Astro 210

Lecture 41

December 8, 2010

Announcements

- Final Exam: next Monday Dec 13, 7–10 pm, here as usual
  `www: info online`

Last time: expanding universe

- two objects with distance r at present time t_0
  will at time t have distance $d(t) = a(t)\, r$
  so $a(t)$ encodes history of cosmic expansion
  Q: present value $a(t_0)$? what is a for $t < t_0$?
- expansion rate $H = \dot{a}/a$

Followup to question from last time:

Hubble law: all galaxies move w.r.t. all others

$\rightarrow$ in any one frame, only *one* galaxy at rest

all others recede according to Hubble law

so: compare views from three evenly spaced points

- cosmic equation of motion: Friedmann eq

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G\rho - \frac{\kappa}{a^2} \tag{1}$$

- matter-only universe disagrees with data (too young!)
- *Q: given cosmic expansion, what's U like in the past?*

Expanding Universe: The Past

In the past, Galaxies closer together: $a(t) < 1$
U. was **denser**, also *hotter*

Universe began in very
hot
dense
state: $\Rightarrow$ big bang

expanded, cooled to present state

Where did the Big Bang Happen?
Q: Already know enough–where?

Where Was the Big Bang?

Universe is homogeneous & isotropic: no special points!
$\rightarrow$ big bang has no center $\rightarrow$ happened everywhere

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The Future

Q: given that U expanding today
what are possible fates in future?

The Fate of the Universe

The story until ~8 years ago
fate of universe is competition:
outward inertia of expansion vs *inward gravity*
...just like *pop fly* (ball hit upward)

currently: U expanding
like ball (pop fly) launched upward

future possibilities:

- gravity > intertia: *recollapse*
  like $v < v_{\text{esc}}$–ball falls back
- gravity < intertia: *expand forever*
  like $v > v_{\text{esc}}$–ball (rocket!?) leaves earth!
- gravity = intertia: *expand forever but $H \to 0$ at $t \to \infty$*
  like $v = v_{\text{esc}}$–ballt escapes but $v \to 0$ at $t \to \infty$

Last iClicker Poll! Cosmic Acceleration/Deceleration

How should the cosmic expansion *rate* change w/ time?

A *increase*: U. accelerates, $d^2a/dt^2 > 0$

B *decrease*: U. decelerates, $d^2a/dt^2 < 0$

C *constant*: U. coasts, $d^2a/dt^2 = 0$

Since gravity attactive, expect *deceleration* $\rightarrow$ just like upgoing pop fly

...BUT...

Current data:
Universe is *accelerating* !?!?

What does this mean?
need repulsive force to overcome gravity
only important on cosmo scales
$\rightarrow$ **dark energy**

A huge surprise!

A huge mystery!

What is dark energy? Will it change with time?

Perhaps related to very high energy processes (quantum gravity)?

Perhaps related to goings-on in very early Universe?

What little we do know:

if dark energy takes simples form (“cosmological constant”)

then dark enregy force between particles (galaxies) is $F_{\rm DE} \propto r$

Q: what does this imply for fate of U.?

Dark Energy and a Dark Future

dark energy force $F_{\mathrm{DE}} \propto r$
$\rightarrow$ force *increases* as particles move apart
$\rightarrow$ more repulsion as galaxies recede
so acceleration only increases with time!
$\rightarrow$ U. fate is to expand forever!

"the Big Chill"

Taking the Temperature of the Universe

when U. very dense: "good thermal contact"
$\rightarrow$ U has temperature

Q: How can we measure T of universe?

Measure T from spectrum

`www: Penzias & Wilson`

radiation everywhere

cosmic microwave background radiation (CMBR)

universe spectrum is very accurate blackbody

transp: CMB spectrum, errors $\times$ *100*

$$\boxed{T = 2.728 \pm 0.004 \text{ K}}$$

• if had microwave eyes, sky very bright
in radiation from big bang

• 10% of "snow" on TV
is radiation from big bang

Big Bang Nucleosynthesis

Theory

atomic nuclei made of protons p and neutrons n
bound together by nuclear force
at high temperature $\rightarrow$ early times
U so hot, collisions so violent, that nuclei "ionized" into n, p
then U cools until $n, p \rightarrow$ nuclei

$t =$ 1sec - 3 min: $kT = 10^{10}$ K to 10^{6} K
nuclei "ionized" (n & p only) $\rightarrow$ "neutral" (combined in nuclei)
24% helium
traces of D, ^{3}He, ^{7}Li
76% "leftover" protons (^{1}H)

Observation

measure He in universe:

$\rightarrow$ 24%

matches theory!

theory & obs. agree!

$\rightarrow$ big bang theory works well back to $t = 1s$!

Matter: Big Bang to Now

1. Big bang nuke: light elements

2. Universe cools, matter clumps
stars, Galaxies born

3. stars:
all heavy elements

Solar system has products of
- big bang (H, He, Li)
- low mass stars (ex: C from red Giants)
- high mass stars (ex: O, Fe from supernovae)

a cosmic symphony; we are results

another perspective:
cosmologists M. Python
"The Galaxy Song" from The Meaning of Life *(1983)*

CENSORED!

The Very Early Universe

before big bang nuke:

- $T > 10^{10}$ degrees
- very high-energy collisions:

study with particle acclerators

▷ Fermilab, Batavia IL (Chicago suburb–go visit!)

▷ Large Hardonic Collider (LHC), Geneva Switzerland to visit)

`www: Fermilab`

`www: tunnel`

`www: LHC`

`www: collision`

Inner Space and Outer Space

1. Fermilab and LHC are *microscopes*
   probing nature on the smallest scales

2. Fermilab and LHA are also *telescopes*
probeing conditions of
universe at $kT = 1$ TeV $= 10^{12}$ eV
$\rightarrow t = 10^{-12}$sec

2. Early Universe:
$\rightarrow$ "poor man's accelerator"
exotic particles created
perhaps these are dark matter?
weakly interacting massive particles: WIMPs

deep connections between
the very small and
the very large

Remaining Questions

To name a few:

- what is the dark energy?
- how will the dark energy influence the fate of the Unvierse?
- what is the dark matter?
- how did galaxies form?
- when did the first stars form? the first black holes?
  what are their observable “fossils” today?
- what happened at $t = 0$ (singularity)?

THANK YOU