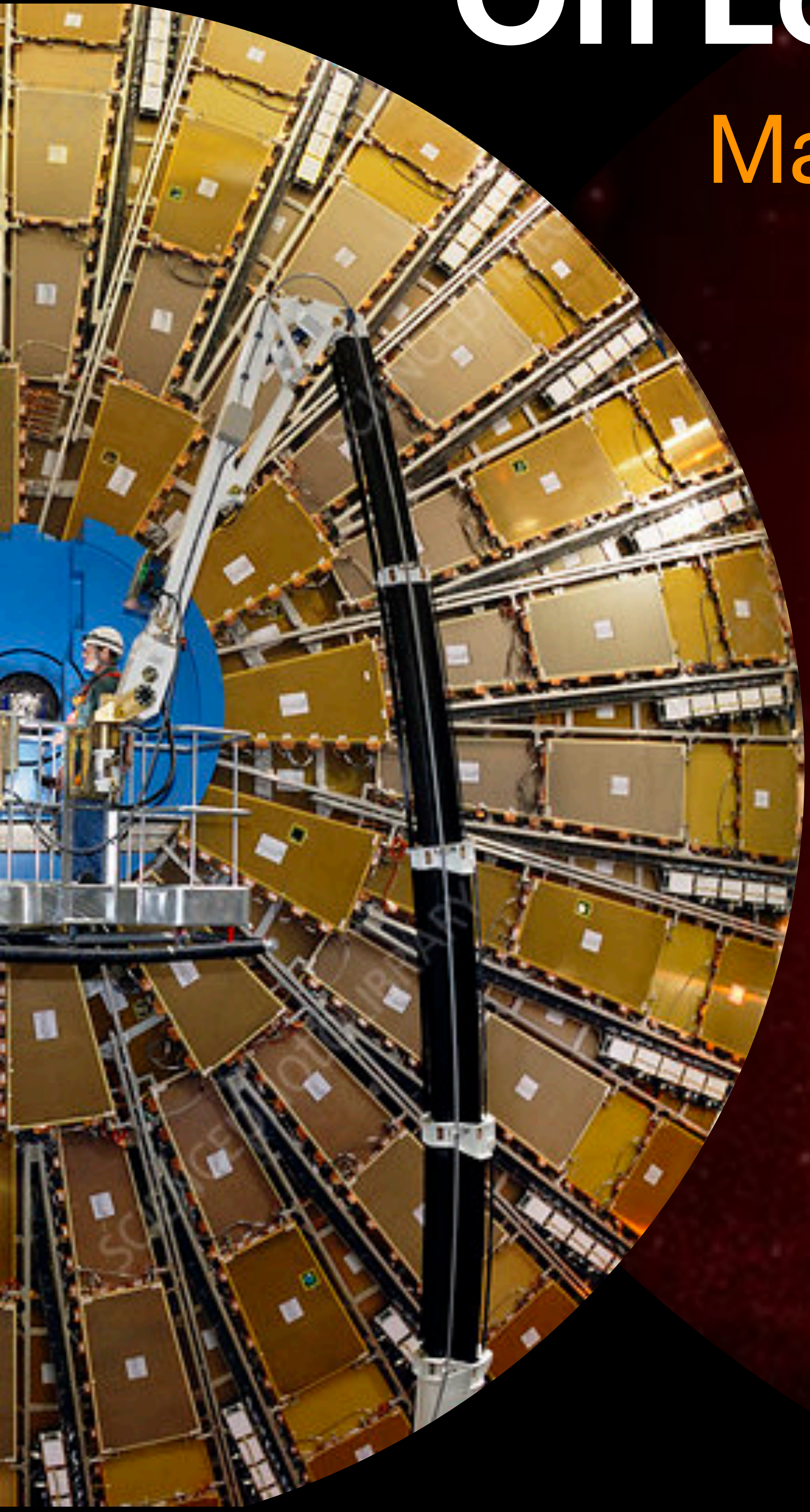
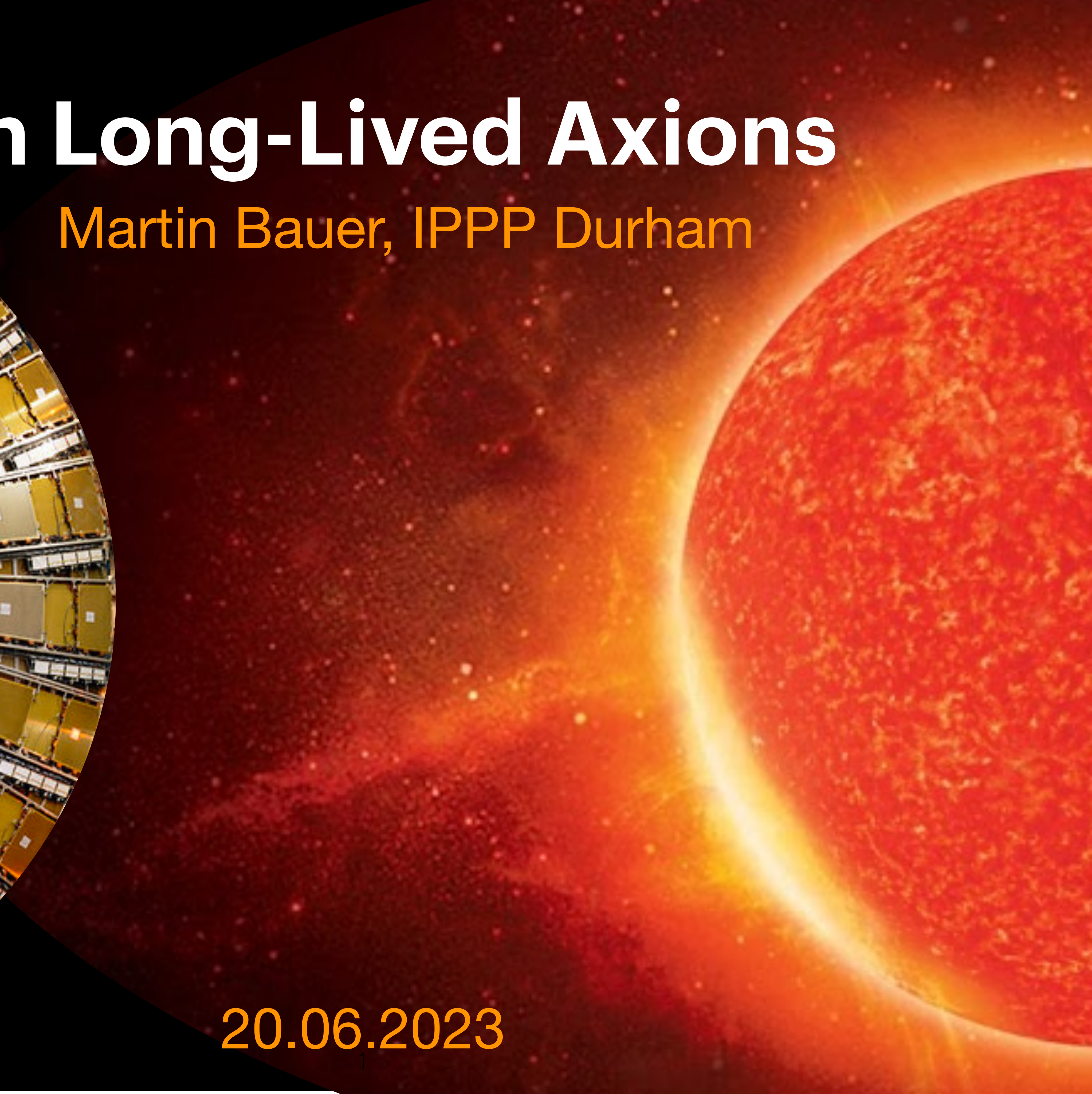


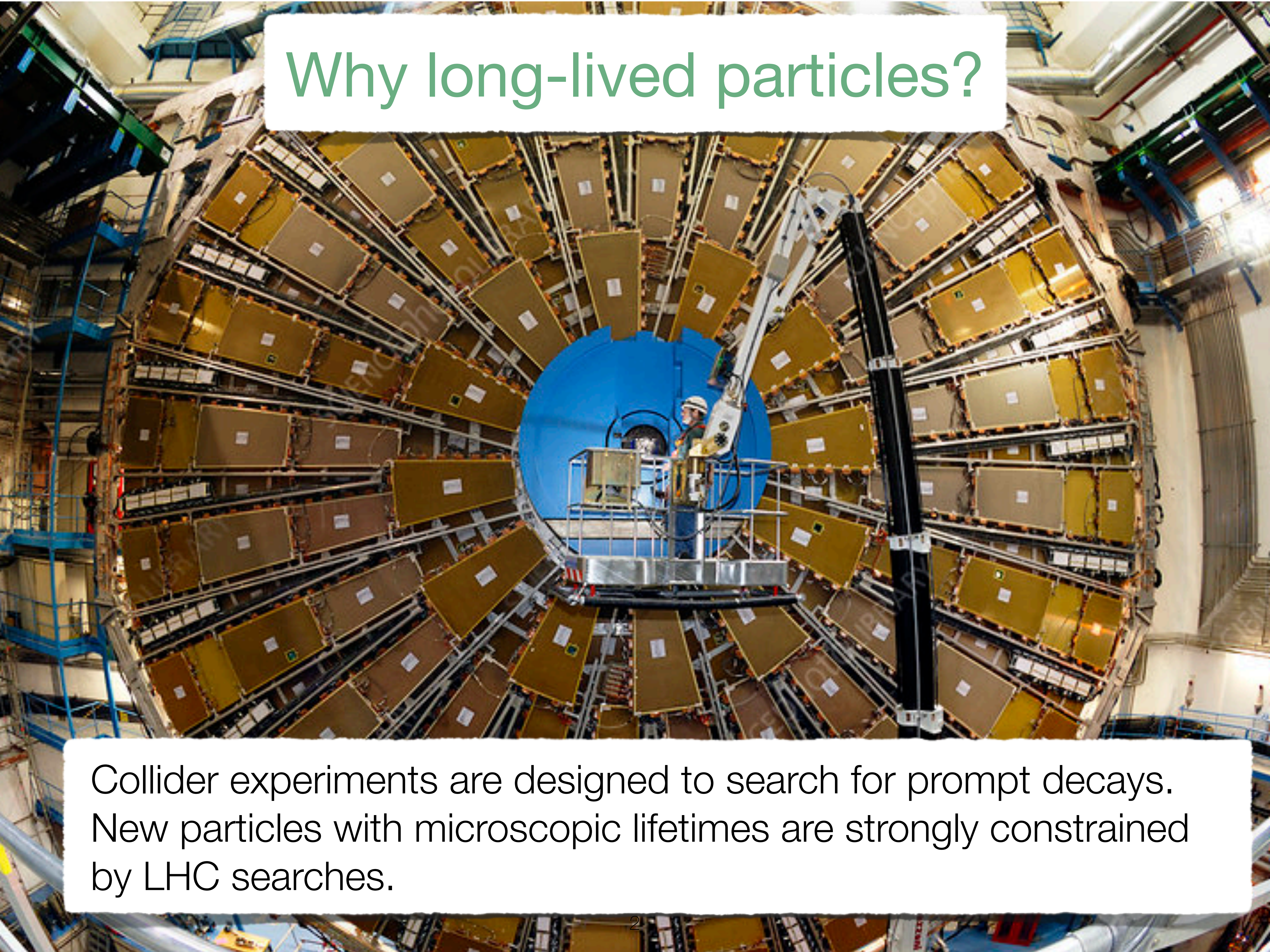


On Long-Lived Axions

Martin Bauer, IPPP Durham

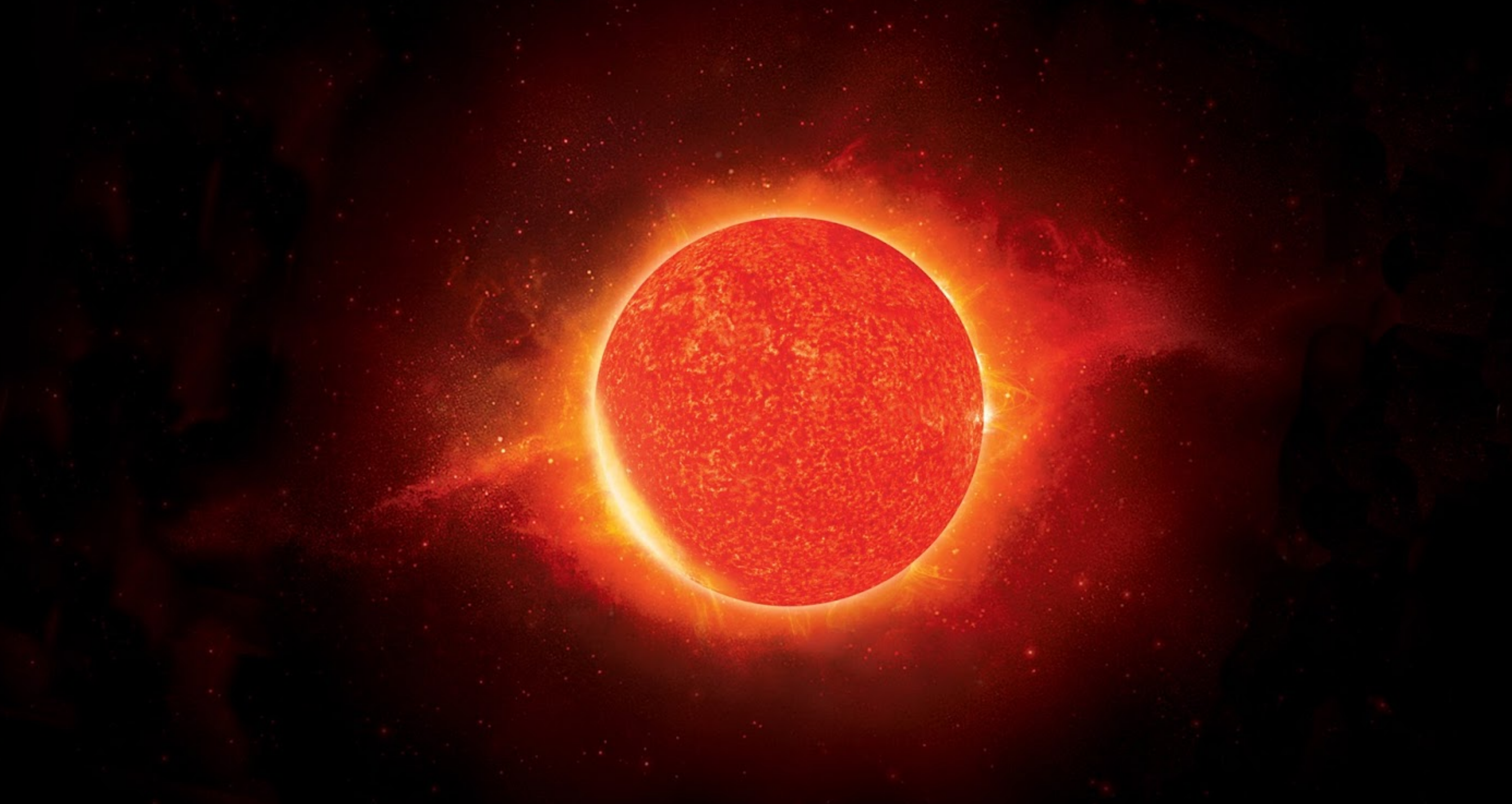
20.06.2023

Why long-lived particles?



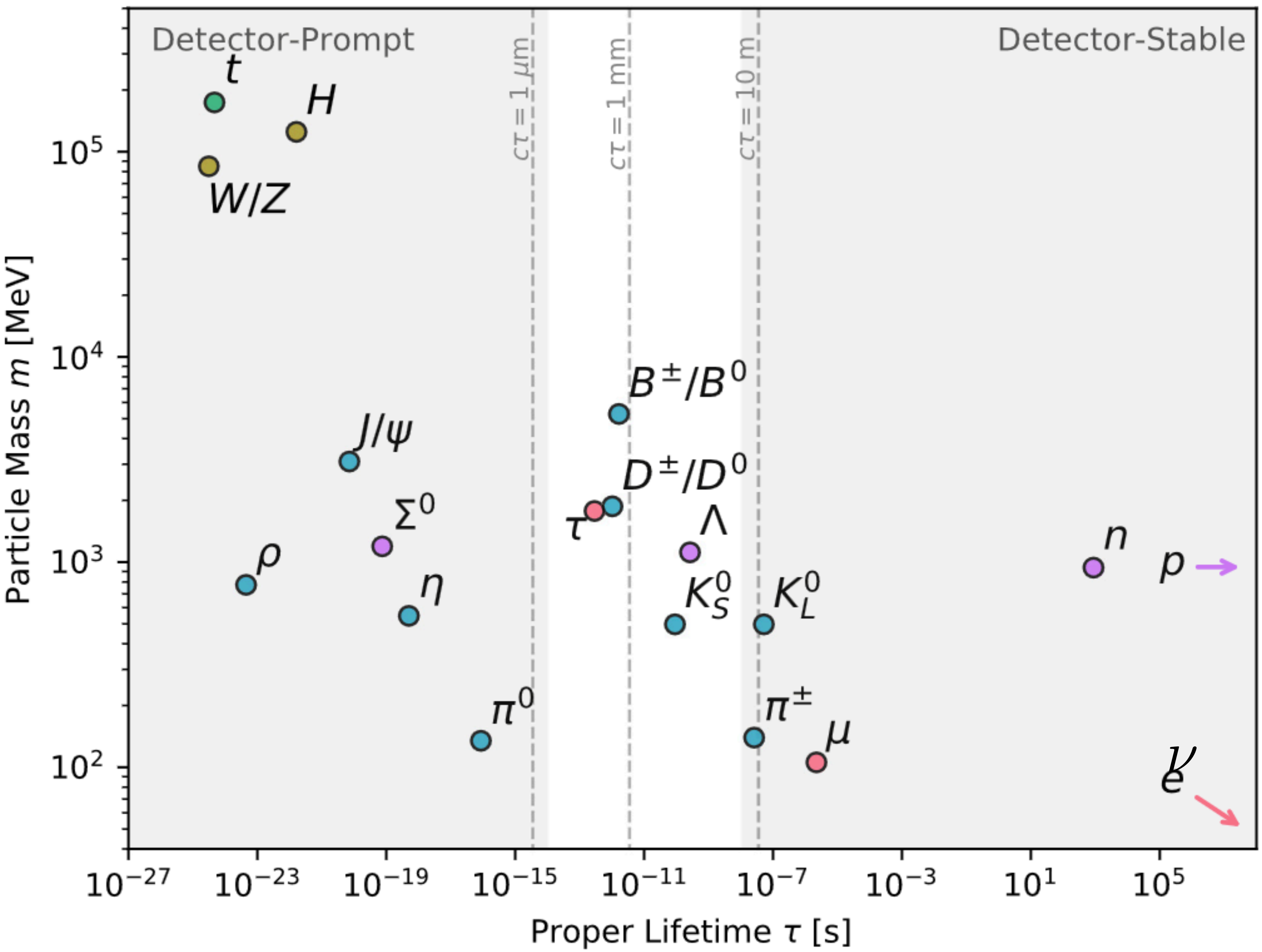
Collider experiments are designed to search for prompt decays. New particles with microscopic lifetimes are strongly constrained by LHC searches.

Why long-lived particles?



Very long-lived particles are constrained by astrophysical observables and beam-dump experiments.

Why long-lived particles?



Lee, Ohm, Soffer, Yu, Prog.Part.Nucl.Phys. 106 (2019)

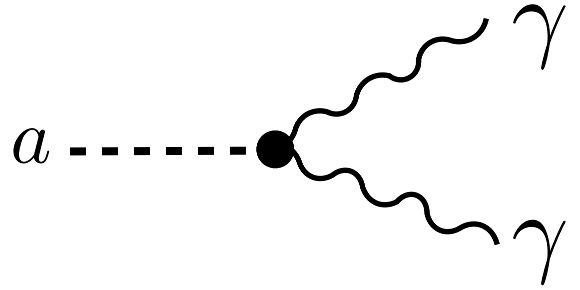
Why long-lived particles?

What makes particles long-lived?

$$\ell_a = \frac{\gamma_a \beta_a}{\Gamma_a}$$

Typically: Large boosts and small decay width. E.g. Axion-like particles coupled to photons

$$\mathcal{L} = c_{\gamma\gamma} \frac{\alpha}{4\pi f} a \, F_{\mu\nu} \tilde{F}^{\mu\nu}$$



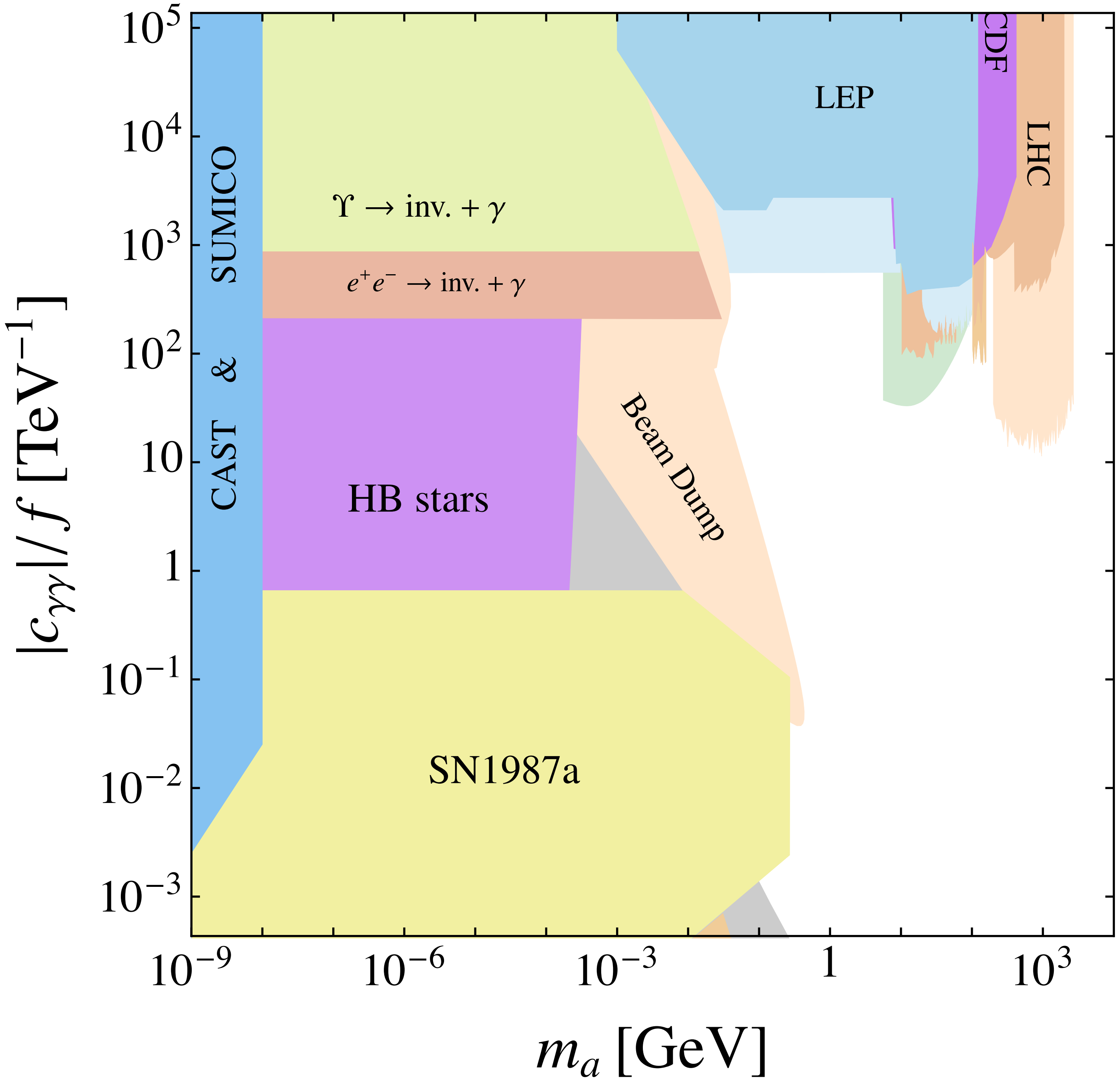
$$\Gamma_a = \frac{\alpha^2}{64\pi^3 f^2} c_{\gamma\gamma}^2 m_a^3$$

Typically: Long lifetime = Weak couplings and small masses

Why long-lived particles?

Constraints on axions interacting with photons

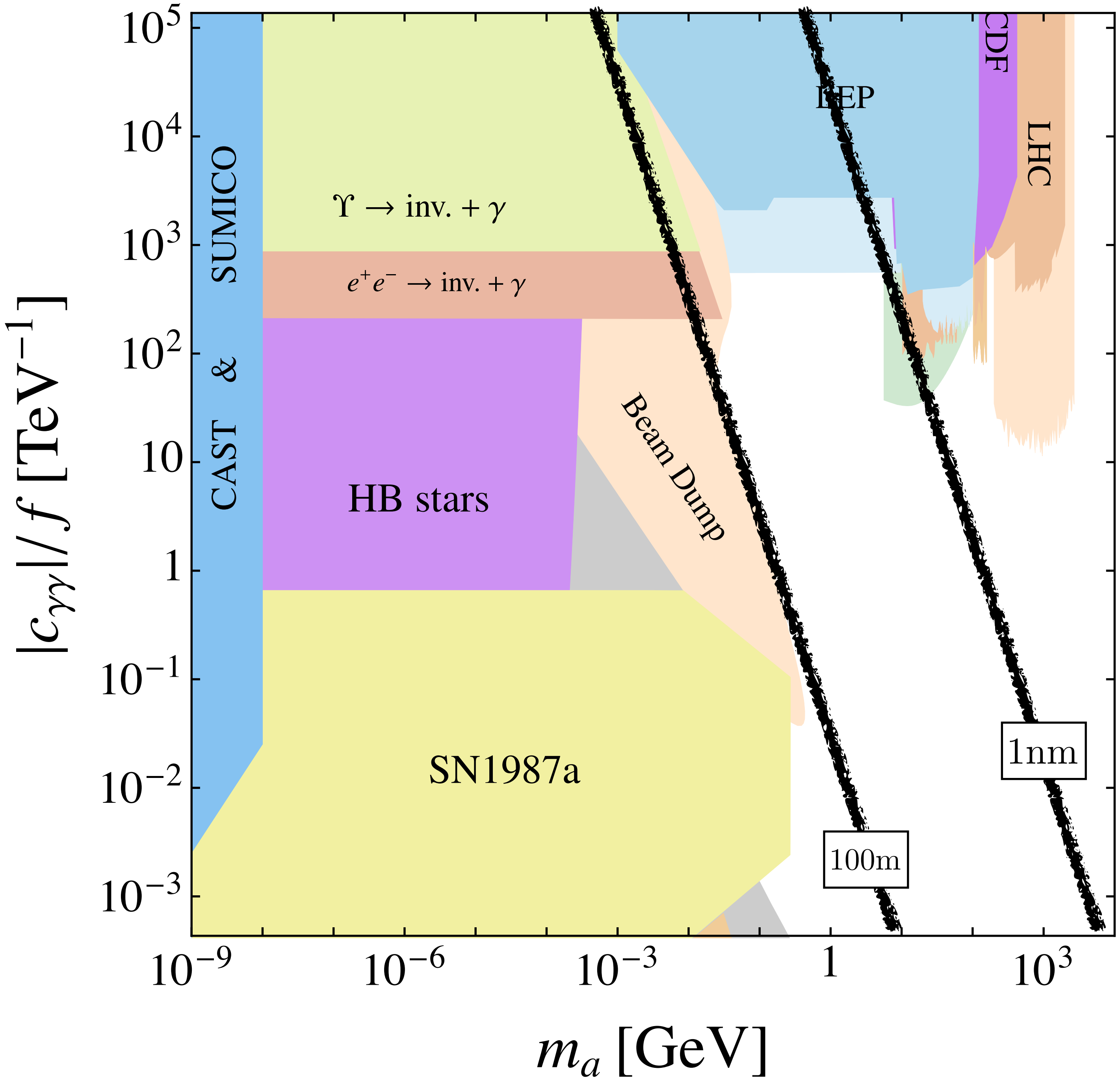
$$\mathcal{L} = c_{\gamma\gamma} \frac{\alpha}{4\pi f} a \, F_{\mu\nu} \tilde{F}^{\mu\nu}$$



Why long-lived particles?

‘Lifetime gap’ for Axions coupled to photons

$$\mathcal{L} = c_{\gamma\gamma}\frac{\alpha}{4\pi f}a\,F_{\mu\nu}\tilde{F}^{\mu\nu}$$



Axions

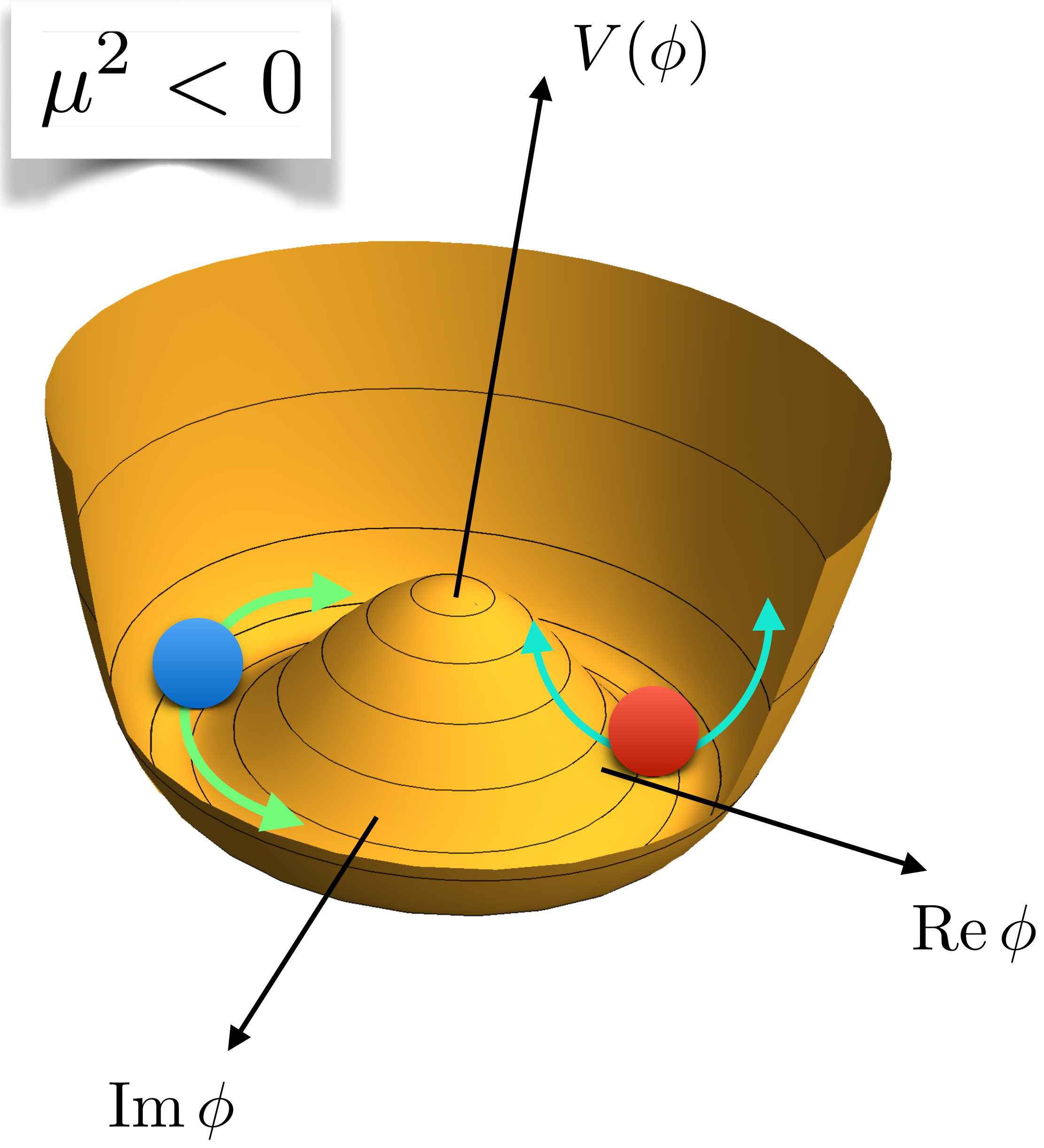
Every spontaneously broken continuous symmetry gives rise to massless spin-0 fields.

$$V(\phi) = \mu^2 \phi\phi^\dagger + \lambda(\phi\phi^\dagger)^2$$

$$\phi = (f+s)e^{ia/f}$$

$$m_s^2 = 4\lambda f^2 = |\mu^2|$$

$$m_a^2 = 0$$



Axions

Since the GB corresponds to the phase of a complex field, it is protected by a shift symmetry

$$\phi = (f + s)e^{ia/f}$$

it is protected by a shift symmetry

$$e^{ia(x)/f} \to e^{i(a(x)+c)/f} = e^{ia(x)/f}e^{ic/f}$$

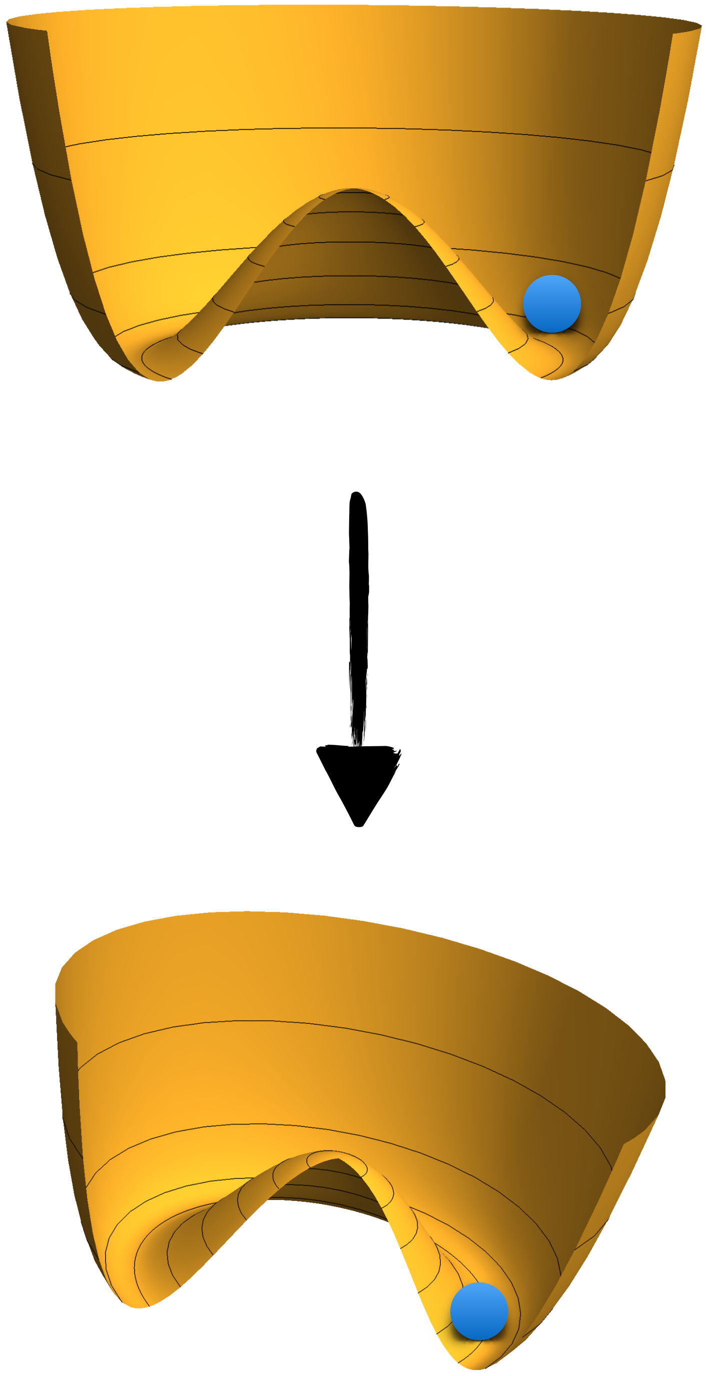
This symmetry forbids a mass term, and all couplings are suppressed by the UV scale

$$\mathcal{L} = \frac{1}{2}\partial_\mu a\,\partial^\mu a + c_\mu \frac{\partial^\nu a}{4\pi f}\,\bar{\mu}\gamma_\nu\mu + \dots$$

Axions

An exactly massless boson is very problematic.

The global symmetry can be broken by explicit masses or anomalous effects



$$\mathcal{L} = \frac{1}{2}\partial_\mu a\, \partial^\mu a + c_\mu \frac{\partial^\nu a}{4\pi f}\, \bar{\mu}\gamma_\nu \mu + \ldots + \frac{1}{2} m_a^2 a^2$$

$$m_a = \frac{\mu^2}{f}$$

Weak couplings and small masses

Axions

The most famous example is the pion

$$\mathcal{L}_{\rm QCD} = \bar{q}_L i\not{D}\, q_L + \bar{q}_R i\not{D}\, q_R + m_q \bar{q}_L q_R$$

$$\langle \bar{q}_L q_R \rangle = \Lambda^3_{\rm QCD} \approx {\rm GeV}^3$$

The pion mass is controlled by the explicit breaking through light quark masses

$$m_\pi^2 = \frac{m_u + m_d}{f_\pi^2} \Lambda^3_{\rm QCD} \quad \approx (140\,{\rm MeV})^2$$

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Scales at f

Axion

The QCD axion

The most famous example is the QCD axion

$$\mathcal{L}_{\text{QCD-axion}} = \frac{\partial_\mu a}{f}\bar{q}\gamma_\mu\gamma_5 q + c_{GG}\frac{\alpha_s}{4\pi f}a\,G_{\mu\nu}\tilde{G}^{\mu\nu}$$

The mass of the QCD axion is linked to it’s couplings

$$m_a^2 = \cdot\, c_{GG}^2\frac{f_\pi^2 m_\pi^2}{f^2}\frac{2m_u m_d}{(m_u+m_d)^2}$$

Explains the small strong CP phase

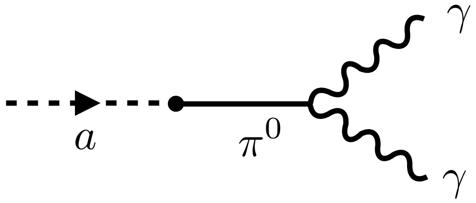
$$\theta\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \rightarrow \qquad \left(\theta + 2c_{GG}\frac{a}{f}\right)\frac{\alpha_s}{4\pi}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

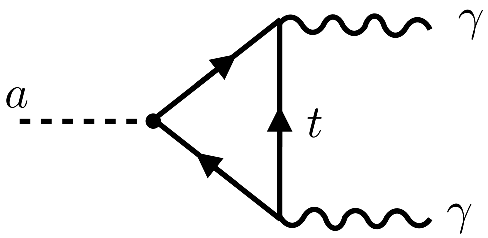
Neutron EDM $$\frac{d_n}{e} \propto -\theta\frac{m_u m_d}{(m_u+m_d)(2m_s-m_u-m_d)}$$

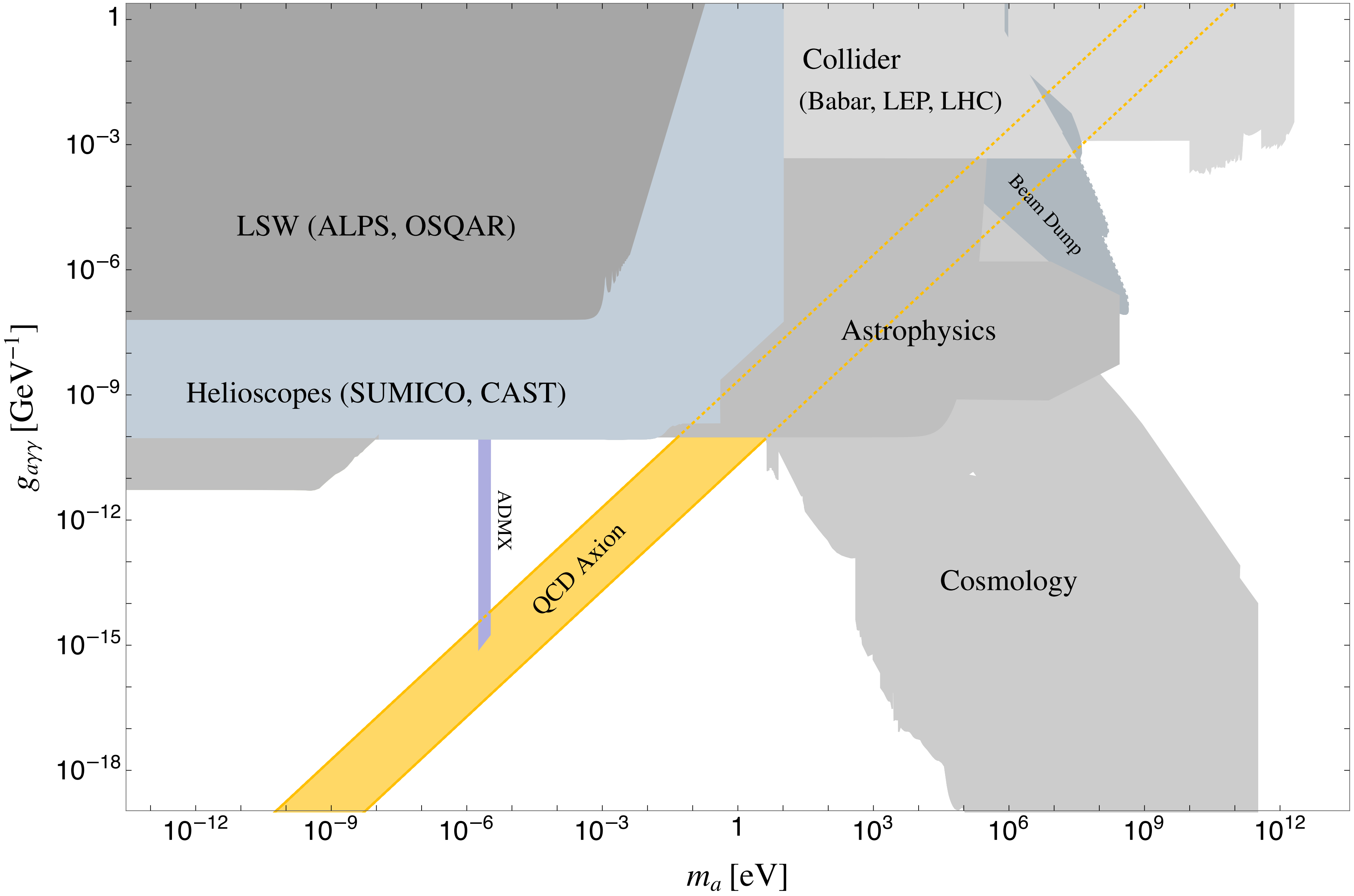
The QCD axion

The Axion-photon coupling is related to its mass

Both gluon- and fermion couplings contribute







Axionlike Particles

Most general dimension five Lagrangian at the UV scale

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\,\sum_F \bar\psi_F\,\boldsymbol{c}_F\,\gamma_\mu\,\psi_F + c_\phi\frac{\partial^\mu a}{f}\,\left(\phi^\dagger iD_\mu\phi + \text{h.c.}\right)$$

$$+ c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde G^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde B^{\mu\nu}\,.$$

All couplings are suppressed by the UV scale f

Georgi, Kaplan, Randall, Phys. Lett. 169B, 73 (1986)

Axionlike Particles

Most general dimension five Lagrangian at the UV scale

explicit mass term

couplings to fermions
F=Q,u,d,L,e

coupling to the Higgs current

$$\mathcal{L}_{\rm eff}^{D\le 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\,\sum_F \bar\psi_F\,\boldsymbol{c}_F\,\gamma_\mu\,\psi_F + c_\phi\,\frac{\partial^\mu a}{f}\,\big(\phi^\dagger i D_\mu \phi + \text{h.c.}\big)$$

$$+\, c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G_{\mu\nu}^a\,\tilde G^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W_{\mu\nu}^A\,\tilde W^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde B^{\mu\nu}\,.$$

coupling to gluons

coupling to $SU(2)_L$ gauge bosons

coupling to hypercharge

All couplings are suppressed by the UV scale f

Georgi, Kaplan, Randall, Phys. Lett. 169B, 73 (1986)

Axionlike Particles

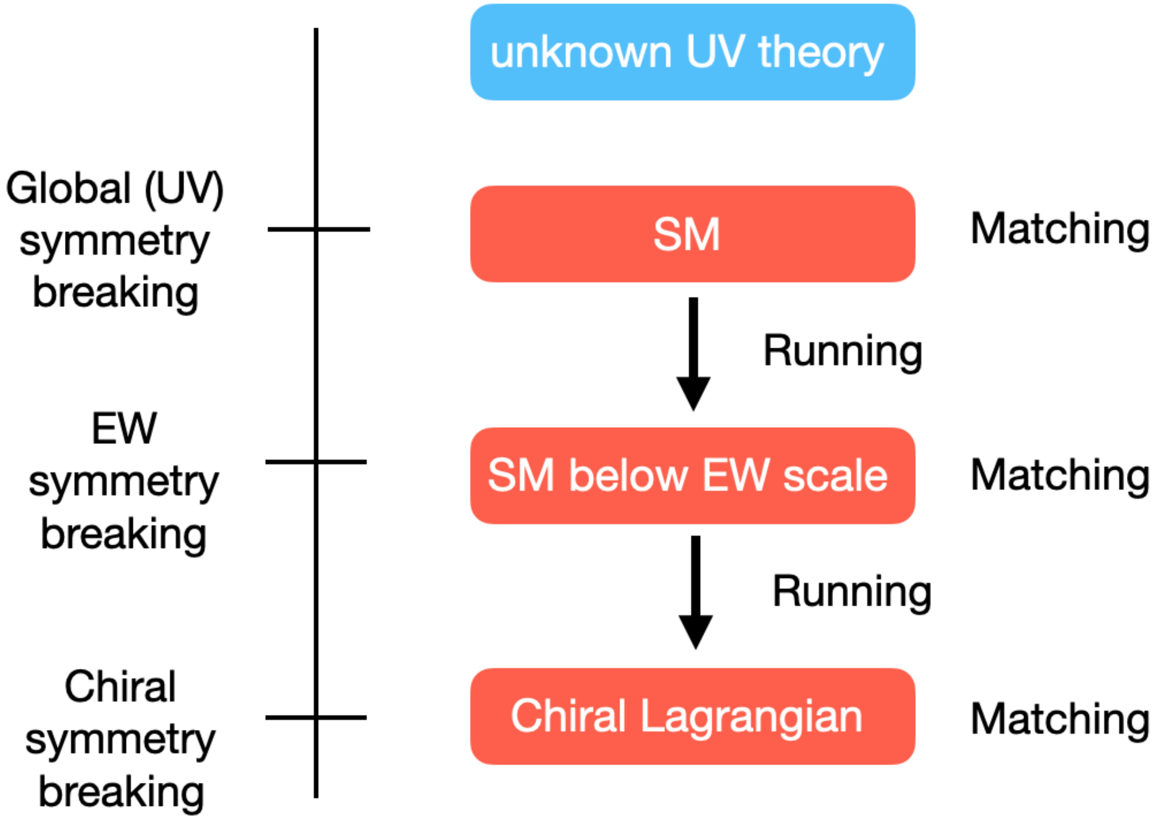
For ALPs the link between coupling and mass is broken

$$m_a^2 = m_{a,0}^2 \left[1 + \mathcal{O}\left(\frac{f_\pi^2}{f^2} \right) \right] + c_{GG}^2 \, \frac{f_\pi^2 \, m_\pi^2}{f^2} \, \frac{2 m_u m_d}{(m_u + m_d)^2}$$

Solution to the strong CP problem not only for the ‘axion band’

The phenomenology is very different depending on the interactions induced at the UV scale

RG effects are important!



unknown UV theory

Global (UV) symmetry breaking

SM

Matching

Running

EW symmetry breaking

SM below EW scale

Matching

Running

Chiral symmetry breaking

Chiral Lagrangian

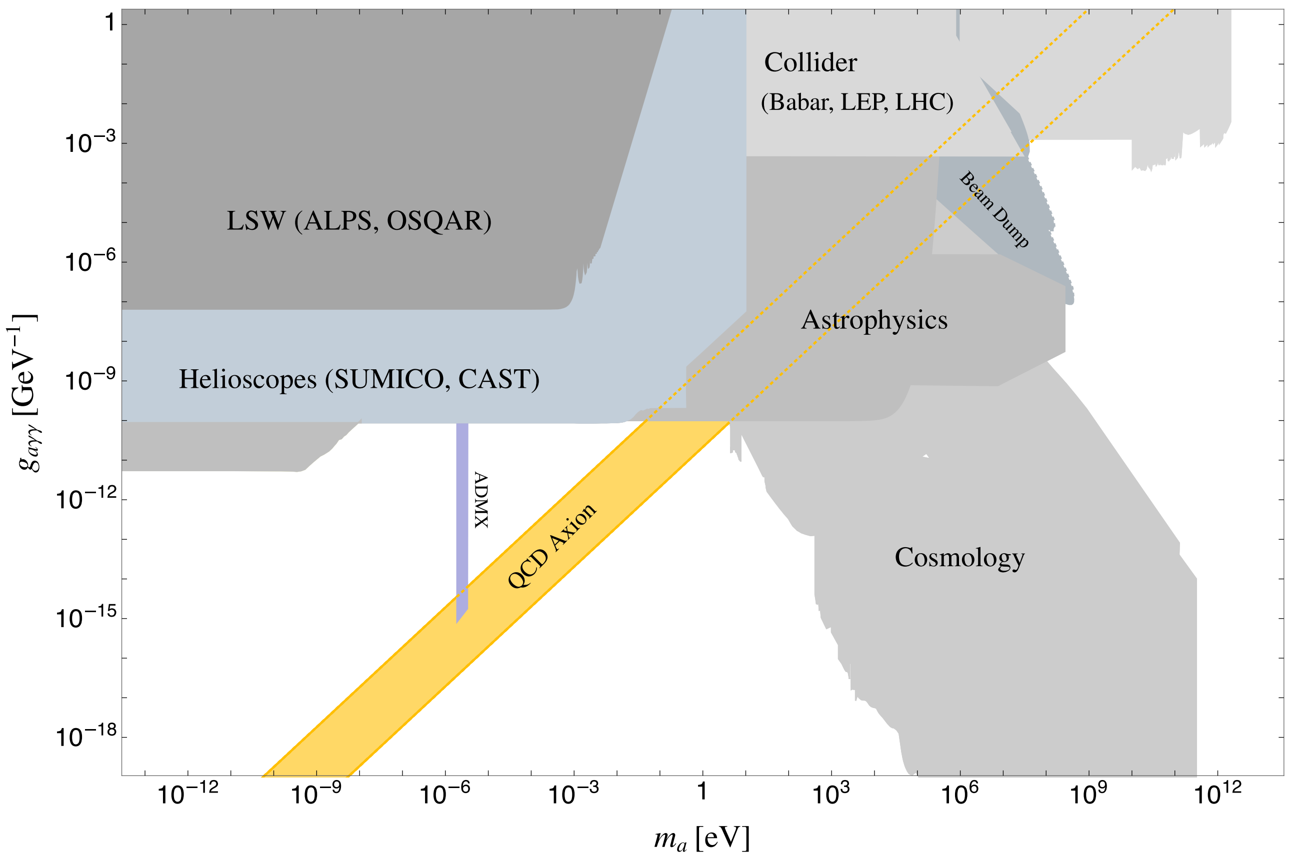
Matching

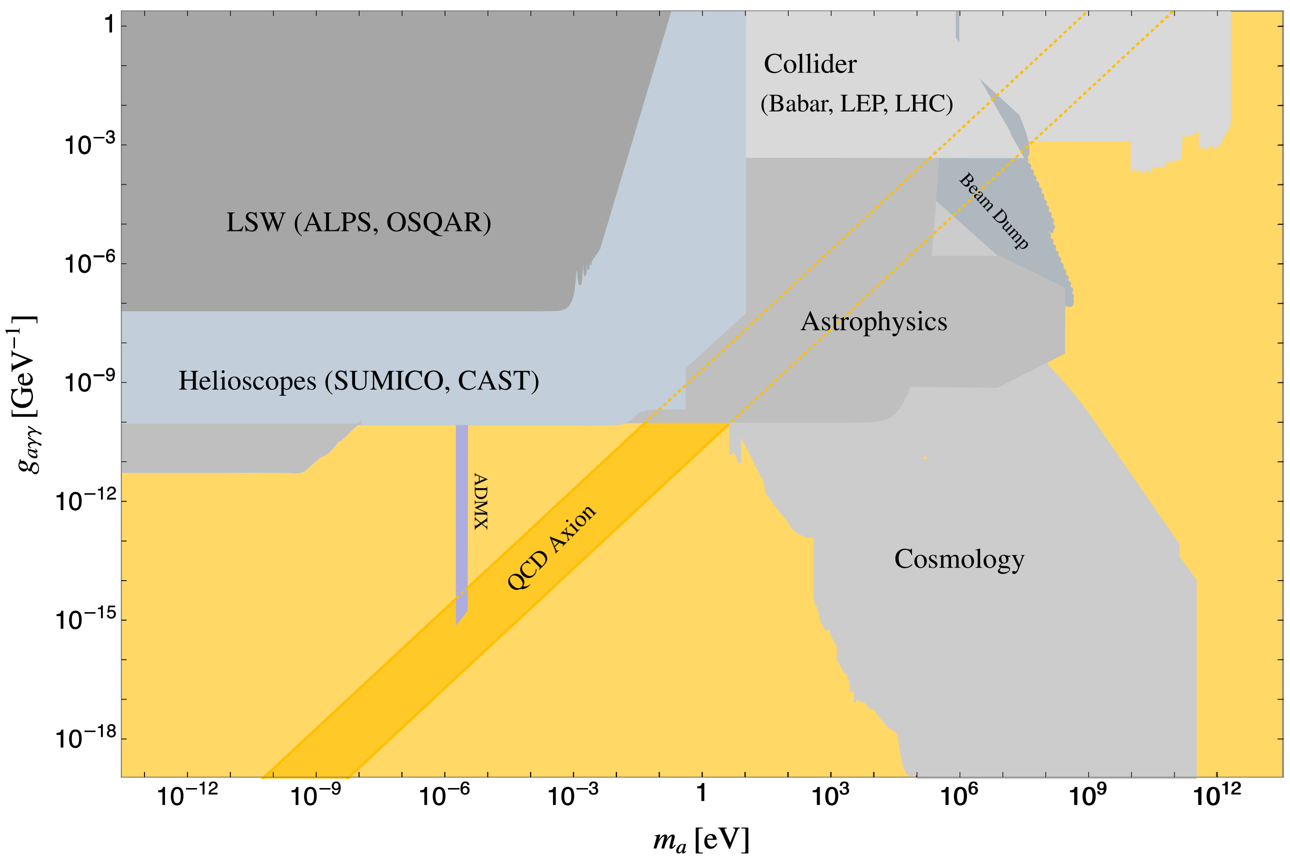
Chala et al.,
Eur.Phys.J.C 81 (2021) 2

MB, Neubert, Renner, Schnubel,
Thamm, *JHEP* 04 (2021) 063

Axionlike Particles

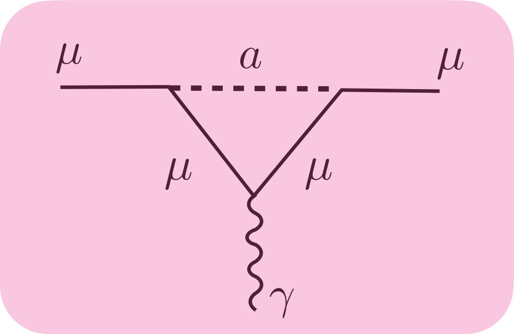
For ALPs the link between coupling and mass is broken. In principle the strong CP problem can be explained outside the QCD axion band

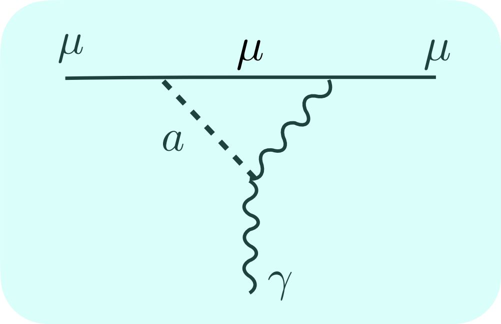




Valenti, Vecchi, Xu, *JHEP* 10 (2022) 025 and references

Axionlike Particles

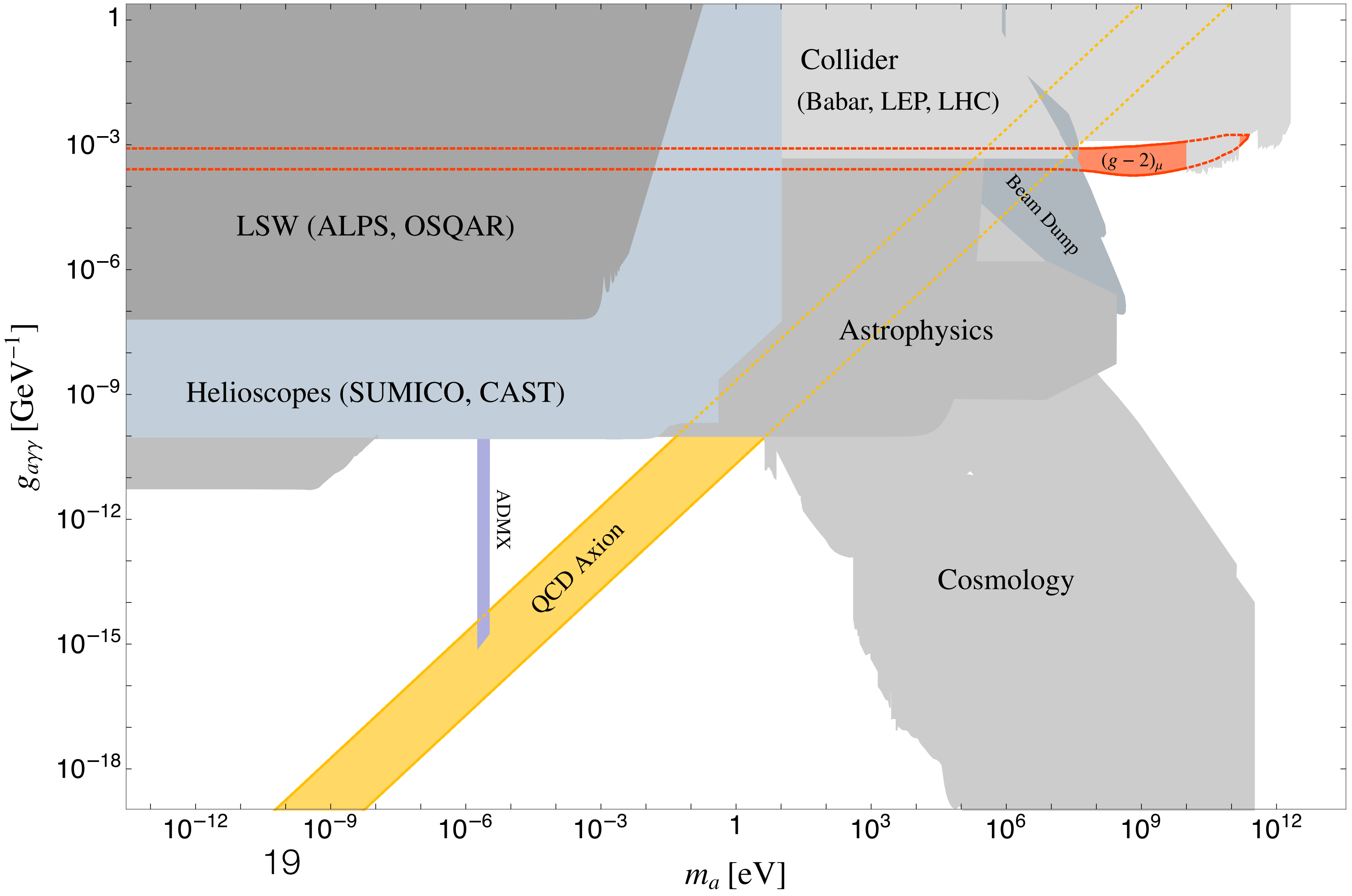




For small muon couplings the muon anomalous magnetic moment can be explained

$$\Delta a_\mu = \frac{m_\mu^2}{\Lambda^2}\left\{K_{a_\mu}(\mu) - \frac{(c_{\mu\mu})^2}{16\pi^2}\,h_1\!\left(\frac{m_a^2}{m_\mu^2}\right) - \frac{2\alpha}{\pi}\,c_{\mu\mu}\,C_{\gamma\gamma}\left[\ln\frac{\mu^2}{m_\mu^2} + \delta_2 + 3 - h_2\!\left(\frac{m_a^2}{m_\mu^2}\right)\right]\right\}$$

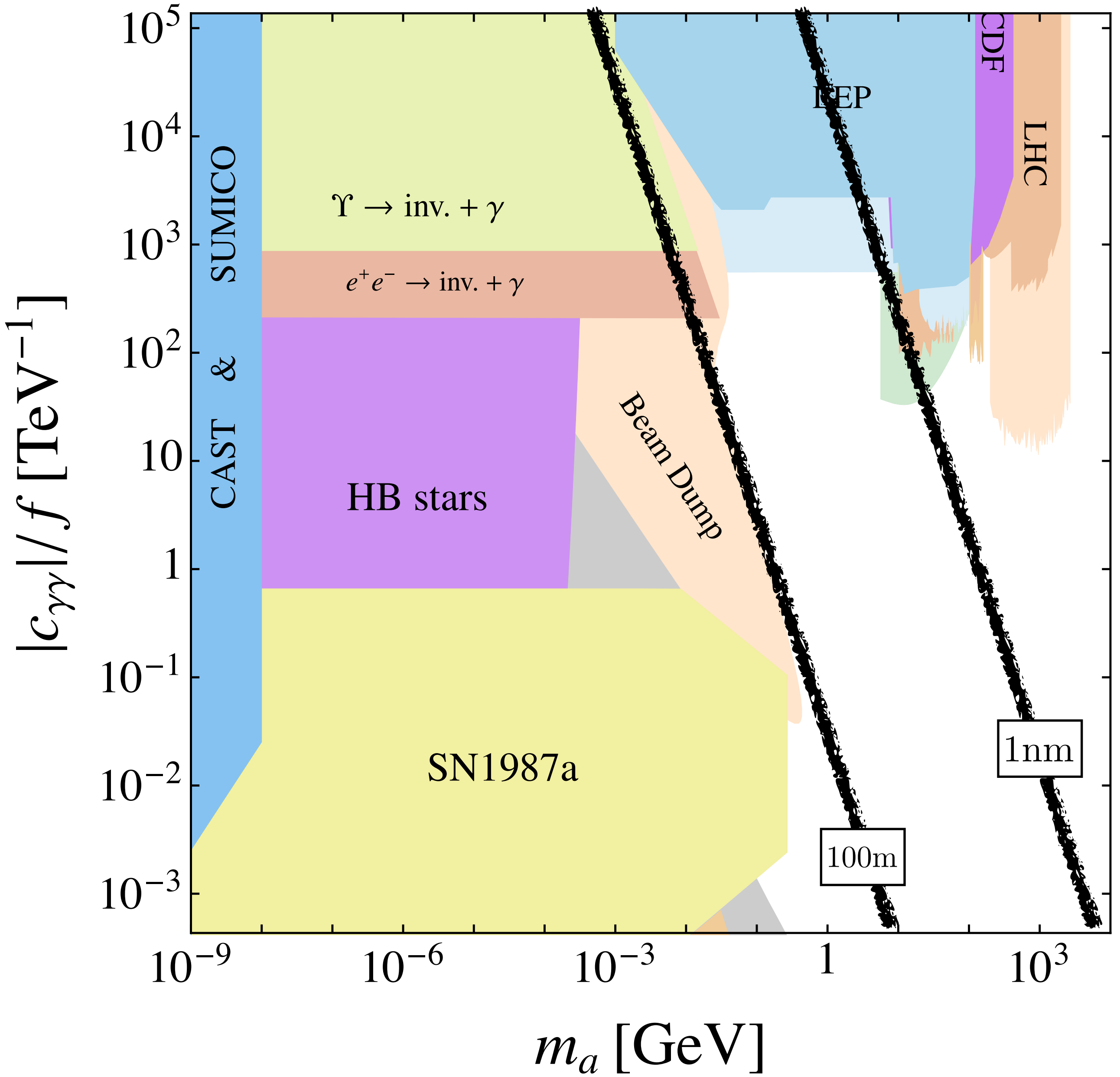
The allowed parameter space is right in the ‘lifetime gap’



MB, Neubert, Renner, Schnubel, Thamm, Phys.Rev.Lett. 124 (2020)

How to close the gap?

Different strategies:



1. High statistics

2. (Very) displaced vertices

3. Flavor observables

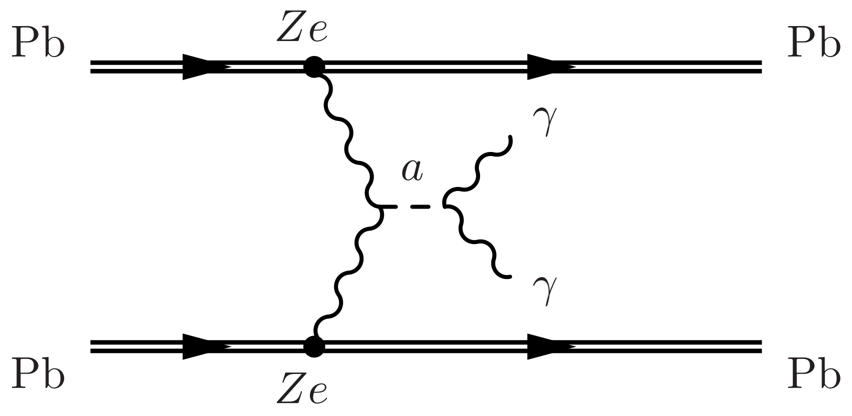
4. Exotic decays

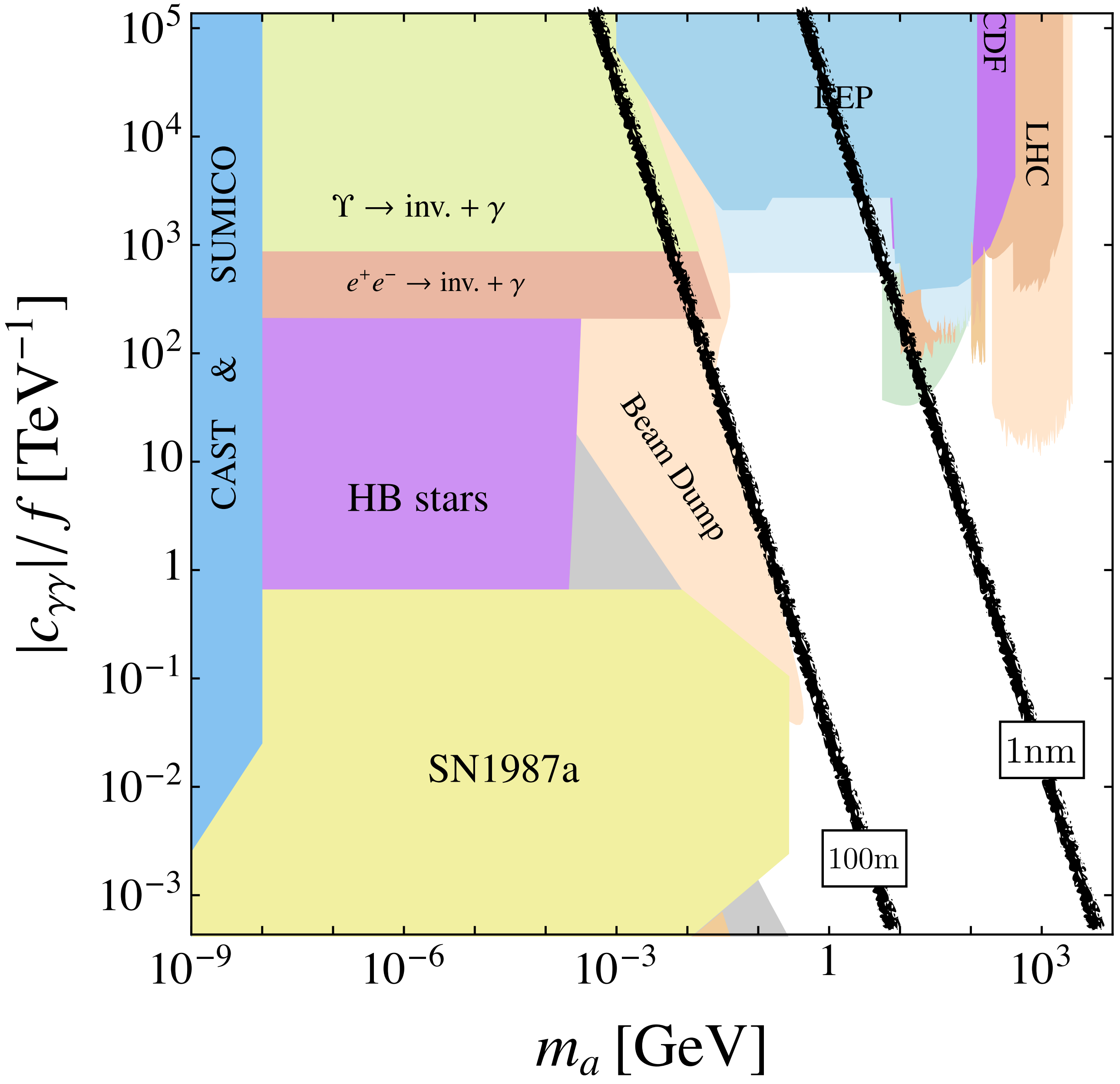
Knapen et al. Phys. Rev. Lett. **118** (2017)
ATLAS, Nature Phys **13**, no. 9, 852 (2017)
CMS 1810.04602

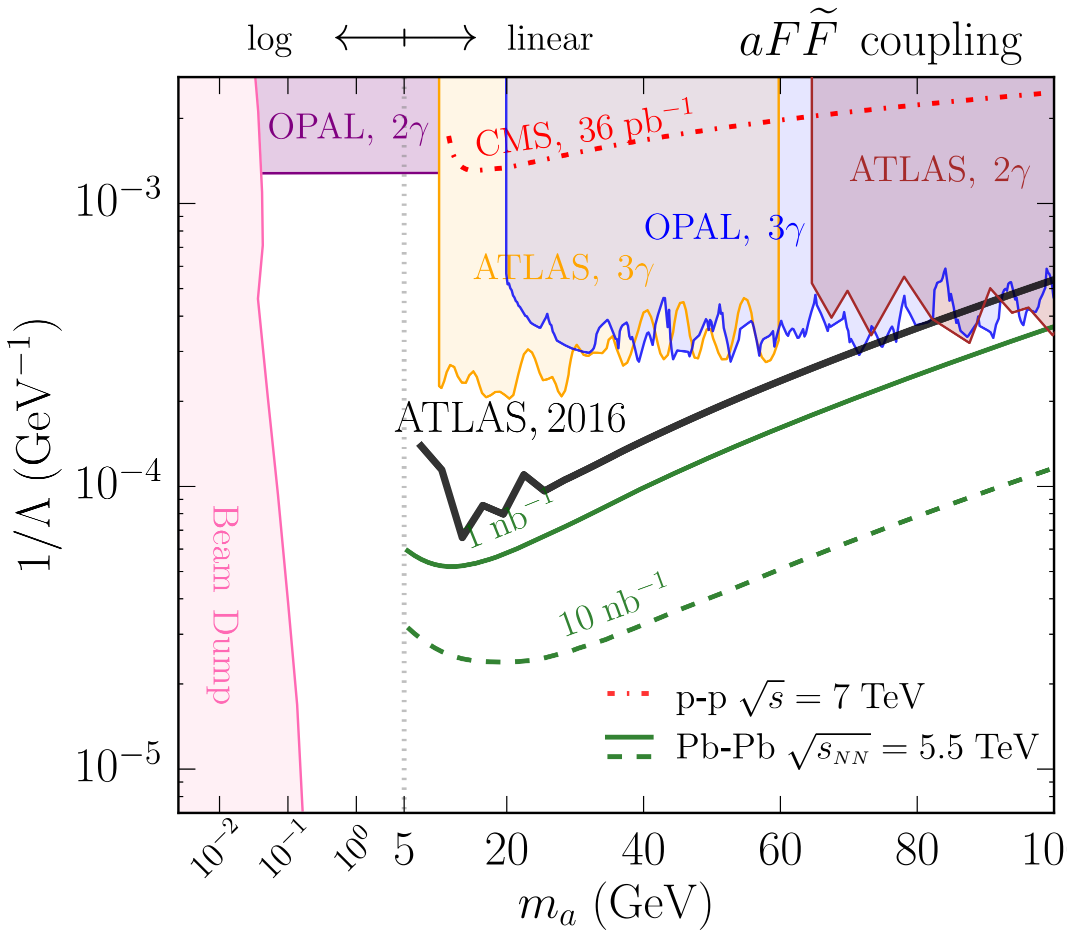
How to close the gap?

High statistics:

Photon fusion in Ion scattering







Knapen et al. Phys. Rev. Lett. **118** (2017)

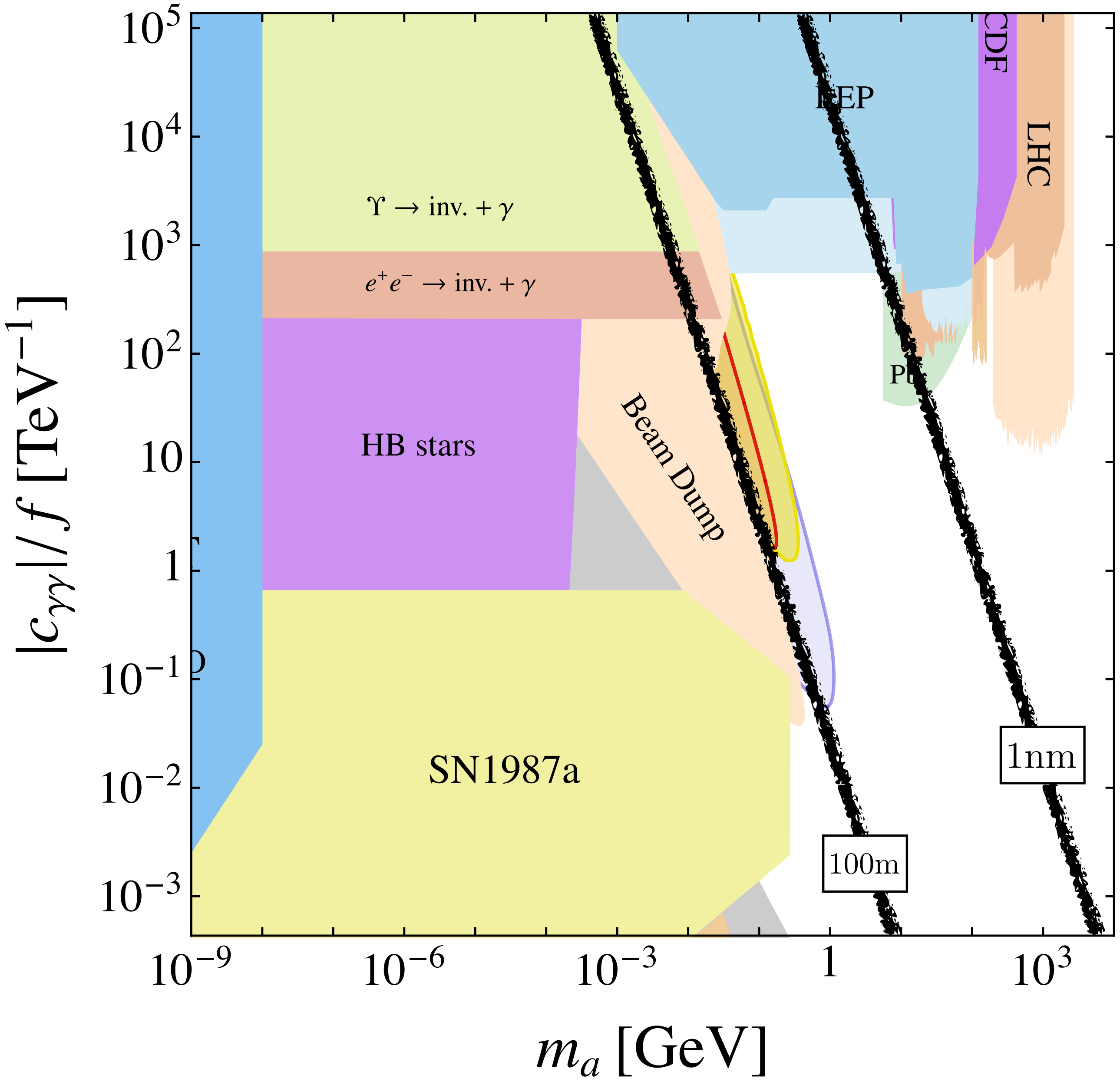
ATLAS, Nature Phys **13**, no. 9, 852 (2017)

CMS 1810.04602

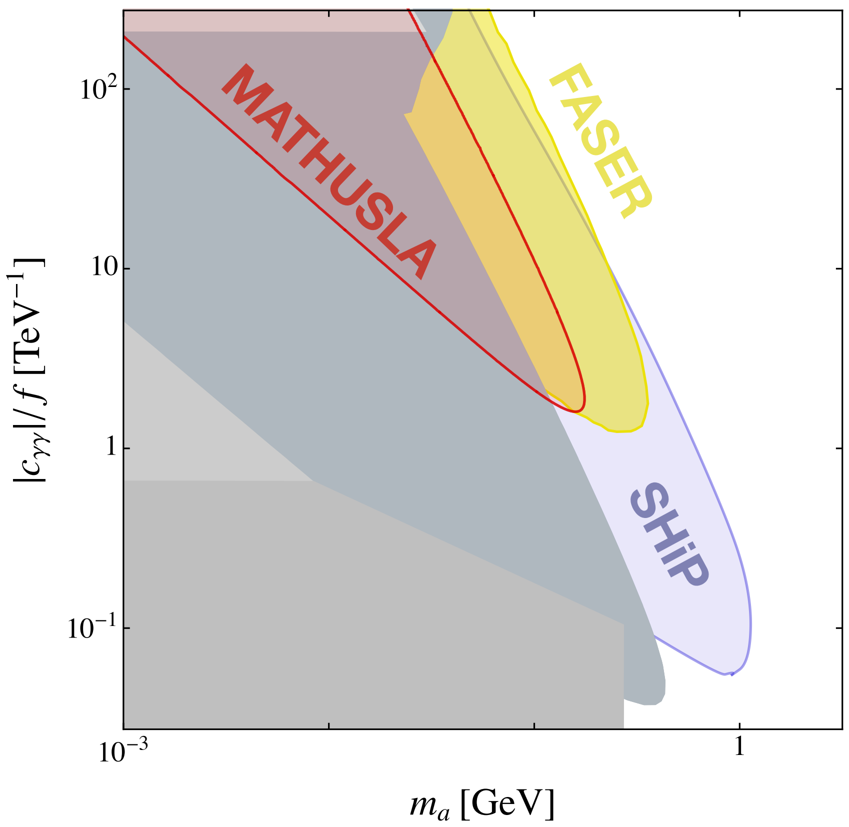
How to close the gap?

(Really) displaced vertices:

ANUBIS, CodexB, FASER, MATHUSLA, SHIP,…



$Z \to a + \gamma \to 3\gamma$



Curtin et al 1806.07396

Feng et. al. Phys. Rev. D **98**, 055021

Gligorov et al. Phys. Rev. D **97**, no.1 015023, (2018)

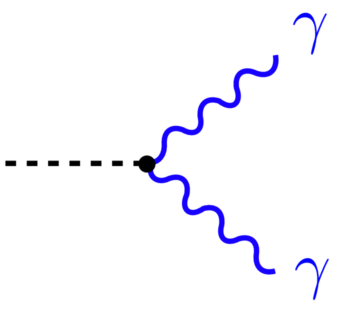
Alekhin et. al. Rept. Prog. Phys. **79**, 124201 (2016)

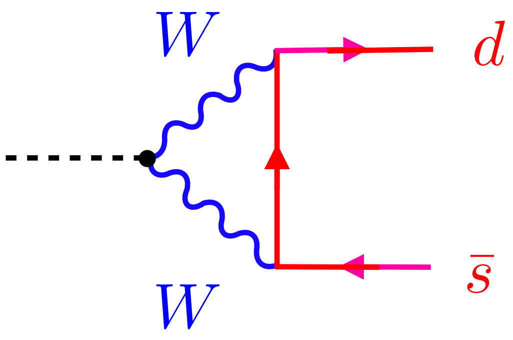
MB, Neubert, Thamm, Eur.Phys. J.C **79**

MB, Brandt, Lee, Ohm1909.13022

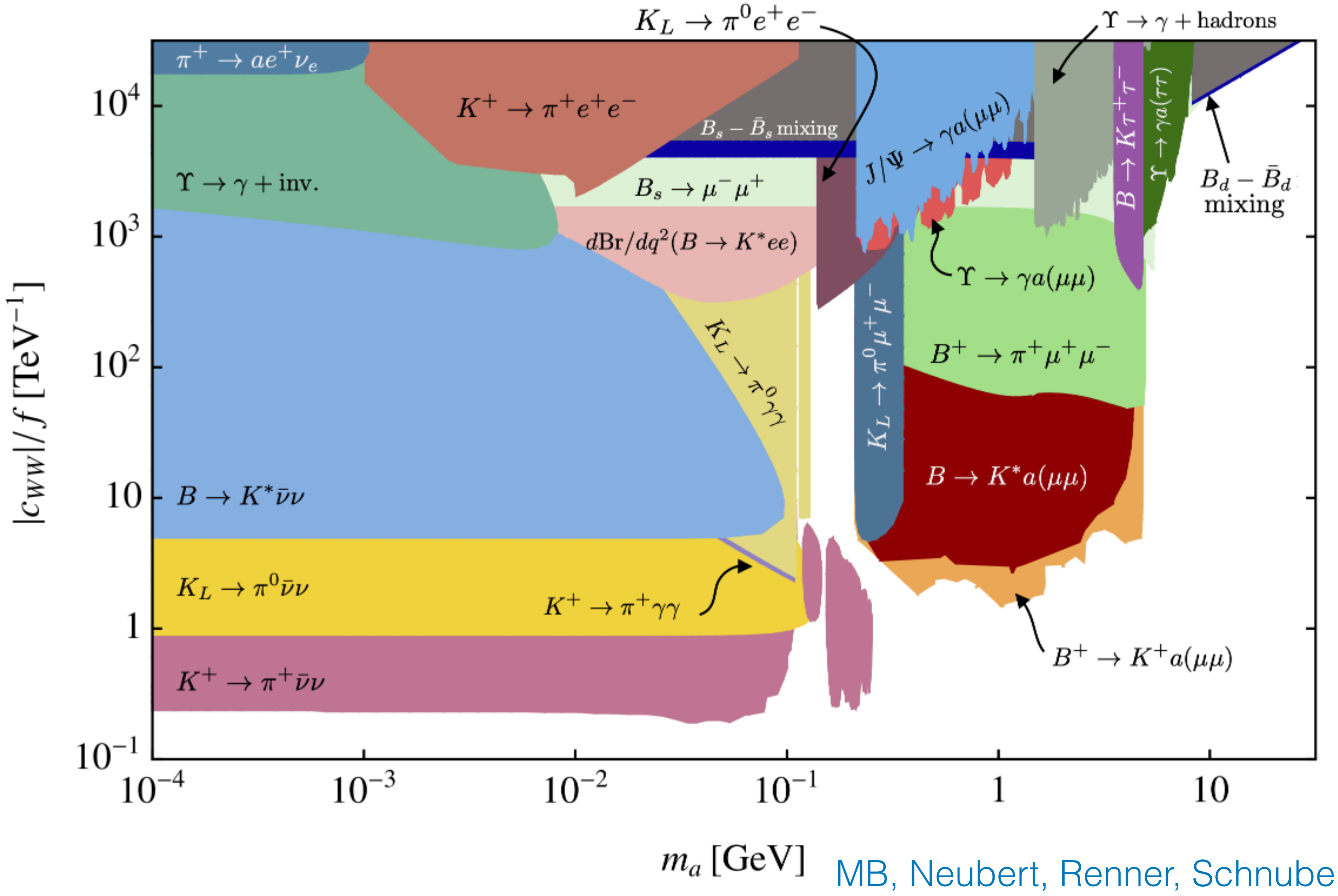
How to close the gap?

Flavor observables: FV couplings are inherited from the SM





Lifetime effects are very important!



MB, Neubert, Renner, Schnubel, Thamm, *JHEP* 04 (2021) 063

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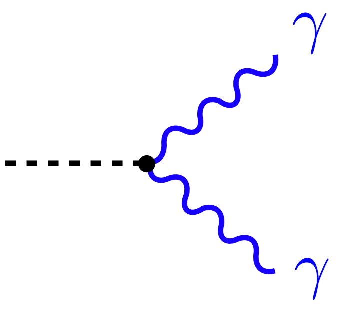
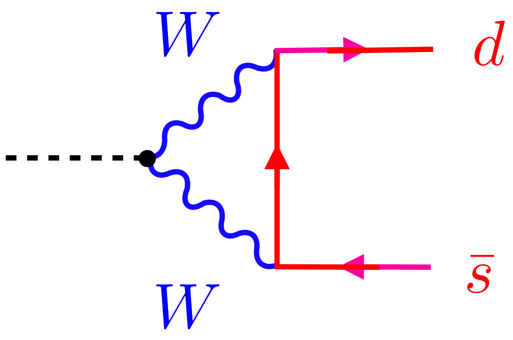
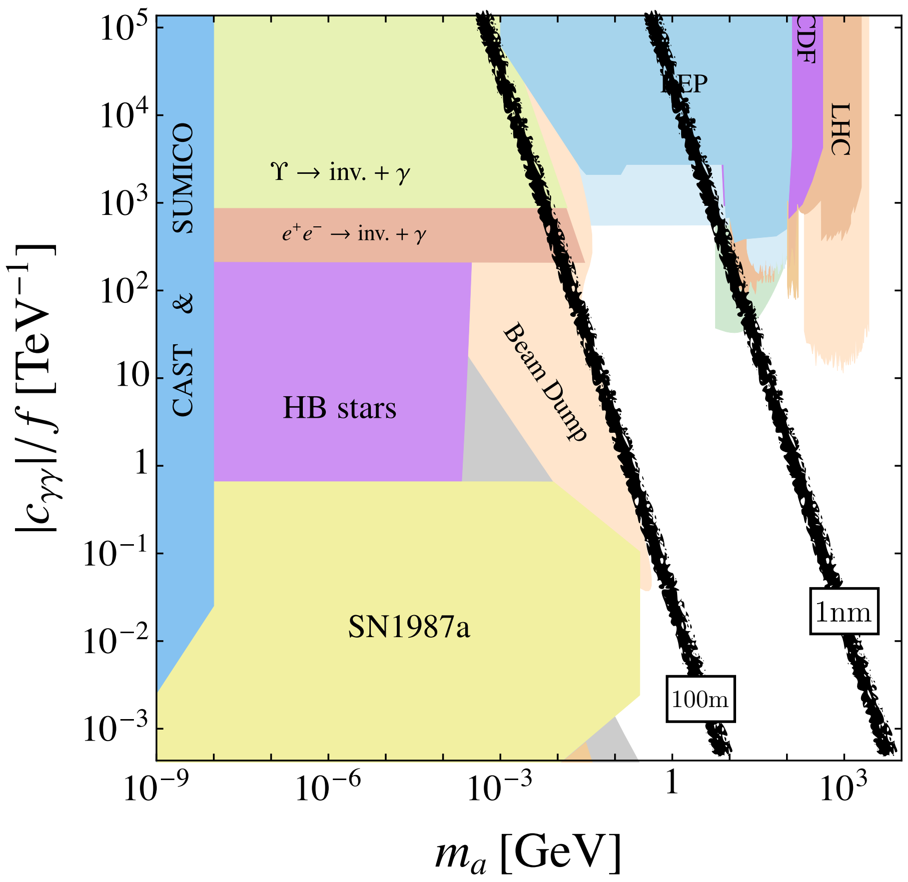
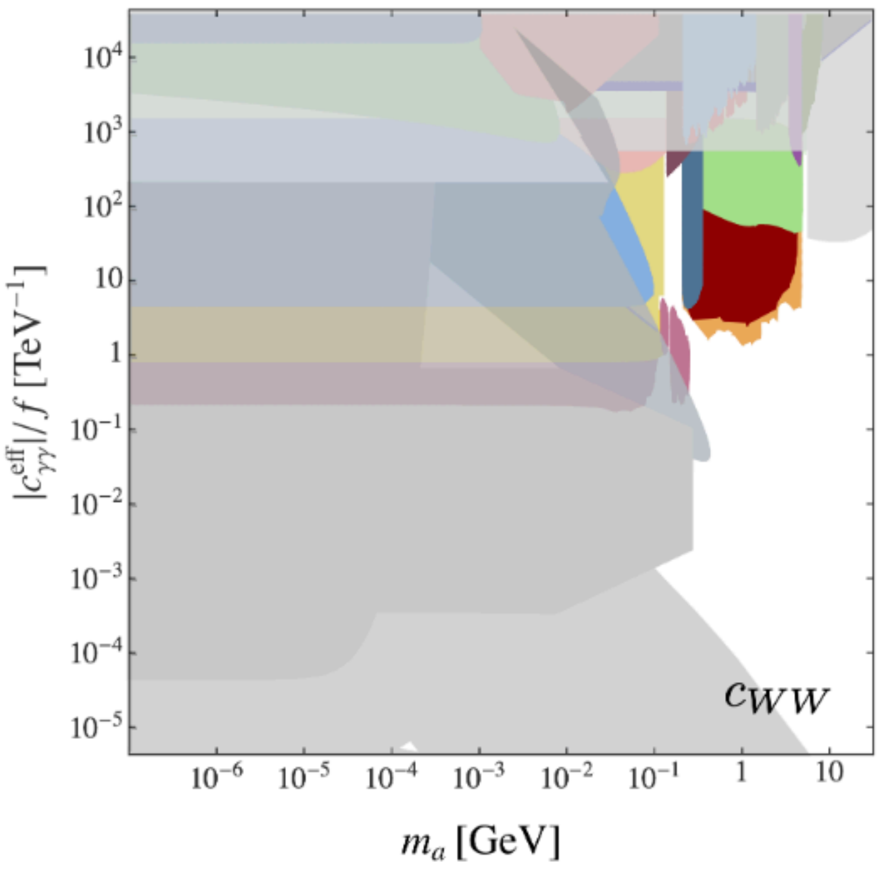
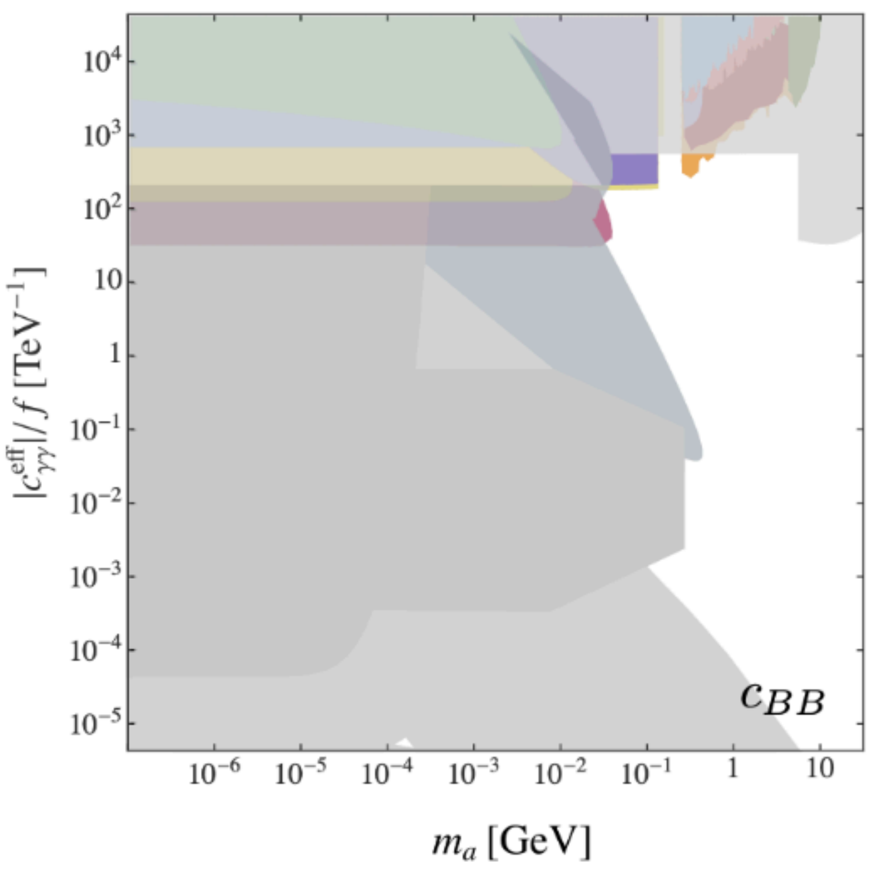










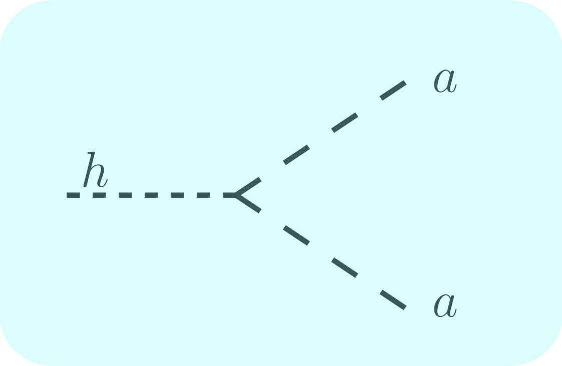
Very sensitive to the structure of the UV theory

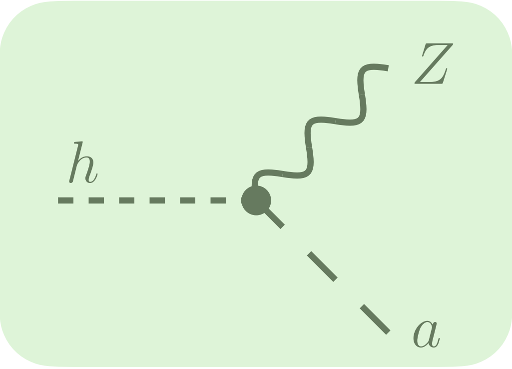
MB, Neubert, Renner, Schnubel, Thamm, *JHEP* 04 (2021) 063

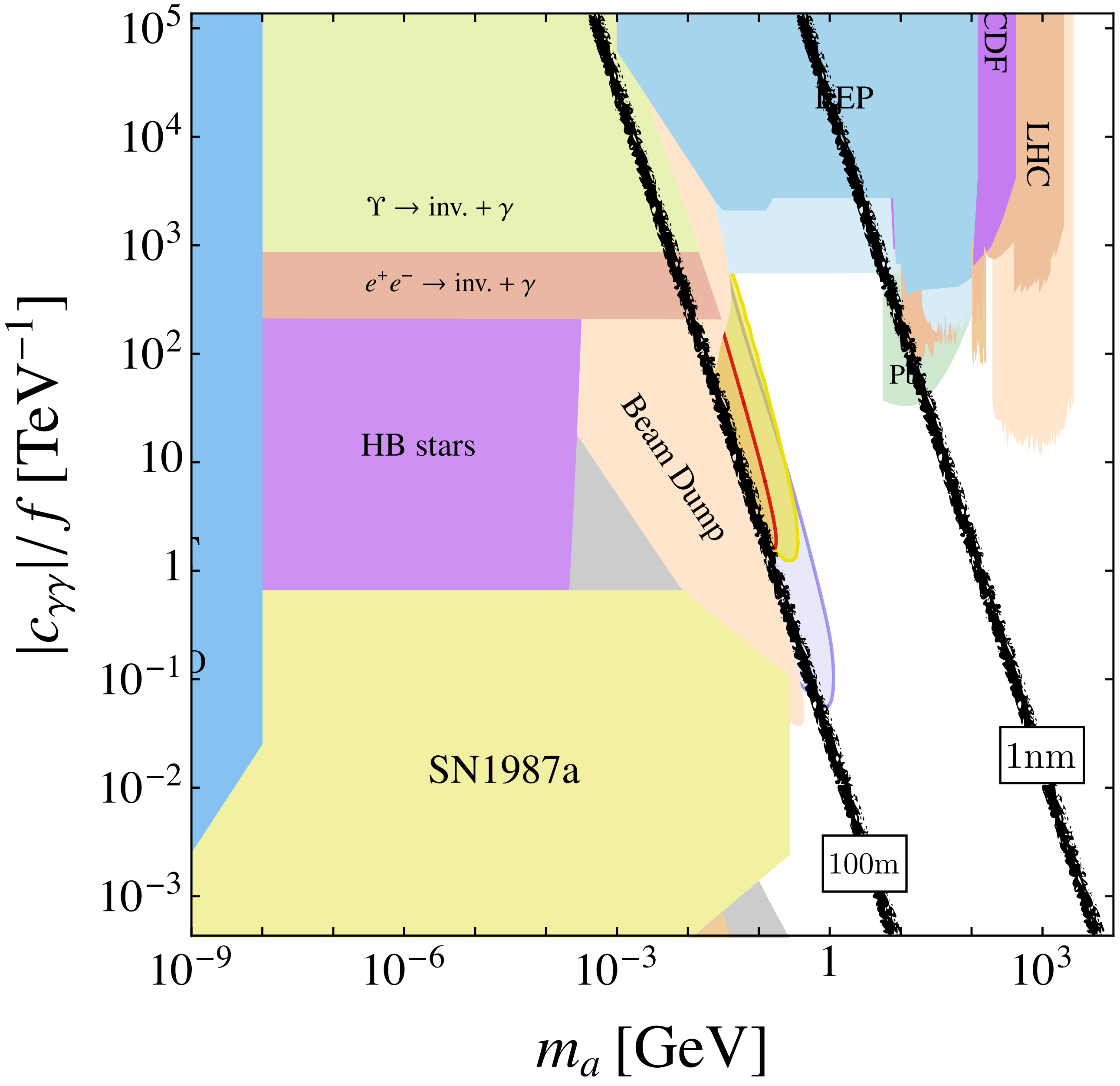
How to close the gap?

Big Advantage of the LHC:

The only place to make the Higgs!







$$\mathcal{L}_{>5} = \frac{c_{ah}}{f^2}\left(\partial_\mu a\right)\left(\partial^\mu a\right)\phi^\dagger\phi$$

$$+\frac{c_{Zh}^5}{f}\left(\partial^\mu a\right)\left(\phi^\dagger iD_\mu\phi + \text{h.c.}\right)\ln\frac{\phi^\dagger\phi}{\mu^2}$$

$$+\frac{c_{Zh}}{f^3}\left(\partial^\mu a\right)\left(\phi^\dagger iD_\mu\phi + \text{h.c.}\right)\phi^\dagger\phi$$

MB, Neubert, Thamm, PRL 117, 181801 (2016)

MB, Neubert, Thamm, JHEP 1712 044 (2017)

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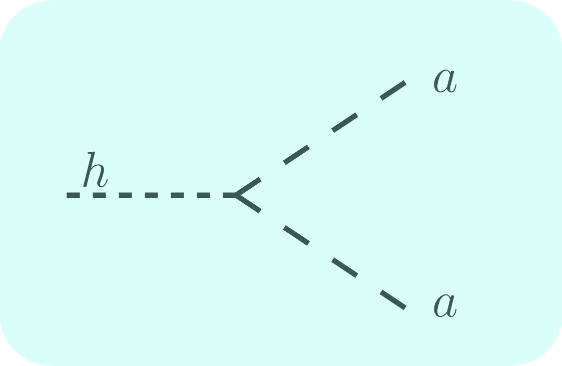

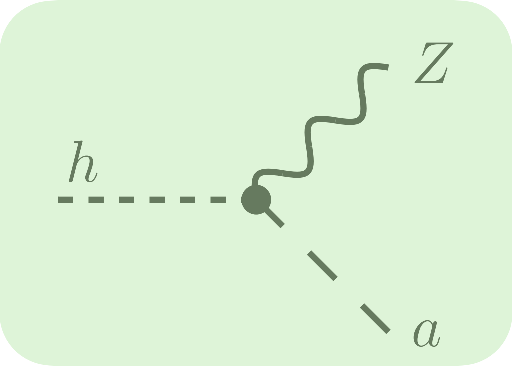

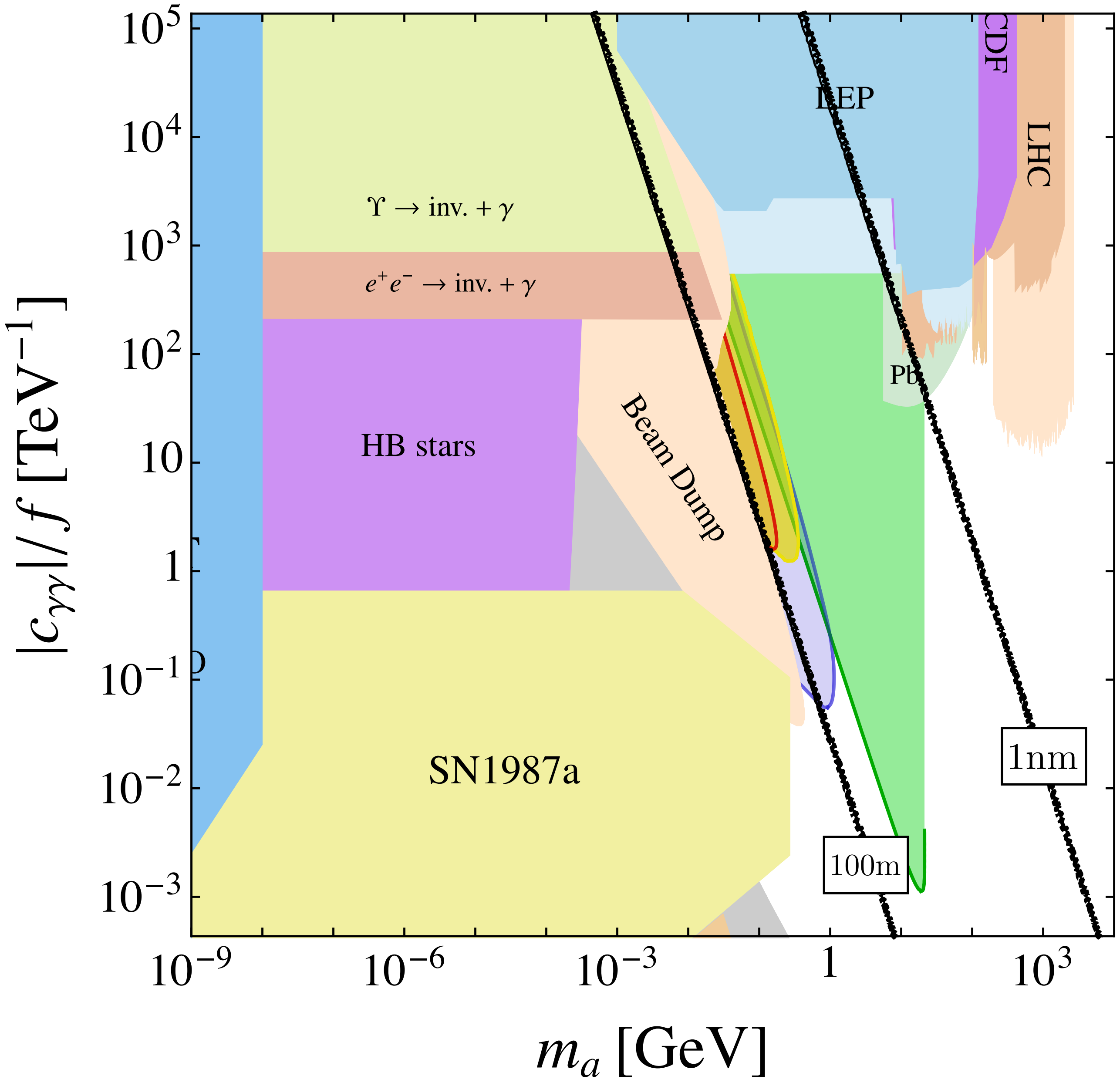

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$$+\frac{c_{Zh}}{f^3}\left(\partial^\mu a\right)\left(\phi^\dagger iD_\mu\phi + \text{h.c.}\right)\phi^\dagger\phi$$

$$\mathrm{Br}(h \to Za) < 1\,‰ \qquad c_{Zh}^{\text{eff}} = 0.015$$

MB, Neubert, Thamm, PRL 117, 181801 (2016)

MB, Neubert, Thamm, JHEP 1712 044 (2017)

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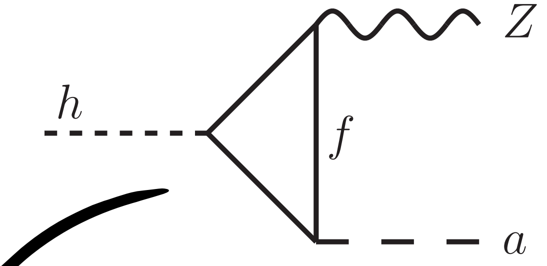

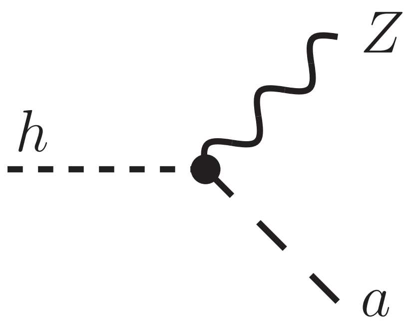

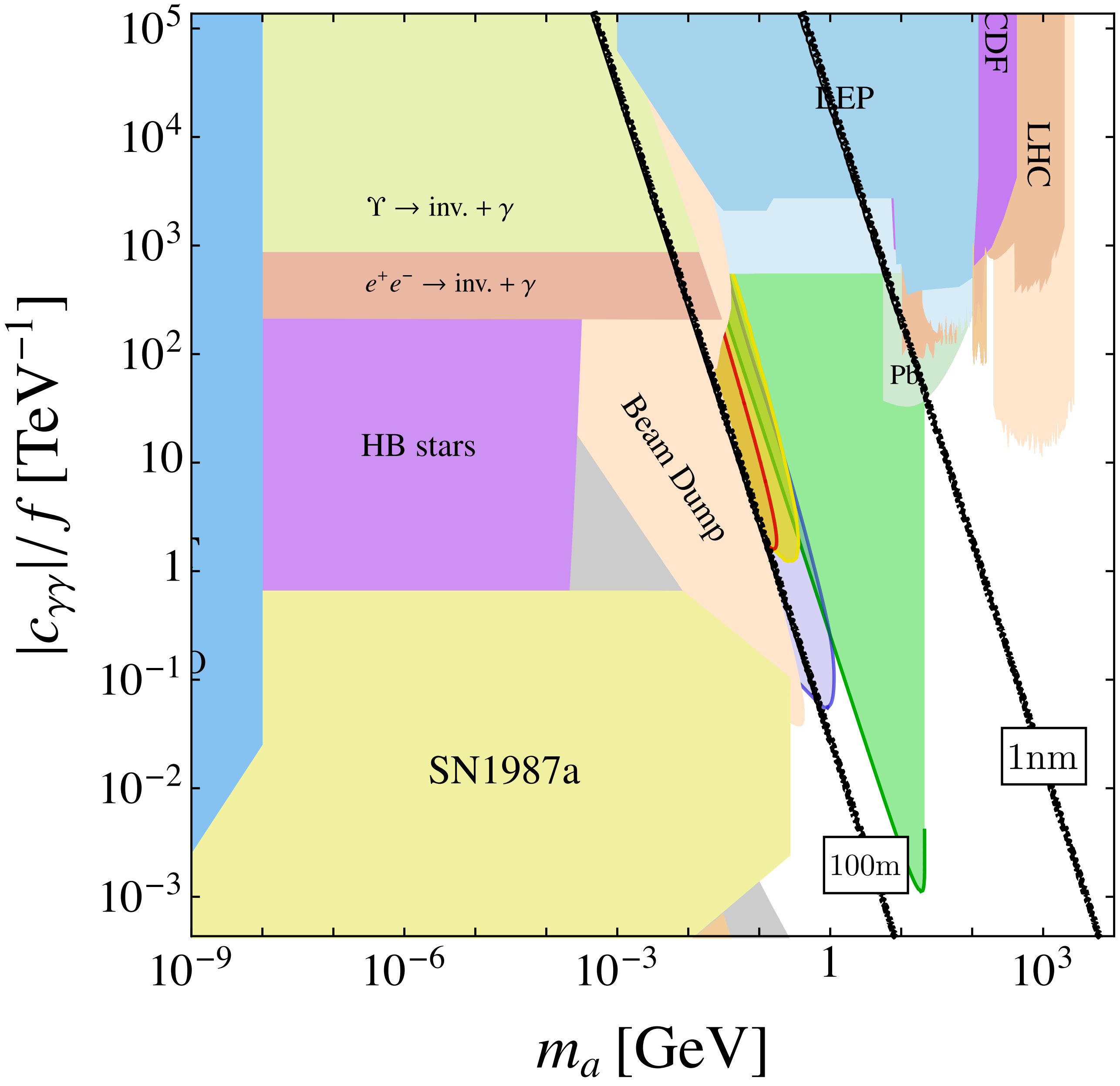

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$$+\frac{c_{Zh}^5}{f}(\partial^\mu a)\left(\phi^\dagger iD_\mu\phi + \text{h.c.}\right)\ln\frac{\phi^\dagger\phi}{\mu^2}$$

$$+\frac{c_{Zh}}{f^3}(\partial^\mu a)\left(\phi^\dagger iD_\mu\phi + \text{h.c.}\right)\phi^\dagger\phi$$

$\text{Br}(h \to Za) < 1\,‰$ $\quad c_{Zh}^{\text{eff}} = 0.015$

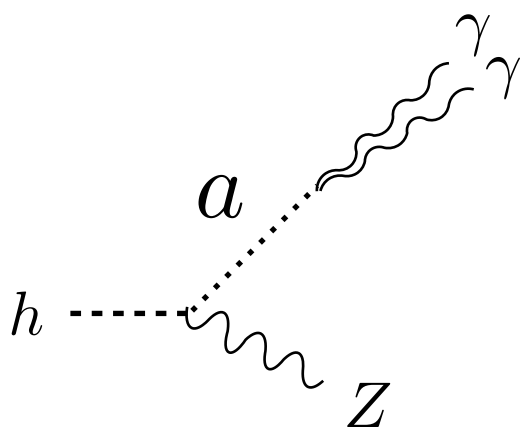
MB, Neubert, Thamm, PRL 117, 181801 (2016)

MB, Neubert, Thamm, JHEP 1712 044 (2017)

How to close the gap?

Many experimental signatures:

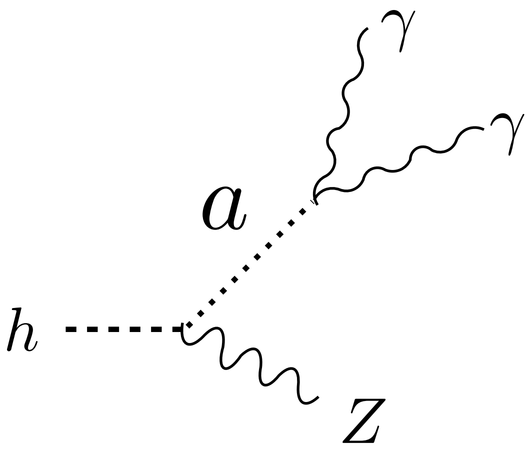
Low mass,
small coupling



$\mathrm{Br}(h \to Z\gamma) > \mathrm{Br}_{\mathrm{SM}}(h \to Z\gamma)$

Always enhanced!

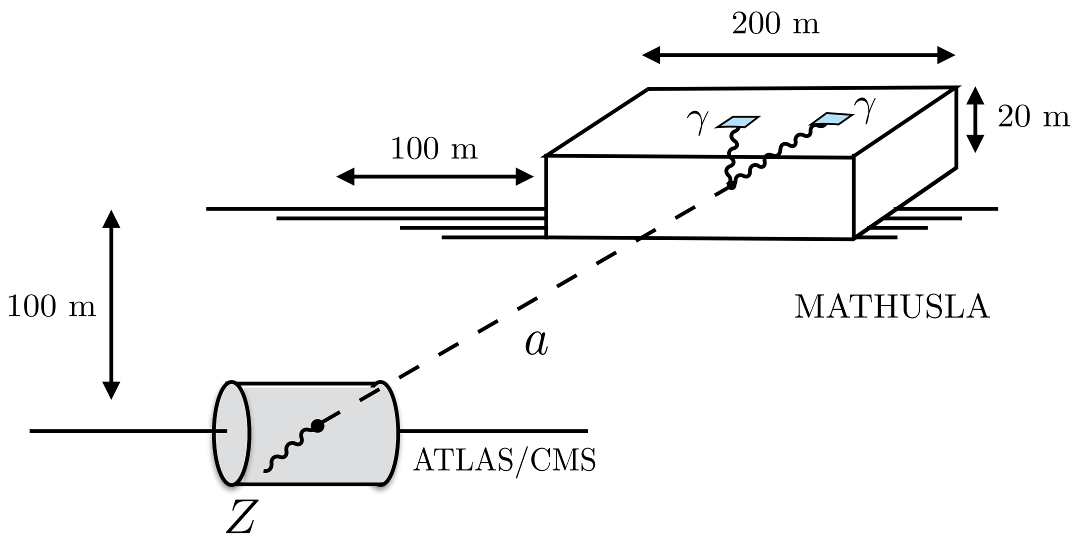
medium mass,
small coupling



Exotic signatures

$$h \to Z\gamma\gamma$$

very small coupling



Very challenging
exotic signatures

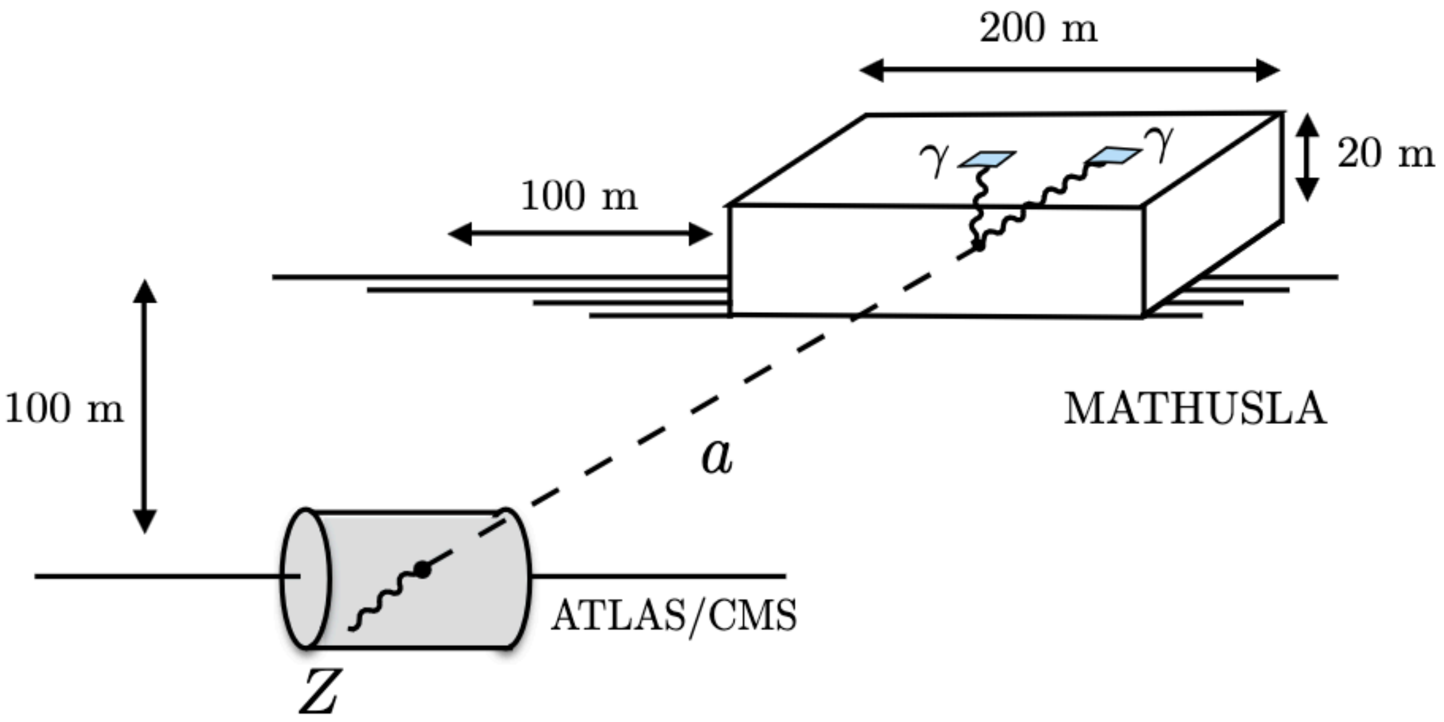
$$h \to Z + E_{T,\text{ miss}}$$

$$a \to \gamma\gamma$$

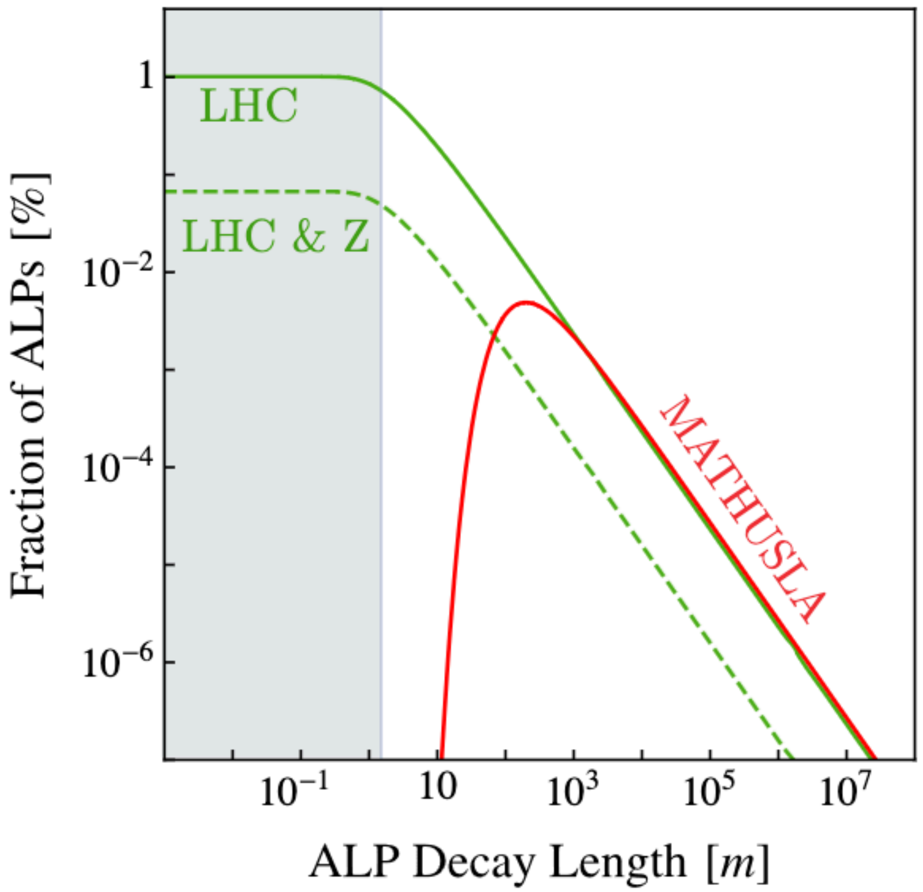
MB, Neubert, Thamm, JHEP 1712 044 (2017)

How to close the gap?

The fraction of ALPs decaying within ATLAS/CMS compared to e.g. MATHUSLA



$pp \to h \to aZ$

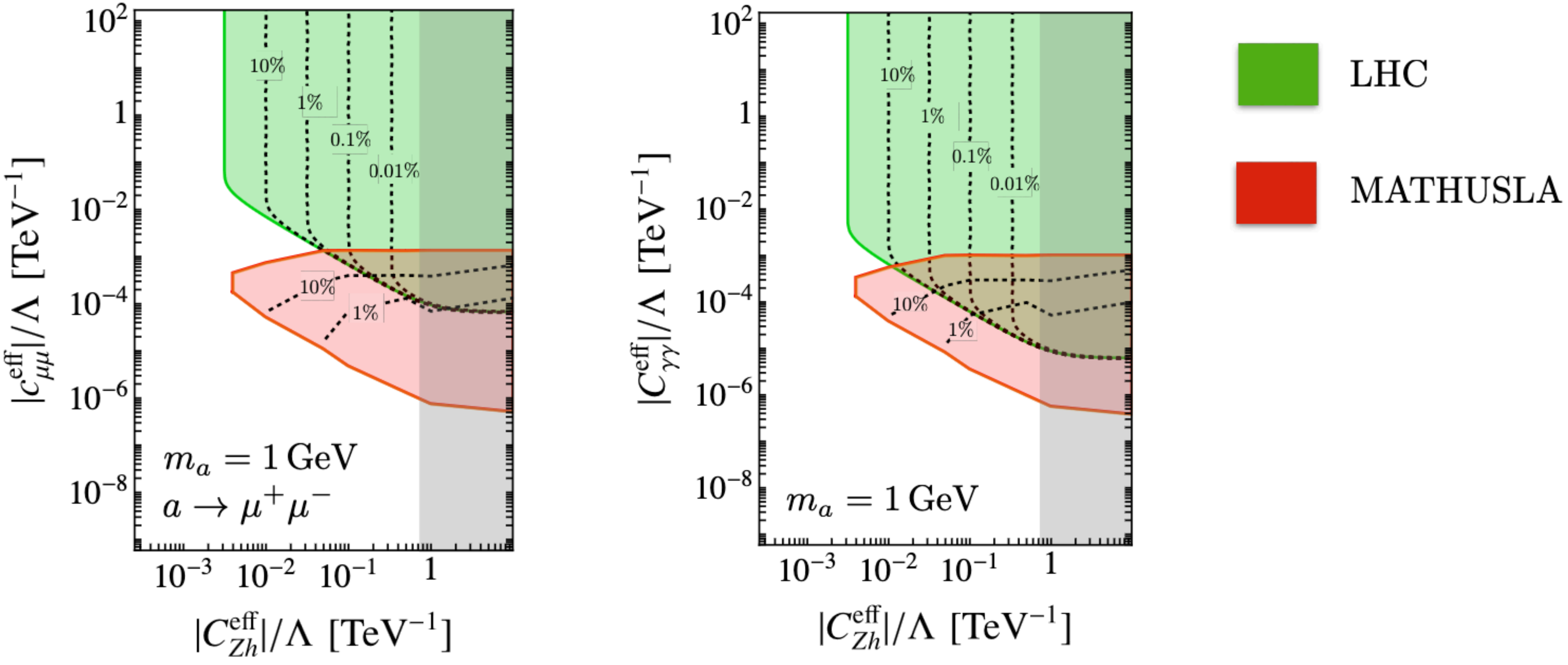


Comparable numbers, but for ~ GeV masses LHC searches need to reconstruct the Z boson

MB, Neubert, Thamm, JHEP 1712 044 (2017)

Far Detectors

Searches at far detectors probe parameter space that can't be reached by the LHC

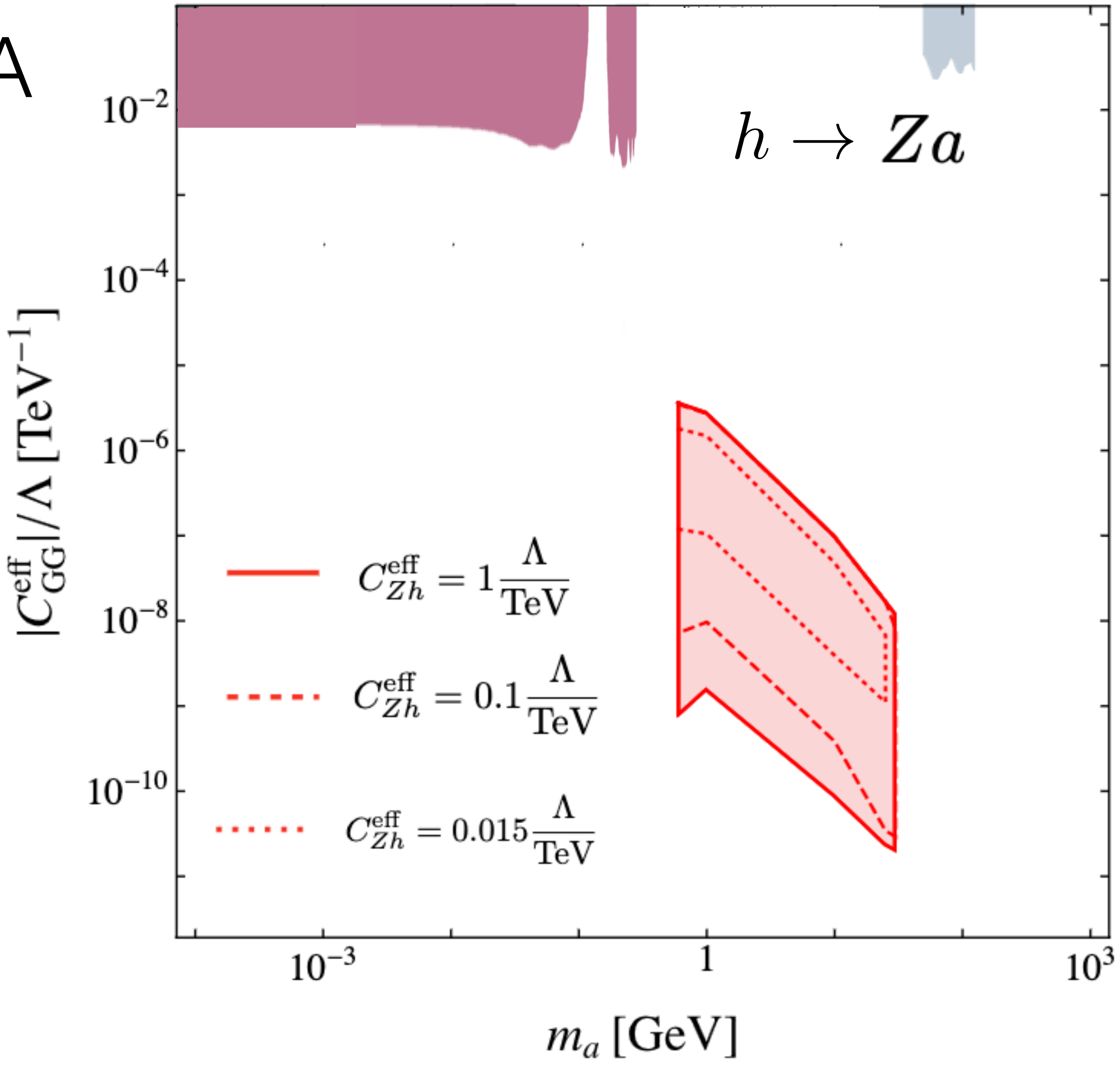


MB, Neubert, Thamm, JHEP 1712 044 (2017)

Far Detectors

Searches at far detectors probe parameter space that can't be reached by the LHC or any lab search

Comparison between MATHUSLA sensitivity estimate and bounds from flavor observables

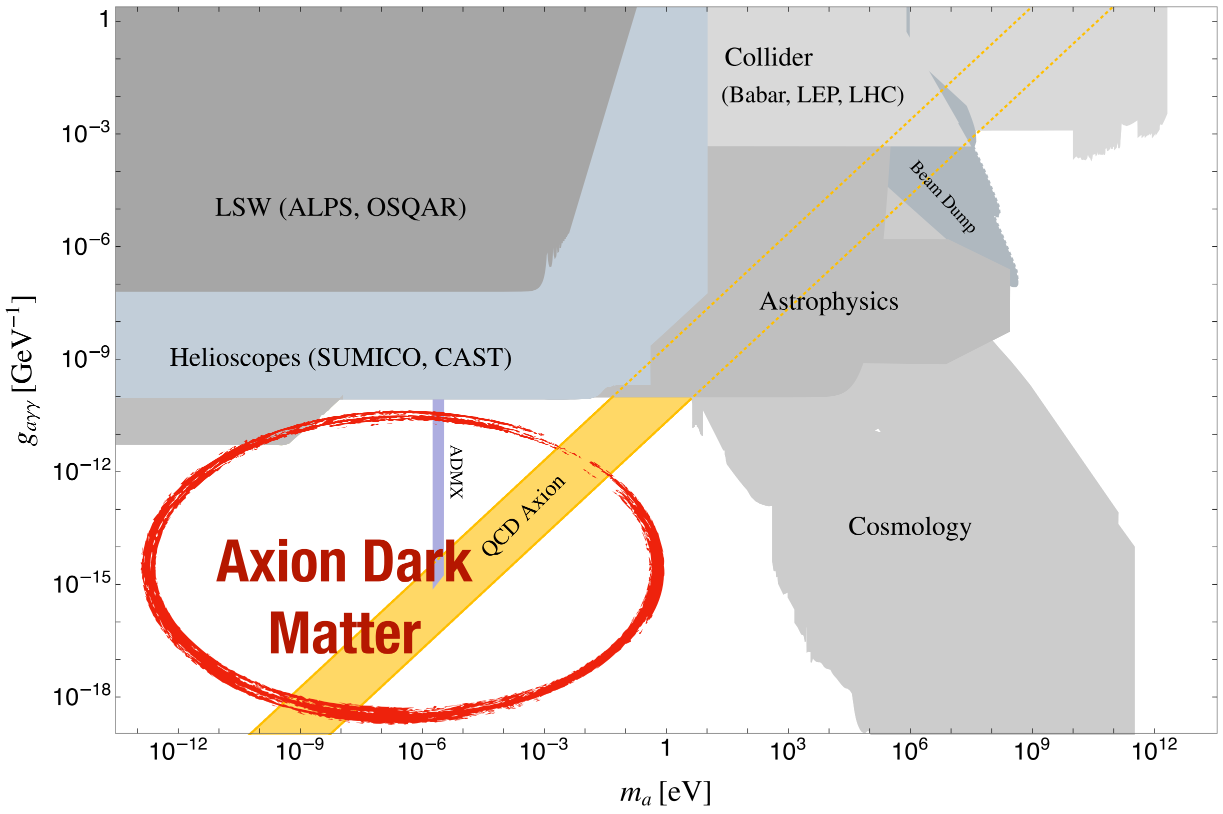


MB, Neubert, Thamm, JHEP 1712 044 (2017)

ALPs and dark matter

Typically axions are good dark matter candidates if they're very light and the relic density is set by misalignment.

Otherwise they decay into photons which is almost impossible to avoid barring enormous fine-tuning.



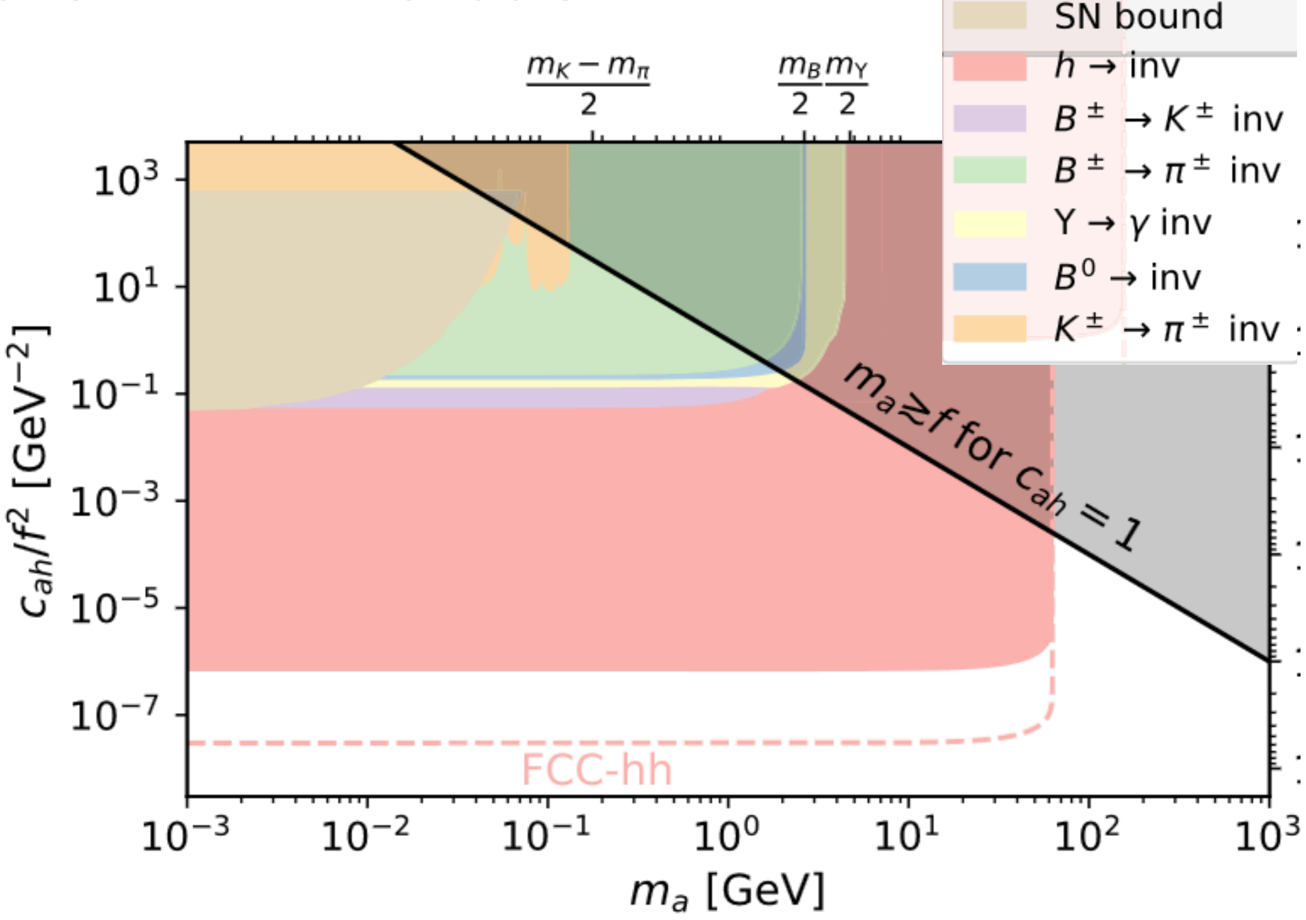
If there is a Z_2 symmetry $a \to -a$ every single dim 5 operator is forbidden. In this case all axion interaction are via the Higgs portal

$$\mathcal{L}_a^6 = \frac{c_{ah}}{f^2} \partial_\mu a \partial^\mu a \, \phi^\dagger \phi$$

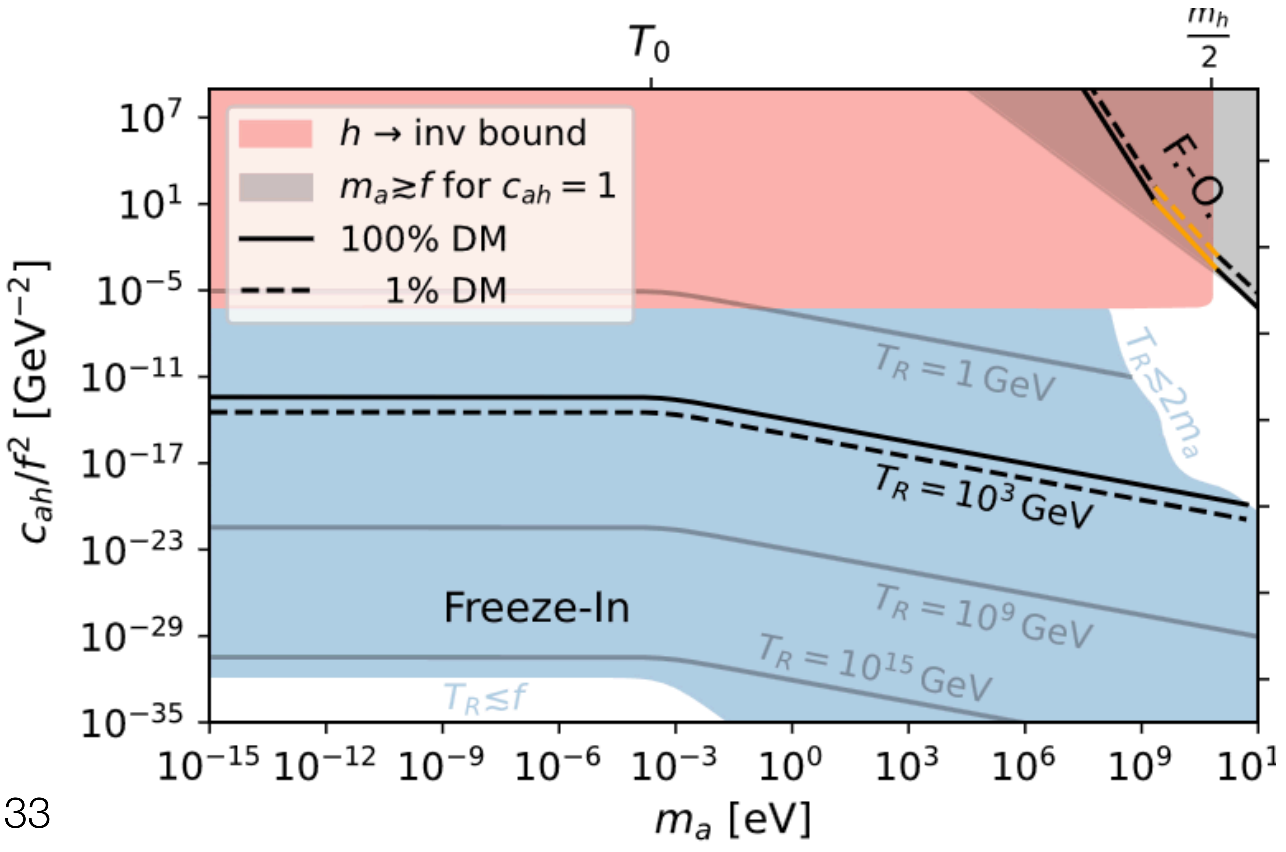
MB, Spinner, Rostagni, *Phys.Rev.D* 107 (2023) 1

ALPs and dark matter

Searches for Higgs decays are mores sensitive than any other observable even for light axions

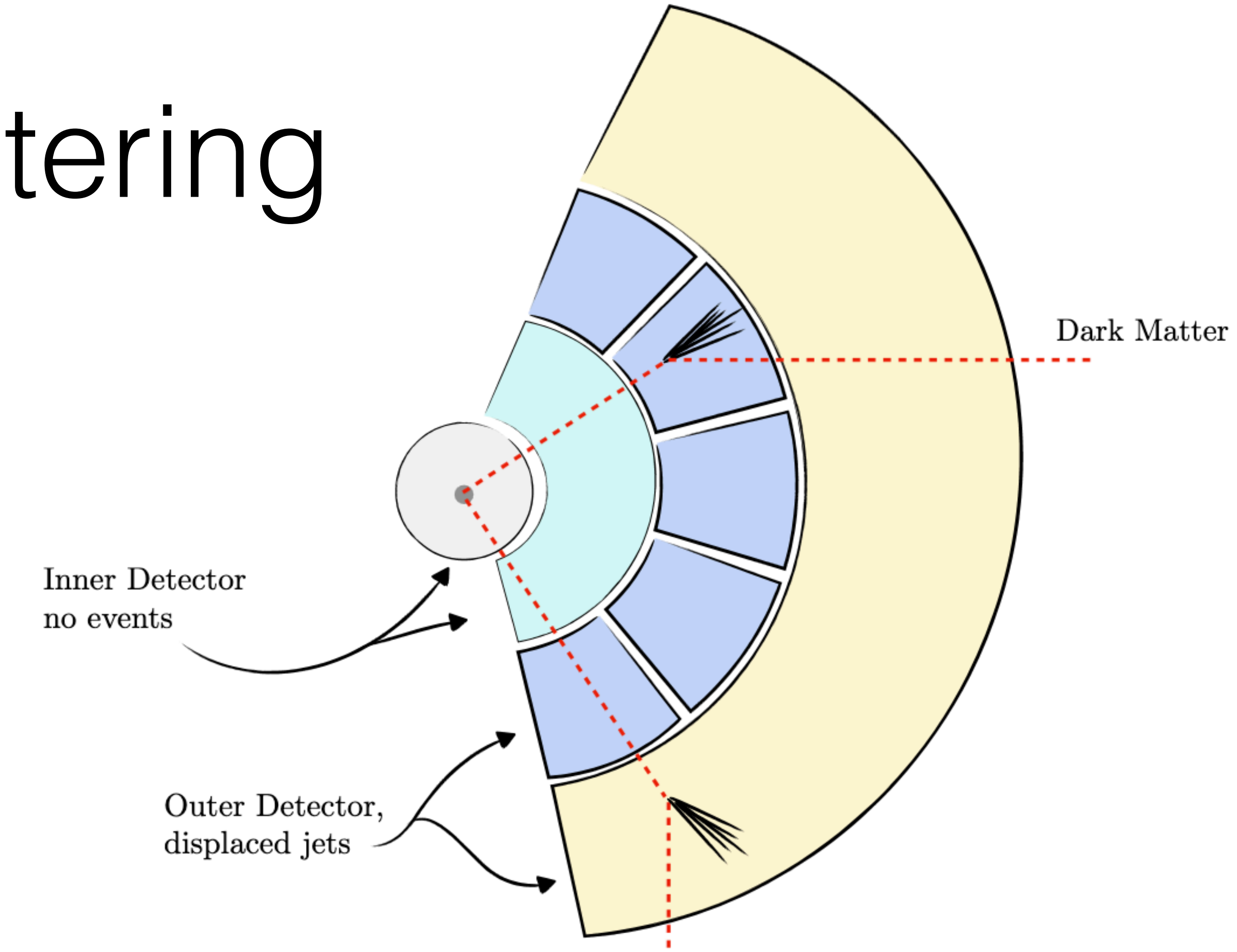


Higgs decays into axions probe the reheating temperatures for freeze-in DM



MB, Spinner, Rostagni, *Phys.Rev.D* 107 (2023) 1

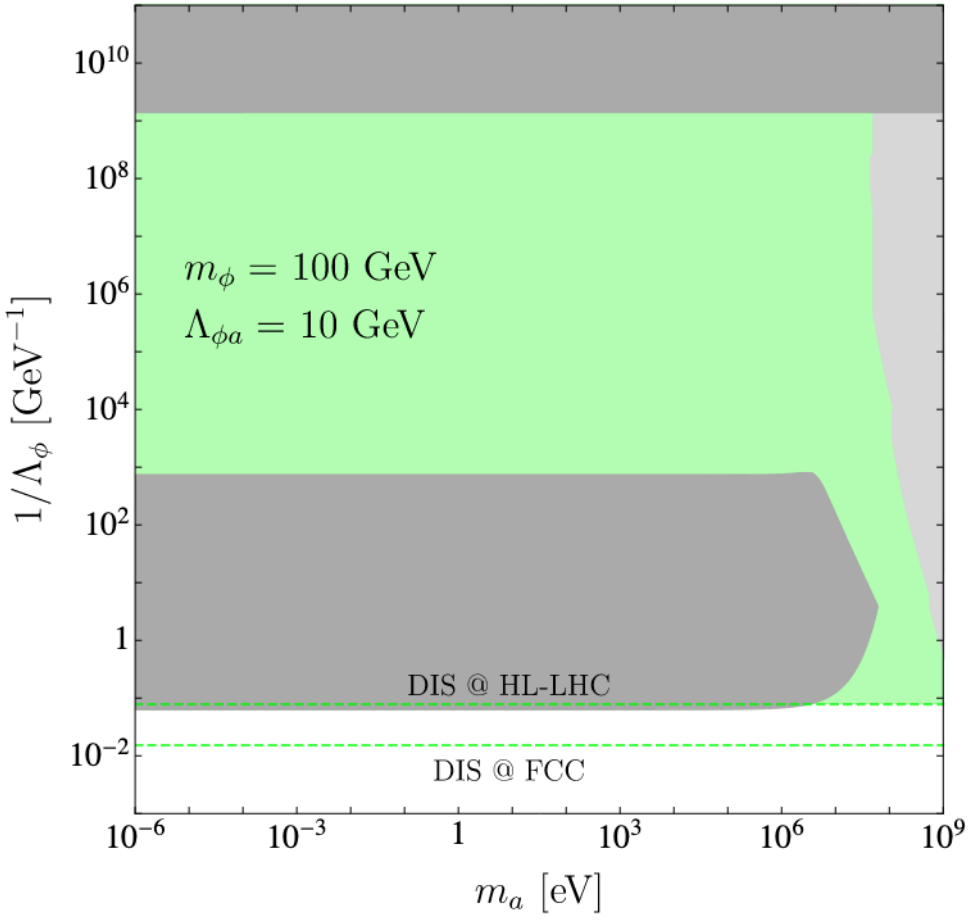
DIS Scattering



If the axion is too stable even searches for displaced vertices can be hopeless, but it can scatter off the detector!

Higgs portal interactions are to weak, but if there were new mediators it's possible

$$\mathcal{L} \supset -\frac{1}{2} m_\phi^2 \phi^2 - \frac{\partial_\mu a \, \partial^\mu a}{2\Lambda_{\phi a}} \phi - \frac{\alpha_s}{\Lambda_\phi} \, \phi \; \mathrm{Tr} \, G_{\mu\nu} G^{\mu\nu}$$



MB, Foldenauer, Reimitz, Plehn SciPost Phys. 10 (2021)

Conclusions

Goldstone bosons appear in any theory with a spontaneously broken global symmetry

There is a ‘lifetime gap’ in our current sensitivity.

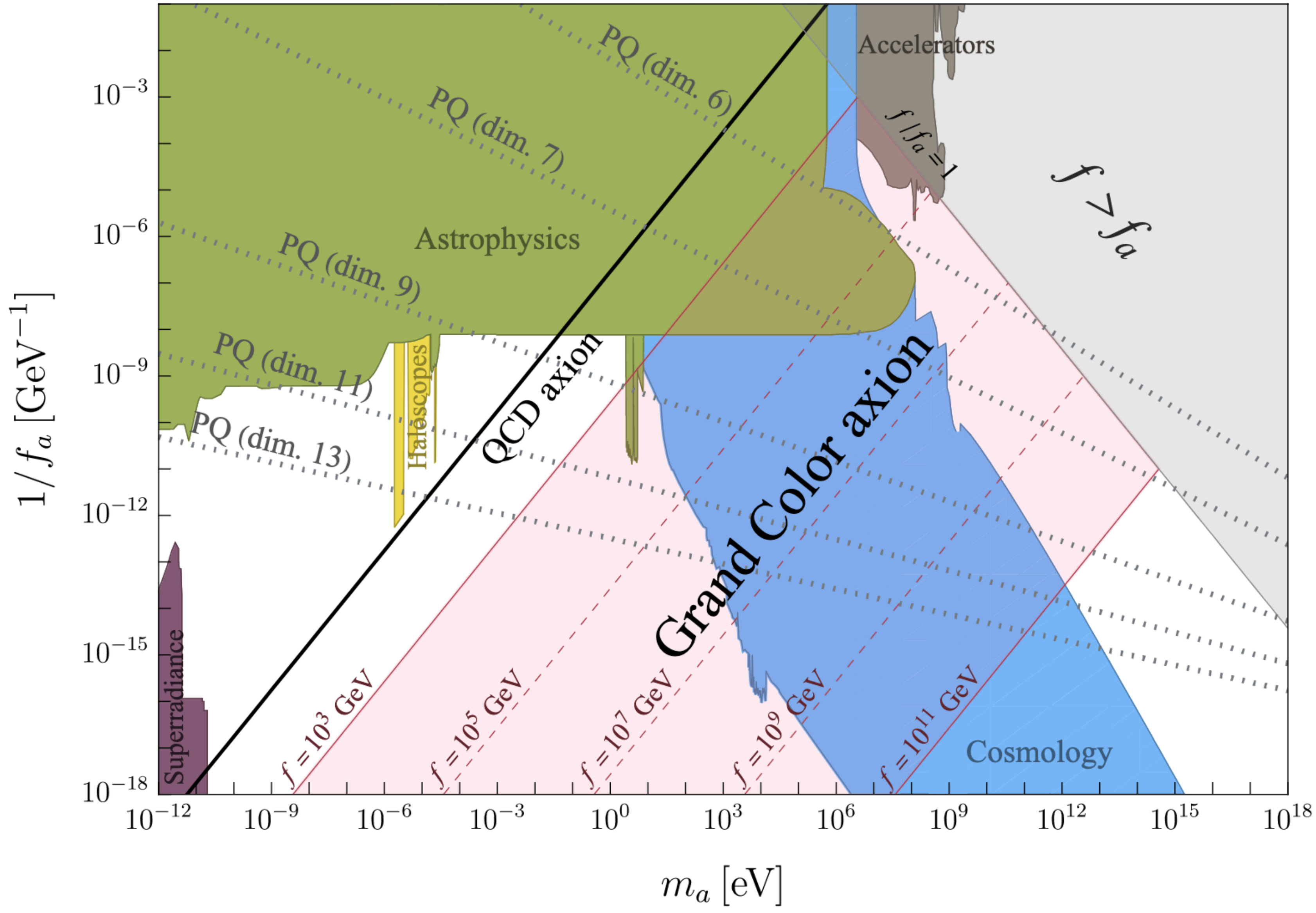
Complementary strategies can access this gap (statistics, flavor, displaced vertices, exotic decays)

Searches for exotic Higgs decays are very promising and are sensitive to the structure of the UV theory

Extended QCD axion models

Extended color sector

$$\mathcal{L}_{\text{axion}} \supset \left(\bar{\theta}_{\text{C}} + \frac{a}{f_a}\right)\frac{g_{\text{C}}^2}{32\pi^2} G^a_{\mu\nu}\widetilde{G}^{a\,\mu\nu} + \left(\bar{\theta}_{\text{C}'} + \frac{a}{f_a}\right)\frac{g_{\text{C}'}^2}{32\pi^2} G'^a_{\mu\nu}\widetilde{G}'^{a\,\mu\nu}$$



Valenti, Vecchi, Xu, *JHEP* 10 (2022) 025

The Puzzle of the top contribution

This is not new. Integrating out New Physics leads to the operators

$$\mathcal{O}_1 = c_1 \frac{\alpha_s}{4\pi v^2} G^a_{\mu\nu} G^{\mu\nu}_a H^\dagger H \qquad \mathcal{O}_2 = c_2 \frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu}_a \log\left(\frac{H^\dagger H}{\mu^2}\right)$$

with consequences for Higgs pair production. The top only generates c_2 and $C^{(5)}_{Zh}$.

Pierce, Thaler, Wang, JHEP 0705, 070 (2007)

The Puzzle of the top contribution

Vectorlike Quarks

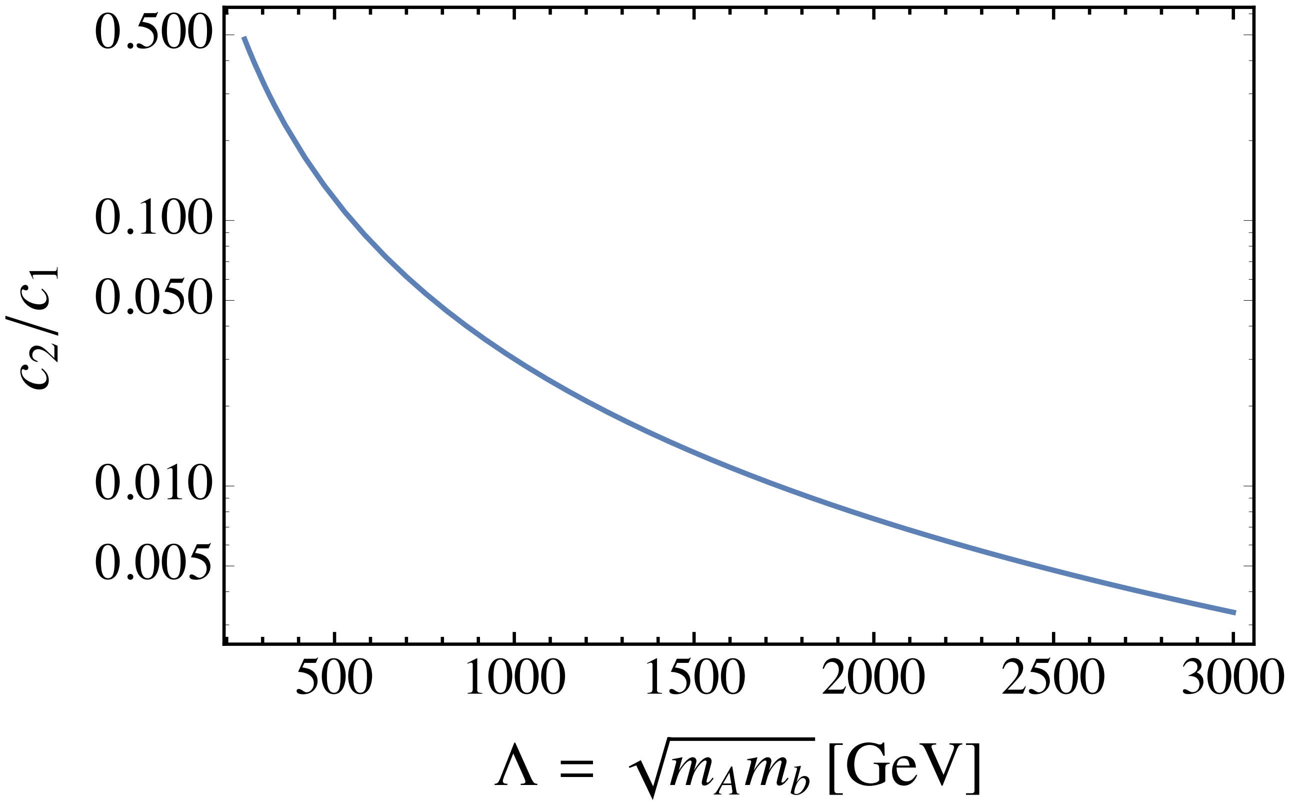
$$-\mathcal{L}_{\text{mass}} = \lambda_1\left(QHT^c + Q\tilde{H}B^c\right) + \lambda_2\left(Q^c\tilde{H}T + Q^cHB\right) + m_A QQ^c + m_B(TT^c + BB^c) + \text{h.c.},$$

generate

$$c_1 = \frac{4}{3}\frac{-\beta}{(1-\beta)^2}$$

$$c_2 = \frac{4}{3}\frac{1}{(1-\beta)^2}$$

$$\beta \equiv \frac{2m_A m_B}{\lambda_1\lambda_2 v^2}.$$



$$\mathcal{O}_1 = c_1\frac{\alpha_s}{4\pi v^2}G^a_{\mu\nu}G^{\mu\nu}_a H^\dagger H$$

$$\mathcal{O}_2 = c_2\frac{\alpha_s}{8\pi}G^a_{\mu\nu}G^{\mu\nu}_a \log\left(\frac{H^\dagger H}{\mu^2}\right)$$

Pierce, Thaler, Wang, JHEP 0705, 070 (2007)