KIT – Die Forschungsuniversität in der Helmholtz-Gemeinschaft **www.kit.edu**

 $HIDDeU$ Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Large neutrino mass in cosmology: sterile neutrinos as the rescue

EuCAPT Astroneutrino Theory Workshop 2024 Prague, Czech Republic, Sept. 2024

Neutrino oscillations: • $|m_3^2 - m_1^2| \approx (2.5 \pm 0.03) \times 10^{-3} \text{ eV}^2$ $\bullet m_2^2 - m_1^2 = (7.42 \pm 0.21) \times 10^{-5} \text{ eV}^2$

Absolute mass determinations:

- beta-decay spectrum(KATRIN)
- neutrinoless double-beta decay (assuming Majorana neutrinos)
- cosmology

Neutrino masses

$$
m_{\beta} = \sqrt{\sum_{i} |U_{ei}|^2 m_i^2} < 0.45 \text{ eV}
$$

$$
m_{\beta\beta} = \left| \sum_{i} U_{ei}^2 m_i \right| \lesssim 0.07 \text{ eV}
$$

$$
\sum_{i} m_i \lesssim 0.1 \text{ eV}
$$

Neutrino mass from cosmology s. talk bertólez-Martínez

$$
\Sigma \equiv \sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m_{21}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2} \\ m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2} \end{cases}
$$

Neutrino mass from cosmology

$$
\Sigma \equiv \sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m_{21}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2} \\ m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2} \end{cases}
$$

• minimal values predicted from oscillation data for $m_0 = 0$:

$$
\Sigma_{\min} = \begin{cases} 98.6 \pm 0.85 \,\text{meV} & (\text{IO}) \, \text{--} \\ 58.5 \pm 0.48 \,\text{meV} & (\text{NO}) \, \text{--} \end{cases}
$$

Neutrino mass from cosmology

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$$

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$$
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$$

•Upper bounds from current data:

- \bullet $\sum m_{\nu}$ < 0.12 eV (95 % CL) Planck CMB+BAO 2018
- \bullet Σm_{ν} < 0.072 eV (95 % CL) DESI + CMB 2024

4 Th. Schwetz - DESY seminar, 6 June 2024

Emerging tension between cosmology and terrestrial data

Gariazzo, Mena, Schwetz, 2302.14159

Gariazzo, Mena, Schwetz, 2302.14159

possible (near-term) future scenarios:

Complementarity between mass determinations from heaven and earth

fig. by I. Esteban based on NuFit 5.0

link between neutrino mass observables *in the standard scenario*:

-
-

• What if cosmology does not see finite neutrino mass and upper bounds become tighter than the minimal value predicted by neutrino oscillation?

-
- What if terrestrial experiments see a positive signal? How could this be consistent with cosmology?

• What if cosmology does not see finite neutrino mass and upper bounds become tighter than the minimal value predicted by neutrino oscillation?

-
- What if terrestrial experiments see a positive signal? How could this be consistent with cosmology?

A seesaw model for "large" neutrino mass consistent with cosmology, including sterile neutrino dark matter

work with Miguel Escudero, Jorge Terol-Calvo, 2211.01729 Cristina Benso, Drona Vatsyayan, to appear

Sterile neutrino at which mass scale?

Sterile neutrino at which mass scale?

Cosmology bounds can be relaxed in non-standard scenarios $\frac{170000}{100000}$

- neutrino decay into dark radiation Chacko et al. 1909.05275; 2002.08401; Escudero et al., 2007.04994;
- time dependent neutrino mass Lorenz et al. 1811.01991; 2102.13618; Esteban, Salvado, 2101.05804; Sen, Smirnov, 2407.02462, 2306.15718; talk by A. Smirnov
- modified momentum distribution Cuoco et al., astro-ph/0502465; Barenboim et al., 1901.04352; Alvey, Sabti, Escudero, 2111.14870
- reduced neutrino density + dark radiation Beacom, Bell, Dodelson, 04; Farzan, Hannestad, 1510.02201; Renk, Stöcker et al., 2009.03286; Escudero, TS, Terol-Calvo, 2211.01729

Barenboim et al.,2011.01502; Chacko et al. 2112.13862: ∑*m^ν* < 0.42 eV

Cosmology bounds can be relaxed in non-standard scenarios $\frac{\mu_{\text{N}}\sigma_{\text{O}}}{\mu_{\text{O}}}}$

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Barenboim et al.,2011.01502; Chacko et al. 2112.13862: ∑*m^ν* < 0.42 eV

Counting the number of neutrino flavours detection to discriminate between cosmological scenarios. Moreover, we provide a simple rule to \mathbf{d} counting the number of Counting the number of we publicate the CNB sensitivity in a given control model. The CNB sensitivity in a given control model with t
Englished a given control model with the CNB sensitivity in a given control model. The CNB sensitivity is a giv

$N_{\rm eff}$ affects

• formation of light elements (BBN), $T \sim MeV, t \sim 1$ min global BBN analysis [5] (see also [6, 7]) obtains: Vidination of fight cicritonics (DDIV),
The reliability of the relic neutrinos in the reliance of the reliability of the reliab the Universe of the Universe o

 $N_{\text{eff}} = 2.78 \pm 0.28$ (68% CL)

\bullet CMB decoupling, T ~ eV, t ~ 400 000 yr UPD accouping, reaction reaction reaction is \bullet CMB decoupling, T \sim eV, t \sim 400 000 yr

$N_{\text{eff}} = 2.99 \pm 0.17 \, (68\% \, \text{CL})$ $PZ(GQ0ZCT)$

each other, as well as with the prediction of the standard standard

• energy density in non-relativistic neutrinos (late times)

 $\rho_{\nu}^{\text{non-rel.}} \approx n_{\nu}$ $\sum m_{\nu} < 14 \text{ eV cm}^{-3}$

• energy density in relativistic neutrinos (early times, BBN, CMB)

 $N_{\text{eff}}^{\text{relat.}} = 2.99 \pm 0.17$

Relaxing the neutrino mass bound from cosmology

Cosmology is sensitive to:

• energy density in non-relativistic neutrinos (late times)

 $\rho_{\nu}^{\text{non.rel.}} \approx n_{\nu}$ $\sum m_{\nu} < 14 \text{ eV cm}^{-3}$

• energy density in relativistic neutrinos (early times, BBN, CMB)

 $N_{\text{eff}}^{\text{relat.}} = 2.99 \pm 0.17$

Relaxing the neutrino mass bound from cosmology

Cosmology is sensitive to: The relax bound on m_ν by reducing neutrino number density

$$
N_{\rm eff}^{\rm relat.} = N_{\rm eff}^{\nu} + N_{\rm eff}^{\rm DR} \approx 3
$$

$$
\sum m_{\nu} < 0.12 \,\mathrm{eV} \left(\frac{n_{\nu}^{\mathrm{SM}}}{n_{\nu}} \right)
$$

introduce "dark radiation" to keep *N*relat. relat. \approx 3

-
-
- after BBN but before CMB decoupling

Relaxed bound from cosmology 10 eV . *T* . 100 keV. Since after neutrino decoupling

relaxing the present bo **COLIVELL** ing ne $\mathsf{c}\mathsf{s}$ farr $\overline{1}$ *<* 0*.*12 eV [95% CL] *,* (2.4) degrees of freedom: dard Model plasma, neutrinos cannot be produced any- $\frac{1}{10}$ more production of $\frac{1}{10}$ and $\frac{1}{10}$ $\frac{1}{10}$ of $\frac{1}{10}$ $\frac{1}{10}$ of $\frac{1}{10}$ $\frac{1}{10}$ $\frac{1}{10}$ of $\frac{1}{10}$ $\frac{1}{10}$ $\frac{1}{10}$ of $\frac{1}{10}$ $\frac{1}{10}$ $\frac{1}{10}$ $\frac{1}{10}$ $\frac{1}{10}$ converting neutrinos into I_{χ} generations 70 of massless fermions with g_χ internal g_χ internal relaxing the present bound by $\mathop{\mathsf{converting}}$ neutrinos into N_χ generations

$$
\sum m_{\nu} < 0.12 \,\text{eV} \left(1 + g_{\chi} N_{\chi}/6 \right) \tag{30}
$$

$\cos \theta > 10$ measoless species for $m = 1$ means \sim to measures species for m_{ν} , , then $\rm{med}\ \gtrsim 10 \ \rm{massless\, species}$ for $m_\nu \sim 1 \ \rm{eV}$ and 10^{-10}

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The mechanism operates before recombination. In the mechanism operation of the mechanism operator of the mecha

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Fecudero TS TeroLCalvo 2211 01729 (which is the sensitivity of *N* is the sensitivity of *N* \sim 7 would be a world in the sensitivity of *N* \sim 7 would be a world in the sensitivity of \sim 7 would be a world in the sensitivity of \sim 7 would be a wor Farzan, Hannestad, 1510.02201 Escudero, TS, Terol-Calvo, 2211.01729

A seesaw model for large neutrino mass and dark radiation

- 3 heavy right-handed neutrinos (seesaw)
- new abelian symmetry $U(1)_X$ local or global *U*(1)*^X*
- \bullet a scalar Φ charged under Φ charged under $U(1)_X$
- \bullet a set of N_χ massless fermions charged under N_χ massless fermions charged under $U(1)_X$

Escudero, TS, Terol-Calvo, 2211.01729

Escudero, TS, Terol-Calvo, 2211.01729 eutrinos (seesaw)

A seesaw model for large neutrino mass and dark radiation global or local,

- 3 heavy right-handed neutrinos (seesaw)
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- \bullet a scalar Φ charged under Φ charged under $U(1)_X$ • a set of *N* fermions with *U*(1)*^X* charge 1.
- \bullet a set of N_χ massless fermions charged under N_χ massless fermions charged under $U(1)_X$ \mathbb{R} s fermions charged under $I/(1)_x$ terms in the Lagrangian:

 $-\mathcal{L} = N_R Y_\nu \ell_L H^{\dagger} +$ **Yukawa sector**

1 2 $\overline{N_R} M_R N_R^c + \overline{N_R} Y_\Phi \chi_L \Phi + \text{h.c.}$ (3.1)

- 3 heavy right-handed neutrinos (seesaw) \bullet new abelian symmetry $U(1)_X$ local or global Escudero, TS, Terol-Calvo, 2211.01729 global or local, eutrinos (seesaw) lution of neutrino and dark-sector particle densities as a sector particle densities as a sector ℓ **Finded** of photon in photon temperature. For the parameters contained temperature containing the parameters cho Escudero, 15, Ierol-Calvo, 2211.01729 respectively, and $\boldsymbol{\mu}$ mass matrix for *NR*, and *Y*⌫ and *Y* are 3⇥3 and 3⇥ *N*
	- new abelian symmetry $U(1)_X$ local or global
- \bullet a scalar Φ charged under Φ charged under $U(1)_X$ • a set of *N* fermions with *U*(1)*^X* charge 1. a scalar Φ charged under $U(1)$ sen in the plot, the bound on the sum of neutrino masses $\left(\begin{smallmatrix} \cdot \end{smallmatrix}\right)$ \bullet a scalar Φ charged under $U(1)_v$
	- \bullet a set of N_χ massless fermions charged under N_χ massless fermions charged under $U(1)_X$ \mathbb{R} s fermions charged under $I/(1)_x$ terms in the Lagrangian: $\frac{1}{\sqrt{2}}$ assiess rermions charged under $U(1)_X$ ad under $II(1)$ \mathbf{r} and \mathbf{r} is negative.

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A seesaw model for large neutrino mass and dark radiation fermions (blue), and the mediator boson *X* with mass *m^X* = 1 keV (purple). For reference we show relevant events taking

Yukawa sector
$$
-\mathcal{L} = \overline{N_R} Y_{\nu} \ell_L \widetilde{H}^{\dagger} + \frac{1}{2} \overline{N_R} M_R N_R^c + \overline{N_R} Y_{\Phi} \chi_L \Phi + \text{h.c.}
$$

Scalar potential
$$
V = \mu_H^2 H^{\dagger} H + \lambda_H (H^{\dagger} H)^2 + \mu_{\Phi}^2 |\Phi|^2 + \lambda_{\Phi} |\Phi|^4 + \lambda_{H\Phi} |\Phi|^2 H^{\dagger} H
$$

- 3 heavy right-handed neutrinos (seesaw) • new abelian symmetry $U(1)_X$ local or global \bullet new abelian symmetry $U(1)_X$ local or global Escudero, TS, Terol-Calvo, 2211.01729 global or local, • 3 heavy right-handed neutrinos (seesaw) lution of neutrino and dark-sector particle densities as a sector particle densities as a sector ℓ Escudero, 15, Ierol-Calvo, 2211.01729 respectively, and $\boldsymbol{\mu}$ mass matrix for *NR*, and *Y*⌫ and *Y* are 3⇥3 and 3⇥ *N*
	-
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A seesaw model for large neutrino mass and dark radiation fermions (blue), and the mediator boson *X* with mass *m^X* = 1 keV (purple). For reference we show relevant events taking

Th. Schwetz - Prague, Sept 2024 Universe due to its interactions with the SM Higgs. Elec-

$$
-\mathcal{L} = \overline{N_R} Y_\nu \,\ell_L \,\widetilde{H}^\dagger + \frac{1}{2} \,\overline{N_R} \, M_R \, N_R^c + \overline{N_R} Y_\Phi \, \chi_L \, \Phi + \text{ h.c.}
$$

$$
V = \mu_H^2 H^\dagger H + \lambda_H \left(H^\dagger H \right)^2 + \mu_\Phi^2 |\Phi|^2 + \lambda_\Phi |\Phi|^4 + \lambda_{H\Phi} |\Phi|^2 H^\dagger H
$$

 μ ^{*u*} χ

 \mathcal{L}

and *H, , H* dimensionless. We assume *H* = 0,

Gauge interac $\mathscr{L}_{int} = g_X Z'_\mu \overline{\chi} \gamma^\mu \chi$ Gauge interaction $\mathscr{L} = \varrho$

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") which play the usual role to generate active active active active active active active active active active

A seesaw model for large neutrino mass and dark radiation • a new abelian symmetry *U*(1)*^X* which can be either rk ra \overline{d} 1 *m* $\overline{}$

- 3 heavy right-handed neutrinos (seesaw) • a scalar with *U*(1)*^X* charge +1, and
- new abelian symmetry $U(1)_X$ local or global *U*(1)*^X* **•** new abelian symmetry $U(1)_x$ local or global
- \bullet a scalar Φ charged under Φ charged under $U(1)_X$ α salar Φ charged under $U(1)_Y$ ~ 2 in eq. (3.1) in the neutral lep-induce $I^{(1)}$ **d** scalar Ψ charged under $U(1)_X$
- \bullet a set of N_χ massless fermions charged under a set of N_χ massless fermions charged under $U(1)_X$ λ \overline{I} \bullet a set of N_χ massless fermions charged under $U(1)_X$ $\hspace{1cm}$ V^{\perp} $\hspace{1cm}$ $\$

Escudero, TS, Terol-Calvo, 2211.01729 udivo,
Lidivo, $\overline{2}$ $\overline{ }$ *W* = @ *M*¹ *^R m^T ^D* 1 0 ero, IS, Ierol-Calvo, 2211.01/29 **0** *m*⁰ $\frac{1}{2}$ *M*-Calvo, 2211.

(3.1)

 Λ and the mixing pattern of Λ $\mu \ll m_D \ll m_R$ Δ introduce Δ introduce Δ $\Lambda \ll m_D \ll M_R$

 $m \sim m^2/M$ h_{active} is h_{D} and h_{E} $m = 0$ eq. (3.7), both angles are small. keep *N* flavors of massless sterile states and ✓⌫ rep $m_{\text{heavy}} \approx M_R$ $m_{\text{active}} \approx m_D^2/M_R$ $m_\chi = 0 \, , \quad \theta_{\nu \chi} \approx \Lambda/m_D$ where these relations are understood for the typical scales *m*_{heavy} \sim $m_{\text{active}} \sim m_{D} m_{R}$ $m = 0, \theta \approx \Lambda/m_D$

$$
-\mathcal{L} = \overline{N_R} Y_\nu \ell_L \widetilde{H}^{\dagger} + \frac{1}{2} \overline{N_R} M_R N_R^c + \overline{N_R} Y_{\Phi} \chi_L \Phi + \text{h.c}
$$

$$
\mathcal{M}_n = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & M_R & \Lambda \\ 0 & \Lambda^T & 0 \end{pmatrix}
$$

² *Y*⌫ and ⇤ = ^p

² *Y*. We assume the fol-

0

 $m_E = \frac{V_{EW}}{V}$ $\Lambda = \frac{V_{\Phi}}{V}$ $\sqrt{2}$ or $\sqrt{2}$ or $\sqrt{2}$ the one-flavour approximation for the active and heavy \mathbf{r} $m_D =$ *v*EW 2 Y_{ν} , $\Lambda =$ *v*Φ 2 $m_D = \frac{EW}{\sqrt{2}} Y_\nu, \quad \Lambda = \frac{\Psi}{\sqrt{2}} Y_\Phi$ *v* $\Delta = \frac{\Phi}{\sqrt{2}} Y_{\Phi}$

 $I_R^c + N_R Y_\Phi \chi_L \Phi + \text{h.c.}$

1

16 **Th. Schwetz - Prague, Sept 2024**

A seesaw model for large neutrino mass and dark radiation • a new abelian symmetry *U*(1)*^X* which can be either rk ra

- 3 heavy right-handed neutrinos (seesaw)
- new abelian symmetry $U(1)_X \rightarrow$ gauged $U(1)_X \rightarrow$
- \bullet a scalar Φ charged under Φ charged under $U(1)_X$ ralar (1) charged under $I/(1)$
- \bullet a set of N_χ massless fermions charged under N_χ massless fermions charged under $U(1)_X$ a set of N massless fermions charged under $I/(1)$. χ increases in $-\mathcal{L} = N_R Y_\nu \ell_L H$ $H^{\dagger} +$ 1 2 $\overline{N_R} \, M_R \, N_R^c$ $\chi_L \Phi + \text{h.c.}$ (3.1) $\lambda^{XX} = \sigma_{\rm v}$ \mathbb{Z}^n sensitive corrections \mathbb{Z}^n $n \nu 1/$ $\mathscr{L}_{\text{int}} = g_X Z'_{\mu}$ *^μ χγ^μ χ* couplings to neutrinos induced by mixing: *Z*′ ↔ *νν*/*νχ*/*χχ* $g_X =$ *mZ*′ $v_Φ$ *λχχ Z*′ $= g_X$ *λχν Z*′ $= g_X \theta_{\nu\chi}$ $\lambda_Z^{\nu\nu} = g_X \theta_{\nu\chi}^2$

Escudero, TS, Terol-Calvo, 2211.01729 udivo,
Lidivo, $\overline{2}$ $\overline{ }$ 0172

A seesaw model for large neutrino mass and dark radiation • a new abelian symmetry *U*(1)*^X* which can be either rk ra

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Escudero, TS, Terol-Calvo, 2211.01729 udivo,
Lidivo, $\overline{2}$ $\overline{ }$ 0172

$\chi_L \Phi + \text{h.c.}$ \blacksquare inden narams for phenor particularly sensitive to radiative corrections [48–50]. In specific **indep. params for pheno:**

(3.1)

$$
-\mathcal{L} = \overline{N_R} Y_{\nu} \ell_L \widetilde{H}^{\dagger} + \frac{1}{2} \overline{N_R} M_R N_R^c + \overline{N_R} Y_{\nu}
$$

$$
\mathcal{L}_{int} = g_X Z_{\mu}' \overline{\chi} \gamma^{\mu} \chi \qquad g_X = -\frac{1}{2} \overline{\chi} \chi \qquad \mathcal{L}_{X} = -\frac{1
$$

mZ′

v_{Φ}

m_{ν} , M_{R} , $\theta_{\nu\chi}$

v_{Φ} , $m_{Z'}$

Available parameter space

Available parameter space

Available parameter space

• thermalization of the dark sector:

 $\Rightarrow \langle \Gamma(\nu \nu \rightarrow Z') \rangle \gtrsim H(T = m_{Z'}/3)$

• avoid thermalization of the dark sector before BBN: $\langle \Gamma(\nu \nu \rightarrow Z') \rangle$ < $H(T = 0.7 \text{ MeV})$

$$
\Rightarrow \langle \Gamma(\nu \nu \rightarrow Z') \rangle \gtrsim H(T = m_{Z'}/3)
$$

Available parameter space

• thermalization of the dark sector:

- avoid thermalization of the dark sector before BBN: $\langle \Gamma(\nu \nu \rightarrow Z') \rangle$ < $H(T = 0.7 \text{ MeV})$
- **free-streaming of neutrinos & dark** radiation before/around recombination for Taule, Escudero, Garny, 2207.04062 $\langle \Gamma \rangle < H$ for $z < 10^5$

$$
\Rightarrow \langle \Gamma(\nu \nu \rightarrow Z') \rangle \gtrsim H(T = m_{Z'}/3)
$$

Available parameter space

• thermalization of the dark sector:

- avoid thermalization of χ prior neutrino decoupling due to oscillations *χ*
- \bullet take into account effective potential due to self-interactions

Neutrino mixing with massless states *θνχ*

black lines correspond to the maximum *M^R* value in GeV given by the requirement of perturbativity for *Y*, see eq. (5.3), or by 10⁻¹ upper range potentially testable in oscillation experiments constant *g^X* = *m^Z*0*/v*. We also indicate the region where standard thermal leptogenesis can work (purple shading). black lines correspond to the maximum *M^R* value in GeV given by the requirement of perturbativity for *Y*, see eq. (5.3), or by $10^{-4} < \theta < 10^{-1}$ $\frac{10}{20}$ $\frac{10}{20}$ $\frac{1}{20}$ work in progress [Escudero, Maltoni, Ota, TS] $10^{-4} \le \theta_{\nu\chi} \le 10^{-1}$

Th. Schwetz - Prague, Sept 2024 teraction between *X* particles and neutrinos and sterile the ⌫–*X* interactions are not ecient at *z <* 10⁵ there are

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The provided that provided that provided that provided that provided that provided that provided the provided

••• CMB Constraints on ^X–⌫ *interactions:* The in-

Neutrino mixing with massless states $θ_{\nu\gamma}$

see eq. (5.3) or by the requirement of *H* ¹⁰⁶ when stronger. The purple line indicates the region where *^m > v*, where the explicit breaking (ESB) of the *U*(1)*^X* symmetry by the scalar mass would dominate over the spontaneous breaking. The **Constraints on heavy RH neutrinos**

 $M_R \lesssim 10^{10} - 10^{14}$ GeV

- perturbativity of Yukawa $Y_{\Phi} \overline{N}_R \chi_L \Phi$
- loop-induced Higgs portal $\lambda_{\Phi H} |\Phi|^2 H^\dagger H$ remains small to avoid thermalization of Φ prior BBN

see eq. (5.3) or by the requirement of *H* ¹⁰⁶ when stronger. The purple line indicates the region where *^m > v*, where the explicit breaking (ESB) of the *U*(1)*^X* symmetry by the scalar mass would dominate over the spontaneous breaking. The **Constraints on heavy RH neutrinos**

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- perturbativity of Yukawa $Y_{\Phi} \overline{N}_R \chi_L \Phi$
- loop-induced Higgs portal $\lambda_{\Phi H} |\Phi|^2 H^\dagger H$ remains small to avoid thermalization of Φ prior BBN

Comment on leptogenesis:

- standard thermal LG works if $N \rightarrow HL$ dominates over $N \rightarrow \phi \chi$
- otherwise χ would thermalize and conflict with N_{eff} \Rightarrow require $T_{RH} < M_R$ (allows still for $T_{RH} \gg T_{EW}$)

• Future galactic SN at 10 kpc: neutrino signal in HyperK from $Z' \to \nu \nu$: sensitivity down to

 $\lambda_{Z'}^{\nu\nu} \sim 10^{-9} (\text{keV}/m_{Z'})$ Akita, Im, Masud, 2206.06852

$$
3 \times 10^{-7} \frac{\text{keV}}{m_{Z'}} \le \lambda_{Z'}^{\nu\nu} \le 10^{-4} \frac{\text{keV}}{m_{Z'}} \quad \text{Vitagli}
$$

 $m_{Z'} \quad \text{2209.}$

weaker than BBN constraint $\lambda_{Z'}^{\nu\nu}\lesssim 10^{-7}(\text{keV}/m_{Z'})$

Signatures in a super nova

• SN cooling arguments for SN1987A exclude

Extending the model to include keV sterile neutrino dark matter

- 3 heavy right-handed neutrinos (seesaw) *^N*
- new abelian symmetry $U(1)_X$ local or global *U*(1)*^X*
- \bullet a scalar Φ charged under Φ charged under $U(1)_X$
- \bullet a set of N_{χ} massless fermions χ charged under N_χ massless fermions χ charged under $U(1)_X$
- add one more heavy RH neutrino *N'* ⇒one of the *χ* will also pick up a seesaw induced mass → *ψ*

C. Benso, TS, D. Vatsyayan, to appear

Original model: [Escudero, TS, Terol-Calvo]

Extending the model to include keV sterile neutrino dark matter

neutral fermion mass matrix in the basis $(\chi_L^c, \nu_L^c, \psi_L^c, N', N)$

assume hierarchies: $M \gg M' \gg m_D \gg \kappa' \gg \Lambda \gg m'_D, \kappa, \Lambda'.$ $M'm_D^2 \ll M{\kappa'}^2$

$$
m_{\chi} = 0
$$

\n
$$
m_{\nu} \approx m_D M^{-1} m_D^T
$$

\n
$$
m_{\psi} \approx \kappa' M'^{-1} \kappa'^T
$$

\n
$$
m_{N'} \approx M'
$$

\n
$$
m_N \approx M.
$$

C. Benso, TS, D. Vatsyayan, to appear

Extending the model to include keV sterile neutrino dark matter

neutral fermion mass matrix in the basis $(\chi_L^c, \nu_L^c, \psi_L^c, N', N)$

assume hierarchies: $M \gg M' \gg m_D \gg \kappa' \gg \Lambda \gg m'_D, \kappa, \Lambda'.$ $M'm_D^2 \ll M{\kappa'}^2$

$$
m_{\chi} = 0
$$

\n
$$
m_{\nu} \approx m_D M^{-1} m_D^T
$$

\n
$$
m_{\psi} \approx \kappa' M'^{-1} \kappa'^T
$$

\n
$$
m_{N'} \approx M'
$$

\n
$$
m_N \approx M
$$
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keV DM candidate

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 $\begin{split} m_\chi &= 0 \\ m_\nu &\approx m_D M^{-1} m_D^T \\ m_\psi &\approx \kappa' M'^{-1} \kappa'^T \\ m_{N'} &\approx M' \end{split}$ $m_N \approx M$.

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keV DM candidate

$$
\theta_{\nu\psi} = \frac{m'_D}{\kappa'}, \quad \theta_{\chi\psi}
$$

$$
\mathscr{L}_{\text{int}} = g_X Z'_\mu \overline{\psi} \gamma
$$

mixing and interactions:

- assume
- \bullet ψ thermalizes with the dark fluid via • DM freeze-out for ψ thermalizes with the dark fluid via $\psi \psi \leftrightarrow Z'$ $T_{DS} \lesssim m_{\psi}$

$\Omega_{\psi} h^2 \simeq x_f \frac{10^{-10}\,\text{GeV}^{-2}}{\langle \sigma v \rangle_{\psi\psi \to \chi\chi}}$ $\langle \sigma v \rangle_{\psi\psi\rightarrow \chi\chi} = N_\chi \frac{g^4}{4\pi} \frac{m_\psi^2}{(m_{Z'}^2 - 4m_\psi^2)^2}$

DM production via dark freeze-out

• DM mass $15 \text{ keV} \lesssim m_{\psi} \lesssim 100 \text{ keV}$

• DM stability and X-ray constraints: , *ψ* → *νχχ ψ* → *νγ* suppressed by require θ_ν^2 *νψ θνψ* ≲ 10−⁸

Right DM abundance in the relevant parameter region

- Relaxing cosmo bound on $\sum m_\nu$ requires exciting new physics
- Presented simple seesaw model:
	- large number of massless sterile neutrinos ($N_\chi \gtrsim 10-30$)
	- dark U(1) symmetry with breaking scale between 10 MeV and 10 GeV
	- weakly coupled Z' with mass 1 100 keV with $\lambda_{Z'}^{\nu\nu} \sim 10^{-9}$
- production due to DS interactions, mixing w active neutrinos can be very small
- possible signatures:
	- galactic SN observations
	- sterile neutrino searches at oscillation experiments [work in progress w M. Escudero, T. Ota, M. Maltoni]

• keV sterile neutrino DM naturally integrated in the model [w C. Benso, D. Vatsyayan, to appear]

Summary & Outlook

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