Astro 350

Lecture 15

Sept. 28, 2011

Announcements:

- HW4 due Friday
- Discussion Question 4 due today
- Hour Exam 1 back next time

FYI: Bigshot cosmologist in the house!

Dr. Jonathan Gardner

a lead scientist on James Webb Space Telescope
successor to Hubble

- Astro Colloquium: Tue Oct 4, 4pm, 134 Astronomy bldg
  "The James Webb Space Telescope"
- Public Talk: Tue Oct 4, 7:30pm, 151 Loomis (Physics bldg)
  "A Scientific Revolution: the Hubble and James Webb Space Telescopes"

## Superluminal Payoff!

Last time: **Reports of faster-than-light neutrinos**

- *Q: what was the experiment?*
- result is *not* warp speed! allegedly $v_\nu = 1.000025c$
- yet a Big Deal if true *Q: why?*
- I made two wagers: one has come true!
  theory papers by Friday? `www: Yes! four by Tuesday!`
  *Collect and digest your sweet rewards!*
- Fermilab soon begins similar experiment
  `www: MINOS` – will confirm/refute!

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Milky Way: *Q: where do we live?*

# Milky Way Dynamics

Milky Way stars orbit Galactic center
orbits roughly circular

MW rotation pattern:
plot **rotation curve:** orbit speed vs distance from center

as a warmup:
*Q: rotation curve for points on frisbee (all same period $P$)?*

## iClicker Poll: Solar System Rotation Curve

Rotation curve: plot orbit speed $v$ vs distance $R$

What is the rotation curve shape for solar system objects?

A  $v$ increases with increasing $R$

B  $v$ constant with increasing $R$

C  $v$ decreases with increasing $R$



*Q: why this trend?*

# Milky Way Rotation Curve

`www: Milky Way rotation curve data`

find $v \sim const$ beyond $R \sim 2$ kpc

"flat rotation curve"

speed stays constant (still flat) out to largest $R$

*even when there are no more stars/gas/dust!*

compare/contrast: solar system rotation curve

*Q: what does the MW/SS difference mean?*

recall (HW2): orbits provide measure of gravity
stronger gravity $\rightarrow$ larger accel $\rightarrow$ faster orbits
and stronger gravity $\rightarrow$ more mass
$\Rightarrow$ orbits measure mass interior to motion

in detail (HW5): circular velocity
$v_{\rm circ} = \sqrt{GM_{\rm enclosed}/R}$: use to get mass interior to $R$
$\rightarrow M(R) = v_{\rm circ}^2 R/G$

Solar System: $M(R) = M_\odot = const$ for all orbits
$\rightarrow$ so $v \propto 1/\sqrt{R}$: rotation curve *decreases* with $R$
i.e., Mercury is speedy, Pluto slowpoke

But for outer Milky Way: $v(R) = const$
*Q: what does this mean for $M(R)$?*

# Milky Way Rotation Curve

disk stars: $\sim$ circular orbit $\rightarrow$ disk rotates

plot **rotation curve:** orbit speed vs distance

find $v \sim const$ beyond $R \sim 2$ kpc

"flat rotation curve"

Newton's gravity and Newton's laws of motion say

$$M_{\text{enclosed}}(R) = \frac{v_{\text{circ}}(R)^2 \ R}{G} \propto v^2 R \tag{1}$$

for flat rotation curves $v = const$, so

$M(R) \propto R$: Galaxy mass keeps *increasing* with $R$

...*even when there's no more stars/gas/dust!*

MW mass estimate (rot curves): $M_{\rm MW} = 5 - 10 \times 10^{11} M_\odot$ total
but stars & gas: $M_\star \simeq 10^{11} M_\odot$
$\rightarrow$ only $10 - 20\%$ of total!

Forced to conclude: a large amount of mass is unseen!
*most* (80-90%) of Galaxy mass
is in the form of **dark matter**!

Revised view of Milky Way structure:

- disk: most stars, all gas/dust $R_{\rm disk} \approx 15$ kpc
- bulge/stellar halo: older stars, globular clusters
- ...but *most* of Galaxy in dark halo $R_{\rm dark} > 50$ kpc
  Milky Way much more massive, larger, than meets the eye!

∞

*Q: what do rot curves say about the nature of dark matter?*

# Dark Matter

**most** of MW matter is dark

What is the dark matter? Unknown! (yet!)
rotation curves don't specify details, only:

▷ **dark**: must not glow
(i.e., must be very dim in EM radiation)
▷ **matter**: must have mass (gravity)

Multiple possibilities exist:
*Q: suggestions?* ... no peeking!

What is the DM? Unknown (to date). Guesses:

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

} compact objects

hot $\sim 10^6$K gas (emits X-rays, but not visible light)

neutrinos

relic particles from big bang

in the rest of the semester, we will work through list

*Q: how do you confirm/refute a candidate?*

## The Hunt for Dark Matter: Case Study

Example: imagine DM is in form of white dwarfs

If white dwarfs are our Milky Way's dark matter
- MW halo composed of a large number ($> 10^{11}$) of WD
- they had to get there

*Q: How could this have happened?*
*What evidence would be left today?*
Hint–what are white dwarfs? How are they made?

# White Dwarfs as Dark Matter

Recall–white dwarfs are corpses of $0.8 - 8 M_{\odot}$ stars
WD recipe:
(1) form star with mass in range $0.8 - 8 M_{\odot}$
(2) star dies 200 million to billions of years later
(3) $\gtrsim 50\%$ of mass ejected as gas enriched in He, C
(4) white dwarf left over

If white dwarfs are dark matter, then
⋆ had to make very many $0.8 - 8 M_{\odot}$ stars
⋆ they had to have time to die
⋆ white dwarfs not initially dark $\rightarrow$ need time to cool & dim
⋆ more mass ejected than left as WD, full of C and He

Would leave evidence: making many omlettes $\rightarrow$ lotsa broken eggs!
- old, cool, dim white dwarfs in dark halo
- huge amount of He & C-rich gas ejected from MW should still be nearby

Observations weigh in:

- Hubble Telescope: no halo white dwarfs seen
- no evidence for helium & carbon-rich gas nearby
- looking outward $\rightarrow$ back in time
  don't see formation, death of enormous numbers
  of $0.8 - 8 M_{\odot}$ stars in other galaxies

$\Rightarrow$ *white dwarfs ruled out as dark matter!*

in next weeks, will see::
*most* dark matter candidates can now be ruled out!
and the most(?) exotic option–exotic elementary particles
is the most favored!
**`www: particle dark matter detection experiment`**

actually, another logical explanation can account
for flat rotation curves... *Q: namely?*