Enhancing prospects of sub-GeV majoron at intensity frontier experiments through flavor-changing processes

Matter To The Deepest 2025

September 17th

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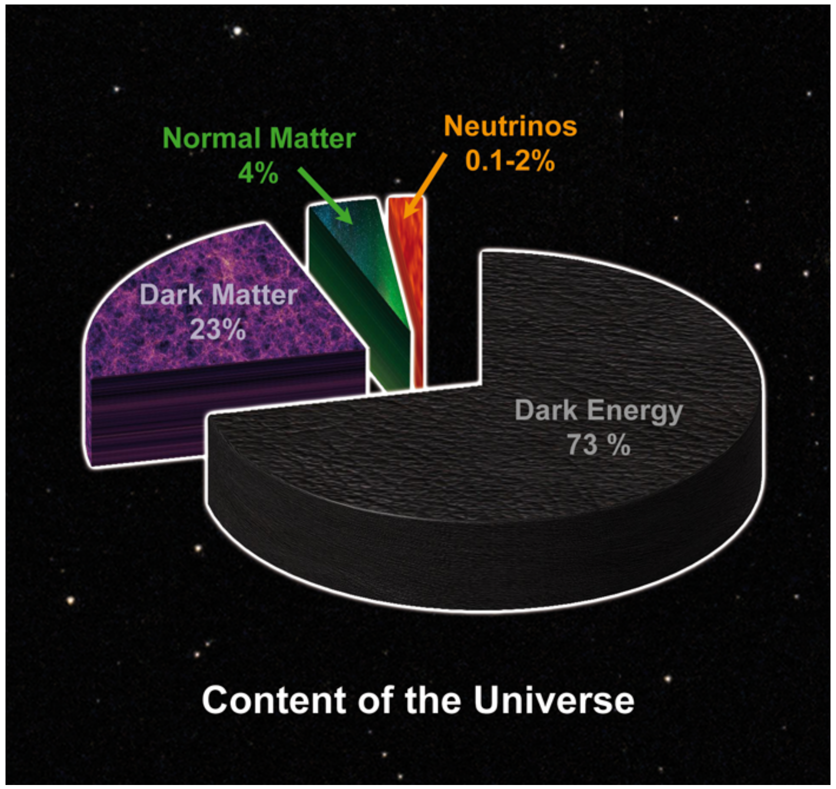
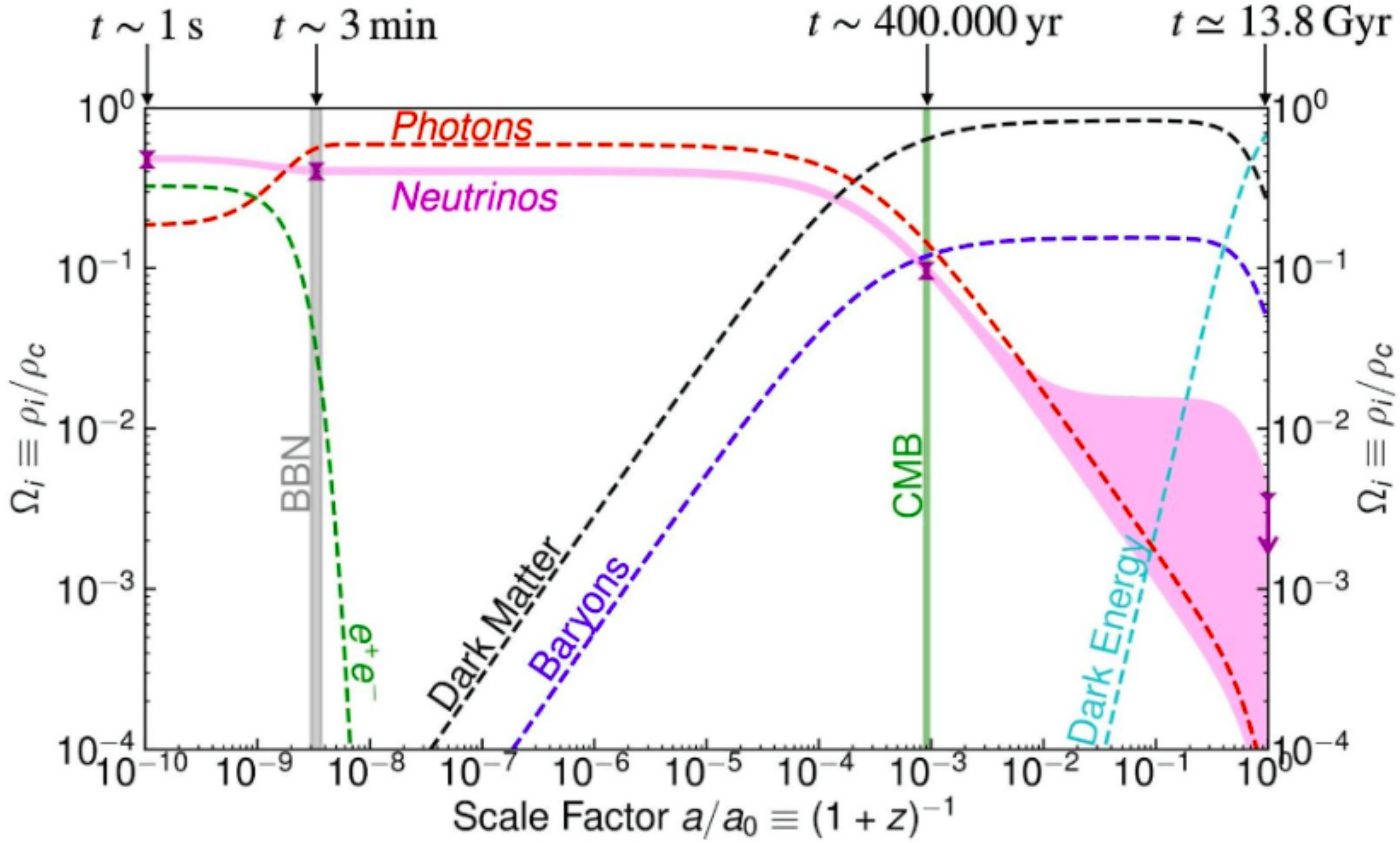
Based on:
KJ, Chih-Ting Lu (in prep)
KJ, Phys.Rev.D 108 (2023) 11, 11, KJ, JHEP 2025, 22 (2025)

ΛCDM: The Dark Universe





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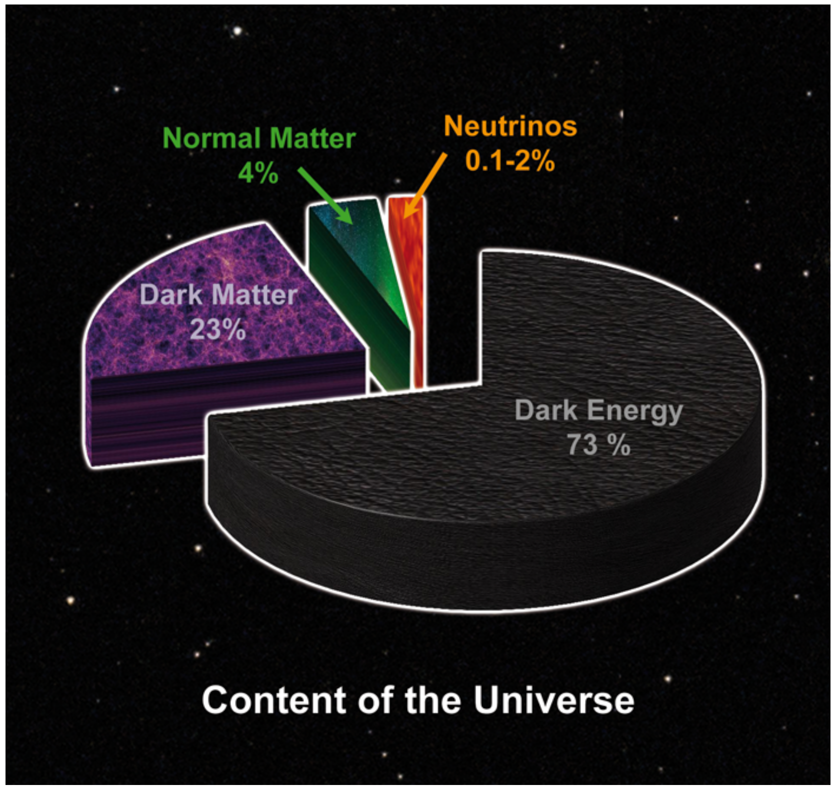
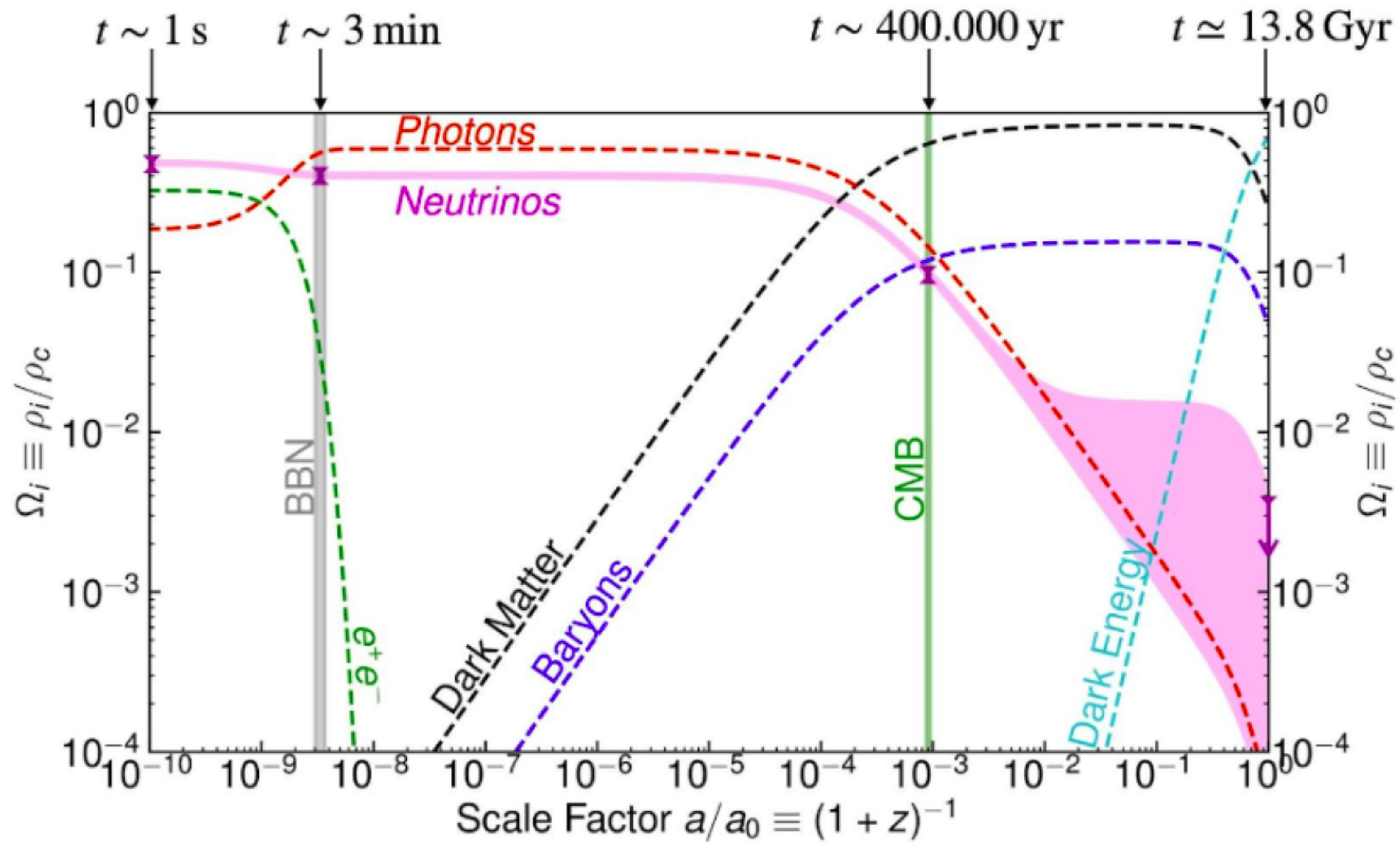
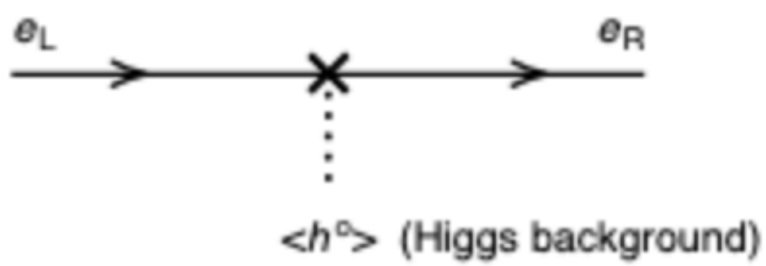
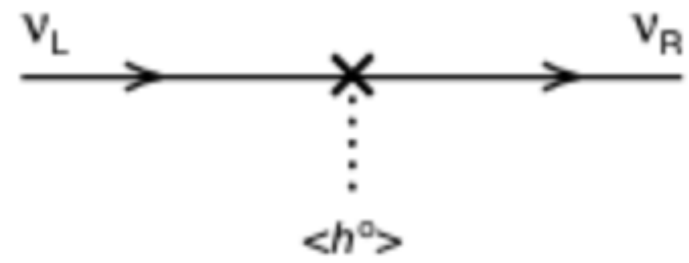




- Neutrinos are the only directly known part of the Dark Universe
- However, precise nature of neutrinos is *unknown* (Dirac/Majorana), as is their mass generation mechanism.
- Seesaw is an elegant UV completion of the Weinberg operator, pointing towards large scale $\Lambda \sim 10^{13}$ GeV for $m_\nu \sim 1$ eV: $\frac{v^2}{\Lambda}\nu_L^T C \nu_L$

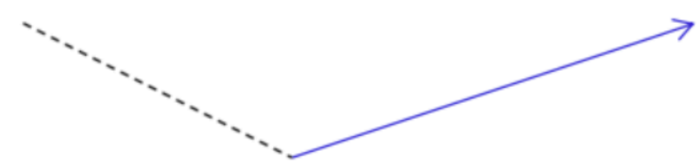
Dirac



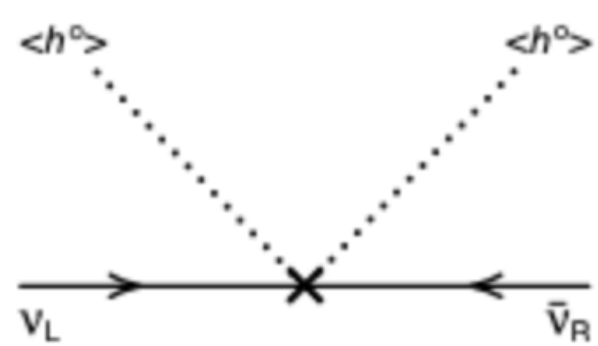


Majorana

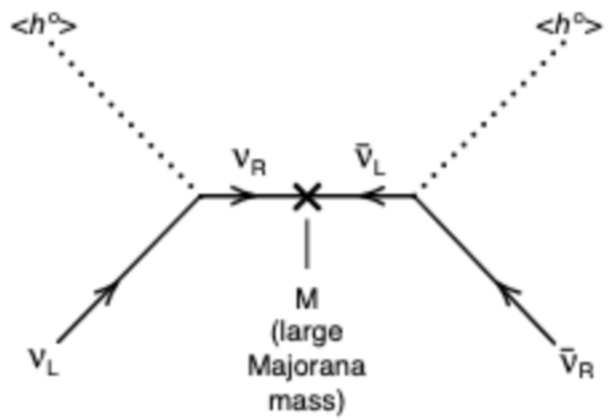
$$(L\Phi) = \nu_L \phi^0 - e_L \phi^+$$



1. Effective Majorana mass term



Seesaw



$$\mathscr{L} = -\frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{\nu_R^c}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D^T & M_R\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix}$$

Small neutrino masses are obtained,
$m_i \simeq m_D^2/M_R \;\rightarrow\;$ need $m_D \ll M_R$.

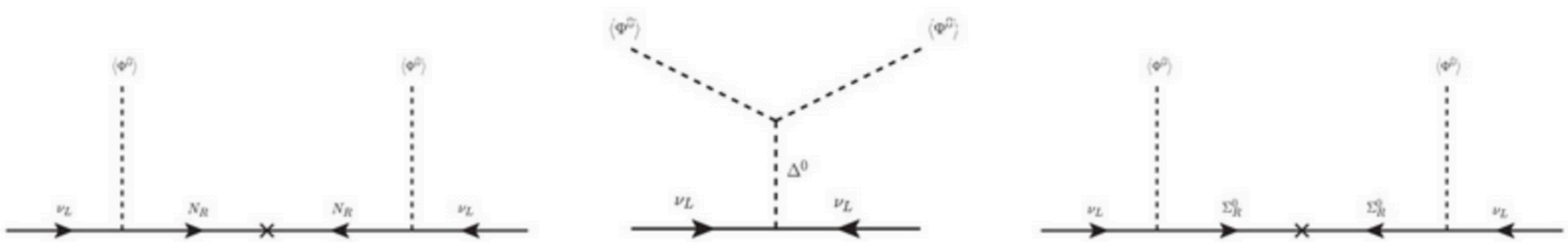
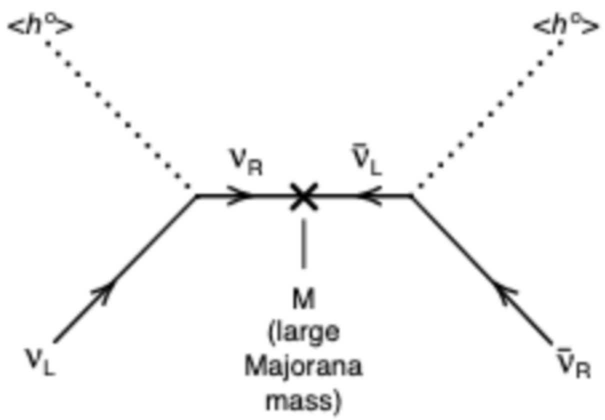


Figure 1. Feynman diagram generating Majorana masses in Type I, II and III seesaw mechanism.

Figure 1 illustrates three UV–complete seesaw realizations of the same Weinberg operator of (2), differing from each other in the nature of the messenger fields involved. In the left–panel diagram of Fig. 1, corresponding to type-I seesaw, the field N_R is a heavy fermion which transforms as a singlet under $SU(2)_L$ and carries no $SU(3)_C$ or $U(1)_Y$ charge. In the middle diagram corresponding to type-II seesaw, the field Δ^0 is the neutral component of a heavy scalar multiplet transforming as triplet under $SU(2)_L$. In the right–panel diagram corresponding to type-III seesaw, Σ_R^0 is the neutral component of the heavy fermion multiplet transforming as triplet under $SU(2)_L$ symmetry.

Seesaw



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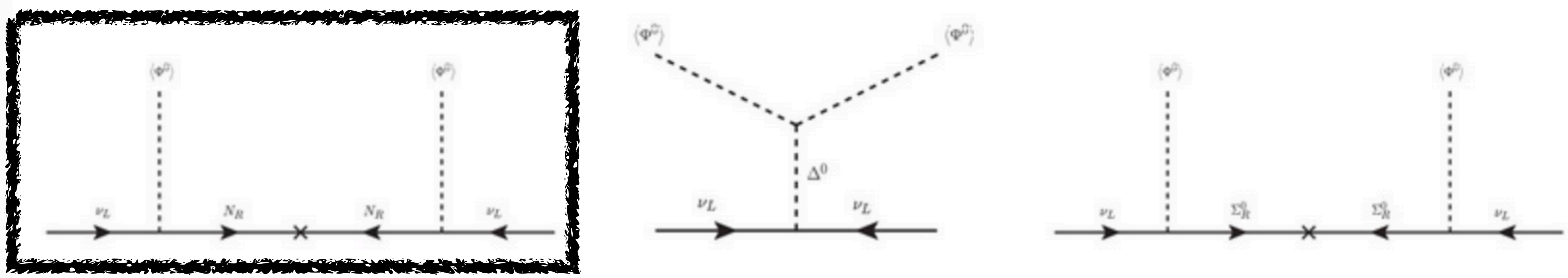
Type I from breaking $U(1)_L$.



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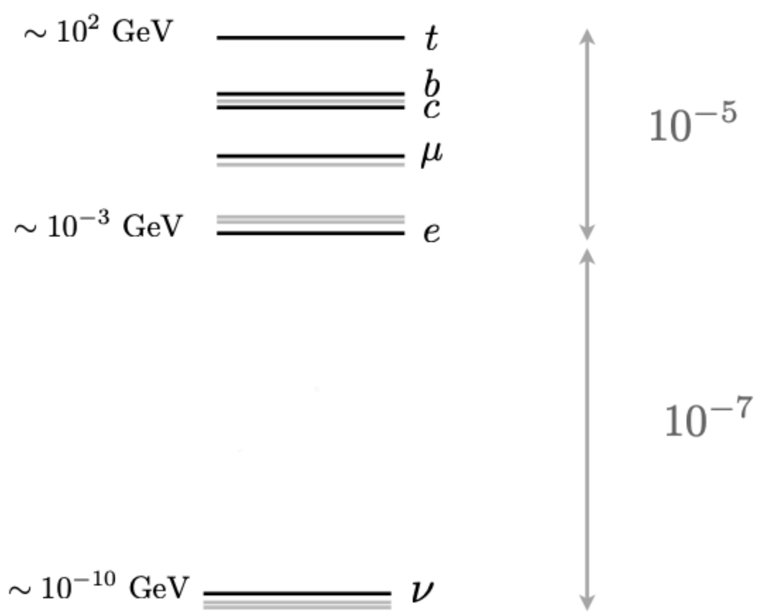

Neutrino mass: Dirac or Majorana?

- Dirac Neutrinos (Higgs Mechanism)

$$\mathcal{L} = -\frac{1}{2}\left(\overline{\nu_L} \quad \overline{\nu_R^c}\right)\begin{pmatrix} 0 & m_D \\ m_D^T & 0 \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.} \qquad m_i = m_D \sim 10^{-2}\,\text{eV}$$

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for $M_R \gg m_D = \mathcal{O}(m_W)$

M_R may be explained by the spontaneous Global U(1)L symmetry breaking

Majoron model

Majorana neutrinos do not conserve the lepton number but preserve $B - L \rightarrow$ baryon asymmetry via leptogenesis

e.g., Zoltan Trocsanyi talk

Type I from breaking $U(1)_L$

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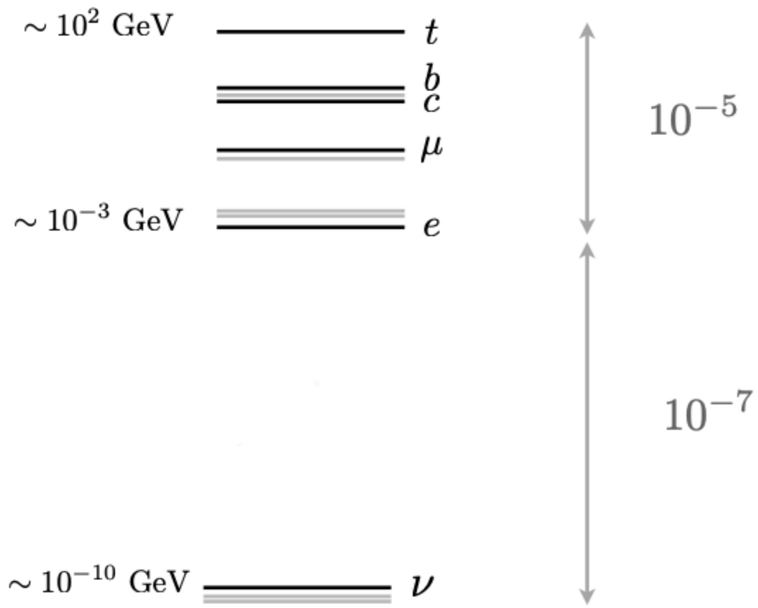

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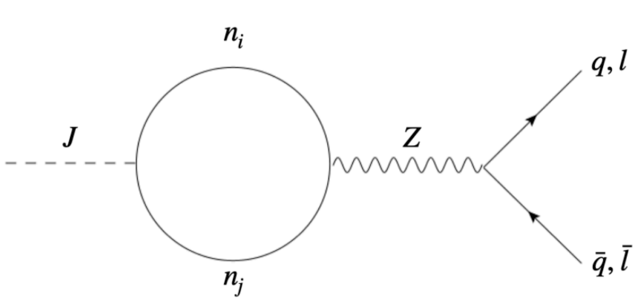
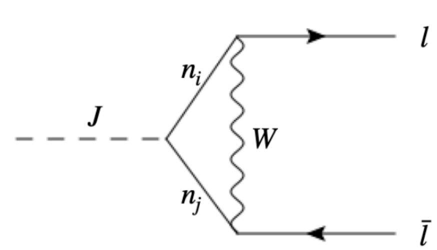
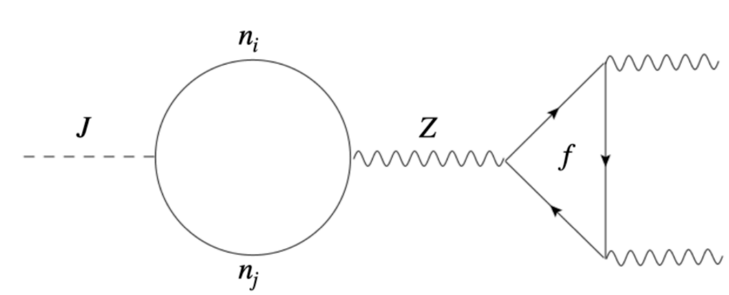
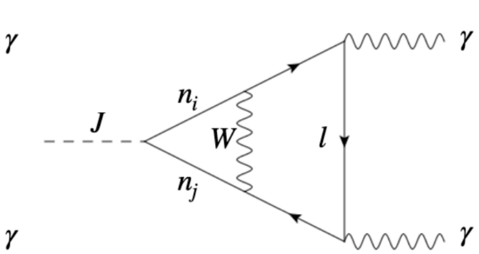
- $U(1)_L$ pNGb is naturally long-lived, flavor violating, and with ALP couplings to gauge bosons.









Singlet Majoron

$$\mathscr{L} = \mathscr{L}_{\rm SM} + i\overline{\nu_R}\gamma_\mu\partial_\mu\nu_R + \partial_\mu\Sigma^\dagger\partial_\mu\Sigma - \lambda_D\Phi^*\overline{E_L}\nu_R$$

$$-\frac{\lambda_R}{2}\overline{\nu_R^c}\Sigma\nu_R - \lambda_\Sigma\left(\Sigma^\dagger\Sigma - \frac{f^2}{2}\right)^2 + \text{ESB}$$

Chikashige, Mohapatra, Peccei, Phys. Lett. 98B, 265 (1981)

Schechter and J. W. F. Valle, Phys. Rev. D 25, 774 (1982)

Singlet $\Sigma = \frac{1}{\sqrt{2}}\left(f + \sigma(x) + i\,J(x)\right)$ with $LN = -2$.

Since $f \gg v_{SM}$, $\sigma(x)$ decouples and only the phase remains.

ESB terms $\rightarrow J$ is pNGB.

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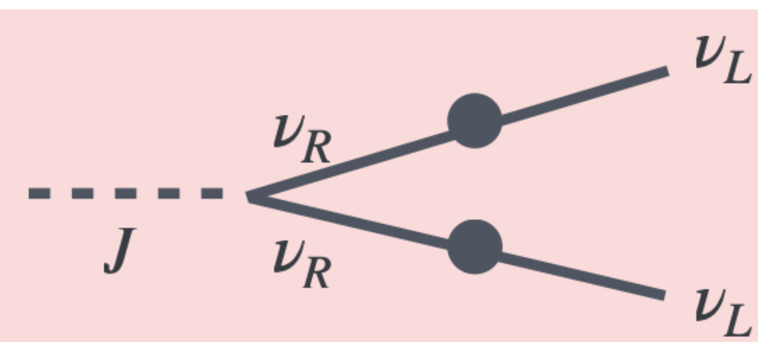
Singlet $\Sigma = \frac{1}{\sqrt{2}}\left(f + \sigma(x) + i\,J(x)\right)$ with $LN = -2$.

Since $f \gg v$, $\sigma(x)$ decouples and only the phase remains. ESB terms $\rightarrow$ J is pNGB.

At tree level, J interacts only with neutrinos directly and through mixing. Other couplings are generated at 1 and 2-loops.

Chikashige, Mohapatra, Peccei, Phys. Lett. 98B, 265 (1981)

Heeck, Patel, Phys. Rev. D 100, 095015 (2019)



$$\mathcal{L}_{\rm int} = -\frac{iM_R}{2f}J\overline{\nu_R^c}\nu_R + \text{h.c.}$$

Majoron interactions

Chikashige, Mohapatra, Peccei, Phys. Lett. 98B, 265 (1981)

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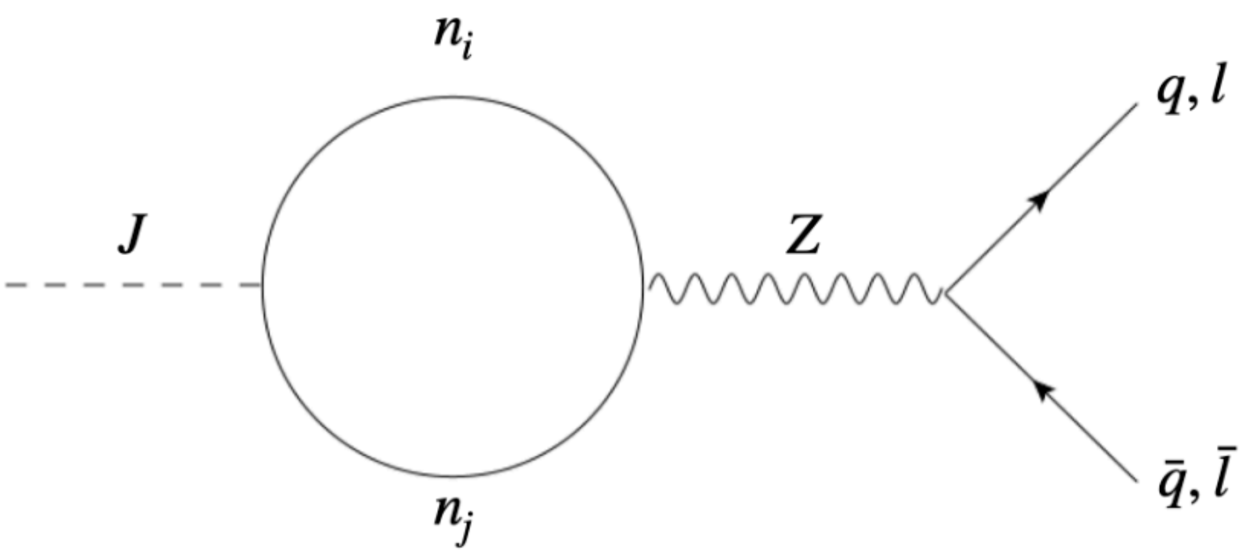
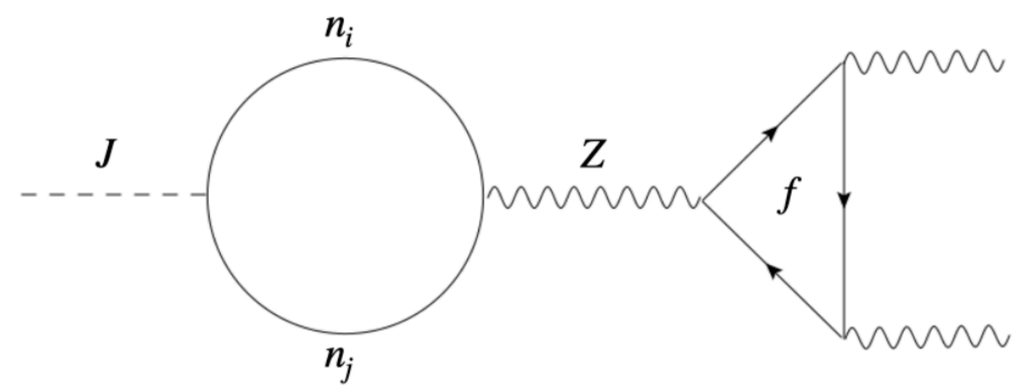
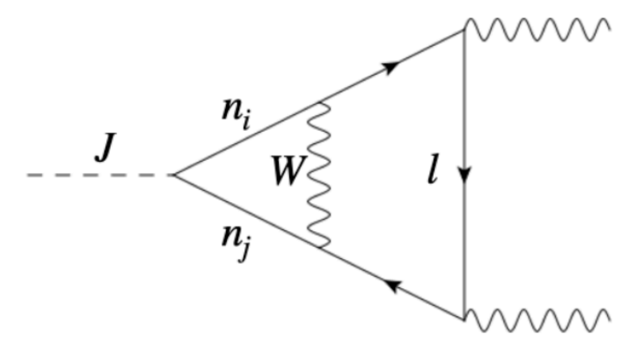
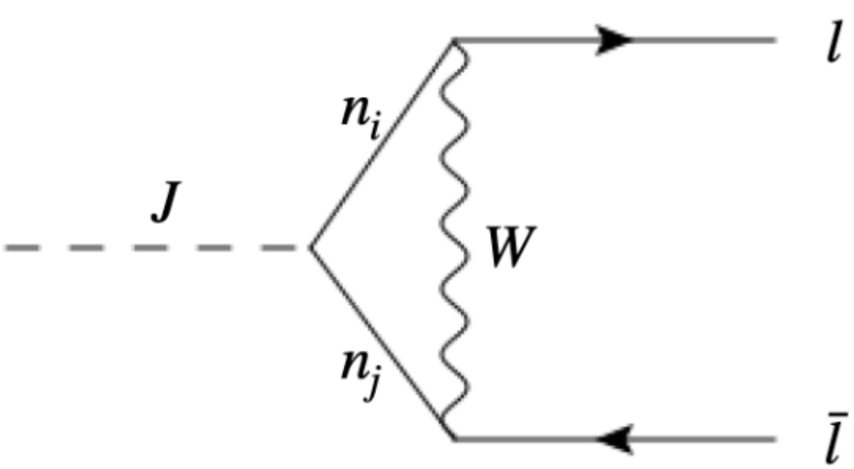




$$\Gamma(J \to q\bar{q}) \simeq \frac{3m_J}{8\pi}\left|\frac{m_q}{8\pi^2 v}T_3^q \mathrm{tr}K\right|^2$$





$$K = \frac{m_D m_D^\dagger}{vf} = \lambda_D \lambda_D^\dagger \frac{v}{f}$$

Davidson–Ibarra parametrization

$$\Gamma(J \to 2\gamma) \simeq \frac{\alpha^2}{4096\pi^7}\frac{m_J^3}{v^2}\ K'^{\,2}$$

$$\Gamma(J \to l\bar{l}') \simeq \frac{m_J}{8\pi}\left(\left|\frac{m_l + m_{l'}}{16\pi^2 v}(\delta_{ll'}T_3^l \mathrm{tr}K + K_{ll'})\right|^2 + \left|\frac{m_l - m_{l'}}{16\pi^2 v}K_{ll'}\right|^2\right)$$

Some recent works on majoron

1. Dark Matter and the Hubble Tension

Majoron as a warm or decaying dark matter, which could help alleviate the Hubble tension.

- 2304.04430, 2402.04368, 2306.01222, 2211.08538

2. Gravitational waves from lepton number breaking

Stochastic background of gravitational waves from first-order phase transition.

- 2406.04404, 2403.11580, 2310.15830, 2203.04322

3. Novel signatures in neutrinoless double beta decay

Continuous energy spectrum instead of a shark peak.

- 1802.08019, 2305.18526, 2210.03848

4. ALP-like searches for decays or missing energy.

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Production from flavor violating decays at beam dumps, FASER

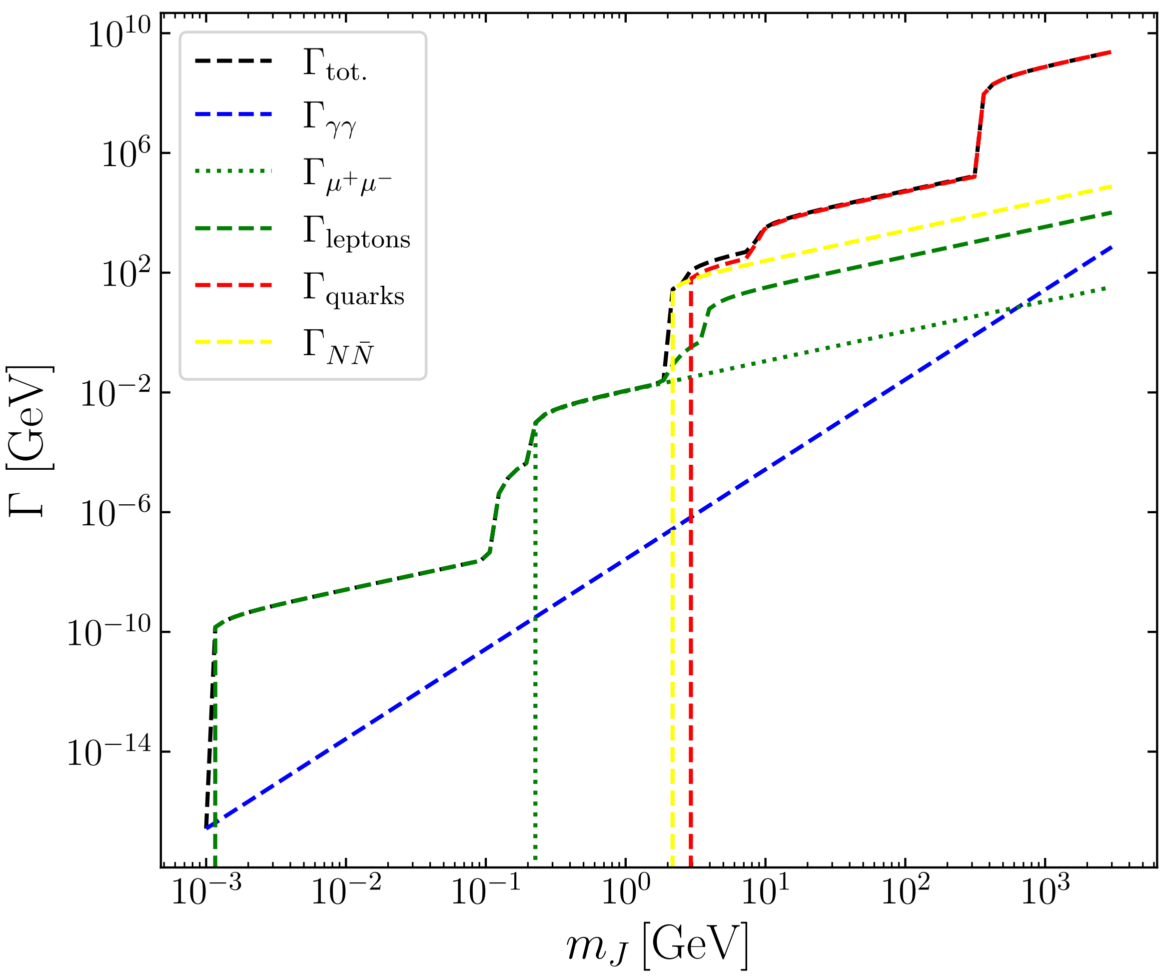
$$\tau \to \mu J$$
$$\mu \to eJ$$

Vector axial coupling interplay

$$\mathscr{L} \supset \frac{\partial_\mu a(x)}{f} \bar{\ell} \gamma^\mu \left(C_V + C_A \gamma_5 \right) \ell + \frac{\alpha_{EM}}{4\pi} \frac{a(x)}{f} F \tilde{F} \,,$$

Define $R = C_A^{diag} / C_A^{off-diag}$ and compute decay width. Use Heeck, Patel, Phys. Rev. D 100, 095015 (2019) for parton couplings and Cheng, Li, Salvioni JHEP 01 (2022) 122 for ChPT.

For $R \sim O(0.1 - 10)$, $J \to \mu\mu$ dominates in the sub-GeV region.

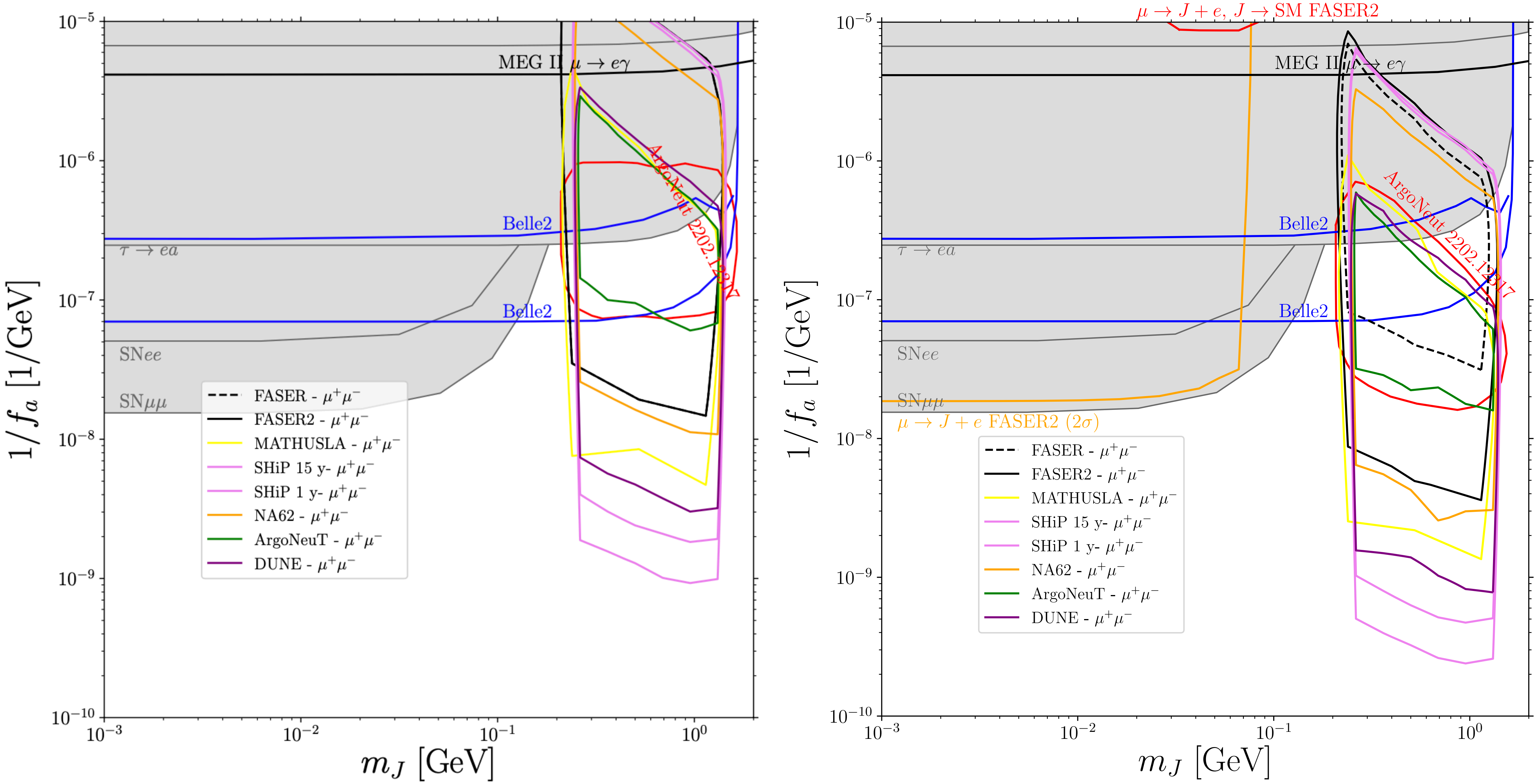


Leading production mechanism comes from taon decays: $\tau \to \mu J, \quad \tau \to eJ$

$$\Gamma(\ell_\alpha \to \ell_\beta X) = \frac{m_\alpha^3}{16\pi\Lambda^2} \times O(0.1)$$

In beam dumps, taons are produced from D meson decays.
One can also use muons, $\mu \to eJ$. For example, $N_\mu \sim 10^{11}$ at FASER2.

Preliminary results



$R = C_A^{diag}/C_A^{off-diag} = 1$ $\qquad$ $R = 10$

Taons provide leading production mechanism for sub-GeV Majoron, covering parameter space in-between SN1987 and FV searches.

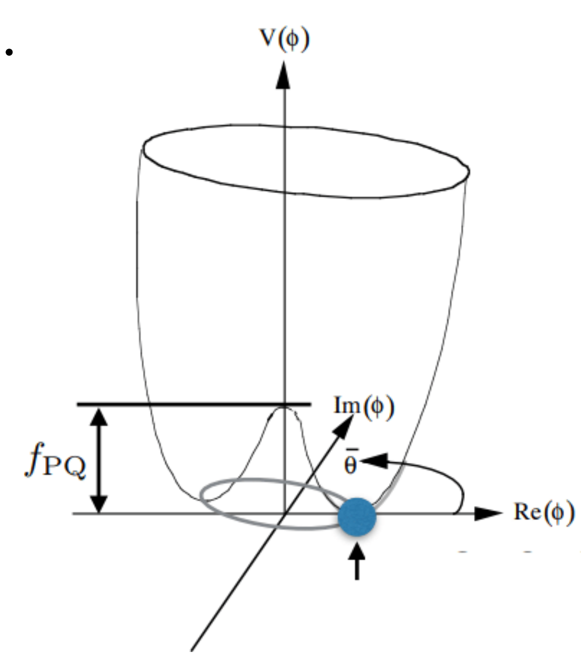
Axions and ALPs

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

$$\mathscr{L} \supset \theta G\tilde{G} = \partial_\mu K^\mu, \quad K_\mu = \theta \frac{\alpha_s}{8\pi}\epsilon_{\mu\nu\rho\sigma}\left(A_a^\nu G_a^{\rho\sigma} - \frac{g_s}{3} f^{abc} A_a^\nu A_b^\rho A_c^\sigma\right)$$

This is CP odd topological term - it's a total derivative. But K_μ is *not* gauge-inv and its integral is nonzero. It measures the change of winding number of gauge configurations; θ is a global property of the state (θ vacuum).

Promote $\theta \to a(x)$: dynamical pseudoscalar field associated with global, anomalous $U(1)_{PQ}$. Non-perturbative QCD effects provide a nontrivial potential and axion relaxes to CP-conserving minimum.



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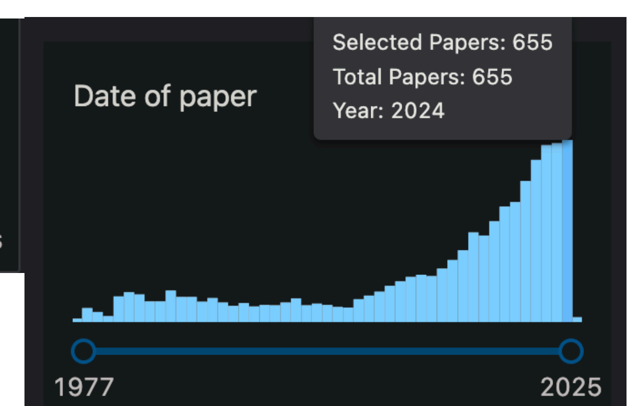
$$\mathcal{L} \supset \theta\, G\tilde{G} = \partial_\mu K^\mu, \quad K_\mu = \theta\, \frac{\alpha_s}{8\pi} \epsilon_{\mu\nu\rho\sigma} \left(A^\nu_a G^{\rho\sigma}_a - \frac{g_s}{3} f^{abc} A^\nu_a A^\rho_b A^\sigma_c \right)$$

This is CP odd *topological* term - it's a total derivative. But i) K_μ is *not* gauge-inv and ii) its integral is nonzero. It measures the change of winding number of gauge configurations; θ is a global property of the state (θ vacuum).

Promote $\theta \to a(x)$: dynamical pseudoscalar field associated with global, anomalous $U(1)_{PQ}$. Non-perturbative QCD effects provide a nontrivial potential and axion relaxes to CP-conserving minimum.

Spontaneous or explicit breaking of global symmetries is successfully employed by many BSM scenarios. In particular, the axion solution to the strong CP problem is an intense (and growing) research activity.

CP Conservation in the Presence of Instantons #1
R.D. Peccei (Stanford U., ITP), Helen R. Quinn (Stanford U., ITP) (Mar, 1977)
Published in: *Phys.Rev.Lett.* 38 (1977) 1440-1443
links DOI cite claim reference search 8,308 citations

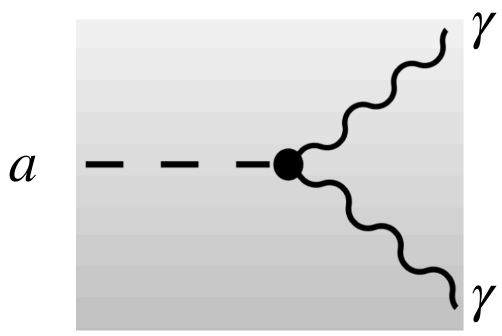


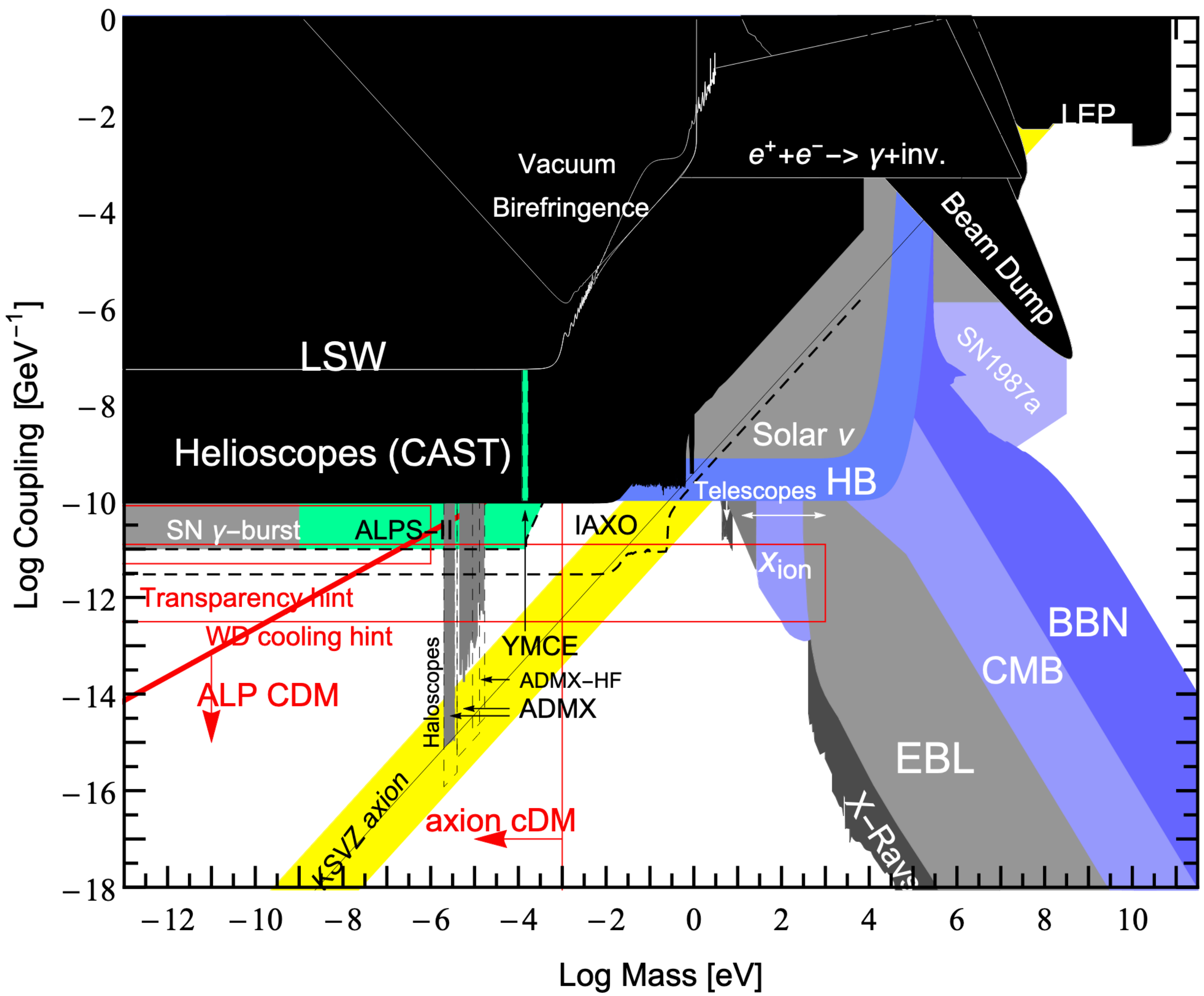
PBC benchmark 9
photon-coupled ALP

$$\mathscr{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Consider sub-GeV
weakly coupled ALP

- pseudoscalar unrelated to the strong CP problem
- wide experimental program: astronomy, cosmology, and lab
- ...

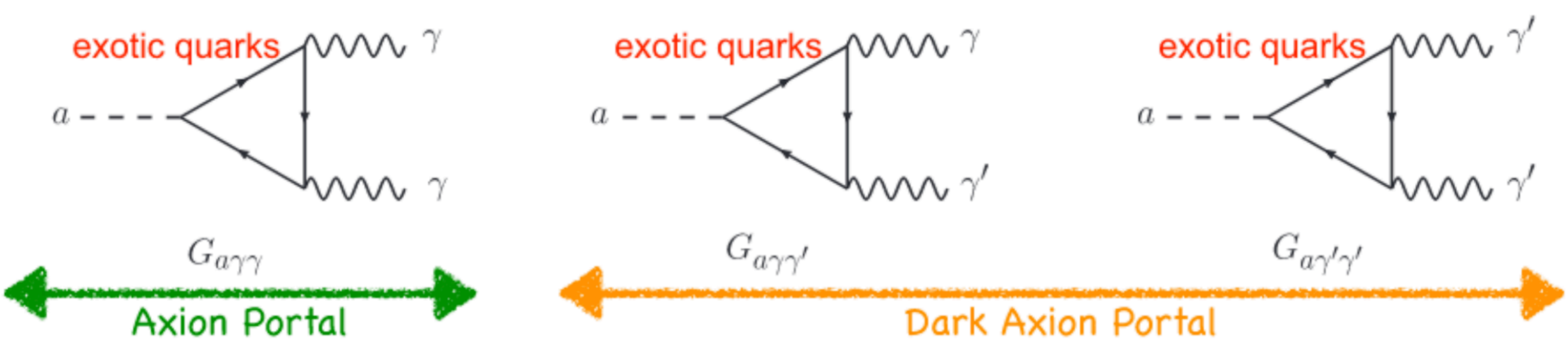




Dark Axion Portal: pseudoscalar-vector dim-5 portal

- Introduce an ALP (can be QCD axion) and a dark photon
- KSVZ-like setup: loops with heavy quarks induce $g_{a\gamma\gamma}$, $g_{a\gamma\gamma'}$, $g_{a\gamma'\gamma'}$ if they are charged under both $U(1)_D$ and $U(1)_Y$.

Ejlli, 1609.06623, Kaneta, Lee, Yun, 1611.01466



- Introduce an ALP and a dark photon
- KSVZ (dark) ALP: loops with heavy quarks induce $g_{a\gamma\gamma}$, $g_{a\gamma\gamma'}$, $g_{a\gamma'\gamma'}$ if they are charged under both $U(1)_D$ and $U(1)_Y$.

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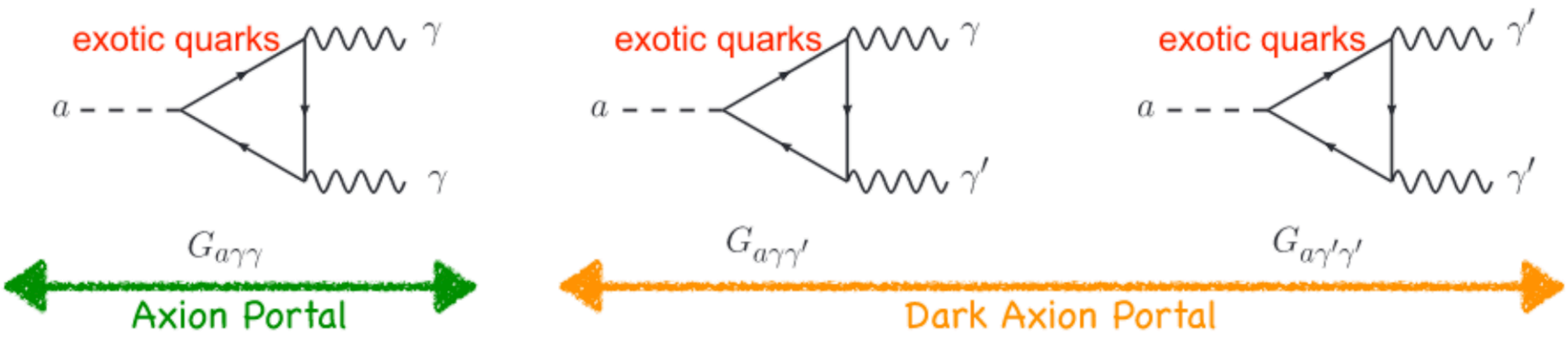


$$G_{a\gamma\gamma} = \frac{e^2}{4\pi^2}\frac{PQ_\Phi}{f_a}N_C\left[Q_\psi^2\right]$$

$$G_{a\gamma\gamma'} = \frac{ee'}{4\pi^2}\frac{PQ_\Phi}{f_a}N_C\left[D_\psi Q_\psi\right] + \varepsilon G_{a\gamma\gamma}$$

$$G_{a\gamma'\gamma'} = \frac{e'^2}{4\pi^2}\frac{PQ_\Phi}{f_a}N_C\left[D_\psi^2\right] + 2\varepsilon G_{a\gamma\gamma'}$$

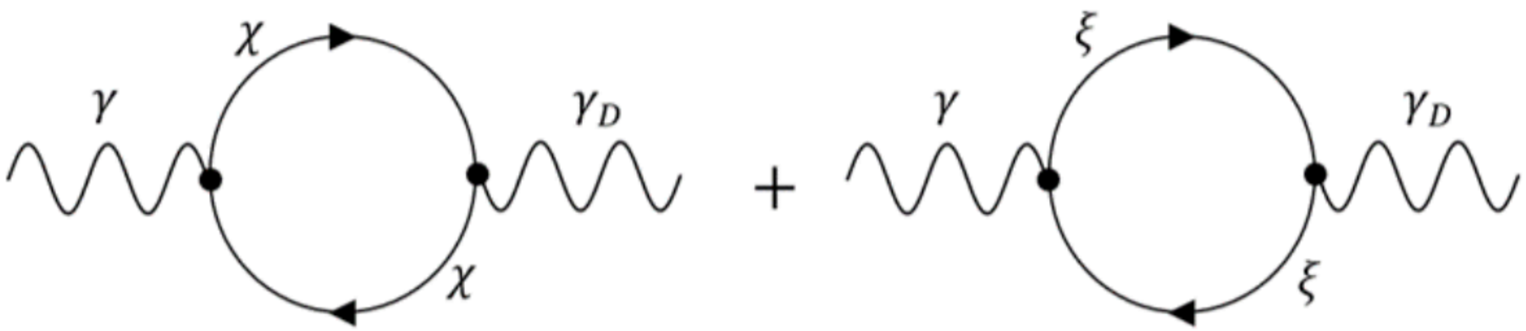
$$\epsilon \sim \frac{1}{12\pi^2}N_C\, eQ_\psi e' D_\psi \log\left(\frac{\Lambda}{m\psi}\right)$$

In this setup, there is too-large kinetic mixing and $G_{a\gamma\gamma'} < G_{a\gamma'\gamma'}$ unless $e' \ll e$.
→ need a pair of fermions in the loop.

Dark Axion Portal:
pseudoscalar-vector dim-5 portal

$$\mathcal{L} = \mathcal{L}_{SM} + \mathcal{L}_{kinetic} - V(\Phi) + y(\Phi\chi\chi^c + \Phi^*\xi\xi^c) + h.c.\ ,$$

Hook, Marques-Tavares, Ristow 1611.01466



$$\propto\ Q^{\chi}_{EM}Q^{\chi}_{D} + Q^{\xi}_{EM}Q^{\xi}_{D} = 1 - 1 = 0$$

	Q_{EM}	Q_D
χ	2	2
χ^c	-2	-2
ξ	2	-2
ξ^c	-2	2

Introduce 2 pairs of chiral fermions χ and ξ and impose charge-conjugation symmetry which forbids kinetic mixing to all orders in perturbation theory.

$$\chi \longleftrightarrow \xi \qquad \chi^c \longleftrightarrow \xi^c$$

After SSB, the charge assignment leads to vanishing of all couplings but $g_{a\gamma\gamma'}$.

$$\mathcal{L} \supset \frac{\phi(x)}{16\pi^2 f}\Big(\quad \left((eQ^{\chi}_{EM})^2 F_{\mu\nu}\tilde{F}^{\mu\nu} + 2ee_D Q^{\chi}_{EM}Q^{\chi}_{D} F_{\mu\nu}\tilde{F}^{\mu\nu}_{D} + (e_D Q^{\chi}_{D})^2 F^{D}_{\mu\nu}\tilde{F}^{\mu\nu}_{D}\right)$$
$$- \left((eQ^{\xi}_{EM})^2 F_{\mu\nu}\tilde{F}^{\mu\nu} + 2ee_D Q^{\xi}_{EM}Q^{\xi}_{D} F_{\mu\nu}\tilde{F}^{\mu\nu}_{D} + (e_D Q^{\xi}_{D})^2 F^{D}_{\mu\nu}\tilde{F}^{\mu\nu}_{D}\right)\Big).$$

Dark Axion Portal - some recent works

- Dark photon DM

  Kaneta, Lee, Yun 1704.07542, Gutiérrez et al. 2112.11387
- Cosmological relaxation

  Choi, Kim, Sekiguchi 1611.08569; Domcke, Schmitz, You 2108.11295
- $(g-2)_\mu$

  deNiverville, Hye-Lee, Seo, 1806.00757; Ge, Ma, Pasquini 2104.03276
- Axion-photon-dark photon oscillation

  Choi, Kim, Sekiguchi 1802.07269; Choi, Lee, Seong, Yun 1806.09508, 1911.00532
- Lab searches - displaced vertices, missing energy,...

  deNiverville, Hye-Lee, Seo 1806.00757, 1904.13061, 2011.03276
- Astrophysical searches - supernovae, white dwarves...

  Arias et al. 2007.12585; Hook, Marques-Tavares, Ristow 2105.06476
- Laser/LSW searches

  Hye-Lee, Lee, Yi 2201.11906

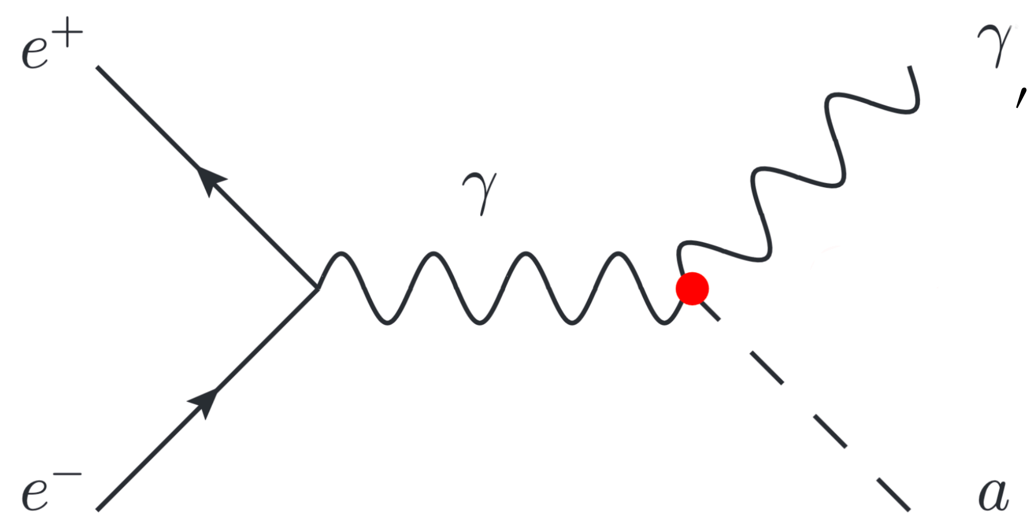
Dark Matter

- Misalignment mechanism for ALP Peccei, Quinn 1977
- Freeze-in Kaneta, Lee, Yun, 1611.01466 Gutiérrez et al. 2112.11387,
- Freeze-out Arias, Diaz Saez, Jaeckel, JCAP 06 (2025) 060

LLPs at intensity frontier

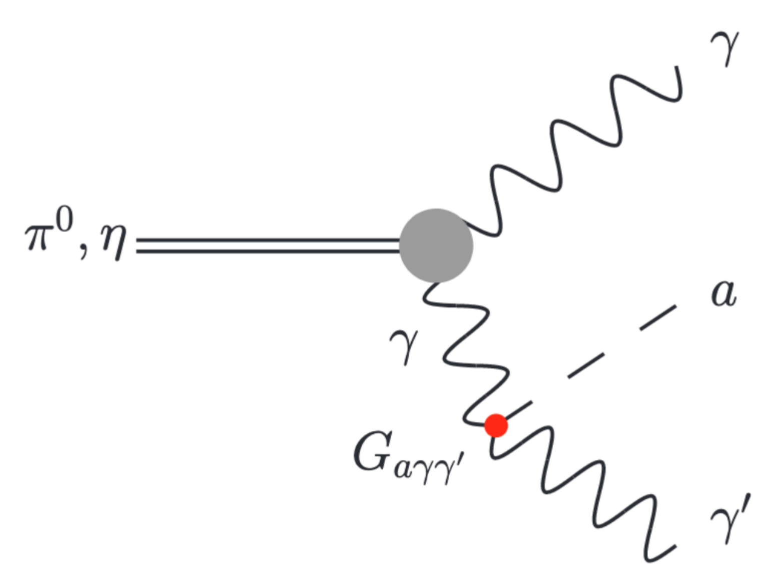
e^+e^- colliders

BaBar, Belle, LEP, FCC

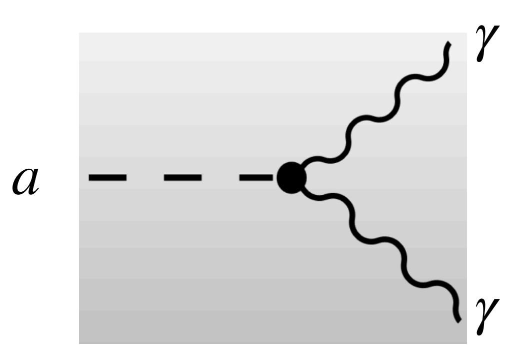


Beam dumps, fixed Target, neutrino experiments

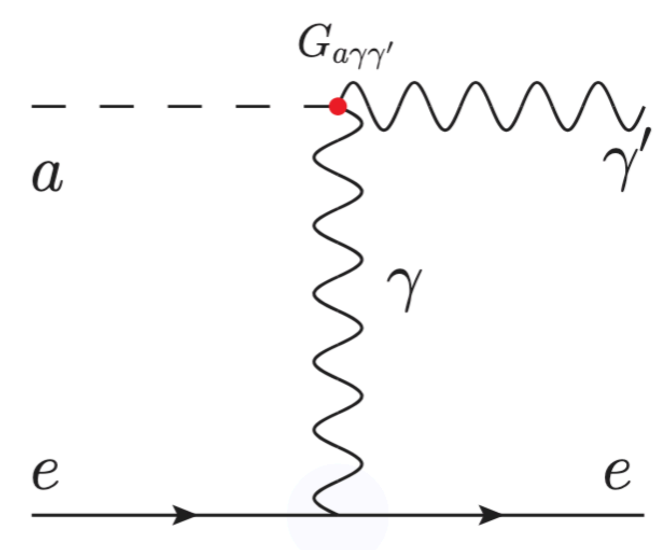
SHiP, FASER, CHARM, LSND, MiniBooNE, ...



Displaced decays



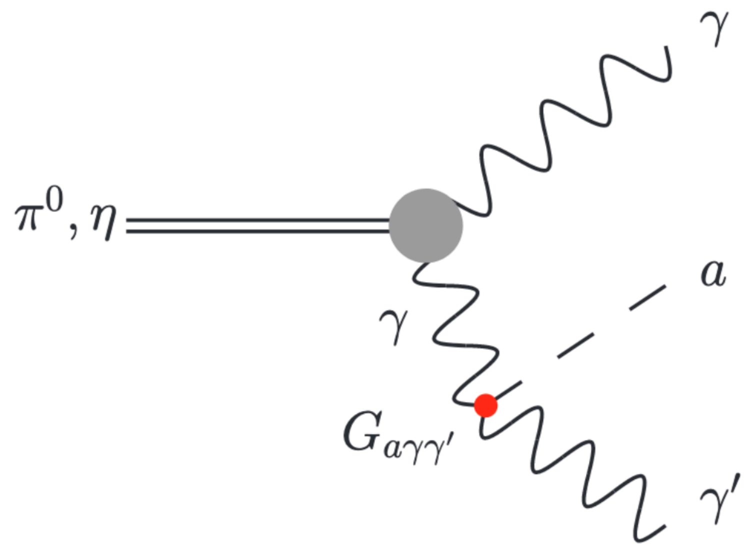
$\mathcal{N}_{events} \propto g^4$



Scattering

Dark Axion Portal at intensity frontier

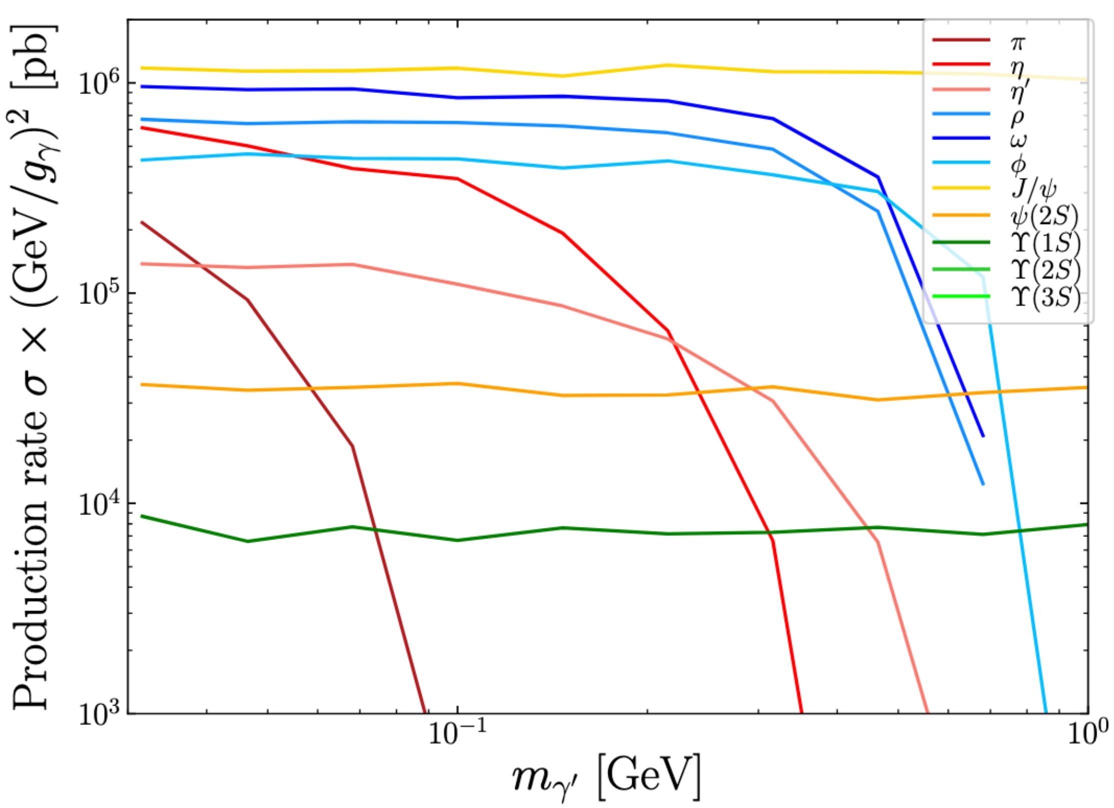
$$\mathscr{L}_{\text{dark axion portal}} = \frac{g_{a\gamma\gamma'}}{2} a F_{\mu\nu} \tilde{F}'^{\mu\nu}$$

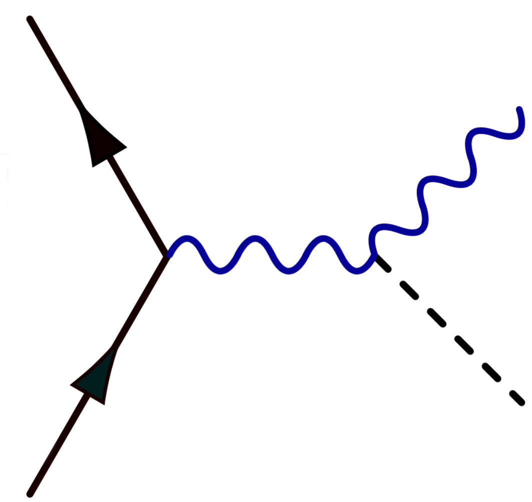


Production

no Primakoff production!
Instead, Primakoff upscattering, $\sigma_{\gamma' N \to a N} \propto \alpha_{em} g^2_{a\gamma\gamma} Z^2$.

KJ Phys. Rev. D 108, 115017





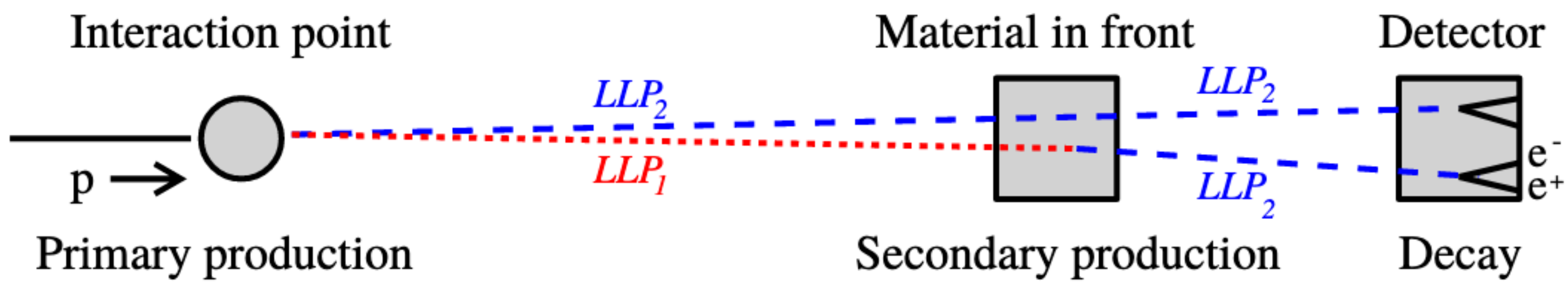
vector meson decays are *more* efficient than pseudoscalar meson decays

$$\frac{\mathrm{BR}_{V\to a\gamma'}}{\mathrm{BR}_{V\to ee}} = \frac{g^2_{a\gamma\gamma'}\left((-M^2+m_a^2+m_{\gamma'}^2)^2 - 4m_a^2 m_{\gamma'}^2\right)^{3/2}}{32\pi\alpha_{\mathrm{EM}} M\sqrt{M^2-4m_e^2}\,(M^2+2m_e^2)},$$

$$\sim M^2$$

LLPs at beam dumps

Secondary production on tungsten layers of FASERν2 - upscattering of very long-lived LLP_1 into LLP_2 by coherent nucleus scattering



KJ, F. Kling, L. Roszkowski, S. Trojanowski, 1911.11346

$$\mathscr{P}_{decay} = \begin{cases} \dfrac{L_{max} - L_{min}}{d} \equiv \dfrac{\Delta}{d} & : \text{ for } d \gg L_{min} \\ \exp(-L_{\text{min}}/\bar{d}) & : \text{ for } d \ll L_{min} \quad \rightarrow d \textit{ is exponentially sensitive to } L_{min} \end{cases}$$

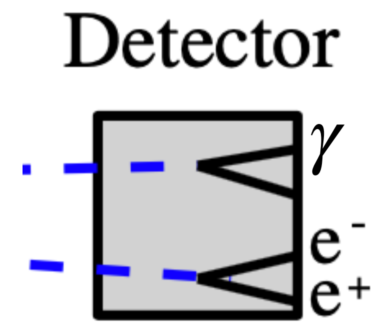
Primary production is limited to the LLP lifetime regime of $d \sim L_{min}$.

Secondary production: $\text{LLP}_1 + \text{SM} \rightarrow \text{LLP}_2 + \text{SM}$

Signal due to $\text{LLP}_2 \rightarrow \text{LLP}_1 + \text{ visible}$ or $\text{LLP}_{1,2} + e^- \rightarrow \text{LLP}_2 + e^-$.

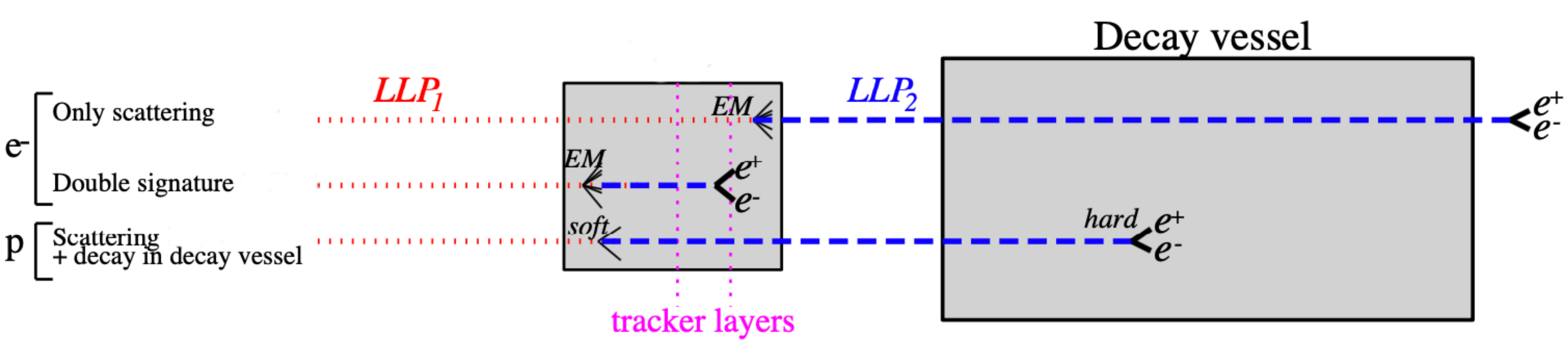
Coherent upscattering on nucleus ($\propto Z^2$) mediated by photon exchange is enhanced by the photon propagator $\sim 1/t \rightarrow$ Primakoff-like process for photon-coupled LLPs can be particularly effective.

LLP signatures at FASER



- **LLP signal inside the decay vessel – $\gamma\gamma$ or $\gamma + X$**
    - $E_{vis} > 100$ GeV
    - e^+e^- search: negligible background due to high energies of LLP's
    - γ search:
        - neutrino-induced BG minimized by preshower put in front of the calorimeter
        - BG from muon-induced photons vetoed by scintillators detecting a time-coincident muon going through the detector → *excess of single-photon events unaccompanied by any muon indicative of new physics*

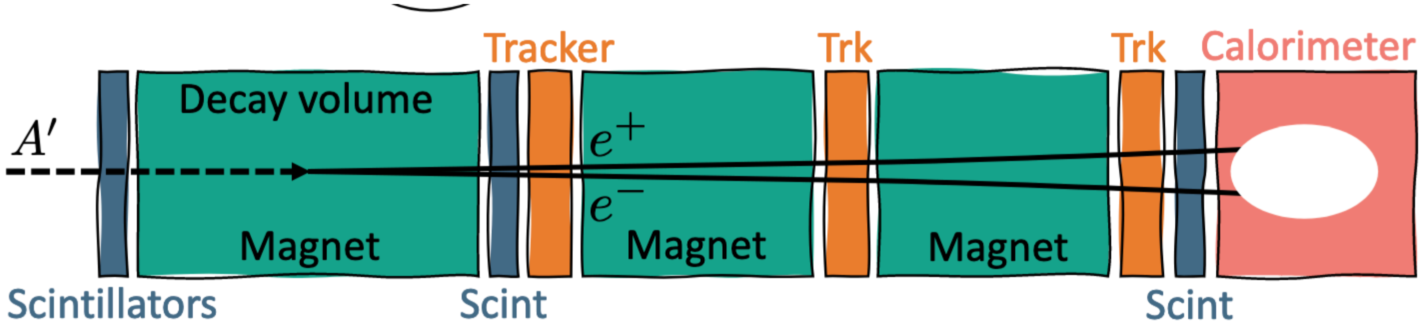
- **Scattering off electrons**
    - new-physics-induced neutrino scatterings off electrons producing electron recoils inside the neutrino detector.
    - *Energy and angular cuts:*
        - Electron energy and angular cuts following the DM scattering signature 2101.10338
        - The cuts have been designed to minimize the neutrino-induced BG to the level of $O(10)$ such expected events in FASERν2.

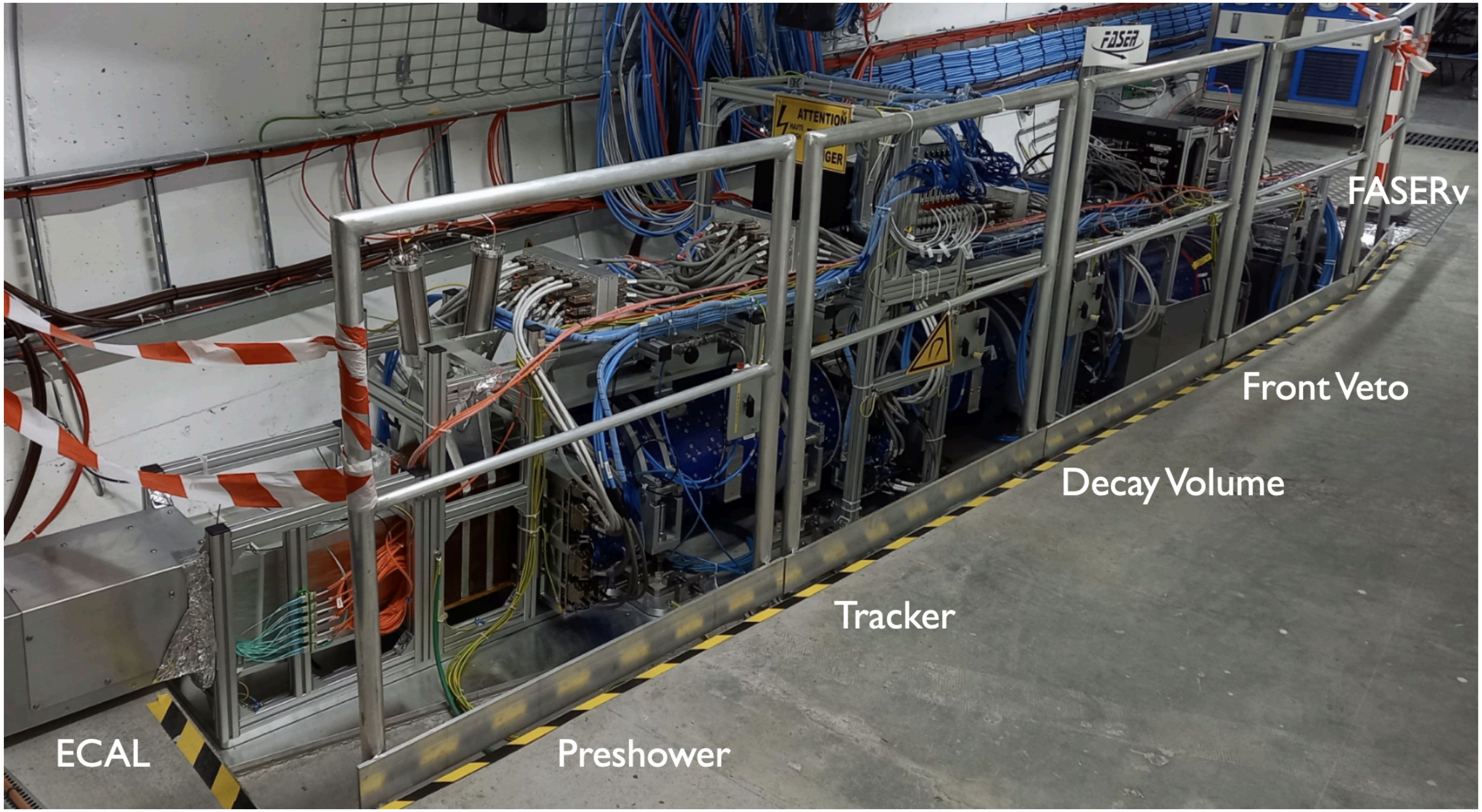


ForwArd Search ExpeRiment

FASER - start with LHC RUN3 (2022-2024), $\mathscr{L} = 150\text{fb}^{-1}$
$R = 0.1m$, $L = 1.5m$
FASER2 - start with HL-LHC
$\mathscr{L} = 3000\text{fb}^{-1}$; $R = 1m$, $L = 5m$

Feng, Gallon, Kling, Trojanowski, 1708.09389
Letter of Intent for FASER: ForwArd Search ExpeRiment at the LHC, 1811.10243; Technical Proposal for FASER: ForwArd Search ExpeRiment at the LHC, 1812.09139

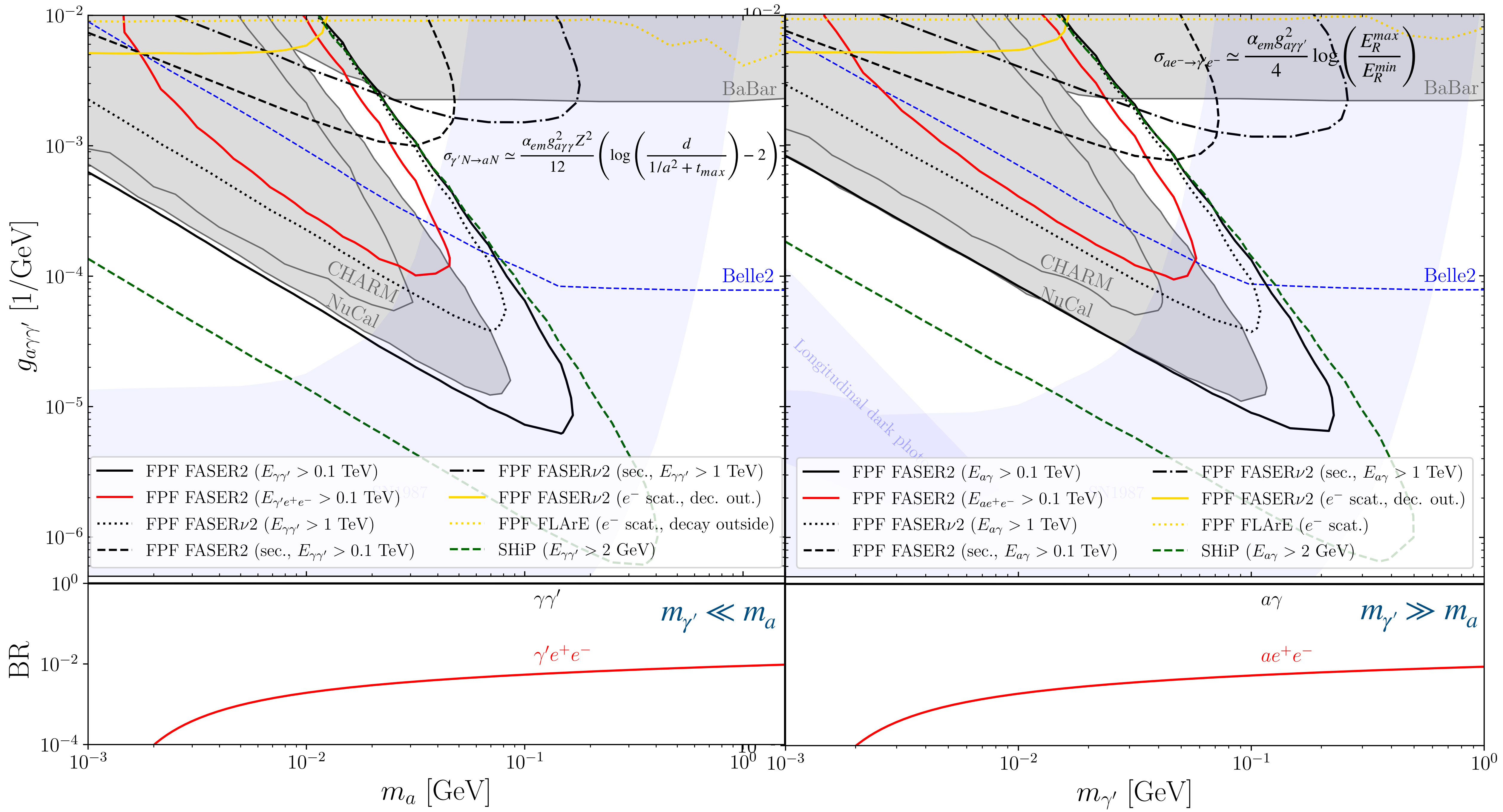




Dark Axion Portal at intensity frontier

$$\mathscr{L}_{\text{dark axion portal}} = \frac{g_{a\gamma\gamma'}}{2} a F_{\mu\nu} \tilde{F}'^{\mu\nu}$$

KJ Phys. Rev. D 108, 115017

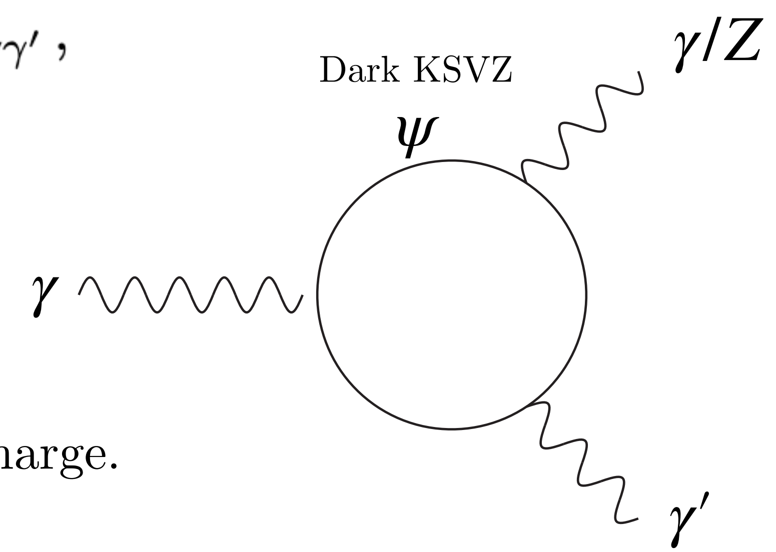


$$d_a \simeq 100\, m \times \left(\frac{E}{1000\, GeV}\right)\left(\frac{0.1\, GeV}{m_a}\right)^4 \left(\frac{4\times 10^{-5}}{g_{a\gamma\gamma'}}\right)^2,$$

$$d_{\gamma'} \simeq 100\, m \times \left(\frac{E}{1000\, GeV}\right)\left(\frac{0.1\, GeV}{m_{\gamma'}}\right)^4 \left(\frac{7\times 10^{-5}}{g_{a\gamma\gamma'}}\right)^2,$$

DAP and Z boson coupling

$$\mathcal{L} \supset \frac{g_{a\gamma\gamma'}}{2}\, a\, F_{\mu\nu}\tilde{F}_D^{\mu\nu} + \frac{g_{aZ\gamma'}}{2}\, a\, Z_{\mu\nu}\tilde{F}_D^{\mu\nu}\,, \text{ where } g_{aZ\gamma'} = -\tan\theta_W\, g_{a\gamma\gamma'}\,,$$

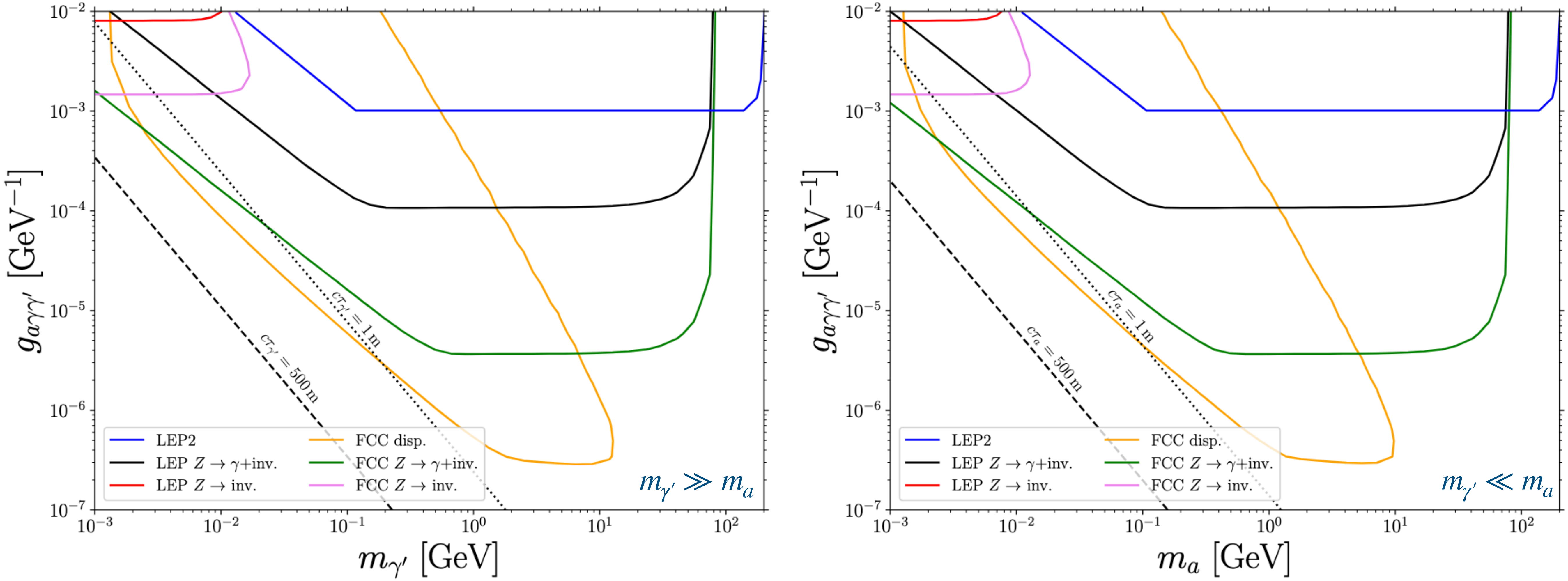


$$\mathcal{O}^{\mu\nu} B_{\mu\nu} = c_W \mathcal{O}^{\mu\nu} F_{\mu\nu} - s_W \mathcal{O}^{\mu\nu} Z_{\mu\nu}$$

For full *gauge-invariance*, one needs to replace photon field with hypercharge.

This allows to probe DAP at Z boson factories. In particular, LEP has already set stringent limits that constrain DM scenarios.

KJ, JHEP 2025, 22 (2025)



DAP and Z boson coupling

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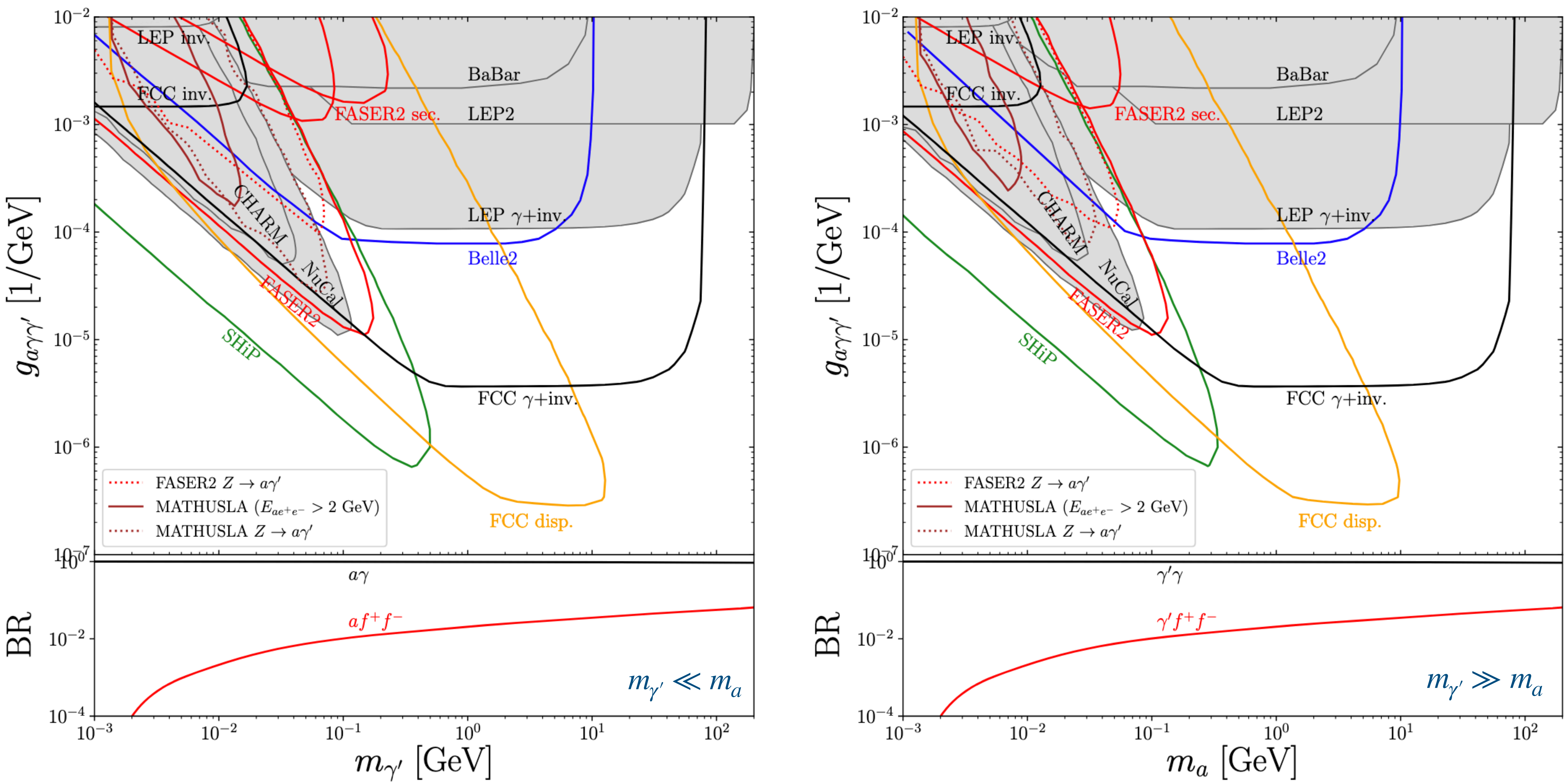
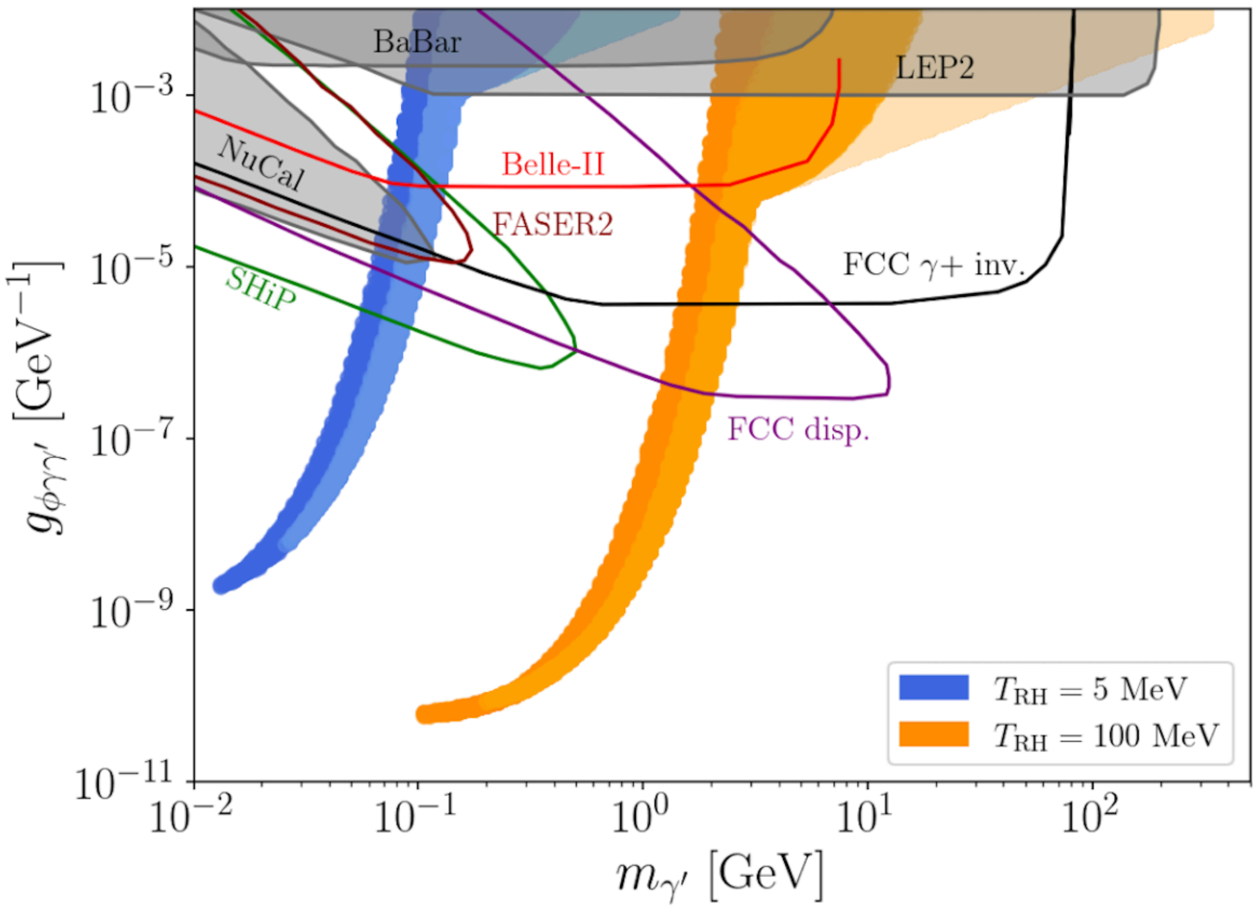
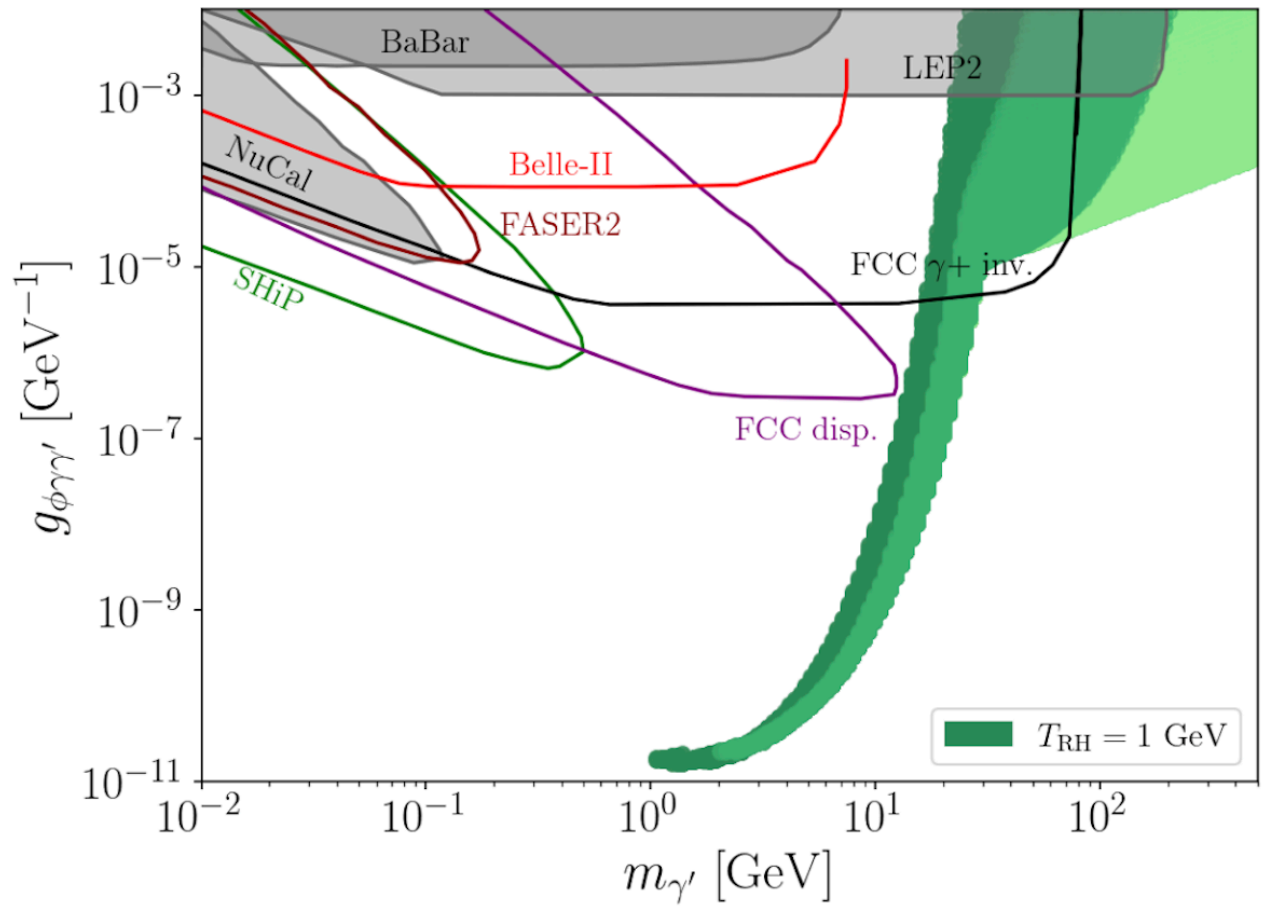


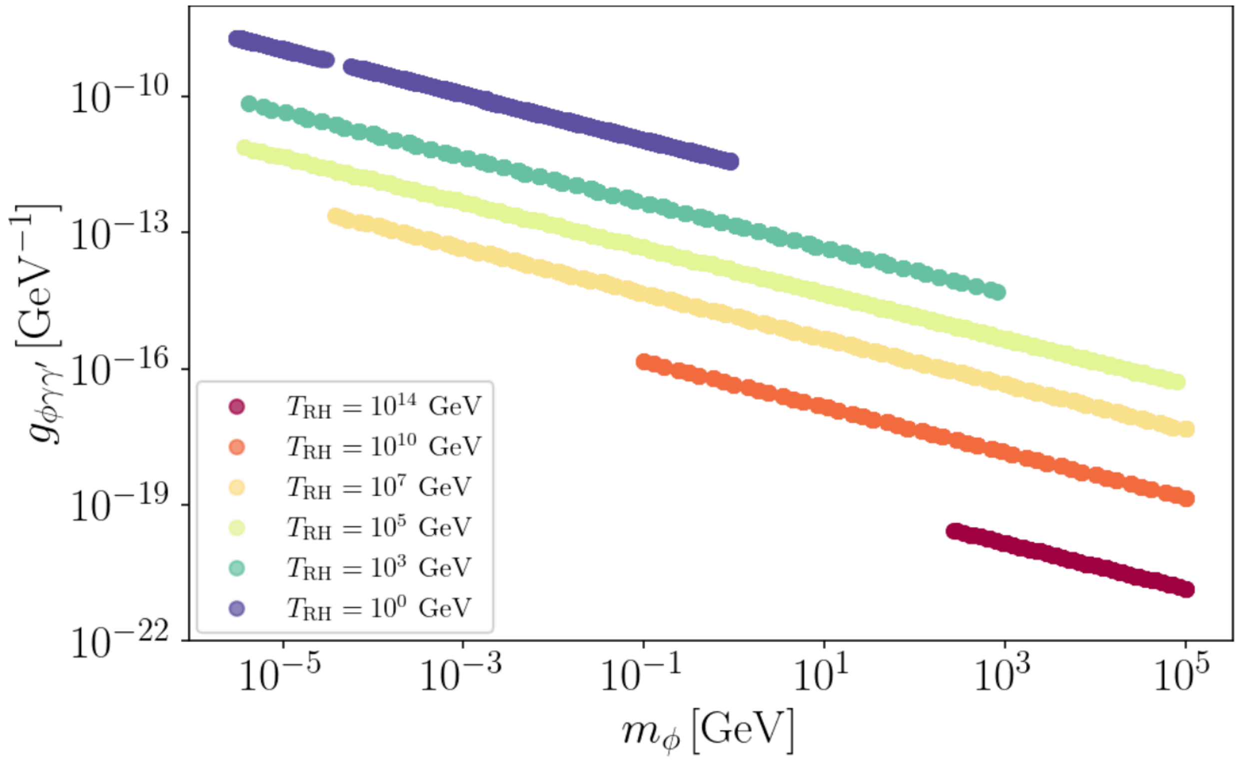
KJ, JHEP 2025, 22 (2025)

DAP and DM from freeze-in

Arias, Diaz Saez, Jaeckel, JCAP 06 (2025) 060







Conclusions

- Nature of neutrino masses provide one of the strongest motivation for physics BSM.
- Type-1 seesaw can be elegantly realized within Majoron singlet model, with Majorana mass occurring due to breaking of U(1) lepton global symmetry.
- We found that taon decays, $\tau \to \mu J$ provide leading production mechanism of sub-GeV majoron at beam dump experiments and we determined their sensitivities. They are competitive with bounds from astrophysics and FV experiments.

- We also studied another ALP model, DAP, which extends the invisible QCD axion by massive dark photon, allowing richer pheno possibilities: multiple DM candidates, relaxation, ...
- We determined leading bounds from intensity frontier experiments: beam dumps, Z boson factories (lepton colliders and LHC), finding coverage of sizable part of parameter space, where correct DM relic density is satisfied.