

Probing cosmic sterile neutrino background with beta-decay experiments

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DM and neutrino around Milky Way

L. Calcada/European Southern Observatory)

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Sterile Neutrino

Motivation for sterile neutrino,

- to explain neutrino mass for explaining the oscillation of the active neutrinos

- to explain possible anomalies in the neutrino oscillation in the short baseline experiments

- to explain the asymmetry of matter-antimatter in the Universe through leptogenesis

sterile Neutrino Capture on a Beta Decaying Nucleus (NCB)

Neutrino Mass Measurement

dearly matter matter matter. In the early universe the early universe the early universe the early universe th from a relativistic bath at T ∼ 1 MeV, leading to a relic bath at T ∼ 1 MeV, leading to a relic bath at T ∼ 1
T ← 1 MeV, leading to a relic bath at T → 1 MeV, leading to a relic bath at T → 1 MeV, leading to a relic bath v Neutrino in cosmology constant and increases the distance to *z* ' 0.5–1, which is tightly eutrino in cosmology of modern cosmological observations that neutrino masses can

The only EM neutral and stable particles in SM, neutrino, is hot dark matter with small fraction. $\overline{3}$, $\overline{1}$, $\overline{2}$, $\overline{1}$, $\overline{2}$, $\overline{1}$, $\overline{2}$, • Moore profile (Moore et al., 1999), where α = $\mathsf d$ stable particles in SM, neutrino, is hot dark matter $\|\cdot\|$ sion history. With the improvement in the low-` data of this final *Planck*

Neutrinos decouple from a relativistic thermal bath at $T \sim 1$ MeV in the early Universe with a relic density today for non-relativistic ones (at least two) α decouple from a relativistic thermal bath at T~ 1 MeV in the early Universe with a relic defisity today for hon-relativistic ones (at least two) $\frac{1}{5}$. $\frac{1}{5}$ and $\frac{1}{5}$ and $\frac{1}{5}$ and Rs $\frac{1}{5}$ release, which helps break degeneracies with *A*^s and ⌧, the neuelic density today for non-relativistic ones (at least two) the smoothing of the smoothing of the temperature and polarization spectra, and polarization spectra, and polariz
The temperature and polarization spectra, and polarization spectra, and polarization spectra, and polarizati

$$
\left(\frac{T_{\nu}}{T_{\gamma}}\right)^3 = \frac{4}{11}
$$
\n
$$
\Omega_{\nu}h^2 = \frac{\sum_i m_{\nu_i}}{94eV} \ll \Omega_{DM}h^2
$$
\nIt is too small amount

$$
\ll \Omega_{DM} h^2
$$

It is too small amount! It is too small amount! definitions of light across cosmic time provide a
Time provide a time provide a time

With observational constraints $\frac{1}{2}$ generic hot date, such as axi-such as axi-s With observational constraints and the sum of the neutrino masses of the neutri-

 \setminus^3

=

4

11

$$
\sum m_{\nu} < 0.12 \text{ eV}
$$
 (95 % CL). [Planck 2018]

The fluctuations are damped if smaller than the neutrino free streaming scale \mathcal{A} and the scales where deviations where deviations where deviations \mathcal{A} eutrino free streaming scale mped if smaller than the neutrino free streaming scale

 $\lambda_{FS} \sim 20 \left(\frac{\text{30 eV}}{m}\right)$ m_ν $\sum_{i=1}^{n}$ Mpc lt is too hc top-down structure formation Mpc lt is too hot! top-down structure formation ning to be disfavoured by robust, cosmological data. $\frac{1}{2}$

Tremaine-Gunn bound (1979): minimal mass f nos world at 600 μ is around 400 μ roughly the size of supercluster. Furthermore, hot dark matter would predict a top-down hierarchy in the forma-Tremaine-Gunn bound (1979): minimal mass for fermion DM (if it is 100%) simulations density in the $\frac{1}{2}$ curs coongiles brightens 8 It is too light! is around 400 eV due to exclusion principle.

Cosmic Neutrino background (CNuB) $\overline{}$ Γ osmic Ne \mathbf{a} osmic Nei

$$
\langle v_{\nu} \rangle \simeq 1.6 \times 10^3 (1+z) \left(\frac{0.1 \,\mathrm{eV}}{m_{\nu}} \right) \,\mathrm{km/s}
$$

time scale *t*heat defined as the RHS of the entropy equa-The average kinetic energy of the neutrinos time scale *t*heat defined as the RHS of the entropy equa-*,* 10¹⁴) M, with orange, green, and red col**orally in the average kinetic energy.** and α is 2 α 1031 cm²

$$
T_{\nu} = \frac{1}{2} m_{\nu} \left\langle v_{\nu}^2 \right\rangle \simeq 1.4 \times 10^{-9} \,\text{keV} (1+z)^2 \left(\frac{0.1 \,\text{eV}}{m_{\nu}} \right)
$$

/ **Crolution of reasting 2** in the matter dominated oniverse $(1+z)^3 =$ $\int t_{\rm age}$ *t* \setminus^2 * $(1+z)^3 = \left(\frac{\mu_{\text{age}}}{4}\right)^3$ evolution of redshift z in the matter-dominated Universe

Neutrino mass from beta decay ¹¹*Institute for Nuclear and Particle Astrophysics and Nuclear Science* N autrino-mass from heta \mathbf{m}

KATRIN experiment **WITH AND AN UNPRECEDENTED SERVICE SERVICE SENSITIVE INTEGRATION CAPERIMENT** narrow energy interval around the tritium endpoint at **Exponsion of the three contracts** mass exponsion **EXAMPLANCK-INSTITUTE FOR APPRILEMENT FOR APPRILEMENT FOR FIGHT FOR FIGHT FURT FOR FIGHT FURT FOR FIGHT FUNCHEN** ⁹*Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599, USA* $VATDINL₂$ **KATRIN experiment** Karlsruhe Tritium Neutrino **E** electron energy as well as to a slight spectral shape disto be small compared to the energy resolution of KA- $VATDINLoxronim₁$ INAIIN CAPCIIIICII Karlsruhe Tritium Neutrino Experiment

2007 - 2008 Mark values of the ADO Conception of the Street States

11 Emredicted and Tritium Neutrino Experiment

 $i\% \times 10^6$ tritium ß-electrons **Energy resolution** $\Delta = 1$ Measurement campaign. : 40 eV - E0 with $\frac{1}{1}$ b $\frac{1}{10}$ such the second KBC sterile neutrino search from the second KaTRIN measurement step second K campaign in $m_{\nu} \ge 0.0 \text{ eV}$ (50% 0.2.) [Nature in sites, 2022]
2105.08533]
i $\Delta = 1 \text{ eV}$ Cone **F** Cone cameral campaign $\text{m}_V \geq 0.86$ $p_{\text{av}} = p_{\text{av}}$ in the $p_{\text{av}} = \frac{p_{\text{av}}}{p_{\text{av}} + p_{\text{c}} + p_{\text{c}} + p_{\text{c}}}}$ of the endpoint, our sterile-neutrino and the subtle sterile-neutrino and the present subsequent is respectively.
The presentive to measure the subsequent of the subsequent of the subsequent subsequent subsequent subsequen $K_{\nu} = 0.00$ $K_{\nu} = 0.00$ $K_{\nu} = 0.00$ $K_{\nu} = 0.00$ (2105.08533) 2.76×10^6 tritium β -electrons **Energy resolution** $\Delta = 1 \text{ eV}$

to light sterile de light sterile neutrinos at the extension of the extension of the extension of the extension
The extension of the exte

energy windown to 10 minutes that the tritium extending the tritium end to the tritium endpoint and the tritium endpoint at the tritium endpoint at the tritium endpoint at the tritium end of the tritium end of the tritium

w*here receive* a hombit delement in a mediation hombit in met in a subset of the received and the Pontecorrolles in the metallistic of the extension of the positive state of the extension of the positive state of the exte

 10^6 tritium β -electrons **Energy resolution** $\Delta = 1 \text{ eV}$ with of the *Zoop width of the Zoop in the South of the South of the South of the South Off* the South of (2105.08533)] Largy resolution $\Delta=1\;\mathrm{eV}$ \parallel

-decay endpoint *E*⁰ = 18*.*575 keV [45]. The sterile neutrino background peak should be

tor experiment kindled a controversial discussions and the controversial discussion in the control of the cont
The controversial discussion in the controversial discussion in the controversial discussion of the control of

 L .) [Nature Priysics, 2024]

baseline neutrino oscillation experiments, to search for

 \mathbf{z}_i

rameters that could explain the GA and the RAA, KA-

 \mathbf{r}

Cosmic Neutrino Background

Electron spectrum from Cosmic Neutrino Background (CnuB)

Beta decay spectrum Considering the energy resolution , the electron spectrum is convoluted with a Gauselectrons. The energy resolution of **i** \mathbf{r} sample of the triangle of the neutrino mass. Which is the neutrino mass is the neutrino mass in the neutrino m Considering the energy resolution , the electron spectrum is convoluted with a Gaus-Both docay spoctrum Considering the energy resolution \mathcal{L} electrons. The energy resolution of **i** \mathcal{C}^{max} resolution of \mathcal{C}^{max} e of the order of the neutrino mass of the neutrino mass \mathbf{C} and \mathbf{C} the neutrino mass \mathbf{C} Considering the energy resolution , the electron spectrum is convoluted with a Gaus-

 \overline{m} a t er convol<mark>ı</mark> *dE*0 *e* $\overline{\mathbf{A}}$ ith resolution $\Delta =$ 2² \mathbf{a} $\sqrt{2 \ln 2\sigma} \simeq 2.35\sigma$ set was of the convolution with resolution $\Delta = 2\sqrt{2\ln 2}\sigma \approx 2.5\sigma$ Ged and after convolution with **resolutio**n *dE^e* $\overline{\mathsf{O}}$ volution <mark>w</mark> *i*th *dE*0 \blacksquare
 $\Delta = 2\sqrt{2\ln 2}$ $2 \vee 2$ i
P $\simeq 2.35\sigma$ d spectrum after convolution with resolution $\Delta = 2\sqrt{2\ln 2}\sigma \simeq 2.35$ *dE^e |Uej |* cc $\Delta = 2V$. $\frac{1}{2}$ Gosci ved spectrum after convolution with reso Observed spectrum after convolution with resolution $\Delta = 2\sqrt{2\ln 2}\sigma \simeq 2.35\sigma$

$$
\frac{d\tilde{\Gamma}}{dE_e} = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{+\infty} dE'_e \frac{d\Gamma}{dE'_e} (E'_e) \exp\left[-\frac{(E'_e - E_e)^2}{2\sigma^2}\right]
$$

from the beta decay spectrum decay and the cosmic neutrino contributions. The sterile neutrino background can give a decay spectrum to the main subject in this paper. eta decay spectrum *from the* hota decay spectrum decay speculuitions. The cosmic neutrino contributions of the step sterile neutrino background can give α given background can give α from the beta decay spectrum

$$
\frac{d\Gamma_{\beta}}{dE_e}(E_e) = \sum_{j=1}^{3} |U_{ej}|^2 \frac{\bar{\sigma}}{\pi^2} H(E_e, m_{\nu_j}) N_T,
$$

 U_{ej} Pontecorvo-Maki-Nakagawa-Sakata(PMNS) matrix where \mathcal{U} is the Poisson \mathcal{U} is the Poisson Maki-Nakagawa-Sakata (PMNS) matrix \mathcal{U} U_{ej} Pontecorvo-Maki-Nakagawa-Sakata(PMNS) matrix where *Uej* is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [], ¯ is the capture Ite *y y* + 7-i *y* + Sak: $_{\text{fn}}$ *(DMNIS)* ma 1<mark>tecorvo-Mal</mark> \overline{a} *|Uej |* aka Kagawa-Sakata(PPIINS*) m*atrix \mathbf{f}

cross section of the electron neutrino defined in [18] and for neutrino defined in [18] and for non-relativiti
The electron neutrino defined in [18] and for non-relativities in [18] and for neutrino defined in [18] and fo

$$
N_T = m_T/m_{^3\text{H}}
$$

\n
$$
\bar{\sigma} \simeq \sigma_e v_\nu \simeq 3.834 \times 10^{-45} \text{ cm}^2,
$$

\n
$$
H(E_e, m_{\nu_j}) = \frac{1 - m_e^2/(E_e m_{^3\text{H}})}{(1 - 2E_e/m_{^4} + m_e^2/m_{^3\text{H}}^2)^2} \sqrt{y \left(y + \frac{2m_{\nu_j} m_{^3\text{He}}}{m_{^4}}\right)} \left[y + \frac{m_{\nu_j}}{m_{^3\text{H}}}(m_{^3\text{He}} + m_{\nu_j})\right]
$$

\n
$$
y = m_e + K_{\text{end}} - E_e
$$

$Capture$ rate of $CnuB$ *m*^H *m*³^H \mathbf{F} rate or \mathbf{C} nup

This process can happen even with non-relativistic neutrinos and their energy is converted **PTOLEMY-Like Expectrum from CnuB capture** \blacksquare using the inverse beta decay by measuring precisely the energy spectrum of the final Spectrum from Chub capture Spectrum from CnuB capture Figure 1: The expected event rate in terms of observed electron energy for sterile neutrinos $\sum_{i=1}^{n} P_i$ bectrum from Cnub captur e same with $10₁₀$ in PTOLEMY with 100 g of tritium and $10₁₀$ in PTOLEMY with 100 g of tritium and $10₁₀$ in PTOLEMY with 100 g of tritium and $10₁₀$ in PTOLEMY with 100 g of tritium and $10₁₀$

$$
\frac{d\Gamma_{C\nu B}}{dE_e} = \Gamma_{C\nu B} \,\delta[E_e - (E_{\text{end}} + 2m_\nu)],
$$

*K*end = ${\sf um\,\,after\,\,convolution\,\,energy\,\,r}$ Ohserved spectrum after convolution energy resolution Gaussian. The observed spectrum after convolution [18], Observed spectrum after convolution using benchmark values of *m^s* = 2 eV, *|Ue*4*|* $2 \times 3 \times 5 \times 5$ Observed spectrum after convolution energy resolution electrons. The energy resolution of ⇠ 0*.*15 eV is expected to be obtained with a 100 g sample of tritium, which is the order of the neutrino mass is the neutrino mass of the neutrino mass \mathbf{r}

$$
\frac{d\tilde{\Gamma}}{dE_e} = \frac{1}{\sqrt{2\pi}\sigma} \int_{-\infty}^{+\infty} dE'_e \frac{d\Gamma}{dE'_e} (E'_e) \exp\left[-\frac{(E'_e - E_e)^2}{2\sigma^2}\right] \qquad \Delta = 2\sqrt{2\ln 2}\sigma \simeq 2.35\sigma
$$

using the inverse beta decay by measuring precisely the energy spectrum of the final spec

^C⌫*^B* = 2¯*n*0*N^T ,* (10)

² ¯

Considering the energy resolution , the electron spectrum is convoluted with a Gaus-

$$
p\left[-\frac{(E_e'-E_e)^2}{2\sigma^2}\right] \qquad \Delta = 2\sqrt{2\ln 2}\sigma \simeq 2.35\sigma
$$

j=1

⇡² *^H*(*Ee, m*⌫*^j*)*N^T ,* (5)

 $F_{n_0}N_T$ for Dirac neutrino
 example 20 + 27 average neutrino density \overline{P} $\overline{$ decay and the cosmic neutrino contributions. The sterile neutrino background can give ^D *^C*⌫*^B* = ¯*n*0*N^T ,* (9) for Dirac neutrino ^M **C** neutrino *average* neutrino density der

 $\Gamma_{C\nu B}^{\text{M}}=2\bar{\sigma}n_0N_T$ *for Majorana neutrino* PTOLEMY-like experiment [17] has been proposed to probe the background neutrinos $\Gamma_{C\cup B}^{\text{M}} = 2 \bar{\sigma} n_0 N_T$ for Maiorana neutrino $n_0 = 56 \, \text{cm}^{-3}$ assumed that clustering effects for the neutrino is negligible and also used the unitarity of unitarity of unitarity of \mathcal{L}_1 where *^d dE*0 *e* $\mathsf{neutrino}$ and the sterile neutrino background can give $\mathsf{neutrino}$

² = 1.

be smaller than half of the neutrino mass, . *m*⌫*/*2.

3

cross section of the electron neutrino defined in formal in formal in \mathcal{I}_1 and for \mathcal{I}_2 and \mathcal{I}_3

d

ⁱ |Uei|

with the cosmological average of the neutrino number density *n*⁰ = 56 cm3. Here we

the blue solid line for the inverse beta decay of background neutrino. To distinguish the inverse between the
To distinguish the inverse between the inverse between the inverse between the inverse between the inverse betw

sian envelope of FWHM = 2^p

² = 1.

² = 1.

^M

the PMNS matrix P

additional contribution to the main subject in the main subject in this paper. Which will be the main subject i
This paper. Which will be the main subject in this paper. Which will be the main subject in this paper. Which $n_0 = 56 \text{ cm}^{-3}$

The beta decay spectrum is given by the beta decay spectrum is given by the beta decay spectrum is given by th
The beta decay spectrum is given by the beta decay spectrum is given by the beta decay spectrum is given by th

Energy resolution $\Delta \sim 0.15 \text{ eV}$ using hydrogenated graphene sample of tritium, which is the order of the neutrino mass. (*Ee*) = ^X *j*=1 $\frac{15 \text{ eV}}{25 \text{ eV}}$ *ising hydrogenated graphene* where *Uej* is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [], ¯ is the capture \blacktriangle Energy resolution $\blacktriangle \sim 0.15 \text{ eV}$ using hydrogen assumed that clustering effects for the neutrino is neutrino is neutrino is negligible and also used the unitarity of used the unitari **I** Energy resolution $\Delta \sim 0.15$ eV using hydrogenated graphene In Fig. 1, the expected event rate is shown with the dotted line for the beta decay and the blue solid line for the inverse beta decay of background neutrino. To distinguish the \mathbf{r} signal of the neutrino capture from the tritium beta decay, the energy resolution \mathbf{r} [PTOLEMY, 1808.01892] *d dE^e* (*Ee*) = ^X *|Uej |*

with 100 g of Tritium

Expected event rates with PTOLEMY [PTOLEMY, 2019] 1902.05508

dotted: assuming perfect energy resolution solid: total with assumed energy resolution

Sterile Neutrino Dark Matter

Neutrino Minimal Standard Model (nuMSM) N_{in} type- M_{in} is defined by adding adding M_{in} . M_{in} **fermions with RH chiral stations of the SM (That 1917)** The type-I seesaw model is defined by adding *n* RH neutrinos ⌫*^R* to the SM, i.e., singlet Noutring Minimal **The isomeone is defined by an American SM, i.e., singlet by an american point of** \mathbb{F}_2 autring Minimal Standard Model (nuMSM) a Majorana mass term ⌫*Lm*⌫⌫*^c ^L*, with *m*⌫ is given by as obtained by integrating out the fields ⌫*^R* instead of (1.25). The Higgs mechanism generates **Neutrino Minimal Standard Model (nuMSM)** large. One usually defines the right-chiral component of a sterile neutrino field as ⌫*R*, i.e., ⌫*^R* \mathcal{T}_{max}

[Asaka, Blanchet, Shaposhnikov, 2005] $(\nu_R)^c \equiv C \, \overline{\nu_R}^T$ fermions with RH chirality to the SM that couple to the SM neutrinos ⌫*^L* in the same way

e.g. [67, 159]. There are several scenarios that predict eigenvalues of *M^M* at or below the

The CP-conjugate (⌫*L*)*^c* ⌘ *^C* ⌫*^L*

$$
\mathcal{L} = \mathcal{L}_{\text{SM}} + i \overline{\nu_R} \phi \nu_R - \overline{\ell_L} F \nu_R \tilde{\Phi} - \tilde{\Phi}^\dagger \overline{\nu_R} F^\dagger \ell_L - \frac{1}{2} (\overline{\nu_R^c} M_M \nu_R + \overline{\nu_R} M_M^\dagger \nu_R^c).
$$
\n
$$
\downarrow
$$
\n
$$
\
$$

Throo DH noutrings with Majorana mass and *Vulcawa souplings* a specific realization of the term individually realized that the eigenvalue of the eigenvalues $\frac{1}{2}$ After electroweak symmetry breaking, the mass term Three RH neutrinos with Majorana mass and Yukawa couplings. After electroweak symmetry breaking, the mass term *M* M are far above the electroweak scale. The electroweak scale is the experimental scale of α section 6. The full neutrino mass term after extending reads to the contribution of the symmetry breaking read
In the case of the contribution of the contribution of the contribution of the contribution of the contributio r electroweak symmetry breaking, the mass term right-chiral antineutrinos is number of right chiral neutrinos is under the number of right chiral neutrinos i be and randiva evapings. Three RH neutrinos with Majorana mass and Yukawa couplings.

electroweak scale, including the inverse seesaw $\frac{1}{2}$ and linear seesaw $\frac{1}{2}$

$$
\frac{1}{2}(\overline{\nu_L} \ \overline{\nu_R^c}) \left(\begin{array}{cc} 0 & m_D \\ m_D^T & M_M \end{array}\right) \left(\begin{array}{c} \nu_L^c \\ \nu_R \end{array}\right) + h.c.,
$$

as obtained by $m_D = r v \ll m_M$ gives mess eigenvelues with The hierarchy $\;m_D\equiv Fv\ll M_M\;$ gives mass eigenvalues with where *m^D* ⌘ *F v* and *v* = 174 is the Higgs field vacuum expectation value. For *M^I* 1 eV The hierarchy $\;m_D \equiv Fv \ll M_M\;$ gives mass eigenvalues with *L^D* = *m^D* (⌫*L*⌫*^R* + ⌫*R*⌫*L*)*,* (1.20)

three light active neutrinos and three heavy sterile neutrinos. three light active neutrinos and three heavy sterile neutrinos. number *L*, but violates weak isospin by 1*/*2 unit. It can be generated by the Higgs mechanism, (See-saw mechanism)

$$
\Theta = m_D M_{\nu_R}^{-1} \ll 1,
$$

and the light active neutrino mass

$$
m_{\nu}\simeq -m_{D}\frac{1}{M_{\nu_{R}}}m_{D}^{T}=-\Theta M_{\nu_{R}}\Theta^{T}.\quad \text{ seesaw mechanism}
$$

Interaction of RH Neutrino

RH sterile neutrinos can interact with SM sector through a_n ith CMA postor through observed neutrino oscillations $\overline{\mathbf{C}}$. For $\overline{\mathbf{C}}$ the parametrization of $\overline{\mathbf{C}}$

- Mass mixing after electroweak symmetry breaking $\qquad \qquad \mid \Theta = m_D M_{\nu_R}^{-1} \ll 1,$
- Yukawa interaction with Higgs and LH neutrino $\int y_{\nu\alpha i} \frac{v}{\sqrt{2}} = i U (m_\nu^{\rm diag})^{1/2} \Omega(M_{\nu_R})$

The interaction induces

- Decay of sterile neutrinos into SM neutrino and photon (X-ray) on the DM mass. \mathbf{I} $\frac{1}{\sqrt{2}}$ 0.000 $\frac{1}{\sqrt{2}}$

$$
\nu_s \to 3\nu \qquad \qquad \nu_s \to \nu + \gamma
$$

$$
\mathbf{g} \qquad \qquad \Theta = m_D M_{\nu_R}^{-1} \ll 1,
$$

$$
y_{\nu \alpha i} \frac{v}{\sqrt{2}} = iU (m_{\nu}^{\text{diag}})^{1/2} \Omega (M_{\nu_R})^{1/2},
$$

with ! being a complex parameter. If the imaginary values for the complex orthogonal matrix are large, the components of Yukawa couplings (10) and mixings (7) can be enhanced

 $\overline{}$

 $v_{\rm s} \rightarrow \nu + \gamma$

Cosmic Sterile Neutrino Background

aggressive limits in the aggressive limits \mathbb{N} Now, Sterile neutrino 100% DM is ruled out?

Sterile neutrino DM in nuMSM Sterile neutrino DM in nuMSM **The Milky Way was counted the free streaming counts counts counts counts counts counts counts counts counts co** rile ı sin θ $|UU|$ $|UU|$ in nuMSM

To explain the two mass differences in the neutrino observations, two RH neutrinos are enough. The third RH neutrino, the lightest one around keV, can be DM candidate. two RH neutrinos are enough. The third RH neutrino, the lighte:

[Dodelson, Widrow, 1994] [Dolgov, Hansen, 2002] [Asaka, Blanchet, Shaposhnikov, 2005] rest, som being some other form. A 10% to 20% fraction of Dodelson–Widerson–Widerson–Widerson–Widerson–Widerson–Wid
The 3.57 keV signal, and produce the 3.55 keV signal, and produce the 3.55 keV signal, and produce the 3.5 with angle is commentations is commensurately approximately approximately α are are suppressed by the suppressed by the mixing angles of the mixing angles, since the mixing angles of the
2000 FD . It is that the see tha [Dodelson, vvidrow, 1994] [Dolgov, Hansen, 2002] [Asaka, Blanchet, Shaposi

Production of DM of a freeze-out ² .

ction of DM soscillation from active neutrinos alleviate small-scale structure challenges [130].
Alleviate structure challenges [130].

- Dodelson-Widrow mechanism (Non-resonant production)

In the relevant range of parameters, one can relevant range of parameters, one can roughly approximate the numerical results for α

$$
\Omega_s \sim 0.2 \left(\frac{\sin^2 \theta}{3 \times 10^{-9}} \right) \left(\frac{m_s}{3 \,\text{keV}} \right)^{1.8}
$$

- Shi-Fuller (Resonant production) with lepton asymmetry

$$
\begin{array}{ll}\n\text{Decay rate of DM} & \nu_s \rightarrow 3\nu \\
\frac{\Gamma_\gamma(m_s, \sin^2 2\theta) \approx 1.36 \times 10^{-30} \,\mathrm{s}^{-1}}{\left(\frac{\sin^2 2\theta}{10^{-7}}\right) \left(\frac{m_s}{1 \,\mathrm{keV}}\right)^5},\n\end{array}
$$

Production of sterile neutrino \blacksquare all or part of the dark matter. In this mechanism, the sterile neutrinos are produced when \mathcal{L}_max $\ln a$ denoting matter. In this mechanism, the sterile neutrinos are produced when $\ln a$ the active neutrinos are in thermal equilibrium (*T* MeV). The Boltzmann equation for \sum_{x} and \sum_{y} as \sum_{y}^{x} as \sum_{y}^{y} as \sum_{y}^{y} **F**roduction of sterile neutrino

@*fs*(*E, t*) e *quation*

Boltzmann equation **of the evolution** of the step of t the active neutrinos are in the active neutrinos are in the Boltzmann equation for the ⁴ sin2(2✓*M*)↵(*f*↵ *^fs*) (28) ⁴ sin2(2✓*M*)↵(*f*↵ *^fs*) (28) *dT T* [Abazajian, Fuller, Pate, 2001]

. (30)

IDENTIFY	Equation
$\frac{\partial f_s(E,t)}{\partial t} - HE \frac{\partial f_s(E,t)}{\partial E} = \frac{1}{4} \sin^2(2\theta_M) \Gamma_\alpha (f_\alpha - f_s)$	

with mixing angle in the matter and the interaction rate with thermal particle freedom of the relativistic particles in the thermal equilibrium. Here, the effective mixing with mixing angle in the matter and the interaction rate with thermal particles atter al raction rate ! V ↵*dT.* (33)

$$
\sin^2(2\theta_M) = \frac{\sin^2(2\theta)}{\sin^2(2\theta) + [\cos(2\theta) - 2E V_T(T)/m_s^2]^2}, \qquad \Gamma_\alpha \approx 1.27 \times G_F^2 T^4 E,
$$

 \mathbf{z} $\text{partial in matter} \quad V_T = -BT^4E, \quad \text{and} \quad \Delta$ $B \sim \begin{cases} 10.88 \times 10^{-9} \text{ GeV}^{-4} & T > 2m_e, 0.2$ (¹⁰*.*⁸⁸ ⇥ ¹⁰⁹ GeV⁴ *T >* ²*m^e* $\frac{1}{2}$ $\frac{211}{e}$ $V_T = -BT^4E$, and $B \sim$ $\int 10.88 \times 10^{-9} \text{ GeV}^{-4}$ $T > 2m_e$ $3.04 \times 10^{-9} \text{ GeV}^{-4}$ *T* < $2m_e$ potential in matter neutrinos mixing is small enough. Here, we count *g*⇤ of the thermal particles in the standard moterial is seetter V $DT^{4}E$ and D 10.88×10^{-9} GeV⁻⁴ $T > 2m_e$ potential in matter r_I by L , $\frac{1}{2}$ and L $\frac{1}{2}$ $\frac{1}{3.04 \times 10^{-9} \text{ GeV}^{-4}}$ T .

 \sim The maximum production rate happens at

$$
T_{\text{max}} \simeq 108 \text{ MeV} \left(\frac{m_s}{\text{keV}}\right)^{1/3}
$$

25 Ki-Young Choi, Sungkyunkwan University, Korea

³*.*⁰⁴ ⇥ ¹⁰⁹ GeV⁴ *T <* ²*m^e*

However, sterile neutrino as small fraction of DM is still viable!

- Reduced constraints from X-ray observation
- Smaller mass is also viable, safe from the structure formation
- CMB constraints can be reduced

We focus on eV - 100 eV sterile neutrino with fraction less than 10% of DM energy density

Electron peak spectrum from CSNuB EIECLI'ON PEAK SPECLI'UM II'OM CONUD

 \overline{a} \overline{b} \overline{c} $\overline{c$ $\frac{1}{\sqrt{1-\frac{1$ $\Delta \sim 0.15 \text{ eV}$ with 100 g of Tritium

Local density of sterile neutrinos due to gravitational clustering on the production models and the evolution of the early Universe. **C** is the construction of the rate of the rate for step α is the rate for α in β *I* O rile $\frac{1}{2}$ due to gravitational clustering Local density of sterile neutrinos due to gravitational clustering $\overline{}$ is the local number density of the sterile number of the sterile neutrino neutrino neutrino near the sterile n **Earth** For massive sterile neutrinos, their number density near the Sun in the Milky is larger due to gravitational clustering. The cosmological relic

tering effect near the Earth is often parameterized with a parameter *f^c* given by

$$
\Gamma_{C\nu_s B} = N_T |U_{e4}|^2 \int dE_{\nu_4} \sigma_e v_{\nu_4} \frac{dn_{\nu_4}}{dE_{\nu_4}} \simeq N_T |U_{e4}|^2 \bar{\sigma} n_{s,\text{loc}}
$$

is the local number density of the sterile number density of the sterile neutrino neutrino near the sterile ne
In the sterile neutrino near the sterile neutrino near the sterile neutrino neutrino neutrino neutrino neutrin

The local number density of sterile neutrino with clustering and **notative designation** is the local number density of the local number density of the sterile neutrino neutrino neutrino neutrino nea
The sterile neutrino The local number density of sterile neutrino with clustering where density of starile noutring with clustering. contribution is shown to see that the bound from the bound from the bound from the local phase space of the local phase space constraints of the local phase space constraints of the local phase space constraints of the loc

$$
n_{s,{\rm loc}}=(1+f_c)n_s=n_s+n_{s,{\rm cls}}
$$

Capture rate of CSNuB in DW model

less than 0.1 events per year with 100 gram Tritium

Constraints

Oscillation experiments

Beta-decay experiments

X-ray telescope

Phase space bound

CMB, BBN: Neff bound

Lyman-alpha: structure formation

Constraints on ΔN_{eff} U unstrallius Uni ΔN_{eff}

 Δ dditional u The extra relativistic decoupled particles is parameterized by Δx relationships Δx Additional relativistic decoupled particles is parameterized by $\,\Delta N_{\rm eff}$

$$
\rho_s = \Delta N_{\text{eff}} \frac{7}{8} \bigg(\frac{4}{11} \bigg)^{4/3} \rho_\gamma,
$$

Big Bang Nucleosynthesis (BBN) and cosmic microwave background (CMB) $\text{constraints} \quad \Delta N_{\text{eff}}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ matrix $\frac{1}{2}$ m constrains ΔN_{eff}

$$
N_{\text{eff}} < 3.29,
$$

\n
$$
m_{\nu,\text{sterile}}^{\text{eff}} < 0.65 \text{ eV},
$$

$$
+ \text{lensing+BAO},
$$

\n[Planck 2018]

where
$$
m_{\text{sterile}}^{\text{DW}} = (\Delta N_{\text{eff}})^{-1} m_{\nu,\text{sterile}}^{\text{eff}}
$$

Constraints on Warm DM from Lyman-alpha

Lyman-alpha forest data constrains the mass of WDM

Constraints on subdominant WDM However the extension of the ⇤CDM parameters may broaden this constraint to *N*eff *<*

 F the constraints from the constraints from the constraints on the constraints on the theorem is the thermal operations, we use the the theorem is the thermal operations, we use the thermal operations, we use the therma For subdominant vvDM) component, the constraints on the mass is relaxed, For subdominant WDM component, the constraints on the mass

$$
m_w \gtrsim m_w^{L-\alpha} \equiv 7.2\,{\rm keV}\left(\frac{\Omega_w}{\Omega_{\rm DM}}-0.1\right) \ \, \text{[Hooper etal, 2206.08188]}
$$

 $\frac{100}{100}$ for the step $\frac{100}{100}$ of $\frac{100}{100}$ for $\frac{100}{100}$ of $\frac{100}{100}$ of sterile neutrino which gives the same free-streaming scale, and the lower bound scale, and the lower bound :mass larger than 7.2 keV or abundance smaller than 10% of DM

Convert the constraints on WDM to the constraints on sterile neutrino DM for the same amount of relic density,

$$
m_s^{L-\alpha} = 4.46 \text{ keV} \left(\frac{m_w^{L-\alpha}}{\text{keV}}\right)^{4/3} \left(\frac{10.75}{g_*}\right)^{1/3} \left(\frac{0.12}{\Omega_s h^2}\right)^{1/3} \quad \text{[Viel etal, 2005]}
$$

Other scenarios for the sterile neutrino production

Capture rate of CSNuB in Low-TR model $C_{\text{non-tuning}}$ is $6, \text{CNL.D}$ in L_{out} TD is add Capture rate of Corvub in Ly of CSNuB in Low-TR model

When the reheating temperature is smaller than $T_{\text{max}} \simeq 108 \text{ MeV} \left(\frac{m_s}{1.5V}\right)^{1/3}$ \forall KeV inflation is very low or the phase transition inflation is very low or the phase transition for the phase transit When the reheating temperature is smaller than $T_{\rm max} \simeq 108 \text{ MeV} \left(\frac{m_s}{\rm keV}\right)$ keV ⌘1*/*³

the production is suppressed compared t *n* and it denote by the unkertime temperature. and it depends on the reheating temperature. ب
ا2נ α values, α and the relic density is $\frac{1}{35}$ and the relic density is $\frac{1}{35}$ with *m* sterile neutrino. The mass of the sterile neutrino. The numerical coefficient is slightly different is from the compared to DVV values,
the nelsesting terms are three the reneating temperature. \vert

$$
\Omega_s h^2 \simeq 0.5 \left(\frac{|U_{e4}|^2}{10^{-3}} \right) \left(\frac{10.75}{g_*} \right)^{1/2} \left(\frac{m_s}{\text{keV}} \right) \left(\frac{T_R}{5 \text{ MeV}} \right)^3 \qquad T_R \ll T_{\text{max}}
$$

Thus, larger mixing angle is required to produce the same amount. Compared to the standard Dodelson-Widrow relic density, a large mixing is needed for rinus, iai ger mixing angie is required to produce the same amount. Thus, larger mixing angle is required to produce the same amount. and the present Hubble parameter *H*⁰ = 100 *h* km*/*(sec Mpc).

*f***herefore, the co**
the number dens Therefore, the constraints CMB, BBN, Lyman-alpha, which depends on
the number density only, change accordingly to larger mixing values. $\frac{1}{2}$ change accord **g** To the graduate of the control of the values. the number density only, change accordingly to larger mixing values.

ptu
I \blacksquare **EXTERNATION CONSTRUCE MORE (UPPER TRANSFERENCES)**

> where *a* is the scale factor and *a*⁰ is its value at present. Since the number density of the which depends on mixing angle as well as number density.

Probing cosmic sterile neutrino in the Low-reheating Temperature

 $\Omega_4 \sim \theta^2 \Gamma$

CSNuB in late time phase transition In this section, we consider a hidden sector where the phase transition for generating $1 \text{ MeV } \gtrsim L_c < L_{EW}$ transition and after electro-weak symmetry breaking, the RH neutrino becomes Dirac \blacksquare $f_{\rm H} \leqslant 1/\Delta t_{\rm H} < 1/E$ $t \sim \ln \left(1 + \frac{1}{2} \right)$ MMC \sim LEW Majorana mass occurs very late after reheating. Before the phase transition, the Majorana $1 \text{ MeV} \leq T < T_{\text{EUV}}$ where *N* is the right-handed (RH) neutrino with Yukawa interaction with Higgs *H* and $1 \, \text{MeV} \lesssim T_c < T_{EW}$ fermion with LH neutrino with Dirac mass *M^D* = *Y*↵h*H*i. After the phase transition at $\int \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L}$ temperature **T**_c, the hidden sector sector sector sector sector sector scalar in \mathcal{L} Γ Me

mass is vanishing and neutrinos comprise Dirac fermion. THE Fiajorana mass is generated and the non-valusing $y E y$ The Majorana mass is generated after the non-vanishing VEV of a scalar ϕ the RH neutrino *M* = hi. $\ddot{}$ $\ddot{}$ The Majorana mass is generated after the non-vanishing VEV of a scalar ϕ

$$
\mathcal{L}=i\bar{N} \ \beta N + Y_{\nu}H\bar{\nu}_{\alpha}N + \frac{\lambda}{2}\phi \bar{N^{c}}N + h.c.,
$$

oscillation using the mixing angle in Eq. (29). However, for *T^c <T <TR*, there is no

transition and after electro-weak symmetry breaking, the RH neutrino becomes Dirac Dirac Dirac Dirac Dirac Dir
Dirac Dirac Di

After the phase transition at $T_{\rm e}$ sterile neutrino get Majorana mass \mathbf{L} neutrino \mathbf{L} and also couples to the hidden sector scalar \mathbf{C} , which gives to the hidden sector scalar \mathbf{C} After the phase transition at $\, T_c$, sterile neutrino get Majorana mass. the RH neutrino *M* = hi. Λ fter the phase transition at T atorile poutring set M oscillation using the mixing angle in Eq. (29). However, for *T^c <T <TR*, there is no **dixide and Alter the phasi**

 \sqrt{N} and \sqrt{N} after the phase transition \sqrt{N} and \sqrt{N} and \sqrt{N} and \sqrt{N} Above T_c and below EW-symmetry breaking $T_c < T < T_{EW}$ **Above** T_c and below EW-symmetry breaking $T_c < T < T_{EW}$ Above T_c and below EW-symmetry breaking $T_c < T < T_{EW}$ T o get the sterile neutrino abundance in this model, we can integrate the Boltzmann T $\begin{array}{|c|c|c|c|c|}\n\hline\n\text{ADOVE} & I_C & \text{aIII UCIOVV LV V-SylIIIICU } \text{y Ul CANIIS} & I_C & \text{y} \end{array}$ mass term. Therefore the abundance of the sterile neutrino has two contributions (*Tc, TR*). When *^T^c* ⌧ *^T*max, we can approximate ⌦*ch*² as in Eq. (42), with replacing *^T^R* $T_c < T < T_{EW}$

Active neutrino-sterile neutrino make Dirac particles. mass term. The contribution of the sterile neutrino make Dirac particles oscillation using the mixing angle in Eq. (29). However, for *T^c <T <TR*, there is no temperature *Tc*, the hidden sector scalar develops VEV and gives a Majorana mass to *T* T CUVE TIEULITIO-SLETTIE TIEULITIIO THANE DITAL par LICTION CONTROLLER CONTROLLER STERN CONTROLLER STERN STERN STERN CONTROLLER STERN **i** $\overline{$ Active i ⇣ *m^s* **ACCLIVE NEUT** rino-sterile ne

equation Eq. (31) about background temperature *T*, from *T^R* to the present temperature

 $\begin{array}{lll} \multicolumn{3}{l}{{\color{red}c}} & \multicolumn{3}{l}{\color{green}c}} & \multicolumn{3}{l}{\color{green}c} & \multicolumn{3}{l$ $\Omega_{s,R}$ with chirality flip The sterile neutrino abundance in the step μ Sterile neutrinos can be produced through its Dirac mass mixing with chirality flip mass term. Therefore the abundance of the sterile neutrino has two contributions To get the sterile neutrino abundance in this model, we can integrate the Boltzmann o angle since angle since the stead through its Dirac mass mixing equation Eq. (31) about background temperature *T*, from *T^R* to the present temperature $\Omega_{s,R}$ sterille fieutrinos can be produced through its Dirac
with chirality flip $\propto M^2/n^2$ mixing angle since *M* = 0, and the sterile neutrino can be generated through the Dirac $\Omega_{s,R}$ befile is (*Tc, TR*). When *^T^c* ⌧ *^T*max, we can approximate ⌦*ch*² as in Eq. (42), with replacing *^T^R* keV \sim \mathbf{w} with chirality flip \propto M_D^2/p^2 .

 $T < T_c$

 $\begin{array}{|c|c|c|c|c|}\n\hline\n\textbf{P}_\textbf{0} & \textbf{P}_\textbf{0} & \textbf$ **PULLEY PRESC CRISICION** TC $T \setminus T_C$ **Explow phase transition** T_c $T < T_c$ with α , from the generature between (T ^{0, T}*c*) and α , T*^c*) and α , T*^c*) and α , T*c*) and α , T*c*) and α **Selow phase transition** T_c $T < T_c$ $\frac{1}{2}$

 $\Omega_{s,c}$

Therefore the Boltzmann equation, Eq. (31) is now modified to

◆1*/*²

 Ω Dirac mass+Majorana mass makes mixing between active and sterile Nu. $\mathbb{R}^{2\ell s,c}$ Sterile neutrinos are produced through the mixing. mass term. Therefore the abundance of the sterile neutrino has two contributions eutrinos are _l broduced through the mi: ²²s,^c Sterile neutrinos are produced through the mixing. oscillation using the mass the mixing the matrix of the mixing the matrix of *T*
Comparent in Eq. (20). The property of *Dirac mass makes mixing between active and sterile Nu* $\Omega_{s,c}$ Sterile neutrinos are produced through the mixing. mass term. Therefore the abundance of the sterile neutrino has two contributions *.* (45)

$$
\boxed{T_c < T < T_R} \quad \Omega_{s,R} h^2 \approx 2 \times 10^{-9} \left(\frac{|U_{e4}|^2}{10^{-3}} \right) \left(\frac{10.75}{g_*(T_R)} \right)^{1/2} \left(\frac{m_s}{\text{keV}} \right)^3 \left(\frac{T_R}{5 \text{ MeV}} \right)
$$
\nvery suppressed

Discussion

Sterile neutrino may exist as a background around Milky Way, with subdominant component of cold or warm DM.

In standard Dodelson-Widrow, it may not be possible to probe in the near future.

In scenarios with low-reheating temperature or late-phase transition, the suppressed production rate of the sterile neutrinos requires a large mixing and thus enhance the capture rate in the beta decay experiment. Therefore it becomes possible to probe them in the near future.

Thank You!

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