Astro 596/496 NPA
Lecture 20
March 6, 2019

Announcements:

- **Preflight 4** next Friday

Last time: BBN observations–light element abundances

- good news: cosmo principle $\rightarrow$ primordial abundances universal
  same everywhere after "first 3 min"
- bad news: can't observe universe then
  but much later, after star-formation has begun
  must measure & correct for lite element "pollution"

Q: how?

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

$$\rho_{B,0} \approx m_p n_{B,0} = 4.1 \times 10^{-30} \text{ g/cm}^3$$

Q: is this larger or small?
Q: to what should this be compared?

Friedmann Revisited

Recall Friedmann (energy) equation:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G \rho - \frac{\kappa c^2}{R^2 a^2} \tag{1}$$

- $a(t)$ encodes cosmic evolution history
- Friedmann is equation of motion for a
- evolution depends on *cosmic contents* via $\rho = \rho_{\text{matter}} + \rho_{\text{rad}} + \cdots$ and on *cosmic geometry* via $\kappa \in (-1, 0, +1)$ and R

rewrite:

$$1 = \frac{\rho}{3H^2/8\pi G} - \frac{\kappa c^2}{R^2 H^2} \equiv \frac{\rho}{\rho_{\text{crit}}} - \frac{\kappa c^2}{R^2 H^2}$$

Q: units of ρ_{crit}? physical significance?

Geometry, Density, and Dynamics

rewrite Friedmann

$$1 = \frac{8\pi G\rho}{3H^2} - \frac{\kappa c^2}{R^2}(aH)^{-2} = \Omega - \frac{\kappa c^2}{R^2}(aH)^{-2} \tag{2}$$

where the **density parameter** is

$$\Omega = \frac{\rho}{\rho_{\rm crit}} \tag{3}$$

and the **critical density** is

$$\begin{aligned} \rho_{\rm crit} &= \frac{3H^2}{8\pi G} \\ \rho_{\rm crit,0} &= \frac{3H_0^2}{8\pi G} = 1.0 \times 10^{-29}\ {\rm g/cm^3} \left(\frac{H_0}{73\ {\rm km/s/Mpc}}\right)^2 \end{aligned} \tag{4}$$

Note: for a particular density component ρ_i
corresponding density parameter is $\Omega_i = \rho_i/\rho_{\rm crit}$
and thus total sums all species: $\Omega \equiv \Omega_{\rm tot} = \sum_i \Omega_i$

Note that

$$\kappa = \left(\frac{aHR}{c}\right)^2 (\Omega - 1) = (\text{pos def}) \times (\Omega - 1)$$

geometry (and fate*) of Universe $\Leftrightarrow \kappa \Leftrightarrow \Omega - 1$

if $\Omega = 1$ ever:

- $\Omega = 1$ always; $\kappa = 0 \rightarrow$ no curvature, expand forever

if $\Omega < 1$ ever:

- $\Omega < 1$ always; $\kappa = -1 \rightarrow$ negative curvature, expand forever

if $\Omega > 1$ ever:

- $\Omega > 1$ always; $\kappa = +1 \rightarrow$ positive curvature, recollapse

Q: but if Ω just a stand-in for κ, why useful?

*κ always gives geometry, but κ and fate decoupled if $\Lambda \neq 0$

Geometry and Fate are Knowable!

we saw: κ found from Ω

and: we can determine $\Omega \propto \rho/H^2$
from *locally measurable quantities* ρ and H:
$\rightarrow$ cosmic fate & geometry knowable!
...and become *experimental questions!*

BBN gives the cosmic baryon density today
Q: and soooo?

BBN and the Baryon Density Parameter

BBN gives the cosmic density of baryons ... in any form!

from this, compute: baryon density parameter $\Omega_B = \rho_B/\rho_{\text{crit}}$

$$0.039 \leq \Omega_B \leq 0.045$$

begs for comparison with

- other density parameters
- results of direct searches for baryonic matter

Q: what can we say already just form Ω_{B}?

Subcritical Baryons and Two Kinds of Dark Matter

$$0.039 \leq \Omega_B \leq 0.045$$

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

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

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

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

Q: Where are they?