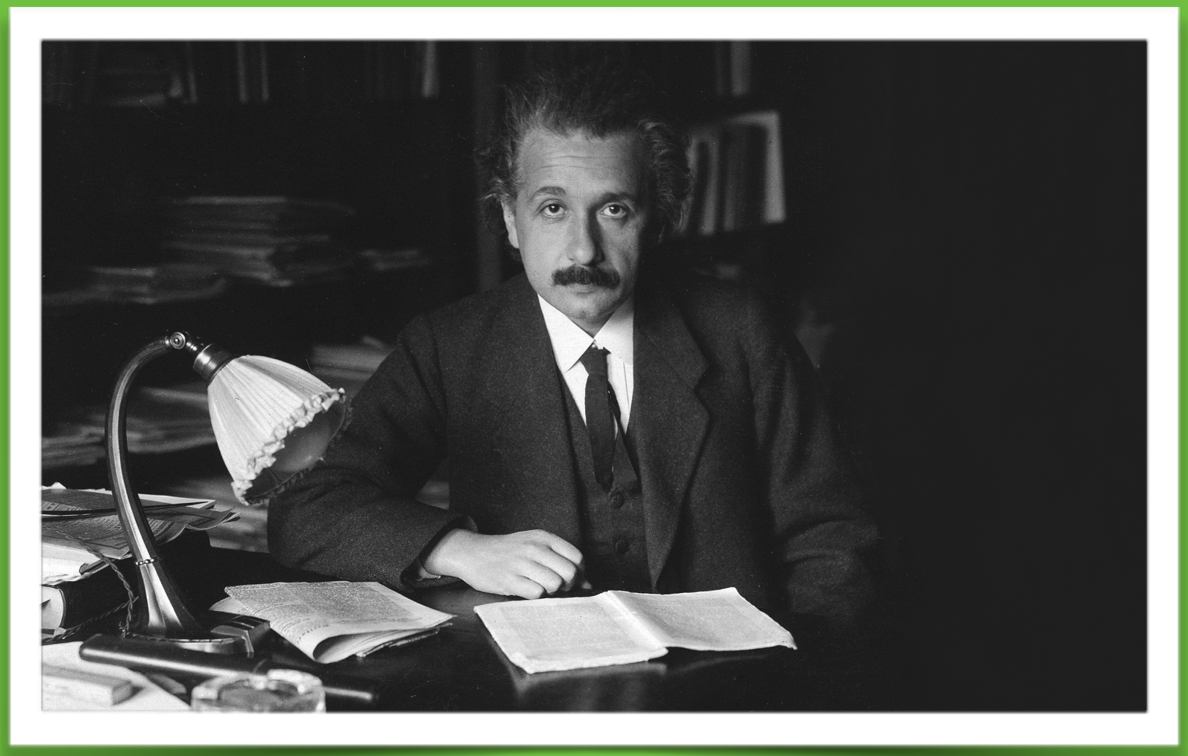
hi

Day 20, 27.03.2018

Einstein’s Theory of General Relativity, 2 & Cosmology 4



housekeeping

Gotta come to class

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

Special Relativity:

Hobson_GR.pdf is chapter 11 out of Hobson

MasteringAstronomy registration expiration now set to March 30

Homework and readings: MasteringAstronomy!

Homework #9 is part from MasteringAstronomy and part from MasteringPhysics

honors project began

https://qstbb.pa.msu.edu/storage/Homework_Projects/honors_project_2018/

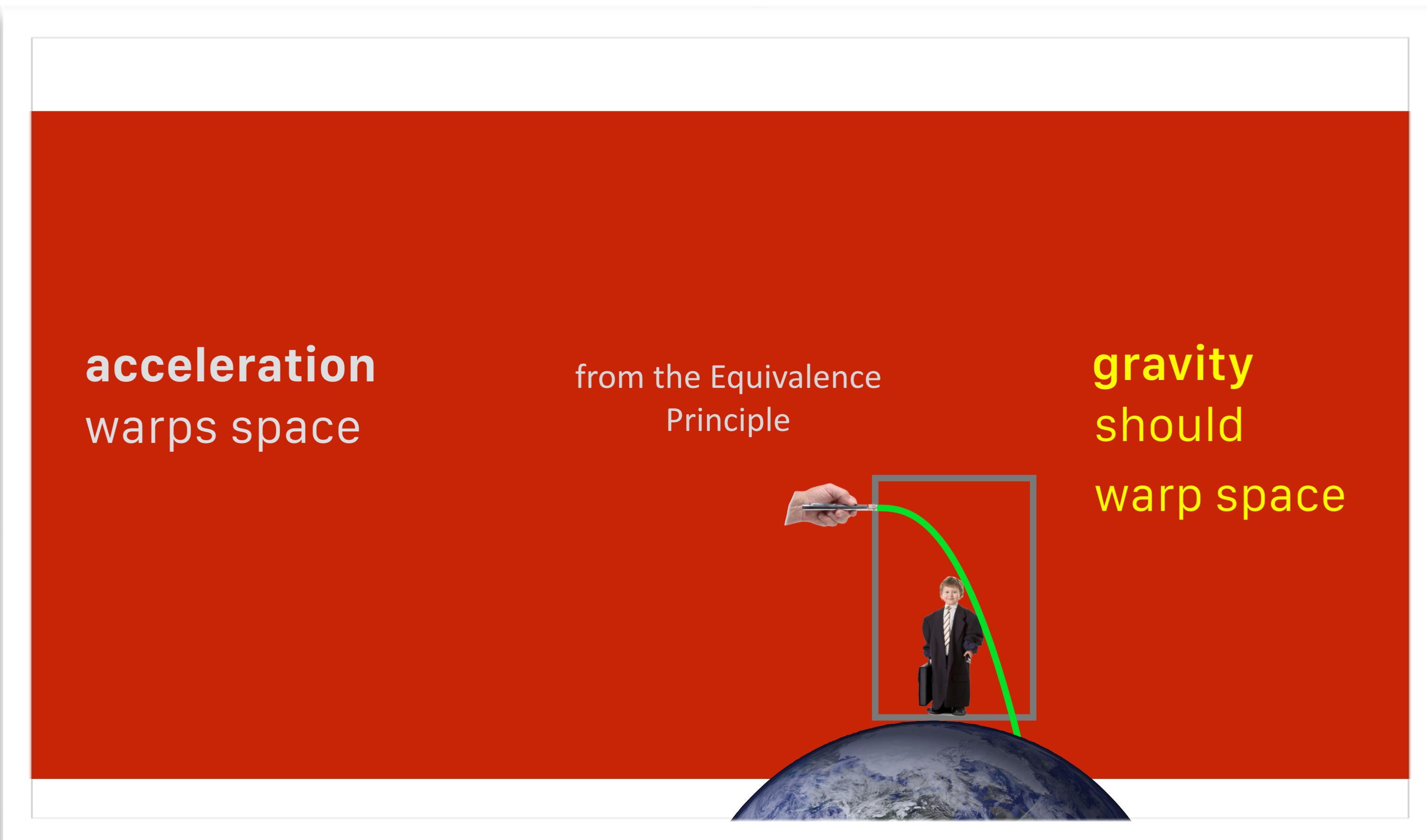
contains the first instructions: the plan & tutorial

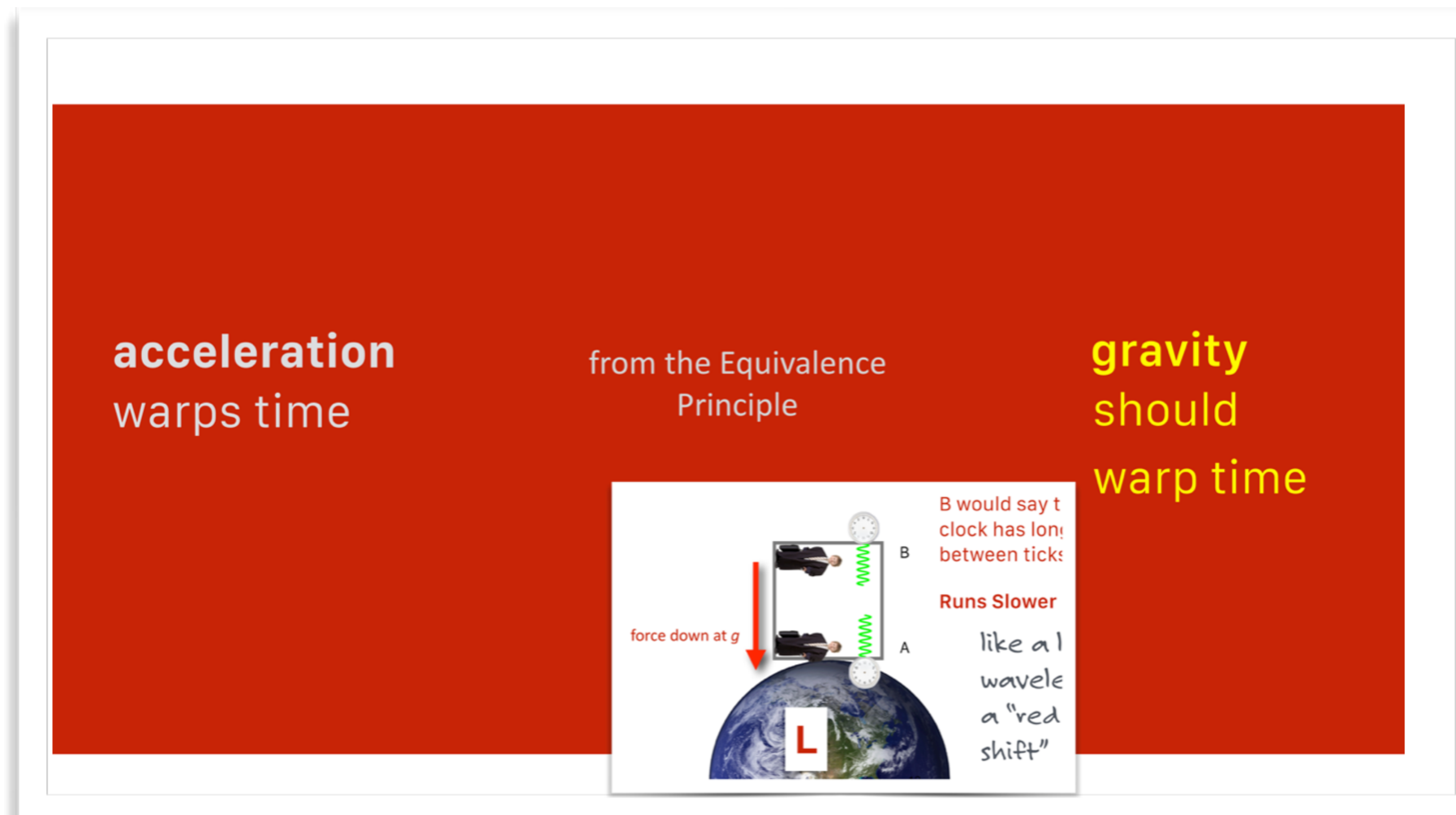
- MinervaInstructions1_2018.pdf

dates:

- complete first part, March 16
- analyze data and complete writeup, April 20

what we've found:

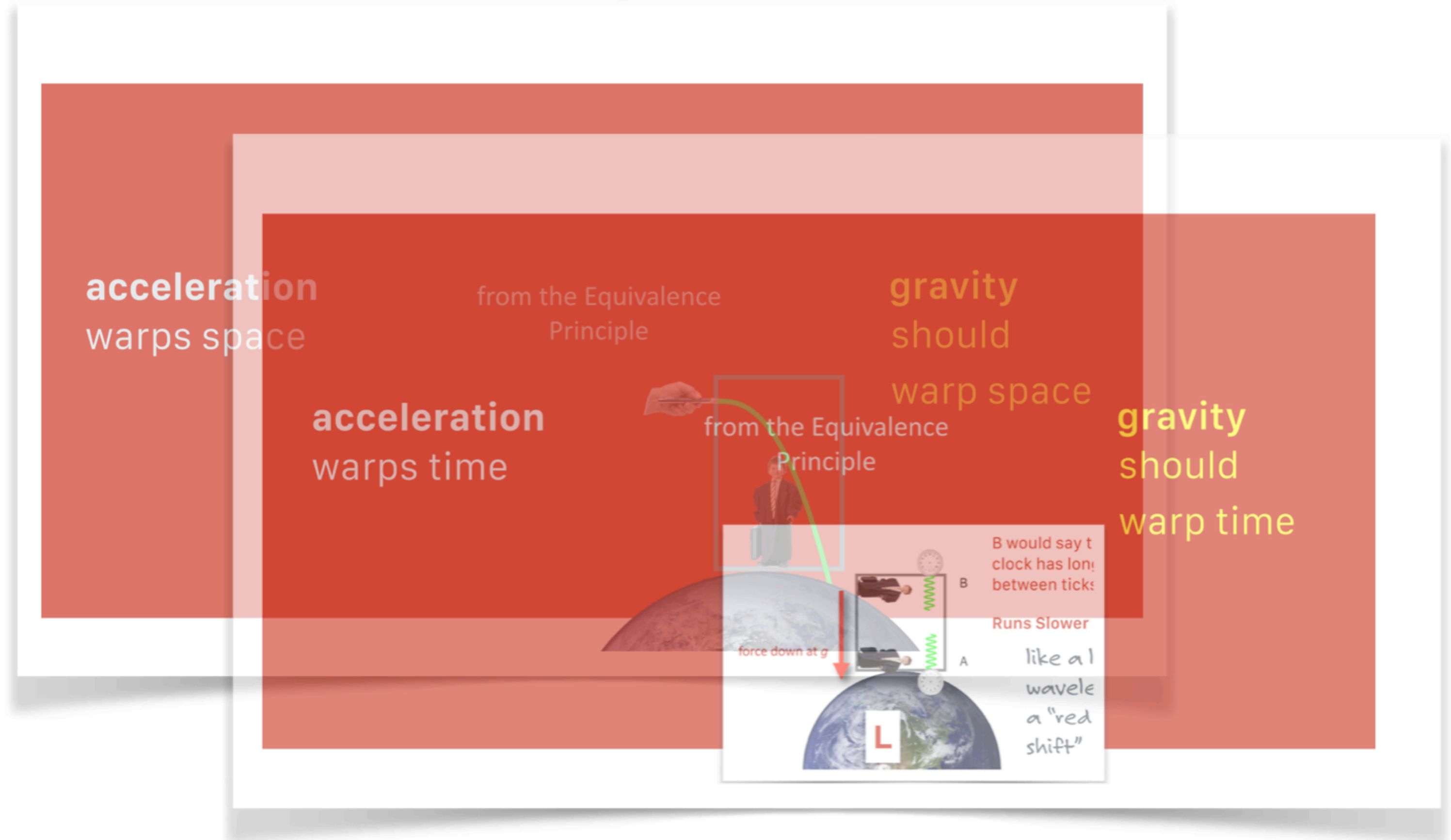




gravitating bodies…masses:

warp both space and time.

They warp: **spacetime**



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

``warping''

means that geometry

spacetime geometry

mixes with mass, energy, and pressure

General Relativity

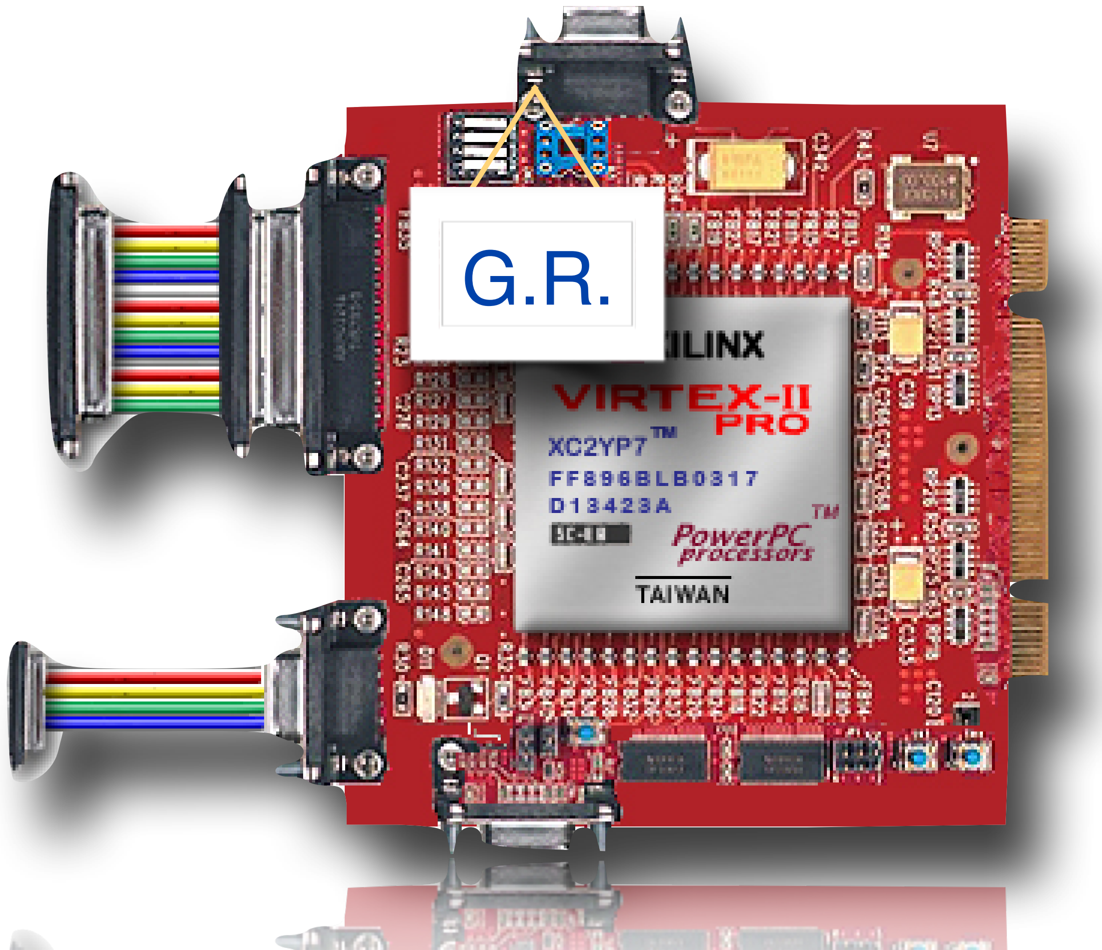
Einstein's GR equation

complicated mathematics

geometry of spacetime ↔ 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

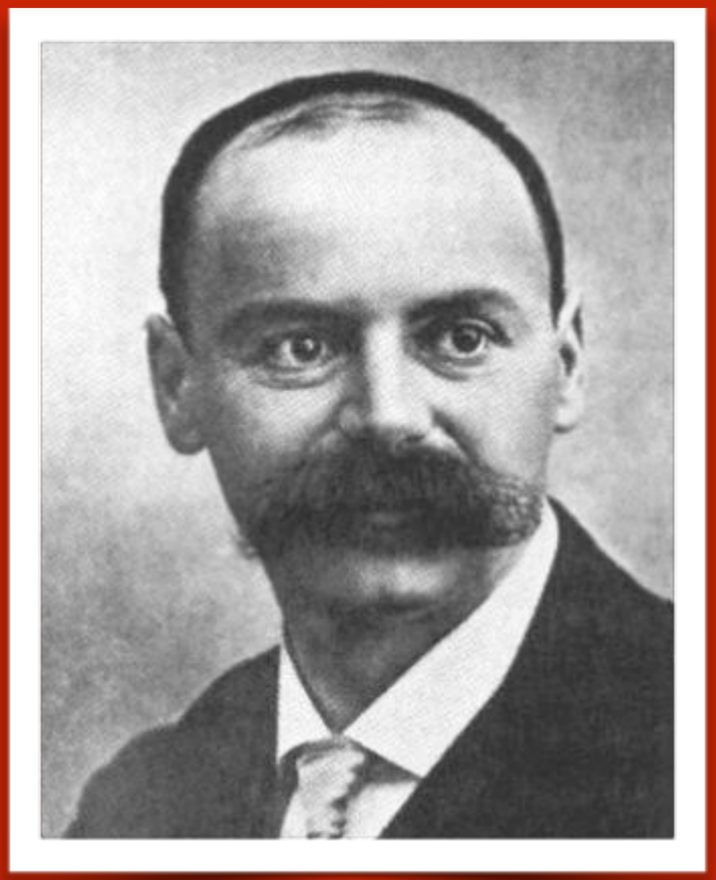
the richness of his theory

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



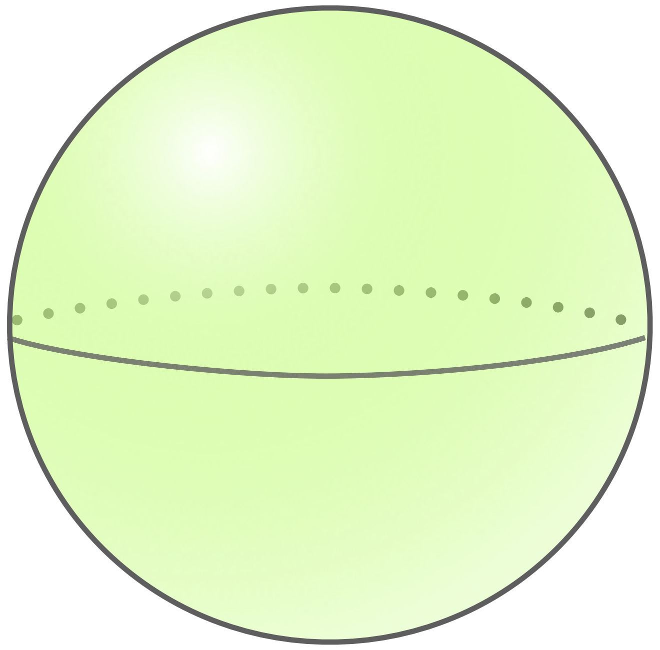
Karl Schwarzschild, 1873-1916

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.

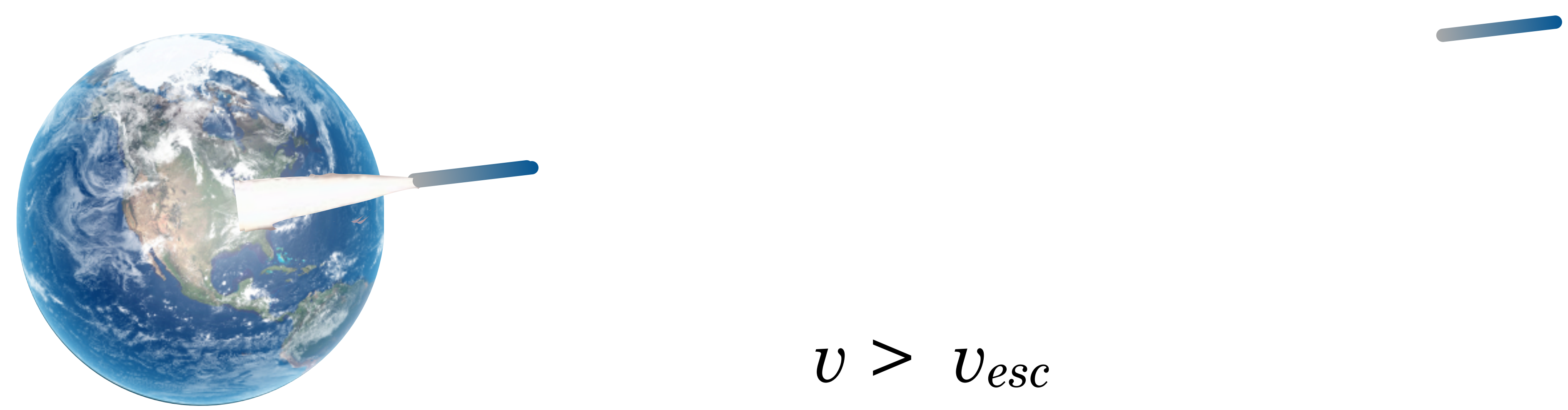
a big mass.



escape

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

It depends.



$v > v_{esc}$

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

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

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

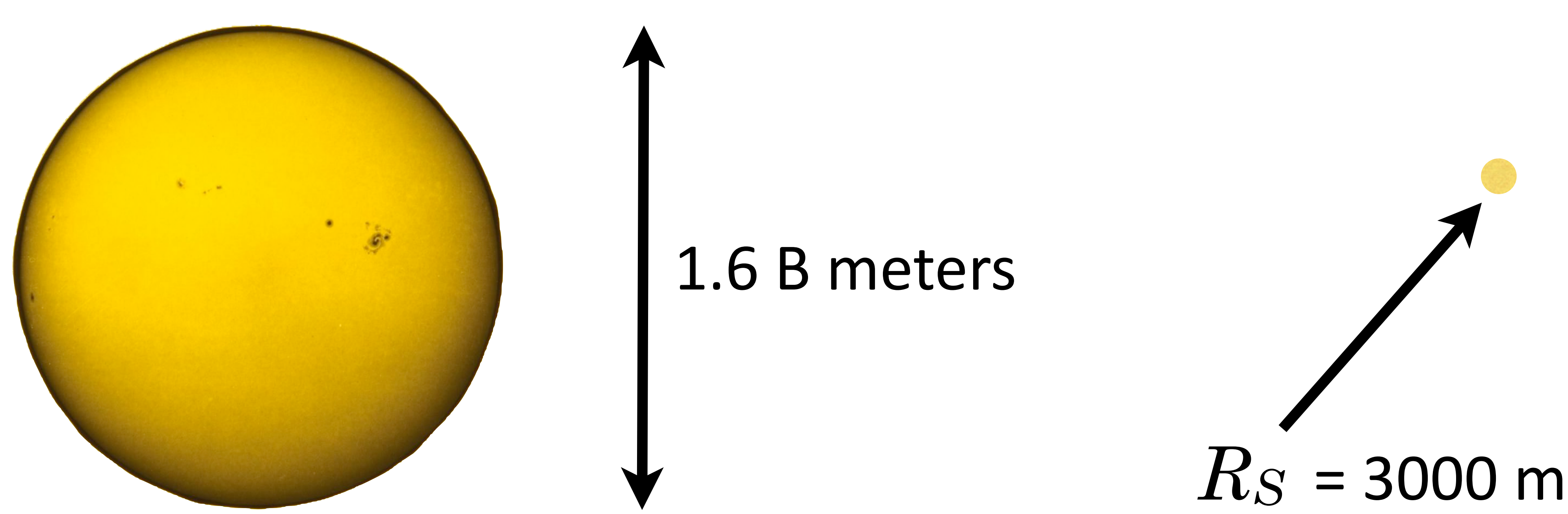
"What's the radius of a mass *M* for which the escape velocity is = *c*?"

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

R_S called the Schwarzchild Radius

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

It seemed to be a magic radius...



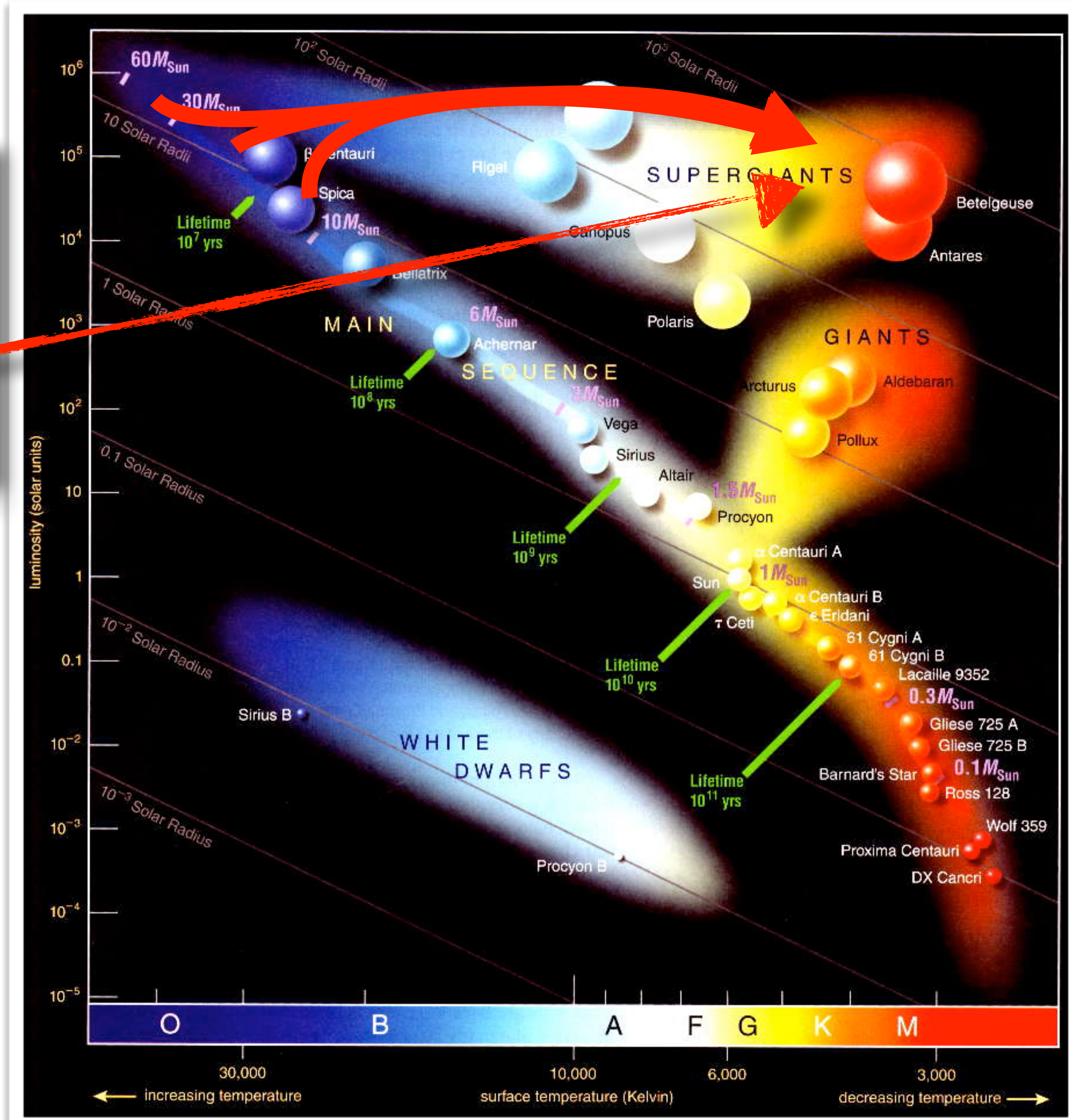
a balancing act

VERY MASSIVE...

>1.3 Msun

H → He → C...

...→ Fe

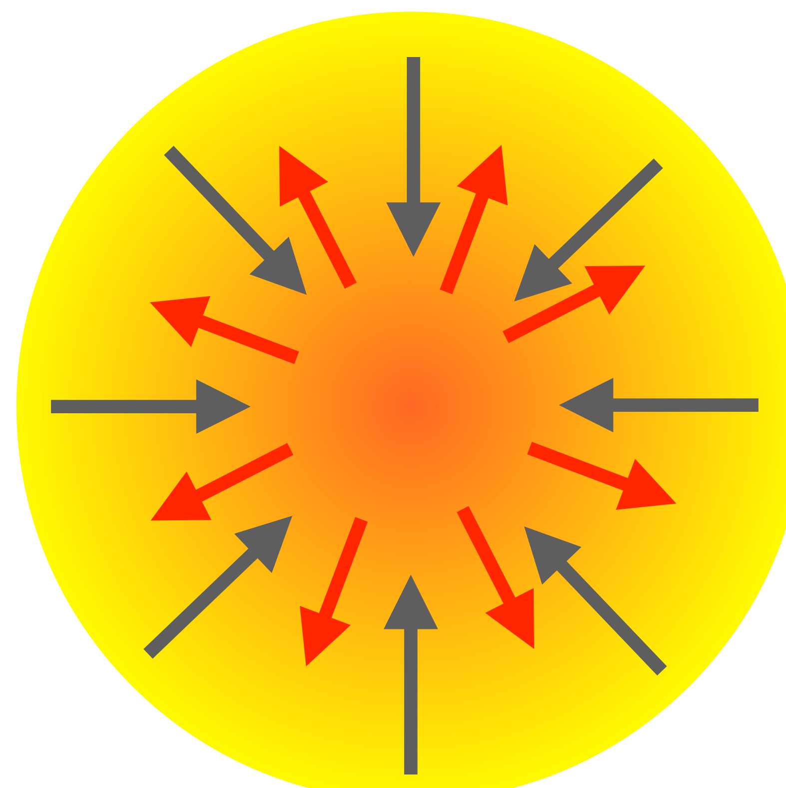


a balancing act

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

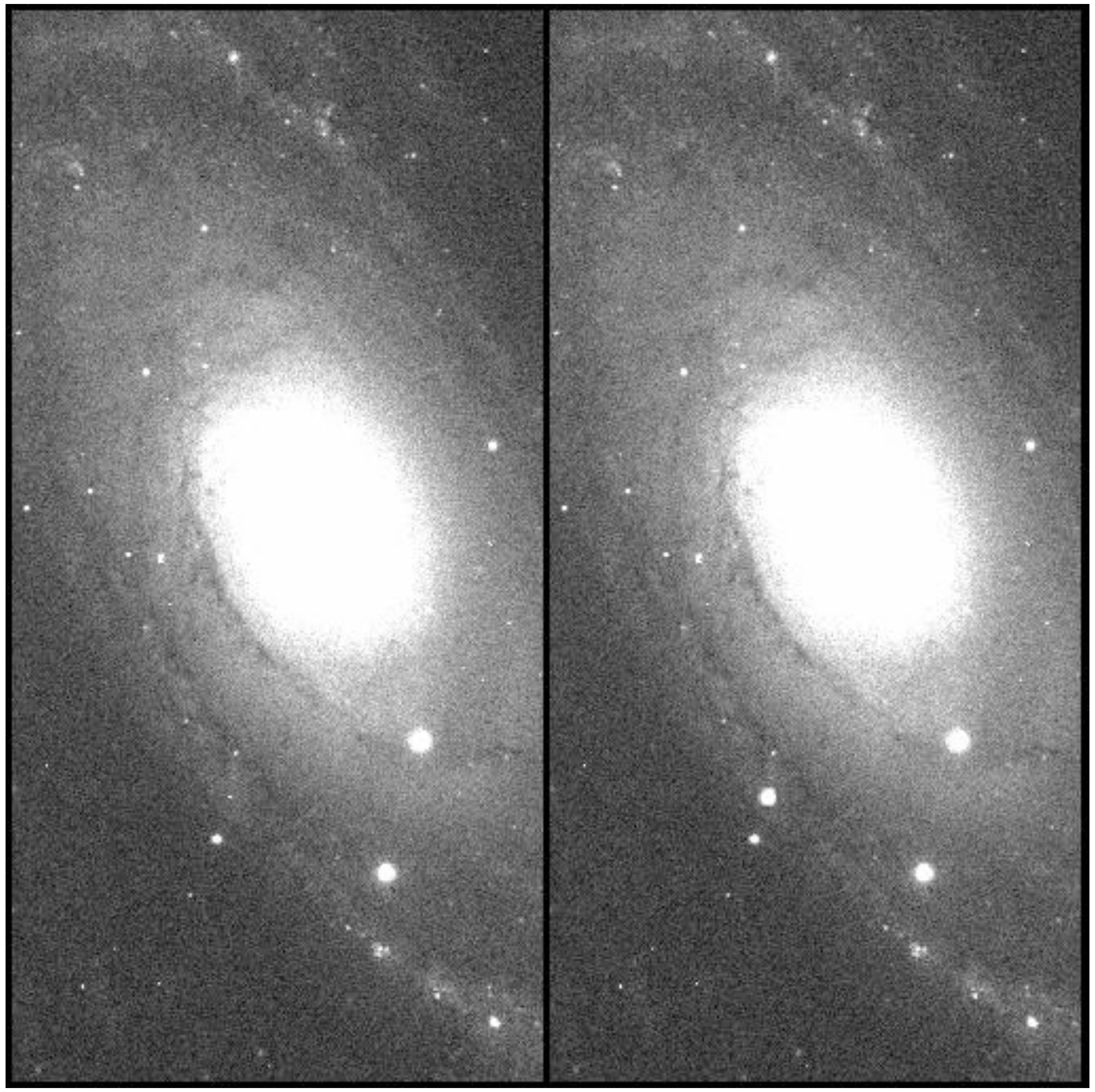
and then a special effect takes over:

neutrons cannot all be on top of one-another

It stops abruptly in seconds

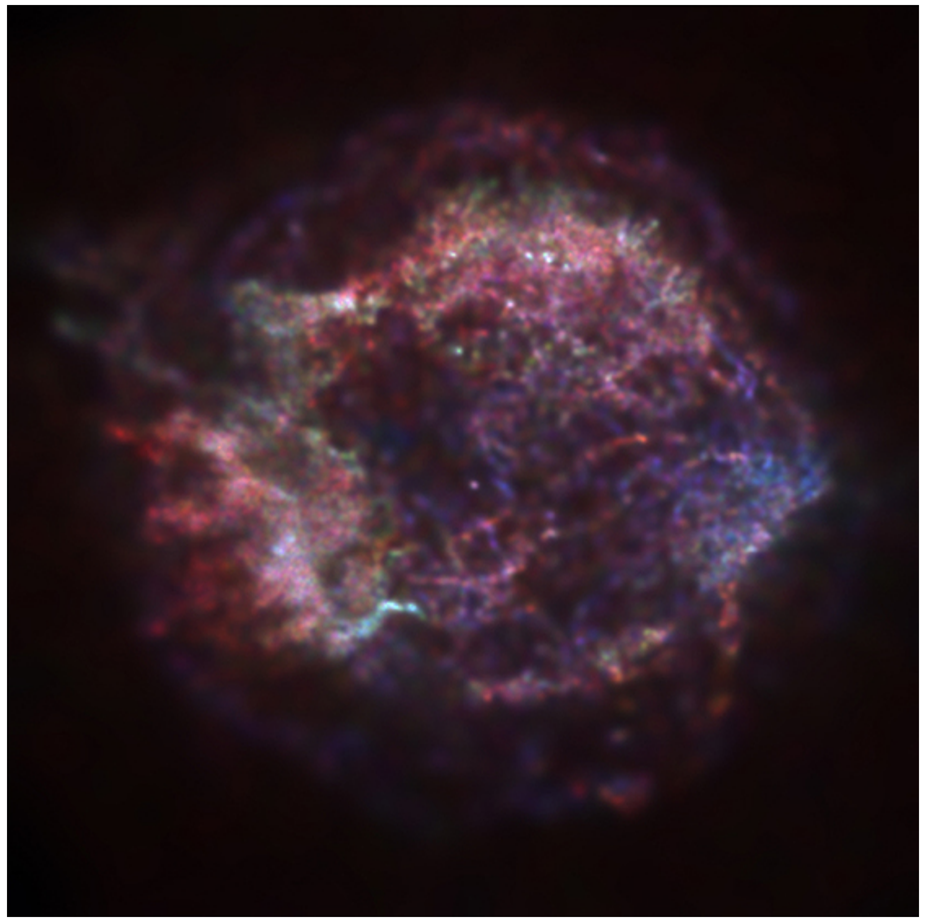
Explosively.

supernova!

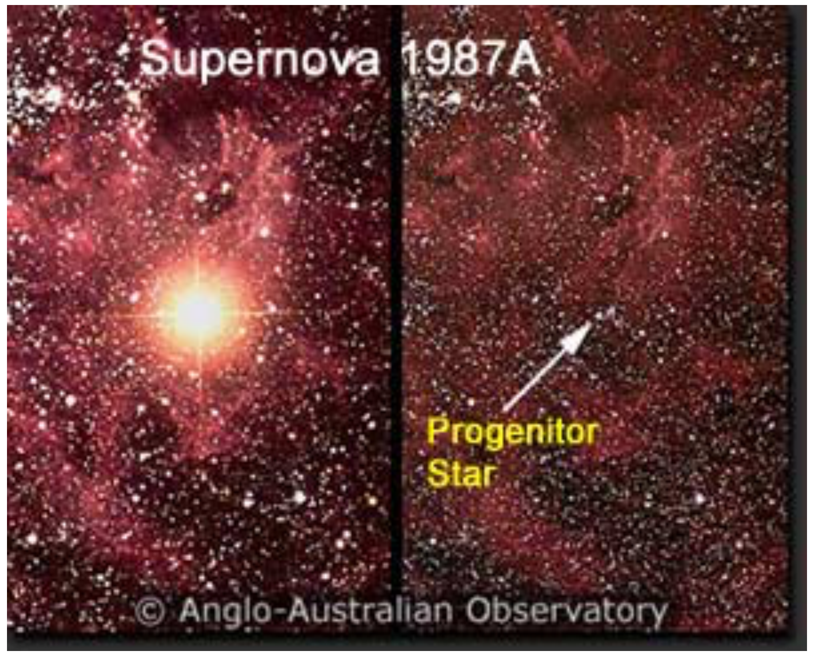


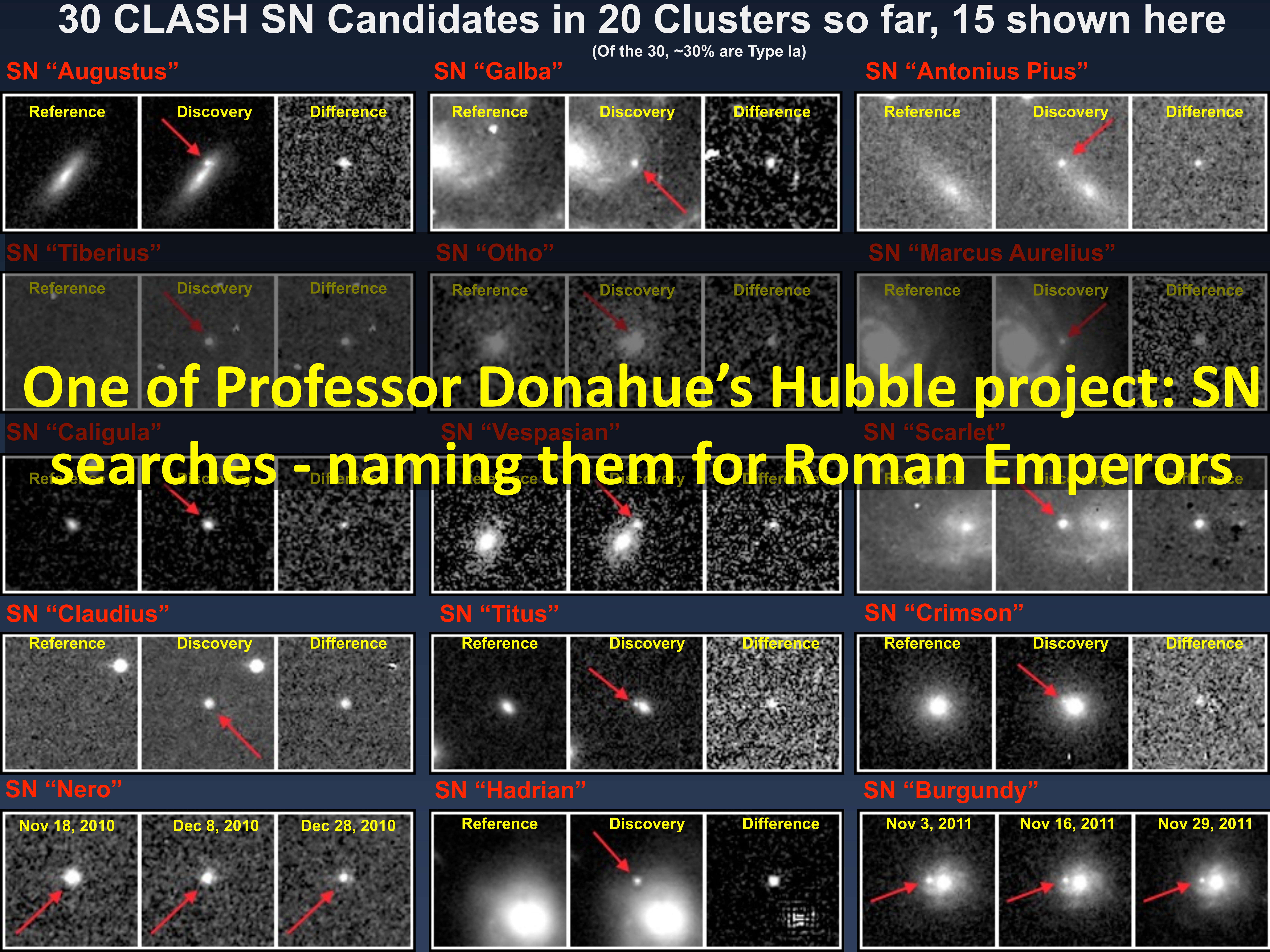
SN 1993J
M81

Crab Nebula…supernova remnant from 1054 AD



Tycho's Supernova, 1572




30 CLASH SN Candidates in 20 Clusters so far, 15 shown here
(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"
Reference
Discovery
Difference
Nov 18, 2010
Dec 8, 2010
Dec 28, 2010
Nov 3, 2011
Nov 16, 2011
Nov 29, 2011
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

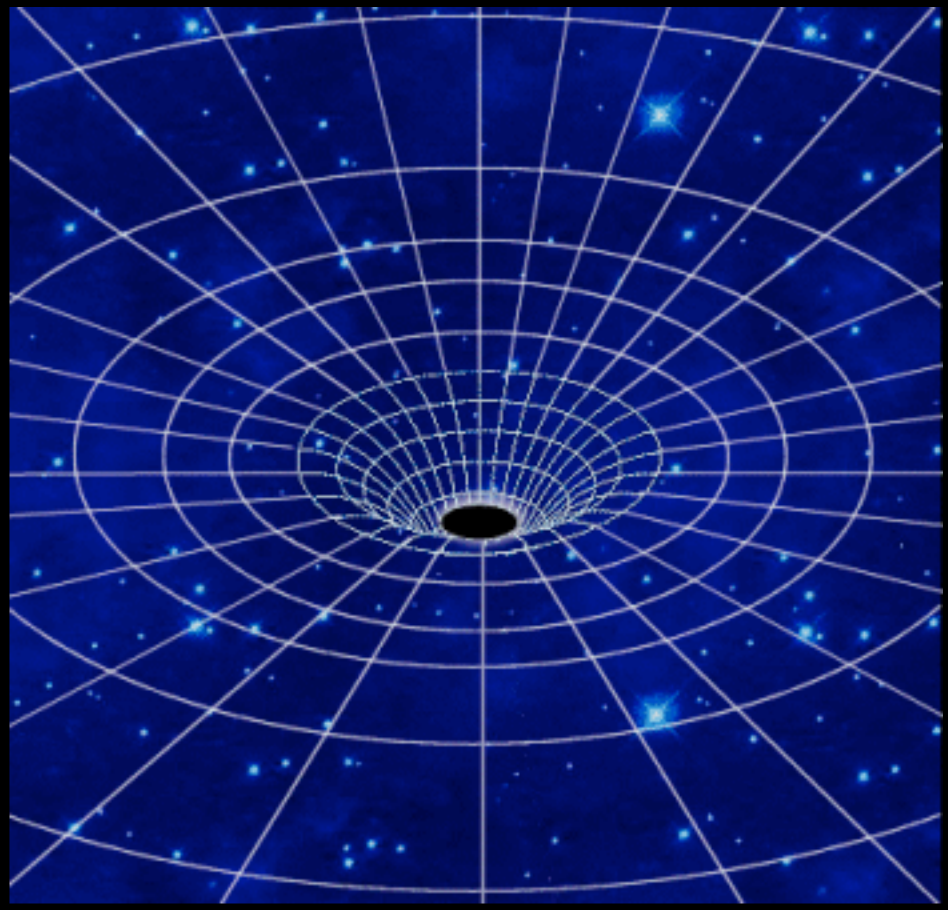
Stellar BLACK HOLE

very peculiar

Gravity wins. Nothing gets out, not even light:

BLACK no light

HOLE the most extreme warping of spacetime in Nature

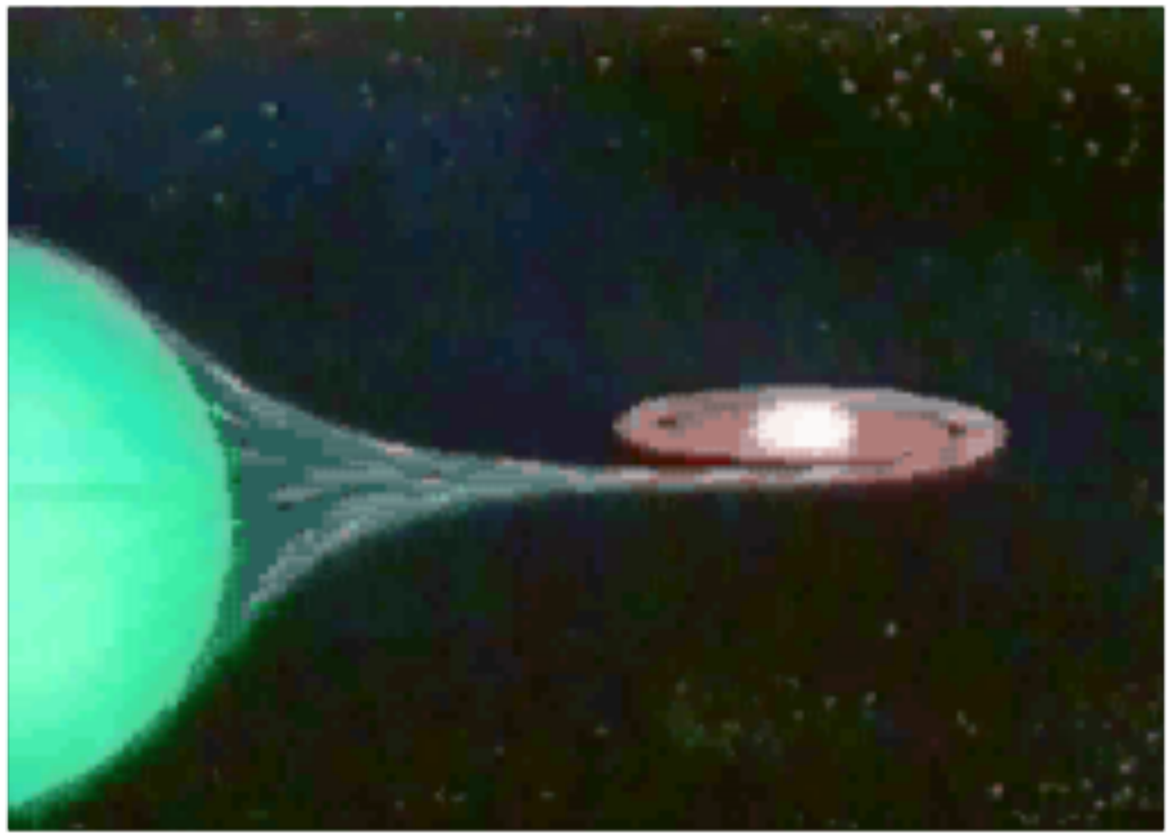


outside of ~$3R_s$

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

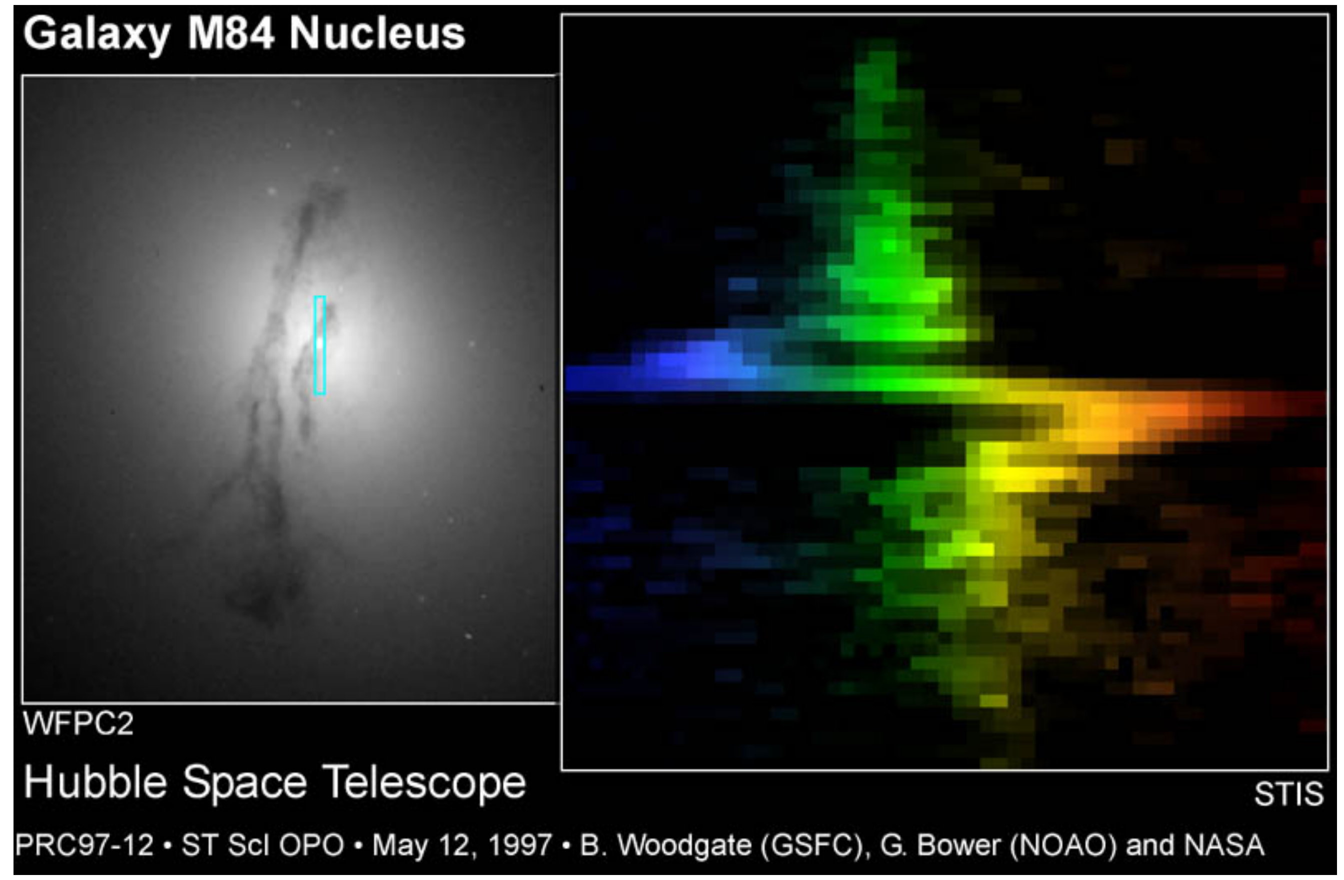
$4 \times 10^6 \times M_{sun}$

M84

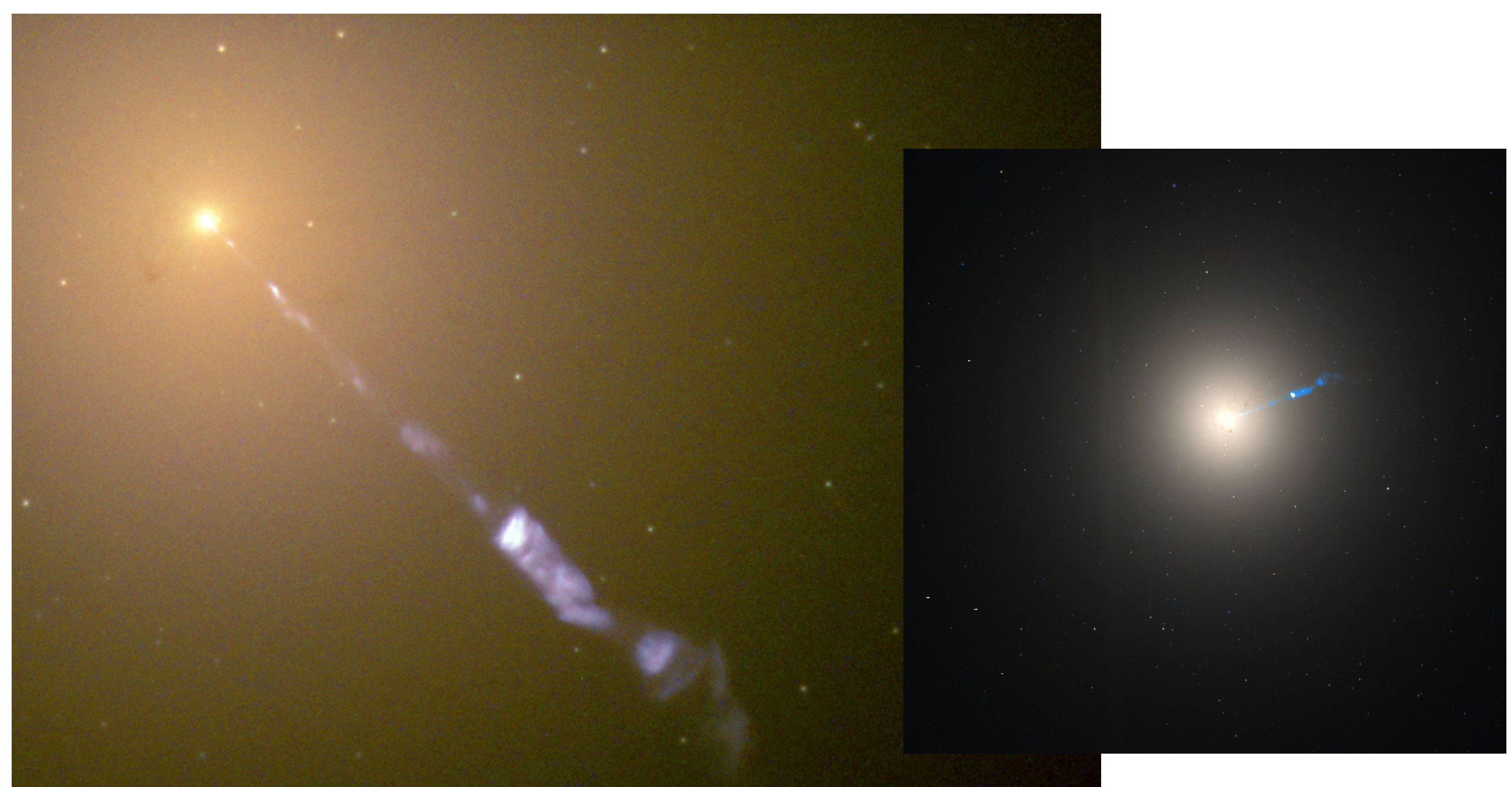
$300 \times 10^6 \times M_{sun}$

M87

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



M87 Active Glactic Nucleus (AGN)



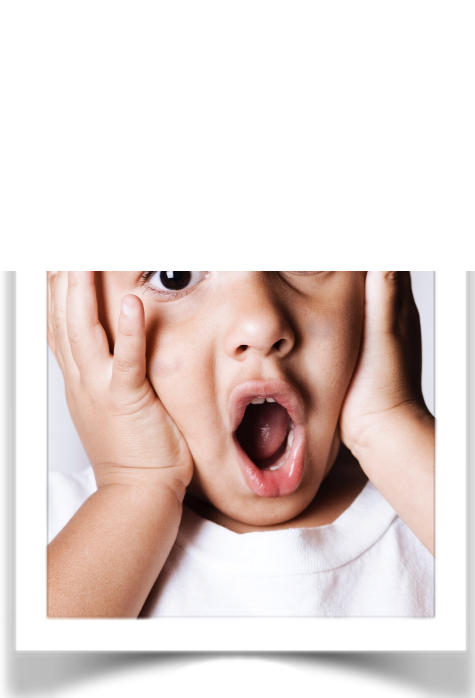
spacetime

warped into submission

"spacetime interval" in Special Relativity: $\Delta s^2 = c^2 \Delta t^2 - \Delta r^2$

Δs^2 ◇ spacetime interval in Schwarzchild's General Relativity:

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



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”

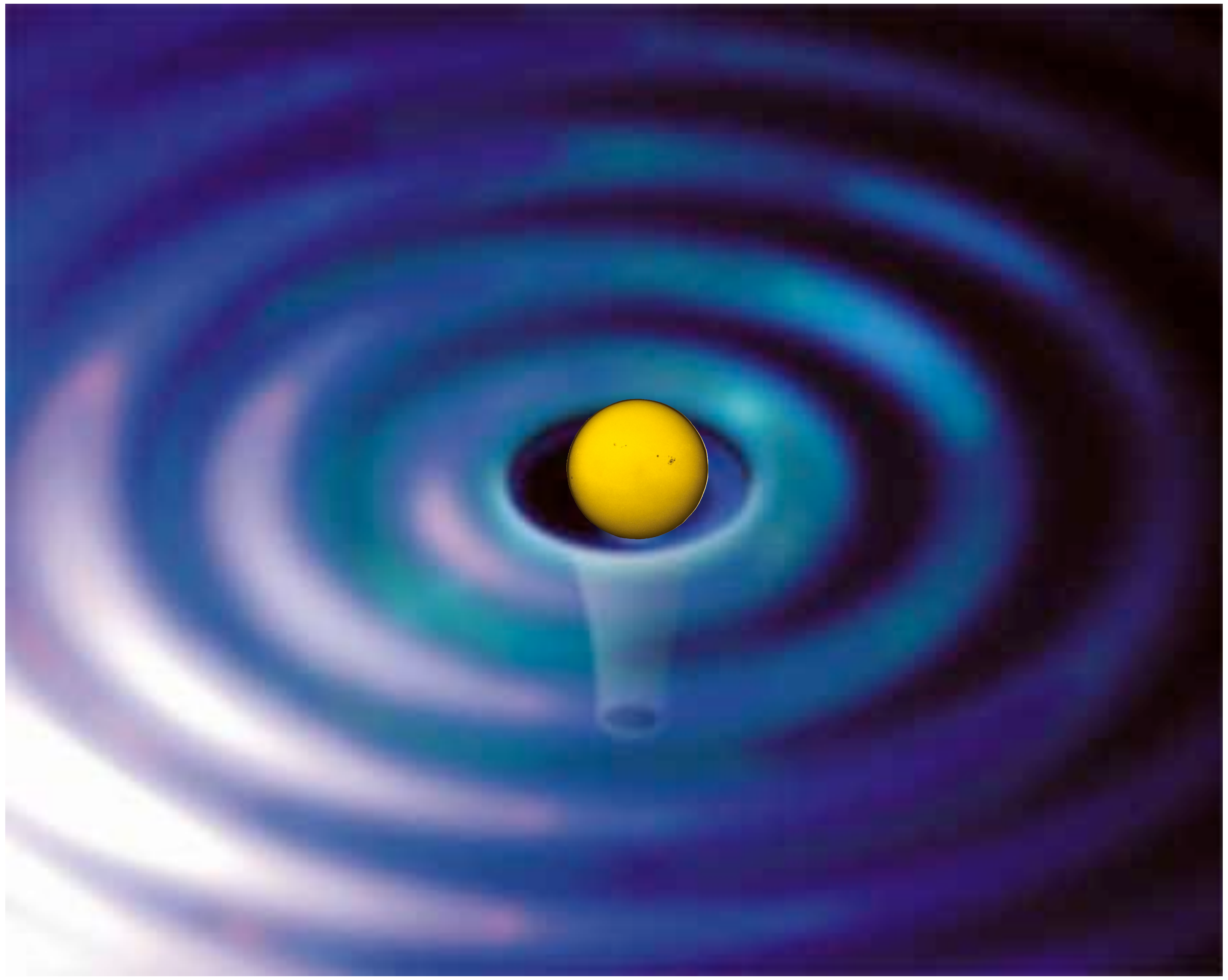
Black Holes

accelerating charges

remember?

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

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



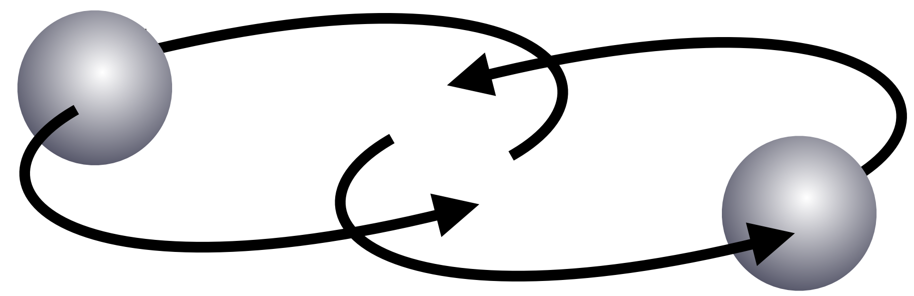
Disturbances in geometry of spacetime itself.

"Binary Pulsar period"

remarkable test of General Relativity

A binary star system...of neutron stars

they are accelerating and so radiate gravitational waves

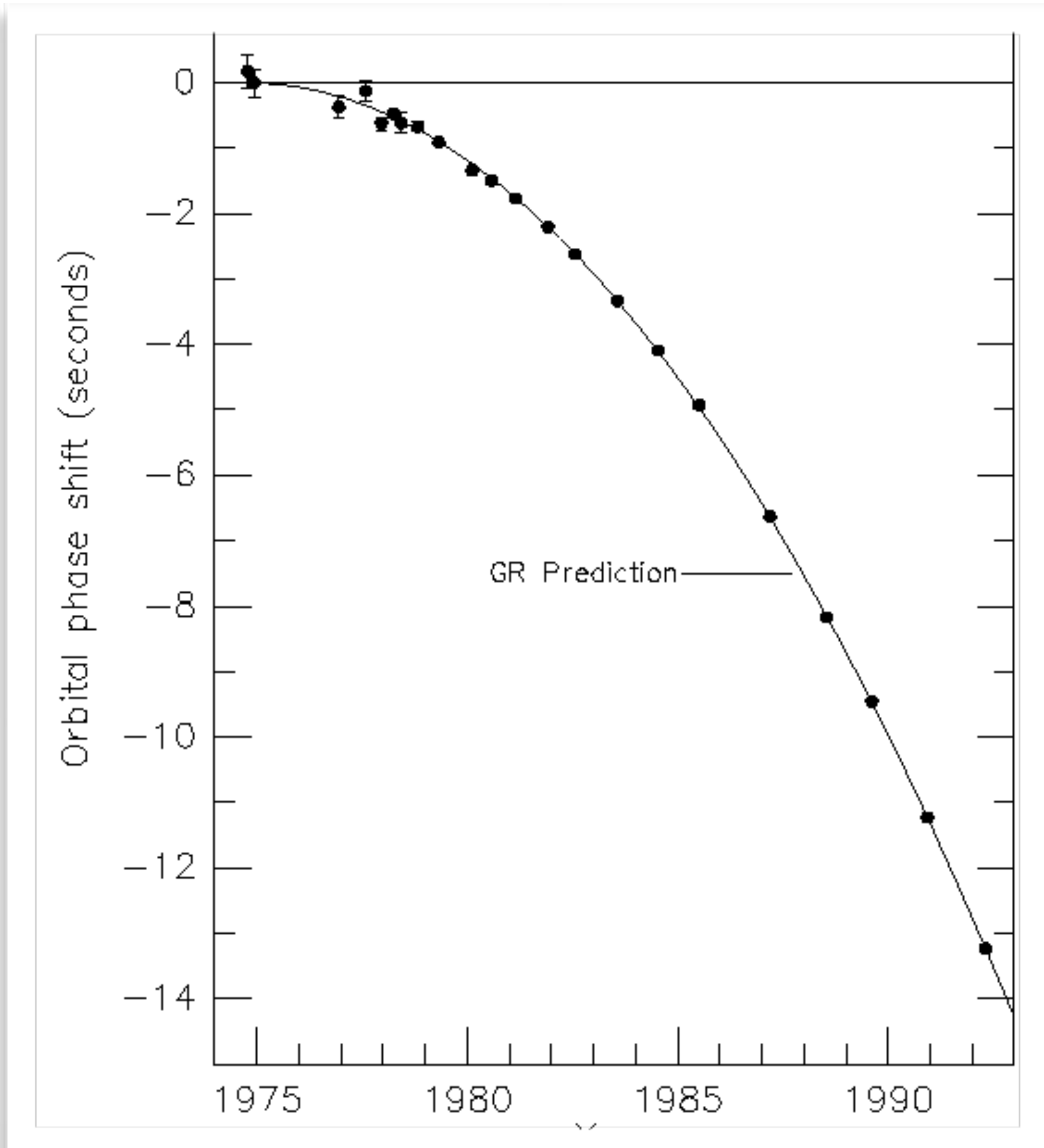


PSR1913+16 discovered 1974

Emits very regular radio pulse every 59 ms: "pulsars"

and its period is reduced by 67 ns each orbit

1993



Joseph H. Taylor Jr.

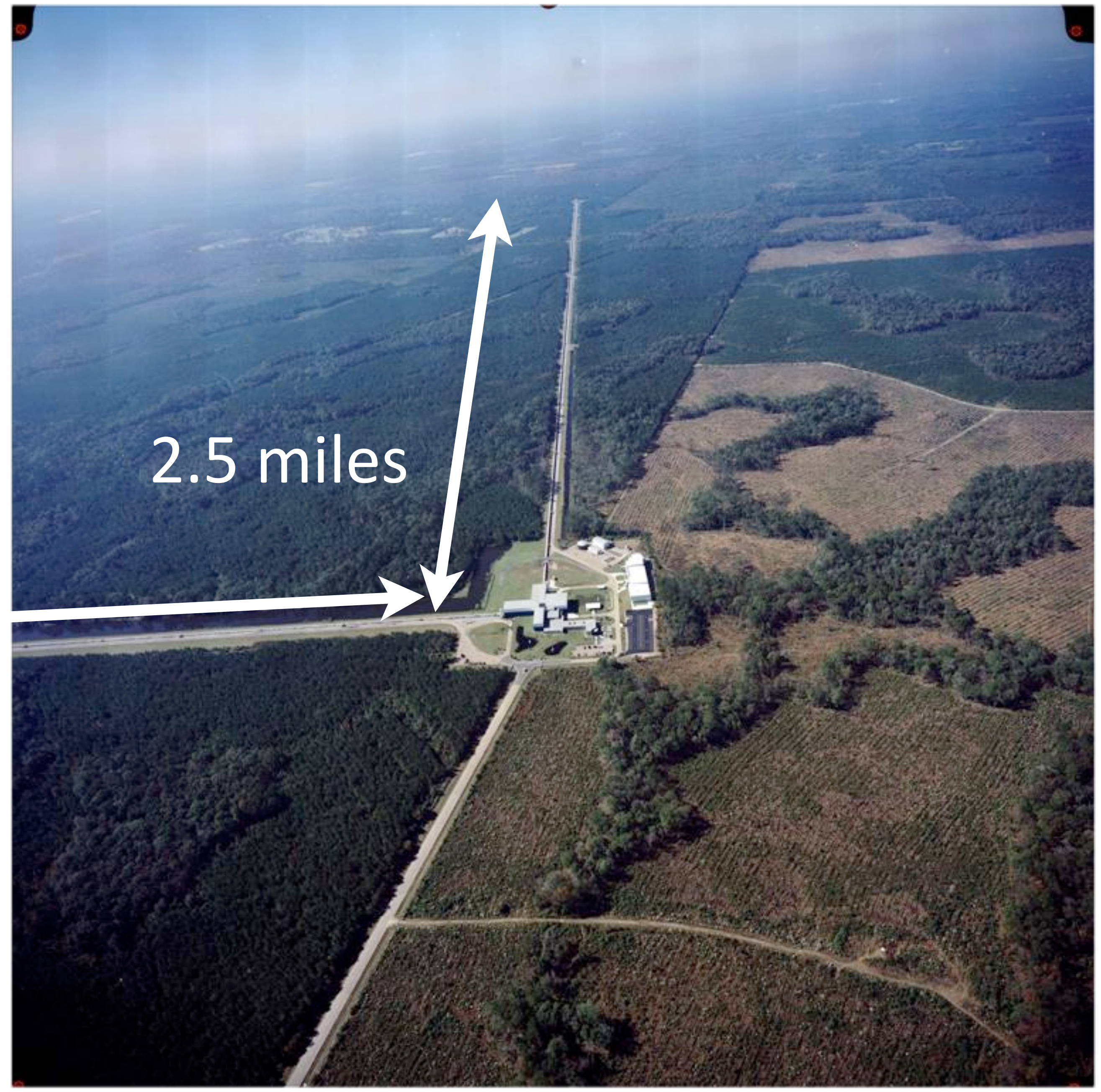
Russell A. Hulse

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

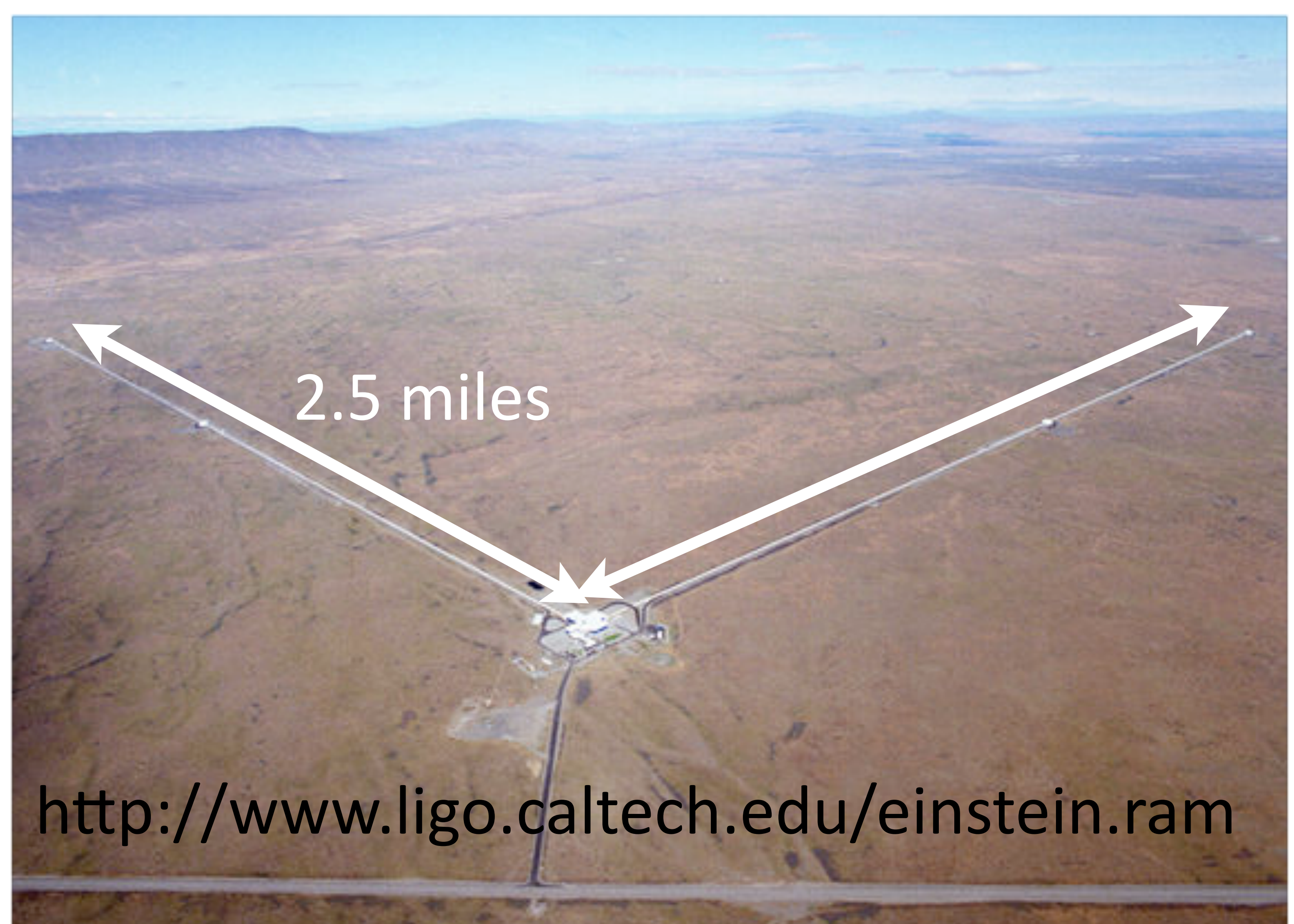
intergalactic, colliding binary, neutron stars, gamma ray bursts, black holes, colliding galaxies,



looking for shrinkage of one arm when gravitational wave passes by

need precision smaller than a proton radius

Livingston, LA



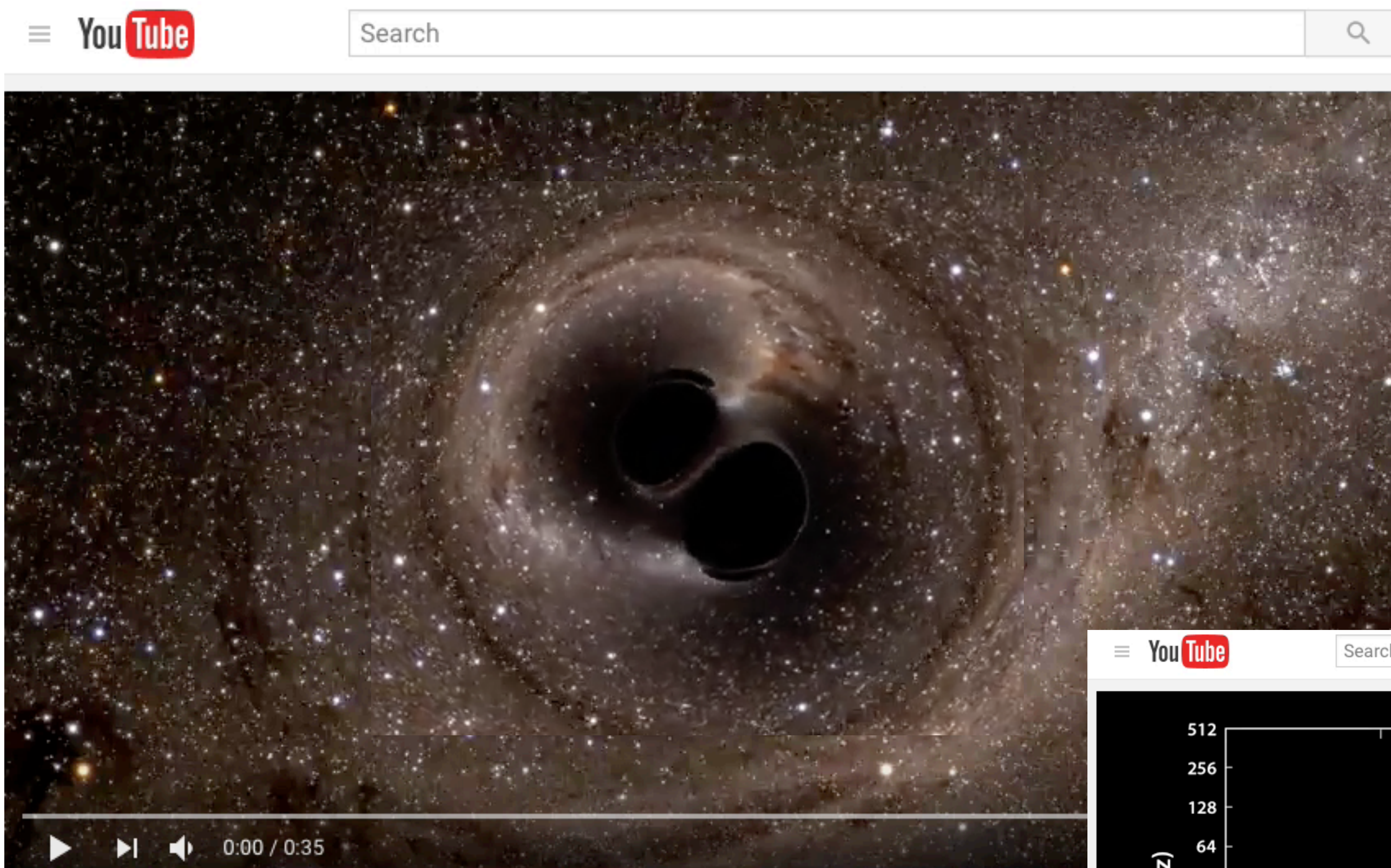
Hanford, WA

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

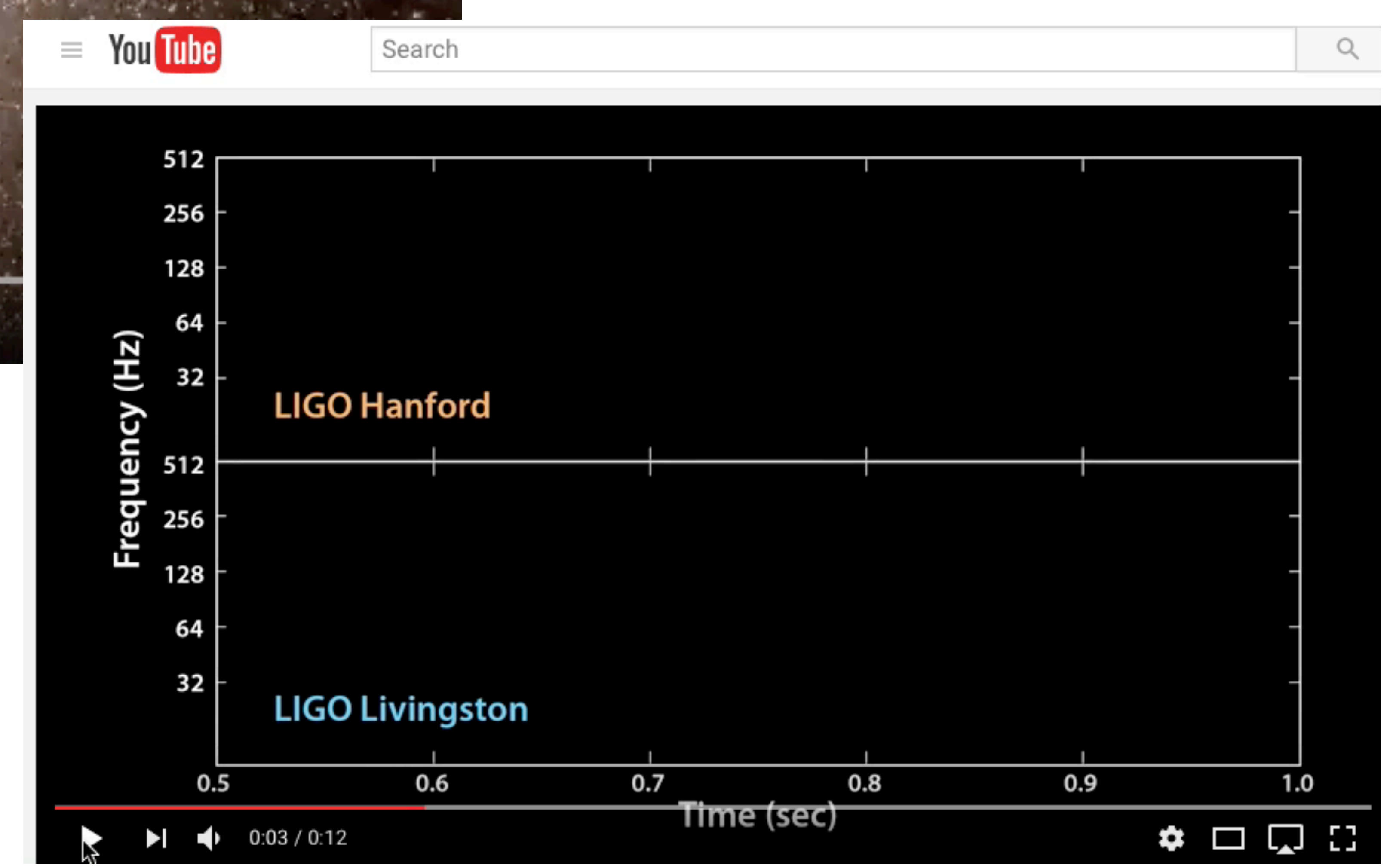
what's going on

GW150914: merging black holes



September 14, 2015 at 09:50:45 GMT

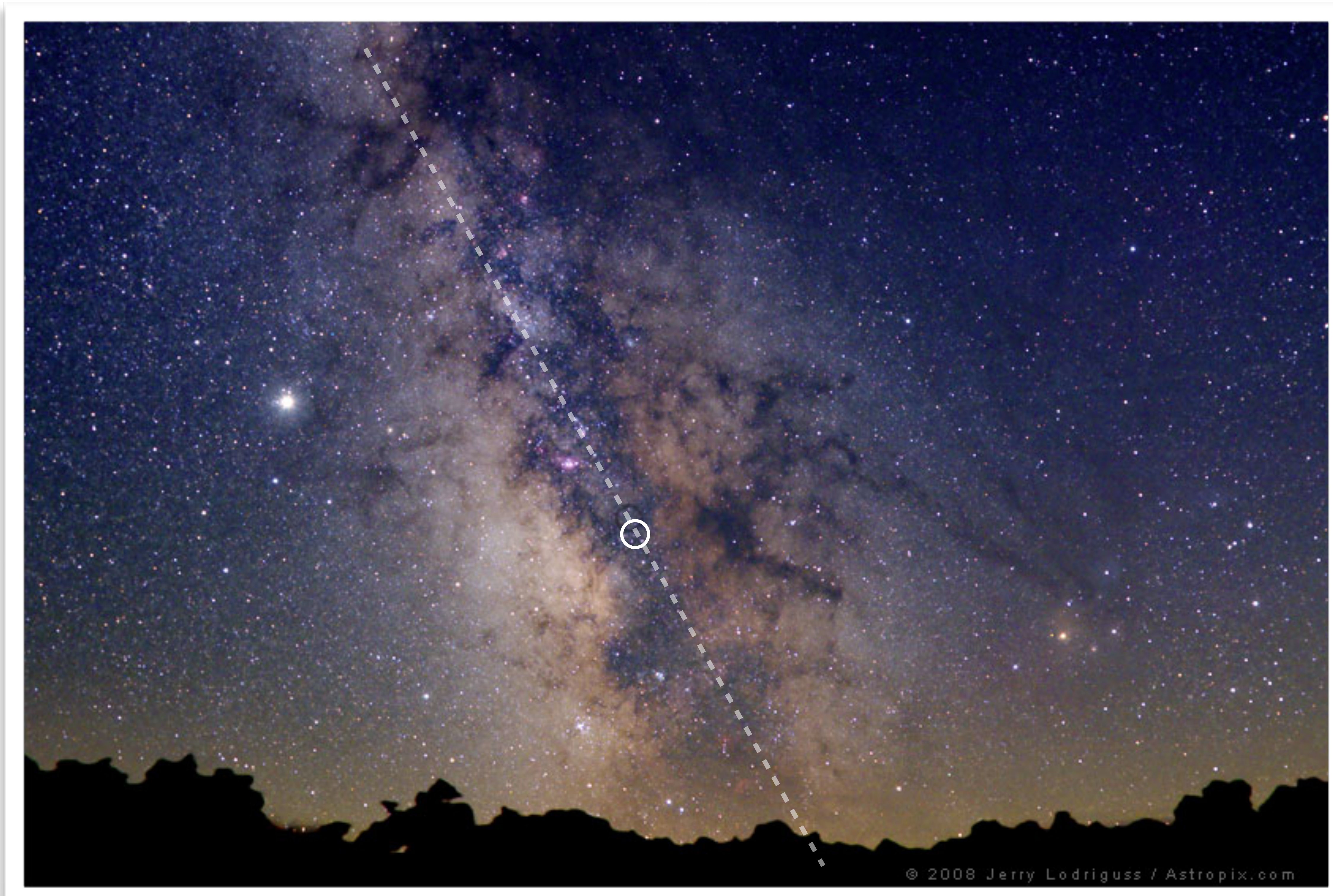
36 Msun + 29 Msun → 62 Msun



in 1915 scientific cosmology didn’t exist

does now.

home

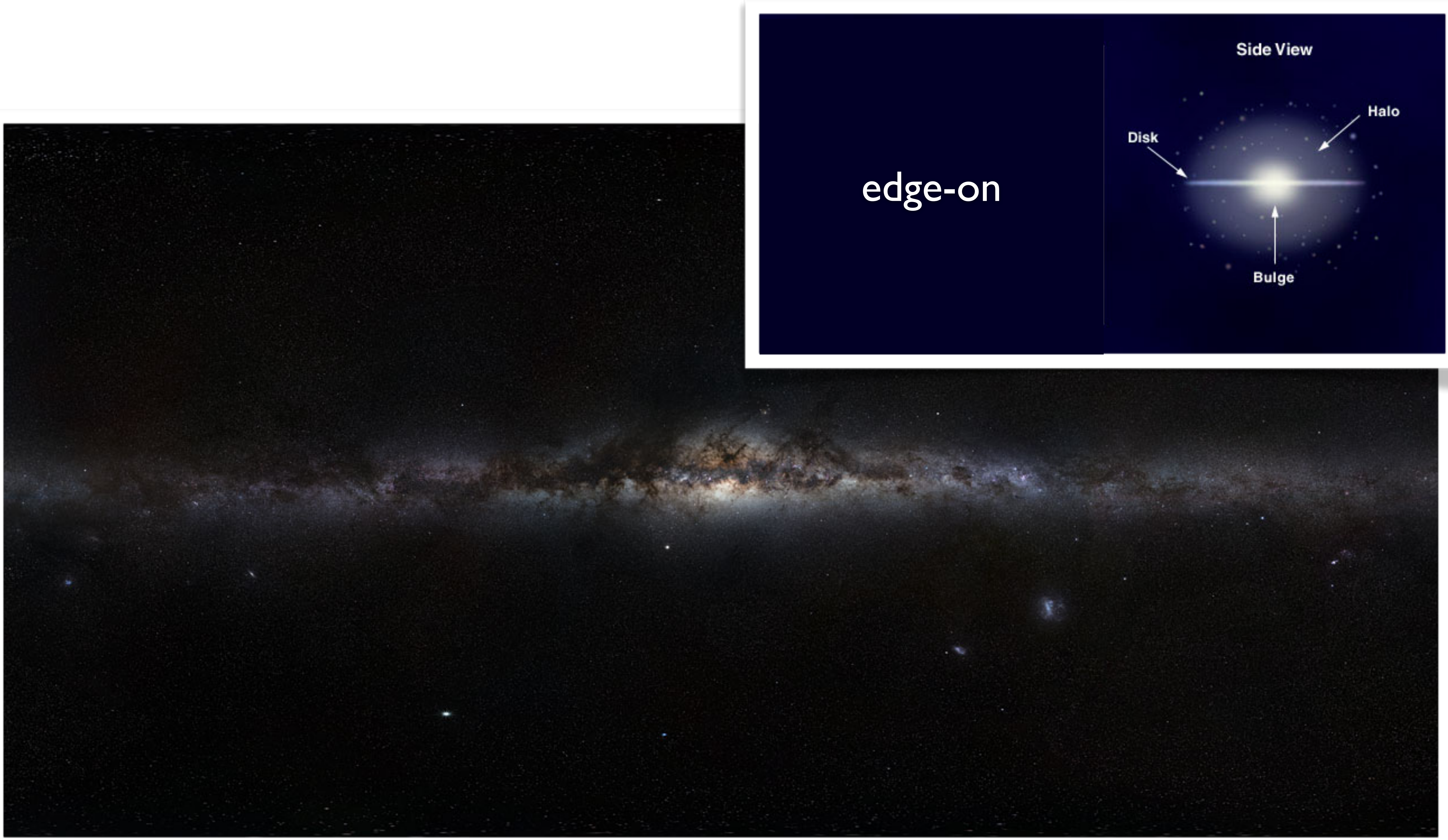


supermassive black hole in Sagittarius... Sagittarius A

Digital Astrophotography by Jerry Lodriguss

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

panorama view of the Milky Way from ESO



100,000ly-ish

Einstein

began the first truly scientific field of cosmology

applying GR to the entire universe

1917:

Cosmological Considerations in the General Theory of Relativity

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

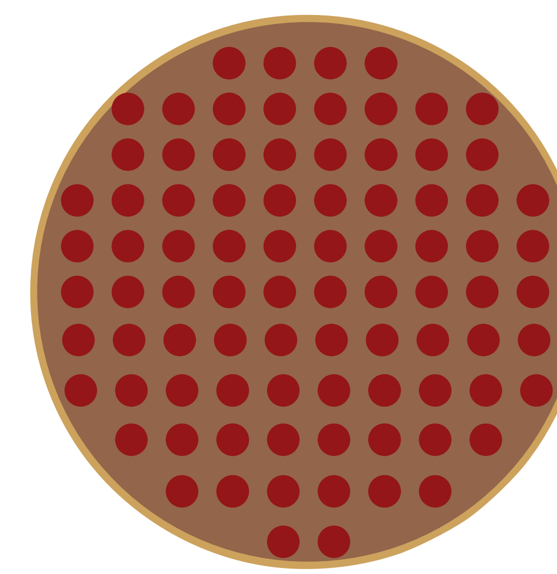
It doesn't matter where you are.

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

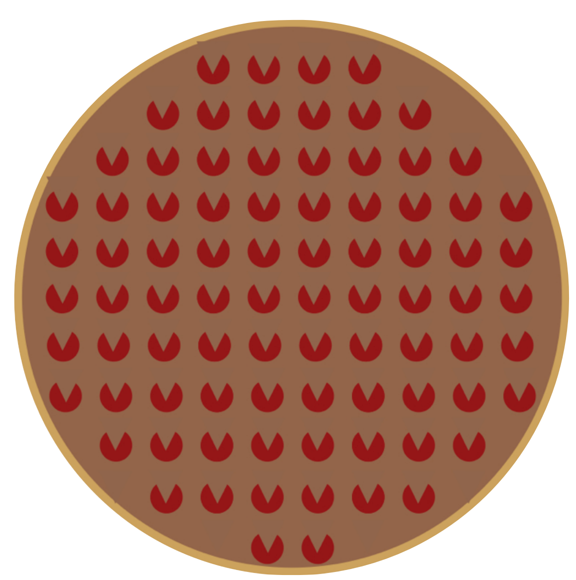
The Universe is presumed to be
homogeneous: average density same & uniform everywhere
and
isotropic: no special directions

my Famous
Probable Planar Pepperoni Pizza Probe

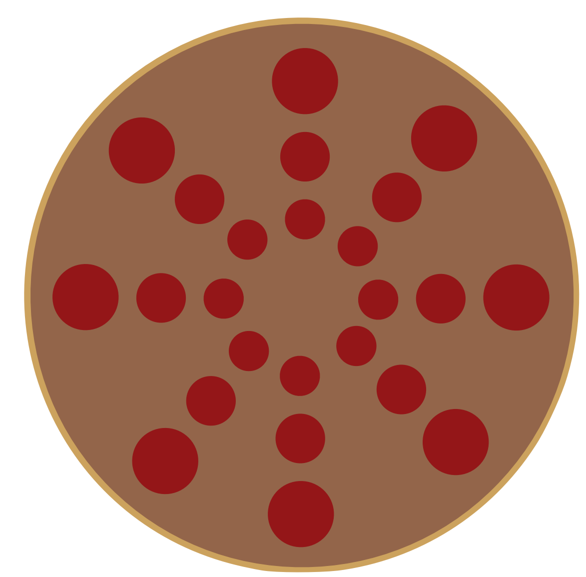
…as viewed from the center:



homogeneous and isotropic



not isotropic and yet homogeneous



not homogeneous and yet 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?

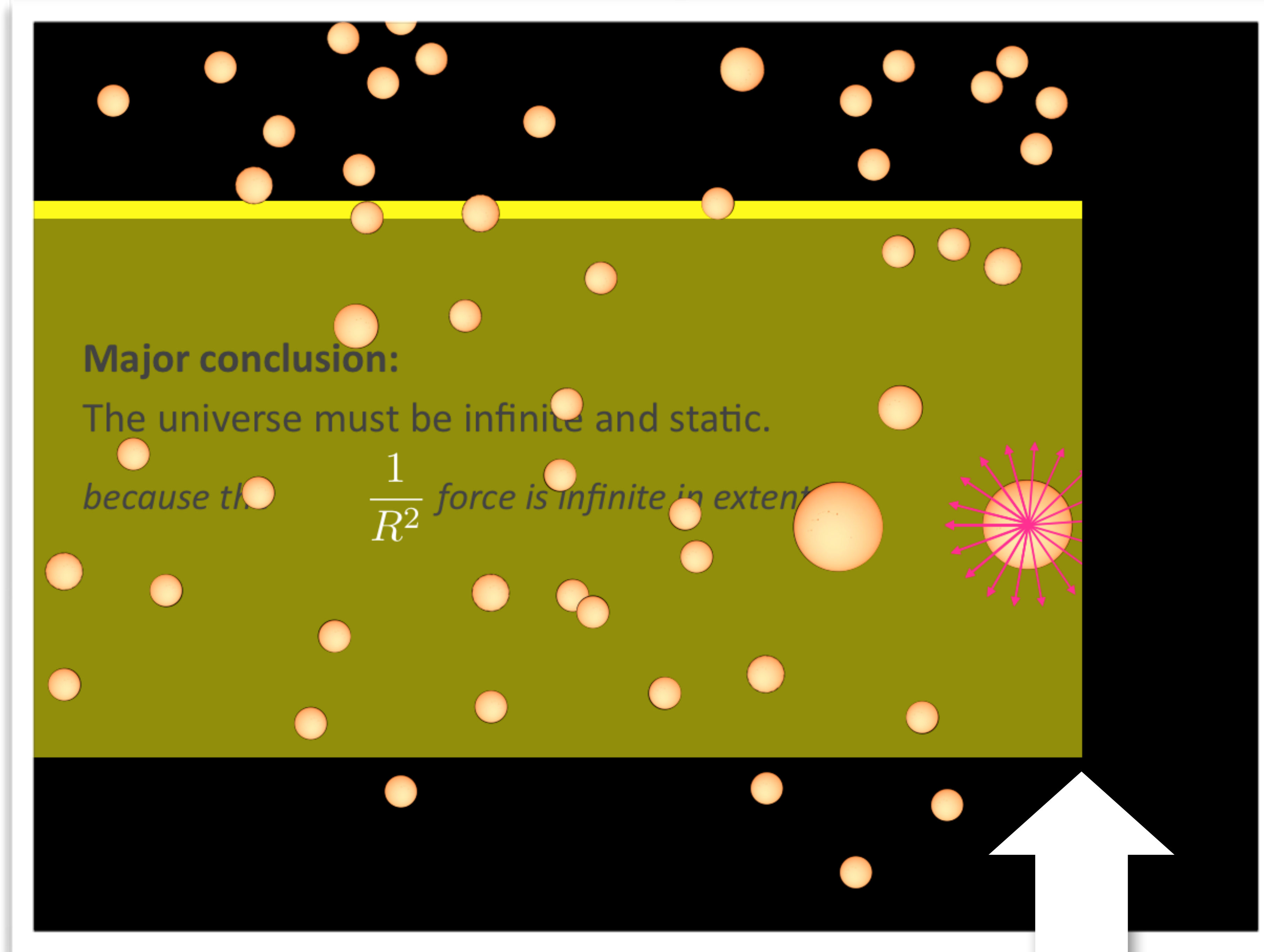
The current density of matter in the universe is about 6 protons/m^3

He was plagued by infinity

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

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

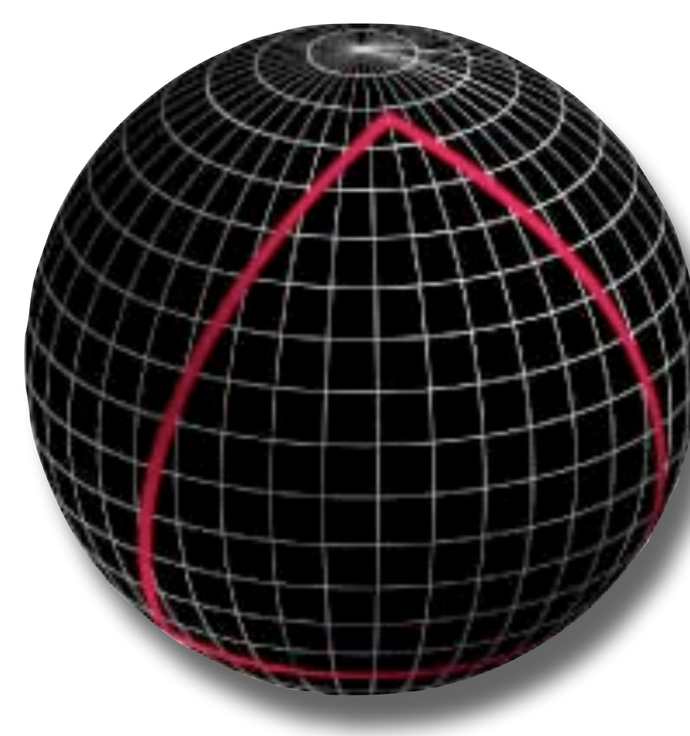
strangely in balance!



an edge to the universe was Newton's worry

But he was smarter than Newton

And he owned a tool to erase infinity!



That was his goal: to get rid of infinity

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

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!

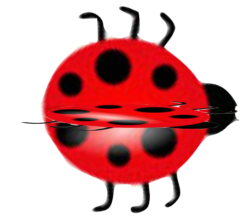
suppose you could start out in a spaceship

always keeping your starting spot behind you

you could then return to where you started!

hypervolumes: multidimensional geometry

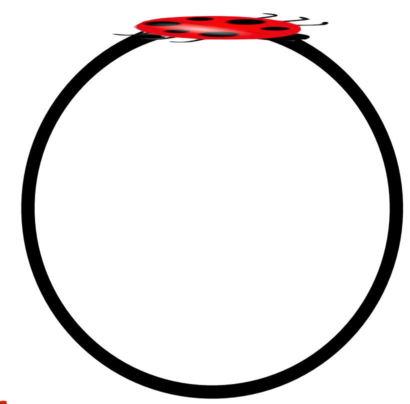
Suppose you're a 1 dimensional being.



your world is a **line**

it could be infinite...

it could be finite...



It's not a very exciting existence

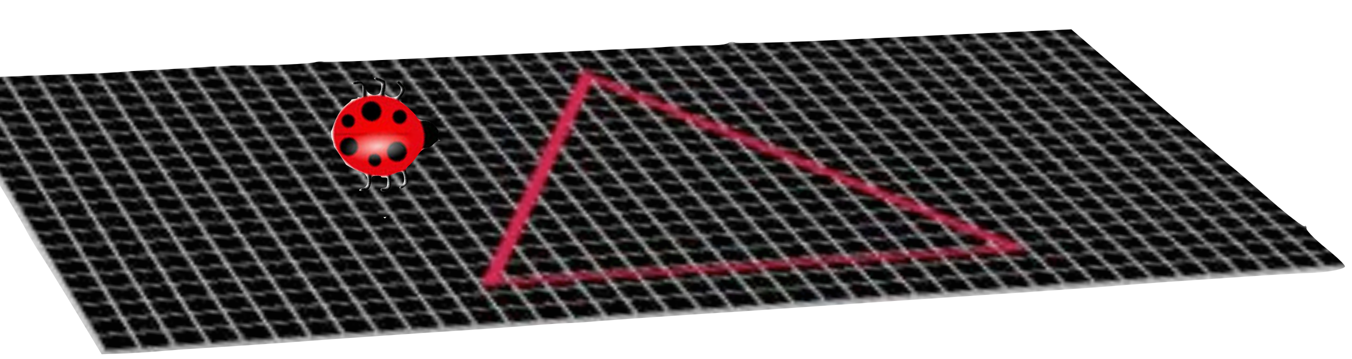
Notice something: this is a
1 dimensional world
embedded in – expand your mind
now – a *2 dimensional plane* -
which is where the curvature is.
Outside of the "view" of the bug.

Bug only knows forward and backward...
"left," "right," "up," "down" have no meaning.

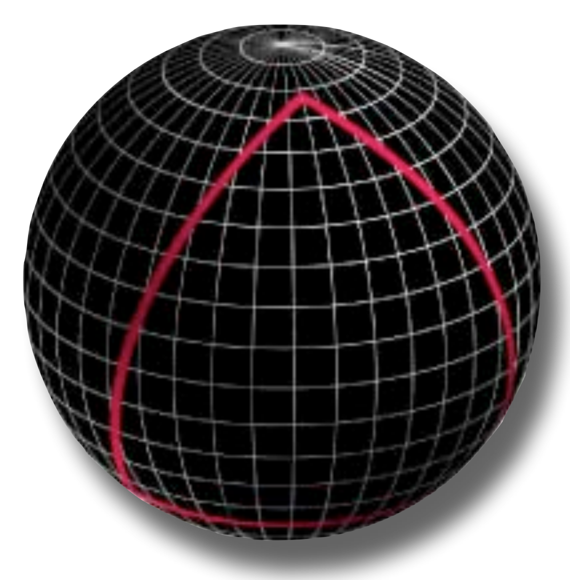
Suppose you're a 2 dimensional being.

your world is a **surface**

it could be infinite...



it could be finite...



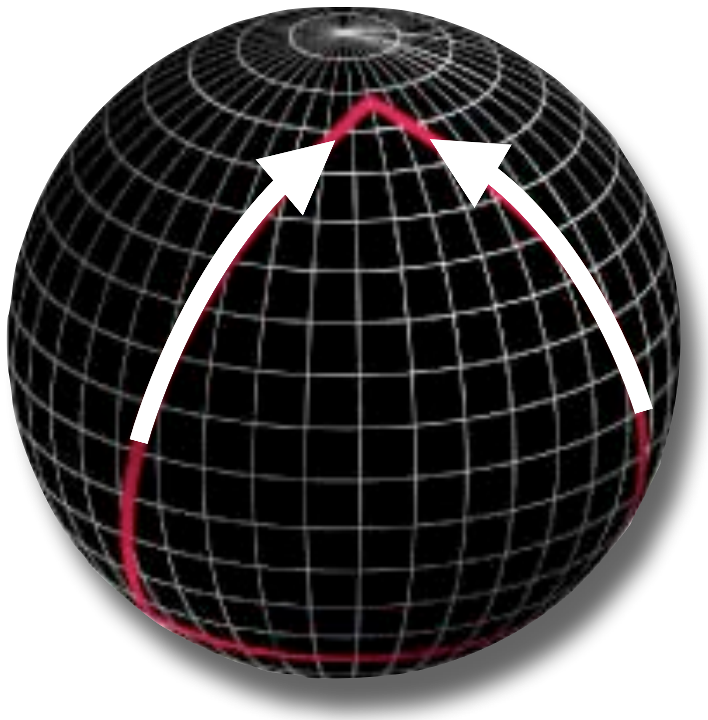
It's a little more exciting

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

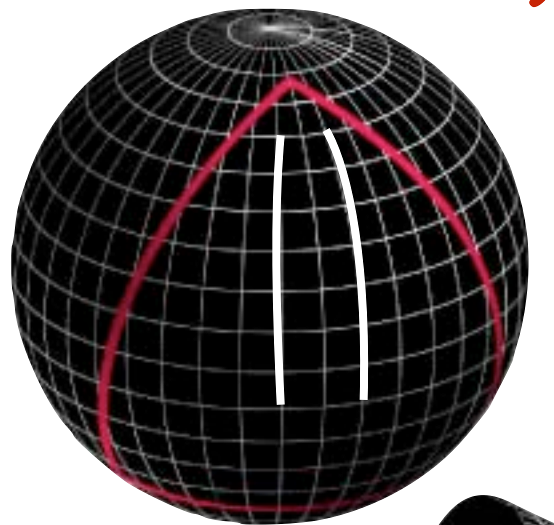
<u>We</u> know up, down, front, back, left, right...but have no knowledge of that 4th spatial embedding dimension - *which is where the curvature is*

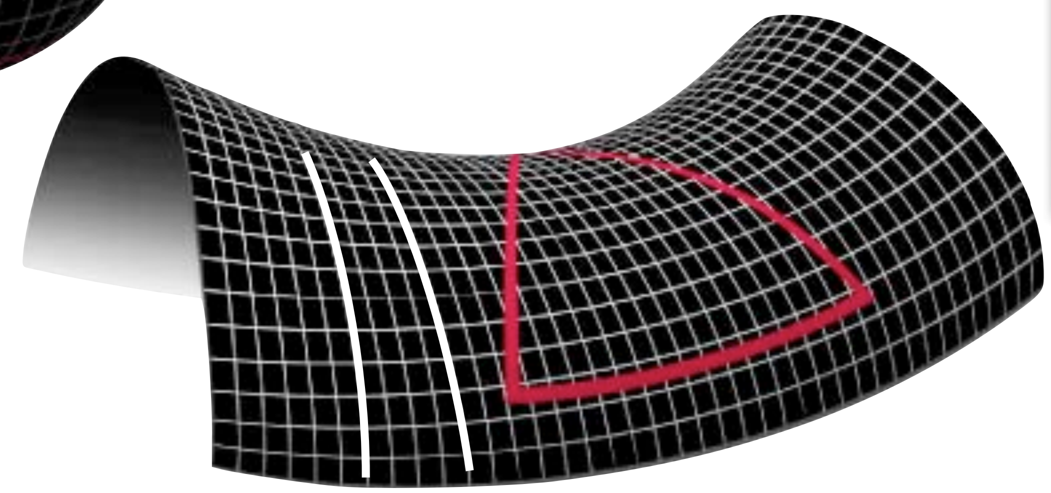
How could you know whether you live in flat space or a curved space?

Start truckin'

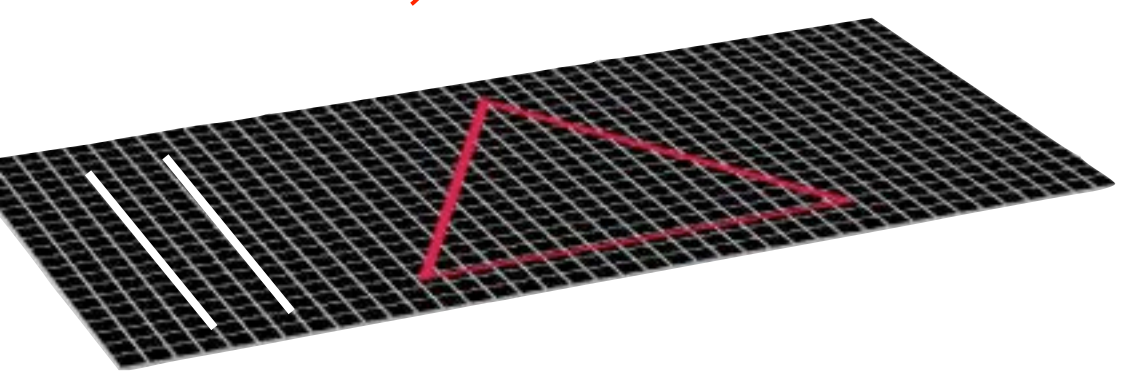
curvature, "k" - hypervolumes

$k = +1$,
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

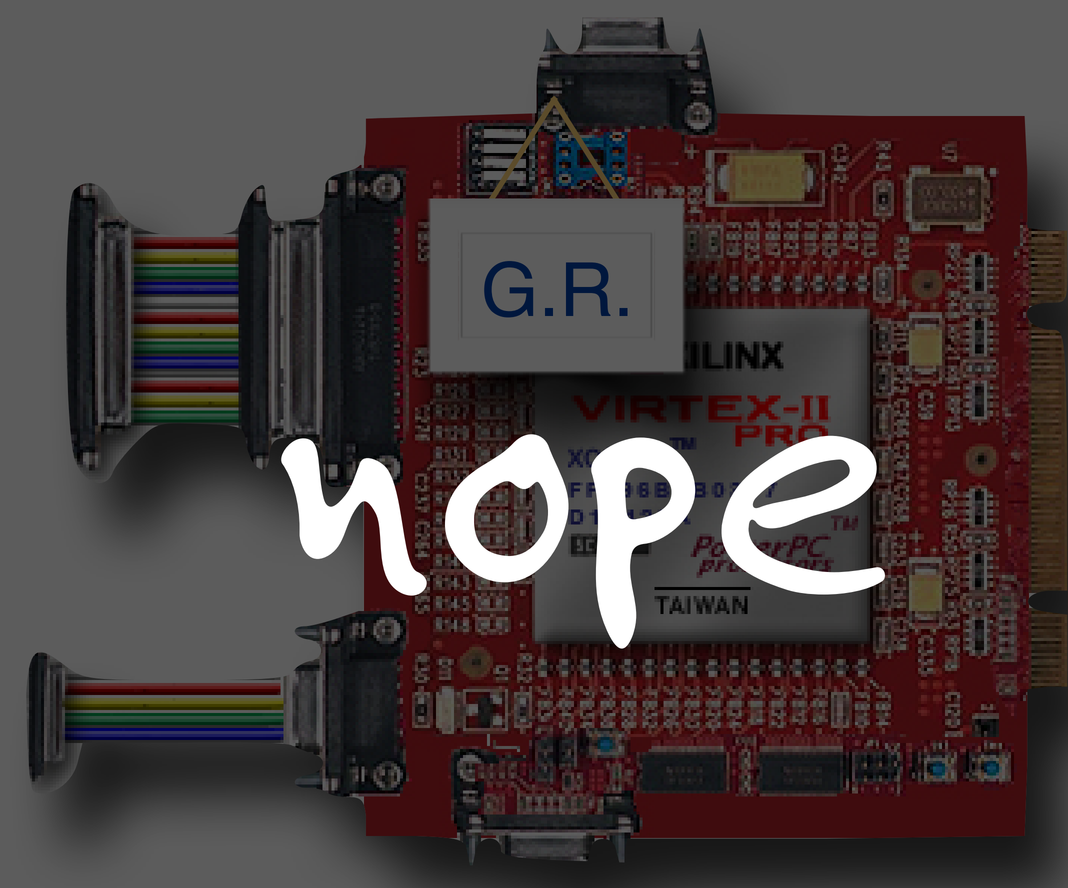
but if you try some time, you might just find you get what you need

or not.

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

What Einstein wanted:

$$G = T$$



Stable.
Finite.
Boundless.

So, no problem at infinity!

you can't always get what you want

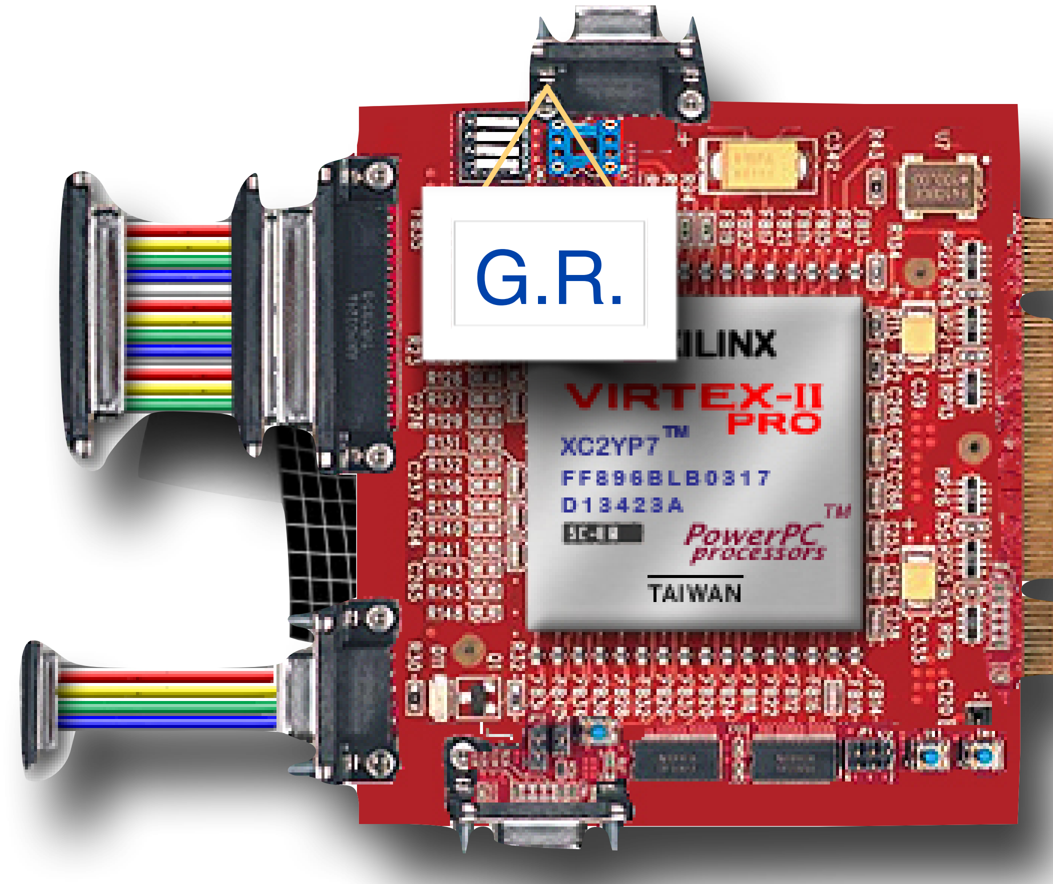
but if you try some time, you might just find you get what you need

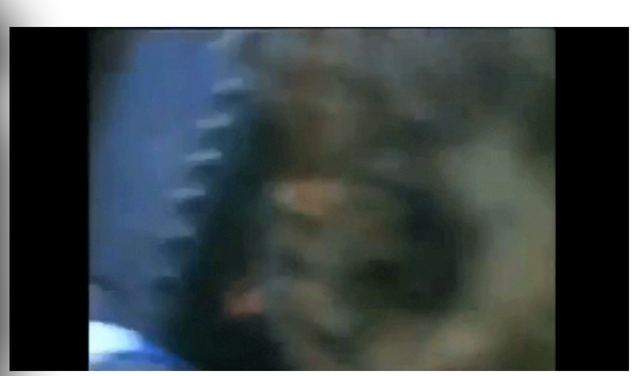
or not.

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

What Einstein actually got:

$$G = T$$





UNStable.
INFinite.
Boundless.

That's right. 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

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

$$G + \Lambda = T$$

the "Cosmological Constant"

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

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

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

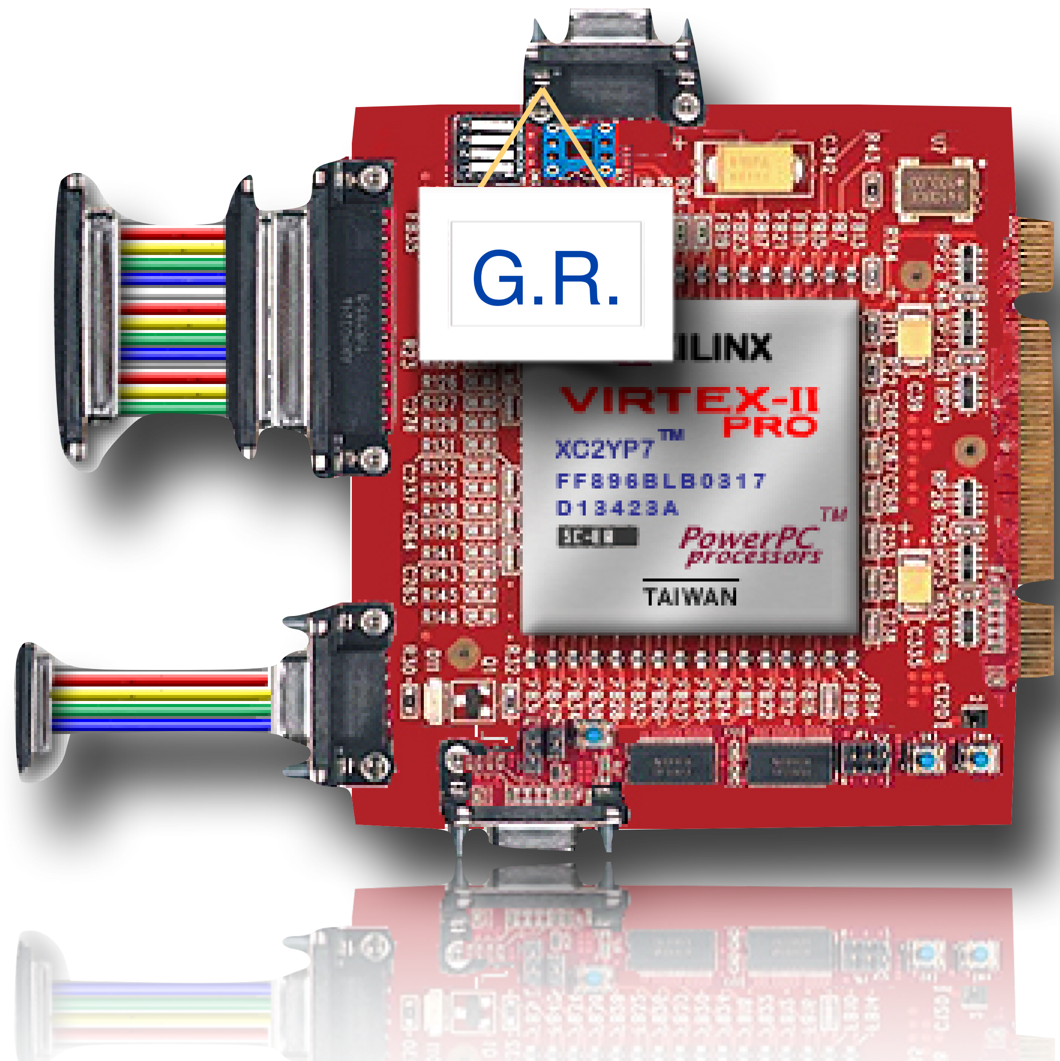
$$G = T$$

or

$$G + \Lambda = T$$

Wrong

$$G + \Lambda = T = 0 \text{ (no matter density)}$$

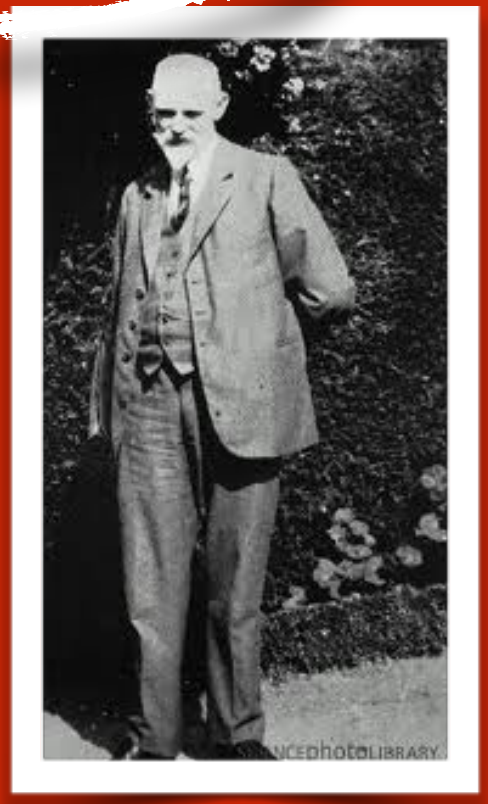


~~static.~~

about the uniqueness of his solution

Willem de Sitter

1917



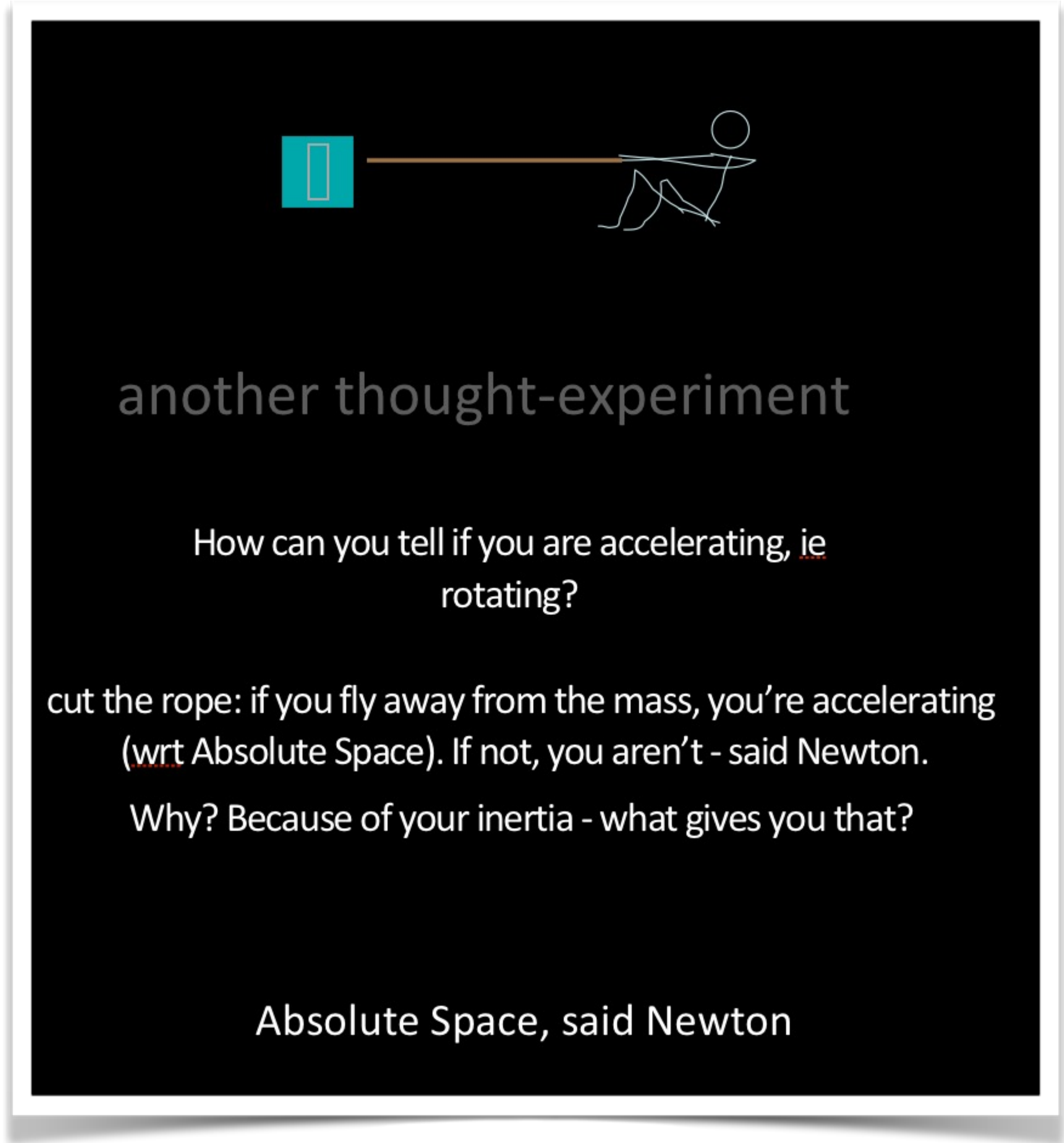
strictly geometry...so, what's the matter?

*Now wait a minute... **NO MATTER***
in de Sitter's model, empty universe!

Geometry of spacetime - by itself - actually causes spacetime to bend!! Einstein presumed only matter could do that.

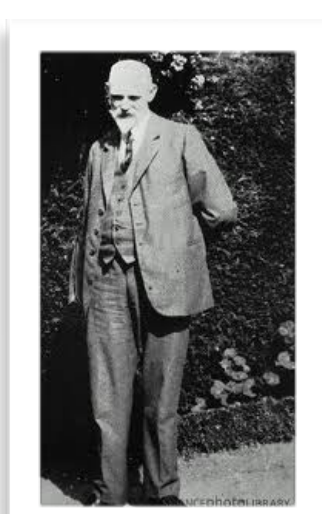
Einstein took it badly...even though colleagues and friends, he was very critical of de Sitter in print

remember the rope and knife?



The Prevailing Wisdom...matter in the Universe accounts for universally accelerated motion.

Einstein fervently believed that...named the principle Mach's Principle after his hero in Prague.

Along comes  with a Universe-solution that has NO MATTER, but gravity, nonetheless.

Einstein was convinced that only MATTER could warp spacetime!

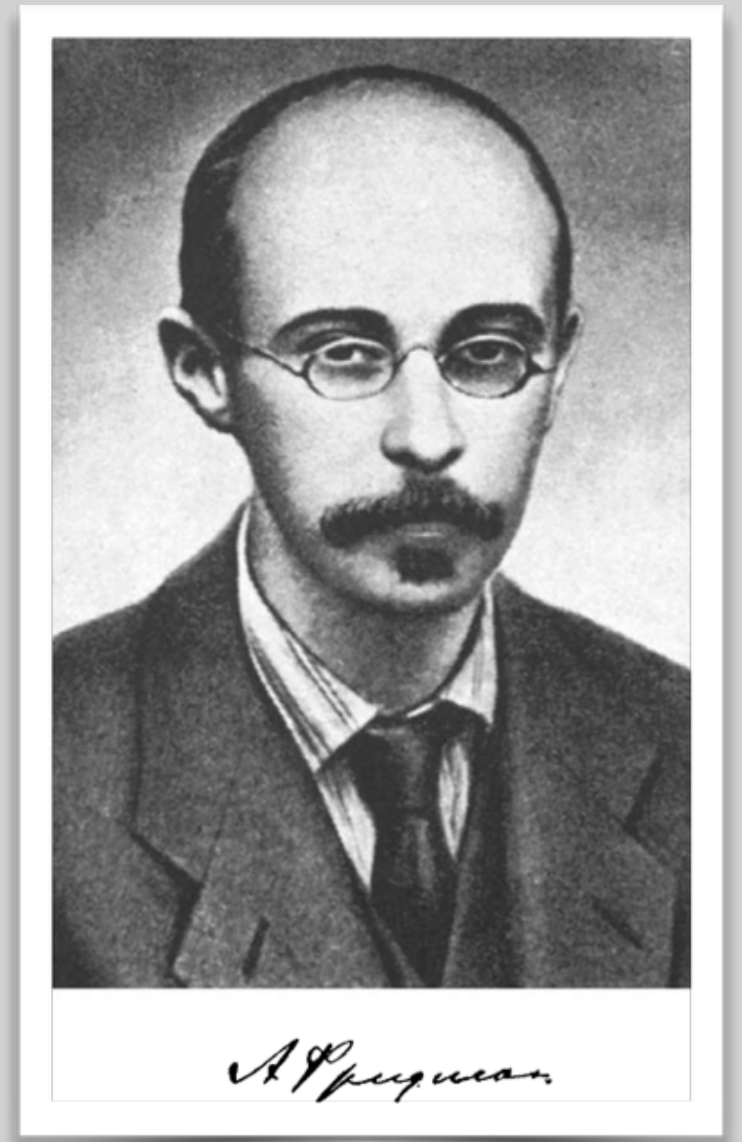
but as Feynman's advisor said many years later:

Alexander Friedman (1888-1925)

in 1922, 23

finds a **whole class** of solutions!

with and without Λ



Adding insult to injury, an unknown mathematical meteorologist from Russia opened The General Relativity Pandora's Box.

$$G = T$$
$$G + \Lambda = T$$

Now, the modern basis of GR solutions:

the "Friedman Solutions"

29 June 1922, submits paper "On the curvature of Space" to to *Zeitschrift für Physik*

Einstein didn't take it well.

“ The results concerning the non-stationary world, contained in [this] work, appear to me suspicious. In reality, it turns out that the solution given in it does not satisfy the [general relativity] equations.

18 September 1922

Einstein in a letter of complaint to the premier journal considering publication of Friedman’s work

Zeitschrift für Physik

“Considering that the possible existence of a non-stationary world has a certain interest, I will allow myself to present to you here the calculations I have made ... for verification and critical assessment. [The calculations are given] ... Should you find the calculations presented in my letter correct, please be so kind as to inform the editors of the Zeitschrift für Physik about it; perhaps in this case you will publish a correction to your statement or provide an opportunity for a portion of this letter to be published.

Friedman to Einstein, 6 December 1922

“ In my previous note I criticised [Friedman's work On the curvature of Space]. However, my criticism, as I became convinced by Friedman's letter communicated to me …, was based on an error in my calculations. I consider that Mr Friedmann's results are correct and shed new light.

May 1923
Einstein capitulating later in a letter to
Zeitschrift fur Physik

"

To punish me for my contempt for authority, Fate made me an authority myself.

Einstein in typical bumper-sticker mode. *mea culpa*

Friedman then traveled Europe promoting his work

In July 1925 took a record-breaking 7.4km balloon flight with meteorological instruments

By the end of August he was dead of Typhoid Fever...
badly, deliriously lecturing to an imaginary classroom
while separated from his pregnant wife.

“Edwin Hubble, I have watched for four years and I have never seen you study for ten minutes." He then paused for what was an awful moment for Edwin, and continued, "Here is a scholarship to the University of Chicago.”

Wheaton, Illinois HS Principal to Edwin Hubble at his 1906 graduation

Edwin Hubble 1889-1953

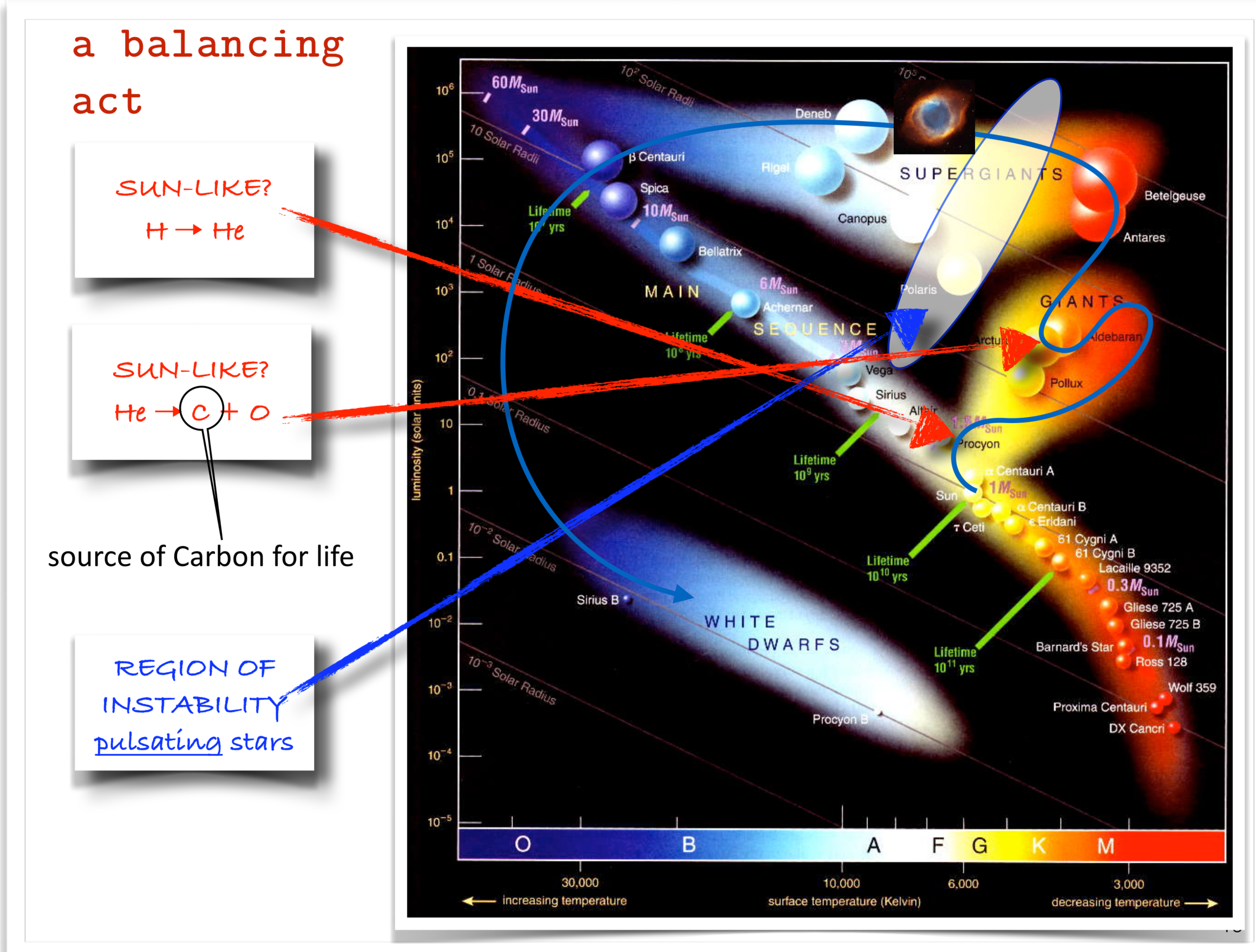
astronomer

discoverer of:

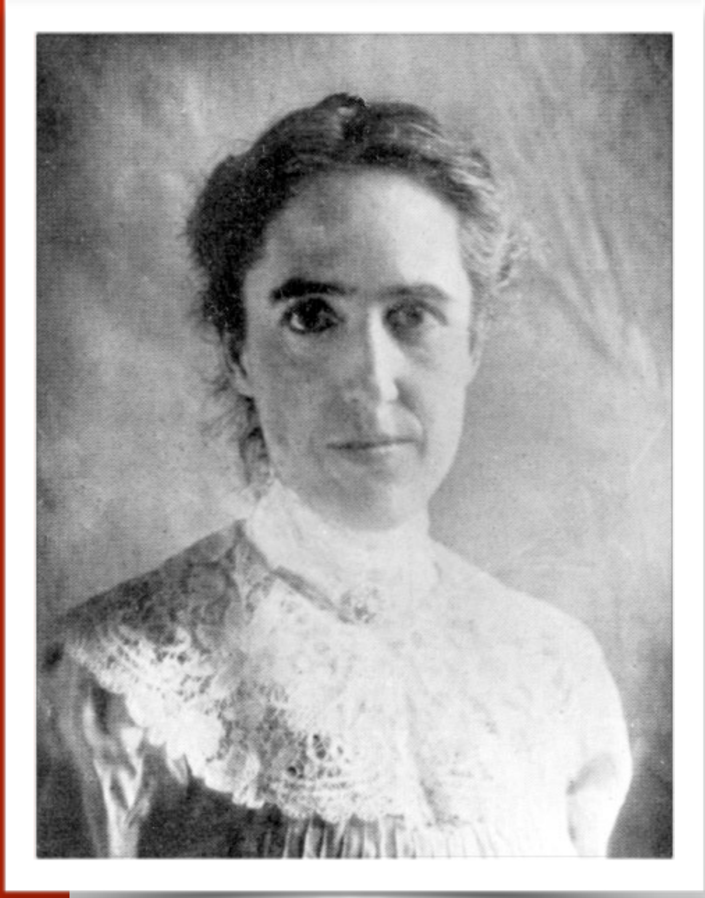
- the whole universe
- the expanding universe

remember HR diagram

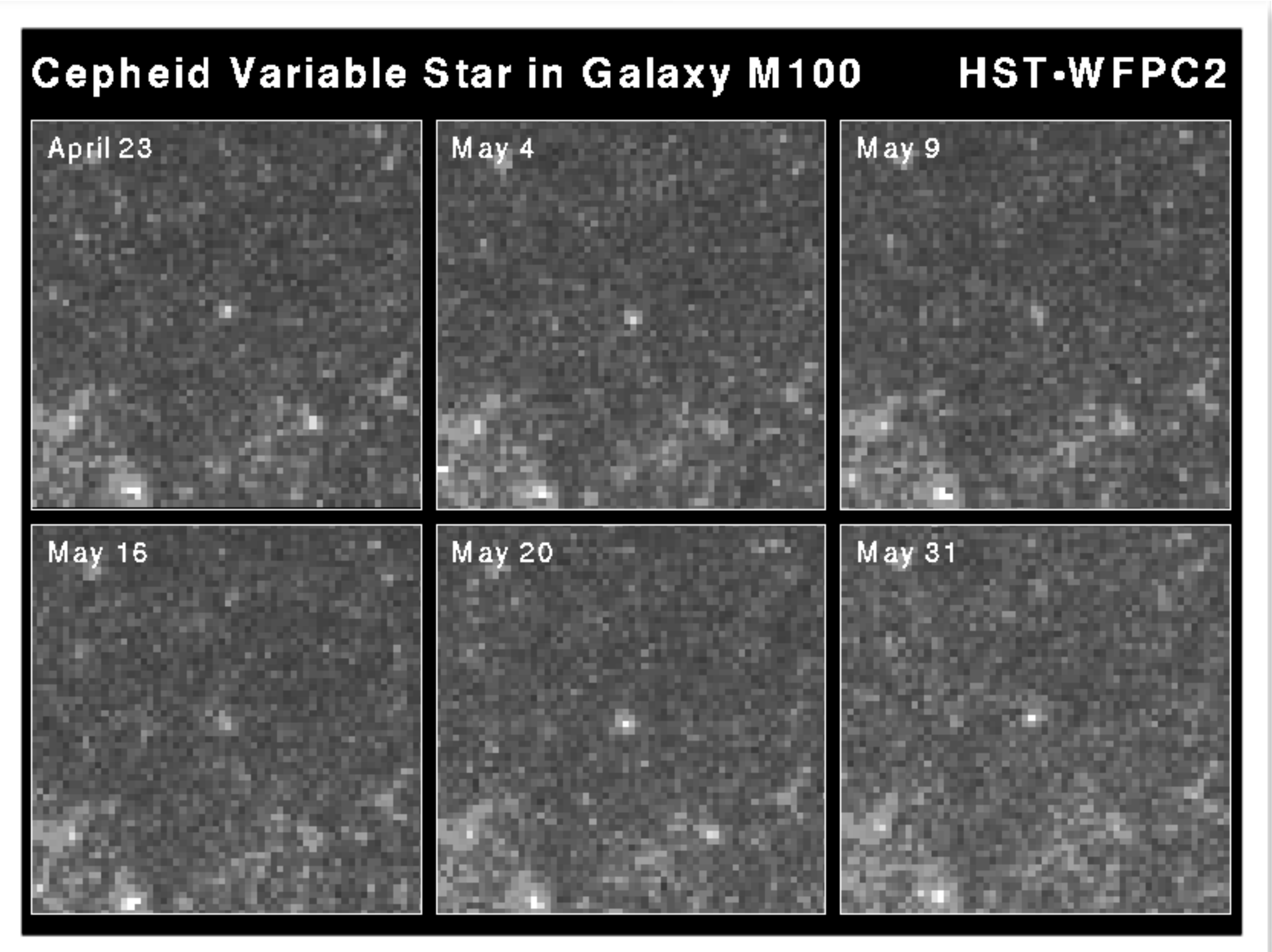
"instability" strip



distances are hard to determine



discovered by Henrietta Leavitt at Harvard

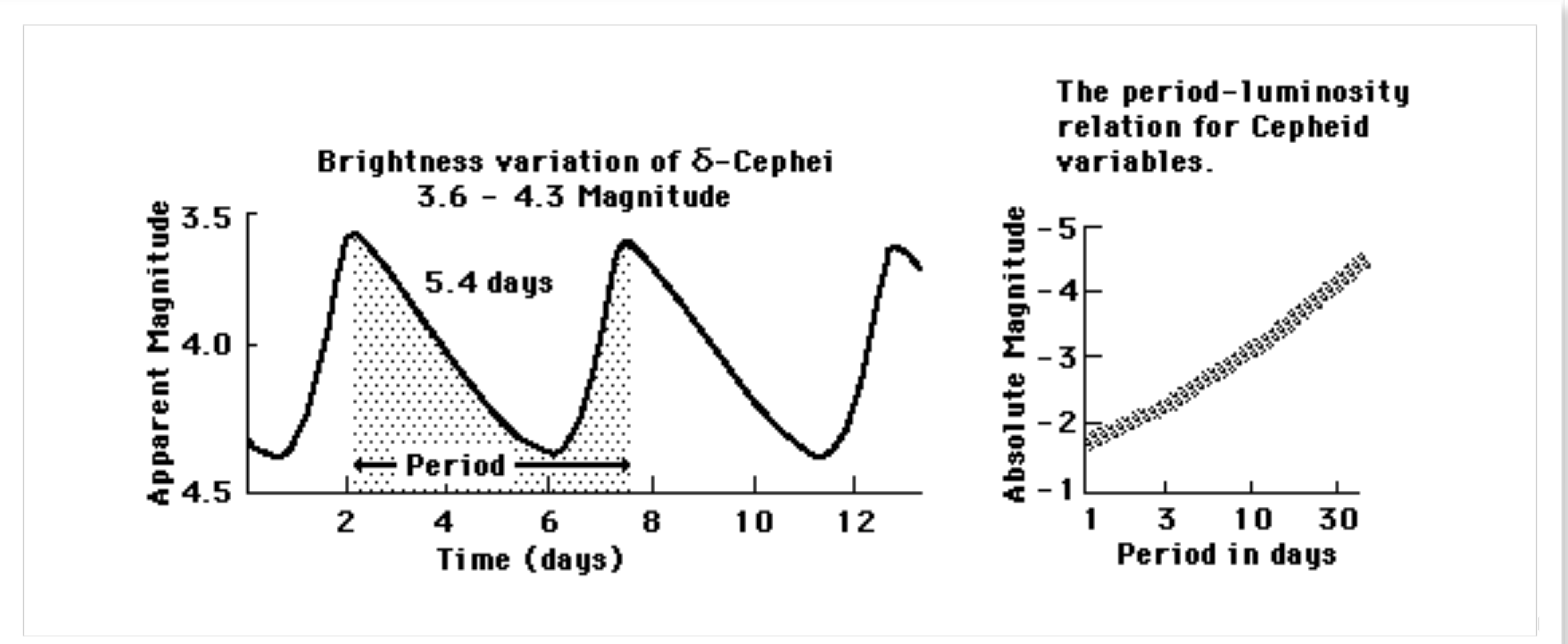


Cepheid Variable stars: the clue to galactic distances

absolute brightness is related to their period

since brightness goes like $1/R^2$ —> distance!

1912



bootstrapping

Knowing the absolute amount of light from an object

can calculate the distance

Cepheid Variable Stars are a yardstick

Hubble used Leavitt's formulation

Cepheids were everywhere!

were "nebulae" in the Milky Way?

or, is the universe much bigger?

M31, Andromeda

2900 thousand light years

1924: Andromeda is its own galaxy

A famous public argument ended.

The universe became HUGE... **overnight**!

M33, Triangulum

3000 thousand light years

NGC 6822, Barnard's Galaxy

1700 thousand light years

But wait. There's more.

Hubble was just warming up.