hi

Day 17, 19.03.2019

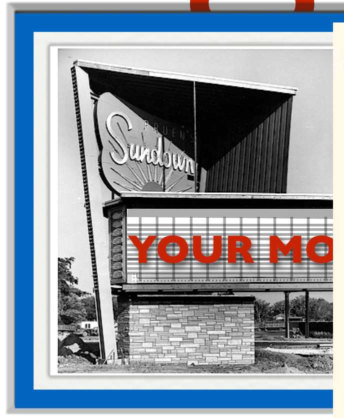
Einstein’s General Theory of Relativity, 3

Cosmology 3

10 days until opening day

Joe Bonamassa week

housekeeping



Gotta come to class

- question about anything?
- I'll make a movie for you:

Madame Curie movie - Tuesday: Tonight!

- 6pm, 3239 BPS (our group's conference room)
- I think there are ~7 of you

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

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

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:

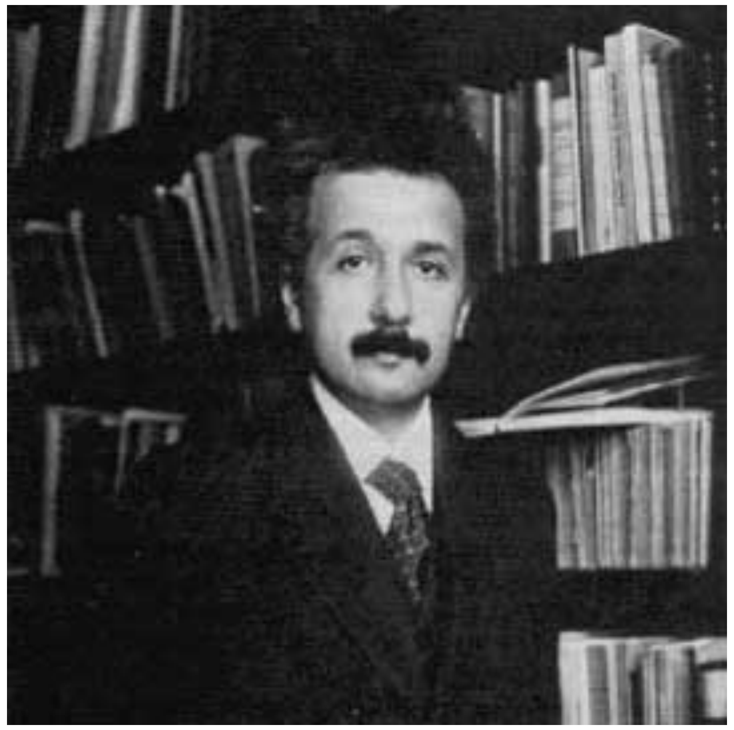
- Course ID: MABROCK41459; free code: WSSPCT-BLIDA-INANE-TOGUE-RIGOT-UNRWA
- I configured it wrong. I've extended the due date to Sunday.

March 2019

Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
24	25	26	27	28	1	2
3	4 ←	5	6 spring break	7	8 →	9 HW6
10	11	12 lecture	13	14 lecture	15 HW6 due	16 HW7
17	18	19 le[illegible]e 	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

KEEP
CALM
AND
LET’S
REVIEW

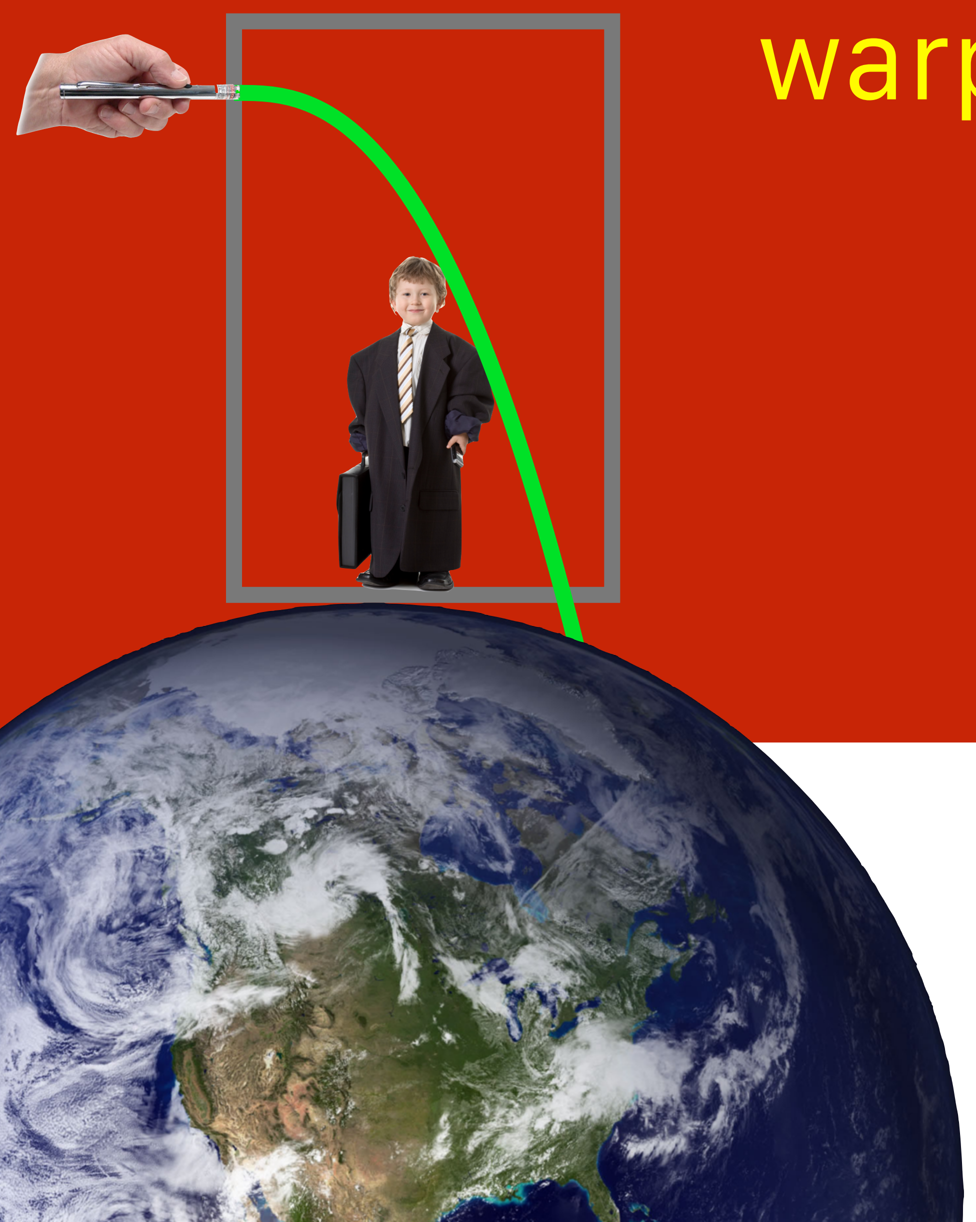
‘‘principle of equivalence’’



acceleration
warps space

from the Equivalence Principle

gravity
should
warp space



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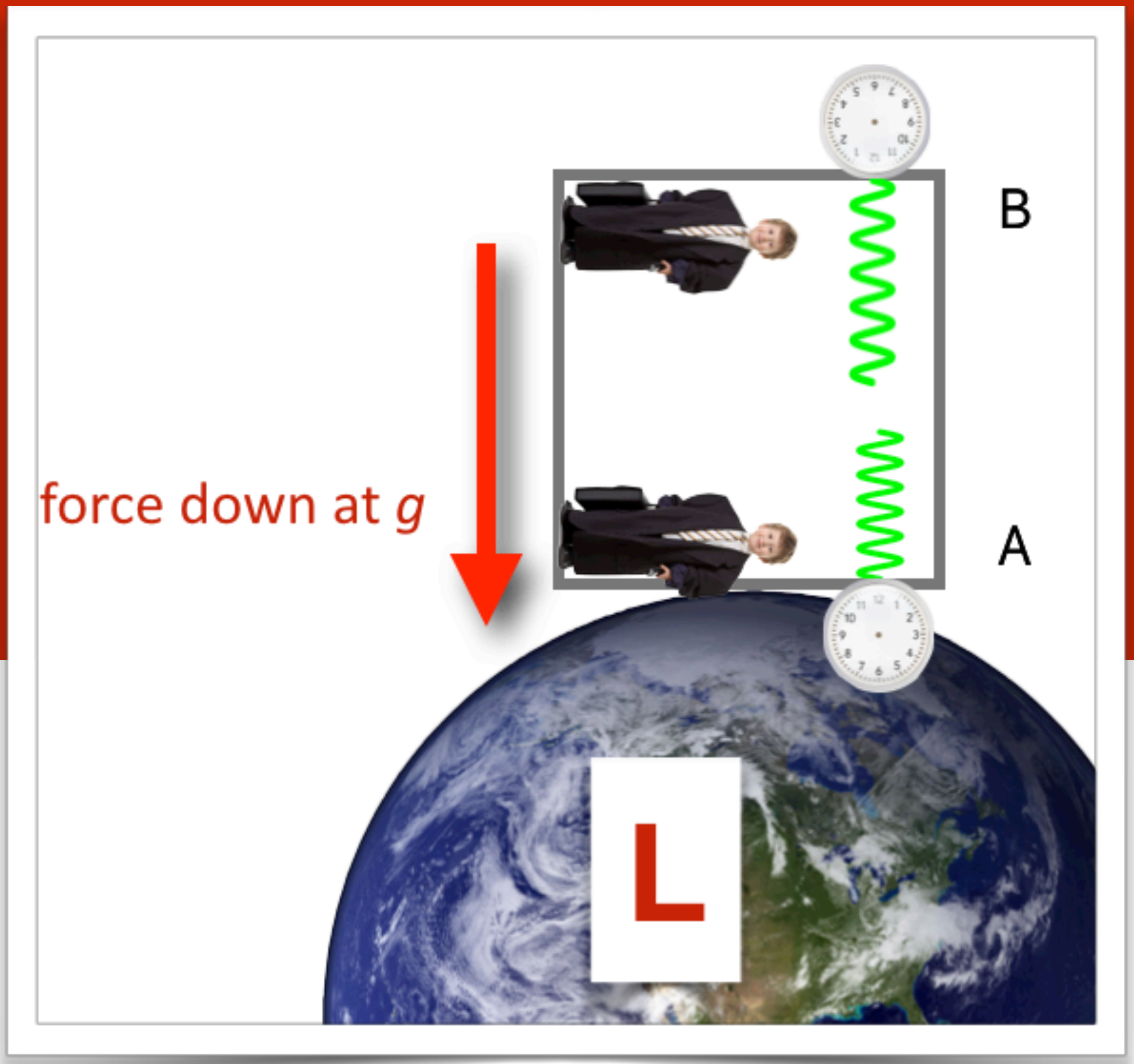


gravitating bodies…masses:

warp both space and time.

They warp: **spacetime**

`the free-fall recognition`

`became:`

Maybe gravity is not a force at all?

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

spacetime in general relativity

Einstein's mathematics of GR

led him to have to consider **non-Euclidean Geometries**

which were still timidly being studied by mathematicians

Euclid's 5th Postulate

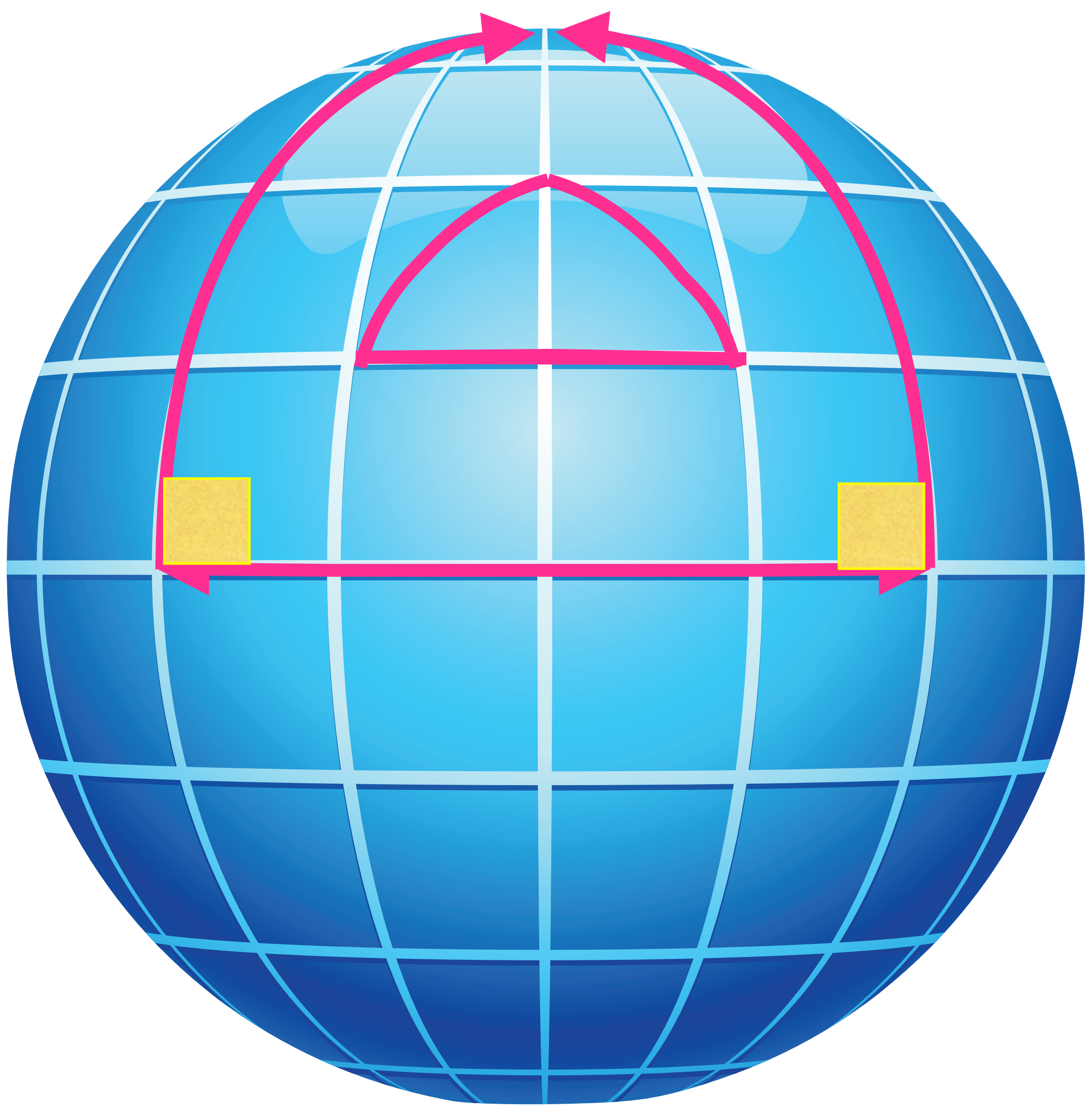
parallel lines never meeting?

only in a flat space

sum of interior angles in a triangle = 180^{o}?

only in flat space

on sphere > 180^{o}



‘‘warping’’

means that geometry

spacetime geometry

mixes with mass, energy, and pressure

General Relativity

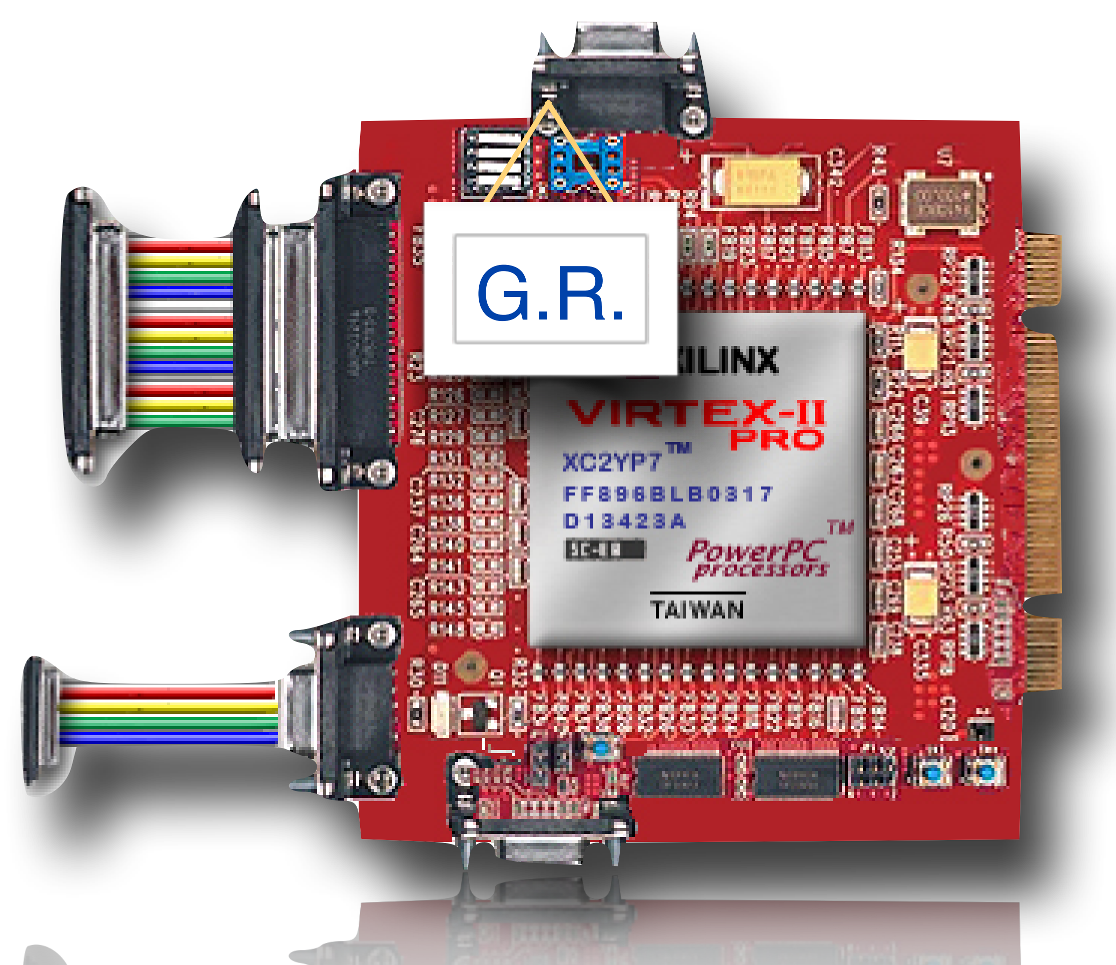
Einstein's GR equation

complicated mathematics

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

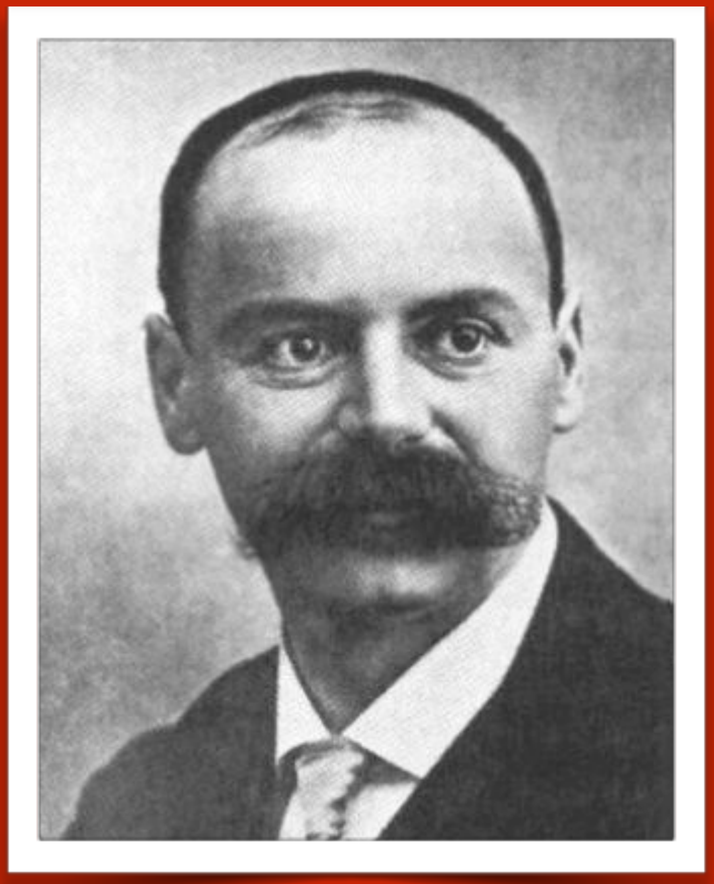
$$\underbrace{R_{\mu\nu} - \frac{1}{2}R g_{\mu\nu}} = \underbrace{\frac{8\pi}{c^4}T_{\mu\nu}}$$

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



wrong. Almost immediately:

from the foxhole, 1915



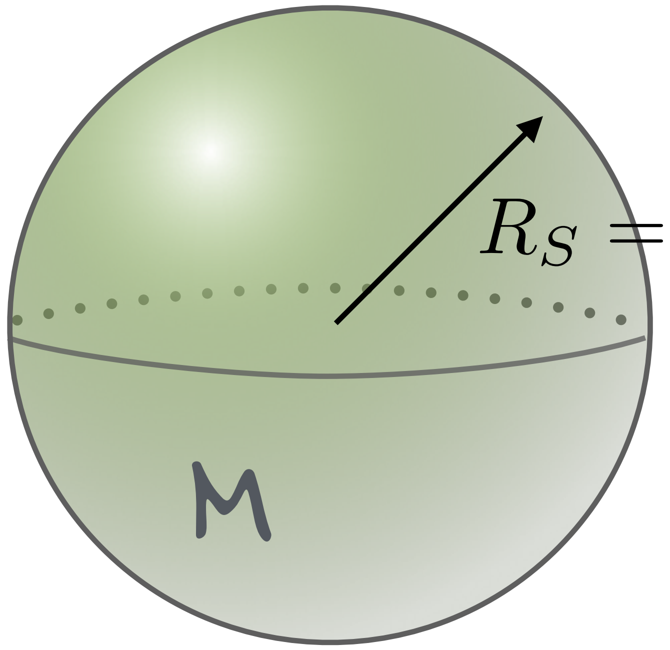
Karl Schwarzschild, 1873-1916

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.



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

R_S called the Schwarzschild Radius

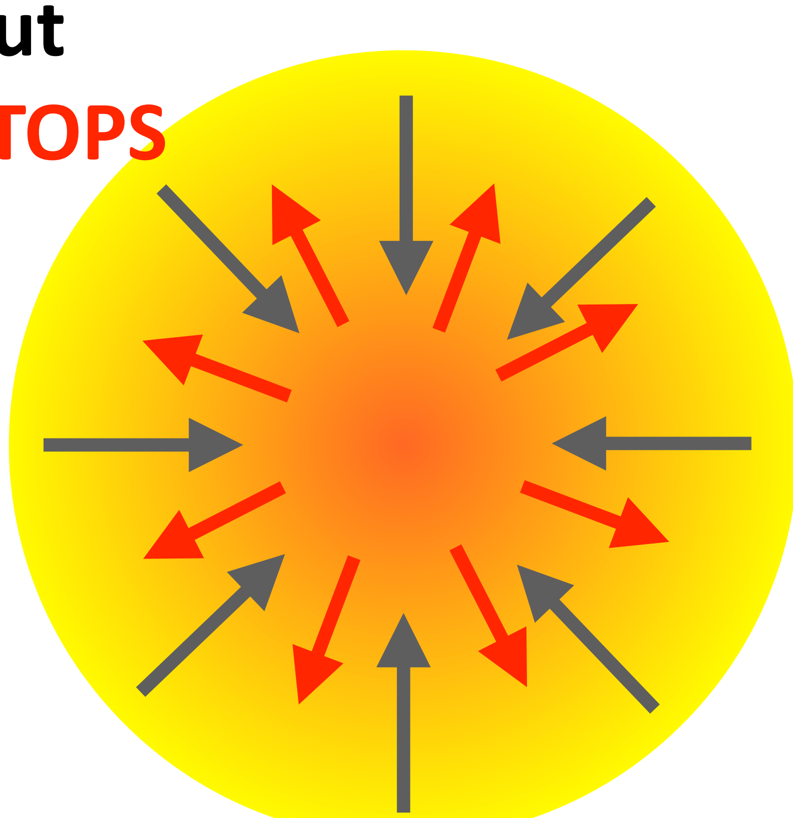
A mass M will produce an escape velocity of c. Light is trapped!

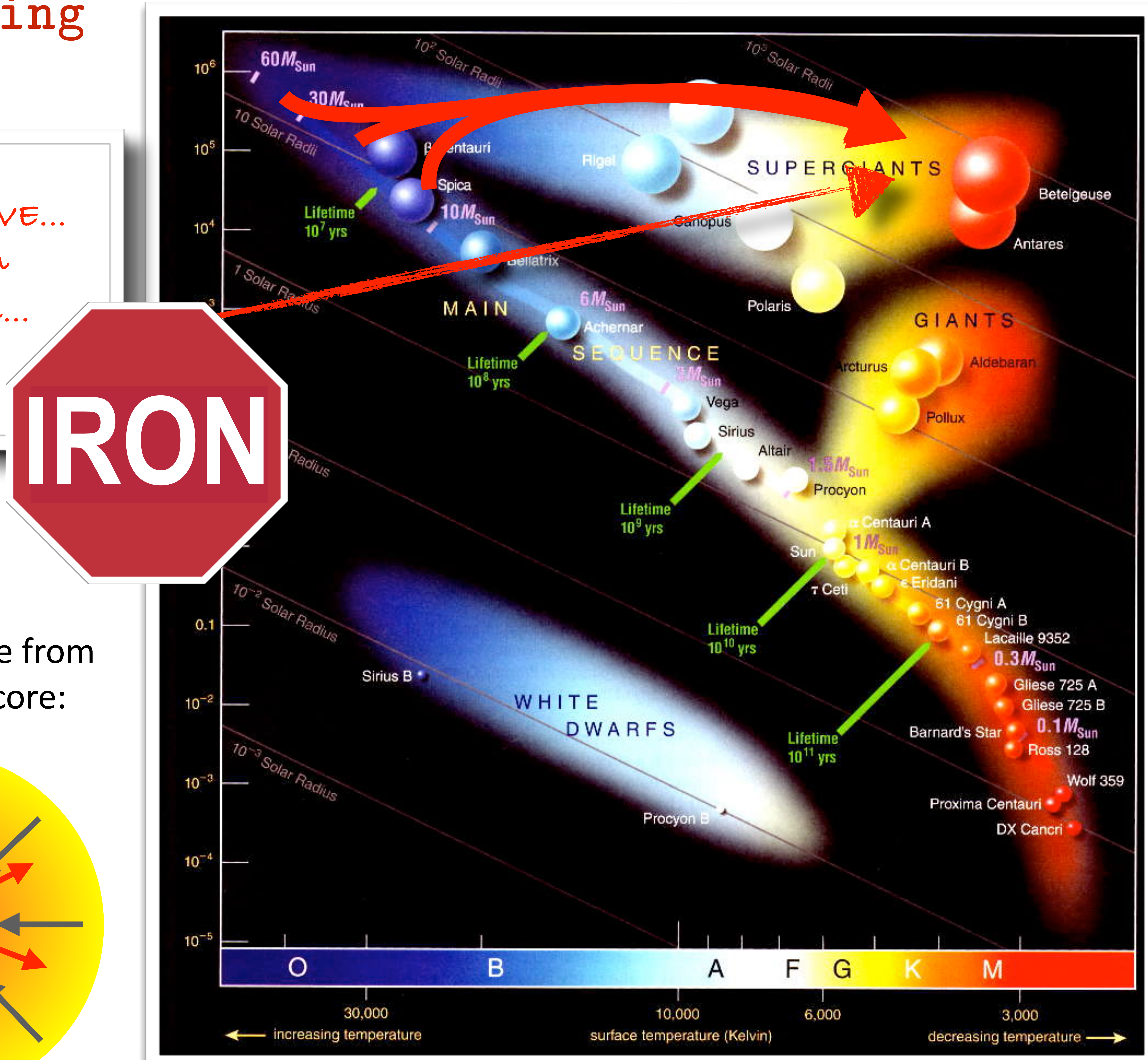
a balancing act

VERY MASSIVE...
>1.3 Msun
H → He → C...
...→ Fe

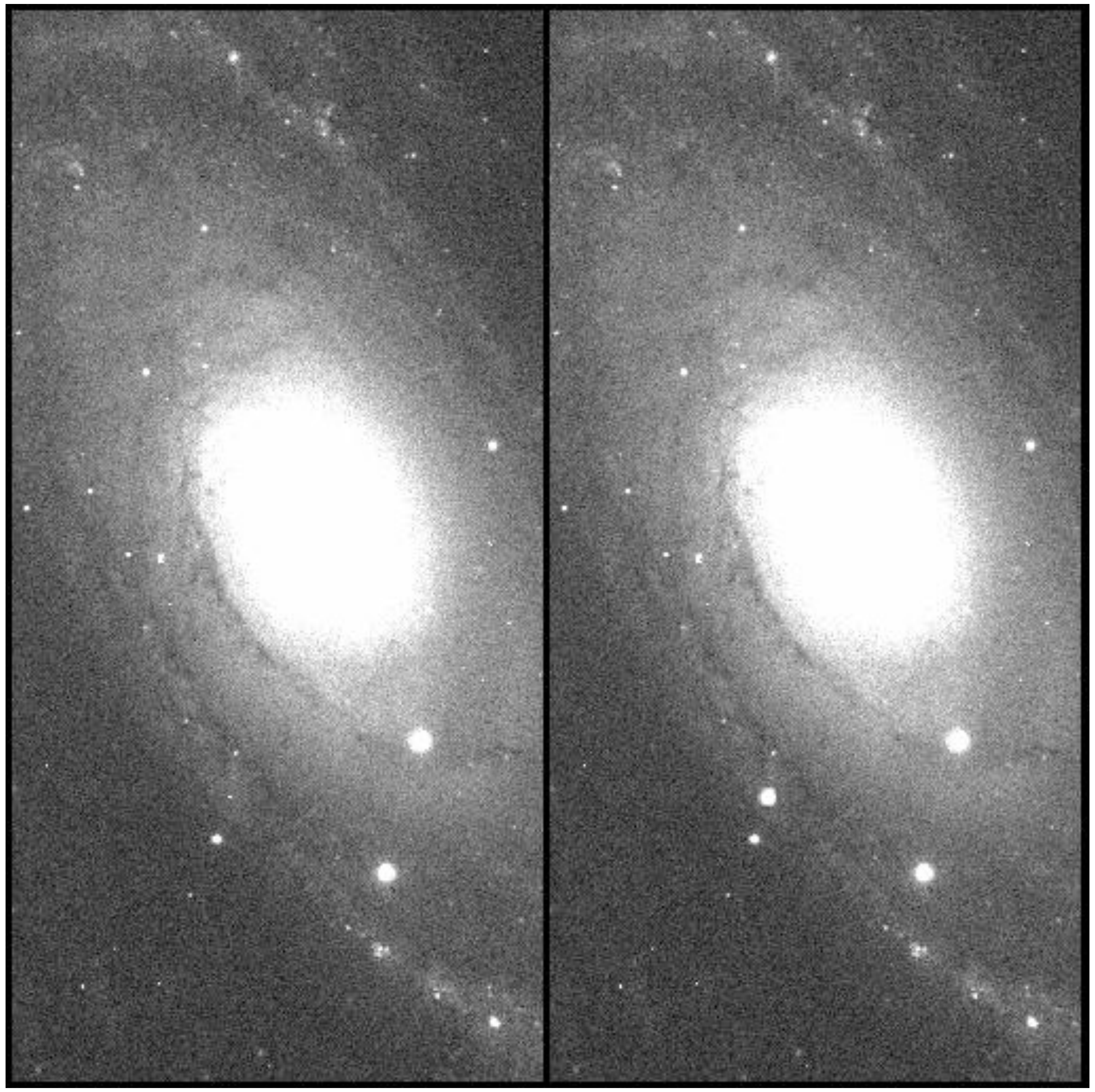
gravity pulls core/ atmosphere: **in**
WINS

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





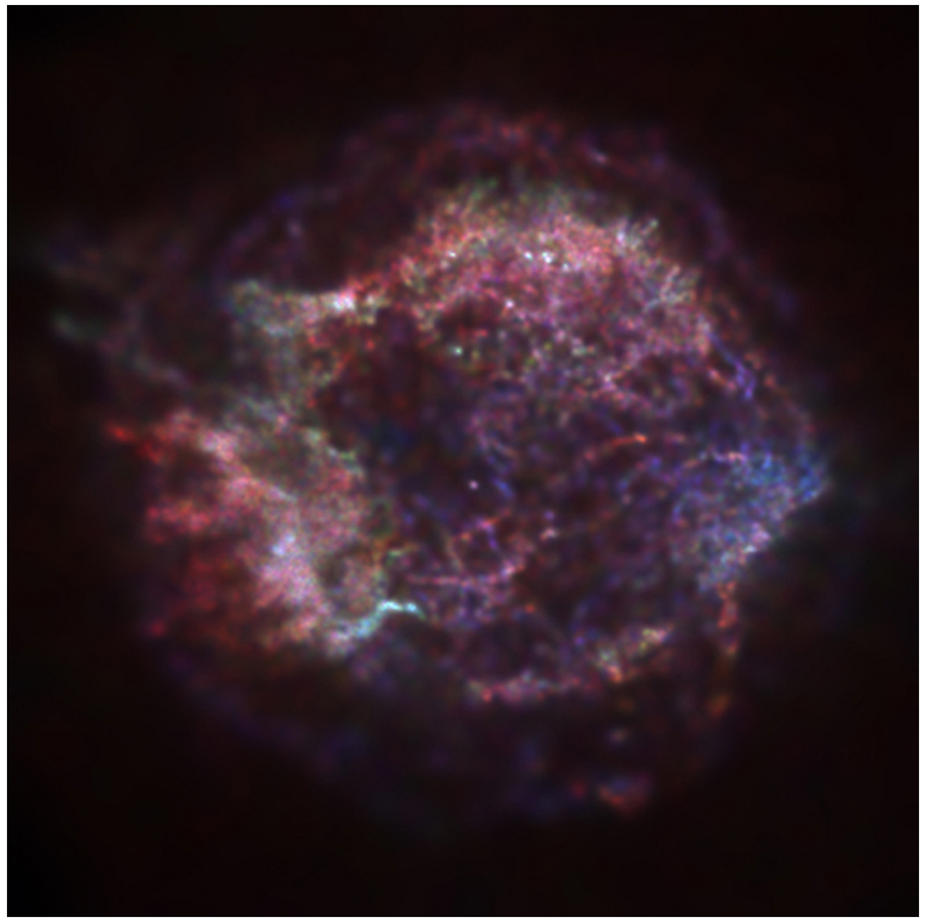
supernova!

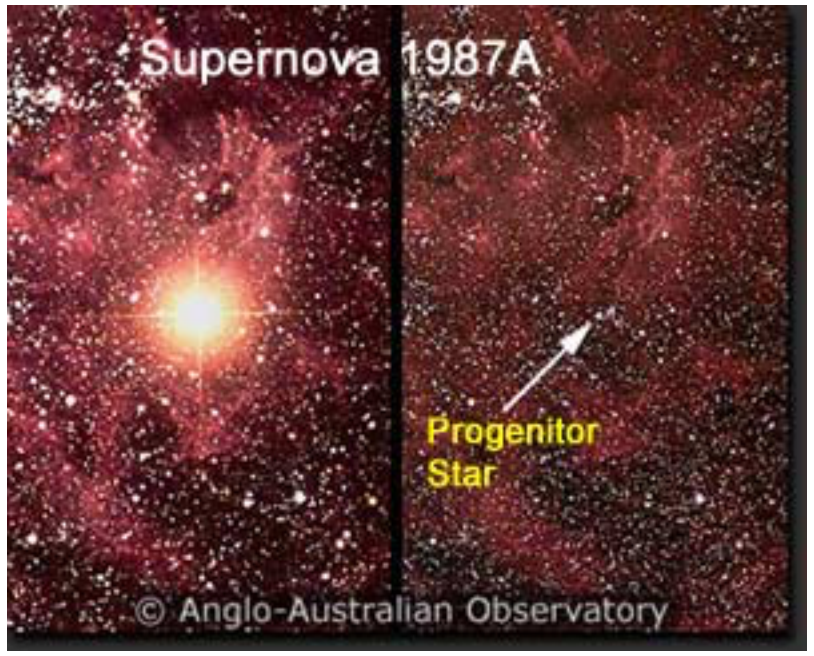


SN 1993J
M81

Crab Nebula…supernova remnant from 1054 AD

Tycho's Supernova, 1572





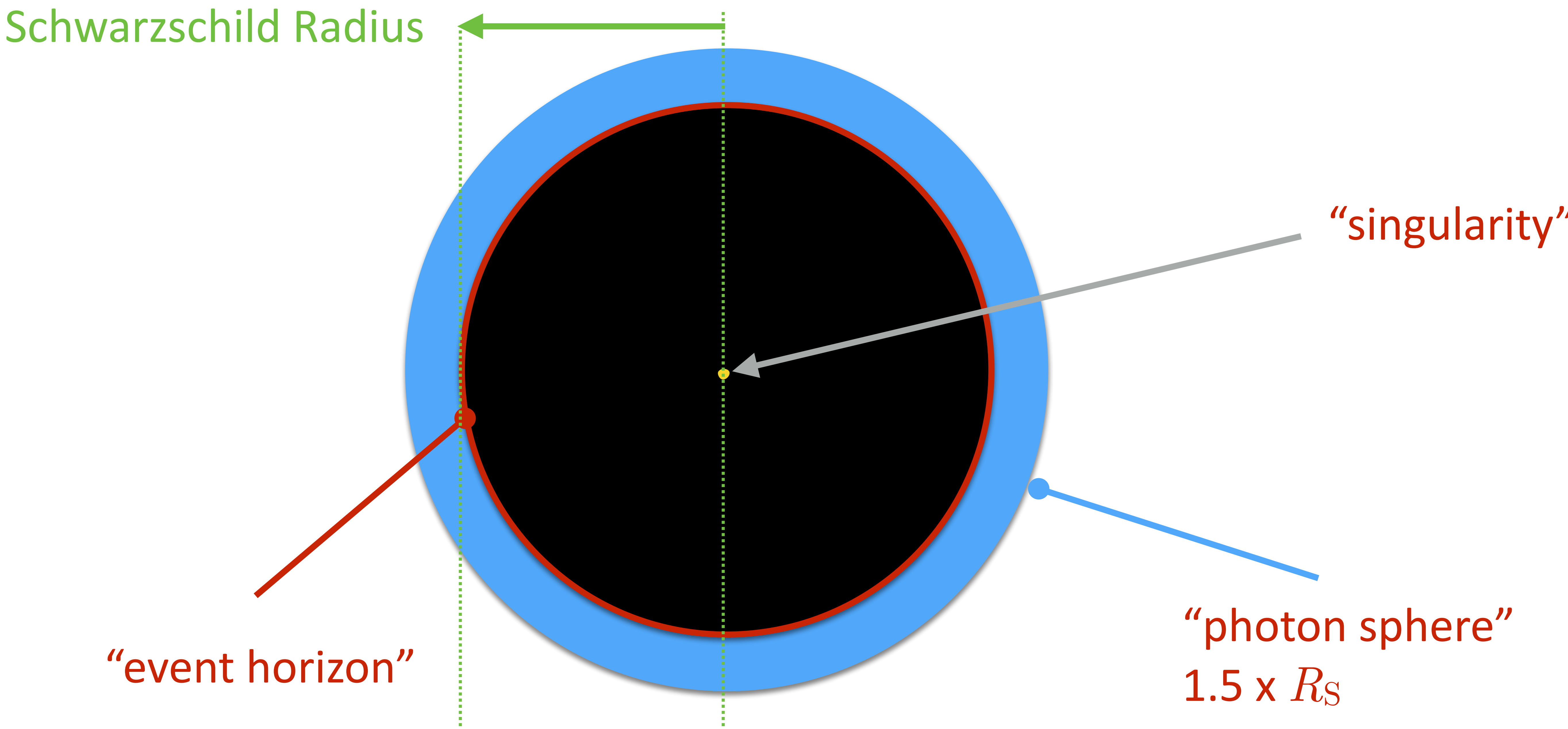
if M(star) > 3-15 x M_{sun}?

Nature turns viscous

Stellar Black Holes

many stars’ fate

black hole anatomy



simplest black hole: not rotating and not charged

realistic black hole: rotating...Kerr Black Holes

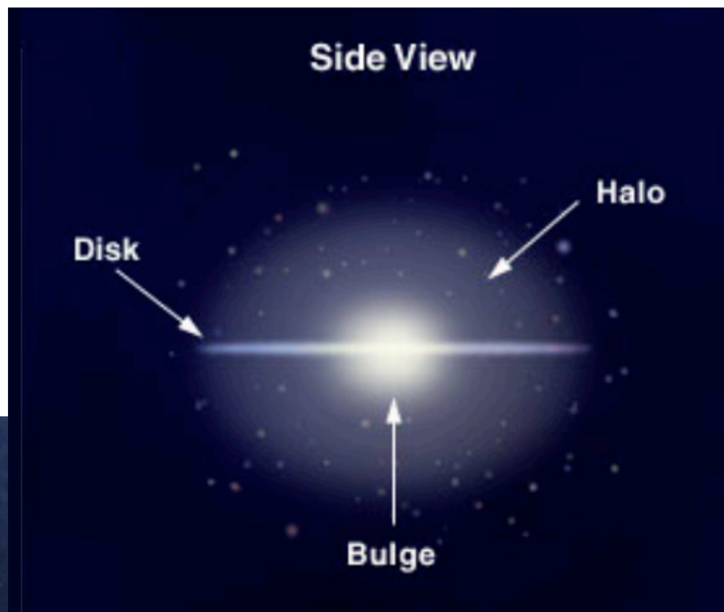
Supermassive

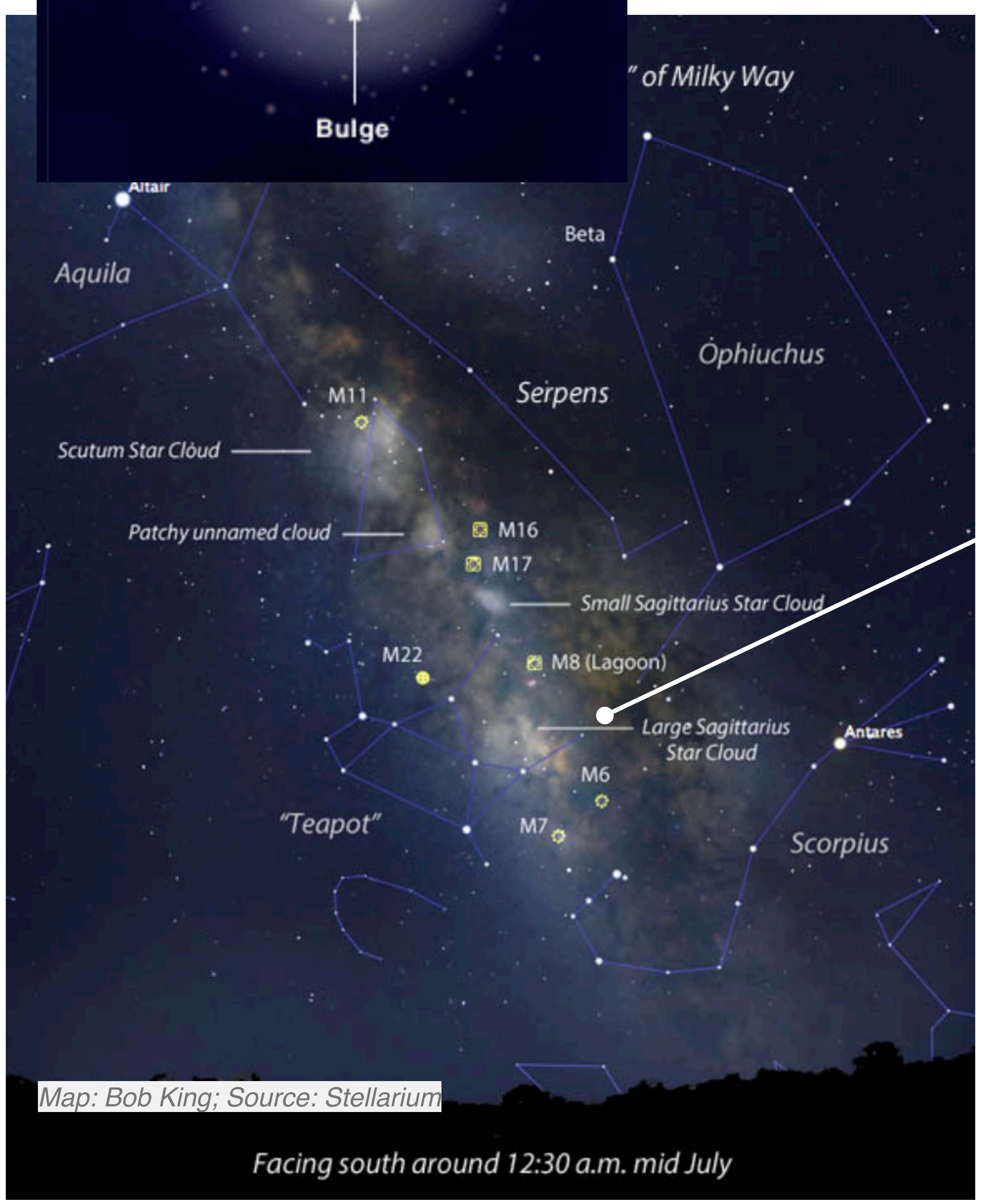
Black Holes

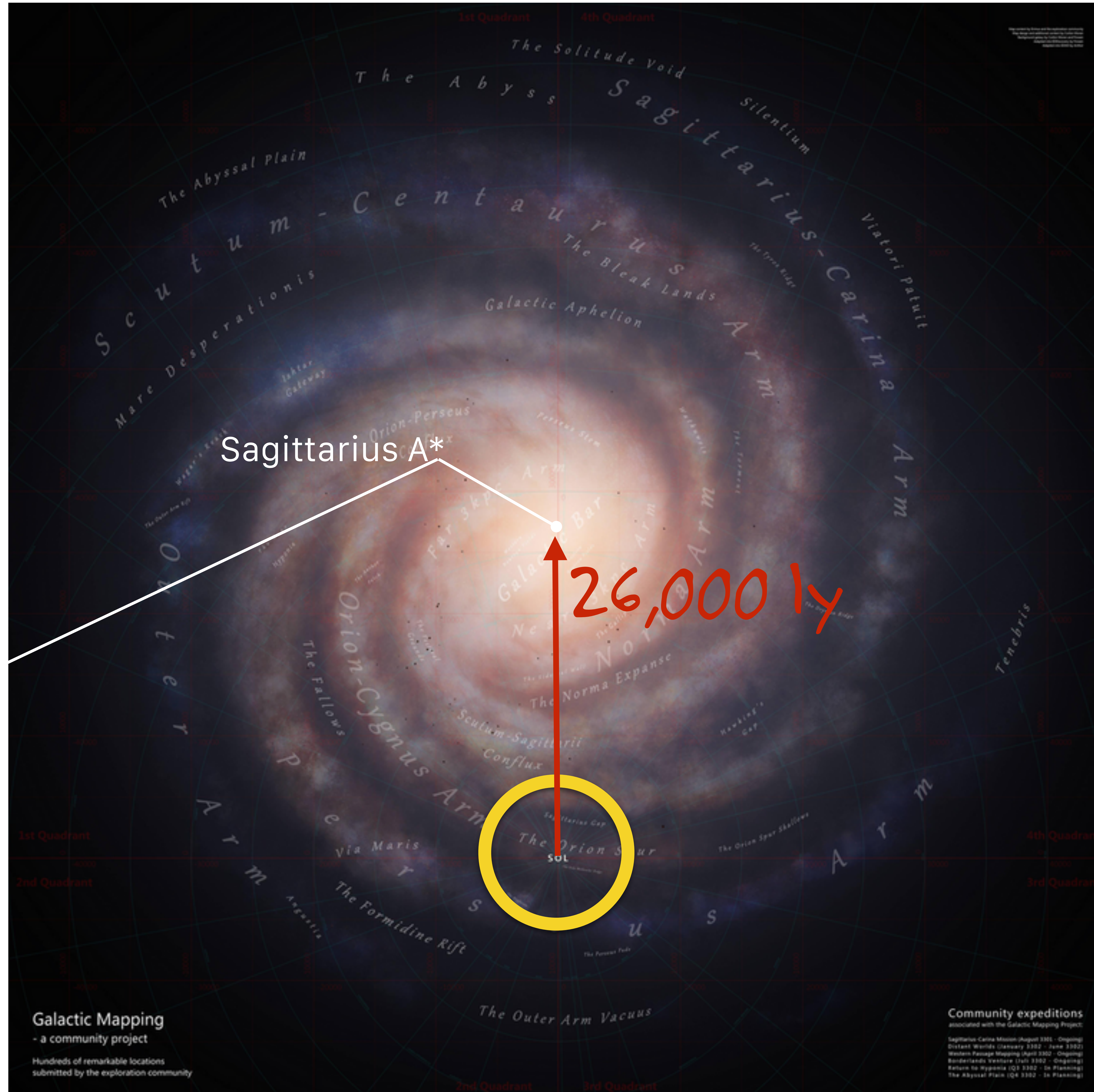
center of every (?) galaxy

let's orient ourselves

Sagittarius A and A*







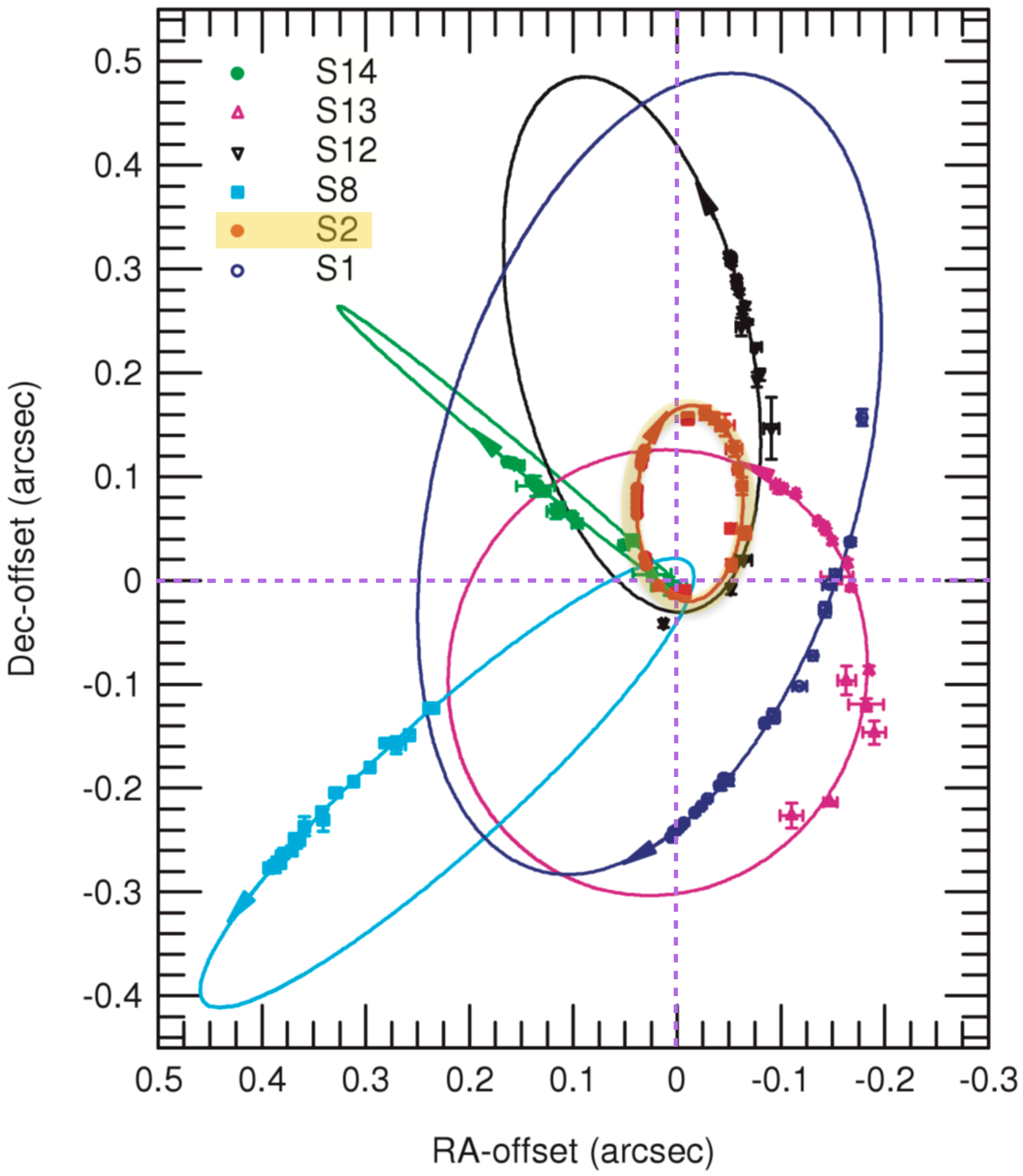
https://www.reddit.com/r/eliteexplorers/comments/92li23/galactic_map_with_labeled_regions/

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!

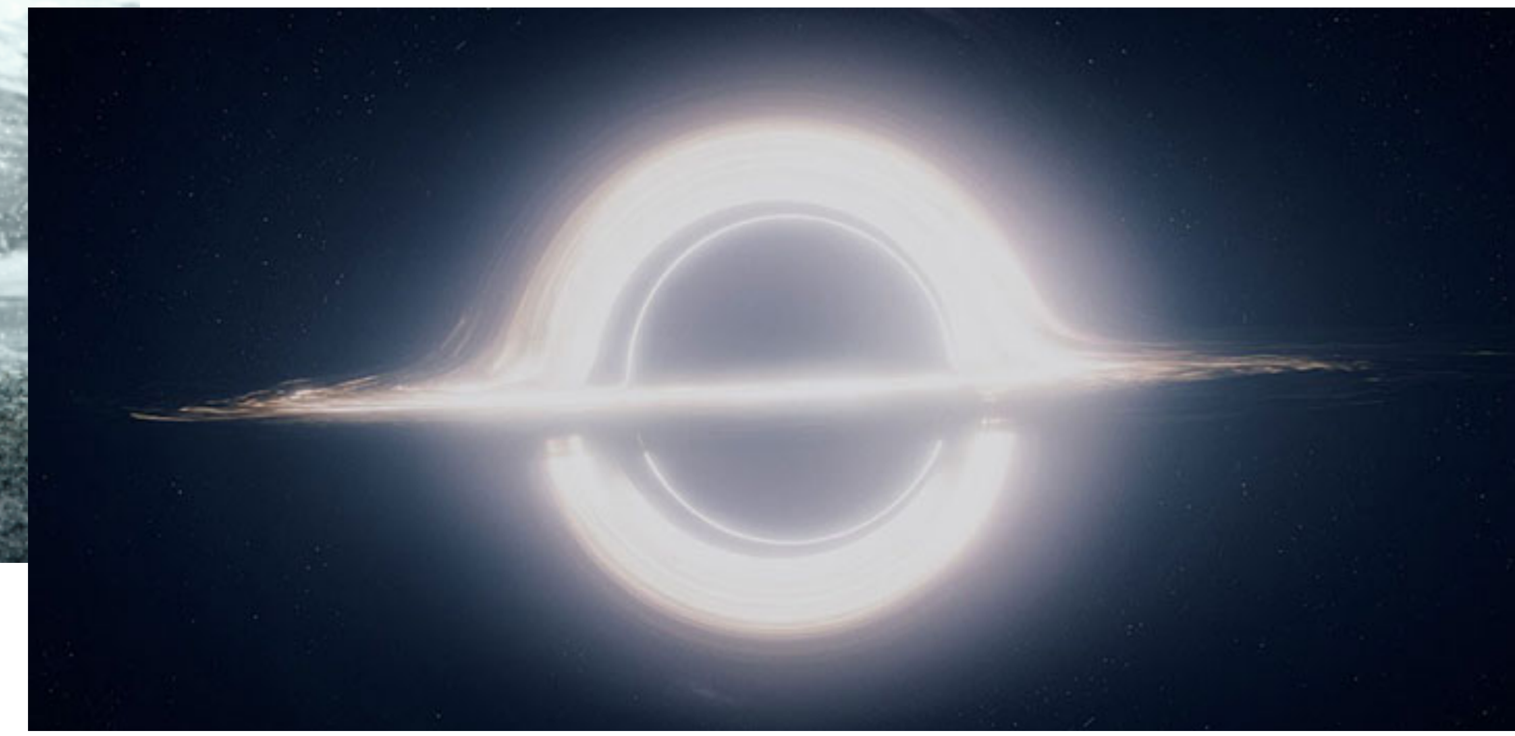
Interstellar

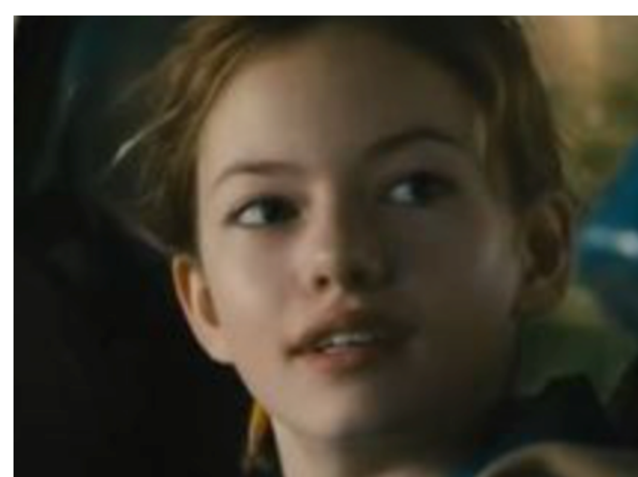
Kip Thorne

science @ 3 levels:

1. real
2. plausible
3. speculation

Gargantua





Murph

`some more`

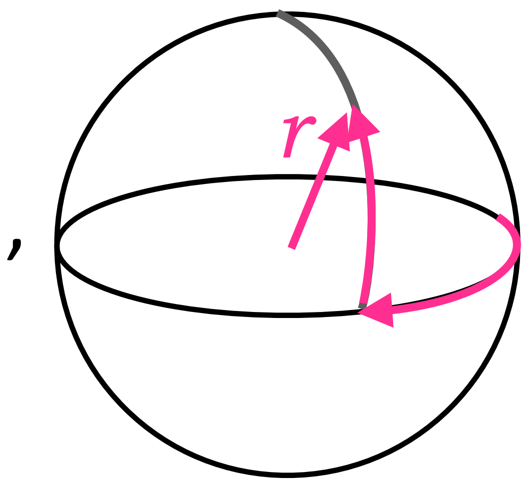
“what if this is bigger than that” whiteboard exercises

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"

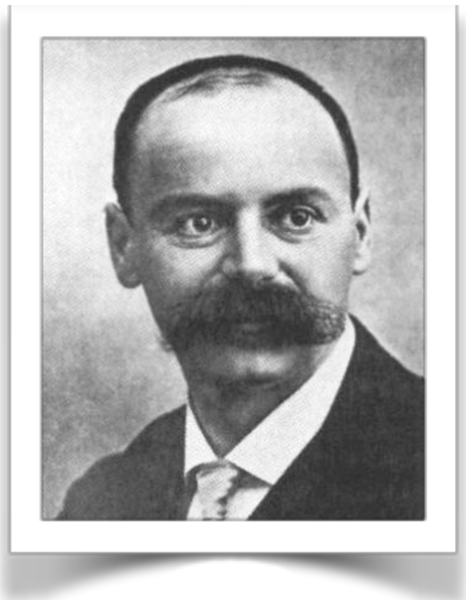
$$g_{00} = 1 \quad g_{11} = -1$$

"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 Schwarzschild

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

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

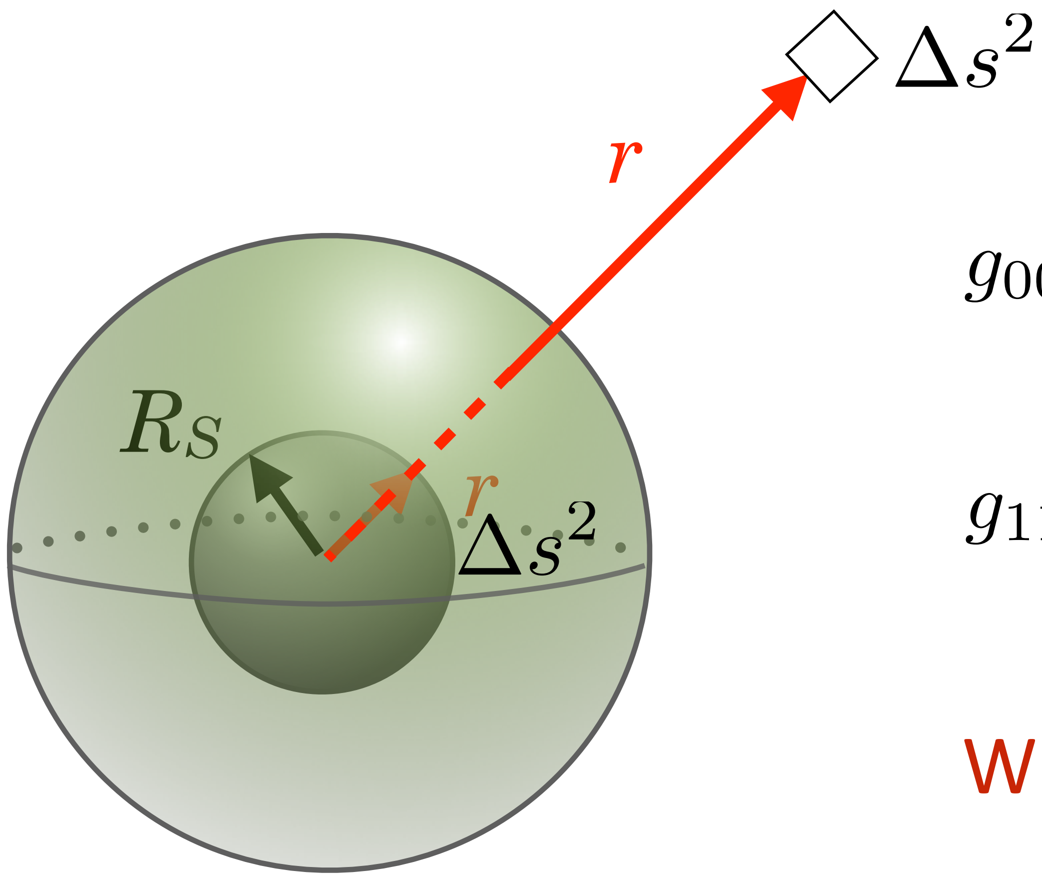
$$g_{00} = 1 - \frac{R_S}{r}$$

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

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 Schwarzschild solution...is in part solving for the g's. $R_S = \dfrac{2GM}{c^2}$



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

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

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

$$g_{00} = 1, \quad g_{11} = -1$$ ✓

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

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 $r < R_S$?

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

so

the event horizon is the boundary between sorta normal

and totally bizarre

Miniature Black Holes

center of some theoretical physicists' imaginations

There are a handful of “classic tests”

of these ideas:

that space and time [obscured] gravitation

- Pound Rebka Gravitational Red Shift
- The perihelion of Mercury’s Orbit
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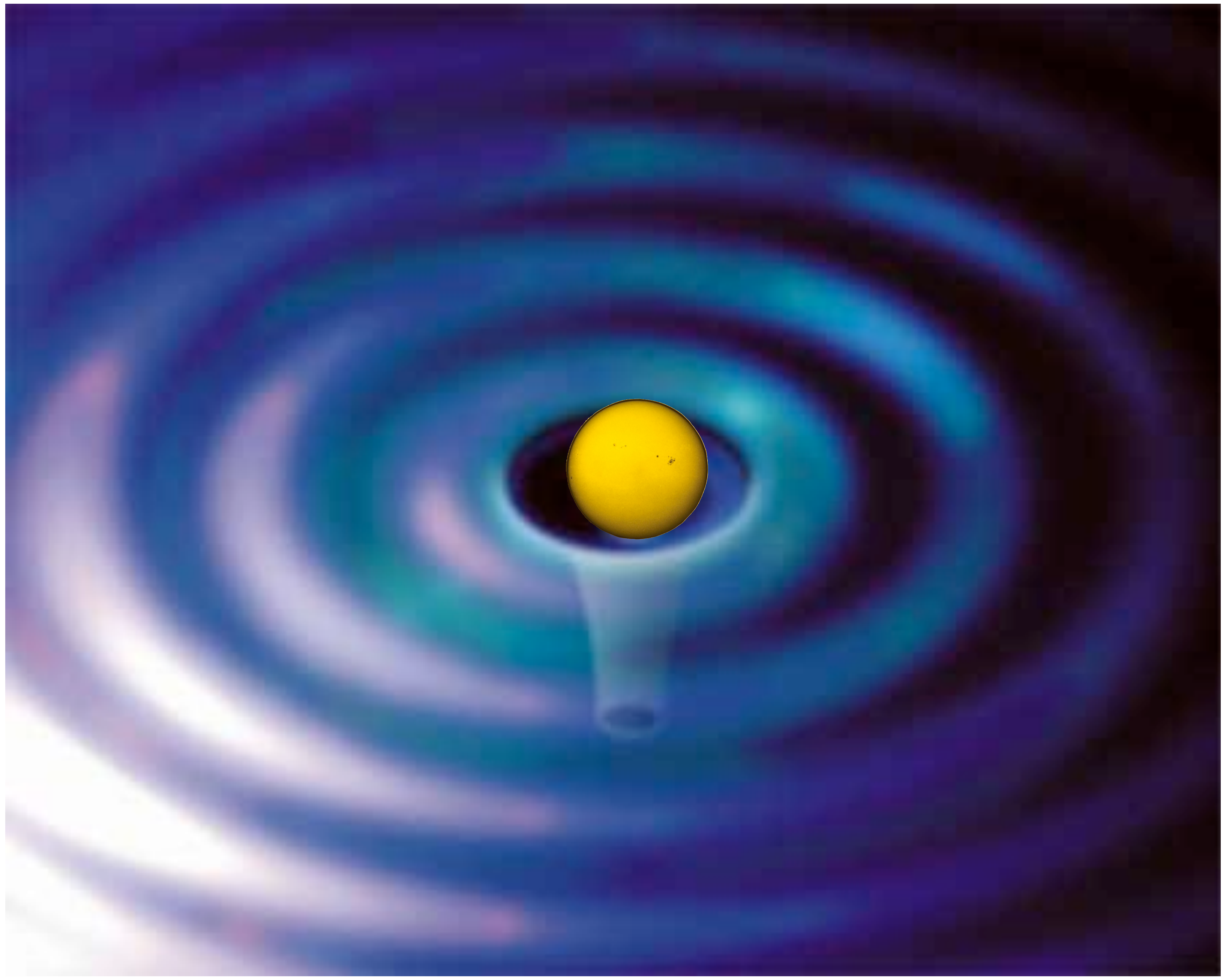
- “Binary Pulsar period”
- Black Holes
- “Gravitational Waves”

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

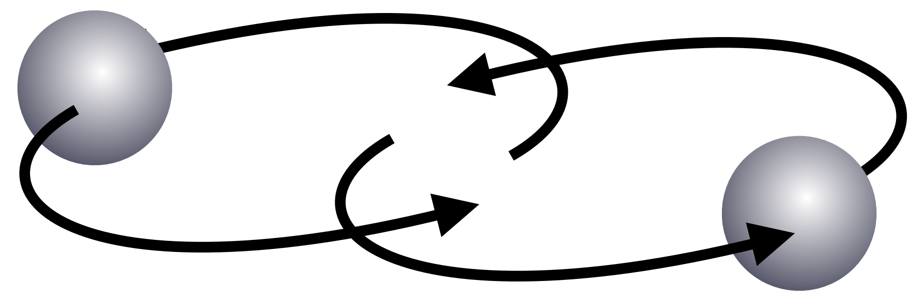
1993

Joseph H. Taylor Jr.

Russell A. Hulse

A binary star system...of neutron stars

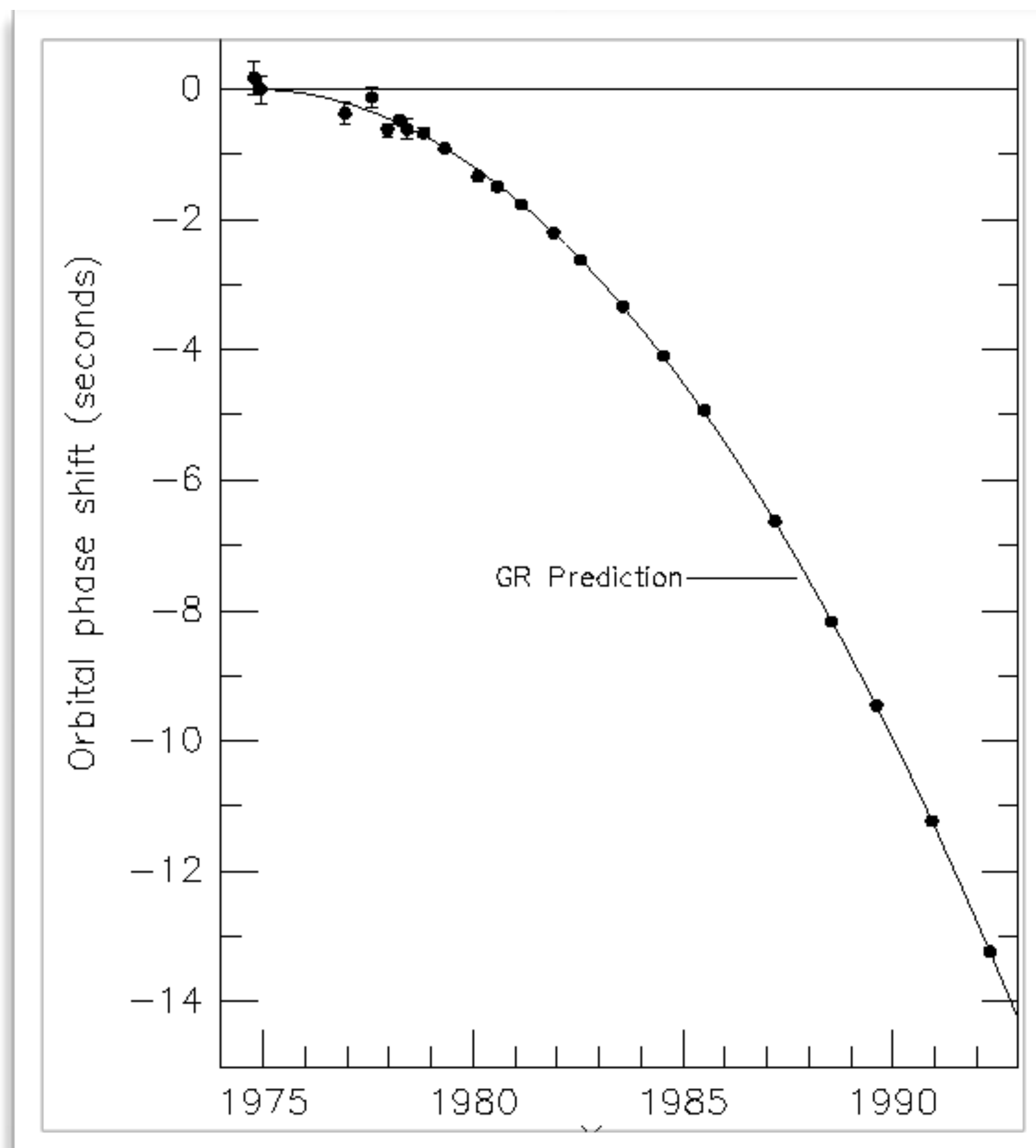
they are accelerating and so radiate gravitational waves



PSR1913+16 discovered 1974

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

and its period is reduced by 67 ns each orbit

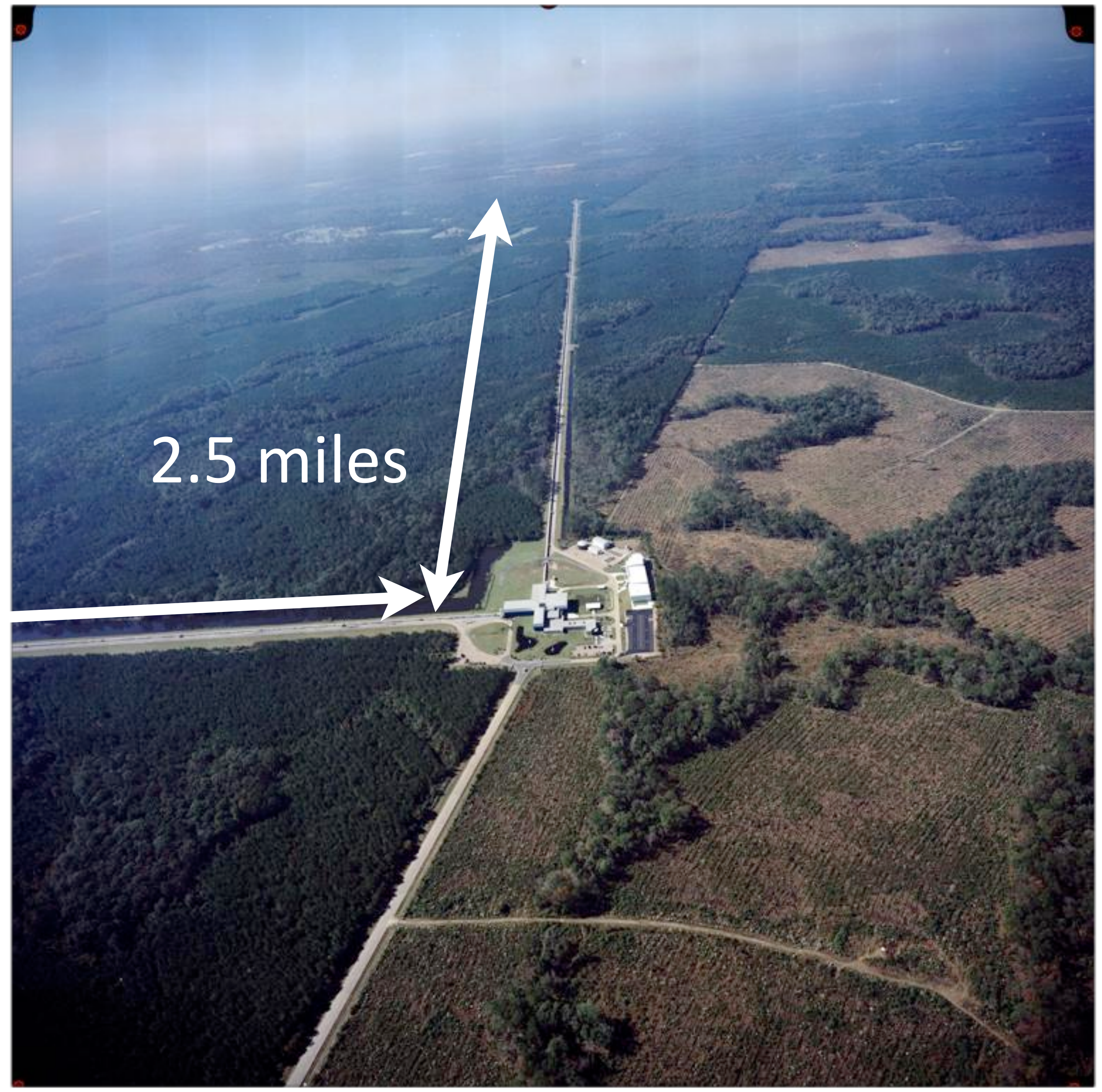


Pulsars discovered earlier and awarded the 1974 Nobel Prize to Martin Ryle and Antony Hewish (and not Jocelyn Bell...) in 1968

LIGO

Laser Interferometer Gravitational-Wave Observatory

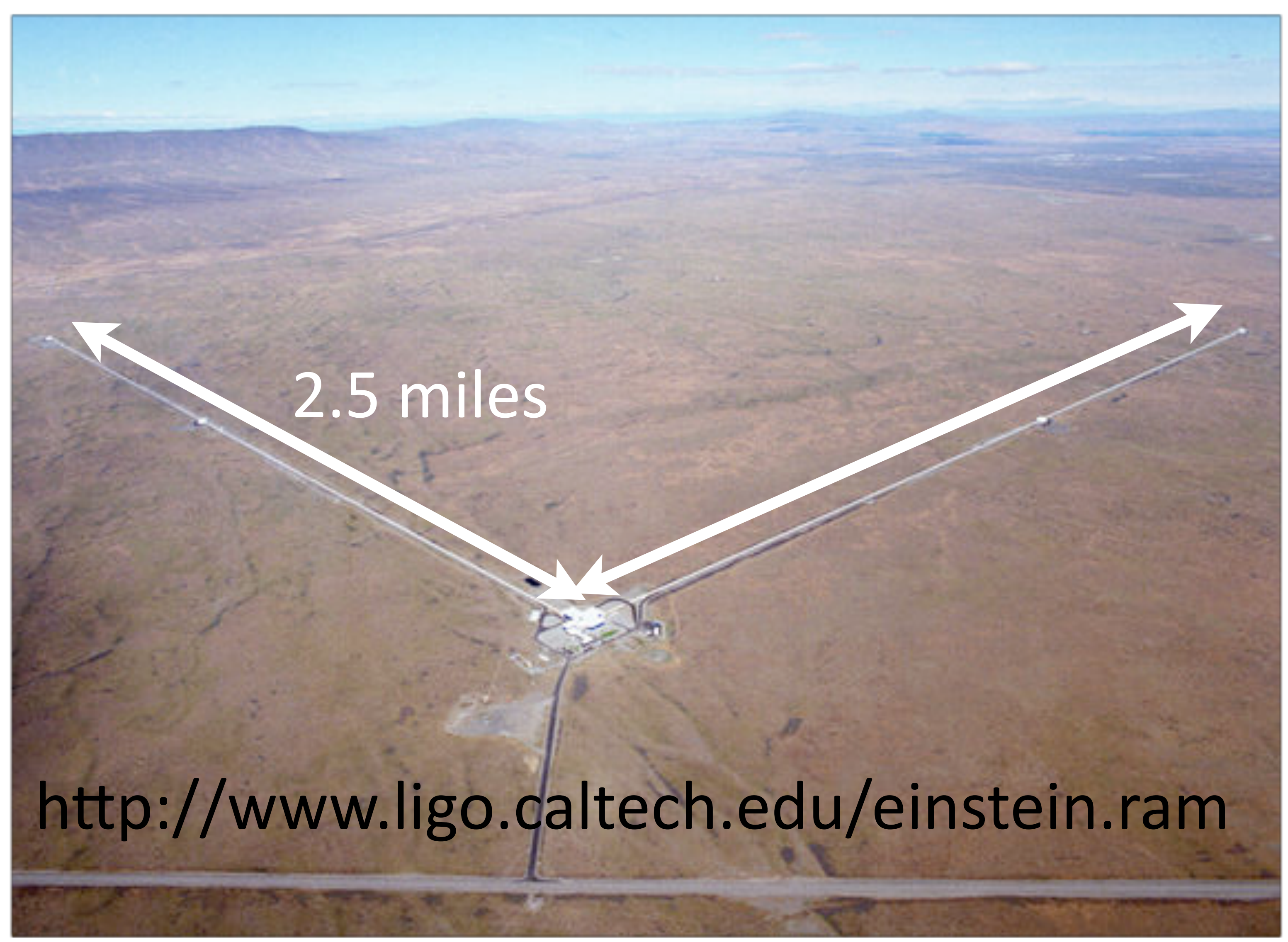
intergalactic, colliding binary, neutron stars, gamma ray bursts, black holes, colliding galaxies,



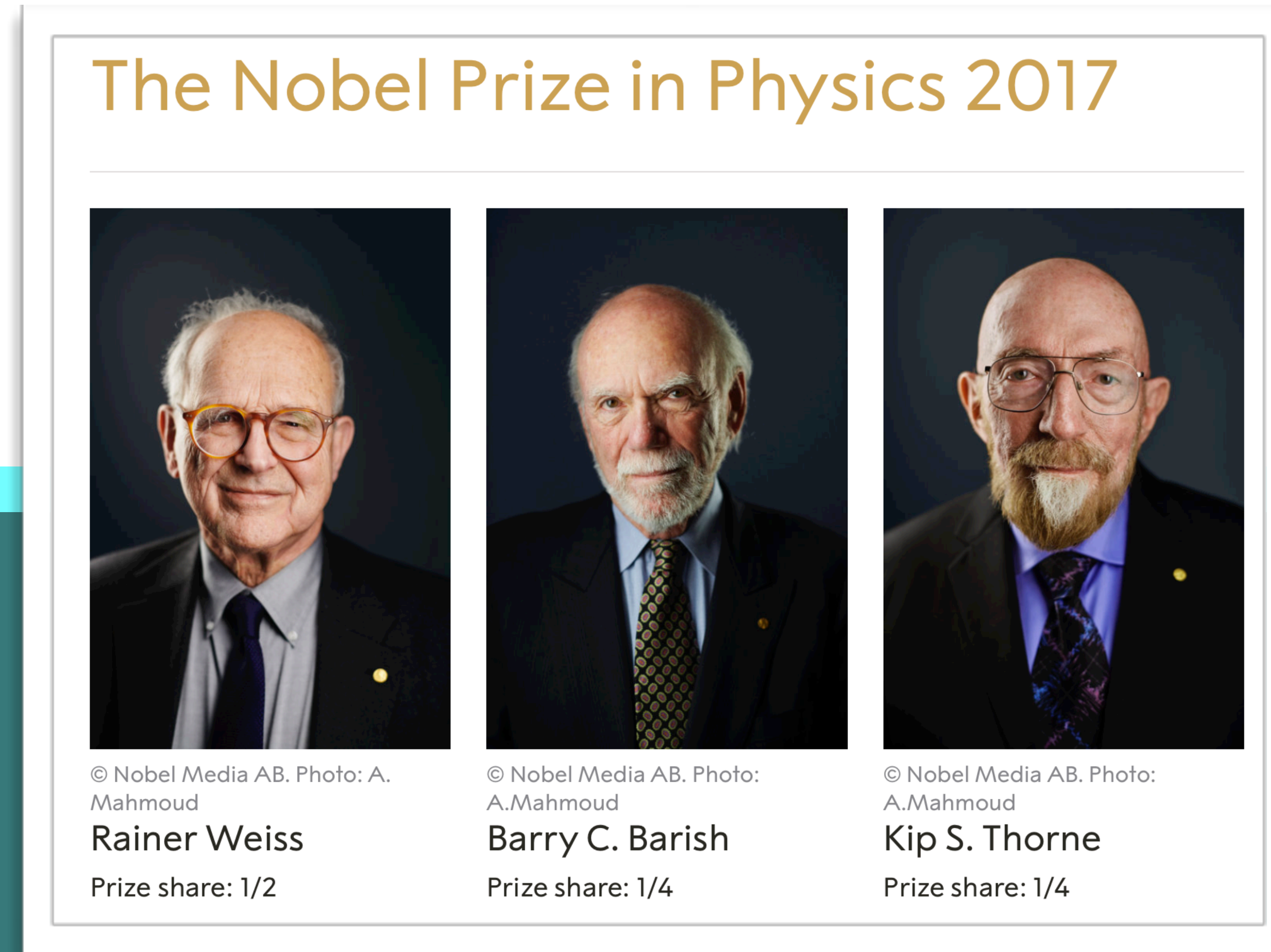
looking for shrinkage of one arm when gravitational wave passes by

need precision smaller than a proton radius

Livingston, LA



Hanford, WA



laboratory: **LIGO**

location: Lawrence, LA & Hanford, WA

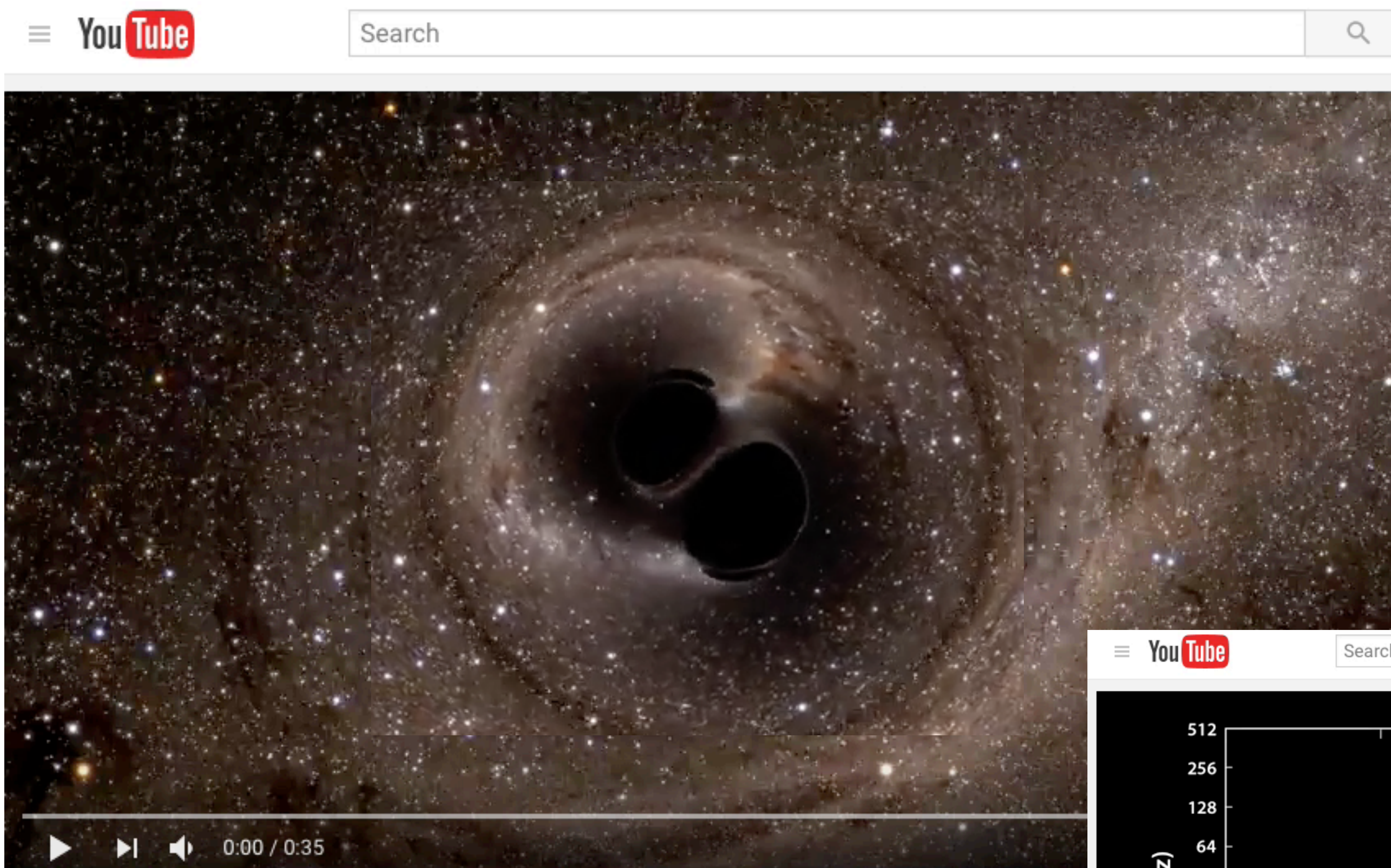
established: 1999

notable directors: Barry Barish, now Jay Marx

type of lab: Laser interferometer for measuring gravitational waves

what's going on

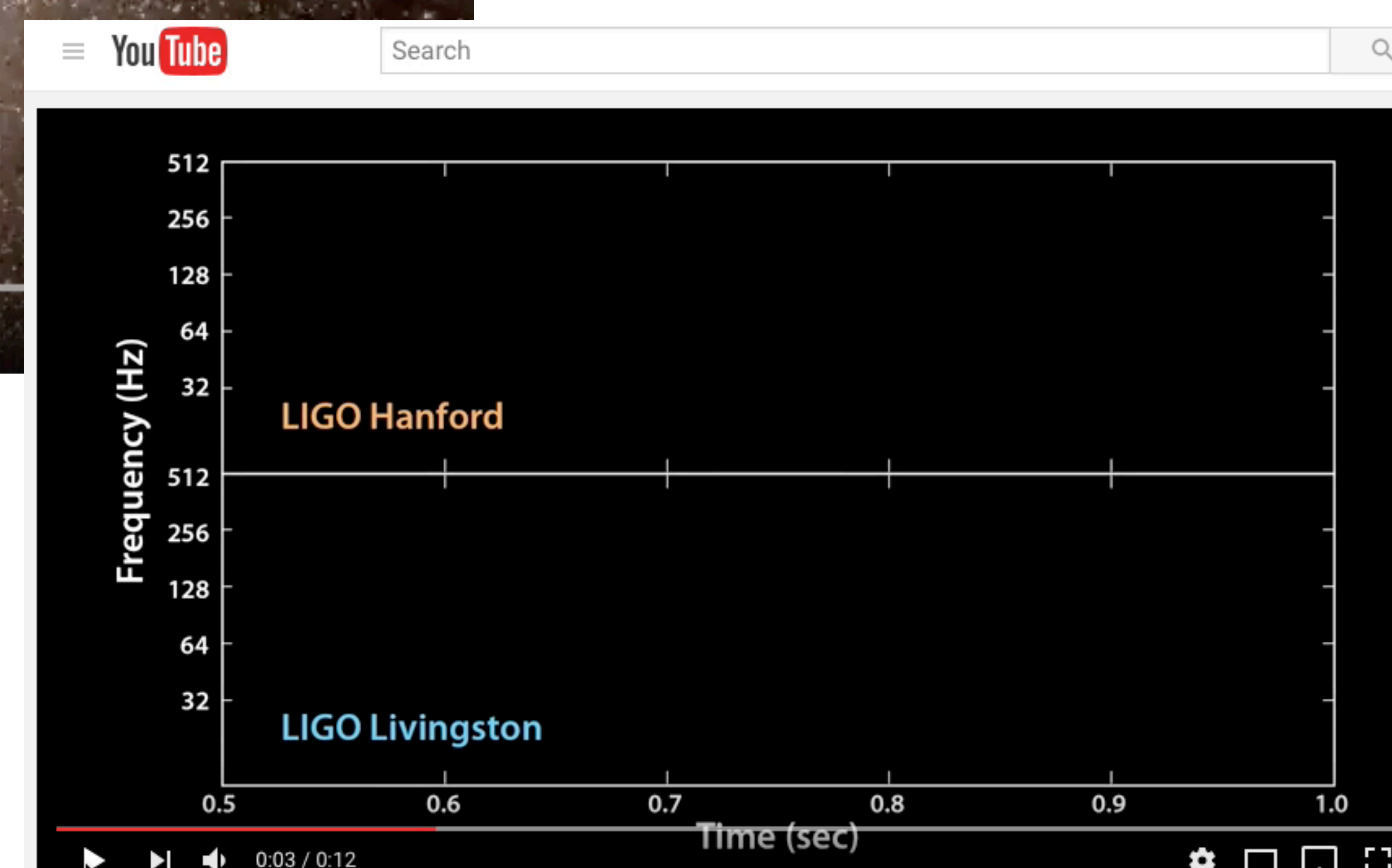
GW150914: merging black holes



September 14, 2015 at 09:50:45 GMT

36 Msun + 29 Msun → 62 Msun

3 Msun's worth of E_m released and radiated



There are a handful of "classic tests"

- Pound Rebka Gravitational Red Shift
- The perihelion of Mercury's Orbit
- Light bending around the Sun
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- "Binary Pulsar period"
- Black Holes
- "Gravitational Waves"

in 1915 scientific cosmology didn’t exist

does now.

in 1917 the universe presumed by all to be:

- static, eternal
- limited to the Milky Way

that's it.

cozy.

how big?

a battle in 1920, the **"Great Debate"**

April 26, 1920, in the hall of the National Academy of Sciences in Washington D.C

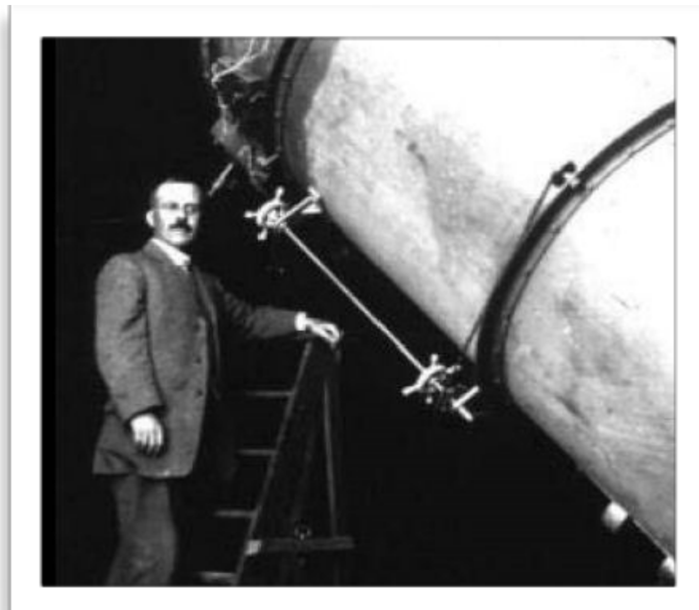
Heber Curtis (Muskegon) and Harlow Shapley

Shapley: The Milky Way is 300,000 ly across and contains all of the visible nebulae

```
When we accept that the distance of the
Hercules cluster is such that its stellar
phenomena are all harmonious with local
stellar phenomena, then it follows
that...the diameter of the whole system
of globular clusters is about 300,000
light-years. Since the affiliation of the
globular clusters with the Galaxy is
shown...it also follows that the galactic
system of stars is as large as this
subordinate part...There seems to be good
reason, therefore, to believe that the
star-populated regions of the galactic
system extend at least as far as the
globular clusters.
```

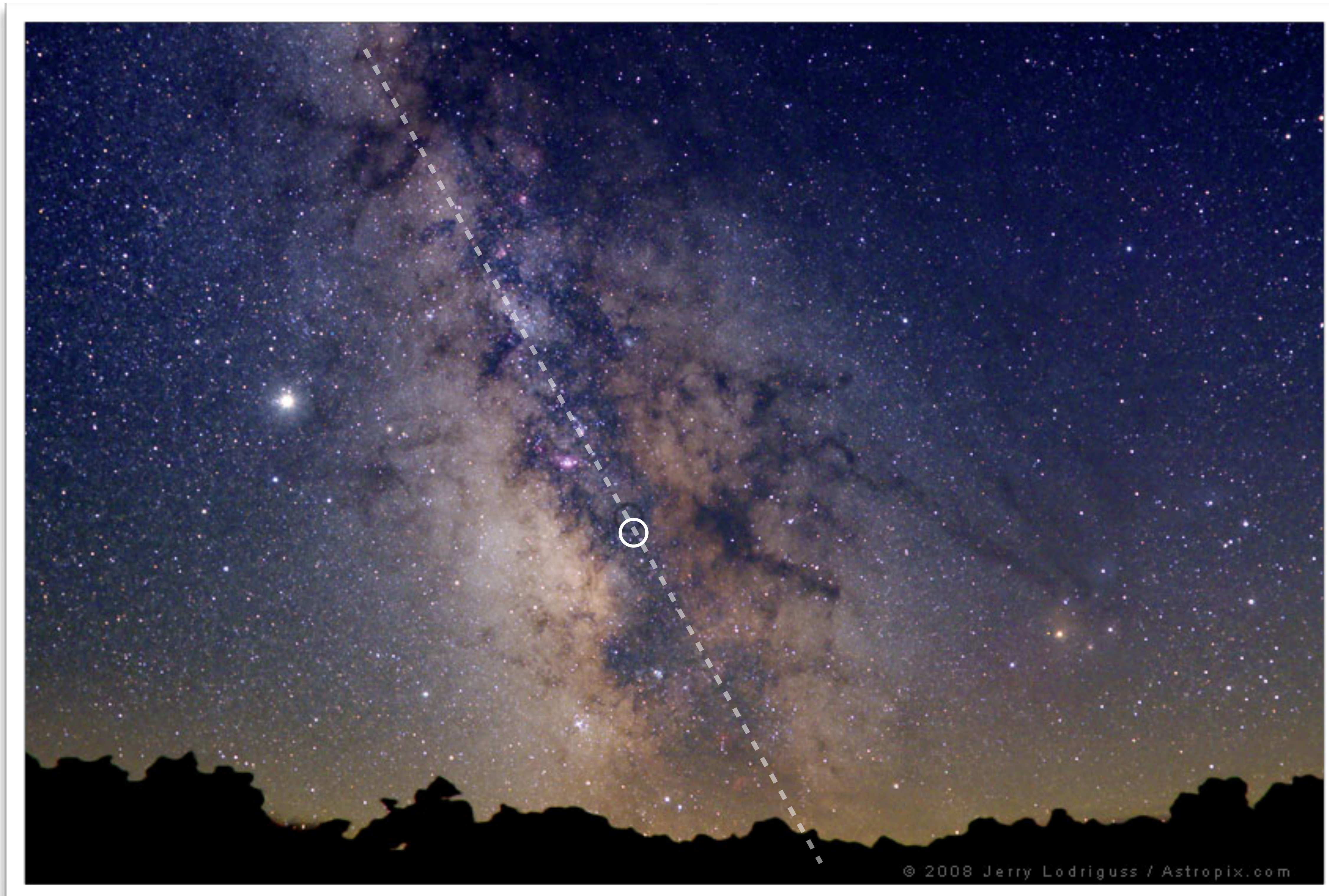
Curtis: "Island Universe Model"...that the fuzzy nebulae were external galaxies... "island universes"

```
I hold, therefore, to the belief that the
galaxy is probably not more than 30,000
light-years in diameter; that the spirals
are not intra-galactic objects but island
universes, like our own galaxy, and that
the spirals, as external galaxies,
indicate to us a greater universe into
which we may penetrate to distances of ten
million to a hundred million light-years.
```



Decision: Shapley... until 1929 when Hubble showed that Curtis was right.

home



supermassive black hole in Sagittarius... Sagittarius A

Digital Astrophotography by Jerry Lodriguss

http://www.astropix.com/HTML/SHOW_DIG/Milky_Way_Cherry_Springs.HTM

Einstein

began the first truly scientific field of cosmology

applying GR (1915) to the entire universe

1917: *Cosmological Considerations in the General Theory of Relativity*

"It exposes me to the danger of being confined to a madhouse."

need a starting point & assumptions

in order to be able to solve the GR equations

Einstein enunciated the “Cosmological Principle”

On the largest scale:

the universe is homogeneous

the average density of matter is about the same and uniform at all places in the Universe: there are no special places

the universe is isotropic

the universe looks the same to all observers: there are no special directions

quantitative cosmology

rests on the Cosmological Principle

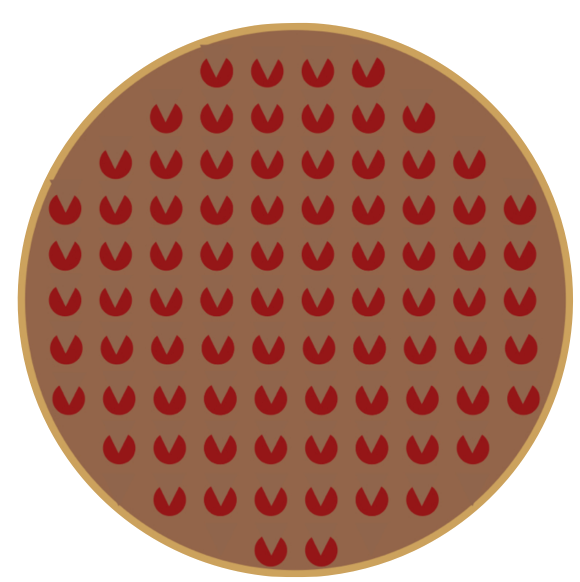
It doesn’t matter where you are.

Viewed on sufficiently large distance scales, there are no preferred directions nor are there preferred places in the Universe.

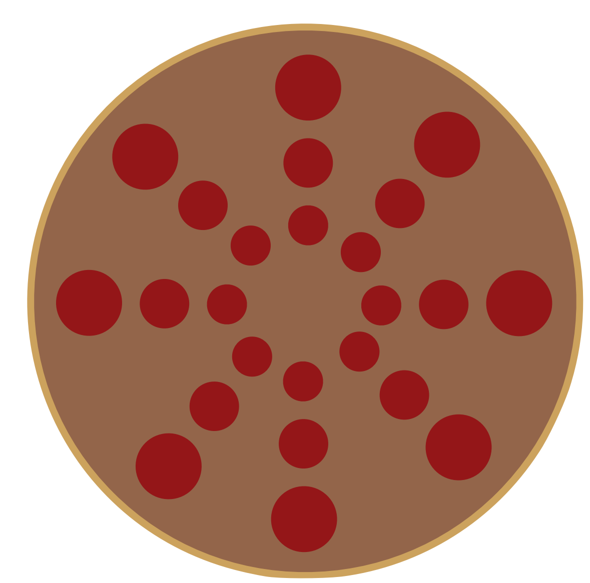
The Universe is presumed to be
homogeneous: average density same & uniform everywhere
and
isotropic: no special directions

my Famous
Probable Planar Pepperoni Pizza Probe

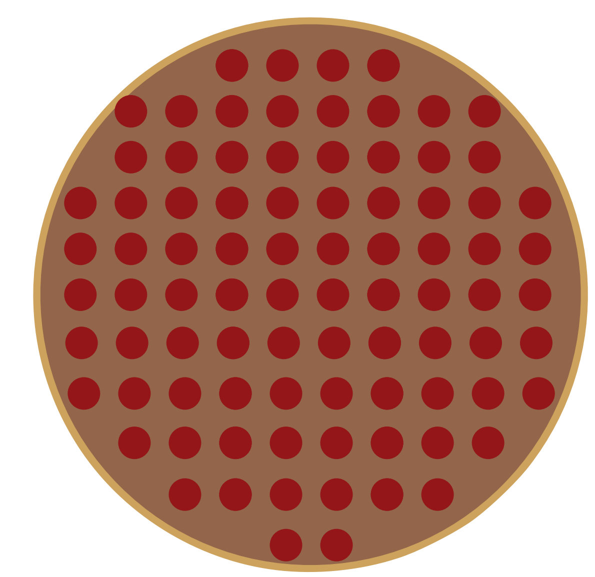
…as viewed from the center:



not isotropic and yet homogeneous



not homogeneous and yet isotropic



homogeneous and isotropic

homogenous?

the only way to calculate!

smear all of the stars (nebulae out) into a dust, or fluid

density, not individual masses, is the meaningful quantity

How good is that approximation?

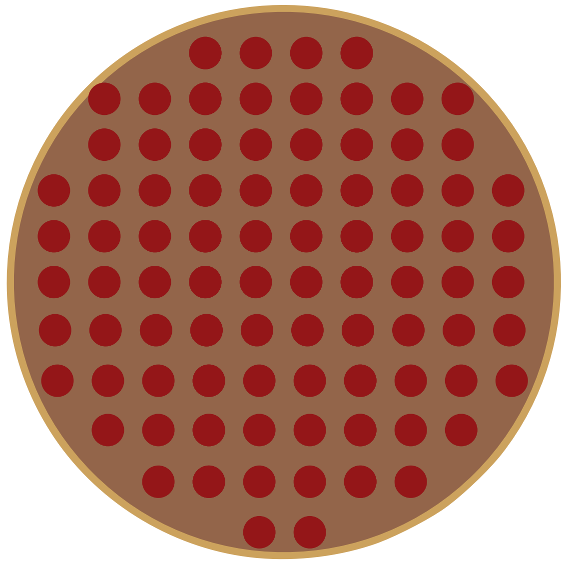
The current density of matter in the universe is about 6 protons/m^3

Oh
that reminds me

Did I mention Pizza?

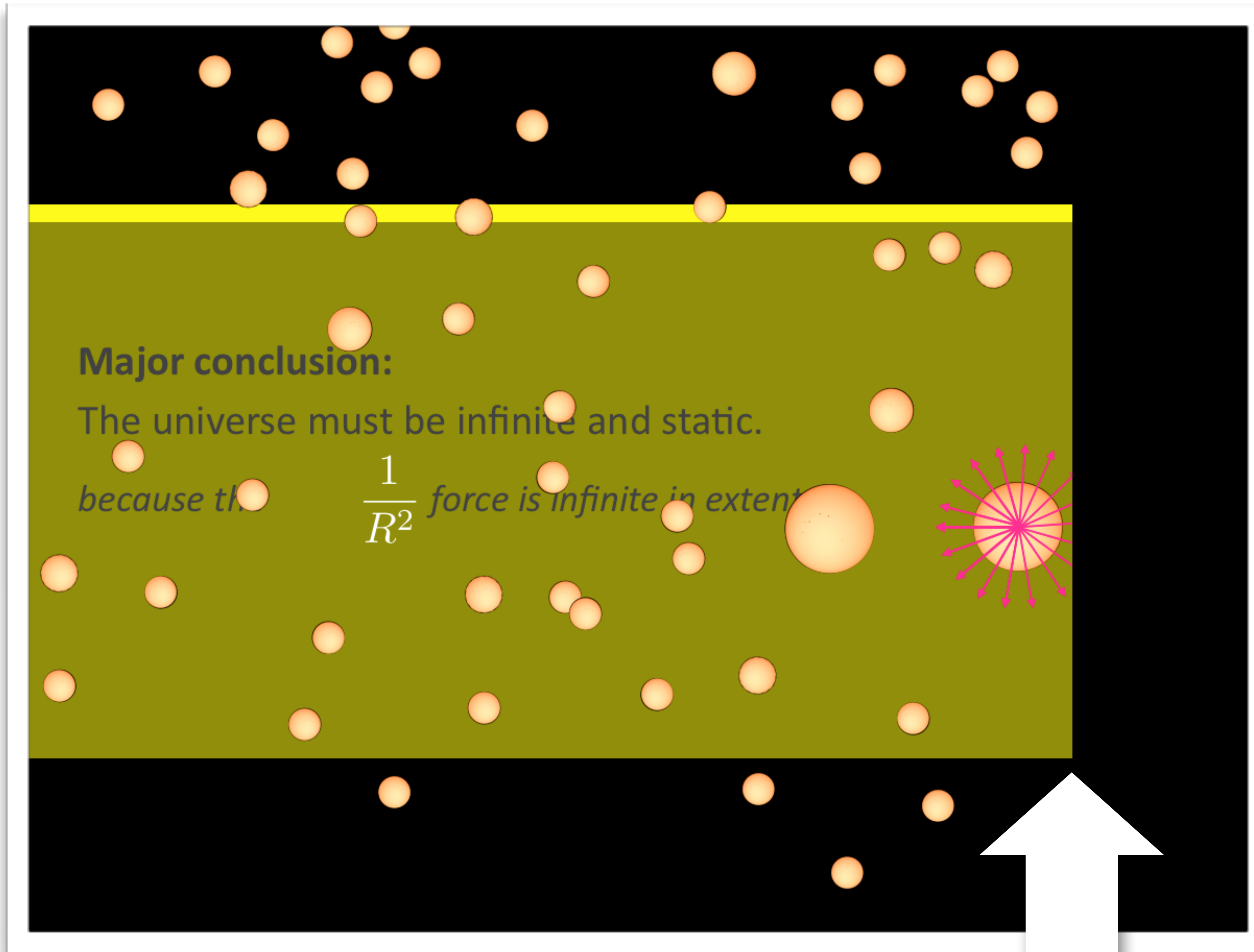
- with roughly 7 of you…
- 2 cheese and 2 pepperoni?

You get drinks from Sparty's



He was plagued by infinity

He ran into a similar problem that Newton did...



an edge to the universe was Newton's worry

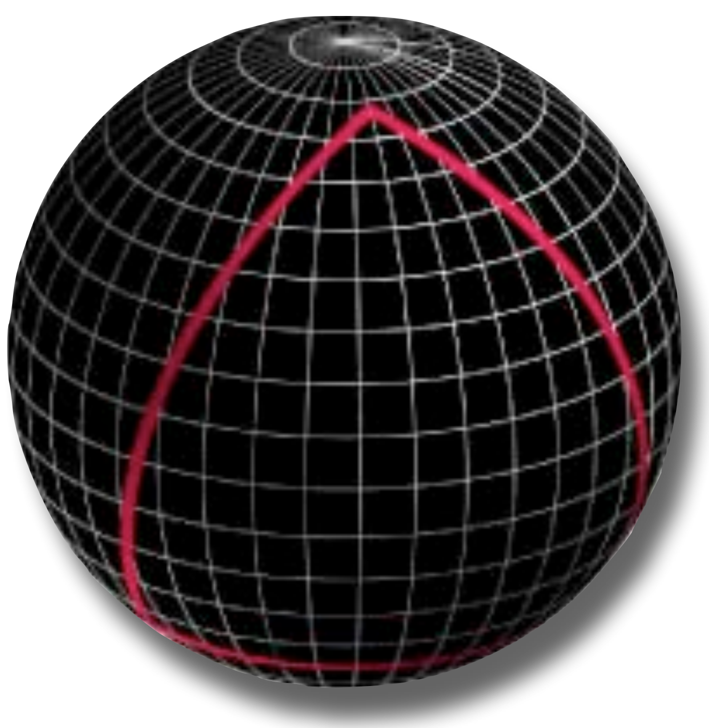
The weird delicate balance of an infinite universe...with an infinite gravitational force on all objects

strangely in balance!

But he was smarter than Newton

And he owned a tool to erase infinity!

Make use of his geometric-tool and assume enough mass in the whole Universe ***to cause space to bend around on itself...***



That was his goal: to get rid of infinity

oh...and by the way...

make sure that the universe is... **S T A T I C** ...unmoving

a prejudice that he was fanatical about

this would be a strange universe!

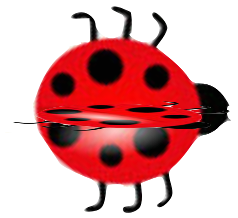
suppose you could start out in a spaceship

always keeping your starting spot behind you

you could then return to where you started!

hypervolumes: multidimensional geometry

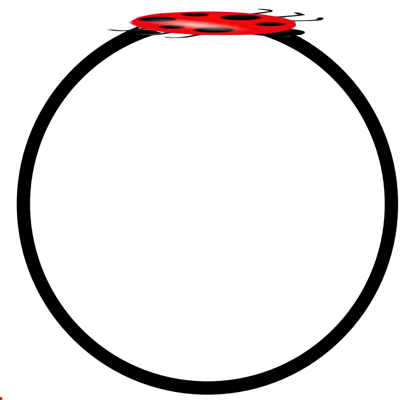
Suppose you're a 1 dimensional being.



your world is a **line**

it could be infinite...

it could be finite...



It's not a very exciting existence

Notice something: this is a

1 dimensional world

embedded in – expand your mind now – a *2 dimensional plane - which is where the curvature is.*

<u>Outside</u> of the "view" of the bug.

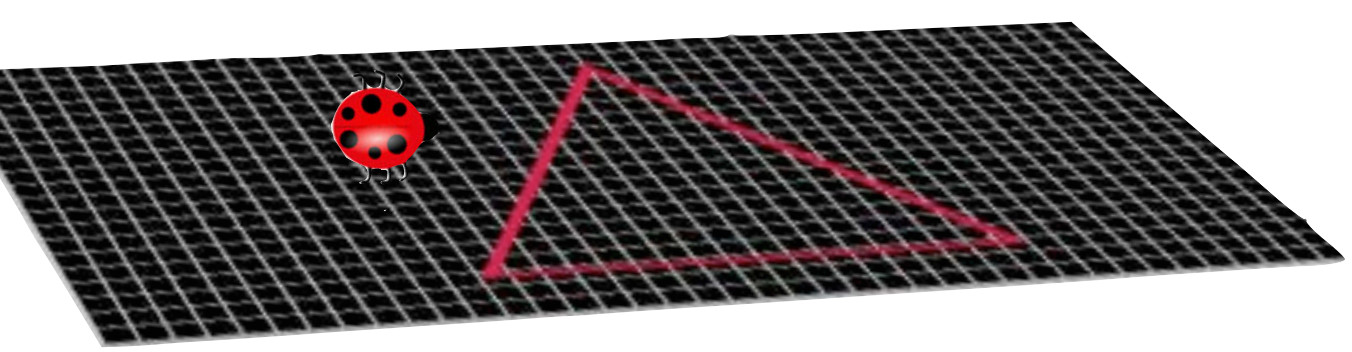
Bug only knows forward and backward...

"left," "right," "up," "down" have no meaning.

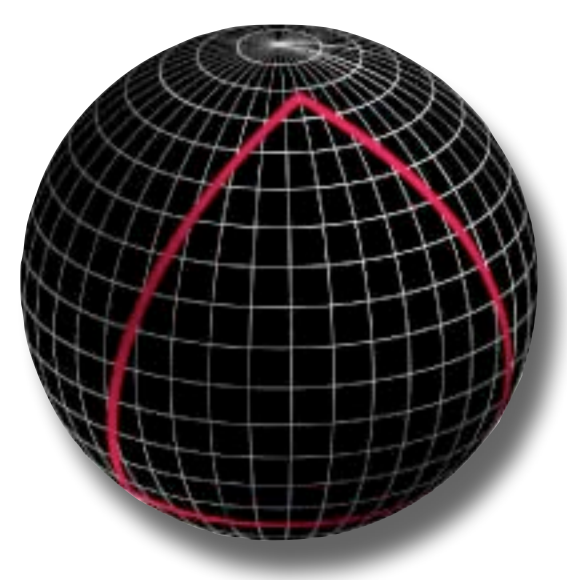
Suppose you're a 2 dimensional being.

your world is a **surface**

it could be infinite...



it could be finite...



It's a little more exciting

Notice something: this is a

2 dimensional surface

embedded in a

3 dimensional volume -

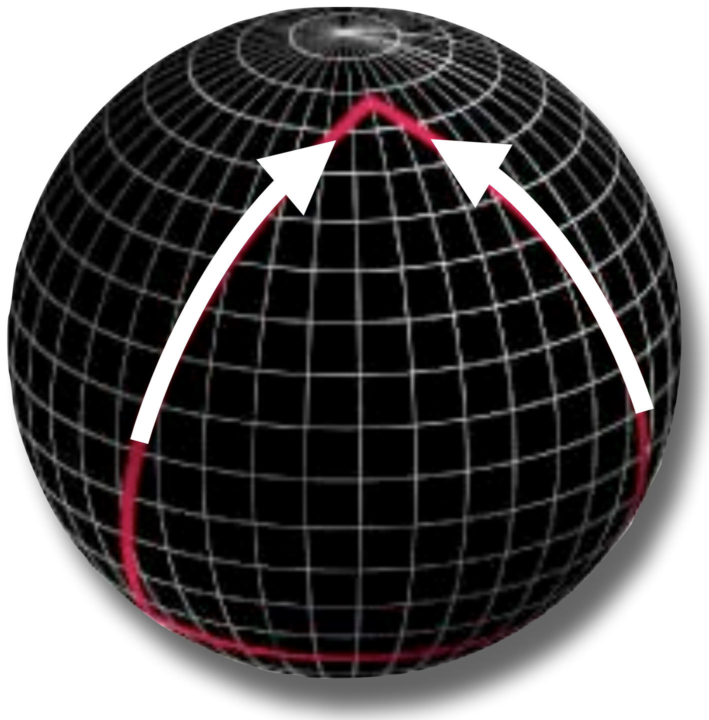
which is where the curvature is...

again, outside of the bug's world

Bug only knows left and right...

"up" and "down" have no meaning.

“curvature”



Einstein’s space was a

3 dimensional surface **embedded** in a 4 dimensional spacetime hypervolume

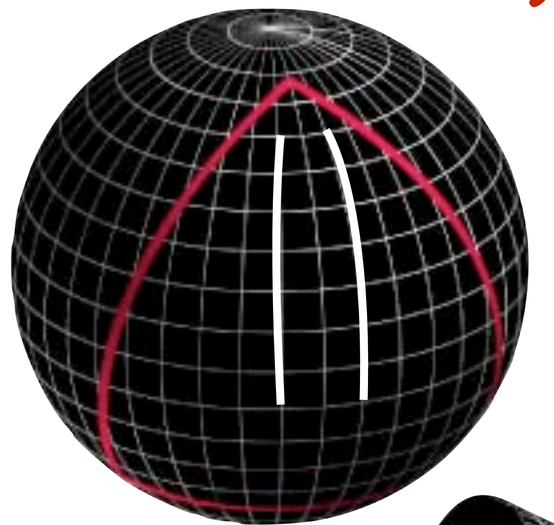
We know up, down, front, back, left, right...but have no knowledge of that 4th spatial embedding dimension - *which is where the curvature is*

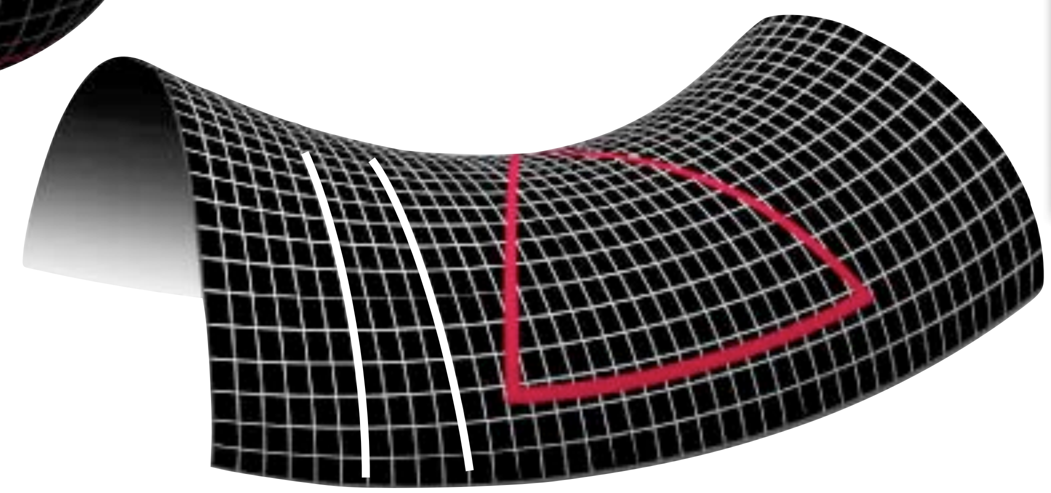
How could you know whether you live in flat space or a curved space?

Start truckin’

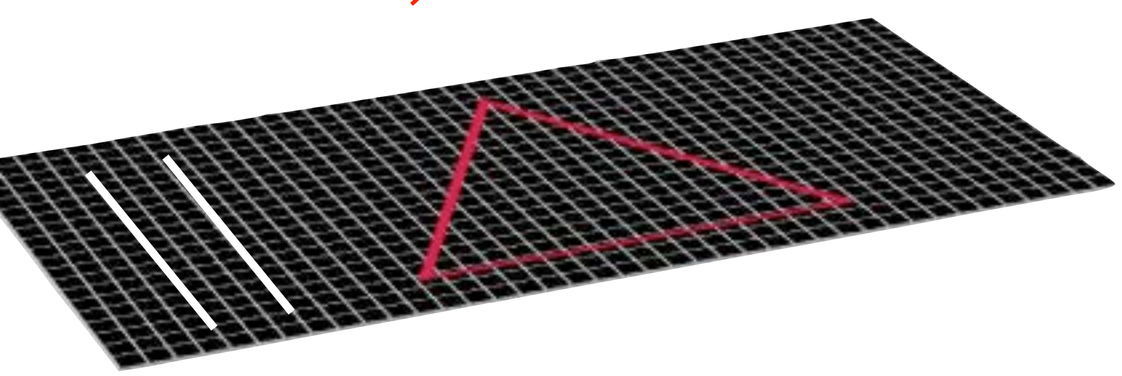
curvature, "k" - hypervolumes

$k = +1$, positive curvature
finite, unbounded





$k = 0$, no curvature
infinite, unbounded



$k = -1$, negative curvature
infinite, unbounded

is impossible to visualize the negative curvature 3d shape...
it's like a saddle, or mmm mmm good
Pringles Potato HyperChips

A mathematical fact:
These 3 are the only geometries that can be both homogeneous and isotropic

you can't always get what you want

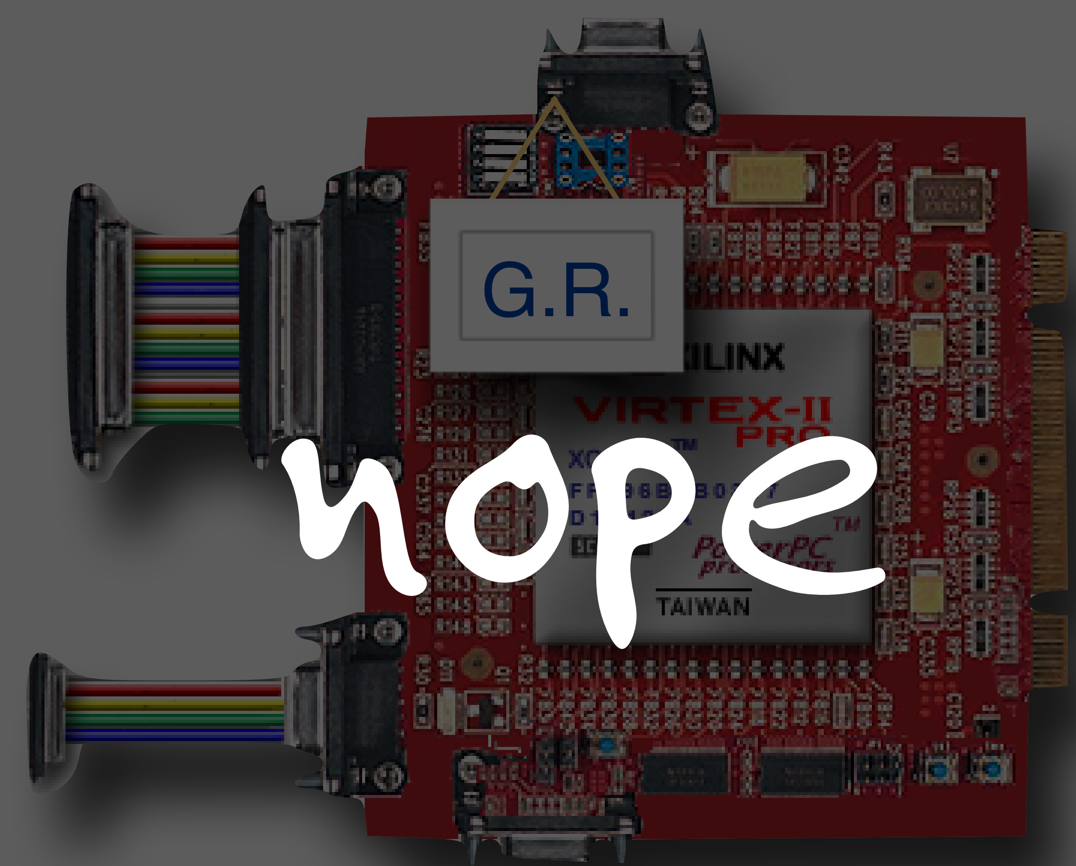
but if you try some time, you might just find you get what you need

or not.

Here's what happened...very schematically, okay?

What Einstein wanted:

$$G = T$$



Stable.
Finite.
Boundless.

"The great charm resulting from this consideration lies in the recognition that the universe of these beings is finite and yet has no limits."

So, no problem at infinity!

you can't always get what you want

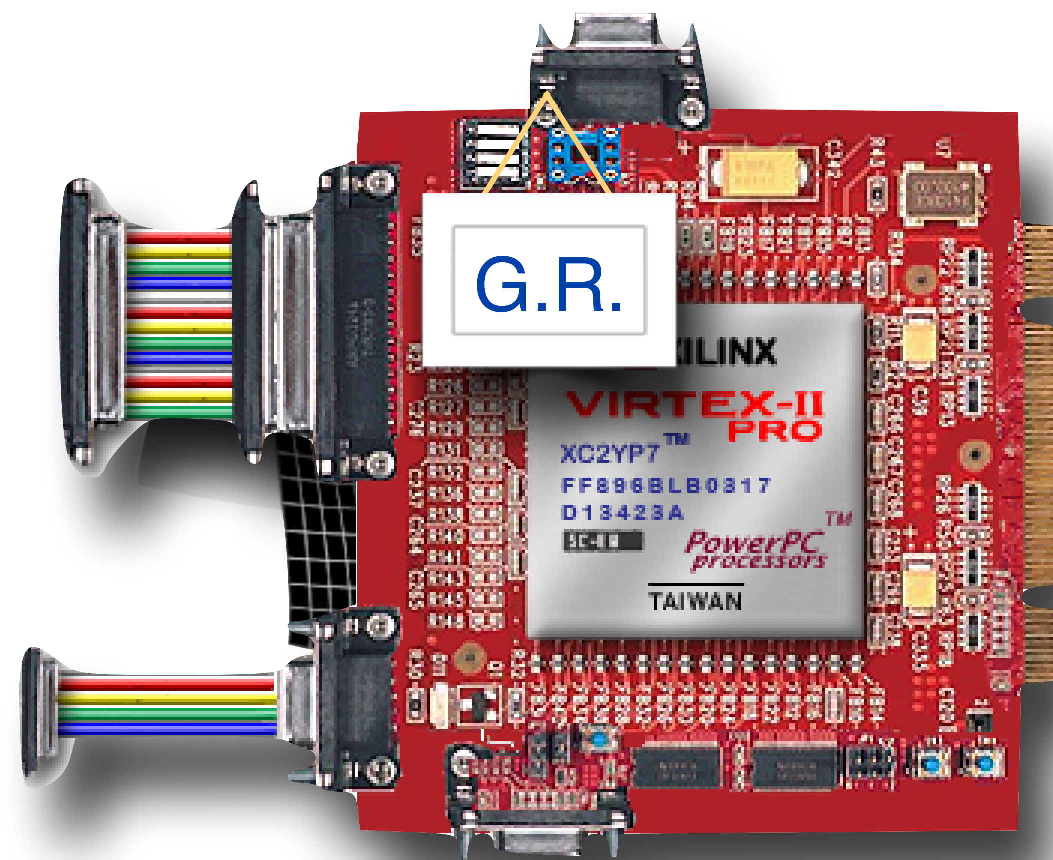
but if you try some time, you might just find you get what you need

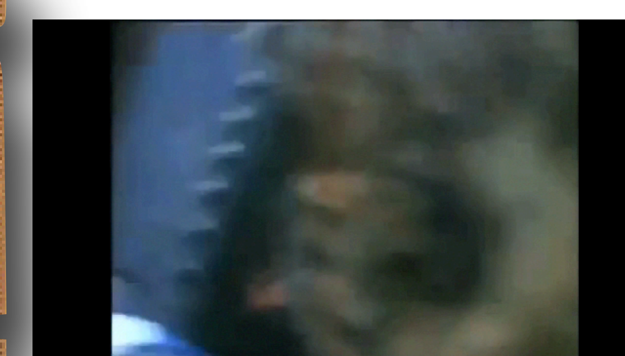
or not.

Here's what happened...very schematically, okay?

What Einstein actually got:

$$G = T$$





UNStable.
INFinite.
Boundless.

A RUNAWAY UNIVERSE!

The space in his universe would **EXPAND or CONTRACT**.

infinity is back!

uh oh

this wasn't going well

What to do? GR appeared to be right...the Classic Tests!

He mucked with his beloved equation.

the dreaded

...if it were certain that the field equations which I have hitherto employed were the only ones compatible with the postulate of general relativity, we should probably have to conclude that the theory of relativity does not admit the hypothesis of a spatially finite universe.

However, the system of equations allows a readily suggested extension which is compatible with the relativity postulate...

Cosmological Constant, Λ

geometry $G = T$ energy, pressure, mass

"...the introduction of this second member constitutes a complication of the theory, which seriously reduces its logical simplicity."

he added a **negative pressure** term...

$$G + \Lambda = T$$

the "Cosmological Constant"

a **negative pressure**-like term...that only is relevant on huge scales

Makes the Universe static...not expanding or contracting

later:

"My biggest blunder."

for 2 reasons: Hubble and instability

He believes his to be the only possible solutions

to

$$G = T$$

or

$$G + \Lambda = T$$