Novel ways to probe effective neutrino interactions

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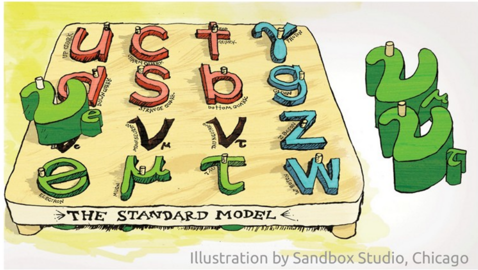
Technische Universität München

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Outline

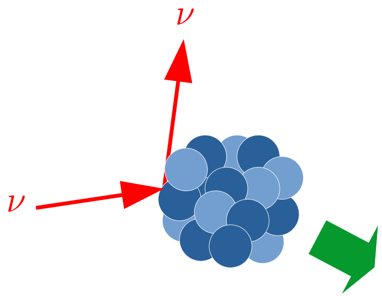
Motivation

- Neutrinos – the missing piece in the puzzle
- A tight link to the matter-antimatter asymmetry?



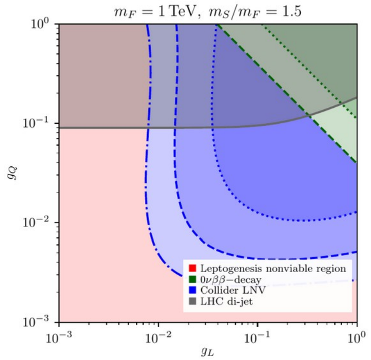
Dim-5 neutrino magnetic moment

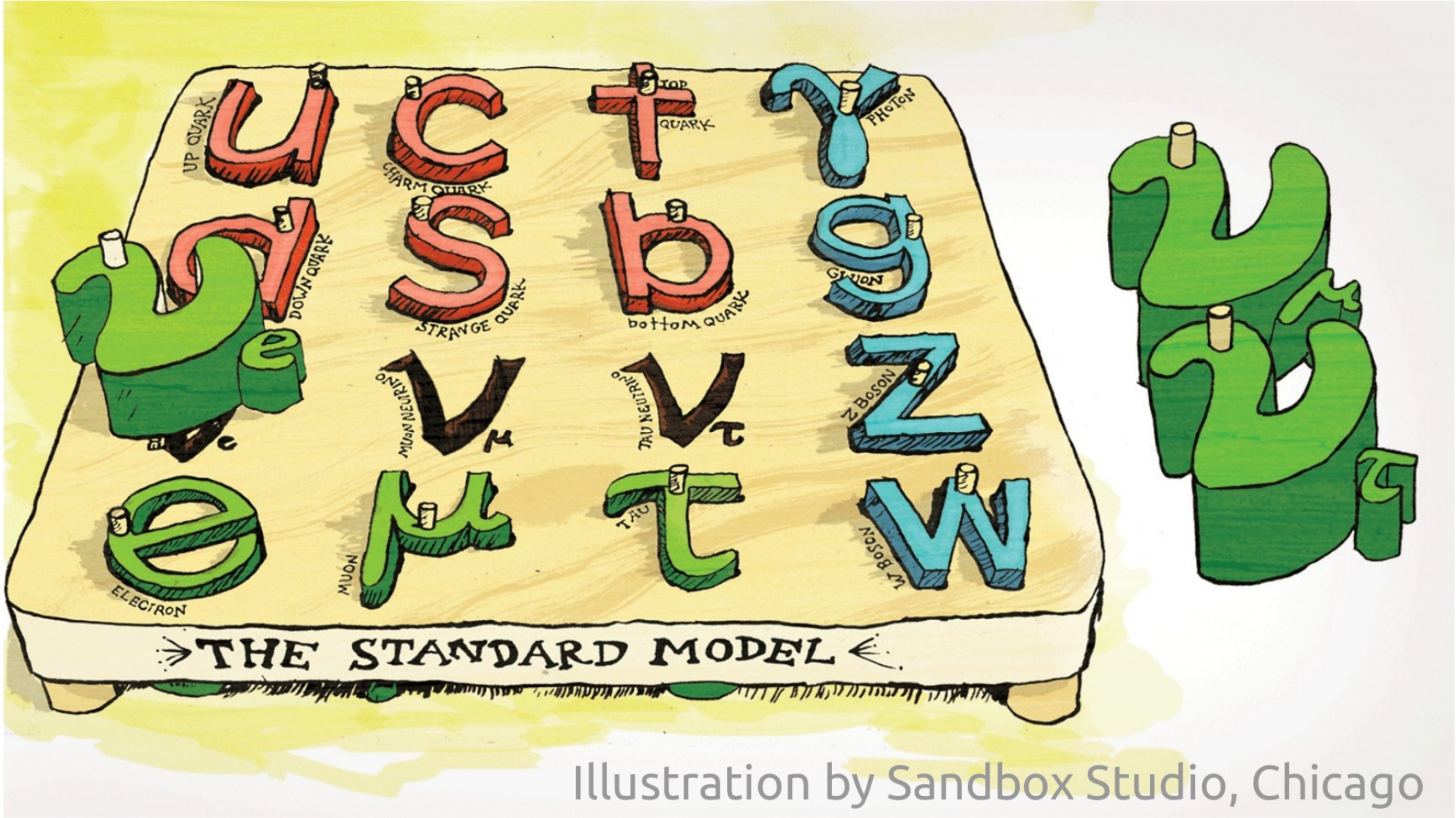
- Coherent elastic neutrino nucleus scattering
- Photon emission off Primakoff up-scattering
- Implications on Majorana vs. Dirac neutrinos



Dim-7 and 9 lepton number violating interactions

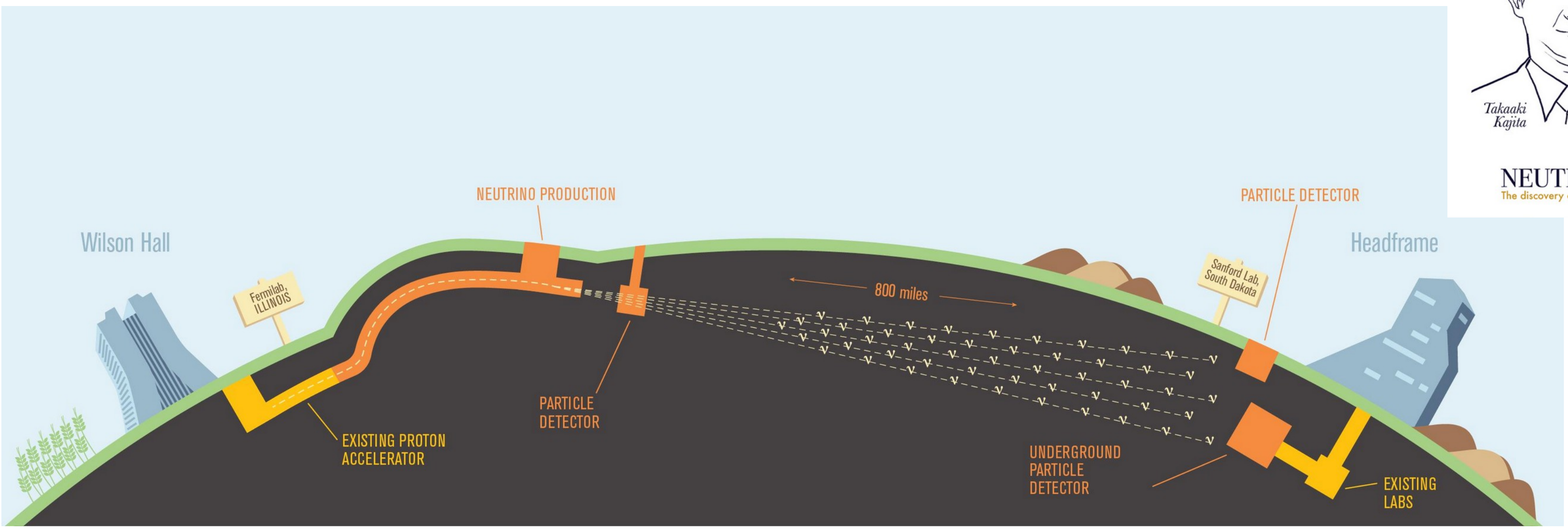
- Constraining LNV with kaon decays
- Complementarity of neutrinoless double beta decay and LHC
- Implications for baryogenesis

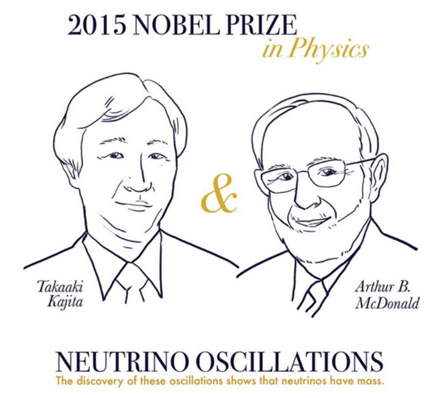




Neutrinos –
the standard model misfits

Neutrinos – what do we know?





ν_μ ν_e

$$P(\nu_\alpha \to \nu_\beta) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

Neutrino **oscillations** require **massive** neutrinos.

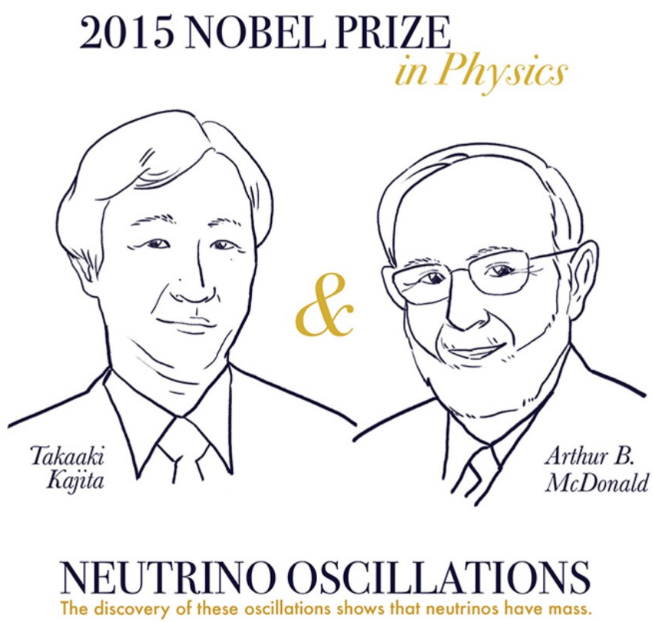
Neutrinos – what do we know?

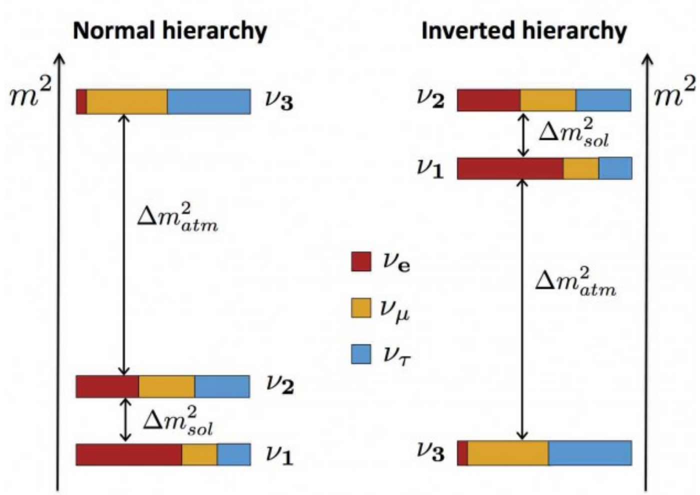
- Neutrinos in the Standard Model are **massless**
- Neutrino **oscillations** require **massive** neutrinos

$$\Delta m_{12}^2 \sim 7.59 \times 10^{-5}\mathrm{eV}^2$$
$$\Delta m_{23}^2 \sim \Delta m_{31}^2 \sim 2.3 \times 10^{-3}\mathrm{eV}^2$$

- **Normal** vs. **inverted** hierarchy
- Neutrino **mixing**

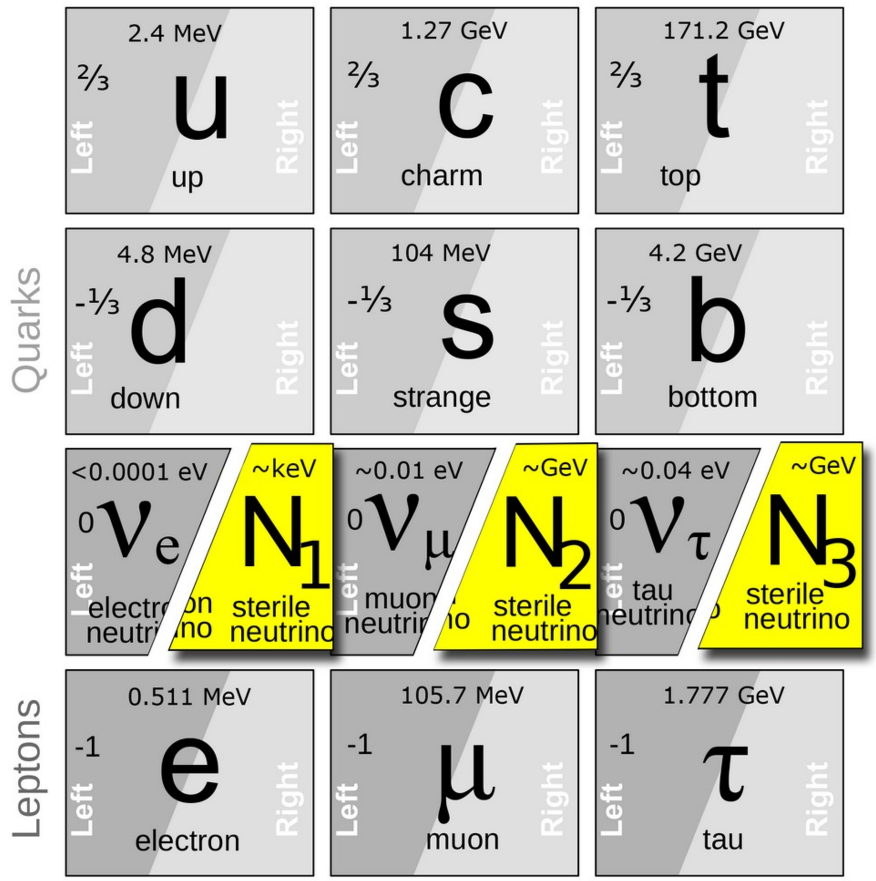
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$





How do neutrinos get their masses?
What nature do neutrinos have? Are they their own anti-particles?

Right-handed Neutrinos (RHNs)



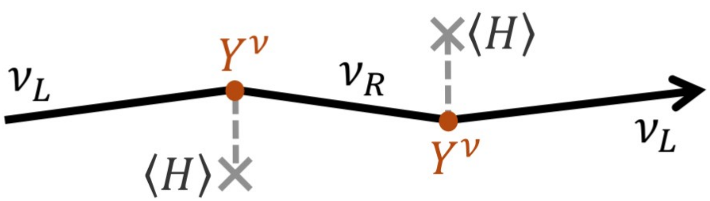
Right-handed neutrinos could explain the neutrino masses.

Neutrinos - Dirac or Majorana?

Dirac mass

$$y_\nu L \epsilon H \overline{\nu}_R \supset m_D \nu_L \overline{\nu}_R$$

→ **lepton number no accidental symmetry anymore**



Majorana mass

$$m_M \overline{\nu}_R \nu_R^c$$

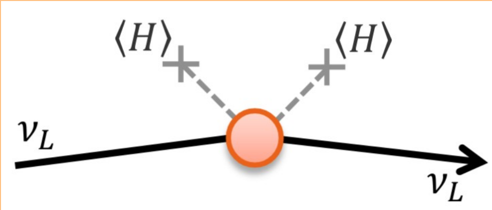
→ higher dimensional operator

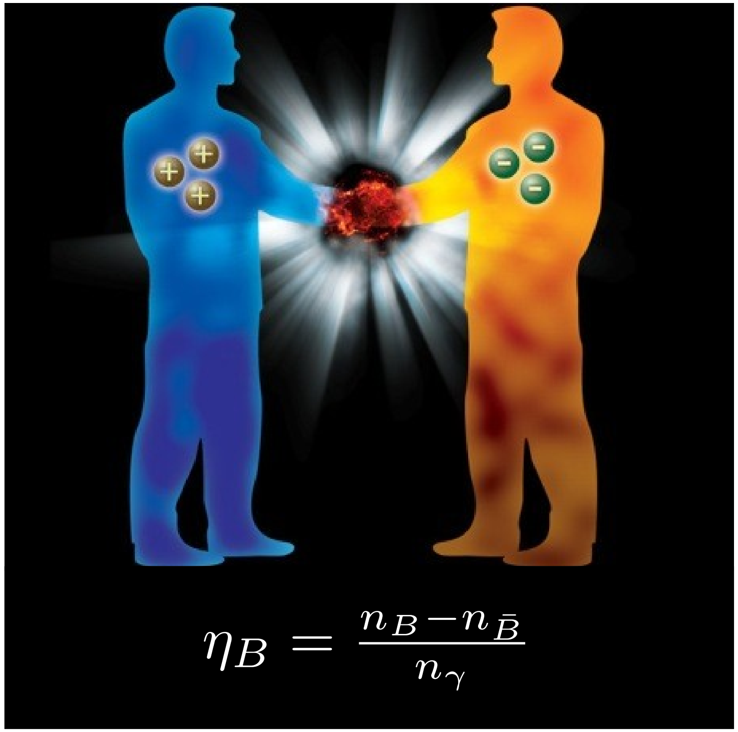
$$m_M \overline{\nu}_L \nu_L^c \qquad LLHH$$

not at tree-level within the SM possible

dim-5 Weinberg-operator

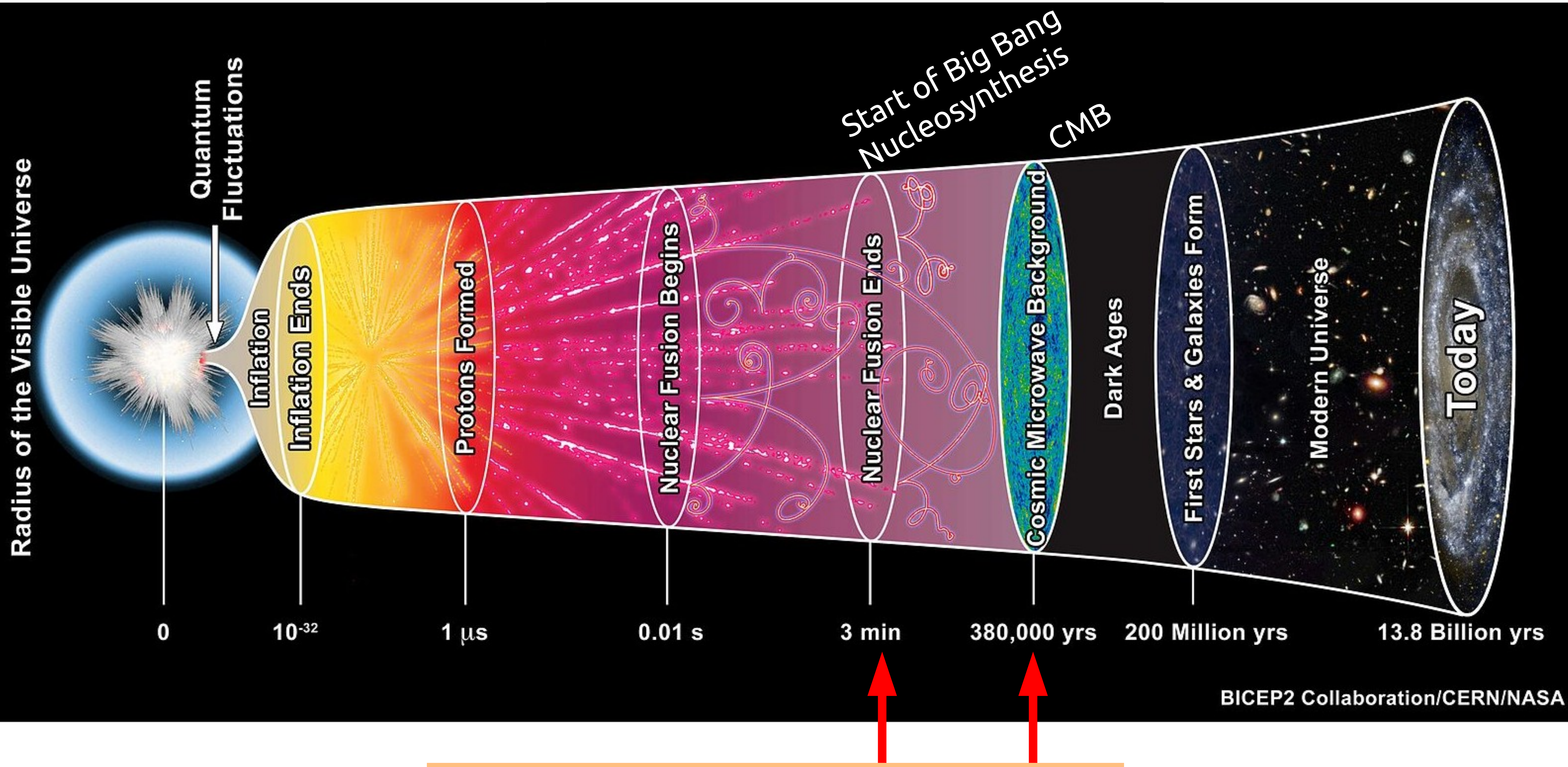
→ **Lepton number violation (LNV)**





Why is there more matter than anti-matter?

How big is the baryon asymmetry?

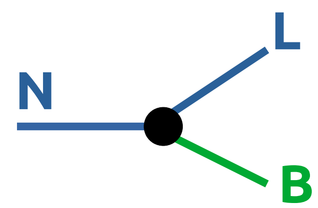


$$\eta_B^{\mathrm{obs}} = (6.09 \pm 0.06) \times 10^{-10}$$

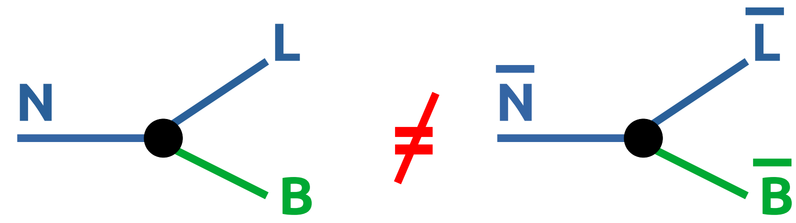
Why do we need new physics?

Theoretical conditions that have to be fulfilled (Sakharov conditions):

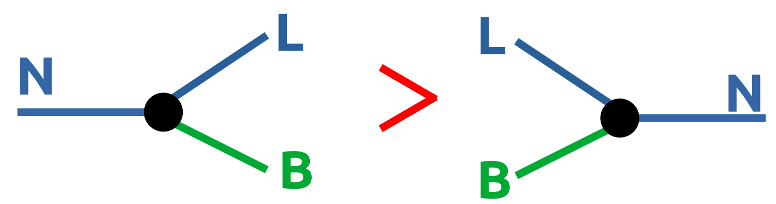
☐ B-L violation



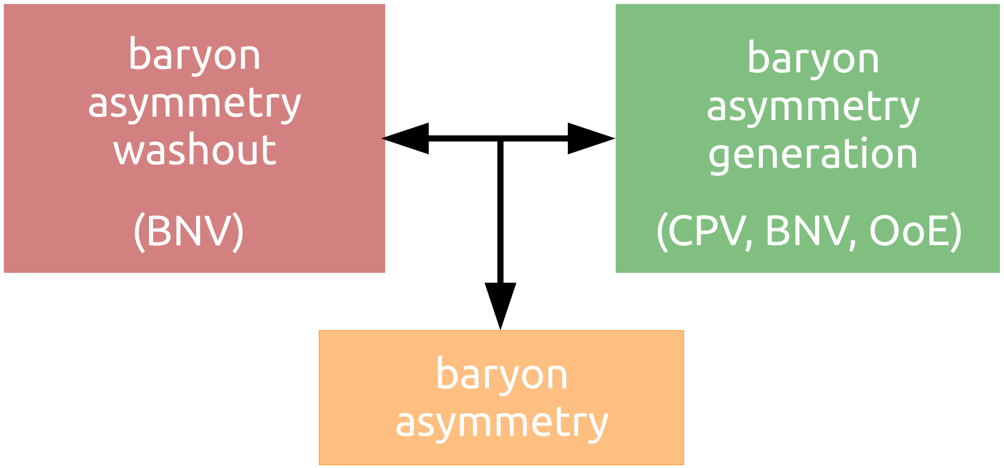
☐ C and CP violation



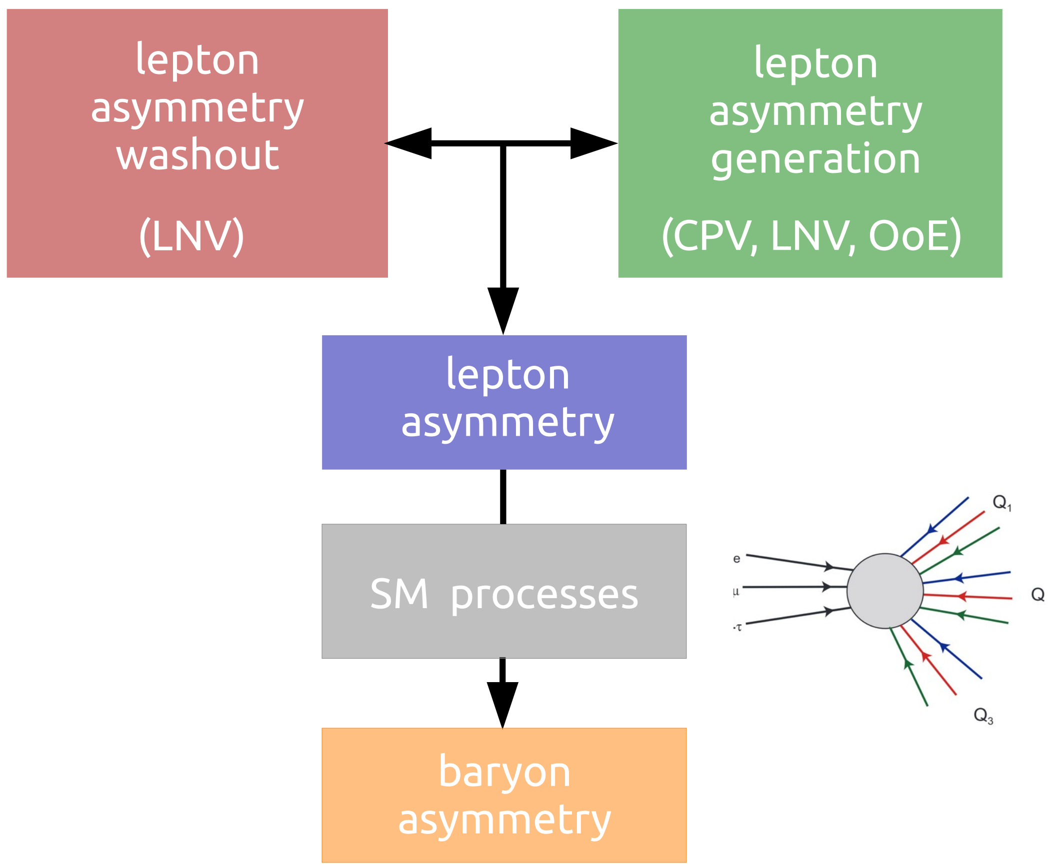
☐ departure from thermal equilibrium



Basic principle of standard baryogenesis



Basic principle of standard leptogenesis



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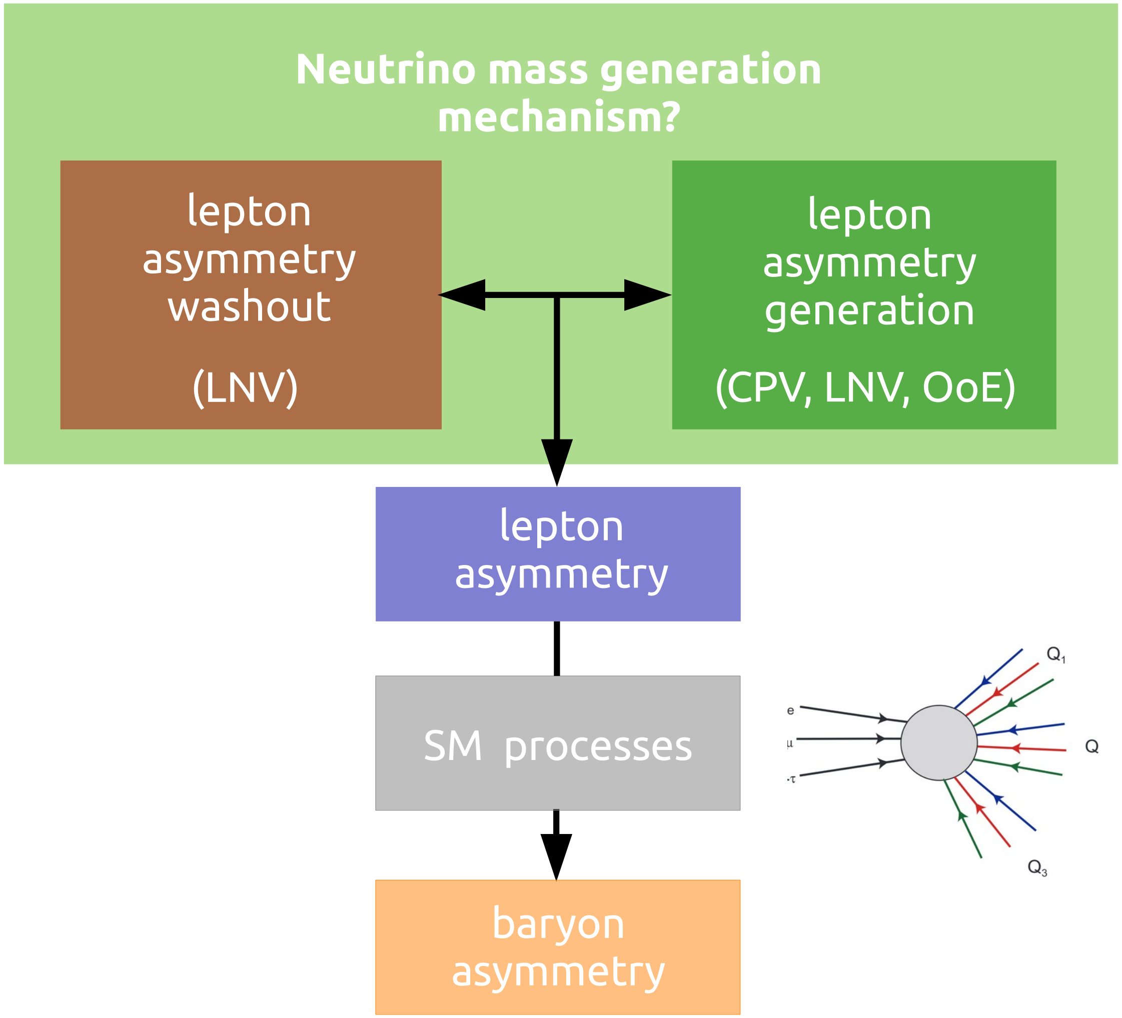

Effective field theory for neutrinos

- **Above the EW scale, interactions can be described by the Standard model effective field theory (SMEFT)**

$$\mathcal{L}_{\mathrm{SMNEFT}} = \mathcal{L}_{\mathrm{SM+N}} + \sum_i \sum_{d \geq 5} C_i^{(d)} \mathcal{O}_i^{(d)}$$

- **Below the EW scale, interactions can be described by the low-energy effective field theory (LEFT)**

$$\mathcal{L}_{\mathrm{LNEFT}} = \mathcal{L}_{\mathrm{d}\leq 4} + \sum_i \sum_{d \geq 5} C_{i,L}^{(d)} \mathcal{O}_{i,L}^{(d)}$$

$$\begin{aligned}
\mathcal{O}_{\nu\nu F} &= (\overline{\nu^C} \sigma_{\mu\nu} \nu) F^{\mu\nu} + h.c. \,, \\
\mathcal{O}_{q\nu N1}^{V} &= (\overline{q_L} \gamma_\mu q_L)(\overline{\nu^C} \gamma^\mu N) + h.c. \,, \\
\mathcal{O}_{q\nu 1}^{S} &= (\overline{q_R} q_L)(\overline{\nu^C} \nu) + h.c. \,, \\
\mathcal{O}_{qN1}^{S} &= (\overline{q_R} q_L)(\overline{N^C} N) + h.c. \,, \\
\mathcal{O}_{q\nu}^{T} &= (\overline{q_R} \sigma^{\mu\nu} q_L)(\overline{\nu^C} \sigma_{\mu\nu} \nu) + h.c. \,, \\
\mathcal{O}_{NNF} &= (\overline{N^C} \sigma_{\mu\nu} N) F^{\mu\nu} + h.c. \,, \\
\mathcal{O}_{q\nu N2}^{V} &= (\overline{q_R} \gamma_\mu q_R)(\overline{\nu^C} \gamma^\mu N) + h.c. \,, \\
\mathcal{O}_{q\nu 2}^{S} &= (\overline{q_L} q_R)(\overline{\nu^C} \nu) + h.c. \,, \\
\mathcal{O}_{qN2}^{S} &= (\overline{q_L} q_R)(\overline{N^C} N) + h.c. \,, \\
\mathcal{O}_{qN}^{T} &= (\overline{q_L} \sigma^{\mu\nu} q_R)(\overline{N^C} \sigma_{\mu\nu} N) + h.c. \,.
\end{aligned}$$

Lepton number violating (LNV)

$$\begin{aligned}
\mathcal{O}_{\nu NF} &= (\overline{\nu} \sigma_{\mu\nu} N) F^{\mu\nu} + h.c. \,, \\
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\mathcal{O}_{q\nu N2}^{S} &= (\overline{q_R} q_L)(\overline{\nu} N) + h.c. \,,
\end{aligned}$$

Lepton number conserving (LNC)

Here, L(ν) = L(N) = 1.

See e.g. Li, Ma, Schmidt (2020)

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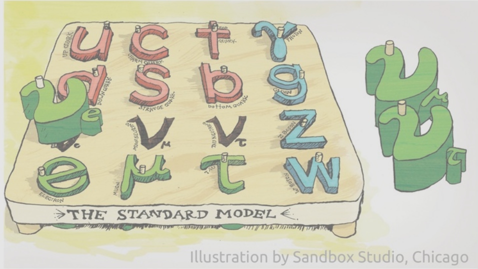

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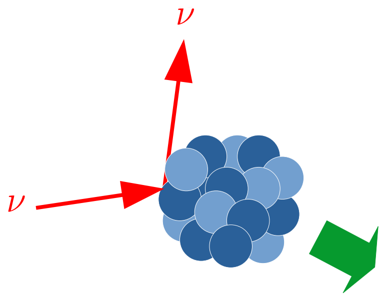

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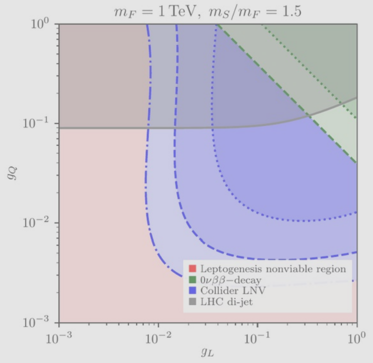
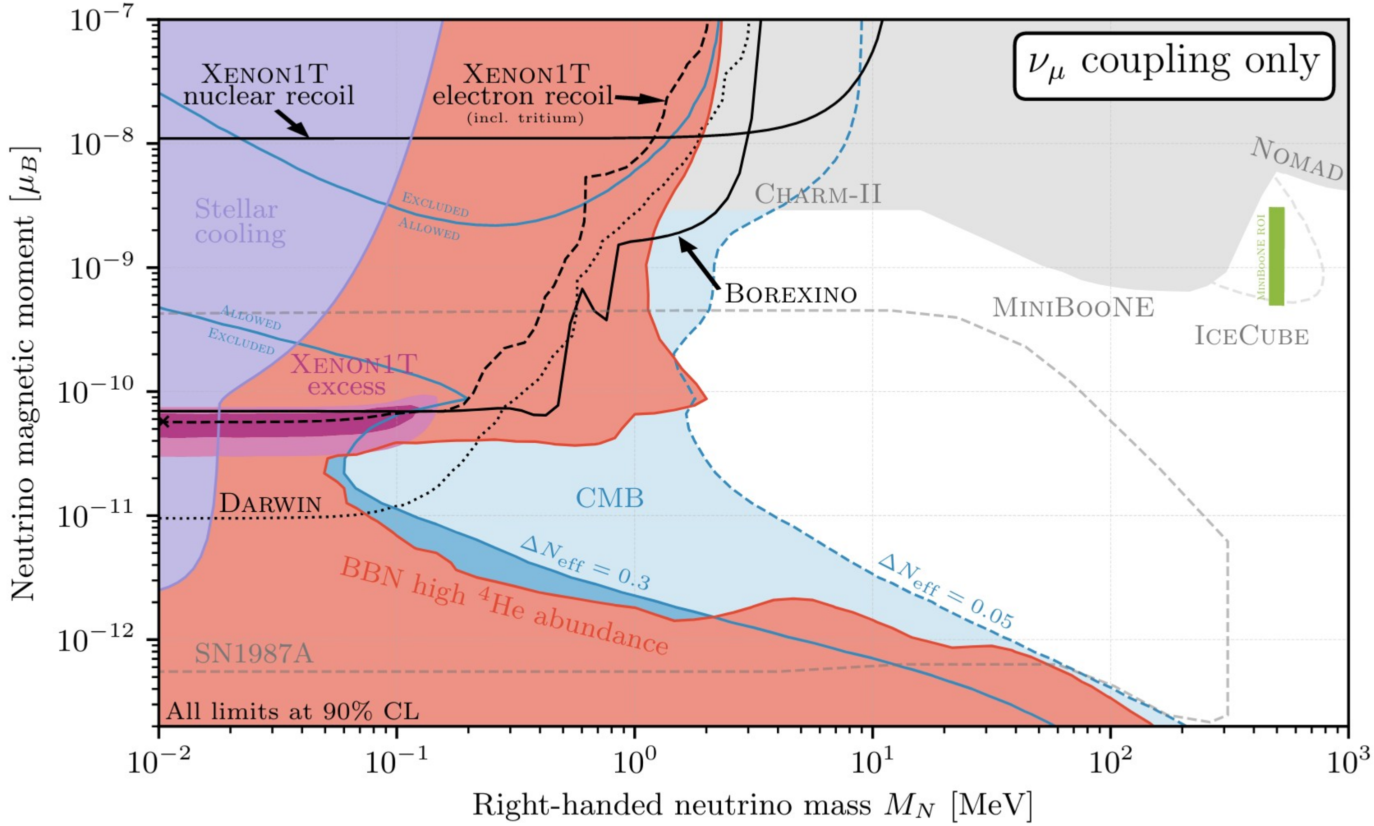


Dim-5 transition magnetic moments

$$\mathcal{L} \supset \mu_{\nu N}^{\alpha} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N F^{\mu\nu} + \text{h.c.}$$



Brdar et al. (2021)

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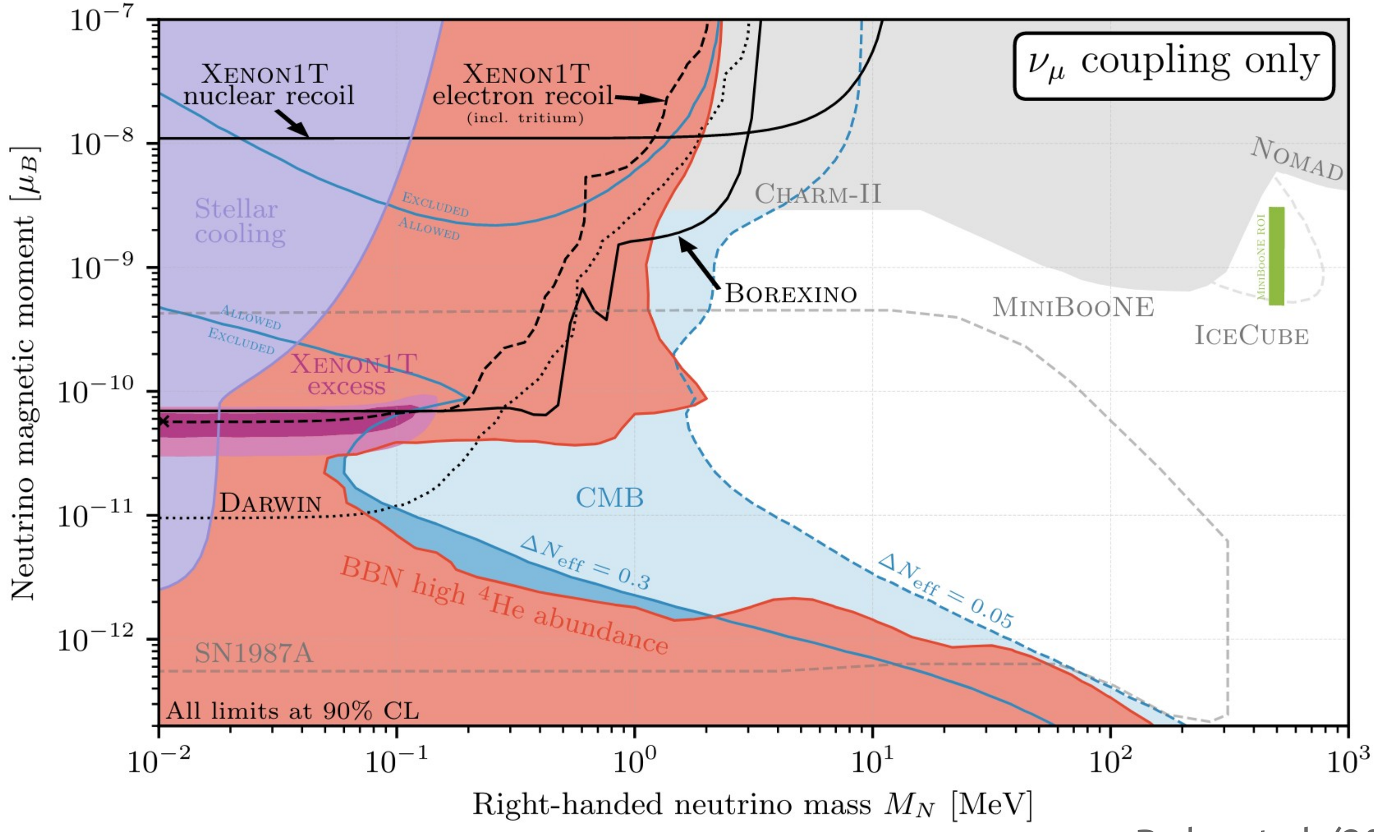


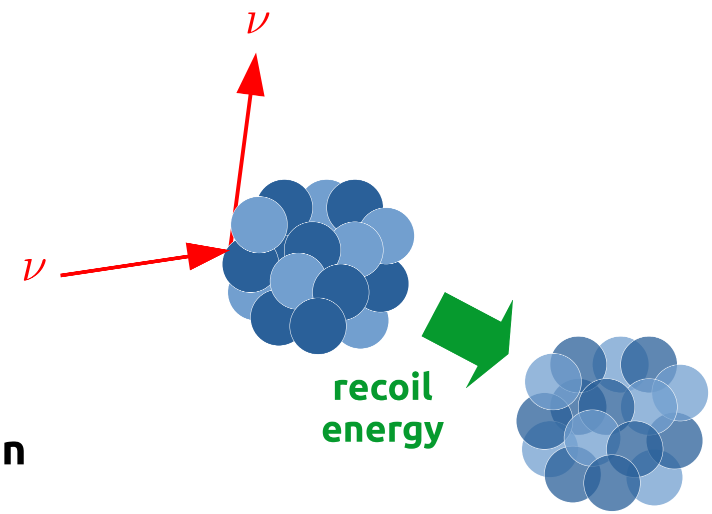
Brdar et al. (2021)

What can we learn from coherent elastic neutrino nucleus scattering?

Window to new physics: CEνNS

Coherent elastic neutrino-nucleus scattering:

$$\nu A \to \nu A$$



Postulated in the standard model in 1974 by D. Freedman

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

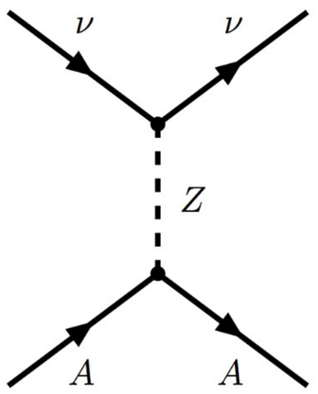
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

Window to new physics: CEvNS



Neutrino energy for coherence:

$$\Delta q \cdot \Delta R_N \leq 1$$

momentum transfer — extension of nucleus

$$E_\nu \leq \frac{hc}{R_N} \approx O(50\text{MeV})$$

Cross-section of CEvNS in the Standard Model:

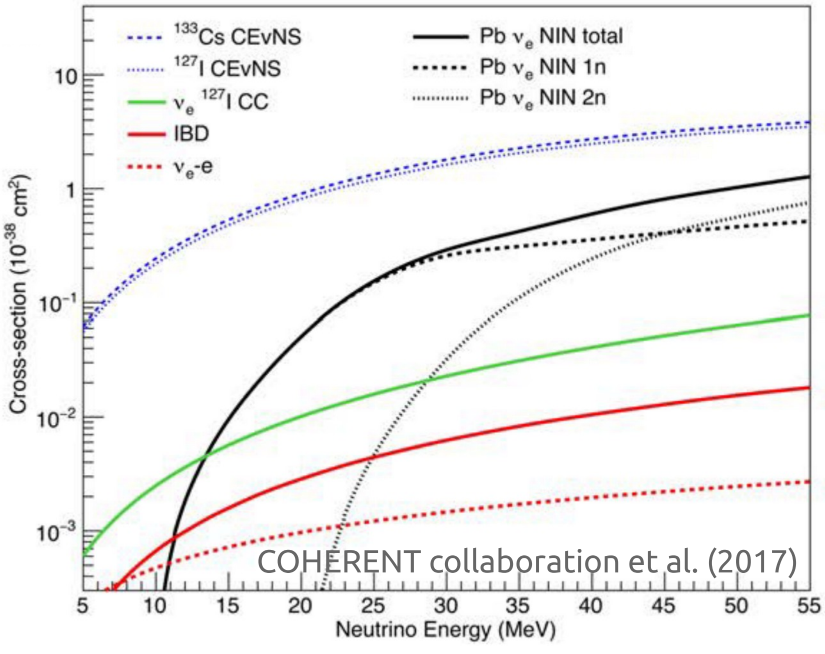
$$\frac{d\sigma}{d\Omega} = \frac{G_F}{16\pi} \cdot E_\nu^2 \cdot (1+\cos\theta) \cdot (N - Z(1-4\sin^2\theta_W))^2 \cdot F(Q^2)$$

ν kin. energy; recoil angle; neutron #; proton #; ~ 1 for full coherence

Maximal nucleus recoil energy:

$$E_r^{\max} = \frac{2E_\nu^2}{M_A} \approx O(\text{keV})$$

mass nucleus



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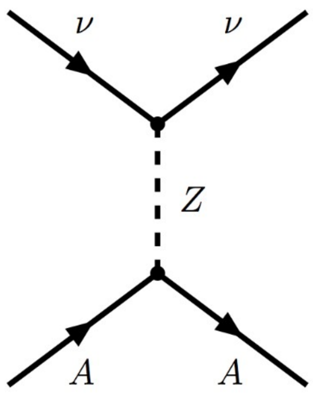

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ν kin. energy — recoil angle — neutron # — proton # — ~ 1 for full coherence

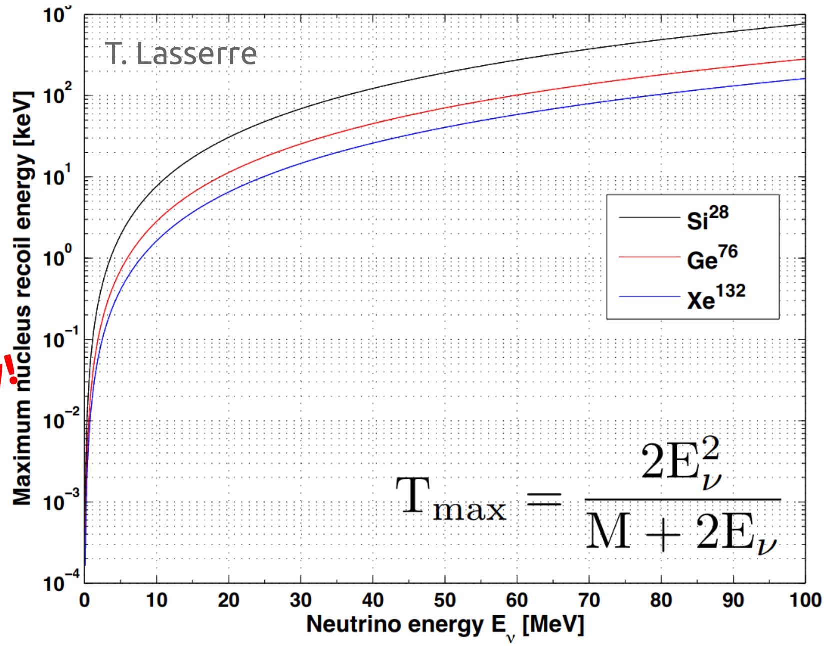
Maximal nucleus recoil energy:

$$E_r^{\mathrm{max}} = \frac{2E_\nu^2}{M_A} \approx O(\mathrm{keV})$$

mass nucleus

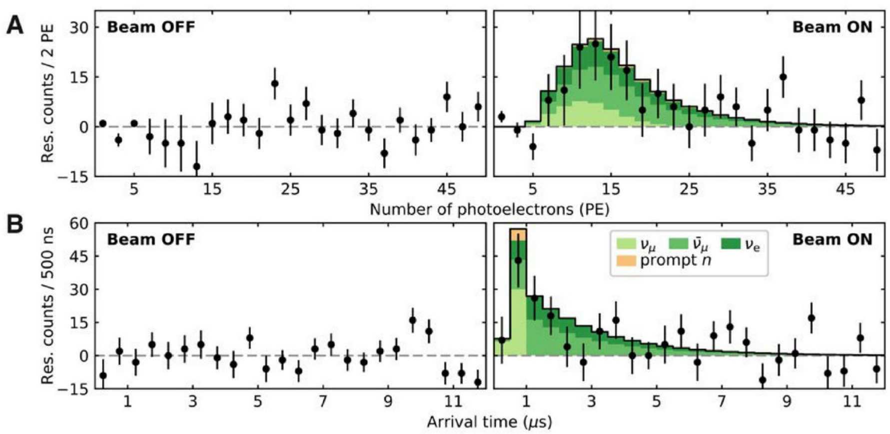
Extremely small nucleus recoil energy!

Hubris?



2017: First observation of CEvNS

COHERENT Experiment @ Spallation Neutron Source (SNS) at Oak Ridge National Laboratory



First measurement! "Hubris" transformed into reality!

Accelerator neutrinos:

$$E_\nu < 50\text{MeV} \qquad E_r < O(10)\text{keV}$$

e- and μ-flavor (anti-)neutrinos

close to decoherence

Reactor neutrinos:

$$E_\nu < 10\text{MeV} \qquad E_r < O(100)\text{eV}$$

single e-flavor antineutrinos

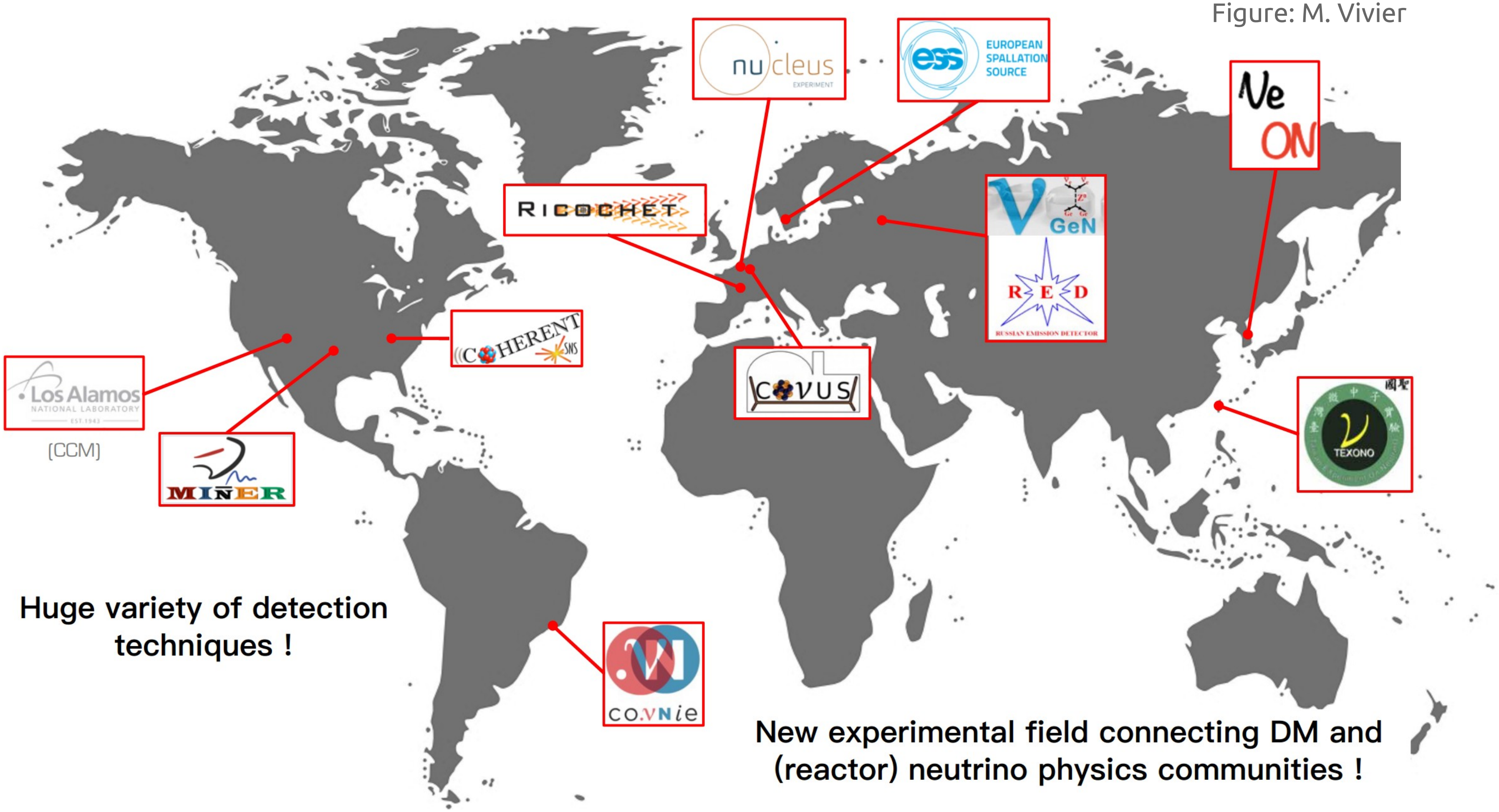
full coherence

Next Hubris to challenge!

nucleus EXPERIMENT

Landscape of new experiments

Figure: M. Vivier



Huge variety of detection techniques !

New experimental field connecting DM and (reactor) neutrino physics communities !

Landscape of new experiments

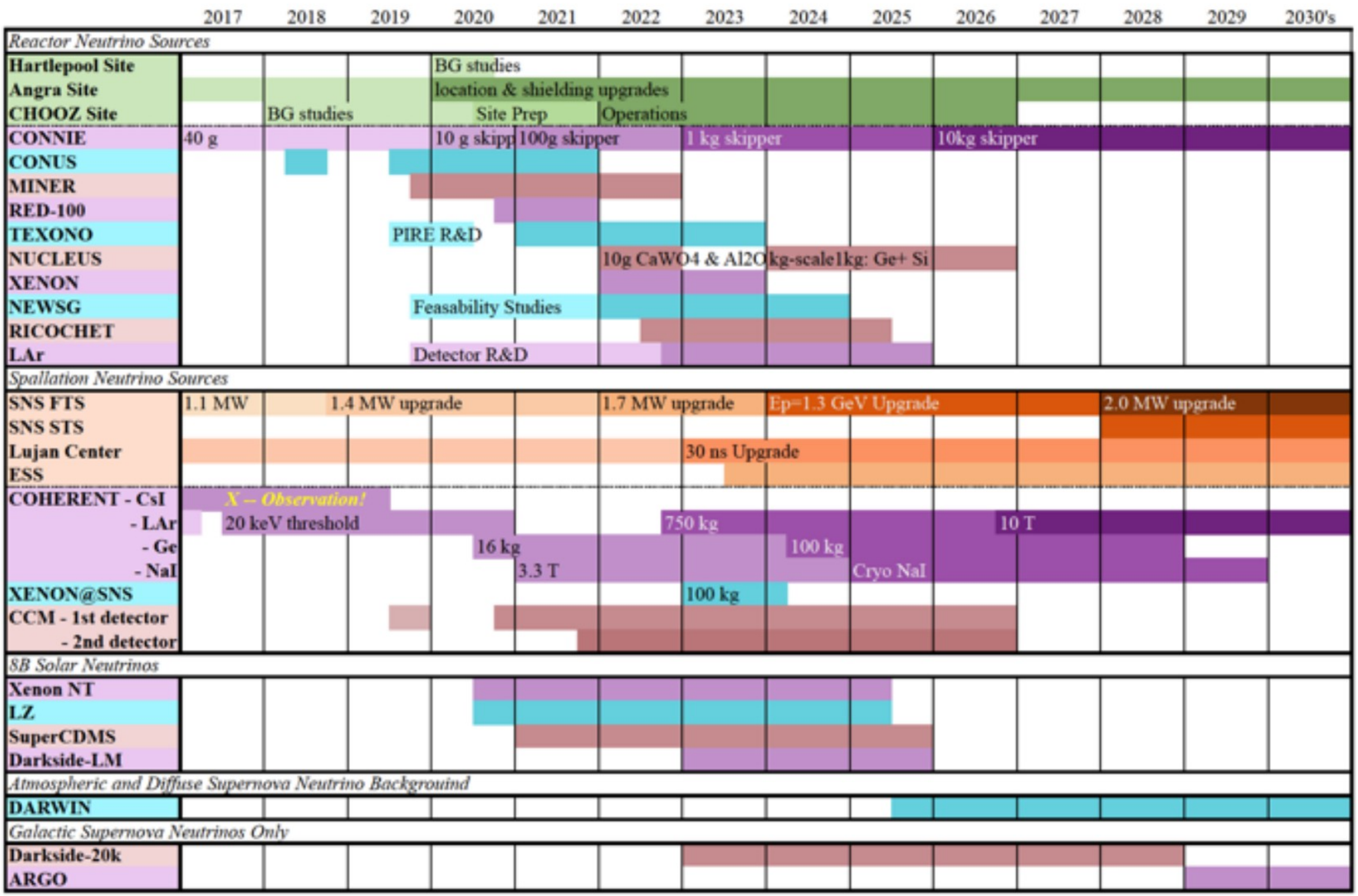


Figure: Phil Barbeau

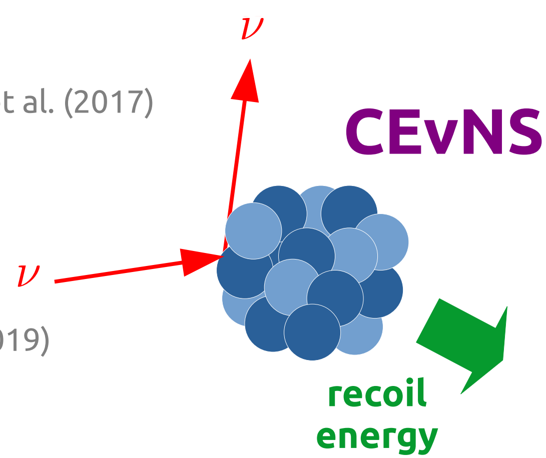
Landscape of new physics

Plethora of theoretical efforts to identify new physics with CevNS:

Neutron radius, Caddedu et al. (2017)

Link to Dark Matter, Brdar et al. (2018)

CEvNS and neutrino oscillations, Colama et al. (2017)



Neutrino magnetic moments, Kosmas et al. (2015), Miranda et al. (2019)

CP-violating vector mediator, Sierra et al. (2019)

Form factors, Nuclear physics, Amanik + McLaughlin, K. Patton et al. (2012)

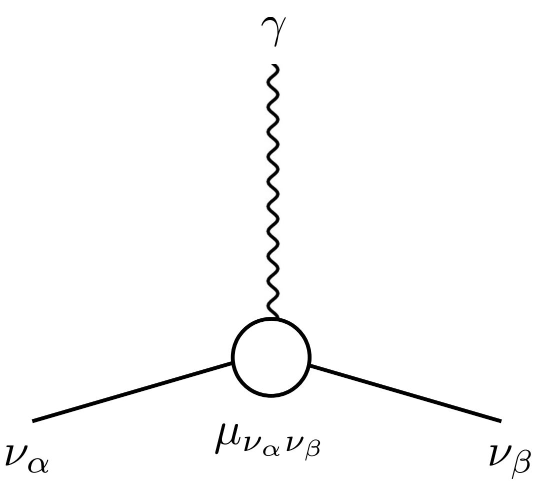
Light mediators, Billard et al. (2019)

Neutrino non-standard interactions, Lindner et al. (2017), Bischer et al. (2019)

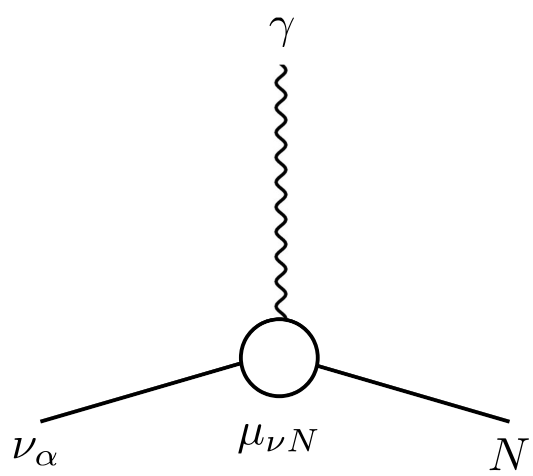
Supernovae dynamics, Wilson et al.

References exemplary, non-exhaustive

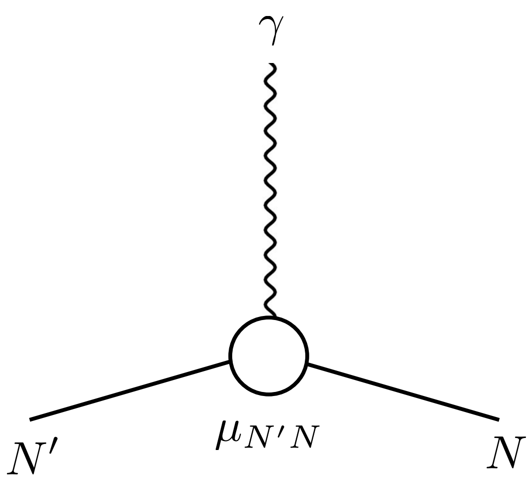
Probing neutrino magnetic moments with CEvNS



active neutrino magnetic moment

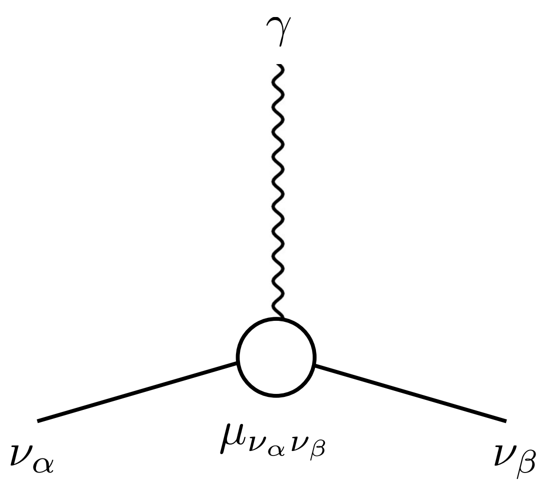


Active-sterile transition neutrino magnetic moment

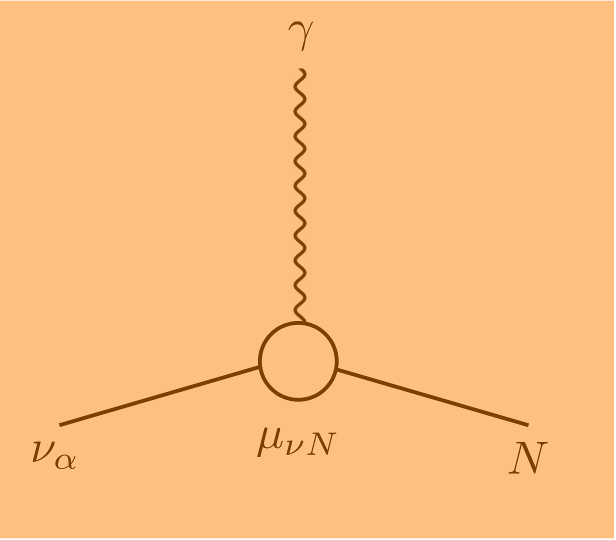


sterile neutrino magnetic moment

Probing neutrino magnetic moments with CEvNS



active neutrino magnetic moment



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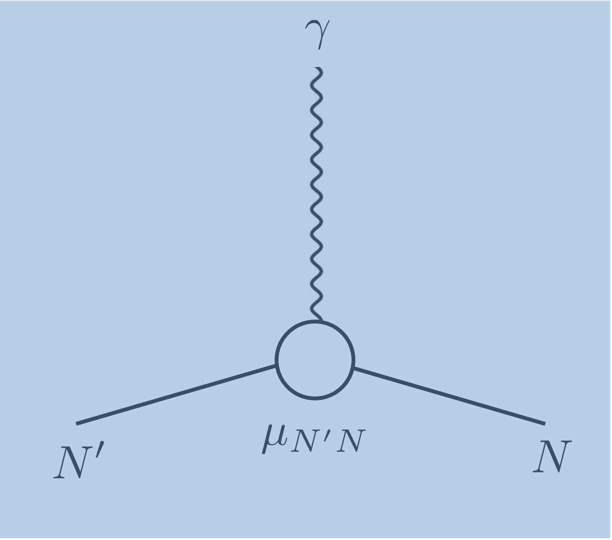


sterile neutrino magnetic moment

$$\mathcal{L} \supset \mu^{\alpha}_{\nu N} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N F^{\mu\nu} + \mu^{\alpha}_{N' N} \bar{N}' \sigma_{\mu\nu} P_R N F^{\mu\nu} + \text{h.c.}$$

Probing neutrino magnetic moments with CEvNS

$$\mathcal{L} \supset \mu^{\alpha}_{\nu N} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N F^{\mu\nu} + \mu^{\alpha}_{N' N} \bar{N}' \sigma_{\mu\nu} P_R N F^{\mu\nu} + \text{h.c.}$$

Dirac: $\nu_\alpha = \nu_{\alpha L} + \nu_{\alpha R}$

Majorana: $\nu_\alpha = \nu_{\alpha L} + \nu^c_{\alpha L}$

Dirac: $N = N_L + N_R$

Majorana: $N = N^c_R + N_R$

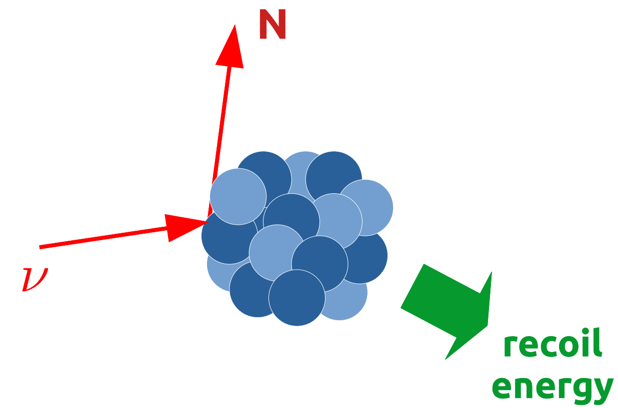
For scales much larger than the light active neutrinos $m_\nu \ll E_\nu$, rates are identical for Dirac and Majorana active neutrinos → agreement with Dirac-Majorana confusion theorem

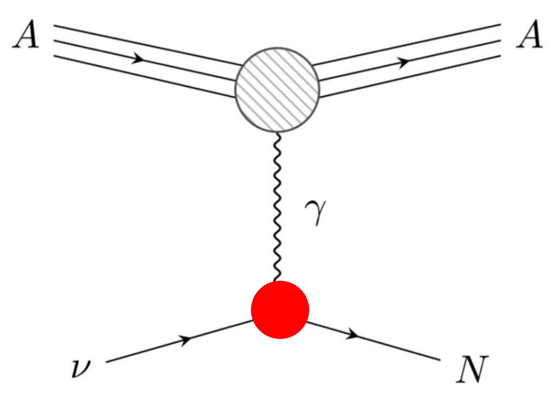
→ How can we distinguish Dirac vs. Majorana right-handed neutrinos (RHNs)?

Probing neutrino magnetic moments with CEvNS

Coherent elastic neutrino-nucleus scattering:

$$\mathcal{L} \supset \mu^{\alpha}_{\nu N} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N F^{\mu\nu} + \mu^{\alpha}_{N' N} \bar{N}' \sigma_{\mu\nu} P_R N F^{\mu\nu} + \text{h.c.}$$



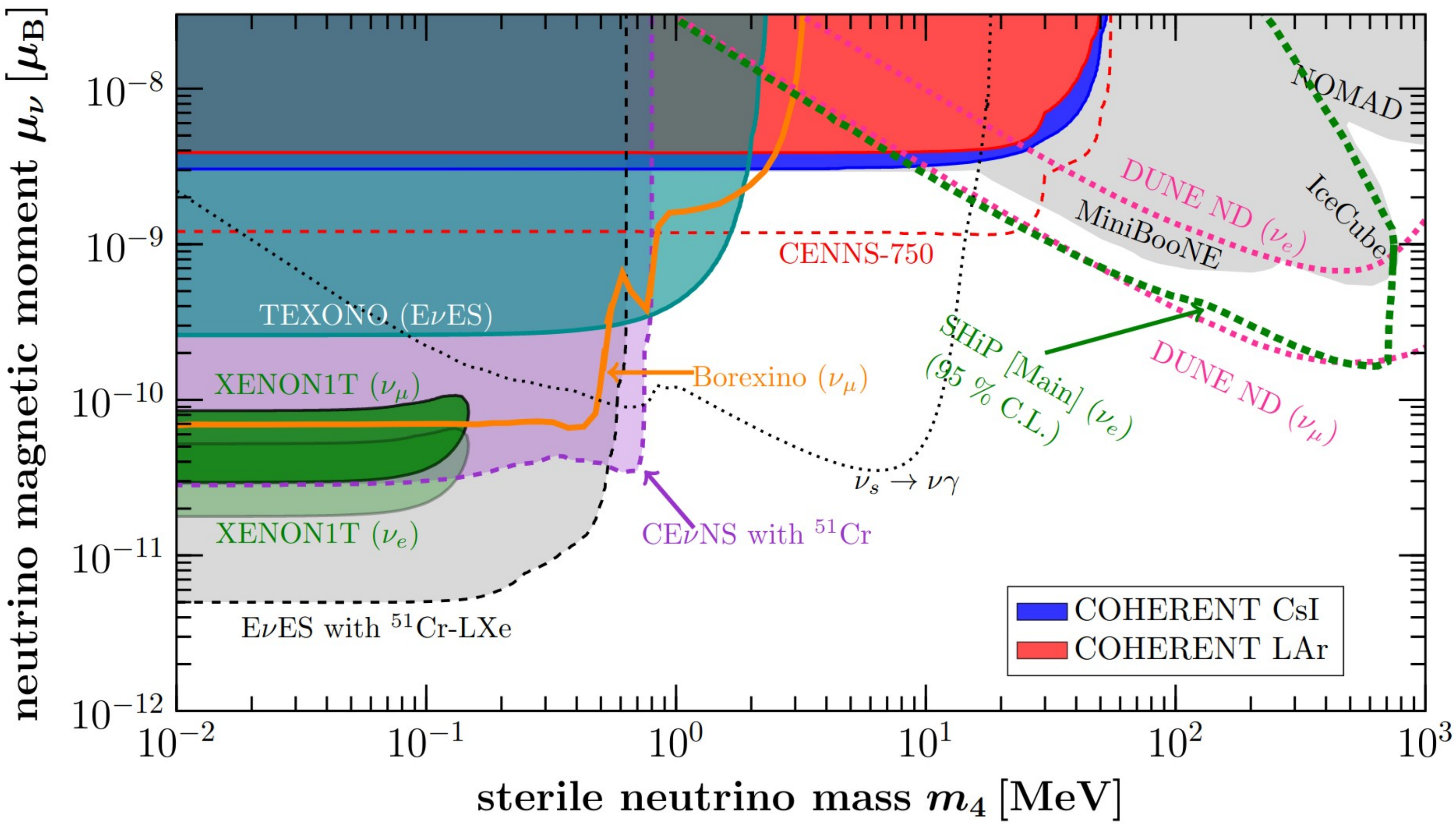


$|\mu_{\nu N}|^2$

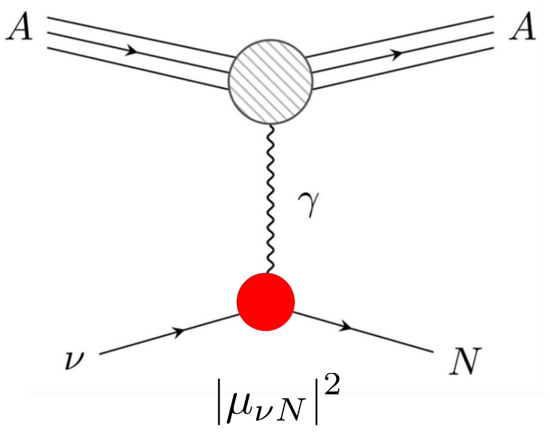
Primakoff-upscattering

e.g. Magill, Plestid, Pospelov, Tsai (2018)

Probing neutrino magnetic moments with CEvNS



Primakoff-upscattering

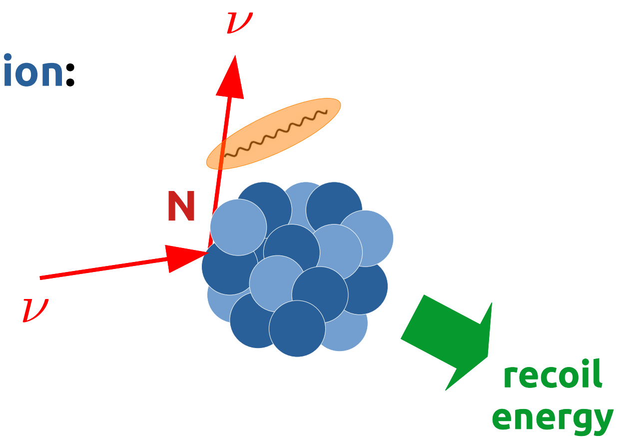


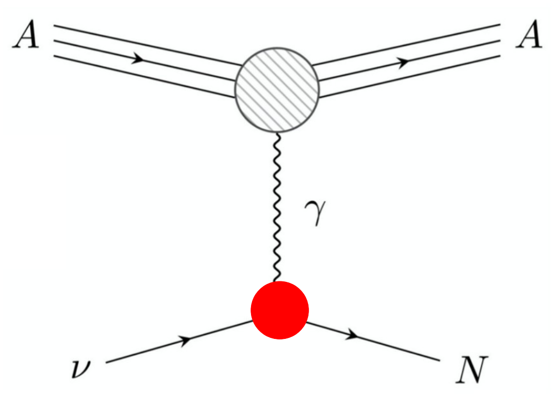
Miranda, Papoulias, Sanders, Tortola, Valle (2021)

CEvNS with Photon Emission

Coherent elastic neutrino-nucleus scattering with photon emission:

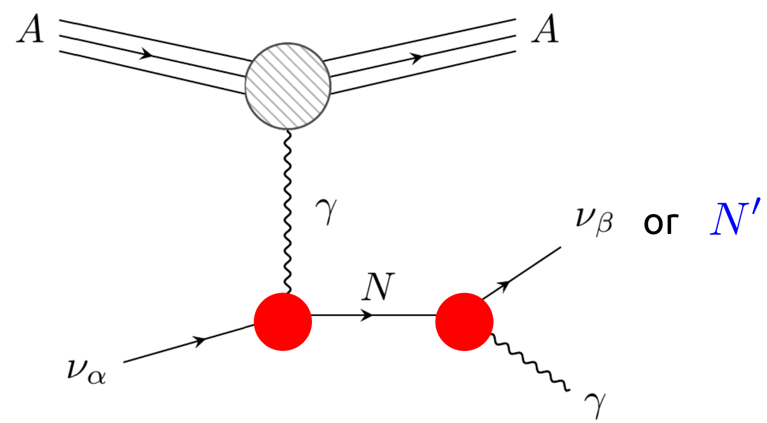
$$\mathcal{L} \supset \mu^{\alpha}_{\nu N} \bar{\nu}_{\alpha L} \sigma_{\mu\nu} P_R N F^{\mu\nu} + \mu^{\alpha}_{N' N} \bar{N}' \sigma_{\mu\nu} P_R N F^{\mu\nu} + \text{h.c.}$$





$|\mu_{\nu N}|^2$

Primakoff-upscattering



$|\mu^{\alpha}_{\nu N} \mu^{\beta}_{\nu N}|^2$ or $|\mu^{\alpha}_{\nu N} \mu_{N N'}|^2$

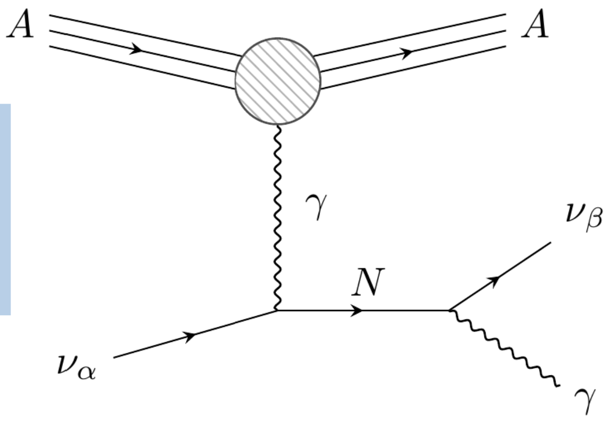
Primakoff-upscattering with photon emission

Suppressed, but new smoking gun signal!

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

CEvNS with Photon Emission

$$i\mathcal{M}^{\mathrm{D}}_{\nu_\alpha A\to\nu_\beta A\gamma} = \mu^{\alpha}_{\nu N}\mu^{\beta}_{\nu N}[\bar{u}_{\nu_\beta}\sigma_{\mu\nu}P_R(p_N + m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}]X^{\mu\nu\rho\sigma}$$
$$i\mathcal{M}^{\mathrm{M}}_{\nu_\alpha A\to\nu_\beta A\gamma} = \mu^{\alpha}_{\nu N}\mu^{\beta}_{\nu N}[\bar{u}_{\nu_\beta}\sigma_{\mu\nu}(p_N + m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}]X^{\mu\nu\rho\sigma}$$

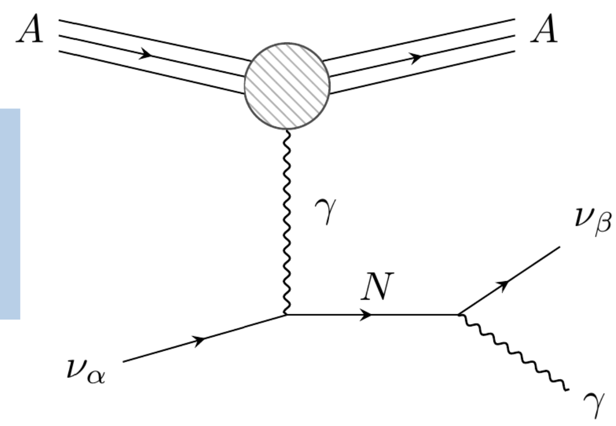


Electron-recoil distribution:

$$\left.\frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R}\right|_{\mathrm{NWA}} = \frac{d\sigma_{\nu_\alpha A\to N A}}{dE_R}\,\frac{\Gamma^{\mathrm{D(M)}}_{N\to\nu_\beta\gamma}}{\Gamma_N}$$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

CEvNS with Photon Emission



$$i\mathcal{M}^{\mathrm{D}}_{\nu_\alpha A\to\nu_\beta A\gamma} = \mu^{\alpha}_{\nu N}\mu^{\beta}_{\nu N}[\bar{u}_{\nu_\beta}\sigma_{\mu\nu}P_R(p_N+m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}]X^{\mu\nu\rho\sigma}$$

$$i\mathcal{M}^{\mathrm{M}}_{\nu_\alpha A\to\nu_\beta A\gamma} = \mu^{\alpha}_{\nu N}\mu^{\beta}_{\nu N}[\bar{u}_{\nu_\beta}\sigma_{\mu\nu}(p_N+m_N)\sigma_{\rho\sigma}P_L u_{\nu_\alpha}]X^{\mu\nu\rho\sigma}$$

Electron-recoil distribution:

$$\left.\frac{d\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_R}\right|_{\mathrm{NWA}} = \frac{d\sigma_{\nu_\alpha A\to NA}}{dE_R}\frac{\Gamma^{\mathrm{D(M)}}_{N\to\nu_\beta\gamma}}{\Gamma_N}$$

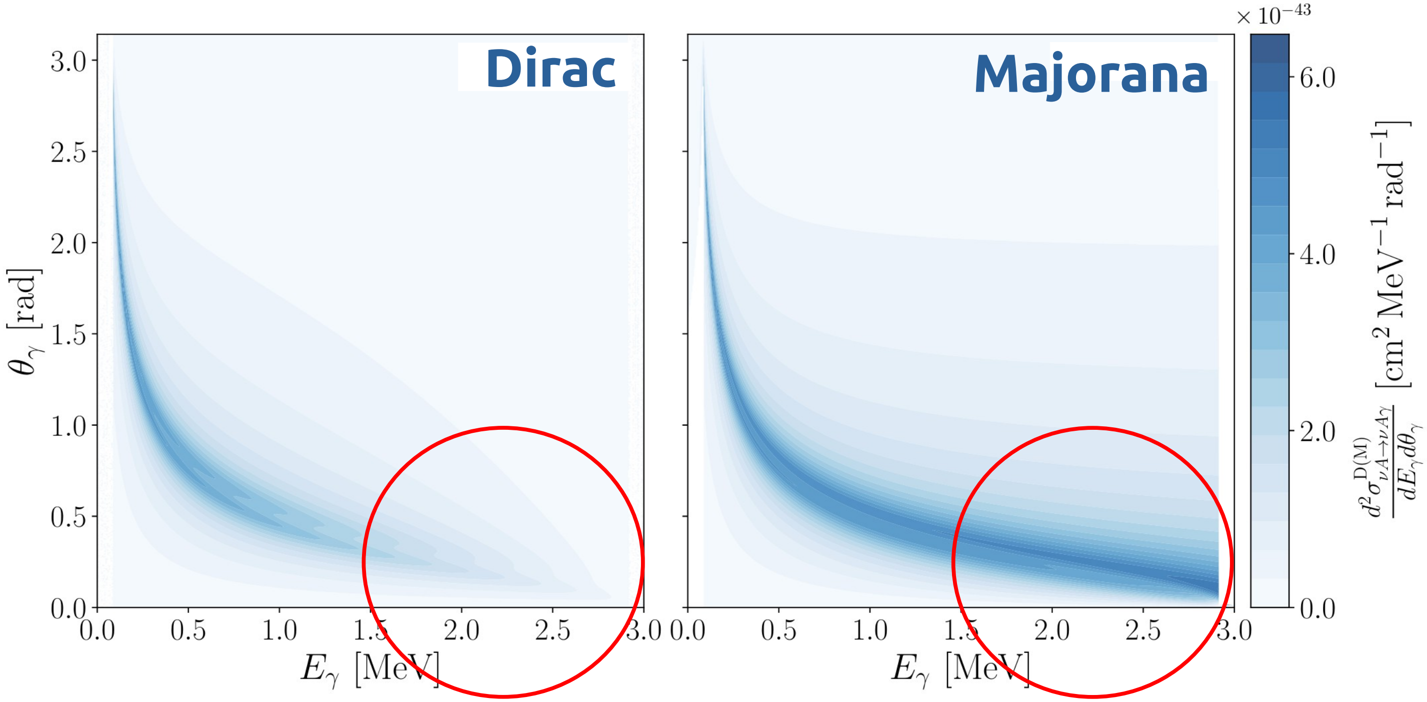
Energy and angular distribution of the photon:

$$\left.\frac{d^2\sigma^{\mathrm{D(M)}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{dE_\gamma d\theta_\gamma}\right|_{\mathrm{NWA}} = |\mu^{\alpha}_{\nu N}\mu^{\beta}_{\nu N}|^2\frac{\alpha Z^2 E_\gamma\sin\theta_\gamma}{128\pi^2 m_A E_\nu m_N\Gamma_N}\int_{t_1^-}^{t_1^+}dt_1\left.\frac{L^{\gamma,\,\mathrm{D(M)}}_{\mu\nu}H^{\mu\nu}\mathcal{F}^2(t_1)}{t_1^2\sqrt{-\Delta_4}}\right|_{s_1=m_N^2}$$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

CEvNS with Photon Emission – Majorana vs Dirac

$$E_\nu = 3\text{MeV}, m_N = 1\text{MeV}, \mu^\alpha_{\nu N} = 3 \times 10^{-8}\mu_B, \Gamma_N = 10^{-11}\text{MeV}$$



$$\frac{d^2\sigma^{\text{M}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{ds_1 dt_1} \Big/ \frac{d^2\sigma^{\text{D}}_{\nu_\alpha A\to\nu_\beta A\gamma}}{ds_1 dt_1} = 1 + \frac{m_N^2}{s_1}$$

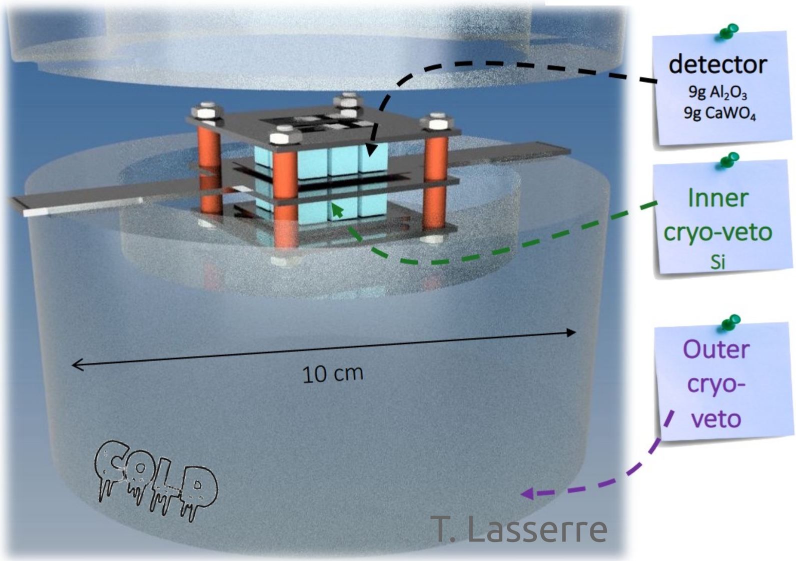
$\nu_\alpha A \to \nu_\beta A\gamma$ $\quad$ $\nu_\alpha A \to \bar{\nu}_\beta A\gamma$

- **Clear difference for larger photon energies / smaller angles**
- **Different reactor neutrino energy → access to different sterile neutrino masses**

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Experimental realisation: NUCLEUS experiment

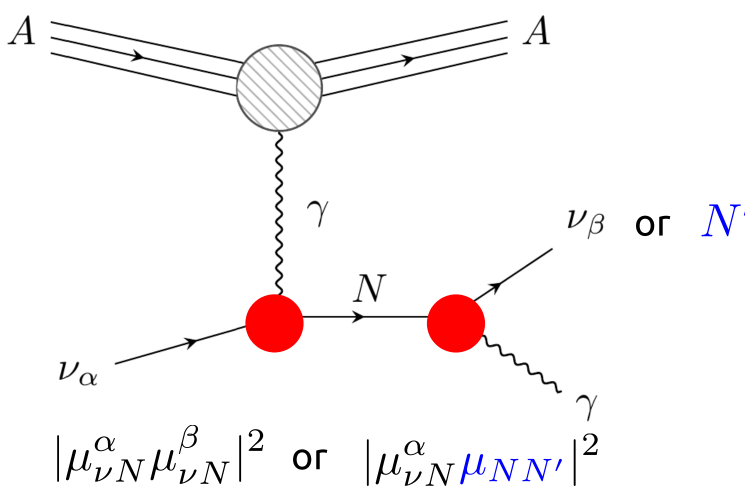
- **At Double-Chooz site**
- **NUCLEUS-phase 1: 10g $Al_2O_3/CaWO_4$**
- **NUCLEUS-phase 2: 1kg ^{73}Ge upgrade**
- **Distance to cryogenic outer veto < 5cm for phase 1**
- **Energy threshold: 10 eV**
- **Sensitivity to photon energy: 1keV to 10 MeV**
- **Ionisation resolution: 50-100 keV**



$$\frac{dR^{\mathrm{D(M)}}_{\bar{\nu}_e A\to\bar{\nu}_e A\gamma}}{dE_\gamma} = \frac{1}{m_A}\int_{E_\nu^{\min}(E_\gamma)}^{E_\nu^{\max}} dE_\nu \frac{d\phi_{\bar{\nu}_e}}{dE_\nu}\frac{d\sigma^{\mathrm{D(M)}}_{\bar{\nu}_e A\to\bar{\nu}_e A\gamma}}{dE_\gamma}$$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

RHN neutrino decay width



Example scenario: neutrino decays within the detector (NUCLEUS: 5cm):

$$\Gamma_N = \frac{\beta\gamma}{l_0} \approx 4\times 10^{-12}\ \mathrm{MeV}\frac{5\ \mathrm{cm}}{l_0}\beta\gamma$$

$$\Gamma_N > 10^{-11}\mathrm{MeV}$$

Decay width of N limited by Borexino limits to: $\Gamma(N\to\nu\gamma) = \frac{(\mu^e_{\nu N})^2 m_N^3}{4\pi} \lesssim 10^{-15}\ \mathrm{MeV}$

Case 1:

- There are other light RHNs states

$$\Gamma^{\mathrm{D(M)}}_{N\to X\gamma} = \Gamma^{\mathrm{D(M)}}_{N\to\nu_\beta\gamma} + \Gamma^{\mathrm{D(M)}}_{N\to N'\gamma}$$

$$\Gamma(N\to N'\gamma) = \frac{(\mu^e_{N'N})^2 m_N^3}{4\pi} \gtrsim 10^{-11}\ \mathrm{MeV} \quad \text{for} \quad \mu^e_{N'N} \gtrsim 10^{-4}\mu_B$$

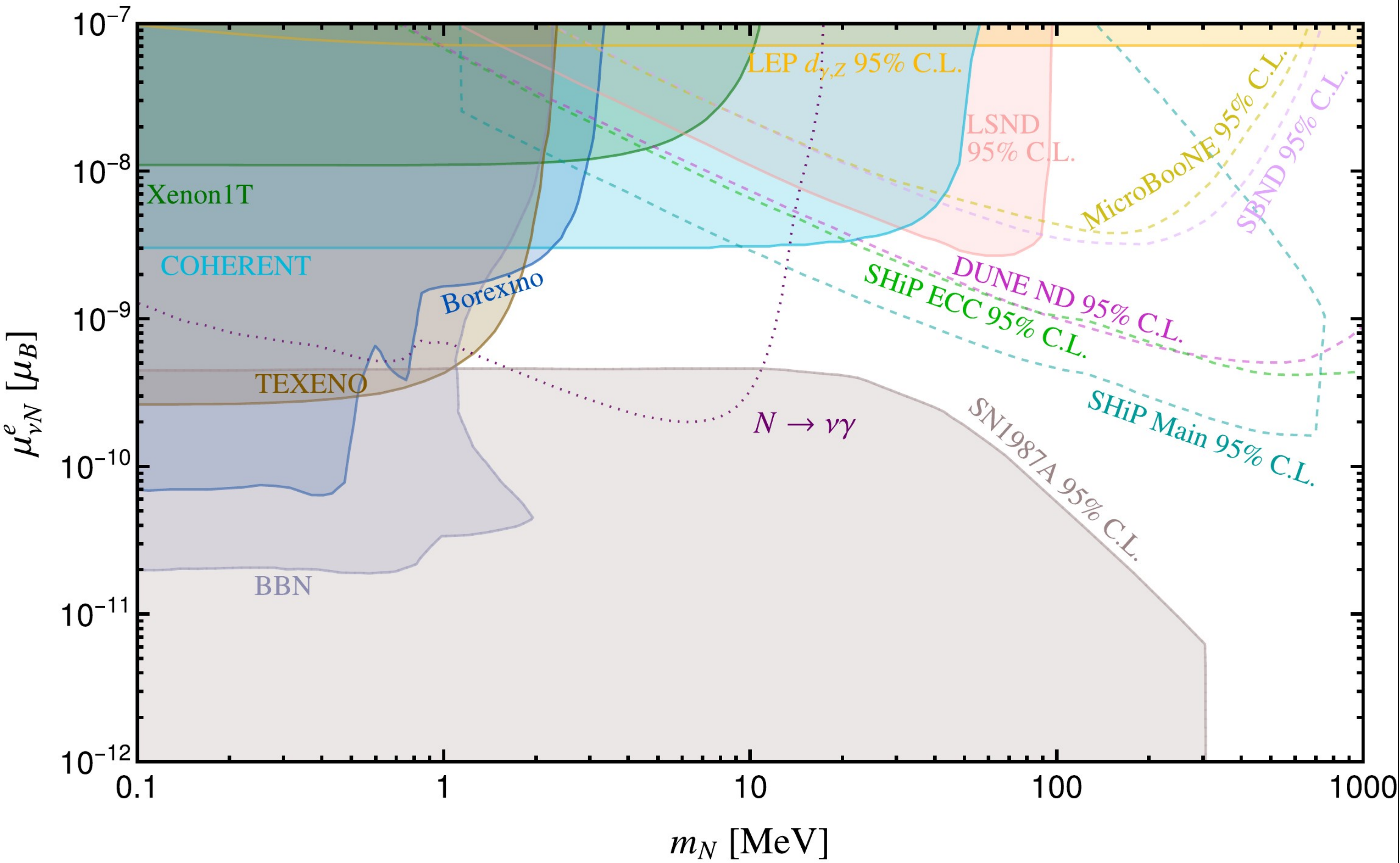
Case 2:

- RHN decays in other non-radiative modes such as light dark states

$$\Gamma^{\mathrm{D(M)}}_{N\to X\gamma} = \Gamma^{\mathrm{D(M)}}_{N\to\nu_\beta\gamma} + \Gamma^{\mathrm{D(M)}}_{N\to \mathrm{dark}}$$

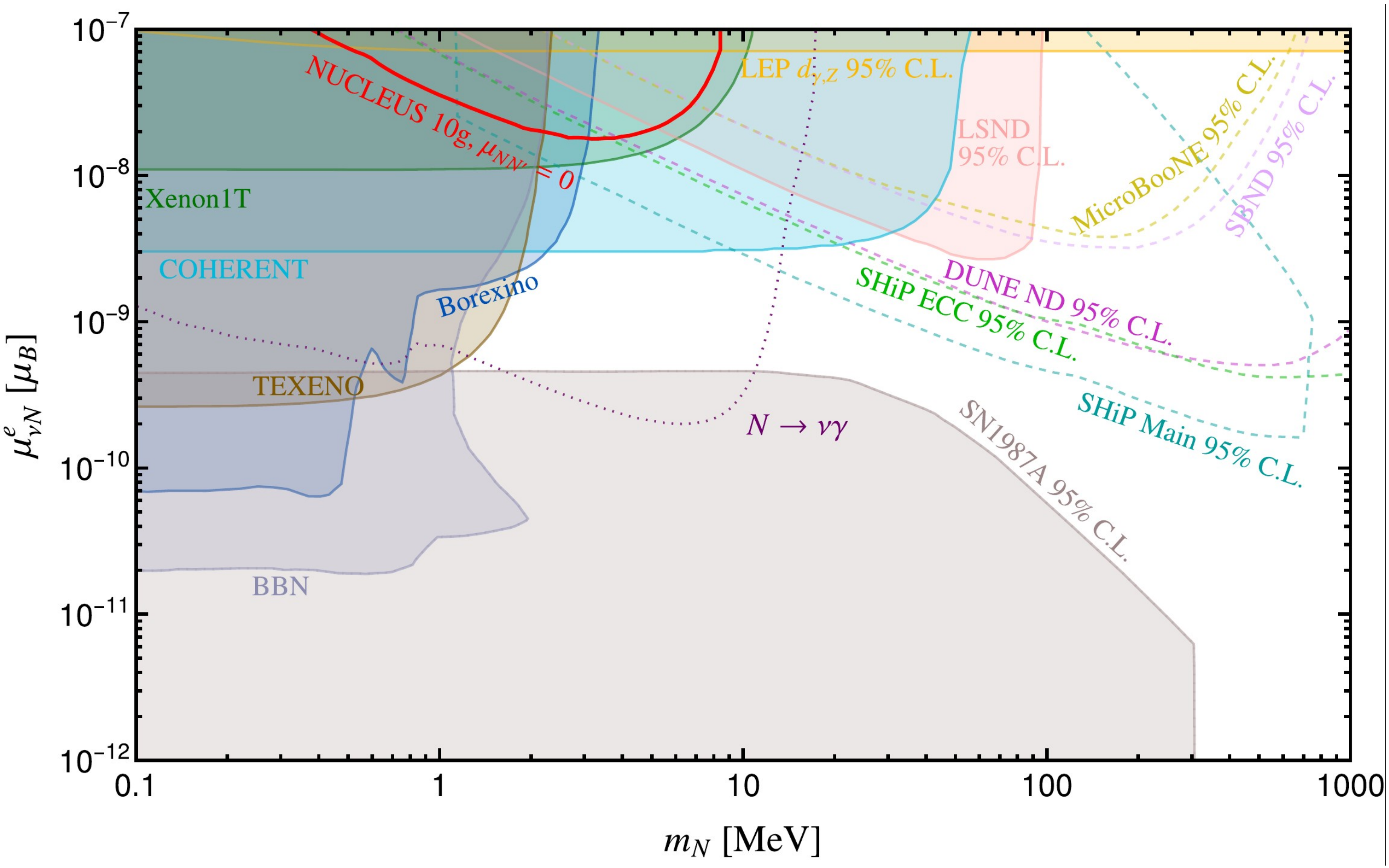
Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission



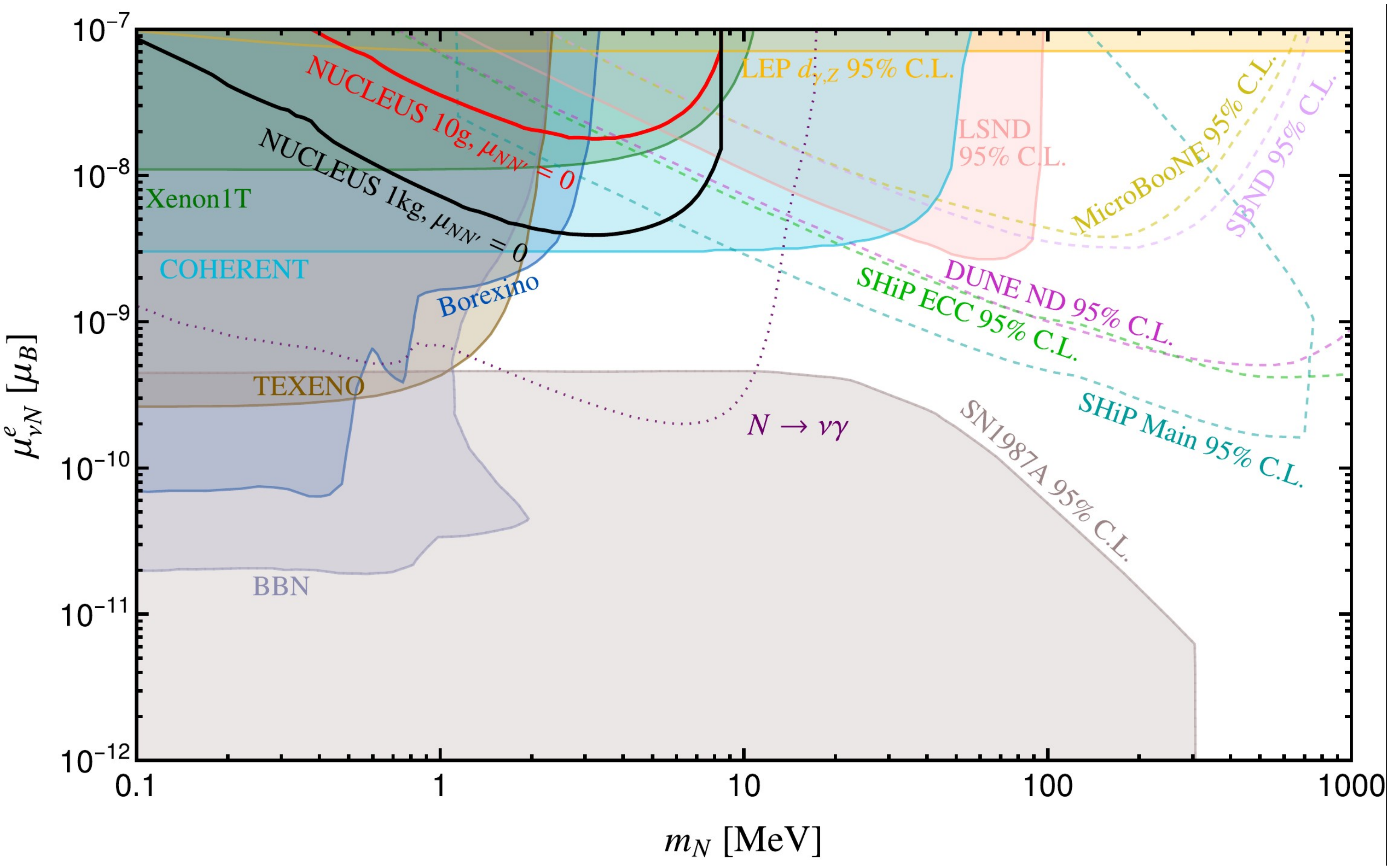
Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission



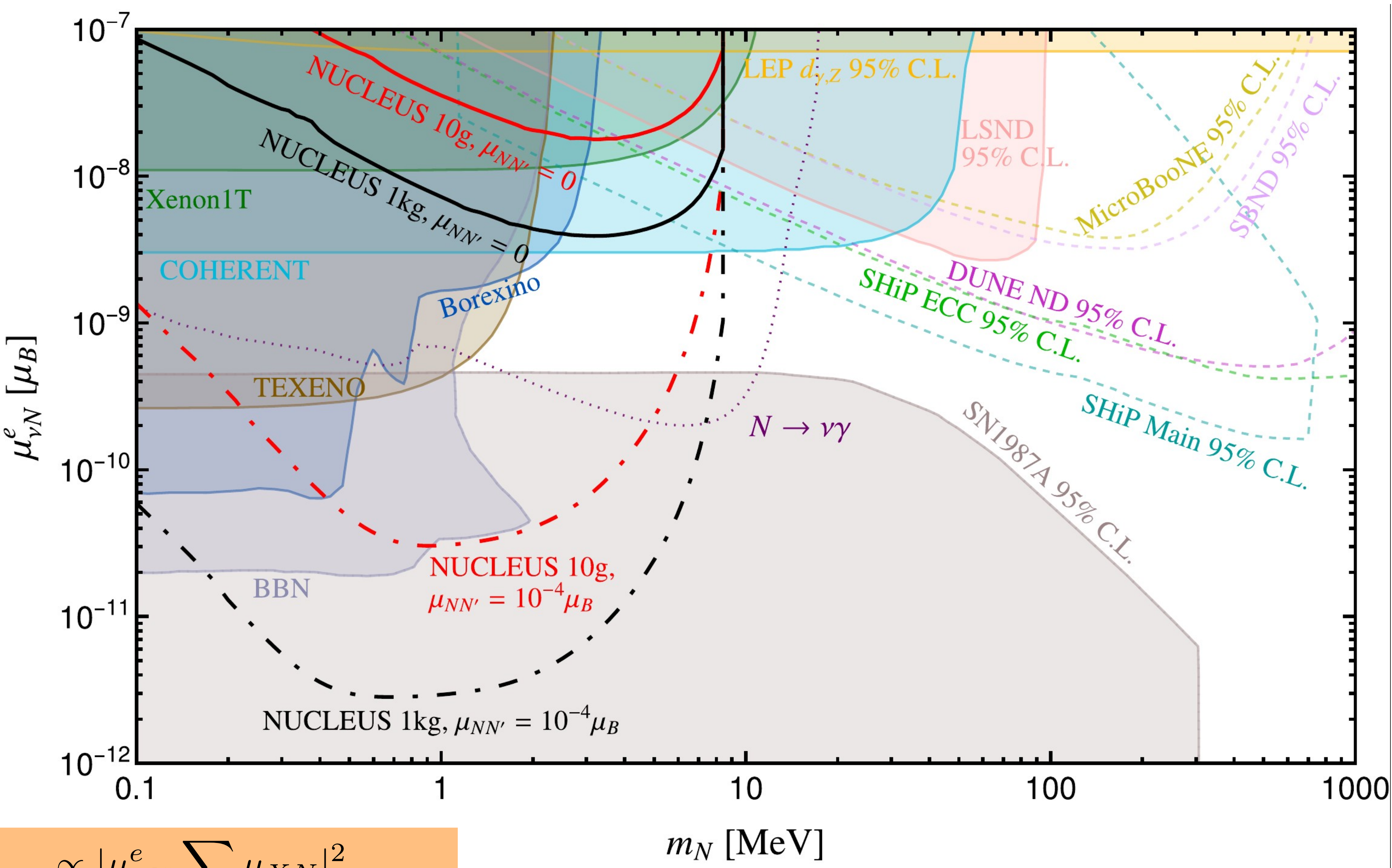
Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission



Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Sensitivity to CEvNS with Photon Emission

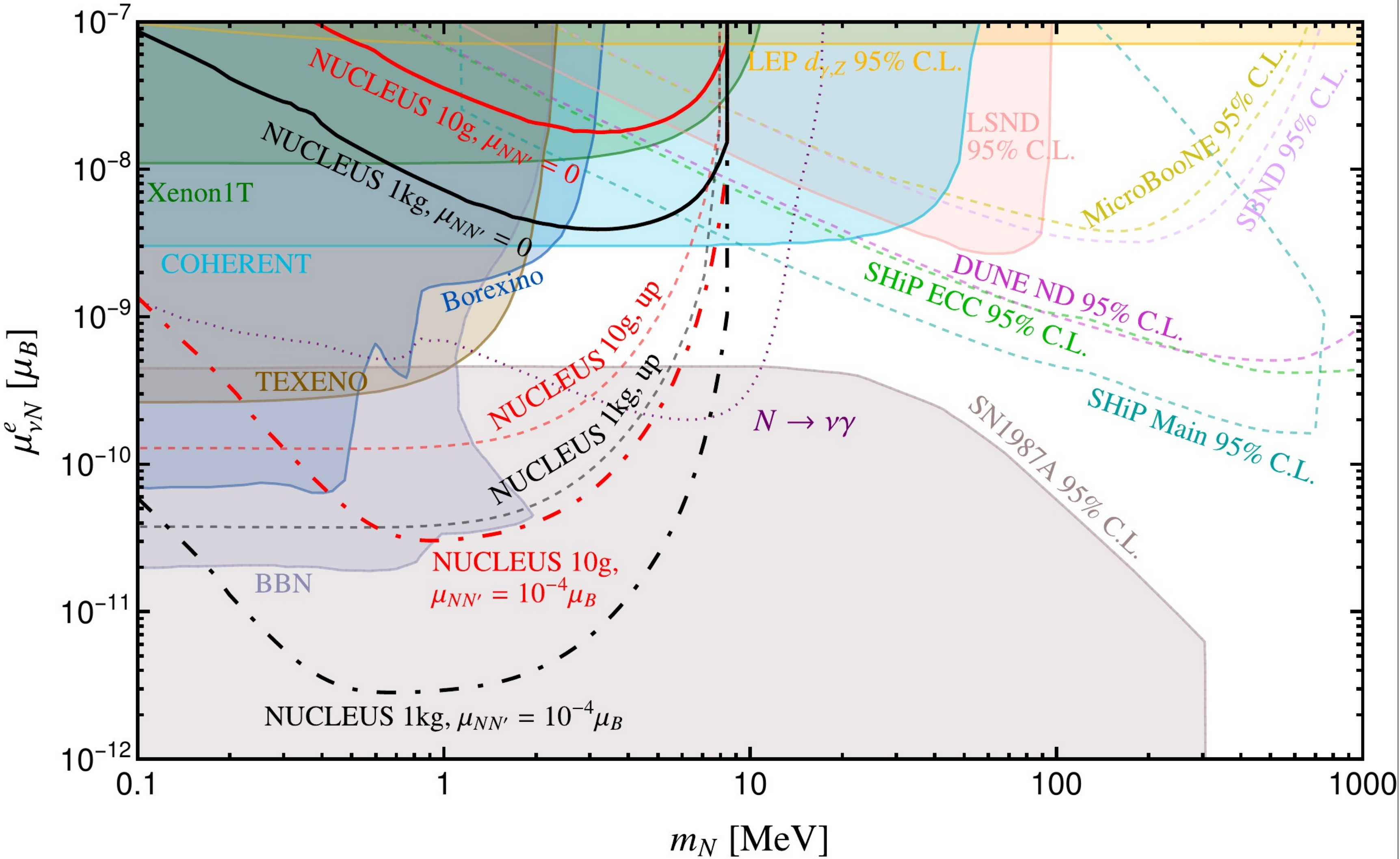


$$\propto |\mu^e_{\nu N} \sum_X \mu_{XN}|^2$$

$$\Gamma^{\mathrm{D(M)}}_{N\to X\gamma} = \Gamma^{\mathrm{D(M)}}_{N\to\nu_\beta\gamma} + \Gamma^{\mathrm{D(M)}}_{N\to N'\gamma}$$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

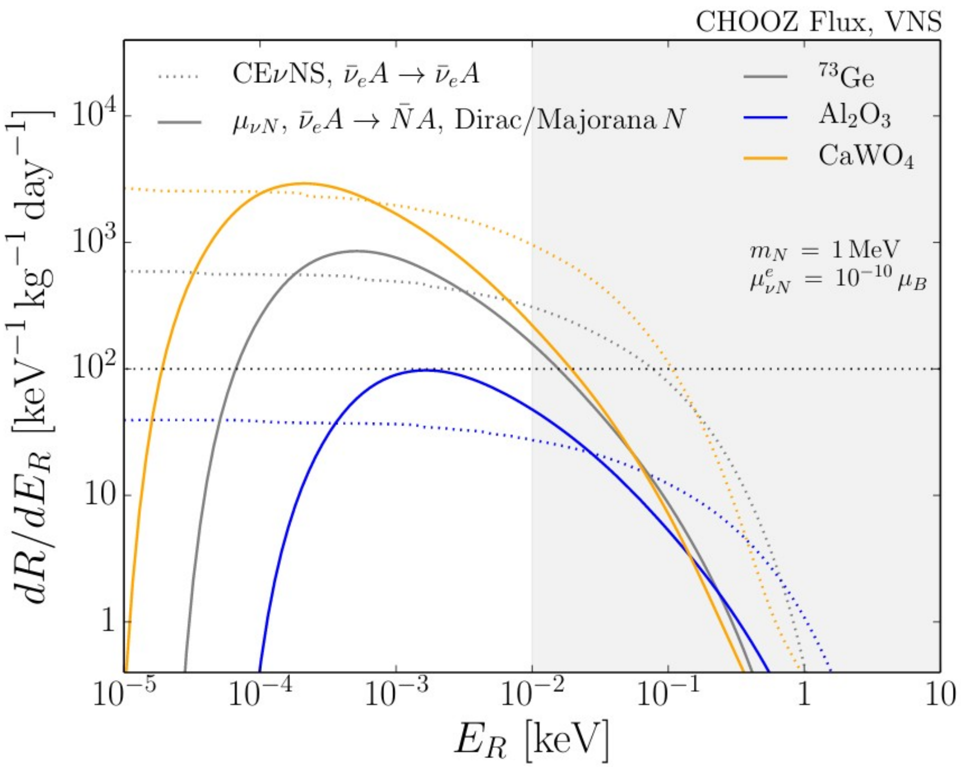
Sensitivity to CEvNS with Photon Emission

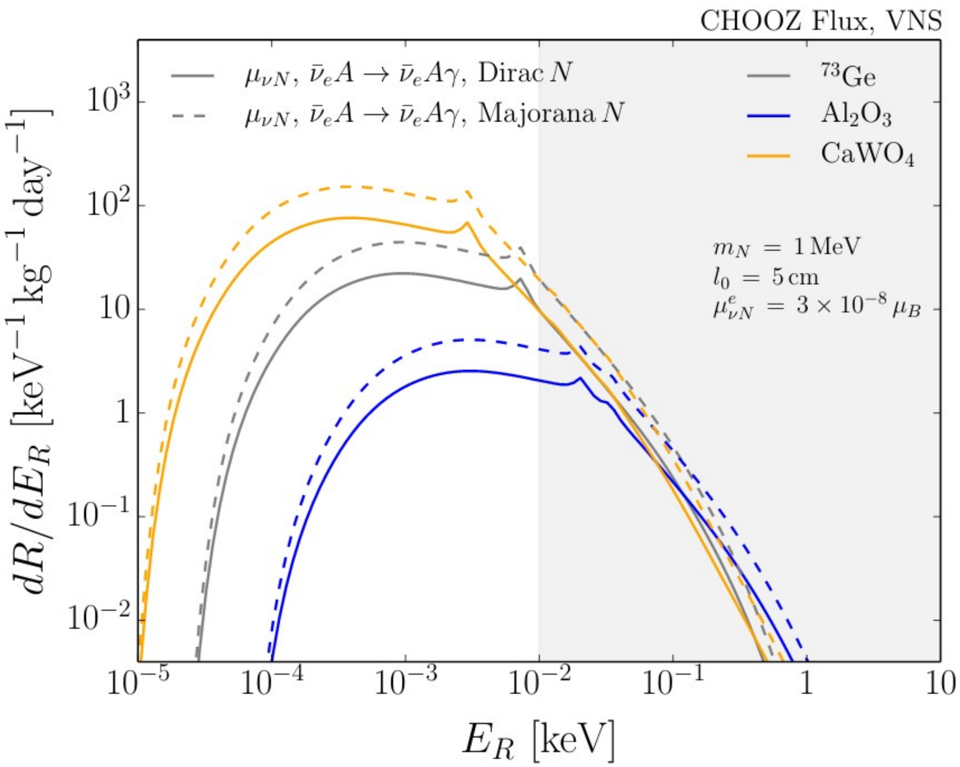


Radiative up-scattering has the potential to out-perform standard up-scattering mode!

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

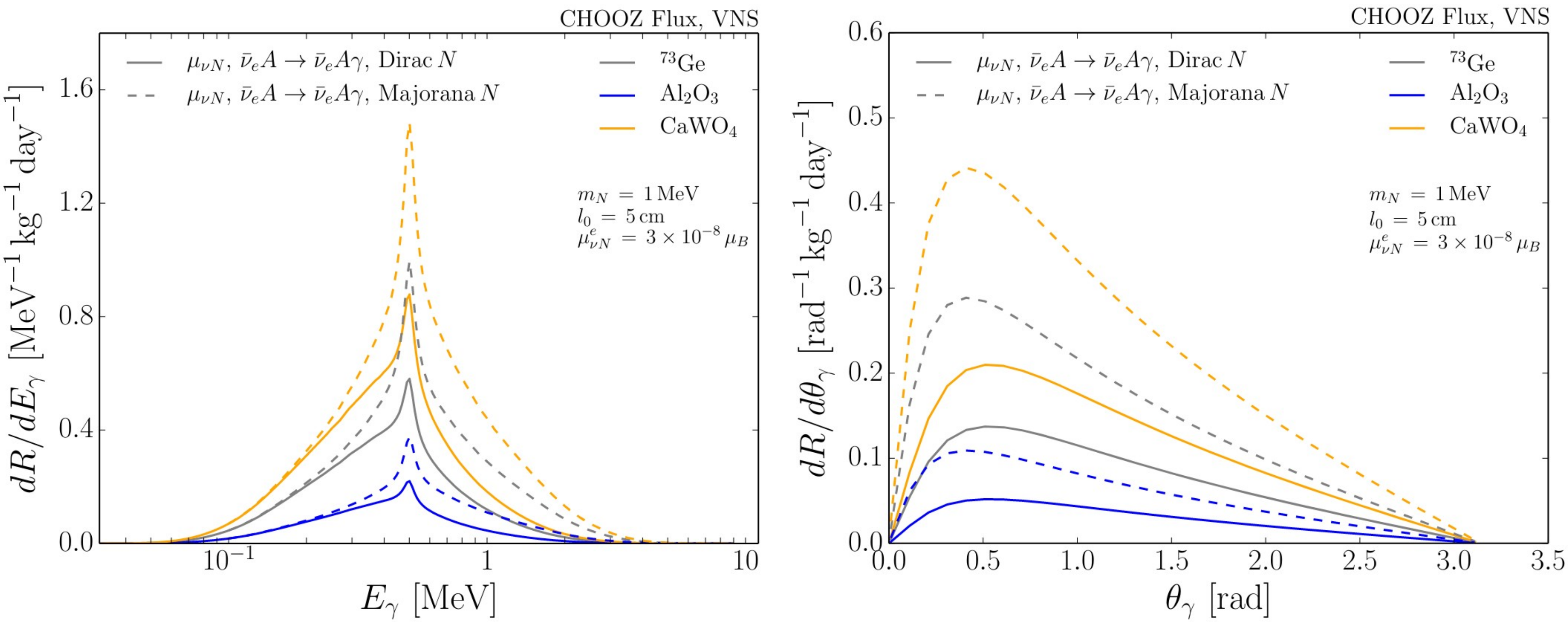
Majorana vs Dirac RHN – nuclear recoil





Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Majorana vs Dirac RHN – photon spectrum



→ **Different photon distributions for Dirac vs. Majorana RHNs**

Another Hubris to challenge?

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

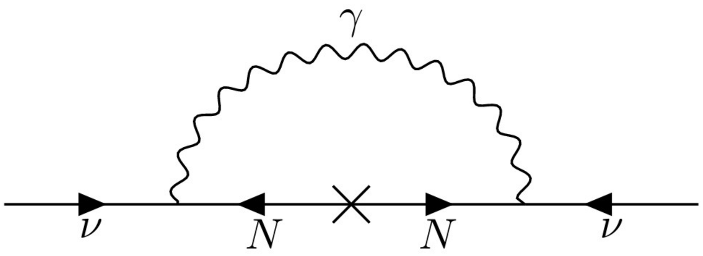
Insight in the nature of active neutrinos?

- **In case of contribution consistent to Dirac RHN:**

  → no conclusive statement possible

- **In case of contribution consistent to Majorana RHN:**

$$m_\nu \sim \frac{1}{16\pi^2}\mu_{\nu N}^2 m_N \Lambda^2$$
$$\sim \left(\frac{\mu_{\nu N}}{\mu_B}\right)^2 \frac{\alpha}{16\pi}\frac{m_N \Lambda^2}{m_e^2}$$



→ implies lepton-number violation and a Majorana mass term for active neutrinos

→ complementary probe to LNV at LHC or neutrinoless double beta decay

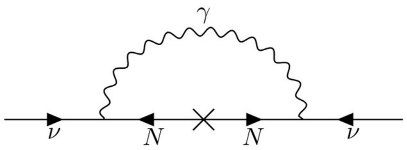
For example, $m_N \sim 1$ MeV, $\Lambda \sim 1$ TeV and $m_\nu < 1$ eV → $\frac{|\mu_{\nu N}|}{\mu_B} < 10^{-8}$

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Hint towards the neutrino mass mechanism?

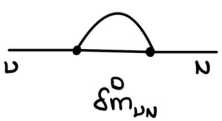
- **Majorana mass term**

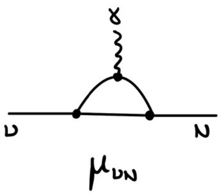
$$\delta m_\nu^M \sim \left(\frac{\mu_{\nu N}}{\mu_B}\right)^2 \frac{\alpha}{16\pi}\frac{m_N \Lambda^2}{m_e^2}$$



- **if transition magnetic moment gets loop induced via heavy NP**

$$\mu_{\nu N} \sim \frac{e}{\Lambda^2}\delta m_{\nu N}^D \qquad \frac{\mu_{\nu N}}{\mu_B} \sim \frac{m_e \delta m_{\nu N}^D}{\Lambda^2}$$

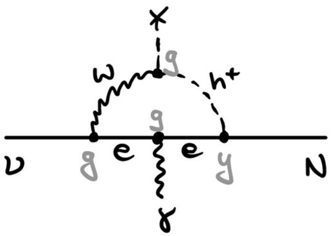




$$\frac{|\mu_{\nu N}|}{\mu_B} \sim 10^{-13}\frac{\delta m_{\nu N}^D}{1keV}$$

- **active-to-sterile mixing**

$$\mu_{\nu N} \sim \frac{g^3 y v}{16\pi^2 m_W^2} \qquad \frac{\mu_{\nu N}}{\mu_B} \sim \frac{m_{\nu N}^D m_e G_F}{16\pi^2\sqrt{2}}$$



$$\frac{|\mu_{\nu N}|}{\mu_B} \sim 10^{-14}\frac{m_{\nu N}^D}{1keV}$$

For example, see-saw type I with $m_N \sim 50$ MeV, $\Lambda \sim 1$ TeV and $m^D_{\nu N} \sim 1$ keV $\rightarrow m_\nu \sim 0.2$eV

A sign for radiative CEvNS would imply a neutrino mass mechanism beyond see-saw type I!

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

How magnetic can the neutrino be?

$$\mathcal{L}_{\rm eff} = \sum_{n,j} \frac{C_j^n(\mu)}{\Lambda^{n-4}} \, \mathcal{O}_j^{(n)}(\mu) \; + \; \text{h.c.}$$

$$\begin{aligned} \mathcal{O}_1^{(6)} &= g' \bar{L} \tilde{H} \sigma_{\mu\nu} N_R B^{\mu\nu} \\ \mathcal{O}_2^{(6)} &= g \bar{L} \tau^a \tilde{H} \sigma_{\mu\nu} N_R W^{a\mu\nu} \\ \mathcal{O}_3^{(6)} &= \bar{L} \tilde{H} N_R \left(H^\dagger H \right) \end{aligned}$$

$$C_3^{(6)}(\mu = \Lambda_{\rm NP}) = 0 \;\Rightarrow\; C_3^{(6)}(\mu = v) \neq 0$$

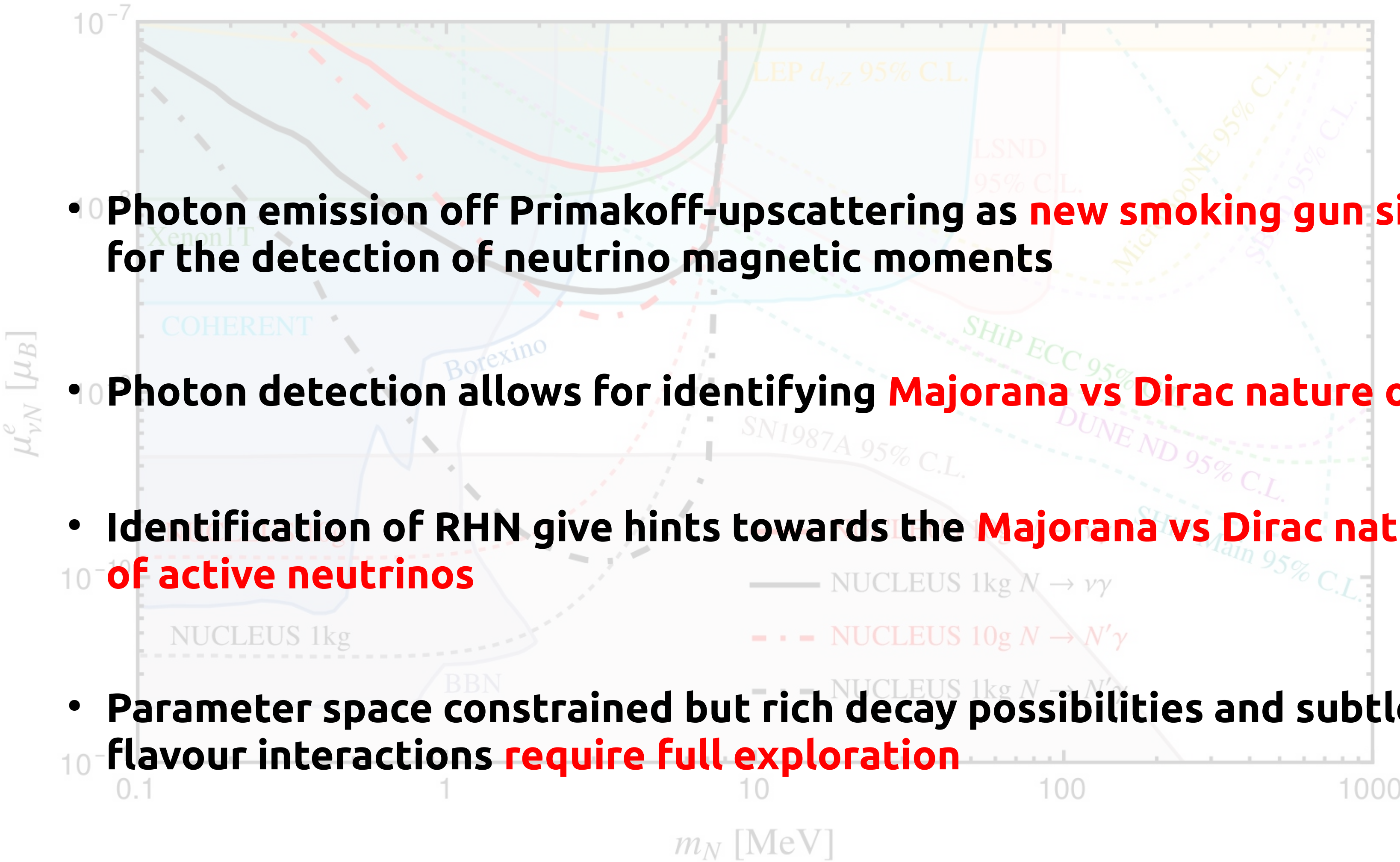
$$\delta m_{\nu N} = \frac{v^2}{16 m_e} \, \frac{C_3^{(6)}(v)}{C_1^{(6)}(v) + C_2^{(6)}(v)} \, \frac{\mu_{\nu N}}{\mu_B}$$

$$\frac{|\mu_{\nu N}|}{\mu_B} \sim 10^{-15} \left(\frac{\delta m_{\nu N}}{1 \text{ eV}} \right)$$

Bell, Cirigliano, Ramsey-Musolf, Vogel, Wise (2005)

Discrepancies would help to disentangle mass mechanism!

Summary: dim-5 neutrino magnetic moment



- **Photon emission off Primakoff-upscattering as new smoking gun signature for the detection of neutrino magnetic moments**
- **Photon detection allows for identifying Majorana vs Dirac nature of RHNs**
- **Identification of RHN give hints towards the Majorana vs Dirac nature of active neutrinos**
- **Parameter space constrained but rich decay possibilities and subtle flavour interactions require full exploration**

Bolton, Deppisch, Fridell, JH, Hati, Kulkarni (2021)

Outline

Motivation

- Neutrinos – the missing piece in the puzzle
- A tight link to the matter-antimatter asymmetry?

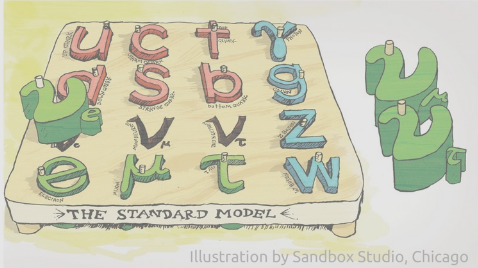
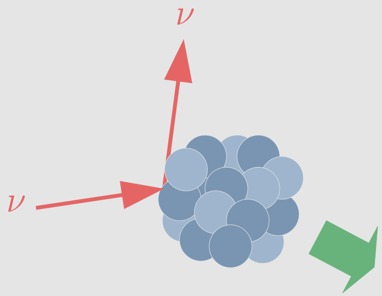


Illustration by Sandbox Studio, Chicago

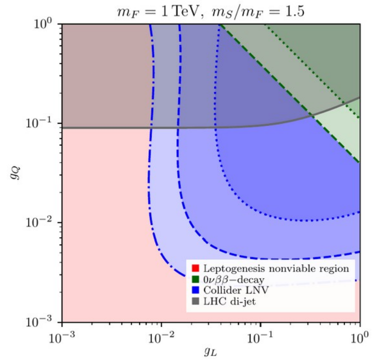
Dim-5 neutrino magnetic moment

- Coherent elastic neutrino nucleus scattering
- Photon emission off Primakoff upscattering
- Implications on Majorana vs. Dirac neutrinos



Dim-7 and 9 lepton number violating interactions

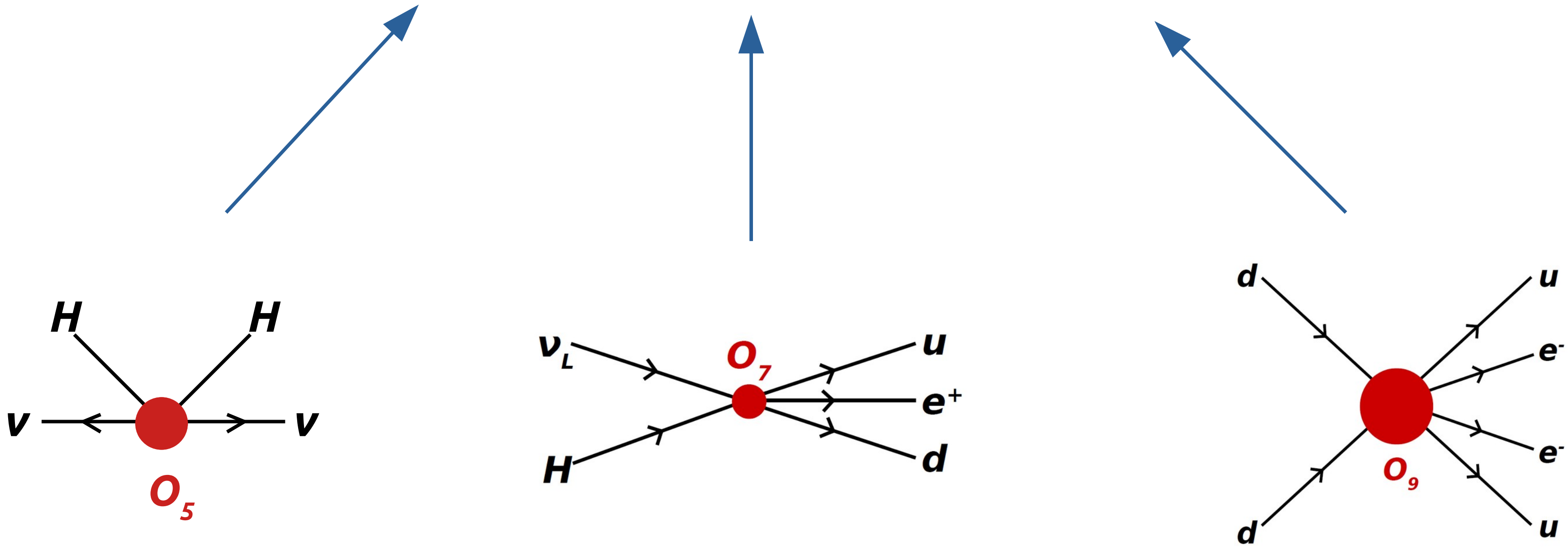
- Constraining LNV with kaon decays
- Complementary of neutrinoless double beta decay and LHC
- Implications for baryogenesis



Lepton number violating neutrino interactions

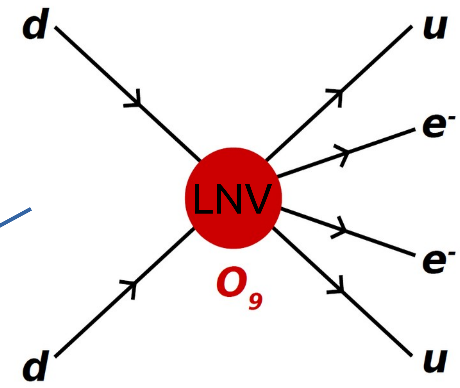
LNV occurs only at odd mass dimension beyond dim-4:

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_1}\mathcal{O}_1^{(5)} + \sum_i \frac{1}{\Lambda_i^3}\mathcal{O}_i^{(7)} + \sum_i \frac{1}{\Lambda_i^5}\mathcal{O}_i^{(9)} + \cdots$$

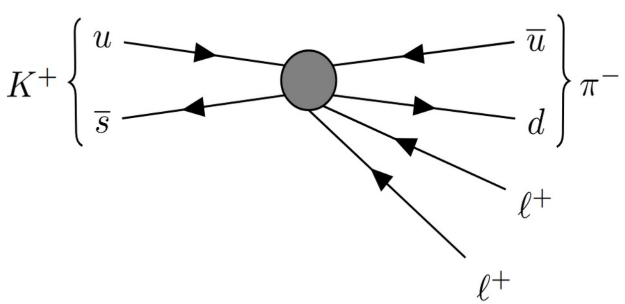


See surveys of all LNV operators up to dim-11 e.g. in
Babu, Leung (2001), Gouvea, Jenkins (2008), Graf, JH, Deppisch, Huang (2018)

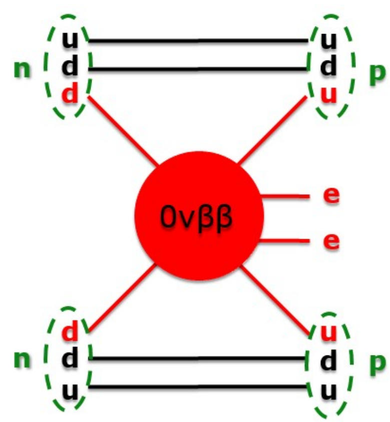
Probing LNV interactions



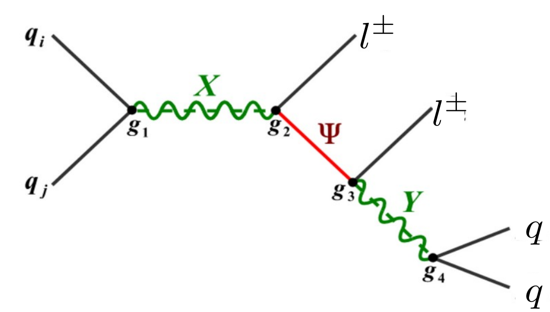
rare meson decays



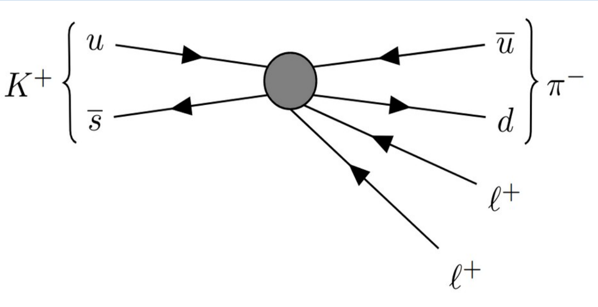
neutrinoless double beta decay



colliders



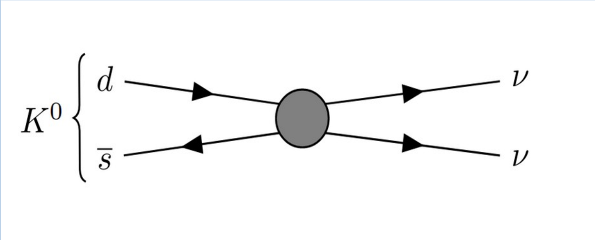
Probing LNV interactions – Meson decays



Same-sign leptonic final state

- LNV is directly tested
- dim-9 only
- for first generation, 0νββ stronger
- constraints very weak

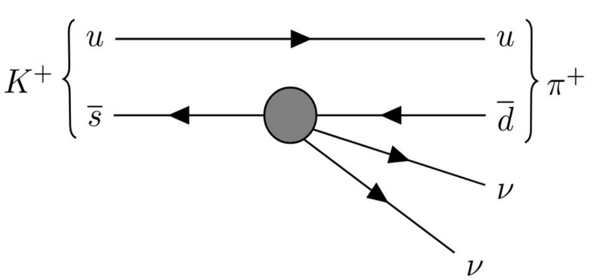
Liu, Zhang, Zhou (2016)
Quintero (2017)
Chun, Das, Mandal, Mitra, Sinha (2019)



Decay into neutrino final state

- No experimental searches?
- dim-7

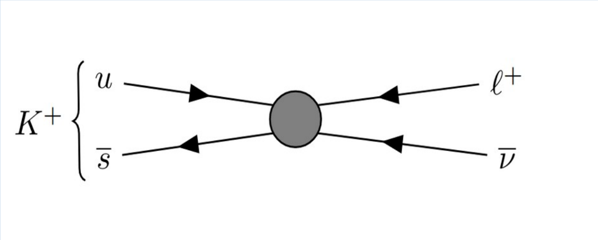
Gninenko (2014)



Neutrino final state

- LNV needs to be independently confirmed
- dim-7

Deppisch, Fridell, JH (2020)

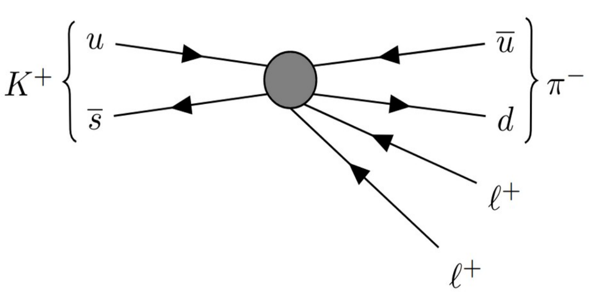


Charged lepton + neutrino final state

- Neutrino needs to be detected (Cooper et al. 1982)
- dim-7

Deppisch, Fridell, JH (2020)

Probing LNV interactions – Meson decays



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Liu, Zhang, Zhou (2016)
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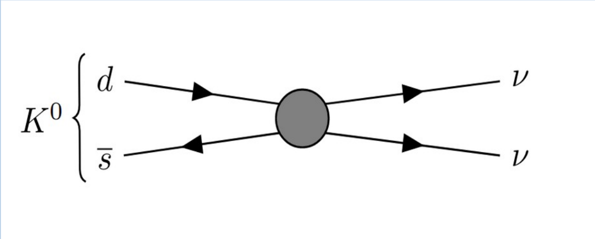
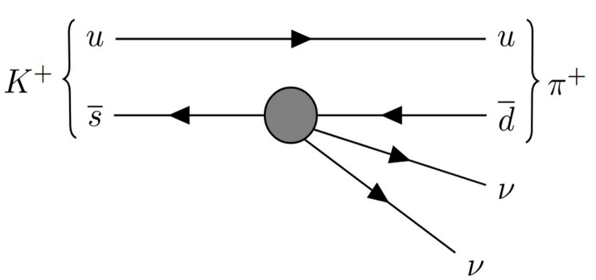


Decay into neutrino final state

- No experimental searches?
- dim-7

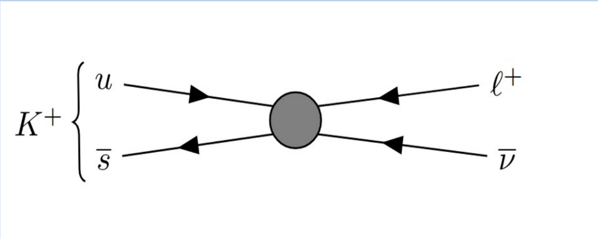
Gninenko (2014)



Neutrino final state

- LNV needs to be independently confirmed
- dim-7

Deppisch, Fridell, JH (2020)

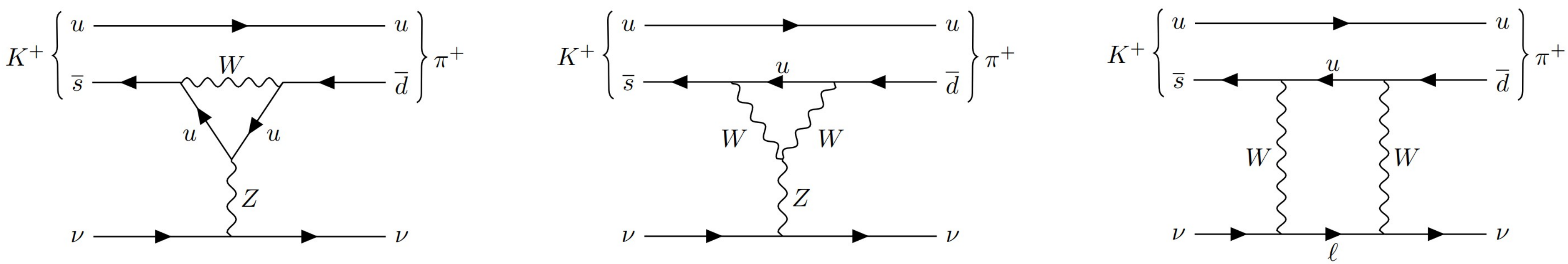


Charged lepton + neutrino final state

- Neutrino needs to be detected (Cooper et al. 1982)
- dim-7

Deppisch, Fridell, JH (2020)

$K^+ \rightarrow \pi^+\nu\nu$ and $K_L \rightarrow \pi^0\nu\nu$ in the Standard Model



Branching Ratios:

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu}) = \kappa^+ (1+\Delta_{EM}) \left[\left(\frac{\mathrm{Im}(V_{ts}^* V_{td} X_t)}{\lambda^5} \right)^2 + \left(\frac{\mathrm{Re}(V_{cs}^* V_{cd})}{\lambda} P_c + \frac{\mathrm{Re}(V_{ts}^* V_{td} X_t)}{\lambda^5} \right)^2 \right]$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu}) = \kappa_L \left(\frac{\mathrm{Im}(V_{ts}^* V_{td} X_t)}{\lambda^5} \right)^2$$

GIM suppression!

Buchalla, Buras (1999)

Small hadronic uncertainty!

Mescia, Smith (2007)

$$\kappa^+ = (0.5173 \pm 0.025) \times 10^{-10} (|V_{us}|/0.0225)^8$$

$$\kappa_L = (2.231 \pm 0.013) \times 10^{-10} (|V_{us}|/0.0225)^8$$

Due to relation to more frequent decay $K \to \pi \ell^+ \nu_\ell$

Theoretical and experimental status

Theoretical prediction

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{SM}} = \left(8.5^{+1.0}_{-1.2}\right) \times 10^{-11}$$

$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{SM}} = (3.4 \pm 0.6) \times 10^{-11}$$

Buras, Buttazzo, Girrbach-Noe, Knegjens (2015)

Golden Channel!

Experimental measurements

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{E949}} = \left(1.73^{+1.15}_{-1.05}\right) \times 10^{-10}$$

E949 collaboration (2009)

$$\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})_{\mathrm{NA62}} = \left(10.6^{+4.0}_{-3.5} \pm 0.9\right) \times 10^{-11}$$

NA62 collaboration (2021)

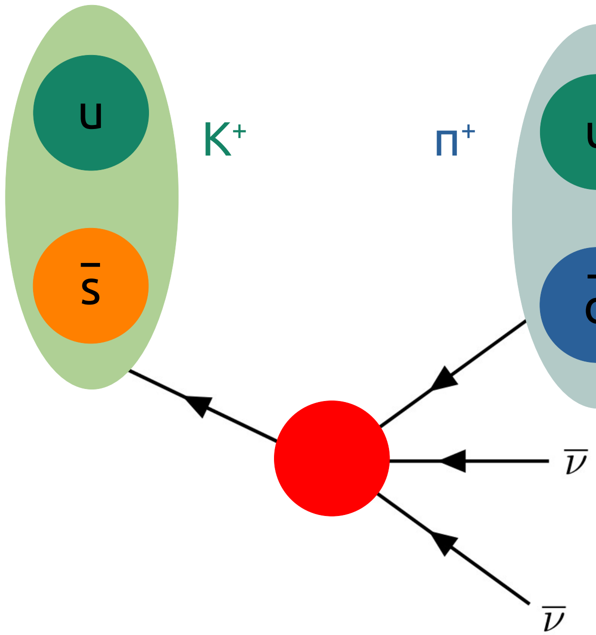
$$\mathrm{BR}(K_L \to \pi^0 \nu\bar{\nu})_{\mathrm{KOTO}} = \left(2.1^{+2.0(+4.1)}_{-1.1(-1.7)}\right) \times 10^{-9}$$

KOTO collaboration (2019)

→ **NA62 aims to reach SM sensitivity in the future!**

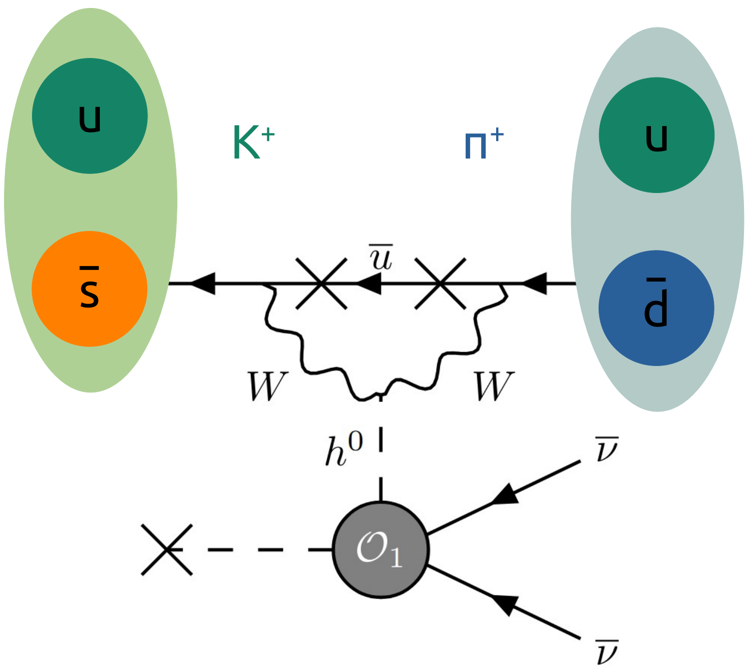
What would a deviation of the SM expectation imply for new physics?

Constraining new physics in rare kaon decays



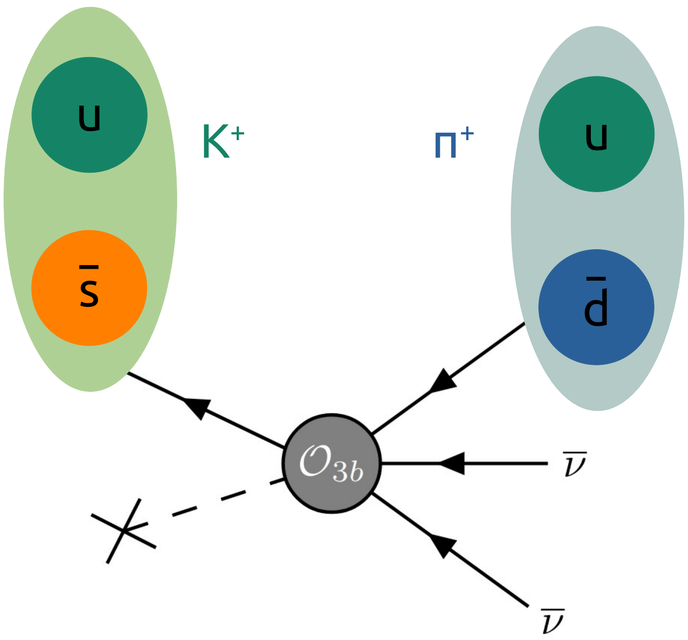
As neutrinos are not explicitly measured, a new physics contribution could be also lepton number violating!

Constraining LNV interactions with rare kaon decays



$$\mathcal{O}_1^{(5)} = L^\alpha L^\beta H^\rho H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

- GIM suppressed



$$\mathcal{O}_{3b}^{(7)} = L^\alpha L^\beta Q^\rho d^c H^\sigma \epsilon_{\alpha\rho}\epsilon_{\beta\sigma}$$

- No GIM suppression
- Includes first and second generation

Not explicit LNV!

Footprints of lepton number violation in rare meson decays?

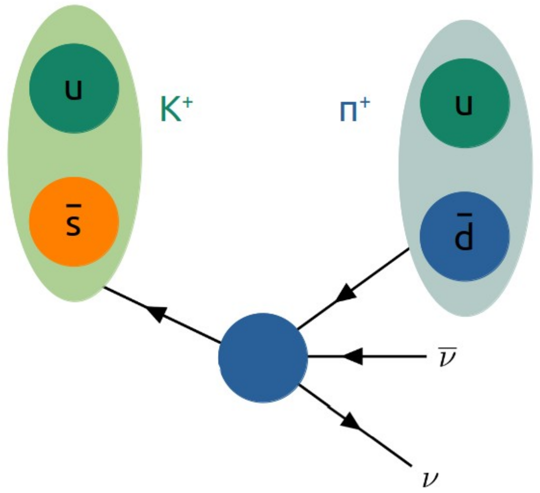
Lepton number violating vs conserving current

$$\frac{\Gamma\left(K \to \pi \nu_i \nu_j\right)}{ds\, dt} = \frac{1}{1+\delta_{ij}} \frac{1}{(2\pi)^3} \frac{1}{32 m_K^3} |\overline{\mathcal{M}}|^2$$

- **SM**, lepton number **conserving** **vector** current

$$\mathcal{L}_{\rm SM}^{K\to\pi\nu\bar{\nu}} = \frac{1}{\Lambda_{\rm SM}^2} \left(\bar{\nu}_i \gamma^\mu \nu_i\right) \left(\bar{d}\gamma_\mu s\right)$$

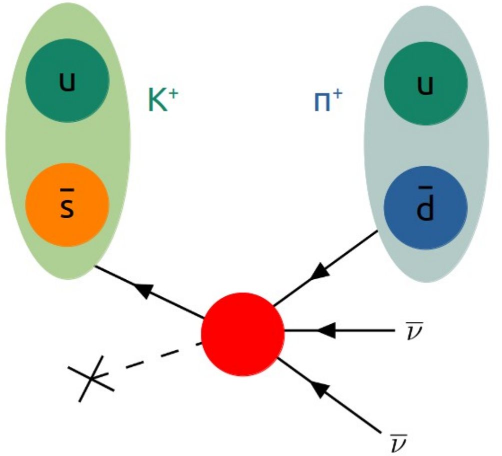
$$|\mathcal{M}|^2 = \frac{6}{\Lambda_{\rm SM}^4} \left[m_K^2 \left(t - m_\pi^2\right) - t\left(s + t - m_\pi^2\right)\right] f_+^K(s)^2$$



- **BSM**, lepton number **violating** **scalar** current

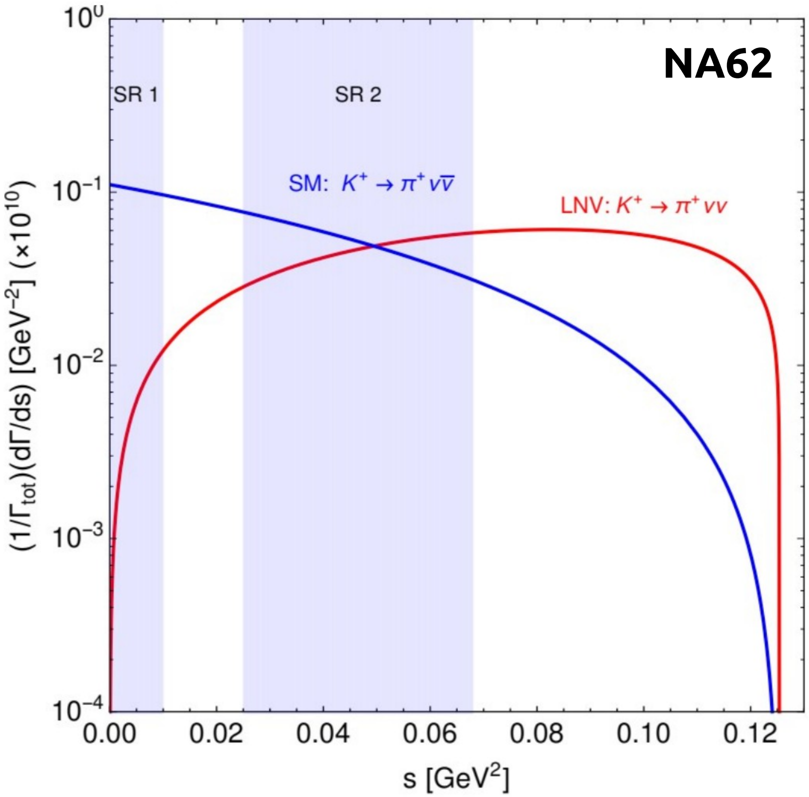
$$\mathcal{L}_{\rm BSM}^{K\to\pi\nu\nu} = \frac{v}{\Lambda_{\rm BSM}^3} \left(\nu_i \nu_j\right) \left(\bar{d} s\right)$$

$$|\mathcal{M}|^2 = \frac{v^2}{\Lambda_{\rm BSM}^6} \left(\frac{m_K^2 - m_\pi^2}{m_s - m_d} f_0^K(s)\right)^2 s$$



Li, Ma, Schmidt (2019)
Deppisch, JH, Fridell (2020)

Constraining LNV with Kaon decays: NA62



$$s = (E_K - E_\pi)^2$$

$$\mathrm{BR}_{\mathrm{LNV}}(K^+ \to \pi^+ \nu_i \nu_j) = 10^{-10} \left(\frac{19.2\ \mathrm{TeV}}{\Lambda_{ijsd}} \right)^6$$

$$\mathrm{BR}_{\mathrm{LNV}}(K_L \to \pi^0 \nu_i \nu_j) = 10^{-10} \left(\frac{24.9\ \mathrm{TeV}}{\Lambda_{ijsd}} \right)^6$$

Process	Experimental limit	$\mathcal{O}$	$\Lambda^{\mathrm{NP}}_{ijkn}$ [TeV]
$K^+ \to \pi^+ \nu\nu$	$\mathrm{BR}^{\mathrm{NA62}}_{\mathrm{future}} < 1.11 \times 10^{-10}$	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 19.6$
$K^+ \to \pi^+ \nu\nu$	$\mathrm{BR}^{\mathrm{NA62}}_{\mathrm{current}} < 1.78 \times 10^{-10}$	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 17.2$
$K_L \to \pi^0 \nu\nu$	$\mathrm{BR}^{\mathrm{KOTO}}_{\mathrm{current}} < 3.0 \times 10^{-9}$	$\mathcal{O}_{3b}$	$\sum_i \Lambda_{iisd} > 12.3$

Rare kaon decays as window to constrain lepton number violation!

Deppisch, Fridell, JH (2020)

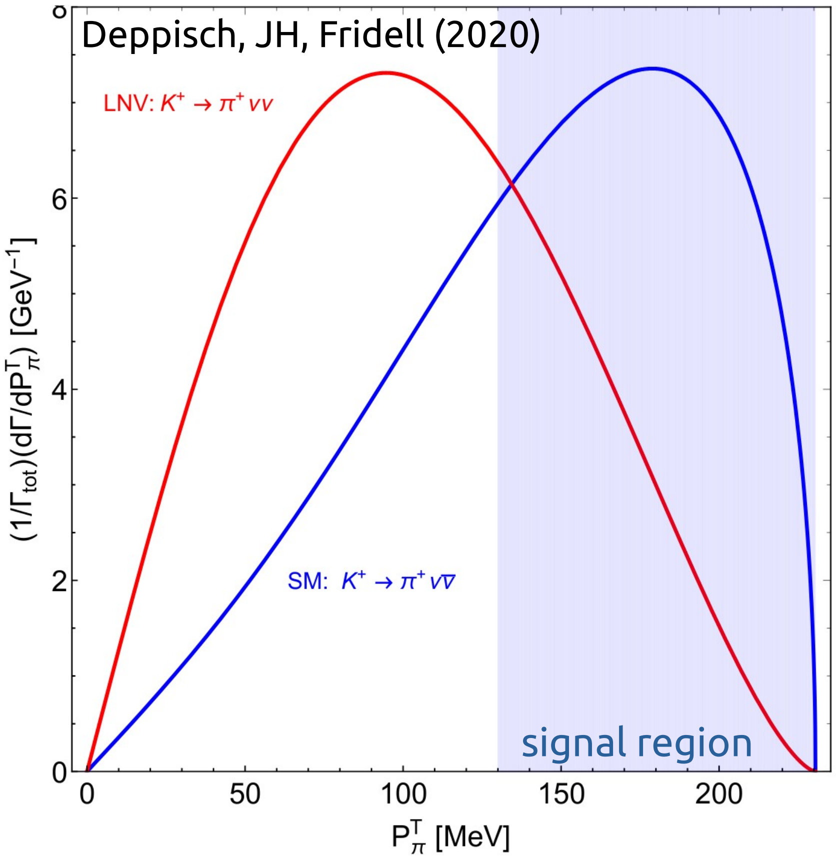
Limits from KOTO

$$\langle \pi^0 | \bar{d} s | \bar{K}^0 \rangle = \langle \pi^0 | \bar{s} d | K^0 \rangle$$
$$\langle \pi^0 | \bar{d} \gamma^\mu s | \bar{K}^0 \rangle = - \langle \pi^0 | \bar{s} \gamma^\mu d | K^0 \rangle$$

$$i\mathcal{M}\left(K_L \to \pi^0 \nu\nu\right) = \frac{1}{\sqrt{2+2|\epsilon|^2}} \Big(F(1+\epsilon) \langle \pi^0 | C | K^0 \rangle + F^*(1-\epsilon) \langle \pi^0 | C | \bar{K}^0 \rangle \Big) \nu\nu$$

LNV mode → scalar current → real part

LNC mode → vector current → imaginary part

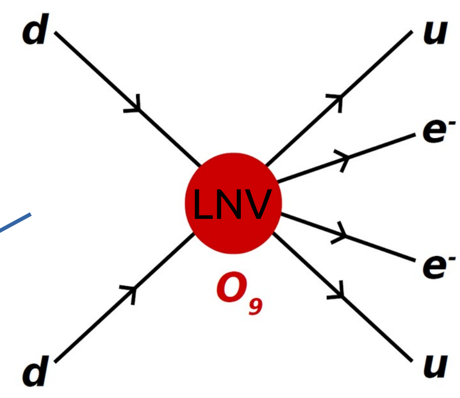


→ no CP phase needed in the LNV case

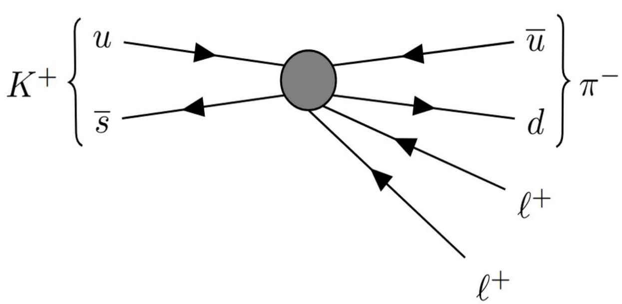
→ different phase space distribution

→ current signal region more sensitive to SM current

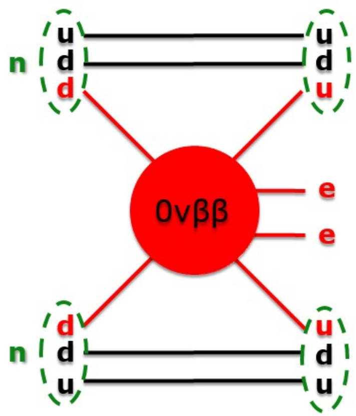
Probing LNV interactions



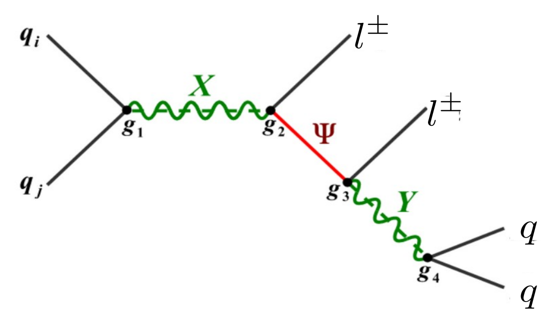
rare meson decays



neutrinoless double beta decay



colliders



Probing higher-dimensional LNV interactions

Survey of higher dimensional LNV operators

$\mathcal{O}$	Operator
1	$L^iL^jH^kH^l\epsilon_{ik}\epsilon_{jl}$
2	$L^iL^jL^ke^cH^l\epsilon_{ij}\epsilon_{kl}$
3_a	$L^iL^jQ^kd^cH^l\epsilon_{ij}\epsilon_{kl}$
[illegible]	[illegible]
5	$L^iL^jQ^kd^cH^lH^m\overline{H}_i\epsilon_{jl}\epsilon_{km}$
6	$L^iL^j\overline{Q}_k\bar{u}^cH^lH^k\overline{H}_i\epsilon_{jl}$
7	$L^iQ^j\bar{e}^c\overline{Q}_kH^kH^lH^m\epsilon_{il}\epsilon_{jm}$
8	$L^i\bar{e}^c\bar{u}^cd^cH^j\epsilon_{ij}$
9	$L^iL^jL^ke^cL^le^c\epsilon_{ij}\epsilon_{kl}$
10	$L^iL^jL^ke^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$
11_a	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ij}\epsilon_{kl}$
11_b	$L^iL^jQ^kd^cQ^ld^c\epsilon_{ik}\epsilon_{jl}$
12_a	$L^iL^j\overline{Q}_i\bar{u}^c\overline{Q}_j\bar{u}^c$
12_b	$L^iL^j\overline{Q}_k\bar{u}^c\overline{Q}_l\bar{u}^c\epsilon_{ij}\epsilon^{kl}$
13	$L^iL^j\overline{Q}_i\bar{u}^cL^le^c\epsilon_{jl}$
14_a	$L^iL^j\overline{Q}_k\bar{u}^cQ^kd^c\epsilon_{ij}$
14_b	$L^iL^j\overline{Q}_i\bar{u}^cQ^ld^c\epsilon_{jl}$
15	$L^iL^jL^kd^c\overline{L}_i\bar{u}^c\epsilon_{jk}$
16	$L^iL^je^cd^c\bar{e}^c\bar{u}^c\epsilon_{ij}$
17	$L^iL^jd^cd^c\bar{d}^c\bar{u}^c\epsilon_{ij}$
18	$L^iL^jd^cu^c\bar{u}^c\bar{u}^c\epsilon_{ij}$
19	$L^iQ^jd^cd^c\bar{e}^c\bar{u}^c\epsilon_{ij}$
20	$L^id^c\overline{Q}_i\bar{u}^c\bar{e}^c\bar{u}^c$
21_a	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}$
21_b	$L^iL^jL^ke^cQ^lu^cH^mH^n\epsilon_{il}\epsilon_{jm}\epsilon_{kn}$
22	$L^iL^jL^ke^c\overline{L}_k\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
23	$L^iL^jL^ke^c\overline{Q}_k\bar{d}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
24_a	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jk}\epsilon_{lm}$
24_b	$L^iL^jQ^kd^cQ^ld^cH^m\overline{H}_i\epsilon_{jm}\epsilon_{kl}$
25	$L^iL^jQ^kd^cQ^lu^cH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}$
26_a	$L^iL^jQ^kd^c\overline{L}_i\bar{e}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
26_b	$L^iL^jQ^kd^c\overline{L}_k\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
27_a	$L^iL^jQ^kd^c\overline{Q}_i\bar{d}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
27_b	$L^iL^jQ^kd^c\overline{Q}_k\bar{d}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
28_a	$L^iL^jQ^kd^c\overline{Q}_j\bar{u}^cH^l\overline{H}_i\epsilon_{kl}$
28_b	$L^iL^jQ^kd^c\overline{Q}_k\bar{u}^cH^l\overline{H}_i\epsilon_{jl}$
28_c	$L^iL^jQ^kd^c\overline{Q}_l\bar{u}^cH^l\overline{H}_i\epsilon_{jk}$
29_a	$L^iL^jQ^ku^c\overline{Q}_k\bar{u}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
29_b	$L^iL^jQ^ku^c\overline{Q}_l\bar{u}^cH^lH^m\epsilon_{ik}\epsilon_{jm}$
30_a	$L^iL^j\overline{L}_i\bar{e}^c\overline{Q}_k\bar{u}^cH^kH^l\epsilon_{jl}$
30_b	$L^iL^j\overline{L}_m\bar{e}^c\overline{Q}_n\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
31_a	$L^iL^j\overline{Q}_i\bar{d}^c\overline{Q}_k\bar{u}^cH^kH^l\epsilon_{jl}$

$\mathcal{O}$	Operator
31_b	$L^iL^j\overline{Q}_m\bar{d}^c\overline{Q}_n\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
32_a	$L^iL^j\overline{Q}_j\bar{u}^c\overline{Q}_k\bar{u}^cH^k\overline{H}_i$
32_b	$L^iL^j\overline{Q}_m\bar{u}^c\overline{Q}_n\bar{u}^cH^k\overline{H}_i\epsilon_{jk}\epsilon^{mn}$
33	$\bar{e}^c\bar{e}^cL^iL^je^ce^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
34	$\bar{e}^c\bar{e}^cL^iQ^je^cd^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
35	$\bar{e}^c\bar{e}^cL^ie^c\overline{Q}_j\bar{u}^cH^jH^k\epsilon_{ik}$
36	$\bar{e}^c\bar{e}^cQ^id^cQ^jd^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
37	$\bar{e}^c\bar{e}^cQ^id^c\overline{Q}_j\bar{u}^cH^jH^k\epsilon_{ik}$
38	$\bar{e}^c\bar{e}^c\overline{Q}_i\bar{u}^c\overline{Q}_j\bar{u}^cH^iH^j$
39_a	$L^iL^jL^kL^l\overline{L}_i\overline{L}_jH^mH^n\epsilon_{km}\epsilon_{ln}{}^\dagger$
39_b	$L^iL^jL^kL^l\overline{L}_m\overline{L}_nH^mH^n\epsilon_{ij}\epsilon_{kl}$
39_c	$L^iL^jL^kL^l\overline{L}_i\overline{L}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$
39_d	$L^iL^jL^kL^l\overline{L}_p\overline{L}_qH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}$
40_a	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}$
40_b	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_lH^mH^n\epsilon_{jm}\epsilon_{kn}$
40_c	$L^iL^jL^kQ^l\overline{L}_l\overline{Q}_iH^mH^n\epsilon_{jm}\epsilon_{kn}$
40_d	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_mH^mH^n\epsilon_{jk}\epsilon_{ln}$
40_e	$L^iL^jL^kQ^l\overline{L}_i\overline{Q}_mH^mH^n\epsilon_{jl}\epsilon_{kn}$
40_f	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_iH^mH^n\epsilon_{jk}\epsilon_{ln}$
40_g	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_iH^mH^n\epsilon_{jl}\epsilon_{kn}$
40_h	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_nH^mH^n\epsilon_{ij}\epsilon_{kl}$
40_i	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_nH^pH^q\epsilon_{ip}\epsilon_{jq}\epsilon_{kl}\epsilon^{mn}$
40_j	$L^iL^jL^kQ^l\overline{L}_m\overline{Q}_nH^pH^q\epsilon_{ip}\epsilon_{lq}\epsilon_{jk}\epsilon^{mn}$
41_a	$L^iL^jL^kd^c\overline{L}_i\bar{d}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
41_b	$L^iL^jL^kd^c\overline{L}_l\bar{d}^cH^lH^m\epsilon_{ij}\epsilon_{km}$
42_a	$L^iL^jL^ku^c\overline{L}_i\bar{u}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
42_b	$L^iL^jL^ku^c\overline{L}_l\bar{u}^cH^lH^m\epsilon_{ij}\epsilon_{km}$
43_a	$L^iL^jL^kd^c\overline{L}_l\bar{u}^cH^l\overline{H}_i\epsilon_{jk}$
43_b	$L^iL^jL^kd^c\overline{L}_j\bar{u}^cH^l\overline{H}_i\epsilon_{kl}$
43_c	$L^iL^jL^kd^c\overline{L}_l\bar{u}^cH^m\overline{H}_n\epsilon_{ij}\epsilon_{km}\epsilon^{ln}$
44_a	$L^iL^jQ^ke^c\overline{Q}_i\bar{e}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
44_b	$L^iL^jQ^ke^c\overline{Q}_k\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{jm}$
44_c	$L^iL^jQ^ke^c\overline{Q}_l\bar{e}^cH^lH^m\epsilon_{ij}\epsilon_{km}$
44_d	$L^iL^jQ^ke^c\overline{Q}_l\bar{e}^cH^lH^m\epsilon_{ik}\epsilon_{jm}$
45	$L^iL^je^cd^c\bar{e}^c\bar{d}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
46	$L^iL^je^cu^c\bar{e}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
47_a	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_jH^mH^n\epsilon_{km}\epsilon_{ln}$

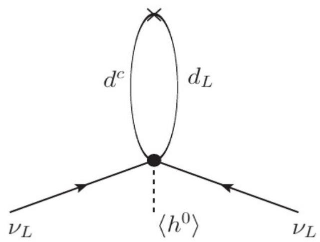
$\mathcal{O}$	Operator
47_b	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_kH^mH^n\epsilon_{jm}\epsilon_{ln}$
47_c	$L^iL^jQ^kQ^l\overline{Q}_k\overline{Q}_lH^mH^n\epsilon_{im}\epsilon_{jn}$
47_d	$L^iL^jQ^kQ^l\overline{Q}_l\overline{Q}_mH^mH^n\epsilon_{jk}\epsilon_{in}$
47_e	$L^iL^jQ^kQ^l\overline{Q}_i\overline{Q}_mH^mH^n\epsilon_{jn}\epsilon_{kl}$
47_f	$L^iL^jQ^kQ^l\overline{Q}_k\overline{Q}_mH^mH^n\epsilon_{ij}\epsilon_{ln}$
47_g	$L^iL^jQ^kQ^l\overline{Q}_k\overline{Q}_mH^mH^n\epsilon_{il}\epsilon_{jn}$
47_h	$L^iL^jQ^kQ^l\overline{Q}_p\overline{Q}_qH^mH^n\epsilon_{ij}\epsilon_{km}\epsilon_{ln}\epsilon^{pq}$
47_i	$L^iL^jQ^kQ^l\overline{Q}_p\overline{Q}_qH^mH^n\epsilon_{ik}\epsilon_{jm}\epsilon_{ln}\epsilon^{pq}$
47_j	$L^iL^jQ^kQ^l\overline{Q}_p\overline{Q}_qH^mH^n\epsilon_{im}\epsilon_{jn}\epsilon_{kl}\epsilon^{pq}$
48	$L^iL^jd^cd^c\bar{d}^c\bar{d}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
49	$L^iL^jd^cu^c\bar{d}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
50	$L^iL^jd^cd^c\bar{d}^c\bar{u}^cH^k\overline{H}_i\epsilon_{jk}$
51	$L^iL^ju^cu^c\bar{u}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
52	$L^iL^jd^cu^c\bar{u}^c\bar{u}^cH^k\overline{H}_i\epsilon_{jk}$
53	$L^iL^jd^cd^c\bar{u}^c\bar{u}^c\overline{H}_i\overline{H}_j$
54_a	$L^iQ^jQ^kd^c\overline{Q}_i\bar{e}^cH^lH^m\epsilon_{jl}\epsilon_{km}$
54_b	$L^iQ^jQ^kd^c\overline{Q}_j\bar{e}^cH^lH^m\epsilon_{il}\epsilon_{km}$
54_c	$L^iQ^jQ^kd^c\overline{Q}_l\bar{e}^cH^lH^m\epsilon_{im}\epsilon_{jk}$
54_d	$L^iQ^jQ^kd^c\overline{Q}_i\bar{e}^cH^lH^m\epsilon_{ij}\epsilon_{km}$
55_a	$L^iQ^j\overline{Q}_i\overline{Q}_k\bar{e}^c\bar{u}^cH^kH^l\epsilon_{jl}$
55_b	$L^iQ^j\overline{Q}_j\overline{Q}_k\bar{e}^c\bar{u}^cH^kH^l\epsilon_{il}$
55_c	$L^iQ^j\overline{Q}_m\overline{Q}_n\bar{e}^c\bar{u}^cH^kH^l\epsilon_{ik}\epsilon_{jl}\epsilon^{mn}$
56	$L^iQ^jd^cd^c\bar{e}^c\bar{d}^cH^kH^l\epsilon_{ik}\epsilon_{jl}$
57	$L^id^c\overline{Q}_j\bar{u}^c\bar{e}^c\bar{d}^cH^jH^k\epsilon_{ik}$
58	$L^iu^c\overline{Q}_j\bar{u}^c\bar{e}^c\bar{u}^cH^jH^k\epsilon_{ik}$
59	$L^iQ^jd^cd^c\bar{e}^c\bar{u}^cH^k\overline{H}_i\epsilon_{jk}$
60	$L^id^c\overline{Q}_j\bar{u}^c\bar{e}^c\bar{u}^cH^j\overline{H}_i$
61	$L^iL^jH^kH^lL^re^c\overline{H}_r\epsilon_{ik}\epsilon_{jl}$
62	$L^iL^jL^ke^cH^lL^re^c\overline{H}_r\epsilon_{ij}\epsilon_{kl}$
63_a	$L^iL^jQ^kd^cH^lL^re^c\overline{H}_r\epsilon_{ij}\epsilon_{kl}$
63_b	$L^iL^jQ^kd^cH^lL^re^c\overline{H}_r\epsilon_{ik}\epsilon_{jl}$
64_a	$L^iL^j\overline{Q}_i\bar{u}^cH^kL^re^c\overline{H}_r\epsilon_{jk}$
64_b	$L^iL^j\overline{Q}_k\bar{u}^cH^kL^re^c\overline{H}_r\epsilon_{ij}$
65	$L^i\bar{e}^c\bar{u}^cd^cH^jL^re^c\overline{H}_r\epsilon_{ij}$
66	$L^iL^jH^kH^l\epsilon_{ik}Q^rd^c\overline{H}_r\epsilon_{jl}$
67	$L^iL^jL^ke^cH^lQ^rd^c\overline{H}_r\epsilon_{ij}\epsilon_{kl}$
68_a	$L^iL^jQ^kd^cH^lQ^rd^c\overline{H}_r\epsilon_{ij}\epsilon_{kl}$
68_b	$L^iL^jQ^kd^cH^lQ^rd^c\overline{H}_r\epsilon_{ik}\epsilon_{jl}$
69_a	$L^iL^j\overline{Q}_i\bar{u}^cH^kQ^rd^c\overline{H}_r\epsilon_{jk}$
69_b	$L^iL^j\overline{Q}_k\bar{u}^cH^kQ^rd^c\overline{H}_r\epsilon_{ij}$

$\mathcal{O}$	Operator
70	$L^i\bar{e}^c\bar{u}^cd^cH^jQ^rd^c\overline{H}_r\epsilon_{ij}$
71	$L^iL^jH^kH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ik}\epsilon_{jl}$
72	$L^iL^jL^ke^cH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}\epsilon_{kl}$
73_a	$L^iL^jQ^kd^cH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}\epsilon_{kl}$
73_b	$L^iL^jQ^kd^cH^lQ^ru^cH^s\epsilon_{rs}\epsilon_{ik}\epsilon_{jl}$
74_a	$L^iL^j\overline{Q}_i\bar{u}^cH^kQ^ru^cH^s\epsilon_{rs}\epsilon_{jk}$
74_b	$L^iL^j\overline{Q}_k\bar{u}^cH^kQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}$
75	$L^i\bar{e}^c\bar{u}^cd^cH^jQ^ru^cH^s\epsilon_{rs}\epsilon_{ij}$

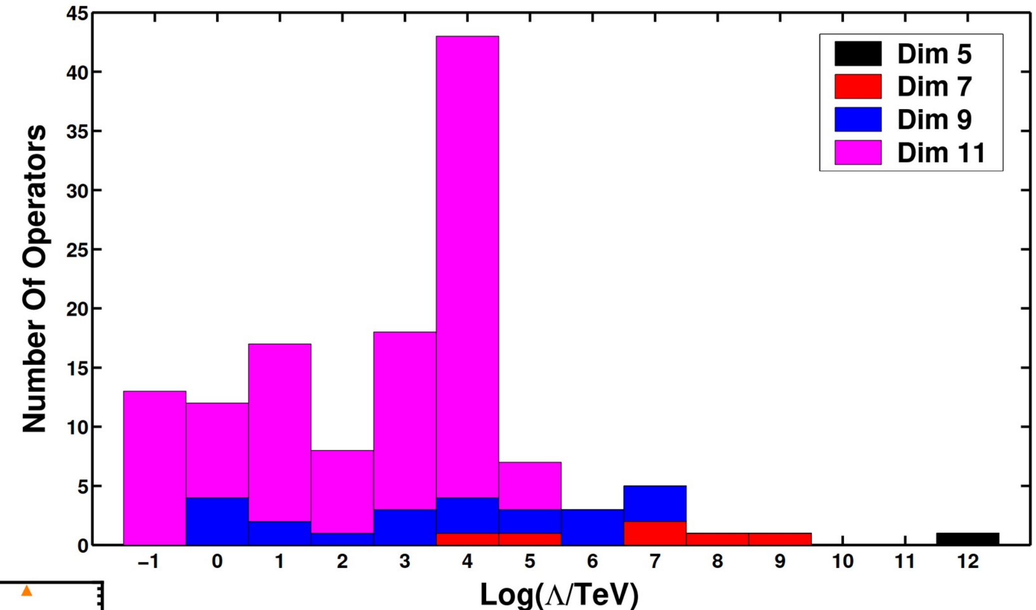
Babu, Leung (2001)
Gouvea, Jenkins (2008)
Graf, JH, Deppisch, Huang (2018)

Contributions to different observables

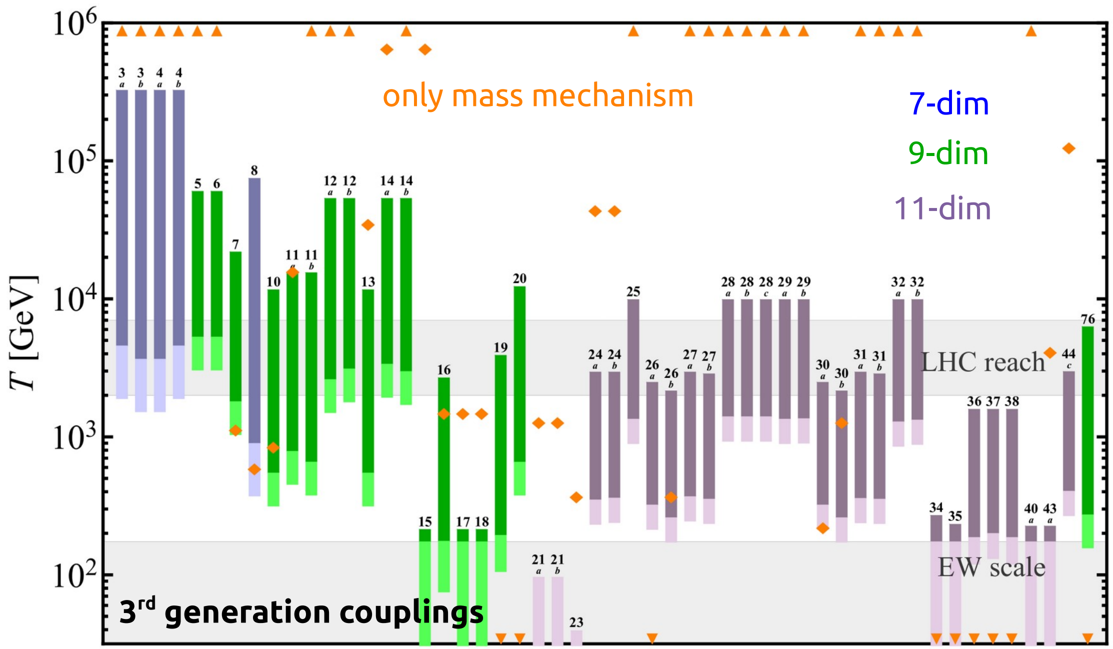
- **Radiative neutrino masses**



$$\mathcal{O}_7{}^{3b} = L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}$$

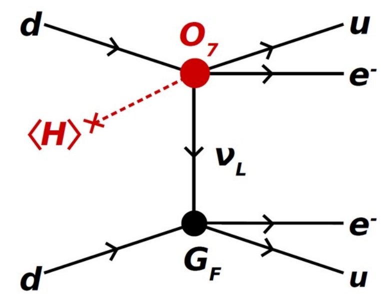


de Gouvea, Jenkins (2008)



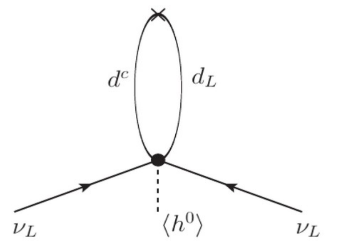
Deppisch, Graf, JH, Huang (2017)

- **Neutrinoless double beta decay**

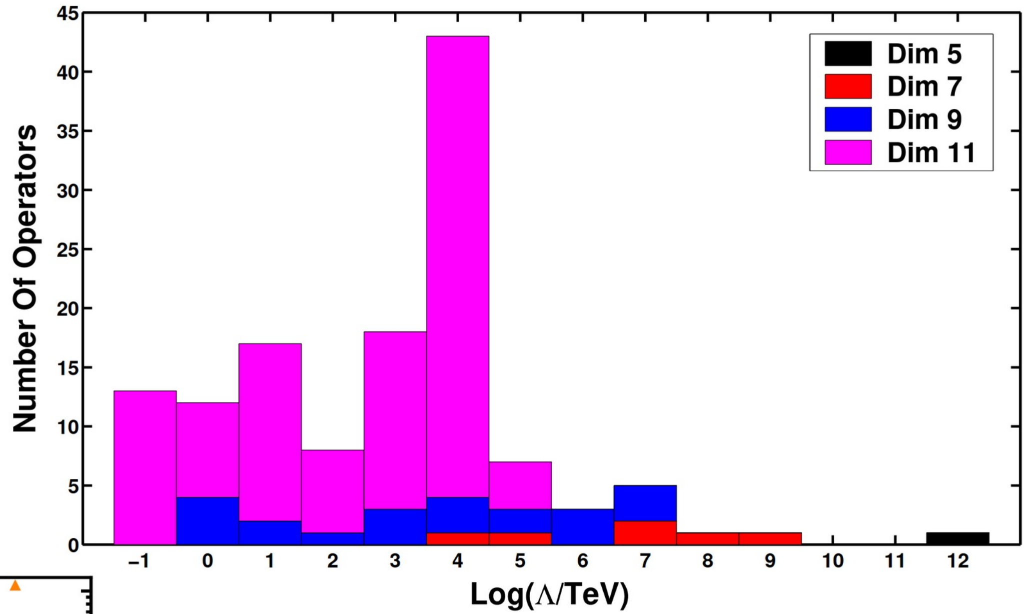


Contributions to different observables

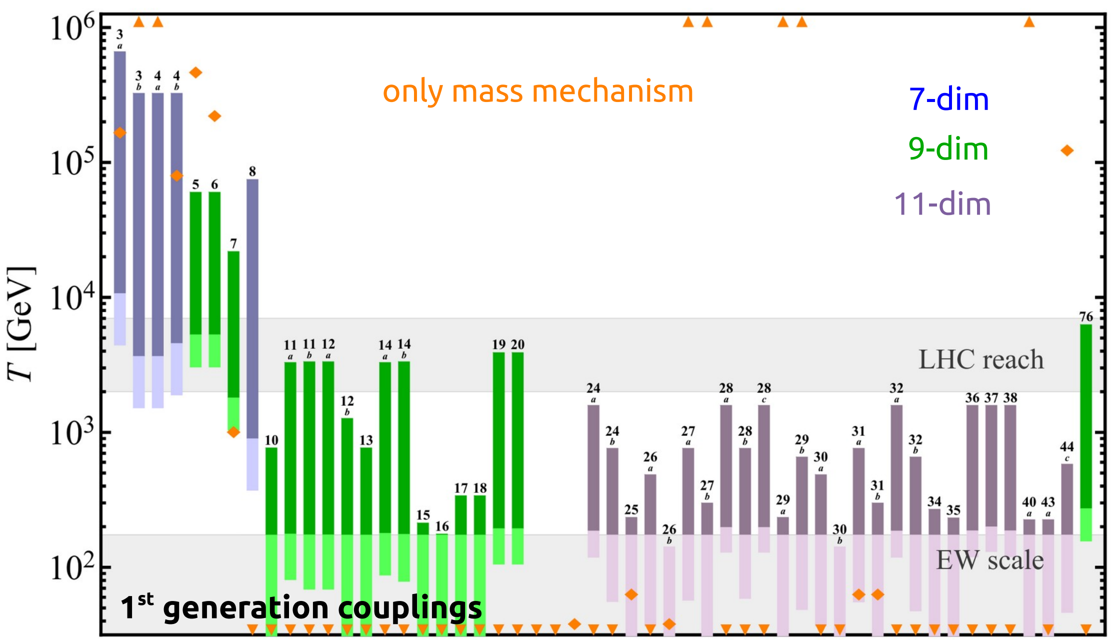
- **Radiative neutrino masses**



$$\mathcal{O}_7{}^{3b} = L^i L^j Q^k d^c H^l \epsilon_{ik}\epsilon_{jl}$$

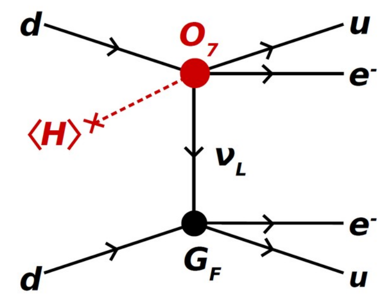


de Gouvea, Jenkins (2008)



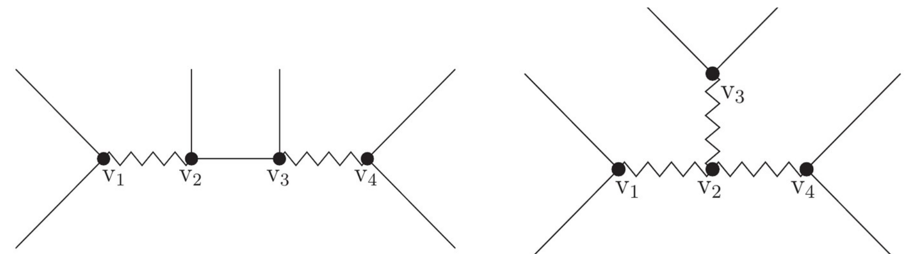
Deppisch, Graf, JH, Huang (2017)

- **Neutrinoless double beta decay**

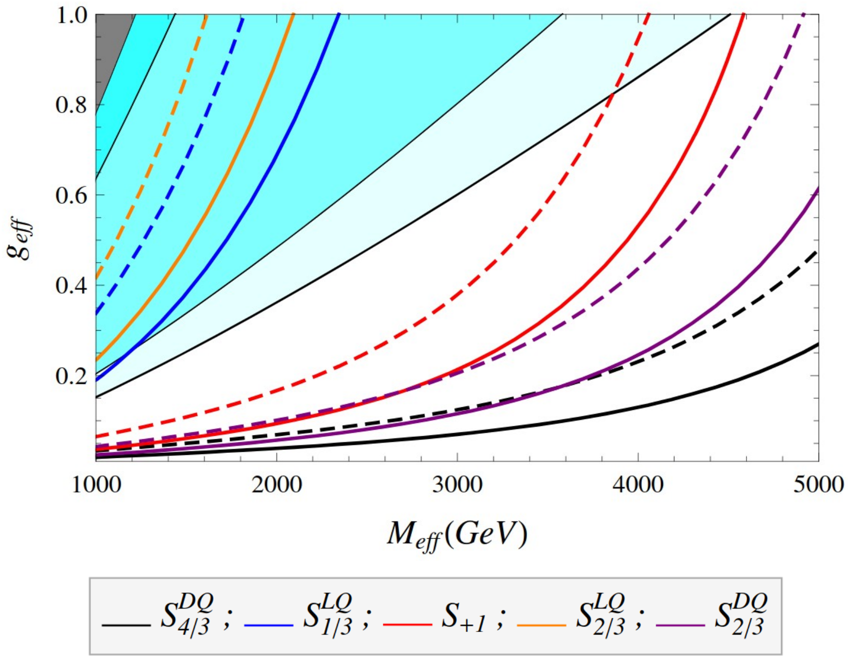


Topologies | Interplay between LHC & 0νββ decay

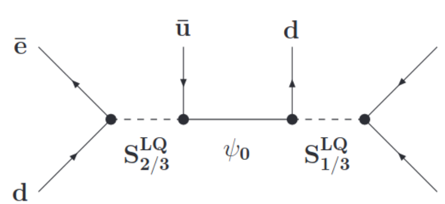
#	Decomposition	Long Range?	Mediator $(U(1)_{em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ	Models/Refs./Comments
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	(a)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(-1, \mathbf{1})$	Mass mechan., RPV [58–60], LR-symmetric models [39], Mass mechanism with ν_S [61], TeV scale seesaw, e.g., [62, 63]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(-1, \mathbf{8})$	[64]
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	
			$(+1, \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$		$(+1, \mathbf{1})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$	
			$(+1, \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	(b)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(+1/3, \overline{\mathbf{3}})$	RPV [58–60], LQ [65, 66]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$		$(+1, \mathbf{1})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
			$(+1, \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	(b)	$(+1, \mathbf{1})$	$(0, \mathbf{1})$	$(+2/3, \mathbf{3})$	RPV [58–60], LQ [65, 66]
			$(+1, \mathbf{8})$	$(0, \mathbf{8})$	$(+2/3, \mathbf{3})$	
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	(c)	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1})$	$(+1/3, \overline{\mathbf{3}})$	RPV [58–60]
			$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	RPV [58–60]



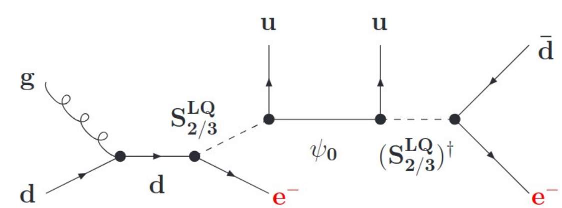
Bonnet, Hirsch, Ota, Winter (2014)



0νββ decay



LHC

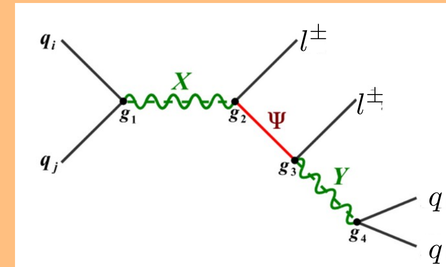


Helo, Kovalenko, Hirsch, Päs (2013)
Bonnet, Hirsch, Ota, Winter (2013)
Hirsch, Klapdor-Kleingrothhaus, Kovalenko (1995)
Mohapatra (1986)

Implications of TeV-scale LNV interactions

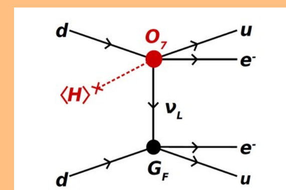
Observation of any LNV washout process at the LHC would falsify high-scale baryogenesis

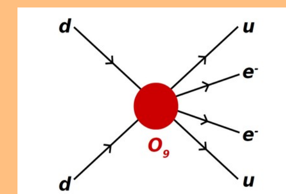
Deppisch, JH, Hirsch (2014)



Observation of neutrinoless double beta decay with new physics from > dim-5 LNV operators would falsify high-scale baryogenesis

Deppisch, Graf, JH, Huang (2018)
Deppisch, JH, Huang, Hirsch, Päs (2015)





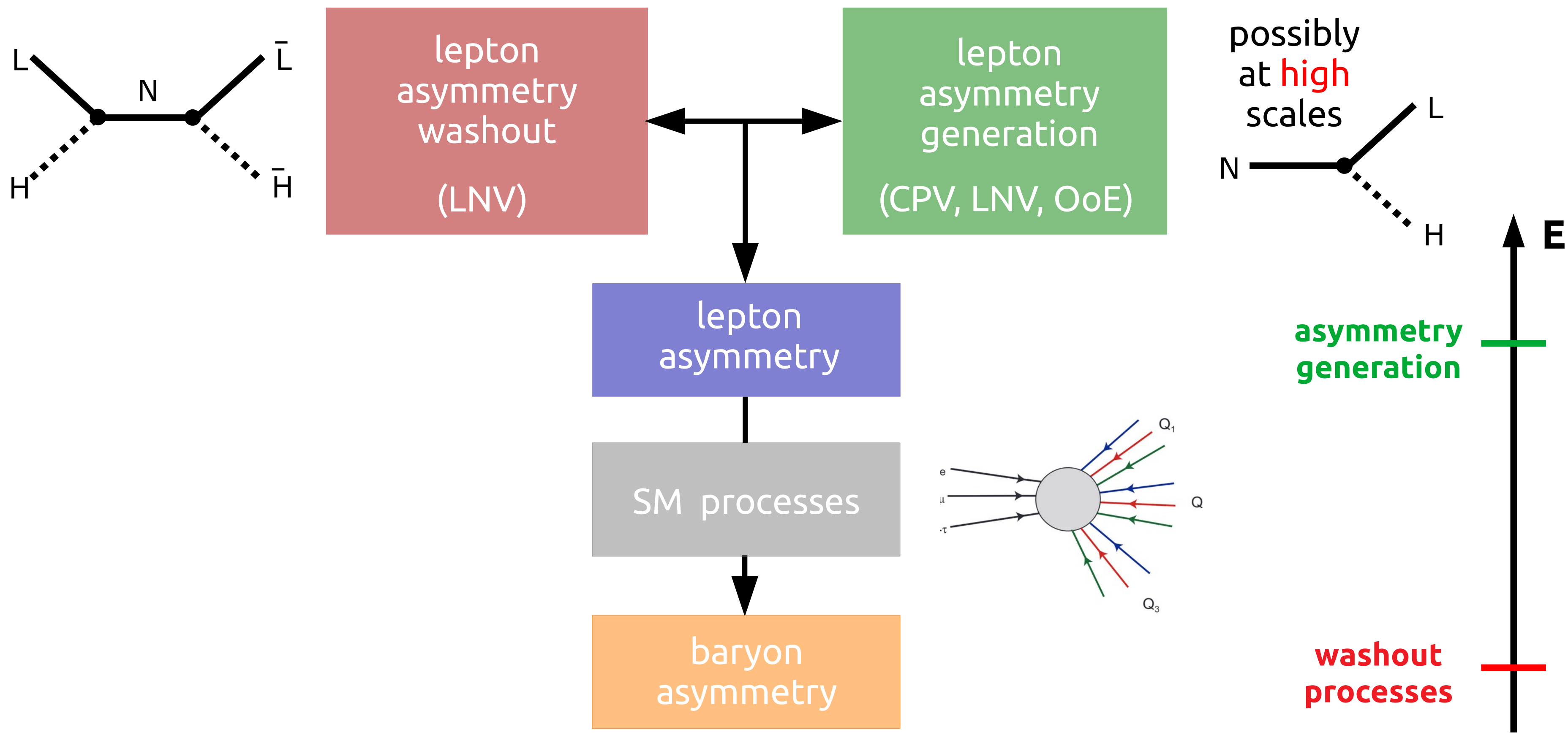
Caveats might apply, e.g.:

- **Flavor specific leptogenesis**
- **Dark U(1) symmetries**

Aristizabal Sierra, Fong, Nardi, Peinado (2014)
Frandsen, Hagedorn, Huang, Molinaro, Päs (2018)

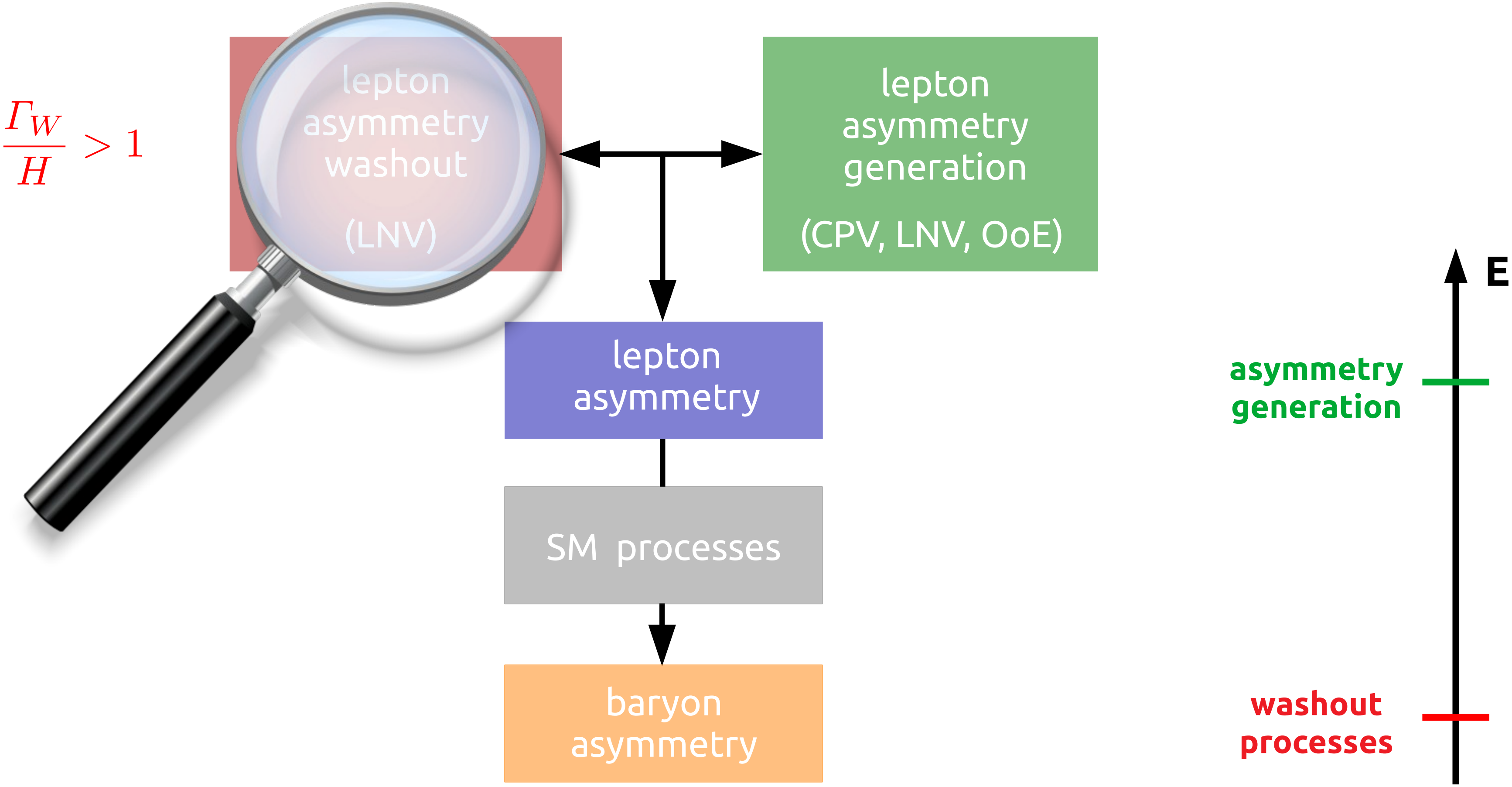
Baryogenesis & Leptogenesis

Basic principles of leptogenesis mechanisms:



Baryogenesis & Leptogenesis

Basic principles of leptogenesis mechanisms:



Strategy: Search for washout processes with the potential to falsify baryogenesis models!

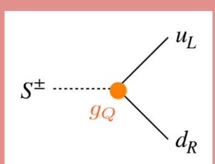
A simplified model study of TeV scale LNV

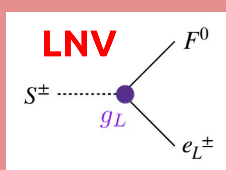
Right-handed neutrino interactions ("standard thermal LG"):

$$\mathcal{L} \supset y_\nu \bar{L} H N - \frac{m_N}{2} \bar{N}^c N + \text{h.c.}$$

Additional TeV-scale interactions

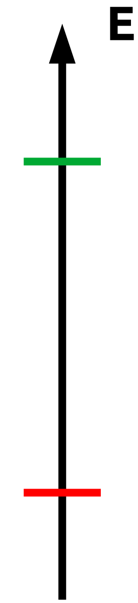
$$\tilde{\mathcal{L}} \supset g_Q \overline{Q} S d_R + g_L \overline{L}(i\tau^2) S^* F - m_S^2 S^\dagger S - \frac{m_F}{2} \overline{F^c} F + \lambda_{HS} (S^\dagger H)^2 + \text{h.c.}$$





high-scale source of lepton asymmetry

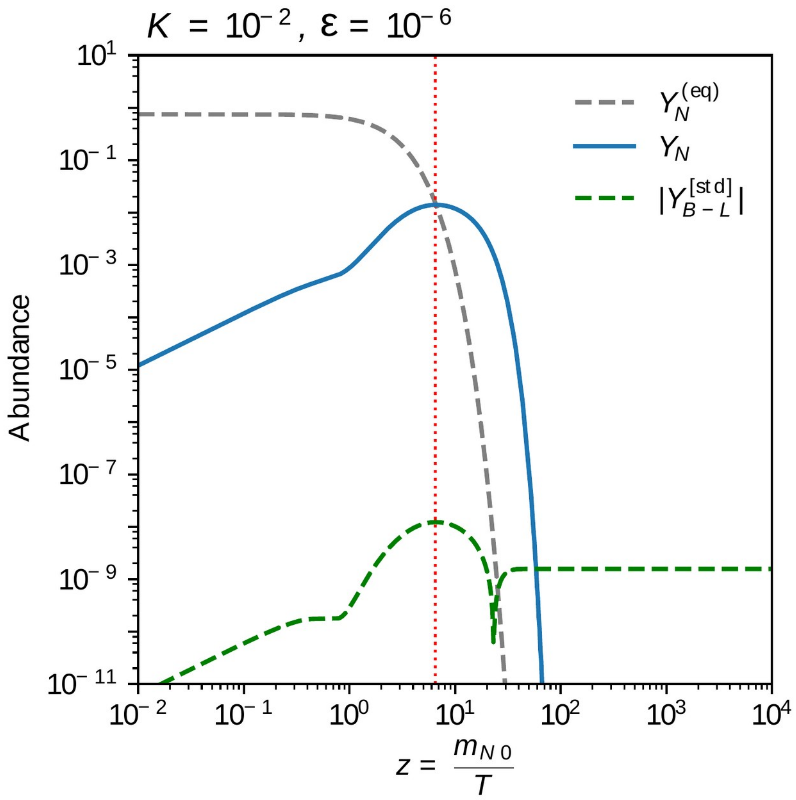
TeV-scale LNV "washout" interactions



Can TeV-scale LNV destroy the generated asymmetry from standard thermal LG?

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

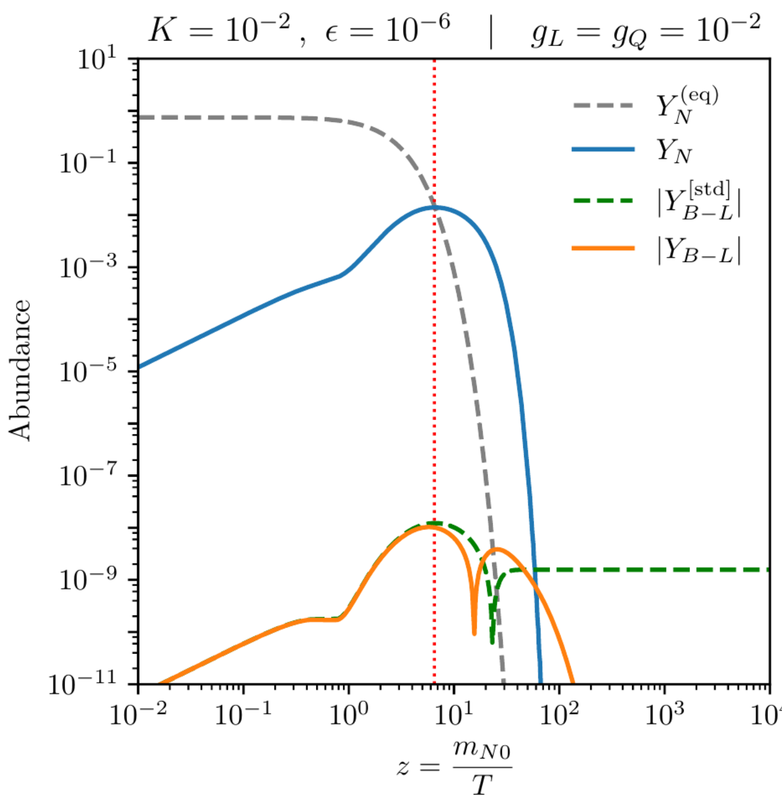
Implications for Leptogenesis

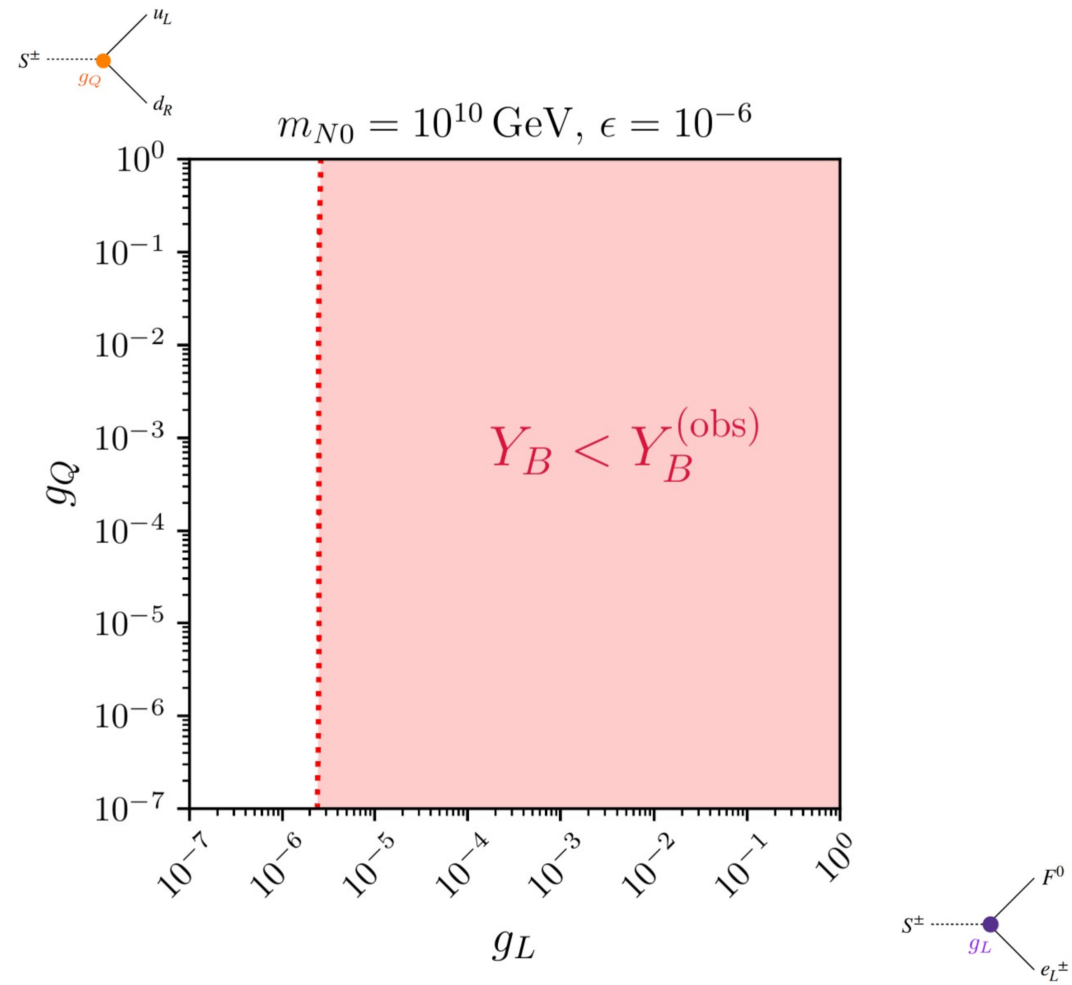


JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Implications for Leptogenesis

$\mathcal{O}(m_S) \approx \mathcal{O}(m_F) \approx \mathcal{O}(\text{TeV})$

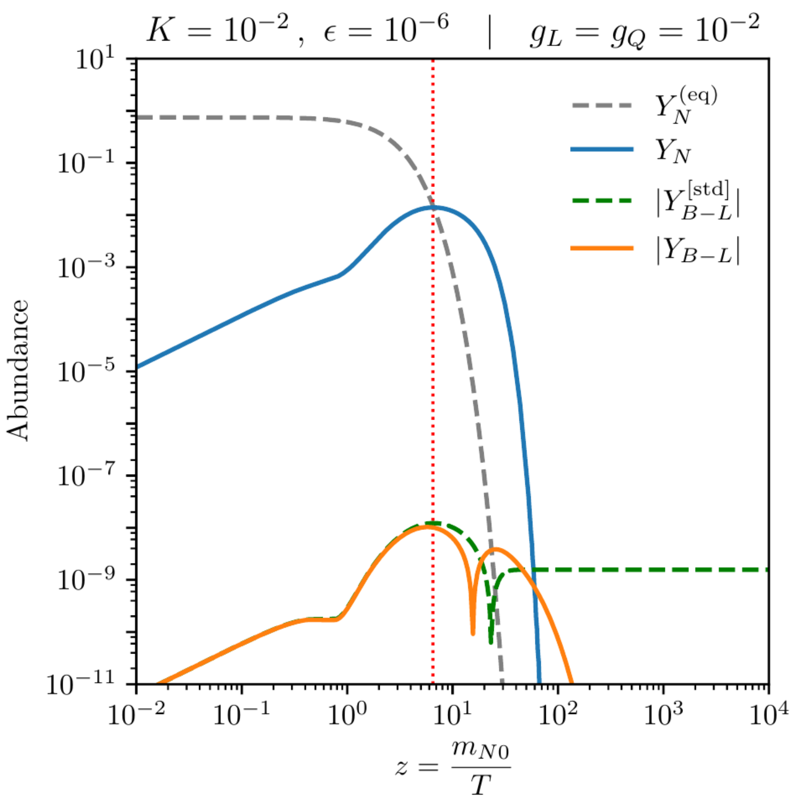


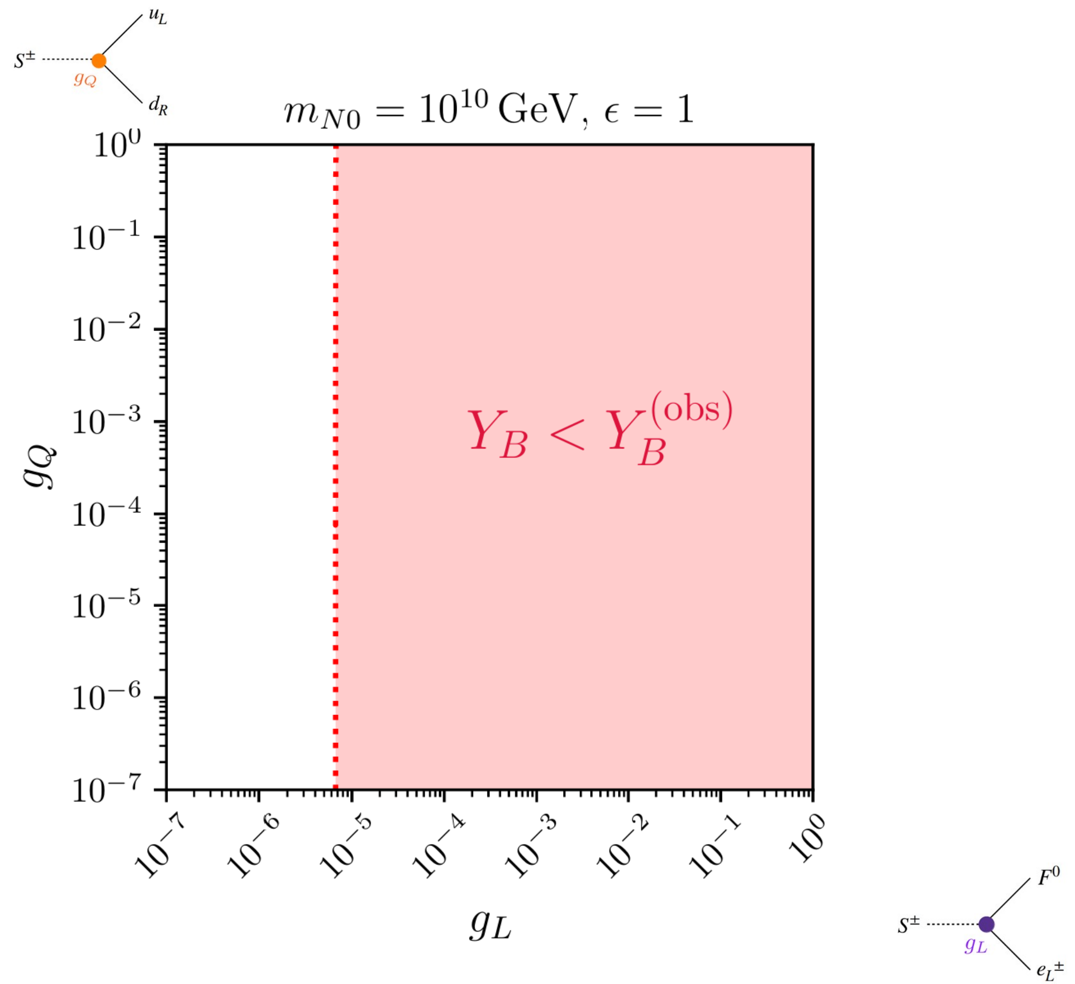


JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Implications for Leptogenesis

$\mathcal{O}(m_S) \approx \mathcal{O}(m_F) \approx \mathcal{O}(\mathrm{TeV})$

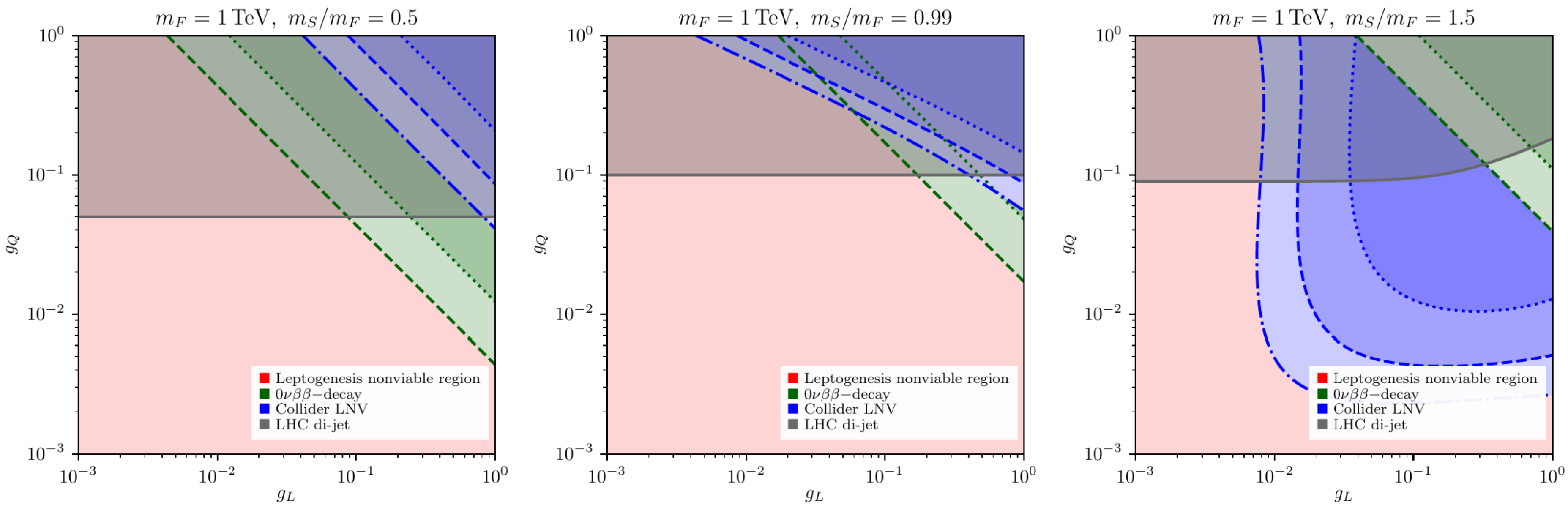




Low-scale LNV destroys lepton asymmetry previously generated by standard LG scenario.

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Combined results: Leptogenesis, LHC & 0νββ decay



→ Important complementarity between collider and 0νββ decay reach

→ Observation of TeV LNV would render standard thermal LG unviable!

JH, Ramsey-Musolf, Shen, Urrutia-Quiroga (2021)

Conclusions

- **Neutrinos point towards new physics and might have tight interconnection with the mechanism behind the baryon asymmetry**
- **CEvNS is a great probe for neutrino magnetic moments and has potential to disentangle the Majorana vs Dirac nature in case of observation**
- **Meson decays, neutrinoless double beta decay and colliders are complementary probes for lepton-number violation**
- **An observation of LNV around the TeV-scale would render standard thermal leptogenesis & baryogenesis scenarios invalid**

Great future ahead to (hopefully) nail down the nature and mass mechanism of neutrinos!

Thank you for your attention!