

# Long-lived particles at current and future collider experiments

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# Outline

1. What are long-lived particles?
2. Axion-like particles
  - at the LHC
  - at MATHUSLA
3. Conclusions

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- Long decay lengths = long life time  $\lambda = c\tau$
- Light or heavy wrt to electroweak scale
- Can decay to quarks, leptons or gauge bosons,...

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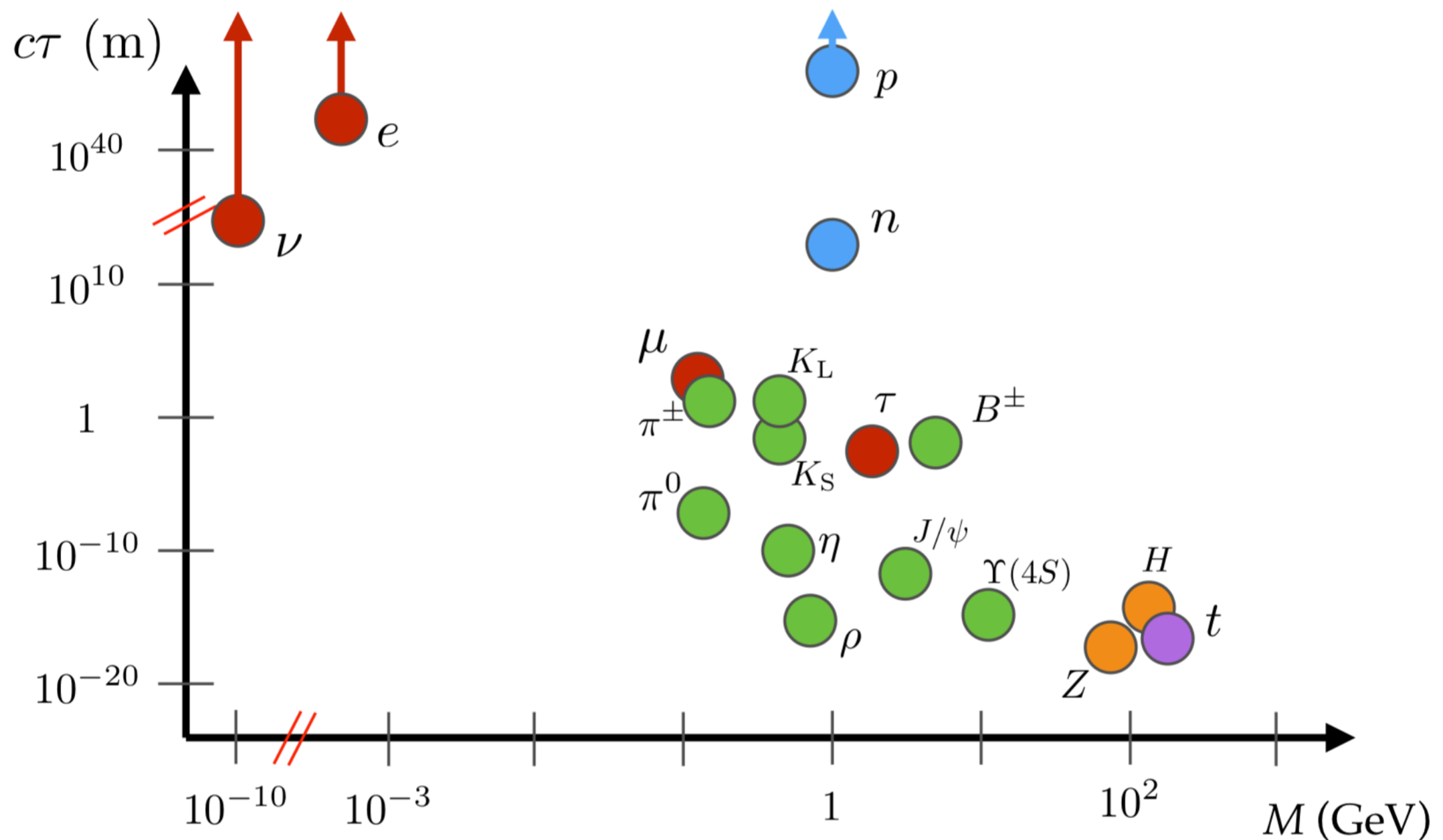
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- Small matrix element
  - ★ Approximate symmetry
  - ★ Small coupling to lighter states
- Suppressed phase space

# What are long-lived particles (LLP)?

- Plenty of long-lived particles in the Standard Model



[Taken from 1903.04497]

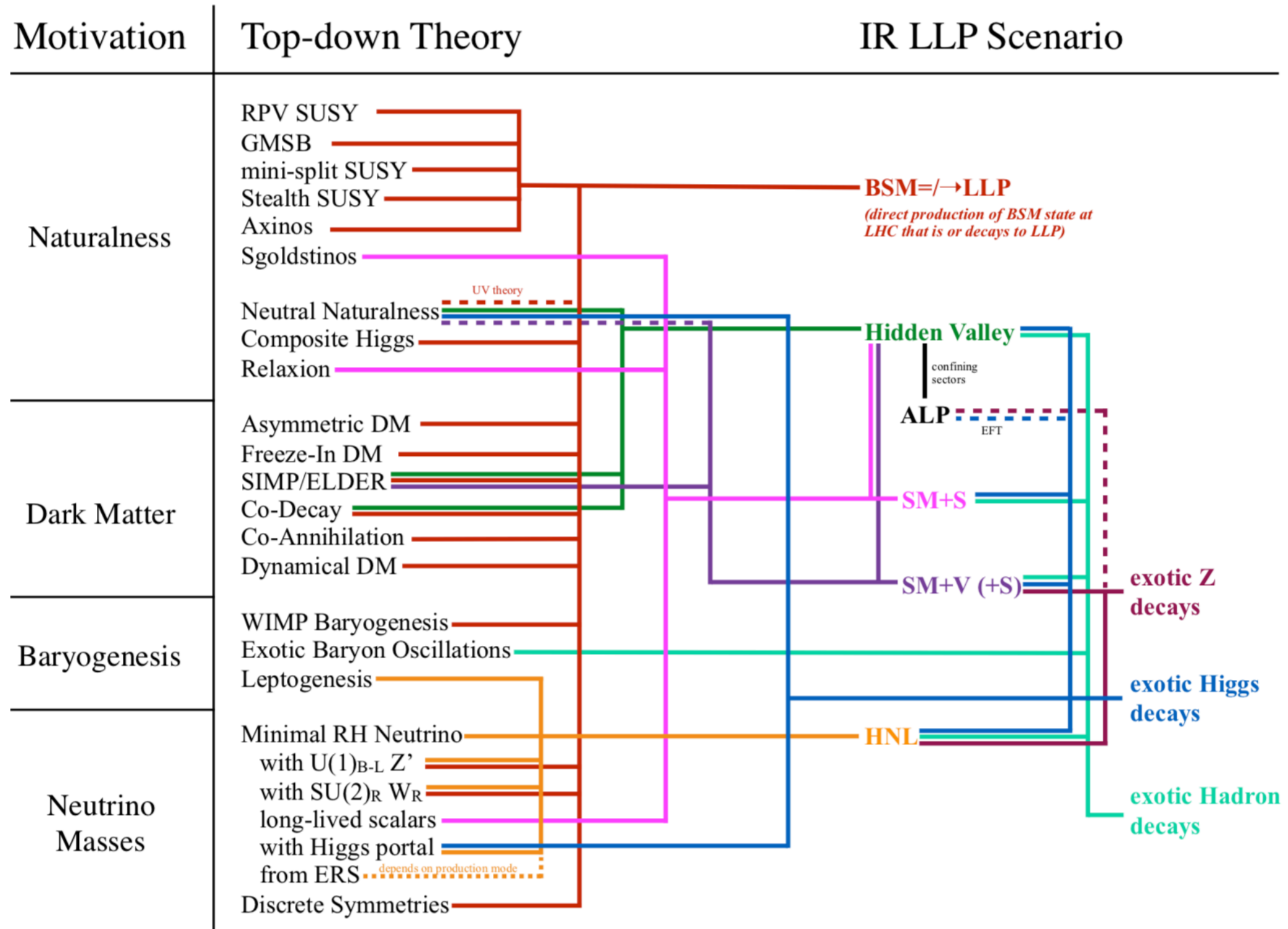
# LLP beyond the SM

Motivation	Top-down Theory	IR LLP Scenario
Naturalness		
Dark Matter		
Baryogenesis		
Neutrino Masses		

# LLP beyond the SM

Motivation	Top-down Theory	IR LLP Scenario
Naturalness	RPV SUSY GMSB mini-split SUSY Stealth SUSY Axinos Sgoldstinos	
	Neutral Naturalness <small>UV theory</small> Composite Higgs Relaxion	
Dark Matter	Asymmetric DM Freeze-In DM SIMP/ELDER Co-Decay Co-Annihilation Dynamical DM	
Baryogenesis	WIMP Baryogenesis Exotic Baryon Oscillations Leptogenesis	
Neutrino Masses	Minimal RH Neutrino with $U(1)_{B-L} Z'$ with $SU(2)_R W_R$ long-lived scalars with Higgs portal from ERS <small>depends on production mode</small> Discrete Symmetries	

# LLP beyond the SM



[Taken from 1806.07386 - Long lived particles of the Energy Frontier: The MATHUSLA Physics Case]

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# Axion-like particles

- Interactions at dimension-5

[Weinberg: PRL 40 (1978) 223]

[Wilczek: PRL 40 (1978) 279]

[Georgi, Kaplan, Randall: Phys. Lett. 169 B (1986)]

$$\begin{aligned}\mathcal{L}_{\text{eff}}^{D \leq 5} = & \frac{1}{2} (\partial_\mu a)(\partial^\mu a) + \sum_f \frac{c_{ff}}{2} \frac{\partial^\mu a}{\Lambda} \bar{f} \gamma_\mu \gamma_5 f + g_s^2 C_{GG} \frac{a}{\Lambda} G_{\mu\nu}^A \tilde{G}^{\mu\nu, A} \\ & + e^2 C_{\gamma\gamma} \frac{a}{\Lambda} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w} C_{\gamma Z} \frac{a}{\Lambda} F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2} C_{ZZ} \frac{a}{\Lambda} Z_{\mu\nu} \tilde{Z}^{\mu\nu}\end{aligned}$$

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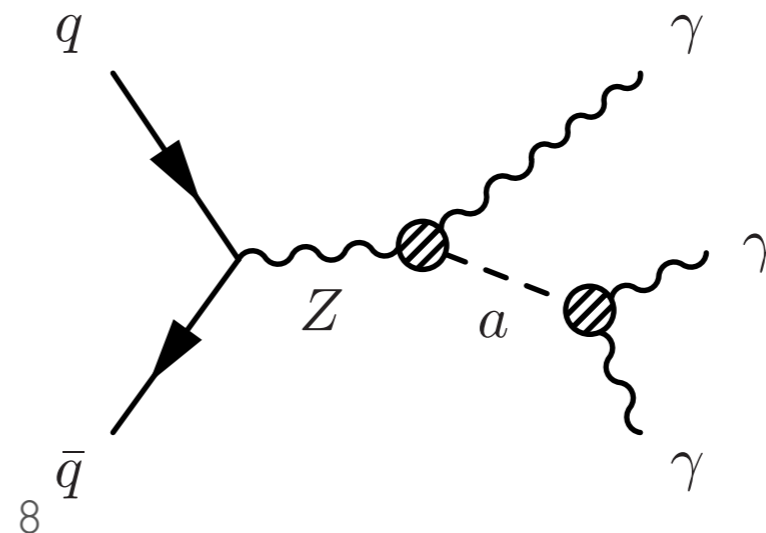
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- Exotic Z-decay



# Axion-like particles

- Higgs interactions at dimension-6 and 7

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

$$h \rightarrow aa$$

[Dobrescu, Landsberg, Matchev: 0005308]  
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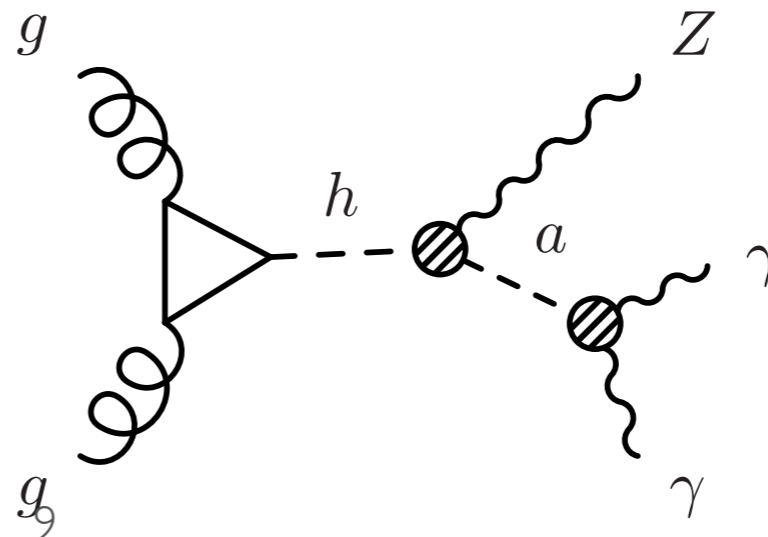
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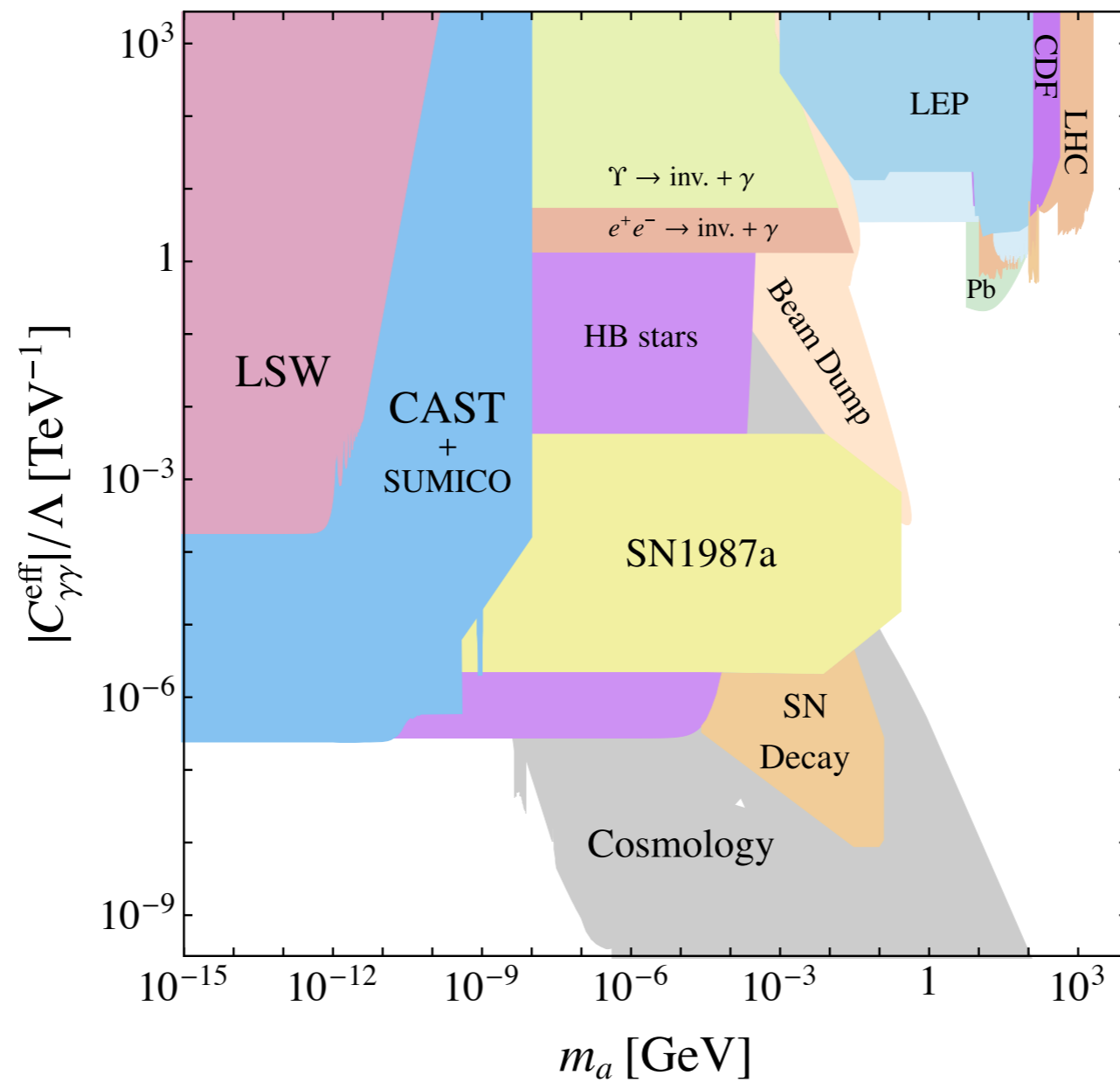
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- Exotic Higgs decay

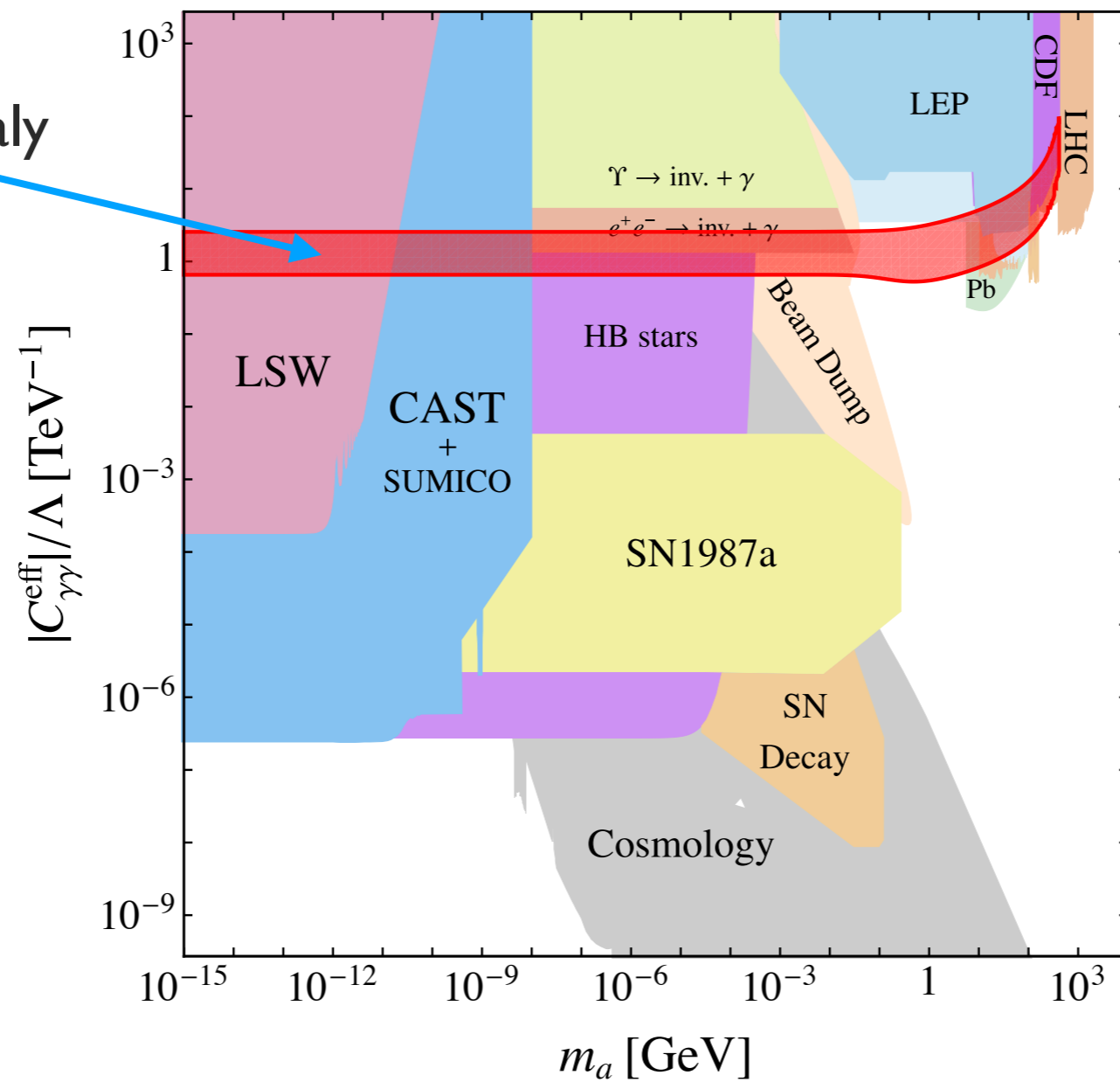


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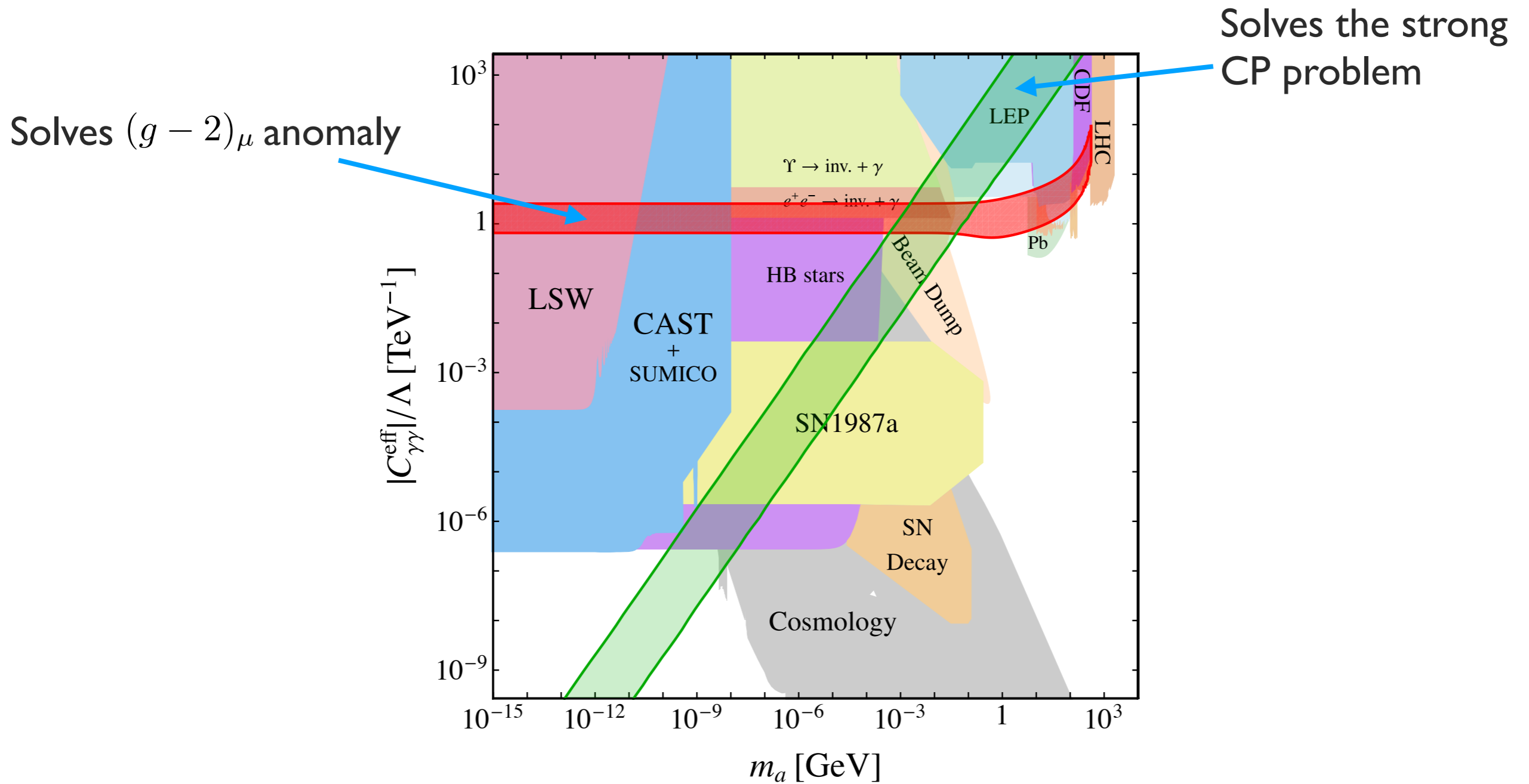


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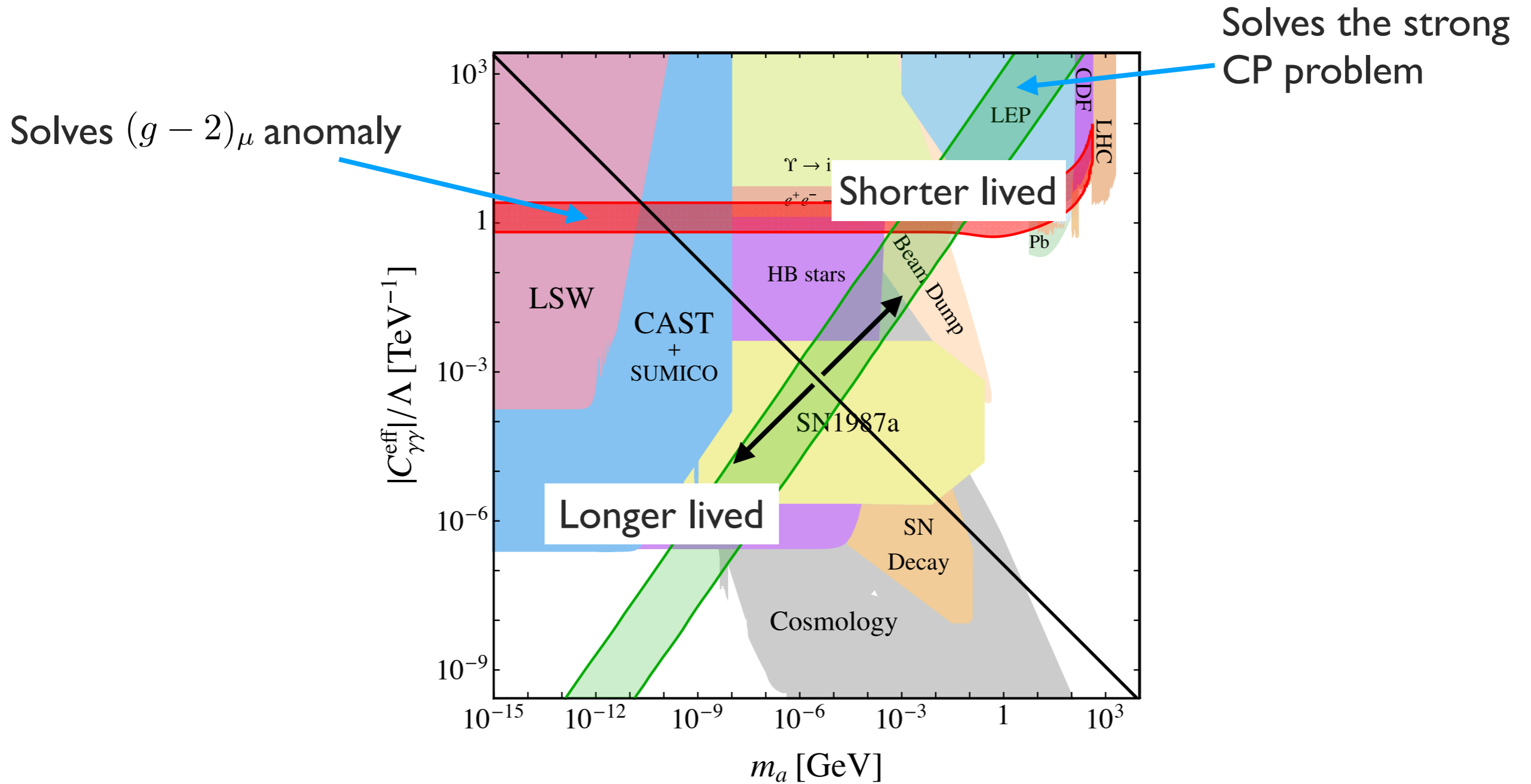
Solves  $(g - 2)_\mu$  anomaly



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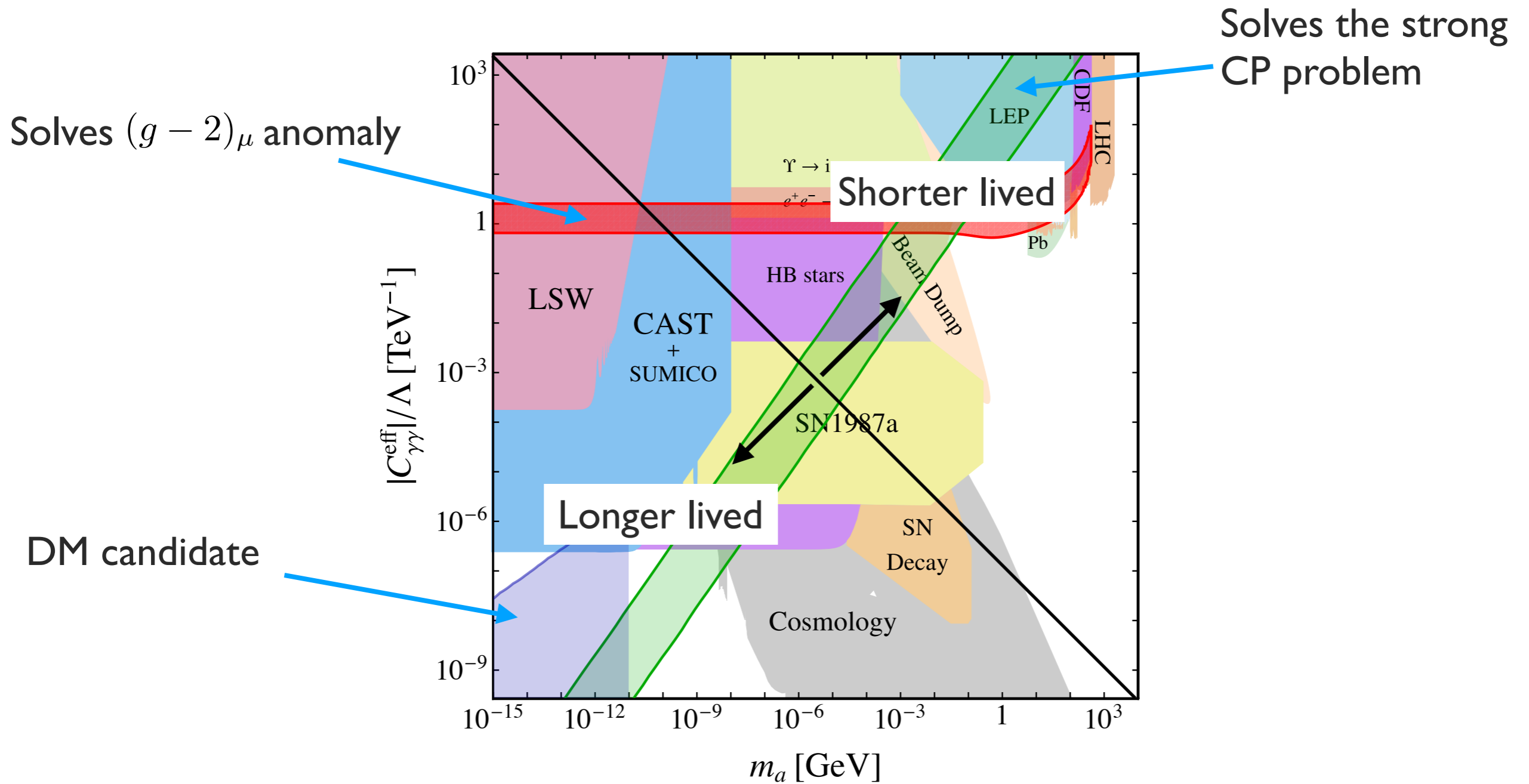


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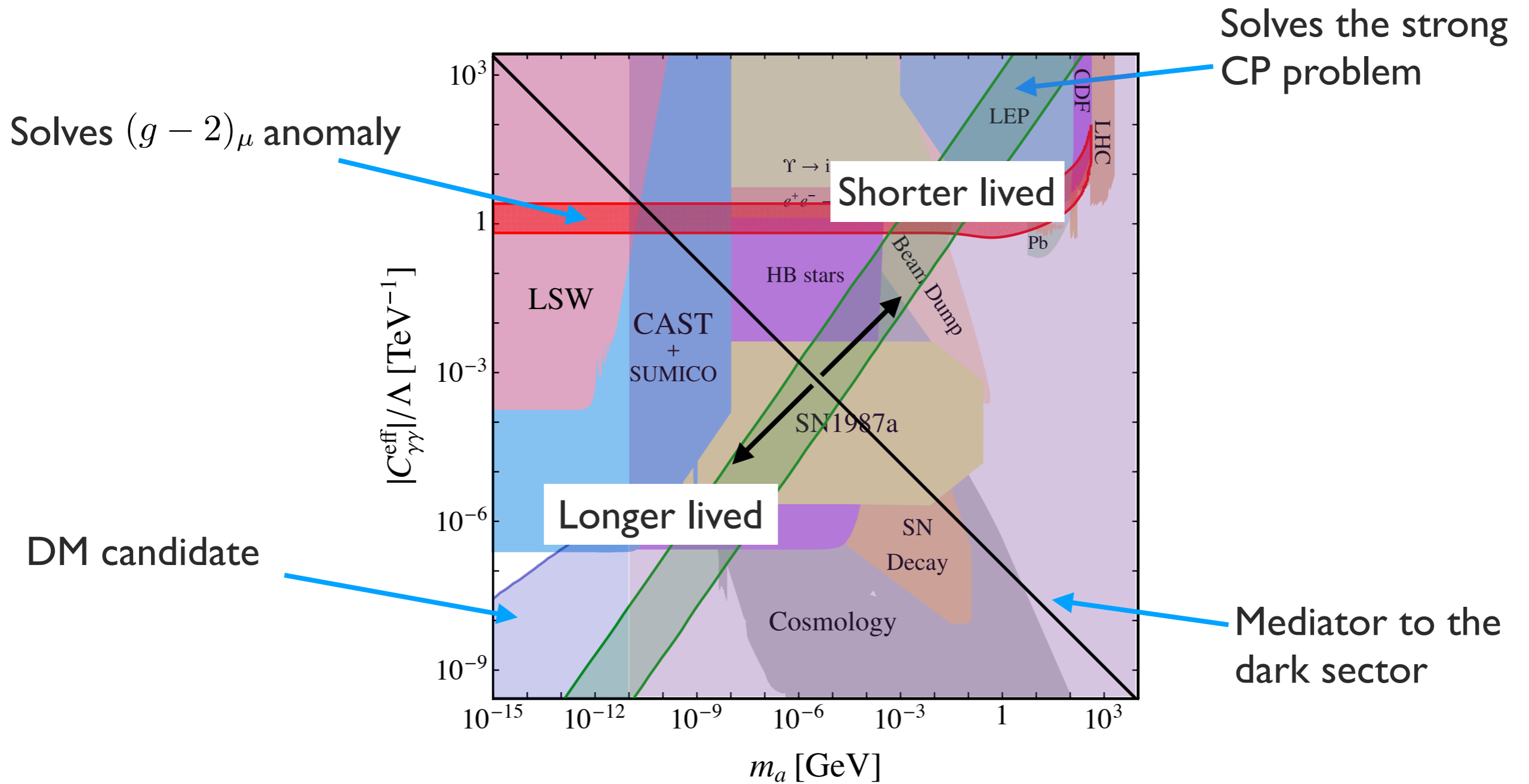




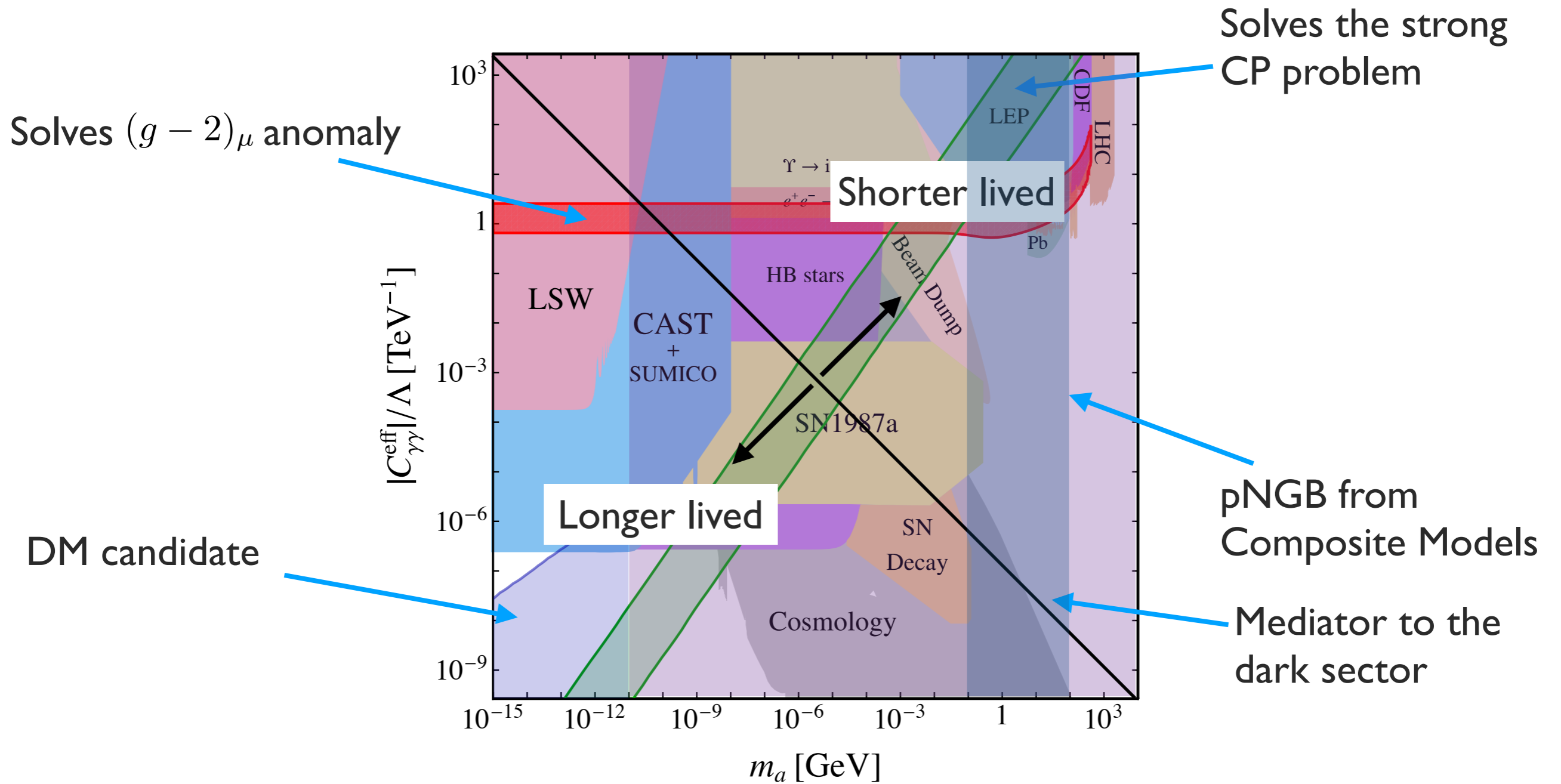
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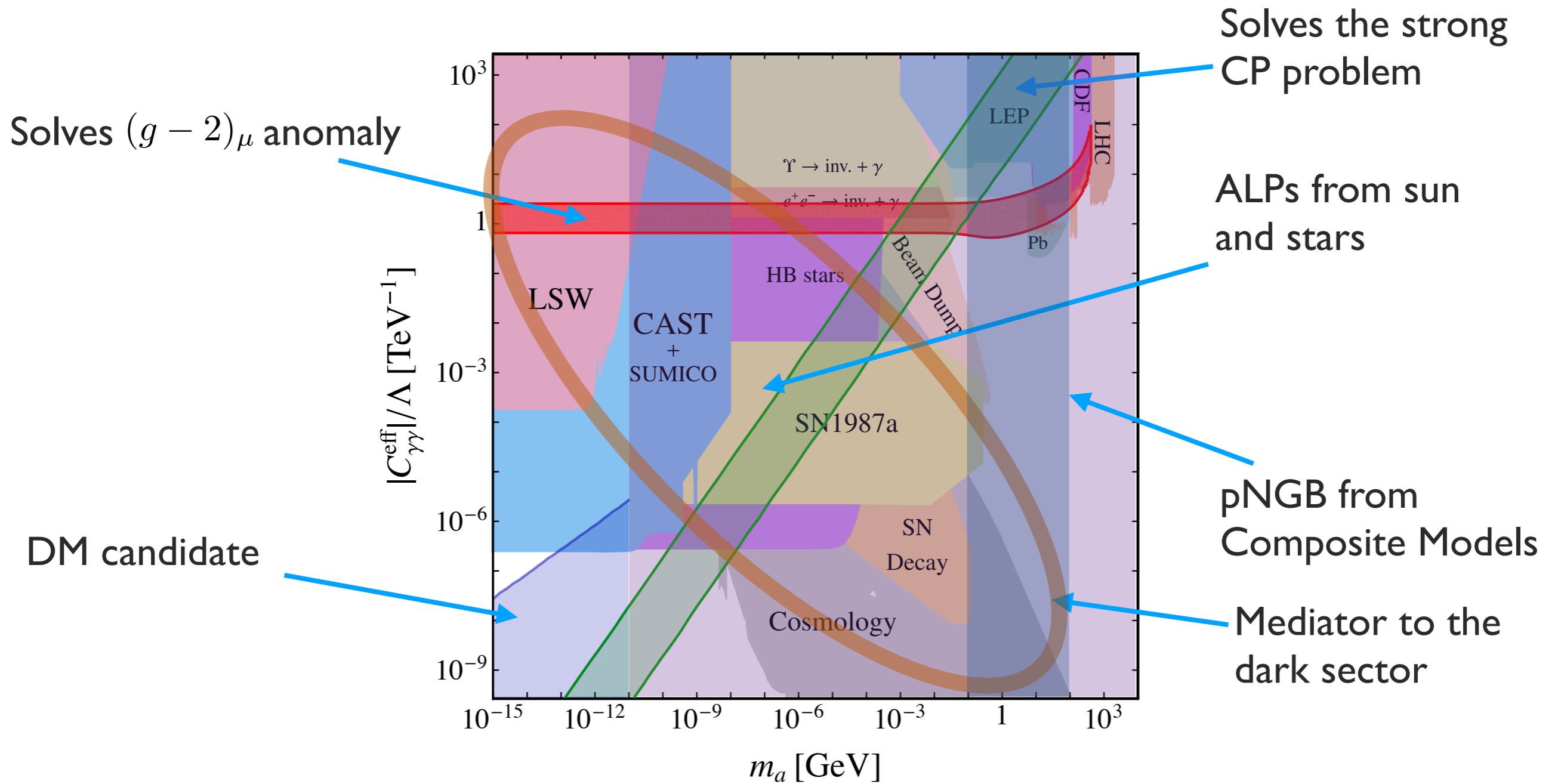
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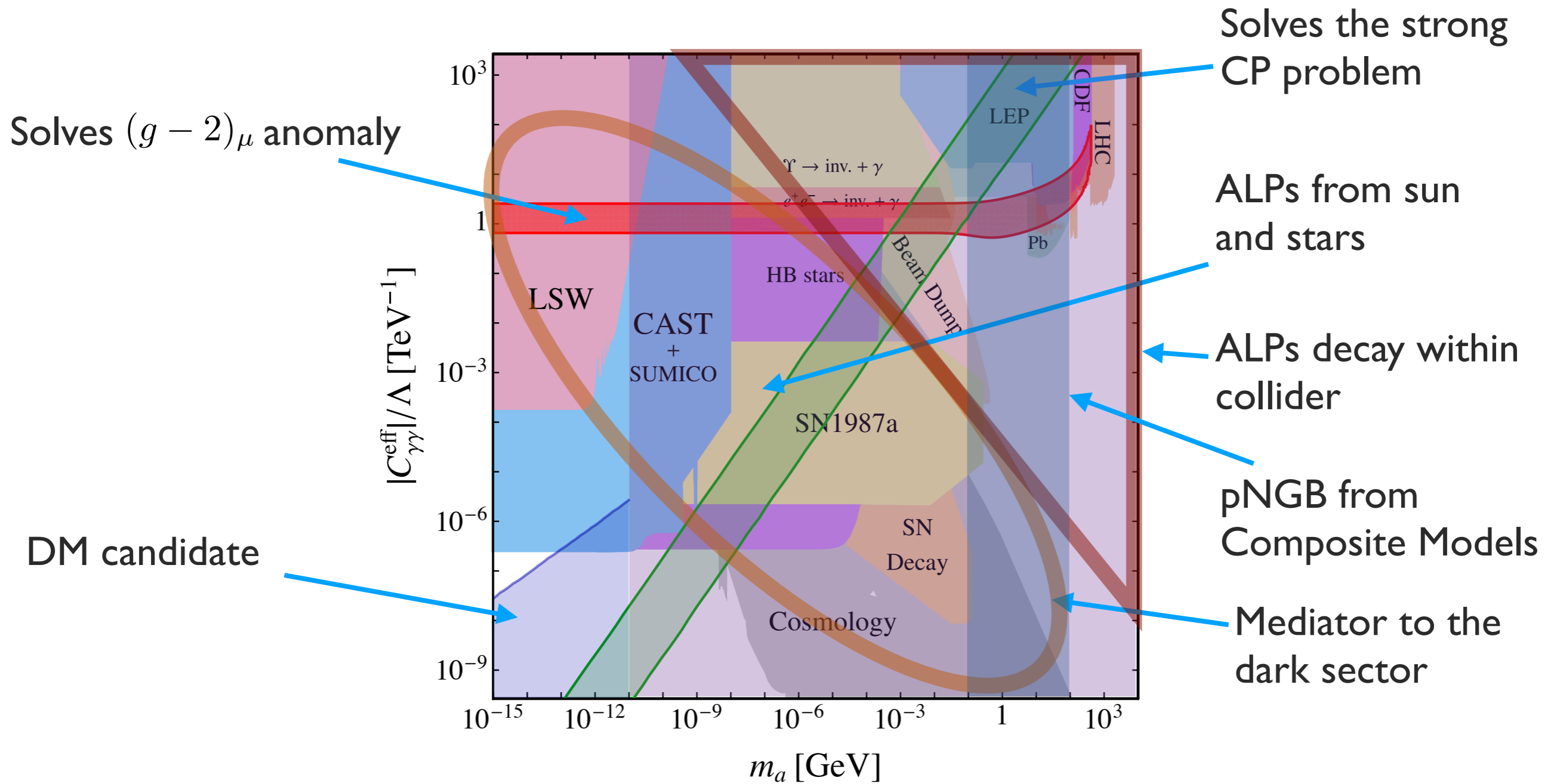
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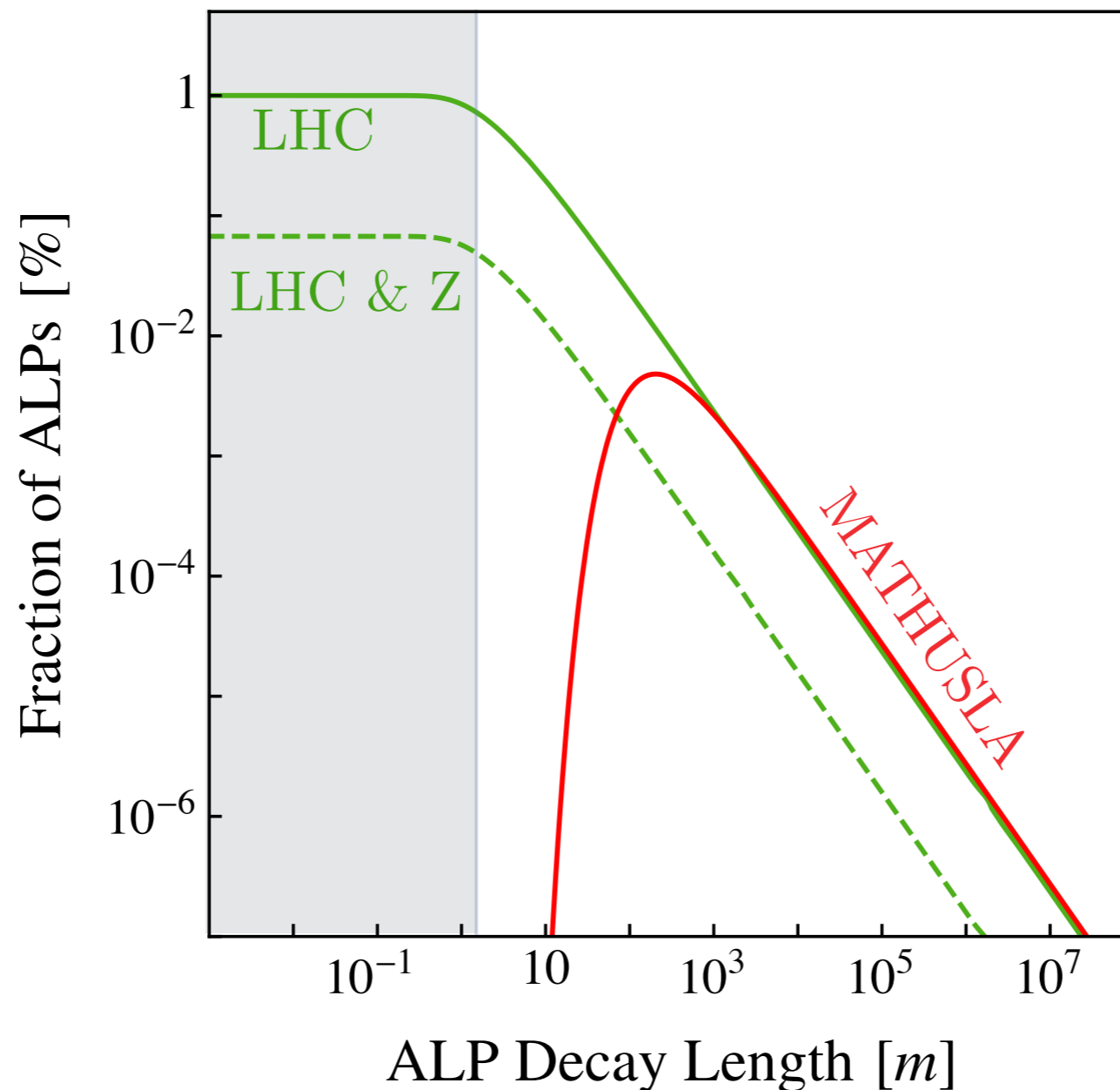


# Axion-like particles



# Axion-like particles

- Decay probability



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# Detecting ALPs in H and Z decays

- Average decay length perpendicular to beam axis

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

- Fraction of ALPs decaying before travelling a certain distance

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

Decay into photons  
before EM calorimeter

$$L_{\text{det}} = 1.5 \text{ m}$$

Decay into electrons  
before inner tracker

$$L_{\text{det}} = 2 \text{ cm}$$

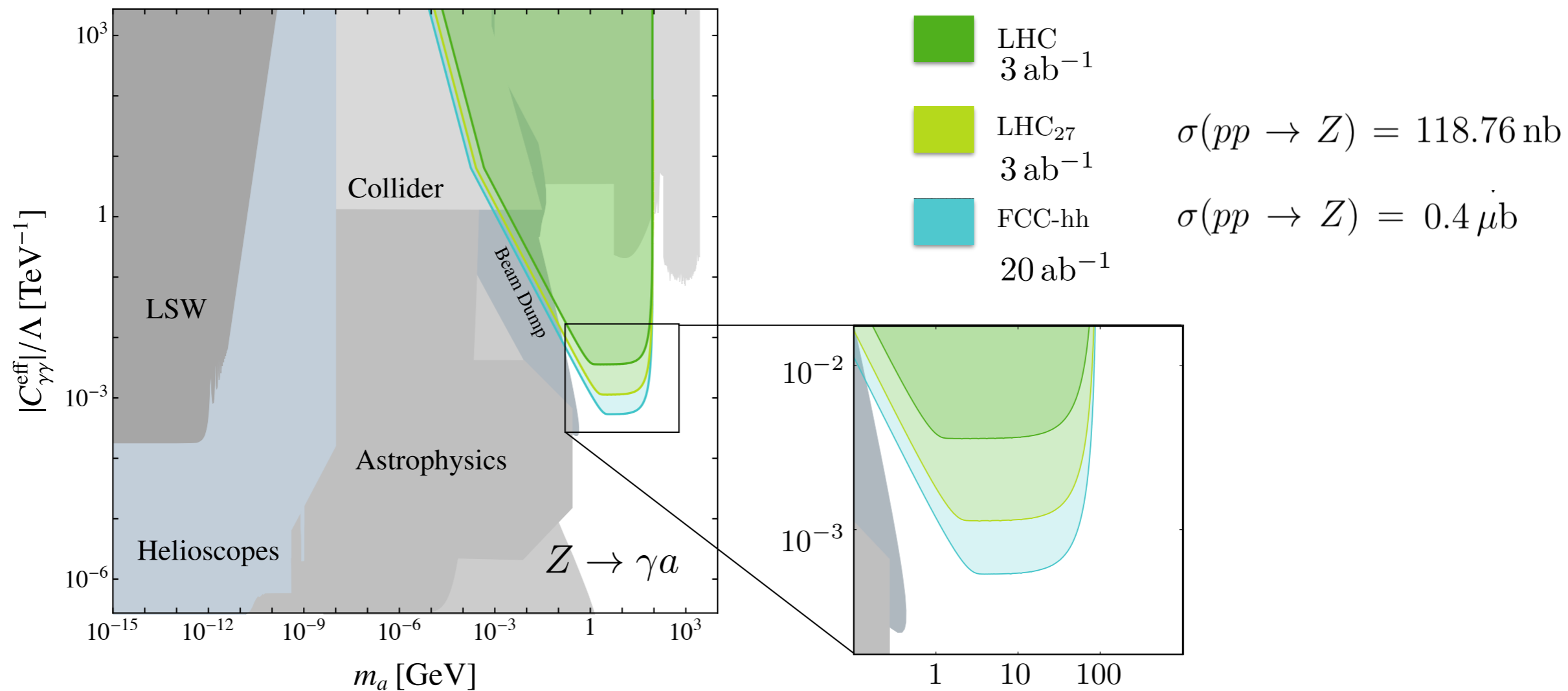
- Effective branching ratios

$$\text{Br}(h \rightarrow Z a \rightarrow \ell^+ \ell^- X \bar{X}) \Big|_{\text{eff}} = \text{Br}(h \rightarrow Z a) \times \text{Br}(a \rightarrow X \bar{X}) f_{\text{dec}} \text{Br}(Z \rightarrow \ell^+ \ell^-)$$



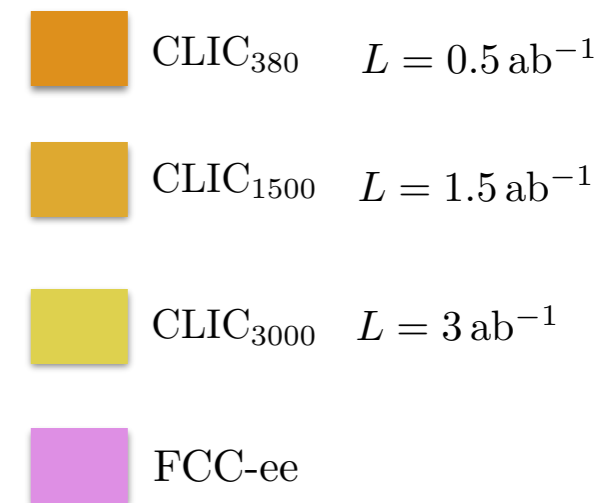
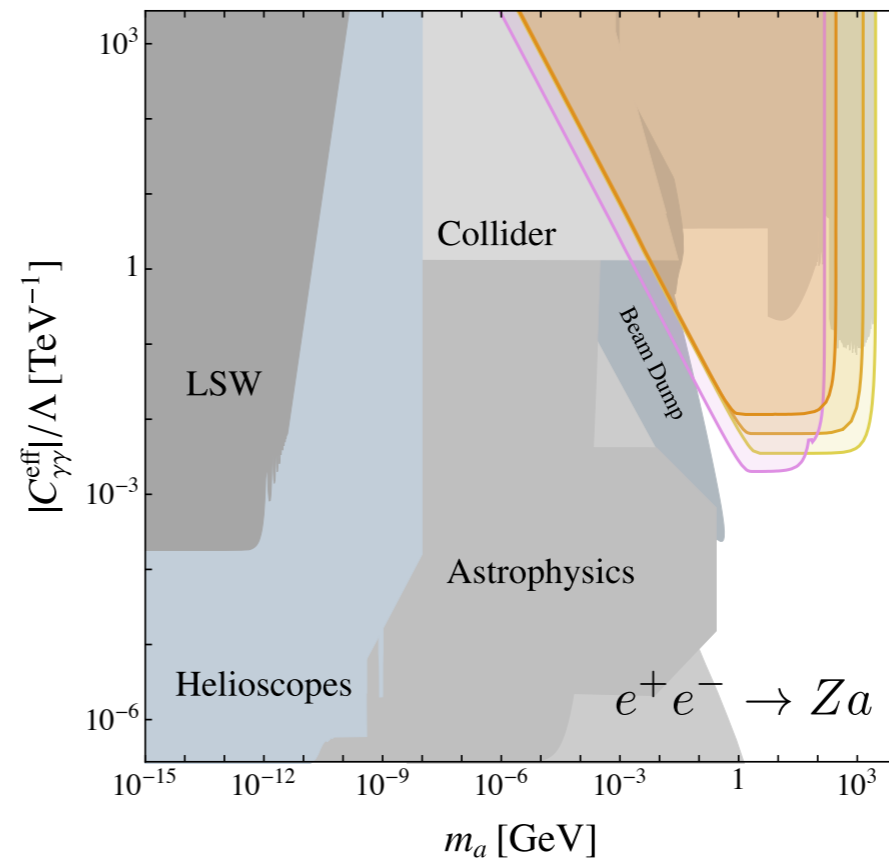
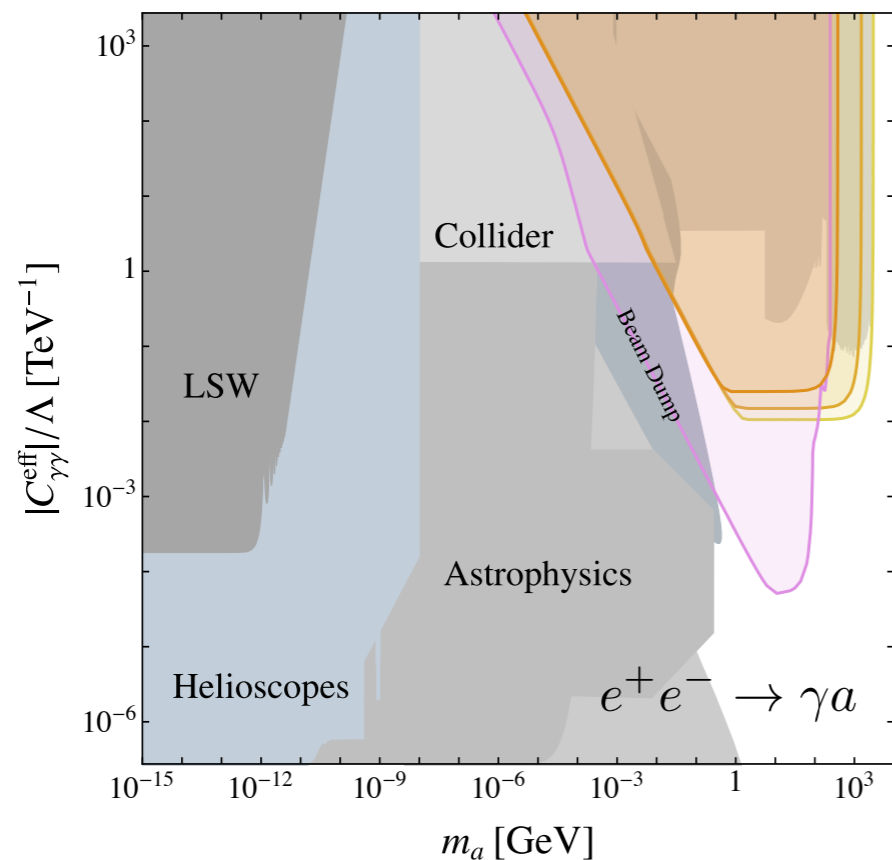
# Hadron colliders

- Current bounds on  $Z \rightarrow \gamma a$



# Future lepton colliders

- ALP associated production



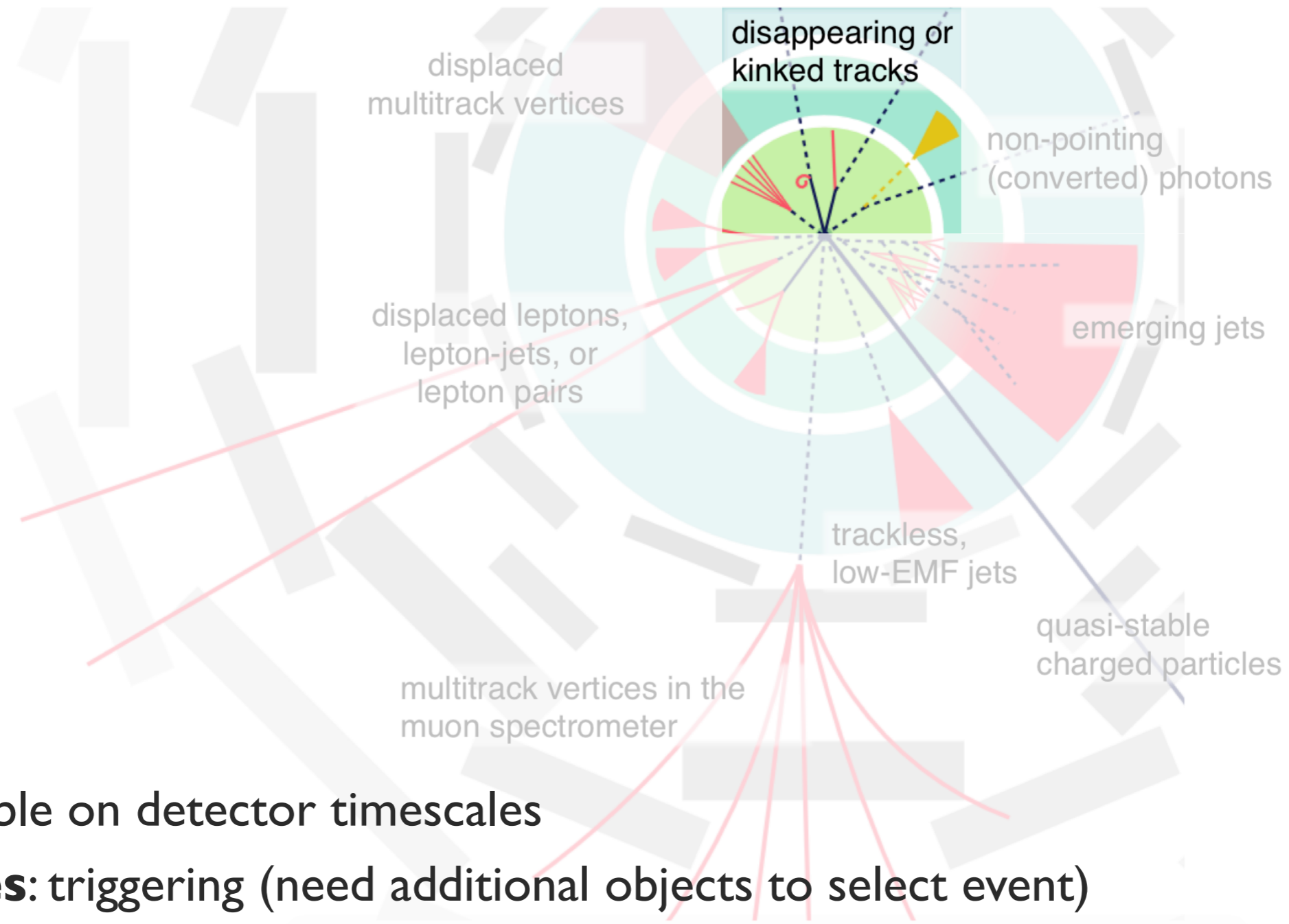
# Experimental signatures

- Longer lived particles become very rare signals in detector
- Background suppression and good trigger efficiency

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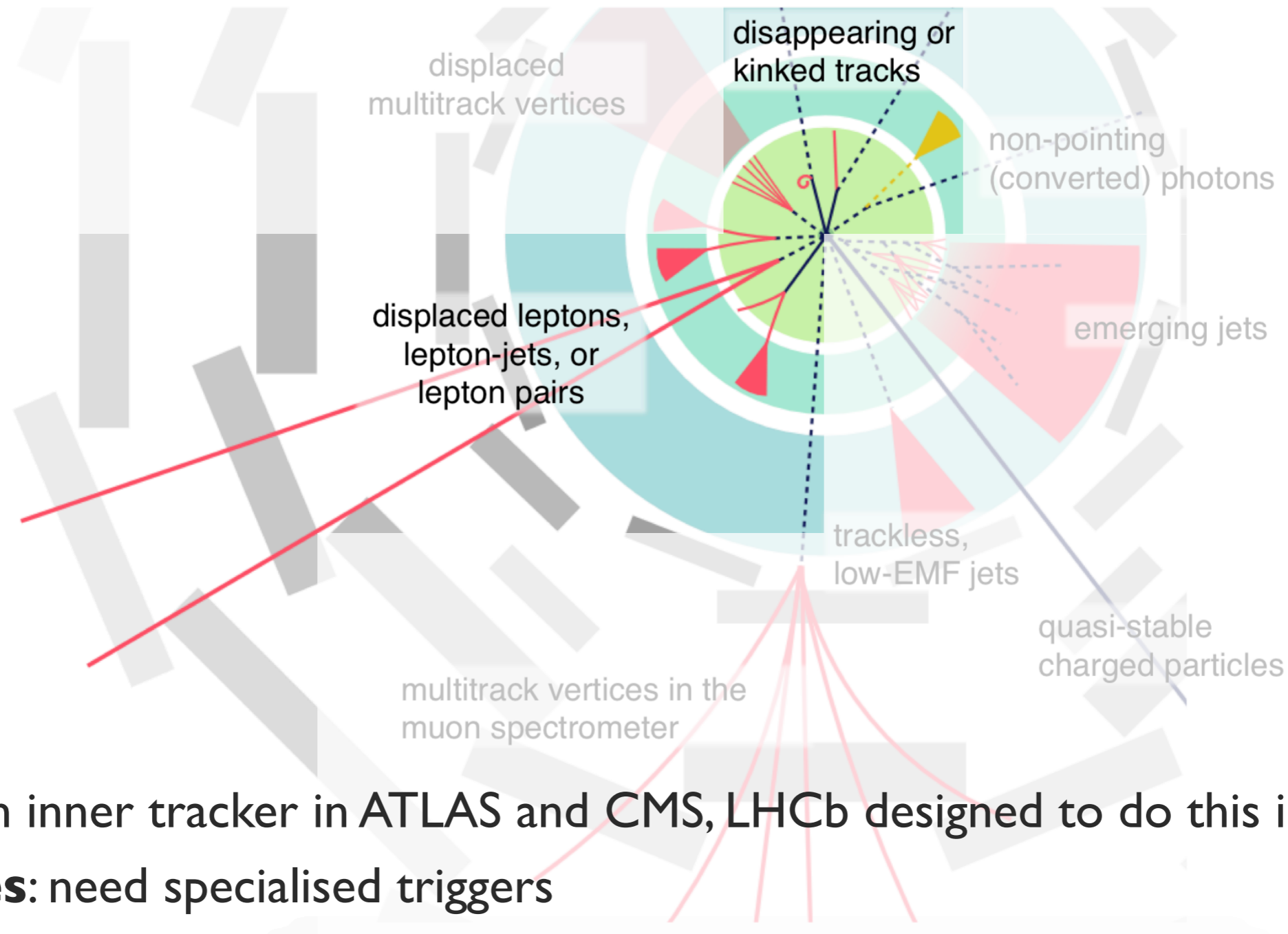
- Longer lived particles become very rare signals in detector
- Background suppression and good trigger efficiency
- Signatures in ATLAS and CMS
  - ★ Identification of displaced objects
  - ★ Non-standard tracks (e.g. disappearing tracks)
  - ★ Trackless signals (e.g. stopped particles)

# Experimental signatures



[Taken from Heather Russell: An experimental introduction to long-lived particle searches at the LHC]

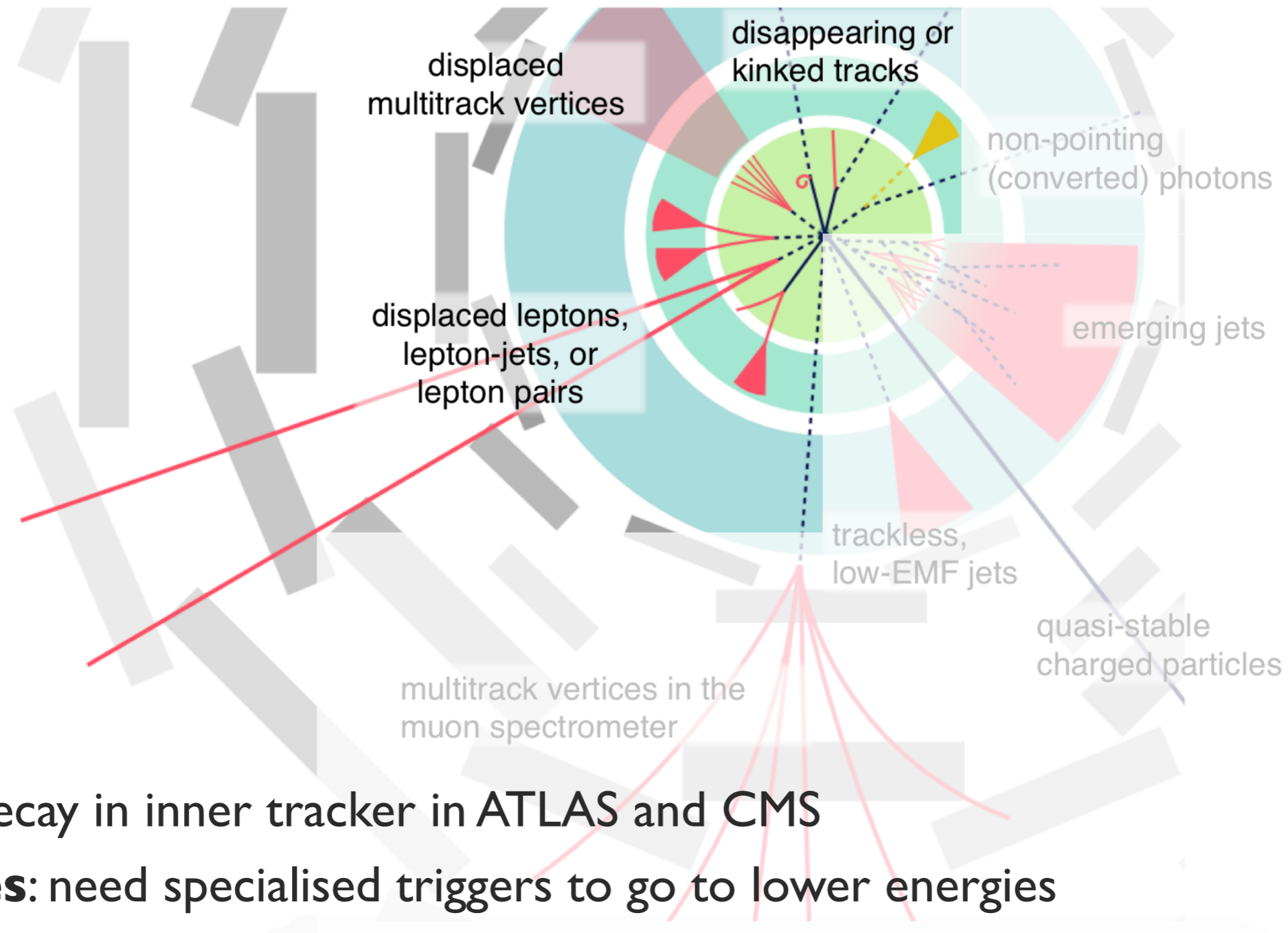
# Experimental signatures



Some hits in inner tracker in ATLAS and CMS, LHCb designed to do this in B decays  
**difficulties:** need specialised triggers

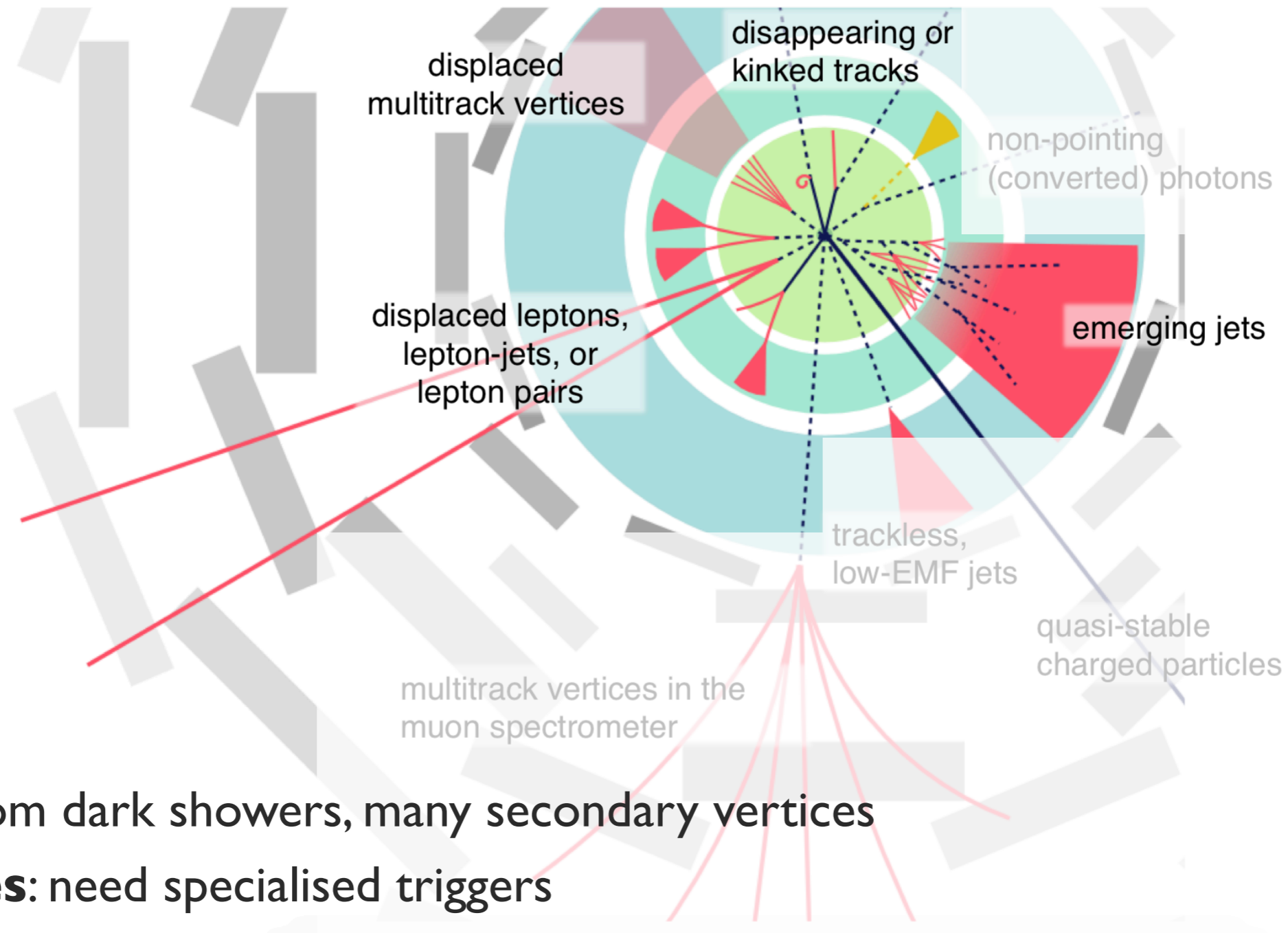
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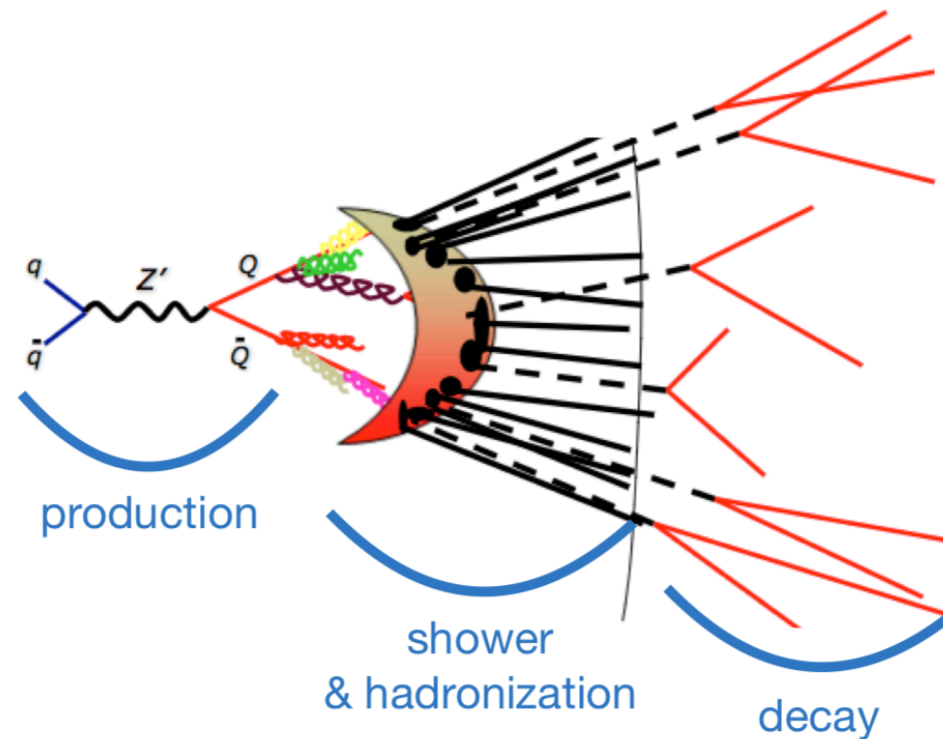
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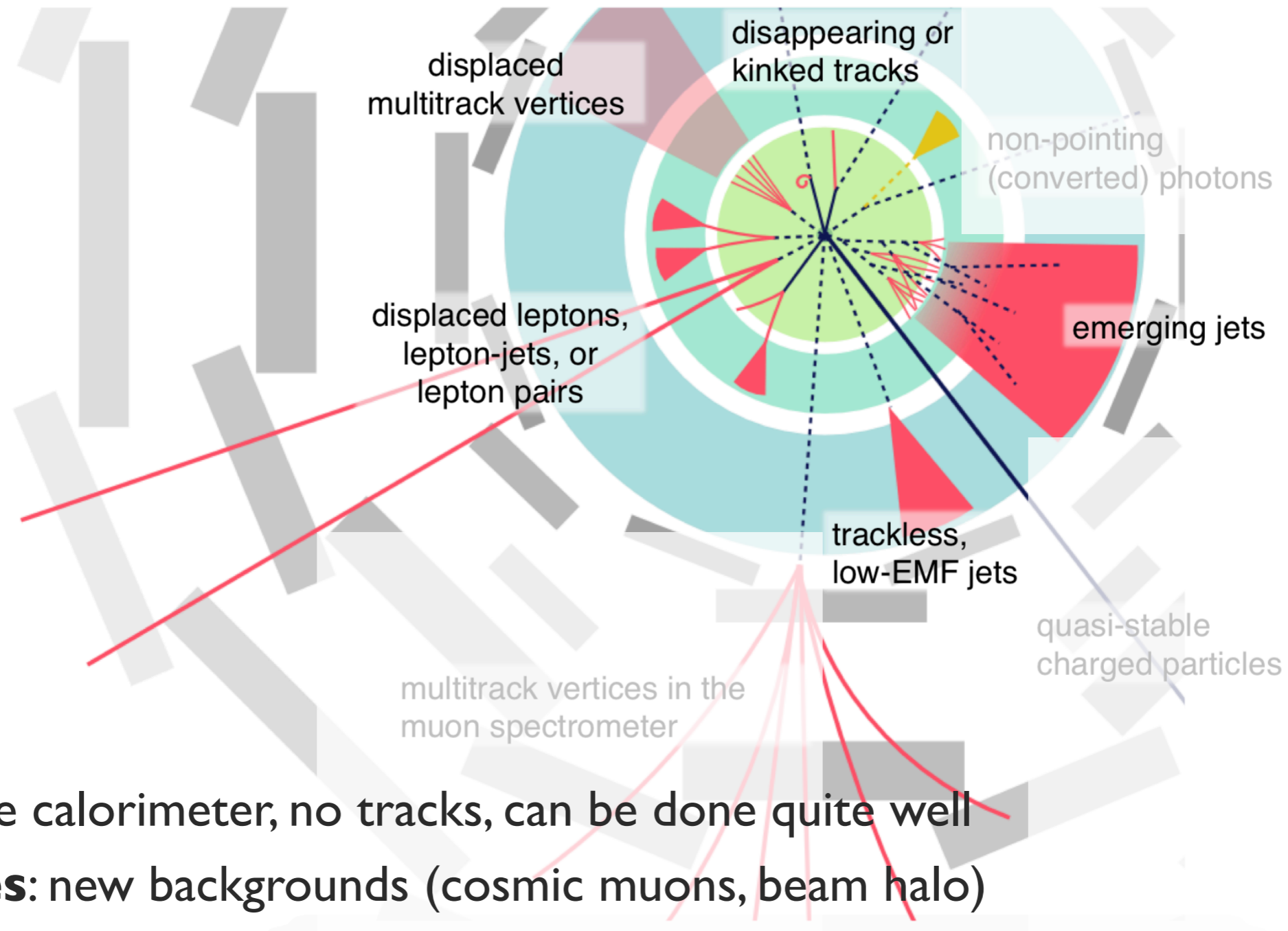
# Dark Showers



[Taken from 1903.04497]

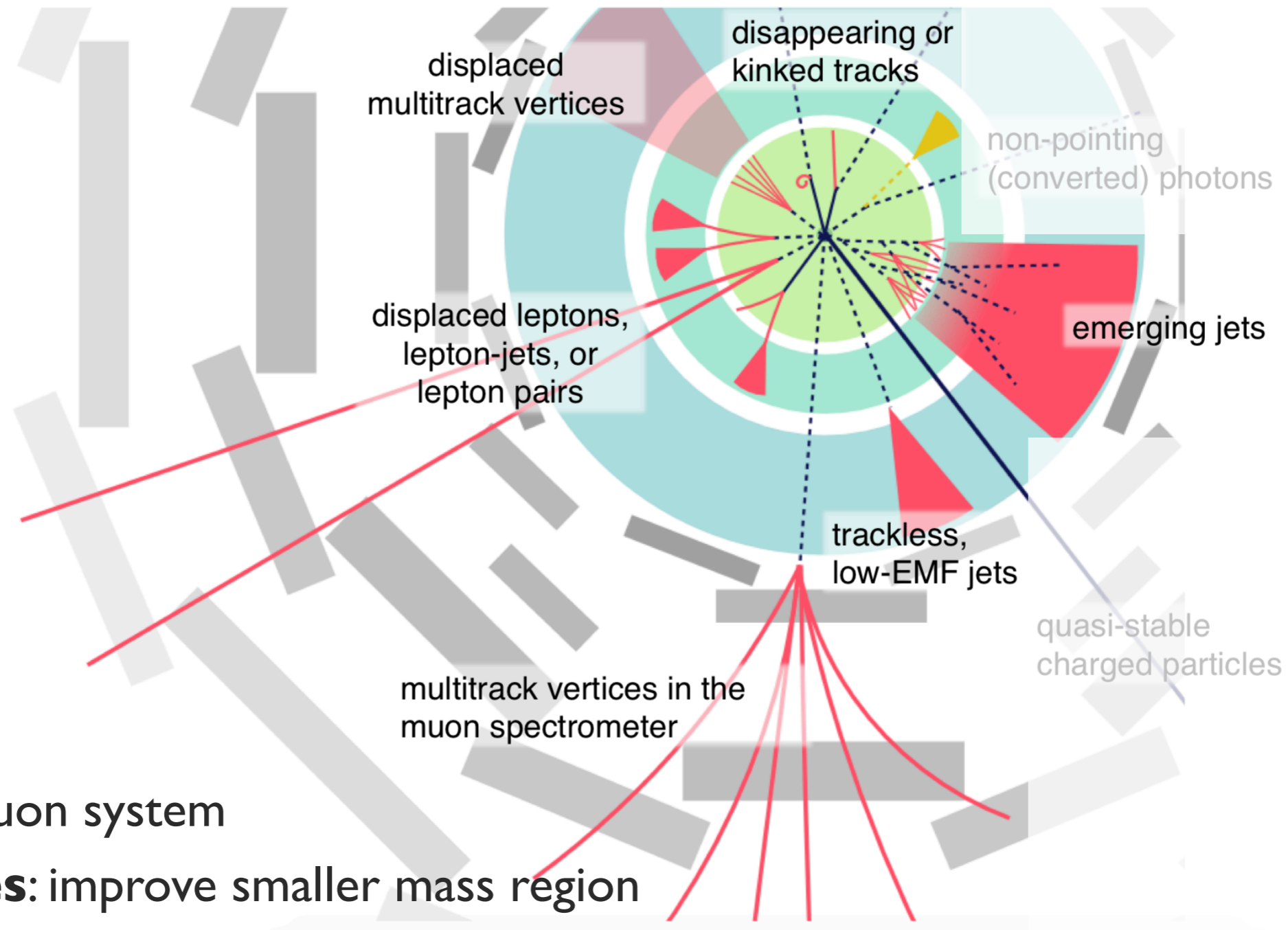
- Large amount of energy goes into a hidden sector
- High multiplicity of (soft and light) dark states
- Need triggers for soft and/or high multiplicity objects

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# Prospects

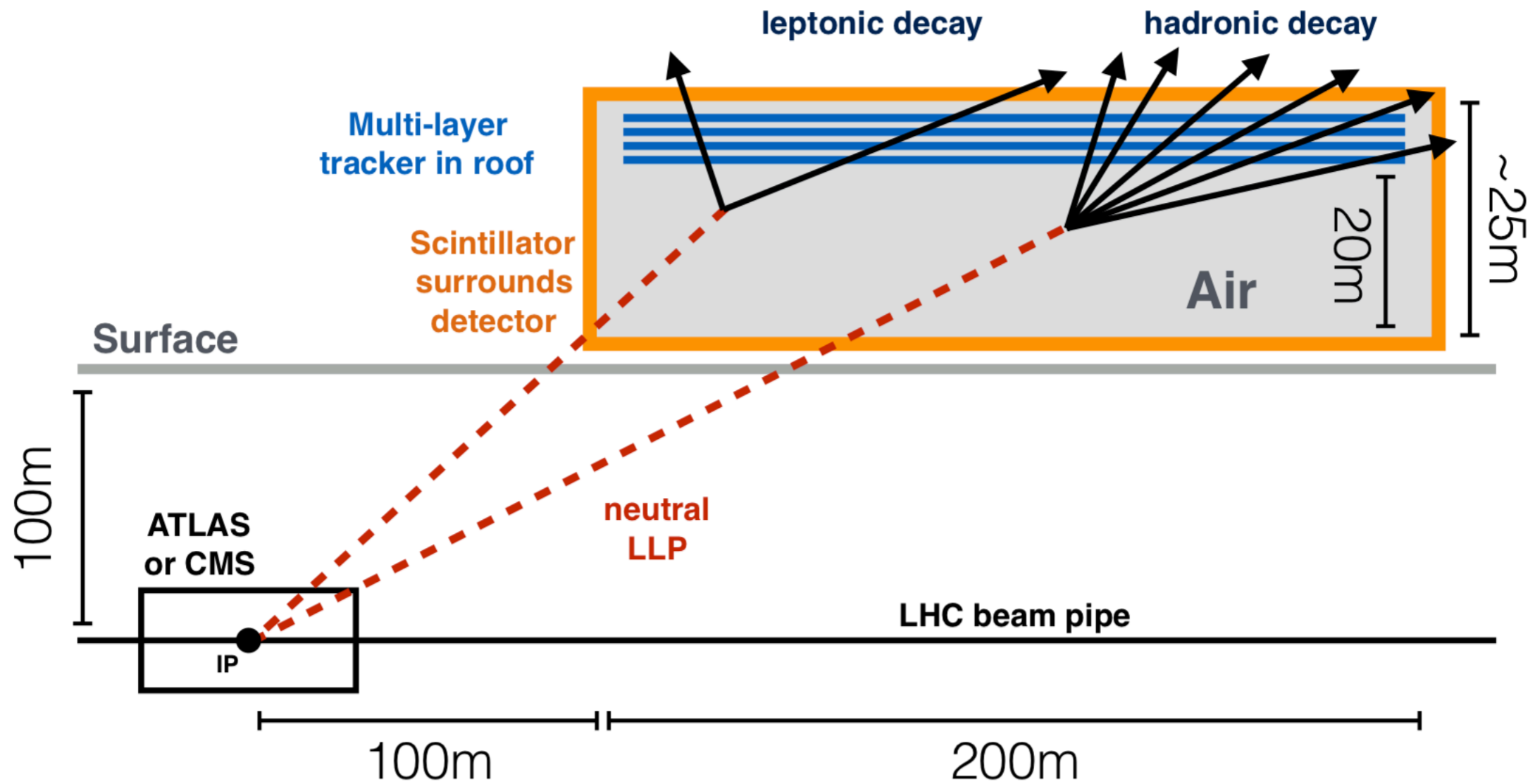
- Need searches in all subdetectors in a unified framework
- Currently a lot of work to establish simplified models
- Improvements in triggers, pileup, new signatures,...
- Might need new experiments...

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# Mathusla

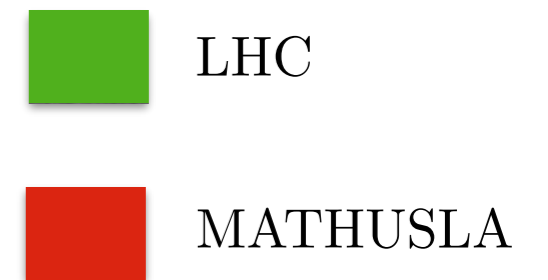
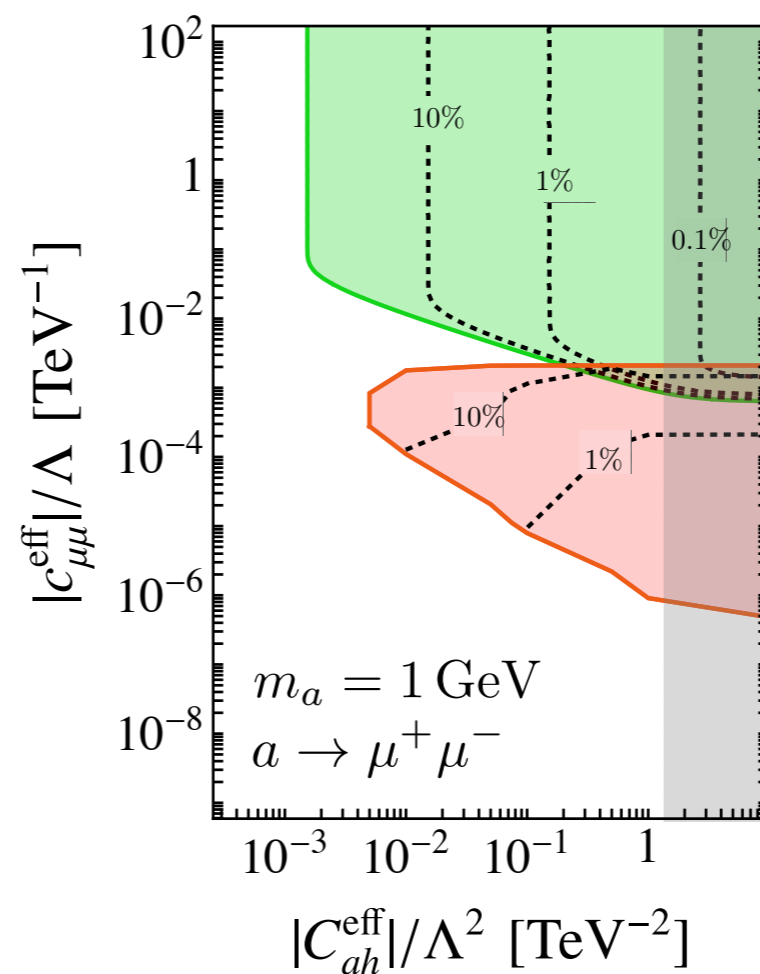
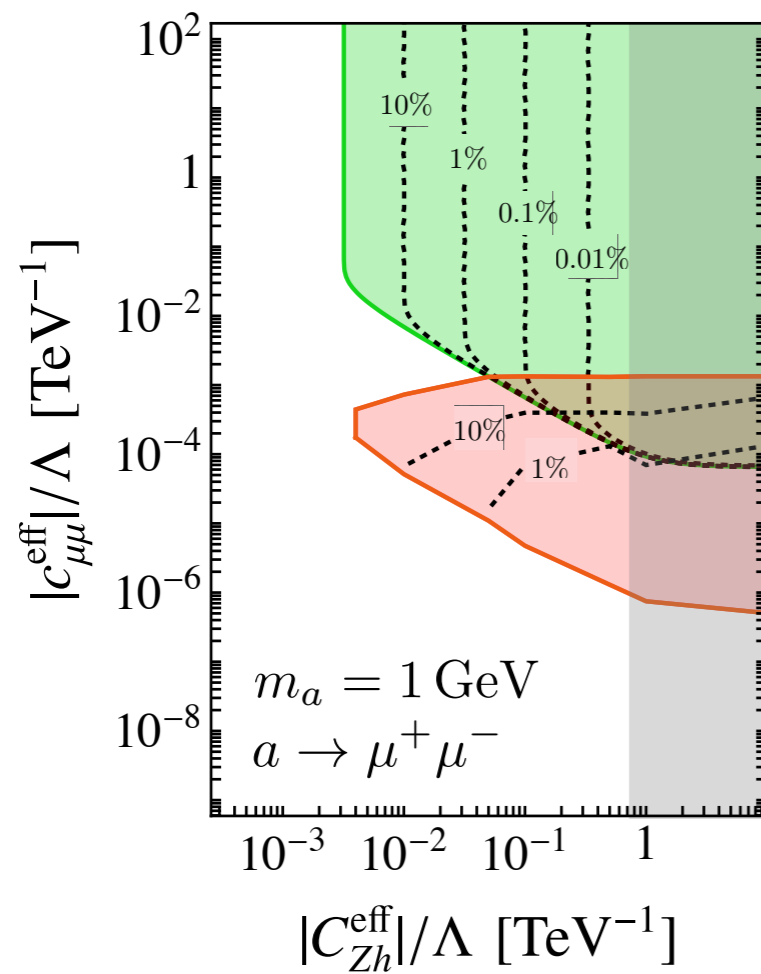
- Experimental setup



[Taken from 1806.07386]

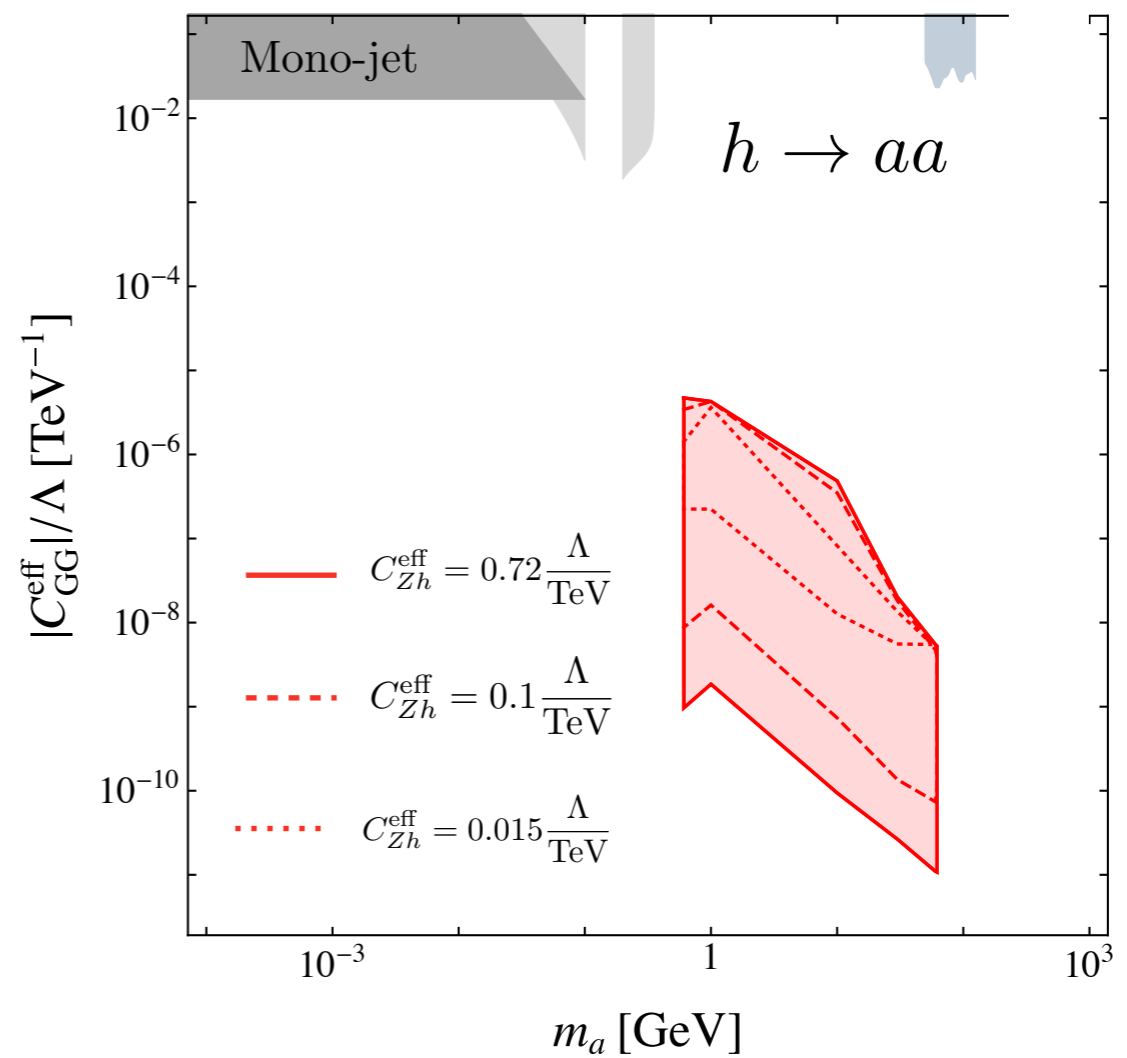
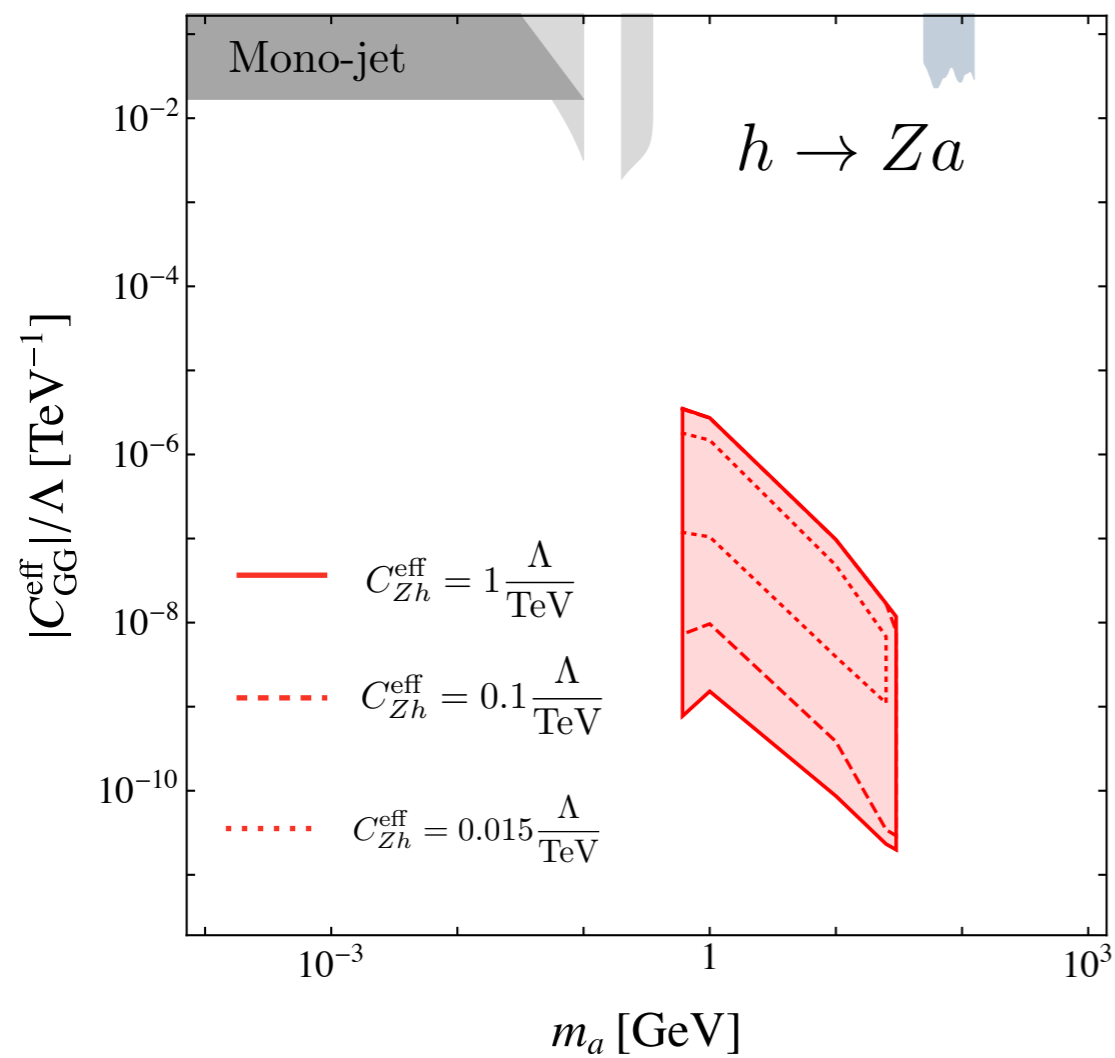
# Mathusla

- Exotic Higgs decays



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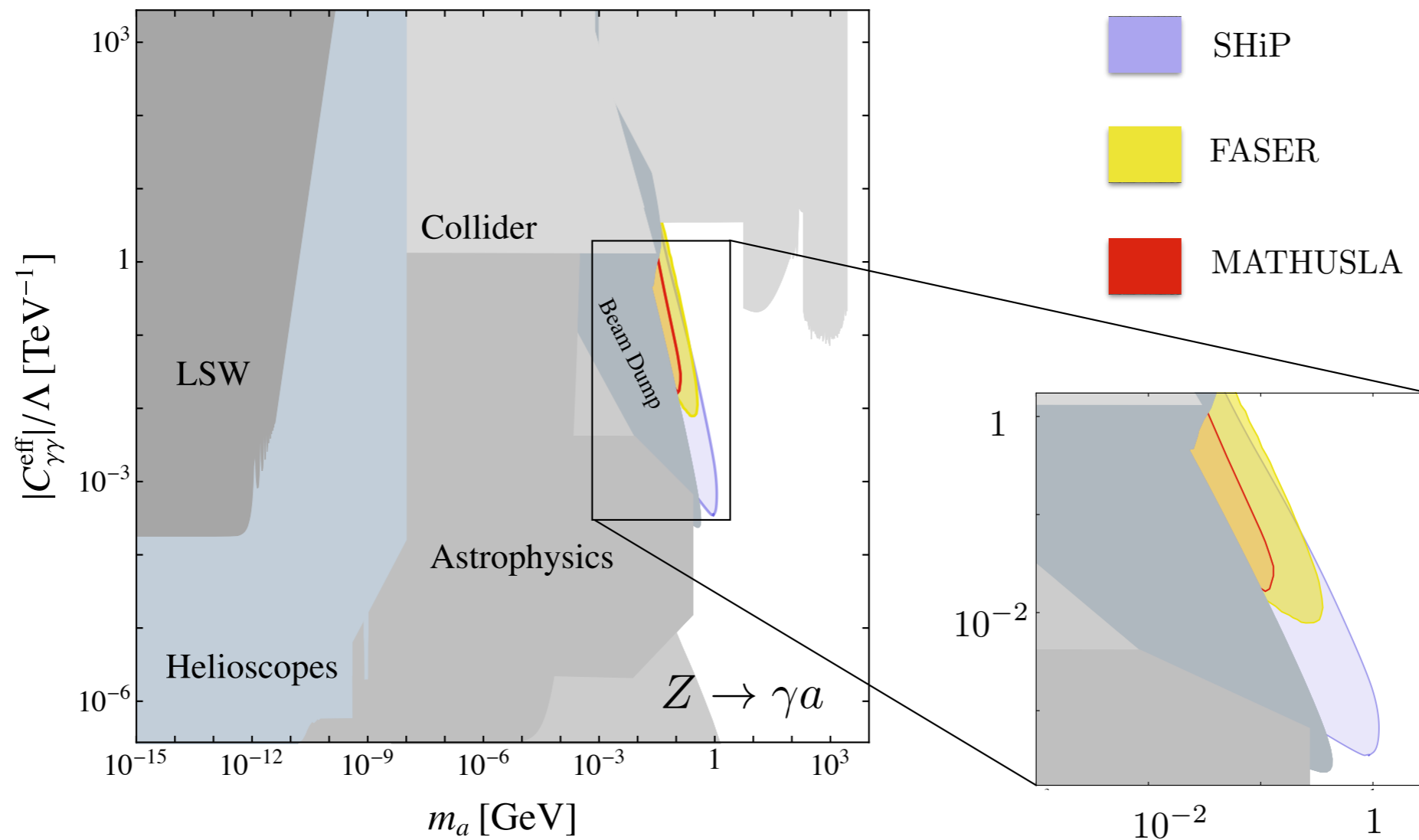
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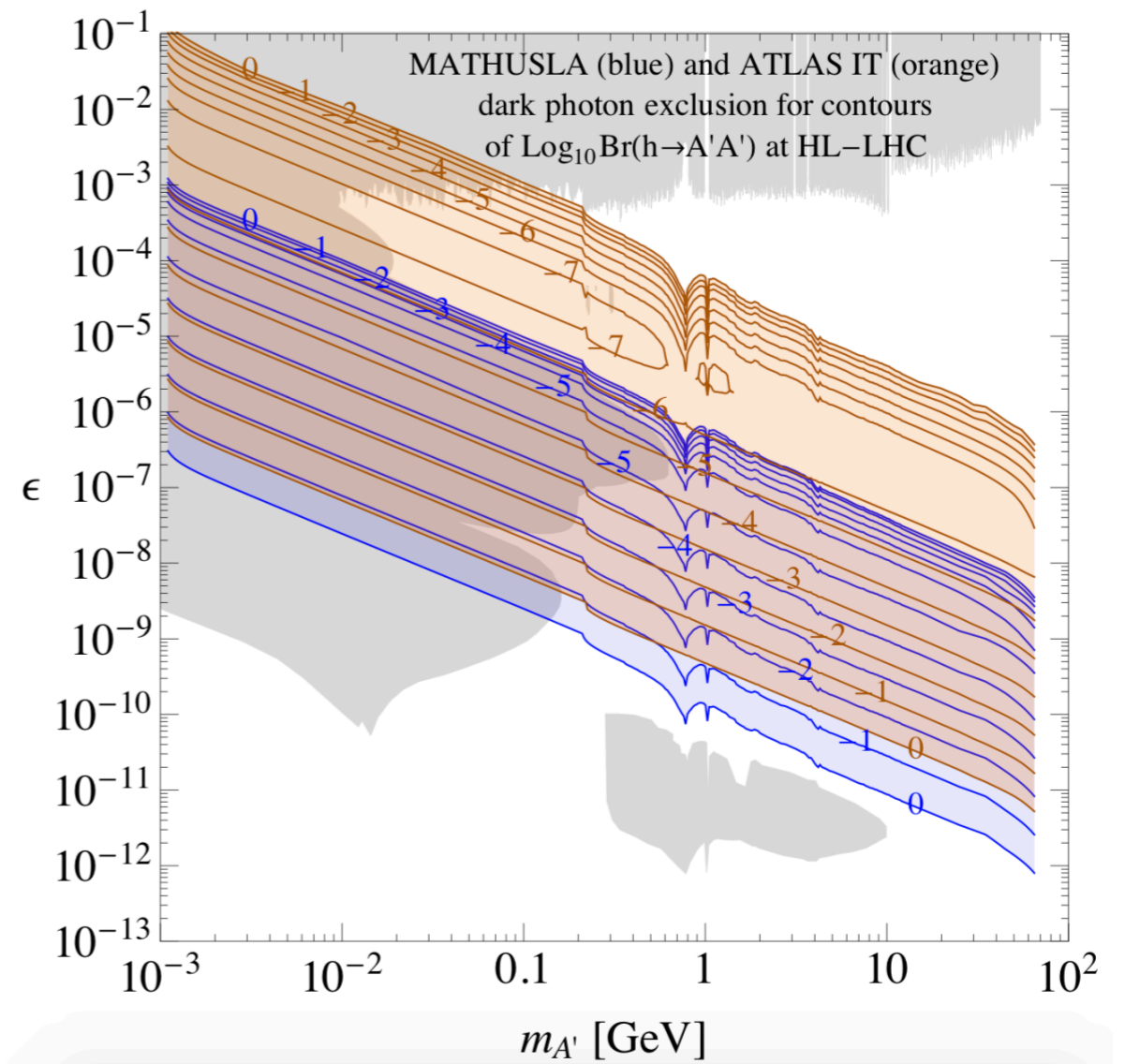
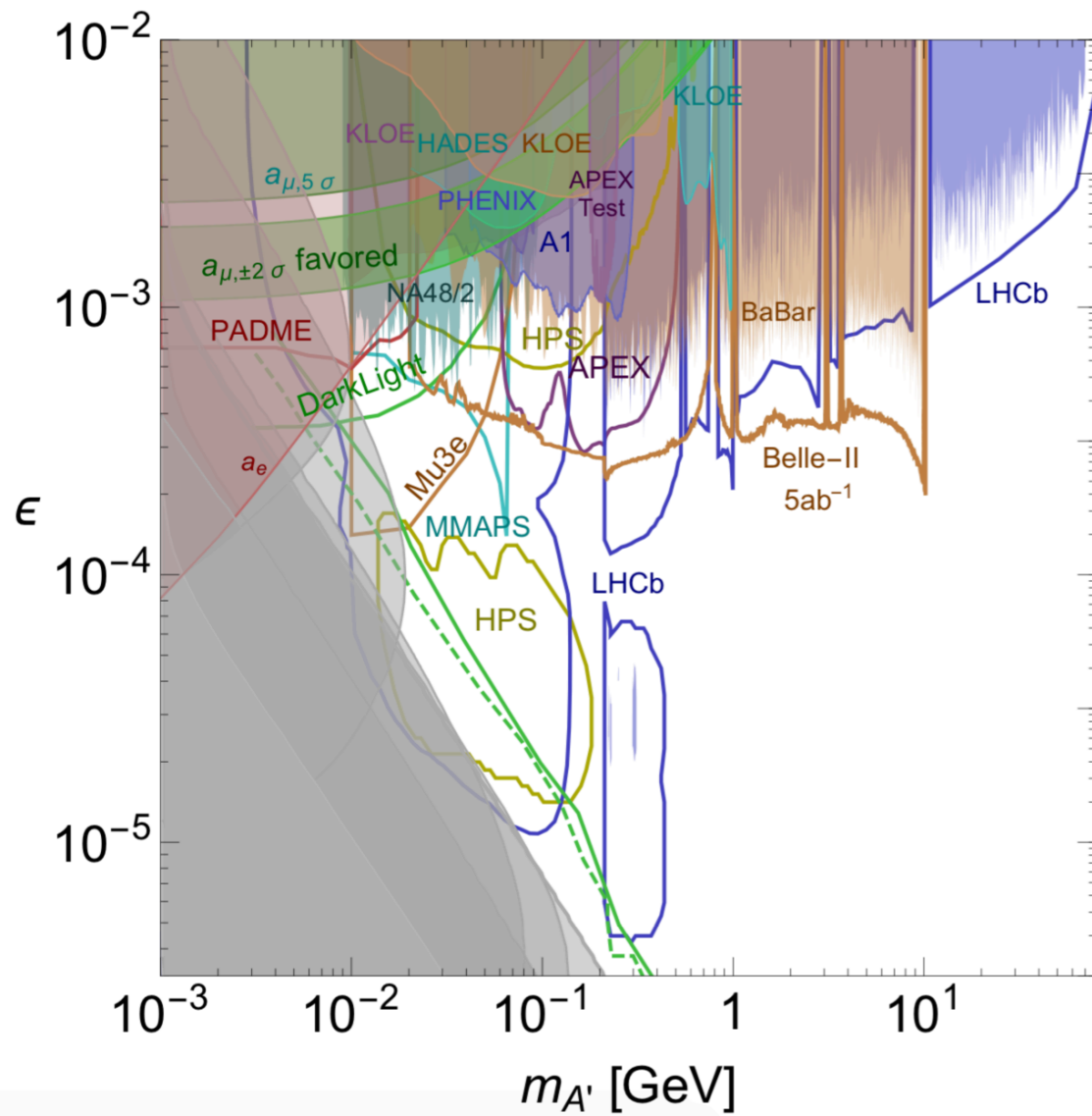
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- Recent progress in LLP theory and experiment
- Already some LHC searches
- Optimise LHC and future experiments for LLPs

# Conclusions

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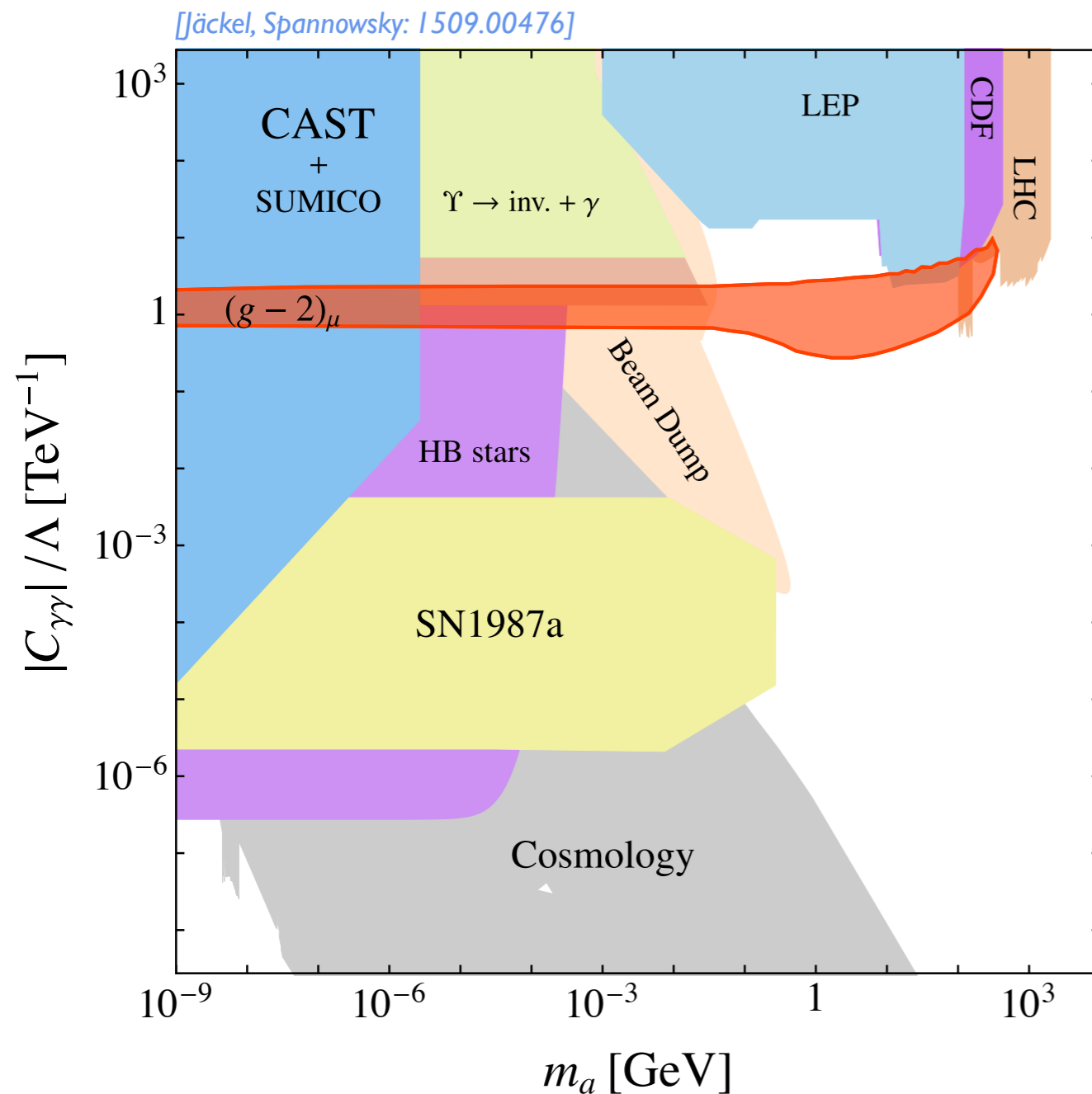
Thank you!

# Dark Photon



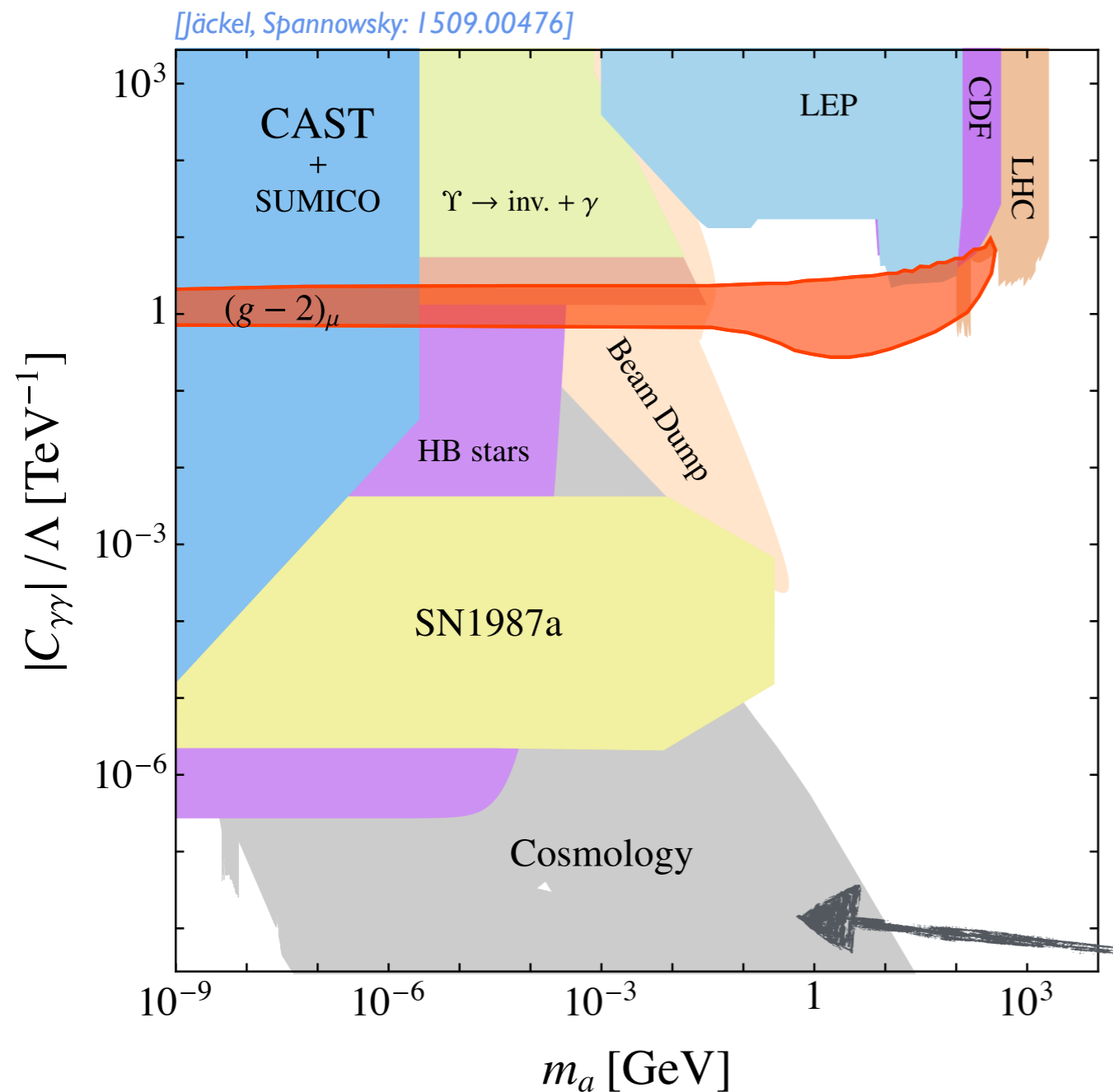
# Probing the parameter space

- Constraints on ALP mass and coupling to photons



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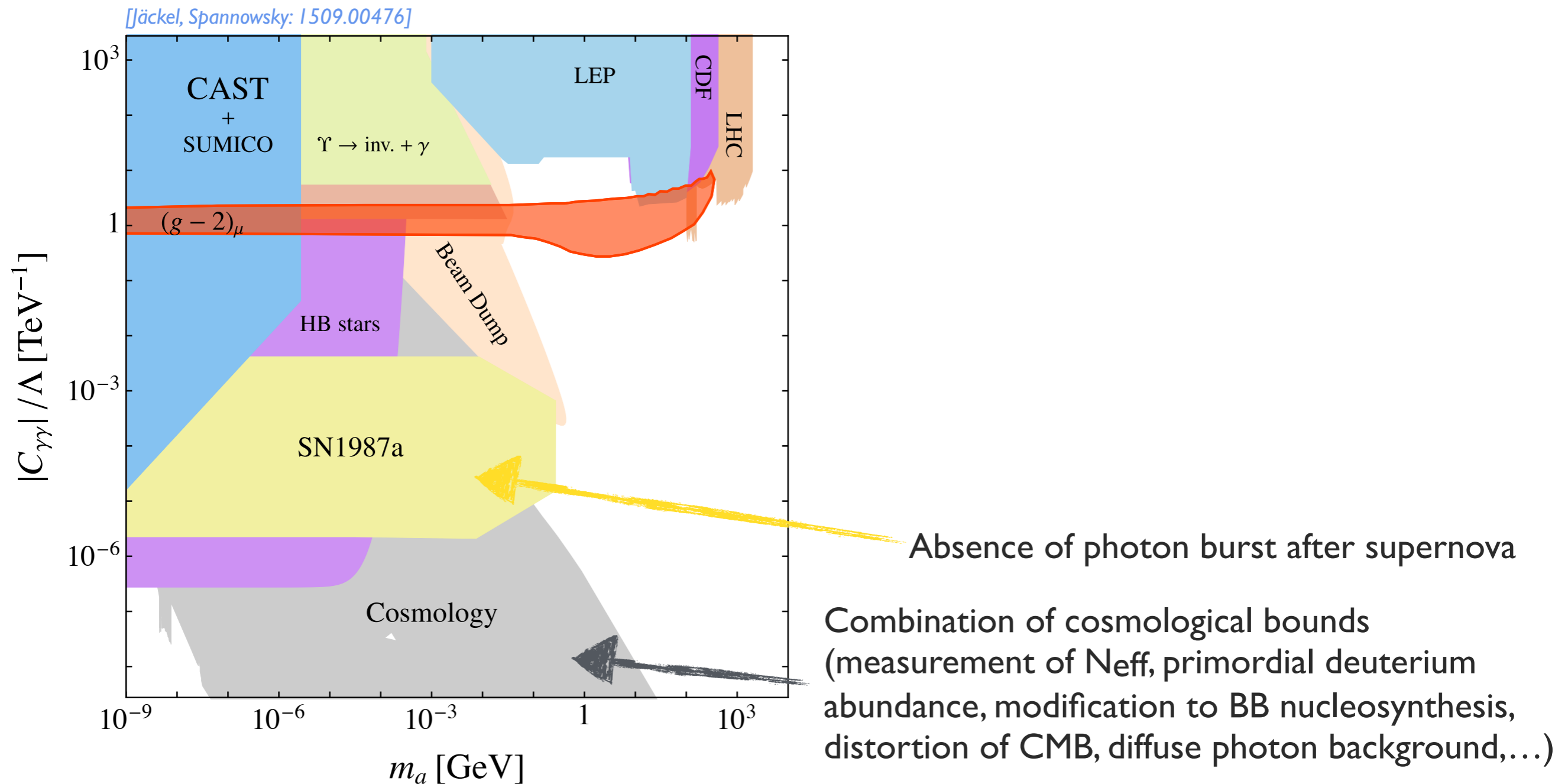
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Combination of cosmological bounds  
(measurement of  $N_{\text{eff}}$ , primordial deuterium abundance, modification to BB nucleosynthesis, distortion of CMB, diffuse photon background,...)

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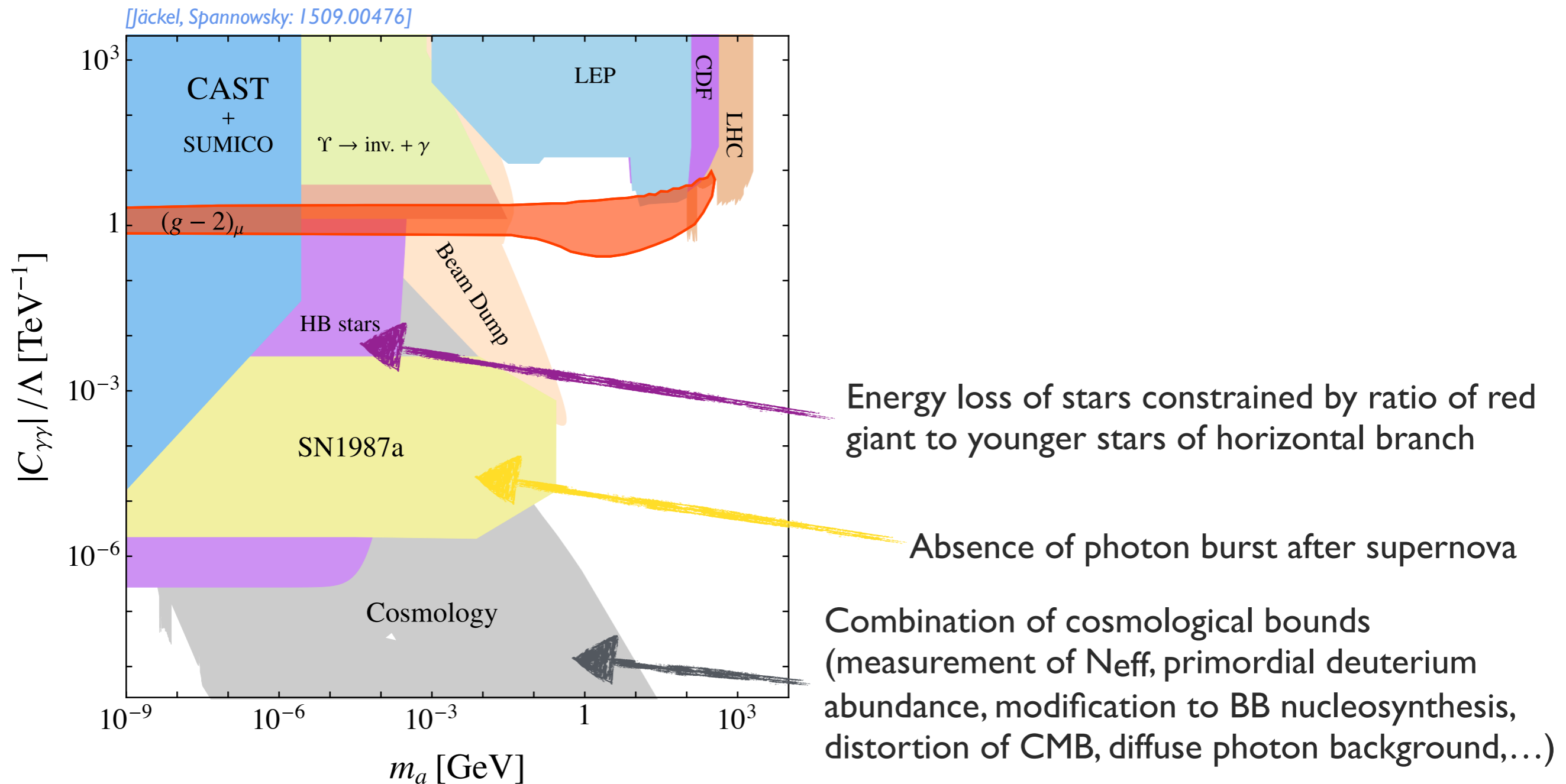
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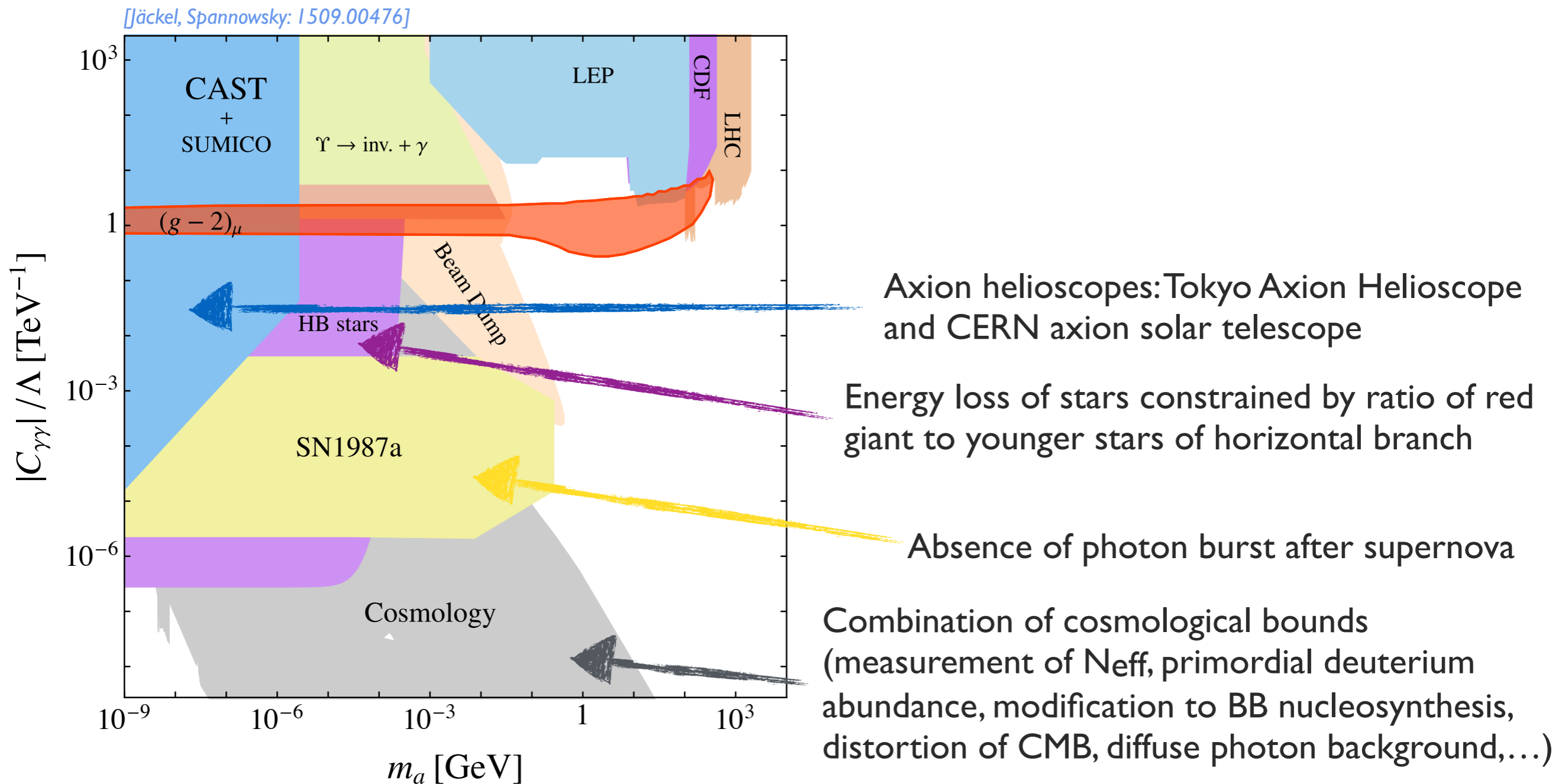
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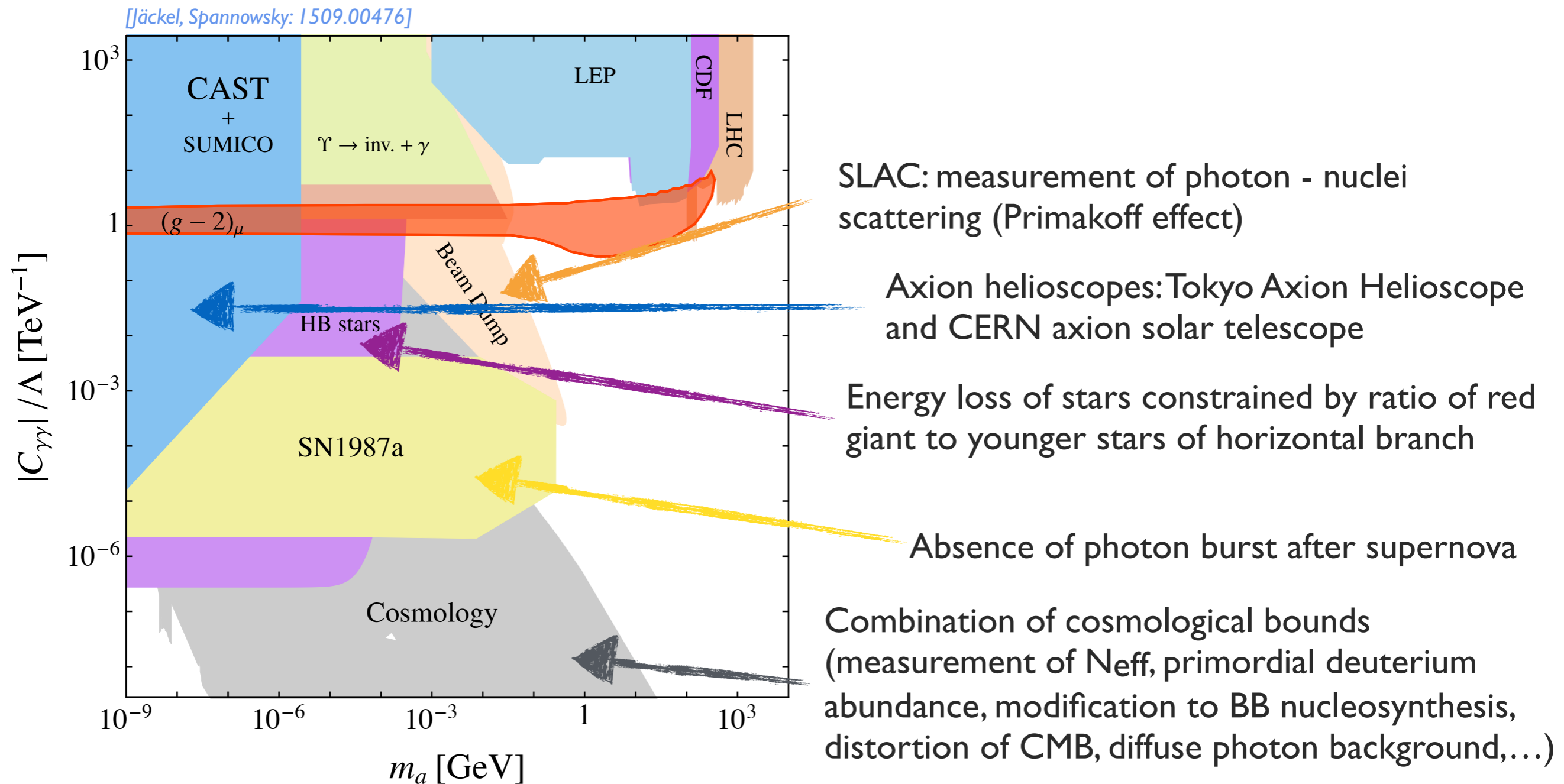
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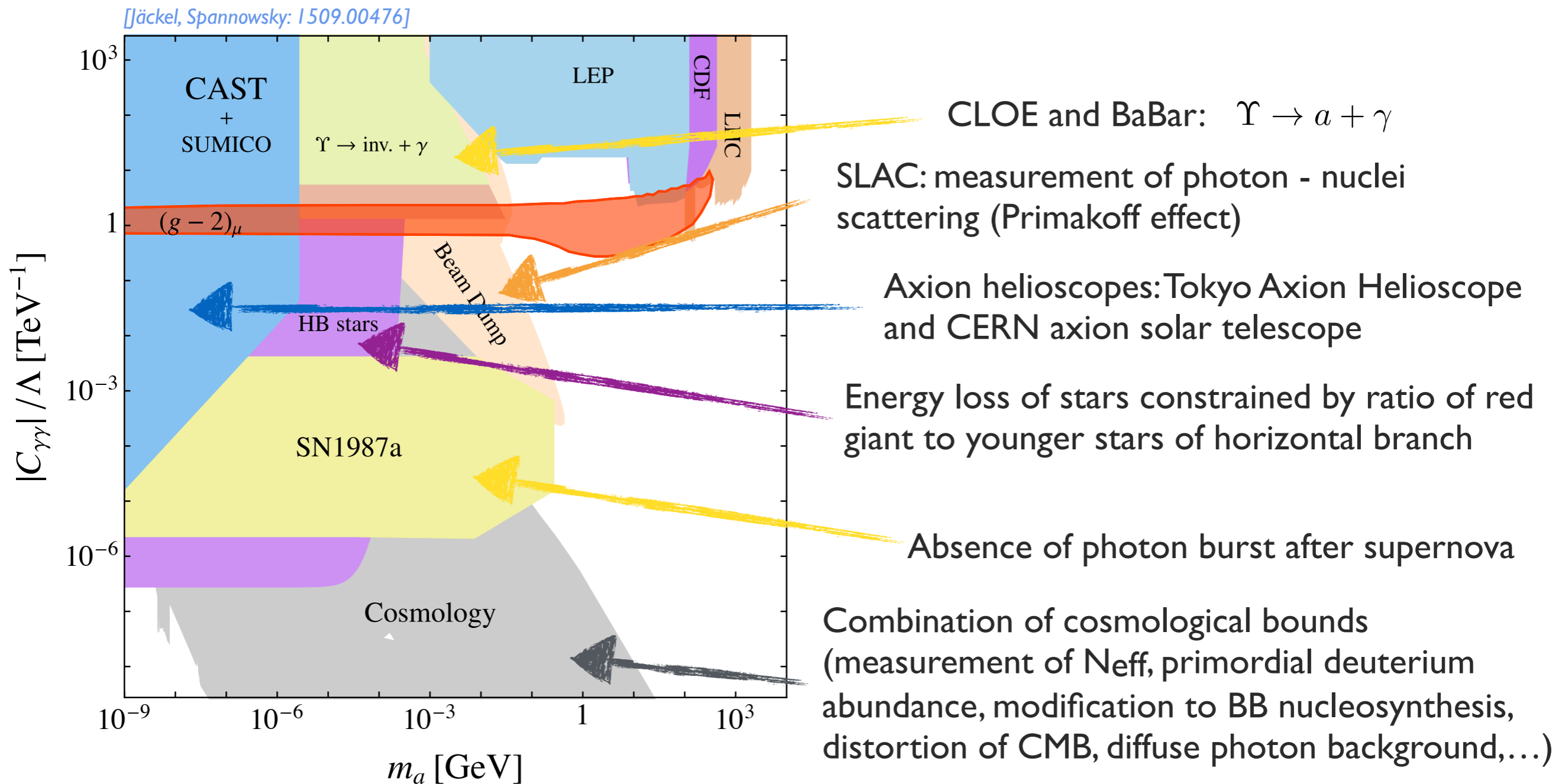
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