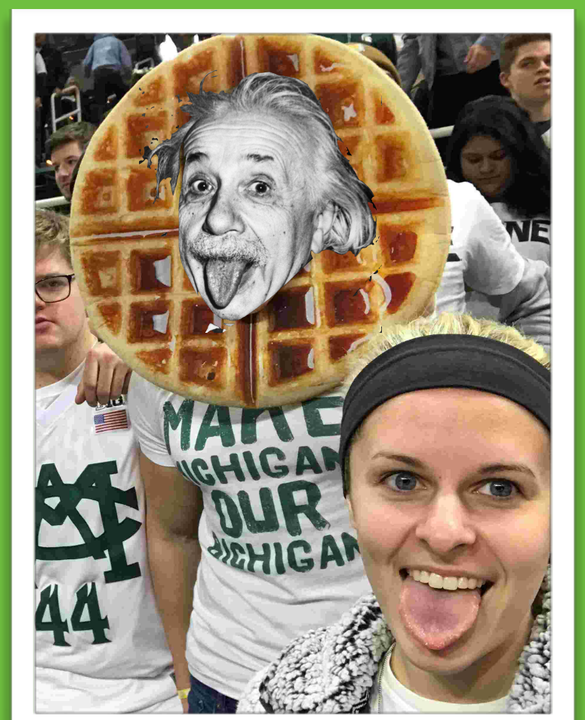
17 days until opening day

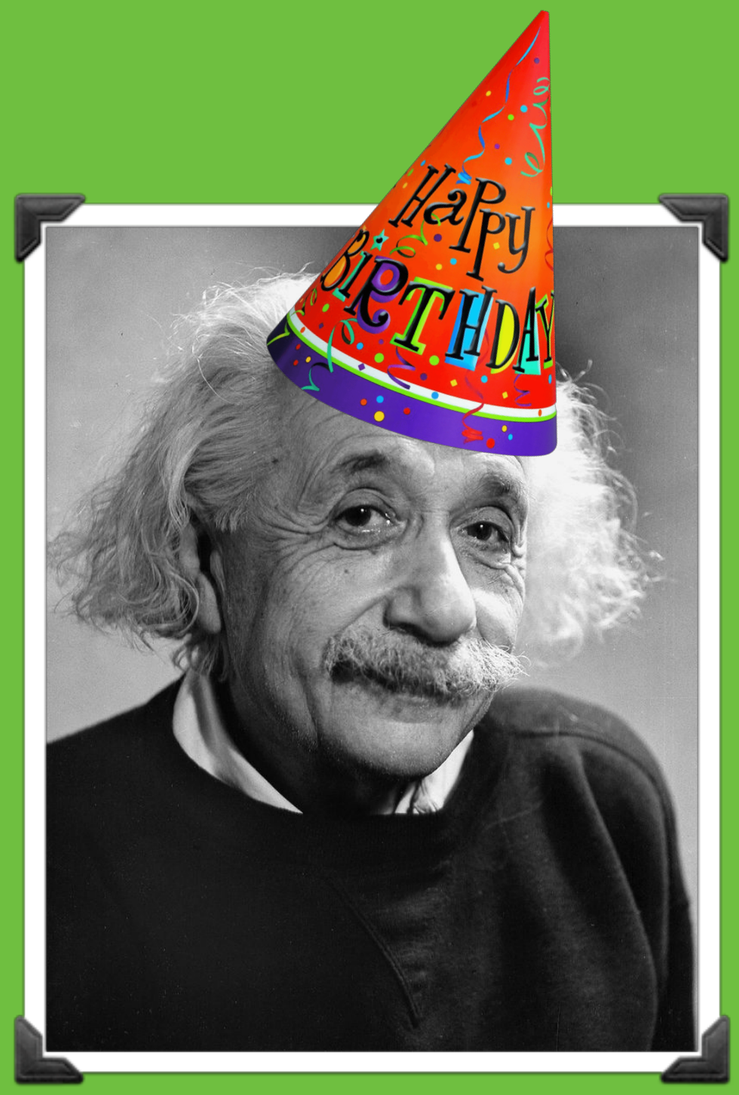
Kiss week

hi

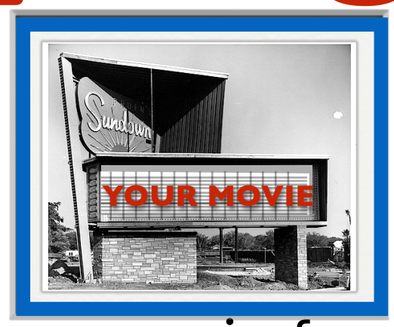


Day 16, 14.03.2019

Einstein’s General Theory of Relativity, 2



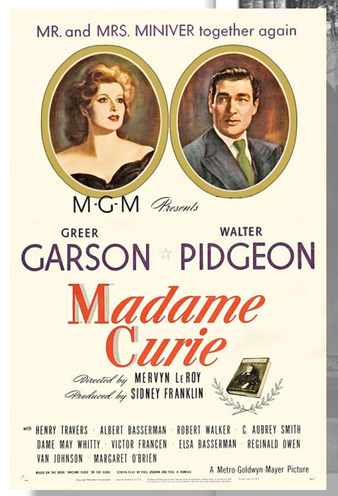
housekeeping

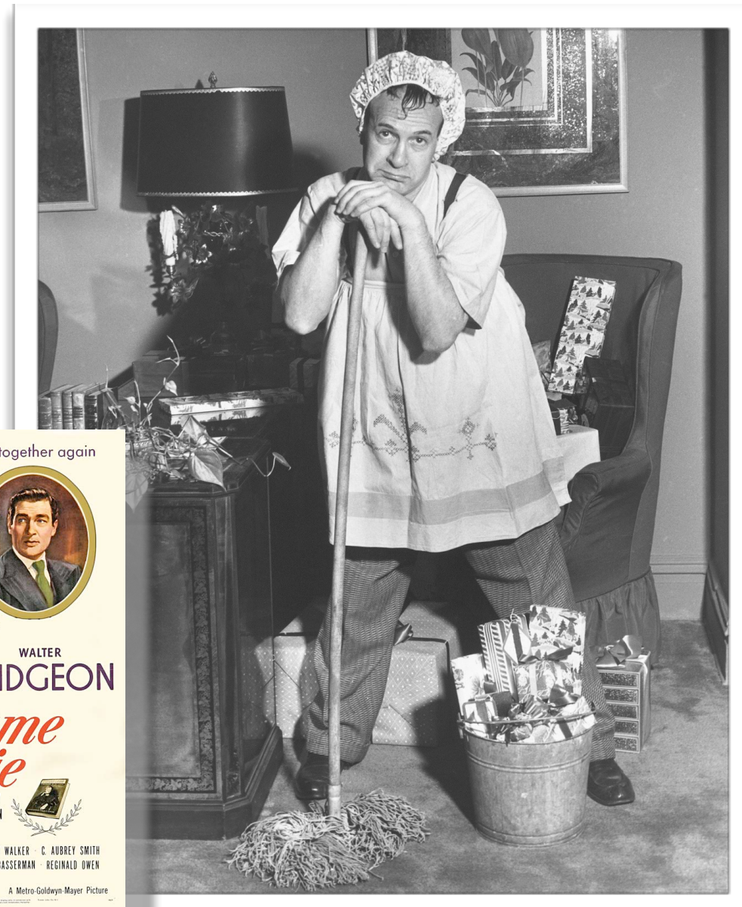


Gotta come to class

question about anything?

I'll make a movie for you:





Madame Curie movie - we have a quorum in favor

right now: looks like Monday, March 18

Pizza FB poll established. Closes Sunday night.

Section 2 folks:

Project has begun in phases:

Document 1: software, introduction, tutorial: due March 22

Document 2: your individual dataset and project instructions: due Final Exam

https://qstbb.pa.msu.edu/storage/QS&BB2019/Homework_Projects/honors_project_2019/MinervaInstructions1_2019.pages.pdf

MasteringAstronomy, finally after 3 emails and phone calls:

Course ID: MABROCK41459; free code: WSSPCT-BLIDA-INANE-TOGUE-RIGOT-UNRWA

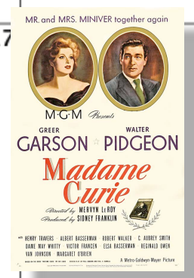
check it! let me know if it is now working...

Grades to date: Projects, quizzes, notes in a pdf in the slides area

the rest of your grades are in LON-CAPA or MasteringPhysics

March 2019

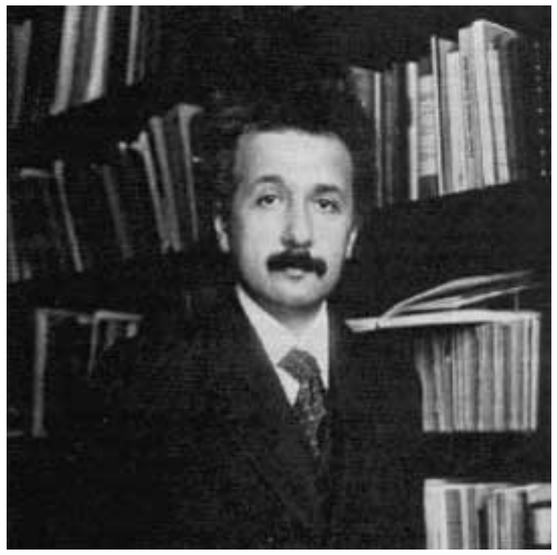
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
24	25	26	27	28	1	2
3	4	5	6	7	8	9 HW6
	← spring break →					
10	11	12 lecture	13	14 lecture	15 HW6 due	16 HW7
17	18 6pm, watch FB for room	19 lecture	20	21 lecture	22 HW7 due	23 HW8
24	25	26 lecture	27	28 lecture	29 HW8 due	30 HW9
31	1	2 lecture	3	4 lecture	5 HW9 due	6



Eastern Time Time Zone


KEEP
CALM
AND
LET'S
REVIEW

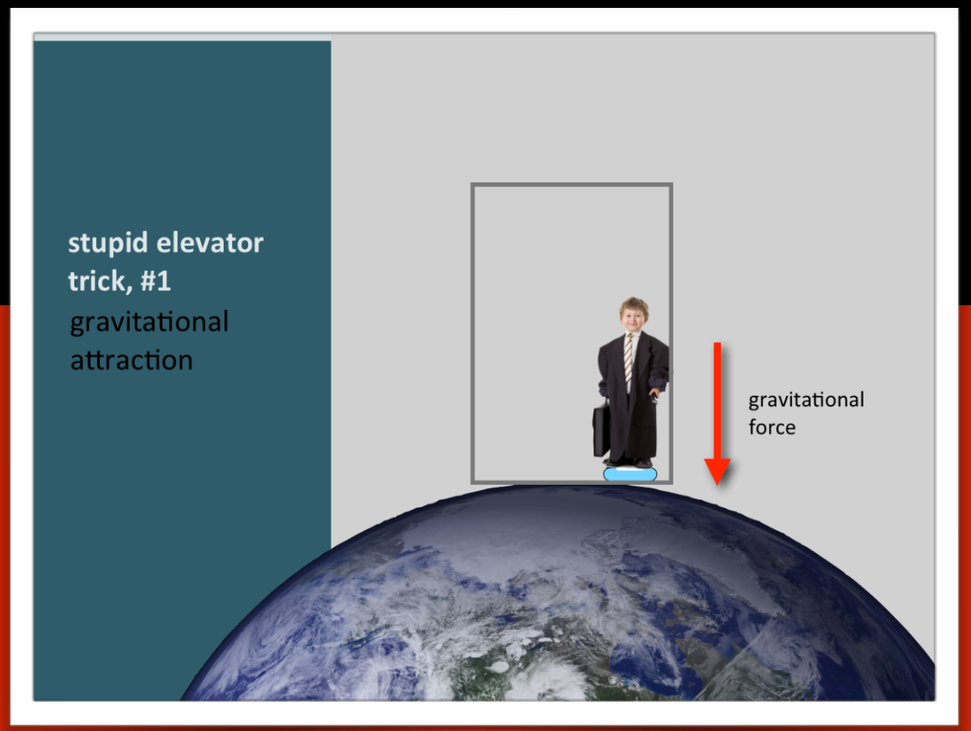
‘‘principle of equivalence’’



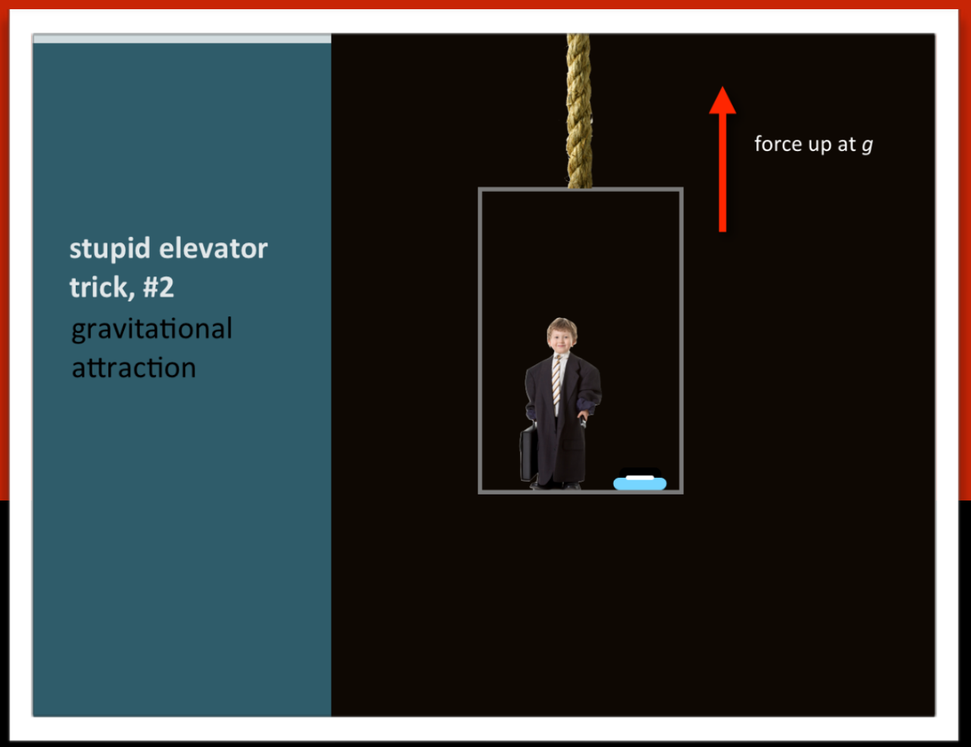
Equivalence Principle

his first aha moment

there’s something the same about acceleration and gravitation



identical



The Equivalence Principle demands that

If some phenomenon happens in a gravitational field,

then it must happen an accelerated frame.

and

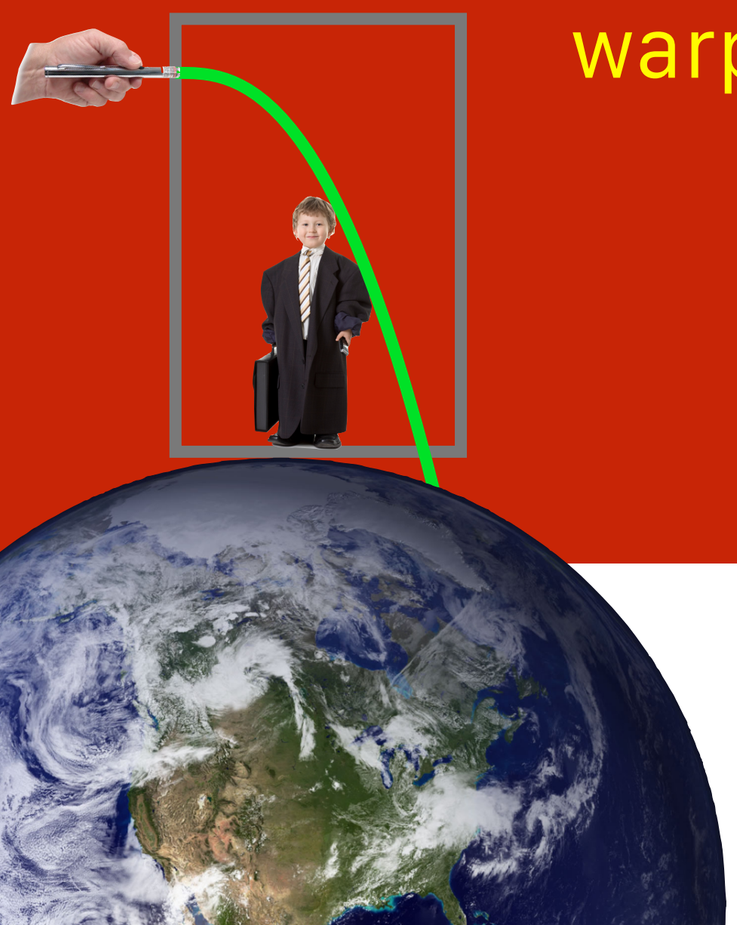
If some phenomenon happens in an accelerated frame field,

then it must happen a gravitational field.

acceleration
warps space

from the Equivalence Principle

gravity
should
warp space



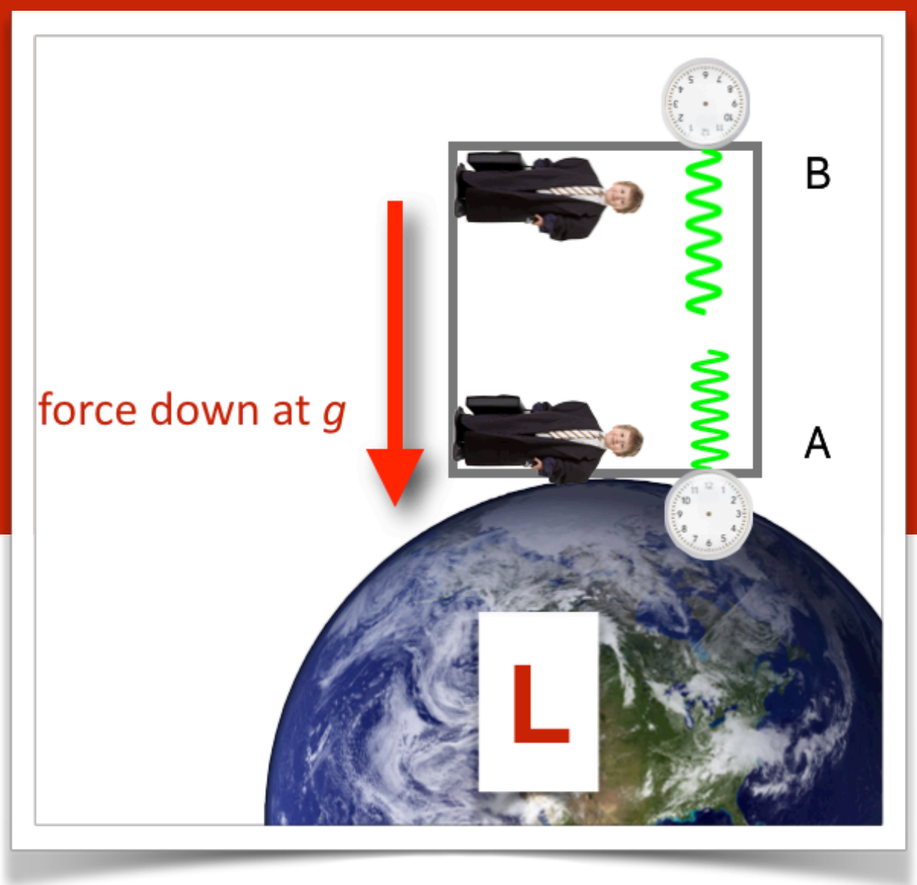
a beam of light in a high gravitational field

should appear to bend

acceleration warps time

from the Equivalence Principle

gravity should warp time



a clock in a high gravitational field

should appear to run slower than a clock in a weaker gravitational field

“gravitational red shift”

gravitating bodies…masses:

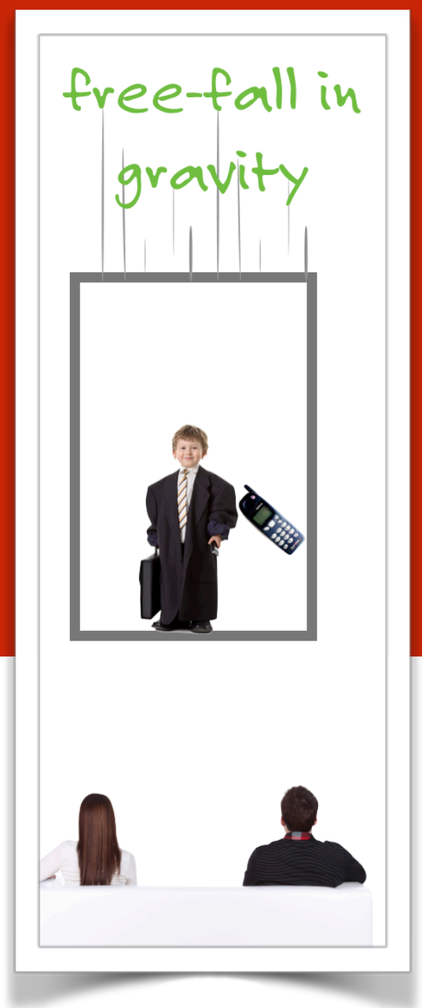
warp both space and time.

They warp: **spacetime**

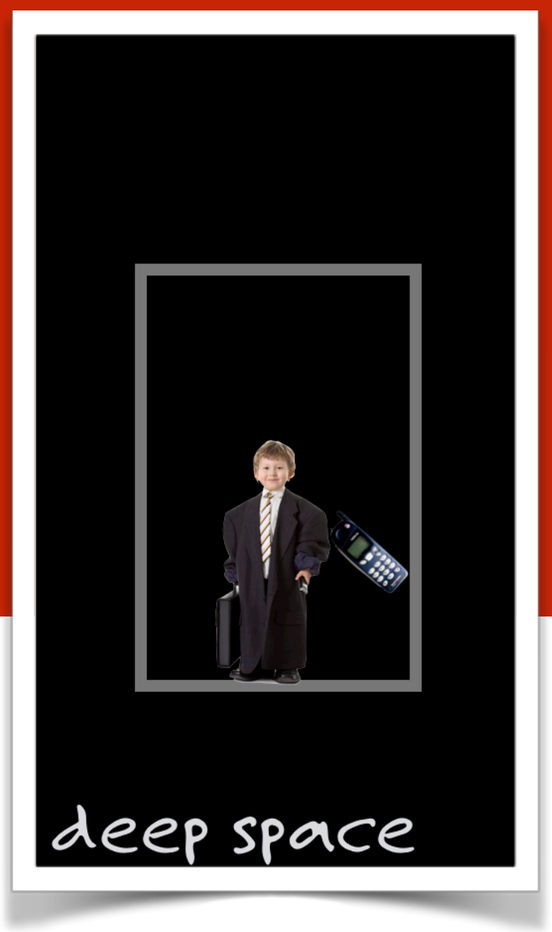
furthermore!

free fall

in a gravitational field eliminates gravity



indistinguishable



empty

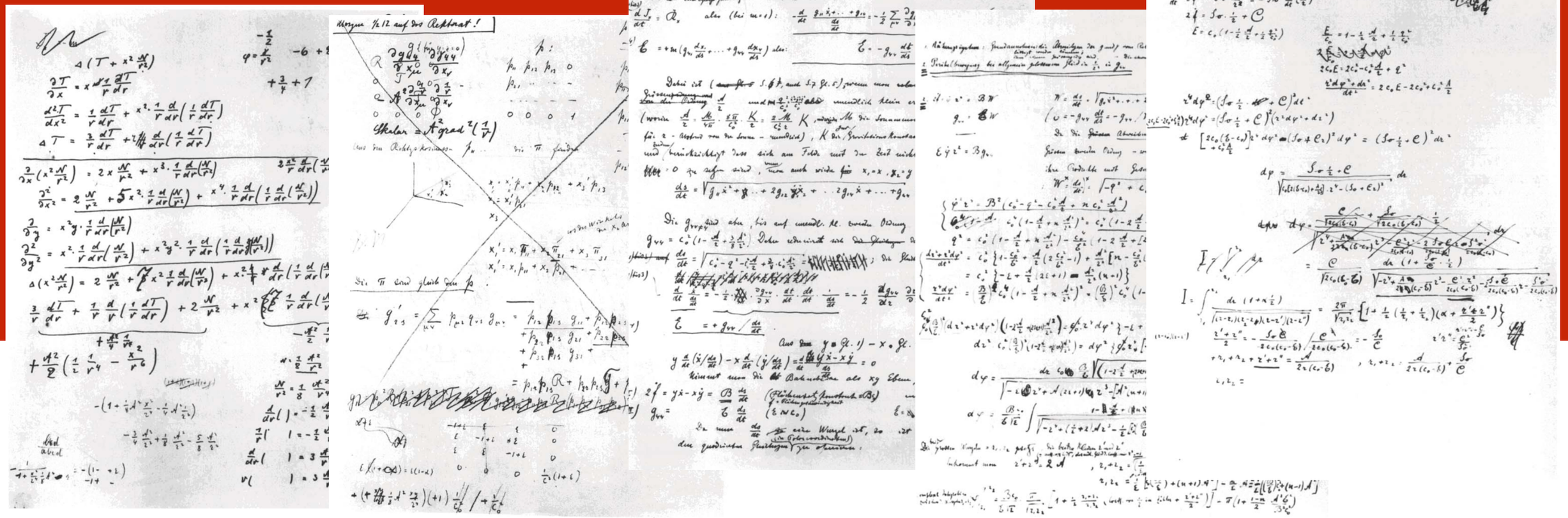
outer space without any gravitational fields

the free-fall recognition *became*:

Maybe gravity is not a force at all?

modeling this was heroic

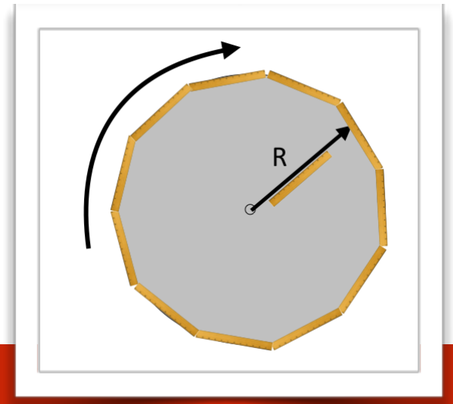
the most technically challenging piece of physics ever



there should be observable consequences to the Equivalence Principle

and Einstein knew it

and calculated them - half a decade of Newton-like concentration



Einstein had to learn that geometry & energy-mass

interact & that space and time respond

he had to go back to school...privately with his buddy Marcel Grossman

tests of general relativity

There are a handful of “classic tests”

of these ideas:

that space and time are warped by gravitation

- Pound Rebka Gravitational Red Shift
- The perihelion of Mercury’s Orbit
- Light bending around the Sun
- “Gravitational Lensing”
- “The Hafele-Keating experiment”
- “Binary Pulsar period”
- Black Holes

light beam

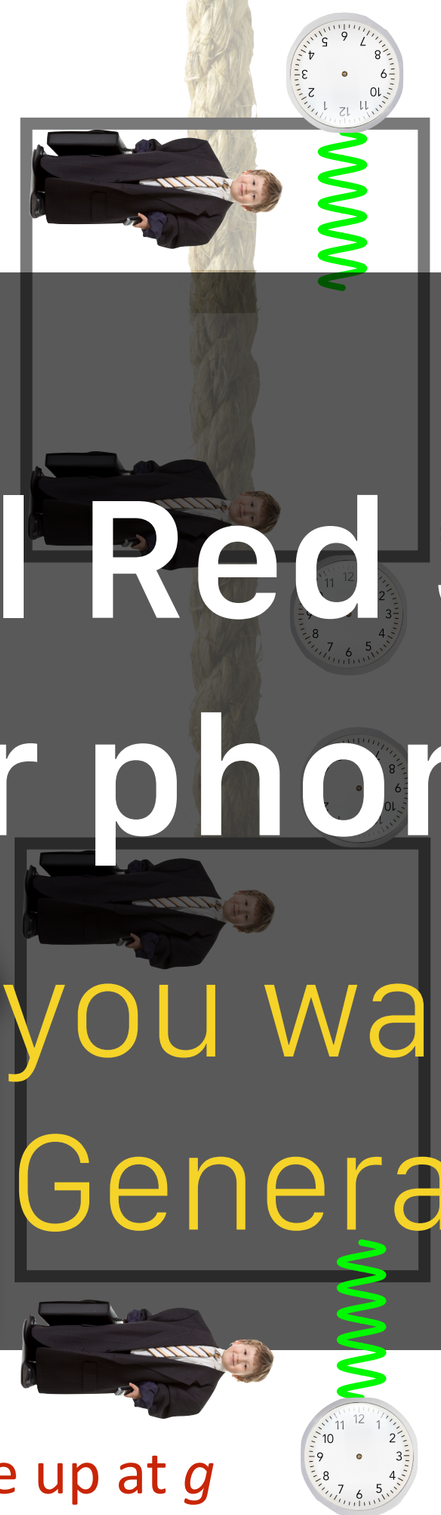
what about time?

use a clock

accelerating....

so **B** moving away from **A**

A and B are different inertial frames at each time

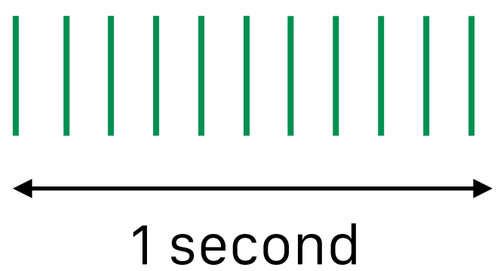


receives at say 5 ticks per second

B would say that A's clock has longer between ticks:

Runs Slower

sends at say 10 ticks per second



Gravitational Red Shift is built into your phone's GPS

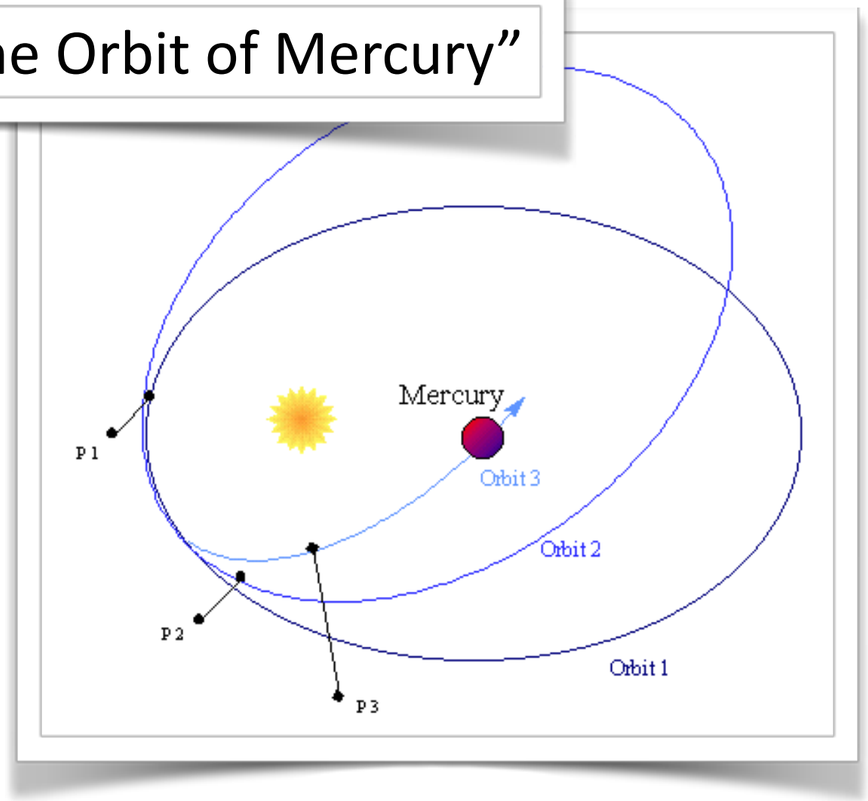
if you get where you want to go, you just confirmed General Relativity

“Advance of the Perihelion of the Orbit of Mercury”

Vulcan?

Mercury misbehaves “advance of the perihelion”

Einstein calculated it including the sun’s warping of space



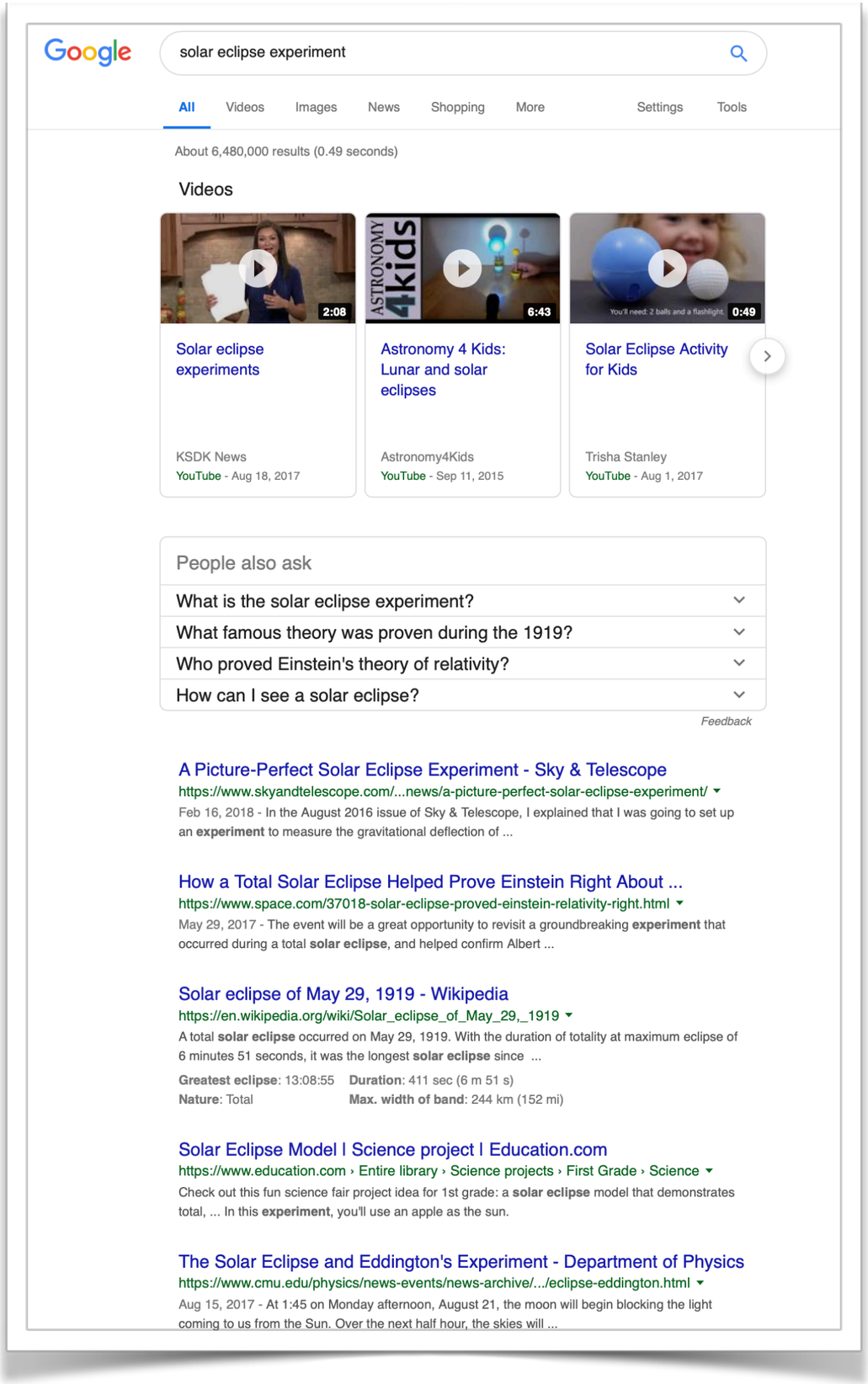
point of closest approach of the orbit advances by 43 seconds of arc per century

1916: Got precisely the right amount.

Heart palpitations when he scribbled the result on his paper...

the mother of all experiments

the “solar eclipse” experiment

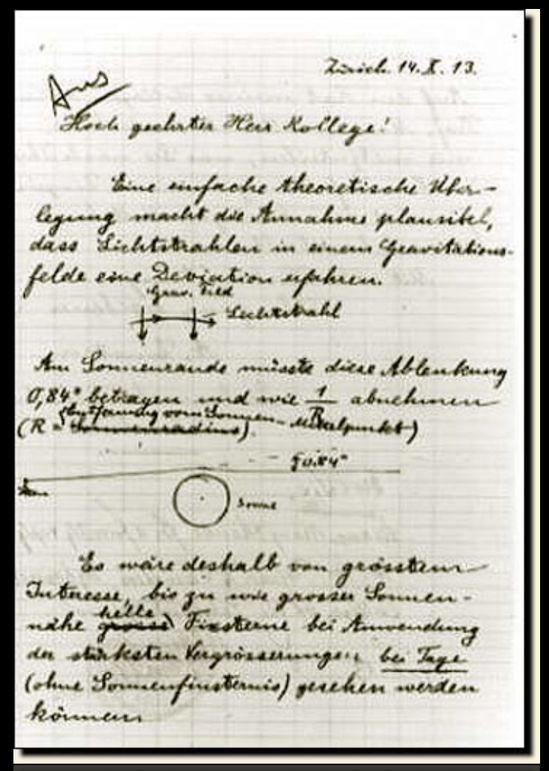


“Solar Eclipse Experiment”

light

obeys the strong Equivalence Principle

the laser pointer…for real


Zürich, 14. X. 13.

Hoch geehrter Herr Kollege!

Eine einfache theoretische Überlegung macht die Annahme plausibel, dass Lichtstrahlen in einem Gravitationsfelde eine Deviation erfahren.

Grav. Feld
Lichtstrahl

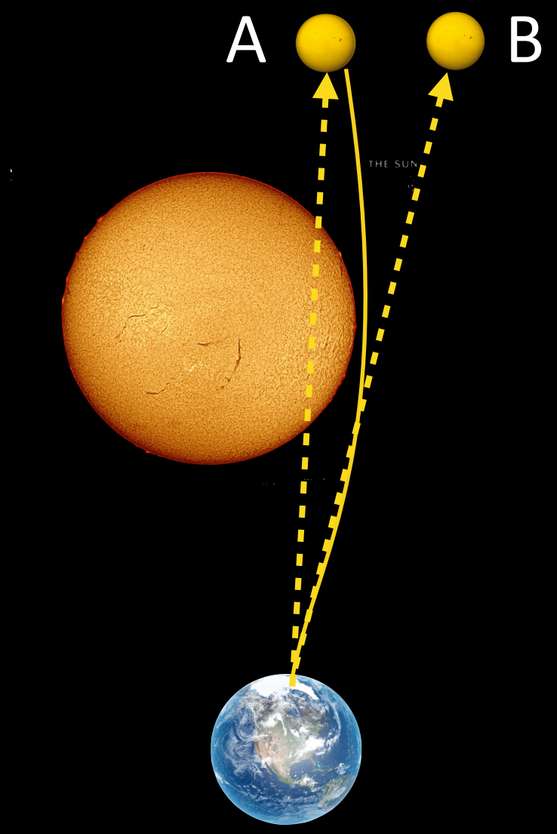
Am Sonnenrande müsste diese Ablenkung 0,84" betragen und wie $\frac{1}{r}$ abnehmen (R Sonnenradius).

0,84"
Sonne

Es wäre deshalb von grösstem Interesse, bis zu wie grosser Sonnennähe helle Fixsterne bei Anwendung der stärksten Vergrösserungen bei Tage (ohne Sonnenfinsternis) gesehen werden können

The star is actually at A

The deflection should be about 1/4 milli-degree



But it would appear to be at B

1911 calculation – initially wrong, only the $E=mc^2$ component…

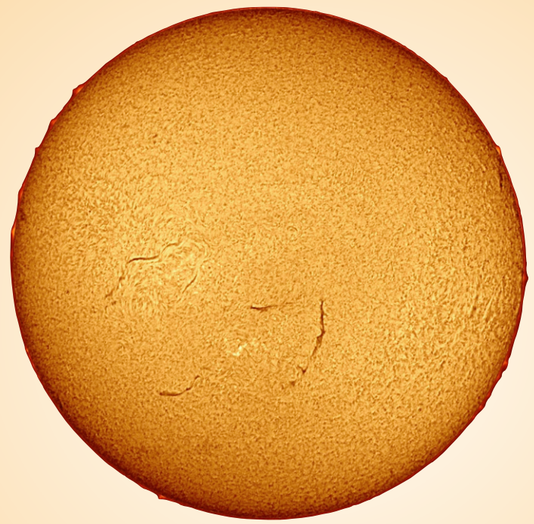
In 1915 he changed his 1911 calculation to include the warping of space…worth x2

eclipse experiment May 29,1919

Sir Arthur Eddington led 2 teams:

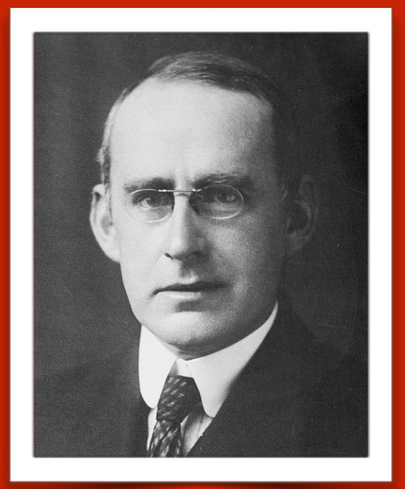
Gulf of Guinea

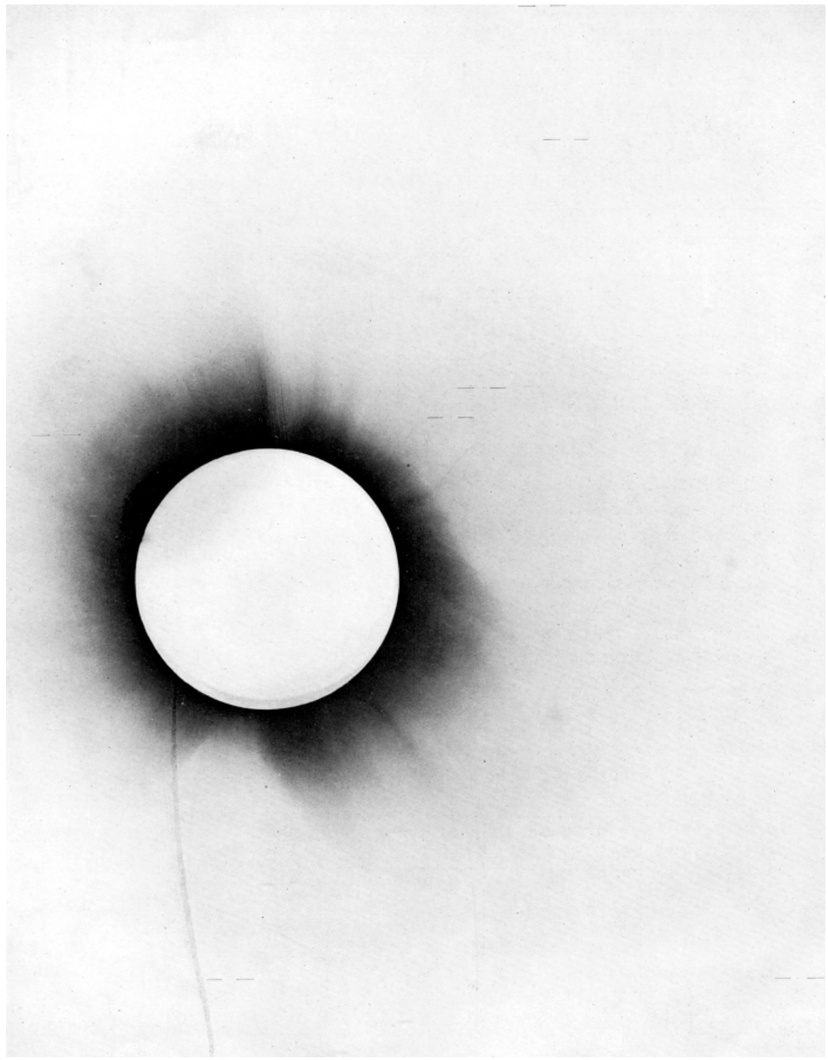
& Brazil



there was some cloudiness!

Eddington had 10 seconds to get a photograph





1/16 plates had usable data

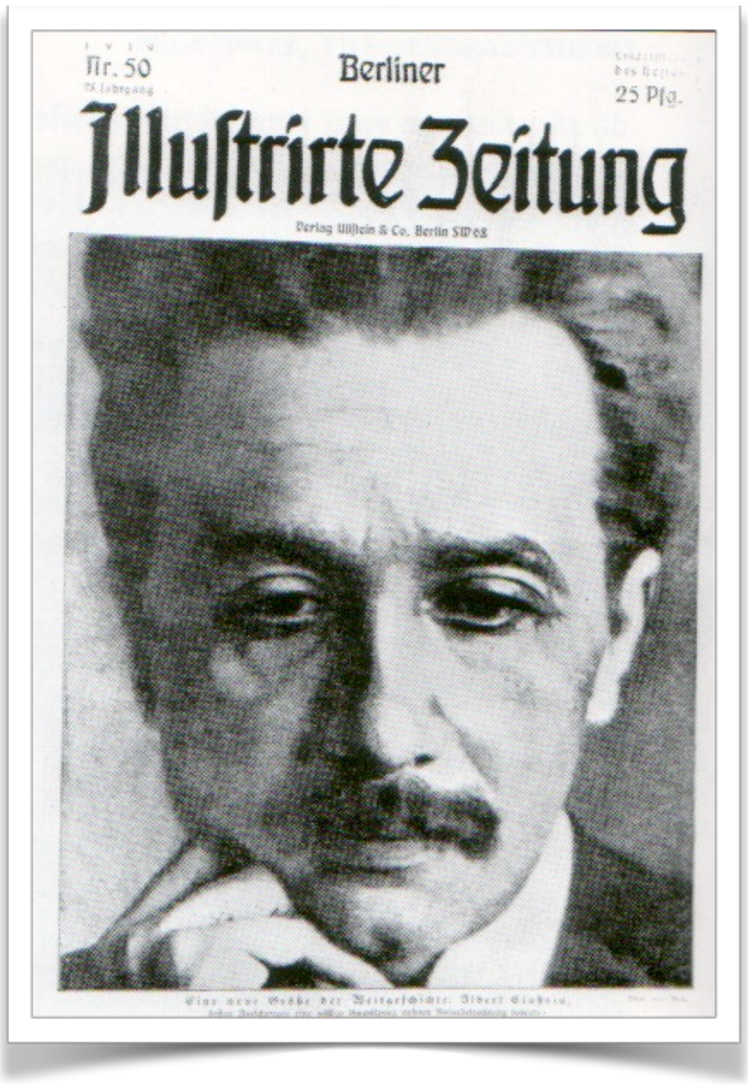
Eddington announced the result November 6, 1919 at the Royal Astronomical Society meeting

Einstein woke up in Berlin the next morning and was famous.

eclipse announcement at scientific meeting, 11/06/19:

instant celebrity, 11/07/19

cover of December 14, 1919 issue of *Berliner Illustrirte*


Nr. 50 Berliner 25 Pfg.

Illustrirte Zeitung

Verlag Ullstein & Co. Berlin SW 68

Eine neue Größe der Weltgeschichte: Albert Einstein.

caption: "A new great figure in world history: Albert Einstein, whose investigations signify a complete revision of our concepts of Nature, and are on a par with the insights of a Copernicus, a Kepler, and a Newton."

the Times golf editor

New York Times,
November 10, 1919

LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BOOK FOR 12 WISE MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

Special Cable to THE NEW YORK TIMES.

LONDON, Nov. 9.—Efforts made to put in words intelligible to the non-scientific public the Einstein theory of light proved by the eclipse expedition so far have not been very successful. The new theory was discussed at a recent meeting of the Royal Society and Royal Astronomical Society, Sir Joseph Thomson, President of the Royal Society, declares it is not possible to put Einstein's theory into really intelligible words, yet at the same time Thomson adds:

"The results of the eclipse expedition demonstrating that the rays of light from the stars are bent or deflected from their normal course by other aerial bodies acting upon them and consequently the inference that light has weight form a most important contribution to the laws of gravity given us since Newton laid down his principles."

Thompson states that the difference between theories of Newton and those of Einstein are infinitesimal in a popular sense, and as they are purely mathematical and can only be expressed in strictly scientific terms it is useless to endeavor to detail them for the man in the street.

One of the speakers at the Royal Society's meeting suggested that Euclid was knocked out. Schoolboys should not rejoice prematurely, for it is pointed out that Euclid laid down the axiom that parallel straight lines, if produced ever so far, would not meet He said nothing about light lines.

Some cynics suggest that the Einstein theory is only a scientific version of the well-known phenomenon that a coin in a basin of water is not on the spot where it seems to be and ask what is new in the refraction of light.

Albert Einstein is a Swiss citizen, about 50 years of age. After occupying a position as Professor of Mathematical Physics at the Zurich Polytechnic School and afterward at Prague University, he was elected a member of Emperor William's Scientific Academy in Berlin at the outbreak of the war. Dr. Einstein protested against the German professors' manifesto approving of Germany's participation in the war, and at its conclusion he welcomed the revolution. He has been living in Berlin for about six years.

When he offered his last important work to the publishers he warned them there were not more than twelve persons in the whole world who would understand it, but the publishers took the risk.

New York Times, December 3, 1919

EINSTEIN EXPOUNDS HIS NEW THEORY

It Discards Absolute Time and Space, Recognizing Them Only as Related to Moving Systems.

IMPROVES ON NEWTON

Whose Approximations Hold for Most Motions, but Not Those of the Highest Velocity.

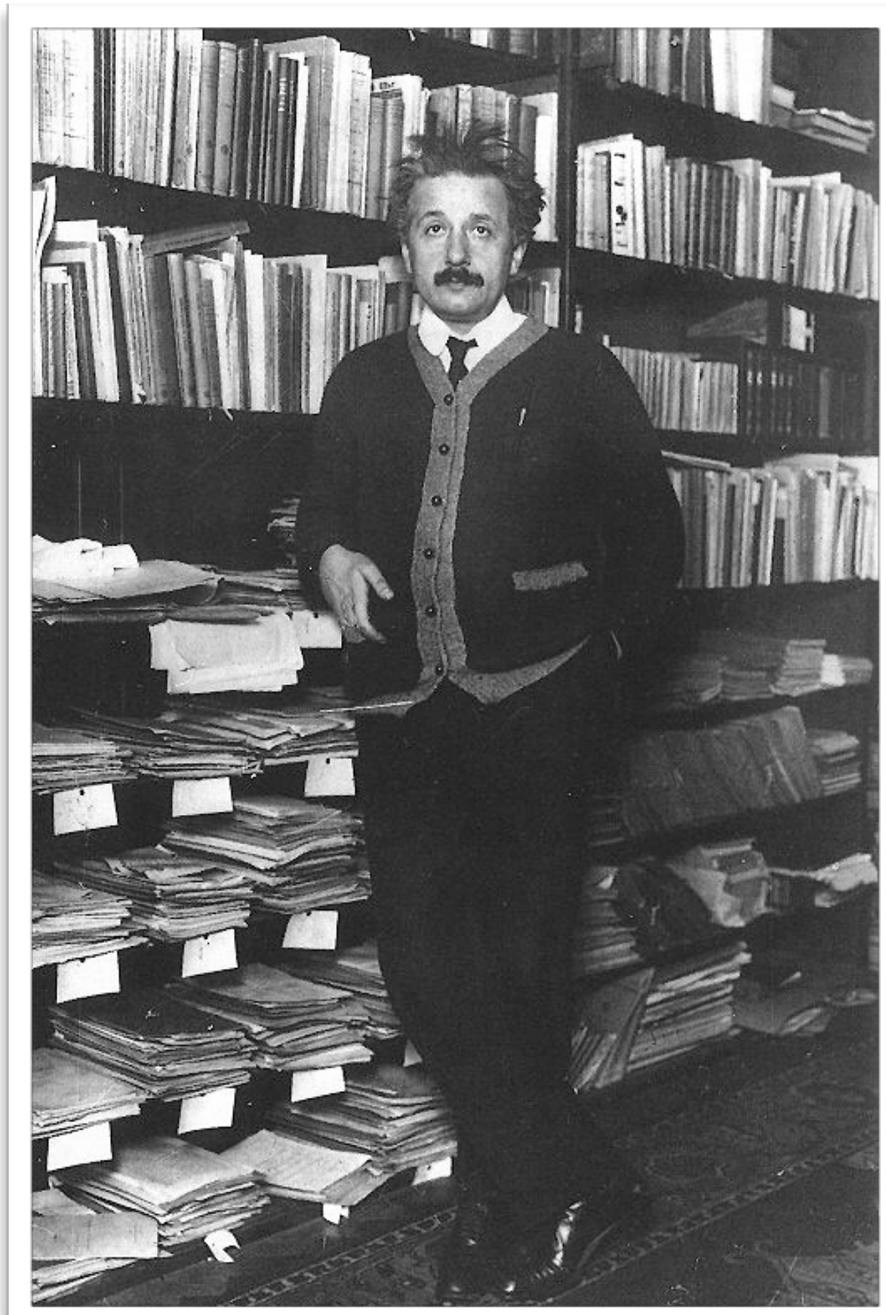
INSPIRED AS NEWTON WAS

But by the Fall of a Man from a Roof Instead of the Fall of an Apple.

Special Cable to THE NEW YORK TIMES.

BERLIN, Dec. 2.—Now that the Royal Society, at its meeting in London on Nov. 6, has put the stamp of its official authority on Dr. Albert Einstein's much-debated new "theory of relativity," man's conception of the universe seems likely to undergo radical changes. Indeed, there are German savants who believe that since the promulgation of Newton's theory of gravitation no discovery of such importance has been made in the world of science.

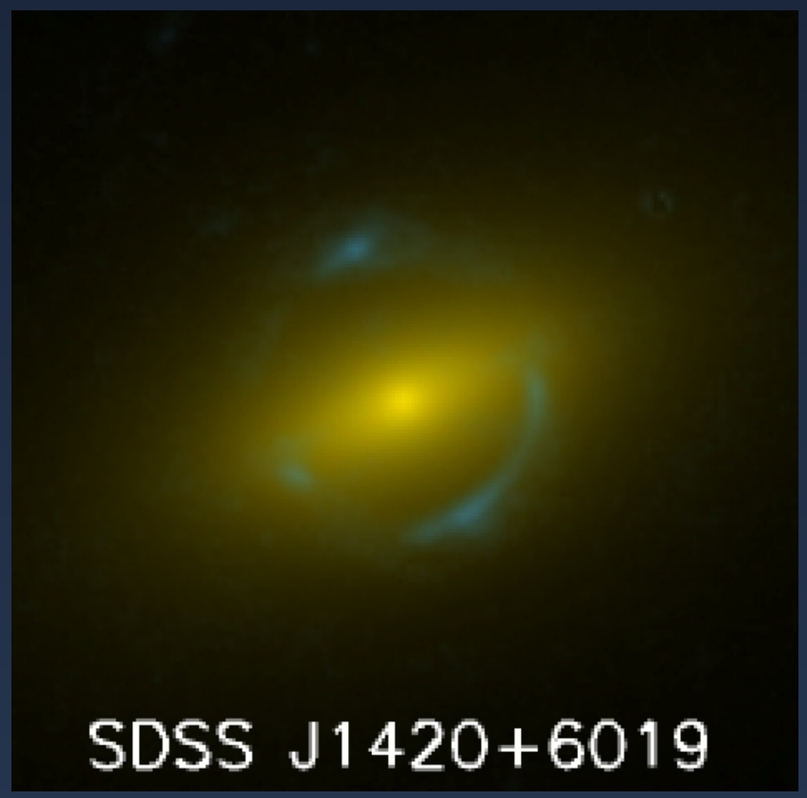
When THE NEW YORK TIMES correspondent called at his home to gather from his own lips an interpretation of what to laymen must appear the book with the seven seals, Dr. Einstein him-



now recovered from exhaustion and photogenic: 1920

Gravitational Lensing - an off-hand prediction of Einstein

Foreground objects can distort, and magnify distant background galaxies.

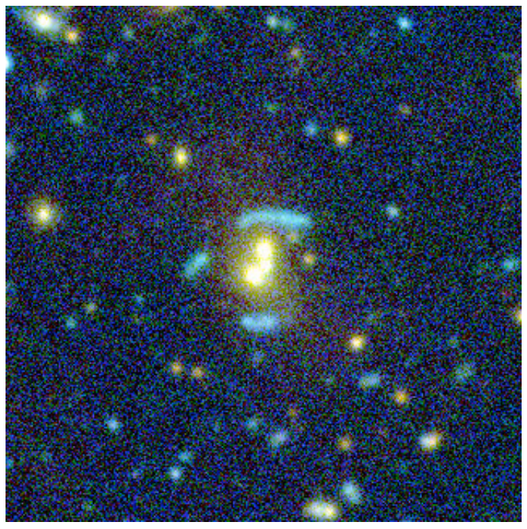


gravitational lensing now a tool

no longer a discovery!

studying dark matter: looking for Massive Astrophysical Compact Halo ObjectS

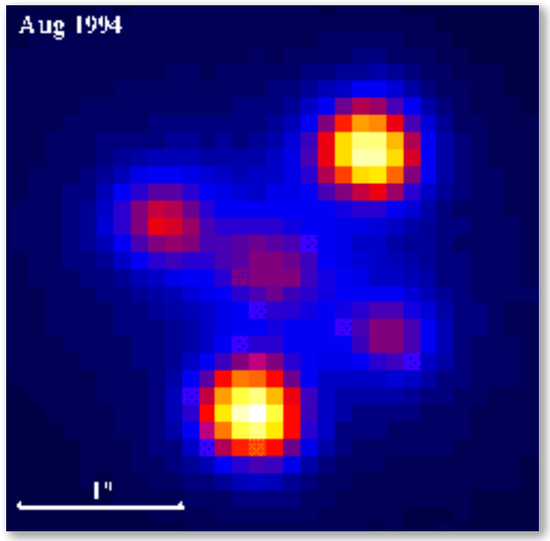
"Gravitational Lensing"

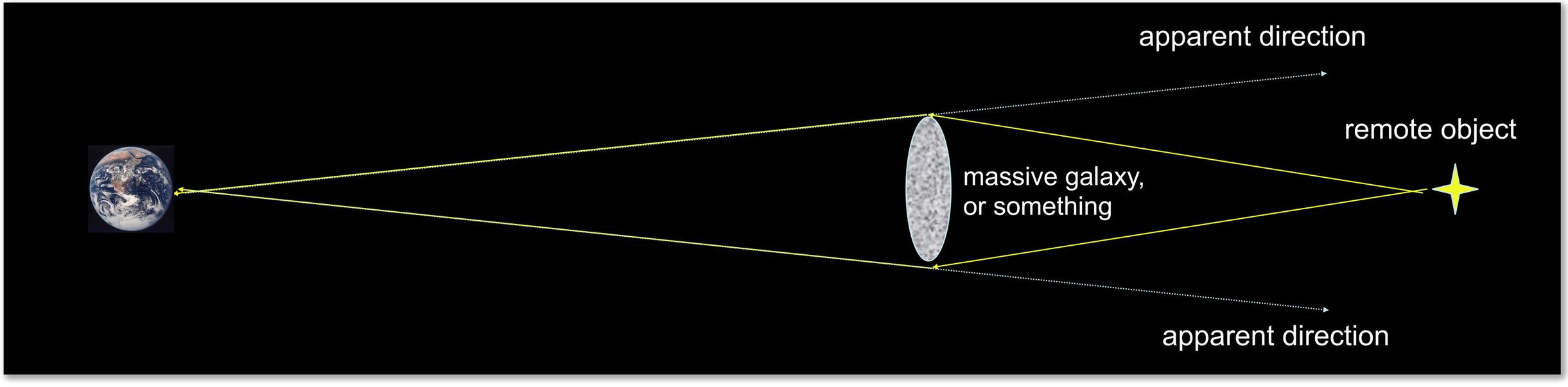


MACHOS

Credit: Canada-France-Hawaii Telescope Corporation 2006.

"Einstein Cross" - 4 images of a quasar





Second view of this:

"The Hafele-Keating experiment"

an atomic clock was carefully carried around the world in 1972 and carefully calibrated and compared with ground-based clocks

J. Hafele and R. Keating

There are a number of corrections: accelerations, decelerations, the rotation of the orbit, the fact that the earth is not inertial - but relativity was absolutely correct

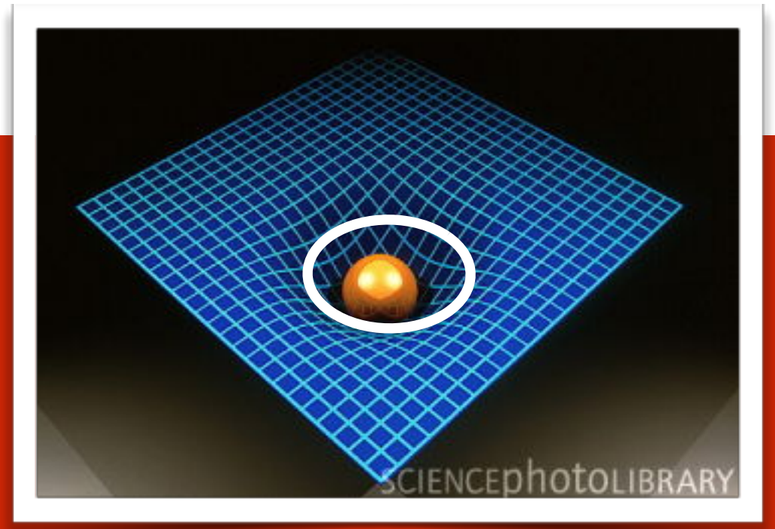
Predicted Effect	Flying East	Flying West
GTR (Gravitation)	+ 144 ± 14 ns	+ 179 ± 18 ns
STR (Velocity)	- 184 ± 18 ns	+ 96 ± 18 ns
Total	- 40 ± 23 ns	+ 275 ± 21 ns
measured:	- 59 ± 10 ns	+273 ± 7 ns

about half of their effect was due to the gravitational difference between Earth and the flight's altitude

redone twice more in airplanes and rockets/satellites

spacetime in general relativity

Earth's orbit is then just us following the shortest distance around the sun...not a gravitational force



Einstein got rid of gravitational forces in GR

Masses warp spacetime...

Since the shortest distance between two spacetime points is a light-path, this "maps" the shape

In GR gravity is not a force, but a "topography" of spacetime that forces objects to take the shortest curved path in spacetime

okay.

Spacetime might be curvy, bumpy, …"warped"

a "non-Euclidean geometry"?

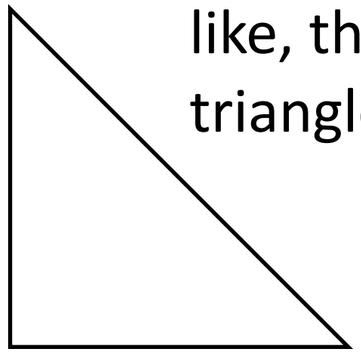
Euclid's Geometry starts with 4 terms and 4+1 postulates:

Point, Line, Plane, Space

1. A straight line can be drawn between any two points
2. A finite line can be extended infinitely in both directions
3. A circle can be drawn with any center and any radius
4. All right angles are equal to each other

5. Given a line and a point not on the line, only one line can be drawn through the point parallel to the line

a System of a series of proofs, each building on the previous, to a whole system of mathematics



like, the sum of the interior angles of any triangle is 180^o

like, Pythagoras' Theorem

like, actually... a lot of algebra problems before algebra was invented

Einstein’s mathematics of GR

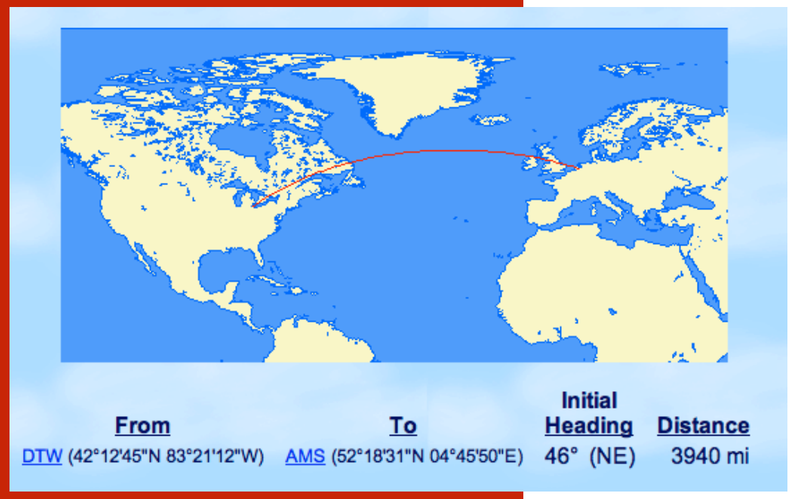
led him to have to consider non-Euclidean Geometries

which were still timidly being studied by mathematicians

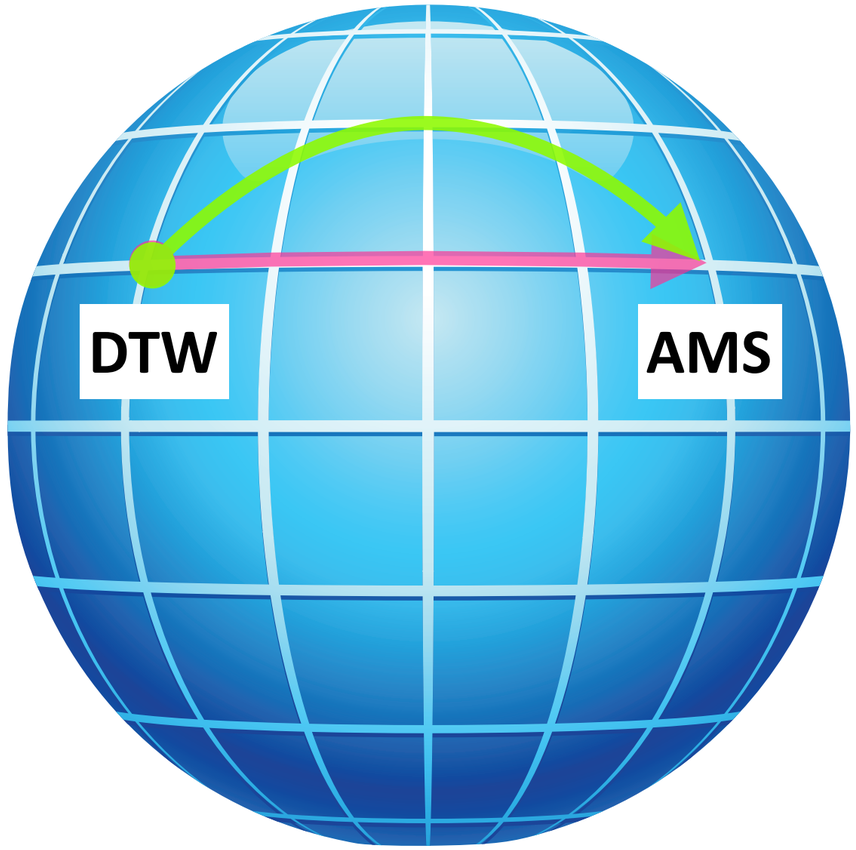
not so far-fetched

we live in such a geometry

what’s a “straight line”

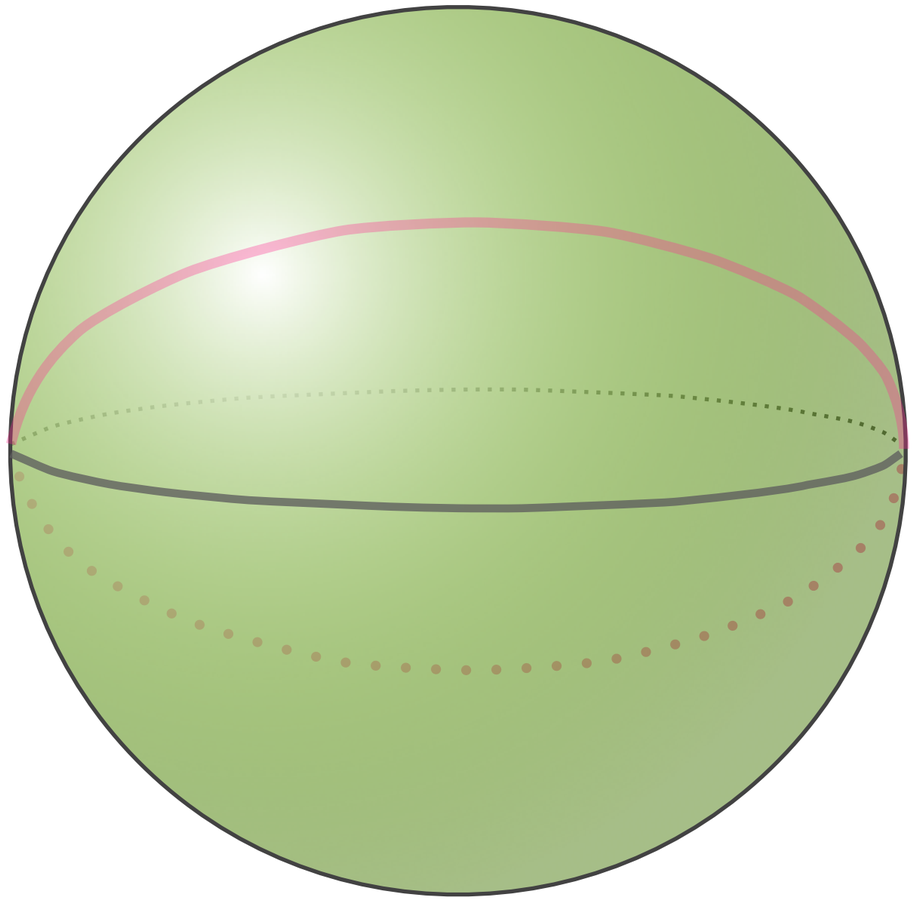


From	To	Initial Heading	Distance
DTW (42°12'45"N 83°21'12"W)	AMS (52°18'31"N 04°45'50"E)	46° (NE)	3940 mi



on a sphere?

shortest distance between 2 points



http://gc.kls2.com/

Euclid's 5th Postulate

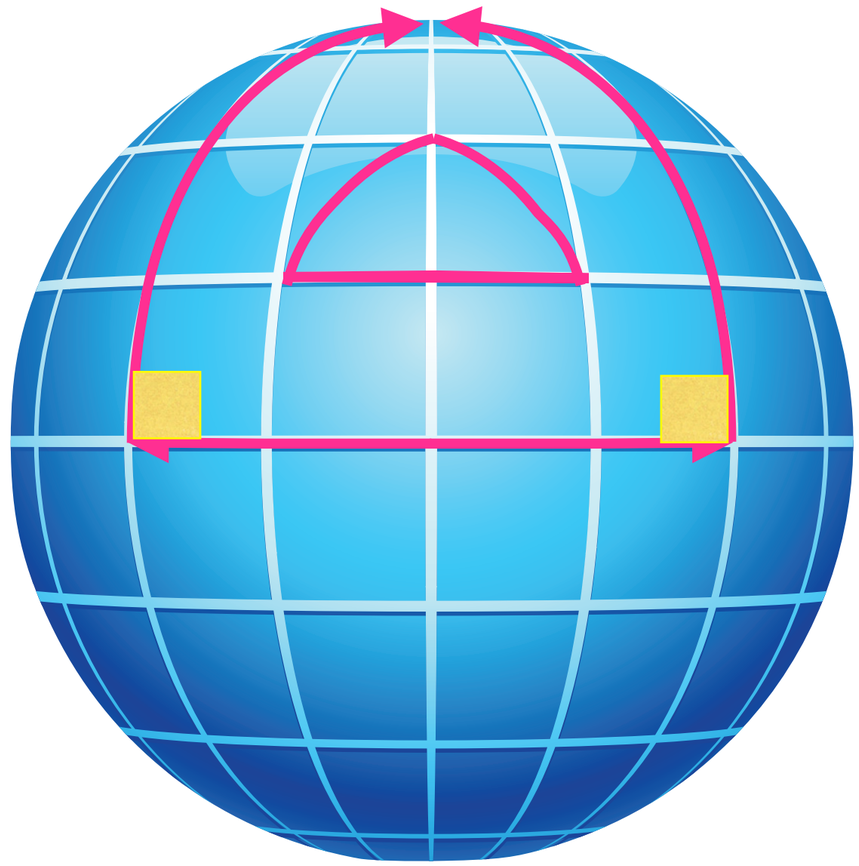
parallel lines never meeting?

only in a flat space

sum of interior angles in a triangle = 180°?

only in flat space

on sphere > 180°



‘‘warping’’

means that geometry

spacetime geometry

mixes with mass, energy, and pressure

General Relativity

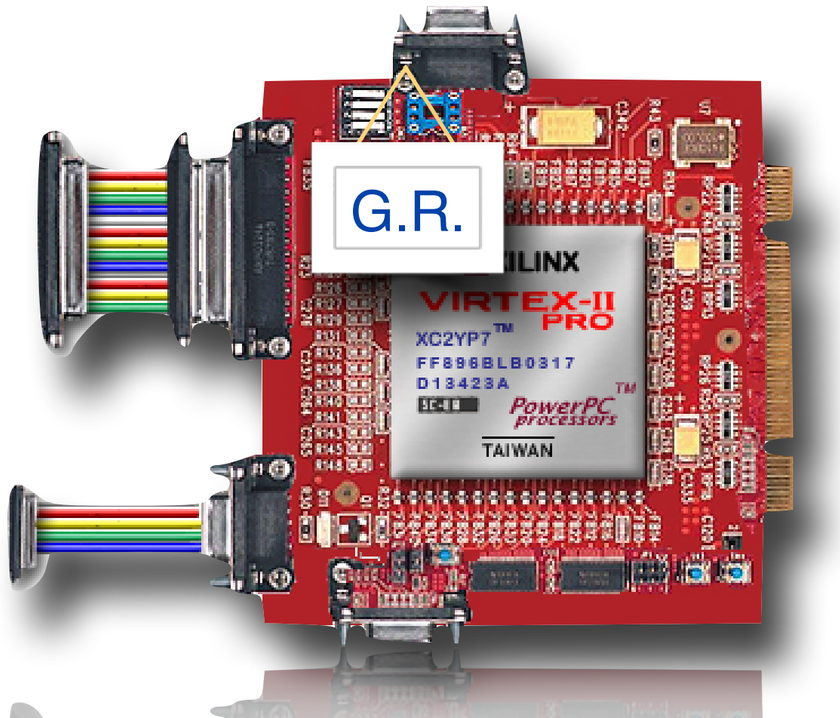
Einstein's GR equation

complicated mathematics

geometry of spacetime $\leftrightarrow$ mass-energy, pressure, & momentum

$$\overbrace{R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu}}^{} = \overbrace{\frac{8\pi}{c^4}T_{\mu\nu}}^{}$$

we'll call it: "$G = T$"



Einstein grossly underestimated

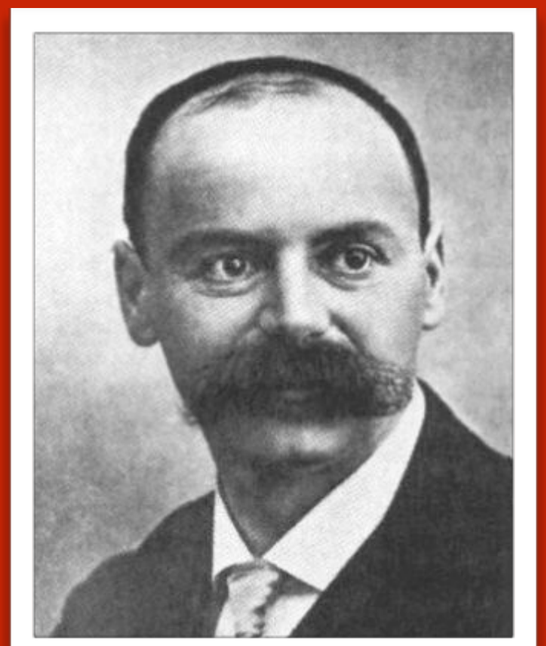
the richness of his theory

he knew he'd exhausted the possible solutions to the GR equations

He was wrong…and irritable about it

wrong.
Almost
immediately:

from the
foxhole, 1915



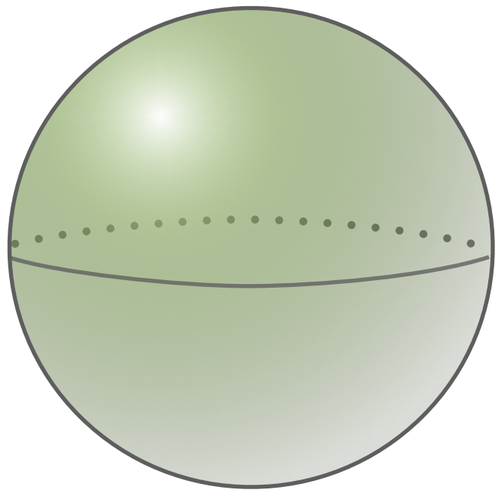
Karl Schwarzschild, 1873-1916

Yes. I mean *from* a foxhole.

The **first exact solution** to GR...Einstein had used some approximations for light-bending, etc.

The equations of spacetime outside of a spherical mass.

a big mass.



escape

Suppose a rocket is shot straight up... when it goes "ballistic" (no propulsion)...what happens?

It depends.

$v \gtrless v_{esc}$

More initial velocity, the more likelihood that the rocket will escape the pull of the Earth's gravity.

This happens when the kinetic energy = potential energy

$$v_{\mathrm{esc}} = \sqrt{\frac{2GM_E}{R_E}}$$

From Earth: 11.2 kilometers per second...~25,000 mph

what about light?

suppose the question is not:

"What's the escape velocity from a sphere of mass M?"

BUT

"What's the radius of a mass *M* for which the escape velocity is = *c*?"

$$v_{\rm esc} = \sqrt{\frac{2GM_E}{R_E}} \longrightarrow c = \sqrt{\frac{2GM}{R_S}}$$

R_S called the Schwarzschild Radius

$$R_S = \frac{2GM}{c^2}$$

It seemed to be a magic radius...

the Schwarzschild Radius falls out of his solution to G.R.

it's not likely

R_S is incredibly small

and density, incredibly high

All of the mass of:

1.6 B meters

inside of R_S:

R_S = 3000 m

12 M meters

R_S = 1 cm

Impossible, right?...thought to be a disaster for the theory.

everyone fretted over this for more than a decade

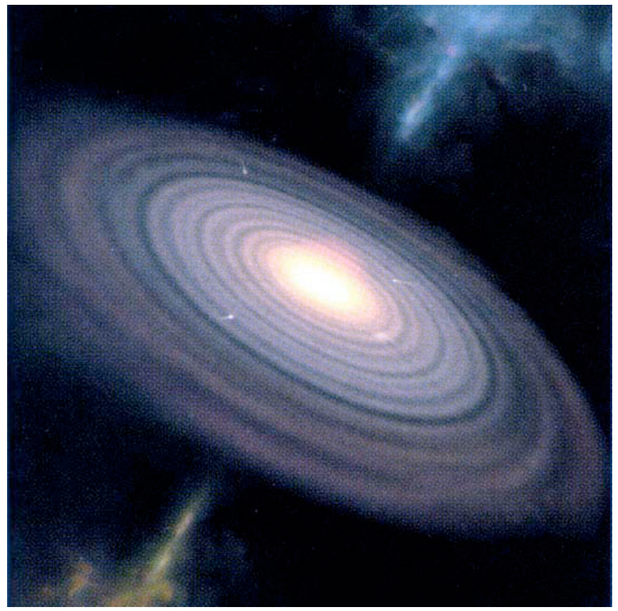
1932, Georges Lemaître found that a slight change of coordinate axes

changed the problem completely

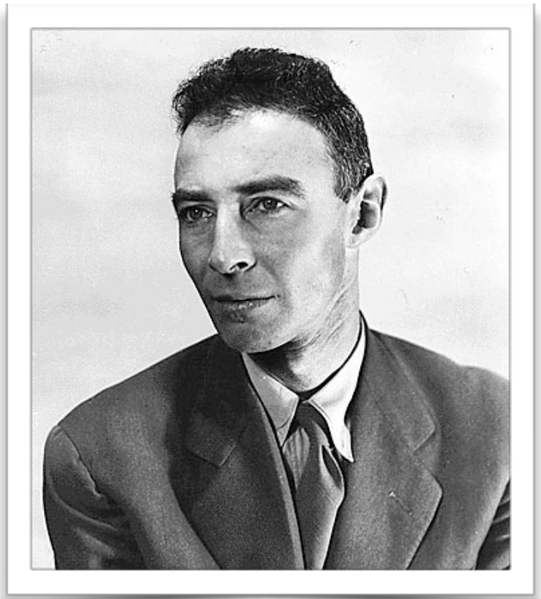
Black Holes

The Schwarzchild Radius was not a flaw in the theory

simply an insult from Nature!



Einstein calculated that the normal formation of a star of gravitational accretion could never form in so small a volume...and stars get bigger not smaller, right?

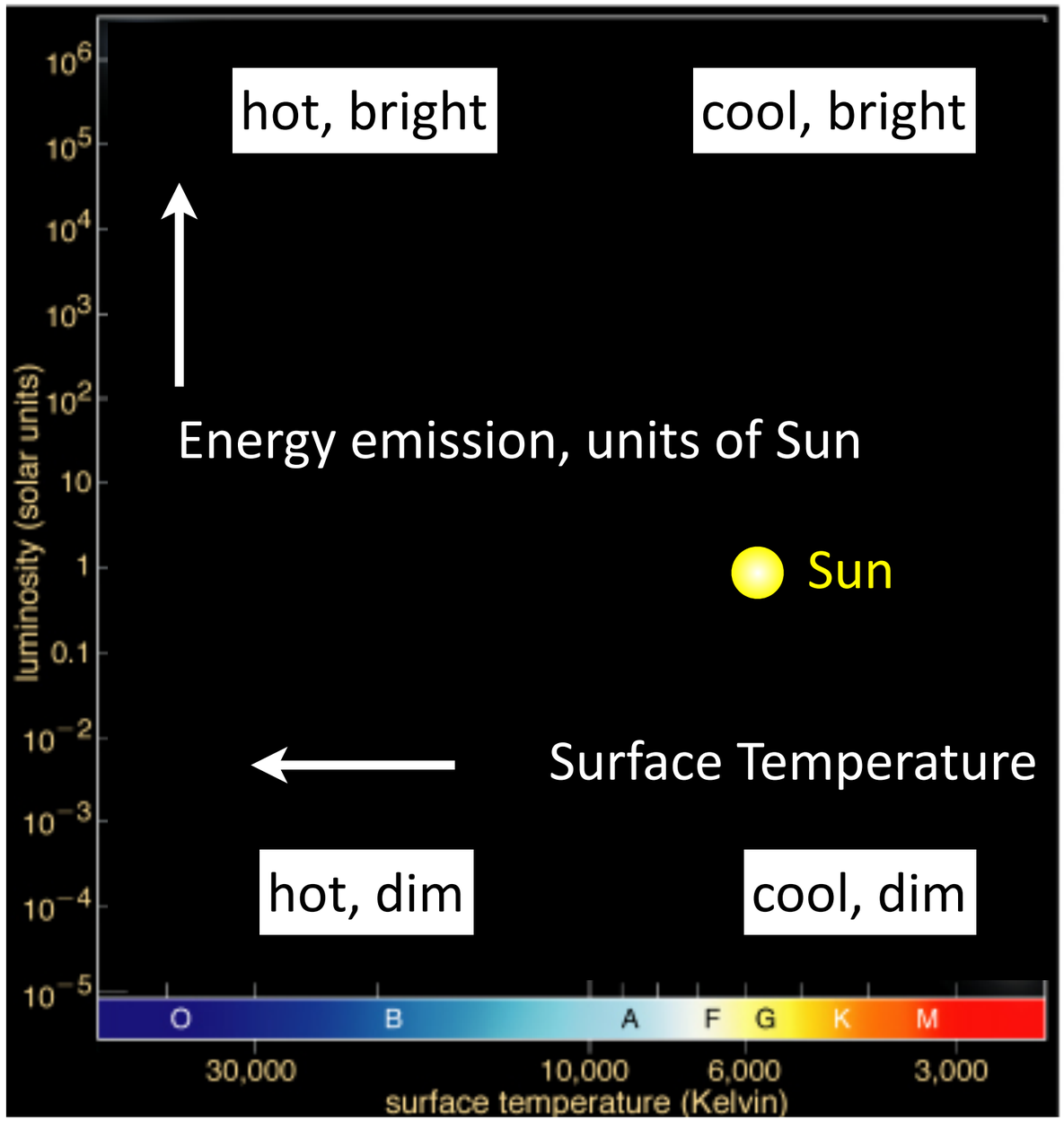


1939: Robert Oppenheimer & Hartland Snyder showed how.

5¢ worth of stellar physics

no charge

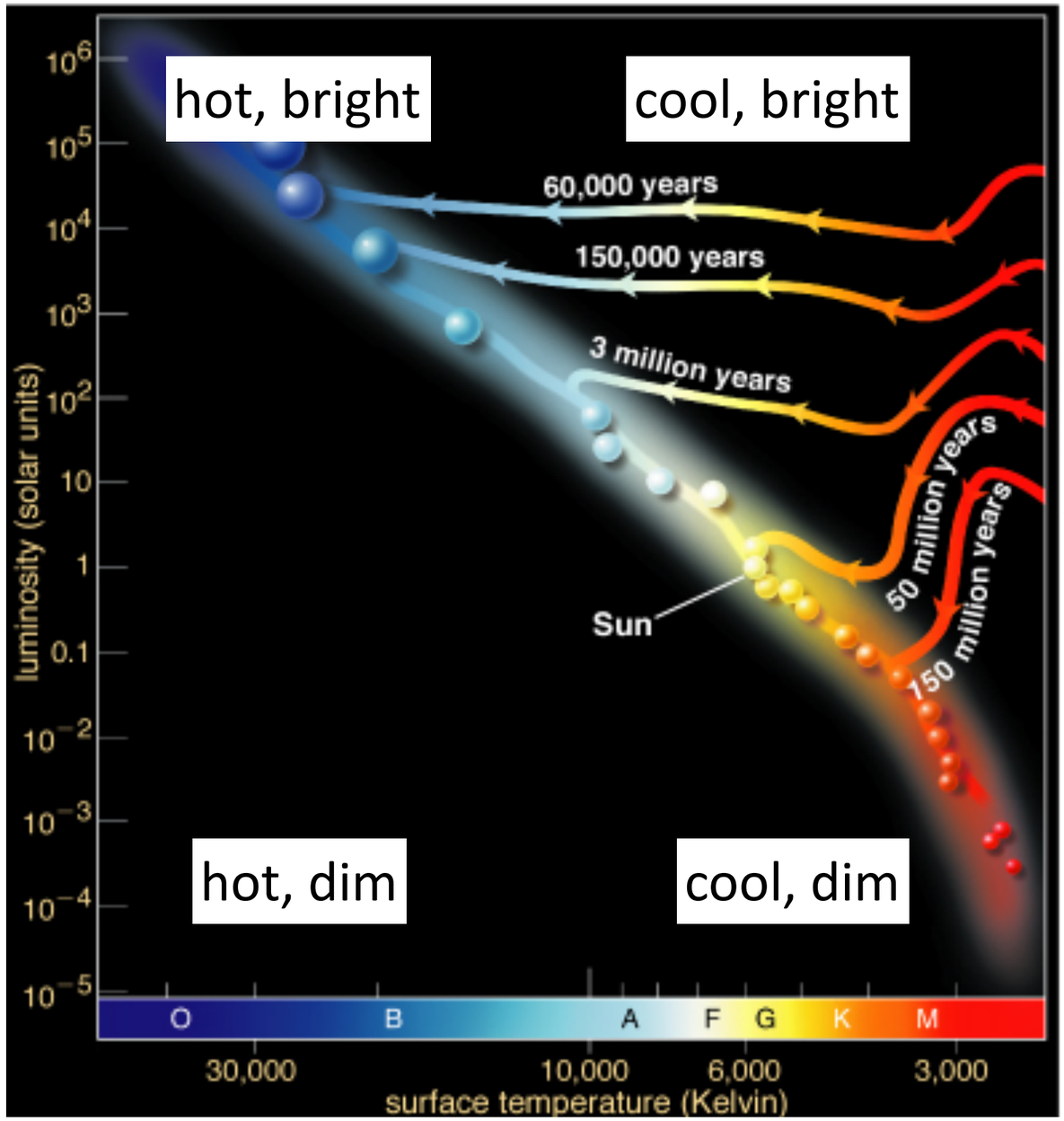
Hertzsprung-Russell Diagram...aka H-R Diagram



5¢ worth of stellar physics

no charge

Hertzsprung-Russell Diagram...aka H-R Diagram



balls of Hydrogen brought together by gravity

The "main" sequence

stars radiate energy – that's their job!

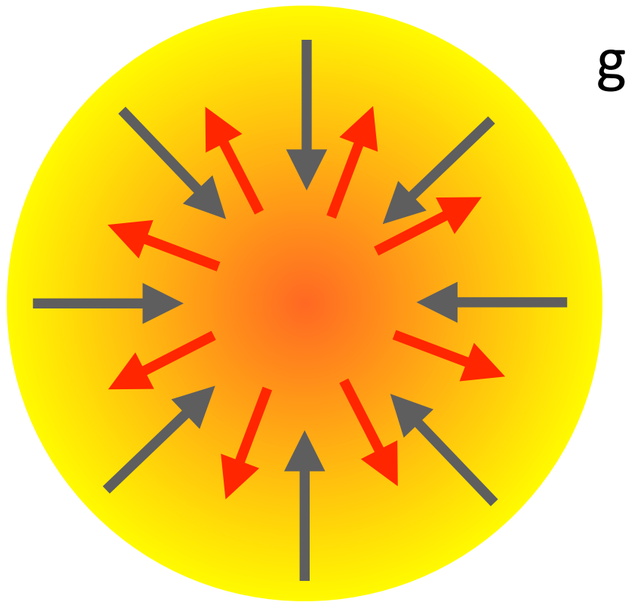
being stable is their challenge...

a balancing act

inward pressure from gravity

vs

outward pressure from radiation



gravity pulls core/atmosphere: **in**

Radiation pressure from nuclear fusion in core: **out**

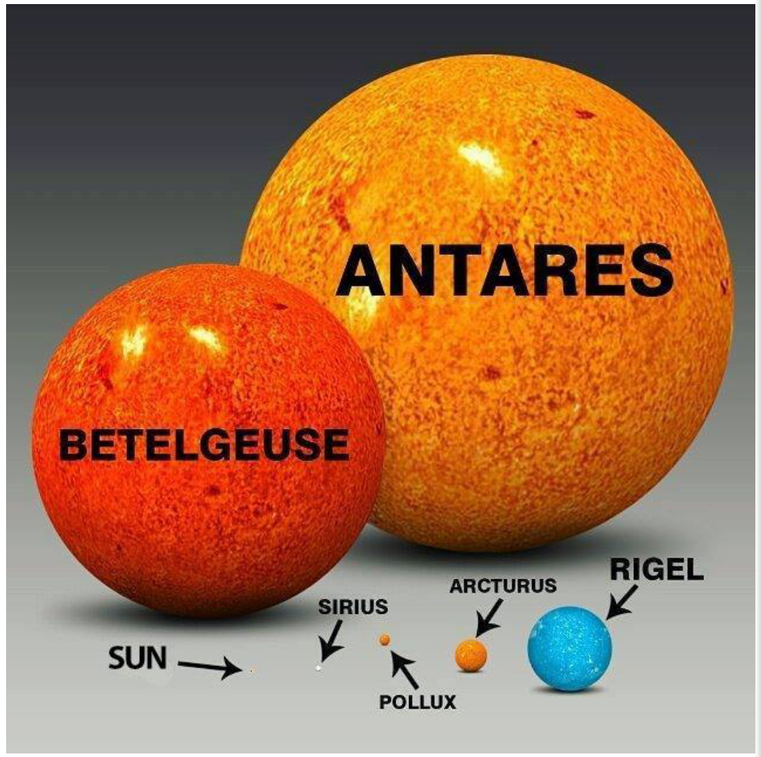
H begins to “burn” to He

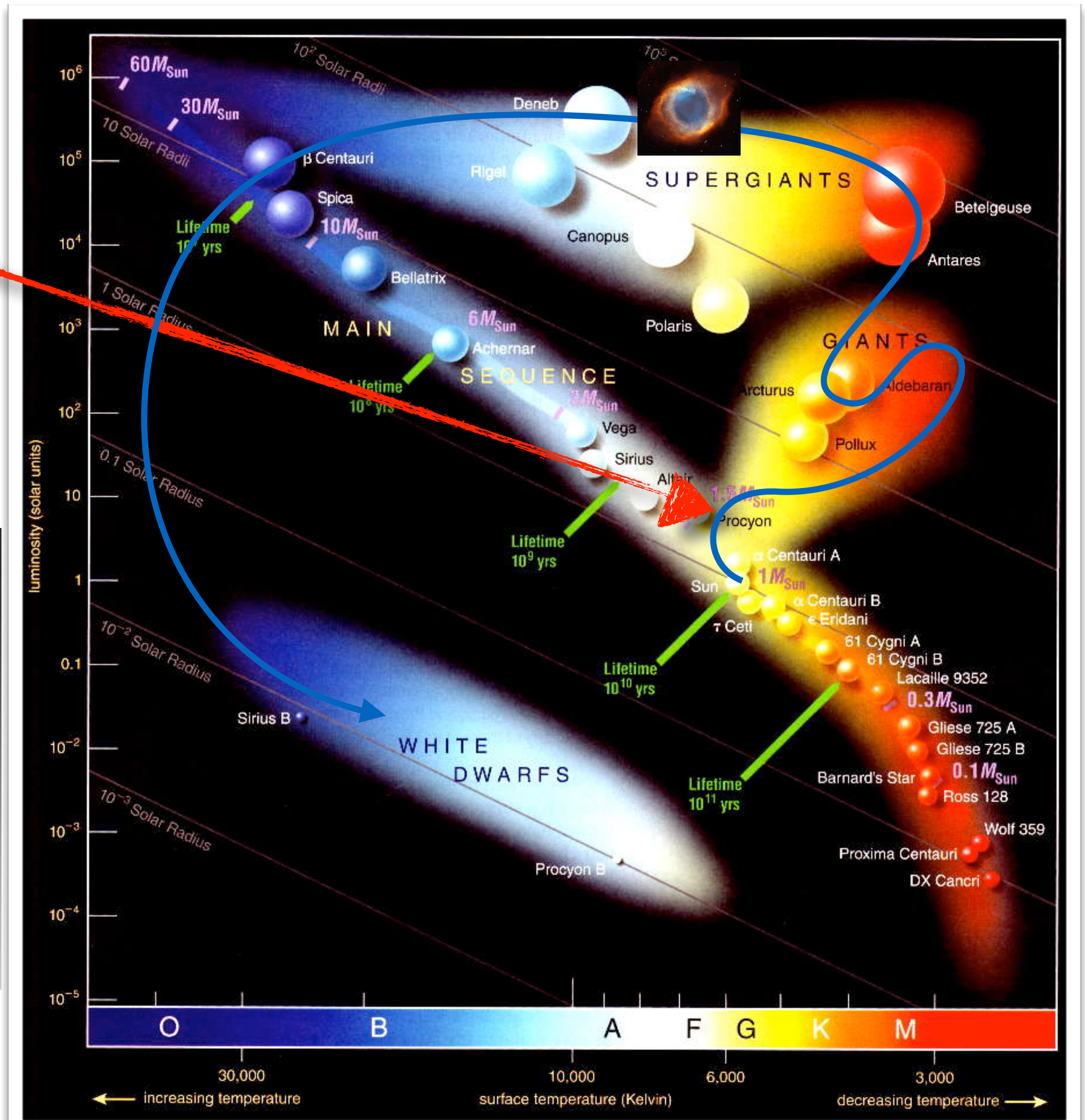
A star’s fate is determined by how massive it is.

a balancing act

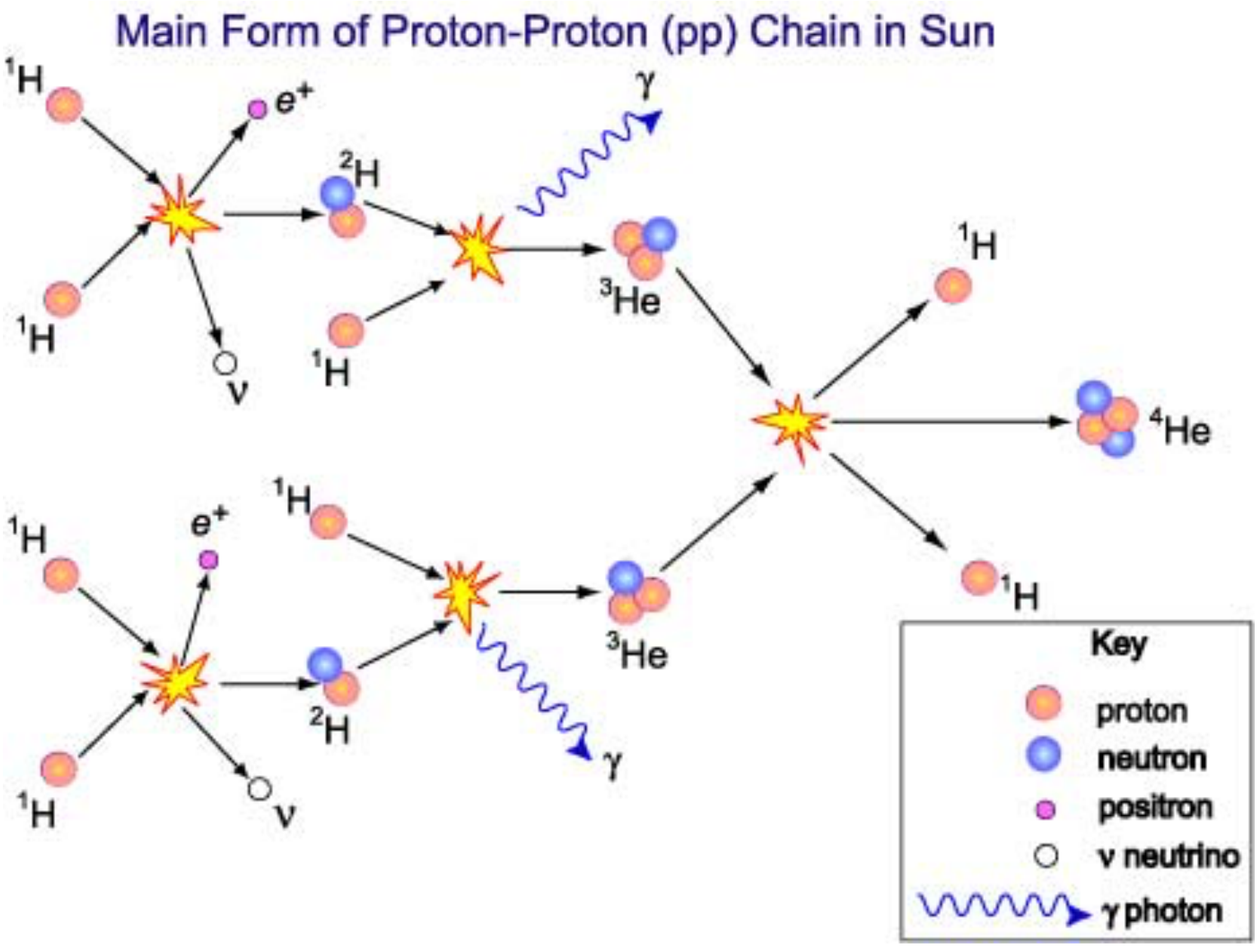
SUN-LIKE?

H → He





pp cycle


Main Form of Proton-Proton (pp) Chain in Sun
^{1}H
e^+
γ
^{2}H
^{1}H
^{3}He
^{1}H
ν
^{1}H
^{4}He
^{1}H
^{1}H
e^+
^{1}H
^{3}He
^{2}H
γ
^{1}H
ν
Key
proton
neutron
positron
ν neutrino
γ photon

a balancing act

SUN-LIKE?

H → He

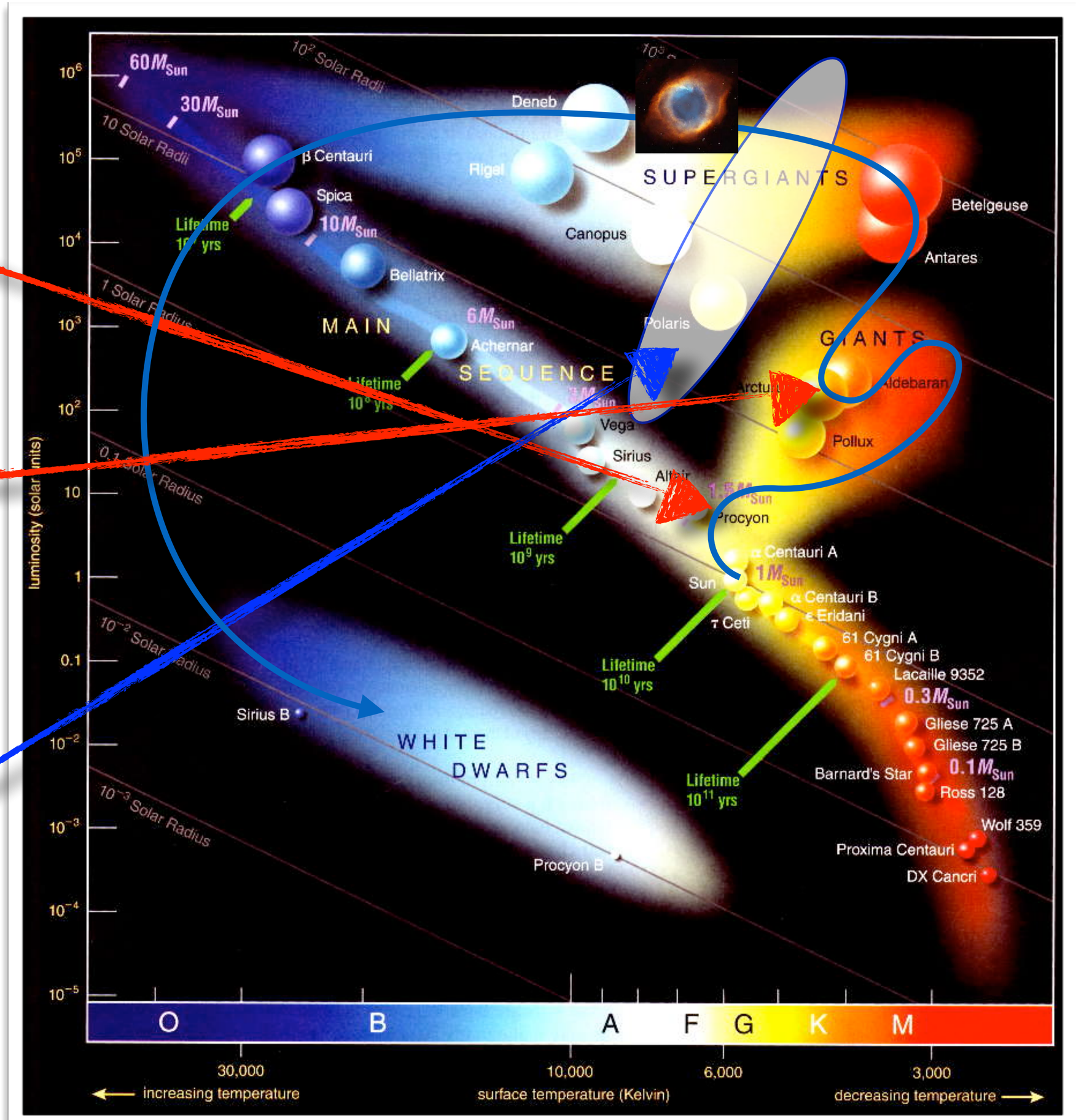
SUN-LIKE?

He → C + O

source of Carbon for life

REGION OF INSTABILITY

pulsating stars



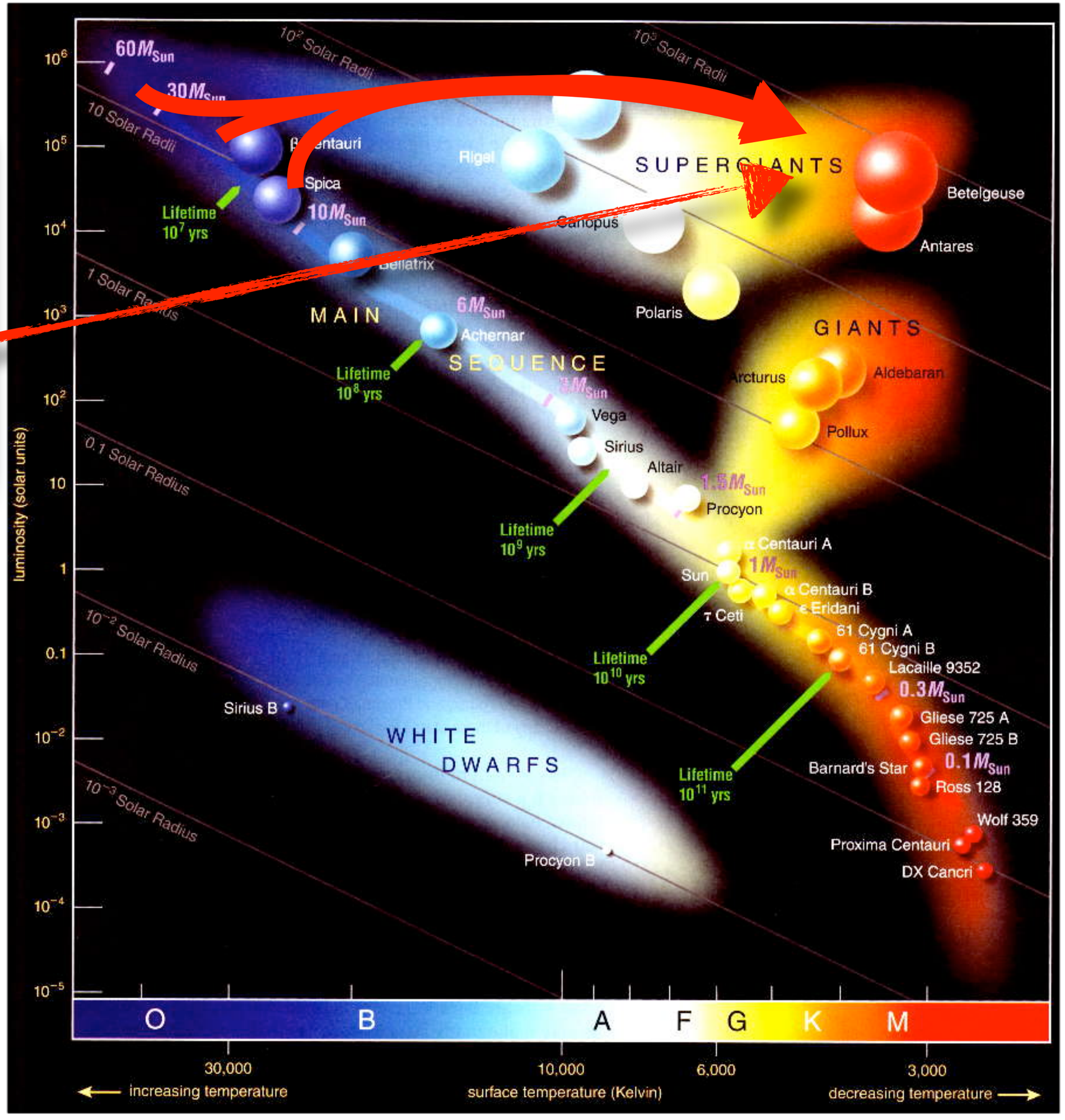
a balancing act

VERY MASSIVE...

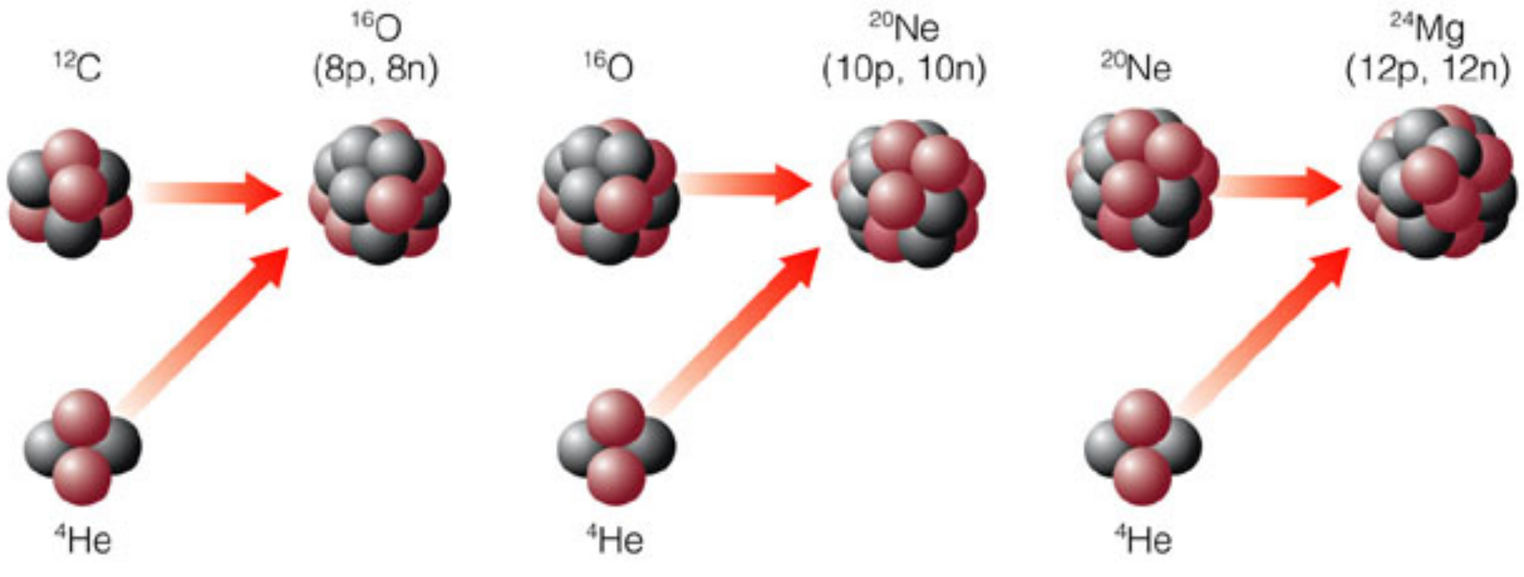
>1.3 Msun

H → He → C...

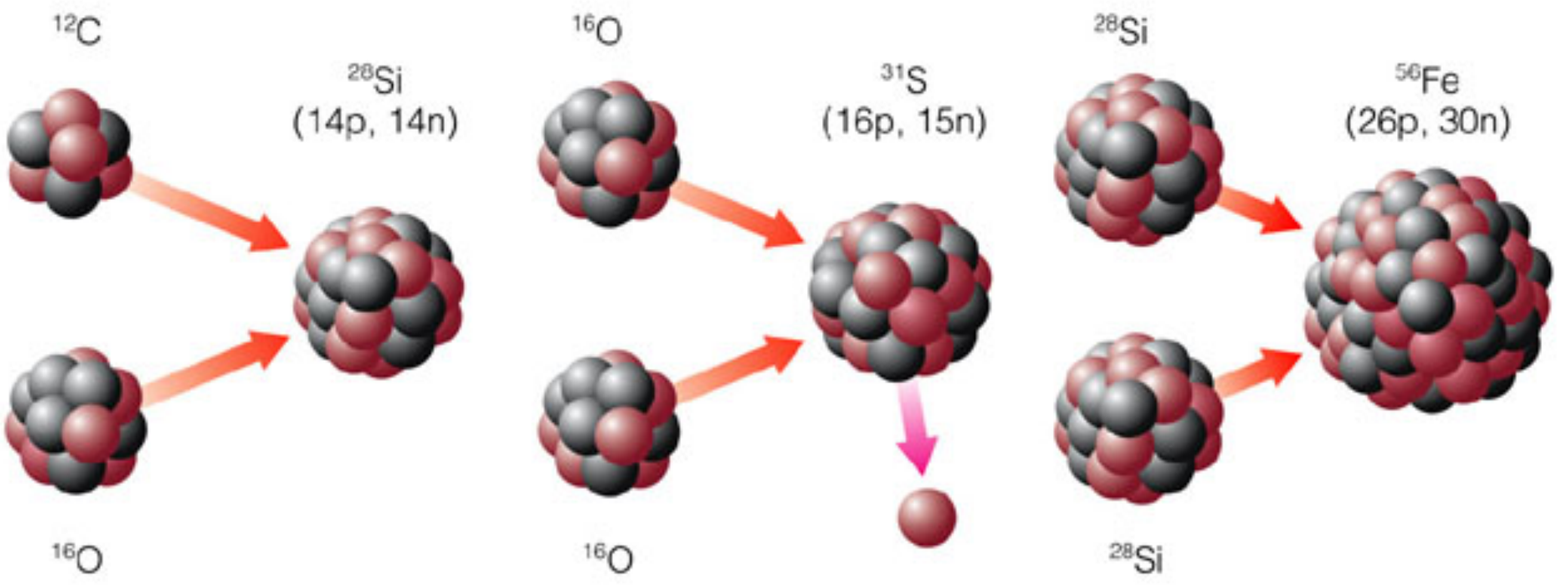
...→ Fe



Helium-capture reactions



Other reactions



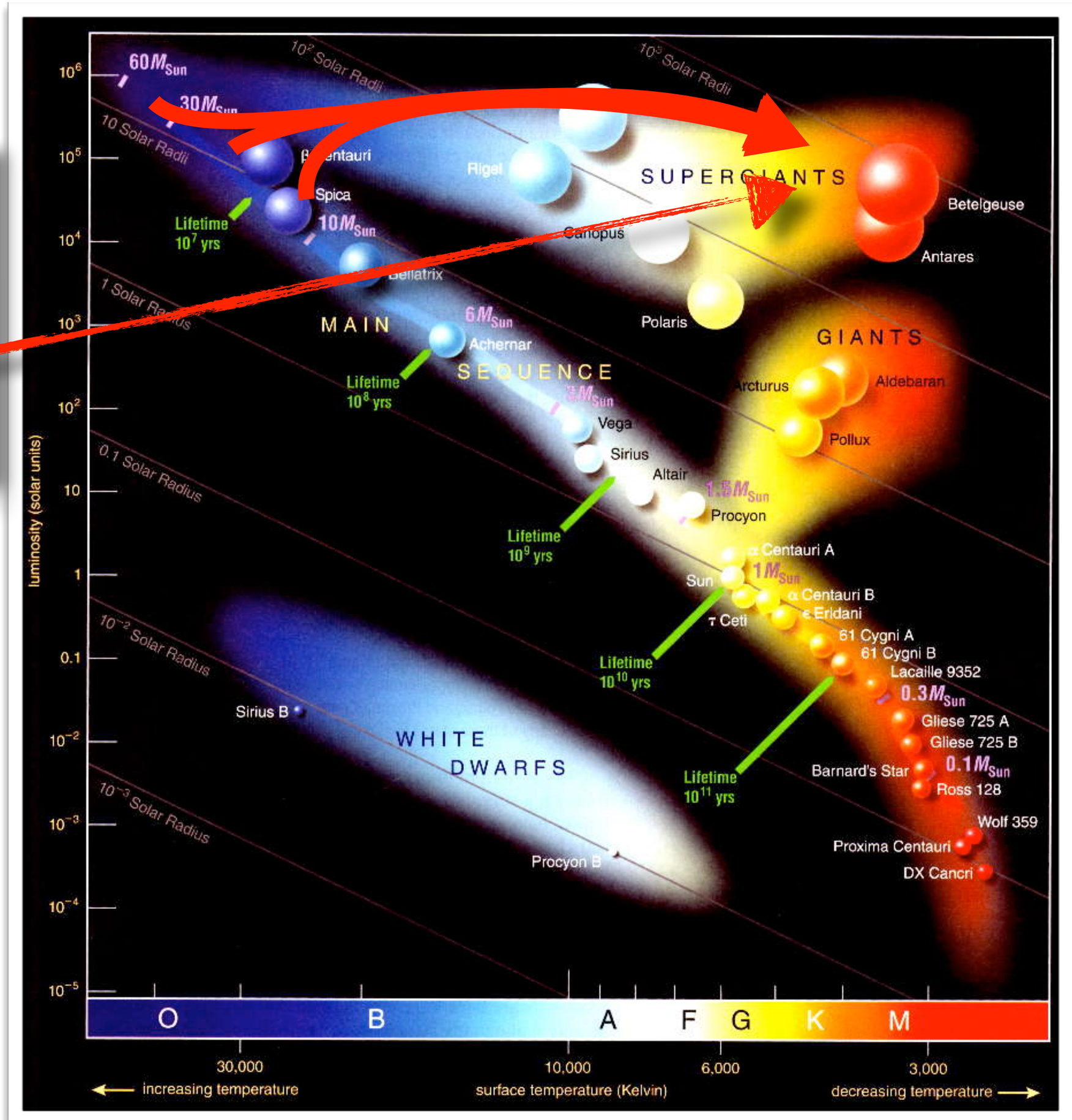
a balancing act

VERY MASSIVE...

>1.3 Msun

H → He → C...

...→ Fe

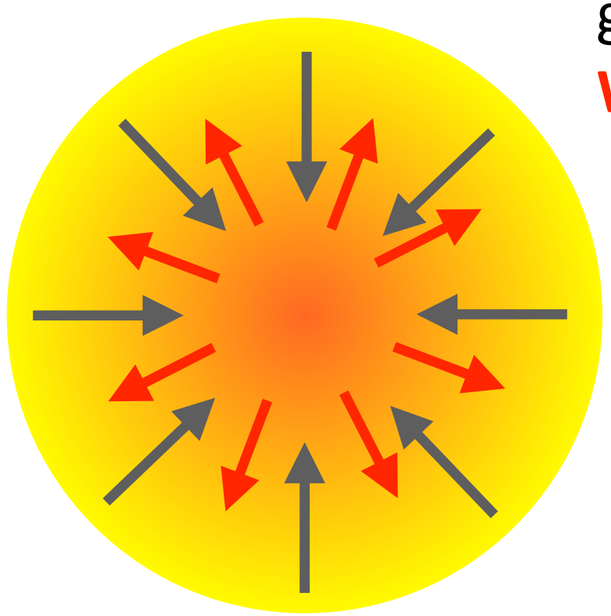


a balancing act

inward pressure from gravity

vs

outward pressure from radiation



gravity pulls core/atmosphere: **in**

WINS

Radiation pressure from nuclear fusion in core: **out**

STOPS

$e + p \longrightarrow n + \nu_e$ everywhere...

the star shrinks dramatically

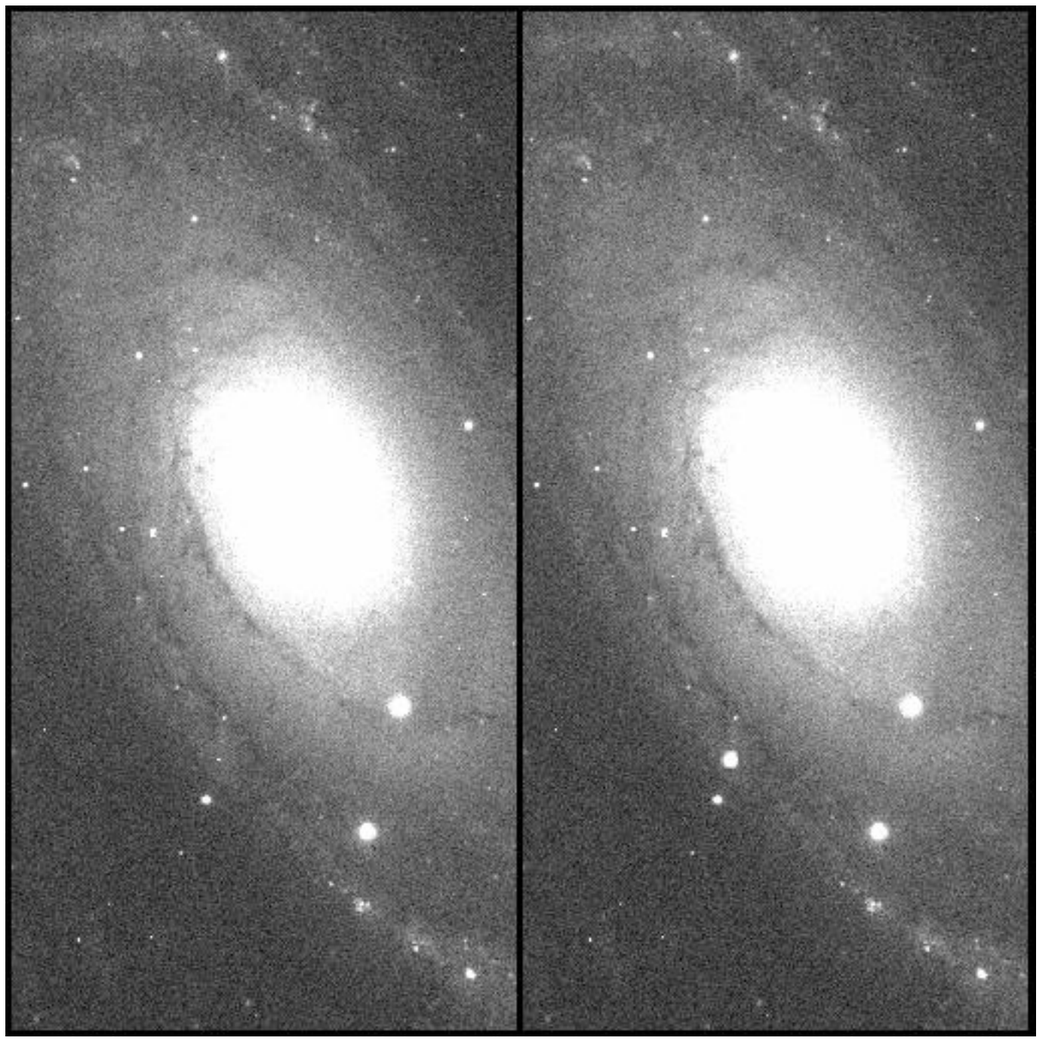
and then a special effect takes over:

neutrons cannot all be on top of one-another

It stops abruptly in seconds

Explosively.

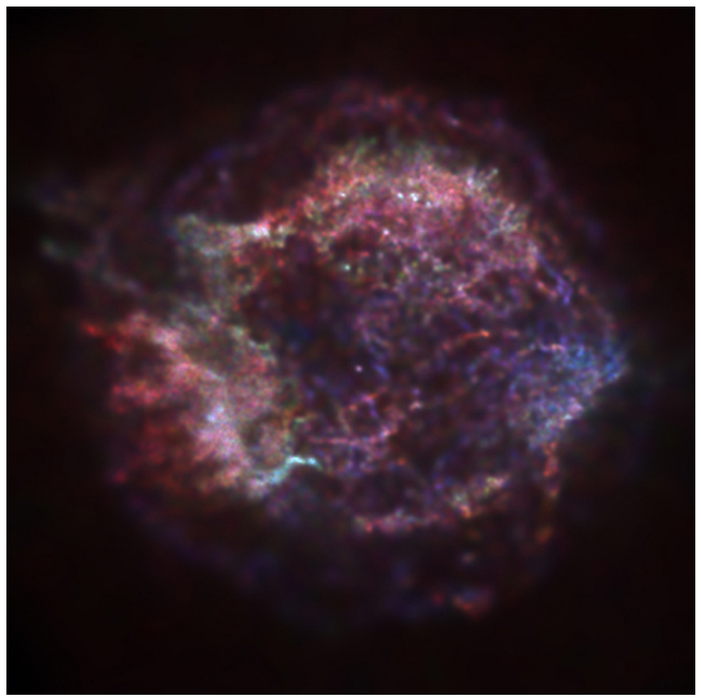
supernova!

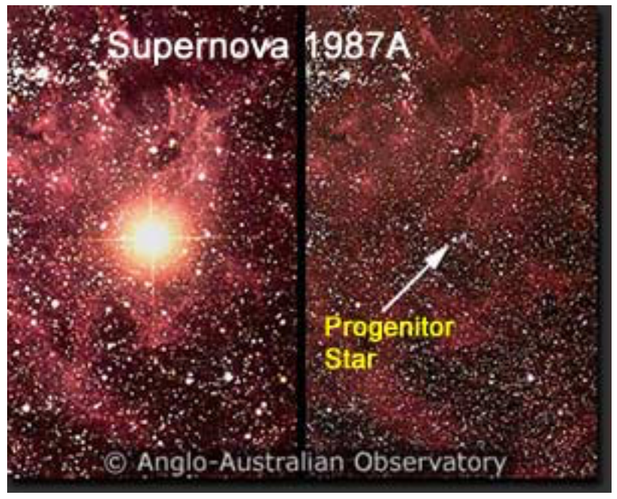


SN 1993J
M81

Crab Nebula…supernova remnant from 1054 AD

Tycho’s Supernova, 1572

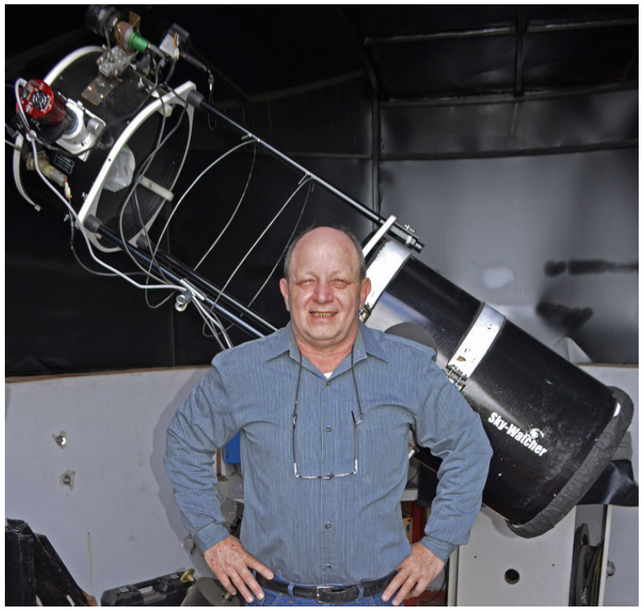


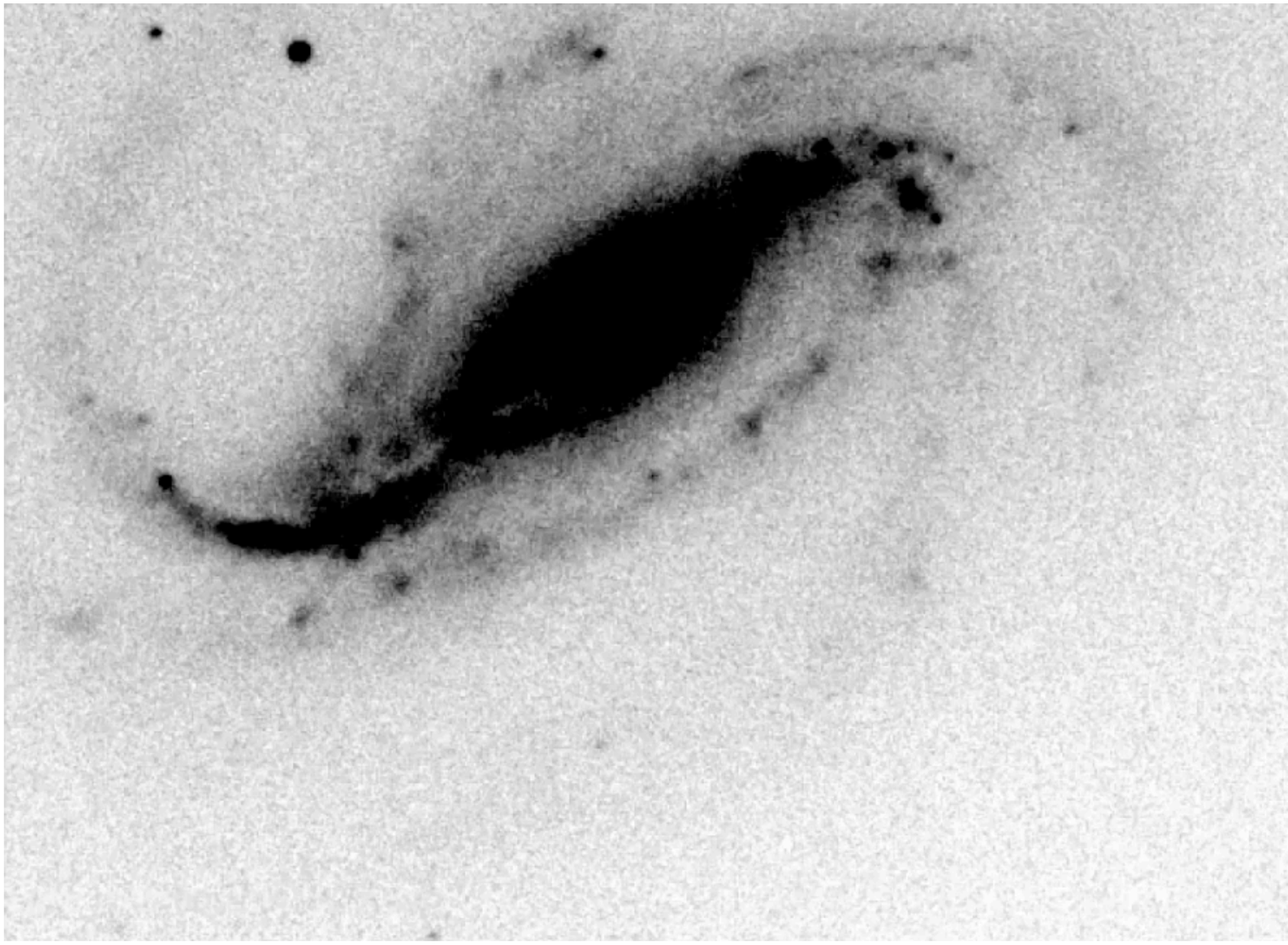


first infant picture of SN

20 September
2016

Victor Buso:

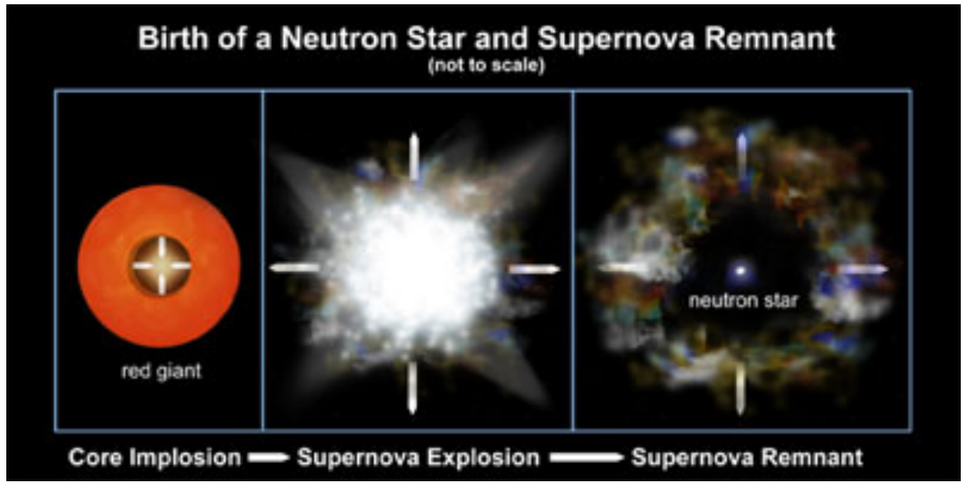




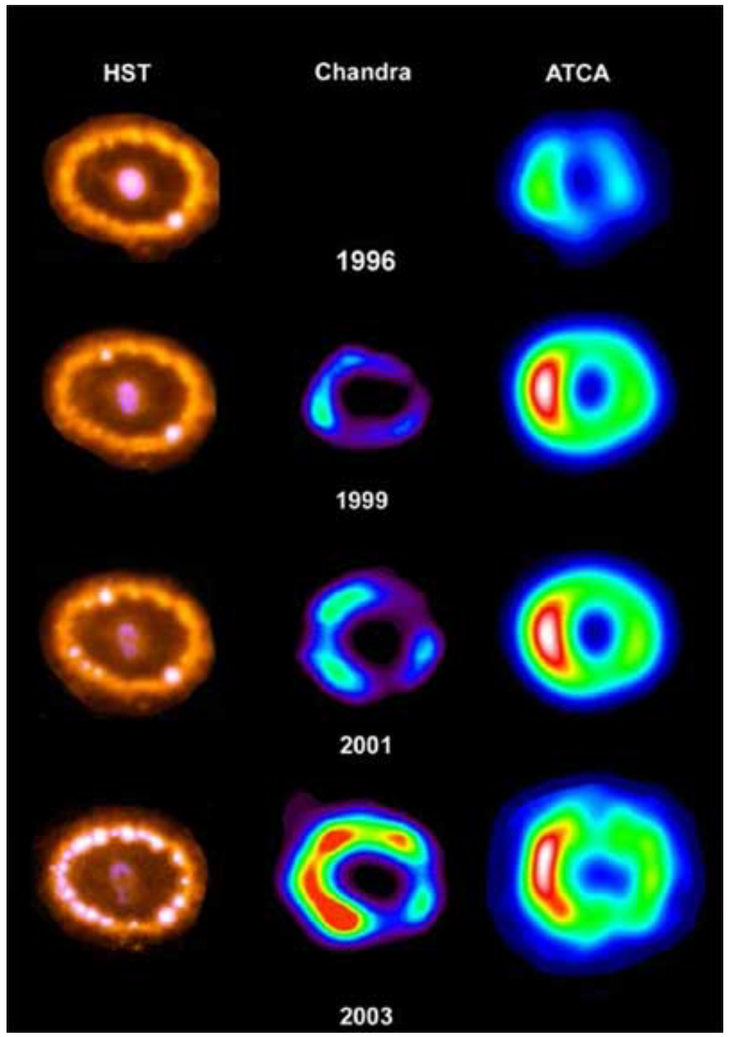
NGC 613
65M ly away

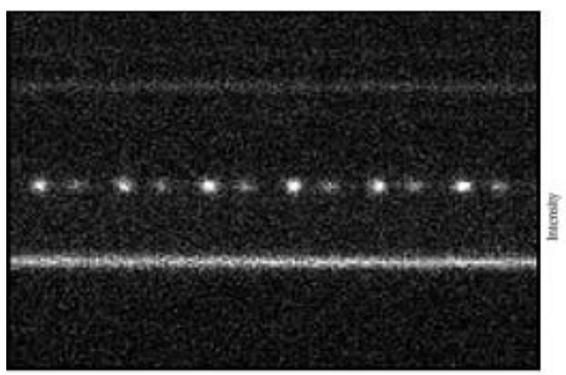
aftermath of a SN

mass-ejection and a neutron star

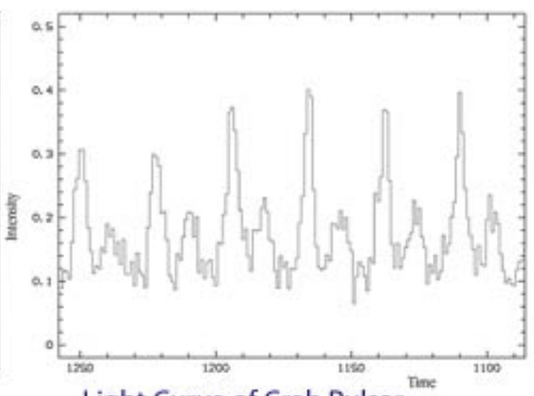


a star made of only neutrons…sizes 10's km
densities 10^{17} kg/m^3





Time Sequence of Crab Pulsar



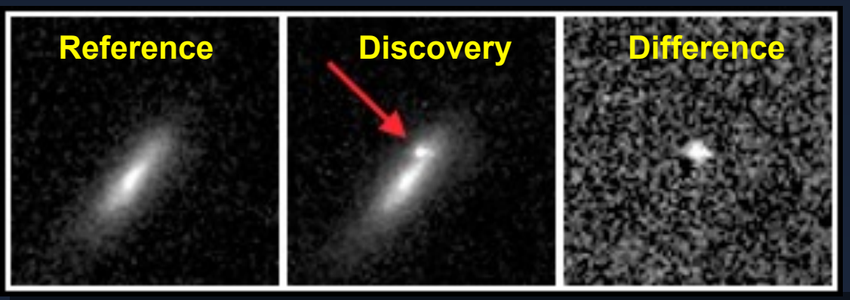
Light Curve of Crab Pulsar
(VLT KUEYEN + FORS2 + FIERA) © ESO

"pulsar"…a rapidly rotating neutron star: few milliseconds to seconds in rotation rate

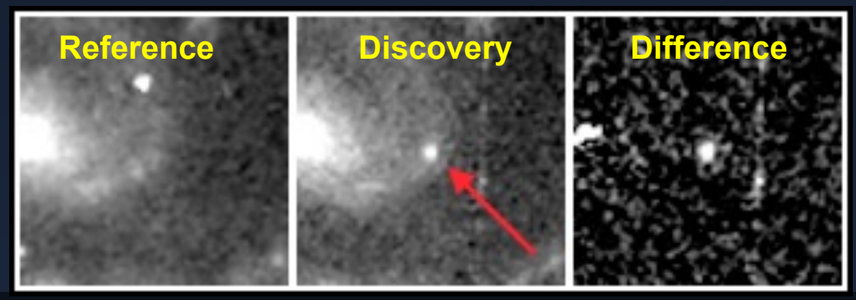
The source of all elements < Fe. We are made of star-stuff

Cluster Lensing And Supernova survey (**CLASH) SN Candidates in 25 Clusters**
(Of the 30, ~30% are Type Ia)

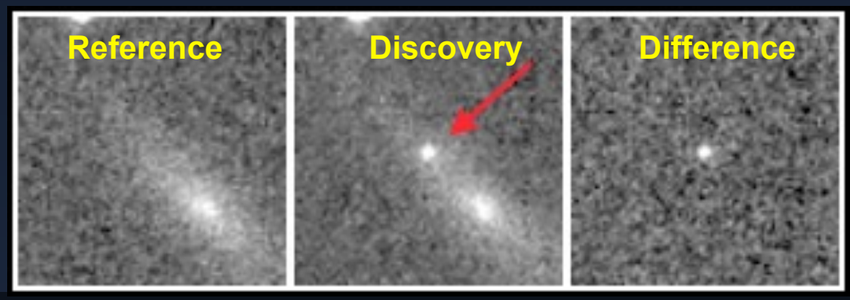
SN "Augustus"



SN "Galba"

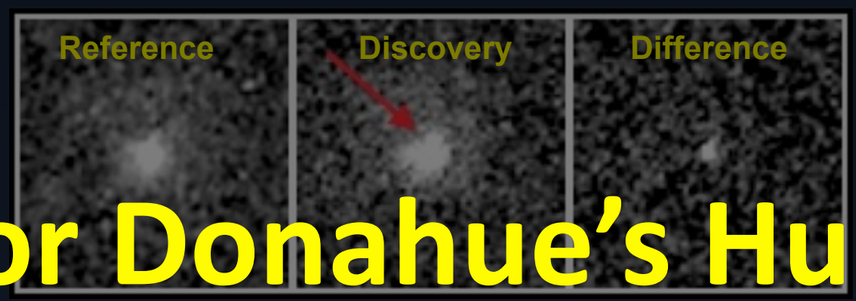


SN "Antonius Pius"



SN "Tiberius"

SN "Otho"



SN "Marcus Aurelius"

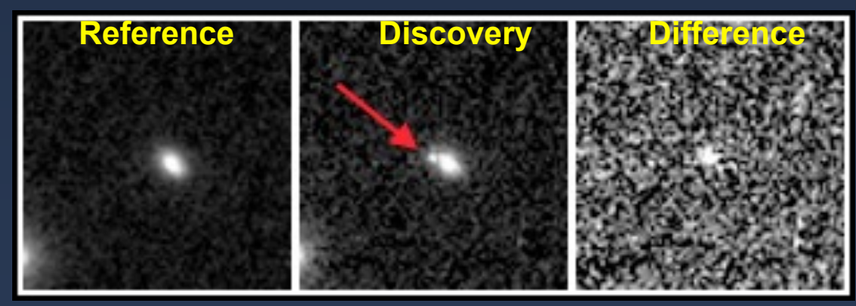
SN "Caligula"

SN "Vespasian"

SN "Scarlet"

SN "Claudius"

SN "Titus"

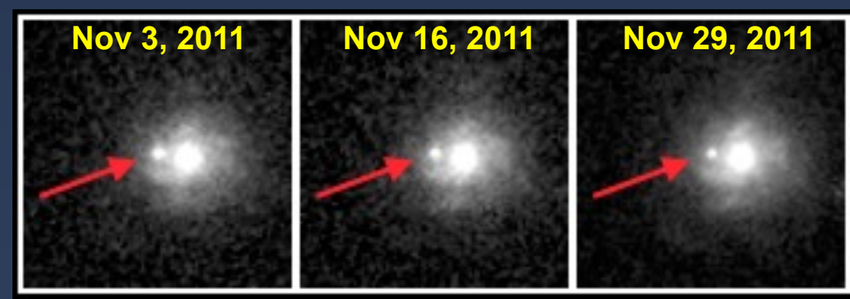


SN "Crimson"

SN "Nero"

SN "Hadrian"

SN "Burgundy"



One of Professor Donahue's Hubble project: SN searches - naming them for Roman Emperors

what if M > 3-15 x M_{sun}?

Nature turns viscous

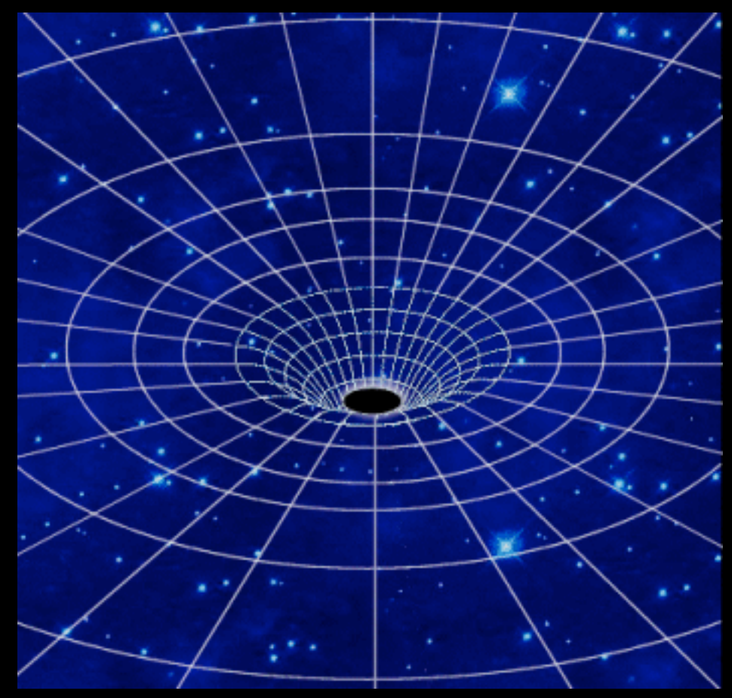
very peculiar

Gravity wins. Nothing gets out, not even light:

BLACK HOLE

no light

the most extreme warping of spacetime in Nature

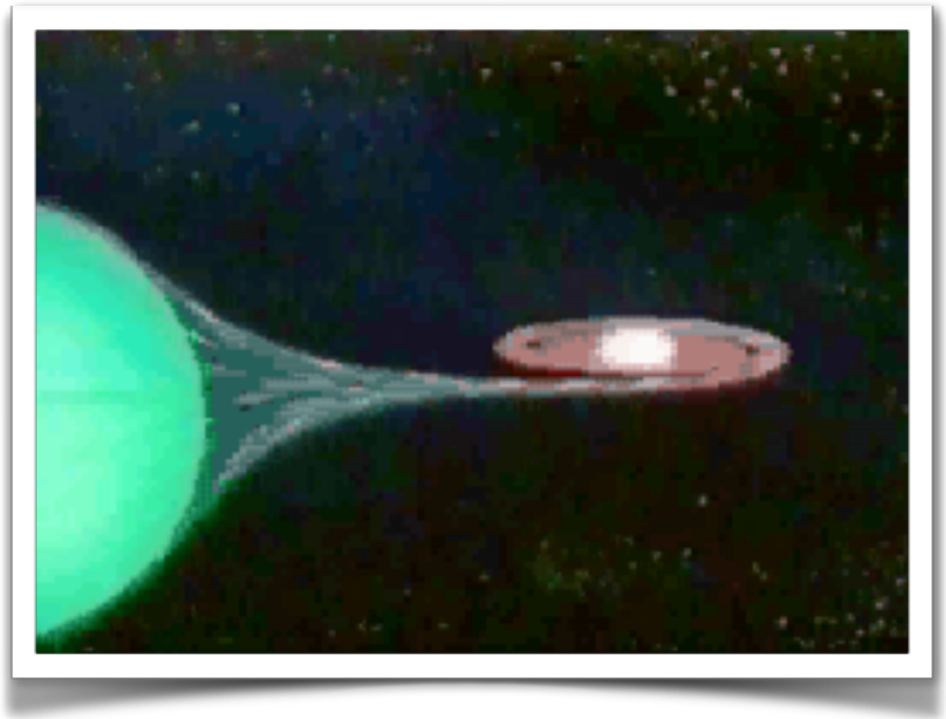


outside of ~3R_S

a black hole behaves like a normal object with Newtonian-like gravity

So, how are they found?

Because they're hungry.



the matter sucked in accelerates...
and accelerating charges do what?

Radiate...**X-Ray, radio frequencies** typically

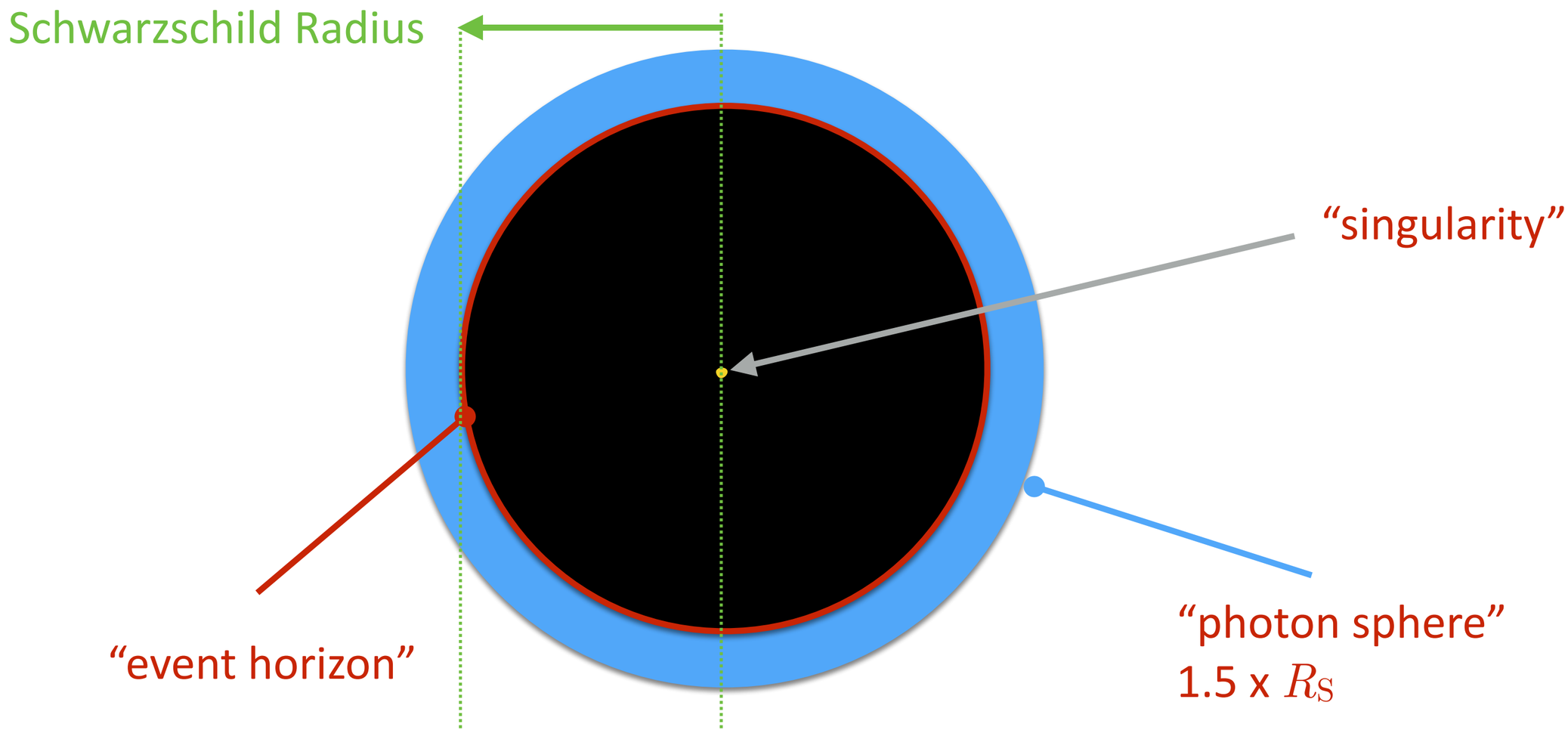
Three kinds:

1. **Stellar black holes** - 100's found with Hubble
2. **Supermassive black holes** - seems that all galaxies have one: billion's of stars' worth
3. **miniature black holes**. - complete speculation, a gleam in some theorists' eyes

Stellar Black Holes

many stars’ fate

black hole anatomy



simplest black hole: not rotating and not charged

realistic black hole: rotating...Kerr Black Holes

often in binary systems

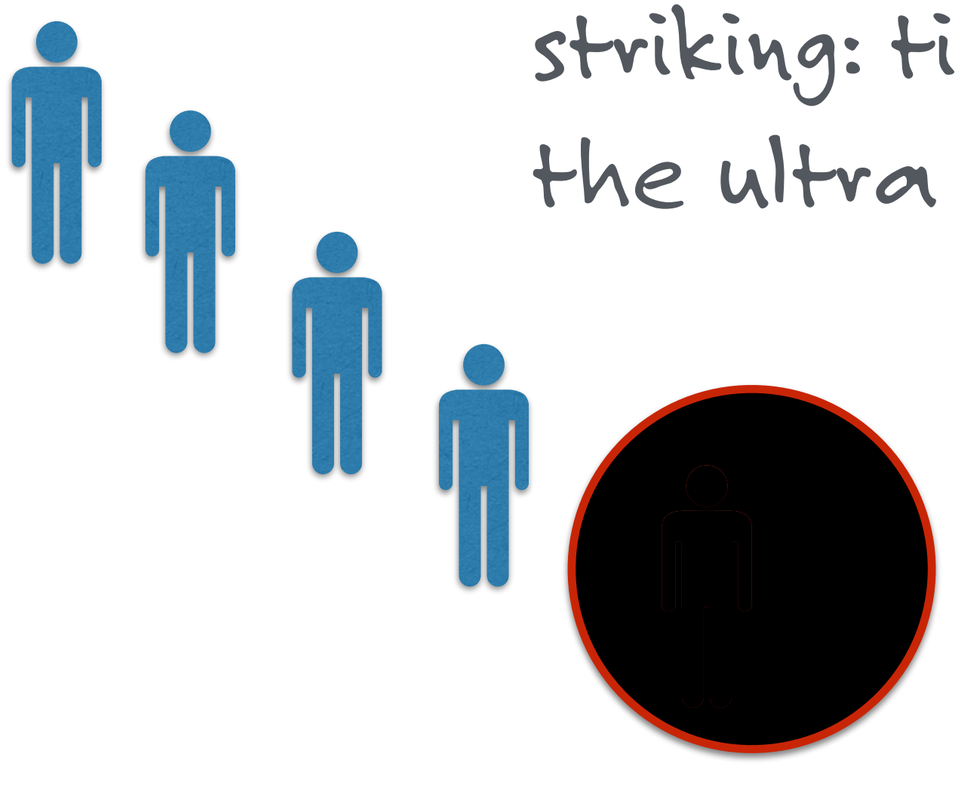
with characteristic X-ray emission

Cygnus X-1/HDE 226868 1972

what if you fell in?

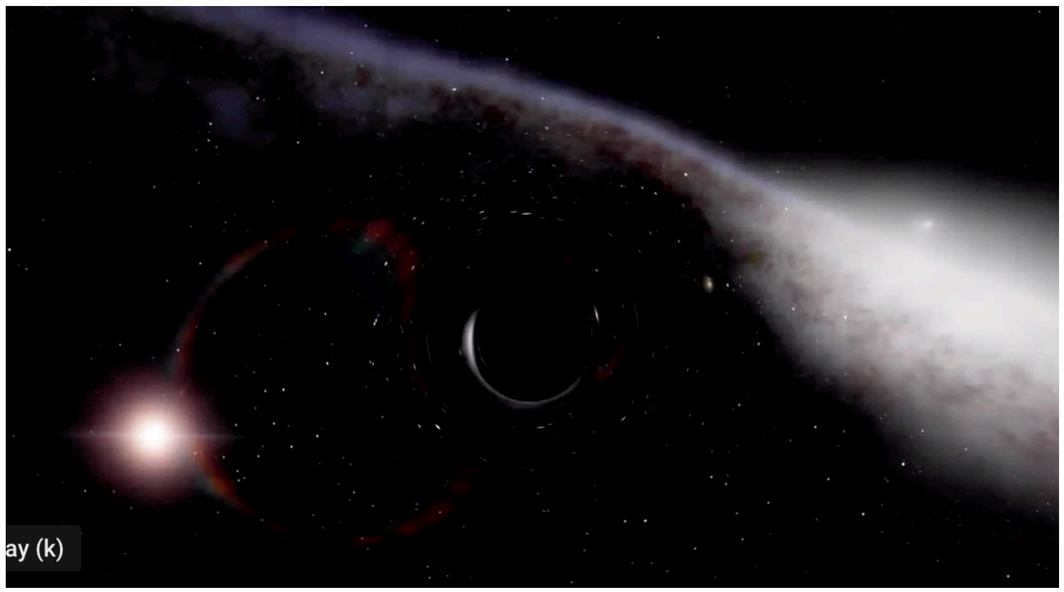
everyone asks this!

from the outside:



striking: time slows near the ultra strong gravity

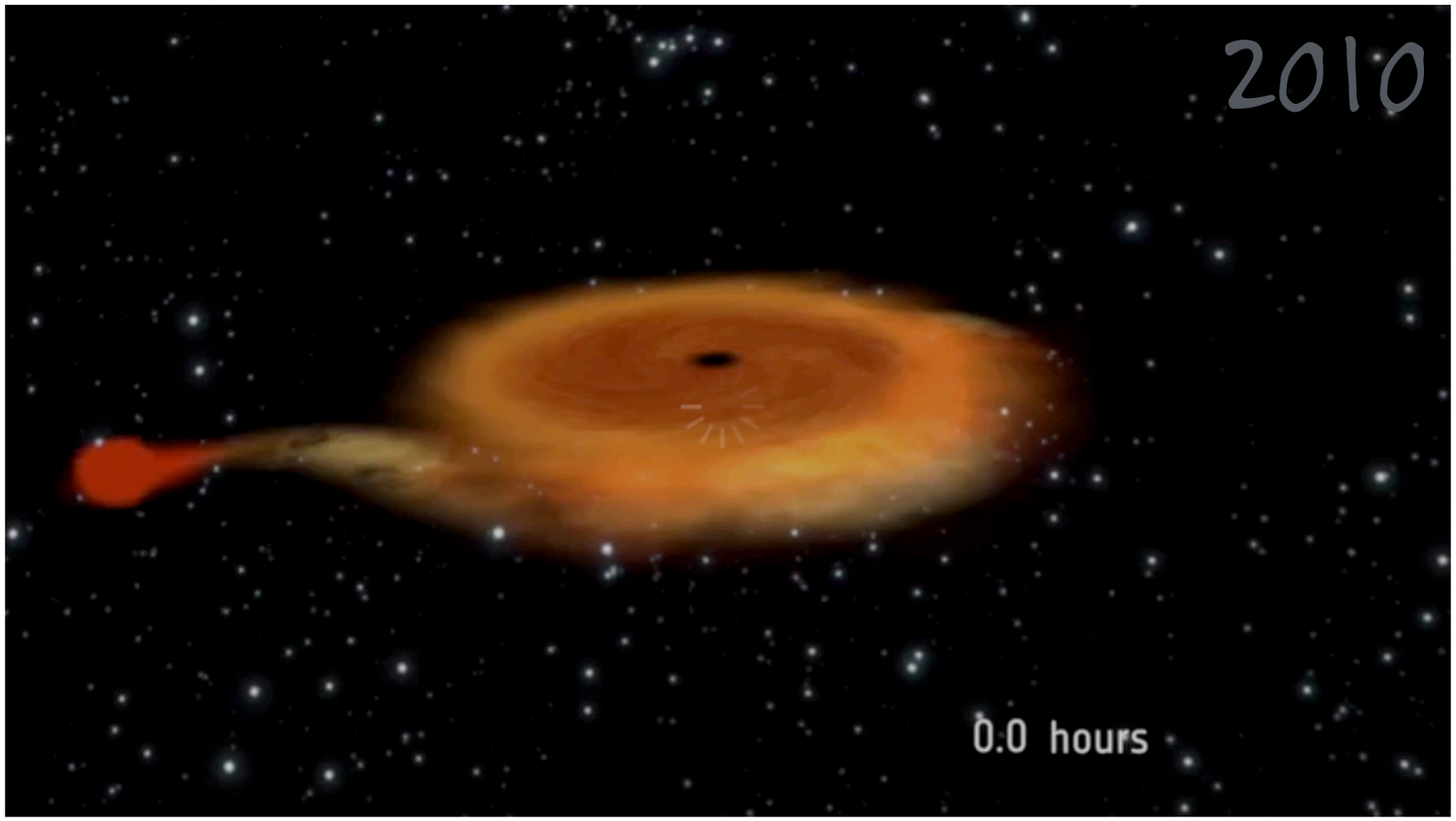
from the inside:



also, atomic spaghetti

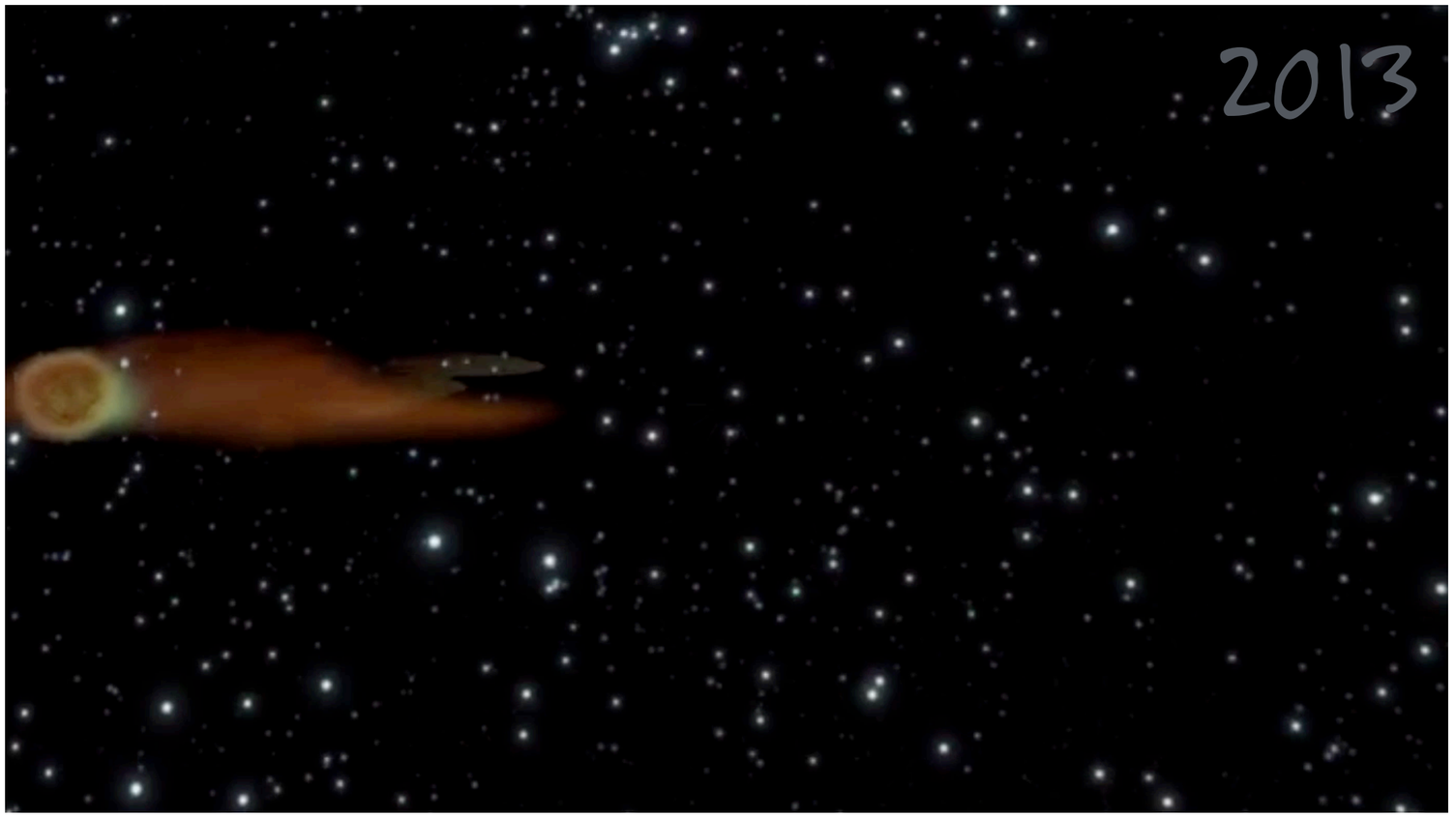
black holes are in the news

and on the silver screen



Watch in:

Embed Code

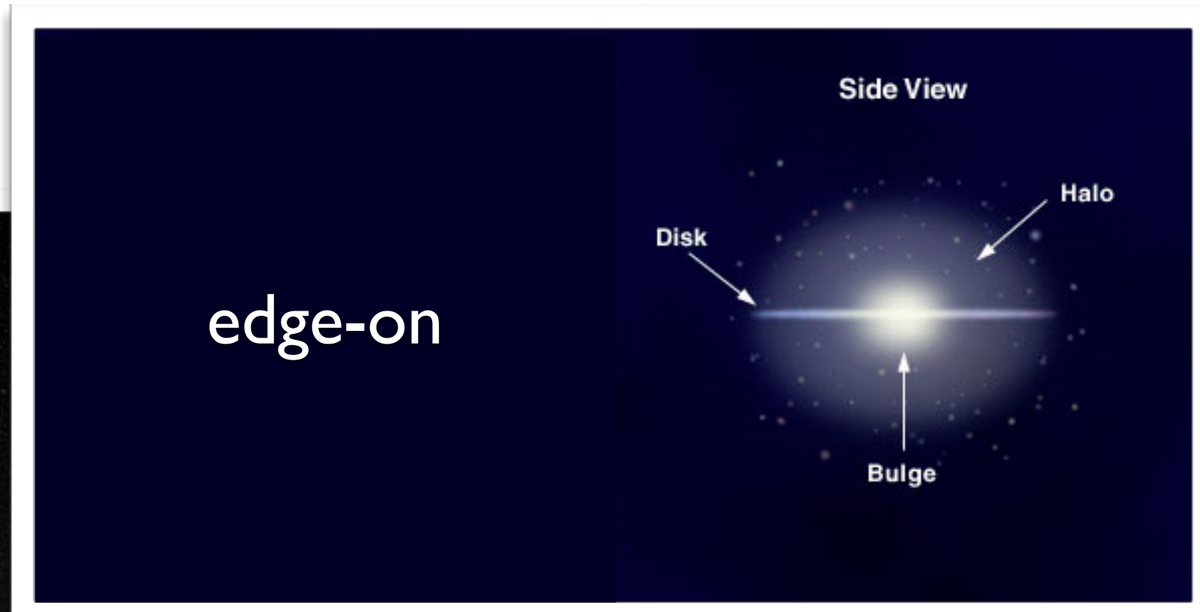


Supermassive

Black Holes

center of every (?) galaxy

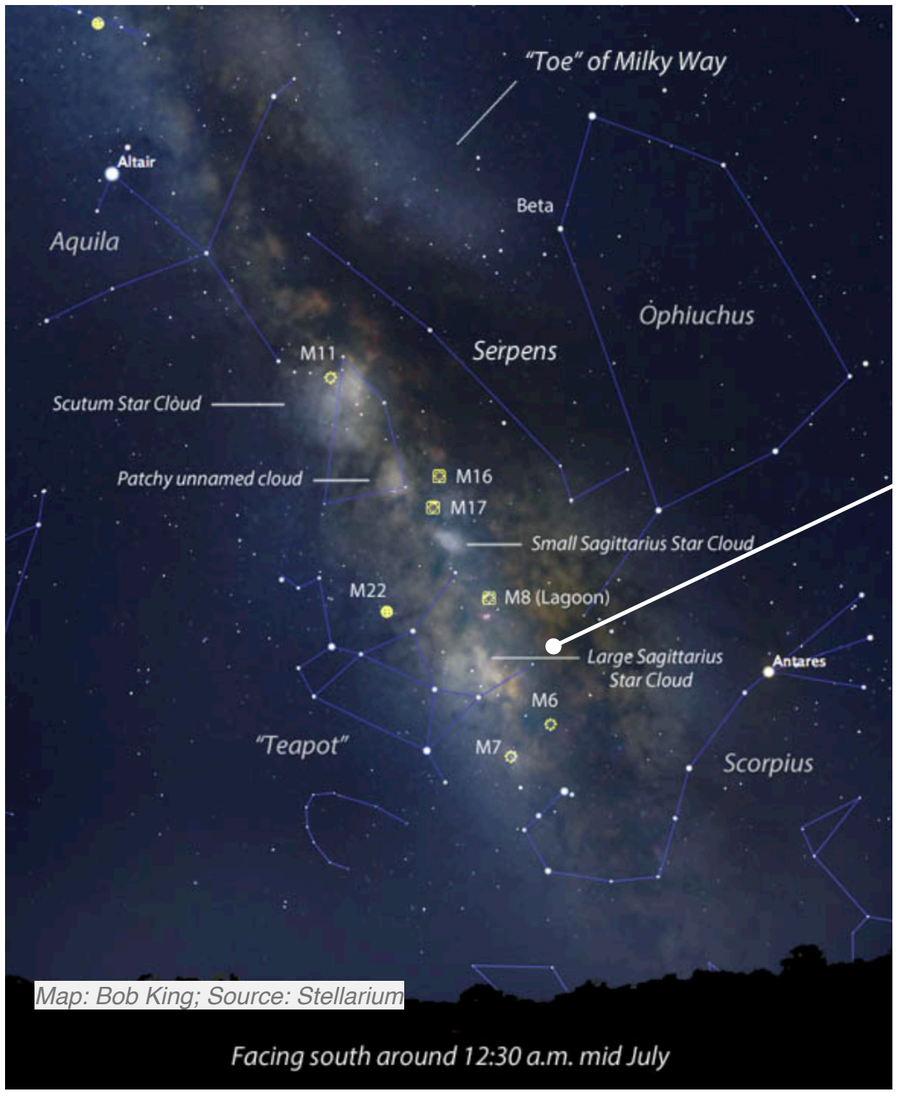
panorama view of the Milky Way from ESO

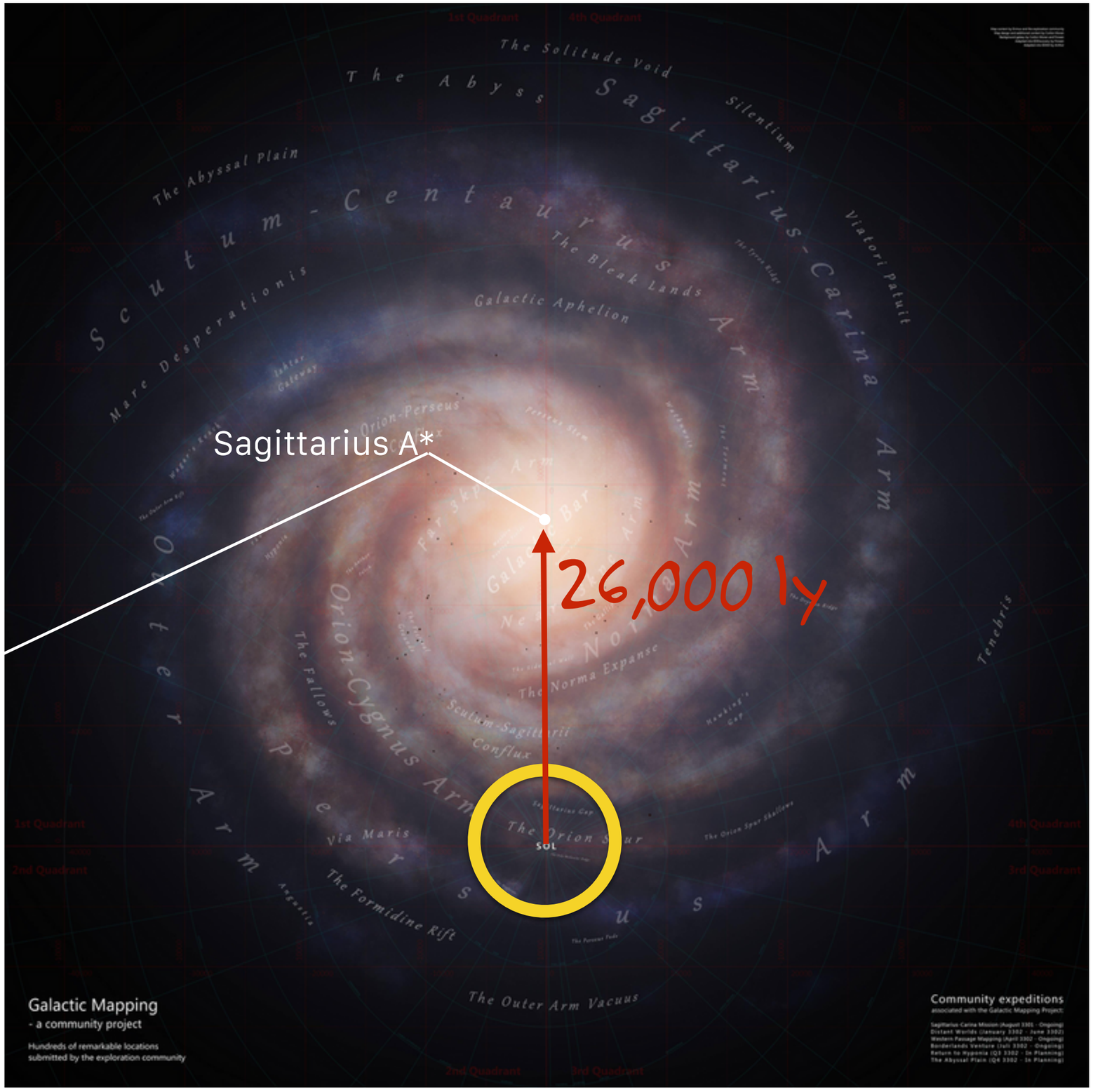


100,000ly-ish

let's orient ourselves

Sagittarius A and A*





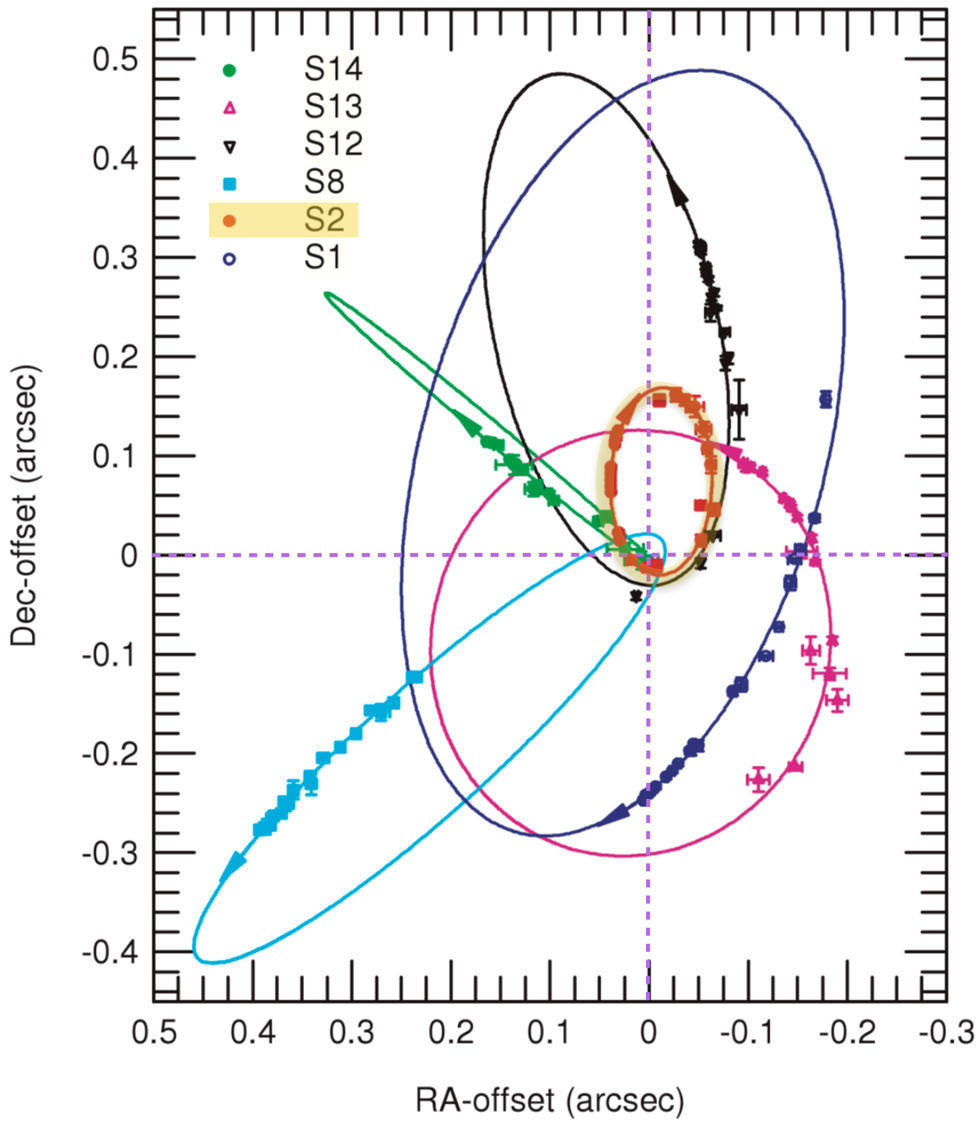
https://www.reddit.com/r/eliteexplorers/comments/92li23/galactic_map_with_labeled_regions/

Milky Way in the news

enormous, central black hole confirmed

S2:

- has a period of 15 years and comes close - 17 light-hours - so center object is smaller than that
- orbit implies M(center) = 4.1M solar masses



S14:

- comes closer - 6.25 light-hours - so center object is smaller than that!

Galactic black holes:

Milky Way

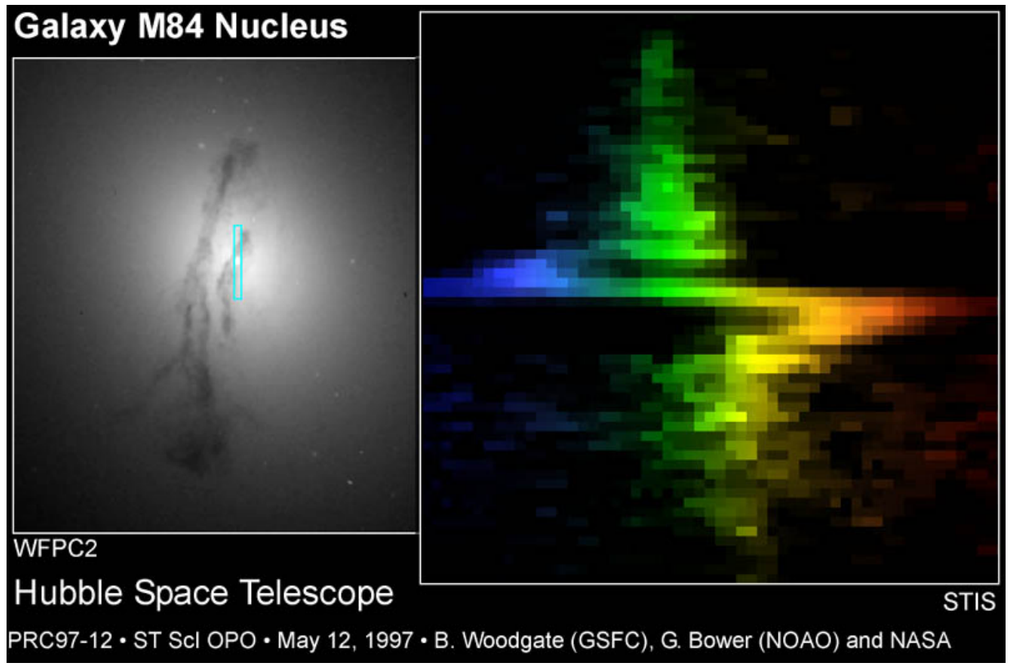
$4 \times 10^6 \times M_{sun}$

M84

$300 \times 10^6 \times M_{sun}$

M87

$3.5 \times 10^9 \times M_{sun}$



M87 Active Glactic Nucleus (AGN)