Astro 350

Lecture 38

Nov. 30, 2011

Announcements:

- HW11 due Friday
- Discussion Question 11 due today–please cast 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!

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
  verfies isotropy, homogeniety
  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

Trouble in Paradise

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

Cosmic Puzzles: Flatness

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

But unless in Friedmann $K = 0$ exactly, 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:
$0.9999999999999999999998 \leq \Omega \leq 1.0000000000000000000002$

What set $\Omega = 1$ so precisely?

Cosmic Puzzles: Horizon

recall from special relativity:
light cones play special role in spacetime
for any event X (localized place, time)...

Future:
- on future light cone: light signals travel from X
- inside future light cone: events that X can influence
- outside future light cone: X can't influence

Past:
- on past light cone: light signals travel to X
- inside past light cone: events that could have influenced X
- outside past light cone: couldn't have influenced X

So: cause/effect only occur inside light cone

$\rightarrow$ light cone marks region of "causal" contact

Q: twists in big bang universe?

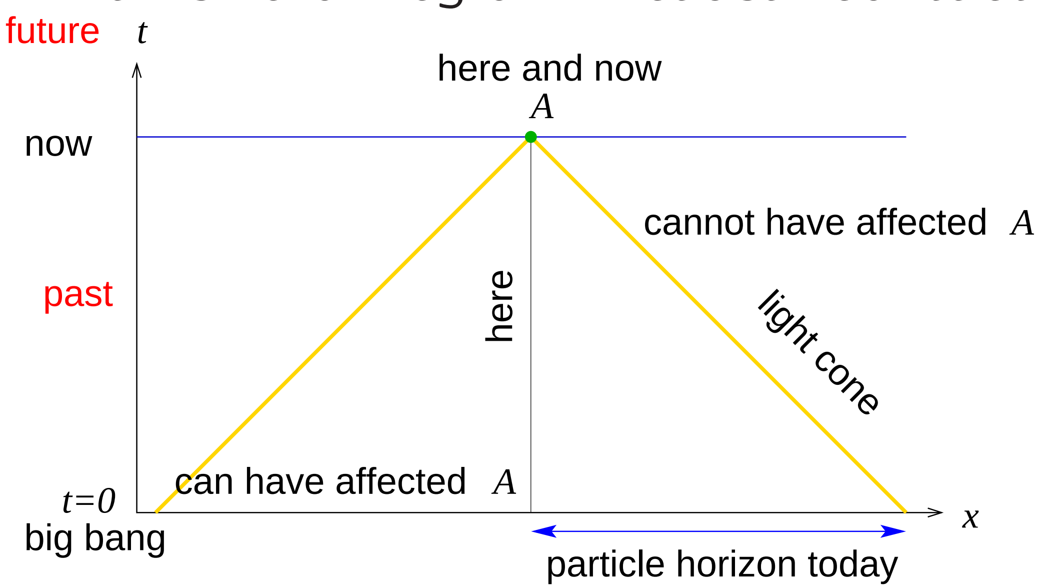
Twists in big bang universe:

- expanding: light has to "overtake" receding observers

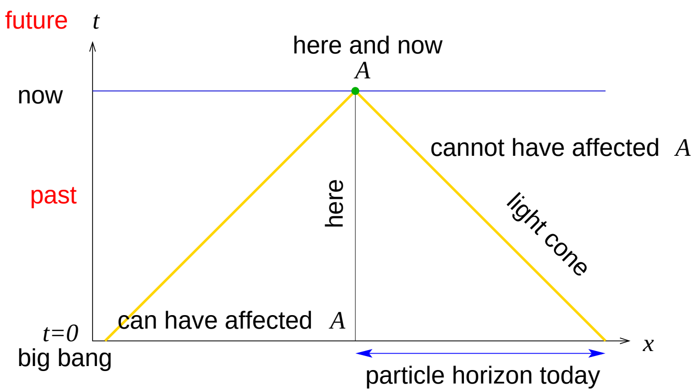
★ finite age: past does not stretch infinitely far back

particle horizon $d_{\text{hor}}(t)$ is

- physical distance light travels in t
- size of observable U. at t
- max size of region in causal contact at t



iClicker Poll: Cosmic Horizons

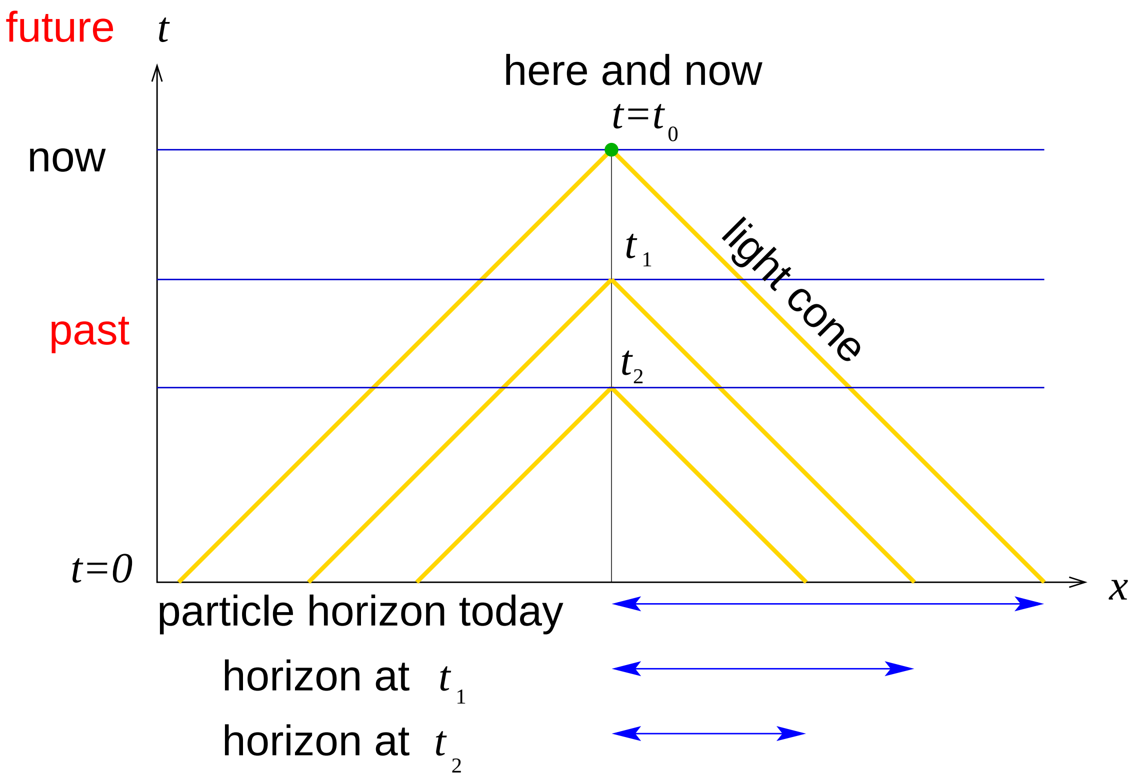


In the past, our cosmic horizon d_{hor}

A smaller than it is today

B the same size as it is today

C larger than it is today



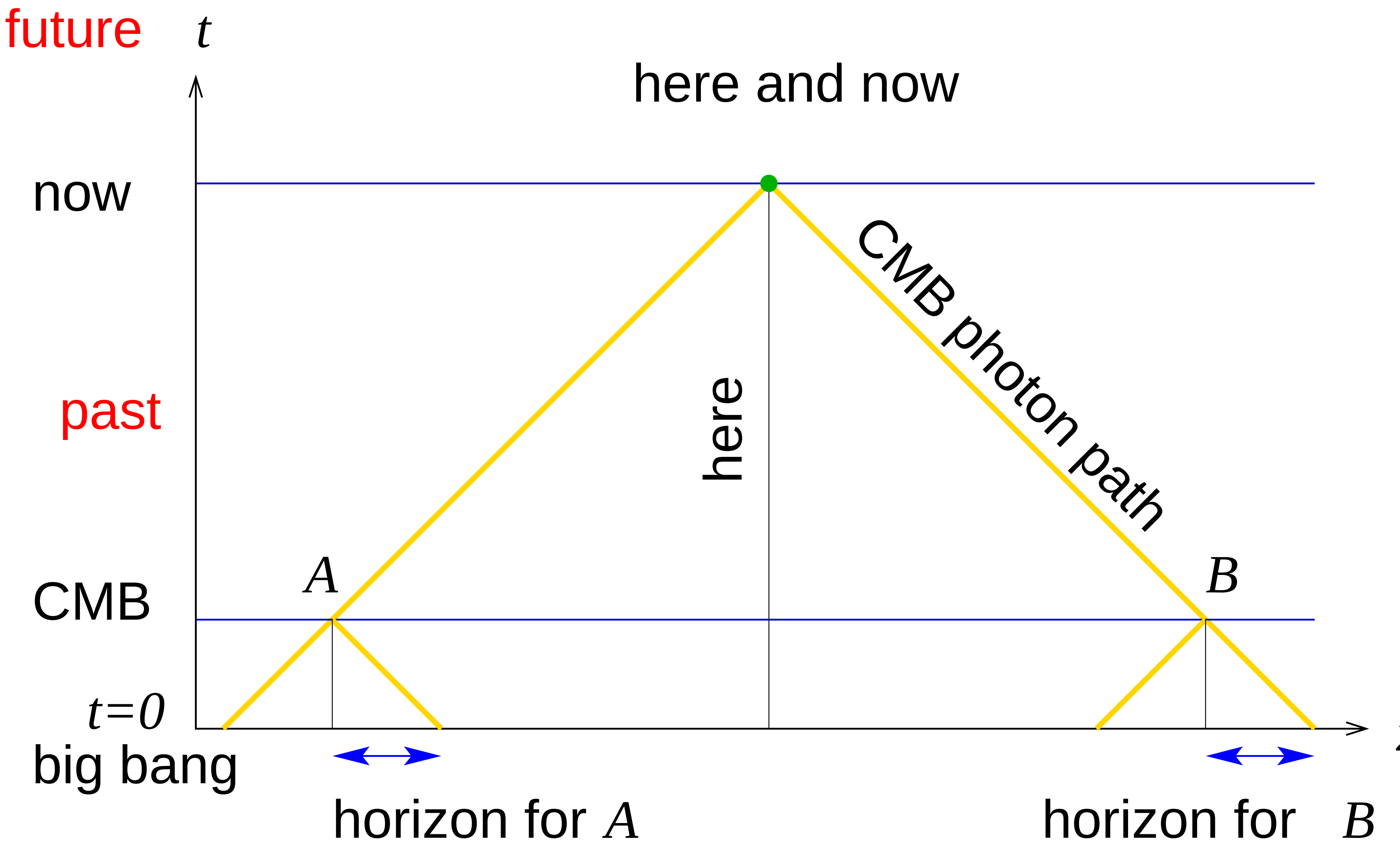
in past, cosmic horizon smaller

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


future
t
here and now
now
CMB photon path
past
here
A
B
CMB
t=0
big bang
horizon for A
horizon for B

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 $d_{\mathrm{hor}}(t_{\mathrm{rec}}) =$ 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`

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

What created fluctations?

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 $\Rightarrow$ 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 exapansion
  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 $e^{60} \simeq 10^{26}$!

Inflation Solves Cosmic Puzzles

1. 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. horizon

   ▷ tiny initial causal region ($\ll 1\ \mathring{A}$: microscopic!)

   ▷ 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. 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
$\rho_{\mathrm{vac}} \approx$ 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")?