Astro 406

Lecture 39

Dec. 4, 2013

Announcements:

- **PS 12 due Friday** last problem set!
- Office Hours: today 1–2pm or by appt

  TA Office Hours: tomorrow 1–2 pm
- pay it forward: do your **ICES**

Last time: primordial nucleosynthesis

Q: qualitative predictions?

Q: quantitative

BBN: Implications

Qualitatively

extrapolated big bang to $t = 1$ s, predicted lite elts
lots of ^{1}H and He; traces of D, ^{3}He, and ^{7}Li

Quantitatively

predicted abundance values agree in detail with observations!
observed lite elements select $\eta = n_B/n_\gamma \Rightarrow$ $\boxed{0.024 \lesssim \Omega_{\mathsf{B}} \lesssim 0.050}$

1. $\Omega_{\mathsf{B}} \ll 1$: baryons don't close the U.

2. $\Omega_{\mathsf{lum}} \sim 0.007 \ll \Omega_{\mathsf{B}}$
   baryonic dark matter hot (10^{6-7} K) intergalactic gas?

3. $\Omega_{\mathsf{matter}} \approx 0.3 \gg \Omega_{\mathsf{B}}$:
   non-baryonic dark matter

The Very Early Universe

CMB success $\Rightarrow$ understand Univ at $t \sim 400,000$ yr
$z \sim 1100$ and $T \sim 1$ eV

BBN success $\Rightarrow$ understand Universe at $t \sim 1$ s
$z \sim 10^{10}$ and $T \sim 1$ MeV

success gives confidence:
boldly extrapolate to $t \ll 1$ s
and $T \gg 1$ MeV

Q: what are conditions like?
Q: what physics needed to describe?
Q: what about $t = 0$: T? ρ?

Cosmic Singularity

recall: cosmic scale factor $a(t)$

• is now, and has been, increasing with time

• *define $t = 0$ to be when $a \to 0$*
  and then age today t_0 is time to go to $a = a_0 = 1$

$t = 0$: **the big bang**

Transp: *Big Bang in French*

Q: what's wrong with this picture?

Lifestyles at the big bang

• lengths $\ell \propto a$, and $T \propto 1/a$, $\rho_{\mathrm{rad}} \propto 1/a^4$

$\Rightarrow$ so at $t = 0$: all *separations* $\to 0$
  densities, temperatures $\to \infty$

at big bang, our description gives infinity singularity

Q: what's the problem? what's breaking down?

A Brief History of Time
The Very Early Universe & Ultra-High-Energy Physics

Planck Epoch: $0 \leq t \lesssim 10^{-43}$ s

general relativity invalid − quantum effects large

$\Rightarrow$ need quantum gravity − string theory? wavefunction of U?

spacetime infected w/ quantum fuzziness (?)

black holes created and evaporated (?)

braneworld (?)

Inflation: $t \sim 10^{-38}$ s **(???)**

more today and next week

Baryogenesis: $t \sim 10^{-37}$ s **(???)**

matter-antimatter asymmetry created

Particle Physics Today: Success and Its Discontents

Current theory of elementary particles:
"the Standard Model of Particle Physics"

- extremely successful–*no known disagreement with expt!*
  e.g., e^- magnetic moment $(g - 2)$ measurement
  agrees with theory to 1 part in 10^{10}!

- But: Standard Model only tested in lab
  to Fermilab/LHC energies $E \sim 10\,\text{TeV} = 10^{13}\,\text{eV}$

- And: Standard Model begs the questions:
  why the patterns of quarks and leptons? why 3 families?
  why four forces? are they unified (like E&M are)?
  where does mass come from?
  why is matter fermions, force carriers bosons?

Standard Model a "victim of its own success"
carries the seeds of its destruction/supplanting

To address these questions: new particle theories
give possible answers to these questions
as a by-product, forced to invent new particles:
- almost always high-mass $(m \gtrsim \text{TeV})$ *Q: why high mass?*
- almost always weakly interacting
  (at "low" energies $=$ Fermilab/LHC)

Today: new particles hard to make
But in early U: created everywhere!
Q: possible fossils today? what conditions needed?

The Heavenly Accelerator and Dark Matter

If exotic massive particles exist
$\rightarrow$ created in early universe

If stable: remain today
$\rightarrow$ natural candidates for **dark matter**
bonus: naturally weakly interacting

"just what the doctor ordered"
Weakly Interacting Massive Particles: **WIMP**s!
key point: not invented for cosmology
but for particle physics reasons

So: if particle theorists are right:
can't *avoid* a U filled with crazy WIMPs
assume they are the DM:
Q: how detect them in the lab?

∞

Direct Detection of WIMPs

Difficult! ...but not impossible

weakly interacting $\rightarrow$ expt issues similar to ν detection
- go underground *Q: why?*
- expect small count rate ($\lesssim$ few events/month)

`www:  WIMP experiments`

WIMP-nucleus collisions: nucleus recoils with ~ 1 keV
measure recoil energy: cryogenic detectors

strategy: look for periodic changes
- day/night variations *Q: why?*
- annual/seasonal variations

$\vec{v}_{\mathsf{WIMP}} = \vec{v}_{\odot} + \vec{v}_{\mathsf{Earth,orbit}}$
$\rightarrow$ modulated by $v_{\mathsf{Earth}} \sim 10\% v_{\odot}$

iClicker Poll: WIMP Direct Detection Status

Many WIMP searches are active or planned

What have they found?

A   no evidence for WIMPs (so far)

B   conflicting evidence for WIMPs

C   strong evidence for WIMPs

WIMP Search Results

1998: Italian expt (DAMA) claims dark matter *evidence*!
by now: they claim their evidence is very strong $\gtrsim 6\sigma$
very controversial result!

2012–2013: *Hints from other experiments*!

But:
- *competing groups don't see signal*
- could be different WIMP interactions for different nuclei
- …or could be false alarm

How to resolve dispute? Better experiments
- will be coming online
- either will find WIMPs, or rule out favorite theories
- stay tuned!

Trouble in Paradise

Despite impressive cosmic successes
lingering, fundamental questions remain

Cosmic Puzzles: Flatness

Today: $0.9972 \leq \Omega_0 \leq 1.0038$ Planck 95% confidence range

But Ω evolves:

$$|\Omega - 1| = \frac{c^2}{R_0^2 H^2 a^2} \tag{1}$$

at recombination:

$$0.9999998 \leq \Omega_{\text{recomb}} \leq 1.0000006 \tag{2}$$

at BBN:

$$0.999999999999999999998 \leq \Omega_{\text{bbn}} \leq 1.000000000000000000006 \tag{3}$$

If Ω was out of these ranges then
today would have $\Omega_0 \ll 1$ or $\Omega_0 \gg 1$

What set $\Omega = 1$?

Cosmic Puzzles: Horizon

particle horizon $d_{\mathsf{hor}}(t)$ is
- physical distance light travels in t
- size of observable U. at t
- *max size of region in causal contact at t*

but: when U is radiation dominated (and matter dom)
$d_{\mathsf{hor}} \sim ct \to 0$ as $t \to 0$
$\Rightarrow$ as $t \to 0$, causal region vanishes
$\to$ *all points causally disconnected at $t = 0$!*

Observe:
T_{CMB} uniform to 1 part in 10^5
but CMB photons on opposite sides of sky
come from regions that haven't communicated
yet today, let alone at recombination!