Astro 350
Lecture 21
March 9, 2022

Announcements:

- **Discussion 5 due today** video added for inspiration
- no HW this week, but:
  Paper Topic and Abstract due Friday
  info on Canvas

Last time: special relativity
Q: what's special about it?

today: begin to generalize

Special Relativity Executive Summary

⋆ Special Relativity:
includes high-speed motions (near c)
but doesn't include gravity, hence is a "special case"

⋆ Space & Time
apparent distances, time intervals, simultaneity
not universal but depend on relative motion

⋆ Energy & Mass
can be converted into each other, mass is form of energy
to accelerate object to $v \to c$ requires $E \to \infty$: impossible!

⋆ Cause & effect ("causality")

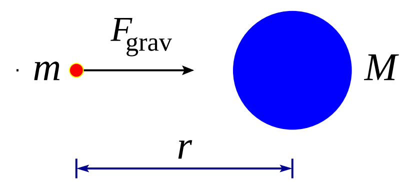
- information cannot travel instantaneously
- actions are "local" in the sense that
  effects transmitted over finite distance in finite time

What About Gravity?

Special relativity beautifully accommodates light
(and all of electricity & magnetism)
but ignores gravity

How to include? consider Newton gravity
force law

$$F_{\text{grav}} = \frac{GMm}{R^2}$$

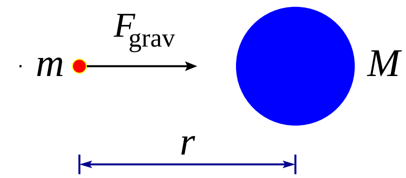


gravity force due to mass M
depends on present distance R
and spreads over all space
so $F \neq 0$ for any $R < \infty$

ω Einstein sez: this is totally illegal! an unmitigated disaster!
Q: why? what's the problem?

Newton: mass M force on *any* mass m

determined by *present* distance R



$$F_{\text{grav}} = \frac{GMm}{r^2}$$

implies that *if M moves* and thus r *changes:*

$\rightarrow$ *gravity force changes instantaneously* over all space!

Einstein sez: *this is totally illegal! an unmitigated disaster!*

no signal–including gravity–can move faster than c!

Big Al concludes: *verboten! gotta be wrong!*

major changes needed!

The Equivalence Principle Revisited

How to go about revising gravity? Where to start?

Recall Galileo atop the Tower of Pisa:
gravity $\rightarrow$ all objects move (accelerate) the same way in free fall
regardless of object mass, shape, composition not new result,
but different explanations...

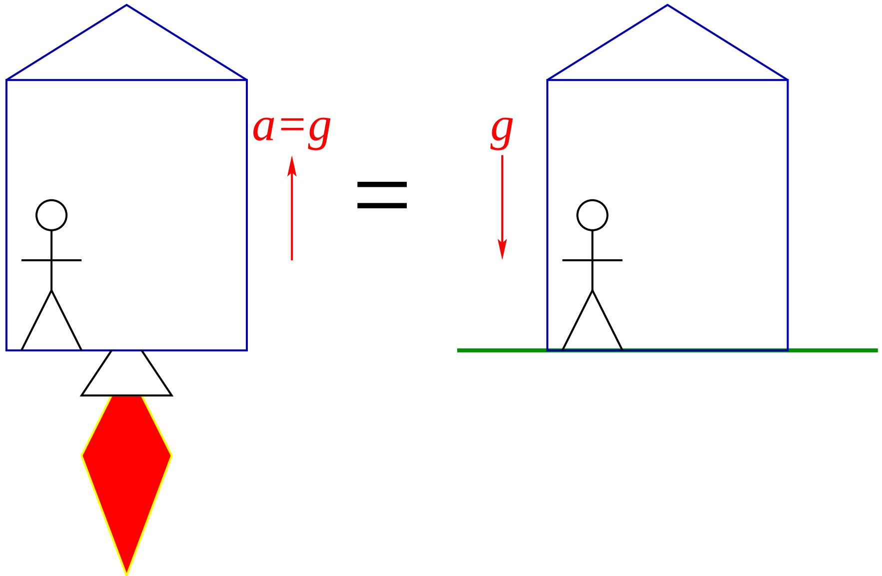
Newton sez:
it just so happens that gravitational mass
the way objects "feel" or "couple to" gravity $F_{\text{grav}} = m_{\text{grav}} g$
is always exactly the same as inertial mass
the way objects resist acceleration $a = F/m_{\text{inert}}$

Einstein sez:
too amazing to be a coincidence, must be deeper...

Einstein's Equivalence Principle

Einstein notes: Gravity causes acceleration in "democratic" way: all objects accelerate the same

Einstein's Equivalence Principle:
in a closed room, no experiment can distinguish (non-gravitational) acceleration from gravity



Note similar "feel" to Einstein's Relativity Principle

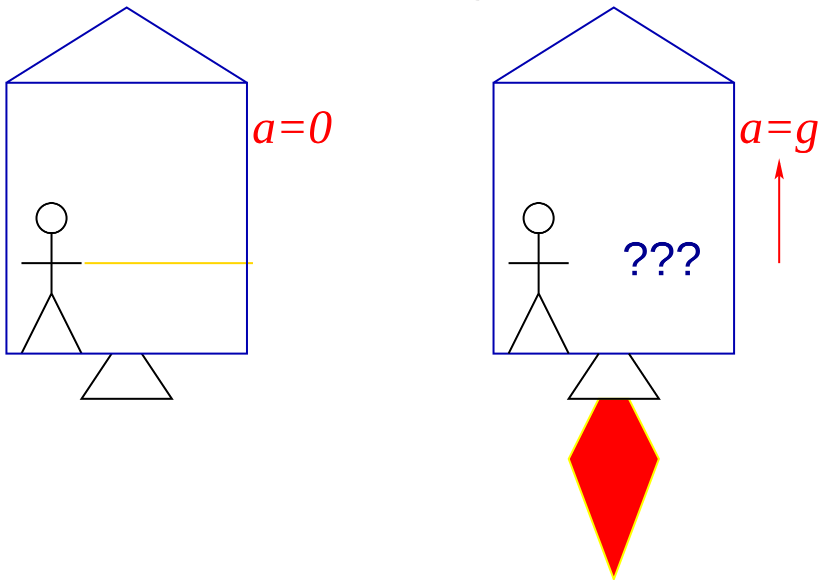
Experiments Inside an Accelerating Rocket

Consider a rocket in otherwise empty space

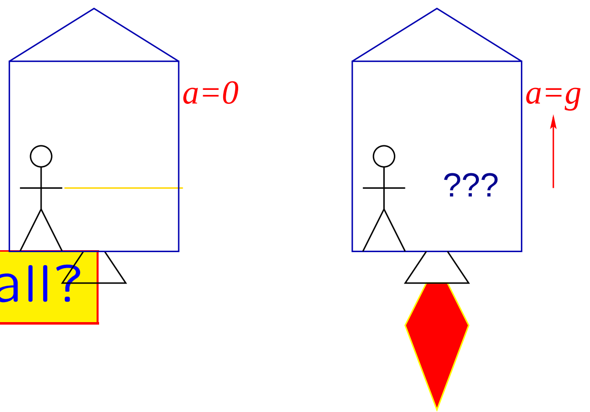
- that is, no gravity!
- moving with constant acceleration a

Experiment:

Astronaut Bart, standing on floor of rocket, has flashlight points horizontally, shines towards wall



iClicker Poll: Light Beam in Accelerating Rocket



in rocket with constant acceleration
flashlight at height h
aimed horizontally

At what height will beam hit the far wall?

A at same h

B higher than h

C lower than h

∞ hint: easier to think about when looking at experiment from non-accelerating viewpoint `www: illuminating animation`

key ideas:

light takes time to move across spaceship

during which, spaceship accelerates $\rightarrow$ gains v, moves vertically

in non-accelerating frame, see that

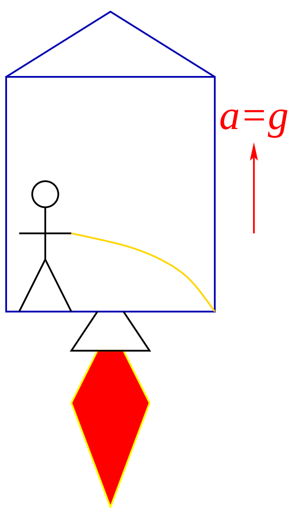
- light path is straight (horizontal) line
- spaceship vertical motion $\rightarrow$ far wall moved higher

$\Rightarrow$ light hits below where aimed in accelerating frame (i.e., according to Bart):

agrees that light hits below where aimed, and concludes

⋆ light ray deflected

⋆ entire light path bent (in fact, a parabola!)



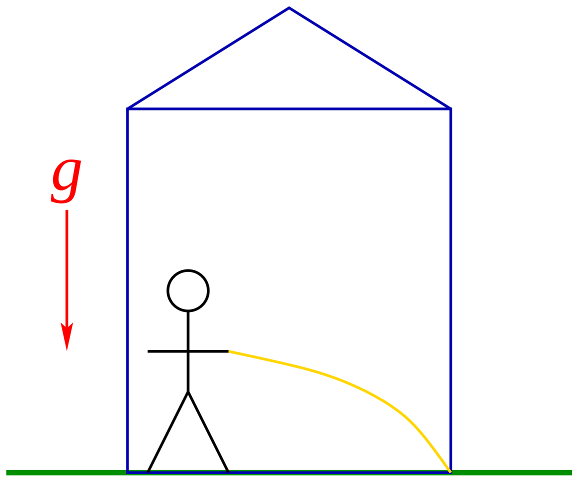
Q: but what does this mean, according to Al's Equiv Principle?

Gravitational Lensing

In accelerating spaceship: light rays bent

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

★ gravity bends light rays
★ light "falls" too!
★ gravitating objects "attract" light rays
  distort light paths differently depending on
  how strong the gravity over each path



gravitating objects distort passing light
leads to distorted images of objects behind gravity sources

gravitational lensing

- observable effect, and in fact
- an increasingly powerful tool!

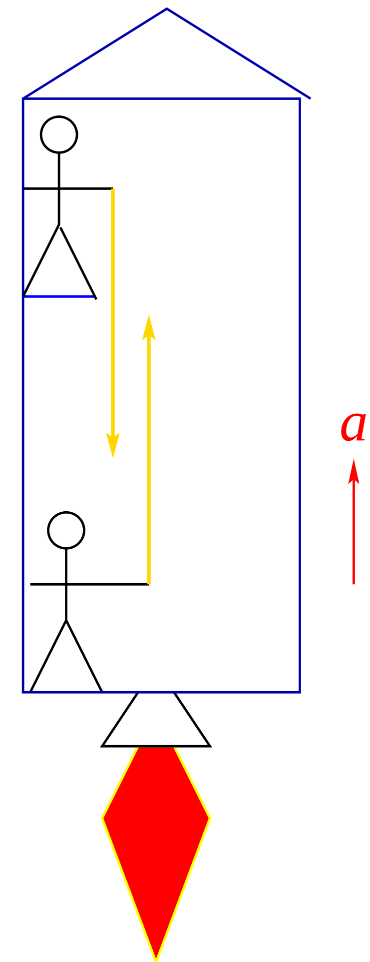
Accelerating Rockets & Clocks

consider "light clocks" installed in spaceship

- manufactured identically in Switzerland
- each emits light pulse every Δt microseconds

clocks and astronauts stationed
in attic (Abe)
and basement (Bart)

Q: if rocket not accelerating: $a = 0$
do A & B see the other's clock tick at same rate as his own?



Now fire rockets

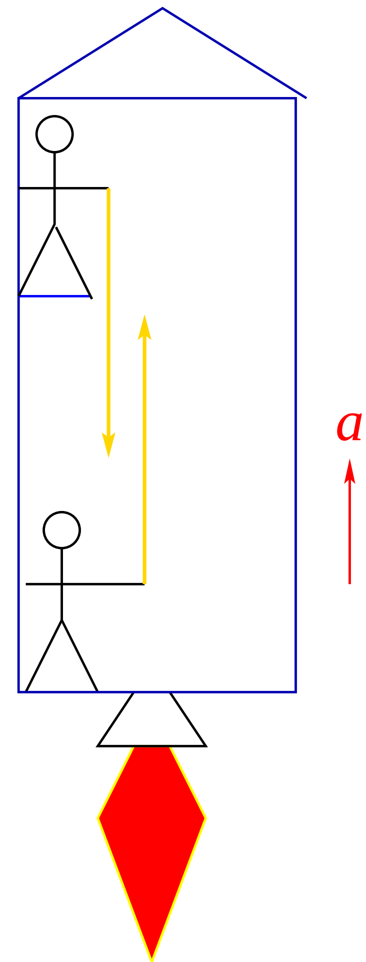
$\rightarrow$ spaceship has constant acceleration $a = g$

Compared to non-acceleration light travel time

Q: does the downgoing flash take longer/shorter/same time?

Q: does the upgoing flash take longer/shorter/same time?

Q: and by the equivalence principle...?



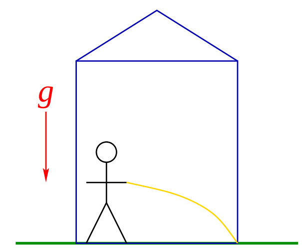
Time Warp: Gravitational Time Dilation

Clocks in accelerating spaceship:
Bart (basement observer) accelerating towards downgoing light
  sees it sooner than if $a = 0$
  B sez A's clocks running fast
Abe (attic) accelerating away from upgoing light ray
  sees it later than if $a = 0$
  A sez B's clocks running slow

But equivalence principle says: gravity must do same thing! So...

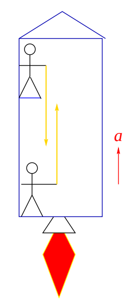
⋆ clocks in basement appear to run slower
    than clocks in attic!
  in fact, attic clocks appear faster by amount
  $\Delta t = t_{\text{attic}} - t_{\text{basement}} = gh^2/c^3$ a tiny effect unless g huge
⋆ time "warping" but now due to gravity:
  "**gravitational time dilation**"
⋆ gravity influences "flow" of time!

Testing Einstein



Einstein's equivlaence principle predicts:

- gravity bends light rays
- gravity leads to time dilation
- also: **gravitational redshifting**
  upgoing light redshifted
  downgoing light blueshifted



Q: how to test these ideas?

Lab Tests of Gravitational Redshifting

prediction:
upgoing photons emitted from basement, wavlength $\lambda_{\rm emit}$
will be redshifted when detected in attic: $\lambda_{\rm obs} > \lambda_{\rm emit}$

to test: measure wavelength of upgoing photons
in laboratory attic

challenge: wavelength shift is **tiny!**
must meausre exremetly precisely

Pound & Rebka (1960): experiment performed!
from basement to attic of tower at Harvard

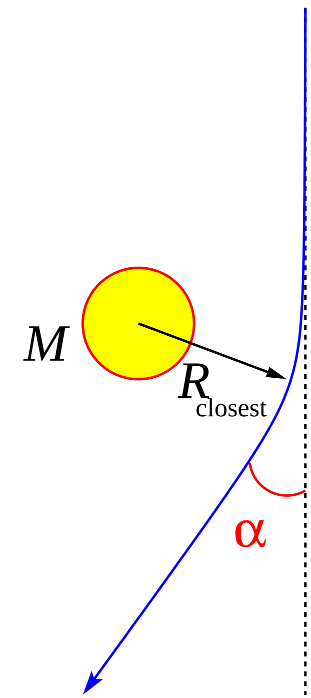
- used ultra-sensitive Mössbauer effect to search for λ change
- *redshift detected!* exactly at level predicted by Einstein theory!

but by then Einstein's ideas had already passed another test...

Light Bending: The Sun

In principle: *all* gravitating objects bend light
including you, me, the earth...
In practice: need strong gravity source to create
effect large enough to observe

Einstein (1915) devised first test: the Sun
- Sun's gravity deflects starlight rays
- the stronger the gravity along the path
  the bigger the deflection
  ...in fact, bending angle $\alpha = \dfrac{4GM_{\odot}}{c^2 R_{\text{closest}}}$



$\Rightarrow$ biggest effect for starlight just "grazing" edge of Sun
Q: why is this technically challenging to see?
Q: how to get around the problem?

1919 Eclipse: Give it up for Big Al!

Problem: Sun's glare obscures surrounding starlight
Solution: block glare with eclipse!

1919: total solar eclipse in Southern hemisphere
expedition led by Sir Arthur Eddington
⋆ starlight bent! Woo hoo!
⋆ relativistic gravity confirmed!
⋆ Einstein an instant celebrity
`www: NYTimes headlines`

Now tested many times, and very accurately
- all starlight bending experiments confirm Einstein!

Moreover, once established, grav lensing is a very powerful tool
Q: why would it be useful?

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!

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

Searching for Milky Way Dark Matter: MACHOs

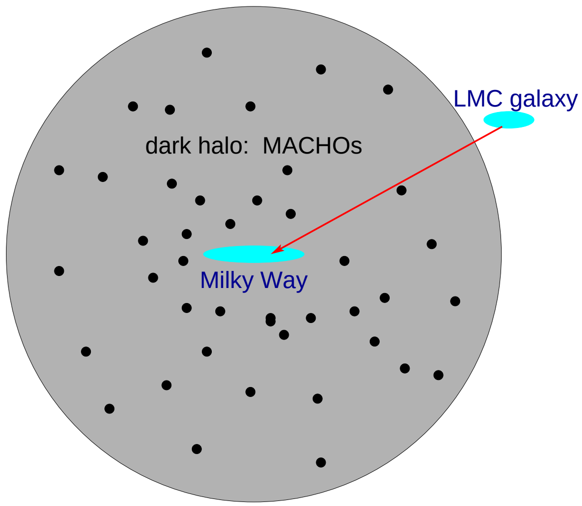
Recall: "conventional" dark matter candidates include
"compact" star-like objects:
brown dwarfs, white dwarfs, neutron stars, black holes

if dark matter = MAssive Compact Halo Objects (**MACHO**s)
then these all act gravitaional 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 (here, MACHOs) in motion: $v \approx 200$ km/c

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

Q: what will happen–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 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`

$\sim$ 12 events seen! gravitational lensing reconfirmed!

but – where are lenses: halo or LMC?

if halo lenses: $m \sim 0.5 M_\odot$ 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

$\Rightarrow$ **no/very few compact objects in halo**

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

$\rightarrow$ 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!

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!