NEUTRINO POLARIZABILITY

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based on Bansal, Paz, Petrov, Tammaro, JZ, 2210.05706

6th Trilateral meeting, Ljubljana, Dec 20 2022

MAIN MESSAGE

- neutrinos can have parametrically enhanced polarizability
  - probe nonminimal neutrino models

NEUTRINOS AND NEW PHYSICS

- neutrino masses ⇒ potentially a sign of new see saw scale
- Majorana neutrinos ⇔ Weinberg operator

$$\mathcal{L} \supset y'_{ij}\big(\bar{L}_i^c H^{c\dagger} H^\dagger L_j\big)/\Lambda.$$

- however, could as well be Dirac
  - renormalizable interactions, no new scale

$$\mathcal{L} \supset y_{ij}\big(\bar{\nu}_{Ri} H^\dagger L_j\big)$$

- in the remainder of this talk assume ν are Majorana

NEUTRINO-PHOTON INTERACTIONS

- situation different for $\nu-$photon interactions
  - if discovered $\Rightarrow$ immediately imply existence of a new scale

ν dipole moments

$$\mathcal{L}_{\rm EFT} \supset \sum_{i>j} \frac{\mathcal{C}^{(5)}_{1,ij}}{\Lambda} \frac{e}{8\pi^2} (\bar\nu_i \sigma^{\mu\nu} P_L \nu_j) F_{\mu\nu} + \frac{1}{2}\sum_{i,j}\Big[\frac{\mathcal{C}^{(7)}_{1,ij}}{\Lambda^3}\frac{\alpha}{12\pi}(\bar\nu_i P_L\nu_j)F_{\mu\nu}F^{\mu\nu} + \frac{\mathcal{C}^{(7)}_{2,ij}}{\Lambda^3}\frac{\alpha}{8\pi}(\bar\nu_i P_L\nu_j)F_{\mu\nu}\tilde F^{\mu\nu}\Big] + \text{h.c.} + \cdots\,,$$

Rayleigh ops (ν polarizability)

NEUTRINO DIPOLE MOMENTS

NEUTRINO DIPOLE MOMENTS

- somewhat more conventional notation

$$\mathcal{L}_{\rm eff} \supset \sum_{i>j} \frac{1}{2}(\lambda_\nu)_{ij}(\bar{\nu}_i\sigma^{\mu\nu}P_L\nu_j)F_{\mu\nu} + \text{h.c.},$$

  - λ a complex 3x3 antisymmetric matrix

$$\lambda = \mu - id$$

ν elect. dip. mom.

ν magn. dip. mom.

  - relation to EFT notation

$$(\lambda_\nu)_{ij}\mu_B \equiv \frac{\mathcal{C}^{(5)}_{1,ij}}{\Lambda}\frac{e}{4\pi^2},$$

Bohr magneton

- Borexino bound $\mu_\nu^{\rm eff} < 2.8 \cdot 10^{-11}\mu_B$
  - for $C^{(5)}_{1,ij} \Rightarrow \Lambda \gtrsim 10^6\,\text{GeV}$
  - sounds impressive, but Λ really an effective scale

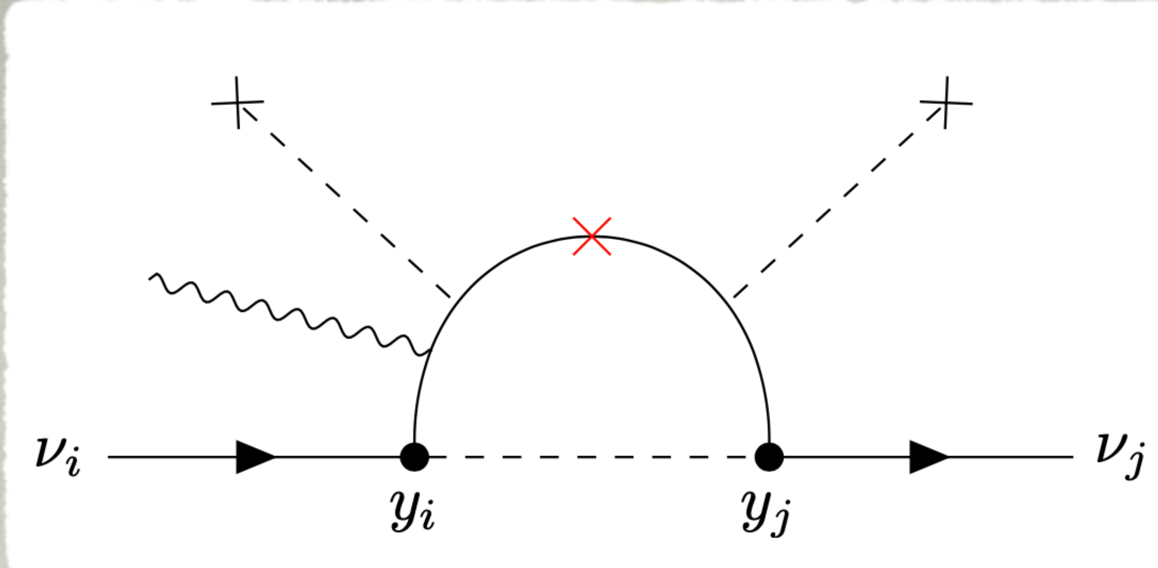
NEUTRINO DIPOLE MOMENTS

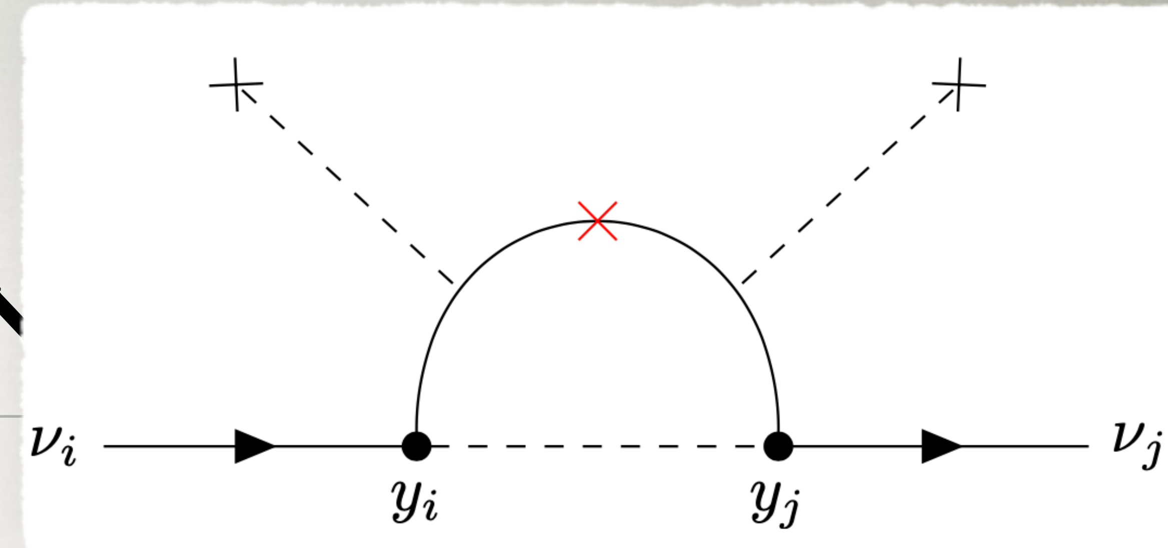
- generically the same loop contributes to neutrino masses
- NDA scaling

$$(\lambda_\nu)_{ij}\mu_B \equiv \frac{\mathcal{C}^{(5)}_{1,ij}}{\Lambda}\frac{e}{4\pi^2} \sim e\frac{y_i y_j}{16\pi^2}\frac{v^2}{M^3} = 2.8\times 10^{-11}\,\mu_B\frac{y_i y_j}{\left(M/2.4\ \text{TeV}\right)^3},$$

$$m_\nu \sim \frac{y_i y_j}{16\pi^2}\frac{v^2}{M} = 0.05\ \text{eV}\,\frac{y_i y_j}{\left(M/7.7\cdot 10^9\ \text{TeV}\right)}.$$

- ⇒ for ν dipole moments to be observable in the near future
  - loop contrib to ν masses need to be suppressed





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ENHANCED NEUTRINO DIPOLES

- the *Voloshin mechanism*

Voloshin, Sov. J. Nucl. Phys. 48 (1988) 512

  - use the symmetry properties under flavor exchange

$$\mathcal{L} \supset -\frac{1}{2}(m_\nu)_{ij}\bar{\nu}_i P_L \nu_j + \text{h.c.}.$$

$$\mathcal{L}_{\text{eff}} \supset \sum_{i>j} \frac{1}{2}(\lambda_\nu)_{ij}(\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j) F_{\mu\nu} + \text{h.c.},$$

    - mass term symmetric: $\bar{\nu}_i P_L \nu_j = +\bar{\nu}_j P_L \nu_i$
    - dipole antisymmetric: $\bar{\nu}_i P_L \sigma^{\mu\nu} \nu_j = -\bar{\nu}_j P_L \sigma^{\mu\nu} \nu_i$

- explicit realization: approximate SU(2)$_H$

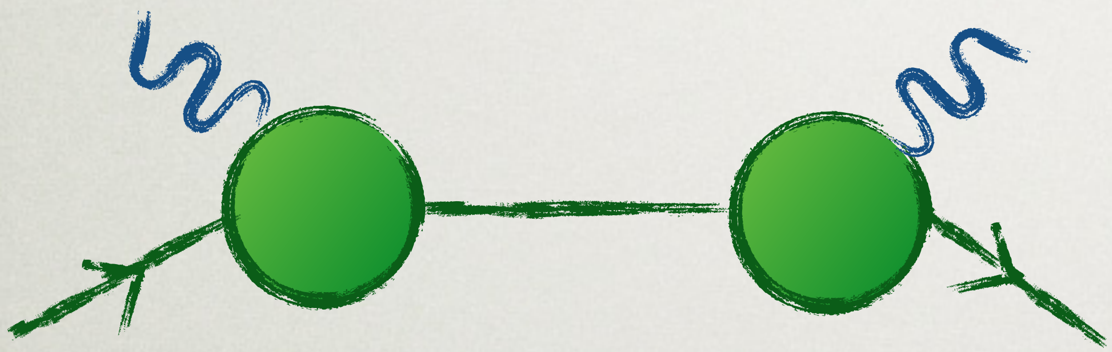
Babu, Mohapatra, PRL 63, 228 (1989)
Babu, Jana, Lindner, 2007.04291

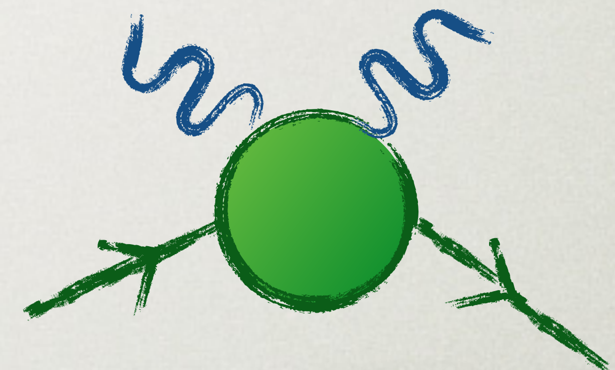
  - (ν_e, ν_μ) doublet, ν_τ singlet
  - alows for nonzero $\nu_e - \nu_\mu$ dipole, $\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j \epsilon^{ij}$
  - neutrino mass term vanishes, $\bar{\nu}_i \nu_j \epsilon^{ij} = 0$
    - ν_e, ν_μ neutrino masses proportional to SU(2)$_H$ breaking

NEUTRINO POLARIZABILITY

POLARIZABILITY

- the name borrowed from physics of NR nucleons
- nucleon *polarizability* signal of its composite nature
  - two photon interactions given by





- similarly define for nonrelativ. neutrinos

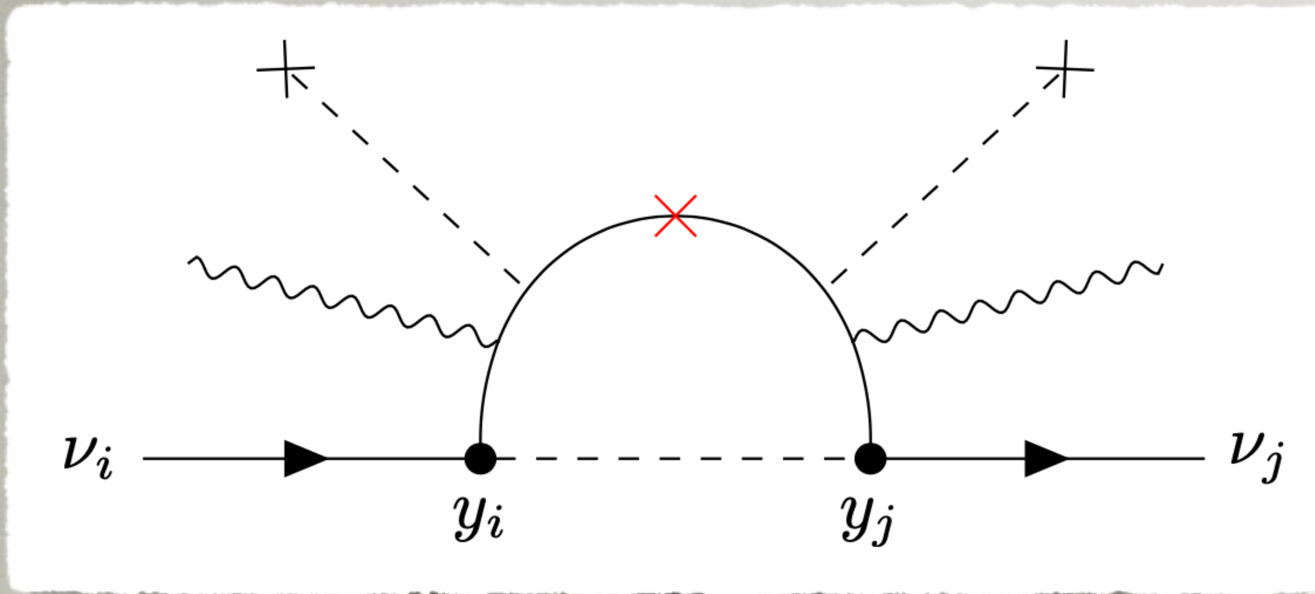
$$\mathcal{L}_{\rm NR} = 2\pi \left(\alpha_{E1,i}\vec{E}^2 + \beta_{M1,i}\vec{B}^2\right) \otimes 1_{\nu_i}.$$

electric scalar polarizability

magnetic scalar polarizability

$$\alpha_{E1,i} = \beta_{M1,i} = \frac{\alpha}{24\pi^2\Lambda^3}\mathcal{C}^{(7)}_{1,ii}.$$

- nonzero neutrino polarizability a signal of new off-shell states coupling to neutrinos
  - loop level or tree level



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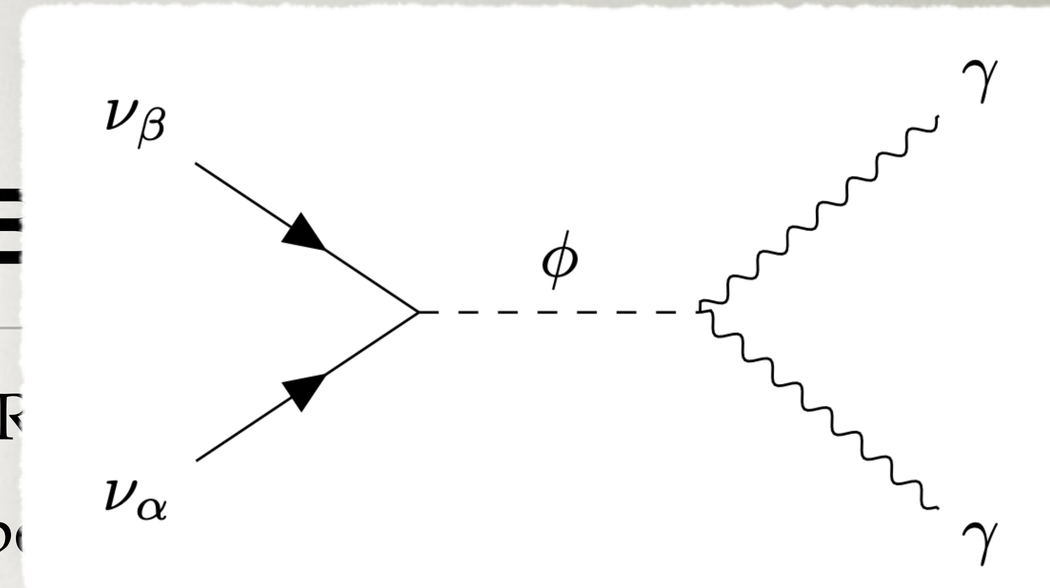

s of NR

comp

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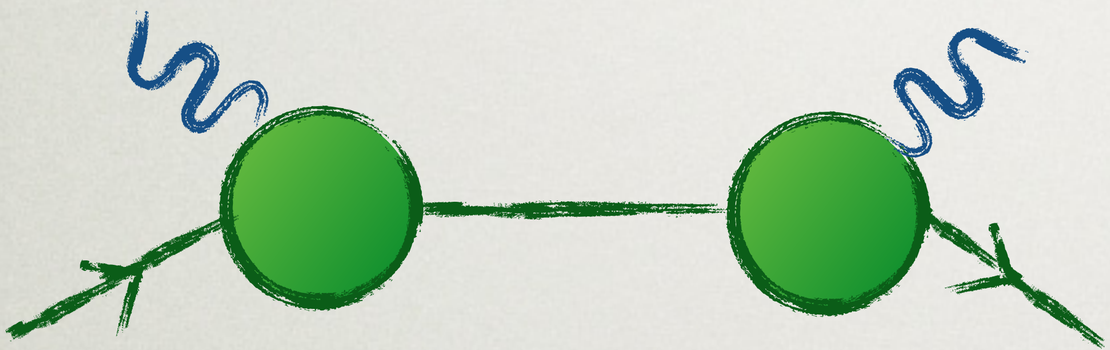

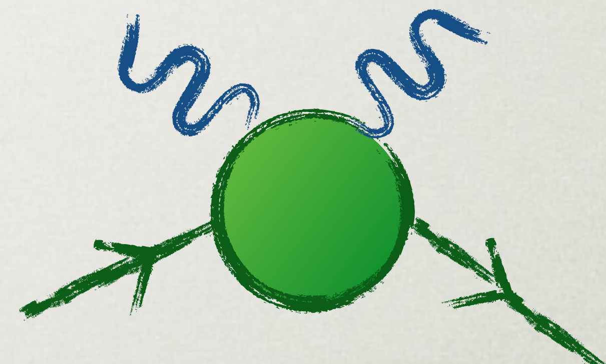

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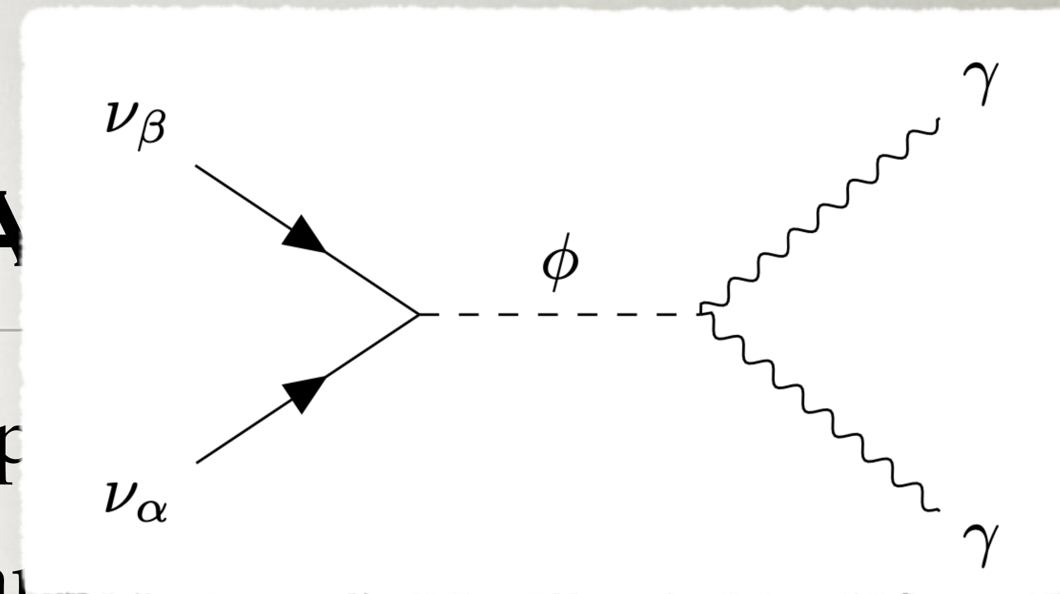
ENHANCED POLARIZABILITY

- two crucial differences with respect to ν dipole moments
  - ν polarizability exactly the same flavor symmetry structure as m_ν
    - $\Rightarrow \nu$ polarizability always suppressed by m_ν
    - only way to enhance it by lowering effective scale Λ
  - can be generated by tree-level exchanges of a light scalar
- sample toy model

$$\mathcal{L}_{\rm int} \supset -\frac{\alpha}{12\pi}\frac{c_\gamma}{f_\phi}\phi F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{c'_\gamma}{f_\phi}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}c_\nu^{ij}\left(\bar{\nu}_i P_L \nu_j\right)\phi + \text{h.c..}$$

ENHANCED POLA



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NEUTRINO POLARIZABILITY

- for heavy enough ϕ masses
- ϕ integrated out $\Rightarrow$ EFT description

$$\frac{\mathcal{C}^{(7)}_{1,ij}}{\Lambda^3} = c_\nu^{ij} c_\gamma \frac{1}{m_\phi^2 f_\phi}, \qquad \frac{\mathcal{C}^{(7)}_{2,ij}}{\Lambda^3} = c_\nu^{ij} c'_\gamma \frac{1}{m_\phi^2 f_\phi}.$$

  - in concrete models expect $c_\nu \propto m_\nu$
  - effective scale Λ small if m_ϕ light and/or f_ϕ small
- whether EFT description appropriate depends on the typical energy of the process

NEUTRINO POLARIZABILITY

Process	$\mathcal{C}_2^{(7)}/\Lambda^3$ (GeV^{-3})	EFT thr. (GeV)
BBN	–	$\sim 10^{-3}$
ν decay	1.2×10^{11}	$\sim 10^{-10}$
ν self-interaction	–	$\sim 10^{-6}$
HB star	1.9×10^{6}	$\sim 10^{-5}$
SN1987a	–	$\sim 10^{-1}$
Borexino	1.5×10^{3}	$\sim 10^{-4}$
Xenon-nT	0.5×10^{3}	$\sim 10^{-4}$
MiniBoone	4×10^{-3}	~ 1
BaBar	0.2	~ 10
$\pi^0 \to \gamma\gamma \to \nu\nu$	4.7×10^{3}	~ 0.1
$B^0 \to \gamma\gamma \to \nu\nu$	3.7×10^{4}	~ 5
$h \to \gamma\gamma \to \nu\nu$	1.2	$\sim 10^{2}$

IN THE NEXT SLIDES

- neutrino polarizability in several models
  - minimal singlet majoron
  - majoron as QCD axion
  - majoron from inverse see-saw + extra VL fermions
  - enhanced neutrino polarizability from $U(1)_L \times U(1)'$
- exp. constraints

MINIMAL SINGLET MAJORON

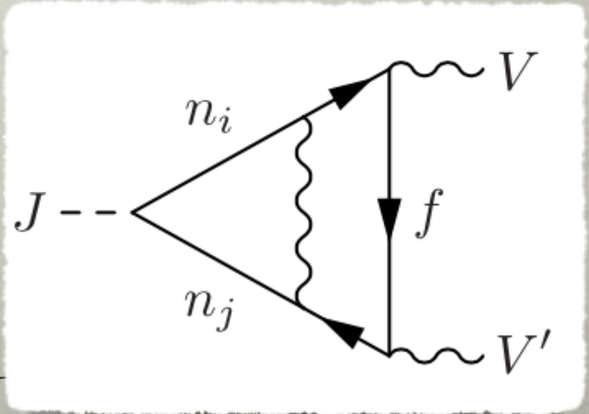
- SM+ N_R+S: $$\mathcal{L} = -\bar{L} y N_R H - \frac{1}{2}\bar{N}_R^c \lambda N_R S + \text{h.c.},$$
    - spontaneously broken L number $$S = (f_\phi + \sigma + i\phi)/\sqrt{2}.$$
- pNGB ϕ : majoron
    - mass term introduced as free parameter, explicit breaking
    - tree level coupings to neutrinos

Heeck, Patel, 1909.02029

$$\mathcal{L}_\phi \supset \frac{i\phi}{2f_\phi}(m_\nu)_{ij}\bar{\nu}_i\gamma_5\nu_j + \cdots$$

- one loop to quarks, leptons ⇒ requires large f_ϕ
- two loops to gluons, photons + additionally suppressed by $m_\phi^2/m_{f_i}^2$
- leads to highly suppressed neutrino polarizability

$$C_2^{(5)} \sim \frac{\alpha}{12\pi}\frac{m_\phi^2 m_\nu}{m_\ell^3 f_\phi}$$



MAJORON AS A QCD AXION

color octet fermions
$L=1$, ew. singl.

color octet scalars
L=0, ew. doublets

color singlet scalar
L=2, ew. singl

Ma, Ohata, Tsumura, 1708.03076

- SM+ $\Psi_R^A + \Phi^A$+S
  - $\Rightarrow U(1)_L$ anomalous under QCD
  - majoron is the QCD axion

$$m_\phi \simeq 6\,\mathrm{keV} \times \left(\frac{1\,\mathrm{TeV}}{f_\phi/(3n_\Psi)}\right)$$

- couplings to neutrinos still

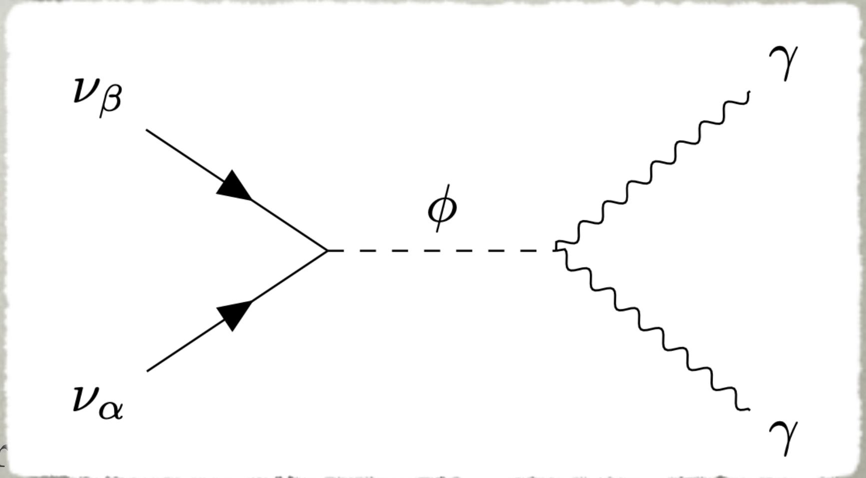
$$c_\nu^{ij} = -i\frac{(m_\nu)_{ij}}{f_\phi}.$$

- couplings to photons from QCD anomaly

$$c'_\gamma \simeq 2.0 \times 3n_\Psi.$$

- neutrino polarizability

$$\frac{\mathcal{C}_{2,ij}^{(7)}}{\Lambda^3} = i\frac{(m_\nu)_{ij}c'_\gamma}{f_\phi^2 m_\phi^2} \simeq i\left(\frac{1}{81\,\mathrm{GeV}}\right)^3 \times \frac{1}{n_\Psi} \times \frac{(m_\nu)_{ij}}{0.1\,\mathrm{eV}}.$$



MAJORON AS A QC

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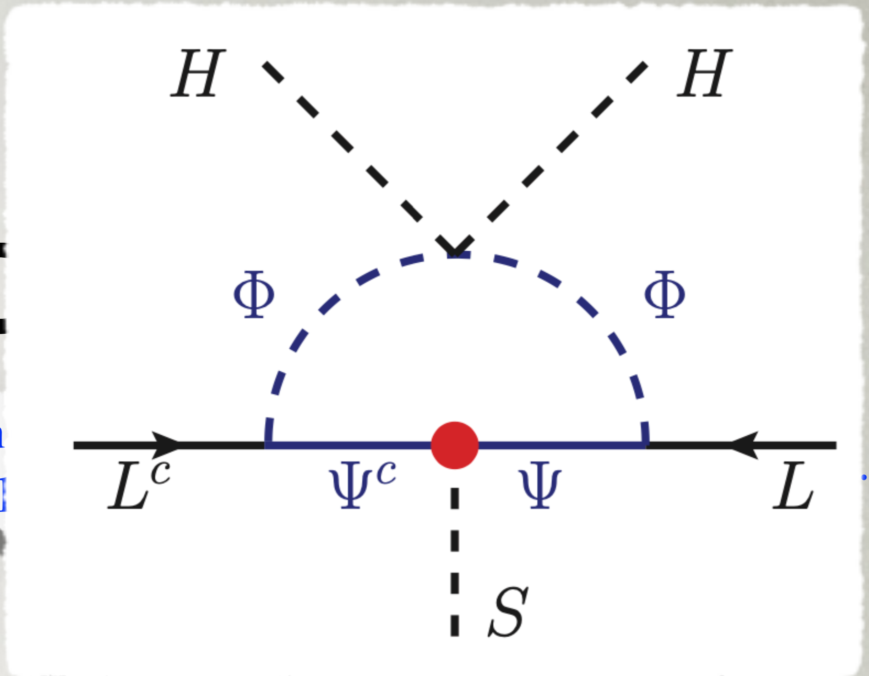
L=0, ew. doublets

color singlet sca
L=2, ew. singl

.03076



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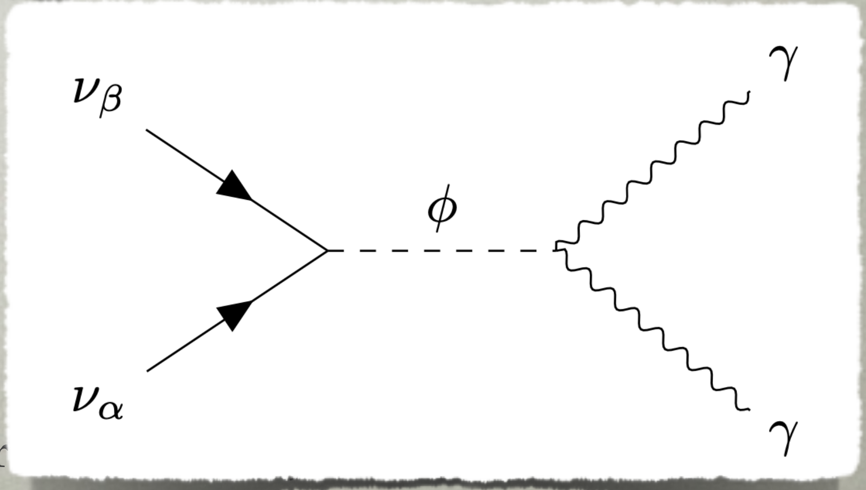


INVERSE SEE-SAW MAJORON

- inverse see-saw neutrino mass matrix

$$\mathcal{M} = \begin{pmatrix} 0 & M_D & 0 \\ M_D^\top & \mu_R & M_N^\top \\ 0 & M_N & \mu_L \end{pmatrix},$$

$\propto S \to \phi$

- majoron coups. to ν still

$$c_\nu^{ij} = -i\frac{(m_\nu)_{ij}}{f_\phi}.$$

  - however f_ϕ can be small, even $\mathcal{O}(eV)$
- if extra $L = -1$ states that couple to S
  - $\Rightarrow$ majoron couples to photons
  - e.g. for extra ew triplets that obtain mass from $\langle S \rangle$

$$\frac{\mathcal{C}_{2,ij}^{(7)}}{\Lambda^3} = i\frac{(m_\nu)_{ij}c'_\gamma}{f_\phi^2 m_\phi^2} = i\frac{9}{8}\frac{(m_\nu)_{ij}n_\Psi s_w^2}{f_\phi^2 m_\phi^2}$$

$$\simeq i\left(\frac{1}{7.3\,\mathrm{GeV}}\right)^3\left(\frac{100\,\mathrm{GeV}}{f_\phi}\right)^2\times\left(\frac{1\,\mathrm{keV}}{m_\phi}\right)^2\times n_\Psi\times\frac{(m_\nu)_{ij}}{0.1\,\mathrm{eV}}.$$

  - note: this requires $f_\phi \gtrsim$ few 100 GeV

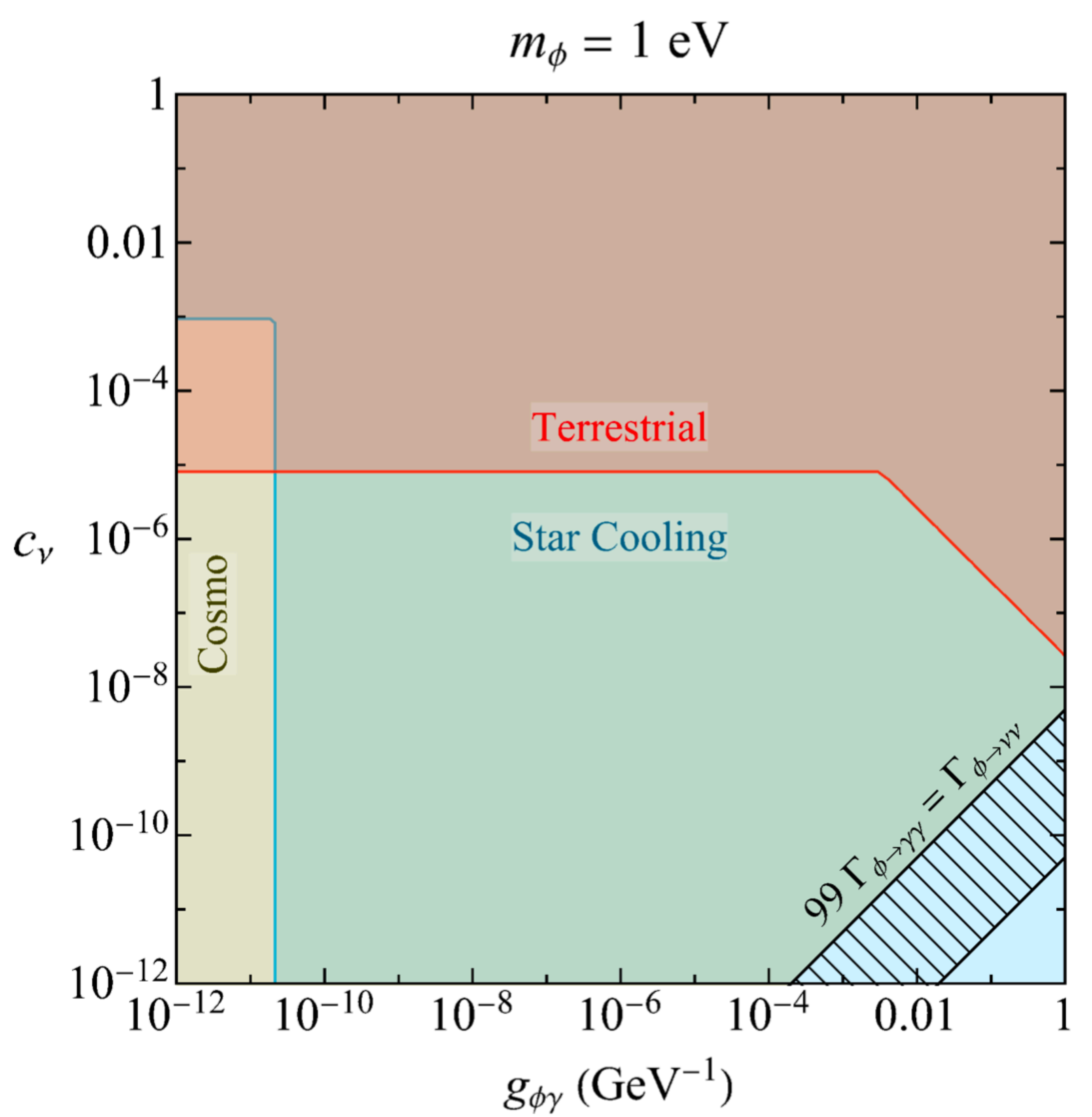
$U(1)_L \times U(1)'$ INVERSE SEE-SAW MODEL

- two global groups $U(1)_L \times U(1)'$
  - $\Rightarrow$two pNGBs
  - ϕ couples to ν's
  - ϕ' couples to γ's
- the pNGBs mass matrix breaks the shift symmetry, treated as free params
  - for $m_{\phi_1} \ll m_{\phi_2}$

$$\frac{|\mathcal{C}^{(7)}_{2,ij}|}{\Lambda^3} \simeq \left(\frac{1}{16\,\mathrm{MeV}}\right)^3 \left(\frac{100\,\mathrm{GeV}}{f'_\phi}\right)\left(\frac{1\,\mathrm{keV}}{f_\phi}\right)\left(\frac{1\,\mathrm{keV}}{m_{\phi_1}}\right)^2 \times n_\Psi c_\theta s_\theta \times \left(\frac{(m_\nu)_{ij}}{0.1\,\mathrm{eV}}\right).$$

- note: that $f_\phi \ll f'_\phi$ now allowed

PHENO CONSTRAINTS



$$g_{\phi\gamma} \equiv \frac{\alpha}{2\pi}\frac{c'_\gamma}{f_\phi}.$$

$$c_\nu^{ij} = i c_\nu \delta_{ij},$$

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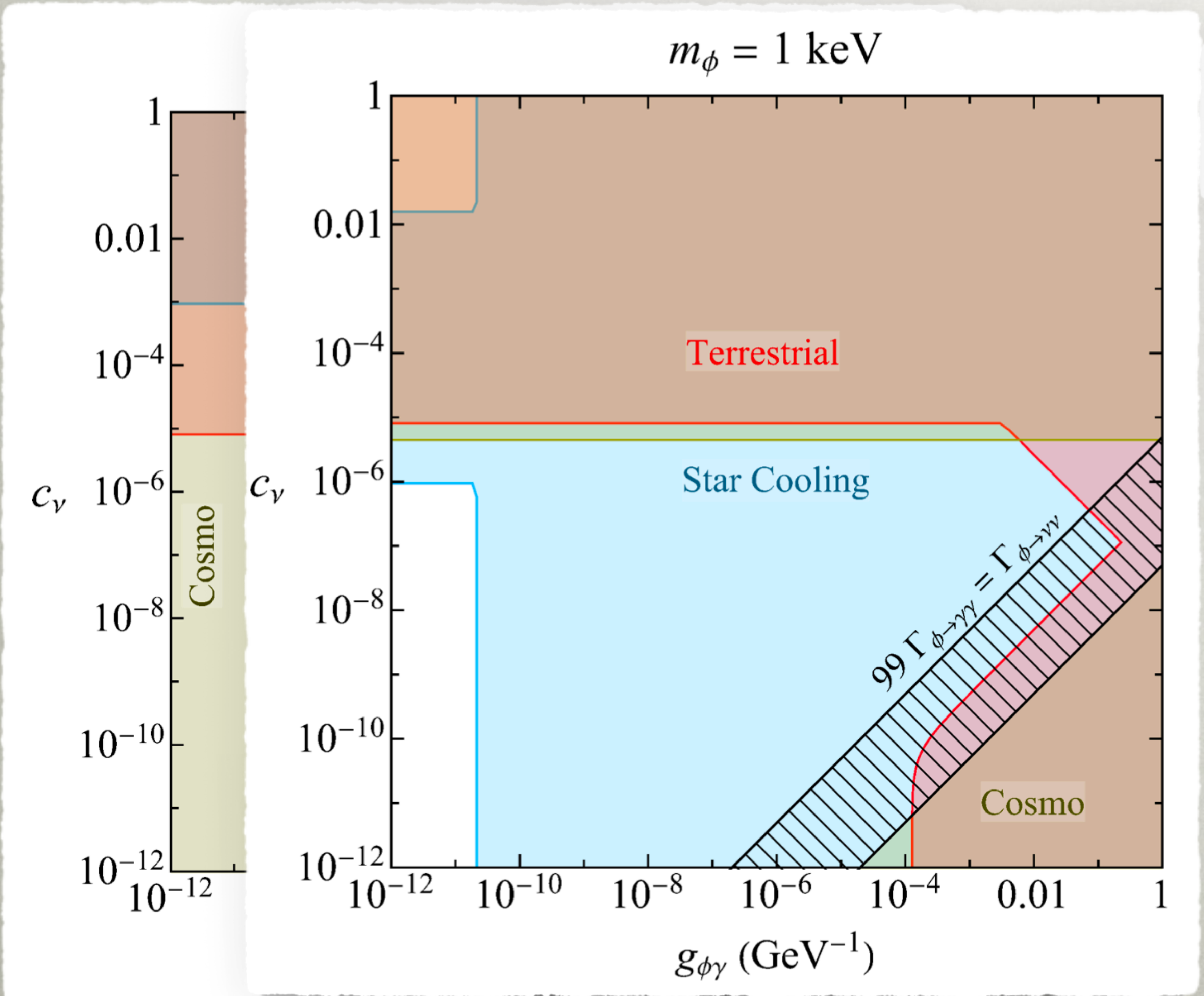

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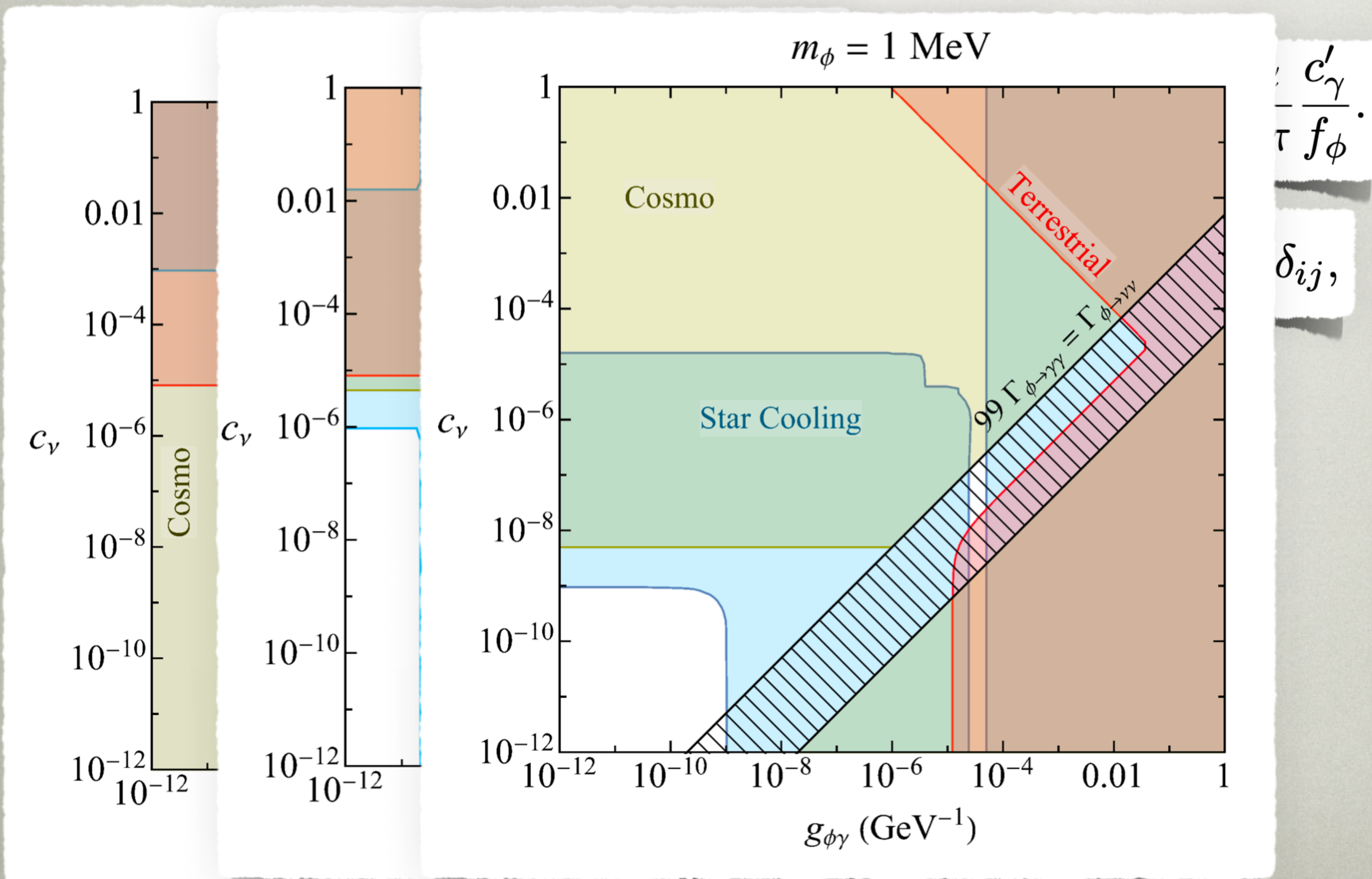

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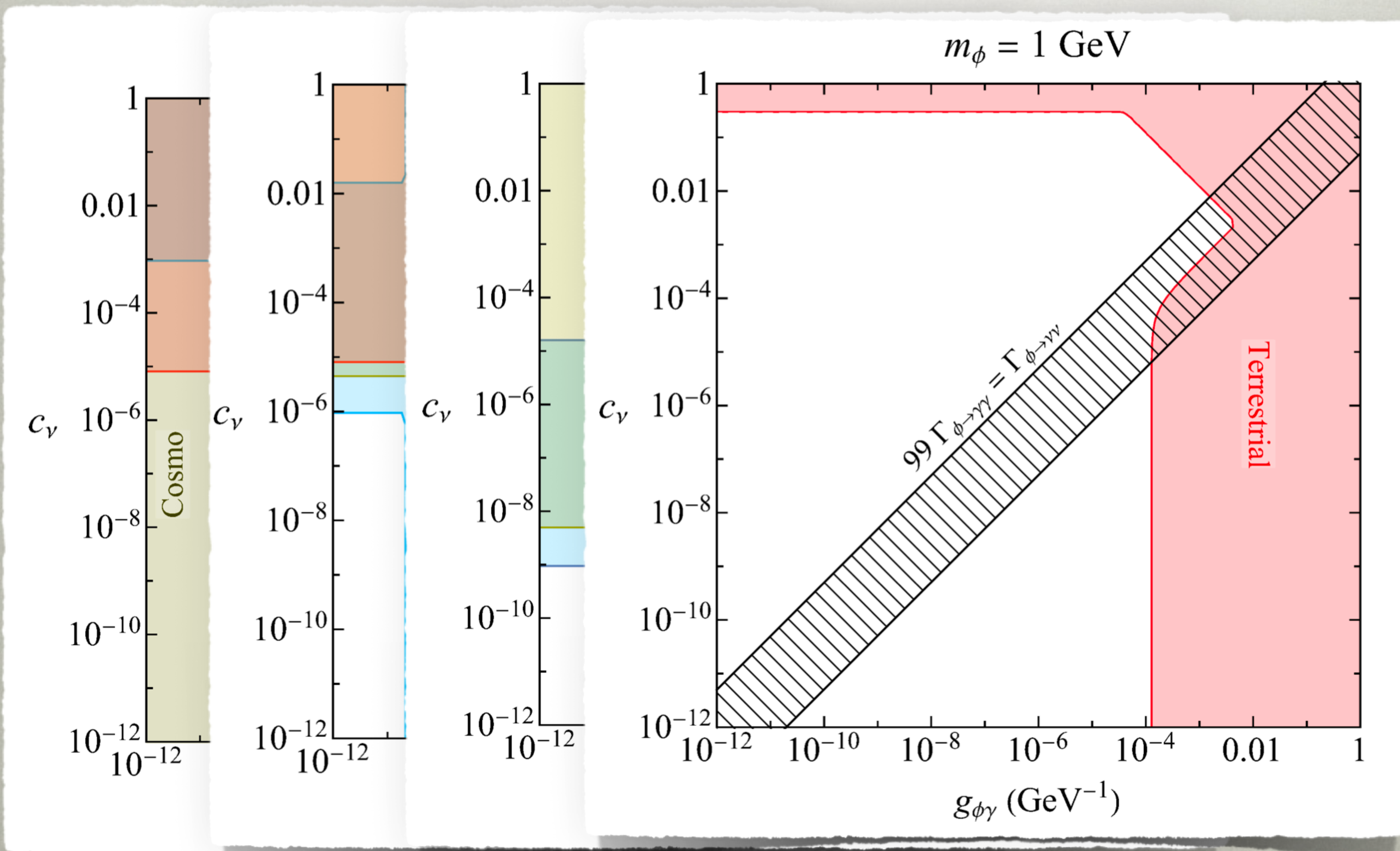
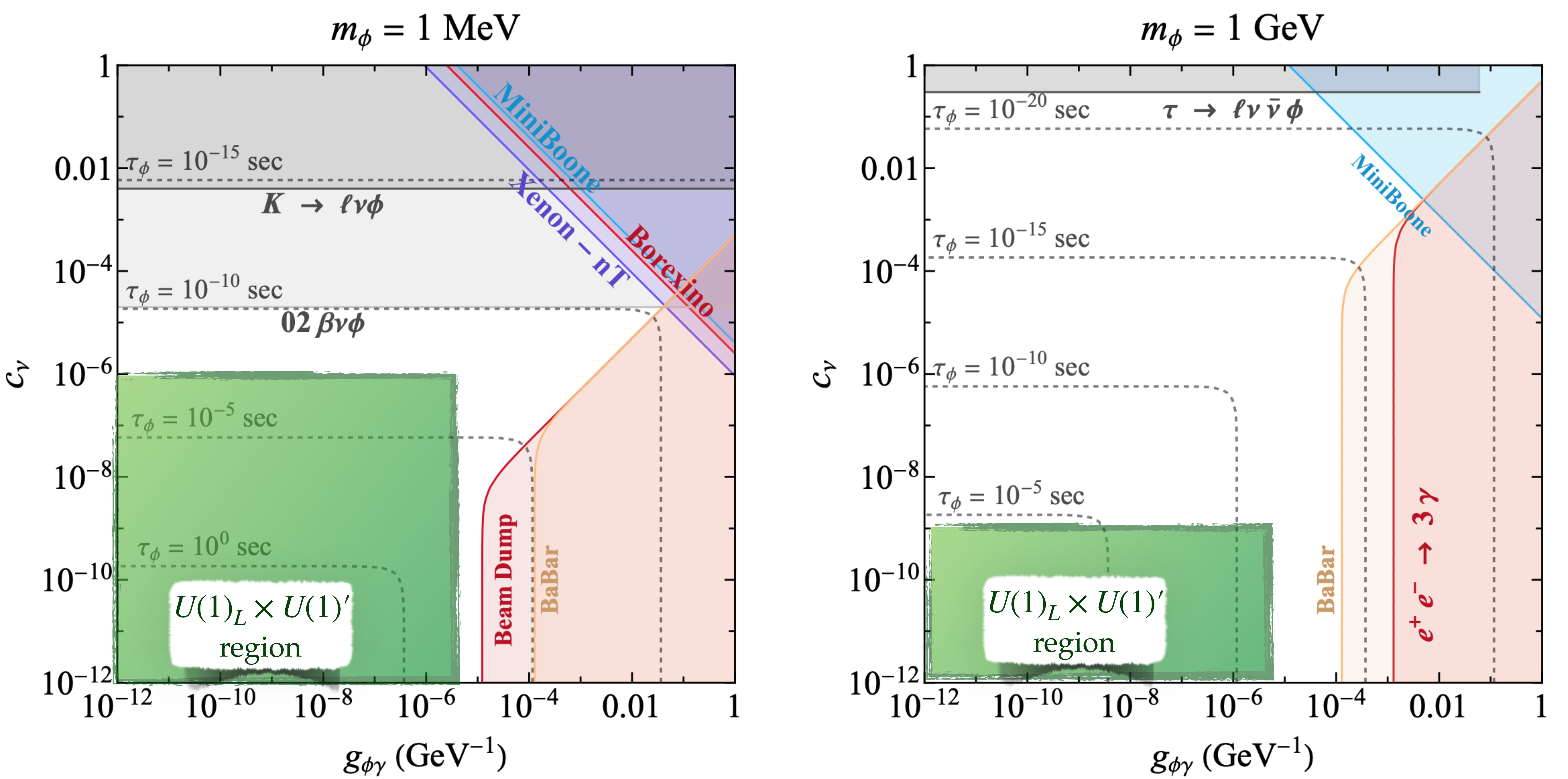


TERRESTRIAL CONSTRAINTS



FUTURE

- future improvements/questions in direct searches
  - MiniBoone anomaly from neutrino polarizability $\nu \to N$ transitions?
  - improved XENONnT constraints
  - searches for neutrino polarizability at DUNE

CONCLUSIONS

- neutrino polarizability an interesting probe of light NP
- can be enhanced in non-minimal neutrino mass models

BACKUP SLIDES

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- SM+ $\Psi_R^A + \Phi^A$+S
  - $\Rightarrow U(1)_L$ anomalous under QCD
  - majoron is the QCD axion
- neutrino masses loop generated, $m_\nu \propto f_\phi \Delta M_\Phi^2 / M_\Phi^2$
- $M_\Psi \sim y_\Psi f_\phi \Rightarrow f_\phi \gtrsim \mathcal{O}(1\text{TeV})$