

Astro 350
Lecture 19
Oct. 12, 2012

Announcements:

- **HW 5** due now
- **HW 6** available, due at start of class Friday
- **Discussion 6** due Wednesday
- Guest Cosmologist: Prof. Andrea Ghez
“The Galactic Center: Unveiling the Heart of our Galaxy”
Tues Oct 17, 7pm, Lincoln Hall Theater

Last time: a relativistic theory of gravity

Q: What is the equivalence principle?

Q: What does the rocket experiment imply about gravitational effects on light, clocks?

*Q: What is gravitational lensing?
why is it useful for cosmology?*

Gravitational Lensing and Dark Matter

gravitational lensing reveals presence, strength of gravity
whether or not the gravitating objects emit light!

→ just what the doctor ordered to test for dark matter!
and/or black holes

General strategy:

- find “background” light source **behind** unseen gravity source
- observe image of background objects
- from image distortion → infer presence, amount, distribution of unseen mass!

↳ *Q: how might we test for DM in our own Galaxy?*

Searching for Milky Way Dark Matter: MACHOs

Recall: “conventional” dark matter candidates include
“compact” star-like objects:
brown dwarfs, white dwarfs, neutron stars, black holes

if dark matter = **M**Assive **C**ompact **H**alo **O**bjects (**MACHOs**)
then find via lensing

setup *diagram: sketch*

- use nearby galaxy (Large Magellanic Cloud)
as background light source
- monitor lotsa LMC stars (i.e., millions)

recall: DM (here, MACHOs) in motion: $v \approx 200$ km/c
sometimes: MACHO will wanders close to line of sight
towards a LMC star

ω Q: *what will happen—if MACHO exactly in sightline?
if near sightline?*

Gravitational Microlensing

if MACHO **exactly** aligned

- all incoming rays bent equally → see a **ring**
the “Einstein ring”
- more light deflected towards observer → total flux higher
→ brightness amplification

if MACHO comes close to sightline but never aligned

- ring splits to 2 images (arcs of circles)
- brightness amplification still observed

In practice:

- rings, arcs from MACHOs too small to see, but
- ↳ ● *can* detect amplification of brightness
experiments performed to look for this

iClicker Poll: Microlensing and Dark Matter

Vote your conscience!

It's 1993. First microlensing results are in.

Will they find MACHOs as Milky Way dark matter?

A Yes: MACHOs found in halo, masses point to black holes

B Yes: MACHOs found in halo, masses point to neutron stars

C Yes: MACHOs found in halo, masses point to white dwarfs

D No: no/few MACHOs found in halo, dark matter is something else

Microlensing Experiments and Results

MACHO project: monitored $> 10^6$ LMC stars for 5.7 years

www: MACHO lightcurve

~ 12 events seen! gravitational lensing reconfirmed!

but – where are lenses: halo or LMC?

if halo lenses: $m \sim 0.5M_{\odot}$ white dwarf?

total mass $\sim 20\%$ of dark halo, definitely not 100%!

however: substantial evidence lenses are

- in LMC itself, or
- in MW thick disk

⇒ **no/very few compact objects in halo**

Lineup of Dark Matter Suspects



Note that all “conventional” candidates now gone!
Only exotic particles remain!

∩
Q: *But do microlensing results mean there's no dark matter in Milky Way?*

Microlensing results **do say**:

- Milky Way halo *not* made of **compact** objects = MACHOs
a very important negative result!

Microlensing results **do not say**:

- anything about DM that is not compact, more diffusely spread
e.g., gas (but this has other problems) or elementary particles!
cannot rule out (or in!), need to test in other ways
e.g., underground experiments for particle DM

But wait! There's more...

Recall: Dark matter also seen in external galaxies

Q: how might we use gravitational lensing to detect it?

Lensing by Dark Matter in Other Galaxies

If background galaxy (or quasar) light passes thru foreground galaxy or galaxy cluster
can resolve lensed arcs of background object `www: arcs`
use to reconstruct **total** mass distribution of foreground gal
⇒ direct probe of dark matter distribution!

Status: already done for tens of objects
conclude: total gravitating mass \gg visible mass
→ independent evidence for dark matter!
not only that, but can infer DM distribution!
`www: map of DM in cluster`

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 → 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

→ acts like stars in galaxy

should be seen with galaxies

If no dark matter but modified gravity

most gravity where most ordinary matter:

→ should see gravity source with intracluster gas

www: Bullet Cluster

lensing data → gravitation source centered on galaxies

→ consistent with weakly interacting dark matter

→ not consistent with alternative gravity!

The General Theory of Relativity

1915: Einstein publishes General Theory of Relativity
a.k.a. **General Relativity**, a.k.a. **GR**
landmark intellectual achievement

keeps all key concepts from Special Relativity

- no absolute space, time
- light always moves at c , matter $< c$
- mass is form of energy
- causality: no particles, signals, info travel $> c$

but now fully includes gravity: **GR is the modern theory of gravity**

Key GR Idea I:

equiv principle \rightarrow gravity affects all objects the same

\rightarrow gravity is not a force but a property of space & time!

but gravity source is matter, so:

GR is theory connecting matter, space, and time!