Cosmic Neutrinos and Other Light Relics

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Moriond Cosmology
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Based on:
arXiv:1508.06342 with Daniel Baumann, Dan Green, and Benjamin Wallisch
arXiv:1604.xxxxx with Dan Green and Alex van Engelen
Moore’s Law for CMB Experiments
A Theorist’s (Abridged and Biased) Timeline of CMB Science

• 1948 – Alpher, Gamow, and Herman predict existence of CMB

• 1964 – Penzias and Wilson accidentally make first measurements of CMB

• 1992 – COBE – Big Bang Cosmology, Anisotropies

• 2003 – WMAP – $\Lambda$CDM Cosmology

• 2013 – Planck – Non-Gaussianity

• 2015+ – CMB Stage III and CMB Stage IV – Gravitational Waves, Neutrino Mass, and $N_{\text{eff}}$
The “effective number of neutrino species” $N_{\text{eff}}$ measures the total energy density in radiation excluding photons. Because it receives contributions from all sorts of radiation, $N_{\text{eff}}$ need not have anything to do with neutrinos. $N_{\text{eff}}$ is observable due to the gravitational influence of the radiation in the early universe.

$$\rho_r = \rho_\gamma \left( 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right)$$
CvB Contribution to $N_{\text{eff}}$

- Electron positron pairs annihilated after neutrino decoupling, heating photons relative to neutrinos
- Comoving entropy conservation fixes the neutrino temperature relative to photon temperature
- Residual coupling of neutrinos leads to a slight increase in energy density over the simple instantaneous decoupling picture

$N_{\text{eff}}^{\text{SM}} = 3.046$

PDG (2013); Mangano, et al. (2005)
Observing $N_{\text{eff}}$

- Primordial Abundances
  \[ N_{\text{eff}}^{\text{BBN}} = 3.28 \pm 0.28 \]

- CMB Measurements
  \[ N_{\text{eff}}^{\text{CMB}} = 3.04 \pm 0.18 \]

- Combining these constraints gives insight into time-dependent changes in $N_{\text{eff}}$

Big Bang Nucleosynthesis

- Measurements of primordial light element abundances put a constraint on $N_{\text{eff}}$ at around 3 minutes after the end of inflation.
- BBN is weakly sensitive to the neutrino spectrum as well as the total radiation energy density.

$$N_{\text{eff}}^{\text{BBN}} = 3.28 \pm 0.28$$

Effects of Neutrinos on the CMB

- Increased radiation density leads to increased damping (when holding the scale of matter-radiation equality fixed).
- Anisotropic stress due to radiation free streaming has two effects:
  - Shift in amplitude at small scales
  - Phase shift of acoustic peaks at small scales

\[ N_{\text{eff}}^{\text{CMB}} = 3.04 \pm 0.18 \]

Forecasted Constraints

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Timeline</th>
<th>$\sigma(N_{\text{eff}})$</th>
<th>$\sigma(\Sigma m_\nu)$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planck</td>
<td>Present</td>
<td>0.18</td>
<td>0.23</td>
</tr>
<tr>
<td>AdvACT/SPT3G</td>
<td>2016-2019</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>CMB-S4</td>
<td>2020-?</td>
<td>0.02</td>
<td>0.016 (with DESI)</td>
</tr>
</tbody>
</table>

- CMB constraints on $N_{\text{eff}}$ are rapidly improving due to several ongoing and future observations.
- Errors are likely to shrink by an order of magnitude within the next decade due to high resolution ground-based measurements of CMB temperature and polarization.

Benson, et al. (2014); Naess, et al. (2014); Snowmass (2013)
Dark Radiation

• Current observations agree with the standard model predictions for the cosmic neutrino background
• Measurements of $N_{\text{eff}}$ give constraints on all forms of decoupled radiation, including:
  – Gravitational waves
  – Sterile neutrinos
  – Dark photons
  – Many others

Chu, Cirelli (2006); Boyle, Buonanno (2007); Ackerman, et al. (2008); Steigman (2012); Meerburg, Hadzhiyska, Hlozek, JM (2015) ...
Light Thermal Relics

- Planck mostly rules out particles which decouple after the QCD phase transition
- CMB-S4 has the reach to exclude or detect all thermal relics which decoupled at essentially arbitrarily high temperature

Brust, Kaplan, Walters (2013); Chacko, Cui, Hong, Okui (2015)
The Special Role of the Phase Shift

- Fluctuations in free-streaming radiation lead to a characteristic phase shift of the acoustic peaks of the CMB power spectrum at small angular scales.
- This phase shift is particularly important for several reasons:
  - It is difficult to reproduce in the absence of free-streaming radiation.
  - The phase shifts break degeneracies which would otherwise be present.
  - Various forms of dark radiation can be distinguished by the phase shift.
  - Future constraints will be driven by the phase shift.

Bashinsky, Seljak (2004); Baumann, Green, JM, Wallisch (2015)
The phase shift can be used to distinguish between free streaming and non-free streaming radiation species.

The phase shift is most easily detectable in the delensed EE spectrum due to the sharper peaks.
Delensing Forecasts

- Delensing sharpens peaks and reduces lensing-induced covariance, thereby tightening errors on $N_{\text{eff}}$
- Using unlensed power spectra results in overly optimistic forecasts
- Realistic forecasts need to include delensing in the presence of noise

Green, JM, van Engelen (In Prep.)
Conclusions

• There is a great deal of interesting physics left to be explored with ongoing measurements of the CMB
• $N_{\text{eff}}$ in particular holds a great deal of promise for constraining physics beyond the standard model, and has a well motivated theoretical target at $\Delta N_{\text{eff}} = 0.027$ within reach of CMB-S4
• The phase shift which results from free-streaming radiation breaks degeneracies, drives constraints on $N_{\text{eff}}$ and distinguishes various forms of radiation
• We stand to learn a huge amount by measuring $N_{\text{eff}}$ even without a significant deviation from the standard model prediction

$10^9$ cosmic neutrinos pass through this snowflake each second!