Non standard Neutrinos and Cosmology

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(CNRS & IPhT-CEA/Saclay)

thanks to: A.Strumia (Pisa)
Y.-Z. Chu (Yale)
G.Marandella (UC Davis > $$)
F.Vissani (Gran Sasso)
Neutrinos in the Cosmo

The Universe is made of: radiation, matter (DM+b+e), dark energy

The graph shows the evolution of the universe from the Big Bang to the present day, with different epochs marked by key events:

- Big Bang (3 min)
- Radiation (RD) and Matter (M) equality (R\text{Meq})
- Redshift (1+z)
- Matter Dominance (MD)
- Cold Dark Matter (CDM)
- Dark Energy (\Lambda)
- Today

Event Timelines:
- BBN (3 min)
- CMB (400 million y)
- Last Scattering Surface (L S S) (1-10 billion y)
Neutrinos in the Cosmo

The Universe is made of: radiation, matter (DM+b+e), dark energy and neutrinos

Neutrinos are significant because:
- main component of the rel energy density that sets expansion rate of the Universe
- (ordinary neutrinos have a mass, so) turn from Rel to NRel at a crucial time
- may free-stream or interact among themselves, or with new light particles

[thanks to M.Frigerio]
Neutrinos in the Cosmo

So what “neutrinos”?

- 3 ordinary, SM neutrinos
- Extra light degrees of freedom, very weakly coupled to SM forces

So what properties are probed by cosmology?

- Neutrino number
- Total neutrino mass
- Non-conventional interactions

What are the relevant cosmological probes?

- BBN \( (T \sim \text{MeV}, \text{flavor is important, primordial plasma}) \)

- Later cosmology i.e. CMB+LSS \( (T \lesssim \text{eV}, \approx m_\nu, \text{gravity is the only force}) \)

Cosmological data are (mostly) not sensitive to:

\[ \theta_{\text{active}}, m_{1,2,3} \text{ (or } \Delta m^2_{\text{active}}), \text{ CP-violation...} \]
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Neutrinos in CMB+LSS

Neutrinos affect (indirectly, i.e. gravitationally) the evolution of cosmological perturbations in radiation and matter.

Neutrinos in CMB+LSS

$N_\nu \sum m_\nu$

... 

cosmological perturbations evolution

$\Omega_b, \Omega_{DM}, \tau, A_s, H_0, n_s$

WMAP

2dF, SDSS, Ly-A

CMB

LSS

Power spectrum in Mpc$^{-3}$
Neutrinos affect (indirectly, i.e. gravitationally) the evolution of cosmological perturbations in radiation and matter.

\[ N_\nu \sum m_\nu \]

... 

\[ \Omega_b, \Omega_{DM}, \tau, A_s, H_0, n_s \]

CMBfast/CAMB or your own code

CMB

LSS

WMAP

2dF, SDSS, Ly-A
Formalism
(=cosmological perturbation theory in one slide)

\[ \dot{\Theta} + ik\mu\Theta = -\dot{\Phi} - ik\mu\Psi - \dot{\tau} \left[ \Theta_0 - \Theta + \mu v_b - 1/2 \mathcal{P}_2(\mu)\Pi \right] \]

\[ \dot{\Theta}_P + ik\mu\Theta_P = -\dot{\tau} \left[ \Theta_P + 1/2 (1 - \mathcal{P}_2(\mu))\Pi \right] \]

\[ \dot{\delta}_{dm} + ikv_{dm} = -3\dot{\Phi} \]

\[ \dot{\nu}_{dm} + \frac{\dot{a}}{a} \nu_{dm} = -ik\Psi \]

\[ \dot{\delta}_b + ikv_b = -3\dot{\Phi} \]

\[ \dot{\nu}_b + \frac{\dot{a}}{a} \nu_b = -ik\Psi + \frac{\dot{\tau}}{R} \left[ \nu_b + 3i\Theta_1 \right] \]

\[ \mathcal{N} + i \frac{q_\nu}{E_\nu} k\mu\mathcal{N} = -\dot{\Phi} - i \frac{E_\nu}{q_\nu} k\mu\Psi \]

\[ k^2 \dot{\Phi} + 3 \frac{\dot{a}}{a} \left( \dot{\Phi} - \Psi \frac{\dot{a}}{a} \right) = 4\pi G_N a^2 \left[ \rho_m \delta_m + 4\rho_r \delta_r \right] \]

\[ k^2 (\Phi + \Psi) = -32\pi G_N a^2 \rho_r \Theta_{r,2} \]
The dataset

CMB Temperature and Polarization:
- **WMAP 3-years** (TT, TE, EE spectra) WMAP Science Team, astro-ph/0603449
- ACBAR (TT) Kuo et al., astro-ph/0212289
- CAPMAP (EE) Barkats et al., astro-ph/0409380
- DASI (TE, EE) Leitch et al., astro-ph/0409367
- VSA (TT) Grainge et al., astro-ph/0212495

LSS galaxy redshift surveys: dealing with bias and non-linearities as
- SDSS SDSS Coll., astro-ph/0310725
- 2dF 2dF Coll., astro-ph/0501174

Baryon Acoustic Oscillations: in terms of a measurement of
- Eisenstein et al., astro-ph/0501171

Lyman-α Forest:
- Croft Croft et al., astro-ph/0012324
- SDSS SDSS Coll., astro-ph/0407377

Type Ia Supernovae:
- SST Gold sample Riess et al., astro-ph/0402512
- SNLS Astier et al., astro-ph/0510447

Hubble constant:
- HST Project, Freedman et al., astro-ph/0012376

\[ h = 0.72 \pm 0.08 \quad H_0 = 100h \text{ km/sec/Mpc} \]
Results

Massive neutrinos affect the growth of matter perturbations during MD:

$$\ddot{\delta}_{dm} + \frac{\dot{a}}{a} \dot{\delta}_{dm} \simeq 4\pi G_N a^2 \rho_m \delta_m$$

(Newton equ.)

massive neutrinos contribute to evolution of $a$ w.r.t. time

$\delta_{\nu} = 0$ because neutrinos free stream on small scales

Effect: suppression of matter power spectrum at small scales:

$$k_{NR} = 0.018 \Omega_m^{-1/2} \left( \frac{\sum m_{\nu}}{eV} \right)^{1/2} h_0 \ Mpc^{-1}$$

$$\frac{\Delta P}{P} \simeq -8 f_{\nu} = -8 \frac{\sum m_{\nu}}{(93 \ eV^2) h^2 \Omega_m}$$

a bound on $\sum m_{\nu}$:

$$\sum m_{\nu_i} < 0.40 \ eV$$

(50.9% CL, global fit)

without Lyman-$\alpha$:

$$\sum m_{\nu_i} < 0.73 \ eV$$

Caveat: plot for illustration only, all parameters fixed except neutrino mass.

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$N_\nu$ sets the total relativistic energy content and affects the CMB (and LSS) spectra:

\[ (\ell+1)C_\ell^{TT} \text{ in } \mu K^2 \]

\[ \begin{align*}
\text{Multipole } \ell & \\
0 & \leq \ell \leq 1400
\end{align*} \]

- \( N_\nu = 3 \)
- \( N_\nu = 5 \)

\[ \Delta N_\nu \]

a determination of $N_\nu$:

\[ N_\nu = 5 \pm 1 \quad \text{(global fit)} \]

Seljak 2006, Mangano 2007...

BUT dropping Ly-\(\alpha\) gives back

\[ N_\nu \simeq 3 \]

Cirelli, Strumia 2006

Caveat: plot for illustration only, all parameters fixed except $N_\nu$. 

Tension with BBN?
Ichikawa et al (2007): production of d.o.f. between BBN and CMB

Just systematics?
Hamann et al 2007, bias parameter and non-linearities
Results

New sticky particles?
\[ \dot{\Theta} + i k \mu \Theta = -\dot{\Phi} - i k \mu \Psi - \dot{\tau} \left[ \Theta_0 - \Theta + \mu v_b - 1/2 P_2(\mu) \Pi \right] \]

\[ \dot{\Theta}_P + i k \mu \Theta_P = -\dot{\tau} \left[ \Theta_P + 1/2 (1 - P_2(\mu)) \Pi \right] \]

\[ \dot{\delta}_{dm} + i k v_{dm} = -3 \dot{\Phi} \]
\[ \dot{v}_{dm} + \frac{\dot{a}}{a} v_{dm} = -i k \Psi \]

\[ \dot{\delta}_{b} + i k v_{b} = -3 \dot{\Phi} \]
\[ \dot{v}_{b} + \frac{\dot{a}}{a} v_{b} = -i k \Psi + \frac{\dot{\tau}}{R} [v_b + 3i \Theta_1] \]

\[ \dot{\mathcal{N}} + i \frac{q_\nu}{E_\nu} k \mu \mathcal{N} = -\dot{\Phi} - i \frac{E_\nu}{q_\nu} k \mu \Psi \]

\[ \dot{\delta}_x + i \frac{4}{3} k v_x = -4 \dot{\Phi} \]
\[ \dot{v}_x + \frac{i}{4} k \delta_x = -i k \Psi \]

\[ k^2 \Phi + 3 \frac{\dot{a}}{a} \left( \dot{\Phi} - \frac{\dot{\Psi}}{a} \right) = 4\pi G_N a^2 \left[ \rho_m \delta_m + 4 \rho_r \delta_r \right] \]
\[ k^2 (\Phi + \Psi) = -32\pi G_N a^2 \rho_r \Theta_r \]

Massless particles, interacting among themselves (i.e. non freely streaming) at the time of CMB formation.

- e.g. a scalar $\varphi$ with $\lambda \varphi^4$
- e.g. scalar + fermion with $\lambda' \varphi v_s^2$
- e.g. fermions with $\langle NN \rangle$ ...

A relativistic fluid: $\delta_x, v_x$.

Contributes $\Delta N_\nu \cdot \delta_x$ to the rel energy density.
\( \Delta N_\nu \) extra massless particles interacting among themselves.

**Results**

**New sticky particles?**

\[ \Delta N_\nu = 0 \pm 1.3 \]

**Global fit:**

**Bottom Line:** Cosmology constrains extra massless sticky particles.
Results

New massive, sticky particles?
Results

New massive, sticky particles?

\[ \dot{\Theta} + i k \mu \Theta = -\dot{\Phi} - i k \mu \Psi - \hat{\tau} \left[ \Theta_{0} - \Theta + \mu v_{b} - 1/2 \mathcal{P}_{2} \right] \]

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\[ \mathcal{N} + \frac{q_{\nu}}{E_{\nu}} k \mu \mathcal{N} = -\dot{\Phi} - i \frac{E_{\nu}}{q_{\nu}} k \mu \Psi \]

\[ \dot{\delta}_{x} = -(1 + w) \left( 3\dot{\Phi} + ik v_{x} \right) \]

\[ \dot{v}_{x} = -i k \dot{\Psi} + \frac{\dot{a}}{a} \left( 1 - 3w \right) iv_{x} - \frac{w}{1+w} ik \delta_{x} \]

\[ k^{2} \dot{\Phi} + 3 \frac{\dot{a}}{a} \left( \dot{\Phi} - \Psi \frac{\dot{a}}{a} \right) = 4\pi G_{N} a^{2} \left[ \rho_{m} \delta_{m} + 4\rho_{r} \delta_{r} \right] \]

\[ k^{2} \left( \Phi + \Psi \right) = -32\pi G_{N} a^{2} \rho_{r} \Theta_{r,2} \]

Massive particles, interacting among themselves (i.e. non freely streaming).

A fluid defined by \( \delta_{x}, v_{x} \),

with \( w = 1/3 \) when rel,

\( w = 0 \) when NR.

Contribute to the Rel/NR energy densities.
Cosmology constrains extra sterile neutrinos (freely-streaming or interacting): they better be few and light.

\[10^{-3} \leq 10^{-1} \leq 1 \]

Number density \(\Delta N_{\nu}\)

10 standard neutrinos + \(\Delta N_{\nu}\) with mass \(m_s\), interacting among themselves

\(\nu_s\) as interacting CDM are more constrained

Results

New massive, sticky particles?

3 standard neutrinos + \(\Delta N_{\nu}\) with mass \(m_s\), interacting among themselves

\[
\begin{align*}
\text{allowed} & \quad \text{excluded} \\
\text{LSND} & \quad \text{Standard cosmology}
\end{align*}
\]

Bottom Line: Cosmology constrains extra sterile neutrinos (freely-streaming or interacting): they better be few and light.
Results
Can some neutrinos be sticky?

\[ N^\text{norm}_\nu \{ \circ \circ \} N_\phi \]

\[ N^\text{int}_\nu \{ \circ \circ \circ \circ \} \]
Results

Can some neutrinos be sticky?

\[ \dot{\Theta} + i k \mu \Theta = - \dot{\Phi} - i k \mu \Psi - \dot{\tau} \left[ \Theta_0 - \Theta + \mu \nu_b - 1/2 P_2(\mu) \Pi \right] \]
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Neutrinos interacting with extra particles such that free-streaming is prevented.

\[ g \nu \nu \varphi \]
\[ g' \nu \nu_s \varphi \]

Can some neutrinos be sticky?

\[ N^\text{norm}_\nu \]
\[ N^\text{int}_\nu \]
\[ N_\phi \]

photons

dark matter

baryons

e.g. effective couplings

\[ g \nu \nu \varphi \]
\[ g' \nu \nu_s \varphi \]

freely-streaming neutrinos

interacting particles

\[ N^\text{norm}_\nu + \frac{4}{7} N_\phi \]

contribute to Rel energy density.

extra

baryons

can some neutrinos be sticky?

\[ N^\text{norm}_\nu \]
\[ N^\text{int}_\nu \]
\[ N_\phi \]

photons

dark matter

baryons

e.g. effective couplings

\[ g \nu \nu \varphi \]
\[ g' \nu \nu_s \varphi \]

freely-streaming neutrinos

interacting particles

\[ N^\text{norm}_\nu + \frac{4}{7} N_\phi \]

contribute to Rel energy density.

extra
Sticky neutrinos don’t stream out of gravitational wells: contribute power to CMB. For massless neutrinos the effect on $P(k)$ is minor.

Quantitatively: \cite{Friedland2007}

\[
\left\{ \frac{\Delta C_\ell}{C_\ell}, \Delta \ell \right\} \approx - \{0.53, 57\} \frac{\rho_{\text{free}}}{\rho_{\text{free}} + \rho_{\text{sticky}} + \rho_{\gamma}}
\]

\cite{Hannestad2005, Bell2006}
Results

Can some neutrinos be sticky?

\[ N_{\nu}^{\text{norm}} \] \[ N_{\nu}^{\text{int}} \] \[ N_{\phi} \]

Results

Can some neutrinos be sticky?

\[ \sim 1 \text{ sticky } \nu \text{ allowed} \] (@ 99% CL, global fit)

3 sticky \( \nu \) excluded (at 5\( \sigma \))

Planck will greatly improve (will test 1 sticky at 4\( \sigma \))

[see also Bell, Pierpaoli, Sigurdson, PRD73 (2006)]

[Planck, Friedland, Zurek, Bashinsky(2007)]
Results

Can all neutrinos be sticky?

Massive neutrinos and massless boson: \( m_\nu \)

- e.g. Neutrinoless Universe
  [Beacom et al. PRL '04]
- e.g. Mass Varying Neutrinos,
  [Fardon et al. JCAP '04]
- Late Neutrino mass models
  [Chacko et al. PRD '04]

Massless neutrinos and massive boson: \( m_\phi \)

- disfavored at 3 to 5 \( \sigma \)

Bottom Line: Cosmology strongly disfavors fully interacting (non-freely streaming) neutrinos.
Conclusions & Messages

- Cosmology is a sensitive probe of neutrinos and possible new light particles; let’s put at work the formalism (and a new code) for cosmological perturbation to extract the most from the full cosmo dataset.

- Cosmology gives dominant bound on $\sum m_{\nu_i}$; $\sum m_{\nu_i} < 0.40$ eV (global fit, 99.9% C.L.)

- Cosmology seems to suggest 5 neutrinos (2 extra); but Ly-alpha are mainly driving the suggestion. The massive extra neutrino of LSND was already strongly disfavored.

- Cosmology disfavors at various degrees neutrino interactions and other light particles: neutrinos ought to free-stream.

- Future observations will be powerful probes.
Extra slides
Lyman-alpha forest

Distant quasar light, redshifted and absorbed at Ly-α frequency by intervening matter, allows to reconstruct matter distribution along the line of sight. But: systematics and uncertainties.

Skepticism on Lyman-α:
- very complicated measurement and analysis (from flux to matter spectra), different groups disagree (even on same data)
- non linearities
- HMD simulations don’t include neutrinos
Comparing our code

Our analysis:

WMAP Science Team analysis:

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agreement is at few % level and within current precision of data
Neutrinos in the Cosmo

LEPTONS

Neutrino Properties

SUM OF THE NEUTRINO MASSES, $m_{\text{tot}}$

(Defined in the above note), of effectively stable neutrinos (i.e., those with mean lives greater than or equal to the age of the universe). These papers assumed Dirac neutrinos. When necessary, we have generalized the results reported so they apply to $m_{\text{tot}}$. For other limits, see SZA-LAY 76, VYSOTSKY 77, BERNSTEIN 81, FREESE 84, SCHRAMM 84, and COWSIK 85.

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(from Particle Data Book 2008)

Number of Neutrino Types

The neutrons referred to in this section are those of the Standard SU(2) x U(1) Electroweak Model possibly extended to allow nonzero neutrino masses. Light neutrinos are those with $m < m_{\chi}/2$. The limits are on the number of neutrino mass eigenstates, including $\nu_1$, $\nu_2$, and $\nu_3$.

Number of Light $\nu$ Types

(“light” means < about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestrial experiments, see DENEGRI 90. Also see “Big-Bang Nucleosynthesis” in this Review.

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<td>COSM</td>
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<td>95</td>
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<td>BBN</td>
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<td>Cosmology</td>
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<td>HATA 97B</td>
<td>High D/H quasar abs.</td>
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<td>OLIVE 97</td>
<td>BBN; high $^4$He and $^7$Li</td>
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<td>FIELDS 96</td>
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<td>BBN; $\geq 3$ massless $\nu$</td>
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<td>&lt; 3.3</td>
<td>91</td>
<td>WALKER 91</td>
<td>Cosmology</td>
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</table>
On neutrino masses

present bounds

future sensitivities

Legenda: the bound or measurement will fall somewhere in the colored box; “where it’ll fall exactly” depends on the author, the experiment considered, priors, the weather...

best summary reference: Lesgourgues, Pastor review
On neutrino masses

FIG. 5: Response of the four reduced CMB observables to the variation of $\omega_\nu$. The isolated points show the values at $\omega_\nu = 0$, which do not connect to the $\omega_\nu \neq 0$ values smoothly.

Ichikawa et al, 2004
Degeneracies

$m_\nu$ effect can be cancelled by $w < -1$.
(SNIa data allow less $\Omega_\Lambda$, hence more $\Omega_m$, if $w < -1$; more $\Omega_m$ brings back up the $P(k)$)

Large $N_\nu$ can be cancelled by large $\Omega_m$ or $h$

or by low $\sigma_8$


Friedland et al. 2007

[back to Nnu]
Degeneracies

\[ \sum m_\nu \] will **not** be forever degenerate with other parameters:

Why is the signature of massive neutrinos non-degenerate with other cosmological parameters?

Light neutrinos             step-like suppression
massless neutrinos
massive neutrinos
primordial tilt \( n \)
running tilt

\[ \frac{P(k, a)}{a^2} = (1 + z^2) P(k, z) \]

massess neutrinos
massive neutrinos

step-like suppression as redshift increases
\( \sum m_\nu \) will not be forever degenerate with other parameters:

\( \sum m_\nu \) 

Planck + precision Ly-\( \alpha \):

Planck + very precise Ly-\( \alpha \)

Planck + precise Ly-\( \alpha \)

Planck alone

Planck (with lensing extraction):

\( f_\nu \propto \sum m_\nu \)

Gratton, Eisenhauer 2007

Perrotta, Lesgourgues, et al. 2006

Julien Lesgourgues, talks in 2007