Collider Probes of Axion-like Particles

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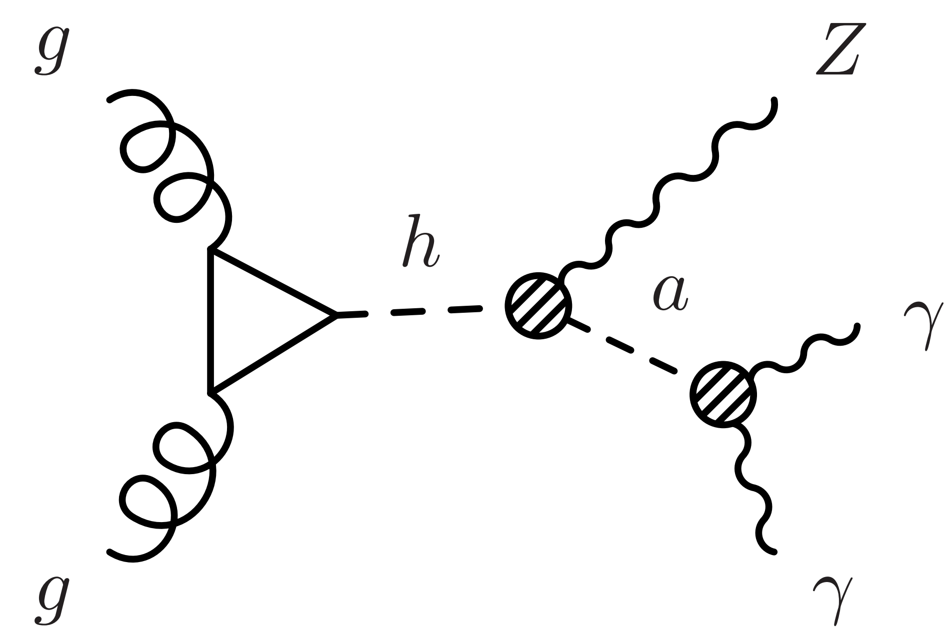
CERN

with Martin Bauer and Matthias Neubert

based on arXiv:1610.00009, 1704.08207, 1708.00443
and work in progress

15 May 2018
Grenoble

Outline



- Motivation
- ALPs and collider probes
    - Effective Lagrangian
    - Exotic Higgs and ALP decays
    - Probing the ALP parameter space
    - Muon $(g-2)_\mu$
- Conclusions and Outlook

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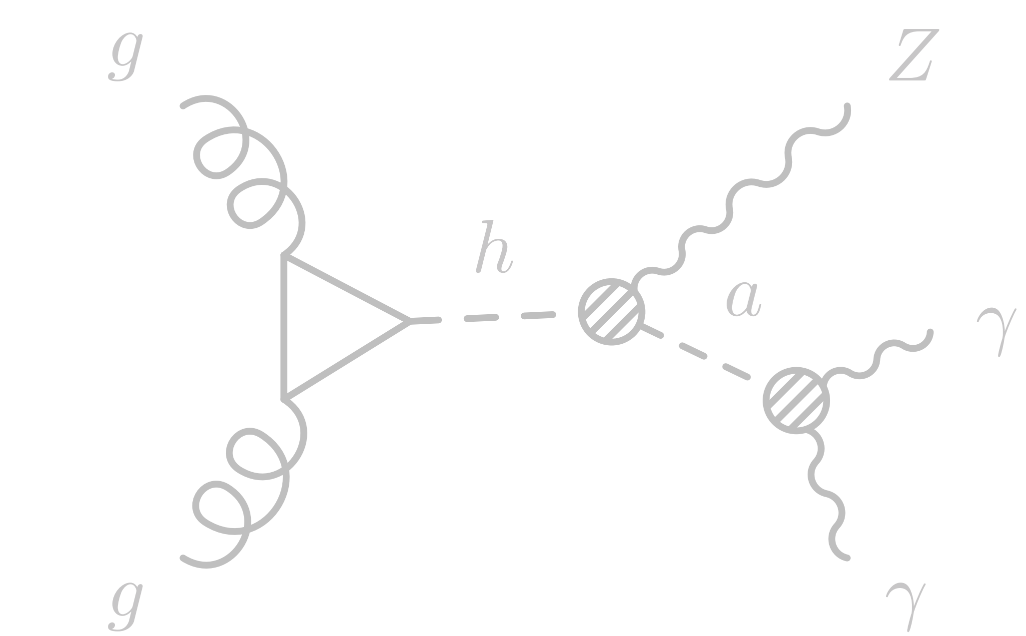

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Motivation

- Pseudo-scalars in many extensions of the SM
  - QCD axion - solution to strong CP-problem
  - Nambu-Goldstone bosons of a broken symmetry
  - mediators to the dark sector
  - explanations of various anomalies
- Good reason to study them!
- Large regions of parameter space already probed by many different experiments
- We add a region that can be probed through exotic Higgs decays in run 2 of LHC

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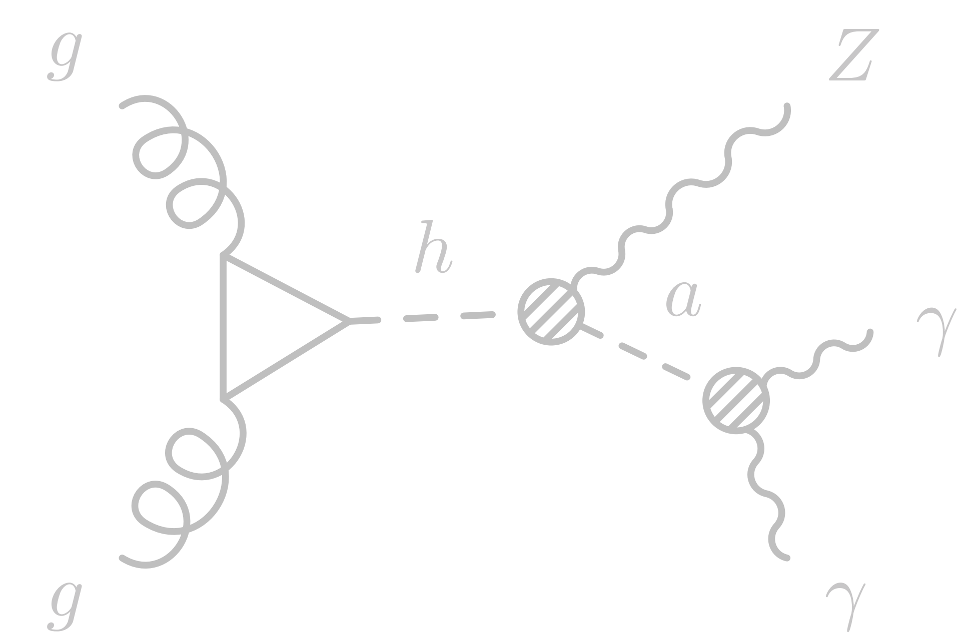

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Effective Lagrangian

- Interactions at dimension-5

[Weinberg: PRL 40 (1978) 223]
[Wilczek: PRL 40 (1978) 279]
[Georgi, Kaplan, Randall: Phys. Lett.169 B (1986)]

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) + \sum_f \frac{c_{ff}}{2}\,\frac{\partial^\mu a}{\Lambda}\,\bar{f}\gamma_\mu\gamma_5 f + g_s^2\,C_{GG}\,\frac{a}{\Lambda}\,G_{\mu\nu}^A\,\tilde{G}^{\mu\nu,A}$$
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$$C_{VV} = \bar{C}_{VV}/4\pi$$
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$h \to aa$ $\qquad$ $h \to Za$

[Dobrescu, Landsberg, Matchev: 0005308]
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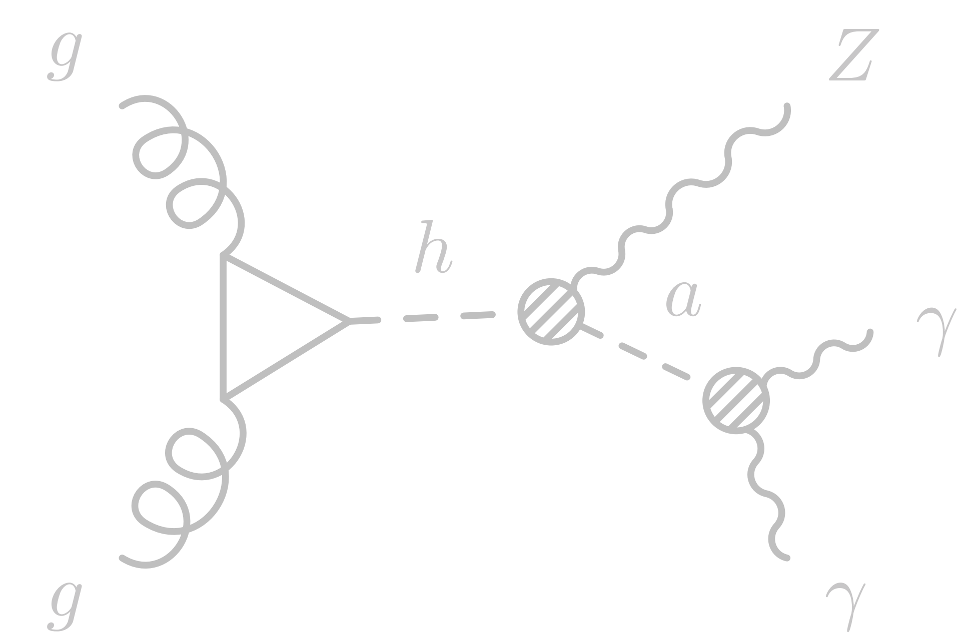

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- Contributions

$$\Gamma(h \to Za) = \frac{m_h^3}{16\pi\Lambda^2} \left| C_{Zh}^{(5)} - \frac{N_c\, y_t^2}{8\pi^2}\, T_3^t\, c_{tt}\, F + \frac{v^2}{2\Lambda^2}\, C_{Zh}^{(7)} \right|^2 \lambda^{3/2}\!\left(\frac{m_Z^2}{m_h^2}, \frac{m_a^2}{m_h^2} \right)$$

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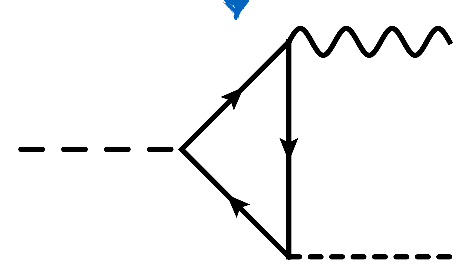
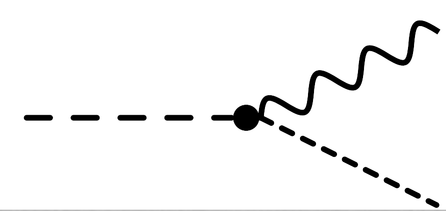
Vanishes through EOM





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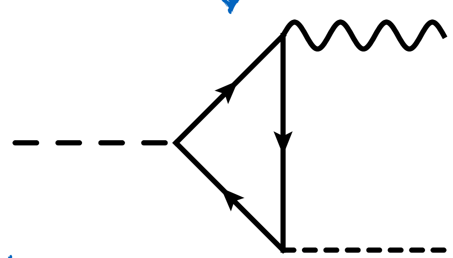

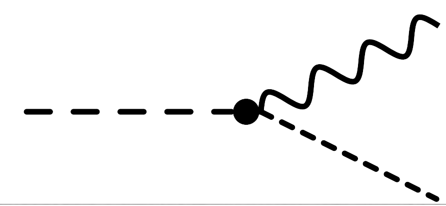

Non-polynomial operator for models with new heavy particles whose mass arises from EWSB

$$\frac{(\partial^\mu a)}{\Lambda}\left(\phi^\dagger\, iD_\mu\, \phi + \text{h.c.}\right) \ln \frac{\phi^\dagger \phi}{\mu^2}$$

[Pierce, Thaler, Wang: 0609049]
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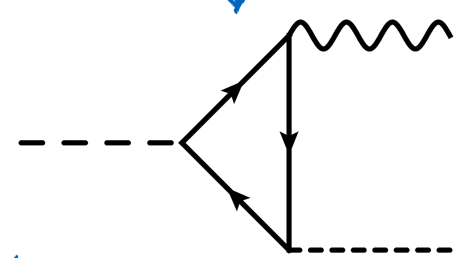

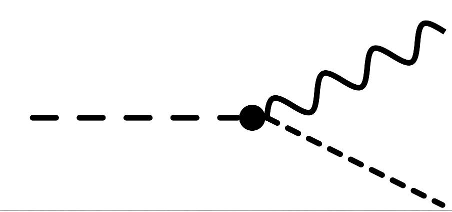

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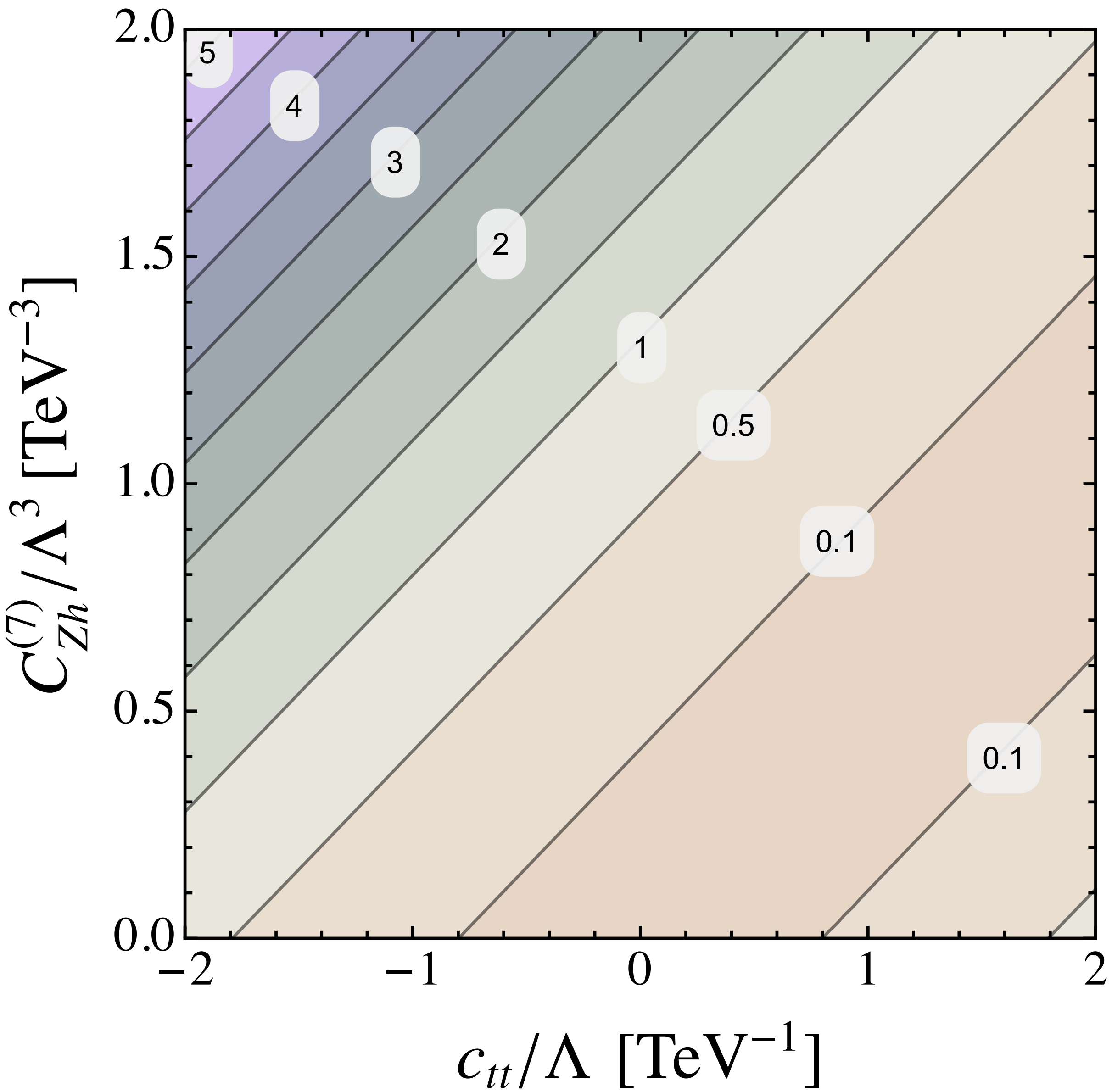
- Numerically

$$C_{Zh}^{\text{eff}} \approx C_{Zh}^{(5)} - 0.016\, c_{tt} + 0.030\, C_{Zh}^{(7)} \left[\frac{1\,\text{TeV}}{\Lambda}\right]^2$$

Exotic Higgs Decays $h \to Za$

- Decay rate normalised to SM $\Gamma(h \to Z\gamma)_{\rm SM} = 6.32 \cdot 10^{-6}\,$GeV



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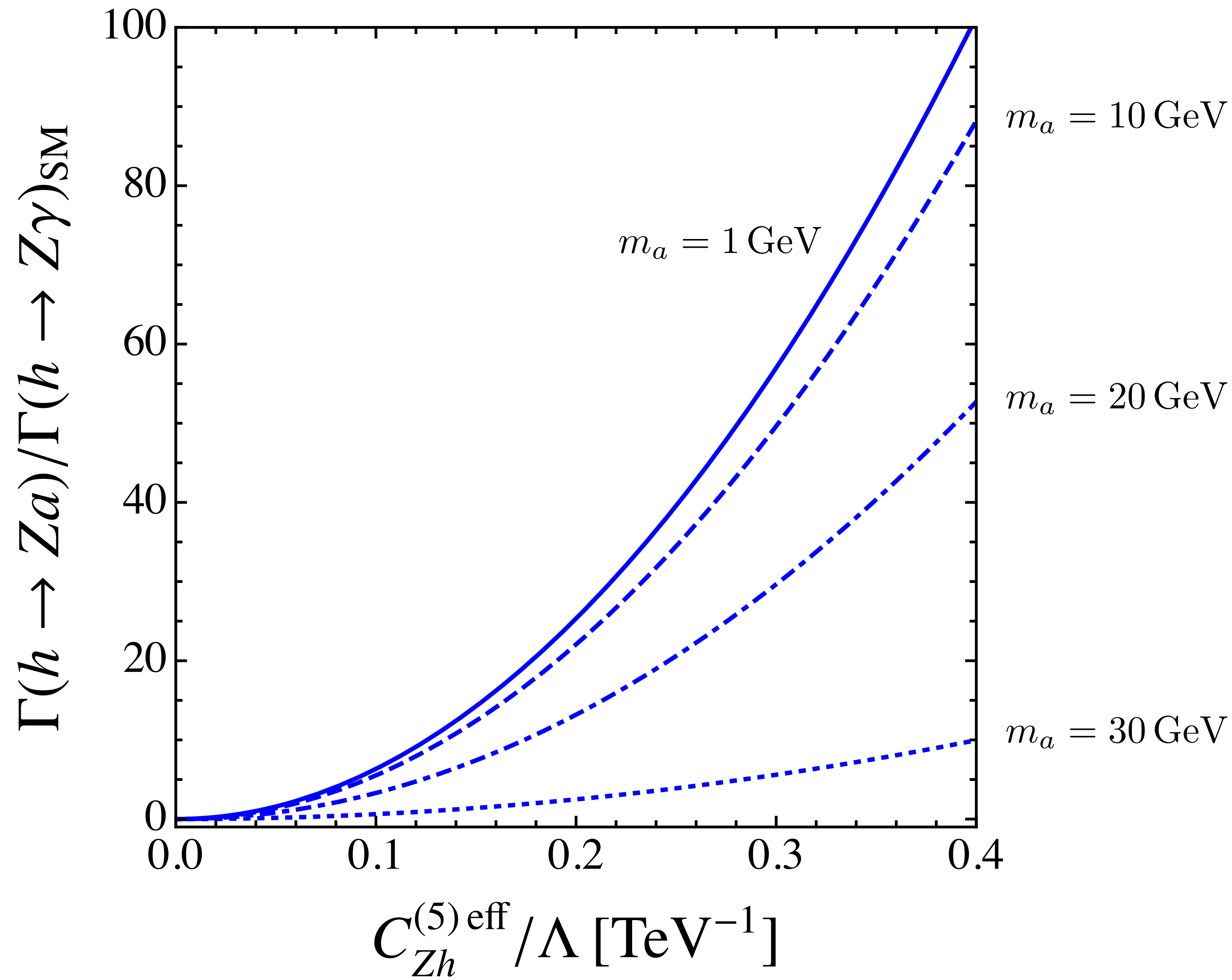
- Enhanced rates for this process



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- From top loop and dim-7: $\mathrm{Br}(h \to Za) = \mathcal{O}(10^{-3})$

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  - ✦ $h \to Za \to Z\,2jets$
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- All these modes can be reconstructed at run II

Exotic Higgs Decays $h \to aa$

- Dim-6 Higgs portal and loop diagrams

[Dobrescu, Landsberg, Matchev: 0005308]
[Dobrescu, Matchev: 0008192]
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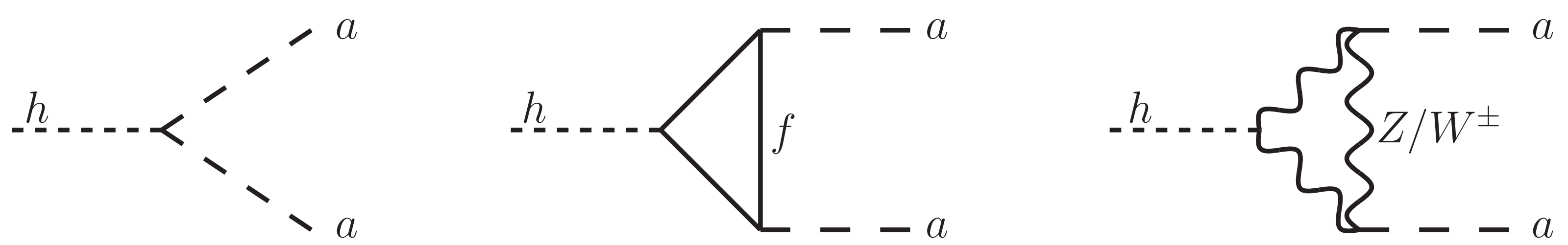

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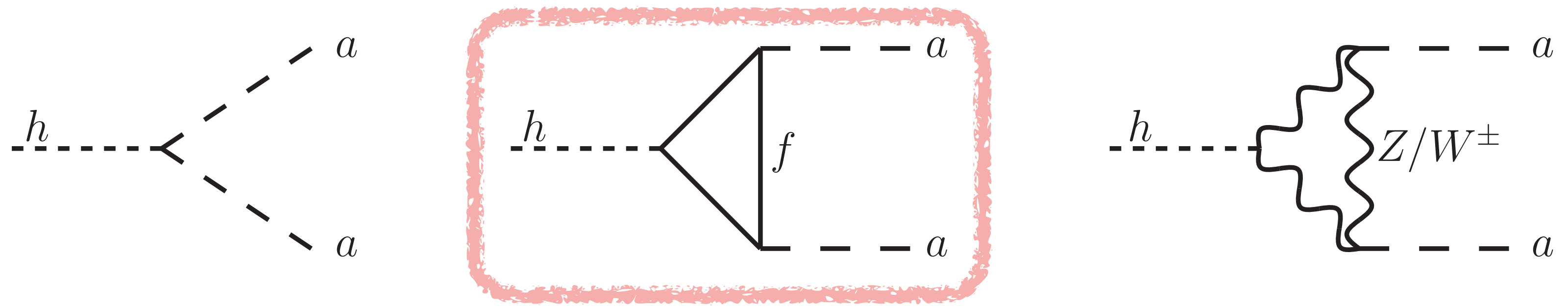

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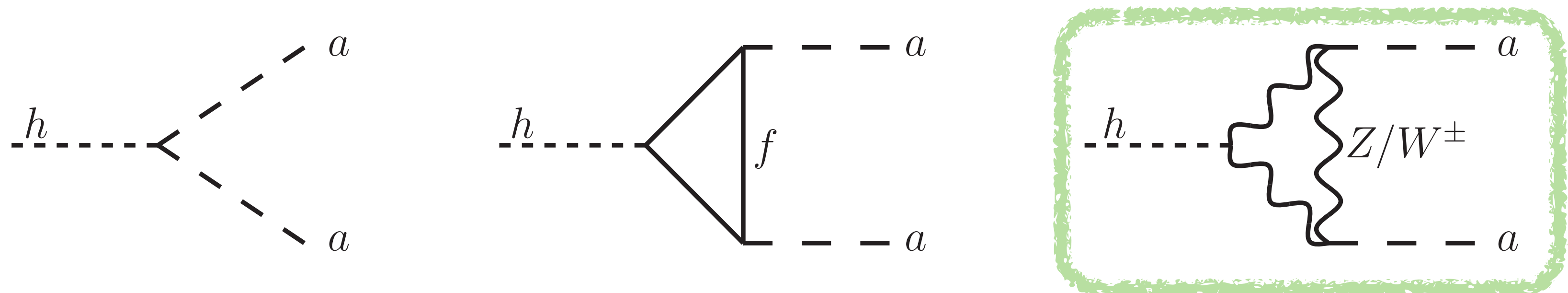

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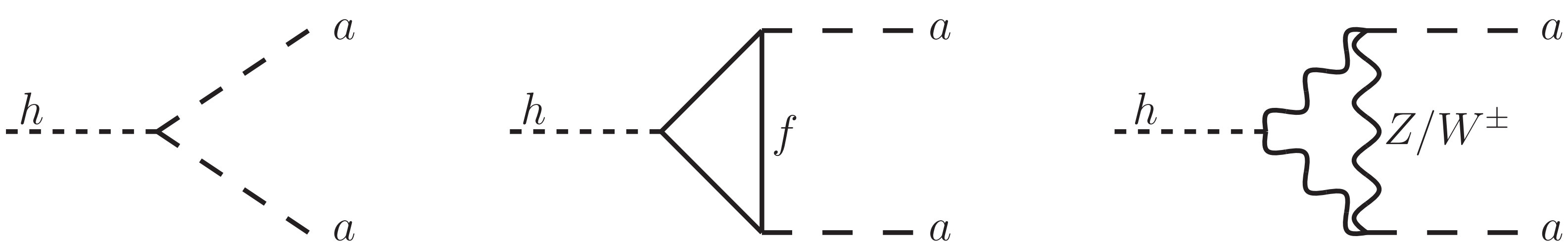

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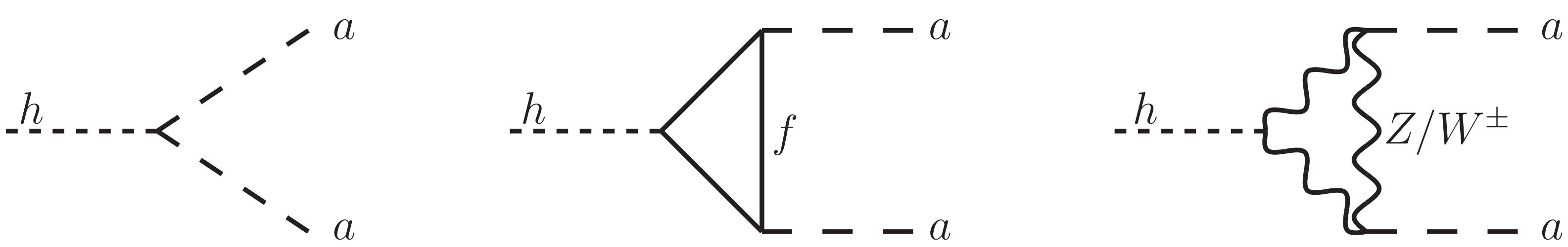

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$$\Gamma(h \to aa) = \frac{v^2 m_h^3}{32\pi\Lambda^4}\left|C_{ah}^{\rm eff}\right|^2 \left(1 - \frac{2m_a^2}{m_h^2}\right)^2 \sqrt{1 - \frac{4m_a^2}{m_h^2}}$$

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- For $\text{Br}(h \to aa) = 0.1$ need $|C_{ah}|/\Lambda^2 \approx 0.62\,\text{TeV}^{-2}$
- From top-loop only: $\text{Br}(h \to aa) = 0.01$ for $|c_{tt}|/\Lambda \approx 1.04\,\text{TeV}^{-1}$

Exotic Higgs Decays $h \to aa$

- Current upper limit $\mathrm{Br}(h \to \mathrm{BSM}) < 0.34$ [ATLAS and CMS:1606.02266]

$$\implies \quad \Gamma(h \to \mathrm{BSM}) < 2.1\,\mathrm{MeV}$$
$$\implies \quad \left|C_{ah}^{\mathrm{eff}}\right| < 1.34 \left[\frac{\Lambda}{1\,\mathrm{TeV}}\right]^2$$

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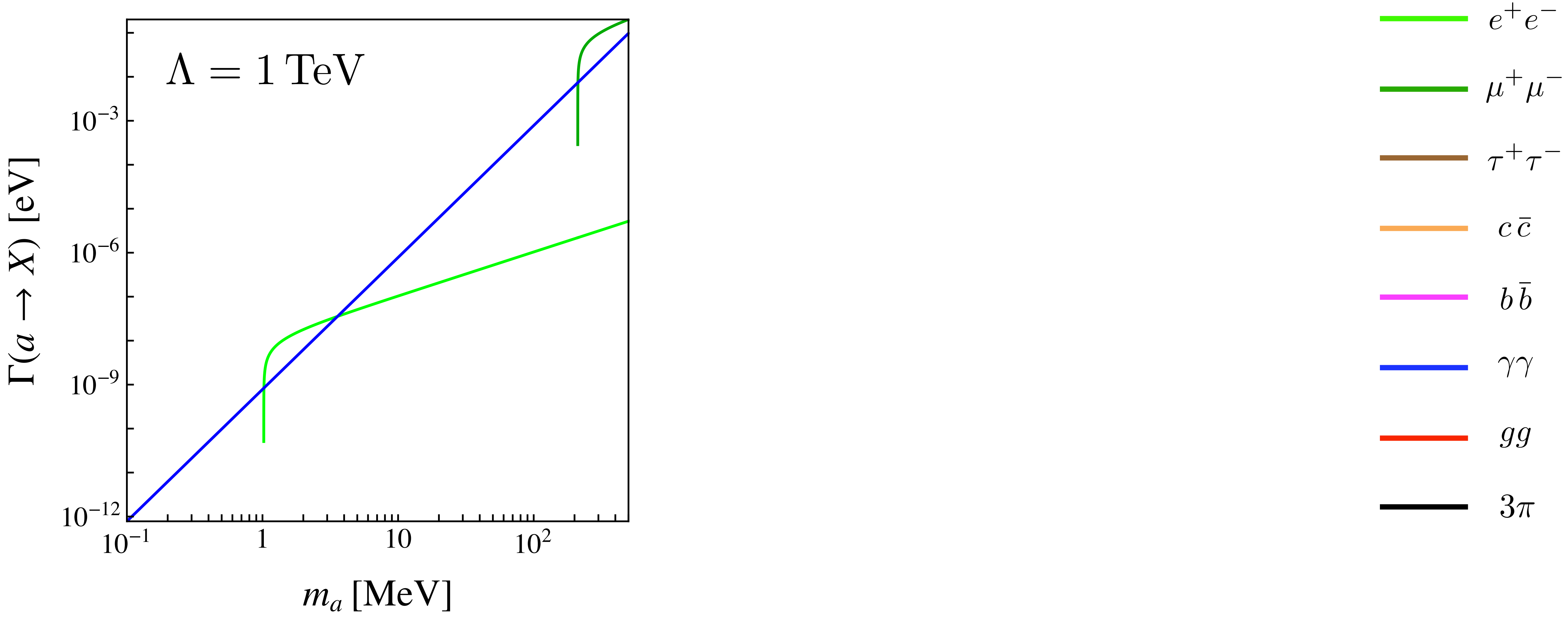
- Interesting final states
  - $h \to aa \to \gamma\gamma\gamma\gamma$
  - $h \to aa \to l^+l^-l^+l^-$
  - $h \to aa \to 4\mathrm{jets}$
  - $h \to aa \to \mathrm{invisible}$

- All these modes can be reconstructed at run II

ALP decays

- Assuming effective Wilson coefficients to be 1



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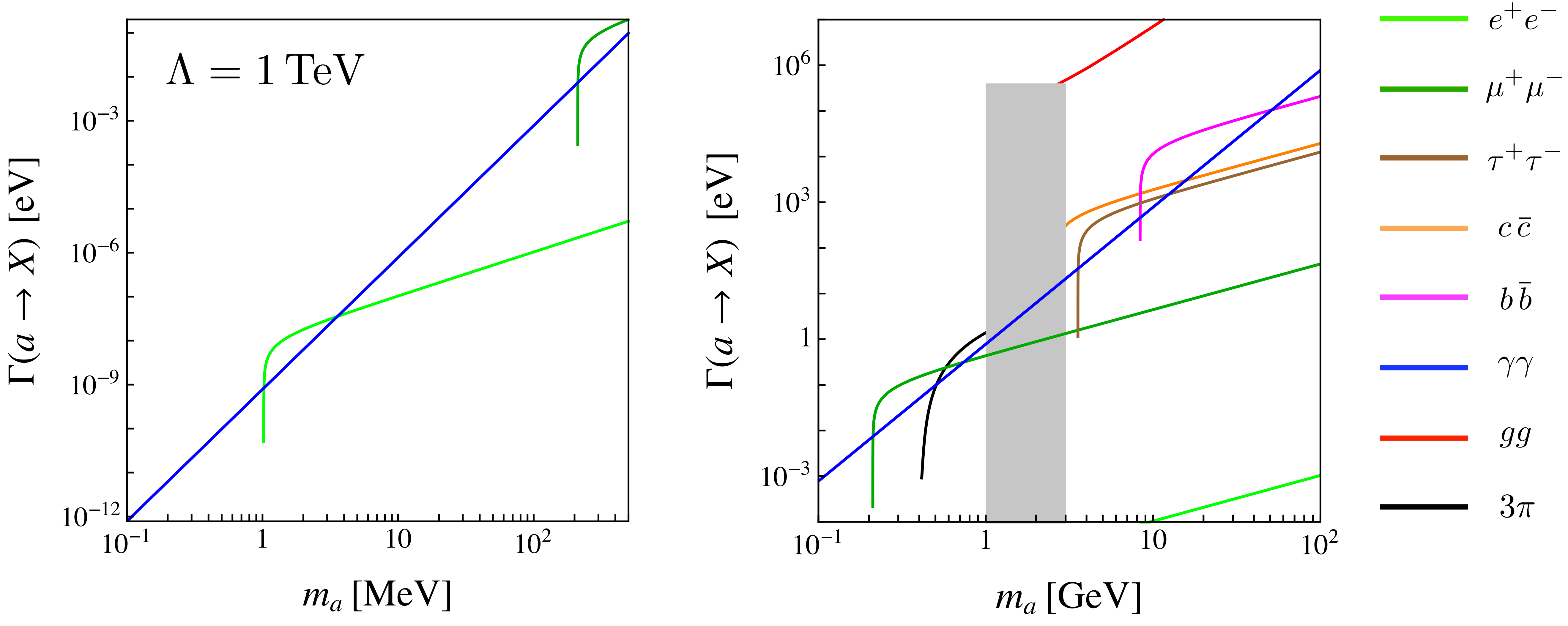
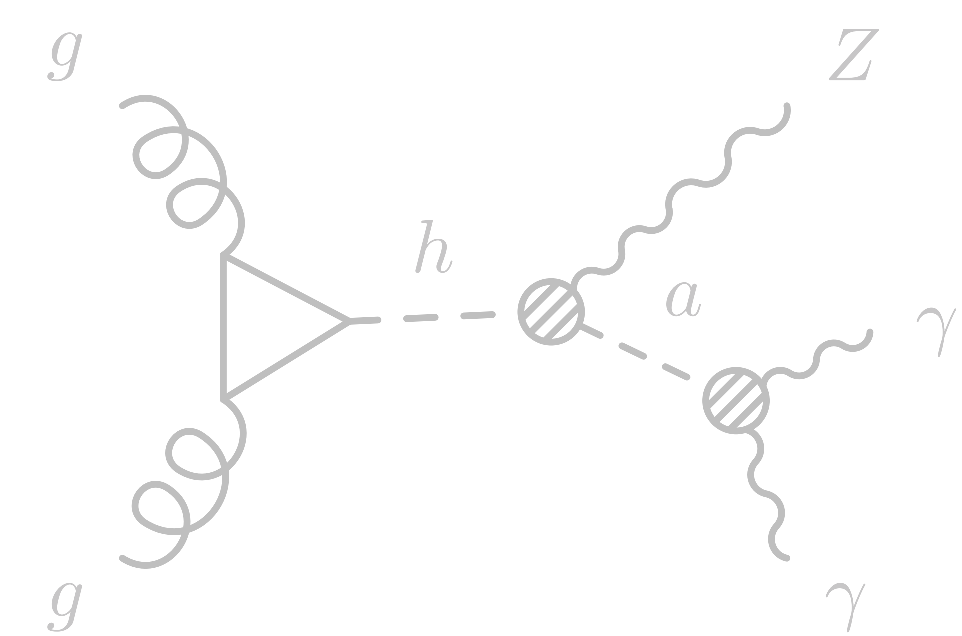


Outline



- Motivation
- ALPs and collider probes
  - Effective Lagrangian
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  - Muon $(g-2)_\mu$
- Conclusions and Outlook

Detecting ALPs in $h \to Za$

- Average decay length perpendicular to beam axis

$$L_a^\perp(\theta) = \sin\theta\,\frac{\beta_a\gamma_a}{\Gamma_a} = \sin\theta\sqrt{\gamma_a^2 - 1}\;\frac{\mathrm{Br}(a\to X\bar{X})}{\Gamma(a\to X\bar{X})}$$

- Fraction of ALPs decaying before travelling a certain distance

$$f_\mathrm{det} = \int_0^{\pi/2} d\theta\,\sin\theta\left(1 - e^{-L_\mathrm{det}/L_a^\perp(\theta)}\right)$$

Decay into photons before EM calorimeter

$L_\mathrm{det} = 1.5\,\mathrm{m}$

Decay into electrons before inner tracker

$L_\mathrm{det} = 2\,\mathrm{cm}$

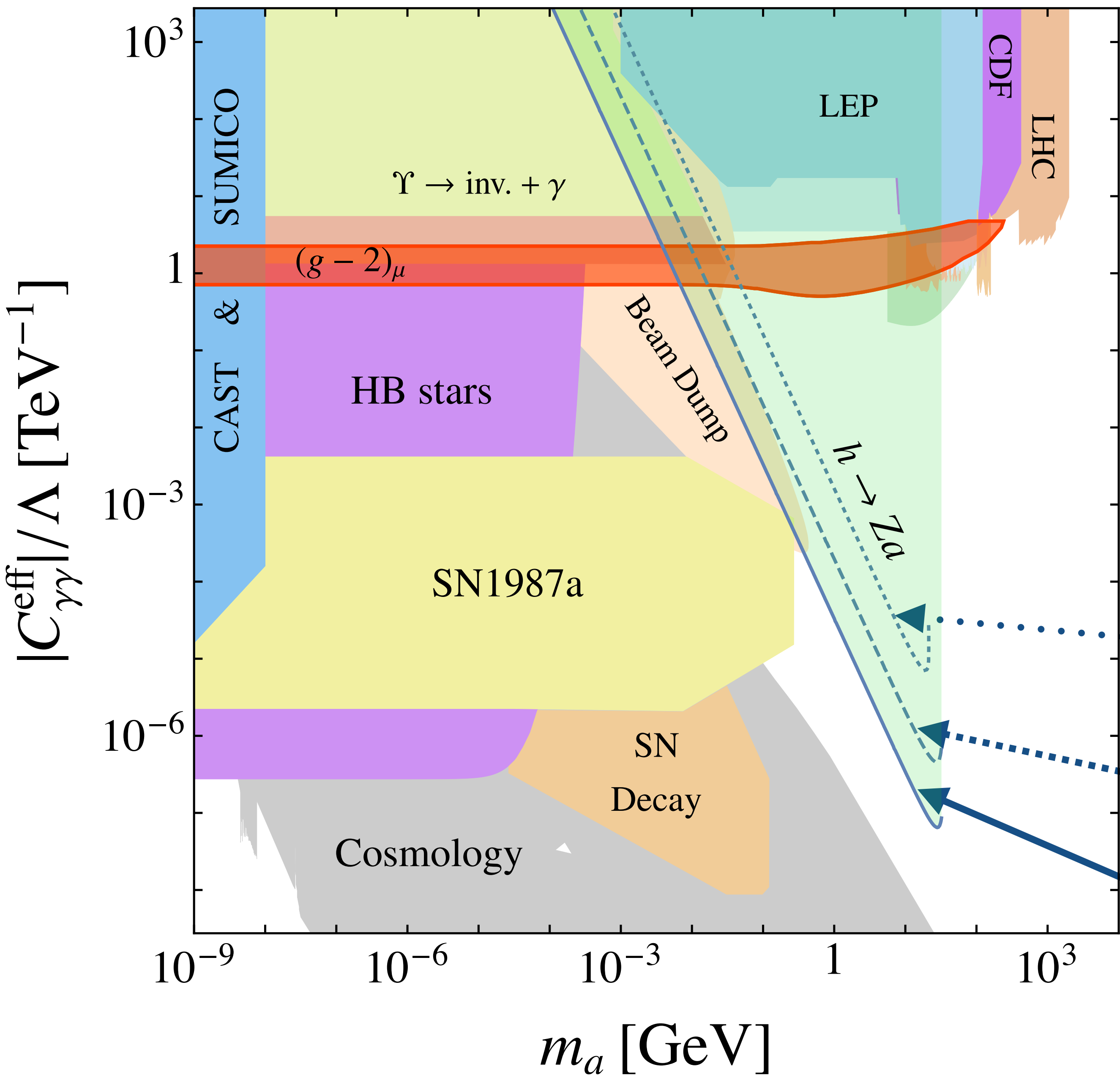
- Effective branching ratios

$$\mathrm{Br}(h\to Za\to \ell^+\ell^- X\bar{X})\big|_\mathrm{eff} = \mathrm{Br}(h\to Za)\times\mathrm{Br}(a\to X\bar{X})\,f_\mathrm{dec}\,\mathrm{Br}(Z\to\ell^+\ell^-)$$

Probing the parameter space

- Constraints on ALP mass and coupling to photons

[Jäckel, Spannowsky: 1509.00476]



$|C_{Zh}| = 0.015,\ \mathrm{Br}(a \to \gamma\gamma) > 0.46$

$|C_{Zh}| = 0.1,\ \mathrm{Br}(a \to \gamma\gamma) > 0.011$

$|C_{Zh}| = 0.72,\ \mathrm{Br}(a \to \gamma\gamma) > 3 \cdot 10^{-4}$

(for $\Lambda = 1$ TeV)

[Bauer, Neubert, Thamm: 1704.08207]

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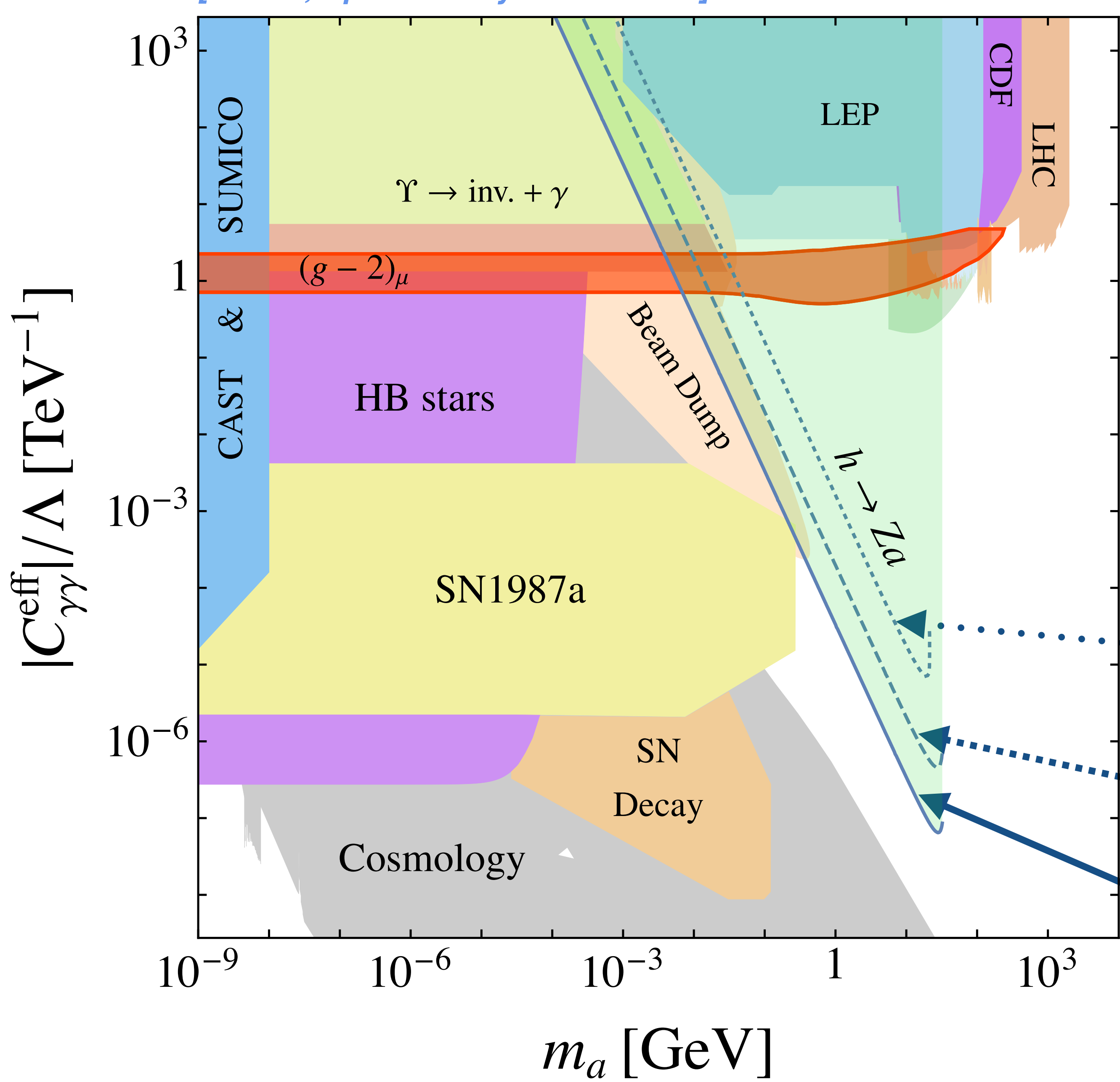

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- Large hierarchy in couplings can be plausible

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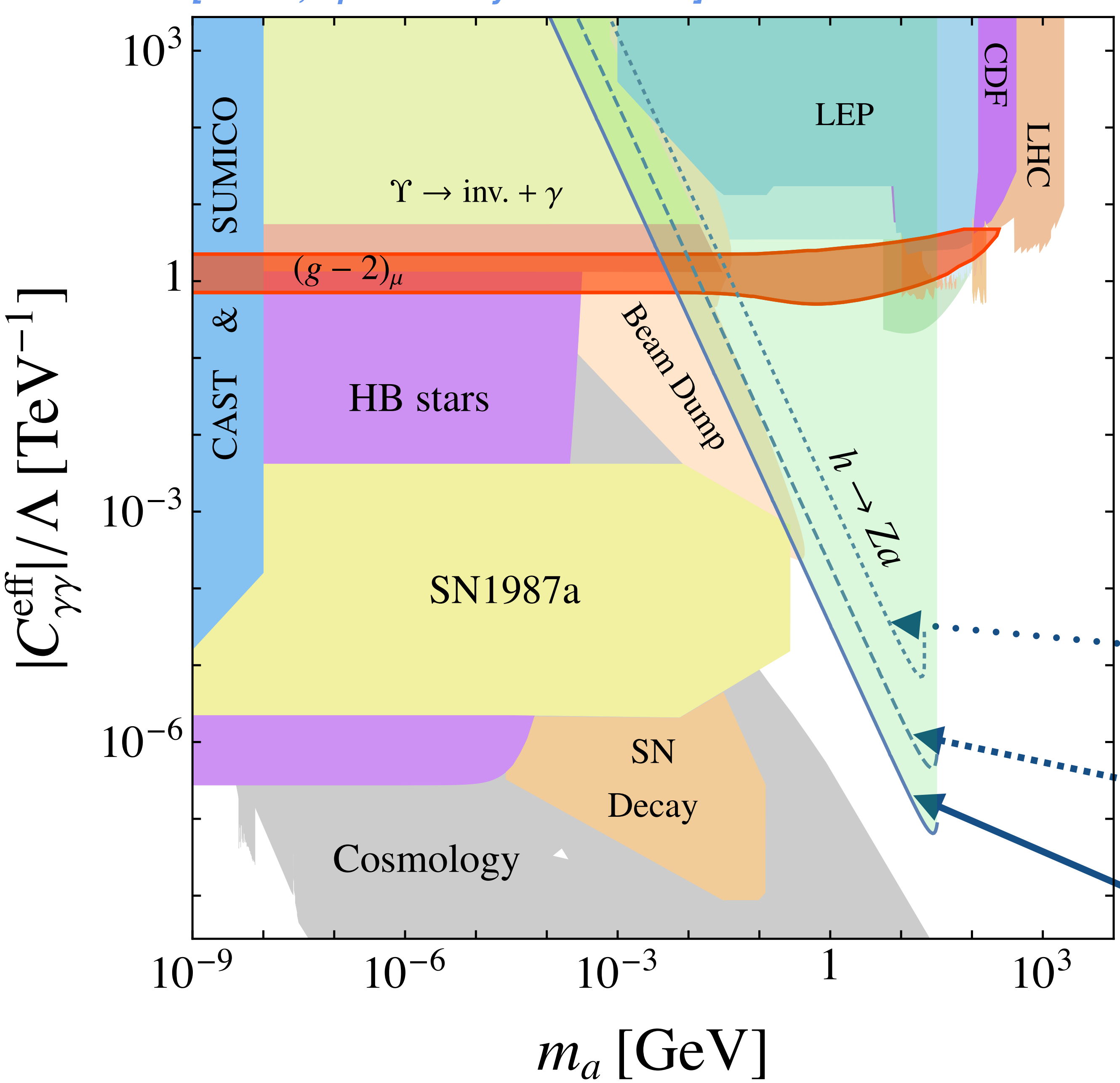

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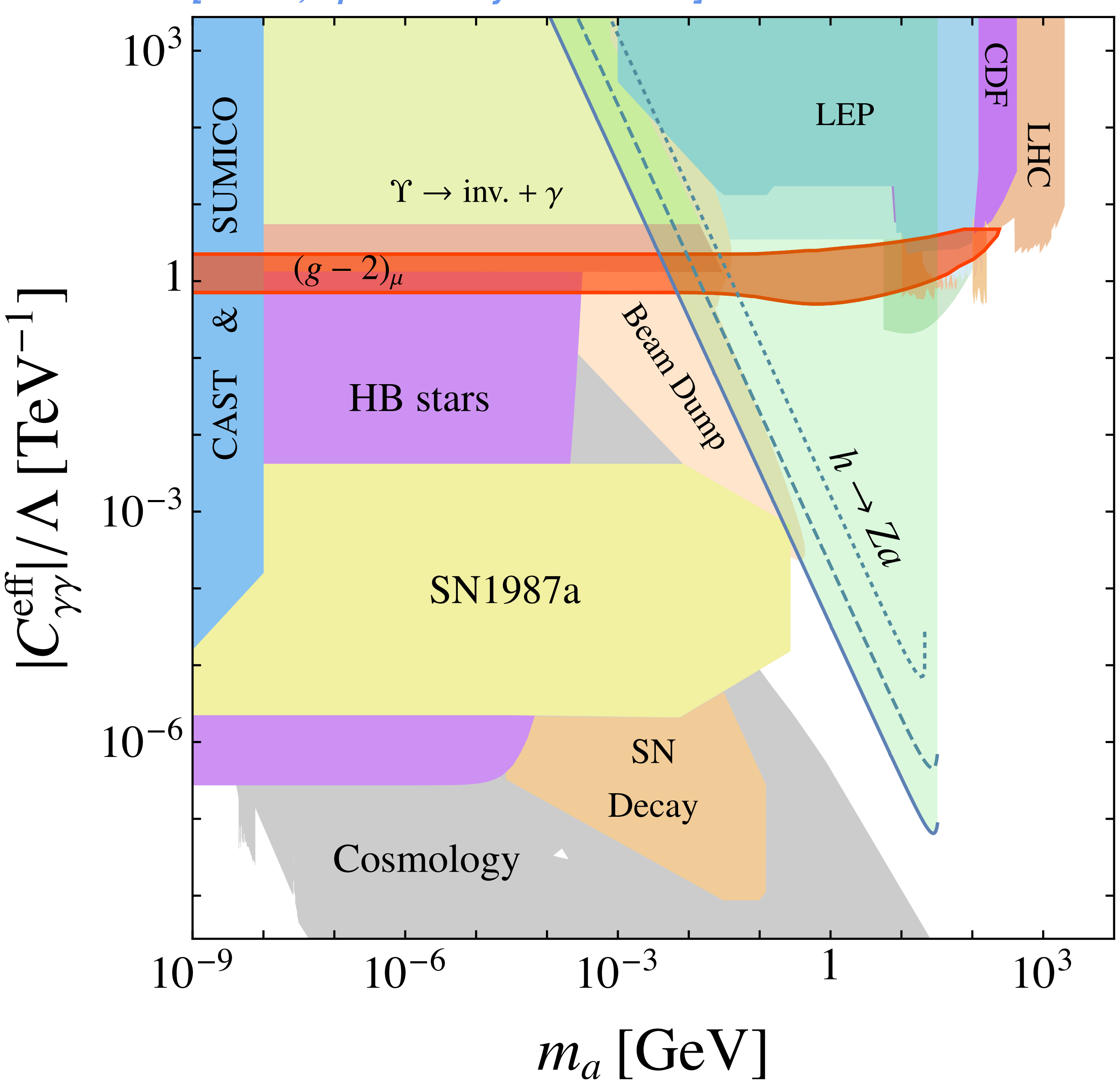
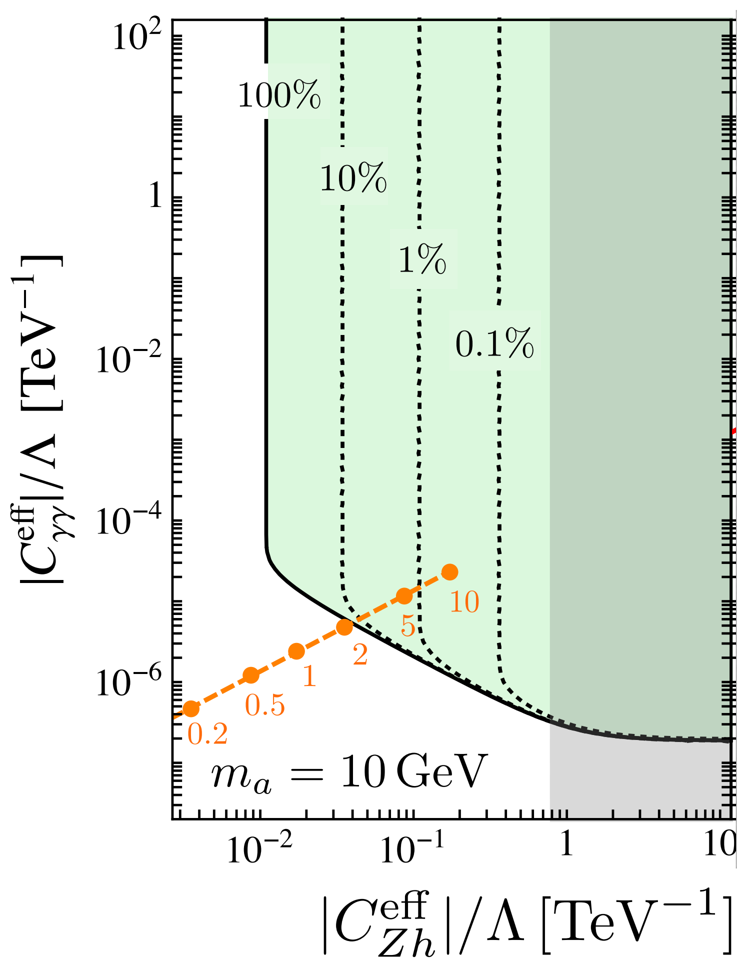
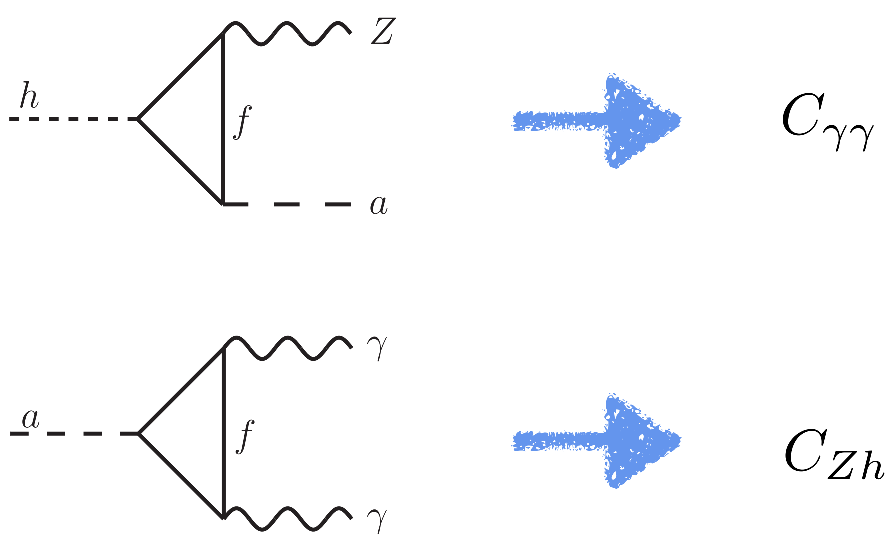
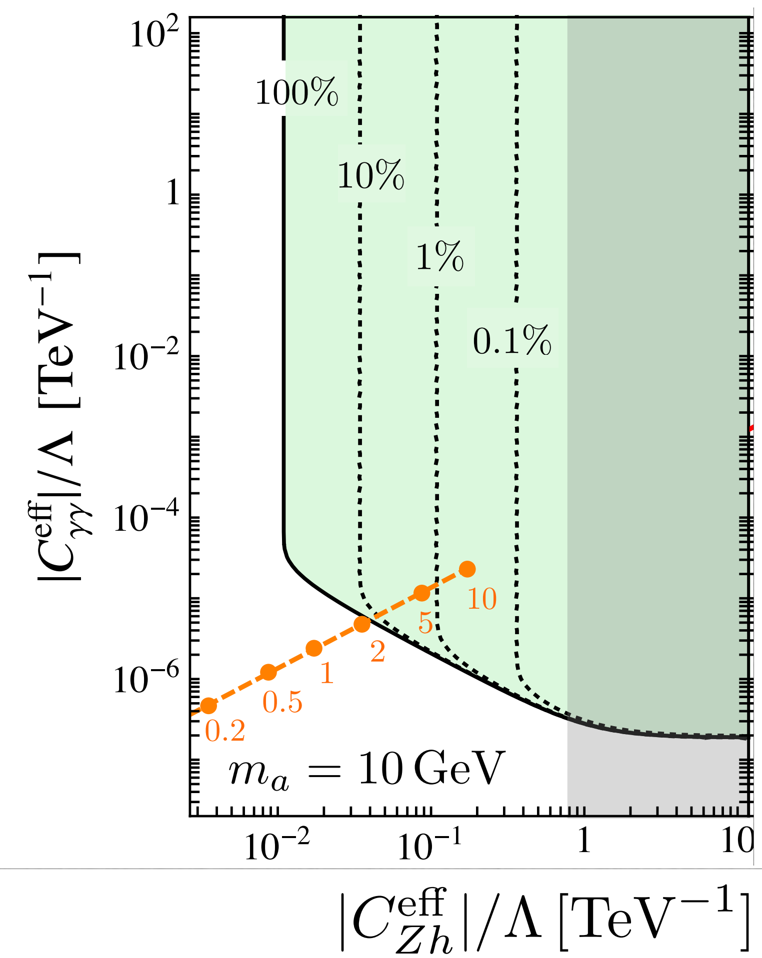




Probing the parameter space

- Large hierarchy in couplings can be plausible
- Integrating out the top





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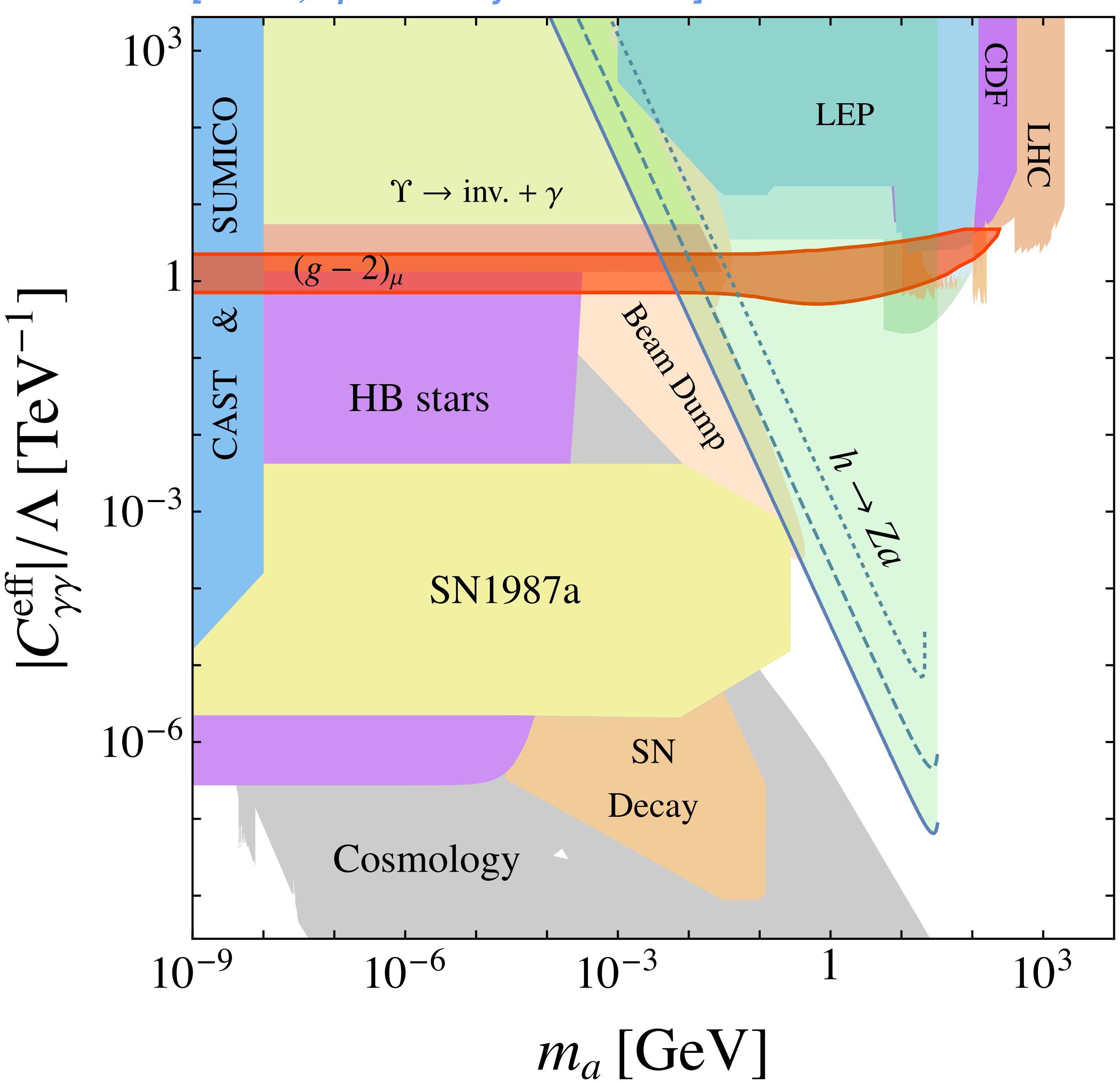

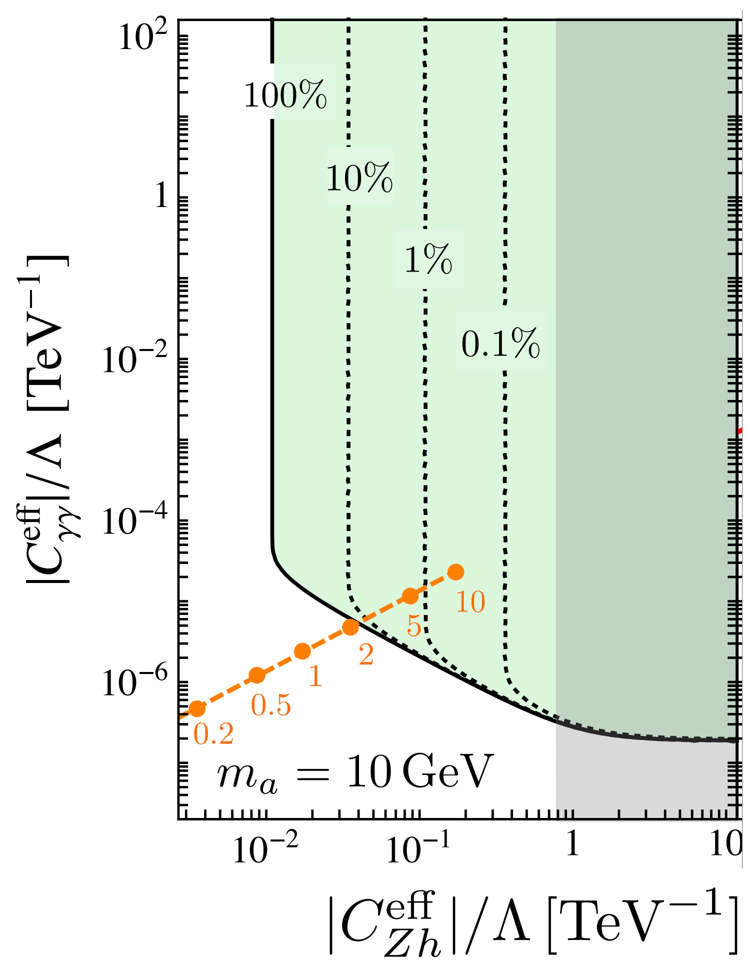

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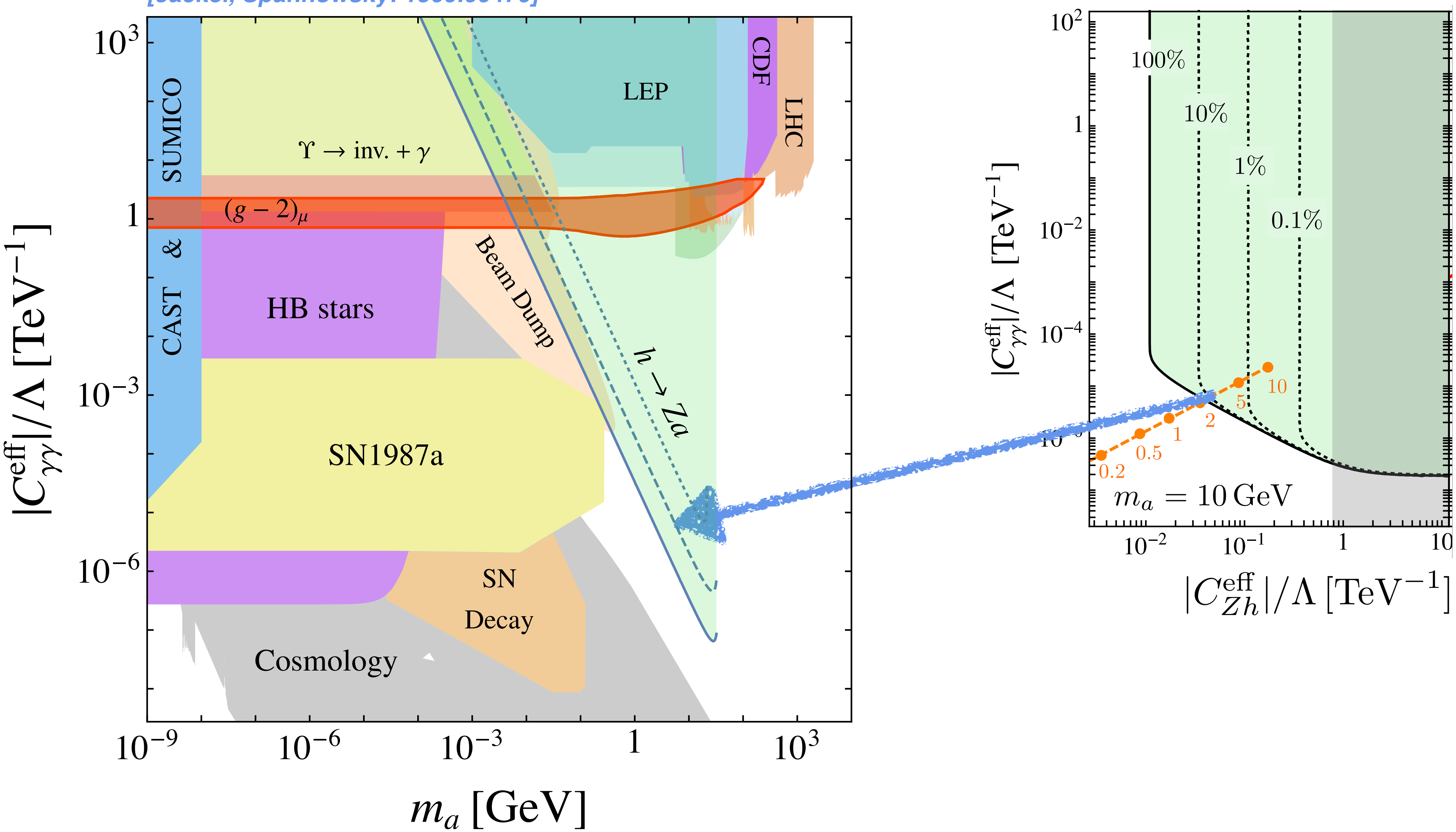
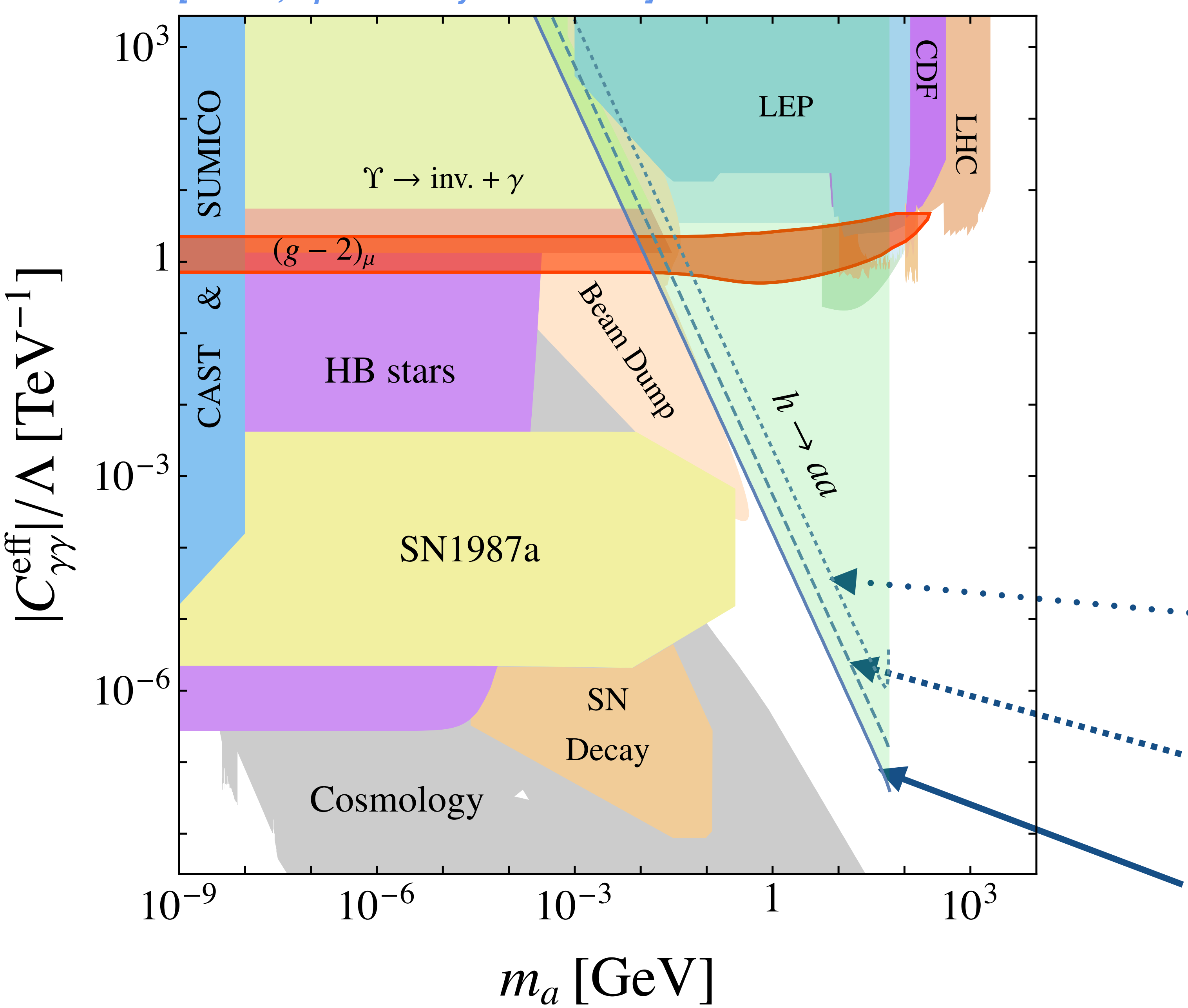


Probing the parameter space

- Constraints on ALP mass and coupling to photons

[Jäckel, Spannowsky: 1509.00476]



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$|C_{ah}| = 0.1,\ \text{Br}(a \to \gamma\gamma) > 0.049$

$|C_{ah}| = 1,\ \text{Br}(a \to \gamma\gamma) > 0.006$

(for $\Lambda = 1\,\text{TeV}$)

[Bauer, Neubert, Thamm: 1704.08207]

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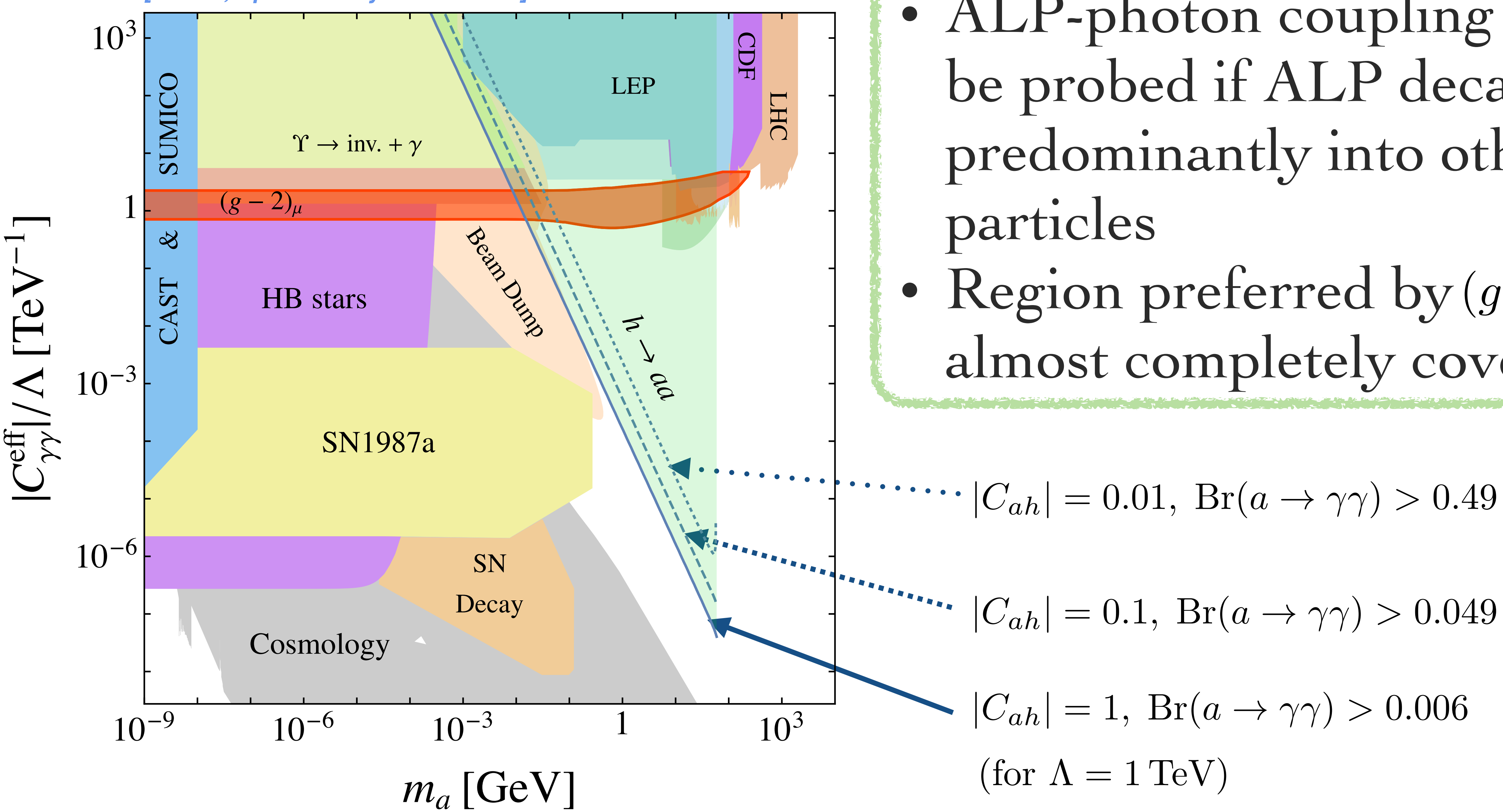

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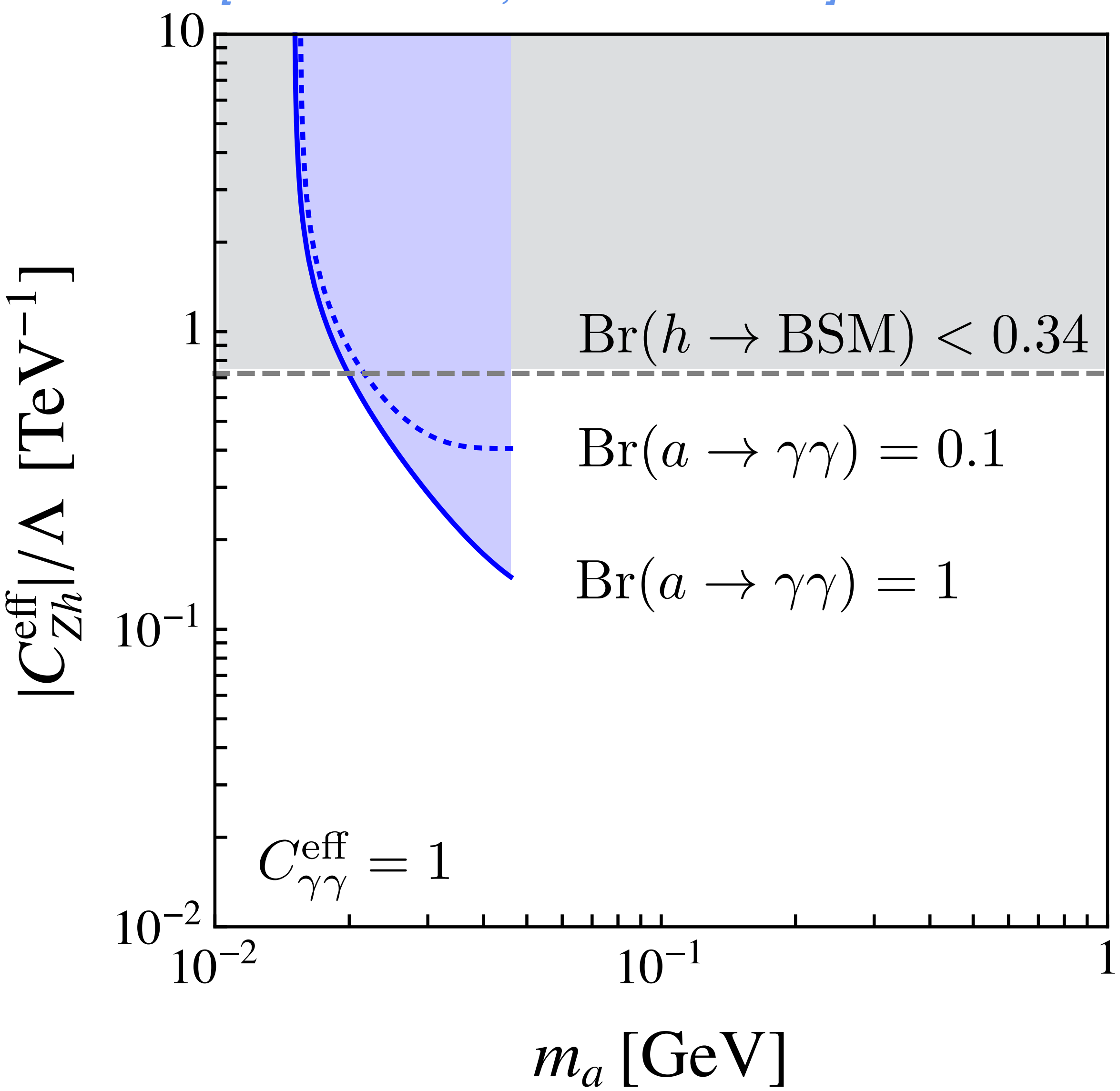
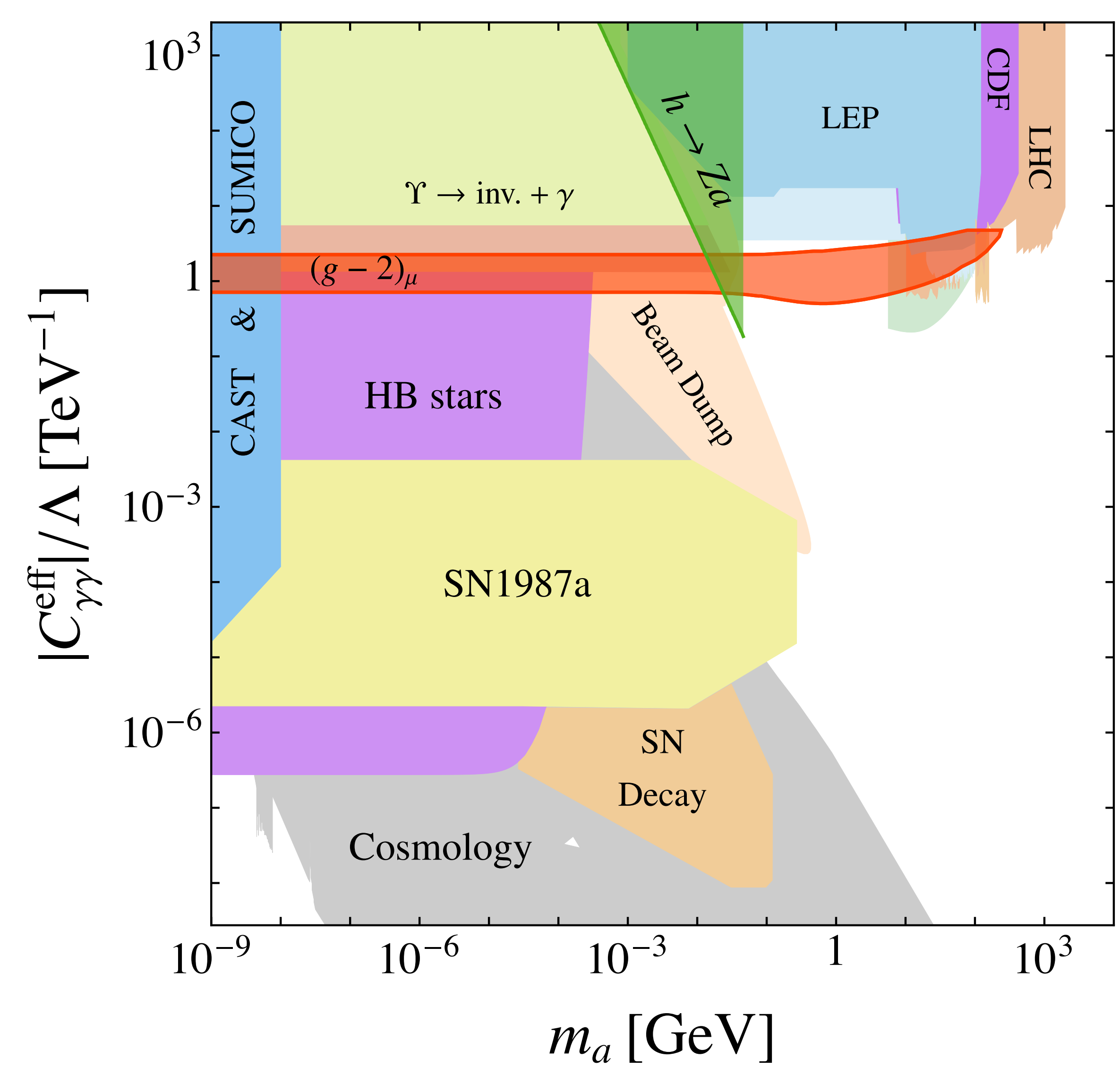
Current exclusion bounds

- Current bounds on $h \to Za$

[CMS: 1307.5515, ATLAS: 1402.3051]





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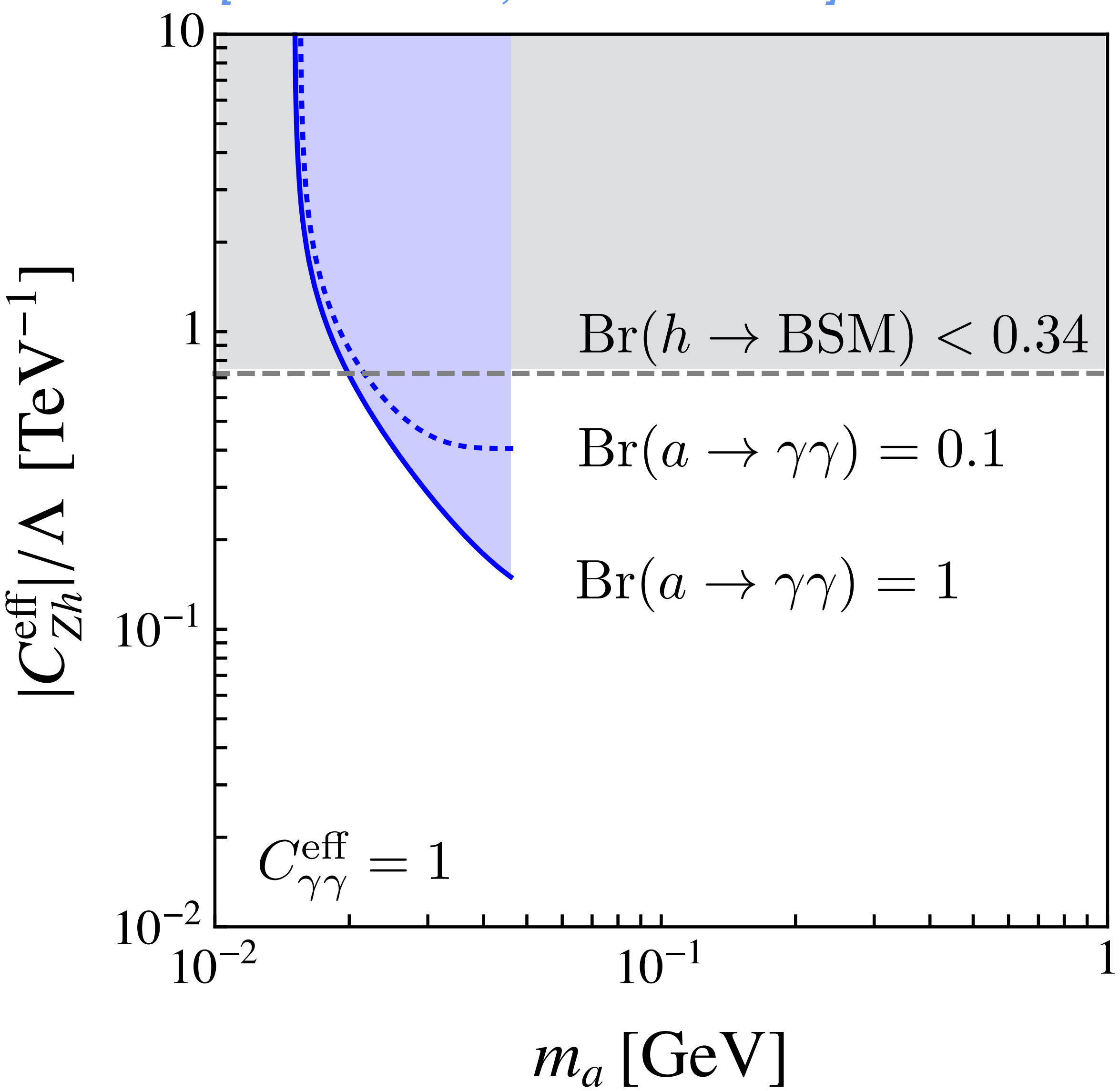

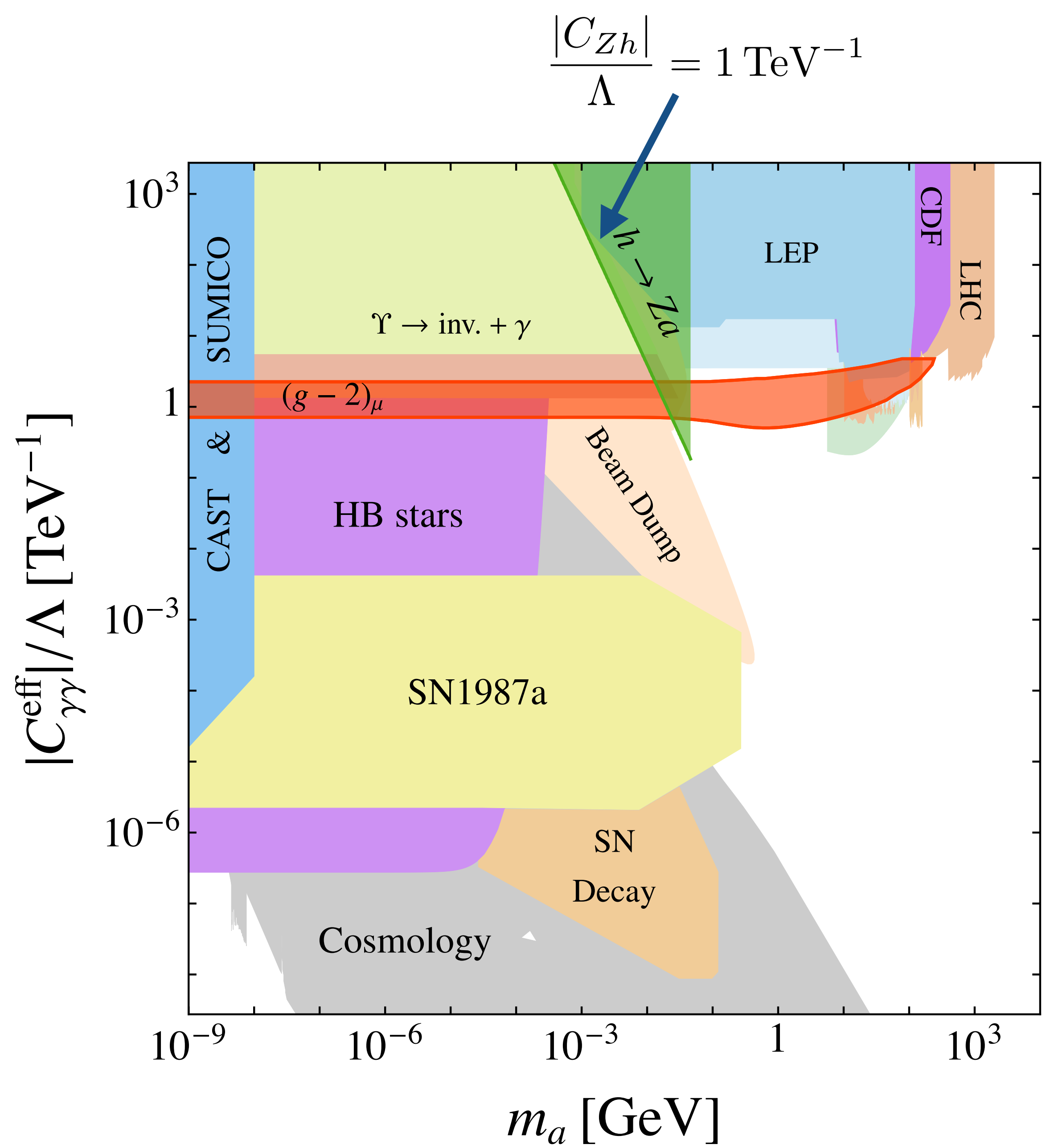

[Bauer, Neubert, Thamm: 1708.00443]

Current exclusion bounds

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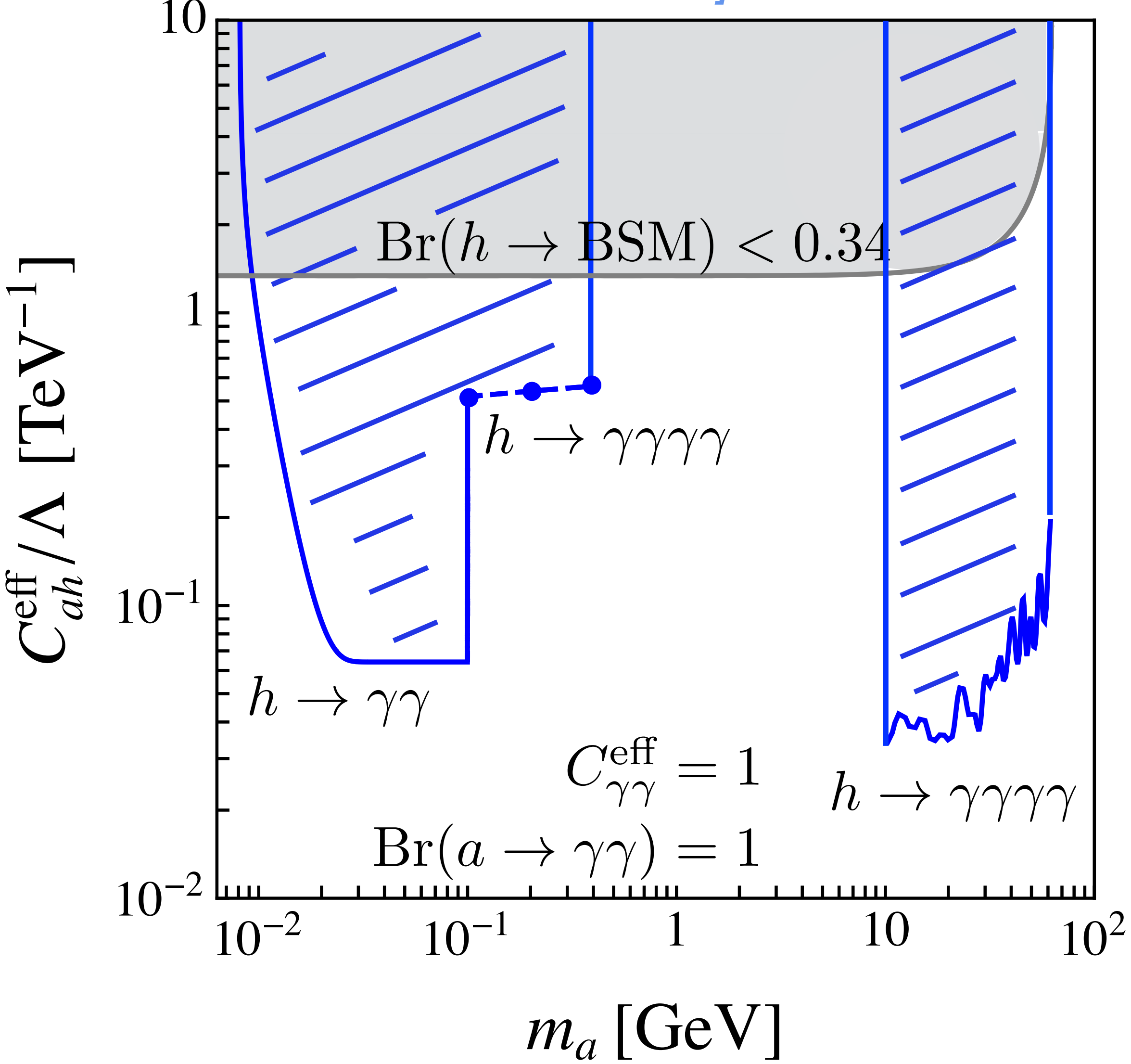
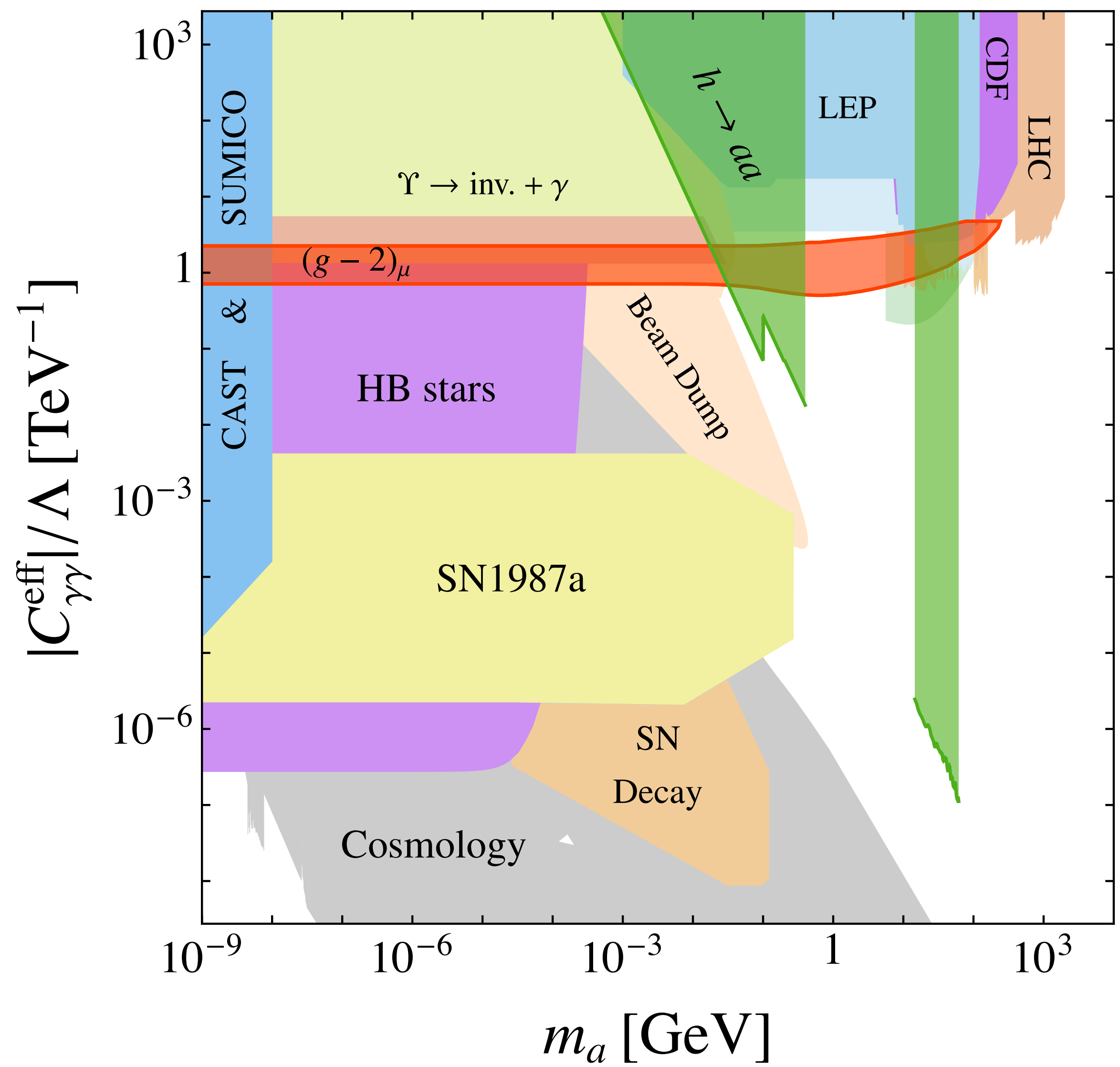
[ATLAS-CONF-2012-079, ATLAS: 1509.05051, ATLAS and CMS: 1606.02266]





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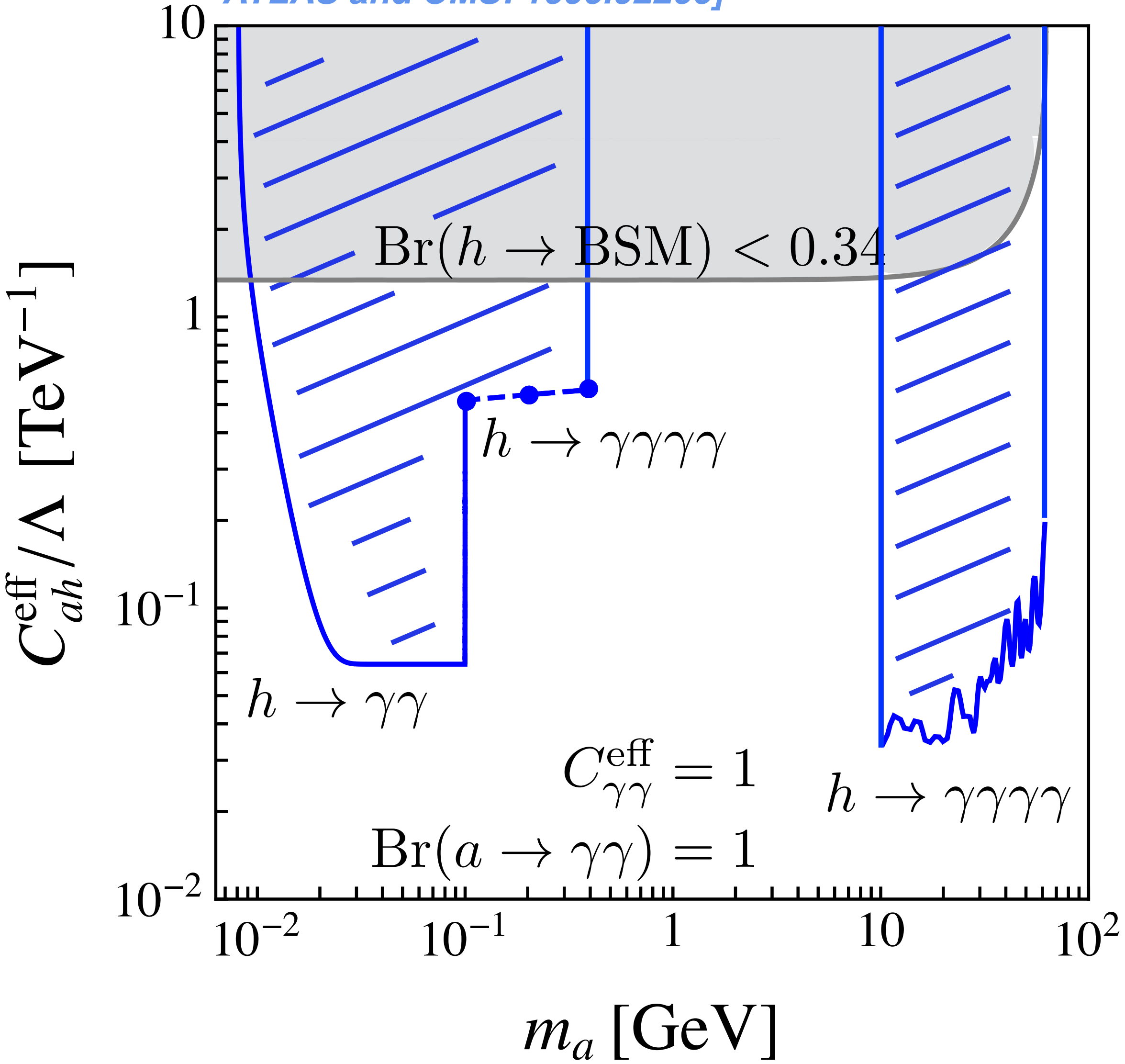
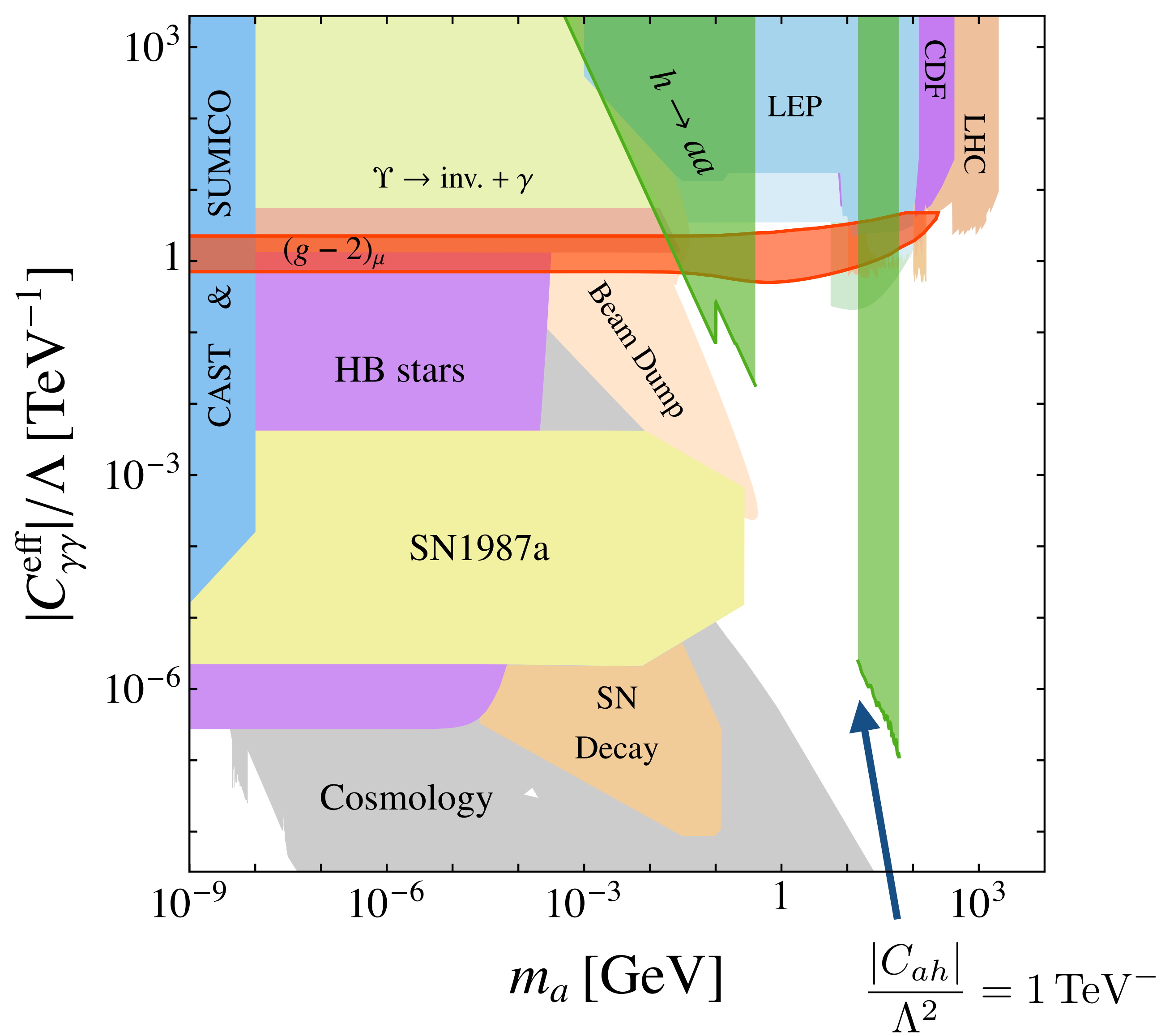
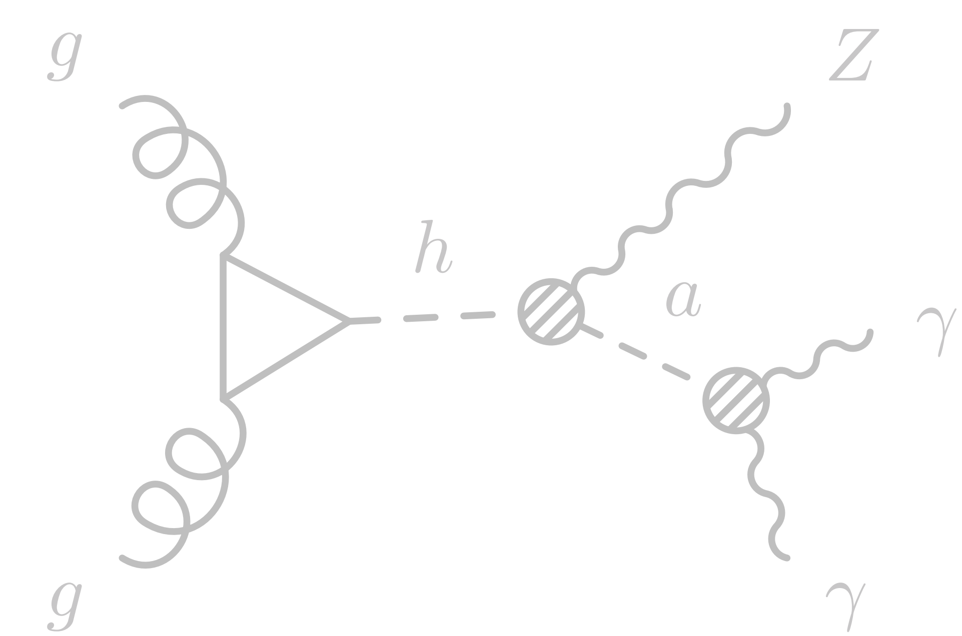




[Bauer, Neubert, Thamm: 1708.00443]

Outline



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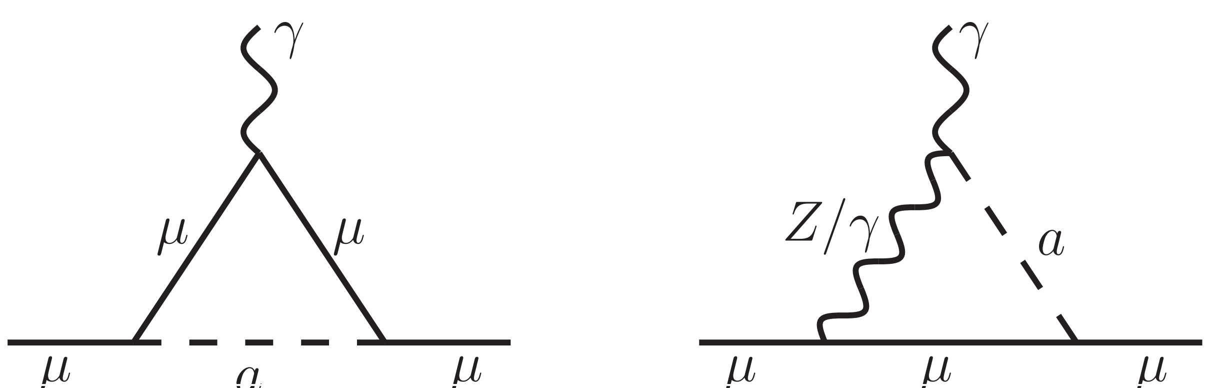
Muon $(g-2)_\mu$

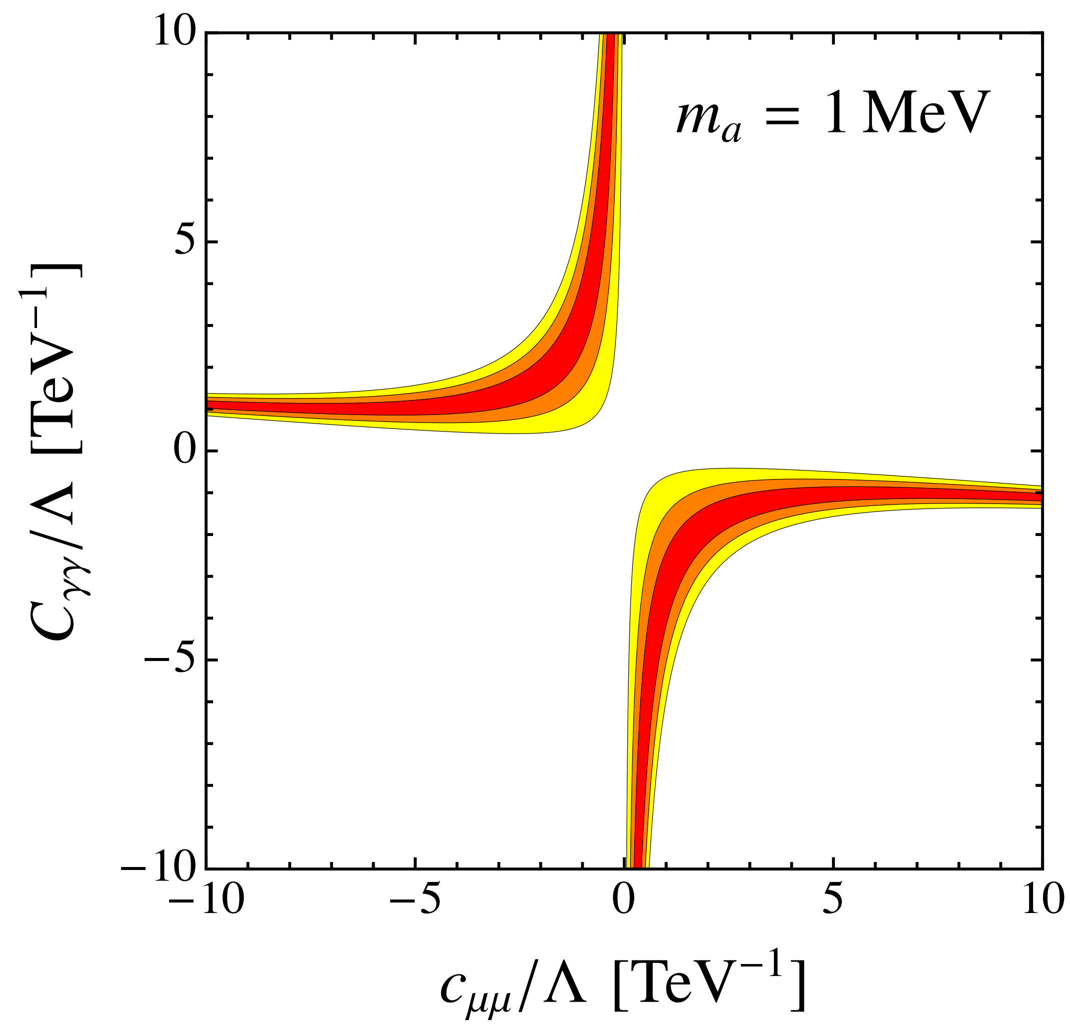
- Persistent 3σ deviation

[Particle Data Group 2016]

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (288 \pm 63 \pm 49) \cdot 10^{-11}$$

- ALP can account for discrepancy





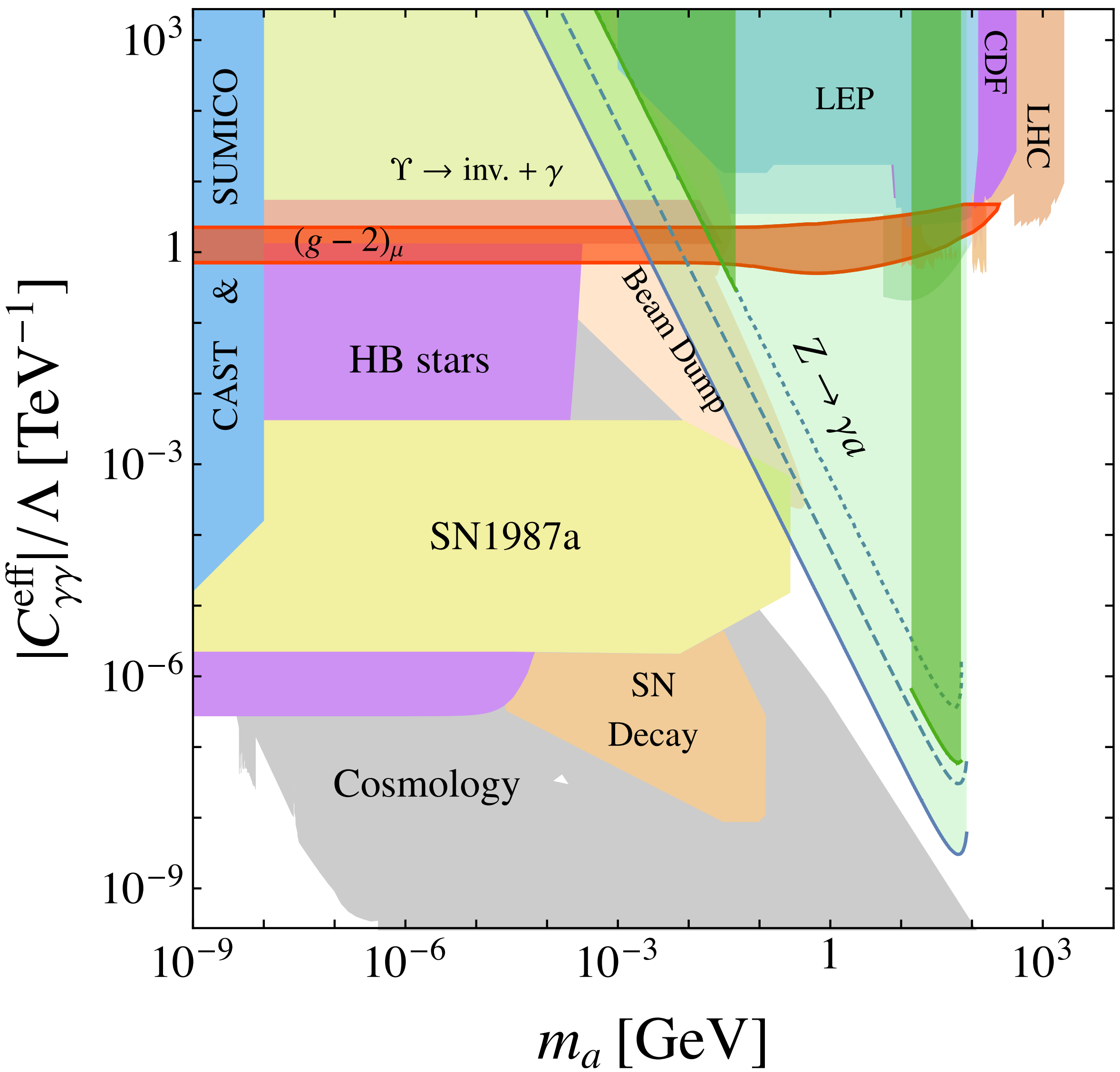
[Haber, Kane, Sterling: Nucl. Phys. B 161 (1979)]
[Chang, Chang, Chou, Keung: 0009292]
[Marciano, Masiero, Paradisi, Passera: 1607.010122]

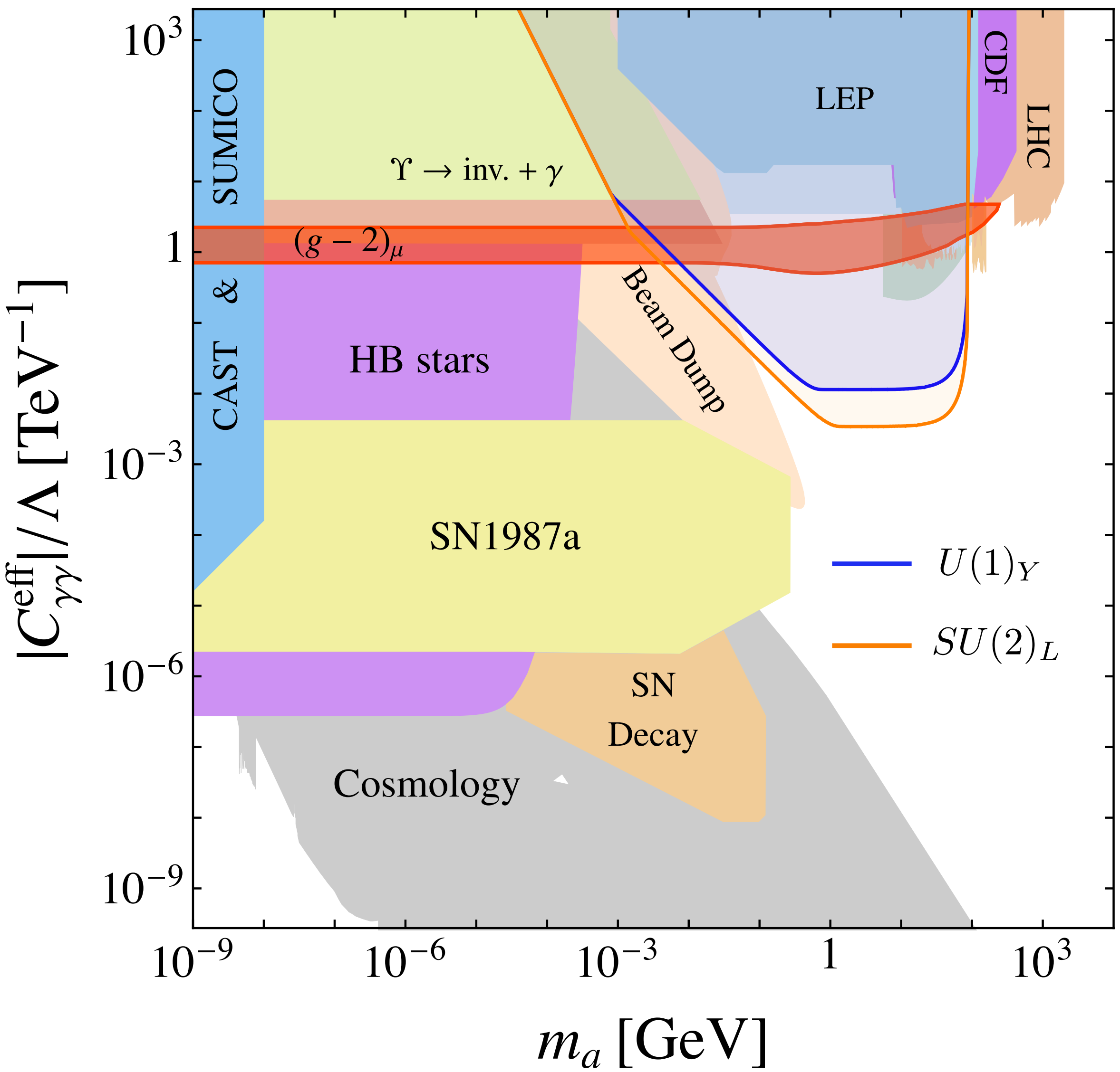
Conclusions

- Rare Higgs decays provide a powerful way to probe the existence of ALPs with masses between 30 MeV and 60 GeV and couplings suppressed by the 1 - 100 TeV scale
- Connection to low-energy physics probes such as $(g-2)_\mu$

Probing the parameter space

- Reach in $Z \to \gamma a$

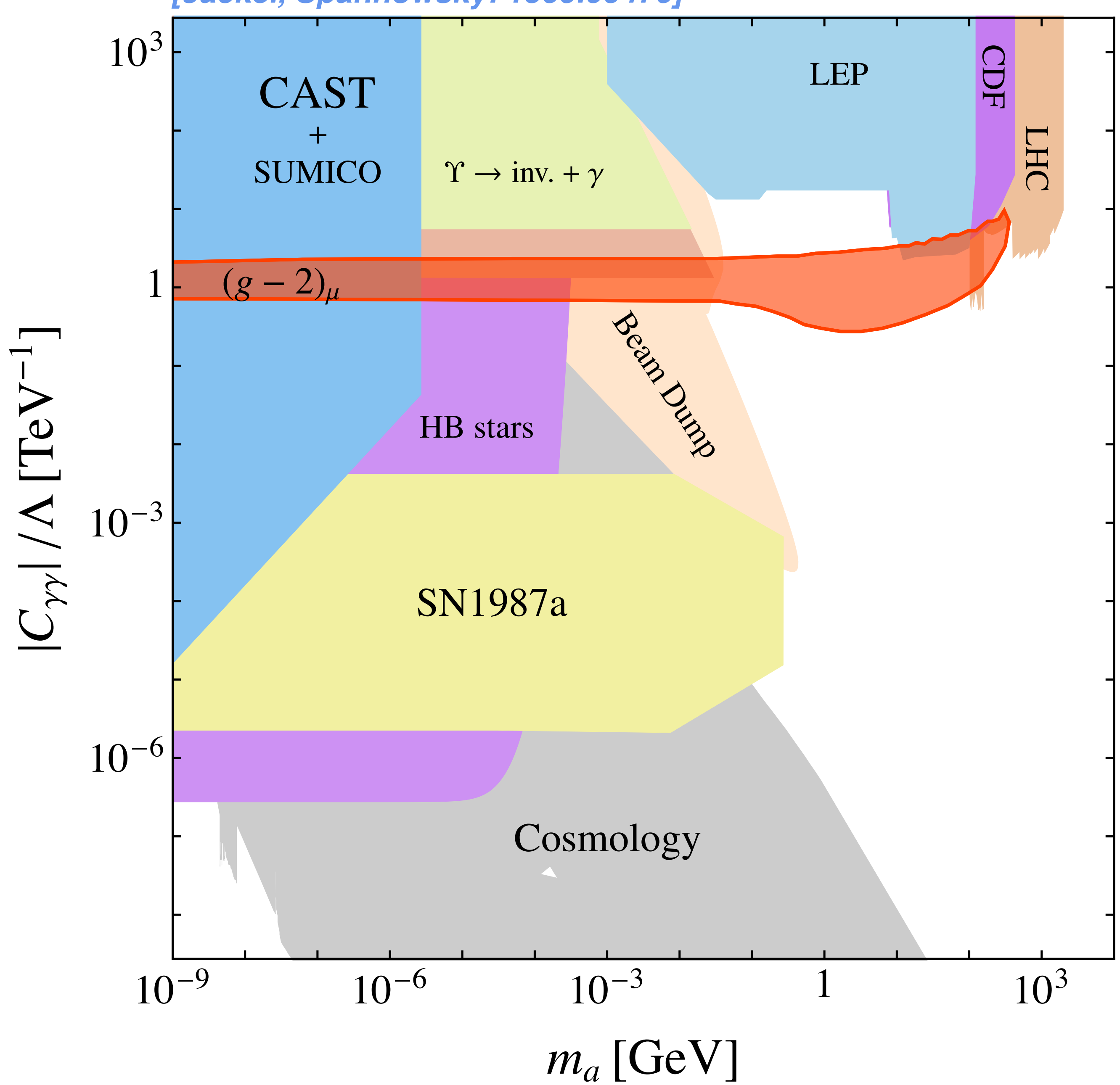




Probing the parameter space

- Constraints on ALP mass and coupling to photons

[Jäckel, Spannowsky: 1509.00476]



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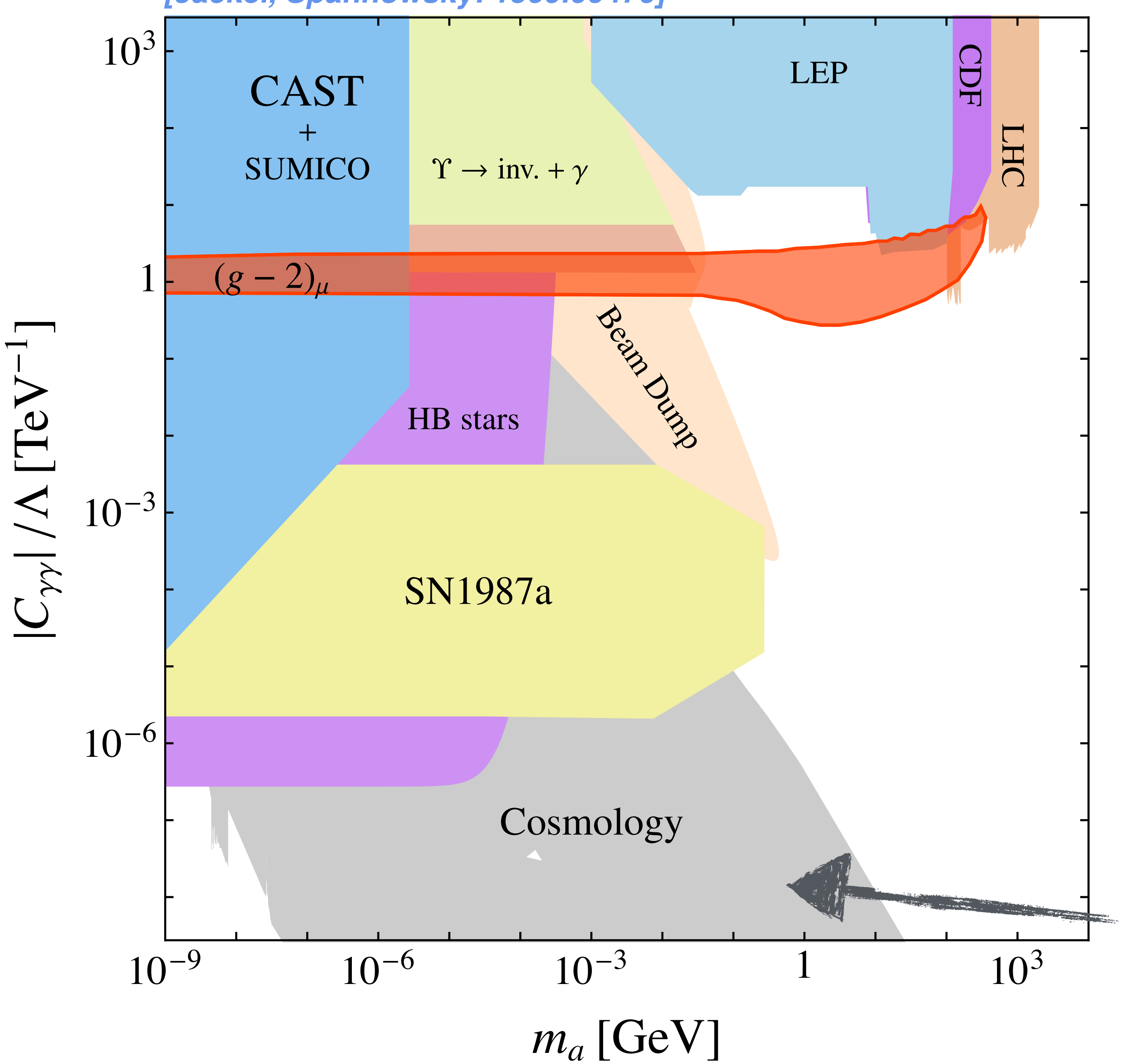

Combination of cosmological bounds (measurement of Neff, primordial deuterium abundance, modification to BB nucleosynthesis, distortion of CMB, diffuse photon background,…)

Probing the parameter space

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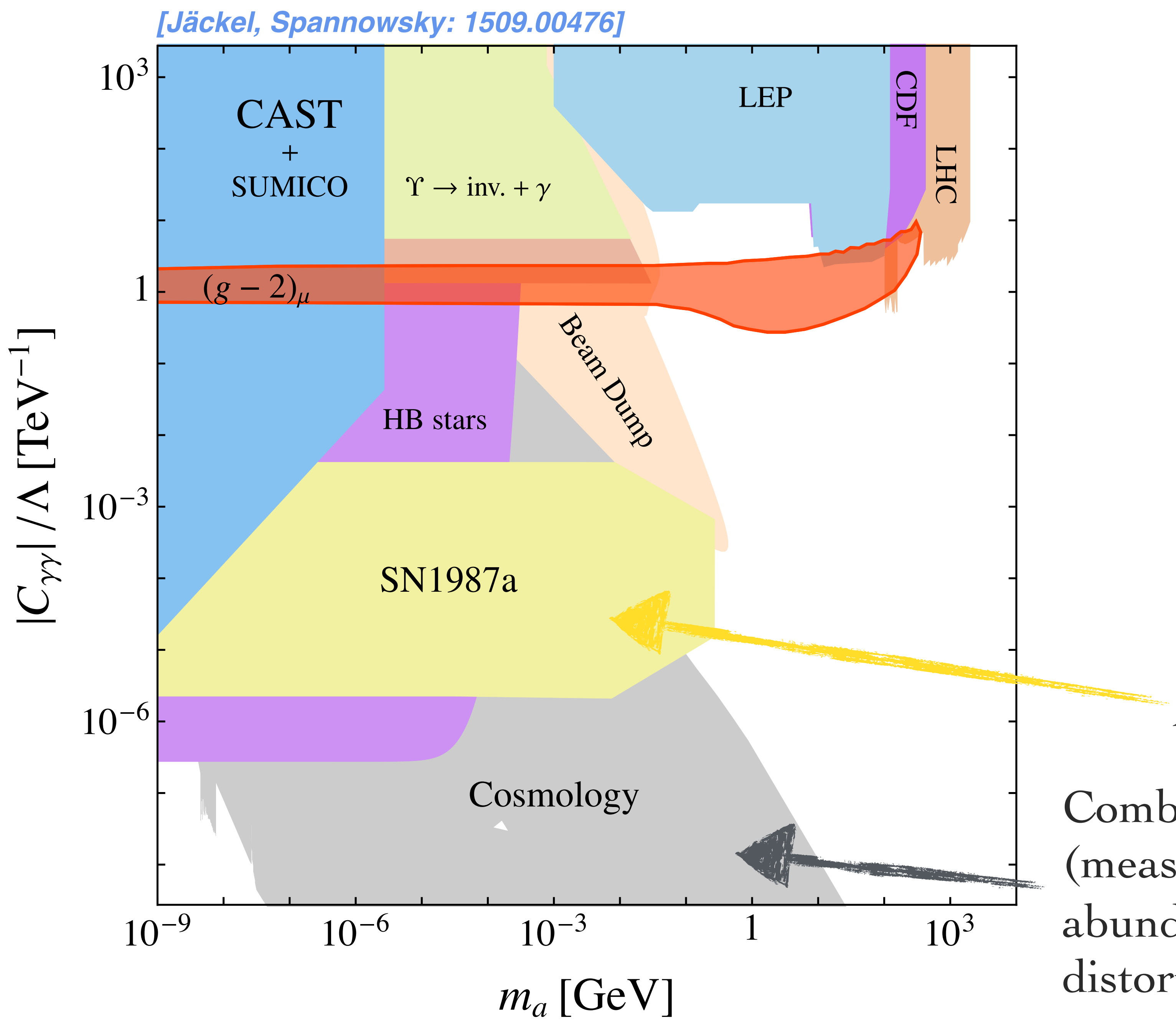

Absence of photon burst after supernova

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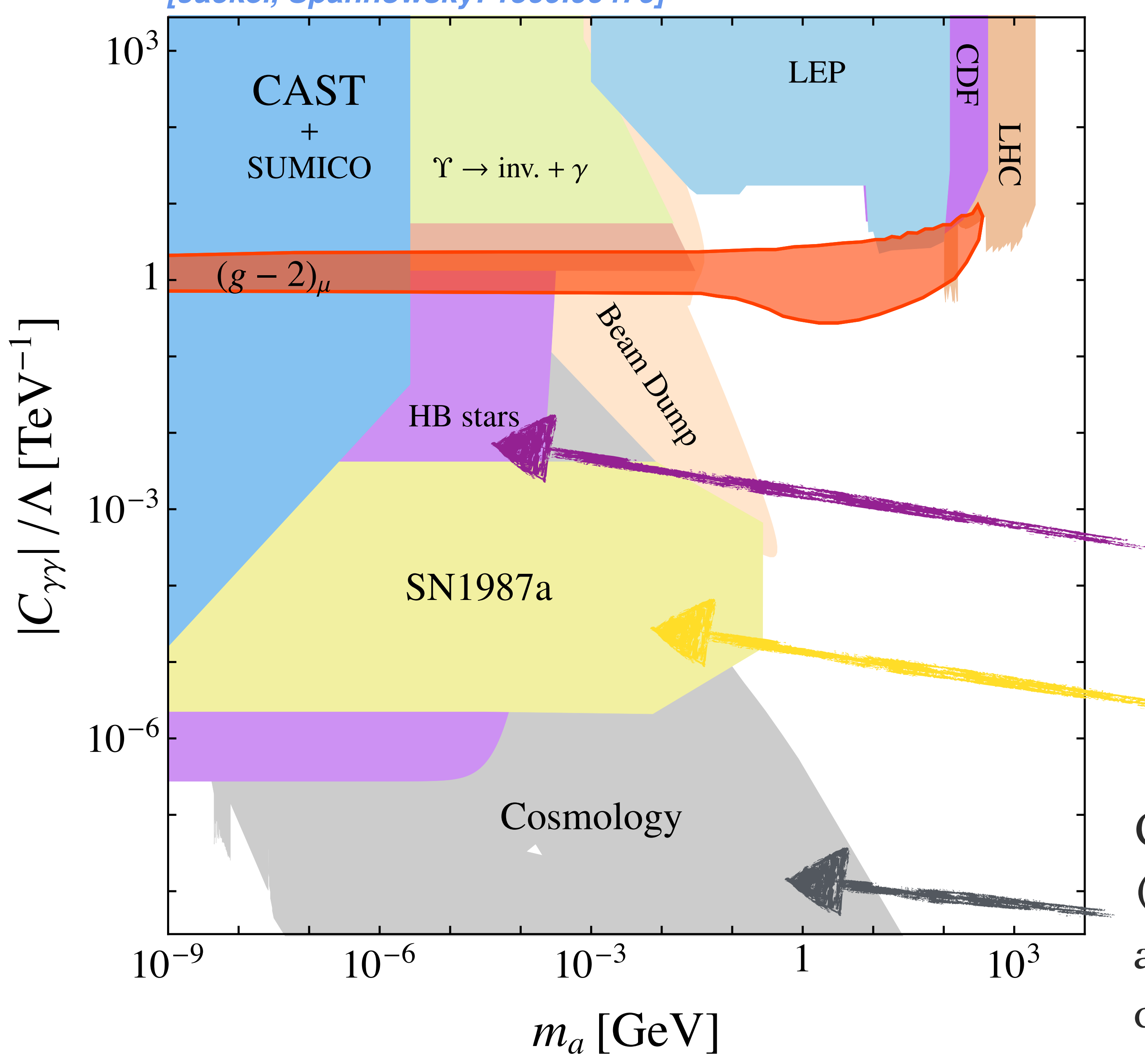

Energy loss of stars constrained by ratio of red giant to younger stars of horizontal branch

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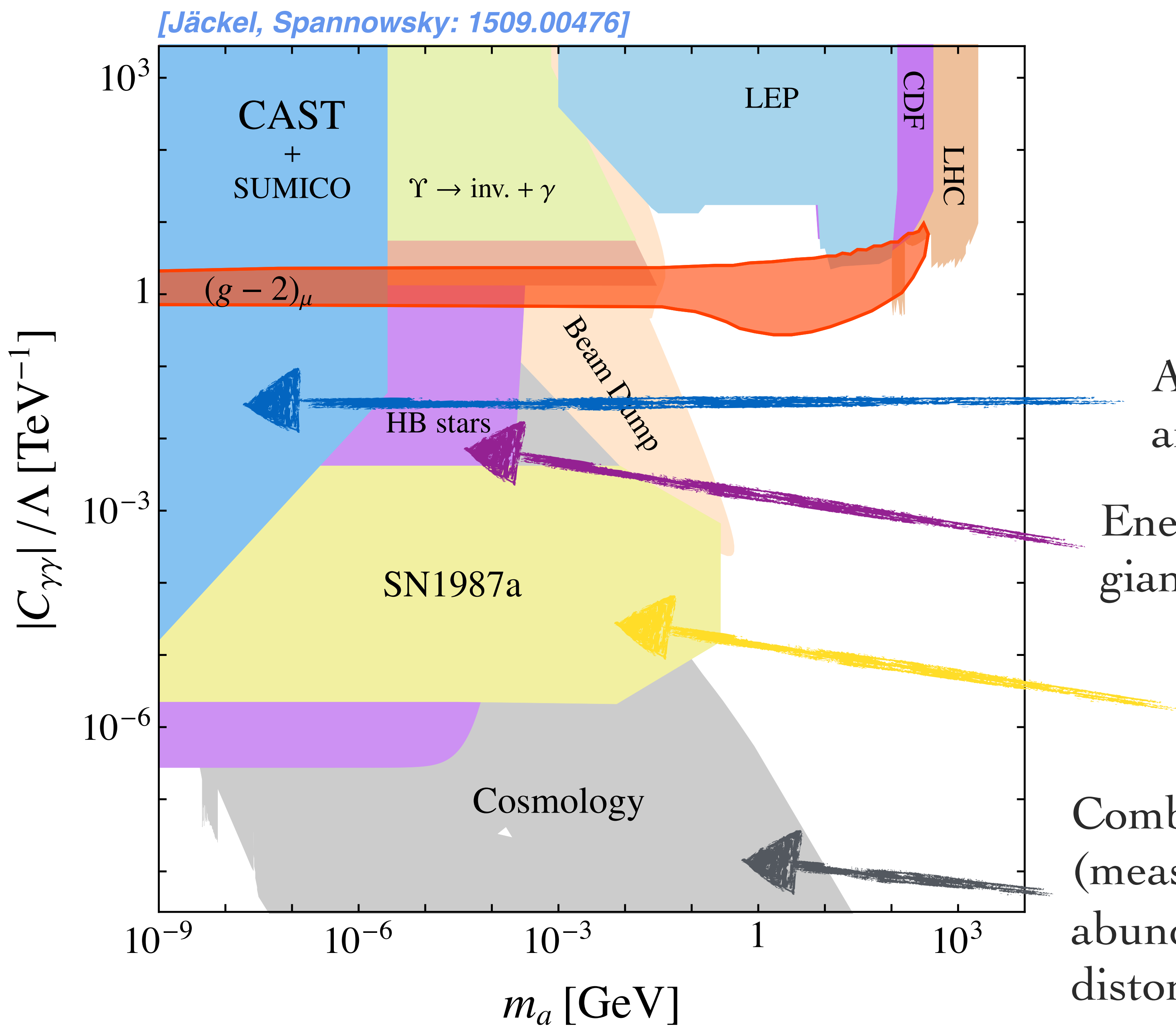

Axion helioscopes: Tokyo Axion Helioscope and CERN axion solar telescope

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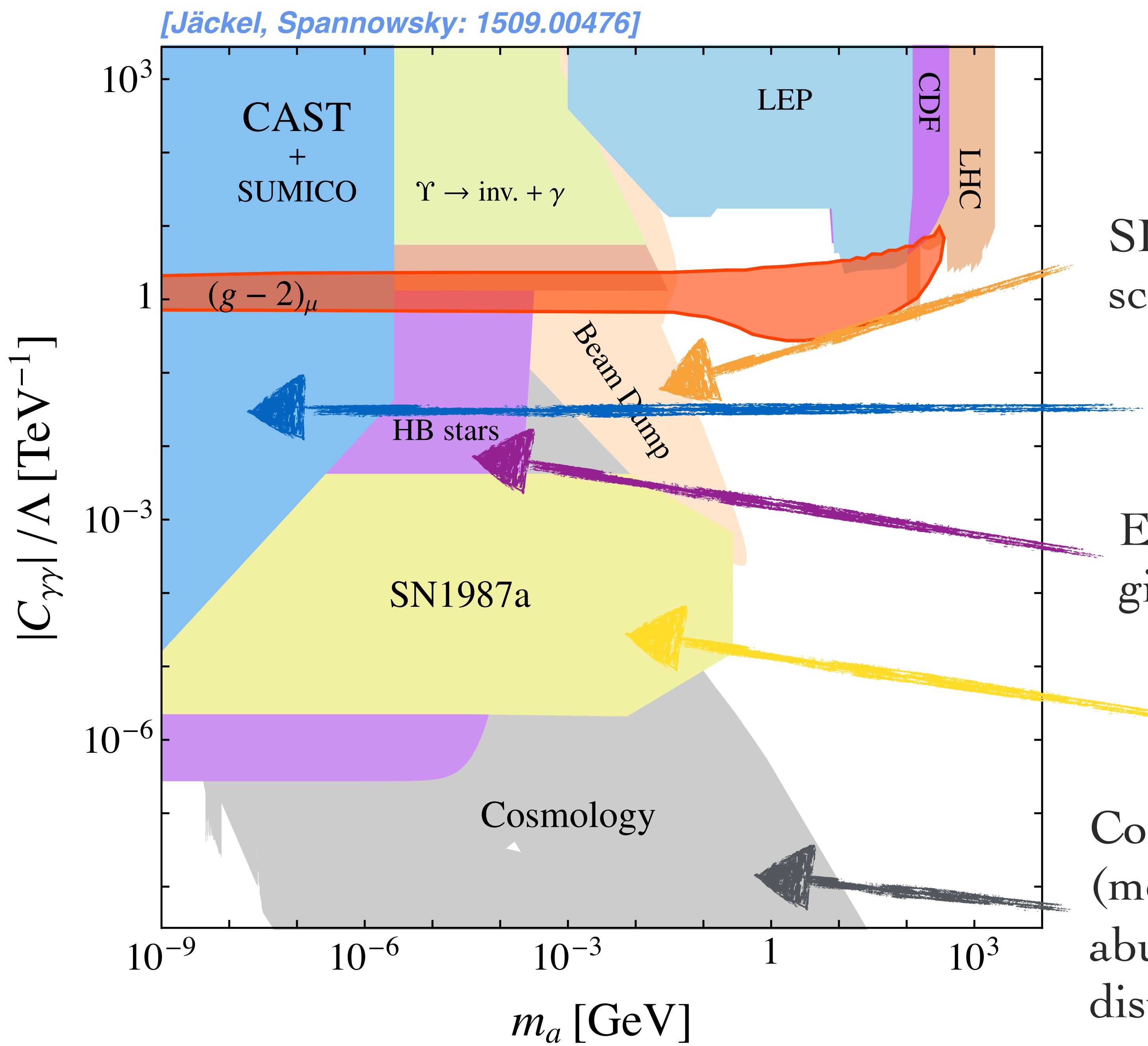

SLAC: measurement of photon - nuclei scattering (Primakoff effect)

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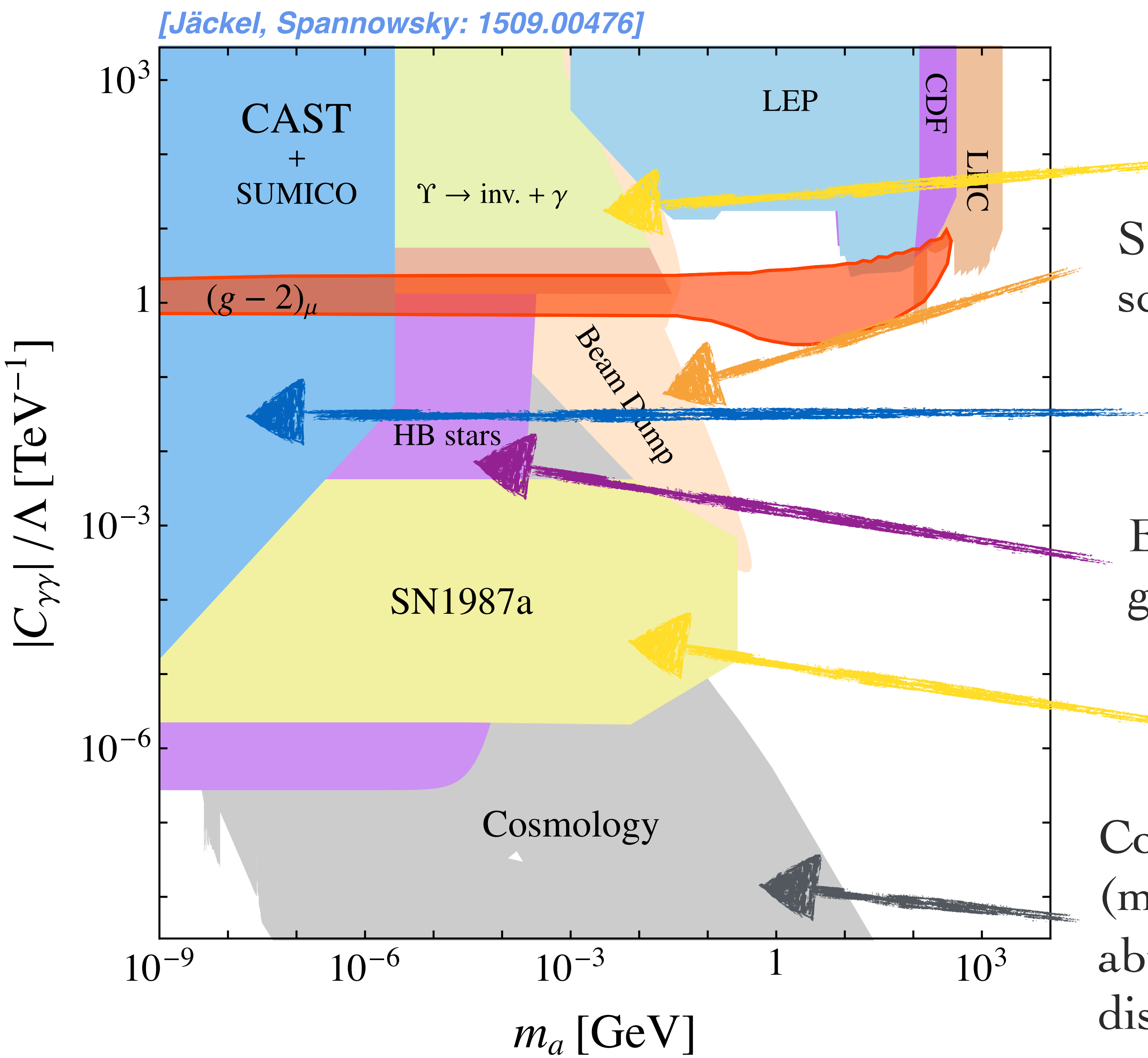

CLOE and BaBar: $\Upsilon \to a + \gamma$

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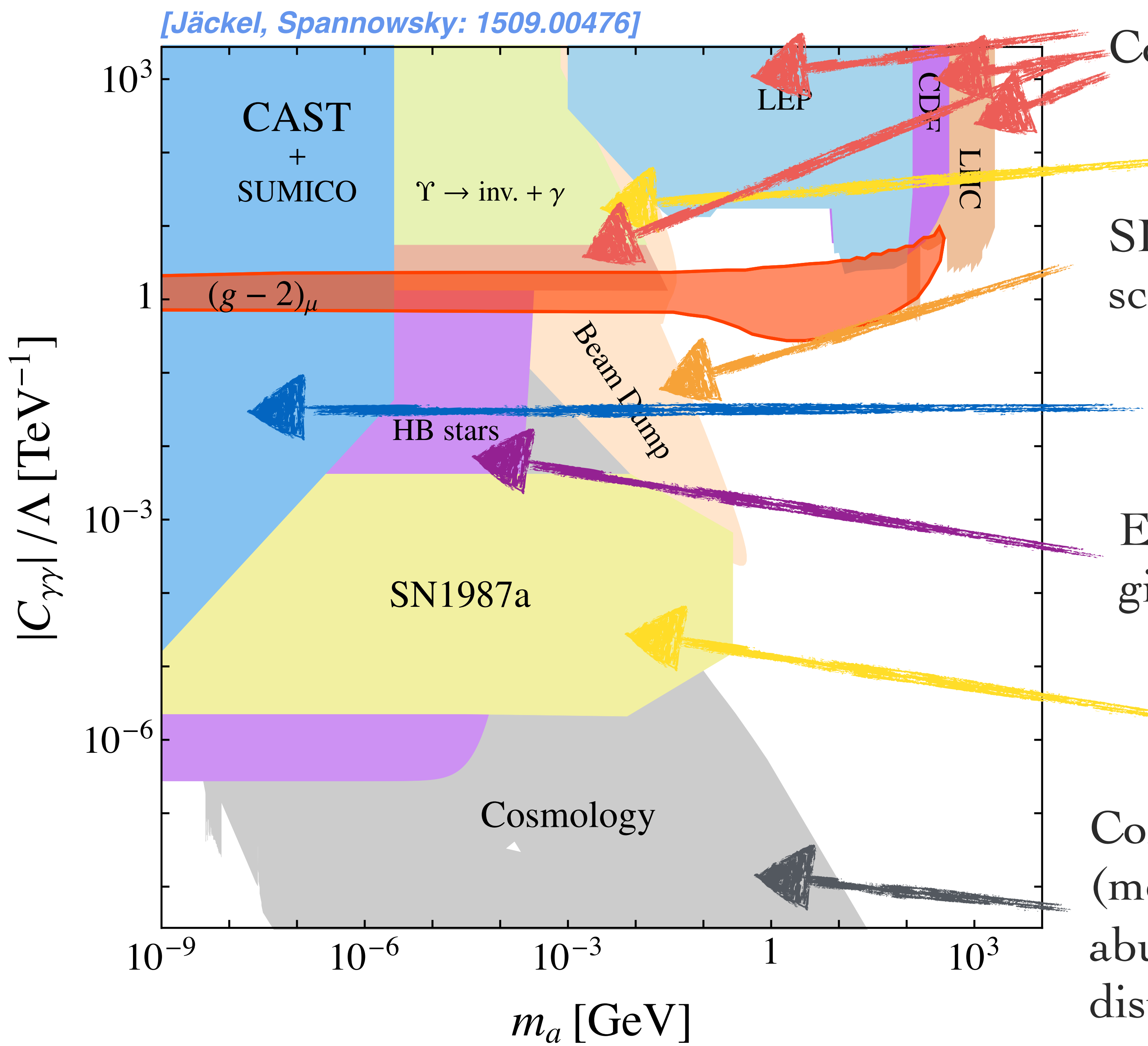

Collider searches for $e^+e^- \to a + \gamma, 3\gamma$

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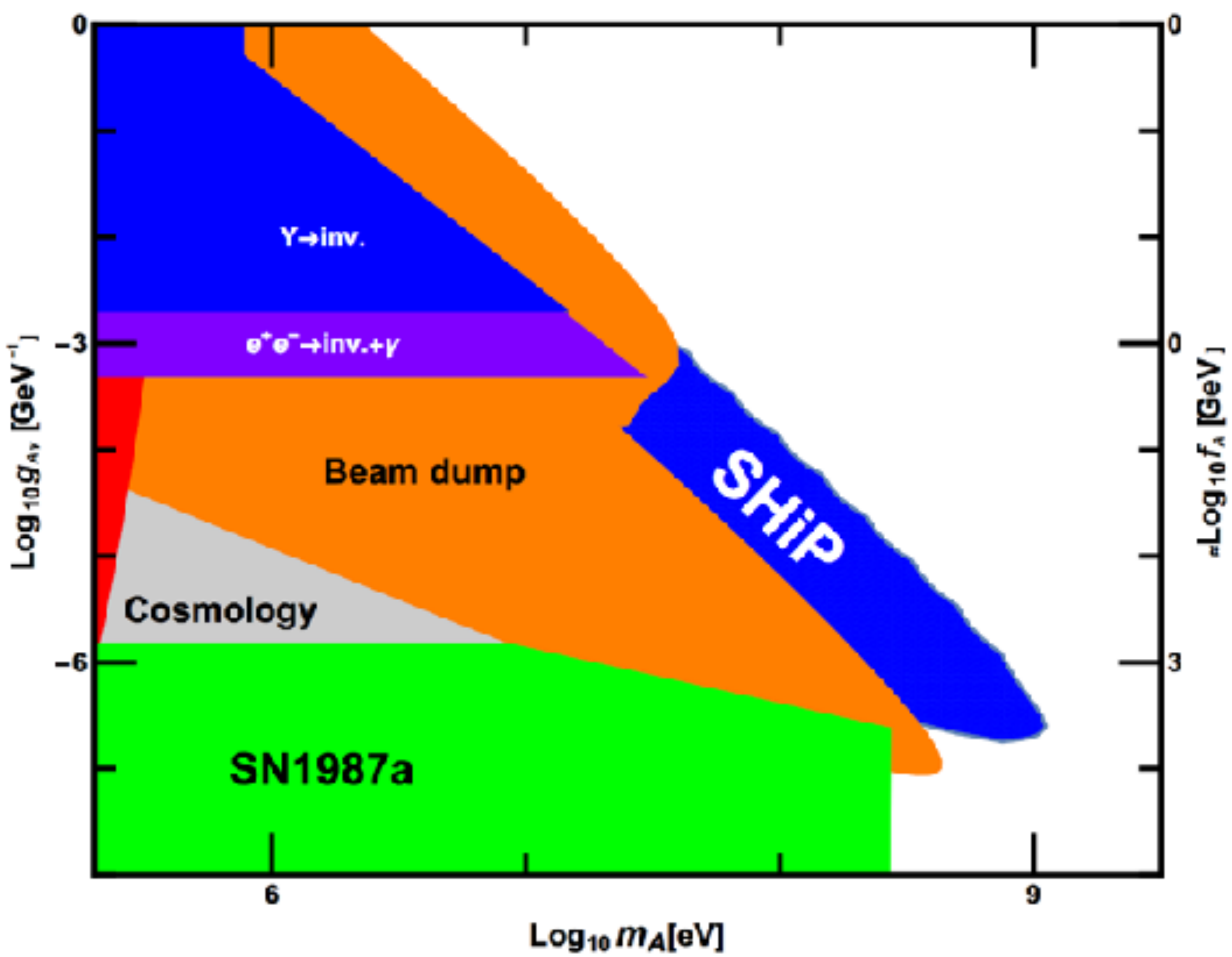
SHiP expected reach

- Fixed target facility at CERN SPS
  (Search for Hidden Particles)



[Alekhin et al.: 1504.04855]