Astro 596/496 NPA
Lecture 20
Oct. 9, 2009

Announcements:
- Problem Set 3 due
- Preflight 4 out, due noon next Friday
- **Fermilab Tour** `www: Fermitour info`
  tomorrow, Oct 10, 8am to ∼ 7pm

Last time: BBN concordance and implications
- CMB + BBN agreement on cosmic baryon content
- ...but lurking lithium problem
- FLRW cosmology working back to $t \sim 1$ sec, $z \sim 10^{10}$
- baryonic dark matter
- non-baryonic dark matter

Standard BBN Assumptions?
Q: which safest? most dubious?

Beyond the Standard Model

Standard BBN Assumes:

- gravity $\equiv$ General Relativity
- FLRW universe (homogeneous, isotropic)
- Standard Model physics (particles, interactions, couplings)
- $N_\nu = 3$ non-degenerate, left-handed ν species

If any not true $\rightarrow$ different nuke

Steigman, Schramm, & Gunn (1977)

What if $N_\nu > 3$?

at the time, lab limit $N_\nu \lesssim few \times 10^3$

BBN with Extra Relativistic Degrees of Freedom

Imagine adding extra light ($m_\nu \ll 1$ MeV) neutrino species

Q: how would this affect $n \leftrightarrow p$ *conversion?*

Q: how would this affect the cosmic environment?

Q: does more neutrinos $\Delta N_\nu > 0$ *mean more* ^{4}He *or less?*

Q: how to use $Y_{\rm obs}$ *to limit* ΔN_ν*?*

If add neutrinos (other other relativistic species)

- $n \leftrightarrow p$ interconversion only due to $\nu_e, \bar{\nu}_e$
  $\rightarrow$ no change to microphysics with new ν species
- each species adds radiation density $\delta\rho_{\mathrm{rad}} = g/g_\gamma\ \rho_\gamma$
  and since $H^2 \approx 8\pi G\rho_{\mathrm{rad}}/3$, expansion rate goes up!
- higher H $\rightarrow$ earlier freezeout $\rightarrow$ higher $(n/p)_{\mathrm{f}} = e^{-\Delta m/T_{\mathrm{f}}}$
  $\Rightarrow$ more n $\Rightarrow$ **more** ^{4}He

`www: primordial abundances for different` N_ν

If know $\eta_{10} \gtrsim 3$ (conservative),
predict $Y_p \gtrsim 0.240$ for $N_\nu = 3$

observations: $Y_p < 0.248$ (conservative),
so $\delta Y < 0.008$
and thus $\Delta N_\nu < 0.6$
can't have more than 3.6 species
$\rightarrow$ require 3 "normal" species!
if include CMB info, can do better...

Note: ΔN_ν really measures
any increase in energy density
due to any relativistic species in equil
ΔN_ν = "# effective neutrino species"

e.g., scalar ($S = 0 \rightarrow$ boson), $g = 1$ particle: $N_{\nu,eff} = 4/7 = 0.57$
"barely alive" /ruled out

BBN constrains particle physics!
Y. Zel'dovich:
The universe is the poor man's particle accelerator.

`www: David Norman Scrhamm`

Future Prospects

light elements from the CMB
$\longrightarrow$ can test BBN with CMB alone!

• ^{4}He already possible, interesting
(Huey, Cyburt, Wandelt 04)
...and agrees with $\eta_{\rm WMAP}$

• ^{7}Li harder, but a possibility

stay tuned...

The Early Universe: Particle Dark Matter

Particle Dark Matter

Consider stable particle species χ (& antiparicle $\bar{\chi}$)

- nonrelativistic today: $m_\chi \gg T_0 \sim 3 \times 10^{-4}$ meV
- thermally produced in the early universe

What determines its abundance today?

Q: if χ is still in thermal (chemical) eq?

Q: and so?