Announcements:
• PS4 due Friday in class

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 \emph{should} agree for some $\eta$
  but need not – nontrivial test of cosmology!
• www: \emph{results} rough agreement–but what about $^7\text{Li}$?
  approaches: (1) don’t worry too much, look at implications
  (1) worry, look at implications
Subcritical Baryons and Two Kinds of Dark Matter

\[ 0.024 \leq \Omega_B \leq 0.049 \]

\[ \Omega_B \ll 1 \]

baryons do not close the universe!

\[ \Omega_B \ll \Omega_{\text{Matter}} \approx 0.3 \]

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 \textit{luminous} form (stars, gas): \( \rho_{\text{lum}} = (M/L)_* \mathcal{L}_{\text{vis}} \)

\[ \Omega_{\text{lum}} \approx 0.0024h^{-1} \sim 0.004 \ll \Omega_B \]

\( \Rightarrow \) 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 $\rightarrow$ infall $\rightarrow$ 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
BBN and the CMB: Battle of the Baryons

Until recently:
BBN was the premier means for measuring $\eta \propto \Omega_B$
→ 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

WMAP (Spergel et al 2003, 2006; Komatsu et al 2008!):

\[ \Omega_{\text{baryon, CMB}} = 0.0462 \pm 0.0015 \]

\[ \Rightarrow \eta_{\text{CMB}} = (6.21 \pm 0.16) \times 10^{-10} \]

- 2.6% precision!
- independent of BBN!

**BBN vs CMB: Testing Cosmology**

pillar vs pillar!

**www: Schramm plot: \( \eta_{BBN} \) vs \( \eta_{CMB} \)**

Concordance!
in more detail:
1. use $\eta_{\text{CMB}}$ as input to (Std) BBN theory,
2. compute light elements
3. compare with observations

**www: abundance likelihoods (CFO)**

- D agreement perfect! $^4\text{He}$ agreement excellent
- $^7\text{Li}$ tension clearer – hot research topic
  “lithium problem” could point to new physics!
What’s up with $^7\text{Li}$?

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

- astrophysical systematics (e.g., depletion)? but what about $^6\text{Li}$? 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: $^3\text{He}(\alpha, \gamma)^7\text{Be}$ (CFO04)

- new physics? if so, nature kind—didn’t notice till now otherwise, would not have believed hot big bang...
Particle Dark Matter
BBN and Particle Dark Matter

BBN motivates dark matter theory & searches two ways:

**Quantitative.** $\Omega_B \ll \Omega_m$: must have non-baryonic dark matter
...and lots of it!

**Qualitative.** BBN success at $t \sim 1 \text{ s} \rightarrow$ 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 \( t_0 \sim 14 \text{ Gyr} \)
\( \rightarrow \) stable or very long-lived

mass: don’t know!
only know mass dens \( \rho_{m,0} \) today on cosmic, galactic scales
but without also knowing \( \# \) dens \( n_{m,0} \), 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):

\[ \Omega_\nu h^2 = \frac{\sum \text{species } m_\nu}{92 \text{ eV}} \]  \hspace{1cm} (1)

...but can show (oscillation data, large scale structure, WMAP)
\[ \sum \text{species } m_\nu \lesssim 1 \text{ eV}; \ \Omega_\nu \sim 0.01 < \Omega_B \ll \Omega_m \]
\(\nu s\) 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”
lighest supersymmetric particle, axion, strangelets...

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