Neutrinos in Cosmology

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History of the universe:
Density and temperature decrease with time

today: $T = 0.2\text{meV}$
History of the universe:
Interesting things happen!

nucleosynthesis: $T=60\text{keV}$
recombination: $T=0.25\text{eV}$

radiation domination
matter domination
vaccum domination
today: $T=0.2\text{meV}$
The role of neutrinos in cosmology: summary

Early Universe: effects of number of neutrino species \((\nu_e, \nu_\mu, \nu_\tau \ldots)\)
- 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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Late Universe: effects of neutrino mass
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  - No complications seen $\Rightarrow m_\nu < 0.2 - 0.1$ eV
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- A dark matter candidate that is easy to kill:
  - $m_\nu \sim 15\,\text{eV}$ (hot dark matter)
- An intriguing unorthodox dark matter candidate:
  - $m_\nu \sim 5\,\text{keV}$ (non-thermal relic, warm dark matter)
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- A super-challenge: detect cosmological neutrinos!
Early universe: Neutrinos = 3 more black bodies

Same as photons except

- Decouple much earlier ($T \sim$ MeV instead of 0.25eV)  
  [Only weak interactions]
- fermions instead of bosons  
  [Slightly different thermal distribution]
- only left-handed $\nu$ and right-handed $\bar{\nu}$ reach thermal equilibrium  
  [Wrong-helicity states not expected to be present.]
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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 $n_\nu = (3/11)n_\gamma \sim 110\text{cm}^{-3}$ (each species)
What can a neutrino do in the early universe

They have only
- weak interactions
- gravitational interactions.

Both interactions play essential roles.
$\nu_e$ weak interactions

$\Rightarrow$ initial conditions for nucleosynthesis

neutron-proton ratio vs. temperature:

$\nu_e n \leftrightarrow e^- p$

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

nucleosynthesis ($T = 60$ keV)

(number of neutrons reduced by decay)
$\nu_e$ weak interactions  
$\Rightarrow$ initial conditions for nucleosynthesis 

neutron-proton ratio vs. temperature:

\begin{itemize}
  \item thermal equilibrium via $\nu_e n \leftrightarrow e^- p$
  \item $n \rightarrow pe^- \bar{\nu}_e$
\end{itemize}

nucleosynthesis ($T = 60\text{keV}$) (number of neutrons reduced by decay)
$\nu_e, \nu_\mu, \nu_\tau$ gravitational interactions

expansion rate (squared) proportional to density

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

(Friedman)

$\Rightarrow$ In radiation epoch expansion rate (squared) proportional to number of black-body spectra.
$\nu_e, \nu_\mu, \nu_\tau$ gravitational interactions

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

$N_\nu > 3 \Rightarrow$ 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 $\Rightarrow N_\nu < 5$

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)

2015: $\text{CMB} \Rightarrow N_\nu = 3$

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 $ct_{walk} \sim 1/\text{expansion rate}$. 
Planck damping for $\ell > 1000 \Rightarrow N_\nu < 4$

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

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

⇒ 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 $m_\nu > 0.05\text{eV}$!

$m_\nu$ 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
  $\Rightarrow m_\nu < 0.23\text{eV}$ (Planck plus BAO)

- Start to contribute to structure formation
  Modify predicted inhomogeneities
  $\Rightarrow m_\nu < 0.12\text{eV}$ (Planck plus Ly$\alpha$ forest)

Palanque-Delabrouille et al [2015]

Question: If it turns out that $m_\nu > 0.2\text{eV}$, how must we modify the cosmological model to recover agreement? (e.g. time-varying dark energy).
Excluded: $m_\nu \sim 15\text{eV}$: hot dark matter

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

$m_\nu$ modifies expansion rate before recombination $\Rightarrow$ CMB spectrum modified

Neutrinos “free stream” at $\nu = c$ until $T = 15\text{eV}$ $\Rightarrow$ 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
$m_\nu \sim \text{keV}: \text{warm dark matter}$

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

Neutrinos “free stream” at $\nu = c$ until $T = 4\text{keV} \Rightarrow$ inhomogeneities on scales of small galaxies removed. This is good because few small galaxies are seen!
$m_\nu \sim$ keV: warm dark matter

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

Neutrinos “free stream” at $\nu = c$ until $T = 4$keV $\Rightarrow$ inhomogeneities on scales of small galaxies removed.
This is good because few small galaxies are seen!
$\Rightarrow$ fine-tuning once again: neutrino mass just big enough allow for the existence of galaxies!
The ultimate challenge: detection of $\nu_{\text{cosmo}}$

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

$$^{3}H \rightarrow ^{3}He \; e^{-} \; \bar{\nu}_{e} \quad E_{e}(\text{max}) = M_{He} - M_{H} - m_{\nu} \sim 17\text{keV}$$

Capture of cosmological neutrinos on tritium:

$$\nu^{3}H \rightarrow ^{3}He \; e^{-} \quad E_{e} = M_{He} - M_{H} + m_{\nu}$$

Capture electrons separated from $\beta$ electrons by $2m_{\nu}$ (S. Weinberg)

100g tritium $\Rightarrow \sim 10$ captures per year (and $\sim 3 \times 10^{24}$ decays!)
Tritium $\beta$-decay plus capture spectrum

Long et al. arXiv:1405:7654:

Ptolomy 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