Constraining the number of neutrinos with CMB data from the South Pole Telescope

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The effective number of neutrinos, \( N_{\text{eff}} \), can be constrained by cosmological data, particularly observations of the cosmic microwave background (CMB).

**Overview**

SPT + WMAP,
\[
N_{\text{eff}} = X \pm 0.62
\]

SPT+WMAP+(Hubble Constant+BAO),
\[
N_{\text{eff}} = Y \pm 0.42
\]
The effective number of neutrinos, $N_{\text{eff}}$, can be constrained by cosmological data, particularly observations of the cosmic microwave background (CMB).

**SPT + WMAP,**

$$N_{\text{eff}} = 3.85 \pm 0.62$$

**SPT+WMAP+(Hubble Constant+BAO),**

$$N_{\text{eff}} = 3.86 \pm 0.42$$  (~$2\sigma$ preference for $N_{\text{eff}}>3$)
Outline

1. What is the CMB, and how does an extra neutrino affect it?
2. Constraints from SPT+WMAP
3. What’s next?
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What is the Cosmic Microwave Background?

The constituents of the early universe (photons, electrons, protons, dark matter, neutrinos, ...) were coupled.

- gravity pulls,
- radiation pressure pushes (on some of them)

$=>$ oscillations
Eventually the universe expands and cools such that **neutral hydrogen can form**. “Recombination”

No more free electrons, no more Thomson scattering between photons and electrons.

=> Photons can travel freely, and we see them today as a blackbody with $T=2.73K$.

The small anisotropies we see in the CMB are due to oscillations in early plasma.
WMAP
Angular Power Spectrum

![Angular Power Spectrum Graph](image)

- **Angular Frequency (multipole)**
- **Power**

**Graph Details:**
- **X-axis:** Angular Frequency (multipole)
- **Y-axis:** Power in $\mu K^2$

**Legend:**
- **WMAP7**

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[Image -448x-156 to 1472x924]
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The Sound Scale

\[ \theta_{\text{sound}} \sim \frac{1}{\theta_{\text{sound}}} \]

\( \theta_{\text{sound}} \) is the (angular) distance a sound wave could have traveled by recombination.
The **Damping Scale**

Photons aren’t perfectly coupled to electrons/protons. Photon has some mean free path and diffuses. **Oscillations on small scales are damped exponentially.**

$\theta_d$ is the (angular) diffusion length at recombination.
Angular Power Spectrum

Angular Frequency (multipole)
Sensitivity to Neutrinos

How does an extra neutrino affect these CMB observables, $\theta_s$ and $\theta_d$?

An extra neutrino species increases the expansion rate during this radiation-dominated era.

$$\left( \frac{\dot{a}}{a} \right)^2 \equiv H^2 \propto (\rho_\gamma + \rho_\nu + \rho_{\text{matter}} + \ldots)$$

More neutrinos $\Rightarrow$ higher density $\Rightarrow$ faster expansion
Sensitivity to Neutrinos

Consider how the real space equivalents, \( r_s \) and \( r_d \), depend on the expansion rate, \( H \):

\[
\begin{align*}
    r_s &\propto \int_0^{a_*} \frac{c_s da}{a^2 H} \\
    r_s &\propto H^{-1}
\end{align*}
\]

\[
\begin{align*}
    r_d &\propto \int_0^{a_*} \frac{da}{a^3 \sigma T n_e H} \propto \frac{1}{H} \\
    r_d &\propto H^{-0.5}
\end{align*}
\]

\[
\frac{r_d}{r_s} = \frac{\theta_d}{\theta_s} \propto H^{0.5}
\]

(see 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)
Sensitivity to Neutrinos

\[ \frac{r_d}{r_s} \propto H^{0.5} \propto (\rho_\gamma + \rho_\nu + \rho_m + \ldots)^{0.25} \]

\[ \frac{\theta_d}{\theta_s} \propto (\rho_\gamma + \rho_\nu + \rho_m + \ldots)^{0.25} \]

- The ratio \( \frac{\theta_d}{\theta_s} \) is measured well using the CMB.
- The photon density \( \rho_\gamma \) is well known from 3K temperature of CMB.
- The ratio \( \frac{\rho_m}{\rho_\gamma + \rho_\nu} = 1 + z_{EQ} \) is also well measured using CMB.

We can solve for the neutrino density \( \rho_\nu \).

(see 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)
in practice...

\[
\frac{\theta_d}{\theta_s} \propto (\rho_\gamma + \rho_\nu + \rho_m + \ldots)^{0.22}
\]

~0.22, not 0.25, due to two competing effects (a*, the scale factor at recombination, is a function of expansion rate, as is electron density). See 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt, for details.
defining $N_{\text{eff}}$

$N_{\text{eff}}$ is the *effective number of relativistic species*.

$$N_{\text{eff}} \equiv \frac{\rho_\nu}{\rho_\gamma} \left( \frac{8}{7} \left( \frac{11}{4} \right)^{4/3} \right)$$

The standard value is $N_{\text{eff}} = 3.046$.

This is

- 3.000 for the 3 neutrino species,
- 0.046 for energy injected by electron/positron annihilation.

$N_{\text{eff}} > 3.046$ could correspond to a new particle species that is relativistic prior to recombination and has the energy density of one of the standard neutrinos.
Take Away #1

\[ \frac{\theta_d}{\theta_s} \]

CMB data that measures \( \frac{\theta_d}{\theta_s} \) can constrain the number of neutrinos, due to the sensitivity of that ratio to the expansion rate prior to recombination.
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   Next talk: ACT+WMAP results from Sudeep Das.

3. What’s next?
The South Pole Telescope: a mm-wave observatory

- 10 meter primary mirror
  ~1 arcminute resolution

- 1st camera: 1000 bolometers.
  3 bands: 3.2, 2.0, 1.4 mm.
  2007-2011

- 2nd camera: 1600 bolometers.
  polarization-sensitive.
  2 bands: 3.2, 2.0 mm
  2012-?
Why the South Pole?

- **Atmospheric transparency and stability:**
  - Extremely dry and cold.
  - High altitude ~10,500 feet.
  - Sun below horizon for 6 months.

- **Unique geographical location:**
  - Observe the clearest views through the Galaxy, 24/365, “relentless observing”
  - Clean horizon.

- **Excellent support from existing research station.**
SPT 2500 deg$^2$ “SZ” Survey

- 2500 deg$^2$ at high galactic latitude in Southern Sky.
- 6% of the sky.
- RA: 20h to 7h
- Dec: -40 to -65

Final survey depths of:
- 90 GHz: 42 uK$_{CMB}$-arcmin
- 150 GHz: 18 uK$_{CMB}$-arcmin
- 220 GHz: 85 uK$_{CMB}$-arcmin

(In these units, tSZ is 1.7 times brighter at 90 GHz than at 150 GHz.)
SPT 2500 deg$^2$ SZ Survey

**Status:** finished in Nov. 2011.
All results shown today use $1/3$ of this data.
SPT has ~20X better resolution and lower noise, but covers only ~5% of the sky.
SPT map

new massive galaxy cluster
Take the angular power spectrum of 1/3 of this:
...and you get this.
Cosmological Analysis

- **MCMC analysis** (cosmoMC/CAMB)

- **Data:**
  - **CMB** from **SPT**
  - **CMB** from **WMAP7**
  - **[H0 from HST, Riess et al]**
  - **[BAO from SDSS, Percival et al]**
Two component model:

- **CMB**, lensed primary CMB from flat \( \Lambda \)CDM, seven parameters:
  \[
  (\Omega_b h^2, \Omega_c h^2, \ell^*, \tau, \Delta^2_R, n_s, \text{Neff})
  \]

- **Foregrounds**, 
  - SZ power (1 parameters)
  - emission from galaxies (shot noise & spatially correlated, 2 parameters)

10 parameters (7 cosmo., 3 “nuisance”)
No Neutrinos vs Standard Neutrinos?

Simple test: compare maximum likelihood in Neff=0 model to that in Neff=3.046 model.

Standard neutrinos are preferred over no neutrinos preferred by $\delta \chi^2 = 56.3$, i.e. 7.5-sigma.

The CMB strongly detects presence of neutrinos in early universe.

Constraints on Neff

- $N_{\text{eff}} = 3.85 \pm 0.62 \text{ (SPT+WMAP7)}$
- $N_{\text{eff}} = 3.86 \pm 0.42 \text{ (SPT+WMAP7+H0+BAO)}$

See RK, C. Reichardt et al, 1105.3182

(1.3σ higher than 3.046)

(1.9σ higher than 3.046)
The CMB data are consistent with standard Neff. Adding the “low-redshift” data (H0+BAO) then favors Neff>3.046 at ~2σ.
Are high-Neff models consistent with galaxy clusters?

- High-Neff models also have high sigma8's and are disfavored by abundance of low-redshift galaxy clusters (Vikhlinin et al).

- However, all of this “tension” goes away if neutrinos are allowed to have total mass of \( \sim 0.3 \text{ eV} \), since that lowers the CMB prediction for sigma8.
And the improvement on $N_{\text{eff}}$ is really due to the improvement on the angle ratio, $(\theta_d/\theta_s)$.

SPT+WMAP measures the angle ratio, $(\theta_d/\theta_s)$, much better than WMAP alone.

If you apply a $(\theta_d/\theta_s)$ prior to the WMAP data, you get the WMAP+SPT result.

(see 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)
Take Away #2

CMB data strongly detect presence of neutrinos in the early universe and measure Neff to be $1.3\sigma$ higher than standard value.

- Neff = 3.85 +/- 0.62

When CMB data are combined with low-redshift data, Neff is measured to be $\sim2\sigma$ higher than standard value.

- Neff = 3.86 +/- 0.42
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Current constraints on Neff:

SPT 800 deg$^2$ (+WMAP7+H0+BAO):
\[ dN_{\text{eff}} \sim 0.42 \]

SPT 2500 deg$^2$ (+WMAP7+H0+BAO):
\[ dN_{\text{eff}} \sim 0.33 \]

Planck:
\[ dN_{\text{eff}} \sim 0.2 \]

CMBpol:
\[ dN_{\text{eff}} \sim 0.05 \]
(see Galli et al. 1005.3808)
Current constraints on Neff:

SPT 800 deg$^2$ (+WMAP7+H0+BAO):
\[ d\text{Neff} \sim 0.42 \]

Planck:
\[ d\text{Neff} \sim 0.2 \]

CMBpol:
\[ d\text{Neff} \sim 0.05 \] (see Galli et al. 1005.3808)

Projections for Neff:

SPT 2500 deg$^2$ (+WMAP7+H0+BAO):
\[ d\text{Neff} \sim 0.33 \]
SPT 2500 sq. deg. Power Spectrum

$\ell (\ell + 1) c^2 / 2 \pi \text{ [}\mu K^2\text{]}$ vs. $\ell$

$\Delta N_{\text{eff}} \sim 0.33$

Work led by Kyle Story, Zhen Hou, Christian Reichardt, RK.
- CMB data can constrain the number of neutrinos due to the neutrinos’ effect on the expansion rate.

- Current CMB data detect neutrinos with high significance and are consistent with standard neutrino content. Adding low-redshift data leads to a 2σ preference for high Neff.

- In the next 3 months we should know Neff to 0.33.

In the next 9 months we should know Neff to 0.2.
extra slides
This ratio is also a function of the **primordial helium abundance, $Y_p$.** In standard BBN, this is a weak function of $N_{\text{eff}}$.

In our fits to the CMB data, we self-consistently change $Y_p$ as a function of the $N_{\text{eff}}$ and $\Omega_b h^2$ using a fitting formula from Simha & Steigman 2008). This actually gives us extra sensitivity to $N_{\text{eff}}$.  

(see 1104.2333, Z. Hou, RK, L. Knox, C. Reichardt)