New Neutrino Physics vetted in the Early Universe and Compact Objects: *Sterile States; Dark Sector; etc*?

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PHYSICS FRONTIER CENTER

NSF

Nuclear Physics, the ***Weak Interaction***, and ***Gravitation***

conspire to set up the early universe and compact objects
as “laboratories” for BSM/Dark Sector physics

EARLY UNIVERSE
High Entropy -- radiation dominated
nearly overdetermined

Gravitational Collapse (SN, NS)
Low Entropy – cold/lepton number degenerate
not well understood/constrained

(neutrino sector – see *Friedland, McLaughlin, Grohs, Scholberg, Babu.*)

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(QCD – EOS, etc.)

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Both Trembling on the Verge of Collapse

PBH’s –
Dark Matter: sterile ν (?); WIMPS (?), ALPS (?)

‘transmuted” NS’s – *Takhistov, Kusenko, etc*.
Dark Matter trapped in NS’s
GW signals: collapse; in-spiral

Gravitation is weak

Gravitation controls/drives the expansion of the universe

Consequently, the expansion rate is *SLOW*, and this allows
very weakly interacting particles
to affect the physics of the early universe

The main take-away message from the experiments:

Neutrinos have nonzero rest masses

Neutrino energy (mass) eigenstates $|\nu_1\rangle, \ |\nu_2\rangle, \ |\nu_3\rangle$

are not coincident with the weak interaction (flavor) eigenstates

$$|\nu_e\rangle, \ |\nu_\mu\rangle, \ |\nu_\tau\rangle$$

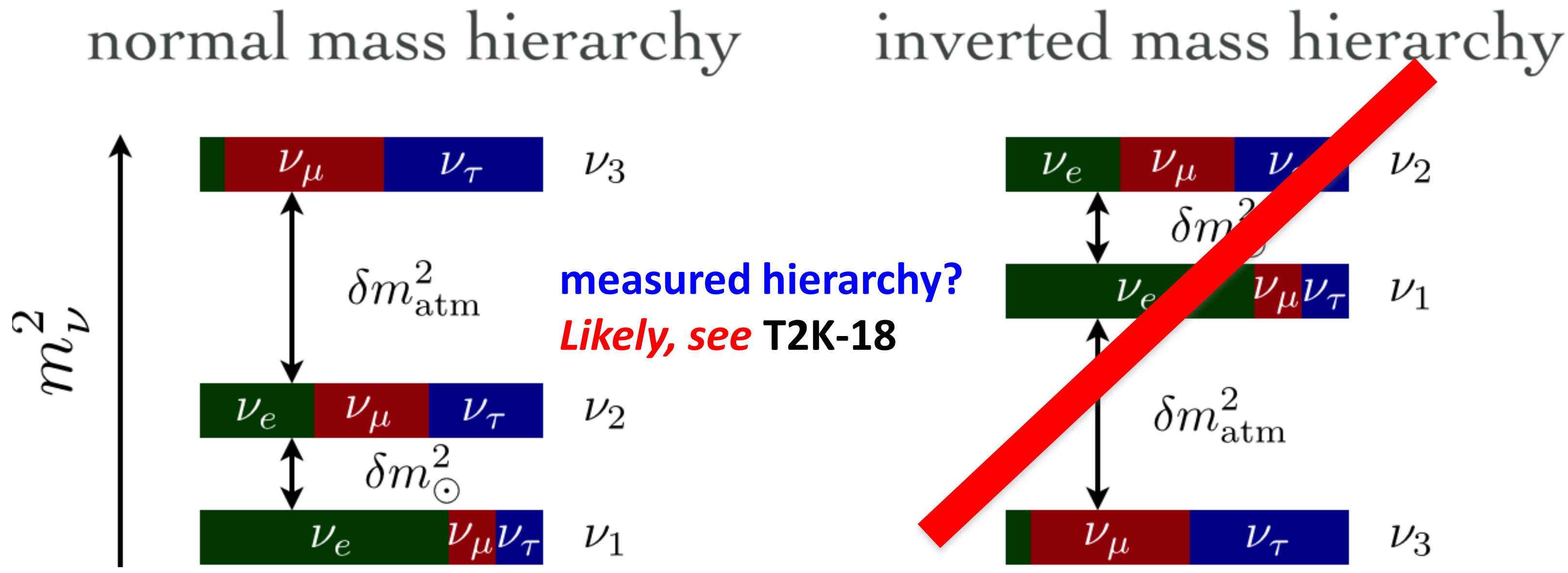
Neutrino Properties

we know the *mass-squared* differences:

$$\begin{cases} \delta m^2_\odot \approx 7.6 \times 10^{-5}\,\mathrm{eV}^2 \\ \delta m^2_{\mathrm{atm}} \approx 2.4 \times 10^{-3}\,\mathrm{eV}^2 \end{cases}$$

$$\boxed{e.g., \quad \delta m^2_{21} \equiv m^2_2 - m^2_1}$$

we *do not* know the *absolute masses*,
but likely we do know the *mass hierarchy*:



measured hierarchy?
Likely, see **T2K-18**

A key development that will ***increase*** the discovery potential of the CMB-Neutrino connection:

DUNE/long baseline experiments:

Will pin down the neutrino mass hierarchy at $5\,\sigma$ within 6 years
Good hints within a few years(?)

$$\boxed{\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = U_m \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}}$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

$$U_m = U_{23}\, U_{13}\, U_{12}$$

If Neutrinos are Majorana . . .

$$M = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_1/2} & 0 \\ 0 & 0 & e^{-i\alpha_2/2} \end{bmatrix}$$

unknown:
Majorana phases α_1, α_2

Hints in 0νββ or supernovae?

$$U_{23} \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$U_{13} \equiv \begin{pmatrix} \cos\theta_{13} & 0 & e^{i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}$$

$$U_{12} \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

4 parameters

$$\theta_{12}, \theta_{23}, \theta_{13}, \delta$$

$$\theta_{12} \approx 0.59^{+0.02}_{-0.015}$$

$$\theta_{23} \approx 0.785^{+0.124}_{-0.124} \approx \frac{\pi}{4}$$

$$\theta_{13} \approx 0.154^{+0.065}_{-0.065}$$

$$\delta = CP \text{ violating phase} = ?$$

much remains mysterious about neutrinos and the weak interaction

- origin of neutrino mass (another Higgs? See-Saw? Heavy sterile states?)
- baryon/lepton numbers (related to neutrino mass physics, e.g., νMSM ?)
- Dark Matter/Dark Sector (Non-standard ν interactions? ν dark sector?)
- other BSM physics may affect relic neutrinos/decoupling

We have: mass-squared differences/mixing angles.

We need: absolute masses; mass-hierarchy (normal?); Majorana/Dirac; CP-violating phase(s); unknown unknowns!

Experiments/observations may shed some light on these mysteries:

- Next generation short- and long-baseline oscillation experiments/$0\nu\beta\beta$-decay
- Advent of GW-observatories & multi-messenger astro
- Cosmology, e.g., high precision Stage 4 CMB observations; advent of 30m-class telescopes

The existence of non-zero neutrino rest masses,
as established by the results of neutrino oscillation experiments,
immediately forces us to ponder a question:

Are there right-handed, e.g., so-called "sterile neutrinos" ??

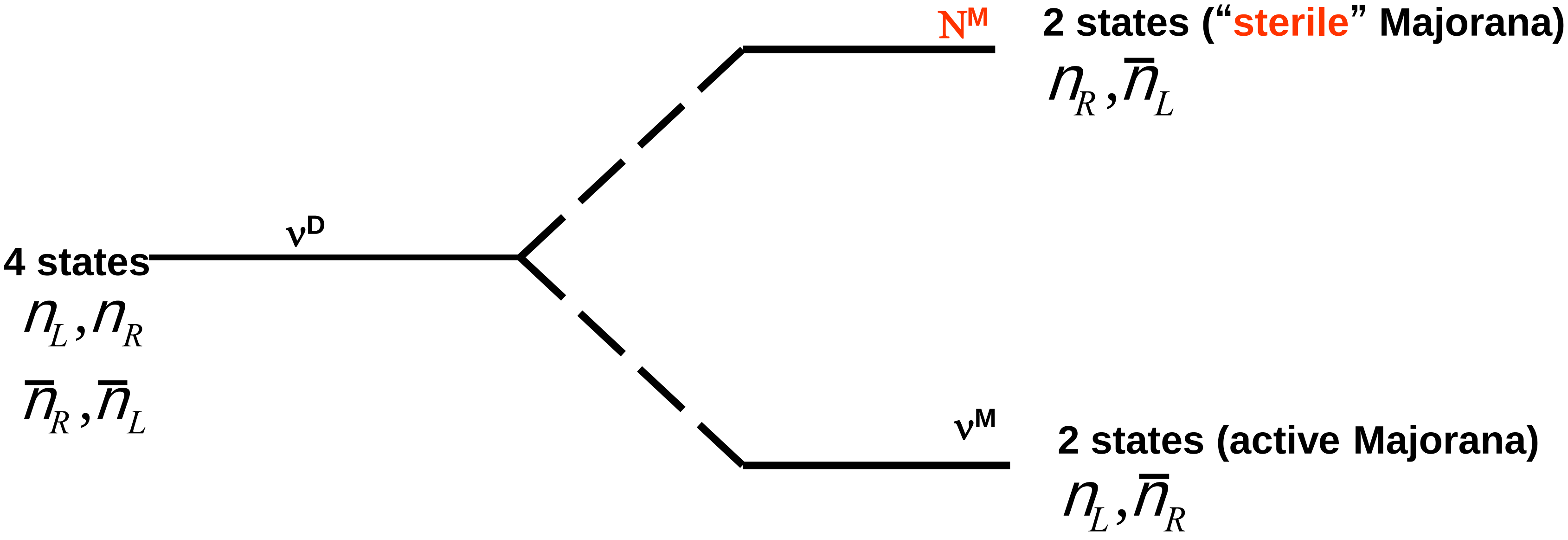
These particles may not really be "sterile" because they can mix in vacuum with ordinary active neutrinos, but their effective coupling strengths may be so tiny that they cannot be probed in the lab . . .

. . . *cosmology is a different matter*.

Why Are Neutrinos So Light?

Dirac Neutrinos $n^1\ \bar{n}$ $n+\bar{n}=4$ **states**

Majorana Neutrinos $n=\bar{n}$ $n+\bar{n}=2$ **states**



N^M

2 states (“sterile” Majorana)

$n_R, \bar{n}_L$

ν^D

4 states

n_L, n_R

$\bar{n}_R, \bar{n}_L$

ν^M

2 states (active Majorana)

$n_L, \bar{n}_R$

See-Saw Relation for the Product of Neutrino Masses: (m_N)(m_ν) ~ (Really Big Mass Scale)^2

↑

Unification Scale?

Gell-Mann, Ramond, Slansky; Yanagida; Mohapatra & Senjanovic

(after a slide by Boris Kayser)

Bruno Pontecorvo

recognized that the handedness of the weak interaction meant that non-zero neutrino rest mass could enable neutrino spin flip from active, left-handed states, to **sterile**, right-handed states.

Soviet Physics – JETP **26**, 984 (1968)

Is there a rich neutrino “dark sector”?

Sterile neutrino dark matter contribution?

A take-away message from the experiments is that neutrinos have *non-zero rest masses*

This fact begs the question: Are there sterile neutrino states?

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

$$|\nu_s\rangle = -\sin\theta\,|\nu_1\rangle + \cos\theta\,|\nu_2\rangle$$

If sterile neutrinos mix with active neutrinos in vacuum like this, then they are not really ***sterile*** !!

active neutrino cross section $\sigma \sim G_{\rm F}^2\, E_\nu^2$

"sterile" neutrino cross section $\sigma \sim (G_{\rm F}^2\, \sin^2\theta)\, E_\nu^2$

Well, can we make dark matter out of ‘em?

(1) Quantum Mechanical Limit: Dodelson & Widrow 1994

active neutrino scattering-induced de-coherence produces a relic density of sterile neutrinos -- *picks out keV scale rest masses, small vacuum mixing angles*

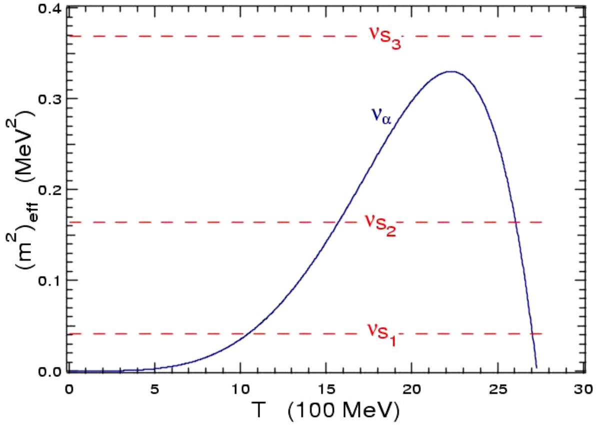
(2) Lepton number-driven resonant production: Shi & Fuller 1998; Abazajian, Fuller, Patel 2001; Abazajian ’14, Abazajian & GMF 2002; Kishimoto & GMF 2008; T. Venumadhav, F. Cyr-Racine, K. Abazajian, C. Hirata arXiv150706655

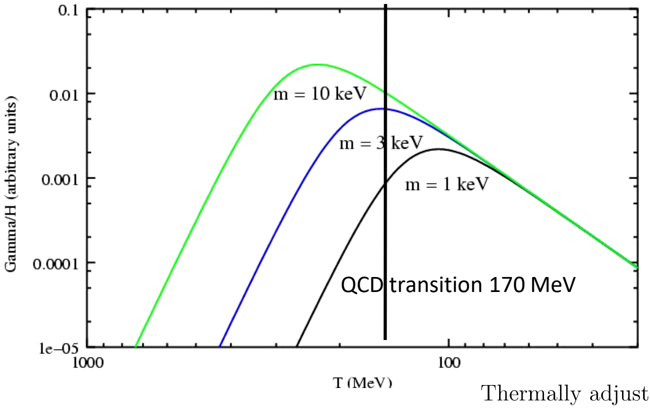
Like MSW: initial lepton number partially converted to a relic sterile neutrino population

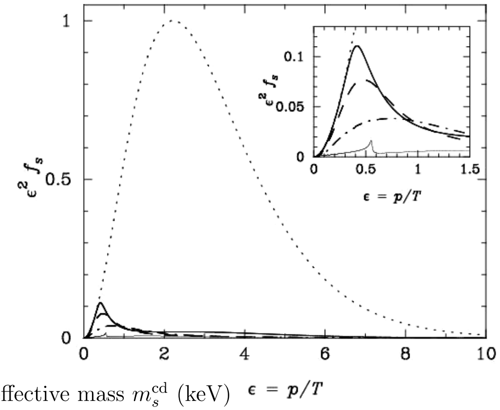
-- *can work for smaller mixing angles, larger (1-10 keV) masses, with colder sterile neutrino relic energy spectrum*

-- *sterile neutrinos may allow you to make the lepton number:*

e.g., Asaka & Shaposhnikov , “The nuMSM, dark matter, and baryon asymmetry ”, PLB ***620****, 17 (2005)*





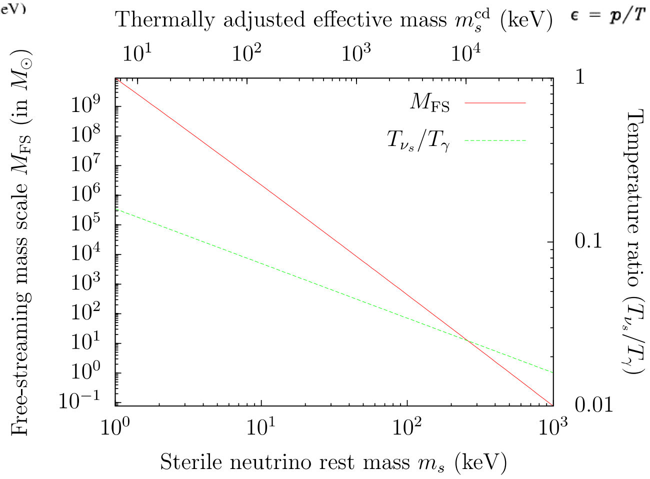


(3) Higgs decay and/or Dilution:

e.g., Kusenko (2006); Asaka, Shaposhnikov, Kusenko (2006); F. Bezrukov, D. Gorbunov arXiv:1403.4638 Patwardhan, GMF, Kishimoto, Kusenko (2015)

thermalize or partially thermalize steriles very early, QKE calculations with scattering/decay then resonant or dilution production

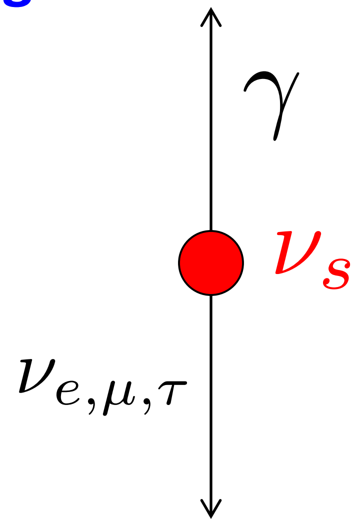
Dilution can produce CDM/evade constraints

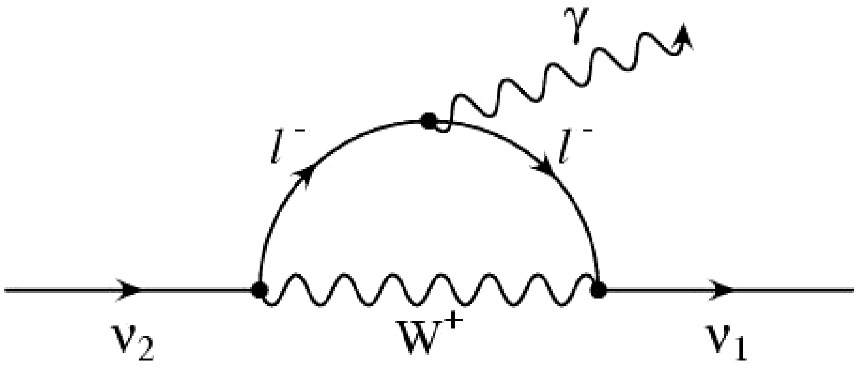


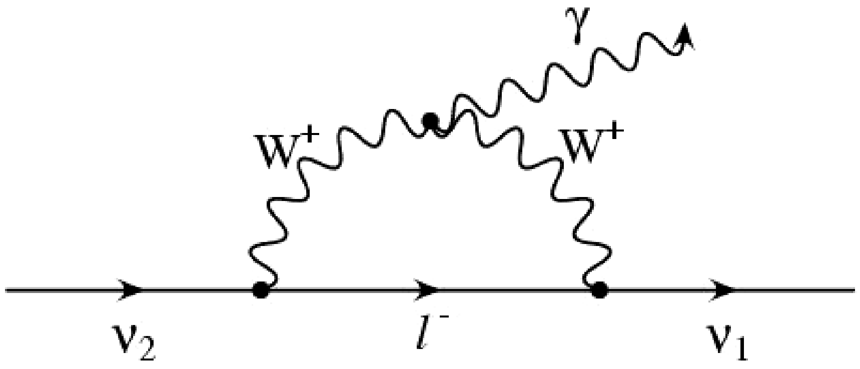
Patwardhan, GMF, C. Kishimoto, A. Kusenko PRD **92**, 103509 (2015)

A heavy “sterile” neutrino can decay into a light “active” neutrino and a photon.

The final state light neutrino and photon ***equally share*** **the rest mass energy of the initial heavy neutrino.**







$$\nu_s \longrightarrow \nu_{e,\mu,\tau} + \gamma$$

photon line $E_\gamma = m_{\rm s}/2$

Abazajian, Fuller, Tucker 2001

- look at clusters of galaxies, because that is where the dark matter is! (e.g., ~ 10^{15} solar masses of dark matter!)

but these are tough places to look for
dark matter-generated X-ray lines in the keV energy range
because there is hot gas with heavy elements
with a temperature ~ keV, meaning lots of atomic lines
and a fierce X-ray background!

ameliorate these issues by stacking spectra for cluster at different redshifts - smears out instrumental effects

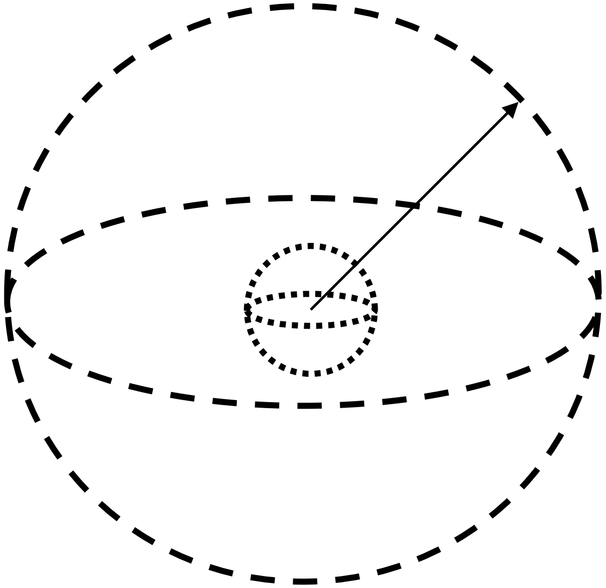
ATHENA and XRISM will have ultra sensitive calorimeters with ~ 4 eV energy resolution: virial line width ~ 36 eV; ions/gas ~ 16 eV

All ***oscillation-based*** channels for producing sterile neutrino dark matter seem at odds with large scale structure data. – Abazajian et al. 2022

Symmetry is (nearly) everything in General Relativity

homogeneity and *isotropy* of this FLRW spacetime dictates that there be ***no spacelike heat flow*** or non-uniform heat sources: evolution is ***adiabatic***

entropy in a co-moving volume is conserved*



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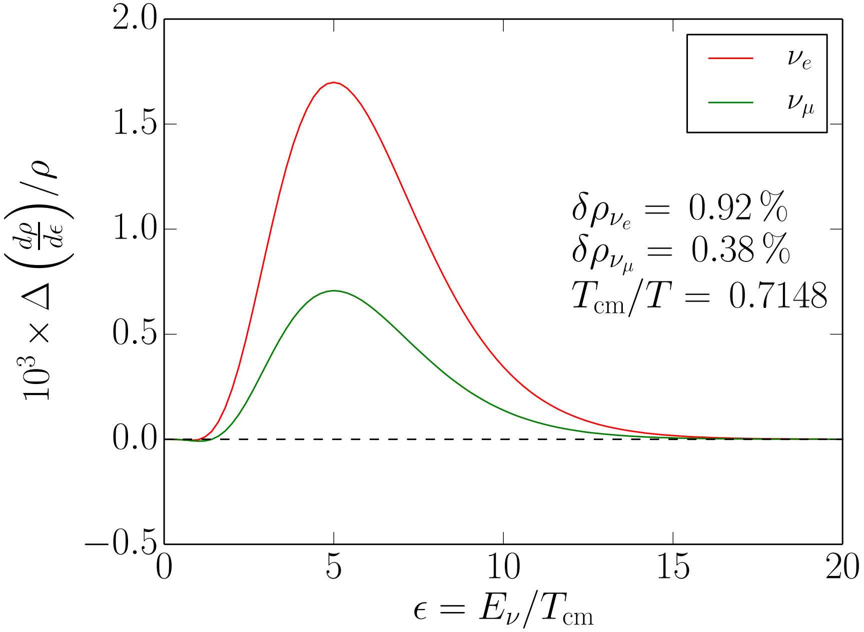
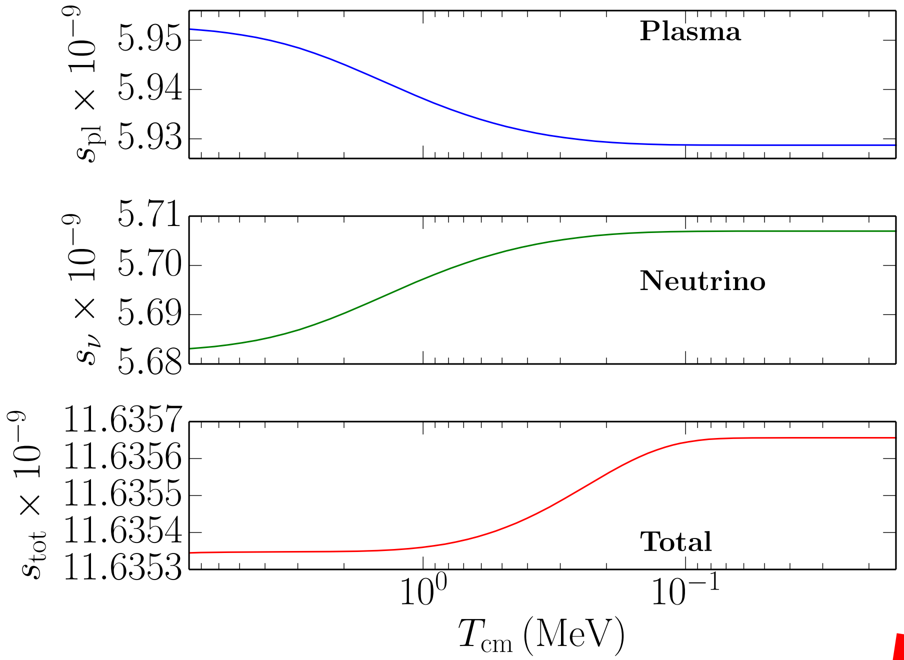
* Symmetry does not preclude ***timelike*** **heat flows, e.g., from decaying particles** ***or*** **from non-equilibrium processes like decoupling ν's scattering on e^-/e^+**

out-of-equilibrium neutrino scattering leads to ***neutrino spectral distortions*** and timelike ***entropy flow/generation***

$$\nu - \nu/e^{\pm} \text{ scattering}$$





"Neutrino energy transport in weak decoupling and big bang nucleosynthesis"
E.Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko Phys. Rev. D **93**, 083522 (2016)

$N_{\rm eff}$

$$\nu_e + n \rightleftharpoons p + e^-$$
$$\bar{\nu}_e + p \rightleftharpoons n + e^+$$
$$n \rightleftharpoons p + e^- + \bar{\nu}_e$$

integrated history of
the rates of these
charged current processes
and ***entropy flow*** determine n/p
which is key to nucleosynthesis

$$Z\,p + N\,n \rightleftharpoons A\,(Z, N) + \gamma$$

D, ^{4}He

The alterations that originate from otherwise
standard model neutrino mass/mixing physics
are ***small*** compared to
the anticipated precision of the observations,
though potentially detectable in an overall assessment
of deuterium and helium abundances and N_{eff}

Some **BSM/Dark Sector** physics can result in dramatic alterations.

. . . or more subtle “fingerprints”.

Full Quantum (QKE solutions)

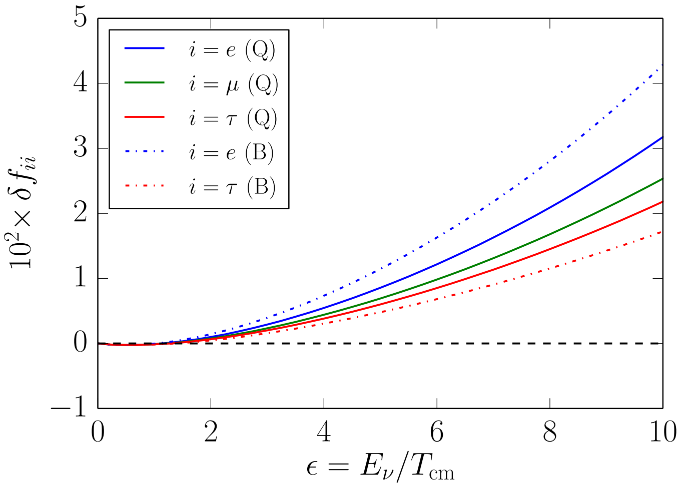
Early universe/weak decoupling-BBN

J. Froustey 2110.11296. N_{eff} = 3.044 (instead of 3.046)

J. Froustey, C. Pitrou, and C. Volpe 2020 JCAP 12 015 (Preprint 2008.01074)

E. Grohs et al. 2022

E. Grohs, preliminary



Core collapse supernovae

isotropic case: Richers, McLaughlin, Kneller, Vlasenko PRD **99**, 123014 (2019)

Particle-in-cell techniques;
(no collisions): Richers, Wilcox, Ford, Myers, PRD **103**, 083013 (2021)

Monte Carlo Techniques: Chinami, Nagakura, Taiki, ApJ Suppl **257**, Issue 2, id.55 (2021)

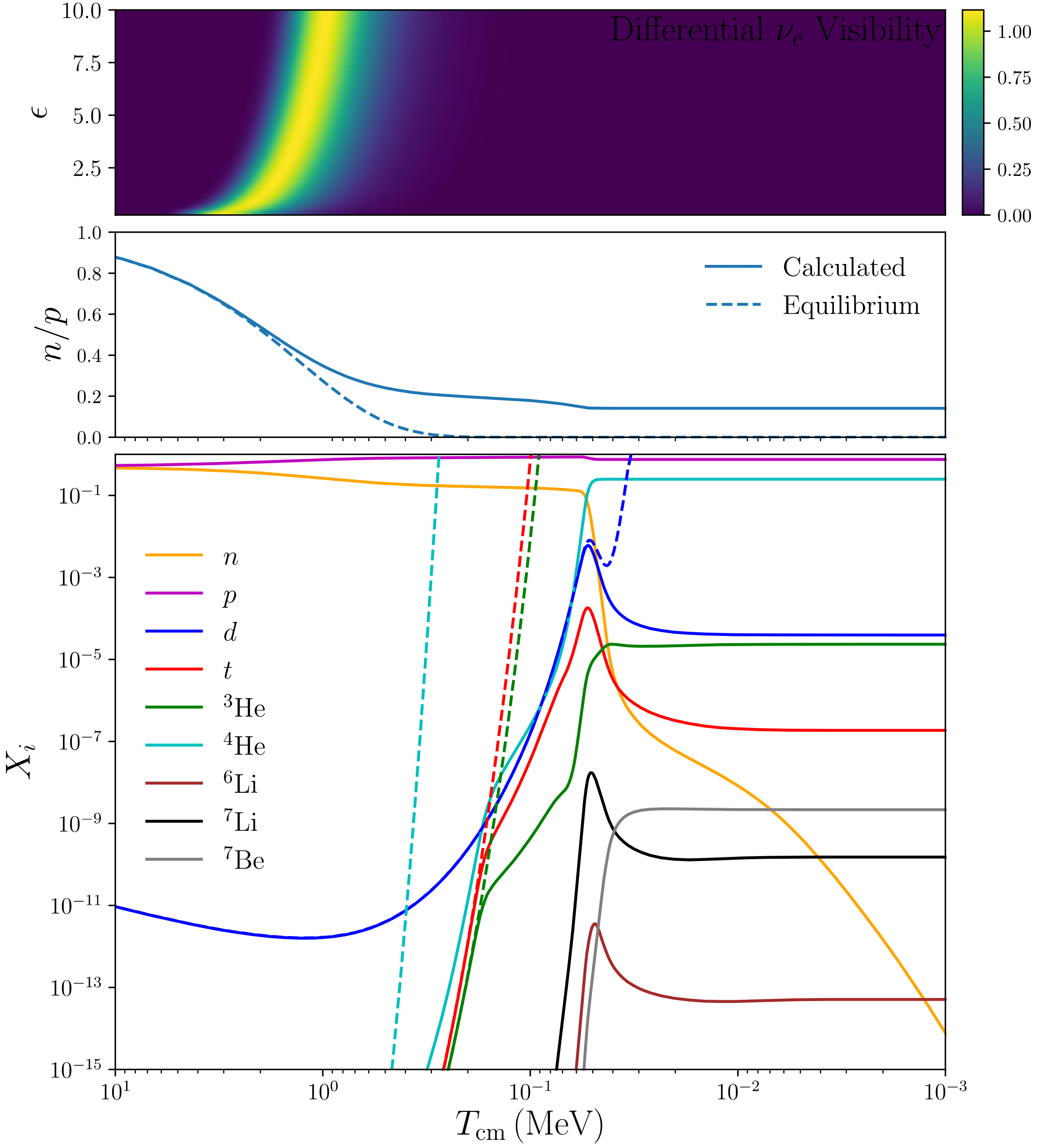
The differential visibility is given by

$$\frac{d}{d\ln a} e^{-\tau_{\nu_i}} = \frac{\Gamma'_{\nu_i}}{H} e^{-\tau_{\nu_i}}$$

evolving n/p ratio

Mass Fraction
(abundance)

see Evan Groh’s talk!



J. R. Bond, G.M. Fuller, E. Grohs, J. Meyers, M. Wilson 2021

. . . *an alluring feature of the early universe ripe for exploitation!*

Any physics operating in the early universe which
alters the scale factor–time-temperature relationship, *a(t),*
during the weak decoupling/BBN epoch (T ~ 30 MeV to T ~ 20 keV)
will manifest as an altered neutrino spectral history which, in turn,
alters deuterium and helium production and N_{eff}

Can we find the fingerprints of BSM physics on D, ^{4}He, and N_{eff} (and Σm_ν) ?

The anticipated higher precision of CMB S4 (for helium and N_{eff})
and 30-m class telescopes (for deuterium) means we have to "***raise our game***"
in modeling the Standard Model + neutrino physics
in the weak decoupling/BBN epoch

Much of what I will talk about is work in

E. Grohs, G. M. Fuller, C. T. Kishimoto, M. W. Paris, A. Vlasenko
"Neutrino energy transport in weak decoupling and big bang nucleosynthesis"
Physical Review D **93**, 083522 (2016)

Other collaborators on this work : S. Shalgar, V. Cirigliano, L. Johns, D. Blaschke, M. Mina,
J. R. Bond, J. Myers, J.T. Li

Example: sterile neutrino decay ($m_s <$ a few GeV)

$$\nu_s \to \pi^0 + \nu_{e,\mu,\tau} \to 2\gamma + \nu_{e,\mu,\tau}$$

$$\begin{tikzcd}
\nu_s \arrow[r] & \pi^+ \arrow[d] & + e^- \arrow[r] & 2\gamma + 3\nu \\
& \mu^+ + \nu_\mu \arrow[d] & & \\
& e^+ + \bar{\nu}_\mu + \nu_e & &
\end{tikzcd}$$

$$\nu_s \to \pi^+ + \mu^- \to 2\gamma + 5\nu$$

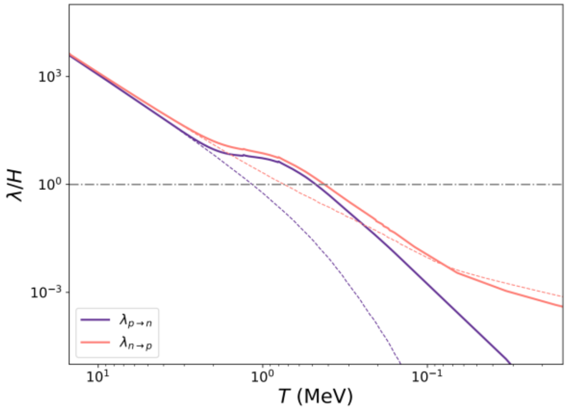
Photons thermalize,
but neutrinos may or may not, depending on their energies and the decay epoch

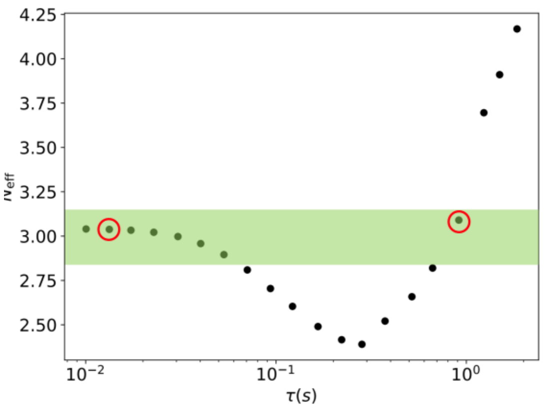
BSM Examples

Heavy sterile neutrinos – decaying during/after BBN

Gelmini et al. 2021; Rasmussen et al. 2021; GMF, Kishimoto, Kusenko 2012

Motivation:
sterile neutrino dark matter ideas
See Gelmini et al 2021
Abazajian, Kusenko, GMF, Dodelson, etc.



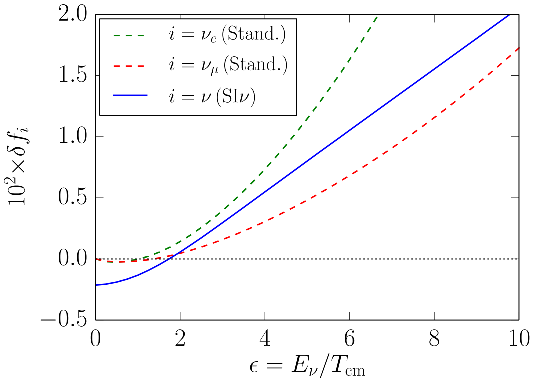


Motivation:
Reconciling discordant
Hubble parameters: Kreisch et al 2019

NSIs: "secret" neutrino-neutrino interactions – decaying during/after BBN

Huang, Ohlsson, Zhou 2018; Grohs, GMF, Sen 2020

$$\mathcal{L}_{\rm int} = g_{ij}\overline{\nu^c_{iL}}\,\nu_{jL}\varphi + g_{ij}\overline{\nu_{iL}}\,\nu^c_{jL}\varphi, \quad G_{ij} = \frac{g_{ij}^2}{m_\varphi^2}, \qquad [g_{ij}] = \begin{pmatrix} g_{ee} & g_{e\mu} & g_{e\tau} \\ g_{\mu e} & g_{\mu\mu} & g_{\mu\tau} \\ g_{\tau e} & g_{\tau\mu} & g_{\tau\tau} \end{pmatrix} \Rightarrow g\begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}.$$



Little Effect on BBN
but . . . *collapse is a different story*

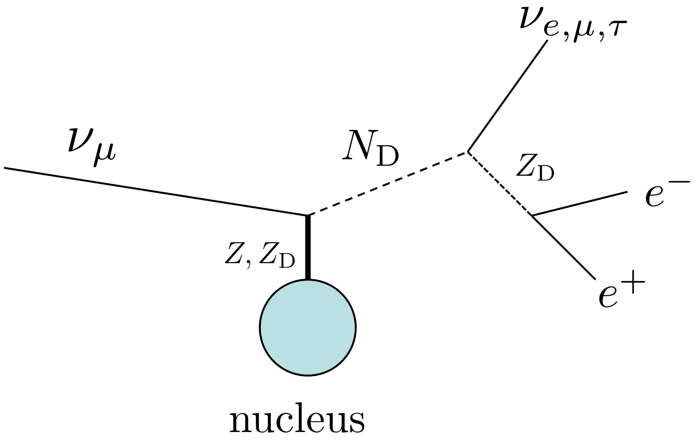
cosmologically-safe (?) Dark Sector “explanations” of the (some) anomalies?

Examples include:

E. Bertuzzo, S. Jena, P. Machado, R. Funchal, PRL **121**, 241801 (2018)
Dark Z (small coupling to standard model quarks), Dark (i.e., sterile) neutrino

A. Datta, S. Kamali, D. Marfatia, arXiv:2005.08920
light scalar singlet (electromagnetic decay gives miniBooNE low energy excess) coupled to a sterile neutrino

For a general “lay of the land” see
“White Paper on New Opportunities at the Next-Generation Neutrino Experiments”, C. A. Aguelles et al, arXiv:1907.08311



Sterile neutrino N_D, mass $\sim 400\,\mathrm{MeV}$??
Dark Z, Z_D, mass $\sim 100\,\mathrm{MeV}$??

NSIs quark-quark coupling? A.Suliga, S. Shalgar, GMF 2021

Intriguing possibilities (BSM & Dark Sector)

A net lepton number $L_{\nu_\alpha} \geq 10^{-4}$ residing in any of the active neutrino species (Abazajian, Bell, Fuller, Wong 2006; Chu & Cirelli 2006)

— interestingly in the range of what we would need to drive resonant sterile neutrino dark matter production for a sterile neutrino with rest mass $m_s \sim 10\,\mathrm{keV}$.

But possible troubles with BBN, N_{eff}, $\sum m_\nu$ for $m_s > 0.6\,\mathrm{eV}^2$ – see N. Saviano et al. 2017 – but need full 4X4 analysis

Low inflation re-heat temperature (e.g., Gabriel, Palmerez-Reiz, Pascoli 2004)

Non-standard ("secret") sterile neutrino interactions
Hannestad et al. 2013; Mirizzi et al. 2013; others

see especially B. Dasgupta & J. Kopp "Cosmologically safe eV-scale sterile neutrinos and improved dark matter structures" Phys. Rev. Lett. **112**, 031803 (2014).

A whole new sterile neutrino self-interacting sector? Other steriles? Interaction with dark matter, whatever that is? *see* L. Johns & G. M. Fuller PRD **100**, 023533 (2019)
M. Sen, A. de Gouvea, W. Tangarife, Y. Zhang (2019)

See J. Cherry, A. Friedland, I. Shoemaker arXiv:1411.1071 – opacity for PeV/ICECUBE neutrinos, engineers dark matter self-interaction;

cosmologically-safe (?) Dark Sector “explanations” of the experiments?

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Summary – Compact Objects

Neutrinos transport and carry much of the energy in
core collapse supernovae (and binary neutron star mergers).

This physics is flavor dependent.

These environments are sensitive to lepton number-violating physics
and neutrino NSIs, sometimes in unique ways

Not well constrained by observation, but the ”handles” we do have
are especially promising:

Handles: nucleosynthesis, DSNB, gravitational waves/compact object systematics,
Maybe someday a signal (DUNE, HyperK, etc.)

“toy problems” that do not include all relevant physics and/or
build-in symmetries in the medium may be revealing, but misleading

Summary – Early Universe, Weak Decoupling/BBN

Any physics that alters the time-temperature-scale factor relationship could show up in measured values of the deuterium and helium abundances, N_{eff}

BSM scenarios can ”move” these quantities from their standard model values -- unique “finger prints” of specific BSM scenarios? (see Bond, Fuller, Grohs, Meyer 2022)

Very well constrained by observation; promises to get even better . . .

Handles: CMB – e.g., Simons Array & Stage-4

“CMB-S4 Science Book, First Edition”, Abazajian et al. arXiv:1610.02743