NuFact 03: 5th International Workshop on Neutrino Factories & Superbeams
Columbia University, New York, 5-11 June 2003

Neutrinos in Cosmology

Georg G. Raffelt
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Neutrinos in Cosmology

1. Neutrino mass limit from cosmological structure formation
2. How many neutrinos in the universe?
3. Neutrino mass and the baryon asymmetry of the universe

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Cosmological Limit on Neutrino Masses

Cosmic neutrino "sea" $\sim 112 \text{ cm}^{-3}$ neutrinos + anti-neutrinos per flavor

$$\Omega_{\nu} h^2 = \sum \frac{m_{\nu}}{94 \text{ eV}} < 0.4$$

$m_{\nu} < 40 \text{ eV}$ For all stable flavors

REST MASS OF MUONIC NEUTRINO AND COSMOLOGY

S. S. Gershtein and Ya. B. Zel'dovich
Submitted 4 June 1966
ZhETF Pis'ma 4, No. 5, 174-177, 1 September 1966

Low-accuracy experimental estimates of the rest mass of the neutrino [1] yield $m(\nu_e) < 200 \text{ eV/c}^2$ for the electronic neutrino and $m(\nu_\mu) < 2.5 \times 10^5 \text{ eV/c}^2$ for the muonic neutrino.

Cosmological considerations connected with the hot model of the Universe [2] make it possible to strengthen greatly the second inequality. Just as in the paper by Ya. B. Zel'dovich and Ya. A. Smorodinskii [3], let us consider the gravitational effect of the neutrinos on the dynamics of the expanding Universe. The age of the known astronomical objects is not smaller than $5 \times 10^9$ years, and Hubble's constant $H$ is not smaller than $75 \text{ km/sec-Mpasec} = (13 \times 10^9 \text{ years})^{-1}$. It follows therefore that the density of all types of matter in the Universe is at the present time [1]

$$\rho < 2 \times 10^{-28} \text{ g/cm}^3.$$
**What is wrong with neutrino dark matter?**

**Galactic Phase Space ("Tremaine-Gunn-Limit")**

**Maximum mass density of a Fermi gas**

\[ \rho_{\text{max}} = m_\nu \ n_{\text{max}} = m_\nu \ \frac{p_{\text{max}}^3}{3\pi^2} = m_\nu \ (m_\nu v_{\text{escape}})^3/3\pi^2 \]

- \( m_\nu > 20 - 40 \text{ eV} \)
- Spiral galaxies
- More restrictive from dwarf galaxies
  - \( m_\nu > 100 - 200 \text{ eV} \)

**Neutrino Free Streaming (Collisionless Phase Mixing)**

- At \( T < 1 \text{ MeV} \) neutrino scattering in early universe ineffective
- Stream freely until nonrelativistic
- Wash out density contrasts on small scales

- Nus are "Hot Dark Matter"
- Ruled out by structure formation

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Formation of Structure

Smooth → Structured
Structure forms by gravitational instability of primordial density fluctuations
Structure forms by gravitational instability of primordial density fluctuations.

A fraction of hot dark matter suppresses small-scale structure.
Probes of Cosmic Structure

WMAP Collaboration:
Power Spectrum of CMBR Temperature Fluctuations

Sky map of CMBR temperature fluctuations

\[ \Delta(\theta, \phi) = \frac{T(\theta, \phi) - \langle T \rangle}{\langle T \rangle} \]

Multipole expansion

\[ \Delta(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta, \phi) \]

Angular power spectrum

\[ C_\ell = \langle a_{\ell m}^* a_{\ell m} \rangle = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m} \]
2dF Galaxy Redshift Survey (May 2002), Northern Slice
http://www.mso.anu.edu.au/2dFGRS/
Cosmic Structure Modified by Hot Dark Matter

Galaxy Distribution (2dF, PSCz)
Scales 1–200 Mpc

Lyman-α forest at large redshift \( \langle z \rangle = 2.72 \)
Scales 0.1–10 Mpc

\( \Omega_0 = 1 \)
\( \Omega_\Lambda = 0.66 \)
\( \Omega_B = 0.04 \)
\( H_0 = 72 \)
\( n_s = 0.94 \)
\( \Omega_v = 0.00 \)

CMBR (WMAP, Maxima, Boomerang, CBI, DASI)
Scales > 200 Mpc

Adapted from S. Hannestad
Cosmic Structure Modified by Hot Dark Matter

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$\Omega_v = 0.05$

Lyman-$\alpha$ forest at large redshift $\langle z \rangle = 2.72$
Scales 0.1–10 Mpc

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Scales > 200 Mpc

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Galaxy Distribution (2dF, PSCz)

- Scales 1–200 Mpc

Lyman-α forest at large redshift

- ⟨z⟩ = 2.72
- Scales 0.1–10 Mpc

Adapted from S. Hannestad

- \( \Omega_0 = 1 \)
- \( \Omega_\Lambda = 0.66 \)
- \( \Omega_B = 0.04 \)
- \( H_0 = 72 \)
- \( n_s = 0.94 \)

- \( \Omega_\nu = 0.25 \)

CMBR (WMAP, Maxima, Boomerang, CBI, DASI)

- Scales > 200 Mpc
### Neutrino Mass Limits from Large-Scale Structure

Statistical 95% C.L. limits depend on used data and on priors for other parameters. For detailed analyses see:
- Hannestad, astro-ph/0303076
- Elgaroy & Lahav, astro-ph/0303089

<table>
<thead>
<tr>
<th>$\Sigma m_\nu$</th>
<th>Limitation</th>
</tr>
</thead>
</table>
| $\leq 2.1 \text{ eV}$ | WMAP (Cosmic microwaves)  
2dF (Galaxy-galaxy correlation) |
| $\leq 1.2 \text{ eV}$ | + Small-scale CMBR  
(breaks degeneracy with bias) |
| $\leq 1.0 \text{ eV}$ | + Priors (1\(\sigma\))  
h = 0.72 ± 0.08  
$\Omega_M = 0.28 ± 0.14$ |
| $\leq 0.7 \text{ eV}$ | + Lyman-α forest data |
Cosmological Mass Limit vs. Neutrino Density

\[ \sum m_\nu \leq 1.0 \text{ eV (95\% C.L.) for } N_\nu = 3 \]
\[ \sum m_\nu \leq 1.4 \text{ eV (95\% C.L.) for } N_\nu = 4 \]
\[ \sum m_\nu \leq 2.1 \text{ eV (95\% C.L.) for } N_\nu = 5 \]

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How Many Relic Neutrinos?

Standard thermal population in one flavor: \( n_{\nu\nu} = \frac{3}{11} n_{\gamma} \approx 112 \text{ cm}^{-3} \)

<table>
<thead>
<tr>
<th>Additional active neutrinos beyond standard population of ( \nu_e, \nu_\mu, \nu_\tau )</th>
<th>Additional families</th>
<th>Excluded by ( Z^0 ) width (( N_\nu = 3 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical potentials for ( \nu_e, \nu_\mu, \nu_\tau )</td>
<td>Possible</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sterile (right-handed) states</th>
<th>Dirac mass</th>
<th>Not effective in sub-eV range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Populated by ( \nu_L \rightarrow \nu_R ) transitions</td>
<td>Right-handed currents</td>
<td>Excluded by energy loss of SN 1987A</td>
</tr>
<tr>
<td></td>
<td>Electromagnetic dipole moments</td>
<td>Excluded by energy loss of globular cluster stars</td>
</tr>
<tr>
<td></td>
<td>Oscillations/collisions</td>
<td>Hot/warm/cold DM possible</td>
</tr>
</tbody>
</table>
At BBN one flavor contributes about 16% to cosmic mass-energy density.

Extra flavors modify expansion parameter accordingly.

Conservative limit $|\Delta N_{\text{eff}}| < 1$

Burles, Nollett & Turner, astro-ph/9903300
Energy density in one neutrino flavor with degeneracy parameter $\xi = \eta / T$

$$\rho_{\nu^\nu} = \frac{7\pi^2}{120} T^4 \left[ 1 + \frac{30}{7} \left( \frac{\xi}{\pi} \right)^2 + \frac{15}{7} \left( \frac{\xi}{\pi} \right)^4 \right] \Delta N_{\text{eff}}$$

Helium abundance essentially fixed by n/p ratio at beta freeze-out

$$\frac{n}{p} = e^{-(m_n - m_p)/T - \xi_{\nu_e}}$$

Effect on helium equivalent to $\Delta N_{\text{eff}} \sim -18 \xi_{\nu_e}$

- $\nu_e$ beta effect can compensate expansion-rate effect of $\nu_\mu, \nu_\tau$
- No significant BBN limit on neutrino number density
Chemical Potentials and Flavor Oscillations

**Flavor mixing (neutrino oscillations)**
- Flavor lepton numbers not conserved
- Only one common nu chemical potential
- Stringent $\xi_{\nu_e}$ limit applies to all flavors: $|\xi_{\nu_e,\mu,\tau}| < 0.07$
- Extra neutrino density: $\Delta N_{\text{eff}} < 0.0064$
- Cosmic neutrino density close to standard value

**Flavor equilibrium before n/p freeze out?**
- yes: Solar LMA solution
- maybe: LOW (depends on $\Theta_{13}$)
- no: SMA or VAC

- Our knowledge of the cosmic nu density depends on the solution of the solar neutrino problem
- KamLAND most relevant experiment

- Lunardini & Smirnov, hep-ph/0012056
- Dolgov, Hansen, Pastor, Petcov, Raffelt & Semikoz, hep-ph/0201287
- Abazajian, Beacom & Bell, astro-ph/0203442
- Wong, hep-ph/0203180
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Baryogenesis in the Early Universe

Sakharov conditions for creating the Baryon Asymmetry of the Universe (BAU)
- C and CP violation
- Baryon number violation
- Deviation from thermal equilibrium

Particle-physics standard model
- Violates C and CP
- Violates B and L by EW instanton effects (B - L conserved)

- However, electroweak baryogenesis not quantitatively possible within particle-physics standard model
- Works in SUSY models for small range of parameters

A. Riotto & M. Trodden: Recent progress in baryogenesis
See-Saw Model for Neutrino Masses

Dirac masses from coupling to standard Higgs field $\phi$

Charged Leptons

- $e_L$
- $e_R$
- $\mu_L$
- $\mu_R$
- $\tau_L$
- $\tau_R$

Neutrinos

- $\nu_1$
- $N_1$
- $\nu_2$
- $N_2$
- $\nu_3$
- $N_3$

Heavy Majorana masses $M_j > 10^{10}$ GeV

Lagrangian for particle masses

$$L_{\text{mass}} = -\bar{\ell}_L \phi g_\ell e_R - \bar{\ell}_L \phi g_\nu N_R - \frac{1}{2} \bar{N}_R^C M N_R^C + \text{h.c.}$$

Light Majorana mass

$$
\begin{pmatrix}
\nu_L \\
N_R
\end{pmatrix}
\begin{pmatrix}
0 & g_\nu \langle \phi \rangle \\
g_\nu \langle \phi \rangle & M
\end{pmatrix}
\begin{pmatrix}
\nu_L \\
N_R
\end{pmatrix}
$$

Diagonalize

$$
\begin{pmatrix}
\frac{g_\nu^2 \langle \phi \rangle^2}{M} & 0 \\
0 & M
\end{pmatrix}
\begin{pmatrix}
\nu_L \\
N_R
\end{pmatrix}
$$

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Leptogenesis by Out-of-Equilibrium Decay

M. Fukugita & T. Yanagida: Baryogenesis without Grand Unification

W. Buchmüller & M. Plümacher: Neutrino masses and the baryon asymmetry
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CP-violating decays by interference of tree-level with one-loop diagram

$\Gamma_{\text{Decay}} = \frac{g_s^2 M}{8\pi}$

W. Buchmüller & M. Plümacher: Neutrino masses and the baryon asymmetry

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Leptogenesis by Majorana Neutrino Decays

In see-saw models for neutrino masses, out-of-equilibrium decay of right-handed heavy Majorana neutrinos provides source for CP- and L-violation

Cosmological evolution:
- $B = L = 0$ early on
- Thermal freeze-out of heavy Majorana neutrinos
- Out-of-equilibrium CP-violating decay creates net L
- Shift L excess into B by sphaleron effects

Sufficient deviation from equilibrium distribution of heavy Majorana neutrinos at freeze-out

Limits on Yukawa couplings

Limits on masses of ordinary neutrinos

Requires Majorana neutrino masses below 0.1 eV
Cosmological structure: $\Sigma m_\nu < 0.7\text{ – }2.1\text{ eV}$, depending on data sets and priors
Assumes cosmological concordance model to be correct

Limit gets worse with neutrino density larger than standard

After KamLAND, neutrino chemical equilibrium before BBN assured
No large neutrino-antineutrino asymmetry possible

Majorana neutrino masses below 0.1 eV can nicely account for baryonic matter in leptogenesis scenario

Apparently massive neutrinos irrelevant as dark matter
but
maybe crucial for ordinary matter
(leptogenesis mechanism for baryon asymmetry)