The Neutrino Puzzle: Anomalies, Interactions, and Cosmological Tensions

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w/ Christina Kreisch, Lloyd Knox, Lachlan Lancaster, Olivier Doré
Disclaimer

• This talk might solicit a strong response from members of the audience. Viewer discretion is advised.

• Spherical cows will be used in this talk. However, they will not be harmed.
Precision Cosmology Era
Precision Cosmology Era?

How much do we really know the expansion history of our Universe?

Planck collaboration (2018)
Not all probes of $H(z)$ are born equal…

On this plot, only Riess et al. (2018) provides a direct measurement of the current Hubble rate.

Other measurements requires the knowledge of the baryon-photon sound horizon, $r_s$.

Time of baryon decoupling

$$ r_s = \int_0^{t_d} \frac{c_s \, dt}{a} = \int_0^{a_d} c_s \frac{da}{a^2 H(a)} $$
The CMB primarily measures angles on the sky.

\[ \theta_s = \frac{r_s}{D_A(z_d)} \]

\[ D_A(z) = \int_0^z \frac{dz'}{H(z')} \]

Assuming a late-time cosmology, can infer \( r_s \) from \( \theta_s \).
Baryon Acoustic Oscillations (BAO)

BAO primarily measures 2 “processed” versions of the baryon-photon sound horizon.

- **Line of sight:** $H(z) r_s$
- **Transverse:** $r_s / D_A(z)$

- If sound horizon if known (from CMB, say), then can use BAO to infer Hubble rate.
- Conversely, if Hubble rate is known, can use BAO to infer sound horizon.

Eric Huff (JPL)
A little misleading?

BOSS data points on this plot use CMB-measured value of the sound horizon as calibration!

Planck collaboration (2018)
Calibrate BAO with local distance ladder

Can make BAO compatible with local $H_0$ measurement with a smaller baryon-photon sound horizon.

For comparison, Planck’s CMB value is:

\[ r_s = 147.05 \pm 0.30 \text{ Mpc} \]

Aylor et al, (2018)
Discrepancy in the baryon sound horizon

Aylor et al. (2018)
See also Bernal et al. (2016)
How to modify the Baryon-Photon Sound Horizon

- Can either change the sound speed, or the Hubble rate at early times.

$$r_s = \int_0^a \frac{d a}{a} \frac{c_s(a)}{a^2 H(a)}$$

Can we change the Hubble rate before recombination without ruining everything else?

$$H^2(a) = \frac{8 \pi G}{3} \sum_i \rho_i(a)$$

$$c_s = \sqrt{1 + \frac{\frac{3 \rho_b}{4 \rho_\gamma}}{\frac{3 \rho_\gamma}{4 \rho_b}}}$$
Issue: Sound horizon vs Damping scale

\[ \rho_R = \left[ 1 + N_{\text{eff}} \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} \right] \rho_\gamma. \]

FIG. 1: Effects of \( P_{m \nu} \), \( G_{\text{e}} \), and \( N_{\text{e}} \) on the phase and amplitude of the TT and EE power spectra. Colors denote different values of \( G_{\text{e}} \). Solid spectra correspond to \( P_{m \nu} = 0.06 \text{ eV} \) and dashed spectra correspond to \( P_{m \nu} = 0.23 \text{ eV} \). Measurements from the Planck 2015 data release are included [109].

\( N_{\text{e}} \), defined via the relation

\[ \rho_{R} = \frac{\rho_{\text{R}}}{\rho_{\gamma}} = \frac{1 + N_{\text{eff}}}{8} \left( \frac{4}{11} \right)^{4/3}, \]

(13)

where \( \rho_{R} \) and \( \rho_{\gamma} \) are the total energy density in radiation and in photons, respectively. The effects on the CMB of increasing \( N_{\text{e}} \) have been well-studied in the literature (see e.g. Ref. [117]) for the case of free-streaming neutrinos. For fixed values of the angular scale of the sound horizon, the epoch of matter-radiation equality, and the physical baryon abundance, it was found that the most important net impact of increasing \( N_{\text{e}} \) was to damp the high-\` tail of the TT spectrum and to induce a phase shift towards larger scales (low-\`). Interestingly, self-interacting neutrinos can partially compensate for these effects, hence pointing to a possible degeneracy between \( G_{\text{e}} \) and \( N_{\text{e}} \). An example of this can be seen in the dotted red line in the lower left panel of Fig. 1, where the excess of damping caused by \( N_{\text{e}} = 4.046 \) (dotted black line) is compensated by suppressing neutrino free-streaming with \( G_{\text{e}} = 10^{2} \text{ MeV}^{2} \).

\( G_{\text{e}} \) affects the EE polarization power spectrum in a similar manner as the temperature spectrum. The right panel of Fig. 1 shows that the phase shift between the standard \( \text{CDM} \) model and that with self-interacting neutrinos is more visible in this case due to the sharp, well-defined peaks of the polarization spectrum [113]. This allows to directly see in which direction the spectrum is shifted compared to \( \text{CDM} \) since the oscillations in the residuals lean in the direction of the phase shift, that is, there is a sharper drop in the residuals in the direction of the phase shift.
The problem with $N_{\text{eff}}$

- The presence of extra relativistic species is a hallmark of many extensions of the Standard Model ($N$-Naturalness, Twin Higgs, etc.)

- However, it leads to too much damping in the temperature spectrum of the CMB!
The problem with $N_{\text{eff}}$

- But, wait, can’t the damage to the damping tail can be undone by changing the helium abundance? Sure…

- However, a phase shift of the CMB peaks towards lower $l$ remains.
  - Baumann et al. (2016)

- Need to examine the behavior of fluctuations.

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![Graph showing the impact of $N_{\text{eff}}$ on CMB fluctuations.](image)
Free-streaming Radiation and the CMB

Baryon-photon perturbations interact with all relativistic species through their gravitational coupling.

\[ d_\gamma(\tau, k) = 3\zeta_{\text{in}}(1 + \Delta_\gamma) \cos(\varphi_0 + \delta\varphi) + O(\varphi_0^{-1}) , \]

where

\[ \Delta_\gamma \simeq -0.2683 R_\nu + O(R_\nu^2) , \]
\[ \delta\varphi \simeq 0.1912 \pi R_\nu + O(R_\nu^2) . \]

\[ R_\nu = \frac{\rho_\nu}{\rho_\gamma + \rho_\nu} \simeq 0.403 \]

for \( N_{\text{eff}} \simeq 3.046 \)

Cyr-Racine & Sigurdson (2014)

Bashinsky & Seljak (2004)
The problem with $N_{\text{eff}}$

Aylor et al. (2018)

See also Bernal et al. (2016)
Sound horizon discrepancy and relativistic species

• One way to interpret the current tension among cosmological datasets is that the baryon-photon sound horizon estimates from early time and late time probes is discrepant.

• This could be fixed by changing the Hubble expansion rate in the two decades in scale factor before recombination.

• Adding relativistic species is a natural way to achieve this, but it introduces more problems than it solves (damping tail, phase shift, matter fluctuation amplitude, etc.)
Any way to rescue $N_{\text{eff}}$?

- Since most (if not all) of the non-photon radiation at early times is made of neutrinos, let’s have a look at the status of neutrino physics.
The current status of neutrino physics

From Michele Maltoni’s talk at the Neutrino 2018 conference:

- Anomalies in $\nu_e \rightarrow \nu_e$ disappearance and $\nu_\mu \rightarrow \nu_e$ appearance experiments point towards conversion mechanisms beyond the well-established 3$\nu$ oscillation paradigm;

⇒ sterile neutrino models fail to simultaneously account for all the $\nu_e \rightarrow \nu_e$ data, the $\nu_\mu \rightarrow \nu_e$ data and the $\nu_\mu \rightarrow \nu_\mu$ data. This conclusion is robust;

- if the $\nu_e \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ anomalies are confirmed, and the $\nu_\mu \rightarrow \nu_\mu$ bounds are not refuted, new physics will be needed. Such new physics may well involve extra sterile neutrinos, but together with something else (or some “unusual” neutrino property).

XXVIII International Conference on Neutrino Physics and Astrophysics (Neutrino 2018), Heidelberg, Germany, 4-9 June 2018 (Session Sterile Neutrinos and Interpretations, Part 2)
New Physics in the Neutrino sector

- Introduce new neutrino self-interaction that suppresses neutrino free-streaming at early times.

\[ \nu \quad \quad \quad \quad \quad \quad \nu \]

Kreisch, Cyr-Racine & Doré, 1902.00534
Beyond Free-streaming Neutrinos

• A significant recent interest in non free-streaming (fluid-like) radiation:
  • Affect background cosmology similarly to standard $N_{\text{eff}}$.
  • However, cosmological perturbation evolution is very different.

- Hannestad (2005)
- Trotta & Melchiorri (2005)
- Melchiorri & Serra (2006)
- Bell, Pierpaoli & Sigurdson (2006)
- De Bernardis et al. (2008)
- Basboll, Bjaelde, Hannestad & Raffelt (2009)
- Smith, Das & Zahn (2012)
- Cyr-Racine & Sigurdson (2014)
- Archidiacono & Hannestad (2014)
- Baumann, Green, Meyers & Wallisch (2016)
- Brust, Cui & Sigurdson (2017)
- Lancaster, Cyr-Racine, Knox, Pan (2017)
- Choi, Chiang & Loverde (2018)
- Song, Gonzalez-Garcia & Salvado (2018)
- And many more…
Beyond Free-streaming Neutrinos

New Unknown Interaction

\[ \mathcal{L}_{\text{int}} = g_{ij} \phi \bar{\nu}_i \nu_j \]

4-Fermion Interaction

\[ G_\nu > G_F \]

\[ G_\nu \lesssim 144 \text{ MeV}^{-2} \]

Kolb and Turner (1987)

Lessa and Peres (2007)

TABLE III. Comparison between the strongest bounds (including the scalar \( \chi \)) obtained here and the previous bounds from the same processes. All bounds are at 90% C.L. and the previous bounds are from [14–16].

<table>
<thead>
<tr>
<th>Previous Bounds</th>
<th>Revised Bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sum_a</td>
<td>g_{ea}</td>
</tr>
<tr>
<td>( \sum_a</td>
<td>g_{\mu a}</td>
</tr>
<tr>
<td>none</td>
<td>( \sum_a</td>
</tr>
</tbody>
</table>
Beyond Free-streaming Neutrinos

- Summary of current bounds

Ng & Beacom (2014). See also Arcadi et al. (2018)
Delayed Neutrino Decoupling

Neutrino Opacity:

\[ \dot{\tau}_\nu \propto -aG_{\text{eff}}^2 T_\nu^5 \]

\[ G_{\text{eff}} \propto G_\nu \]

\[ G_\nu = g_\nu / M_\phi^2 \]

\[ g_\nu(\tau) \equiv -\dot{\tau}_\nu e^{-\tau_\nu} \]

Extra Neutrino Interactions \rightarrow
Delayed Neutrino free streaming!

Cyr-Racine & Sigurdson (2014)
Oldengott, Rampf & Wong (2015)
Massive Neutrino Boltzmann Hierarchy

Simplified Boltzmann Hierarchy (assume decoupling in relativistic regime):

\[
\frac{\partial \nu_l}{\partial \tau} + k q \frac{\ell + 1}{2\ell + 1} \nu_{l+1} \left( \frac{l}{2l + 1} \nu_{l-1} \right) - 4 \left[ \frac{\partial \phi}{\partial \tau} \delta_{l0} + \frac{k \epsilon}{3 q} \psi \delta_{l1} \right] \\
\quad = -a \frac{G_{\text{eff}}^2 T_{\nu}^5 \nu_l}{f_{(0)}^{(0)}(q)} \left( \frac{T_{\nu,0}}{q} \right) \left( A \left( \frac{q}{T_{\nu,0}} \right) \right) \\
\quad \quad + B_l \left( \frac{q}{T_{\nu,0}} \right) - 2D_l \left( \frac{q}{T_{\nu,0}} \right)
\]

Relaxation-time approximation

\[\epsilon = \sqrt{q^2 + a^2 m_{\nu}^2}\]

Cyr-Racine & Sigurdson (2014)
Oldengott, Rampf & Wong (2015)
Kreisch, Cyr-Racine+ (2019)
Impact of self-interacting Neutrinos on CMB

\[ z = 5 \times 10^7 \]
\[ G_{\text{eff}} = 10^{-4} \text{ MeV}^{-2} \]

\[ d_\gamma(\tau, k) = 3\zeta \sin(1 + \Delta_\gamma) \cos(\varphi_s + \delta \varphi) + O(\varphi_s^{-1}) , \]

where

\[ \Delta_\gamma = -0.2683 R_\nu + O(R_\nu^2) , \]
\[ \delta \varphi = 0.1912 \pi R_\nu + O(R_\nu^2) . \]

With SI neutrinos, no supersonic radiation can provide a gravitational tug to photons

Cyr-Racine & Sigurdson (2014)
interacting neutrinos can partially compensate for these shifts towards larger scales (low-

physical baryon abundance, it was found that the most important net impact of increasing

horizon, the epoch of matter-radiation equality, and the

FIG. 1: \( E_\nu \), defined via the relation

\[
\frac{C_{\ell,TT} - C_{\ell,TT,\Lambda CDM}}{C_{\ell,TT,\Lambda CDM}}
\]

Fixed \( \sum m_\nu = 0.06 \) eV

Fixed \( \Omega_b h^2, \eta_\text{eq}, \theta_* \)

\( \Lambda CDM \) (\( N_{\text{eff}} = 3.046 \))

\( G_{\text{eff}} = 10^{-2} \text{MeV}^{-2}, N_{\text{eff}} = 3.046 \)

\( \Lambda CDM \) (\( N_{\text{eff}} = 4.046 \))

\( G_{\text{eff}} = 10^{-2} \text{MeV}^{-2}, N_{\text{eff}} = 4.046 \)

Kreisch, Cyr-Racine + (2019)
Impact of self-interacting Neutrinos on matter clustering

Fixed $N_{\text{eff}} = 3.046$

Scales entering the horizon at the onset of neutrino free-streaming

Kreisch, Cyr-Racine + (2019)
Impact of self-interacting Neutrinos on matter clustering: $N_{\text{eff}}$

Kreisch, Cyr-Racine + (2019)
Now that we understand the physics, what does the data say?

Let’s ask Christina

Christina Kreisch
A Tale of two statistical modes

Strongly-Interacting neutrino mode: $\nu$

Moderately-Interacting neutrino mode: $\nu$

Kreisch, Cyr-Racine + (2019)
What is this SIν mode?

\[ \dot{\tau}_\nu = -aG_{\text{eff}}^2 T_\nu^5. \]

\[ g_\nu(\tau) \equiv -\dot{\tau}_\nu e^{-\tau_\nu} \]

Cyr-Racine & Sigurdson (2014)
Lancaster, Cyr-Racine, Knox, Pan (2017)
Oldengott, Tram, Rampf & Wong (2017)
Sound horizon is smaller than in LCDM. Let’s compare the two modes side-by-side. For this reason, the peak locations and posterior shapes are of physical interest rather than the relative heights of the peaks. $N_{\text{eff}} \sim 4$: extra energy density at early times. Hubble constant is compatible with local measurement.

Francis-Yan Cyr-Racine - Harvard

Kreisch, Cyr-Racine + (2019)
Concordant direct and inverse distance ladders

Aylor et al, (2018)

The SNIa sound horizon:

\[ r_s = 138.8 \pm 2.5 \text{ Mpc} \]

The local distance ladder sound horizon:

\[ r_s = (137.6 \pm 3.45) \text{ Mpc} \]
Let’s compare the two modes side-by-side

- Neutrino phase suppressing
- Clearly see effect of suppressing neutrino phase shift

Value of $\sigma_8$ is slightly smaller than LCDM

Francis-Yan Cyr-Racine - Harvard
Kreisch, Cyr-Racine + (2019)
SI\nu Cosmology and matter clustering

- The combined effect of $N_{\text{eff}}$, neutrino masses, self-interaction, $A_s$, and $n_s$ leave large-scale structure largely unchanged on scales where it best measured.

\[ \sigma_8 = 0.786 \pm 0.020 \]

Kreisch, Cyr-Racine + (2019)
• Even without using these data in our analysis, the SInu model can naturally accommodate a lower $\sigma_8$ value and larger $H_0$
Sure, the sound horizon is good, but the fit must be terrible, right?

- The model does **improve** the fit compares to $\Lambda$CDM, even after accounting for the extra parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Strongly Interacting Neutrino Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta \chi^2_{\text{low } \ell}$</td>
<td>0.66</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{high } \ell}$</td>
<td>-1.15</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{lens}}$</td>
<td>0.06</td>
</tr>
<tr>
<td>$\Delta \chi^2_{H_0}$</td>
<td>-6.68</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{BAO}}$</td>
<td>-0.81</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{Total}}$</td>
<td>-7.91</td>
</tr>
<tr>
<td>$\Delta \text{AIC}$</td>
<td>-1.91</td>
</tr>
</tbody>
</table>

$$\Delta \text{AIC} = \text{AIC}_{\text{IL}} - \text{AIC}_{\Lambda \text{CDM}} = \Delta \chi^2 + 2\Delta k,$$

Kreisch, Cyr-Racine + (2019)
How important are the neutrino self-interaction?

- Answer: very much so!

Kreisch, Cyr-Racine + (2019)
Why does the SIν work?

- $N_{\text{eff}}$ increases Hubble at early times, hence reducing the sound horizon.
- The tightly-coupled neutrinos do not over damp or phase shift the photon-baryon fluctuations.
- Changes in the primordial spectrum of fluctuations ($n_s, A_s$) absorbs the remainder of the changes.
- What about matter clustering?

$$r_s = \int_0^a da \frac{c_s(a)}{a^2 H(a)}$$
SIν Cosmology and neutrino physics

- The model allows for a whole new neutrinos species and favors a non-vanishing neutrino mass at 2-σ

\[ N_{\text{eff}} = 4.02 \pm 0.29 \]

\[ \sum m_\nu = 0.42^{+0.17}_{-0.20} \text{ eV} \]

Kreisch, Cyr-Racine + (2019)
SIN Cosmology: The dark side

- The required strength of the neutrino self-interaction might be very difficult to model build.

\[ G_{\text{eff}} \sim 10^{10} G_F \]

- It is still unclear whether CMB polarization data can fully accommodate the SIN cosmology.

- The shape of the matter power spectrum might become problematic.
Important Take Home Messages

• As precision increases, cracks might be appearing in the standard cosmological model.

• Inspired by status of neutrino physics, we have explored a self-interacting neutrino scenario that might help reconcile datasets.

• Main message: It is possible to find radically different cosmological model that nonetheless can provide excellent fit to the data.
The model does improve the fit compared to $\Lambda$CDM + $N_{\text{eff}} + m_\nu$, even after accounting for the extra parameter. 

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<tr>
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<tbody>
<tr>
<td>$\Delta \chi^2_{\text{low } \ell}$</td>
<td>2.40</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{high } \ell}$</td>
<td>-3.40</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{lens}}$</td>
<td>-0.20</td>
</tr>
<tr>
<td>$\Delta \chi^2_{H_0}$</td>
<td>-1.32</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{BAO}}$</td>
<td>-0.81</td>
</tr>
<tr>
<td>$\Delta \chi^2_{\text{Total}}$</td>
<td>-3.33</td>
</tr>
<tr>
<td>$\Delta \text{AIC}$</td>
<td>-1.33</td>
</tr>
</tbody>
</table>
might be expected, the addition of the local Hubble con-
by letting the helium fraction float freely in the fit. As
use polarization data, and (ii) our use of BBN calcula-
zlation optical depth prior from Ref. [126] whenever we
slightly increased the significance of the SI
allows the interacting neutrino model to both be compat-
negatively correlated (see second panel in Fig. 7b). This
entry, leading to a positive correlation between

\[ N \text{ km Mpc}^{-1} \]

Francis when including BAO data causes

\[ \text{TT, TE, EE} \quad \text{TT + lens + BAO} \quad \text{TT + lens + BAO + } H_0 \]

Parameter Strongly Interacting Neutrino Mode Moderately Interacting Neutrino Mode

\[ r \]

\[ (G \text{ eV}) \]

\[ N \text{ eff} \]

\[ (G \text{ eV})^2 \]

\[ \sigma_8 \]

\[ H_0 [\text{km/s/Mpc}] \]

(a) \( H_0 \) correlations.

(b) \( \sigma_8 \) correlations.

Kreisch, Cyr-Racine + (2019)
Backup: Impact of self-interacting Neutrinos on matter clustering

- Dark matter perturbation equation can be written as:

\[ \ddot{d}_c + \frac{\dot{a}}{a} \dot{d}_c = -k^2 \psi, \quad d_c \equiv \delta_c - 3\phi, \]

where

\[ ds^2 = a^2(\tau)\left[-(1 + 2\psi)d\tau^2 + (1 - 2\phi)d\bar{x}^2\right], \]

- The general solution (in radiation domination):

\[ d_c(k, \tau) = -\frac{9}{2} \phi_p + k^2 \int_0^\tau d\tau' \tau' \psi(k, \tau') \ln (\tau'/\tau), \]

- Without free-streaming neutrinos, we have:

\[ \phi - \psi = 0 \quad \text{instead of} \quad \phi = (1 + 2R_\nu/5)\psi \]
Backup: Impact of self-interacting Neutrinos on matter clustering

Kreisch, Cyr-Racine + (2019)