Nuclear Reactors and Haloscopes

Fernando Arias Aragón

COSMIC WISPERS CA21106

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

DESY.

Funded by the European Union

Based on 2310.03631
FAA, Vedran Brdar, Jérémie Quevillon

February, 1st, 2024

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Fundamentals and Motivation

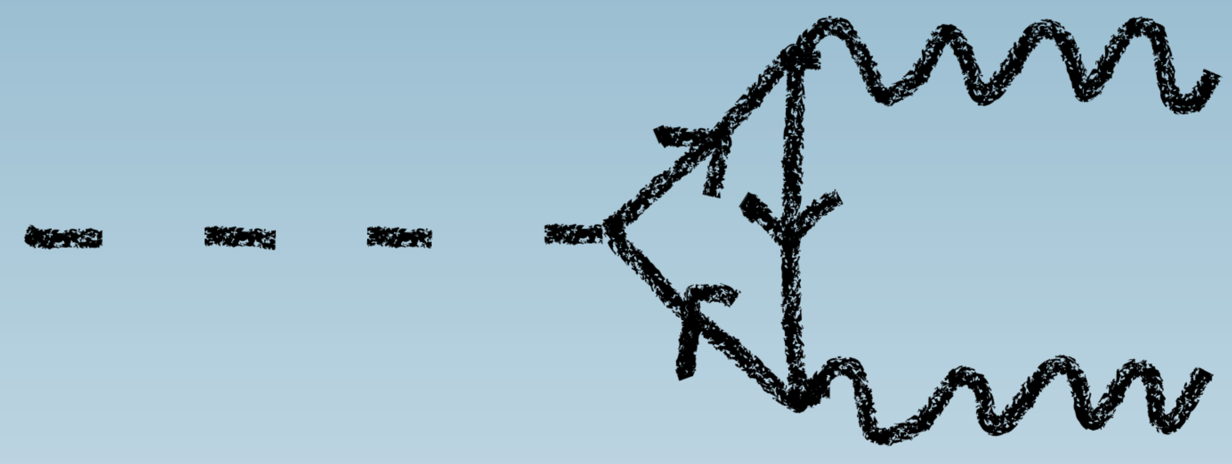
Axions and ALPs - A Versatile BSM Candidate

The Strong CP Problem

- SM Lagrangian allows a purely gauge term

$$\theta_{QCD}\frac{\alpha_s}{8\pi}G^{a\mu\nu}\tilde{G}^a_{\mu\nu}$$

- Related to quark masses via the chiral anomaly



$$\bar{\theta} = \theta_{QCD} + \mathrm{Arg}(\mathrm{Det}(M_u M_d))$$

- The observable parameter, $\bar{\theta}$ is bound by neutron EDM, d_n

$$d_n \sim \bar{\theta}\cdot 10^{-16}\, e\cdot cm, \quad \bar{\theta} \lesssim O(10^{-10})$$

Crewther, Di Vecchia, Veneziano & Witten, 1980

Baker et al., 0602020 Afach et al., 1509.04411

The Strong CP Problem - The Axion Mechanism

- $\bar{\theta}$ becomes dynamical thanks to $U(1)_{PQ}$

Peccei and Quinn, PRL 38 (1977) 1440-1443 and PRD 16 (1977) 1791 1797

$$\mathcal{L}_{aGG} = \frac{a}{f_a} \frac{\alpha_s}{8\pi} G^{a\mu\nu} \tilde{G}^a_{\mu\nu} \longrightarrow \theta_{eff} = \bar{\theta} + \frac{a}{f_a}$$

Weinberg, PRL 40 (1978) 223-226
Wilczek , PRL 40 (1978) 279-282

- Non-perturbative QCD potential ensures CP conservation

$$V_{eff} \sim 1 - \sqrt{\tfrac{1}{2} + \cos\left(\bar{\theta} + \frac{a}{f_a}\right)} \longrightarrow \langle a \rangle = -f_a \bar{\theta}$$

- The original model required two Higgs doublets

$$f_a \sim v \simeq 246 \text{ GeV } !!$$

The Strong CP Problem - Invisible Axion Models

- The QCD axion is a good DM candidate

J. Preskill, M. B. Wise and F. Wilczek, PLB 120 (1983) 127
L. F. Abbot and P. Sikivie, PLB 120 (1983) 133
M. Dine and W. Fischler, PLB 120 (1983) 173

- They arise naturally from string theories

E. Witten, PLB 149 (1984) 351

- Present in solutions to other SM problems

Y. Ema, K. Hamaguchi, T. Moroi, K. Nakayama, 1612.05492
L. Calibbi, F. Goertz, D. Redigolo, R. Ziegler, J. Zupan, 1612.08040
FAA, L. Merlo, 1709.07039

- Relevant cosmological observables

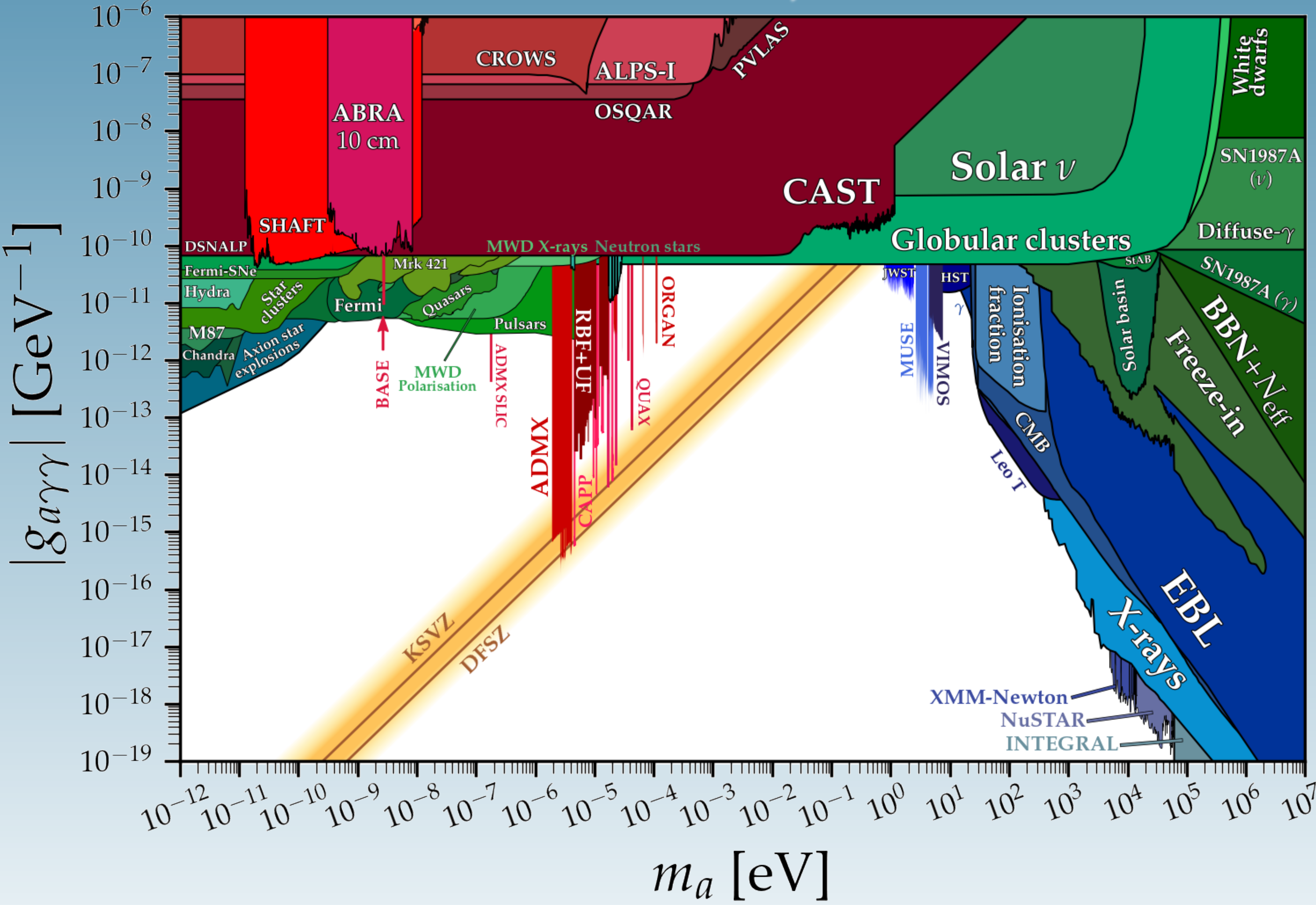
FAA, F. D'Eramo, R. Z. Ferreira, L. Merlo, A. Notari, 2012.04736
F. Bianchini, G. Grilli di Cortona, M. Valli, 2310.08169

The Strong CP Problem - Invisible Axion Models

- Many search strategies
  - Helioscopes
  - Haloscopes
  - Dark matter recoil
  - Stellar cooling
  - Light shining through wall
  - ...

$$m_a \simeq 5{,}7 \left(\frac{10^9\,\mathrm{GeV}}{f_a}\right) \mathrm{meV}$$

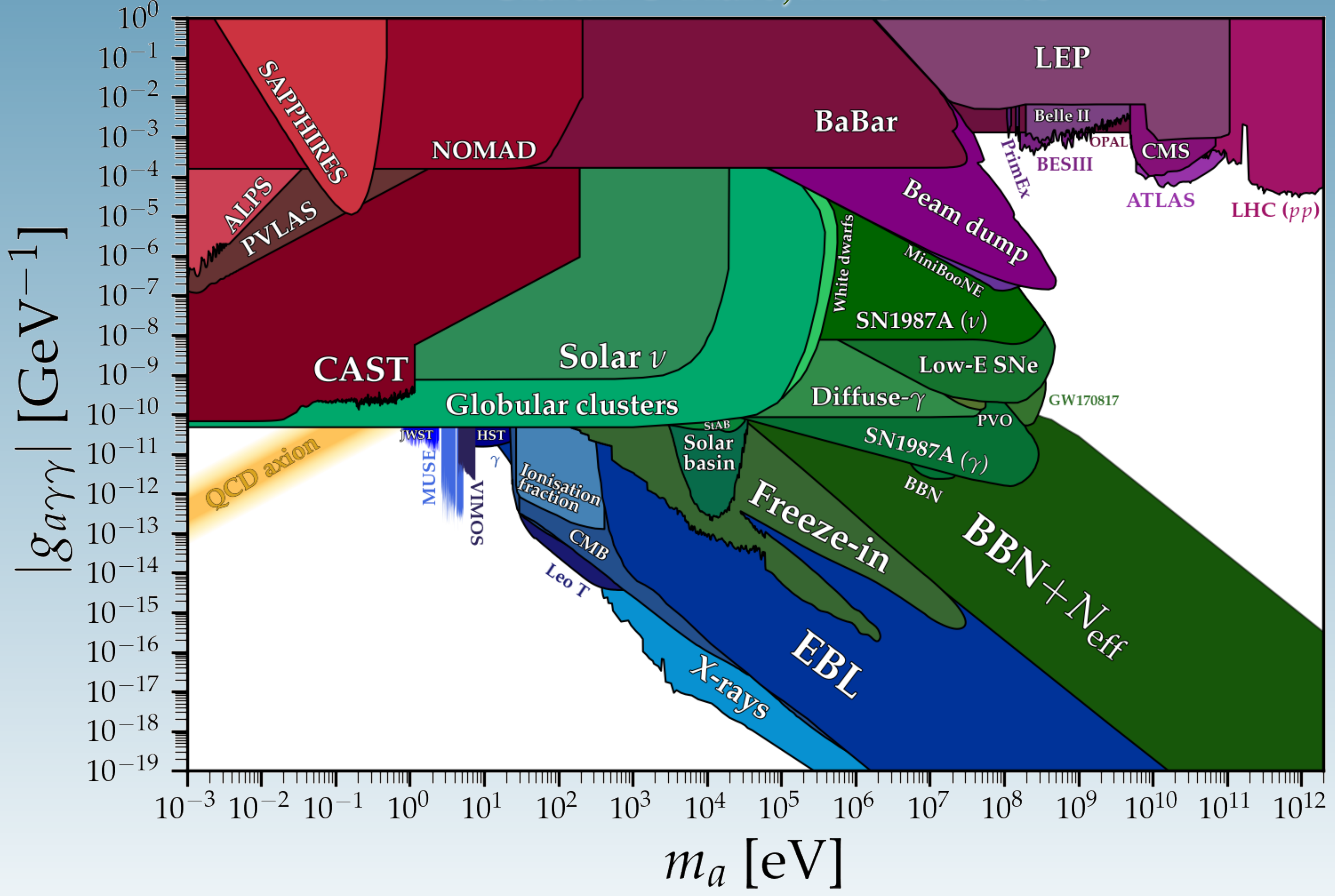
Ciaran O'Hare, AxionLimits



Beyond the QCD Axion Framework: ALPs

- QCD axions feature $m_a(f_a)$
- Axion-like particle: $m_a \neq m_a(f_a)$
- CP odd, $m_a << f_a$
- Also motivated from strings
- Possible signals at colliders

Ciaran O'Hare, AxionLimits

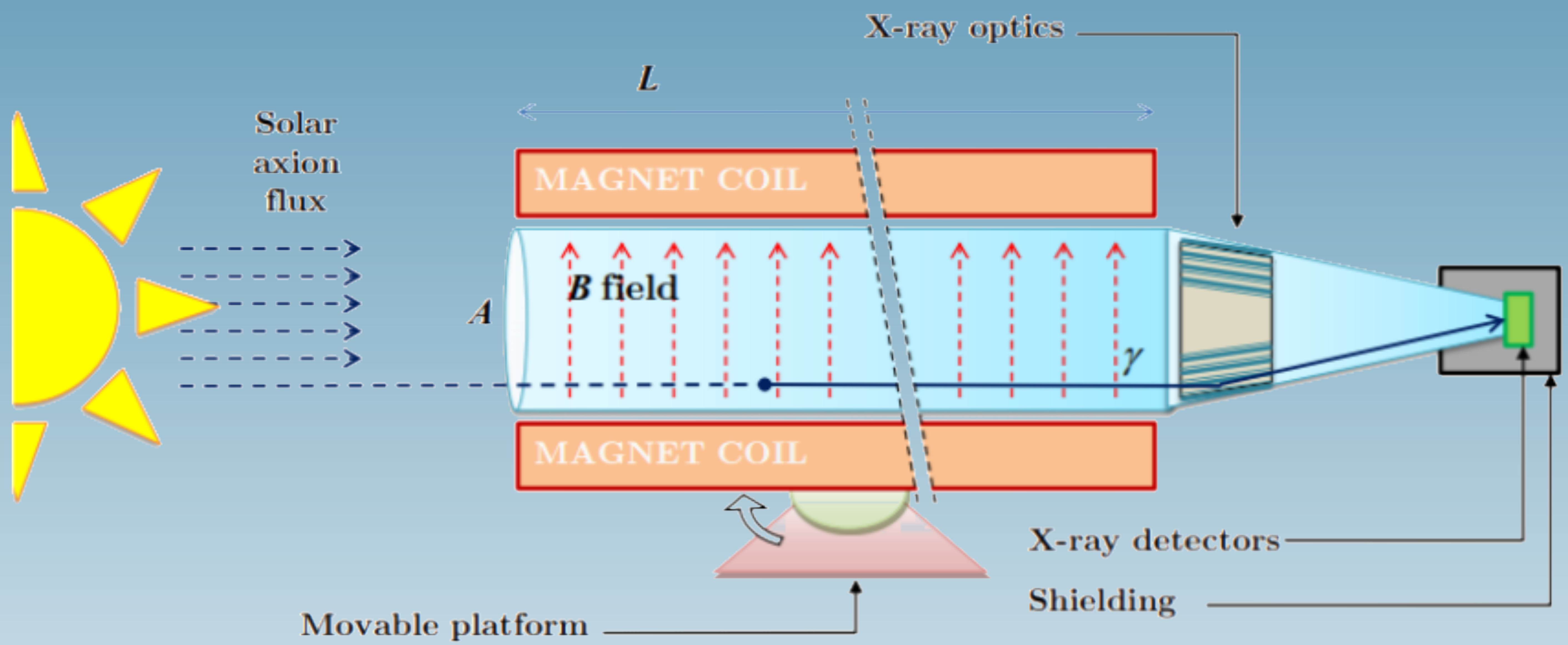


A New Approach for ALP searches: Reactoscopes

FAA, V. Brdar, J. Quevillon, 2310.03631

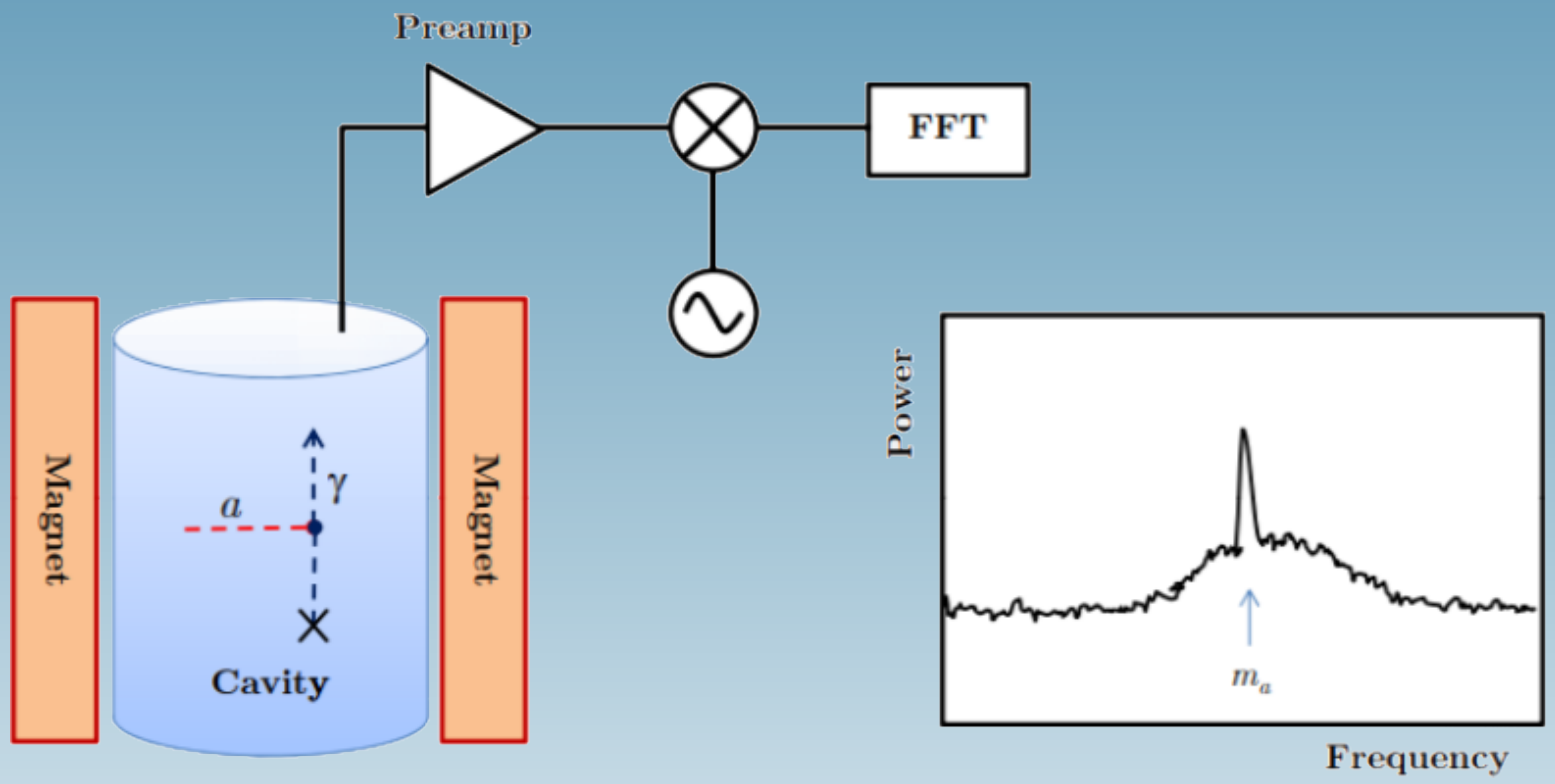
ALP Search Strategies - A Review

- Helioscopes (CAST, IAXO)
  - Production within the Sun
  - Complicated astrophysics
  - Large detection chamber
  - Relevant coupling: $g_{a\gamma\gamma}$
  - Can scan many masses



ALP Search Strategies - A Review

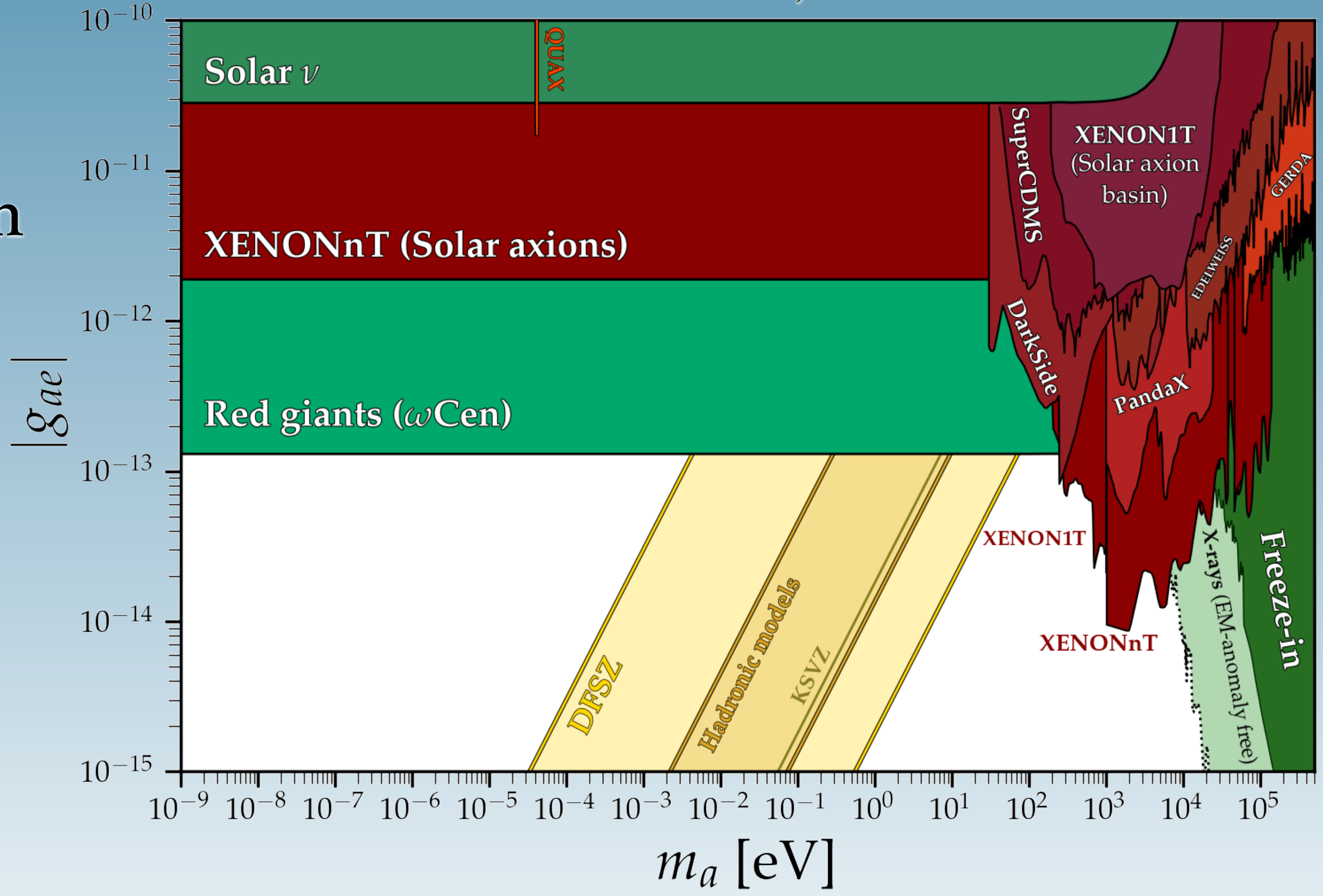
- Haloscopes (ADMX, MADMAX, …)
  - Assumes Axion is DM
  - Several possibilities for production
  - Detection in resonant chamber
  - Narrow m_a windows
  - High precision in $g_{a\gamma\gamma}$



ALP Search Strategies - A Review

- Recoil experiments (XENONnT, PandaX, ...)
  - DM or solar axions
  - Several possibilities for production
  - Astro/cosmo sensitive
  - Main couplings: g_{aee}, g_{ann}

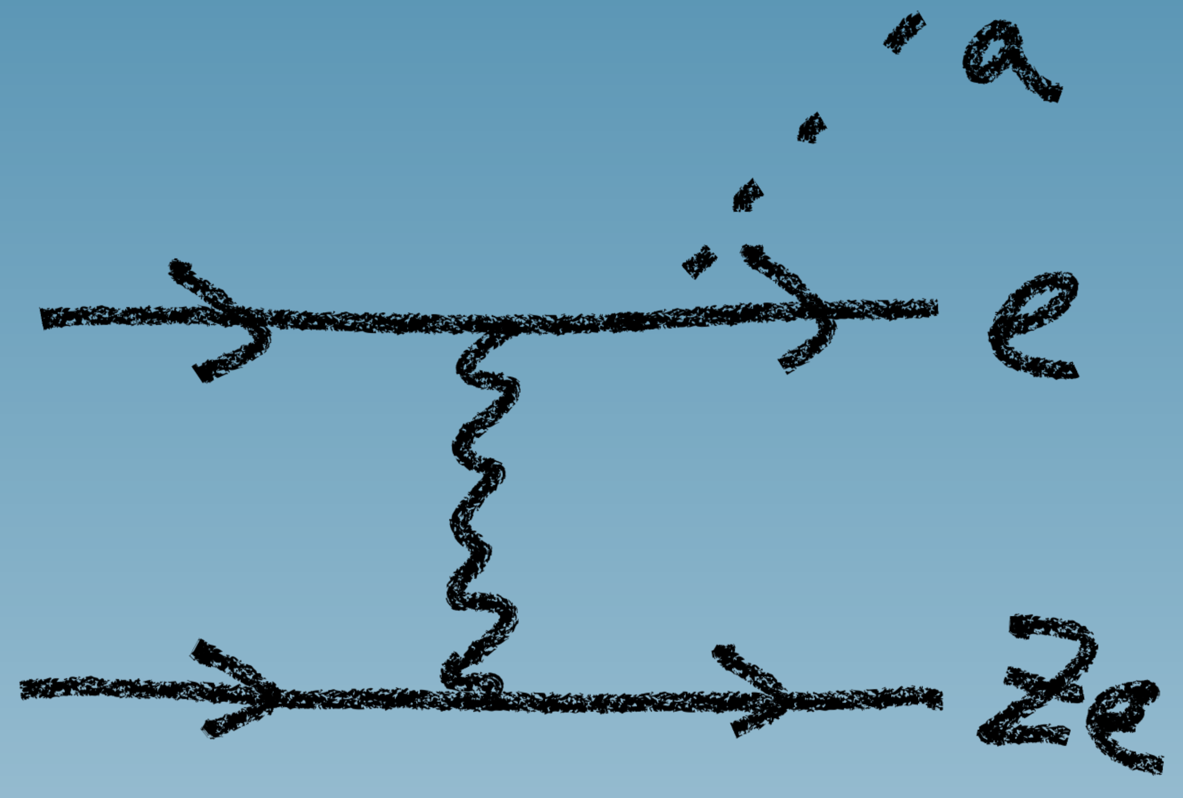
Ciaran O'Hare, AxionLimits

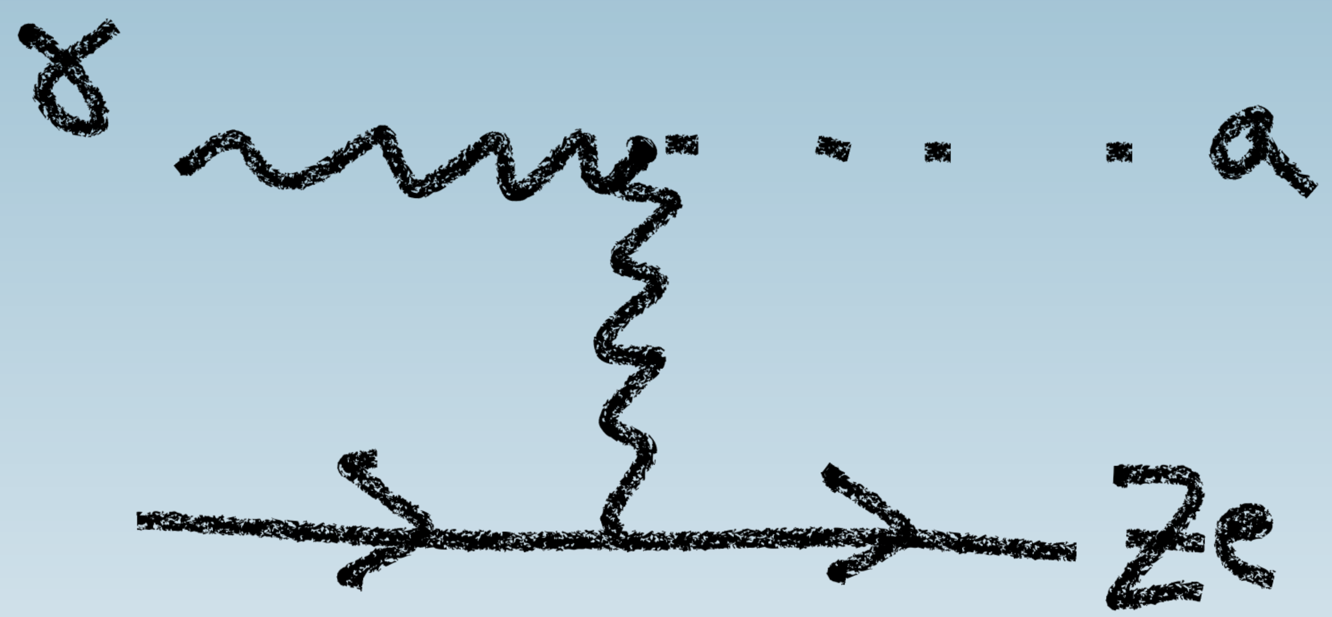


ALP Search Strategies - A Review

M. Gianotti, I. G. Irastorza, J. Redondo, A. Ringwald, K. Saikawa, 1708.02111

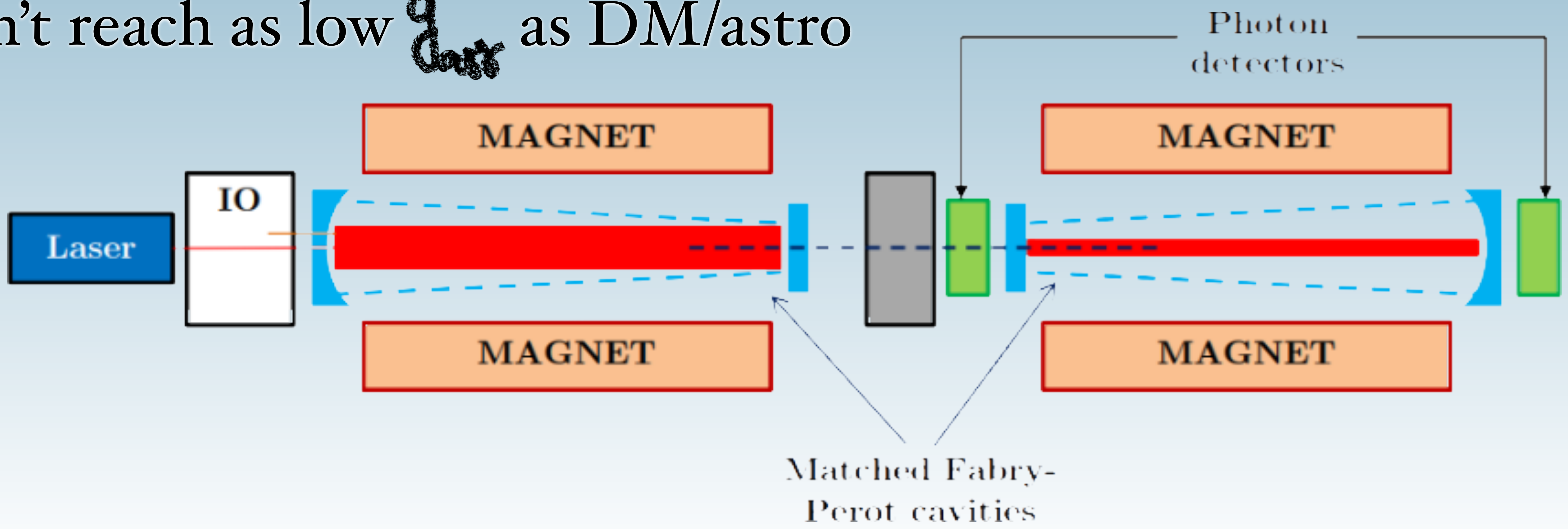
- Stellar cooling
  - Many observables involved
  - Bremsstrahlung and Primakoff production
  - Depend on astrophysical assumptions
  - Main couplings: g_{aee}, $g_{a\gamma\gamma}$





ALP Search Strategies - A Review

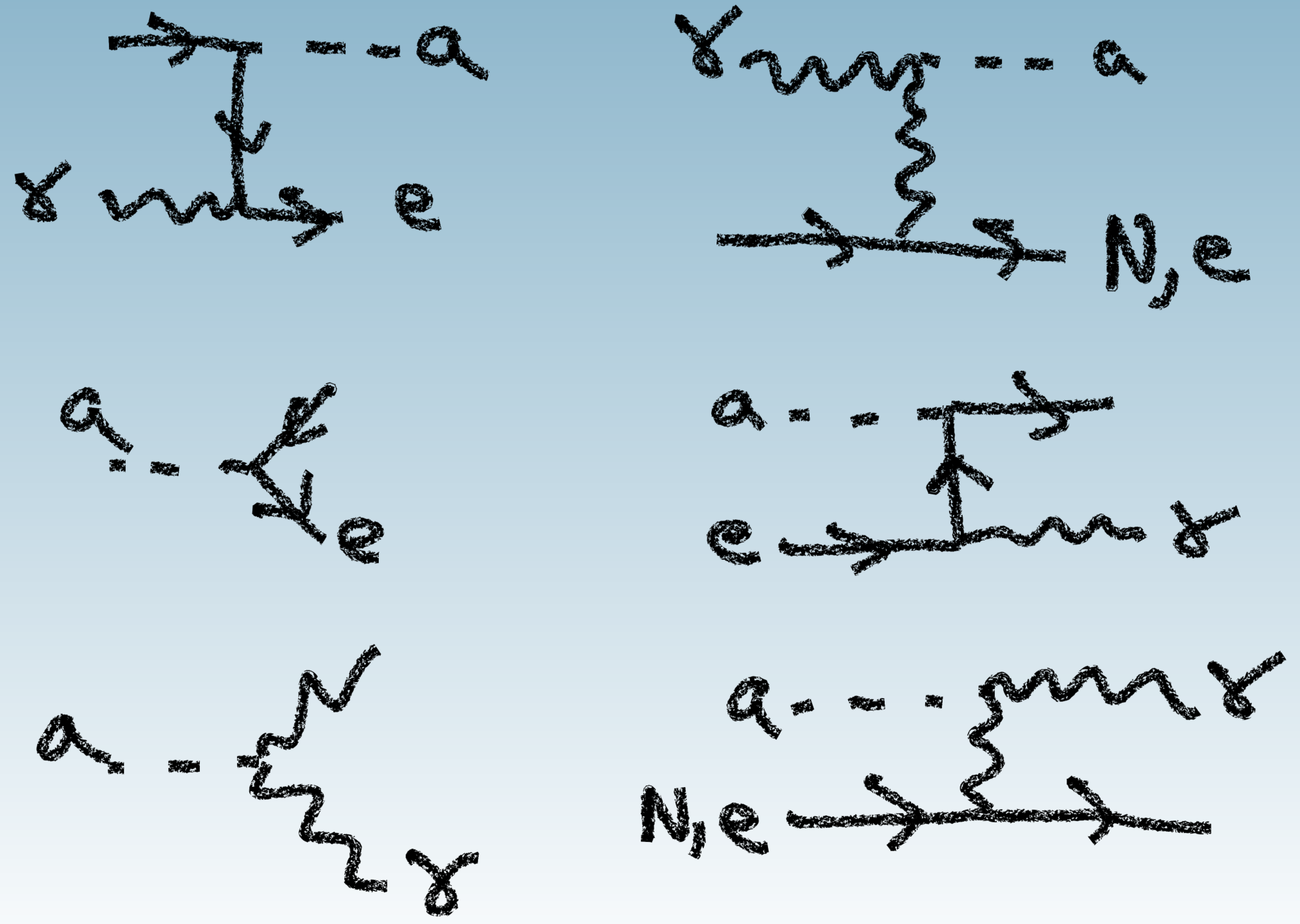
- Light-shining-through-wall (OSQAR, ALPS II)
  - Production and detection in lab
  - Involve high magnetic fields
  - Can explore many ALP masses
  - Doesn't reach as low $g_{a\gamma\gamma}$ as DM/astro



ALP Search Strategies - New Ideas

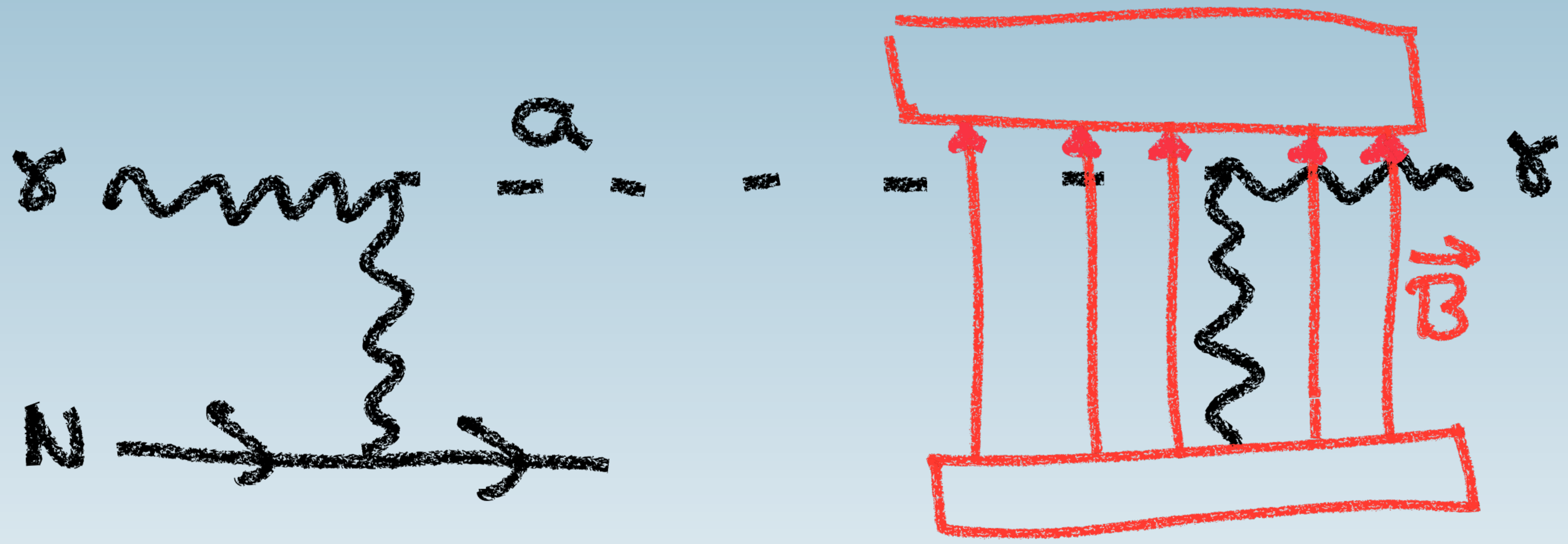
- ALPs can be produced at nuclear reactors
- Detectable at neutrino experiments

J. B. Dent, B. Dutta, D. Kim, S. Liao,
R. Mahapatra, K. Sinha, A. Thompson, 1912.05733
D. Aristizabal Sierra, V. De Romeri, L. J. Flores, D. K. Papoulias 2010. 15712



- ALPs can be produced at beam dumps
- Detectable in magnetic fields

W. M. Bonivento, D. Kim, K. Sinha, 1909. 03071



ALP Search Strategies - Reactoscopes

- ALPs produced at reactors

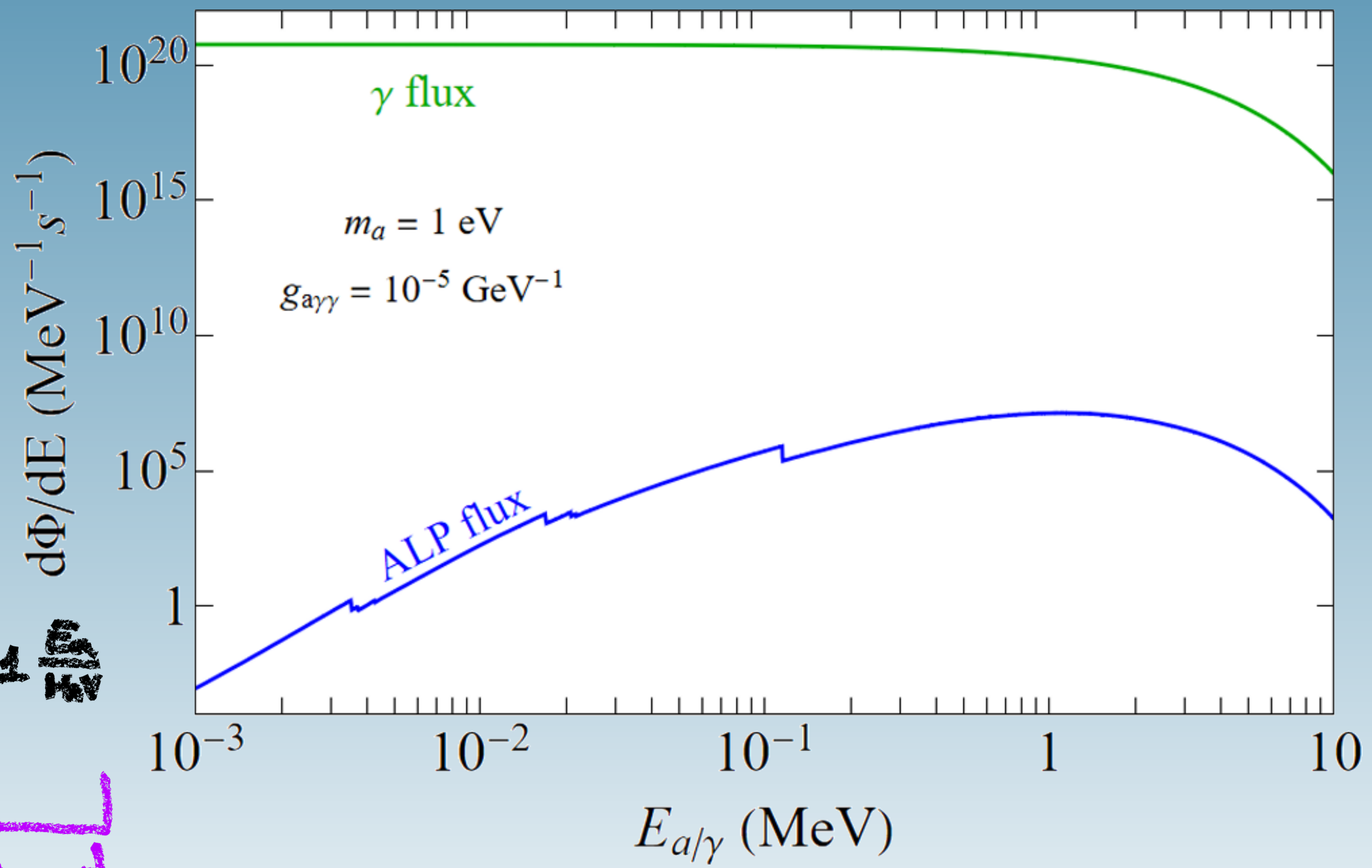
$$\mathcal{L}_a = -\frac{1}{4} g_{a\gamma\gamma}\, a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Survival Prob

$$\frac{d\Phi_a}{dE_a} = \frac{1}{4\pi D^2} e^{-\frac{D}{\tau}} \frac{\sigma_{Prim}(E_a)}{\sigma_{Tot}(E_a)} \frac{5{,}8\cdot 10^{20}}{\mathrm{MeV\ s}} \left(\frac{P}{\mathrm{GW}}\right) e^{-1.1\frac{E_a}{\mathrm{MeV}}}$$

Spherical Flux

Photon Flux in Reactor



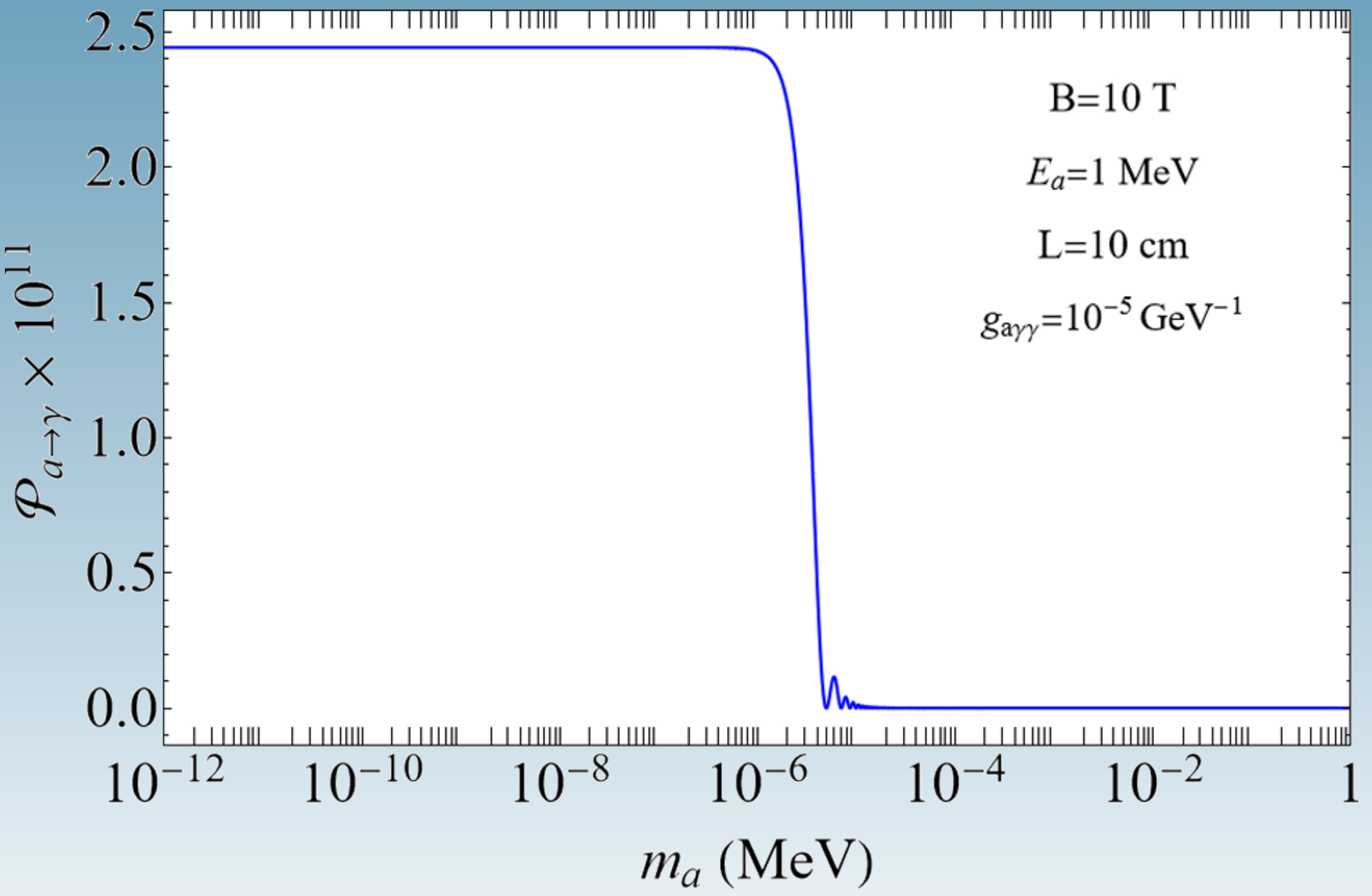
ALP Search Strategies - Reactoscopes

- Detection in magnetic field (non-resonant)

$$N_\gamma = T\pi R^2 \int \frac{d\Phi_a}{dE_a} P_{a\to\gamma}\, dE_a$$

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma\gamma} B}{q}\right)^2 \sin^2\left(\frac{qL}{2}\right)$$

$$q = \sqrt{\left(\frac{m_a^2}{2E_a}\right)^2 + \left(g_{a\gamma\gamma} B\right)^2}$$



ALP Search Strategies - Reactoscopes

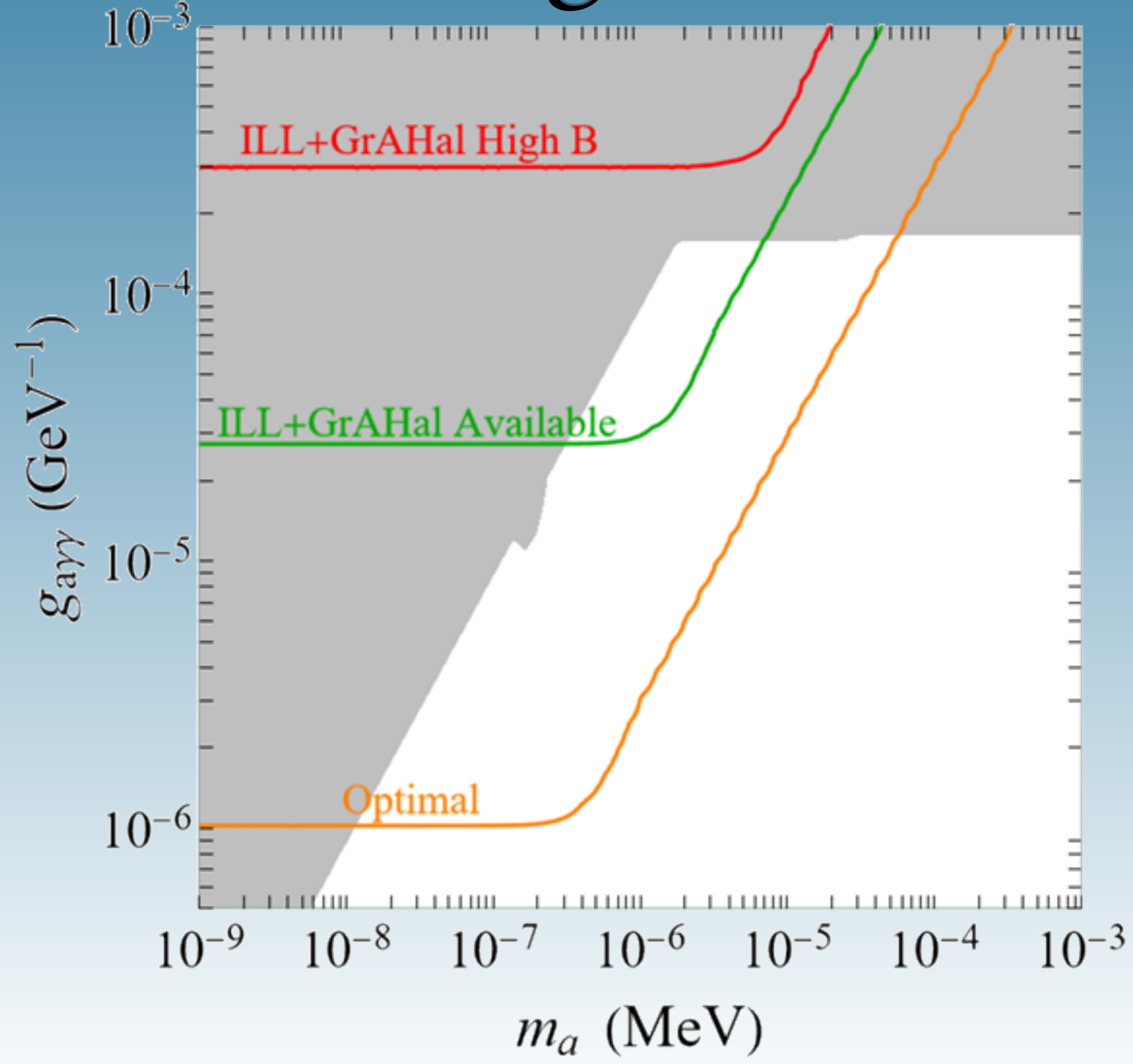
- Look no further, we have one already!

NEUTRONS FOR SOCIETY

GrAHal

ALP Search Strategies - Reactoscopes

B= 43 T
R= 1,7 cm
L = 3,4 cm
P = 58 MW
D = 700 m
B=9,5 T
R = 40 cm
L = 80 cm



P = 8,2 GW
D = 50 m
B= 2T
R= 35 cm
L= 10 m

Conclusions

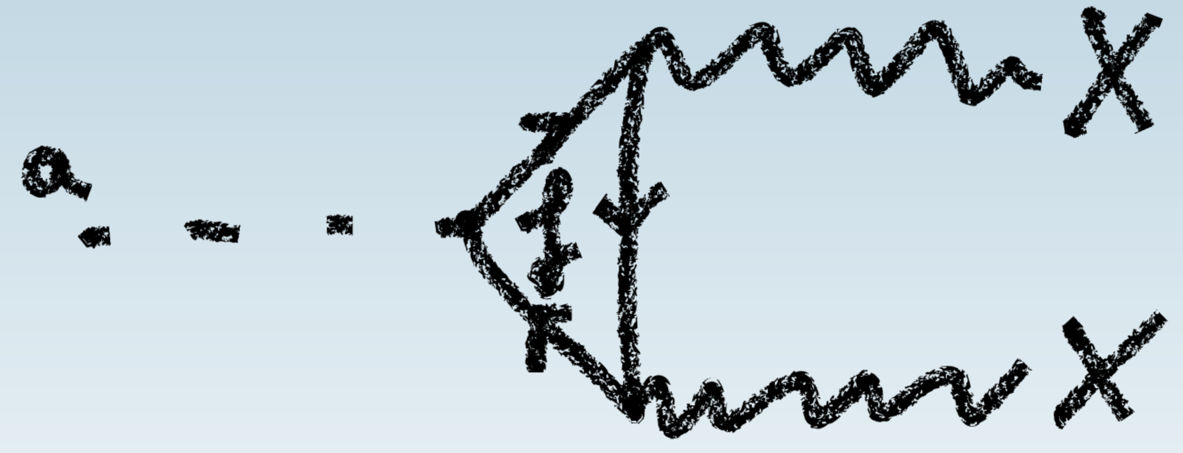
Conclusions

- ALPs, like axions, are a strong BSM candidate
- Both the theoretical and experimental communities are very involved
- Many experiments look for axion/ALPs
- Laboratory experiments complement astro/cosmo probes
- New proposals are still arising
- Among them, reactoscopes may be particularly affordable
- Better sensitivity than current laboratory bounds

Thank you for your attention

The Strong CP Problem - Invisible Axion Models

- DFSZ Axion
  A. R. Zhitnitsky, Sov. J. Nucl. Phys. 31 (1980)
  M. Dine, W. Fischler, M. Srednicki, Phys. Lett. B104 (1981)
  - Adds a new scalar singlet, ϕ , $X_\phi^{PQ} = -1$, $v_\phi \gg v$
  - The axion is a combination of all pseudoscalars $\longrightarrow$ $f_a \simeq \frac{v_\phi}{2} \gg v$
  - $U(1)_{PQ}$ breaking entangled with $SU(2)_L \times U(1)_Y \to U(1)_{EM}$
  - SM fermions and axion couple at tree level
  - Axion couples to SM gauge bosons at 1 loop



The Strong CP Problem - Invisible Axion Models

- KSVZ Axion — J. E. Kim, PRL 43 (1979); M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, Nucl. Phys. B166 (1980)
  - SM particles neutral under $U(1)_{PQ}$
  - New heavy quarks Q and singlet scalar σ, $X_Q^{PQ}, X_\sigma^{PQ} \neq 0$, $v_\sigma \gg v$
  - Gauge representation of Q induces axion-gauge boson coupling
  - Axion coupling to SM fermions arises at 2 loops