Astro 406

Lecture 14

Sept. 27, 2013

Announcements:

- **PS 4 due now**
- **PS 5 due next Friday**
- ASTR 401: introduction draft due Monday

Last time: Gravity 2.0 – **General Relativity** (“GR”)

*Q: what is the Equivalence Principle?*

*Q: how do you explain Galileo’s “Tower of Pisa” results using Equiv. Princ. and the rocket thought-experiment?*

*Q: other GR predictions based on rocket experiment?*

*Q: 2-body problem– Newton vs Einstein explanations?*

Rocket experiment:

- dropped objects: const. speed in inertial frame
  but seen to accelerate in rocket frame
  $\to$ interpret as freefall due to gravity field $g = a_{\text{rocket}}$
- light bending
- upgoing (downgoing) photon seen to redshift (blueshift)

But by equivalence principle:
must find *same result due to gravity*, so:

⋆ gravity bends light rays

**gravitational lensing**

⋆ observers in basement see blueshift of attic photons!
and observers in attic see redshift of basement photons!

**gravitational redshift/blueshift**

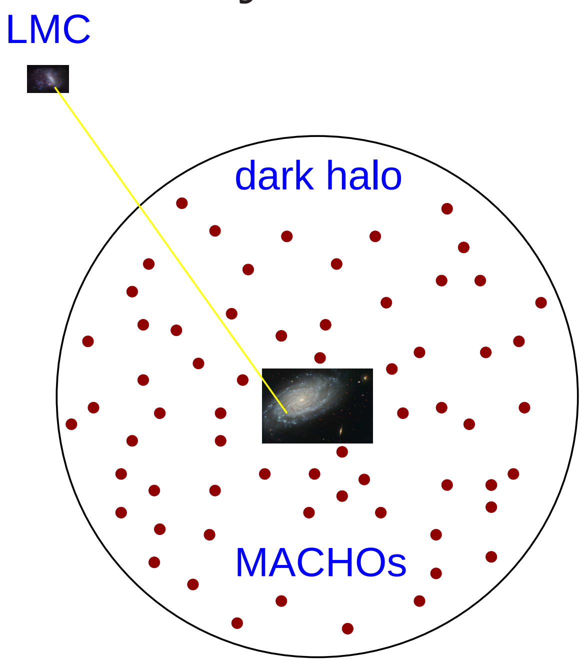
# Gravitational Microlensing

if Milky Way dark matter takes the form of
MAssive Compact Halo Objects (MACHOs)
that is: low-mass $\star$, white dwarfs, neutron stars, black holes
then:

- MACHOs orbit our galaxy and fill its halo
- and will act as gravitational lenses

How to detect?
look *through* the DM halo
at *external light sources*, i.e., galaxies of stars
and see if MACHOs cause lensing in background starlight

Geometry sketch:




If MACHO (mass $m$) lens

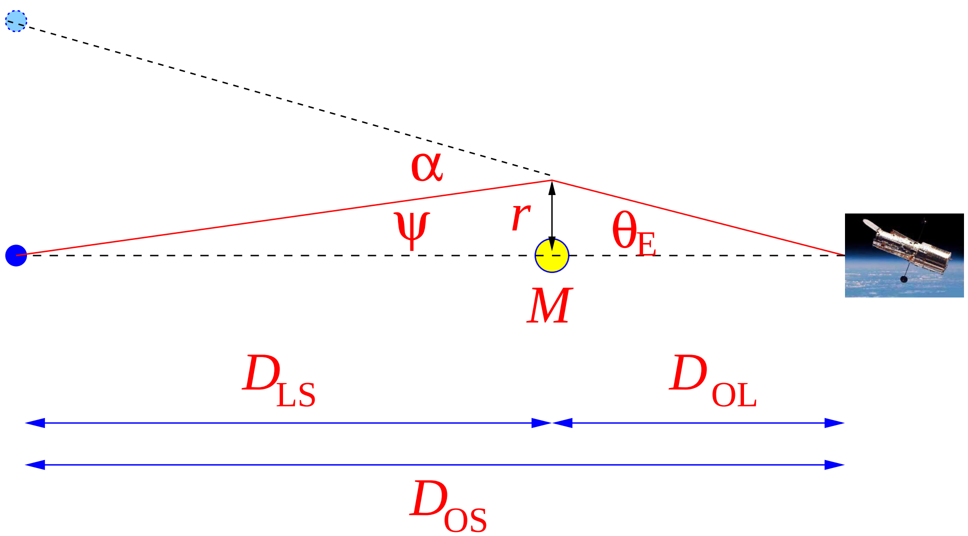
lies exactly in line of sight to source

*Q: what does observer see?*

If perfect source-lens-observer alignment:

observer sees "Einstein ring,"

angular radius $\theta_E$

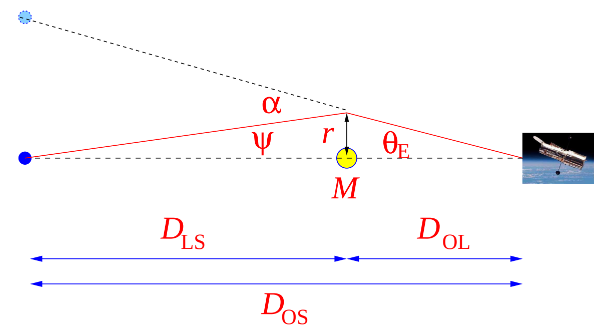



note that $\alpha = \theta_E + \psi$ *Q: why?*

combine usual trigonometry

$$r_{\mathsf{E}} = D_{\mathsf{LS}} \sin\psi \approx D_{\mathsf{LS}}\psi \qquad (1)$$

$$\phantom{r_{\mathsf{E}}} = D_{\mathsf{OL}} \sin\theta_{\mathsf{E}} \approx D_{\mathsf{OL}}\theta_{\mathsf{E}} \qquad (2)$$




with Einstein

$$r_{\mathsf{E}} = \frac{4Gm}{c^2\alpha} \qquad (3)$$

eliminate $r$ and solve:

$$\theta_{\mathsf{E}} + \frac{D_{\mathsf{OL}}}{D_{\mathsf{LS}}}\theta_{\mathsf{E}} = \frac{4Gm}{c^2 D_{\mathsf{OL}}\theta_{\mathsf{E}}} \qquad (4)$$

$$\theta_{\mathsf{E}}^2 = \frac{4Gm}{c^2}\frac{D_{\mathsf{LS}}}{D_{\mathsf{OS}}D_{\mathsf{OL}}} \qquad (5)$$

so angular radius of Einstein ring is:

$$\theta_{\mathrm{E}} = \sqrt{\frac{4Gm}{c^2 D_{\mathrm{eff}}}} \tag{6}$$

where $D_{\mathrm{eff}} = D_{\mathrm{OL}} D_{\mathrm{OS}} / D_{\mathrm{LS}}$

that was special case (perfect alignment)
but sets characteristic angular scale
for general (non-aligned) case
$\Rightarrow$ rule of thumb: lensing is significant
if line of sight comes within
ring "physical" radius $r = D_{\mathrm{OL}} \theta$

if source-lens-observer not aligned: not ring, but

- ring $\rightarrow$ multiple images
- flux amplification

## Microlensing Observables: Quest for the Ring?

if MACHOS are there, what signal do we expect?

for a $1M_{\odot}$ compact object in our halo
Einstein radius is $r_{\mathrm{E}} \simeq 1$ AU
corresponding to angular radius

$$\theta_{\mathrm{E}} = \frac{r_{\mathrm{e}}}{D_{\mathrm{OL}}} = 3 \times 10^{-5} \text{ arcsec } \left(\frac{30 \text{ kpc}}{D_{\mathrm{OL}}}\right) \tag{7}$$

available angular resolution:
Hubble diffraction limit: $\theta_{\mathrm{diff}} \sim 0.06 - 0.10$arcsec
ground-based telescopes: usually much worse (atm seeing)
adaptive optics in near IR: $\theta_{\mathrm{diff}} \sim 0.03 - 0.06$arcsec

∞ *Q: implications?*
*Q: so how do we detect MACHO lensing?*

# Microlensing Observables: Amplification

MACHO Einstein rings too small to see!
unresolved on sky with current technology
$\rightarrow$ lensing image distortion not available as an observable

don't give up! lensing also causes flux *magnification*
great news! brightness is easiest thing to measure

thus: to maximize chance of seeing MACHOs via lensing

- need *many* background objects as sources
- need sources to be pointlike *Q: why?*
  *Q: good candidates to target as sources?*
- but must be sure brightness has been amplified by lensing!
  *Q: how? hint: what are MACHOs doing in halo?*
  *Q: what signal does this lead to?*
  *Q: what could mimic this signal?*
  *Q: how can we reject such "noise"?*

# Microlensing Experiments

pointlike sources have cleanest amplification signal
$\rightarrow$ use *stars*, not gas clouds, galaxies, etc
need a large number of individually resolved stars
in small patch of sky for efficient monitoring
$\rightarrow$ look for nearby galaxies

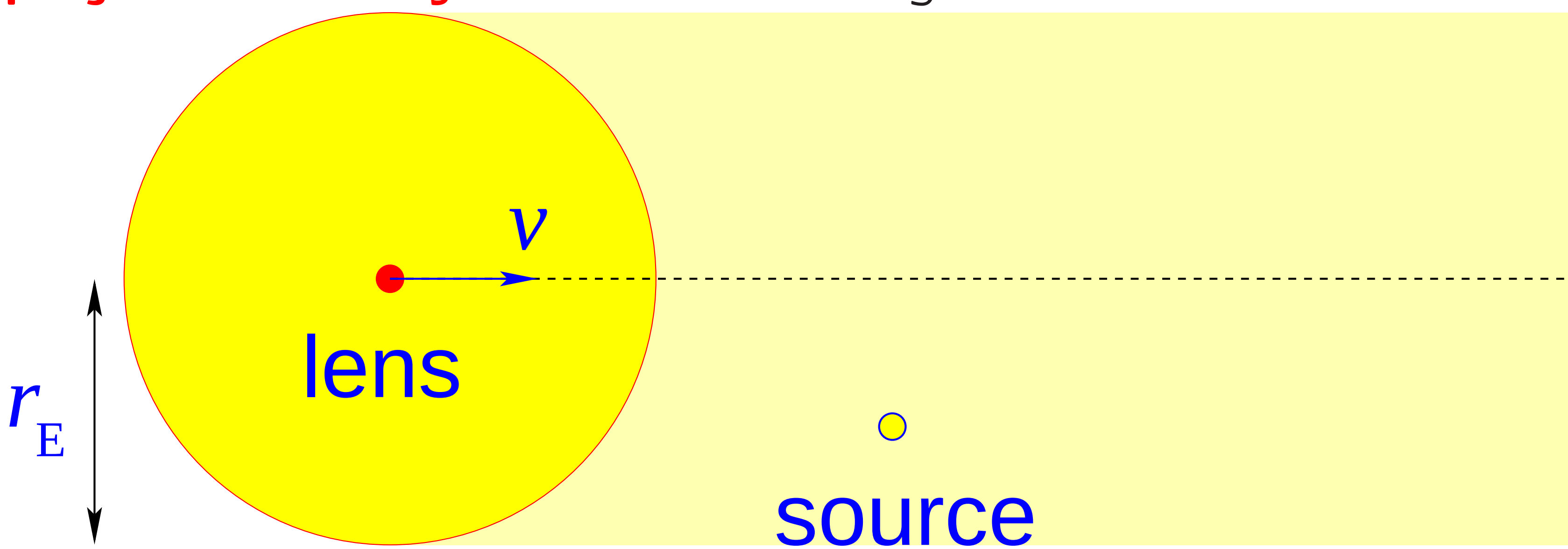
target of choice: "baby" galaxy in our backyard
Large Magellanic Cloud `www: LMC`
Monitor LMC stars at distance $D_s = D_{\rm LMC} \approx 50$ kpc

lenses, like all other objects, feel gravity $\rightarrow$ move

- lens speed roughly $v_c \approx 220$ km/s
- distance to source sightline changes with time
- $\rightarrow$ amplification changes with time
  in very specific, predictable way

# Microlensing: Sky View

**projected on sky**: lens Einstein ring transits source




*Q: what would it look like if you could resolve it?*

*Q: what will it look like if you can't?*

*Sketch: brightness vs time*



*Q: what sets maximum amplification? Q: what sets timescale?*

`www:  microlensing animation`

- symmetric in time

- timescale:

*Q: what sets? look at diagram...*
time to cross ring diameter:
$2r_{\mathsf{E}} = v_c t \rightarrow t = 2r_{\mathsf{E}}/v_c$
where $r_{\mathsf{E}} =$ Einstein ring radius above

- effect is same for all colors:

all wavelengths move at $c$, fall same way

max amplification:
depends on min lens distance to sightline
$\rightarrow$ random! no useful info about lens

## iClicker Poll: How MACHO is our Halo?

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 Dark Matter Searches

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

`www: MACHO lightcurve`

$\sim 12$ events seen!

beautiful confirmation of microlensing as a real phenomenon!

lightcurves are General Relativity movies!

Data:

- number of lensing events
- timescales $\rightarrow$ lens mass $m$

*Q: what does each tell?*

*Q: what do the two together give?*

# Microlensing Results

Data:

- # events → # lenses
- timescales → lens mass $m$

together: total MACHO mass in halo!

but – where are lenses: halo or LMC?

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

total mass $\sim 8 - 20\%$ of dark halo

however: available evidence all suggests lenses are

- in LMC itself, or
- in MW thick disk

`www: binary lens lightcurve`

`www: HST detection of lens from 1993`

No compact objects definitively found in MW halo
$\Rightarrow$ no compact objects exist in halo?

`www: 2007 update to microlensing results`
*Q: implications for Milky Way dark matter?*

# Microlensing and Dark Matter

Microlensing experiments tell us :

1. Milky Way dark halo mostly (entirely?) **not** MACHOs
2. stellar-mass black holes, neutron stars, white dwarfs, Jupiters, and brown dwarfs *totally ruled out!*
3. Milky Way dark matter must be something else!

# 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 already eliminated many favorite candiates!
and the most promising "conventional" candidates

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