

Mapping the Axiverse

Francesca Chadha-Day
IPPP, Durham University

PPC 2026
4th Gordon Godfrey Workshop
University of New South Wales

Based on 2311.13658, 2107.12813 and ongoing work

In collaboration with Daniel Kirkham, James Maxwell, Jessica Turner



Axions



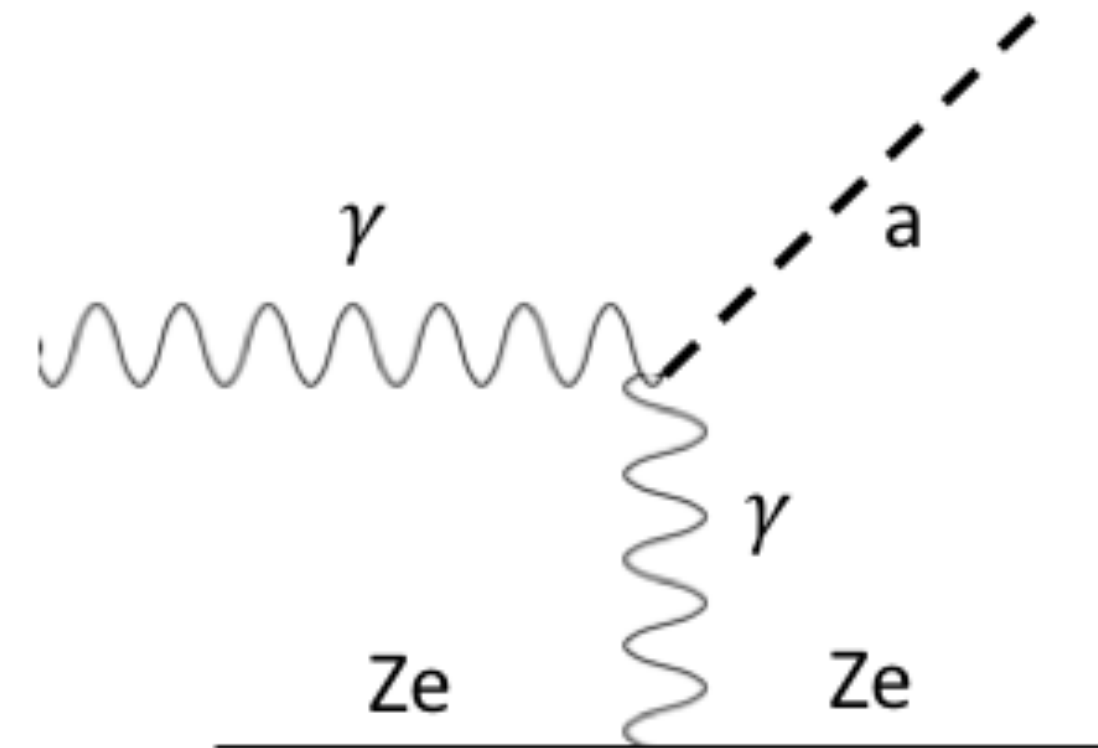
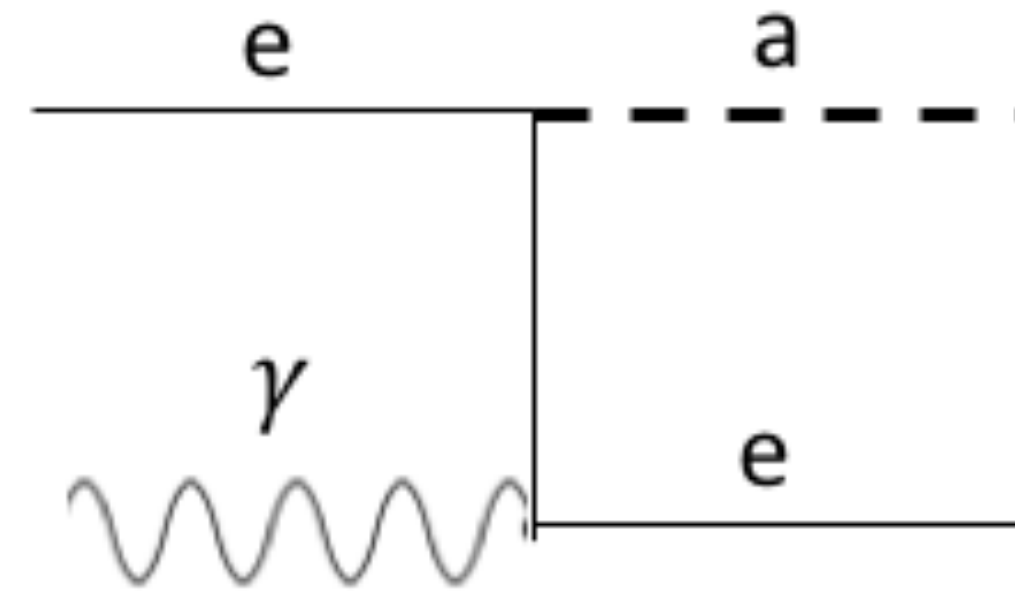
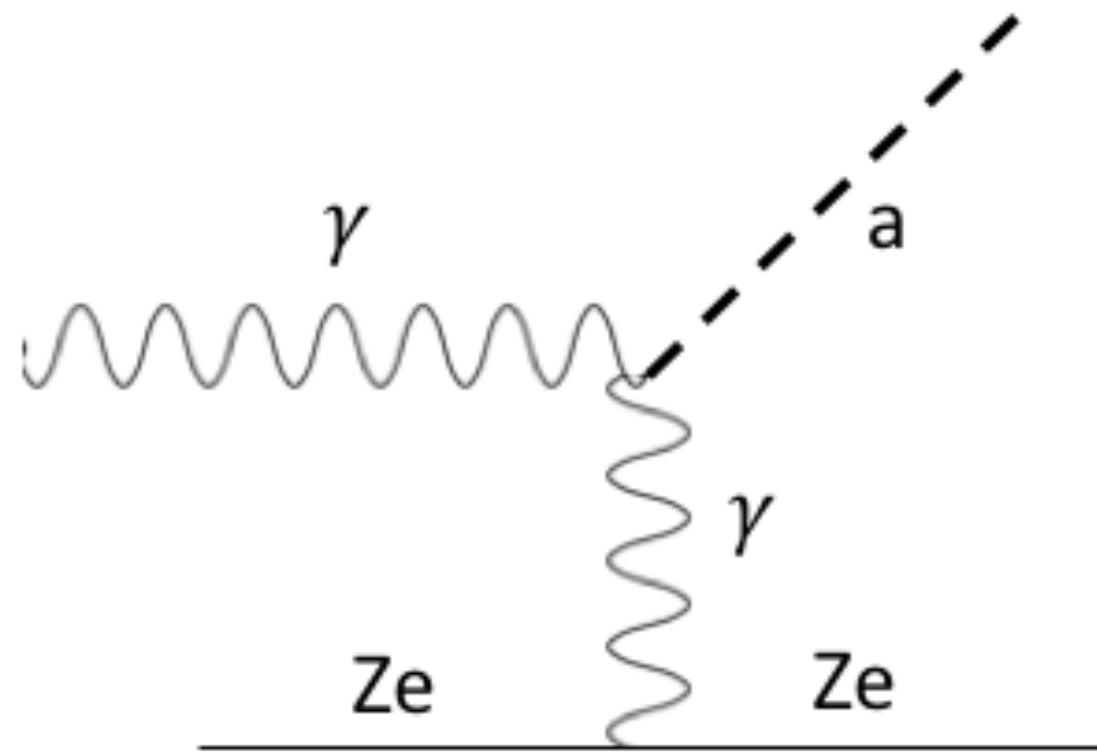
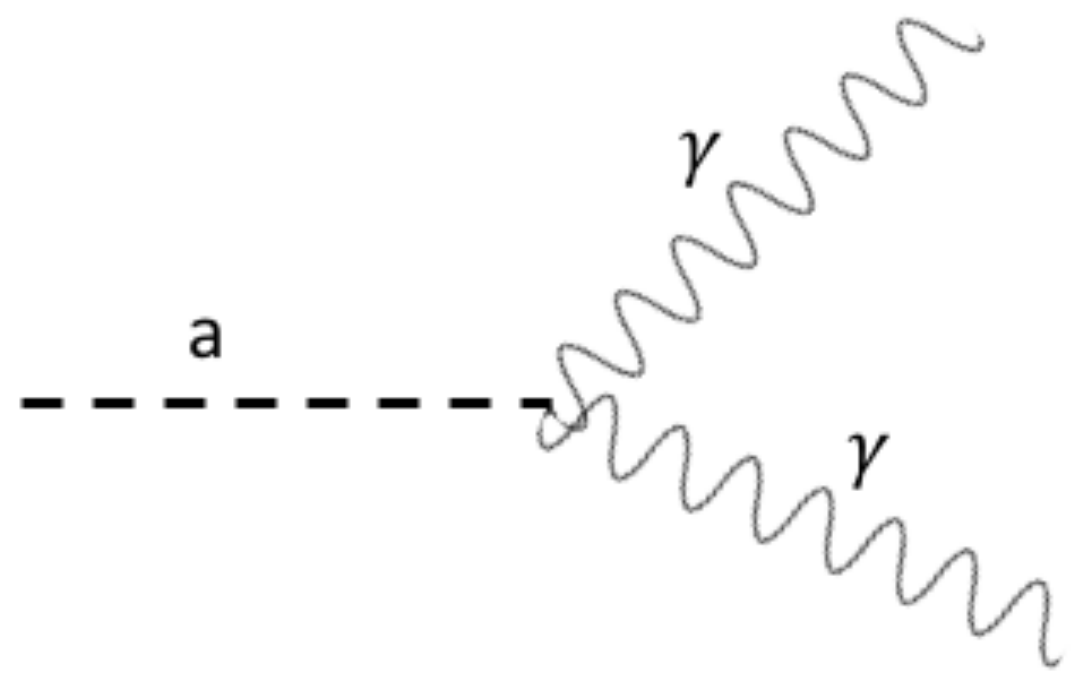
- String theory
- Null measurements of the neutron EDM
- Dark matter
- Dark energy

Axion-like Particles

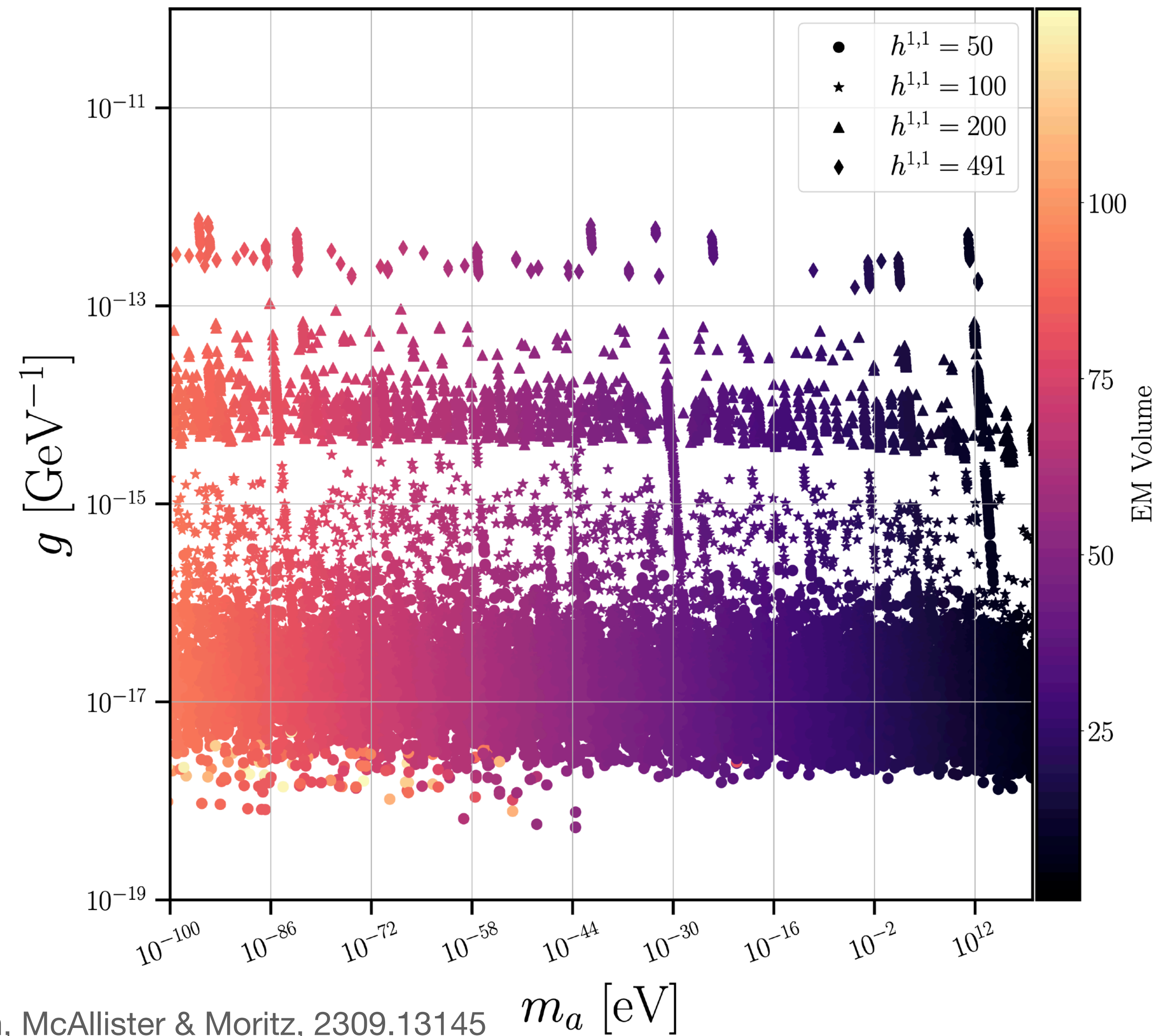
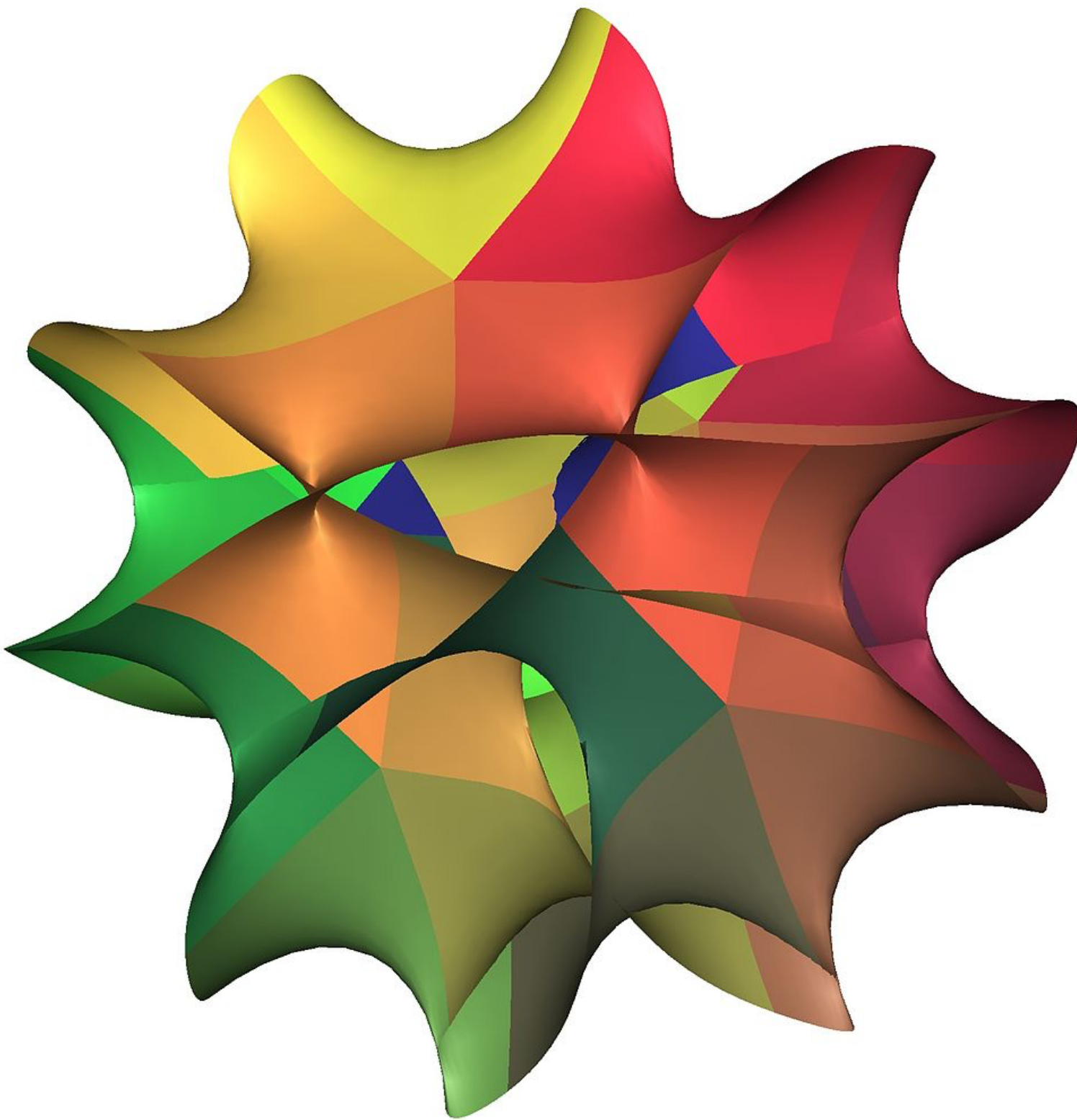
- ALPs are light, CP odd particles that exist in many extensions of the Standard Model.
- They are pseudo-Nambu Goldstone bosons of global U(1) symmetries.
- ALPs do not necessarily couple to gluons or solve the Strong CP problem.
- String theory compactifications give rise to an “axiverse” ALPs at a range of masses.

$$\mathcal{L} = \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - \frac{1}{2} m^2 \phi^2 + g_{\phi gg} \phi G \tilde{G} - \frac{g_{\phi \gamma \gamma}}{4} \phi F \tilde{F} + g_{\phi ff} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f \partial_\mu \phi$$

Axion-like Particles



The String Axiverse (type IIB)



Hanson, Notices of the Amer. Math. Soc. 41 (9): 1156-1163, (November/December 1994)

Figure from Gendler, Marsh, McAllister & Moritz, 2309.13145

The String Axiverse (F theory)

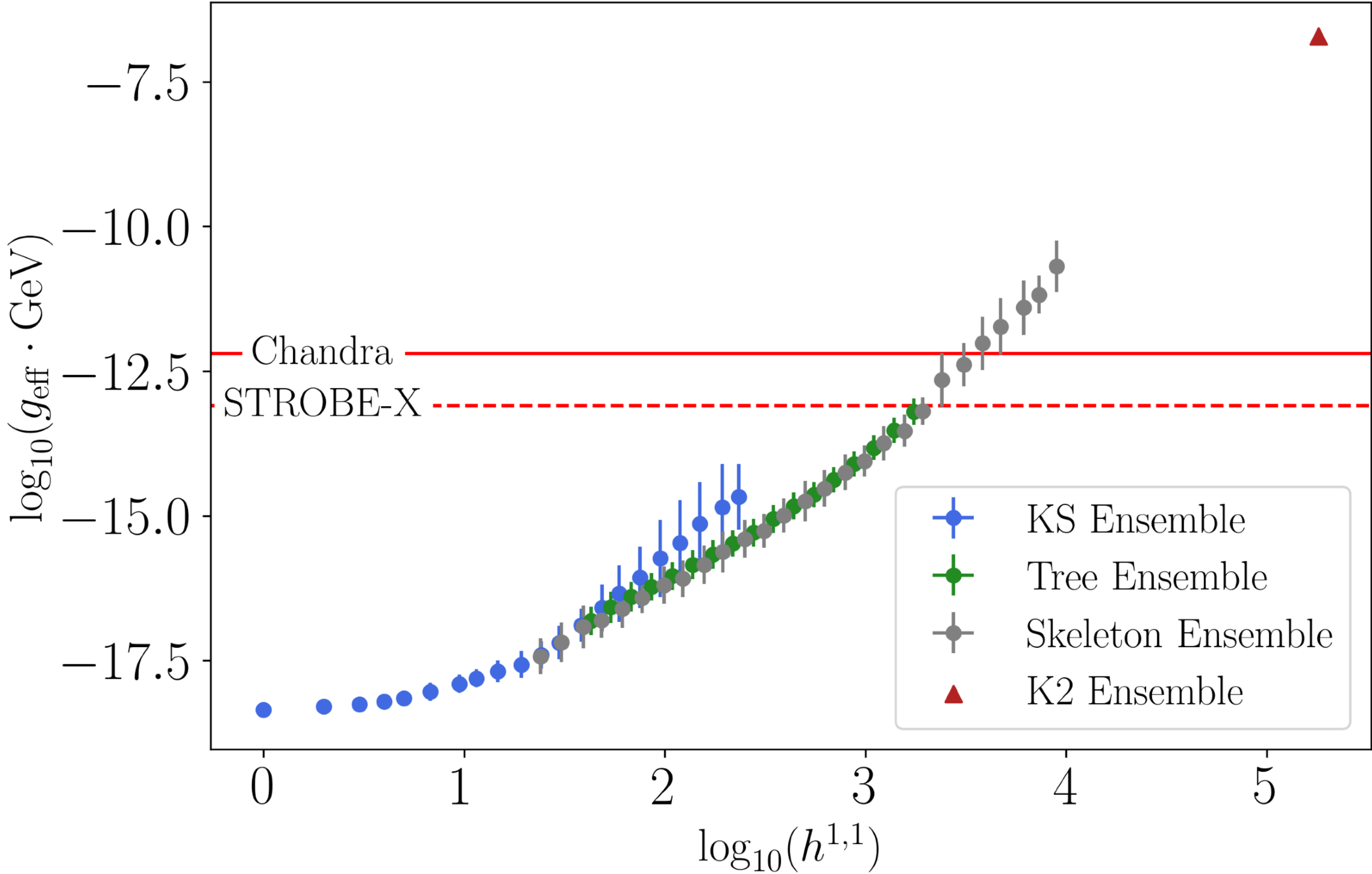
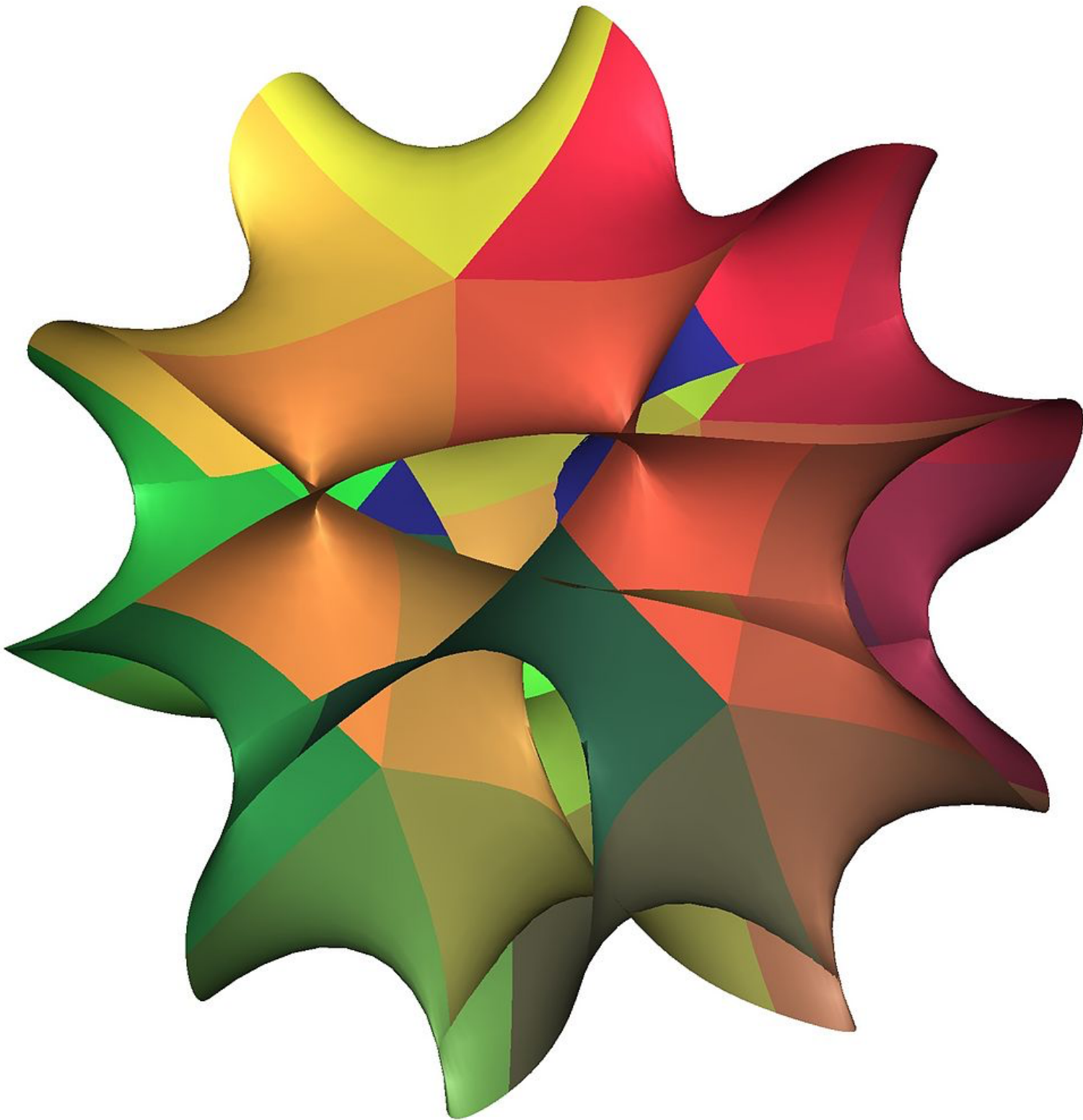
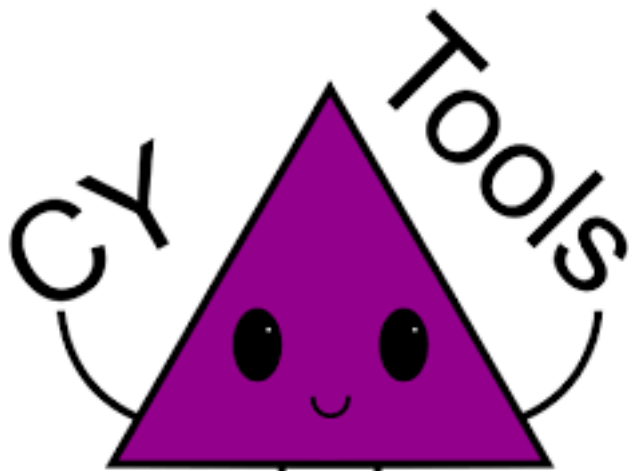
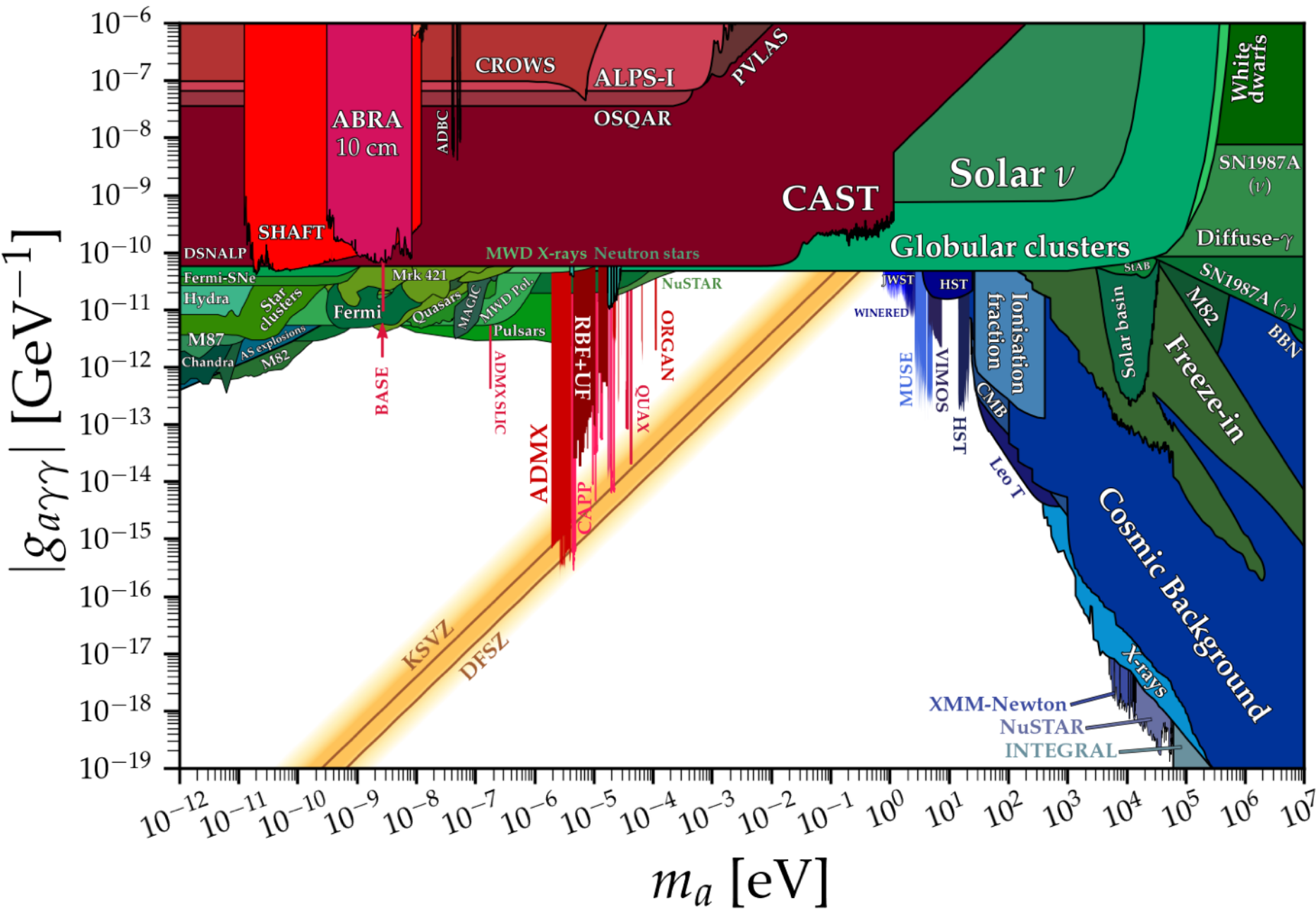


Figure from Fallon, Halverson, McAllister & Zhu, 2511.20458

The String Axiverse

Type IIB String Theory

Kreuzer-Skarke database
hep-th/0002240



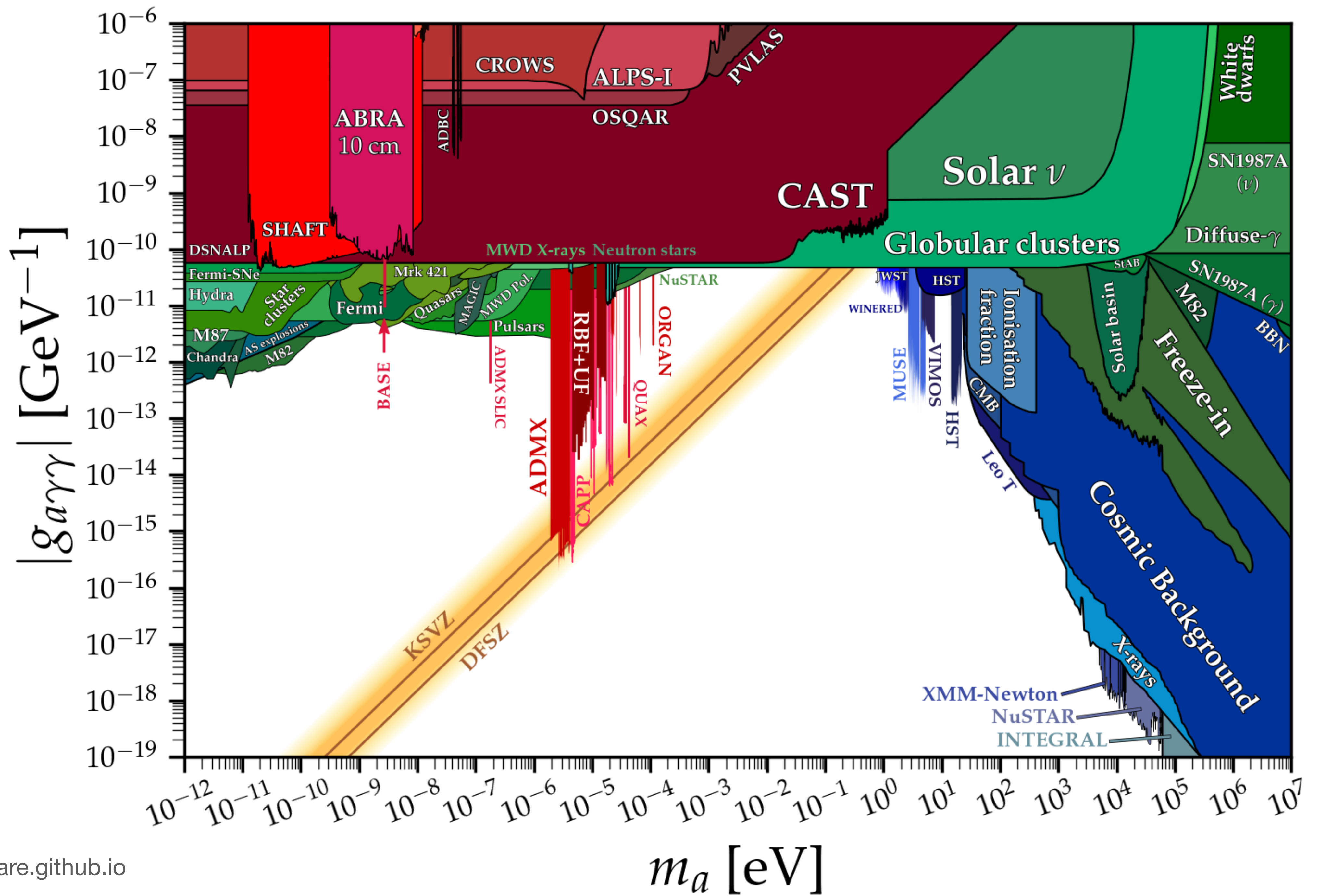
Demirtas, Rios-Tascon & McAllister
2211.03823

Compactification manifold

???

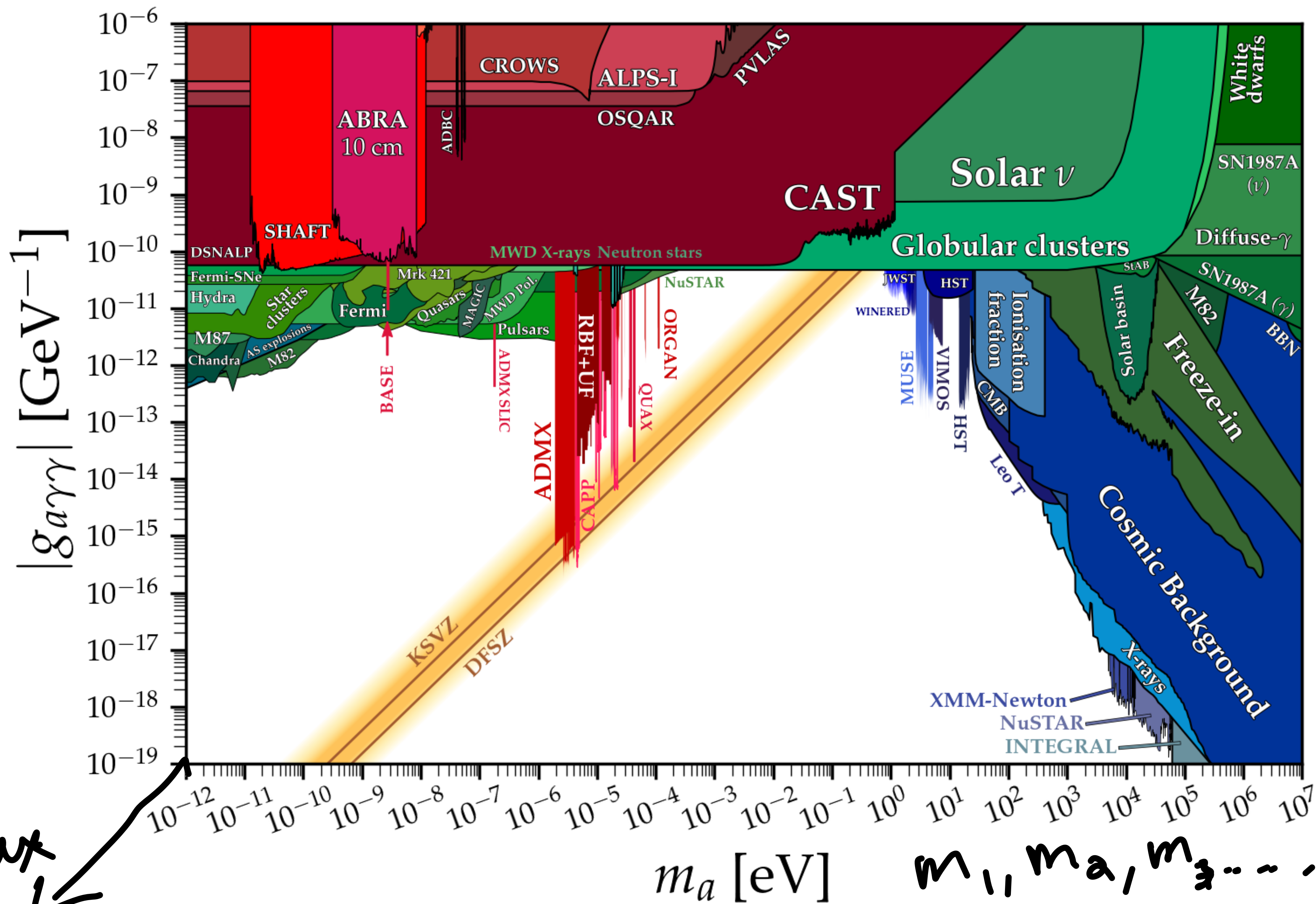
ALP masses
and photon couplings
(Calculation possible in some regimes)

Other ALP couplings to SM



$g_1, g_2, g_3 \dots$

N_{ex}



The String Axiverse

$$\mathcal{L} \supset \sum_i \left(-\frac{1}{2} \partial^\mu \phi_i \partial_\mu \phi_i - \frac{1}{2} m_i^2 \phi_i^2 - g_i^\gamma \phi_i \tilde{F}^{\mu\nu} F_{\mu\nu} + g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi_i \right)$$

Wish to work in a convenient basis:

- **Mass basis:** mass matrix is diagonal, no oscillations between propagating ALP states.
- **Electromagnetic basis:** only one ALP couples to the photon with coupling $g^\gamma = \sqrt{\sum g_i^{\gamma^2}}$.
- **Electronic basis:** only one ALP couples to the electron with coupling $g^e = \sqrt{\sum g_i^{e^2}}$.
- The electromagnetic and electronic ALPs are in general neither orthogonal nor colinear.
- For the QCD basis see Gavela, Quilez & Ramos, 2305.15465.

Basis Choice

$$\mathcal{L} \supset \sum_i \left(-\frac{1}{2} \partial^\mu \phi_i \partial_\mu \phi_i - \frac{1}{2} m_i^2 \phi_i^2 - g_i^\gamma \phi_i \tilde{F}^{\mu\nu} F_{\mu\nu} + g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi_i \right)$$

- In the full theory, all basis choices give the same results.
- QFT with “flavour eigenstates” is non-trivial.
- Different bases may give different results when combined with other approximations.
- Oscillations between states when not in the mass basis, akin to neutrino oscillations.
- Misalignment between electromagnetic and electronic bases.
- Conserved charge in the massless limit must be considered for thermal production (Gendler, Marsh, McAllister & Moritz, 2309.13145; Dessert, Kumar & Ruderman, 2511.09631)

Mass eigenstates

$$\mathcal{L} \supset \sum_i \left(-\frac{1}{2} \partial^\mu \phi_i \partial_\mu \phi_i - \frac{1}{2} m_i^2 \phi_i^2 - g_i^\gamma \phi_i \tilde{F}^{\mu\nu} F_{\mu\nu} + g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi_i \right)$$

- Some experiments search for each mass eigenstate individually.
- Example: axion haloscopes, radio line searches, superradiance
- Cosmology and structure formation are sensitive to the combination of mass eigenstates and their initial conditions

Searches for the Electromagnetic ALP

$$\phi_\gamma = \frac{1}{g_\gamma} \sum_{m_i < m_{\text{thresh}}} g_i^\gamma \phi_i$$

$$g^\gamma = \sqrt{\sum_{m_i < m_{\text{thresh}}} g_i^{\gamma^2}}$$

- When no masses or other couplings are relevant, we can search for a single light ALP with coupling g_γ to photons.
- Example: stellar cooling bounds.

$$|\phi_i^{\text{mass}}\rangle = U_{\alpha i}^\gamma |\phi_\alpha^{\text{EM}}\rangle$$

The Electromagnetic ALP

$$\phi_\gamma = \frac{1}{g_\gamma} \sum_{m_i < m_{\text{thresh}}} g_i^\gamma \phi_i$$

• In the electromagnetic basis, other fields orthogonal to the EM ALP do not couple directly to electromagnetism.

$$g^\gamma = \sqrt{\sum_{m_i < m_{\text{thresh}}} g_i^{\gamma^2}}$$

- When the ALP mass is not relevant, the EM ALP is produced and detected by electromagnetic processes.
- The EM ALP is in general not a mass eigenstate, so will oscillate into the orthogonal “hidden” ALP states.
- Misalignment between electromagnetic and electronic bases.

$$|\phi_i^{\text{mass}}\rangle = U_{\alpha i}^\gamma |\phi_\alpha^{\text{EM}}\rangle$$

The Electromagnetic ALP

$$\phi_\gamma = \frac{1}{g_\gamma} \sum_{m_i < m_{\text{thresh}}} g_i^\gamma \phi_i$$

Electromagnetic ALP to hidden ALP
oscillation probability for two mass
eigenstates:

$$g^\gamma = \sqrt{\sum_{m_i < m_{\text{thresh}}} g_i^{\gamma^2}}$$

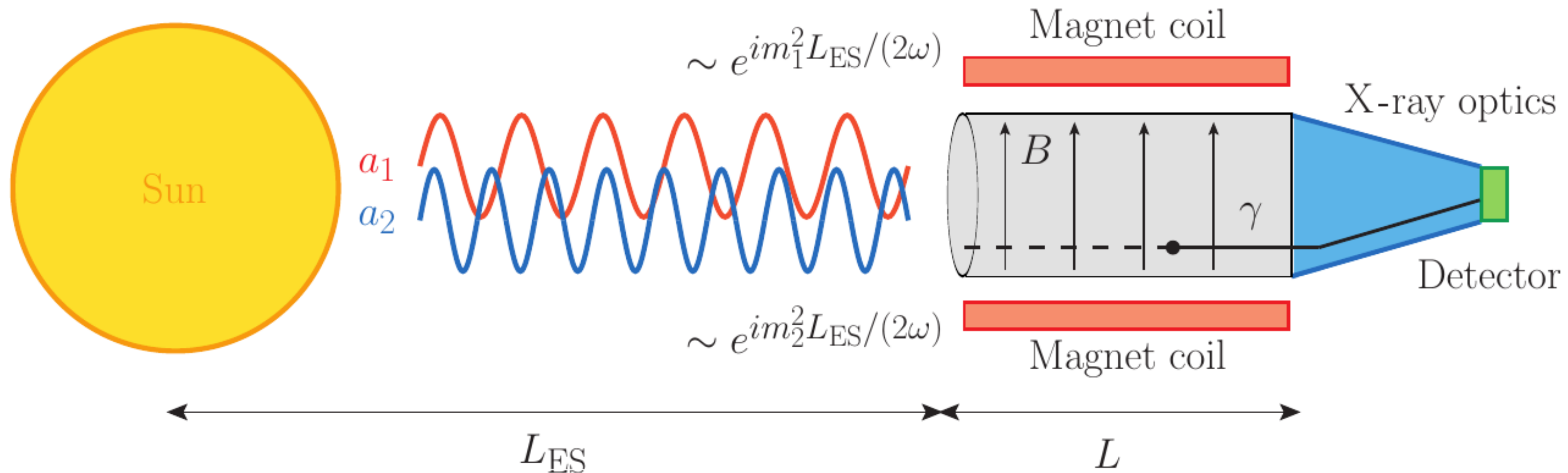
$$P_{\phi_\gamma \rightarrow \phi_h} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right)$$

$$|\phi_i^{\text{mass}}\rangle = U_{\alpha i}^\gamma |\phi_\alpha^{\text{EM}}\rangle$$

ALP Oscillations

- Oscillation effects are relevant whenever an ALP propagates a large distance between production and detection.
- Basis misalignment effects are relevant whenever two ALP-SM couplings are relevant.

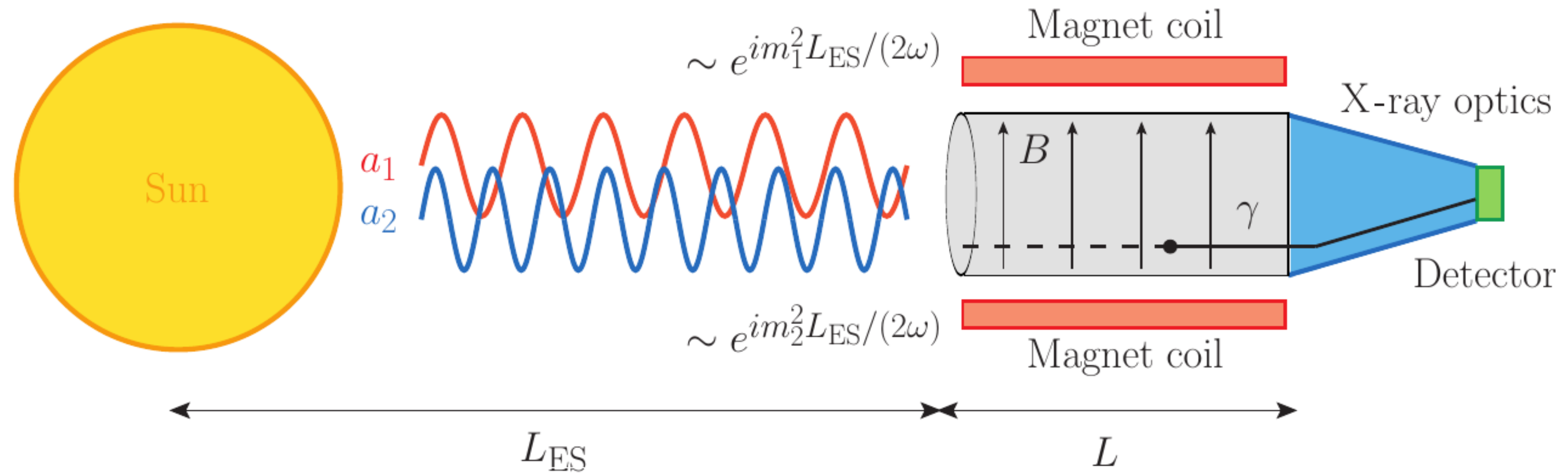
Helioscopes



- ALP states ϕ_γ and ϕ_e are produced in the sun.
- Helioscope with evacuated magnet bores detects the state ϕ_γ .
- ALPs produced in the Sun may oscillate into hidden ALPs as they travel to Earth, and therefore be unobservable to CAST.

Reproduced from Grinstein, Miro and Lastana, 2606.20826

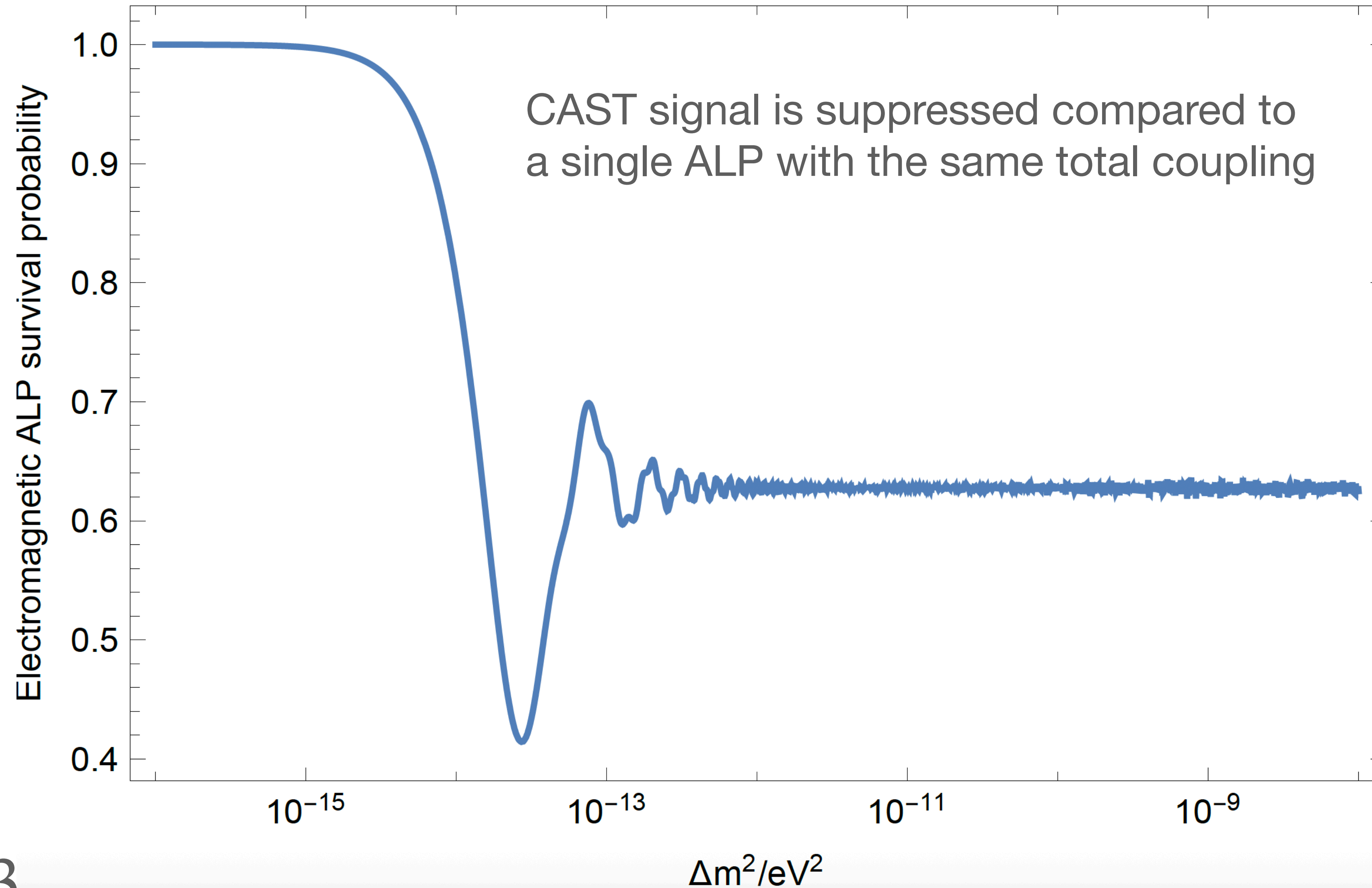
Helioscopes



For 2 mass eigenstates:

$$P_{\phi_\gamma \rightarrow \phi_\gamma} = 1 - \sin^2 2\theta \frac{\int_{2\text{keV}}^{7\text{keV}} \sin^2 \left(\frac{\Delta m^2 L}{4E} \right) \frac{d\Phi_a}{dE} dE}{\int_{2\text{keV}}^{7\text{keV}} \frac{d\Phi_a}{dE} dE}$$

Helioscopes



$$\theta = \pi/3$$

Helioscopes

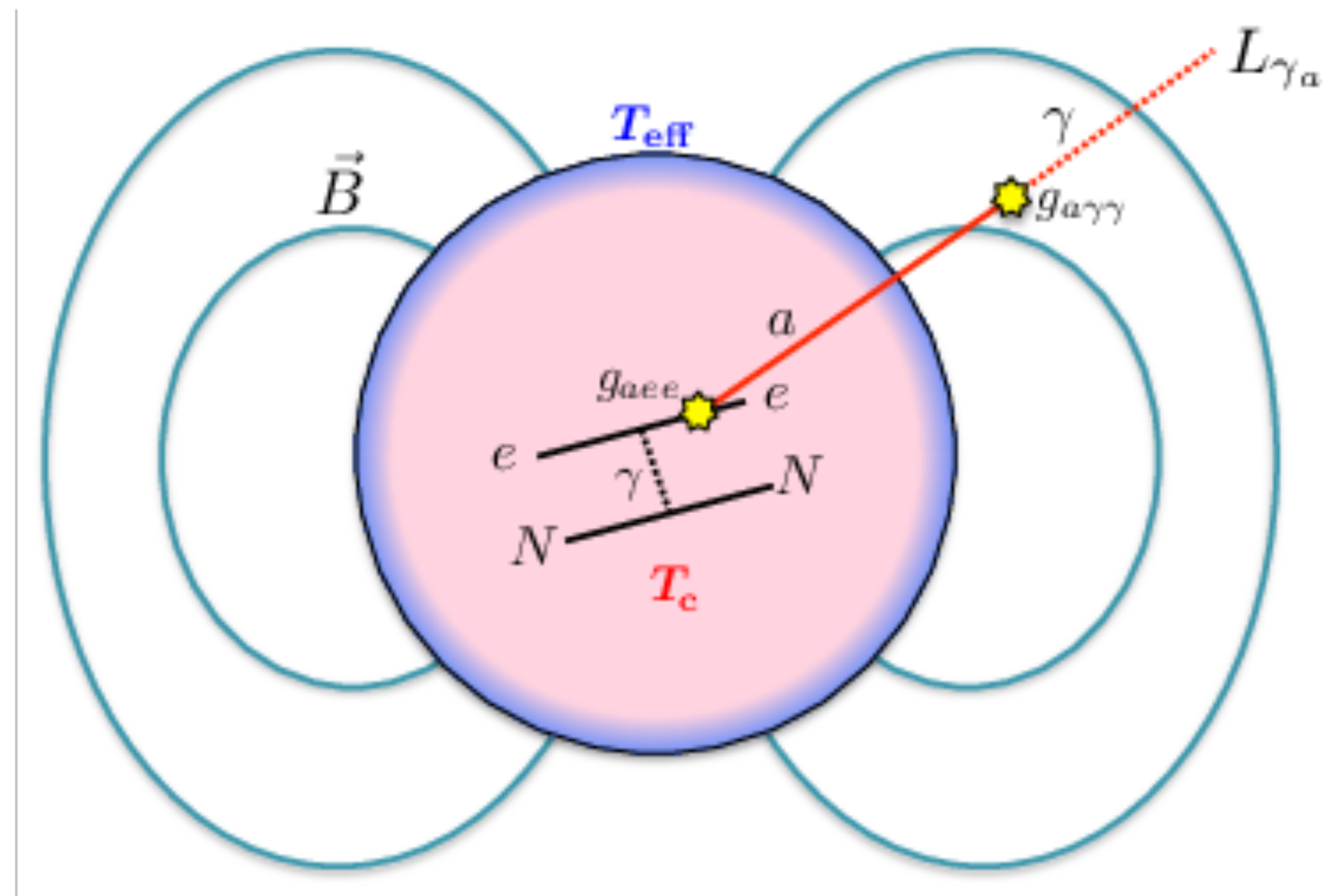
After averaging over energies, helioscopes are sensitive to

$$g_{\text{helio}}^4 \sim \left| \sum_{m_i \ll m_{\text{sun}}} g_i^{\gamma^2} \right|^2 + \sum_{m_i \gg m_{\text{sun}}} g_i^{\gamma^4}$$

$$m_{\text{sun}} = \sqrt{\frac{4\pi E}{L}} \sim 10^{-7} \text{ eV}$$

The energy resolution of CAST and IAXO allows us to search for axion mass splittings directly - See Grinstein, Miro and Quílez Lastana, 2606.20826.

Magnetic White Dwarfs



Dessert, Long and Safdi, 1903.05088

Ning, Dessert, Hong and Safdi, 2411.05041

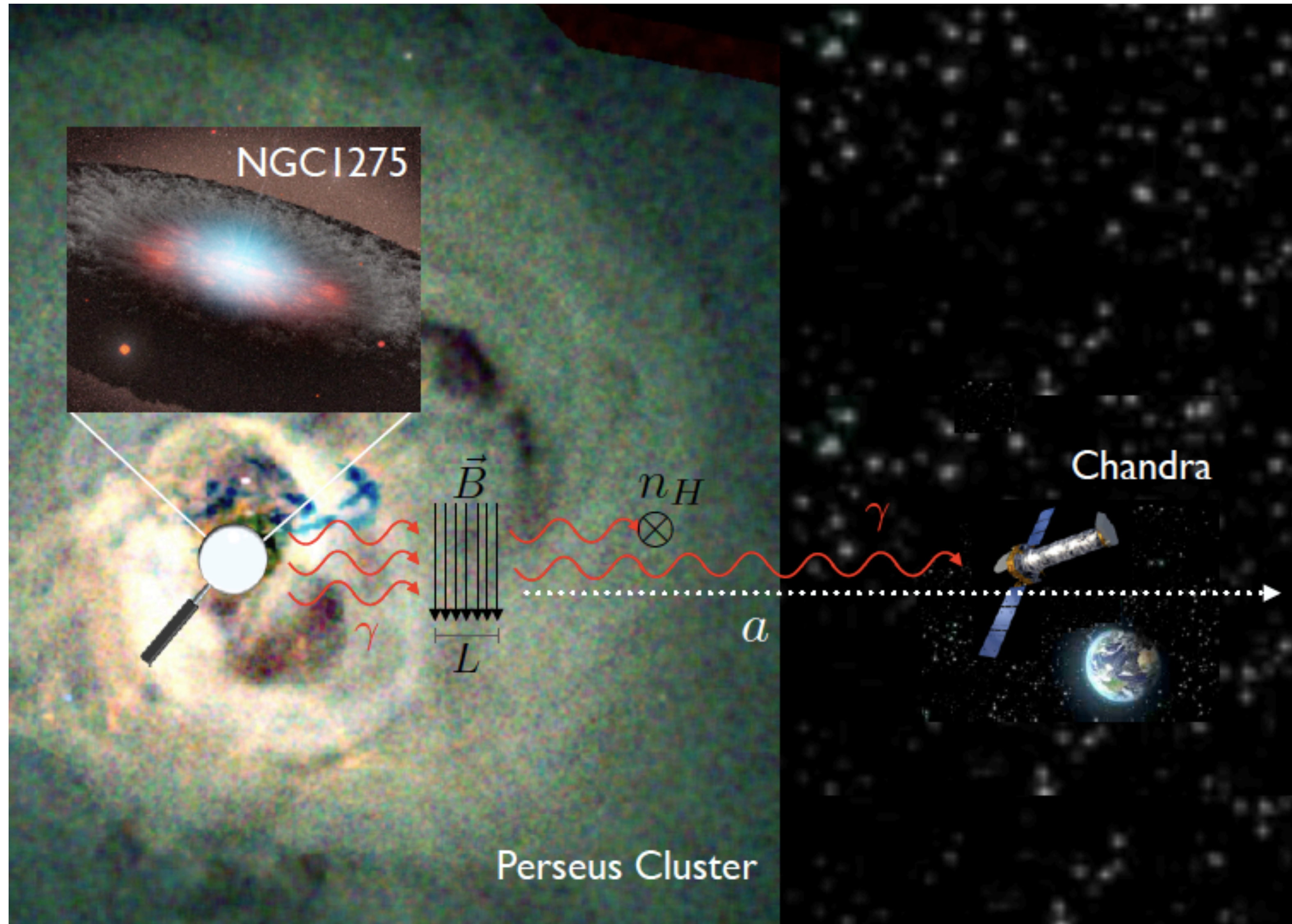
Sensitive to

$$g_{\text{MWD}}^2 \sim \sum_{m_i < m_{\text{MWD}}} g_i^\gamma g_i^e$$

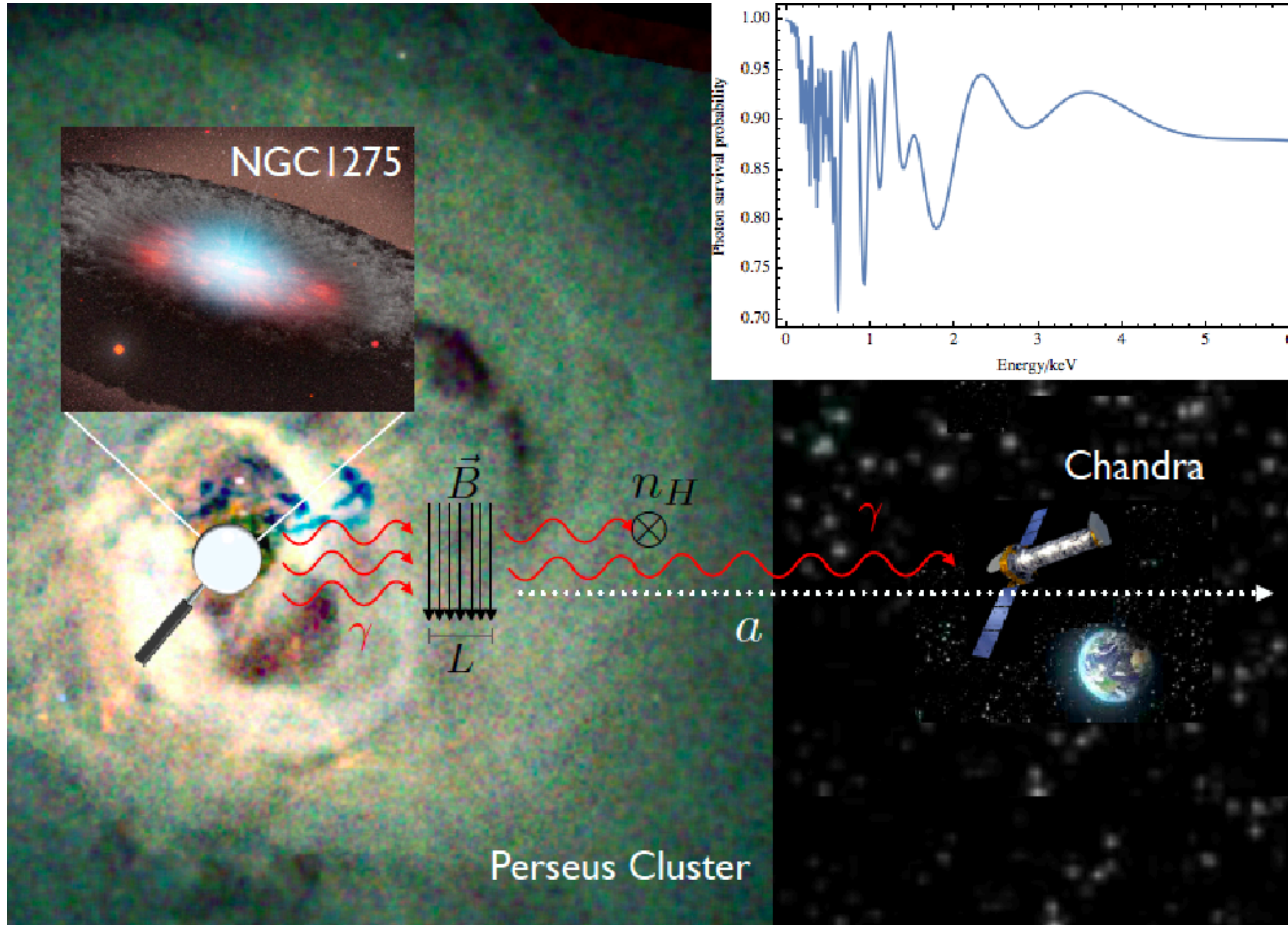
$$m_{\text{MWD}} \sim 10^{-6} \text{ eV}$$

Reproduced from [1903.05088](#)

Spectral Modulations

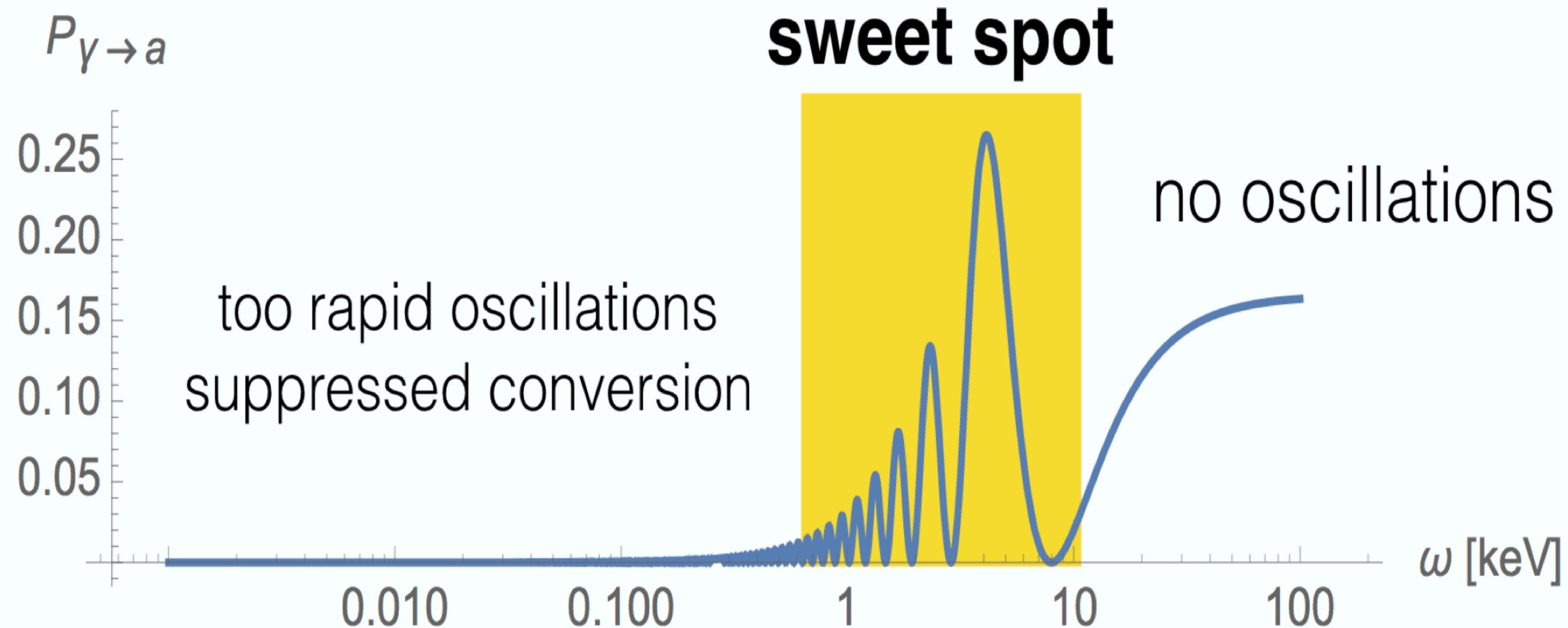


Spectral Modulations



Spectral Modulations

Figure by Joe Conlon

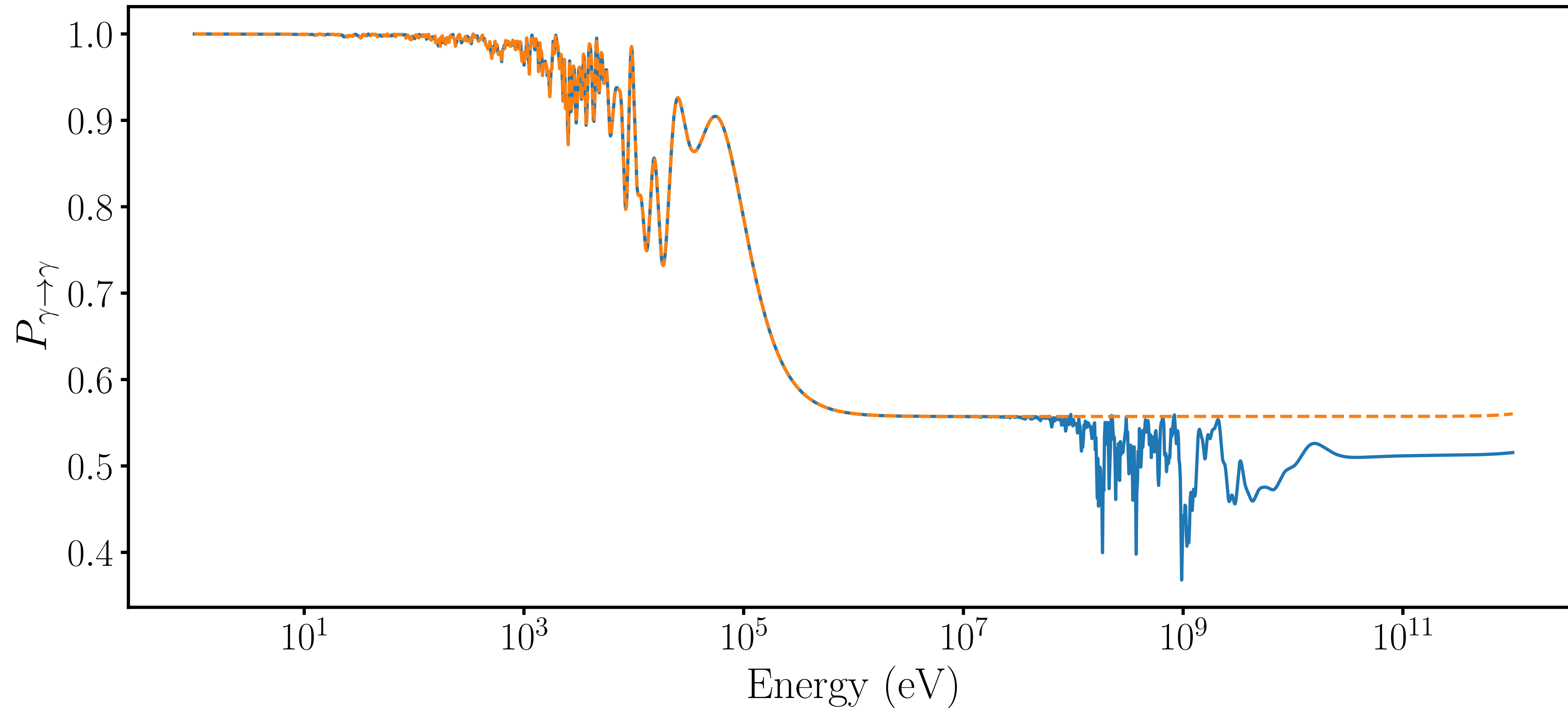


Sweet spot energy: $E_c = \frac{|m_a^2 - \omega_{pl}^2|}{2g_{a\gamma}B_T}$

Sweet spot energy: $m_a \sim \text{neV} \rightarrow \gamma - \text{rays}$

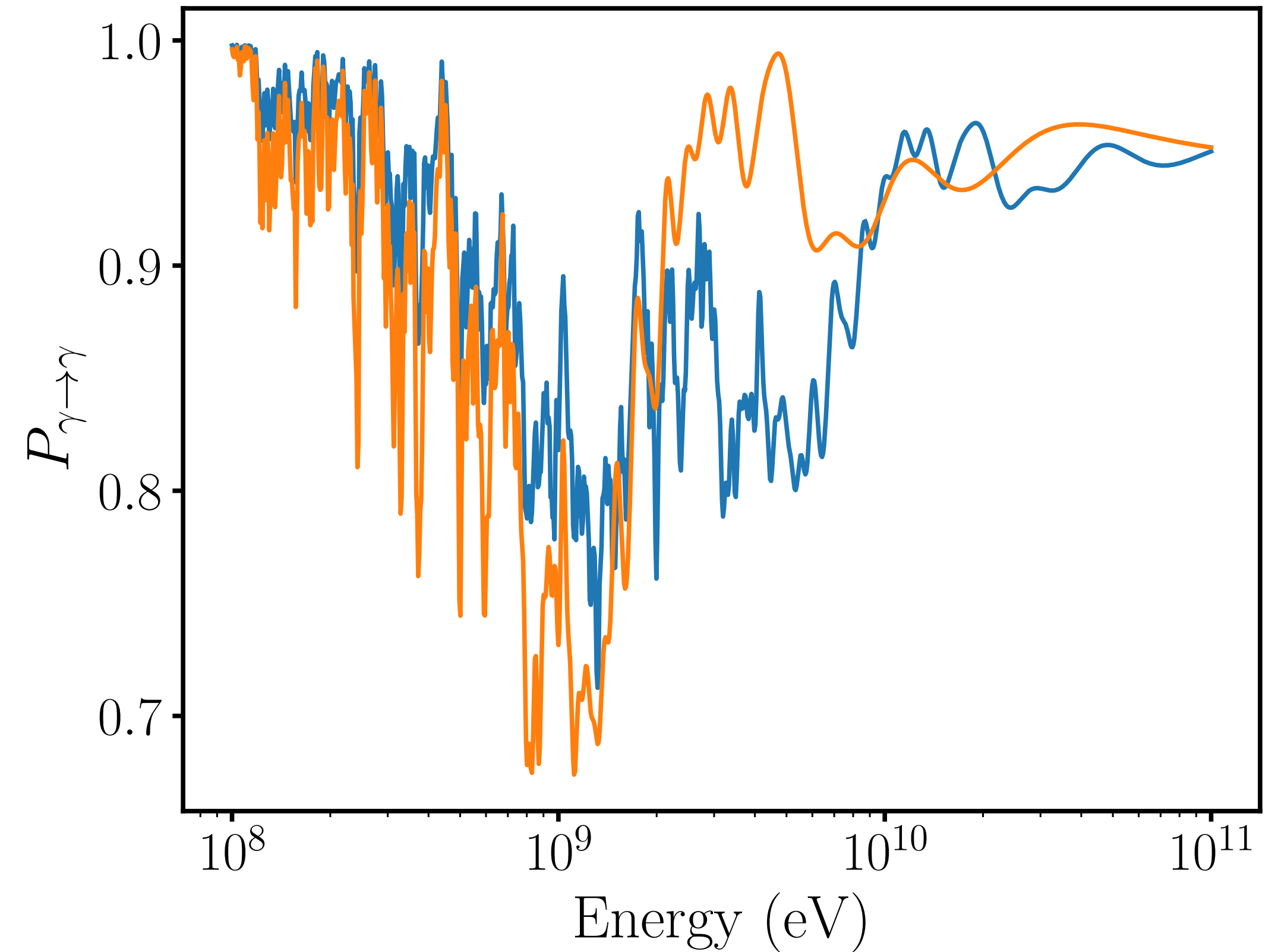
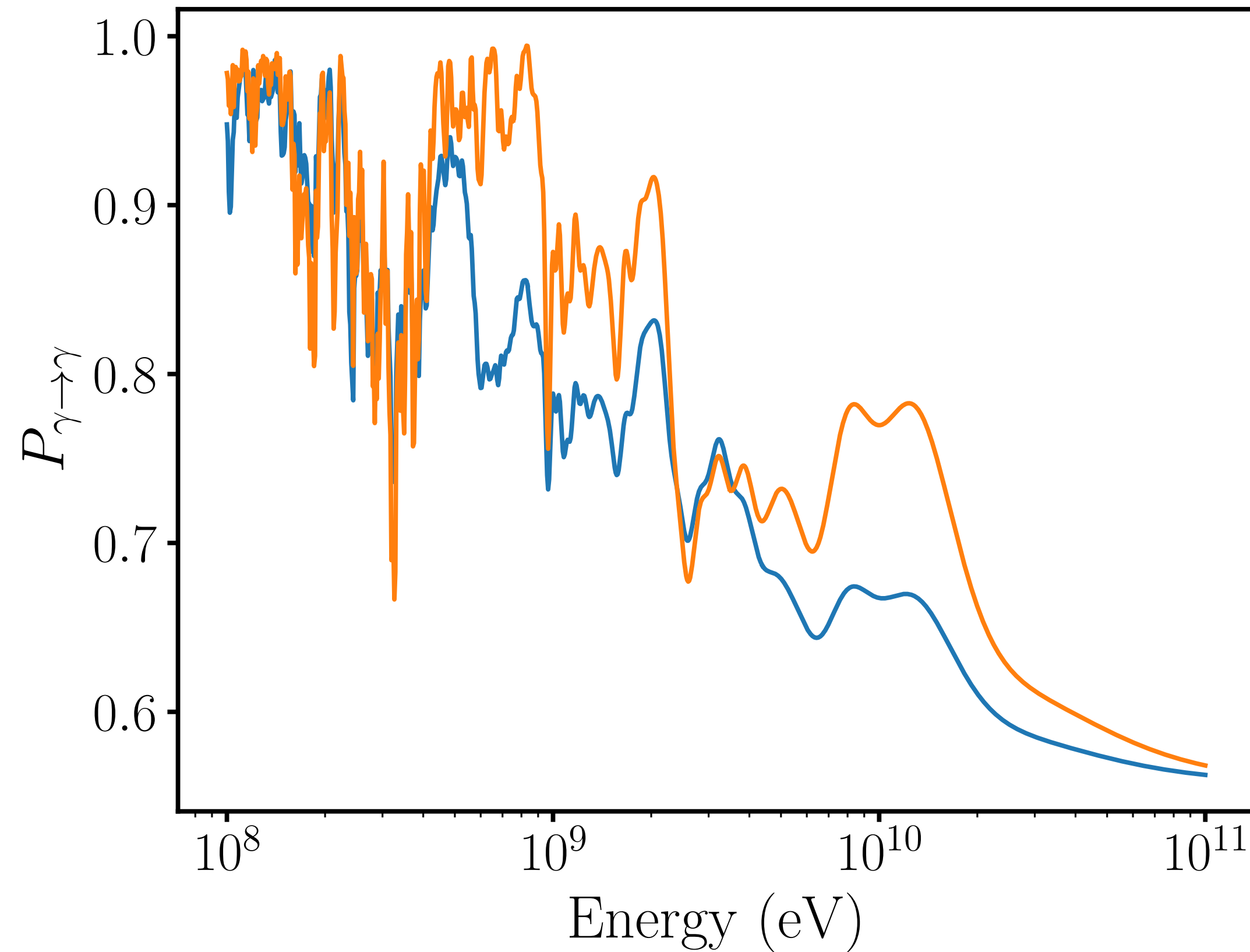
$m_a \ll \text{neV} \rightarrow \text{X} - \text{rays}$

Spectral Modulations



Orange: Single ALP with mass 10^{-3} neV
Blue: Two ALPs with masses 1 neV and 10^{-3} neV

Spectral Modulations



Orange: Single ALP

Blue: Two ALPs with masses 1 neV and 0.5 neV (left) or 1 neV and 2 neV (right)

Normalised to the same total coupling

Plot by Danny Kirkham

Spectral Modulations

X-rays: Approximately sensitive to

$$g_{\text{X-ray}}^2 \sim \sum_{m_i < m_{\text{X-ray}}} g_i^2$$

$$m_{\text{X-ray}} \sim 10^{-11} \text{ eV}$$

γ -rays: Approximately sensitive to

$$g_{\gamma\text{-ray}}^2 \sim \sum_{m_i \subset m_{\gamma\text{-ray}}} g_i^2$$

$$m_{\gamma\text{-ray}} \sim \{10^{-10} \text{ eV}, 10^{-8} \text{ eV}\}$$

Care needed with how this interacts with uncertainty in the magnetic field and with plasma resonances

Summary

- Different searches sensitive to different combinations of “light” ALPs:

$$g_{\text{helio}}^4 \sim \left| \sum_{m_i \ll 10^{-7} \text{ eV}} g_i^{\gamma^2} \right|^2 + \sum_{m_i \gg 10^{-7} \text{ eV}} g_i^{\gamma^4}$$

$$g_{\gamma\text{-ray}}^2 \sim \sum_{10^{-10} \text{ eV} < m_i < 10^{-8} \text{ eV}} g_i^{\gamma^2}$$

$$g_{\text{MWD}}^2 \sim \sum_{m_i < 10^{-6} \text{ eV}} g_i^{\gamma} g_i^e$$

$$g_{\text{X-ray}}^2 \sim \sum_{m_i < 10^{-11} \text{ eV}} g_i^{\gamma^2}$$

- We can count ALPs with resolution in energy or distance space.