Astro 406
Lecture 25
Oct. 25, 2013

Announcements:
- **PS 7 due now**
- **PS 8 due next Friday**
- ASTR 401: draft due next Monday
- thanks to the Planetarium-goers
  alternate makeup activity posted soon

Next semester: you qualify for advanced cosmology `www: info`
⋆ **ASTR 507: Physical Cosmology**
⋆ **ASTR 596/496: Supernovae and Dark Energy**

Last time: galaxy clusters
Q: why are they special–recordholders?
Q: why are they great laboratories for dark matter?
Q: cluster results on hot gas a dark matter?

X-Rays Reveal "Dark" Intracluster Matter

- *hot gas fills clusters!* – "intracluster medium"
- and intracluster gas has *more mass* than the galaxies
- but was (optically) invisible, and unknown until birth of X-ray astronomy in 1970's!

Hot gas really is (optically) dark matter!
Represents about 75% of ordinary matter in galaxy clusters!

Q: What heated the gas? Probably more than one effect!

Dark Matter Puzzle Solved?

Mystery solved?

Partially: galaxy clusters and smaller galaxy groups known to have large amount of hot gas

This is huge progress, but we are not finished

Q: why? What else must we measure about clusters?

Cluster Masses

to see if we have found all cluster mass
need to measure *total cluster mass*
• multiple techniques $\rightarrow$ compare, calibrate

Methods:
• galaxy v dispersion $\rightarrow$ $v_{\rm rms}$ + virial theorem
• hot gas + hydrostatic equilibrium $\rightarrow$ $m_{\rm tot}(r)$
• gravitational lensing: arcs resolved!
`www: cluster and arcs`

Cluster Masses: The Bottom Line

bottom line:

- methods in good agreement
- $M/L \sim 200 M_{\odot}/L_{\odot} \rightarrow$ *much dark matter!*
  $M_{\text{dark}}/M_{\text{lum}} \sim 10$

Lessons:

- dark matter persists at large scales
- all cluster mass measures require it
- cluster have *higher* M/L than galaxies like MW

Q: implications for evolution of galaxies, the Universe?

Lineup of Dark Matter Suspects

~~hot gas~~

~~cold gas~~

~~black holes~~
~~neutron stars~~
~~white dwarfs~~
~~"failed stars" "Jupiters," brown dwarfs~~

} ~~compact objects~~

neutrinos

exotic relic particles from big bang

We have now exhausted all conventional candidates!

The only remaining options:

- *particles–neutrinos being the* least *exotic candidate*
- *Einstein is wrong and gravity must be modified!*

The Bullet Cluster and Dark Matter

Bullet cluster:
two galaxy clusters in process of merging
have already passed through each other(!) once *Q: how?*

Can observe:

- *optical galaxies*
- *X-rays*: *hot gas* that filled cluster interiors before merger
  recall: more (ordinary) matter in gas than in galaxies!
- *lensing* $\rightarrow$ *all gravitating mass*, so dark matter = total - seen

Results:

- X-rays (hot gas) offset from galaxies
  since stars don't collide with each other, but gas "splatters"

iClicker Poll: Bullet Cluster

Bullet cluster:
most of *visible mass* in splattered hot gas
offset from non-colliding *galaxies*

Where will lensing reveal *total* mass?

A if weakly interacting DM: with gas
if gravity modified: with gas

B if weakly interacting DM: with galaxies
if gravity modified: with gas

C if weakly interacting DM: with gas
if gravity modified: with galaxies

D if weakly interacting DM: with galaxies
if gravity modified: with galaxies

If weakly interacting DM:

doesn't collide with anything

$\rightarrow$ acts like stars in galaxy

should be seen with galaxies

If no dark matter but modified gravity

most gravity where most ordinary matter:

$\rightarrow$ should see gravity source with intracluster gas

`www: Bullet Cluster`

lensing data $\rightarrow$ gravitation source centered on galaxies

$\rightarrow$ consistent with weakly interacting dark matter

$\rightarrow$ not consistent with alternative gravity!

Superclusters

next largest objects

clumps of clusters

- 10's of Mpc in lengthscale
- still forming – *not* yet gravitationally bound
- density not as enhanced relative to cosmic average

nearest: Local Supercluster

`www: Local Supercluster`

we are on the edge

Q: next level of structure?

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

• at any given cosmic time ("epoch")

• to "zeroth order":

the Universe is both

1. **homogeneous** average properties same at all points

e.g., mass density anywhere is same as mass density everywhere!

i.e., $\langle\rho\rangle(\vec{r}) = \rho$ indep of $\vec{r}$!

2 **isotropic** looks same in all directions

"Cosmological Principle"

the universe is homogeneous & isotropic

first guessed(!) by A. Einstein (1917)

Q: why must this be only a "zeroth order" approximation?

Example: Cosmo principle and galaxy properties

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

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
  range of types
  range of colors
  range of L, M, ...
  ratios of normal/dark matter

Note that these are very restrictive constraints!

- time evolution:
  must maintain large-scale homogeneity and isotropy
  but otherwise, **by itself** cosmo principle allows any changes!

Real Galaxies in the Real Universe

Beyond Zeroth Order

cosmo principle a very good approximation

on large scales ($\gtrsim 30$ Mpc)

`www: 2dF`

but do observe fluctuations around average galaxy density

`www: 2dF maps`

on small to medium scales ($\lesssim 30$ Mpc),

galaxies **clustered** in space loners = "field" galaxy

few ($\lesssim 50$) gals: group

100's-1000's of gals: cluster

assemblies of groups and clusters: supercluster

Cosmodynamics I

gals have mass $\rightarrow$ gravitate
in general, expect motion

zeroth order:
$\approx$ all galaxies have **redshift**:

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

$\rightarrow$ move away!

If interpret as Doppler shift:
line-of-sight speed $v_r = cz$
Hubble (1929) v_r & distance r related:
`www: Hubble original data`