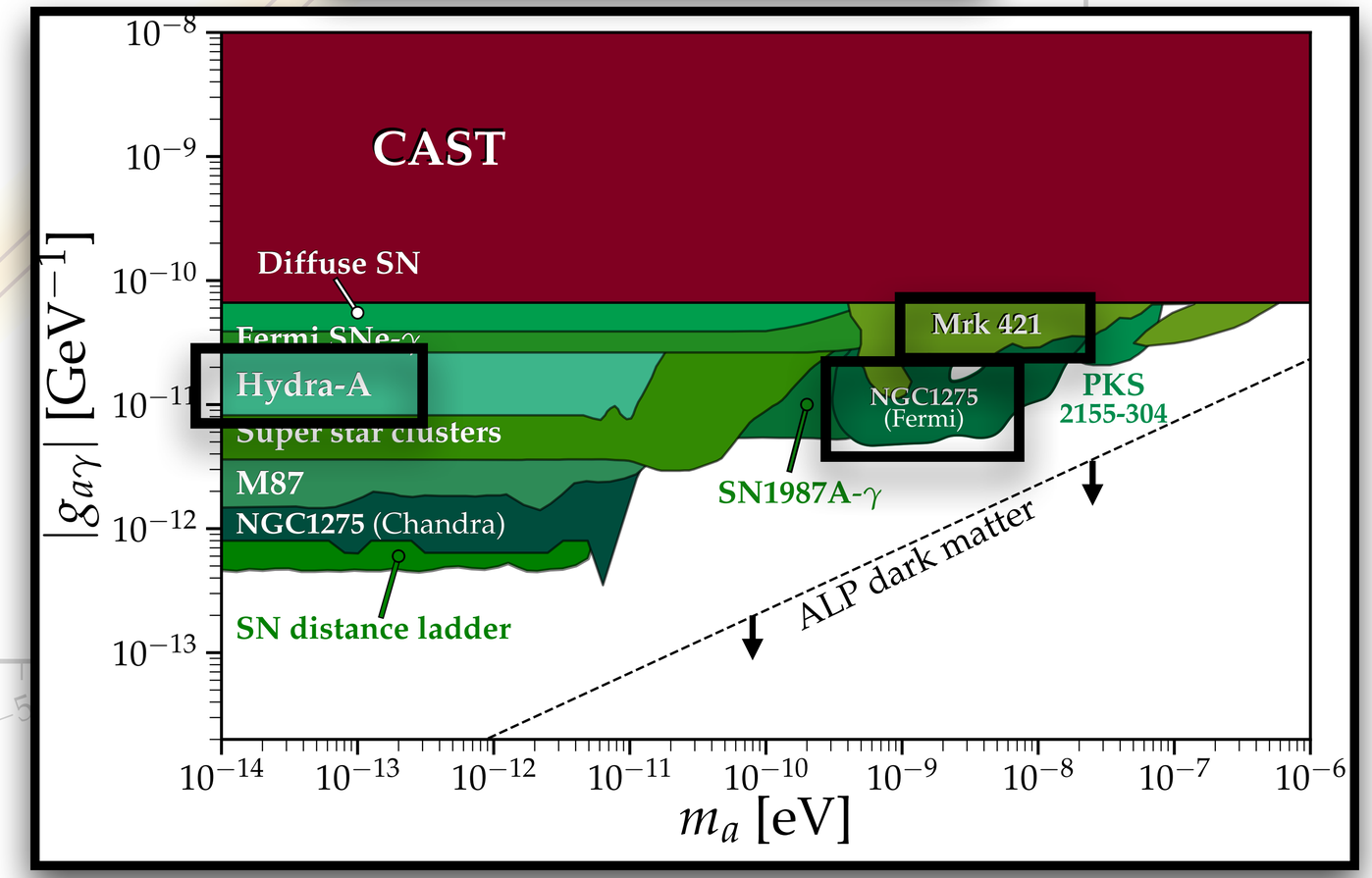
$$\theta \sim g_{a\gamma} \frac{B_\perp \omega}{n_e} \qquad \Delta \sim \frac{n_e L}{\omega}$$




1603.06978
$E^2 \mathrm{d}N/\mathrm{d}E\,(\mathrm{MeV\,cm^{-2}\,s^{-1}})$
$\Delta \ln \mathcal{L}$
Energy (GeV)
Best Fit w/ ALPs; $m_{\mathrm{neV}} = 1.18,\ g_{11} = 1.01$
Best Fit w/o ALPs


2008.09464
$E^2 dN/dE$ (erg/cm^2/sec)
E (TeV)
ARGO-YBJ
Fermi-LAT
without ALP
with ALP


1304.0989
dN / dE [cm^{-2} s^{-1} keV^{-1}]
Energy [keV]
No ALPs
$g_{\gamma a} = 4 \times 10^{-12}$ GeV^{-1}
spurious good fit
$g_{\gamma a} = 5 \times 10^{-11}$ GeV^{-1}
excluded at more than 95% C.L.


CAST
Diffuse SN
Fermi SNe-γ
Hydra-A
Super star clusters
M87
NGC1275 (Chandra)
SN distance ladder
Mrk 421
NGC1275 (Fermi)
PKS 2155-304
SN1987A-γ
ALP dark matter
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]

Key issues to be resolved

Axion dark matter abundance/axion mass

→ Current simulations cannot study the string scaling regime in full due to high required dynamical range, see e.g. [2007.04990]

→ Not clear if the spectrum is dominated by IR modes (meaning large overproduction) or UV modes (Important for predicting the axion mass, see [2108.05368] for recent work with AMR)

Implications of an inhomogeneous axion distribution

→ Formation of gravitationally bound structures "axion miniclusters"

→ Do miniclusters survive to present day? Could be important for direct and indirect searches

→ Can stable axion stars form inside miniclusters? Could there be signals of these e.g. fast radio bursts? May need to solve full SP system to understand this. [1804.05857]