

# Overview of cosmological constraints on neutrino mass, number, and types

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## Recent Reviews

- G. G. Raffelt, Neutrino masses in astroparticle physics, astro-ph/0207220.
- K. N. Abazajian, Telling three from four neutrinos with cosmology, astro-ph/0205238.
- S. Hannestad, Neutrino physics from cosmological observations, astro-ph/0208567.
- K. Kainulainen and K. A. Olive, Astrophysical and cosmological constraints on neutrino masses, hep-ph/0206163.
- A. D. Dolgov, Neutrinos in cosmology, hep-ph/0202122.
- P. Di Bari, Update on neutrino mixing in the early universe, Phys. Rev. D 65, 043509 (2002), hep-ph/0108182.
- G. G. Raffelt, Particle physics from stars, Ann. Rev. Nucl. Part. Sci. 49, 163 (1999) hep-ph/9903472.

## Preliminaries

- Weyl fermion
  - Minimal (two-component) fermionic degree of freedom
  - $\psi_L \leftrightarrow \psi_R^c$  by CPT
- Active Neutrino (a.k.a. ordinary, doublet)
  - in  $SU(2)$  doublet with charged lepton  $\rightarrow$  normal weak interactions
  - $\nu_L \leftrightarrow \nu_R^c$  by CPT
- Sterile Neutrino (a.k.a. singlet, right-handed)
  - $SU(2)$  singlet  $\rightarrow$  no interactions except by mixing, Higgs, or BSM
  - $N_R \leftrightarrow N_L^c$  by CPT
  - Almost always present: Are they light? Do they mix?
- Dirac Mass
  - Connects distinct Weyl spinors (usually active to sterile):  $(m_D \bar{\nu}_L N_R + h.c.)$
  - 4 components,  $\Delta L = 0$
  - $\Delta I = \frac{1}{2} \rightarrow$  Higgs doublet
  - Why small? LED? HDO?

- Majorana Mass

- Connects Weyl spinor with itself:

- $\frac{1}{2}(m_T \bar{\nu}_L \nu_R^c + h.c.)$  (active);

- $\frac{1}{2}(m_S \bar{N}_L^c N_R + h.c.)$  (sterile)

- 2 components,  $\Delta L = \pm 2$

- Active:  $\Delta I = 1 \rightarrow$  triplet or seesaw

- Sterile:  $\Delta I = 0 \rightarrow$  singlet or bare mass

- Mixed Masses

- Majorana and Dirac mass terms

- Seesaw for  $m_S \gg m_D$

- Ordinary-sterile mixing for  $m_S$  and  $m_D$  both small and comparable (or  $m_S \ll m_d$  (pseudo-Dirac))

### ● 3 $\nu$ Patterns

- Solar: LMA favored, LOW possible (VAC, SMA almost excluded)
- $\Delta m_{\odot}^2 \sim (10^{-5} - 10^{-4}) \text{ eV}^2$  for LMA
- Atmospheric:  $\Delta m_{\text{Atm}}^2 \sim 3 \times 10^{-3} \text{ eV}^2$ , near-maximal mixing
- Reactor:  $U_{e3}$  small
- Mixings: let  $\nu_{\pm} \equiv \frac{1}{\sqrt{2}} (\nu_{\mu} \pm \nu_{\tau}) \rightarrow$

$$\nu_3 \sim \nu_+$$

$$\nu_2 \sim \cos \theta_{\odot} \nu_- - \sin \theta_{\odot} \nu_e$$

$$\nu_1 \sim \sin \theta_{\odot} \nu_- + \cos \theta_{\odot} \nu_e$$

- **Hierarchical pattern**
  - \* Analogous to quarks, charged leptons
  - \*  $\beta\beta_{0\nu}$  rate very small
- **Inverted quasi-degenerate pattern**
  - \*  $\beta\beta_{0\nu}$  if Majorana
  - \* SN1987A energetics (if  $U_{e3} \neq 0$ )?
  - \* May be radiative unstable
- **Degenerate patterns**
  - \* Motivated by CHDM (no longer needed)
  - \* Strong cancellations needed for  $\beta\beta_{0\nu}$  if Majorana
  - \* May be radiative unstable

- 4  $\nu$  Patterns

- LSND:  $\Delta m_{\text{LSND}}^2 \sim 1$  (6)  $\text{eV}^2$
- Z lineshape: 2.985(8) active  $\nu$ 's lighter than  $M_Z/2 \rightarrow$  fourth sterile  $\nu_s$
- 3 + 1 patterns

– 2 + 2 patterns

- Pure  $(\nu_\mu - \nu_s)$  excluded for atmospheric by SuperK, MACRO
- Pure  $(\nu_e - \nu_s)$  excluded for solar by SNO, SuperK
- More general admixtures possible, but very poor global fits

## Big Bang Nucleosynthesis

- Parameters

- $\eta = n_B/n_\gamma$  ( $\eta_{10} \sim 274 \Omega_b h^2$ )
- $\Delta N_\nu$  (any new source of energy density, relative to one active  $\nu$  flavor)
- $\xi_e = \mu_{\nu_e}/T$ , related to  $(n_{\nu_e} - n_{\bar{\nu}_e})/n_\gamma$

- SBBN:  $\Delta N_\nu = \xi_e = 0$

- $\nu_e n \leftrightarrow e^- p$  and  $e^+ n \leftrightarrow \bar{\nu}_e p$  keep  $n_n/n_p$  in equilibrium as long as it is rapid enough

- Freezeout at  $T_\star \sim 1$  MeV, when  $\Gamma_{\text{weak}} \sim H$

- $\Gamma_{\text{weak}} = c G_F^2 T^5$

- $H = \left[ \frac{8\pi}{3} G_N \rho \right]^{1/2} \sim 1.66 g_\star^{1/2} T^2 / M_{Pl}$

- $g_\star = g_B + \frac{7}{8} g_F$ , with  $g_F = 10 + 2\Delta N_\nu$

- $T_\star \sim \left( \frac{n_\star^{1/2}}{G_F^2 M_{Pl}} \right)^{1/3}$

- $\frac{n_n}{n_p} = e^{-(m_n - m_p + \mu_{\nu_e})/T_\star} \rightarrow 4He$

- ${}^4He$  mass fraction:  $Y_p = \frac{4n_{{}^4He}}{n_H}$  depends strongly on  $\Delta N_\nu$  ( $\Delta Y_p \sim 0.013 \Delta N_\nu$ ) and  $\xi_e$ , weakly on  $\eta$

- $Y_2 = \frac{D}{H}$  depends on  $\eta$  (baryometer)

- Independent determination of  $\eta$  from CMB

- Data

- “High”:  $Y_p^{\text{exp}} = 0.244(2)$  (IT)
- “Low”:  $Y_p^{\text{exp}} = 0.234(3)$  (OS)
- High  $D/H$  not confirmed (hydrogen interloper?) in absorption of background quasars  
→ use Low  $D/H$
- $\Omega_b h^2(D/H) = 0.020(2)$
- $\Omega_b h^2(\text{CMB}) \sim 0.020(3)$  (DASI, BOOMERanG, MAXIMA). Current?

- Nonstandard BBN

- Typical range:  $-1.5 < \Delta N_\nu - 0.18\xi_e < 0.3$
- Most contributions to  $\Delta N_\nu$  are positive (**decaying  $\nu_\tau$**  could be negative, but small parameter range)
- Compensations with  $\xi_e > 0$  possible
- $\Delta N_\nu \sim 0$  for **right-handed components of light (eV) Dirac  $\nu$**  unless new BSM physics
  - \* Produced by mass effects for  $m_\nu \gtrsim 10$  keV
  - \* New weak interactions (OSS): e.g.  $f\bar{f} \rightarrow N_R \bar{N}_R$  by  $Z'$  or  $Z - Z'$  mixing; model dependent, but typically  $\Delta N_\nu \sim 0.3$  (no mixing) or 0.6 (allowed mixing). Suppressed in  $Z' N_R \bar{N}_R$  decoupling limit (BLL, tbp)

– Ordinary-sterile mixing in 4  $\nu$  schemes

- \* Produce  $\nu_s$  by oscillations and active scattering (decoherence)  $\rightarrow \Delta N_\nu \sim 1$
- \* Solar SMA into sterile would have been allowed, but not larger  $\Delta m^2$  or mixings
- \* Self-suppression (BFV,SFA):  $\Delta L \neq 0 \rightarrow$  could self-generate lepton asymmetries to either (a) suppress sterile production or (b) generate compensating  $\xi_e$
- \* Self-suppression now excluded for all 3+1 and 2+2 parameters (Di Bari, PR D65). (Also, solar + atm. fits (Maltoni et al, hep-ph/0207157)).
- \* Could save with large ( $O(1)$ ) preexisting asymmetry or 5th (heavier) sterile  $\nu_s$

– Neutrino degeneracy

- \*  $\Delta N_\nu - 0.18\xi_e = \sum_{i=e,\mu,\tau} \left[ \frac{30}{7} \left( \frac{\xi_i}{\pi} \right)^2 + \frac{15}{7} \left( \frac{\xi_i}{\pi} \right)^4 \right] - 0.18\xi_e \rightarrow$  compensation possible
- \*  $\xi_i$  also affect CMB (radiation vs matter energy)  $\rightarrow -0.01 < \xi_e < 0.22$ ,  $|\xi_{\mu,\tau}| < 2.6$  (Hansen et al, astro-ph/0105385)
- \* Flavor equilibrium for LMA (and possibly LOW): flavors equilibrate  $\rightarrow \xi_e = \xi_\mu = \xi_\tau \rightarrow |\xi_i| < 0.07 \rightarrow$  irrelevant (verify via Kamland). (LS, astro-ph/0012056; Dolgov et al, hep-ph/0201287; Wong, hep-ph/0203180; ABB, astro-ph/0203442). (Could still compensate large  $|\xi_i|$  by other new energy source.)

## Large Scale Structure (LSS) and CMB

- Hot Dark Matter (HDM)
  - $\Omega_\nu h^2 = \sum_l m_{\nu_i} / 92.5 \text{ eV}$
  - HDM excluded by free-streaming: not enough time for large structures to fragment
  - Also by Tremaine-Gunn bound on phase space in  $\nu$ -dominated galaxy  $\rightarrow m_\nu > 30 \text{ eV}$  (spirals),  $O(100) \text{ eV}$  (dwarfs)
  - Mixed CHDM models, typically  $\Omega_{\text{matter}} \sim 1$  and  $\sum_i m_{\nu_i} \sim \text{few eV} \rightarrow$  motivated degenerate  $\nu$  spectra.
  - Now excluded by (a)  $\Omega_{\text{matter}} \sim 0.3$  (clusters, etc); (b)  $\Omega_{\text{total}} = \Omega_{\text{DE}} + \Omega_{\text{matter}} \sim 1$ , DE = dark energy (1st CMB peak); (c)  $\Omega_{\text{DE}} \neq 0$  (Type Ia supernovae)

- Small admixture of HDM still possible
  - Free streaming suppresses smaller-scale fluctuations by factor  $\sim 8\Omega_\nu/\Omega_{\text{matter}}$  (HET, astro-ph/9712057)
  - 2dF survey:  $\sum_l m_{\nu_i} \lesssim 1.8 - 2.2 \text{ eV}$  (depends on priors for other parameters)
  - Future: sensitive to  $\sim 0.3 \text{ eV}$ , in joint study of LSS and CMB (HET)
  - cf. tritium  $\beta$  decay:  $m_\nu < 2.4 \text{ eV}$  (future: KATRIN,  $\sim 0.3 \text{ eV}$ )
  - Enhanced sensitivity for  $\xi_i \neq 0$
- Warm dark matter (e.g. 10 keV decaying  $\nu$ ) may still be viable
- CMB
  - Main  $\nu$  sensitivity is to  $\xi_i$ , which contributes to radiation density
  - Future:  $\Delta N_\nu \sim 0.1 - 0.2$  (present,  $O(1)$ ) (Bowen et al, astro-ph/0110636)
  - $\Omega_b h^2$  input to BBN.
  - Joint CMB and BBN analyses of  $\xi_i$
  - Needed for full LSS analyses of  $m_\nu$

## Brief Comments

- Supernovae

- Not important for reviving shock for standard 3  $\nu$
- $r$ -process not prevented by  $\nu_\mu \leftrightarrow \nu_e$  and  $\nu_e n \rightarrow e^- p$  for standard 3  $\nu$
- SN1987A energetics may disfavor inverted if  $U_{e3} \neq 0$
- Limits on energy loss, e.g. for LED,  $Z' \rightarrow N_R \bar{N}_R$ , large Dirac masses, millicharge,  $\mu_\nu$  (Dirac)
- New interactions (e.g. Majoron models)
- Sterile conversion could help  $r$ -process by removing active  $\nu$ 's to prevent  $\nu_e n \rightarrow e^- p$

- Magnetic or Electric Moments

- Motivated by alternative RSFP Solar  $\nu$  solution (still viable, even without time dependence)
- Transition (Majorana); transition or direct (Dirac)
- $He$  ignition in globular cluster red giants (plasmon decay):  $\mu_\nu \lesssim 3 \times 10^{-12} \mu_B$  (all types)
- $\mu_\nu$  (Dirac)  $\lesssim 3 \times 10^{-12} \mu_B$
- Radiative decays

- Neutrino Decays
  - Radiative,  $\nu_2 \rightarrow \nu_1 \gamma$ : diffuse background from relic  $\nu$ 's; SN1987A radiation
  - Invisible decays (e.g., into Majorons): matter fraction and growth of structure
- Ultra High Energy Neutrinos
  - Events above GZK cutoff
    - \* Large  $\nu$  N interactions at HE (e.g. LED)
    - \* Z-burst scenarios, probe relic  $\nu$  for  $m_\nu \lesssim$  eV:  $\nu(\text{UHE})\bar{\nu}(\text{relic}) \rightarrow Z \rightarrow \text{hadrons}$
    - \* Source of HE  $\nu$ 's?
- Leptogenesis Phases
  - Baryogenesis via leptogenesis is attractive consequence of seesaw model.
  - Caveat: In general, leptogenesis involves new phases not measurable in principle in oscillations of  $\beta\beta_{0\nu}$  (may be measurable or constrained in specific models)
  - Dirac leptogenesis possible (MP, hep-ph/0206177)