New Theoretical and Experimental Avenues for ALP Searches

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Outline

- Fundamentals and Motivation
- Axion-like ALPs **FAA**, J. Quevillon, C. Smith, 2211.004489
- A New Approach for ALP Searches: Reactoscopes **FAA**, V. Brdar, J. Quevillon, 2310.03631
- Conclusions

Fundamentals and Motivation

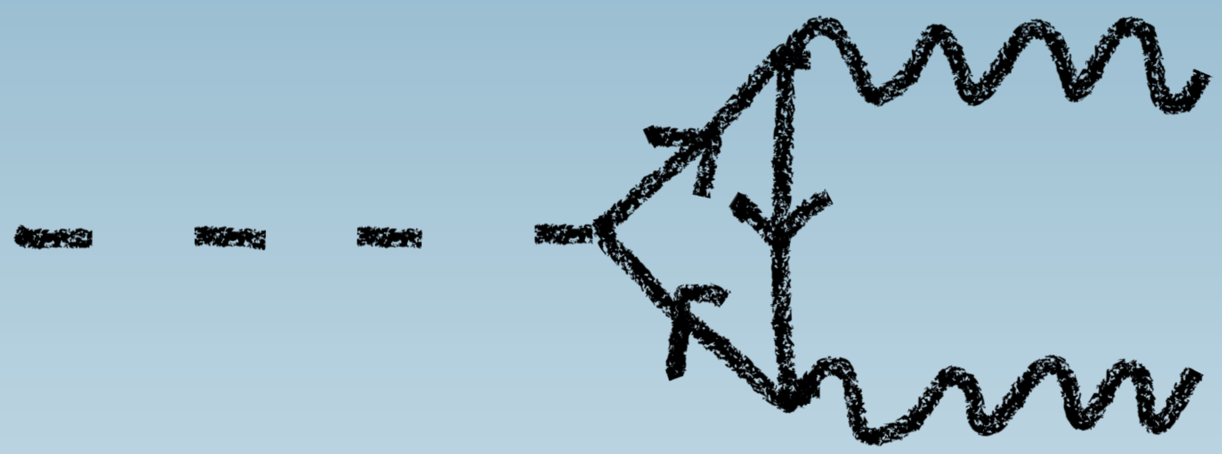
Axions and ALPs - A Versatile BSM Candidate

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

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

- The original model required two Higgs doublets

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

The Strong CP Problem - Invisible Axion Models

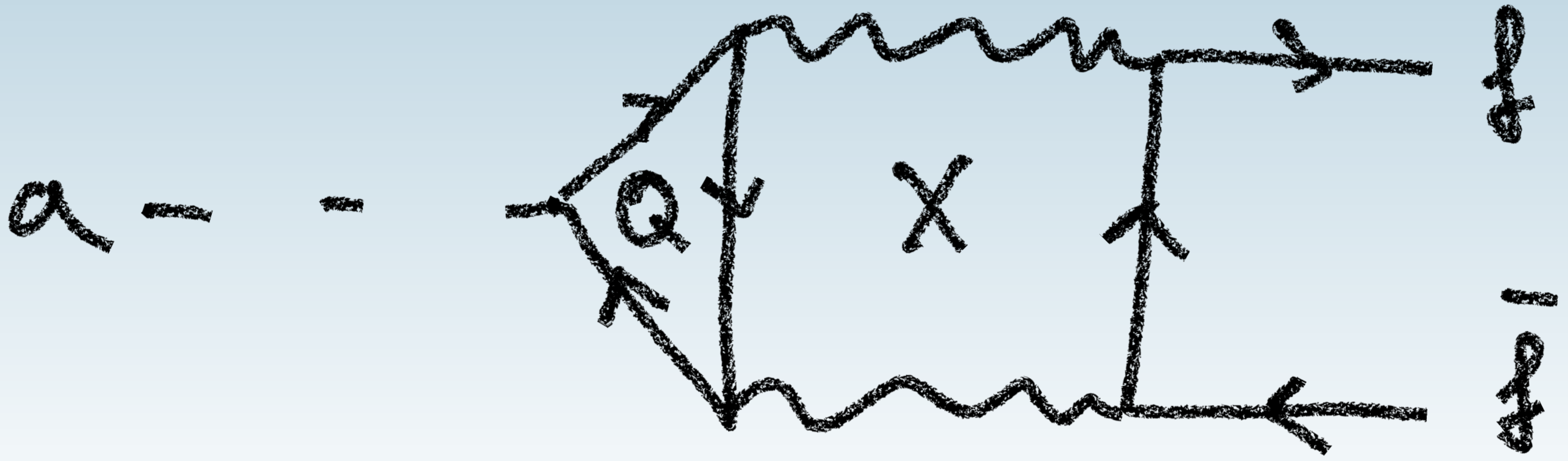
- DFSZ Axion

  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 $\mathcal{U}(1)_{PQ}$
  - 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



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

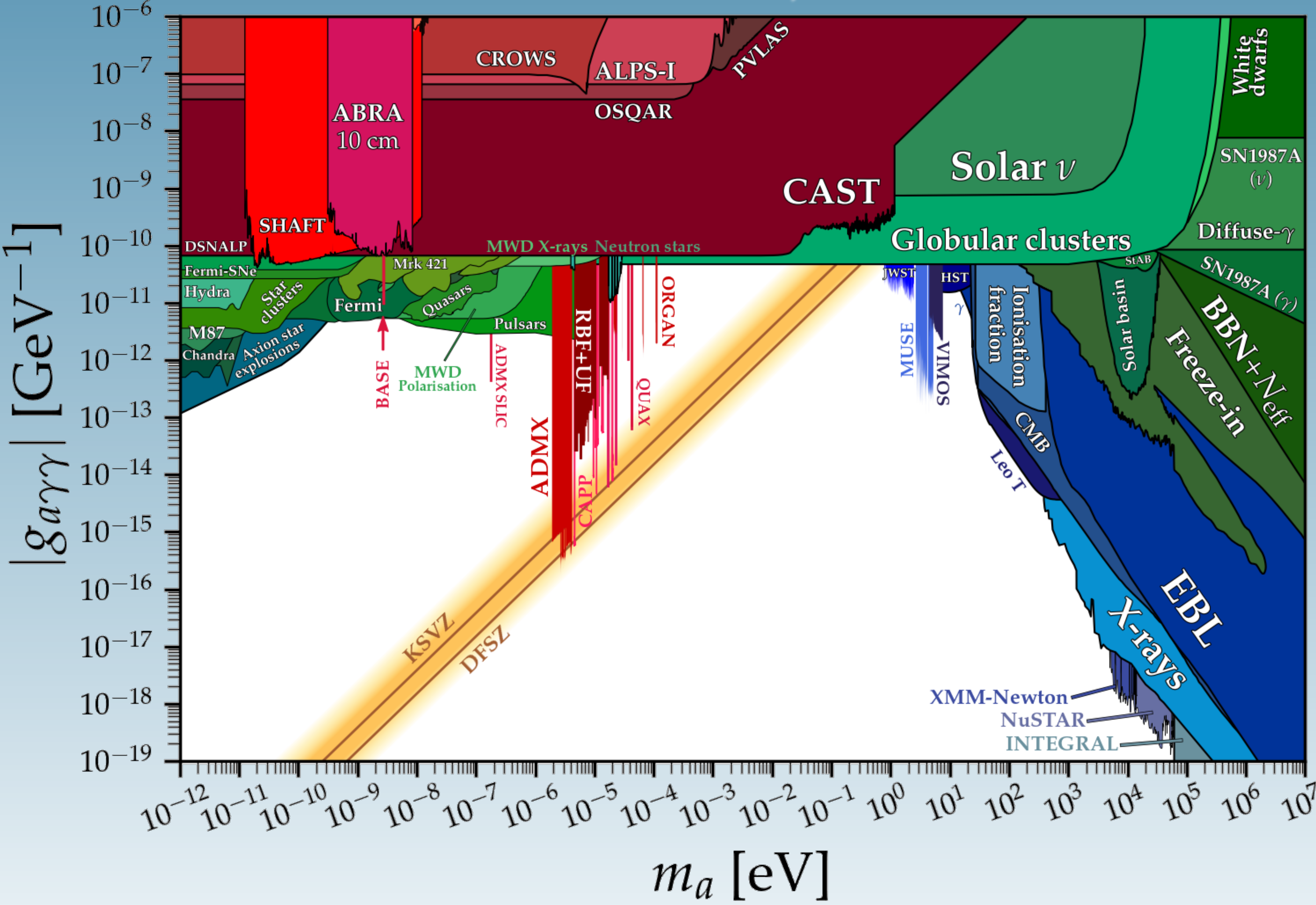
FAA, F. D'Eramo, R. Z. Ferreira, L. Merlo, A. Notari, 2012.04736

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
  - ...

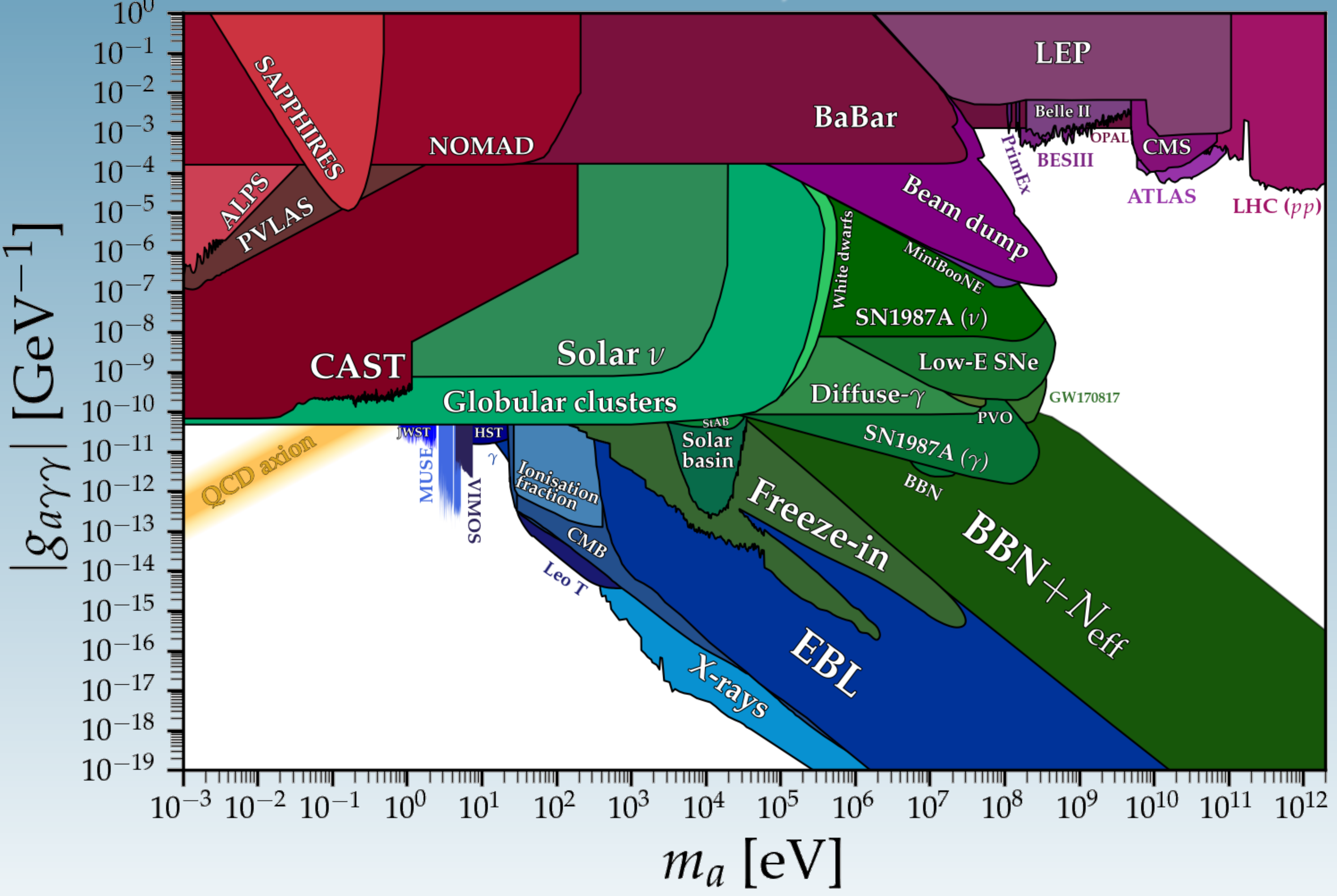
Ciaran O'Hare, AxionLimits



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

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



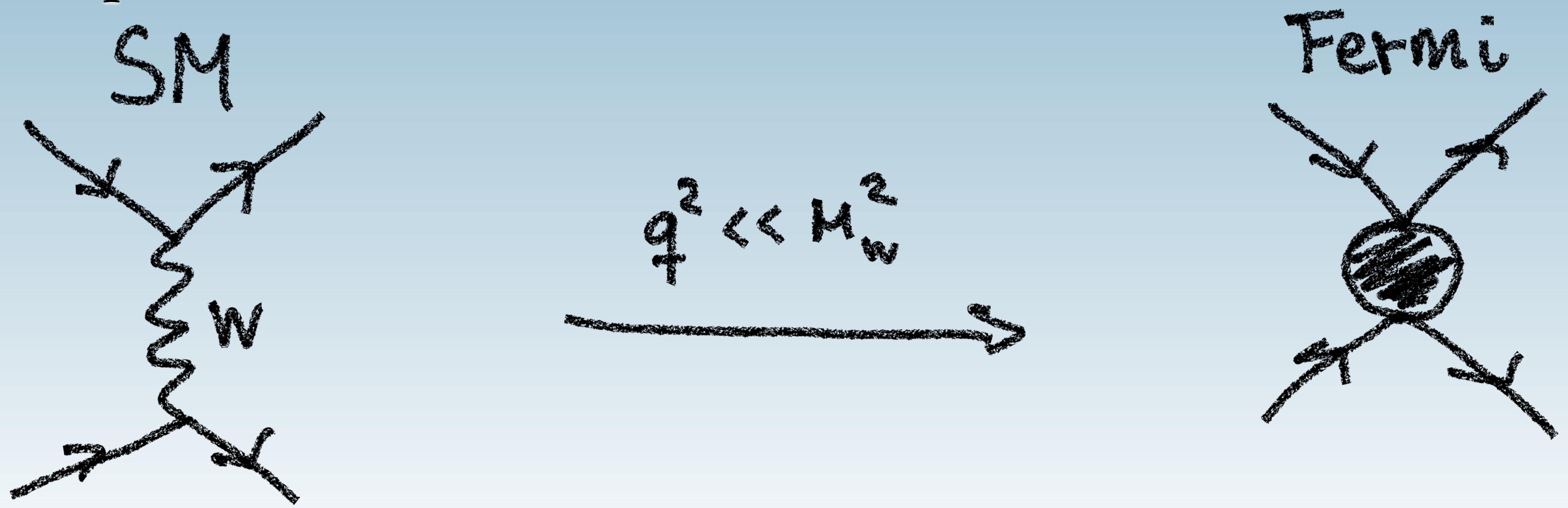
Ciaran O'Hare, AxionLimits

Axion-like ALPs

FAA, J. Quevillon, C. Smith, 2211.004489

A Powerful Tool: EFTs

- No new states found beyond the Higgs
- Top-down approach: model building
- No evidence means no distinction between models
- Bottom-up: Effective Field Theories



A Powerful Tool: EFTs

- Useful for parametrizing the unknown: SMEFT
- Helps characterizing sets of BSM theories
- Effective Field Theory for SM+ALP:

K. Mimasu and V. Sanz, 1409.4792
M. Bauer, M. Neubert, A. Thamm, 1708.00443
I. Brivio, M. B. Gavela, L. Merlo, K. Mimasu, J. M. No, R. del Rey, V. Sanz, 1701.05379

$$\mathcal{L}_{ALP} = \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a a\right) - i \sum_f \frac{x_f}{v_a} \partial_\mu a \bar{f} \gamma^\mu \gamma_5 f$$

$$+ \frac{a}{16\pi^2 v_a}\left(g_s^2 N_c G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + g^2 N_L W^i_{\mu\nu} \tilde{W}^{i\mu\nu} + g'^2 N_Y B_{\mu\nu} \tilde{B}^{\mu\nu}\right)$$

A Powerful Tool: EFTs

- Two possibilities for ALP-fermion coupling:

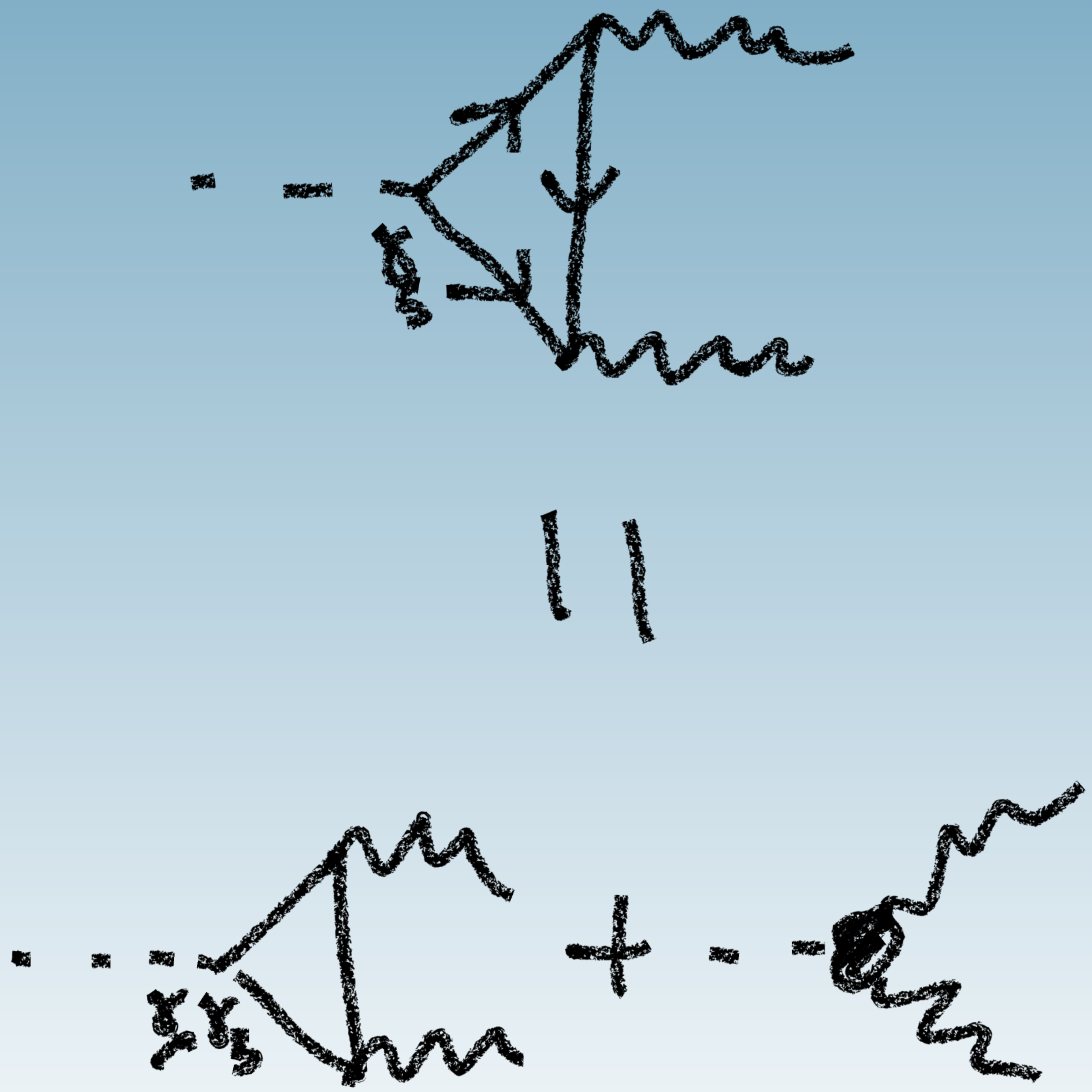
J. Quevillon, C. Smith, 1903.12559

Linear

$$\phi = \sigma + i a + v_a \longrightarrow i \frac{m_\psi}{v_a} a \bar{\psi} \gamma_5 \psi$$

Polar

$$\phi = \frac{\sigma + v_a}{\sqrt{2}} e^{-i \frac{a}{v_a}} \longrightarrow \frac{\partial_\mu a}{v_a} \bar{\psi} \gamma^\mu \gamma_5 \psi + \frac{a}{v_a} X_{\mu\nu} \tilde{X}^{\mu\nu}$$

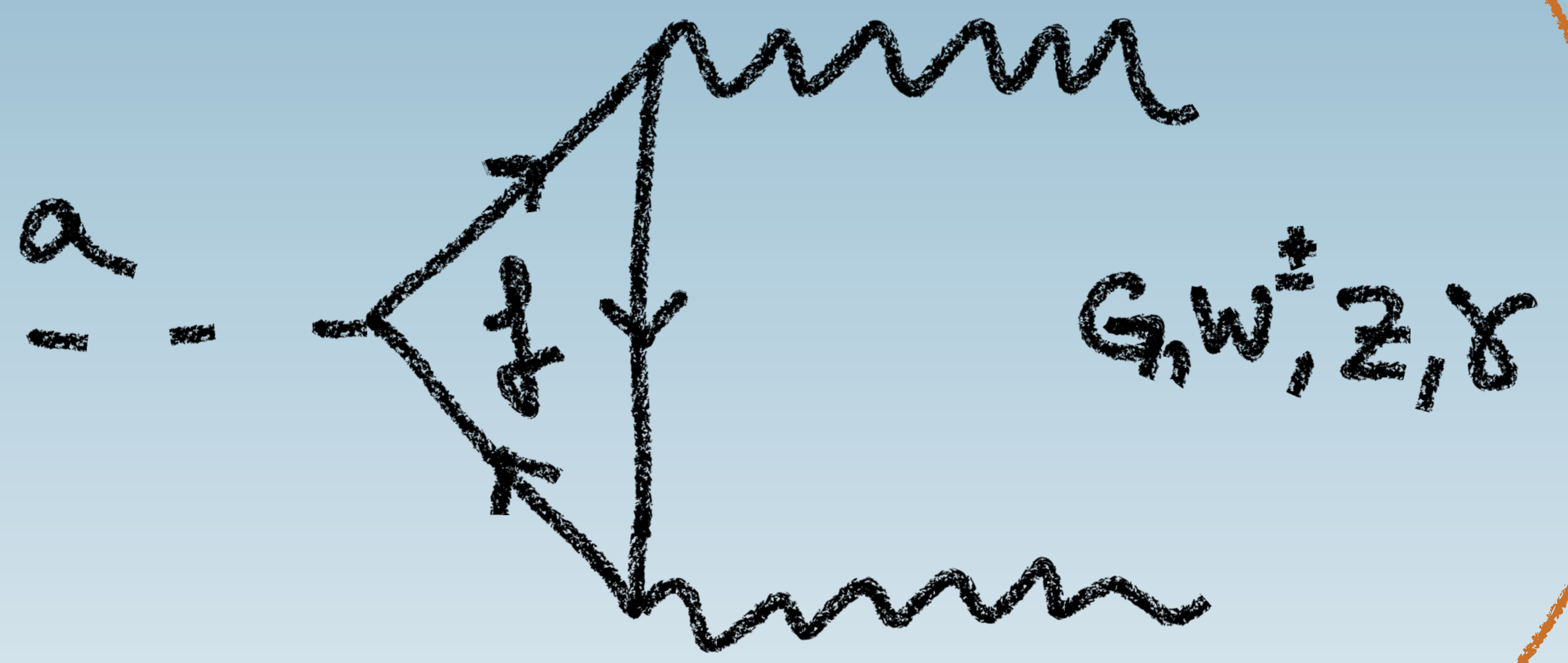


A Powerful Tool: EFTs

- Are ALP theories always so generic?

DFSZ-like

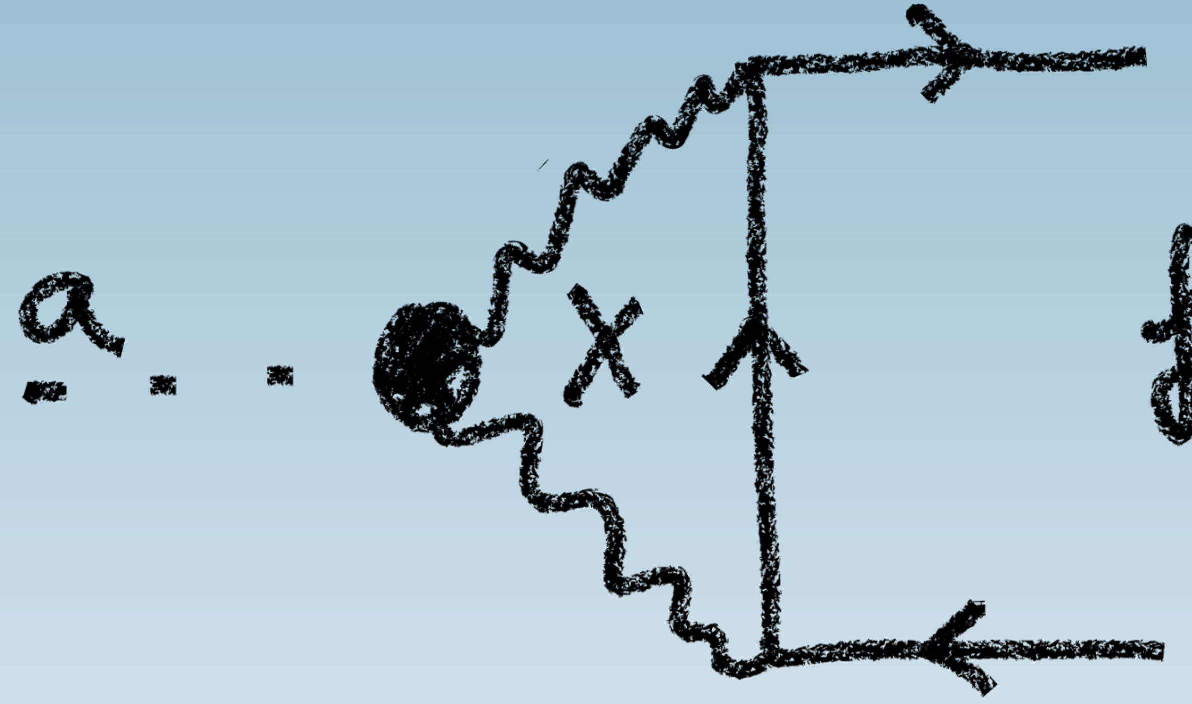
$$-i\sum_{f=u,d,e}\frac{m_f}{2v_a}x_f\, a\,\bar{f}\gamma_5 f$$



$$\frac{a}{4\pi v_a}\, g_{aXX}(m_f, x_f)\, X_{\mu\nu}\tilde{X}^{\mu\nu}$$

KSVZ-like

$$\frac{a}{16\pi^2 v_a}\, g^2_{X}\, \mathcal{N}_X\, X_{\mu\nu}\tilde{X}^{\mu\nu}$$



$$\frac{m_f}{v_a}\, C_{af}(\mathcal{N}_X, m_a, m_f)\, a\,\bar{f}\gamma_5 f$$

DFSZ-like ALPs

- Four free parameters: $\frac{\mathcal{X}_u}{v_a}, \frac{\mathcal{X}_d}{v_a}, \frac{\mathcal{X}_e}{v_a}, m_a$
- A pedagogical example: ALP coupling to W, Z and photons

Generic ALP EFT

$$\frac{a}{16\pi^2 v_a}\left(g^2 \underline{\mathcal{N}_L} W^i_{\mu\nu}\tilde{W}^{i\mu\nu} + g'^2 \underline{\mathcal{N}_Y} B_{\mu\nu}\tilde{B}^{\mu\nu}\right)$$

$$\downarrow$$

$g_{a\gamma\gamma}, g_{a\gamma Z}, g_{aZZ}, g_{aWW}$

Four couplings, two free param.

DFSZ-like

$$\sum_{u,d,e} \frac{m_f}{v_a}\underline{\mathcal{X}_f}\, a \bar{f}\gamma_5 f$$

$$\downarrow$$

$g_{a\gamma\gamma}, g_{a\gamma Z}, g_{aZZ}, g_{aWW}$

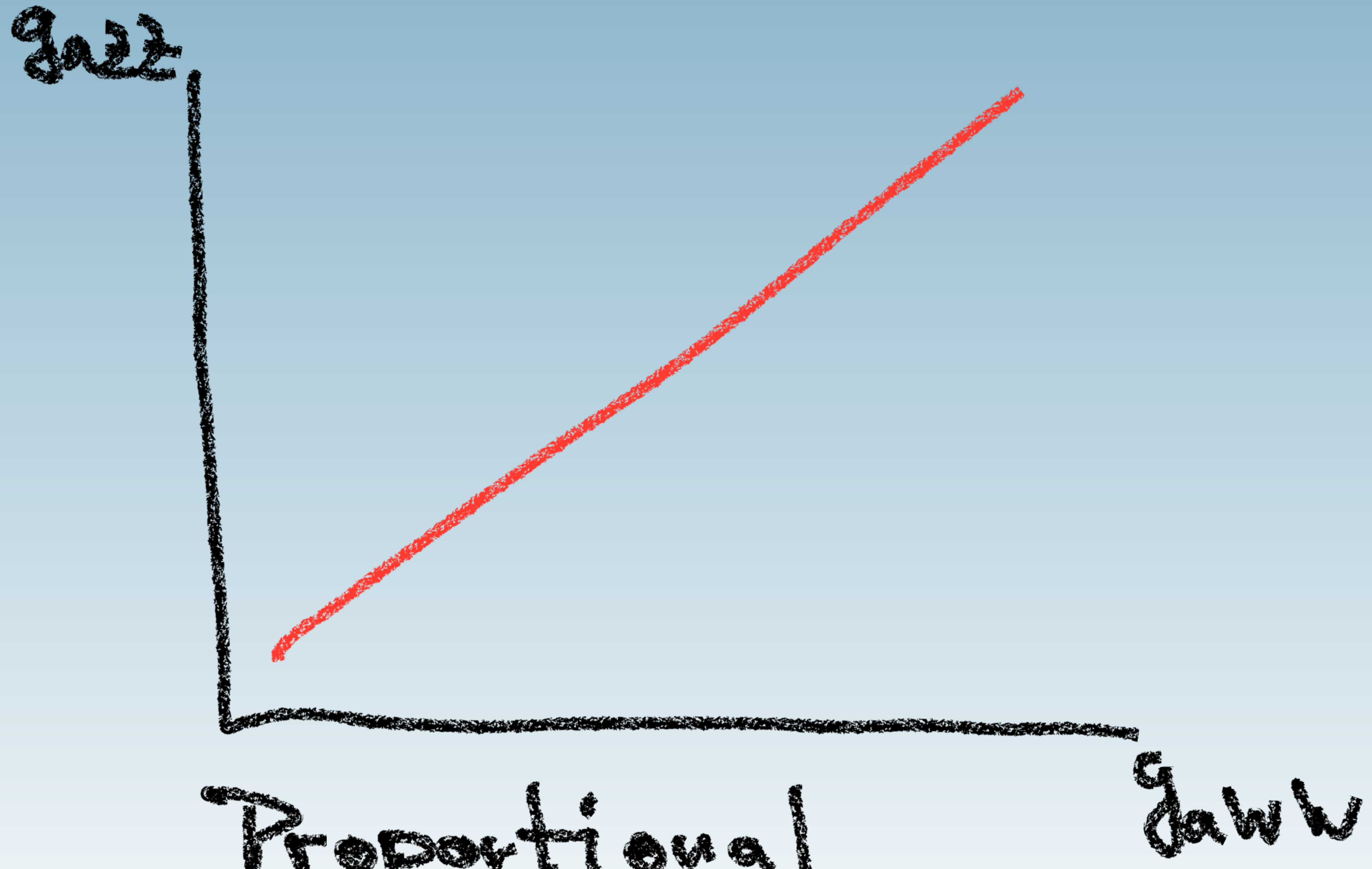
Four couplings, four free param.

DFSZ-like ALPs

Photophobic ALP: $g_{a\gamma\gamma} = 0$

Generic EFT

$\mathcal{N}_L = -\mathcal{N}_Y$

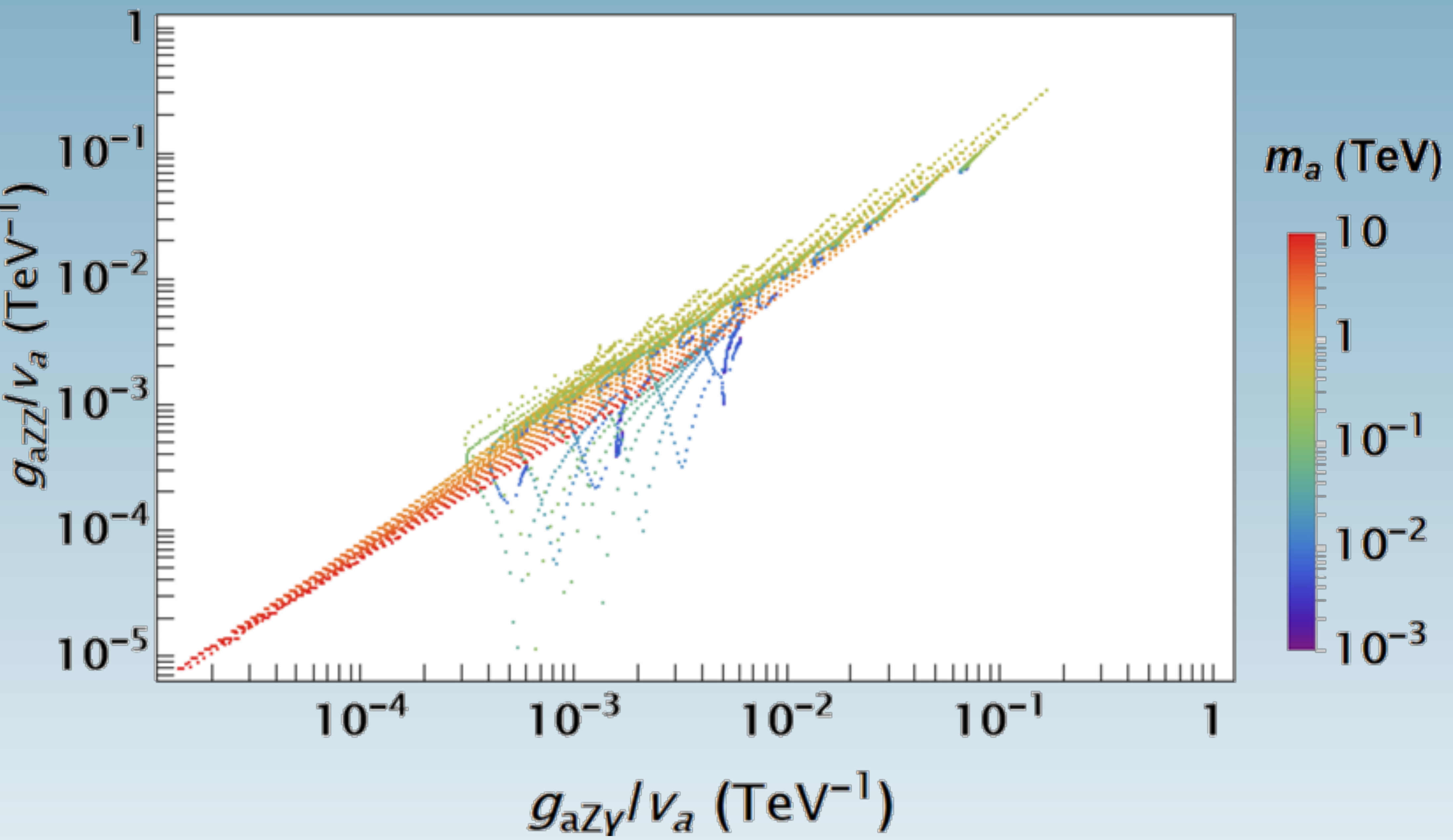


Proportional

No hierarchies

DFSZ-like ALP

$\chi_e(\chi_u, \chi_d, m_a)$



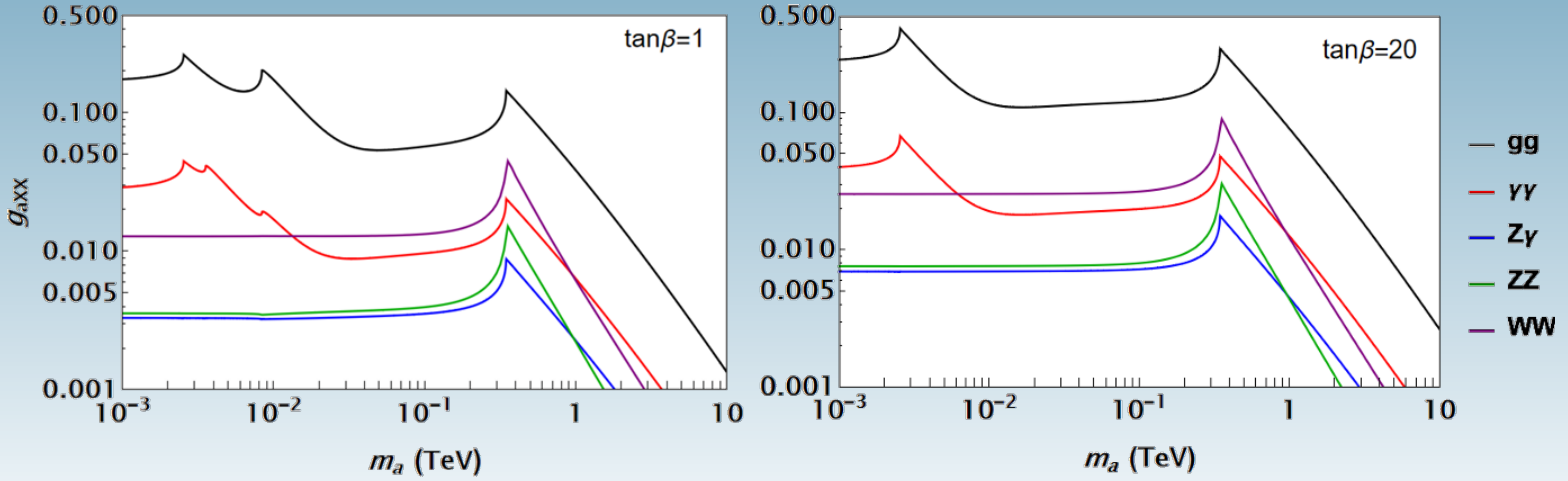
More freedom

Hierarchies are possible

DFSZ-like ALPs

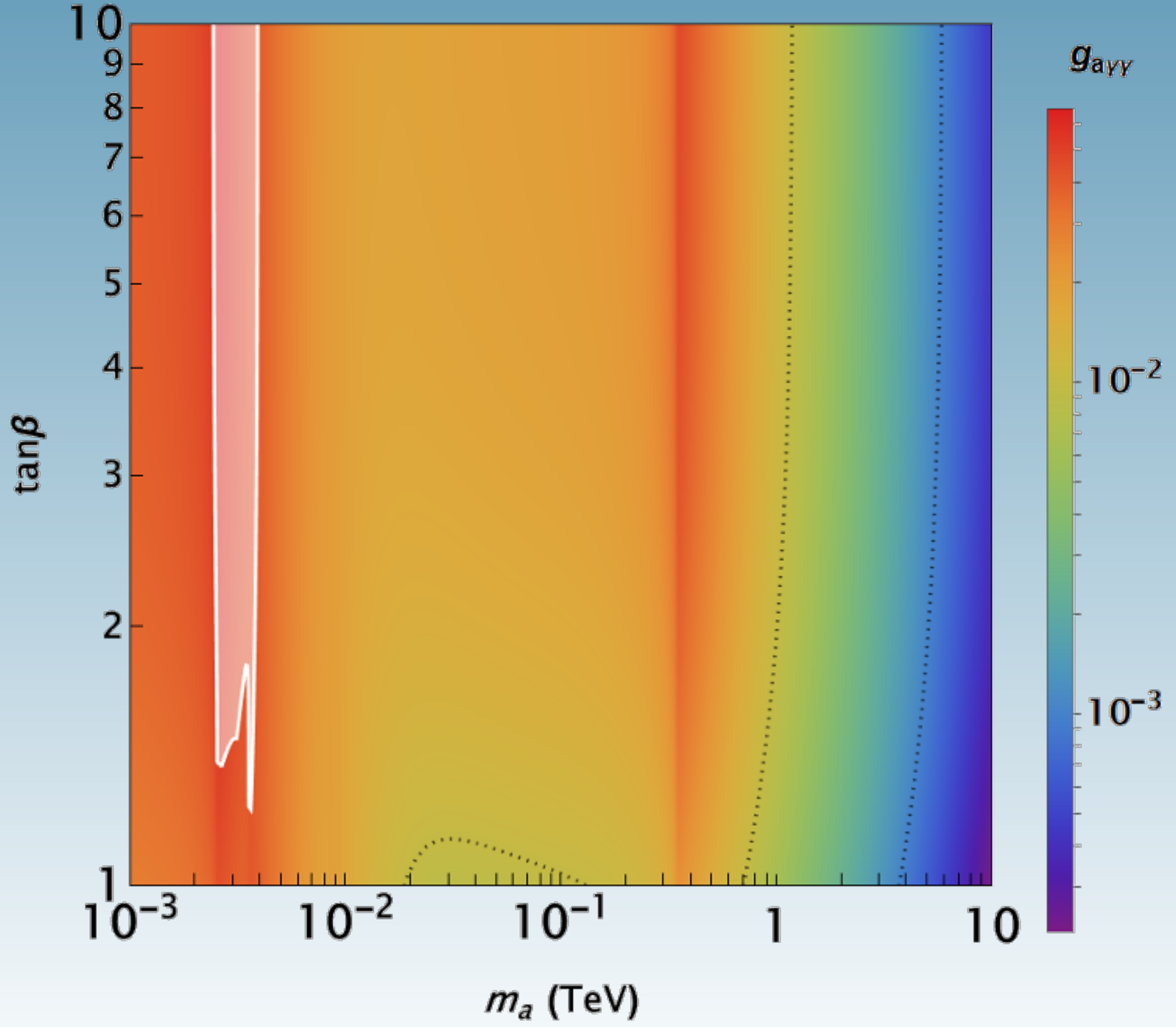
- DFSZ axion is an extended 2HDM

$$\chi_u = \frac{x^2}{1+x^2}\,, \quad \chi_d = \chi_e = \frac{1}{1+x^2}\,, \quad x = \tan\beta = \frac{v_u}{v_d}$$



DFSZ-like ALPs

- This scenario allows to recast bounds on 2HDM for the ALP case



KSVZ-like ALPs

- All SM particles are singlets of $\mathcal{U}(1)_{PQ}$
- Heavy fermions couple to a heavy scalar, all charged under PQ
- After being integrated out, they yield:

$$\mathcal{L}_{KSVZ} = \frac{1}{2}\left(\partial_\mu a \partial^\mu a - m_a^2 a a\right)$$

$SU(2)_L \times \mathcal{U}(1)_Y$ symm.

$$+\frac{a}{16\pi^2 v_a}\left(g_s^2 \mathcal{N}_c G^a_{\mu\nu} \tilde{G}^{a\mu\nu} + g^2 \mathcal{N}_L W^i_{\mu\nu} \tilde{W}^{i\mu\nu} + g'^2 \mathcal{N}_Y B_{\mu\nu} \tilde{B}^{\mu\nu}\right)$$

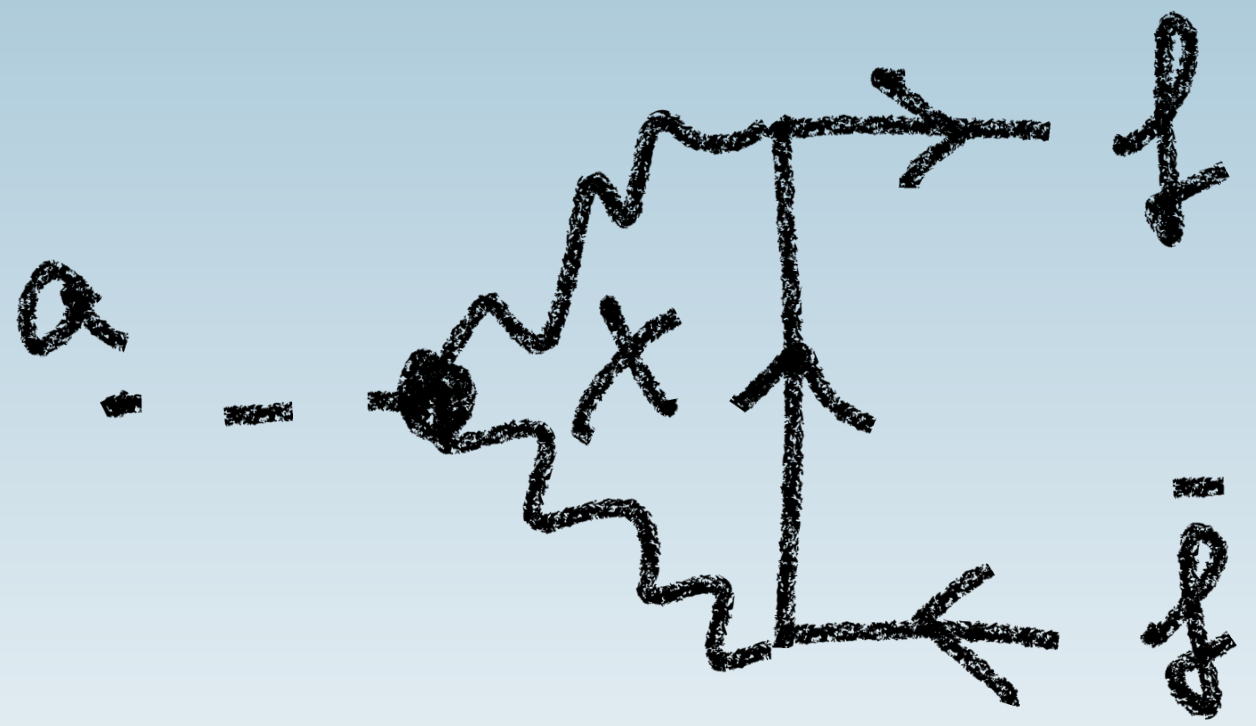
- Arbitrary representations: four free parameters, m_a, $\mathcal{N}_c$, $\mathcal{N}_L$, $\mathcal{N}_Y$

KSVZ-like ALPs

- After EWSB, ALP couples to all gauge bosons and fermions

$$g_{agg} = \alpha_s \mathcal{N}_C \qquad g_{a\gamma\gamma} = \alpha \left(\mathcal{N}_L + \mathcal{N}_Y\right) \qquad g_{a\gamma Z} = 2\alpha \left(-\frac{\mathcal{N}_L}{t_w} + t_w \mathcal{N}_Y\right)$$

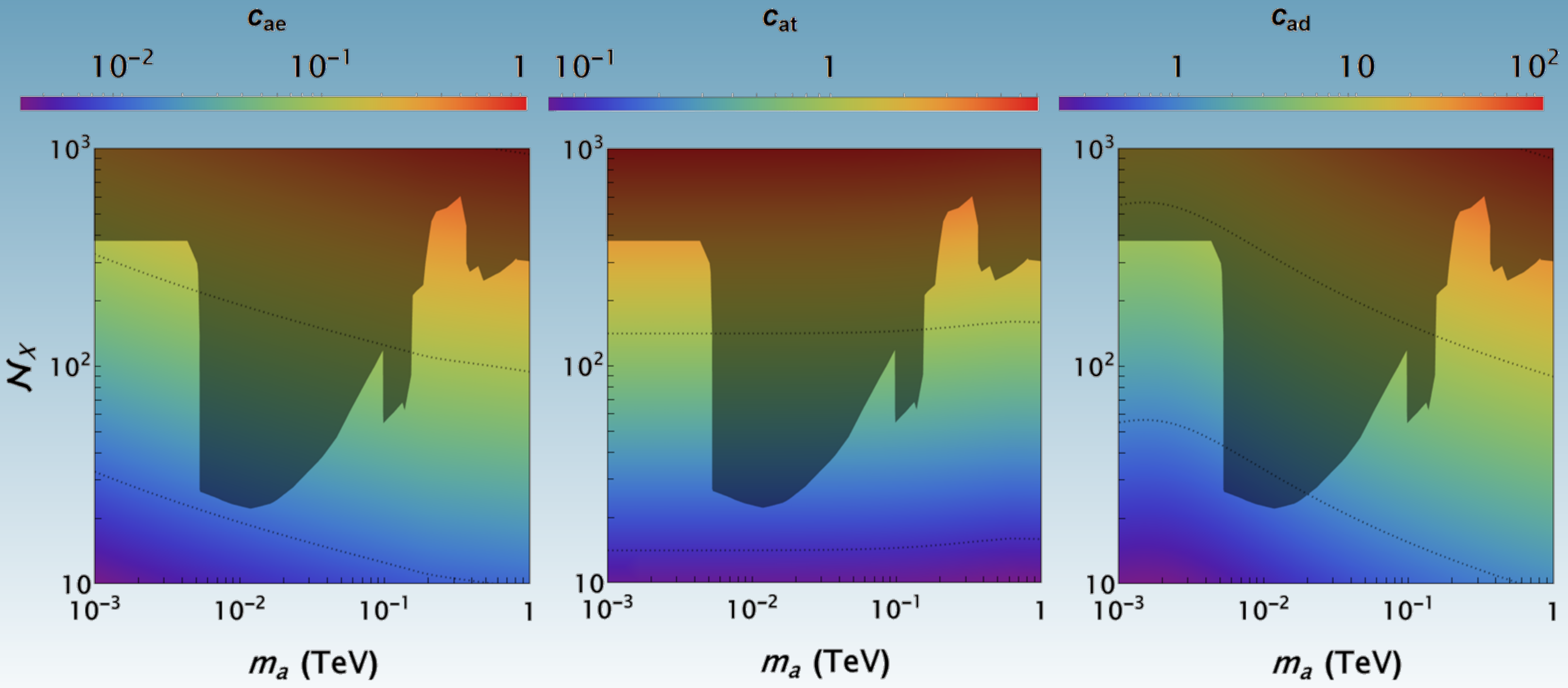
$$g_{aZZ} = \alpha \left(\frac{\mathcal{N}_L}{t_w^2} + t_w^2 \mathcal{N}_Y\right) \qquad g_{aWW} = \frac{2\alpha}{s_w^2} \mathcal{N}_L$$



$$C_{af}\left(\mathcal{N}_X, \underbrace{I_{XX}(m_a, m_f, m_X)}_{\text{Scalar loop integrals}}\right)$$

KSVZ-like ALPs

- Bounds on ALP-photon can be used to set limits on c_{af}



KSVZ-like ALPs

- The loop computation involves the Levi-Civita tensor
- Intrinsically four-dimensional: tricky in dimensional regularization
- Regularization scheme dependence

M. Bauer, M. Neubert, A. Thamm, 1708.00443
J. Bonilla, I. Brivio, M. B. Gavela, V. Sanz, 2107.11392
S. A. Larin, hep-ph/9302240

$$\begin{array}{cccccc} & \gamma_\mu & = & \bar{\gamma}_\mu & + & \hat{\gamma}_\mu \\ \text{dim} & 4-\varepsilon & & 4 & & \varepsilon \end{array} \qquad \{\gamma_5, \bar{\gamma}_\mu\} = [\gamma_5, \hat{\gamma}_\mu] = 0$$

$$c_{af}^{\gamma\gamma} = c\left(D_\varepsilon + \ln\frac{\mu^2}{m_f^2} - \frac{4}{3}\right) + \ldots$$

KSVZ-like ALPs

- The choice of scheme is unphysical. Can it be alleviated?

B. R. Martin, E. de Rafael, J. Smith, PRD 2 (1970) 179-200

- ALP is a pseudoscalar: enforce momentum conservation

$$J^{PC} = 0^{-+} \text{ projector} \rightsquigarrow P_{S=0} = \frac{1}{2\sqrt{2p^2}}\left(-\frac{1}{2}\epsilon_{\rho\sigma\mu\nu}\left(p_1^\rho p_2^\sigma - p_1^\sigma p_2^\rho\right)\sigma^{\mu\nu} + \left(p^2 - 2m_f\left(\not{p}_1 + \not{p}_2\right)\right)\gamma_5\right)$$

$$\mathcal{M}(a \to f\bar{f}) = \bar{u}(p_1)\, T(a \to f\bar{f})\, v(p_2) = \underbrace{\bar{u}(p_1)\gamma_5 v(p_2)}\, F(a \to f\bar{f})$$

$$F(a \to f\bar{f}) = \frac{1}{\sqrt{2p^2}} \mathrm{Tr}\left(P_{S=0} \cdot T(a \to f\bar{f})\right)$$

KSVZ-like ALPs

- Dirac structure outside the loop integral: no scheme dependence
- Same procedure used for dealing with $K_L \to \gamma\gamma \to \mu^+\mu^-$

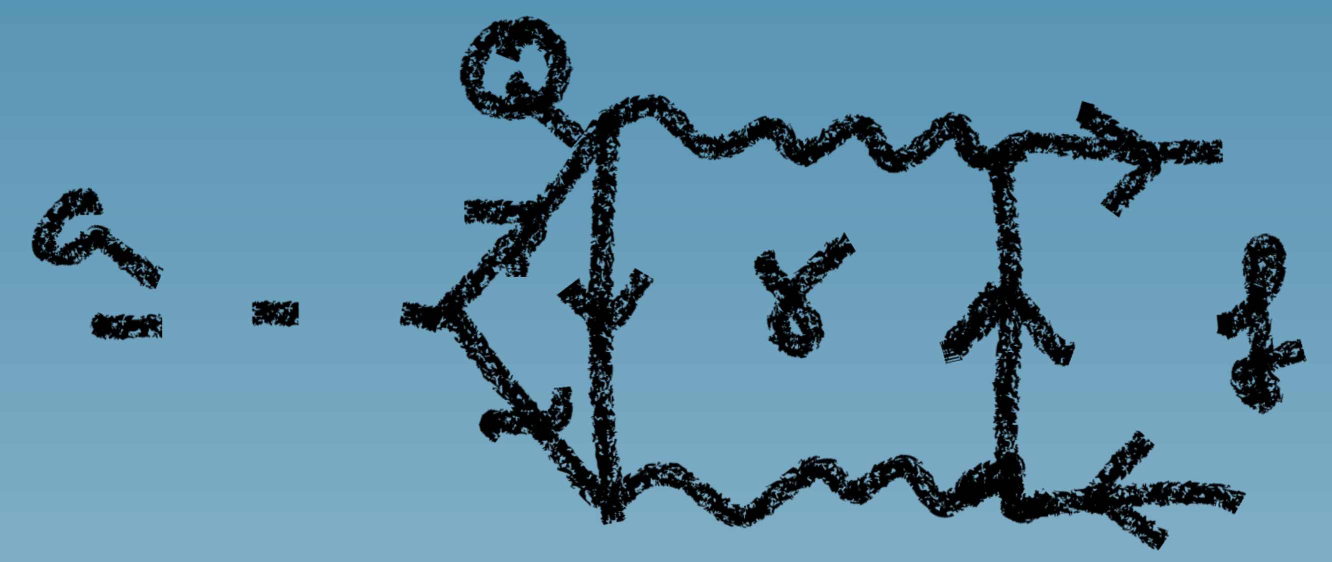
G. Isidori, R. Unterdorfer, hep-ph/0311084

$$c_a^{\gamma\gamma} = c\left(D_\varepsilon + \ln\frac{\mu^2}{m_f^2} + \frac{5}{3}\right) + \dots$$

- Different asymptotic coupling for $m_a \ll m_f$
- What about the renormalization scale μ?

KSVZ-like ALPs

- The 2-loop process in the UV is finite
- Considering only intermediate photons:



$$c_a^{\gamma\gamma} = c\left(0 + \ln\frac{m_Q^2}{m_f^2} + \frac{17}{6} + \frac{5}{27}\frac{m_f^2}{m_Q^2}\ln\frac{m_Q^2}{m_f^2} + \frac{11}{54}\frac{m_f^2}{m_Q^2} + \dots\right)$$

L. Ametller, L. Bergstrom, A. Bramon, E. Masso, NPB 228 (1983) 301-315
G. Ecker, A. Pich, NPB 366 (1991) 189-205

$$\mu = m_Q \simeq v_a$$

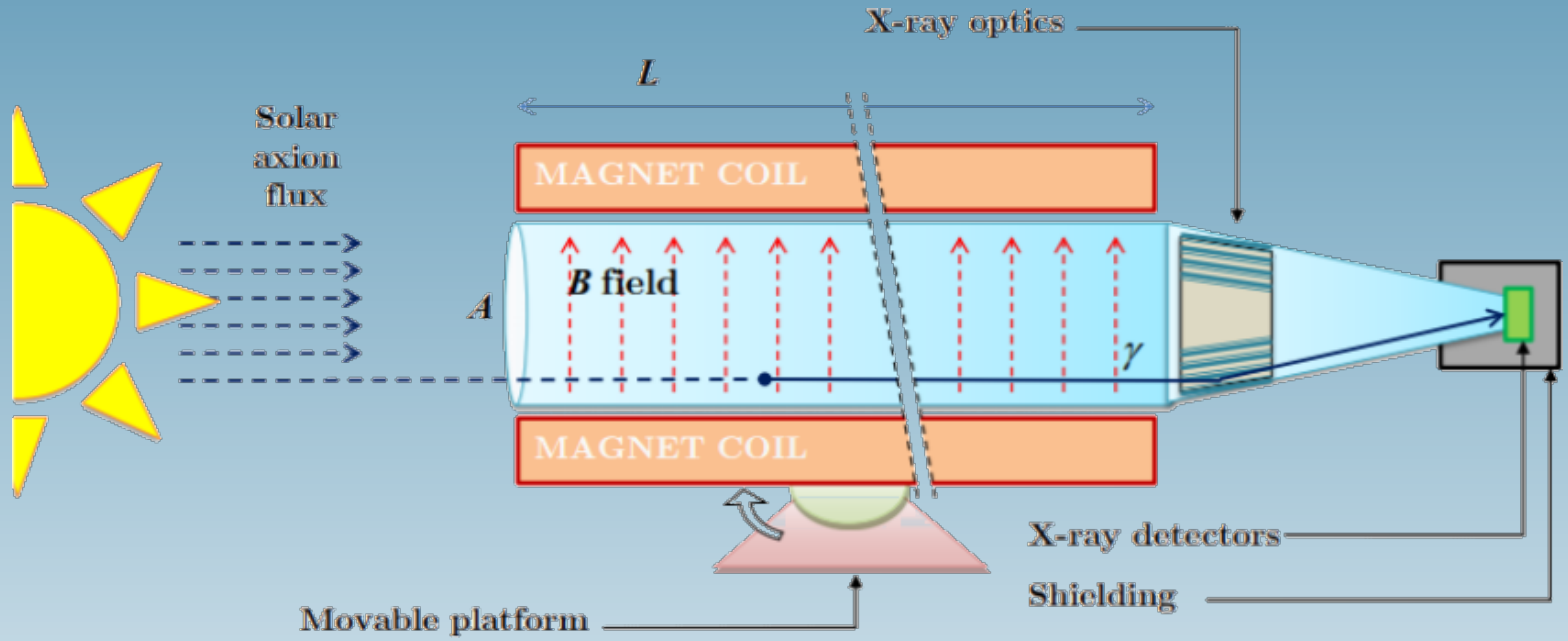
- No O(1) c_{af} at the EW scale, as opposed to generic ALP EFT

A New Approach for ALP searches: Reactoscopes

FAA, V. Brdar, J. Quevillon, 2310.03631

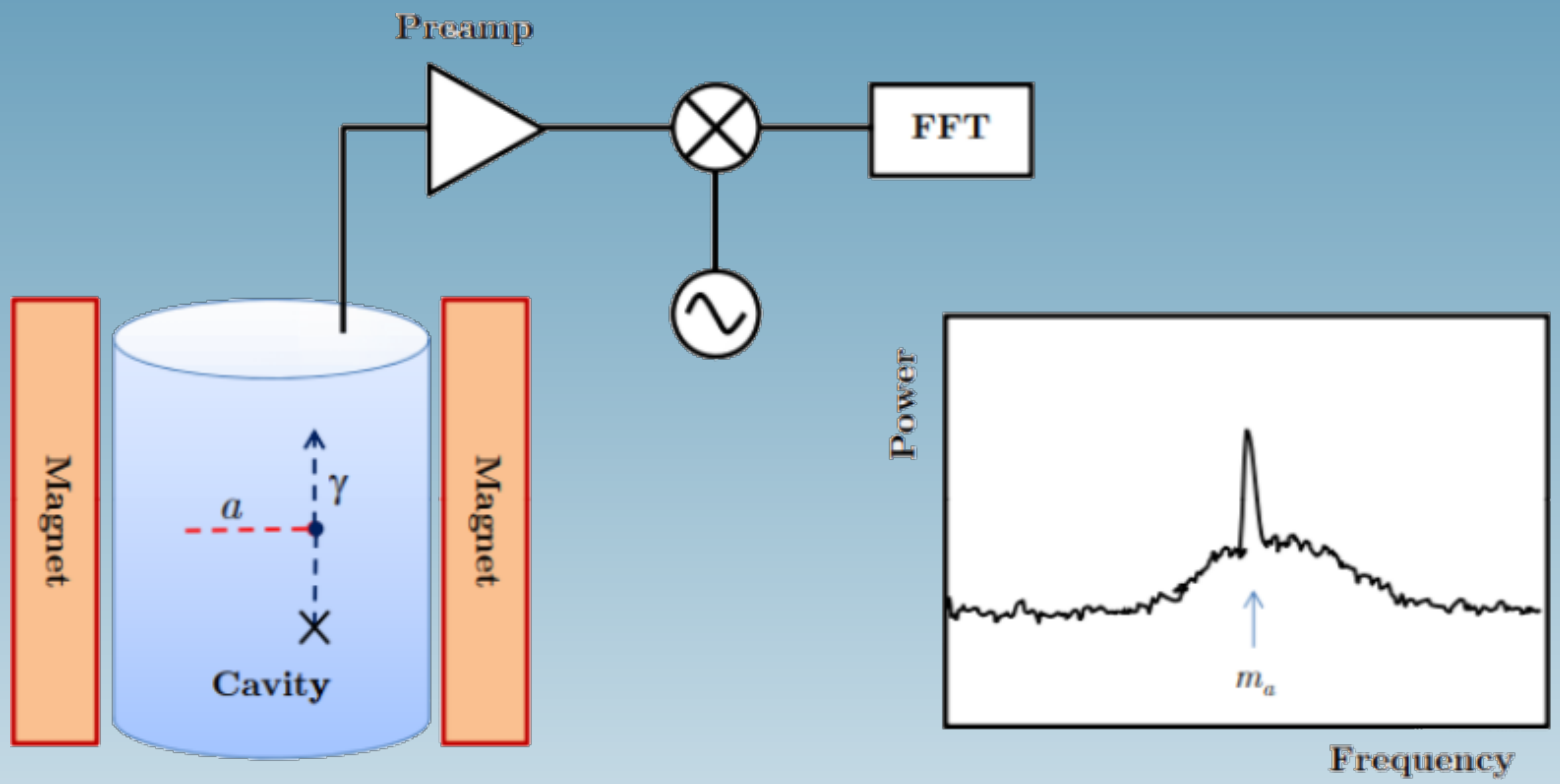
ALP Search Strategies - A Review

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



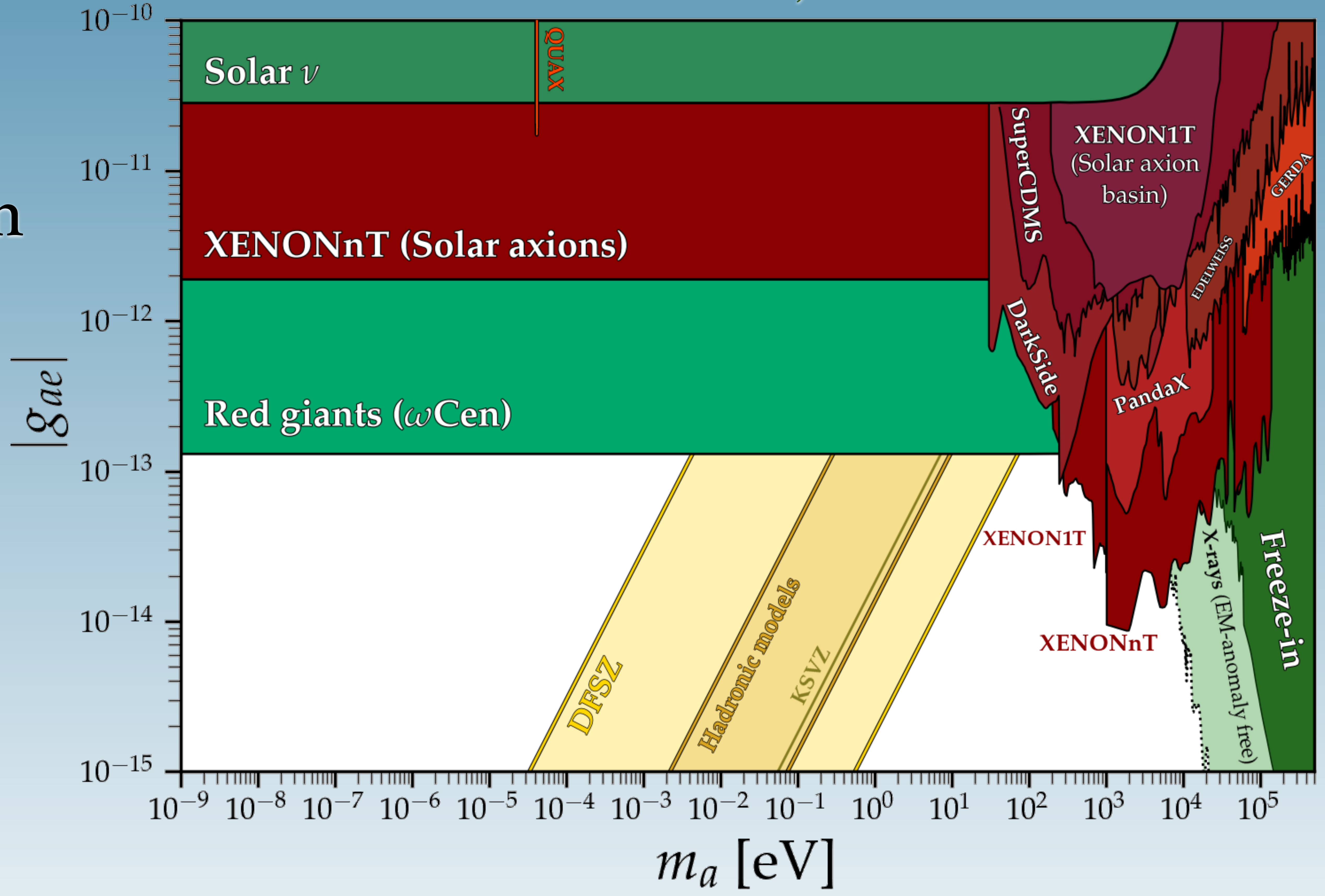
ALP Search Strategies - A Review

- 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}

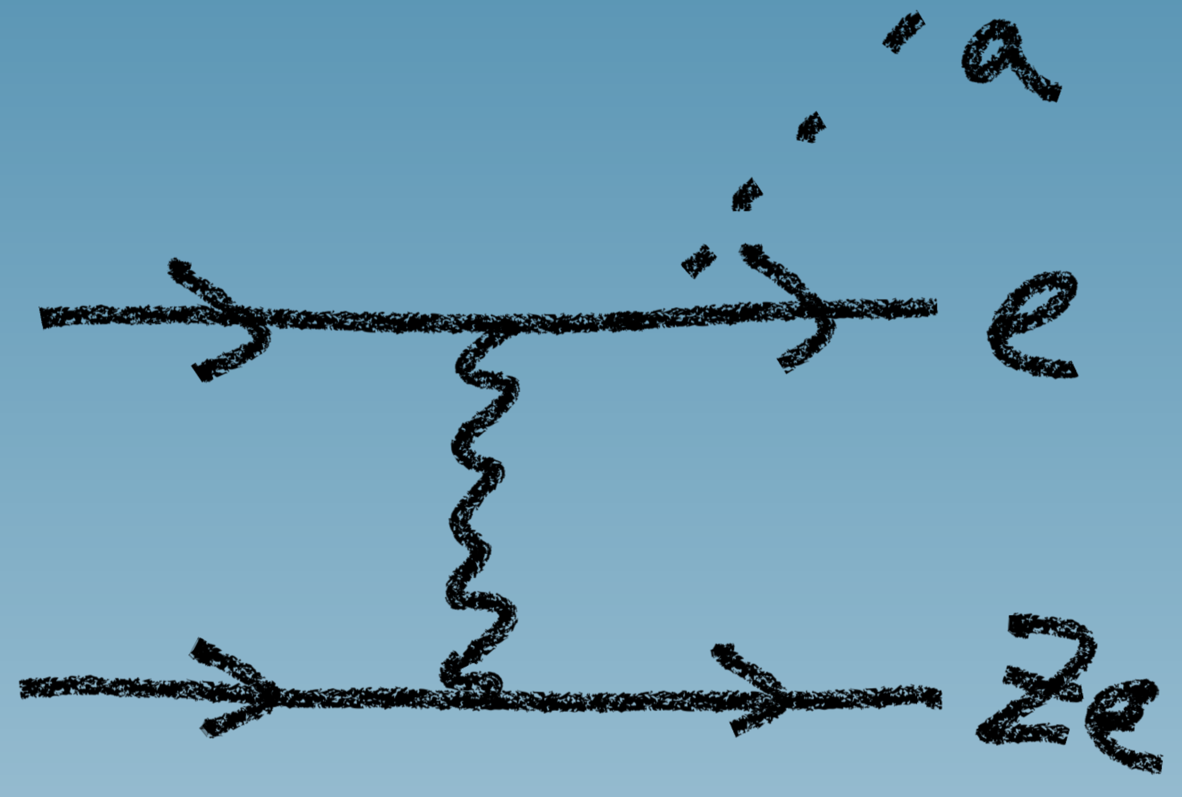


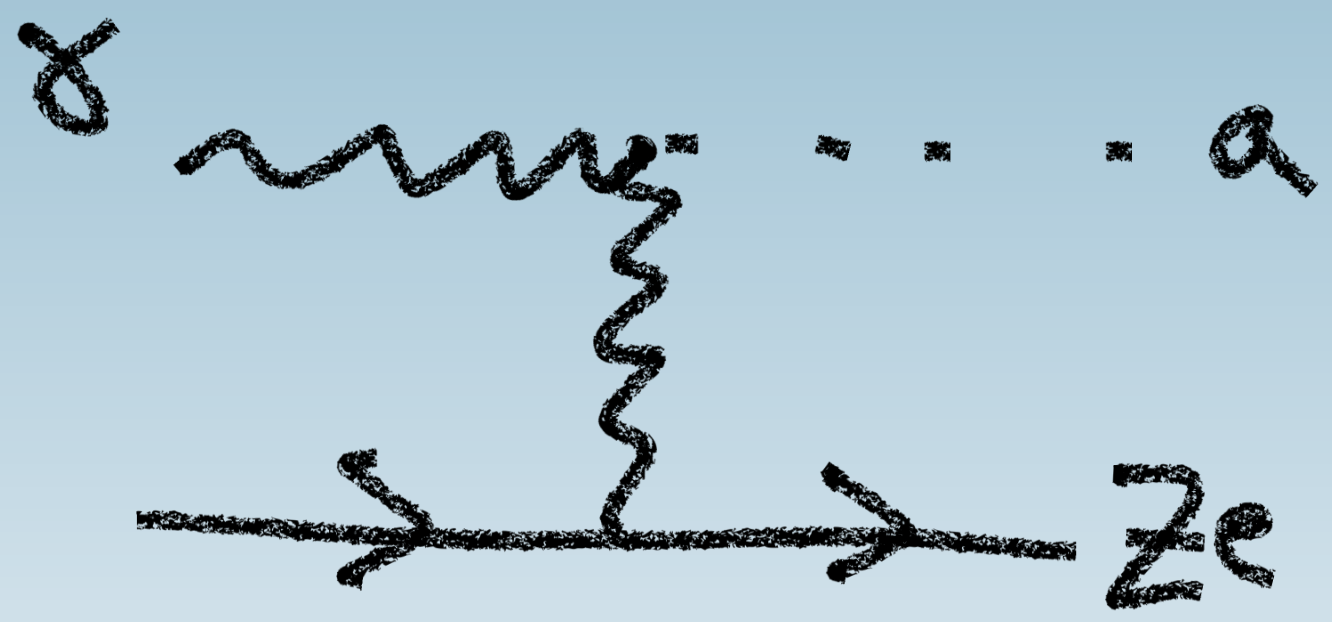
Ciaran O'Hare, AxionLimits

ALP Search Strategies - A Review

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

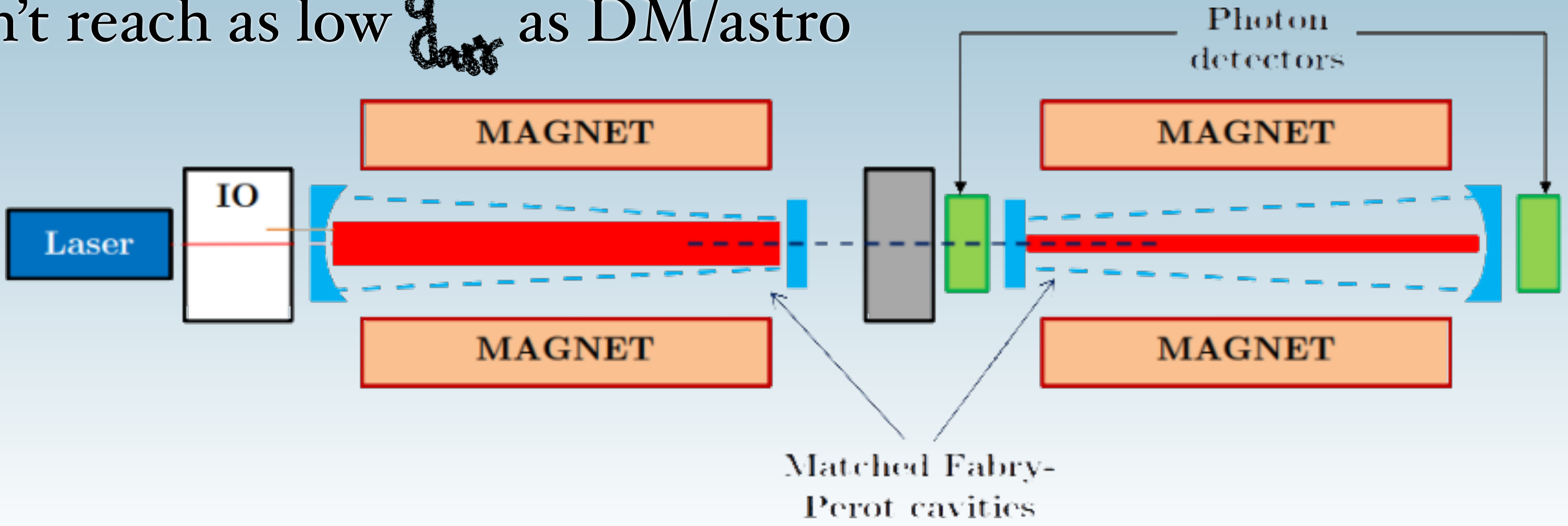
- Stellar cooling
  - Many observables involved
  - Bremsstrahlung and Primakoff production
  - Depend on astrophysical assumptions
  - Main couplings: $g_{aee}, g_{a\gamma\gamma}$





ALP Search Strategies - A Review

- Light-shining-through-wall (OSQAR,)
  - 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



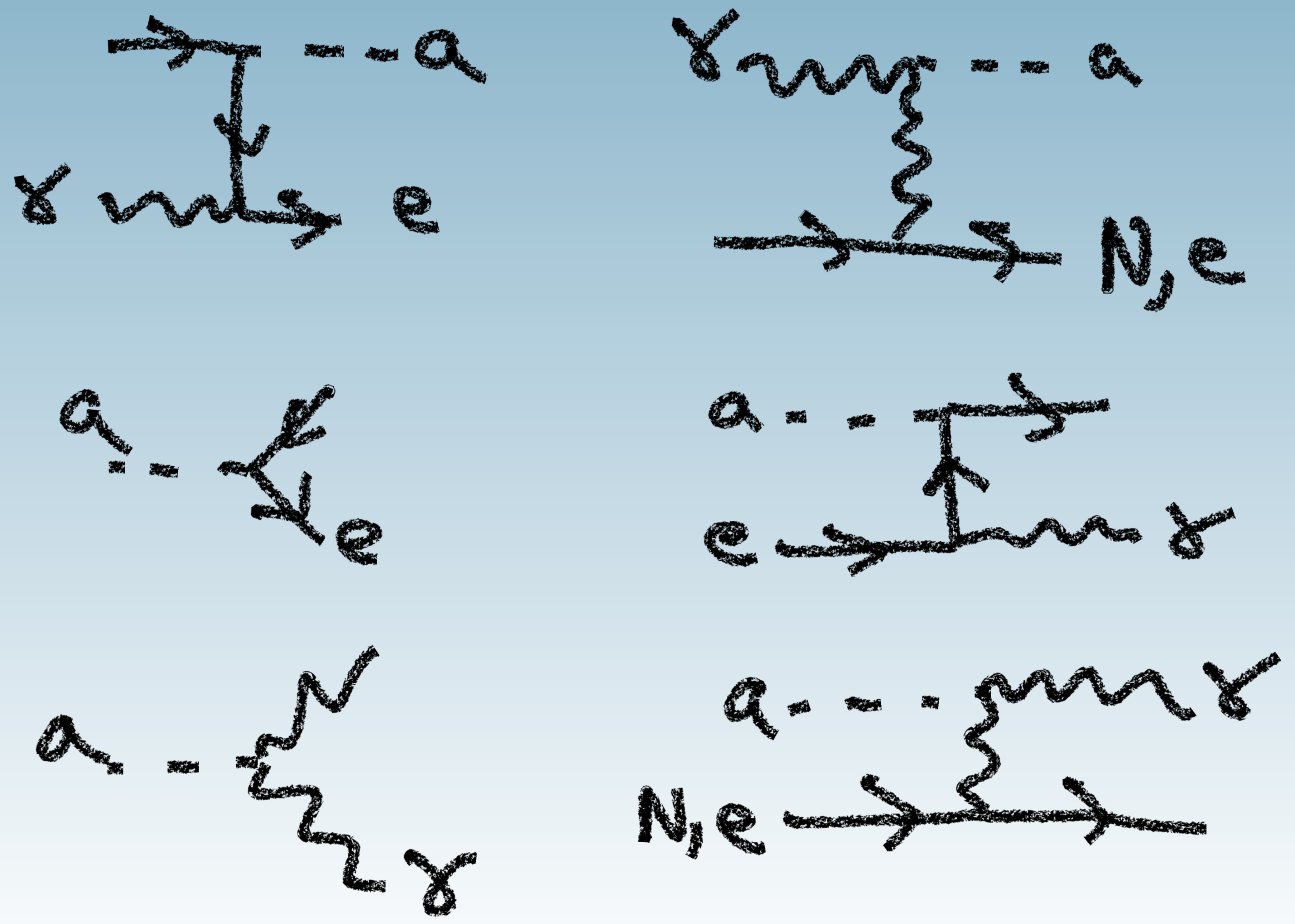
ALP Search Strategies - New Ideas

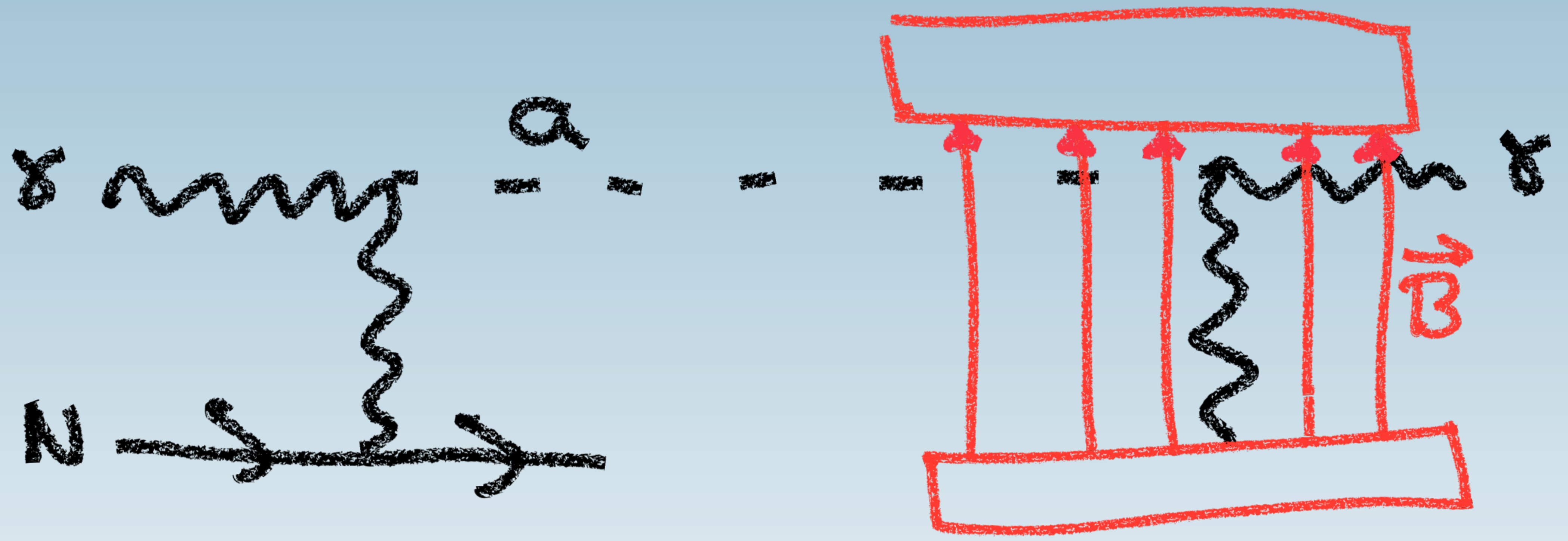
- ALPs can be produced at nuclear reactors
- Detectable at neutrino experiments

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



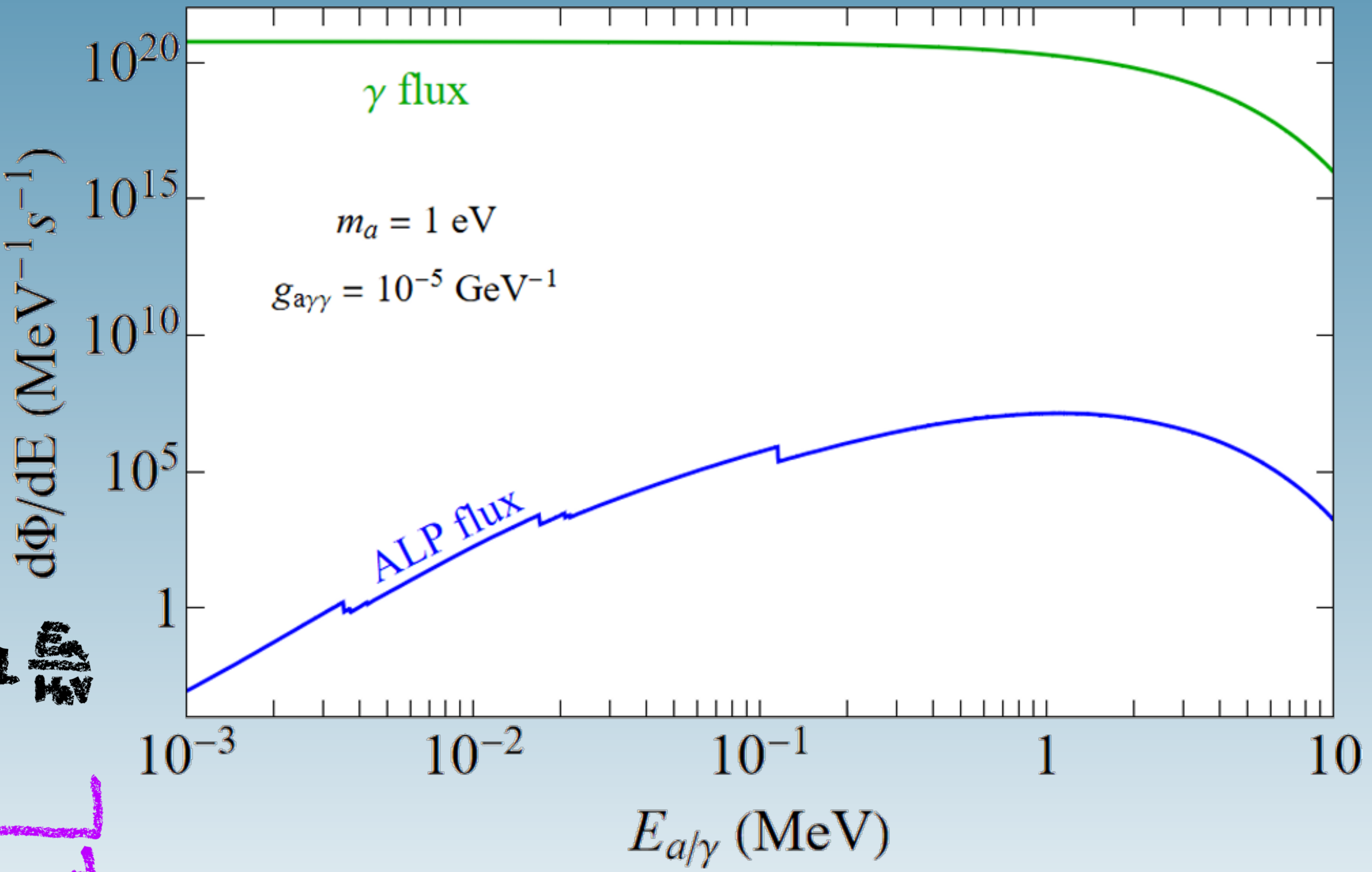


ALP Search Strategies - Reactoscopes

- ALPs produced at reactors

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

$$\frac{d\Phi_a}{dE_a} = \underbrace{\frac{1}{4\pi D^2}}_{\text{Spherical Flux}} \overbrace{e^{-\frac{D}{\tau}}}^{\text{Survival Prob}} \frac{\sigma_{\text{Prim}}(E_a)}{\sigma_{\text{Tot}}(E_a)} \underbrace{\frac{5{,}8\cdot 10^{20}}{\text{MeV s}}\left(\frac{P}{\text{GW}}\right)e^{-11\frac{E_a}{\text{MeV}}}}_{\text{Photon Flux in Reactor}}$$



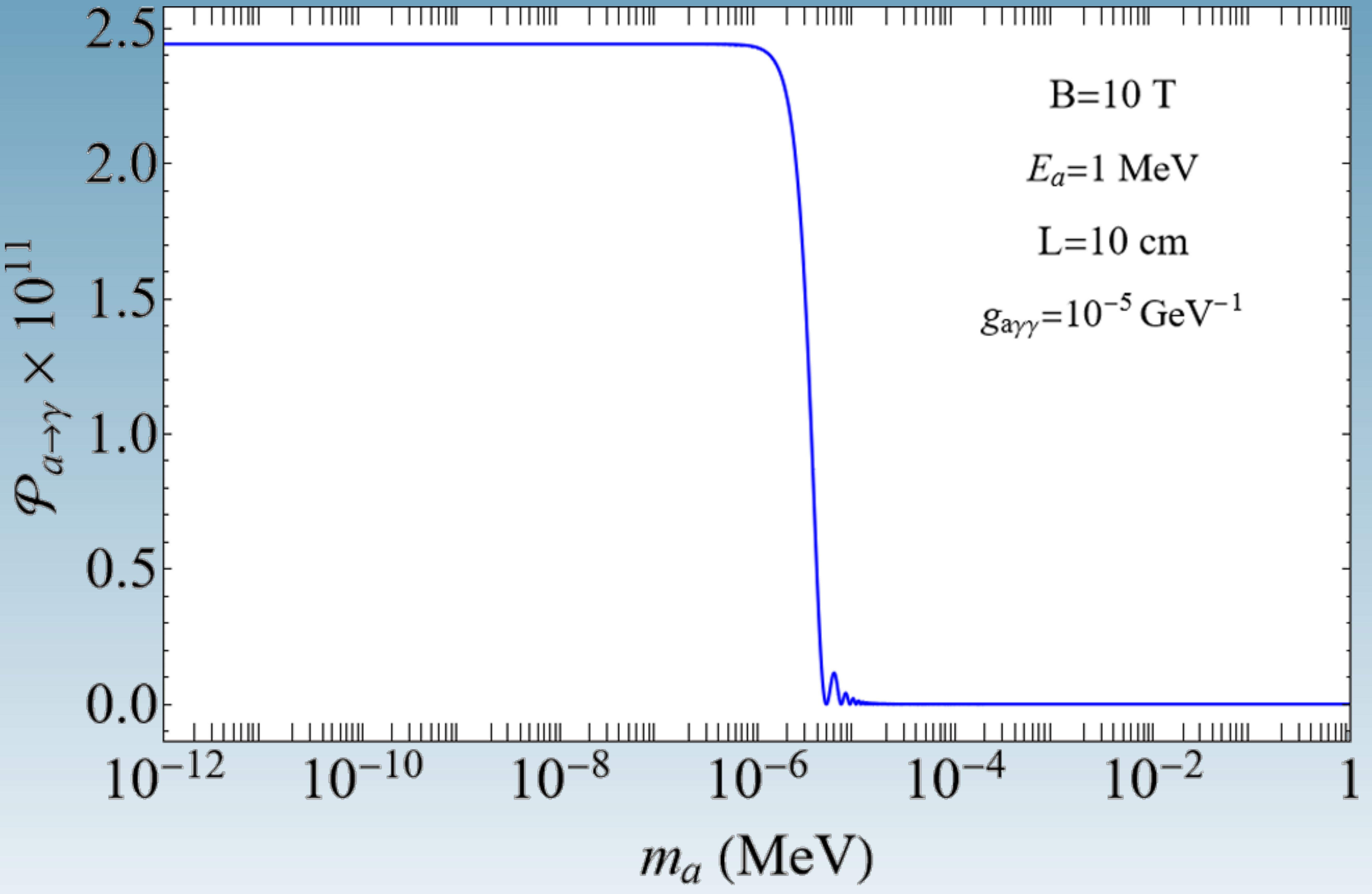
ALP Search Strategies - Reactoscopes

- 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

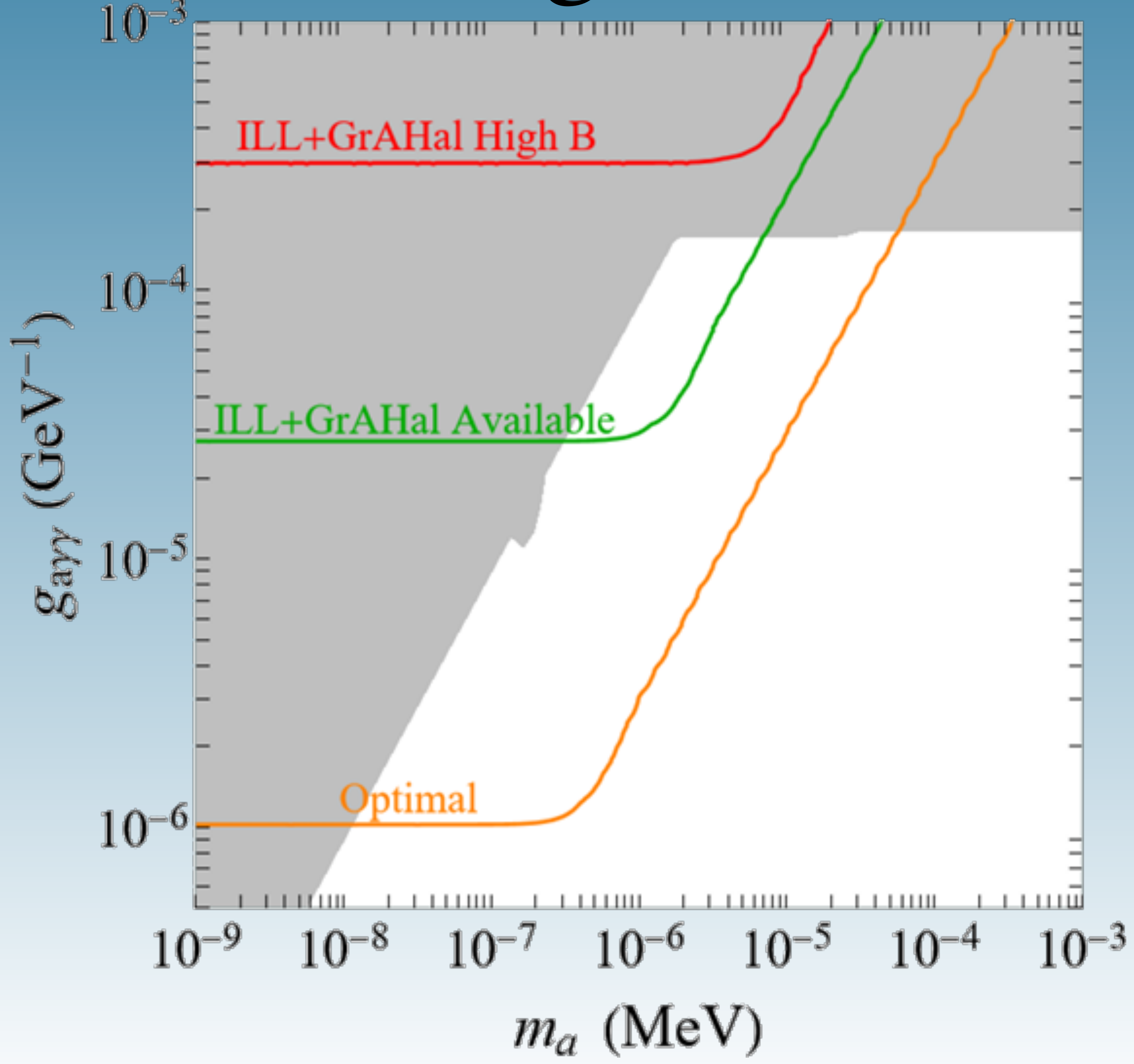
- Look no further, we have one already!

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 = 2 T
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
- EFTs are a very powerful tool
- Bounds deriving from them can be tricky to apply on specific models
- Two well motivated ALP benchmarks: DFSZ-like and KSVZ-like
- DFSZ-like analogous to 2HDM
- KSVZ-like free of scheme dependence
- A dedicated analysis that recasts existing bounds is necessary

Conclusions

- 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