Astrophysical clues of axion-like particles

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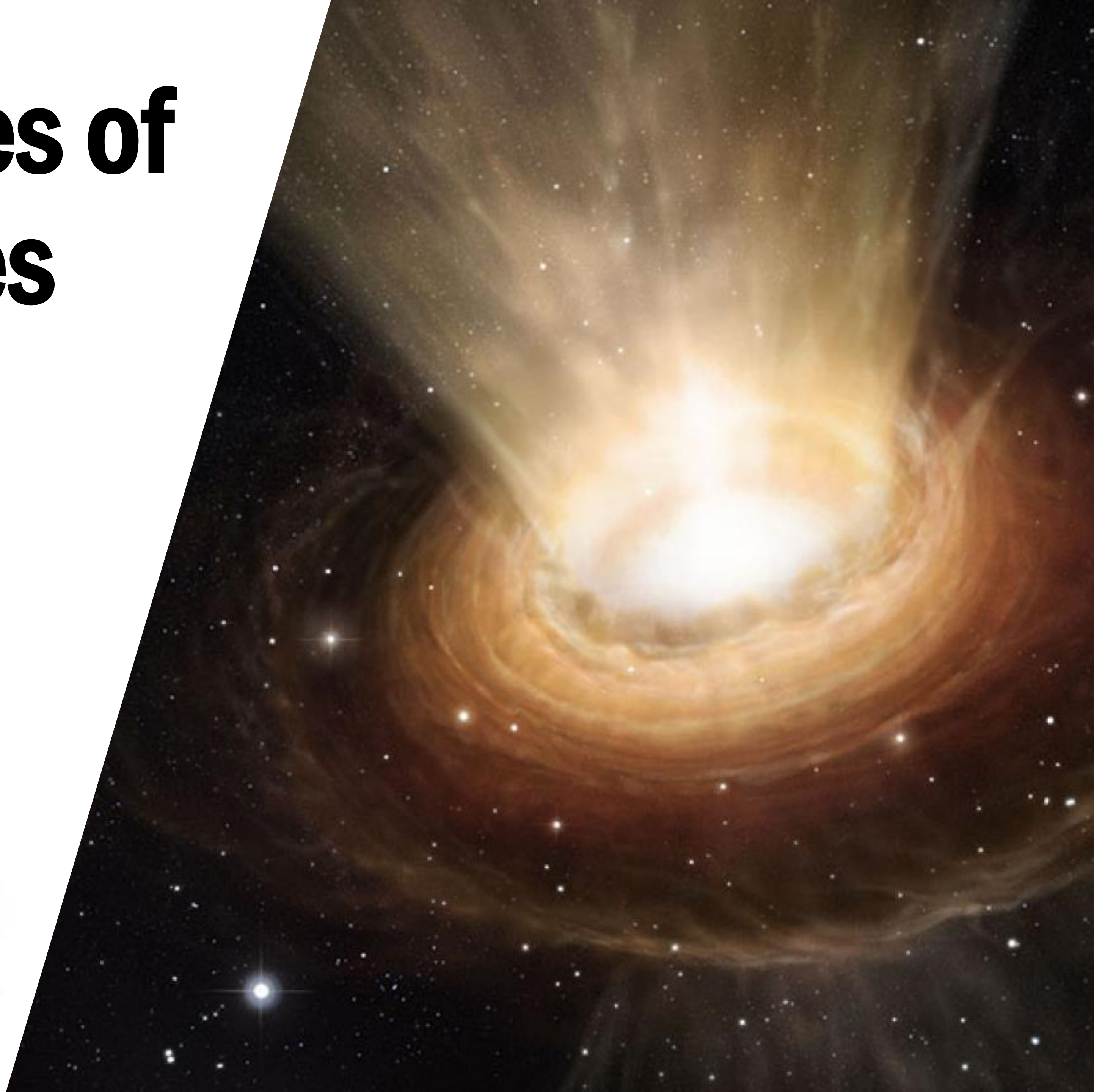


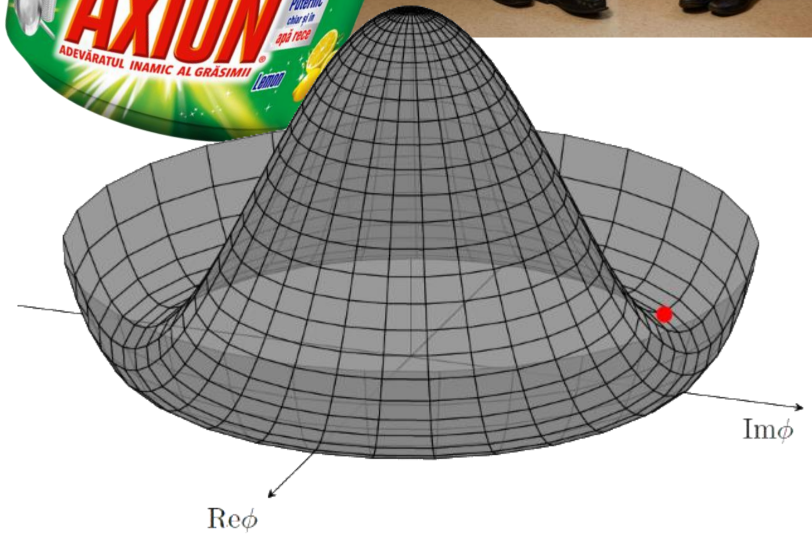
Experimentally, the neutron has no electric dipole moment

Or at least, it must be *very* small.

$$d_N \simeq (0.0 \pm 1.1) \times 10^{-26}\, e \cdot \mathrm{cm}$$

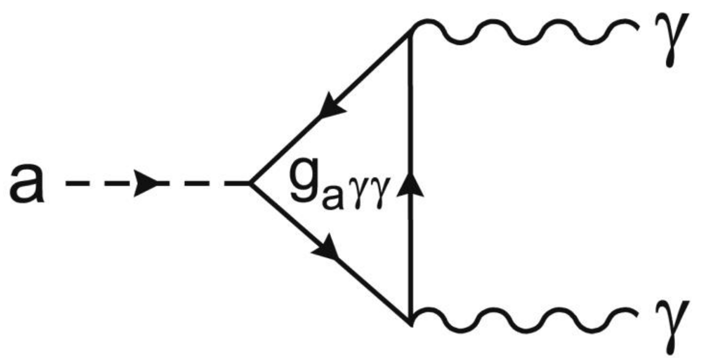
The strong CP problem and the QCD axion

- QCD predicts a neutron EDM depending on an unknown parameter $\bar{\theta}$
- Strong CP problem: to match observations, $\bar{\theta}$ must be «unnaturally» small ($< 10^{-10}$)
- If $\bar{\theta}$ were a field, it could spontaneously «relax» to zero via symmetry breaking (Peccei-Quinn mechanism, 1977)
- The corresponding particle is called an axion
  [Wilczek and Weinberg, 1978]

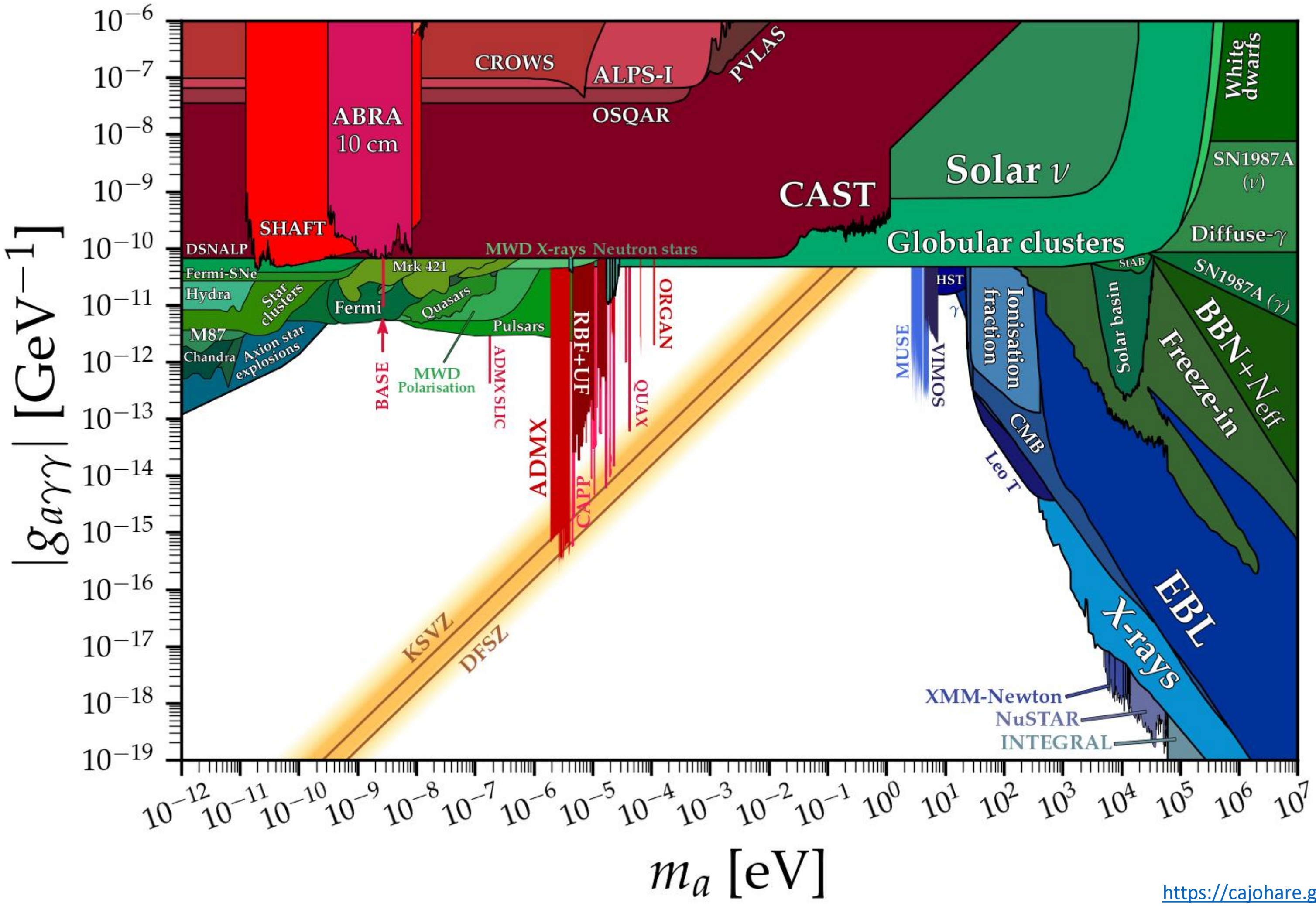


Axion models and couplings

- The QCD axion has an effective coupling to photons $g_{a\gamma\gamma}$ proportional to its mass m_a
- This is *fundamental* for detection!
- String theory also predicts many axion-like particles (ALPs) with no clear m_a-$g_{a\gamma\gamma}$ relationship
- Effectively a «family» of axions



Bounds on ALP-photon coupling

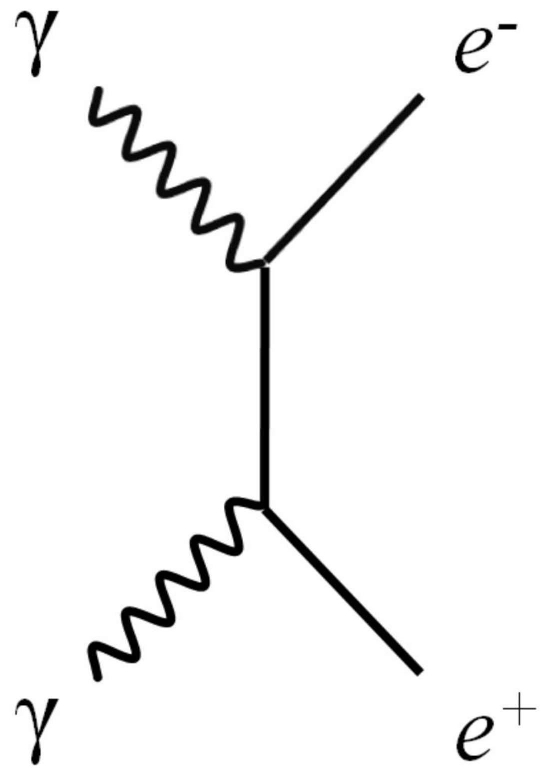


https://cajohare.github.io/AxionLimits/docs/ap.html

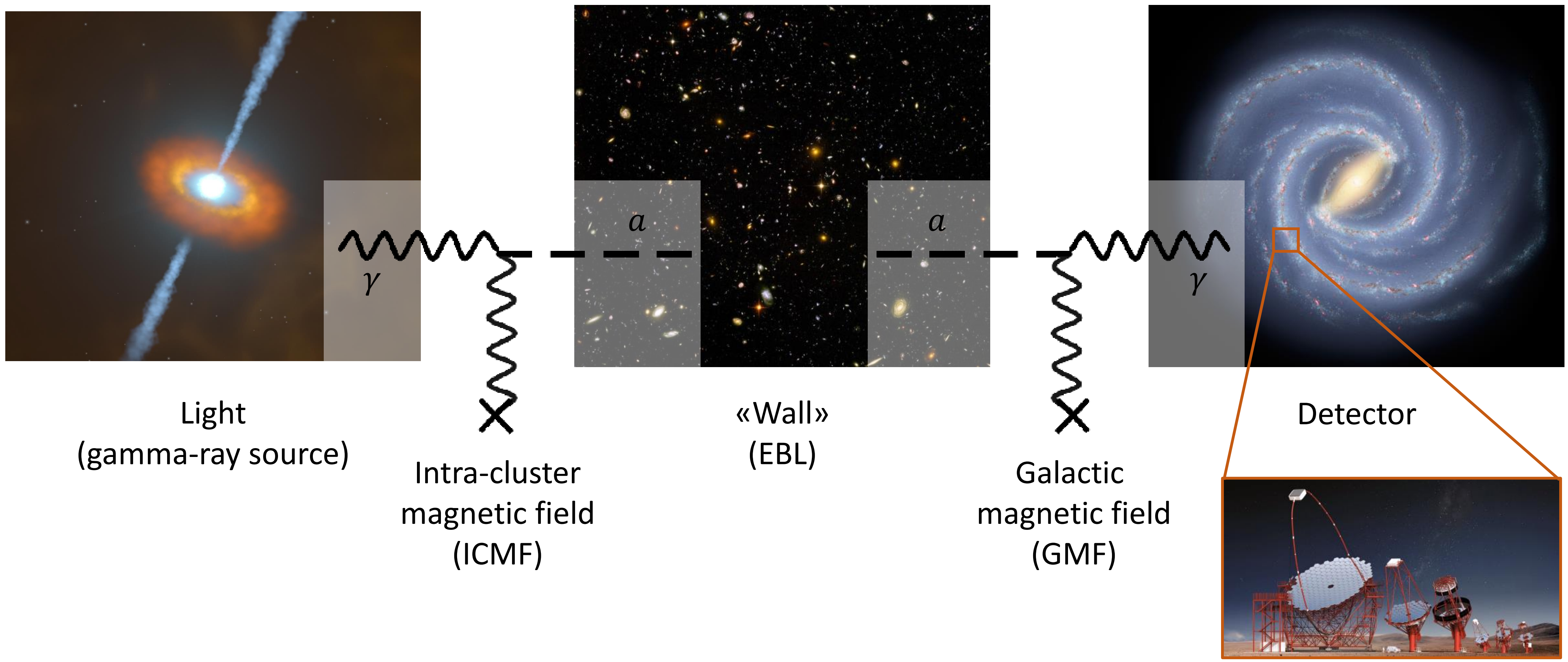
ALPs from gamma-ray sources

Gamma-ray opacity of the Universe

- The Universe is filled with an extragalactic background light (EBL) of astrophysical origin
- Interaction of gamma rays with EBL produces e^+e^- pairs (Breit-Wheeler process)
- The resulting effective *absorption* of gamma rays is parametrized by optical depth $\tau(E, z)$
- Absorption generally increases with z and E, i.e. the Universe is *opaque* to faraway gamma-ray sources

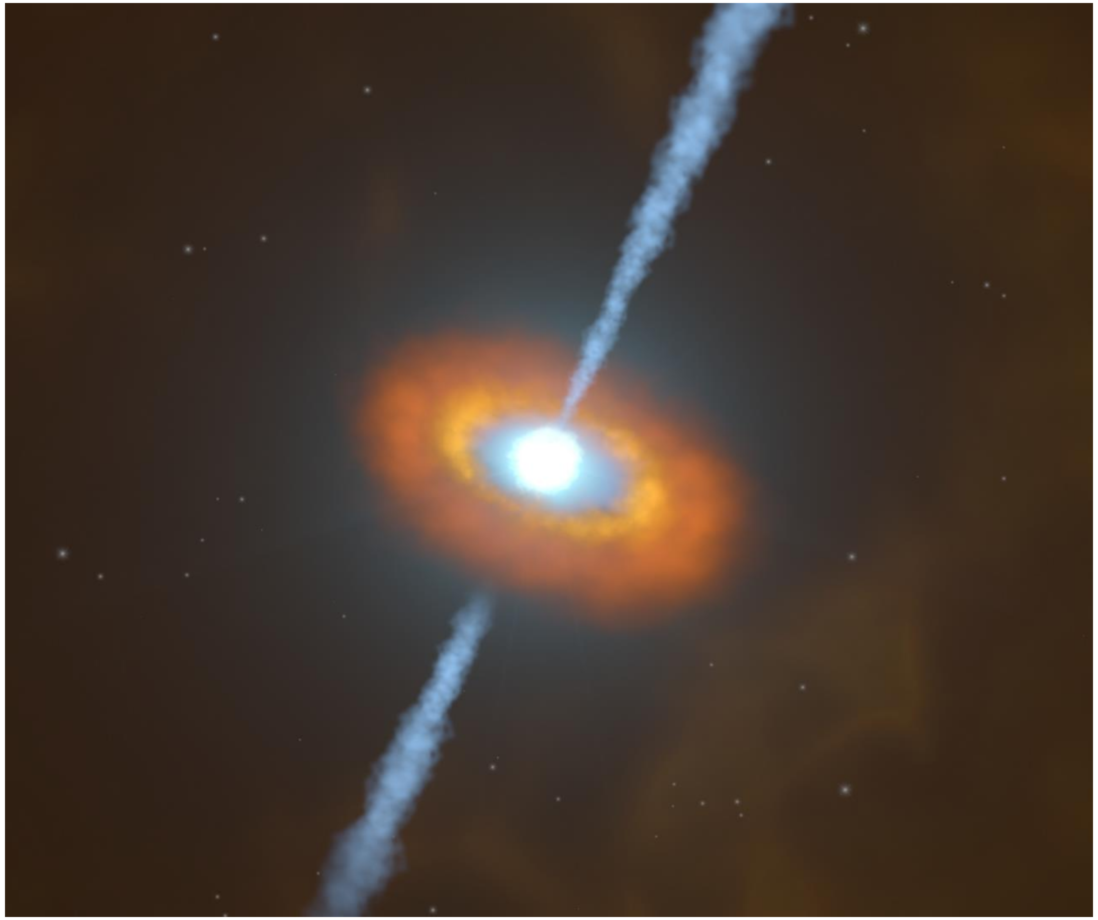


ALPs can reduce gamma-ray opacity



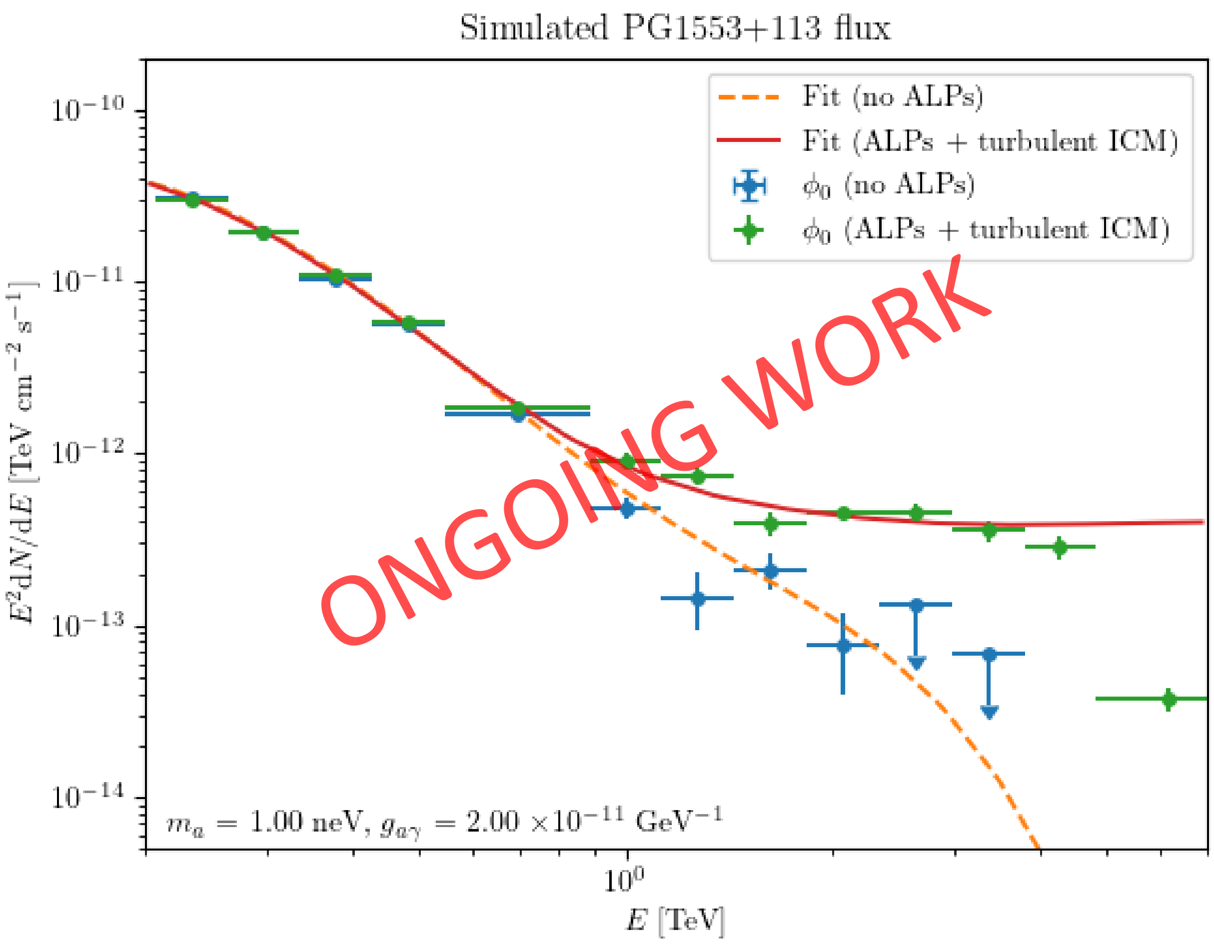
Sources: TeV blazars

- Active galactic nuclei (AGNs) with relativistic jets oriented towards Earth
- Often found in galaxy clusters with intense (turbulent?) magnetic fields $\mathcal{O}(1\ \mu\mathrm{G})$
- Several observations show harder spectra than expected from EBL absorption [Galanti & Roncadelli, arXiv:2205.00940 and refs.]



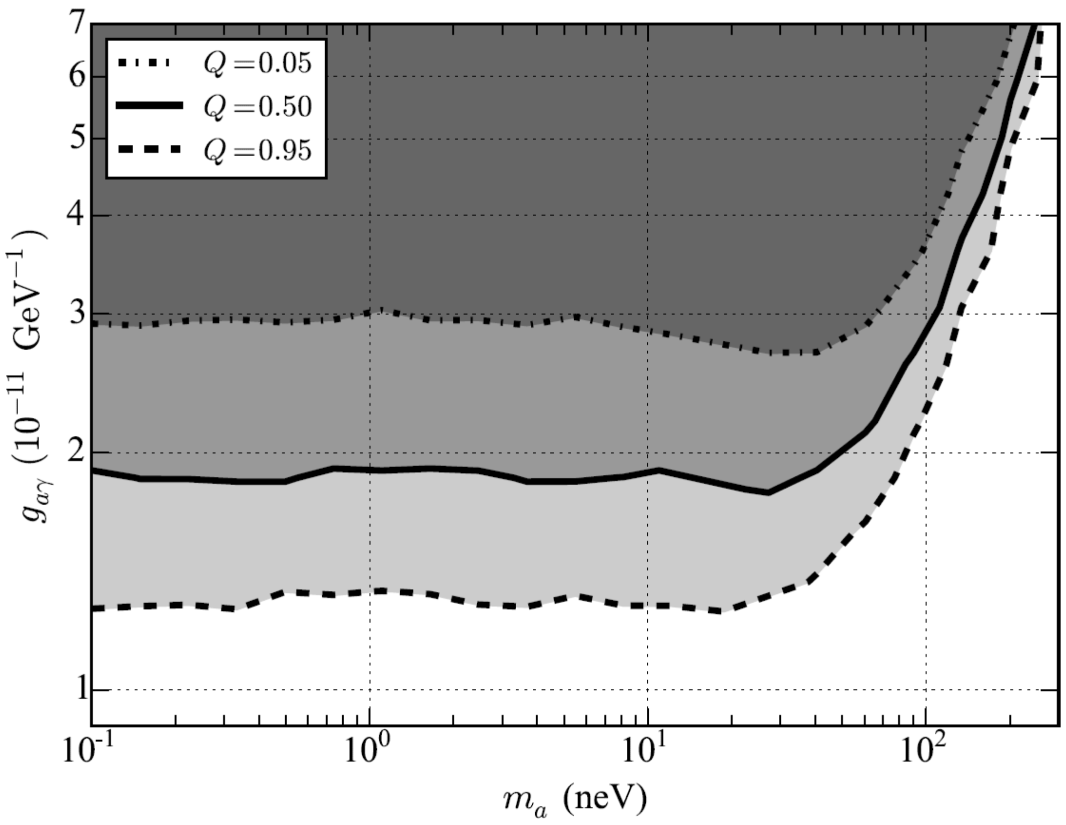
https://www.nasa.gov/content/goddard/black-hole-batteries-keep-blazars-going-and-going

Observed photon flux



Outlooks: CTA sensitivity [Meyer & Conrad, arXiv:1410.1556]

- Turbulent magnetic fields require a complex statistical approach
- A test statistic (TS) distribution is obtained for each point in the $(m_a, g_{a\gamma})$ space
- Improvements: combination of more sources and better magnetic field modeling

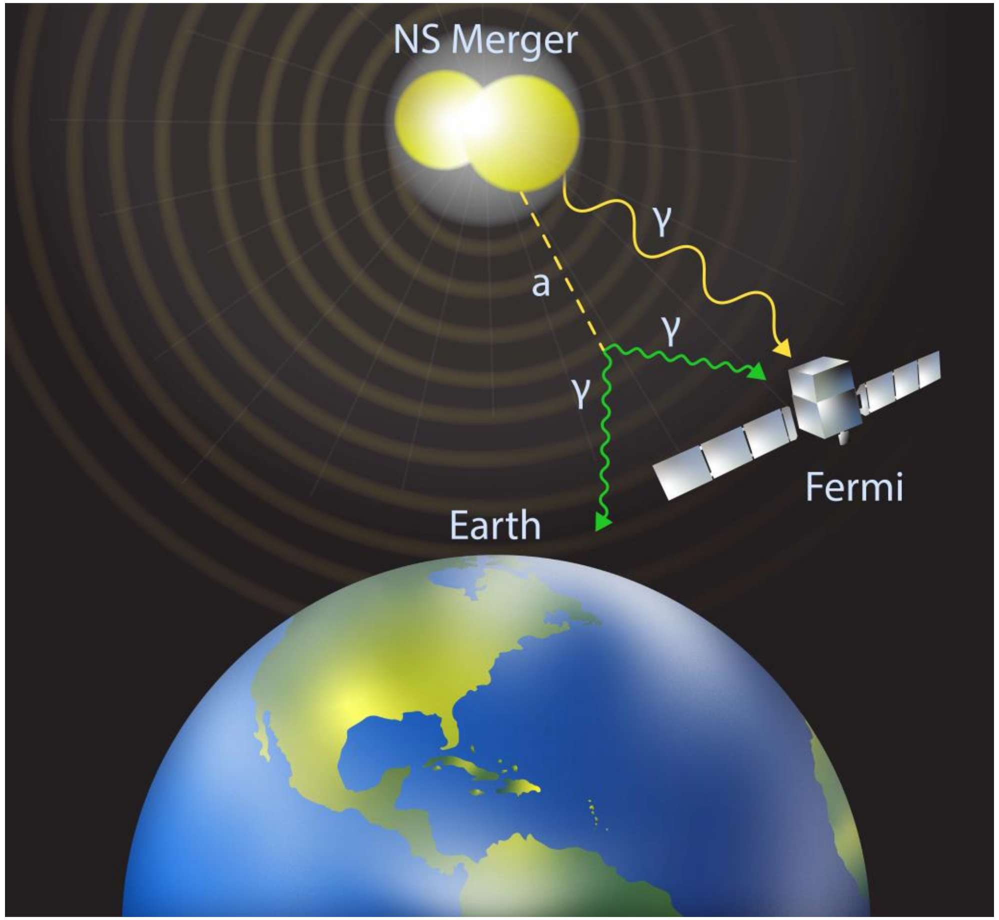


ALPs in multimessenger astronomy

Some recent literature

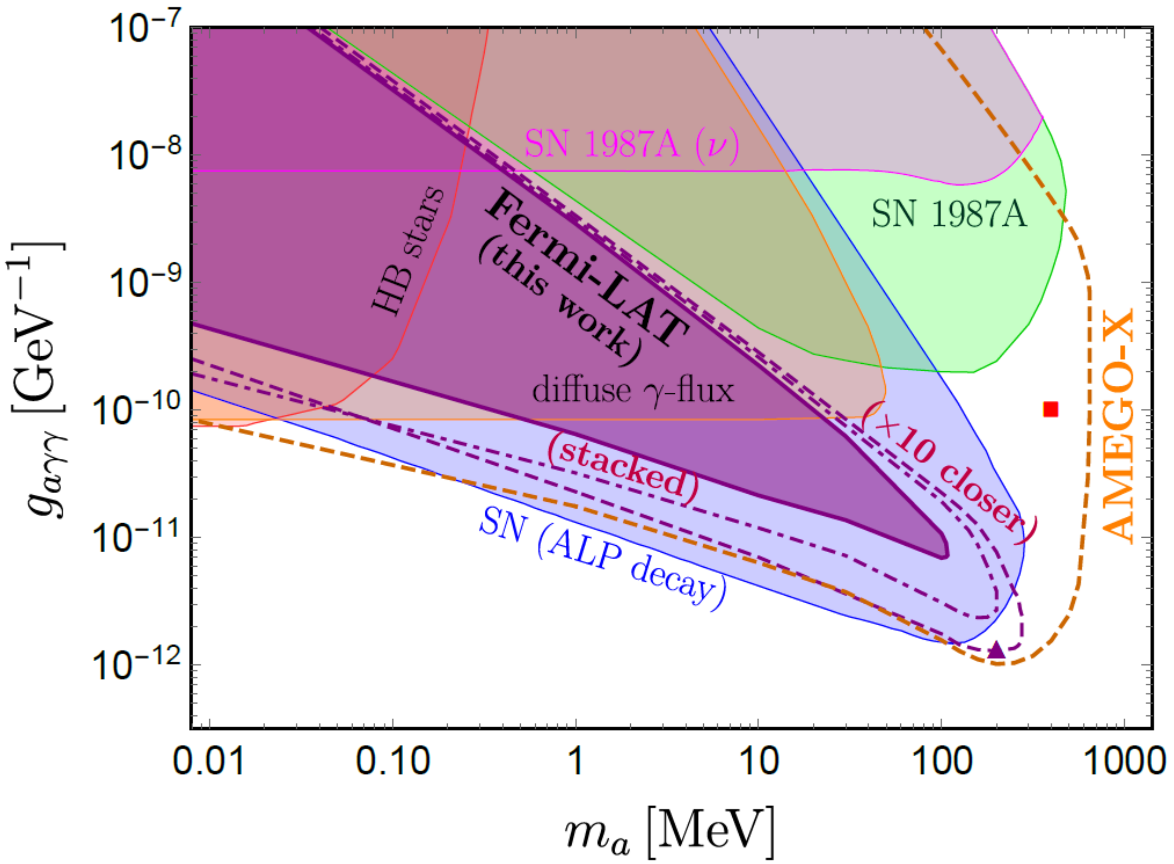
ALP constraints from GW170817 [Bhupal Dev et al, arXiv:2305.01002]

- Massive ALPs could be produced by nuclear processes in neutron star mergers
- Photon signal from $a \to \gamma\gamma$ decay
- Contrary to standard processes (1.7 s delay measured by Fermi-GBM), this should be a *prompt* signal



ALP constraints from GW170817 [Bhupal Dev et al, arXiv:2305.01002]

- Gamma-ray observations of NS mergers can help constrain the ALP parameter space
- In principle, it would be possible to resolve the ALP decay signal within ~ 1 s from a GW event



Other relevant works

- Edwards et al, arXiv:1905.04686
  - ALP-induced gravitational phase shift and radio enhancement from binaries
- Mori et al, arXiv:2304.11360
  - Imprints of ALPs on gamma rays, neutrinos and GWs from supernovae
- De Miguel & Otani, arXiv:2201.04059
  - ALP counterparts to flares from magnetars
- Brito et al, arXiv:1706.06311
  - Gravitational waves from boson clouds around spinning black holes
- Most of these effects exploit ALP-photon coupling!

Conclusions

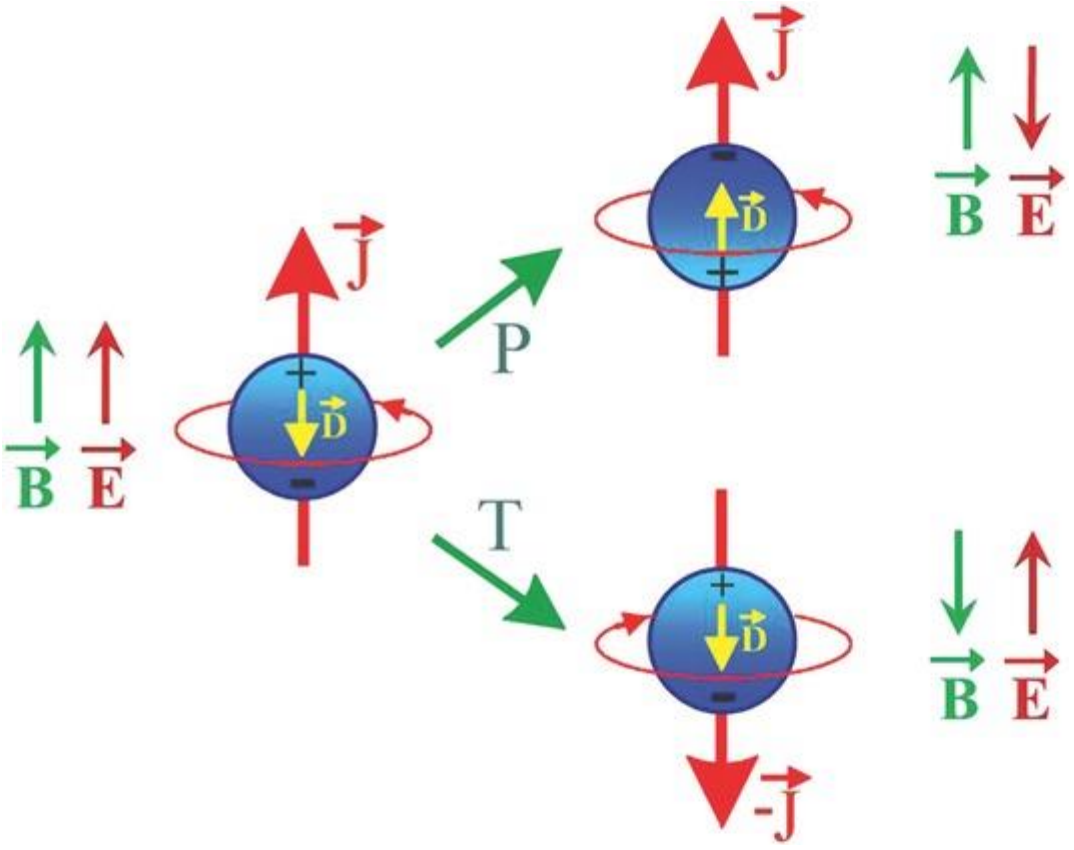
- Axions and axion-like particles are theoretically well-motivated and worth searching for
- They could contribute to several astrophysical effects (e.g. gamma ray transparency)
- There are interesting prospects for multi-messenger constraints
- If detected, ALPs themselves could become another kind of «messenger»
- Promising outlook with the next generation of gamma ray telescopes

Thank you for your attention!

Backup

Neutron EDM violates CP symmetry

$\mathcal{L}_I \simeq -\mu \vec{J} \cdot \vec{B} - d \vec{J} \cdot \vec{E}$



$\mathcal{L}_I \simeq -\mu \vec{J} \cdot \vec{B} + d \vec{J} \cdot \vec{E}$

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Jungmann 2013, Ann. Phys, 525: 550-564

The strong CP problem

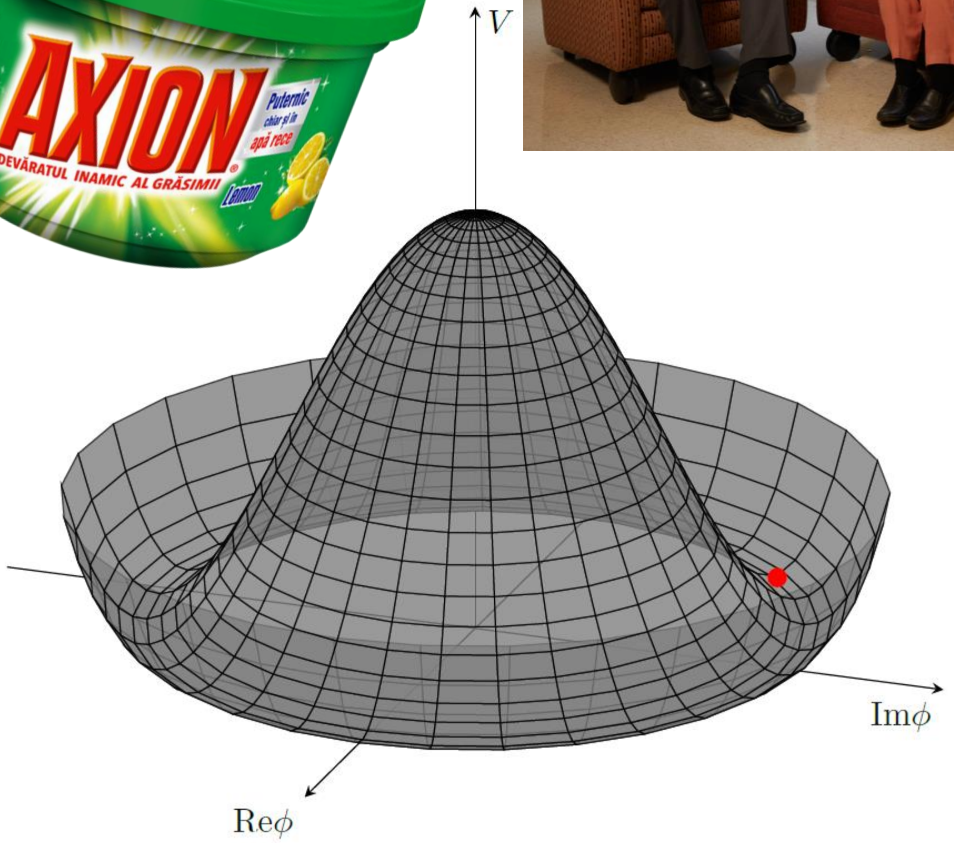
- Experimentally $d_N \simeq (0.0 \pm 1.1) \times 10^{-26}\ e \cdot \mathrm{cm}$, implying CP conservation for strong interactions
- However, the QCD Lagrangian contains a CP-violating term

$$\mathcal{L}_{\mathrm{QCD}} \subset \bar{\theta} \frac{\alpha_S}{8\pi} G_{\alpha\beta} \widetilde{G^{\alpha\beta}}$$

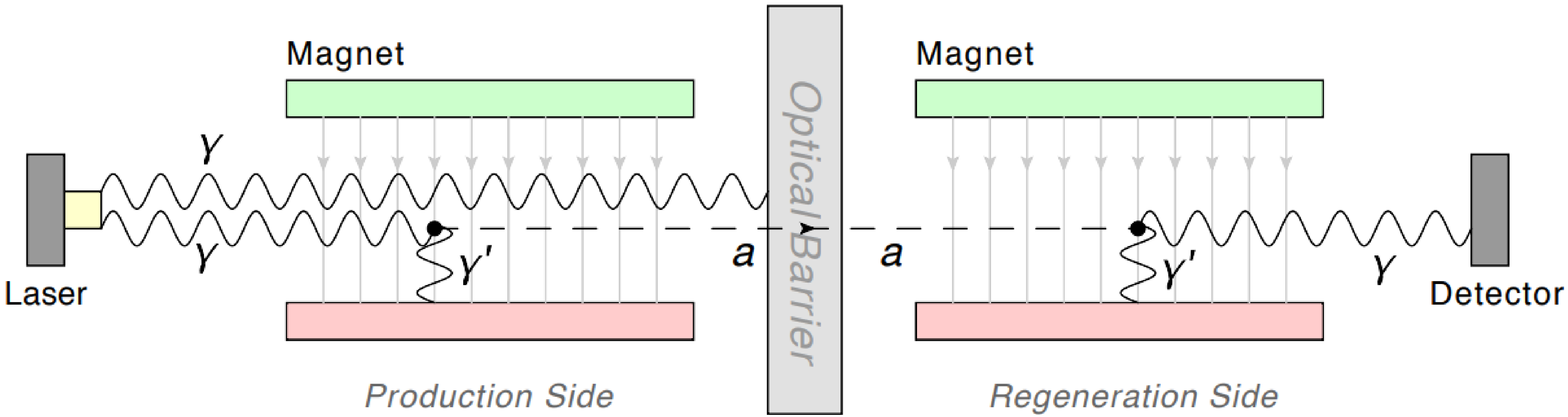
- An unnaturally small value $\bar{\theta} < 10^{-10}$ would be needed to match observations

The Peccei-Quinn mechanism (1977)

- What if $\bar{\theta}$ was the phase of a field rolling down a potential?
- Then it could relax to zero via a symmetry breaking mechanism (Higgs-like)
- The corresponding particle is called an axion



Light shining through walls



Battesti et al, arXiv:1803.07547

Photon survival probability and observed flux

- The observed photon flux is given by $\phi_{\text{obs}} = P_{\gamma\gamma}\phi_{\text{int}}$
- In the standard EBL case, $P_{\gamma\gamma} = e^{-\tau(E,z)}$
- In the ALP case $P_{\gamma\gamma}$ is computed numerically from magnetic field models, e.g. with gammaALPs [https://gammaalps.readthedocs.io/]