Sub-GeV Sterile Neutrino as a Probe of Neutrino Mass Generation in the Minimal Left-Right Symmetric Model

Sida Lu （卢思达）

School of Physics and Astronomy, SYSU

based on **2508.15609**, w/ Gang Li, Ying-Ying Li and Ye-Ling Zhou

@FP 2026, 13/01/2026

Neutrino Masses and the mLRSM

✤ The masses of the neutrinos in the SM is unnaturally small—a major clue to new physics

✤ The (type-I) seesaw mechanism

$$\frac{1}{2}\begin{pmatrix}\overline{\nu_L} & \overline{N_R^C}\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L^C \\ N_R\end{pmatrix} + \text{h.c.} \quad \Rightarrow \quad m \sim \frac{m_D^2}{M_R}$$

[credit: Symmetry Magazine]

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$$\frac{1}{2} \begin{pmatrix} \overline{\nu_L} & \overline{N_R^C} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix} \begin{pmatrix} \nu_L^C \\ N_R \end{pmatrix} + \text{h.c.} \quad \Rightarrow \quad m \sim \frac{m_D^2}{M_R}$$

✤ Majorana nature of neutrinos + RH sector particles

➙ For naive type-I, EW-scale Dirac mass → RH neutrino of 10^{15} GeV

✤ A more experimentally feasible realization of the idea is to embed it in the left-right symmetric models, specifically the minimal left-right symmetric model (mLRSM)

[Pati+, PRD 74';
Mohapatra+, PRD 75';
Senjanovic+, PRD 75']

➙ parity restoration
➙ grand unification at high scale
➙ extraordinary predictability

The Model Setup

✤ The symmetry: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

✤ New particle contents:

➡ 3 RH Majorana neutrinos, 2 scalar triplets, 1 new Higgs doublet

$$L_{L,R} = \begin{pmatrix} \nu_{L,R} \\ \ell_{L,R} \end{pmatrix} \quad \Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix} \quad \Phi = \begin{pmatrix} \phi^0_1 & \phi^+_2 \\ \phi^-_1 & \phi^0_2 \end{pmatrix}$$

$$\langle \delta^0_{L,R} \rangle = v_{L,R}/\sqrt{2} \qquad\qquad \langle \phi^0_1 \rangle = \kappa/\sqrt{2}, \langle \phi^0_2 \rangle = \kappa'/\sqrt{2}$$

➡ CPV phases of the VEV set to 0

✤ Neutrino masses

$$\mathcal{L}_m = -\frac{1}{2} (\bar{\nu}_L, \bar{\nu}^c_R) \begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix} \begin{pmatrix} \nu^c_L \\ \nu_R \end{pmatrix} + \text{h.c.}$$

$$M_L = \sqrt{2}Y_L^\dagger v_L, \quad M_R = \sqrt{2}Y_R v_R, \quad M_D = (\kappa\Gamma_l + \kappa'\tilde{\Gamma}_l)/\sqrt{2}$$

$$M_\nu = M_L - M_D M_R^{-1} M_D^T \quad \textcolor{blue}{M_D \to 0} \quad \textbf{\textcolor{blue}{when no left-right mixing}}$$

➡ the neutrino masses: combination of type-I and type-II seesaw

The Model Setup

✤ We focus on the case of no left-right mixing for predictability

→ No LH and RH neutrino mixing: a vanishing Dirac mass

→ No $W_L - W_R$ mixing: $\kappa \gg \kappa'$

✤ In the absence of left-right mixing, the sterile neutrino only decays hadronically: $\nu_4 \to \ell_j^{\mp} \pi^{\pm}$ [Bondarenko+, JHEP 18']

→ The other channels rely on the $W_L - W_R$ mixing parameter $\xi = \kappa'/\kappa$

✤ Assuming further the generalized charge conjugation $\mathcal{C}$ [Maiezza+, PRD 10']

$$Y_L = Y_R^{\dagger} \quad \Longrightarrow \quad M_L = (v_L/v_R)M_R \quad \widehat{M}_{\nu} = (v_L/v_R)\widehat{M}_N$$

$$m_{\nu_4} \simeq 20 \text{ MeV} \cdot \frac{m_{\nu_6}}{1 \text{ TeV}} \cdot \frac{m_{\nu_1}}{10^{-6} \text{ eV}} \,, \quad m_{\nu_5} \simeq 175 \text{ GeV} \cdot \frac{m_{\nu_6}}{1 \text{ TeV}}$$

→ predictability for the RH neutrino masses

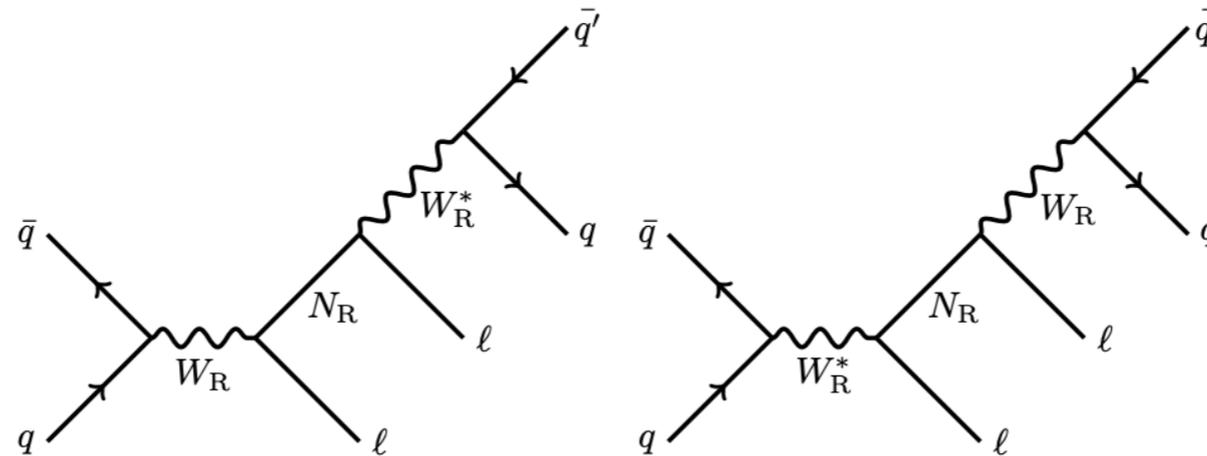→ nice probes can come from the lightest new degree of freedom!

Probing the mLRSM

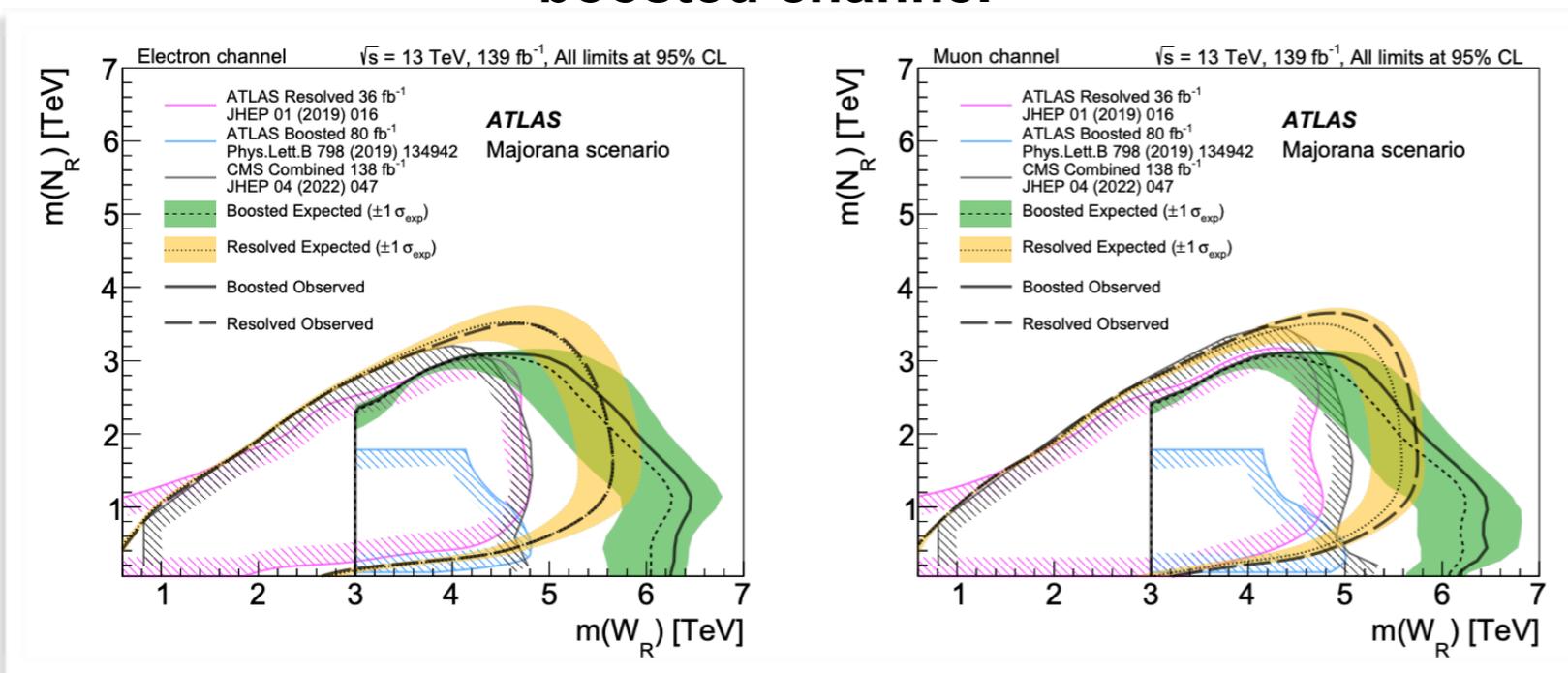✤ For sub-GeV sterile neutrinos, the probes can come from

the LHC

meson decays

0νββ decays

supernovae

cosmology

Probes: the LHC
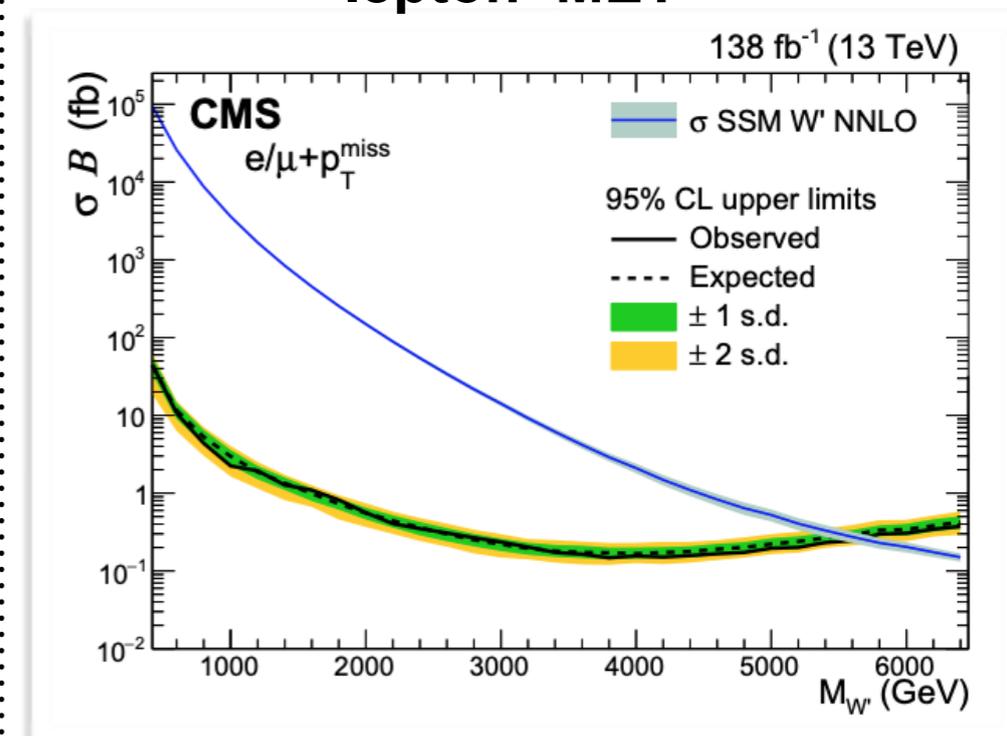
✤ The Keung-Senjanovic process

boosted channel
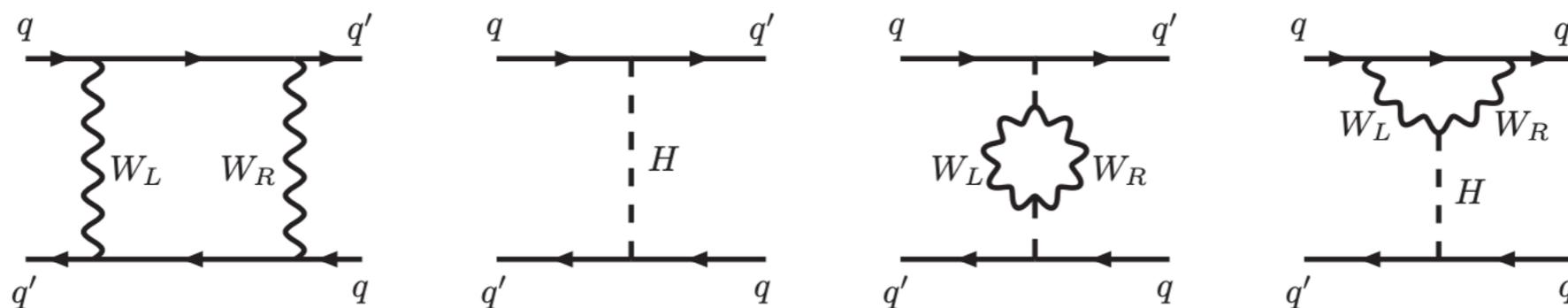
lepton+MET

[ATLAS, EPJC 23']

[CMS, JHEP 22']

→ Both exclude W_R mass to ~ 5.7 TeV

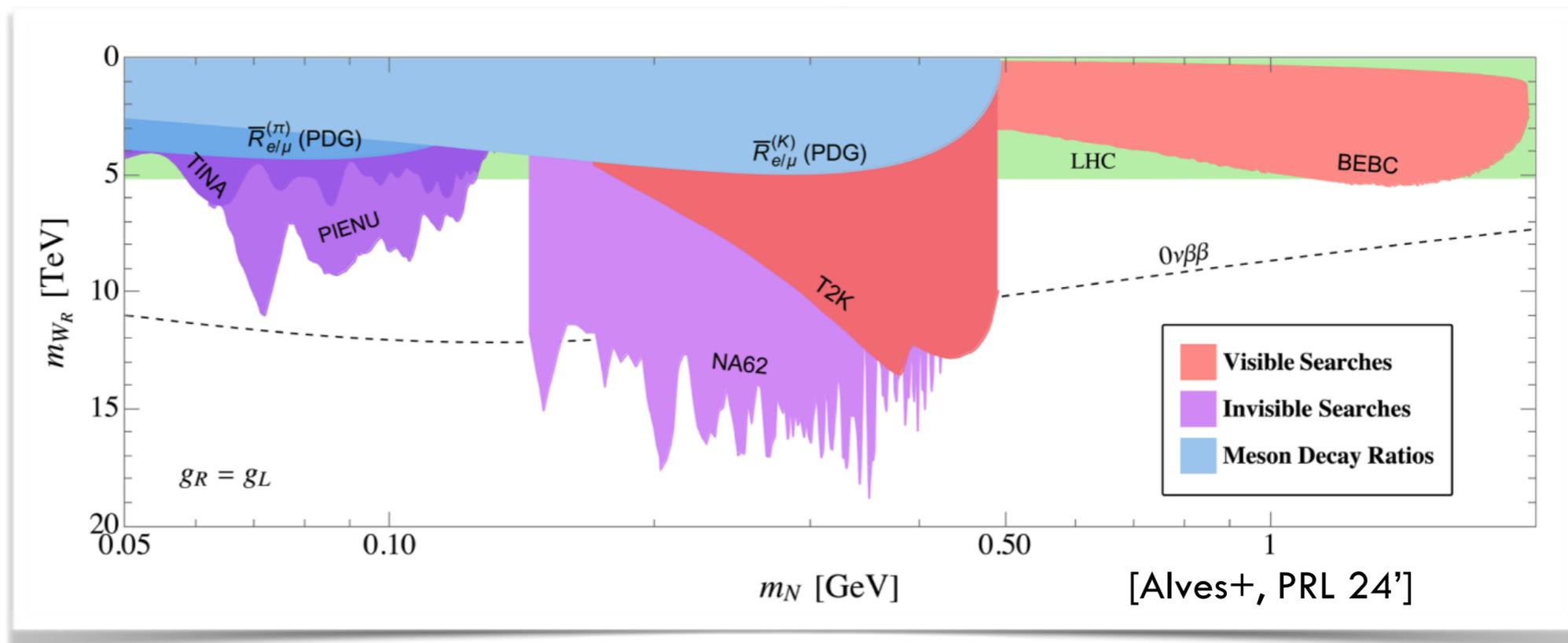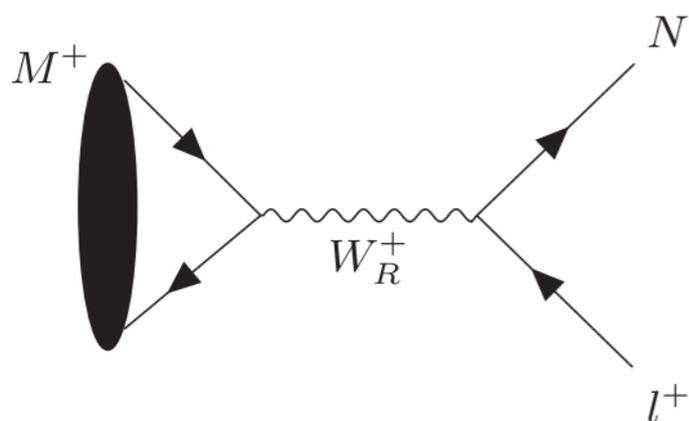# Probes: the Mesons

✤ K and B meson mixing exclude WR mass to ~ 3 TeV (for $\mathcal{C}$)
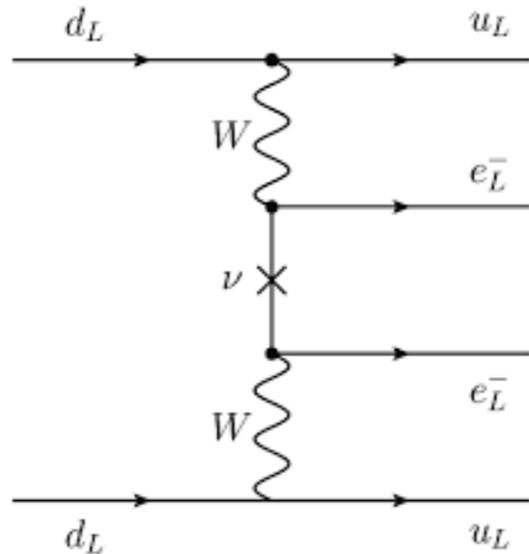

[Bertolini+, PRD 14']

✤ Meson decays exceed the LHC bound on certain mass regions

[Alves+, PRL 24']

Probes: the 0νββ

❖ The neutrinoless double beta decay (*0νββ*) constrains both the RH particles and neutrinos' Majorana nature simultaneously

Current limit:

$$T_{1/2}^{0\nu} > 3.8 \times 10^{26} \text{ yr}$$
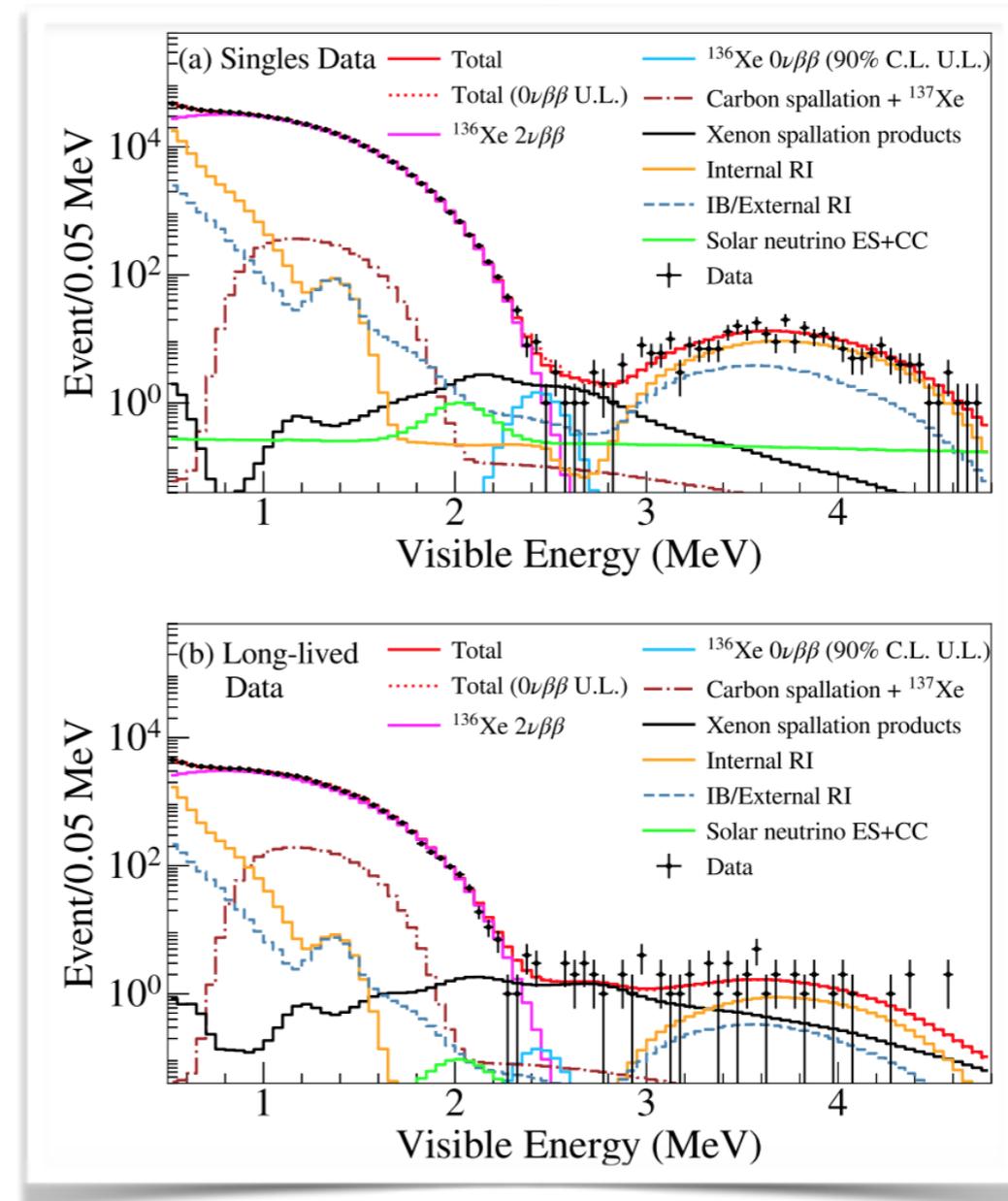
KLZ-800, 970 ton yr, ^{136}Xe

[KamLAND-Zen, 2406.11438]

Projection:

$$T_{1/2}^{0\nu} \sim 10^{28} \text{ yr}$$

e.g., nEXO, ^{136}Xe

[Adams+, 2212.11099]

[KamLAND-Zen, PRL 23']

Probes: the 0νββ

✤ **Half-life**

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \left[G_{01} \left(|\mathcal{A}_L|^2 + |\mathcal{A}_R|^2 \right) - 2(G_{01} - G_{04}) \mathrm{Re}\, \mathcal{A}_L^* \mathcal{A}_R \right]$$

✤ **Partial amplitude**

➙ calculation done with the advanced EFT approach

$$\mathcal{A}_{L,R} = \sum_{i=1}^{6} \mathcal{A}_{L,R}(m_i),$$

$$\mathcal{A}_L(m_i) = -\frac{m_i}{4m_e} \left(\mathcal{M}_V + \mathcal{M}_A \right) \left(C_{\mathrm{VLL}}^{(6)} \right)_{ei}^2 + \mathcal{A}_L^{(\nu)}(m_i),$$

$$\mathcal{A}_R(m_i) = -\frac{m_i}{4m_e} \left(\mathcal{M}_V + \mathcal{M}_A \right) \left(C_{\mathrm{VRR}}^{(6)} \right)_{e(i-3)}^2 + \mathcal{A}_R^{(\nu)}(m_i).$$

combinations of NMEs

Wilson coeffs.

hard-neutrino exchange term

➙ a <u>large systematic error</u> associated with the NME (factor of 2-4)

Probes: the 0νββ

✤ Half-life

$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \left[G_{01}\left(|\mathcal{A}_L|^2 + |\mathcal{A}_R|^2\right) - 2(G_{01} - G_{04})\mathrm{Re}\mathcal{A}_L^*\mathcal{A}_R\right]$$

✤ Partial amplitude

$$\mathcal{A}_L^{(\nu)}(m_i) = -\frac{m_i}{2m_e}\frac{m_\pi^2 g_\nu^{NN}(m_i)}{g_A^2}\left(C_{\mathrm{VLL}}^{(6)}\right)_{ei}^2 M_{F,sd}\,,$$
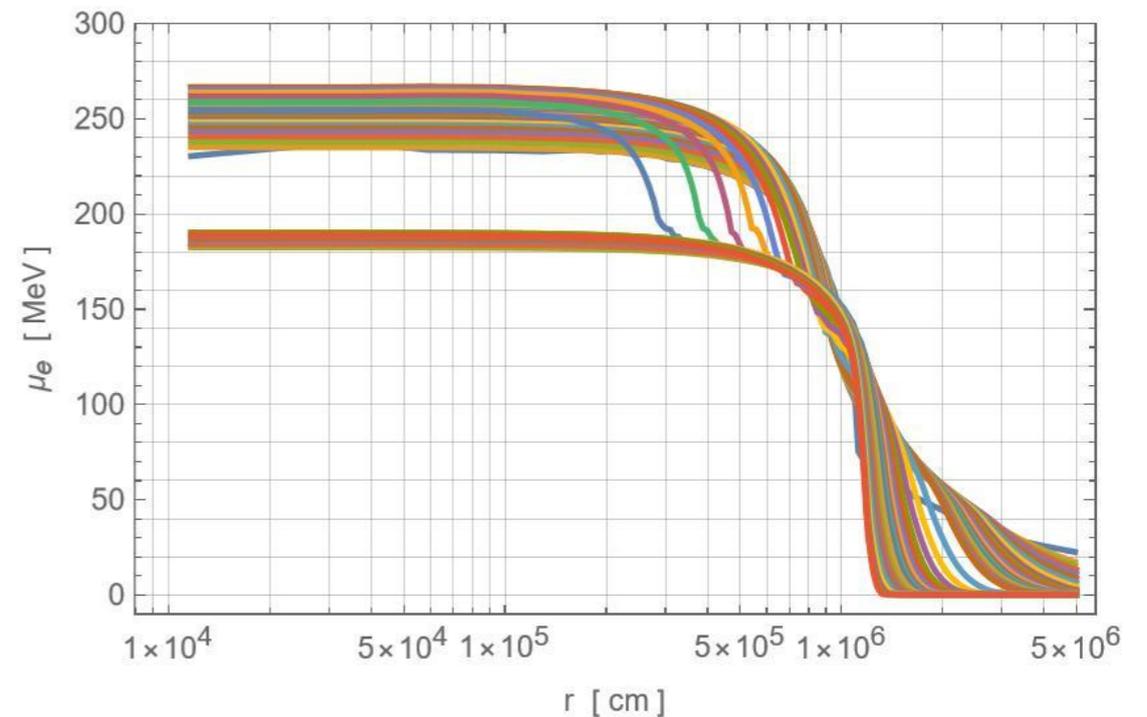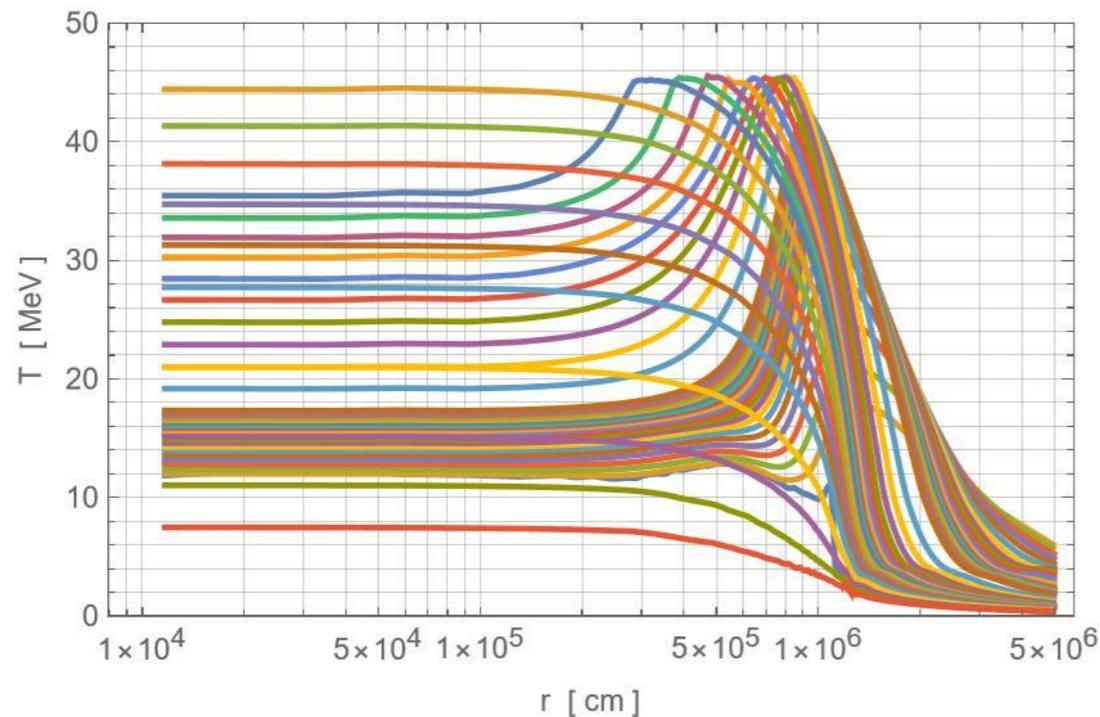
$$\mathcal{A}_R^{(\nu)}(m_i) = -\frac{m_i}{2m_e}\frac{m_\pi^2 g_\nu^{NN}(m_i)}{g_A^2}\left(C_{\mathrm{VRR}}^{(6)}\right)_{e(i-3)}^2 M_{F,sd}\,,$$

$$g_\nu^{NN}(m_i) = g_\nu^{NN}(0)\frac{1 + (m_i/\Lambda_\chi)^2}{1 + (m_i/\Lambda_\chi)^2(m_i/m_\pi)^2}$$

➝ the EFT approach requires the inclusion of the hard-neutrino exchange term (at LO of the power counting)

➝ error not as large as the NMEs

Probes: Supernovae

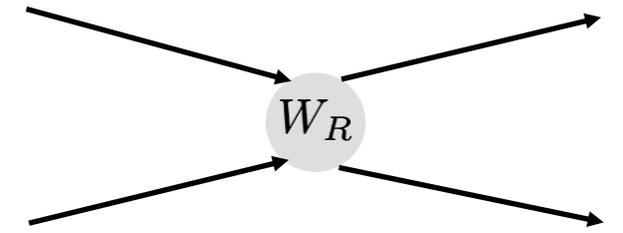✤ Supernovae (SNe) are ideal test grounds for BSM physics, specifically those at the sub-GeV scale

➡ typical energy scale matches

➡ simulation SFHo-18.6 performed by the MPA group used for our calculation
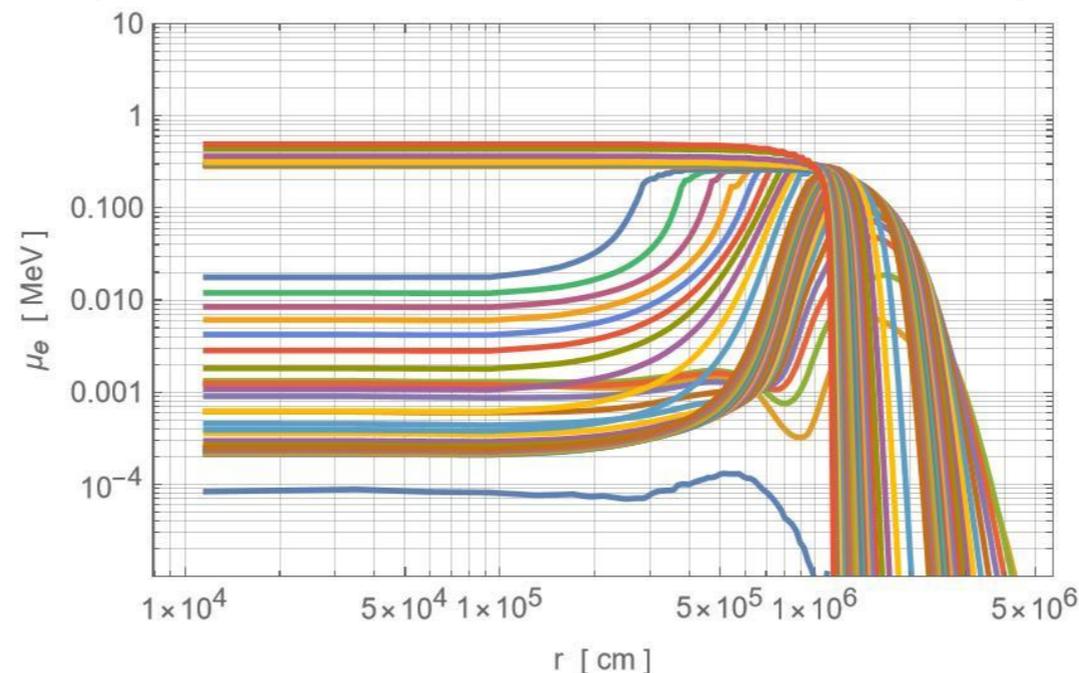
[Bollig+, PRL 20']

Probes: Supernovae

✤ Dominant production channel: $e + p \rightarrow \nu_4 + n$

$$\frac{d^2 n_{\nu_4}}{dE_{\nu_4} dt} \approx \int \frac{d^3 p_e}{(2\pi)^3 (2E_e)} \frac{d^3 p_p}{(2\pi)^3 (2E_p)} \frac{d^3 p_n}{(2\pi)^3 (2E_n)} \frac{p_{\nu_4}}{4\pi^2}$$

$$\times (2\pi)^4 \delta^{(4)}(p_e + p_p - p_{\nu_4} - p_n) \cdot |\mathcal{M}|^2 f_e f_p (1 - f_n)$$

→ the nucleon properties get modified in the dense environment

[Hempel, PRC 15']

→ q^2-dependence ignored in form factors, greatly simplifying the calcs

[Giunti&Kim, 08'; Hannestad+, PRD 95']

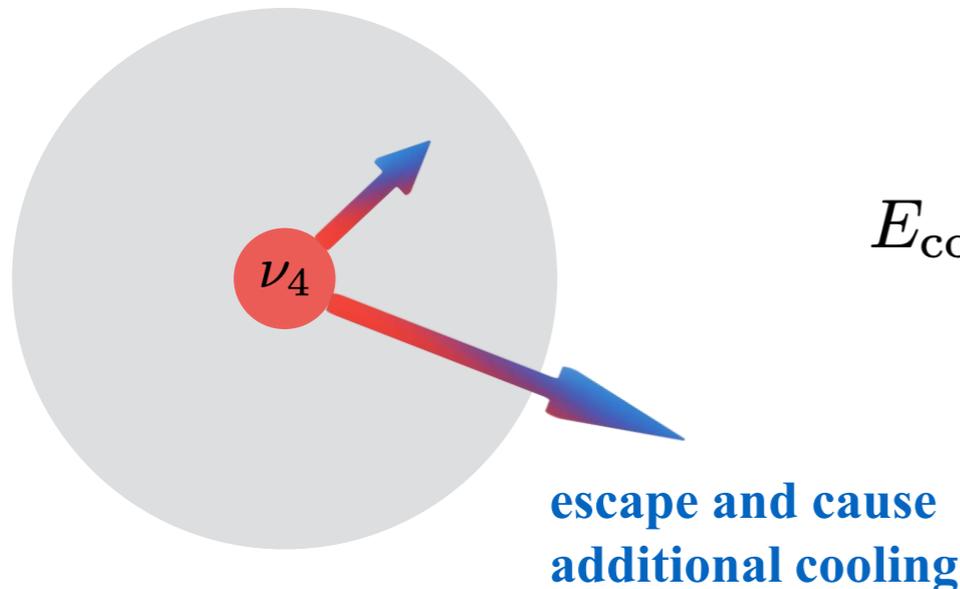→ the muon counterpart of this channel is not as important

[Bollig+, PRL 20']

→ the channel $\nu + \nu \rightarrow \nu_4 + \nu_4$ (through Z_R) turns out to be suppressed

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Probes: Supernovae

✤ The produced sterile neutrinos modify the SN dynamics and get constrained

escape and cause additional cooling

$$E_{\text{cooling}} = \int dE_{\nu_4} dt \int_0^{R_{\text{core}}} 4\pi r_{\text{prod}}^2 dr_{\text{prod}} \frac{d^2 n_{\nu_4}}{dE_{\nu_4} dt}$$
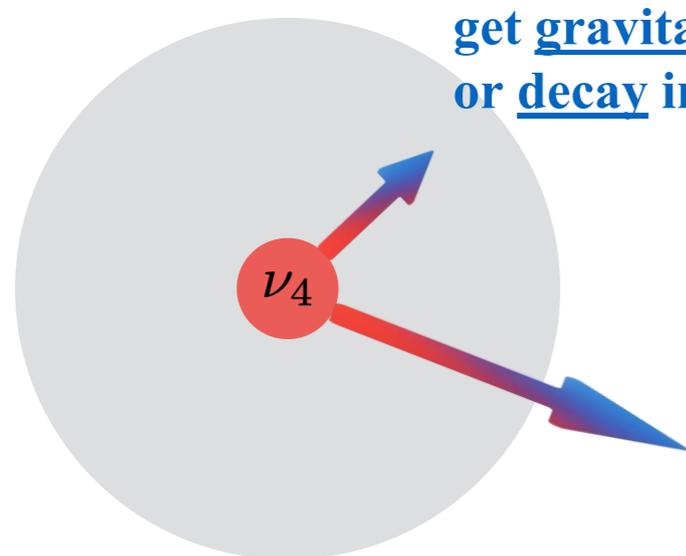$$\cdot P_{\text{srv}}(E_{\nu_4}, r_{\text{prod}}; R_{\text{env}}) E'_{\nu_4}(R_{\text{env}})$$

→ the SN1987A cooling bound: BSM particles should not take away too much energy

→ the upper limit on BSM cooling luminosity $L_{\text{BSM}} \lesssim 3 \times 10^{52}$ erg/s
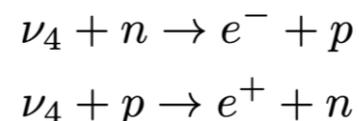
[Raffelt, Stars as laboratories for fundamental physics]

→ roughly equivalent to requiring the total dissipation less than $\sim 3 \times 10^{52}$ erg

[Dreiner+, PRD 03']

Probes: Supernovae

✤ The produced sterile neutrinos modify the SN dynamics and get constrained

get **gravitationally trapped** or get **absorbed** or **decay** in the stellar envelope

$$\nu_4 + n \rightarrow e^- + p$$
$$\nu_4 + p \rightarrow e^+ + n$$

ν_4

gravitational redshifted energy
$$E' = E\,\alpha(r_{prod})/\alpha(l)$$

$$E_{\rm depo} = \int dE_{\nu_4}dt \int_0^{R_{\rm core}} 4\pi r_{\rm prod}^2 dr_{\rm prod} \frac{d^2 n}{dE_{\nu_4}dt}$$

$$\cdot \int_{r_{\rm prod}}^{R_{\rm env}} \frac{dl}{\beta(E'_{\nu_4}(l))} \underbrace{P_{\rm srv}(E_{\nu_4}, r_{\rm prod}; l)}_{\text{survivability}} \sum_i \Gamma_i(E'_{\nu_4}(l)) \cdot \underbrace{E'_{\nu_4}(l)f_{\rm depo,i}}_{\substack{\text{energy deposited} \\ e^\pm, \nu\,(\rho > 10^{12}\mathrm{g/cm}^3)}}$$

[Rembiasz+, PRD 18']

survivability

energy deposited
$e^\pm, \nu\,(\rho > 10^{12}\mathrm{g/cm}^3)$

$$P_{\rm srv}(E, r; r') = \exp\left[-\int_r^{r'} \frac{dl}{\beta_{\nu_4}(E'(l))} \underbrace{\Gamma(E'(l))}_{\substack{\text{dissipation} \\ \text{(decay+absorp.)}}}\right]$$

dissipation
(decay+absorp.)

→ the energy deposition bound: BSM particles should not inject too much energy inside the stellar envelop (i.e. the ejecta)

[Falk+, PLB 78'; Sung+, PRL 19'; Caputo+, PRL 22']

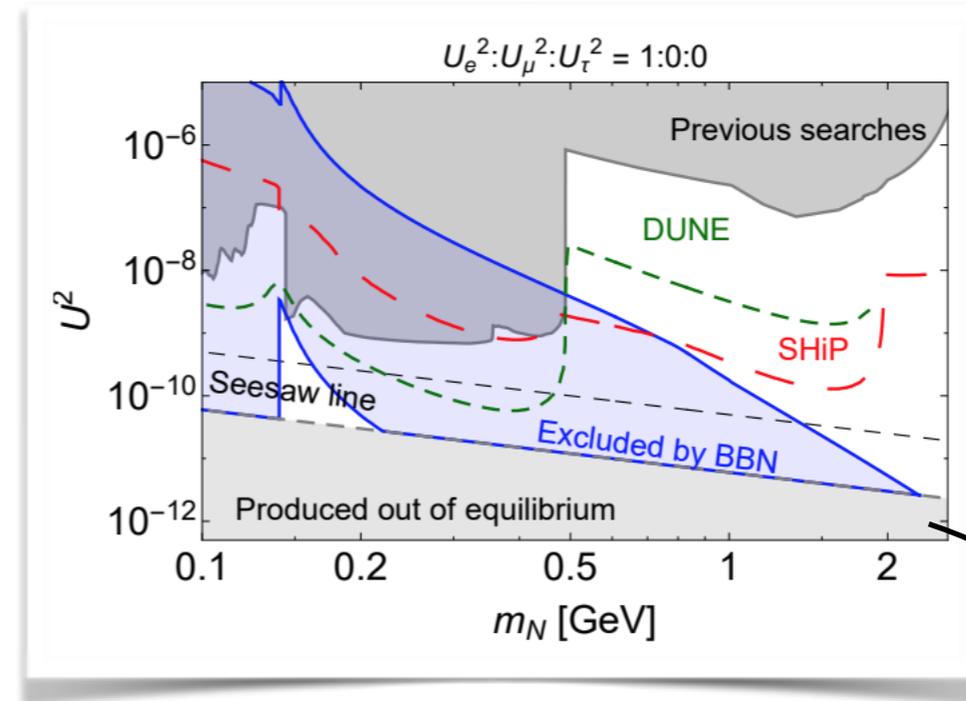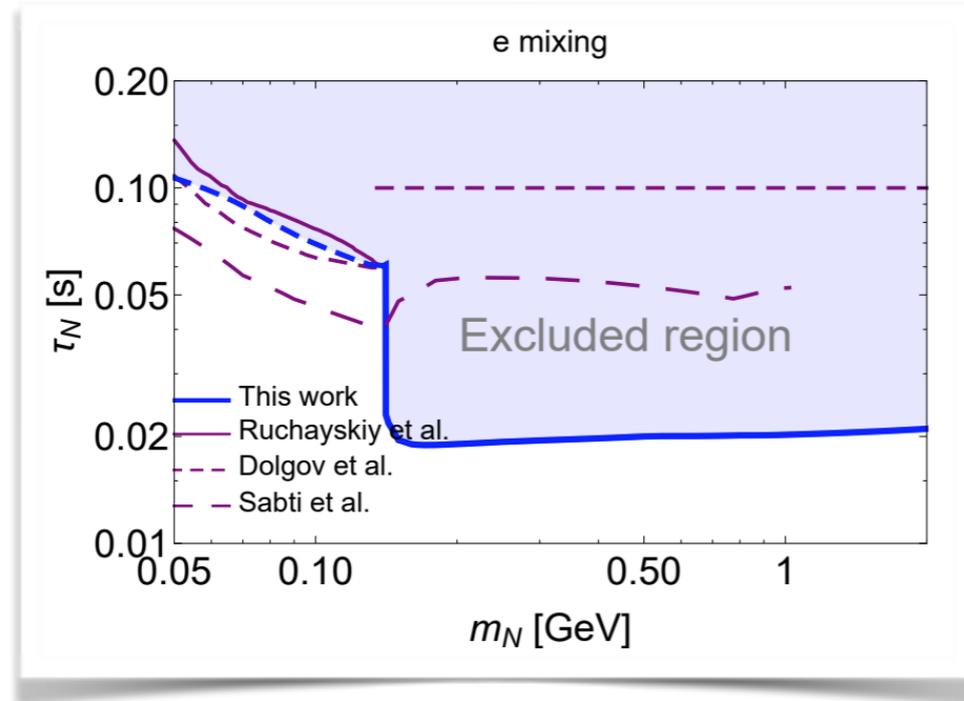→ requiring the total deposition energy to be $E_{\rm depo} \lesssim 10^{50}$ erg

[Carenza+, PRD 24']

Probes: Cosmology

♣ The existence of sterile neutrinos may spoil BBN

→ Entropy injection, extra radiation d.o.f., shifting chemical equilibrium

→ The most relevant constraint here comes from pion injection (shifting
  the $p \leftrightarrow n$ equilibrium), requiring $\tau_{\nu_4} \lesssim 0.023$ s

[Boyarsky+, PRD 21']

→ despite derived a type-I model, this constraint directly apply to us

due to the thermal suppression of the
mixing angle (which we don't have)

$$\Gamma_{N,\text{int}} \approx b G_F^2 T^5 \cdot U_m^2(T)$$

$$U_m^2(T) \approx \frac{U^2}{\left[1 + 9.6 \cdot 10^{-24} \left(\frac{T}{1\,\text{MeV}}\right)^6 \left(\frac{m_N}{150\,\text{MeV}}\right)^{-2}\right]^2}$$

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Probes: Cosmology

✤ Unfortunately, the mLRSM is such a concrete model such that the sterile neutrinos are inevitably thermal in the early universe

$$\Gamma \sim n\langle\sigma v\rangle \sim N\frac{g^4 T^5}{\pi^2 M_V^4}\,,$$

$$T_{\text{dec}} \sim 5 \text{ GeV} \left(\frac{M_V}{100 \text{ TeV}}\right)^{4/3}\left(\frac{g}{0.65}\right)^{-4/3}\left(\frac{N}{20}\right)^{-1/3}$$

→ Neither does low scale freeze-in work

$$Y_\infty \sim \frac{M_{\text{pl}}T_{\text{RH}}^3}{M_V^4} \sim 0.01 \left(\frac{T_{\text{RH}}}{1 \text{ GeV}}\right)^3\left(\frac{M_V}{100 \text{ TeV}}\right)^{-4}$$
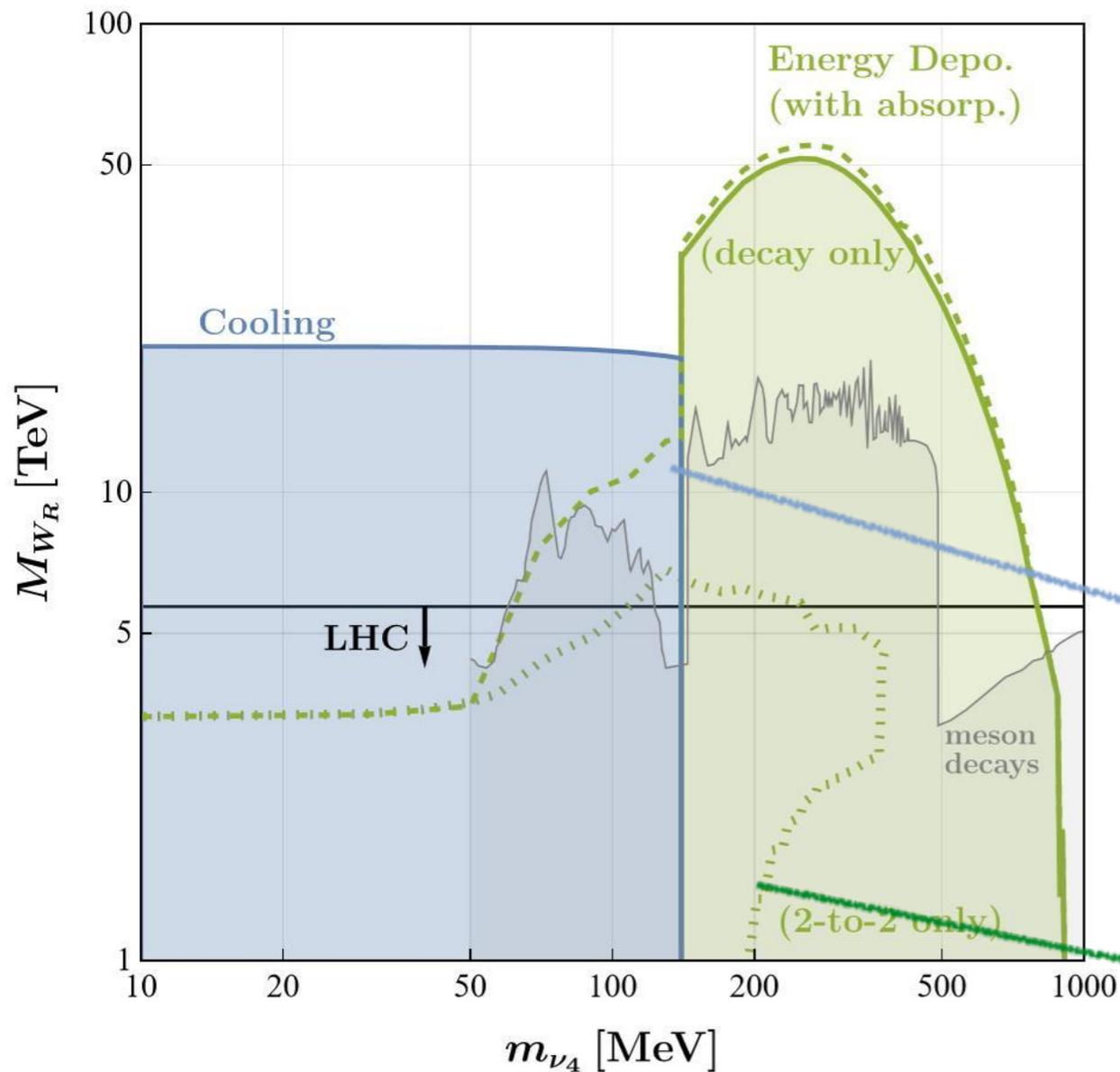
✤ If long-lived

$$\frac{\rho_{\nu_4}}{\rho_{\text{SM}}} = \frac{m_{nu_4}n_{\nu_4}}{\frac{\pi^2}{30}g_{*,\text{BBN}}T_{\text{BBN}}^4} = \frac{m_{nu_4}\left(\frac{1}{\pi^2}T_{\text{fo}}^3\right)\left(\frac{T_{\text{BBN}}}{T_{\text{fo}}}\right)^3}{\frac{\pi^2}{30}g_{*,\text{BBN}}T_{\text{BBN}}^4} = \frac{30}{g_{*,\text{BBN}}\pi^4}\frac{m_{nu_4}}{T_{\text{BBN}}} \gg 1$$

→ change the expansion rate and hence also spoils the BBN

→ excluding both the heavy WR region for $m_{\nu_4} > m_\pi$ and the whole $m_{\nu_4} < m_\pi$

To Sum Up

Despite better than KLZ for sterile neutrino below 600 MeV, SNe hardly constrain anything more than $0\nu\beta\beta$ and cosmo
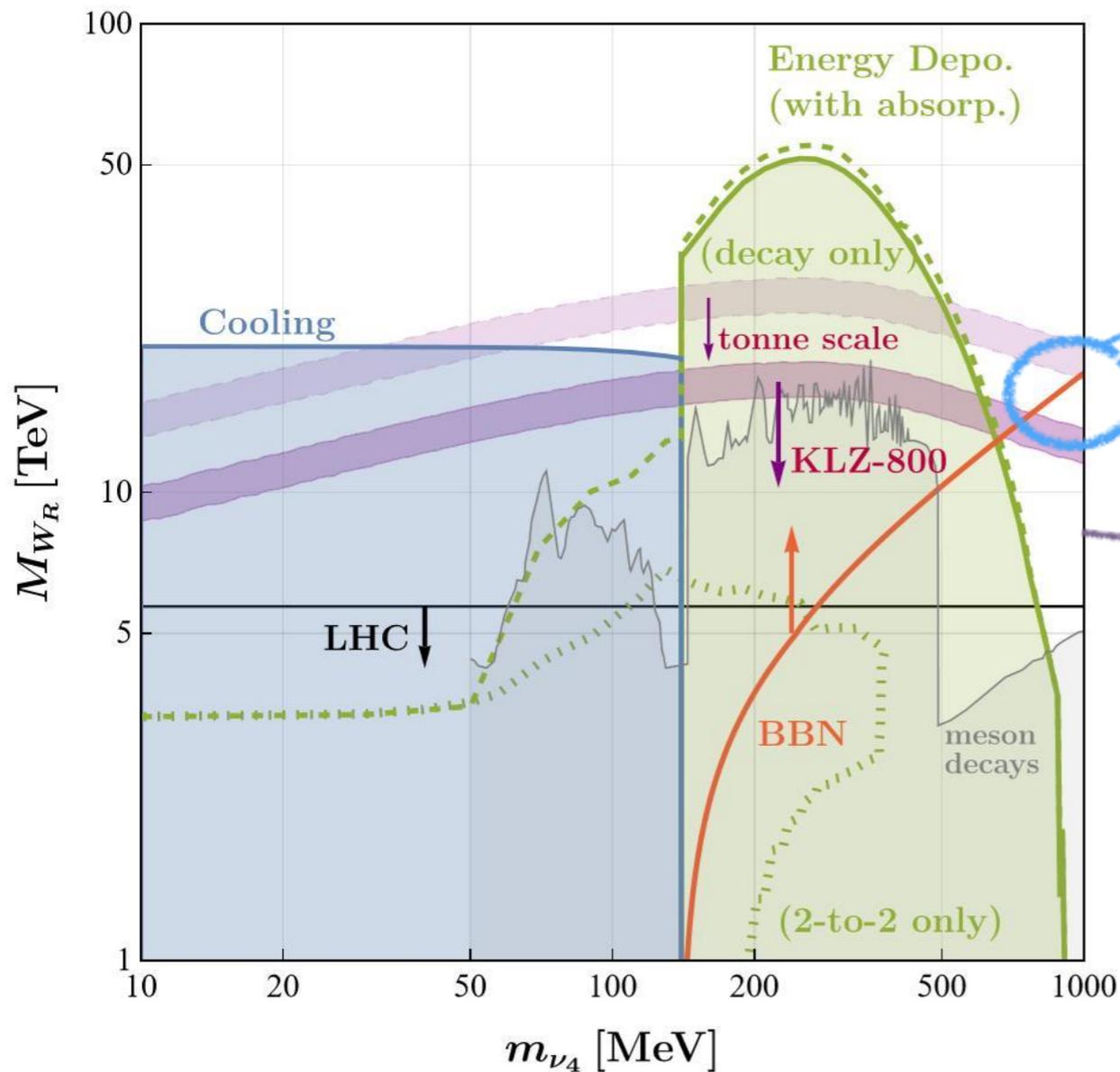
The cooling bound stops at m_π abruptly due to the opening of the hadronic decay channel

The 2-to-2 scatterings don't appear to have a significant impact on the energy deposition

[Mohapatra+, PRD 89']

effects. These give the excluded ranges of M_{W_R} and ζ stated in Eqs. (1) and (2). Note, however, that present laboratory limits[10,11] from μ^+ decay already rule out the lower limits in Eq. (1) ($M_{W_R} \lesssim 514$ GeV for $\zeta = 0$ from μ decay[11]). This combination of supernova observations with laboratory observations would imply $M_{W_R} \geq 23$ TeV and $\zeta < 10^{-5}$ for $m_{\nu_R} \lesssim 10$ MeV. These are the most stringent bounds to date on M_{W_R} and ζ.

To Sum Up

A region uniquely probed by future tonne-scale *0νββ* experiments

***0νββ* dominantly contributed by ν_4**

[Mohapatra+, PRD 89']

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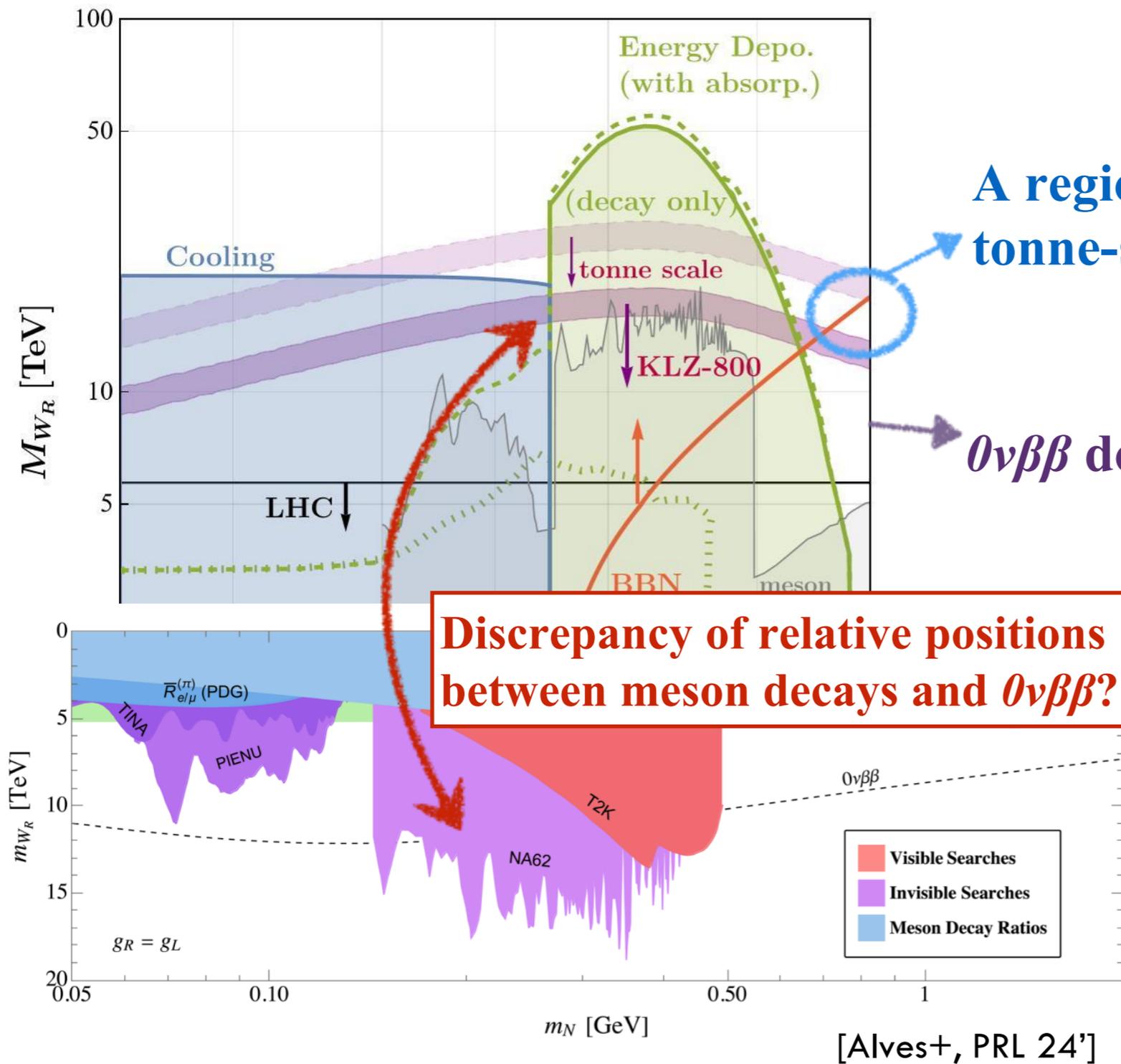
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To Sum Up

A region uniquely probed by future tonne-scale $0\nu\beta\beta$ experiments

$0\nu\beta\beta$ dominantly contributed by ν_4

Discrepancy of relative positions between meson decays and $0\nu\beta\beta$?

[Alves+, PRL 24']

Other phenomenological constraints—We show in Fig. 2 the limit we estimated from KamLAND-Zen [59,65] non-observation of neutrinoless double beta decay in ^{136}Xe using the nuclear matrix elements from Ref. [70]. This limit

[67] A. M. Abdullahi *et al.*, J. Phys. G **50**, 020501 (2023).
[68] S. Mandal, M. Mitra, and N. Sinha, Phys. Rev. D **96**, 035023 (2017).
[69] R. M. Godbole, S. P. Maharathy, S. Mandal, M. Mitra, and N. Sinha, Phys. Rev. D **104**, 095009 (2021).
[70] G. Pantis, F. Simkovic, J. D. Vergados, and A. Faessler, Phys. Rev. C **53**, 695 (1996).

For Completeness

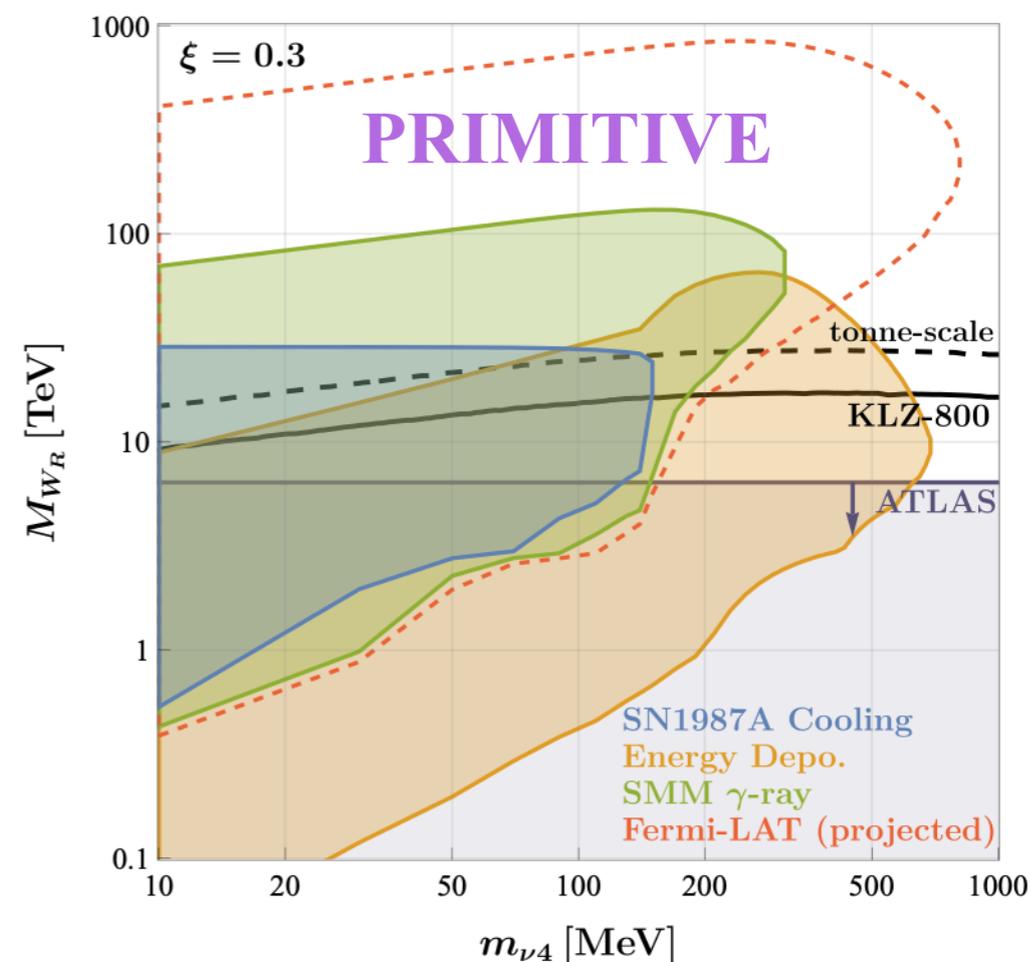- ✤ Two new decay channels are opened at $\xi \neq 0$

  [Bondarenko+, JHEP 18';
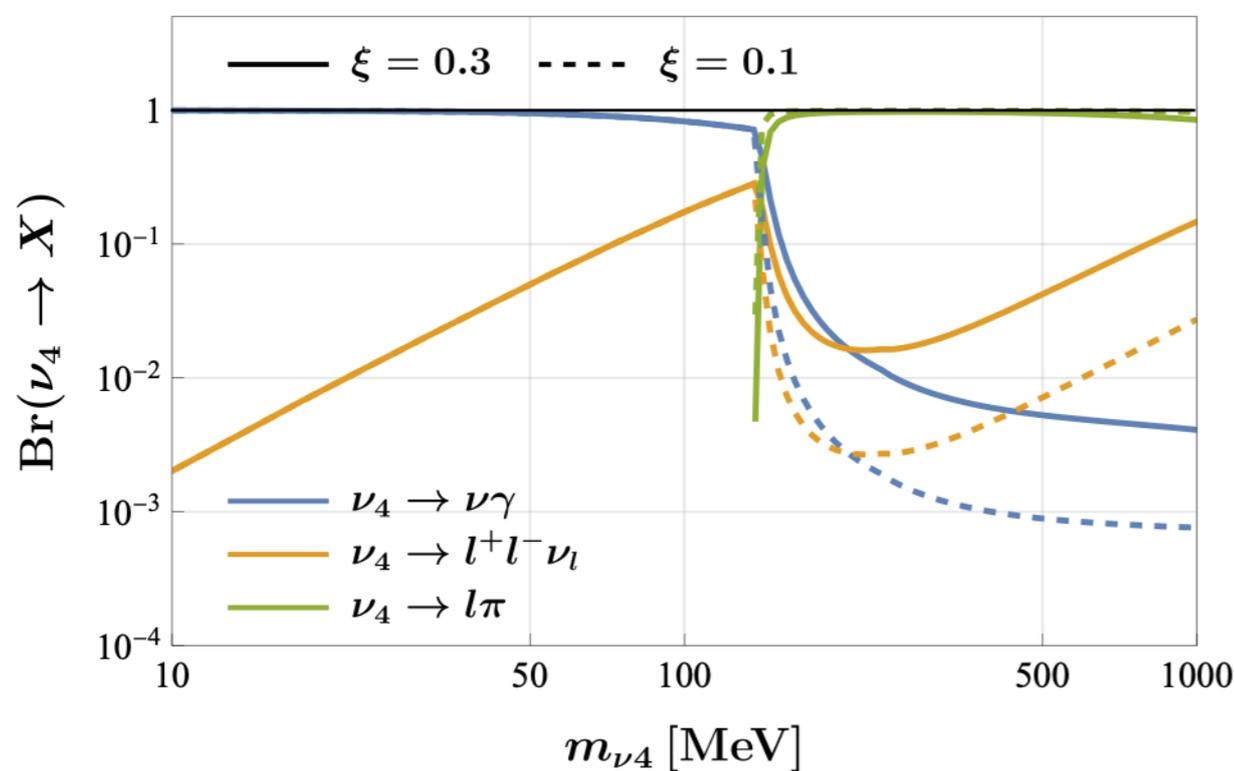 Shrock, NPB 82']

  - ➜ $\nu_4 \to \nu\gamma$

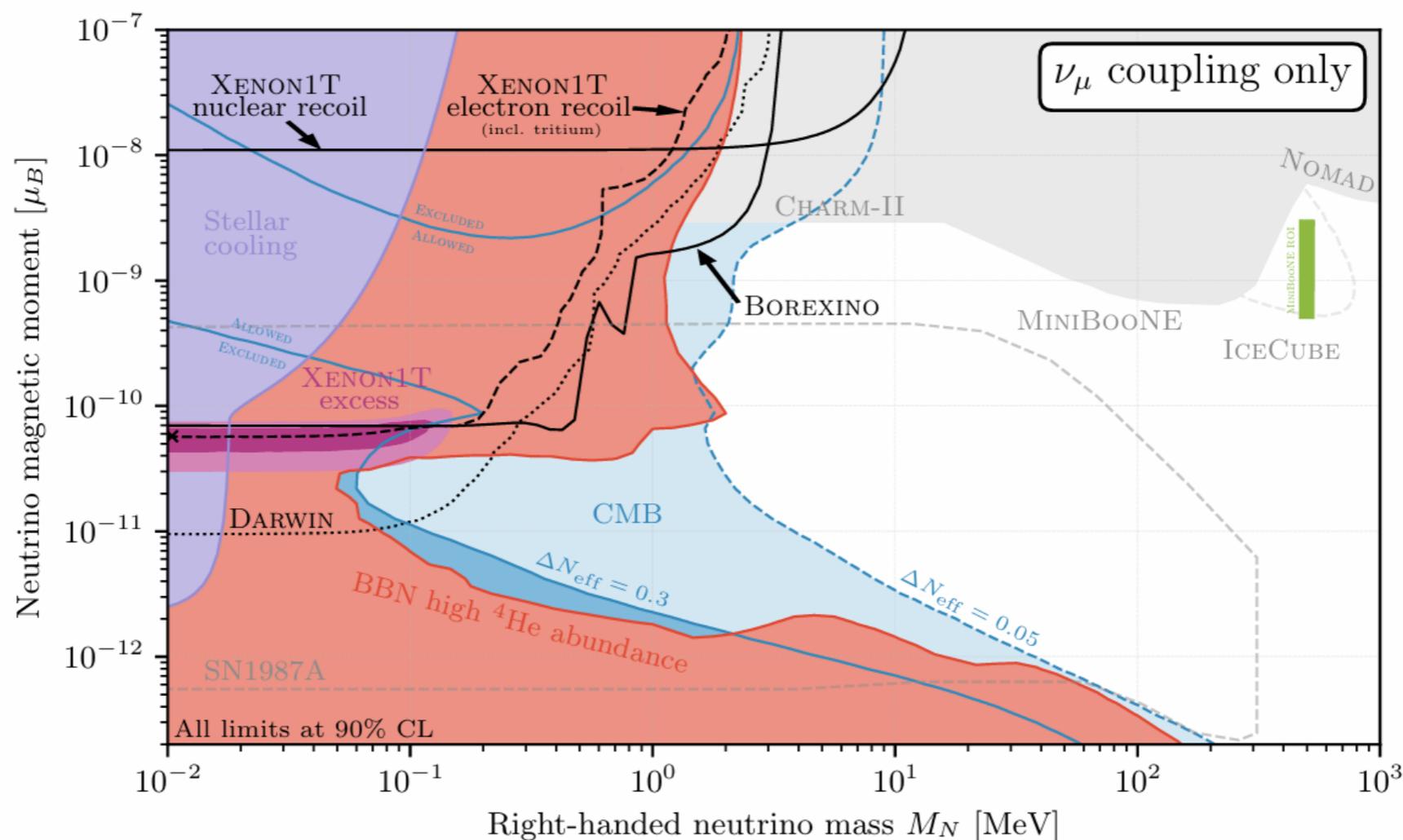 - ➜ $\nu_4 \to l^+ l^- \nu$

- ✤ The hadronic decay get slightly suppressed by a relative factor of $(1 - 2\xi/(1+\xi^2))^2$

- ✤ γ-ray signal at the SN, but can't constrain more

For Completeness

❖ The BBN constraint at $m_{\nu_4} < m_\pi$ has some complications

➝ Most of existing constraints are drawn assuming type-I scenario where leptonic decay dominates

➝ The most relevant one comes from the so-called "magnetic dipole portal" model, constraining $(\mu/2)F_{\rho\sigma}\overline{\nu_L}\sigma^{\rho\sigma}\nu_R$

[Brdar+, JCAP 21']

Conclusion

✤ To test the possible origin of neutrino masses, one need to

- both search for new (RH) particles and verify the Majorana nature

- consider not only the heavy but also the light sterile neutrinos

✤ Probes on the sub-GeV sterile neutrino in mLRSM come from

- the LHC

- meson decays

- $0\nu\beta\beta$

- supernovae

- cosmology

✤ We check the $0\nu\beta\beta$ constraints using the advanced EFT approach, update the SN bounds, and consider the stringent lifetime sterile neutrino lifetime constraint from the BBN

✤ A parameter space uniquely probed by future tonne-scale $0\nu\beta\beta$ experiments is identified

Bkp: The Model Setup

✤ The symmetry: $SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

✤ New particle contents:

➡ 3 RH Majorana neutrinos

➡ 2 scalar triplets (L+R)

➡ 1 additional Higgs doublet

$$L_{L,R} = \begin{pmatrix} \nu_{L,R} \\ \ell_{L,R} \end{pmatrix} \quad \Delta_{L,R} = \begin{pmatrix} \delta_{L,R}^+/\sqrt{2} & \delta_{L,R}^{++} \\ \delta_{L,R}^0 & -\delta_{L,R}^+/\sqrt{2} \end{pmatrix} \quad \Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$$

✤ Symmetry breaking pattern

$$\langle \Delta_L \rangle = \begin{pmatrix} 0 & 0 \\ v_L e^{i\theta_L}/\sqrt{2} & 0 \end{pmatrix}, \quad \langle \Delta_R \rangle = \begin{pmatrix} 0 & 0 \\ v_R/\sqrt{2} & 0 \end{pmatrix}, \quad \langle \Phi \rangle = \begin{pmatrix} \kappa/\sqrt{2} & 0 \\ 0 & \kappa' e^{i\alpha}/\sqrt{2} \end{pmatrix}$$

CPV phases set to 0

➡ $v_R \gg v = \sqrt{\kappa^2 + \kappa'^2} \gg v_L$

Bkp: The Model Setup

✤ The lepton Yukawa sector

$$\mathcal{L}_Y \supset -\bar{L}_L(\Gamma_l\Phi + \tilde{\Gamma}_l\tilde{\Phi})L_R - \left(\bar{L}_L^c i\tau_2 \Delta_L Y_L L_L + \bar{L}_R^c i\tau_2 \Delta_R Y_R L_R\right) + \text{h.c.}$$

$$\mathcal{L}_m = -\frac{1}{2}\left(\bar{\nu}_L, \bar{\nu}_R^c\right)\begin{pmatrix} M_L & M_D \\ M_D^T & M_R \end{pmatrix}\begin{pmatrix} \nu_L^c \\ \nu_R \end{pmatrix} + \text{h.c.}$$

$$M_L = \sqrt{2}Y_L^\dagger v_L\,, \quad M_R = \sqrt{2}Y_R v_R\,, \quad M_D = (\kappa\Gamma_l + \kappa'\tilde{\Gamma}_l)/\sqrt{2}$$

$$M_\nu = M_L - M_D M_R^{-1} M_D^T \quad \textcolor{blue}{M_D \to 0 \textbf{ when no left-right mixing}}$$

➙ the neutrino masses: combination of type-I and type-II seesaw

✤ Assuming further the generalized charge conjugation $\mathcal{C}$

[Maiezza+, PRD 10']

the sterile neutrino

$$Y_L = Y_R^\dagger \implies M_L = (v_L/v_R)M_R \quad \widehat{M}_\nu = (v_L/v_R)\widehat{M}_N$$

$$m_{\nu_4} \simeq 20 \text{ MeV} \cdot \frac{m_{\nu_6}}{1 \text{ TeV}} \cdot \frac{m_{\nu_1}}{10^{-6} \text{ eV}}\,, \quad m_{\nu_5} \simeq 175 \text{ GeV} \cdot \frac{m_{\nu_6}}{1 \text{ TeV}}$$

➙ predictability for the RH neutrino masses

➙ nice probes can come from the lightest new degree of freedom!

Bkp: The Model Setup

✤ The RH gauge bosons and CC interactions

$$\mathcal{L}_{cc} = \frac{g}{\sqrt{2}} \left(\bar{\ell}_L \gamma^\mu \nu_L W_{L\mu}^- + \bar{\ell}_R \gamma^\mu \nu_R W_{R\mu}^- \right) + \text{h.c.}$$

$g_L = g_R = g$

$$M_{W_{L,R}}^2 = \frac{g_{L,R}^2}{4} \left(\kappa^2 + \kappa'^2 + 2v_{L,R}^2 \right) \qquad \begin{pmatrix} W_L^\pm \\ W_R^\pm \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W_1^\pm \\ W_2^\pm \end{pmatrix}$$

$$\tan\zeta = \lambda \frac{2\xi}{1+\xi^2} \,, \quad \xi \equiv \kappa'/\kappa \,, \quad \lambda \equiv M_{W_L}^2 / M_{W_R}^2$$

set to 0 when no left-right mixing

↪ 0νββ, neutron EDM, kaon CPV, the oblique parameter

✤ In the absence of left-right mixing, the sterile neutrino only decays hadronically: $\nu_4 \rightarrow \ell_j^\mp \pi^\pm$
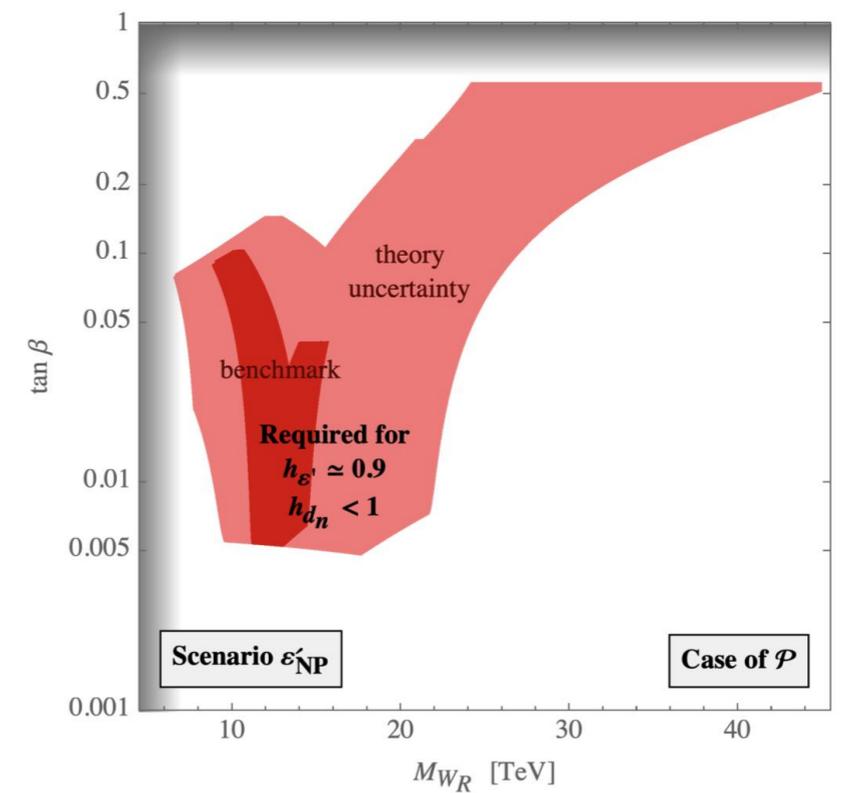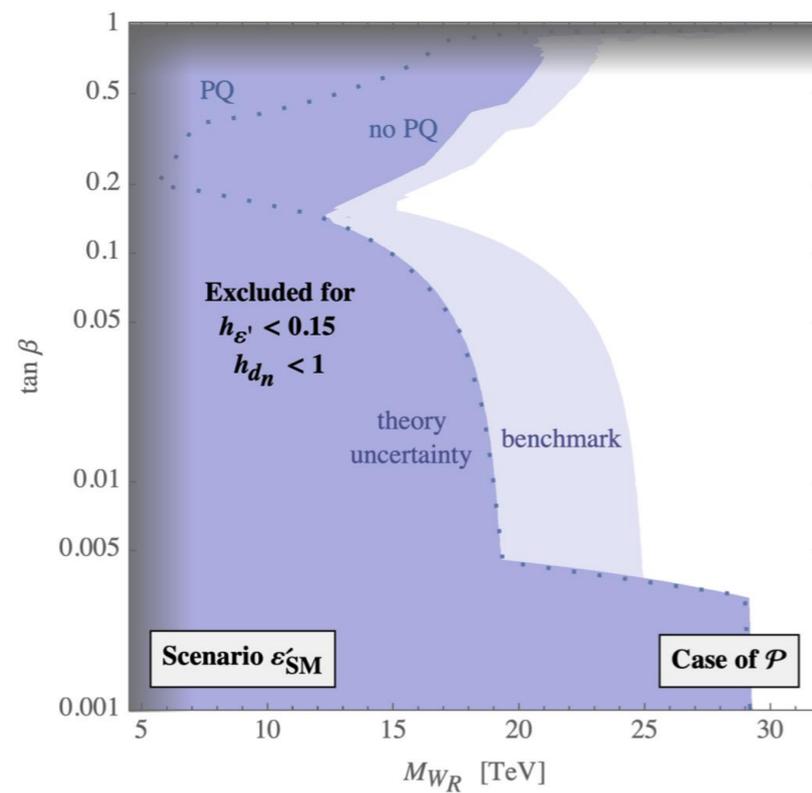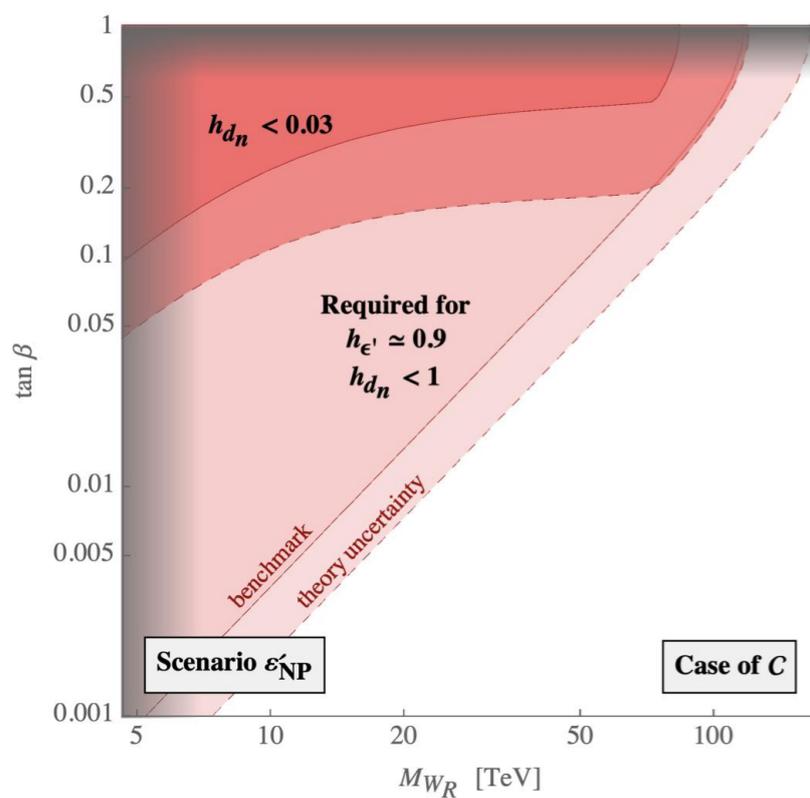
[Bondarenko+, JHEP 18']

$$\Gamma_{\text{dec},0} = \frac{G_F^2 f_\pi^2 m_{\nu_4}^3}{8\pi} |V_{ud}|^2 \lambda^2 \sum_{\alpha=e,\mu} \Big\{ \theta(1 - x_\pi - x_\alpha)$$

$$\cdot |(V_R)_{\alpha 1}|^2 \left[(1 - x_\alpha^2)^2 - x_\pi^2(1 + x_\alpha^2) \right] \beta(1, x_\pi^2, x_\alpha^2) \Big\}$$

$$x_a = m_a/m_{\nu_4} \,, \quad \beta(a,b,c) \equiv (a^2 + b^2 + c^2 - 2ab - 2bc - 2ca)^{1/2}$$

Bkp: Kaon CP

✤ The choice of generalized charge-conjugation (C) or parity (P) is crucial

$$\mathcal{P}: \begin{cases} Q_L \leftrightarrow Q_R \\ \Phi \to \Phi^\dagger \end{cases}, \qquad \mathcal{C}: \begin{cases} Q_L \leftrightarrow (Q_R)^c \\ \Phi \to \Phi^T \end{cases},$$

[Bertolini+, PRD 20']

Bkp: freeze-in

✤ Freeze-in doesn't work for our scenario due to the still-too-large coupling

$$\dot{n}_{\nu_4} + 3Hn_{\nu_4} \approx \frac{3T}{128\pi^5} \int ds \frac{s}{2\sqrt{s}} \frac{(s - m_{\nu_4})}{2\sqrt{s}} \frac{g^4 s^2}{M_V \Gamma_V} \delta(s - M_V^2) \frac{K_1(\sqrt{s}/T)}{\sqrt{s}}$$

$$\approx \frac{3T g^4 M_V^4}{512\pi^5 \Gamma_V} K_1\left(\frac{M_V}{T}\right),$$
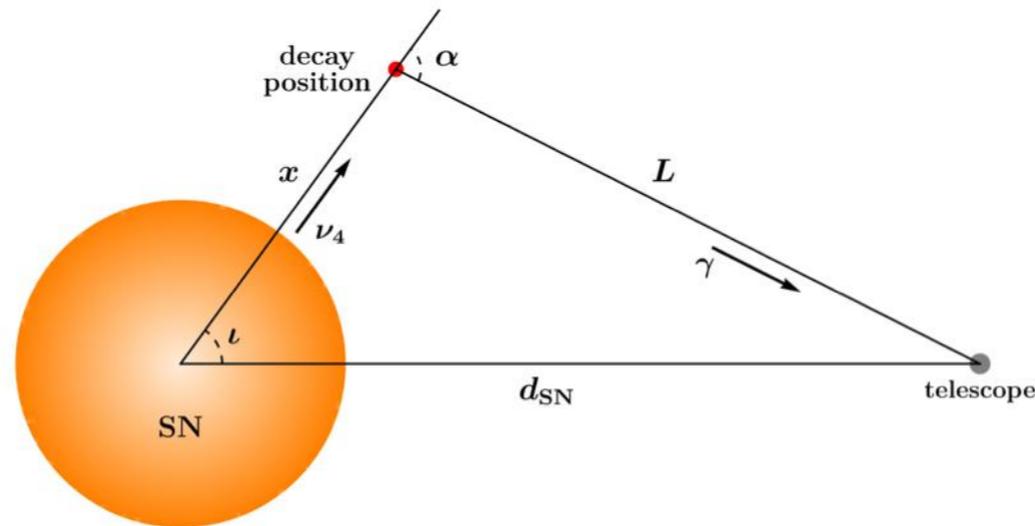
$$\frac{dY}{dT} \approx -\frac{3 g^4 M_V^4}{512\pi^4 \, sH \, \Gamma_V} K_1\left(\frac{M_V}{T}\right)$$

$$Y_\infty \approx \int_0^\infty dT \frac{dY}{dT} \approx 4 \times 10^8 \left(\frac{g}{0.65}\right)^4 \left(\frac{g_*}{106.75}\right)^{-3/2} \left(\frac{1\ \text{TeV}}{\Gamma_V}\right)$$

✤ Even for a low-scale reheating

$$Y_\infty \sim \frac{M_{\text{pl}} T_{\text{RH}}^3}{M_V^4} \sim 0.01 \left(\frac{T_{\text{RH}}}{1\ \text{GeV}}\right)^3 \left(\frac{M_V}{100\ \text{TeV}}\right)^{-4}$$

❖ Number of photon observed at the telescope (assuming the decay to be not extended)

$$N_\gamma = \int \sin \iota \, d\iota \int_0^{R_{\mathrm{core}}} 2\pi r^2 dr \int dE_{\nu_4} dt \frac{d^2 n}{dE_{\nu_4} dt} P_{\mathrm{srv}}(E_{\nu_4}, r; \ R_{\mathrm{env}}) \int_0^\infty \underbrace{e^{-\Gamma_{\mathrm{dec}} x/\beta}}_{\text{remnant flux fraction}} \underbrace{\frac{dx}{\beta} \Gamma_{\mathrm{dec}} \mathrm{Br_{ph.}}}_{\text{photonic decay probability}}$$

$$\times P_\gamma(\iota, x) \times \underbrace{\frac{A_{\mathrm{tele}}}{4\pi L^2}}_{\text{telescope's solid angle}} \times \Theta(T_{\mathrm{obs}} - \delta t)\Theta(E_{\gamma,\mathrm{max}} - E_\gamma)\Theta(E_\gamma - E_{\gamma,\mathrm{min}}),$$

$$\Phi_\gamma \lesssim \begin{cases} 1.38 \, \mathrm{cm}^{-2} & \mathrm{SMM} \\ 5.2 \times 10^{-4} \mathrm{cm}^{-2} & \text{Fermi-LAT (3600s obs. time)} \end{cases}$$