Neutrino and cosmology

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Outline

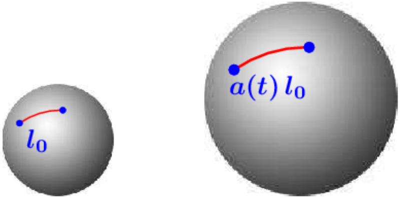
- Basics of Cosmology
    - Neutrino density
- Neutrino and Big Bang Nucleosynthesis
- Neutrino and Large Scale Structure
- Sterile neutrino
    - Bounds on light sterile neutrino
    - Sterile neutrino as dark matter
- Leptogenesis

Dynamical Frameworks

Einstein equations

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G\, T_{\mu\nu}}$$

govern Universe expansion



$$ds^2 = dt^2 - a^2(t)\; dl^2$$

Friedmann equations

Assume ideal fluid for the energy momentum tensor

$$T_{\mu\nu} = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

Einstein equations written for homogeneous isotropic world give

$$\boxed{\begin{aligned} \left(\frac{\dot{a}}{a}\right)^2 &= \frac{8\pi G}{3}\rho - \frac{k}{a^2} \\ \frac{\ddot{a}}{a} &= -\frac{4\pi G}{3}(\rho + 3\,p) \end{aligned}}$$

Friedmann equations: the physics behind

One of the two Friedmann equations can be excluded in favour of

$$\boxed{\frac{d\rho}{dt} + 3\,\frac{\dot{a}}{a}\,(\rho + p) = 0}$$

which is nothing but energy-momentum conseravtion $T^{\mu\nu}{}_{;\nu} = 0$

And this is nothing but the First Law of thermodynamics

$$\boxed{dE + p\,dV = T\,dS}$$

Here $E = \rho\,V = \rho\,a^3$ is energy and S is entropy.

Isentropic expansion

Friedmann expansion driven by an ideal fluid is isentropic, $dS = 0$. Dissipation is negligible usually.
Entropy:

$$S = \frac{2\pi^2}{45} g_* T^3 a^3 = \text{const} ,$$

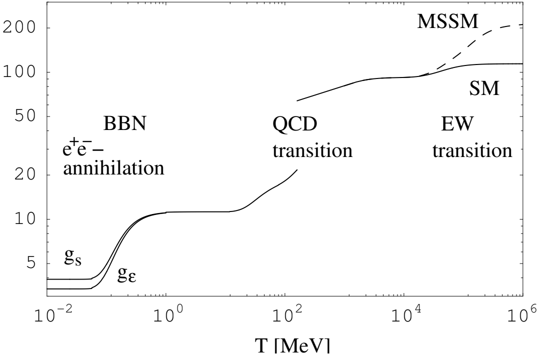
$$g_* = \sum_{i=\text{bosons}} g_i + \frac{7}{8} \sum_{j=\text{fermions}} g_j \, .$$

Useful relation

$$\boxed{a \propto \frac{1}{T}}$$

Relativistic degrees of freedom

Particles with $m \ll T$ should be counted only, i. e. g_* is a function of temperature



Freeze-out temperature

In the expanding Universe particle concentrations are in equilibrium if $\tau < t_u$ or $\sigma n v > H$. After that distributions do not change in a comoving volume, i.e. "freeze-out".

For neutrino:

$$\Gamma_W \approx \sigma_W n \sim G_F^2 T^2 \cdot T^3, \qquad H = \sqrt{\frac{8\pi\rho_R}{3M_{\rm Pl}^2}} \sim \frac{T^2}{M_{\rm Pl}}$$

and rate of weak processes ≈ Hubble expansion rate when

$$G_F^2 M_{\rm Pl} T^3 \approx 1$$

or

$$T \approx 1\,\mathrm{MeV}$$

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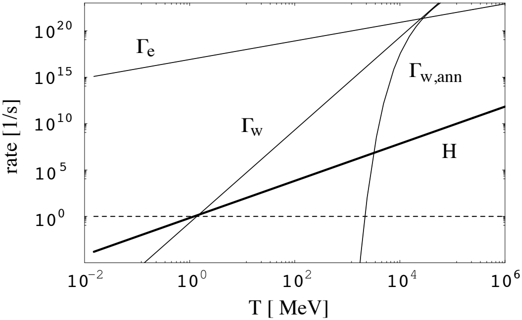


- Electromagnetic interactions are in equilibrium at $T > 1\ \mathrm{eV}$
- Neutrino freeze-out at $T \sim 1\ \mathrm{MeV}$
- WIMP freeze-out at $T \sim M/25$

Cosmological neutrino density

At $T \approx m_e \approx 0.5\ \mathrm{MeV}$ electron-positron pairs start to annihilate.

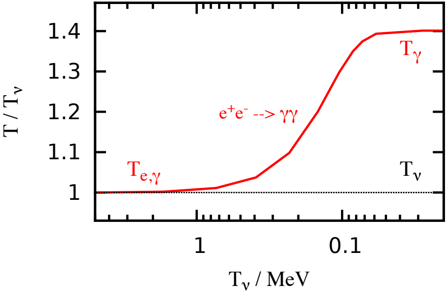
Entropy conservation is a key

Entropy in comoving volume is conserved, $g_* \, T^3 = \mathrm{const}$.

Before annihilation $(g_\gamma + g_e)\, T^3 = [2 + 4 \cdot (7/8)]\, T^3 = (11/2)\, T^3$.

After annihilation $g_\gamma \, T^3 = 2\, T^3$.

Neutrinos are decoupled already and do not participate in these relations.

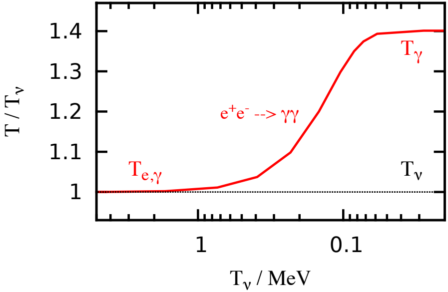


As a consequence of e^+e^- annihilation temperature of photons increases,

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

Cosmological neutrino density

Present day photon temperature $T_\gamma = 2.728\ K$.



Neutrino temperature is lower

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma = 1.947\,K$$

Neutrino number density

$$n_\nu = 115\ \mathrm{cm}^{-3}$$

Since $\rho_\nu = \sum_i m_{\nu i}\, n_{\nu i} < \Omega_m\, \rho_c$ we have constraint

$$\sum_i m_{\nu i} < 93\ \Omega_m h^2\ \mathrm{eV} \approx 10\ \mathrm{eV}$$

Cosmological neutrino density

After "freeze-out" and e^+e annihilation neutrino contribution into cosmological radiation background is parametrized as

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

$N_{eff} \neq 3$, neither it is integer. Subtleties:

- When e^+e annihilate, neutrino are not decoupled completely. This leads to somewhat larger T_ν, which instead is parametrized as larger N,

$$N_{eff} = 3.046$$

- There can be other contributions into radiation
  - Light sterile neutrinos
  - Some other light particles

- All these contributions are included into N_{eff} by cosmologists.

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Big Bang Nucleosynthesis

Neutrinos are playing two fold role:

- Initially keep neutrons and protons in equilibrium
- Change expansion rate contributing to ρ_r

Ratios of chemical elements produced depend on competition between reaction rates and expansion rate.

Big Bang Nucleosynthesis: Helium abundace

Chemical equilibrium between protons and neutrons is maintained by weak interactions

$$n + \nu \rightleftarrows p + e^-, \qquad n + e^+ \rightleftarrows p + \overline{\nu},$$

which get out of thermal equilibrium at $T_f \sim 1\,\mathrm{MeV}$
On the other hand

$$\Delta m \equiv m_n - m_p = 1.29\,\mathrm{MeV}$$

Therefore, at freeze-out

$$\frac{n_n}{n_p} \sim \mathrm{e}^{-\Delta m / T_f} \approx 0.27$$

It is important also that neutron lifetime (980 s) is much longer than the age of the Universe at this time (1 s). $^4\mathrm{He}$ is the most bound among the light elements, $E_{\mathrm{bind}} \approx 28$ MeV. Therefore, almost all neutrons produced in the early universe should end up in $^4\mathrm{He}$.

Baryon to photon ratio

Important cosmological parameter, baryon to photon ratio:

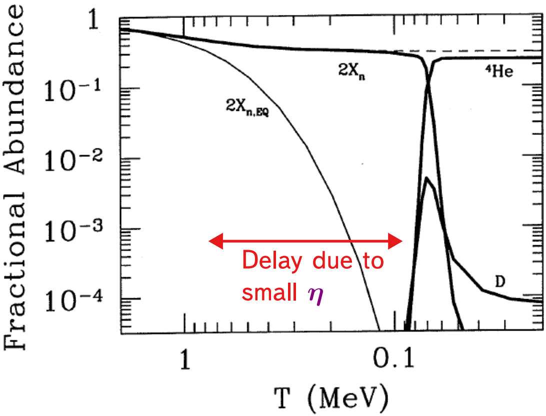
$$\eta = \frac{n_B}{n_\gamma}$$

Observationally $\eta = (6.1 \pm 0.25) \times 10^{-10}$

Can be found as

$$10^{10}\,\eta = 273.9\;\Omega_B h^2$$

Big Bang Nucleosynthesis

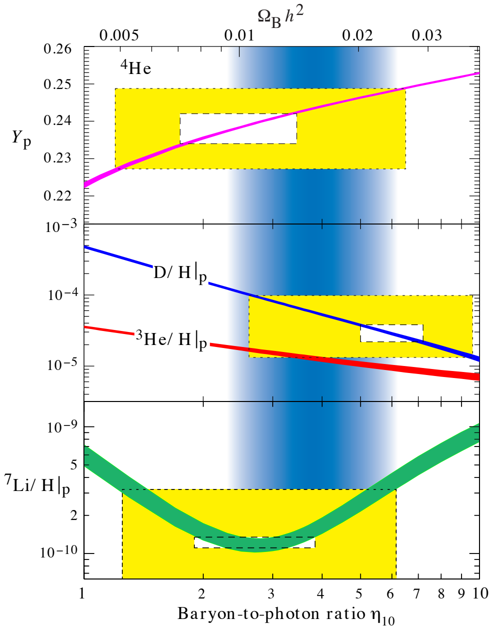


Saha equation

$$\frac{n_D}{n_n} = \frac{3}{4}\,\eta\,\left(\frac{4\pi T}{m_p}\right)^{3/2}\,e^{B/T}$$

where $B = m_n + m_p - m_D = 2.22$ MeV

Element abundances



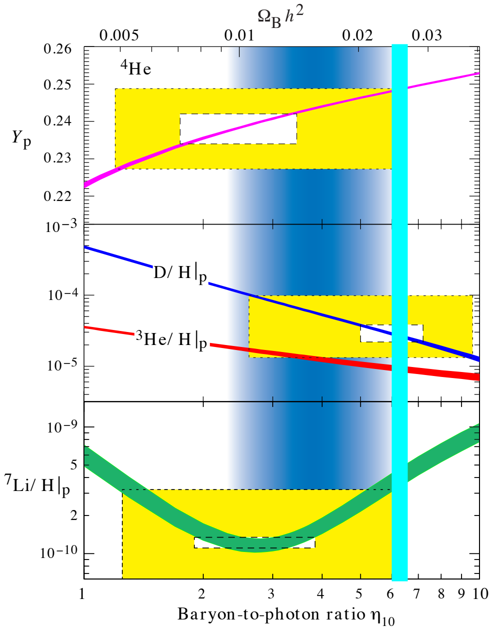
Pre WMAP picture:

Baryon-to-photon ratio was derived from BBN.

Yellow bands: observed element abundances ($\sim$ 10 yrs ago).

$N_\nu = 3$ was derived

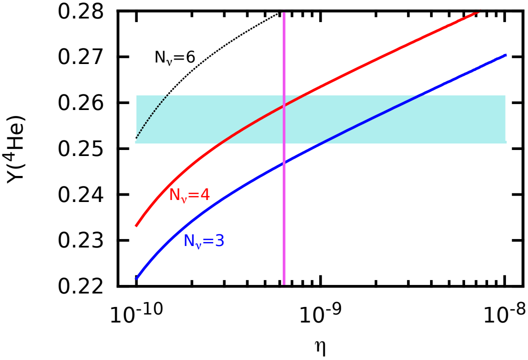
Element abundances



Current situtaion:

- Now we know η from CMBR anisotropies;
- Element abundances had changed;
- Neutron life-time had changed;

Helium abundance



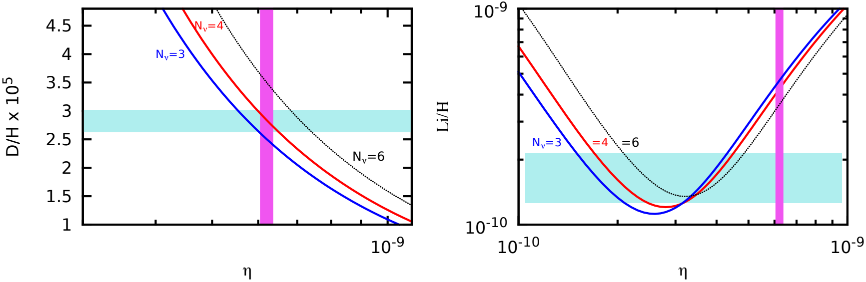
Turquoise band: He abundance from Izotov and Thuan, 2010.

Magenta band: baron-photon ratio η from WMAP7

$N_\nu = 3$ is off by 2σ

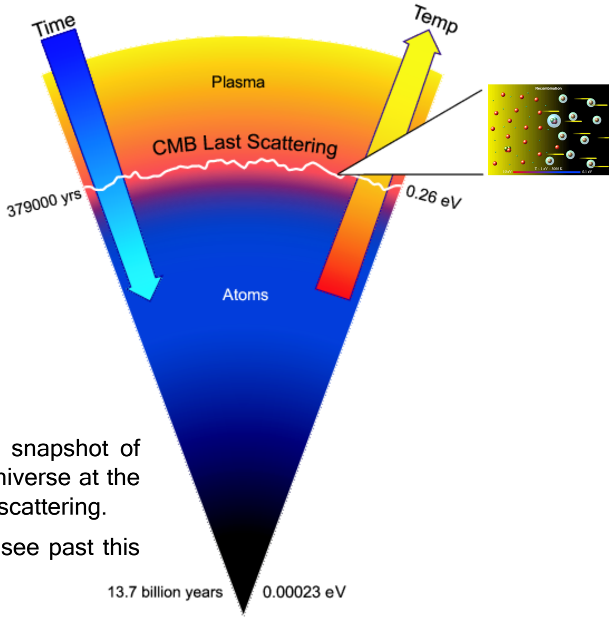
$N_\nu = 4$ gives better fit

D and Li abundances



$N_\nu = 4$ gives better fit for D

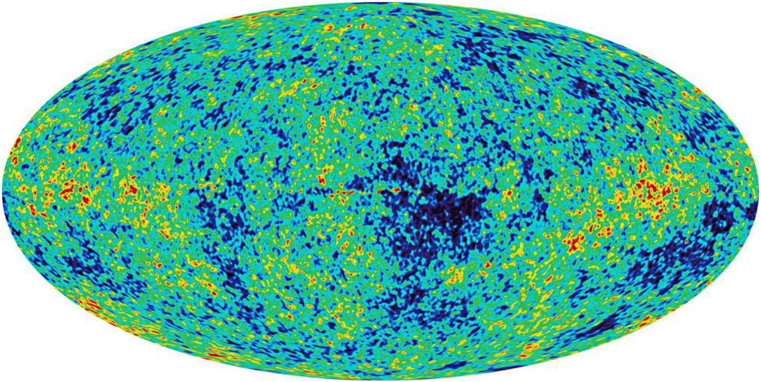
Last scattering of light



CMBR is a snapshot of the early Universe at the time of last scattering.

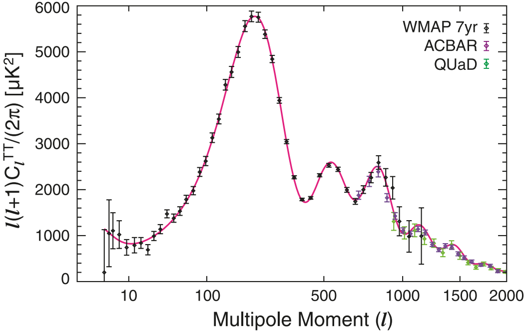
We cannot see past this surface.

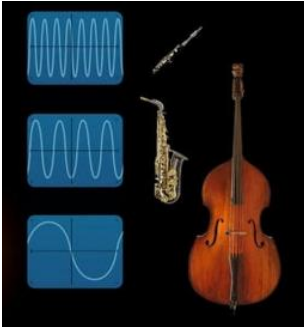
Temperature map of the sky



Temperature slightly different in different patches of the sky - 1 part in 100,000.

CMB power spectrum: tool of Precision Cosmology





Soundscape of the sky

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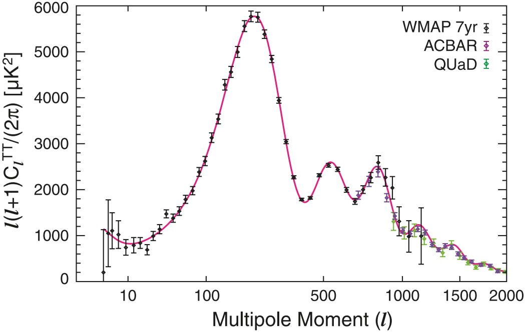
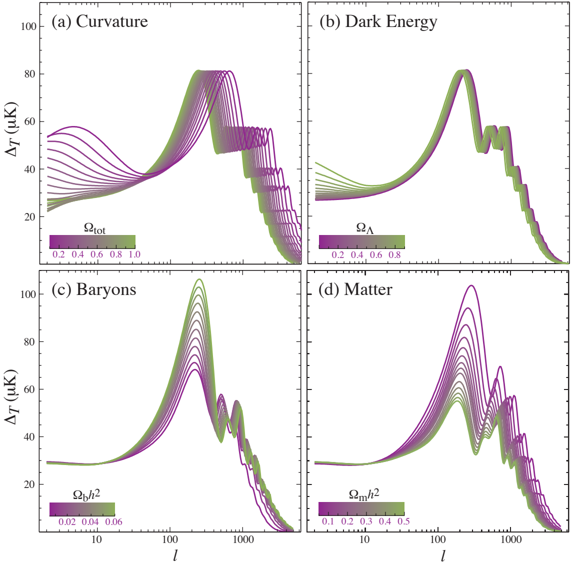
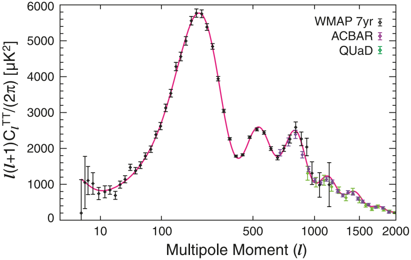


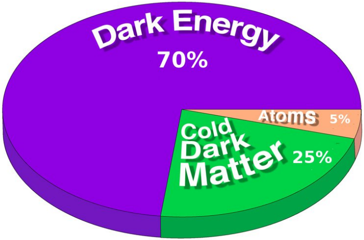
Soundscape of the sky

Parameter sensitivities



Matter content in the Universe





96% of the Universe is made of unknown substance

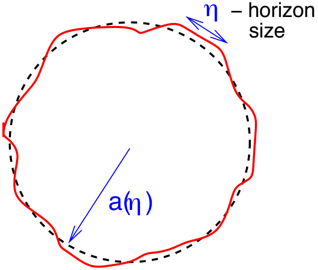
Возмущенная метрика

Удобно работать в конформном времени

$$ds^2 = a^2(\eta)\left[(1+2\Psi)d\eta^2 - (1-2\Phi)dx^i dx_j\right]$$

Φ равняется (минус) возмущение масштабного фактора

$$a^2(\eta,x) = a^2(\eta)\left(1+\frac{\delta a(\eta,x)}{a(\eta)}\right)^2 \equiv a^2(\eta)(1-2\Phi)$$



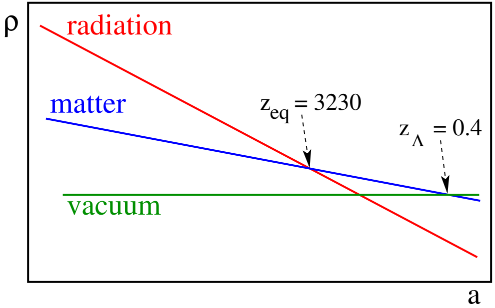
- Пространственная кривизна ${}^{(3)}R \propto a^{-2}$. Поэтому возмущения Φ называют адиабатическими или возмущениями кривизны, $\delta R/R = 2\Phi$
- Для импульсов k меньших горизонта, $k\eta \ll 1$, можно рассматривать область возмущения как независимую Фридмановскую вселенную с другим значением a
- Ψ соответствует Ньютоновскому гравитационному потенциалу
- В случаях представляющих интерес $\Psi = \Phi$

Summary of the expansion history

- Radiation

  $\rho_r = a^{-4} \rho_{r,0}$
- Matter

  $\rho_m = a^{-3} \rho_{m,0}$



Important moment: matter radiation equality

$$1 + z_{eq} = \frac{T_{eq}}{T_0} = \frac{\Omega_m}{\Omega_r} = 3231$$

Extra radiation reduces T_{eq}

Structure formation and Dark Matter

- By today the structure is formed already, $\delta\rho/\rho \sim 1$.
- Initial perturbations were small, $\delta\rho/\rho \sim 10^{-5}$.
- Perturbations do not grow in the radiation dominated epoch, during matter domination $\delta\rho/\rho \sim T_{\mathrm{eq}}/T$.

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Best case for dark matter

Perturbations in baryons can grow only after recombination. But

$$\frac{a_{\mathrm{today}}}{a_{\mathrm{dec}}} = 1 + z_{\mathrm{dec}} = 1090$$

Therefore, in a baryonic universe structure can grow only by a factor

$$10^3$$

One needs non-baryonic dark matter to facilitate structure growth

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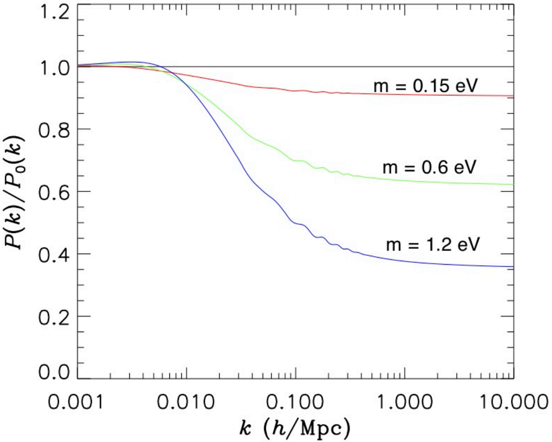
Neutrino impact

- Extra radiation reduces T_{eq}
- This makes less room for structure growth
- Effect is larger for smaller wavelength

Free streaming

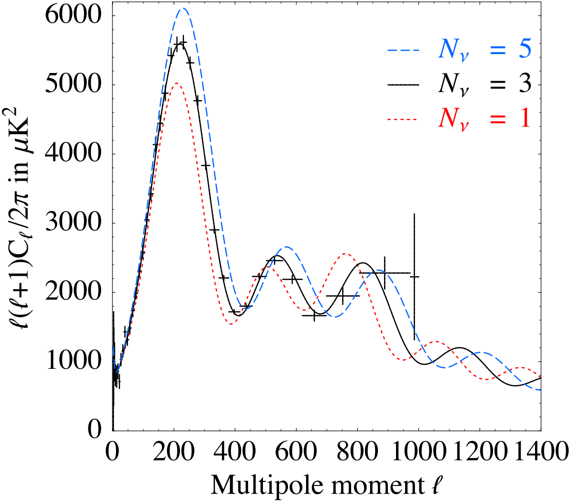
Relativistic particles cannot be confined in a gravitational well. Leaving it they inhibit structure growth.



Neutrino impact on LSS

- Extra radiation reduces $T_{\mathbf{eq}}$
- Free streaming of relativistic neutrinos suppresses the growth of fluctuations.

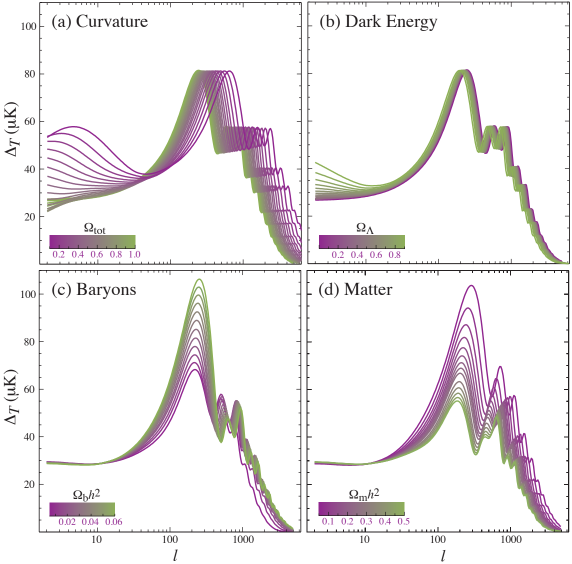
Massless neutrino and CMBR power spectrum



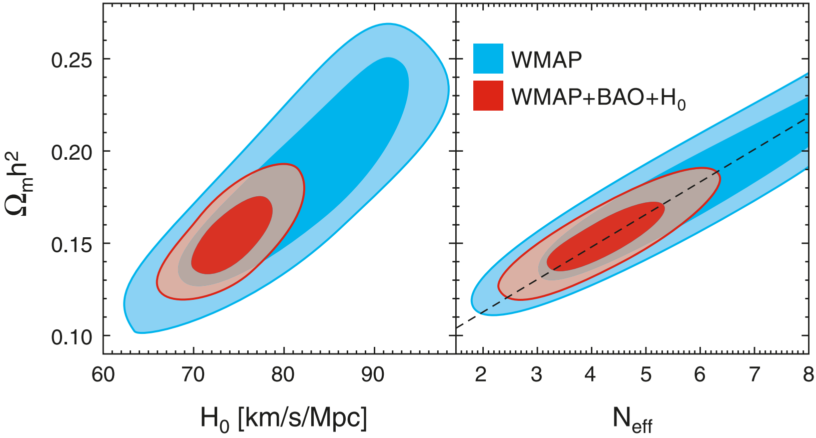
Caution:
other cosmological parameters are fixed to fit $\boldsymbol{N_\nu = 3}$

Strumia and Vissani, hep-ph/0606054

Parameter sensitivities



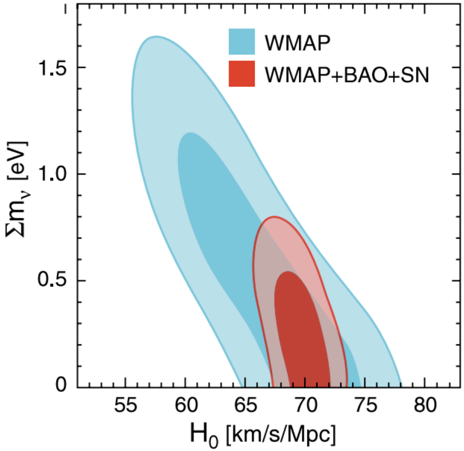
WMAP and number of neutrino



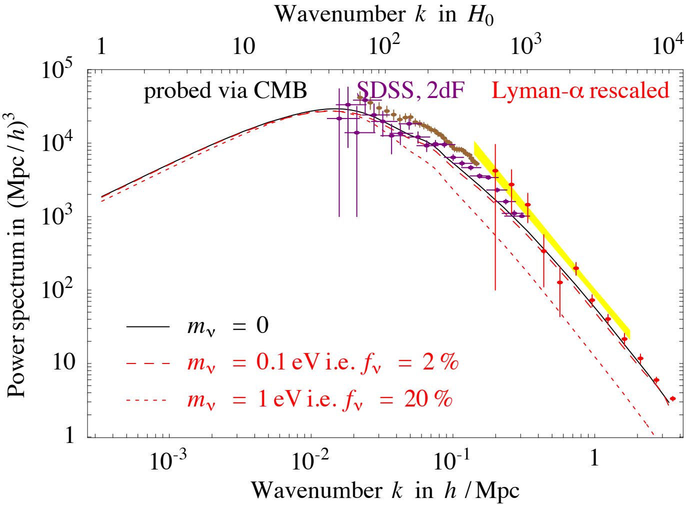
$$N_{eff} = 4.34^{+0.86}_{-0.88}$$

WMAP and neutrino mass

Solar and atmospheric neutrino experiments have shown that $m_\nu \neq 0$ but are measuring $m^2_{\nu i} - m^2_{\nu j}$ only.



Light neutrino and LSS power spectrum



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WMAP and neutrino mass

Komatsu et al. 2011:

$\mathbf{WMAP7 + BAO + H_0}$

$$\sum \mathbf{m}_\nu < \mathbf{0.58\ eV\ (95\%\ CL)(\ for\ w = -1)}$$

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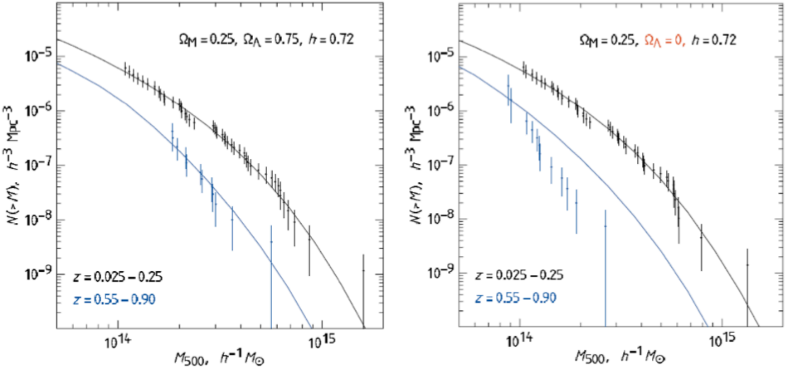
Cluster mass function vs. cosmological model



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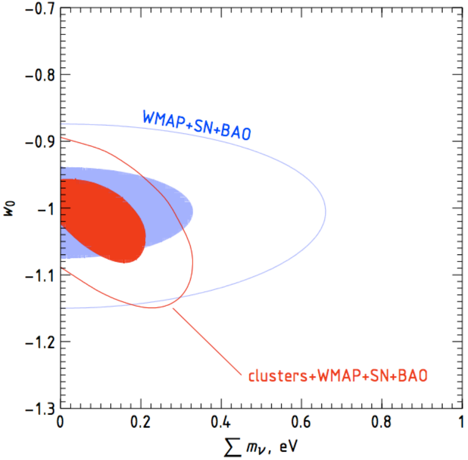

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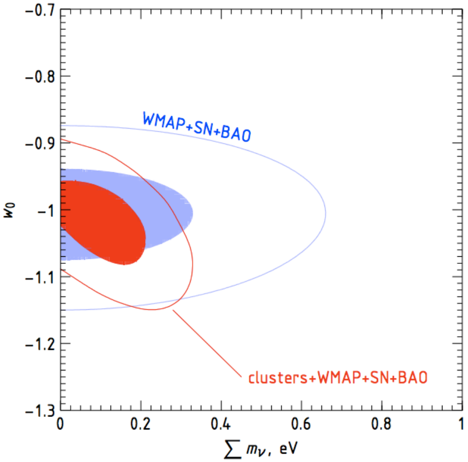
WMAP and neutrino mass



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Neutrino mass is pinned down

- Free streaming of relativistic neutrinos suppresses the growth of fluctuations until ν becomes nonrelativistic
  at $z \sim m_j/3T_0 \sim 1000\ (m_j/\mathrm{eV})$
  Combined WMAP and 2dF analysis yields the constraint
  $$\Omega_\nu h^2 = \frac{\sum_i m_i}{93.5\ \mathrm{eV}} < 0.0076$$
  which translates into upper bound
  $$\sum_i m_i < 0.71\ \mathrm{eV} \qquad (95\%\ \mathrm{CL})$$
- On the other hand atmospheric neutrino oscillations provide a lower bound on the heaviest neutrino mass, since $\sqrt{\delta m^2_{\mathrm{atm}}} \sim 0.03\ \mathrm{eV}$

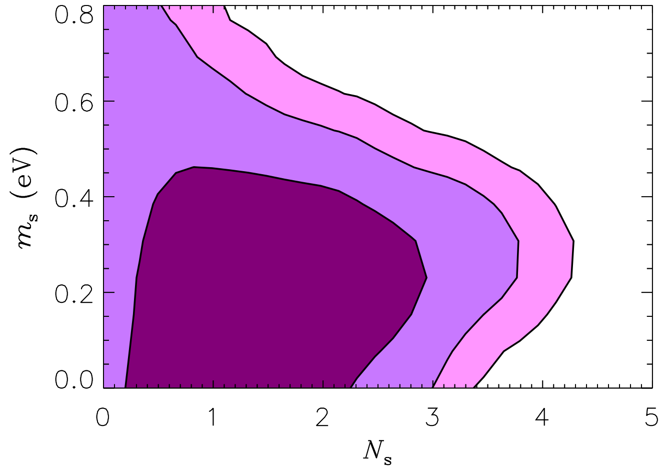
Combining these two limits

$$0.03\ \mathrm{eV} \leq m_{\mathrm{heaviest}} \leq 0.24\ \mathrm{eV}$$

we see that heaviest neutrino mass is now known to an order of magnitude.

Light sterile neutrino

$(3+N_s)$ schenario. Data: CMB+SDSS+H0



68%, 95% and 99% confidence regions

Hamann et al., 2010

Light sterile neutrino

Caveats:

- Assumptions about cosmology
- Numerical simulations of small scales
- Observational systematics
- Model variations
    - neutrino distribution may be non-thermal
    - neutrinos might have non standard properties
    - other light species might populate the Universe
    - fundamental constants may vary
    - etc

SRG

Spectrum-Roentgen-Gamma

The Astrophysical Project

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NEWS **August 18, 2009** Roscosmos (Russia) and DLR (Germany) signed an Agreement "On cooperation in the framework of Spectrum-Roentgen-Gamma orbital astrophysical project"

The **Spectrum-Roentgen-Gamma** mission will be launched in the 2012 year into a L2 orbit with Soyuz launcher and Fregat buster from Baikonur. The mission will conduct all-sky survey with X-ray mirror telescopes eROSITA and ART-XC up to 11 keV. It will allow detection of about 100 thousand clusters of galaxies and discovery large scale Universe structure. It will also discover all obscured accreting Black Holes in nearby galaxies and many (about 3 millions) new distant AGN.