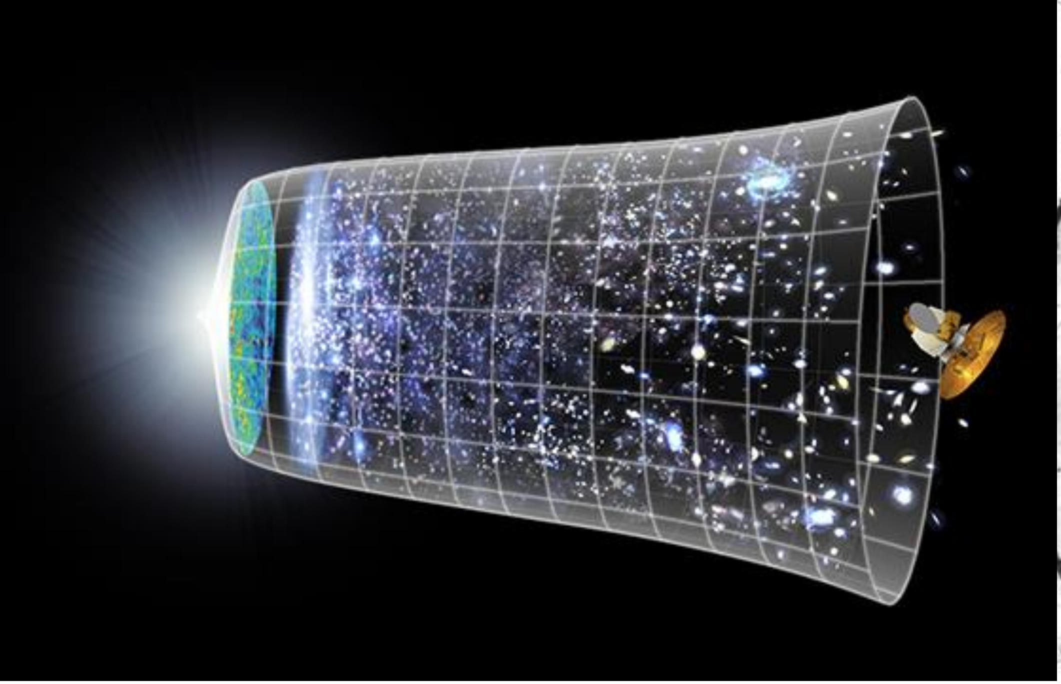
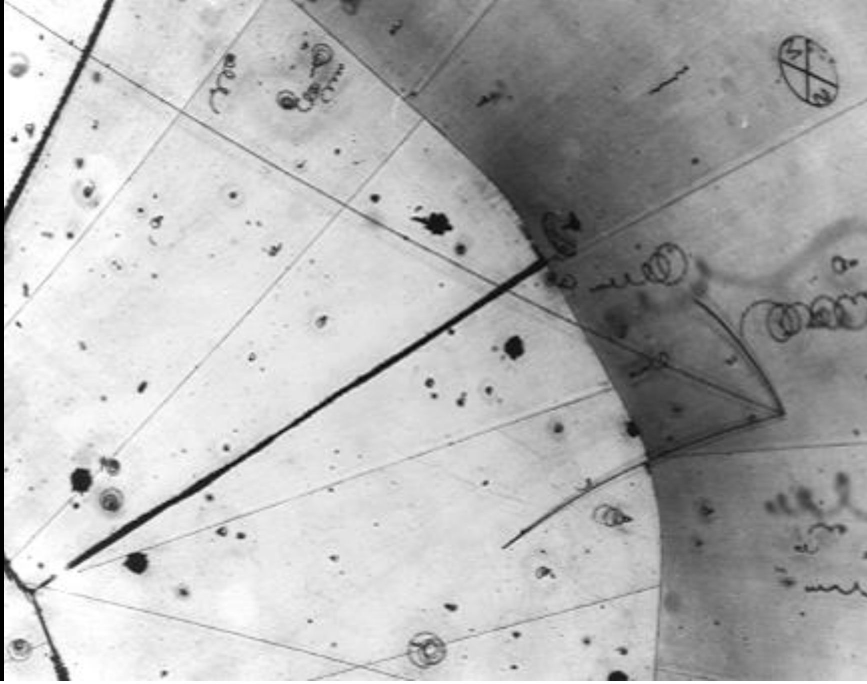



The Cosmic Neutrino Background

Joel Meyers

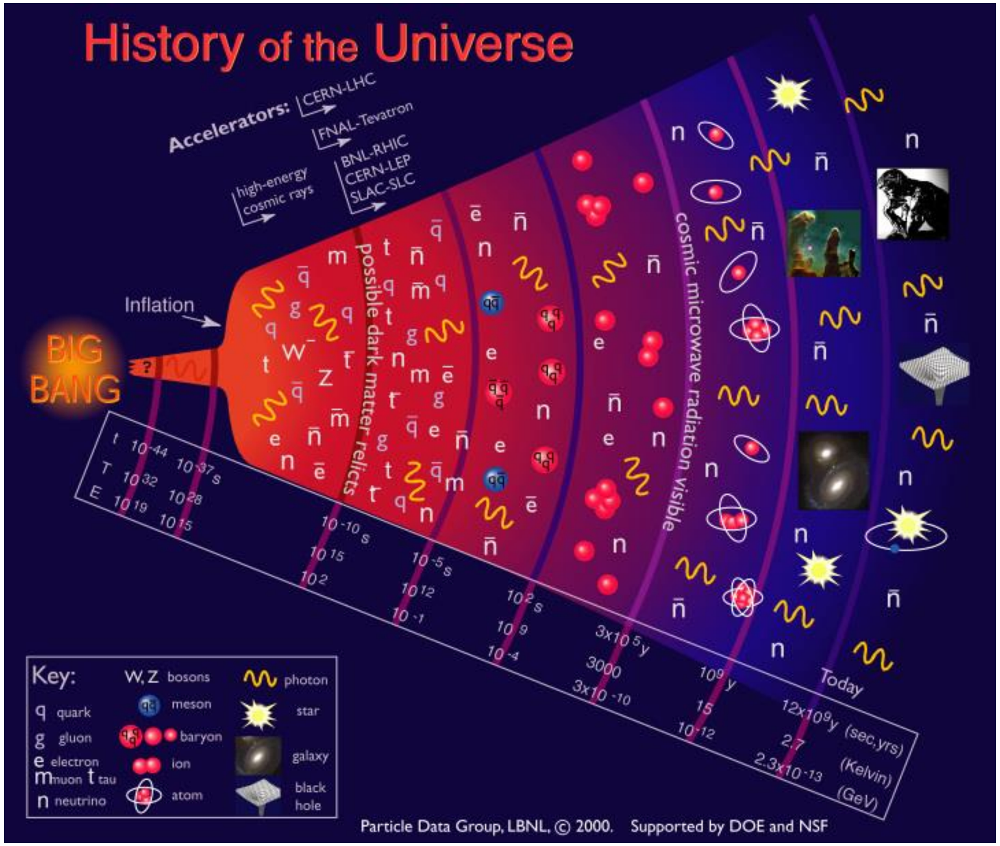
Canadian Institute for Theoretical Astrophysics

Cosmology on Safari

January 27, 2015

Theoretical Expectation

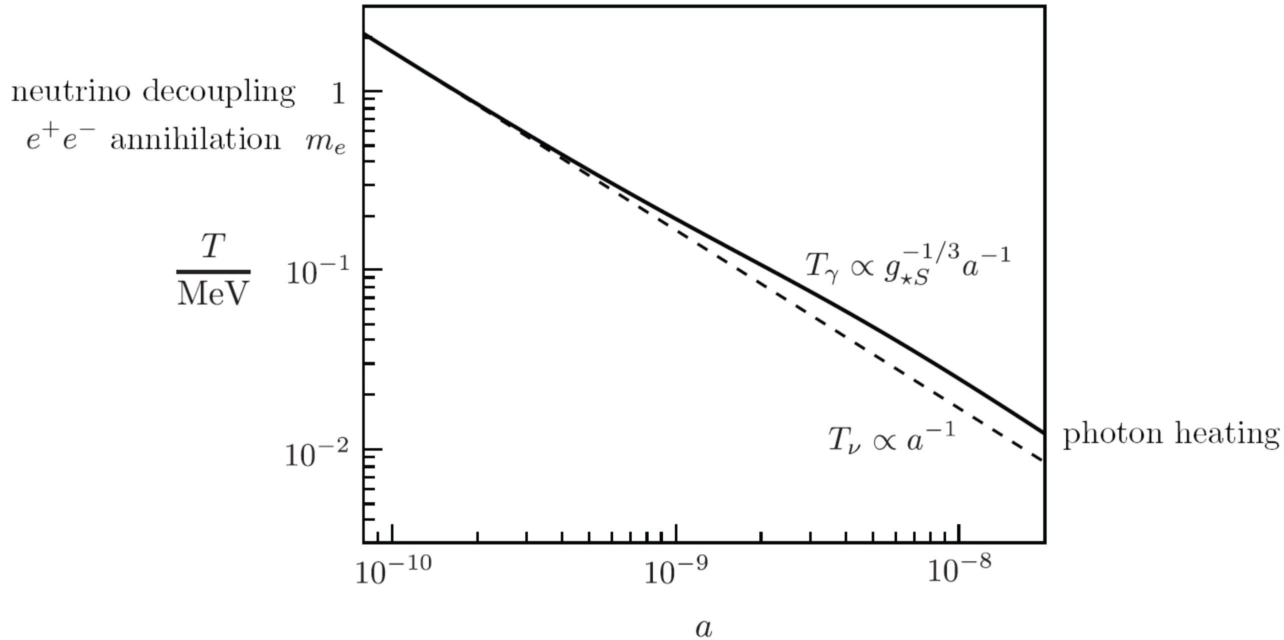
- The standard models of cosmology and particle physics make very definite and detailed predictions about the existence and properties of the cosmic neutrino background
- Neutrinos were in thermal equilibrium, decoupled about 1 second after the end of inflation, and have a nearly perfect Fermi-Dirac distribution



$$f_\nu(p, T_\nu) = \frac{1}{\exp\left(p/kT_\nu\right) + 1}$$

Gammow, et al. (1960s); PDG (2013)

CνB Temperature



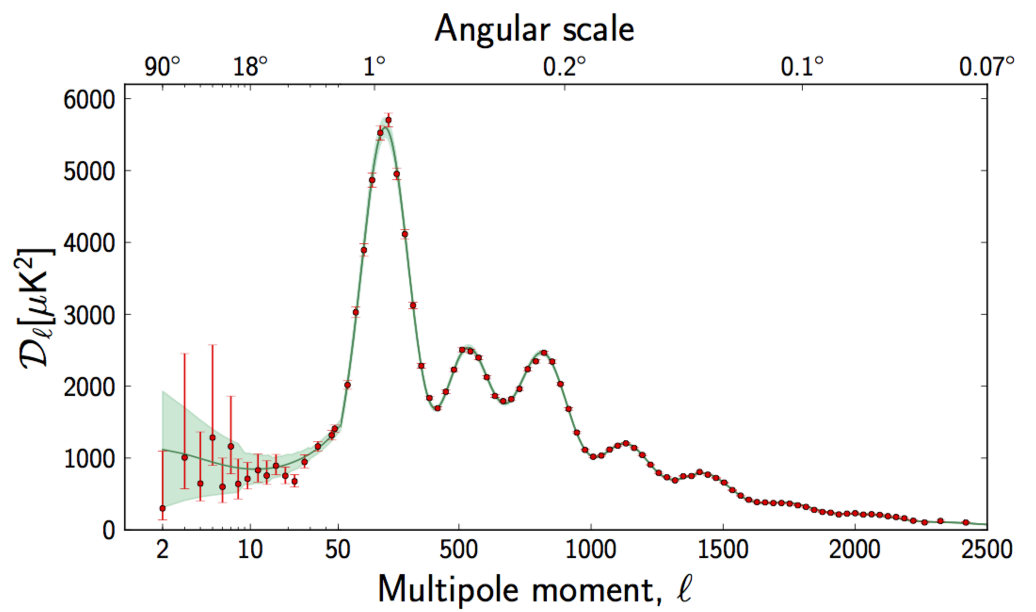
- Electron positron pairs annihilated after neutrino decoupling, heating photons relative to neutrinos
- Comoving entropy conservation fixes the neutrino temperature relative to photon temperature

$$T_\nu/T_\gamma = \left(\frac{4}{11}\right)^{1/3} \qquad T_{\nu,0} = 1.945\,\mathrm{K} \qquad \bar{n}_{\nu_i,0} = \bar{n}_{\bar{\nu}_i,0} = 56\,\mathrm{cm}^{-3}$$

PDG (2013)

Observational Status - CMB

- We have indirectly detected the cosmic neutrino background through its gravitational effects
- Current constraints are primarily summarized in just two numbers giving the total energy density and sum of neutrino masses



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

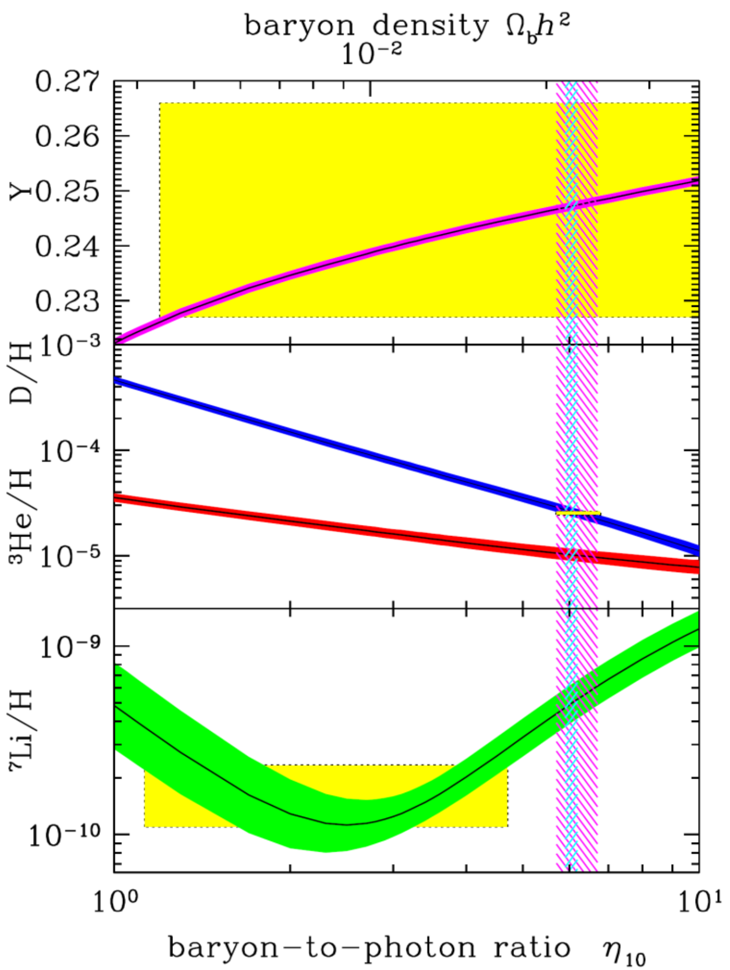
$$N_{\rm eff}^{\rm SM} = 3.046$$

$$N_{\rm eff}^{\rm CMB} = 3.04 \pm 0.18$$

$$\sum m_\nu < 0.23\,{\rm eV}$$

Planck (2014) *Preliminary

Big Bang Nucleosynthesis



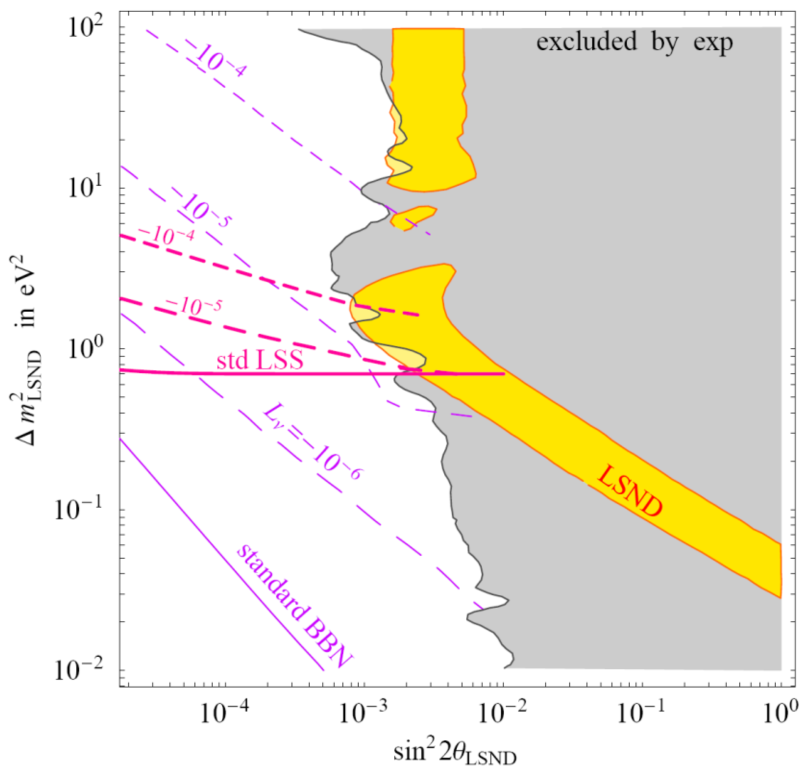
- Measurements of primordial light element abundances put an independent constraint on neutrinos at an earlier time
- BBN is weakly sensitive to the neutrino spectrum as well as the total radiation energy density

$$N_{\rm eff}^{\rm BBN} = 3.14^{+0.70}_{-0.65}$$

PDG (2013), Cyburt, et al. (2005)

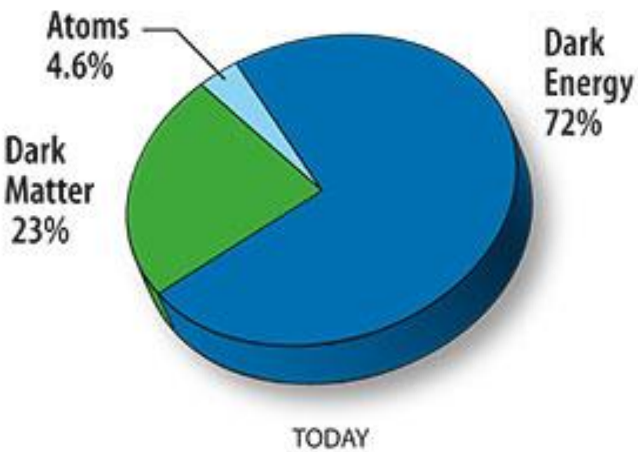
Dark Radiation

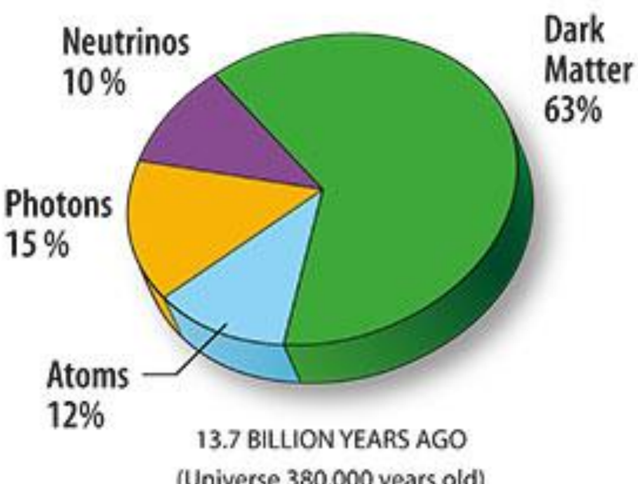
- Current observations agree with the standard model predictions for the cosmic neutrino background
- Additionally, measurements of N_{eff} give constraints on all forms of decoupled radiation, including:
  - Gravitational waves
  - Sterile neutrinos
  - Dark photons
  - Many others



Chu, Cirelli (2006); Boyle, Buonanno (2007); Ackerman, et al. (2008); Steigman (2012); …

Constraining New Physics





- Combining observations from BBN and CMB constrains non-standard cosmic histories, such as:
  - Dark sector decays:

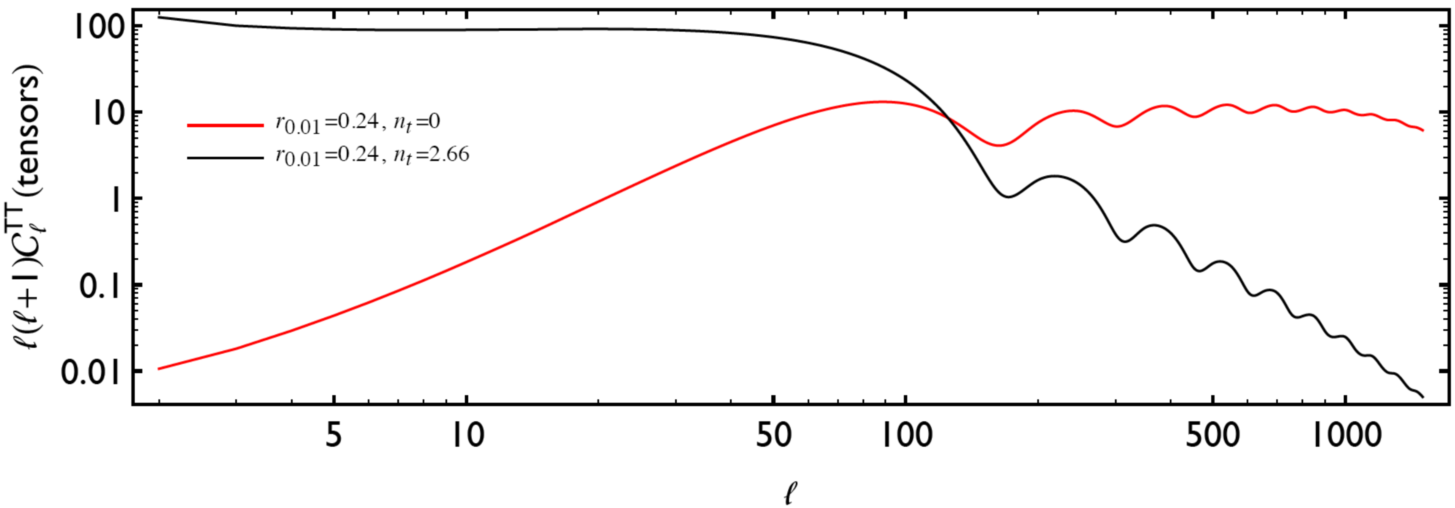
$$N_{\rm eff}^{\rm BBN} < N_{\rm eff}^{\rm CMB}$$

  - Late photon heating:

$$N_{\rm eff}^{\rm BBN} > N_{\rm eff}^{\rm CMB}$$

Fischler, JM (2010); Millea, Knox, Fields (2015)

Constraining Gravity Waves

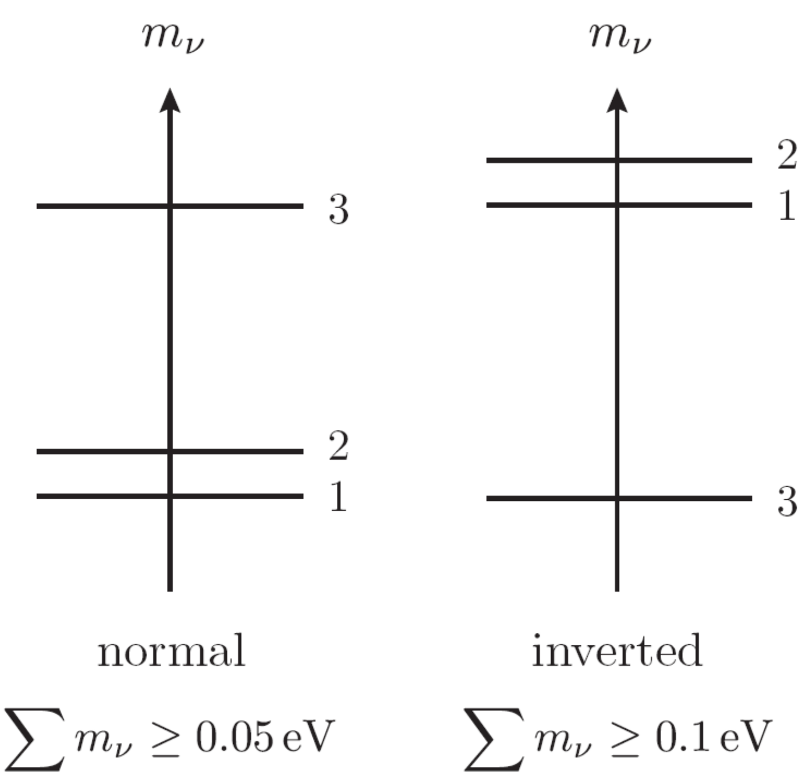


- Detection of B-modes by BICEP2 prompted renewed interest in primordial gravitational waves
- CMB data prefers a blue-tilted tensor spectrum due to low TT power at large scales
- A joint analysis, including the gravity wave contribution to N_{eff} places a more restrictive upper bound on tensor tilt

Meerburg, Hadzhiyska, Hlozek, JM (2015)

Neutrino Mass

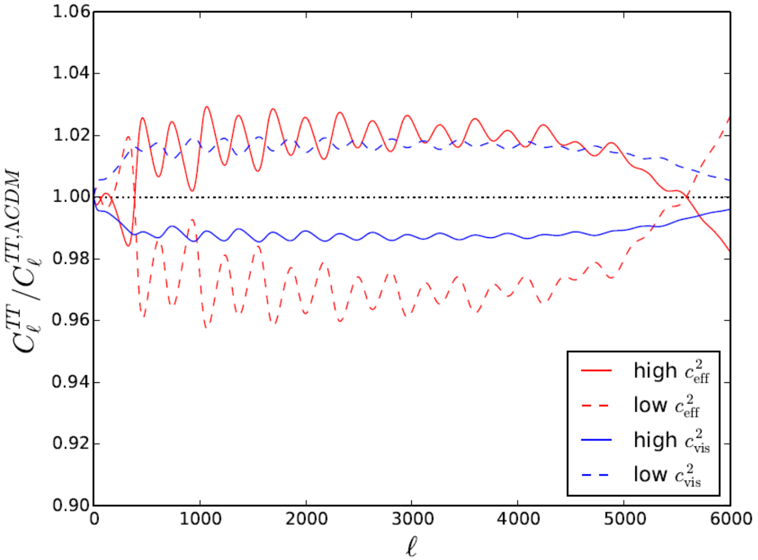
- Oscillation experiments provide neutrino mass splittings, but not absolute mass scale
- Cosmology places constraints on sum of neutrino masses
- Tighter constraints could determine mass hierarchy

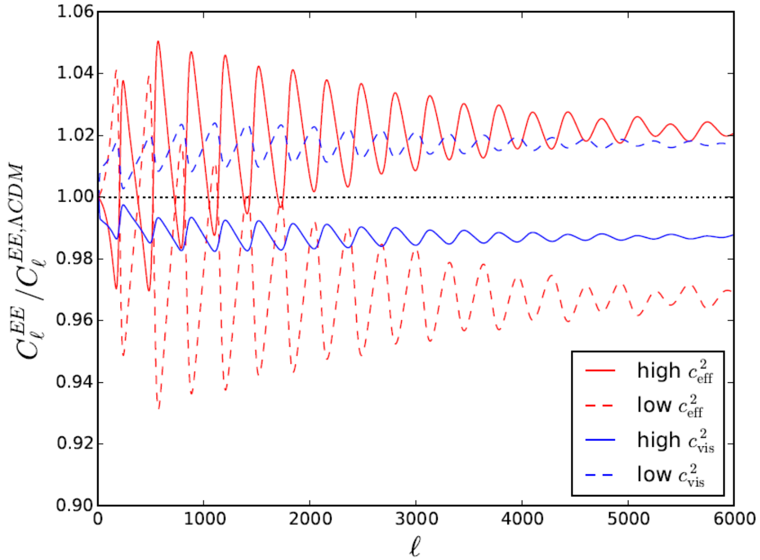


$$\sum m_\nu < 0.23\,\mathrm{eV}$$

Planck (2014) *Preliminary

Neutrino Perturbations





- Neutrino perturbations create anisotropic stress leading a characteristic phase shift in the CMB power spectrum
- Planck detects evidence of neutrino fluctuations at high significance

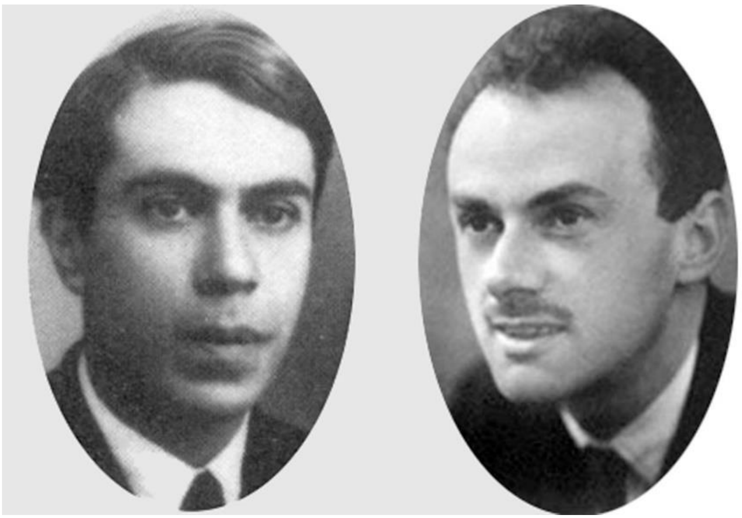
$$c_{\rm eff}^2 = 0.3242 \pm 0.0059$$

$$c_{\rm vis}^2 = 0.331 \pm 0.037$$

$$(\mathrm{SM}): \; c_{\rm vis}^2 = c_{\rm eff}^2 = 1/3$$

Bashinsky, Seljak (2004); Audren, et al. (2014); Planck (2014) *Preliminary

Ultimate Observational Goals for CvB



$$\ell_{\max}^{\mathrm{CMB}} \sim 10^{3.5}$$

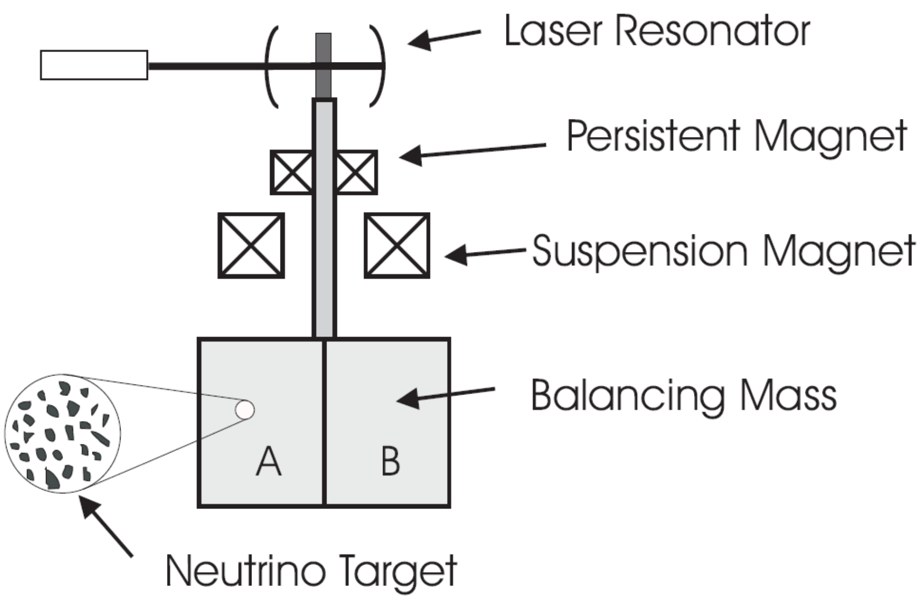
$$\ell_{\max}^{\mathrm{CNB}} \sim 10^{8}$$

- The cosmic neutrino background contains a wealth of information about particle physics and cosmology
- At least two mass eigenstates are non-relativistic today making it possible to distinguish Dirac versus Majorana nature
- Primary CvB fluctuations are damped at a much smaller angular scale as compared to CMB

Hu, Scott, Sugiyama, White (1995)

Challenge of Direct Detection

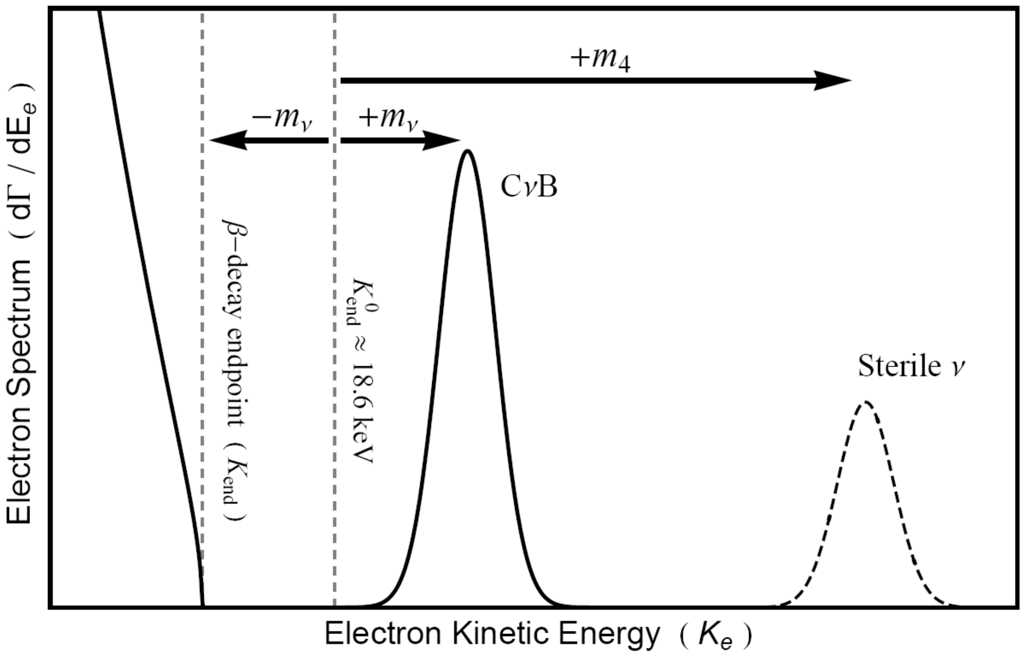
- The mean free path of a massless cosmic neutrino in lead is around 10^9 Gpc
- Torsion balances would need a vast improvement, even with coherent enhancement
- Best current prospect is neutrino capture on beta decaying nuclei
  - Tritium is the best candidate



Weinberg (1962); Hagmann (1999); Cocco, Mangano, Messina (2007)

PTOLEMY

- The Princeton Tritium Observatory for Light, Early Universe Massive Neutrino Yield (PTOLEMY) is under development and will be capable of detecting ~8 events per year for 0.1 eV neutrinos
- Direct detection provides a check of standard assumptions about the neutrino background
- The count rate could distinguish between Dirac and Majorana neutrinos



Tully et al. (2013); Long, Lunardini, Sabancilar (2014)

Conclusions

- Understanding the cosmic neutrino background lies at the interface of cosmology and particle physics
- We have indirect evidence of the existence of the CvB and some weak constraints on its properties
- Our standard model makes much more detailed predictions than can currently be tested with observation
- Observational constraints on the CvB naturally constrain a huge number of extensions to the standard cosmic history

10^{17} cosmic neutrinos pass through this elephant's ear each second!