Astro 350
Lecture 37
Dec. 3, 2012

Announcements:

- **Discussion 11** – last one! Due Wednesday
- **Homework 11** – last one! Due Friday
- 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!

Last time:
dark matter in the universe: where we stand today
you are now up to date!
Q: what do we know about dark matter?
Q: what don't we know about dark matter?
Q: what's a WIMP? how are we looking for them? Q: how's that working out for us?

The Story Thus Far

Hubble: galaxies all receding
Einstein: space expanding
$\rightarrow$ big bang cosmology

The Universe in the recent past:
cosmological befuddlement ("Preposterous Universe")
evidence for accelerated expansion
$\rightarrow$ requires wierdo negative-pressure "dark energy" ?!?!

The Universe in the distant past:
cosmological success stories

- CMB $\rightarrow$ U was once "thermalized" to $\approx$ uniform T
  verifies isotropy, homogeneity
  but small T variations $\rightarrow$ small ρ variations present
- light elements $\rightarrow$ U was once a nuke reactor
  we have good understanding back to ~ 1 sec

A Brief History of Time

The Very Early Universe & Ultra-High-Energy Physics

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

extrapolating back to this time:
general relativity invalid – quantum effects large
$\Rightarrow$ need quantum GR theory: **quantum gravity**
...which we do not have!

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!

The Semester's Silliest iClicker Poll

There seems to be a cosmological comedy show nowadays

Be honest! Answers remain anonymous!

What do you think of *The Big Bang Theory*?

A People still watch TV?

B Seen it. Love it. Must-see TV.

C Seen it. Watch it as a guilty pleasure. Don't tell!

D Seen it. Meh. What else is on?

E Seen it. Hate it, hate it, hate it. I really do.

Fine, But What Maybe Happened at $t = 0$?

We don't (yet) have a firm, agreed-up theory
of quantum gravity

but we do *have a lot of ideas*
which have implications for $t = 0$*:*

- *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!

$\boxed{\text{Trouble in Paradise}}$

Despite impressive cosmic successes (BBN, CMB)
lingering, fundamental questions remain

Cosmic Puzzles: Flatness

Recall: $\Omega = \rho_{\rm total}/\rho_{\rm critical}$
Today: $0.98 \leq \Omega_0 \leq 1.02$: *very close to 1!*

But unless cosmic geometry is precisely "flat" = Euclidean
i.e., unless $K = 0$ exactly in Friedmann eq., then

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

but since both H and a change with time
Ω also changes with time

at recombination:
$0.99998 \leq \Omega \leq 1.00002$

at BBN:
$0.9999999999999999999998 \leq \Omega \leq 1.000000000000000000002$

$\boxed{\text{What set } \Omega = 1 \text{ so precisely?}}$

Effect of a Finite Cosmic Age

Recall: from relativity–Einstein's do's and don'ts

- lightspeed c is fastest any particle can move and only move at c if mass $= 0$!
- if mass > 0, particles move by at speeds $v < c$
- and no information or influence can travel faster than c

Imagine a non-expanding universe
with cosmic age $t =$ time since big bang
Q: How far away can an observer possibly see?
Q: What is the biggest "patch" of the Universe in which objects can have affected each other?

Cosmic Horizon

in non-expanding Univ.,
with finite ($\neq \infty$) age t:

- max distance light can travel is $d = ct$
  i.e., if $t = 14$ billion yrs, then max light travel distance $d = 14$ billion lyr
- this distance is farthest one can see
- since any massive particles move slower
  they travel a distance $< ct$

$\rightarrow$ the **particle horizon** $d_{\text{hor}} = ct$
gives the size of "region of influence"
where objects in U can have affected each other

But the real Universe is expanding!

- so "smaller" in past, light can go farther
- max light travel distance $d_{\text{hor}} > ct$
- but basic idea is sill correct, and
- *particle horizon* still a useful concept
- sets "zone of influence" or region of *causal contact*

iClicker Poll: Cosmic Horizons

Vote your conscience!

In the past, our cosmic horizon d_{hor}

A smaller than it is today

B the same size as it is today

C larger than it is today

in past, cosmic horizon smaller

for decelerating universe: $d_{\rm hor} \sim ct \to 0$ as $t \to 0$

as $t \to 0$, causal region vanishes

$\to$ all points causally disconnected at $t = 0$!

Q: why is this disturbing? Hint–think CMB

Cosmic Puzzles: Horizon

Observe: `www: CMB sky, regular contrast`
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 recomb!

so $d_{\text{hor}}(t_{\text{rec}})$ = particle hor at recomb
= size of region in causal contact
corresponds to 1° patch on CMB sky
$\rightarrow$ regions $> 1^\circ$ apart on CMB sky
  couldn't "thermalize" to same T
`www: anisotropy power spectrum`

$\boxed{\text{Why is the CMB so isotropic?}}$

Cosmic Puzzles: Lumpiness

Observe: `www: CMB sky, high contrast`

CMB "spots" due to ΔT

$\rightarrow$ small variations in density $\Delta\rho$ at recomb

$\boxed{\text{What created fluctuations?}}$

Puzzles vs Crises

Note: these *puzzles* are
not *inconsistencies* in big bang

Q: Possible answers?

Puzzle Solution I: Initial Conditions

Assume the problem away: Declare that U. started as

- ▷ highly homogeneous, and
- ▷ highly isotropic, but with
- ▷ tiny fluctuations present

a "just-so" solution ⇒ Possible but unsatisfying

most (all?) cosmologists prefer "generic*" initial conditions:

- ▷ U. begins inhomogeneous
- ▷ w/ large fluctuations

  but then how to get to today?

* *What's a generic universe??*

Puzzle Solution II: Inflation

Basic idea (Alan Guth, 1980):

in very early U., a period of: **exponential expansion**

$a(t) = a_i e^{H(t-t_i)}$, with

- a_i scale fac at start of inflation
- $H \approx$ const
- note: $\ddot{a} > 0 \rightarrow$ accelerated expansion!
  vs "ordinary" decelerated expansion
  in U dominated by matter or radiation

if this lasted for a "long time"

i.e., $H\Delta t \sim 60$, or $\Delta t \sim 60/H$

"60 e-foldings"

then U. expanded by factor

$e^{60} \simeq 10^{26} = 100,000,000,000,000,000,000,000,000$!

Inflation Solves Cosmic Puzzles

1. $\boxed{\text{flatness}}$

   if $|\Omega - 1| \sim 1$ before inflation

   $|\Omega - 1| \sim 10^{-50}$ after inflation

   $\rightarrow$ curvature inflated away `www: balloon analogy`

   explains (*demands!*) $\Omega = 1$ to high precision

2. $\boxed{\text{horizon}}$

   $\triangleright$ tiny initial causal region ($\ll$ atom size: microscopic!)

   $\triangleright$ expanded to huge scales ($\gg 1$ Mpc: macroscopic!)

   observable U. today (...and far beyond!)

   was in causal contact before inflation

   $\rightarrow$ was once thermalized

   $\rightarrow$ explains CMB isotropy

3. $\boxed{\text{density fluctuations}}$

pre-inflation: microscopic horizon

$\rightarrow$ quantum effects important

quantum fluctuations present & *inevitable*

like "zero-point energy": $\Delta E \Delta t \gtrsim \hbar$

inflated to macroscopic scales

$\rightarrow$ cosmic structures due to
quantum mechanics

How did the Universe get its spots?

From the uncertainty principle!

"Inflation puts the 'bang' in the big bang.' '

–Inflationary Cosmologist Alan Guth

The Physics of Inflation

Ingredients:

to fix cosmic puzzles, need:
phase of exponential expansion
(more generally, accelerated expansion)
$\rightarrow$ like acceleration today due to dark energy
coincidence or deep connection??

exponential expansion $\rightarrow$ U. must have
a component with (energy) density
$\rho_{\text{vac}} \approx \text{const}$

What is this component?

known particles/fields won't work (have tried!)

invent new particle/field:

the "inflaton" ϕ

$m_\phi c^2 \gtrsim 10^{16}$ GeV $\gg m_p c^2$

exists at high energy/early U.

maybe part of unification of forces

("grand unification")?