hi

Lecture 18, 16.03.2017

Einstein's Theory of General Relativity, 2

housekeeping

Question about anything?

I'll make a movie for you:

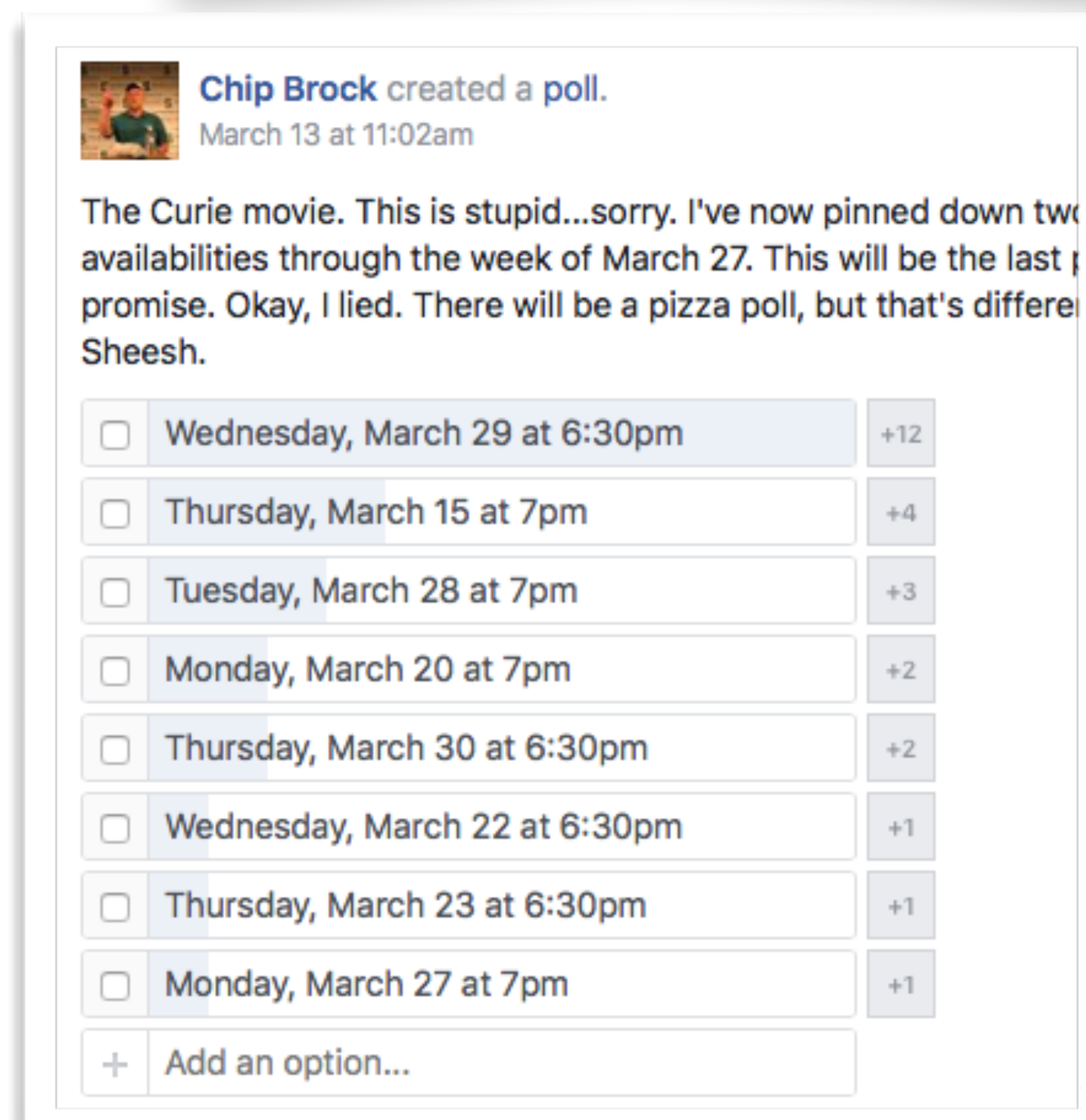
Marie Curie movie anyone?

beginning to look like March 29

Book Review 1 is due Saturday.

FakeFacebook is due April Fools Day. tee hee

Blog read-reflect project will start soon.



Honors Project

has begun. First milestone was last Friday.

Read the Second of two sets of instructions:

MinervaInstructions2_2017.pdf in

www.pa.msu.edu/~brock/file_sharing/QSandBB/2017homework/honors_project_2017/

MasteringAstronomy

free and use of the textbook:

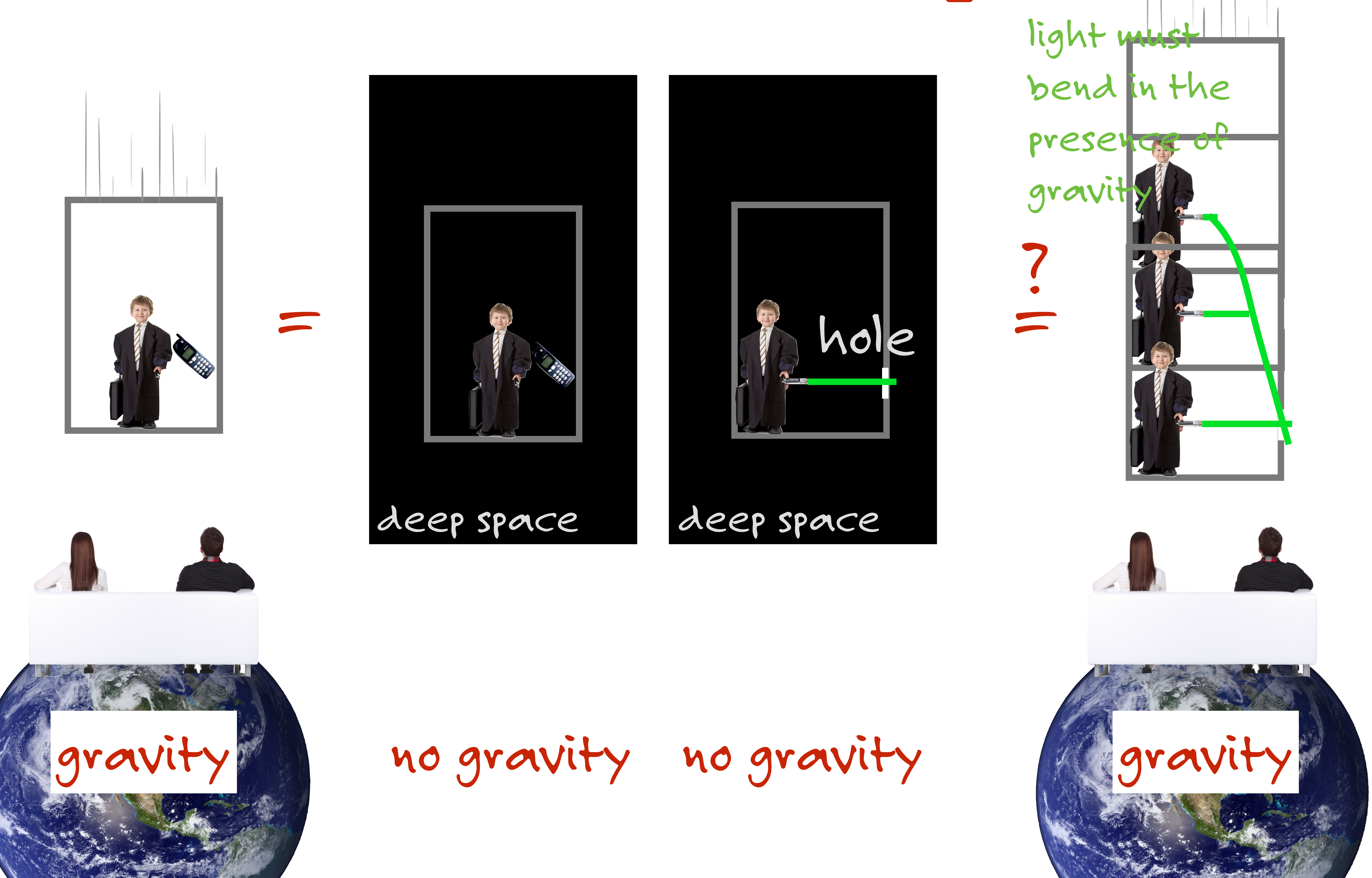
The Essential Cosmic Perspective, Bennett, Megan Donahue, Schneider, Mark Voit

http://www.pearsonmylabandmastering.com/northamerica/masteringastronomy/

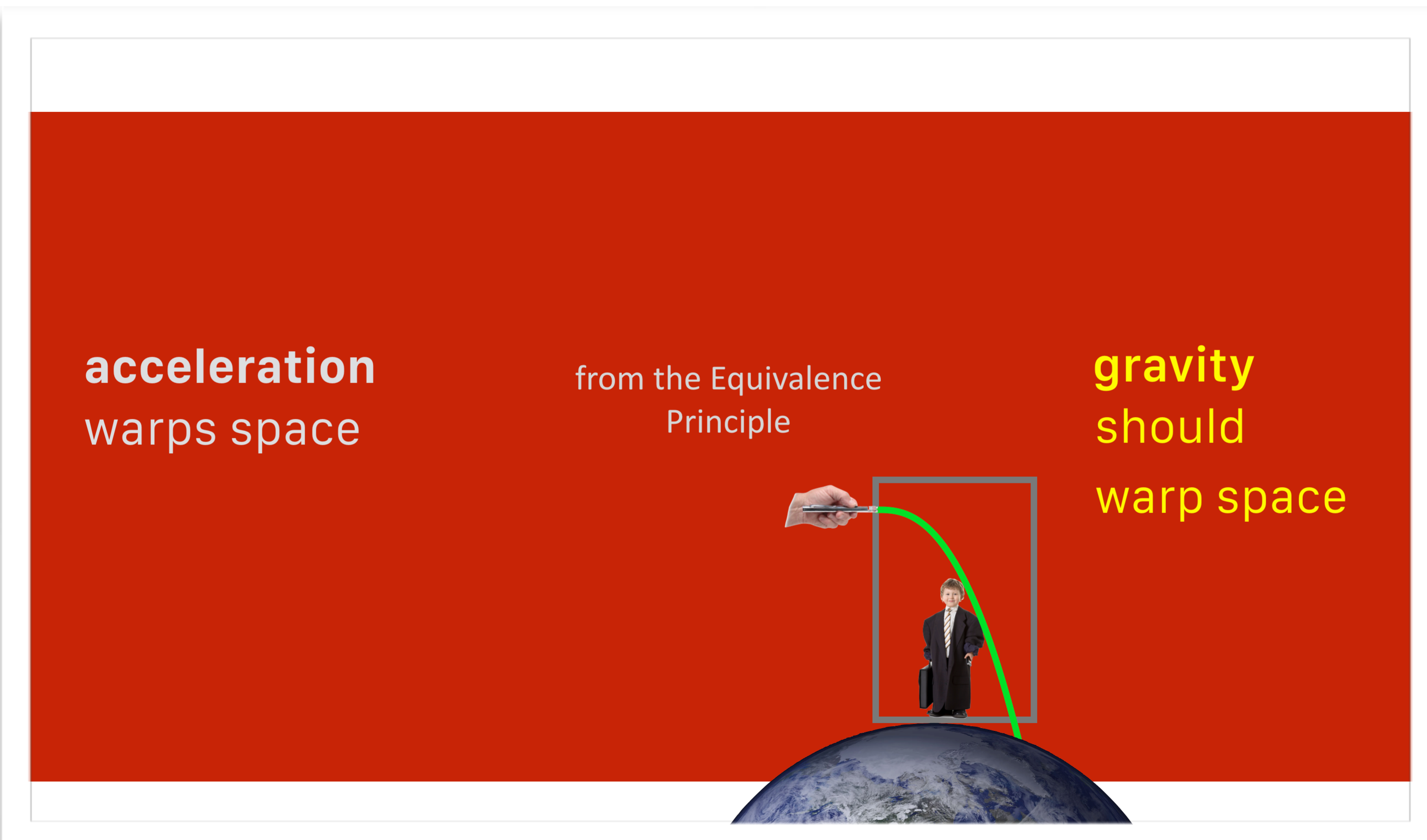
Course ID is ISP220SP17

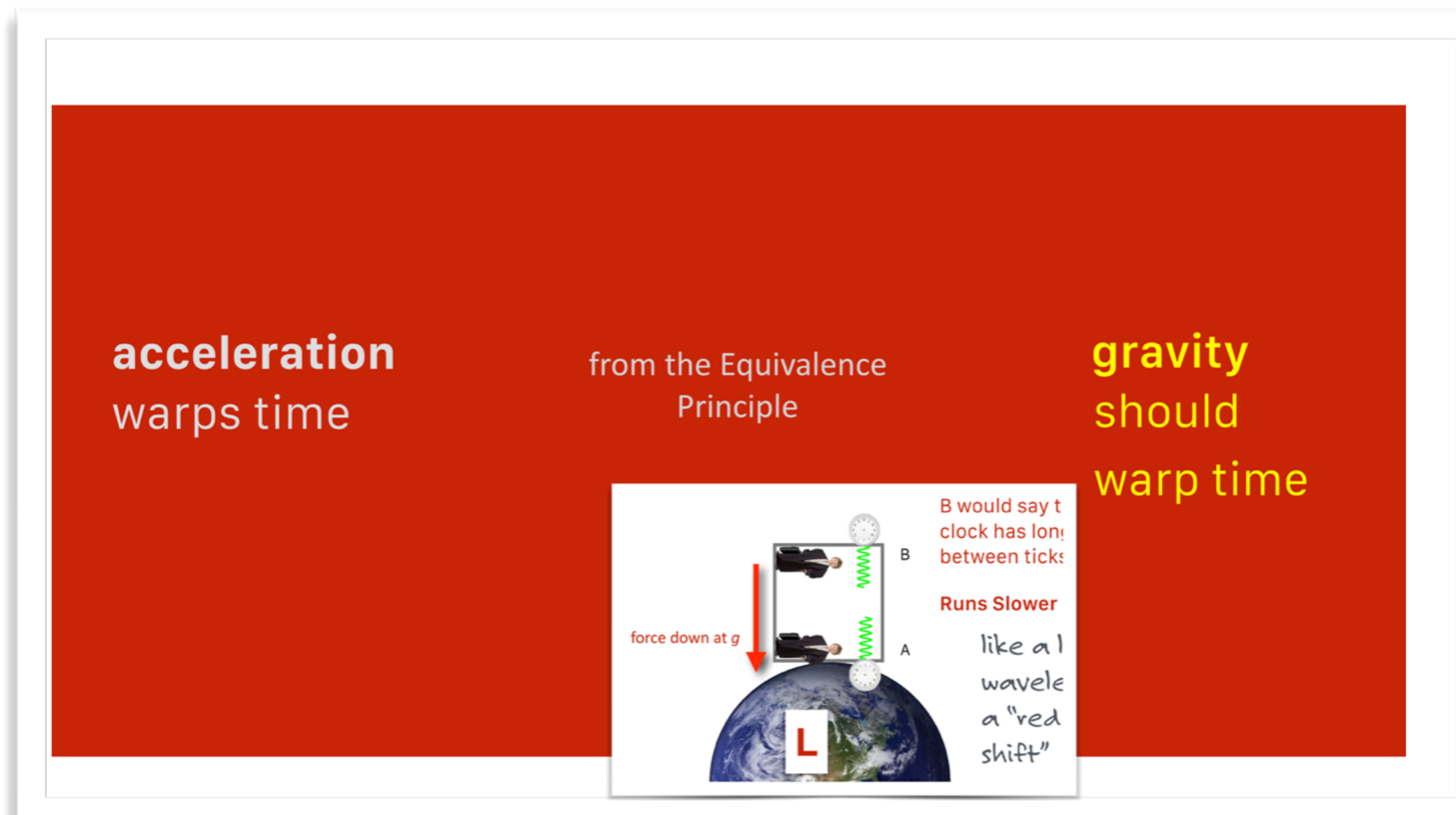
"code" is WSSPCT-SNELL-NAMEN-WEIGH-METIS-NJORD

free fall is special



what we've found:





if:

the path of light is the physical manifestation of

the shortest distance between two points

then:

its curved path under gravity is the shortest distance

which is a geometrical concept

~~space (spacetime) is altered by gravity~~

space (spacetime) is altered by **mass**

gravity

is the shape of spacetime

not a force.

General Relativity

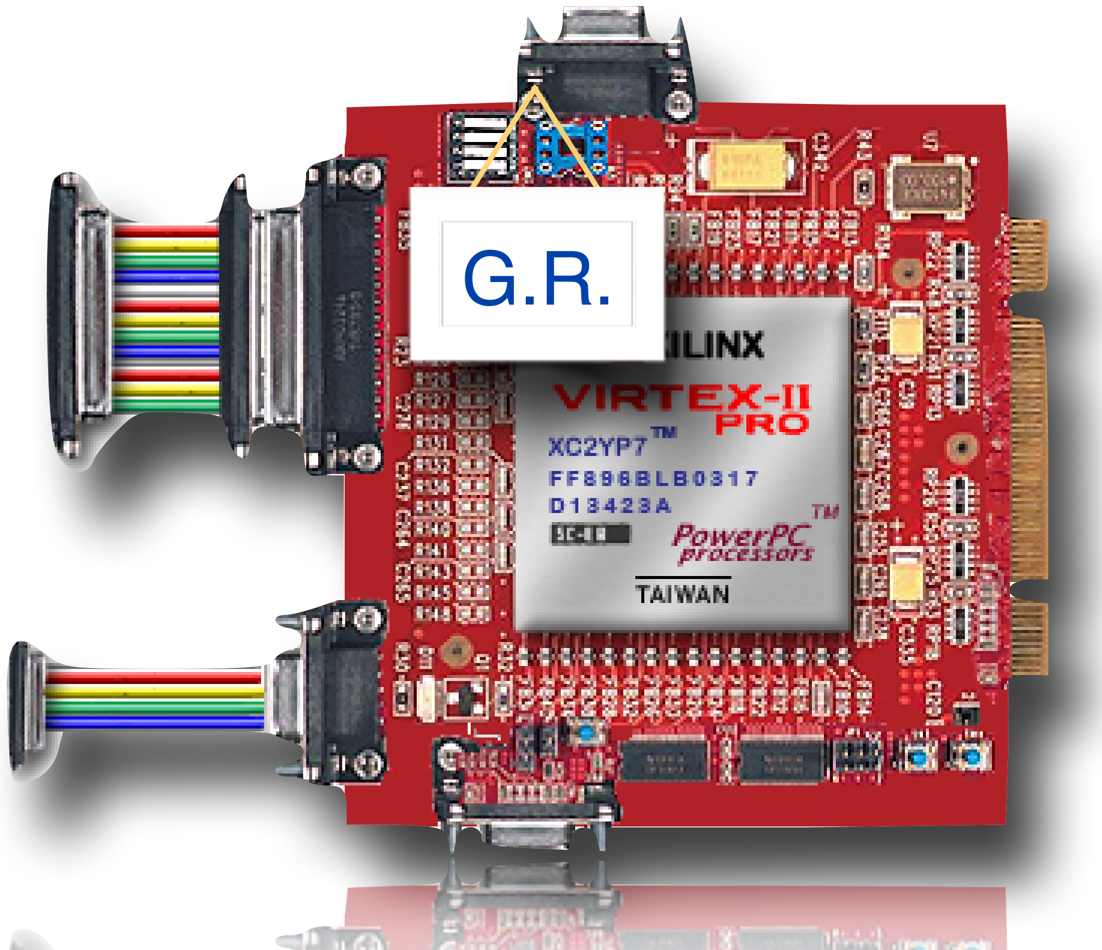
Einstein's GR equation

complicated mathematics

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

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

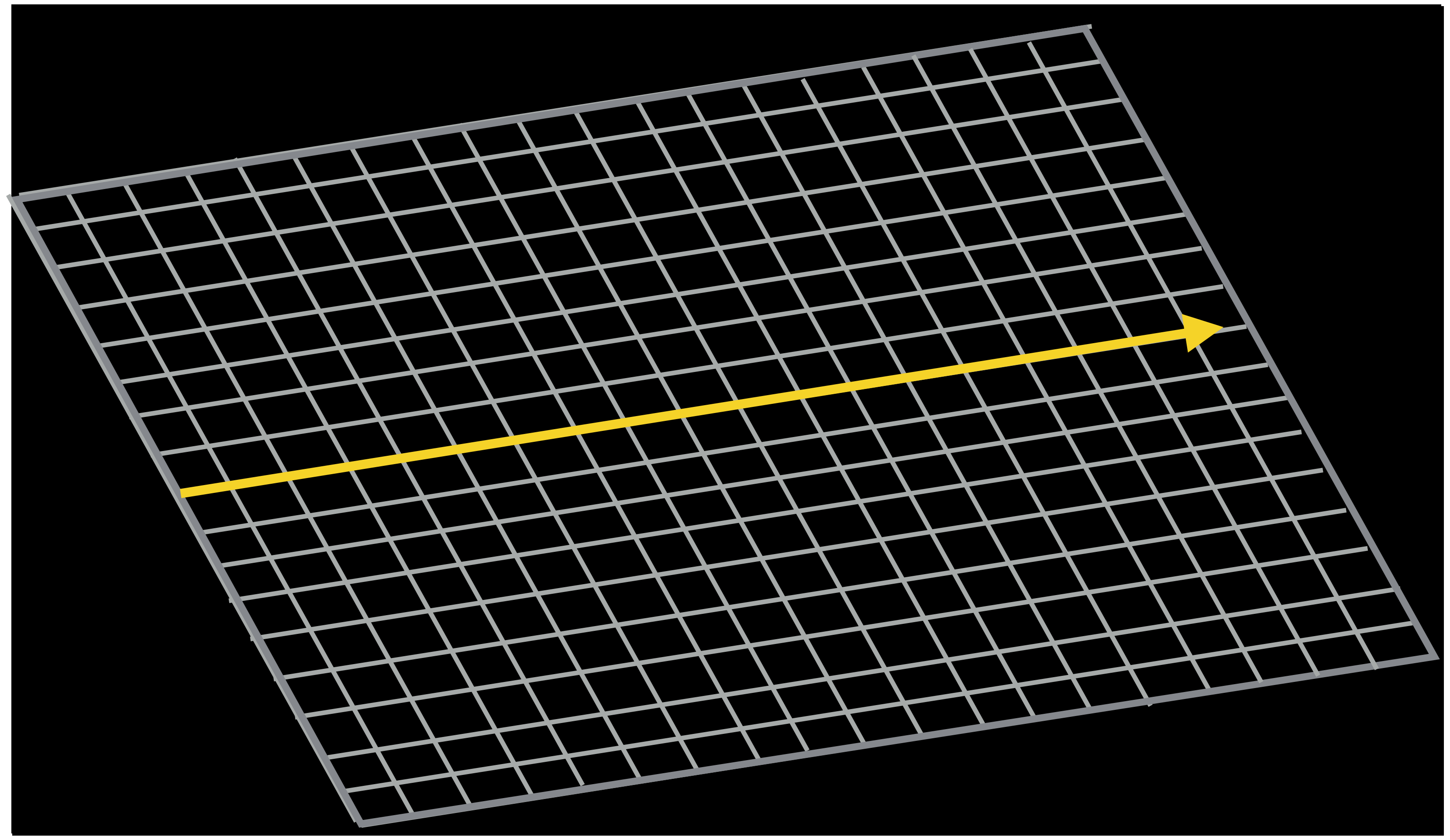
we'll call it: "$G = T$"



3d ‘‘embedding diagram’’

take this surface….

and try to think of it in a volume…



imagine density in air…and you’re in an airplane
and hit an “air pocket”

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*?"

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

R_S called the Schwarzchild Radius

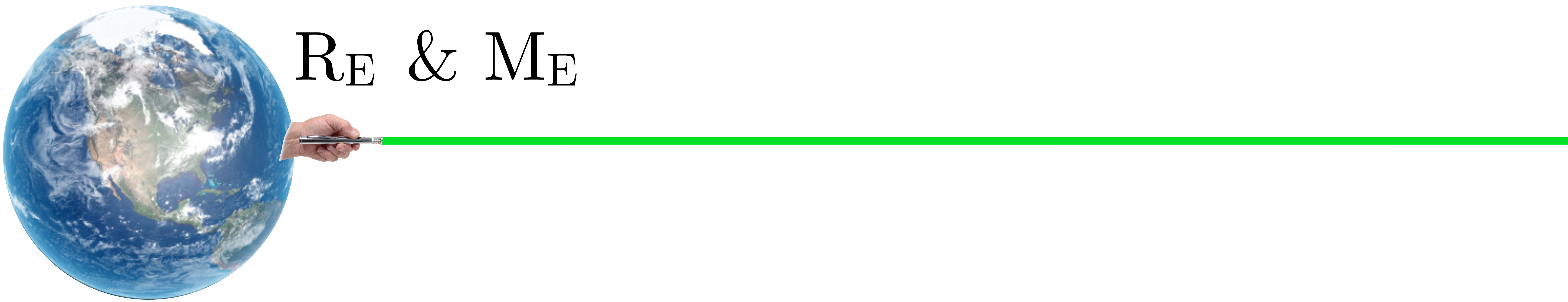
$$R_S = \frac{2GM}{c^2}$$

It seemed to be a magic radius...

shine a light

but not in the path of an airplane.

R_E & M_E



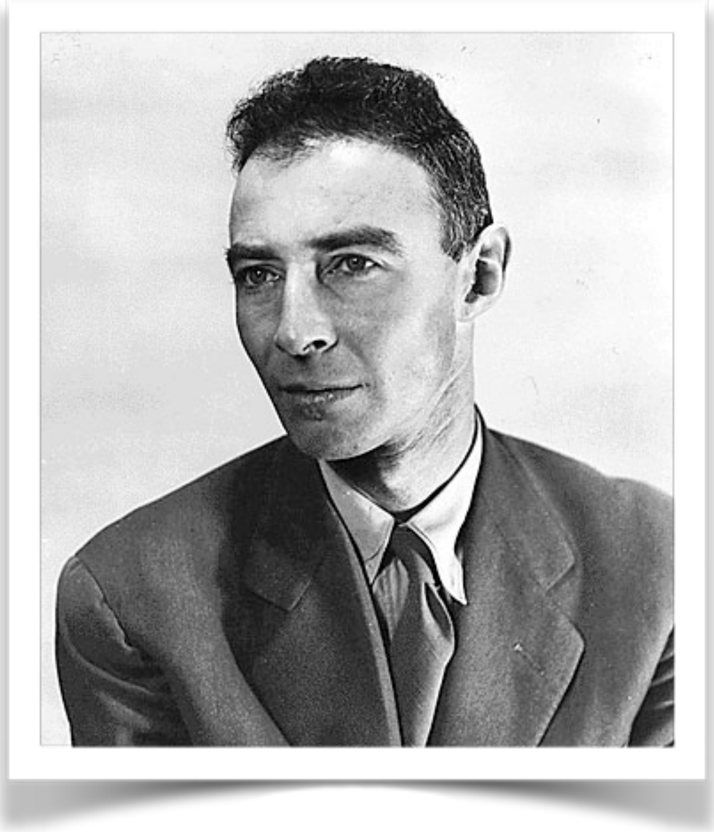
$0.1 \times R_E$ & M_E

$0.00000000833 \times R_E$ & M_E

if the mass of the earth were within 1cm, light cannot escape

silly, right?

who could ever imagine such a thing

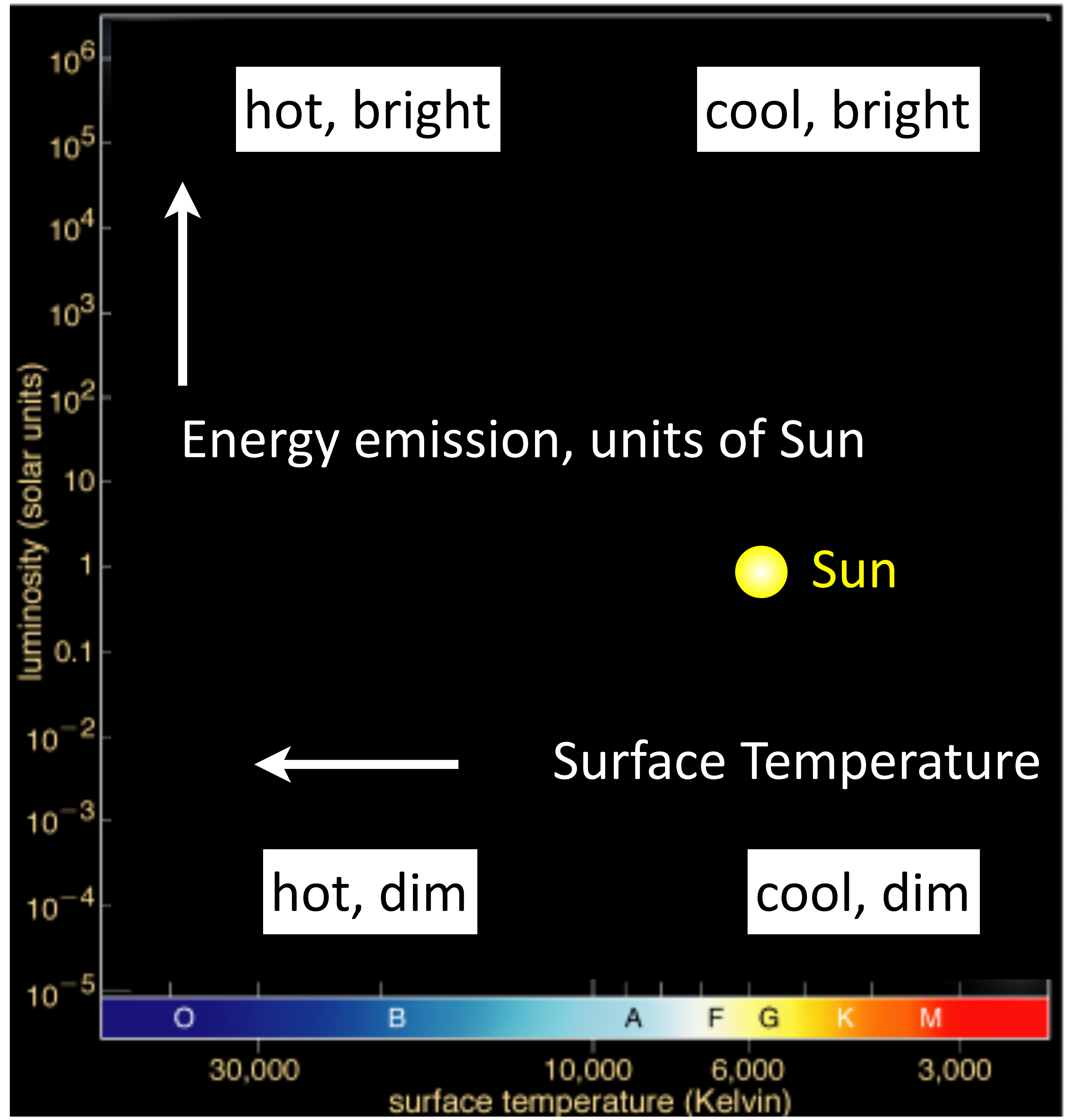


1939: Robert Oppenheimer & Hartland Snyder did.

5¢ worth of stellar physics

no charge

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



5¢ worth of stellar physics

For a sun-like star:

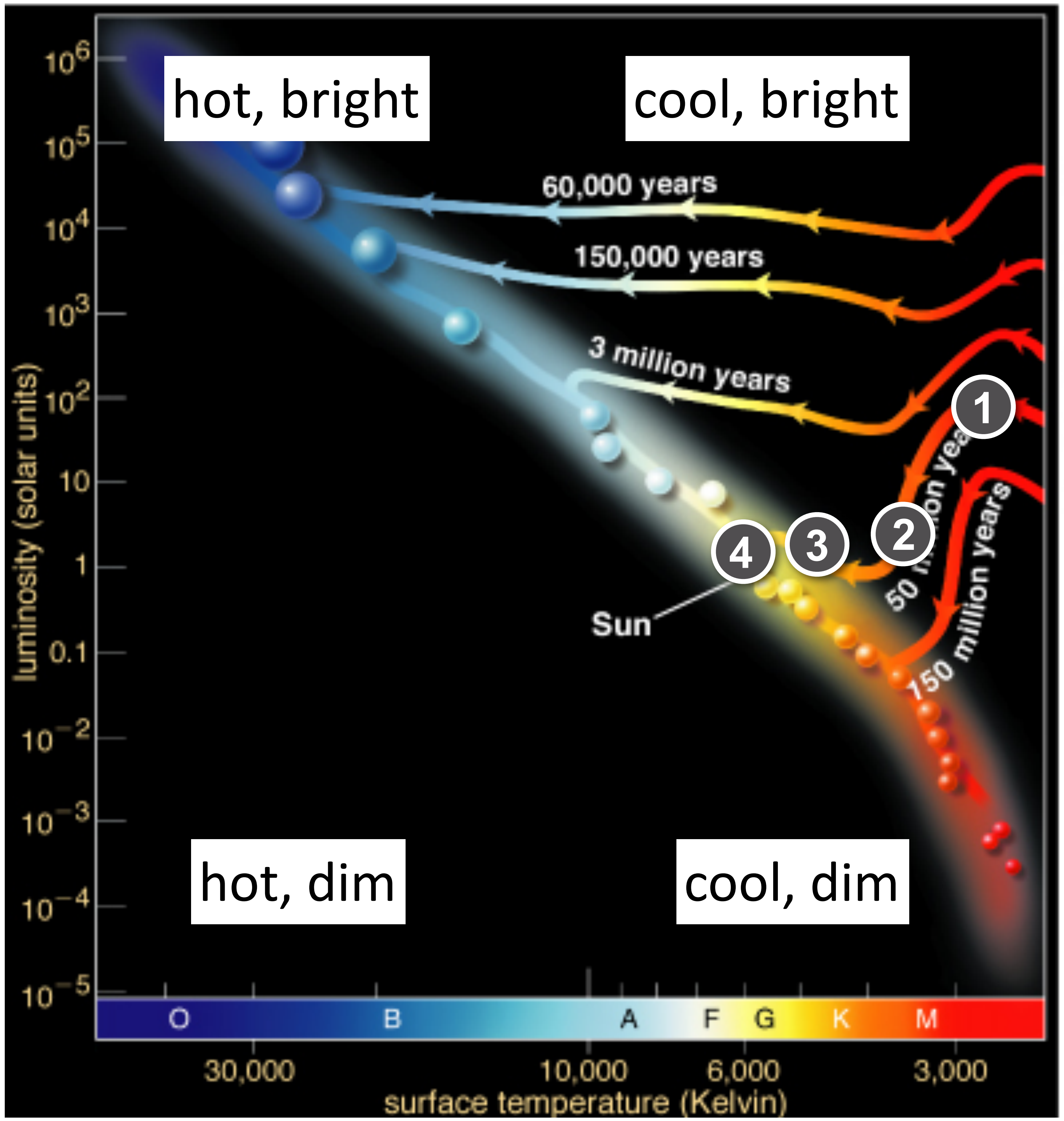
1. H gas begins to heat…very large

2.heat radiates away and coallescence begins

3. at 10M degrees, fusion begins

4. pressure stabilizes

Hertzsprung-Russell Diagram…aka H-R Diagram



balls of Hydrogen brought together by gravity

The "main" sequence

stars radiate energy – that's their job!

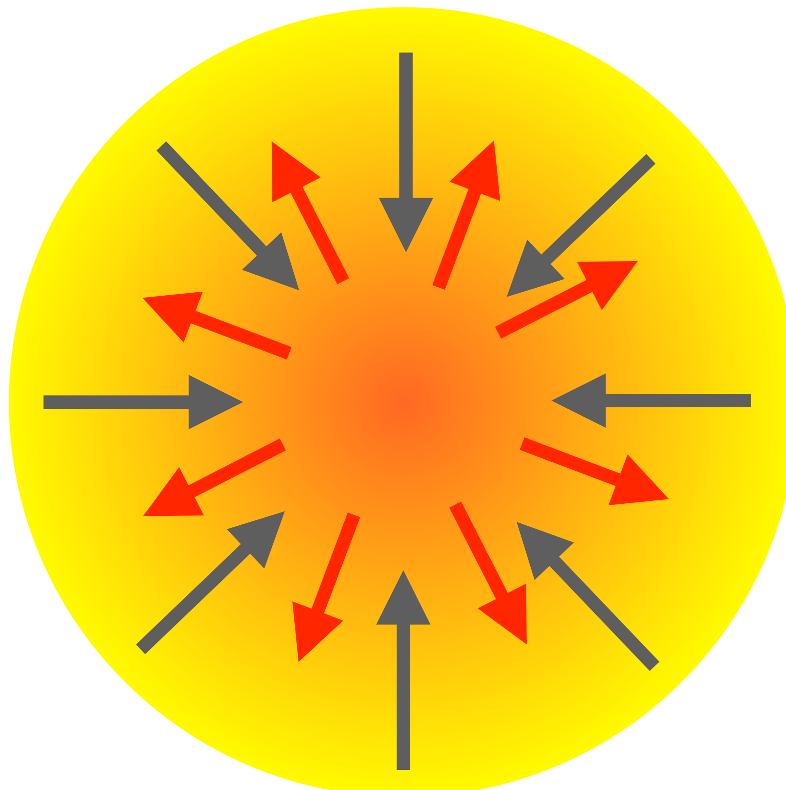
being stable is their challenge…

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**

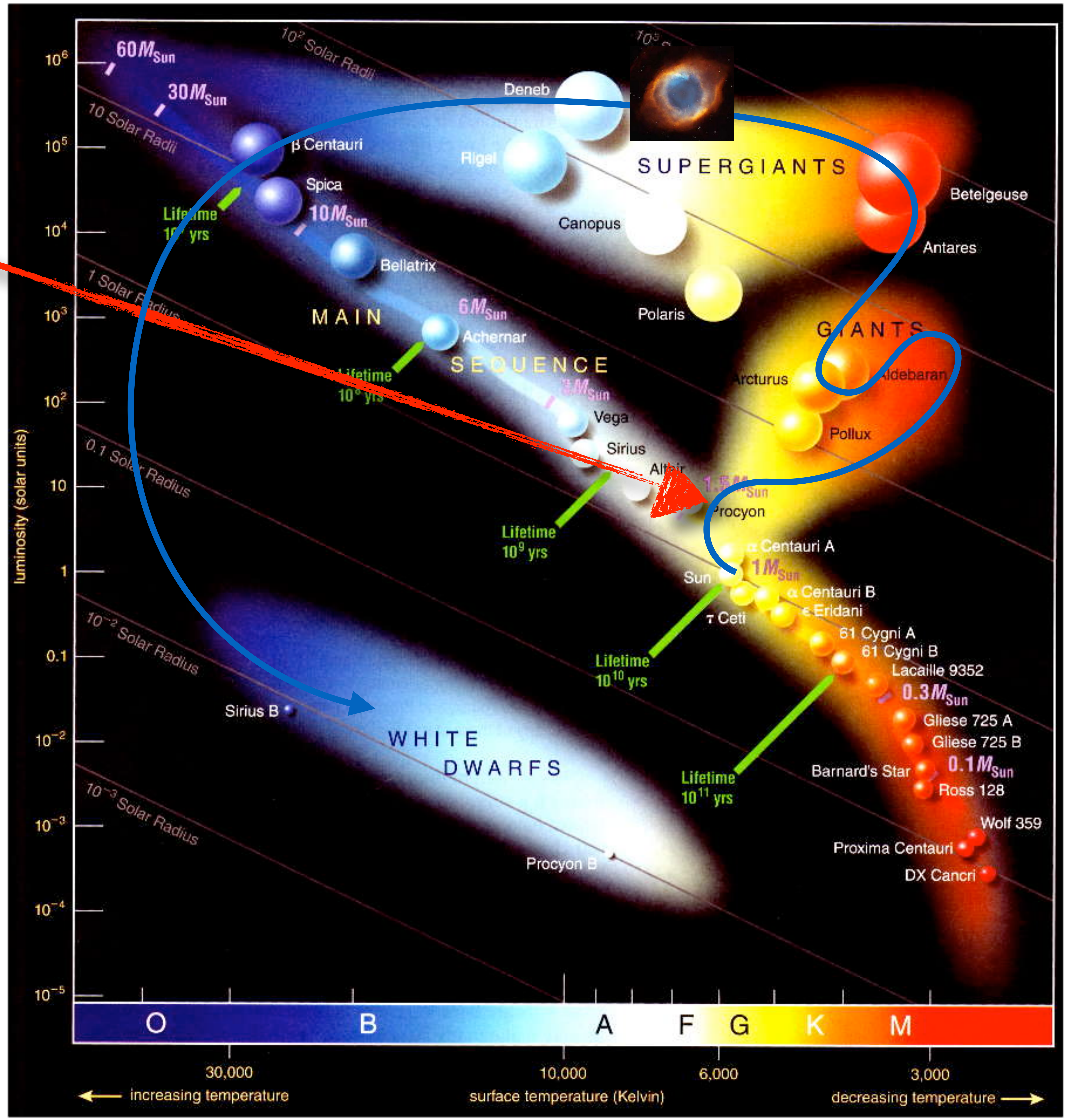
H begins to “burn” to He

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

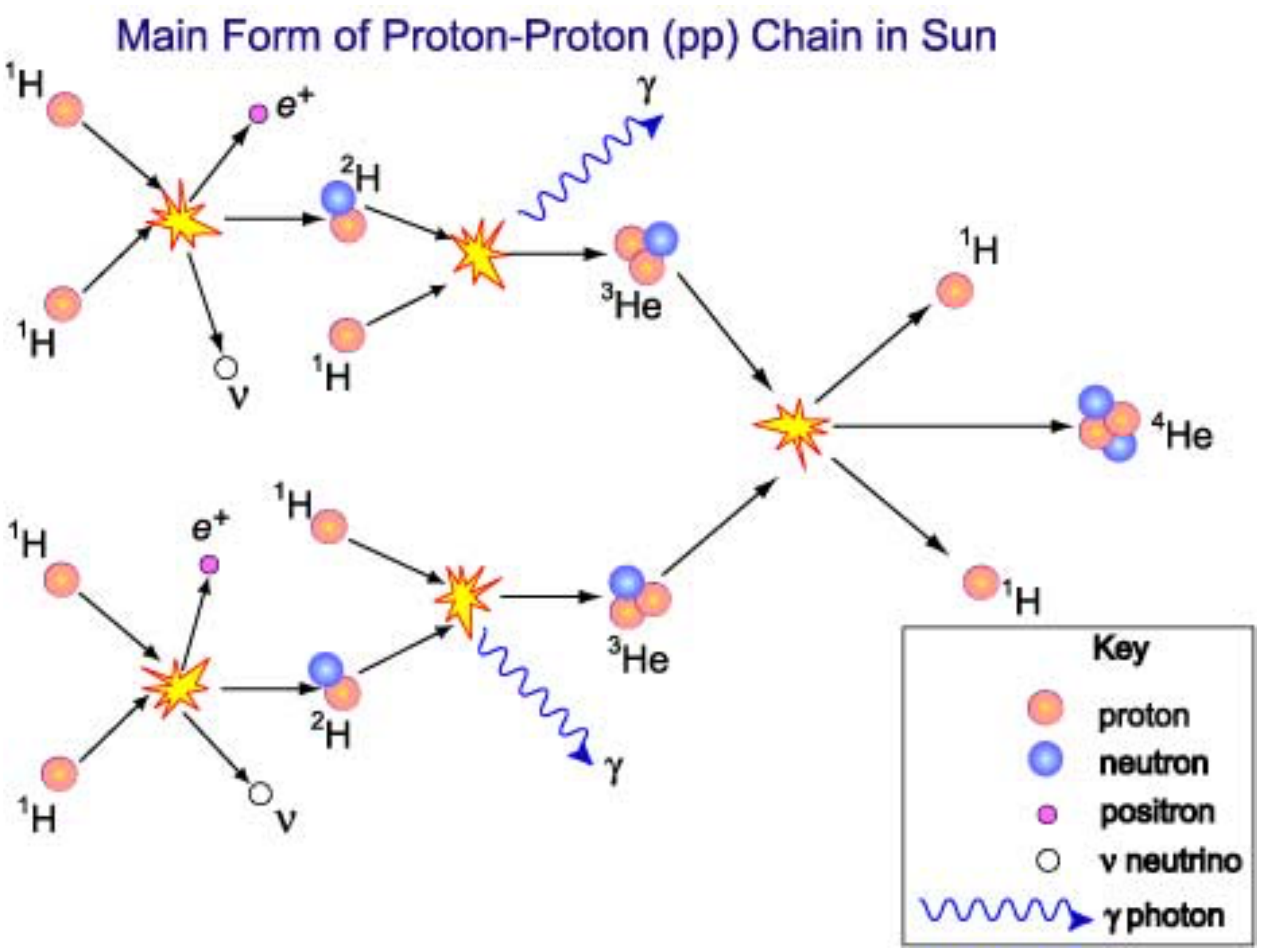
a balancing act

SUN-LIKE?

H → He



pp cycle



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

a balancing act

SUN-LIKE?

H → He

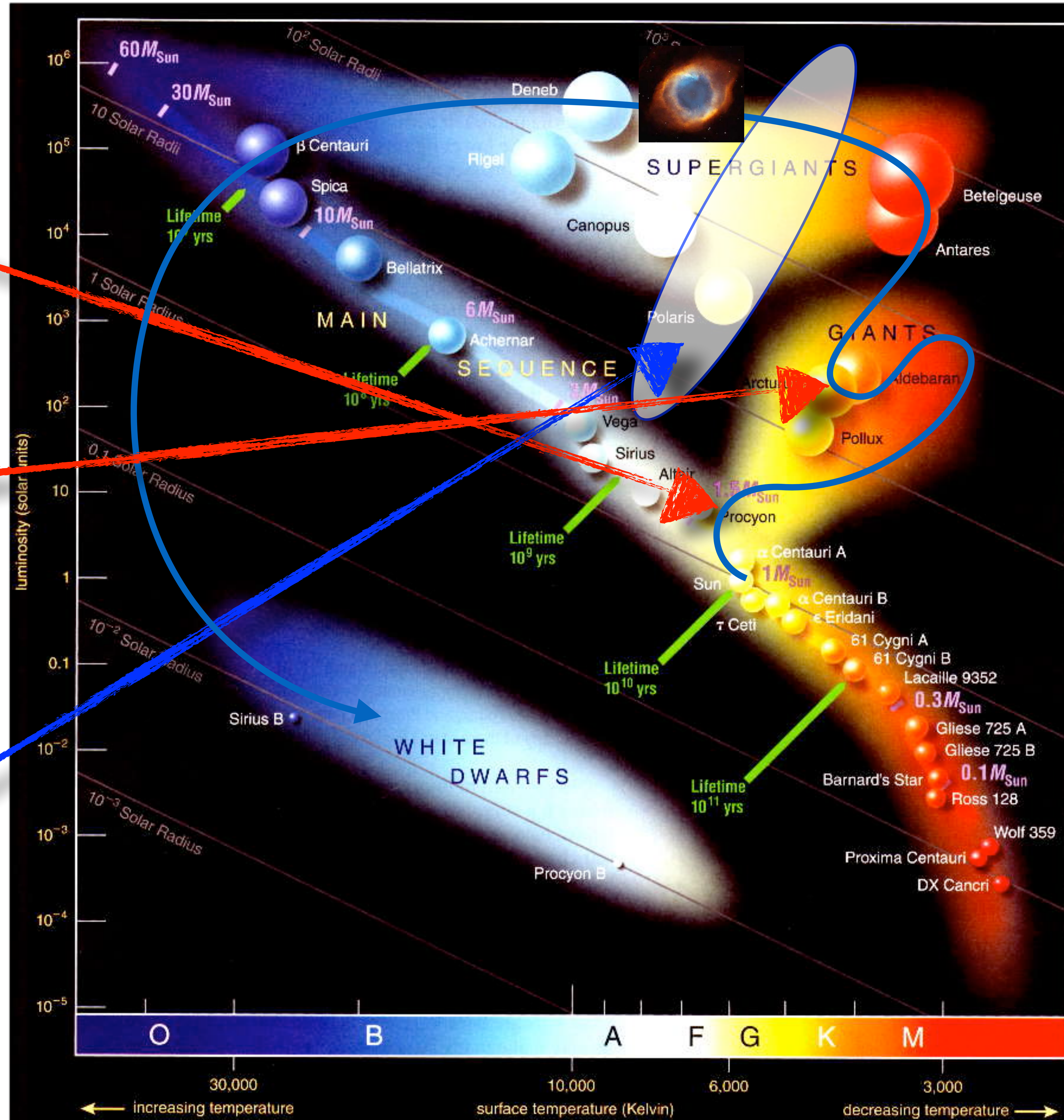
SUN-LIKE?

He → C + O

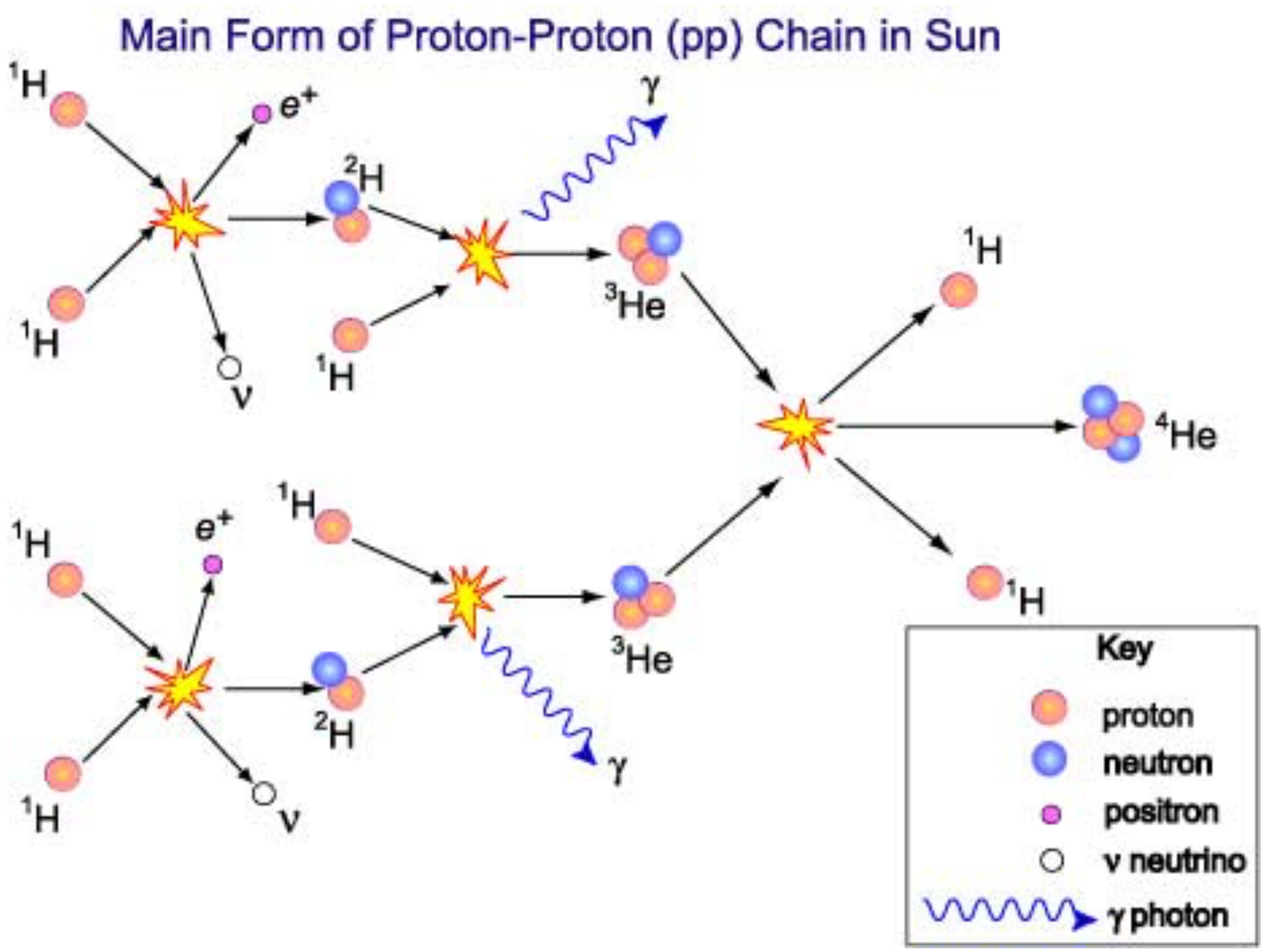
source of Carbon for life

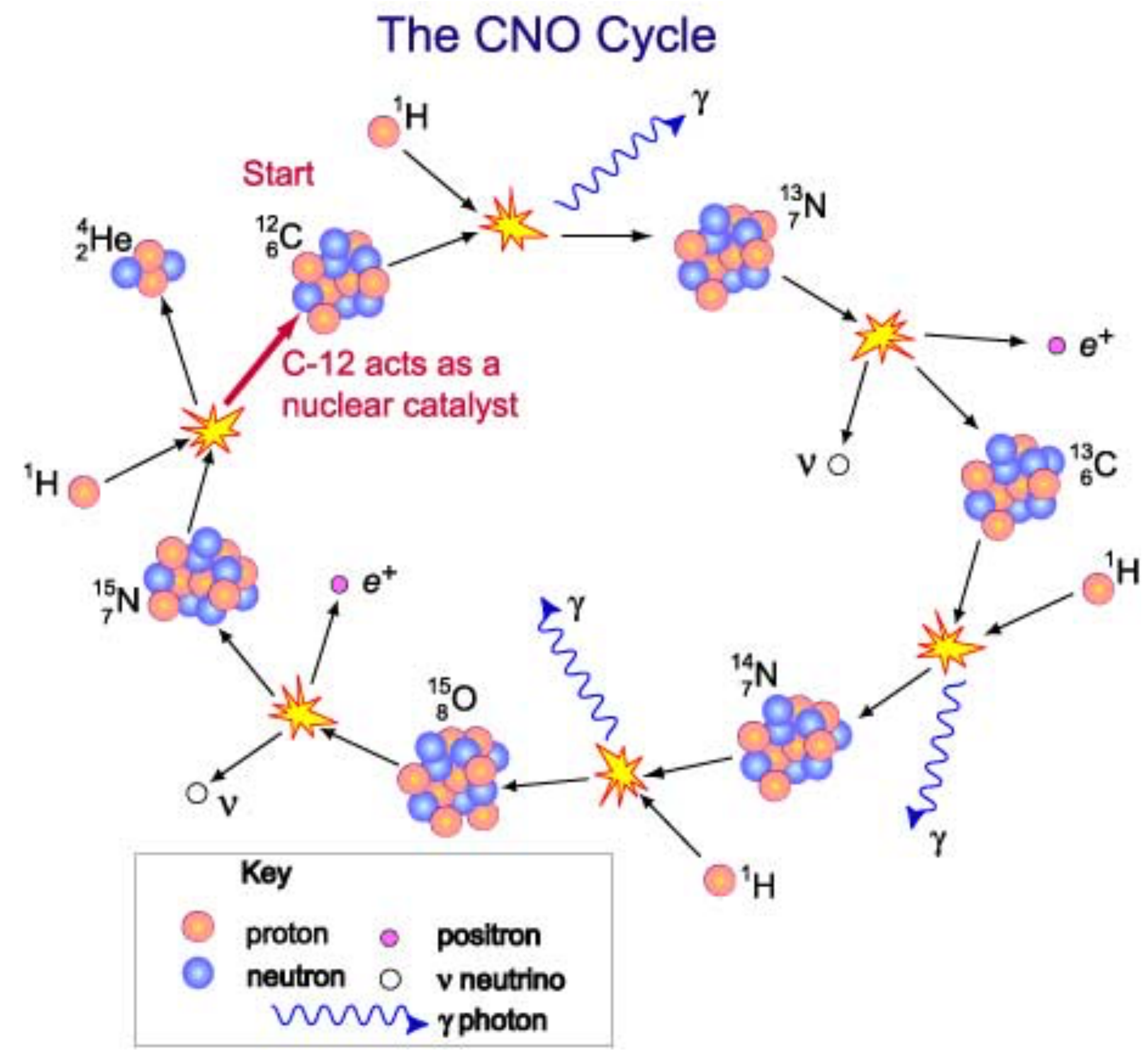
REGION OF INSTABILITY

pulsating stars



pp cycle


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


The CNO Cycle
Start
^{1}H
γ
$^{13}_{7}$N
$^{12}_{6}$C
$^4_2$He
C-12 acts as a
nuclear catalyst
e+
ν
^{1}H
$^{13}_{6}$C
$^{15}_{7}$N
e+
γ
^{1}H
$^{14}_{7}$N
$^{15}_{8}$O
ν
γ
^{1}H
Key
proton
neutron
positron
ν neutrino
γ photon

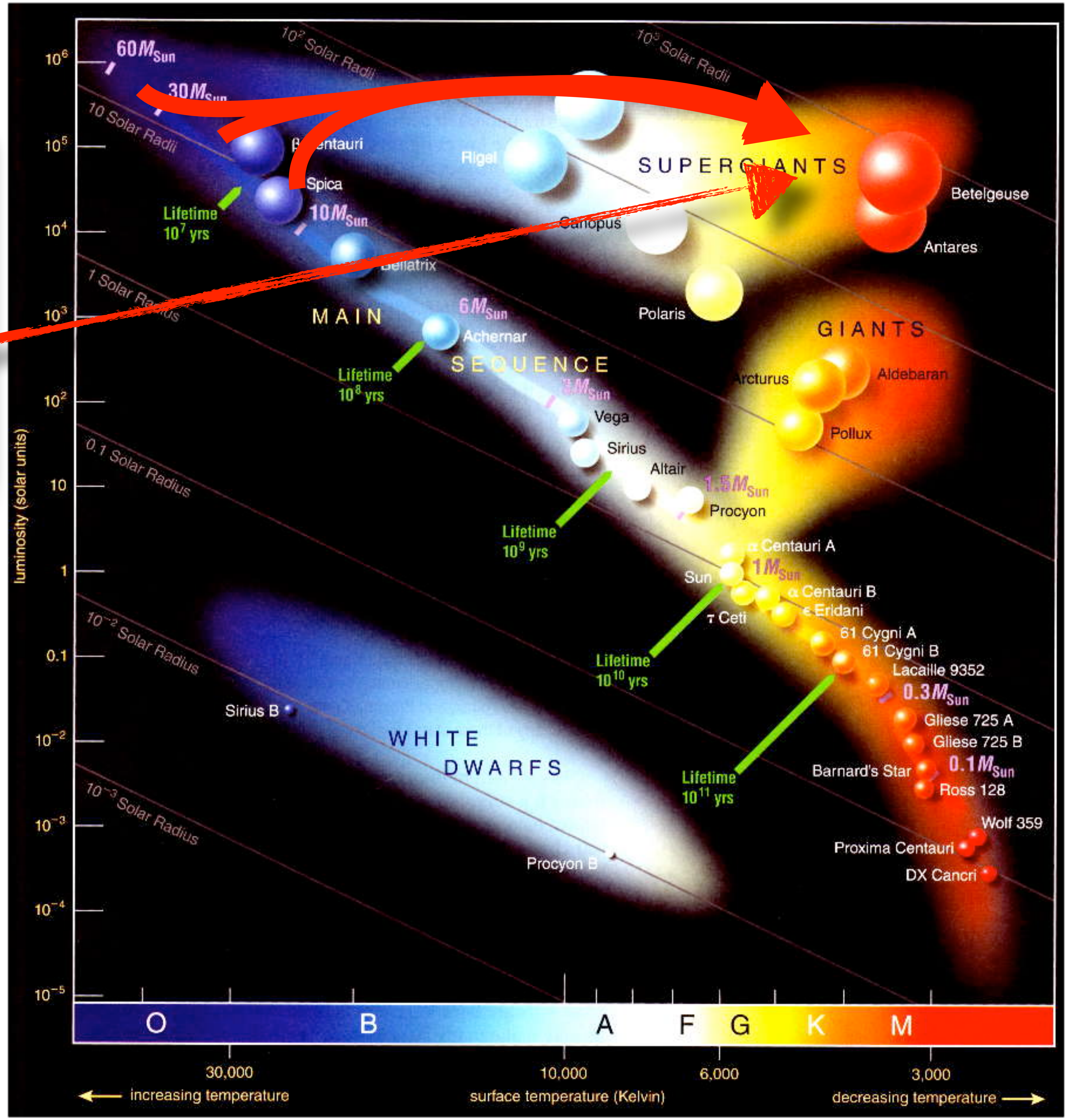
a balancing act

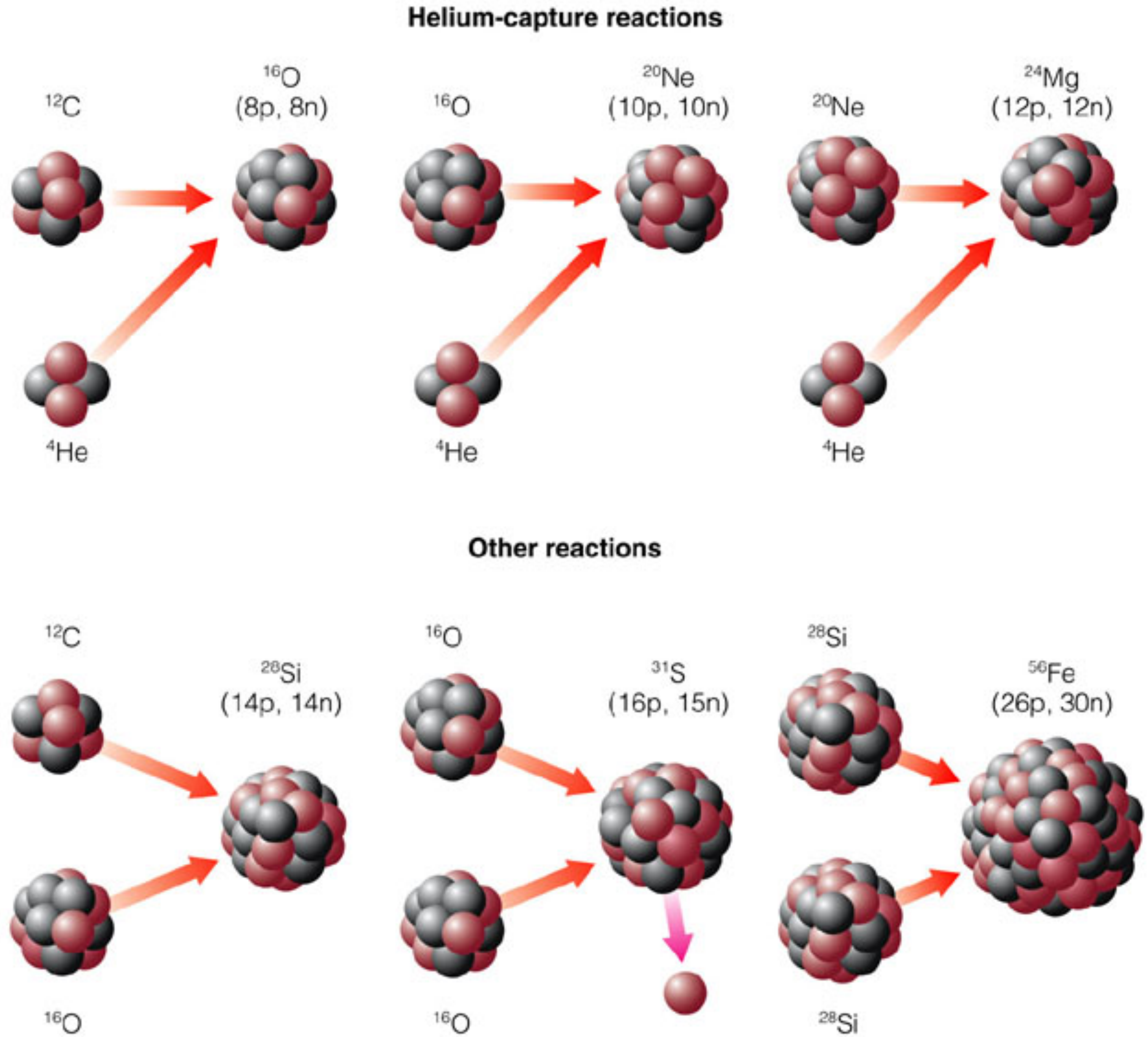
VERY MASSIVE...

>1.3 Msun

H → He → C...

...→ Fe




Helium-capture reactions
12C
16O (8p, 8n)
4He
16O
20Ne (10p, 10n)
4He
20Ne
24Mg (12p, 12n)
4He
Other reactions
12C
16O
28Si (14p, 14n)
16O
16O
31S (16p, 15n)
28Si
28Si
56Fe (26p, 30n)

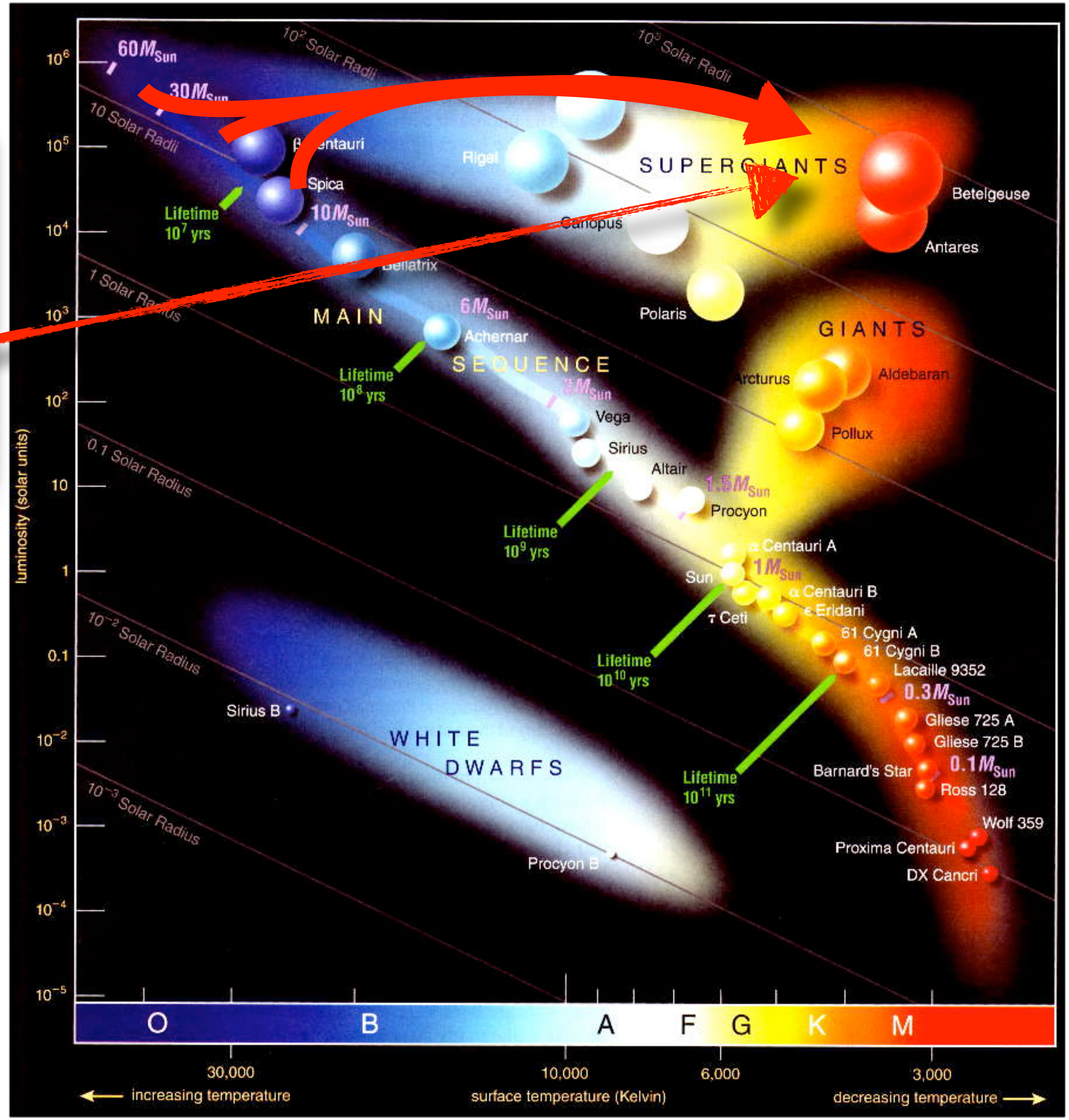
a balancing act

VERY MASSIVE...

>1.3 Msun

H → He → C...

...→ Fe

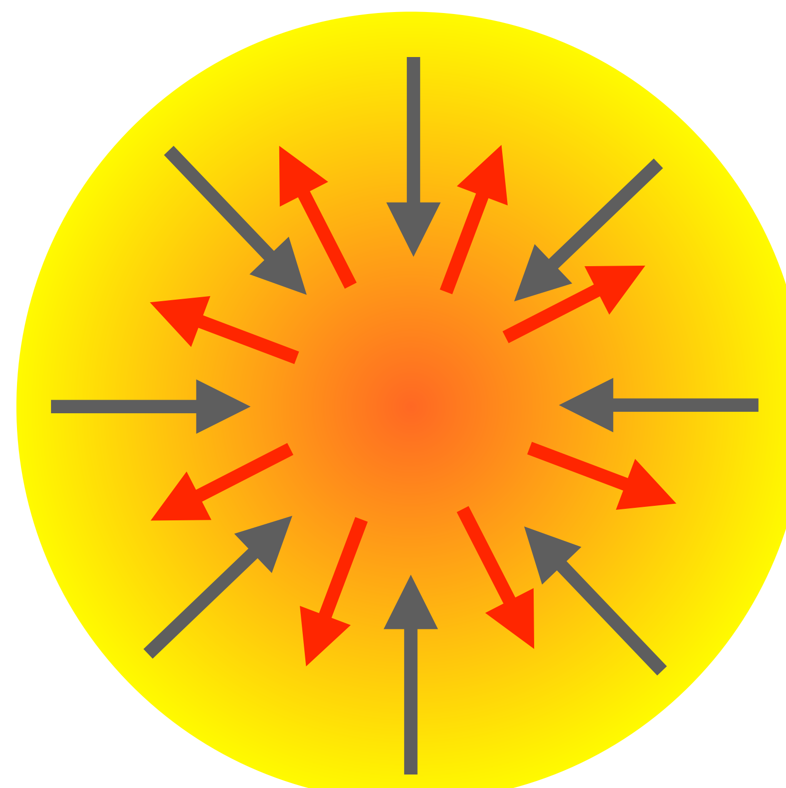


a balancing act

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...

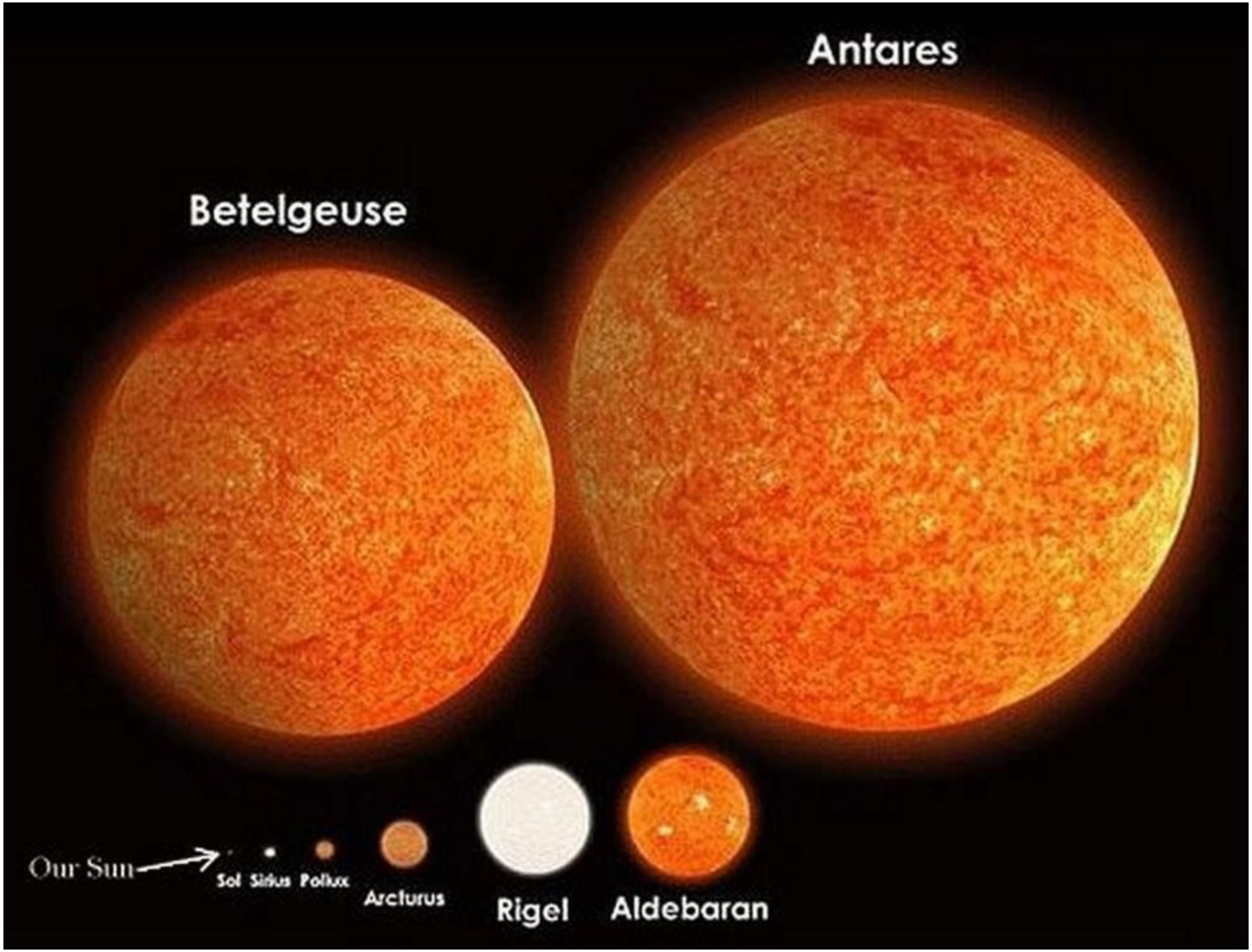
the star shrinks dramatically

and then a special effect takes over:

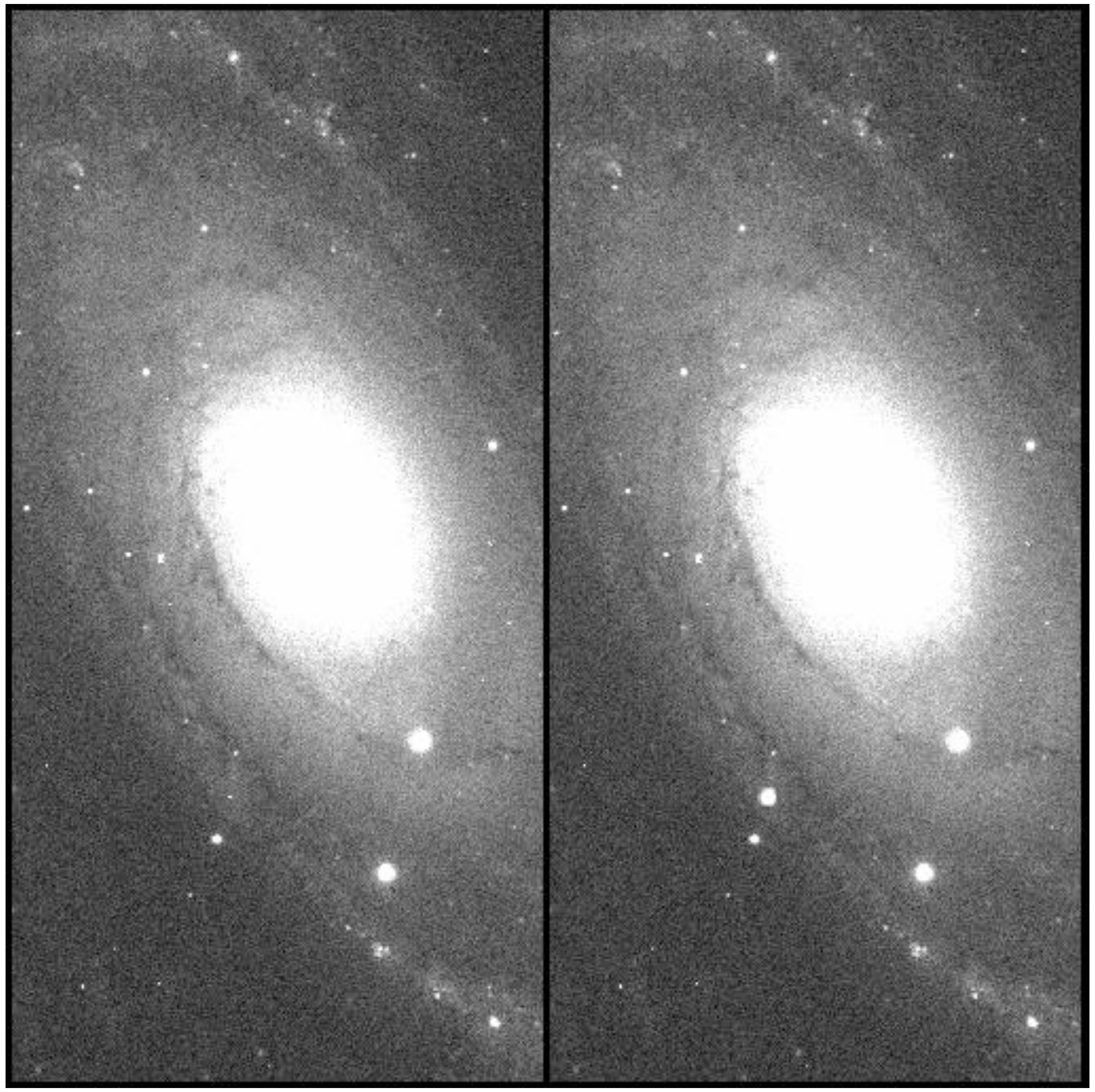
neutrons cannot all be on top of one-another

It stops abruptly in seconds

Explosively.


Antares
Betelgeuse
Our Sun
Sol
Sirius
Pollux
Arcturus
Rigel
Aldebaran

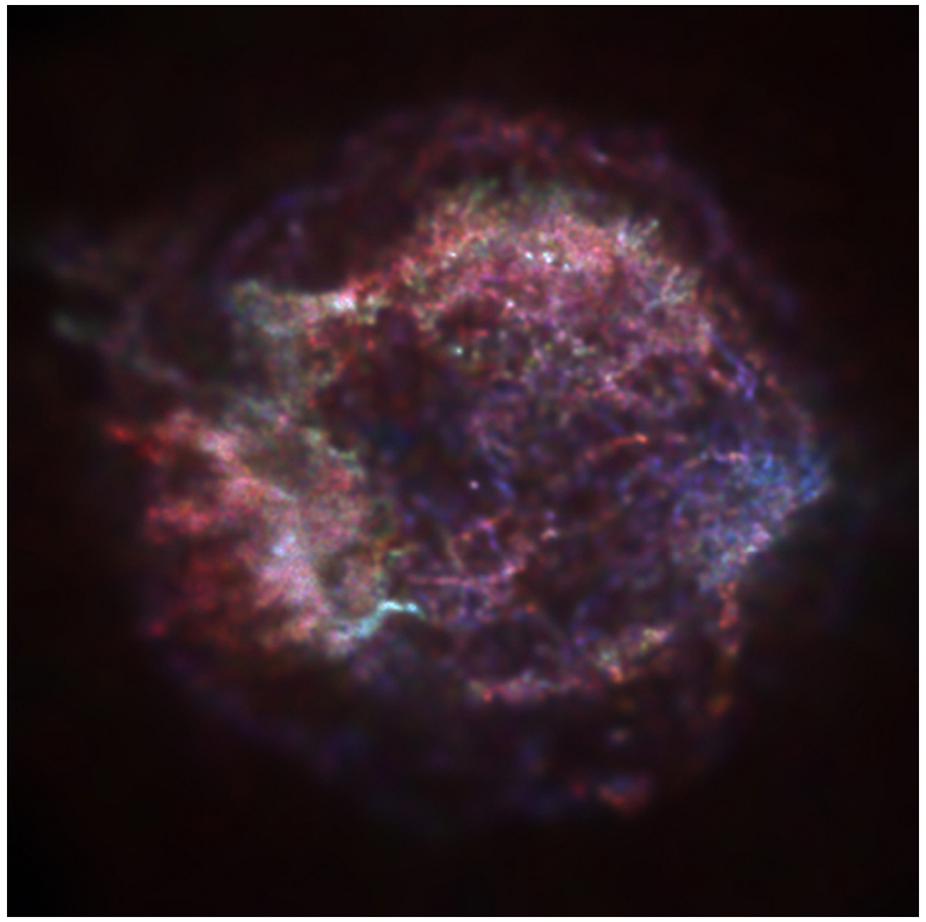
supernova!

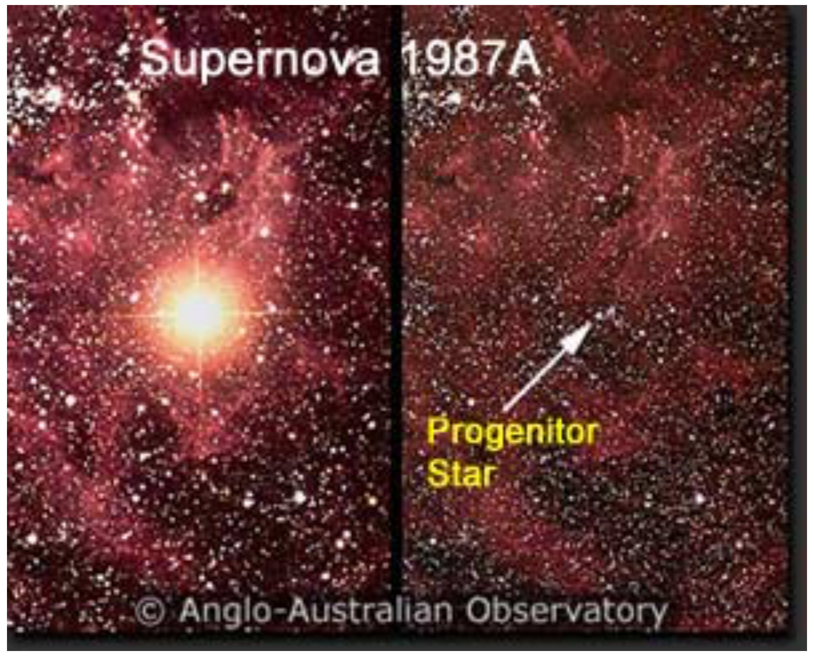


SN 1993J
M81

Crab Nebula…supernova remnant from 1054 AD

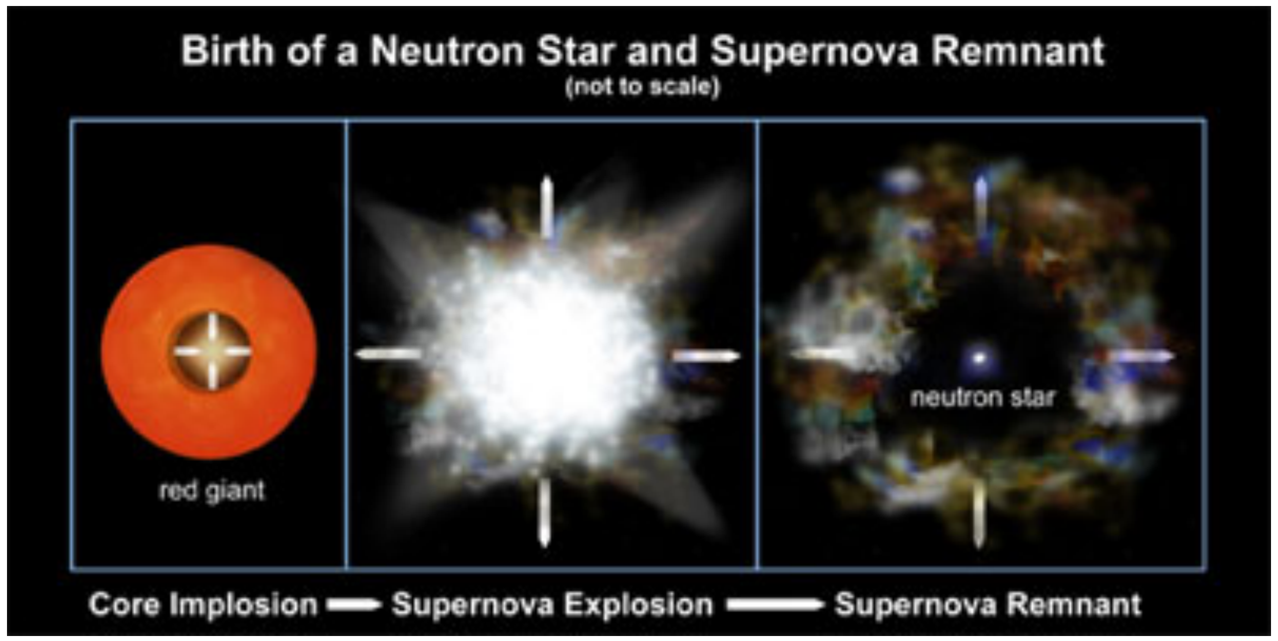
Tycho's Supernova, 1572



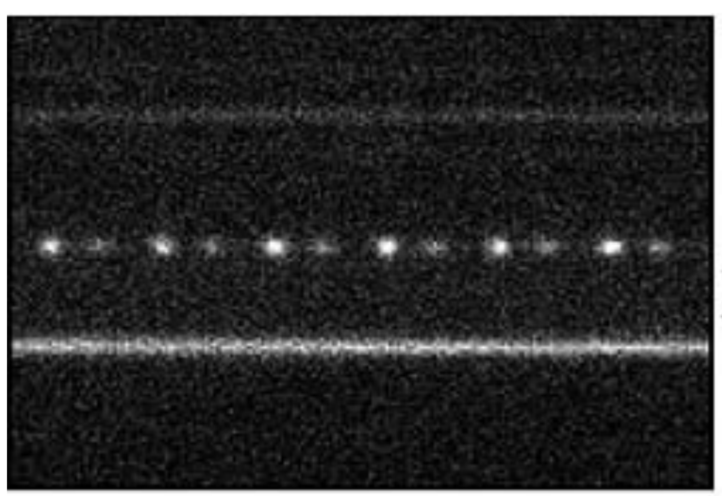


aftermath of a SN

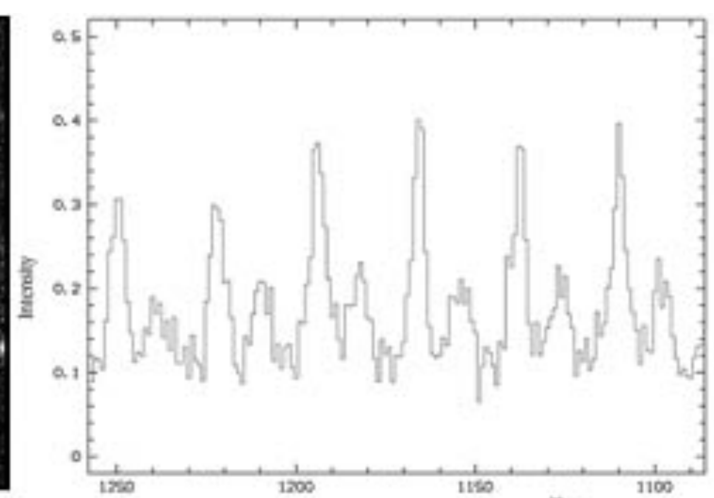
mass-ejection and a neutron star



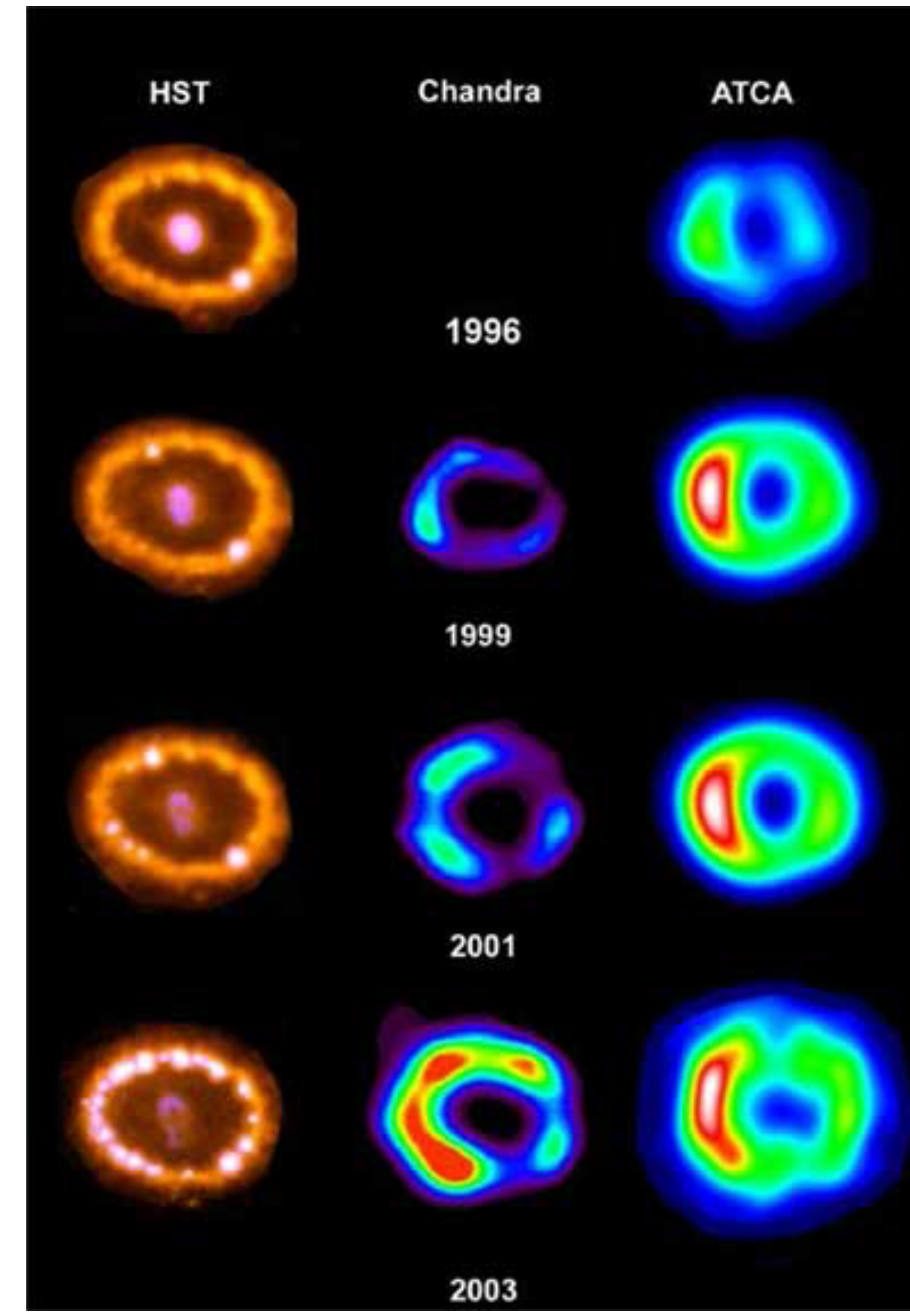
a star made of only neutrons…sizes 10's km
densities 10^{17} kg/m^3



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

30 CLASH SN Candidates in 20 Clusters so far, 15 shown here

(Of the 30, ~30% are Type Ia)

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

what if $M > 3\text{-}15 \times M_{sun}$?

Nature turns viscous

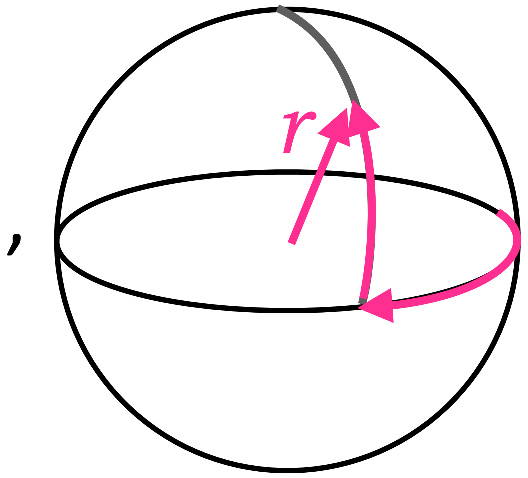
Stellar BLACK HOLE

remember the interval?

I wrote the interval this way: $\Delta s^2 = (c\Delta t)^2 - (\Delta x)^2$

$$\Delta s^2 = (c\Delta t)^2 - (\Delta r)^2$$

r: radius of spherical region, not x and y anymore



Now that we're talking about bending space and time and spacetime...we'll need a more general version

$$\Delta s^2 = g_{00}(c\Delta t)^2 + g_{11}(\Delta r)^2$$

These coefficients will characterize the shape of the interval - the "Metric"

Flat, "Minkowski Metric"

$g_{00} = 1$ $g_{11} = -1$

"regular" Special Relativity

For curved spacetime...the "g's" will not be +1 and -1...

write it out...blackhole arithmetic

the interval for spacetime regions outside of a spherical mass

ala' Mr Schwarzchild

$$\Delta s^2 = (1 - \frac{R_S}{r})c^2\Delta t^2 + (\frac{-1}{1 - R_S/r})\Delta r^2$$

$$\Delta s^2 = g_{00}(c\Delta t)^2 + g_{11}(\Delta r)^2$$

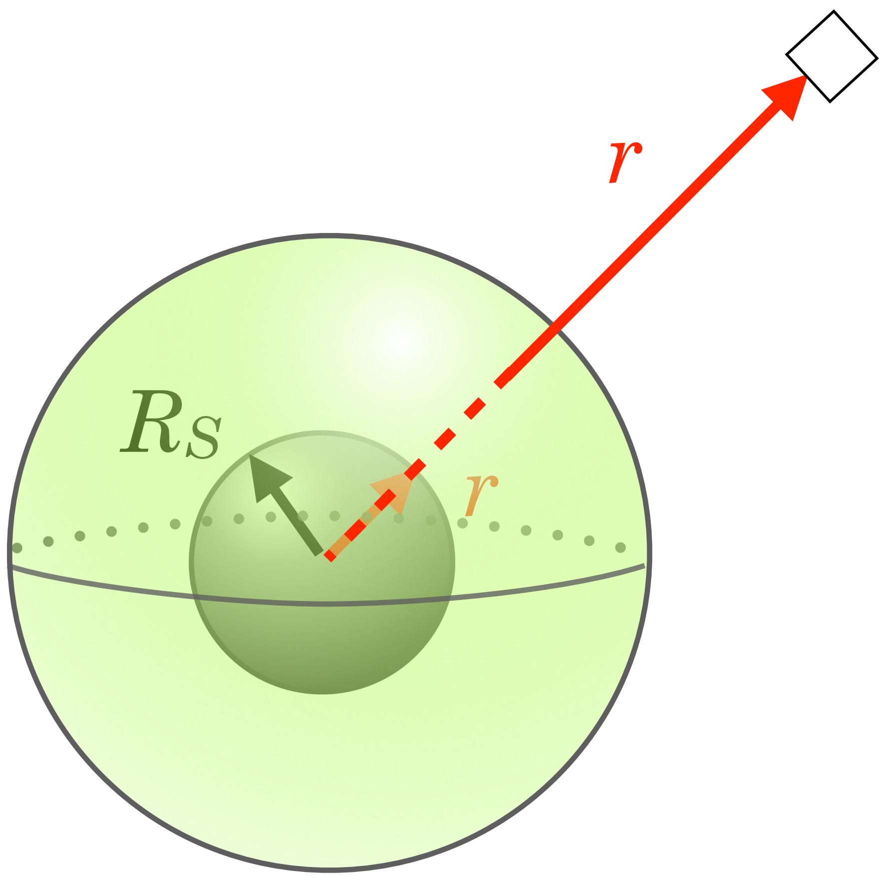
$$g_{00} = 1 - \frac{R_S}{r}$$

$$g_{11} = \frac{-1}{1 - R_S/r}$$

using the “interval”

The GR analog involves constants, “*g*” the metric. $\Delta s^2 = (g_{00})c^2\Delta t^2 + (g_{11})\Delta r^2$

The Schwarzchild solution...is in part solving for the g’s. $R_S = \frac{2GM}{c^2}$



$$g_{00} = 1 - \frac{R_S}{r}$$

$$g_{11} = \frac{-1}{1 - R_S/r}$$

remember, for most objects:
$R_S << r$ what are g_{00} and g_{11}?

$g_{00} = 1, \quad g_{11} = -1$ ✓

What if all of the M is inside of R_S and $r = R_S$?

time appears to stop for an outside observer!

What if all of the M is inside of R_S and $r < R_S$?

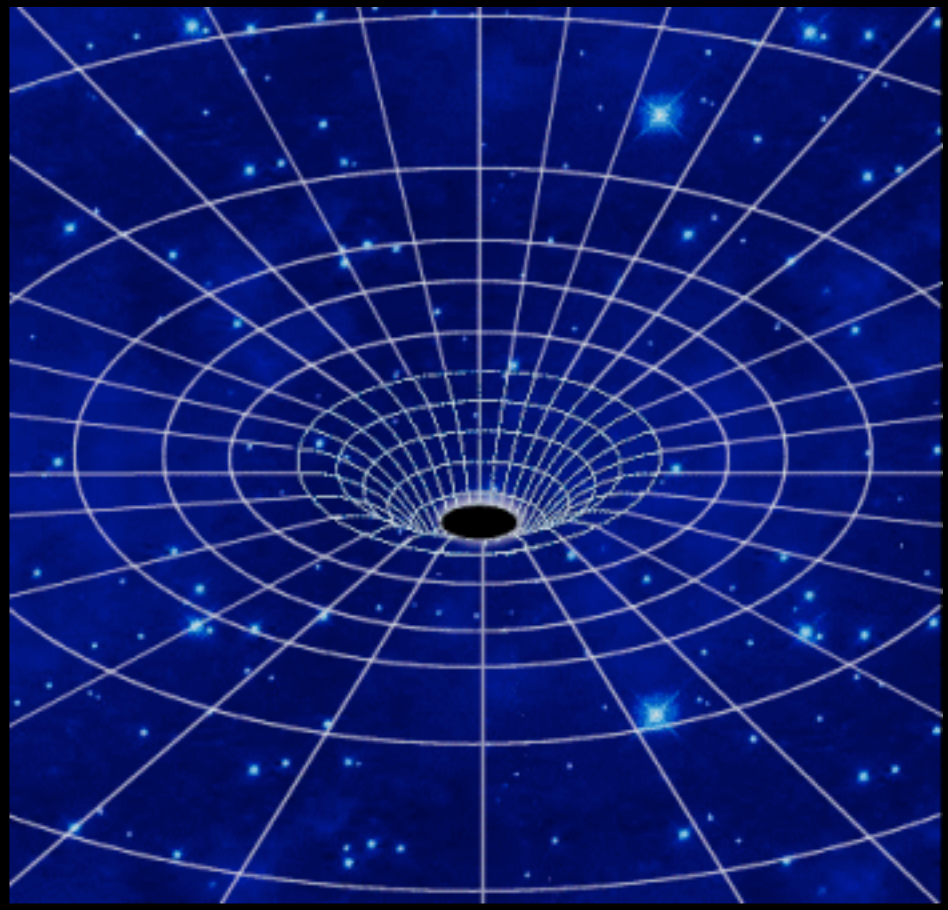
$$\Delta s^2 = (1 - \frac{R_S}{r})c^2\Delta t^2 + (\frac{-1}{1 - R_S/r})\Delta r^2$$

very peculiar

Gravity wins. Nothing gets out, not even light:

BLACK no light

HOLE the most extreme warping of spacetime in Nature

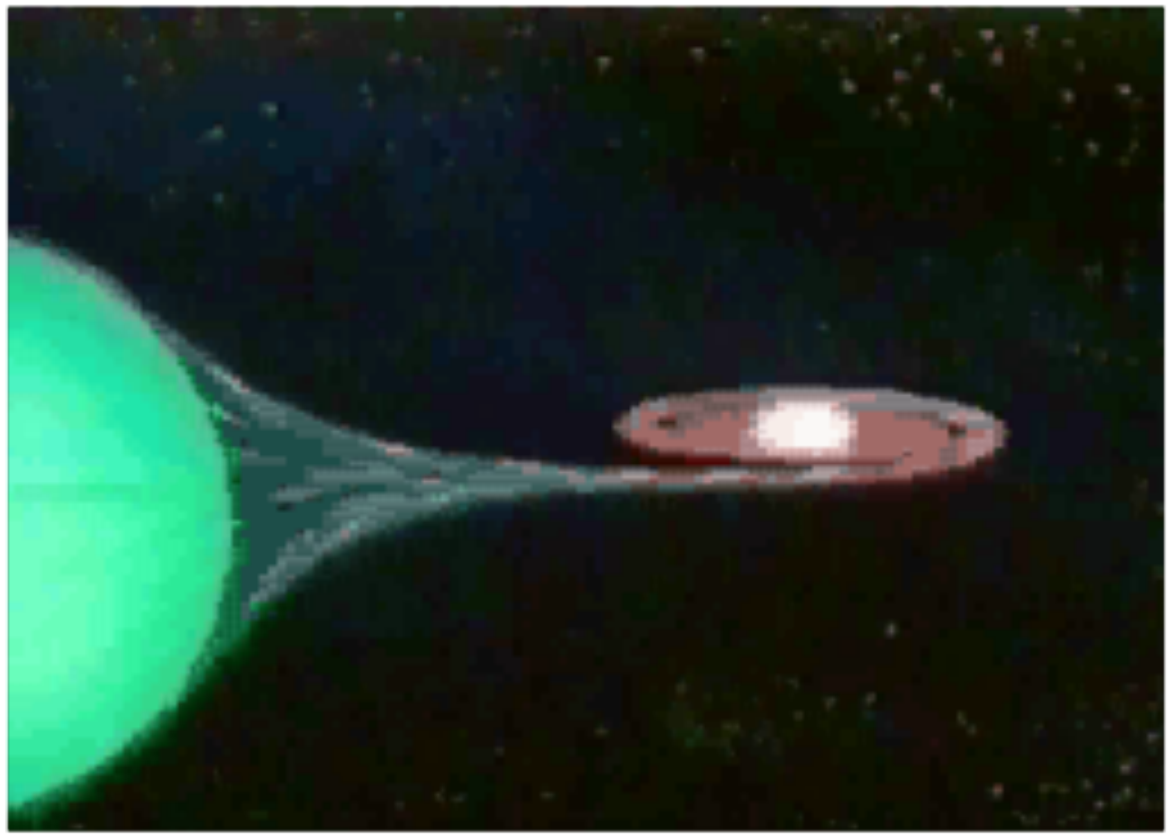


outside of ~3R_S

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

Galactic black holes:

Milky Way

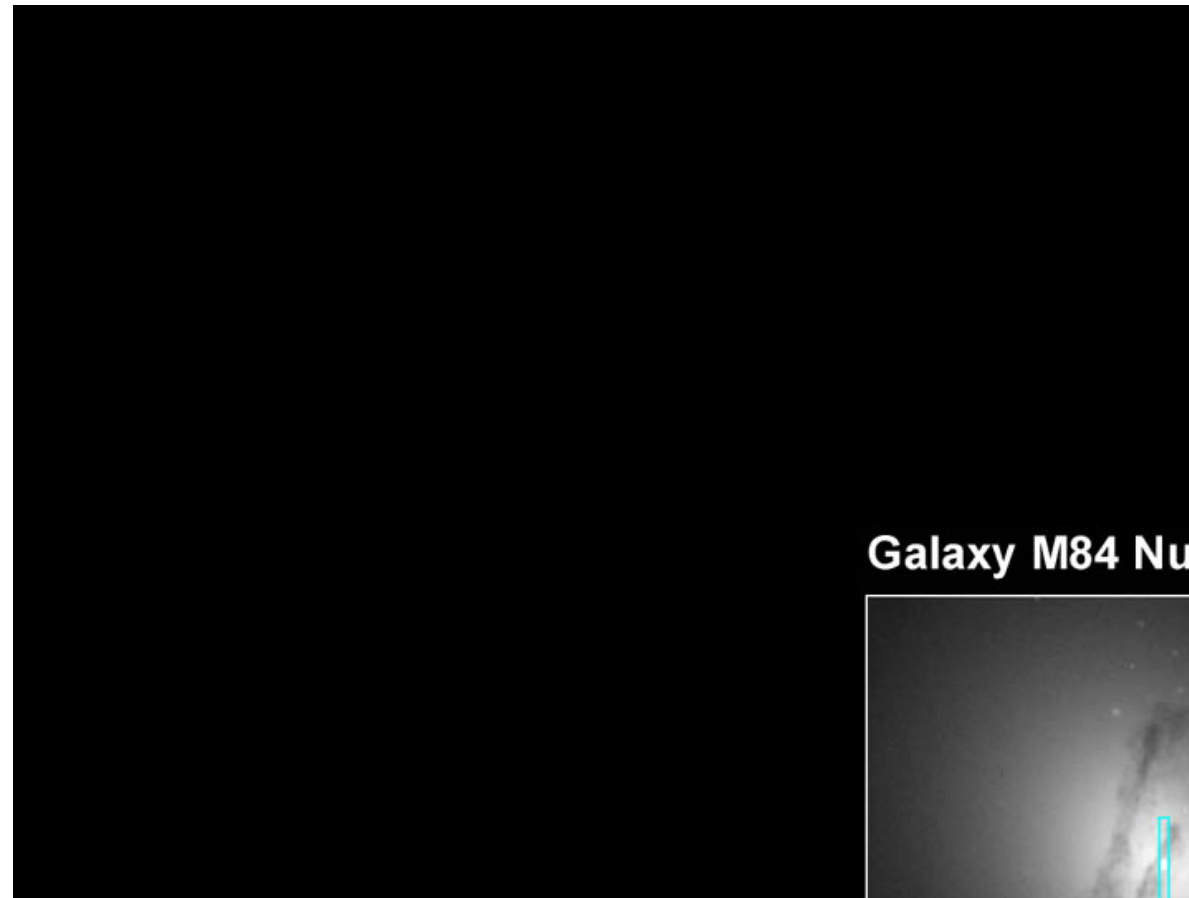
$4 \times 10^6 \times M_{sun}$

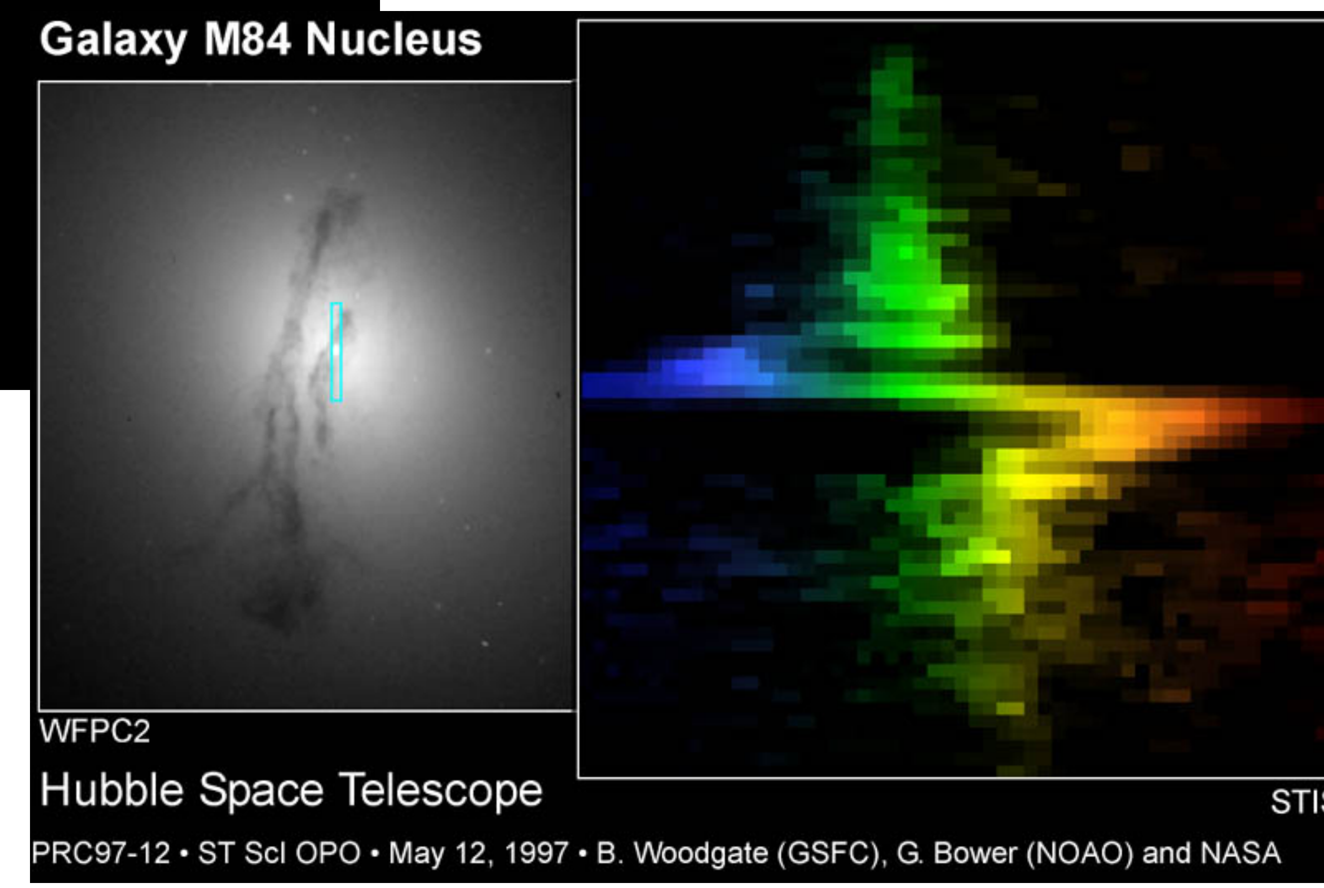
M84

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

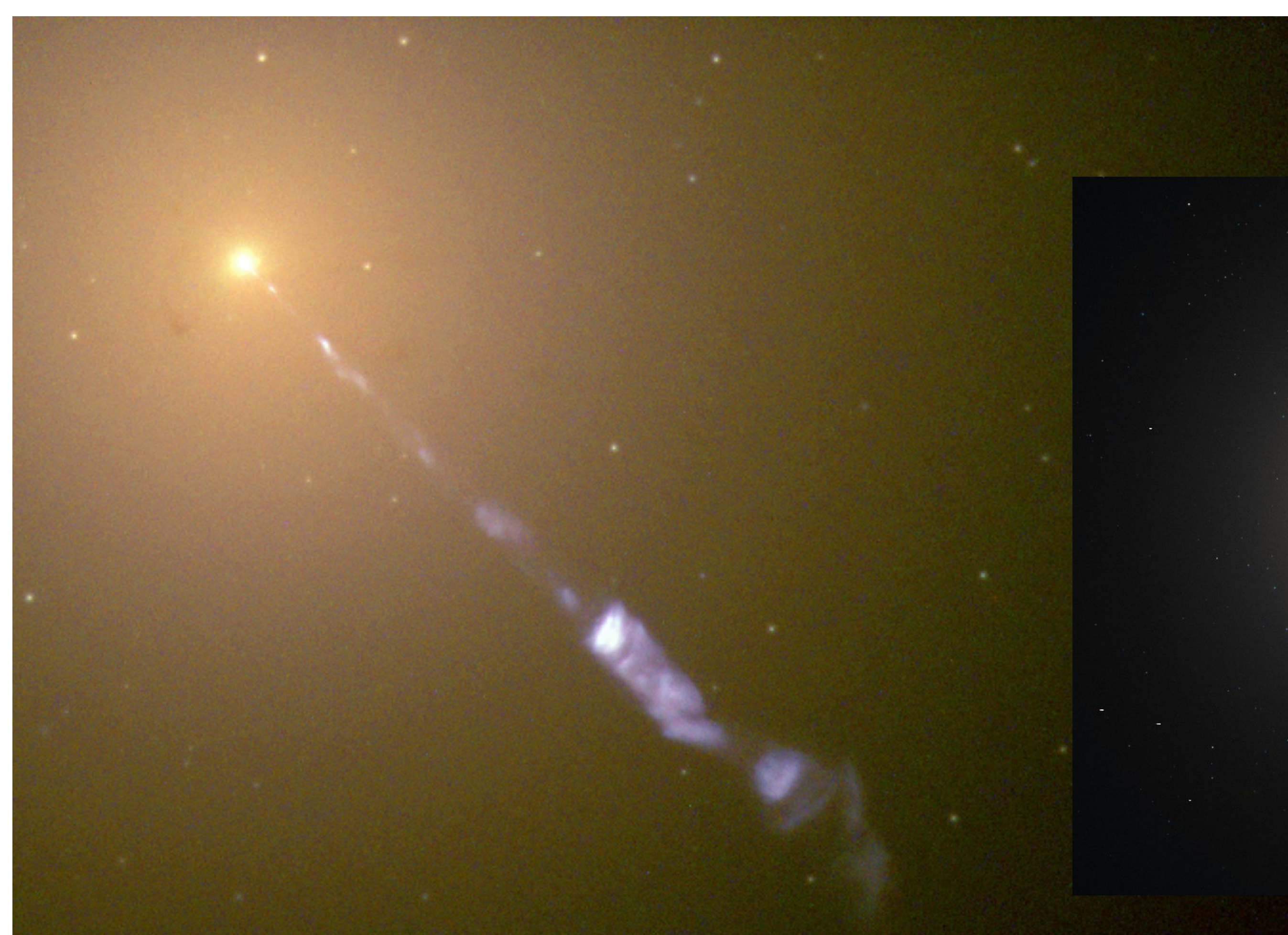
M87

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





M87 Active Glactic Nucleus (AGN)



There are a handful of "classic tests"

of these ideas:

that space and time are warped by gravitation

GRAVITATIONAL WAVES!!!

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"

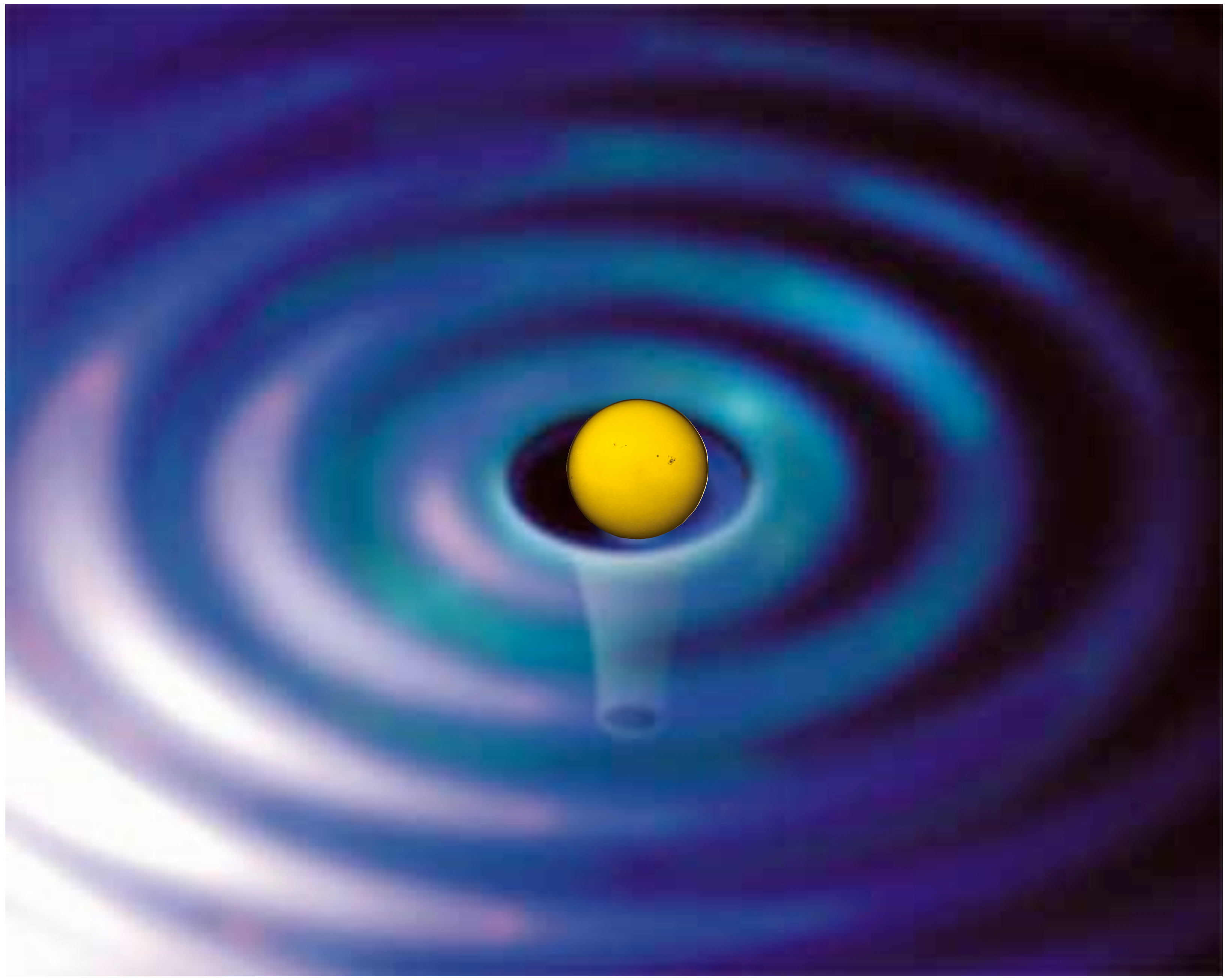
Black Holes

accelerating charges

remember?

Well, mass can be thought of as the “charge” of gravitational fields.

wiggle a big mass..it will radiate “gravitational waves”



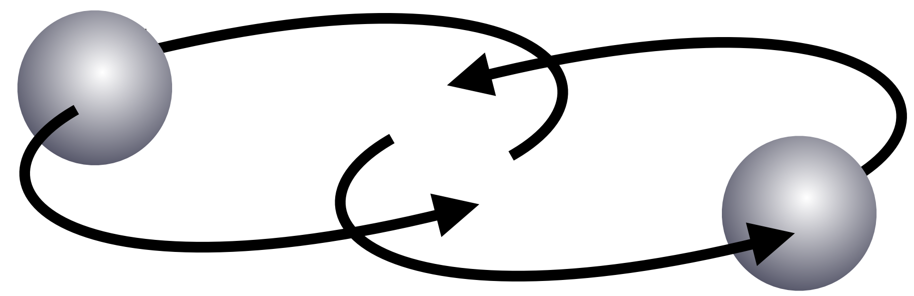
Disturbances in geometry of spacetime itself.

“Binary Pulsar period”

remarkable test of General Relativity

A binary star system...of neutron stars

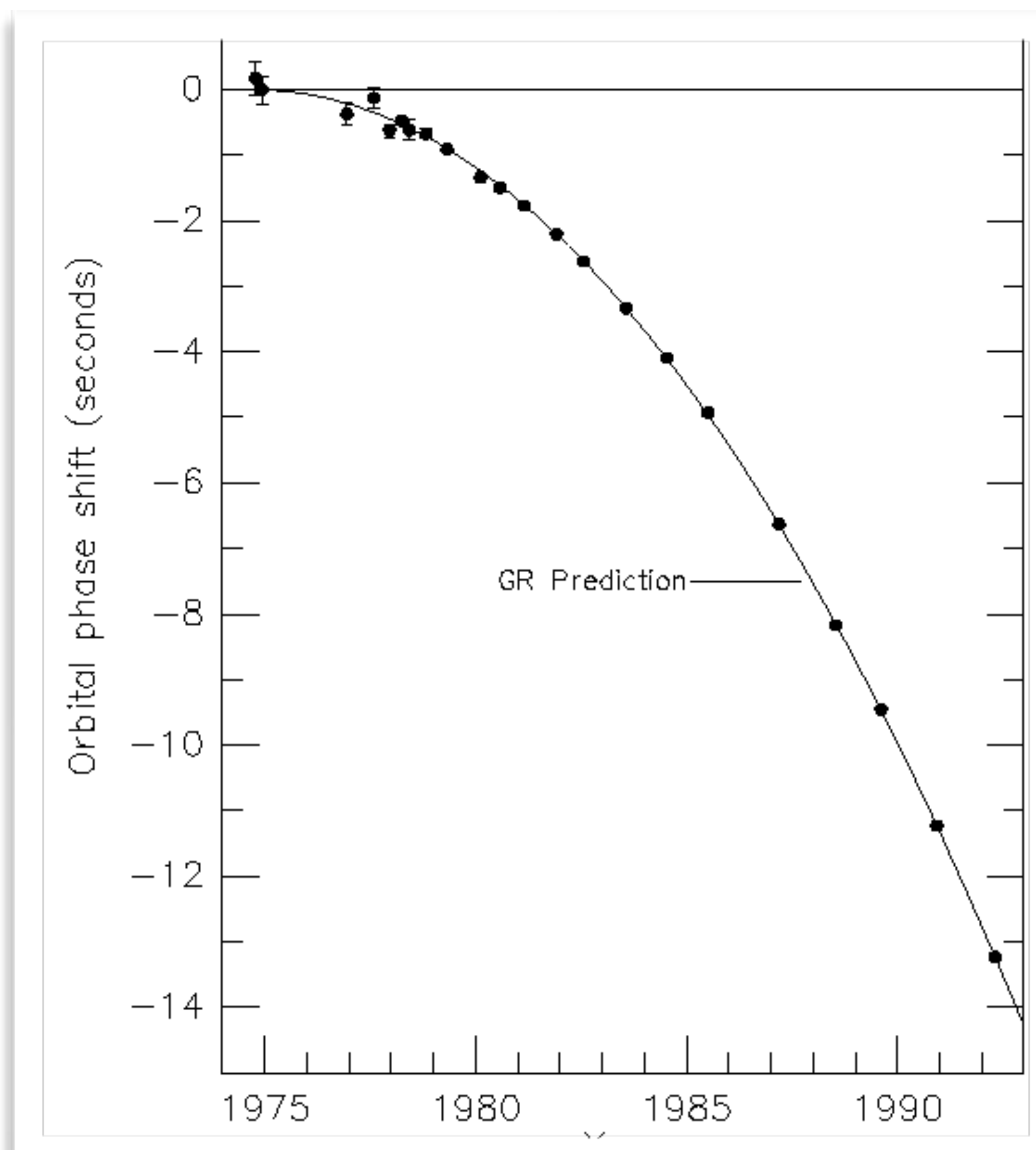
they are accelerating and so radiate gravitational waves



PSR1913+16 discovered 1974

Emits very regular radio pulse every 59 ms: “pulsars”

and its period is reduced by 67 ns each orbit



1993

Joseph H. Taylor Jr.

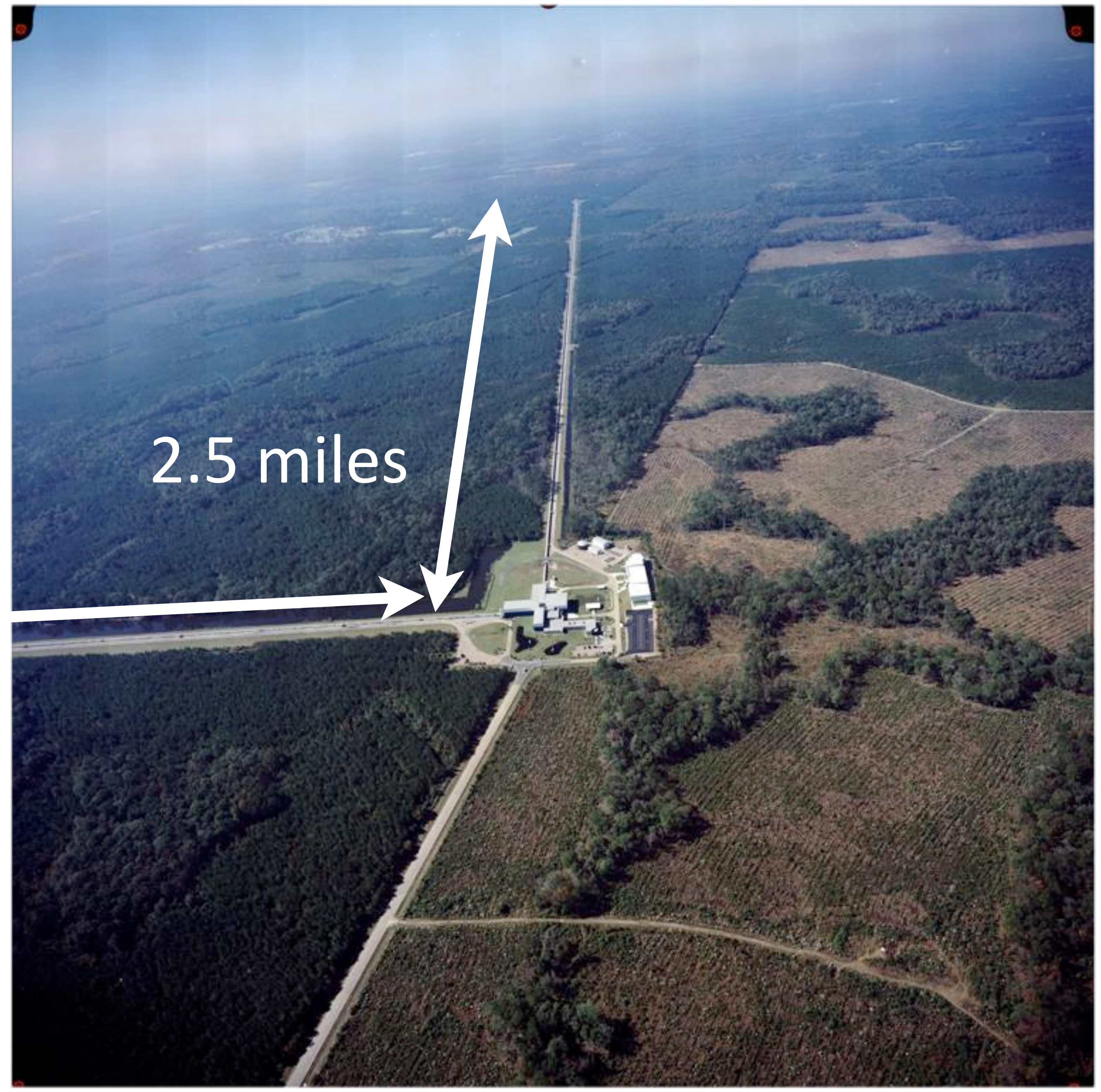
Russell A. Hulse

Pulsars discovered earlier and awarded the 1974 Nobel Prize to Martin Ryle and Antony Hewish (and not Jocelyn Bell...) in 1968

LIGO

Laser Interferometer Gravitational-Wave Observatory

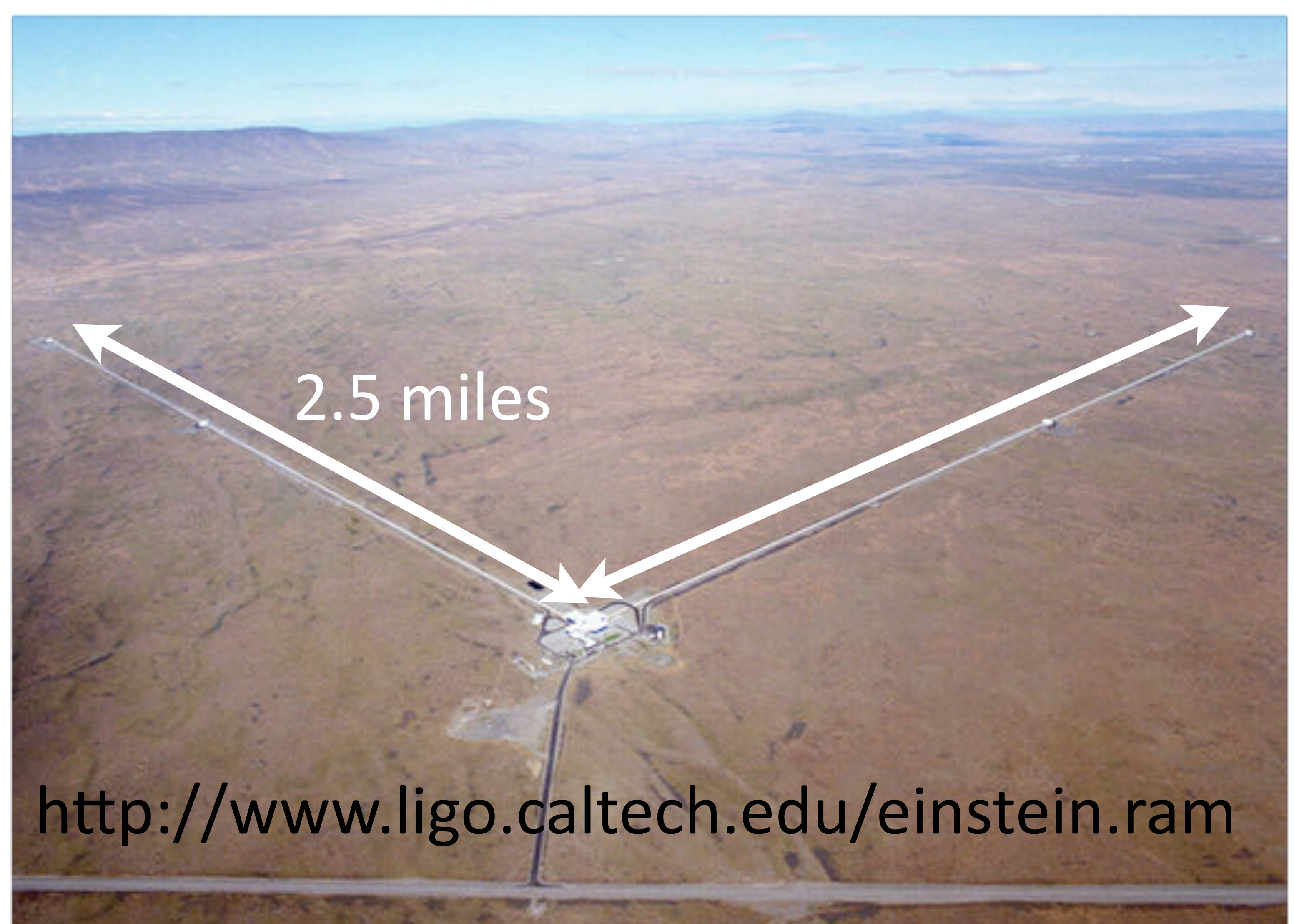
intergalactic, colliding binary, neutron stars, gamma ray bursts, black holes, colliding galaxies,



looking for shrinkage of one arm when gravitational wave passes by

need precision smaller than a proton radius

Livingston, LA



Hanford, WA

laboratory: **LIGO**

location:	Lawrence, LA & Hanford, WA
established:	1999
notable directors:	Barry Barish, now Jay Marx
type of lab:	Laser interferometer for measuring gravitational waves

let Brian Greene explain

Brian was on campus last spring…did you go?

MSU Science Festival: http://sciencefestival.msu.edu