Astro 507
Lecture 26
March 21, 2014

Announcements:

- **PS4: due now or upload by next Monday**
- **PF 5 posted, due Friday after break**

Last time: testing big bang nuke

- theory: light elements after $\sim 3$ min
  each is a function of $\eta \equiv n_{\text{baryon}}/n_\gamma$
- observations: abundances extrapolated to zero metallicity
  each picks it's own $\eta$
- overconstrained system–one parameter, several abundances:
  elements *should* agree for some $\eta$
  but need not – nontrivial test of cosmology!
- `www: results` rough agreement–but what about $^7$Li?
  approaches: (1) don't worry too much, look at implications
  (1) worry, look at implications

# 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 $\eta$ 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 → 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 $\Omega_B = \rho_B/\rho_{\text{crit}}$

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

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

# Subcritical Baryons and Two Kinds of Dark Matter

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

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

*baryons do not close the universe!*

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

*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): $\rho_{\mathrm{lum}} = (M/L)_\star \mathcal{L}_{\mathrm{vis}}$

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

$\Rightarrow$ 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"
`www: Chandra spectra`

# BBN and the CMB: Battle of the Baryons

Until recently:
BBN was the premier means for measuring $\eta \propto \Omega_B$
$\rightarrow$ the best cosmic "baryometer"

Now: CMB independently measures $\eta$

**battle of the baryons**
compare independent measures of $\eta$
test of cosmology!

If agreement: big bang working very well!
$z \sim 10^{10}$ theory & light elements
quantitatively consistent with $z \sim 10^3$ theory & CMB

If disagreement: a pressing problem!

## BBN in Light of the CMB

Planck 2013:

$\Omega_{\text{baryon,CMB}} h^2 = 0.02207 \pm 0.00027$

$\Rightarrow \eta_{\text{CMB}} = (6.047 \pm 0.074) \times 10^{-10}$

- 1.2% precision!
- independent of BBN!

**BBN vs CMB: Testing Cosmology**

pillar vs pillar!

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

**Concordance!**

in more detail:

1. use $\eta_{\rm CMB}$ 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 – hot research topic
  "lithium problem" could point to new physics!

# 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: $^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$ (CFO04)

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

## BBN: Beyond the Standard Model

Thus far, we have looked at *Standard* BBN

*Q: what assumptions did we make*
*e.g., about cosmology, particle properties?*

*Q: which seem safest? most dubious?*

# BBN: Beyond the Standard Model

*Standard* BBN Assumes:

- *Gravity* is correctly described by General Relativity
- *Cosmology* is given by a FLRW universe
- *Particle content and interactions* are those of Standard Model
- *Neutrinos* consist of $N_\nu = 3$ *non-degenerate species*

If any not true $\rightarrow$ different nucleosynthesis!

Steigman, Schramm, & Gunn (1977)
*What if $N_\nu > 3$?*
at the time, lab limit $N_\nu \lesssim few \times 10^3$

if we add a new $\nu_x \bar{\nu}_x$ species:
*Q: what about BBN will be affected? what unchanged?*
*Q: would light element abundances be perturbed? how?*

# Adding Neutrinos to the Early Universe

Neutrinos and BBN:

- $\nu_e$ affect $n \leftrightarrow p$ interconversion
  but $\nu_\mu, \nu_\tau, \nu_x$ ... do *not*
- $\nu$s frozen out before nuke reactions, don't affect them
- but any and all relativistic $\nu \to$ contribute to $\rho \to H$
  *more $\nu$ $\Leftrightarrow$ expansion speed-up!*
- expansion speedup $\to$ *earlier weak freezeout*

*Q: and so?*

*more* $\nu \Rightarrow$ *faster expansion* $\Rightarrow$ *earlier freezeout*

earlier freeze $\rightarrow$ higher $T_{\text{freeze}}$

in equilibrium: $(n/p)_{\text{eq}} = e^{-\Delta m/T}$
so higher $T_{\text{freeze}} \Rightarrow$ *higher* $(n/p)_{\text{freeze}} = e^{-\Delta m/T_{\text{freeze}}}$

and finally: higher $(n/p)_{\text{freeze}} \rightarrow$ *more neutrons per proton*
and since $^4$He mass fraction is

$$Y_{\text{p}} \simeq \frac{2(n/p)_{\text{freeze}}}{1+(n/p)_{\text{freeze}}} \tag{1}$$

*net result:* more $\nu \Rightarrow$ more $^4$He

for more detail: see Director's Cut Extras below

# Neutrino Counting with BBN

**cosmic helium measures cosmic neutrino content!**

$$\delta Y_p = 0.013\ \Delta N_\nu \qquad (2)$$

if know $\eta_{10} \gtrsim 3$ (conservative)

BBN theory sez $Y_p \gtrsim 0.240$ for $N_\nu = 3$

observations: $Y_p < 0.252$ (reasonable but not max conservative)

so allowed excess over standard prediction: $\delta Y < 0.012$

and thus $\Delta N_\nu < 0.9$

can't have more than 3.9 species!

$\rightarrow$ helium observations *require* 3 "normal" neutrino species!

but accelerator experiments give precision measurement

$N_\nu = 2.9840 \pm 0.0082$ ($Z^0$ width from LEP, SLC)

*Q for experts: does this really measure the same thing?*

*Q: so who cares anymore?*

*Q: what if we have a new relativistic species that not $\nu$?*

Note: $\Delta N_\nu$ really measures

*any* increase in energy density

due to **any** *relativistic species* in equilibrium

$\Delta N_\nu$ = "*effective number* of neutrino species"

e.g., scalar ($S = 0 \to$ boson), $g = 1$ particle:

$N_{\nu,eff}^{\text{scalar}} = 4/7 = 0.57$

"endangered"

BBN constrains particle physics!

Y. Zel'dovich:

The universe is the poor man's particle accelerator.

# Particle Dark Matter

# BBN and Particle Dark Matter

BBN motivates dark matter theory & searches two ways:

Quantitative. $\Omega_B \ll \Omega_{\rm m}$: must have non-baryonic dark matter
...and lots of it!

Qualitative. BBN success at $t \sim 1$ s $\rightarrow$ early U as physics lab

"The universe is the poor man's particle accelerator"
– Ya. Zel'dovich

Big implications for–and motivations from–particle physics

*Q: what can we say about DM properties generally?*

*Q: what can we say if DM is in particle form?*
*lifetime, mass, interactions, quantum #s?*

*Q: what known particles are candidates for non-baryonic DM?*

*Q: does particle theory offer dark matter candidates?*

# Elementary Particle Physics and Dark Matter

Dark matter

dark: no/feeble EM, strong interactions

matter: behaves as nonrelativistic material $\rightarrow \rho \propto a^{-3}$, $P \ll \rho c^2$

naturally leads to hypothesis of DM as

Weakly Interacting Massive Particles: WIMPs

If DM is swarms of WIMPs, what are their properties?

lifetime: must exist today $t_0 \sim 14$ Gyr

$\rightarrow$ stable or very long-lived

mass: don't know!

only know mass dens $\rho_{\mathrm{m},0}$ today on cosmic, galactic scales

but without also knowing # dens $n_{\mathrm{m},0}$, can't get $m = \rho/n$

$\rightarrow$ in fact, with specific model, from $m$ get $n_0$

interactions/quantum #s:

BBN: dark matter not baryonic

Standard Model of particle physics *does* provide a candidate for non-baryonic DM

stable + massive: neutrinos; can show (PS5):

$$\Omega_\nu h^2 = \frac{\sum_{\rm species} m_\nu}{92 \text{ eV}} \tag{3}$$

...but can show (oscillation data, large scale structure, WMAP)

$\sum_{\rm species} m_\nu \lesssim 1$ eV: $\Omega_\nu \sim 0.01 < \Omega_B \ll \Omega_{\rm m}$

$\nu$s *are* non-baryonic DM, but negligible contribution to density

no other viable Standard Model particle candidates

non-baryonic DM demands physics beyond the Standard Model

particle candidates available "off the shelf"

lightest supersymmetric particle, axion, strangelets...

*Q: how are WIMPs produced in early U?*

# Director's Cut Extras

# Expansion Speedup from Neutrino Addition

Recall: $H = 1/2t \sim \sqrt{g_*} T^2$

Before weak freeze, rel. degrees of freedom:

$$\begin{aligned} g_* &= 2 + \frac{7}{8}(2 \times 2 + 2 \times N_\nu) && (4) \\ & \quad \gamma \qquad\qquad e^\pm \qquad\qquad \nu\bar{\nu} && (5) \\ &= \frac{22}{4} + \frac{7}{4} N_\nu = 10.75 \text{ for } N_\nu = 3 && (6) \end{aligned}$$

fix $\eta$, but let $N_\nu = 3 + \Delta N_\nu$

if $\Delta N_\nu > 0$, the $\delta g_* = 7/4\ \Delta N_\nu$

$\rightarrow$ higher $H$ at fixed $T$

*Q: and then what?*

(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 $T$

$$\frac{\delta X_{n,f}}{X_{n,f}} = \frac{\delta (n/p)_f}{(n/p)_f [1 + (n/p)_f]} = \frac{1}{6} \frac{1}{1 + (n/p)_f} \frac{m_n - m_p}{T_f} \frac{\delta g_*}{g_*} \quad (7)$$

(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



*Q: so what will this mean for abundances? e.g.,* $^4$He*?*

## Estimate $\delta Y_p$:

Recall: at $t_d$, $X_n = X_{n,f} e^{-t_d/\tau_n}$
and $Y_p = 2X_n$, so

$$\frac{\delta Y_p}{Y_p} = \frac{\delta X_{n,f}}{X_{n,f}} - \frac{t_d}{\tau_n}\frac{\delta t_d}{t_d} \quad (8)$$

$$\text{hotter freeze} \qquad \text{less decay} \quad (9)$$

$$= \left(\frac{1}{6}\frac{1}{1+(n/p)_f}\frac{m_n - m_p}{T_f} + \frac{1}{2}\frac{t_d}{\tau_n}\right)\frac{\delta g_*}{g_*} \quad (10)$$

$$\simeq 0.06\ \Delta N_\nu \quad (11)$$

estimate $\delta Y_p \sim 0.014\ \Delta N_\nu$

full numerics: **$\delta Y_p = 0.013\ \Delta N_\nu$**
*more $\nu$ $\rightarrow$ more He*

`www:  Schramm plot for different` $N_\nu$