Astro 350

Lecture 25

March 25, 2022

Announcements:

- **Discussion 6 due Wednesday**
- **Homework 6 due Friday**
- Office Hours after class today

Last time: **supermassive black holes**

- found at the centers of most (all?) galaxies
- black hole growth linked to galaxy growth

gravitational waves

space and time are dynamic, affected by gravitating objects

moving massive cause ripples in spacetime:

gravitational radiation–moves at speed c!

Gravitational Wave Observatories

online now: ground-based detectors sensitive to binary mergers with stellar masses

Advanced LIGO: operational since 2015 `www: LIGO`
interferometers (detectors) in Washington state and Louisiana

VIRGO: operational since 2017
one detectors near Pisa, Italy; less

when possible signal reported:

- confirm with multiple detectors
- localize on the sky
- scan that region with telescopes!

GW 150914

Sept. 14, 2015:

gravitational wave signal appears in both LIGO detectors!

`www: GW 150914 signal`

strain pattern $h(t)$ matches textbook predictions
for **merging black holes**!!

- early signal: increasing frequency and amplitude – **inspiral**
- peak signal: maximum amplitude, very rapid variability – **merger**
- late signal: decreasing amplitude – **ringdown**

binary masses: $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$

final mass: $62^{+4}_{-4} M_\odot$

converted to gravity wave energy: $3.0^{+5}{-5} M_\odot c^2$

distance: ~ 400 Mpc ≈ 1 billion light years

AMAZING! *Q: because?*

First LIGO Event: Revolution

this single detection of binary black hole merger
which lasted ~ 0.1 sec in total
has profound implications

LIGO for the first time:

- directly detected gravitational radiation
- revealed nature produces black holes $> 10 M_\odot$
- showed that BH binary systems exist
- ...and can collide within the age of the Universe
- observed the birth of the final black hole
- verified and quantified the gravity wave energy release

And: **LIGO inaugurated the age of gravity wave astronomy**

Update: LIGO/Virgo Black Holes

LIGO/Virgo ran until COVID shutdown

90 gravitational wave events detected!

signal is strongest for nearest, most massive events

$\rightarrow$ biased towards binary black holes (BH-BH) mergers

`www: LIGO/Virgo detections`

detected black hole masses before merger:

- lowest: $5.9^{+4.4}_{-1.3} M_\odot$
  consistent with origin in core-collapse explosion
- highest: $87^{+40}_{-23} M_\odot$ – very massive!
  could this be the result of a prior merger?

Open questions:

- how and where are these binaries formed?
- what is the (unbiased) distribution of black hole masses?
- do BH mergers have a detectable electromagnetic signal?

Stay tuned!

Black Hole Questions

Thanks for your great questions on black holes!

`www: Discussion Questions`

General Relativity: Executive Summary

General Relativity = Einstein's gravity theory

- agrees with all known experiments/observations (so far)
- gravity $\neq$ force, but rather "spacetime curvature"
- matter tells spacetime how to curve
  curvature tells matter how to move
- in GR, the nature of spacetime:
  - is dynamic, i.e., spacetime responds to matter within it
  - cannot be deduced from pure thought, but
  - must be experimentally measured/mapped,
    i.e., the nature of space and time can be different
    depending on the matter/energy content of the Universe;
    have to measure our Universe and its contents
    to see what we have been dealt

Relativisitic Cosmology

Cosmology: The Big Picture

Take science to the largest arena possible:
study the Universe as a physical system

- structure
- dynamics
- composition
- origin
- evolution

Mapping the Universe: The Real Data

recall: galaxies are the "building blocks" of the universe today

so to find the structure of the Universe today
need to map galaxies across all of the observable universe
$\rightarrow$ a big and ongoing job!

space is 3-dimensional, so cosmic maps should be 3-D too
but to get started, let's look at 2-D "slices" `www: 2dF galaxy survey--scan strategy`
`www: 2dF galaxy survey--results`
`www: SDSS galaxy survey--results`

Q: what do you notice when looking closely?
Q: what do you notice when "stepping back and squinting"?
Q: how does on slice compare to another?
Q: why the dropoff at large distances?
Q: so what do we learn about how do galaxies fill the universe?

The Large-Scale Structure of the Universe: I

Observations teach us that, to a "first approximation":
the Universe *today* is

1. homogeneous: average properties same at all points
e.g., mass density anywhere is same as mass density everywhere!

and

2 isotropic: looks same in all directions

universe is homogeneous & isotropic:
the **"cosmological principle"**
first guessed(!) by A. Einstein (1917)

Q: as exact (not approximate) statement,
cosmo principle obviously false! Why?
In what sense could it be true?

Example: Cosmo principle and galaxy properties

Q: if cosmo principle true, how reflected in observations of galaxies at any given time?

Q: how could you test this?

Q: what does cosmo principle say about how galaxy properties evolve with time?

Cosmo principle and galaxy properties:

at any given time:

- **average** density of galaxies same everywhere
- distribution of galaxy properties same everywhere

e.g., types, colors, L, M, ...

- time evolution: must maintain large-scale homogeneity and isotropy

but otherwise, **by itself** principle allows any changes!

Real Galaxies in the Real Universe

Beyond the First Approximation

cosmo principle a very good approximation

on large scales ($\gtrsim 10$ Mpc) `www: 2dF`

recall 1 Mpc $= 10^6$ pc $\sim$ typical distance between galaxies

but do observe fluctuations around average galaxy density

`www: 2dF maps`

on small to medium scales ($\lesssim 10$ Mpc),

galaxies **clustered** in space:

- loners: "field" galaxy
- few ($\lesssim 50$) galaxies: group
- 100's-1000's of galaxies: cluster
- assemblies of groups and clusters: supercluster

The Logic of the Cosmo Principle

Cosmo Principle:
On large scales ($\gtrsim 50$ Mpc), universe is
- homogeneous $\rightarrow$ smooth
- isotropic

Q: do you need both?
Q: e.g., how can you be isotropic but not homogeneous?
Q: e.g., how can you be homogeneous but not isotropic?

Cosmo principle as cosmic democracy:
Universe has no center, no edge
no special places, directions!

The cosmo principle, in song

I'm just average, common too
I'm just like him, the same as you
I'm everybody's brother and son
I ain't different from anyone
It ain't no use a-talking to me
It's just the same as talking to you.

Cosmologist and Nobel Prizewinner Bob Dylan (1964)

Cosmological Principle: Implications

- demands enormous regularity

"maximal symmetry" $\rightarrow$ simplifies analysis!

- places stringent constraints on
  (i.e., simplifies!) the possible nature and behavior
  of the Universe and its contents
  i.e., is "the cosmologist's friend"

- "trying to tell us something"
  about how universe formed?
  (e.g., cosmic inflation in early universe?)

iClicker Poll: Cosmodynamics

galaxies have mass $\rightarrow$ gravitate
in general, expect galaxies to be in motion

What pattern of motions (relative to us) will we find?

A most galaxies move towards us

B roughly half move away, half towards us

C most galaxies move away from us

iClicker Poll: Cosmodynamics Twofer

in fact: the *majority* of galaxies move away from us

What percentage of galaxies are observed to move away?

A between 50% and 75%

B between 75% and 90%

C between 90% and 95%

D between 95% and 99%

E $>$ 99%

Cosmodynamics I

of >1 million galaxies with redshift/blueshift measurements

<20 galaxies have blueshifts! (only nearest ones)

so: $>99.9999\%$ of galaxies have redshifts!

$\Rightarrow$ essentially all galaxies have **redshift**:

$$z \equiv \frac{\lambda_{\rm obs} - \lambda_{\rm rest}}{\lambda_{\rm rest}} > 0 \qquad (1)$$

$\rightarrow$ move away!

line-of-sight speed: Doppler law sez $v = cz$

first approximation:

Hubble (1929) v & distance r related:

`www: Hubble original data`

Q: how are v and r related mathematically?

Hubble: galaxy speed and distance *proportional*

$\Rightarrow v \propto r$

$\boxed{v = H_0 r}$ Hubble law

in fact: $\vec{v} = H_0 \vec{r}$

that is, speed and distance directions the same

$\rightarrow$ galaxies all move *radially* away from us!

Q: why did it have to be this way?

Hubble Law $v = H_0 r$

Hubble parameter (a.k.a. "Hubble constant")

$$H_0 \simeq 72 \text{ km s}^{-1} \text{ Mpc}^{-1} \tag{2}$$

e.g., galaxy at $r = 10$ Mpc moves away at 720 km/s

Try it!
draw field with MW, other galaxies, $\vec{v}$
Comment on pattern

Note: to zeroth order, z + Hubble law $\rightarrow r$
distance measure