Astro 507

Lecture 24

March 17, 2014

Announcements:

- **PS4: due Friday or upload by next Monday**
- Office Hours: Thurs. 3:10-4pm or by appt

Today is a great day for Cosmology...

story: MST and COBE

BICEP2 Announcement

$$r = 0.20^{0.07}_{-0.05}$$

$$r > 0 \quad \text{at} \quad 7\sigma$$

Detection of Cosmic Gravity Wave Background

CMB polarization experiment BICEP2
finds "B-mode" (curl-type) primordial polarization
consistent with gravity wave (tensor) perturbations
laid down during cosmic inflation
along with ordinary mass-energy (scalar) perturbations
tensor-to-scalar ratio

$$r = \frac{\text{tensor}}{\text{scalar}} = 0.20^{+0.07}_{-0.05}$$

probes energy scale of cosmic inflation $r = \varepsilon_{\text{inf}}/(3.3\times 10^{16}\ \text{GeV})^4$

$$P\,(\text{Nobel} \mid \text{no unplugged cables}) = 1$$

ω A landmark result! Much more after spring break!

Last time: big bang nuke – theory
initial condition for element synthesis: n/p **ratio**

Q: what sets n/p *at* $T \gtrsim 1$ *MeV?*

Q: what sets cosmic expansion rate?
Q: what if there were "extra" neutrino species in equilibrium?

Q: how does n/p *evolve vs* T*?*

Weak Freezeout Temperature

Weak interactions freeze when $H = \Gamma_{\text{weak}}$, i.e.,

$$\sqrt{G_{\text{N}}}T^2 \sim \sigma_0 m_e^{-2} T^5 \tag{1}$$

$$\Rightarrow T_{\text{weak freeze}} \sim \frac{(G_{\text{N}})^{1/6}}{(\sigma_0/m_e^2)^{1/3}} \sim 1 \text{ MeV} \tag{2}$$

gravity & weak interactions conspire to give $T_{\text{f}} \sim m_e \sim B_{\text{nuke}}$!

for experts: note that $G_{\text{N}} = 1/M_{\text{Planck}}^2$, so

$$\frac{T^2}{M_{\text{Pl}}} \sim \alpha_{\text{weak}} \frac{T^5}{M_W^2} \tag{3}$$

$$\Rightarrow T_{\text{freeze}} \sim \left(\frac{M_W}{M_{\text{Pl}}}\right)^{1/3} M_W \sim 1 \text{ MeV} \tag{4}$$

freeze at nuclear scale, but by accident!

Q: what happens to n, p then? what else is going on?

Element Synthesis

first step in building complex nuclei: $n + p \rightarrow d + \gamma$
but $d + \gamma \rightarrow n + p$ until $T \ll B(d)$; see Extras

when photodissocation ineffective, $n + p \rightarrow d + \gamma$ fast
rapidly consumes all free n and builds d
which can be further processed to mass-3:

$$d + p \rightarrow {}^3\text{He} + \gamma \quad d + d \rightarrow {}^3\text{H} + p \quad d + d \rightarrow {}^3\text{He} + n \tag{5}$$

and to ^{4}He

$$^3\text{H} + d \rightarrow {}^4\text{He} + n \quad {}^3\text{He} + d \rightarrow {}^4\text{He} + p \tag{6}$$

some of which can then make mass-7:

$$^3\text{H} + {}^4\text{He} \rightarrow {}^7\text{Li} + \gamma \quad {}^3\text{He} + {}^4\text{He} \rightarrow {}^7\text{Be} + \gamma \tag{7}$$

Q: what limits how long these reactions can occur?
Q: which determines which products are most abundant?

BBN Reaction Flows

Binding Energy

nuclei are bound quantum structures, confined by nuclear forces among the "nucleons" n, p

can quantify degree of stability–i.e., resistance to destruction via binding energy: for nucleus with Z protons, N neutrons, $A = N + Z$ nucleons

$$\begin{aligned} B_A &= \text{energy of individual parts} - \text{energy of bound whole} \\ &= (Zm_p + Nm_n - m_A)c^2 \\ &> 0 \quad \text{if bound} \end{aligned}$$

note: generally B_A increases with A

but that's not the whole story on stability

binding shared among all A nucleons,
so binding per nucleon is B_A/A

nuclear stability $\leftrightarrow$ high B_A/A

`www: plot of` B_A/A `vs` A
lowest binding/nucleon: d!
highest: ^{56}Fe, but among light elements, ^{4}He highest by far
Q: implications for BBN

Reaction flows: tightest binding favored

$\rightarrow$ essentially all pathways flow to ^{4}He

`www: nuke network`

almost all $n \rightarrow {}^4$He:

$n(^4\text{He})_{\text{after}} = 1/2 \; n(n)_{\text{before}}$

$$Y_p = \frac{\rho(^4\text{He})}{\rho_B} \simeq 2(X_n)_{\text{before}} \simeq 0.24 \tag{8}$$

$\Rightarrow \sim 1/4$ of baryons into ^{4}He, $3/4 \; p \rightarrow$H

result weakly (log) dependent on η

Robust prediction: large universal ^{4}He abundance

But $n \rightarrow {}^4$He incomplete: as nuke rxns freeze,
leave traces of:

- D
- ^{3}He (and ^{3}H$\rightarrow$^{3}He)
- ^{7}Li (and ^{7}Be$\rightarrow$^{7}Li)

abundances $\leftrightarrow$ nuke freeze T
trace species D, ^{3}He, ^{7}Li: strong $n_B \propto \eta$ dependence

BBN theory predictions summarized in **"Schramm Plot"**

Lite Elt Abundances vs η

`www: Schramm plot`

Note: no $A > 7$...so no C,O,Fe... *Q: why not?*