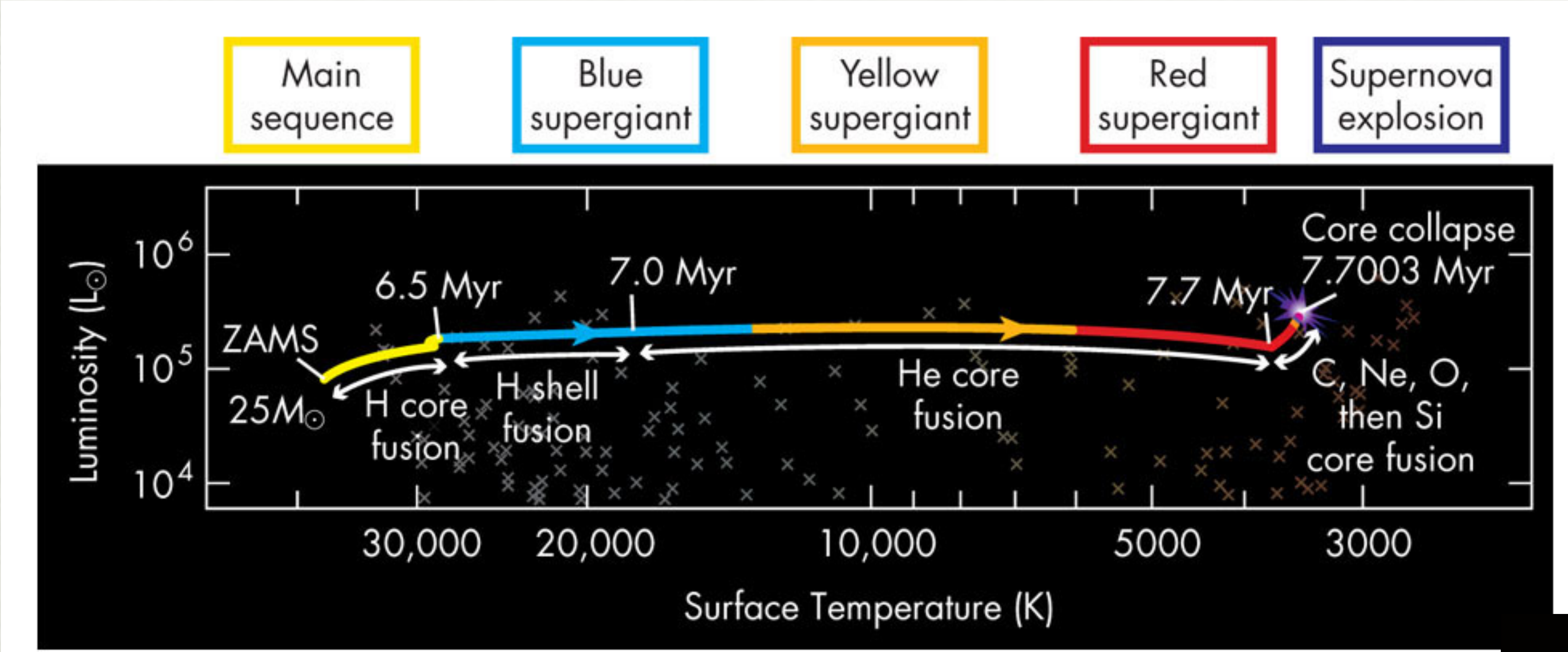
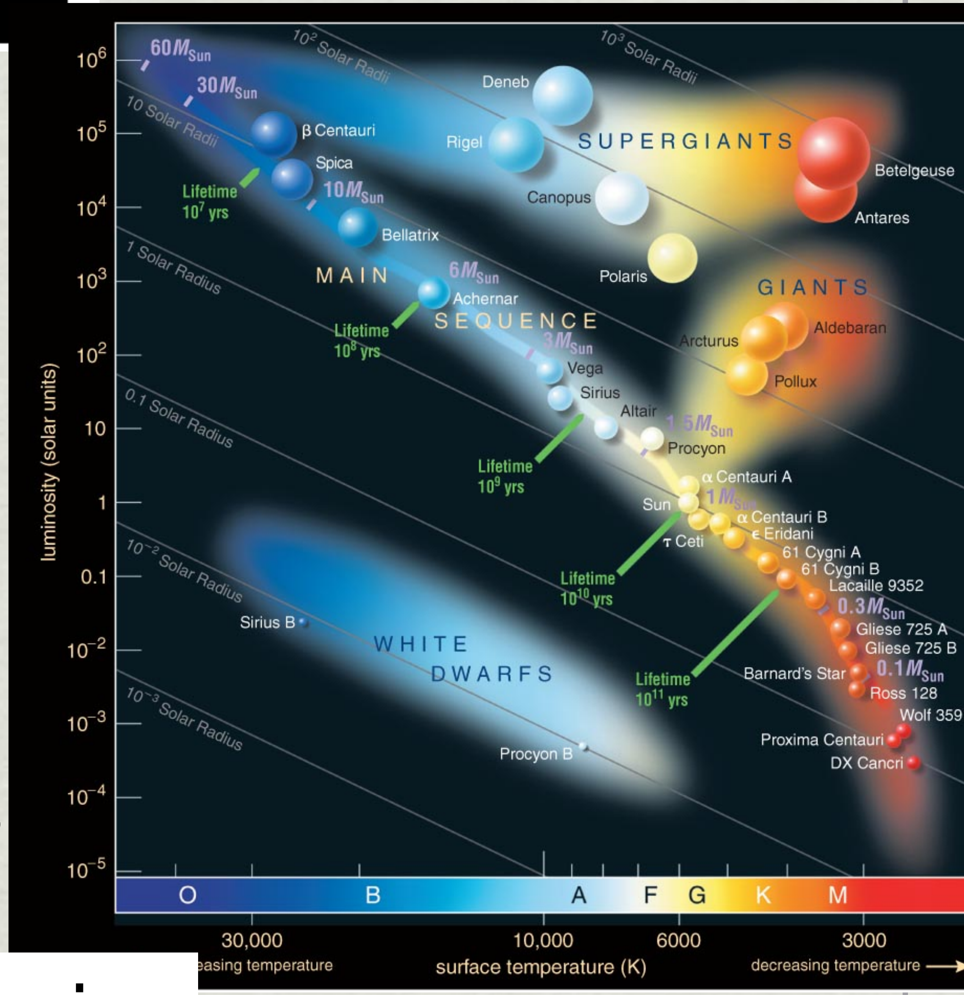
High Mass Stars: Post Main Sequence Evolution



Not enough time for the core to collapse far enough to become degenerate: New fusion reactions initiated before that can happen.

MS time (H core fusion): 6.5 million years
H-shell fusion: 0.5 million years
He core fusion: 0.7 million years
All the rest: 0.0003 million years = 300 years



Star ends as a core collapse supernova explosion

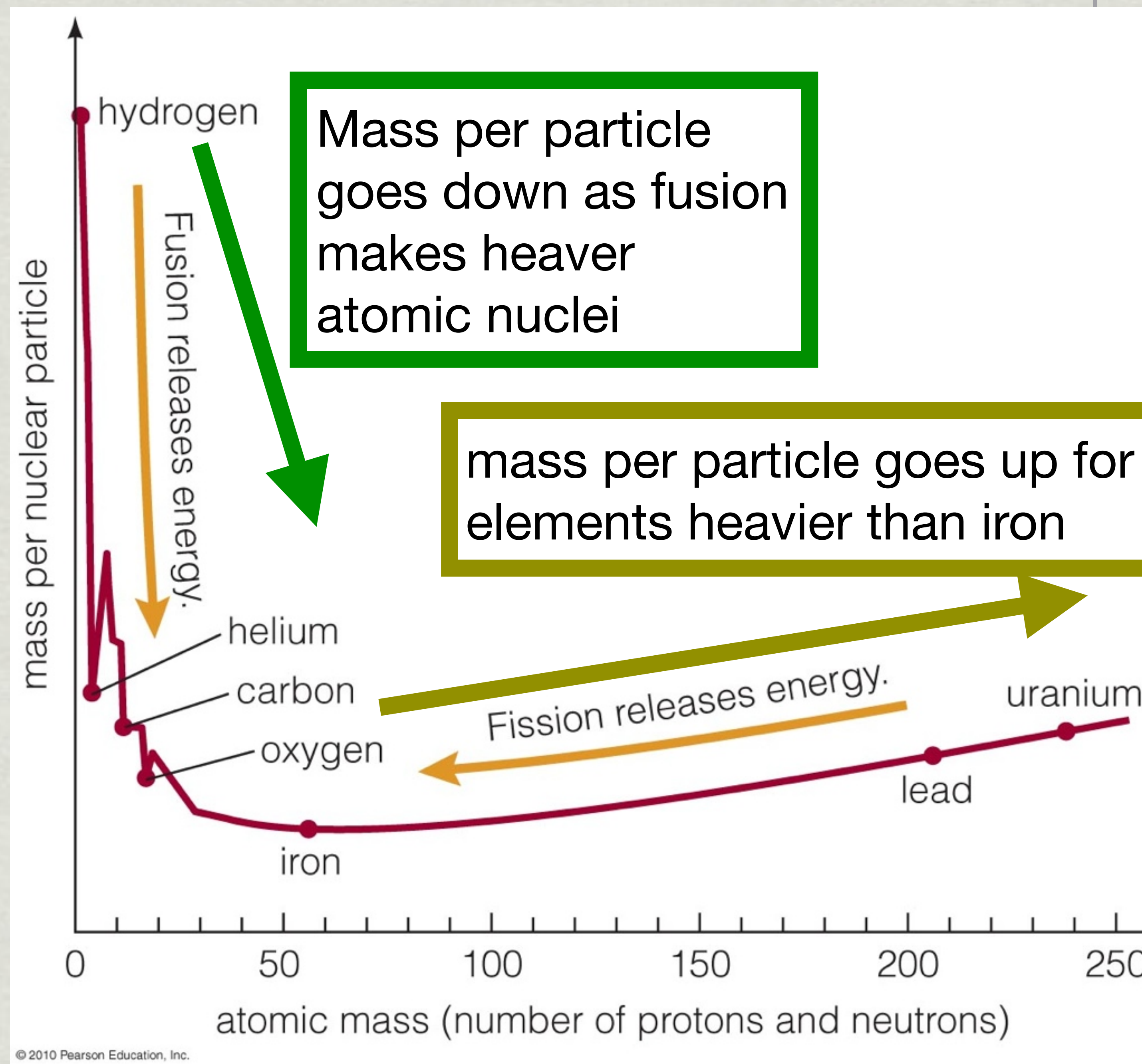
High Mass Stars: Post Main Sequence Evolution

Mass per particle (neutron, proton) in the nucleus increases for elements heavier than Fe.

Mass per particle of a lead nucleus > Mass per particle of an iron nucleus.

$\Delta m = \text{Mass}_{Fe} - \text{Mass}_{Pb} < 0$
No energy out by fusing nuclei to make lead!

How are these elements made? Put energy ***in*** during the explosions that end the lives of massive stars

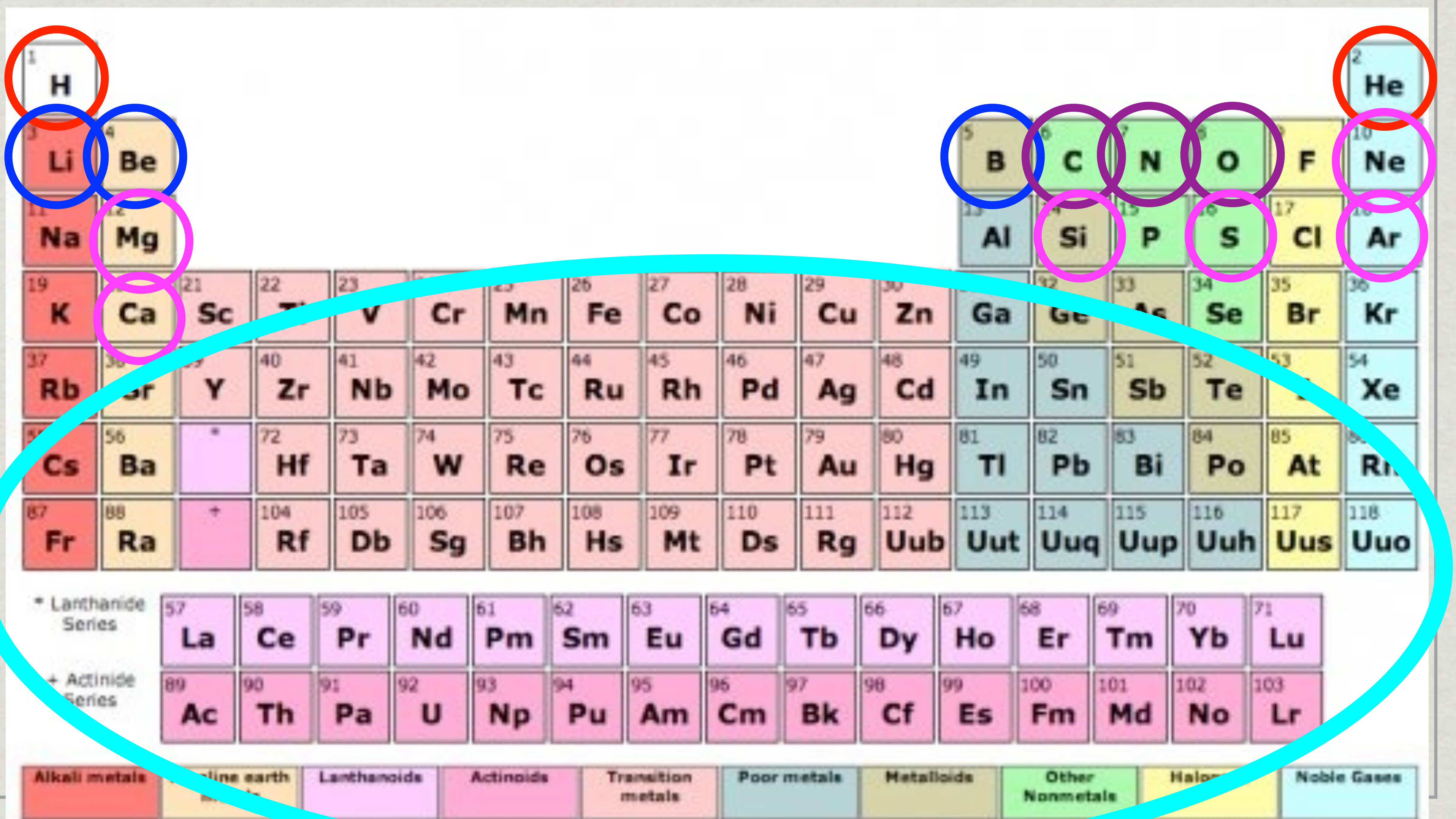


H, He, ... C...Fe...Ag...Pb...U → increasing number of particles in nucleus for elements in the periodic table

Ends of High Mass Stars: Core Collapse Supernovae

High energy, density in the explosion makes a heavy element factory.

Energy available to make elements heavier than iron



Other Kinds of Supernovae

White dwarfs normally end as inert cinders, like charcoal briquets.

They are the cooling He cores of low-mass stars no longer capable of doing nuclear fusion to make energy.

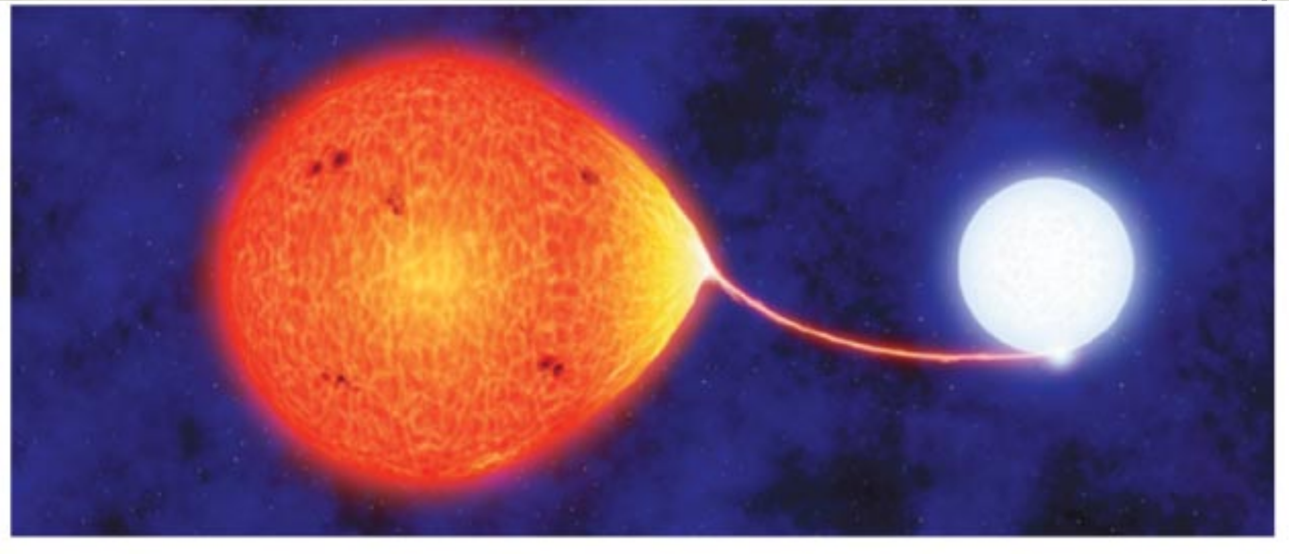
The core is held up against gravity by degeneracy pressure.

What if a white dwarf is part of a binary star?

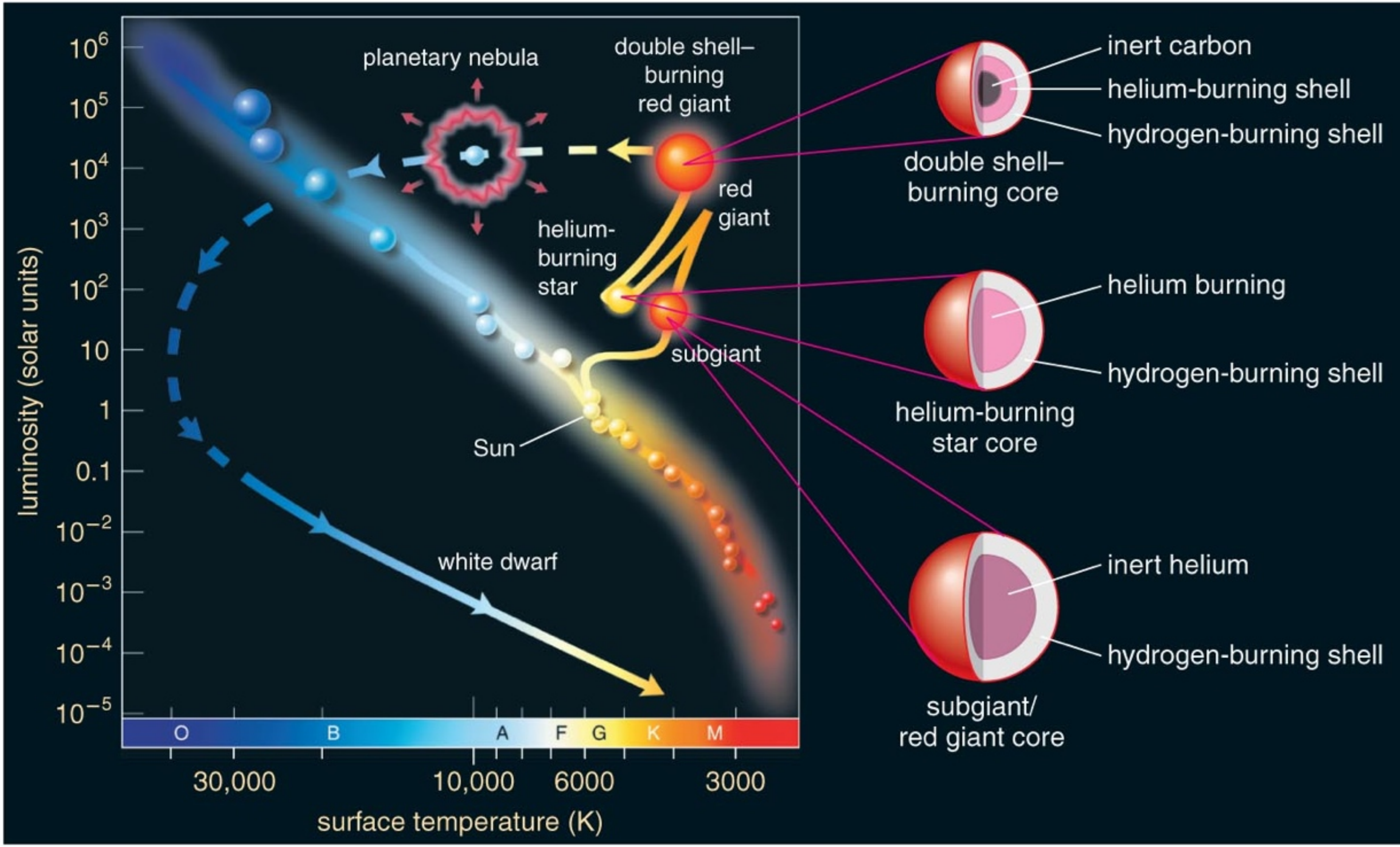
Other Kinds of Supernovae

The white dwarf's binary companion finishes burning H on the main sequence and becomes a red giant.

Its envelope expands.



Low Mass Stars: Post Main Sequence Evolution



Other Kinds of Supernovae

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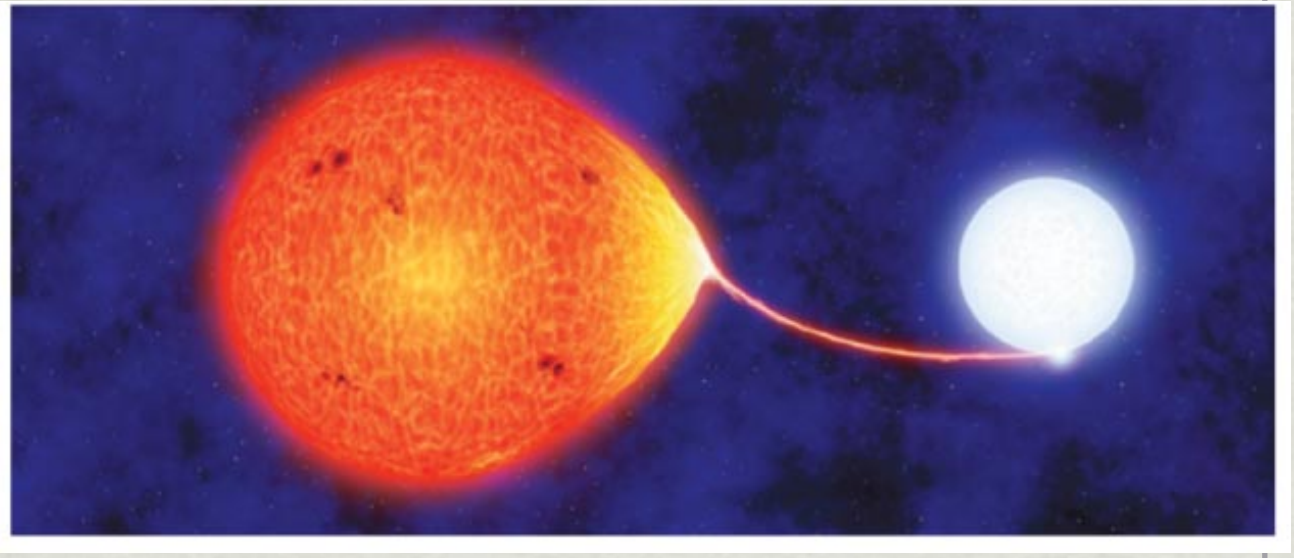


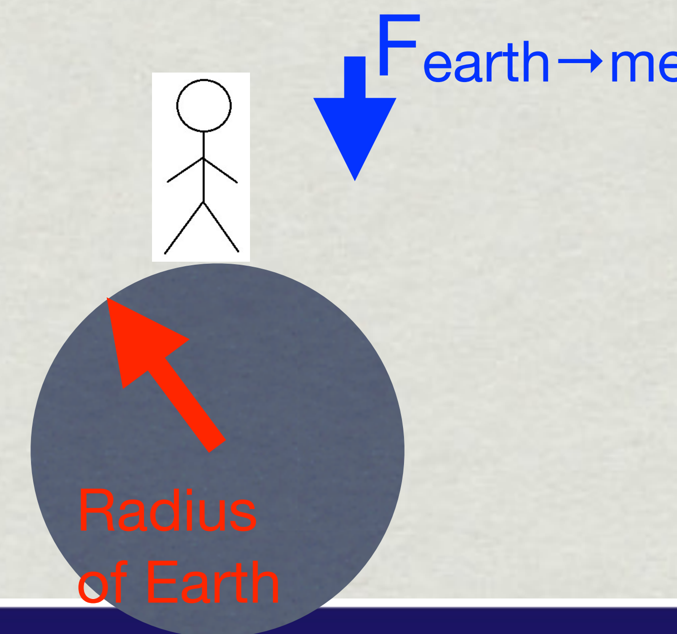
If the white dwarf star is nearby, its gravitational pull captures the envelope, and the white dwarf gains mass in a shell around the degenerate core

Other Kinds of Supernovae

The strong gravity at the surface of the white dwarf compresses the shell.

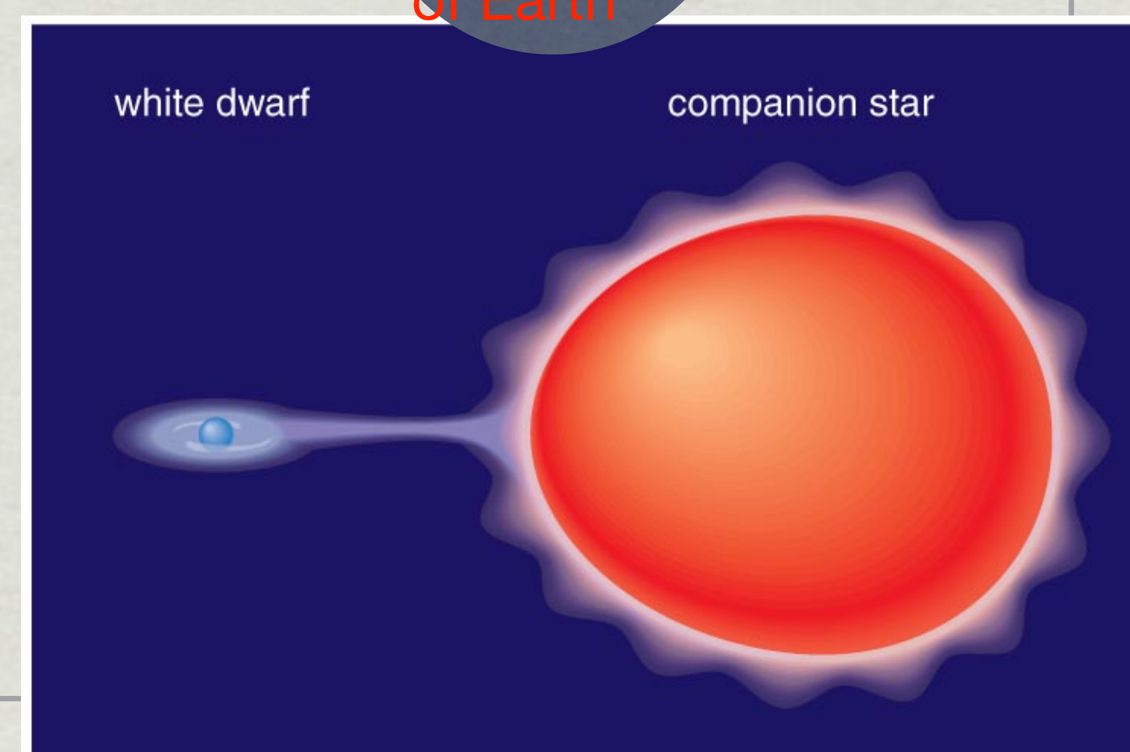
Remember: white dwarfs are very dense. Lots of mass in a small volume = small radius

Surface Gravity: $F_{earth \rightarrow me} = \dfrac{G\, M_{me}\, M_{earth}}{R^2_{earth}}$



Radiation from the still-hot white dwarf heats the shell of new material

The growing shell mass compresses the lower layers of the shell more. Like the white dwarf, degeneracy pressure takes over in the shell



Other Kinds of Supernovae

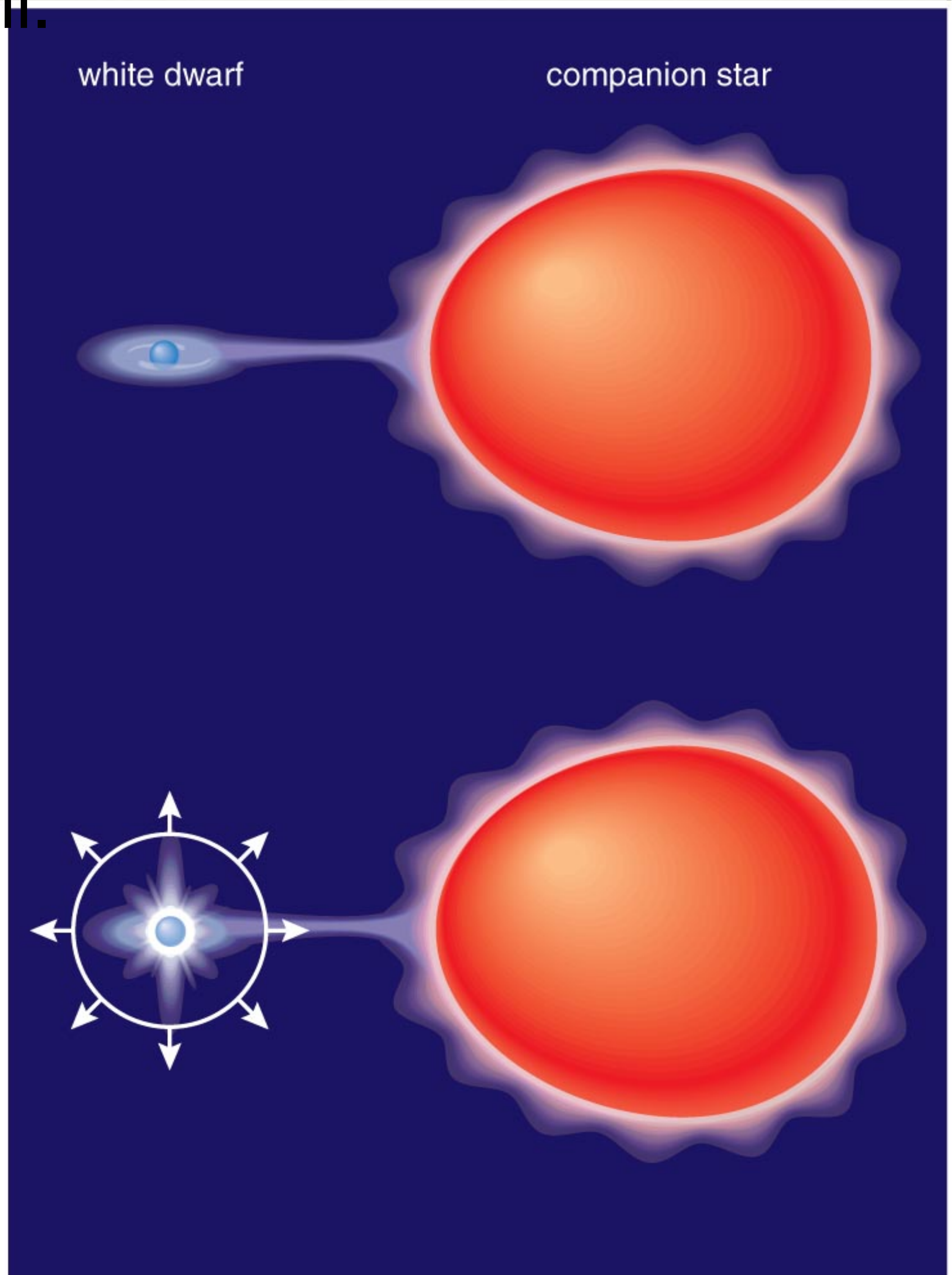
The strong gravity at the surface of the white dwarf compresses the shell.

The still-hot white dwarf heats the shell.

The growing shell mass compresses the shell more. Degeneracy pressure takes over

Eventually, nuclear fusion starts in the shell. Like the helium flash (where the core is degenerate), it starts all at once, like a bomb

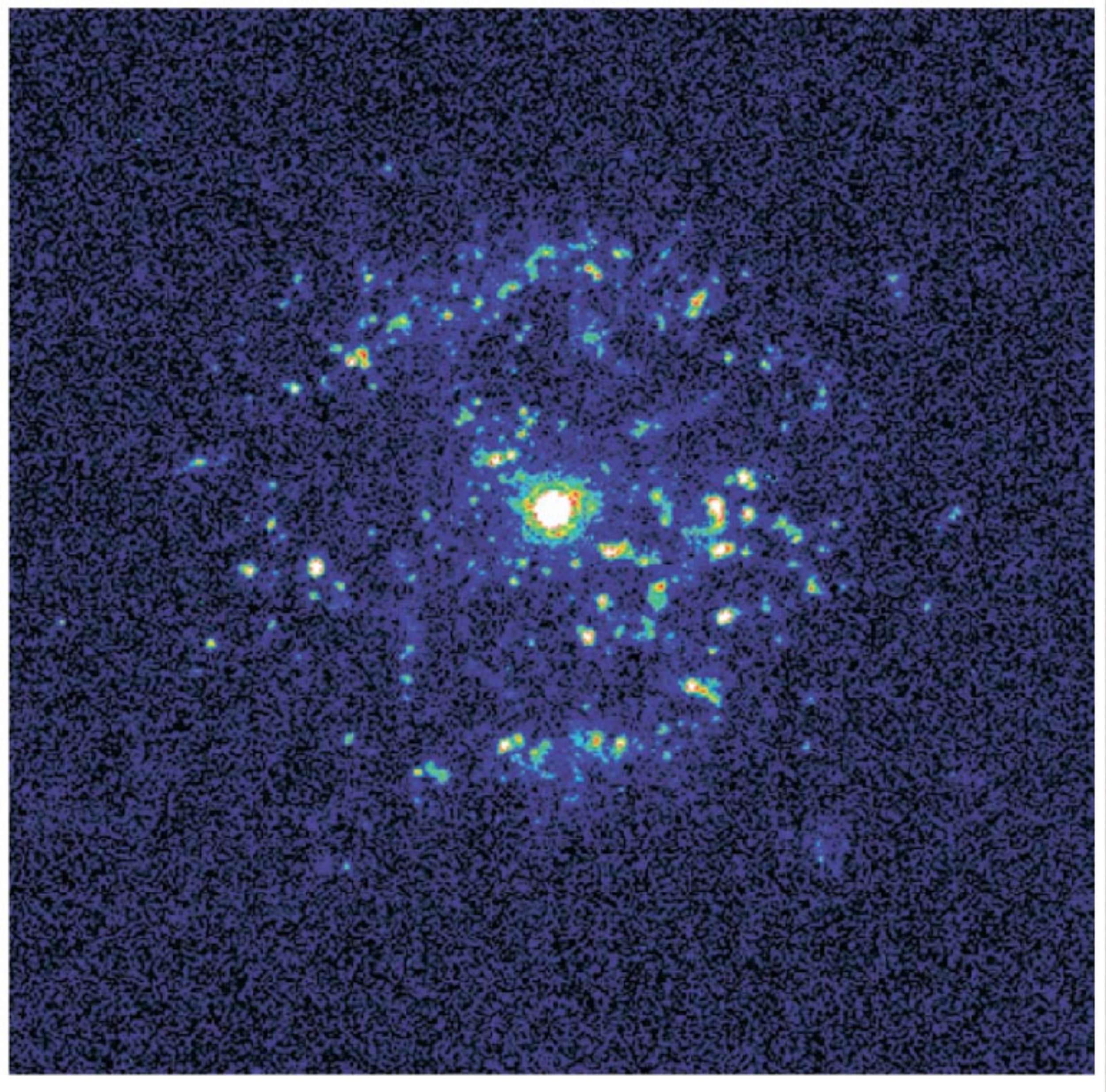
Nova explosion: bright enough to be seen as a “new star”



Other Kinds of Supernovae

Nova explosion
- fainter than supernovae, “only” 100,000 L_{sun}
- SNe from massive stars are 10^{10} L_{sun}

Expels some of the outer envelope of accreted material.



Makes a shell of low-density gas, like a puny planetary nebula

The rest is added to the white dwarf He core

Other Kinds of Supernovae

Pattern of mass accretion, nova explosion, repeats.

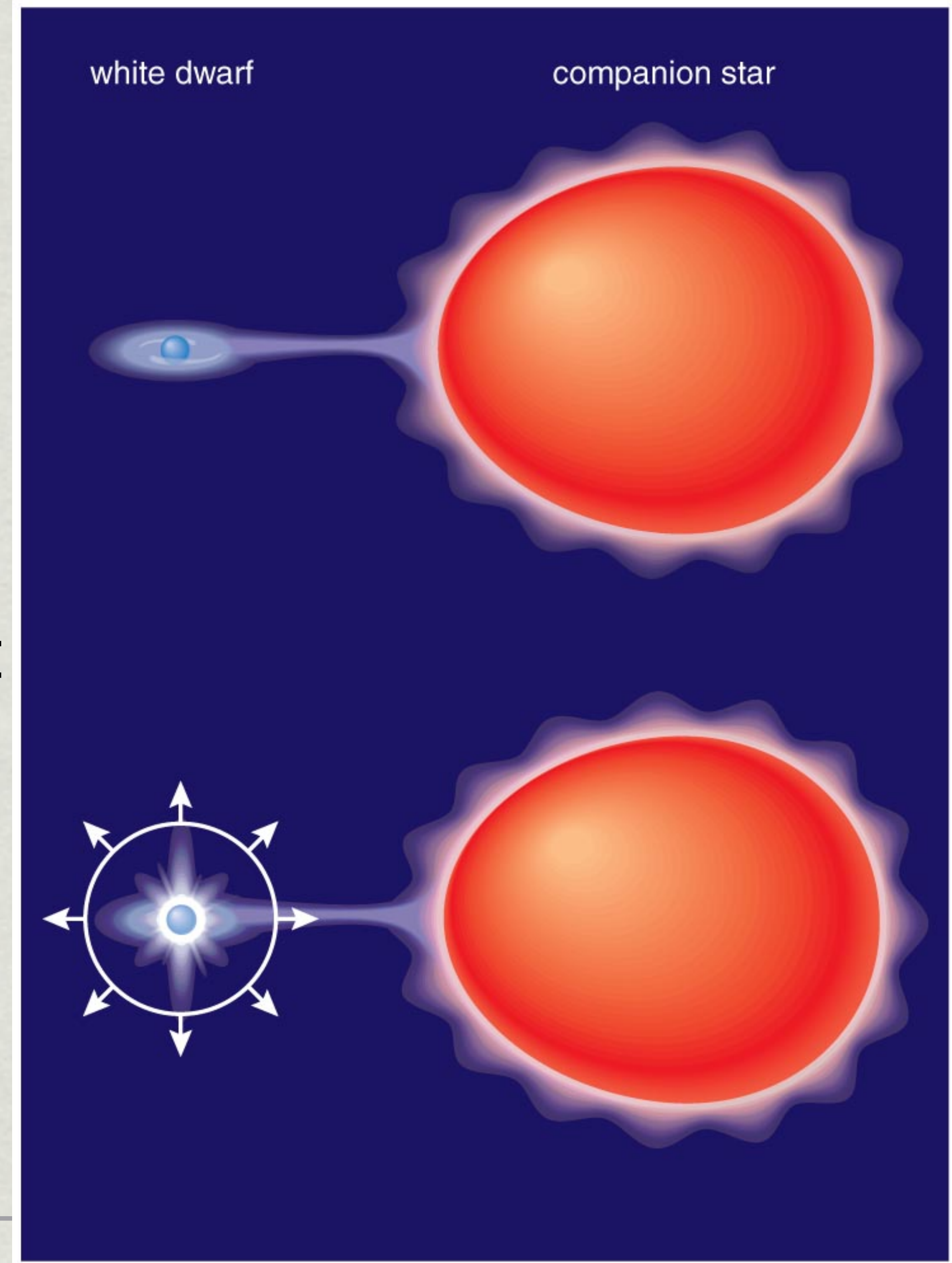
White dwarf slowly gains mass.

Eventually, $M_{WD} = 1.4\ M_{sun}$

This is the maximum mass that can be held up with electron degeneracy pressure

Remember, core collapse supernovae that end the lives of massive stars can't be stopped by electron degeneracy pressure, either.

This mass limit of 1.4 Msun called the "Chandrasekhar limit" in honor of the person who figured this out



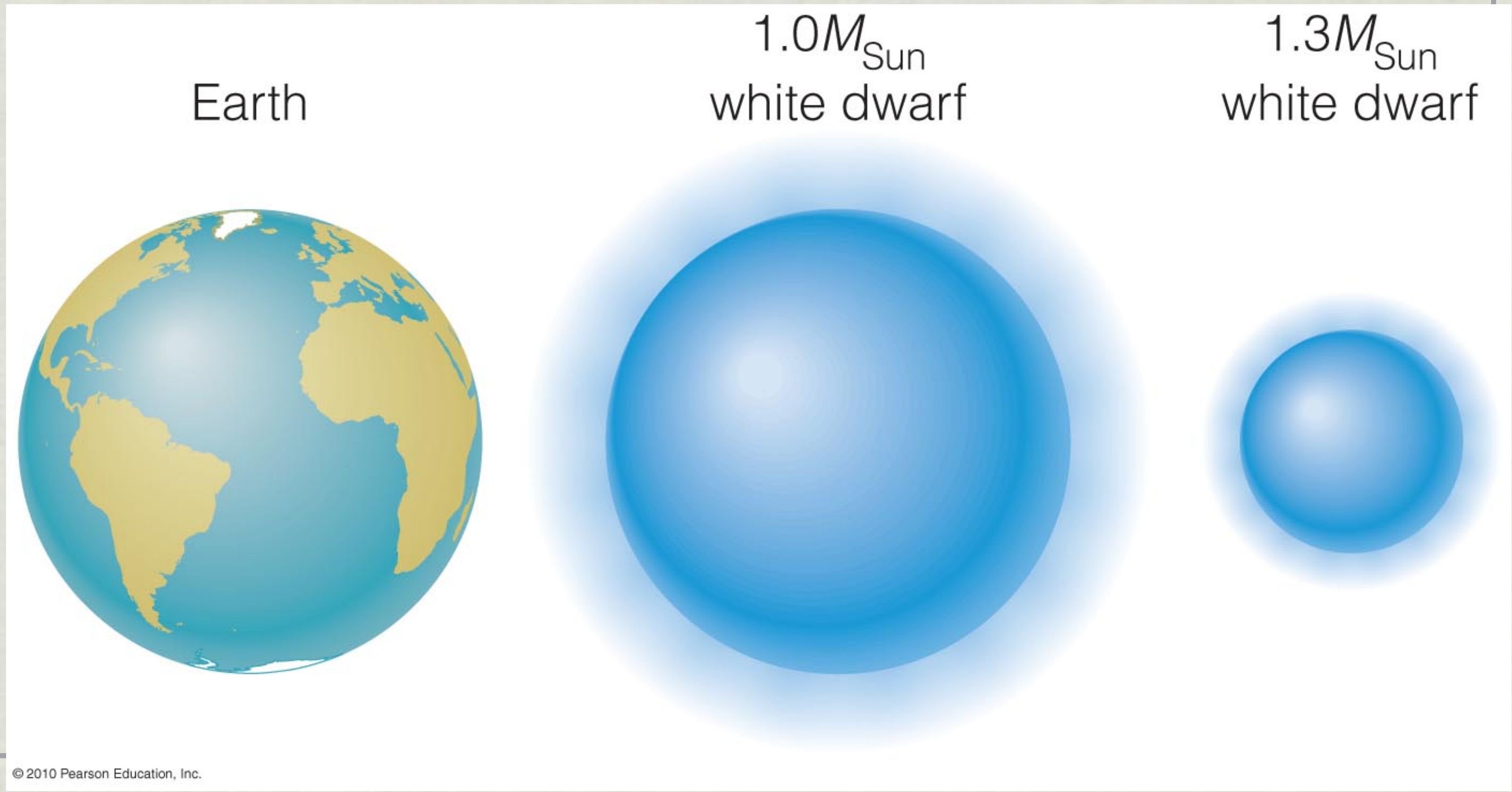
Other Kinds of Supernovae

$M = 1.4\ M_{sun}$ is the maximum mass that can be held up with electron degeneracy pressure.

Degeneracy pressure works by increasing the momentum of particles as their density increases.

So to hold up larger mass, the density must increase.

Weird consequence: objects held up by degeneracy pressure get smaller as they get more massive.



Other Kinds of Supernovae

M = 1.4 M_{sun} is
electron degen

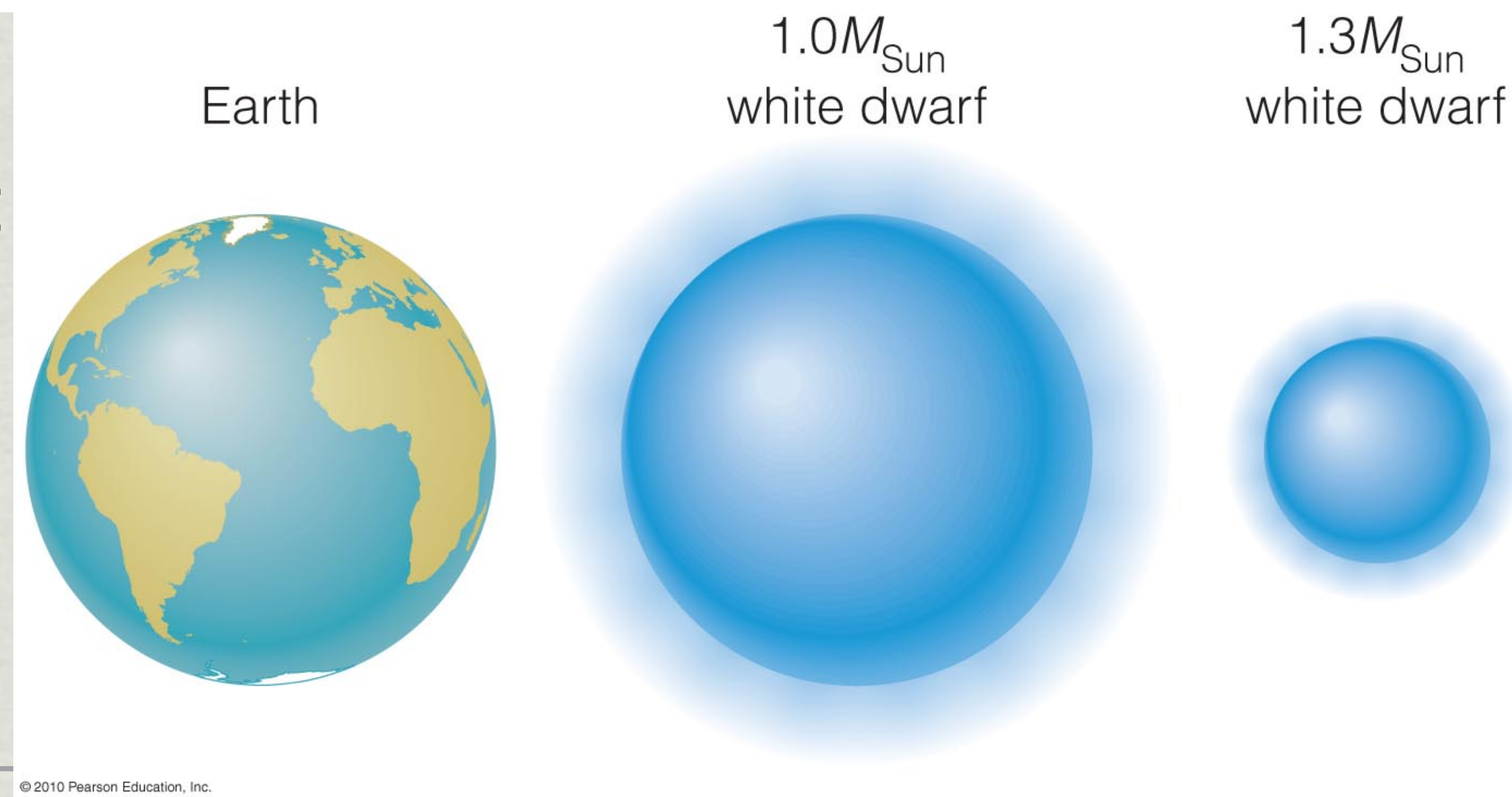
Degeneracy pr
particles as the

So to hold up l

Weird consequence:
objects held up by degeneracy pressure get smaller as they get more massive.

If I have a 1 lb chocolate cake and a 1.3 lb chocolate cake, baked from the same recipe (no disasters), I expect:

A the 1 lb cake will be larger
B the 1.3 lb cake will be larger



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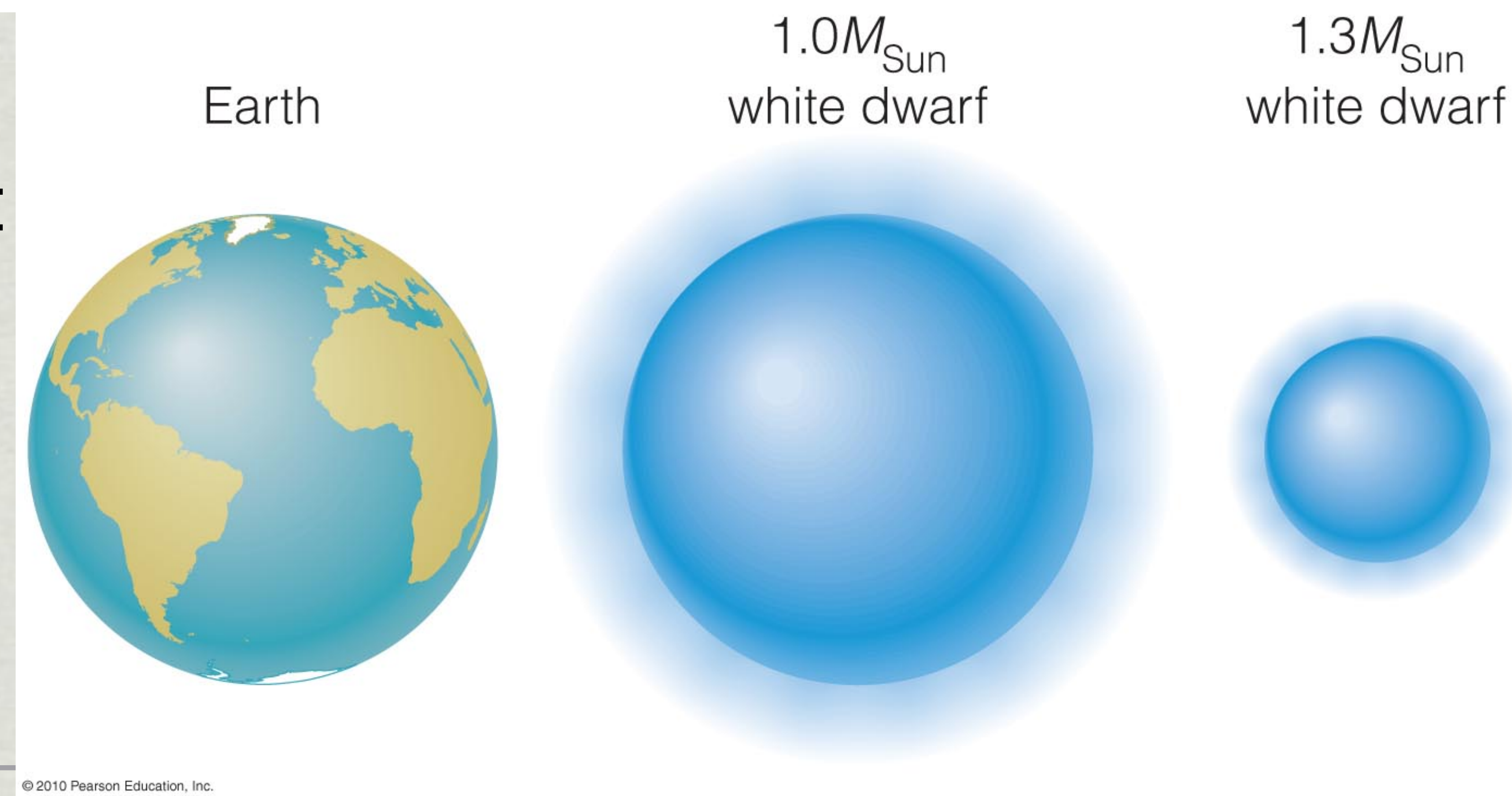


Other Kinds of Supernovae

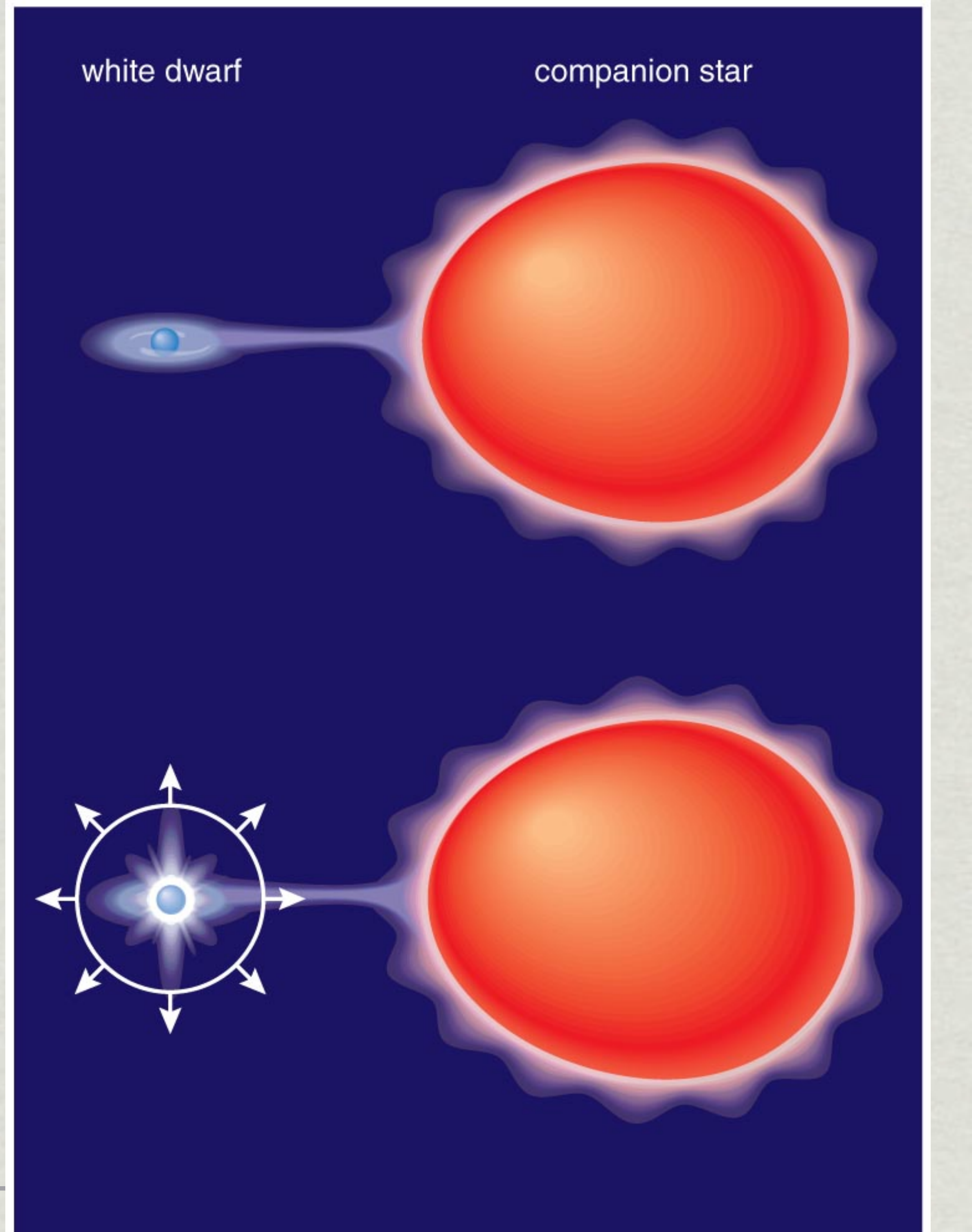
Pattern of mass accretion, nova explosion repeats. White dwarf slowly gains mass.

Eventually, $M = 1.4\ M_{sun}$

Electron degeneracy pressure can't hold it up. Star starts to collapse,

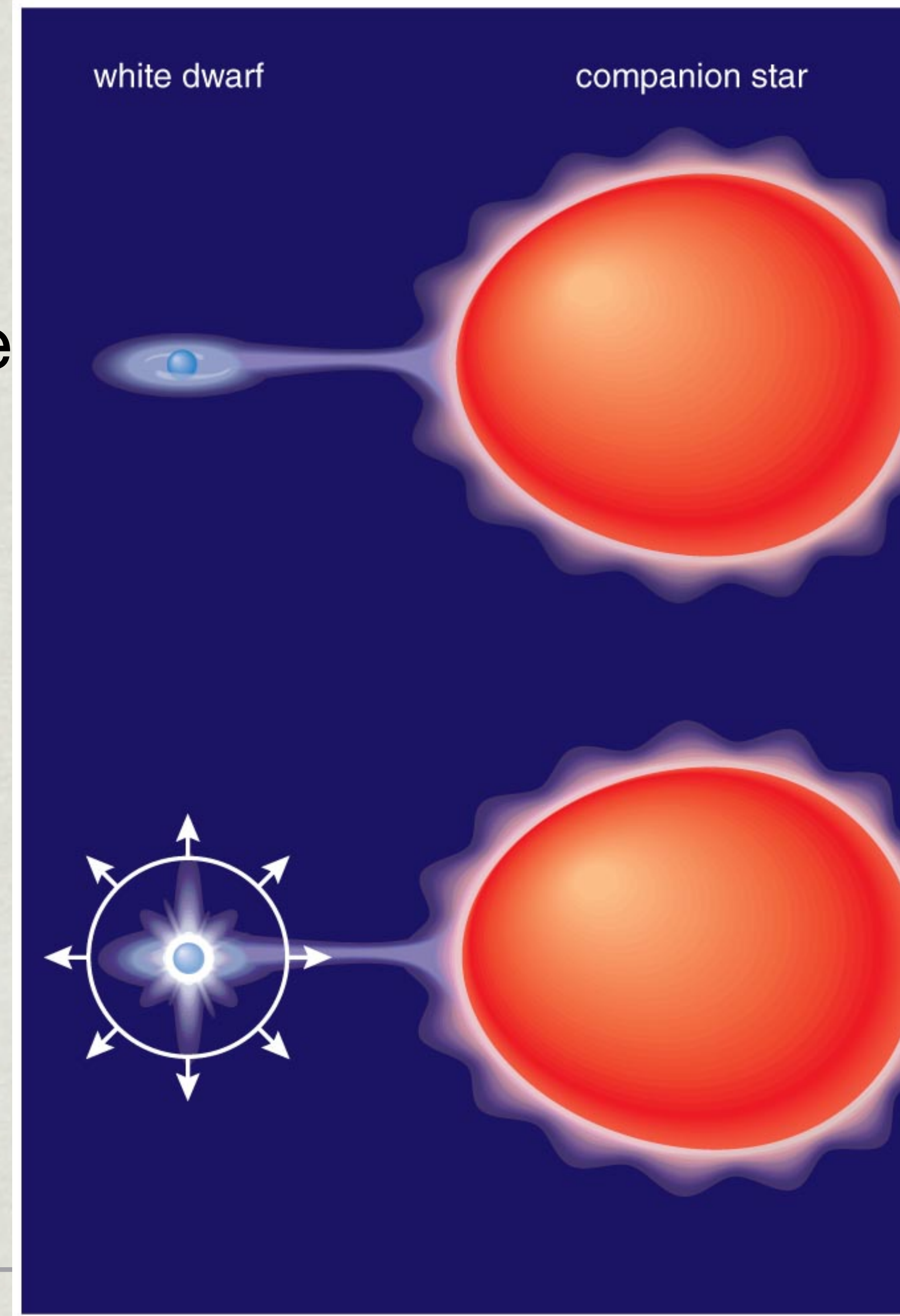
Eventually dense enough to start
$3\ He \rightarrow C$ fusion

But still so dense that degeneracy pressure is what matters. So adding energy from fusion doesn't help hold up the core by adding thermal pressure



Other Kinds of Supernovae

White dwarf slowly gains mass until $M = 1.4\ M_{sun}$
Electron degeneracy pressure can't hold it up. Star starts to collapse, starts 3 He → C fusion



Degeneracy pressure still applies, so energy from fusion can't hold up the white dwarf by increasing thermal pressure

White dwarf density increases, so fusion rate increases, heats core more

Fusion runs out of control, explodes as a white dwarf supernova

Like the He flash when 3 He → C fusion starts in low-mass stars at the top of the giant branch

Other Kinds of Supernovae

White dwarf supernovae: ~10 billion L_{sun}, even brighter than the core collapse supernovae that end the lives of massive stars

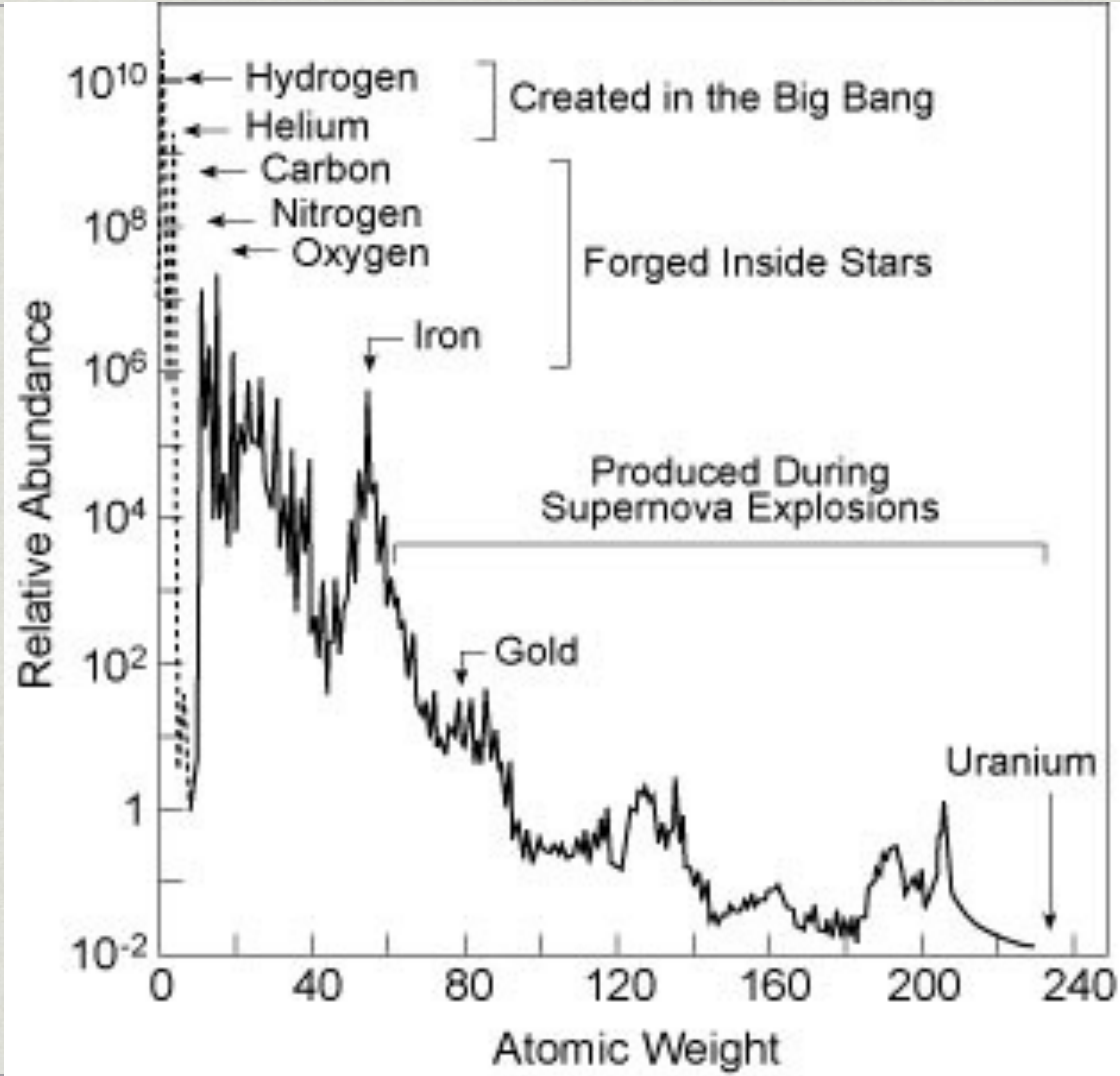
Entire white dwarf undergoes nuclear fusion

Makes Ni^{56} which changes to Fe^{56} by radioactive decay

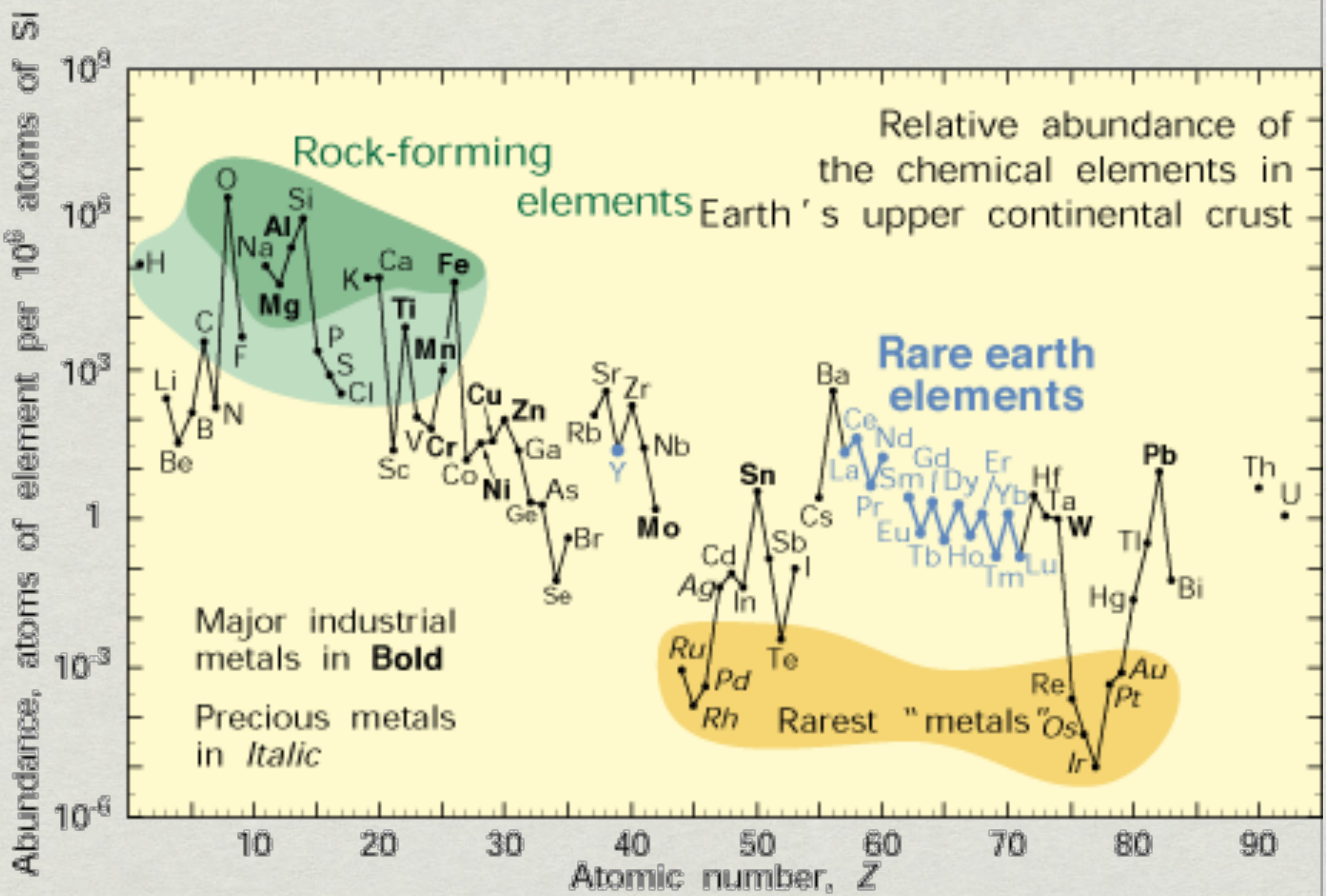
Because they are triggered at $M = 1.4\ M_{sun}$, we know exactly how much fuel there is for the explosion

Everything becomes Fe, so we know how much energy is released: all the nuclear fusion reactions to get to Fe

This means we know the total luminosity of every white dwarf supernova.



Hydrogen
Helium
Carbon
Nitrogen
Oxygen
Created in the Big Bang
Forged Inside Stars
Iron
Produced During
Supernova Explosions
Gold
Uranium
Relative Abundance
Atomic Weight
10¹⁰
10⁸
10⁶
10⁴
10²
1
10⁻²
0
40
80
120
160
200
240


Relative abundance of the chemical elements in Earth's upper continental crust
Rock-forming elements
Rare earth elements
Rarest "metals"
Major industrial metals in Bold
Precious metals in Italic
Abundance, atoms of element per 10^6 atoms of Si
Atomic number, Z
H
Li
Be
B
C
N
O
F
Na
Mg
Al
Si
P
S
Cl
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Ga
Ge
As
Se
Br
Rb
Sr
Y
Zr
Nb
Mo
Ru
Rh
Pd
Ag
Cd
In
Sn
Sb
Te
I
Cs
Ba
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Hf
Ta
W
Re
Os
Ir
Pt
Au
Hg
Tl
Pb
Bi
Th
U

Other Kinds of Supernovae

1.4 M_{sun} → Fe by nuclear fusion, so we know how much energy is released.

This means we know the luminosity. Can use the measured flux to get the distance to white dwarf supernova

$$L = \text{apparent brightness} \times (4\pi d^2)$$

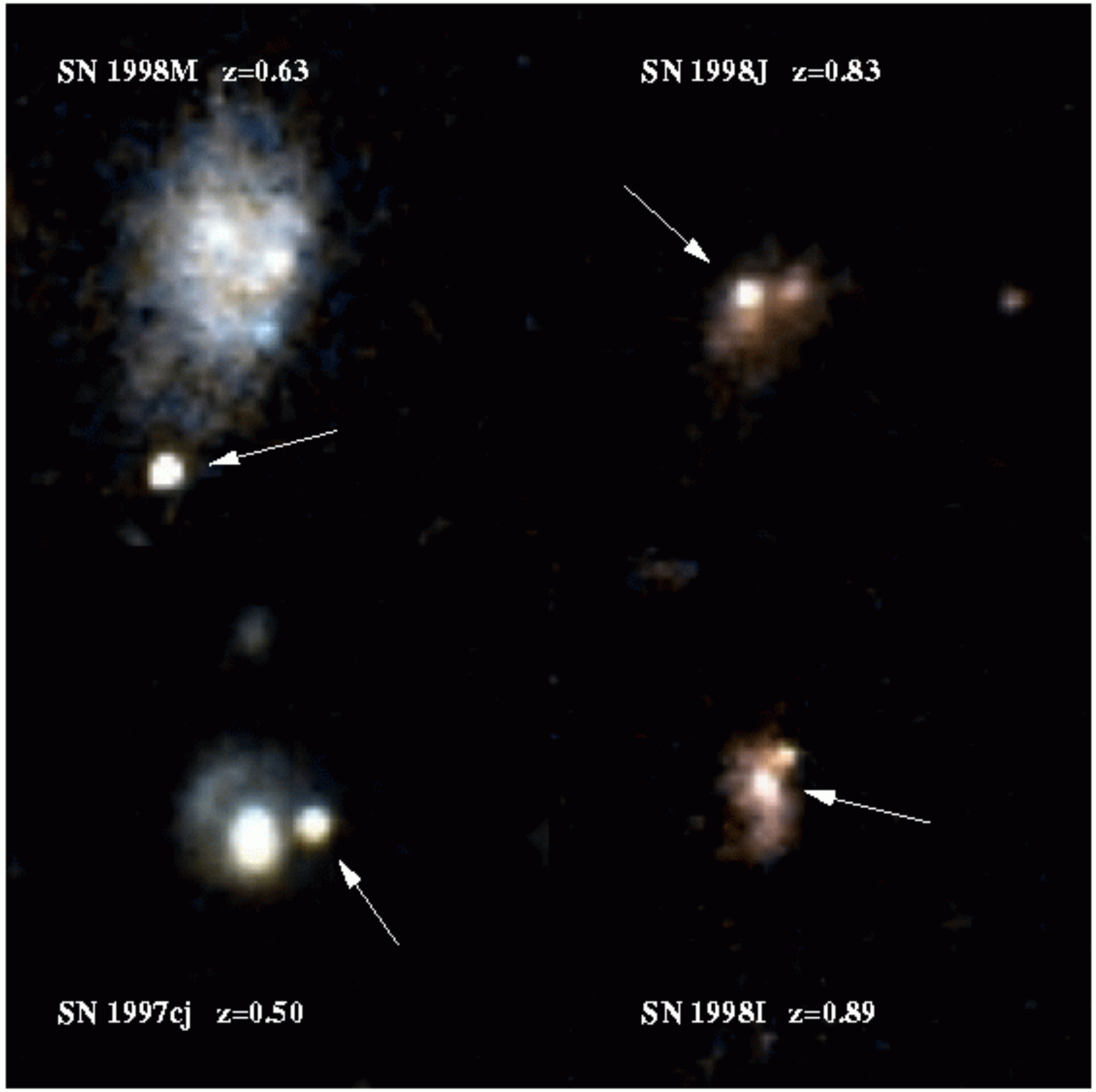
Other Kinds of Supernovae

10 billion L_{sun} is about the luminosity of our Galaxy.

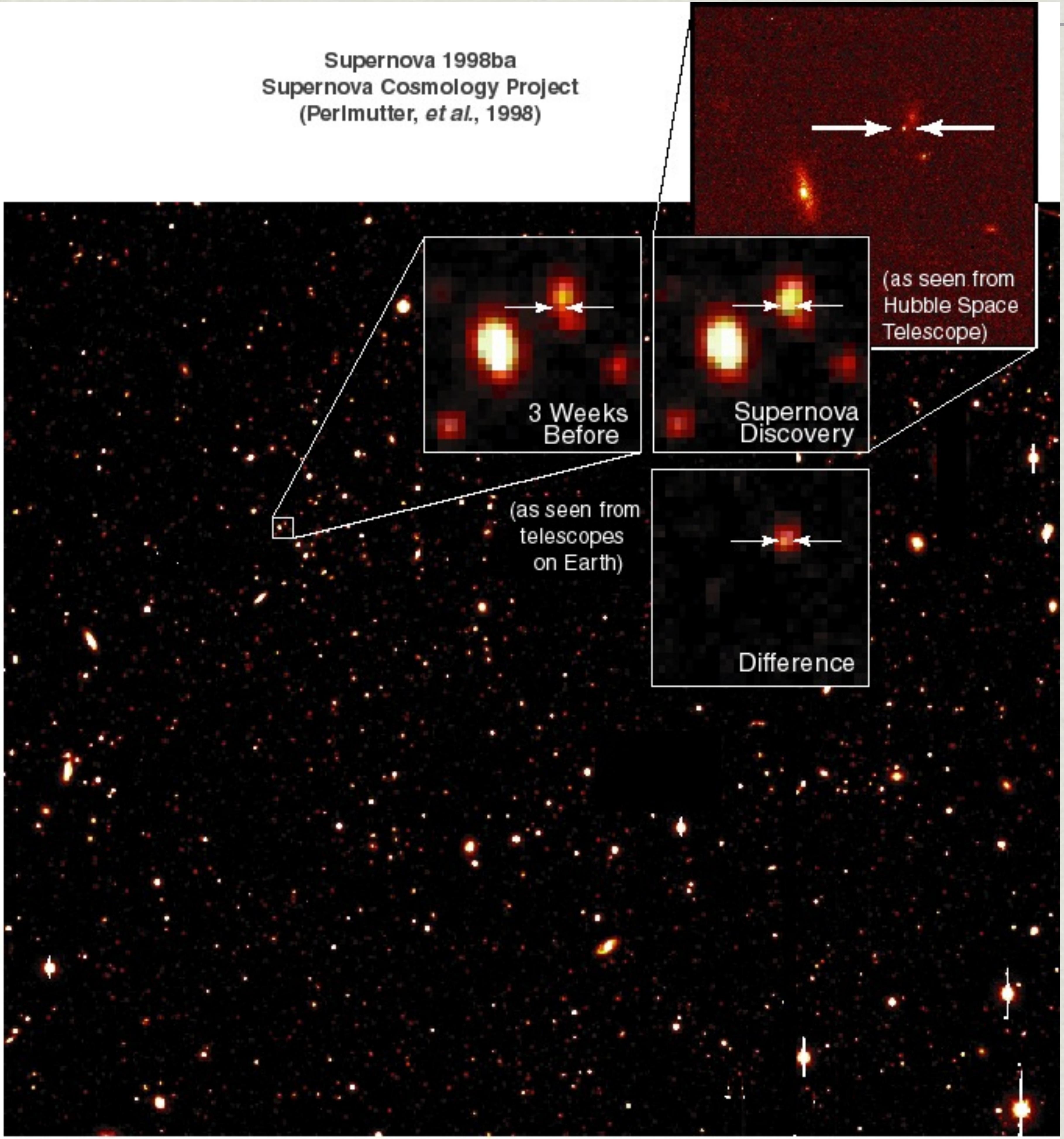
That means we can see supernovae in other galaxies.

Can use the luminosity of white dwarf supernova to measure distances to other galaxies!

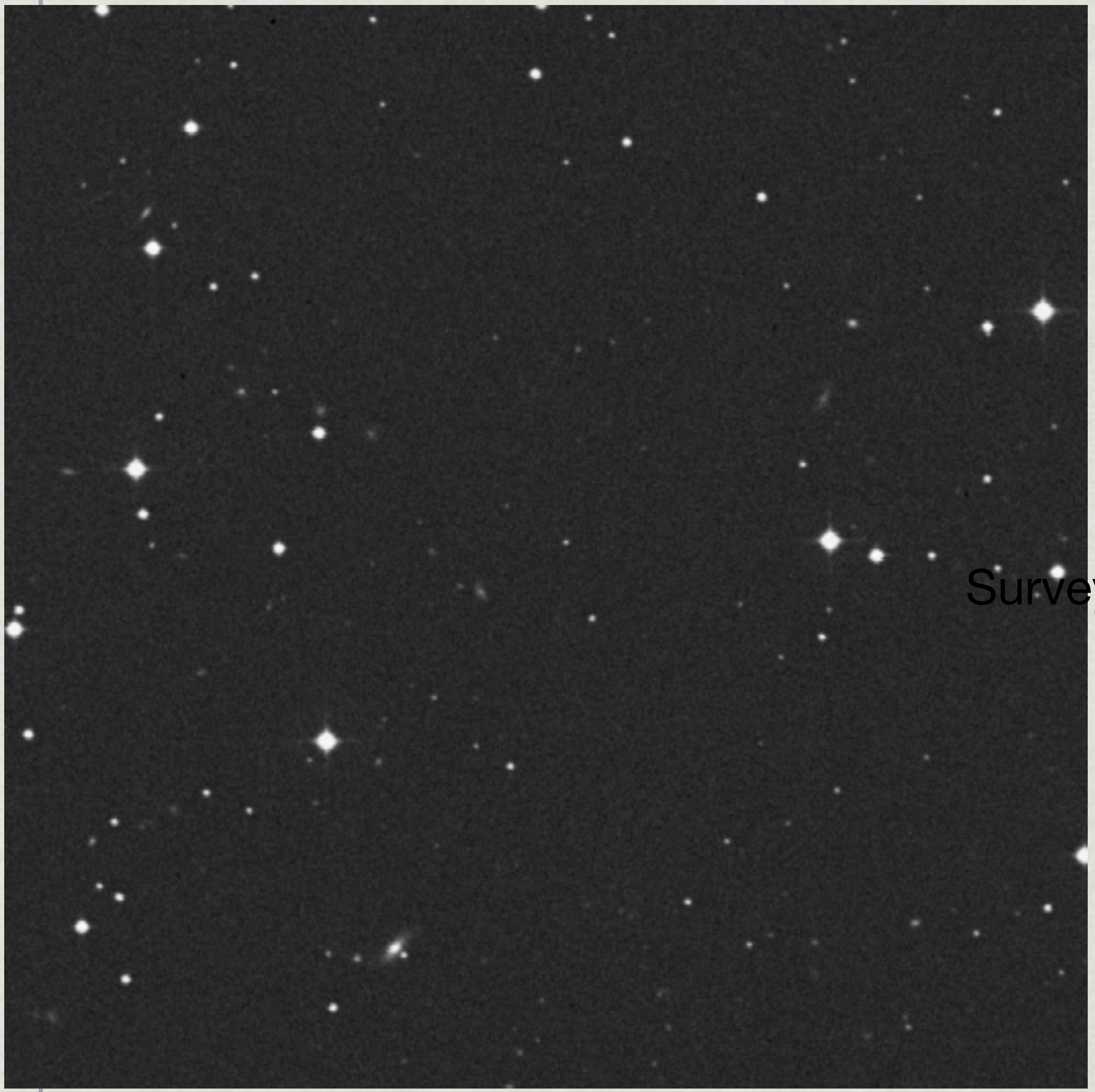
$L =$ apparent brightness $\times (4\pi d^2)$


SN 1998M z=0.63
SN 1998J z=0.83
SN 1997cj z=0.50
SN 1998I z=0.89

Supernova 1998ba
Supernova Cosmology Project
(Perlmutter, *et al.*, 1998)



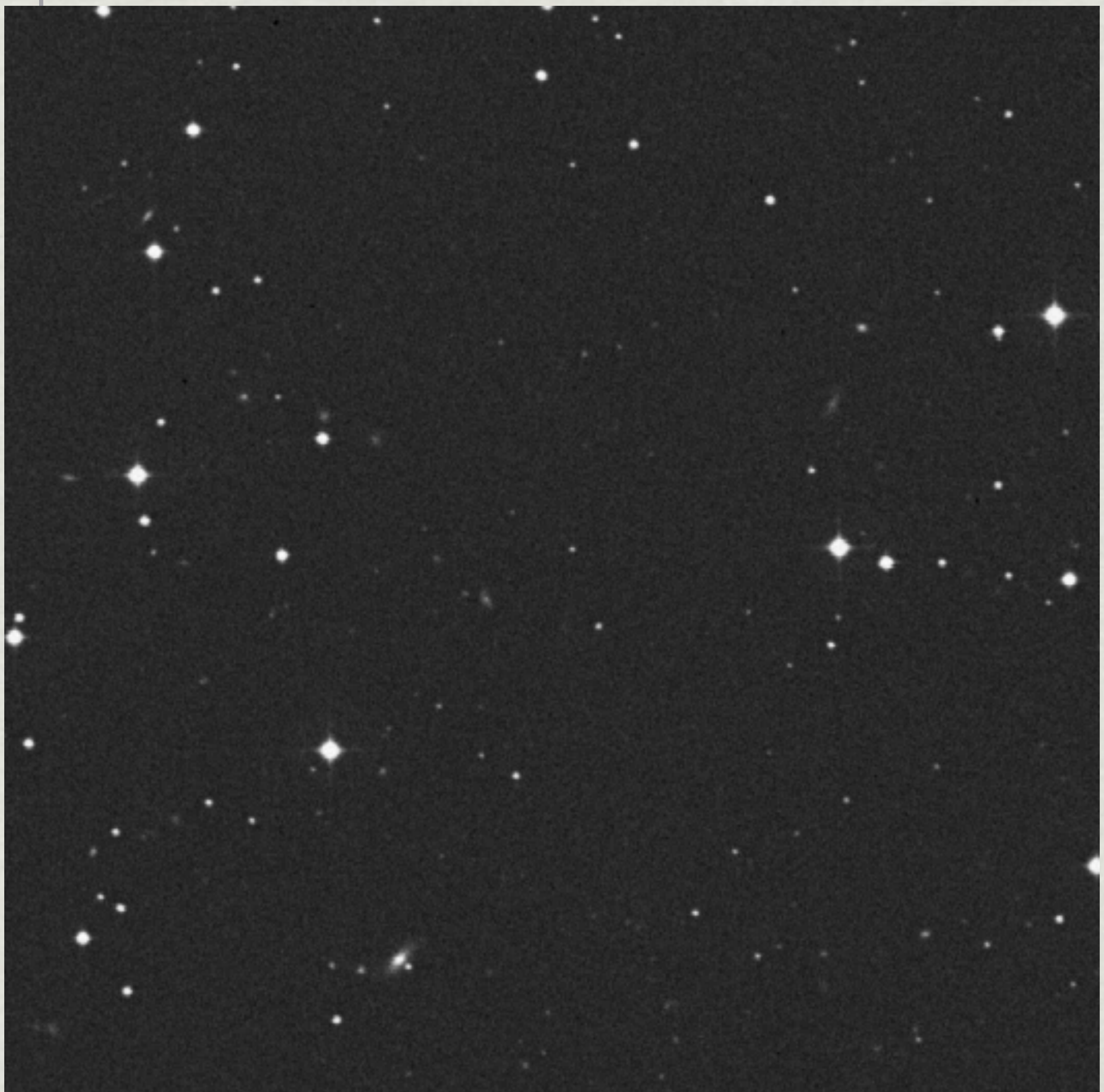
Palomar Observatory Sky Survey
1950's



Sloan Digital Sky Survey Early Data Release
2001

Survey

http://skyserver.sdss.org/dr2/en/proj/advanced/skysurveys/poss.asp



http://skyserver.sdss.org/dr2/en/proj/advanced/skysurveys/poss.asp

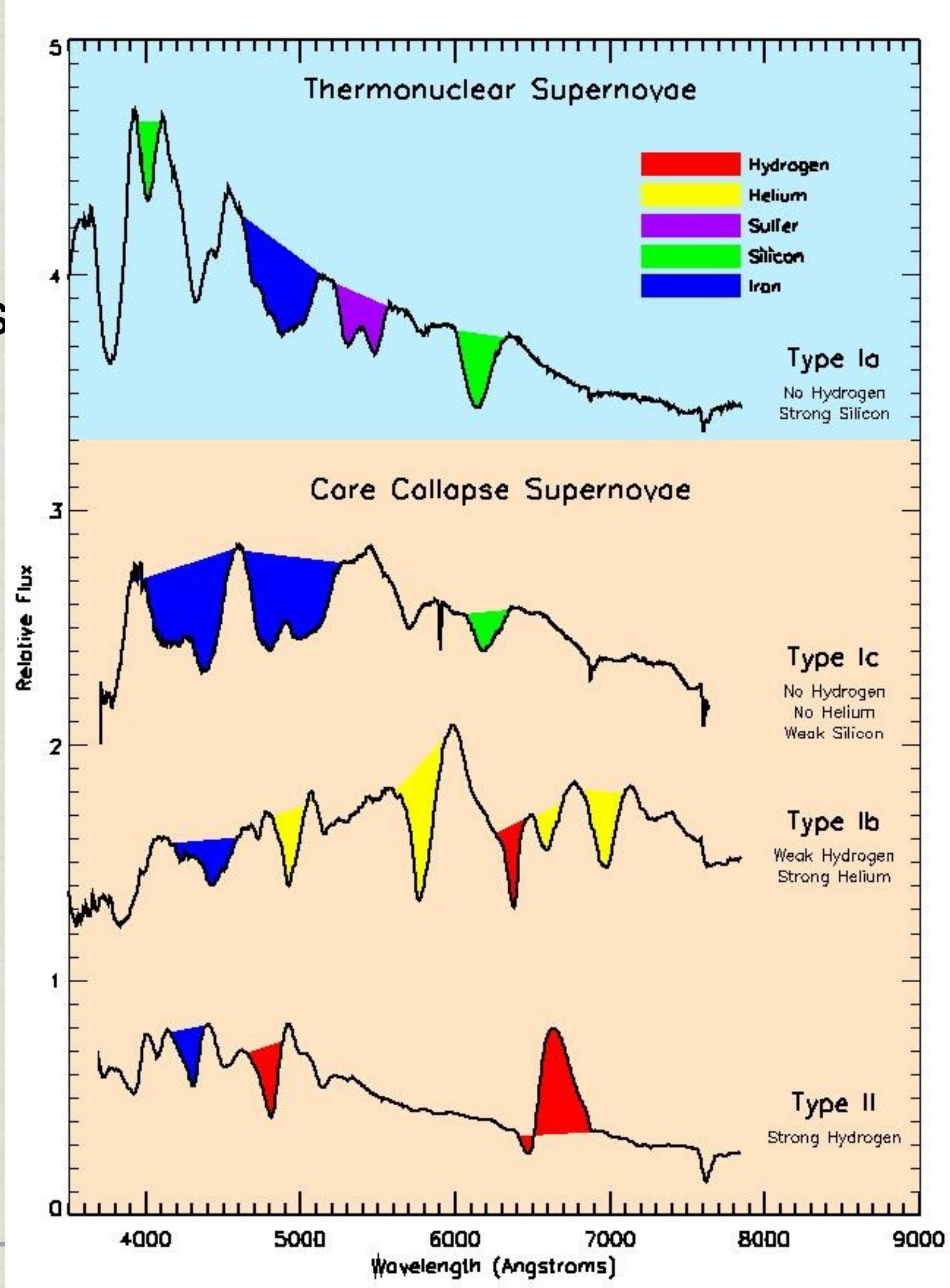
Supernova Zoo

Type 1a: White dwarf that exceeds the 1.4 M_{sun} Chandrasekhar limit.
- Observed property: does not have hydrogen lines
- H is a tiny component of the He white dwarf

Type II: core collapse of a massive star
- Observed property: spectrum has H lines
- H envelope of the massive star is being ejected by the supernova explosion

The zoo gets more complicated and confusing: "Type 1b, Type 1c" are strange supernovae from massive stars....

Confusing because all we see in other galaxies is the explosion, not the star it came from.



Supernova Zoo

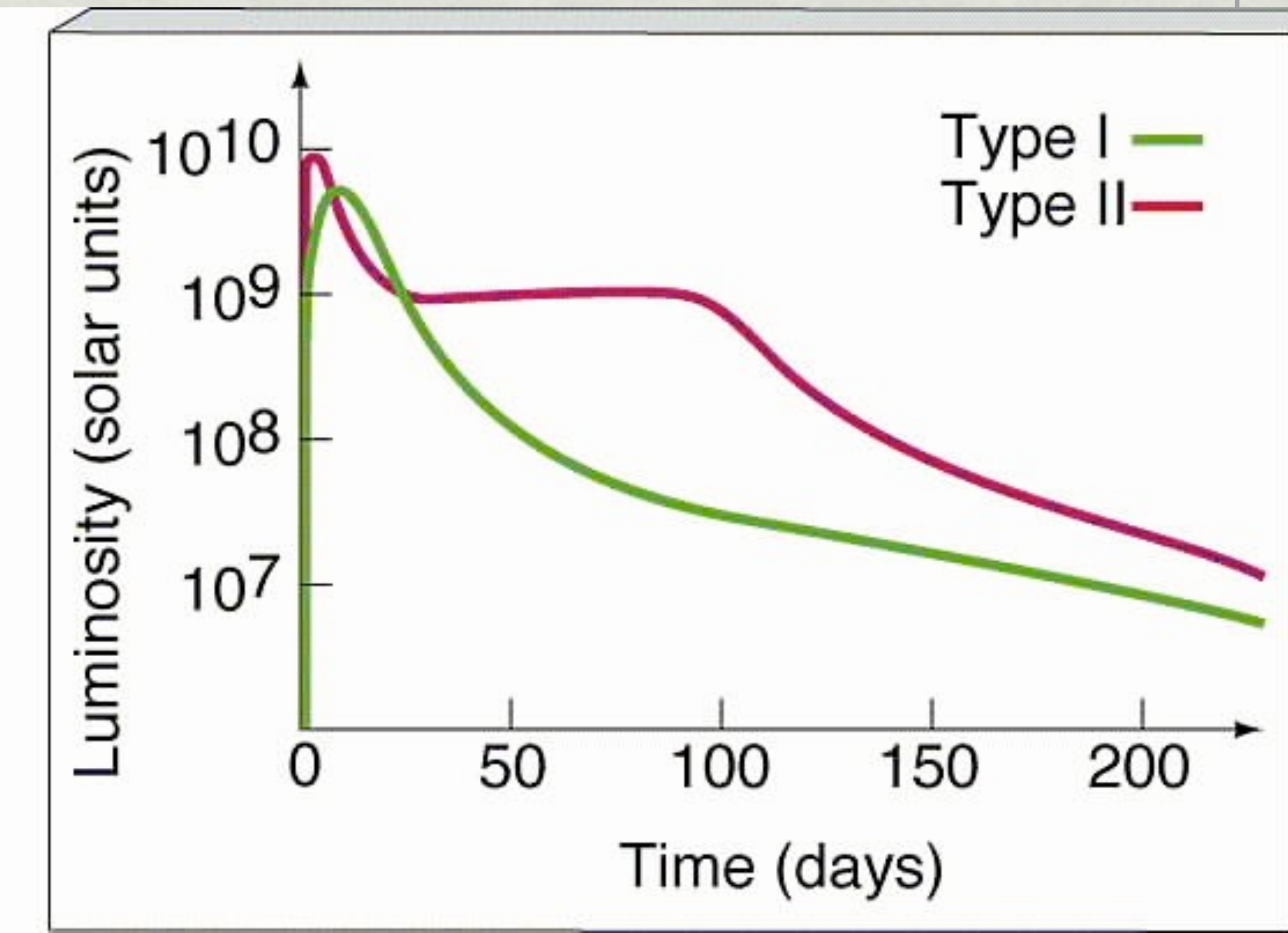
Supernova explosions fade over time.

The two kinds (White Dwarf and massive star) have different Light Curves: the trend of brightness vs. time after explosion.

A handy way to identify the type of a supernova without taking a spectrum: measure its luminosity vs. time and plot

White dwarf supernovae = Type I

Massive star supernovae
= core collapse supernovae
= Type II



Supernova as “Standard Candles”

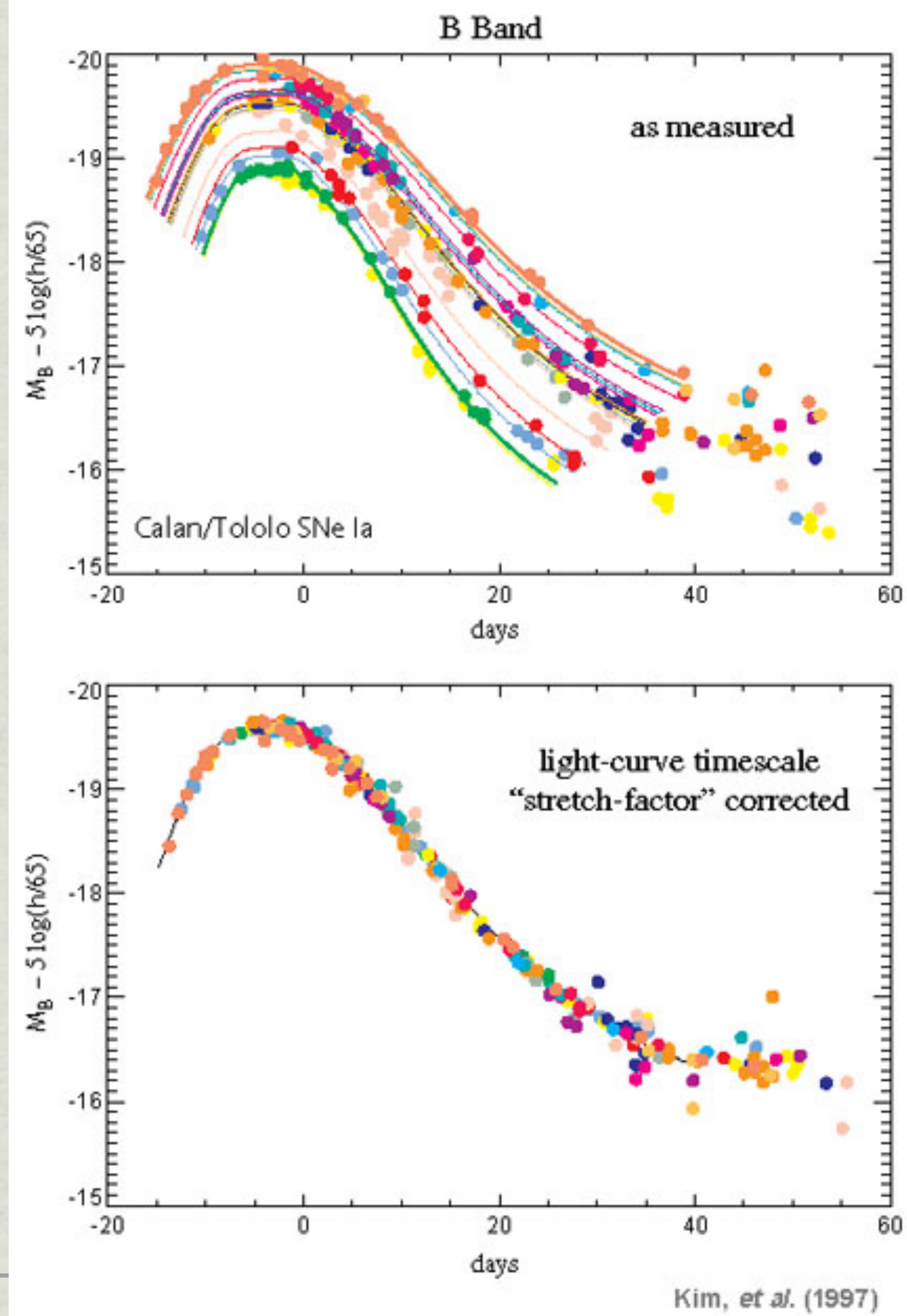
1.4 M_{sun} → Fe by nuclear fusion, so we know how much energy is released.

This means we know the total luminosity of the supernova. Use the measured flux to get the distance to white dwarf supernova:

$$L = \text{Apparent Brightness} \times (4\pi d^2)$$

Use white dwarf supernova to measure distances to other galaxies!

Not quite so simple: need to “standardize” the luminosity by measuring the width of the light curve



Black Holes

What if a star is so massive that neutron degeneracy pressure doesn't hold, either?

Core collapse continues.

Nothing for outer envelope to bounce from, so it continues to collapse, too.

Nothing to stop the collapse after neutron degeneracy pressure.

So what happens?

What do we observe?

Black Holes

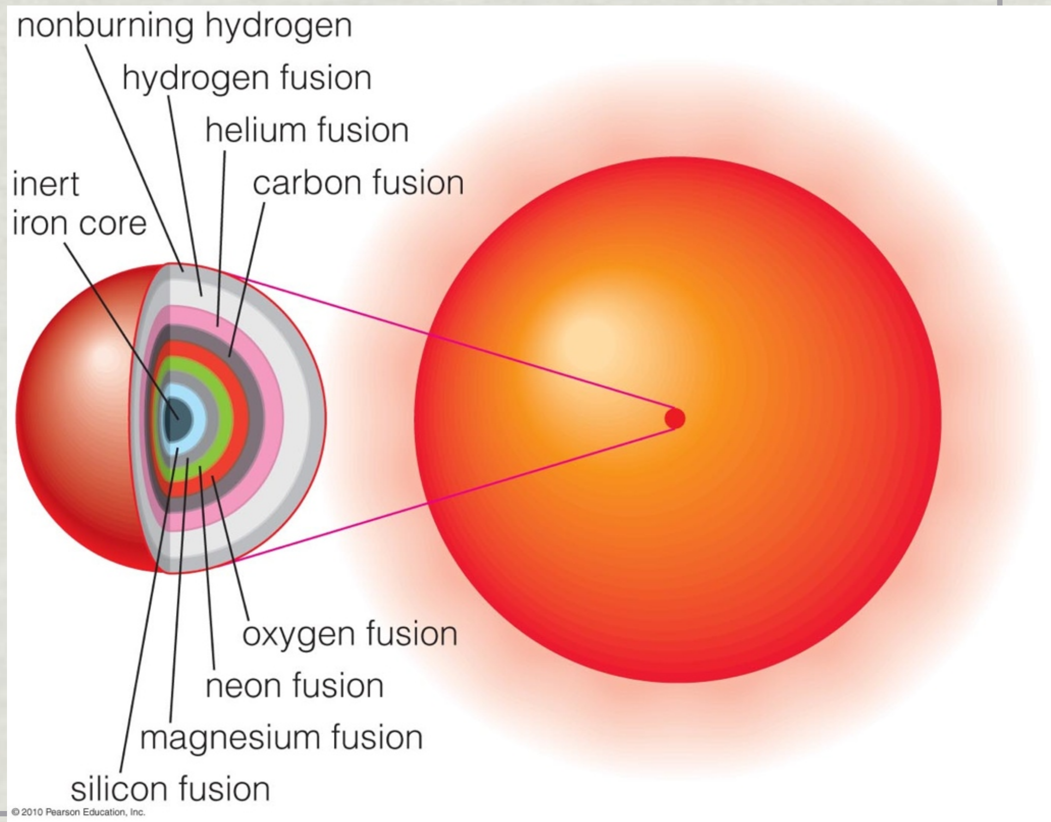
Nothing to stop the collapse of a very massive star after neutron degeneracy pressure.

What do we observe?

Bob is on the surface of the star as it collapses.

Bob is talking to me on his cell phone, describing what he sees.

How does information get sent in cell phone conversations?



Black Holes

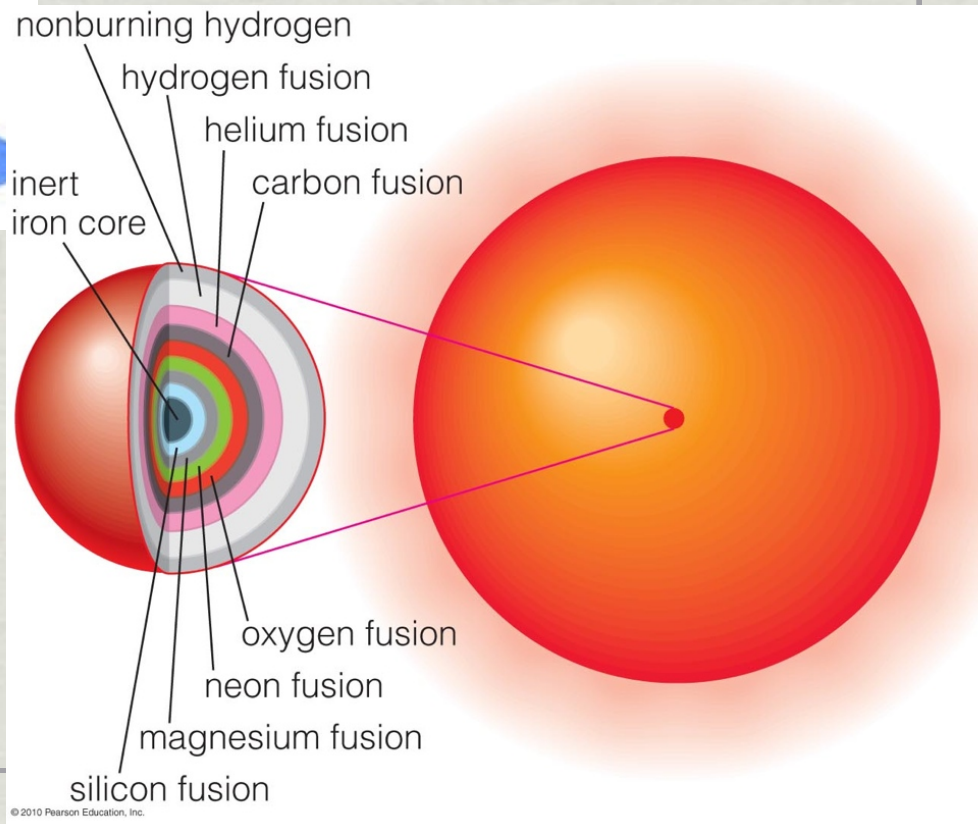
Bob is talking to me on his cell phone, describing what he sees.

As the star collapses, the surface of the star gets smaller.
Bob's messages get farther and farther apart.

Eventually, nothing.

No information from Bob.

Why?



Black Holes

As the star collapses, the surface of the star gets smaller. Bob's messages get farther and farther apart.

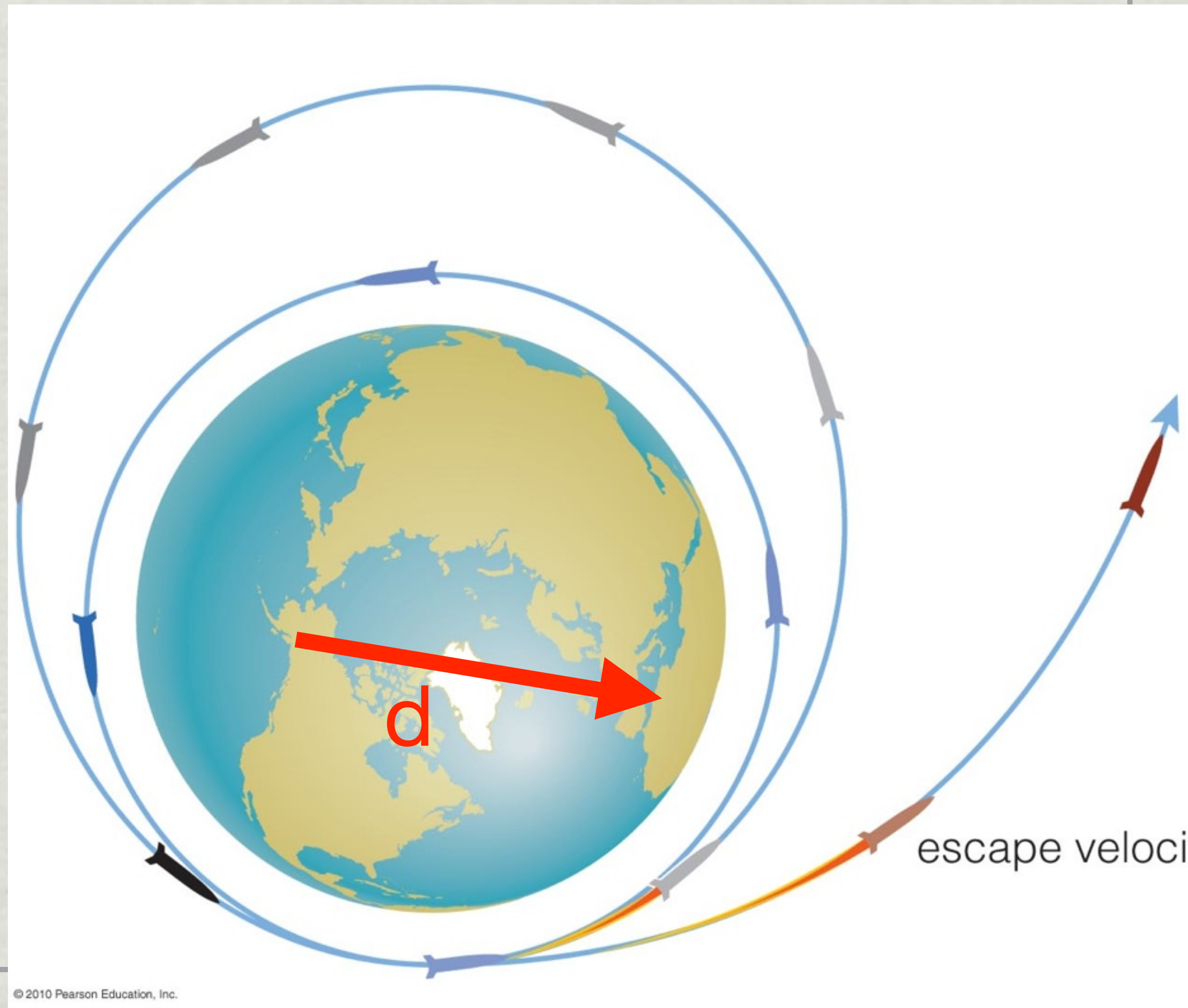
Eventually, nothing. No information from Bob.

Why?

Remember escape velocity: velocity needed to get free of an object's gravitational pull.

$$v_{escape} = \sqrt{\frac{2\,G\,M}{d}}$$

M = mass, d = distance from the center of the object you are trying to escape from



Black Holes

Escape velocity: velocity needed to get free of an object's gravitational pull.

$$v_{escape} = \sqrt{\frac{2\,G\,M}{d}}$$

M = mass, d = distance from the center of the object you want to escape from

For a star, light is emitted at its surface, so **d** is the radius of the star, **R**

If M is very big and/or R is very small, then V_{escape} can be bigger than c, the speed of light.

NOTHING can have speed bigger than c, so NOTHING can escape, not even light.
Star becomes a Black Hole

Artist's rendition, not a real picture

Black Holes

For any mass define a radius, the Schwarzschild radius R_s, where $V_{escape} = c$

$$v_{escape} = \sqrt{\frac{2\,G\,M}{R}}$$

Then rearrange:

$$R_s = \frac{2GM}{c^2} = \left(\frac{2G}{c^2}\right) M$$

If $M = M_{sun}$, $R_s = 3$ km

So for any star, $R_s = 3 \text{ km} \times \frac{M_*}{M_{sun}}$

Artist's rendition, not a real picture

Black Holes

How much mass do you need to make a black hole?

Schwarzschild Radius, where $V_{escape} = c$: $$R_s = \left(\frac{2G}{c^2}\right) M$$

Artist's rendition, not a real picture

Black Holes

How much mass do you need to make a black hole?

Schwarzschild Radius, where $V_{escape} = c$: $$R_s = \left(\frac{2G}{c^2}\right) M$$

Artist's rendition, not a real picture

Mass doesn't matter: just need high density.

If R is small enough, any mass can become a black hole.

Just need V_{escape} bigger than c

Black Holes

What is the Schwarzschild radius for Earth?

$$R_s = \left(\frac{2G}{c^2}\right) M$$

$$M_{earth} = 6x10^{24}\text{ kg} = 3x10^{-6}\ M_{sun}$$

$$\left(\frac{2G}{c^2}\right) = 3000\text{ m} = 3\text{ km}$$

$$R_s = 3\text{ km} \times \frac{M}{M_{sun}}$$

Artist's rendition, not a real picture

Black Holes

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$$\left(\frac{2G}{c^2}\right) = 3000 \text{ m} = 3 \text{ km}$$

$$R_s = 3 \text{ km} \times \frac{M}{M_{sun}}$$

$= (3 \text{ km}) \text{ x } (3x10^{-6})$
$= (3000 \text{ m}) \text{ x } (3x10^{-6}) = 9 \text{ x } 10^{-3} \text{ m}$
$= 0.009 \text{ m}$
$= 9 \text{ mm}$

About the size of a marble.

Artist's rendition, not a real picture

Black Holes

$$R_s = \left(\frac{2G}{c^2}\right) M$$

$$R_s = 3\text{ km} \times \frac{M}{M_{sun}}$$

What is Rs for a 20 M_{sun} star?

A 30 km
B 60 km
C 15 km
D 3 km

Artist's rendition, not a real picture

Black Holes

$$R_s = \left(\frac{2G}{c^2}\right) M$$

$$R_s = 3 \text{ km} \times \frac{M}{M_{sun}}$$

What is Rs for a 20 M_{sun} star?

A 30 km

B 60 km

C 15 km

D 3 km

Artist's rendition, not a real picture

Black Holes

How does something get dense enough to become a black hole?

What happens when a massive star collapses?

Neutron degeneracy pressure can't hold it up.

Core keeps collapsing.

How do I know? I just told you we can't get any information out since $V_{escape} > c$!

Artist's rendition, not a real picture

Black Holes

We observe black holes indirectly, through the influence of their gravity.

There are giant black holes in the centers of galaxies, including ours.

Stars orbit the black hole like planets orbit a star.

Strong gravitational pull means speed must be large for stable orbit near the black hole.

Remember, speed for a circular orbit around an object of mass M at distance d: $v_{orbit} = \sqrt{\frac{G\,M}{d}}$

We can actually see the stars move!

Black Holes

We observe black holes indirectly, through the influence of their gravity.

Good evidence we have one in the center of our own Galaxy.

Hard to see anything in the center of the Galaxy because of the dust.

Infrared is better.

BH: lots of mass in a small volume.

Need to see into a small area. But the galaxy is a big place.

Black Holes

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BH: lots of mass in a small volume.

Need to see into a small area. But the galaxy is a big place, the center is far away.

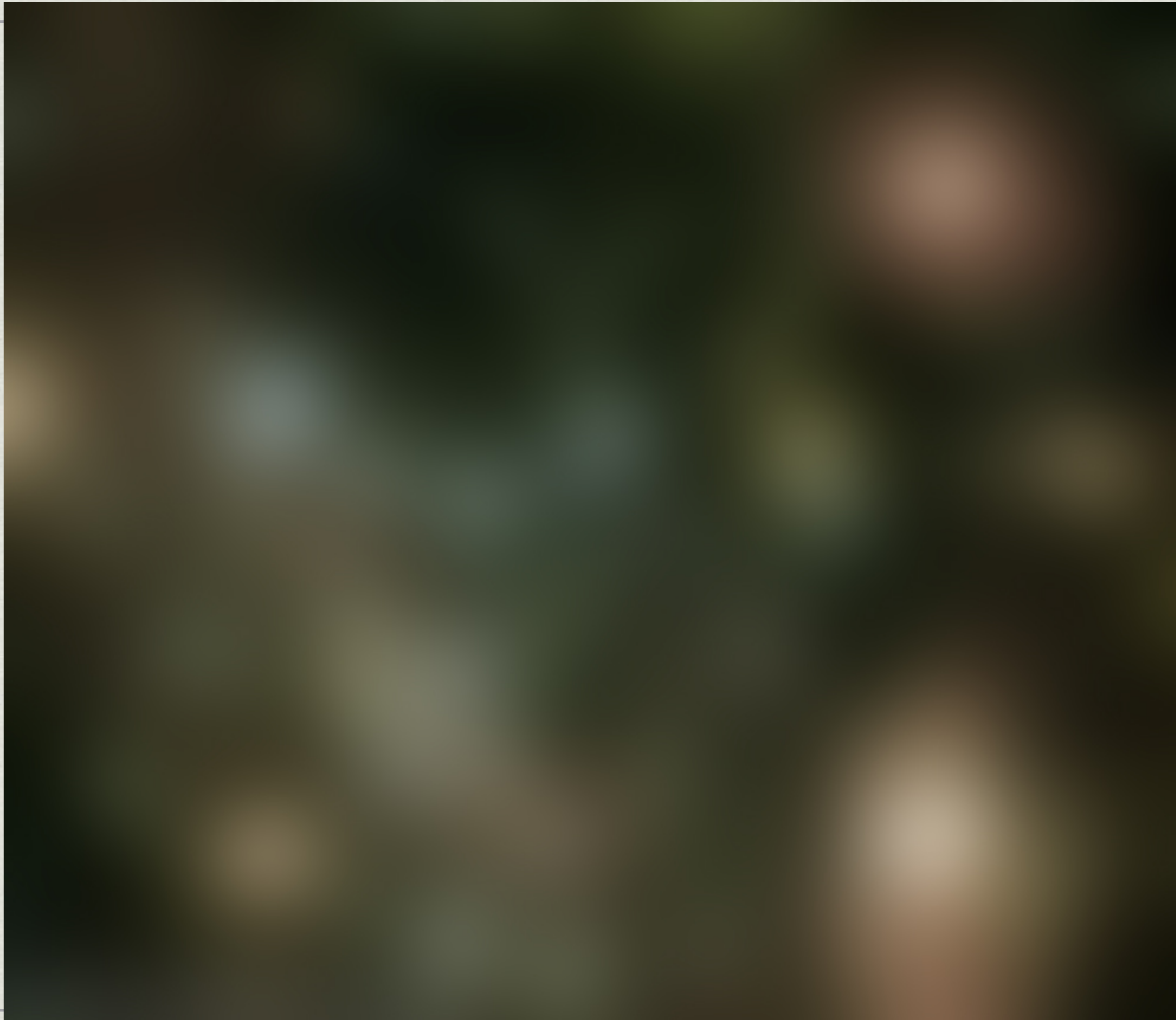
Angular-size distance relation says that a small area far away will be a small angle on the sky.

BH: lots of mass in a small volume.

Need to see into a small area. But the galaxy is a big place, the center is far away.

Angular-size distance relation says that a small area far away will be a small angle on the sky.

Smaller than we can measure because of turbulence in the atmosphere



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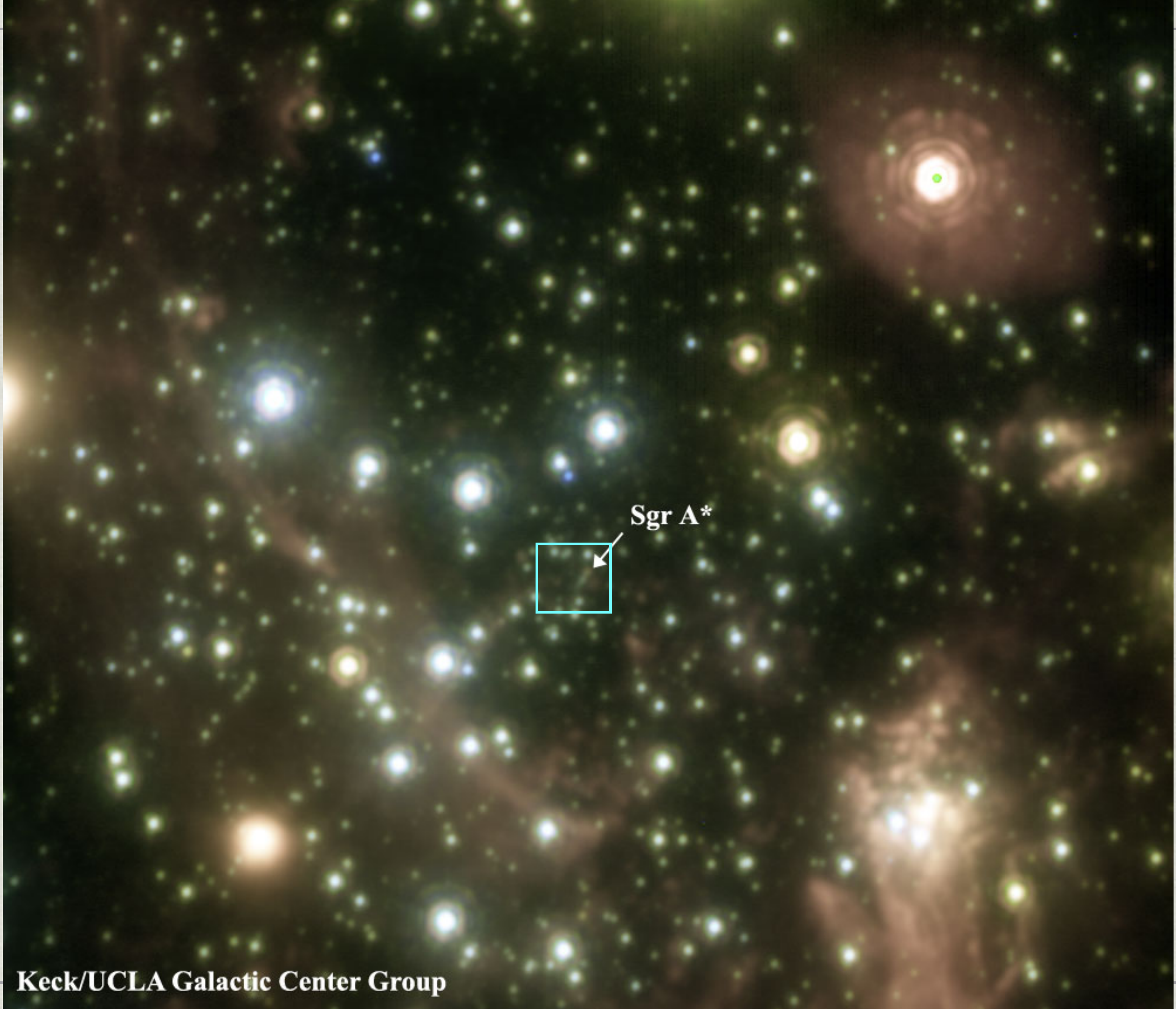
Smaller than we can measure because of turbulence in the atmosphere.

We can correct the blur from turbulence using a technique called Adaptive Optics.


Sgr A*
Keck/UCLA Galactic Center Group

Black Holes

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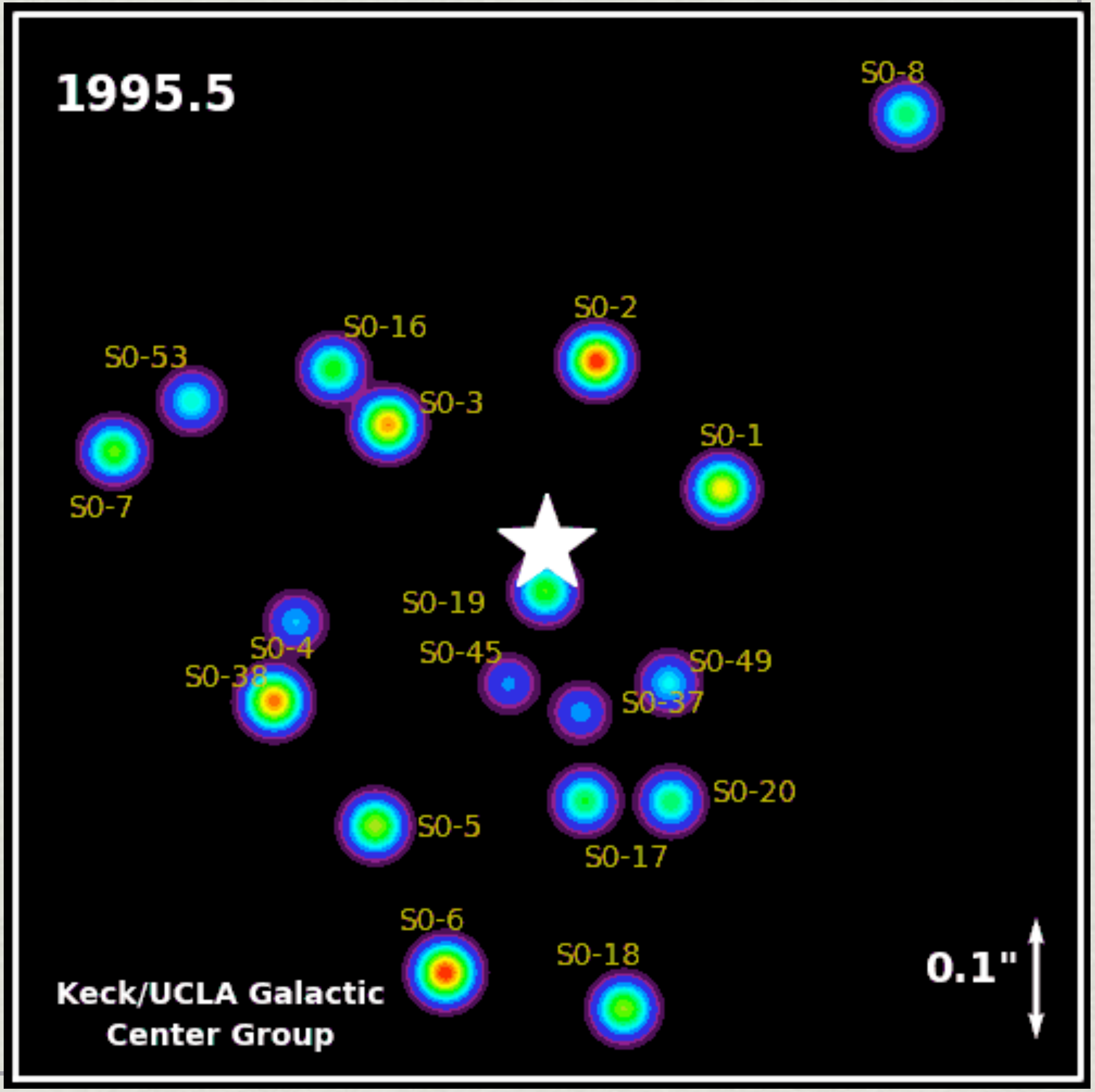
Good evidence we have one in the center of our own Galaxy.

Star S0-2:

Orbital period = 15.78 years.
Closest approach 120 AU
Top speed: 5000 km/s
(11,000,000 mph!) 2% of c

We can use Kepler's 3rd Law to weigh the mass S0-2 is orbiting!

S0-16 gets as close as 90 AU from the BH.
(Pluto is only 40 AU from the sun)



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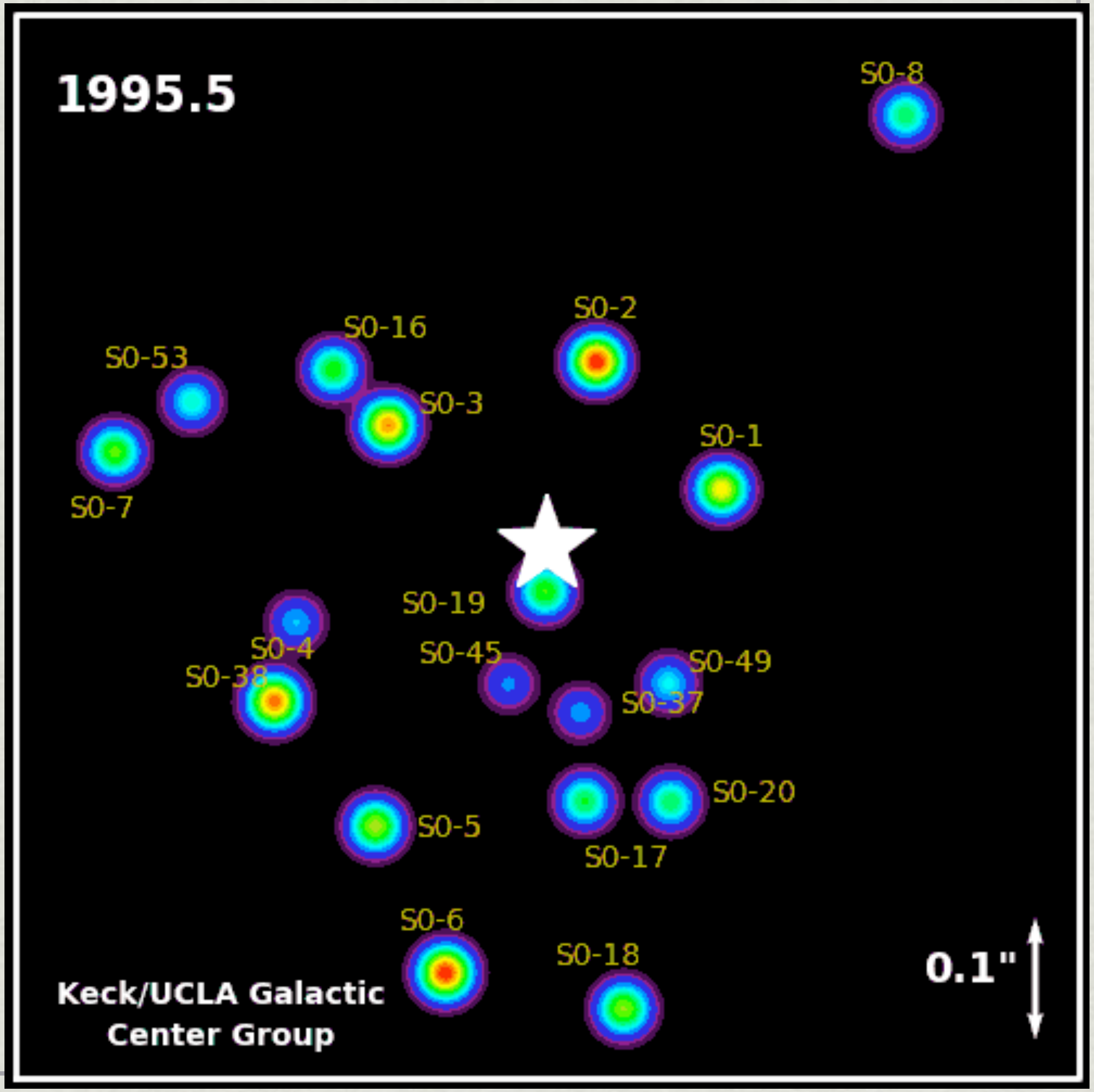
Closest approach 120 AU
Top speed: 5000 km/s
(11,000,000 mph!) 2% of c

We can use Kepler's 3rd Law to weigh the mass S0-2 is orbiting!



Black Holes

We observe black holes indirectly, through the influence of their gravity.

How do we know it's a Black Hole and not just a really heavy star?

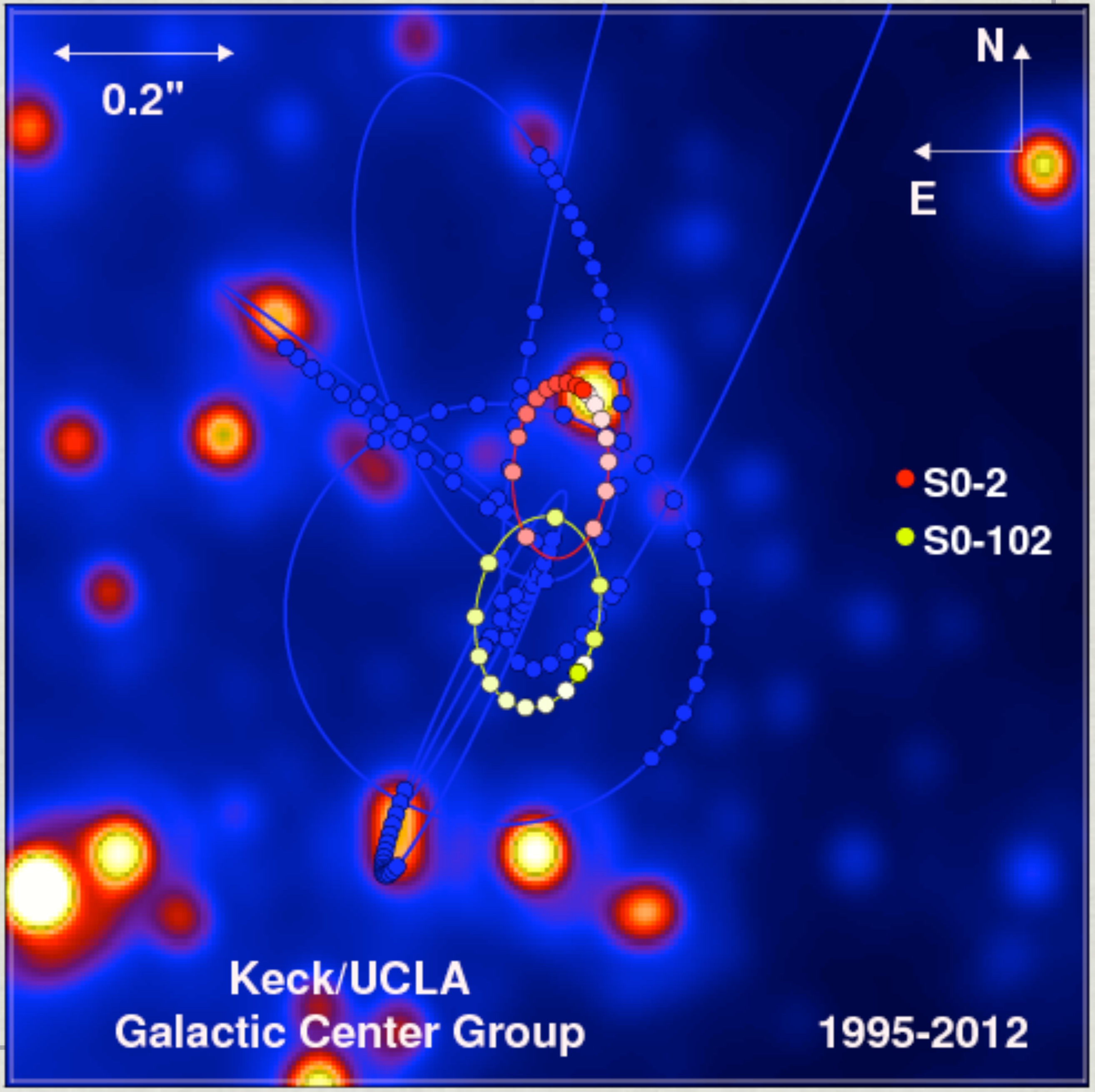
Speed in a circular orbit:

$$v_{orbit} = \sqrt{\frac{G\,M}{d}}$$

Measure d, v_{orbit}, get M

But Black Holes require high density, not just lots of mass.

So need to measure lots of mass in a tiny volume (small d). Want stars as close as possible.

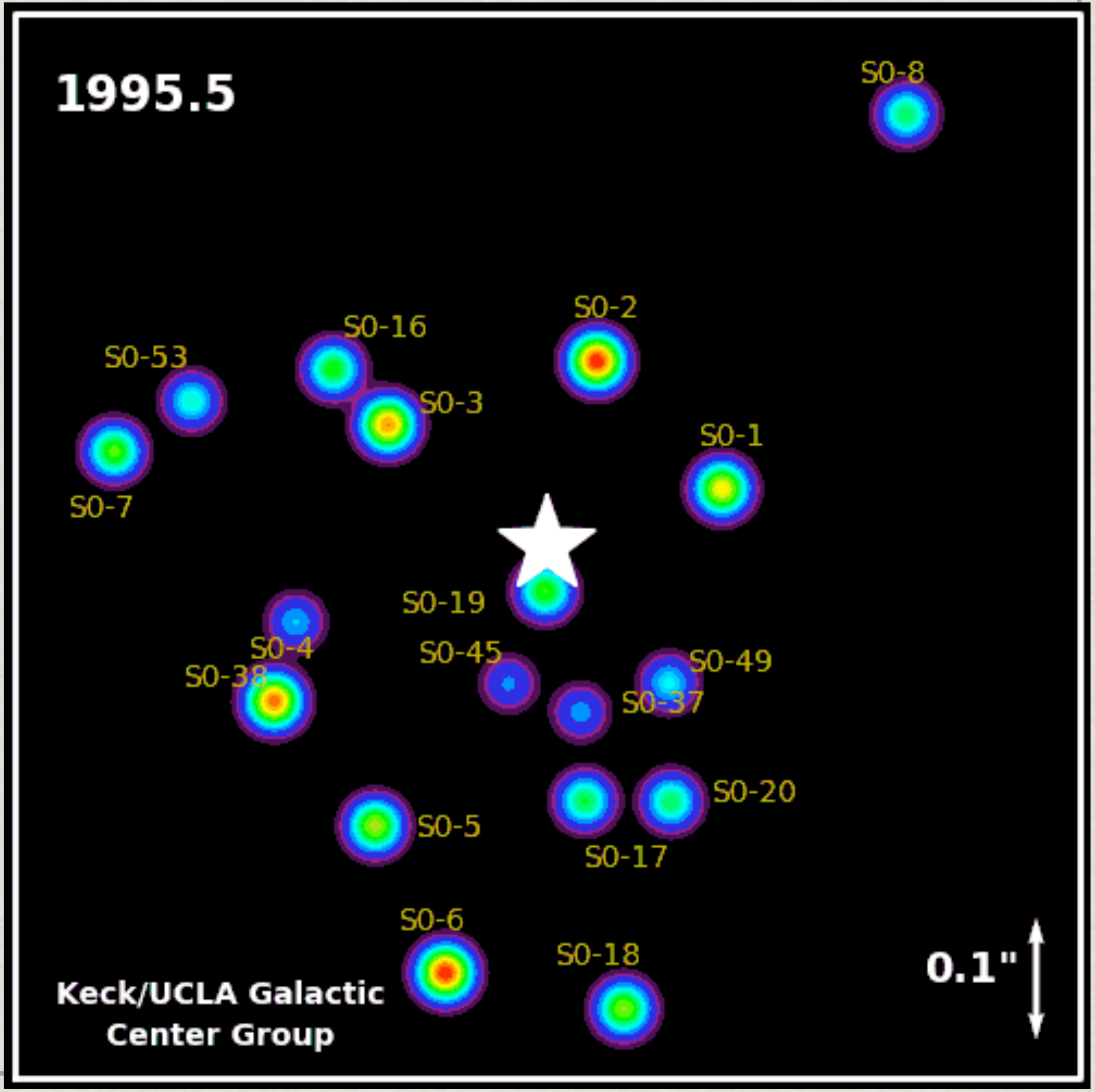


Black Holes

We observe black holes indirectly, through the influence of their gravity.

S0-2:
Orbital period = 15.78 years.
Closest approach 120 AU
Top speed: 5000 km/s
(11,000,000 mph!) 2% of c

S0-16 gets as close as 90 AU
from the BH.
(Pluto is only 40 AU from the sun)

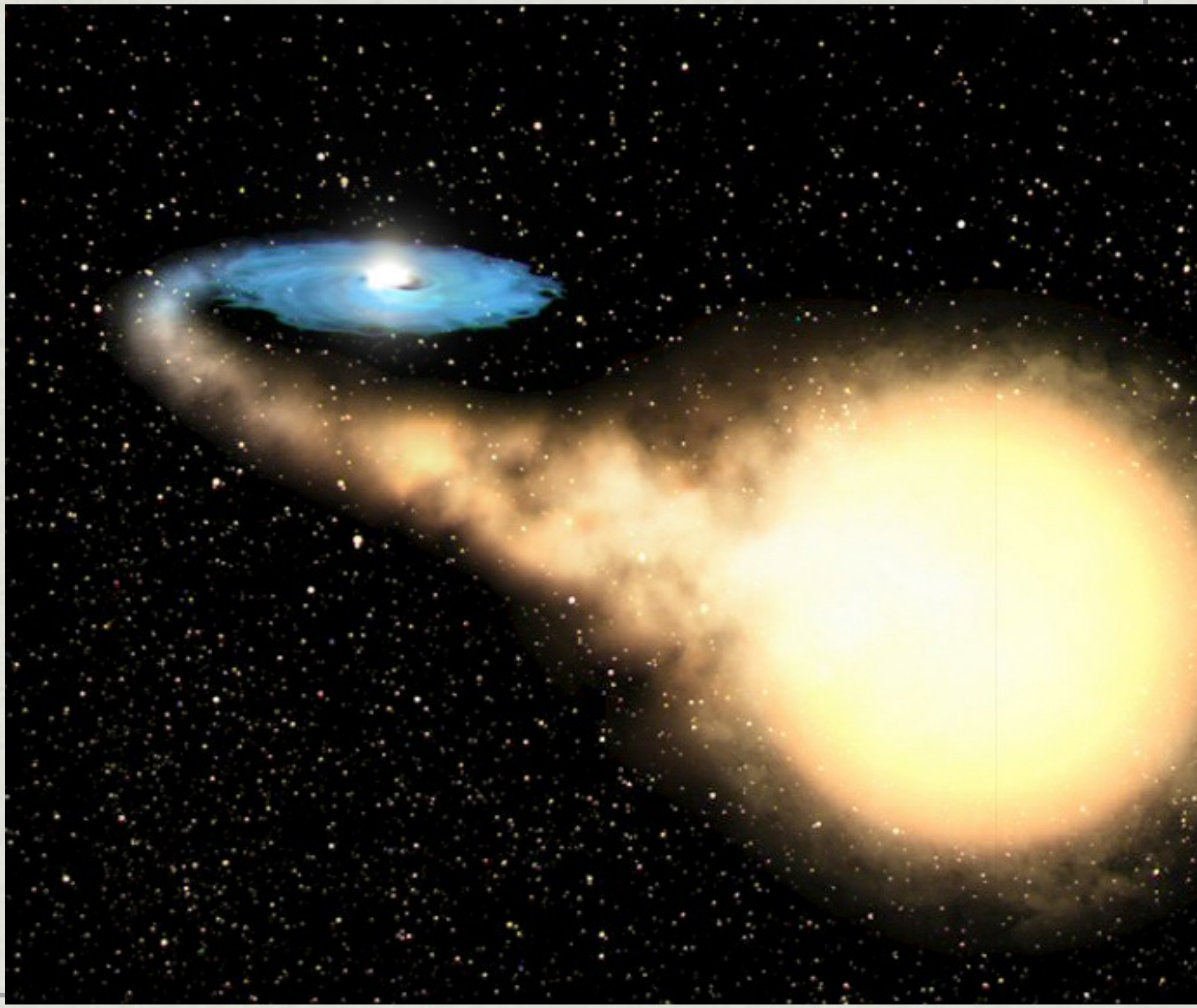


Black Holes

We observe black holes indirectly, through the influence of their gravity.

Black holes have strong gravitational pull on stuff that gets close: $F_{grav} = \frac{GMm}{r^2}$

If a star that collapses to a black hole has a nearby companion that becomes a red giant, the BH pulls in the gas from the expanding envelope.



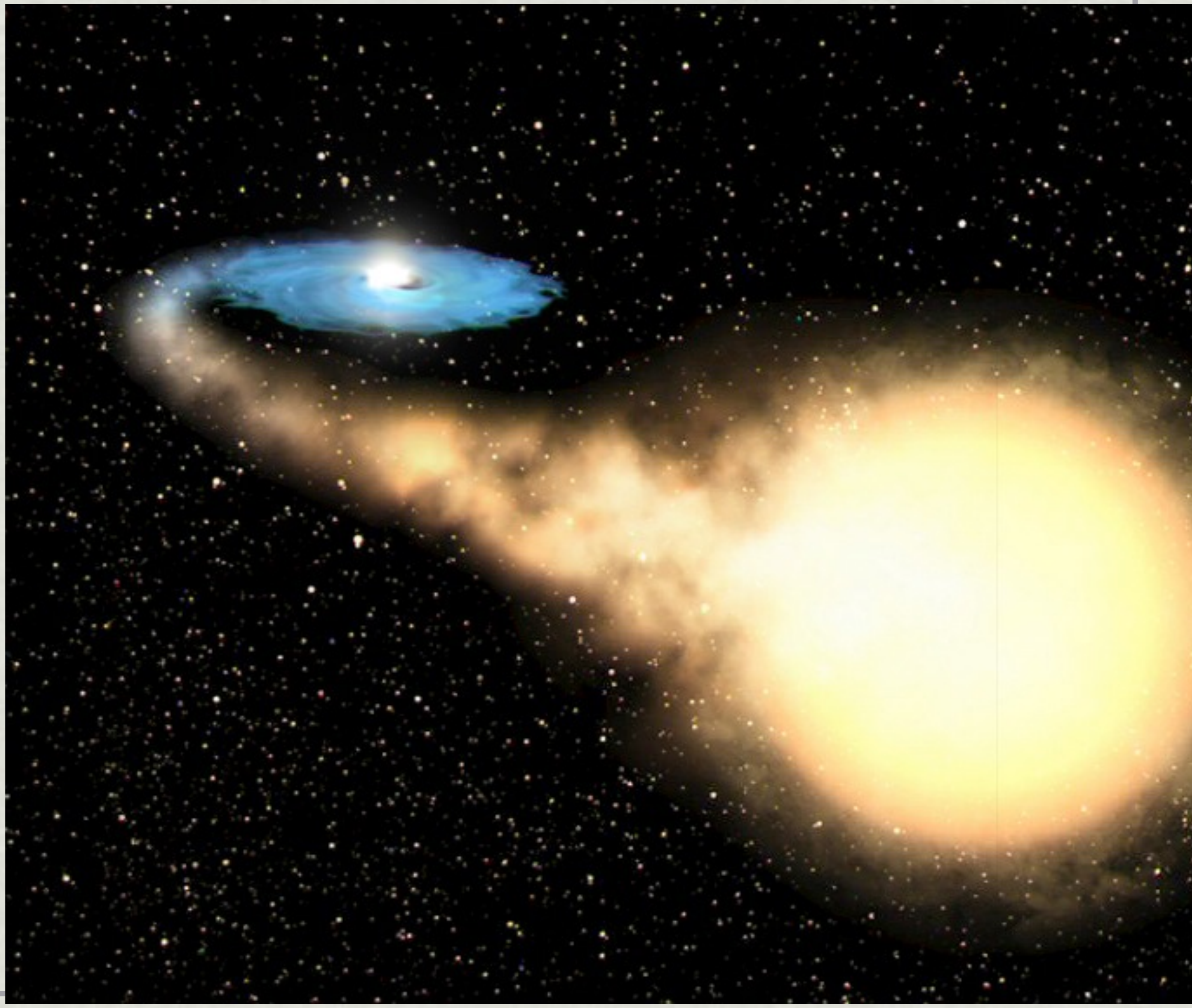
Black holes in the centers of galaxies can pull in gas from the rest of the galaxy.

Black Holes

As the gas falls in the atoms collide. The gas heats up due to friction and the release of gravitational potential energy.

The gas emits radiation, but not a thermal spectrum.

Can be incredibly bright, out-shine an entire galaxy.



Quasars

Quasars first discovered in 1963

"Quasi-Stellar Radio Source": very bright, star-like objects that also emit in the radio part of the EM spectrum. Not expected for a thermal spectrum.

Realized that the spectra showed chemical fingerprints of hydrogen, but with gigantic Doppler shifts.

Very distant* but still have large observed apparent brightness: must be ***really*** luminous!

$$\text{apparent brightness} = \frac{L}{4\pi d^2}$$

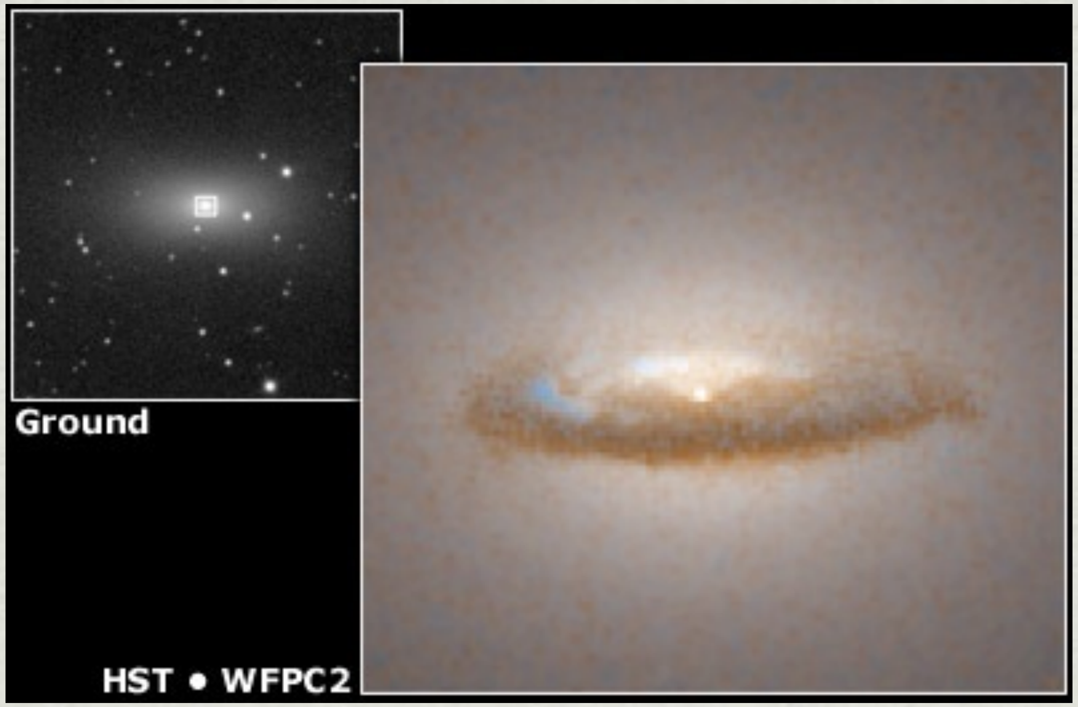
*we'll get to why a big doppler shift means a big distance when we talk about cosmology

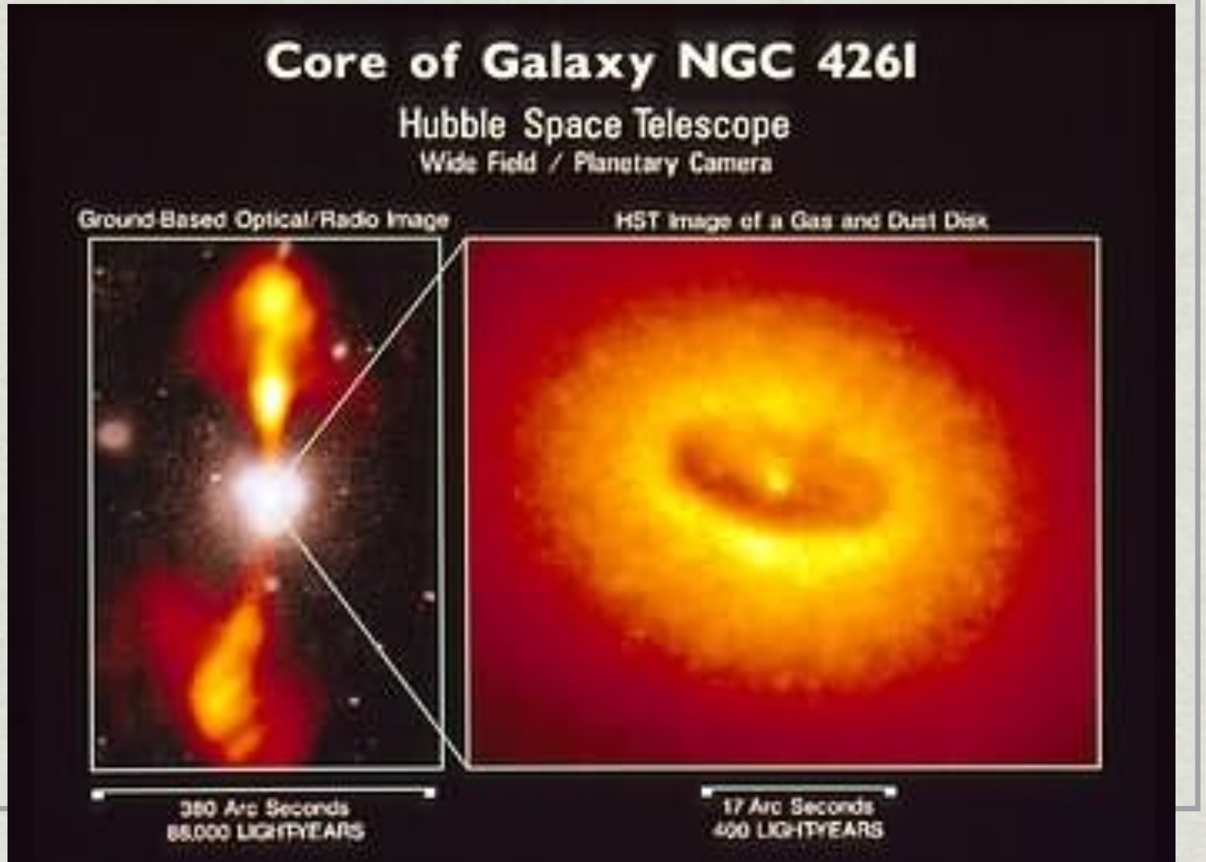
Quasars

Eventually, realized that quasars are black holes in the centers of galaxies.

That huge luminosity is the light from gas that is glowing from the energy it gains as it falls in to the black hole.

Infall converts gravitational potential energy to other kinds of energy. Stored in the energy levels of atoms, released as emission line spectra and other interactions



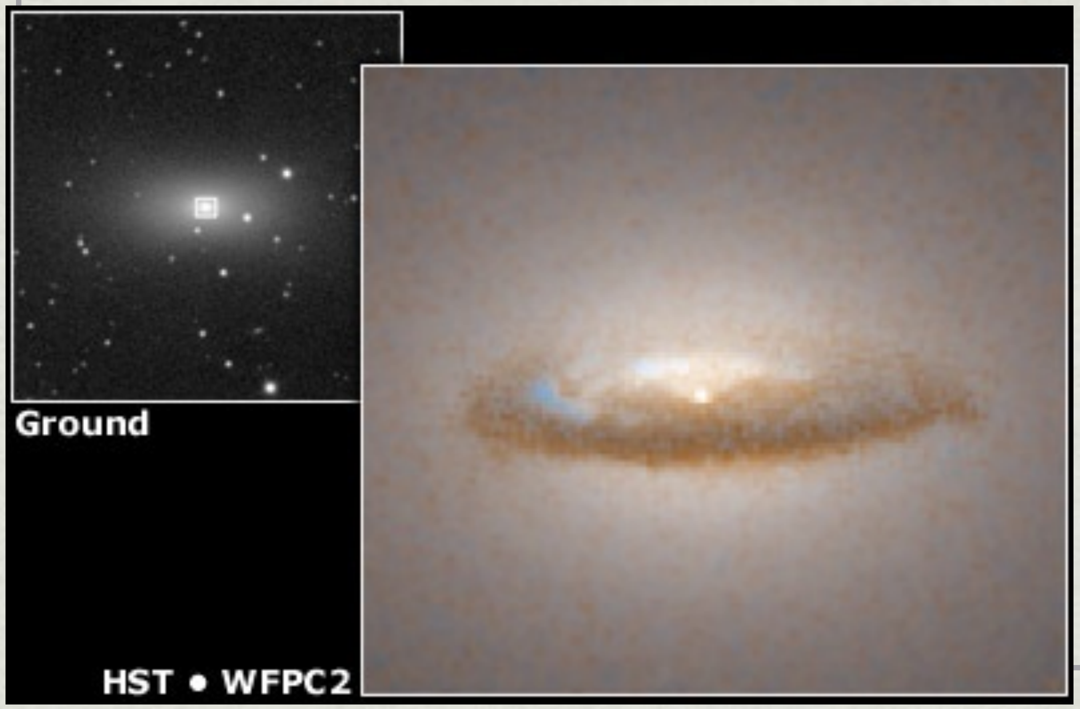


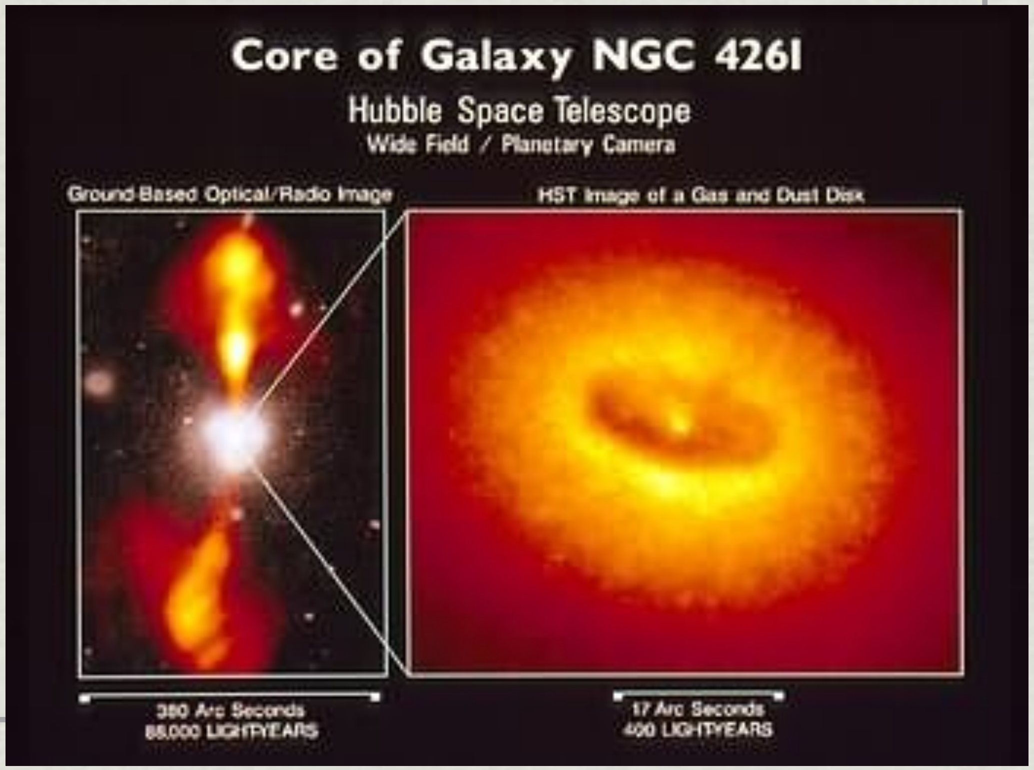
Quasars

Black holes gain mass as gas, stars, etc. fall in

They grow in mass over time if they have fuel.

Black holes in galaxies have plenty of fuel: stars, gas clouds, etc.





Quasars

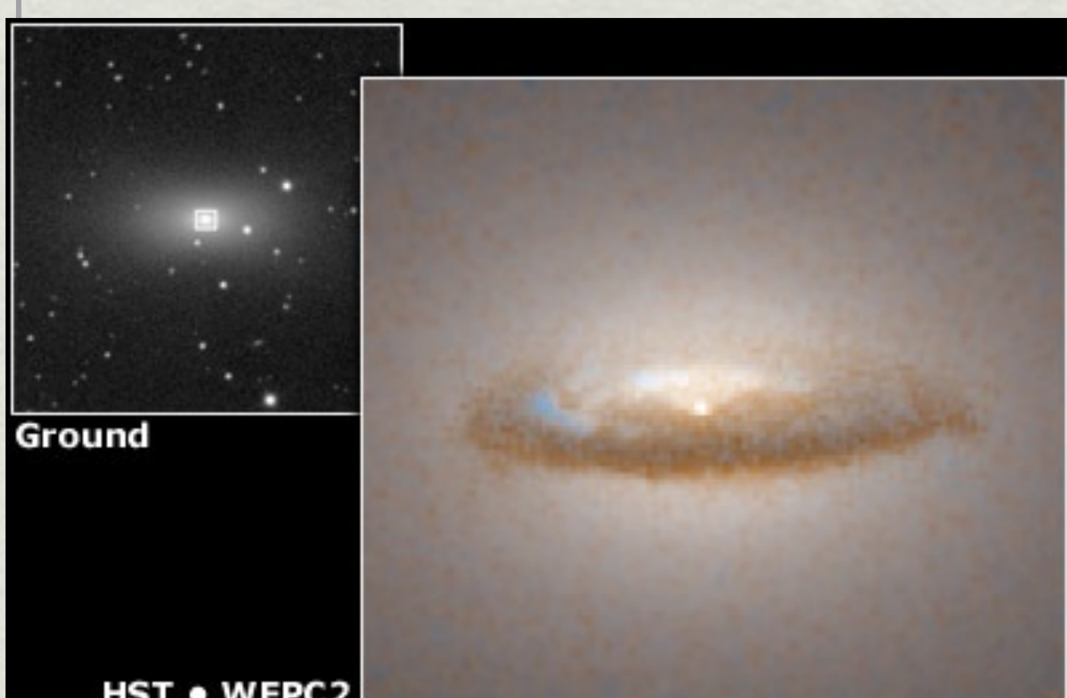
Quasars are very luminous so we can see them at very large distances

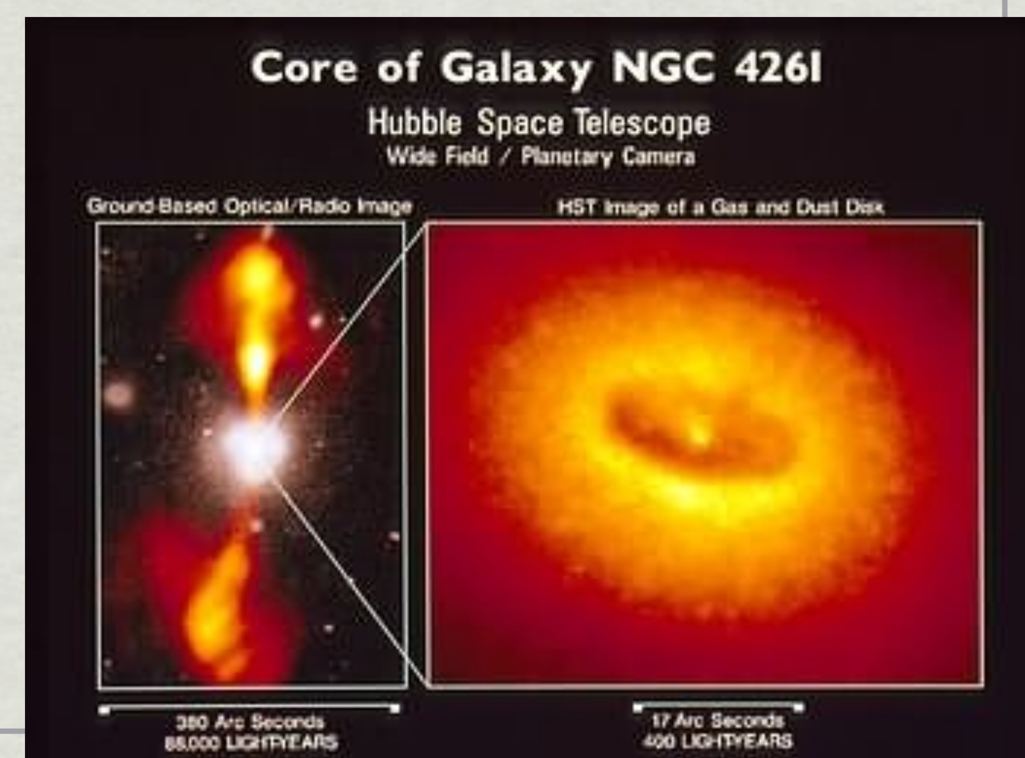
The constant speed of light means we see distant quasars as they were a very long time ago - light emitted by distant quasars is just getting here now

Most distant quasar known: seen when the universe was 6% of its current age, 770 million years after the big bang

Quasar masses: billions of times the mass of the sun

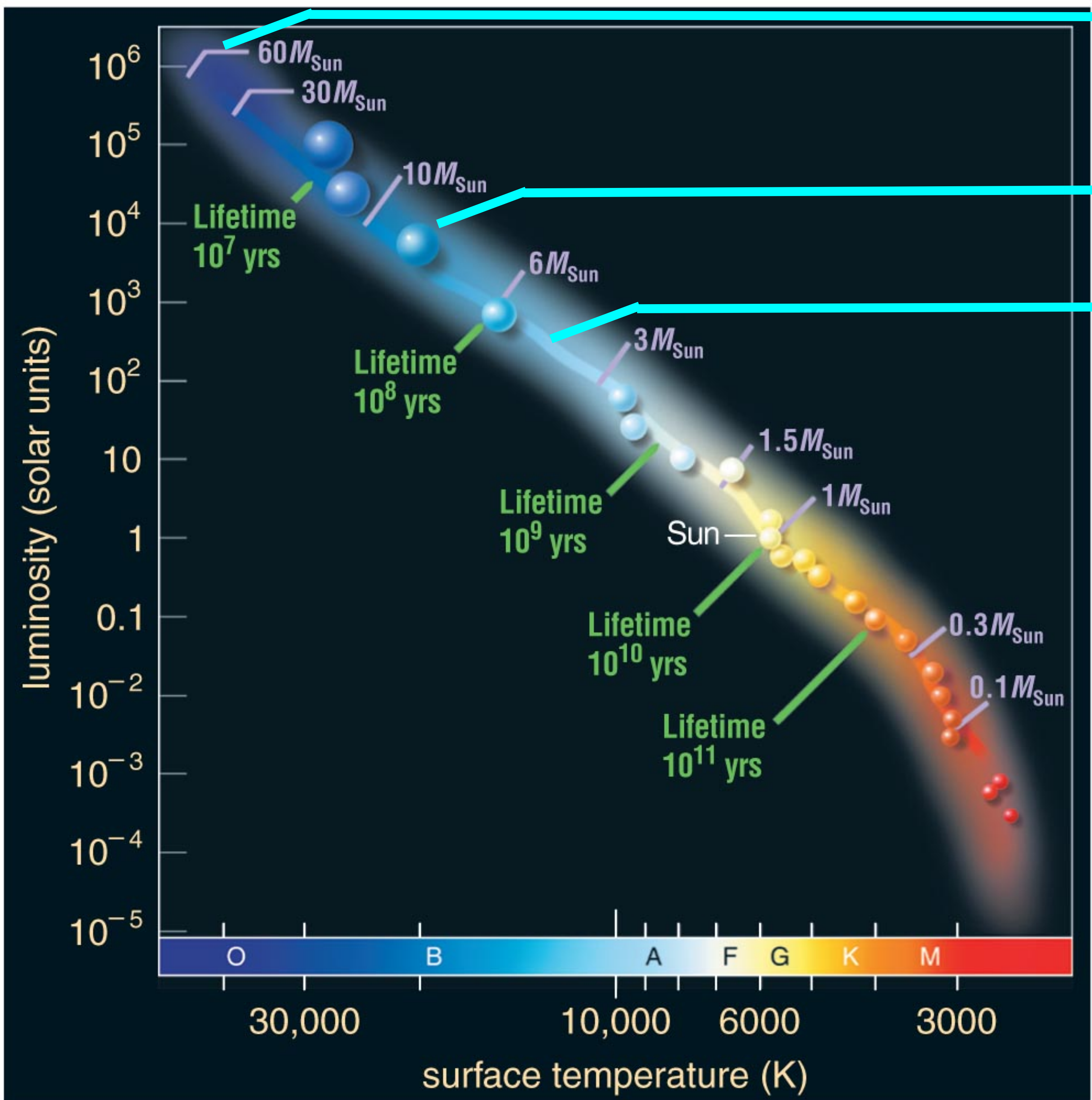
If BH start out as the collapsed core of a massive star, there is not a lot of time for a BH grow so much!





What Happens After the Main Sequence ?

Everything depends on mass.



Some definitions:

High mass stars:
$M > 8\ M_{sun}$

Intermediate mass:
$2 < M < 8\ M_{sun}$

These have similar evolution

Low mass stars:
$M < 2\ M_{sun}$

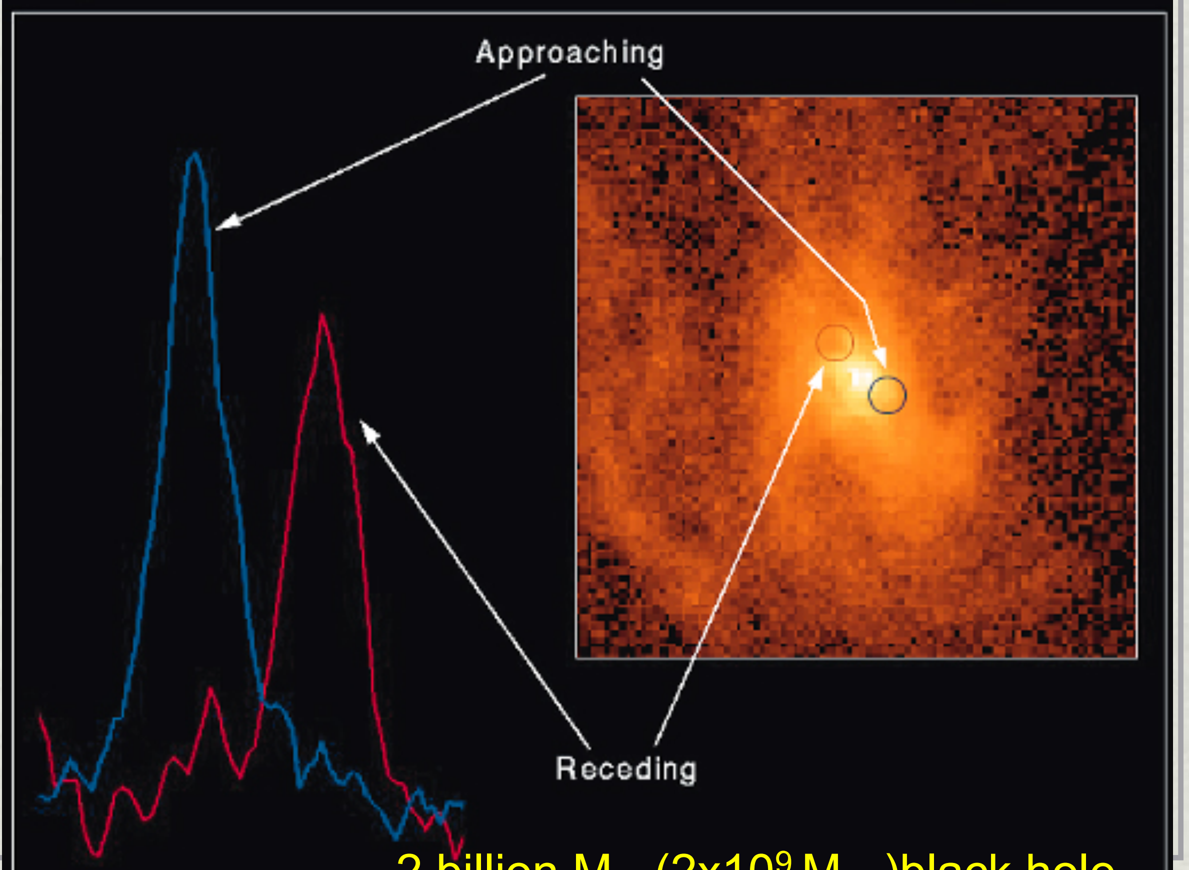
General Relativity

Centers of galaxies = supermassive black holes

Stars and gas close to the centers of Galaxies have huge Doppler shifts

Shows huge mass exists in a tiny volume

R_s = 40 AU



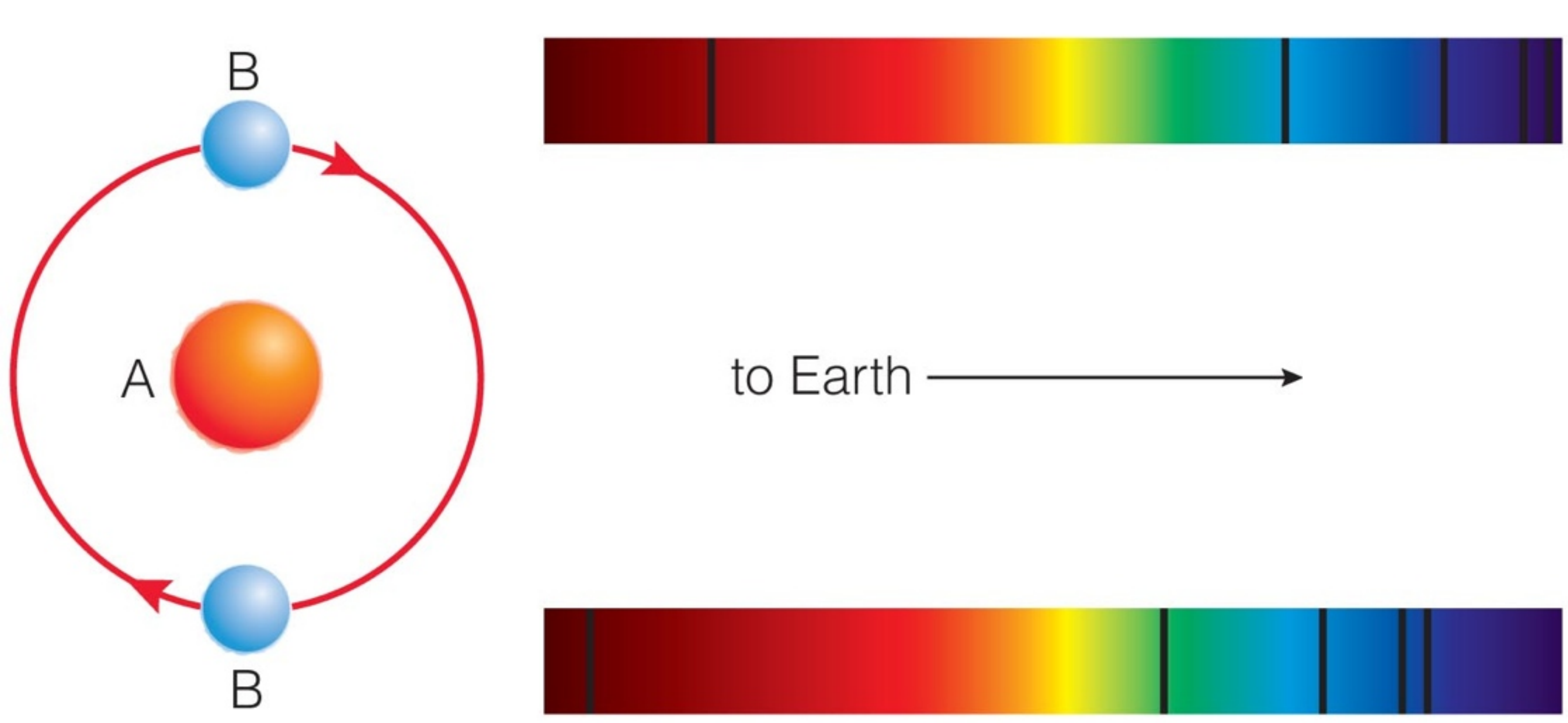
2 billion $M_\odot$ ($2\times10^9\ M_\odot$)black hole

Measuring Masses of Stars: 2

How can we measure the velocities of stars in their orbits?

Doppler shift of spectral lines → velocity of stars in orbits

View orbit looking down from top



General Relativity

Albert Einstein, 1916, wonders, “What if I throw light into a black hole ?”

General Relativity

Fact #1:

Inertial mass: $F = \mathbf{m}a$

and

Gravitational mass: $F_{grav} = \frac{GM\mathbf{m}}{r^2}$

are the same.

To put it another way: Acceleration due to gravity is exactly the same as the acceleration by any other force

General Relativity

Fact #1:

Inertial mass: $F = \mathbf{m}a$ and Gravitational mass: $F_{grav} = \frac{GM\mathbf{m}}{r^2}$
are the same.

Acceleration due to gravity is exactly the same as the acceleration by any other force

There is no particularly good reason this has to be true in our universe, but it is.

For example, the electromagnetic force on particle 1 depends on the charges q:

$$F_{em,1} = m_1 a = \frac{Kq_1 q_2}{r^2}$$

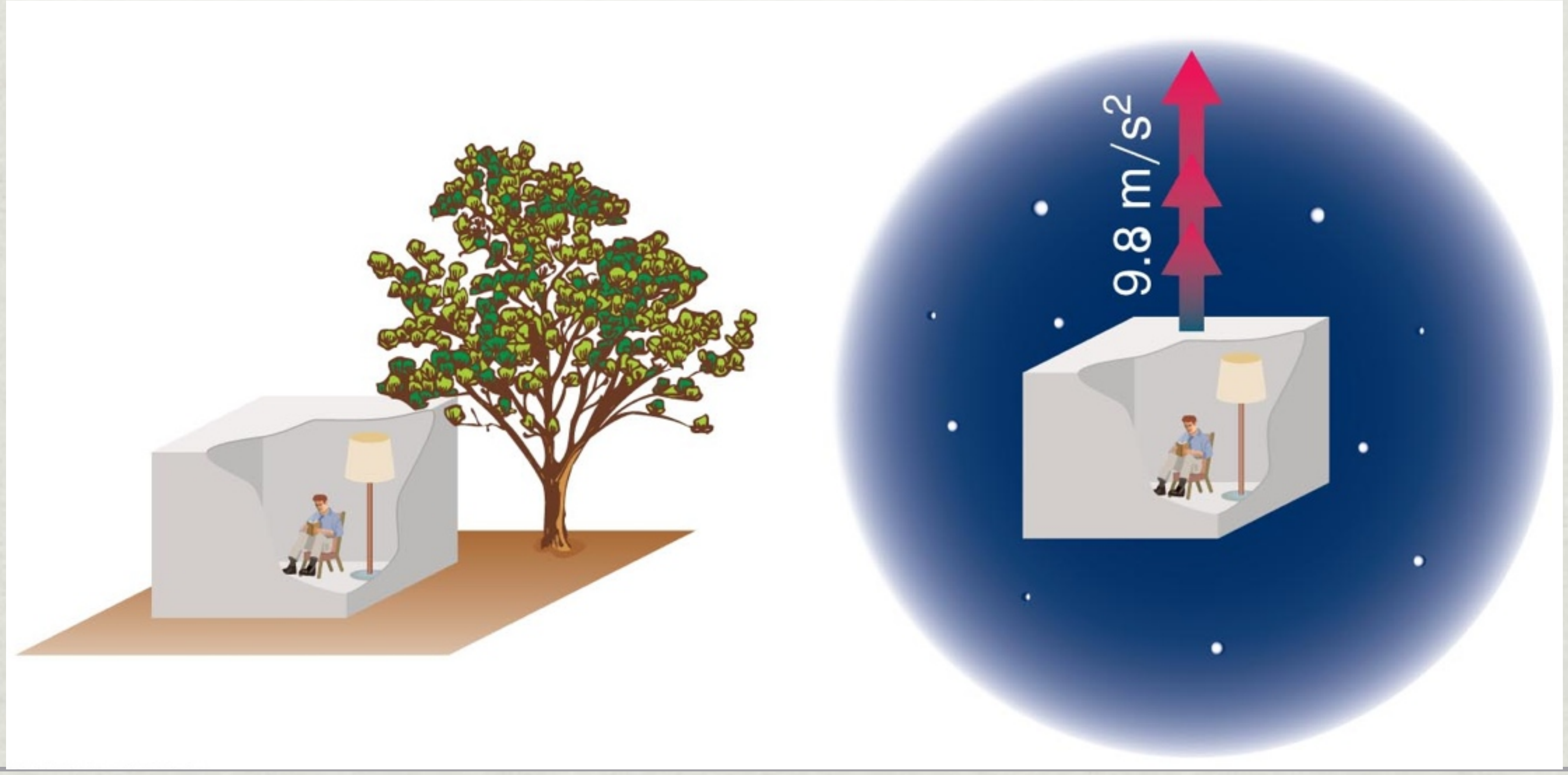
Gravity: $F_{grav,1} = m_1 a = \frac{GMm_1}{r^2}$

What if gravity depended on "gravitational charge" that was different from the inertial mass?

General Relativity

Fact #1:
Inertial mass IS gravitational mass.

Equivalence principle: being in a spaceship accelerating at $9.8\ m/s^2$ is the same to you (and to photons) as sitting on the surface of the earth, held down by gravity

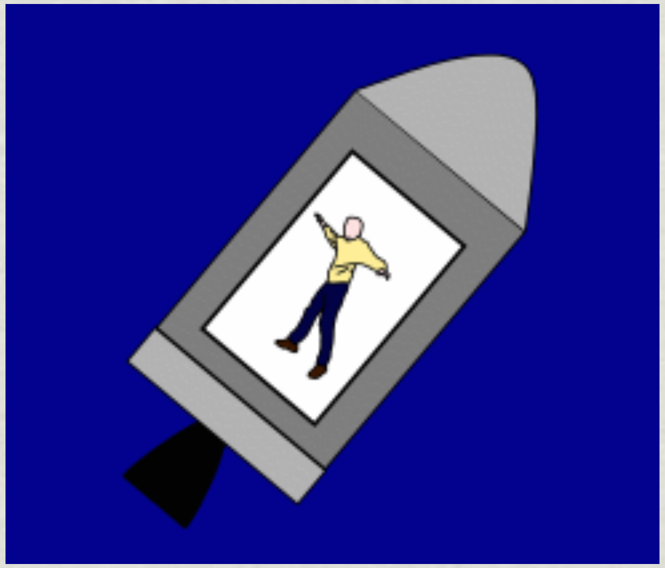


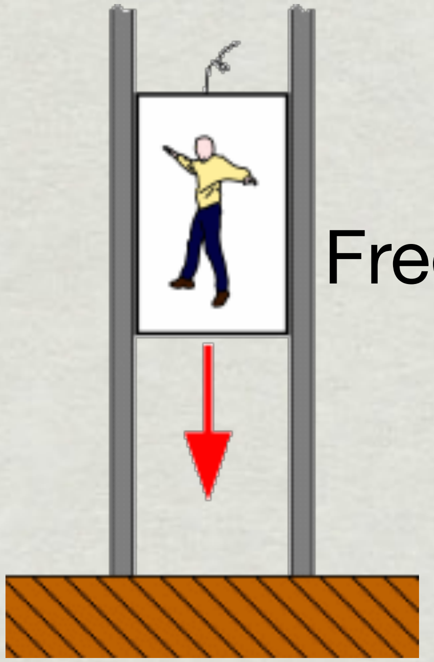
General Relativity

Equivalence principle: Being in free-fall is the same to you and to photons as being in no gravitational field.

"Wait a minute! If something is in free-fall, it is accelerating, right? Being far away from mass means no acceleration in a gravitational field! What's equivalent about those two situations?"

Rocket very far away from any mass, no gravitational force acting on it





Free-falling elevator

General Relativity

A It accelerates up past your head in the rocket and accelerates to the floor in the elevator

B It floats next to you in both situations

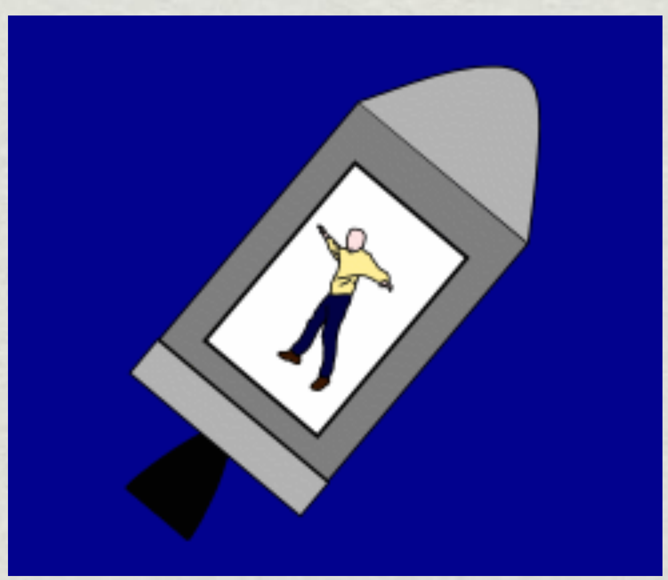
C The pen floats next to you in the rocket and falls to the floor in the elevator

Equivalenc … e to you and to photons as

“Wait a mi … celerating, right? Being far a … in a gravitational field! Wha … ns?”

What happens if you drop a pen in both these situations?

Rocket very far away from any mass, no gravitational force acting on it



Free-falling elevator

General Relativity

Equivalenc … e to you and to photons as

"Wait a mi … celerating, right? Being far a … in a gravitational field! Wha … ns?"

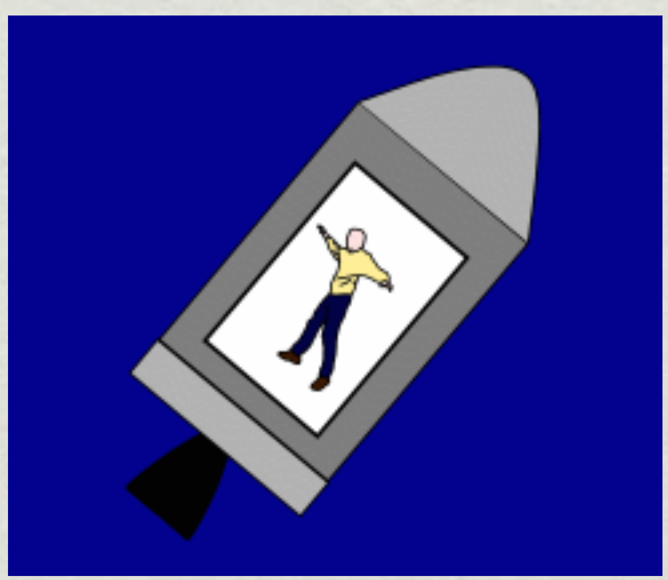
A It accelerates up past your head in the rocket and accelerates to the floor in the elevator

B It floats next to you in both situations

C The pen floats next to you in the rocket and falls to the floor in the elevator

What happens if you drop a pen in both these situations?

Rocket very far away from any mass, no gravitational force acting on it



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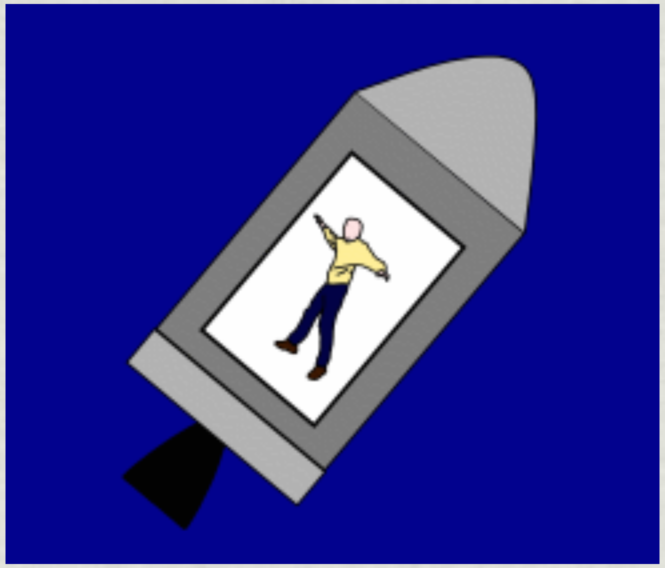
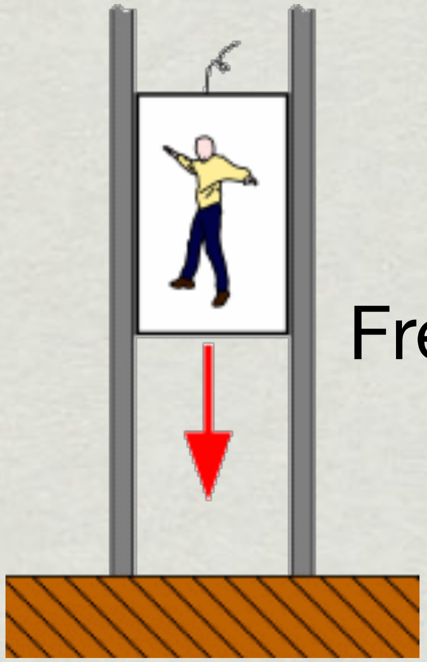




Free-falling elevator

In free-fall everything accelerates at the same rate, you and the pen. Nothing is pushing back to exert a force — “weightlessness”

So you can’t tell whether you are far away from any mass with no acceleration, or in free-fall and accelerating freely. So those two conditions are equivalent: physics works the same in both situations.

The pen “floats”

General Relativity

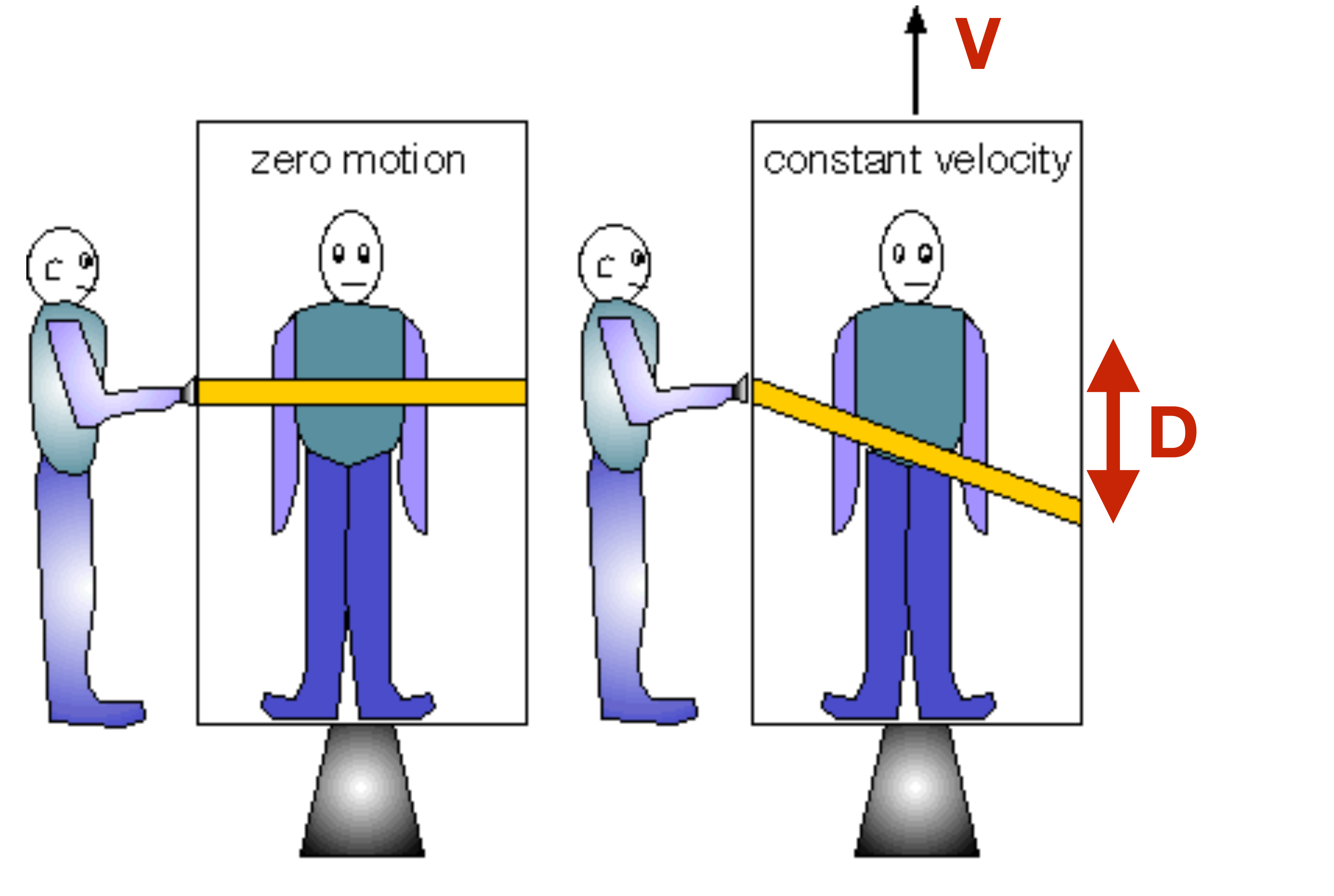
Fact #1:
Inertial mass IS gravitational mass.

If the elevator is moving at constant velocity, the elevator moves up in the time it takes for photons to travel across the elevator.

Distance=Speed*Time

In the time T it takes the light to cross the elevator, the elevator moves up distance D at speed S

So the light hits the opposite wall distance D lower than your friend's flashlight



General Relativity

Fact #1:

Inertial mass IS gravitational mass.

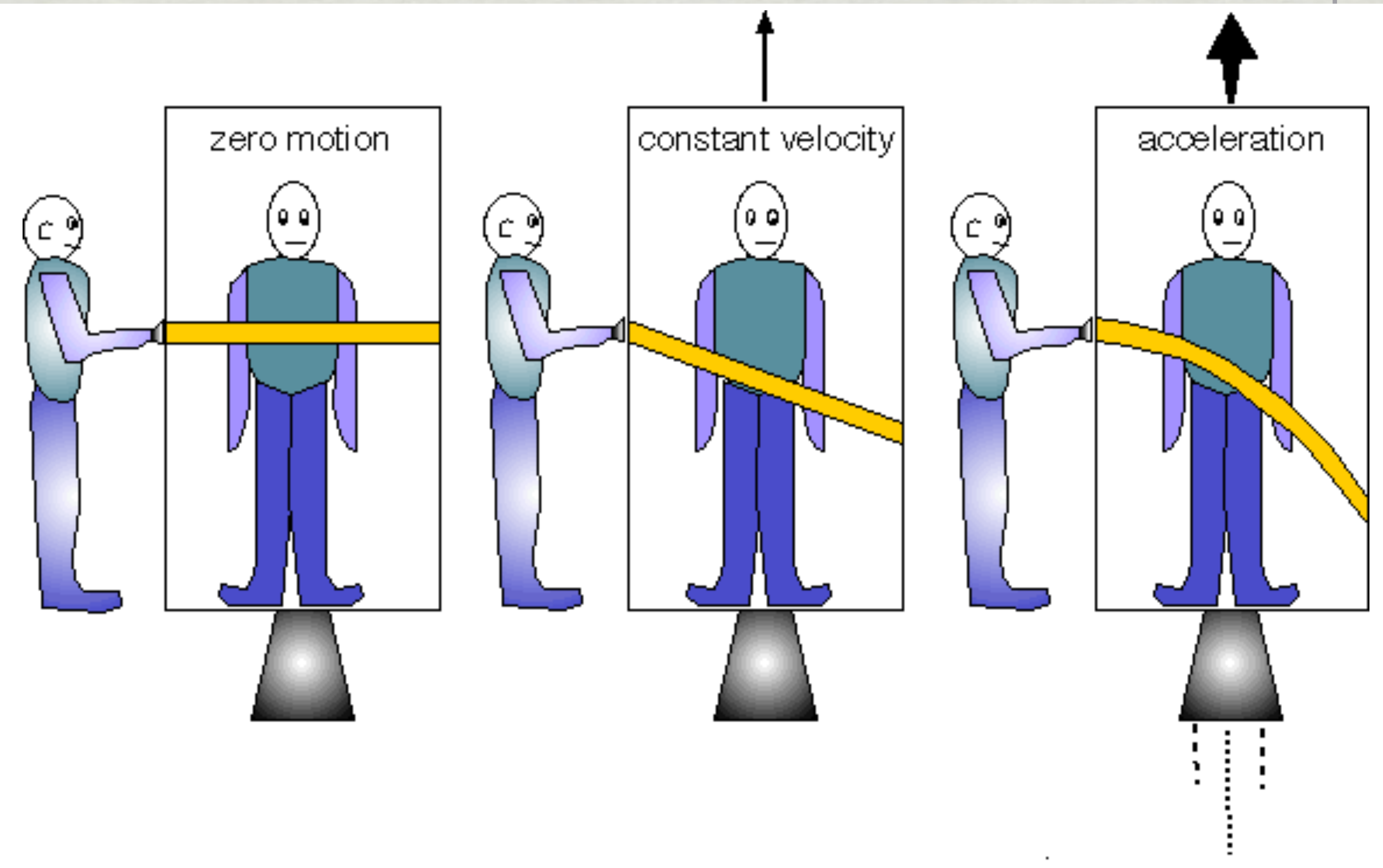
What if your elevator is accelerating? If your stationary friend shines a beam of light across you elevator, you should see it bend as you accelerate past it

Distance=Speed*Time.

If you and your elevator are accelerating, your speed is changing.

So the elevator is moving up faster when the light hits the wall than when it left the flashlight.

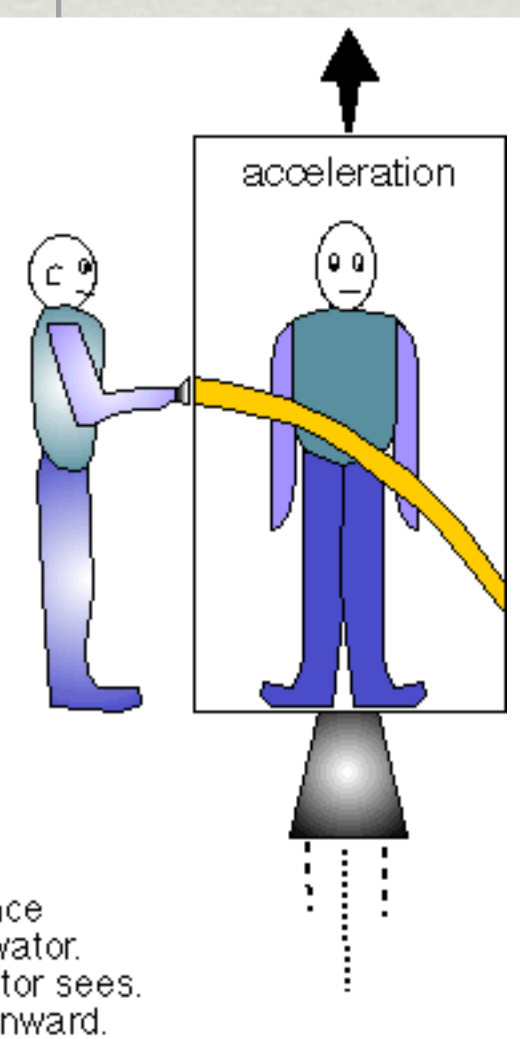
You see the light bend



General Relativity

Fact #1:
Inertial mass IS gravitational mass.

You should see a beam of light from a stationary friend bend if you are accelerating OR in a gravitational field!



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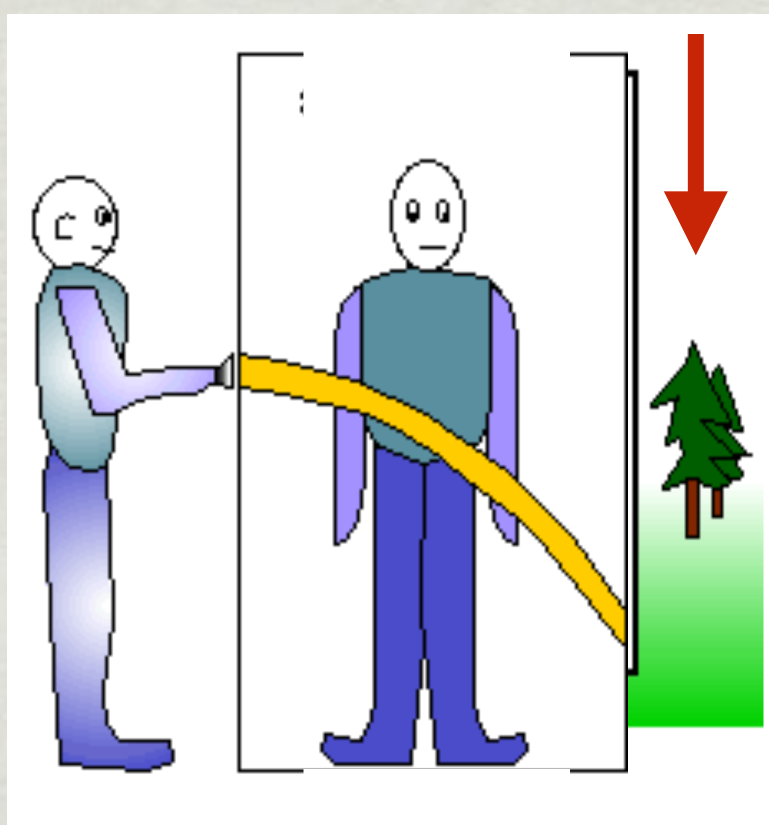
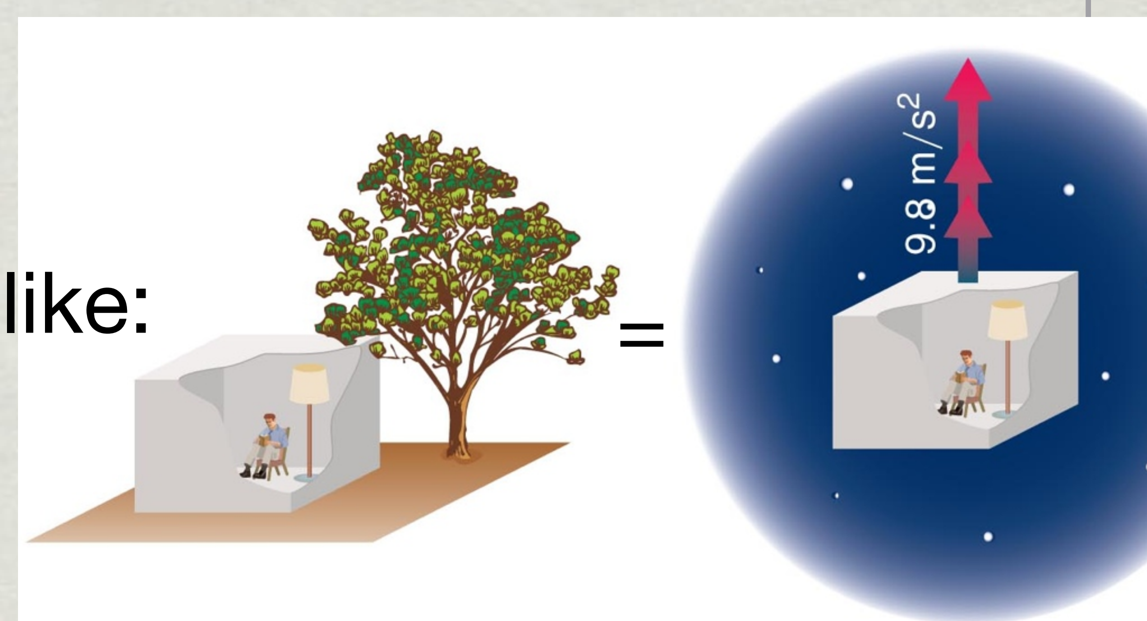
Gravity



Just like:

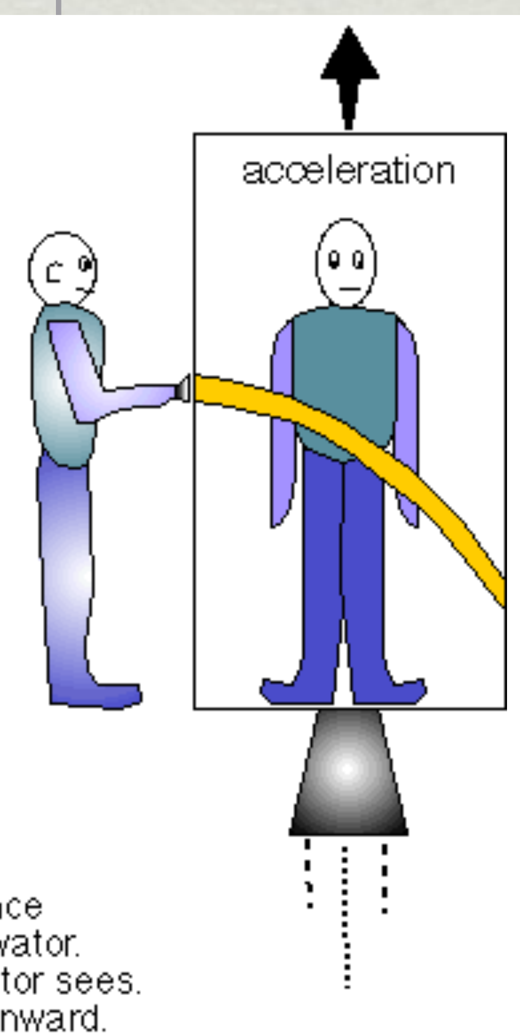


General Relativity

Fact #2:
Photons do not have mass

So how does gravity act on photons to bend the path (accelerate!) of light?

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



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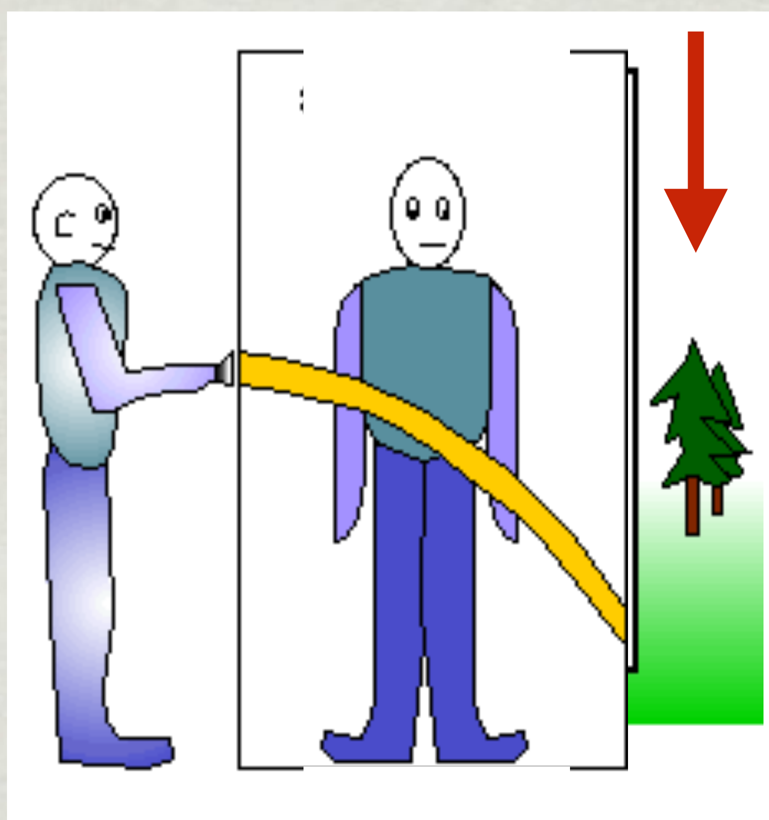
Gravity



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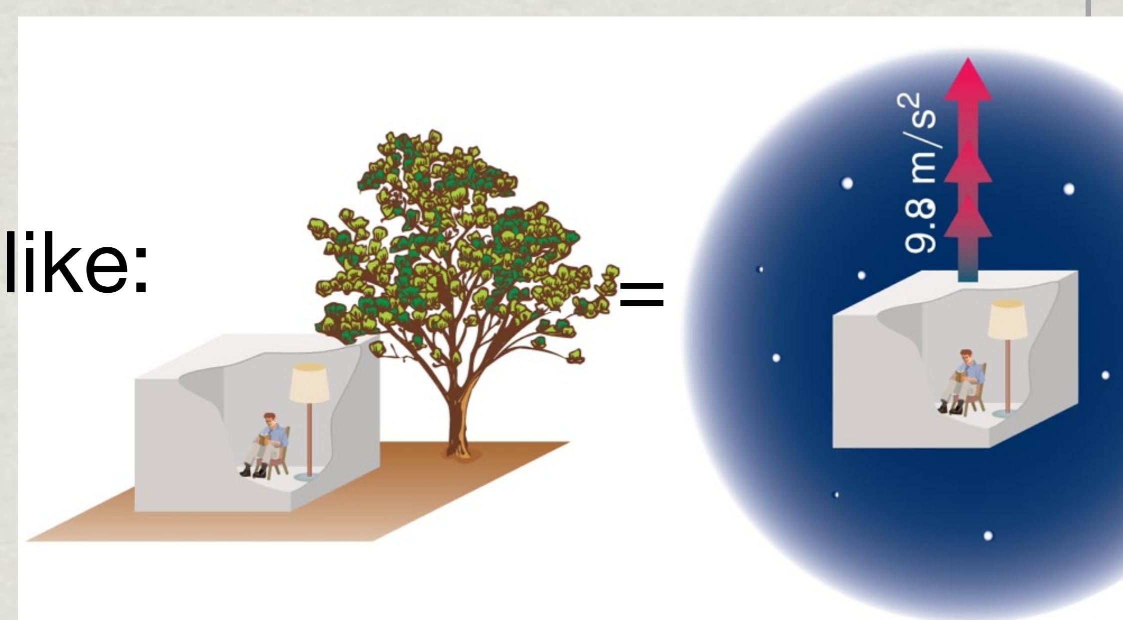


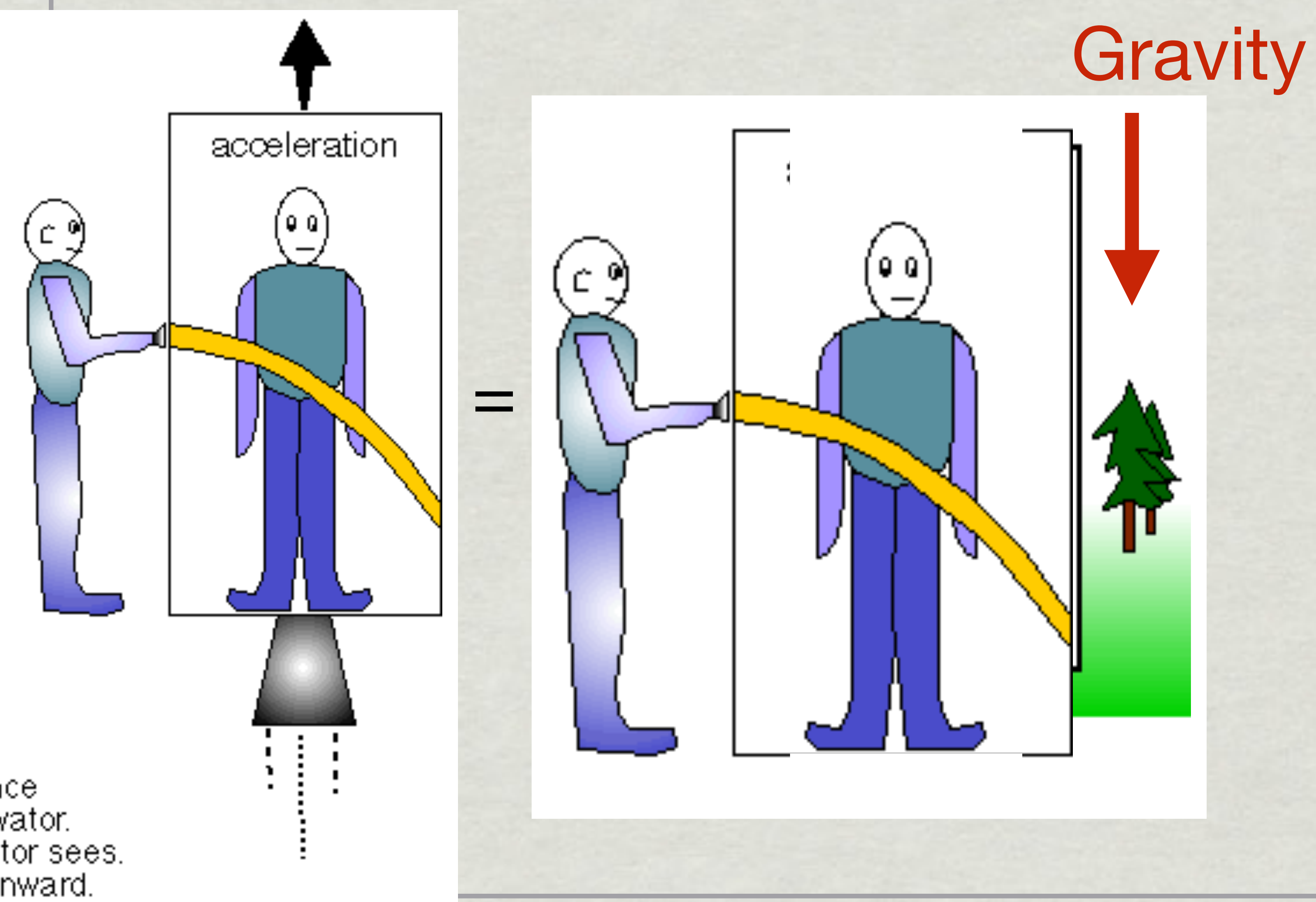
General Relativity

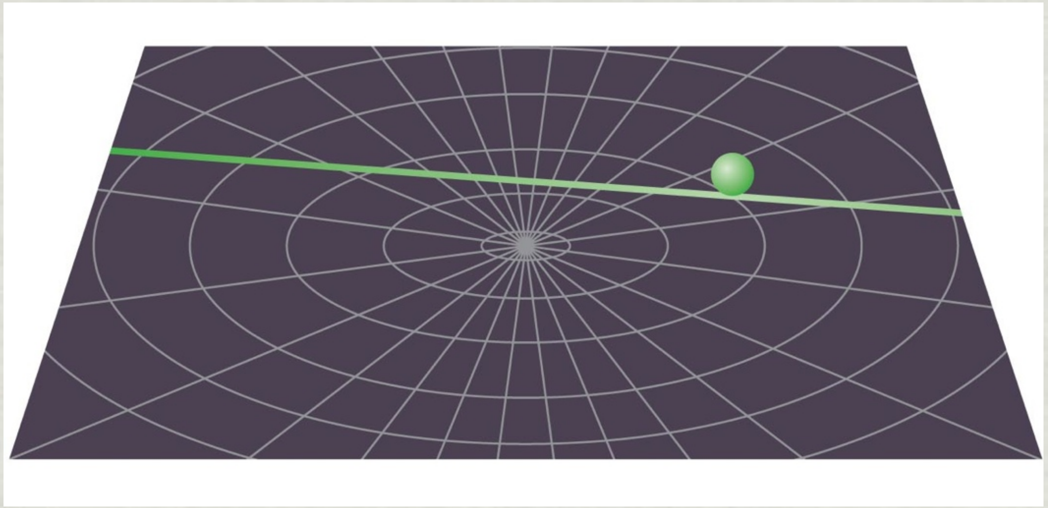
Fact #2:
Photons do not have mass

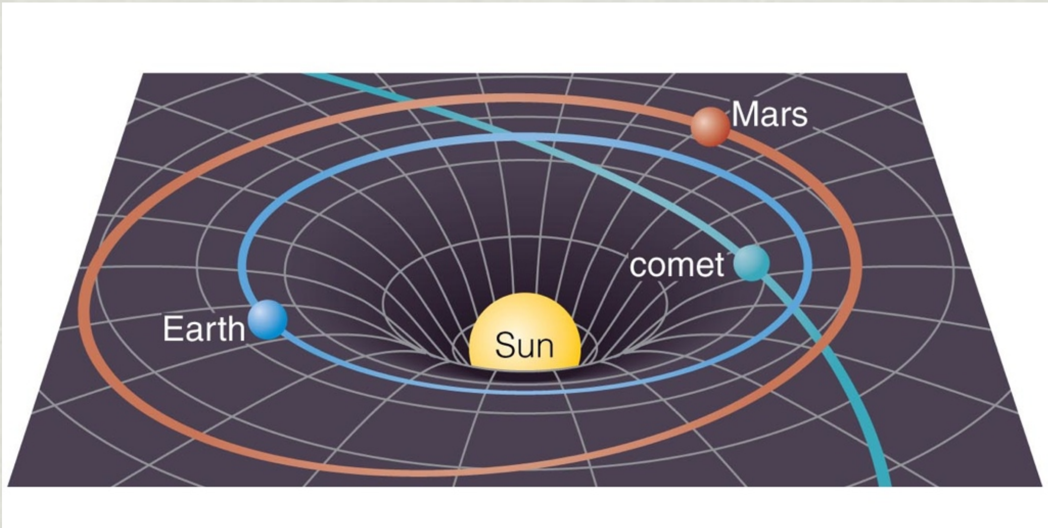
So how does gravity act on photons to bend the path (accelerate!) of light?

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

It can't: space itself curves in a gravitational field!

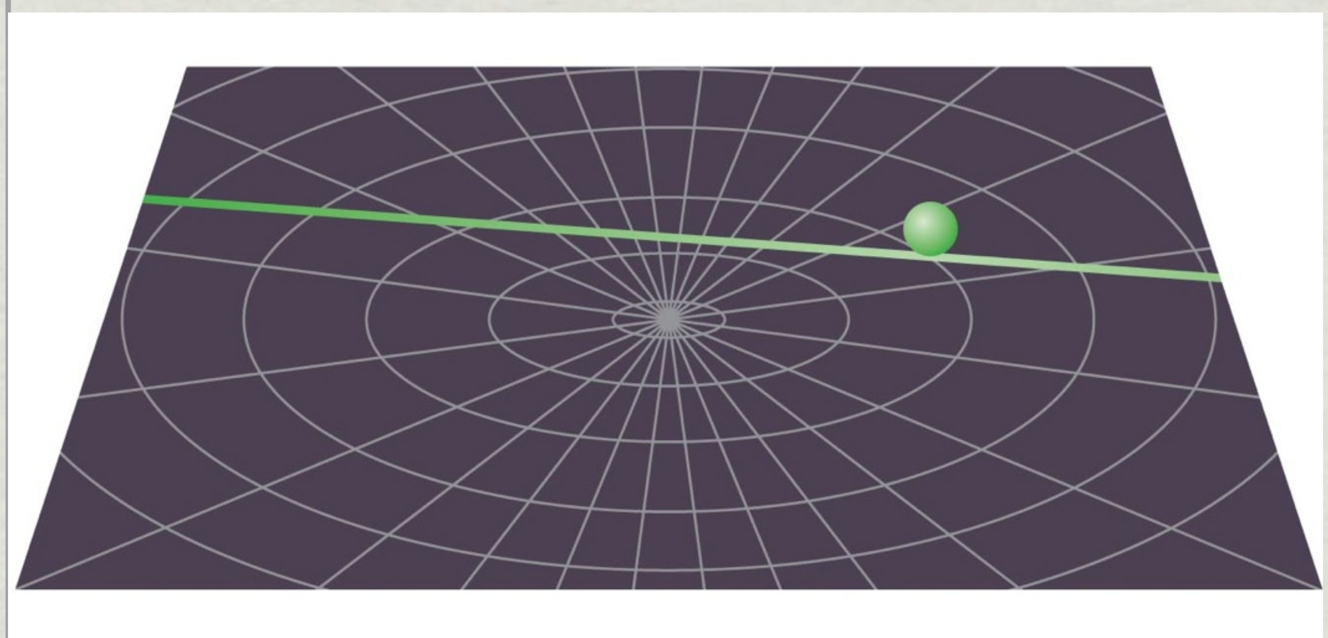


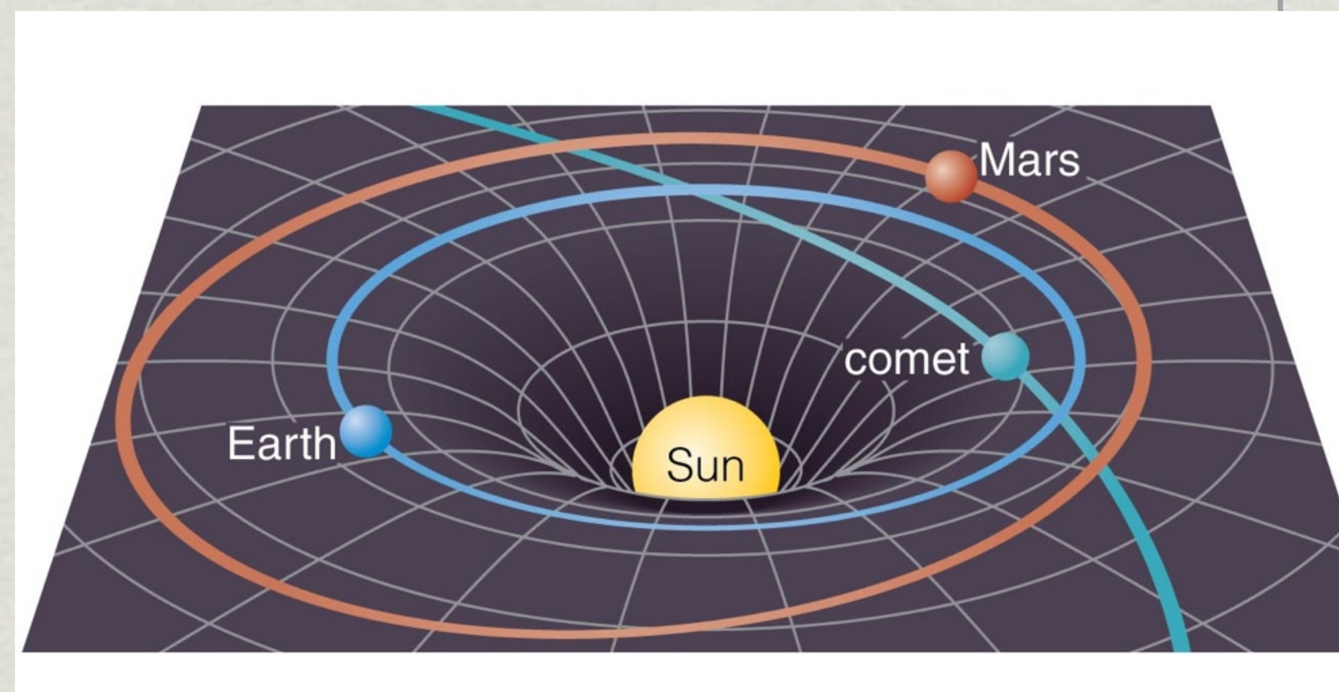




General Relativity

Implication #1:
The path of light is always "straight", but the space the light is traveling in is bent by gravity.

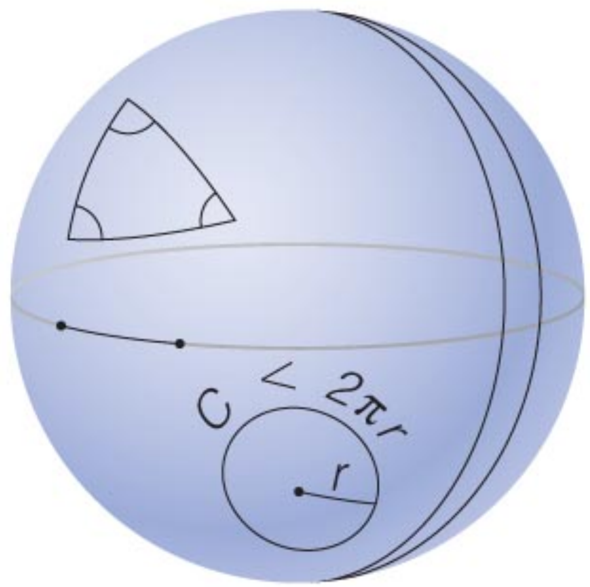




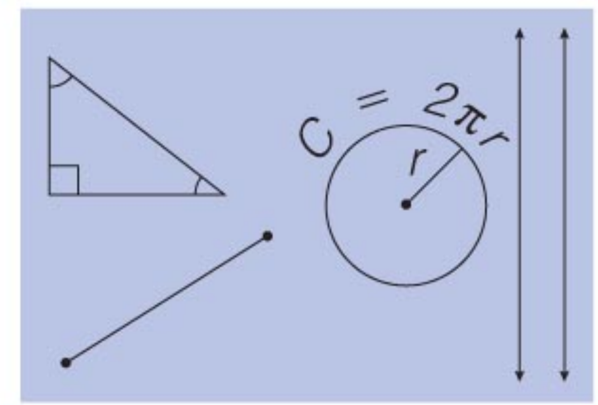
"straight line" = the shortest distance between two points.

The geometry changes, so the definition of "straight line" changes

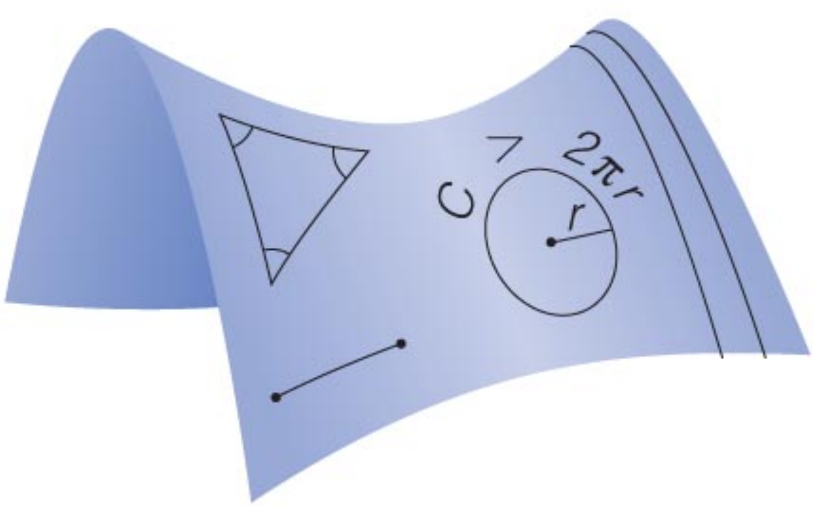
Spacetime and Geometry



Rules of spherical geometry.



Rules of flat geometry.



Rules of saddle-shaped geometry.

Shortest path between two points depends on geometry:

Flat geometry: line

Sphere: arc of Great Circle

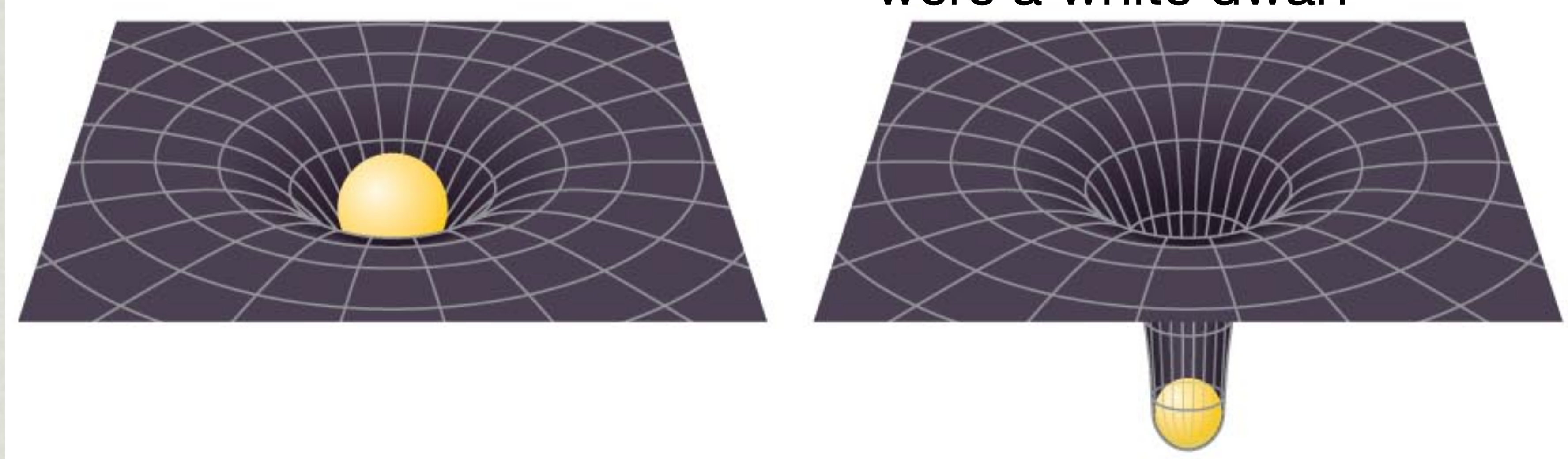
Saddle: piece of Hyperbola

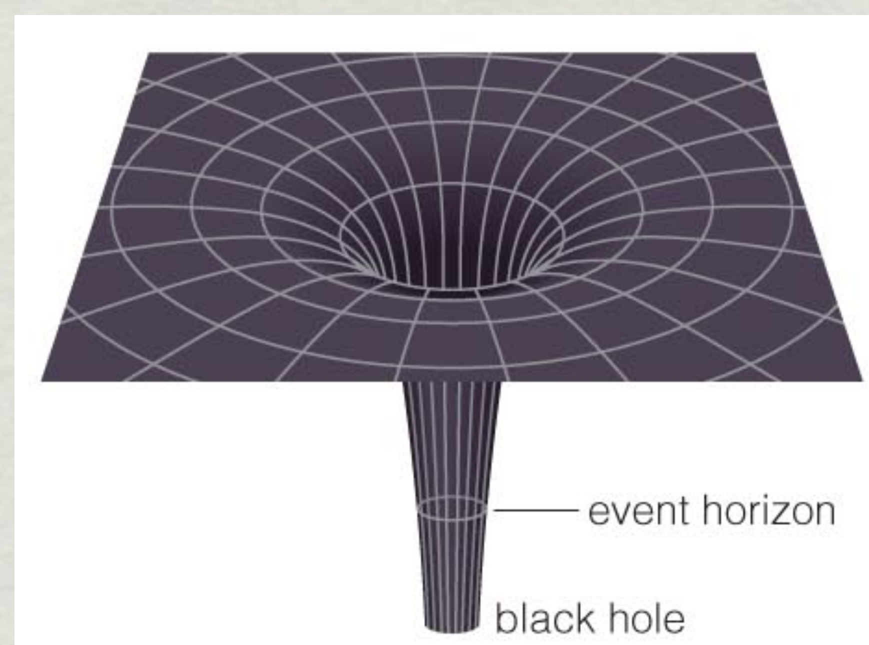
General Relativity

Implication #1:
The path of light is always straight, but space is bent by gravity.

Space curved near the sun

Space more curved if the sun were a white dwarf





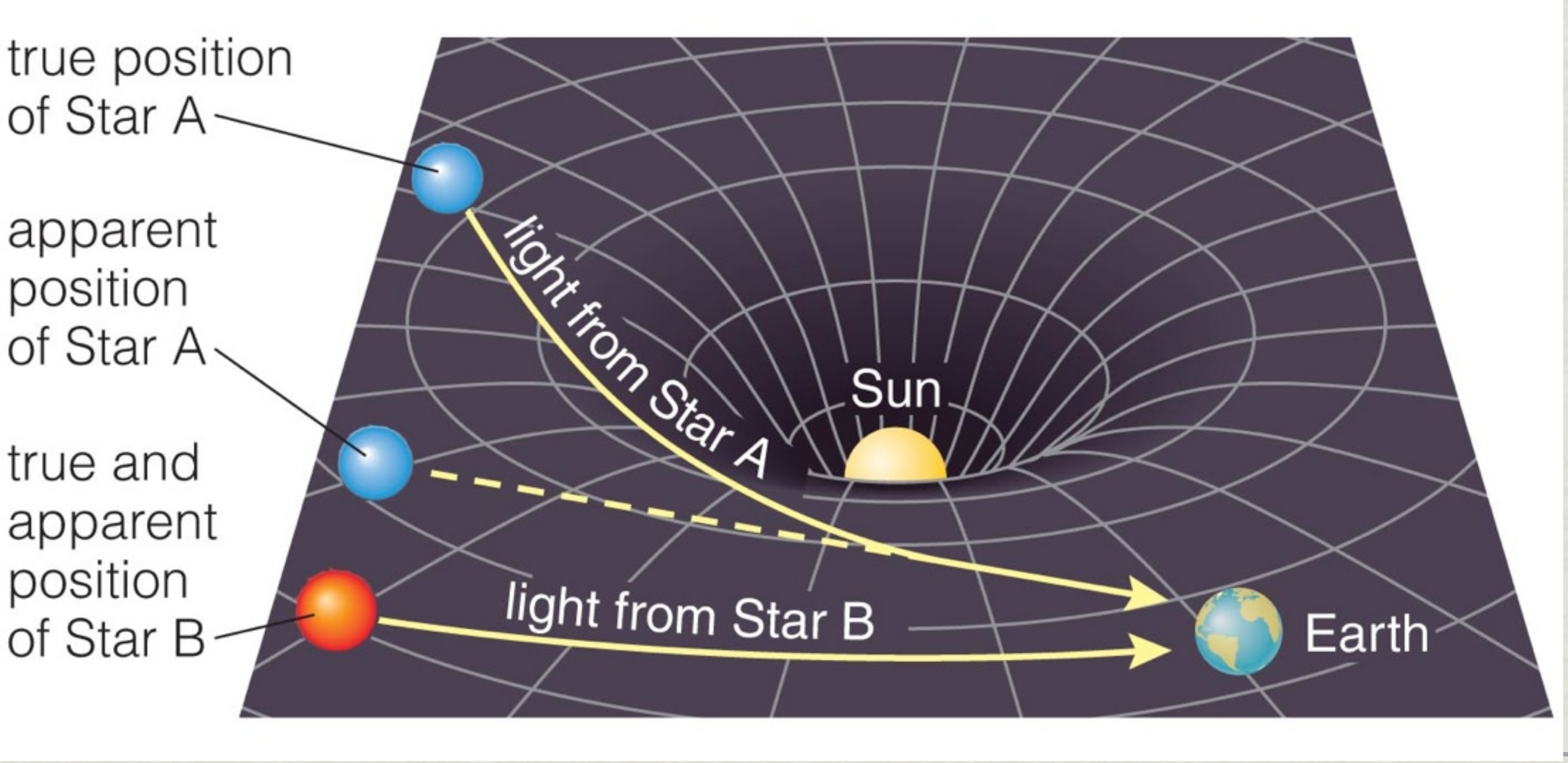
Space ***very*** curved if the sun were a black hole

The denser the mass, the more it warps space, the more strongly space is curved.

General Relativity

Implication #1.5:
Gravitational Lensing: background stars will appear to move when observed along a sight-line near a massive object. Like the sun.

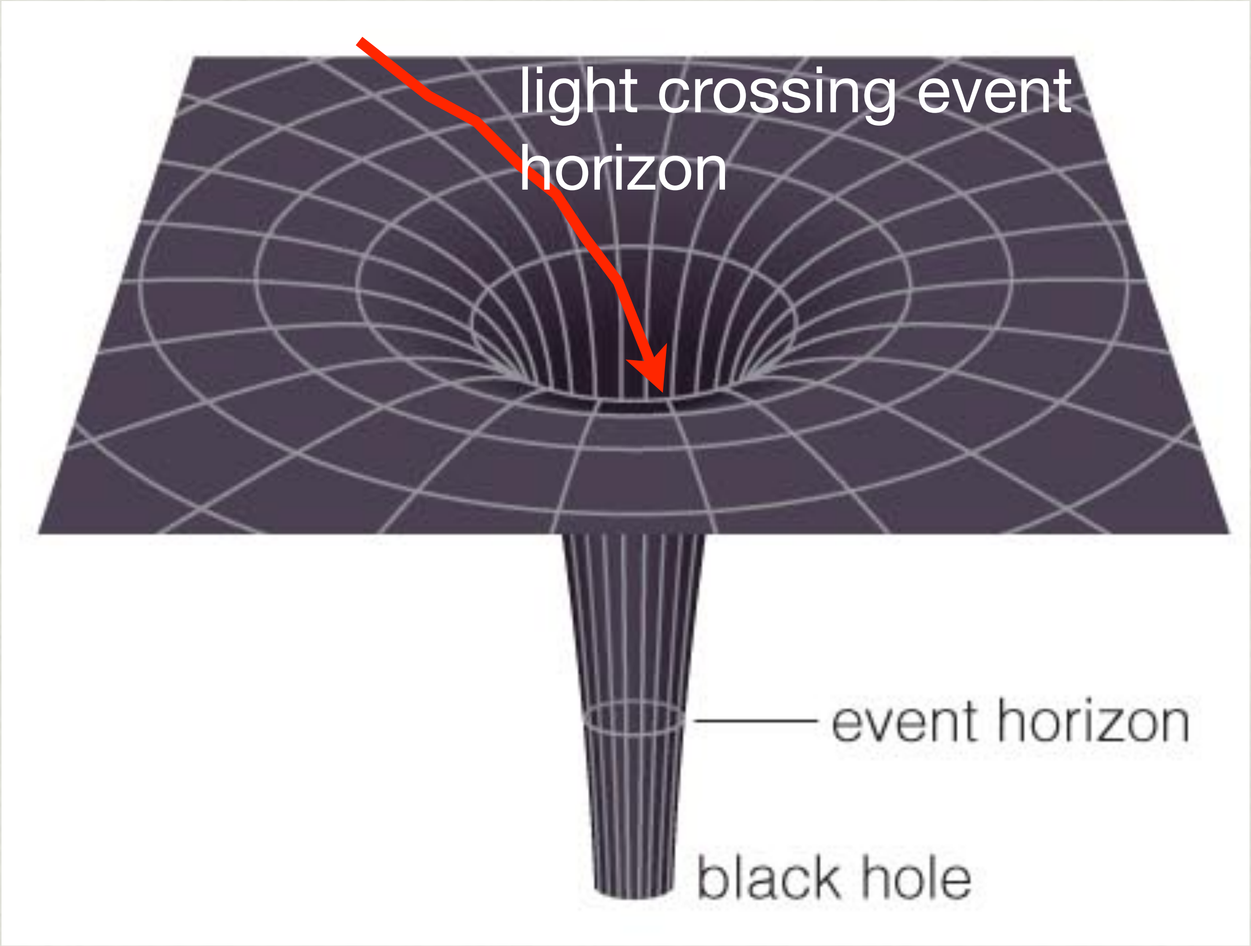
Observation of apparent change in star positions during a solar eclipse (when we can see close to the sun) in 1919 was a first proof of General Relativity.



General Relativity

Implication #1:
The path of light is always straight, but space is bent by gravity.

Space curved if the sun were a black hole



If mass is dense enough, there is a radius from which light can't escape.

Radius of this "Event Horizon" = Schwarzschild Radius

Remember: Black Holes

Escape velocity: velocity needed to get free of an object's gravitational pull.

$$v_{escape} = \sqrt{\frac{2\,G\,M}{d}}$$

M = mass, d = distance from the center of the object you want to escape from

For a star, light is emitted at its surface, so **d** is the radius of the star, **R**

If M is very big and/or R is very small, then $V_{escape} > c$, the speed of light.

NOTHING can have speed > c, so NOTHING can escape, not even light.
Star becomes a Black Hole

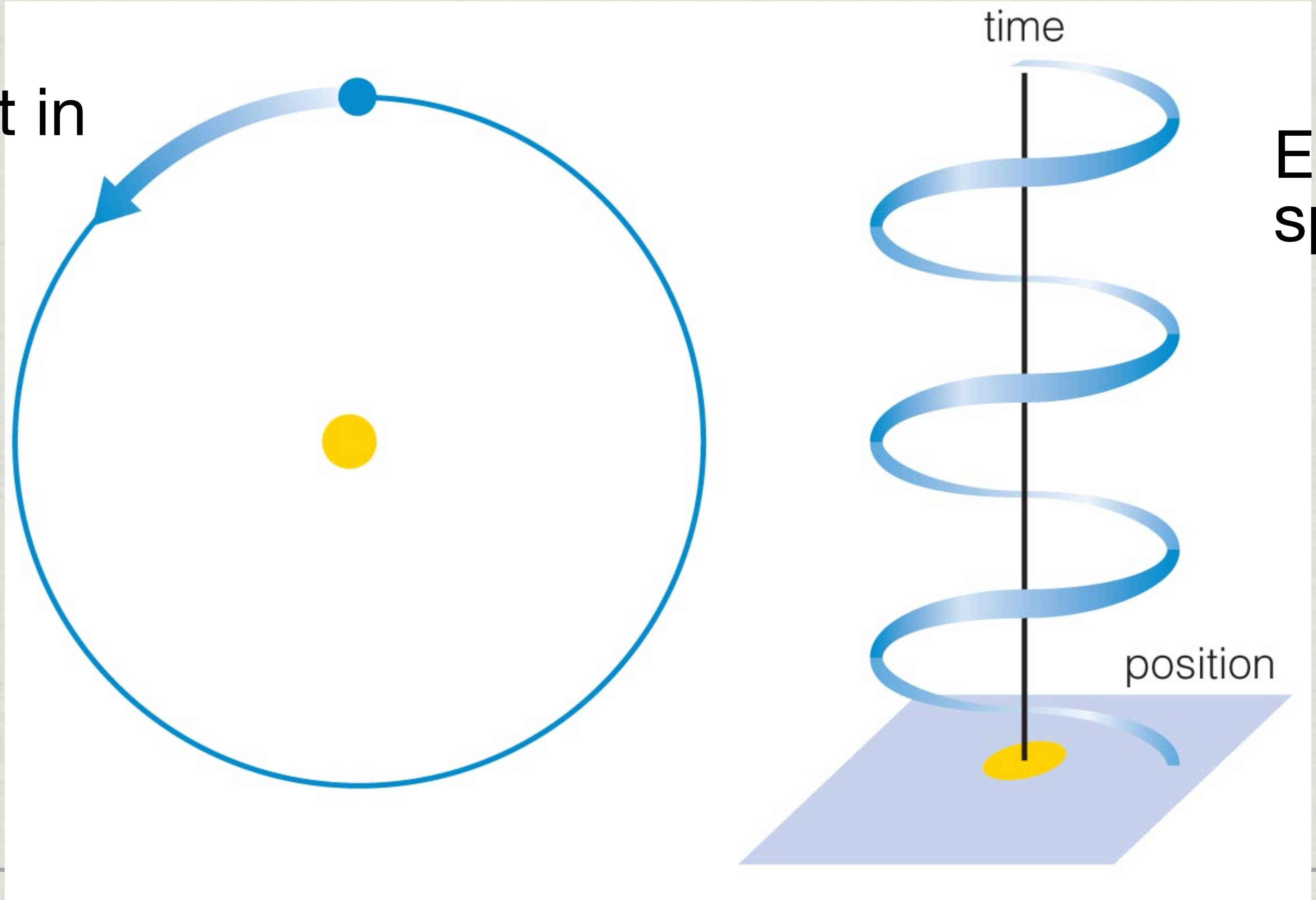
Artist's rendition, not a real picture

Spacetime

A 4-dimensional space: X,Y,Z and time.

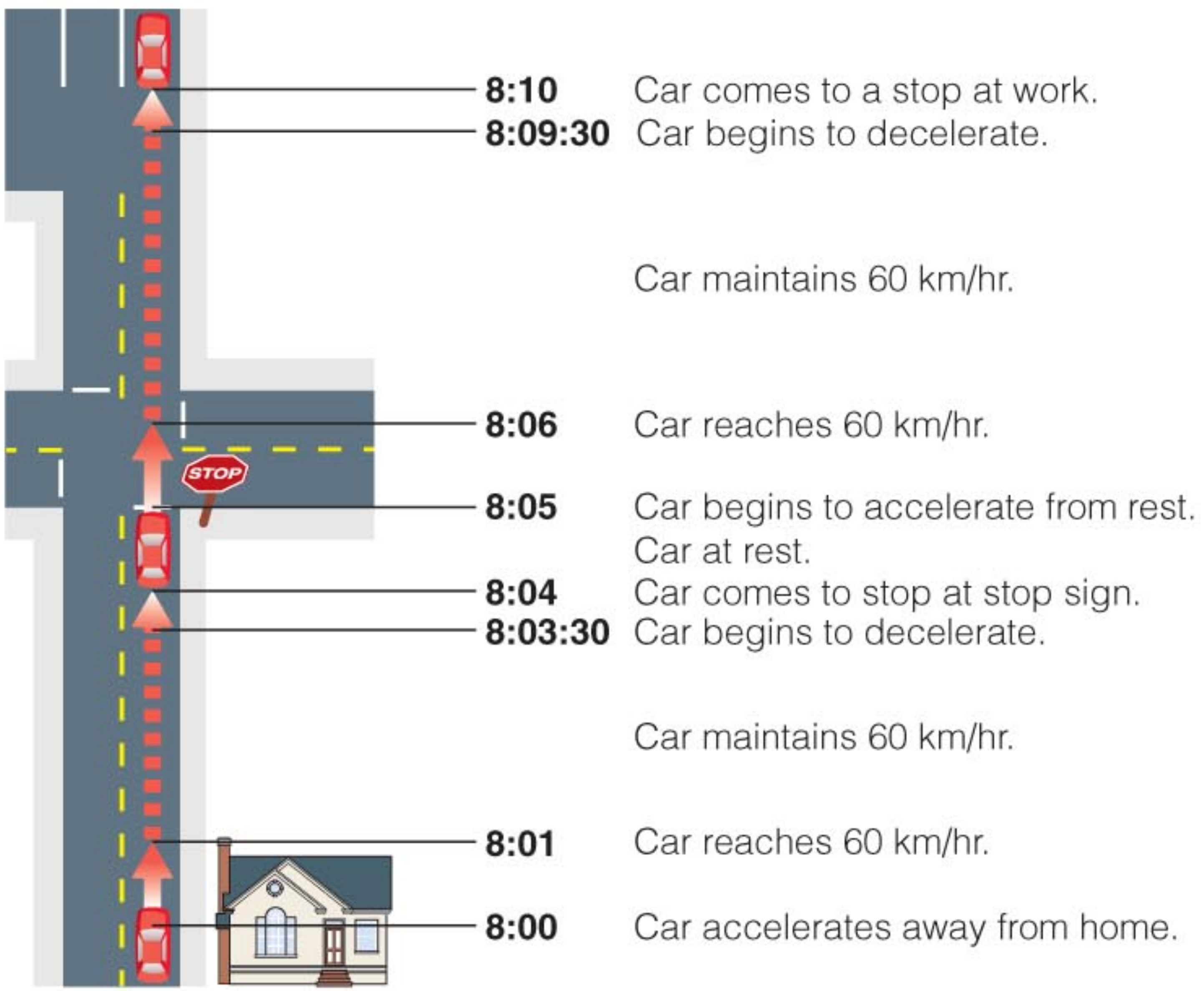
How can time be an axis?

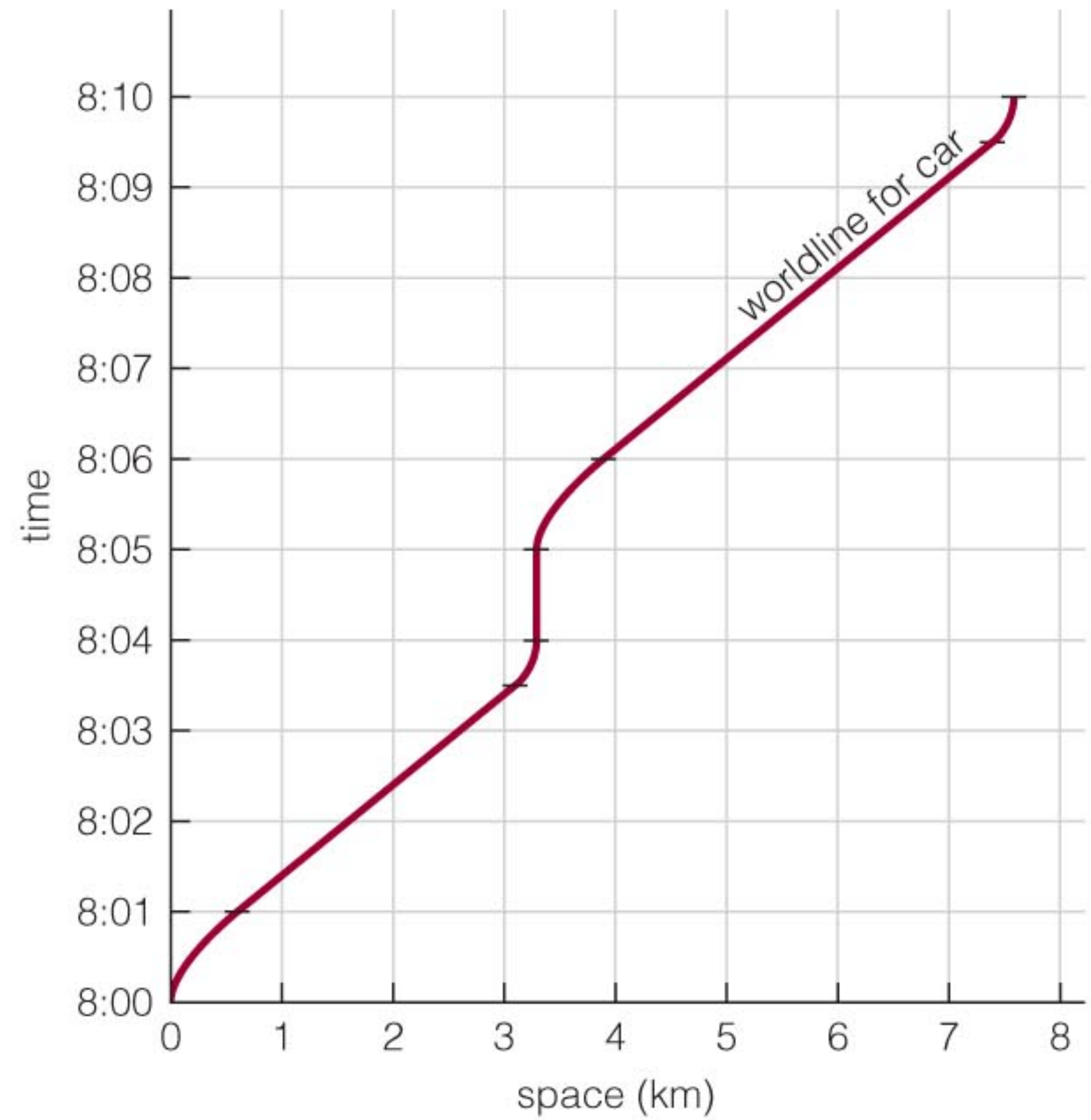
Earth's orbit in space (2D projection)



Earth's orbit in spacetime

Spacetime



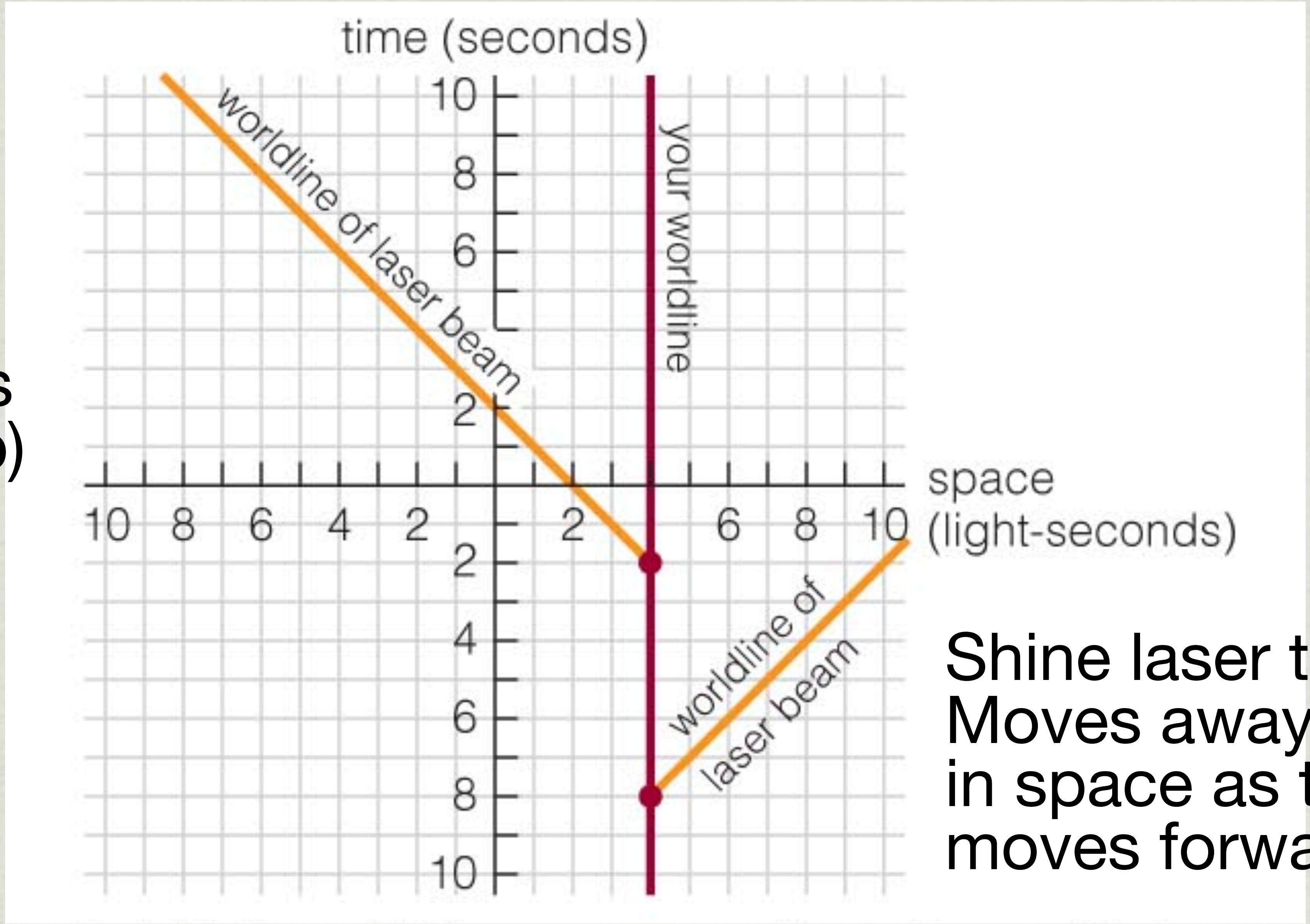


A list of events: driving to work

Driving to work: a spacetime diagram

Spacetime

Shine laser to left. Moves away from you to the left in space as time moves forward (up)

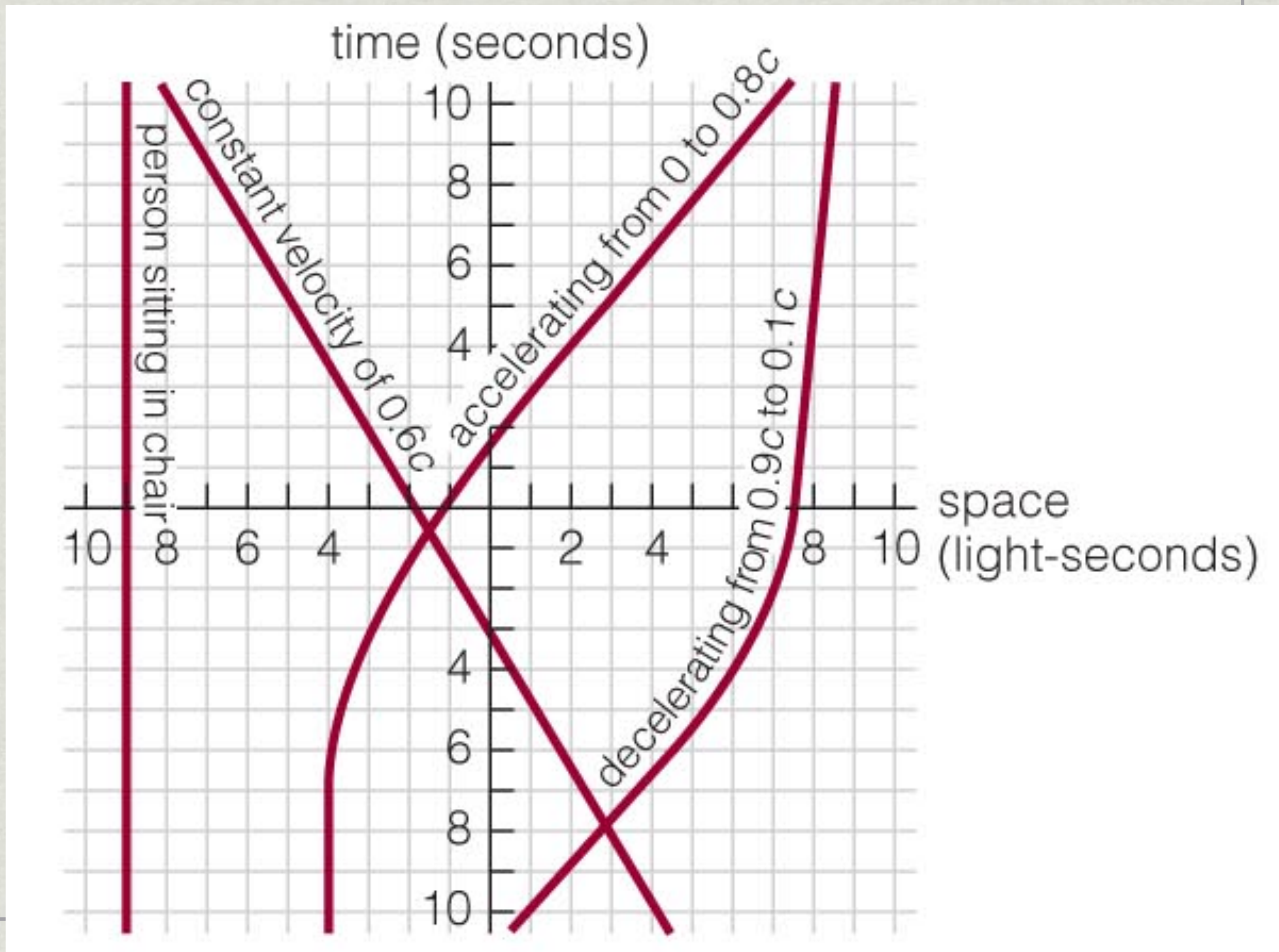


Shine laser to right. Moves away from you in space as time moves forward (up).

You: sitting still.
No motion in space.
Time moves forward (up).

Spacetime

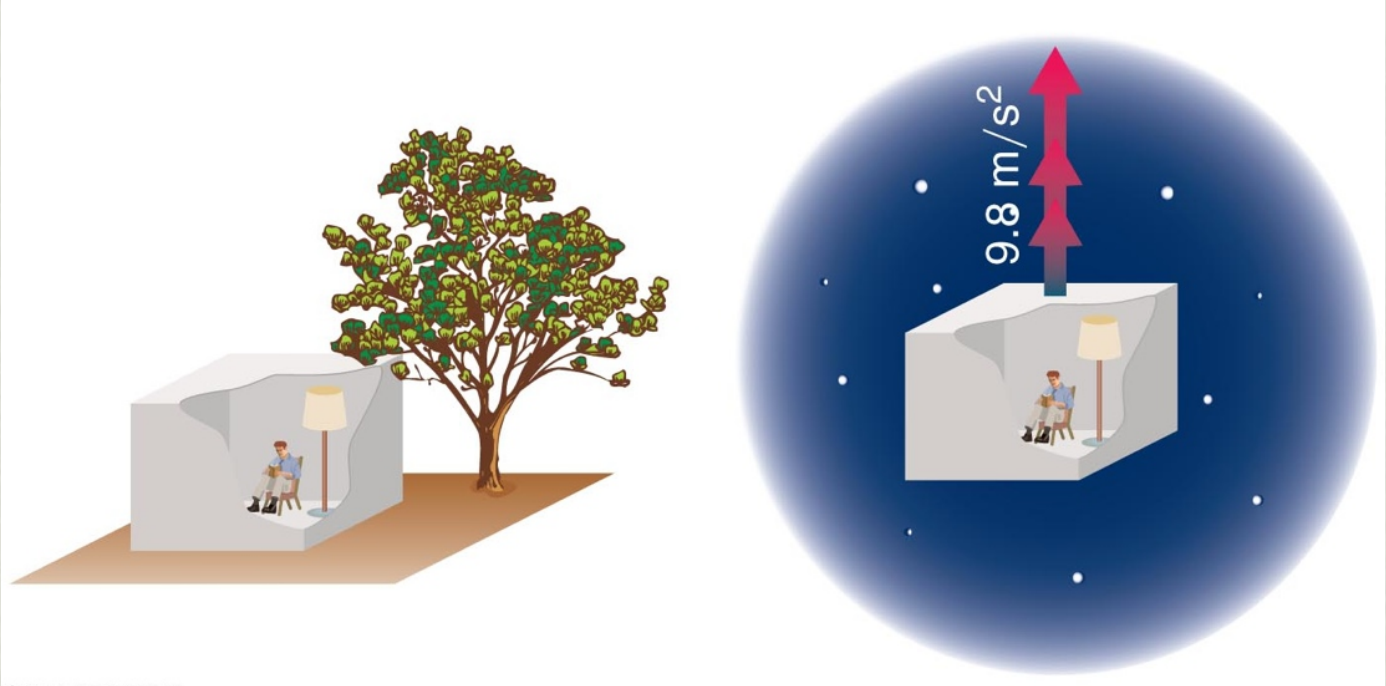
More spacetime diagrams



Spacetime and Geometry

Remember this:

Being in a spaceship accelerating at 9.8 m/s^2 is the same to you (and to photons) as sitting on the surface of the earth, held down by gravity



Being in free-fall is the same to you and to photons as being in no gravitational field.

If no gravitational field, then no force, and can travel at constant (possibly zero) velocity.

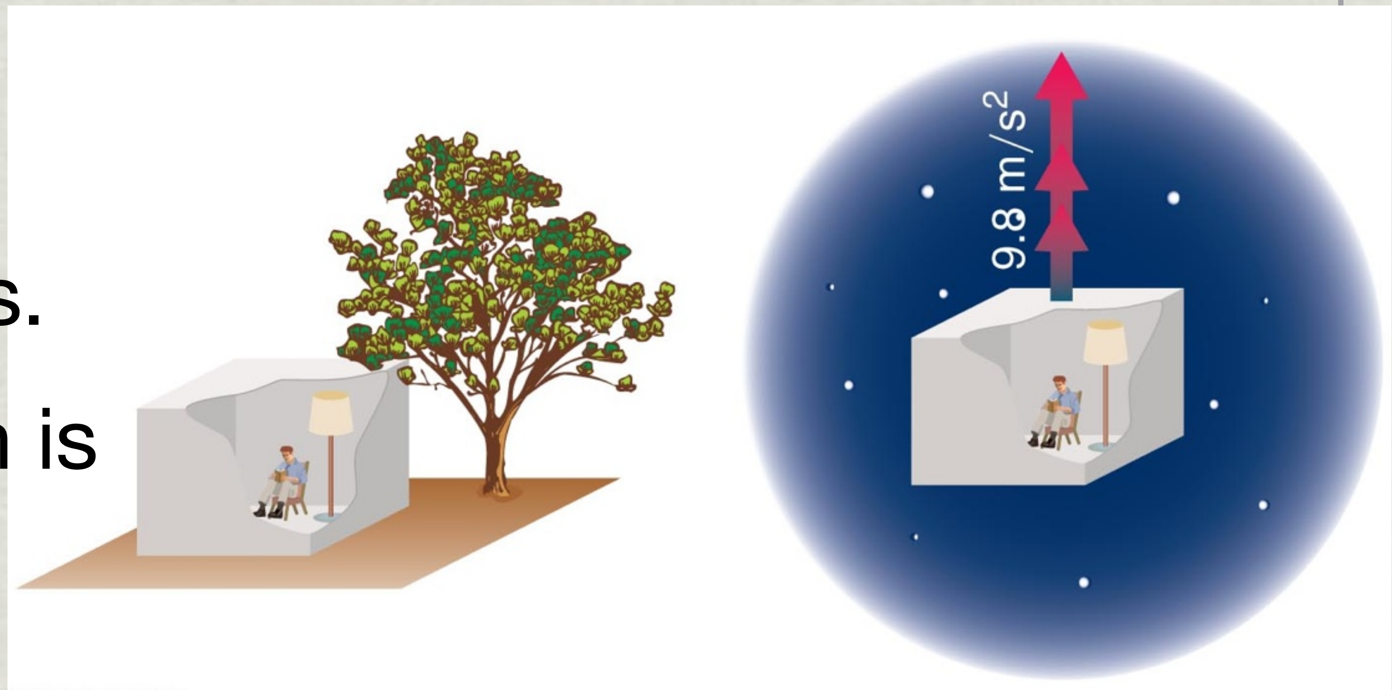
Spacetime and Geometry

Being in free-fall is the same to you and to photons as being in no gravitational field.

If no gravitational field, then no force, and can travel at constant (possibly zero) velocity.

Move at constant velocity = move in a straight line = take shortest path between two points.

(Remember a change of direction is an acceleration, and acceleration requires force.)



If free-fall is the same as being in no gravitational field, then an object in free-fall must be following the shortest possible path through space time.

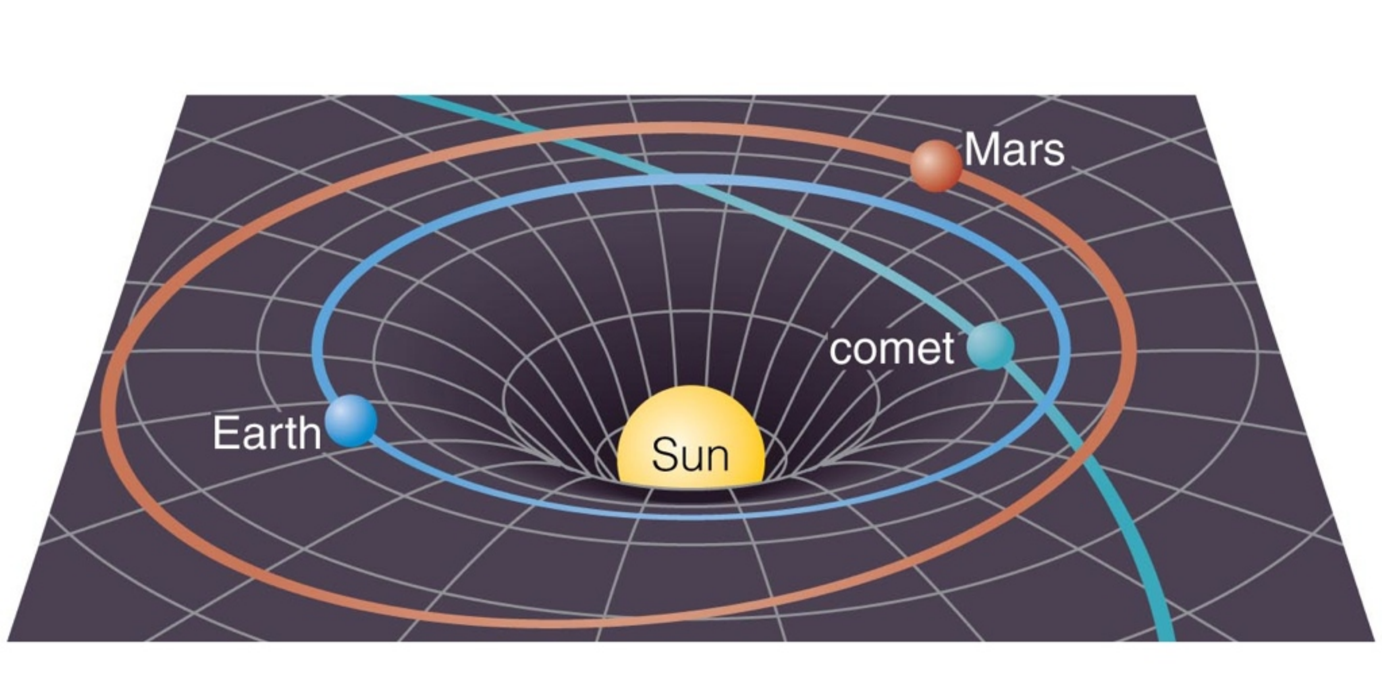
What's in free-fall? An object in an orbit!

Curved Spacetime

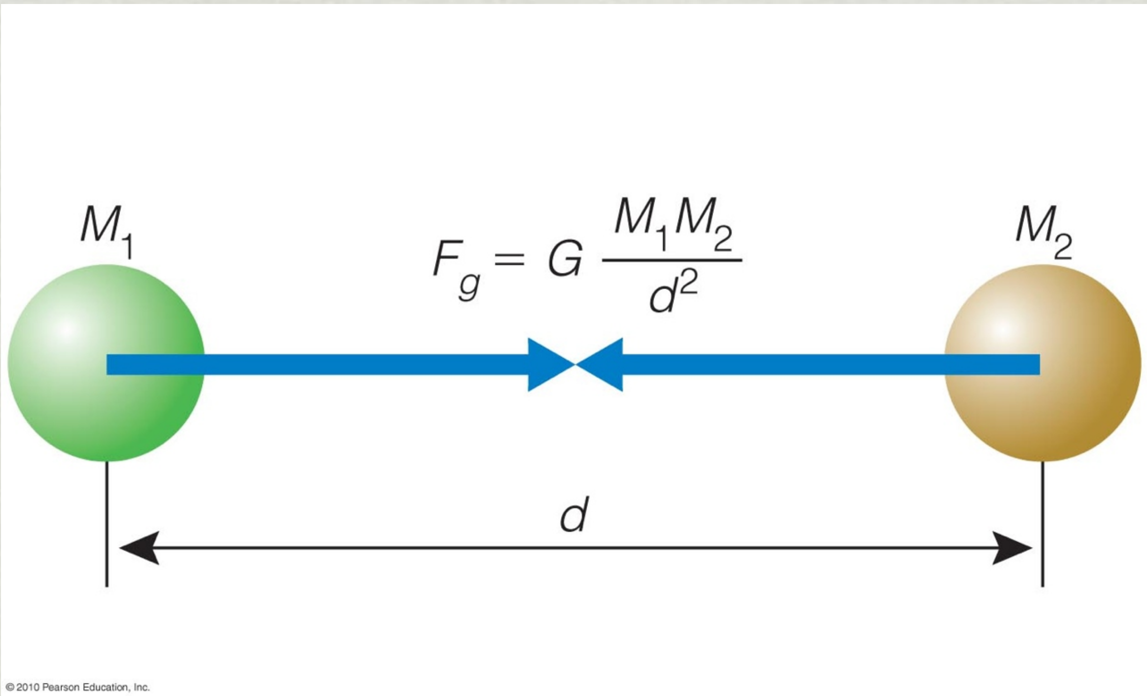
Mass curves spacetime.

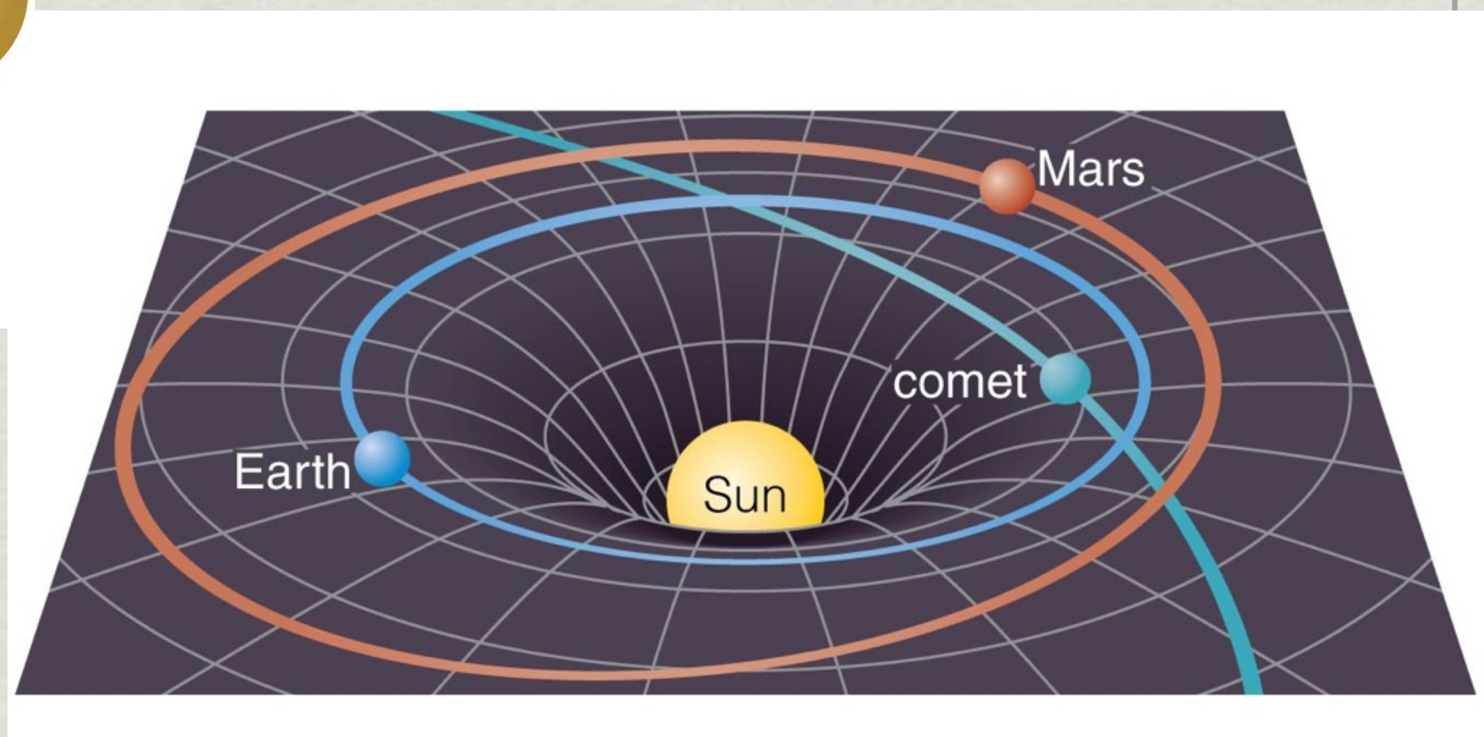
Objects in orbit are in free-fall, are following the shortest possible path in spacetime. But spacetime is curved so that shortest path isn't a straight line

How can we measure the curvature of spacetime? Measure the paths of objects in free-fall (orbit)



Curved Spacetime





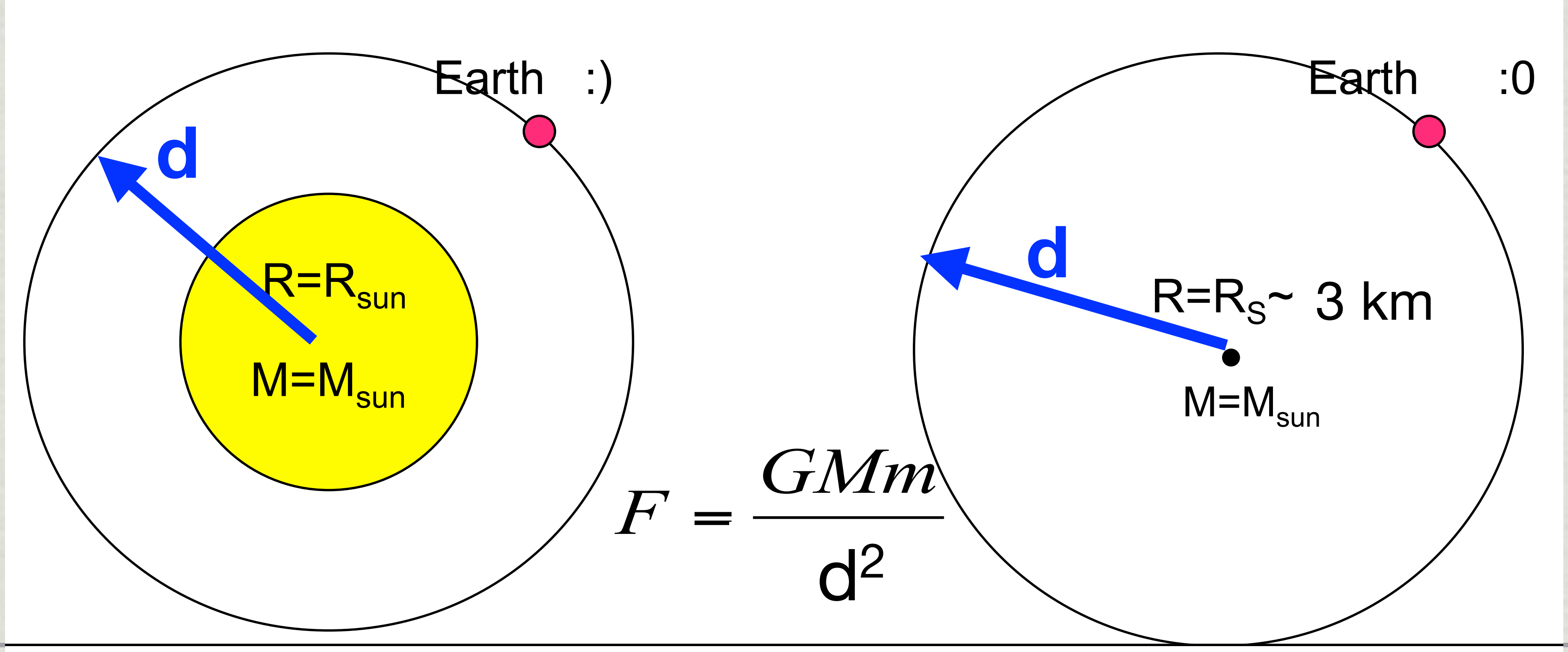
This is a nice way to think about gravity.

Objects are attracted to each other by Gravity because mass curves space-time. Objects "run downhill" along the curvature of spacetime toward each other. No need for two objects to "communicate" about their mass

General Relativity

What would happen to the Earth if the sun suddenly turned into a black hole?

A We would be sucked in to the event horizon
B The orbits of all the planets would get closer to the sun
C The Earth would get very cold (no energy from sunlight)
D Jets from the black hole would cook the Earth



$$F = \frac{GMm}{d^2}$$

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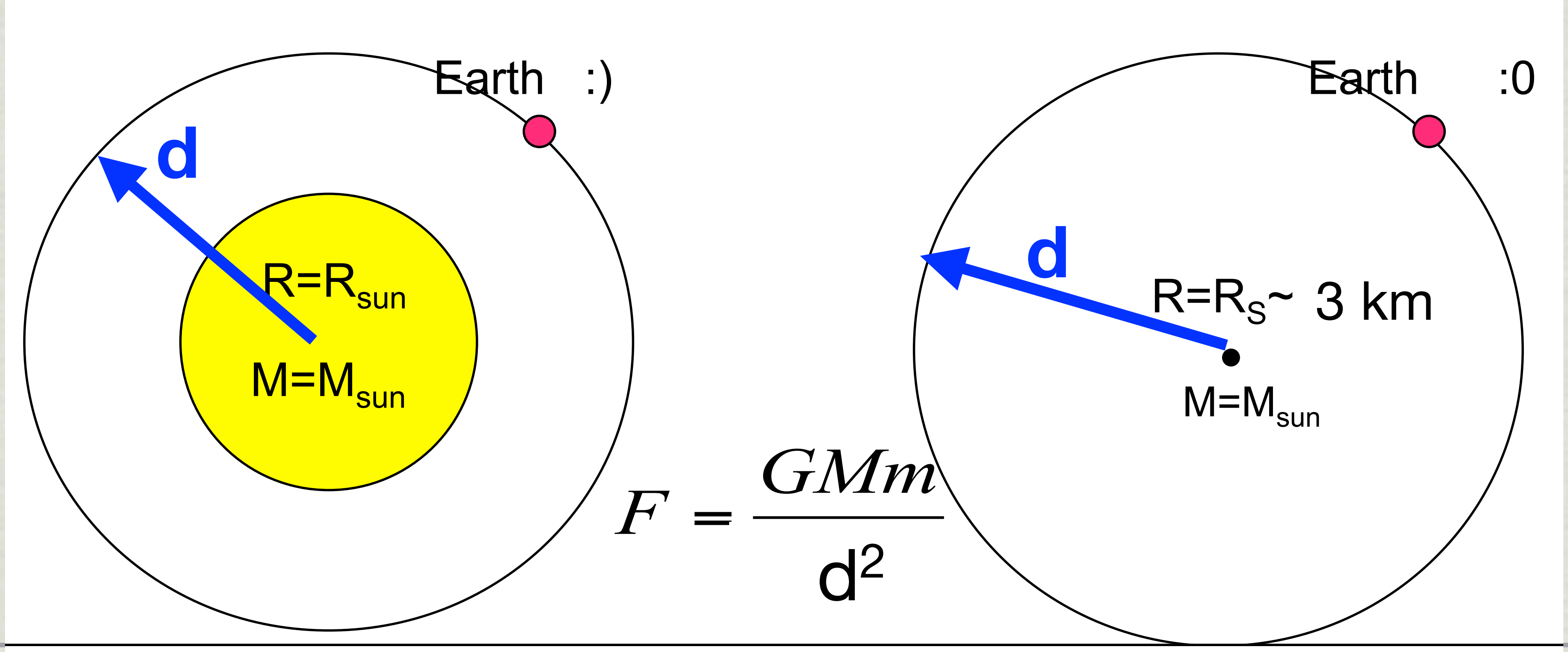

$$F = \frac{GMm}{d^2}$$