Astro 350

Lecture 37

Nov. 28, 2011

Announcements:

- HW11 due Friday
- Discussion Question 11 – please give your vote
- Check syllabus: lowest HW and Discussion score dropped but you are still responsible for all of the material
- **ICES** available online – please do it!
  I do read and use comments!

Before break: primordial nucleosynthesis

• Theory: nuclear reactions in the early universe
at times $t = 1$ sec to 3 minutes
make lightest elements:
76% hydrogen, 24% ^{4}He, traces of D, ^{3}He, ^{7}Li
amounts each depend on cosmic density of
baryons = anything made of atoms
and nothing heavier! all other elements made by stars

• Observation: measure light elements in real universe
not easy to do: have to find samples
with minimum "pollution" by element production in stars

Result

Combine observations (+ errors!)
observed light elements agree with theory (and each other!)
if baryon density $\Omega_B = \rho_B/\rho_{crit}$ in range

$$0.040 \lesssim \Omega_B \lesssim 0.050 \tag{1}$$

recap: extrapolated big bang to $t = 1$ s, predicted lite elts
kinda amazing: not only qualitative agreement ("lotsa helium")
but even detailed quantitative agreement with observations!
Cosmo bragging rights: BBN is earliest probe!

BBN: Implications

Qualitatively

extrapolated big bang to $t = 1$ s
predicted lite elts $\rightarrow$ agreement with observations
big bang working well back to 1 sec!

Quantitatively

observed lite elements measure cosmic baryons
i.e., total amount of matter in form of atoms
$\Rightarrow 0.040 \lesssim \Omega_B \lesssim 0.050$

1. $\Omega_B \ll 1$: baryons don't close the U.

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

3. $\Omega_{\rm matter} \approx 0.3 \gg \Omega_{\rm B}$:

non-baryonic dark matter

confirms: **most dark matter** is **not**
made of atoms of any kind in any arrangement!
$\rightarrow$ must be exotic form of matter!

known matter = anything on the periodic table
is a tiny fraction of the makeup of the cosmos!

Early Universe Cosmology Scorecard

Recall strategy:

- inventory universe today
- extrapolate back to early epochs
- apply known laws of nature to expanding, cooling U
- identify observable consequences (“fossils”) persisting today
- measure fossils $\rightarrow$ learn about early U!

Cosmo Report Card

Epoch	Recombination	Big Bang Nuke
cosmic time t	$\sim 400,000$ yr	$\sim$ 1 sec–3 min
micro-processes	nuclei$+e \rightarrow$ atoms	$p+n \rightarrow$ nuclei
predicted fossils	thermal radiation	baryons $\rightarrow$ H, He, Li
observed?	Yes! $\rightarrow$ CMB	Yes! $\rightarrow$ primordial abundances
grade	A	A

iClicker Poll: ICES

Vote your conscience!

Did you get one or more ICES notification emails for this course?

A Yes, and I promise to fill out the form if I have not already

B No, but I promise to go to `https://ices.cte.uiuc.edu/` and fill out the form if I have not already

The Very Early Universe

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

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?

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

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

general relativity invalid – quantum effects large
$\Rightarrow$ need quantum GR theory: quantum gravity
i.e., we don't know what happens at 10^{-43} s
which means the one thing we can be sure of is that
we aren't yet "qualified" to go back earlier
to the big bang itself $t = 0$ sec!
$\rightarrow$ the nature of the big bang itself intimately tied
to the unification of gravity and quantum mechanics
the ultimate inner space/outer space connection!

Of course, there are ideas:
- maybe universe described by string theory?
- maybe spacetime infected w/ quantum fuzziness (?)
- quantum black holes created and evaporated (?)
- or maybe the U is a braneworld...

Extra Dimensions on the Brane

Braneworld Scenario for Quantum Cosmology
proposes that our (expanding) 3-dimensional space
is just a "surface" / "membrane" in a much larger
  4-dimensional(!) "bulk" space!
with particles (i.e., us!) confined to brane, but gravity
  extending into the "bulk"
one suggestion: our 3-D "brane" has another "parallel"
  brane very nearby (in a 4th dimension!)
  with side-effect: gravity from matter in sibling brane
  appears to us as DM (and we are DM for them!)

braneworld ideas currently being in the lab!
would show up as departure from $F_{\text{grav}} \propto r^{-2}$
so far: inverse square holds down to ~ 1 mm
$\rightarrow$ "sibling" brane has to be at least this close!

Particle Physics Today: Success and Its Discontents

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

all known particles explained in terms of
- matter particles in "families" of quarks and "leptons" (e, ν and cousins)
- interacting with four fundamental forces: gravity, electromagnetism, and the nuke and weak forces
- with forces "carried" by another set of particles i.e., photons and cousins

How does this stack up against experiment?
- extremely (annoyingly!) successful

⇒ no known disagreement with experiment!
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 energies $E \sim 1\,\text{TeV} = 10^{12}\,\text{eV}$

- And: Standard Model begs the questions:
  why the patterns of particles we see?
  why four forces are they unified (like E&M are)?
  where does mass come from?
  why is matter one class of particles (fermions)
    and force carriers another (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 ($m \gtrsim 1$ TeV = 1000 m_{proton})
- almost always weakly interacting
  (at "low" energies = Fermilab/CERN)
- note: invented to fix particle problems,
  not with cosmology in mind (no ulterior motive!)

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: WIMPs!
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 $\rightarrow$ experiments similar to ν detection

- go underground
- 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 annual variations
$\vec{v}_{\rm WIMP} = \vec{v}_{\odot} + \vec{v}_{\rm Earth,orbit}$
$\rightarrow$ velocity has time change due to earth orbit
$\rightarrow$ modulation in 1-year period, amplitude $v_{\rm Earth} \sim 10\% v_{\odot}$

WIMP Search Results

1998: Italian experiment (DAMA) claims evidence!
by now: claim evidence is strong

- very controversial result!
- most 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!