Theory of Light BSM Particles at the LHC

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University of Massachusetts Amherst

3 June 2024
LHCP2024

Light BSM Particles

- Different light BSM particles

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  Spin 0

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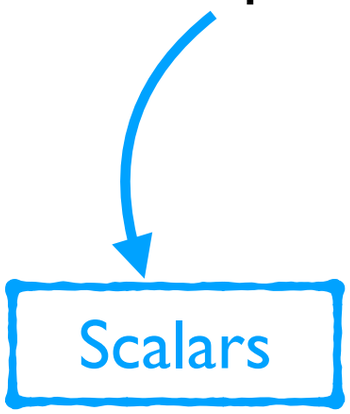

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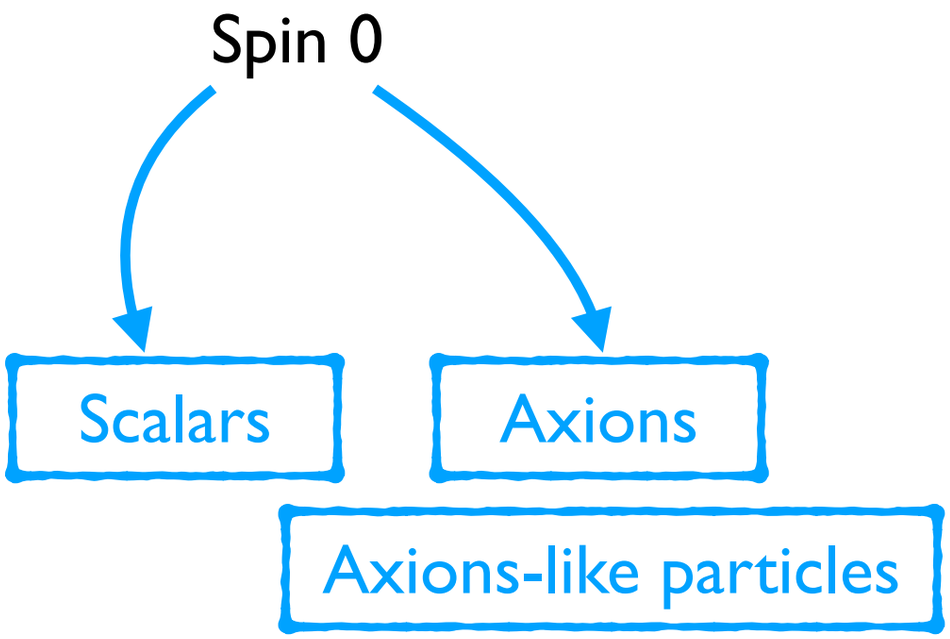

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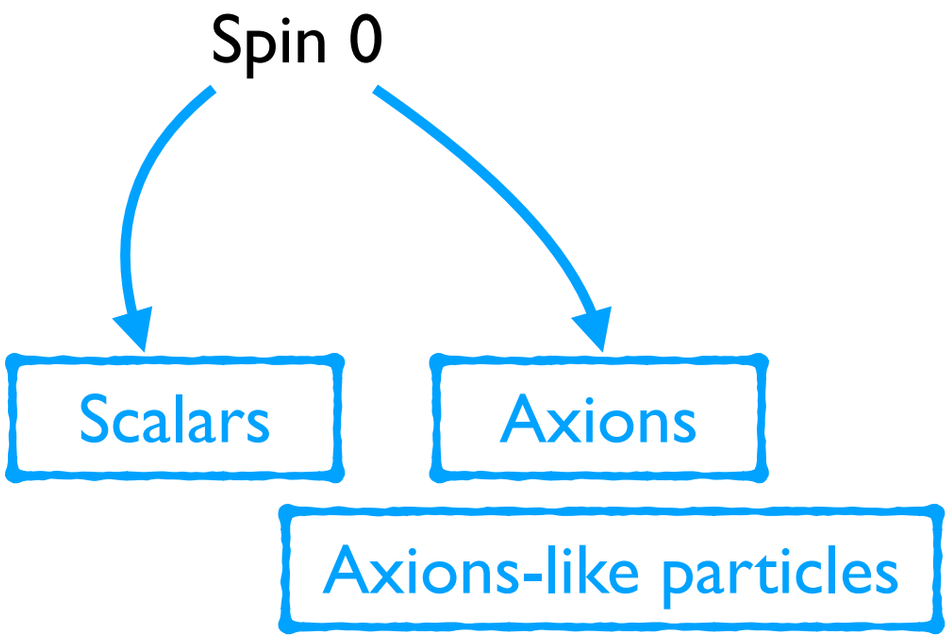

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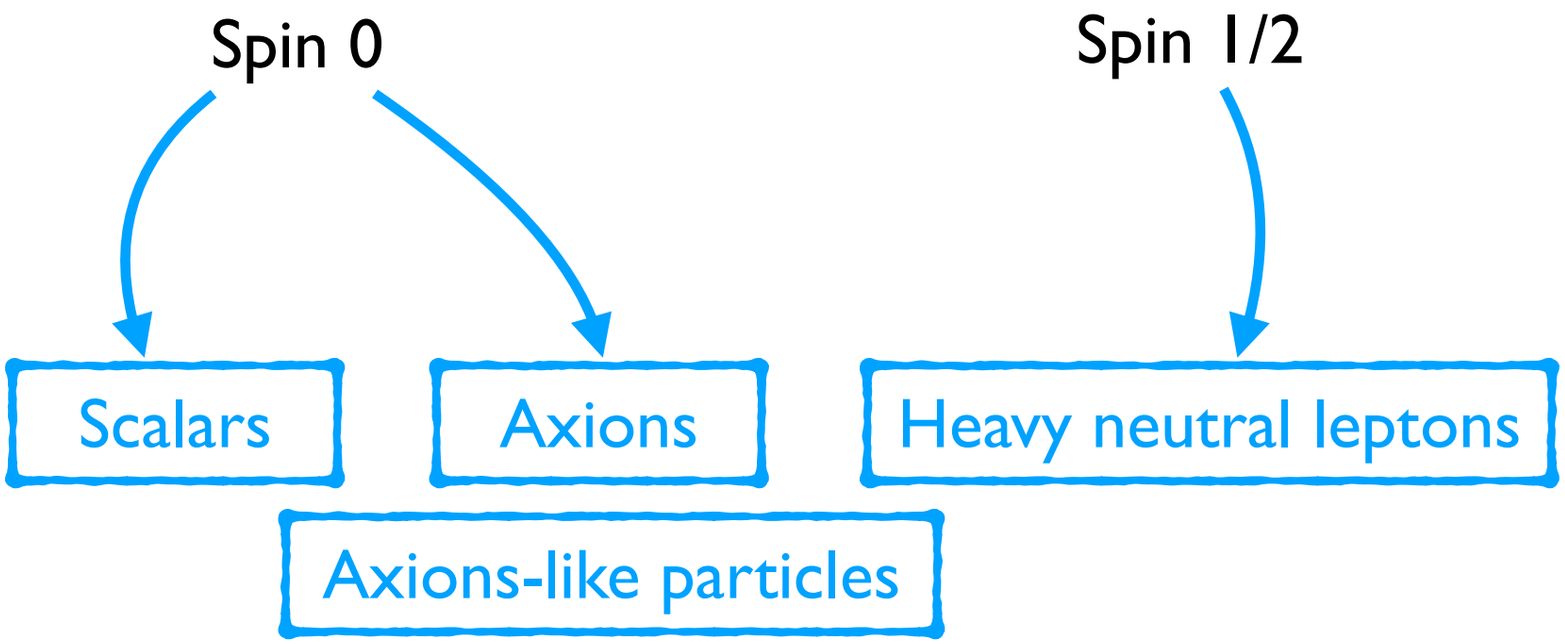

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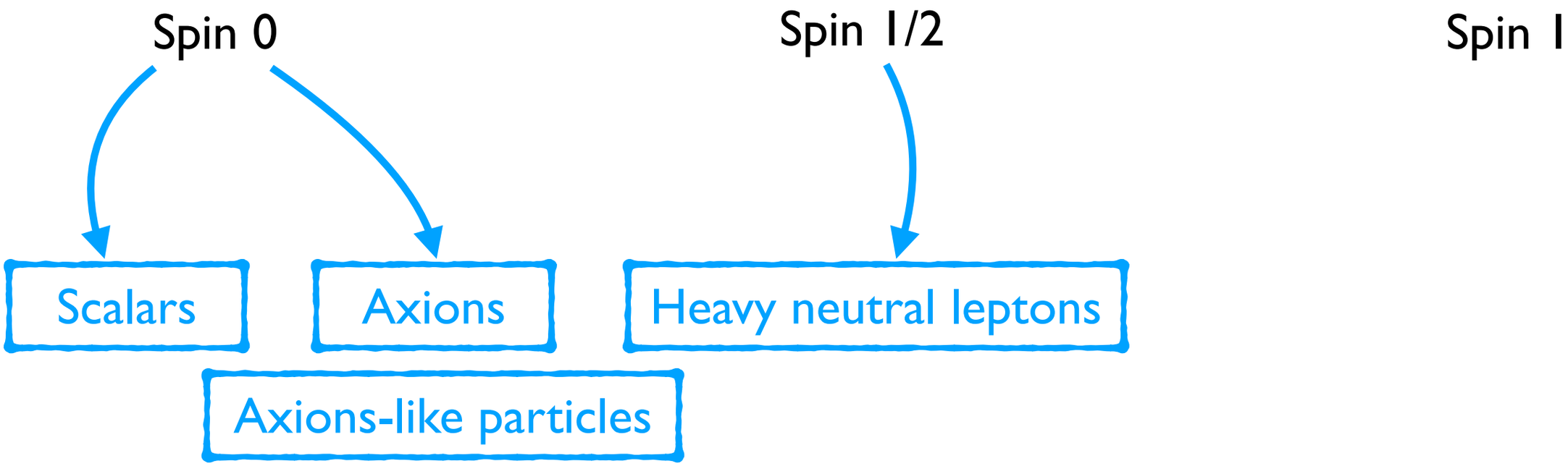

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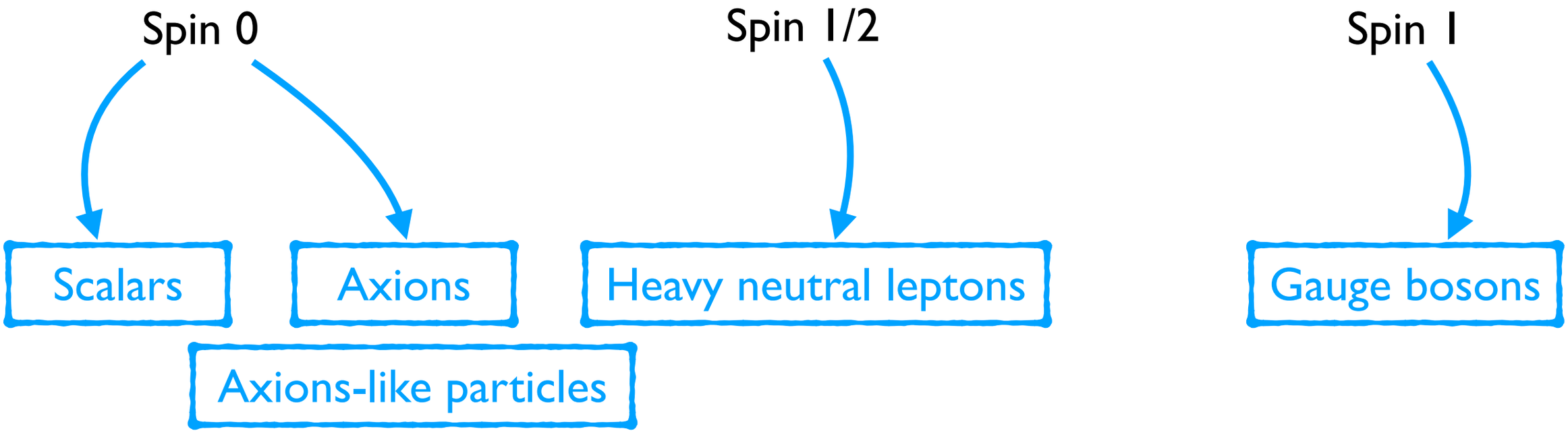

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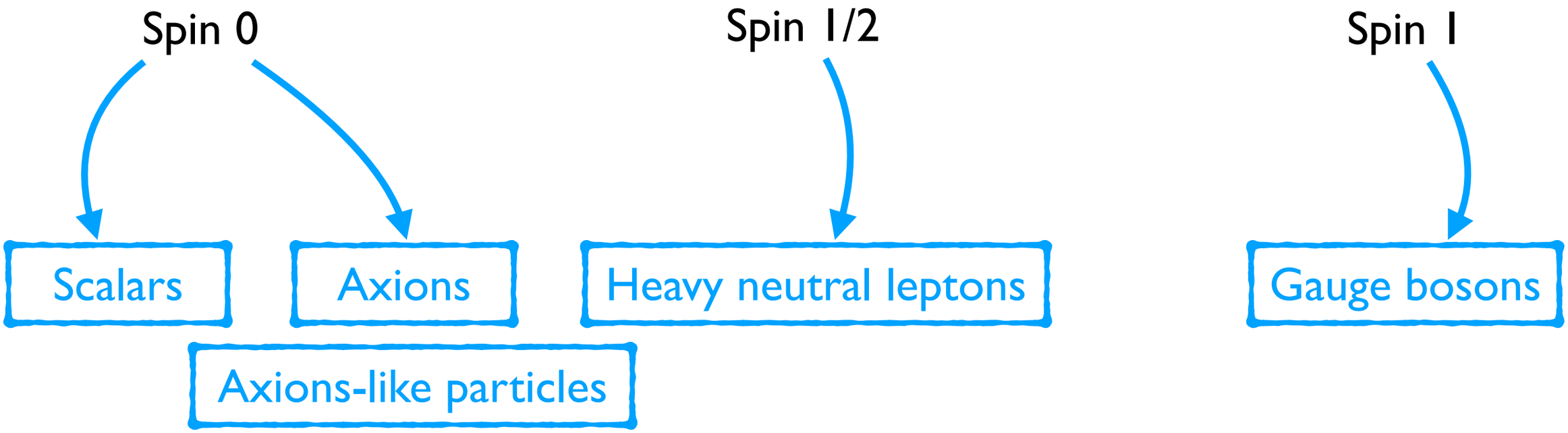

- Many different motivations and UV origins

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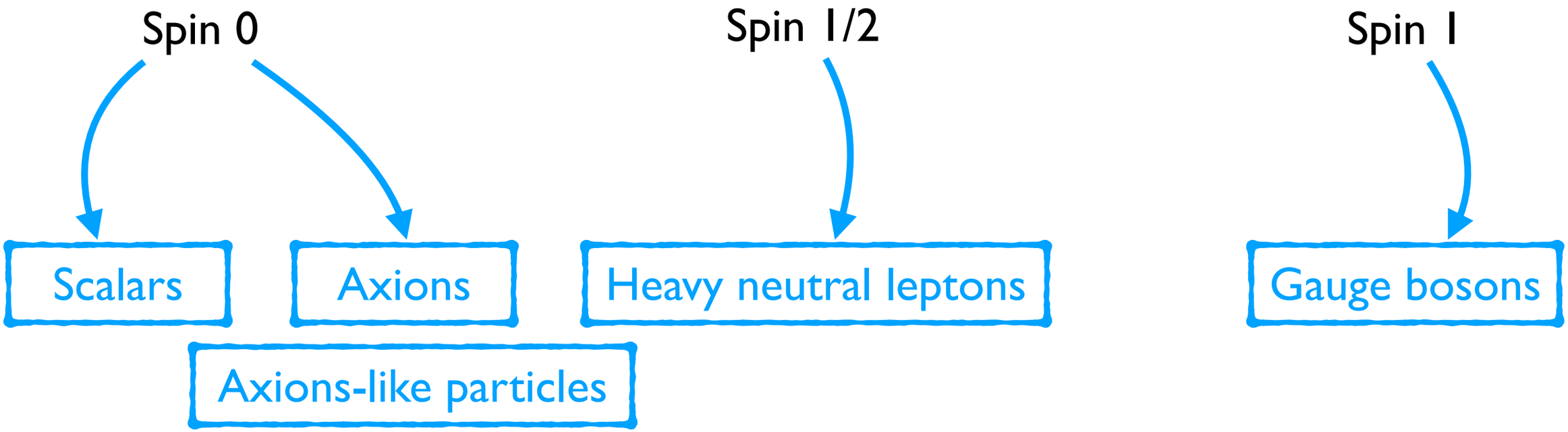

- Many different motivations and UV origins
- Wildly different properties and phenomenology

Outline

1. Motivations for light BSM particles
2. Light BSM particles at the LHC
3. Conclusions

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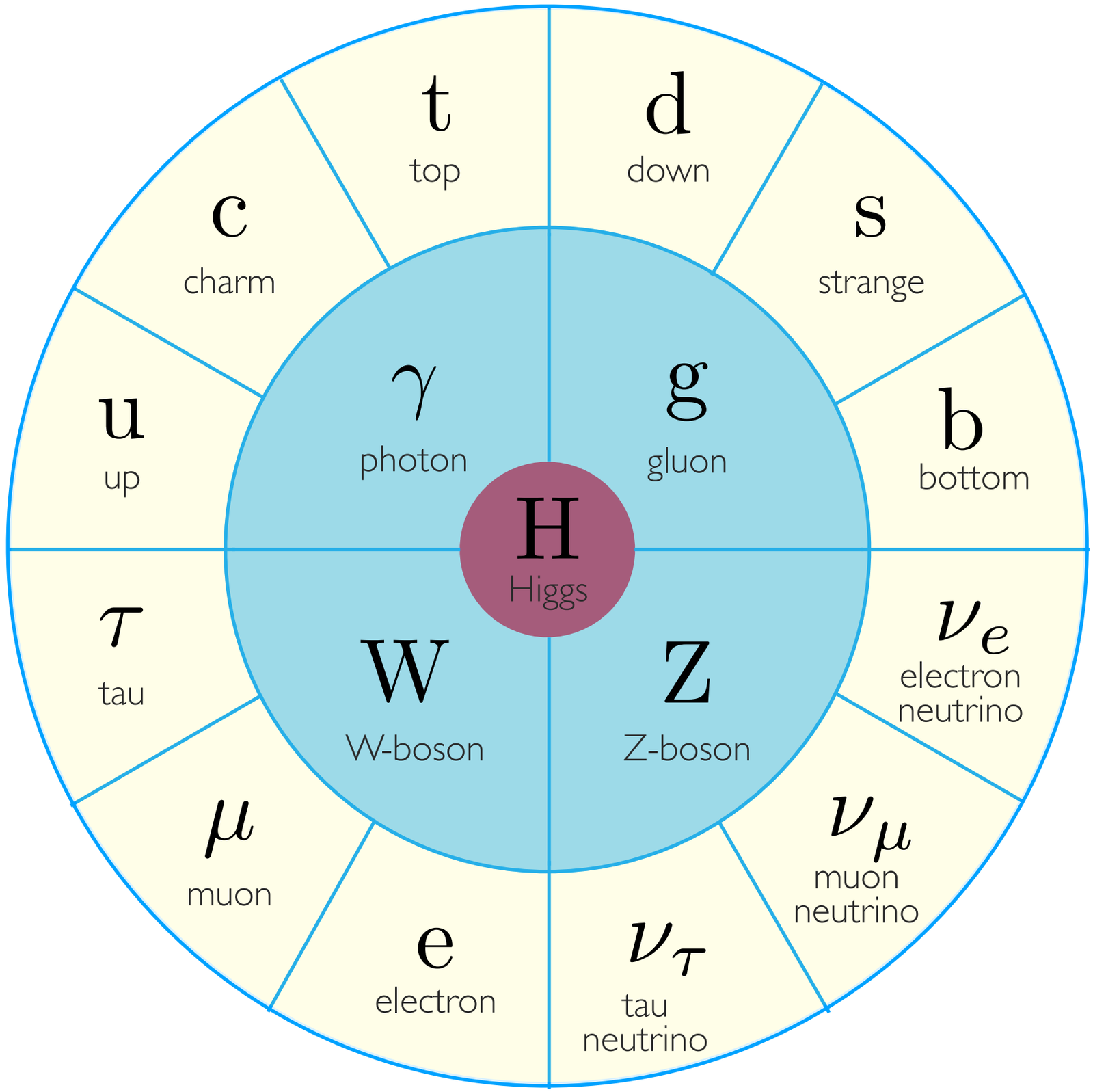
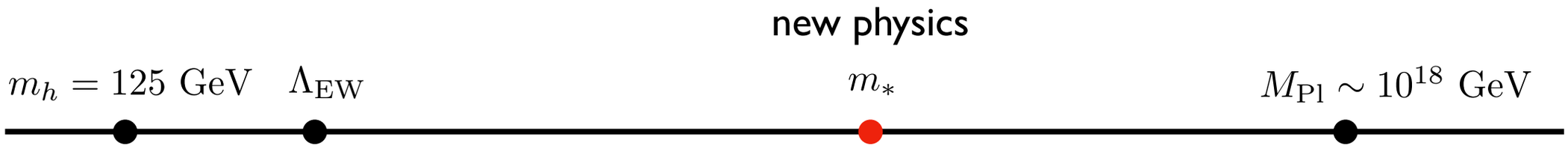
Motivations for Light BSM Particles



Motivations for Light BSM Particles

- Why is the Higgs boson so light?



Quantum fluctuations mean that $m_h \ll m_*$ is very, *very* unlikely!

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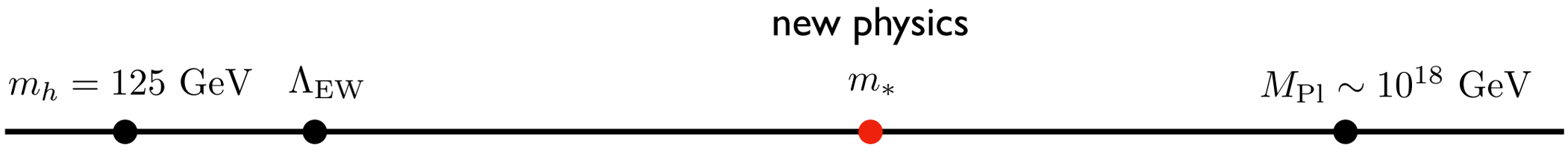

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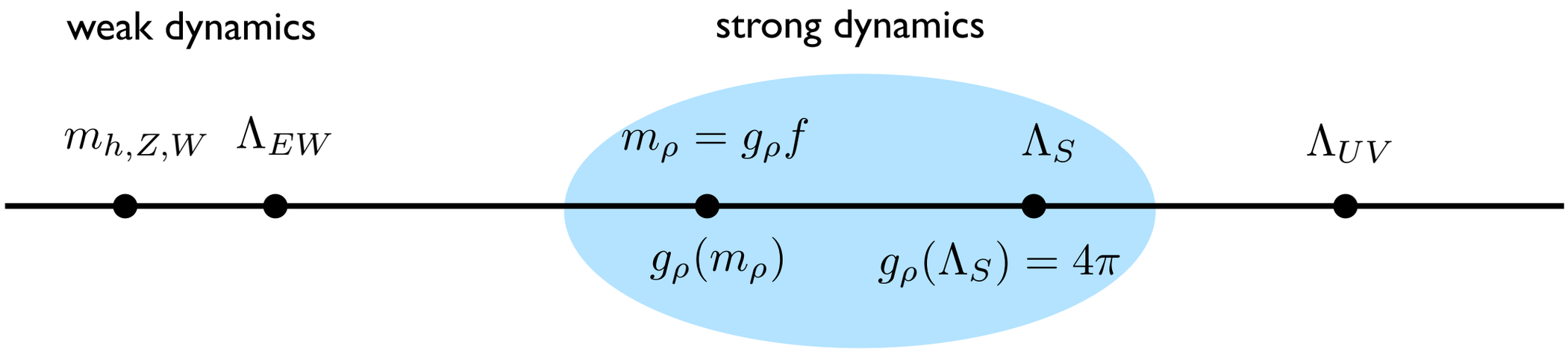
Often addressed by supersymmetric and composite Higgs models

Motivations for Light BSM Particles

Strongly coupled heavy sector at scale m_ρ

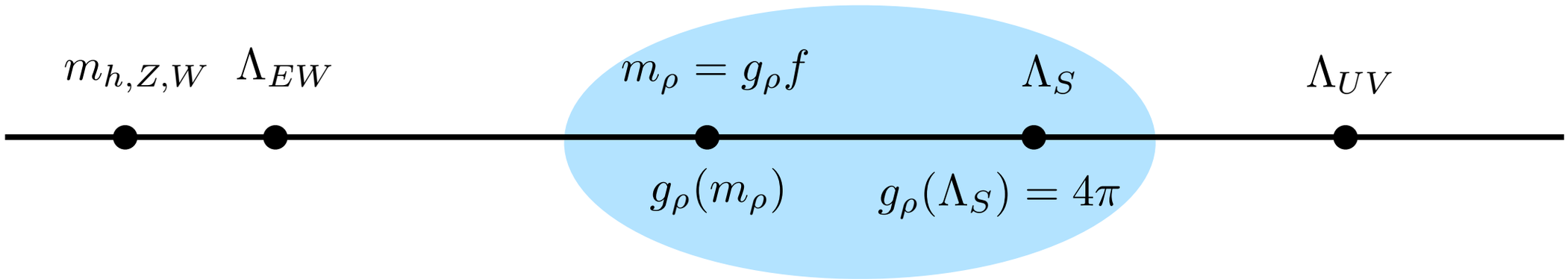
[Contino, Nomura, Pomarol: hep-ph/0306259]
[Agashe, Contino, Pomarol: hep-ph/0412089]
[Agashe, Contino: hep-ph/0510164]
[Contino, Da Rold, Pomarol: hep-ph/0612048]
[Barbieri, Bellazzini, Rychkov, Varagnolo: hep-ph/0706.0432]



- Spontaneous breaking of global symmetry
- Higgs arises as a pseudo-Nambu-Goldstone boson
- Above Λ_S H no longer elementary d.o.f. → solves hierarchy problem

Motivations for Light BSM Particles

Composite Higgs models



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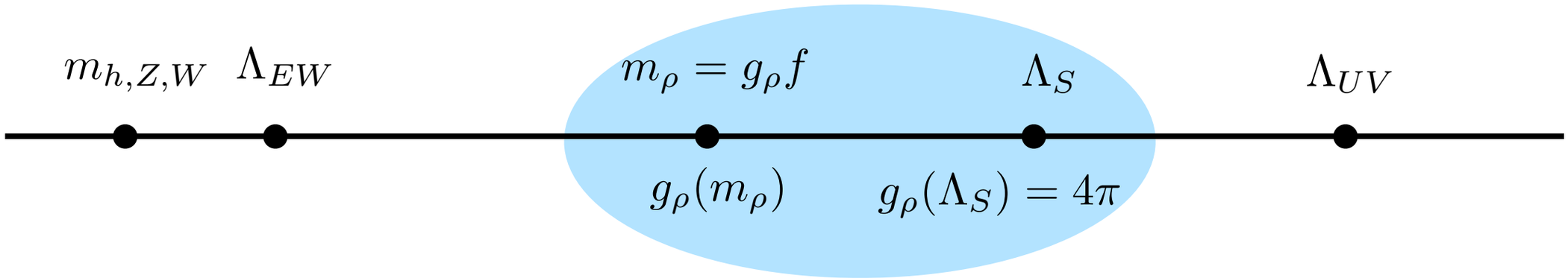

Specify details about heavy sector

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2) \times \mathrm{SU}(2)]$
$\mathrm{SO}(5)$	$\mathrm{SO}(4)$	4	$\mathbf{4} = (\mathbf{2}, \mathbf{2})$

[Agashe, Contino, Pomarol,…]

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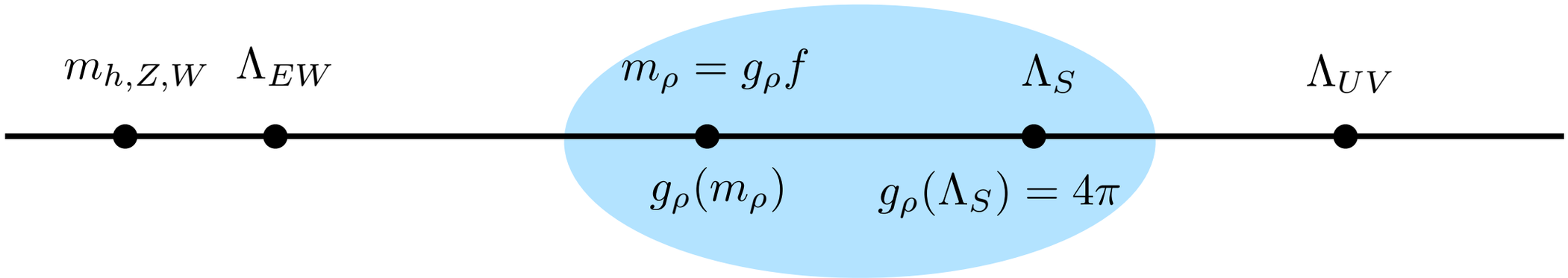

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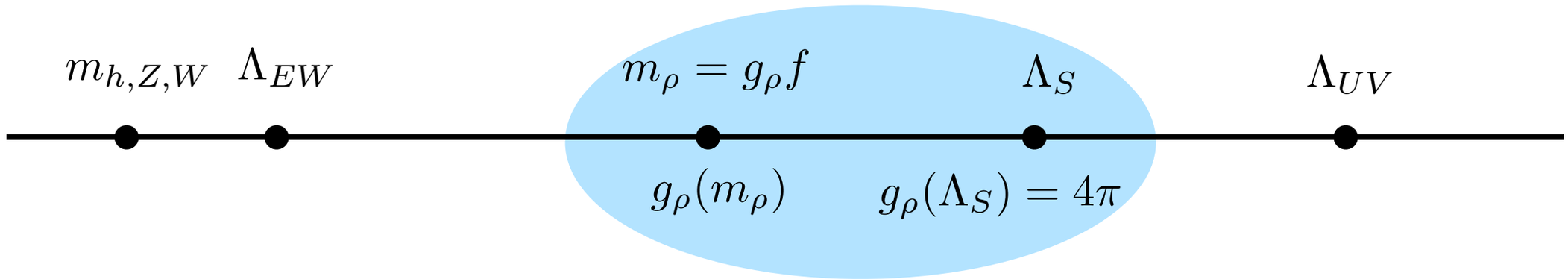

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$\mathrm{SO}(7)$	$\mathrm{SO}(6)$	6	$\mathbf{6} = 2\times(\mathbf{1},\mathbf{1}) + (\mathbf{2},\mathbf{2})$	*[Chala 1210.6208]*
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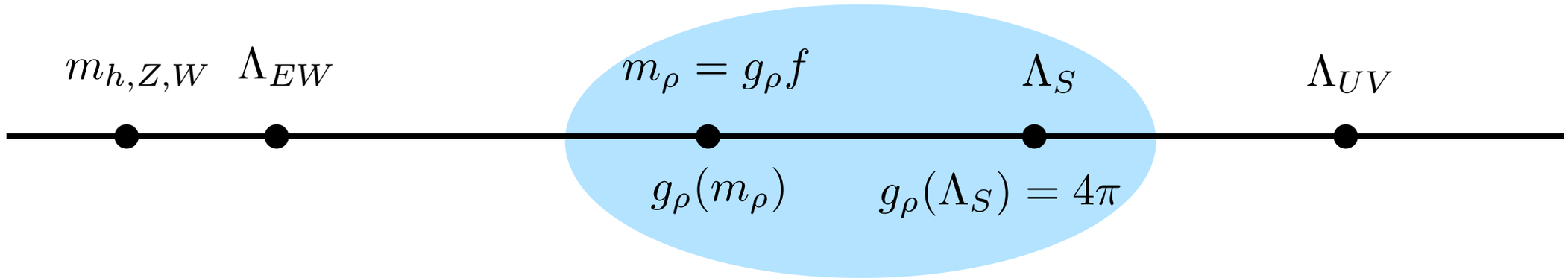

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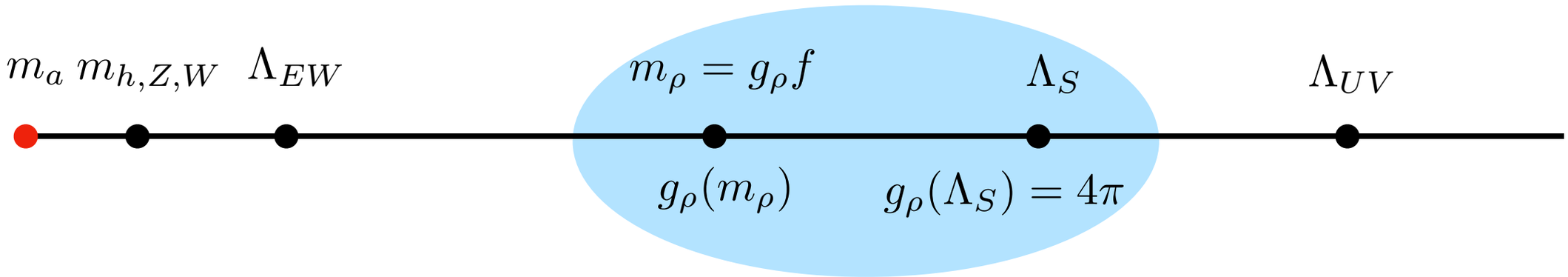

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Light pseudo-scalar particles ⇒ new light axion-like particle [Ferretti 1604.06467]

Motivations for Light BSM Particles

Further light BSM particles motivated by the hierarchy problem

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⇒ weakly coupled light particles below the EW scale

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Further light BSM particles motivated by the hierarchy problem

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⇒ weakly coupled light particles below the EW scale

Neutral naturalness ⇒ light BSM particles in the mirror sector

Coupling via Higgs portal

$$(H^\dagger H) \times m_H^2 \rightarrow (H^\dagger H) \times (m_H^2 + c_1 S + c_2 S^2)$$

⇒ light scalar particles

Motivations for Light BSM Particles

- Why does the strong sector not violate CP symmetry?

Possible CP violation $\mathscr{L} = \bar{\theta}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu}$

Motivations for Light BSM Particles

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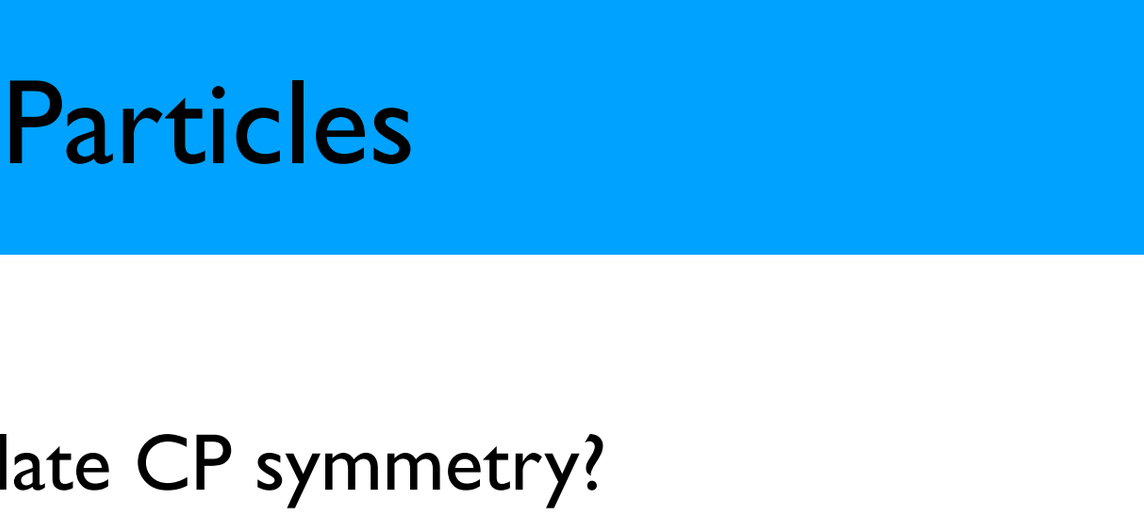
Possible CP violation $\mathscr{L} = \bar{\theta}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu}$

Implies electric dipole moment of the neutron

$$d_N = (5.2 \times 10^{-16} e \cdot \mathrm{cm})\,\bar{\theta}$$



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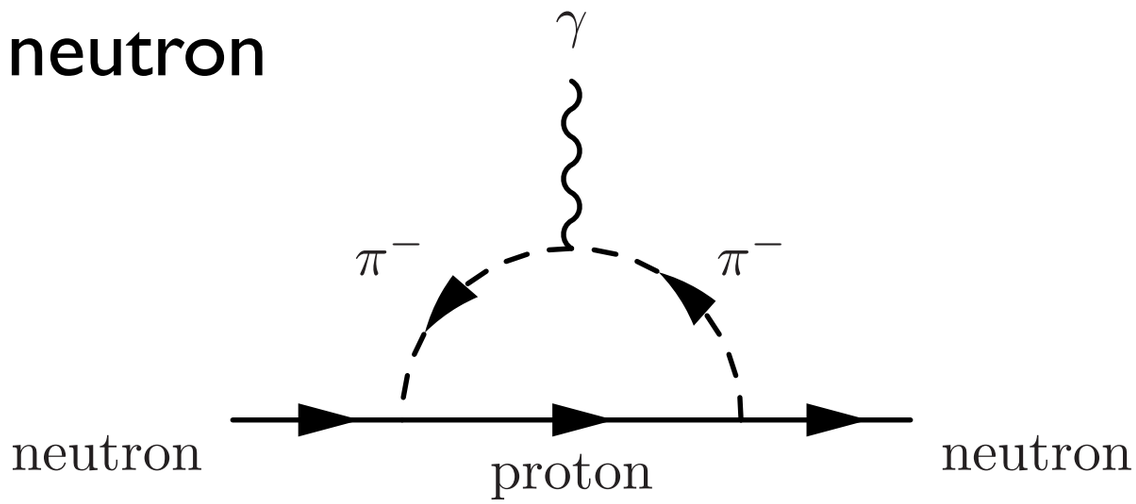

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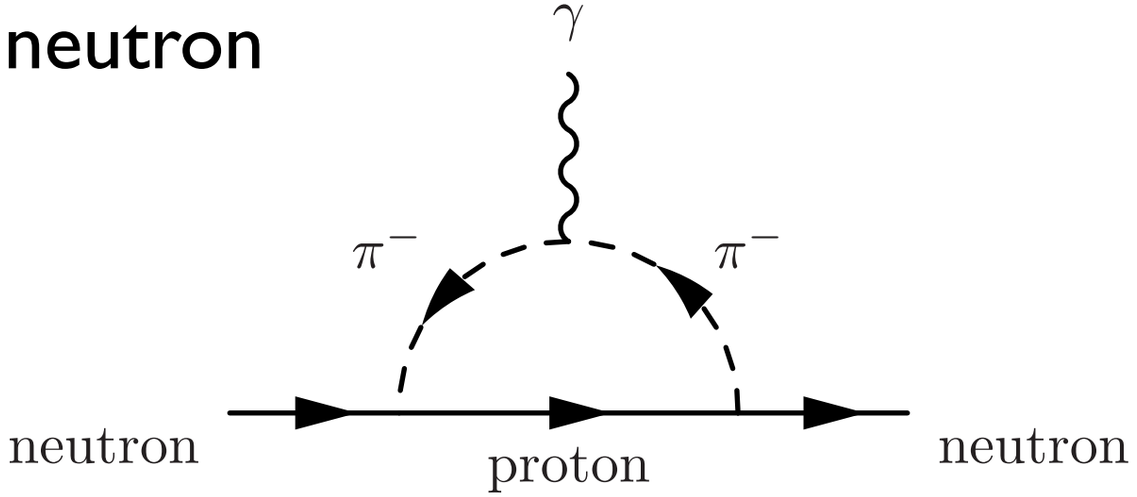

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$$\bar{\theta} < 10^{-10}$$

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Introduce Peccei-Quinn symmetry breaking

Pseudo-Nambu Goldstone boson is

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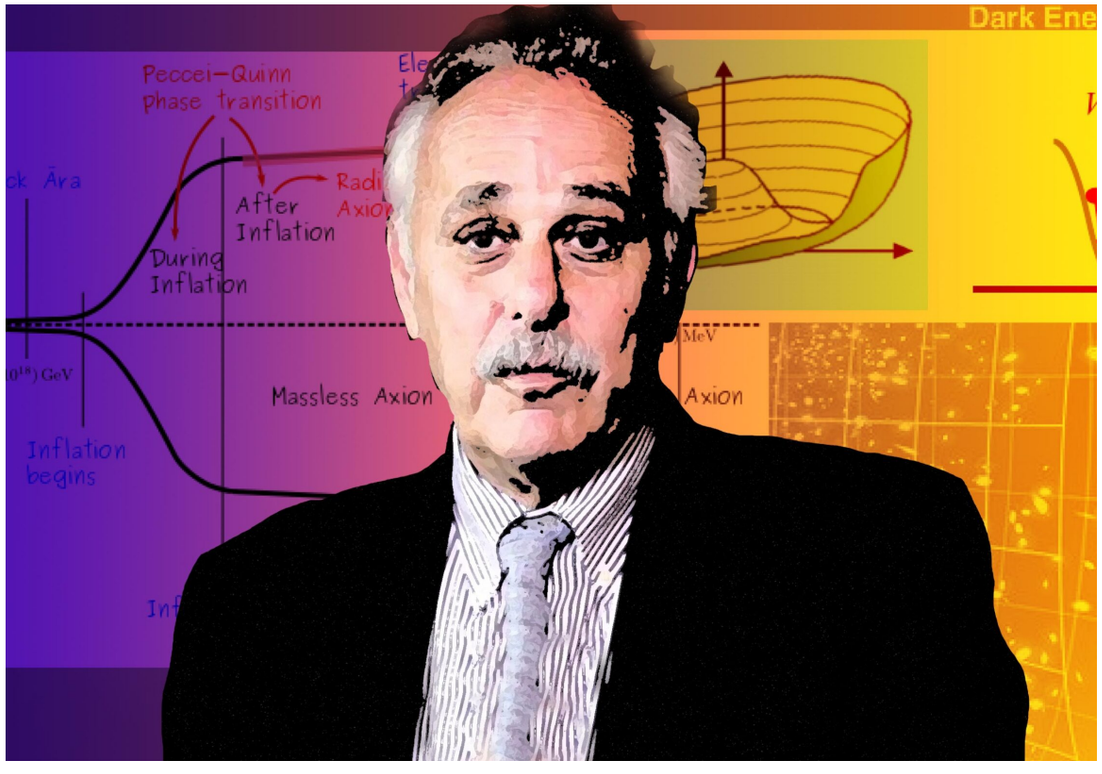


Motivations for Light BSM Particles

- Why does the strong sector not violate CP symmetry?

Introduce Peccei-Quinn symmetry breaking

Pseudo-Nambu Goldstone boson is ⇒ light QCD axion

Which couples as $\mathscr{L} = \frac{a(x)}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu}$

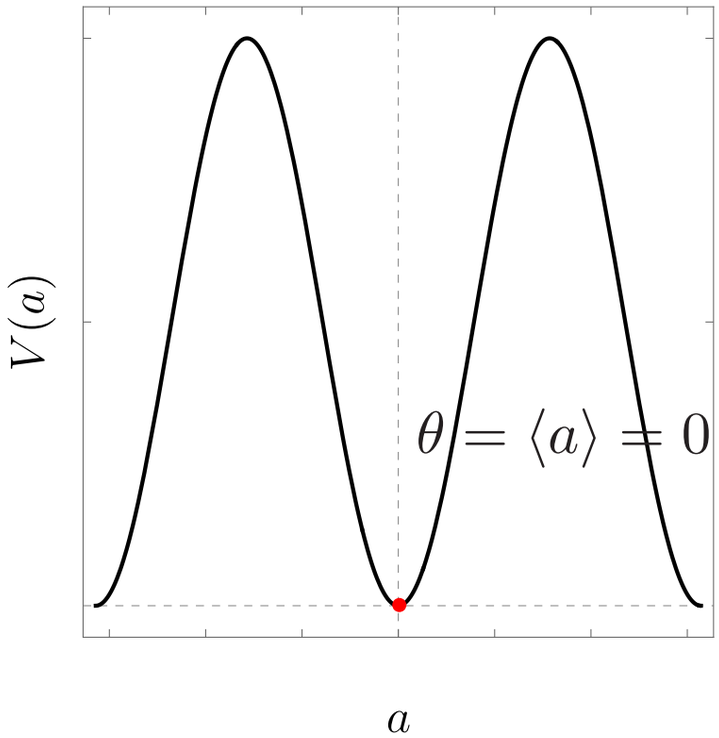
Vacuum expectation value is zero

Explains why CP violation is so small → solves strong CP problem

Motivations for Light BSM Particles

- Axion quality problem

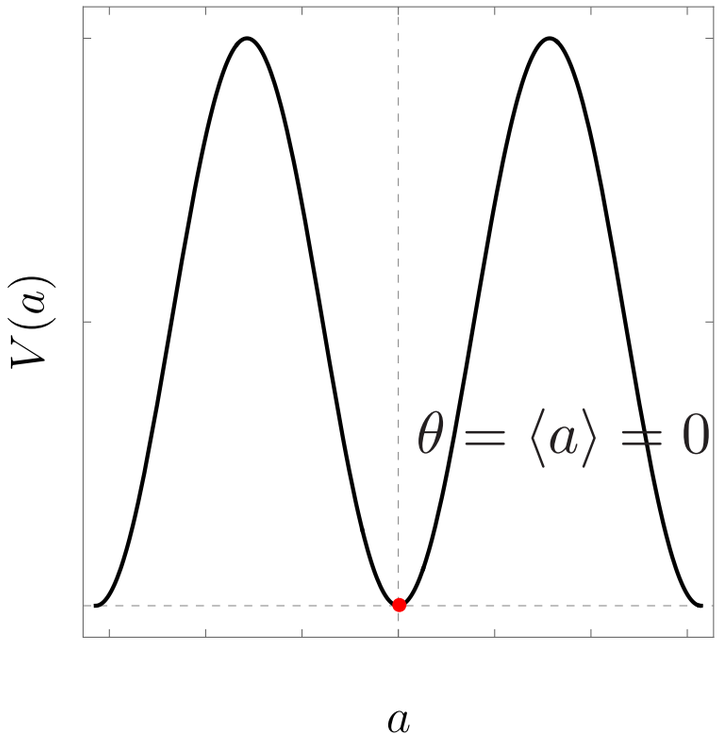
$$V(a) = m_\pi^2 f_\pi^2 \left[1 - \cos\left(\frac{a}{f_a}\right)\right]$$

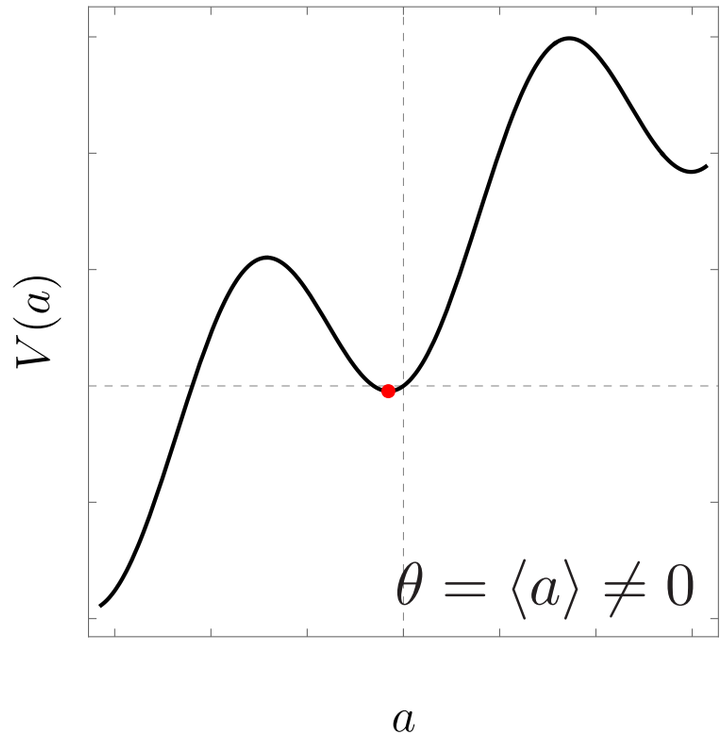


Motivations for Light BSM Particles

- Axion quality problem

$$V(a) = m_\pi^2 f_\pi^2 \left[1 - \cos\left(\frac{a}{f_a}\right)\right] + a\,\frac{f_a^{\Delta-1}}{M_{pl}^{\Delta-4}}$$





New sector contributes to potential and mass

⇒ heavier QCD axion

9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097

Motivations for Light BSM Particles

- Extended gauge theories

$$SU(3)_{QCD} \times SU(2)_L \times U(1)_Y$$

$$\rightarrow SU(3)_{QCD} \times SU(2)_L \times U(1)_Y \times U(1)_X$$

⇒ new light gauge bosons

Motivations for Light BSM Particles

- What about neutrino masses?

Experimentally we know that neutrinos have mass

Need right handed neutrino to generate mass

$$m_{\nu,M}\bar{\nu}\nu \rightarrow \frac{y_\nu^2}{m_N}(\nu H)^c \nu H + \text{h.c.}$$

⇒ new (light) heavy neutral lepton

See talk by Juraj Klaric on Friday

Motivations for Light BSM Particles

- What about dark matter?

WIMP with a ⇒ new (light) scalar or vector coannihilation partner

Freeze-in Dark Matter ⇒ new (light) scalar, fermion or vector DM

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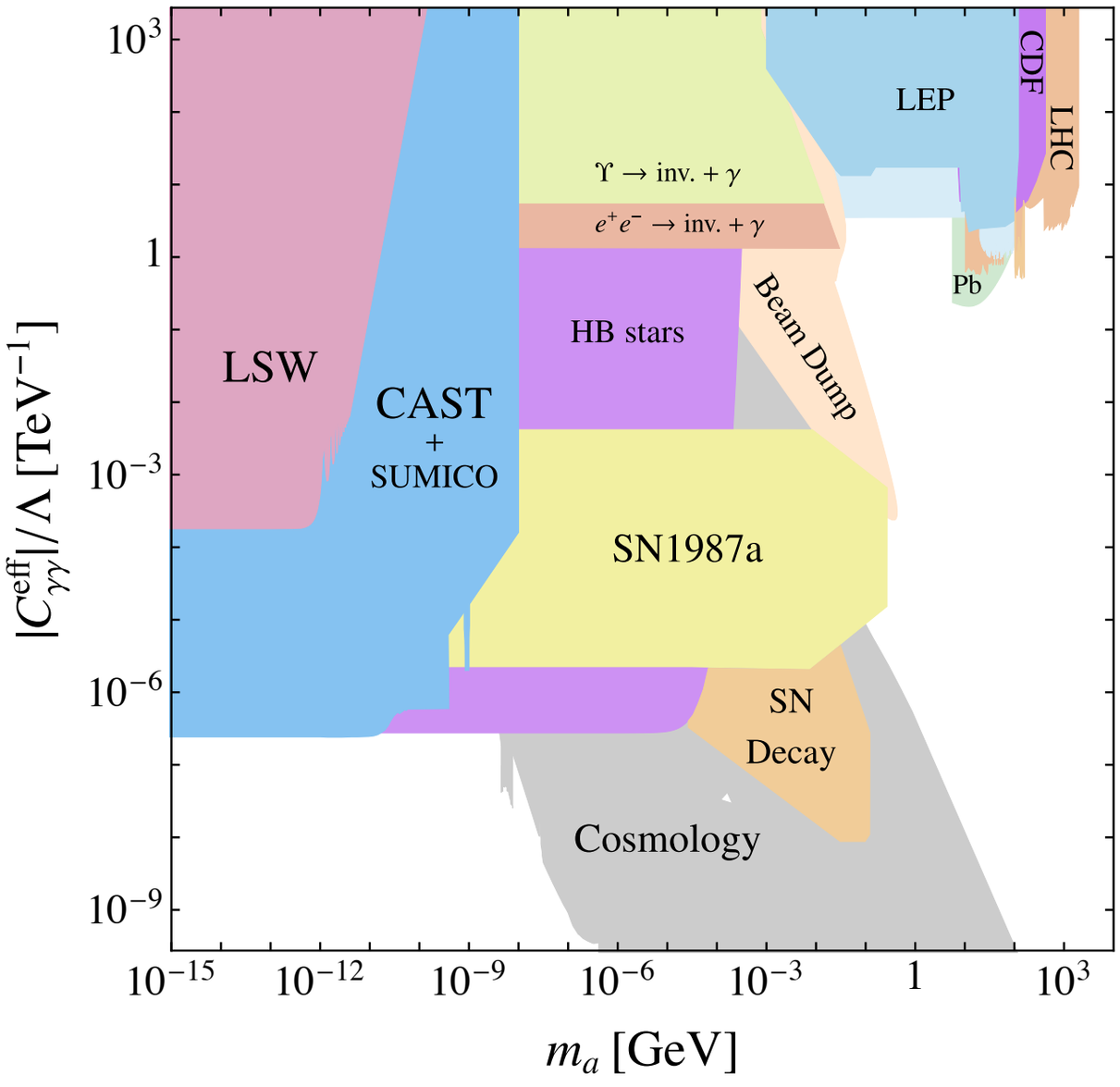
Light BSM particles at the LHC

The origin of the light BSM particles determines their properties

This determine which experiment is most suited

Light BSM particles at the LHC

Example: axion-like-particles



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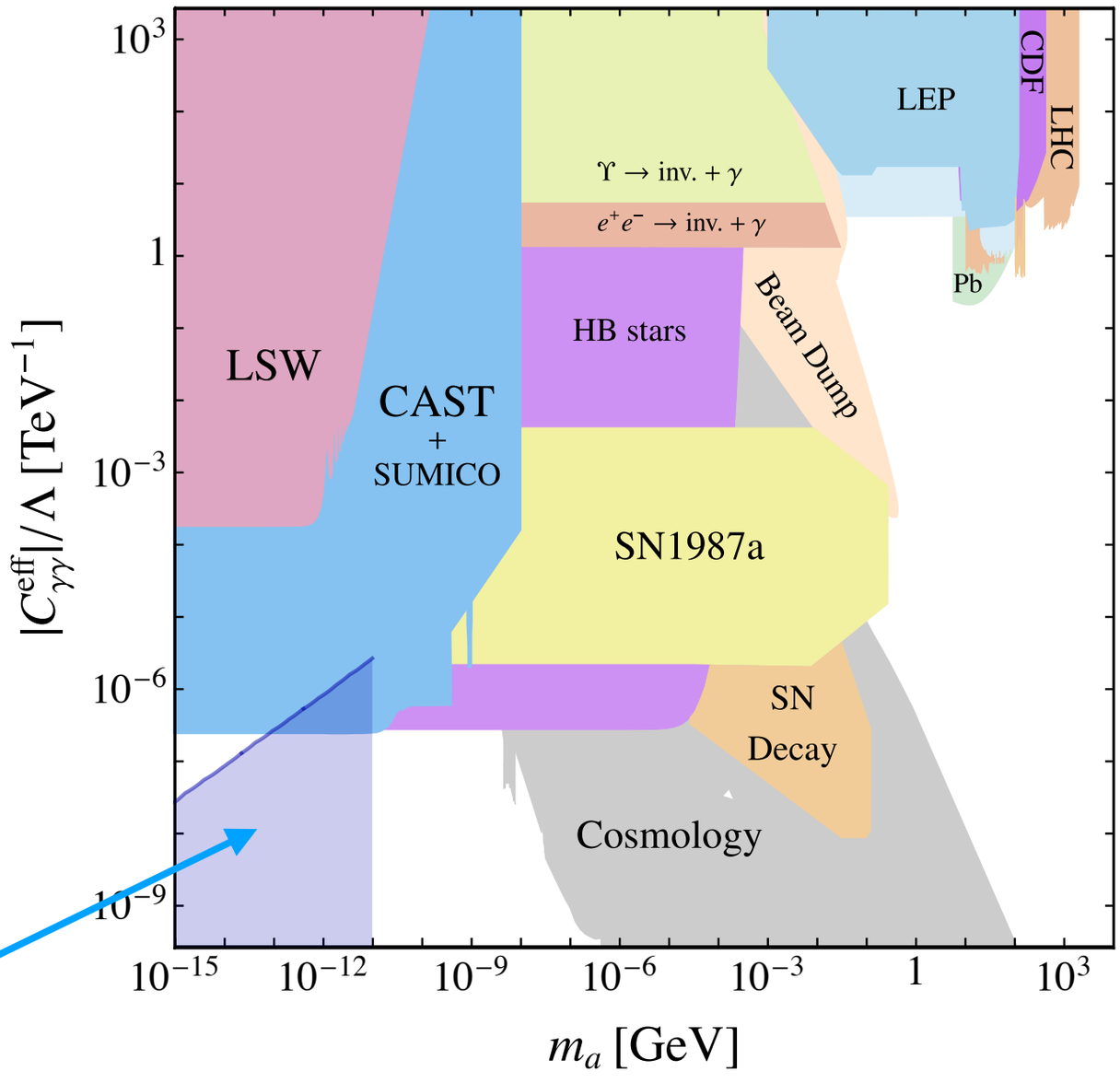
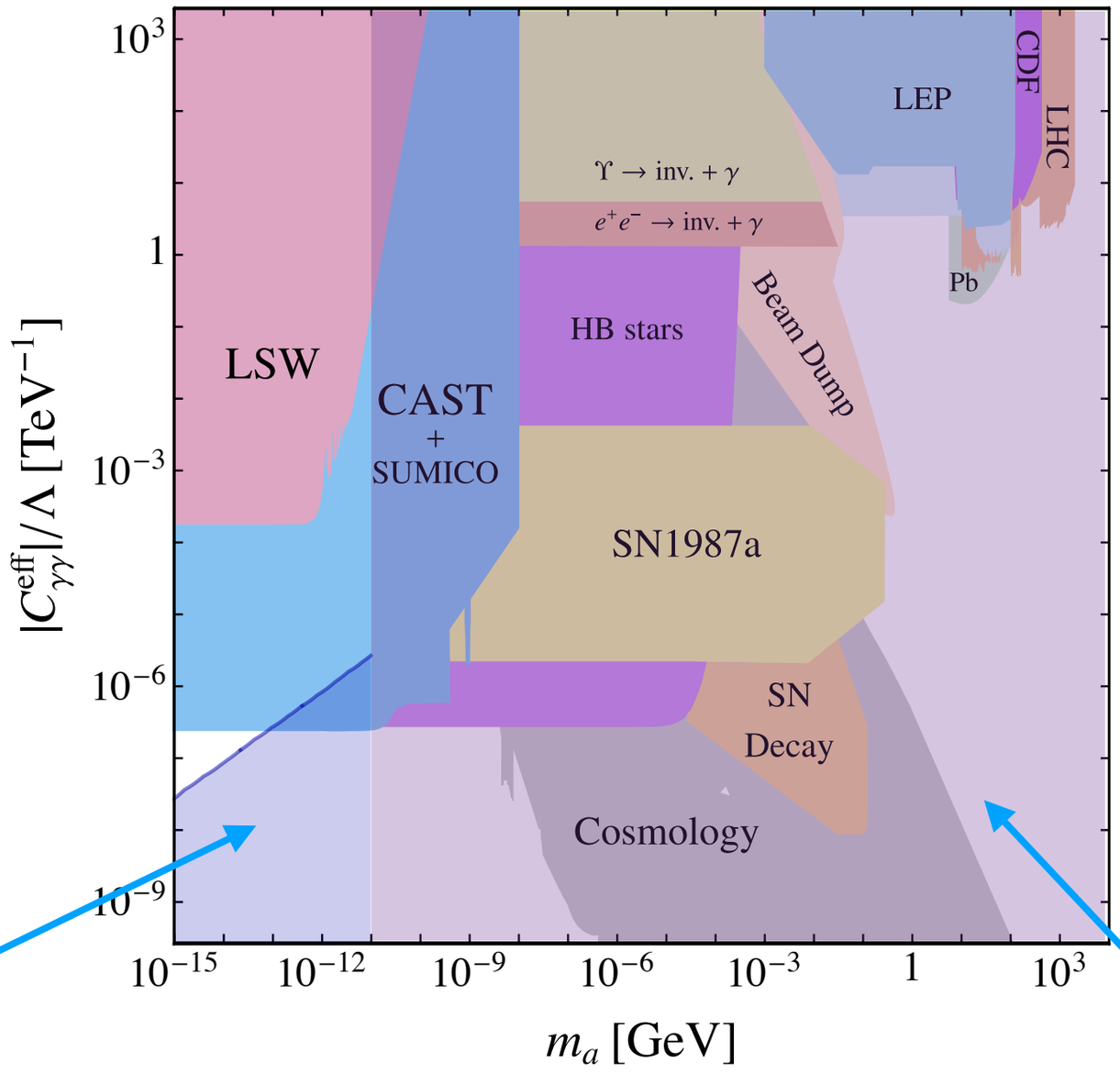


DM candidate

Light BSM particles at the LHC

Example: axion-like-particles



DM candidate

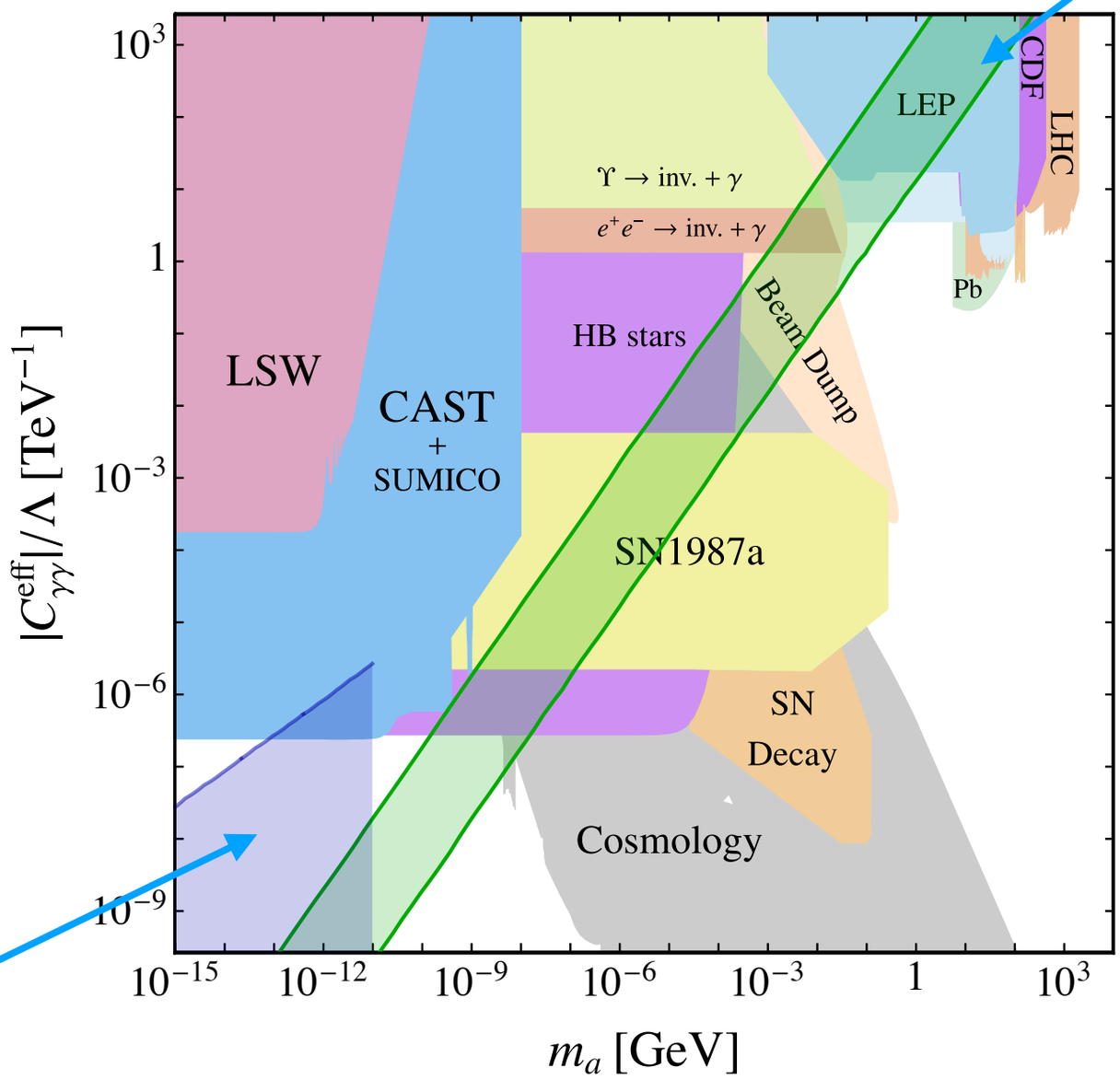
Mediator to the dark sector

Light BSM particles at the LHC

Example: axion-like-particles

QCD axion

9703409, 0009290, 1411.3325, 1504.06084, 1604.01127, 1606.03097



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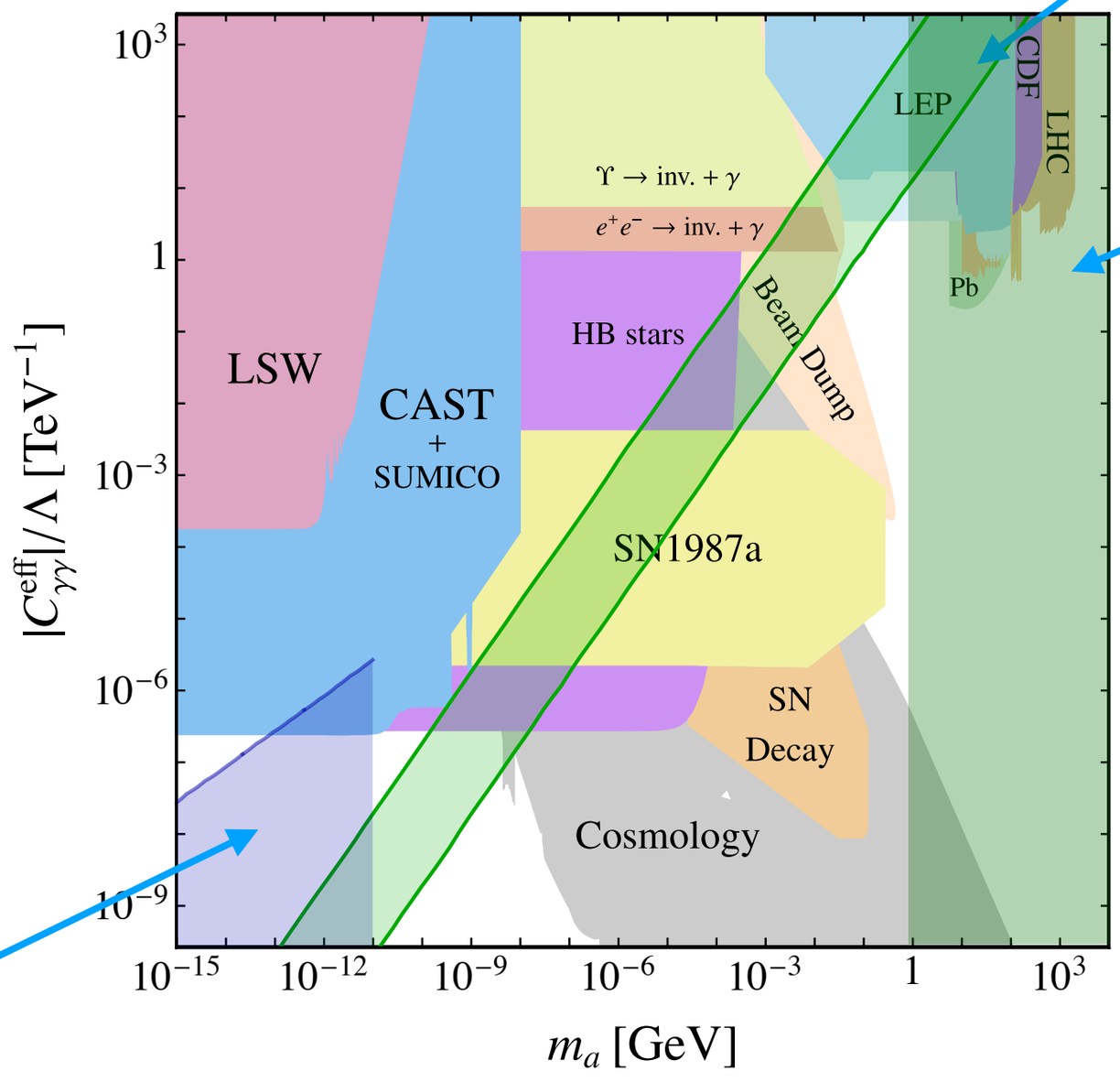

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Heavy axion

DM candidate

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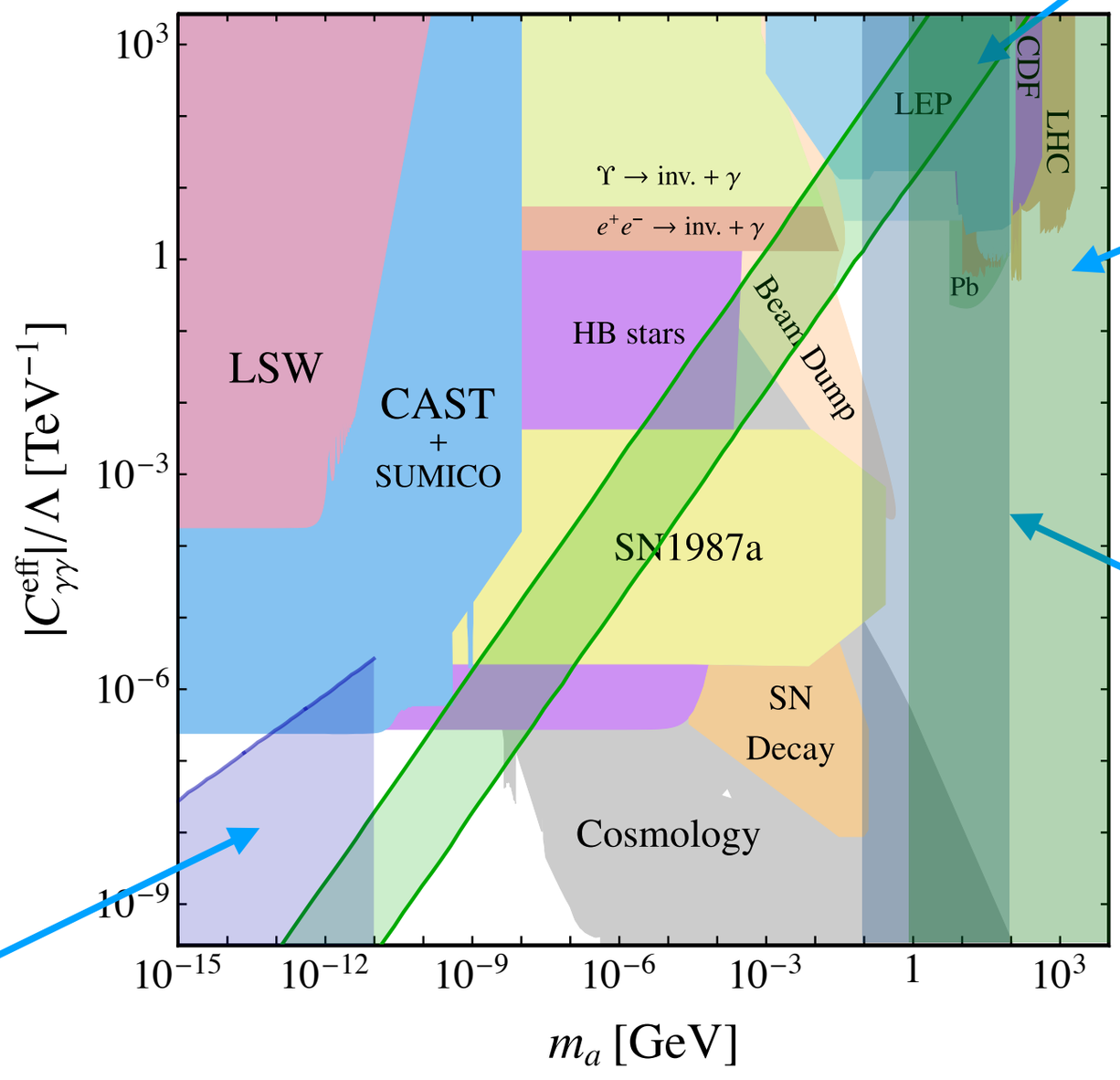

QCD axion

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Heavy axion

pNGB in supersymmetric or composite models

0902.1483, 1312.5330,1702.02152, 2104.11064

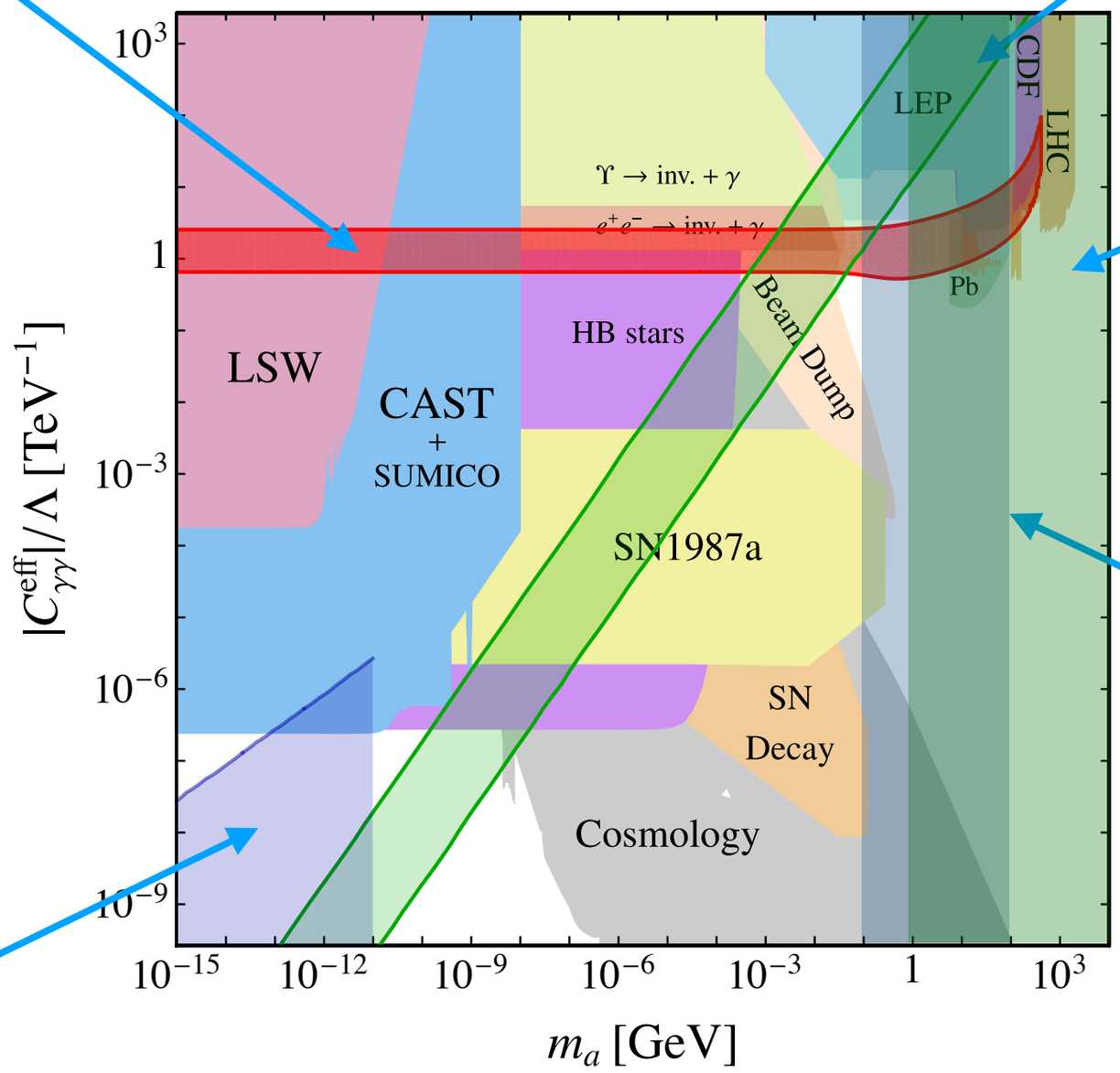
DM candidate

Light BSM particles at the LHC

Example: axion-like-particles

Solves $(g-2)_\mu$ anomaly

1708.00443, 1908.00008



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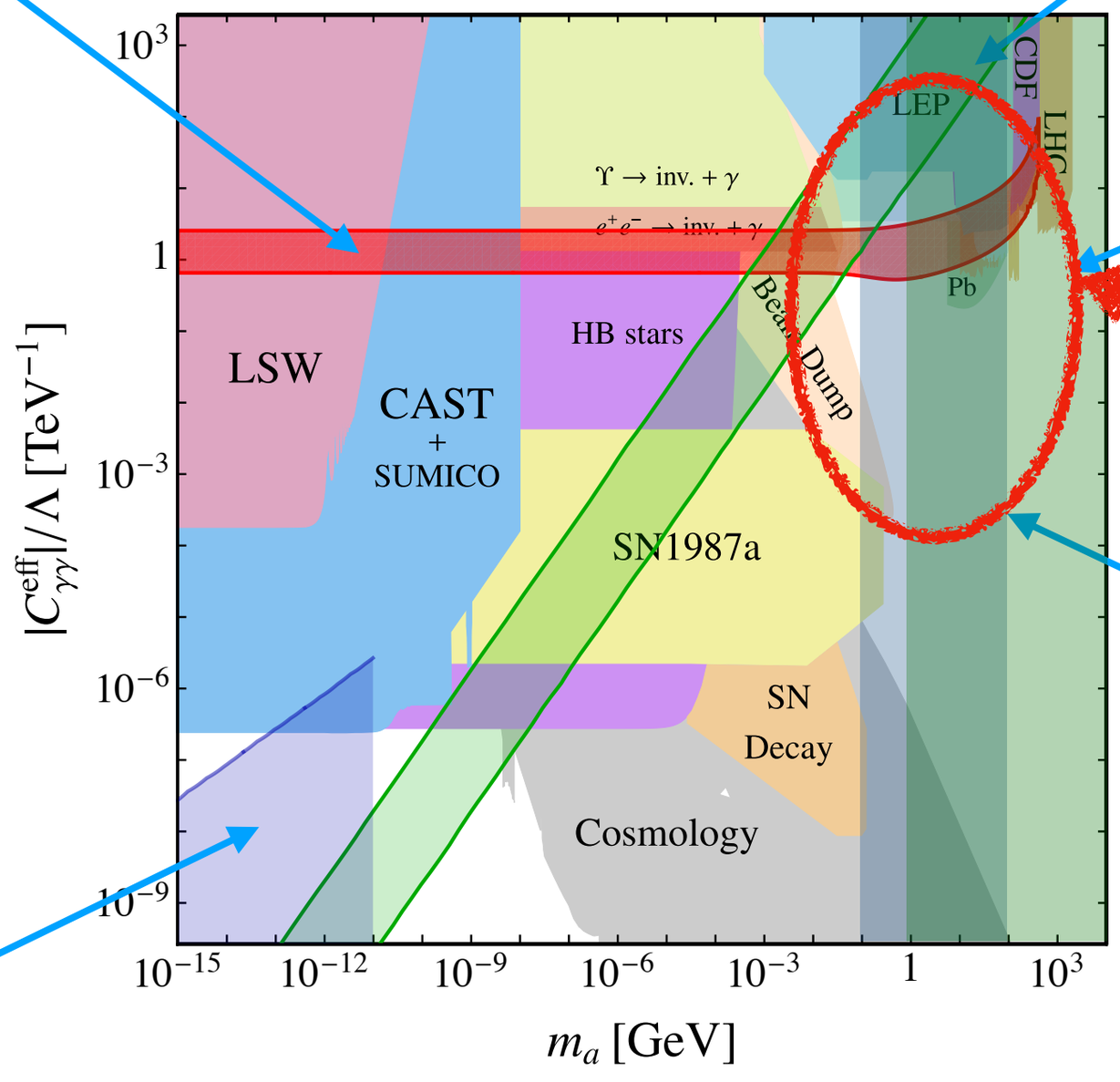

Really interesting but untested region!

pNGB in supersymmetric or composite models

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DM candidate

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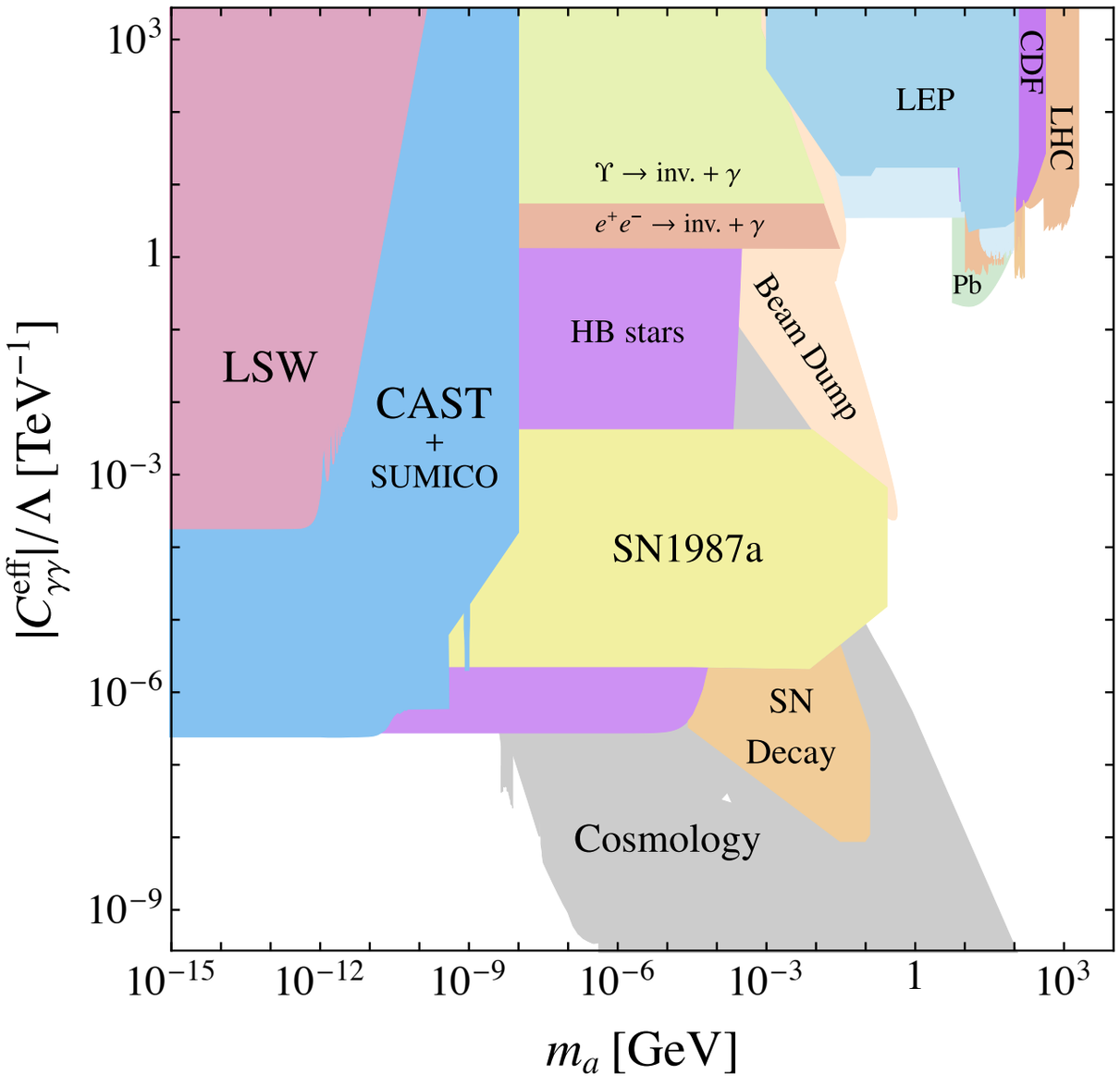

Light BSM particles at the LHC

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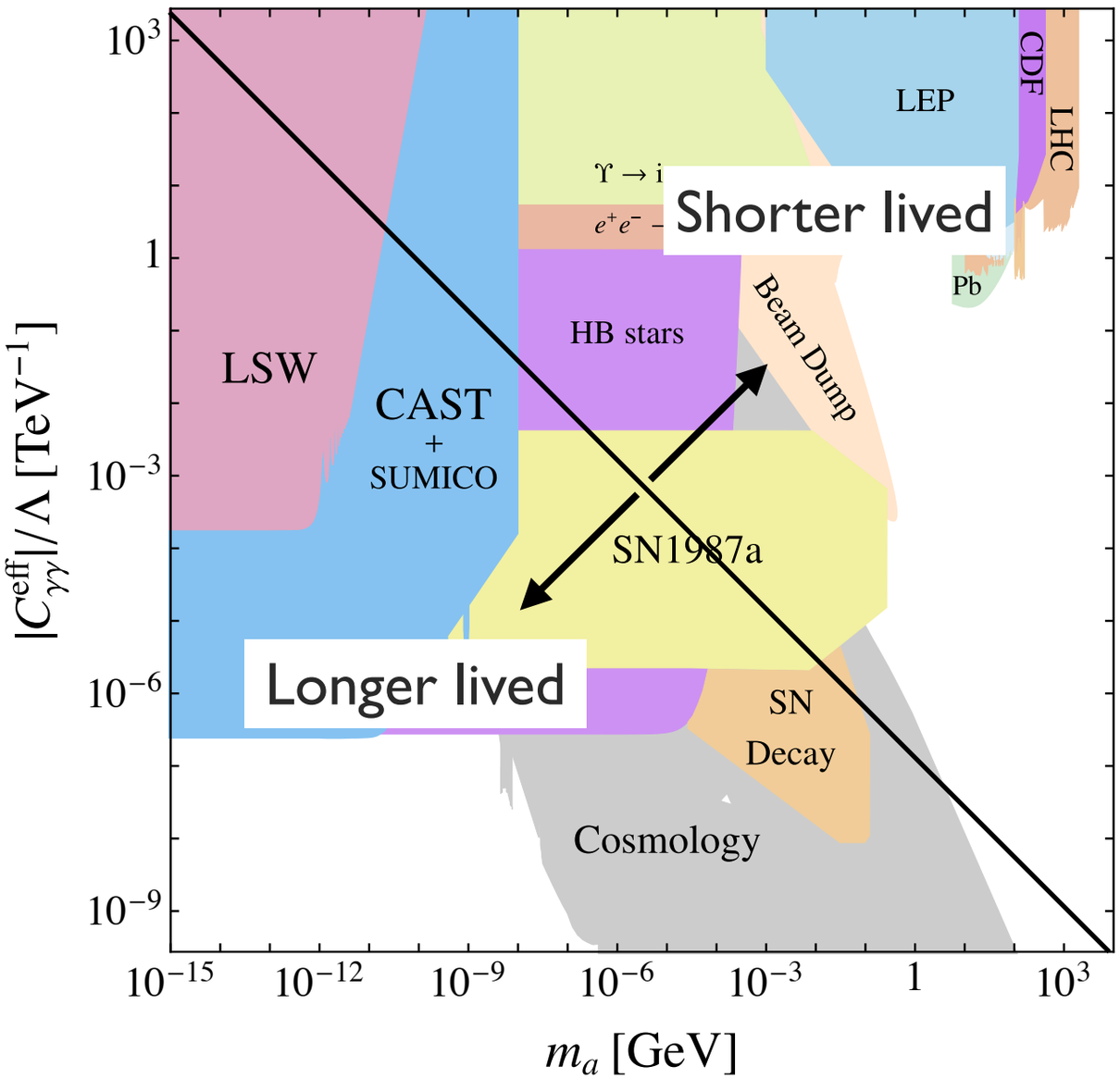

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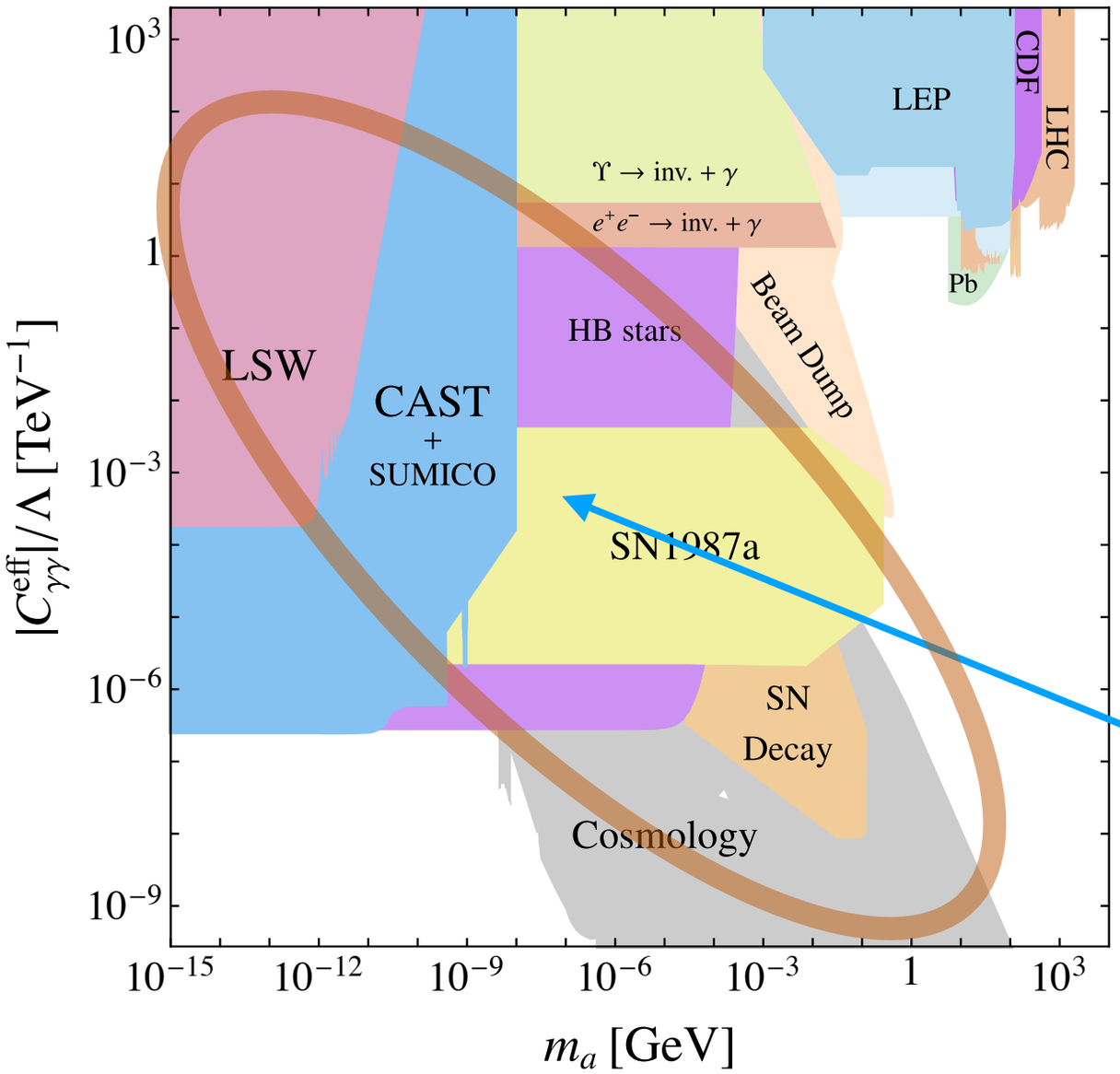
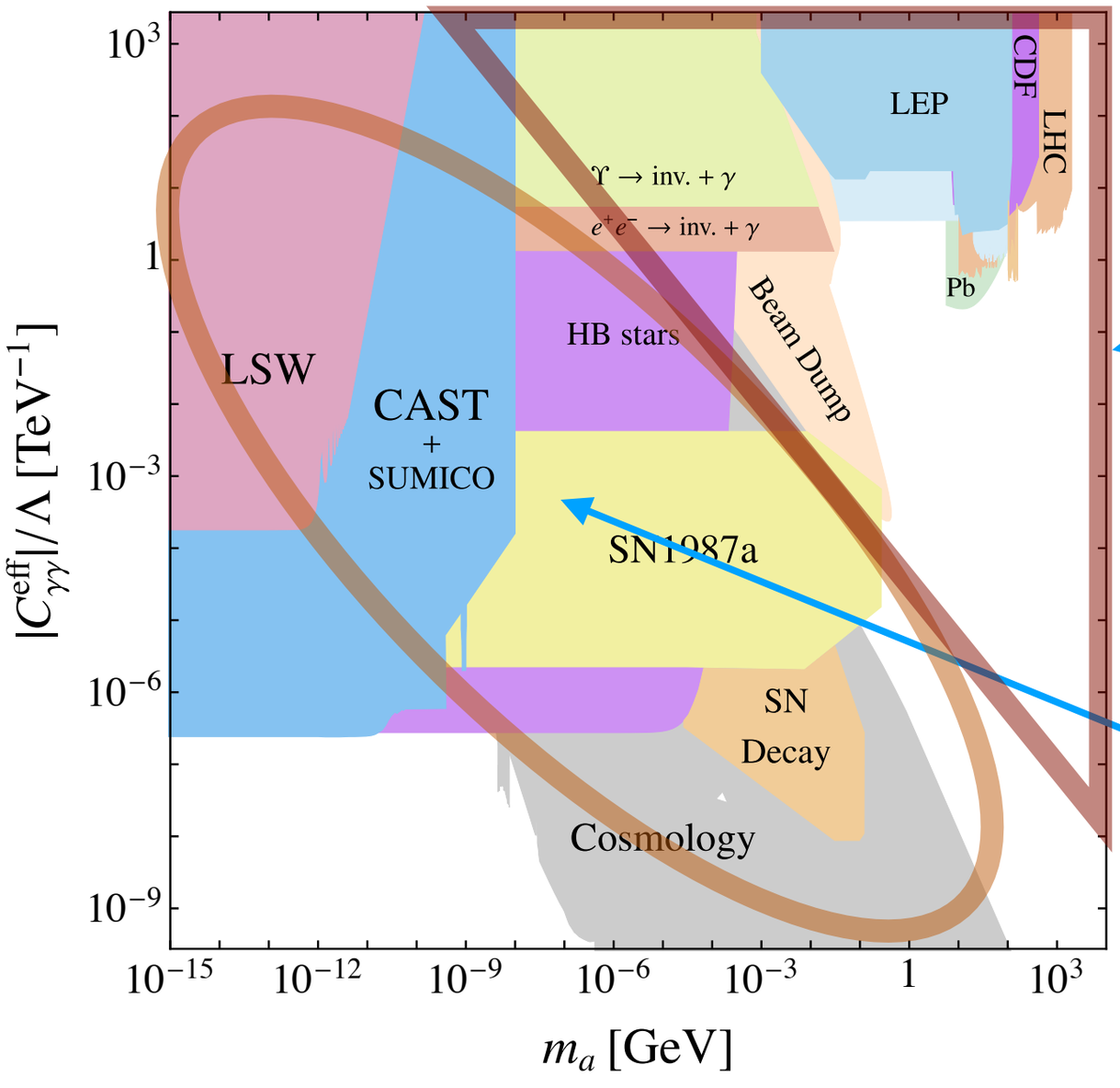


ALPs from sun and stars

Light BSM particles at the LHC

Example: axion-like-particles



ALPs decay within collider

ALPs from sun and stars

Light BSM particles at the LHC

Light BSM particles can be long lived

$$\tau = \frac{1}{\Gamma}$$

Light BSM particles at the LHC

Light BSM particles can be long lived

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$$d\Gamma \sim \frac{1}{M}|\mathcal{M}|^2 d\Phi_n$$

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Various features can imply a long life time

- Suppressed phase space
- Small matrix element

Light BSM particles at the LHC

Light BSM particles can be long lived

$$\tau = \frac{1}{\Gamma}$$

$$d\Gamma \sim \frac{1}{M}|\mathcal{M}|^2 d\Phi_n$$

Various features can imply a long life time

- Suppressed phase space
- Small matrix element
  - Approximate symmetry
  - Small couplings to lighter states

Light BSM particles at the LHC

Prompt decays

- Typically larger couplings and masses
- Well suited for LHC searches

Light BSM particles at the LHC

ALP interactions at dimension-5

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

$$\mathcal{L}_{\text{eff}}^{D\leq 5} = \frac{1}{2}\,(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2}\,a^2 + \frac{\partial^\mu a}{f}\sum_F \bar{\psi}_F\,\boldsymbol{c}_F\,\gamma_\mu\,\psi_F$$
$$+ c_{GG}\,\frac{\alpha_s}{4\pi}\,\frac{a}{f}\,G^a_{\mu\nu}\,\tilde{G}^{\mu\nu,a} + c_{WW}\,\frac{\alpha_2}{4\pi}\,\frac{a}{f}\,W^A_{\mu\nu}\,\tilde{W}^{\mu\nu,A} + c_{BB}\,\frac{\alpha_1}{4\pi}\,\frac{a}{f}\,B_{\mu\nu}\,\tilde{B}^{\mu\nu}$$

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ALP production via

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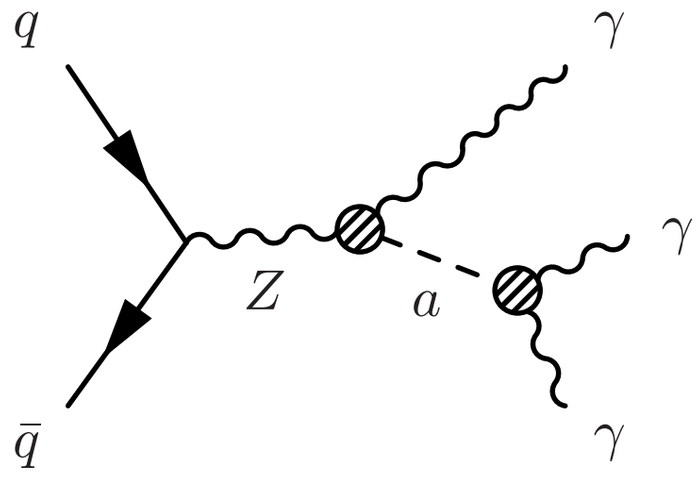

Light BSM particles at the LHC

Higgs interactions at dimension-6 and 7

$$\mathcal{L}_{\text{eff}}^{D\geq 6} = \frac{C_{ah}}{\Lambda^2}\,(\partial_\mu a)(\partial^\mu a)\,\phi^\dagger\phi + \frac{C_{Zh}^{(7)}}{\Lambda^3}\,(\partial^\mu a)\left(\phi^\dagger\, iD_\mu\,\phi + \text{h.c.}\right)\phi^\dagger\phi + \ldots$$

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$$h \to aa$$

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

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[Bauer, Neubert, Thamm: 1610.00009]
[Bauer, Neubert, Thamm: 1704.08207]
[Bauer, Neubert, Thamm: 1708.004433]

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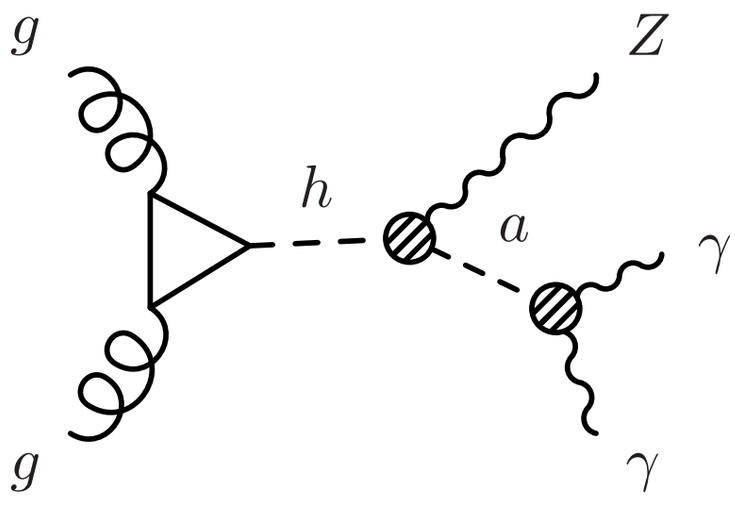
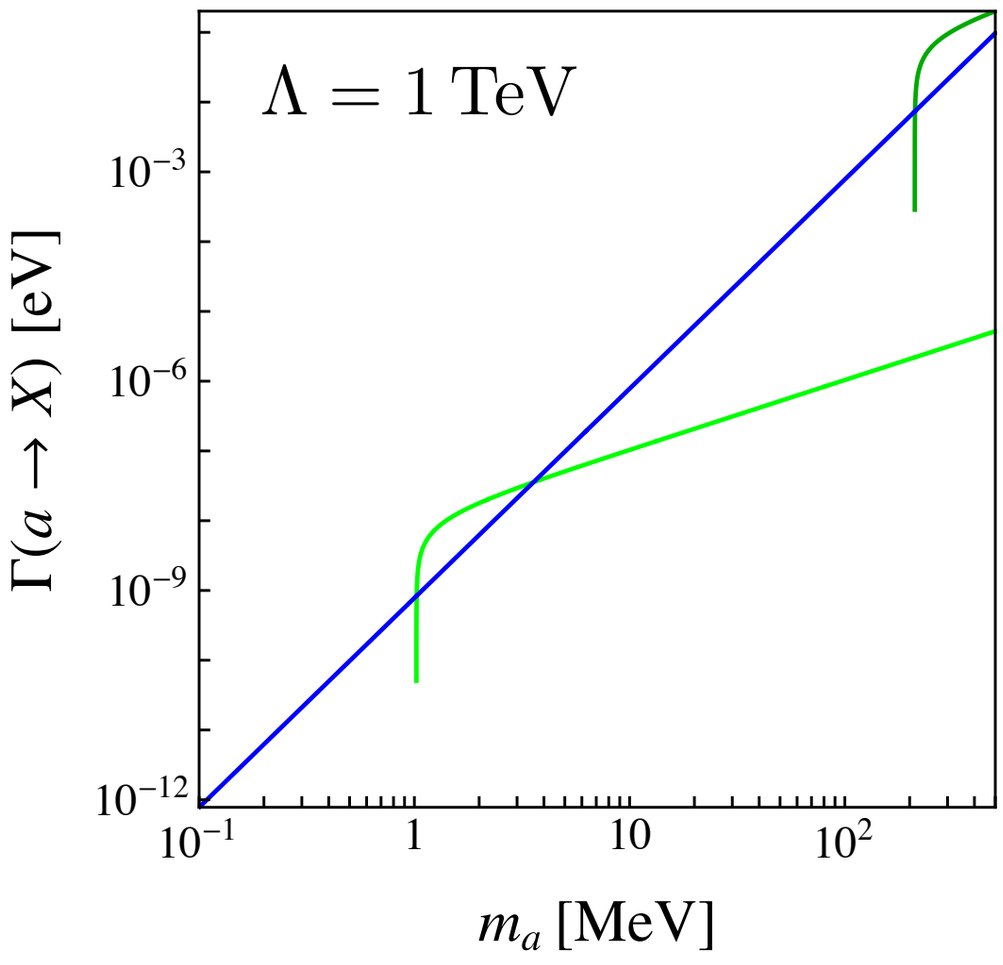
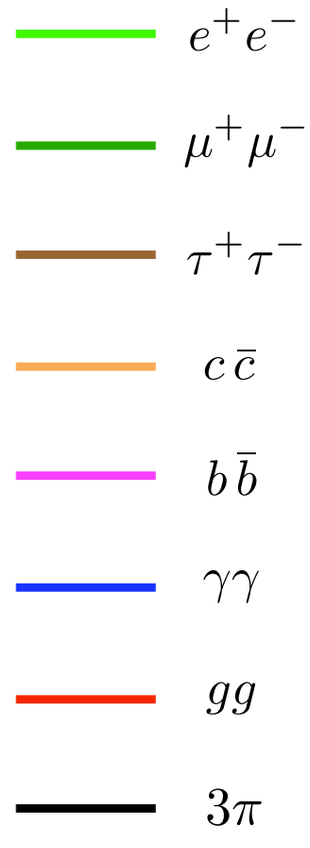


Light BSM particles at the LHC

ALP fermion couplings = 1, ALP gauge boson couplings = 1 in the plot

More motivated: gauge couplings = $1/(4\pi)^2$





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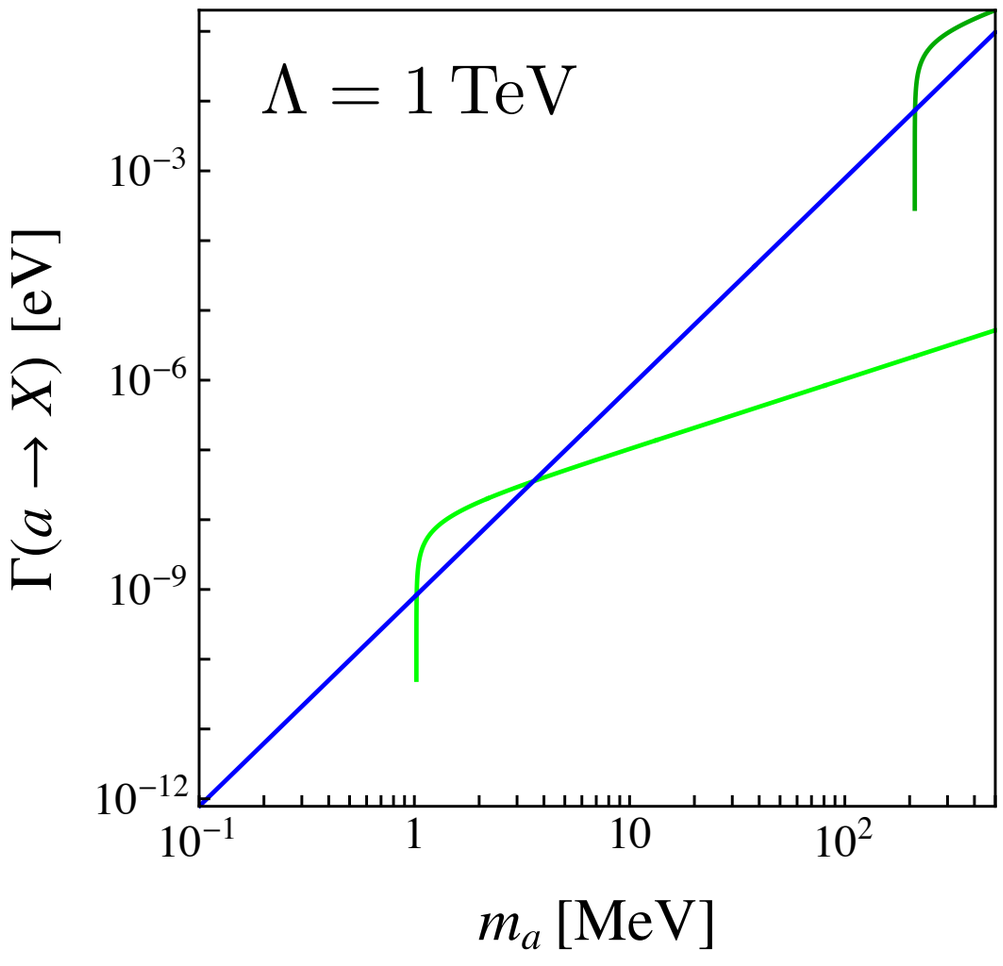

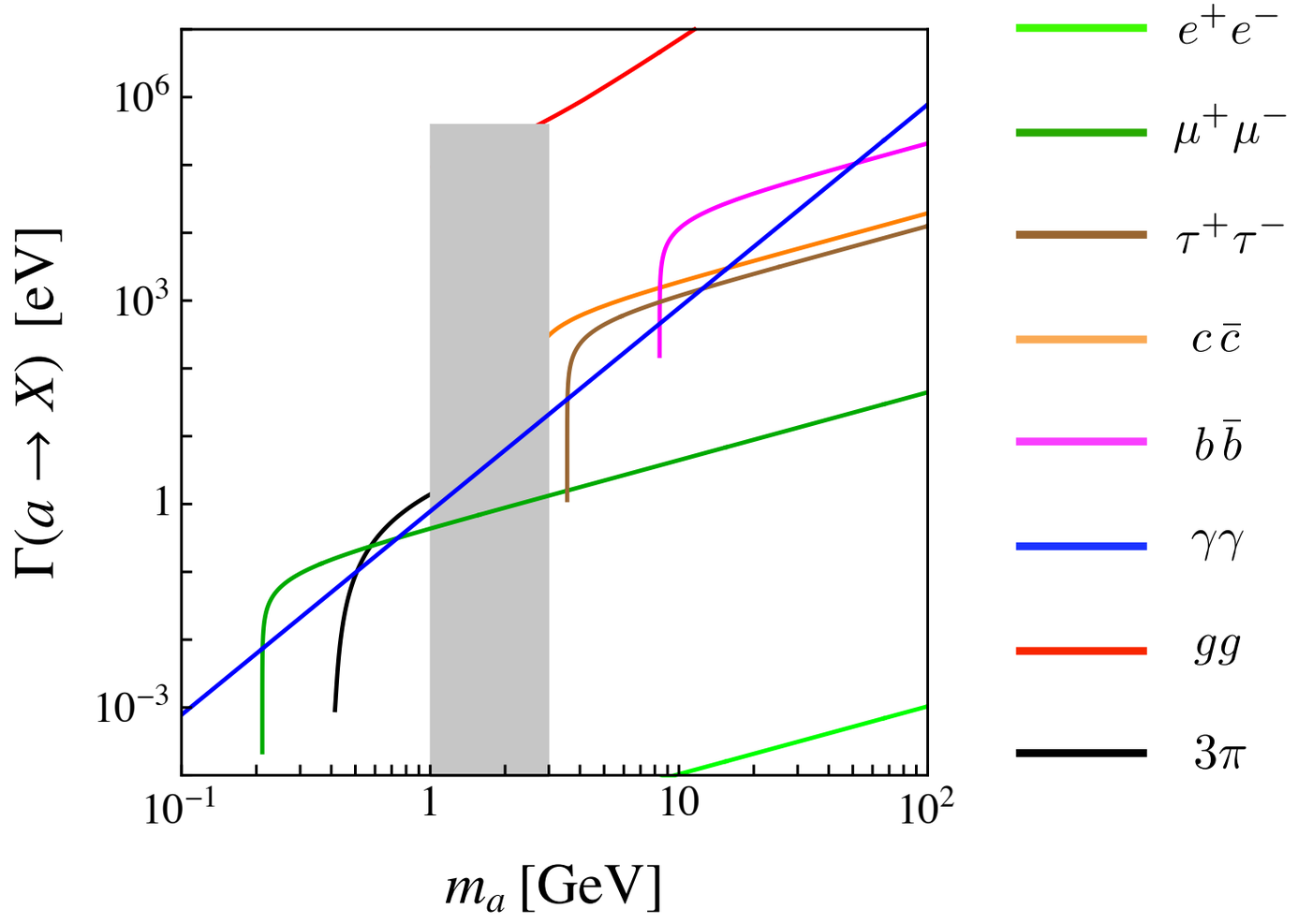

Light BSM particles at the LHC

Dark photon interactions

$$\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_D A_\mu A^\mu - \epsilon\, eQ\, A^\mu \bar{f}\gamma_\mu f$$

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Dark photon production via

- Drell-Yan
- Exotic Higgs decays into a photon and dark photon

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Dark photon decays into

- Leptons
- Hadrons

Light BSM particles at the LHC

Prompt decays

- Typically larger couplings and masses
- Well suited for LHC searches

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Macroscopic decay lengths with decays within the detector

- Displaced objects (e.g. leptons, multitrack)
- Non-standard tracks (e.g. disappearing tracks)
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⇒ need all subdetectors, improved triggers, …

See talk on dark showers by Christiane Scherb on Thursday

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- Mathusla, Faser, Codex-b, Anubis, MoeDAL/MAPP, SHIP

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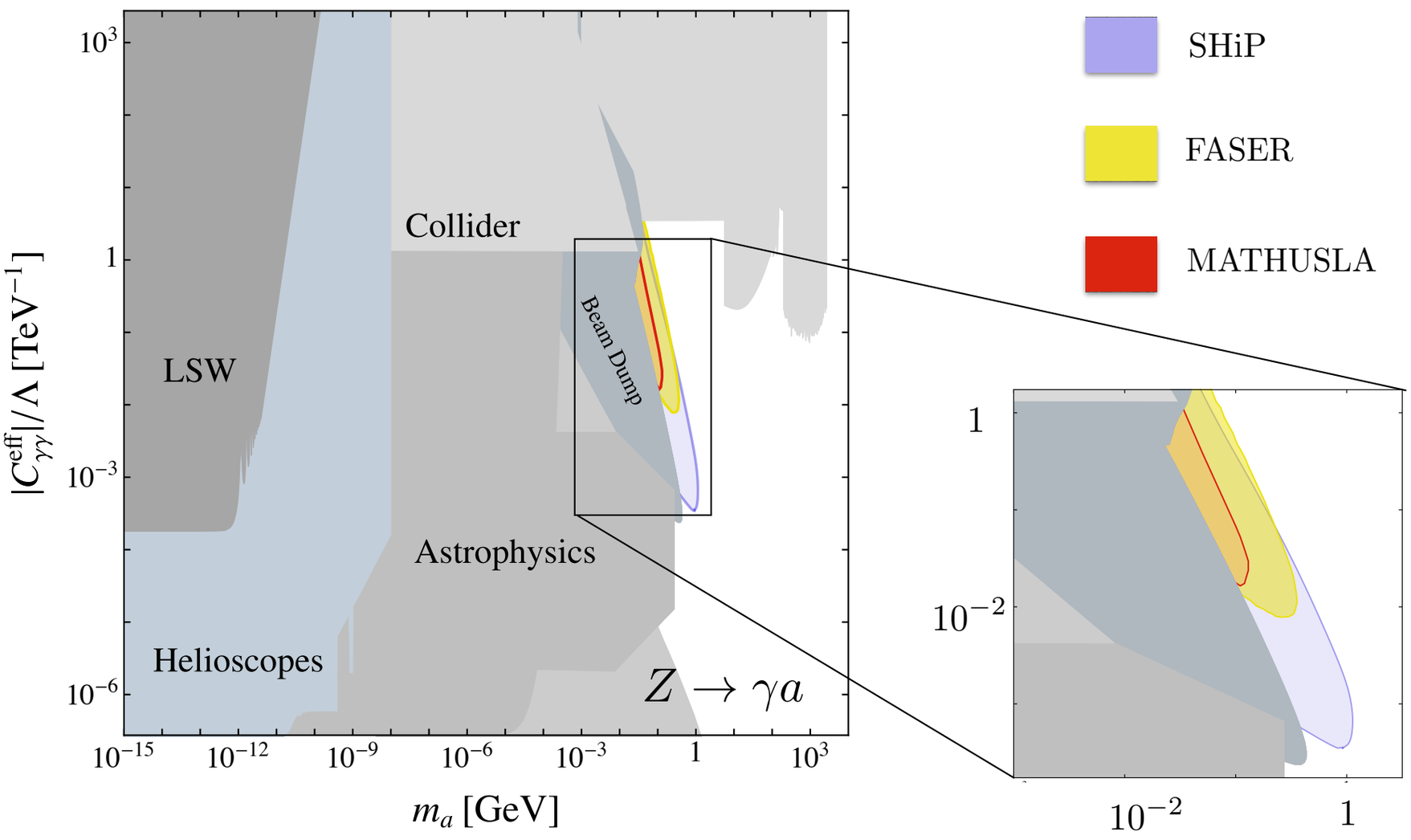
See talk on FIPs for small LHC experiments by Yu-Dai Tsai on Thursday

Light BSM particles at the LHC

ALPs from exotic Z decays at Mathusla, Faser, Ship

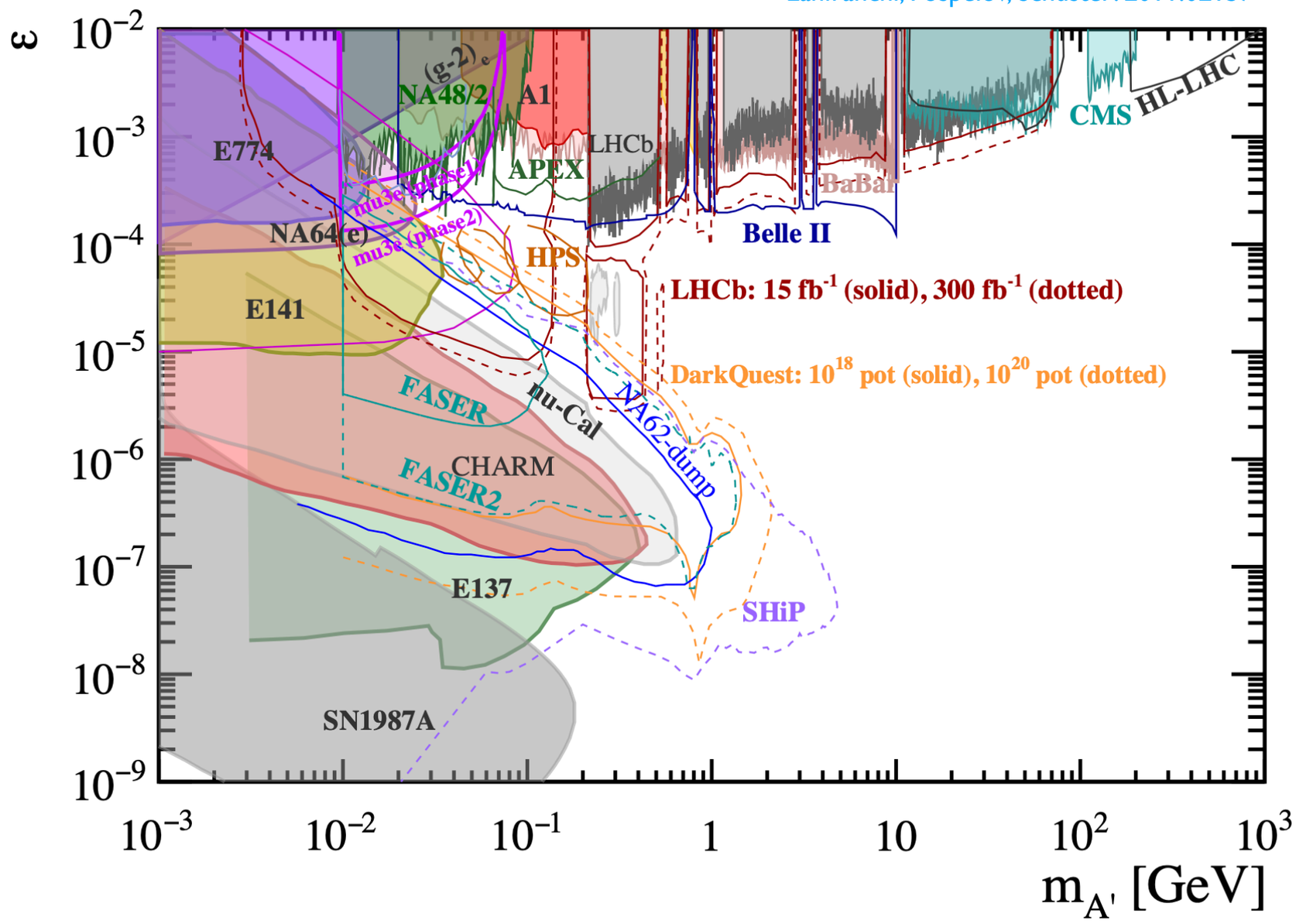
Bauer, Heiles, Neubert, Thamm: 1808.10323



Light BSM particles at the LHC

Dark photons at Faser, Ship

Lanfranchi, Pospelov, Schuster: 2011.02157



Outline

1. Motivations for light BSM particles
2. Light BSM particles at the LHC
3. Conclusions

Conclusions

- Many motivated UV origins of light BSM particles
- UV origin determines spin, mass and coupling
- LHC well suited for larger (light) masses and couplings

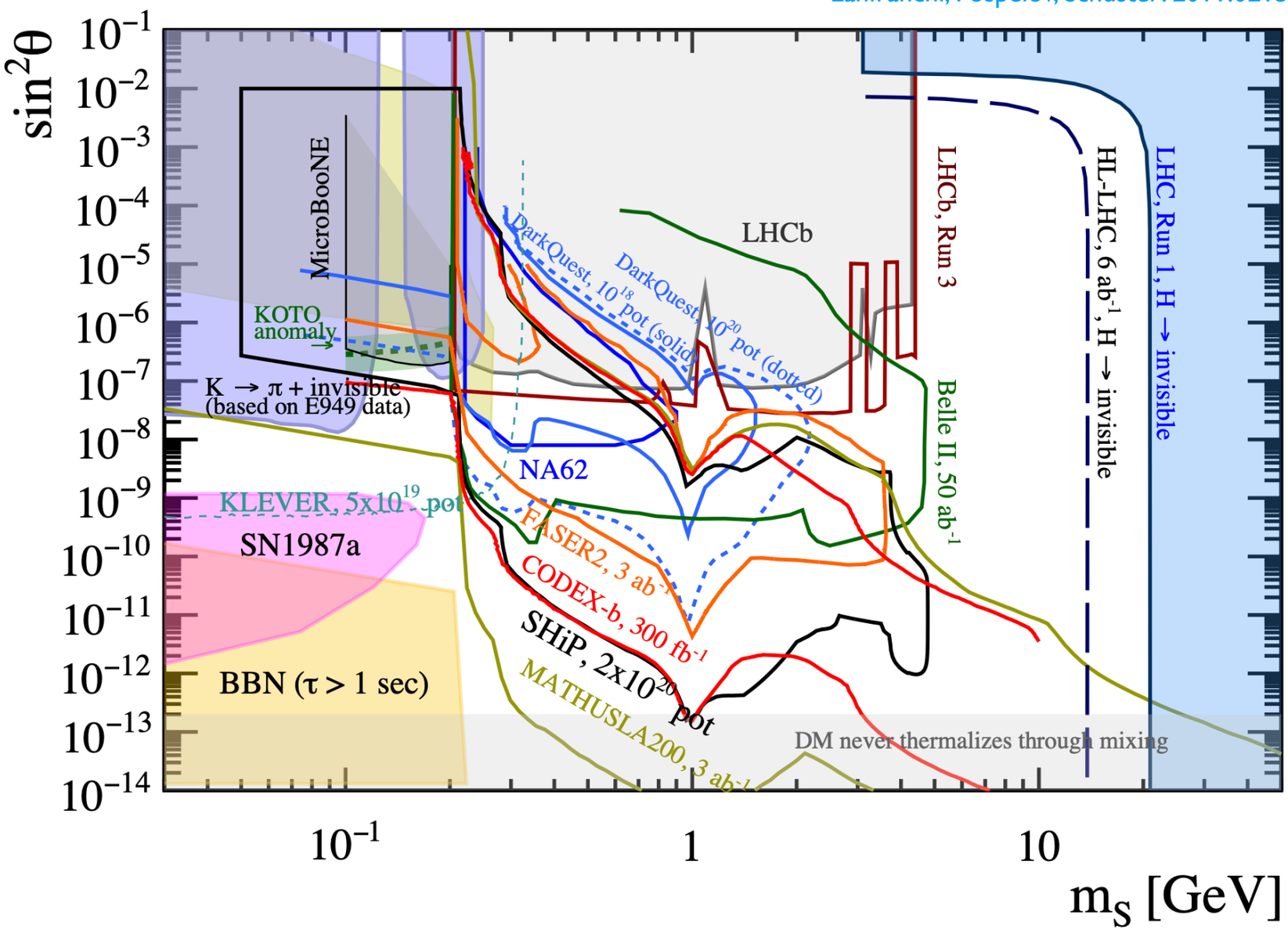
Thank you!

Backup

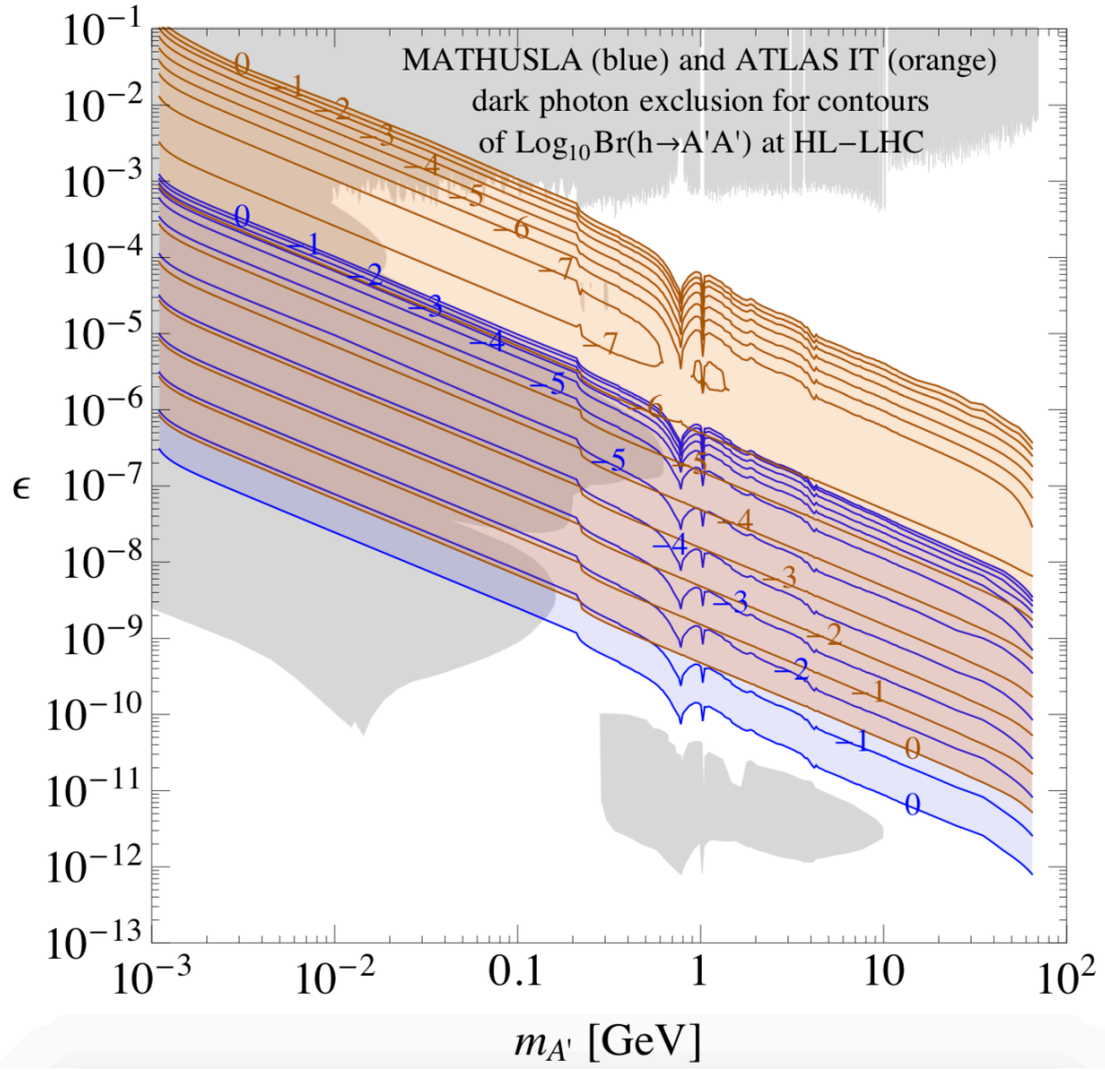
Light BSM particles at the LHC

Dark scalar

Lanfranchi, Pospelov, Schuster: 2011.02157



Dark Photon


MATHUSLA (blue) and ATLAS IT (orange)
dark photon exclusion for contours
of Log10Br(h→A'A') at HL−LHC
ϵ
mA' [GeV]