Neutrino Mass Limits from Cosmology

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This review contains limits obtained in collaboration with:
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Goal of the talk

Cosmology provides the strongest constraints on the sum of the neutrino masses.

There have been many studies of constraints from various combinations of datasets.

The resulting 2σ maximum sums of neutrino masses range from about 0.25 eV to 1.5 eV depending on the choice of datasets and assumptions about systematic errors.

In this talk I will review the strongest and most reliable bounds, focusing on the main assumptions that they each entail.

Neutrino Mass Differences from Oscillations

The width of the Z boson measured at LEP demonstrates that there are 3 active neutrino mass eigenstates.

The sign and magnitude of the difference between two of these states is fixed by solar and reactor neutrino oscillations respectively:

$$\Delta M^2_{21} = 7.50^{+0.19}_{-0.20} \times 10^{-5}\ \mathrm{eV}^2$$

While the magnitude of another difference is fixed by atmospheric and accelerator neutrinos (Minos results from Xinjie Qiu's talk)

$$|\Delta M^2_{32}| = 2.39^{+0.09}_{-0.10} \times 10^{-3}\ \mathrm{eV}^2$$

The sign of ΔM^2_{32} is called the neutrino mass hierarchy.

Sum of Neutrino Masses from Cosmology

Oscillations of ultrarelativistic neutrinos give no information about the overall scale of the neutrino masses.

In the first part of this talk I will explain why cosmology is sensitive to just this overall scale and in particular the sum of the neutrino masses $m_1 + m_2 + m_3$.

It is much more difficult to extract mass differences from cosmology. A determination of the mass hierarchy appears to lie just beyond the reach of surveys like EUCLID, which is scheduled for launch in 2020.

The Cosmic Neutrino Background - Freeze Out

According to the hot big bang model, during the first second of the universe's evolution it was filled with a dense, homogeneous plasma with a temperature above 2 MeV.

During most of this time, weak interactions kept neutrinos in equilibrium with electrons, positrons, photons, protons and neutrons in the plasma.

As time passed the temperature and density fell, and so the interaction rate also fell.

The average electron neutrino experienced a weak interaction for the last time when the plasma was about 2 MeV, the other flavors had their last interaction slightly earlier.

This period of last interactions is called *freeze out*.

The Cosmic Neutrino Background - Properties

At freeze out the neutrinos had a thermal velocity distribution.

Since then the neutrinos have continued to move along geodesics with a velocity which has red-shifted as a result of the expansion of the universe.

This geodesic movement is called *free streaming*.

These free-streaming neutrinos make up the *cosmic neutrino background*.

Their density and temperature as functions of time are known using properties of thermal equilibrium and general relativity. In practice they are accurately determined by numerically solving the Boltzmann equation.

The Cosmic Neutrino Background - Temperature

The cosmic neutrino background is slightly colder than the cosmic microwave background.

This is because, just after neutrino freeze-out, the universe became sufficiently cold that typical collisions did not produce positrons.

The positrons that already existed annihilated, depositing their energy adiabatically in the plasma of electrons, photons, protons and neutrons, heating it.

After this process the cosmic neutrino background temperature T_ν was lower than the plasma temperature T_γ by a factor of about

$$\frac{T_\gamma}{T_\nu} = \left(\frac{11}{4}\right)^{1/3}.$$

Definition of $N_{\rm eff}$

As a result the effective number of species of neutrino is defined by the following relation between the total energy density of the radiation and that of the photons

$$\frac{\rho_R}{\rho_\gamma} = 1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}.$$

However the neutrinos were not *completely* decoupled when the positrons annihilated, so some energy was transfered to the cosmic neutrino background.

As a result the standard model prediction for the effective number of neutrinos is

$$N_{\rm eff} = 3.046$$

Note that an observation of $N_{\rm eff} > 3.046$ does not imply that there are indeed extra neutrinos, but only that there are additional light particles.

Constraints from the Neutrino Background

In standard cosmologies, the cosmological neutrino background only interacts gravitationally after freeze-out and *all cosmological bounds on neutrino masses arise from gravitational interactions of the cosmic neutrino background.*

The gravitational interaction depends on the sum of the gravity from all of the neutrinos, which is proportional to the sum of the masses once the neutrinos have become nonrelativistic. This is why cosmology constrains the sum of the masses.

As a result of the known mass differences, at least two of the neutrino flavors is now nonrelativistic. If one flavor is now relativistic, it is so light that its contribution to the energy of the universe is now negligible.

At recombination the neutrinos were still too relativistic for their masses to directly affect the CMB.

Determination of Individual Masses?

Cosmology is only sensitive to individual neutrino masses when the neutrinos become nonrelativistic, at $1000 < z < 20$ where now there are few probes, but new deep 21 cm surveys may improve this situation.

Thus the best hope for determining the neutrino mass hierarchy and thus the individual neutrino masses lies with oscillation experiments, such as NOνA and Daya Bay II (see Jun Cao's talk)

With optimistic assumptions, using a 20 kton detector in a tunnel near DongKeng (158 km WSW of here) or under BaiYunZhang (48 km NNE of here) Daya Bay II can yield a 2σ determination of the hierarchy in 6 years (Ciuffoli et al., 2012).

We found that interference effects from multiple reactors lead to a preference for shorter baselines and that an energy dependent weight in the Fourier transform eliminates its spurious dependence on the high energy tail of the reactor neutrino spectrum.

Potential Locations for Daya Bay II

Direct Consequences of the Neutrino Background

The neutrinos of the cosmological neutrino background directly lead to two main effects, from which nearly all constraints can be derived:

I) They contribute to the recent expansion of the universe identically to dark matter.

II) Since freeze out they free stream a distance called the *free-streaming length*. This disrupts structure formation on scales below the free-streaming length.

In the next part of the talk I will describe how these two effects can be observed and will argue that they imply that cosmological models with massive neutrinos necessarily have a higher dark matter density than those with massless neutrinos.

Epoch of Matter-Radiation Equality

Today the matter density ρ_m is 3,000 times higher than the radiation (relativistic matter) density ρ_r.

Neglecting interactions, as a result of the Doppler effect, ρ_r falls faster than ρ_m as the universe expands

$$\rho_m \propto \frac{1}{(1+z)^3}, \qquad \rho_r \propto \frac{1}{(1+z)^4}.$$

Therefore the redshift z_{eq} when the density of matter and radiation were equal can be computed from the density ratio today

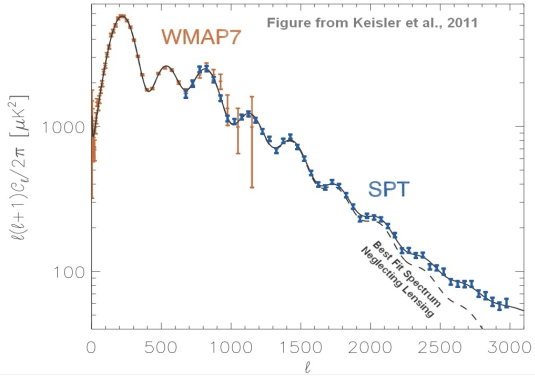
$$1 + z_{eq} = \frac{\rho_m^0}{\rho_r^0}.$$

The CMB and large scale structure (LSS) are very sensitive to z_{eq}.

This calculation is affected by neutrino masses because they were radiation at matter-radiation equality, but now most of their energy is nonrelativistic, so they contribute to ρ_m^0.

CMB Power Spectrum

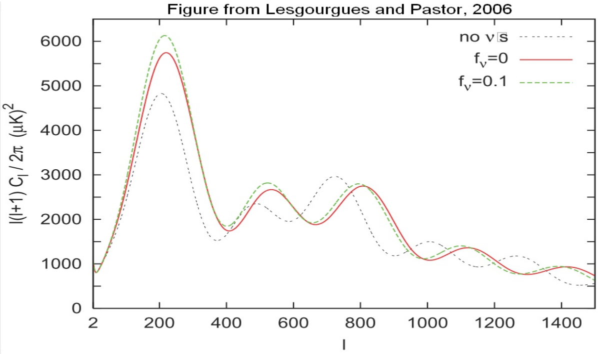
The first three peaks of the CMB power spectrum have been accurately measured by WMAP 7 while the higher wavenumber features have been measured by the South Pole Telescope (SPT)



The locations and amplitudes of these peaks can be used to constrain neutrino masses

Effect of Neutrino Mass on the CMB

If neutrinos compose f_ν=10% of dark matter density today ρ_m^0 , then z_{eq} would be different from its value in a cosmology with the same value of ρ_m^0 and massless neutrinos:

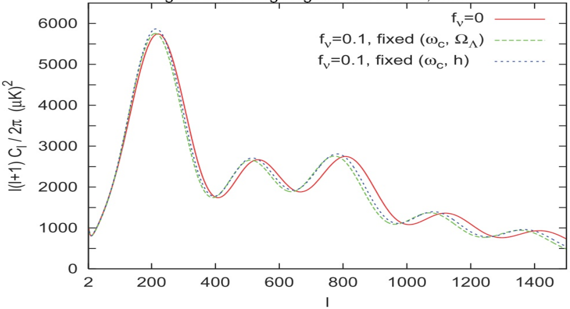


This would be easily detectable in the CMB power spectrum.

Effect of Neutrino Mass on the CMB II

If instead the density of dark matter today is increased together with the neutrino mass, fixing the cold dark matter density $\rho_{\rm cdm}$:

Figure from Lesgourgues and Pastor, 2006



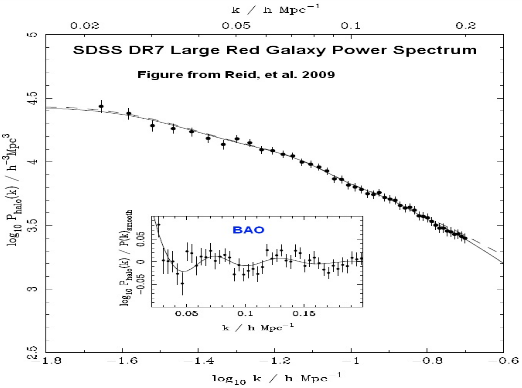
The effect on the CMB is much smaller.

The peak heights are unchanged, but the angular scales grow.

This can be compensated by increasing the primordial Hubble parameter, which can be accomplished by increasing $\rho_{\rm cdm}$, which restores some tension with z_{eq}

Large Scale Structure

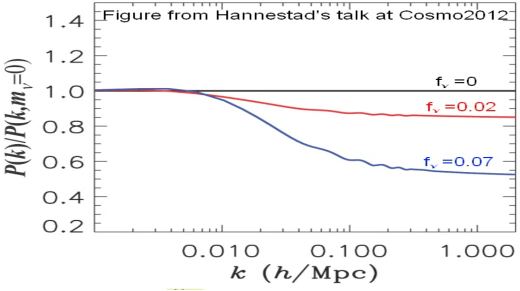
The 2-point function of the distribution of luminous red galaxies near $z = 0.35$ was measured by the Sloan Digital Sky Survey



Both the LSS shape and the location of the BAO peak can be used to constrain neutrino masses

Effect of Free Streaming on Large Scale Structure

Due to free streaming, neutrinos do not contribute to the formation of LSS at scales below the free streaming length.



More importantly, by free streaming out of potential wells, they gravitationally pull matter out with them. They suppress small perturbations by (Hu et al., 1998)

$$\frac{\Delta P}{P} \sim= -8 f_\nu = -8 \frac{\rho_\nu}{\rho_m}.$$

Neutrino Masses/Dark Matter Density Degeneracy

Neutrino masses lead to a deficit of LSS at the smallest scales which can be compensated by increasing the dark matter density.

Similarly we have seen that consistency with the CMB peak positions requires a higher dark matter density, but at the price of a mild tension with z_{eq}.

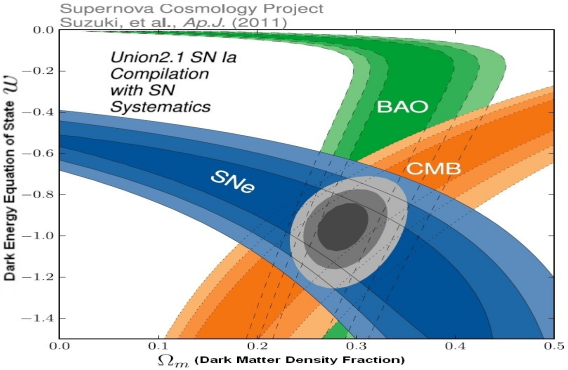
Thus standard cosmologies with massive neutrinos have more dark matter than those with light neutrinos.

The strongest constraints on neutrino mass are indirect, they arise from constraints on the dark matter density which is linked to the neutrino mass via this degeneracy.

The two strongest constraints on the dark matter density, and so the neutrino mass, arise from type Ia supernova and from the Baryon Acoustic Oscillation feature of the LSS.

Tension Between BAO and Ia Supernovae

Recall that the higher the neutrino mass, the higher ρ_m must be.

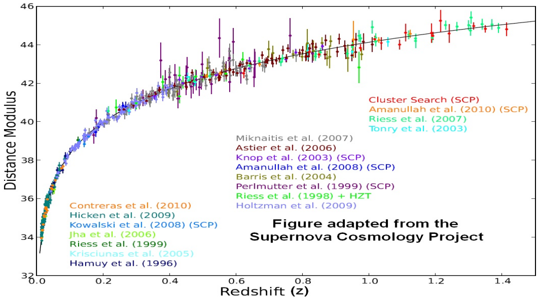


Increasing ρ_m, BAO data require a higher dark energy equation of state while supernovae require a lower value.

This tension leads to the best bounds on neutrino masses.

Ia Supernova Bound Hubble Diagram

The Supernova cosmology project has collected the redshift and magnitude of supernovae from many different surveys.

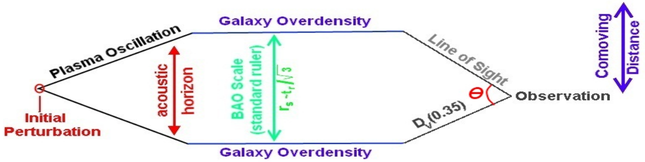


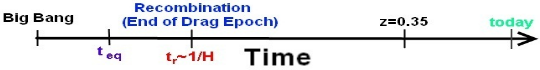
Given assumptions about the brightness, the Hubble diagram yields the relative distances of the supernova and so, up to a multiplicative constant, the Hubble parameter

$$H = \frac{\dot{a}(t)}{a(t)}$$

Baryon Acoustic Oscillation

The baryon acoustic oscillation is a bump in the galaxy 2-point function which provides a standard ruler at redshifts $z < 1100$.





The observed quantity is the ratio θ of the acoustic horizon size r_s at recombination to the distance of the galaxies measured D_V.

More dark matter $\longrightarrow$ higher primordial Hubble parameter $\longrightarrow$ the time t_r of recombination shrinks $\longrightarrow$ smaller r_s.

This can be compensated by *increasing* the Hubble parameter H at low redshifts, to make D_V smaller and so preserve θ.

Supernovae vs BAO

In conclusion, supernova data fixes $H(z)$ and is independent of the neutrino masses but BAO data prefers a larger value of $H(z)$ for higher neutrino masses.

This is the basic tension between supernova and BAO which lead to upper bounds on the neutrino mass fraction f_ν.

This tension can be *reexpressed* in terms of the dark energy equation of state w, related to H by the flat space Friedmann equation

$$H(z) = H_0 \sqrt{\Omega_m (1+z)^3 + (1-\Omega_m)(1+z)^{3+3w}}$$

To keep $H(z)$ constant (for supernova) when Ω_m increases w must decrease whereas H is increased (for BAO) by an increase in w. This is the content of the supernova legacy global fit shown above.

Evading the Constraints

There are several assumptions behind these constraints, when they fail the constraints may be evaded:

I) The density of cold dark matter ρ_{cdm} may be different today than during recombination

II) The dark energy equation of state w may depend on the scale factor a, as the supernova data extends further than the BAO data there is space to reduce the tension

III) There may be other light species of particles, increasing N_{eff}, providing *dark radiation* in the early universe and therefore rendering ρ_m compatible with the z_{eq} measured by the CMB and LSS.

In fact, most recent analyses place N_{eff} between 3.5 and 4.5. This reduces tension with z_{eq}, but the tension between BAO and SN data remains.

A Sterile Neutrino?

If there is a sterile neutrino with a mixing angle high enough to explain the anomalies below, it was in equilibrium $\longrightarrow N_{\mathrm{eff}} \geq 4$.

The converse however is not true, an extra degree of freedom need not be a sterile neutrino.

A strongly coupled sterile neutrino would provide an explanation for the appearance anomalies at LSND and to some extent MiniBooNE consistently with the lack of appearance at KARMEN.

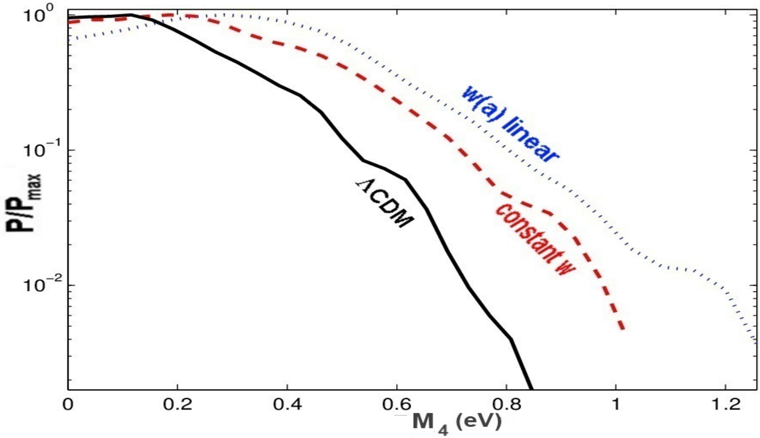
The lack of appearance at ICARUS prefers a mass around 0.5 eV whereas the gallium anomaly requires a mass above 0.8 eV.

Even at lower masses it can explain the anomalous flux deficit at short baseline reactor experiments, which using the new value of θ_{13} we have shown is consistent with 1 km baseline results.

The global fit that we saw in yesterday's talk by Carlo Giunti suggests a sterile neutrino mass above 0.8 eV.

Neutrino Mass Probability Densities at $N_{\text{eff}} = 4$

Combining the present value H_0 of the Hubble parameter measured by the Hubble space telescope, the CMB power and polarization spectra of WMAP7, the LSS of the 7th data release of the SDSS galaxy survey and the third year Supernova Legacy Survey



2σ Bounds on the Sum of the Neutrino Masses

Assuming the best fit value $N_{\rm eff} = 4$ this combination of LSS, CMB, supernova and Hubble constant observations yields the following 2σ bounds on the sum of the masses of the 3 neutrinos and the extra light particle

Cosmological model	2σ Bound
ΛCDM ($w = -1$)	$<$ 0.47 eV
wCDM (w constant)	$<$ 0.62 eV
$w(a)$ linear	$<$ 0.71 eV

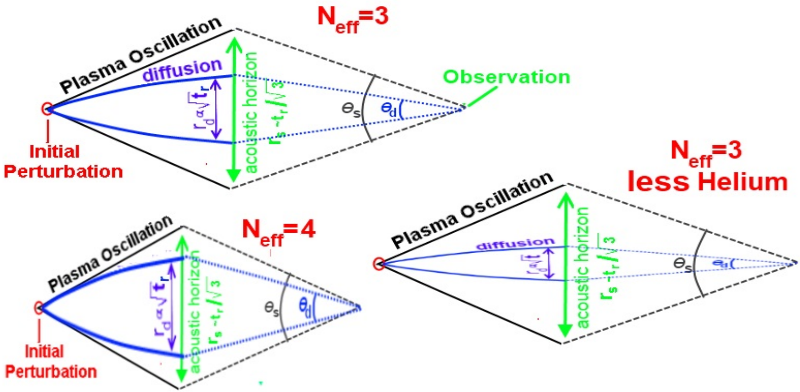
Bounds in the case $N_{\rm eff} = 3$ that rely upon the same data are each about 0.15 eV lower in each model:

ex) Xia et al., 2012 find $\sum m_i < 0.33$ eV in the case of ΛCDM.

CMB Silk Damping and Acoustic Horizon Scales

WMAP: Angular size θ_s of the acoustic horizon at recombination

SPT: Angular size θ_d of the diffusion scale at recombination



If $N_{\rm eff}$ is increased (so t_r is decreased) or the helium fraction Y_p is increased (less free electrons), then the ratio θ_d/θ_s grows.

N_{eff} and Y_P from BBN

As neutrinos came out of thermal equilibrium, the inverse β decay that kept protons and neutrons is thermal equilibrium slowed.

After that neutrons continued to decay and the neutron to proton ratio fell monotonically with time.

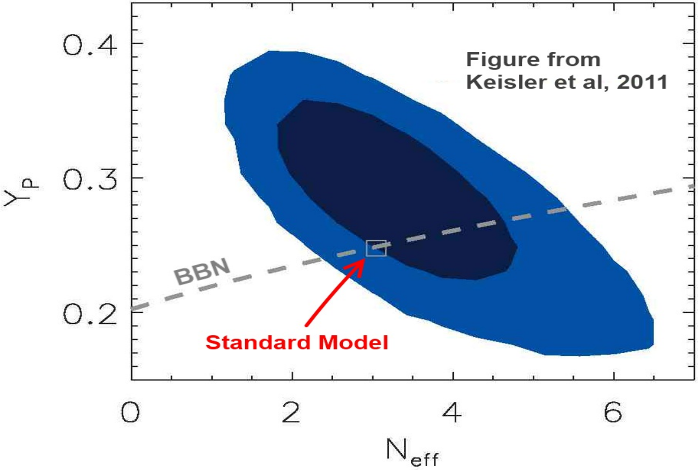
BBN bound essentially all neutrons into Helium nucleii.

Thus the higher N_{eff}, the faster the universe expanded, the earlier BBN took place, the more neutrons that were available, the higher the Helium fraction Y_P.

Summarizing: A high value of N_{eff} leads to a lower value of Y_P applying CMB constraints and a higher value of Y_P applying BBN constraints.

$N_{\rm eff}$ and Y_P Combining CMB and BBN Constraints

Combining WMAP7 and SPT data with standard BBN theory the SPT collaboration obtained the constraints on $N_{\rm eff}$ and Y_P:



Future constraints on $N_{\rm eff}$

The $N_{\rm eff}$ errors shrink to 0.4 including helium abundances in HII regions, extrapolated to zero metallicity to avoid stellar effects

Such studies yield a best fit $N_{\rm eff}$ between 3.5 and 3.9, in several studies excluding the standard model at over 2σ.

The next SPT data (very soon) should reduce the error to 0.33.

Early next year, Planck data could reduce this error to 0.25, settling the question of whether there are extra light species.

In 15 years EUCLID and LSST should reduce the error to 0.05:
Can determine whether an extra species is a boson or fermion.

The nature of such an extra species is unlikely to be determined by any planned cosmological survey, but it may be determined by neutrino experiments here on Earth?