Astro 406
Lecture 42
Dec. 11, 2013

Announcements:

- **Final Exam Dec 20** `www: info online`
  here, 8:00 to 11:00 am ...sorry!

ASTR 401: Paper in final form due **Dec 20**
No extensions are possible!

Last time:
gravitational instability: inhomogeneities grow with time
"the rich get richer and the poor get poorer"
Q: density perturbations at recombination?
Q: evolution to today?

Today: sprint to the Big Finish

today $t_0 = 13.7$ Gyr:

galaxy clusters have $\delta_{\rm today}^{\rm cluster} = \delta\rho/\rho \sim 200$

Milky Way disk has $\delta_{\rm today}^{\rm MW} \sim 10^6$

this room has $\delta_{\rm today}^{\rm room} \sim 10^{24}$

at *recombination* $t = 3 \times 10^{-5} t_0$: CMB tell us

- typical $\delta_{\rm rec} = \delta\rho/\rho \sim 10^{-4}$
- *tiny (but nonzero!) fluctuations* at all scales
  somehow the *"seeds"* of structures today

gravitational instability: $\delta(t)$ grows with time

$\to$ initial fluctuation pattern preserved but amplified

until $\delta \sim 1$, i.e., $\delta\rho \sim \rho_{\rm avg}$

then fluctuations large, patterns morph

Spherical Collapse Model

idealized but instructive example:
uniform, spherical matter overdensity
embedded in 'background" $\rho = \rho_{\text{crit}}$ universe

How will overdensity evolve?

Helpful, gorgeous theorem from General Relativity
any spherical matter distribution
responds gravitationally only to the enclosed mass
regardless of exterior mass
generalization of Gauss' law for Newtonian gravity

Q: implications for a spherical homogeneous overdensity?

a *spherical homogeneous region*
feels the *same gravity* as it would
in an *entire homogeneous universe*
of the same density!

and thus *evolves* exactly the *same as a Friedmann universe*
of the same density!

thus in a background universe with $\rho_{\mathrm{bg}} = \rho_{\mathrm{crit}}$
a spherical overdensity has $\rho > \rho_{\mathrm{bg}}$ and thus
evolves as would a universe with $\Omega > 1$

iClicker Poll: Spherical Overdensity Fate

Consider a spherical overdensity
initially with $\delta\rho/\rho \ll 1$

How will the overdensity evolve?

A immediately collapse to a black hole

B first expand and then collapse

C expand forever

Spherical Collapse

A uniform spherical matter overdensity
correspond to an $\Omega > 1$ universe $\rightarrow$ evolution is the same

1. begin by *expanding*
   initially $\rho \approx \rho_{\text{bg}}$, so $H \approx H_{\text{bg}}$
   $\rightarrow$ initial expansion almost at same rate

2. overdense region *expands to a maximum radius*
   where motion instantaneously stops (*"turnaround"*)
   pulls away from general cosmic expansion

3. overdensity *collapses*
   forms *bound structure*: *dark matter halo*

In real universe:
not so idealized, but overdensities still collapse

and then collapsed objects attract each other
while being carried apart by expansion

Q: what happens next?

Hierarchical Structure Formation

a “bottom-up” scenario

small structure form first

then **merge** to form larger structures

...which merge to form larger structures

...etc

`www: cluster formation`

dense regions connected by linear “filaments”

form knots in “cosmic web”

`www: cosmic web`

∞

Testing Structure Formation

Q: what observations are available?

Q: what complications are there in comparing with predictions?
Hint–think about us:
at the location of the Milky Way, there was a "seed"
i.e., the density was higher than the cosmic average:
$\rho(\text{here}) > \rho(\text{average})$ *Q: why?*

Q: so what determines what the cosmic density excess here?
Q: how does this complicate comparing predictions vs observations?

Since matter is gathered into galaxies
galaxies themselves are much denser than the U on average
and thus galaxies mark regions where cosmic density was
initially higher than average
i.e., galaxies tell (roughly) where the "seeds" were

But: theories like inflation "sow the seeds" **randomly**
i.e., no way to predict whether a specific point (x, y, z)
will be an overdensity or underdensity

So: the mere presence of a galaxy neither verifies or
refutes our models
Q: how can we overcome this problem?

key idea:
density seed prediction for any point *is* random
but: overall **pattern** of density fluctuations
is not at all random, but specifically predicted

can answer questions like this:

- *if* a galaxy found here,
  what is the *probability* of finding another galaxy 1Mpc away?
  i.e., what is the *pattern of clustering?*
- or can ask: what is the average "size" of a density fluctuation?
  technically: what is rms value of $(\rho - \rho_{\rm avg})^2$

In other words:
since the initial seeds are random
embrace this by adopting a *statistical* description
appropriate for finding patterns amidst randomness

Testing Structure Formation

Observations:

▷ measure statistical properties of structures
$\delta\rho$ vs size
clustering: how many nearby neighbors?

▷ measure intergalactic gas
use quasars as backlighting

▷ measure dark matter
use gravitational lensing

Theory:

predict observable properties

- analytic estimates as guidelines
- computer simulations for accuracy
  $\rightarrow$ UIUC, NCSA big players!

Present Status:

★ theory works well for large structures

intergalactic medium, clusters, superclusters

✗ problems with smaller structures

especially galaxy cores, dwarf galaxies

? trouble w/ observations or interpretation?

? oversimplified simulations?

? problems with WIMP dark matter?

stay tuned...

FINALE

A Brief History of the Universe: Prelude

Pytyon, M. (1983) The Galaxy Song

CENSORED!

iClicker Poll: The Big Bang Theory

You are now all experts on the **Big Bang Theory**

It has come to my attention there is a TV show with that name

What do you think about *The Big Bang Theory* TV show?

A People still watch TV?

B Hate it! Hate it! Hate it!

C Meh. I'll watch if nothing else is on.

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

E Love it and I'm proud! Must-see TV!

A Brief History of the Universe I

Speculations on the High-Energy Frontier

$\boxed{\textbf{Planck Epoch: } t \sim 10^{-43}\text{ s}}$

realm of quantum gravity

spacetime infected w/ quantum fuzziness (?)

black holes created and evaporated (?)

$\boxed{\textbf{Inflation: } t \sim 10^{-38}\text{ s } \textbf{(???)}}$

exponential expansion

quantum fluctuations $\to$ seeds of structure

$\boxed{\textbf{Baryogenesis: } t \sim 10^{-37}\text{ s } \textbf{(???)}}$

matter-antimatter asymmetry created

must occur after inflation (why?)

A Brief History of the Universe II

The Early Universe

Quark-Hadron Transition: $t \sim 10^{-5}$ s, $z \sim 10^{15}$

most quarks annihilate with antiquarks

$\rightarrow$ CMB photons created

tiny remainder locked into baryons

Big Bang Nucleosynthesis: $t \sim 1$ s, $z \sim 10^{10}$

neutrinos freeze out, remain as cosmic neutrino background

light elements created

A Brief History of the Universe III
The Growth of Structure

Matter-Radiation Equality: $t \sim 30$ kyr, $z \sim 3200$

matter density begins to dominate radiation density

structures begin to grow

Recombination: $t \sim 380$ kyr, $z \sim$**1100**

plasma $\rightarrow$ neutral gas

opaque $\rightarrow$ transparent

CMB photons free stream

The First Stars: $t \sim 100$ Myr, $z \sim 30$ **(???)**

Population III?

dispersal of metals?

reionization of the universe?

`www: first star simulation`

A Brief History of the Universe IV

The Imaged Past

$\boxed{\textbf{Star Formation Peaks: } t \sim few \text{ Gyr}, z \sim 3 \textbf{ (??)}}$

elliptical galaxies, spheroids formed

$\boxed{\textbf{Matter–Dark Energy Equality: } t \sim 4 \text{ Gyr}, z \sim 1}$

structure formation tails off

exponential expansion begins

$\boxed{\textbf{Sun Born: } t \sim 9 \text{ Gyr}, z \sim 0.5}$

Planets formed soon thereafter

$\boxed{\textbf{Today: } t \sim 14 \text{ Gyr}, z \equiv 0}$

You take Astronomy 406

iClicker Poll: Guess the Cosmic Wrong

Some of today's Galaxies and Cosmology science is surely *wrong*

Vote your conscience!
When your grandchildren take ASTR 406 at U of I:
What fraction of this semester's material will they say is wrong?

A 0% to 20%

B 20% to 40%

C 40% to 60%

D 60% to 80%

E 80% to 100%

OPEN QUESTIONS

Q: remaining loose ends?

Open Questions in Galaxies and Cosmology

- How can we observationally trace the history of the Milky Way?

- Why do most (all?) galaxies have black holes at their centers? What does this have to do with galaxy formation?

- What is the origin of spiral, elliptical galaxies? What role do mergers, dark matter play?

- What is the nature of the dark matter in the Milky Way? Can we detect it?

- What is the nature of the dark energy? Is it related to inflation?

- What is the fate of the U.? Are we doomed to exponential expansion and the cosmic "tunnel vision" of a shrinking horizon?

- Did the universe undergo inflation? If so, what was the microphysics at work–i.e., what was the inflaton ϕ? If not, what is the origin of density fluctuations, and what solves the horizon and flatness problems?

- Is the dark matter a relic particle leftover from the early U.?

- Did the universe undergo a singularity at $t = 0$? What is the nature of quantum gravity and what does this mean for the origin of the U.?

- Are we fooling ourselves? Does modern cosmology contain epicycles which our grandchildren will find quaint? Is there some basic physics we have totally missed and awaits discovery?

- Will all of this be on the final?

THANK YOU!