Cosmological Probes of Standard Neutrino Scenarios

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My main goal with this talk

Convince neutrino physicists that cosmology is an *interesting* way to study neutrinos that is *complementary* to laboratory experiments.
Perhaps my main obstacle

You are comfortable with this:
Perhaps my main obstacle

You are comfortable with this:

![Deep Underground Neutrino Experiment](image1)

but maybe not this:

![Astronomer looking at the sky](image2)

“I look up into the sky…
…and I conclude things.”

(astronomer explaining their work, as imagined by a neutrino physicist)
Model Dependence
Model Dependence

Complementary to laboratory experiments

Expanded opportunity for discovering new physics
Figure 1: Neutrino interaction cross section as a function of energy, showing typical energy regimes accessible by different neutrino sources and experiments. The curve shows the scattering cross section for $\bar{\nu}_e e^- \rightarrow e^- \bar{\nu}_e$ on free electrons, for illustration. Plot modified from [1].
A broad experimental program in neutrino physics

Figure 1: Neutrino interaction cross section as a function of energy, showing typical energy regimes accessible by different neutrino sources and experiments. The curve shows the scattering cross section for $\bar{\nu}_e e^- \rightarrow e^- \bar{\nu}_e$ on free electrons, for illustration. Plot modified from [1].
Weak interactions were fast

\[ e^-/e^+ \text{ annihilation} \]

Evolution of all significant components in the standard cosmological model

\[ \text{Neutrinos} \quad \text{Smallest CMB scales} \quad \text{Last scattering} \]

\[ \text{Dark Matter + Atoms} \quad \text{Photons} \]

\[ \text{Dark Energy} \]

\[ \rho [g/cm^3] \]

\[ \text{scale factor, } a \]
At least for the standard scenario, cosmology is sensitive to two neutrino parameters

\[ \Sigma m_{\nu} \]

\[ N_{\text{eff}} \]
Current Status: CMB+BAO

- **Planck 2018 CMB Temperature and Polarization Power Spectra**
- **Planck 2018 CMB Lensing Power Spectrum**
- **Baryon Acoustic Oscillation (BAO) compilation**

The graph illustrates the cosmological abundance of neutrinos in terms of the sum of neutrino masses $\Sigma m_\nu$ as a function of $N_{\text{eff}}$, the effective number of degrees of freedom of the relativistic sector. The shaded regions represent the current constraints for the inverted and normal neutrino mass hierarchies.
Current Status: BBN

Deuterium abundance + BBN modeling

Helium abundance + BBN modeling

D/H abundance: Cooke et al. (2018)
D/H BBN model: PArthENoPE + Marcucci et al. (2016)

Helium abundance: Aver et al. (2015)
Helium BBN model: PArthENoPE

baryon density

adapted from Planck 2018 Results VI. Cosmological Parameters
Current Status: BBN

- Deuterium abundance + BBN modeling
- Helium abundance + BBN modeling

**Graph:**

- **Planck TT,TE,EE+lowE**
  - adapted from Planck 2018 Results VI. Cosmological Parameters

- **Axes:**
  - $N_{\text{eff}}$ vs. $\omega_b$
  - $0.018$ to $0.026$ for $\omega_b$
  - $0$ to $6$ for $N_{\text{eff}}$

**Sources:**

- **D/H abundance:** Cooke et al. (2018)
- **D/H BBN model:** PArthENoPE + Marcucci et al. (2016)
- **Helium abundance:** Aver et al. (2015)
- **Helium BBN model:** PArthENoPE
“I look up into the sky…
…and I conclude things.”

–Cosmologist
THE HISTORY OF A SINGLE PHOTON

- $z = 0$
- $z = 100$
- $z = 3$

- Horizon
- Last-scattering surface
I look up at the sky...

Optical sky at night

Wavelength = 0.5 × 10^{-3} \text{ mm}
I look up at the sky...

Optical sky at night
Wavelength = $0.5 \times 10^{-3}$ mm

Microwave sky
Wavelength = 2 mm
...and I map out the cosmic microwave background

Now with greatly increased contrast, so we can see very small brightness variations

Optical sky at night

Wavelength = $0.5 \times 10^{-3}$ mm

Microwave sky

Wavelength = 2 mm
Two important length scales

\( r_s \): how far a sound wave travels before the plasma disappears

\( r_d \): typical distance a photon diffuses before last scattering

disturbance propagating through plasma at sound speed
\[ \theta_s = \frac{r_s}{D_A} \]

\[ \theta_d = \frac{r_d}{D_A} \]
\[ \theta_s = \frac{r_s}{D_A} \]  

typical size of hot or cold spot

\[ \theta_d = \frac{r_d}{D_A} \]  

map is smoothed below this scale

\[ N_{\text{eff}} = 1 \]
Sensitivity to Neff via impact on H(α)

The sound horizon $r_s \sim 1/H$

$$H^2 = \frac{8\pi G \rho}{3}$$

$$\theta_s = \frac{r_s}{D_A}$$
Sensitivity to Neff via impact on $H(a)$

$H^2 = \frac{8\pi G \rho}{3}$

The sound horizon $r_s \sim 1/H$

$$\theta_s = \frac{r_s}{D_A}$$

Photon diffusion is a random walk so $r_d \sim 1/H^{0.5}$

$$\theta_d = \frac{r_d}{D_A}$$

$$\frac{\theta_d}{\theta_s} = \frac{r_d}{r_s} \propto H^{1/2}$$
Neff affects the ratio of sound horizon to diffusion scale

\( Neff = 2 \) simulated CMB map
Neff affects the ratio of sound horizon to diffusion scale.
The Future
DESI in a nutshell

• DESI: Stage-IV dark energy survey
• 35 million redshifts (SDSS x20) with 5 target classes

- Requirement on isotropic BAO
  - $\sigma(R) < 0.28\%$ at $z < 1.1$
  - $\sigma(R) < 0.39\%$ at $z > 1.1$

- Requirement on expansion history
  - $\sigma(H) < 1\%$ at $1.9 < z < 3.7$

• Commissioning confirmed that the instrument met design requirements

• Science verification will start in fall 2020, and the 5-year survey early 2021
Weak interactions were fast e-/e+ annihilation Evolution of all significant components in the standard cosmological model

- Neutrinos
- Smallest CMB scales
- Last scattering
- Dark Matter + Atoms
- Photons
- Dark Energy
**Start of Operations:**
~2027

**Duration:**
7 years

**Last Year:**
- **NSF Mid-Scale Research Infrastructure (MSRI):** to support project management and engineering
- **DOE Critical Decision 0 (CD-0):** to support baseline technical design

**Next:**
- **NSF Preliminary Design Review (PDR) and DOE CD-1** in 2021.
Scientific Opportunities

To achieve CMB-S4’s ambitious scientific targets:

• Sensitivity to both large & small angular scales on the sky
• Increase total instrumental sensitivity by orders of magnitude
• Observe at multiple frequencies to reject foregrounds
• New regime for instrumental characterization, calibration, & systematics control

Measure $N_{\text{eff}}$, $H_0$ test $\Lambda$CDM

Map integrated matter density

Constrain inflation

Astrophysics ++

Future: CMB+BAO

\[ \sigma(N_{\text{eff}}) = 0.03 \text{ from CMB-S4} \]

- Minimum mass for inverted hierarchy
- Normal hierarchy

\[ \sigma(\Sigma m_\nu) = 0.02 \text{ eV from CMB-S4 + DESI BAO (shown above)} \]

\[ \sigma(\Sigma m_\nu) = 0.012 \text{ eV from CMB-S4 + DESI BAO (sensitive to reionization modeling)} \]

See the CMB-S4 Science Case, Reference Design and Project Plan (arXiv:1907.04473) and Alvarez et al. 2020

\[ \sigma(\Sigma m_\nu) = 0.026 \text{ eV from DESI probes alone (arXiv:1611.00036 updated to Planck 2018)} \]
Figure 13. Left: Majorana effective neutrino mass $m_{\beta\beta}$ versus $M_\nu$ in the scenario where NLDBD is mediated by light neutrino exchange. The area enclosed by the blue and red solid lines indicate the allowed 95% ranges from neutrino oscillation experiments [236] for normal ordering (NO) and inverted ordering (IO) assuming complete ignorance of the Majorana phases. The vertical blue and red bands show the forecasted 1σ constraints on $M_\nu$ from CMB-S4 for minimal mass NO and IO. The horizontal band shows the sensitivity of future NLDBD experiments. A CMB-S4 detection of $M_\nu$, in combination with a detection of $m_{\beta\beta}$ can constrain the Majorana phases. Right: Sum of individual the neutrino masses as a function of the electron-neutrino effective mass $m_\beta$ for the NO (blue) and the IO (red). Again, the area enclosed by the blue and red solid lines indicate the allowed 95% ranges from neutrino oscillation experiments [236] for NO and IO. The horizontal bands show the future cosmological constraints around each ordering (assuming the mass of the lightest neutrino state $m_{\text{lightest}} = 0$ eV). Also shown are the anticipated limits on $m_\beta$ from the KATRIN experiment in the case of no detection.
What good is $\sigma(N_{\text{eff}})=0.03$?
To conclude:

You are comfortable with this:

I hope you feel encouraged to talk with cosmologists and ask them to fill in these dots.

but maybe not this:

“I look up into the sky…
…and I conclude things.”

(astronomer explaining their work, as imagined by a neutrino physicist)
Summary/Conclusions

• In cosmology we study a naturally produced background of neutrinos by exploiting their gravitational influence on other matter and radiation.

• Conclusions are model dependent

• There are a rich variety of ways to check the models (that I did not get to tell you about).

• Results are complementary to constraints from laboratory experiments.

• Laboratory + cosmology combined ==> improved scope for discovering new physics.

• For more


  • For a broad, short, overview of cosmological probes of light relics: Messengers from the Early Universe: Cosmic Neutrinos and Other Light Relics (https://arxiv.org/abs/1903.04763)
Outtakes
Future probes of light relics

CMB-S4 Science Case, Reference Design and Project Plan
(https://arxiv.org/abs/1907.04473)
all forecasts include DESI BAO + CMB-S4 primary power spectra

prior on optical depth to Thomson scattering in recognized IGM

Alvarez et al. 2020 claim CMB-S4 can achieve \( \sigma(\tau) = 0.002 \) from using kSZ effect
Current Status: BBN

Deuterium abundance + BBN modeling
Helium abundance + BBN modeling

baryon density

D/H abundance: Cooke et al. (2018)
D/H BBN model: PArthENoPE + Marcucci et al. (2016)

Helium abundance: Aver et al. (2015)
Helium BBN model: PArthENoPE
Neutrino bounds with DESI

- Neutrino constraint from galaxy clustering
  - Constraint from BAO position & from scale-dependent broadband
  - Forecast given for 2-pt statistics only (conservative)

- Neutrino constraint from Ly$\alpha$ forest power spectrum
  - Large redshift lever arm ($z=2$ to $z \sim 5$)
  - Sensitivity to small scales ($\lambda/\Delta \lambda \times 1.2 - 1.6$ vs. SDSS)

<table>
<thead>
<tr>
<th>Data (+Planck 2018)</th>
<th>$\sigma(\Sigma m_\nu)$ [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gal. BAO</td>
<td>0.087</td>
</tr>
<tr>
<td>Gal. ($k_{\text{max}} = 0.1$ \text{ h Mpc}^{-1})</td>
<td>0.034</td>
</tr>
<tr>
<td>Gal. (z-optimized $k_{\text{max}}$)</td>
<td>0.027</td>
</tr>
<tr>
<td>Ly$\alpha$ forest</td>
<td>0.041</td>
</tr>
<tr>
<td>Ly$\alpha$ forest + Gal. ($k_{\text{max}} = 0.1$)</td>
<td>0.032</td>
</tr>
<tr>
<td>Ly$\alpha$ forest + Gal. (optimized $k_{\text{max}}$)</td>
<td><strong>0.026</strong></td>
</tr>
</tbody>
</table>
At $kT > 1$ MeV, weak reactions that create and destroy neutrinos are sufficiently rapid that a thermal distribution of neutrinos is created.
Extra species in equilibrium $\rightarrow$ faster expansion rate (at a given temperature)

\[ H^2 = \frac{8\pi G \rho}{3} \]

\[ \rho = g\left(\frac{\pi^2}{30}\right) T^4 \]

\[ \frac{h}{(2\pi)} = k_B = c = 1 \]
History of Contributions to the Expansion Rate

\[ H^2 = \frac{8\pi G \rho}{3} - \frac{K}{a^2} \]

**Components of \( H^2 \):**
- **Radiation**
- **Matter**
- **Curvature (- \( \frac{K}{a^2} \))**
- **Cosmological constant**
Conditions for Equilibrium

Reactions fast enough to keep density = equilibrium density

$\Gamma = \text{per-particle reaction rate}$

Log (Rate)

Log (a = scale factor)

Time -->

<--- Temp
Weak interactions were fast.

\[ e^-/e^+ \text{ annihilation} \]

Evolution of all significant components in the standard cosmological model.
Approximate result of “electron cooling” of neutrinos

\[ \frac{T_{\gamma, \text{after}}}{T_{\nu, \text{after}}} = \left( \frac{11}{4} \right)^{1/3} \]

Cosmological standard model has \( Neff = 3.046 \) because some of electron/positron entropy does go to neutrinos.

Note: \( Neff \) is capturing contributions to energy density that are redshifting like radiation; i.e., no mass!
Approximate result of “electron cooling” of neutrinos

\[ \frac{T_{\gamma, \text{after}}}{T_{\nu, \text{after}}} = \left( \frac{11}{4} \right)^{1/3} \]

Total energy density in relativistic species

\[ \rho_r = \frac{\pi^2 k_B^4}{15 \hbar^3 c^3} \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right] T_\gamma^4 \]

Due to reduced temperature

If electron/positron cooling did \textit{not} happen \( \Delta N_{\text{eff}} \approx 8 \)

\( \sigma(N_{\text{eff}}) \approx 0.3 \rightarrow \sim 25\sigma \) detection of electron cooling
Neutrinos (and other light and dark relics) and Cosmology

- The Source
- The Detectors

- Light element abundances
- CMB temperature and polarization power spectra
- Matter power spectrum at late times
Neutron / proton interconversion

The reactions converting neutrons to protons and vice versa are

\[ n + \nu_e \leftrightarrow p + e^- \]
\[ n + e^+ \leftrightarrow p + \bar{\nu}_e \]

where \( \nu_e \) is an electron neutrino and \( \bar{\nu}_e \) its anti-particle. As long as these interactions remain fast until \( kT \) is about 0.8 MeV.

While they are fast we have:

\[ n_n / n_p \approx \exp \left[ -\frac{(m_n - m_p)c^2}{k_B T} \right] \]
Production of Helium

If $\Gamma > H$ then

$$n_n = n_p \exp(-\Delta mc^2/kT)$$

At freeze-out:

$$n_n/n_p \simeq 1/5 \rightarrow \frac{n_n}{(n_n + n_p)} = 1/6.$$
Production of Helium

If $\Gamma > H$ then

$$n_n = n_p \exp(-\Delta mc^2/kT)$$

1 MeV

$T_{P,n}$ freeze-out

At freeze-out:

$$n_n/n_p \simeq 1/5 \rightarrow n_n/(n_n + n_p) = 1/6.$$  

At $T_{nuc}$:

$$n_n/n_p \simeq 1/7 \rightarrow n_n/(n_n + n_p) = 1/8.$$
1/8 nucleons is a neutron ==> 1/4 of mass in 4He
Production of Helium

If $\Gamma > H$ then

$$n_n = n_p \exp(-\Delta mc^2/kT)$$

Quiz: what is impact of extra neutrino species (or extra light and dark relics?)
Dependence of Helium production on neutrinos

- More $\nu$ species $\Rightarrow$ higher total $\rho$ (at given $T$) $\Rightarrow$ higher $H$
  (at given $T$) $\Rightarrow$ $\Gamma = H$ at higher $T$ $\Rightarrow$ more neutrons around $\Rightarrow$ more Helium

(also less time for neutron decay)

$H^2 = \frac{8\pi G \rho}{3}$

If $\Gamma > H$ then

$n_n = n_p \exp(-\Delta mc^2/kT)$

$\rho$ (per-neutron rate of $p + e \leftrightarrow n + \nu_e$)

Cooler $\Rightarrow$

$p$, $\Gamma$ here is per-neutron rate of $p + e \leftrightarrow n + \nu_e$

More $\nu$ species $\Rightarrow$ higher total $\rho$ (at given $T$) $\Rightarrow$ higher $H$

$T_{p,n}$ freeze-out

$T_{\text{nuc}}$

1 MeV

0.1 MeV
Dependence of Primordial Helium on the number of neutrino species, $N_{\text{eff}}$

$Y = \text{fraction of baryonic mass in Helium}$

Cyburt, Fields & Olive (2001)
An HII region is one where there is ionized Hydrogen (HII), usually from young stars that pump out ultraviolet light.
Spectrum of an HII region

Inference of He/H from data like this is challenging!
An interesting history of $Y_P$ inferences

Figure credit: Erik Aver
An interesting history of $Y_p$ inferences

Abundance Progression

Figure credit: Erik Aver
Is the modeling still overly simplistic?
Cyburt, Olive & Fields (2001)

baryon-to-photon ratio
Based on Deuterium/Hydrogen inferred from quasar absorption line systems
Neutrinos (and other light and dark relics) and Cosmology

• The Source

• The Detectors

• Light element abundances

• CMB temperature and polarization power spectra

• Matter power spectrum at late times
The CMB is Like a Detector of Some Noise Source

1/f noise

Detector output

Transfer function has (e.g.) suppressed high f
The CMB is Like a Detector of Some Noise Source

1/f noise

Transfer function has suppressed high frequencies
The CMB is Like a Detector of Some Noise Source

1/f noise

Transfer function has suppressed high frequencies

Detector output

Noise source (input)
Impact of Neff on CMB power spectra

• Via background cosmology
  • Sound horizon
  • Photon diffusion scale

• Via Perturbations
  • Shift in temporal phase of acoustic oscillations

$N_{\text{eff}} = 3.00^{+0.57}_{-0.53}$ \hspace{1em} (95\%, \textit{Planck} TT+lowE),

$N_{\text{eff}} = 2.92^{+0.36}_{-0.37}$ \hspace{1em} (95\%, \textit{Planck} TT,TE,EE+lowE),

$N_{\text{eff}} = 2.99^{+0.34}_{-0.33}$ \hspace{1em} (95\%, TT,TE,EE+lowE+lensing +BAO).
Neutrinos (and other light and dark relics) and Cosmology

- The Source
- The Detectors
  - Light element abundances
  - CMB temperature and polarization power spectra
- Matter power spectrum at late times
Impact of $\Sigma m_\nu$

$\Sigma m_\nu = 0, 0.05, 0.15, 0.3$ eV

$N_{\text{eff}} = 3$

M. Millea
$\sum m_\nu < 0.16 \text{ eV} \quad (95 \%, \text{ Planck TT+lowE+BAO}),$

$\sum m_\nu < 0.13 \text{ eV} \quad (95 \%, \text{ Planck TT,TE,EE+lowE+BAO}),$

and combining with lensing the limits further tighten to

$\sum m_\nu < 0.13 \text{ eV} \quad (95 \%, \text{ Planck TT+lowE+lensing+BAO}),$

$\sum m_\nu < 0.12 \text{ eV} \quad (95 \%, \text{ Planck TT,TE,EE+lowE+lensing+BAO}).$
Neff + \( m \) and \( n \) constraints important for model building

Example: \( m \sim \text{eV} \) extensions motivated by neutrino oscillation experiments

Typically thermal production is disastrous, but that’s model dependent.

e.g., Cherry, Friedland & Shoemaker: https://arxiv.org/abs/1605.06506
Understanding Power Spectra

Sky map

Power spectrum
Understanding Power Spectra

Sky map

Power spectrum

I = oscillations per great circle
Can infer $\theta_s$ from peak spacing: $\theta_s \approx \pi / \Delta \ell$
if no photon diffusion

angular scale of photon diffusion: $\theta_d$
Short–baseline neutrino oscillations, Planck, and IceCube

John F. Cherry (Virginia Tech.), Alexander Friedland (SLAC), Ian M. Shoemaker (Penn State U.)

(Submitted on 20 May 2016)

We examine a framework with light new physics, which couples to the Standard Model only via neutrino mixing. Taking the hints from the short–baseline anomalies seriously and combining them with modern cosmological data and recent IceCube measurements, we obtain surprisingly effective constraints on the hidden force: keV \( \lesssim M \lesssim 0.3 \text{ GeV} \) for the mediator mass and \( g_h > 10^{-6} - 10^{-3} \) for the coupling constant. Flavor equilibration between the hidden and active neutrinos can be delayed until temperatures of \( \sim 1 \text{ MeV} \), but not below \( \sim 100 \text{ keV} \). This scenario can be tested with next–generation Cosmic Microwave Background, IceCube, and oscillation experiments.