Astro 350

Lecture 22

March 11, 2022

Announcements:

Paper Topic and Abstract due today

- **Discussion 6 due after break**

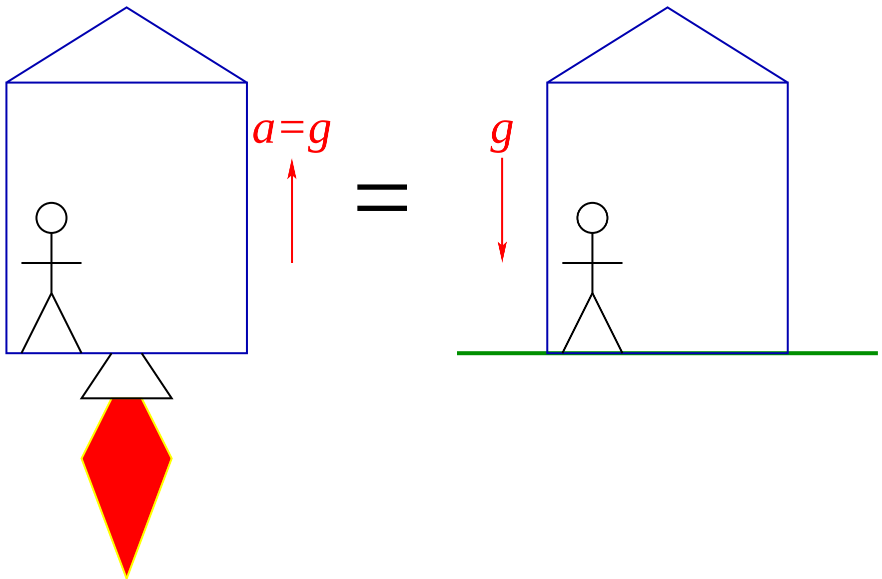
Last time: generalizing relativity

Einstein's equivalence principle

Q: what is it? What are its consequences?

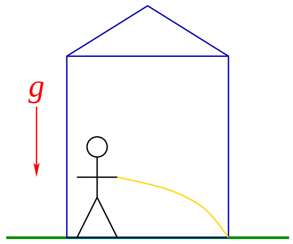
Einstein's Equivalence Principle:

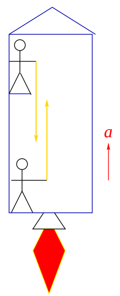
in a closed room, no experiment can distinguish (non-gravitational) acceleration from gravity



Einstein's equivalence principle predicts:

- gravity bends light rays:
  gravitational lensing
  confirmed in 1919 eclipse!
- gravity leads to time dilation
  and **gravitational redshifting**
  confirmed in laboratory!





Gravitational Lensing and Dark Matter

gravitational lensing reveals presence, strength of gravity whether or not the gravitating objects emit light!
$\rightarrow$ 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 $\rightarrow$ infer presence, amount, distribution of unseen mass!

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

Searching for Milky Way Dark Matter: MACHOs

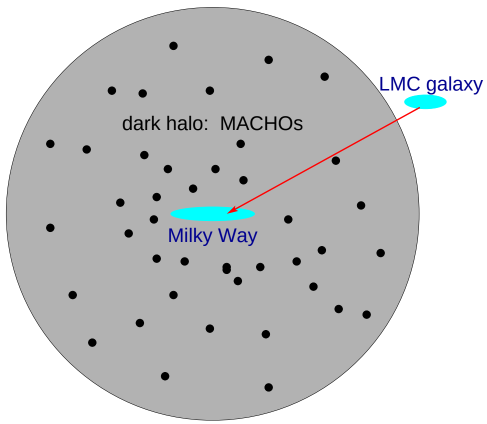
Recall: "conventional" dark matter candidates include
"compact" star-like objects:
brown dwarfs, white dwarfs, neutron stars, black holes

if dark matter = MAssive Compact Halo Objects (**MACHO**s)
then these all act gravitational lenses

experiment:
look for bending of light coming through our dark halo

Searching for Lensing from MACHOs

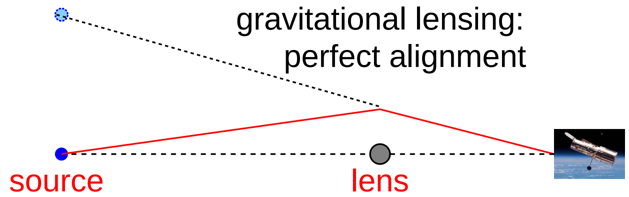
- use nearby galaxy (Large Magellanic Cloud) as background light source
- monitor lotsa LMC stars (i.e., millions)



recall: DM always in motion

MACHO sometimes wanders close to line of sight towards a LMC star

Q: What if MACHO exactly in sightline?
if near sightline?



Gravitational Microlensing

if MACHO exactly aligned

- all incoming rays bent equally $\rightarrow$ see a ring
  the "Einstein ring"
- more light deflected towards observer $\rightarrow$ *total flux higher*
  $\rightarrow$ *brightness amplified*

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?

when lens distance found:

- located in LMC itself
- or located in the disk of our own galaxy

upshot: observed lenses are stars in the LMC or Milky Way

no compact objects found in dark halo

MACHOs at most $\sim 20\%$ of dark halo, definitely not 100%!

compact objects make up little to none of dark matter

But: microlensing remains a powerful tool, now used for planet searches!

Lineup of Dark Matter Suspects

~~hot gas~~ ~~cold gas~~	diffuse ordinary matter: gas
~~black holes~~ ~~neutron stars~~ ~~white dwarfs~~ ~~brown dwarfs~~ ~~planets: “Jupiters”~~	clumpy ordinary matter: compact objects = dead and failed stars
neutrinos relic particles from big bang	diffuse matter: exotic particles

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
$\Rightarrow$ direct probe of dark matter distribution!

Status: already done for tens of objects
conclude: total gravitating mass $\gg$ visible mass
$\rightarrow$ 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 $\rightarrow$ 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

→ 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:
equivalence 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!

If gravity isn't a force, what is it?
hint: already saw that gravity "warps" time

Key GR Idea II:
according to GR, gravity is "curvature" of space & time!?!
i.e., *gravity "warps" both space and time*
$\rightarrow$ spacetime "curved"
- gravitational redshifting, time dilation, light bending are all manifestations of this
- curved orbits of particles due to gravity in GR are really responses to spacetime curvature!
- note: gravity = geometry! harkens back to Greeks!

GR Slogans (T-Shirt/bumper sticker/tweet/tattoo):
- matter tells spacetime how to curve
- curvature tells matter how to move

these ideas are beautiful and powerful
but also not (for most people) intuitive or trivial

best way to learn is from examples
will focus on two key examples of relativistic spacetimes

- example #2: the Universe
  rest of the course after today
- today: example #1....

Escape Speed

to launch object from Earth $\rightarrow$ at rest at ∞:
need final state to have $E_{\rm tot} = 0$:

$$E_{\rm tot} = 0 = \frac{1}{2}mv^2 - \frac{GMm}{R} \tag{1}$$

$\rightarrow$ need launch with $v_{\rm esc} = \sqrt{2GM/R}$ **escape speed**

Q: what if launch with $v > v_{\rm esc}$? with $v < v_{\rm esc}$?

if launch with $v = v_{\rm esc}$, then
$E_{\rm tot} = 0$, and $KE = PE$ always
particle escapes, but at rest when far away ("∞")

If launch with $v > v_{\rm esc}$ then $KE > PE$
$\rightarrow$ when far away, $PE \rightarrow 0$ but still $KE \neq 0$
$\rightarrow$ particle escapes, still moving when far away
$\rightarrow$ $E_{\rm tot} = KE + PE > 0$ $\rightarrow$ particle "unbound"

If launch with $v < v_{\rm esc}$ then $KE < PE$
$\rightarrow$ at some distance, slow down to $v = 0$ $\rightarrow$ $KE = 0$
but still $PE < 0$ $\rightarrow$ can't go farther
$\rightarrow$ turn around, fall back: particle "bound"
$\rightarrow$ $E_{\rm tot} < 0$: not enough energy to escape

Can predict the future: just ask what is $v_{\rm launch}$ vs $v_{\rm esc}$?

- if $v_{\rm launch} < v_{\rm esc}$: object falls back (pop fly)
- if $v_{\rm launch} \geq v_{\rm esc}$: object escapes (rocket)

Black Holes

Laplace (1790's):
escape velocity $v_{\rm esc} = \sqrt{2GM/R}$
What if star has mass M and radius $R < 2GM/c^2$?
then $v_{\rm esc} > c$!
light cannot escape! $\rightarrow$ black hole

Wrong argument (Newtonian gravitation) ...but right answer!

General relativity predicts existence of black holes
and their properties

Have a good break!