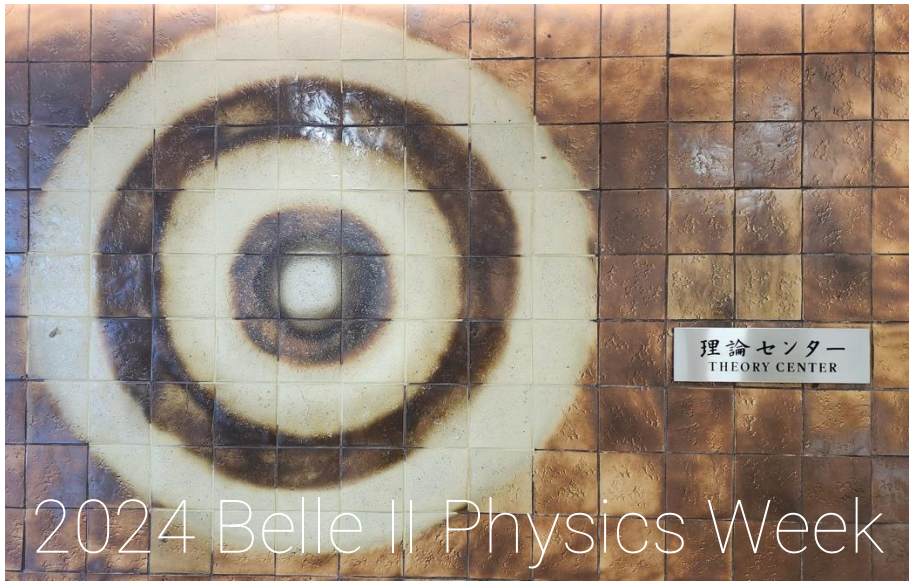
Dark Matter, Baryogenesis, & Naturalness @ Belle II

Robert McGehee

UNIVERSITY OF MINNESOTA



2024 Belle II Physics Week

What am I talking about?

New Signatures @ Belle II?

R McGehee

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→Nope. Cf Gilly's talk, including our "Mesogenesis" papers

[G. Elor, RM PRD 2021]

[F. Elahi, G. Elor, RM PRD 2022]

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Models Discoverable @ Belle II!

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Dark Matter Baryogenesis Naturalness

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[P. Bittar, S. Koren, RM WIP]

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The theory motivation for the BSM searches at Belle II is robust.

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Strongly interacting massive particles through the axion portal

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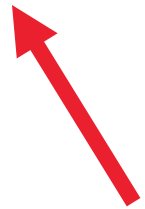


Complementary model to Stefania's! message = SIMPs are cool for Belle II !!!

Strongly Interacting Massive Particles (SIMPs)

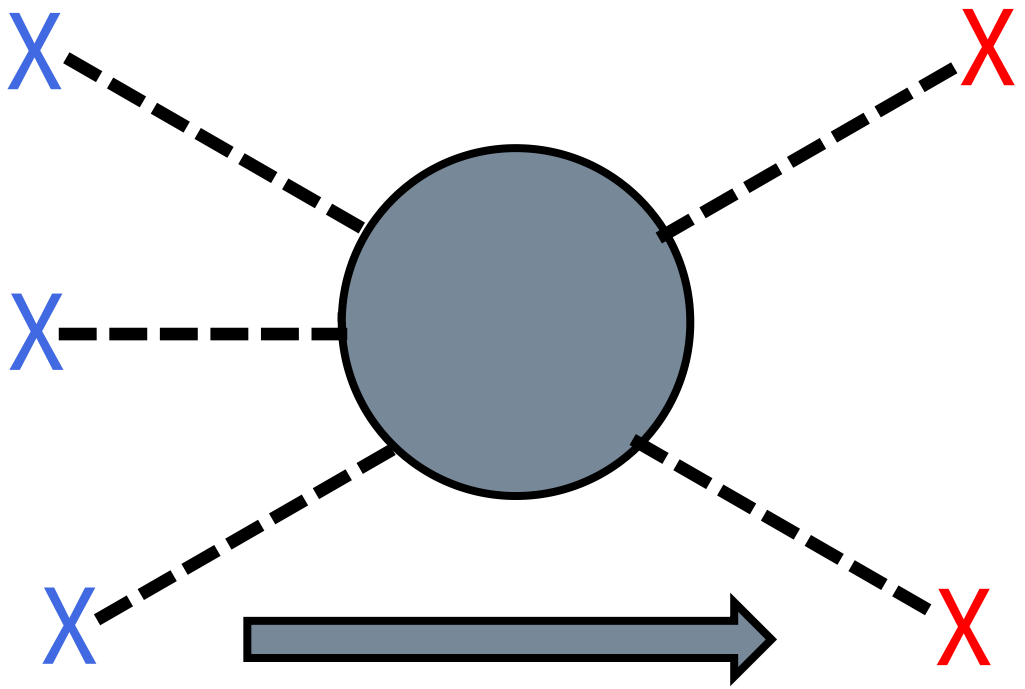
[Y. Hochberg et al. PRL 2014]

Relic density set by 3→2

Equilibrium with SM

Strong self interactions

MeV to GeV masses



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The SIMPlest Miracle

[Y. Hochberg et al. PRL 2015]

Sp(N_c) gauge theory

2 N_f Weyl fermions

Chiral symmetry breaking

Wess-Zumino-Witten (WZW)

$$\mathcal{L}_{\mathrm{WZW}} = \frac{8N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\epsilon_{abcde}\pi^a\partial_\mu\pi^b\partial_\nu\pi^c\partial_\rho\pi^d\partial_\sigma\pi^e$$

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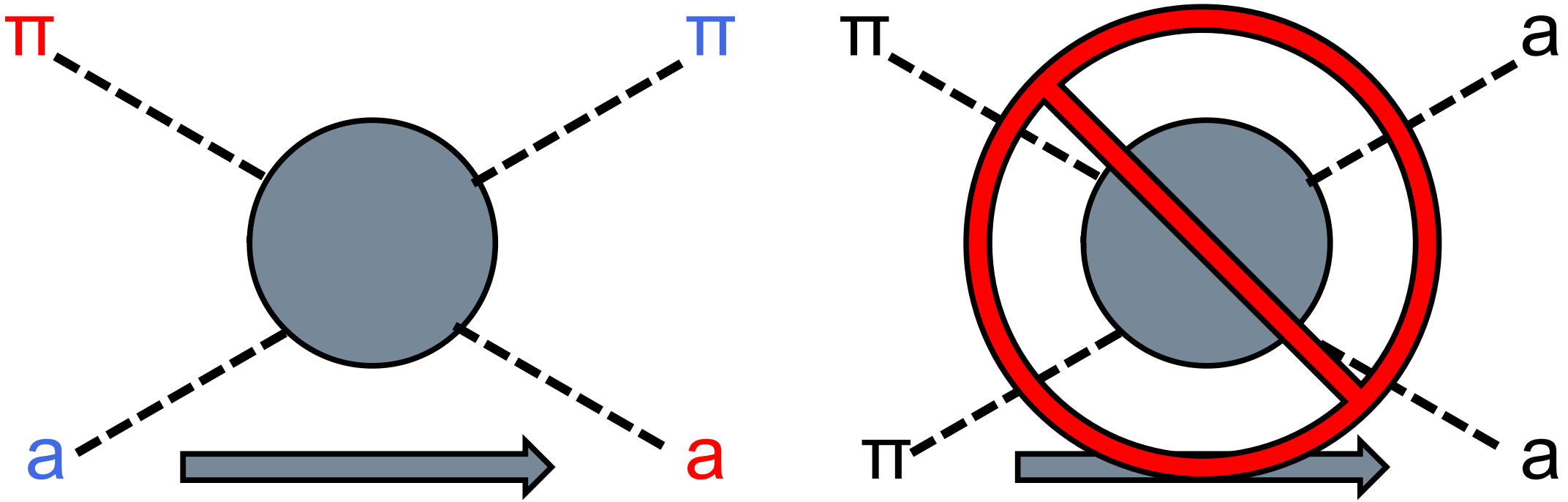
SIMP-Axion Coupling

$$\mathcal{L}_{aq} = -\tfrac{1}{2} m_Q e^{ia/f_{a\pi}} J^{ij} q_i q_j + \text{h.c.} \xrightarrow{\text{Chiral SB}} \mathcal{L}_{aq} = \frac{m_\pi^2}{4 f_{a\pi}^2} a^2 \pi^2 + \cdots$$



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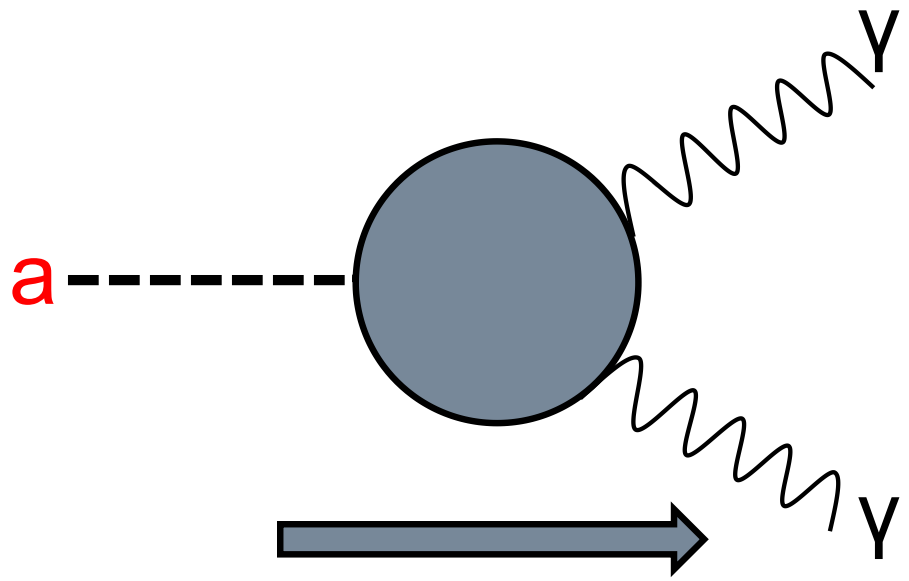
Axion-Photon Coupling

$$\mathcal{L}_{a\gamma} = \frac{1}{4 f_{a\gamma}} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$



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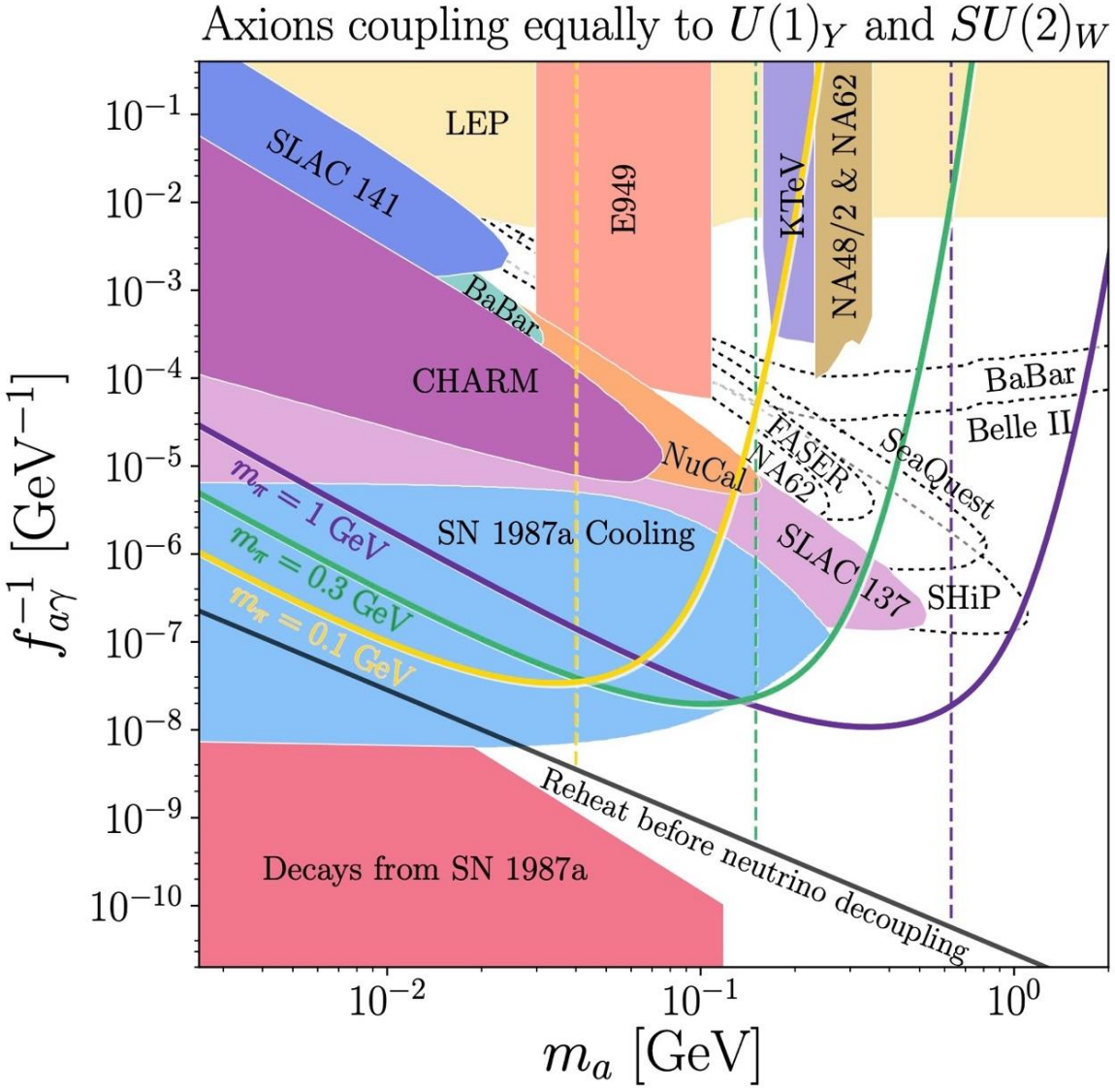
Viable Axion-Photon Parameter Space



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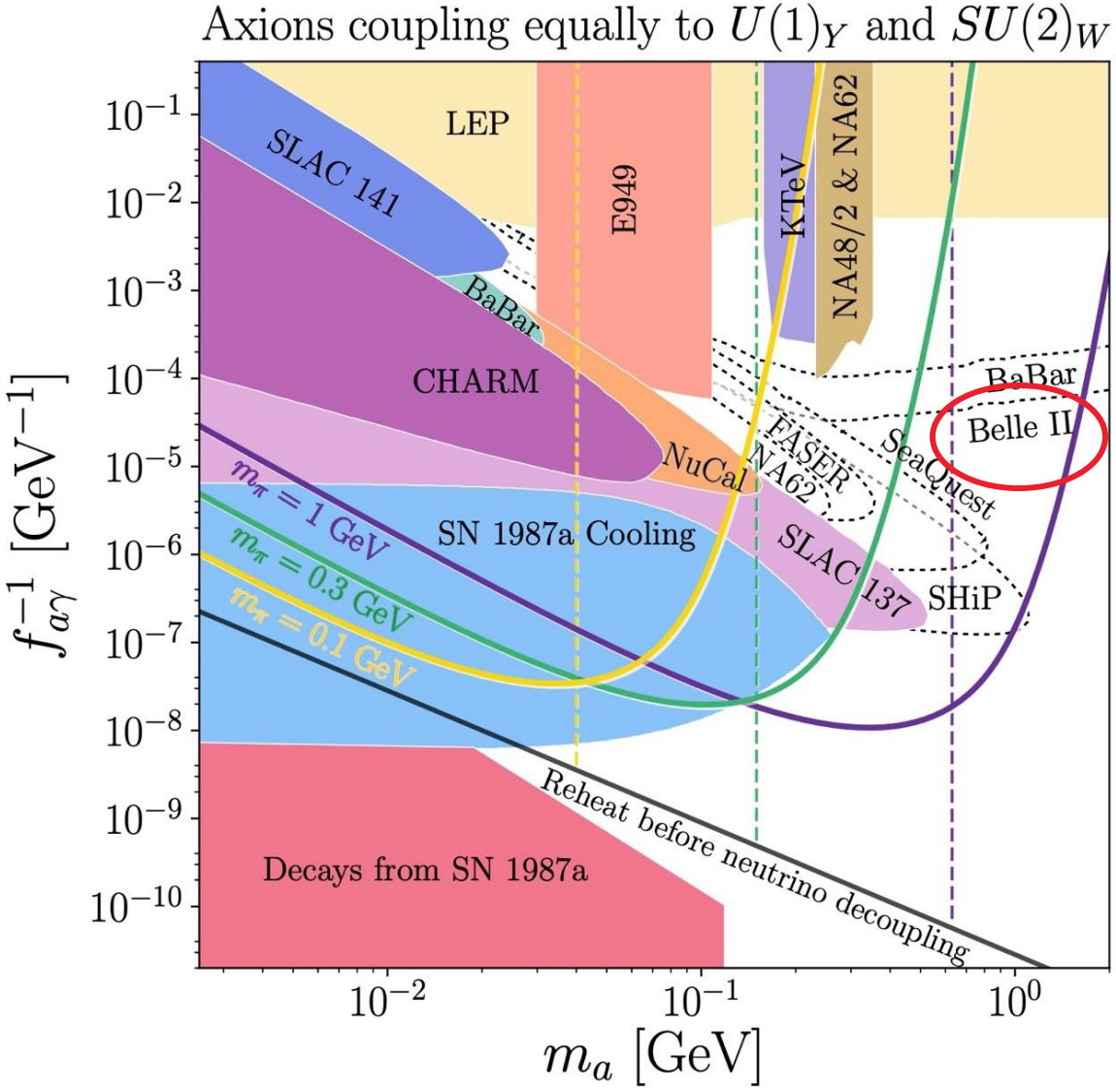

Belle II will hopefully probe the majority of the viable parameter space!

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Asymmetric matter from a dark first-order phase transition

[E. Hall, T. Konstandin, RM, H. Murayama, PRD 2023]

Baryogenesis & Asymmetric DM

Ω_b requires explanation

$\Omega_c \approx 5\Omega_b$ suggests DM may also be asymmetric

Common origin?

ADM + SM gauge copy →

Mirror world models

See e.g. hep-ph/0312335, astro-ph/0407623, 1805.06876, 1811.10232, 1907.03404

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$$SU(3)' \times SU(2)' \times U(1)'$$

$$\Phi_1, \Phi_2$$

$$Q', u'_R, d'_R$$

$$L', e'_R, N'_R \longleftarrow Y_e \text{ large}$$

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Dark-Sector Baryogenesis

1. SFOPT + CP-violating potential + sphalerons in DS
2. 2 Higgs doublets, EW-like baryogenesis in DS → B'+L'

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2. 2 Higgs doublets, EW-like baryogenesis in DS → B'+L'
3. Dark leptons in equilibrium via neutrino portal
4. SM sphalerons then generate some B
5. Symmetric part of dark hadrons annihilate to dark photons, which transfer excess entropy to SM
6. Remaining B' forms (part of) ADM

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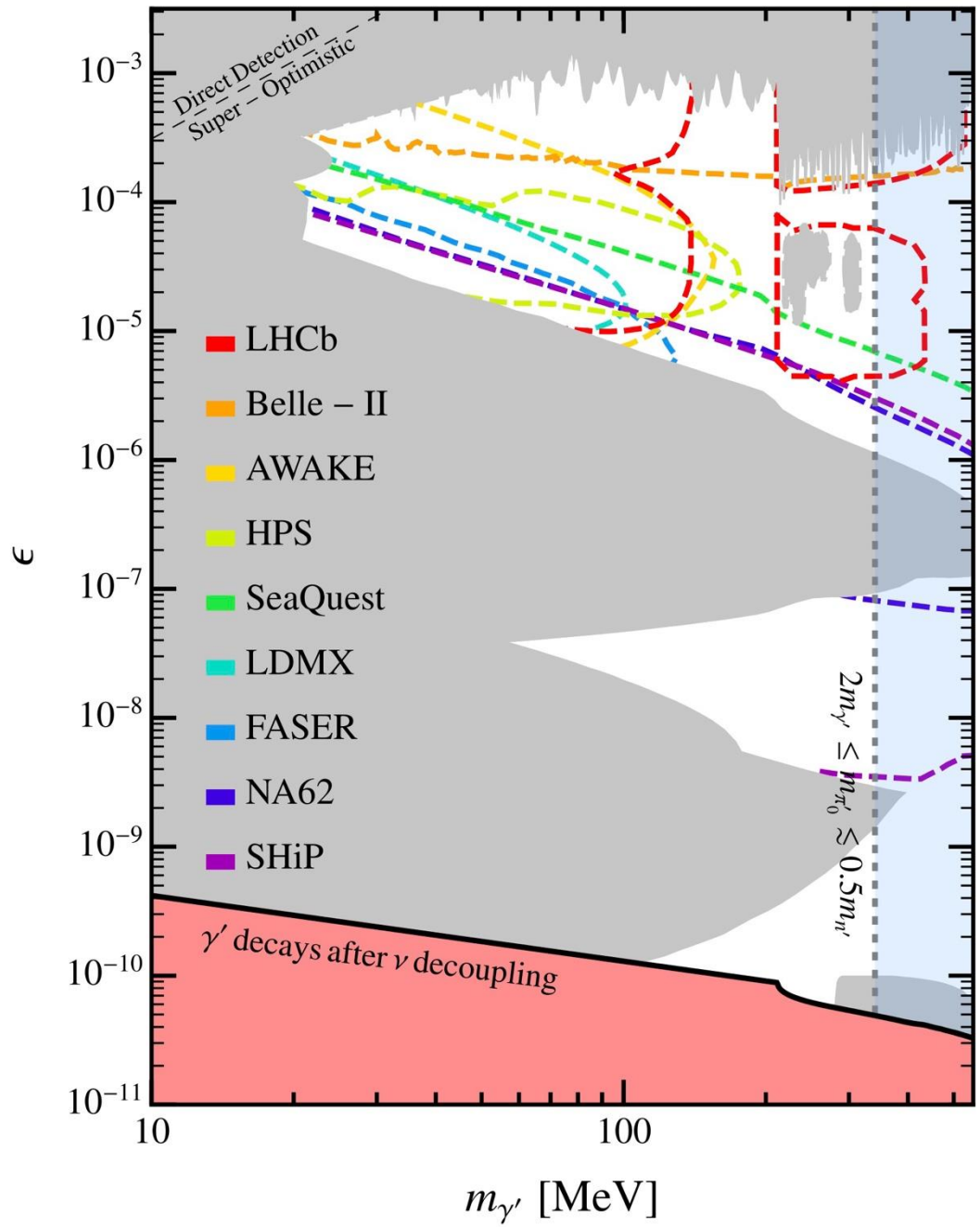
Dark Neutron Dark Matter



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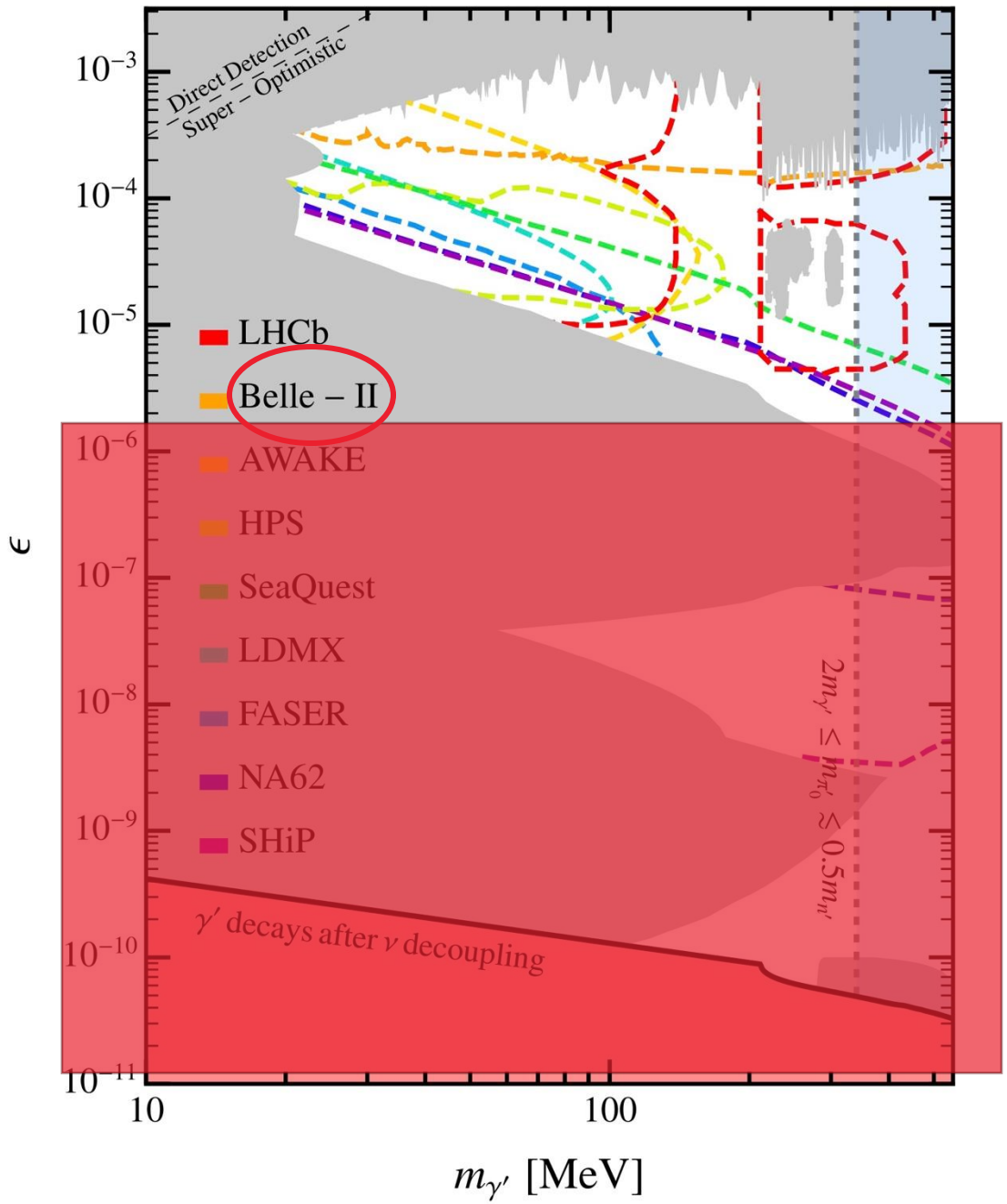

Theory bias: kinetic mixing generated @ 1 loop

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A predictive mirror twin Higgs with small Z2 breaking

[K. Harigaya, RM, H. Murayama, K. Schutz JHEP 2020]

Mirror Twin Higgs

[Z. Chacko, H.-S. Goh, R. Harnik PRL 2006]

$\mathbf{Z_2}$ mirror copy of SM introduced (twin sector)

SU(4) global symmetry permits SM Higgs to be PNGB

$\mathbf{Z_2}$ protects Higgs mass up to ~ 5-10 TeV cutoff

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The $N_{\rm eff}$ Problem

$$\rho_r = \left(1 + \tfrac{7}{8}\left(\tfrac{4}{11}\right)^{4/3} N_{\rm eff}\right)\rho_\gamma$$

$$N_{\rm eff}^{\rm SM} = 3.046$$

$$N_{\rm eff}^{\rm Pl} = 2.99^{+0.34}_{-0.33}$$

$$\Delta N_{\rm eff} = N_{\rm eff}^{\rm Pl} - N_{\rm eff}^{\rm SM} < 0.284$$

[Planck Collaboration A&A 2020]

$$\Delta N_{\rm eff}^{\rm MTH} \sim 5.6$$

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Fraternal Twin Higgs: only 3rd gen. twin fermions & no U(1)'

[N. Craig, A. Katz, M. Strassler, and R. Sundrum, JHEP 2015]

Raise twin neutrino masses, raise the twin photon mass, inject entropy asymmetrically after decoupling, or adjust twin Yukawas

See 1601.07181, 1609.05589, 1611.07975, 1611.07977, 1703.06884, 1706.05548, 1803.03263, 1805.09345, 1805.12139, 1904.10468, 1905.00861

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A New Solution

Raise (non-top) twin Yukawas

Twin neutrinos decouple earlier, as high as a few GeV

Early decoupling dilutes contribution to N_{eff}

Stuckelberg mass for dark photon allows it to transfer excess entropy to the SM

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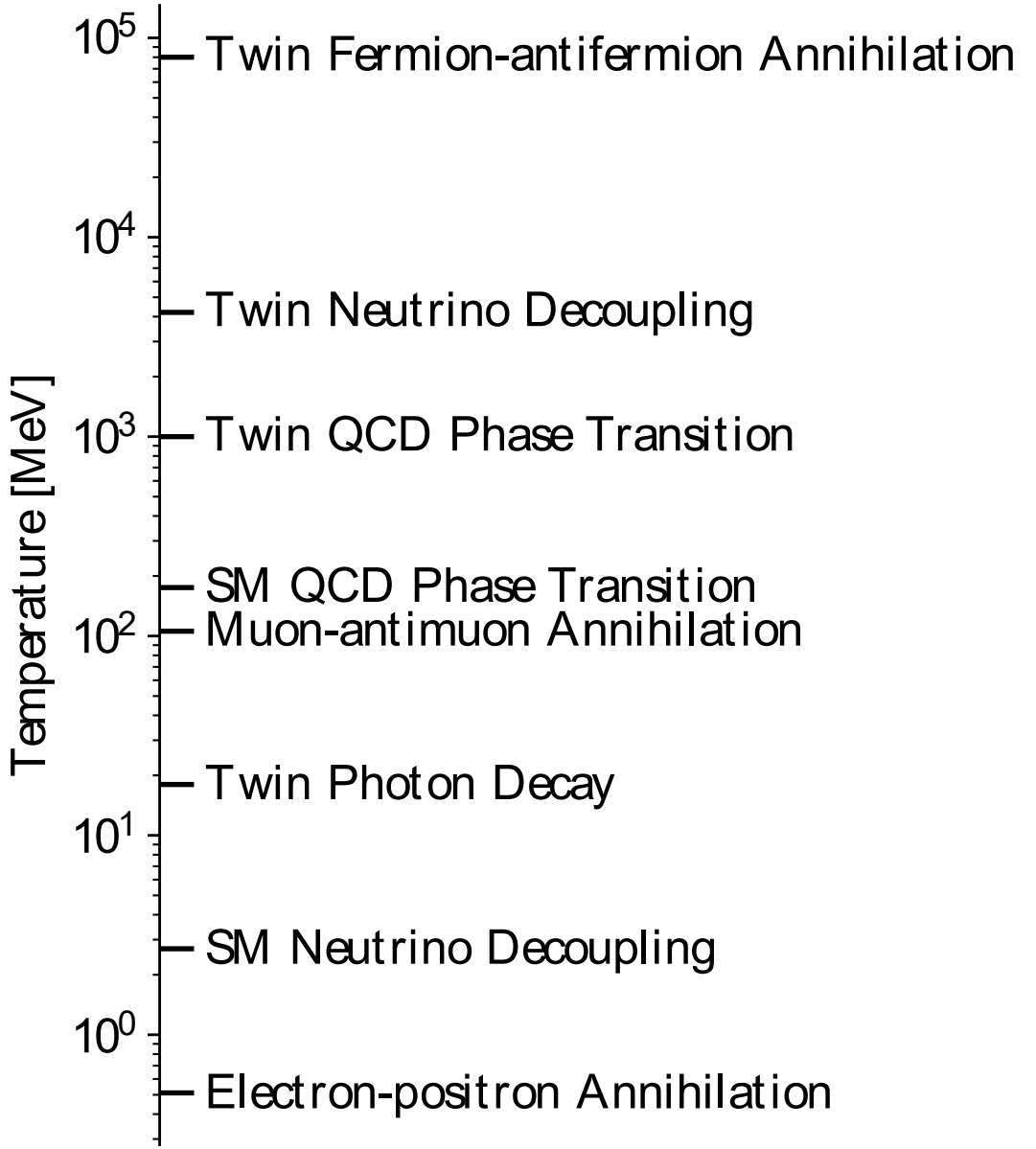
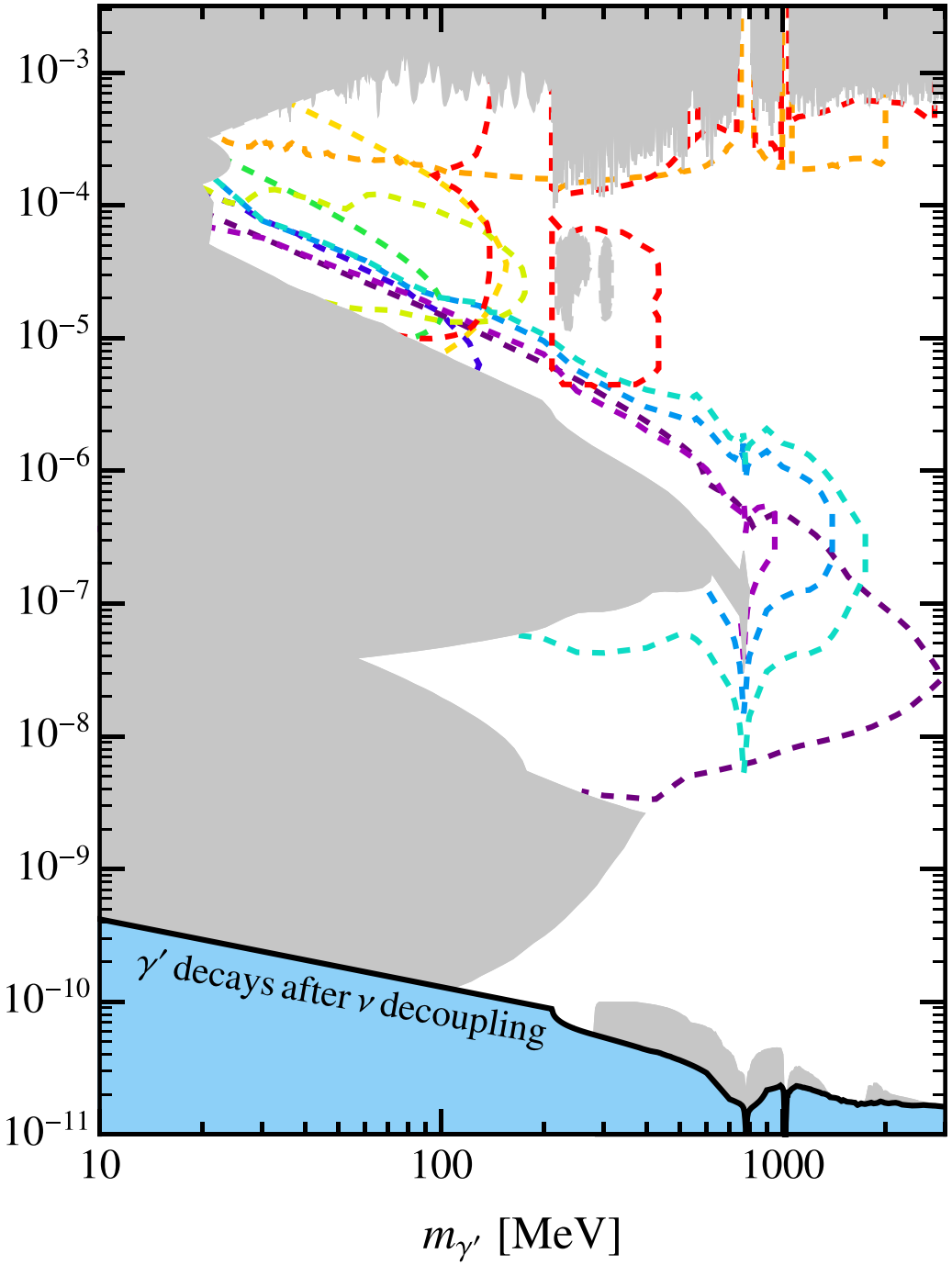


A Predictive Mirror Twin Higgs with Small Z_2 Breaking



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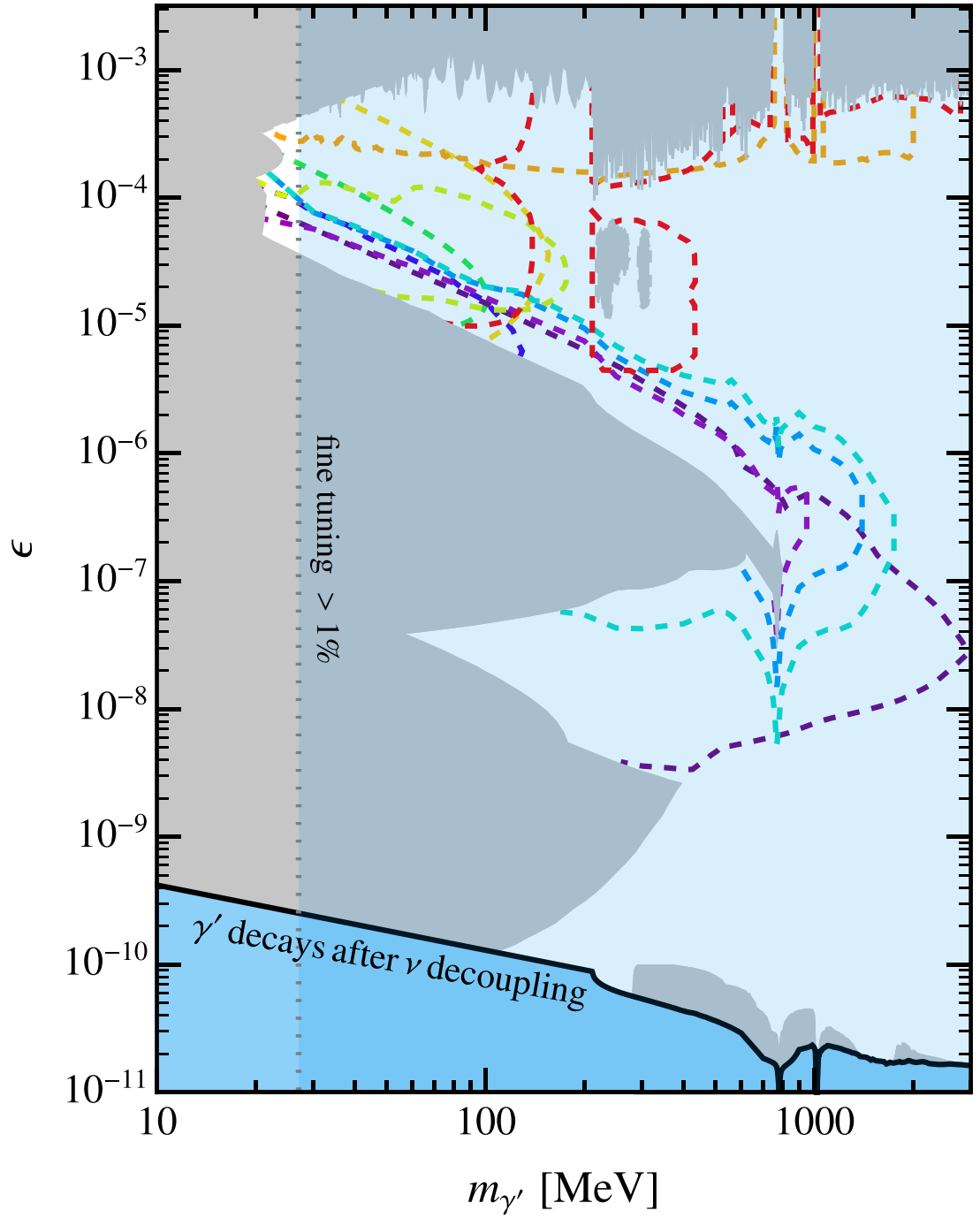

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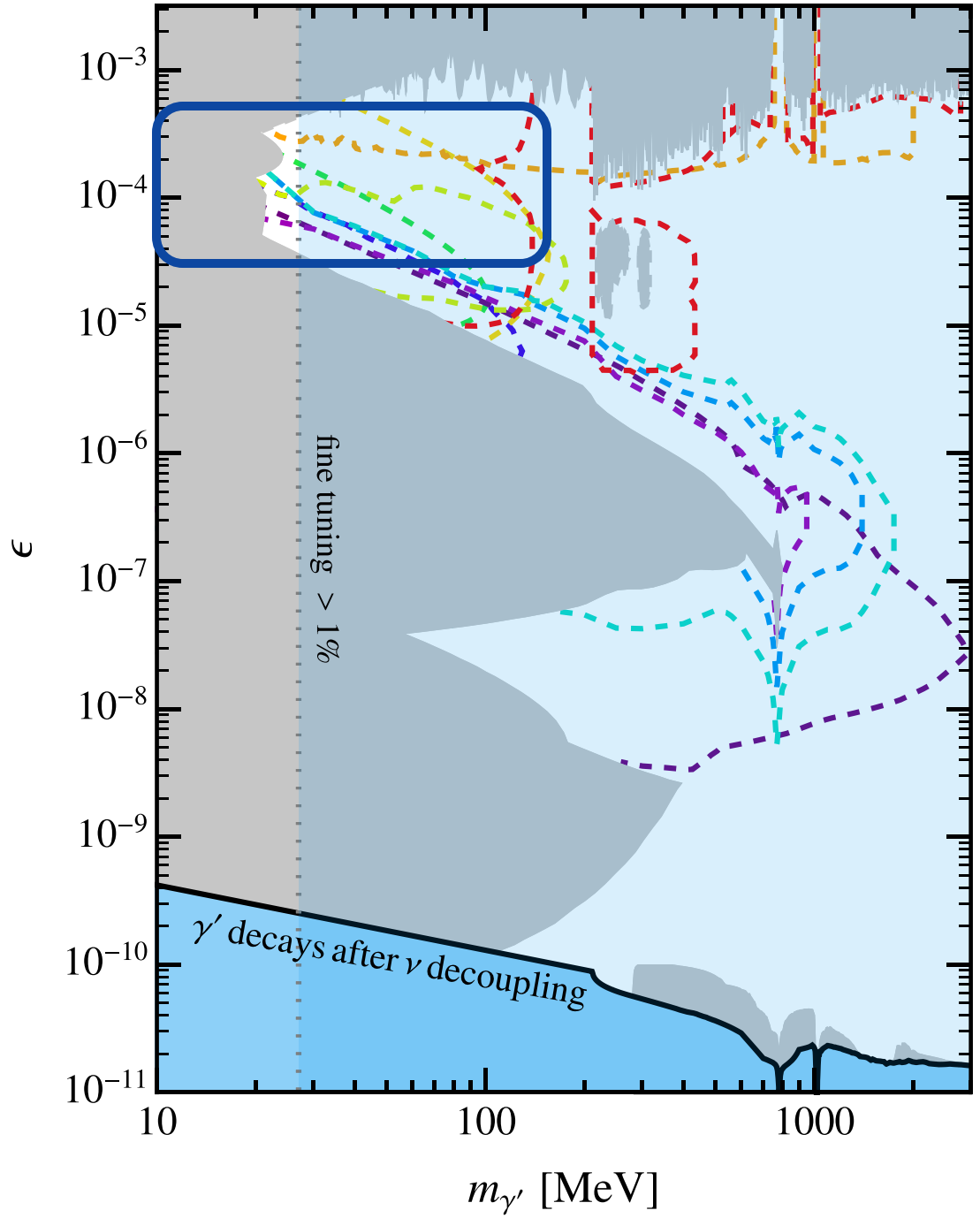

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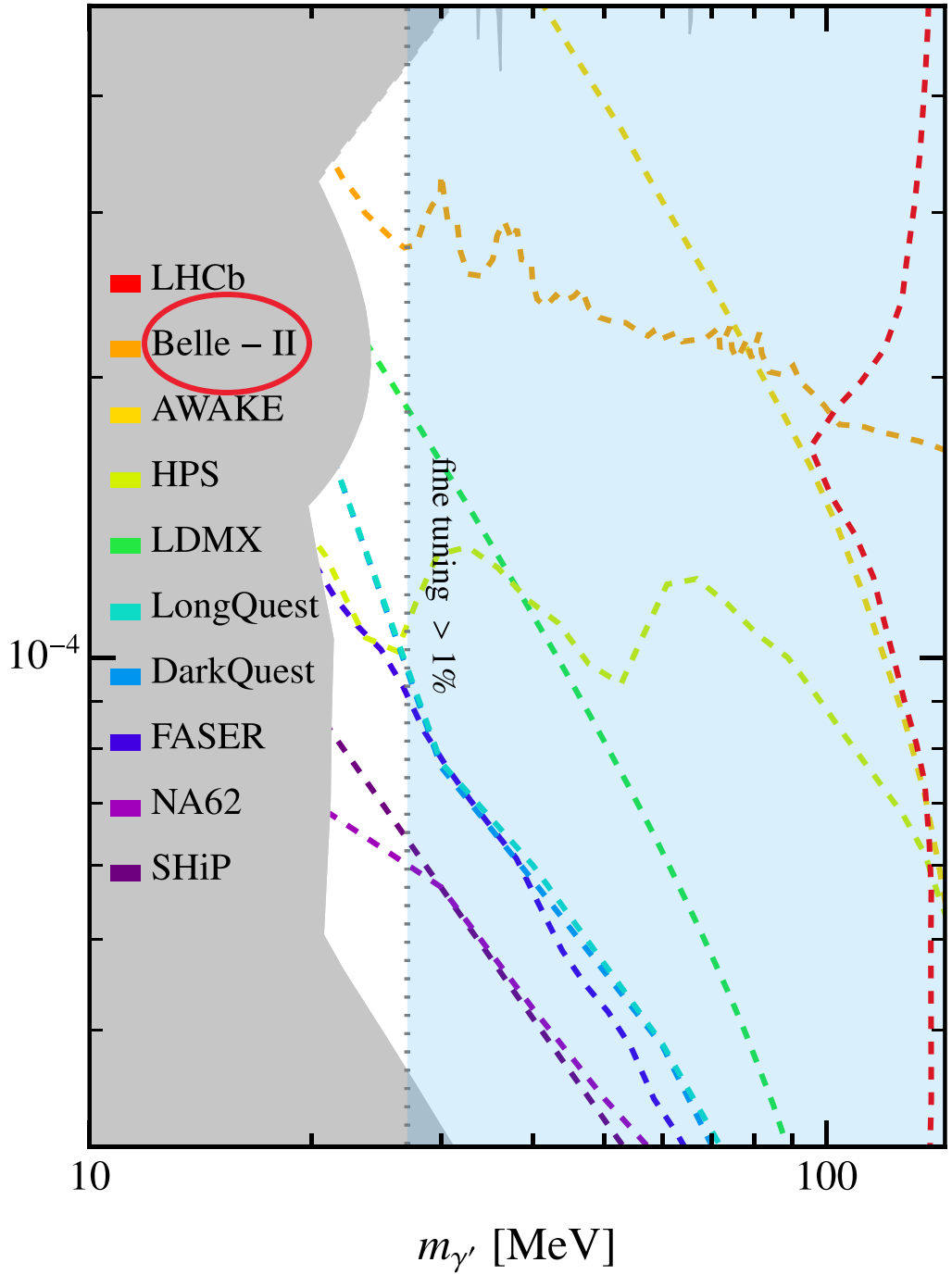

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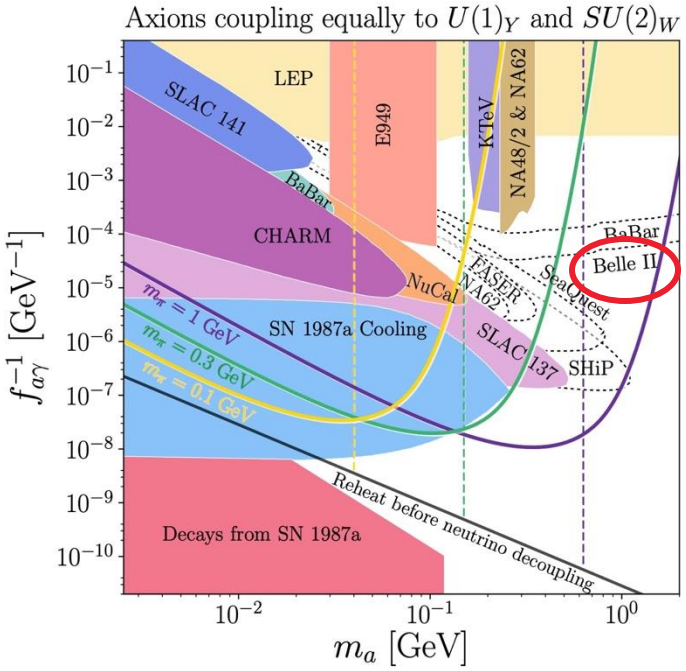

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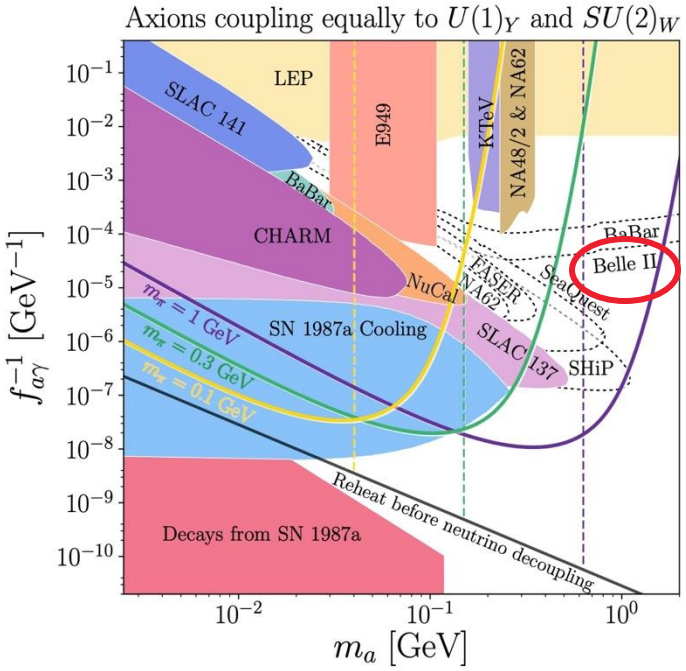

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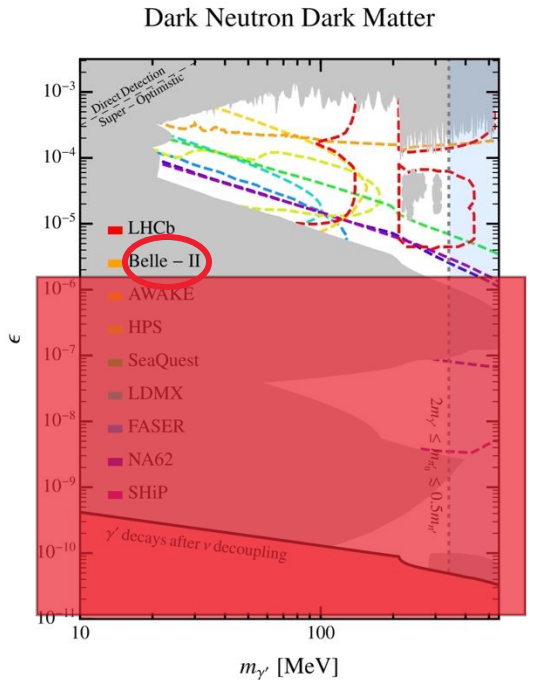

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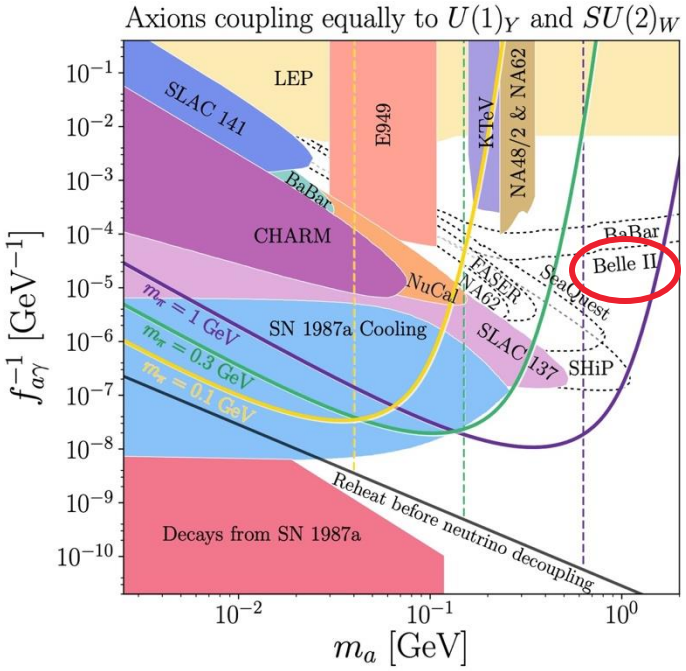

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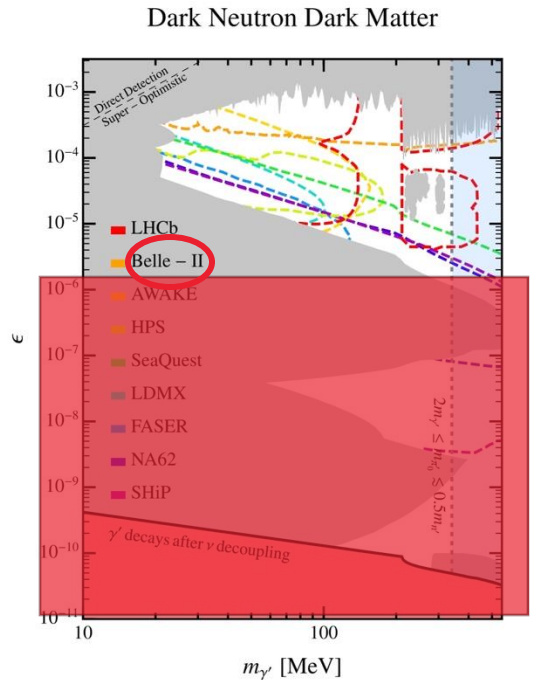

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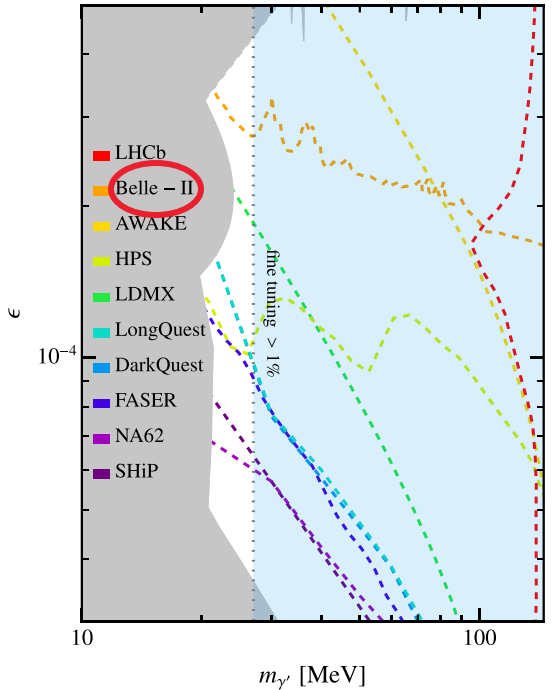

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