Neutrinos in Cosmology

Jan Hamann
Sydney Institute for Astronomy

PPC 2015
2nd July 2015, Deadwood SD
The “standard model” of cosmology

Geometry \hspace{1cm} Energy content

\[
G_{\mu\nu} = 8\pi G T_{\mu\nu}
\]
The “standard model” of cosmology

Geometry

\[ G_{\mu\nu} = 8\pi G T_{\mu\nu} \]

Energy content

Cosmological principle
(slightly perturbed)
The “standard model” of cosmology

Geometry

Energy content

\[ G_{\mu \nu} = 8\pi G T_{\mu \nu} \]

Cosmological principle (slightly perturbed)

SM particles and interactions

Dark energy (Cosmological constant)

Dark matter (cold)
The “standard model” of cosmology

Geometry

\[ G_{\mu\nu} = 8\pi G T_{\mu\nu} \]

Energy content

- Dark energy (Cosmological constant)
- Dark matter (cold)
- SM particles and interactions
- Neutrinos

Cosmological principle (slightly perturbed)
neutrinos decouple

$e^+e^-$ annihilation
The Cosmic Neutrino Background (CνB)

- Neutrino decoupling around $T = 1$ MeV, shortly before $e^+ + e^- \leftrightarrow \gamma + \gamma$ goes out of equilibrium
- Annihilation heats CMB relative to CνB
  \[ T_{\text{CνB}} \approx T_{\text{CMB}} (4/11)^{1/3} \approx 1.95 \text{ K} \]
- Neutrino mixing equilibrates momentum distributions
- If $T_{\text{reheating}} > 10$ MeV, all three flavours populated
  \[ \bar{n}_\nu \approx 6 \times 56 \text{ cm}^{-3} \]
- Direct detection extremely difficult, but may not be entirely impossible? Capture of relic neutrinos by Tritium nuclei (PTOLEMY) [Weinberg 1962; Betts+ 2013]
Impact of cosmological neutrinos

**Structure formation**

- Background evolution
- Evolution of perturbations

**Neutrinos**

- Background evolution
- Nuclear reactions

**Big Bang Nucleosynthesis**
Particle content of the Universe (after BBN)

<table>
<thead>
<tr>
<th></th>
<th>interacting</th>
<th>non-interacting</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>relativistic</em></td>
<td>photons</td>
<td>neutrinos</td>
</tr>
<tr>
<td><em>(radiation)</em></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>non-relativistic</em></td>
<td>baryons</td>
<td>cold dark matter</td>
</tr>
<tr>
<td><em>(matter)</em></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Neutrino parameters

How much energy density do neutrinos contribute... 

... at early times?

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

Fermi-Dirac vs. Bose-Einstein

lower neutrino temperature

Effective number of neutrino species

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

(\( \Lambda \)CDM: small deviation from Fermi-Dirac)
Neutrino parameters

How much energy density do neutrinos contribute...

... at early times?

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

- Photon energy density
- Radiation energy density
- Fermi-Dirac vs. Bose-Einstein
- Lower neutrino temperature
- Effective number of neutrino species

... at late times?

\[ \Omega_\nu h^2 \approx \frac{\sum m_\nu}{93 \text{ eV}} \]

- Neutrino energy density
- Sum of neutrino masses

\( \Lambda CDM: \ N_{\text{eff}} = 3.046 \) (small deviation from Fermi-Dirac)

\( \Lambda CDM: \ \sum m_\nu = 0.06 \text{ eV} \) (assumes lightest mass state is massless)
Planck constraints on neutrinos

[see also Olivier Perdereau’s talk on Monday]
CMB angular power spectrum

- Mostly sensitive to neutrinos’ impact on background evolution
- Other cosmological parameters can to some extent mimic effect of changing neutrino mass or number of neutrino species (geometrical degeneracy)
- In extended models, combining with external data sets can help break degeneracies

[Planck collaboration 2015]
Planck constraints on the sum of neutrino masses

No sign of non-zero neutrino masses...

[Planck collaboration 2015]
Planck constraints on the sum of neutrino masses

Profile likelihood

Constraints from Bayesian and frequentist methods are compatible

<table>
<thead>
<tr>
<th>Data set</th>
<th>Bayesian posterior</th>
<th>Profile likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMB + lensing</td>
<td>0.85</td>
<td>0.88</td>
</tr>
<tr>
<td>CMB + lensing + BAO</td>
<td>0.25</td>
<td>0.26</td>
</tr>
</tbody>
</table>

Table 6. Upper limit (95% confidence) on the neutrino mass (in eV) in the Planck Bayesian framework and in the frequentist one based on Feldman–Cousins prescription.

[Planck collaboration 2013]
Planck constraints on the effective number of relativistic species

Data confirm standard model expectation
(CvB only, no more hints of additional light particles)

[Planck collaboration 2015]
Excellent match with BBN expectation + astrophysical element abundance measurements

[Planck collaboration 2015]
Planck constraints on eV-mass sterile neutrinos

Planck data not compatible with a fully thermalised eV-mass neutrino

Want to save the scenario?
Need to suppress production of steriles (e.g., lepton asymmetry, new interactions, etc.)

\[
N_{\text{eff}} < 3.7
\]
\[
m_{\nu, \text{sterile}}^{\text{eff}} < 0.38 \text{ eV}
\]

95%, Planck TT+lowP+lensing+BAO.

[Planck collaboration 2015]
Neutrinos and large scale structure
Free streaming

Velocity dispersion small wrt size of potential well

Gravitational potential

Cold dark matter

Gravitational potential

Particles remain confined to potential well

Initial time

Later time

Neutrino
**Free streaming**

*Velocity dispersion large wrt size of potential well*

- Gravitational potential
- Cold dark matter
- Neutrino

Initial time:
- Neutrinos escape from potential well, density perturbations get washed out

Later time:
Structure formation with massive neutrinos

\[ \Sigma m_\nu = 0 \text{ eV} \quad \Sigma m_\nu = 7 \text{ eV} \]

Z=32.33

[simulation and movie by T. Haugbølle]
Matter power spectrum with massive neutrinos

\[ \Delta P / P \approx 8 \frac{\omega_\nu}{\omega_m} \]

[Abazajian+ 2013]
Matter power spectrum with massive neutrinos

Suppression of the matter power spectrum wrt massless neutrino case

Linear regime

\[ \Delta \equiv \frac{k^3 P(k)}{2\pi^2} \ll 1 \]

\[ \sum m_\nu = 0 \]

\[ \sum m_\nu = 50 \text{ meV} \]

\[ \sum m_\nu = 100 \text{ meV} \]

\[ \sum m_\nu = 150 \text{ meV} \]

[Abazajian+ 2013]
Nonlinear structure formation with massive neutrinos

Simulations with CDM and neutrino particles

Theoretical prediction of matter power spectrum with massive neutrinos in the non-linear regime is a numerical challenge

N-body simulations with neutrino particles, grid-based, hybrid approach...

Probes of the matter power spectrum

Lyman-α forest

Galaxy clustering

Cluster counts

Cosmic shear

CMB lensing
Lyman-α forest

Results in flux power spectrum which requires hydrodynamical simulations to be related to matter power spectrum.
SDSS III Lyman-α forest data

1d flux power spectra

| Parameter | (1) Lyα + $H_0^{\text{Gaussian}}$ & (2) Lyα + Planck TT+lowP & (3) Lyα + Planck TT+lowP + BAO & (4) Lyα + Planck TT+TE+EE+lowP + BAO |
|-----------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|
| $\Sigma m_\nu$ (eV) | $< 1.1$ (95% CL) | $< 0.12$ (95% CL) | $< 0.13$ (95% CL) | $< 0.12$ (95% CL) |

[Palanque-Delabrouille+ 2015]
In the next 10 years...

• Improvements to CMB lensing data (polarisation!) from ground- and balloon-based CMB observations (e.g., POLARBEAR, SPTPol, BICEP3, etc.), possibly also space-based (LiteBird)

• Next-generation large scale structure surveys (DESI, Euclid, LSST) will map a good part of the local Universe out to redshift $z \approx 2$
Future Large Scale Structure surveys

- **BAO scale**
  - $\xi(r)$ plot with reconstructed CMASS and best-fit lines
  - $\alpha = 1.024 \pm 0.016$
  - $\chi^2 = 34.53/39$ dof

- **Type Ia supernovae**
  - Image of a supernova

- **Cosmic shear**
  - Image of cosmic shear pattern

- **Cluster counts**
  - Image of cluster counts

- **Galaxy clustering**
  - Image of galaxy distribution

- **Geometric observables**
  - Image of geometric observables

- **Perturbation-based observables**
  - Image of perturbation-based observables
Parameter forecast
(for a EUCLID-like experiment)

Beautiful complementarity between different observables: combination breaks parameter degeneracies of individual probes

[Hamann+ 2012]
Parameter forecast
(for a EUCLID-like experiment)

Parameter sensitivities

<table>
<thead>
<tr>
<th>Data</th>
<th>$10^3 \times \sigma(\omega_m)$</th>
<th>$100 \times \sigma(h)$</th>
<th>$\sigma(\sum m_\nu)/eV$</th>
<th>$\sigma(N_{\text{eff}}^{\text{ml}})$</th>
<th>$\sigma(w_0)$</th>
<th>$\sigma(w_p)$</th>
<th>$\sigma(w_a)$</th>
<th>FoM/$10^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>csgx</td>
<td>1.2</td>
<td>0.86</td>
<td>0.022</td>
<td>0.069</td>
<td>0.077</td>
<td>0.010</td>
<td>0.22</td>
<td>0.45</td>
</tr>
<tr>
<td>ccl</td>
<td>0.98</td>
<td>0.32</td>
<td>0.039</td>
<td>0.031</td>
<td>0.038</td>
<td>0.022</td>
<td>0.16</td>
<td>0.29</td>
</tr>
<tr>
<td>csgxcl</td>
<td>0.27</td>
<td>0.23</td>
<td>0.0098</td>
<td>0.019</td>
<td>0.025</td>
<td>0.0052</td>
<td>0.085</td>
<td>2.3</td>
</tr>
<tr>
<td>cscl</td>
<td>0.35</td>
<td>0.29</td>
<td>0.010</td>
<td>0.022</td>
<td>0.031</td>
<td>0.0087</td>
<td>0.10</td>
<td>1.1</td>
</tr>
</tbody>
</table>

$c=$CMB (Planck); $g=$galaxy power spectrum; $s=$cosmic shear; $x=$shear-galaxy cross-correlation, $c_l=$clusters

- Sensitivity up to $10 \text{ meV}$ for sum of neutrino masses, and up to $0.02$ for effective number of neutrino species when observables are combined
- Can cleanly distinguish between effects of dark energy and neutrinos

[Basse+ 2013]
Conclusions

• The Universe continues to be boring: no evidence for anything unexpected in the cosmological neutrino sector

• With the next generation of large-volume galaxy surveys and CMB lensing measurements, a detection of the sum of neutrino masses is extremely likely, but still a lot of work to be done for theorists (non-linearities!)