3.06pt

Neutrinos in Cosmology

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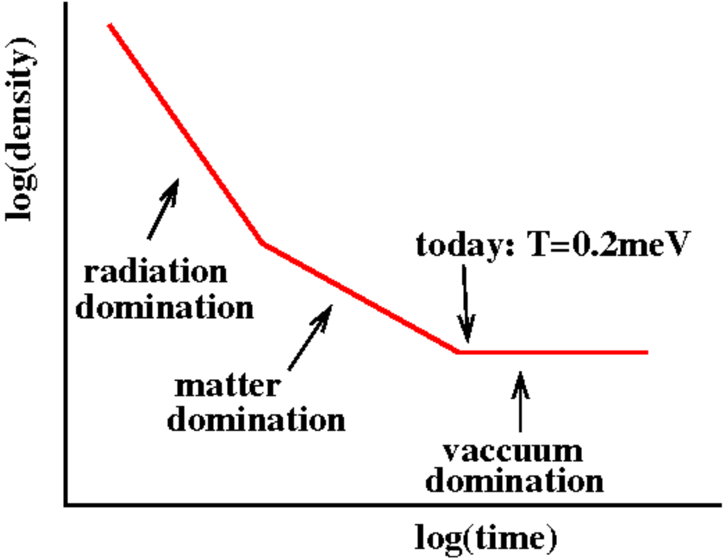
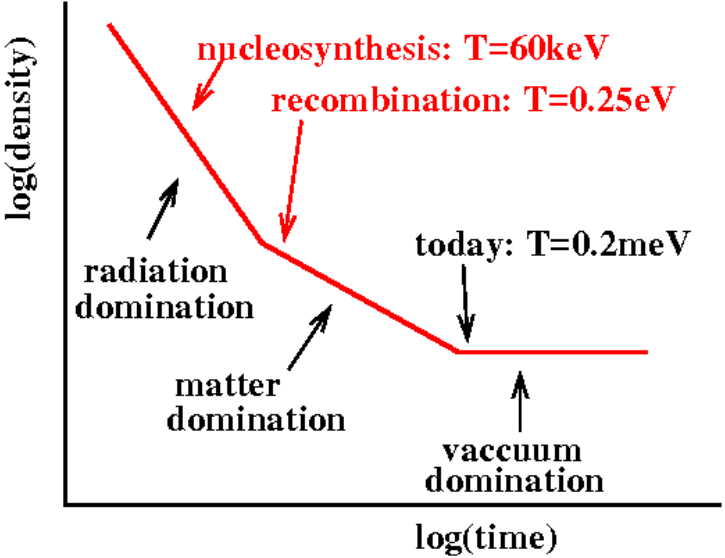
History of the universe:
Density and temperature decrease with time



History of the universe: Interesting things happen!



The role of neutrinos in cosmology: summary

Early Universe: effects of number of neutrino species $(\nu_e, \nu_\mu, \nu_\tau ....)$

- Each species: one black-body spectra in the primordial soup
  Effect on Nucleosynthesis $\Rightarrow N_\nu \sim 3$
  Effect on Recombination $\Rightarrow N_\nu \sim 3$

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- A super-challenge: detect cosmological neutrinos!

Early universe: Neutrinos = 3 more black bodies

Same as photons except

- Decouple much earlier (T ∼MeV instead of 0.25eV)
  [Only weak interactions]
- fermions instead of bosons
  [Slightly different thermal distribution]
- only left-handed ν and right-handed $\bar{\nu}$ reach thermal equilibrium
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Gold mine of questions for exams:

1. Show that $T_\nu = (4/11)^{1/3} T_\gamma$ (as long as $T \gg m_\nu$)
2. Show that $n_\nu = (3/11) n_\gamma \sim 110\mathrm{cm}^{-3}$ (each species)

What can a neutrino do in the early universe

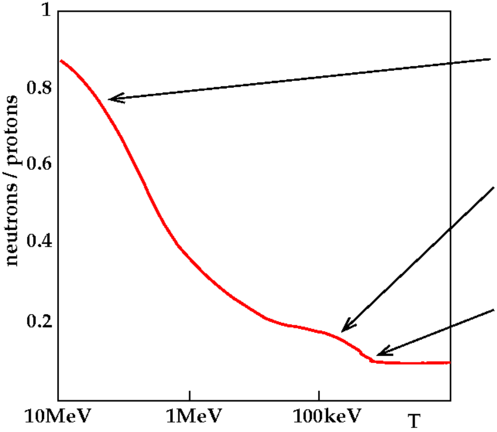
They have only

- weak interactions
- gravitational interactions.

Both interactions play essential roles.

ν_e weak interactions
$\Rightarrow$ initial conditions for nucleosynthesis

neutron-proton ratio vs. temperature:



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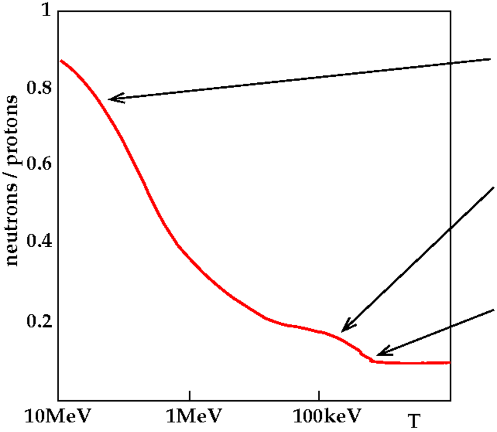


..

thermal equilibrium via
$\nu_e n \leftrightarrow e^- p$

..

$n \rightarrow p e^- \bar{\nu}_e$

nucleosynthesis ($T = 60$keV)
(number of neutrons reduced by decay)

ν_e, ν_μ, ν_τ gravitational interactions

.

expansion rate (squared) proportional to density

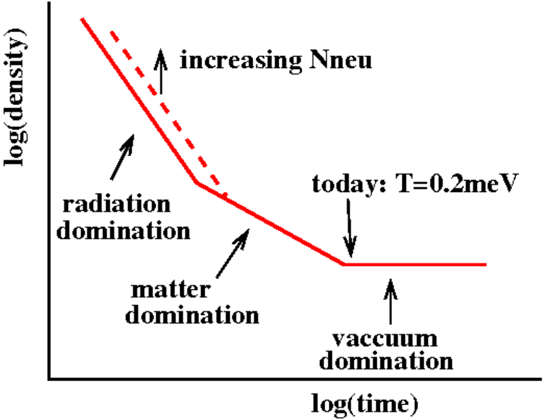
$$\frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3}(\rho_{matter} + \rho_\gamma + \rho_\nu + ...)$$

(Friedman)

$\Rightarrow$In radiation epoch expansion rate (squared) proportional to number of black-body spectra.

ν_e, ν_μ, ν_τ gravitational interactions

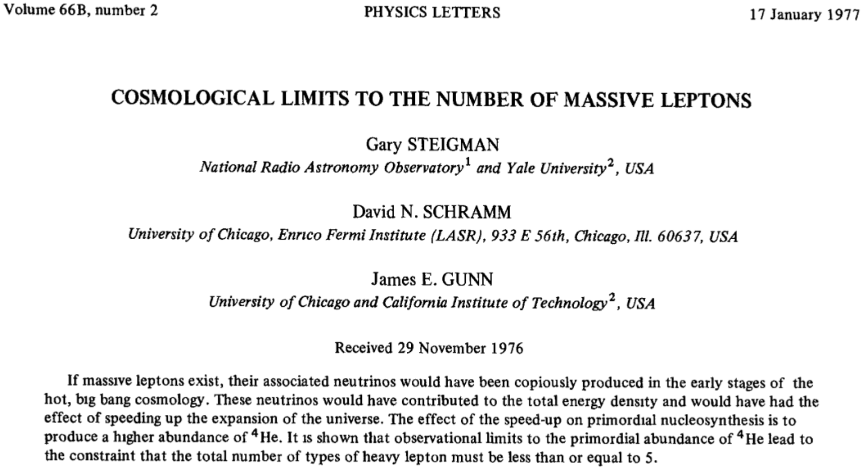
. Expansion rate in Early universe $\sim (N_\gamma + N_\nu) \quad (N_\gamma = 1)$.



$N_\nu > 3 \Rightarrow$ temperature drops faster

- Less time for neutron decay $\Rightarrow$ more helium than the observed 25%
- Recombination faster $\Rightarrow$ sharper CMB image

1977: Observed helium abundance $\Rightarrow N_\nu < 5$



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COSMOLOGICAL LIMITS TO THE NUMBER OF MASSIVE LEPTONS

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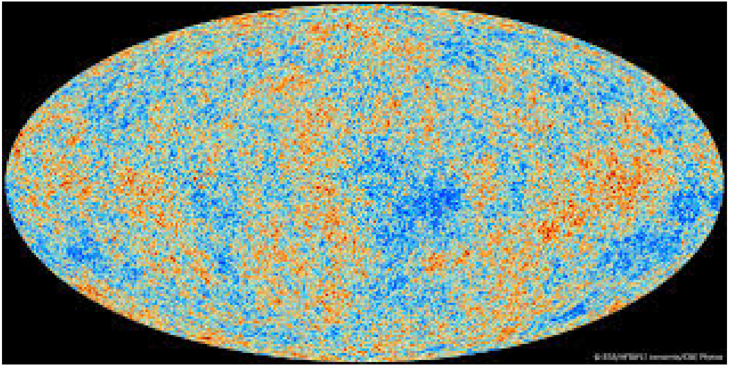
If massive leptons exist, their associated neutrinos would have been copiously produced in the early stages of the hot, big bang cosmology. These neutrinos would have contributed to the total energy density and would have had the effect of speeding up the expansion of the universe. The effect of the speed-up on primordial nucleosynthesis is to produce a higher abundance of ^{4}He. It is shown that observational limits to the primordial abundance of ^{4}He lead to the constraint that the total number of types of heavy lepton must be less than or equal to 5.

2015: $1.8 < N_\nu < 4.5$ (95%CL)
PDG, R.H. Cyburt et al., Astropart. Phys. 23, 313 (2005)

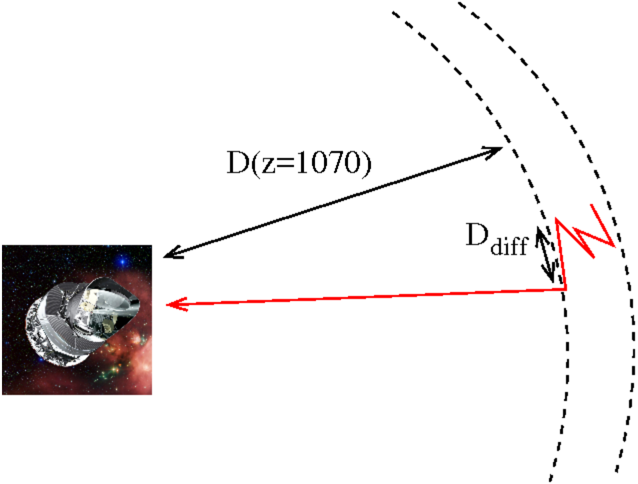
2015: CMB $\Rightarrow N_\nu = 3$

Planck image of our "last-scattering surface":



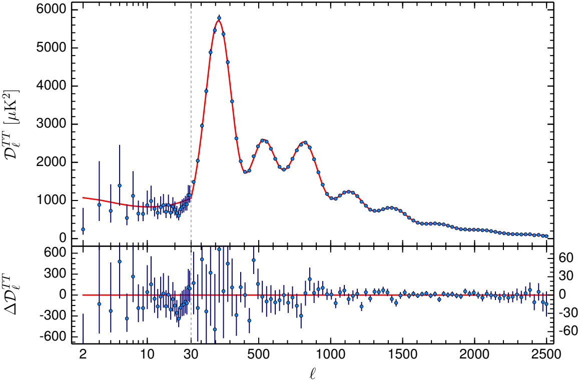
The image is blurred because photons random-walk in the 100,000yr before recombination. Increasing the expansion rate, reduces the time for random walking, and makes the image sharper.

Photon random walk on last-scattering surface



Diffusion distance proportional to geometric mean of photon mean-free-path and $ct_{walk} \sim 1/expansion\ rate$.

Planck damping for $\ell > 1000 \Rightarrow N_\nu < 4$



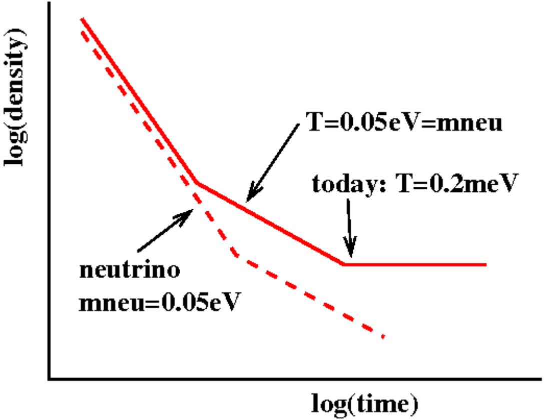
$N_\nu = 2.99 \pm 0.20$
(CMB only)

$N_\nu < 4$ at $\sim 3\sigma$

$\Rightarrow$ Any sterile neutrino must not have thermalized.

Late universe: massive neutrinos become non-relativistic $kT \sim m_\nu c^2$

Neutrino oscillation experiments $\Rightarrow$ at least one neutrino with $m_\nu > 0.05$eV!



m_ν modifies density

$\Rightarrow$ modified expansion rate (Friedman eqn.)

$\Rightarrow$ modified distance-redshift relation

Limits on neutrino mass

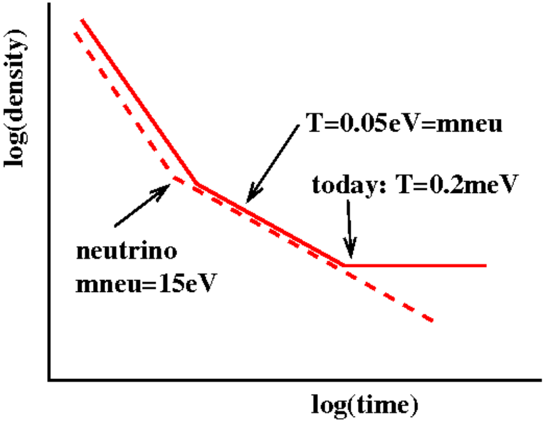
When $T \sim m_\nu$:

- Energy per neutrino becomes constant ($= m_\nu$)
  $\Rightarrow$modified the expansion rate
  $\Rightarrow$modified distance-redshift relationship
  $\Rightarrow m_\nu < 0.23 eV$ (Planck plus BAO)
- Start to contribute to structure formation
  Modify predicted inhomogeneities
  $\Rightarrow m_\nu < 0.12 eV$ (Planck plus Lyα forest)
  Palanque-Delabrouille et al [2015]

Question: If it turns out that $m_\nu > 0.2$eV, how must we modify the cosmological model to recover agreement? (e.g. time-varying dark energy).

Excluded: $m_\nu \sim 15$eV: hot dark matter

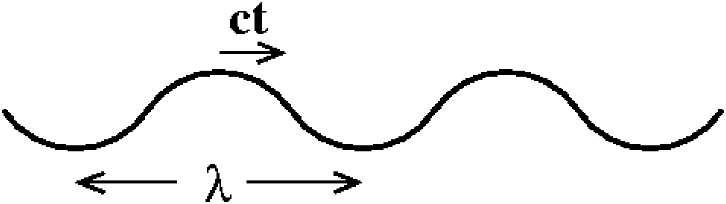
$m_\nu \sim 15$eV gives the right matter density (for $110 cm^{-3}$) but causes problems for CMB spectrum and structure formation.



m_ν modifies expansion rate before recombination $\Rightarrow$ CMB spectrum modified

Neutrinos "free stream" at $v = c$ until $T = 15$eV $\Rightarrow$ inhomogeneities on galactic scales removed.

Neutrino free-streaming destroys short wavelength perturbations

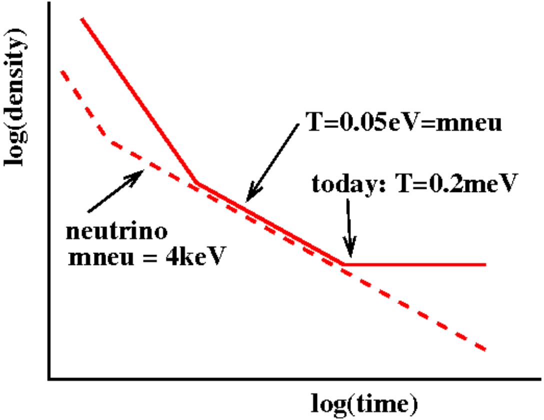


Neutrino perturbation destroyed if $ct > \lambda$ where t is the time between neutrino decoupling and $T = m_\nu$.

- $m_\nu = 15\text{eV} \Rightarrow$ galaxy-size perturbations destroyed
- $m_\nu = 4\text{keV} \Rightarrow$ small-galaxy-size perturbations destroyed

m_ν ~keV: warm dark matter

Matter density too high if $n_\nu = 100cm^{-3}$ ⇒ must not have been in thermal equilibrium in early universe.
Possibility: sterile neutrino produced by oscillations



Neutrinos "free stream" at $v = c$ until $T = 4$keV ⇒ inhomogeneities on scales of small galaxies removed. This is good because few small galaxies are seen!

m_ν ∼keV: warm dark matter

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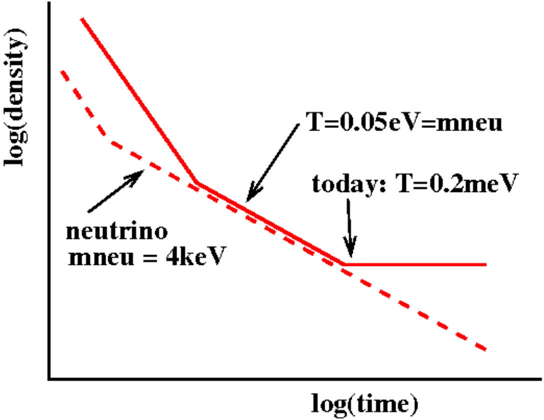

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⇒ fine-tuning once again: neutrino mass just big enough allow for the existence of galaxies!

The ultimate challenge: detection of ν_{cosmo}

Charged current interactions only on radioactive targets.
Tritium β-decay ($T_{1/2} = 12$yr):

$$^3H \rightarrow {}^3He\ e^-\ \bar{\nu}_e \qquad E_e(max) = M_{He} - M_H - m_\nu \sim 17 keV$$

Capture of cosmological neutrinos on tritium:

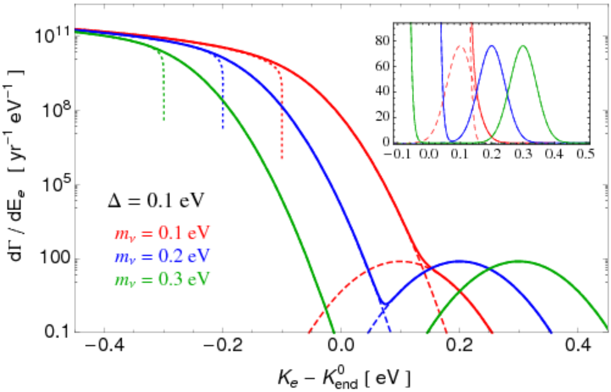
$$\nu\ {}^3H \rightarrow {}^3He\ e^- \qquad E_e = M_{He} - M_H + m_\nu$$

Capture electrons separated from β electrons by $2m_\nu$ (S. Weinberg)

100g tritium $\Rightarrow \sim$ 10 captures per year (and $\sim 3 \times 10^{24}$ decays!)

Tritium β-decay plus capture spectrum

Long et al. arXiv:1405:7654:



Ptolemy project: arXiv:1307.4738

Neutrinos in cosmology: conclusion

- Neutrinos have an essential role in cosmology
  Nucleosynthesis
  Maybe dark matter....
- Cosmological observations consistent with three light neutrinos.
- Direct observation somewhat difficult