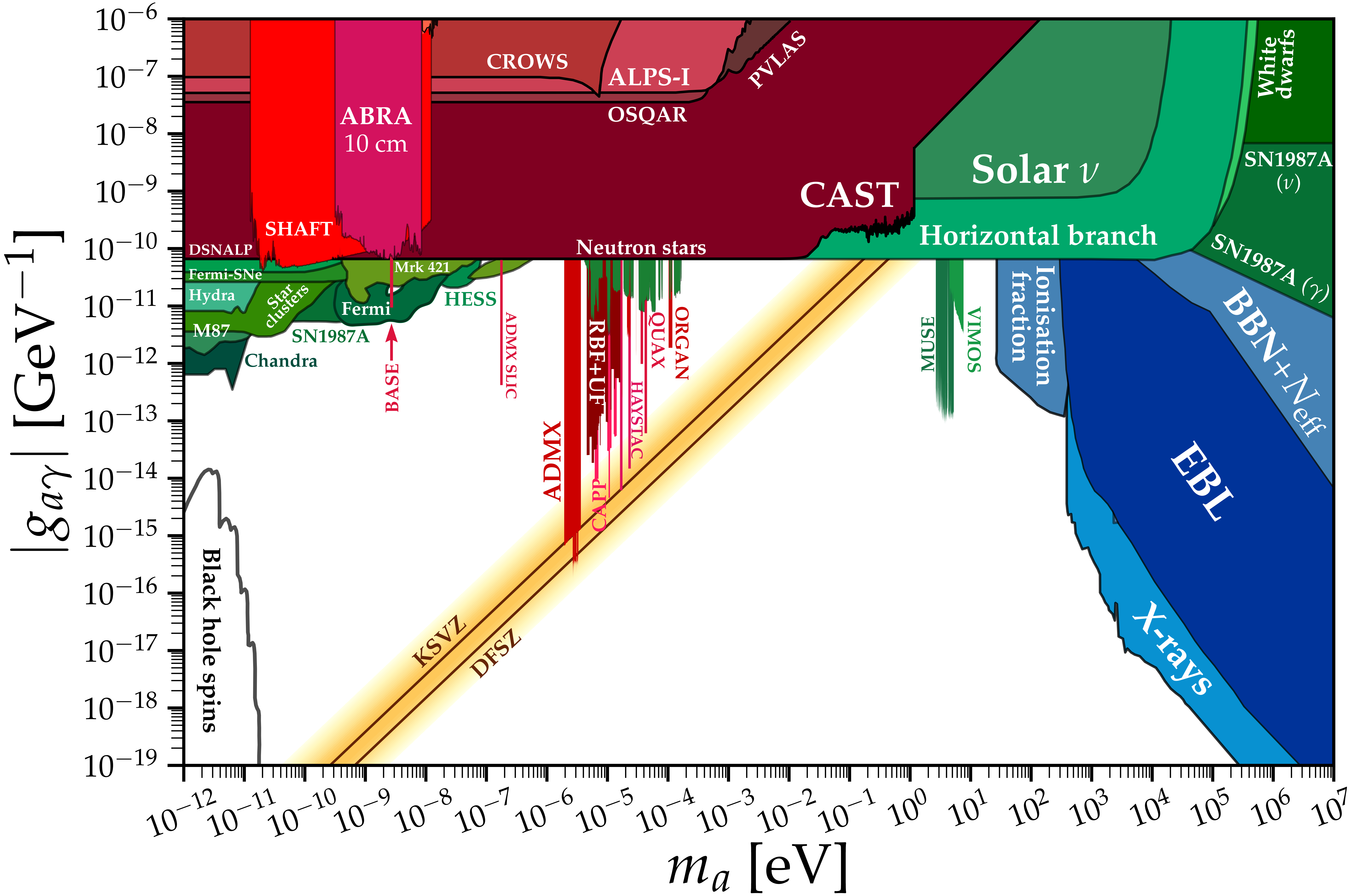
THE UNIVERSITY OF SYDNEY

ARC CENTRE OF EXCELLENCE FOR DARK MATTER

Searches for Axions (2021 edition)

Ciaran O'Hare, U. Sydney

Aim of this talk: explain this busy plot



python code and constraints .txt format can be found at cajohare.github.io/AxionLimits/

The axion, or axion-like particle (ALP)?

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

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

\+ a few model-dependent assumptions

→ Usually pseudo NG boson of spontaneously broken $U(1)_{PQ}$

→ Could solve strong CP problem (= QCD axion)

→ Could be galactic DM

→ Could be produced in astrophysical environments

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For a different day

+ a few model-dependent assumptions

→ Usually pseudo NG boson of spontaneously broken $U(1)_{PQ}$

→ Could solve strong CP problem (= QCD axion)

→ Could be galactic DM

→ Could be produced in astrophysical environments

Coupling to the photon

$$\mathcal{L} = -\frac{1}{4} g_{a\gamma} a(\mathbf{x}, t) F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a(\mathbf{x}, t) \mathbf{E} \cdot \mathbf{B}$$

Coupling to the photon

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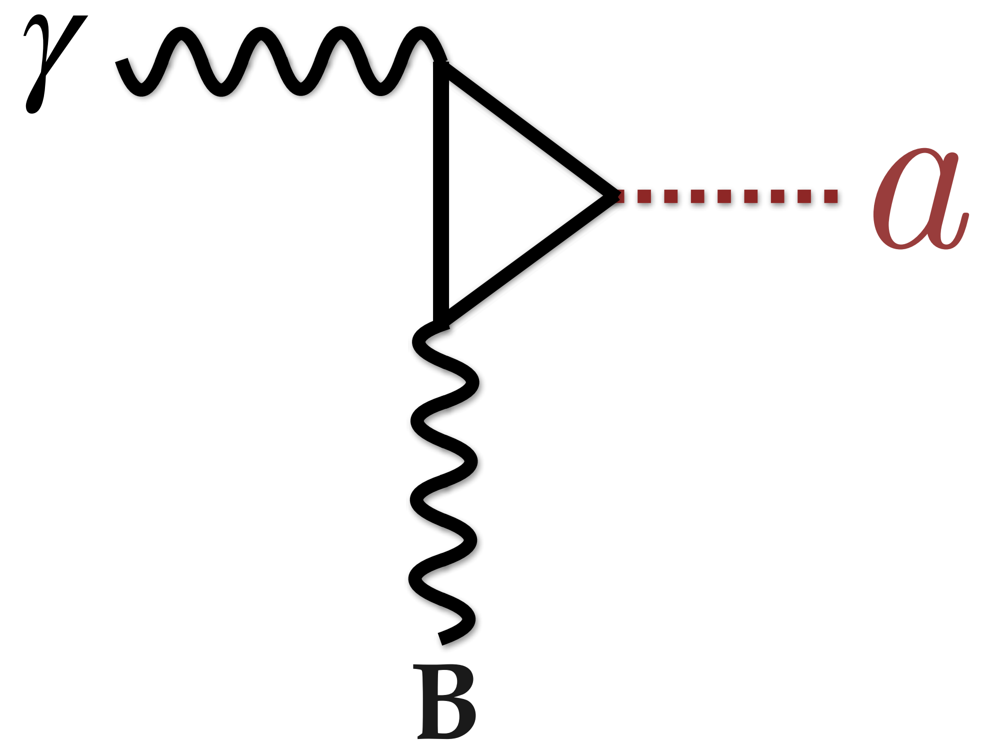
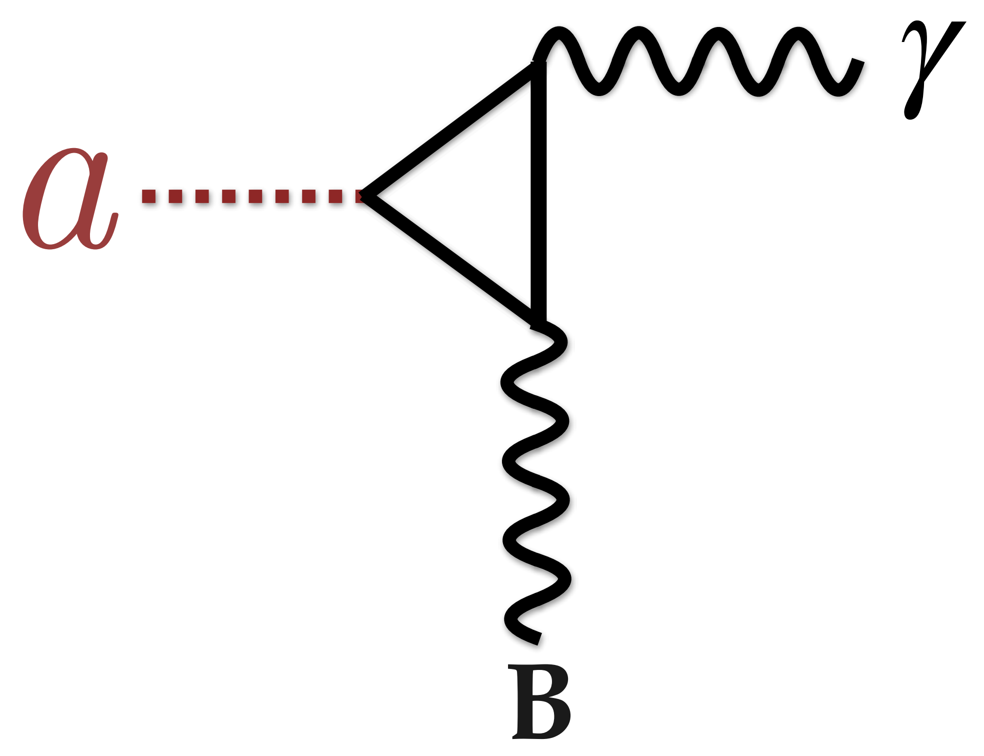
Photon → Axion



Axion → Photon



Coupling to the photon

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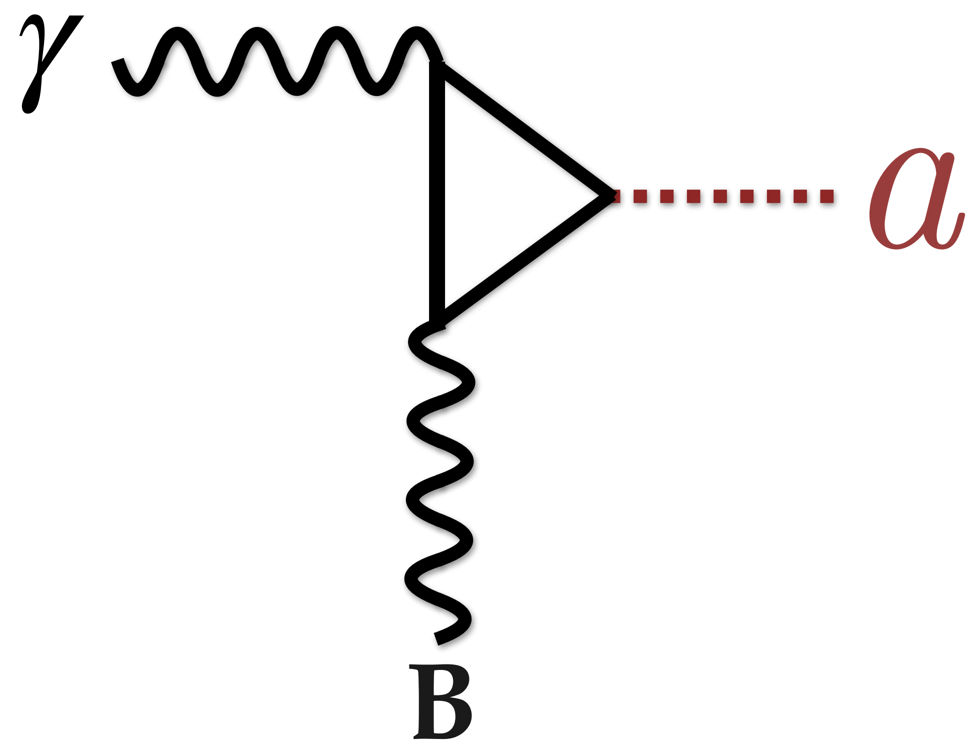
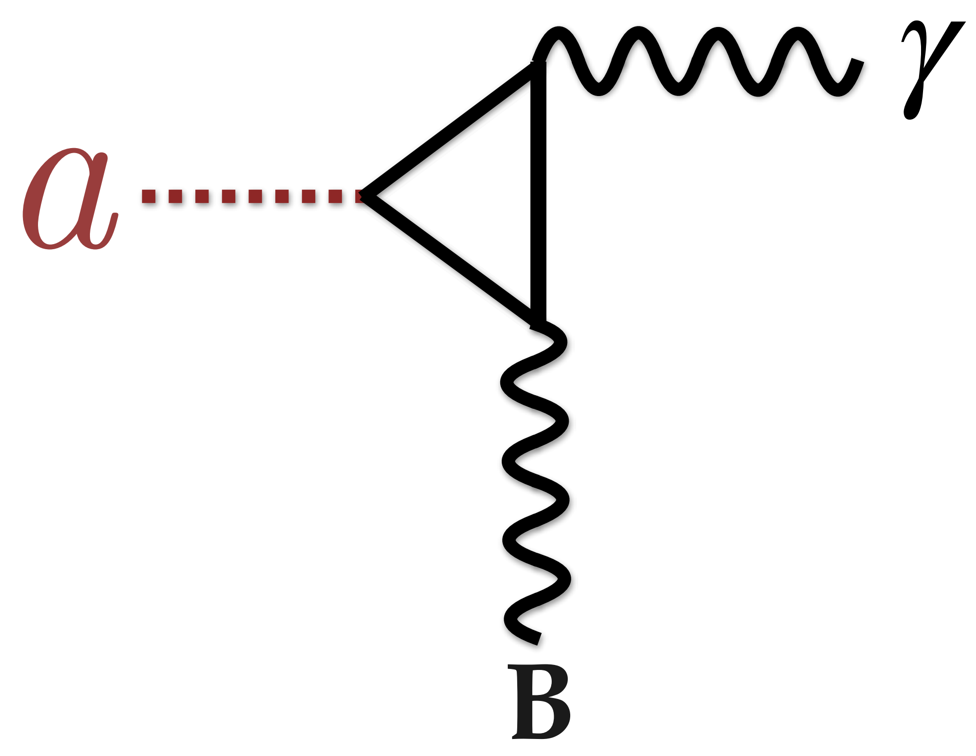
Photon → Axion



- Model independent test of theory
- Weak/ambiguous signal: relies on photon disappearance, or some oscillations due to axion-photon mixing

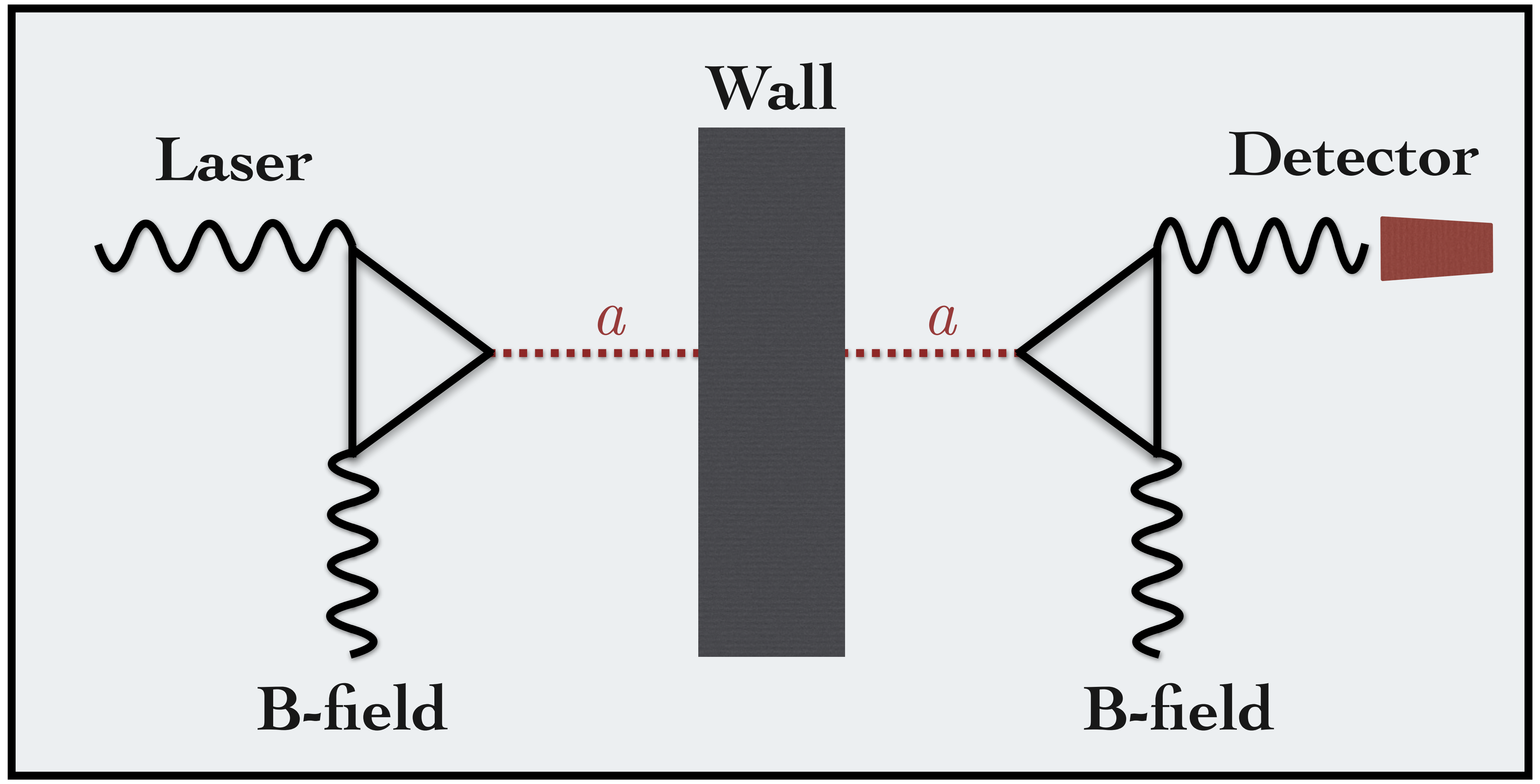
Axion → Photon

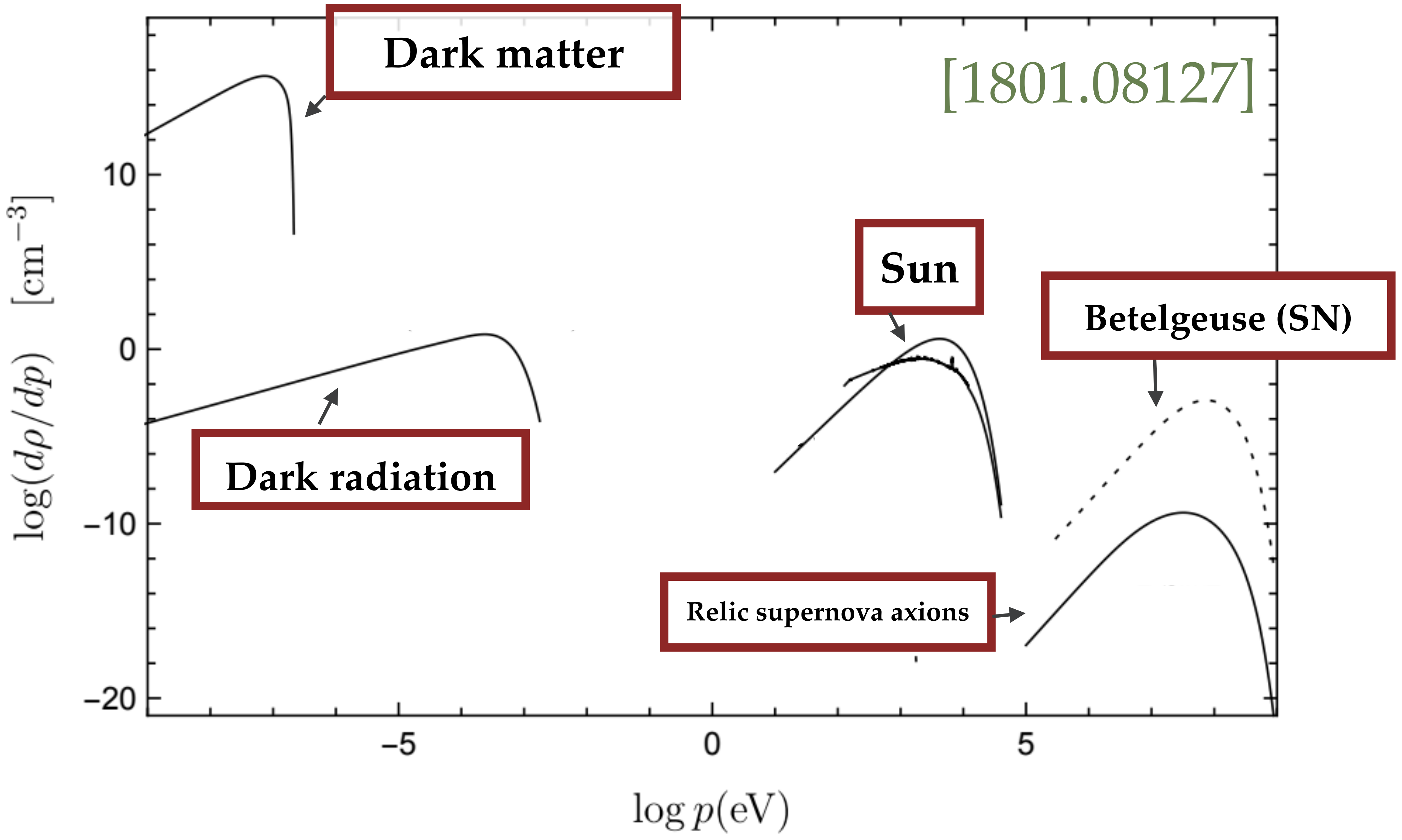


- Typically stronger signal
- Relies on a source of axions (introducing some model dependence)

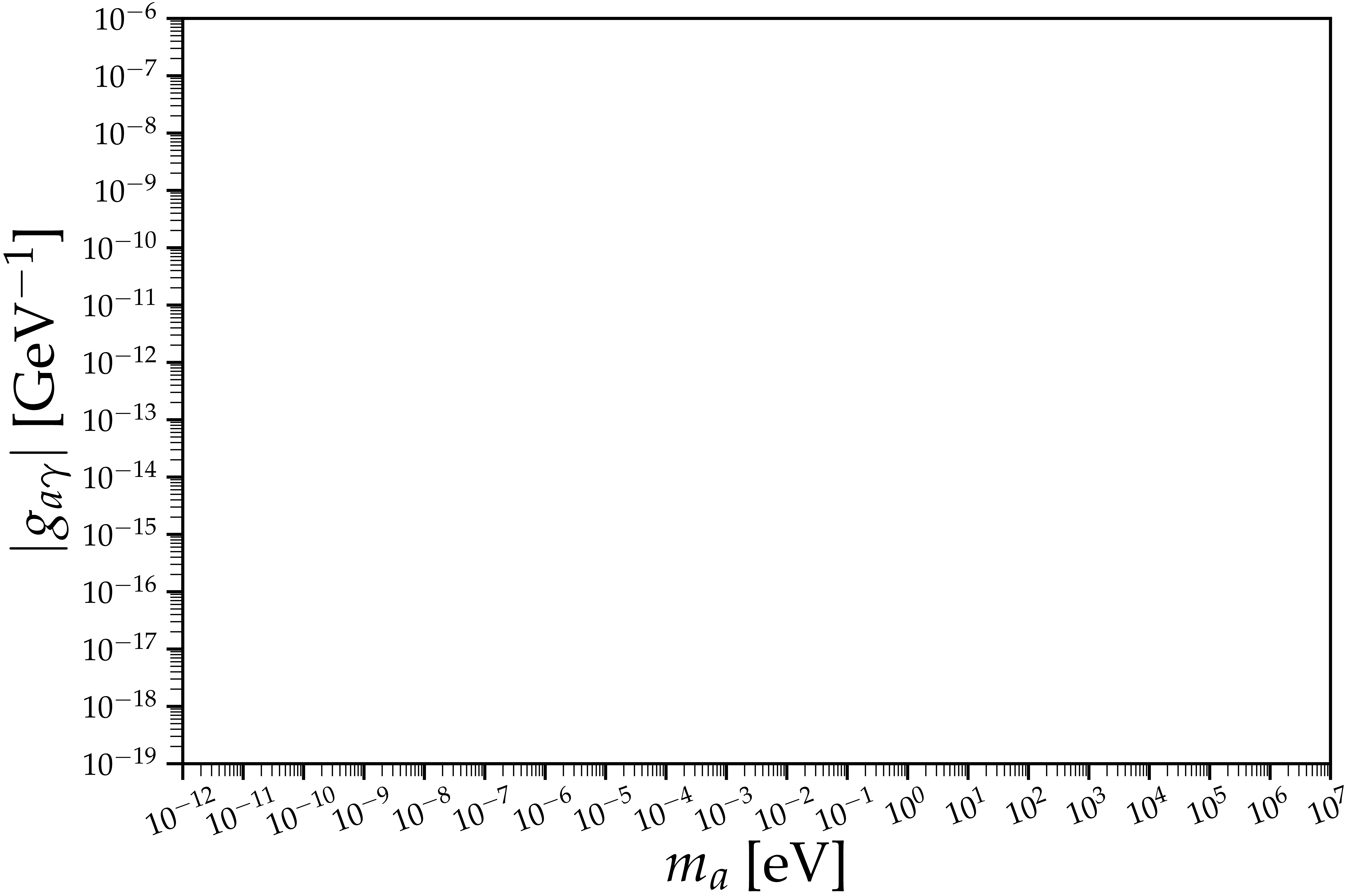
Photon → Axion

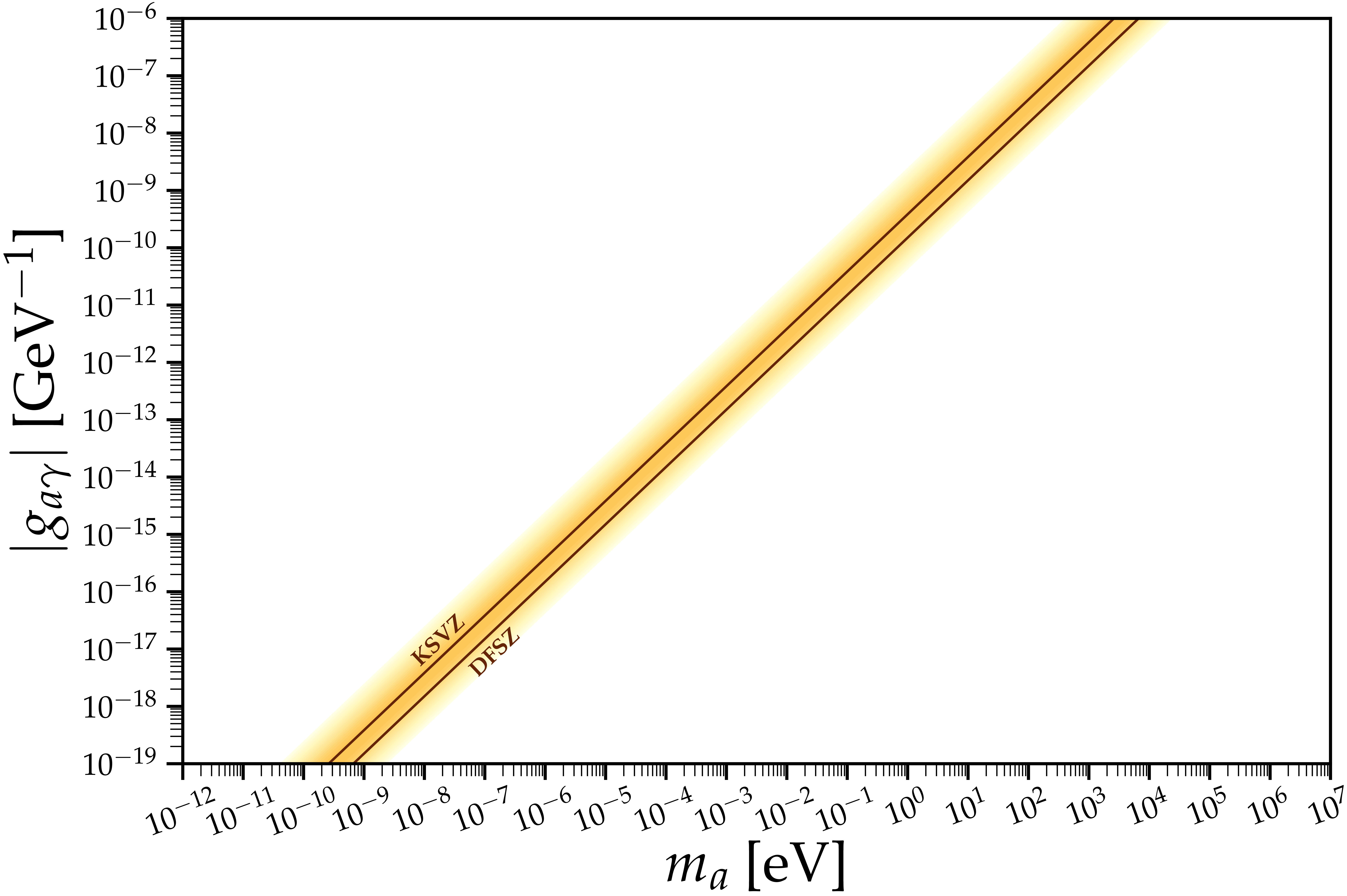
Axion → Photon



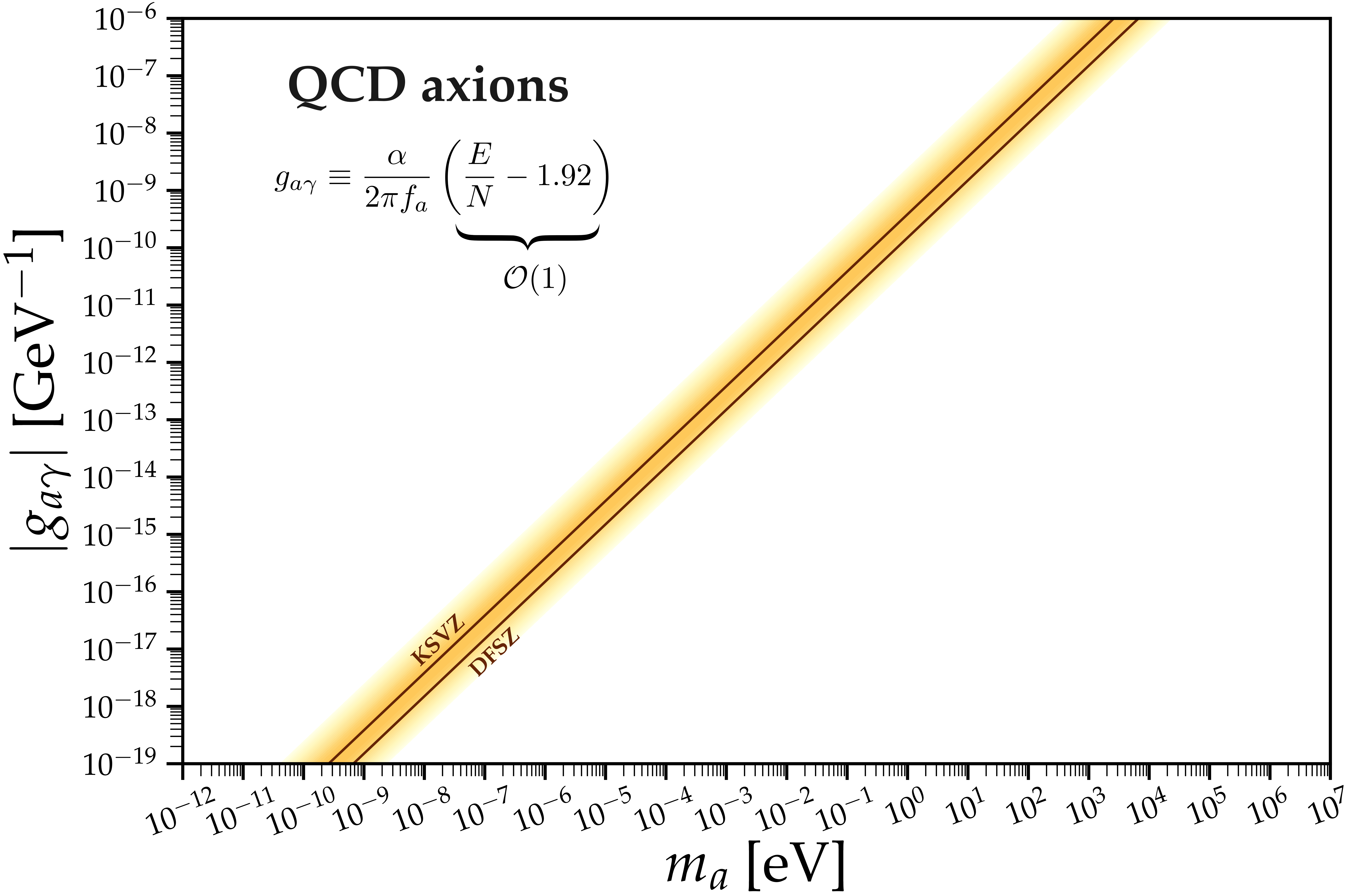


See also: collider searches for heavy ALPs
(I won't talk about these)

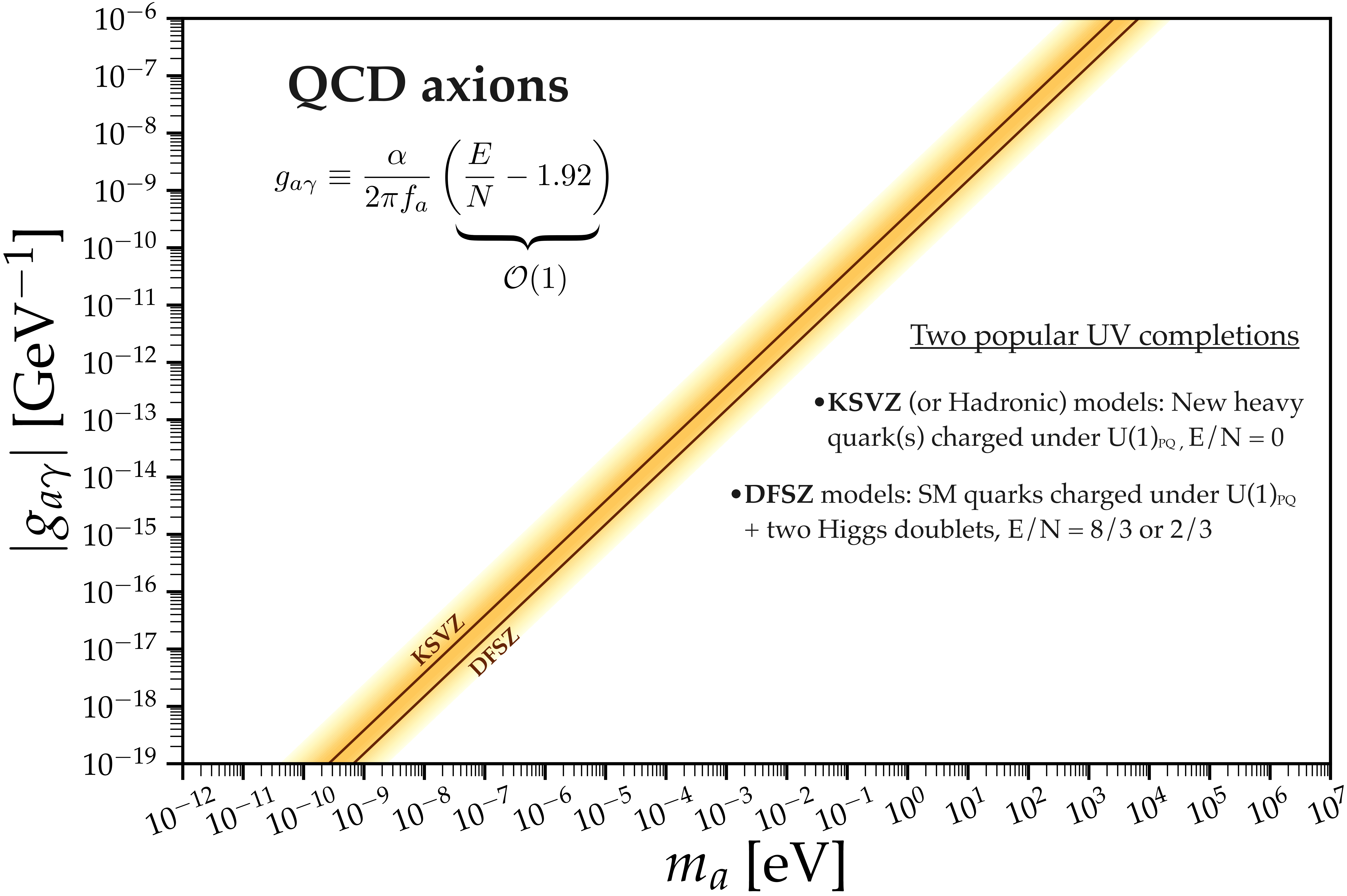

$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}



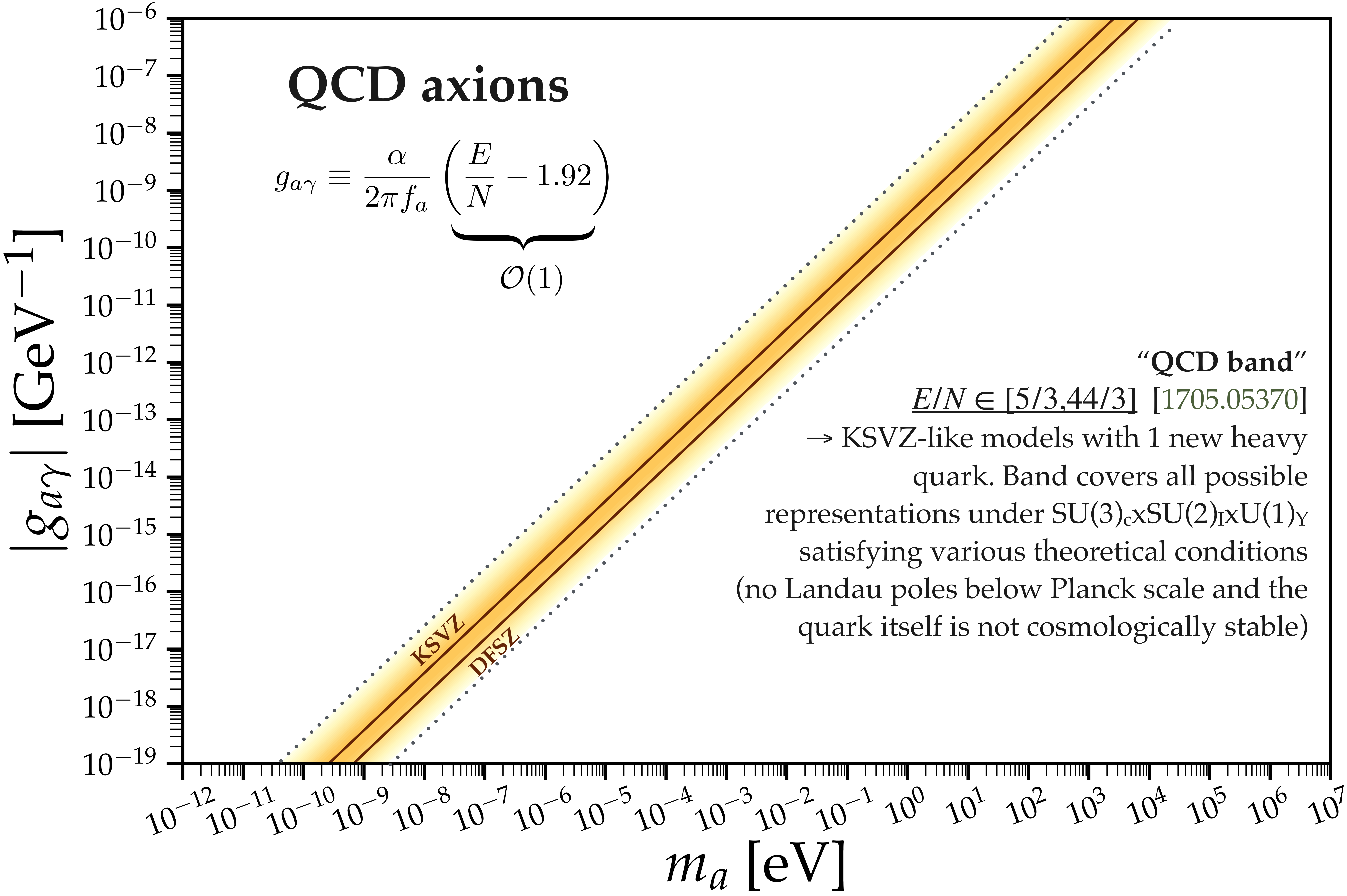
$|g_{a\gamma}|$ [GeV^{-1}]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
KSVZ
DFSZ
10^{-12} 10^{-11} 10^{-10} 10^{-9} 10^{-8} 10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7}
m_a [eV]



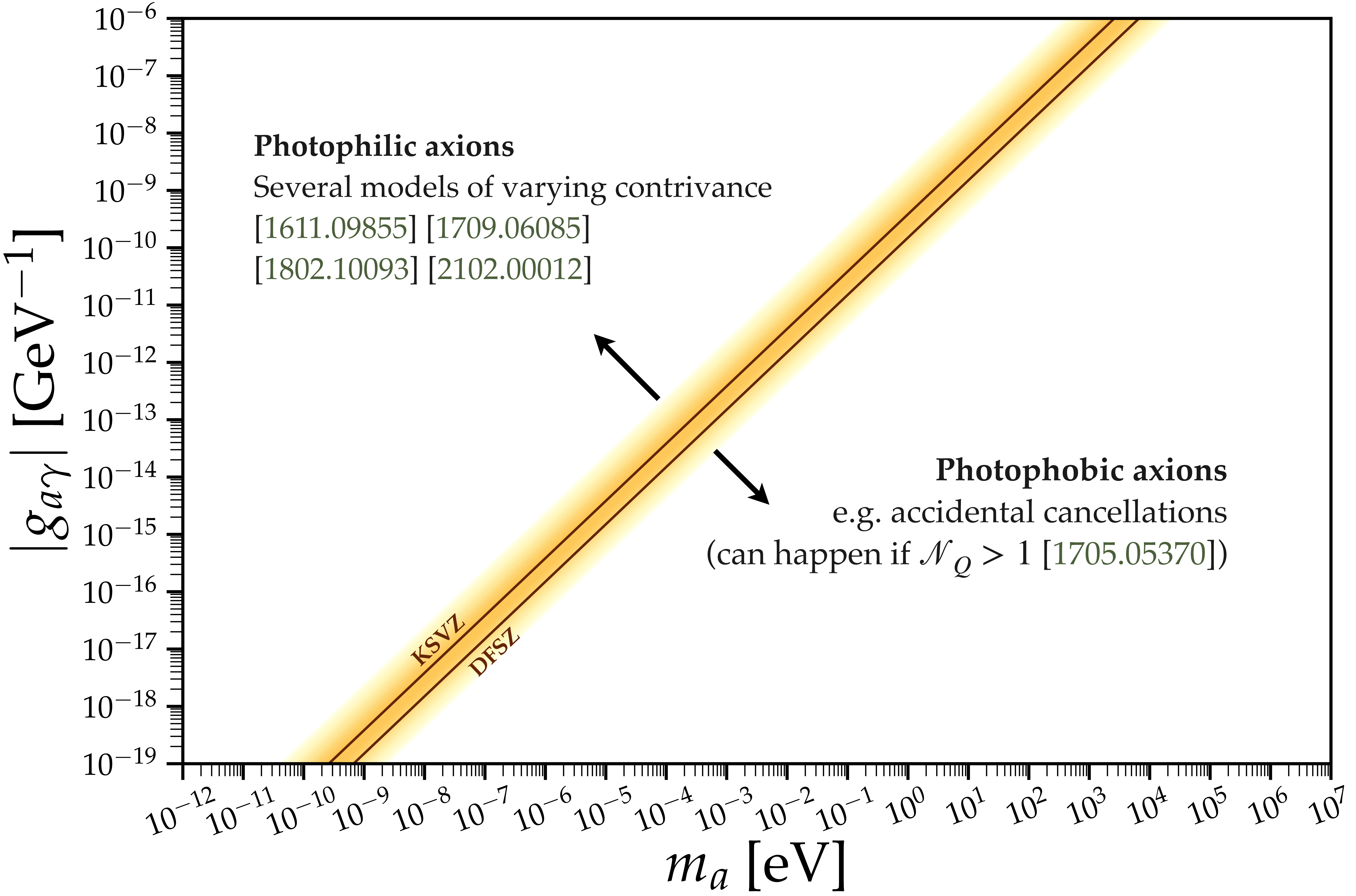
QCD axions
$g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a} \underbrace{\left(\frac{E}{N} - 1.92\right)}_{\mathcal{O}(1)}$
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-12} 10^{-11} 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}



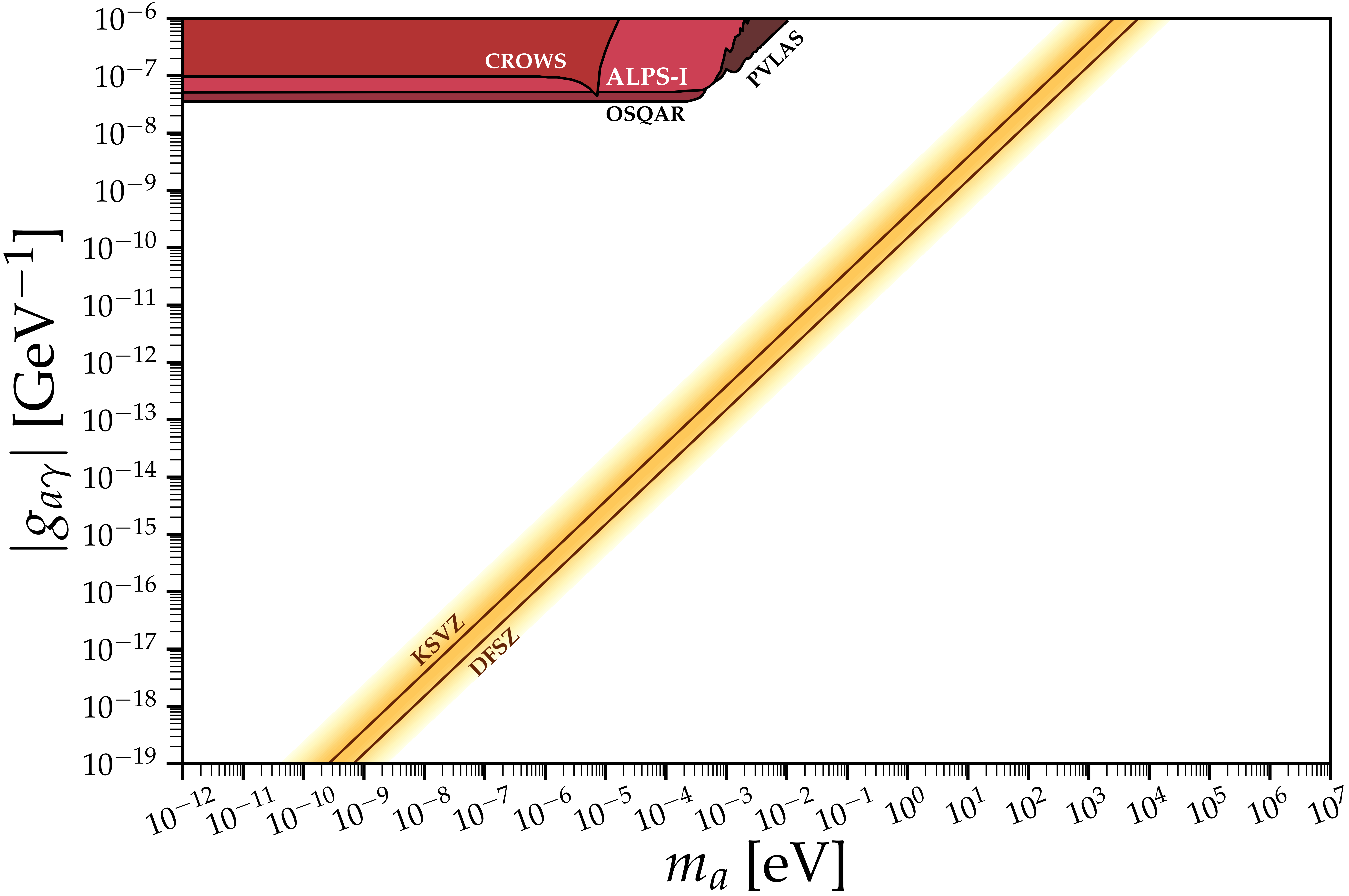
QCD axions
$g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a} \underbrace{\left(\frac{E}{N} - 1.92\right)}_{\mathcal{O}(1)}$
Two popular UV completions
•KSVZ (or Hadronic) models: New heavy quark(s) charged under $U(1)_{PQ}$, E/N = 0
•DFSZ models: SM quarks charged under $U(1)_{PQ}$ + two Higgs doublets, E/N = 8/3 or 2/3
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]



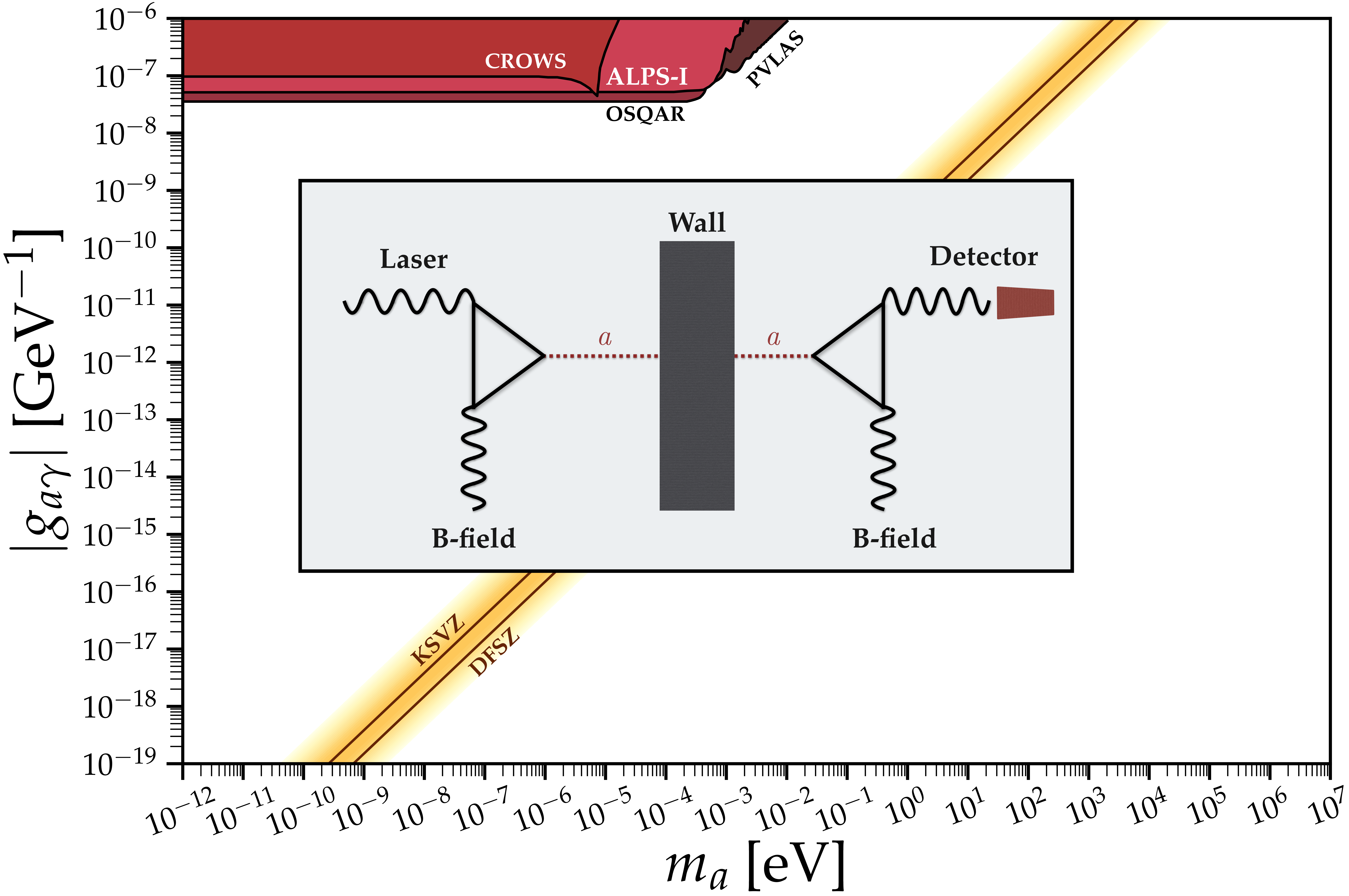
QCD axions
$$g_{a\gamma} \equiv \frac{\alpha}{2\pi f_a}\underbrace{\left(\frac{E}{N} - 1.92\right)}_{\mathcal{O}(1)}$$
"QCD band"
E/N ∈ [5/3,44/3] [1705.05370]
→ KSVZ-like models with 1 new heavy quark. Band covers all possible representations under $SU(3)_c x SU(2)_L x U(1)_Y$ satisfying various theoretical conditions (no Landau poles below Planck scale and the quark itself is not cosmologically stable)
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]



Photophilic axions
Several models of varying contrivance
[1611.09855] [1709.06085]
[1802.10093] [2102.00012]
Photophobic axions
e.g. accidental cancellations
(can happen if $\mathcal{N}_Q > 1$ [1705.05370])
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]



CROWS
ALPS-I
OSQAR
PVLAS
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]


CROWS
ALPS-I
OSQAR
PVLAS
Wall
Laser
Detector
a
a
B-field
B-field
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
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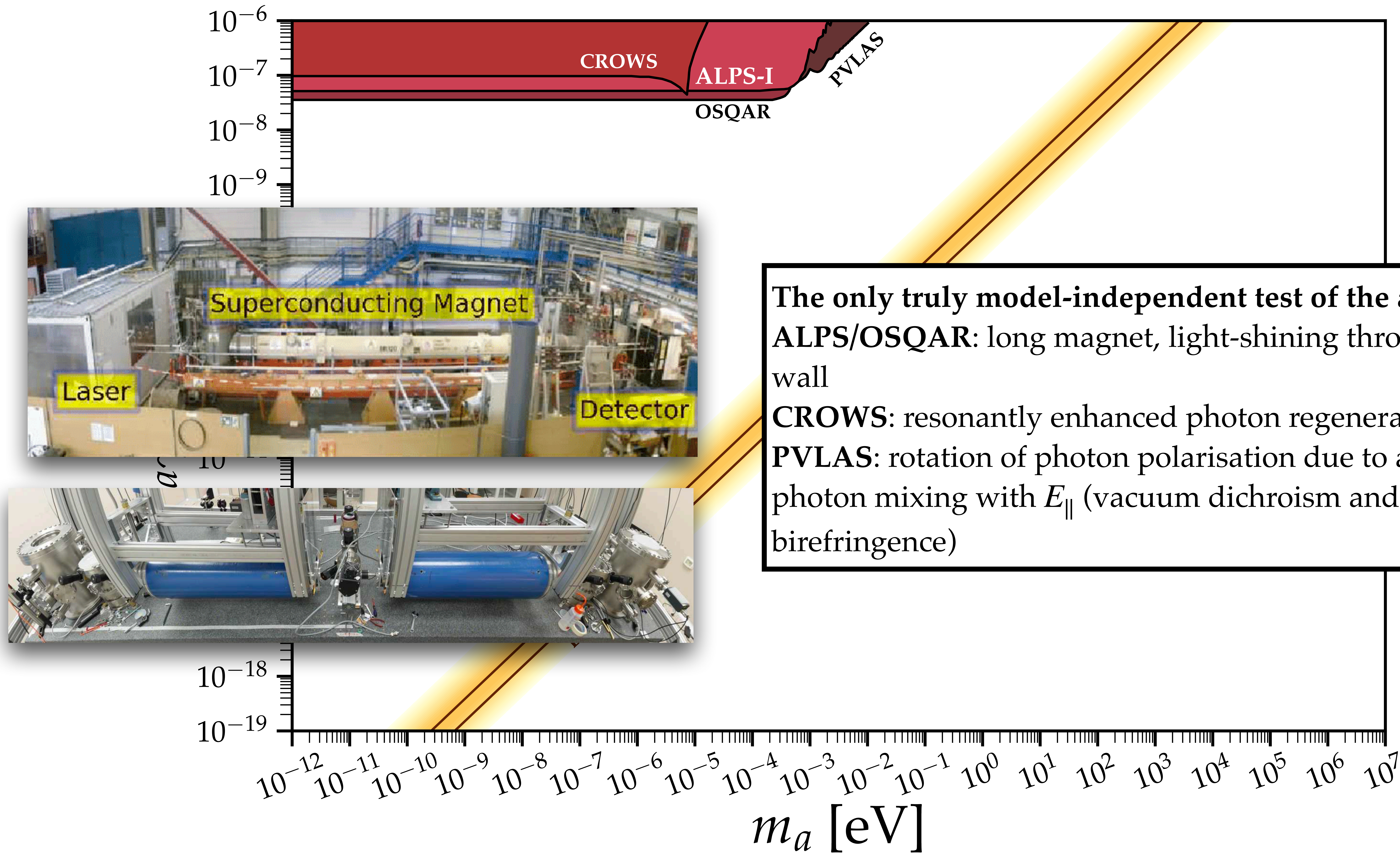
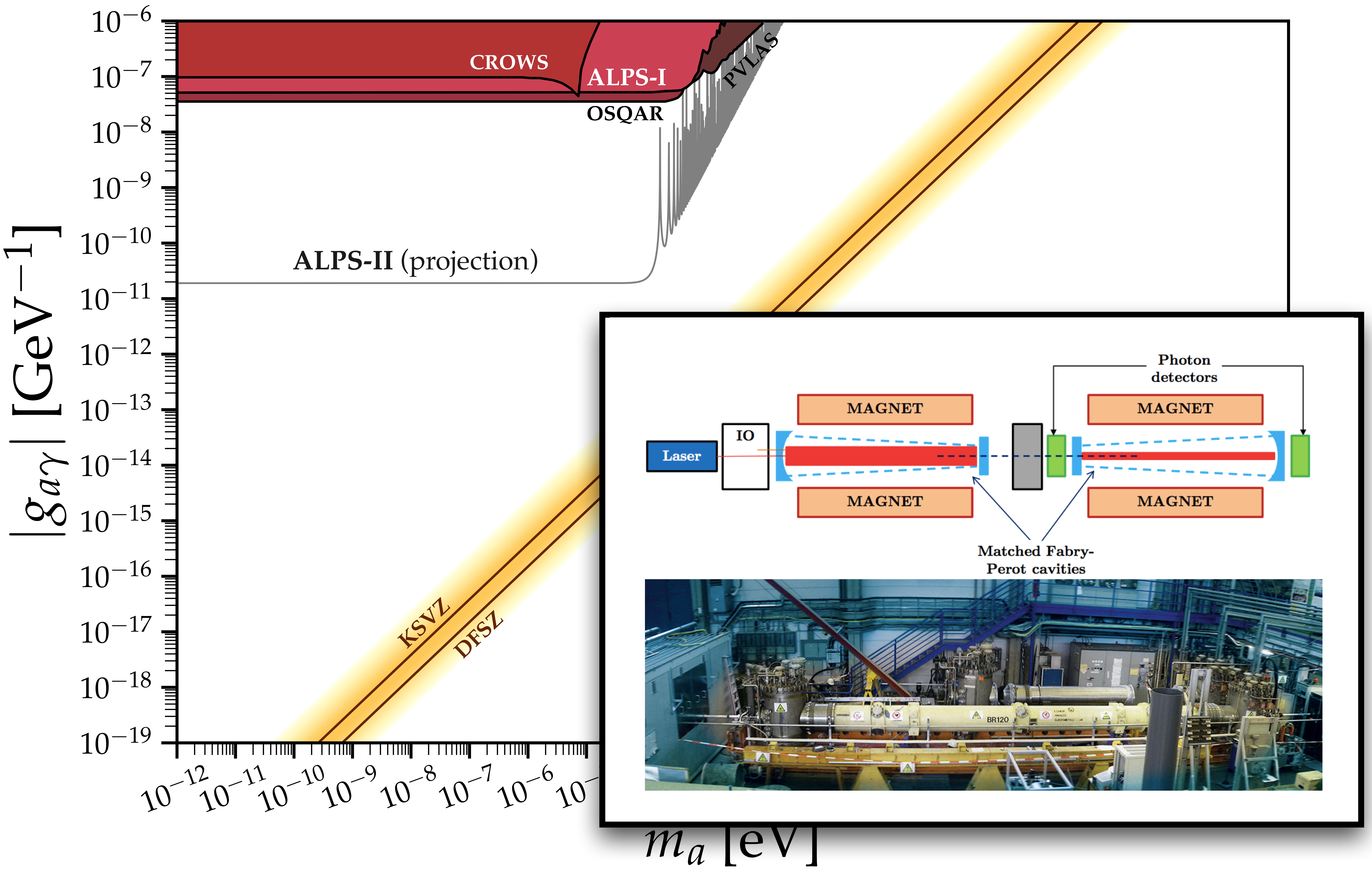


The only truly model-independent test of the axion

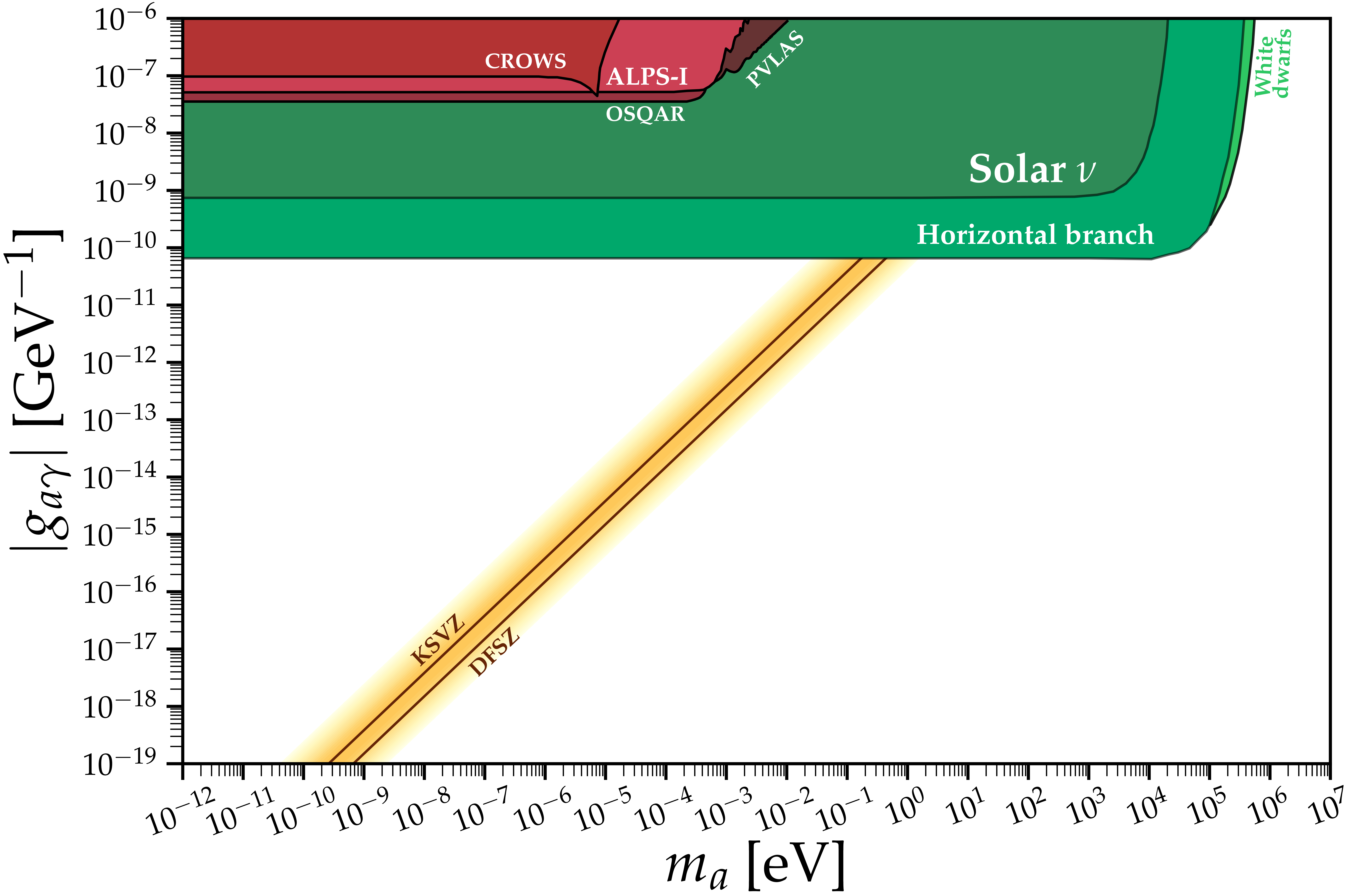
ALPS/OSQAR: long magnet, light-shining through a wall

CROWS: resonantly enhanced photon regeneration

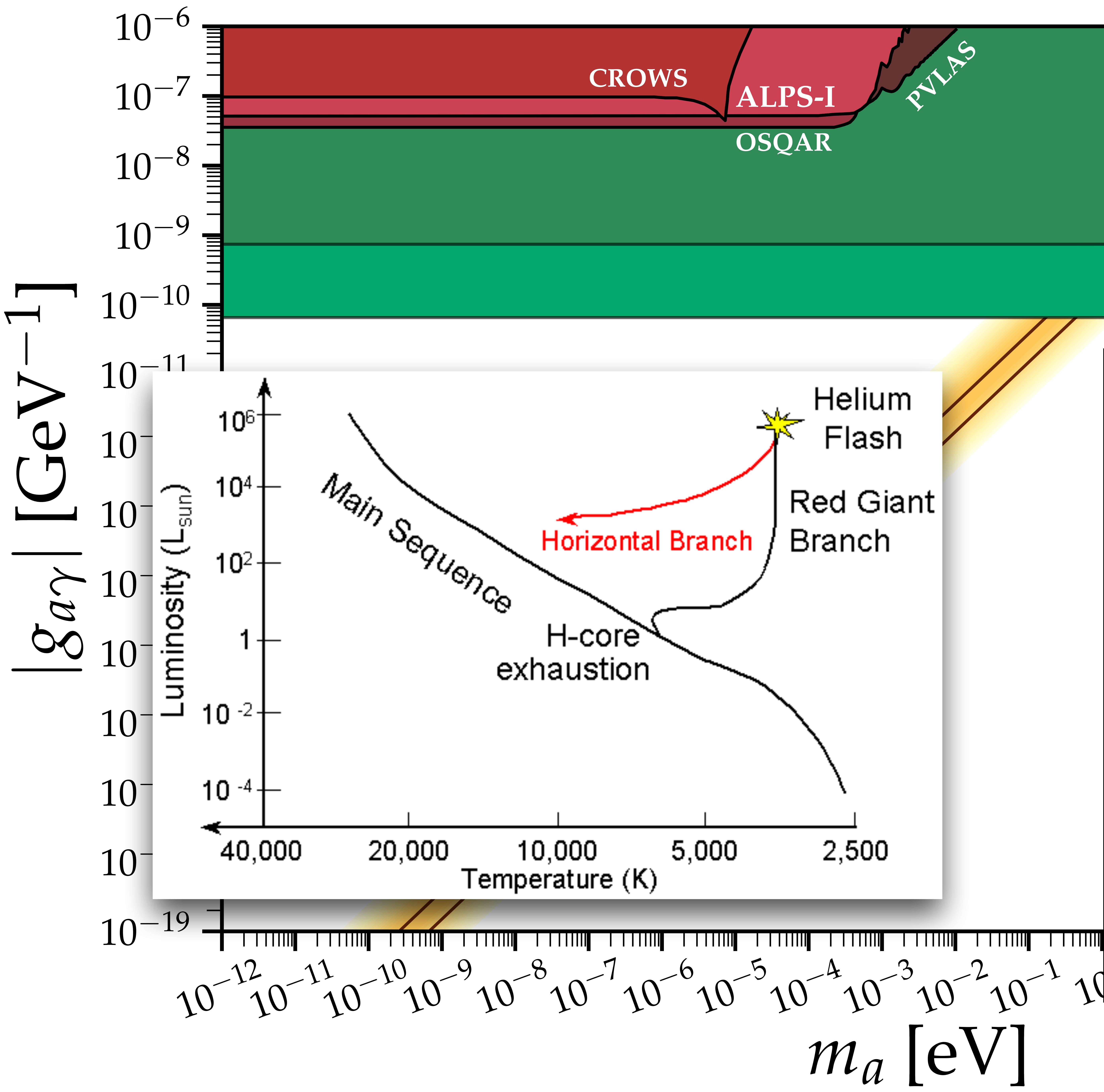
PVLAS: rotation of photon polarisation due to axion-photon mixing with $E_{\|}$ (vacuum dichroism and birefringence)



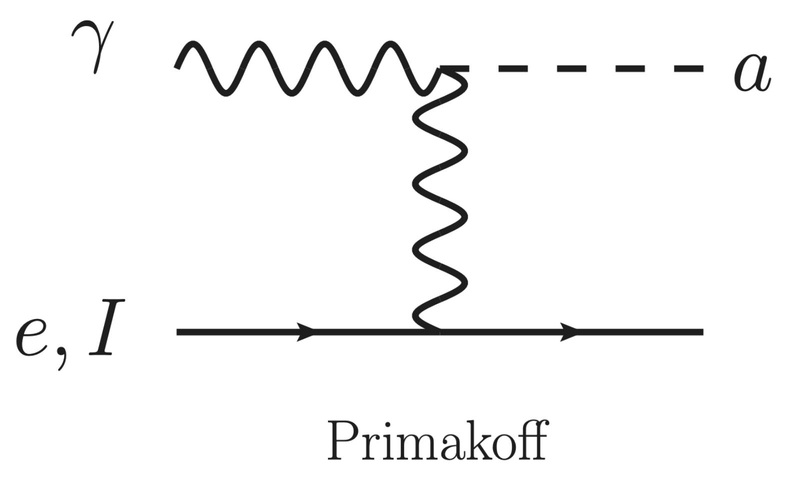
CROWS
ALPS-I
OSQAR
PVLAS
ALPS-II (projection)
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV−1]
m_a [eV]
Photon detectors
MAGNET
MAGNET
MAGNET
MAGNET
Laser
IO
Matched Fabry-Perot cavities
BR120



CROWS
ALPS-I
OSQAR
PVLAS
Solar ν
Horizontal branch
White dwarfs
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]



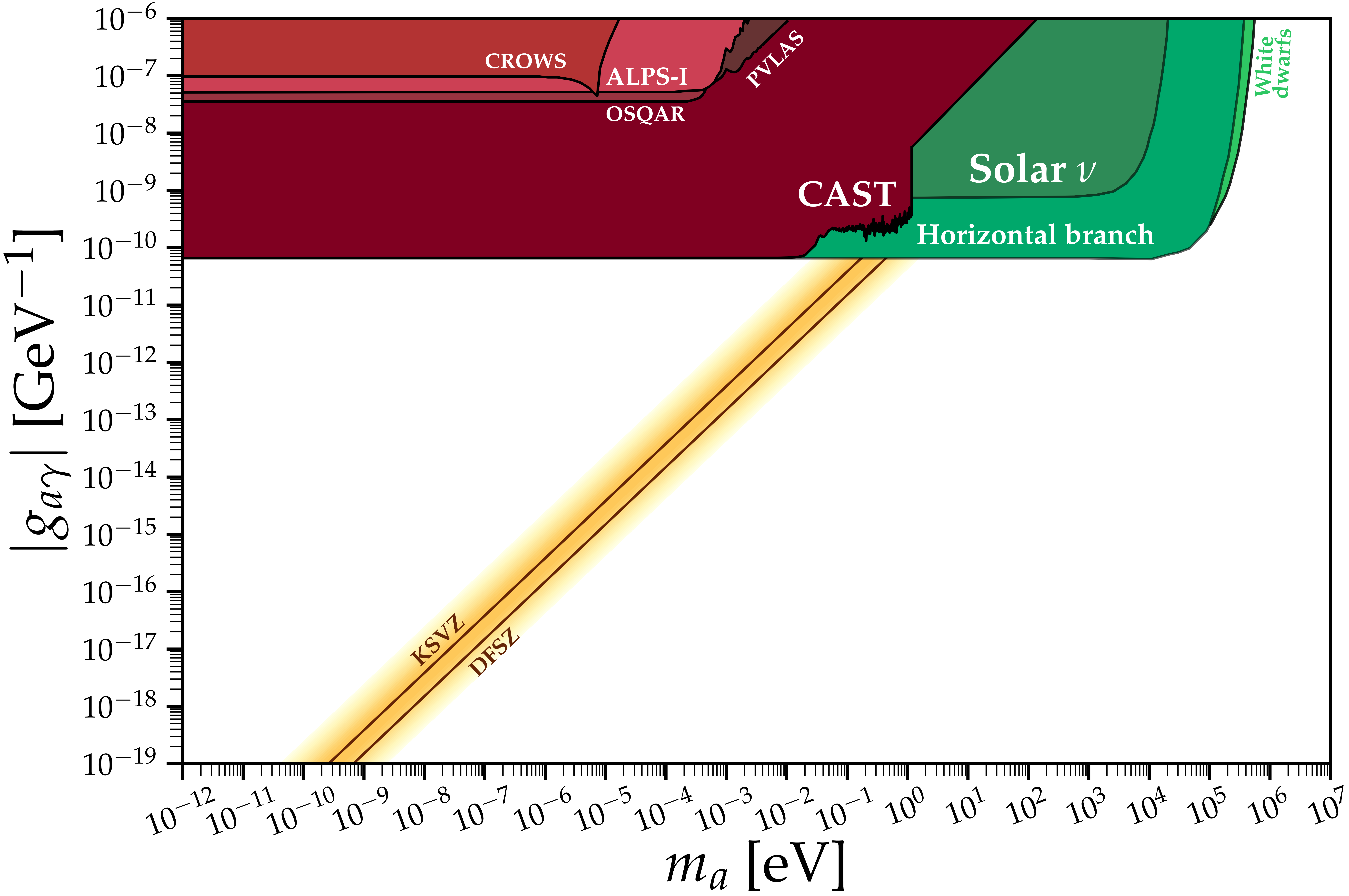
Axions ruled out by stellar physics



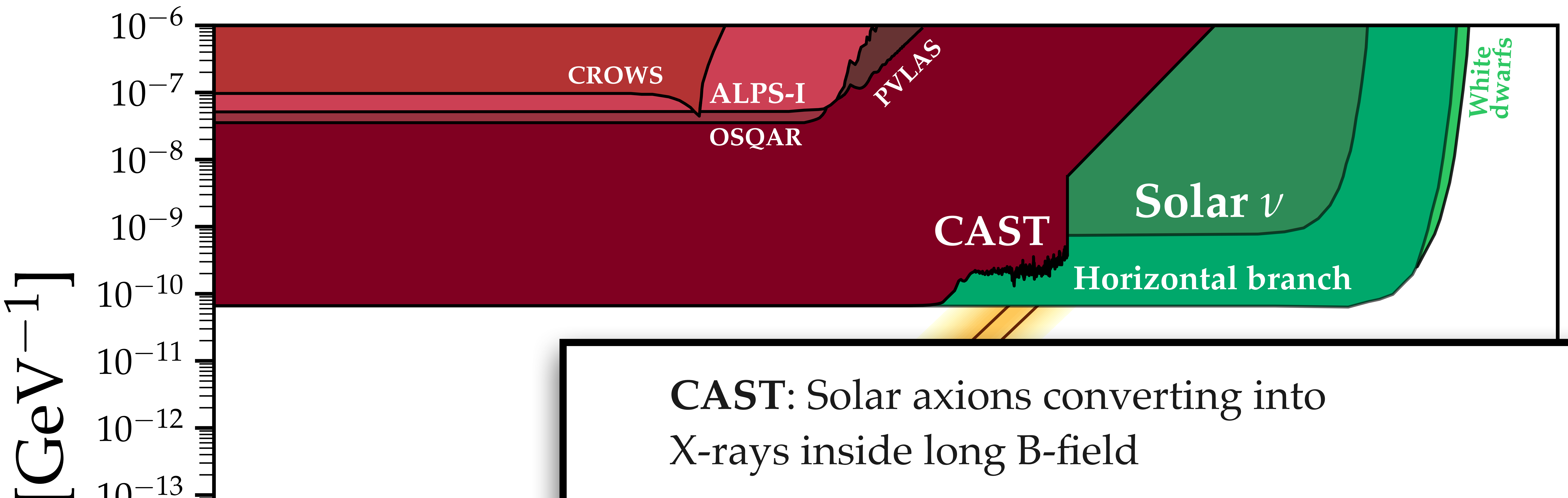
Solar luminosity bound: Primakoff energy loss requires enhanced nuclear energy generation to keep solar luminosity the same

Horizontal branch: Hot/low density helium burning stars. Lifetimes sensitive to Primakoff emission

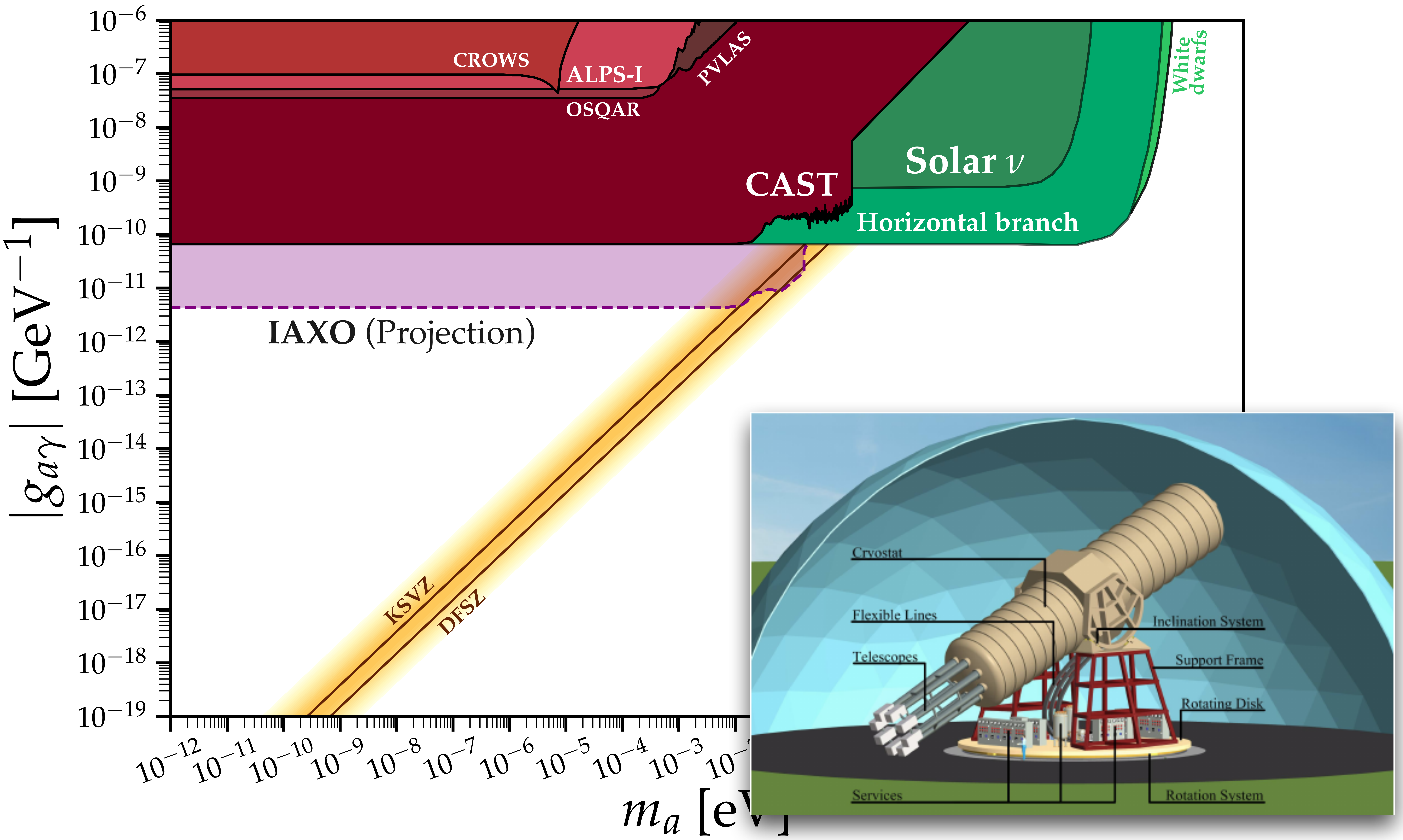
White dwarfs: initial-final mass relation [2102.00379]



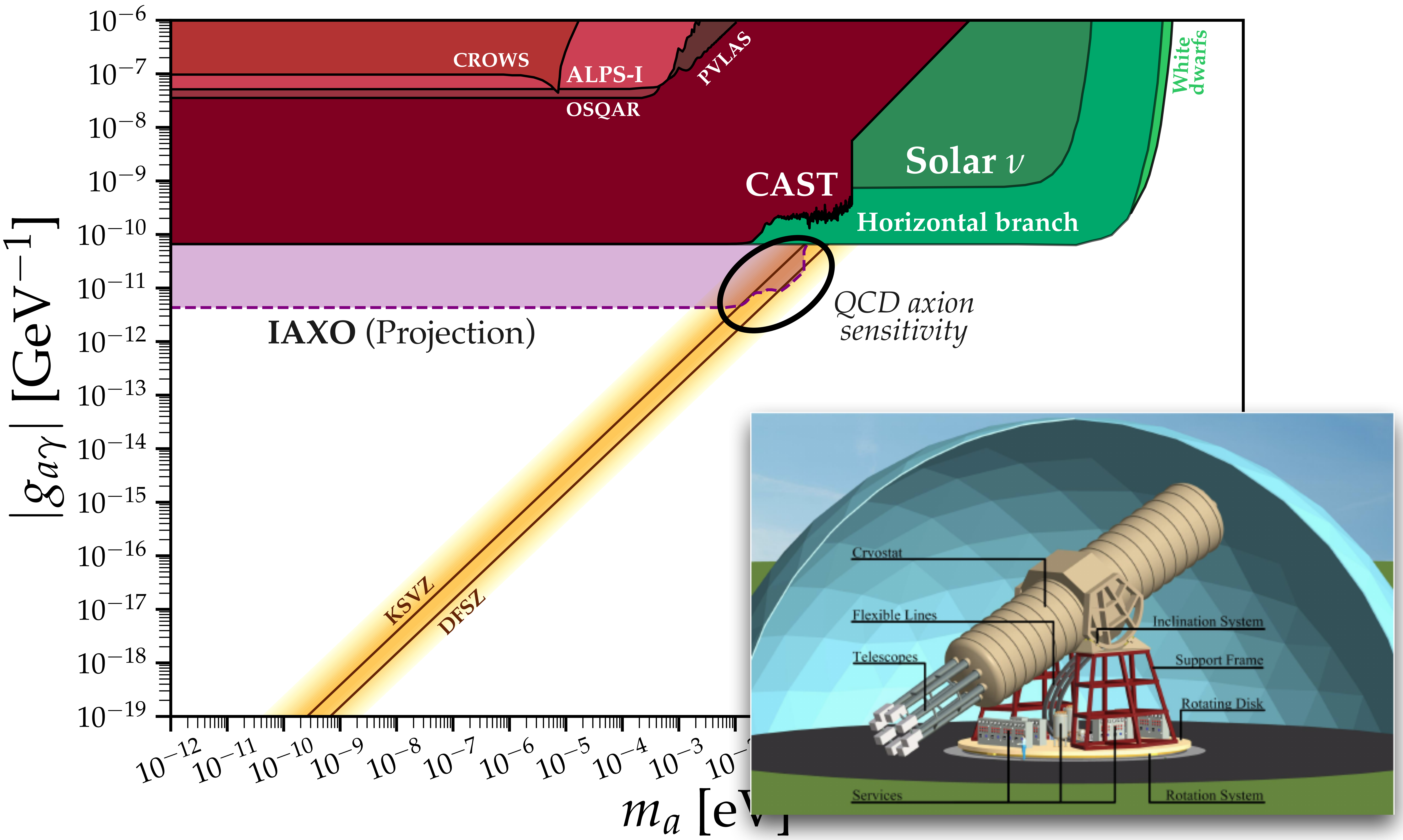
CROWS
ALPS-I
OSQAR
PVLAS
CAST
Solar ν
Horizontal branch
White dwarfs
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]

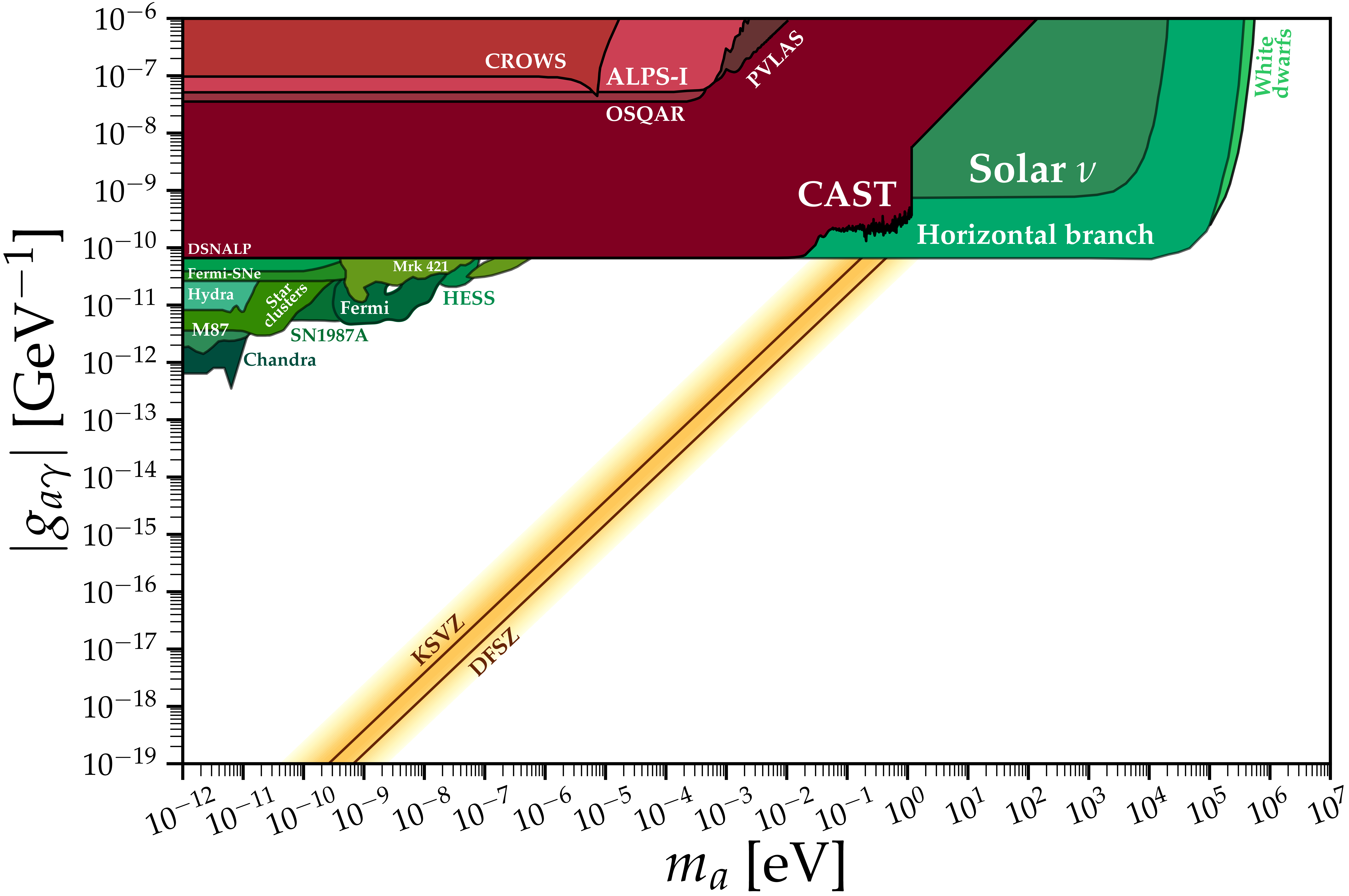


CAST: Solar axions converting into X-rays inside long B-field



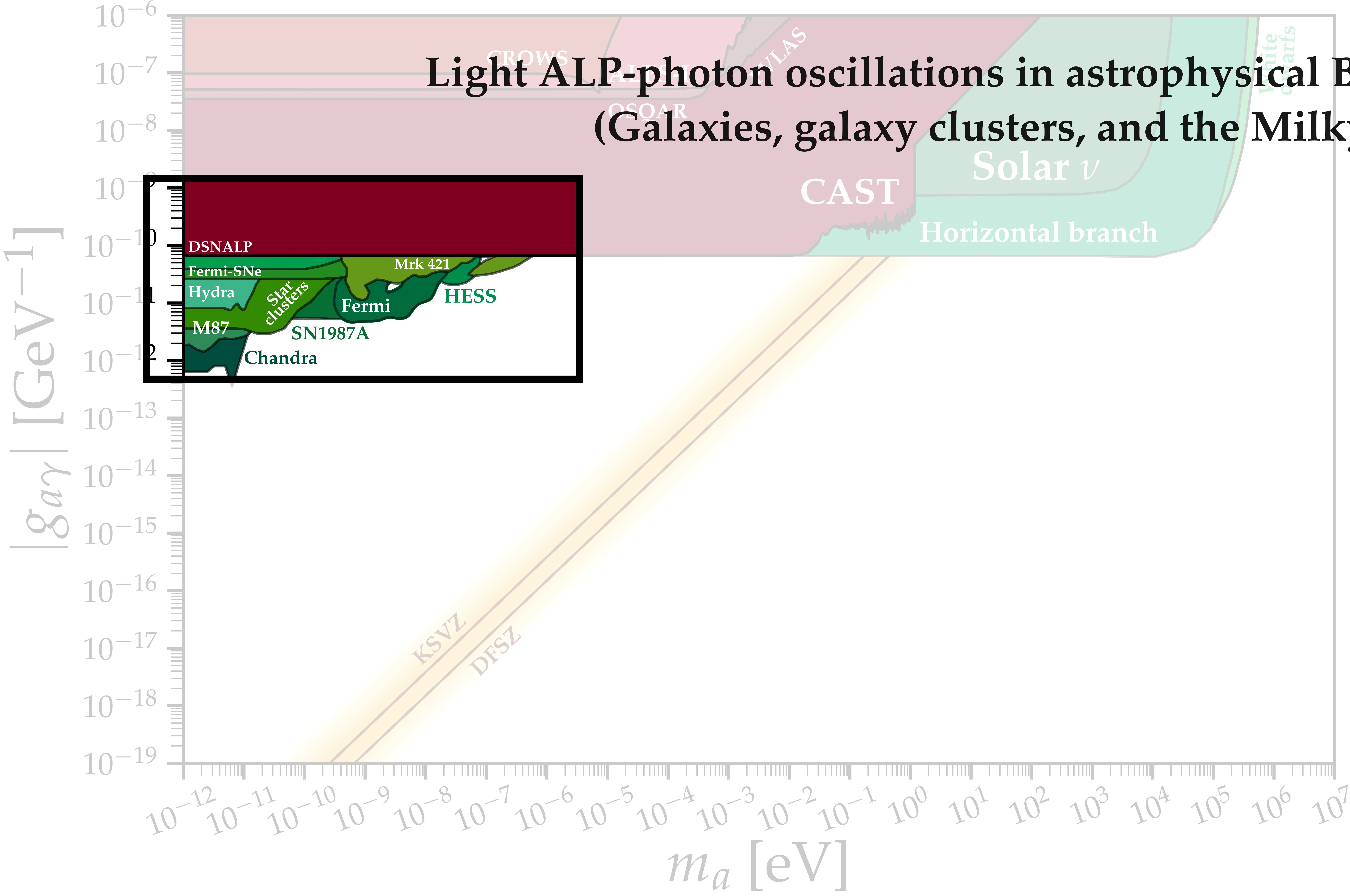
CROWS
ALPS-I
OSQAR
PVLAS
CAST
Solar ν
Horizontal branch
White dwarfs
IAXO (Projection)
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
Cryostat
Flexible Lines
Telescopes
Inclination System
Support Frame
Rotating Disk
Services
Rotation System


CROWS
ALPS-I
OSQAR
PVLAS
CAST
Solar ν
Horizontal branch
White dwarfs
IAXO (Projection)
QCD axion sensitivity
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
Cryostat
Flexible Lines
Telescopes
Inclination System
Support Frame
Rotating Disk
Services
Rotation System



CROWS
ALPS-I
PVLAS
OSQAR
Solar ν
CAST
Horizontal branch
White dwarfs
DSNALP
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]

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



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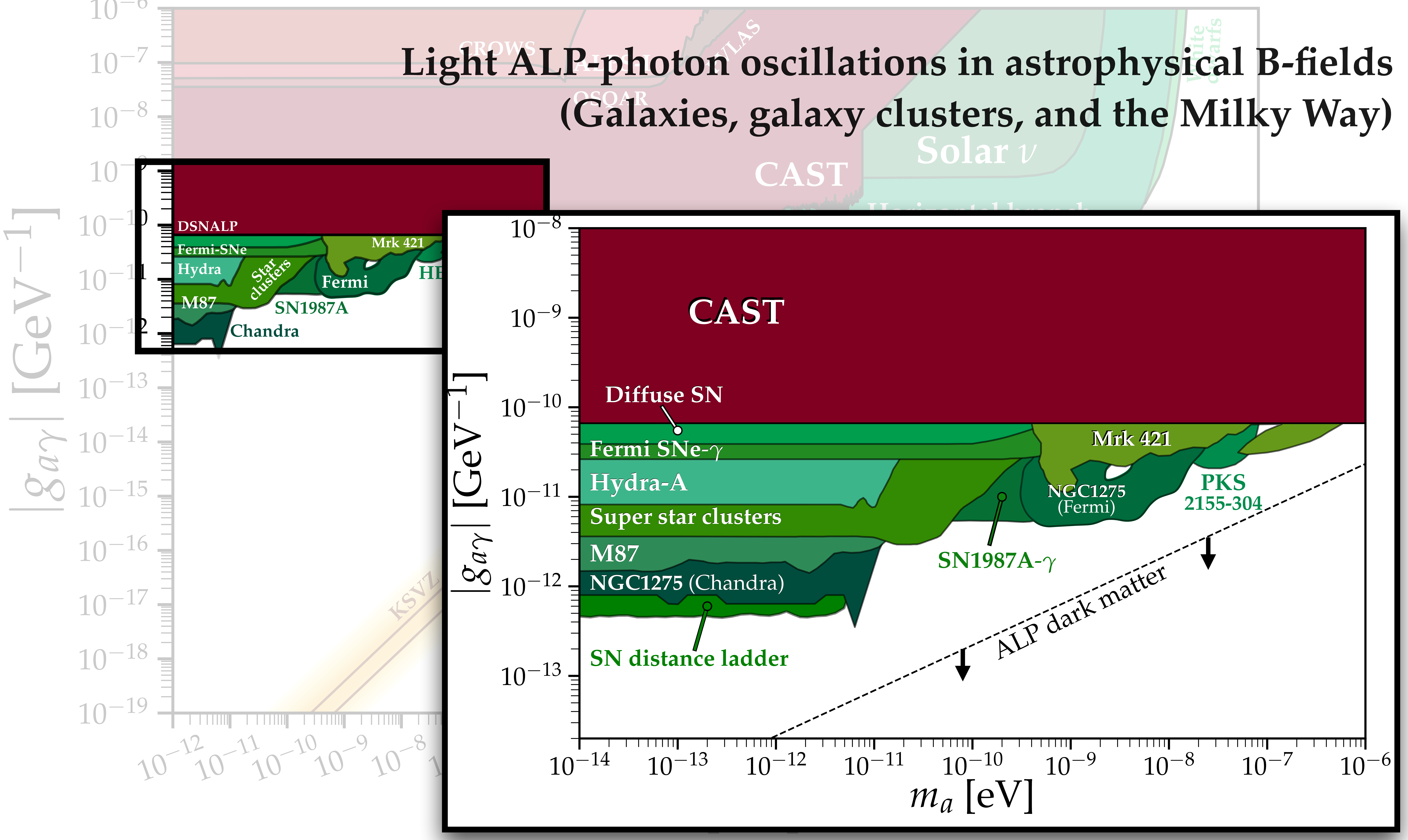

Photon-axion mixing in a B-field

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

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

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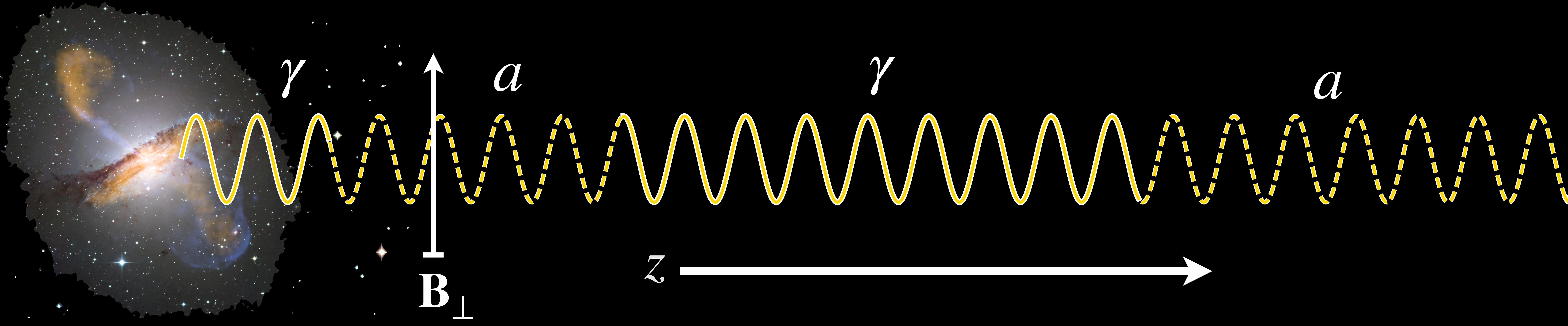

Linearised wave equation for photon-axion mixing

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

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

Mixing element — Axion mass element — Photon mass element

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

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

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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,

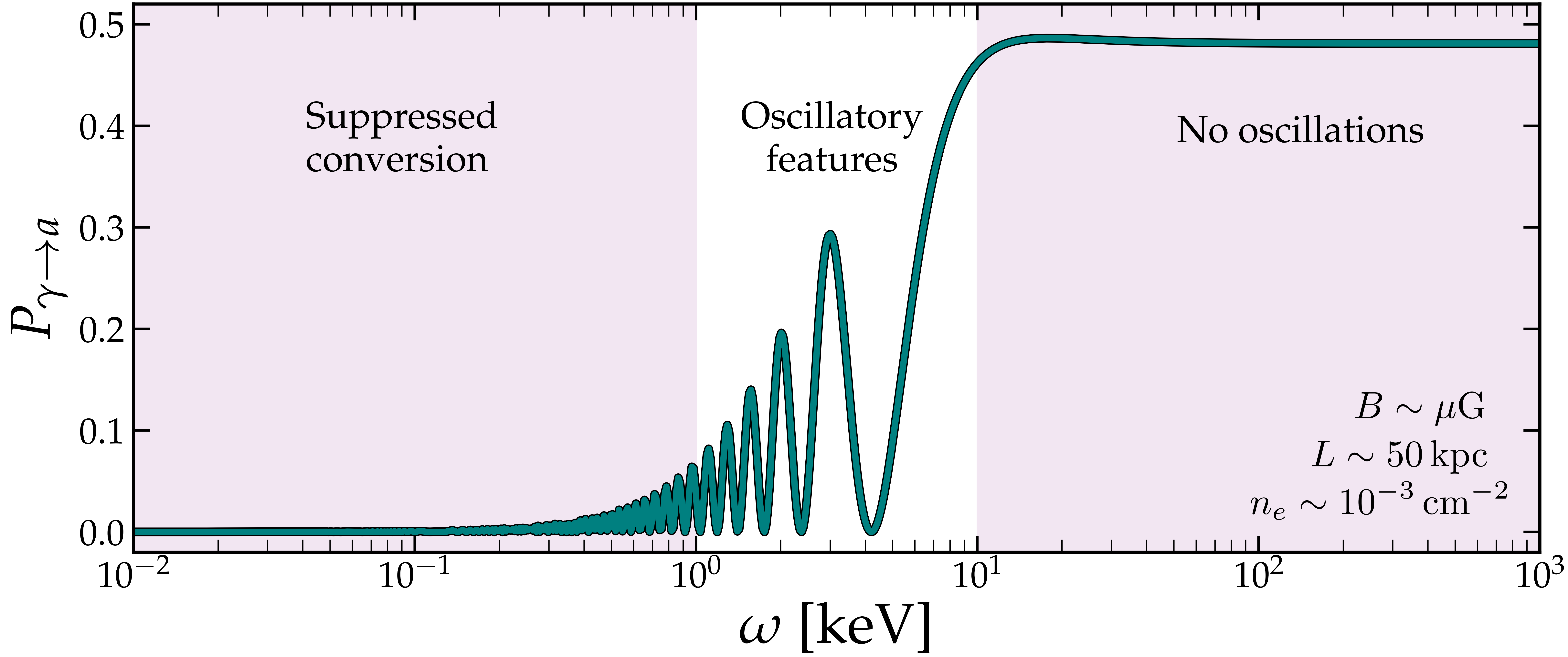
$$\theta = \frac{1}{2}\arctan\left(\frac{2\Delta_{\gamma a}}{\Delta_{\rm pl} - \Delta_a}\right) \qquad \Delta = \frac{|m_a^2 - \omega_{\rm pl}^2|L}{4\omega}$$

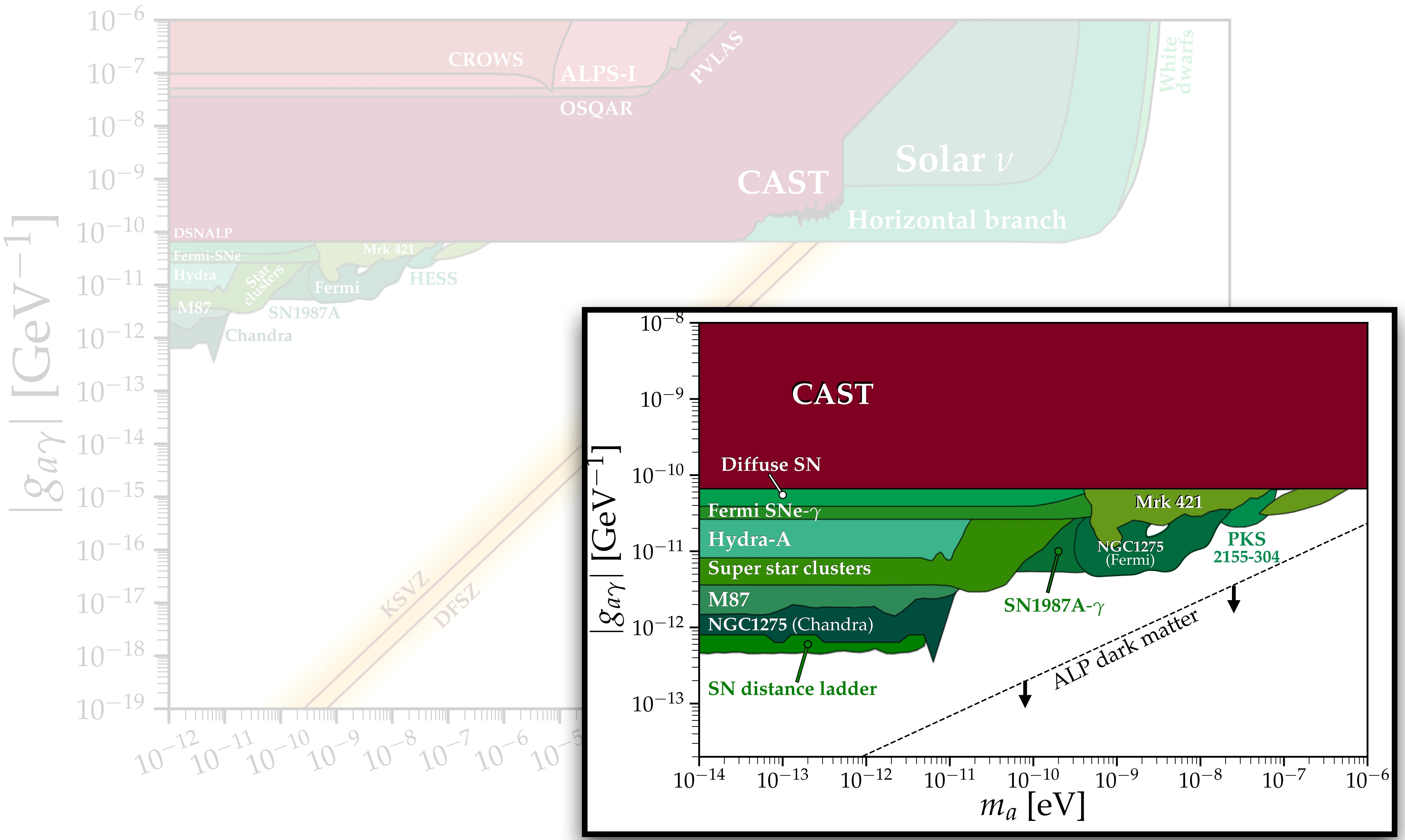
Photon-axion conversion probability

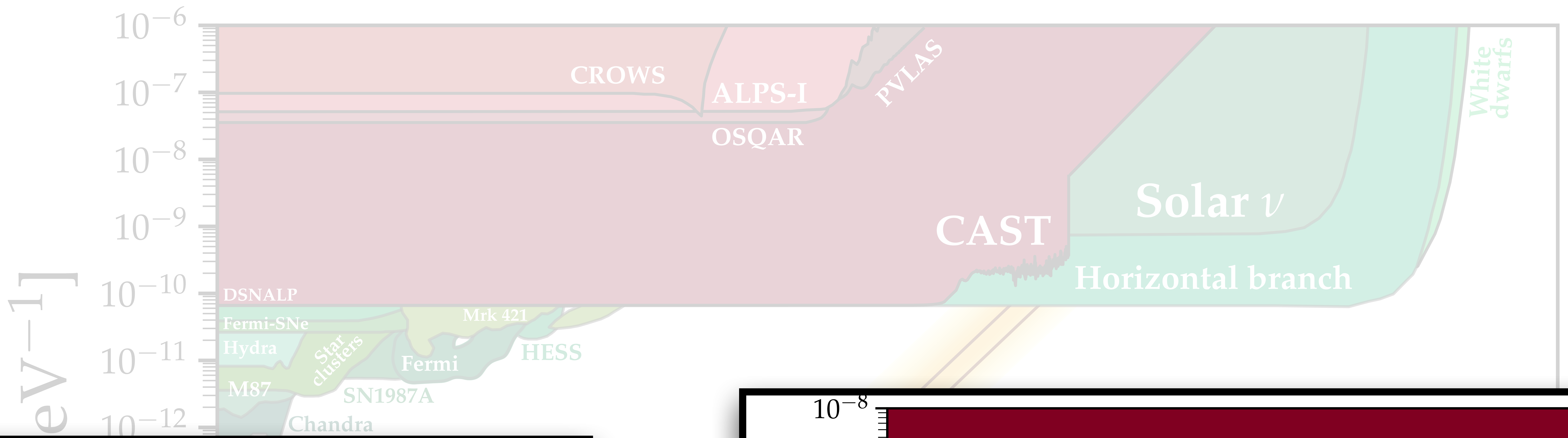
For very light axions, m_a is negligible compared to $\omega_{\rm pl}$

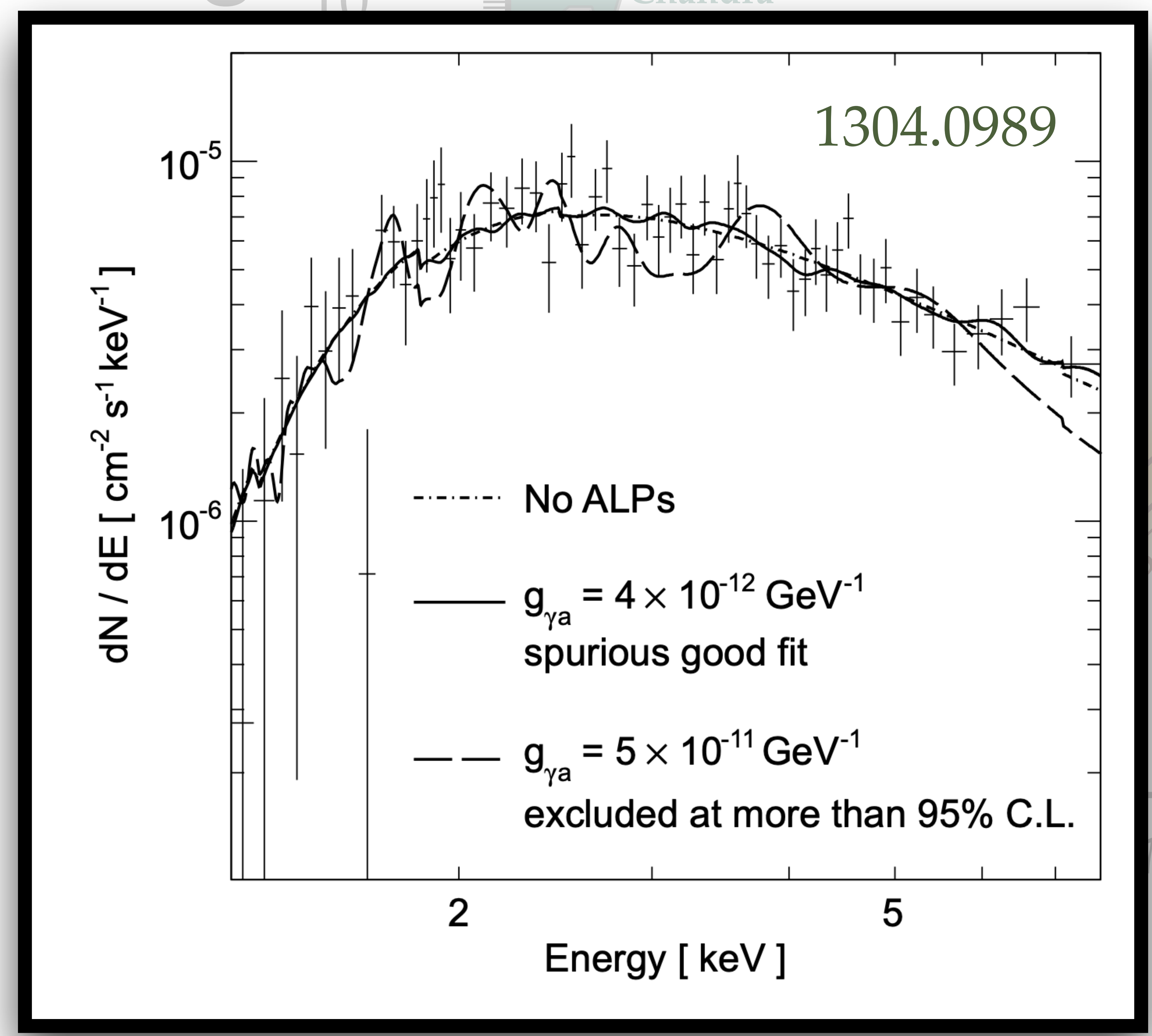
$\rightarrow$ $m_a \lesssim 10^{-12}$ eV for typical astrophysical plasmas $n_e = 10^{-3}$ cm^{-3}

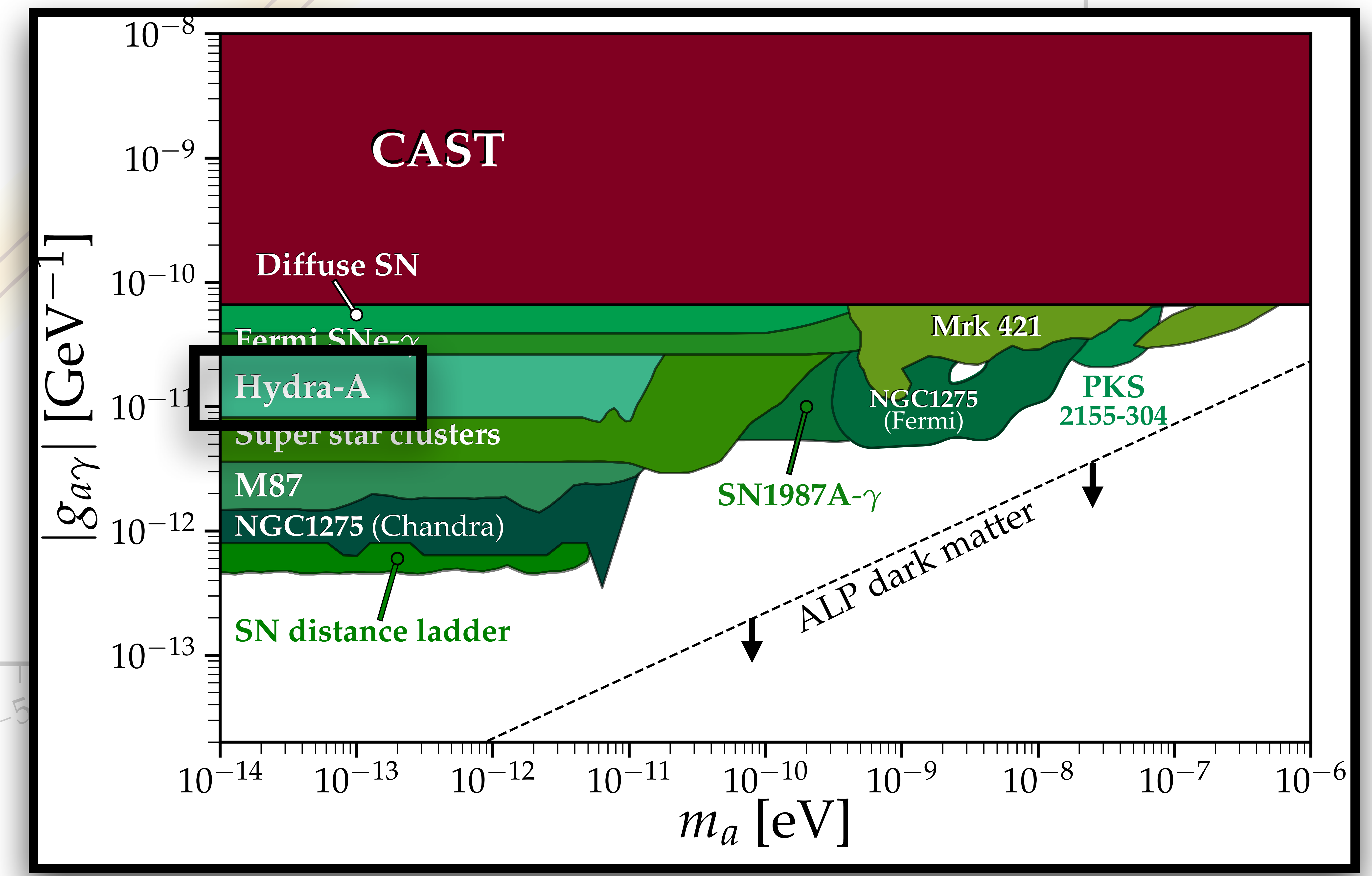
$$\theta \sim g_{a\gamma} \frac{B_\perp \omega}{n_e} \qquad \Delta \sim \frac{n_e L}{\omega}$$

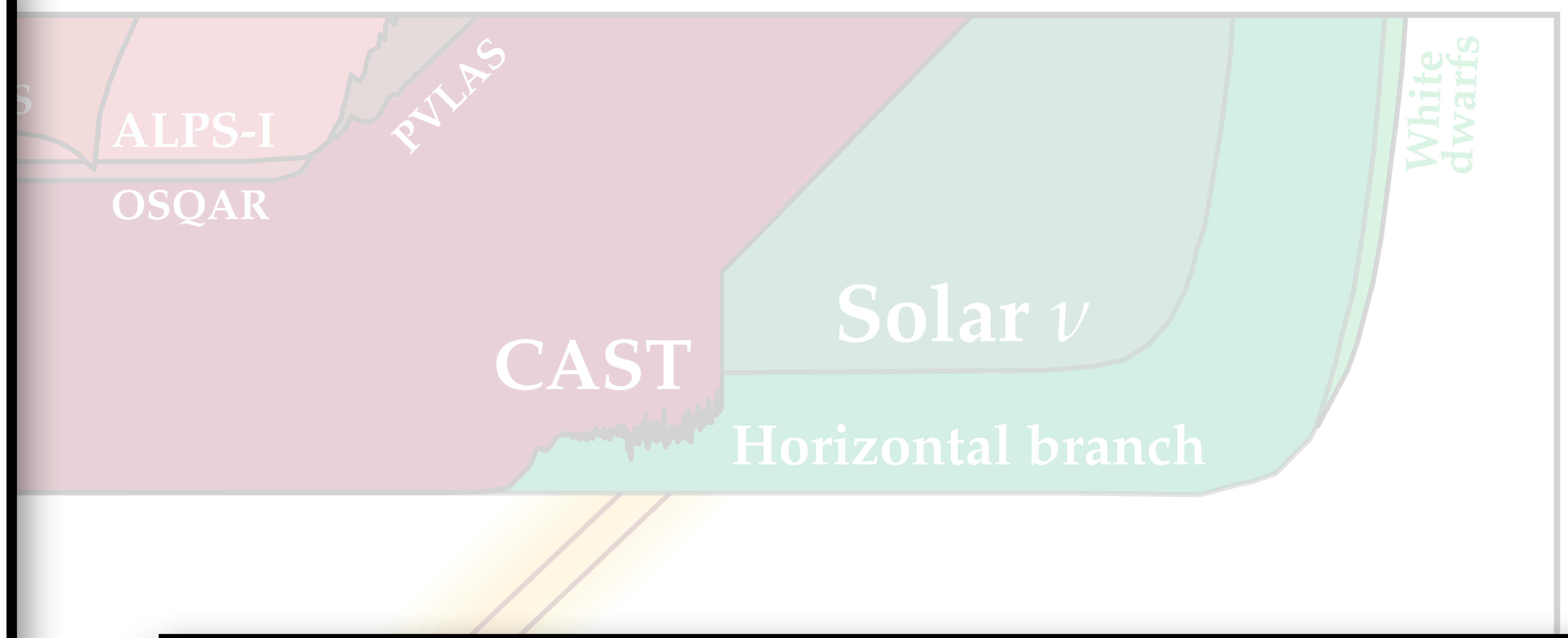


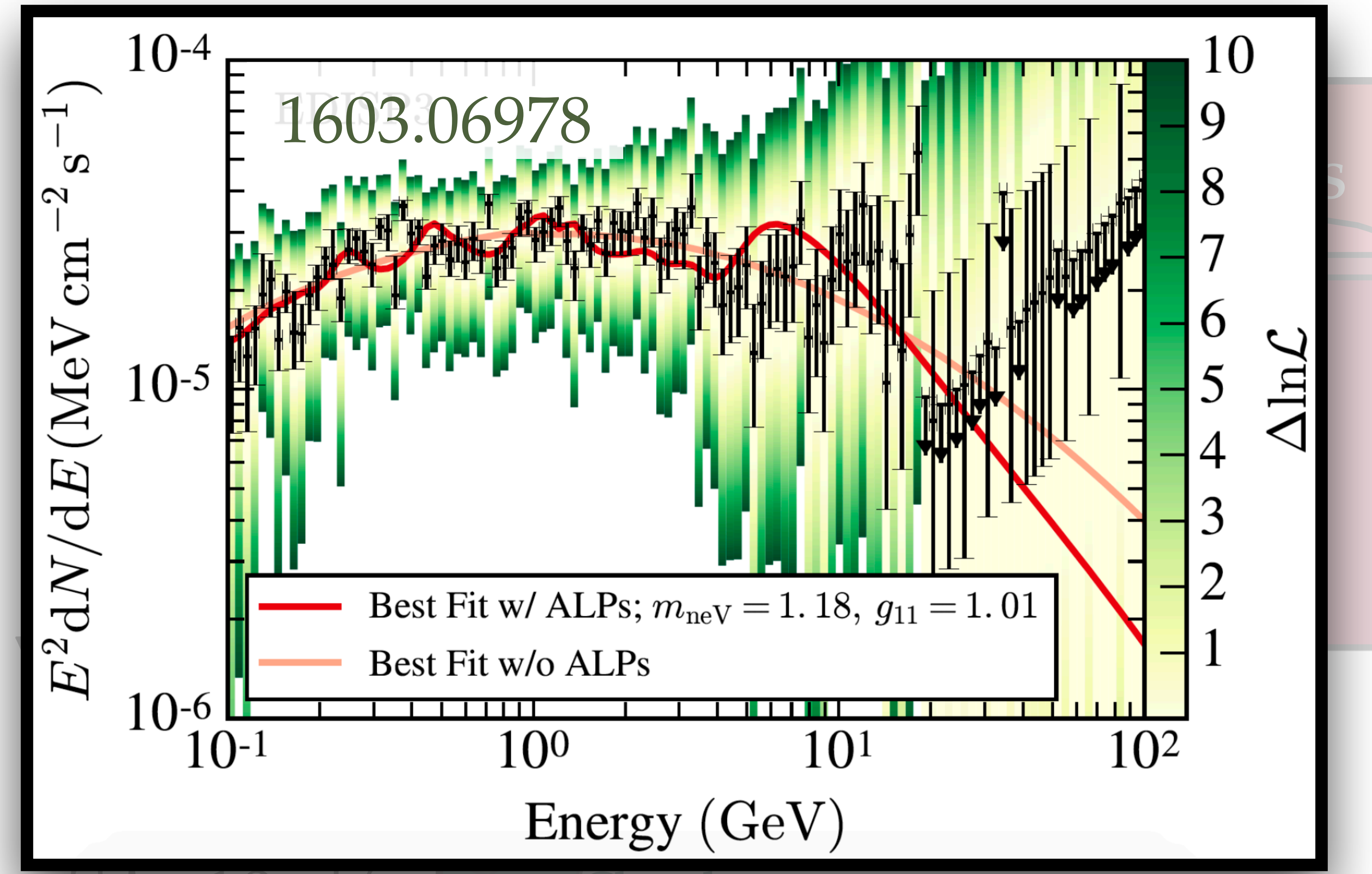

CROWS
ALPS-I
PVLAS
OSQAR
White dwarfs
Solar ν
CAST
Horizontal branch
DSNALP
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
CAST
Diffuse SN
Fermi SNe-γ
Mrk 421
Hydra-A
NGC1275 (Fermi)
PKS 2155-304
Super star clusters
SN1987A-γ
M87
NGC1275 (Chandra)
SN distance ladder
ALP dark matter
m_a [eV]

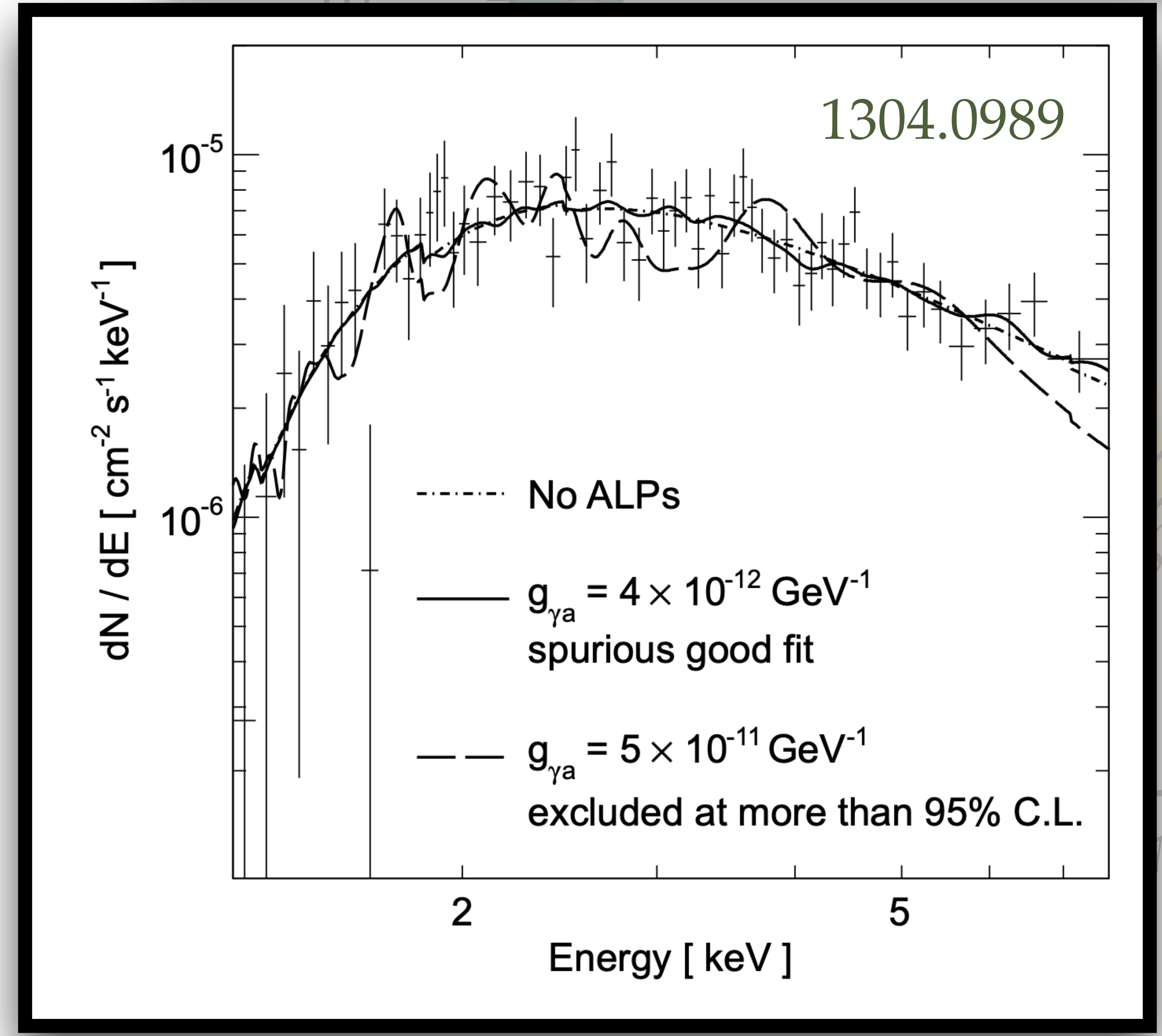

CROWS
ALPS-I
PVLAS
OSQAR
White dwarfs
Solar ν
CAST
Horizontal branch
DSNALP
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra

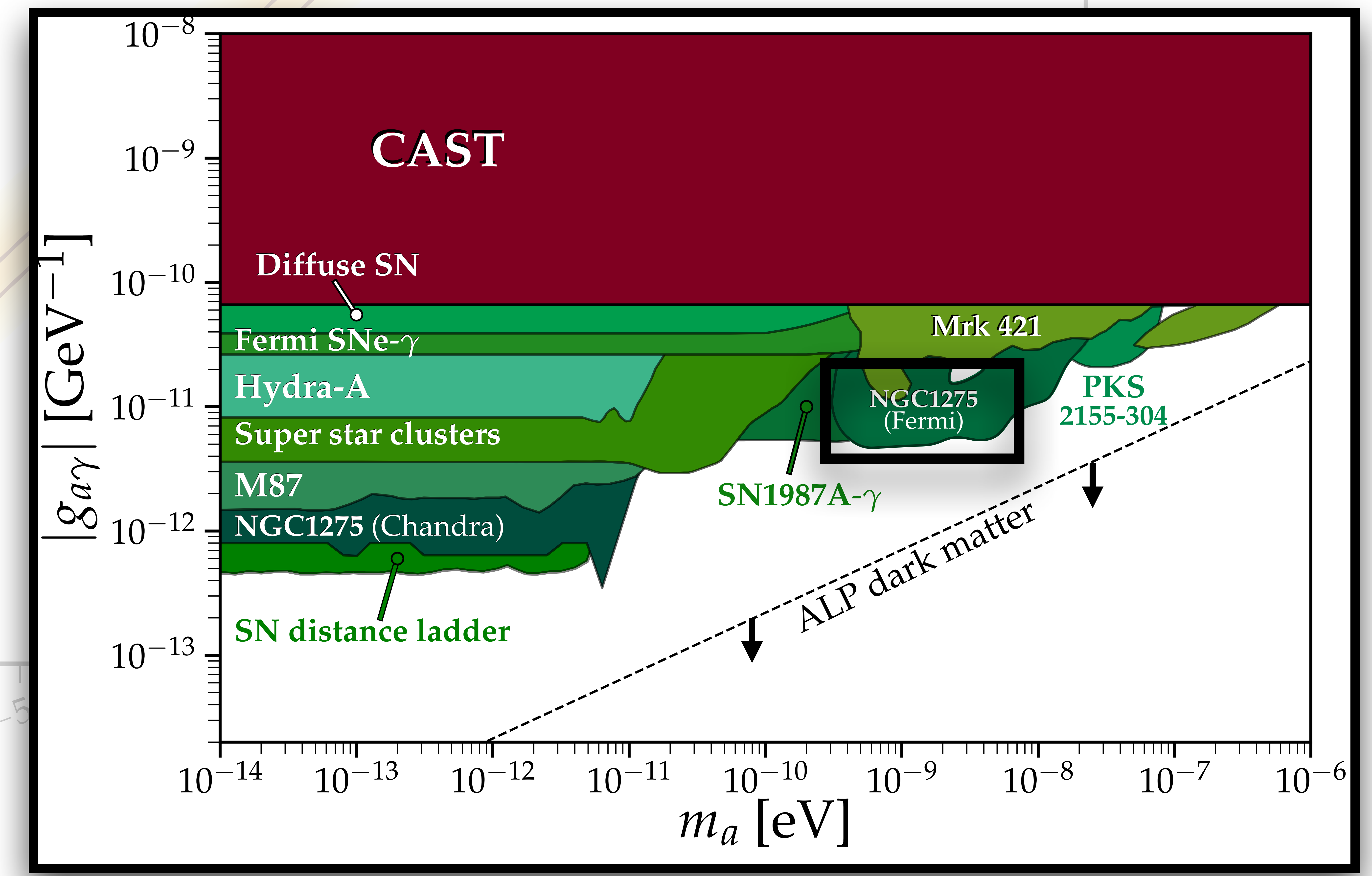

1304.0989
dN / dE [cm^{-2} s^{-1} keV^{-1}]
Energy [keV]
No ALPs
$g_{\gamma a} = 4 \times 10^{-12}$ GeV^{-1}
spurious good fit
$g_{\gamma a} = 5 \times 10^{-11}$ GeV^{-1}
excluded at more than 95% C.L.

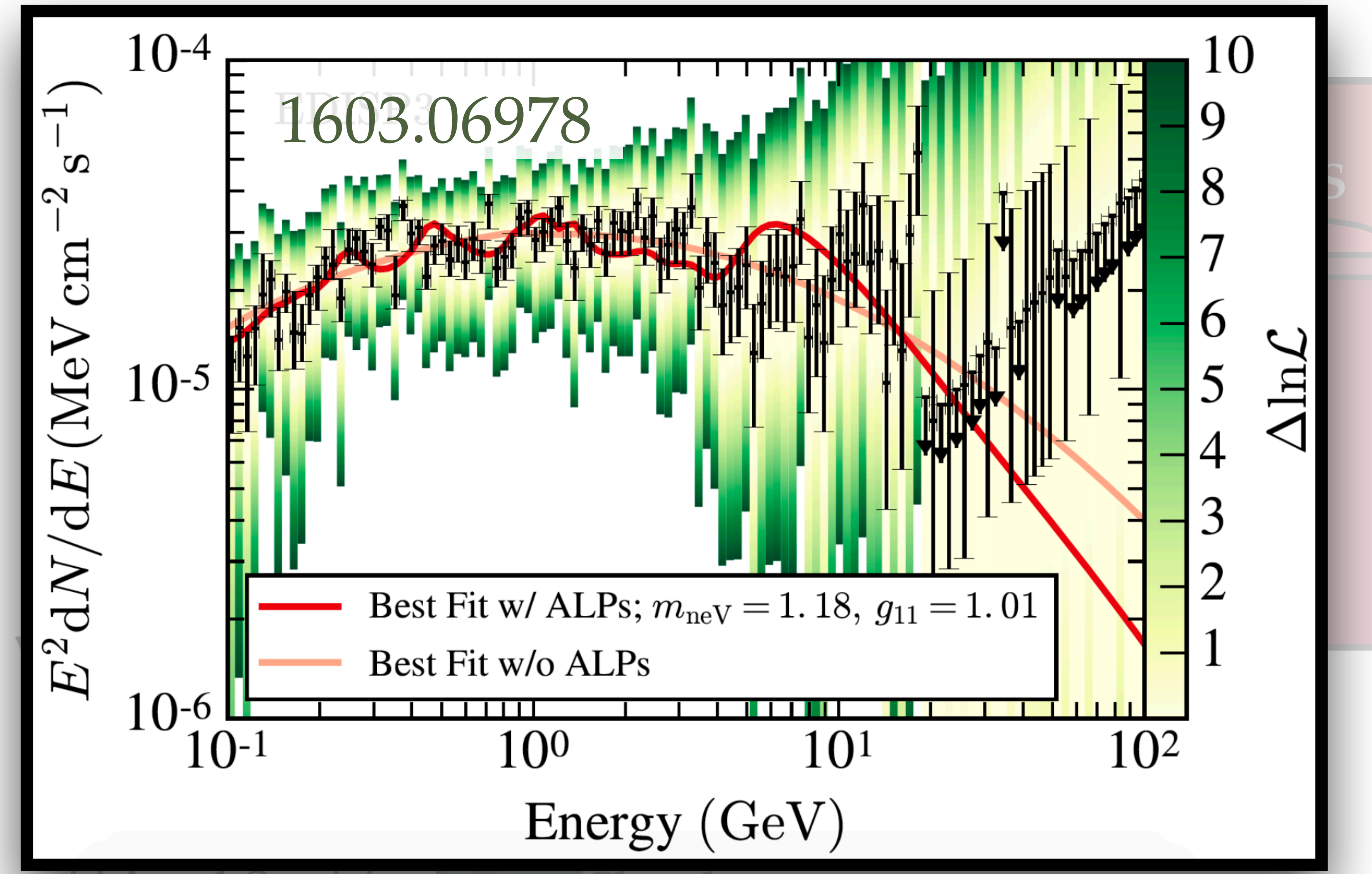

CAST
Diffuse SN
Fermi SNe-γ
Hydra-A
Super star clusters
M87
NGC1275 (Chandra)
SN distance ladder
Mrk 421
NGC1275 (Fermi)
PKS 2155-304
SN1987A-γ
ALP dark matter
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]


ALPS-I
OSQAR
PVLAS
CAST
Solar ν
Horizontal branch
White dwarfs


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


1304.0989
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.
dN / dE [cm^{-2} s^{-1} keV^{-1}]
Energy [keV]


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]


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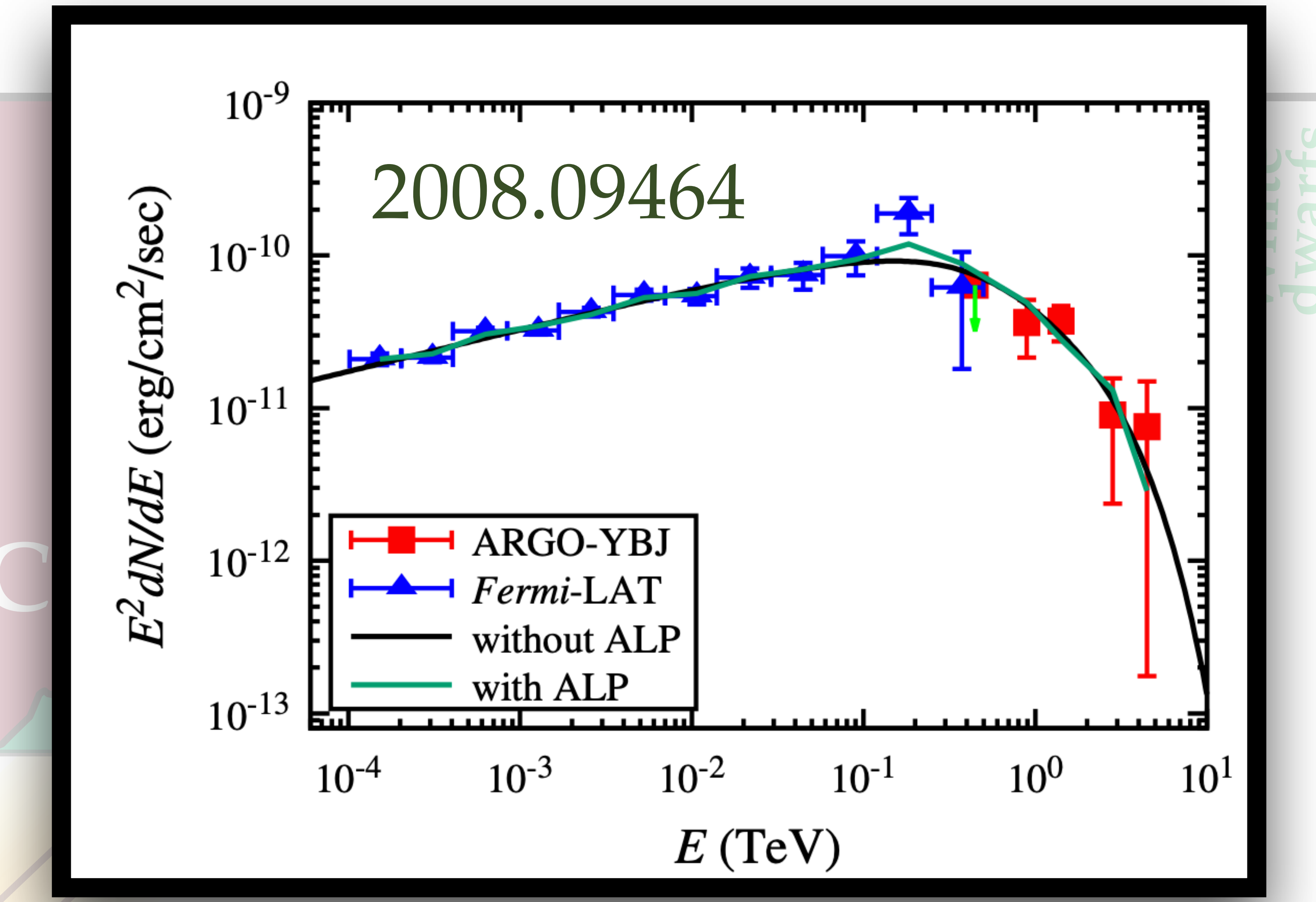
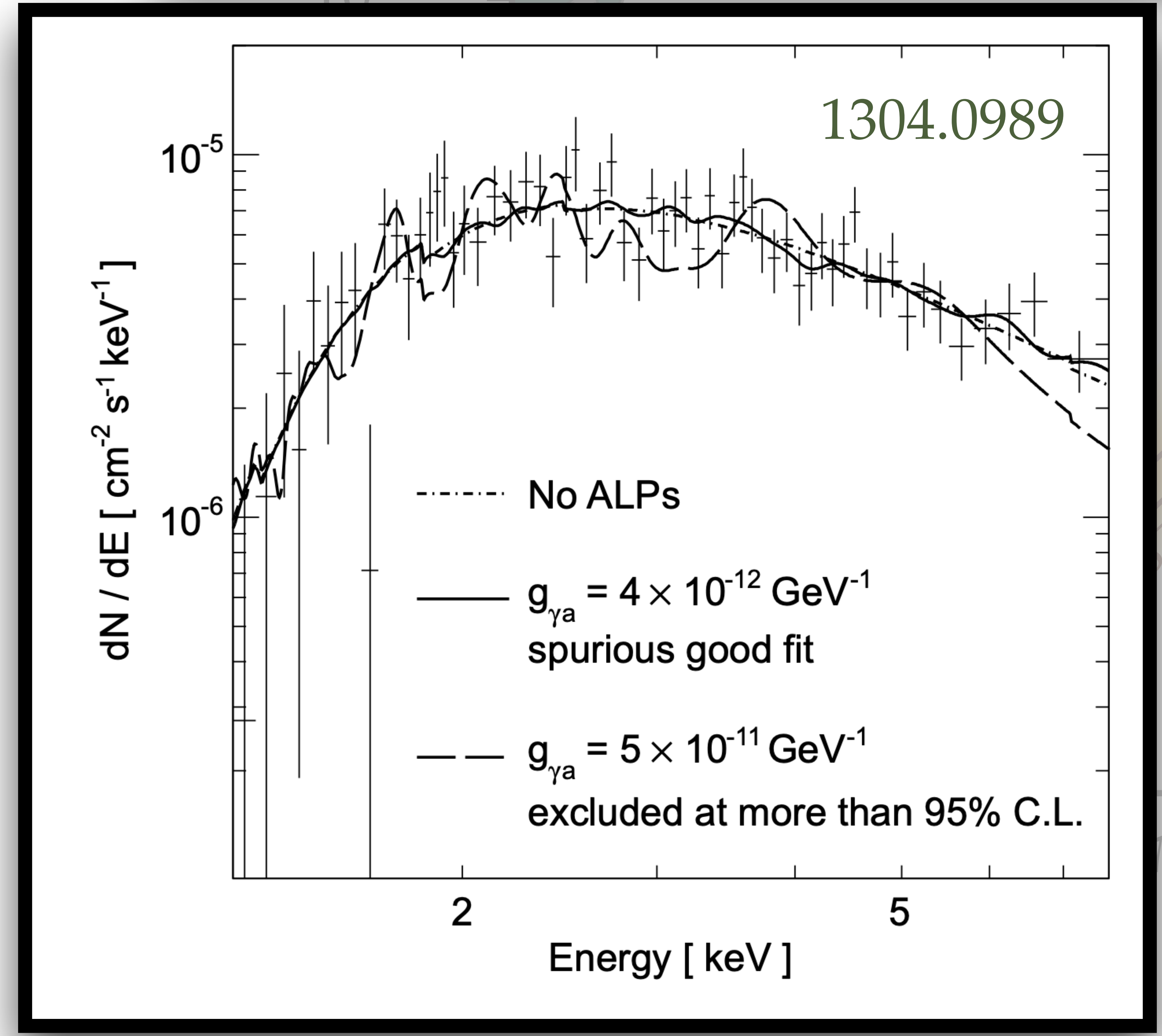

2008.09464
$E^2 dN/dE$ (erg/cm^2/sec)
E (TeV)
ARGO-YBJ
Fermi-LAT
without ALP
with ALP


1304.0989
dN / dE [cm^{-2} s^{-1} keV^{-1}]
Energy [keV]
No ALPs
$g_{\gamma a} = 4 \times 10^{-12}$ GeV^{-1}
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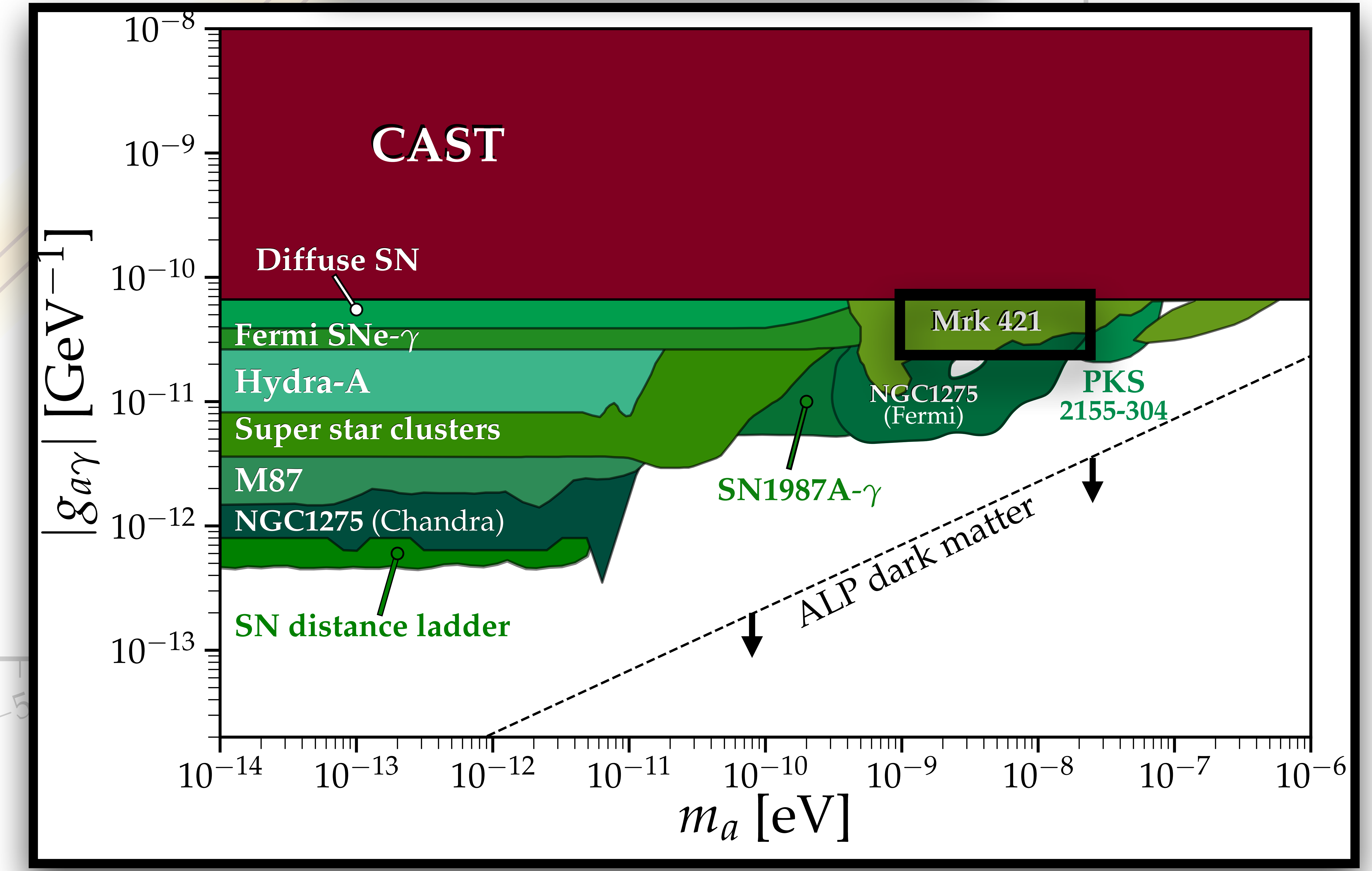
CAST
Diffuse SN
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Super star clusters
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Mrk 421
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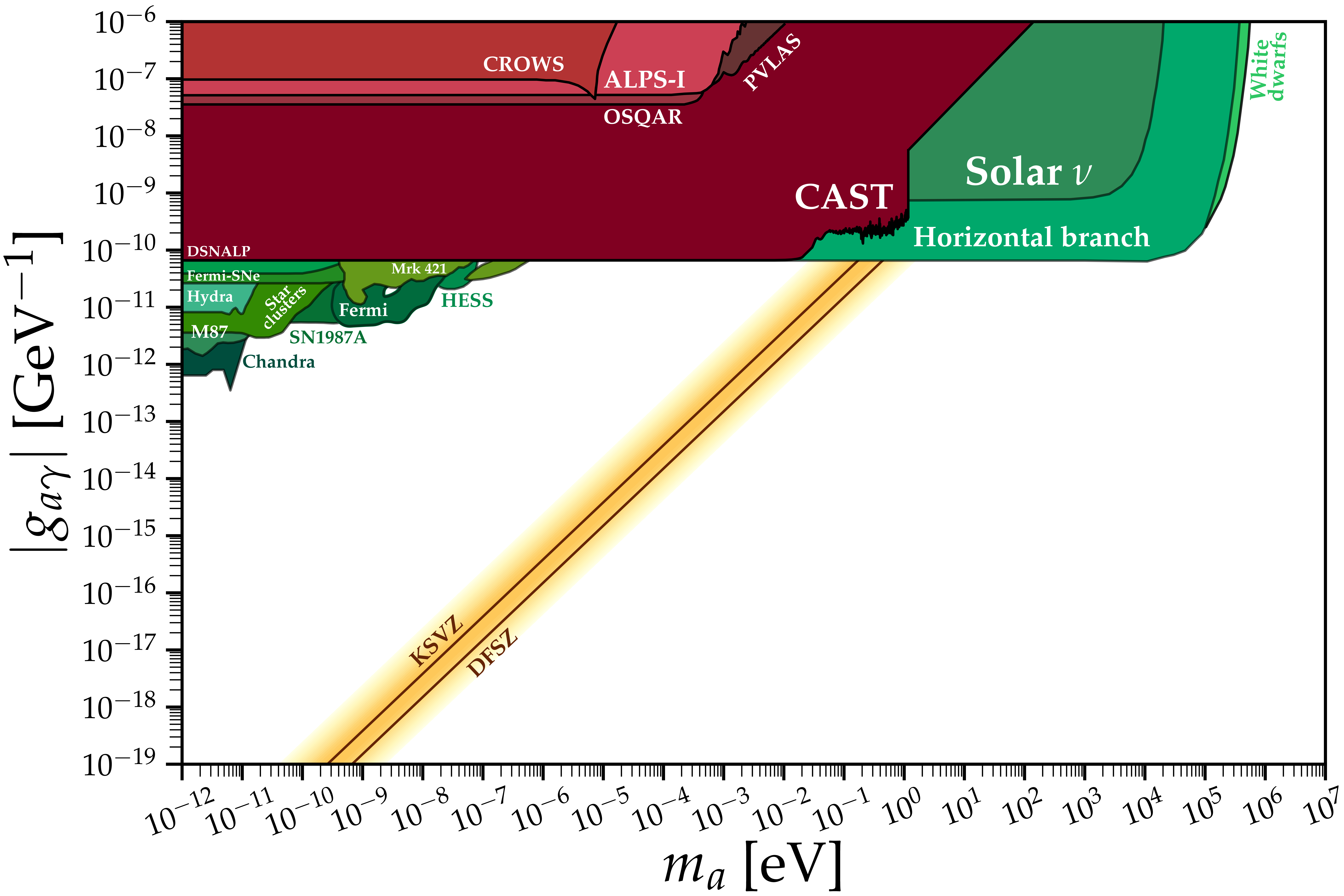
PKS 2155-304
SN1987A-γ
ALP dark matter
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]


CROWS
ALPS-I
PVLAS
OSQAR
Solar ν
CAST
Horizontal branch
White dwarfs
DSNALP
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
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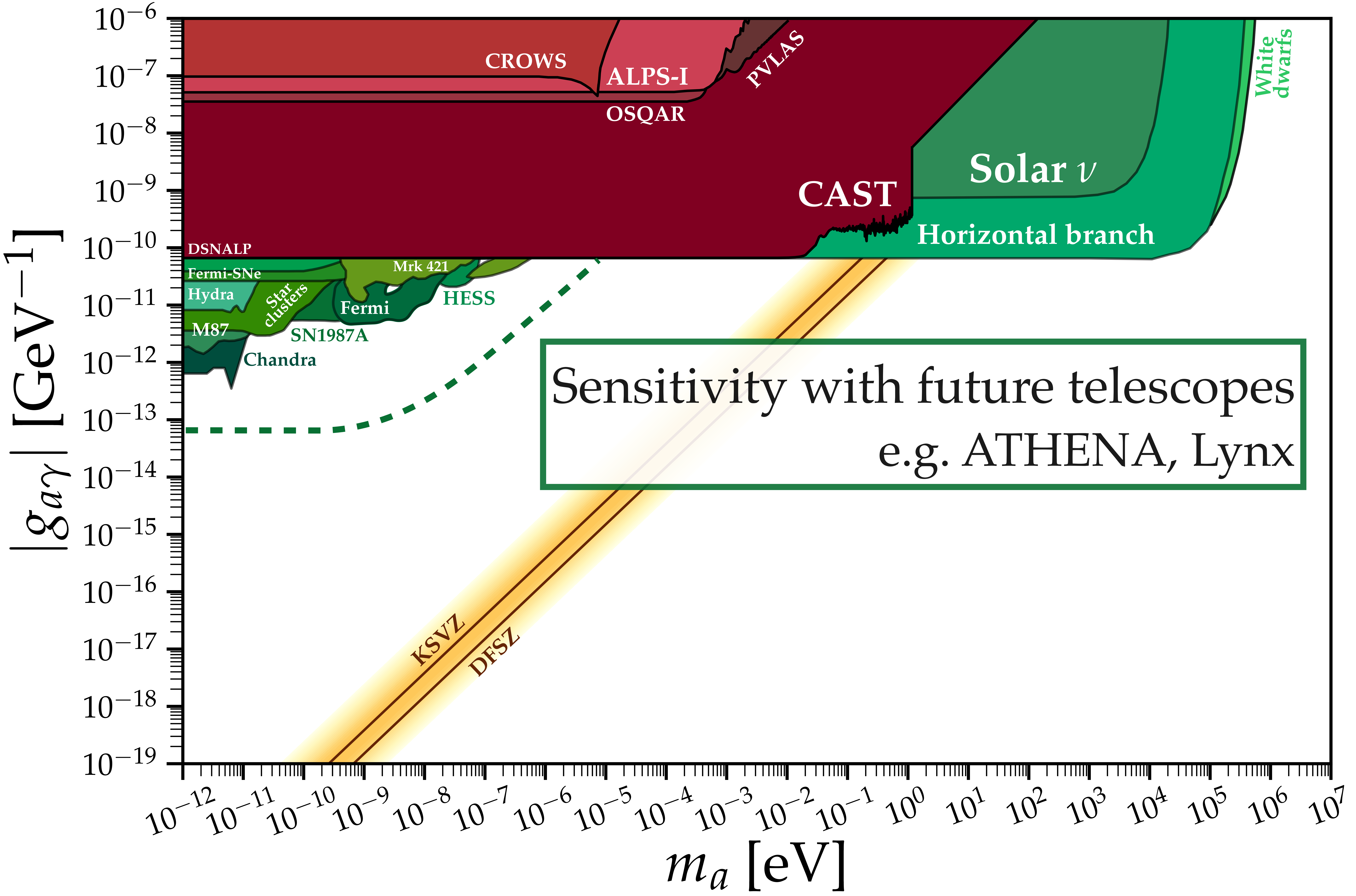
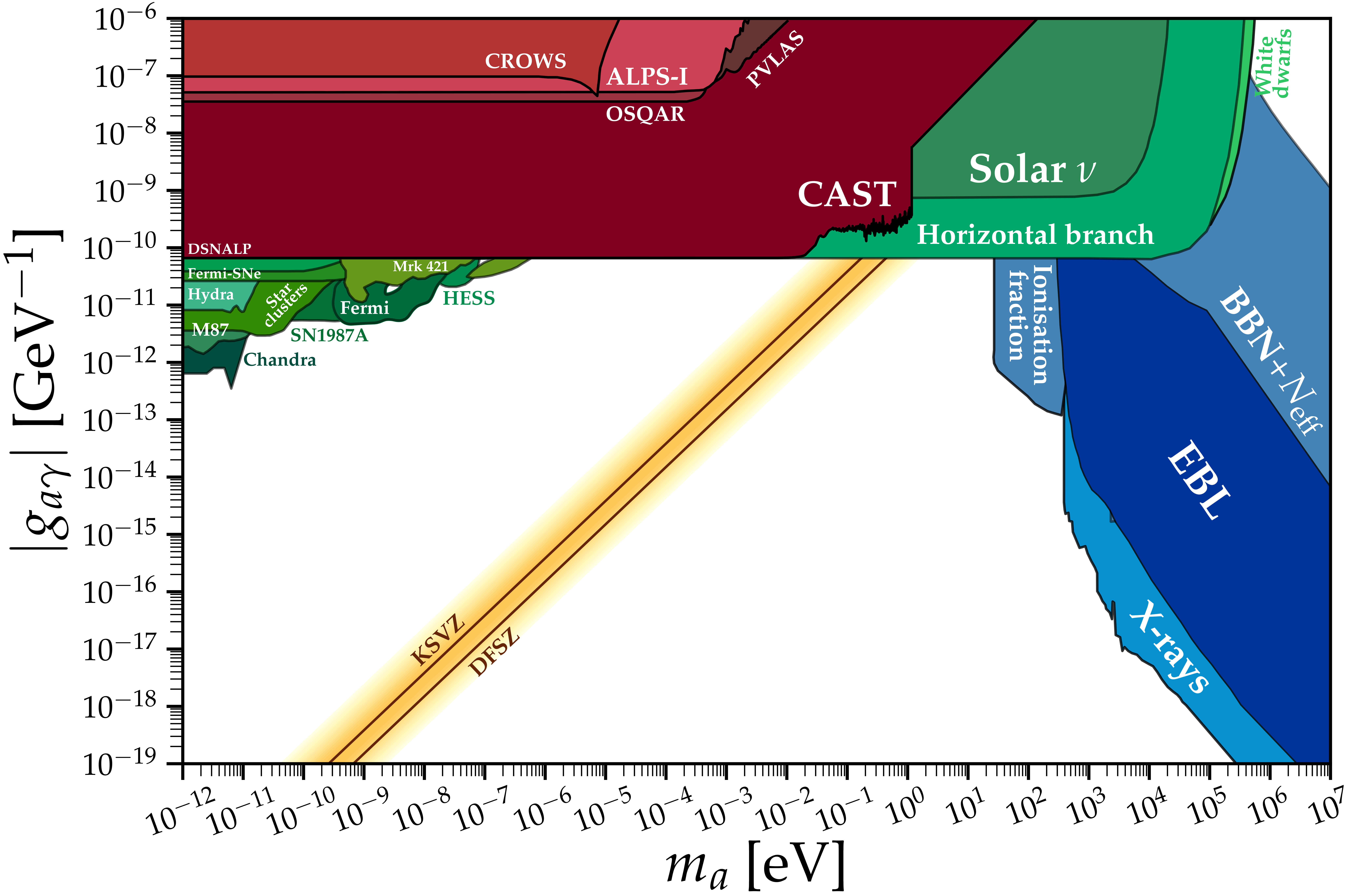
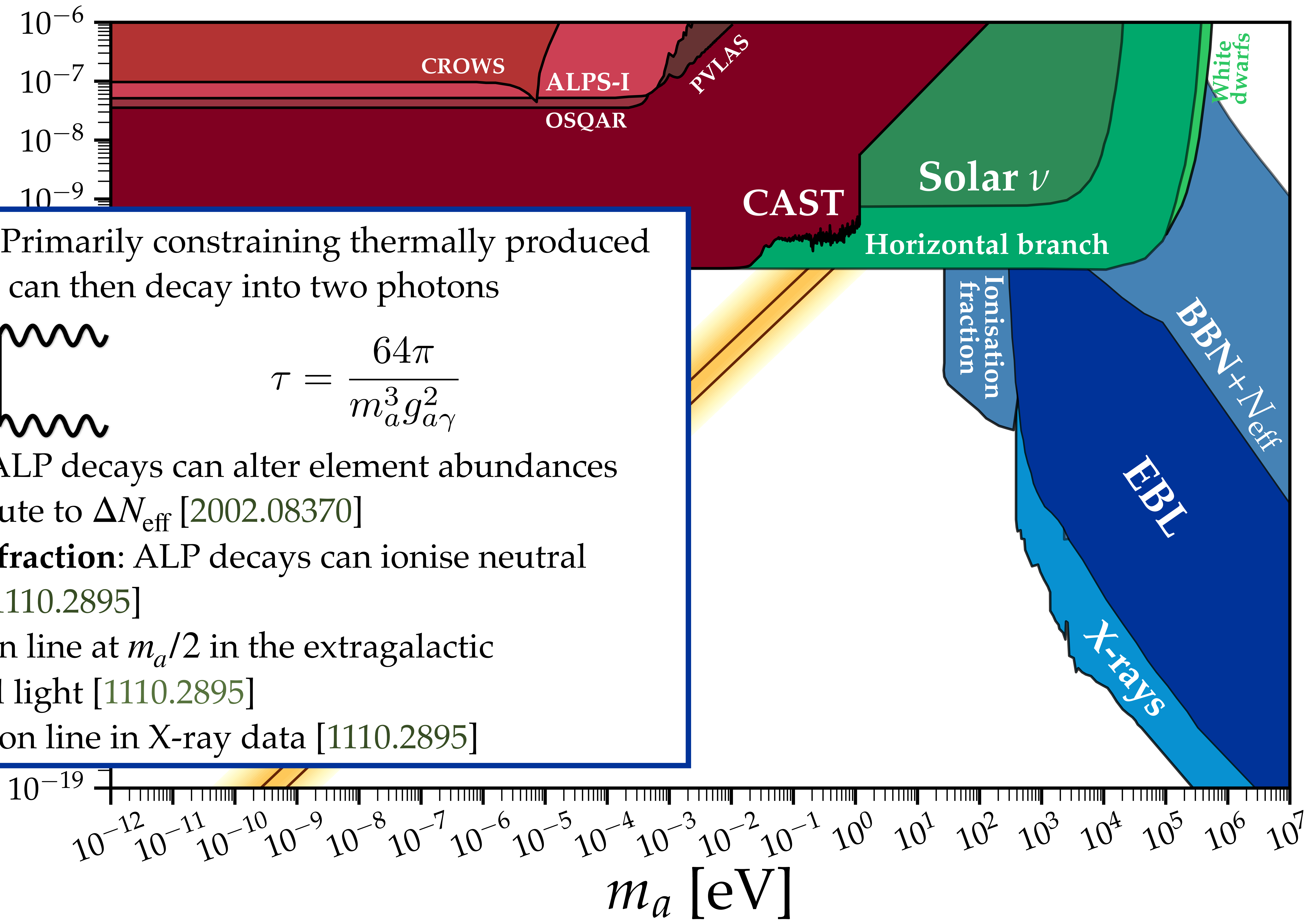
10^{6}
10^{7}



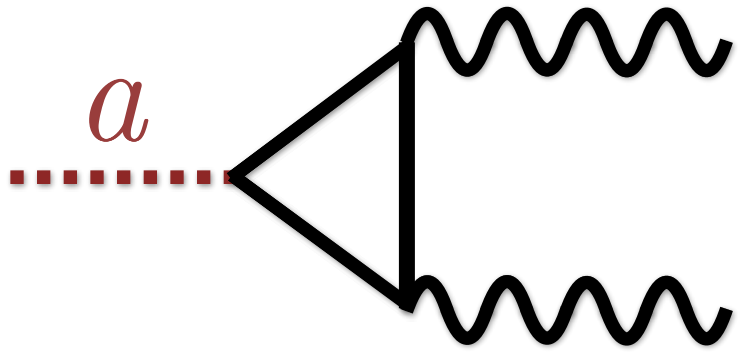
CROWS
ALPS-I
OSQAR
PVLAS
CAST
Solar ν
Horizontal branch
White dwarfs
DSNALP
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
Sensitivity with future telescopes
e.g. ATHENA, Lynx
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]



CROWS
ALPS-I
PVLAS
OSQAR
CAST
Solar ν
Horizontal branch
White dwarfs
DSNALP
Fermi-SNe
Mrk 421
Hydra
Star clusters
Fermi
HESS
M87
SN1987A
Chandra
Ionisation fraction
BBN+N_{eff}
EBL
X-rays
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]

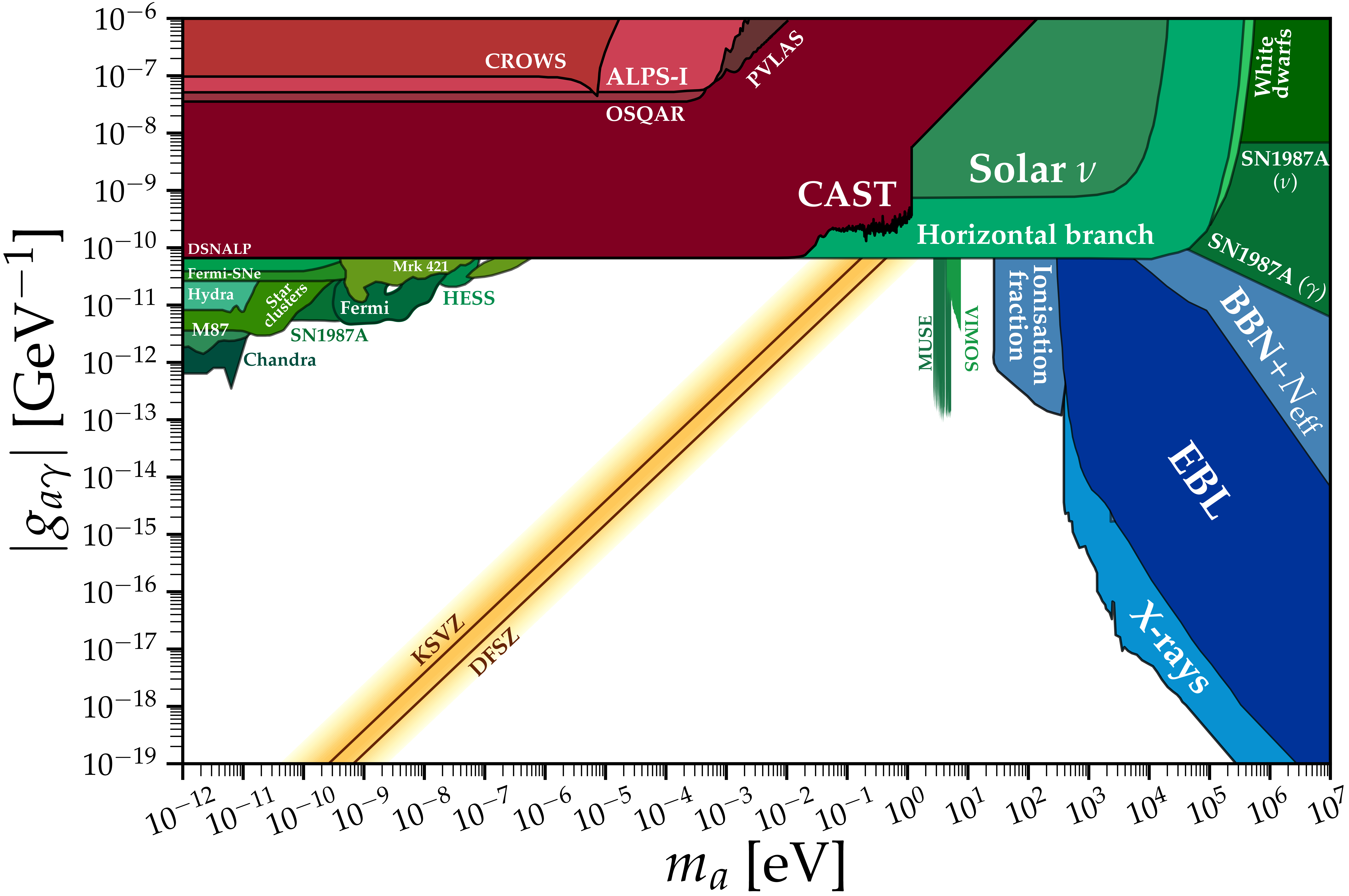


Cosmology: Primarily constraining thermally produced ALPs, which can then decay into two photons

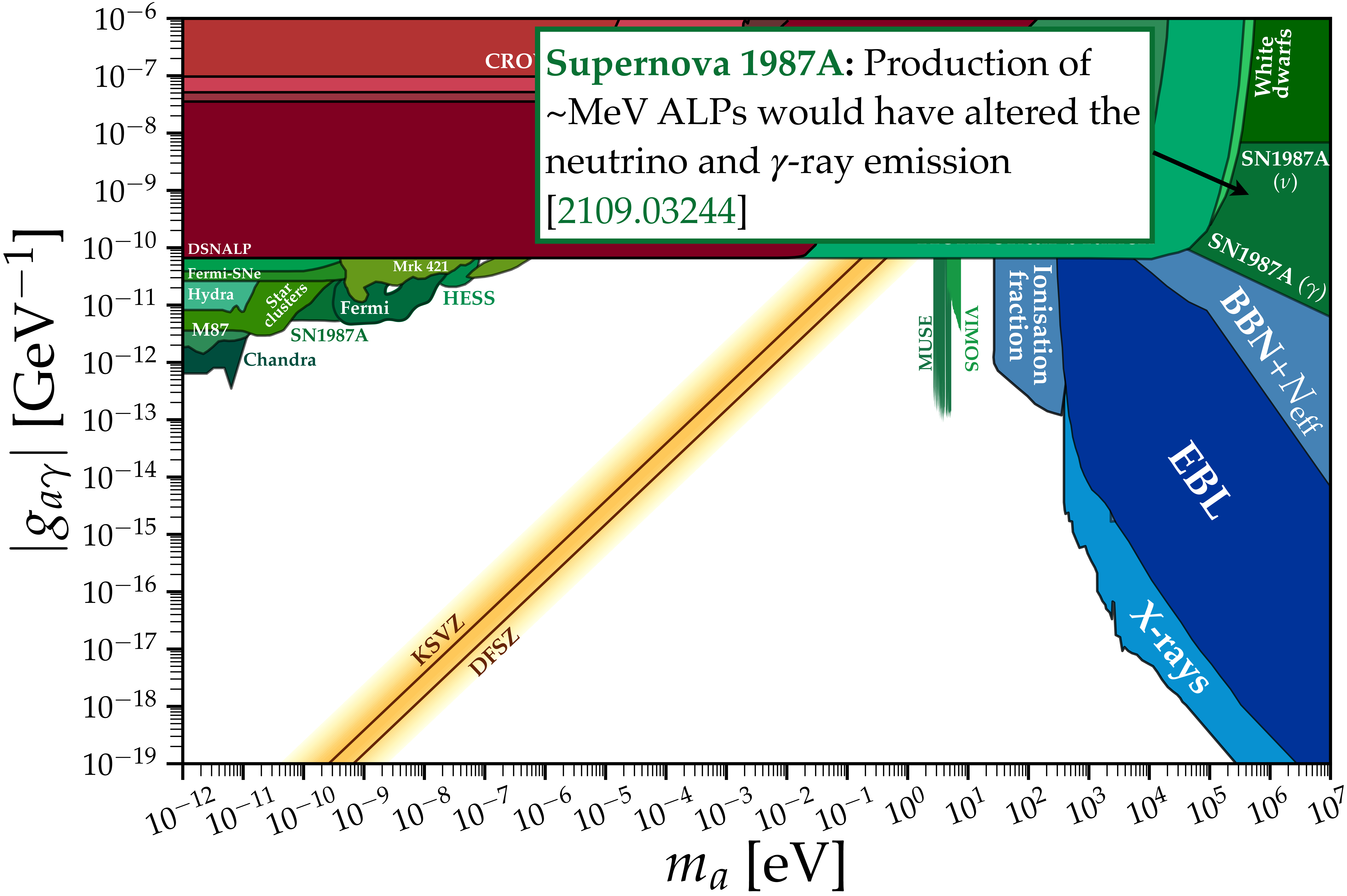


$$\tau = \frac{64\pi}{m_a^3 g_{a\gamma}^2}$$

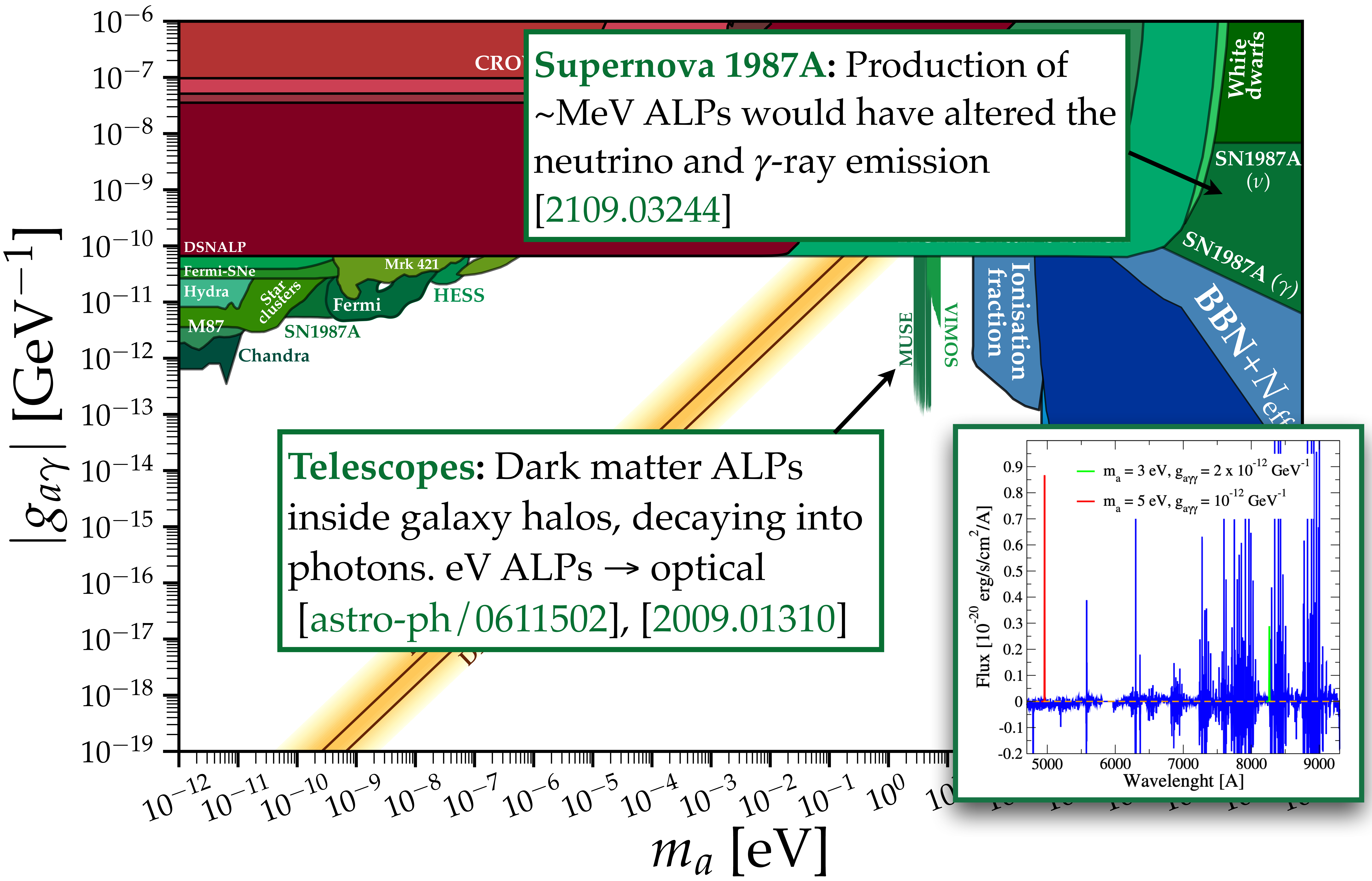
- **BBN/N$_{\text{eff}}$**: ALP decays can alter element abundances and contribute to ΔN_{eff} [2002.08370]
- **Ionisation fraction**: ALP decays can ionise neutral hydrogen [1110.2895]
- **EBL**: photon line at $m_a/2$ in the extragalactic background light [1110.2895]
- **X-ray**: photon line in X-ray data [1110.2895]

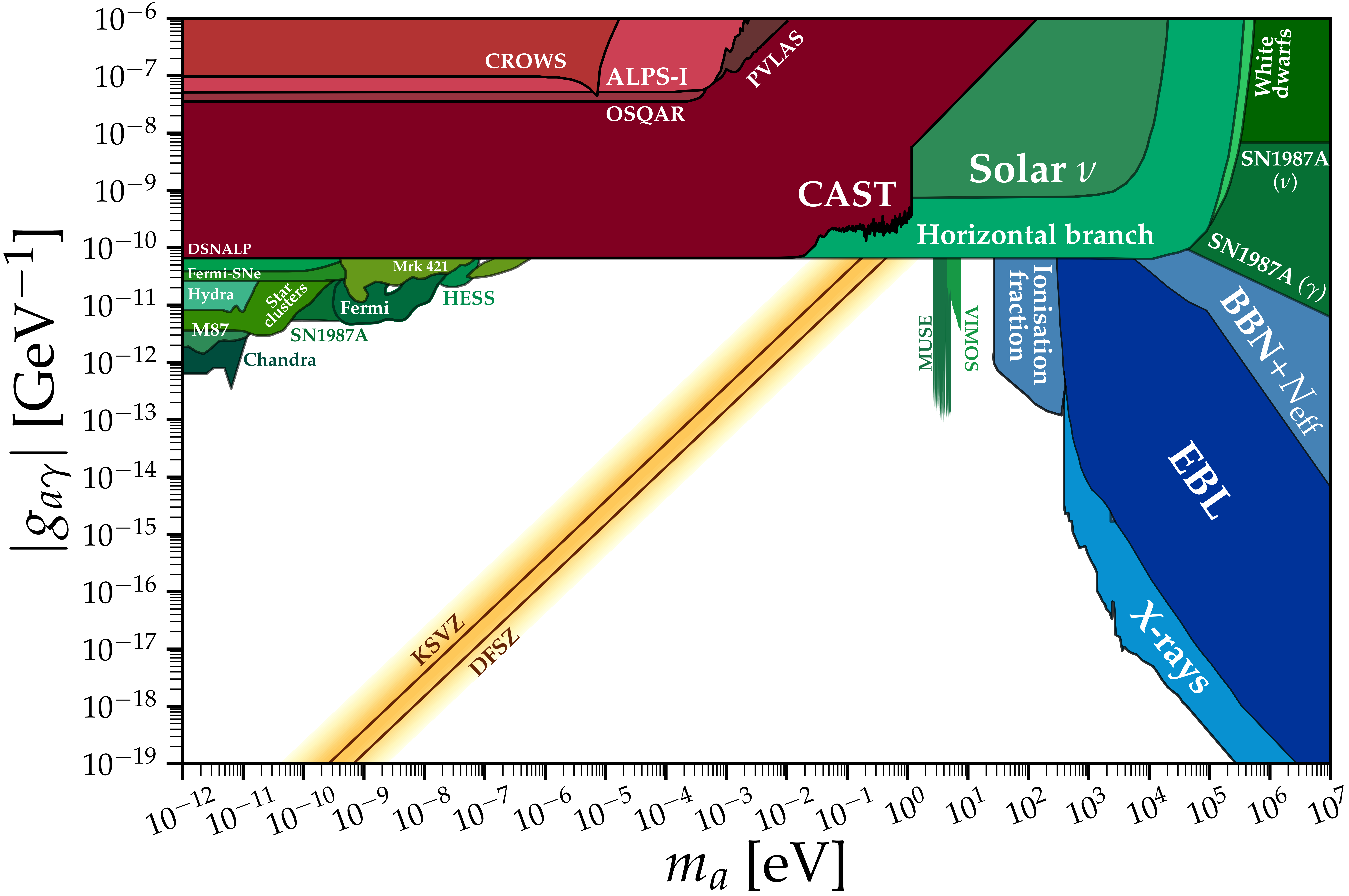


CROWS
ALPS-I
PVLAS
OSQAR
CAST
Solar ν
Horizontal branch
White dwarfs
SN1987A (ν)
SN1987A (γ)
DSNALP
Fermi-SNe
Hydra
Star clusters
M87
Chandra
Mrk 421
Fermi
HESS
SN1987A
MUSE
VIMOS
Ionisation fraction
BBN+N_eff
EBL
X-rays
KSVZ
DFSZ
|g_aγ| [GeV^−1]
m_a [eV]

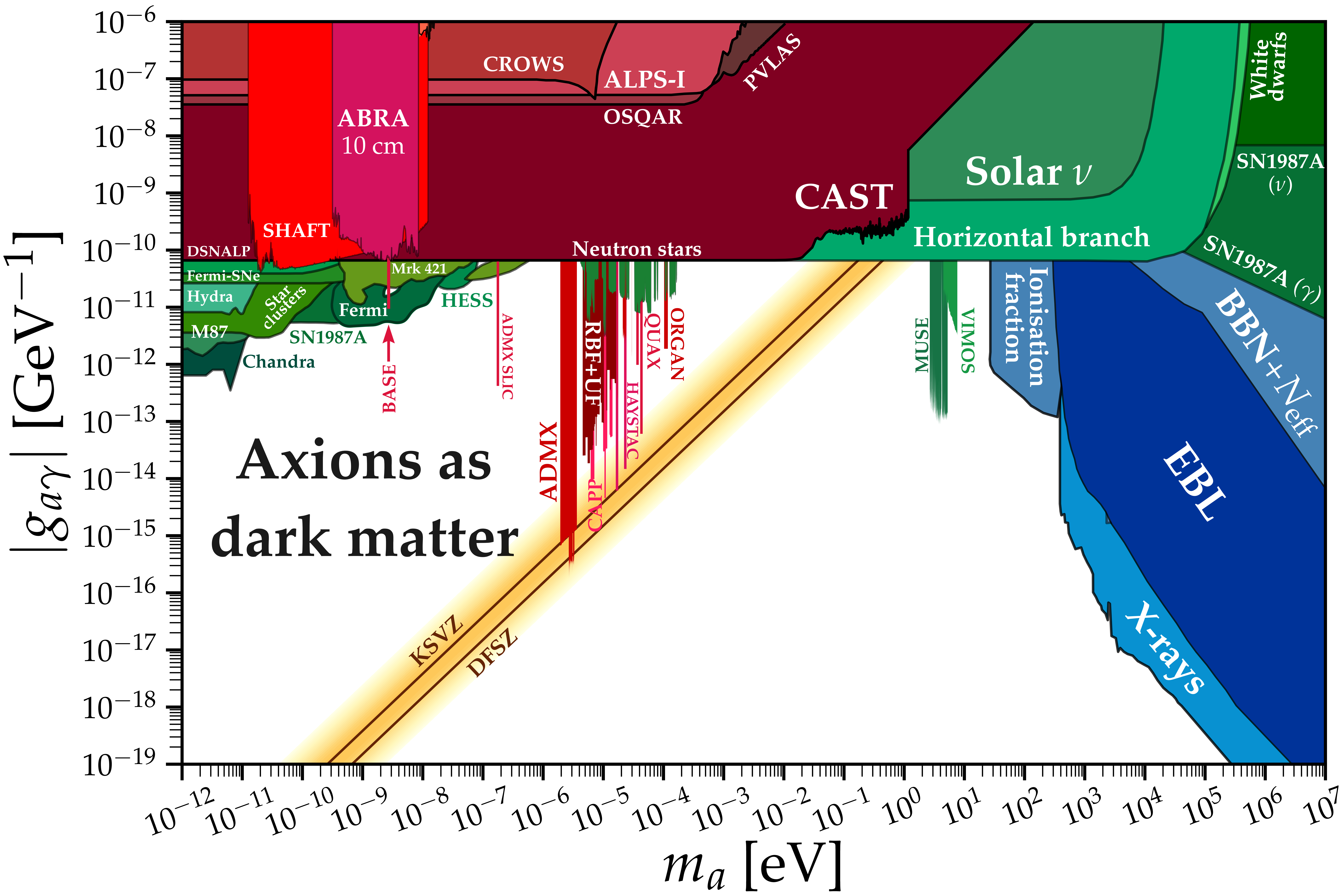


Supernova 1987A: Production of ~MeV ALPs would have altered the neutrino and γ-ray emission [2109.03244]
CRO
DSNALP
Fermi-SNe
Hydra
Star clusters
M87
Chandra
SN1987A
Fermi
Mrk 421
HESS
KSVZ
DFSZ
MUSE
VIMOS
Ionisation fraction
White dwarfs
SN1987A (ν)
SN1987A (γ)
BBN+N_eff
EBL
X-rays
|g_aγ| [GeV^−1]
m_a [eV]


Supernova 1987A: Production of ~MeV ALPs would have altered the neutrino and γ-ray emission [2109.03244]
Telescopes: Dark matter ALPs inside galaxy halos, decaying into photons. eV ALPs → optical [astro-ph/0611502], [2009.01310]
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
CRO
DSNALP
Fermi-SNe
Hydra
Star clusters
Mrk 421
Fermi
HESS
M87
SN1987A
Chandra
MUSE
VIMOS
Ionisation fraction
White dwarfs
SN1987A (ν)
SN1987A (γ)
BBN+N
m_a = 3 eV, $g_{a\gamma\gamma}$ = 2 x 10^{-12} GeV^{-1}
m_a = 5 eV, $g_{a\gamma\gamma}$ = 10^{-12} GeV^{-1}
Flux [10^{-20} erg/s/cm^2/A]
Wavelenght [A]



CROWS
ALPS-I
PVLAS
OSQAR
CAST
Solar ν
Horizontal branch
White dwarfs
SN1987A (ν)
SN1987A (γ)
DSNALP
Fermi-SNe
Hydra
Star clusters
M87
Mrk 421
Fermi
HESS
SN1987A
Chandra
MUSE
VIMOS
Ionisation fraction
BBN+N_eff
EBL
X-rays
KSVZ
DFSZ
|g_aγ| [GeV^−1]
m_a [eV]



Axions as dark matter
CROWS
ALPS-I
PVLAS
OSQAR
ABRA 10 cm
SHAFT
DSNALP
Neutron stars
CAST
Solar ν
Horizontal branch
White dwarfs
SN1987A (ν)
SN1987A (γ)
BBN+N_{eff}
Fermi-SNe
Hydra
Star clusters
Mrk 421
Fermi
HESS
M87
SN1987A
Chandra
BASE
ADMX SLIC
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
MUSE
VIMOS
Ionisation fraction
EBL
X-rays
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]

Dark matter axions

behave like a classical field : $a(\mathbf{x}, t) \approx \frac{\sqrt{2\rho_a}}{m_a} \cos(\omega t - \mathbf{p} \cdot \mathbf{x} + \alpha)$

$\omega \approx m_a$

Oscillating at the axion mass

Axion electrodynamics

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

Axion electrodynamics

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

- EL equation for photon shows we can interpret axion as the source of an effective current: $\partial_{\mu} F^{\mu\nu} = J^{\nu} - g_{a\gamma} \widetilde{F}_{\mu\nu} \partial_{\mu} a$

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

Axion electrodynamics

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

- EL equation for photon shows we can interpret axion as the source of an effective current:

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

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

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$
$$\widetilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\alpha\beta}F_{\alpha\beta}$$
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Axion electrodynamics

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

- Rewrite Maxwell's equations with $J \rightarrow J + J_a$:

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

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

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

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

Ampere's law

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

Ampere's law

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

Ampere's law

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

Usually not important unless experiment larger than

$\lambda_{dB} \sim (\nabla a)^{-1} \sim (m_a \mathbf{v})^{-1} \sim 10^3 \lambda_c$

(Most experiments are actually around $\lambda_c \sim 1/m_a$ or smaller)

Ampere's law

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

Ampere's law

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

Oscillating axion field

Ampere's law

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

Axion-induced electric field

Oscillating axion field

Ampere's law

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

Axion-induced magnetic field

Axion-induced electric field

Oscillating axion field

Ampere's law

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

Axion-induced magnetic field

Axion-induced electric field

Oscillating axion field

What kind of experiment do we need to measure this?

→ Depends on size of Compton wavelength ($1/m_a$) relative to the size of some instrument, say $\mathcal{O}$(metres)

Haloscope strategies

<μeV**:** Compton wavelength long relative to experiment. DC magnetic field induces oscillating magnetic field

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

Haloscope strategies

<μeV: Compton wavelength long relative to experiment. DC magnetic field induces oscillating magnetic field

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

~1-100 μeV: Compton wavelength similar scale to experiment. Axion sources oscillating E&M-fields → couple to an EM mode inside a cavity

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

Haloscope strategies

<μeV: Compton wavelength long relative to experiment. DC magnetic field induces oscillating magnetic field

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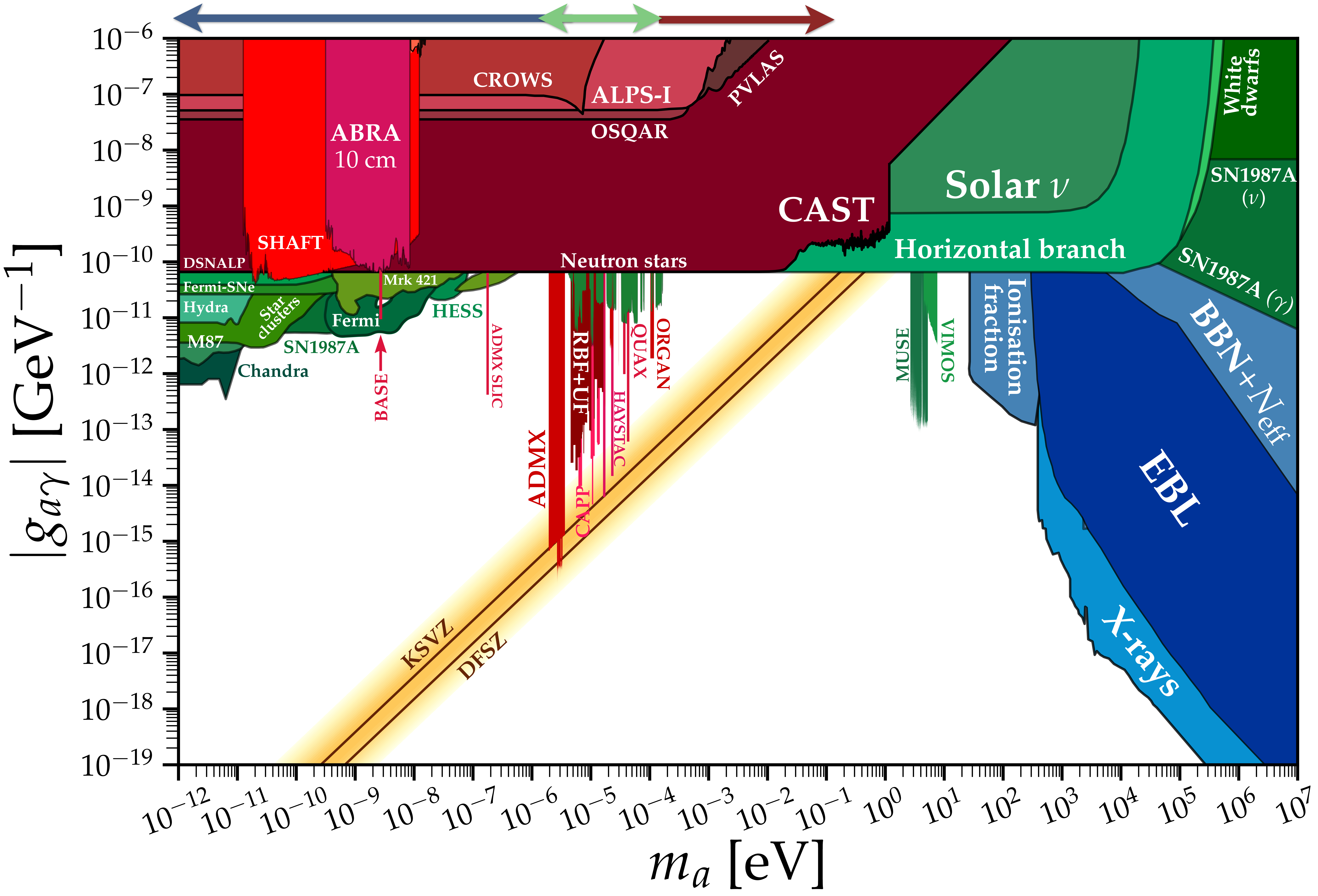
~1-100 μeV: Compton wavelength similar scale to experiment. Axion sources oscillating E&M-fields → couple to an EM mode inside a cavity

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

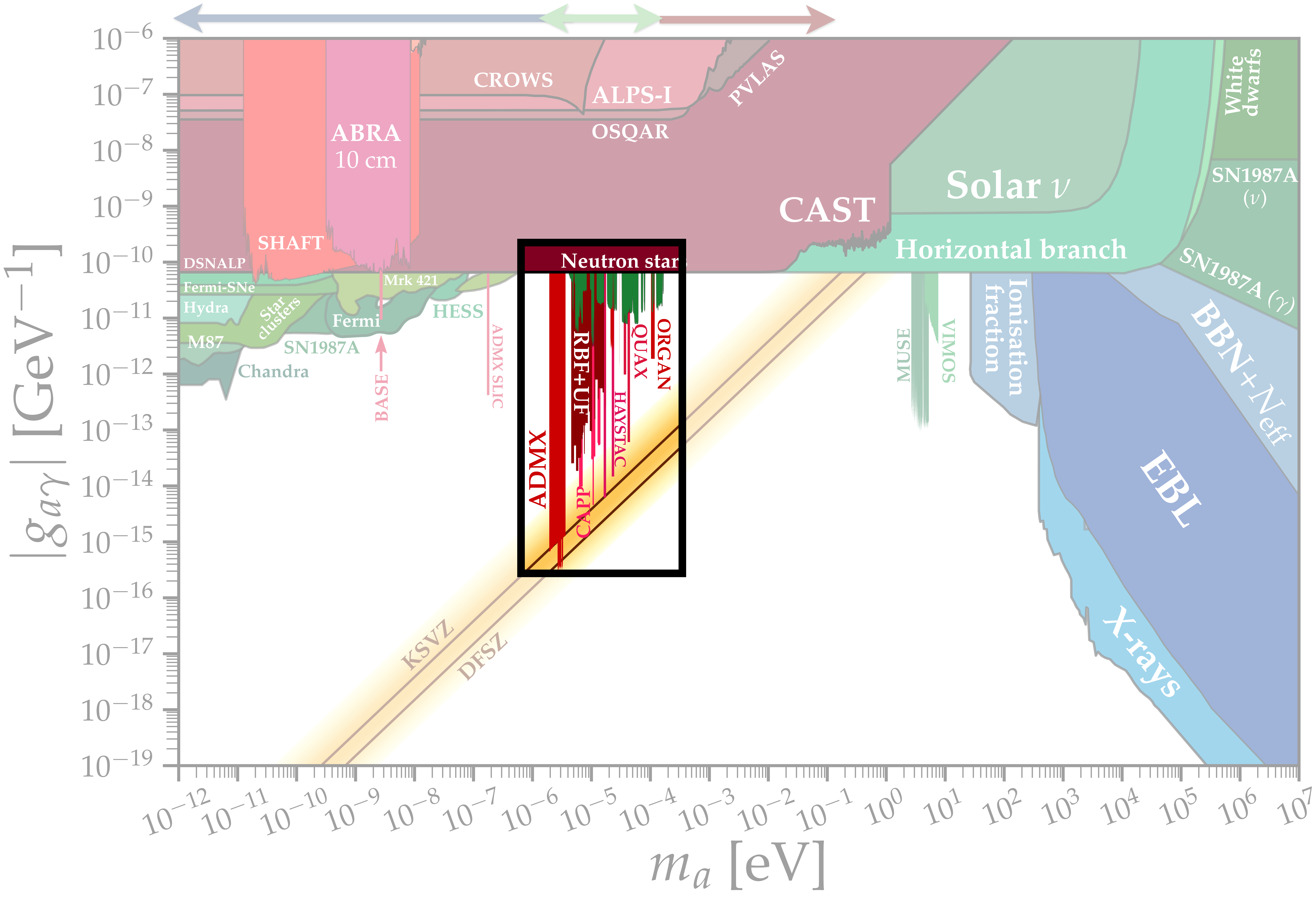
$\gtrsim$ 100 μeV: Compton wavelength short relative to experiment. Axion generates radiation → arrange experiment to have constructive interference

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

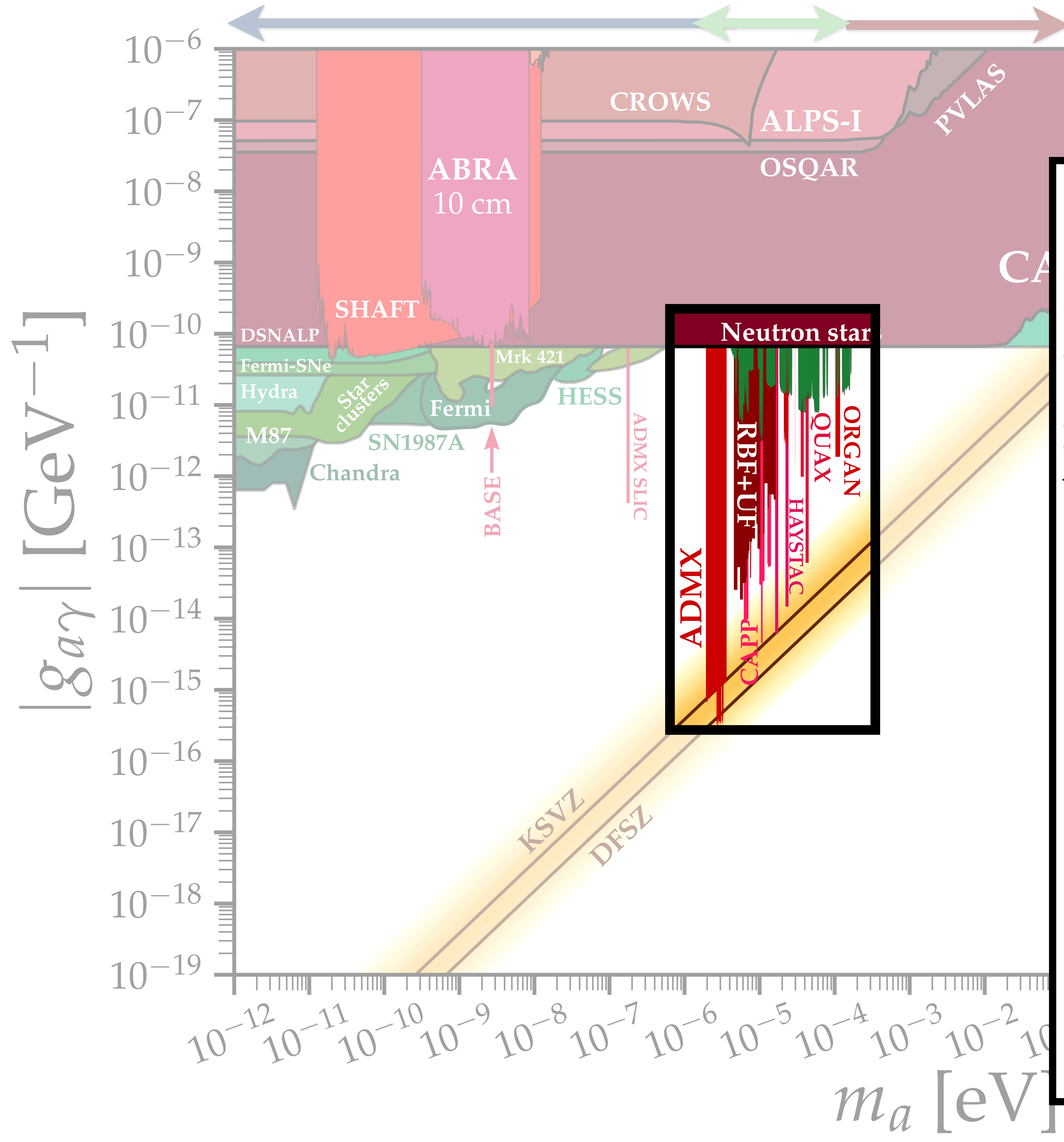


$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

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

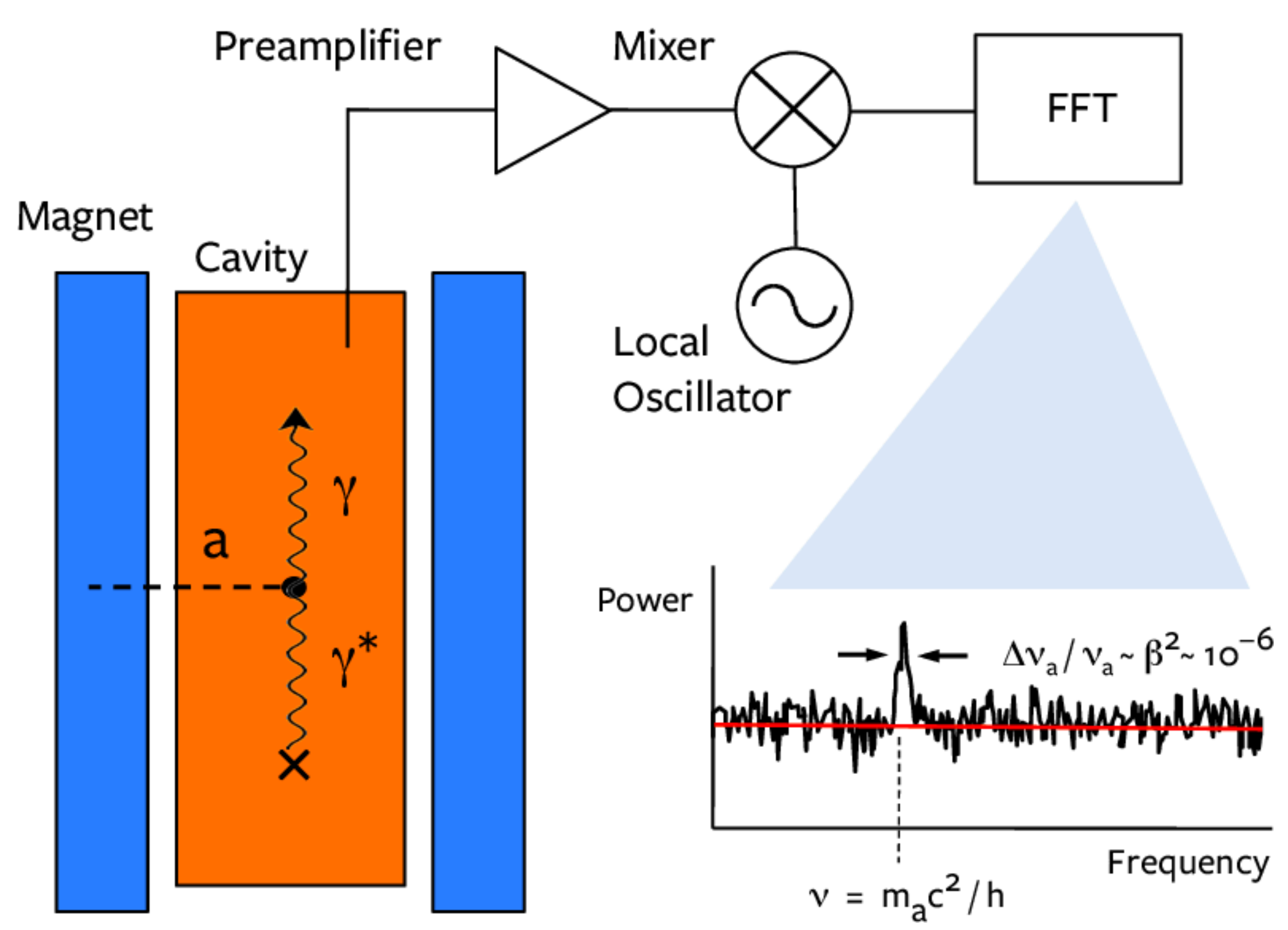


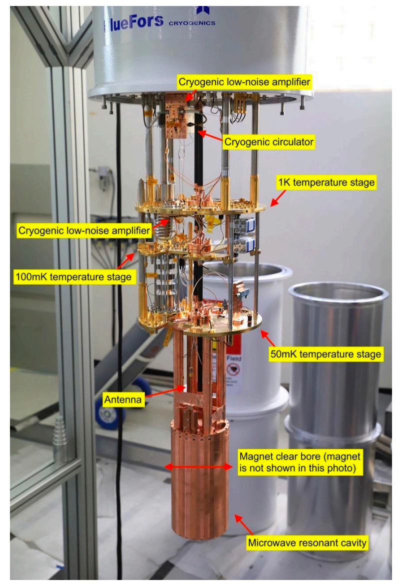
$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma} \mathbf{B}_0 \frac{\partial a}{\partial t}$$

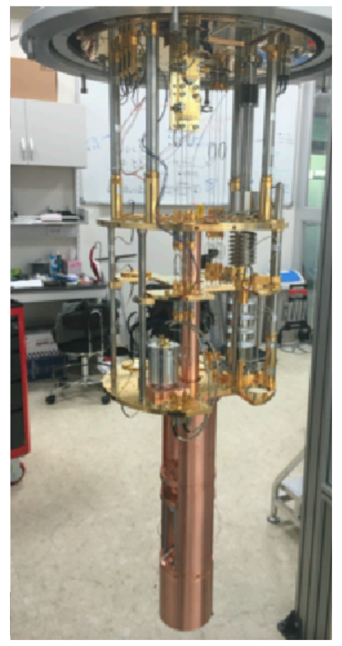


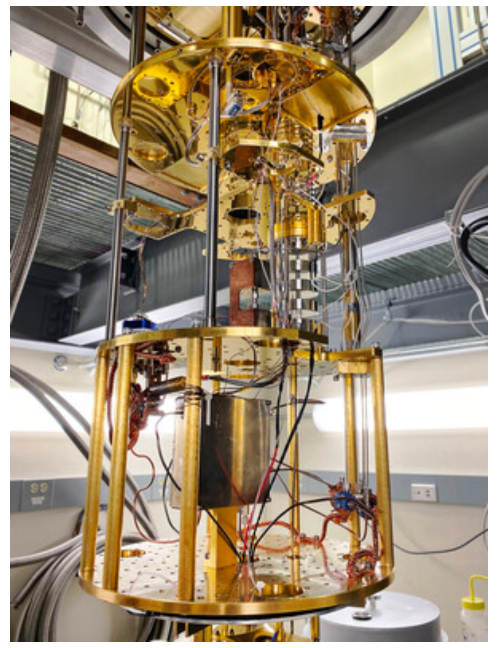
Cavity haloscopes

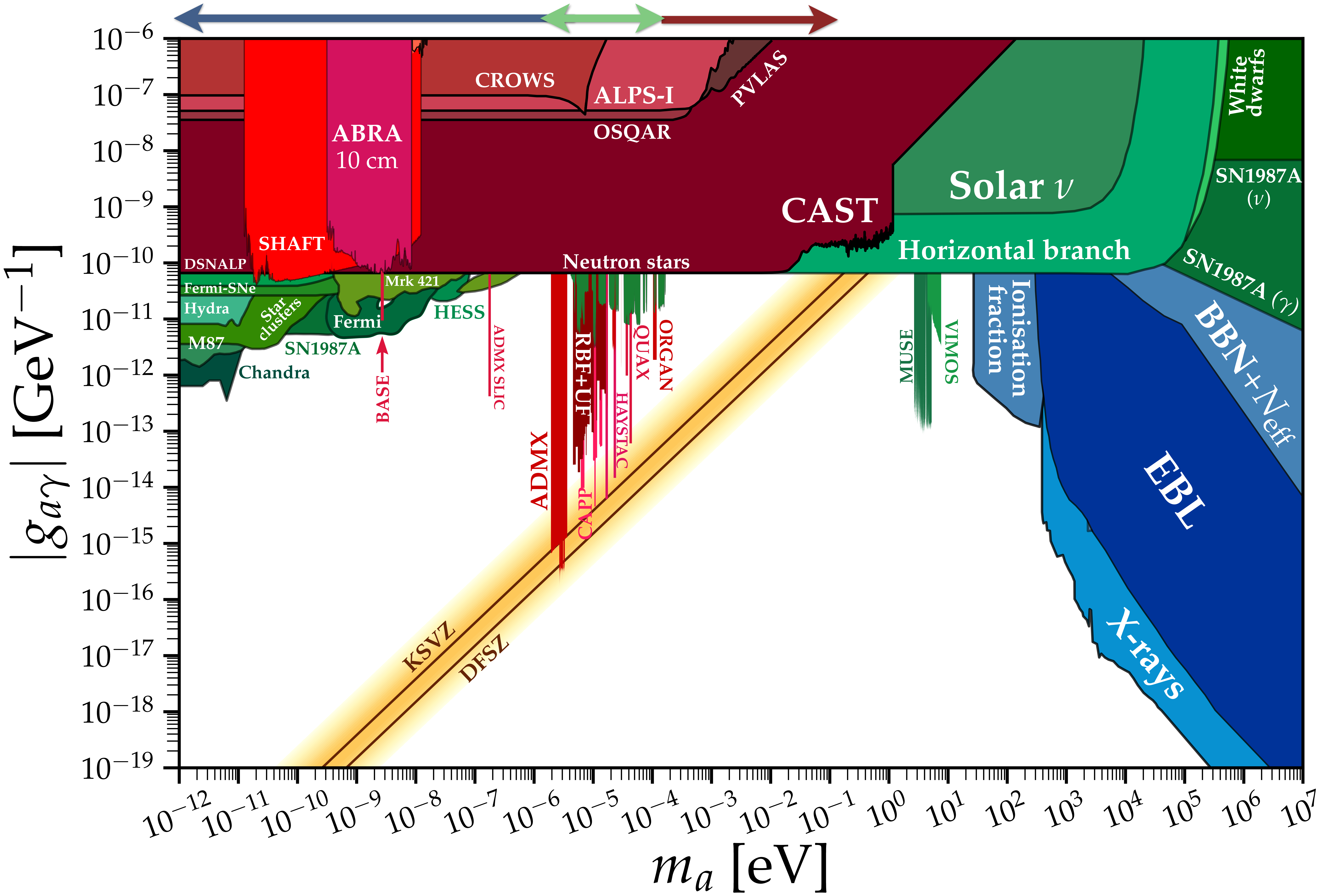
Most well-developed technique. High-Q cavity with modes that couple to the axion giving strong narrow-band signal, a range of axion masses can be scanned using tuning rods





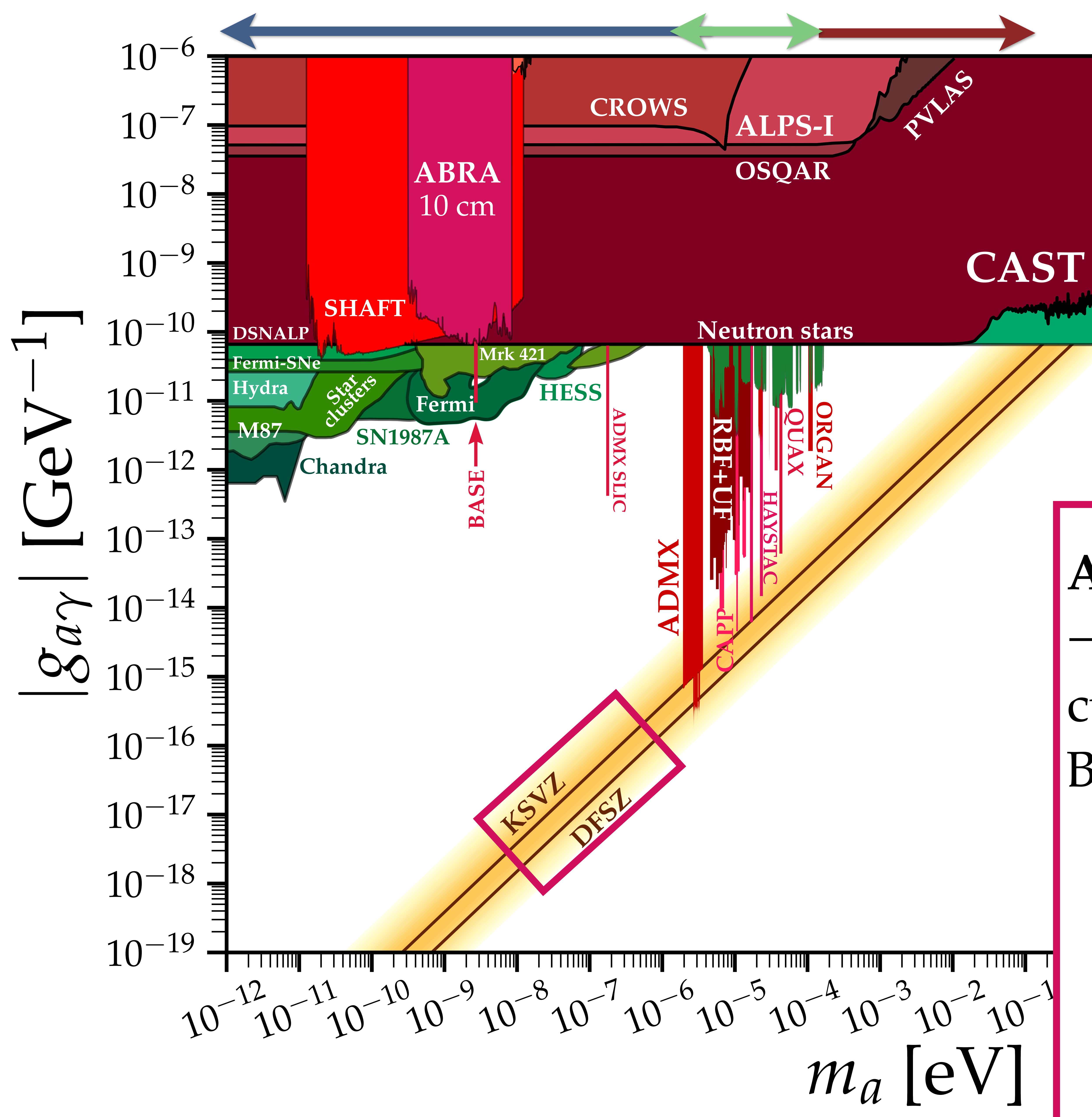






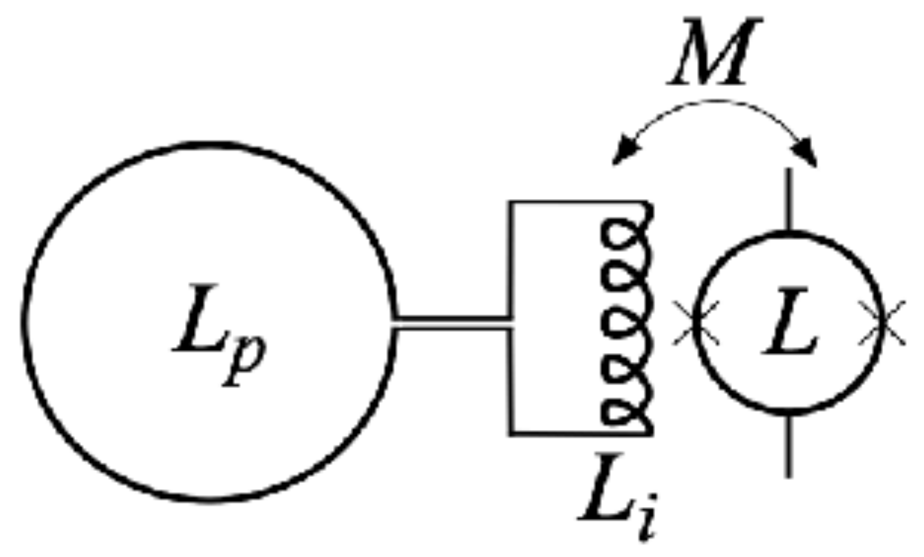
$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

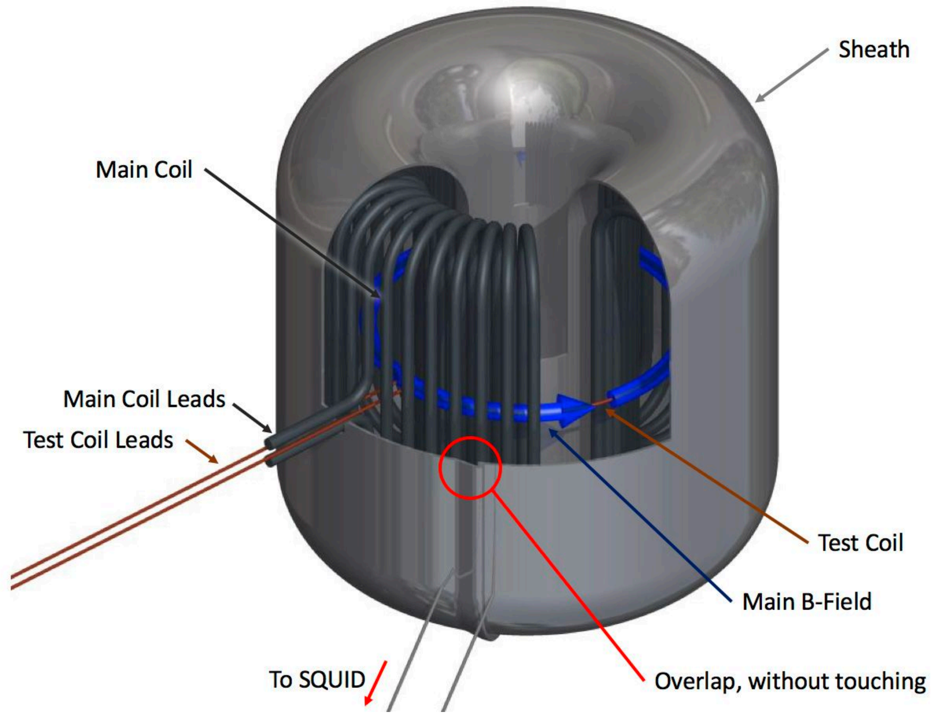
$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$



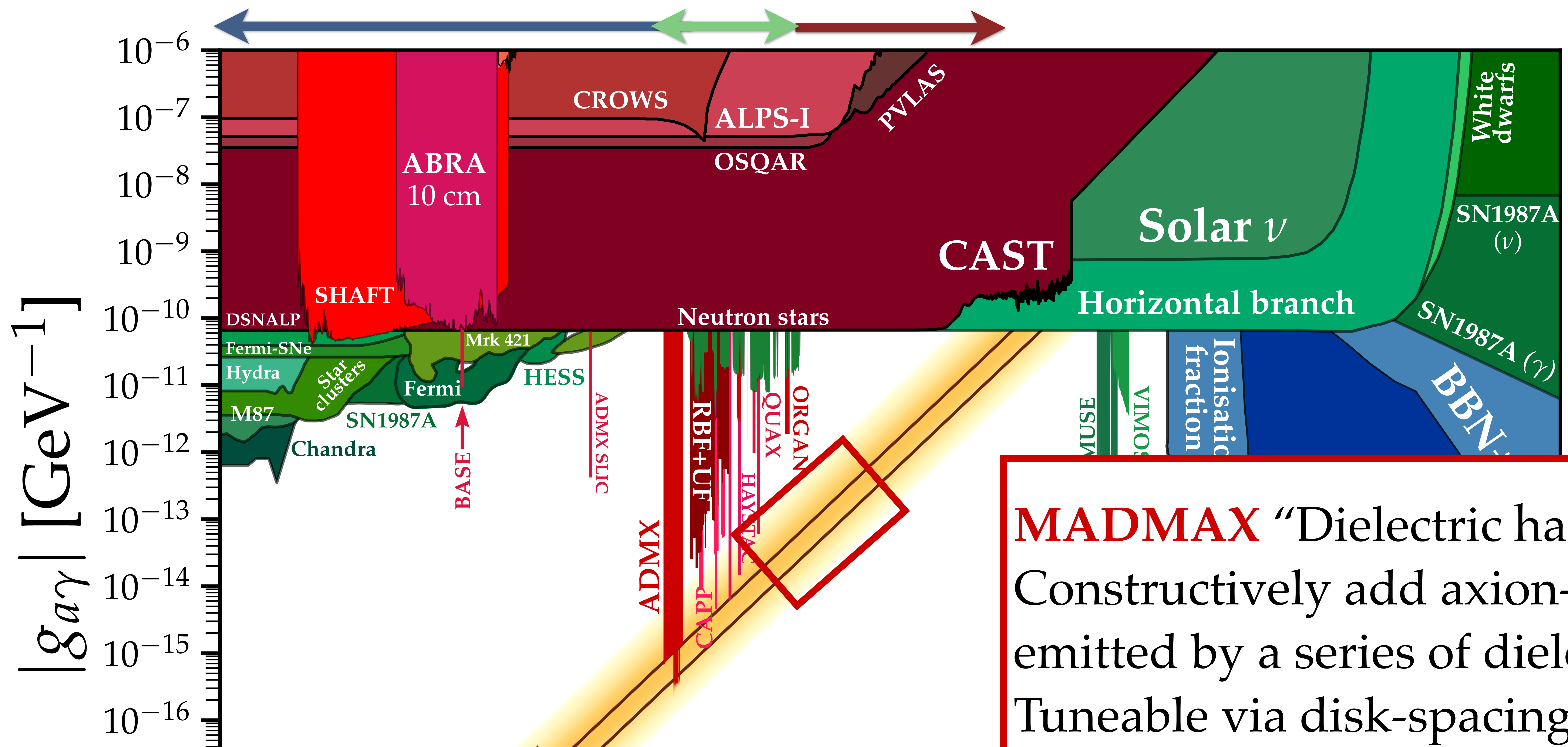
ABRACADABRA/DMRadio [2102.06722]

→ essentially an LC-circuit. Axion effective current sources a B-field inside a pickup loop. Broadband and resonant capabilities





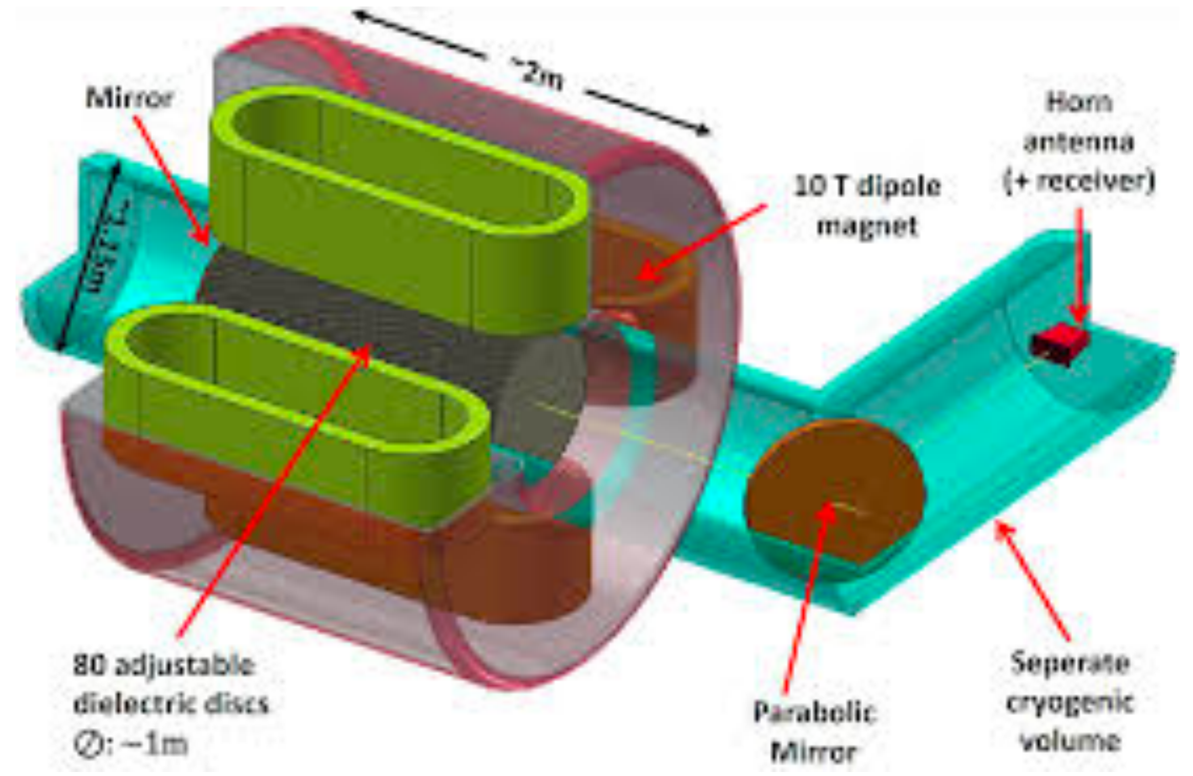
$$\nabla \times \mathbf{B}_a = \frac{\partial \mathbf{E}_a}{\partial t} - g_{a\gamma}\mathbf{B}_0 \frac{\partial a}{\partial t}$$

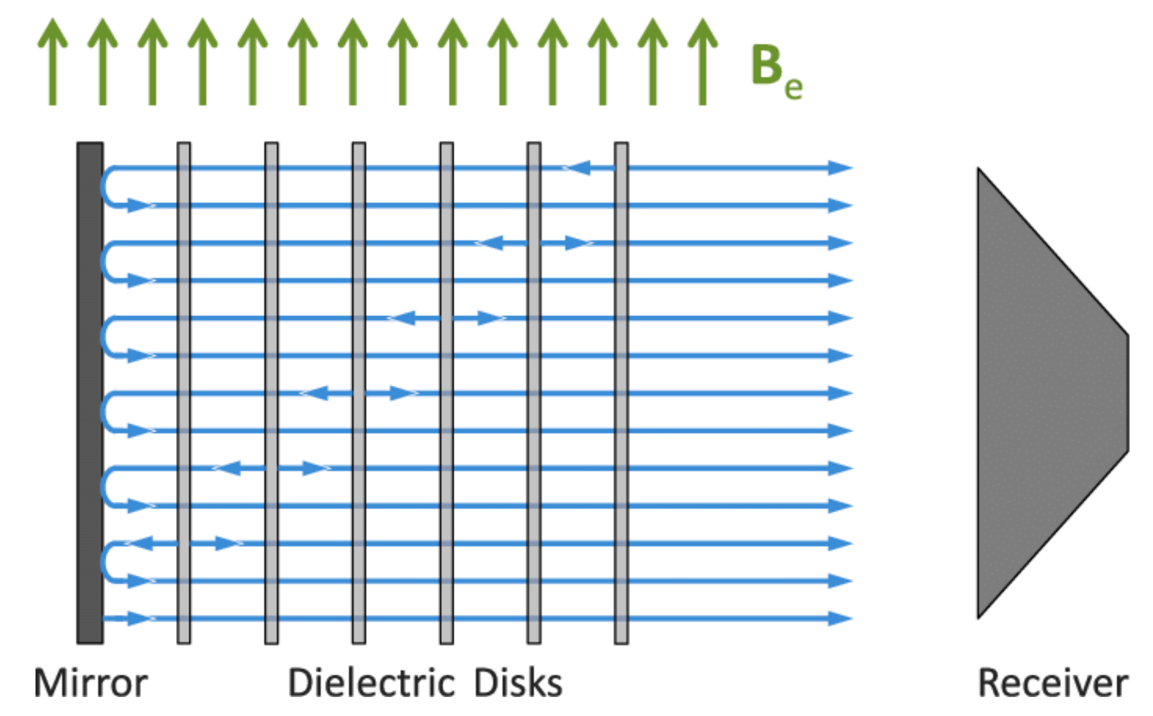


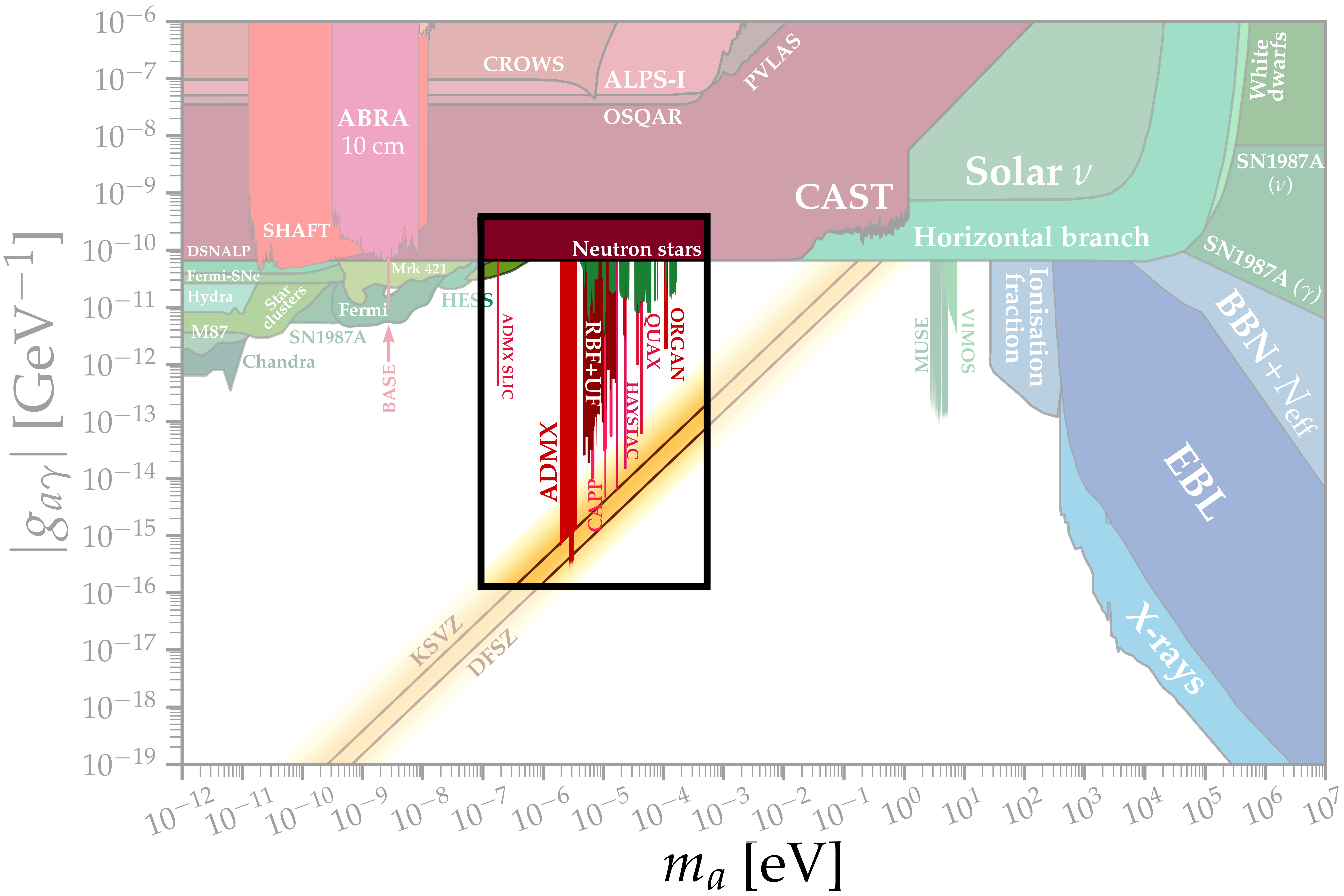
MADMAX “Dielectric haloscope” [2003.10894]

Constructively add axion-induced radiation emitted by a series of dielectric surfaces.

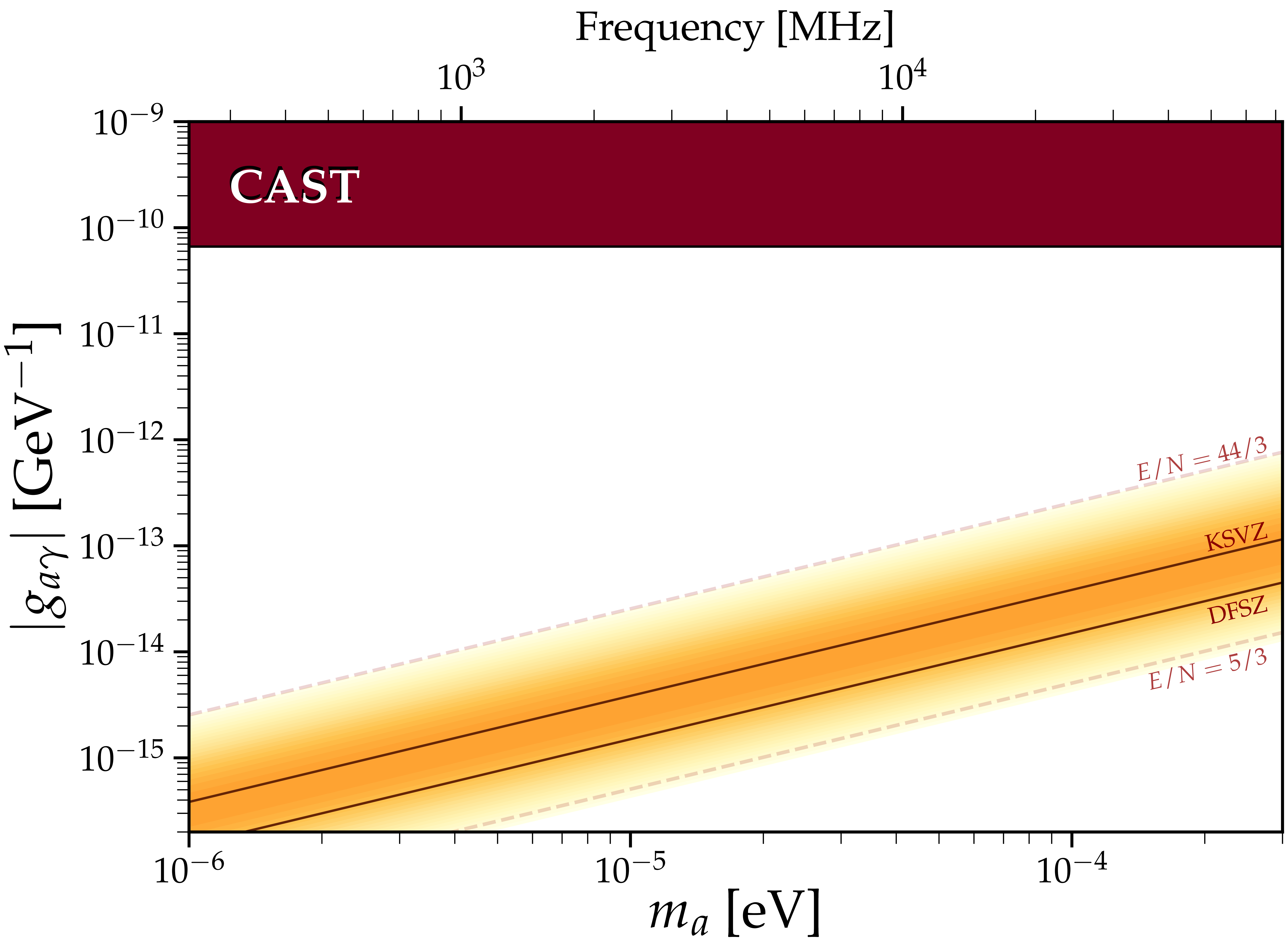
Tuneable via disk-spacing





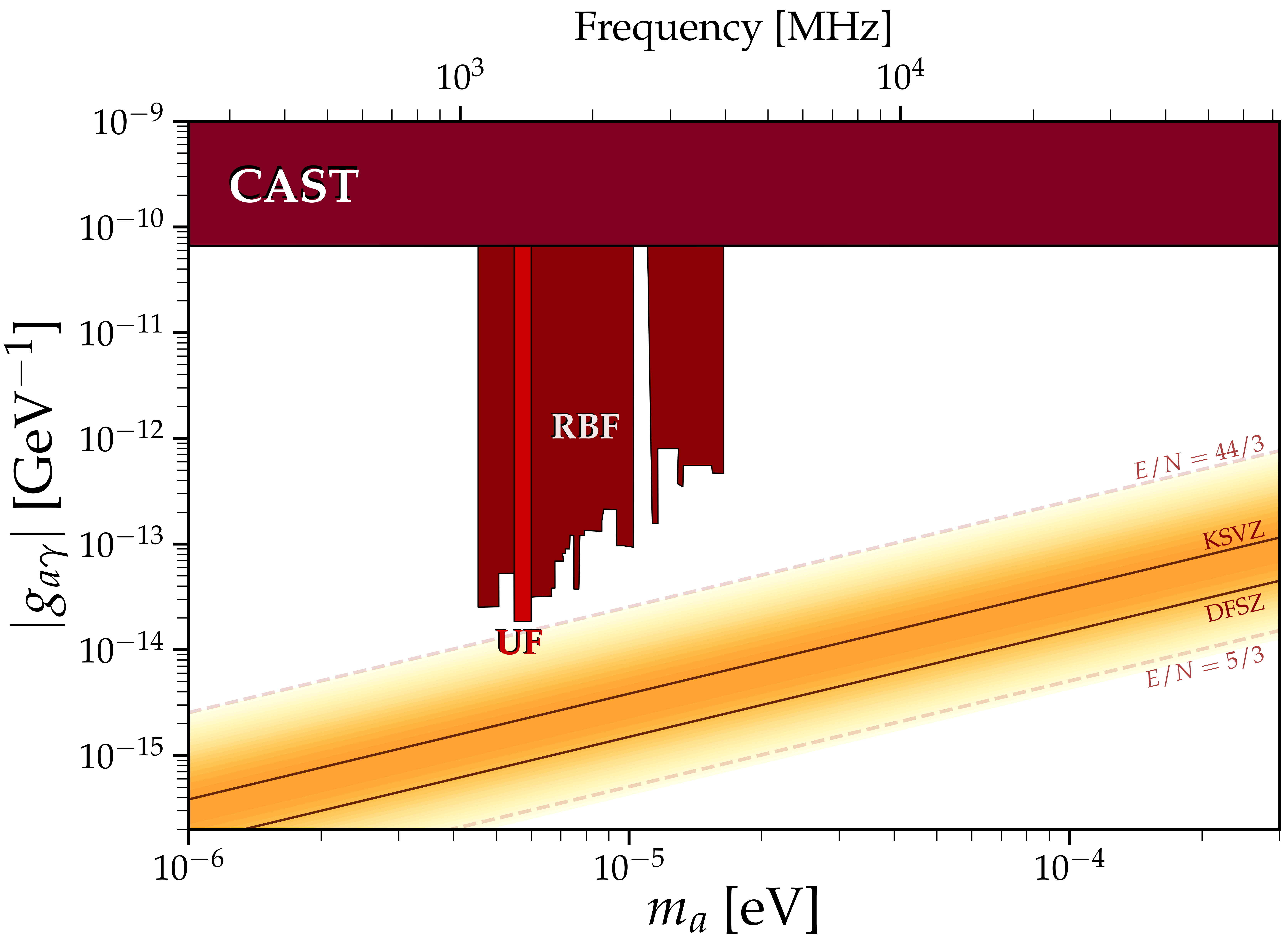


CROWS
ALPS-I
OSQAR
PVLAS
ABRA
10 cm
SHAFT
CAST
Solar ν
Horizontal branch
White dwarfs
SN1987A (ν)
SN1987A (γ)
DSNALP
Fermi-SNe
Hydra
M87
Star clusters
Mrk 421
Fermi
HESS
SN1987A
Chandra
BASE
Neutron stars
ADMX SLIC
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
MUSE
VIMOS
Ionisation fraction
BBN+$N_{\rm eff}$
EBL
X-rays
KSVZ
DFSZ
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]



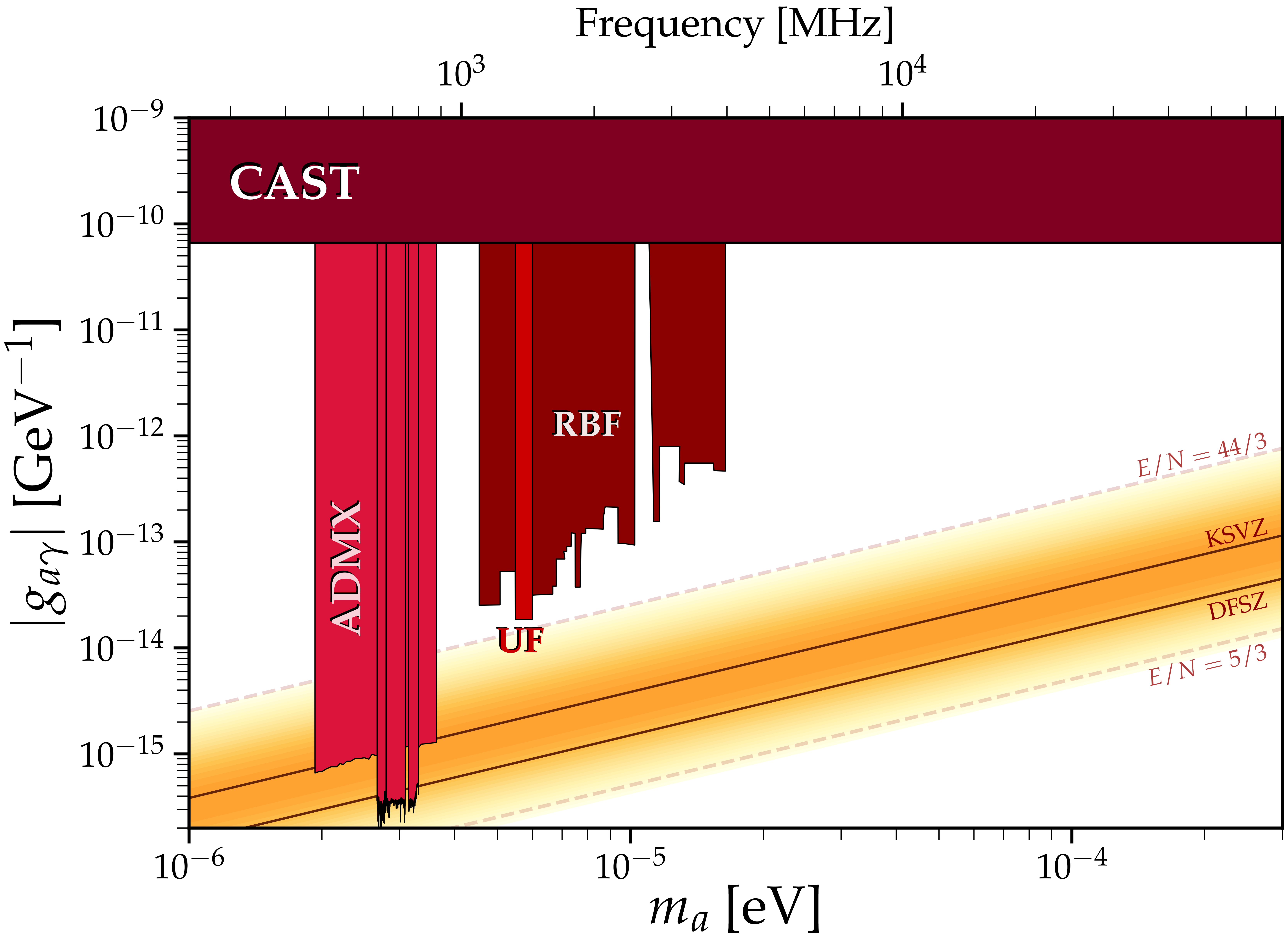
Microwave/RF range:
Most experimental activity, but also strong theory motivation for DM in this range
(pre/post inflationary axions)

Rochester-Brookhaven-Fermilab
and University of Florida
early O(litre) cavity experiments



Phys. Rev. Lett. 59, 839 (1987)
Phys. Rev. D 42, 1297 (1990)

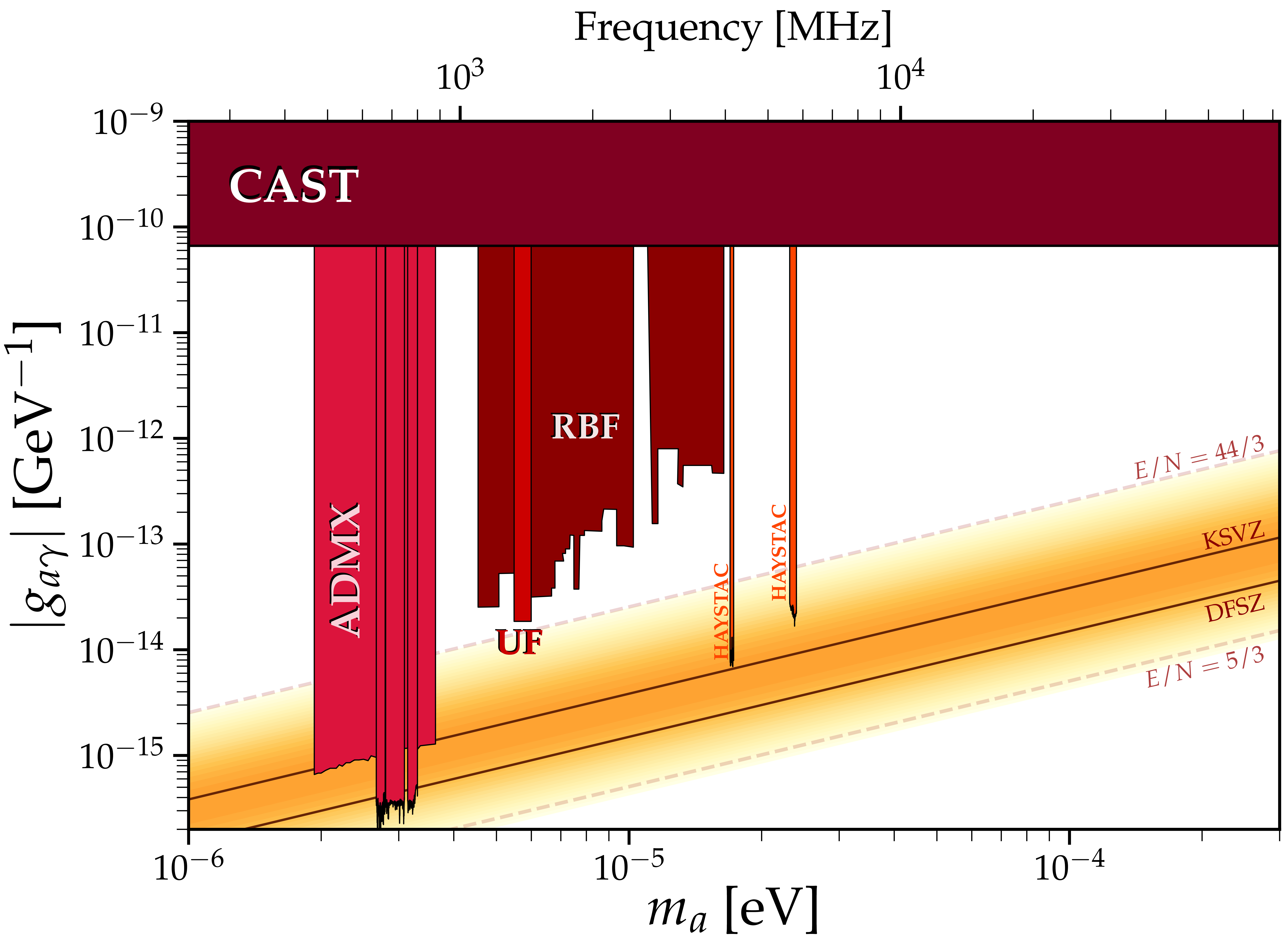
ADMX (U. Washington)

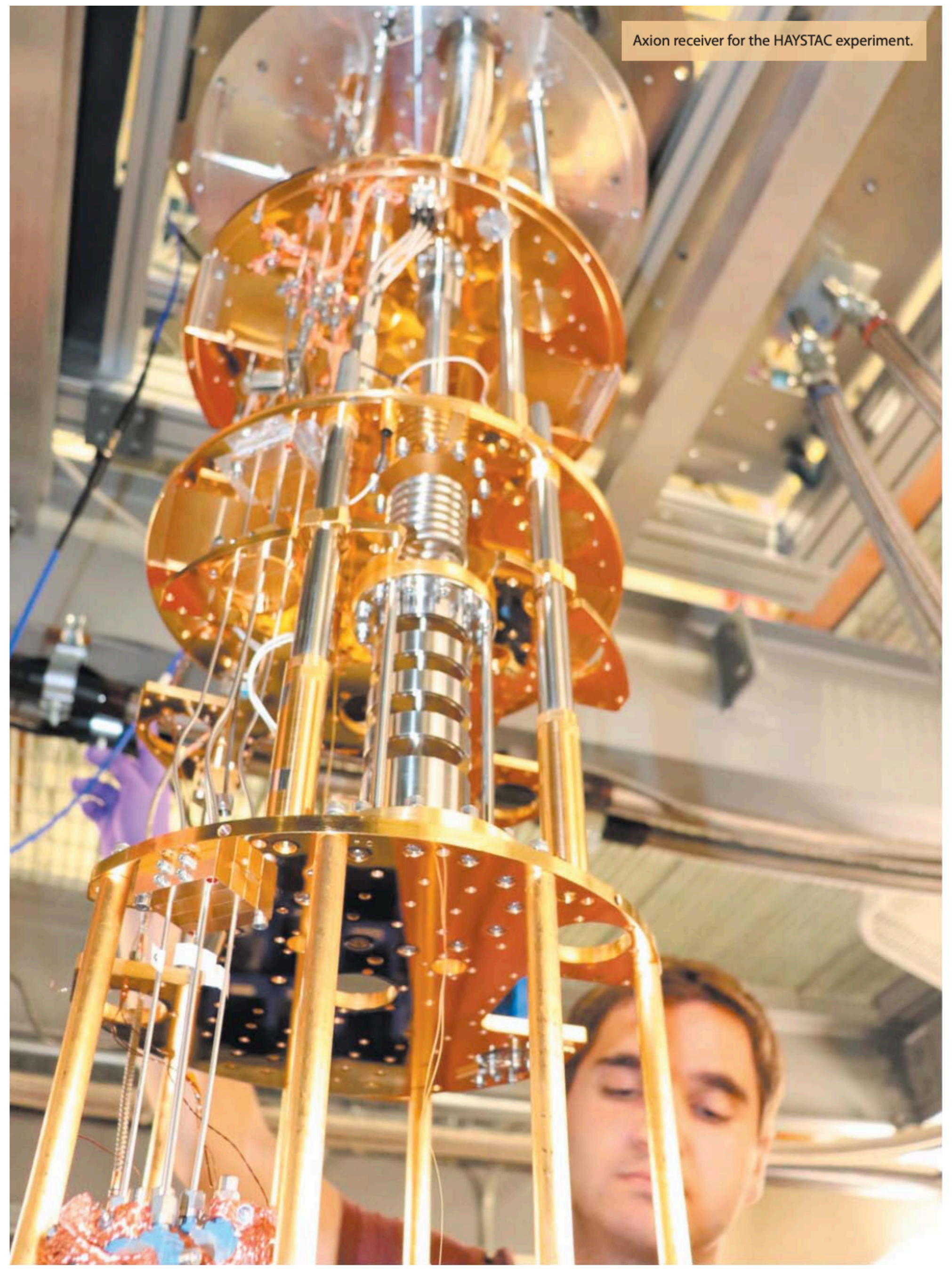


Only expt. probing DFSZ
First result: [astro-ph/9801286] from 1998, easy to forget there is >20 years of work represented here
→ Sensitivity scales as $g_{a\gamma} \sim T^{-1/4}$, and you need to scan!

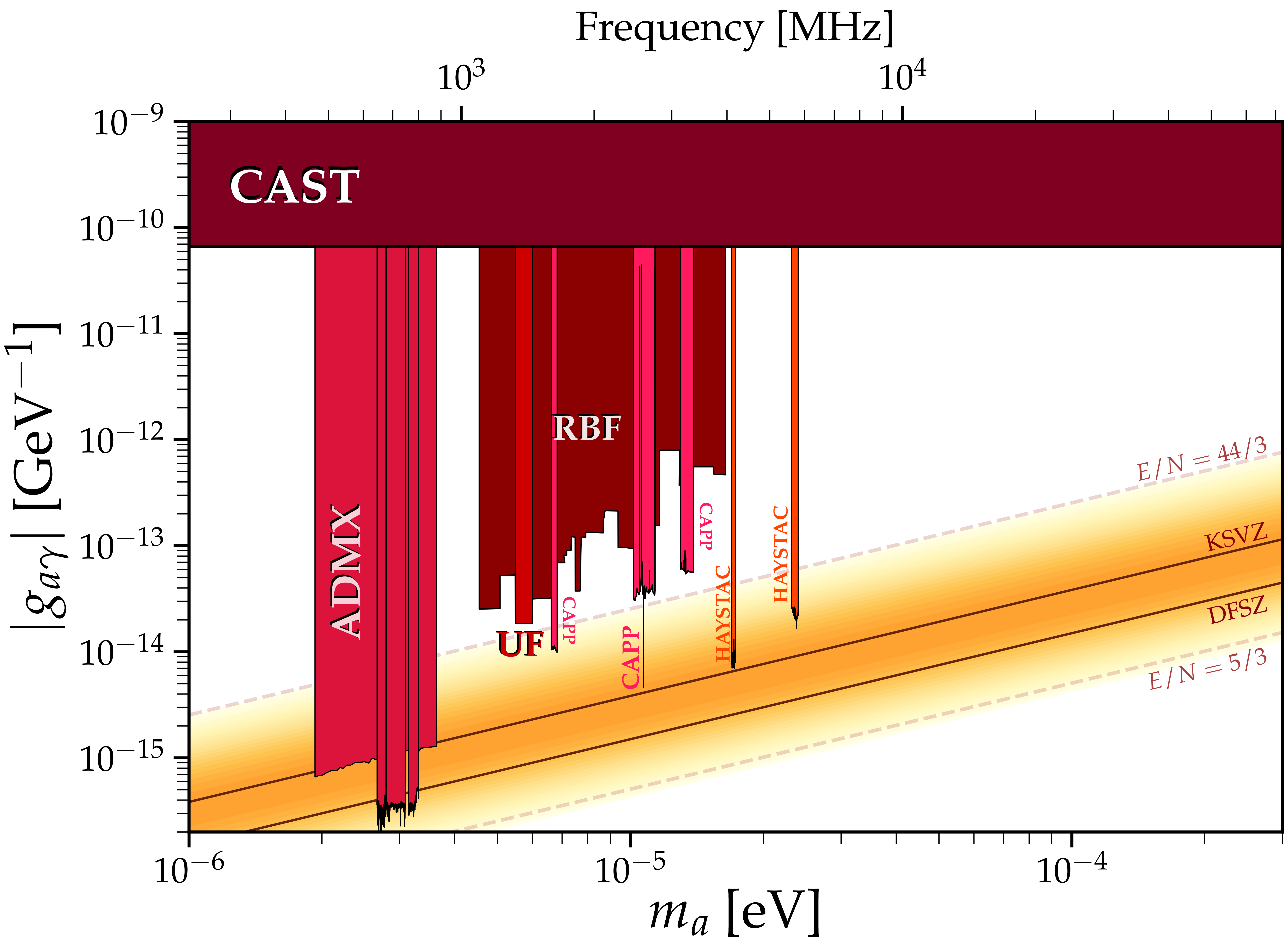
HAYSTAC (Yale)

2008.01853





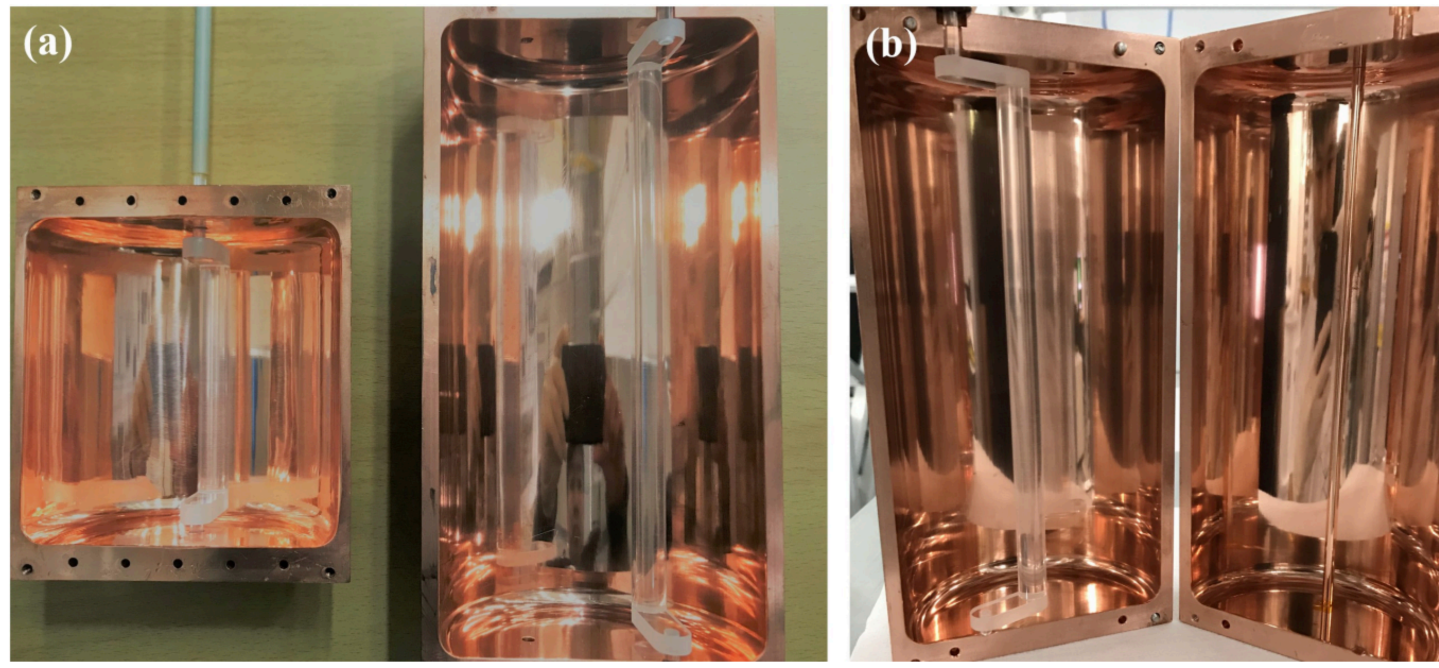
Main innovation is to put a microwave EM-field in a "squeezed state" which allowed them to overcome a fundamental quantum noise limit

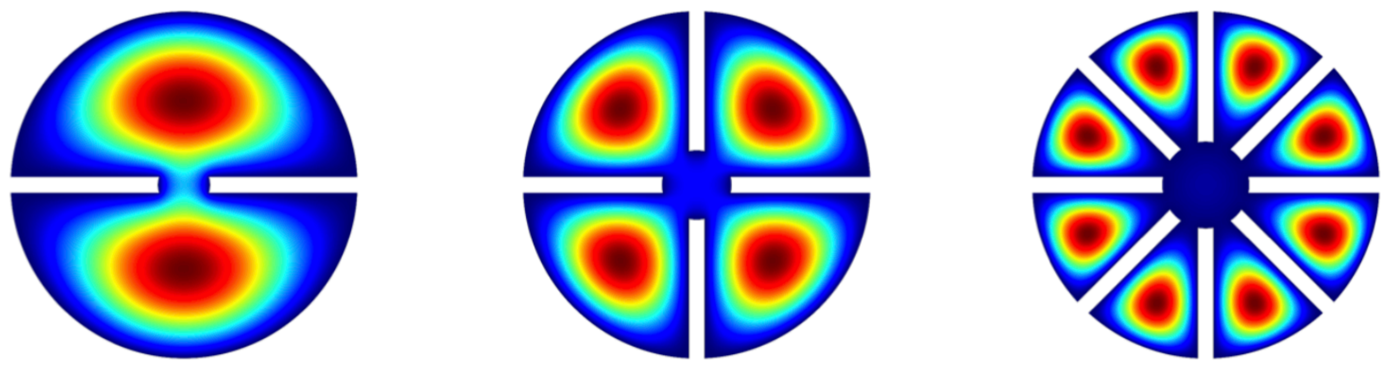


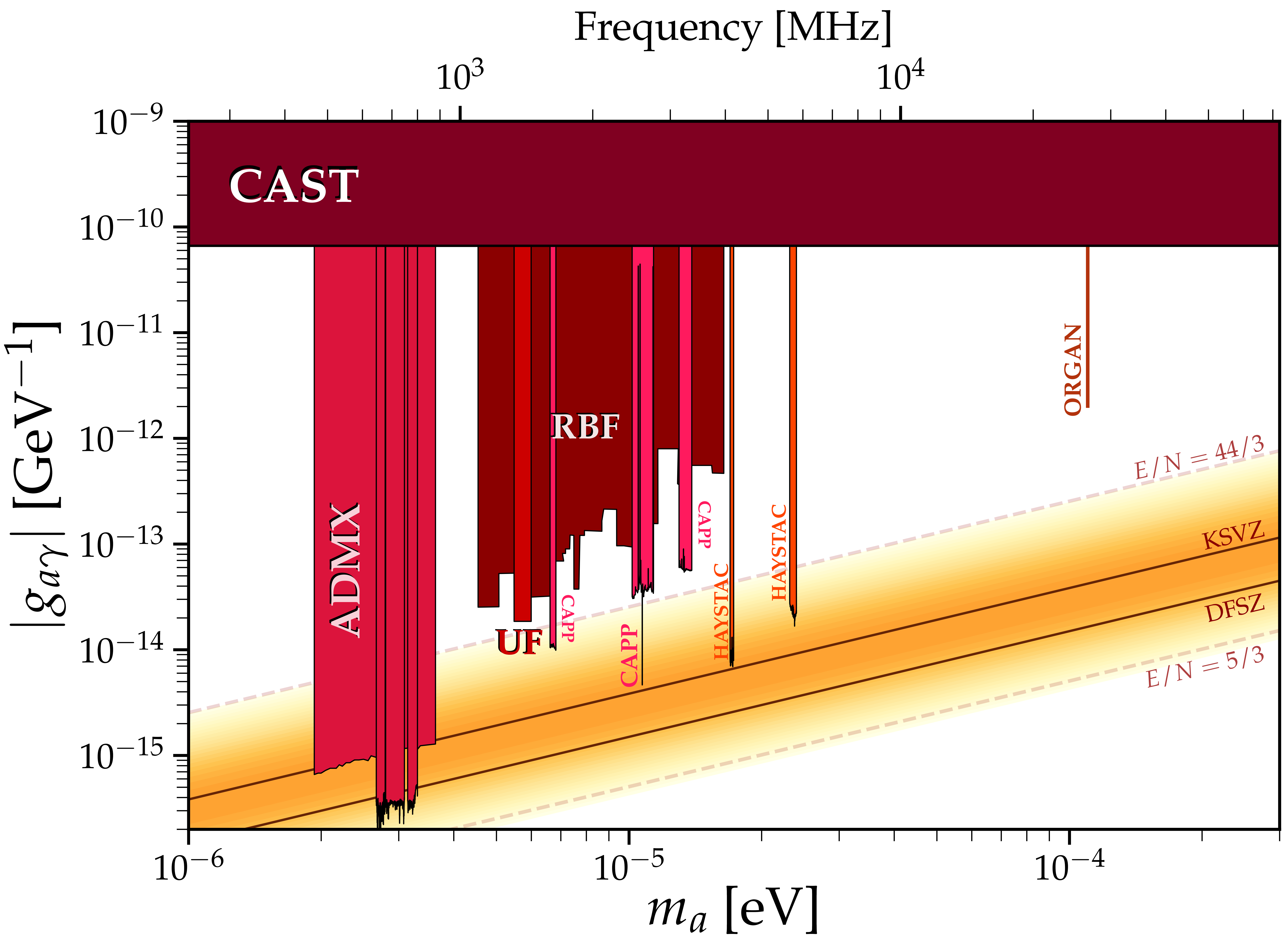
CAPP (Centre for axion and precision physics, Korea)

2012.10764, 2008.10141, 2001.05102

Investigating various high-mass designs, including multi-cell cavities



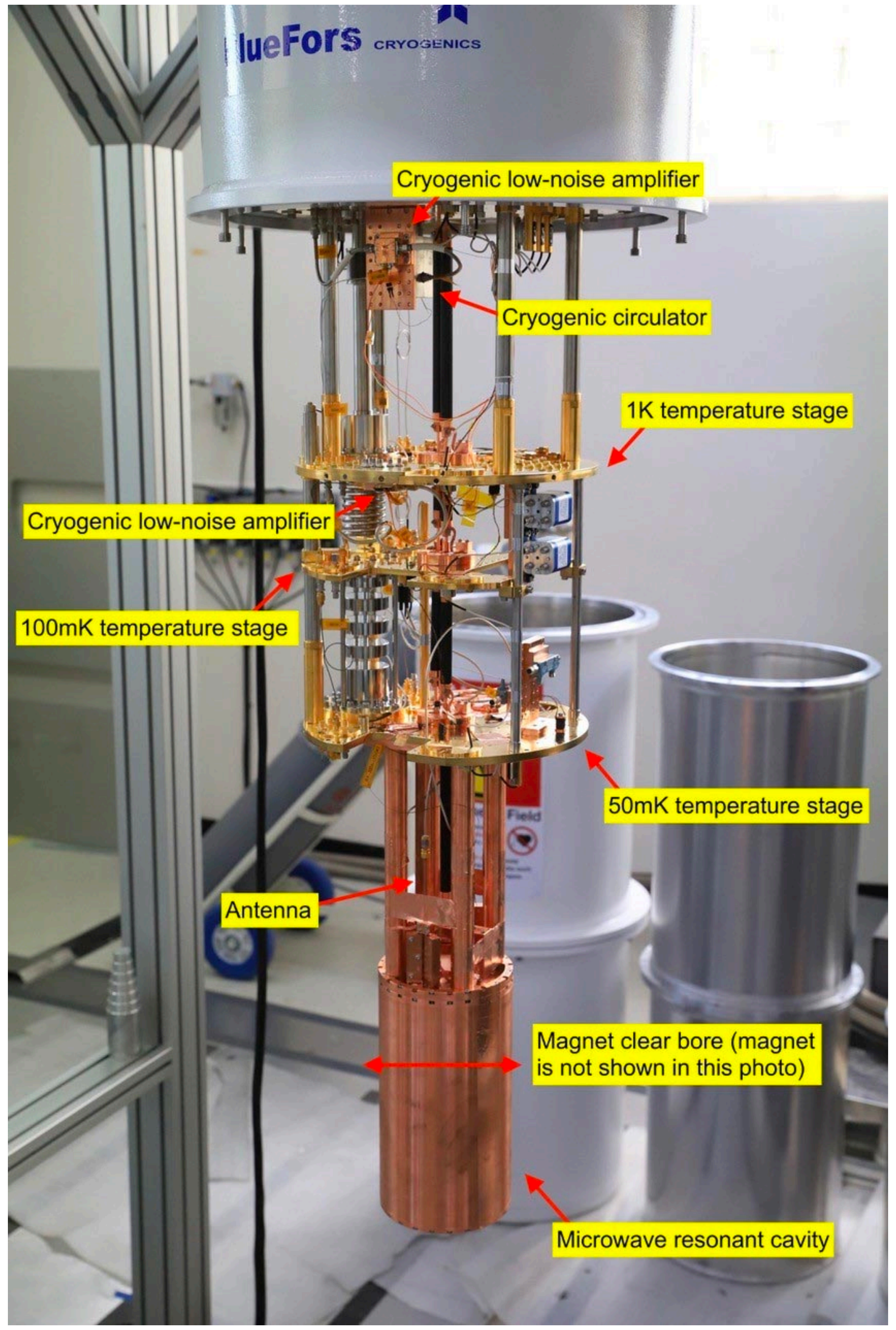




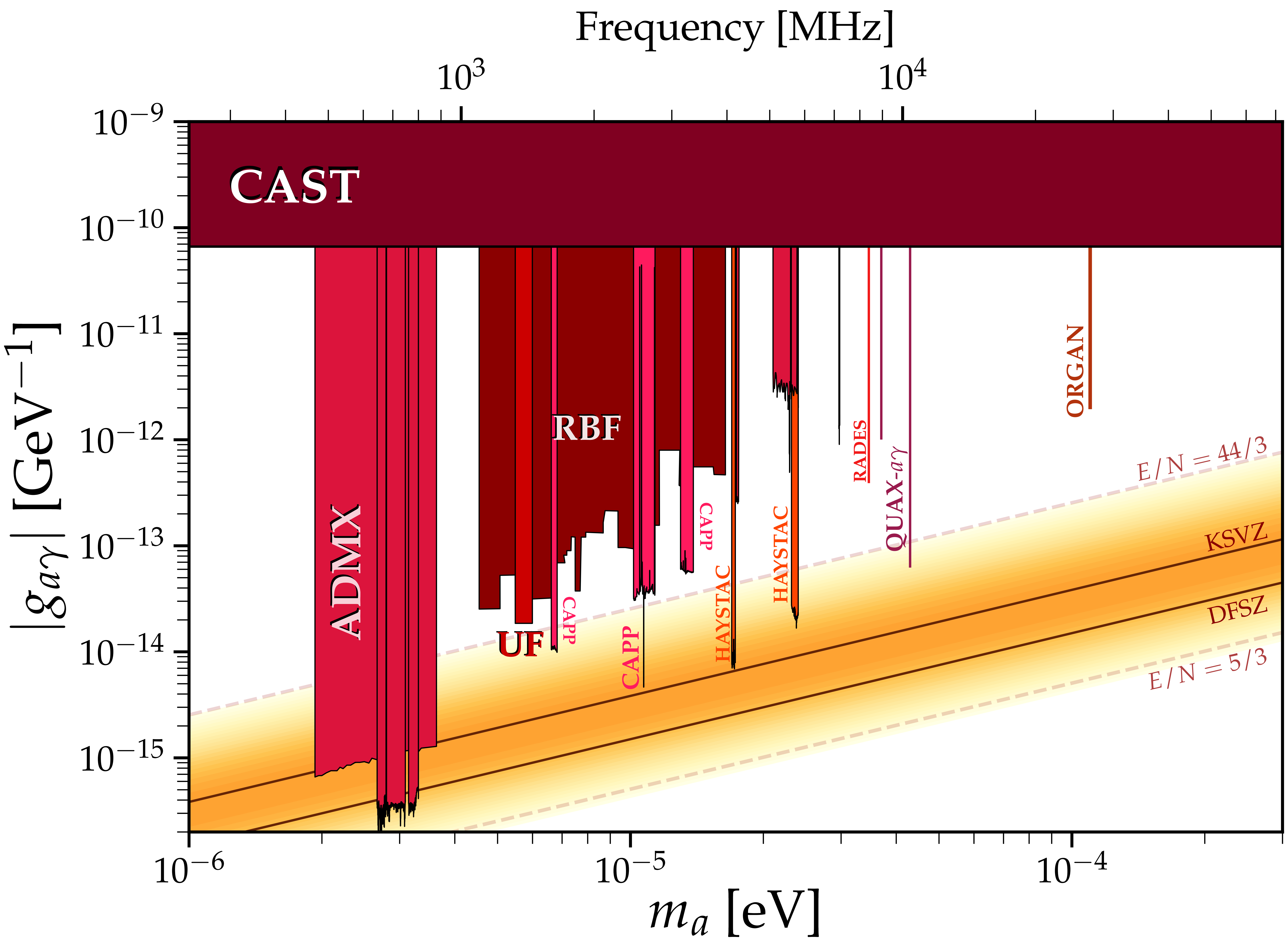
ORGAN

(UWA)

Currently has sensitivity at the highest frequencies

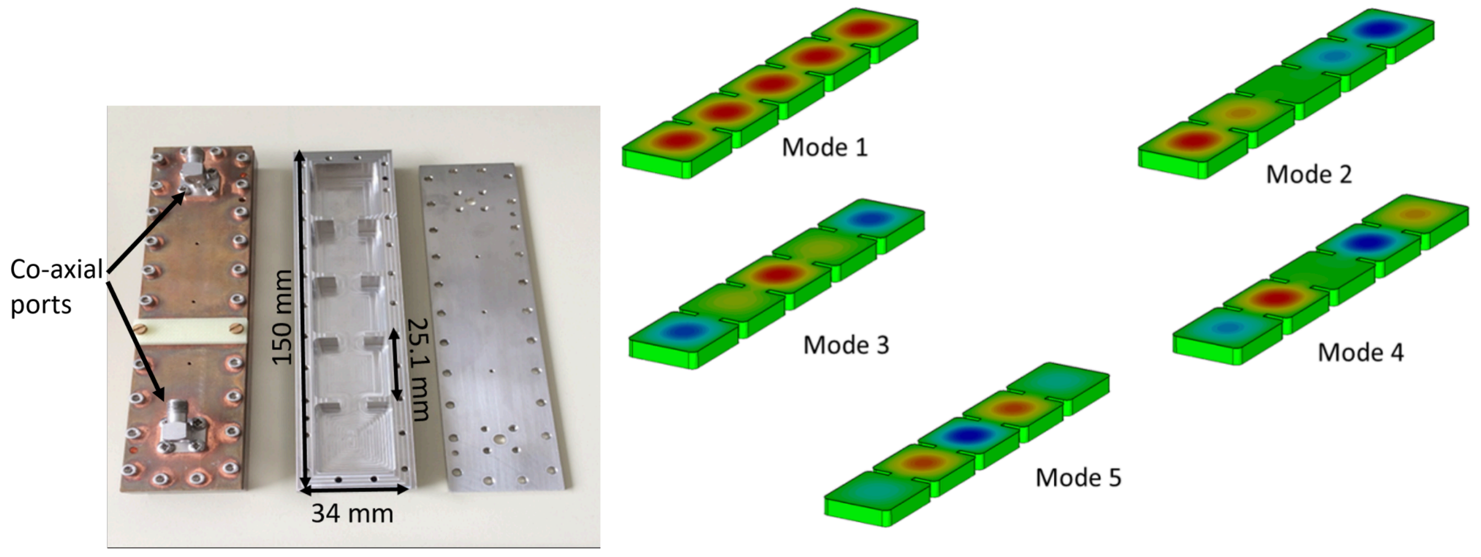


Non-tunable cavities



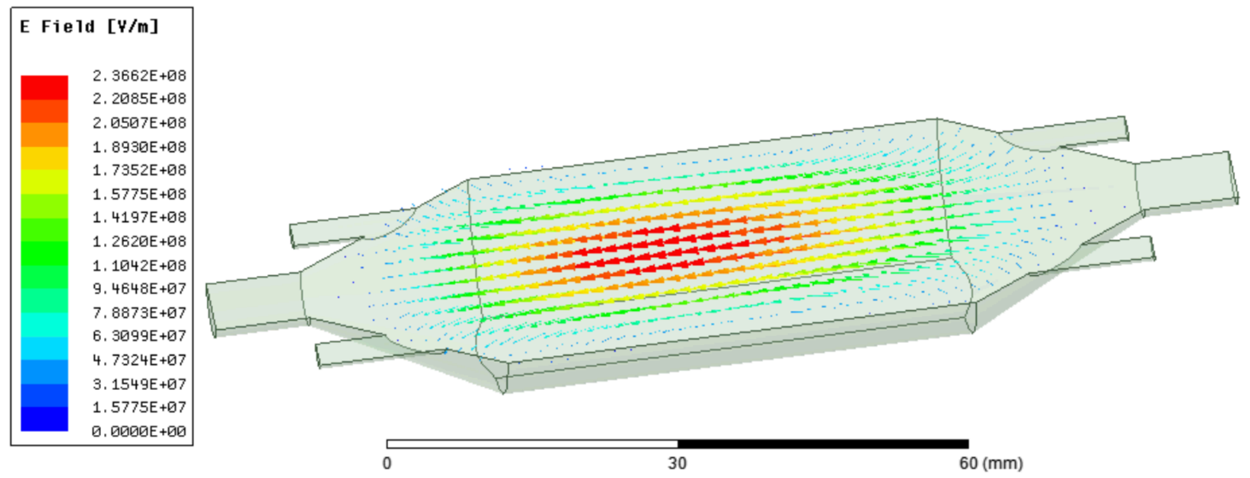
RADES (CERN)

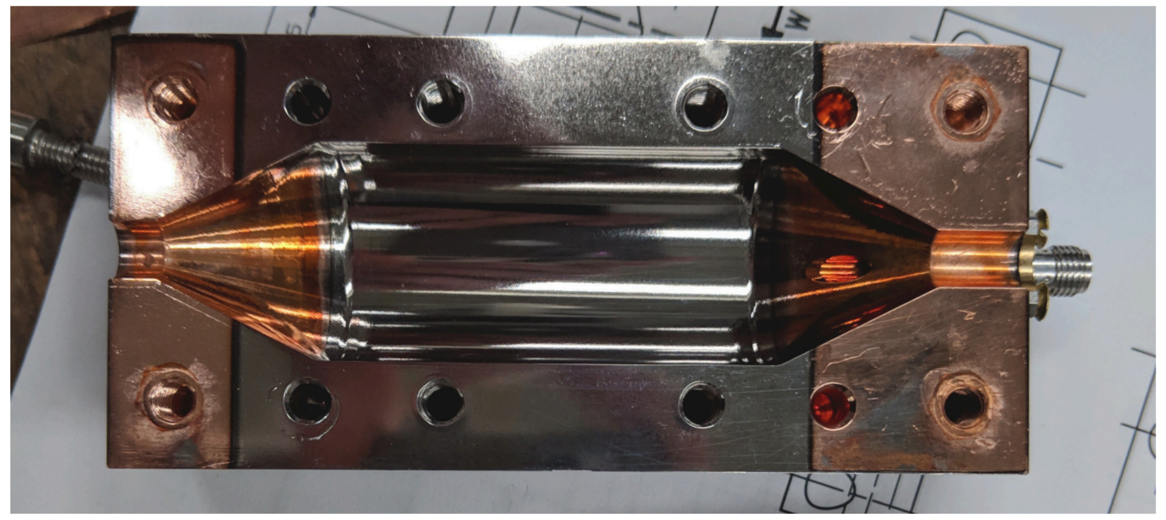
Multi-cell cavity placed inside of the CAST magnet



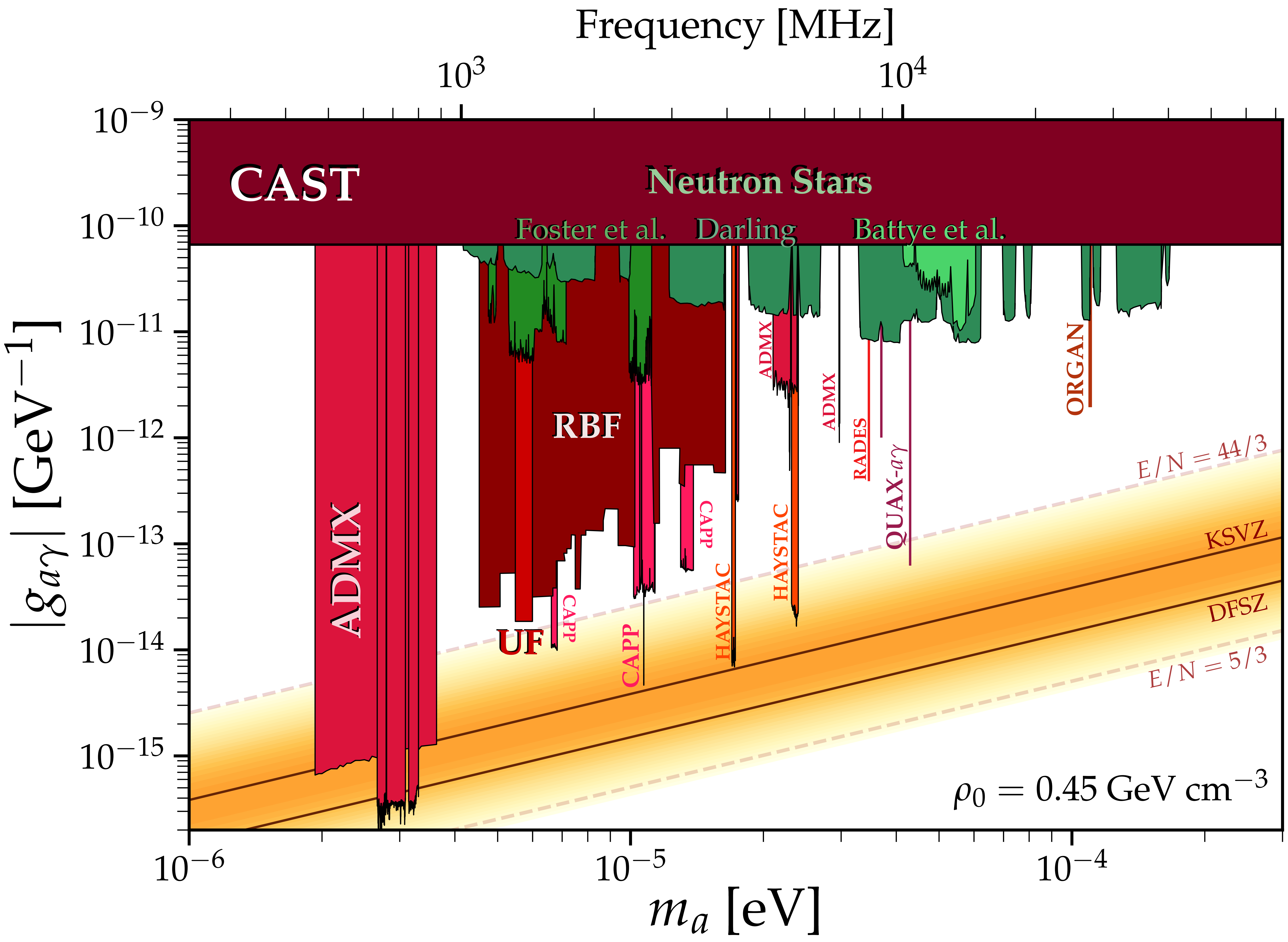
QUAX (Frascati)

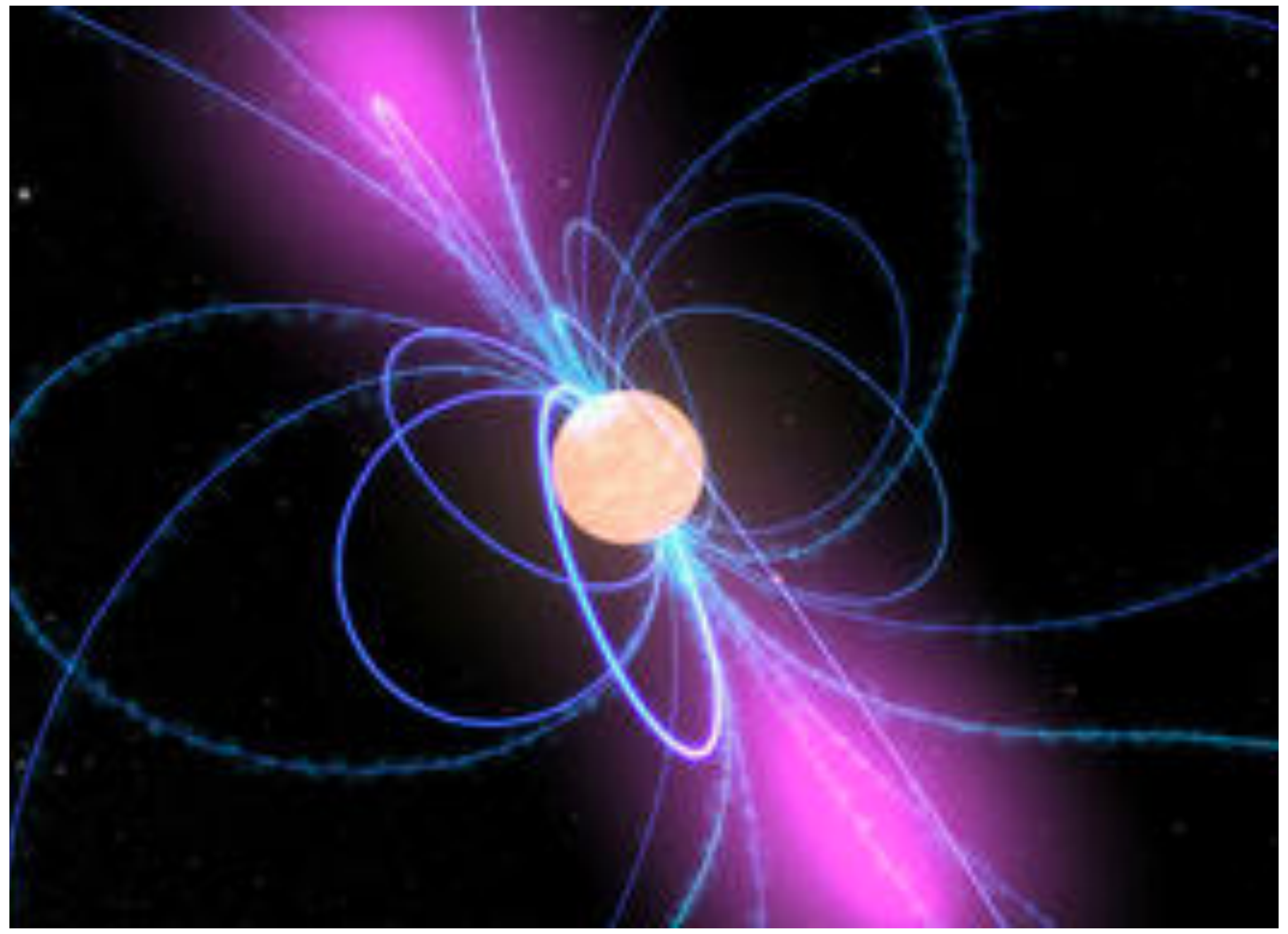
Superconducting cavity



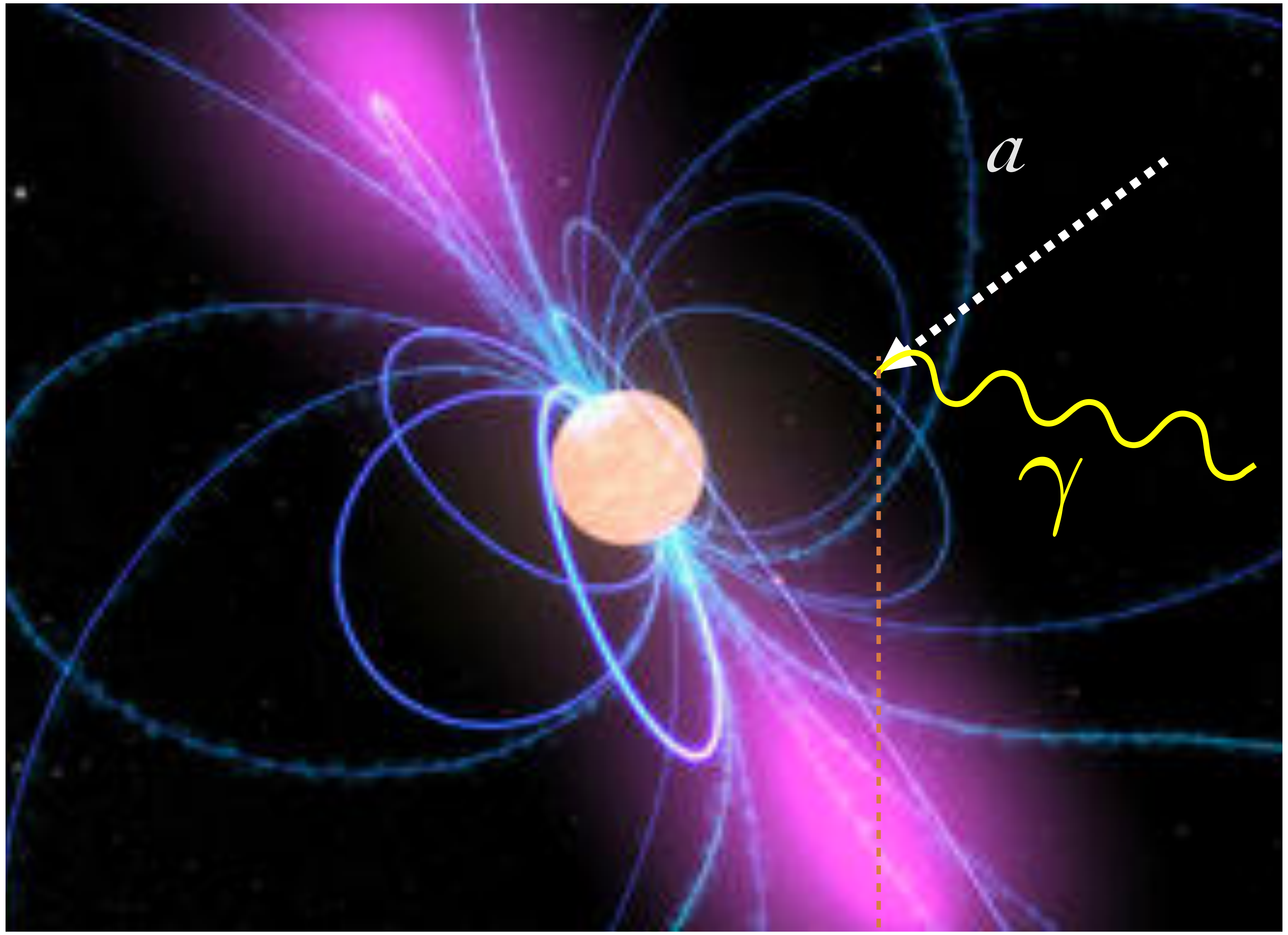


Neutron star haloscopes?

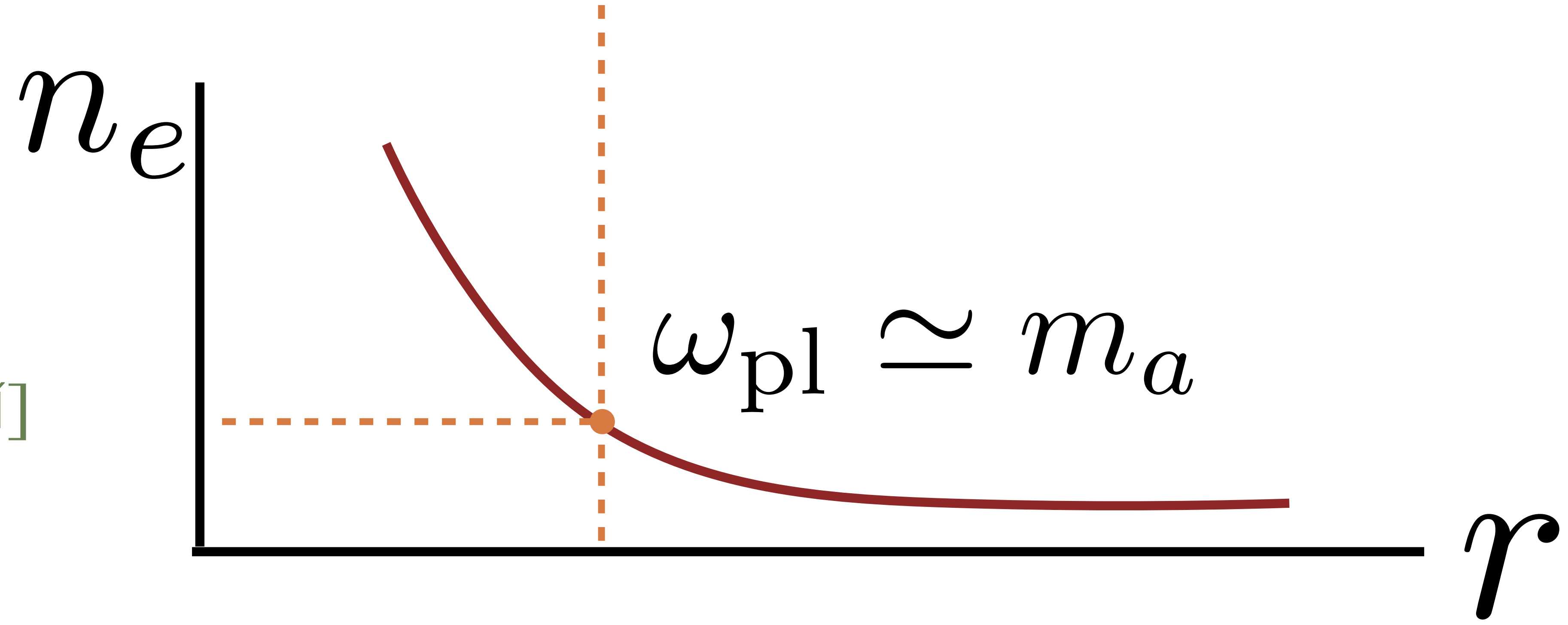




DM axions in neutron star magnetospheres

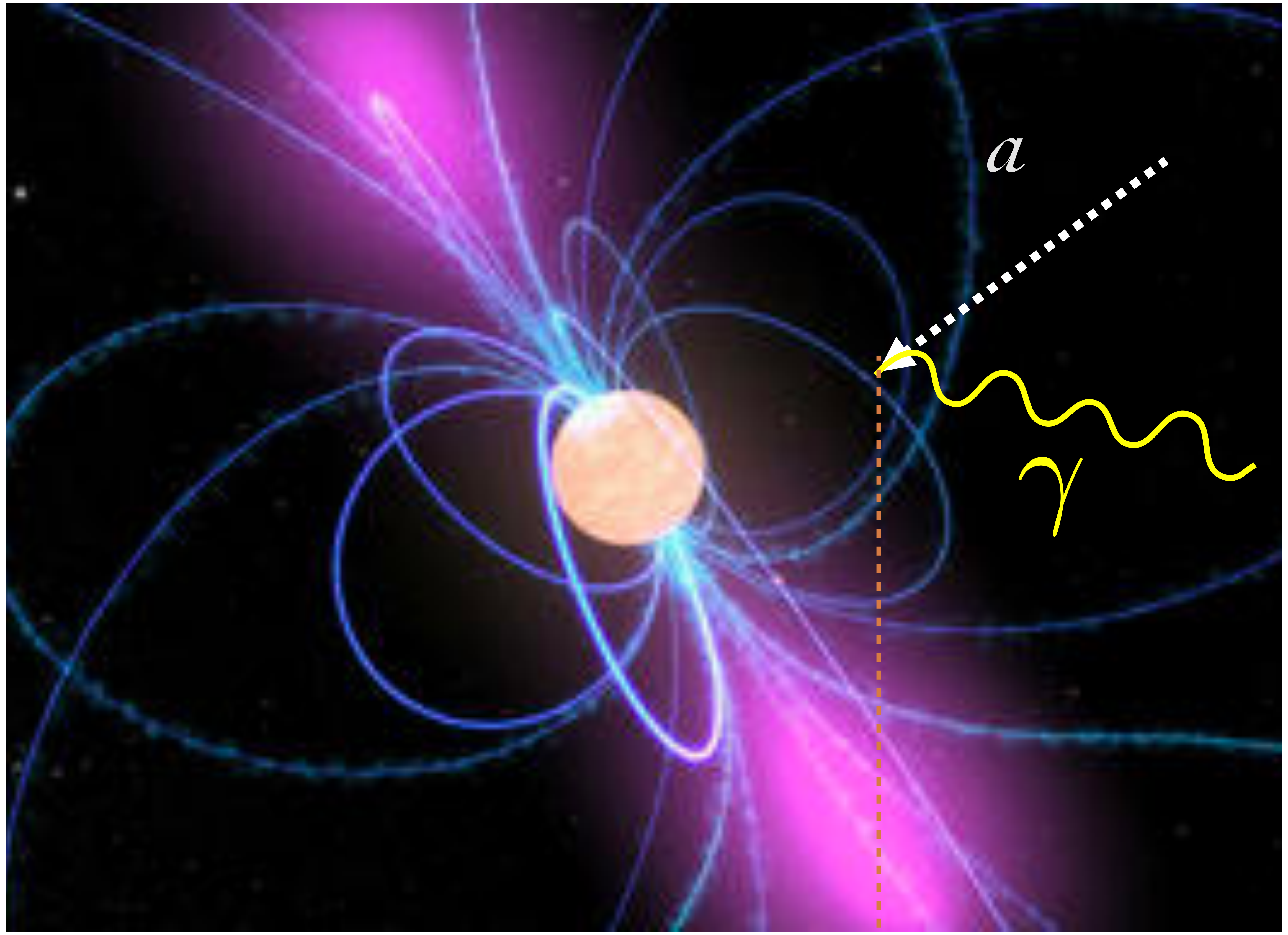


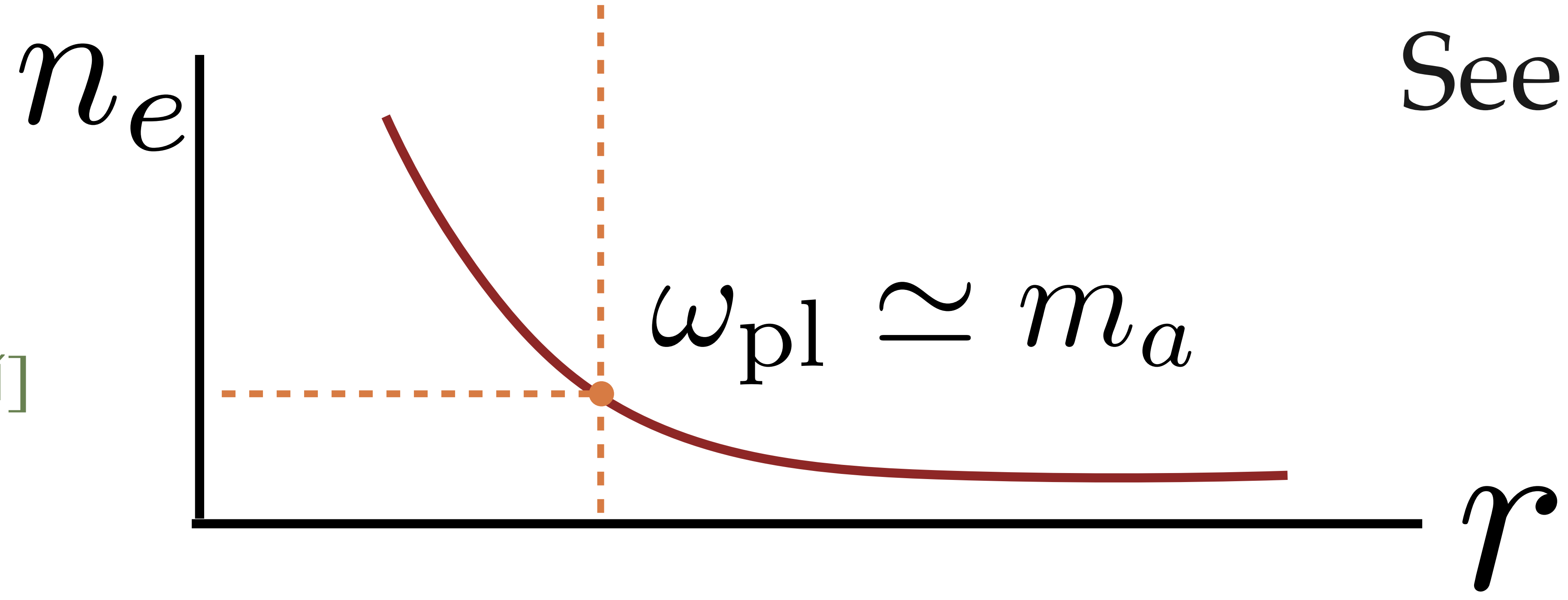
DM axions fall in to magnetar (B~10[10] T) and *resonantly* convert at a radius when plasma freq. = axion mass
→ μeV axions observable via sharp RF line



Pshirkov & Popov [0711.1264]
Huang et al. [1803.08230]

DM axions in neutron star magnetospheres





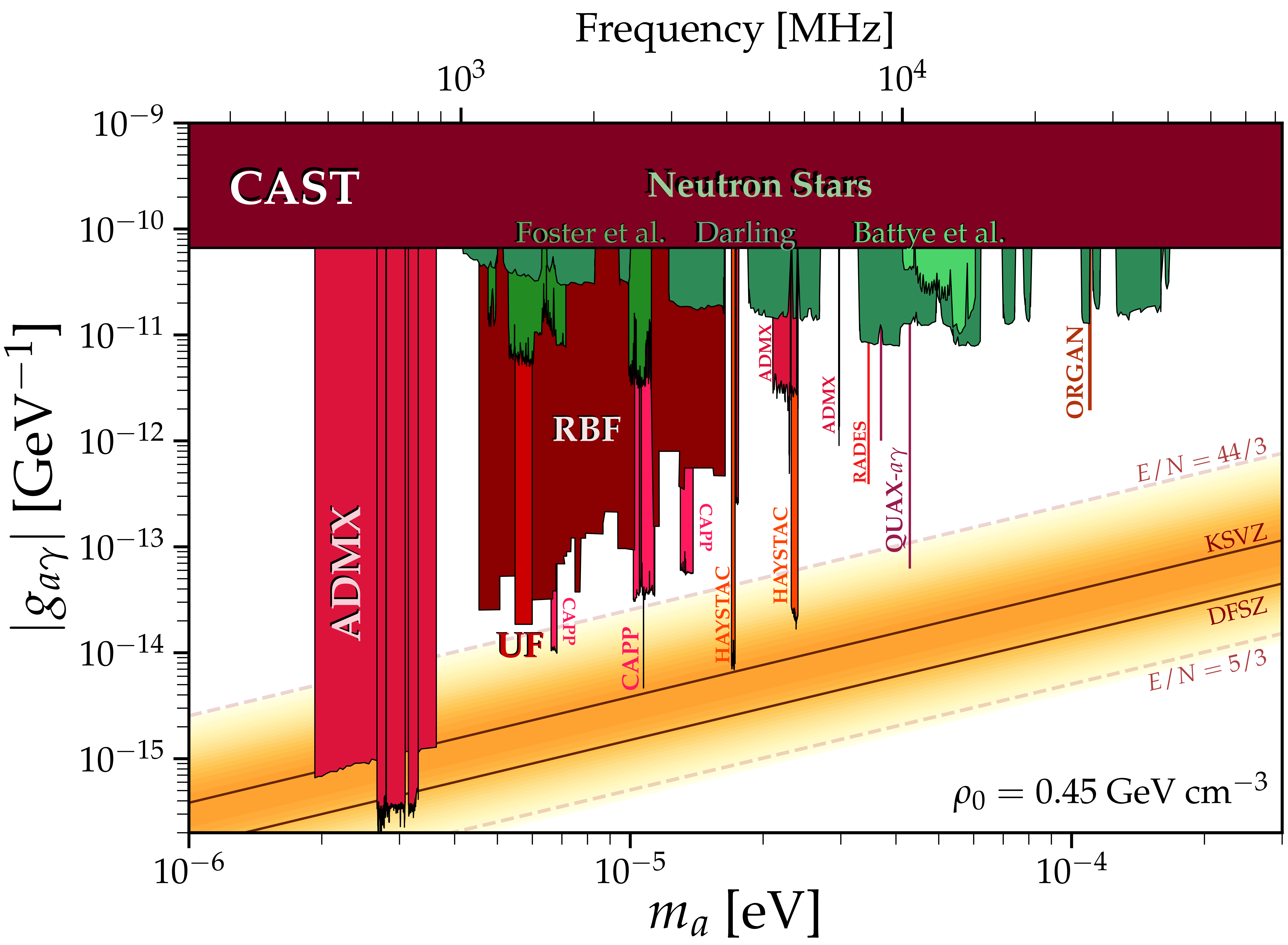
Pshirkov & Popov [0711.1264]
Huang et al. [1803.08230]

DM axions fall in to magnetar (B~10^{10} T) and *resonantly* convert at a radius when plasma freq. = axion mass
→ μeV axions observable via sharp RF line

Heavy uncertainties from

- DM density around NS
- Magnetic field model
- Physics of axion-photon conversion in turbulent B-field / plasma

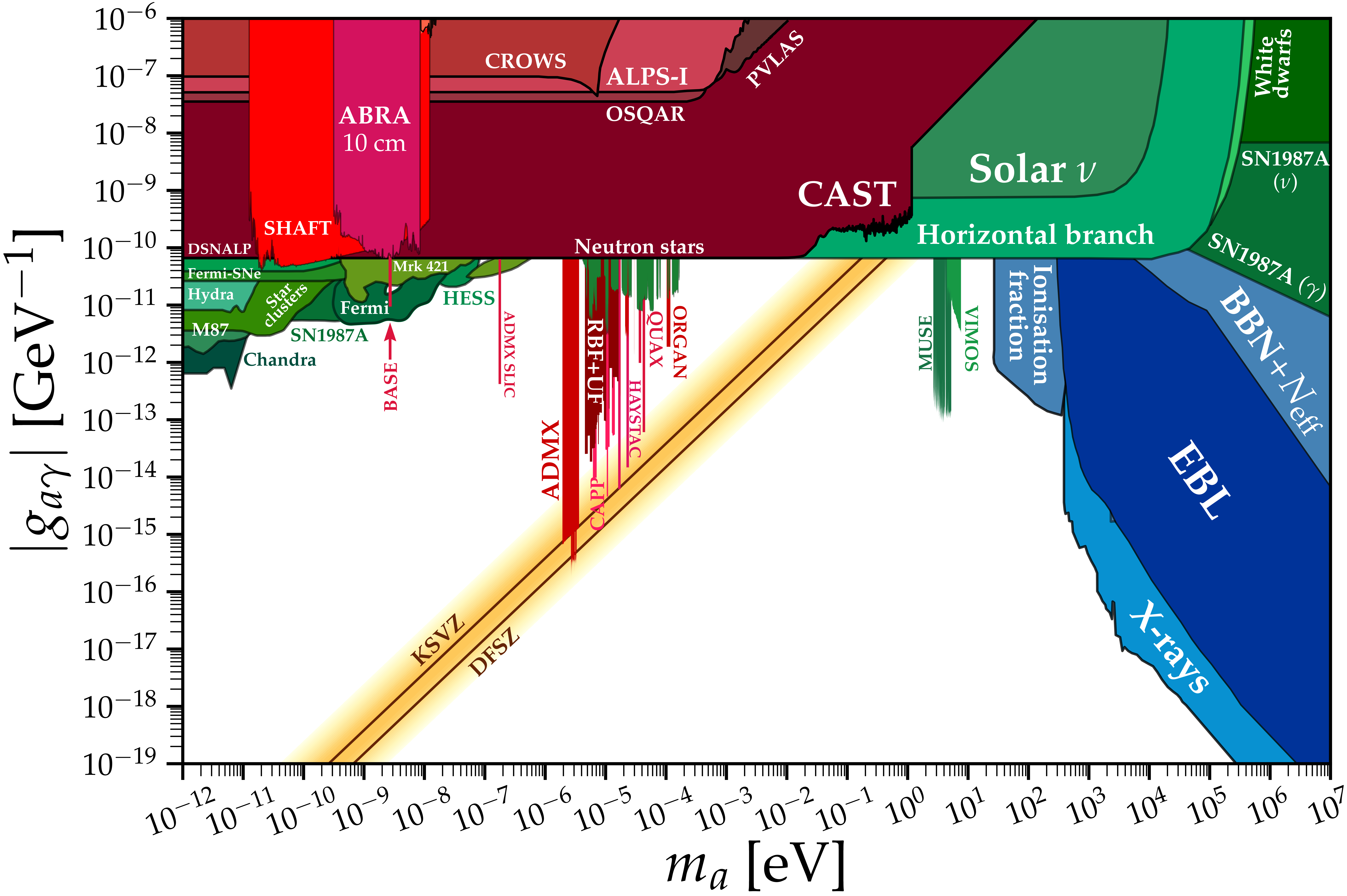
See e.g. [2107.07399], [2104.07670]



Searches for radio lines from axions falling into NS magnetospheres

Darling/Battye et al.
[2008.11188], [2008.01877], [2107.01225]
Jansky VLA data on magnetar PSR J1745-2900 at galactic centre

Foster et al.
Green bank / Effelsberg observations of galactic centre & isolated NSs
[2004.00011]



CROWS
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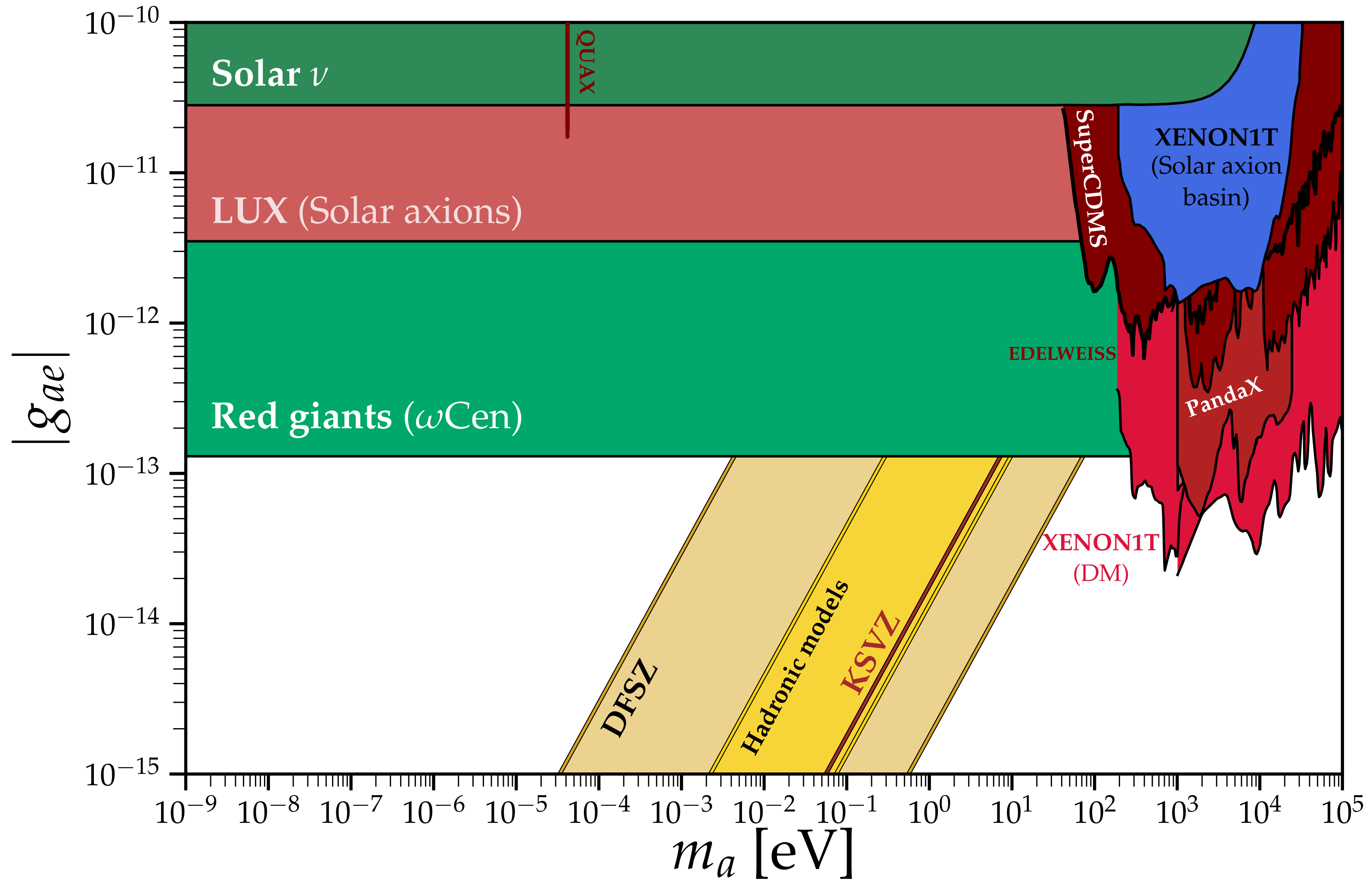
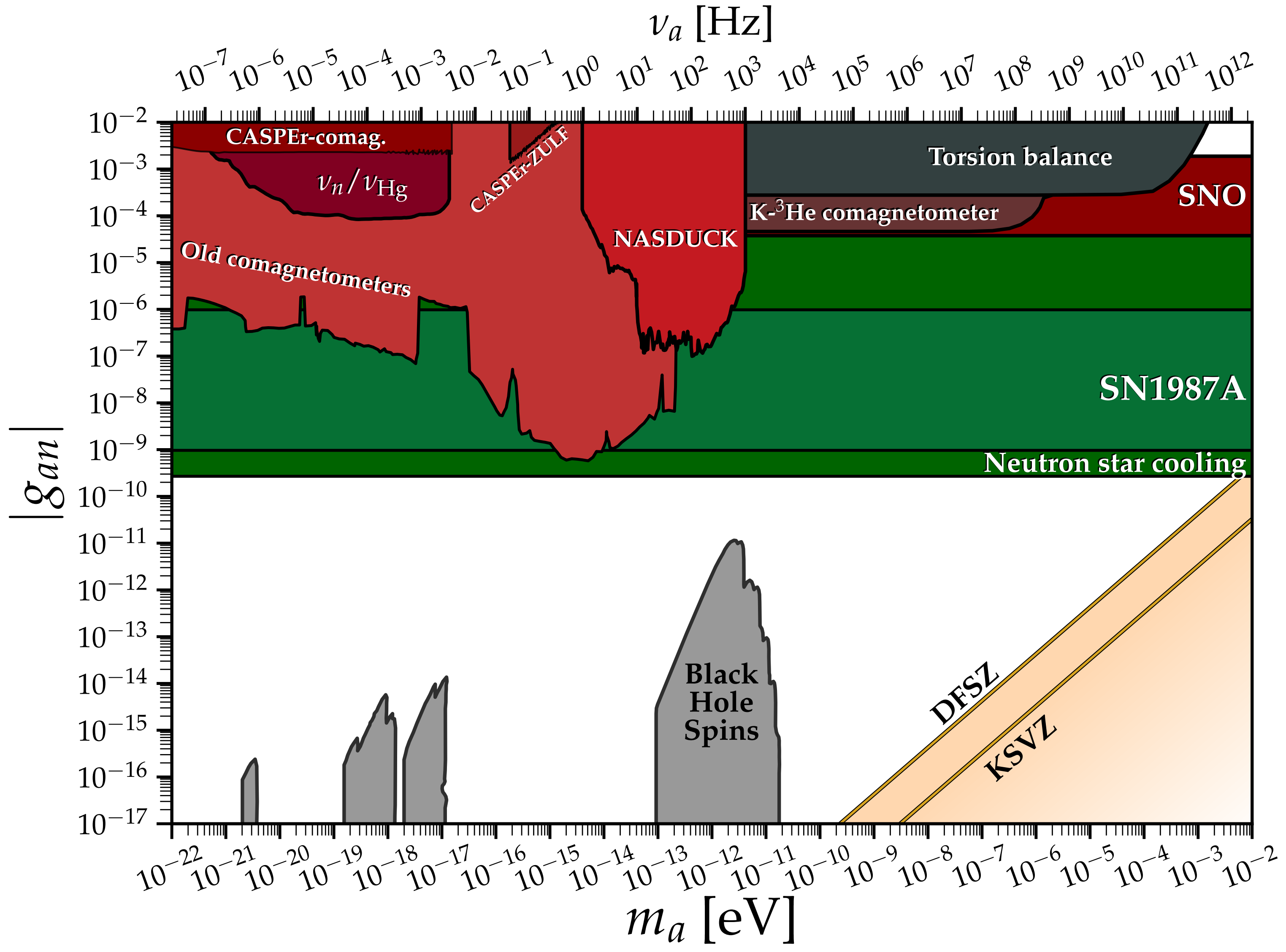
SN1987A (ν)
SN1987A (γ)
BBN+N_eff
Fermi-SNe
Hydra
Star clusters
Mrk 421
Fermi
HESS
M87
SN1987A
Chandra
BASE
ADMX SLIC
ADMX
RBF+UF
CAPP
HAYSTAC
QUAX
ORGAN
MUSE
VIMOS
Ionisation fraction
EBL
X-rays
KSVZ
DFSZ
|g_aγ| [GeV^−1]
m_a [eV]

For another time: Constraints on other axion couplings

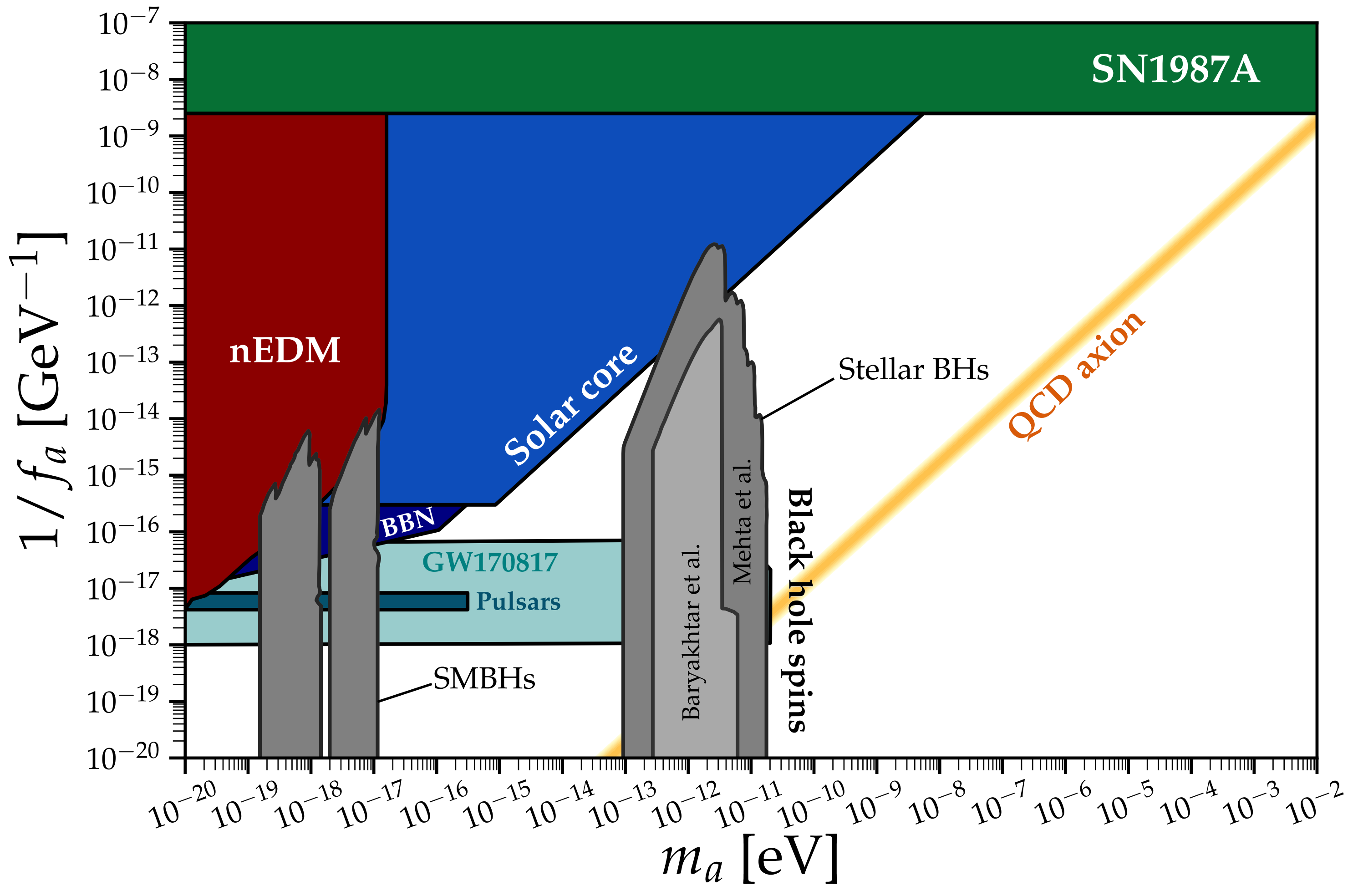
Axion-electron



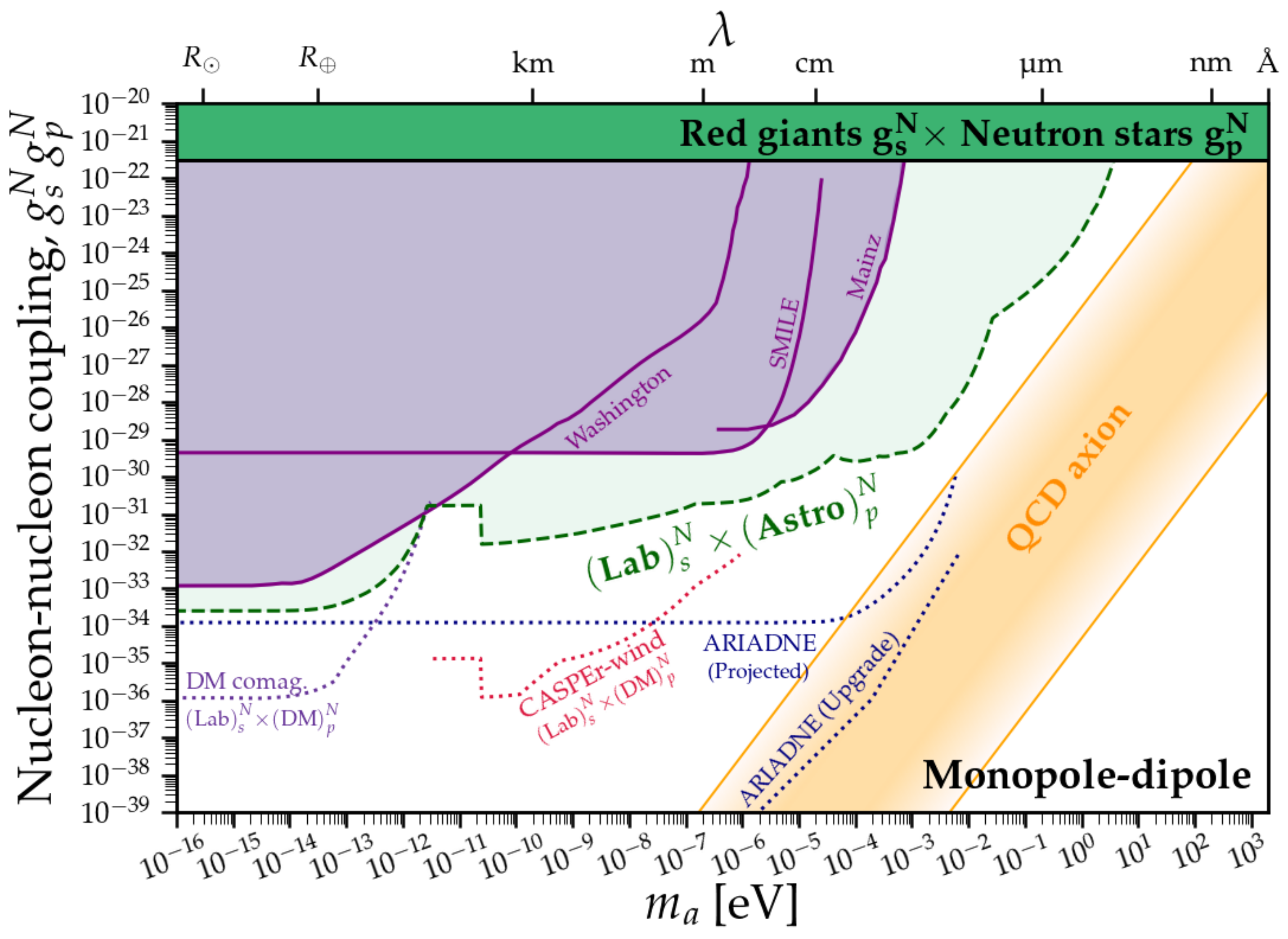
Axion-nucleon



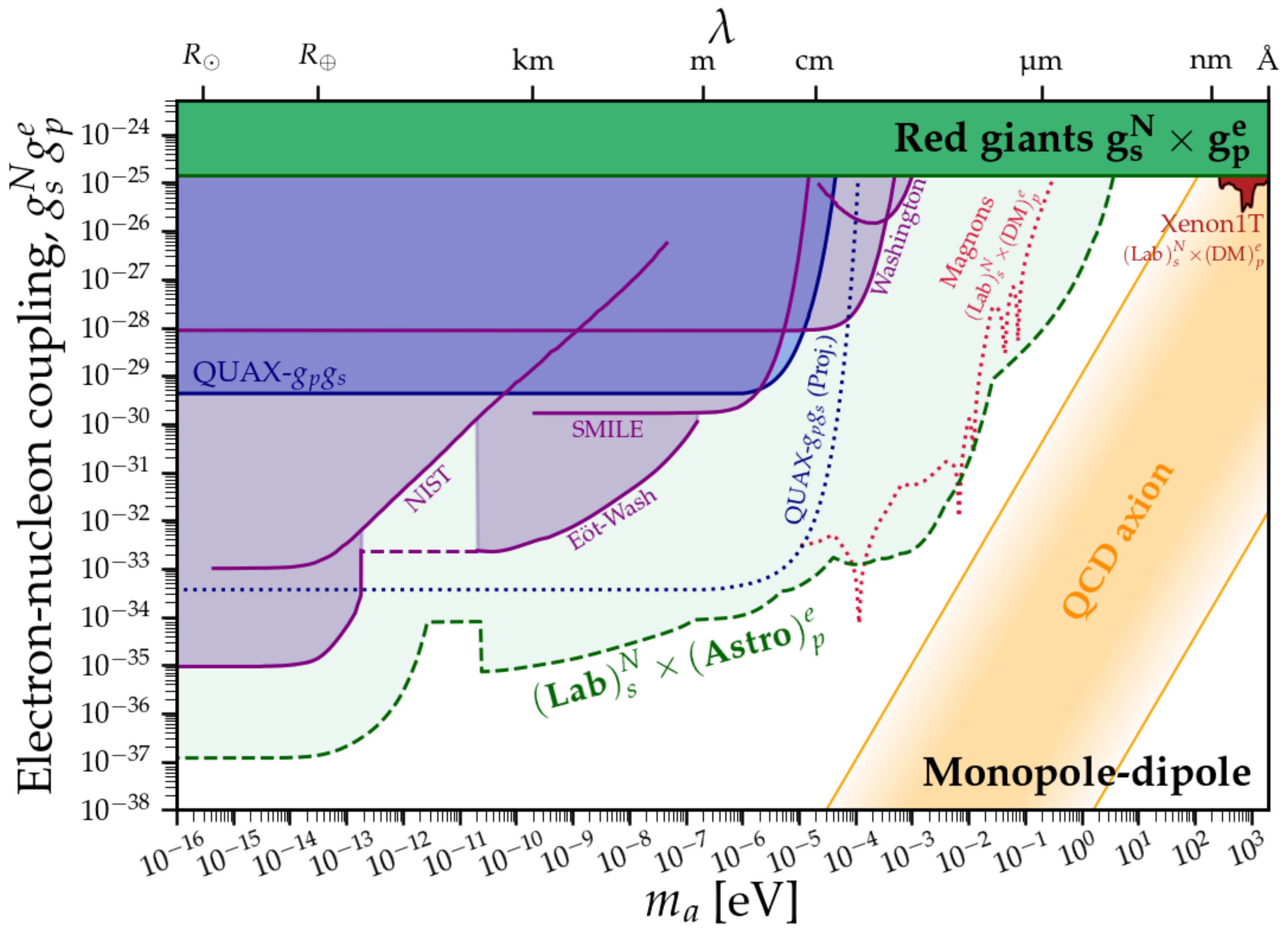
Axion decay constant



CP violating axion-electron



CP violating axion-nucleon



Axion-EDM