Neutrinos and the Universe: Cosmology

- Neutrino Abundance
- Constraints on Neutrino Masses
Neutrinos are produced in the early universe

- Neutrinos interact very weakly: need high temperatures/energies
- Early on, the universe was much hotter, so the rate for, e.g.
  \[ e^-e^+ \rightarrow \nu\bar{\nu} \]
  was very large

Expect about as many neutrinos in the universe today as photons (37 N_\nu \text{ cm}^{-3}, trillions passing through this screen every second)

Alpher, Herman, & Gamow 1953
Number of Neutrinos affects the abundances of light elements

Yang, Schramm, Steigman, & Rood (1979!)

Multiple techniques:
Cosmologists measure densities in units of the *critical density*,

\[ \rho_{\text{cr}} = 1.88 \, h^2 \times 10^{-29} \, \text{g cm}^{-3} \]

where \( h \) defines the Hubble constant

\[ H_0 = 100h \, \text{km sec}^{-1} \, \text{Mpc}^{-1} \]

Two popular ways of writing the baryon density are:

\[ \Omega_b = \rho_b / \rho_{\text{cr}} \]
\[ \omega_b = \Omega_b h^2 \]
Neutrons do not stay in equilibrium because weak interactions become slower than expansion rate.

What happens if the number of neutrino species differs from 3?

Hint: Expansion Rate is proportional to energy density.
Residual Deuterium also affected

Small amount of deuterium does not get converted into helium.

If the expansion rate is larger, conversion reactions become less efficient and more deuterium is left over.

![Graph showing the fractional abundance of deuterium (D) and helium (4He) over temperature (T) in MeV, with a peak at higher temperatures and a rapid decrease at lower temperatures.]
Standard Model \((N_v=3)\) Agrees well with Data

Might expect tight constraints, but ...
Beware of Degeneracies

Can offset extra neutrinos by changing baryon density

The Cosmic Microwave Background (CMB) provides complementary information by measuring the baryon density very accurately
CMB+BBN have 3-sigma evidence for neutrino background

Cuoco et al. 2004
The Planck satellite will tightly constrain neutrino abundance.

We should have a 10-sigma detection within 5 years.

CMB only

Including BBN

Ichikawa & Takahashi 2007
Massive Neutrinos affect large scale structure

- We know the neutrino abundance in the universe:
  \[ \frac{\rho_v}{\rho_{\text{critical}}} = \frac{m_v n_v}{\rho_{\text{critical}}} = 0.02 \frac{m_v}{1 \text{eV}} \]

- Neutrinos stream out of overdense regions \textit{after} structure starts to grow.

- Less clustering in universe with massive neutrinos

Compare this to the total matter density \( \Omega_m \approx 0.25 \).
If neutrino density is a non-negligible fraction of the matter density, small scale structure is inhibited.

Cold Dark Matter (no neutrino mass)

Hot + Cold Dark Matter (non-zero neutrino mass)
To analyze quantitatively, decompose into Fourier modes
In this simple example, all modes have have wavelength/frequency

More generally, at each wavelength/frequency, need to average over many modes to get spectrum
Why are massive neutrinos like a tuning fork?

C string on a ukulele

C note on a tuning fork
Clumping on Scale $k$

- Dimensionless quantity akin to $l^2 C_l$

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

- Variance of density:

\[ \left\langle \left( \frac{\delta \rho}{\rho} \right)^2 \right\rangle = \int \frac{dk}{k} \Delta^2(k) \]

- Onset on nonlinearity: $\Delta^2 > 1$
Massive Neutrinos Suppress Power on Small Scales

\[ \Delta^2(k) \]

\[ k \ (h \text{ Mpc}^{-1}) \]

- \( m_\nu = 0 \)
- \( m_\nu = 0.5 \text{ eV} \)
- \( m_\nu = 5 \text{ eV} \)
Power spectrum depends only on massive neutrino energy density

Large Scale Structure probes $\Sigma m_\nu$
How do we probe the matter distribution?

Most of the matter in the universe is dark, i.e. does not emit light. How can we probe its distribution?
There are several tracers of the matter power spectrum

- **Galaxy Distribution**
  Should trace matter distribution on large scales. Difference is called *bias*.

- **Lyman alpha (n=1→2 transition of H) Forest**
  Regions w/ lots of absorption (neutral Hydrogen) correspond to overdense regions.
Comparing to predictions is easy only on large scales
Several Large Galaxy Surveys

The Sloan Digital Sky Survey (SDSS) and the Two Degree Field (2dF) both have measured positions and redshifts (which are related to distances) of hundreds of thousands of galaxies.

Redshift $z$ is a measure of distance from us.
SDSS Galaxy Power Spectrum

SDSS analysis of >200,000 galaxies

Corrects for luminosity bias

Cannot use small scale results

Tegmark et al. 2004
Degeneracies

- Lowering the matter density suppresses the power spectrum

- Close to degenerate with non-zero neutrino mass
Peaks and troughs in CMB sensitive to matter density: need both CMB and large scale structure to tighten constraints on neutrino mass.

*It has been claimed that the true limits on neutrino masses from the WMAPI CMB maps are tighter than represented in these figures.

Tegmark, et al. 2006
Small scales are hard to predict

Statistical Error goes down as more small scale data are included …

… But systematic error, due to uncertainty in theoretical prediction, goes up
Fluctuations in forest trace fluctuations in density

Flux

Baryon Density

Position along line of Sight

Gnedin & Hui, 1997
Lyman alpha observes universe at early times

At high redshift, even small scales were linear!
SDSS Spectra of 3300 Quasars

1D Power Spectrum of the Flux

McDonald et al. (2004)
This is only half the battle!

- Want to test cosmology
- Need to run simulations which generate 1D flux spectra for every parameter set
- Do likelihood analysis to see which simulations are closest to observations
Constraints are typically sub-eV

Top four use Baryon Acoustic Oscillations
Most aggressive limit disfavors 3 degenerate neutrinos

\[ \sum m_\nu \ [\text{eV}] \]

\[ m_\nu \ [\text{eV}] \]

1-\(\sigma\) Normal Hierarchy

2-\(\sigma\) Inverted Hierarchy

3-\(\sigma\)
Can we do better?

Currently running up against systematics, induced largely because we are depending on mass *tracers.*
1804: Astronomer Johann Soldner computes deflection of light due to Sun

Straightforward exercise in Newtonian gravity to show that particle passing within distance $d$ of point mass $M$ gets deflected by angle $\frac{2GM}{d}$
Over a hundred years later Einstein posits that mass distorts space: even light paths would be affected.
Could this effect be detected?

Einstein writes to George Hale (Director of Mount Wilson Observatory) in 1913. He mentions the 0.84” (2GM☉/R☉c²) deflection expected from the Sun.

Wambsganss 1998
The next total solar eclipse was August 21, 1914. An expedition was sent to observe in the region of greatest eclipse ...
Russian Crimean Peninsula
1914 was not a good time to start a scientific expedition in Europe
The astronomers were captured by Russian soldiers and released a month later ... with no data

... which in retrospect is a good thing. Einstein improved his theory over the next several years. He eventually concluded that the deflection should be twice as large as the Newtonian result ... And this was confirmed by the famous expeditions in 1919.
Exploit this: Gravitational Lensing

Constraints on neutrino mass via growth of structure
Weak Lensing of Faint Galaxies: distortion of shapes

Note: the effect has been greatly exaggerated here

 Courtesy: Josh Frieman
Lensing of real (elliptically shaped) galaxies

Must add the signal from a large number of background galaxies

Background Source shape

Courtesy: Josh Frieman
Big Advantage of Lensing: Sensitive to potential wells due to all matter

No longer need to use tracers
Four seminal measurements in 2000; ~dozen since then

Van Waerbeke & Mellier 2003
Several Upcoming Surveys

Panstarrs

SNAP

LSST

July 6, 2007

Neutrino Physics Summer School:
Scott Dodelson
Tomography: Divide Background (Tracer) Galaxies into High and Low Redshift Bins

Low redshift galaxies sensitive to this

Very high redshift galaxies sensitive to this

Decay of the gravitational potential due to neutrino mass (0.2 eV)
This effect can also be caused by...
Even if you’re here only to learn about neutrinos, you need to understand dark energy

Projection for deep survey over 1/10 of the sky

Abazjian & Dodelson 2003
Neutrinos and CMB

\[ P = \text{Planck} \]
\[ \sigma(m_\nu) = 0.15 \text{ eV} \]
\[ \sigma(N_\nu) = 0.22 \]
\[ E = \text{EPIC: (0.052 eV, 0.12)} \]

With just one frequency channel.

Information about mass from lensing of the CMB while that about \( N_\nu \) from primary CMB.

Kaplinghat
Conclusions

- **Cosmic neutrino abundance** inferred two ways: observations of light elements + large scale structure
- Cosmological **upper limit on sum of neutrino masses**: 0.2-0.7 eV
- Gravitational lensing may ultimately detect 0.05 eV neutrinos
Changing Number of Neutrinos leads to a reduction in the power on small scales

![Graph showing the power spectrum $P(k)$ in $h^{-3}$ Mpc$^3$ as a function of $k$ in $h$ Mpc$^{-1}$. The graph depicts two curves, one for $N_\nu=4$, showing a decrease in power on small scales.]
Cosmic Neutrino Abundance