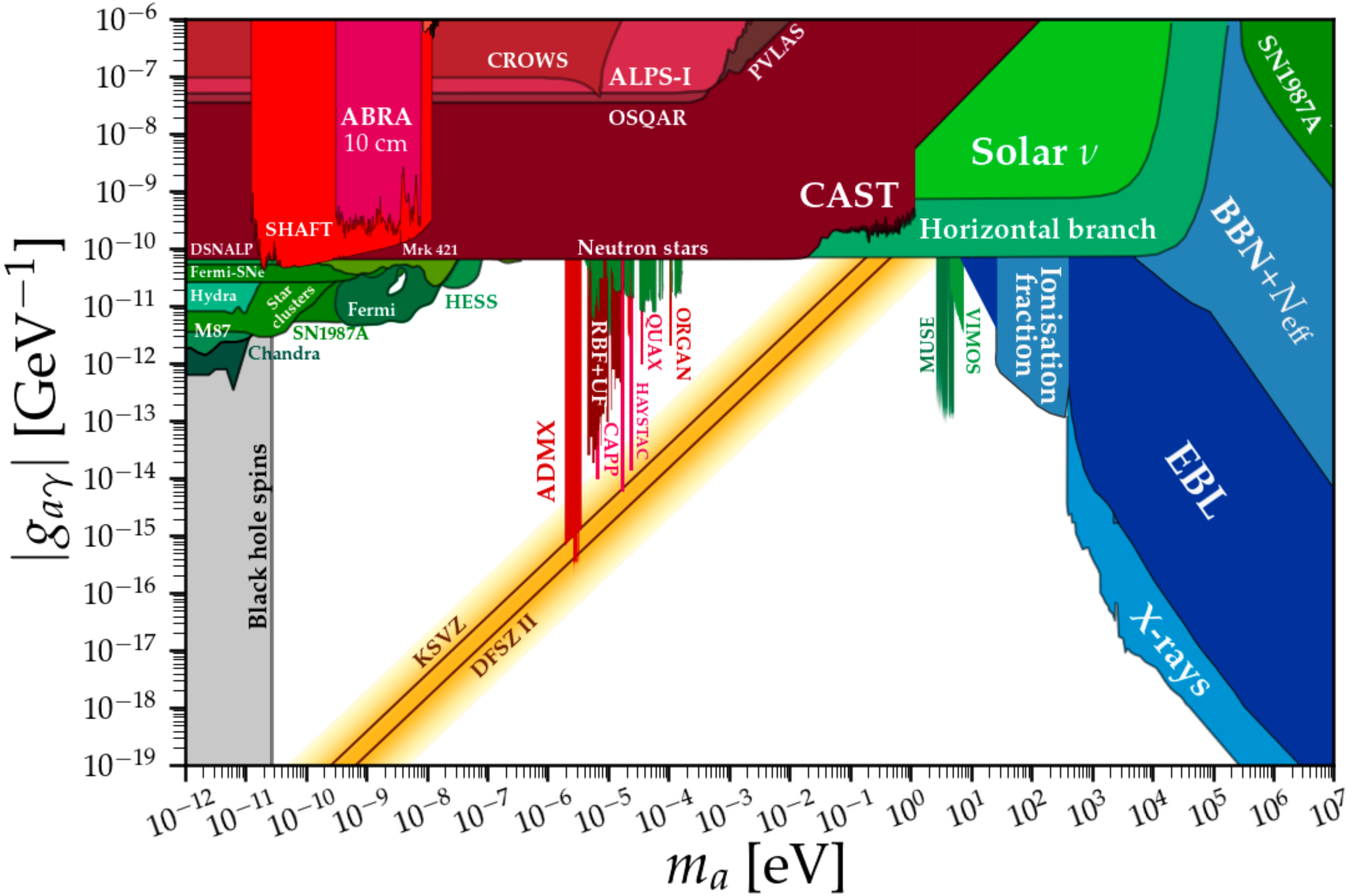
Axion Constraints 2020

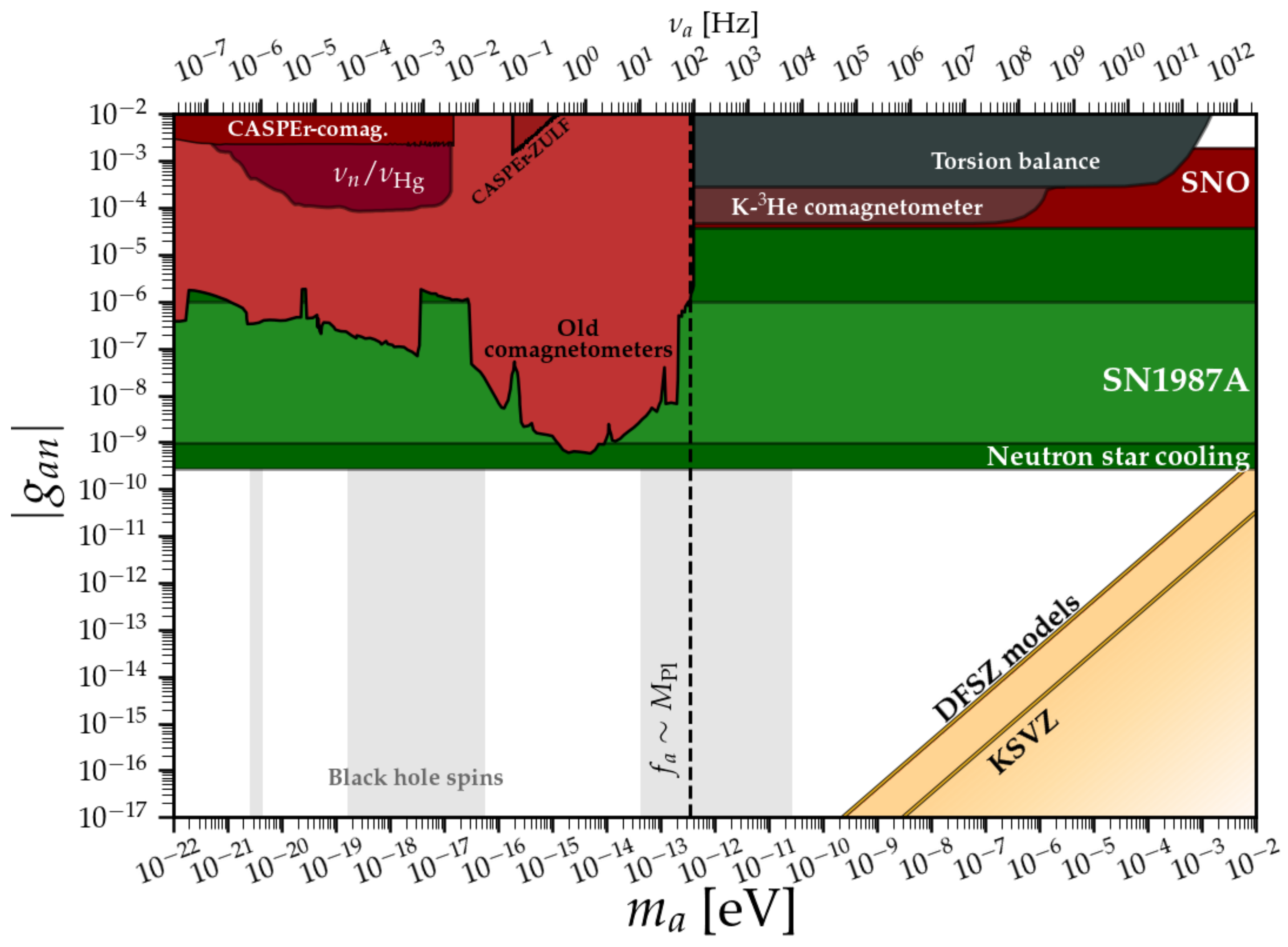
Ciaran O'Hare, U. Sydney

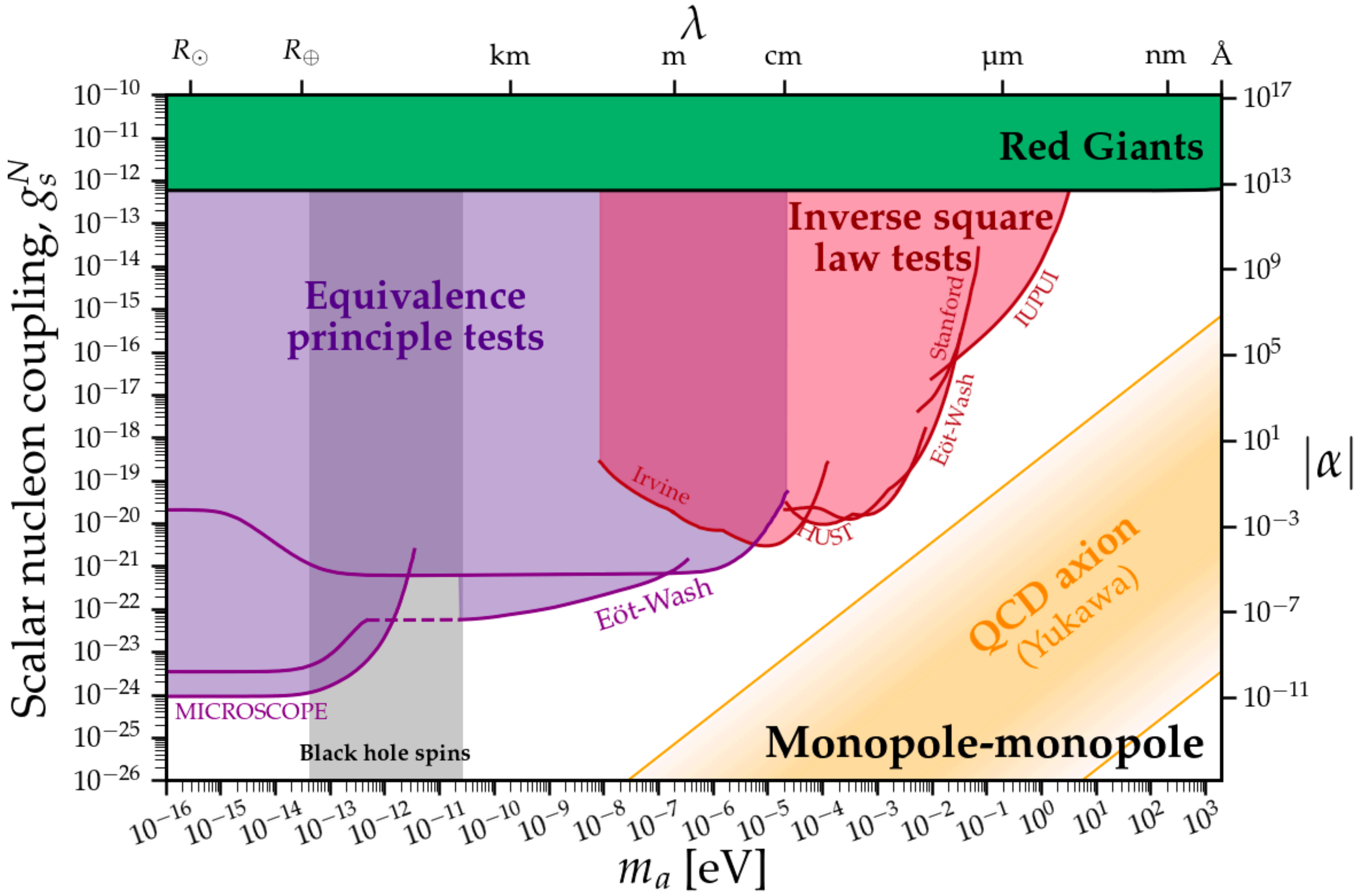
Constraints on axion-photon coupling

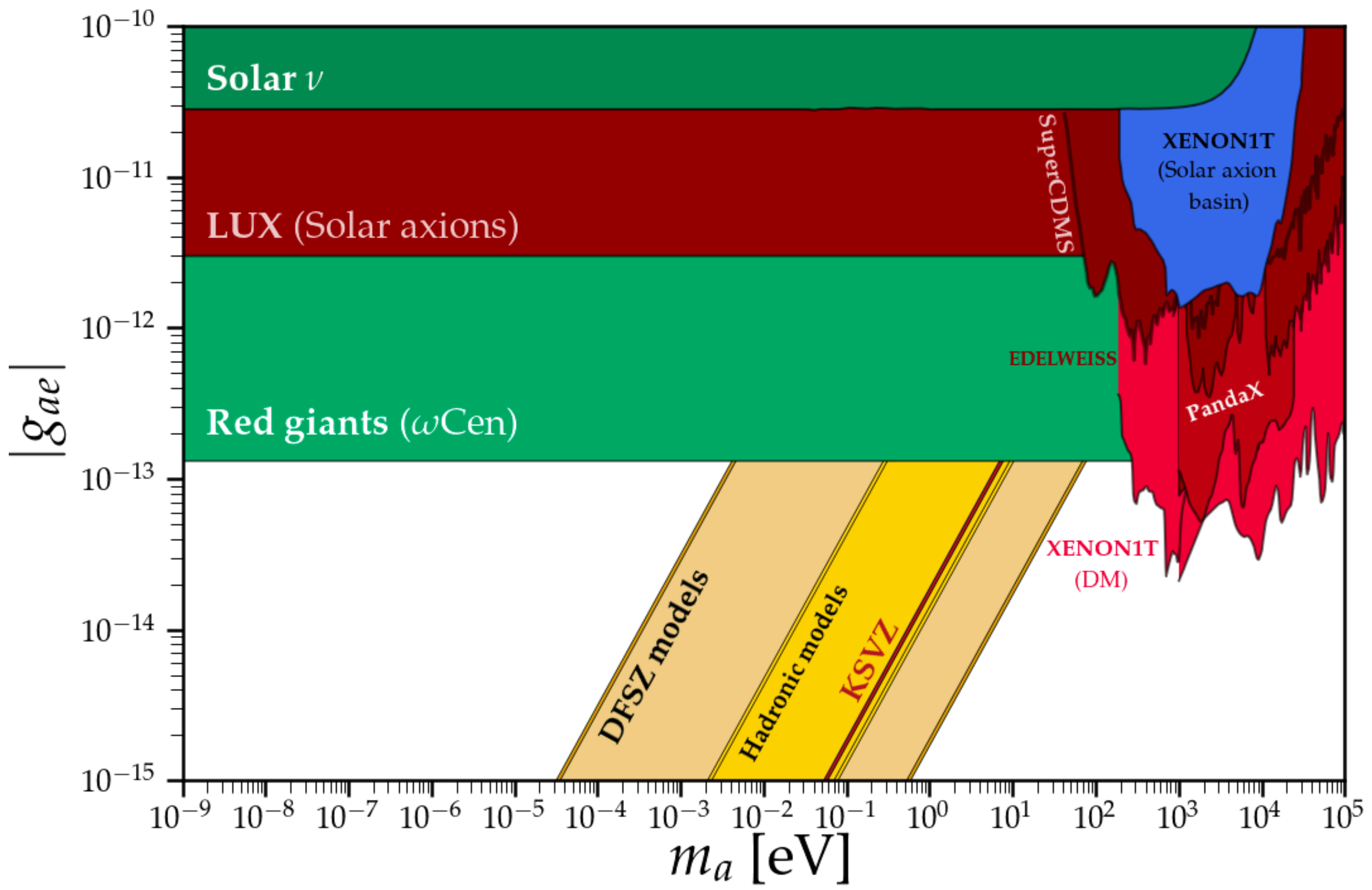


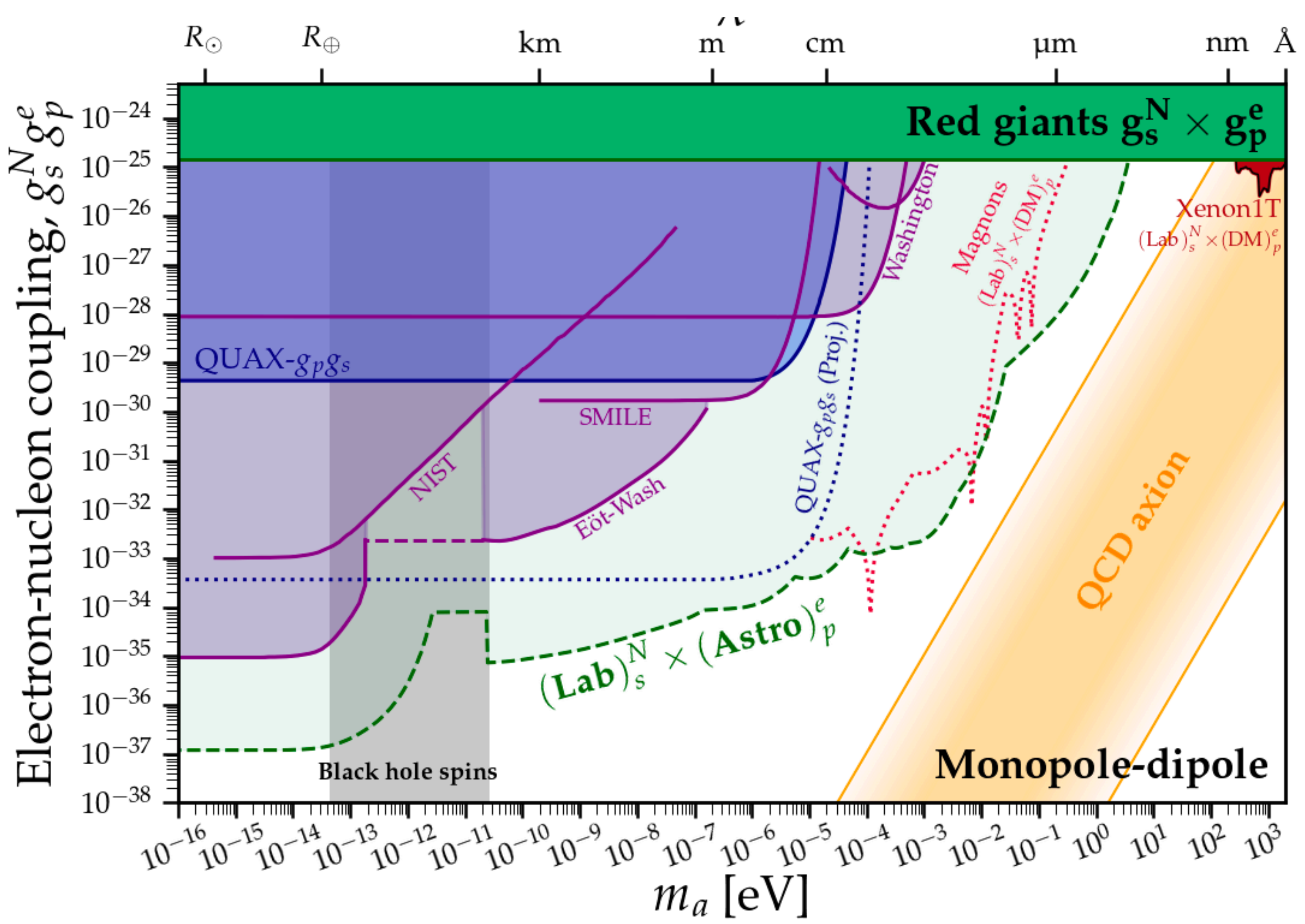
All constraints from this talk downloadable in .txt format from cajohare.github.io/AxionLimits/

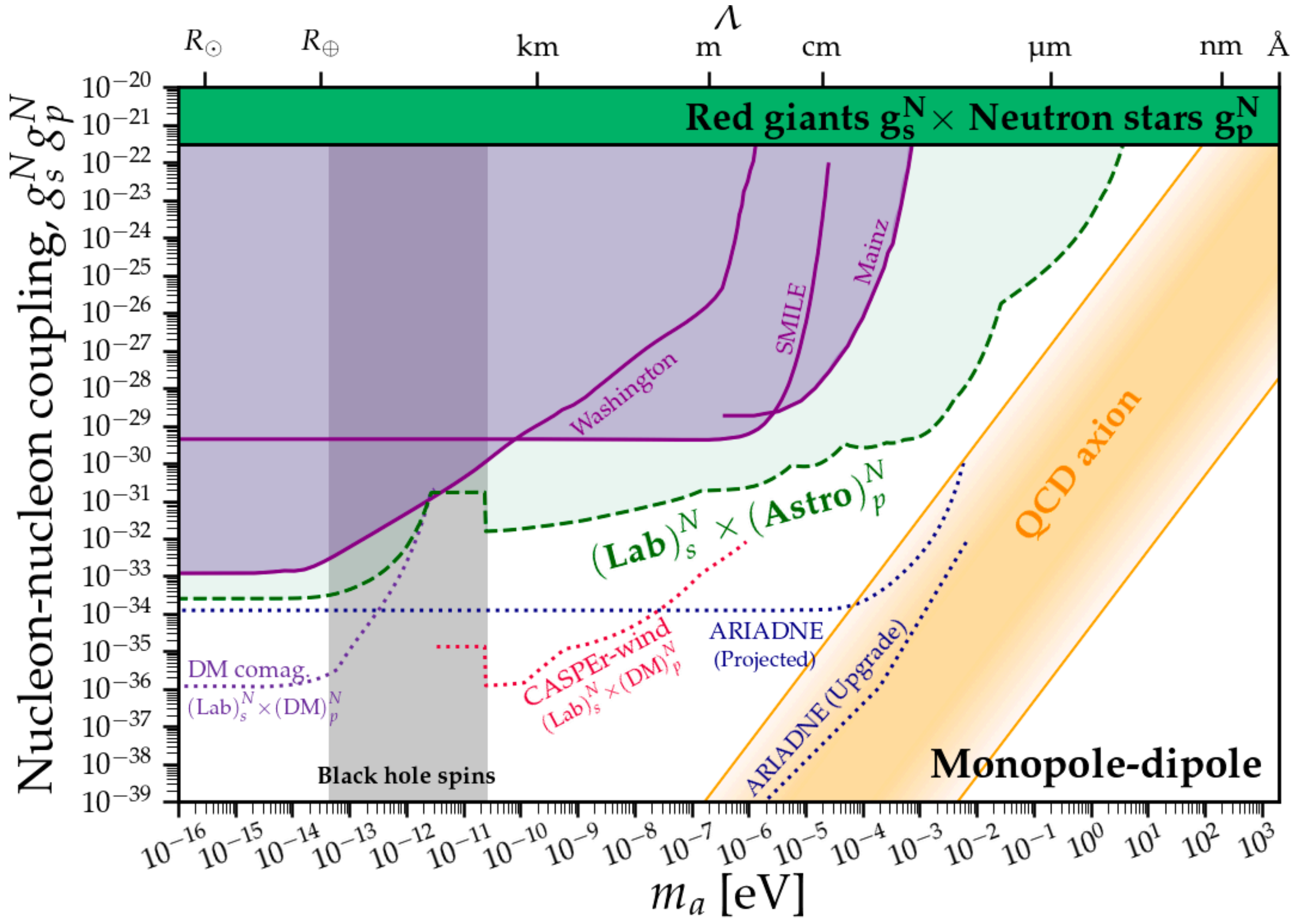
Constraints on other axion couplings











cajohare.github.io/AxionLimits/

The axion

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

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)\left(\partial^\mu a\right) - \mathcal{V}_{\rm QCD}(\theta) - C_{a\gamma}\frac{\alpha}{8\pi}F_{\mu\nu}\widetilde{F}^{\mu\nu}\frac{a}{f_a} + \frac{\partial_\mu a}{2f_a}\sum_\psi C_{a\psi}\left(\bar{\psi}\gamma^\mu\gamma^5\psi\right) + \ldots$$

+ a few model-dependent assumptions
→ Could be galactic DM
→ Could be produced in cosmologically relevant amounts
→ Could solve strong CP problem (aka QCD axion)

⟶ Focus on constraints on possible interactions, less on specific models/ assumptions

Aim of this talk: focus on some new or less-publicised results from this year

1. Axion-Photon coupling

→ Direct searches (detecting natural sources of axions)
→ Purely lab searches (detecting human-made axions)
→ Indirect searches (imprints of axions in astrophysical data)

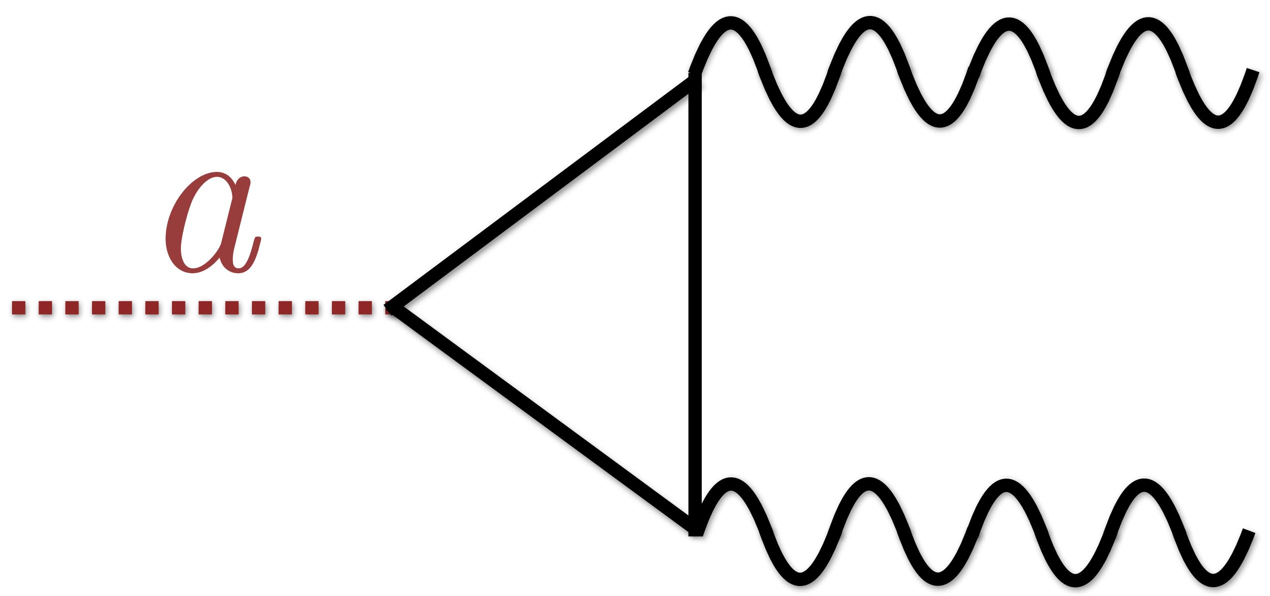
2. Axion-fermion couplings (briefly)

3. Caveats, nuances, messiness and loopholes

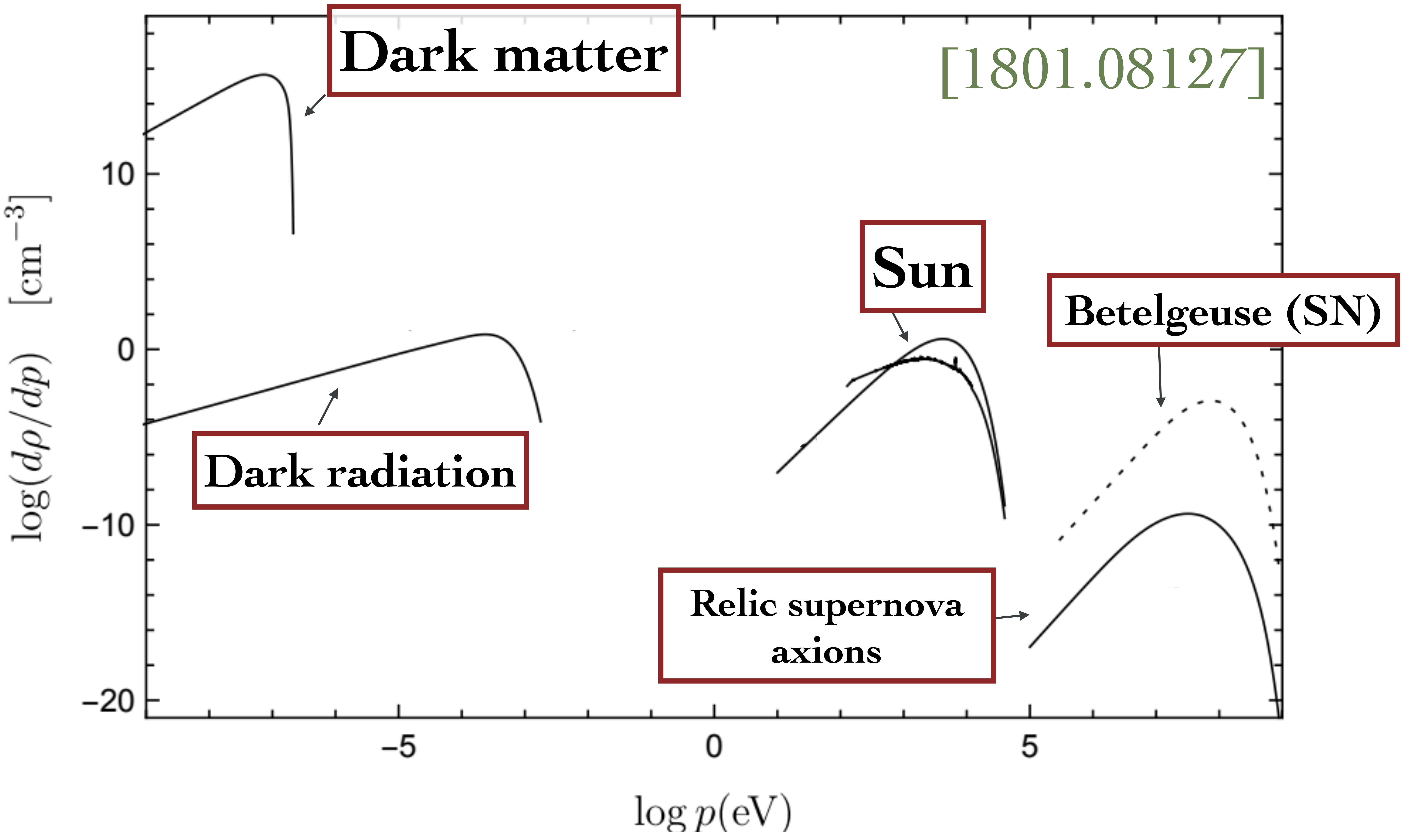
→ Axions as dark matter

Coupling to the photon: $g_{a\gamma}$

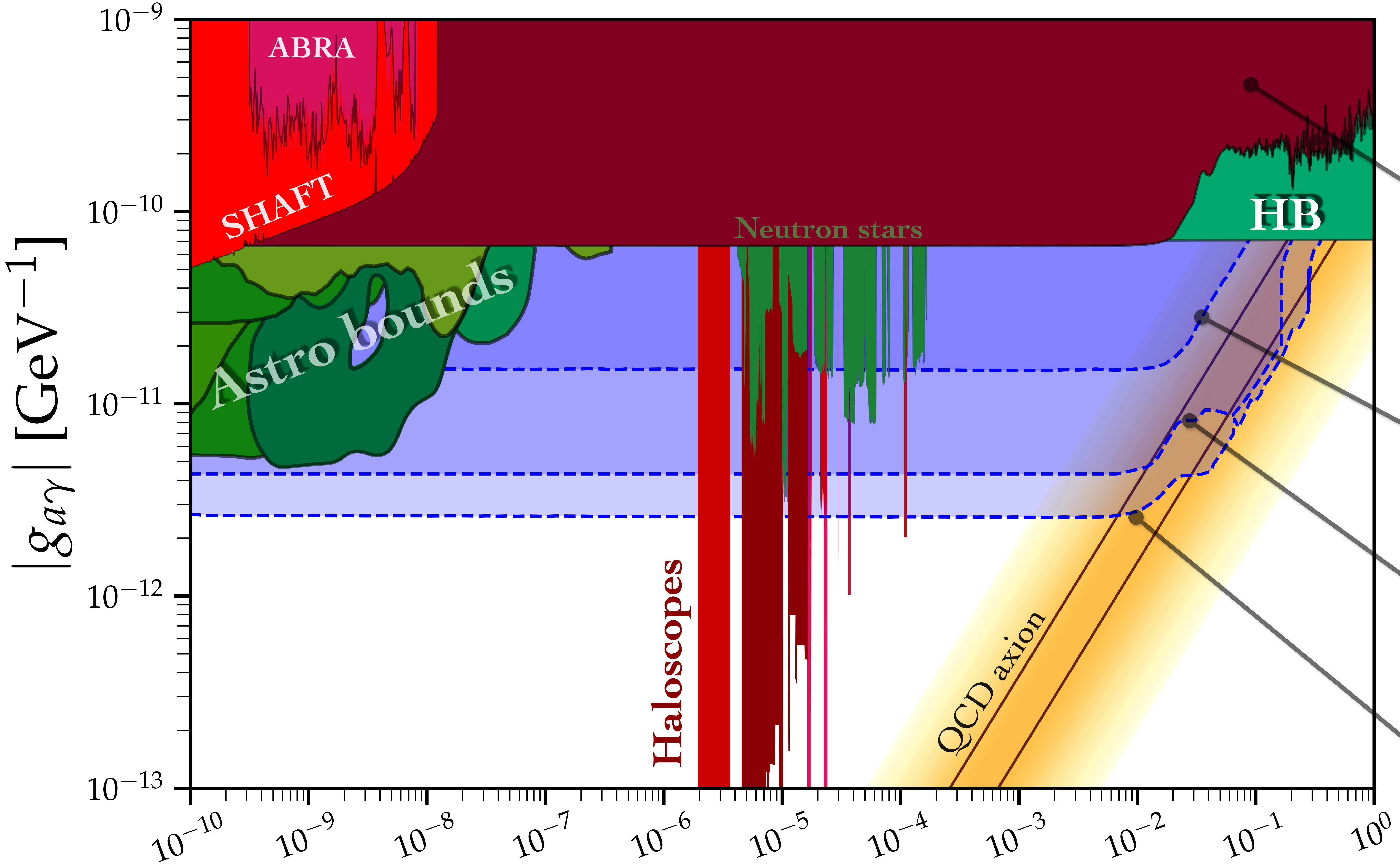
$$\mathcal{L} = \frac{1}{4} g_{a\gamma} a(\mathbf{x}, t) F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Direct detection: natural sources of axions



Sun is most obvious source, but no updates for now



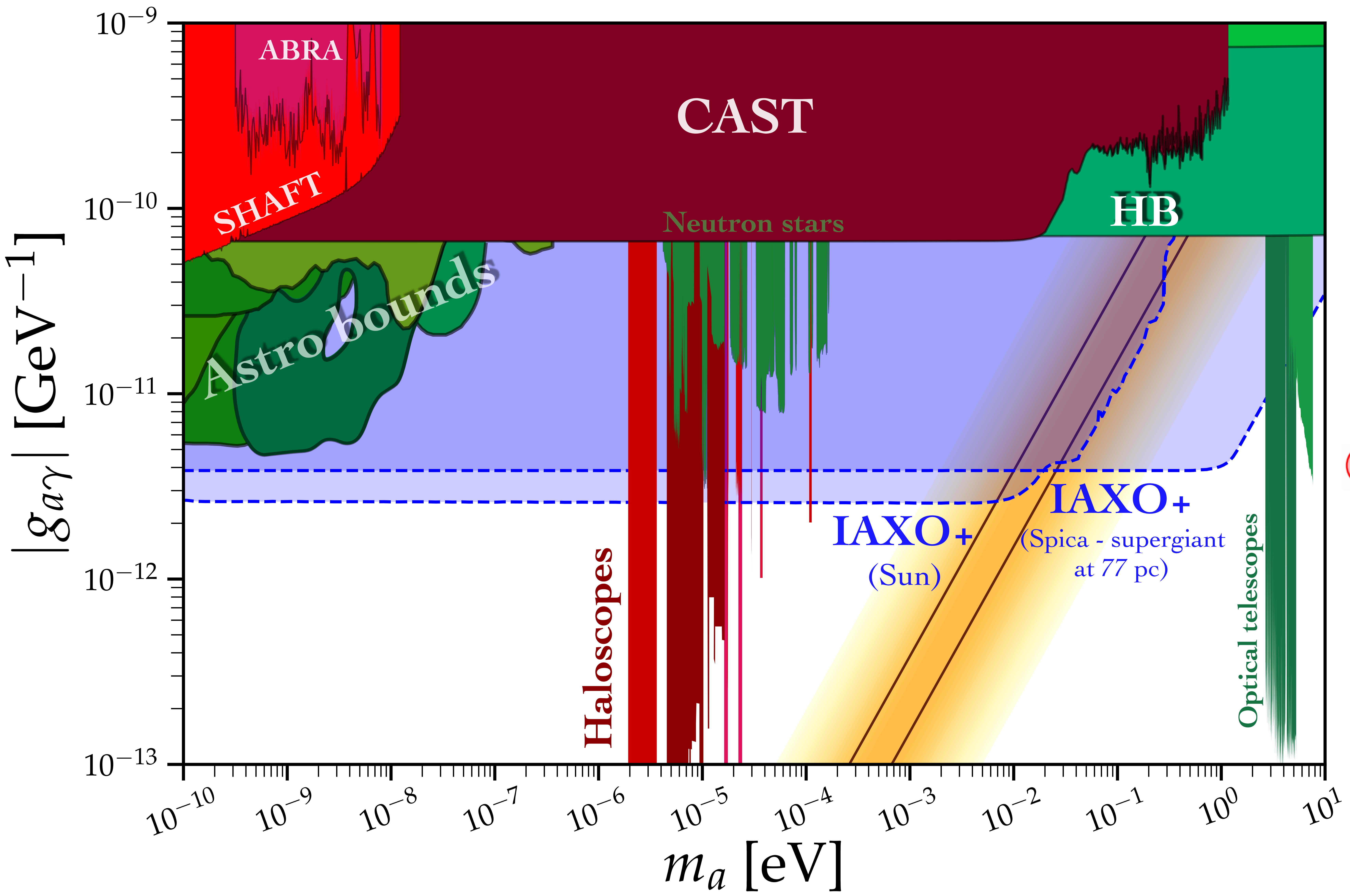
Helioscopes

- 2017: Last **CAST** result [1705.02290]

IAXO

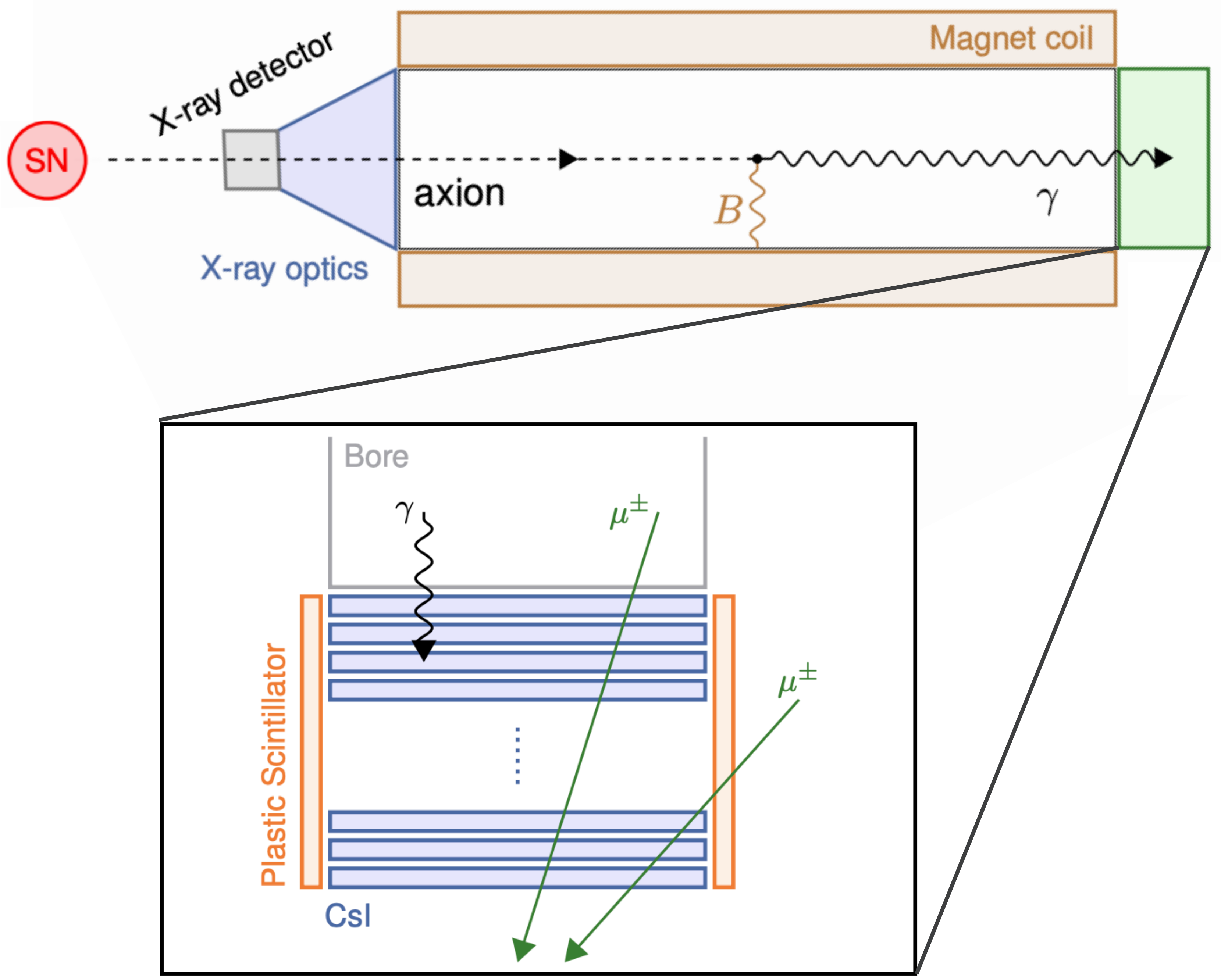
- **babyIAXO** - 2.5T x 2 bores
  Conceptual design: [2010.12076]
- **IAXO** - 2.5 T x 8 bores
- **IAXO+** - 3.5 T x 2 bores

SN axions are similar, but at 10-100 MeV energies instead of keV



Ge et al. [2008.03924]

Could detect in modified IAXO, just need to stick a gamma ray detector at other end to X-ray optics (solar end)



DM axions

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

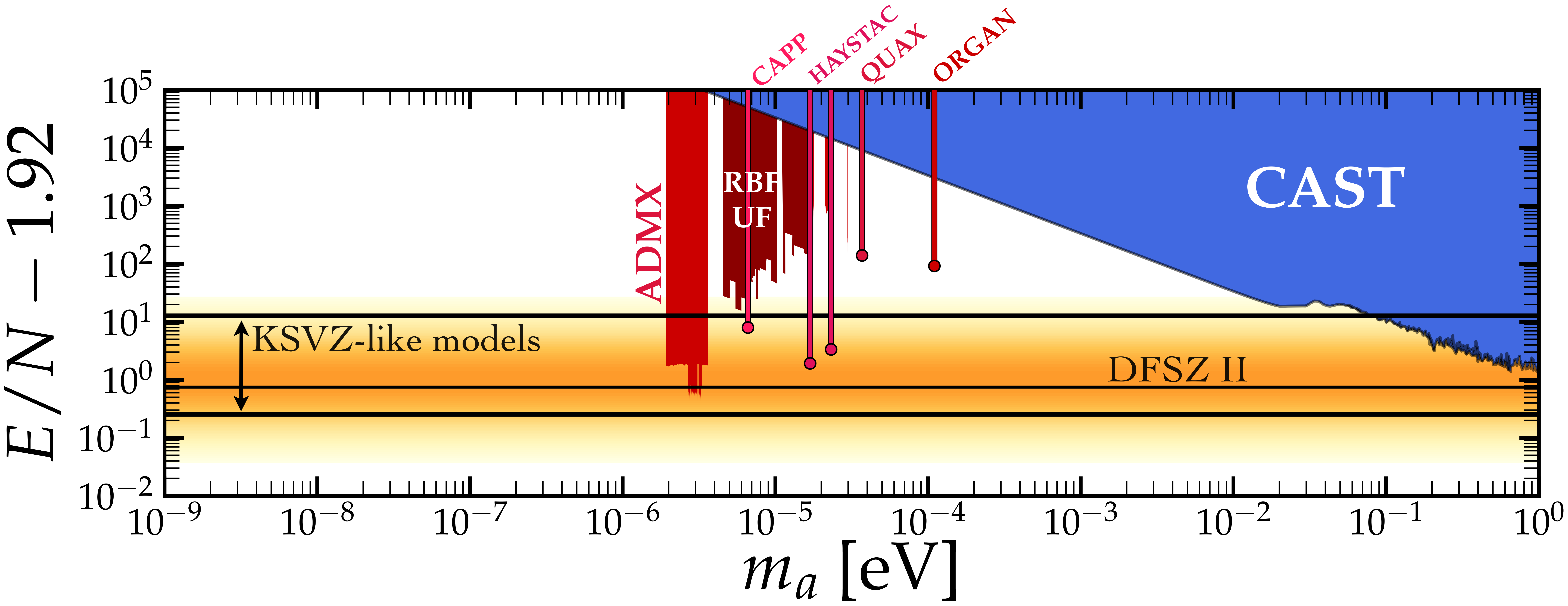
$\omega \approx m_a$

Oscillating at the axion mass

Haloscopes for QCD axion

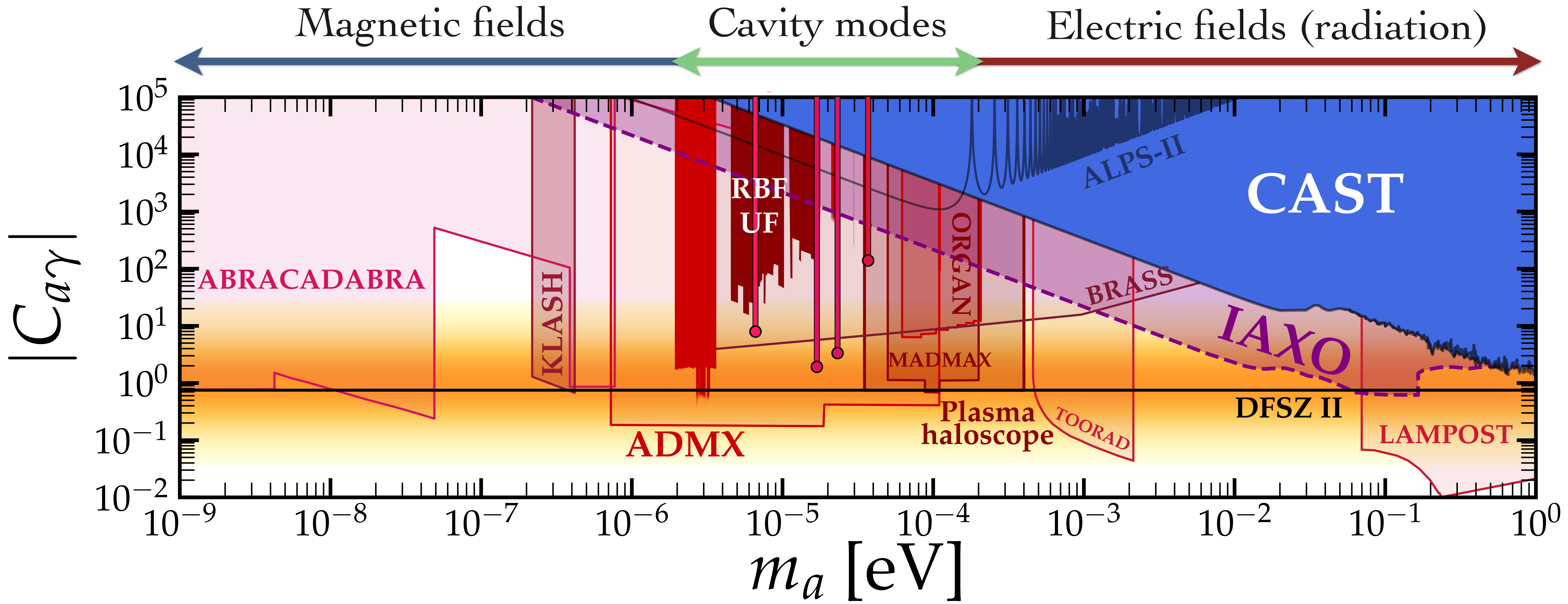
$$g_{a\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} = 2.0 \times 10^{-16} C_{a\gamma} \frac{m_a}{\mu\text{eV}}\ \text{GeV}^{-1}$$

$$C_{a\gamma} = \frac{E}{N} - 1.92$$

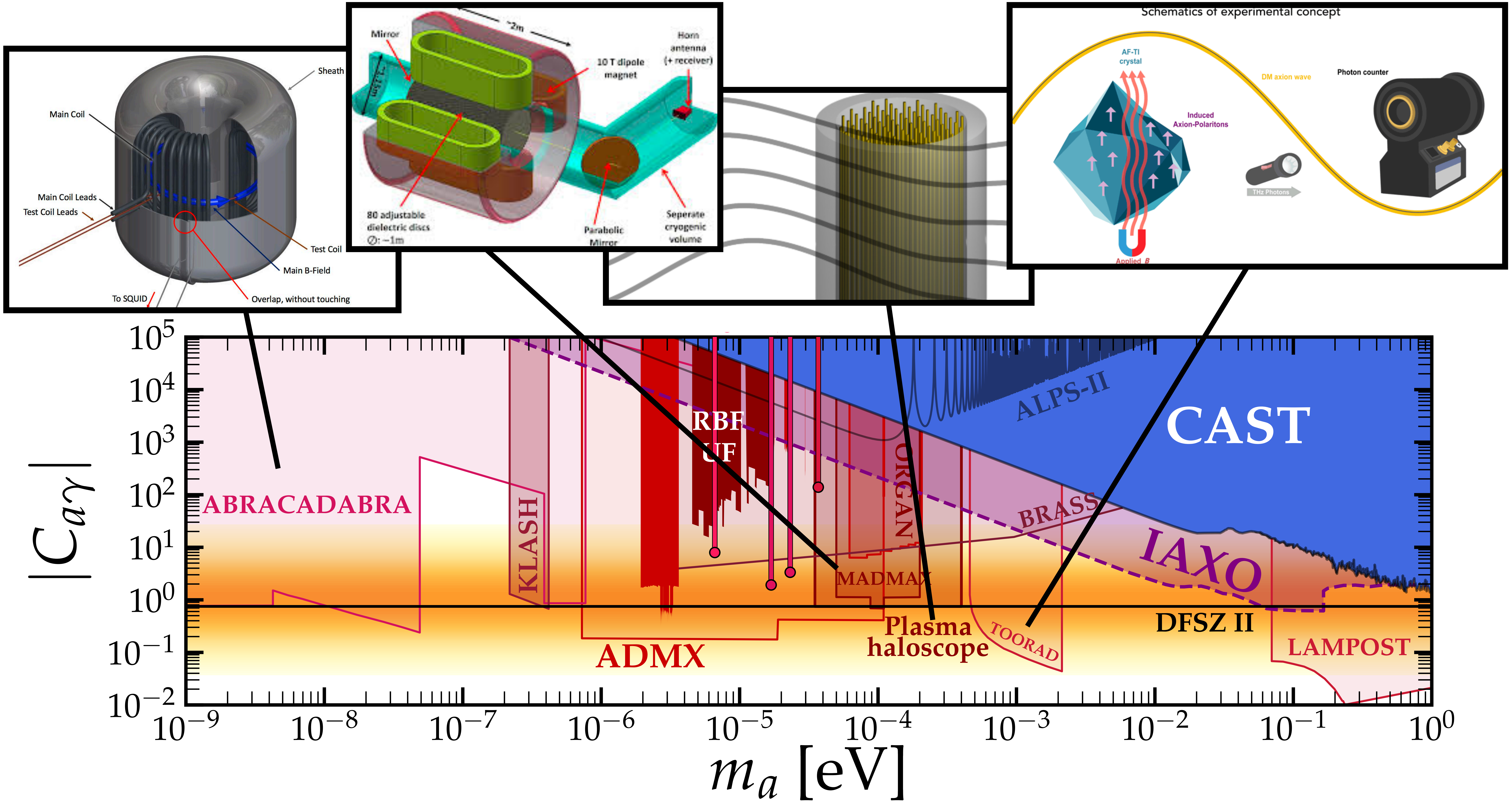


Haloscopes for QCD axion (future prospects)

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



Haloscopes for QCD axion (future prospects)

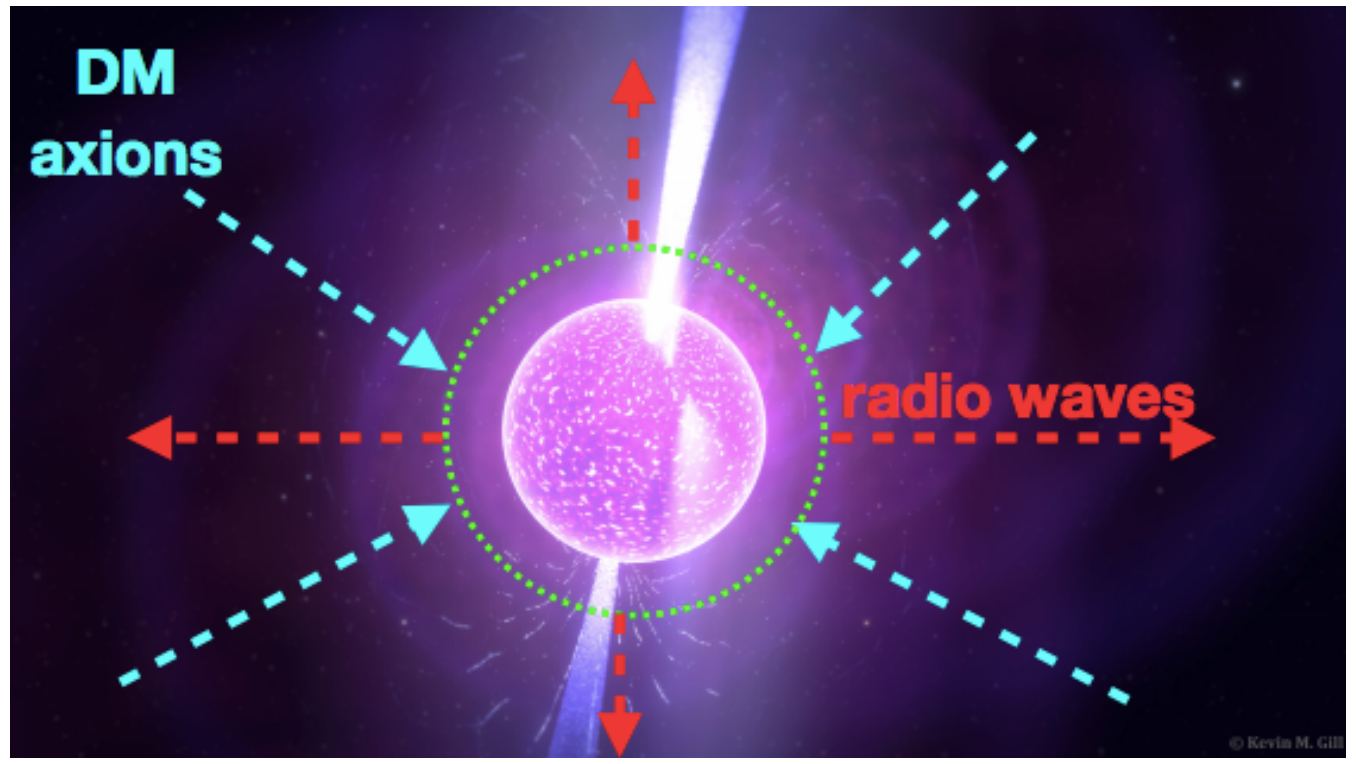


Photon coupling: indirect searches

Astrophysical tests of axions

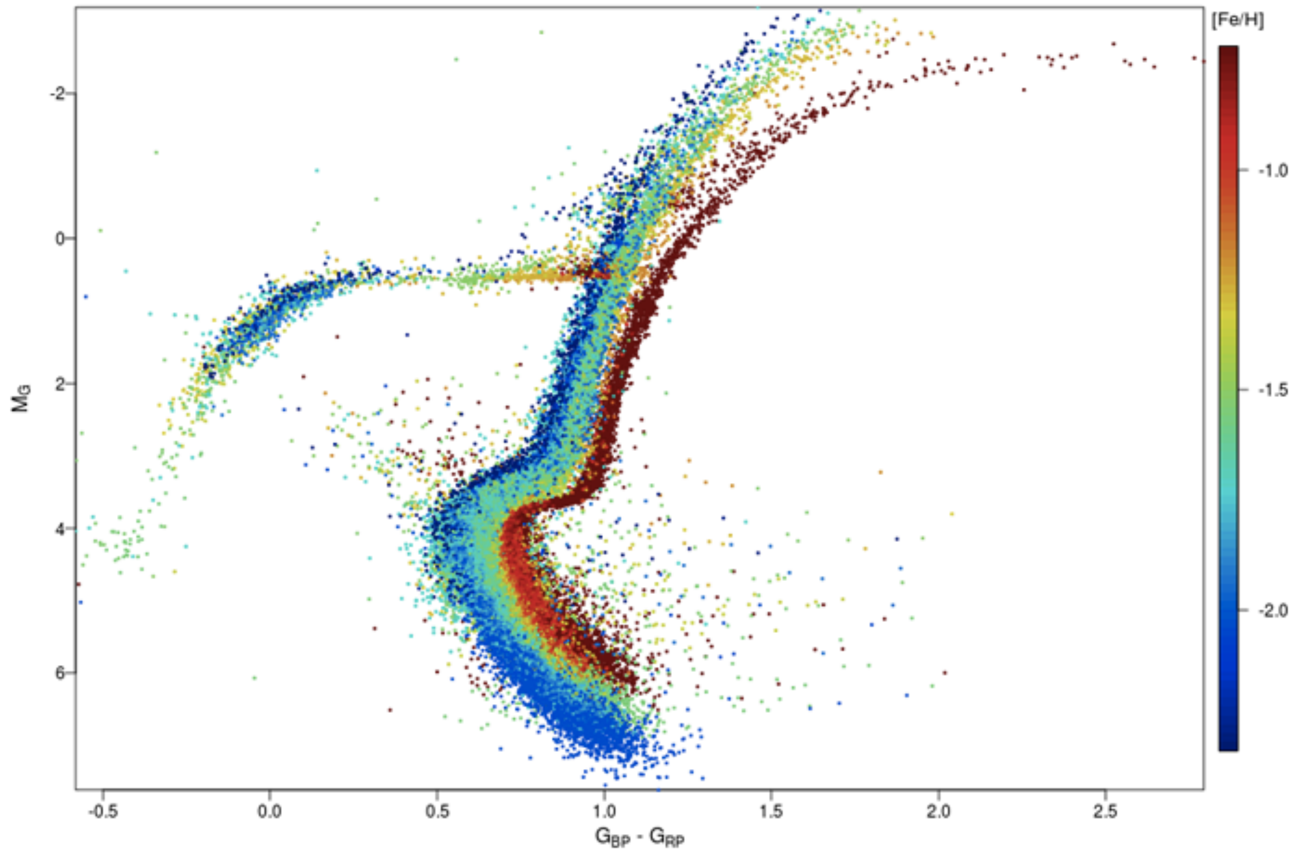
DM axion conversion

→ Spectral lines
→ Transient signals (axion substructure)



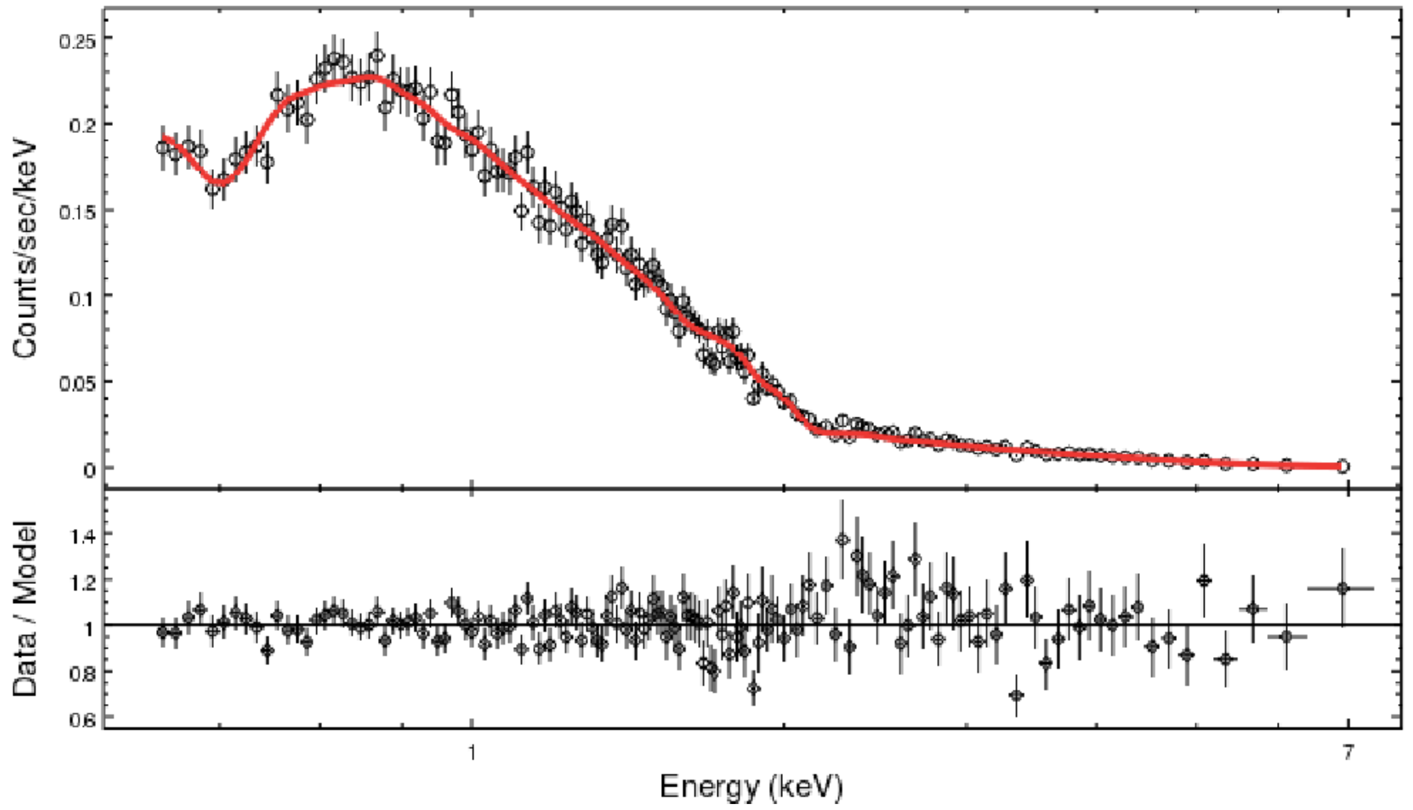
Axion emission affecting stellar lifetimes

→ Horizontal branch/red giant branch in GCs
→ White dwarf luminosity function



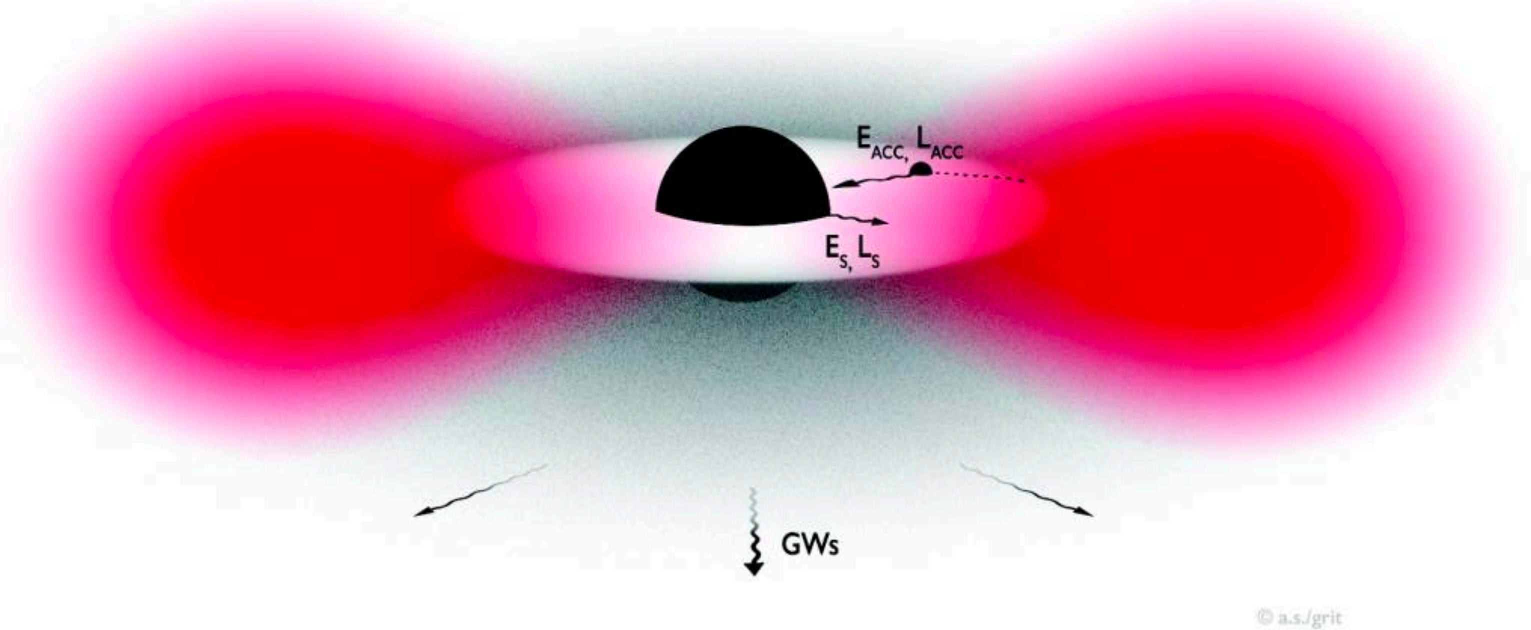
Photon conversion in astrophysical B-fields

→ Spectral oscillatory features
→ Anomalous dimming of sources



Black hole superradiance

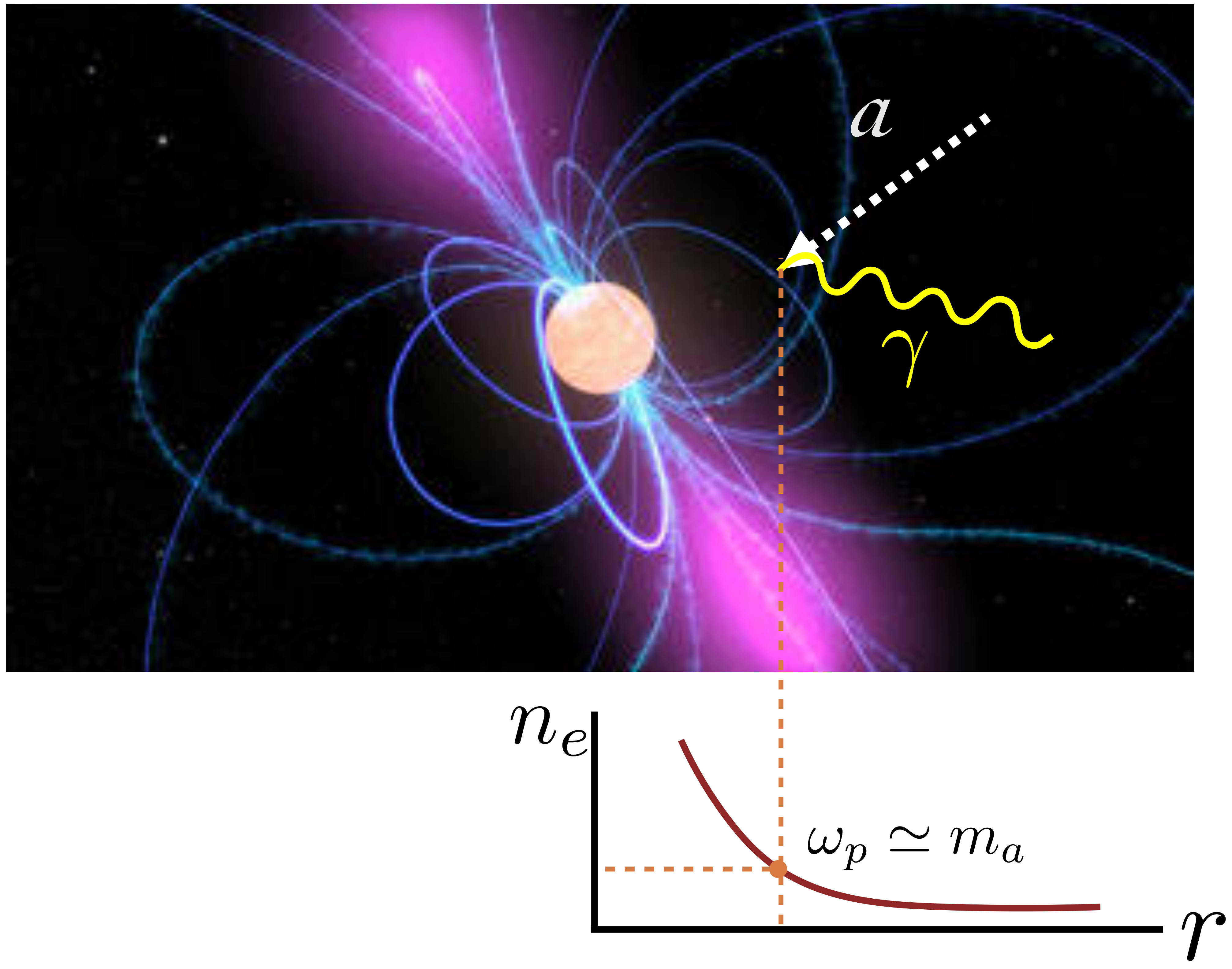
(Observed BH spins exclude axion mass for Schwarzschild rad. ~ axion's Compton wavelength)
→ stellar mass BH spins ~ 10^{-13} — 10^{-11} eV
→ supermassive BH spins ~ 10^{-19} — 10^{-17} eV



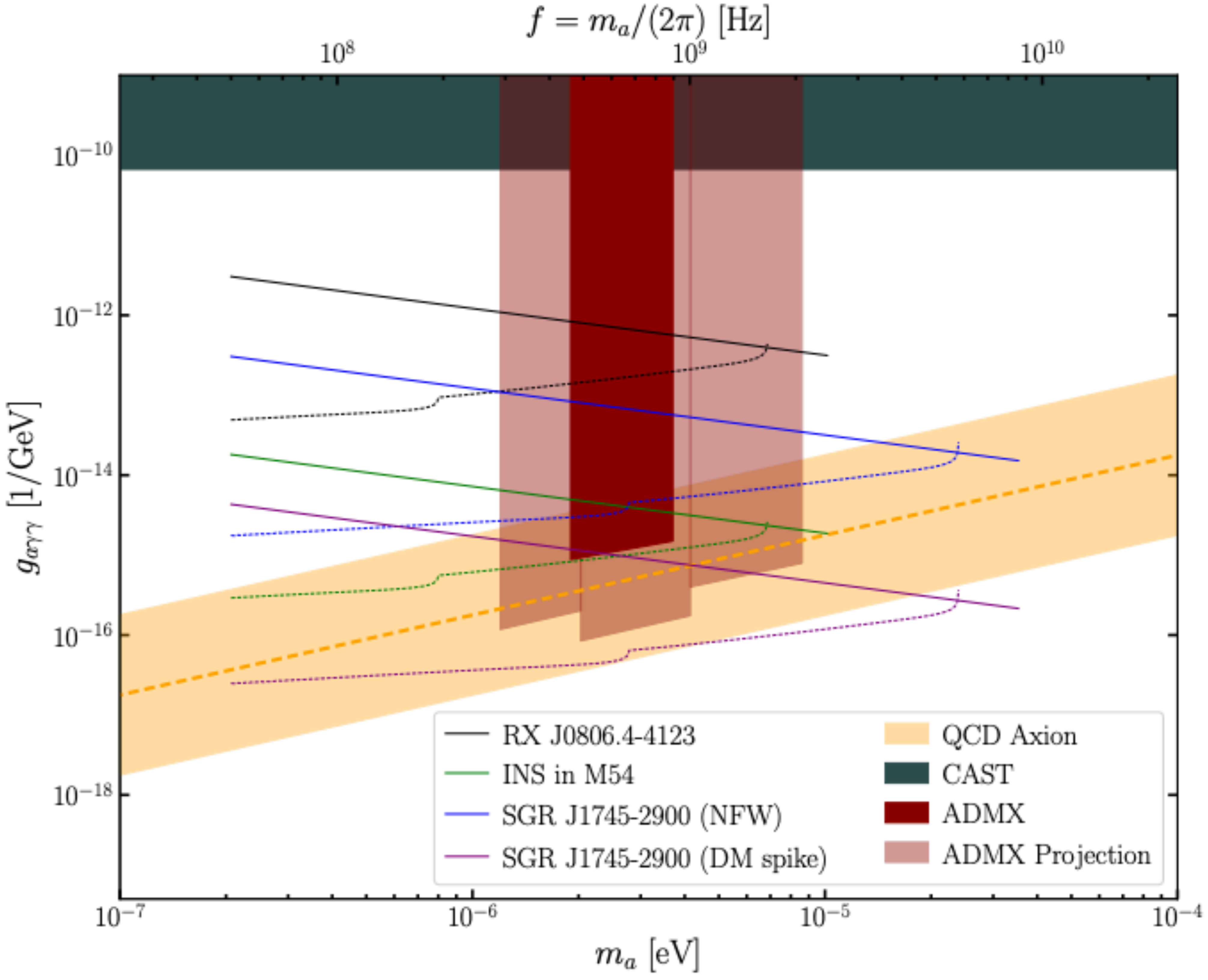
DM axions in neutron star magnetospheres

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

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

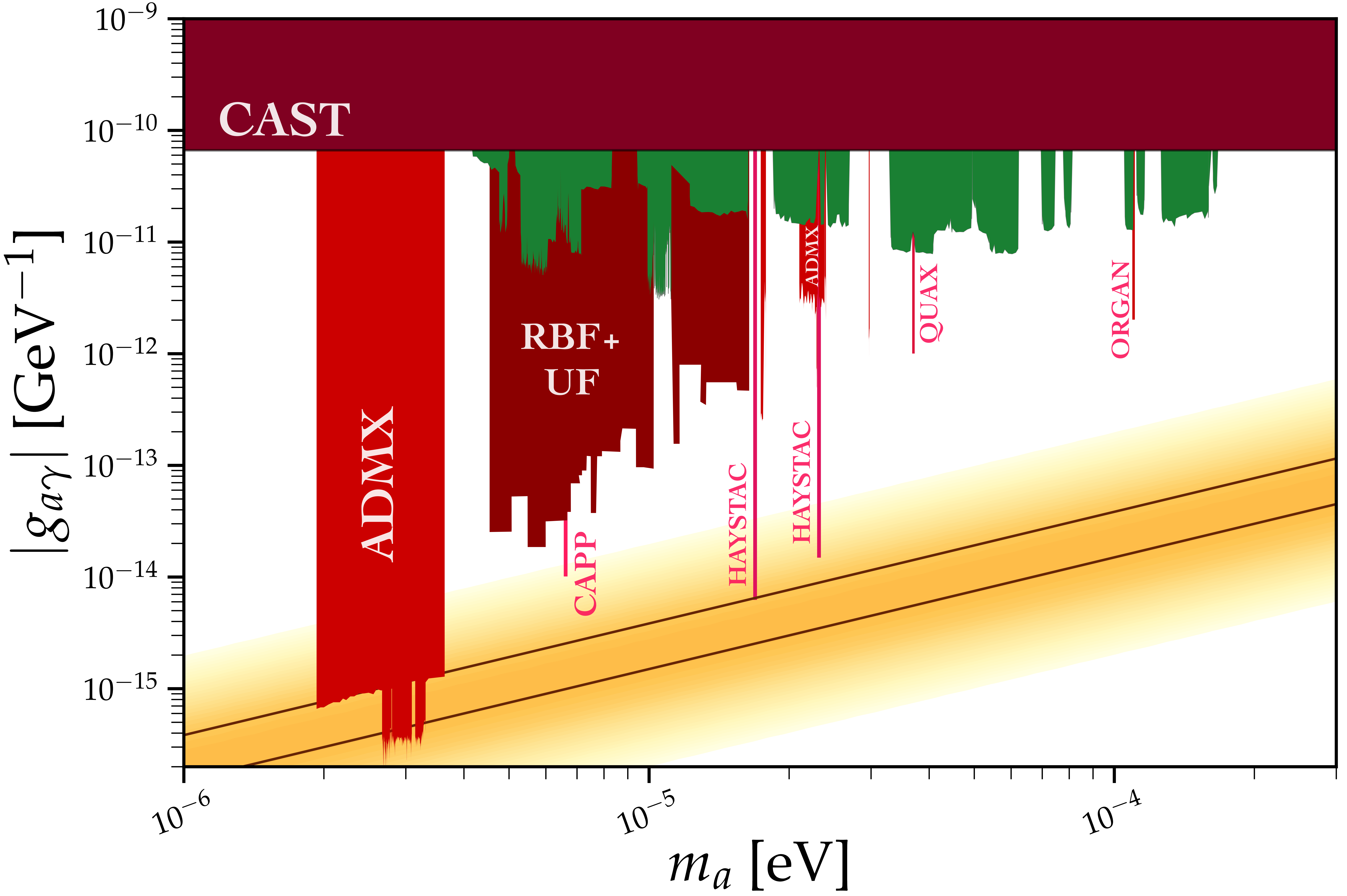


Hook et al. 1804.03145



Heavy theory/astro uncertainties from DM density and NS model

New constraints, complementary to cavity haloscopes

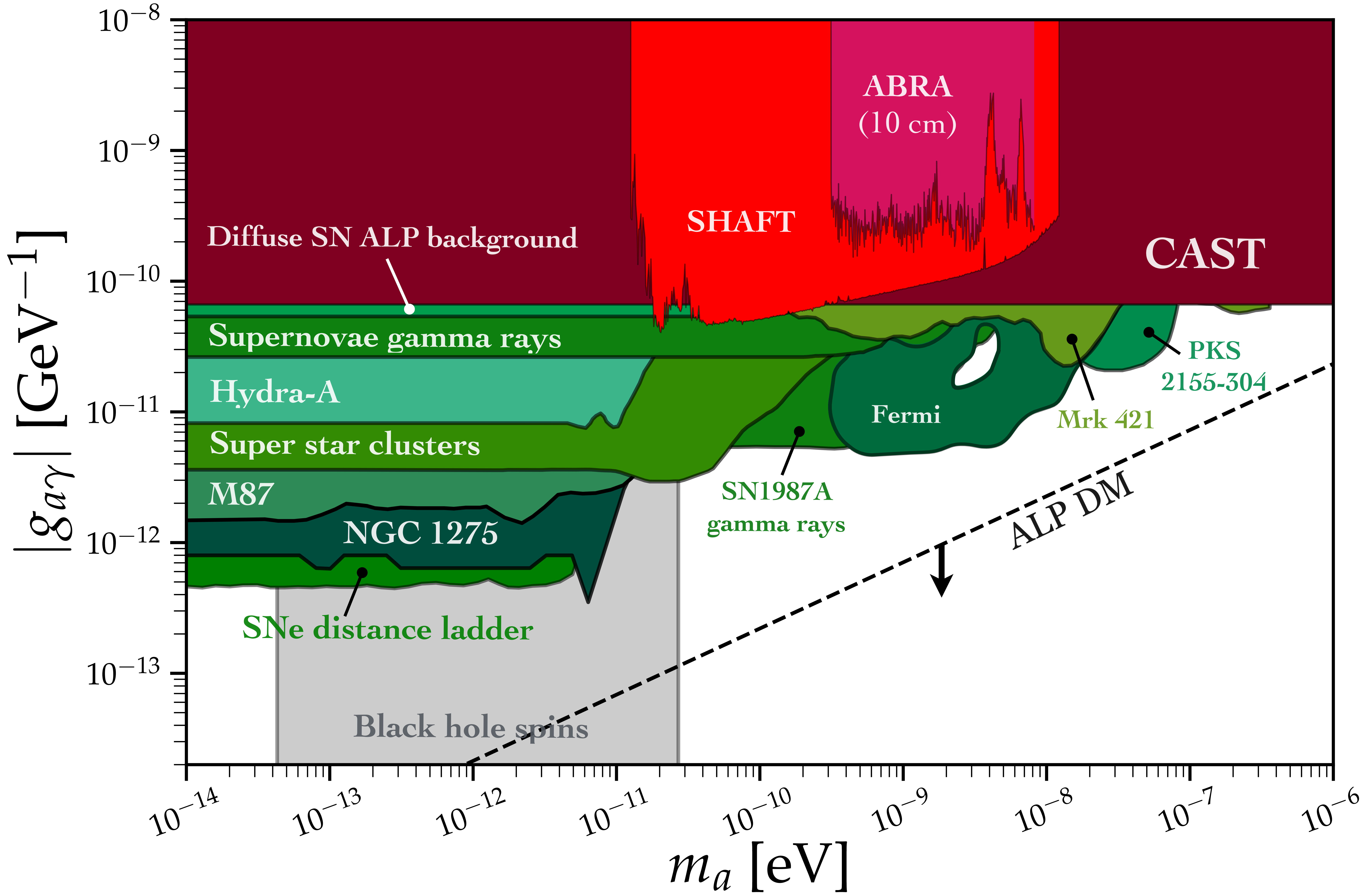


Radio spectral lines from neutron stars

Darling
[2008.11188] & [2008.01877]
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]

Light axions in astrophysical X-ray/gamma ray data



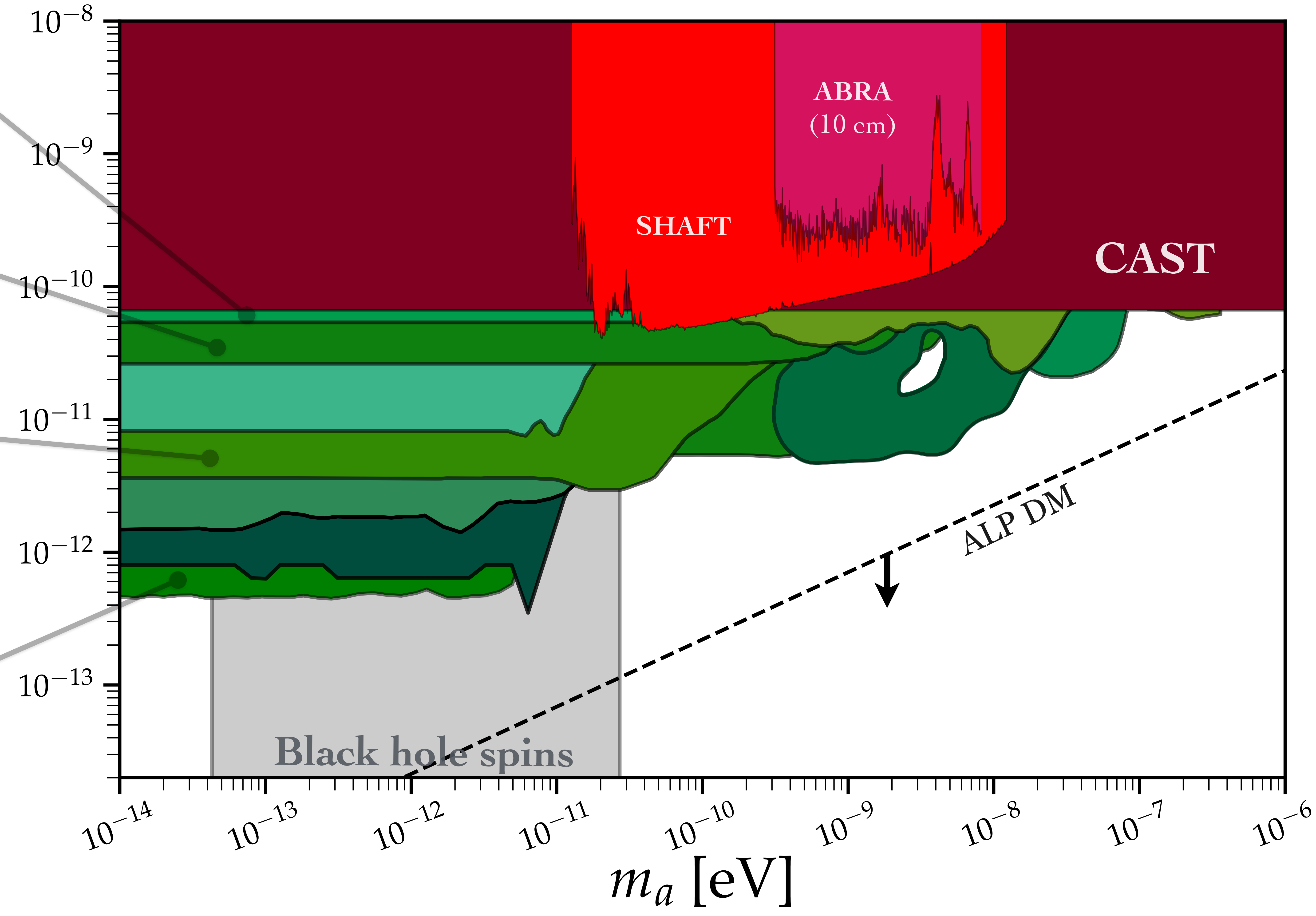
Light axions in astrophysical data: a few interesting cases from this year

Diffuse MeV flux of SN axions converting in MW magnetic field
Calore et al. [2008.11741]

Extragalactic SN-axions converting into gamma-rays in MW, using Fermi data
Meyer & Petrushevka [2006.06722]

Archival NuStar data on MW super star clusters, search for stellar axions converting into X-rays
Dessert et al. [2008.03305]

SNe-1a distance ladder - SNe dimmer at higher z due to axion-photon conversion
Buen-Abad et al. [2011.05993]

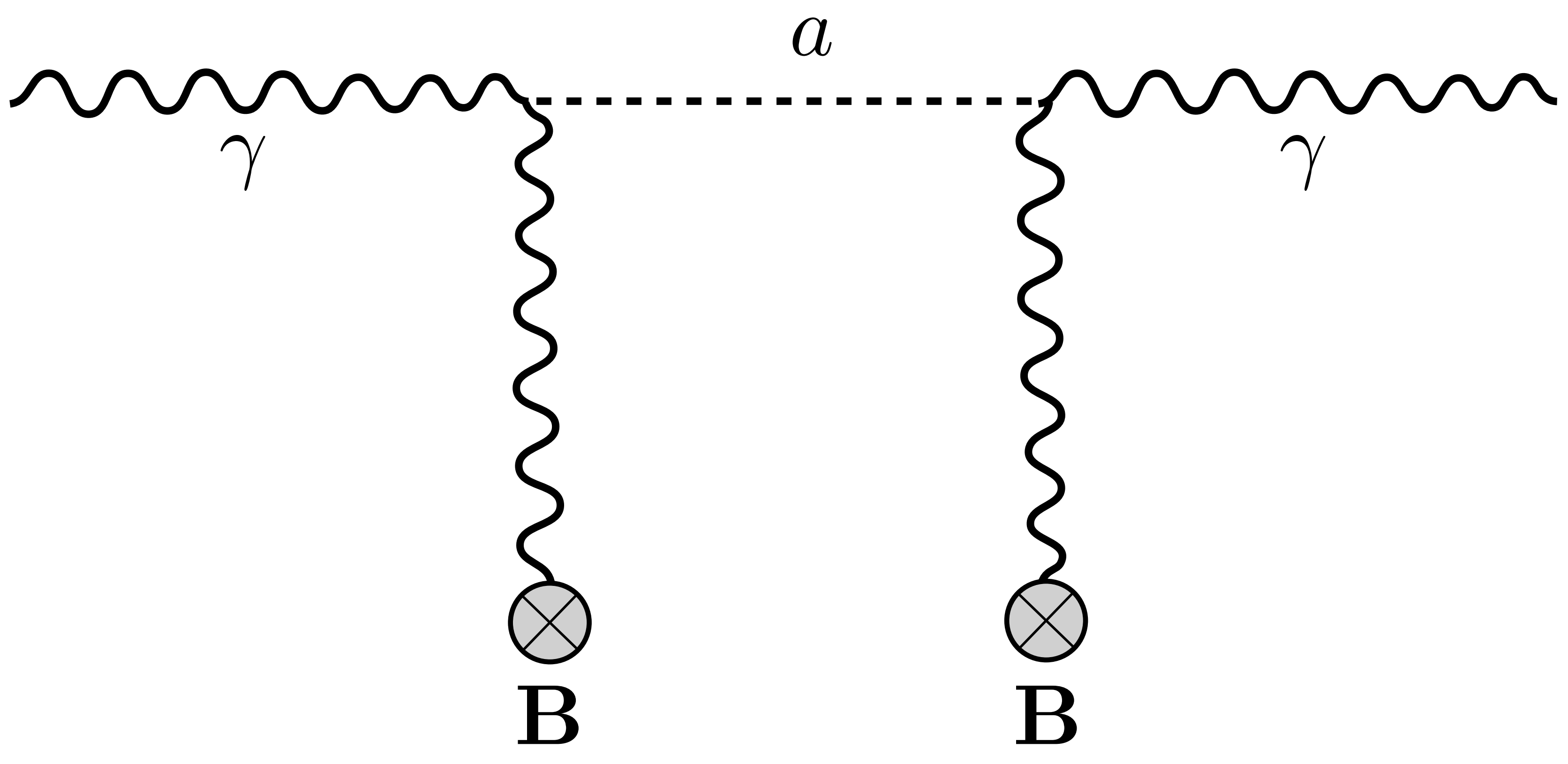


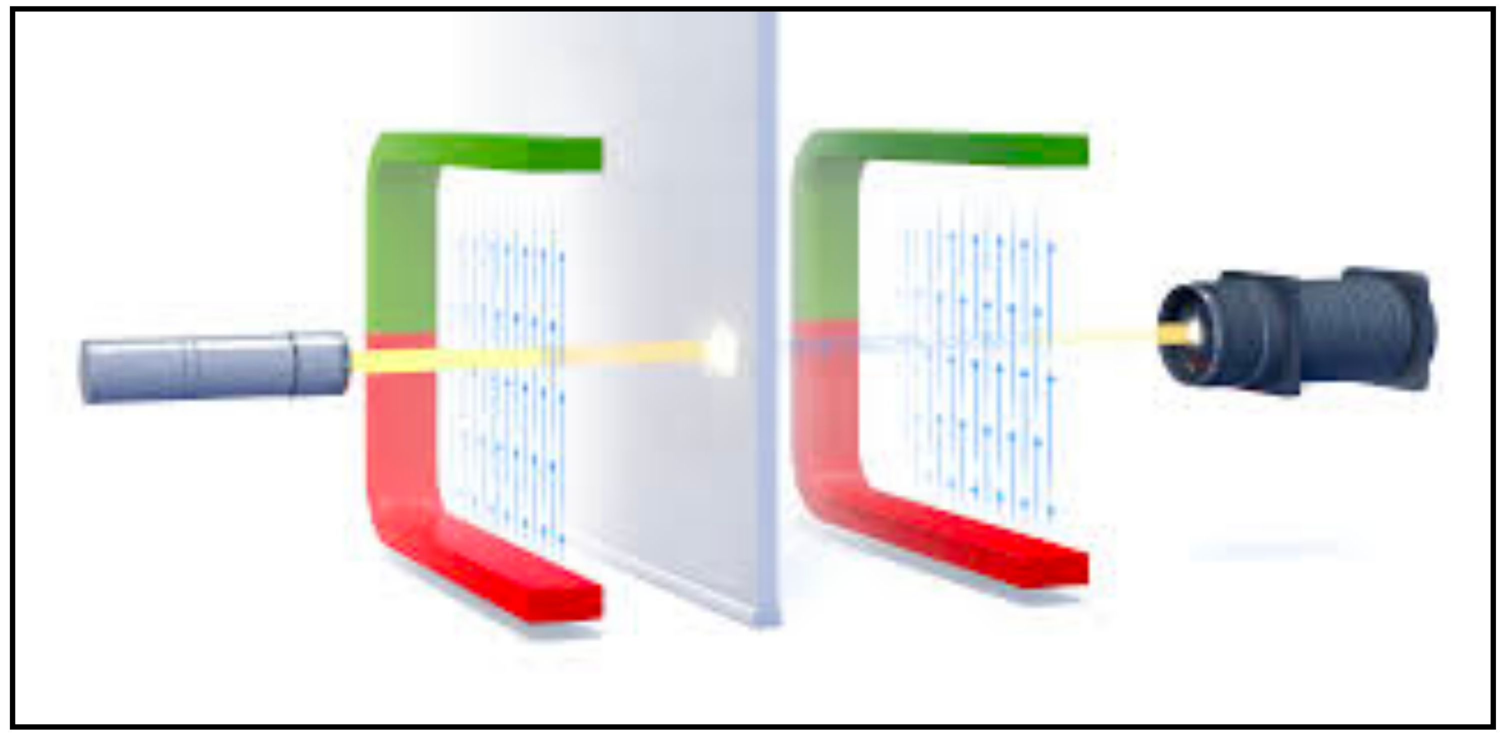
Pure laboratory searches

Cure for uncertainties: pure laboratory tests of axions

Photons

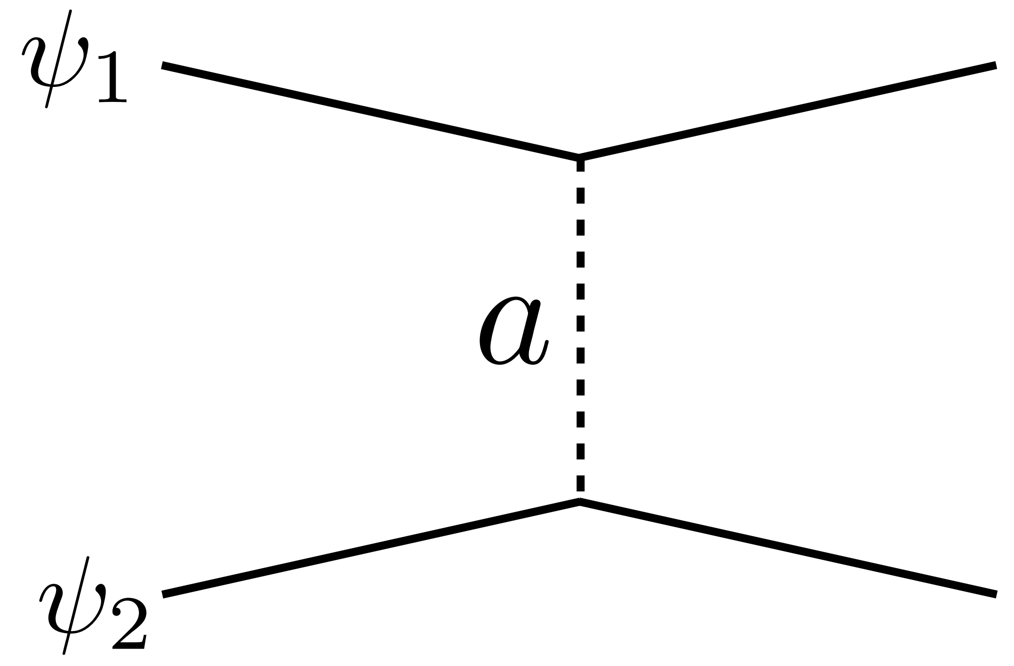
→ light through walls

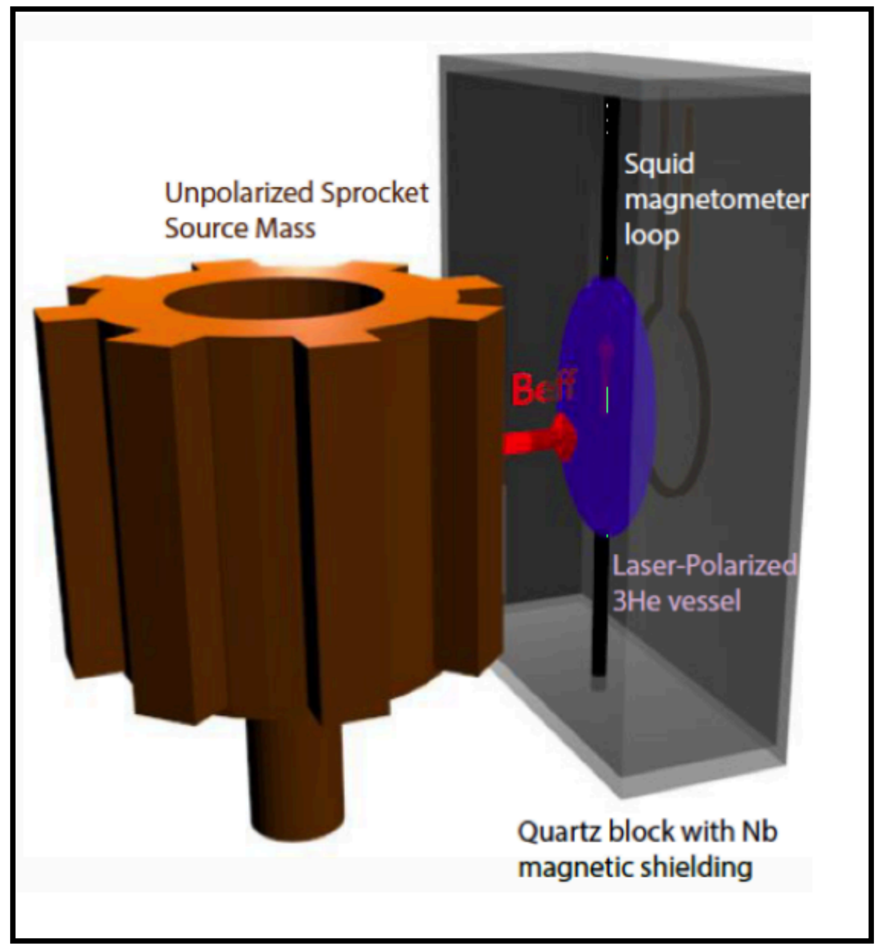




Fermions

→ spin dependent fifth forces

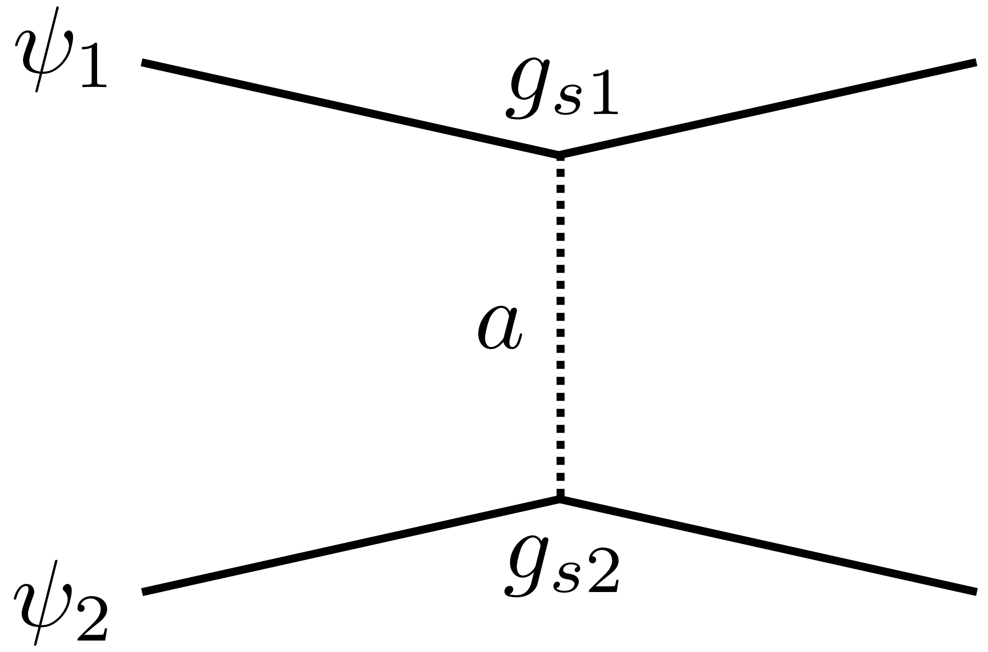




Pure laboratory tests of axion-fermion fifth forces

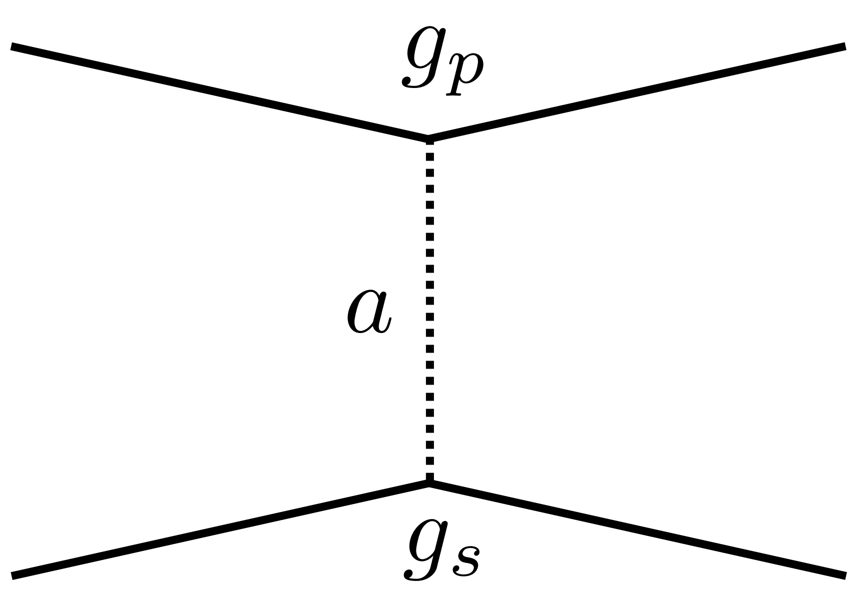
Key point: any SM or BSM CP-violation (e.g. ~Jarlskog invariant of CKM matrix) could shift axion vev and generate **CP-violating** axion-fermion couplings in addition to the usual **CP-conserving** ones

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



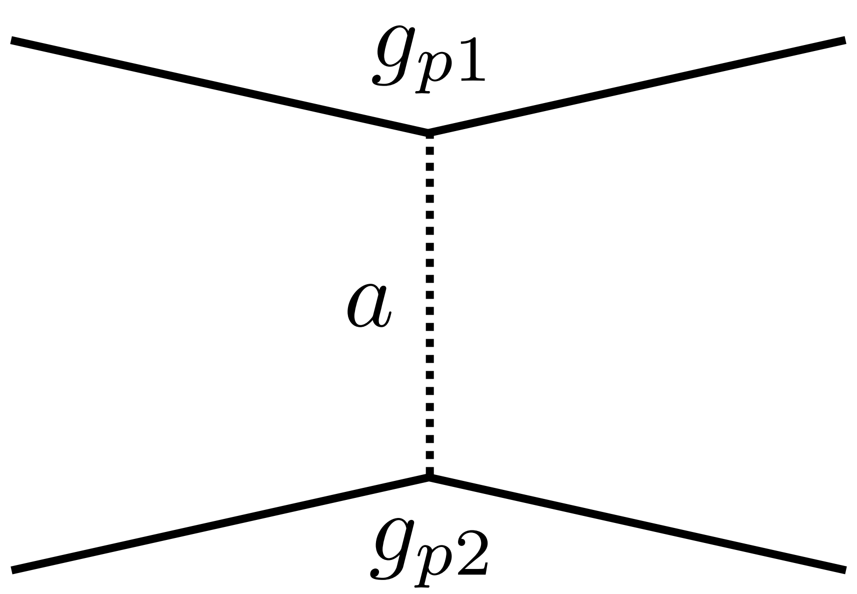
Monopole-monopole (Spin independent)

→ 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

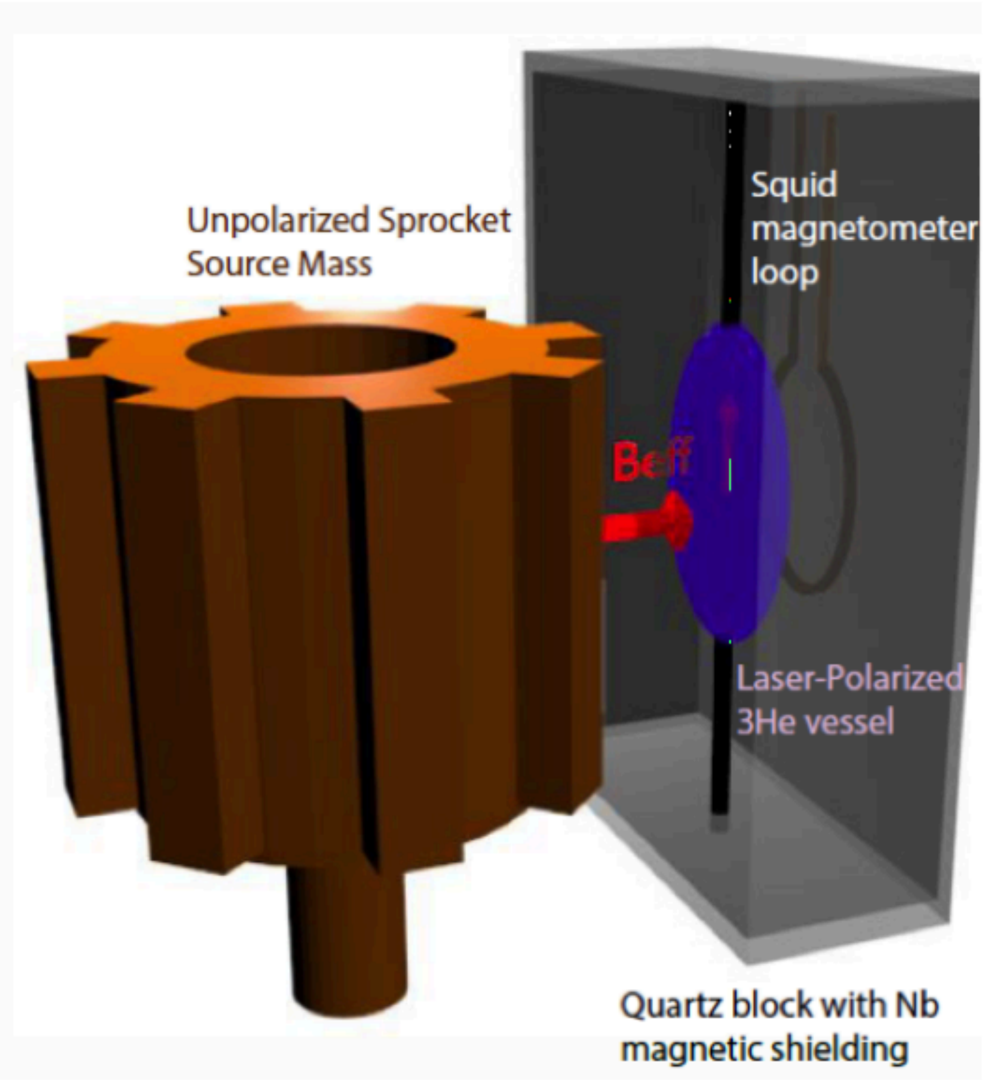
→ Expected level of CP-violation for QCD axion not 100% clear, but this offers a potential way in for experiments

Monopole-dipole searches

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

ARIADNE

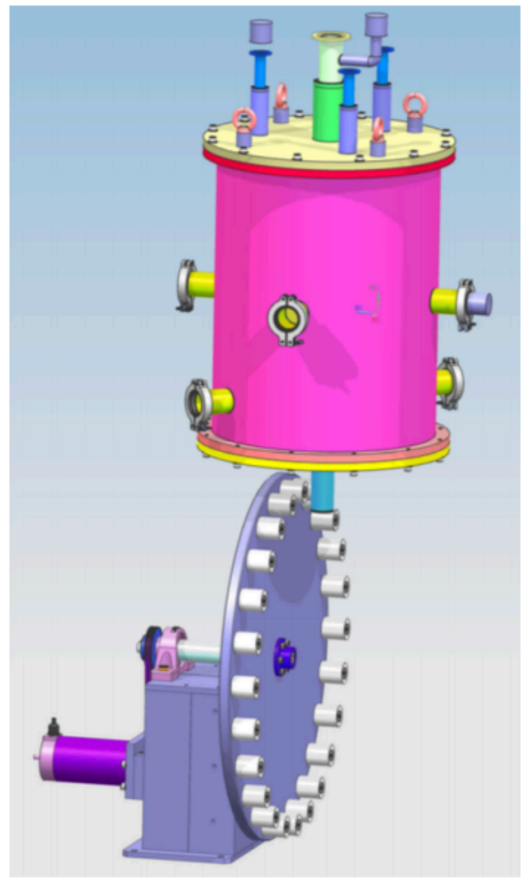
Constrains: g_p g_s (nucleon-nucleon)



QUAX

Constrains: g_p g_s (electron-nucleon)

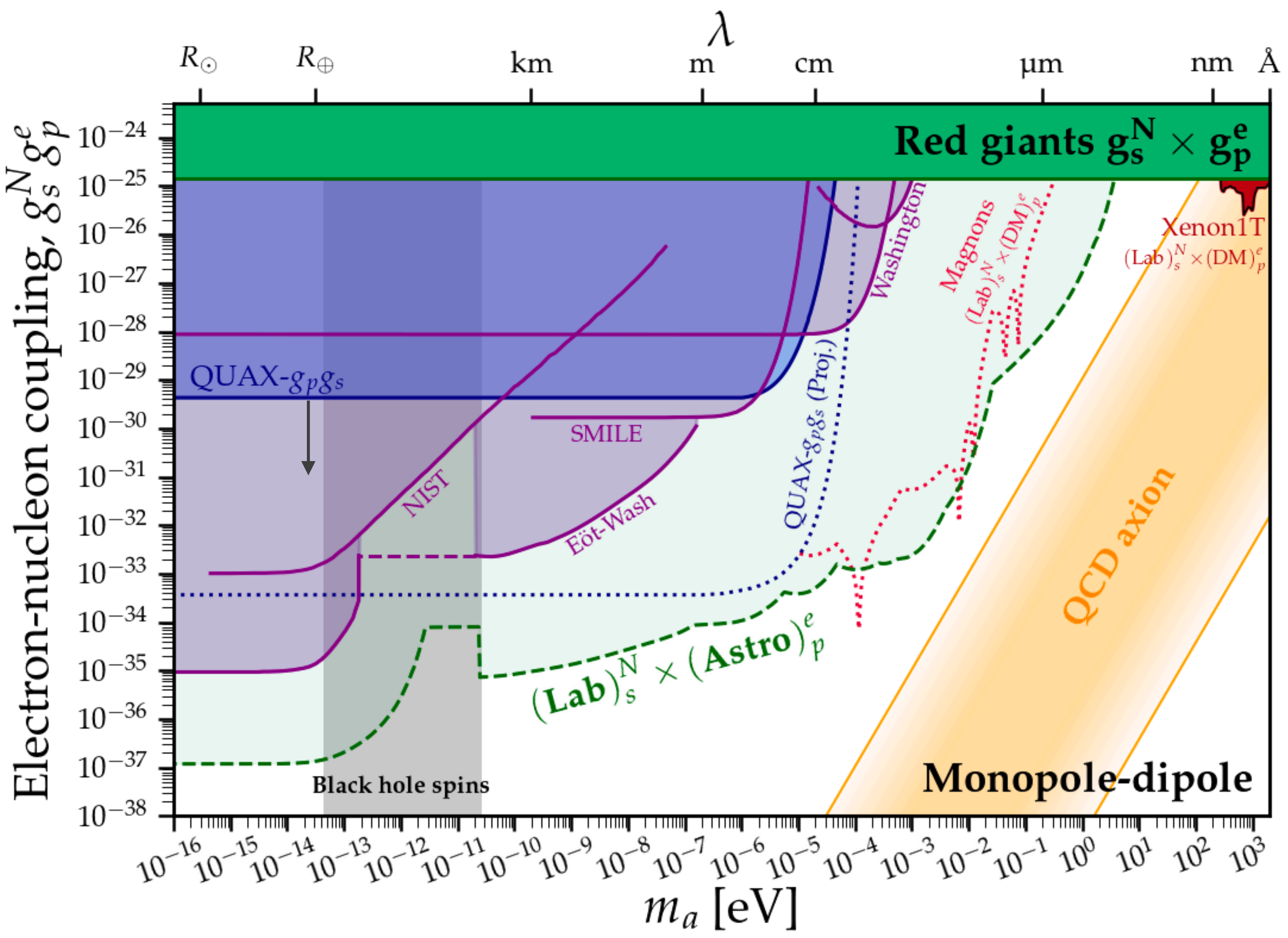
(Latest QUAX result **2011.07100**)



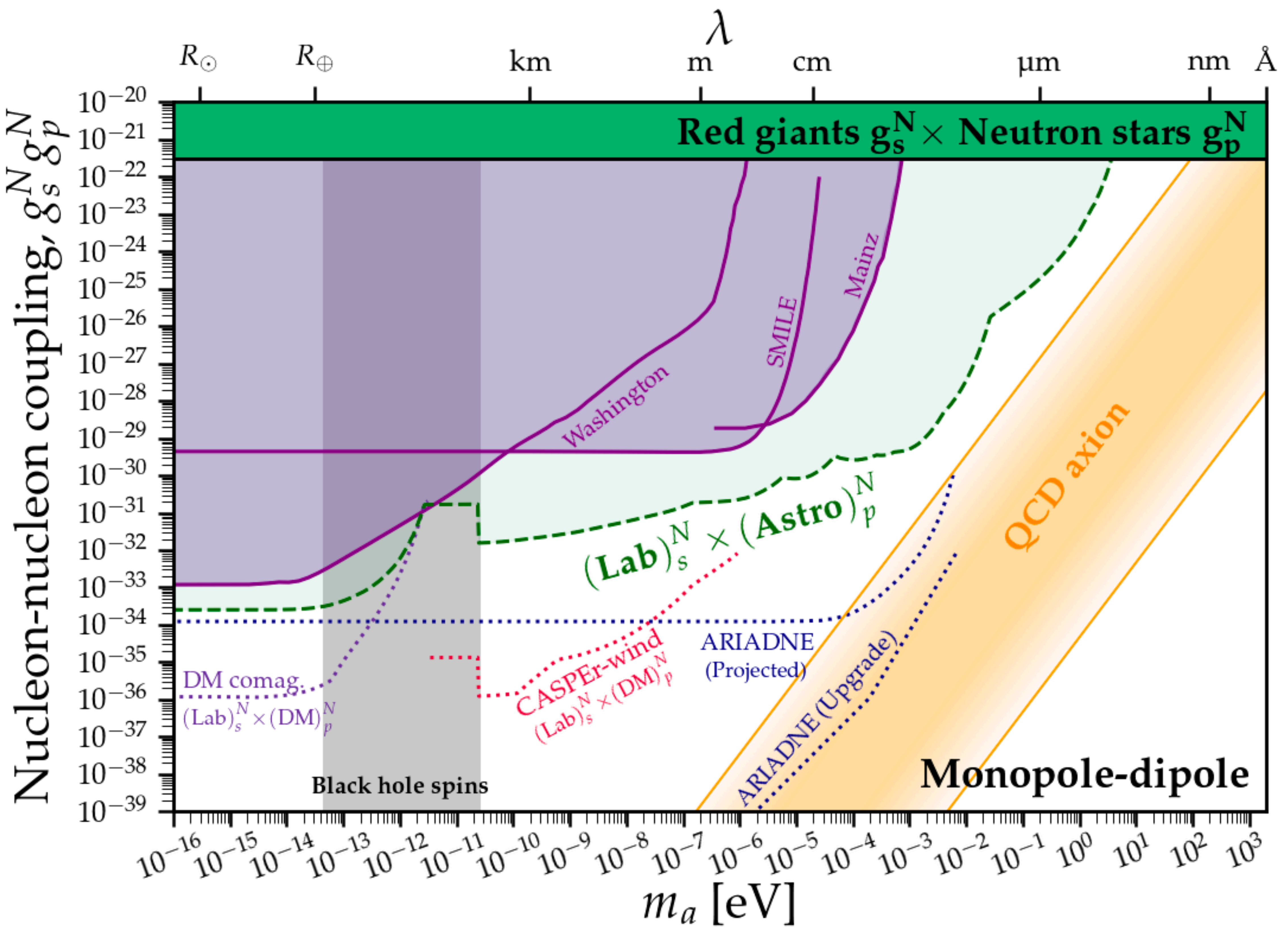
Challenge: stellar bounds tightly constrain g_p, and spin independent fifth force tests easily constrain g_s: so Astro x Lab bound on these coupling combos are very strong

Pure laboratory tests for monopole-dipole axion-mediated forces

Electron-nucleon coupling



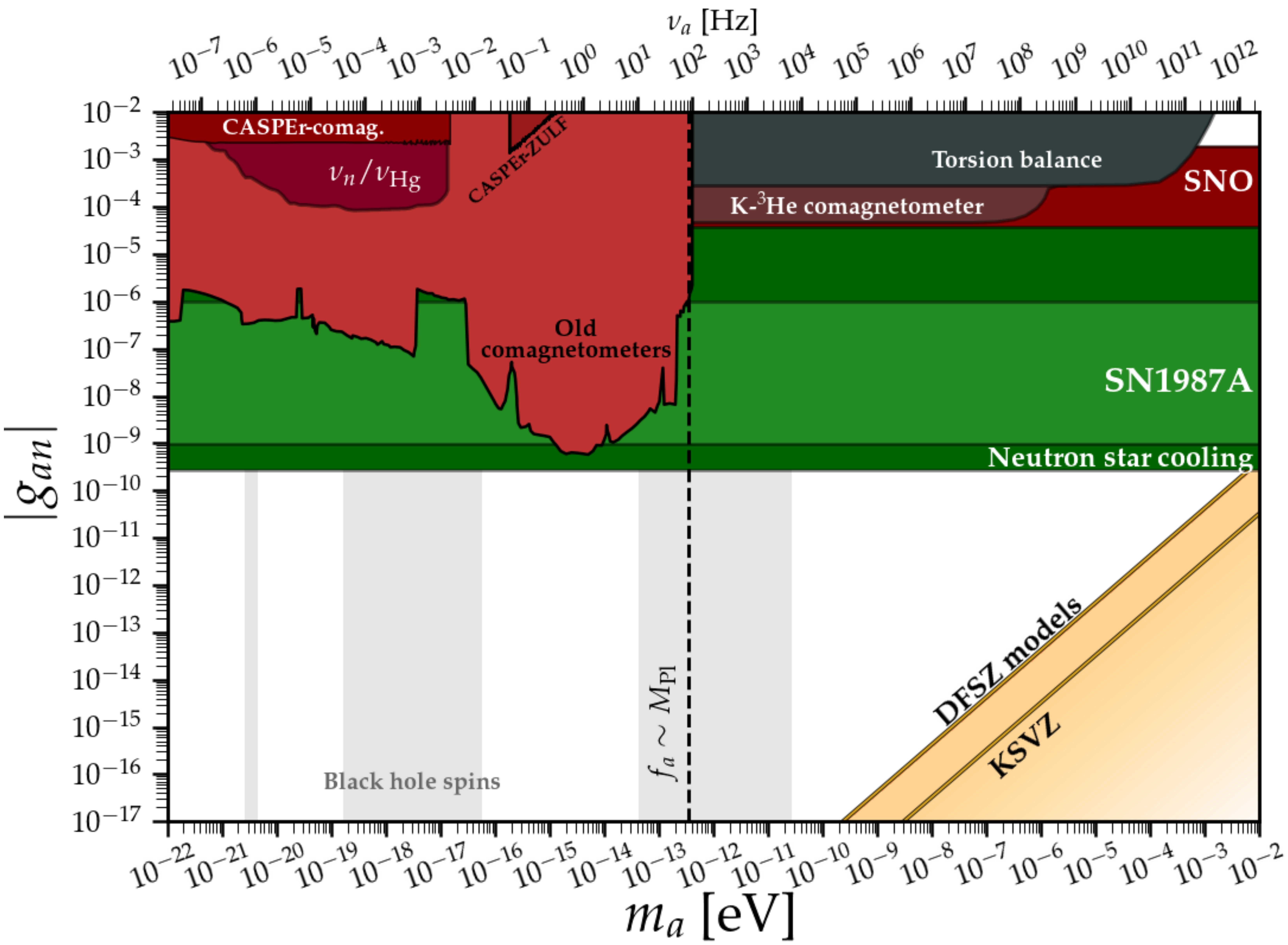
Nucleon-nucleon coupling



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

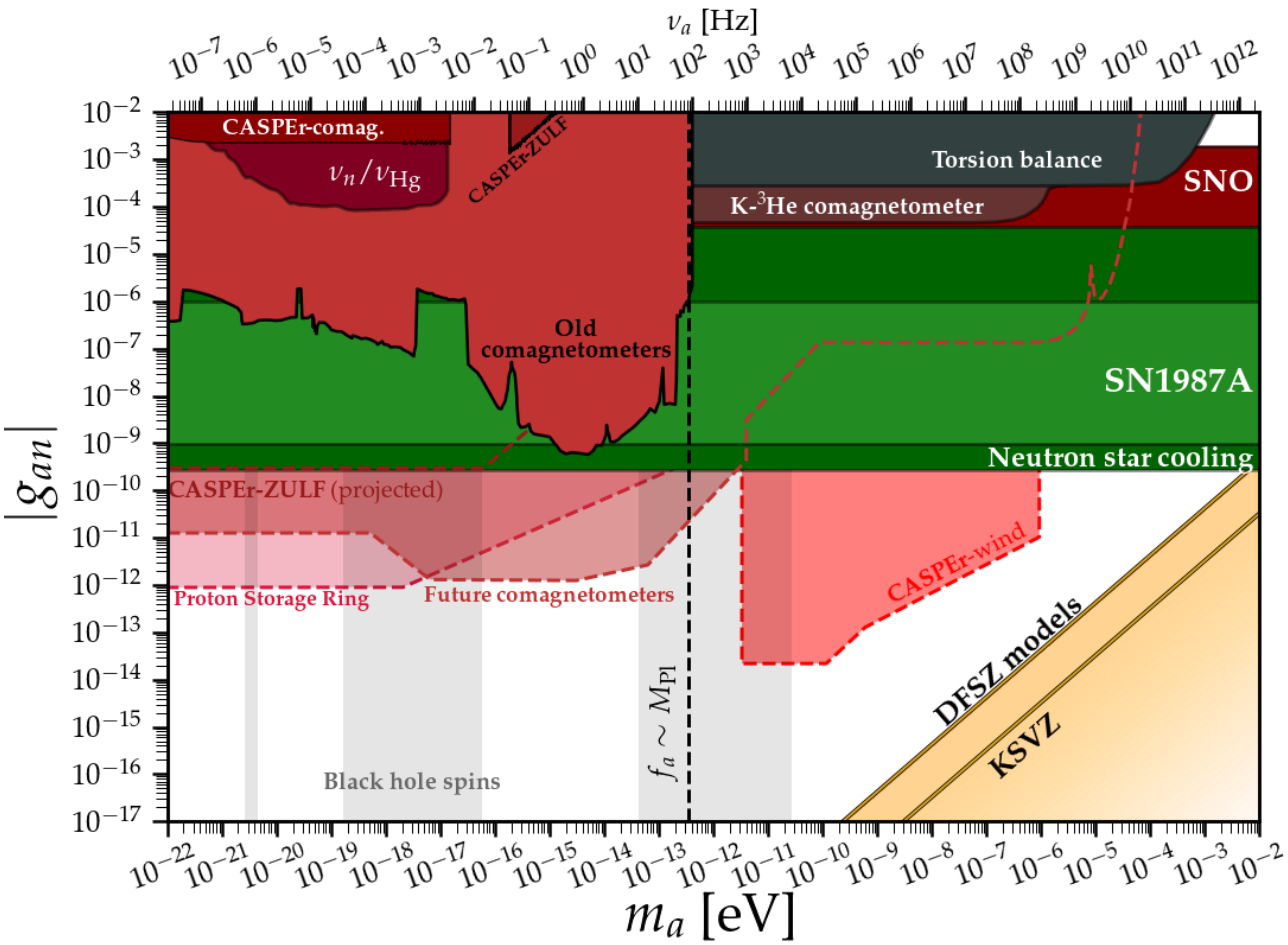
See O'Hare & Vitagliano [2010.03889] for combined bound

Axion-neutron coupling



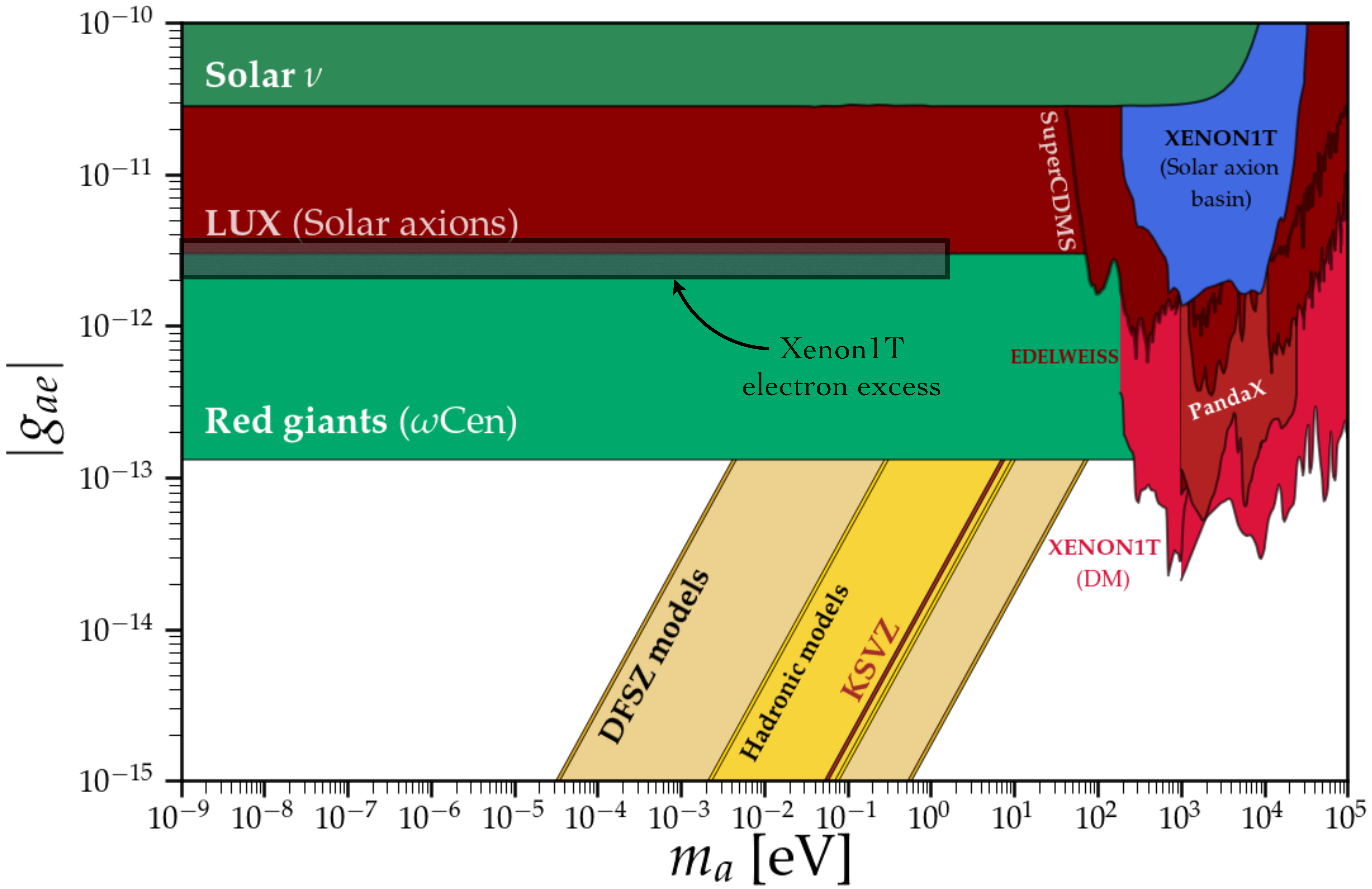
- Lab searches very far from astrophysical bounds

Axion-neutron coupling



- Lab searches very far from astrophysical bounds
- Experiments could be competitive in future, but require source of axions from DM

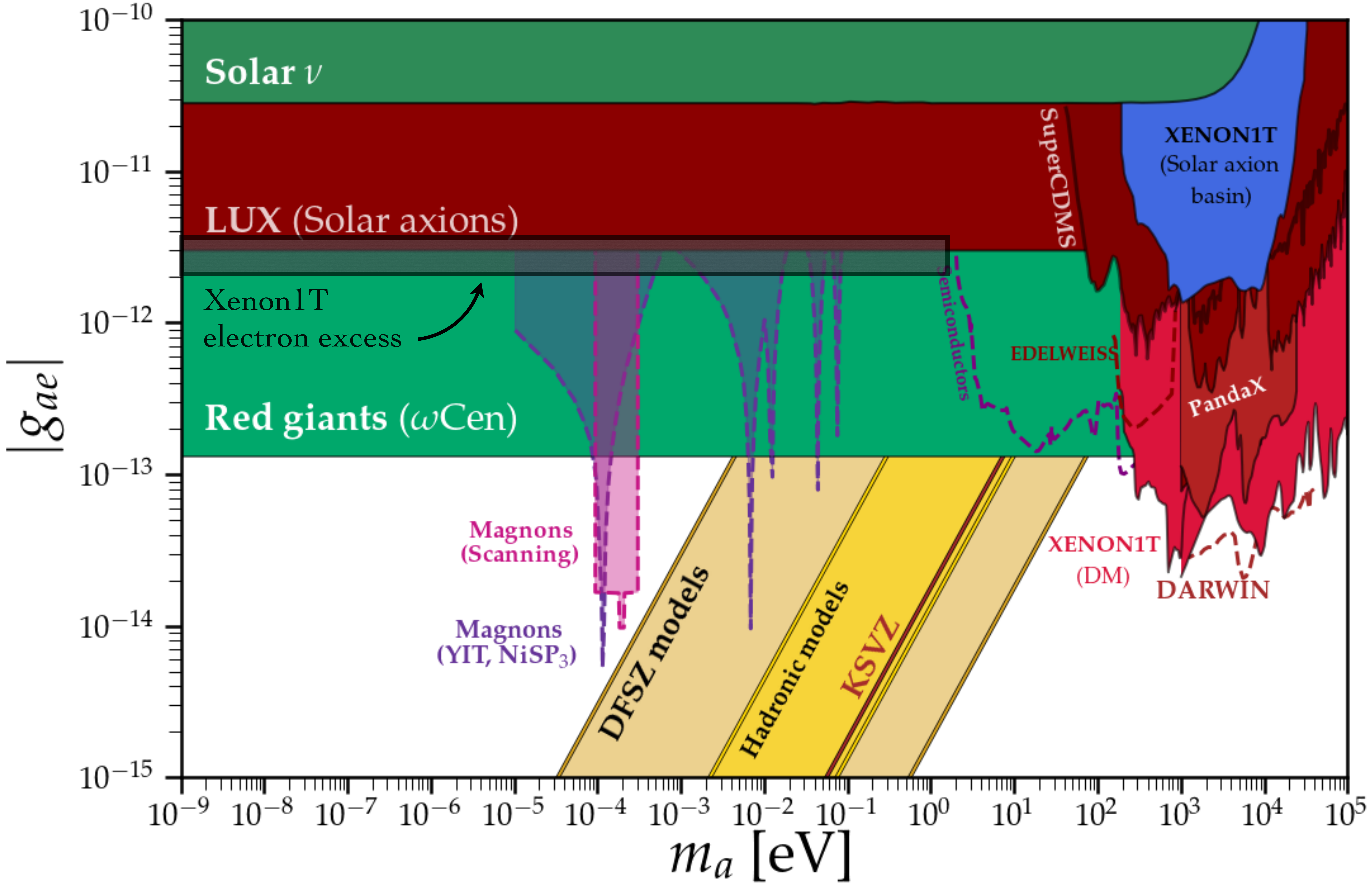
Axion-electron coupling



Parameter space only covered by

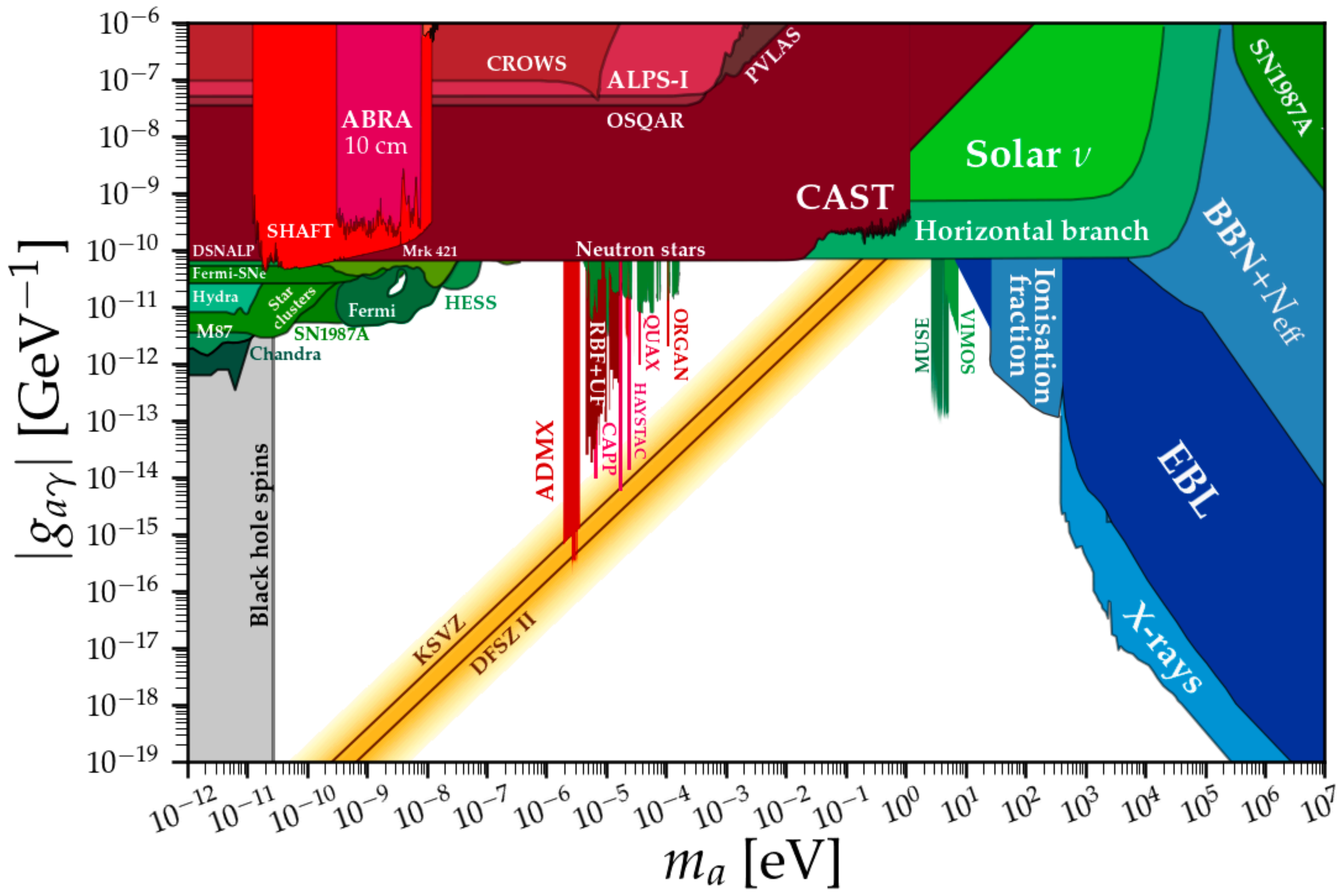
- Stellar bound (Capozzi & Raffelt [2007.03694] with updated *Gaia* distances)
- Underground DM searches for ~keV photoelectrons from axion absorption

Axion-electron coupling (future)

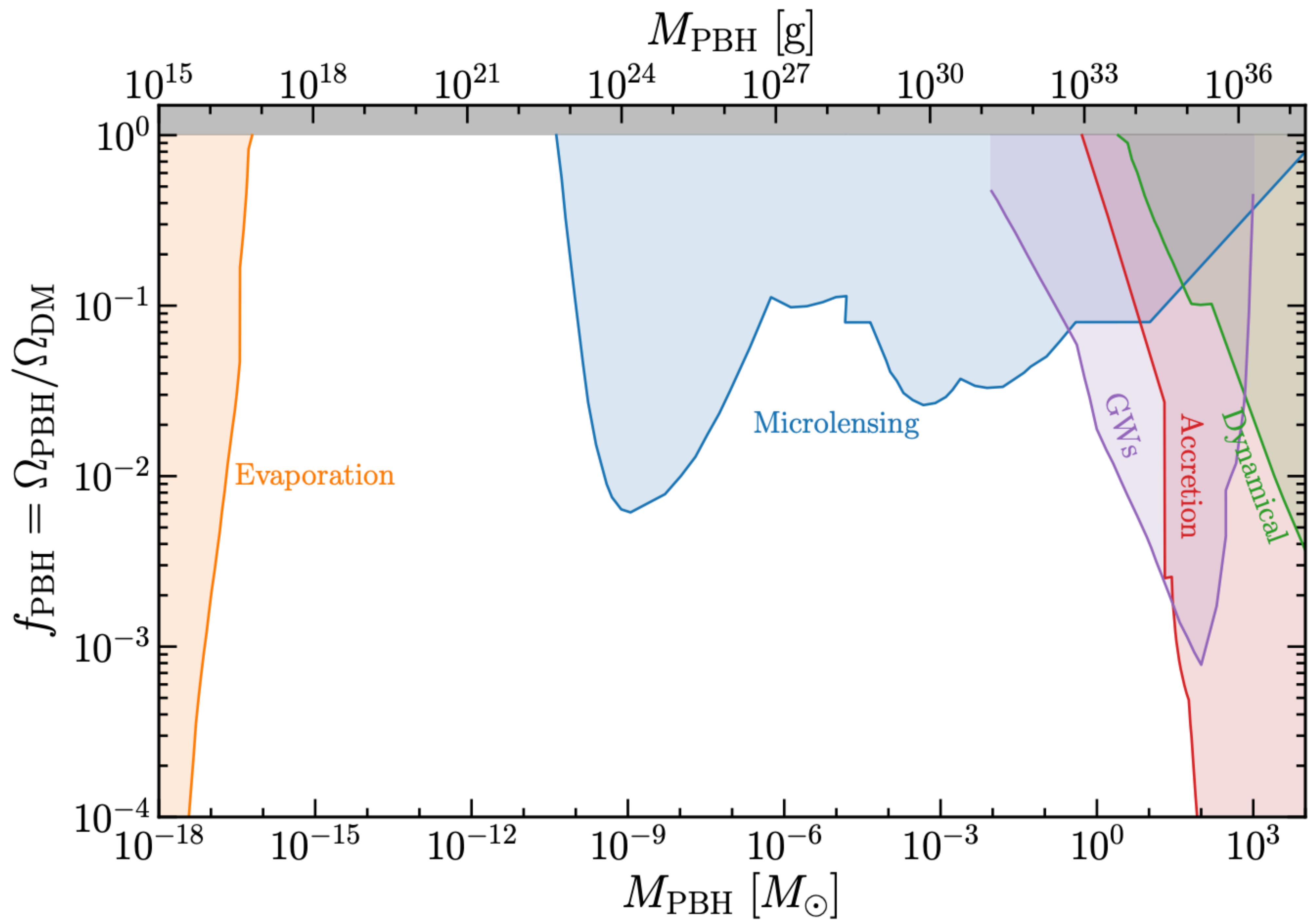


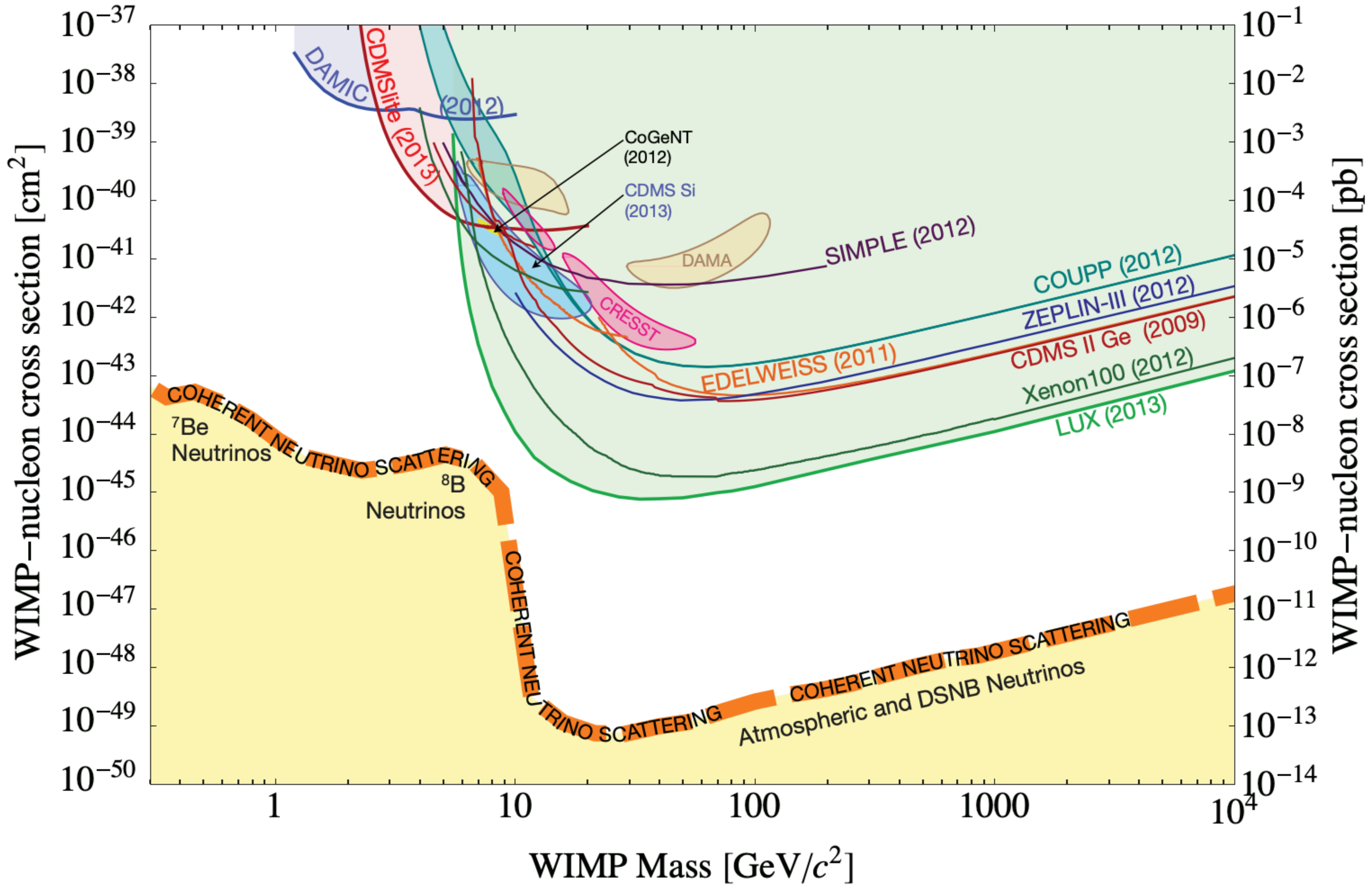
- Many sub-keV DM searches proposed, with varying technological readiness

Caveats/Assumptions/loopholes



Axion constraint landscape more akin to PBHs than to WIMPs

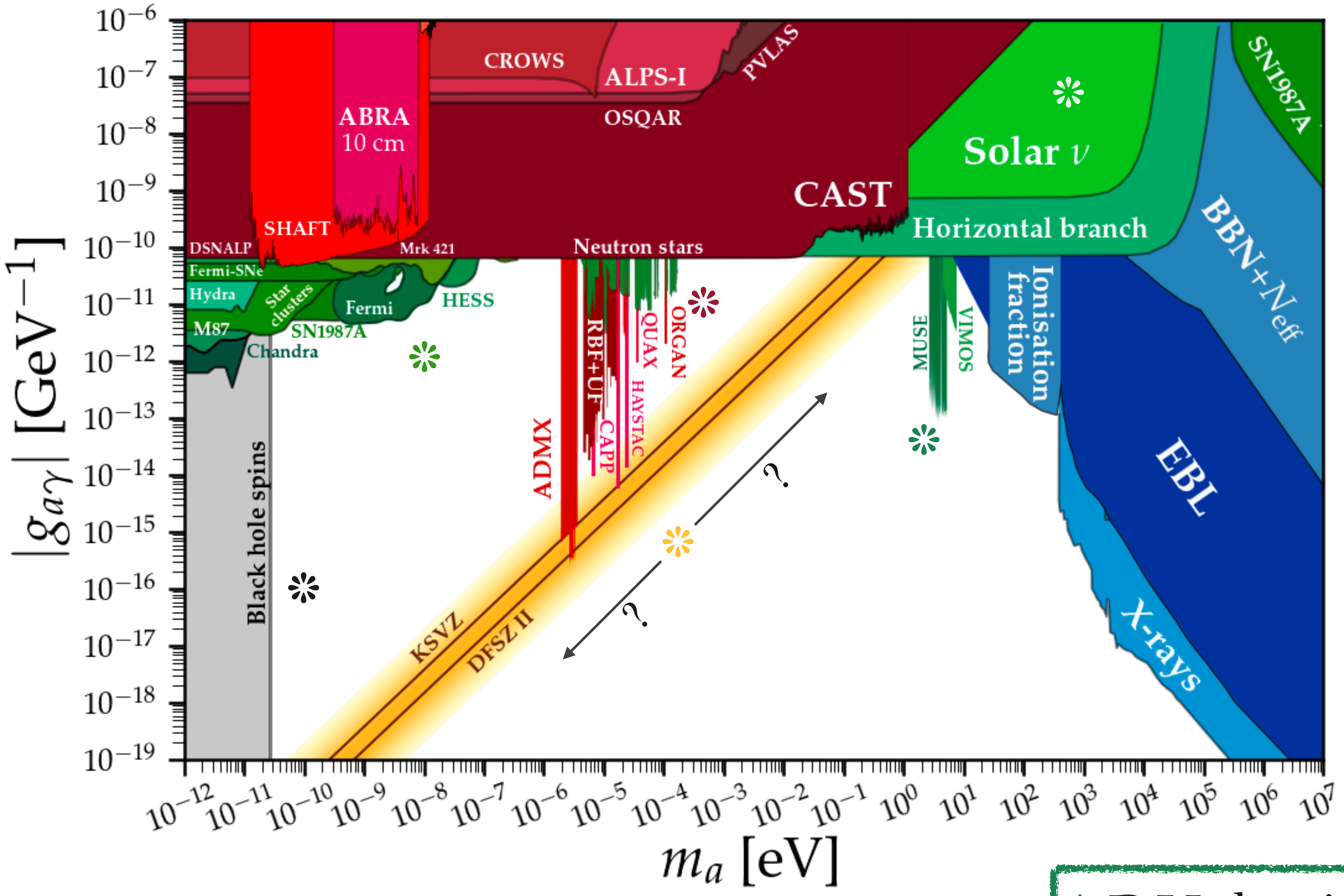




* How model turbulent astrophysical B-fields in MW, galaxies, ICM etc.

* Expected axion DM distribution in MW environments

* What axion masses can be DM?



* Possible chameleonic methods of escaping stellar bounds?

e.g. DeRocco et al. [2006.15112]

* Possible model-dependent ways to escape BH bounds Mathur et al. 2004.12326

* DM density in galaxies/clusters

Where do we expect QCD axion DM to be?

Can we predict or constrain the mass range for QCD axion dark matter?

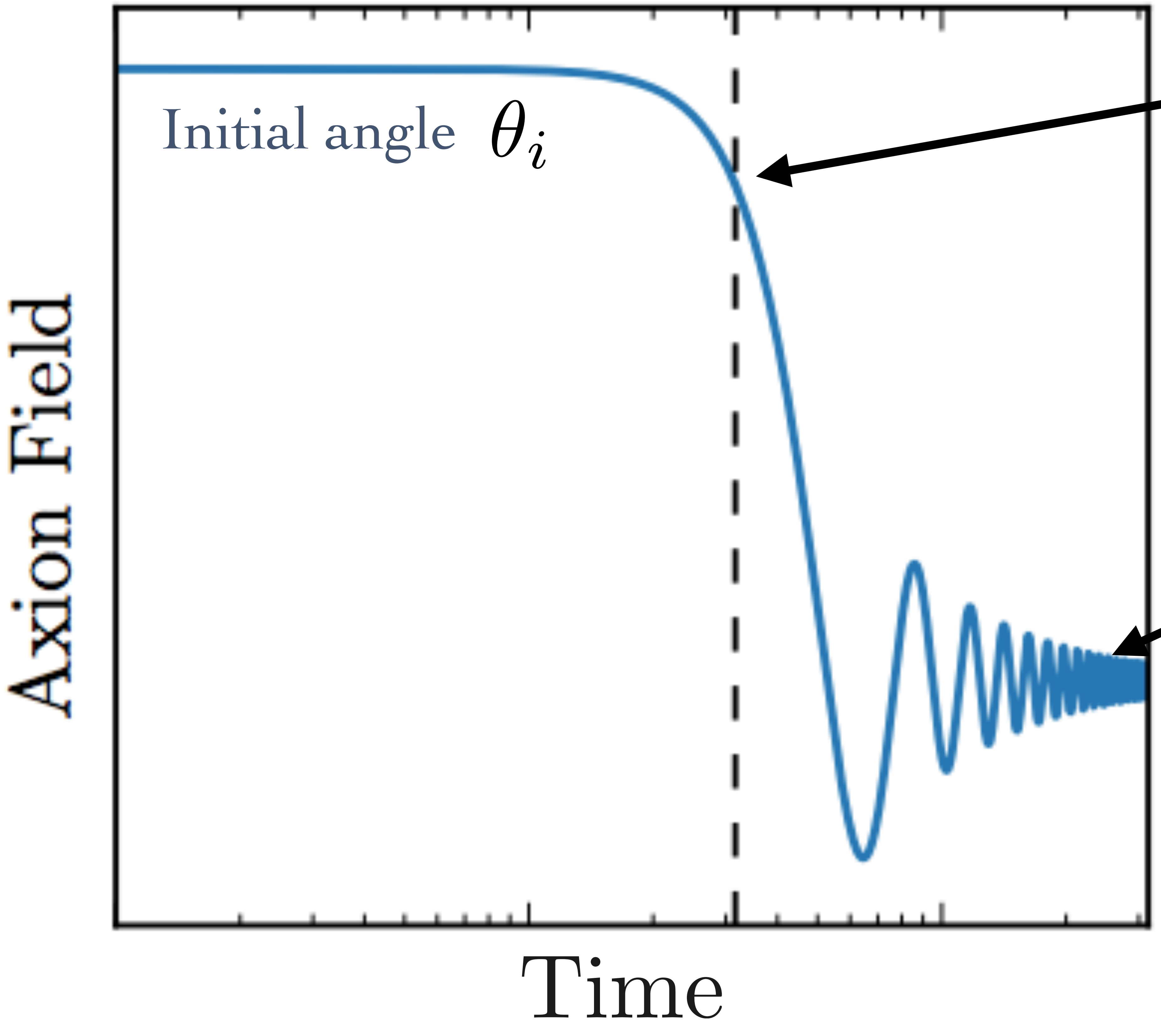
- Axion appears after phase transition at scale f_a
- Axion density depends on initial field value
- At some point inflation happens…

Distribution of initial field values (and therefore axion abundance) will be radically different if the phase transition happens **before or after inflation**

* some wrinkles I won't discuss regarding modified cosmological histories (Blinov et al. [1911.07853]), or scenarios involved in baryon asymmetry (Co et al. [2006.04809])

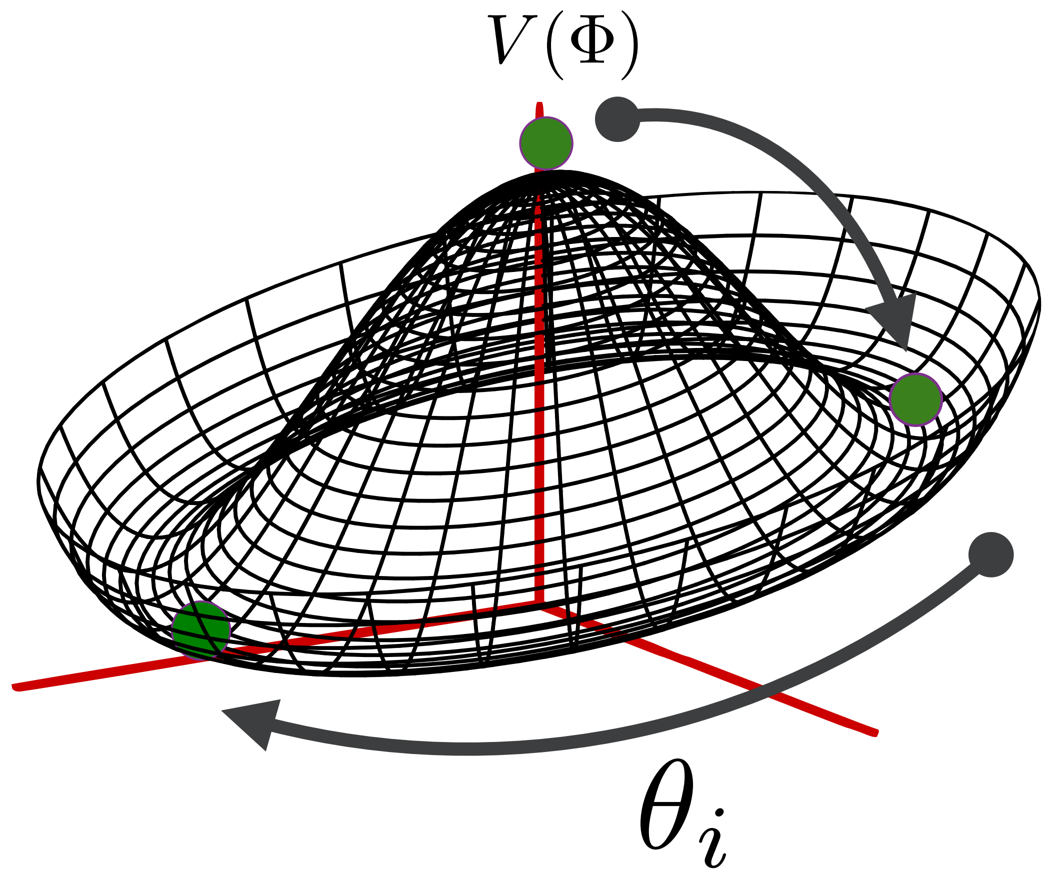
Cosmological evolution of the axion field: misalignment mechanism

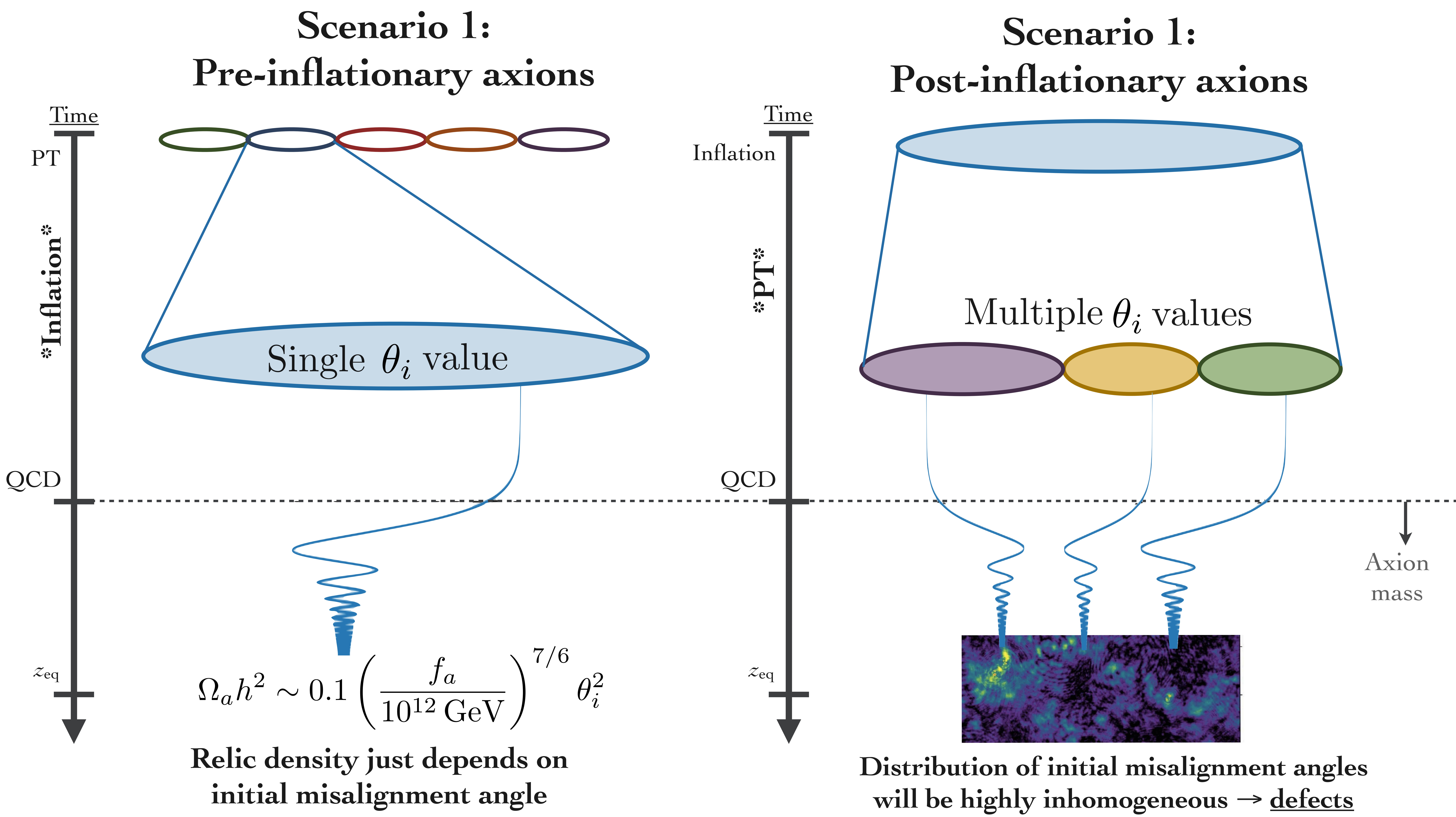
$$\ddot{a} + 3H\dot{a} + \frac{\partial \mathcal{V}(a)}{\partial a} = 0 \quad \text{where,} \quad \mathcal{V}(a) \approx \frac{1}{2} m_a^2 a^2$$



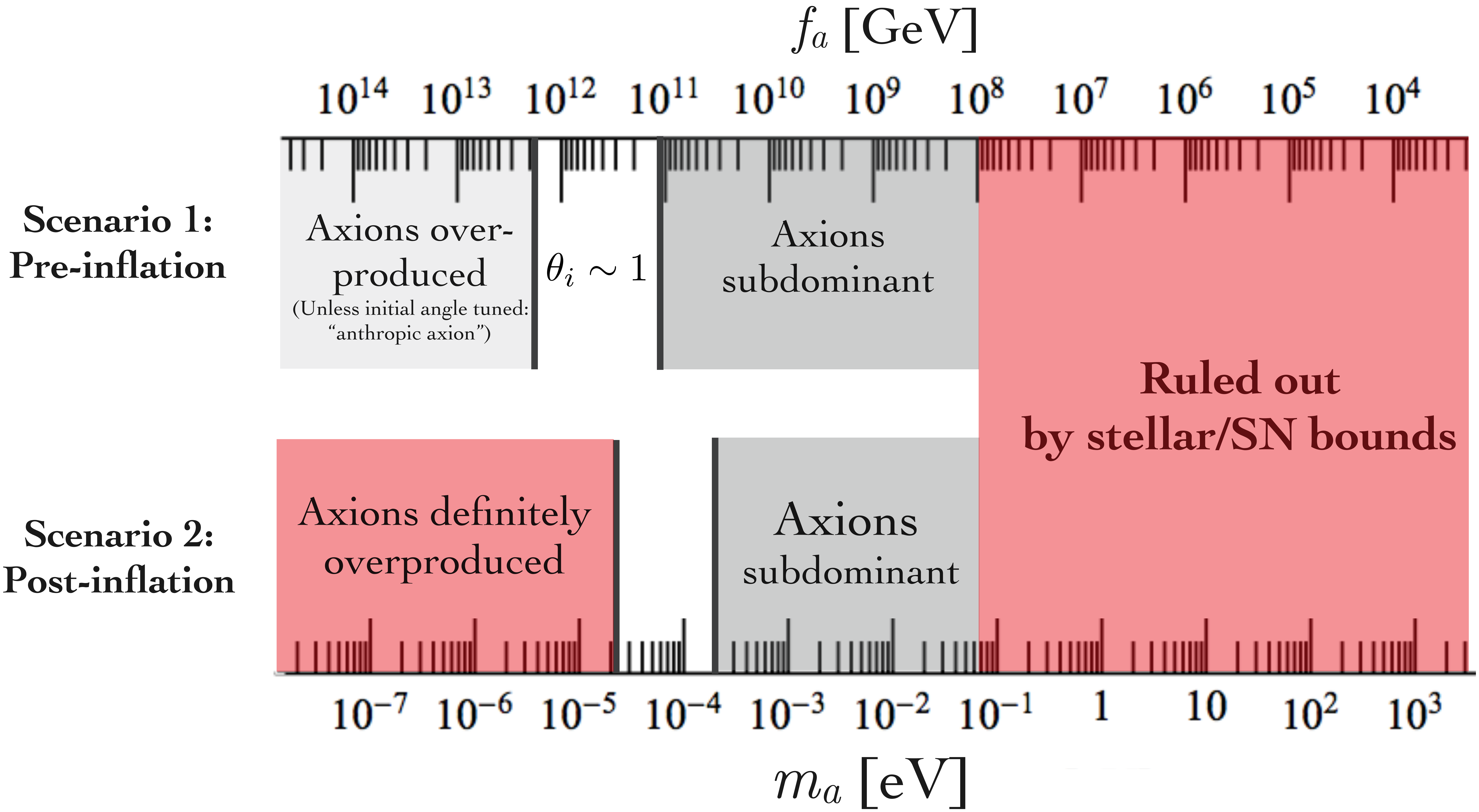
$H \sim m_a$
Axion field rolls down potential

$H < m_a$
Axion field starts damped oscillations with frequency $\sim m_a$
→ **cold axions produced**





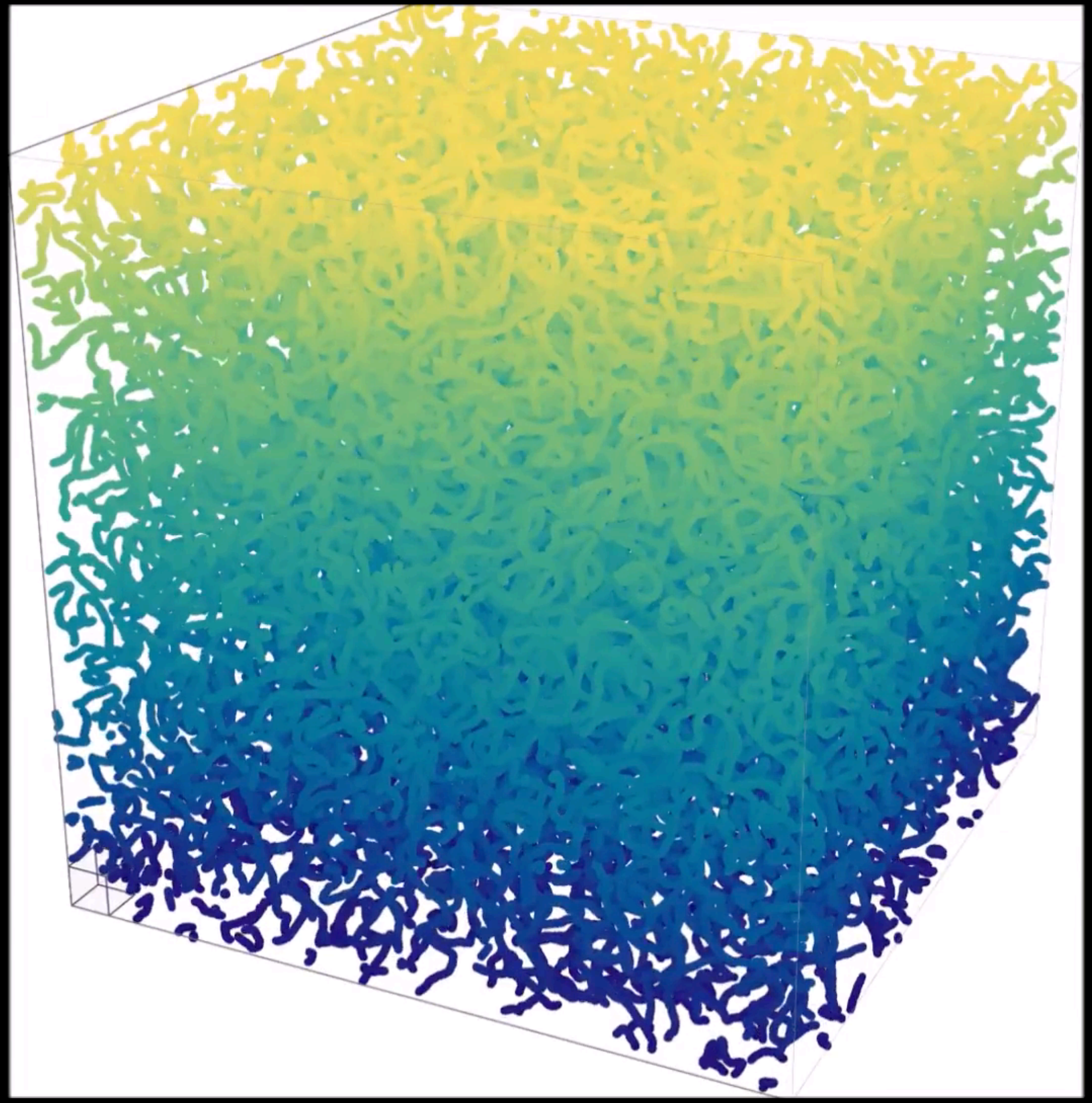
Scenario 1:
Pre-inflationary axions
Time
PT
Inflation
Single θ_i value
QCD
z_{eq}
$\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6} \theta_i^2$
Relic density just depends on initial misalignment angle
Scenario 1:
Post-inflationary axions
Time
Inflation
PT
Multiple θ_i values
QCD
z_{eq}
Axion mass
Distribution of initial misalignment angles will be highly inhomogeneous → defects



f_a [GeV]
10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4}
Scenario 1: Pre-inflation
Axions over-produced
(Unless initial angle tuned: "anthropic axion")
$\theta_i \sim 1$
Axions subdominant
Ruled out by stellar/SN bounds
Scenario 2: Post-inflation
Axions definitely overproduced
Axions subdominant
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3}
m_a [eV]

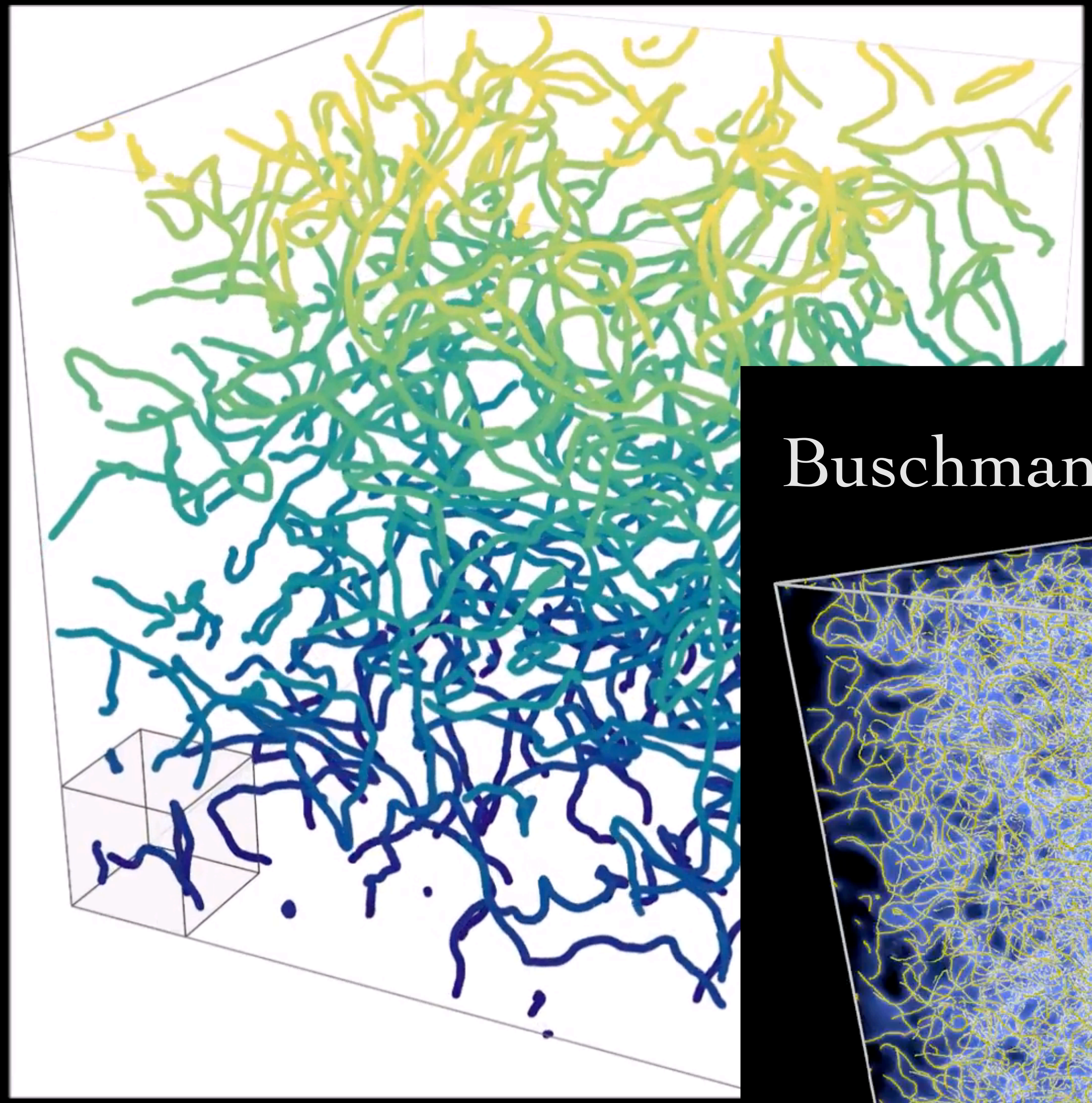
Post-inflationary axion defects and substructure

Gorghetto, Hardy, Villadoro [1806.04677]

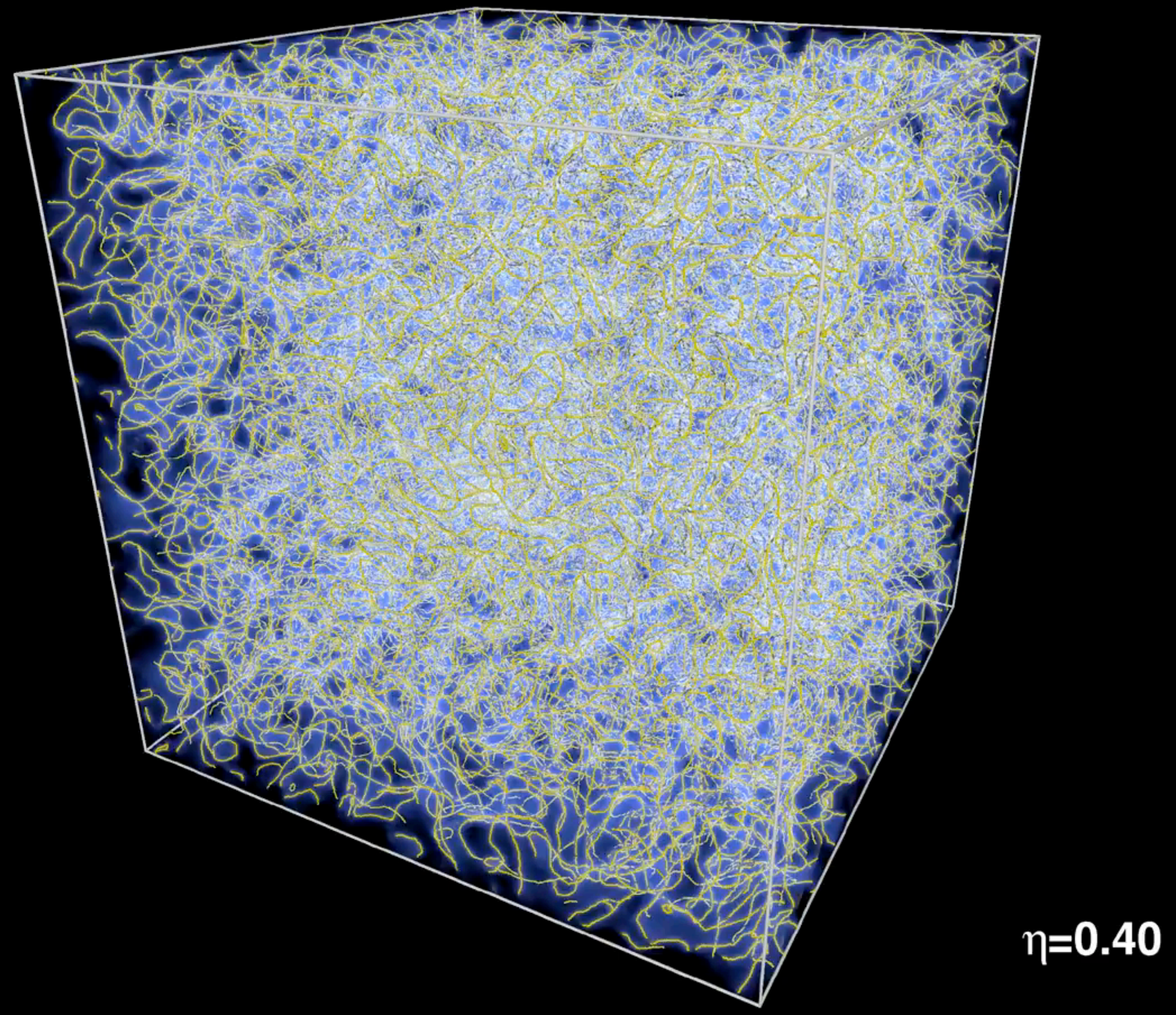


Post-inflationary axion defects and substructure

Gorghetto, Hardy, Villadoro [1806.04677]

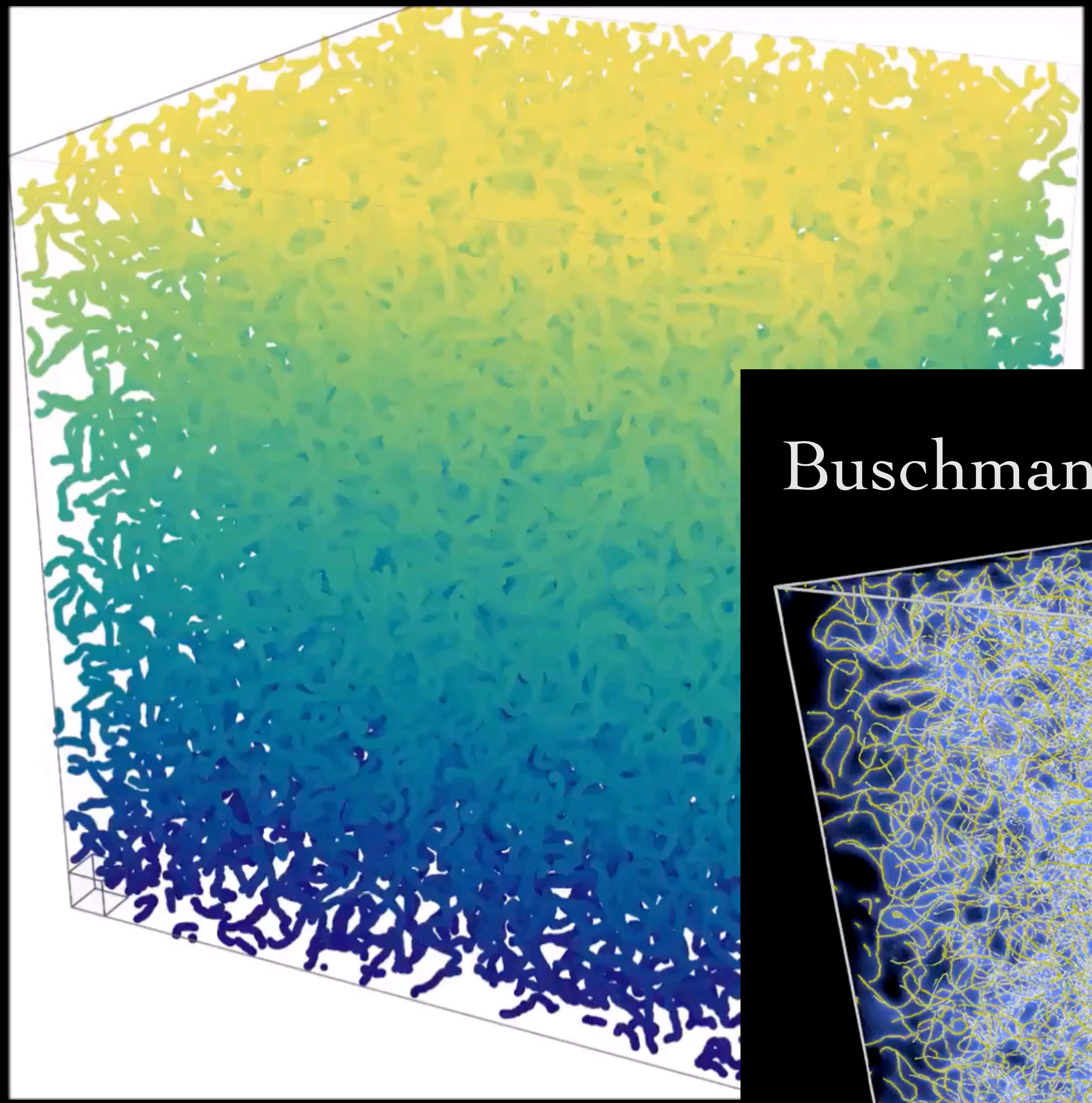


Buschmann, Foster, Safdi [1906.00967]

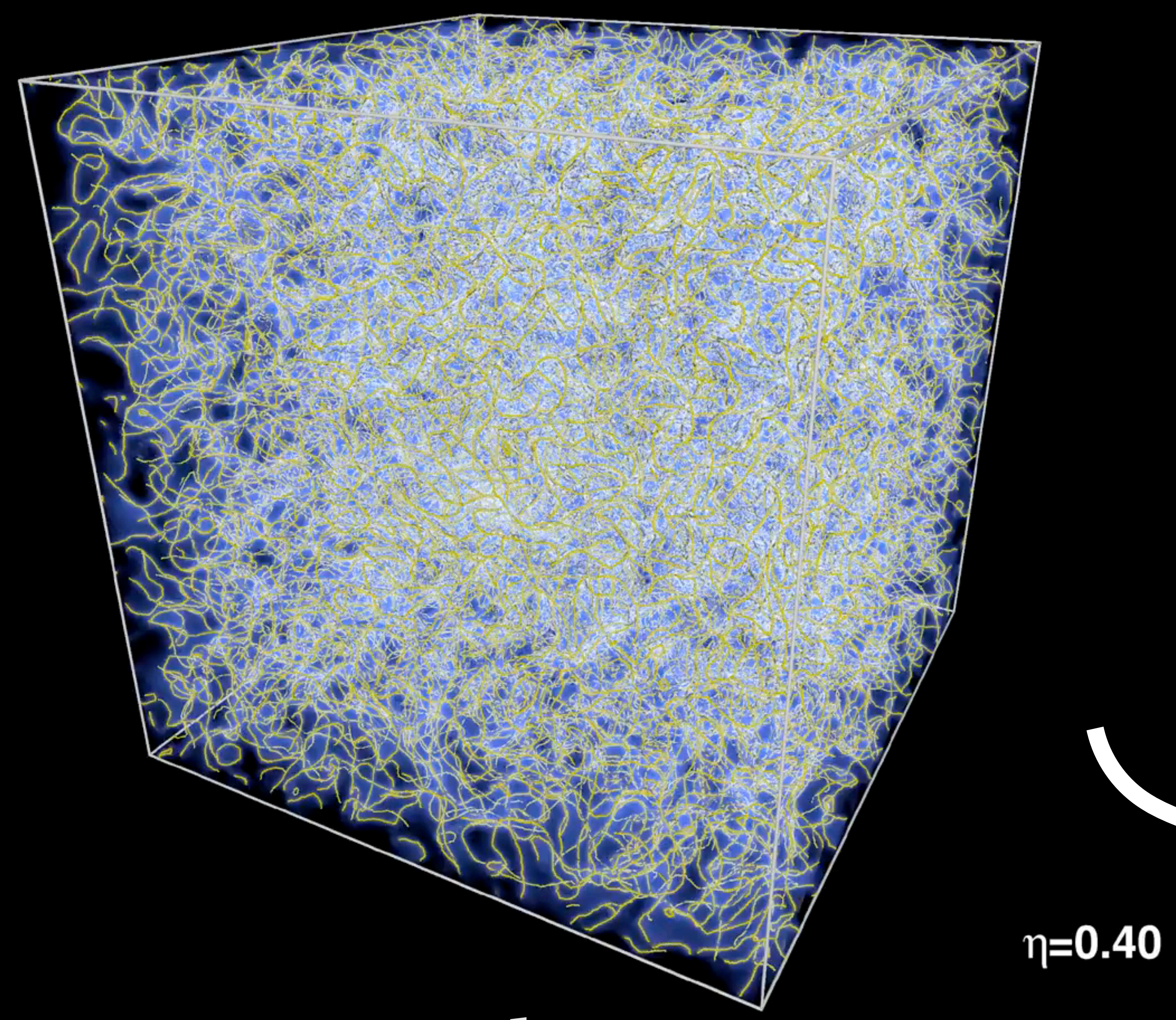


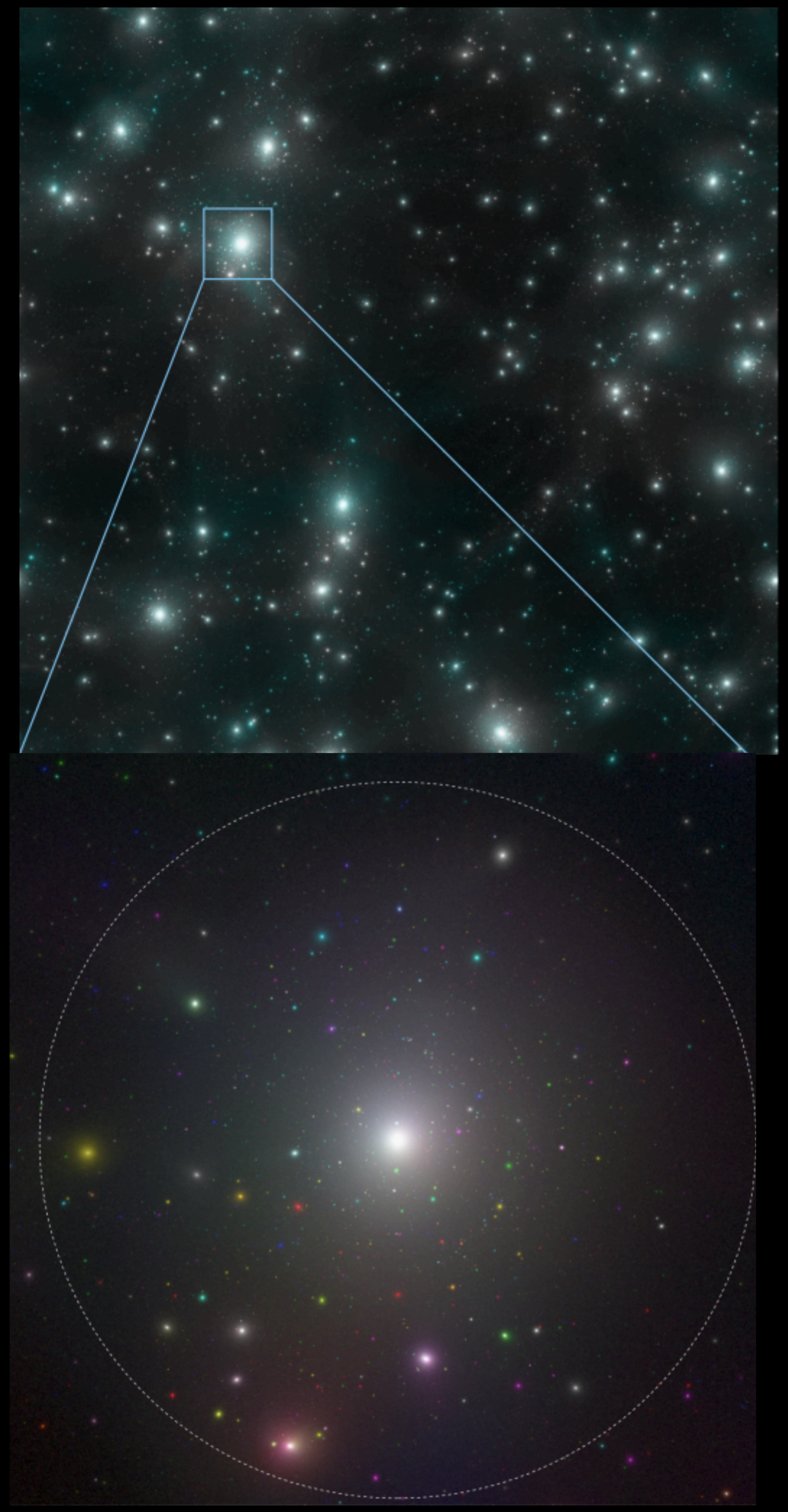
Post-inflationary axion defects and substructure

Gorghetto, Hardy, Villadoro [1806.04677]



Buschmann, Foster, Safdi [1906.00967]



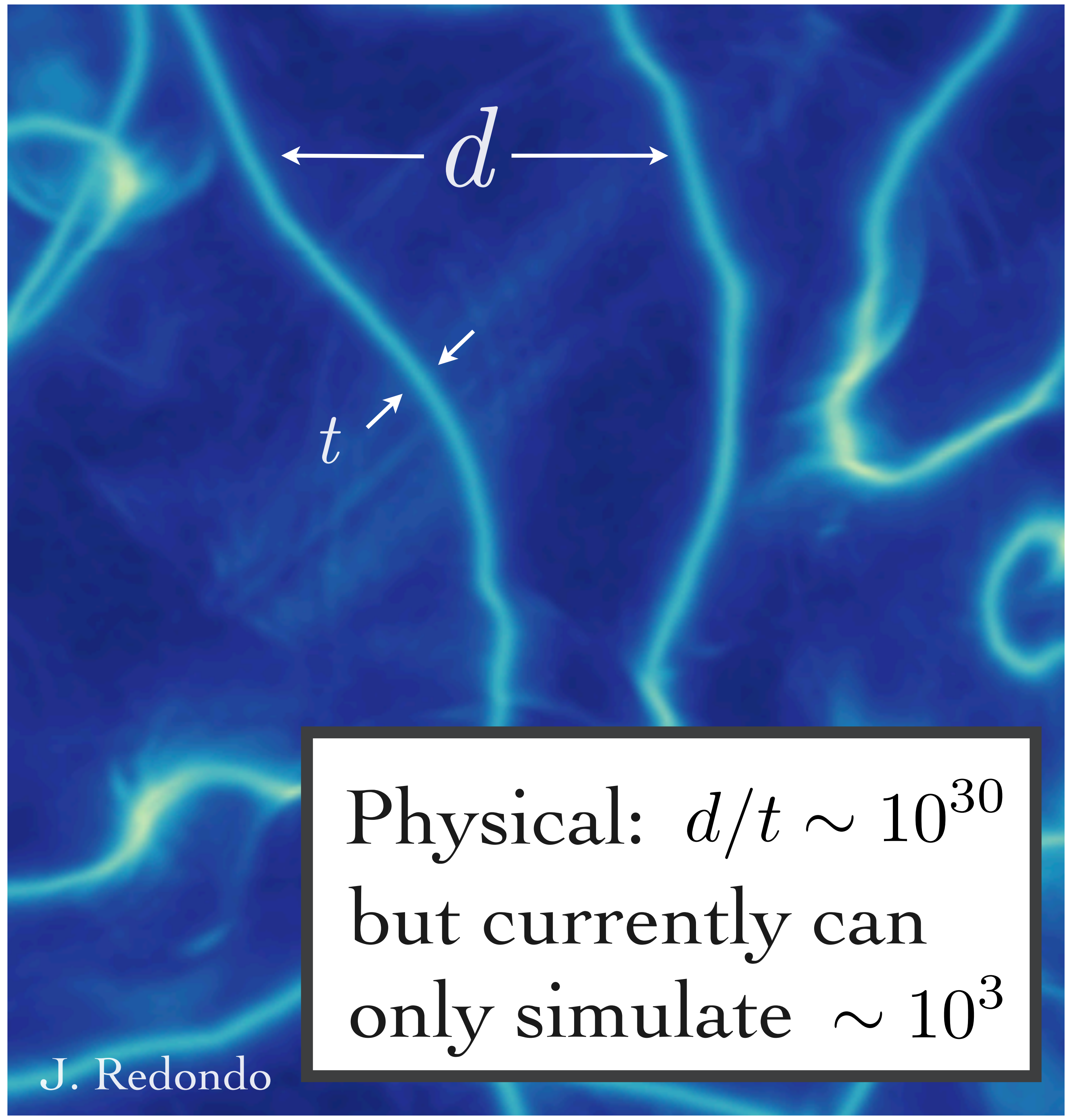


Eggemeier+ [1911.09417]

→ by matter-radiation equality, substantial quantity of axions bound up in clumps with asteroid masses ~ $10^{-12}\,M_{\odot}$

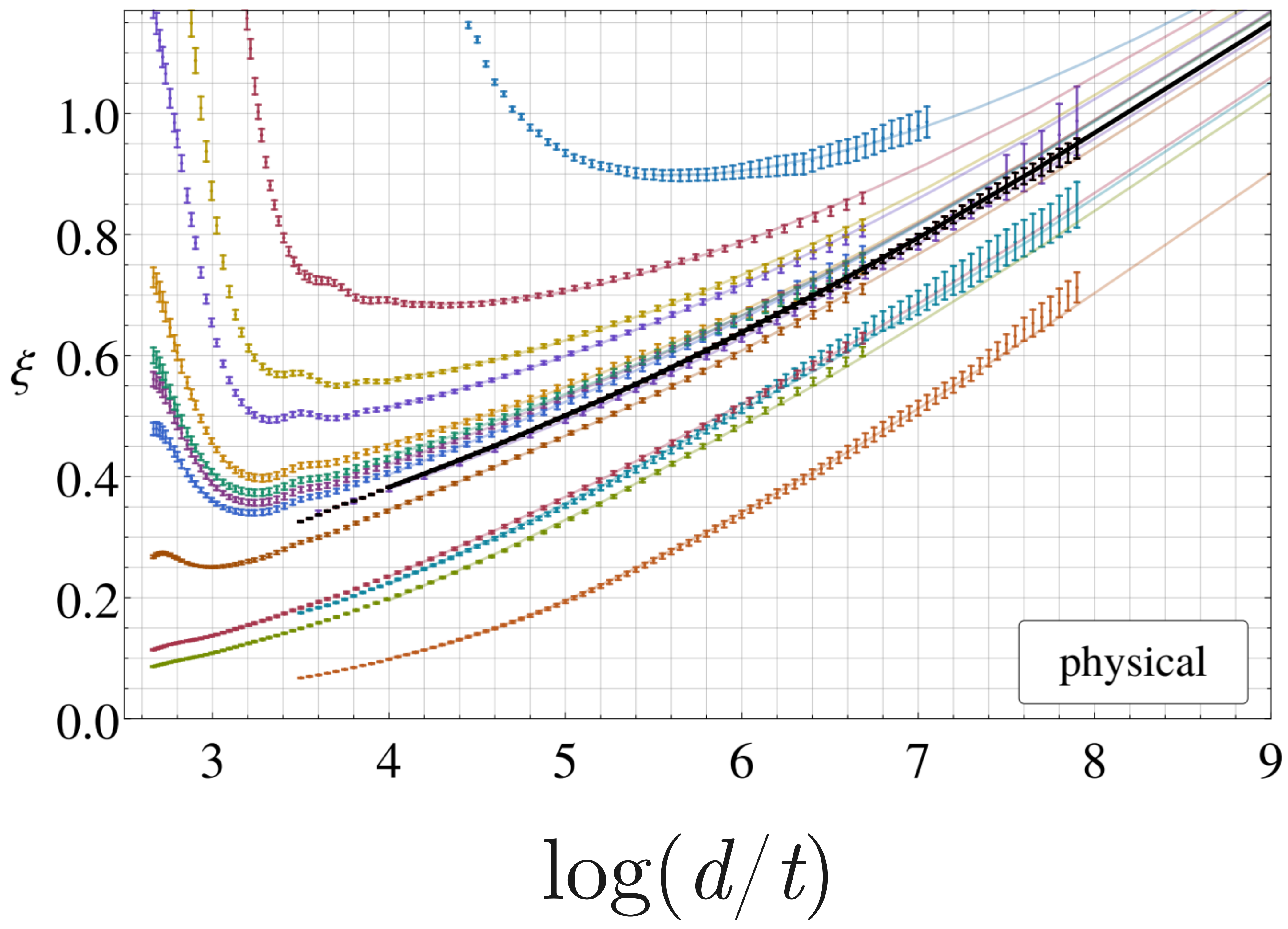
Post-inflation problem #1: Importance of axions from strings

Currently impossible to do physical simulation of axion strings
→ sims. often assume effective growing string width, or fatten strings over time with additional fields



Physical: $d/t \sim 10^{30}$
but currently can only simulate $\sim 10^3$

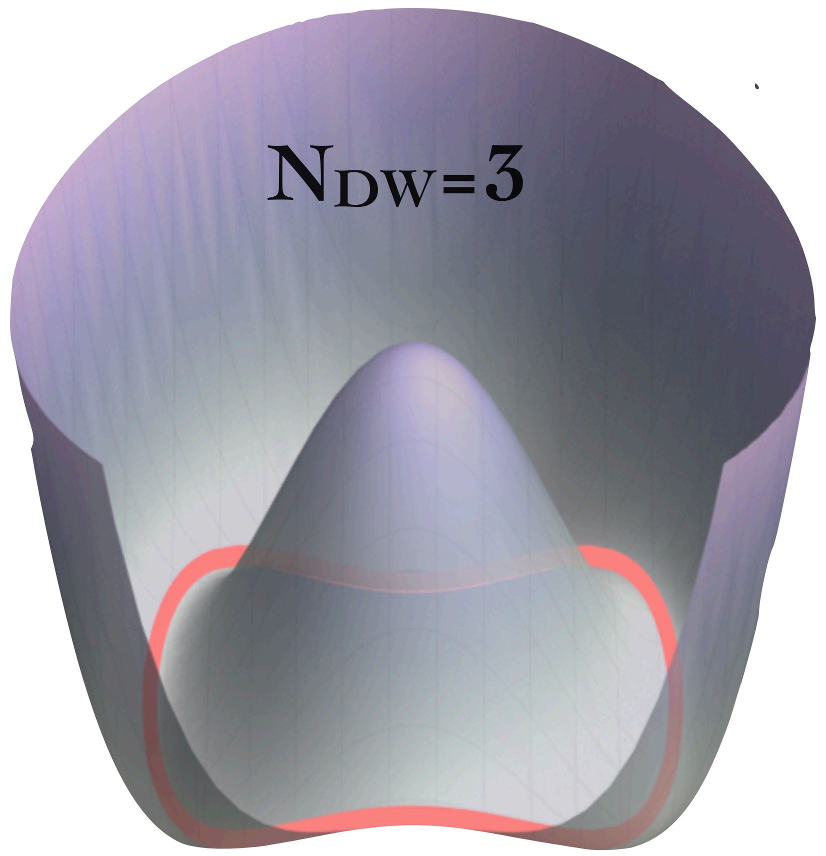
Gorghetto et al. [2007.04990] evidence for attractor solution which would imply many more axions from strings and shifts the preferred DM axion window up to ~ meV



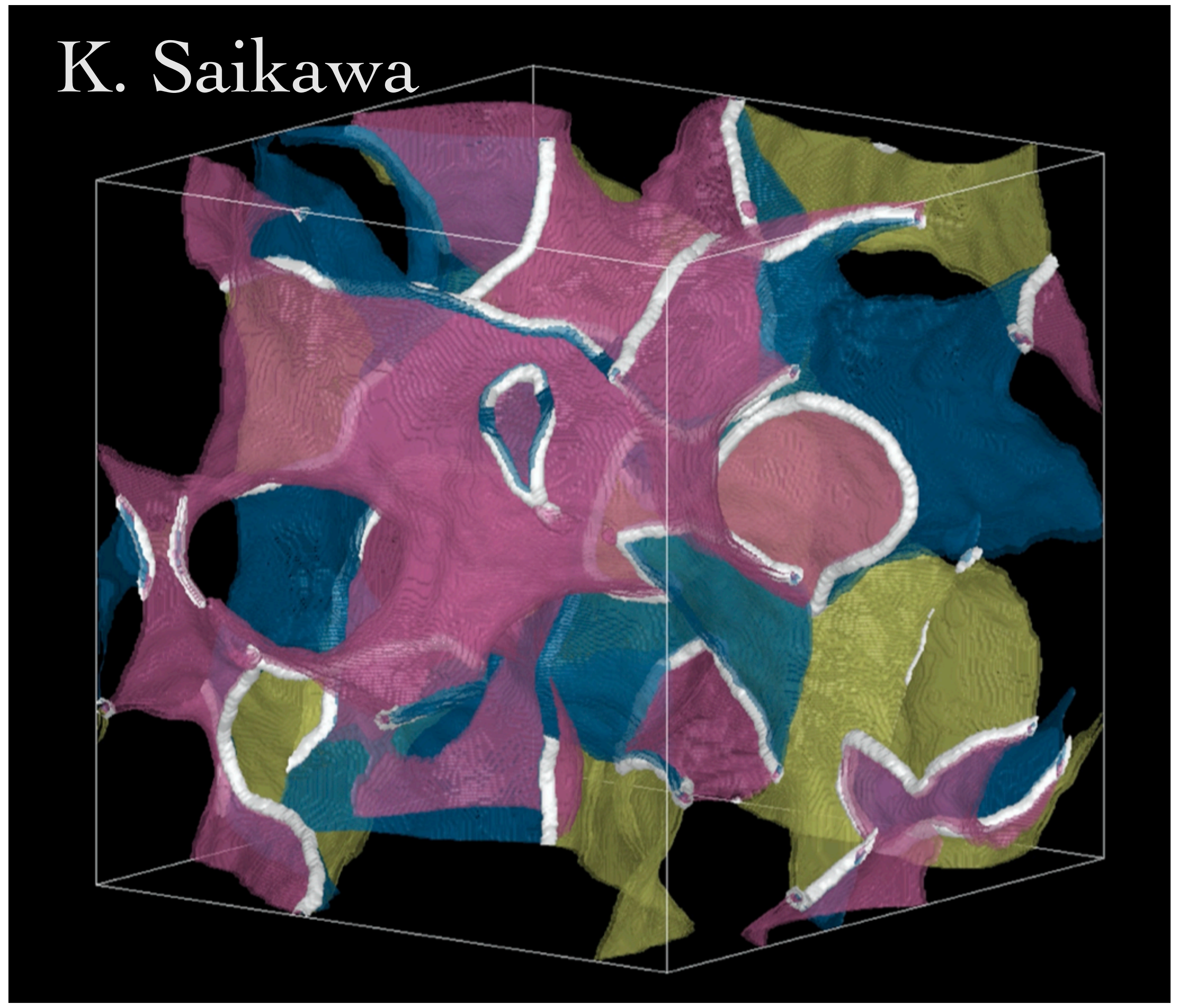
Post-inflation problem #2: $N_{DW}>1$

- QCD Axion model with colour anomaly N>1 (e.g. DFSZ N=6)

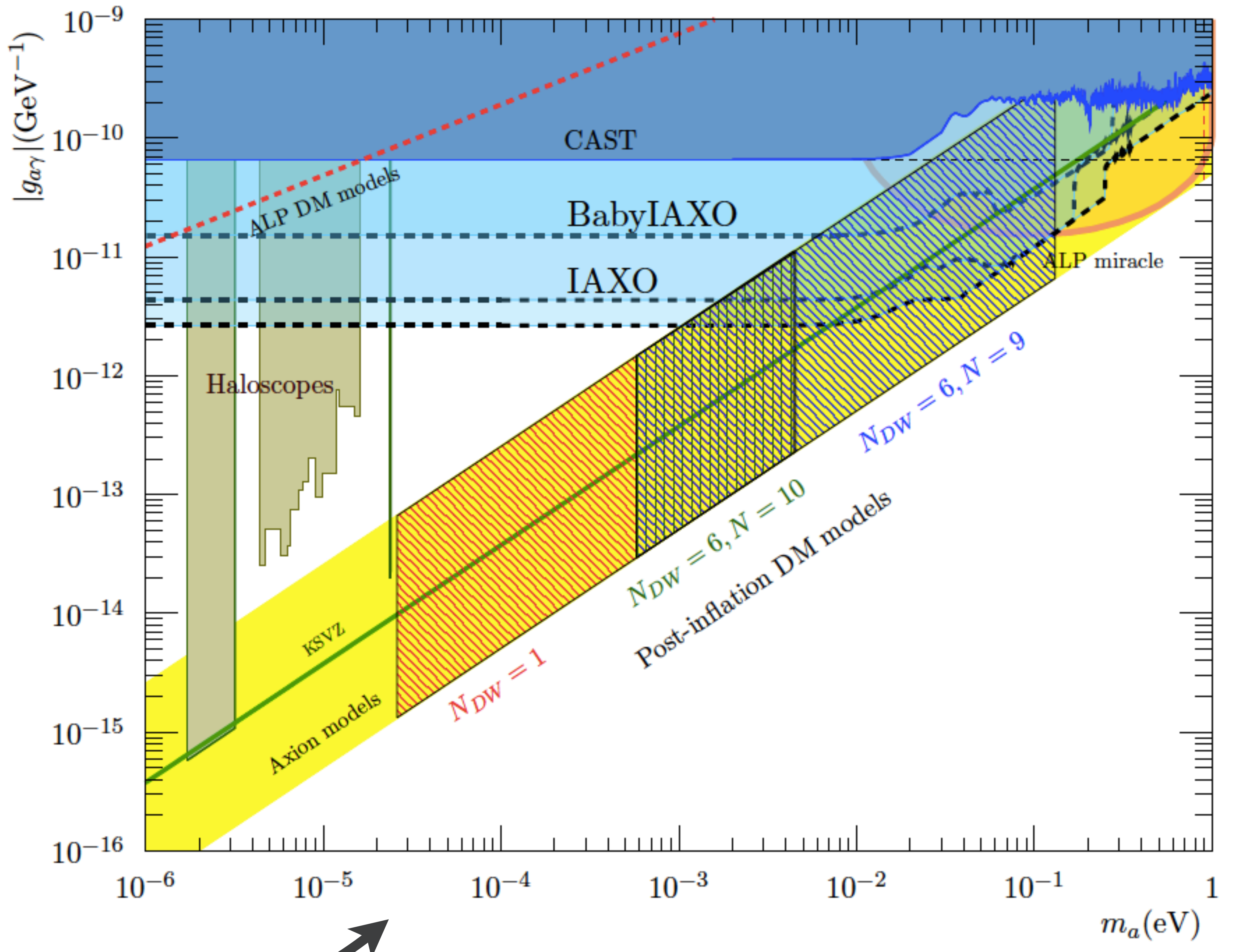
$$V(a) = \chi(T)\left[1 - \cos\left(N_{\rm DW}\frac{a}{v_{\rm PQ}}\right)\right]$$



- Network of strings connected by multiple walls

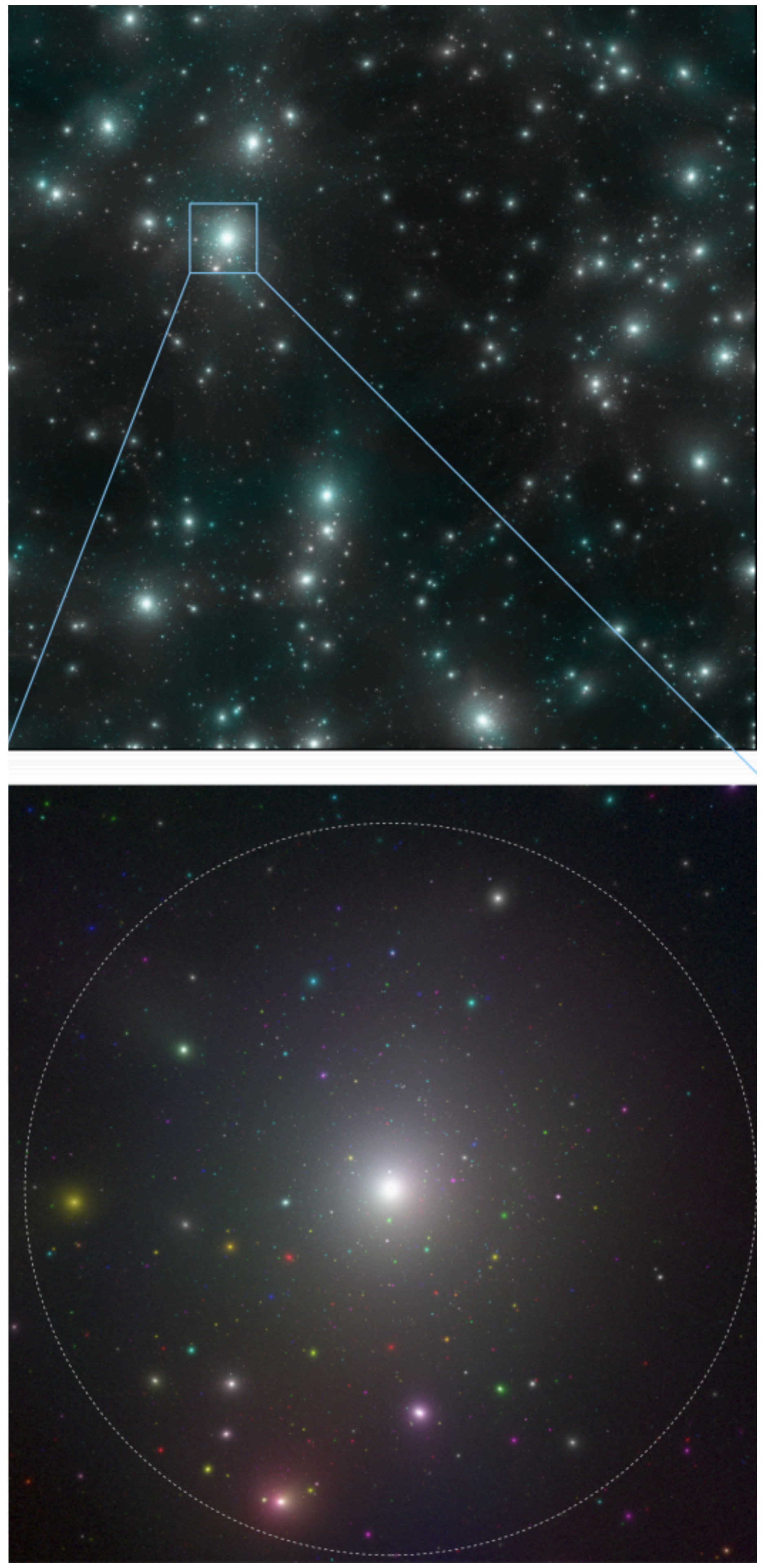


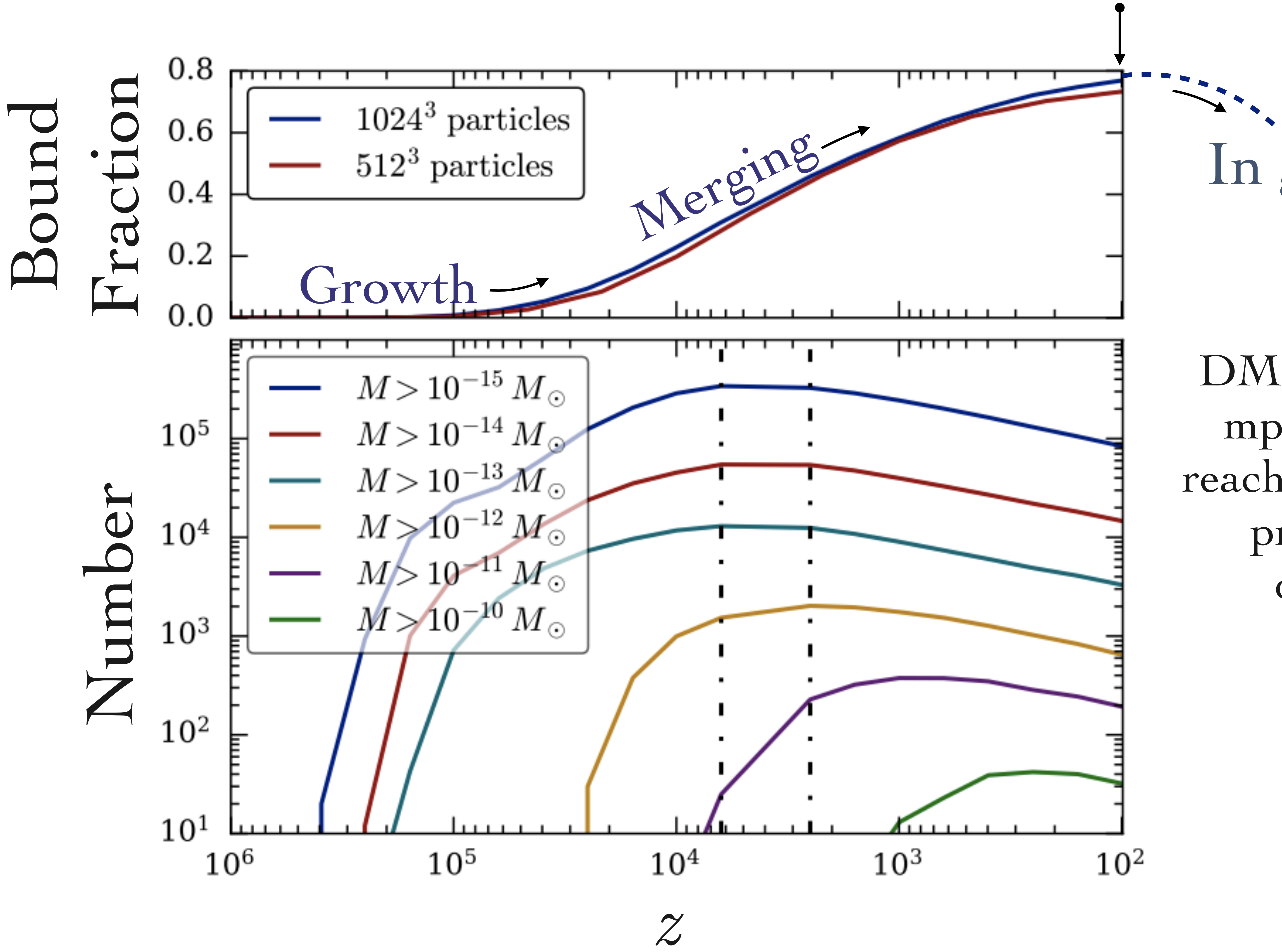
- Change predicted axion mass windows



Post-inflation problem #3: Fate of miniclusters at late times

Eggemeier+ [1911.09417]





In galaxies…

DM clumpy at sub-mpc scales out of reach to conventional probes of DM distribution

Fate of miniclusters in the galaxy

Problems for direct detection → encounter rate ~ 1 per 10,000 – 1,000,000 years

Kavanagh et al. [2011.05377]

Opportunities for indirect detection → collision of miniclusters with neutron stars

Edwards et al. [2011.05378]

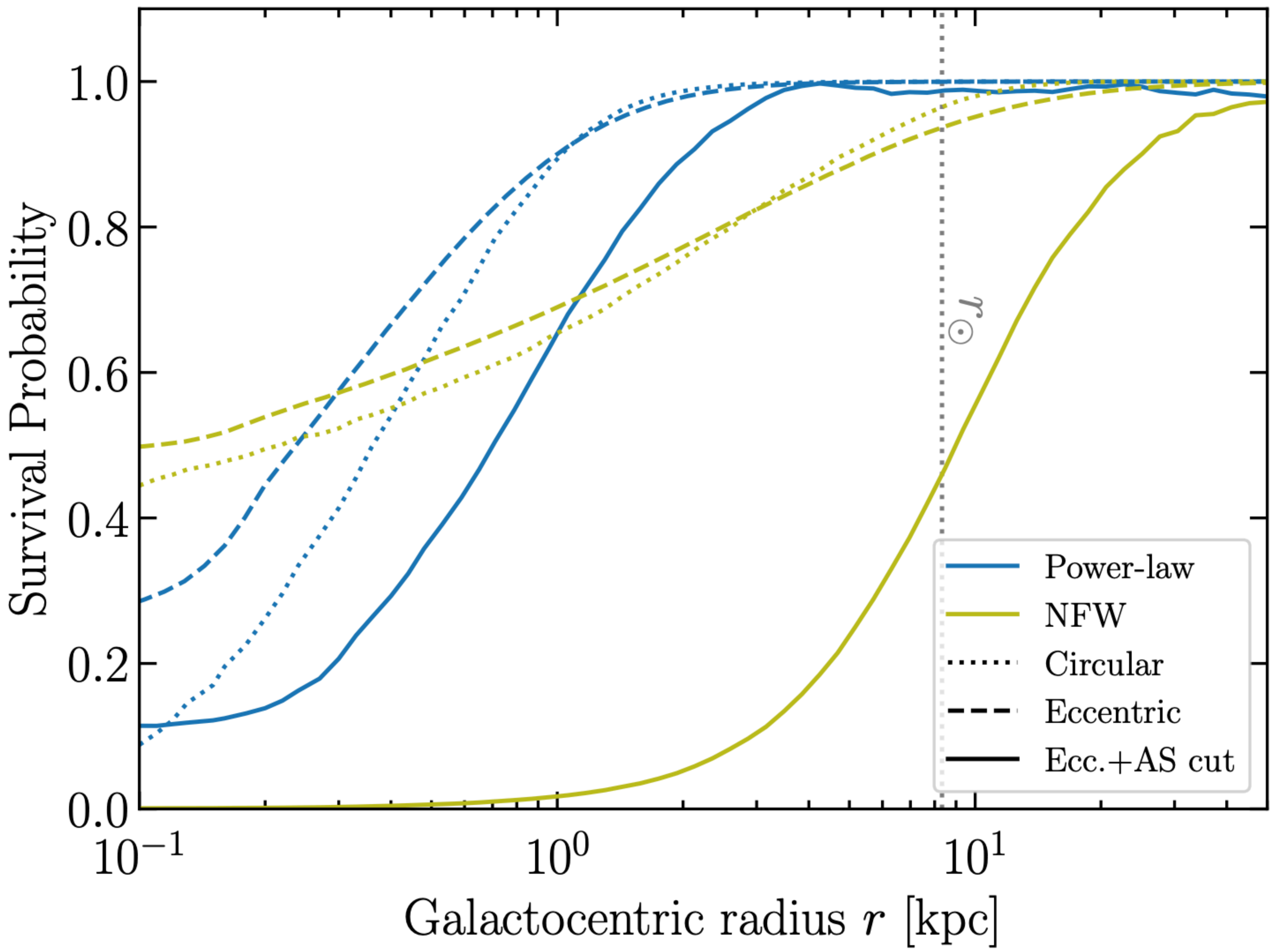
→ Miniclusters passing line of sight

Dai & Miralda Escudé [1908.01773]
Fairbairn et al. [1701.04787]

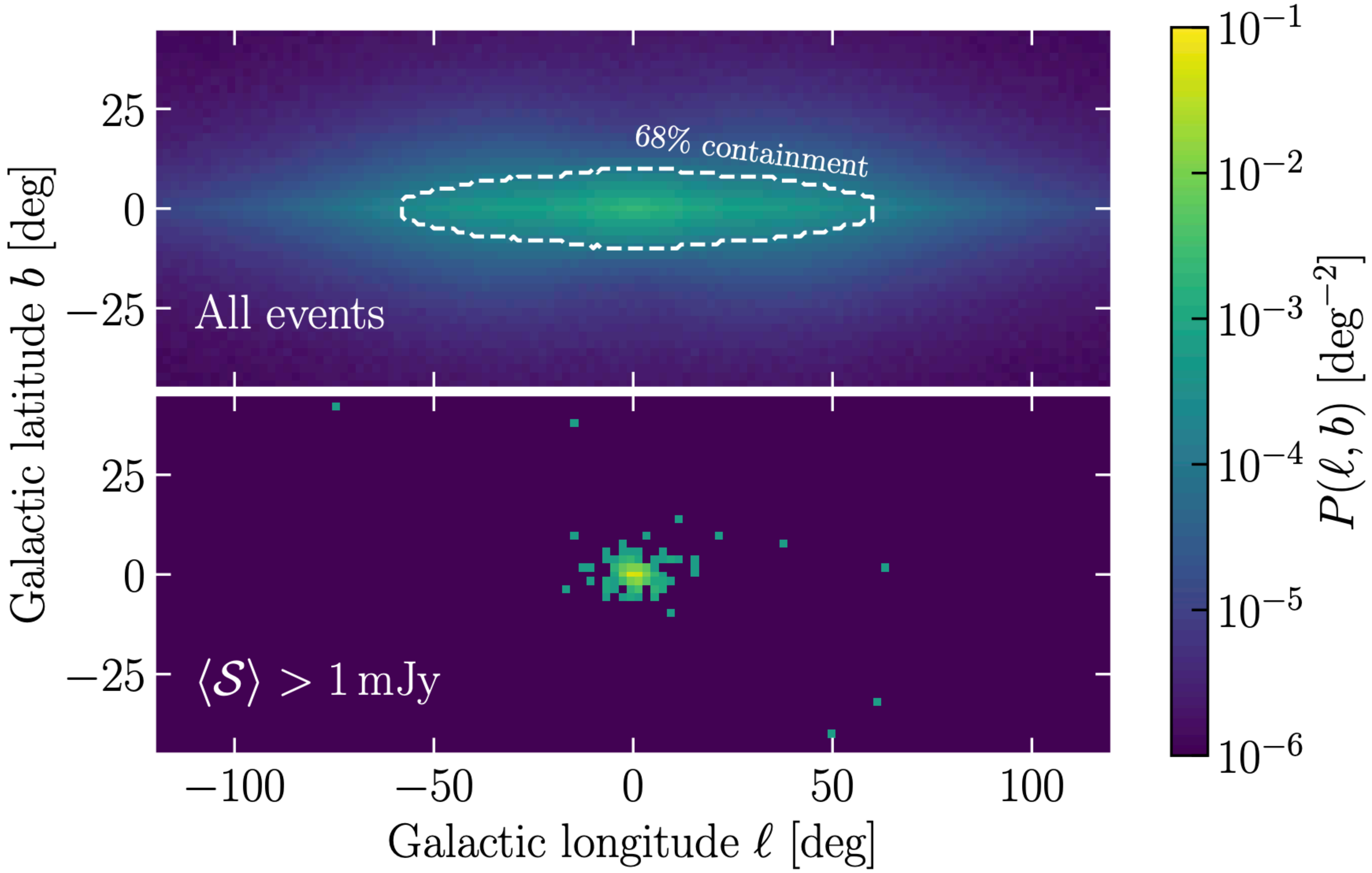
Fate of miniclusters in the galaxy - 2 recent papers

Kavanagh, Edwards, Visinelli, Weniger

[2011.05377] Survival probability of miniclusters versus minicluster density profile and position in galaxy

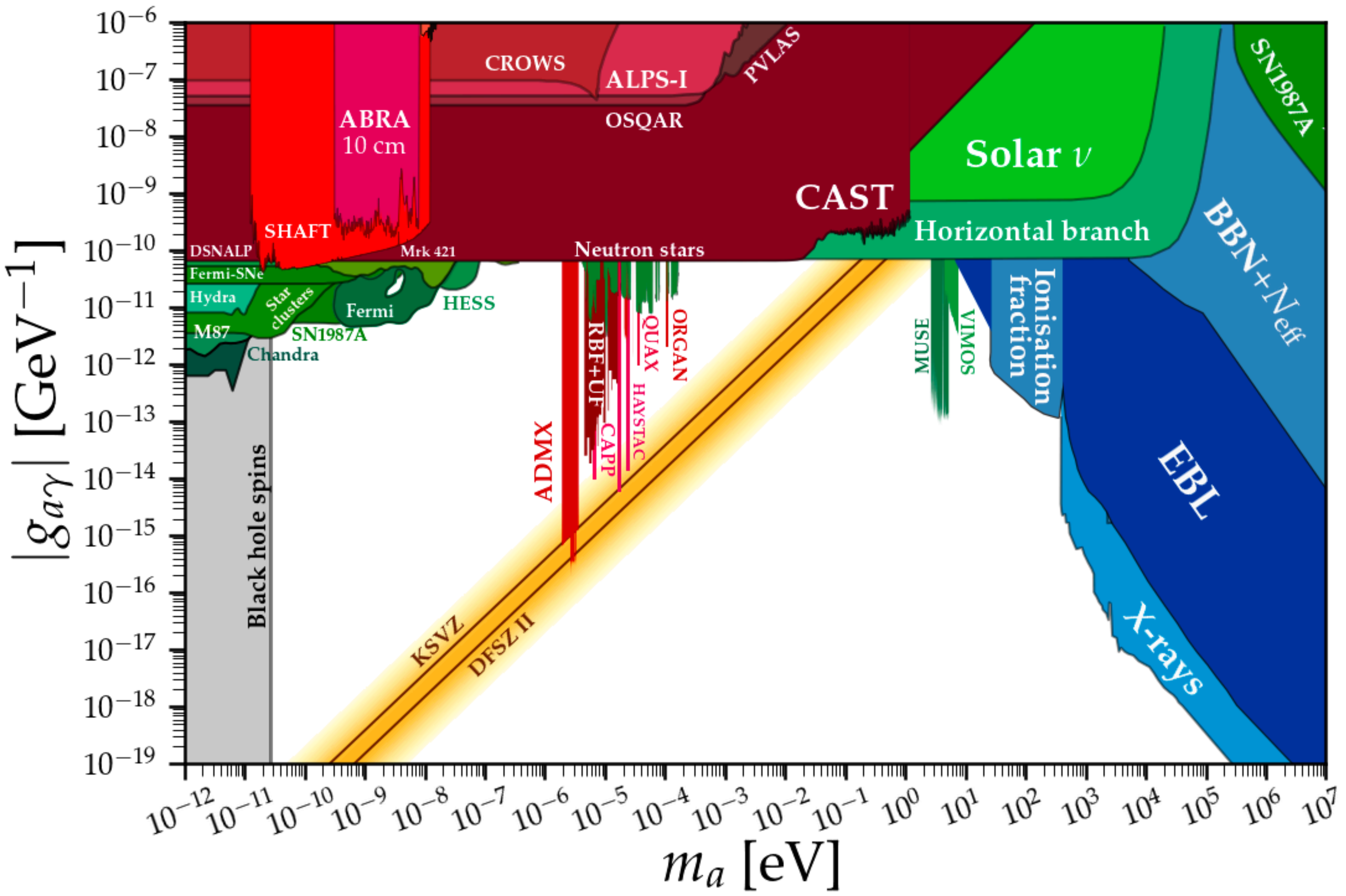


[2011.05378] Encounter rate between miniclusters and neutron stars → radio transients every 1 — 100 days towards GC

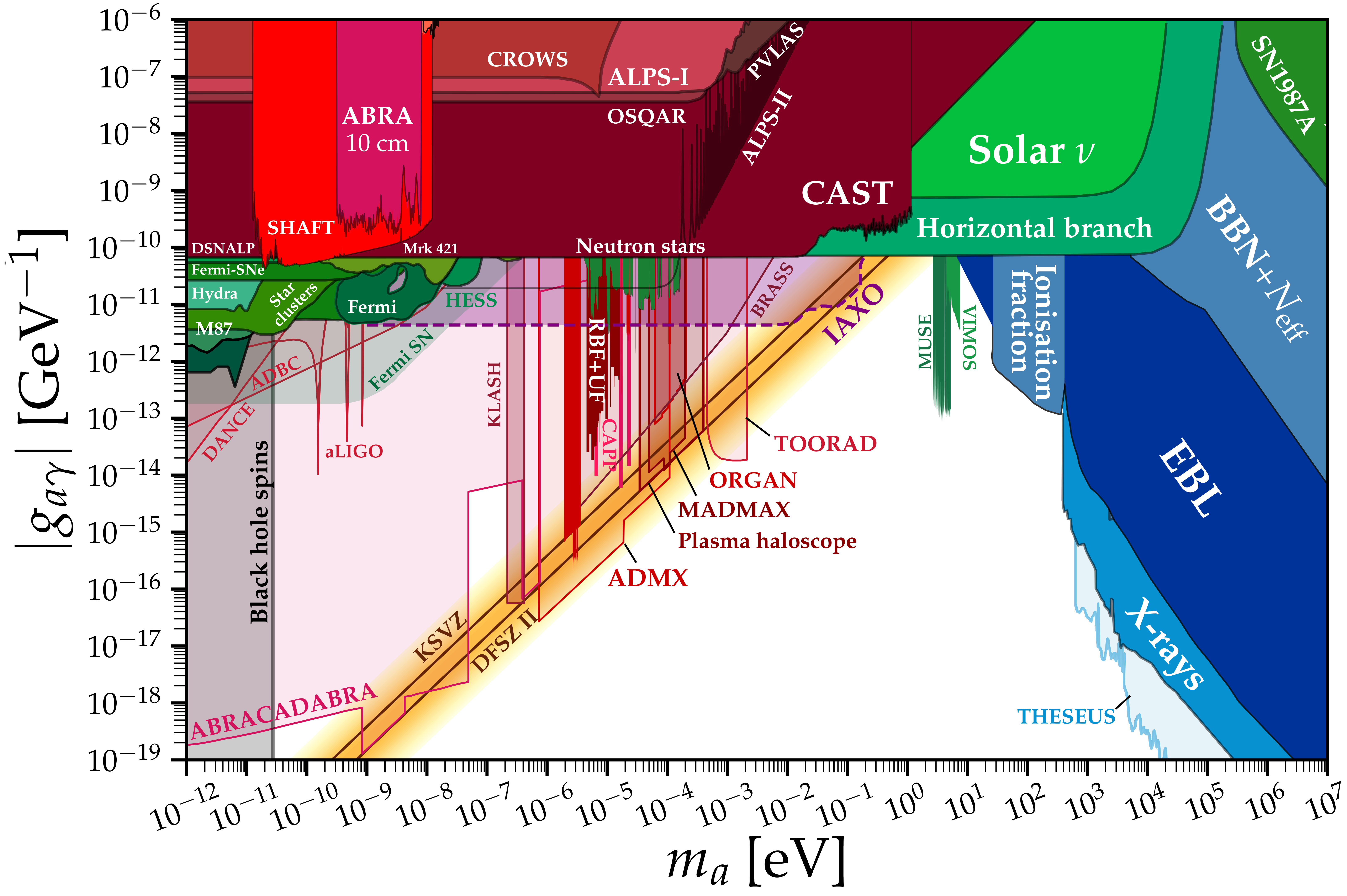


Still many uncertainties remaining → but results suggest that NS radio transients are a promising indirect signal and miniclusters at Earth's position could be disrupted

Take home point: beware of naive reading of axion constraints, many theoretical and observational uncertainties remain



Hopefully at some point in soon the plot will look more like this



Bonus slides

>eV QCD axions constrained as hot dark matter

LCDM
+ thermal axions
+ massive neutrinos