Astro 596/496 PC
Lecture 25
March 17, 2010

Announcements:
- PS4 due Friday in class

Last time: testing big bang nuke
- theory: light elements after ~ 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 η
- overconstrained system–one parameter, several abundances:
  elements *should* agree for some η
  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

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`

BBN and the CMB: Battle of the Baryons

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

Now: CMB independently measures η

battle of the baryons
compare independent measures of η
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:` η_{BBN} `vs` η_{CMB}

Concordance!

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 – 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}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...

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 $\rho_{\rm m,0}$ today on cosmic, galactic scales
but without also knowing # dens $n_{\rm m,0}$, 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):

$$\Omega_\nu h^2 = \frac{\sum_{\text{species}} m_\nu}{92 \text{ eV}} \quad (1)$$

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

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

νs *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?