Astro 350

Lecture 34

Nov. 14, 2011

Announcements:

- HW10 due Friday
- Discussion Question 10 due Wednesday
- at last: Hour Exam back today!

A Gut Feeling for Cosmic Geometry: *Taste the Three Possibilities!*

Last time: The atomic era

- cooling early universe undergoes transition from ionized to neutral
- and so also undergoes transition from opaque to transparent

radiation observed today as **cosmic microwave background**
- "embers of cosmic fireball"
- picture of Universe at recombination: ionized $\rightarrow$ neutral

CMB discovery: Penzias & Wilson 1965 – accidental!
Nobel Prize: 1972

CMB temperature fluctuations
- tiny! T variation are in 5th decimal place!
- correspond to tiny density fluctuations
- strongest evidence that Universe is homogeneous!
- fluctuations act as "seeds" for formation of galaxies, clusters, superclusters, you, me today! they are our ancestors!

CMB fluctuation discovery:
NASA's Cosmic Background Explorer (COBE), 1992
Nobel Prize: 2006, George Smoot & John Mather

Relativity and Cosmology: The Curvature of Space

Recall Friedmann "energy" equation

$$\text{(expansion rate)}^2 = H^2 = \frac{8\pi}{3} G\rho - \frac{K}{a^2} \tag{1}$$

Newton: K corresponds to $-$(total energy)

Einstein General Relativity:

K measures the *curvature* of space!

(if nonzero: $K = \pm c^2/R_{\text{curv}}^2$)

- $K > 0 \rightarrow$ positive curvature
- $K < 0 \rightarrow$ negative curvature

$K = 0 \rightarrow$ no curvature ("flat")

Q: what does it mean for space to be curved? Geometry!

Geometry of the Universe

⋆ $K > 0$ positive curvature, roughly: "like a sphere"
parallel lines eventually meet!
triangle angles sum $> 180°$;
volume finite ("closed" universe)

⋆ $K < 0$ negative curvature, roughly: "like a saddle"
parallel lines eventually diverge!
triangle angle sum $< 180°$;
volume $= \infty$

⋆ $K = 0$ no curvature: "flat," geometry Euclidean
parallel lines keep same distance
triangle angle sum $= 180°$;
volume $= \infty$

Einstein: **geometry is experimental question** *Q: how anwer?*

The CMB and Cosmic Geometry

the CMB is a cosmic goldmine!
example: geometry

CMB and cosmic triangles
- CMB flucuations have all sizes
  but largest on scale $d_{\text{horizon}} \approx ct_{\text{recom}}$
- fluctuations of this size $\rightarrow$ *isosceles triangle*

NASA WMAP (2003):
can measure angular size θ of fluctuations
see if triangle has angle sum 180° or not

`www: WMAP diagram`

iClicker Poll

vote your conscience!

WMAP 2003: measured geometry of Universe
Which did they find?

A positive curvature: “spherical”

B no curvature: “flat” = Euclidean

C negative curvature: “hyperbolic”

The Geometry of the Universe

WMAP 2003: no measurable evidence for curvature!
either positive or negative!

Best fit to data: **geometry Euclidean = flat!**
volume infinite!

more technically:
curvature, "radius" $> 100 \times$ size of observable U
(flat $\Leftrightarrow$ curvature radius $= \infty$)

also note:
from Friedmann: if $K = 0$, then $\rho = \rho_{\text{crit}}$ now and always!
this is how CMB tells us $\Omega = 1$ today

These results cry out for explanation!

Early Universe Cosmology Scorecard

Recall strategy:
- inventory universe today
- extrapolate back to early epochs
- apply known laws of nature
- identify observable consequences ("fossils") persisting today
- measure fossils $\rightarrow$ learn about early U!

First attempt–the "atomic age"

Inventory:
hydrogen gas and blackbody radiation in expanding U

Predictions:
atoms: expect transition when particle energies $\approx$ atomic binding
$\Rightarrow$ recombination: ionized $\rightarrow$ neutral
matter+radiation: photon-electron scattering
$\Rightarrow$ loss of free e^-: opaque $\rightarrow$ transparent

Observable consequence:
"liberated" photons persist $\rightarrow$ observable today

The Test: look for thermal radiation

- CMB detected! thermal, nearly isotropic
- bonus–fluctuations $\rightarrow$ cosmo parameters, "seeds" for structure

Bottom line:
extrapolated back to redshift $z \sim 1000$!
$t \sim 400,000$ yr $\sim 0.00003 t_0$! 99.997% of the time to big bang
big bang working extremely well!
gives confidence to push back farther!

Q: next stop?
Hint: pre-recombination, U ionized $\rightarrow$ atoms ripped apart
Q: as collisions more energetic, what's next to be smashed?

After recombination (e.g., now)

• nuclei and electrons bound together as atoms

Before recombination ($t < 400,000$ yrs)

• nuclei and electrons unbound, free $\rightarrow$ at recombination: atoms first born!

What breaks next?

• electrons: no known substructure
  i.e., not "made of pieces" but truly indivisible!
• nuclei: definitely made of pieces!
  protons and neutrons!

So expect another transition *before* recombination
"ionized" protons and neutron $\rightarrow p, n$ bound in nuclei
at transition: nuclei first born!
big bang nucleosynthesis

Prelude to Nucleosynthesis

consider an atomic nucleus, e.g., ^{4}He$=\boxed{2p+2n}$

Naively, expect it to fly apart

Q: why?

Q: why doesn't it?

Q: what does this imply about things made of n, p = baryons*?*

The Nuclear Force and Nuclear Structure

In nucleus:

Electrical repulsion between protons (like charges)

but stable: repulsion overcome by attractive force

nuclear force between p, n ("baryons")

How strong?

nuclei: size $r_{\text{nucleus}} \sim few \times 10^{-15}$ m $\approx 10^{-5} r_{\text{atom}}$

2 p electric repulsion at $r = 10^{-15}$ m

$$E_{\text{electromagnetic}} = \left[\frac{1}{4\pi\epsilon_0}\right]\frac{e^2}{r} = 1.4 \times 10^6 \text{eV} = 1.4 \text{ MeV} \quad (2)$$

$\sim$ million times atomic binding!

Nuclei in a Nutshell

nuclei are quantum objects governed by nuclear force
i.e., like "juiced" atoms, with stronger force

- still energy levels: ground, excited states
- stronger force $\rightarrow$ larger binding energy $BE \sim few$ MeV
- still unbound if given energy $> BE$ ("sticking strength")

Nuclear force + quantum levels $\rightarrow$ binding
weakest binding: deuterium $d =$ np, $BE = 2.2$ MeV
strongest light nucleus (below C):

^{4}He $=$ 2n+2p, $BE = 26$ MeV

^{4}He $= \alpha$ so stable, *no stable nuclei at mass 5, 8*
"would rather be alphas!"

mass 5 decays $\rightarrow \alpha + n/p$
mass 8 decays $\rightarrow 2\alpha$