Astro 350

Lecture 41: The Final Frontier

Dec. 7, 2011

Announcements:

- **Final Exam**: Tue Dec 13, 8-11am
  `www: info online`
- Discussion Question *second chance*
  can do up to 2 missed questions for half credit each
  must turn in by end of today
- **ICES** available online – please do it!
  I do read and use comments!
- all assignments graded, returned at end of class

Speedy Neutrinos? The Payoff

Recall: OPERA experiment measures neutrino speed $v_\nu = d/t$ finds $v_\nu = 1.000025c$!

My wagers from Sept. 26:

- ⋆ theory explanations/"explanations" by Sept. 30? **YES!**
  to date: 161 research papers cite this result
  "phantom of the OPERA" pun made frequently
- ⋆ debunking of OPERA experiment by today? **NO!**
  so enjoy your pizza!

Will we ever know if OPERA is right?

Yes! independent, dedicated experiments at Fermilab and Japan will measure v_ν

Stay tuned!

Cosmic Structure Formation

Last time: **gravitational instability**
tiny initial density fluctuations (from inflation?)
amplified over time by gravity
"the rich get richer and the poor get poorer"

But note: all of this still occurs
in context of expanding universe

so how does this work?

Spherical Collapse

Instructive simplified case:

- an isolated, uniform, spherical overdensity
- in an otherwise critical density universe: $\rho = \rho_{\rm crit}$, $\Omega = 1$
- blob initially has $\delta\rho = \rho_{\rm blob} - \rho_{\rm universe} \ll \rho_{\rm universe}$
  $\Rightarrow$ tiny fluctuation, so initially expands just like rest of Univ.

Beautiful property of gravity (Newton's and Einstein's both):
the motion of a gravitating sphere
depends only on what's inside that sphere

so: treat overdensity as homogeneous Universe with $\Omega > 1$:

- initially expands
- reaches maximum expansion, minimum density
- then "turns around" and recollapses: a halo/galaxy is born!

`www: simulation of structure growth in non-expanding coordinates`

Hierarchical Structure Formation

cosmic structure grow from the "bottom up" small clumps 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`

Structure Formation Theory: Predictions and Tests

Most cosmic matter is gathered into dark halos
and dark halos are where galaxies form
$\rightarrow$ 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 initial "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

namely, 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 $(\rho - \rho_{\rm avg})^2 = \delta\rho^2$

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

X 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 I

Speculations on the High-Energy Frontier

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

- realm of quantum gravity
- spacetime infected w/ quantum fuzziness (?)
- black holes created and evaporated (?)

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

- exponential expansion
- quantum fluctuations $\rightarrow$ seeds of structure

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

- matter-antimatter asymmetry created
- must occur after inflation (why?)

A Brief History of the Universe II

The Early Universe

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

neutrinos freeze out, remain as cosmic neutrino background

light elements created

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

matter density begins to exceed radiation density

$\rho_{\text{matter}} > \rho_{\text{rad}}$

expansion slows, structures begin to grow

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

plasma $\rightarrow$ neutral gas

opaque $\rightarrow$ transparent

CMB photons free stream

A Brief History of the Universe III

The Growth of Structure

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

very massive ($> 100 M_\odot$) $\rightarrow$ die as supernovae?

reionization of the universe?

www: first star simulation

Star Formation Peaks: $t \sim few$ Gyr, $z \sim 3$ **(??)**

www: cosmic history of star formation

elliptical galaxies, spheroids formed

Matter–Dark Energy Equality: $t \sim 4$ Gyr, $z \sim 1$

$\rho_{\rm dark\,energy} > \rho_{\rm matter}$

structure formation tails off

exponential expansion begins

Sun Born: $t \sim 9$ Gyr, $z \sim 0.5$

Planets formed soon thereafter

Today: $t \sim 14$ Gyr, $z \equiv 0$

You take Astronomy 350

www: Cosmic Wrongness--the votes are in!

Final iClicker Poll: Cosmic Surprises

Of the following aspects of modern cosmology

Which of these seems the most likely to be overturned?

A inflation

B matter-antimatter difference due to early universe particle reactions

C dark matter as fossil exotic particles

D dark energy as origin of cosmic acceleration

Which of these seems the most likely to be confirmed?

OPEN QUESTIONS

⋆ 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.?

⋆ Will all of this be on the final?

Thank You!