Astro 596/496 NPA
Lecture 19
Oct. 7, 2009

Announcements:

- Problem Set 3 due next time
- PS 1 returned
- **Fermilab Tour** `www: Fermitour info`
  this Saturday, Oct 10, 8am to $\sim$ 7pm

Last time: BBN theory vs observations

- each element: abundance changes with η
  $\Rightarrow$ observation $Y_{\rm obs}$ picks η
  multiple abundances: tests consistency
- Results `www: Schramm plot`
  ^{4}He gives broad η range
  D and ^{7}Li each agree with ^{4}He but not each other
  though concordant within factor ~ 2 of η
- Need "baryon tiebreaker" *Q: namely*

Problem Set 3: Hints

Units

usually I use (and encourage you to use) T in energy units,
i.e., $T \rightarrow kT$, so that effectively $k_B = 1$ also often write m in energy units, so $m \rightarrow mc^2$, and $c = 1$

Chemical Potential (see cosmic thermodynamics notes)

- thermodynamic encoding of *particle number conservation* when appropriate (e.g., baryon number conservation)
- without chem potential, $\rho = \rho(T)$
  $\rightarrow$ a gas must have unique density at a given T!?
  which would mean it is impossible to compress air at a fixed T!
- in finding and using $\mu(T)$, useful to define
  "quantum concentration" $n_Q = g(mT/2\pi\hbar)^{3/2}$; the $n_{\rm nonrel} = n_Q e^{-(m-\mu)/T}$

Relativistic Bosons vs Fermions

boson integral $\rho_{\rm b} = g/(2\pi\hbar)^3 \int d^3p\, E(p) f_{\rm b}(p) = 4\pi g/(2\pi\hbar)^3 \int_0^\infty dp\, cp^3 f_{\rm b}(p)$
to show: fermions have $\rho_{\rm f} = 7/8\ \rho_{\rm b}$
$\rightarrow$ need only show that fermion integral with $f_{\rm f}(p)$
can be massaged into $7/8 \times$ (boson integral)

Cosmic Entropy

note that, e.g., energy density is $\varepsilon = \varepsilon(T) = (\partial E/\partial_V)_T$
so that in 2nd law of thermo, $E = E(T, V) = \varepsilon V$ for some volume V
similarly $S = sV$, $N = nV$

BBN in Light of the CMB

CMB temperature fluctuation pattern encodes
a wealth of cosmic parameters ... including *baryon density*
$\Rightarrow$ new, independent, high-precision cosmic **"baryometer"**

WMAP (Spergel et al 2003, 2006; Komatsu et al 2008!):
$\Omega_{\rm baryon,CMB} = 0.0462 \pm 0.0015$
$\Rightarrow \eta_{\rm CMB} = (6.21 \pm 0.16) \times 10^{-10}$
- 2.6% precision!
- independent of BBN!

BBN vs CMB: Testing Cosmology

cosmic "pillar" vs cosmic pillar!

`www: Schramm plot:` $\eta_{\rm BBN}$ `vs` $\eta_{\rm CMB}$

Concordance!

Battle of the Baryons

In more detail:

1. use η_{CMB} as input to (Std) BBN theory,

2. compute light elements

3. compare with observations

`www: abundance likelihoods (CFO)`

- D agreement perfect! ^{4}He agreement excellent
- ^{7}Li tension clearer: "tie" broken– hot research topic
  "lithium problem" could point to new physics!

BBN Quantitative Results and Implications

Theory-Observation comparison

qualitatively: tests concordance, and hot big bang

if concordance found, then

quantitatively: measures cosmic baryon-to-photon ratio

Q: what baryons do, don't count? photons?

What's in a Number?

given η and, say, $T_0 \rightarrow n_{\gamma,0}$

Q: what else can we calculate?

Q: to what should these results be compared?

Q: implications of comparison

A Cosmic Baryon Census

BBN $\rightarrow$ baryon content of U.: "baryometer"
...just from lite elements
not by directly counting baryons today

From $\eta = n_B/n_\gamma$, and CMB $T_0 \rightarrow n_{\gamma,0}$, compute
- baryon number density

$$n_{B,0} = \eta n_{\gamma,0} \sim 2.4 \times 10^{-7} \text{ baryons cm}^{-3} \sim 1 \text{ baryon/cubic meter}$$

- baryon mass density $\rho_{B,0} \approx m_p n_{B,0}$
- baryon density parameter $\Omega_B = \rho_B/\rho_{\rm crit}$

$$0.024 \leq \Omega_B \leq 0.049$$

begs for comparison with
- other density parameters
- results of direct searches for baryonic matter

Subcritical Baryons and Two Kinds of Dark Matter

$0.024 \leq \Omega_B \leq 0.049$

$\Omega_{\rm B} \ll 1$

baryons do not close the universe!

$\Omega_{\rm B} \ll \Omega_{\rm Matter} \simeq 0.3$

most of cosmic matter is not made of baryons!

"non-baryonic dark matter"

huge implications for particle physics–more on this to come

Measure known baryons which are directly observable optically
i.e., in *luminous* form (stars, gas): $\rho_{\rm lum} = (M/L)_\star \mathcal{L}_{\rm vis}$

$\Omega_{\rm lum} \simeq 0.0024h^{-1} \sim 0.004 \ll \Omega_{\rm B}$

$\Rightarrow$ most *baryons* dark! **"baryonic dark matter"**

Q: Where are they?

Where are the dark baryons?

• **compact objects** (white dwarfs, neutron stars, black holes)
search for *MACHOs*: MAssive COmpact Halo Objects
via gravitational microlensing
`www: lensing diagram, MACHO event`
see lensing events towards LMC!
but are they MACHOs or LMC stars? ...probably the latter

• **warm/hot intergalactic medium** (WHIM)
structure formation → infall → shock heat to $T \sim 10^5 - 10^7$ K
note: in galaxy clusters, most baryons in
hot "intracluster" gas, not galaxies!
`www: X-ray cluster`
but X-rays from WHIM gas harder to see...
recent evidence of diffuse "X-ray forest" (PF5)
`www: Chandra spectra`

What's up with ^{7}Li?

- observational systematics (e.g., stellar parameters)? Quite possible.
  (Melendez & Ramirez 2004; FOV05)

- astrophysical systematics (e.g., depletion)? but what about ^{6}Li? and Li dispersion small ($\lesssim 0.2$ dex)...

- BBN calculation systematics: nuke reaction rates? But well-measured, and can use solar neutrinos to test dominant source: ^{3}He$(\alpha, \gamma)^{7}$Be (CFO04)

- new physics? if so, nature kind–didn't notice till now
  otherwise, would not have believed hot big bang...

BBN + CMB: Probing Early U. & Astrophysics

combine BBN & precision CMB η
removes main parameter
two ways to play the game

1. Standard BBN: η is only parameter
$\eta_{\rm CMB}$+BBN theory $\rightarrow$ primordial abundances fixed
compare to observations $\rightarrow$ constrain post-BBN nuke
e.g.: local ISM has $D_{\rm ISM}/D_{\rm p} = 55^{+6}_{-4}\%$
What is the physical significance of this number?

2. Non-standard BBN: $\eta_{\rm CMB}$ fixed,
all elements probe new physics
e.g., now D probes $N_{\nu,{\rm eff}}\cdots$
$\rightarrow$ *BBN a stronger, more robust probe of early U.*

Director's Cut Extras

Neutrino Counting with BBN: In Detail

Recall: $H = 1/2t \sim \sqrt{g_*}T^2$
Before weak freeze, rel. degrees of freedom:

$$
\begin{aligned}
g_* &= 2 + \frac{7}{8}(2 \times 2 + 2 \times N_\nu) && (1)\\
& \quad \gamma \qquad\quad e^{\pm} \qquad\quad \nu\bar{\nu} && (2)\\
&= \frac{22}{4} + \frac{7}{4}N_\nu = 10.75 \text{ for } N_\nu = 3 && (3)
\end{aligned}
$$

fix η, but let
$N_\nu = 3 + \Delta N_\nu$
if $\Delta N_\nu > 0$, then
$\delta g_* = 7/4 \Delta N_\nu$
$\rightarrow$ higher H at fixed T

Estimate δY_p

(1) Weak freeze:

$H(T_f) = \Gamma_{np}(T_f)$

$T_f \propto g_*^{1/6}$

$\delta T_f/T_f = 1/6\ \delta g_*/g_*$

freeze at higher T

$$\frac{\delta X_{n,f}}{X_{n,f}} = \frac{\delta(n/p)_f}{(n/p)_f} = \frac{1}{6}\frac{m_n - m_p}{T_f}\frac{\delta g_*}{g_*} \tag{4}$$

(2) D bottleneck: $T_d \simeq B_2/\ln\eta^{-1}$,

$t_d \propto g_*^{-1/2} T_d^{-2}$

$\delta t_d/t_d = -1/2 \delta g_*/g_*$

nuke buildup sooner $\rightarrow$ less free n decay

(3) Element production

Recall: at t_d, $X_n = X_{n,f} e^{-t_d/\tau_n}$

and $Y_p = 2X_n$, so

$$\frac{\delta Y_p}{Y_p} = \frac{\delta X_{n,f}}{X_{n,f}} - \frac{t_d}{\tau_n} \frac{\delta t_d}{t_d} \quad (5)$$

hotter freeze less decay (6)

$$= \left(\frac{1}{6} \frac{m_n - m_p}{T_f} + \frac{1}{2} \frac{t_d}{\tau_n} \right) \frac{\delta g_*}{g_*} \quad (7)$$

$$\simeq 0.07 \ \Delta N_\nu \quad (8)$$

estimate $\delta Y_p \sim 0.016 \ \Delta N_\nu$

full numerics: $\delta Y_p = 0.013 \ \Delta N_\nu$

more $\nu \rightarrow$ more He

`www: Schramm plot for different` N_ν