

Impact of flavor changing processes on prospects for majoron discovery at intensity-frontier searches

2026 Workshop on New Physics and Interdisciplinary Sciences (NPhiS 2026)

May 18th

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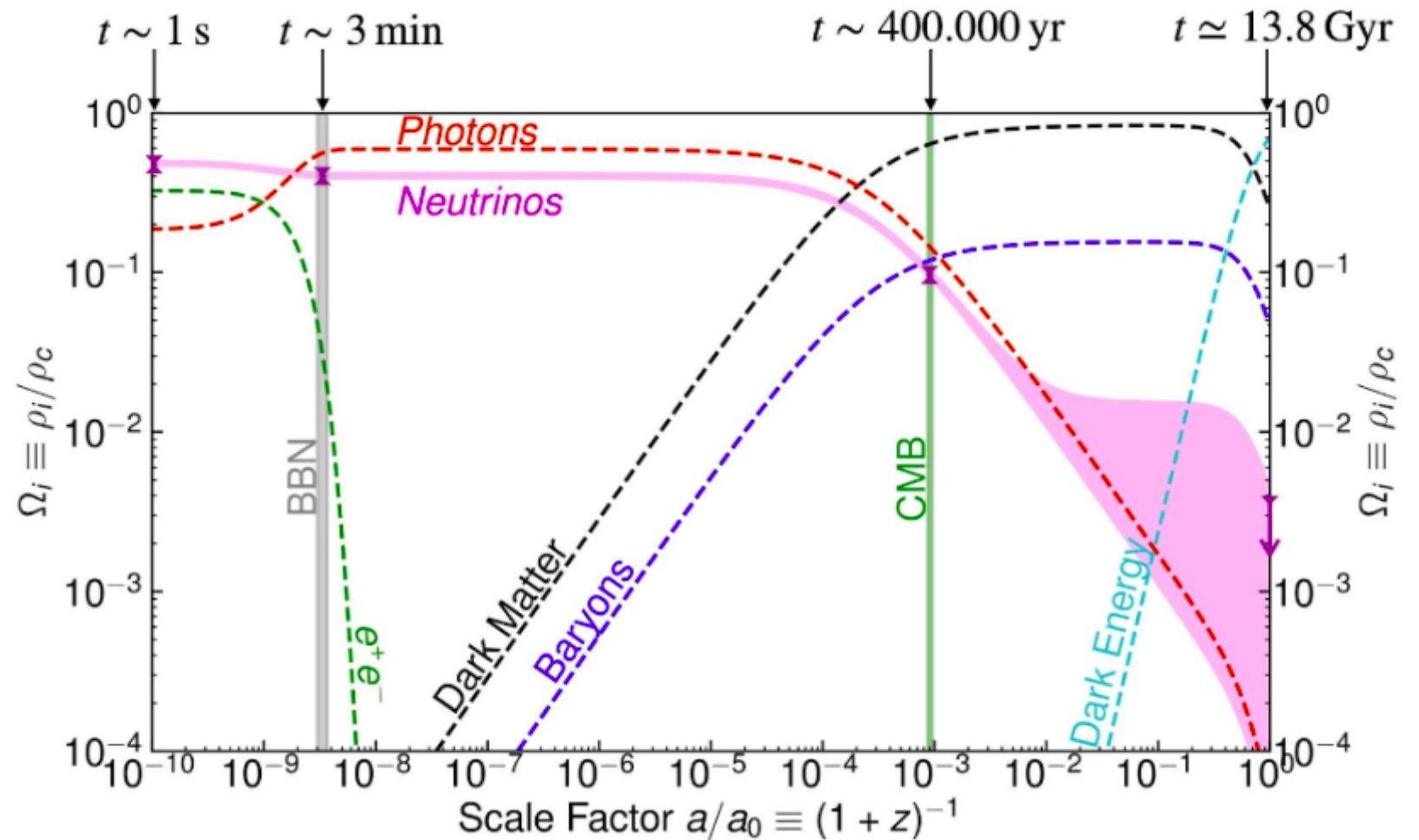
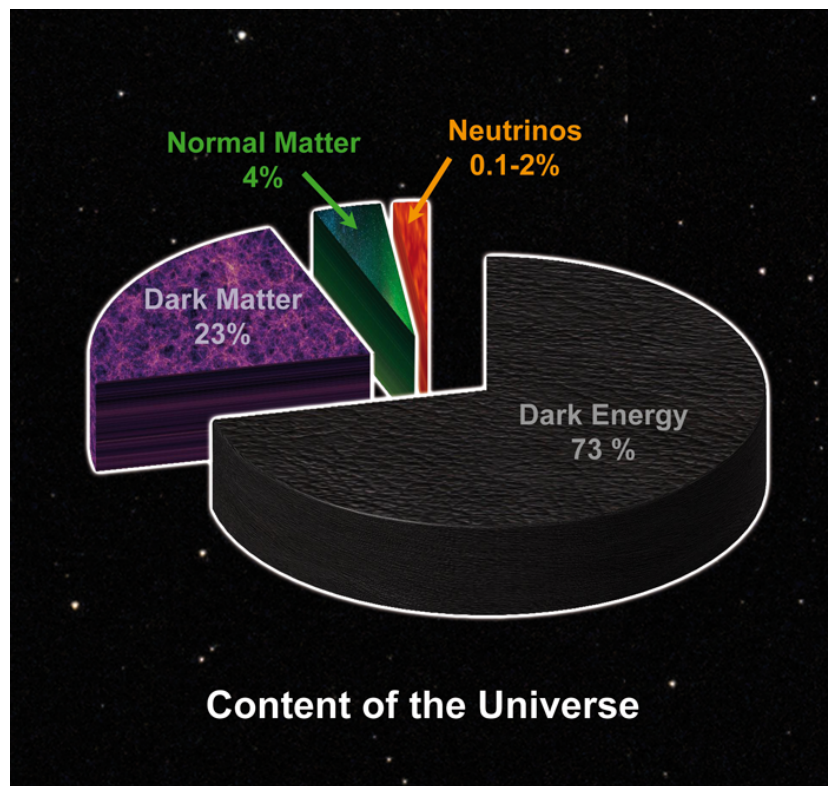
Nanjing Normal University

Based on:

[KJ](#), Chih-Ting Lu 2603.00635 [hep-ph]

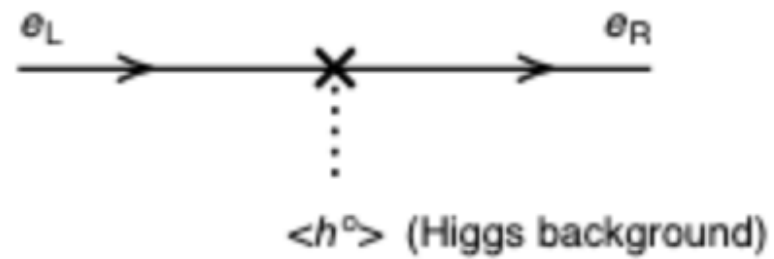


Λ CDM: The Dark Universe



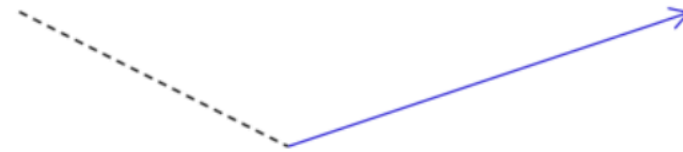
- Neutrinos are the only directly known part of the Dark Universe
- However, precise nature of neutrinos is *unknown* (Dirac/Majorana), as is their mass generation mechanism.
- Seesaw is an elegant UV completion of the Weinberg operator, pointing towards large scale $\Lambda \sim 10^{13}$ GeV for $m_\nu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

Dirac

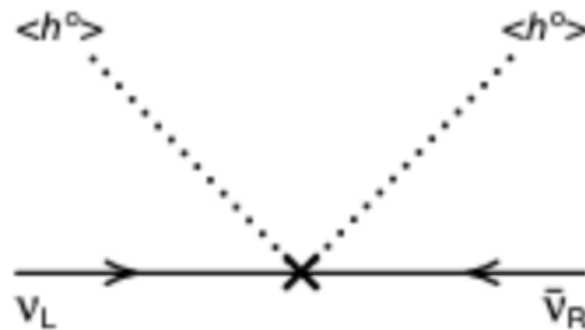


Majorana

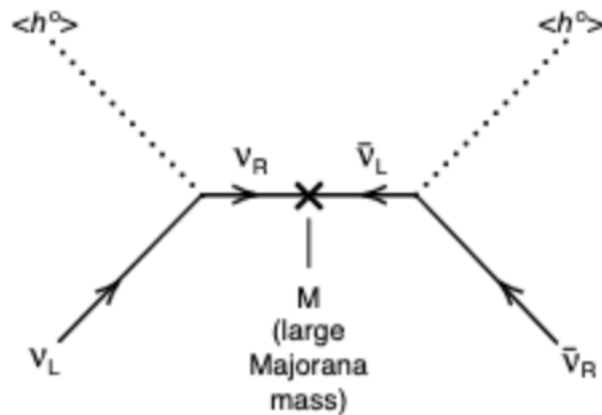
$$(L\Phi) = \nu_L \phi^0 - e_L \phi^+$$



1. Effective Majorana mass term



Seesaw



$$\mathcal{L} = -\frac{1}{2} \begin{pmatrix} \bar{\nu}_L & \bar{\nu}_R^c \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix}$$

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

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

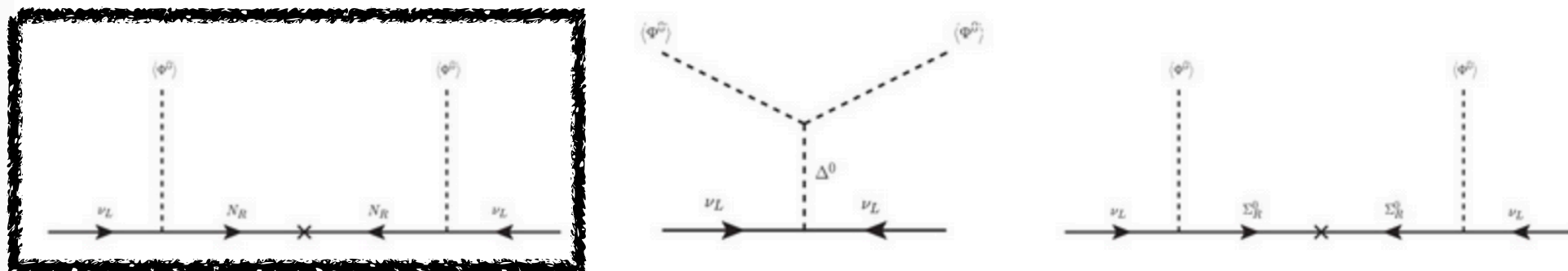
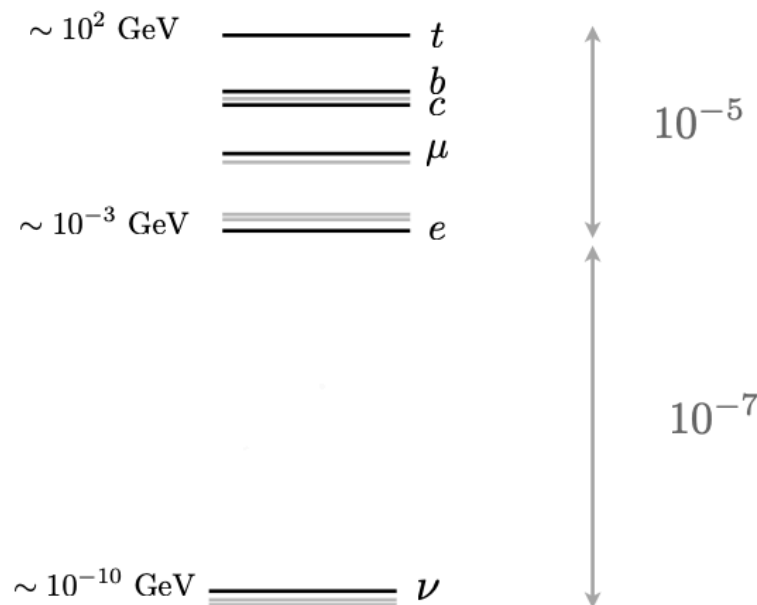


Figure 1. Feynman diagram generating Majorana masses in Type I, II and III seesaw mechanism.

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.

Type I from breaking $U(1)_L$

- neutrino masses



Neutrino mass: Dirac or Majorana?

- Dirac Neutrinos (Higgs Mechanism)

$$\mathcal{L} = -\frac{1}{2} (\bar{\nu}_L \quad \bar{\nu}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & 0 \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.} \quad m_i = m_D \sim 10^{-2} \text{ eV}$$

- Majorana Neutrinos (Seesaw Mechanism)

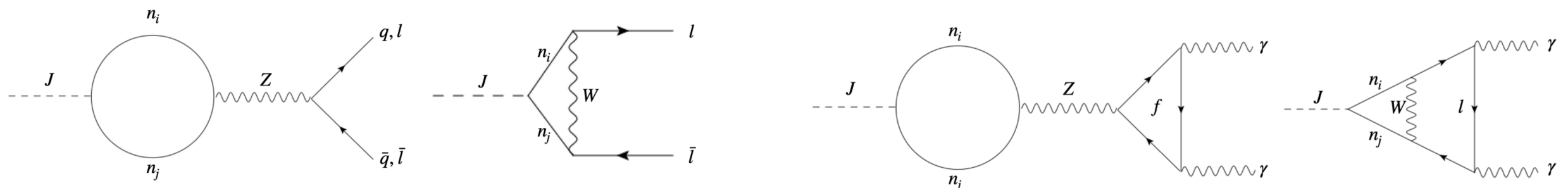
$$\mathcal{L} = -\frac{1}{2} (\bar{\nu}_L \quad \bar{\nu}_R^c) \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.} \quad m_i \sim m_D^2/M_R \sim 10^{-2} \text{ eV}$$

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

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



Singlet Majoron

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + i\bar{\nu}_R \gamma_\mu \partial_\mu \nu_R + \partial_\mu \Sigma^\dagger \partial_\mu \Sigma - \lambda_D \Phi^* \bar{E}_L \nu_R$$

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

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

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

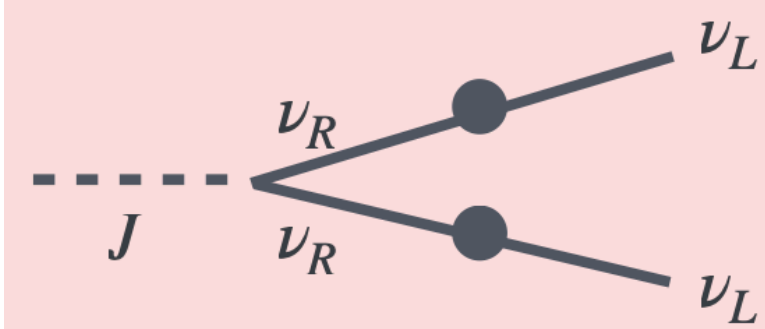
Singlet $\Sigma = \frac{1}{\sqrt{2}} (f + \sigma(x) + i J(x))$ with $LN = -2$.

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)



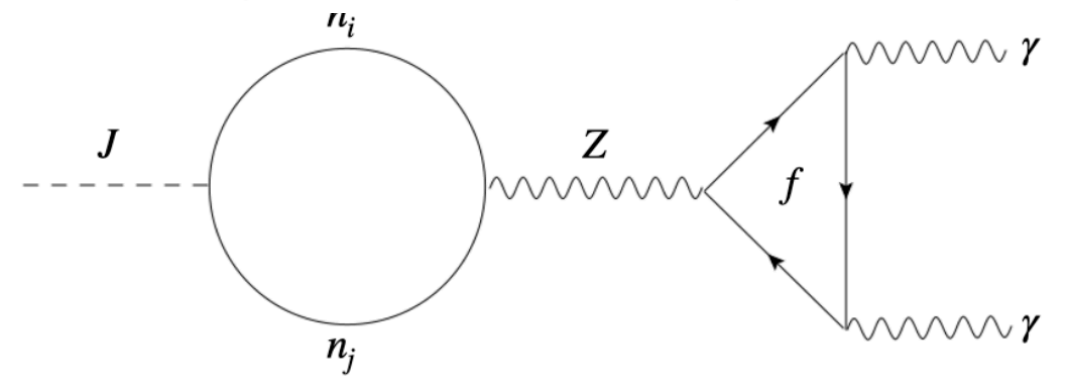
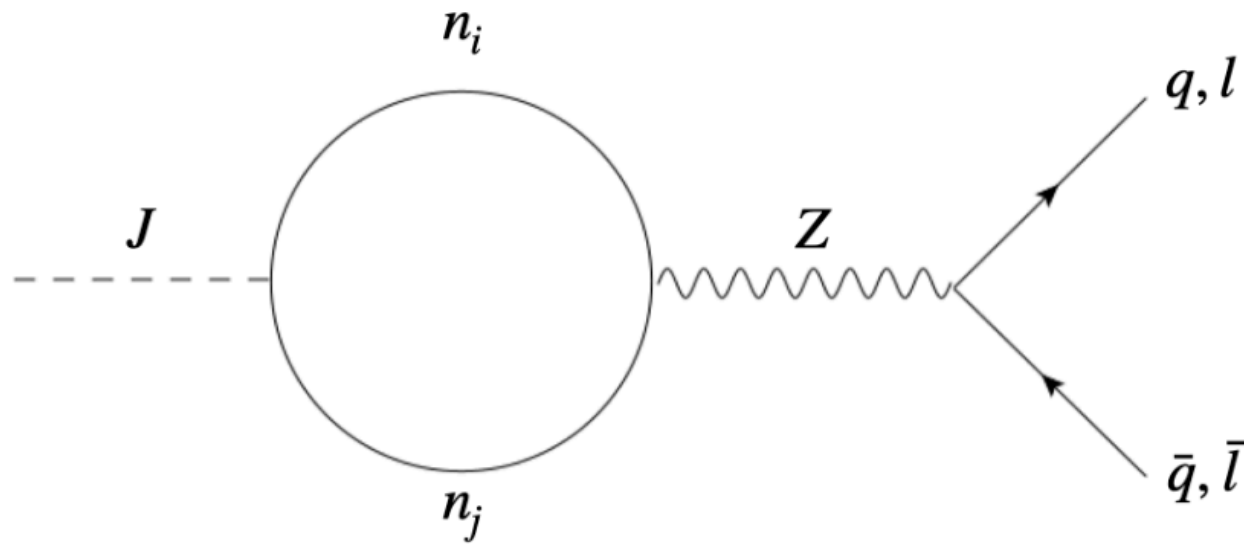
$$\mathcal{L}_{\text{int}} = -\frac{iM_R}{2f} J \bar{\nu}_R^c \nu_R + \text{h.c.}$$

Majoron interactions

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

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

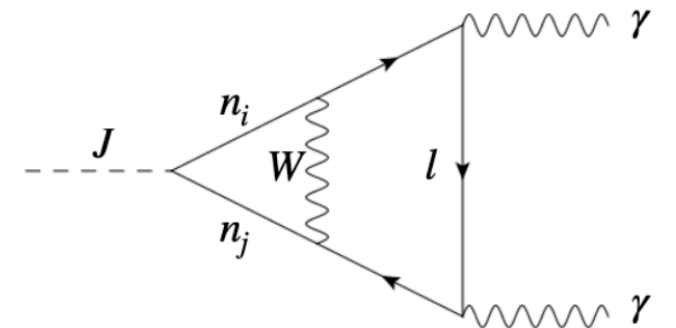
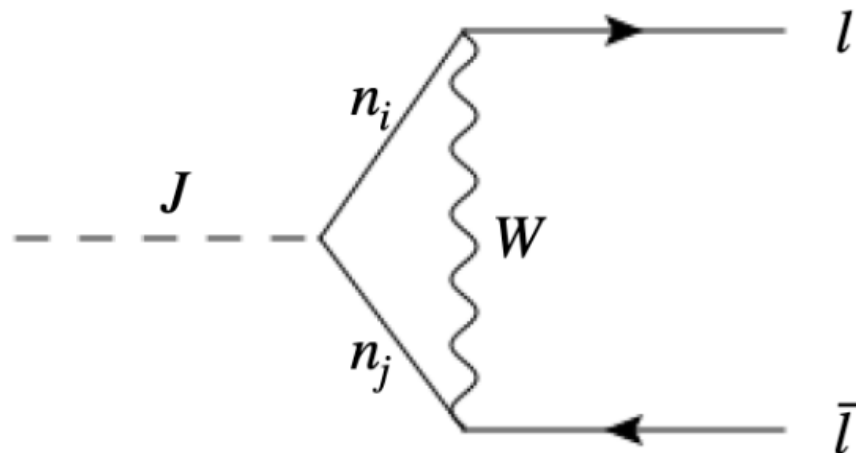
$$\mathcal{L}_{\text{int}}^{\text{tree}} = -\frac{\partial_\mu J}{4f} \sum_{i=1}^3 \bar{\nu}_i \gamma^\mu \gamma_5 \nu_i = \frac{iJ}{2f} \sum_{i=1}^3 m_i \bar{\nu}_i \gamma_5 \nu_i,$$



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

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

Davidson–Ibarra parametrization



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

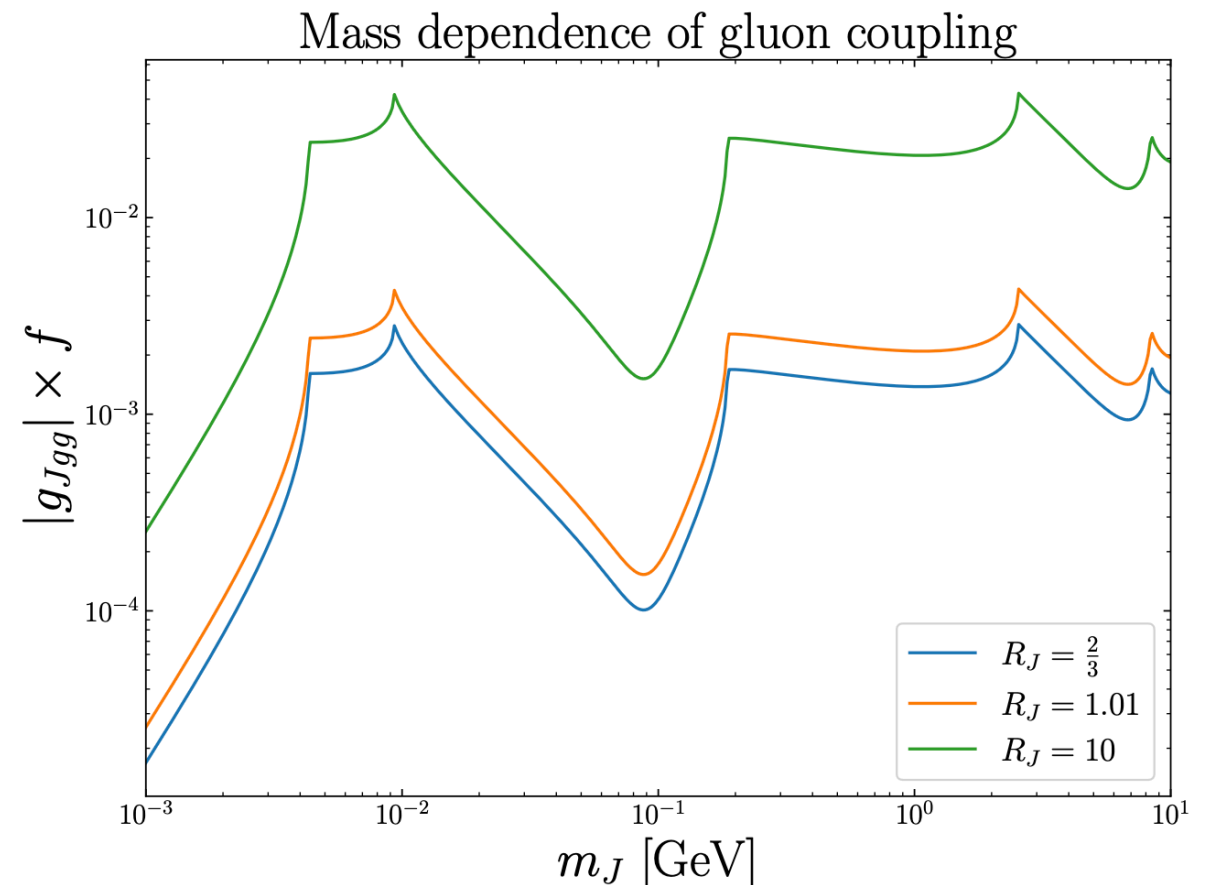
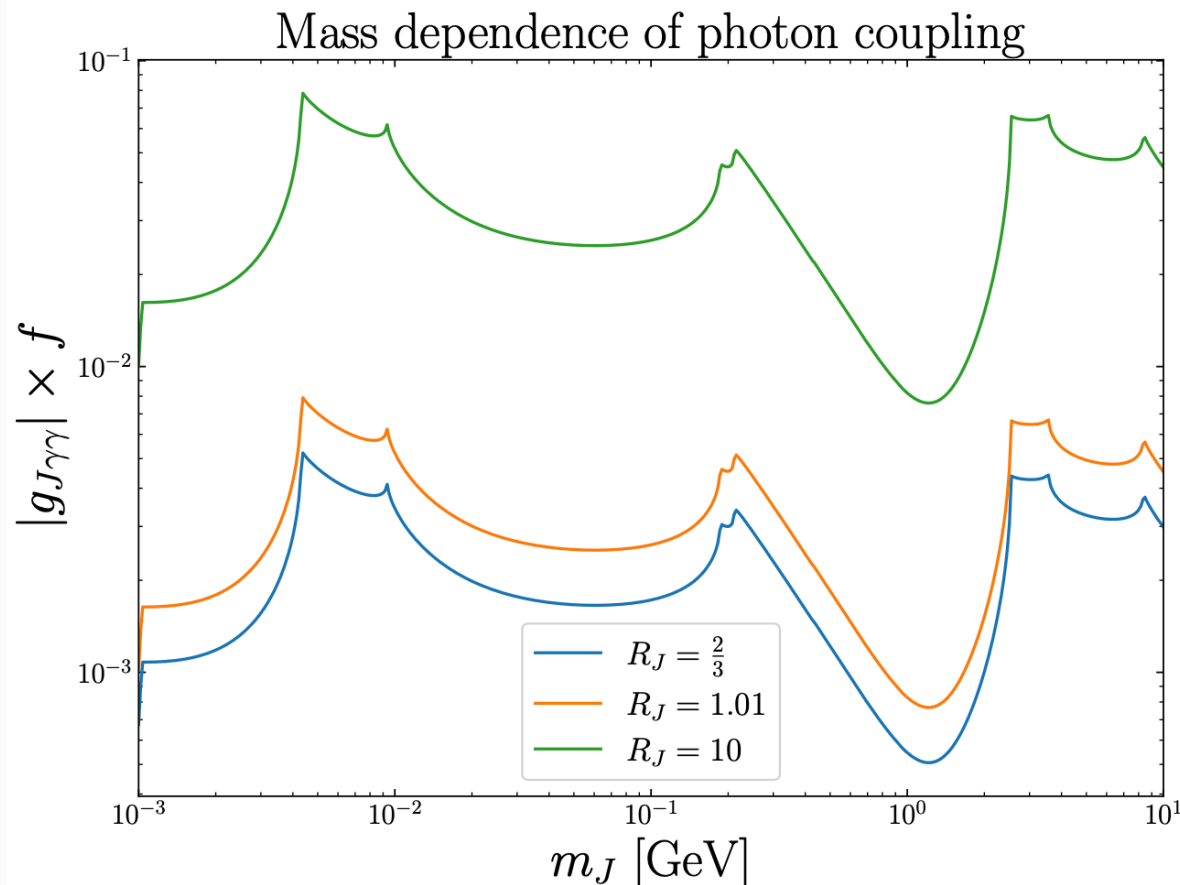
$$\Gamma(J \rightarrow l\bar{l}') \simeq \frac{m_J}{8\pi} \left(\left| \frac{m_l + m_{l'}}{16\pi^2 v} (\delta_{ll'} T_3^l \text{tr} K + K_{ll'}) \right|^2 + \left| \frac{m_l - m_{l'}}{16\pi^2 v} K_{ll'} \right|^2 \right)$$

Couplings: gauge bosons

$$\mathcal{L}_{\text{int}}^{\text{loop}} = \frac{1}{2f} \partial_\mu J \bar{\psi} \gamma^\mu (C_V + C_A \gamma_5) \psi + \frac{g_{J\gamma\gamma}}{4} J F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{g_{J\gamma Z}}{2} J F_{\mu\nu} \tilde{Z}^{\mu\nu} \\ + \frac{g_{Jgg}}{4} J G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{g_{JZZ}}{4} J Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{g_{JWW}}{4} J W_{\mu\nu}^+ \tilde{W}^{-\mu\nu}.$$

$$g_{J\gamma\gamma} \simeq \frac{\alpha m_J^2}{96\pi^3 v} \left[\left(\frac{K_{ee}}{m_e^2} + \frac{K_{\mu\mu}}{m_\mu^2} + \frac{K_{\tau\tau}}{m_\tau^2} \right) - \frac{\text{Tr } K}{2m_e^2} \right],$$

$$g_{Jgg} \simeq \frac{\alpha_S m_J^2}{384\pi^3 m_u^2 v} \text{Tr}(K), \quad g_{JZ\gamma} \simeq -\frac{\alpha}{8\pi^3 v} \text{Tr } K.$$



Couplings: fermions

$$\mathcal{L}_{\text{int.}} \supset \frac{1}{2f} \partial_\mu J (\bar{e} \bar{\mu} \bar{\tau}) \gamma^\mu (C_V^\ell + C_A^\ell \gamma_5) \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix} \\ + \frac{1}{2f} \partial_\mu J (\bar{u} \bar{c} \bar{t}) \gamma^\mu (C_V^u + C_A^u \gamma_5) \begin{pmatrix} u \\ c \\ t \end{pmatrix} + \frac{1}{2f} \partial_\mu J (\bar{d} \bar{s} \bar{b}) \gamma^\mu (C_V^d + C_A^d \gamma_5) \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$\text{Leptons:} \quad C_V^o = -C_A^o, \quad C_V^\ell = \frac{f K}{8\pi^2 v}, \quad C_A^\ell = -\frac{f}{8\pi^2 v} \left(K - \frac{\text{Tr}(K)}{2} \mathbb{1}_{3 \times 3} \right),$$

$$\text{Quarks:} \quad C_V^u = C_V^d = 0, \quad C_A^u = -C_A^d = \frac{f}{16\pi^2 v} \text{Tr}(K) \mathbb{1}_{3 \times 3}$$

$$K \equiv \frac{M_D M_D^\dagger}{v f} = \begin{pmatrix} K_{ee} & K_{e\mu} & K_{e\tau} \\ K_{e\mu}^* & K_{\mu\mu} & K_{\mu\tau} \\ K_{e\tau}^* & K_{\mu\tau}^* & K_{\tau\tau} \end{pmatrix},$$

Benchmarks

$$K_{\text{anarch}} = \begin{pmatrix} K^d & K^o & K^o \\ K^o & K^d & K^o \\ K^o & K^o & K^d \end{pmatrix} = \frac{8\pi^2 v}{f} \begin{pmatrix} R_J & 1 & 1 \\ 1 & R_J & 1 \\ 1 & 1 & R_J \end{pmatrix},$$

$$K_{\mu\tau} = K^d \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \kappa_{\mu\tau} \\ 0 & \kappa_{\mu\tau}^* & 1 \end{pmatrix}, \quad K_{e\tau} = K^d \begin{pmatrix} 1 & 0 & \kappa_{e\tau} \\ 0 & 1 & 0 \\ \kappa_{e\tau}^* & 0 & 1 \end{pmatrix}$$

$$K^{\text{CPV}} = K^d \begin{pmatrix} 1 & i\kappa & i\kappa \\ -i\kappa & 1 & i\kappa \\ -i\kappa & -i\kappa & 1 \end{pmatrix}, \quad |K^d| = 8\pi^2 v/f,$$

Vector-axial coupling interplay

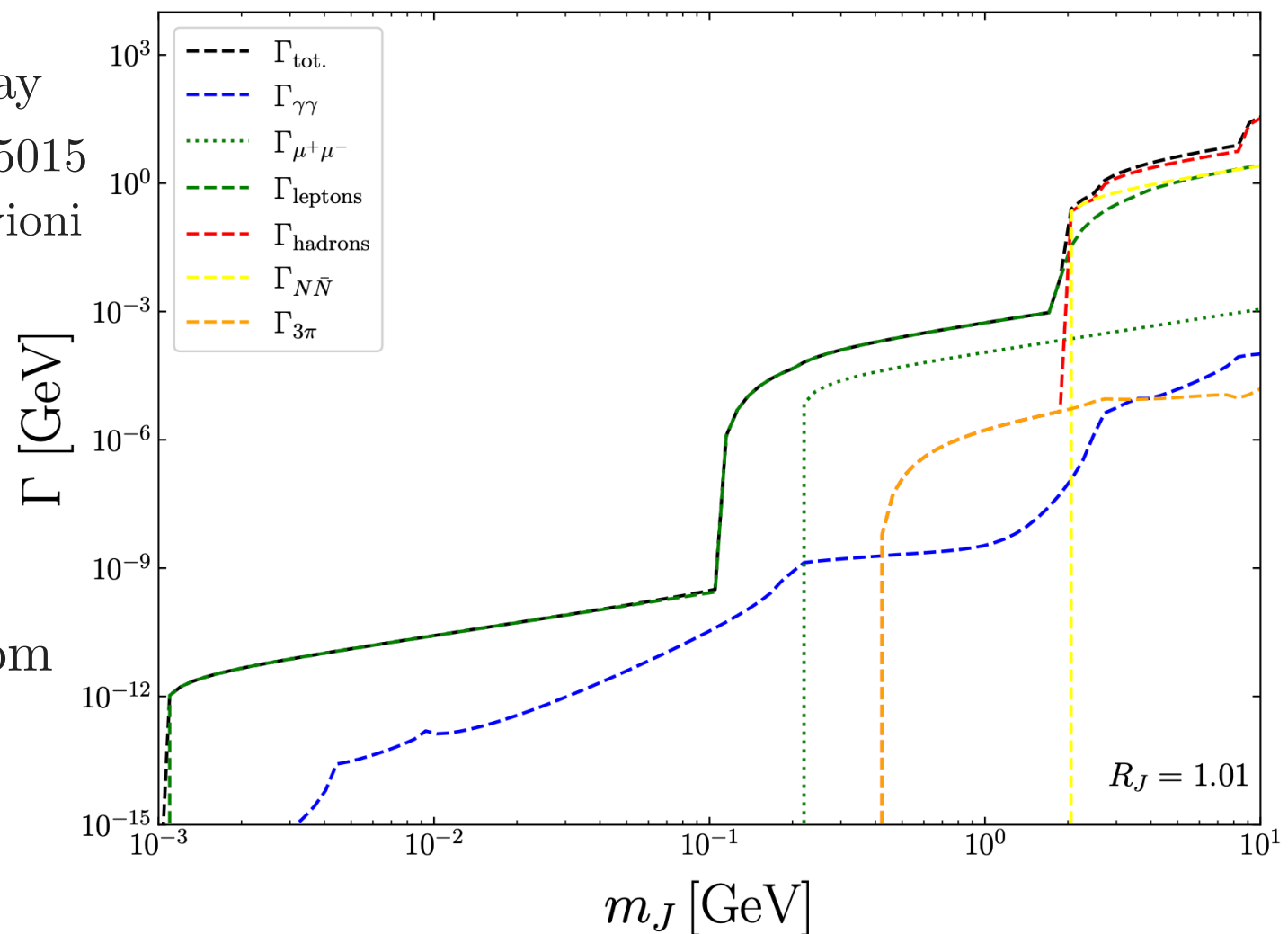
$$\mathcal{L} \supset \frac{\partial_\mu a(x)}{f} \bar{\ell} \gamma^\mu (C_V + C_A \gamma_5) \ell + \frac{\alpha_{EM}}{4\pi} \frac{a(x)}{f} F \tilde{F},$$

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 $R \sim \mathcal{O}(0.1 - 10)$, $J \rightarrow \mu\mu$ dominates in the sub-GeV region.

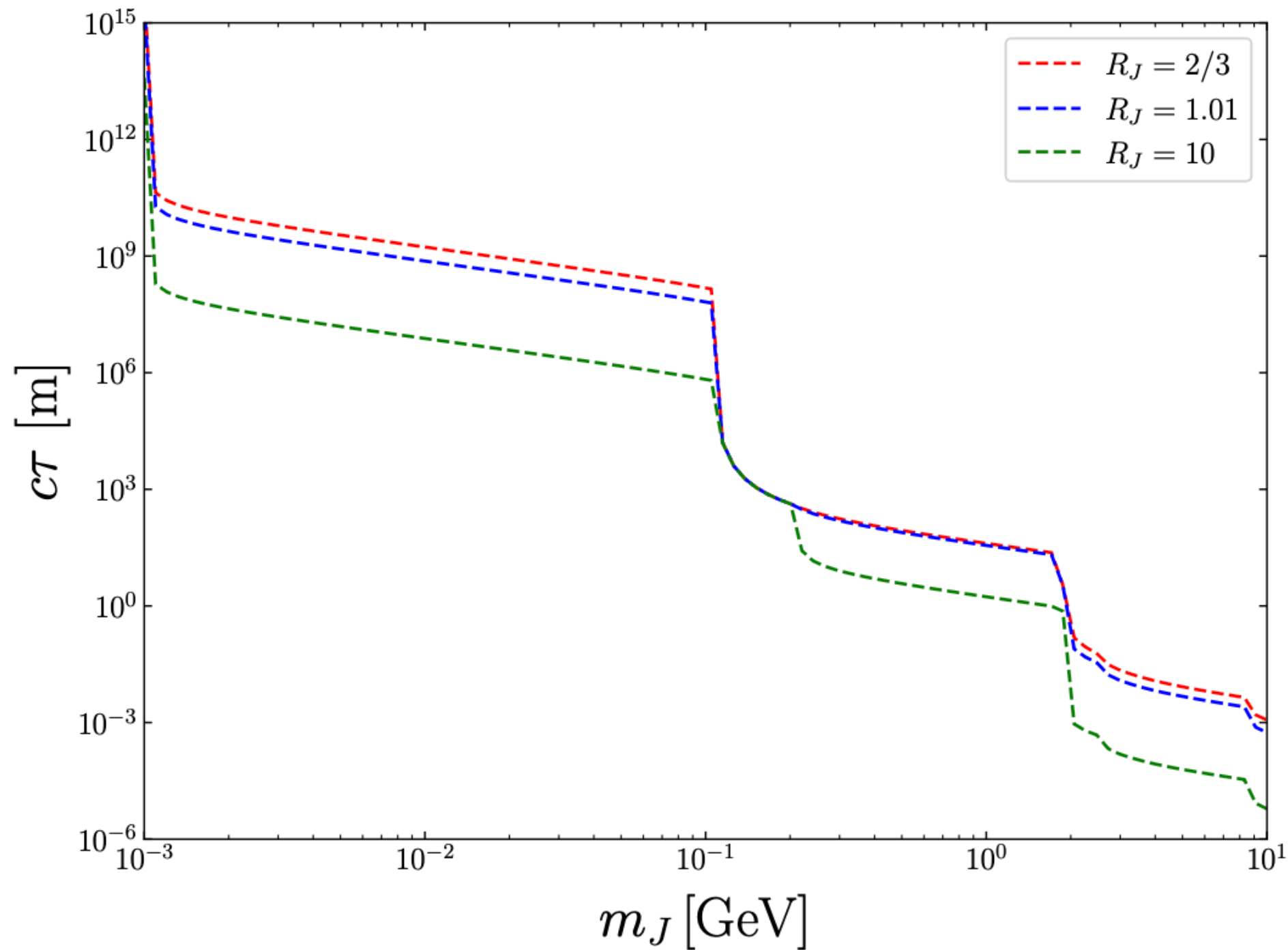
Leading production mechanism comes from taon decays: $\tau \rightarrow \mu J$, $\tau \rightarrow e J$

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



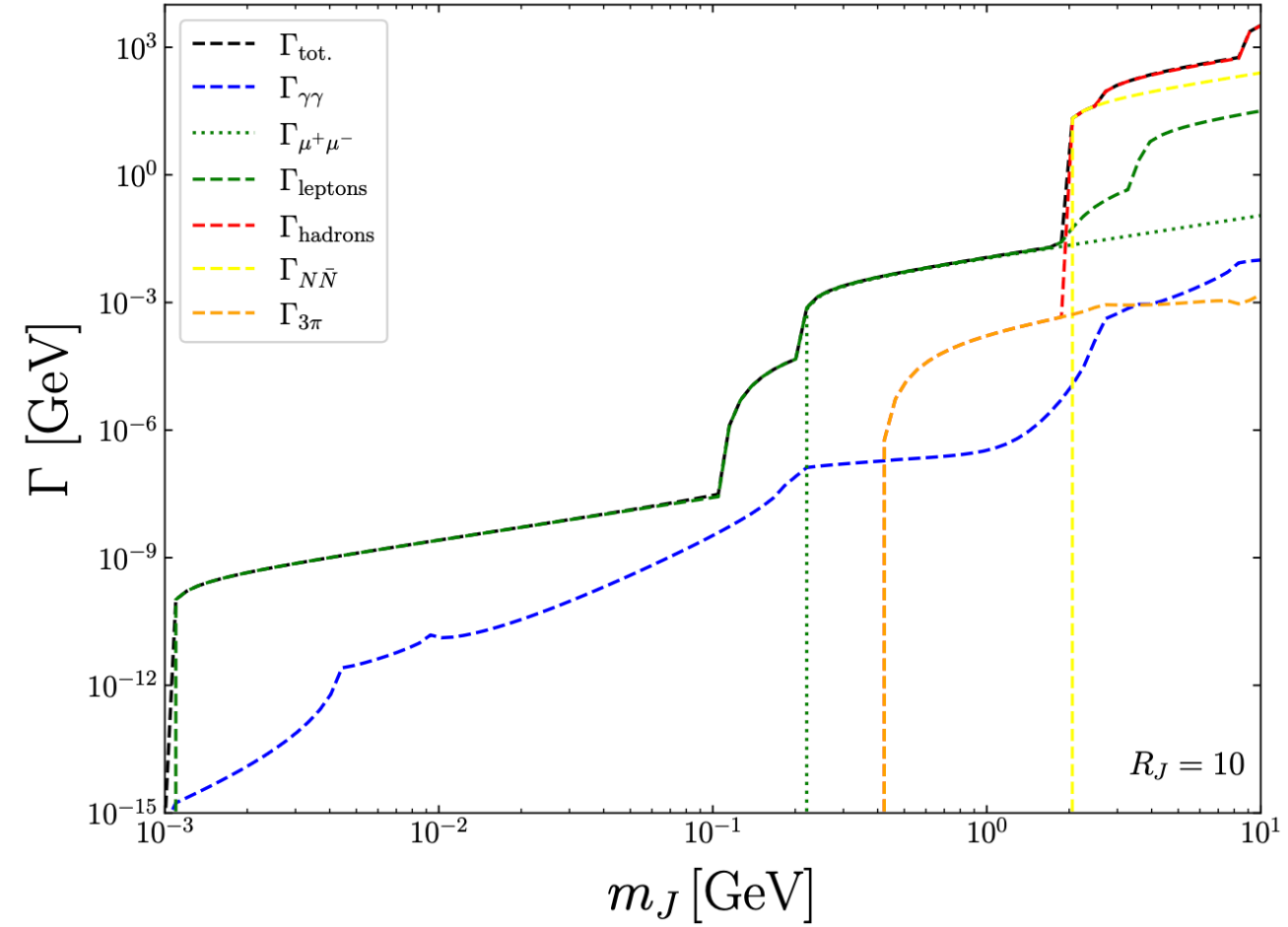
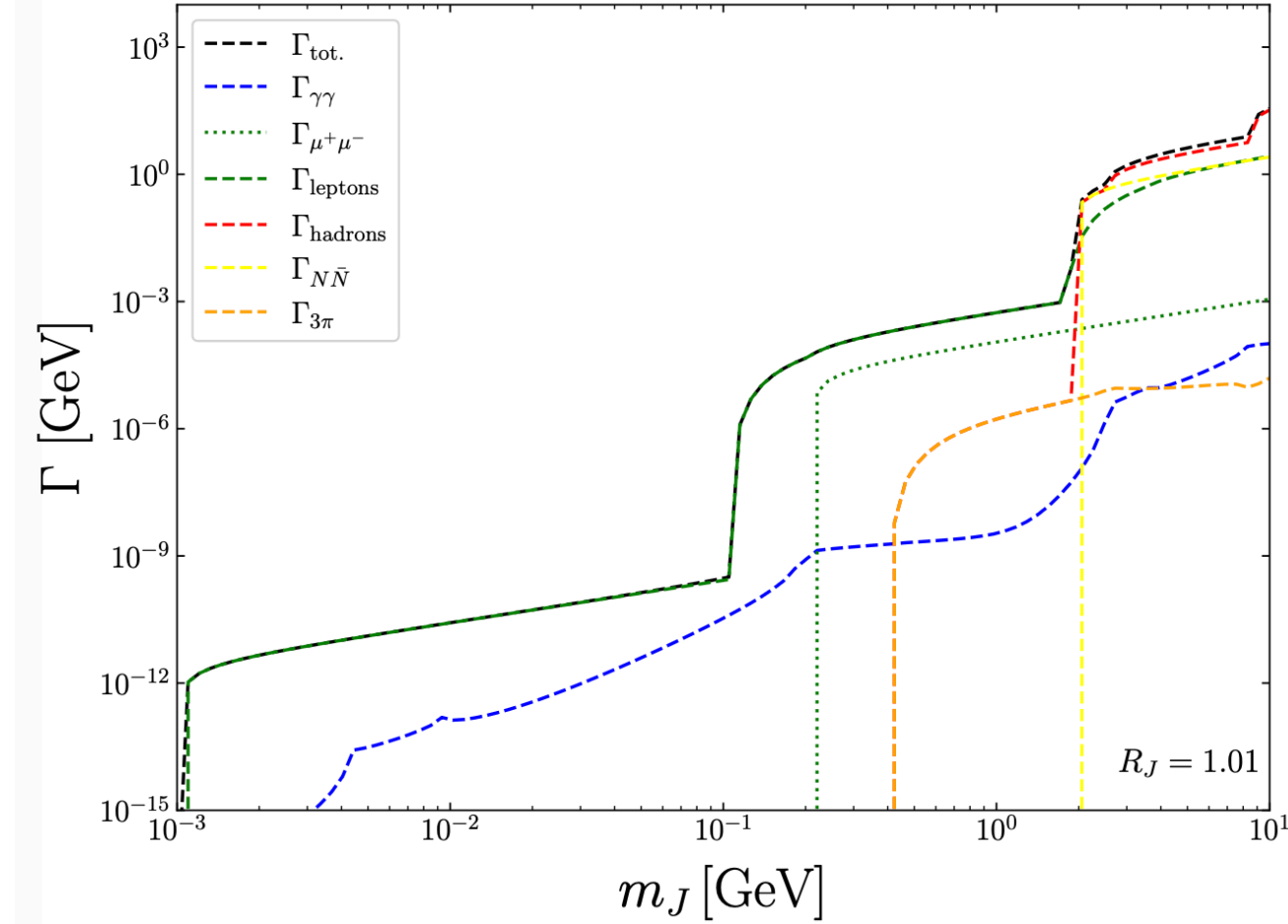
In beam dumps, taons are produced from D meson decays $\rightarrow$ leading J production mode. One can also use muons, $\mu \rightarrow e J$. For example, $N_\mu \sim 10^{11}$ at FASER2.

GeV-scale Majoron



$$\Gamma(J \rightarrow \psi_i \bar{\psi}_i) = \frac{m_i^2 m_J}{8\pi f^2} (C_A^{ii})^2 \sqrt{1 - \frac{4m_i^2}{m_J^2}},$$

GeV-scale Majoron decays



$$\Gamma(J \rightarrow \gamma\gamma) = \frac{g_{J\gamma\gamma}^2 m_J^3}{64\pi}. \quad \Gamma(J \rightarrow \psi_i \bar{\psi}_i) = \frac{m_i^2 m_J}{8\pi f^2} (C_A^{ii})^2 \sqrt{1 - \frac{4m_i^2}{m_J^2}},$$

$$\Gamma(J \rightarrow \pi^0 \pi^0 \pi^0) = \frac{\pi m_J m_{\pi^0}^4}{6 f_\pi^2} \left[\frac{g_{Jgg}}{4 g_s^2} \frac{m_d - m_u}{m_d + m_u} + \frac{C_A^{uu} - C_A^{dd}}{32\pi^2 f} \right]^2 \frac{2}{\left(1 - \frac{m_{\pi^0}^2}{m_J^2}\right)^2} \times$$

$$\times \int_{\frac{4m_{\pi^0}^2}{m_J^2}}^{(1 - \frac{m_{\pi^0}}{m_J})^2} dz \sqrt{1 - \frac{4m_{\pi^0}^2}{m_J^2 z}} \lambda^{1/2} \left(1, z, \frac{m_{\pi^0}^2}{m_J^2}\right), \quad (3.6)$$

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 sharp peak.

- 1802.08019, 2305.18526, 2210.03848

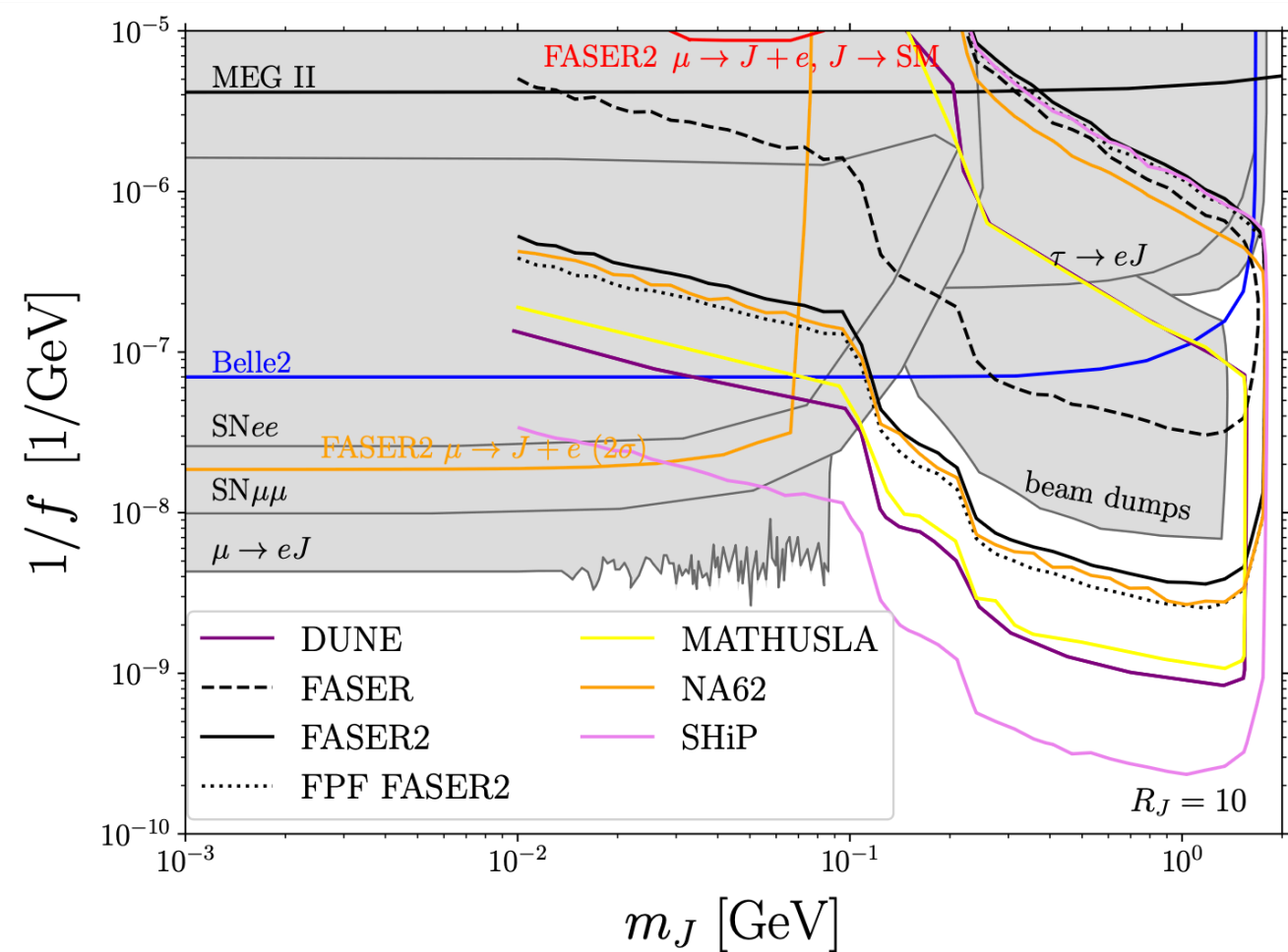
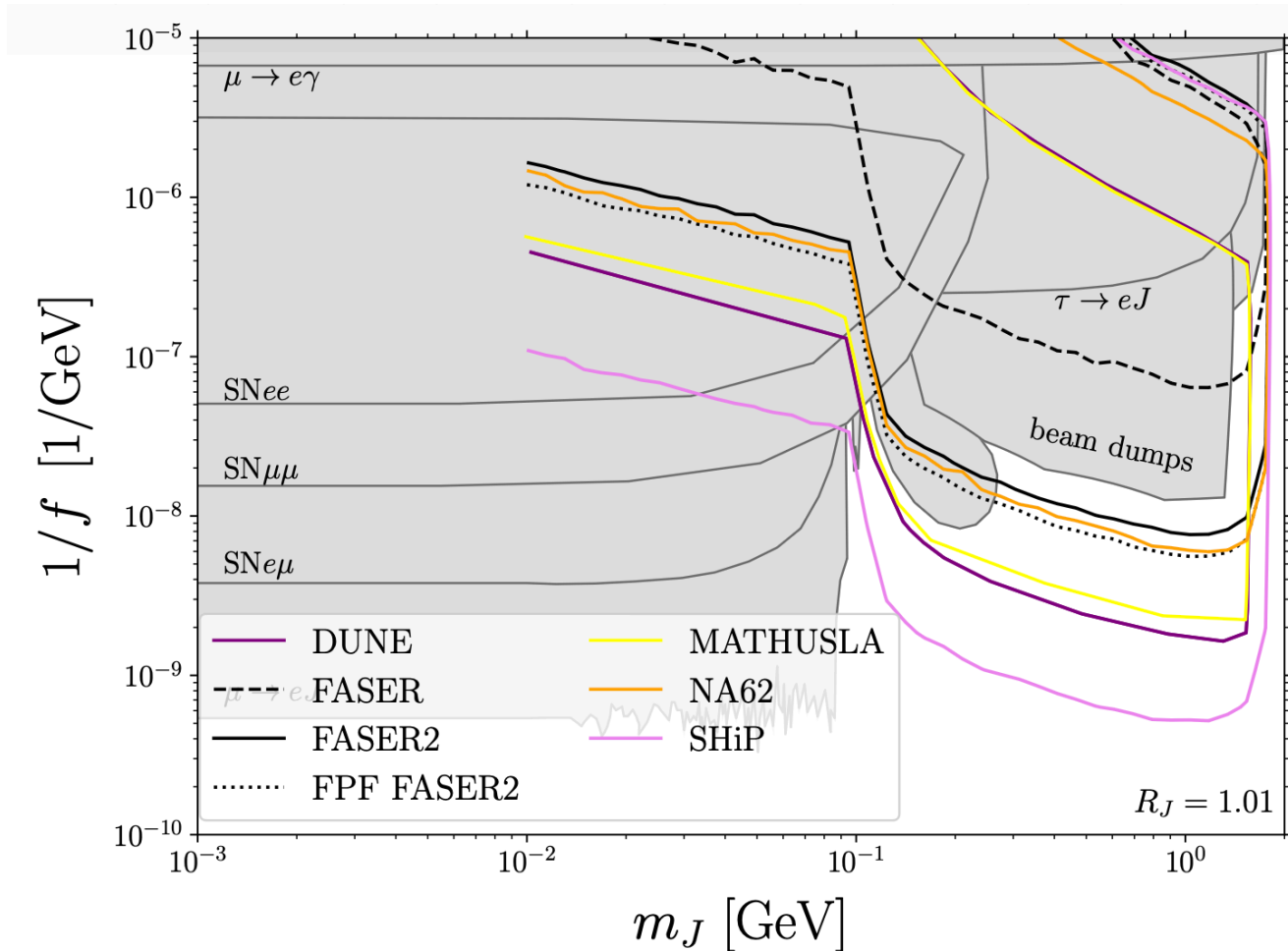
4. ALP-like searches for decays or missing energy.

- 2202.12317, 2507.15271, 2310.02709, 2306.05943

Production from flavor violating decays
at beam dumps, FASER

$$\begin{aligned}\tau &\rightarrow \mu J \\ \mu &\rightarrow e J\end{aligned}$$

Results

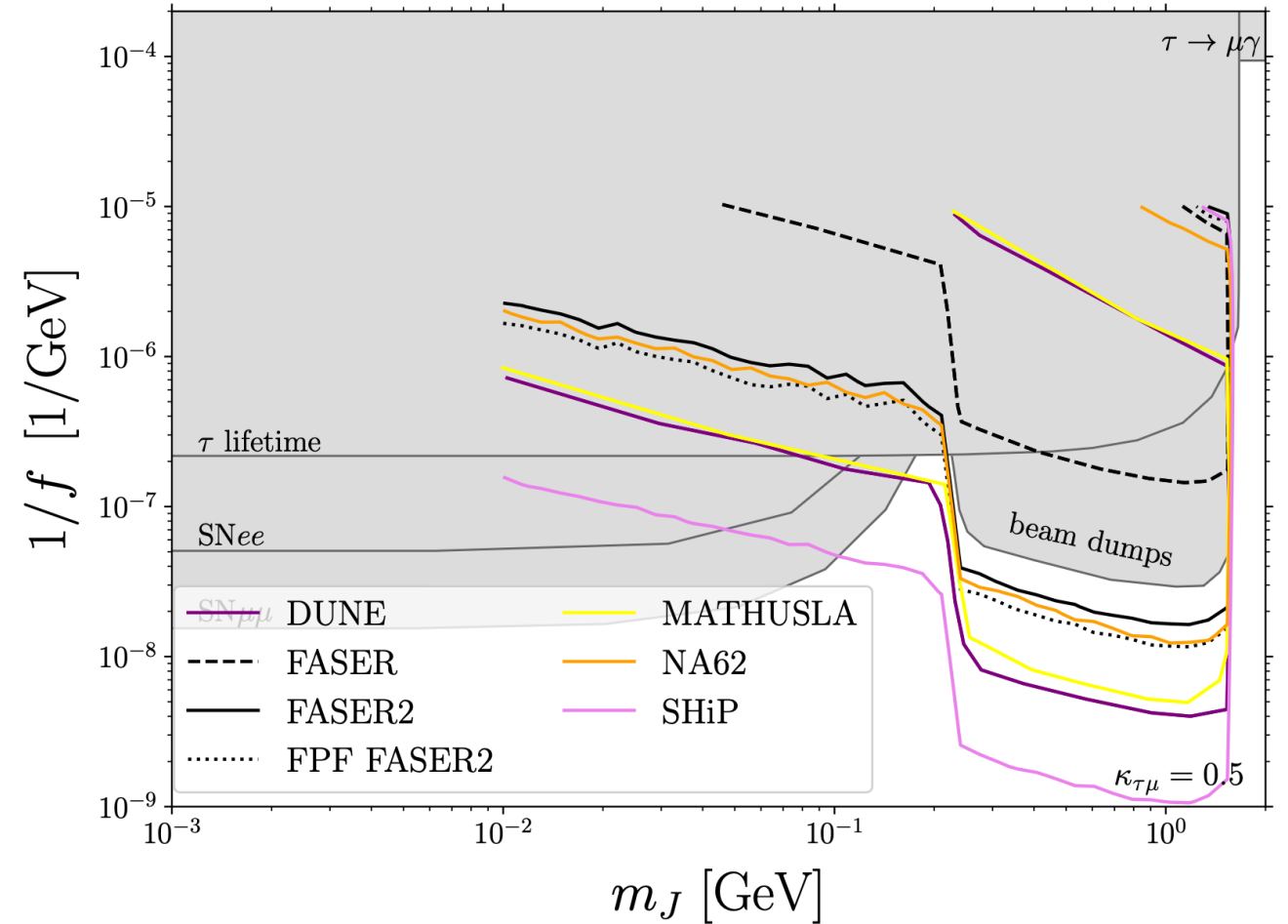
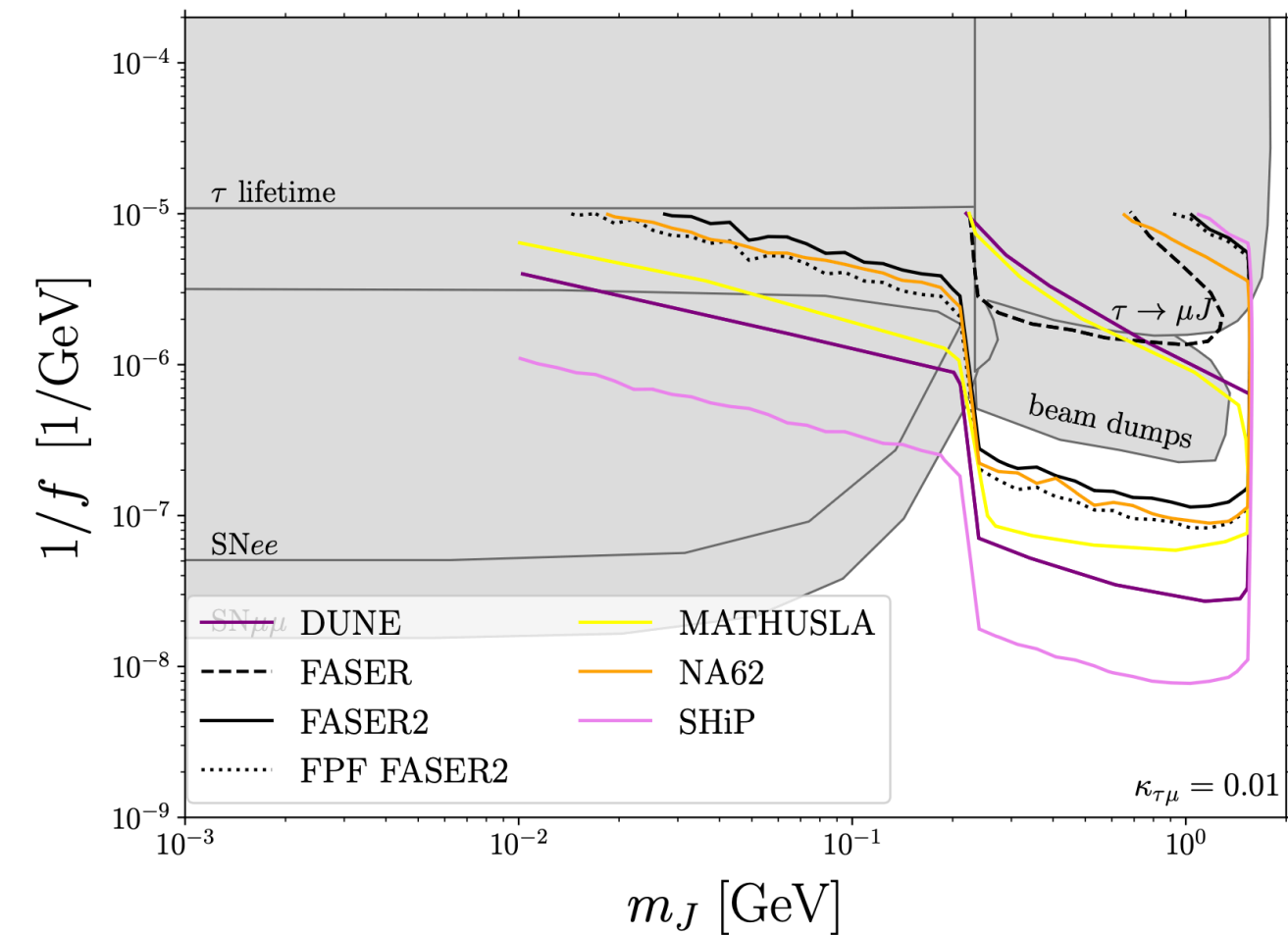


$$N = \int \int dE d\theta \frac{d^2 N}{dE d\theta} p(E, \theta) q_{\text{acc.}}(E, \theta), \quad K_{\text{anarch}} = \begin{pmatrix} K^d & K^o & K^o \\ K^o & K^d & K^o \\ K^o & K^o & K^d \end{pmatrix} = \frac{8\pi^2 v}{f} \begin{pmatrix} R_J & 1 & 1 \\ 1 & R_J & 1 \\ 1 & 1 & R_J \end{pmatrix}$$

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

$$K \equiv \frac{M_D M_D^\dagger}{v f} = \begin{pmatrix} K_{ee} & K_{e\mu} & K_{e\tau} \\ K_{e\mu}^* & K_{\mu\mu} & K_{\mu\tau} \\ K_{e\tau}^* & K_{\mu\tau}^* & K_{\tau\tau} \end{pmatrix},$$

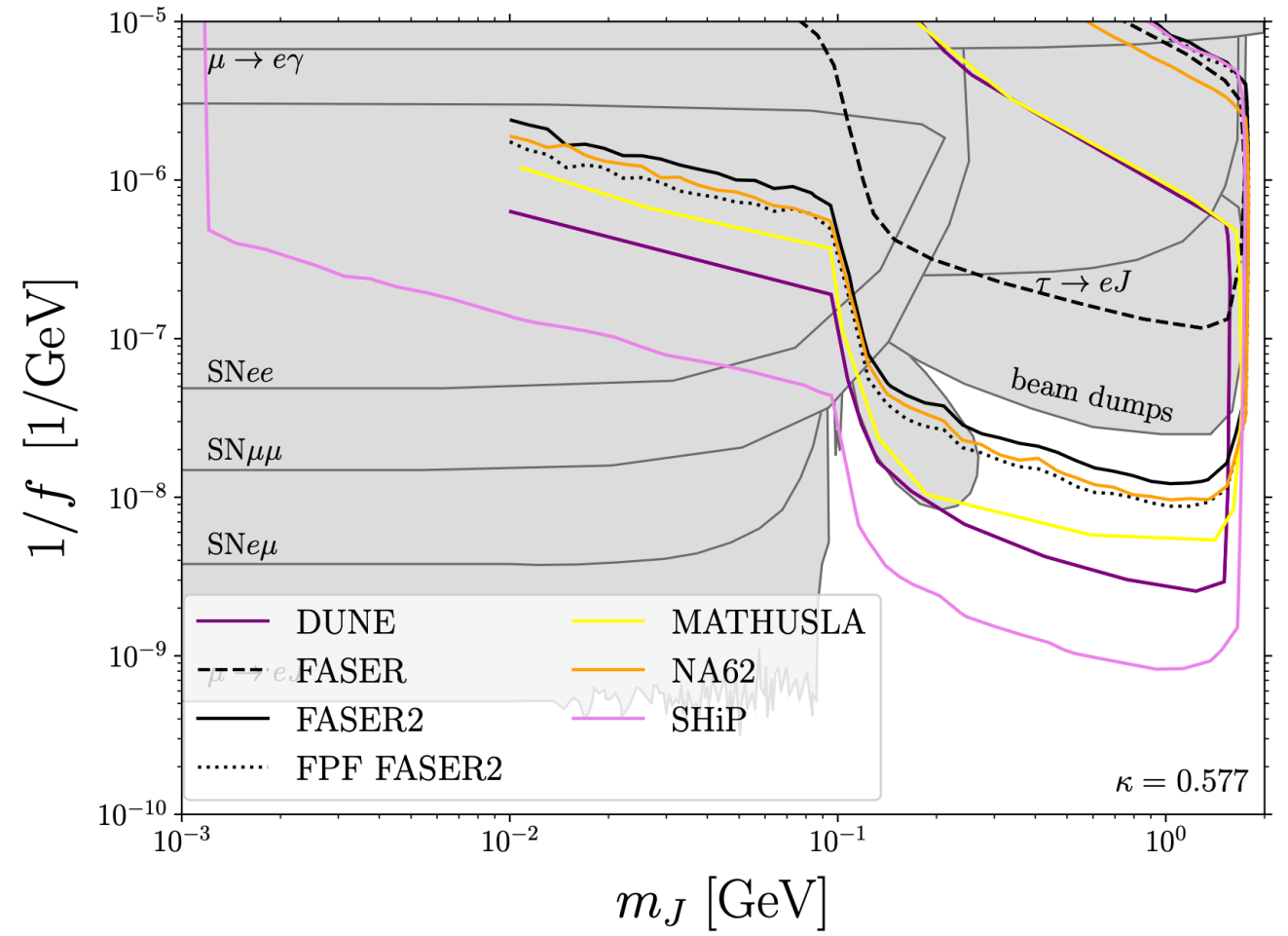
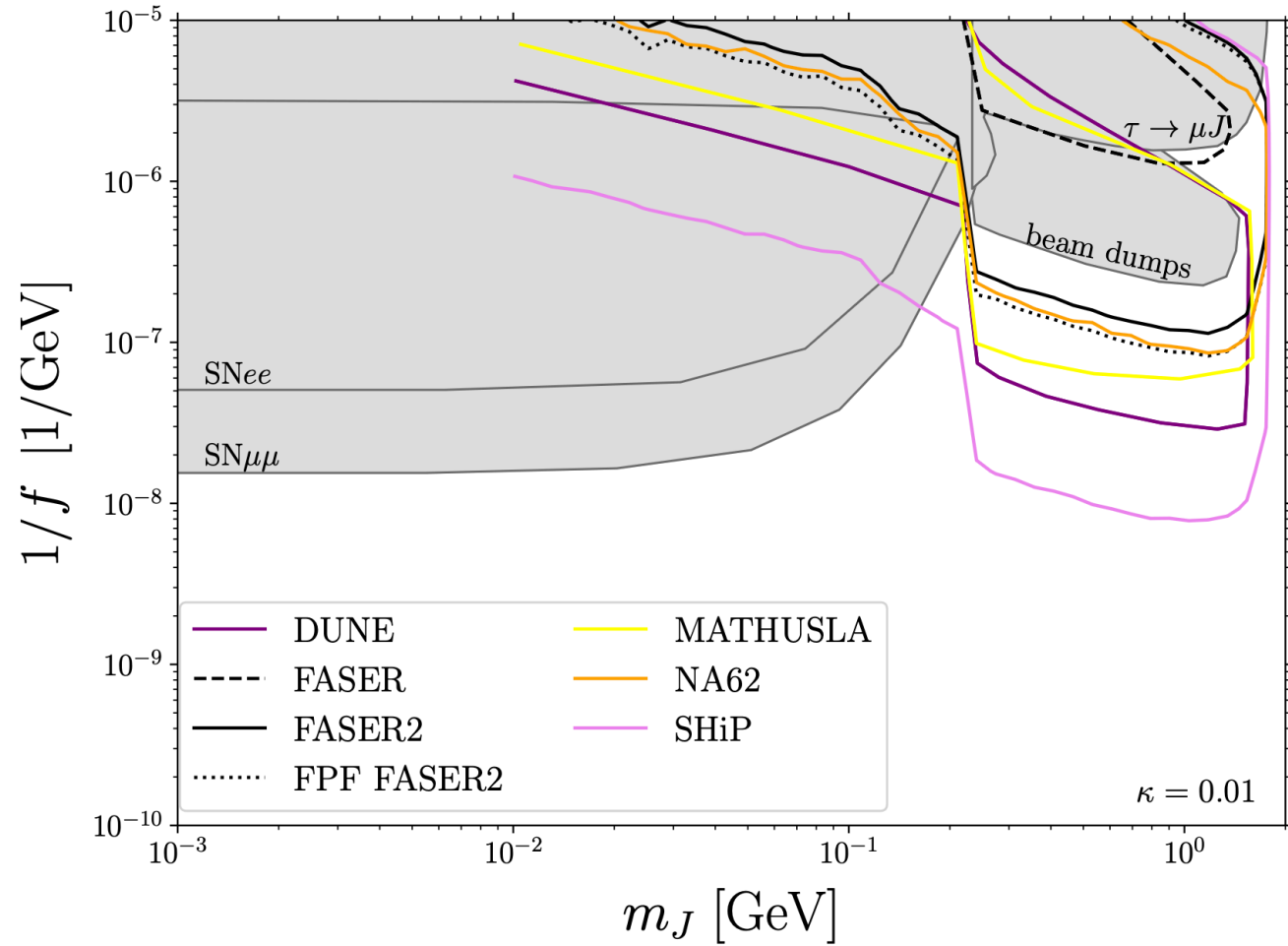
Results



$$K_{\mu\tau} = K^d \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & \kappa_{\mu\tau} \\ 0 & \kappa_{\mu\tau}^* & 1 \end{pmatrix},$$

$$K_{e\tau} = K^d \begin{pmatrix} 1 & 0 & \kappa_{e\tau} \\ 0 & 1 & 0 \\ \kappa_{e\tau}^* & 0 & 1 \end{pmatrix}$$

Results



$$K^{\text{CPV}} = K^d \begin{pmatrix} 1 & i\kappa & i\kappa \\ -i\kappa & 1 & i\kappa \\ -i\kappa & -i\kappa & 1 \end{pmatrix}$$

$$|K^d| = 8\pi^2 v/f,$$

Conclusions

- Uncovering the 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 $U(1)_{B-L}$ global symmetry.
- We found that **LFV** taon decays, $\tau \rightarrow \mu J$ and $\tau \rightarrow e J$, make intensity-frontier experiments powerful probes of sub-GeV Majoron in the **0.2–1.7 GeV regime**, filling the *gap* between astrophysical searches and FV experiments.