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

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

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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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- Majorana nature of neutrinos + RH sector particles
  - For naive type-I, EW-scale Dirac mass $\rightarrow$ 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)
  - parity restoration
  - grand unification at high scale
  - extraordinary predictability

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

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

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

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

  - CPV phases of the VEV set to 0

- Neutrino masses

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

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

$$M_\nu = M_L - M_D M_R^{-1} M_D^T \qquad M_D \to 0$$

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']

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

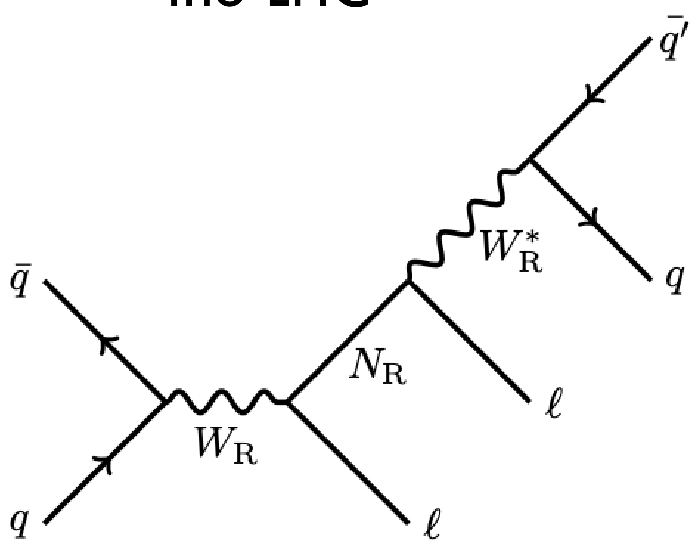
$$m_{\nu_4} \simeq 20 \text{ MeV} \cdot \frac{m_{\nu_6}}{1 \text{ TeV}} \cdot \frac{m_{\nu_1}}{10^{-6} \text{ eV}} \,, \quad m_{\nu_5} \simeq 175 \text{ GeV} \cdot \frac{m_{\nu_6}}{1 \text{ TeV}}$$

  - predictability for the RH neutrino masses
  - nice probes can come from the lightest new degree of freedom!

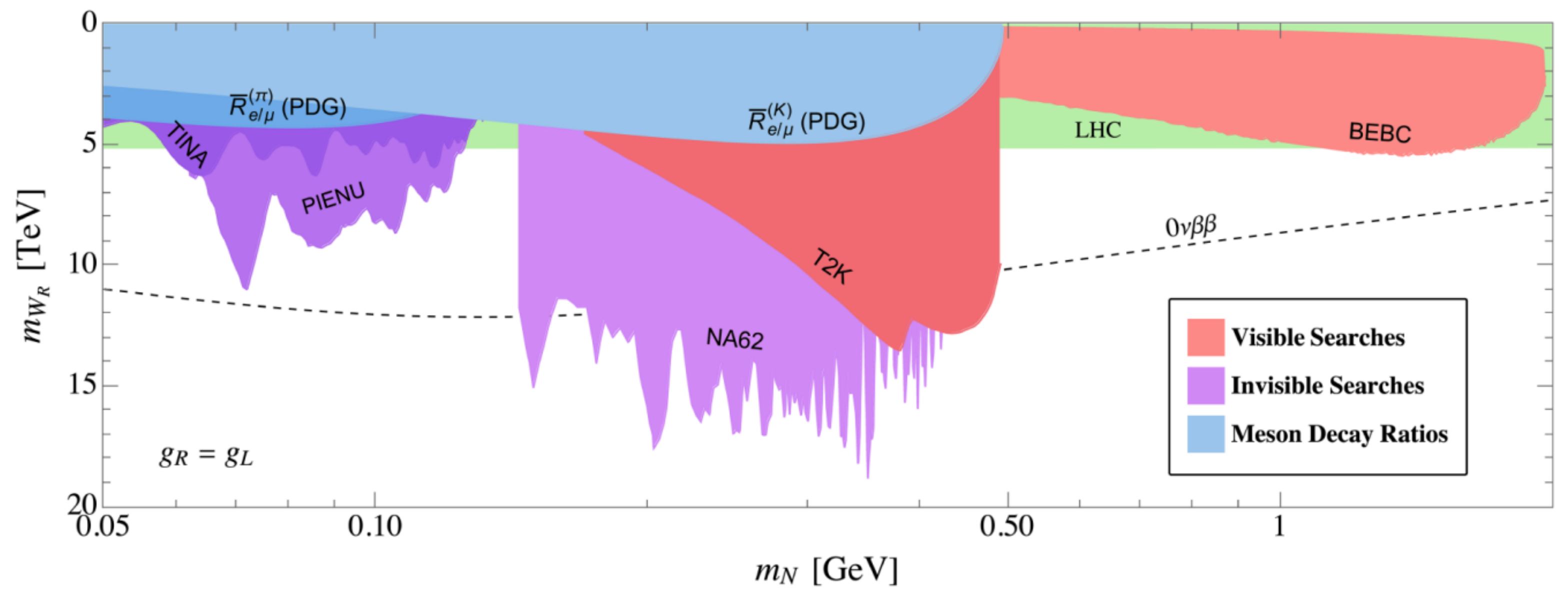
Probing the mLRSM

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

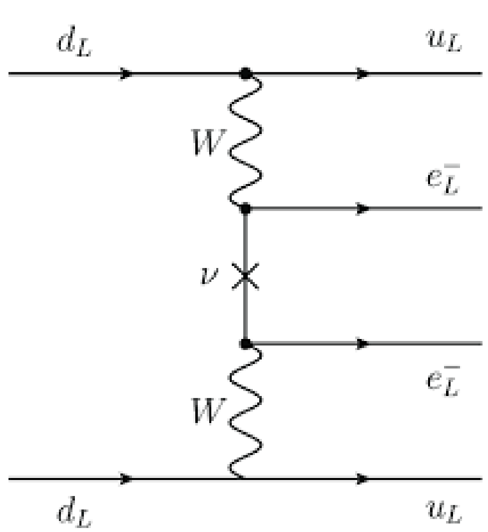
the LHC



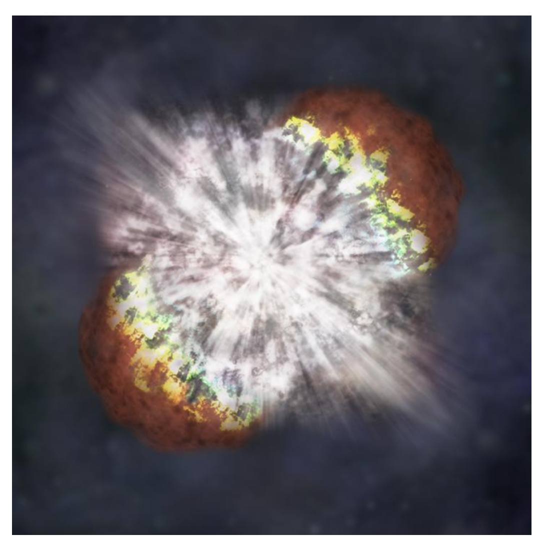
meson decays



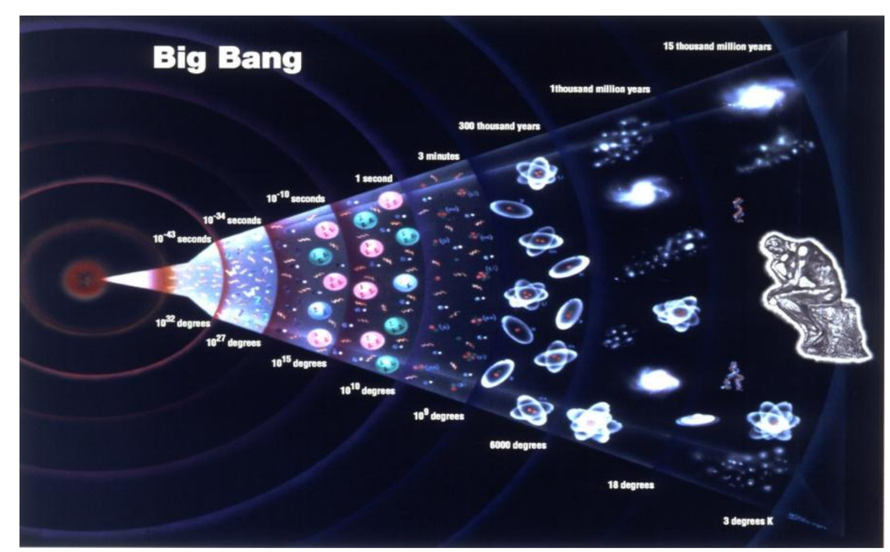
0νββ decays



supernovae

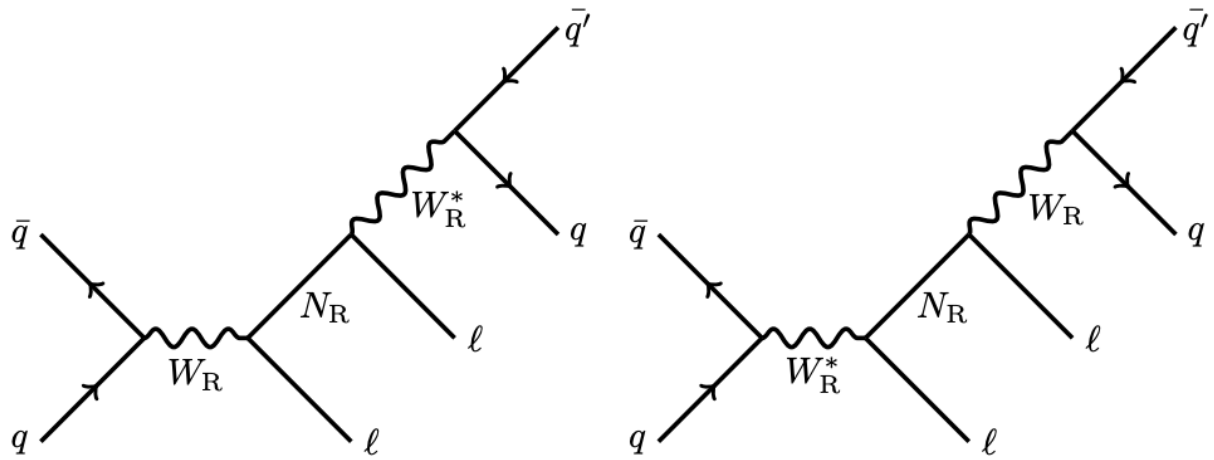


cosmology

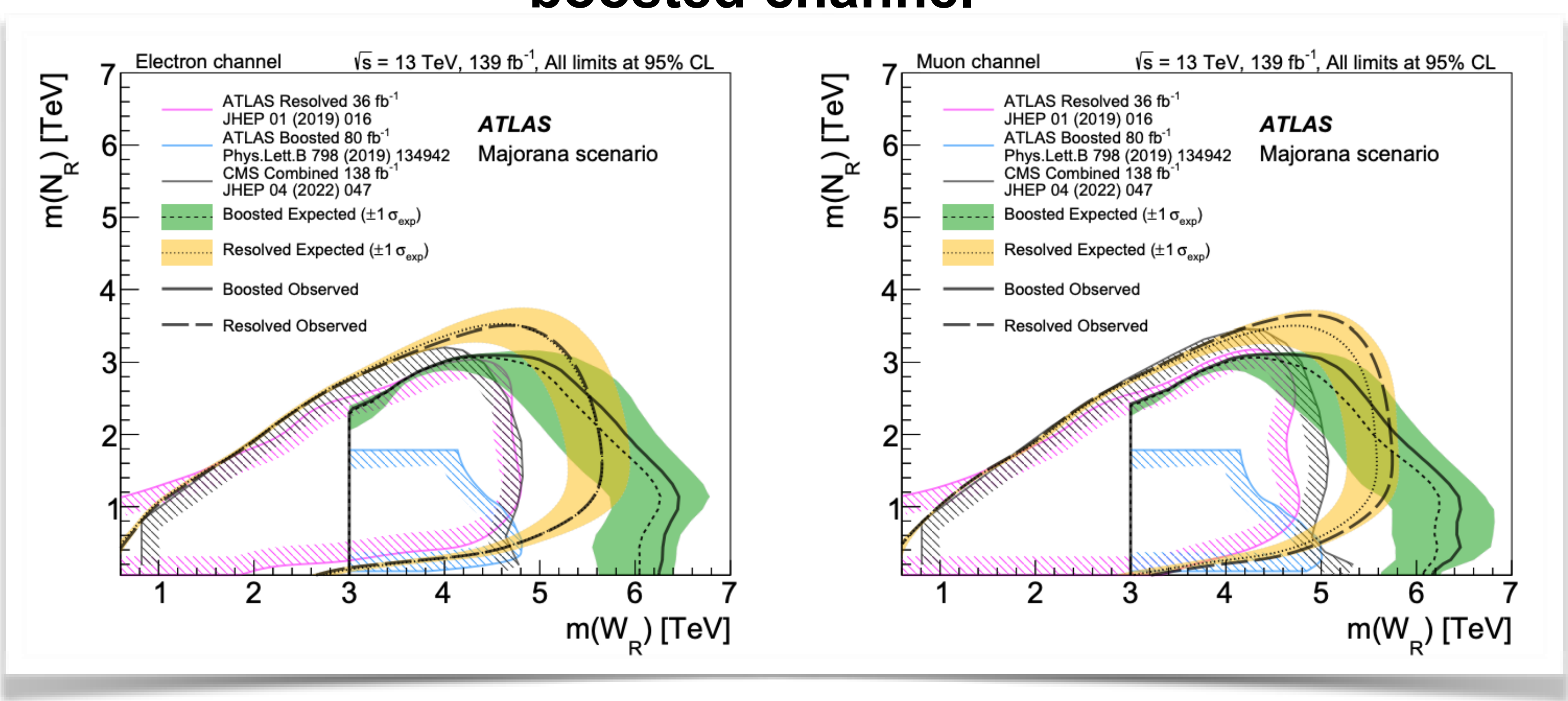


Probes: the LHC

- The Keung-Senjanovic process

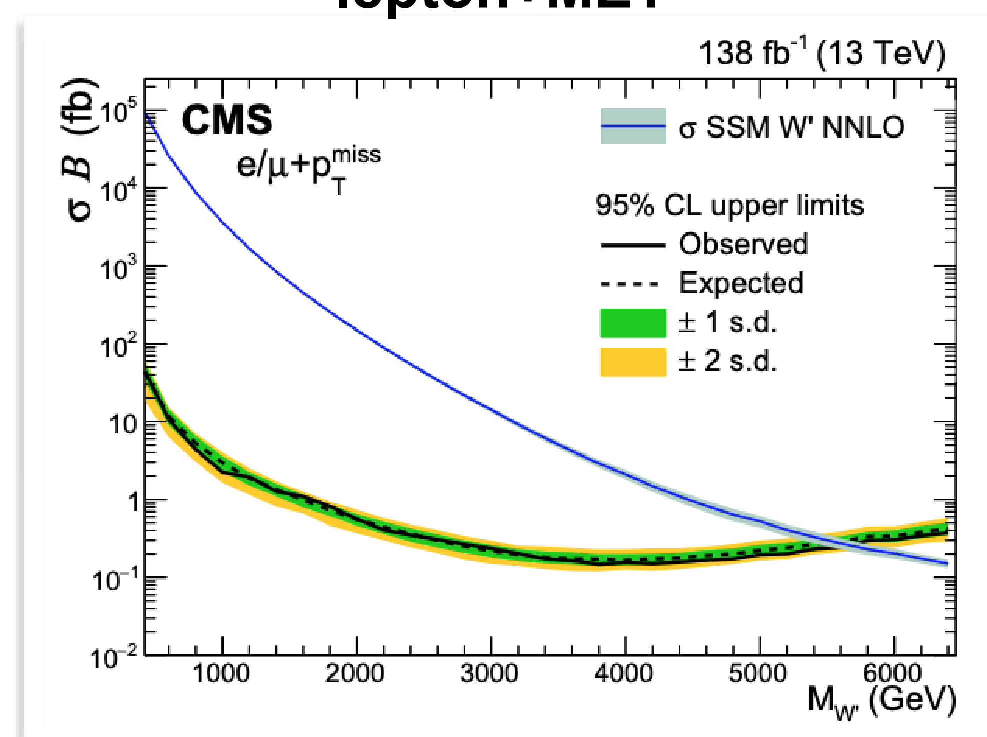


boosted channel



[ATLAS, EPJC 23']

lepton+MET

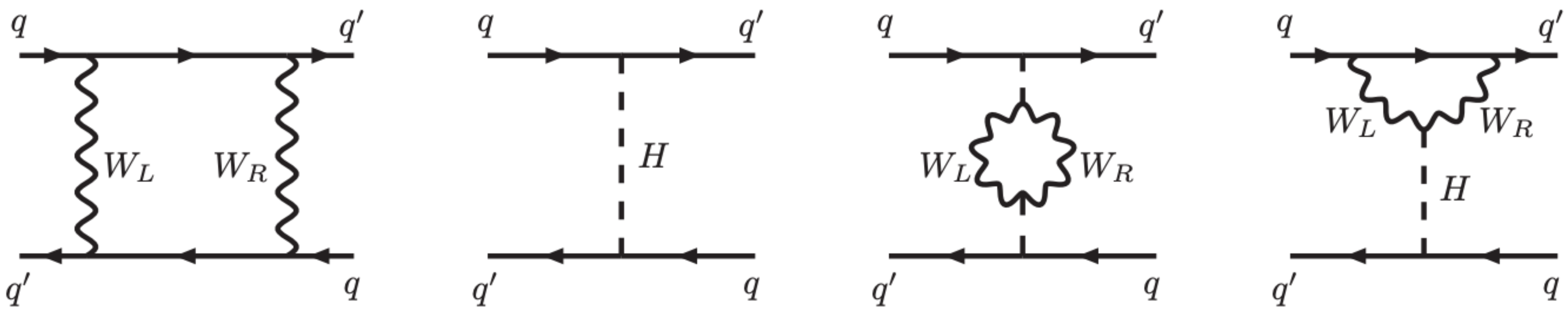


[CMS, JHEP 22']

→ Both exclude W_R mass to ~ 5.7 TeV

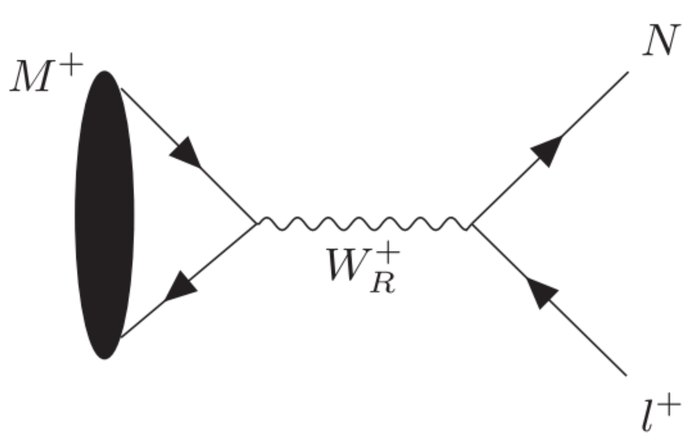
Probes: the Mesons

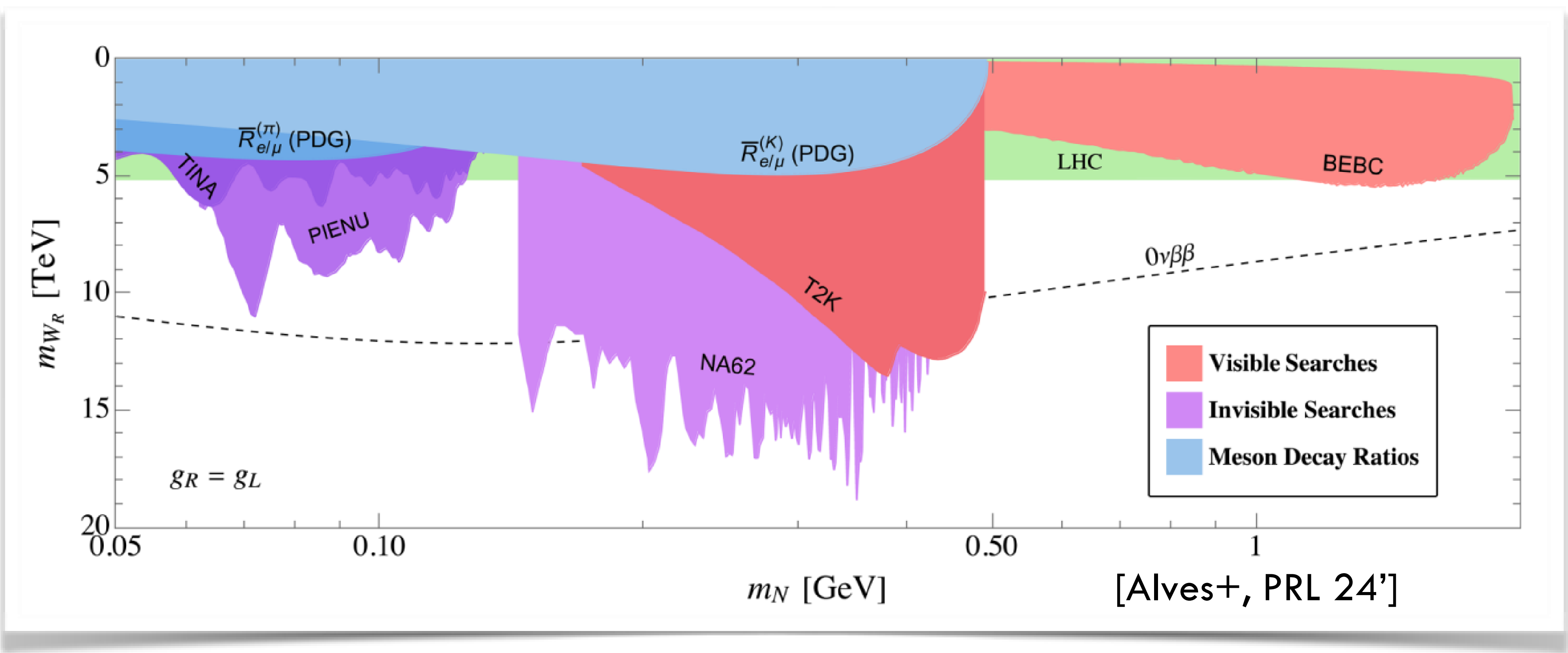
- K and B meson mixing exclude WR mass to ~ 3 TeV (for $\mathcal{C}$)



[Bertolini+, PRD 14']

- Meson decays exceed the LHC bound on certain mass regions

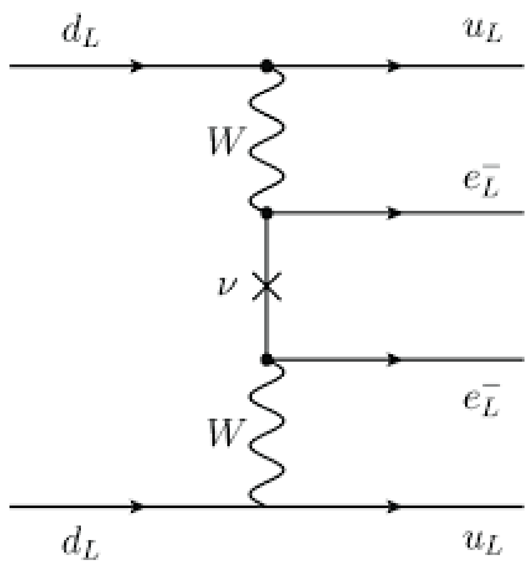




[Alves+, PRL 24']

Probes: the 0νββ

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



Current limit:

$$T_{1/2}^{0\nu} > 3.8 \times 10^{26}\ \mathrm{yr}$$

KLZ-800, 970 ton yr, ^{136}Xe

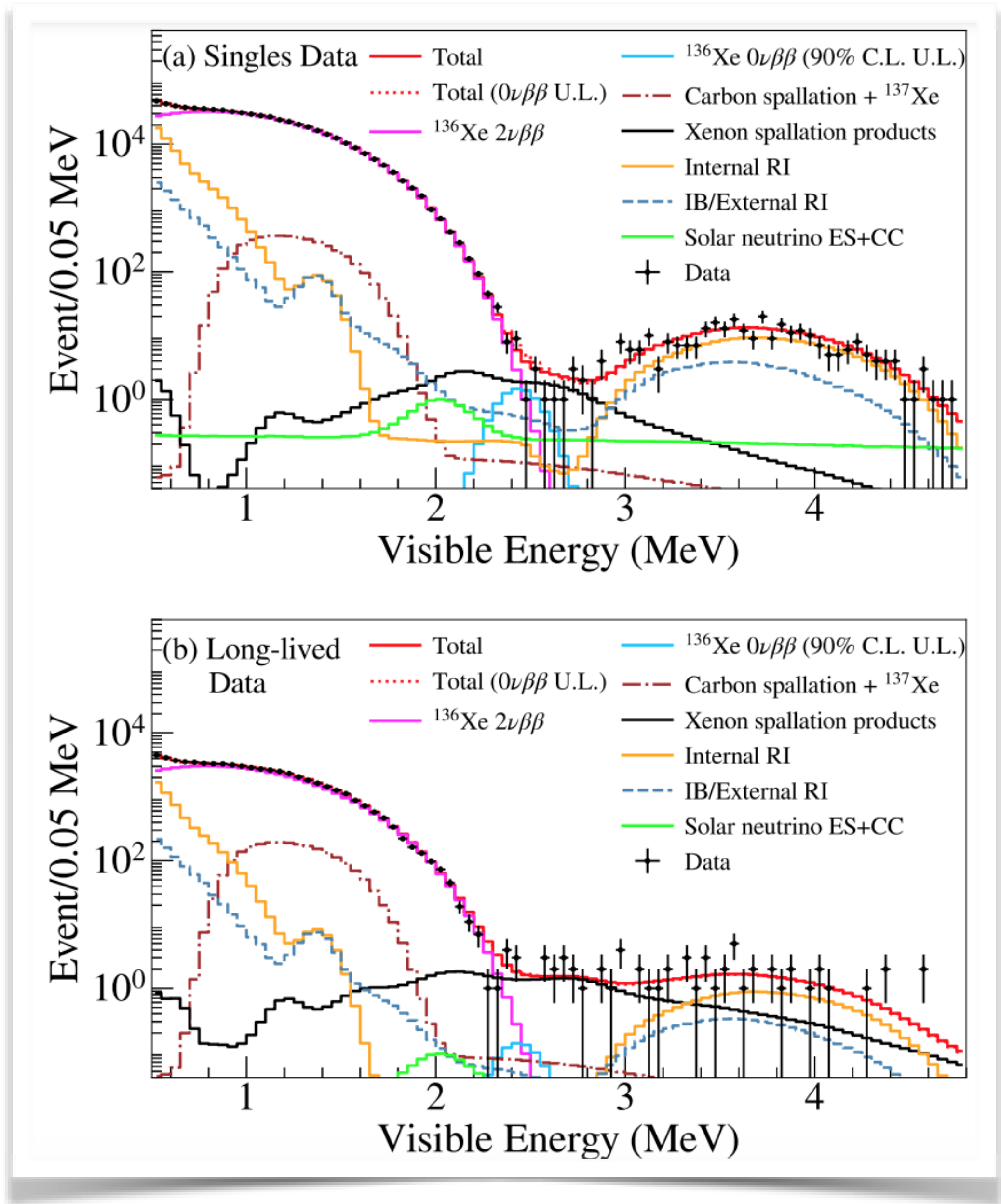
[KamLAND-Zen, 2406.11438]

Projection:

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

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

[Adams+, 2212.11099]



[KamLAND-Zen, PRL 23']

Probes: the $0\nu\beta\beta$

[de Vries+, JHEP 22']

- Half-life

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

- Partial amplitude
  - → calculation done with the advanced EFT approach

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

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

$$\mathcal{A}_R(m_i) = -\frac{m_i}{4m_e}\underbrace{\left(\mathcal{M}_V + \mathcal{M}_A\right)}_{\text{combinations of NMEs}}\underbrace{\left(C^{(6)}_{\mathrm{VRR}}\right)^2_{e(i-3)}}_{\text{Wilson coeffs.}} + \underbrace{\mathcal{A}_R^{(\nu)}(m_i)}_{\text{hard-neutrino exchange term}}\,.$$

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

[de Vries+, JHEP 22']

- 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

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

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

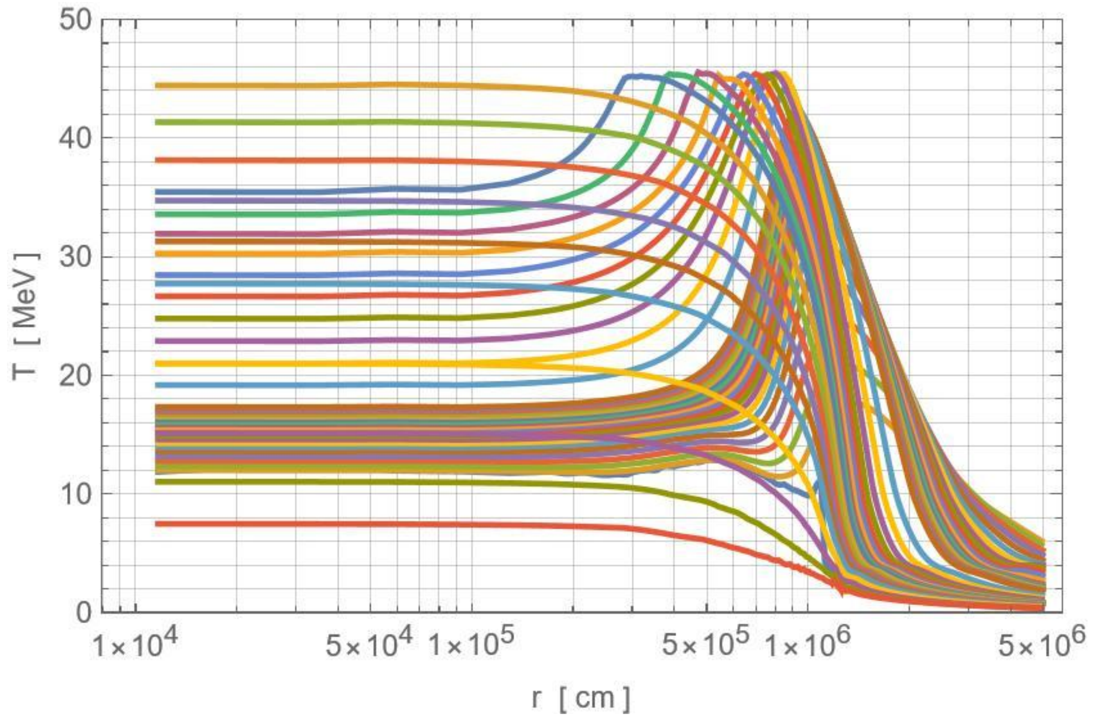
$$g_\nu^{NN}(m_i) = g_\nu^{NN}(0)\frac{1 + (m_i/\Lambda_\chi)^2}{1 + (m_i/\Lambda_\chi)^2 (m_i/m_\pi)^2}$$

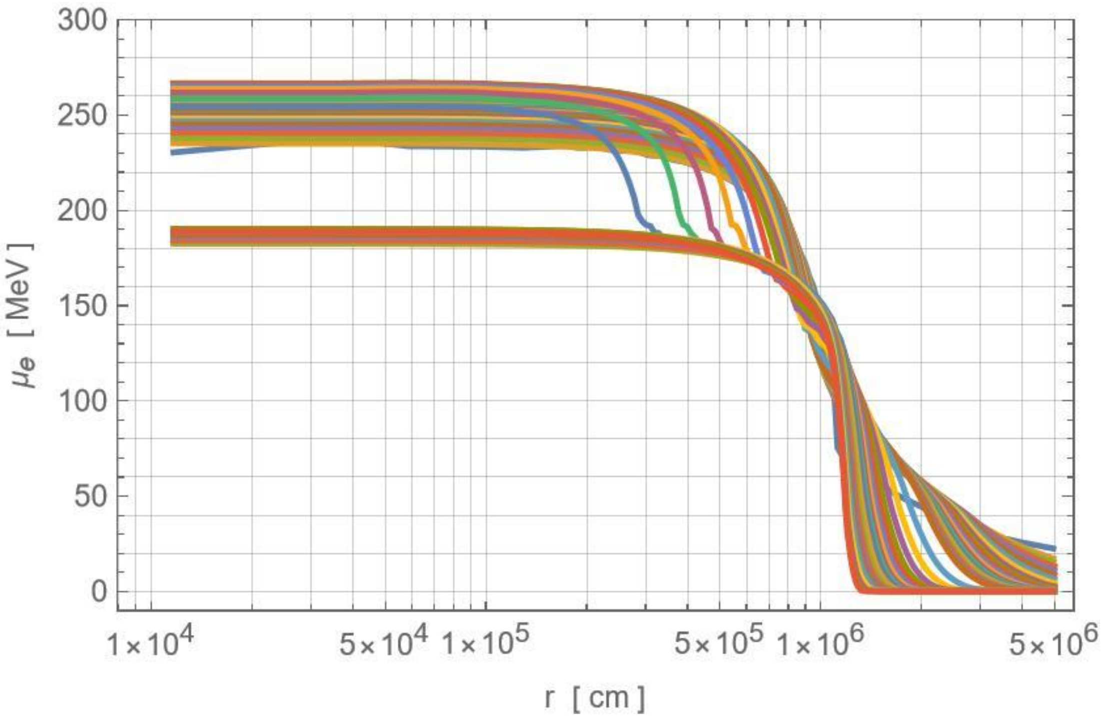
→ the EFT approach requires the inclusion of the hard-neutrino exchange term (at LO of the power counting)

→ 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



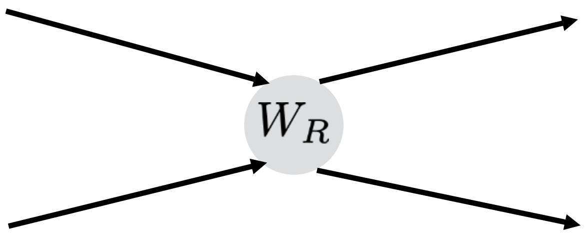


→ typical energy scale matches

→ simulation SFHo-18.6 performed by the MPA group used for our calculation

[Bollig+, PRL 20']

Probes: Supernovae



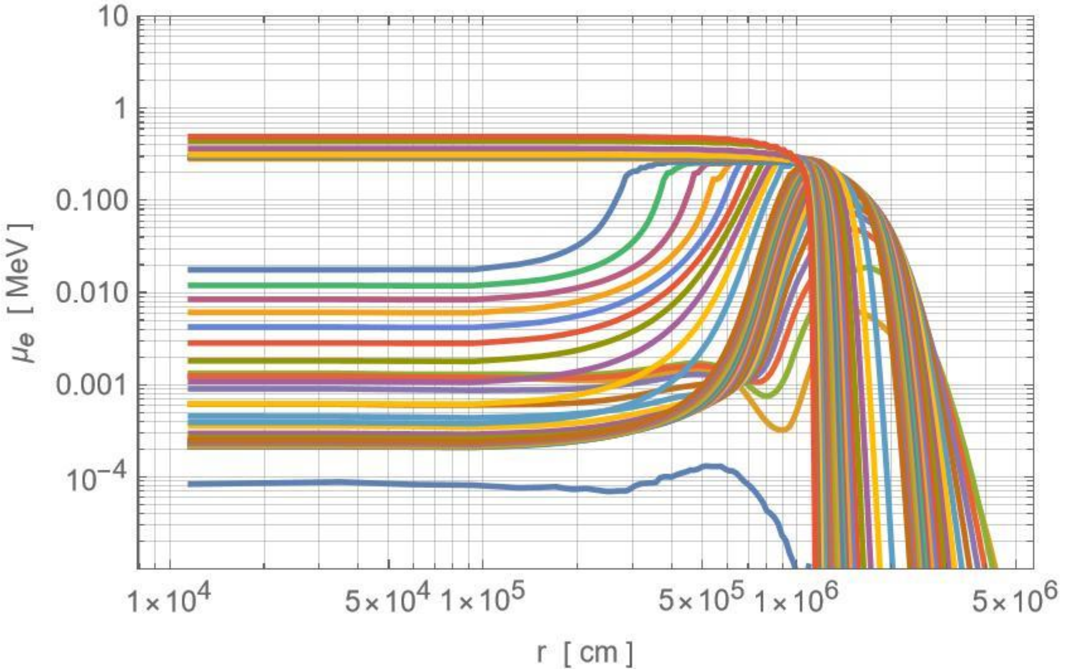
- Dominant production channel: $e + p \to \nu_4 + n$

$$\frac{d^2 n_{\nu_4}}{dE_{\nu_4} dt} \approx \int \frac{d^3 p_e}{(2\pi)^3 (2E_e)} \frac{d^3 p_p}{(2\pi)^3 (2E_p)} \frac{d^3 p_n}{(2\pi)^3 (2E_n)} \frac{p_{\nu_4}}{4\pi^2} \times (2\pi)^4 \delta^{(4)}(p_e + p_p - p_{\nu_4} - p_n) \cdot |\mathcal{M}|^2 f_e f_p (1 - f_n)$$

→ 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

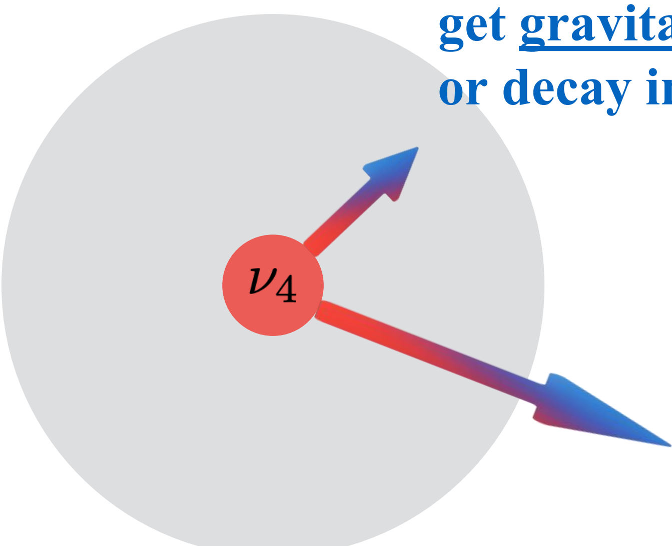


[Bollig+, PRL 20']

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

Probes: Supernovae

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



get <u>gravitationally trapped</u> or get <u>absorbed</u> or decay in the stellar envelope

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

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

$$E_{\rm depo} = \int dE_{\nu_4} dt \int_0^{R_{\rm core}} 4\pi r_{\rm prod}^2 dr_{\rm prod} \frac{d^2 n}{dE_{\nu_4} dt}$$
$$\cdot \int_{r_{\rm prod}}^{R_{\rm env}} \frac{dl}{\beta(E'_{\nu_4}(l))} \underbrace{P_{\rm srv}(E_{\nu_4}, r_{\rm prod};\, l)}_{\text{survivability}} \sum_i \underbrace{\Gamma_i(E'_{\nu_4}(l)) \cdot E'_{\nu_4}(l) f_{{\rm depo},i}}_{\text{energy deposited}}$$

energy deposited
$e^{\pm}, \nu\ (\rho > 10^{12}\,{\rm g/cm^3})$
absorption (???)
[Rembiasz+, PRD 18']

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

dissipation
(decay+absorp.)

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

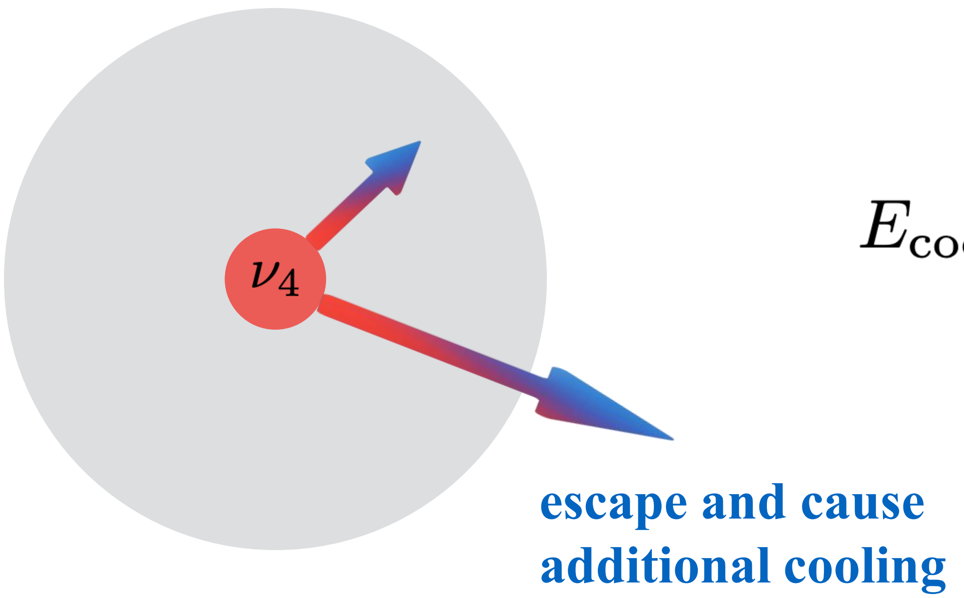
[Falk+, PLB 78'; Sung+, PRL 19'; Caputo+, PRL 22']

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

[Carenza+, PRD 24']

Probes: Supernovae

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



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

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

→ the upper limit on BSM cooling luminosity $L_{\rm BSM} \lesssim 3 \times 10^{52}\ {\rm erg/s}$

[Raffelt, Stars as laboratories for fundamental physics]

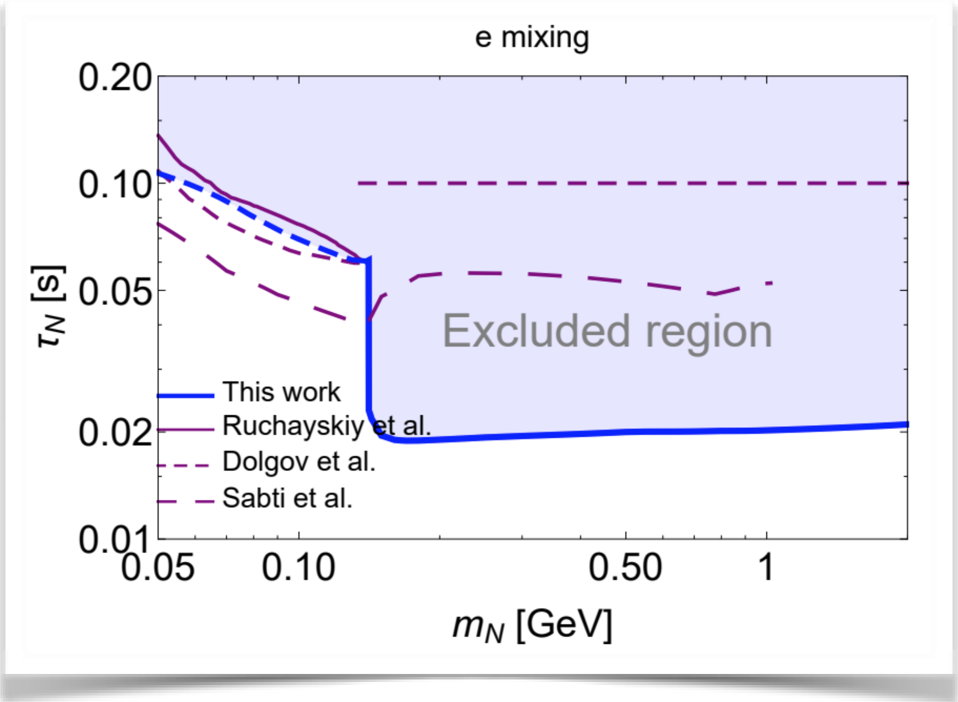
→ roughly equivalent to requiring the total dissipation less than $\sim 3 \times 10^{52}\ {\rm erg}$

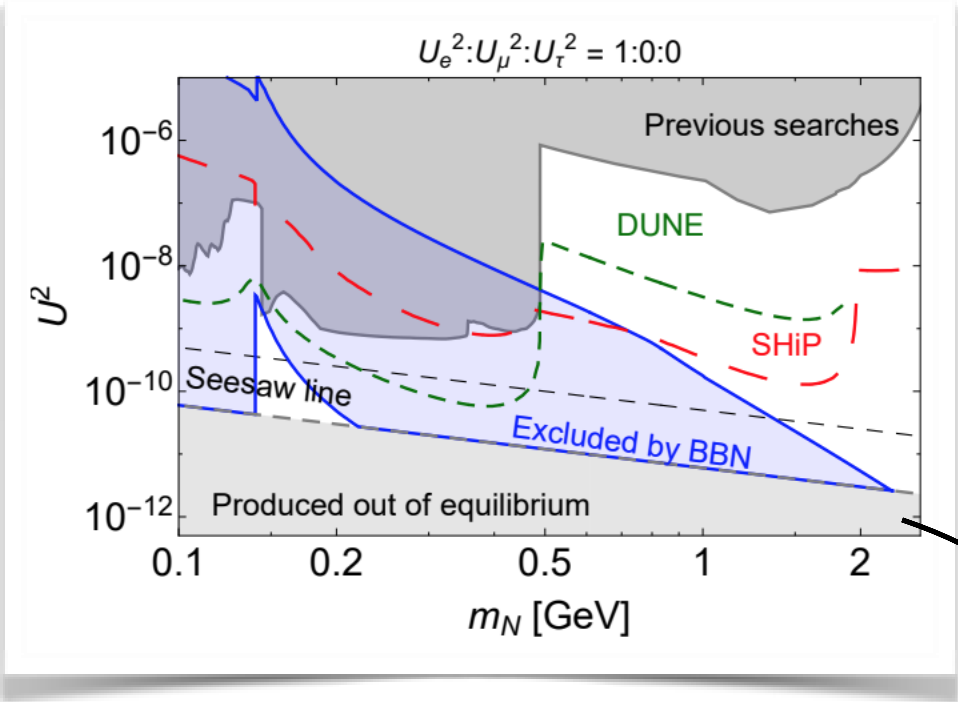
[Dreiner+, PRD 03']

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)

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

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

Probes: Cosmology

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

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

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

→ Neither does low scale freeze-in work

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

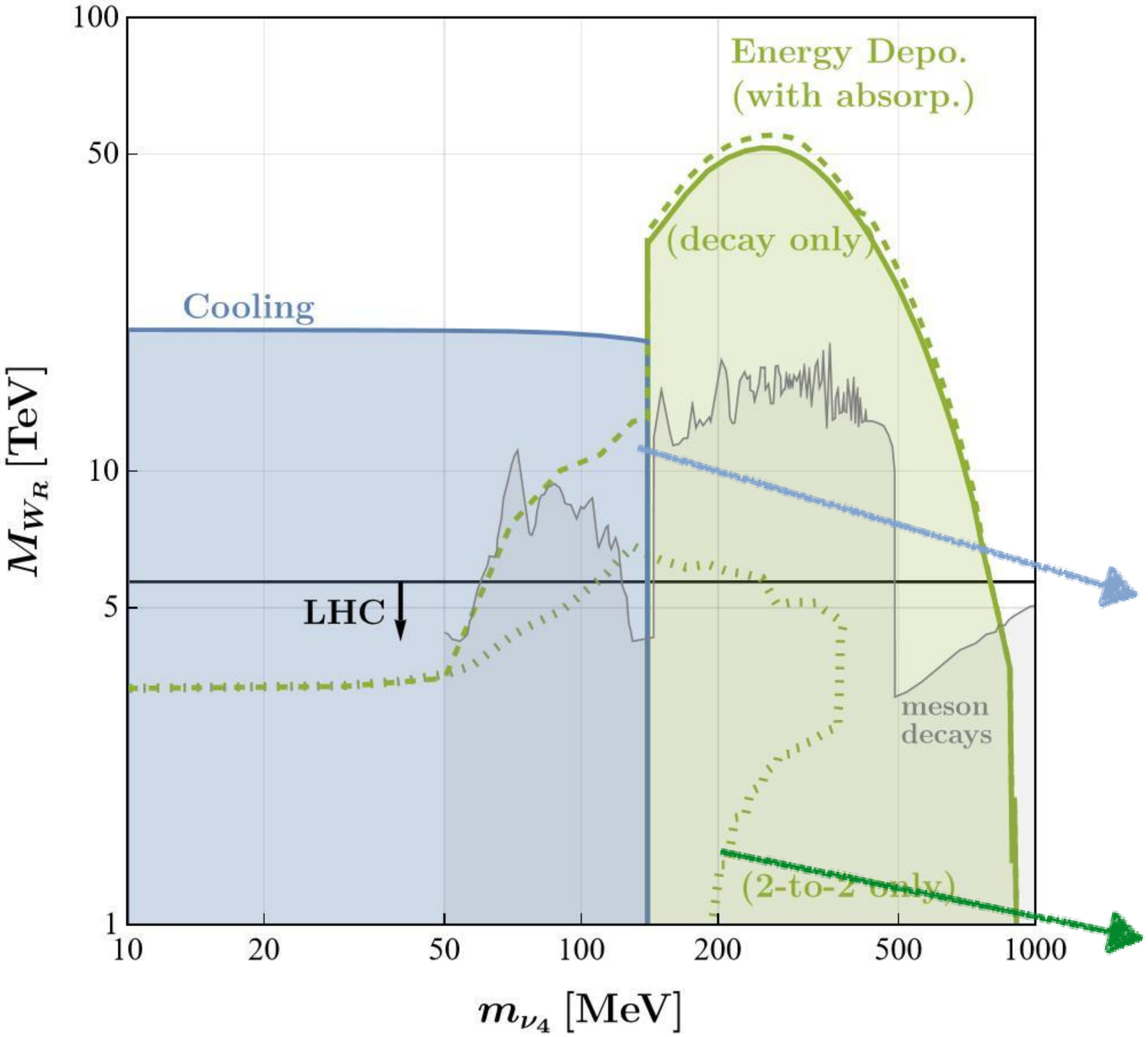
- If long-lived

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

→ 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 *0νββ* and cosmo

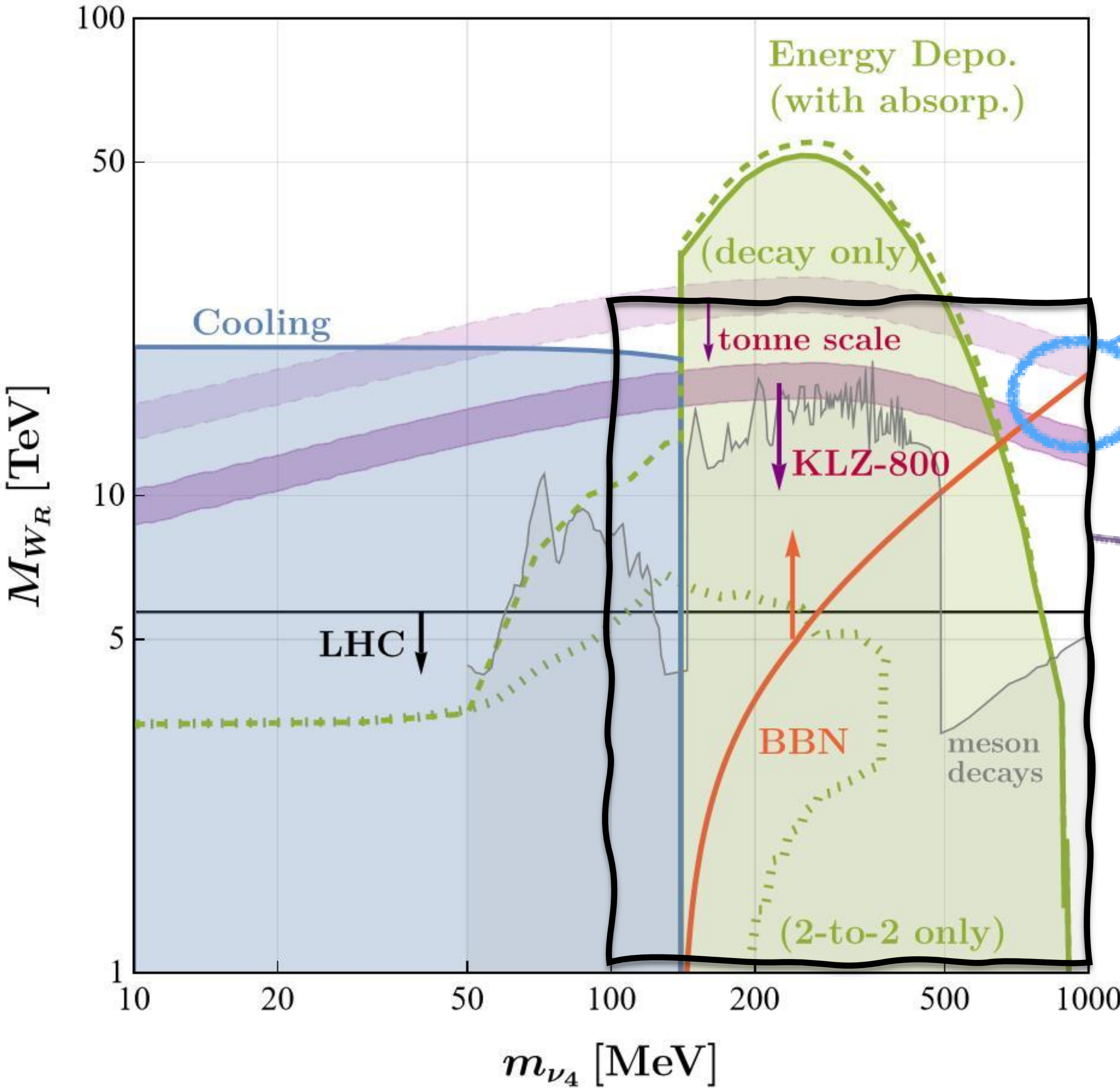
The cooling bound stops at m_π abruptly due to the opening of the hadronic decay channel

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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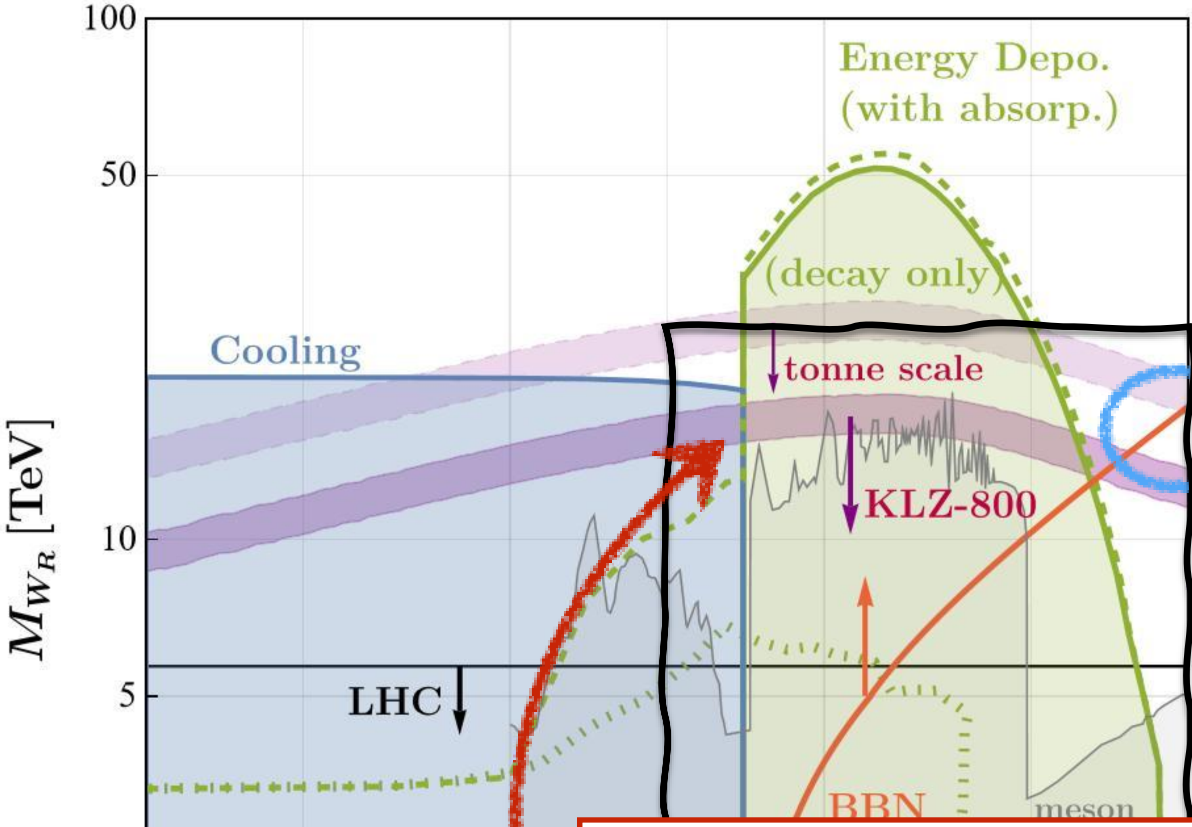
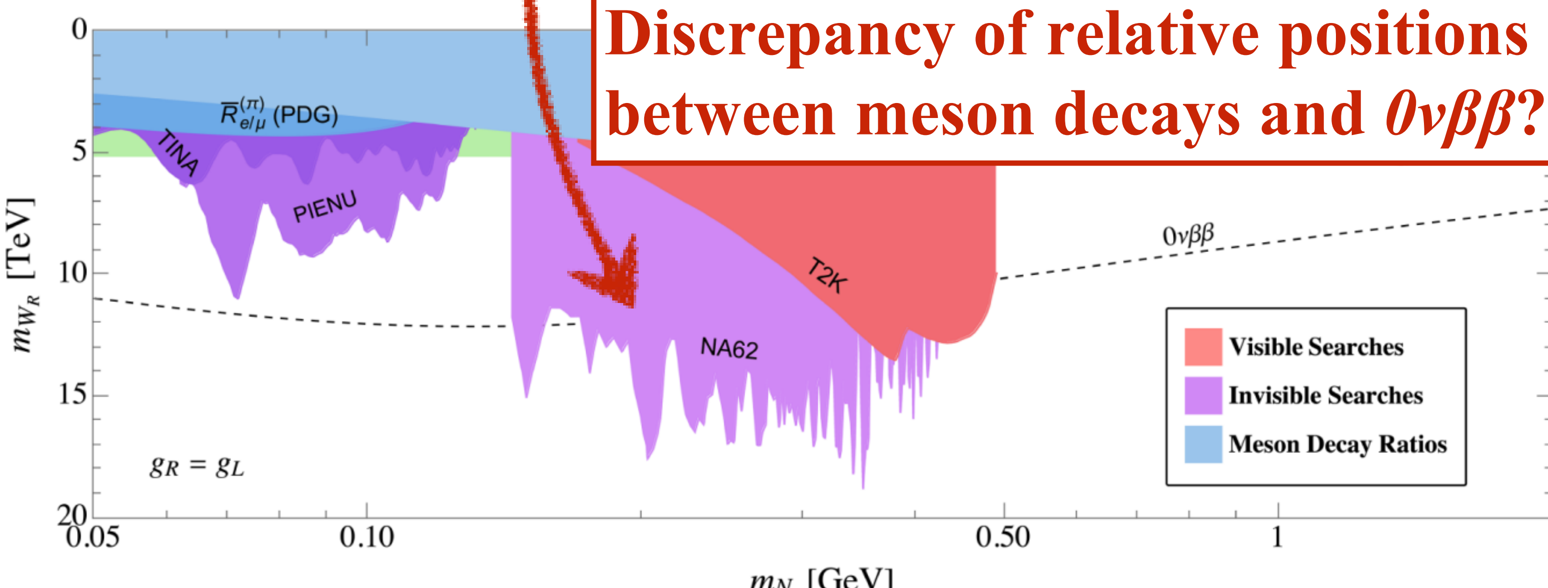


A region uniquely probed by future tonne-scale *0νββ* experiments

0νββ dominantly contributed by ν_4

Discrepancy of relative positions between meson decays and *0νββ*?



[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

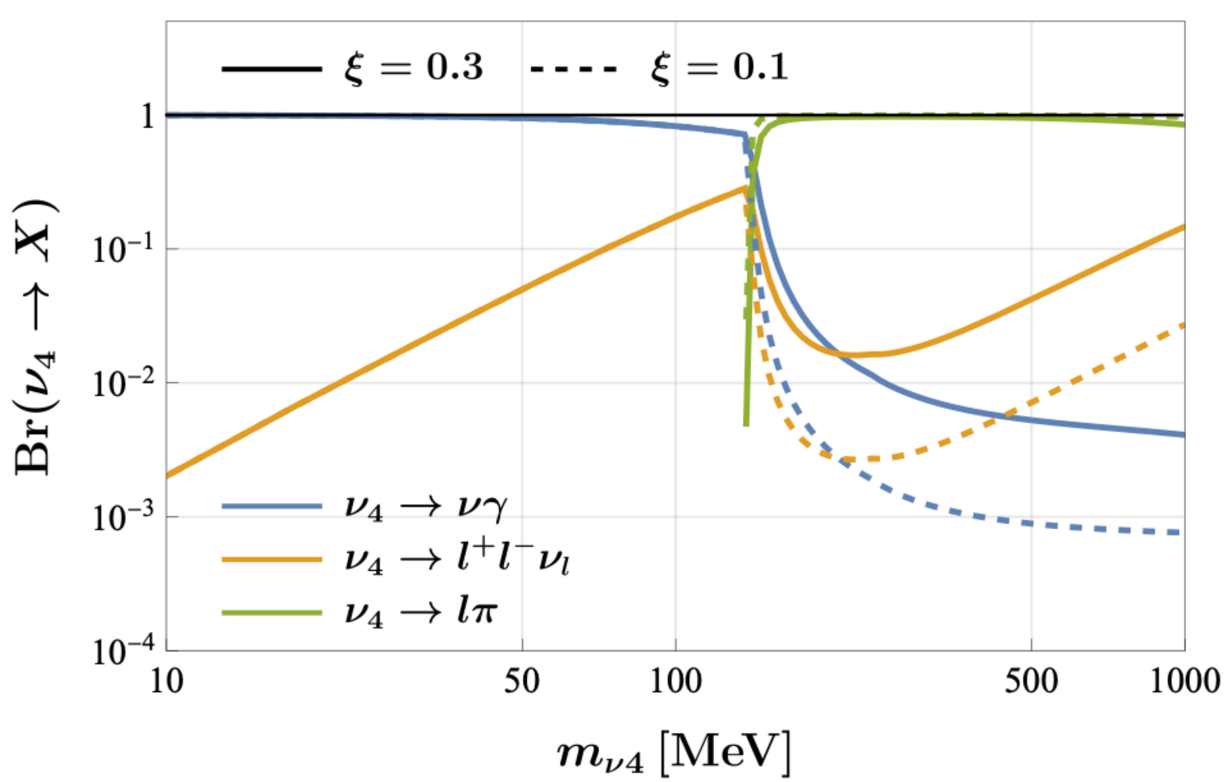
[67] A. M. Abdullahi *et al.*, J. Phys. G **50**, 020501 (2023).
[68] S. Mandal, M. Mitra, and N. Sinha, Phys. Rev. D **96**, 035023 (2017).
[69] R. M. Godbole, S. P. Maharathy, S. Mandal, M. Mitra, and N. Sinha, Phys. Rev. D **104**, 095009 (2021).
[70] G. Pantis, F. Simkovic, J. D. Vergados, and A.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

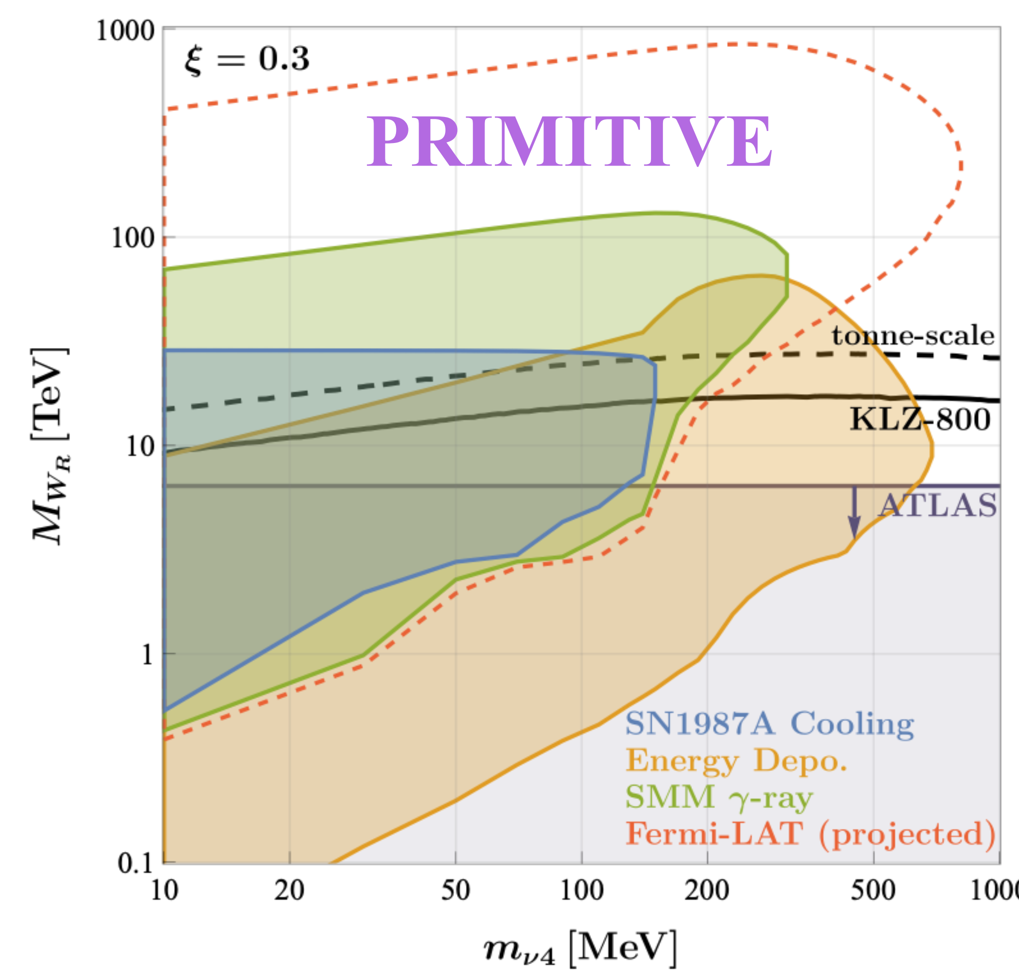
For Completeness

- Two new decay channels are opened at $\xi \neq 0$
  - $\nu_4 \to \nu\gamma$
  - $\nu_4 \to l^+ l^- \nu$

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

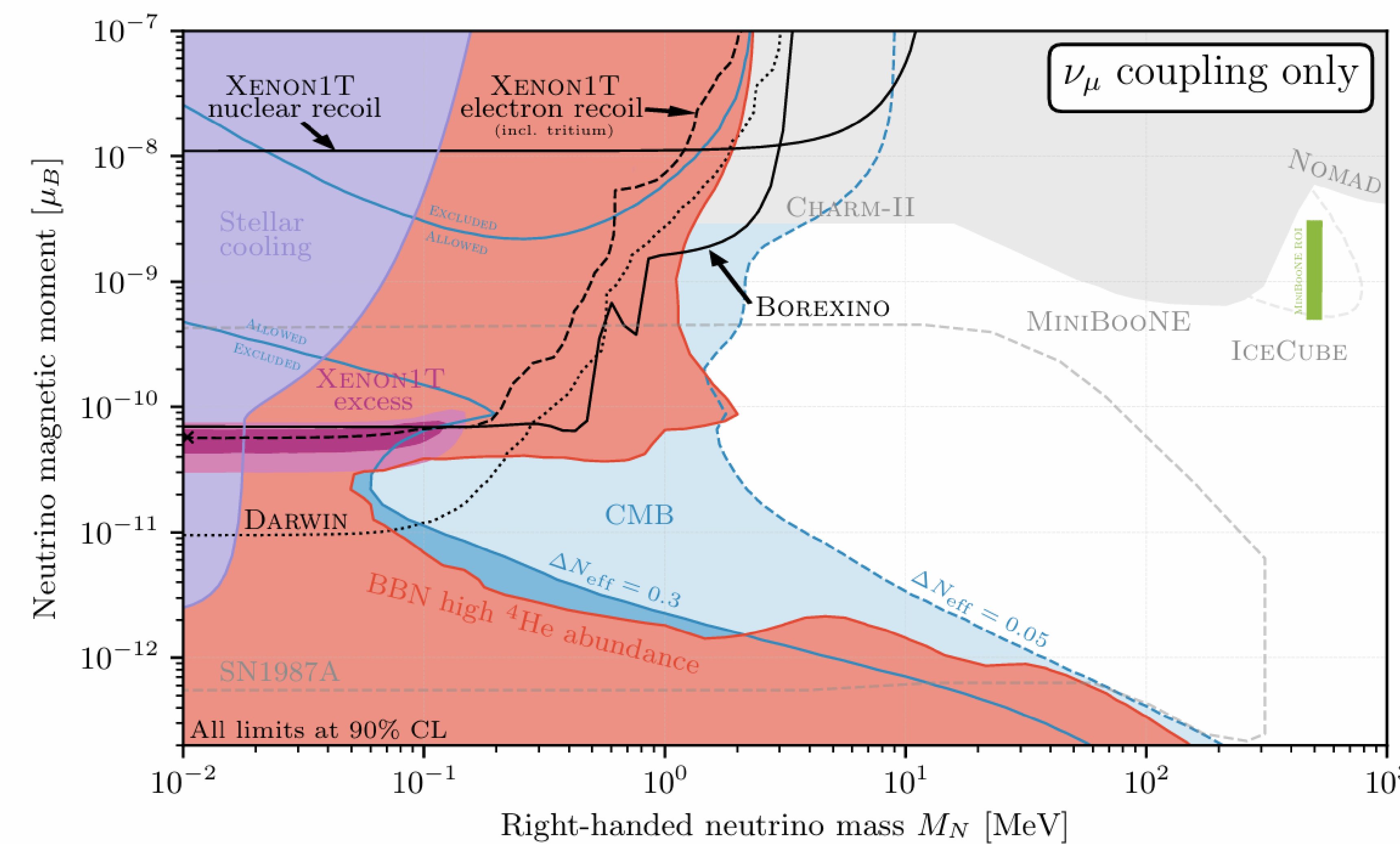
- The hadronic decay get slightly suppressed by a relative factor of $(1 - 2\xi/(1+\xi^2))^2$
- γ-ray signal at the SN, but can't constrain more





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

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

- Symmetry breaking pattern

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

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

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

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

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

$$M_\nu = M_L - M_D M_R^{-1} M_D^T$$ $M_D \to 0$ **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']

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

the sterile neutrino

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

→ 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

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

$g_L = g_R = g$

$$M^2_{W_{L,R}} = \frac{g^2_{L,R}}{4}\left(\kappa^2 + \kappa'^2 + 2v^2_{L,R}\right) \qquad \begin{pmatrix} W^\pm_L \\ W^\pm_R \end{pmatrix} = \begin{pmatrix} \cos\zeta & -\sin\zeta \\ \sin\zeta & \cos\zeta \end{pmatrix} \begin{pmatrix} W^\pm_1 \\ W^\pm_2 \end{pmatrix}$$

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

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: $\nu_4 \to \ell^\mp_j \pi^\pm$

[Bondarenko+, JHEP 18']

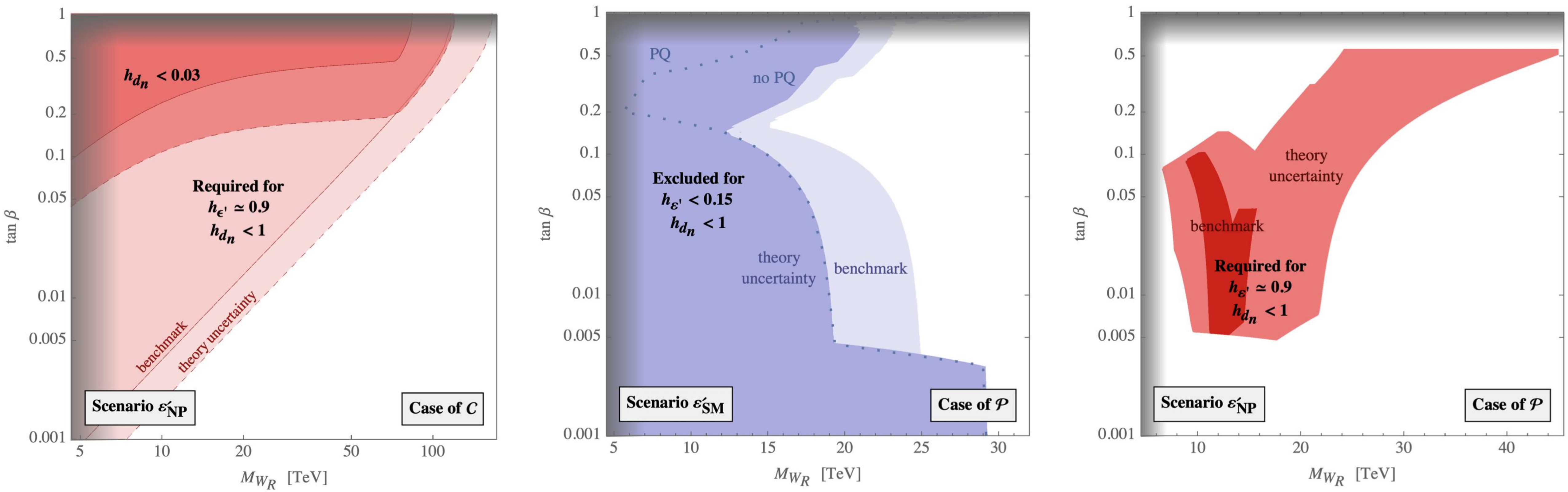
$$\Gamma_{\text{dec},0} = \frac{G_F^2 f_\pi^2 m^3_{\nu_4}}{8\pi} |V_{ud}|^2 \lambda^2 \sum_{\alpha=e,\mu} \Big\{ \theta(1 - x_\pi - x_\alpha) \cdot |(V_R)_{\alpha 1}|^2 \left[\left(1 - x_\alpha^2\right)^2 - x_\pi^2 (1 + x_\alpha^2)\right] \beta(1, x_\pi^2, x_\alpha^2) \Big\}$$

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

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

$$\dot{n}_{\nu_4} + 3Hn_{\nu_4} \approx \frac{3T}{128\pi^5}\int ds \frac{s}{2\sqrt{s}}\frac{(s-m_{\nu_4})}{2\sqrt{s}}\frac{g^4 s^2}{M_V\Gamma_V}\delta(s-M_V^2)\frac{K_1(\sqrt{s}/T)}{\sqrt{s}}$$
$$\approx \frac{3T\,g^4 M_V^4}{512\pi^5\Gamma_V}K_1\left(\frac{M_V}{T}\right),$$

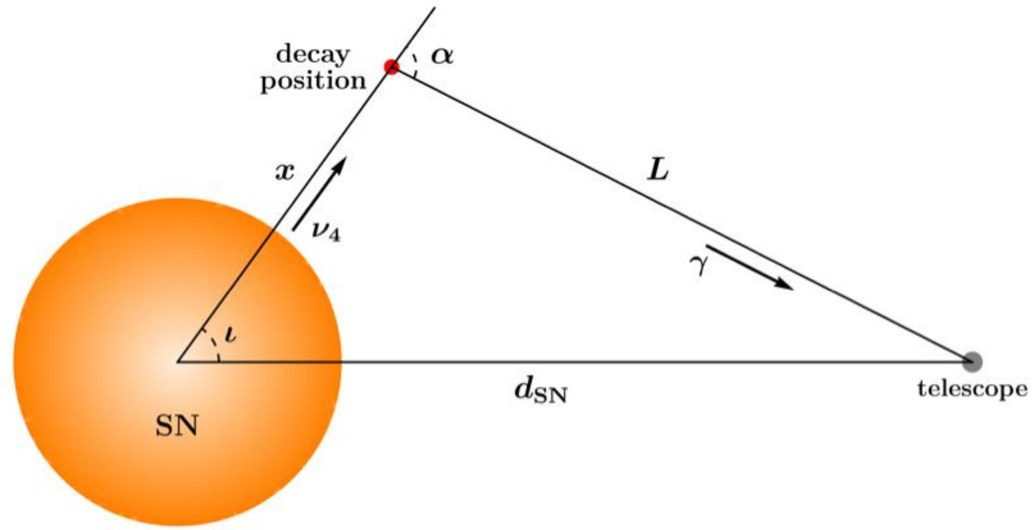
$$\frac{dY}{dT} \approx -\frac{3\,g^4 M_V^4}{512\pi^4\, sH\,\Gamma_V}K_1\left(\frac{M_V}{T}\right)$$

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

- Even for a low-scale reheating

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

Bkp: SN γ-ray



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

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

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

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