hi

Lecture 19, 21.03.2017

Cosmology 4

housekeeping

Question about anything?

I'll make a movie for you:

Marie Curie movie anyone?

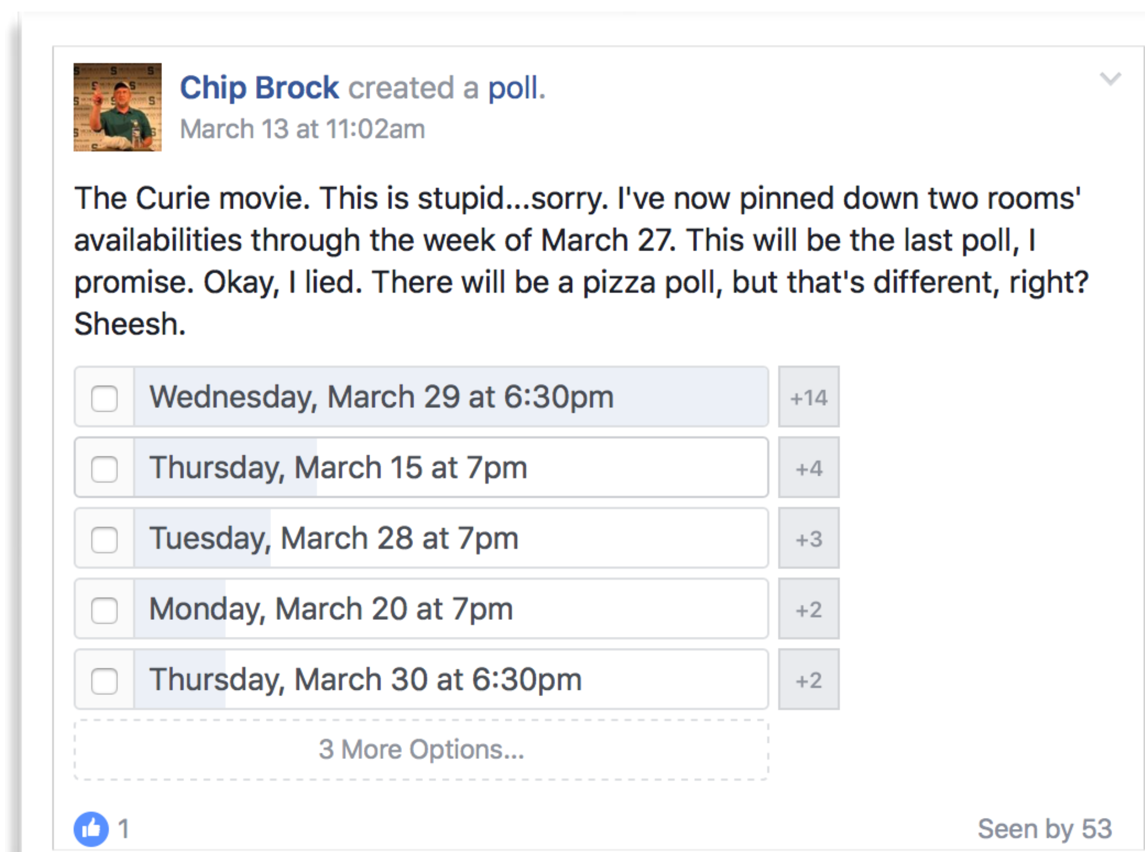
March 29: 6:30pm, BPS 1400

I'll poll for pizza this week

FakeFacebook is due April Fools Day. tee hee

Blog read-reflect project has started.

Did you notice that the homework is in MasteringAstronomy?



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

Cosmology 4

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

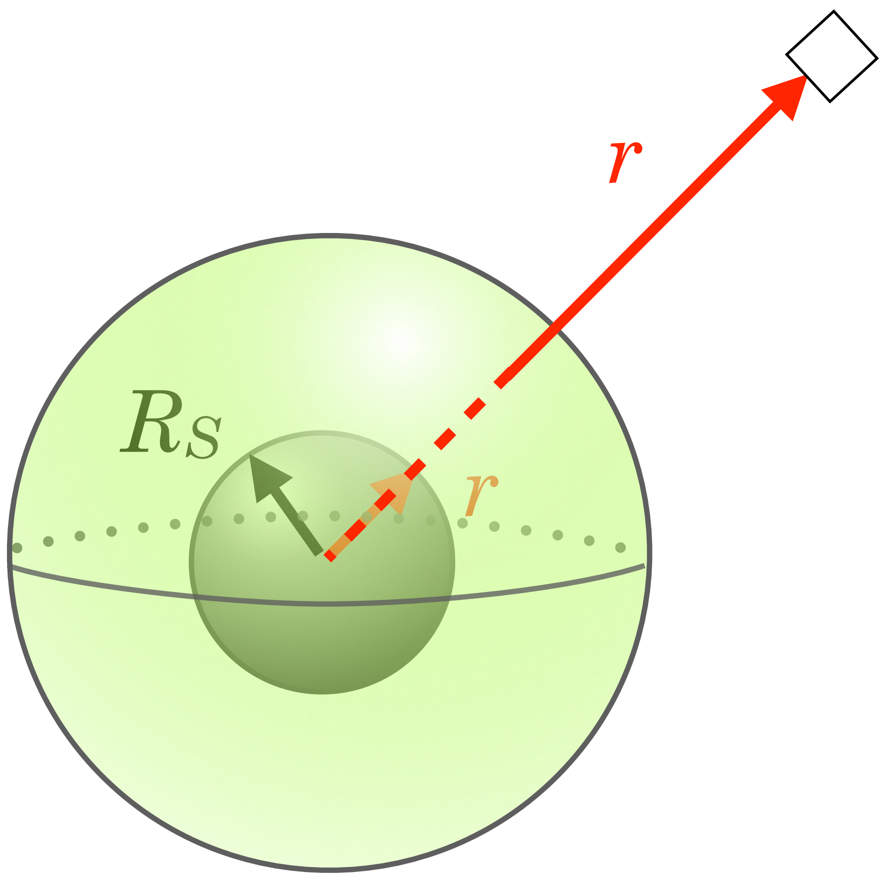
Nature turns viscous

Stellar BLACK HOLE

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 $r = R_S$?

$g_{00} = 0, \quad g_{11} = \infty$

time appears to stop for an outside observer!

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

space and time terms change sign!

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

outside of ~3R_S

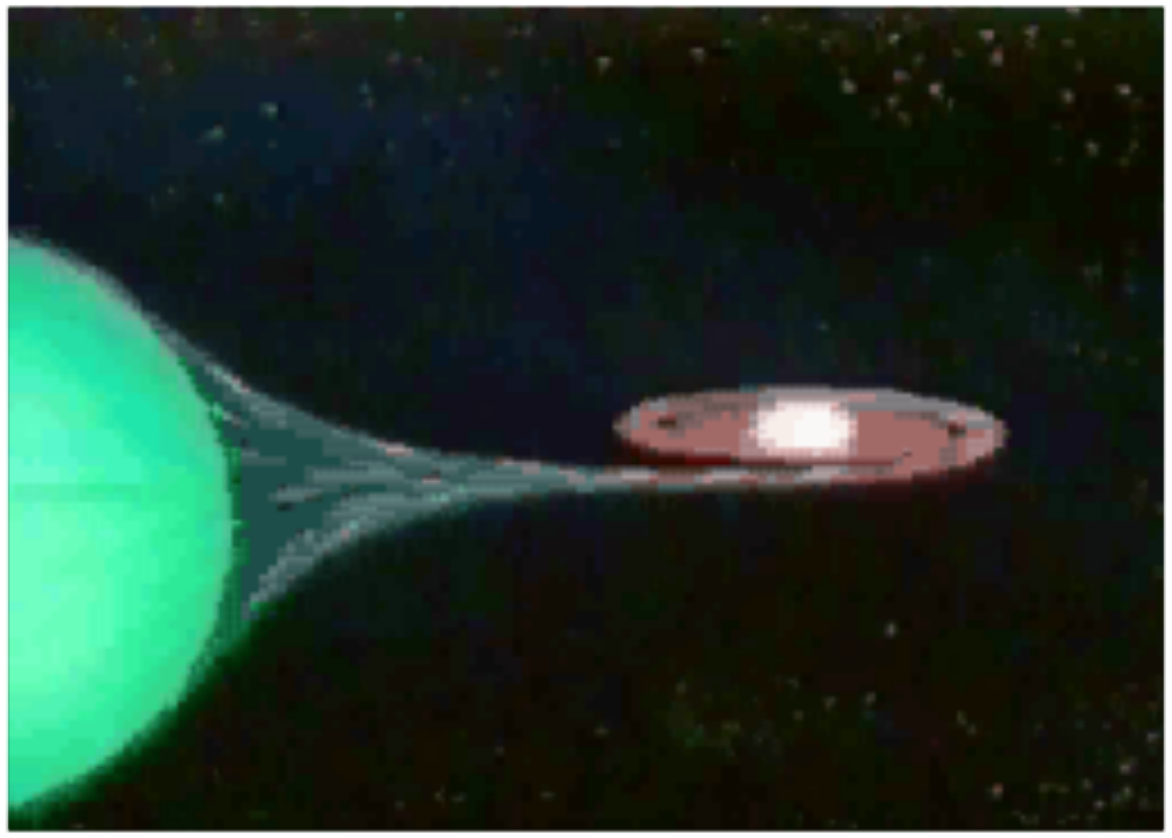
a black hole behaves like a normal object with Newtonian-like gravity

anything within R_S – the "**event horizon**" – is permanently attracted

So, how are they found?

Because they're hungry.

can detect the "accretion disk" which radiates



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

Radiate...X-Ray, radio frequencies typically

Three kinds:

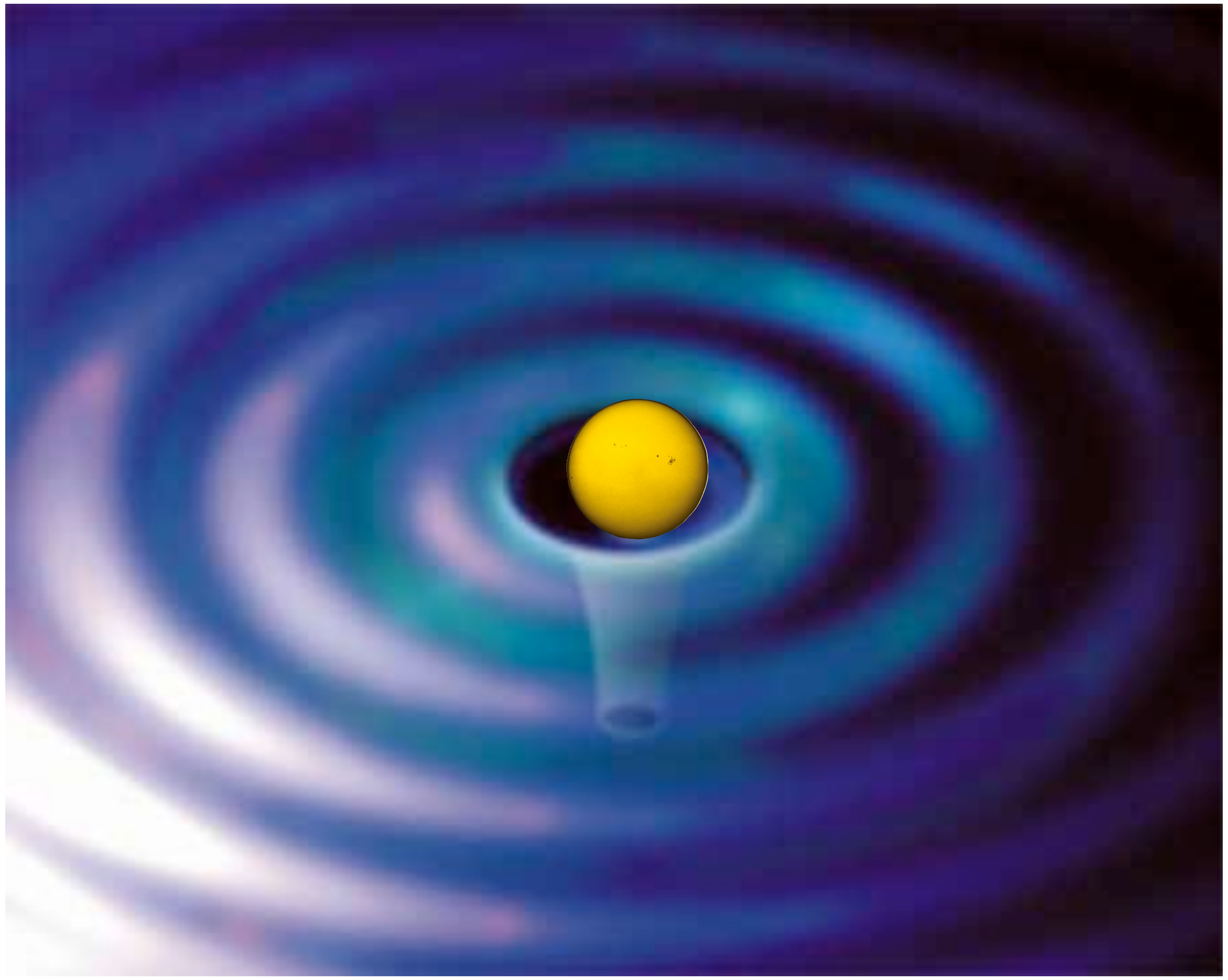
1. **Stellar black holes** - 100's found with Hubble
2. **Supermassive black holes** - seems that all galaxies have one: billion's of stars' worth
3. **miniature black holes**. - complete speculation, a gleam in some theorists' eyes

accelerating charges

remember?

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

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

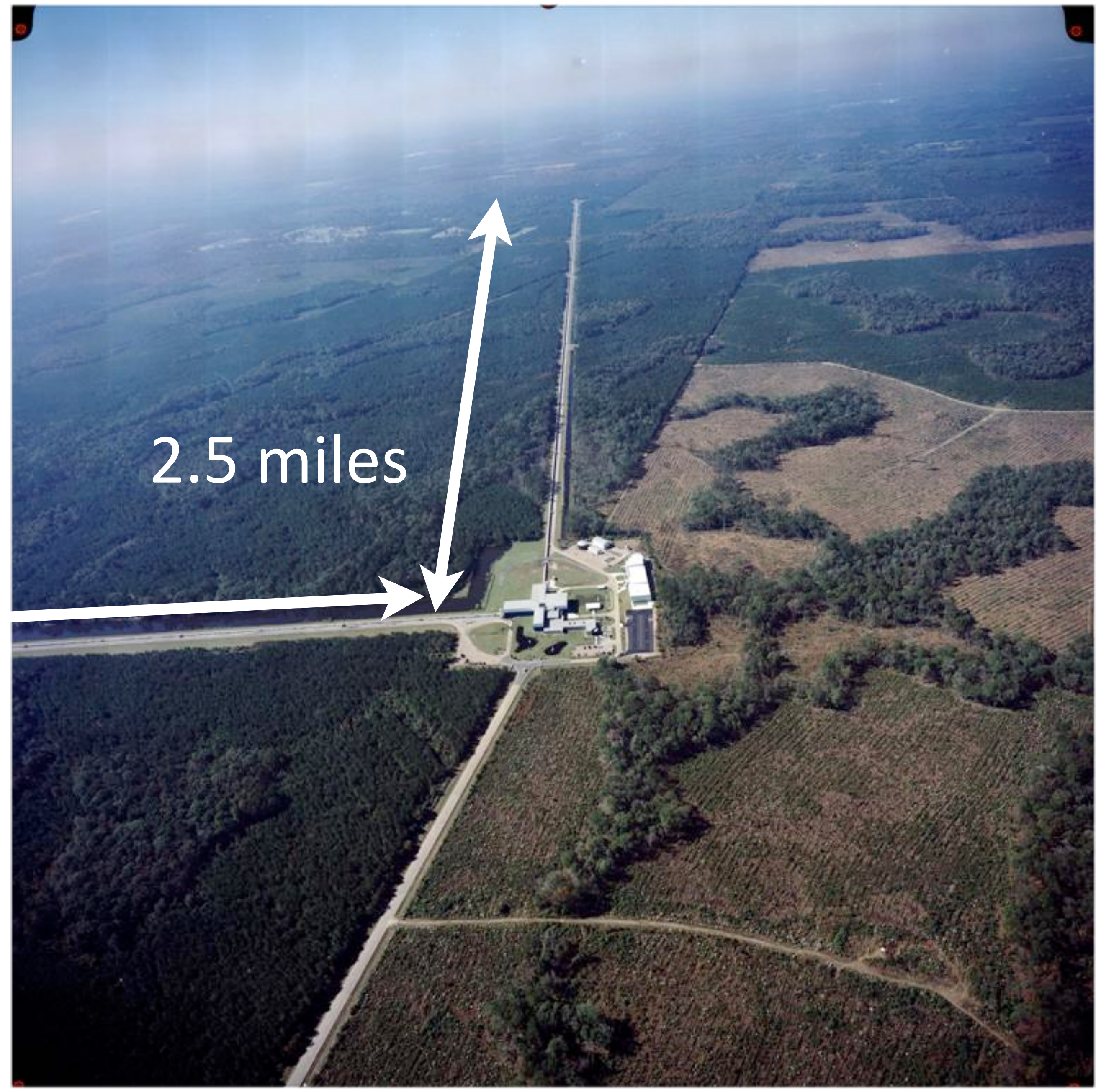


Disturbances in geometry of spacetime itself.

LIGO

Laser Interferometer Gravitational-Wave Observatory

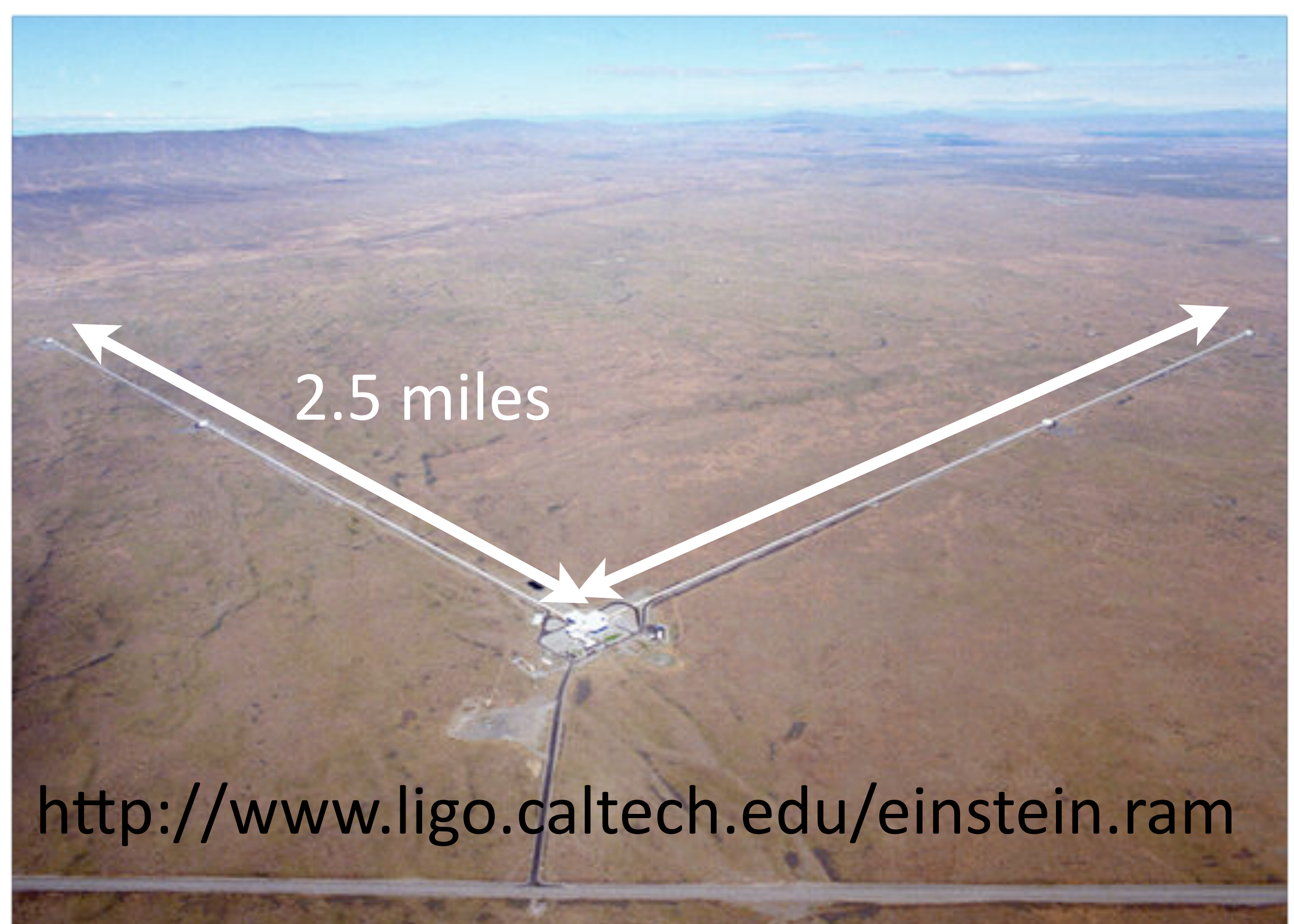
intergalactic, colliding binary, neutron stars, gamma ray bursts, black holes, colliding galaxies,



looking for shrinkage of one arm when gravitational wave passes by

need precision smaller than a proton radius

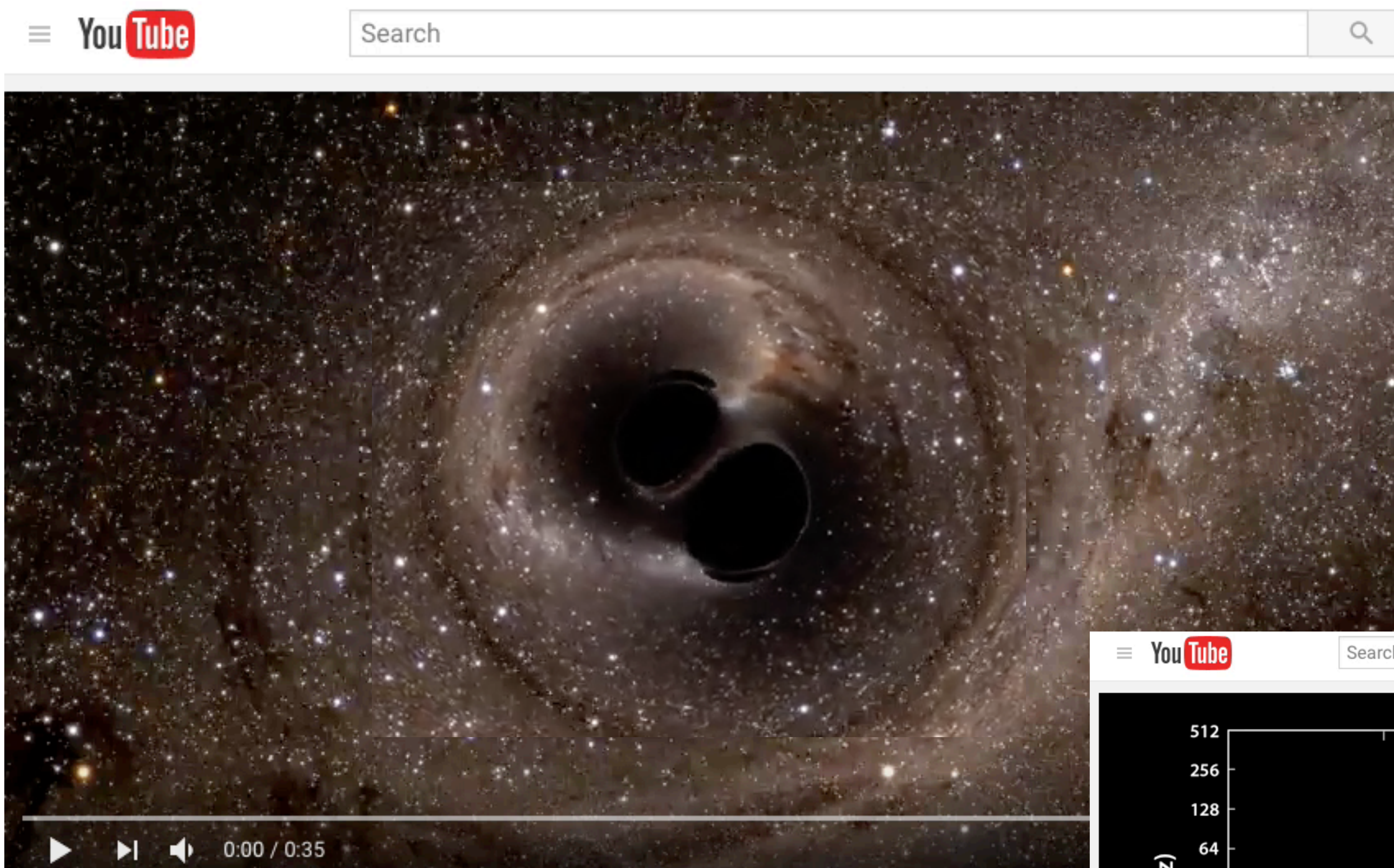
Livingston, LA



Hanford, WA

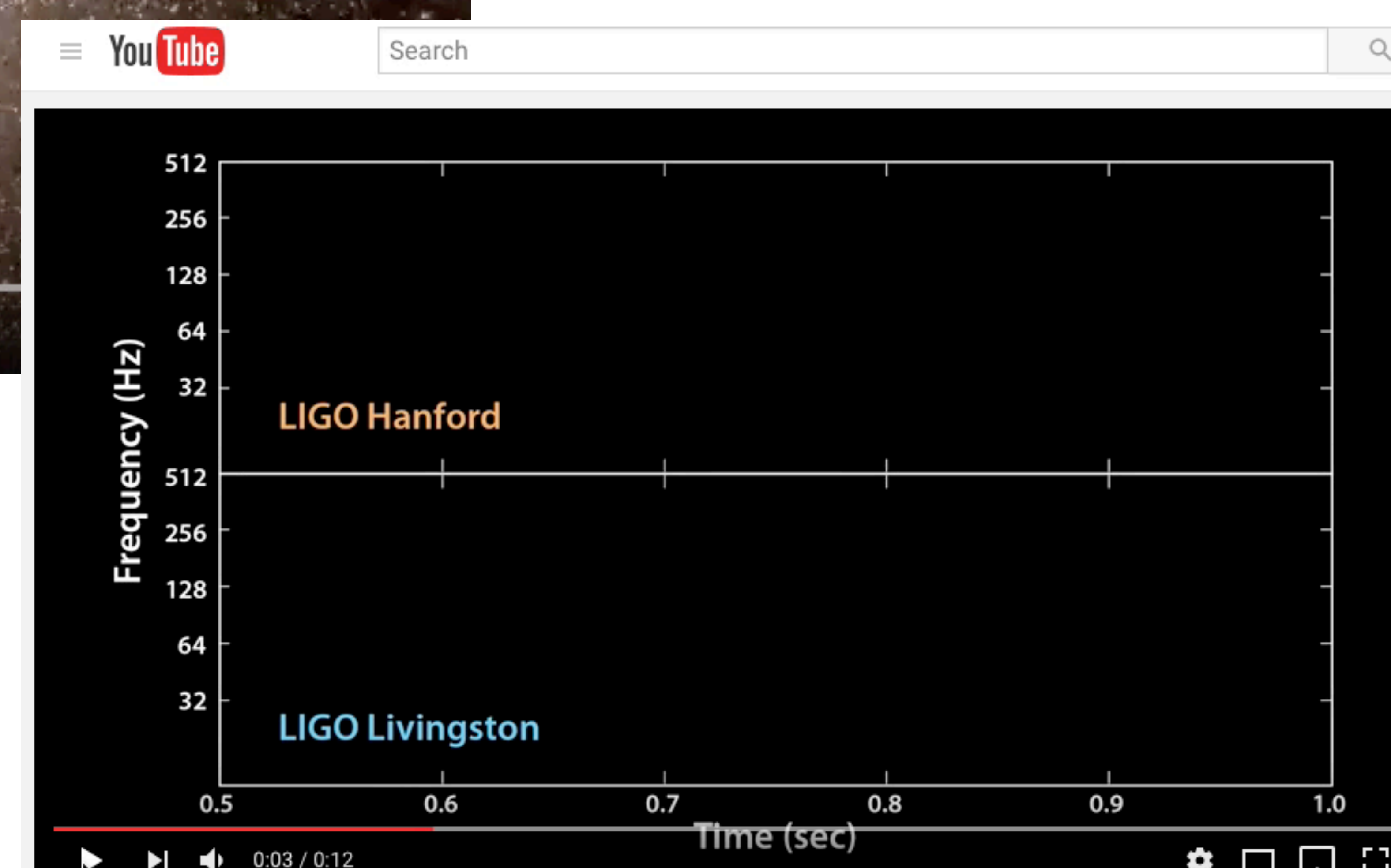
what's going on

GW150914: merging black holes



September 14, 2015 at 09:50:45 GMT

36 Msun + 29 Msun → 62 Msun ?



in 1917 the universe presumed by all to be:

- static, eternal
- limited to the Milky Way

that's it.

cozy.

`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

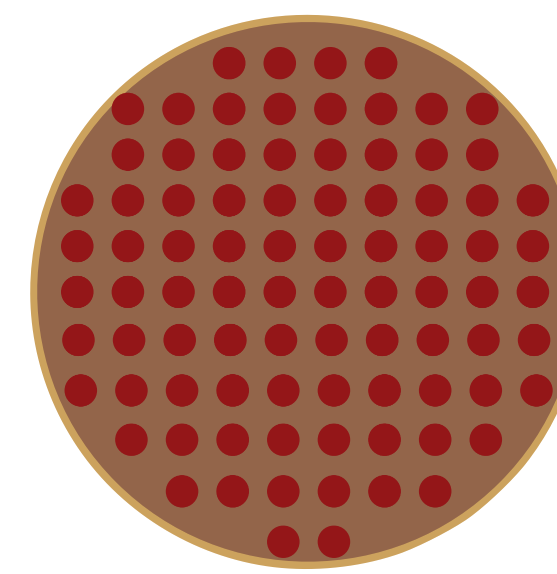
rests on the Cosmological Principle

It doesn't matter where you are.

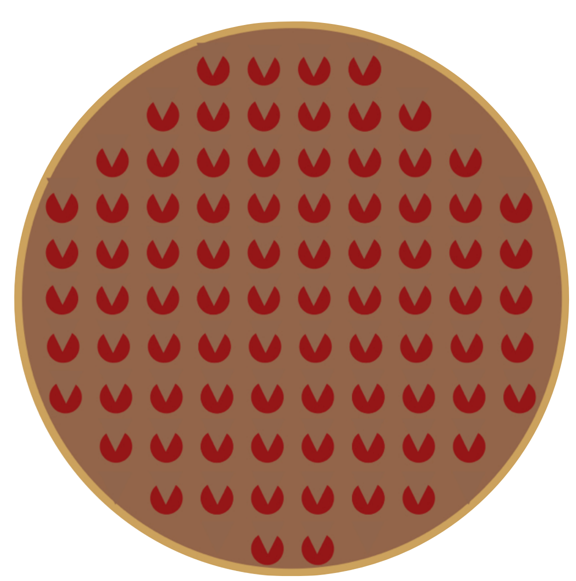
Viewed on sufficiently large distance scales, there are no preferred directions nor are there preferred places in the Universe.

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

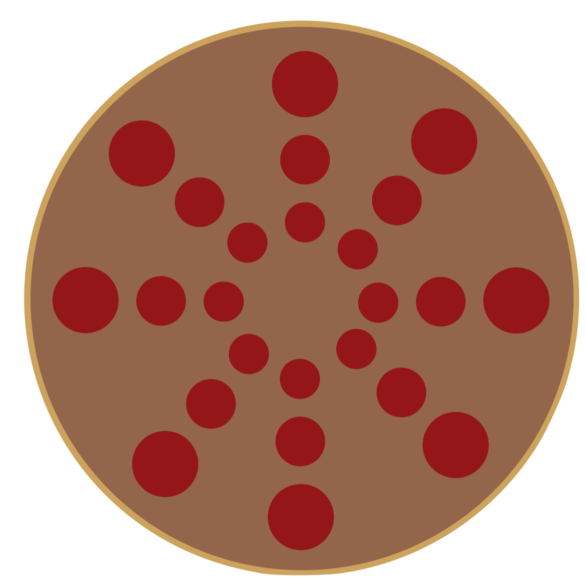
my Famous Probable Planar Pepperoni Pizza Probe



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?

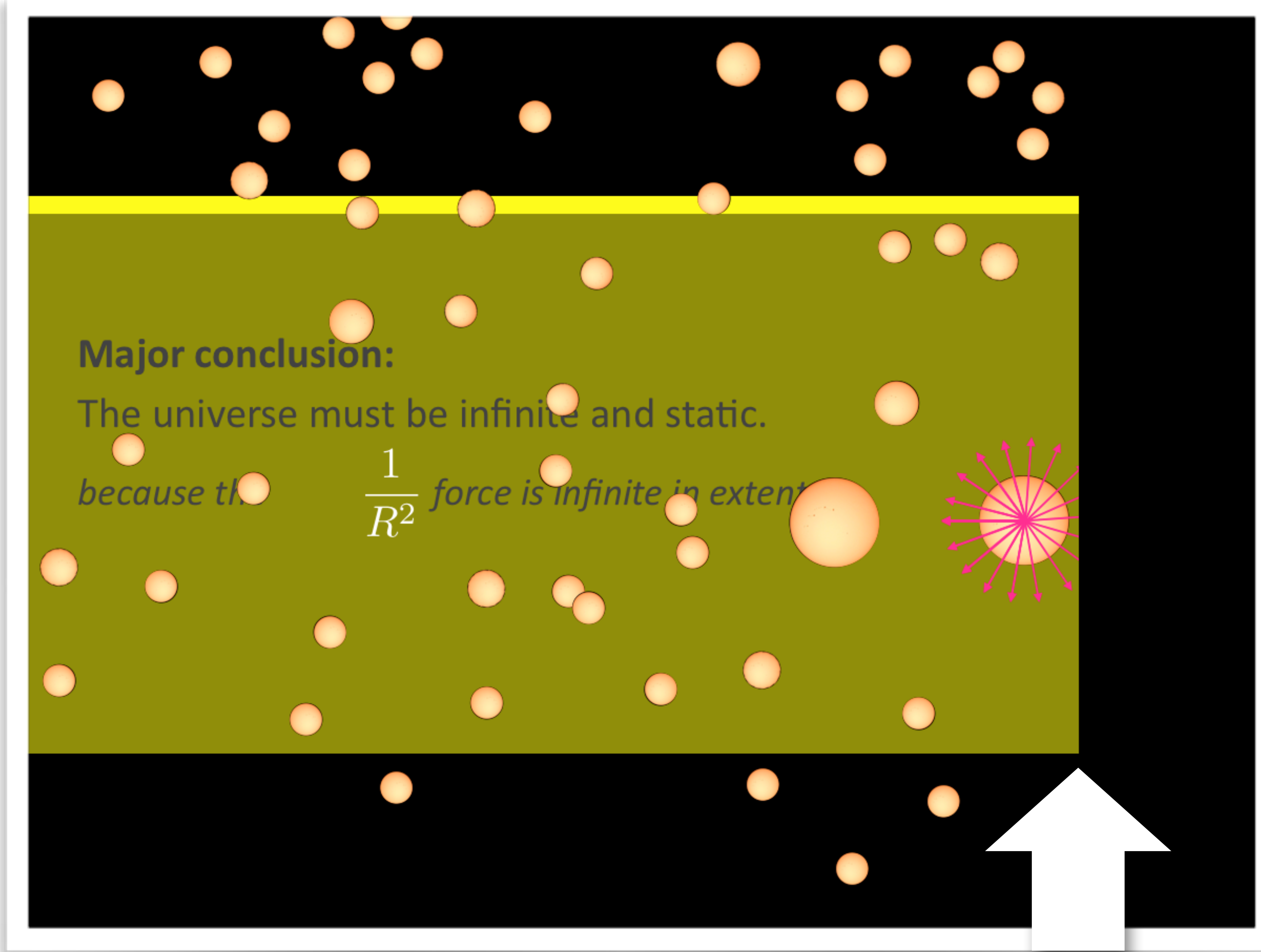
The current density of matter in the universe is about 6 protons/m^3

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!

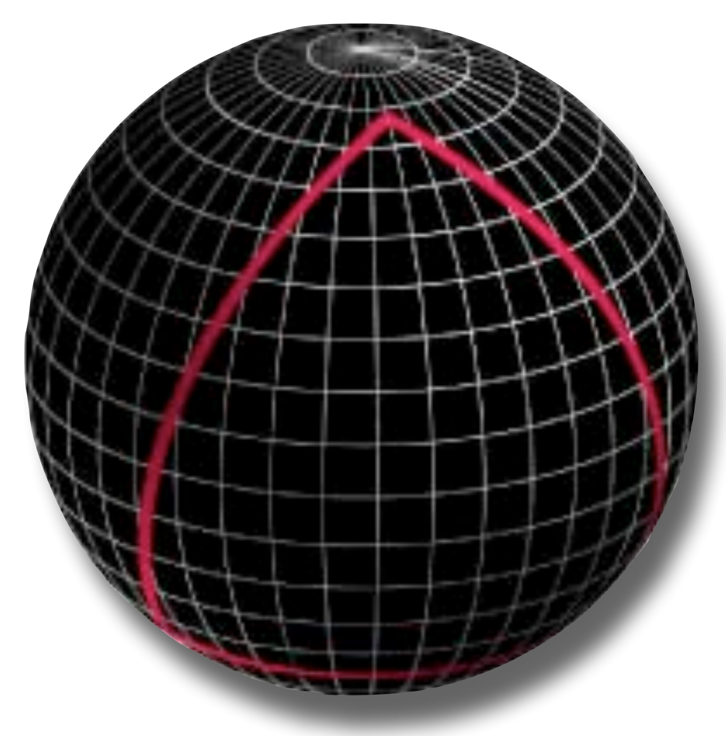


an edge to the universe was Newton's worry

But he was smarter than Newton

And he owned a tool to erase infinity!

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!

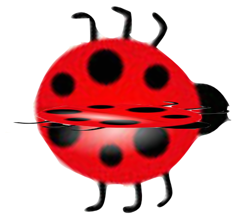
suppose you could start out in a spaceship

always keeping your starting spot behind you

you could then return to where you started!

hypervolumes: multidimensional geometry

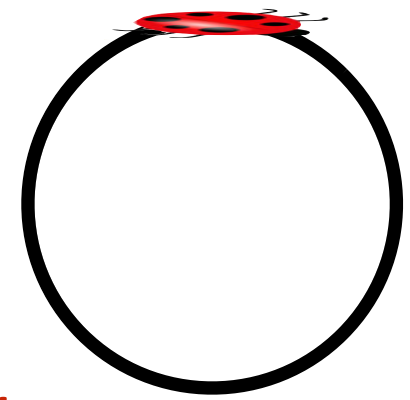
Suppose you're a 1 dimensional being.



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.

Outside of the "view" of the bug.

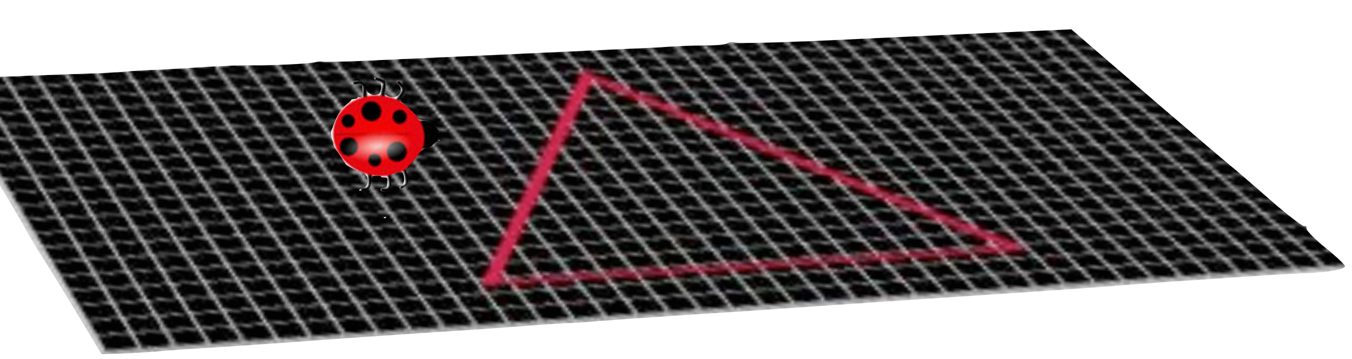
Bug only knows forward and backward...

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

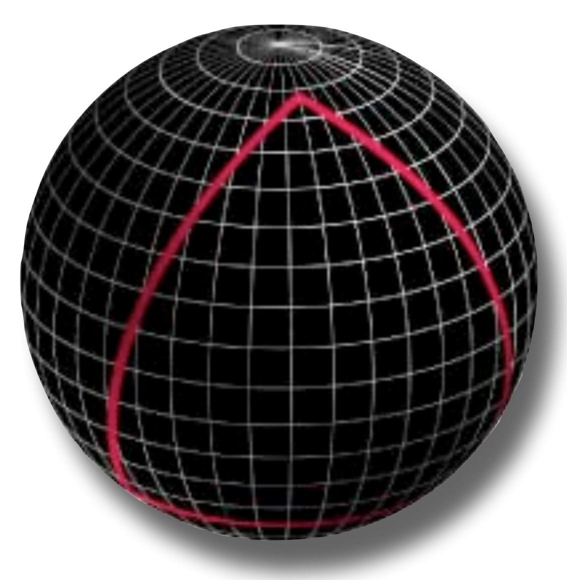
Suppose you're a 2 dimensional being.

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 -

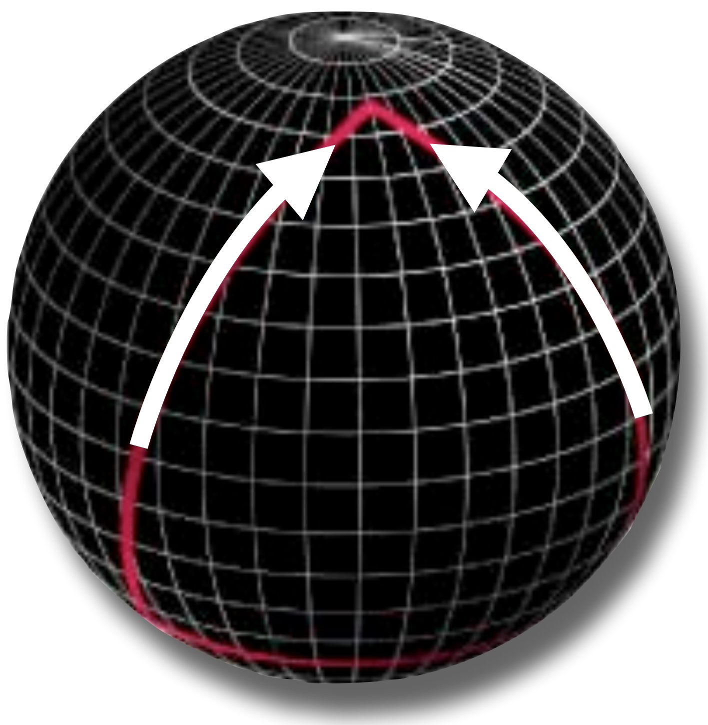
which is where the curvature is...

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

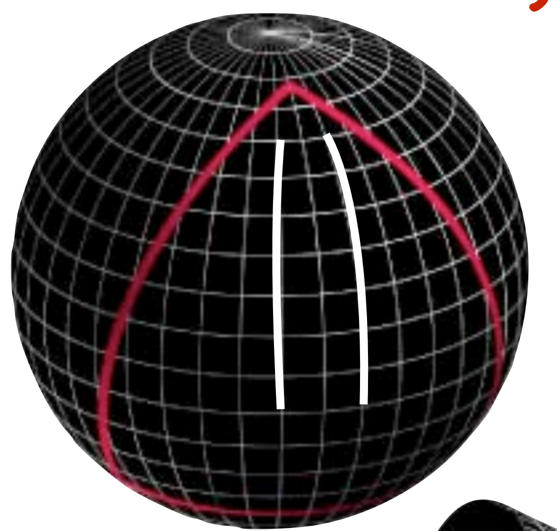
3 dimensional surface
embedded in a
4 dimensional spacetime
hypervolume

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

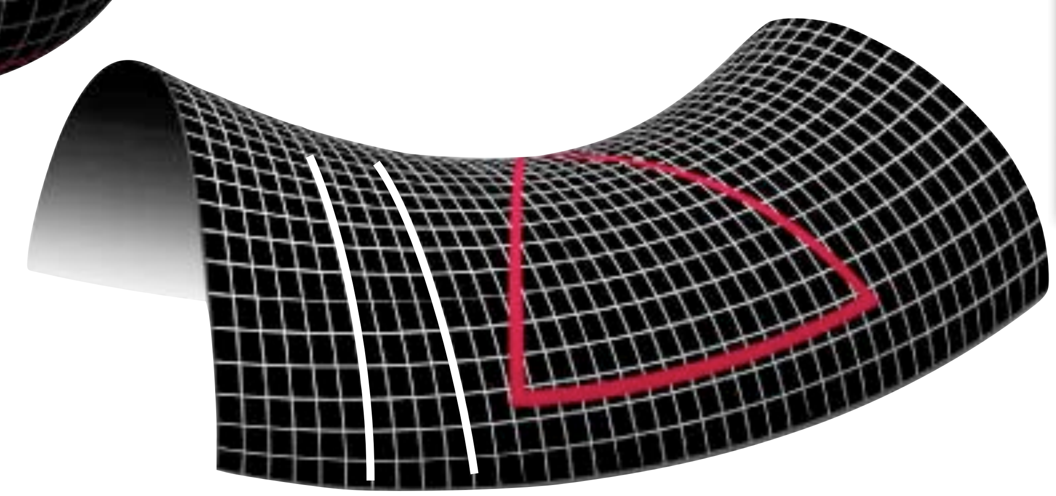
How could you know whether you live in flat space or a curved space?

Start truckin'

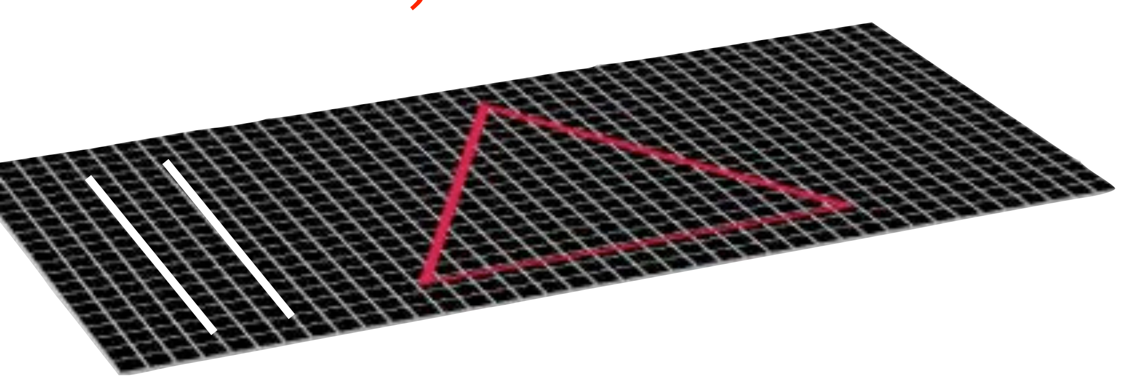
curvature, “k” - hypervolumes



$k = +1$,
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

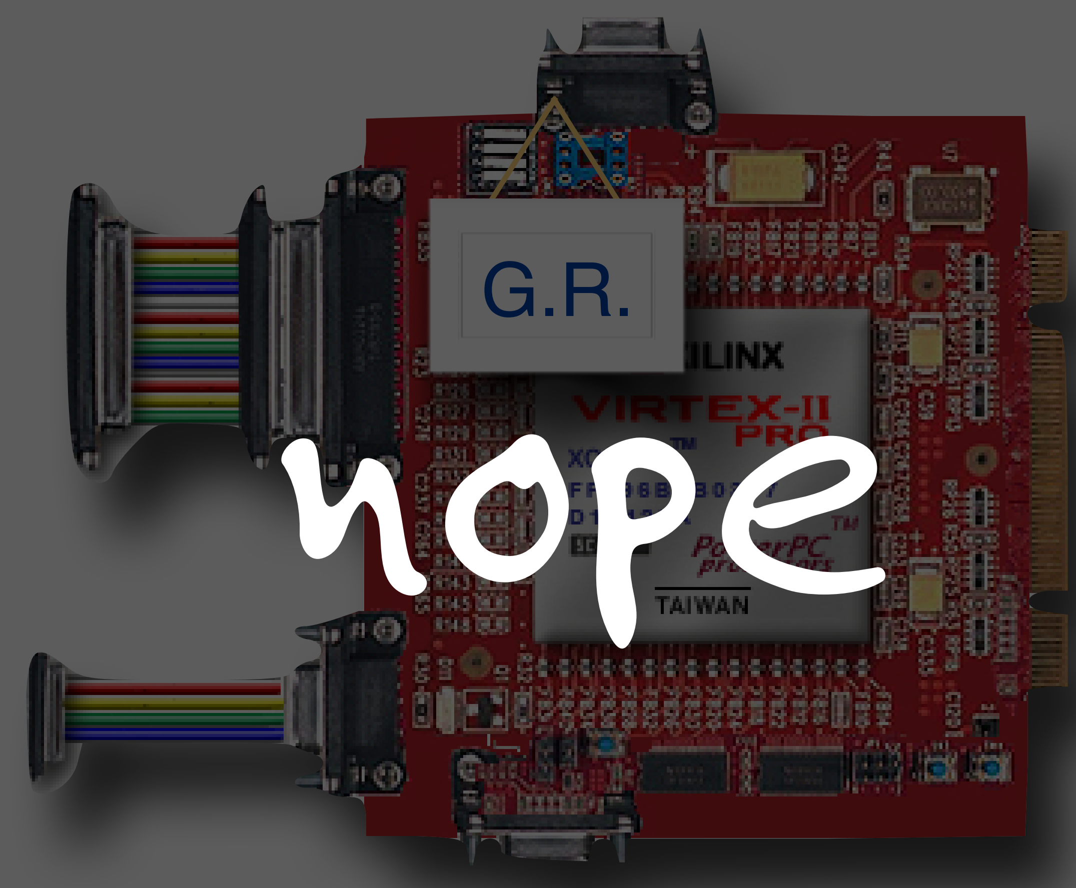
but if you try some time, you might just find you get what you need

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

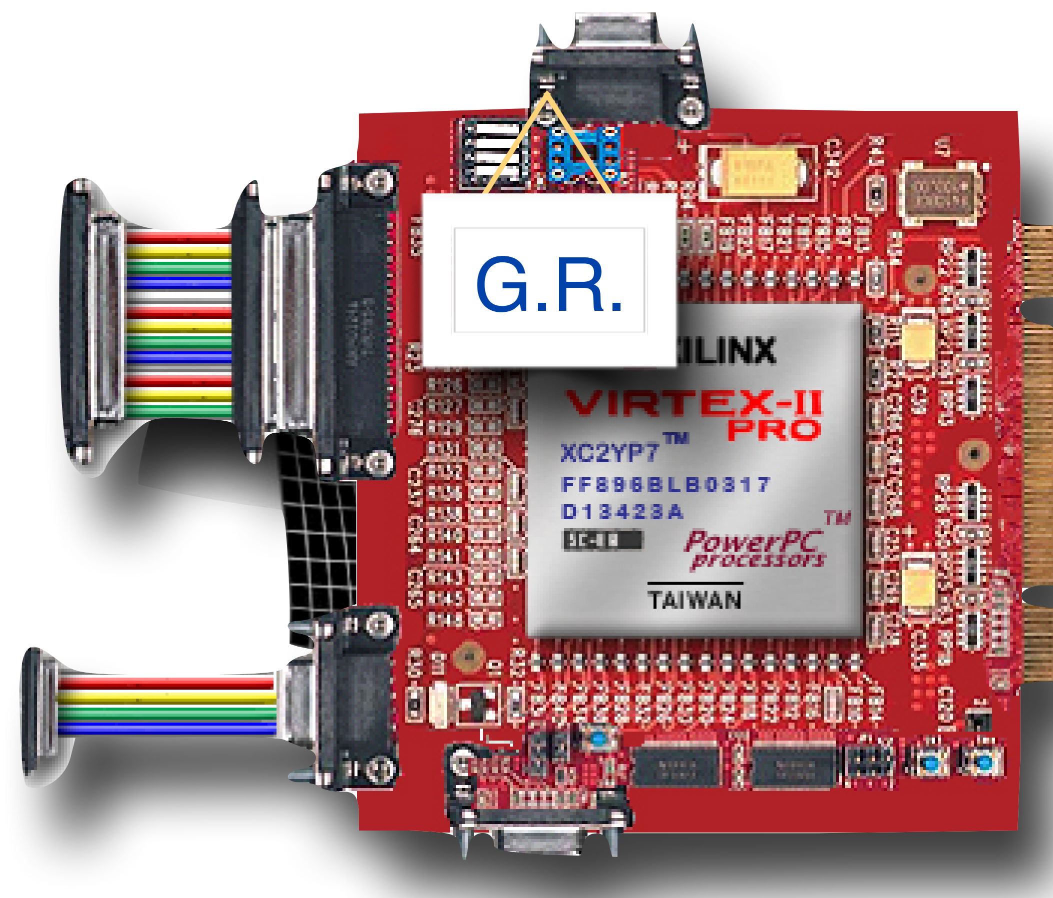
but if you try some time, you might just find you get what you need

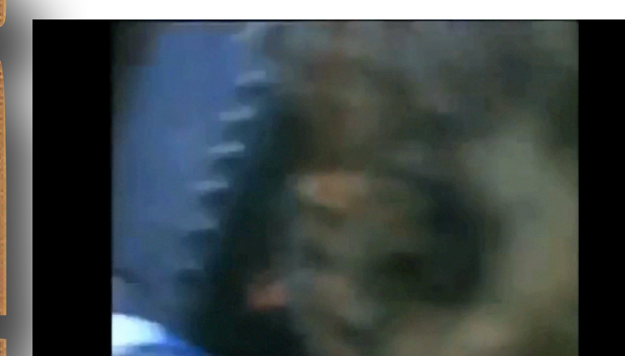
or not.

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...

$$G + \Lambda = T$$

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

the "Cosmological Constant"

"...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

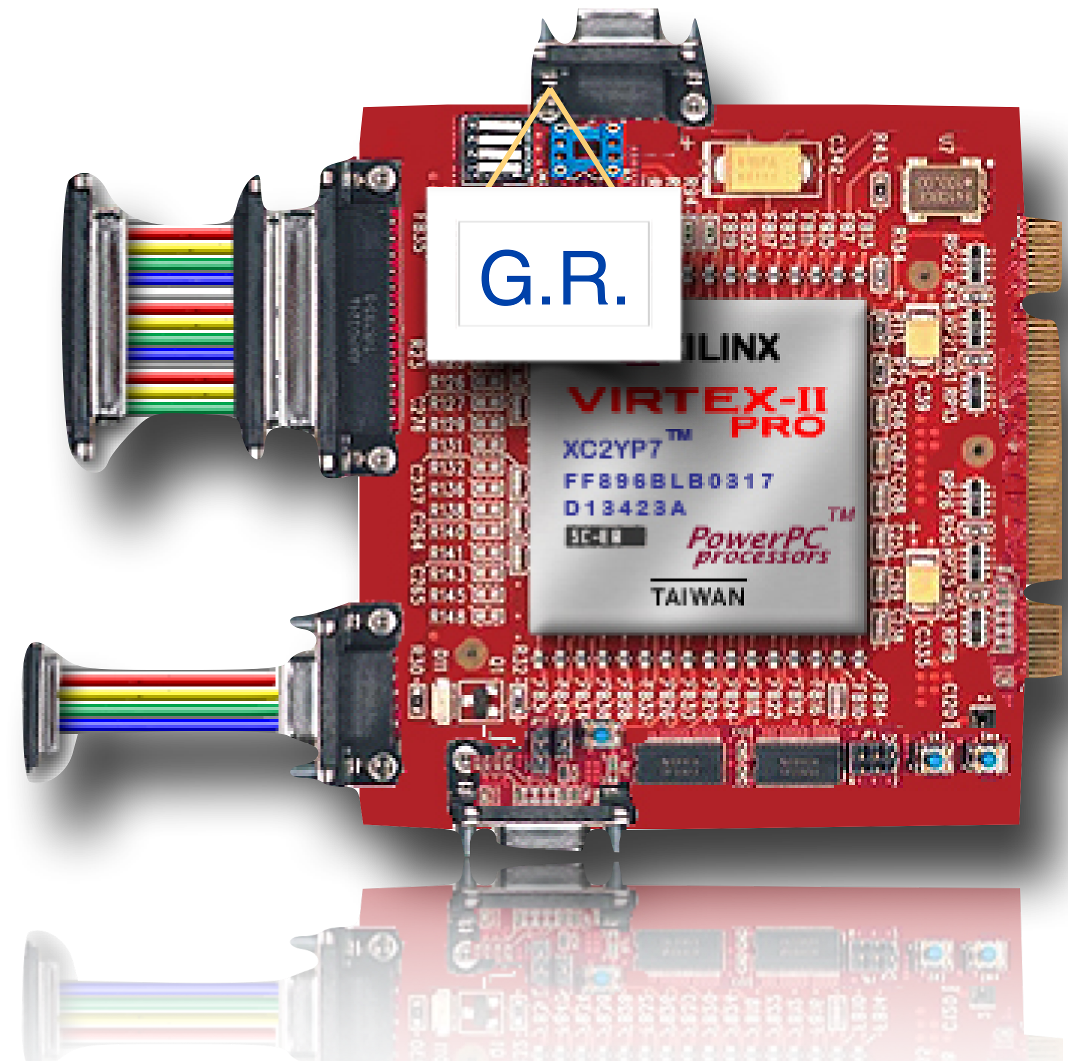
$$G = T$$

or

$$G + \Lambda = T$$

Wrong

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

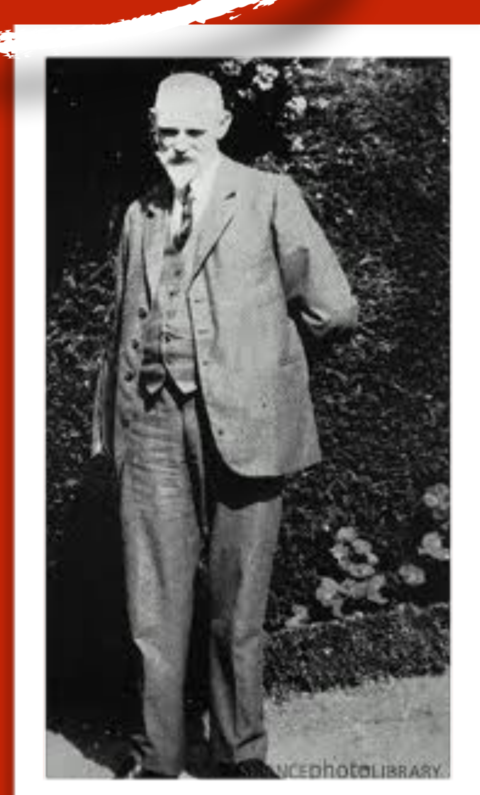


~~static.~~

about the uniqueness of his solution

Willem de Sitter

1917



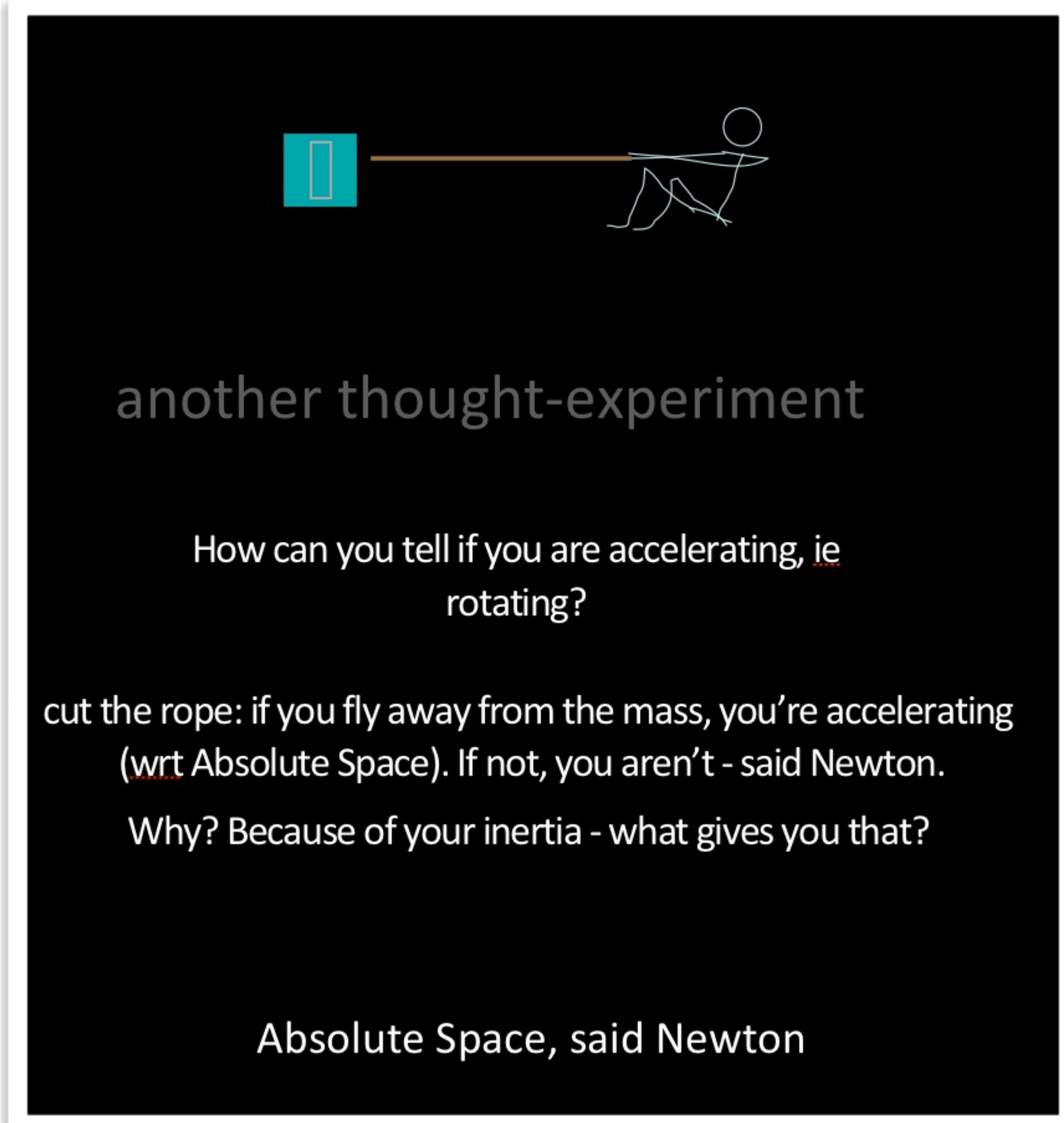
strictly geometry...so, what's the matter?

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.

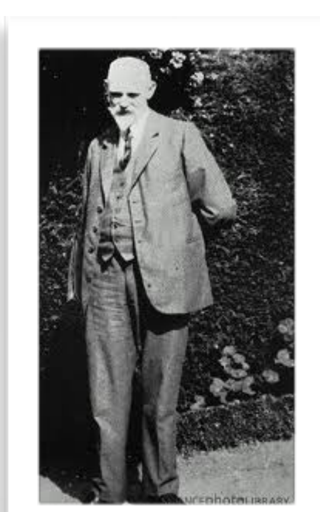
Einstein took it badly...even though colleagues and friends, he was very critical of de Sitter in print

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!

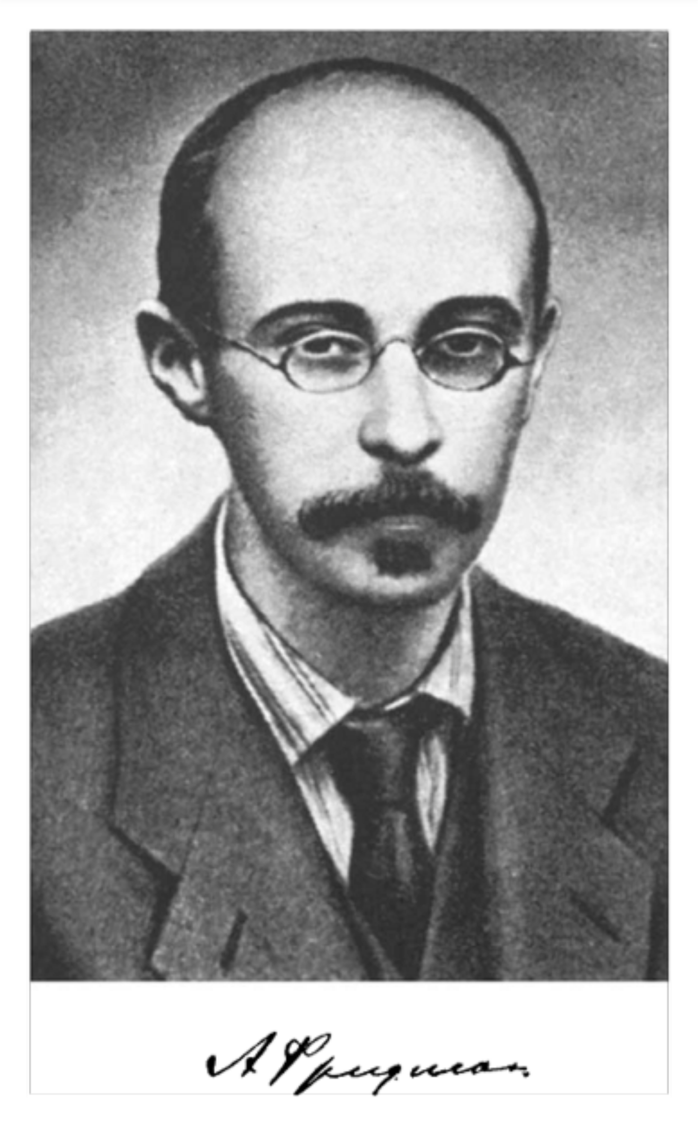
but as Feynman's advisor said many years later:

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.”

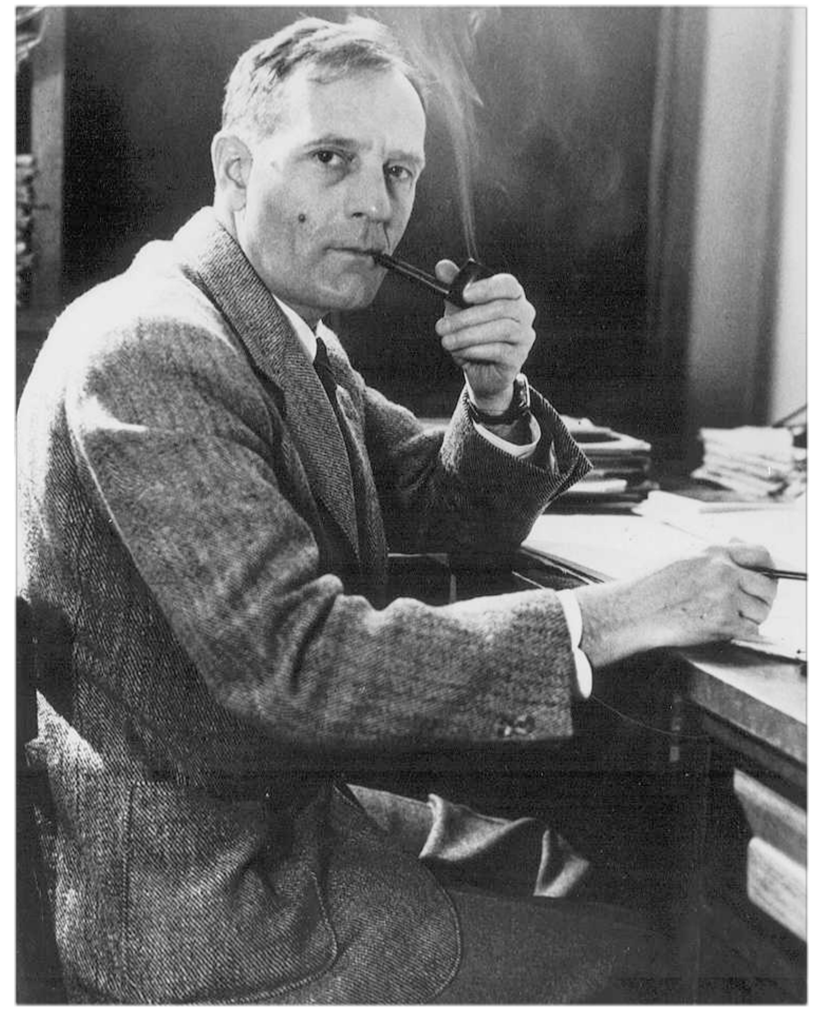
Wheaton, Illinois HS Principal to Edwin Hubble at his 1906 graduation

Edwin Hubble 1889-1953

astronomer

discoverer of:

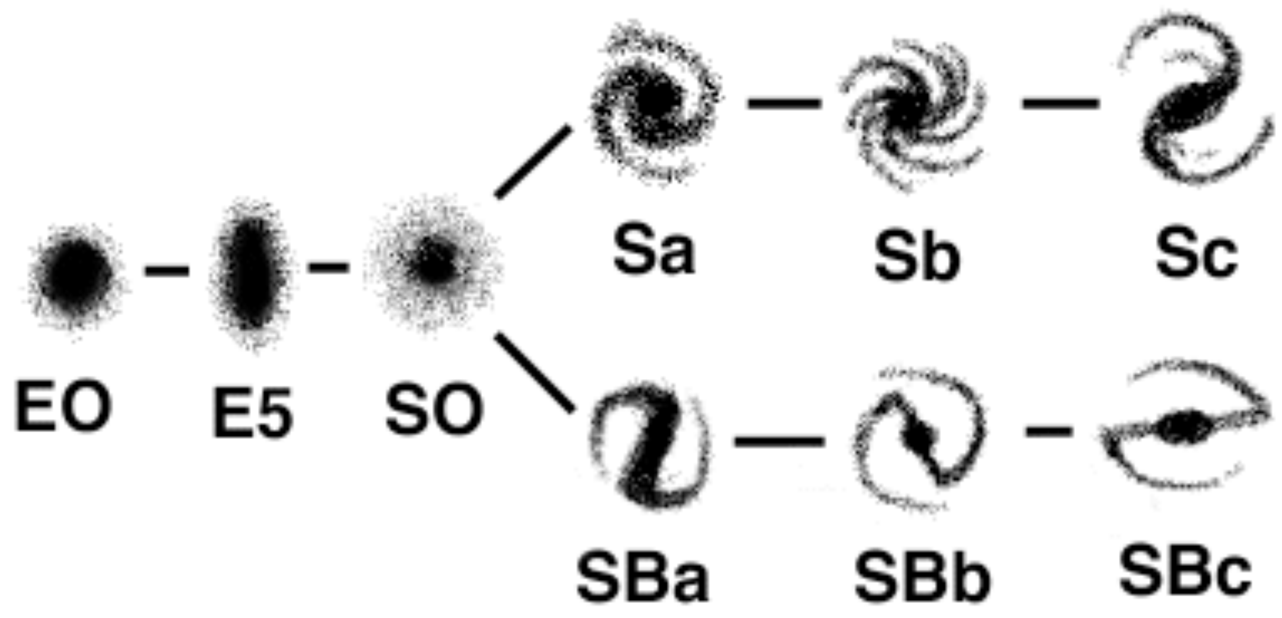
- the whole universe
- the expanding universe



very systematic thinker/ writer

1922-1926:

Hubble classification scheme for “nebulae”



basically: spherical, elliptical, bar, and irregular

remember HR diagram

“instability” strip

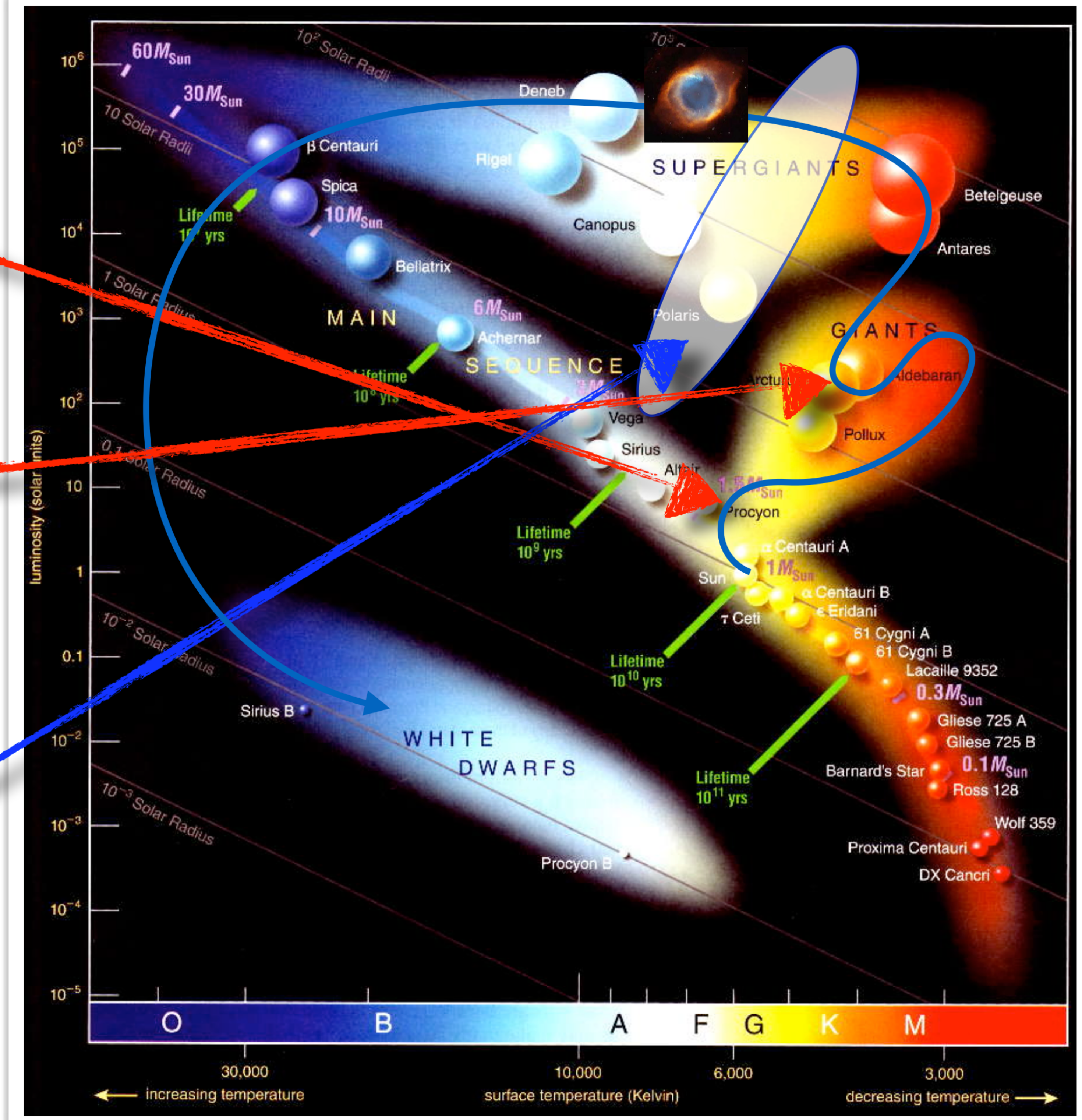
a balancing act

SUN-LIKE?
$H \rightarrow He$

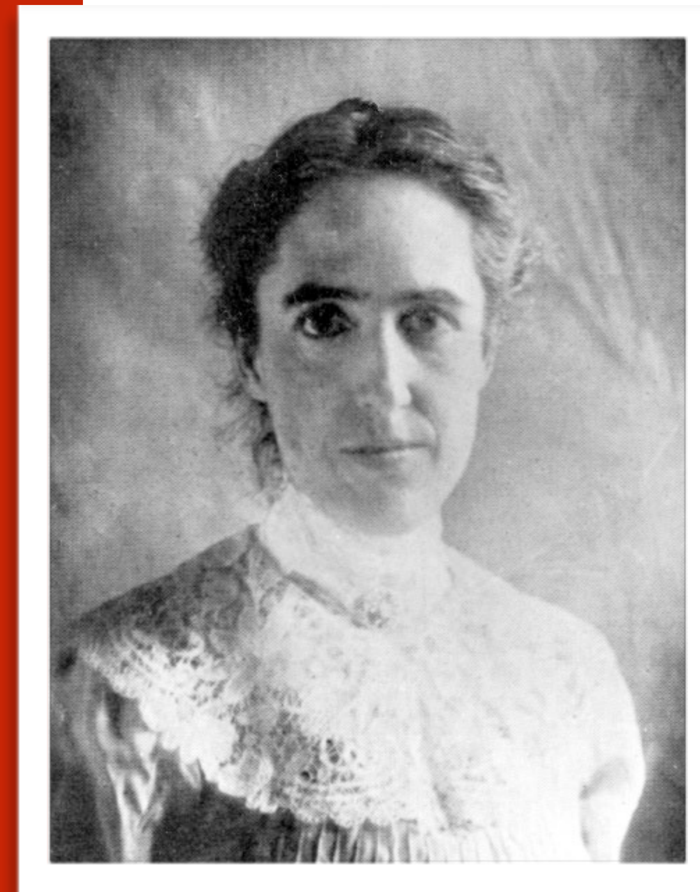
SUN-LIKE?
$He \rightarrow C + O$

source of Carbon for life

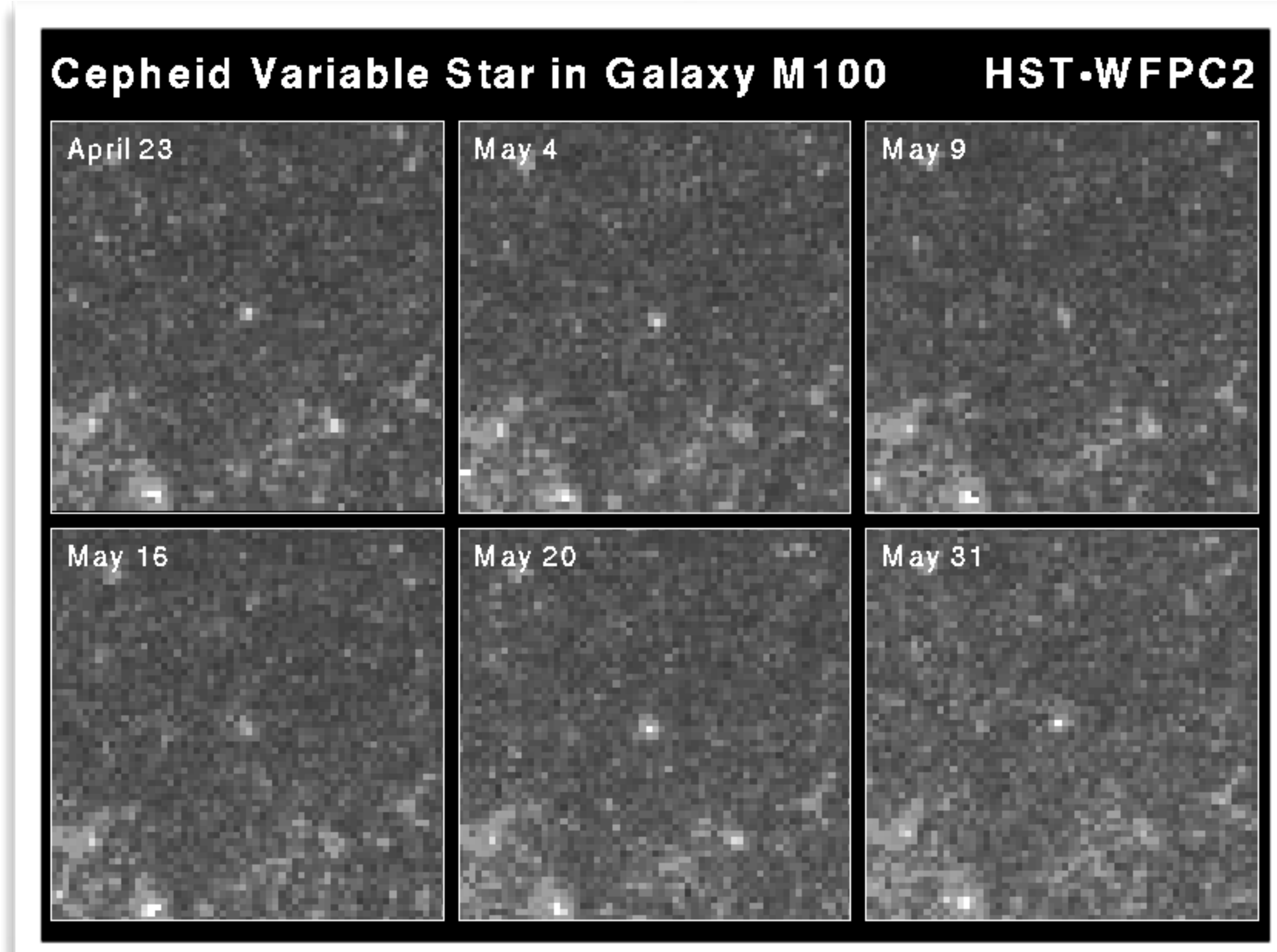
REGION OF INSTABILITY
pulsating stars



distances are hard to determine



discovered by Henrietta Leavitt at Harvard

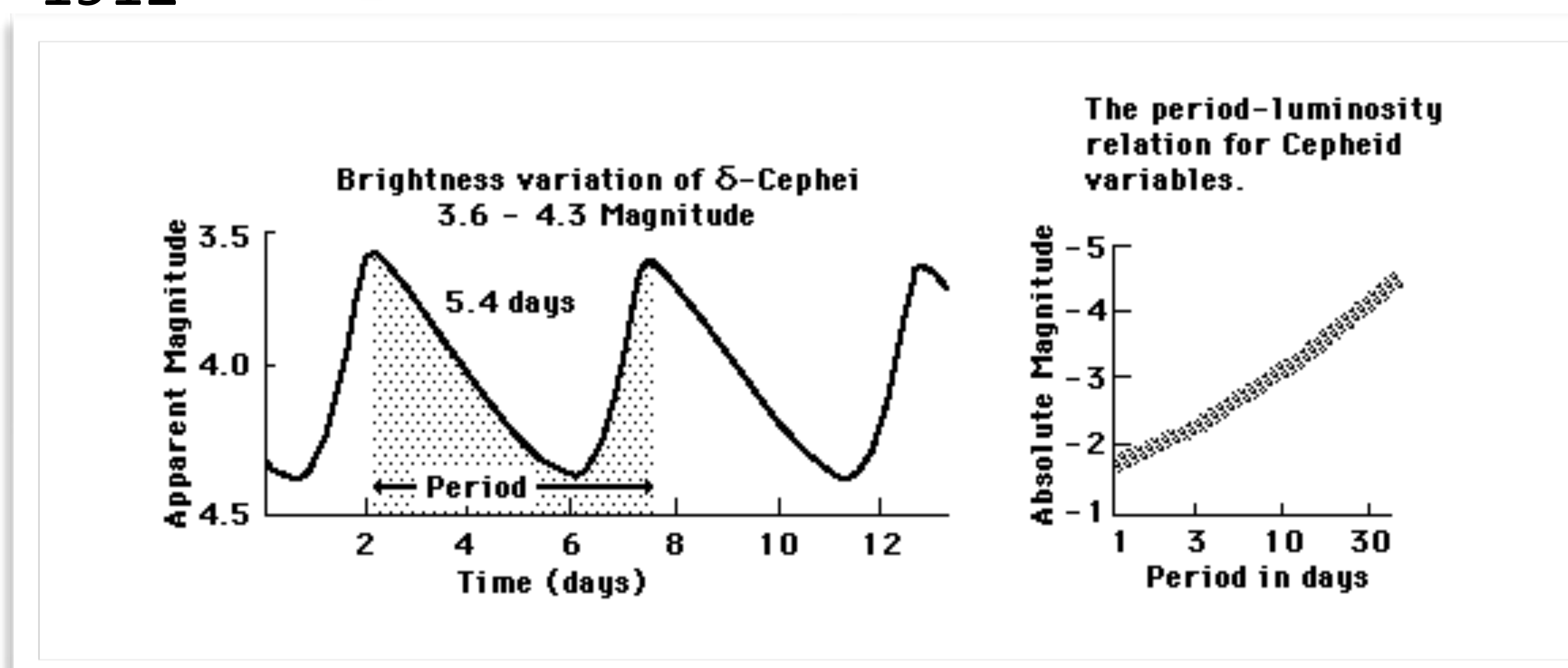


Cepheid Variable stars: the clue to galactic distances

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

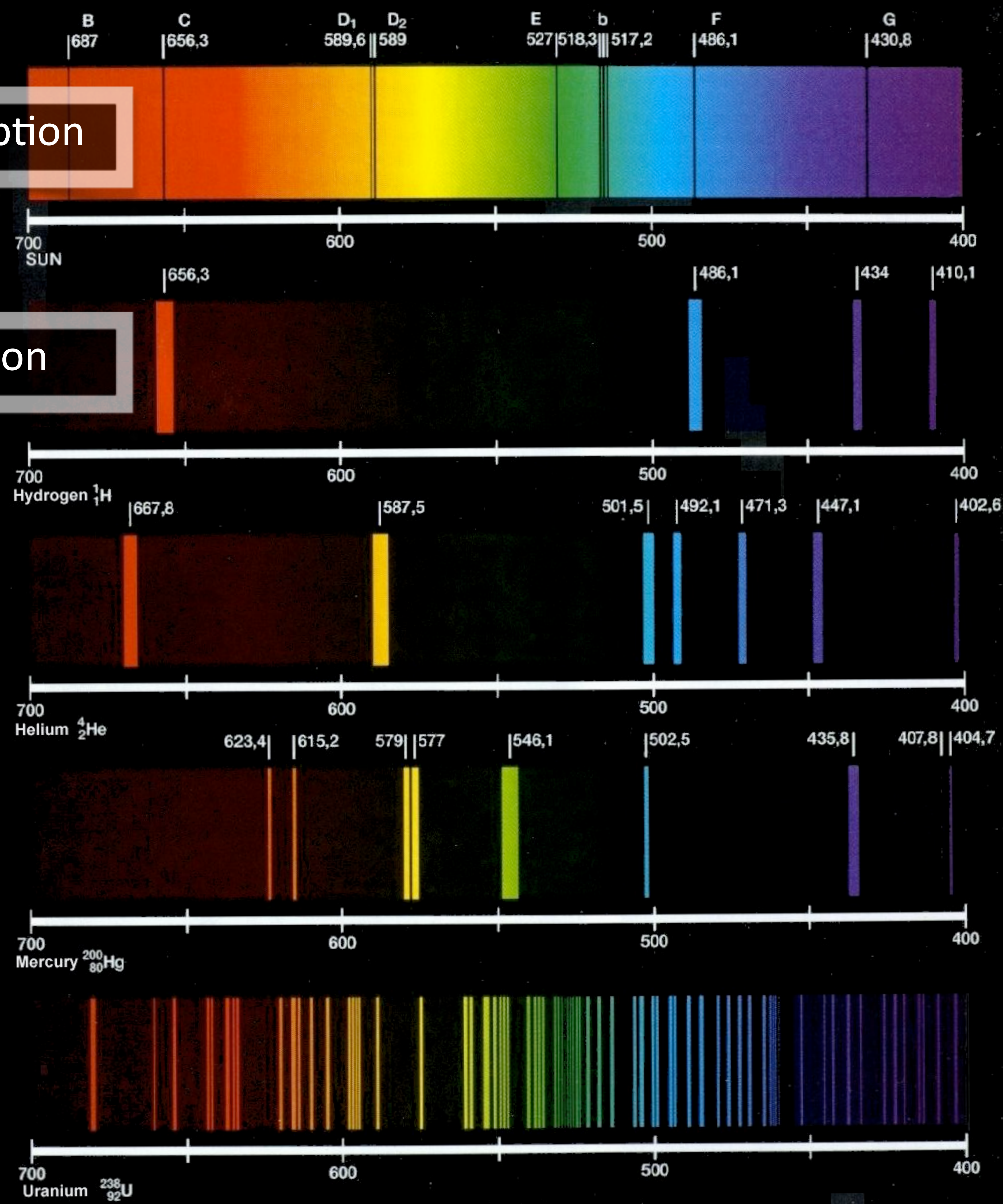
But wait. There's more.

Hubble was just warming up.

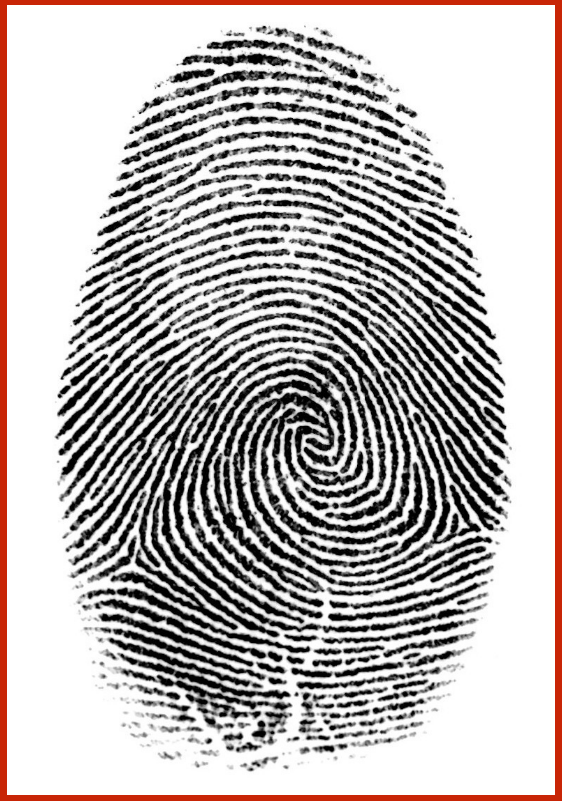
atomic spectra

absorption

emission



unique fingerprint of the atomic species

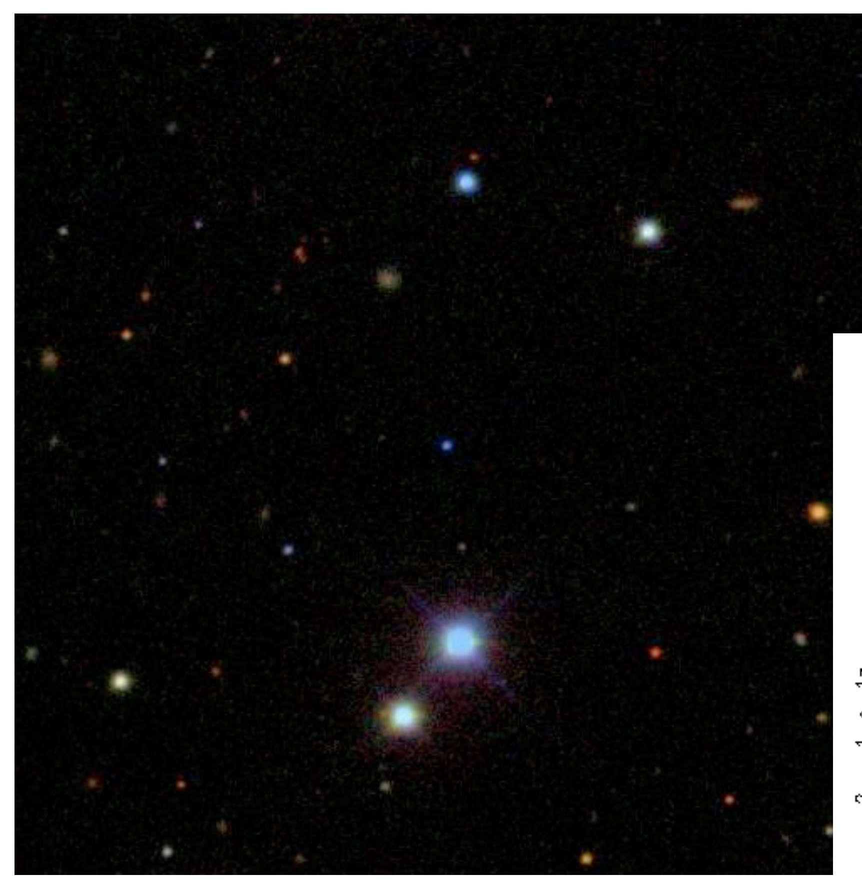


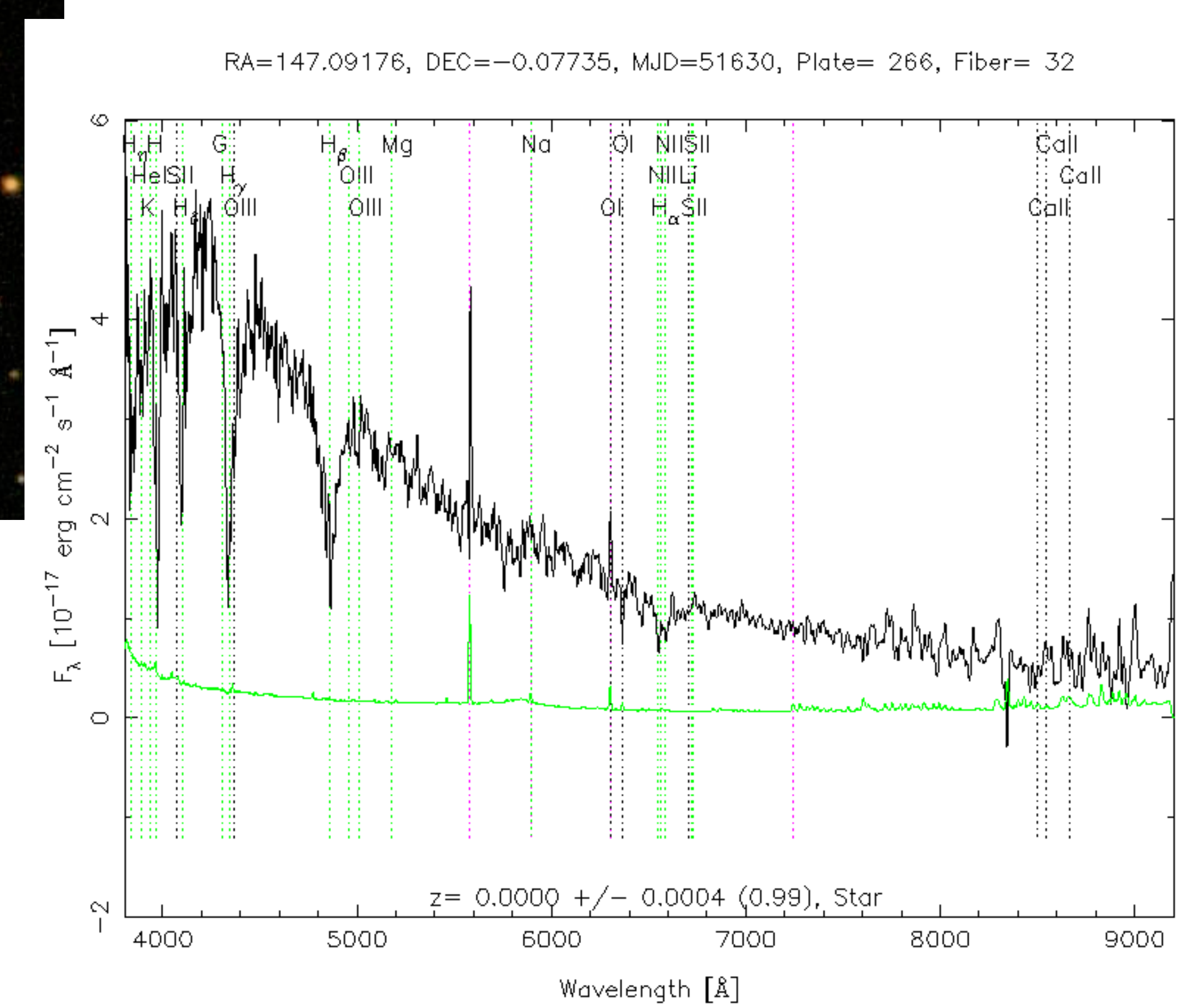
http://www.ruf.rice.edu/~mcannon/Research%20Home/Research%20Home.htm

stars are colorful

line spectra

label stars' outer chemistries





http://cas.sdss.org/dr4/en/tools/explore/obj.asp?id=588848899898278062

Hubble used

the finger-print tool of spectroscopy

plus

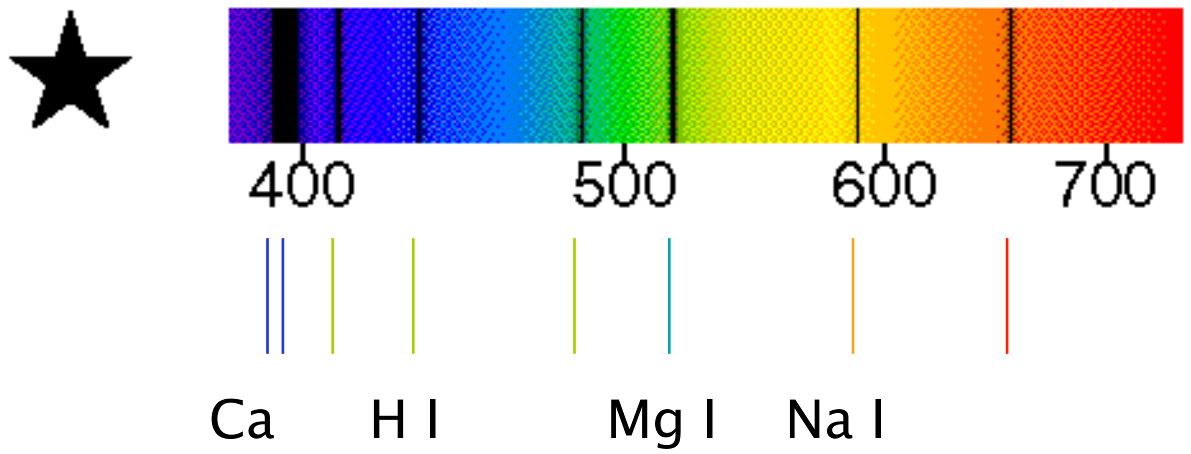
the distance determination tool of Cepheid Variables

His results:

Wavelengths shifted to longer - "**redshifted**"

meaning all of his galaxies seemed to be moving away from us

eg, seemingly, Doppler shifts at work:



http://www.astro.ucla.edu/~wright/doppler.htm

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the finger-print tool of spectroscopy

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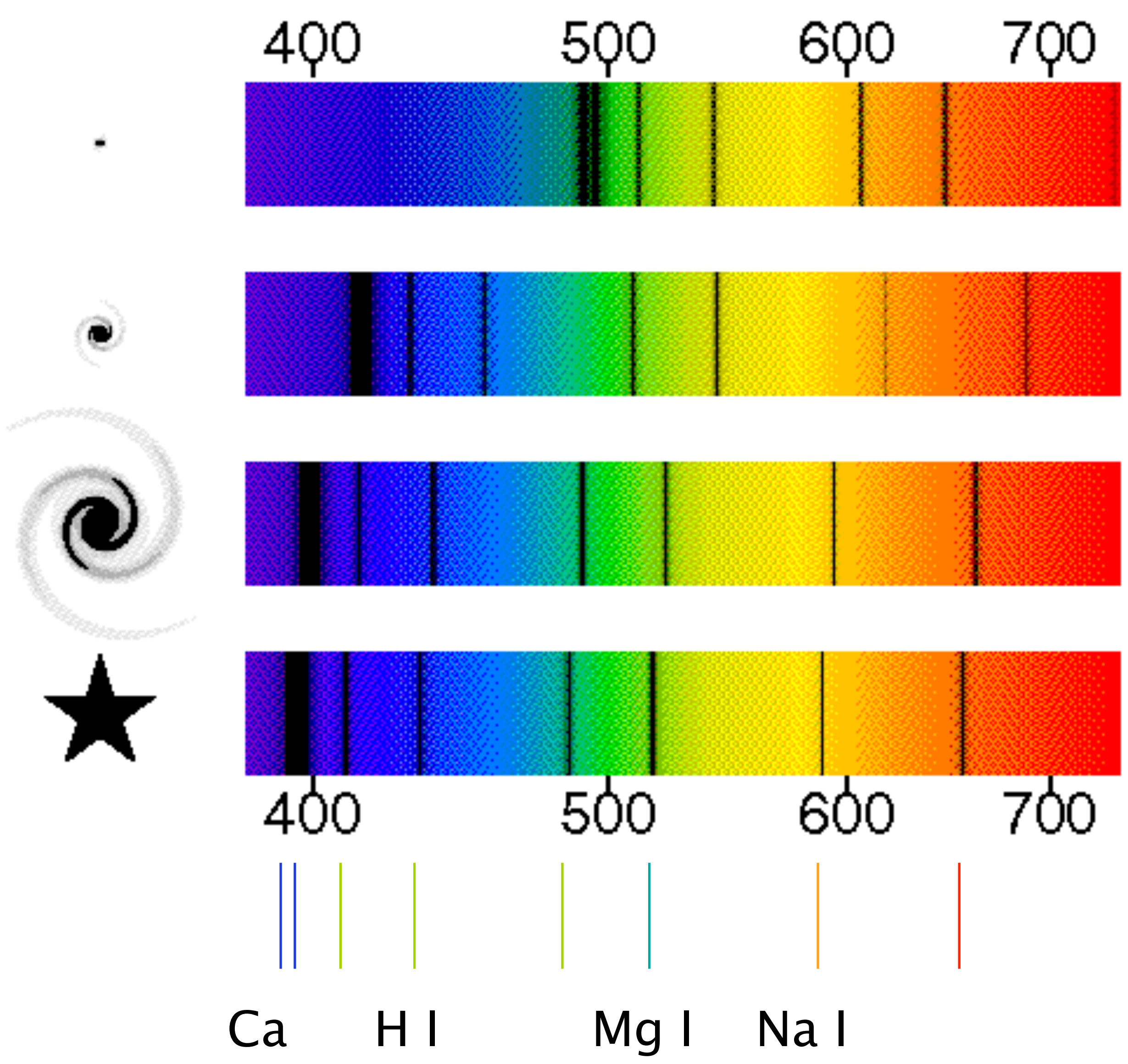
meaning all of his galaxies seemed to be moving away from us

eg, seemingly, Doppler shifts at work:

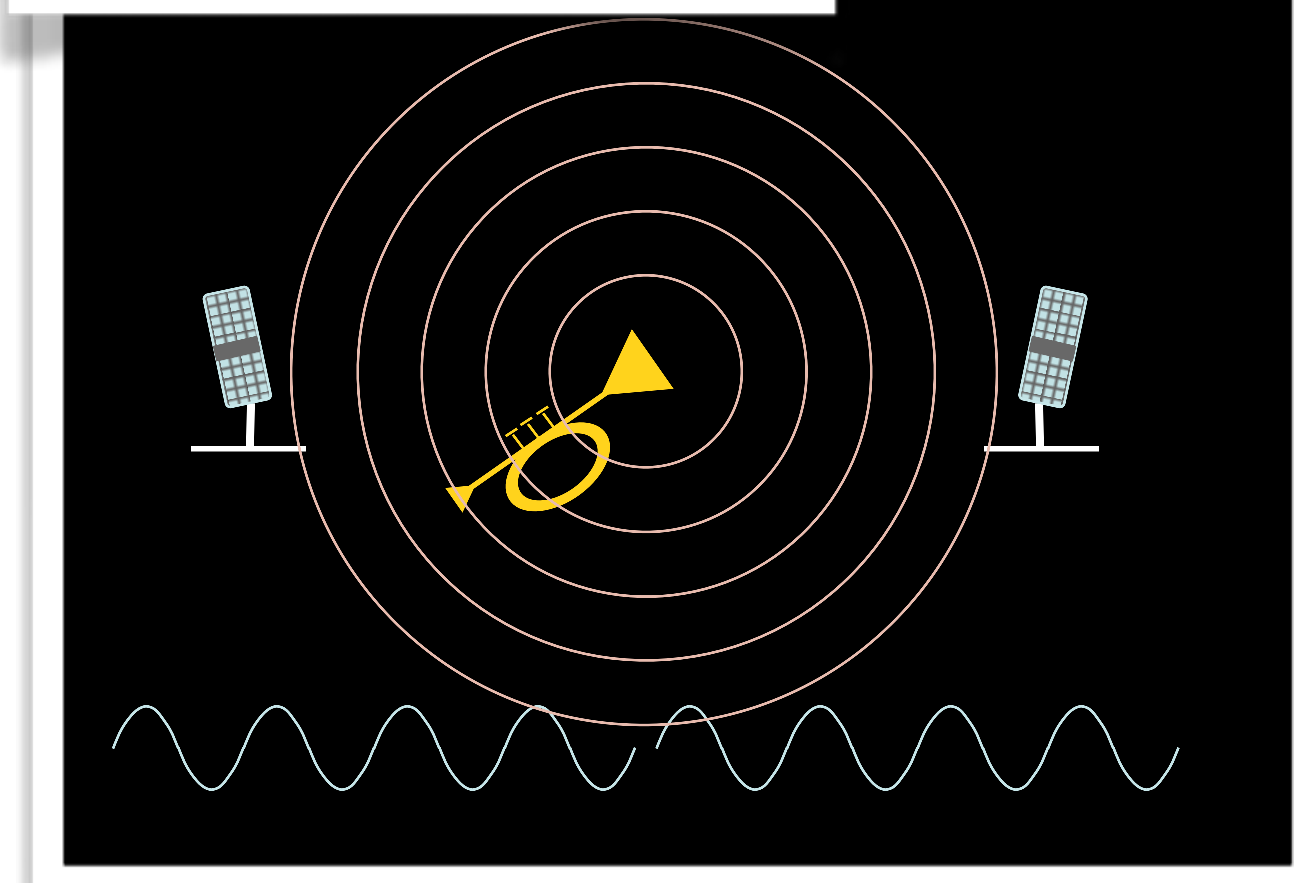


http://www.astro.ucla.edu/~wright/doppler.htm

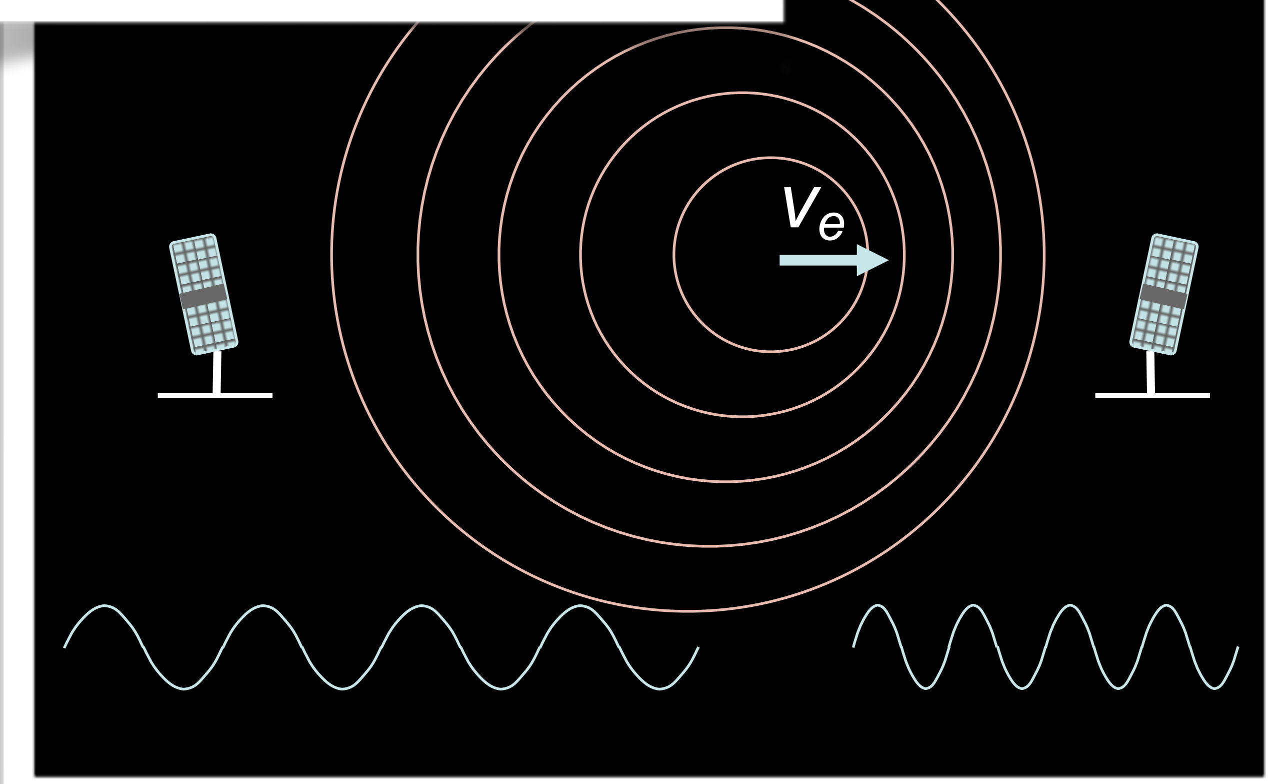
a little doppler'll do 'ya

The Doppler Effect

Everything stationary

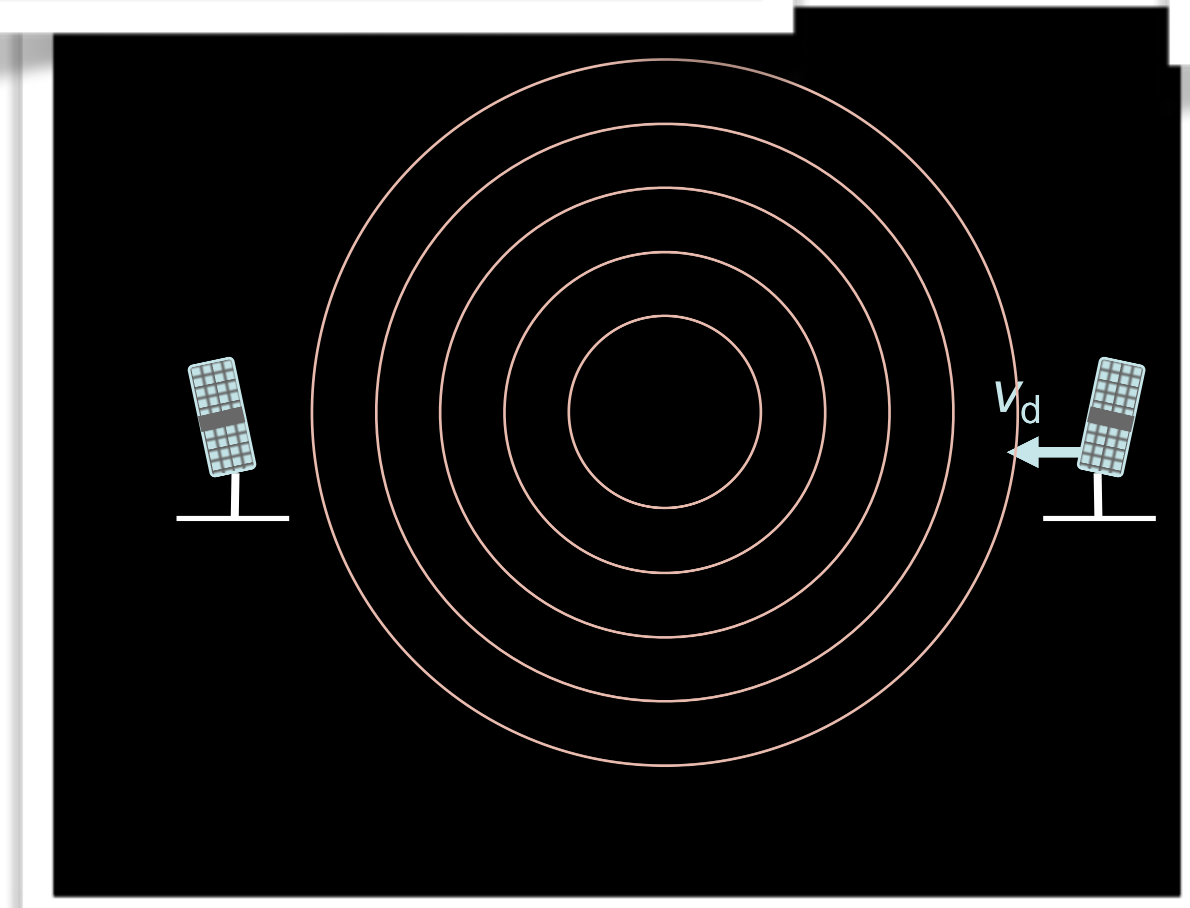


Source moving right



you've all had the experience of listening to the sound of a moving object change pitch

Receiver moving left



the motion toward the left means that R is seeing more peaks in a given time than L

Source moving to Right - Pitch goes up for R, shorter wavelengths.

Sound moving away from L...**pitch goes down for L. lower pitch, longer wavelengths**

Doppler Effect

change of pitch when source of sound

moves towards you

or away from you

$$f_O = \frac{v}{v \pm v_e} f_e$$

v - speed of sound in air

+ receding

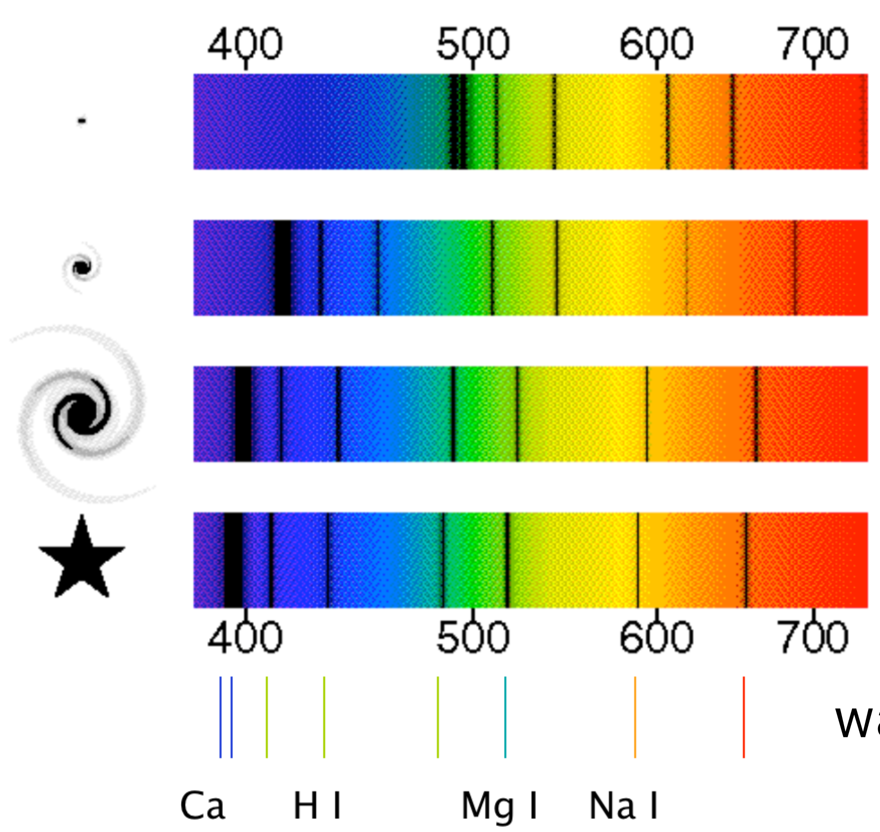
– approaching

$$v = f\lambda$$

$$\frac{v_e}{v} = \frac{\lambda_O - \lambda_e}{\lambda_e}$$

If light?

$$\frac{v_e}{c} = \frac{\lambda_O - \lambda_e}{\lambda_e}$$



wavelengths where elements should emit

$\lambda_O > \lambda_e$ so $v_e > 0$ "away from us"

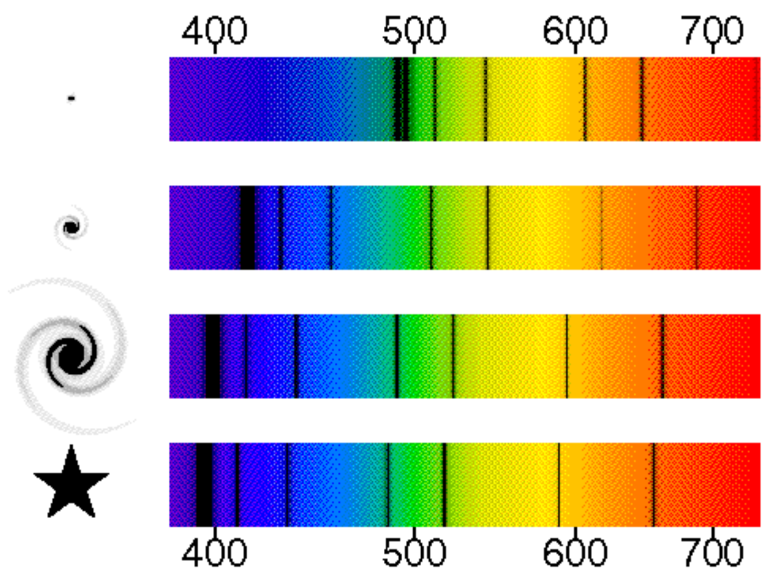
red shifted

Hubble's remarkable conclusion:

all of the galaxies are moving away from us.

1929: a stunning quantitative conclusion

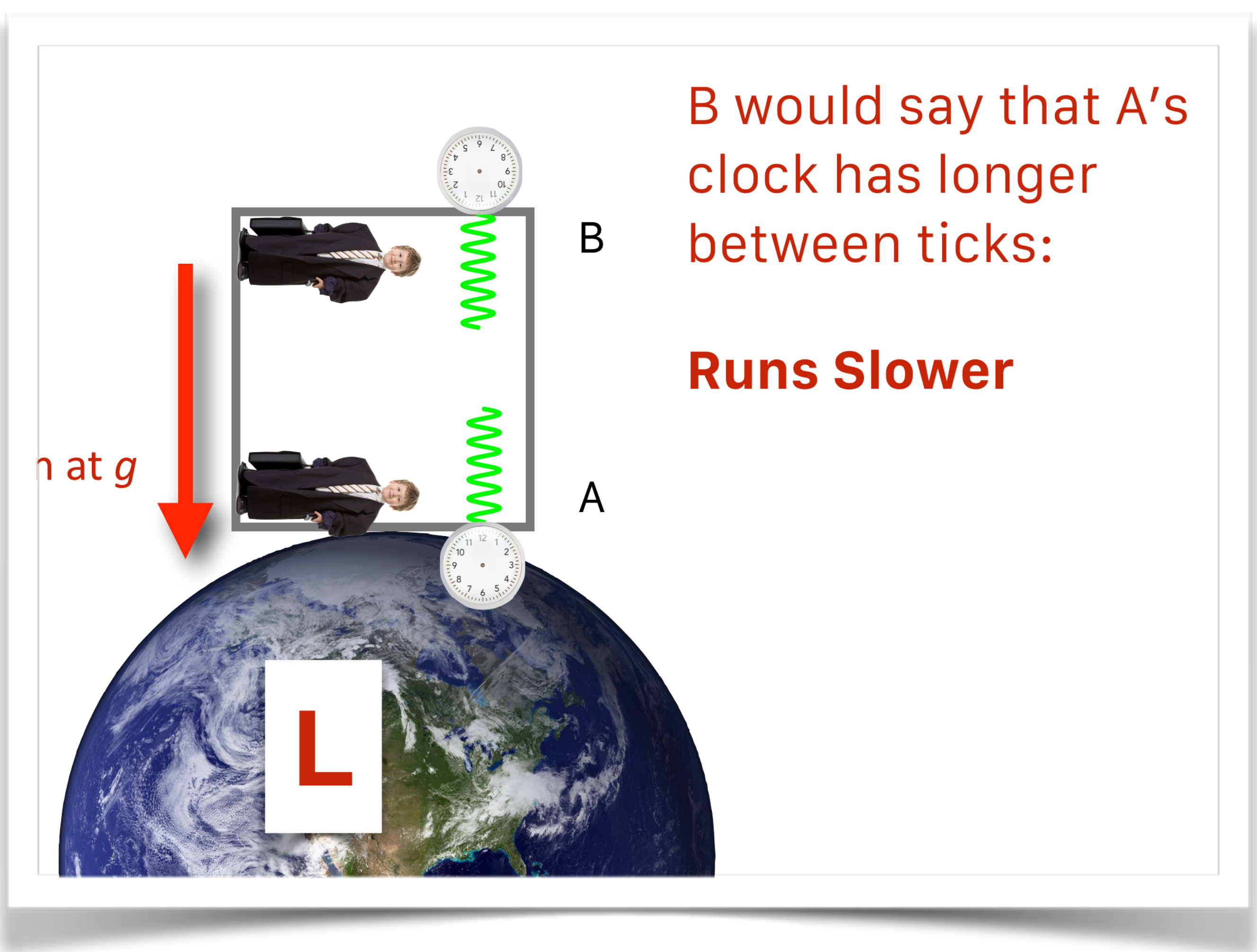
But the actual reason is even more stunning.

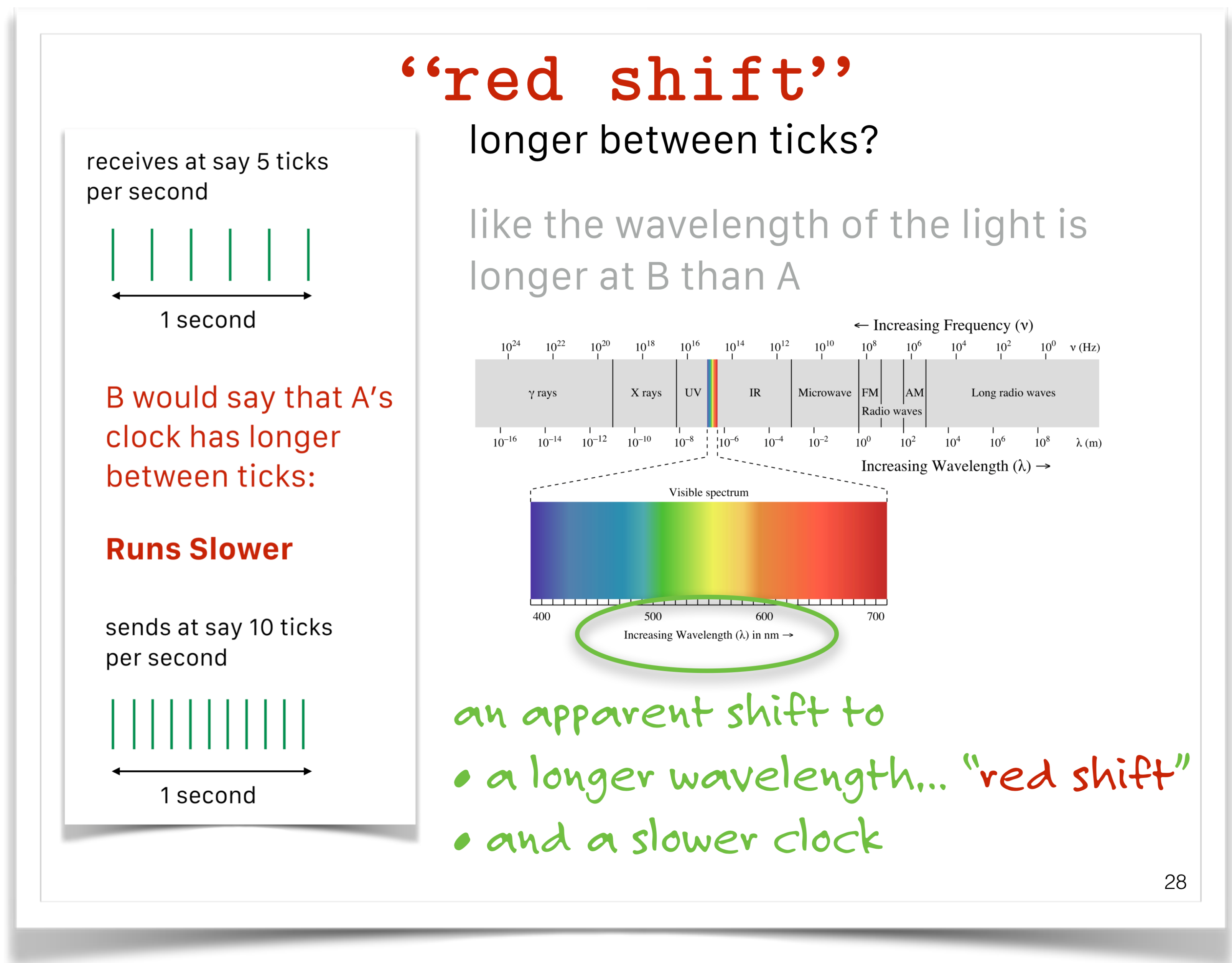


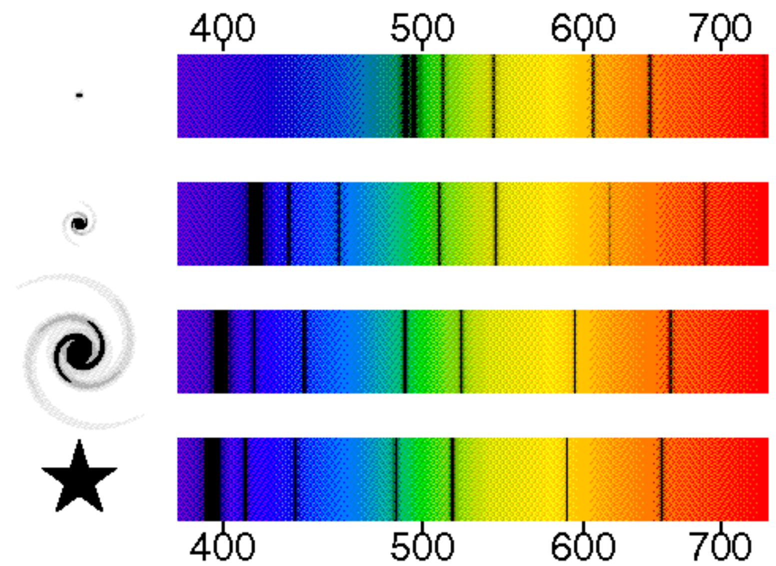
this is not that.

but Hubble presumed that it was

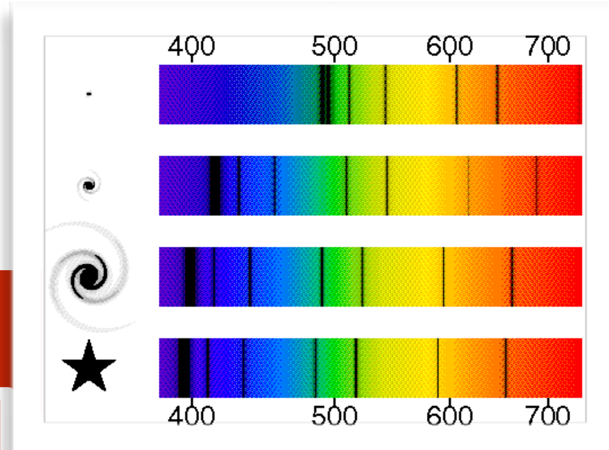
remember the Gravitational Red Shift?







well, this is not that either!



FROM PRESUMED DOPPLER-SHIFTED SPECTRA

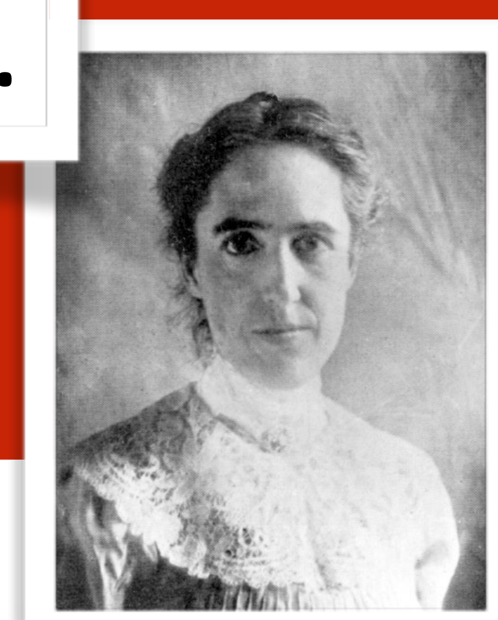
HUBBLE'S CONSTANT = 1/T

Hubble's

H: a measure of the time a galaxy has been "traveling"

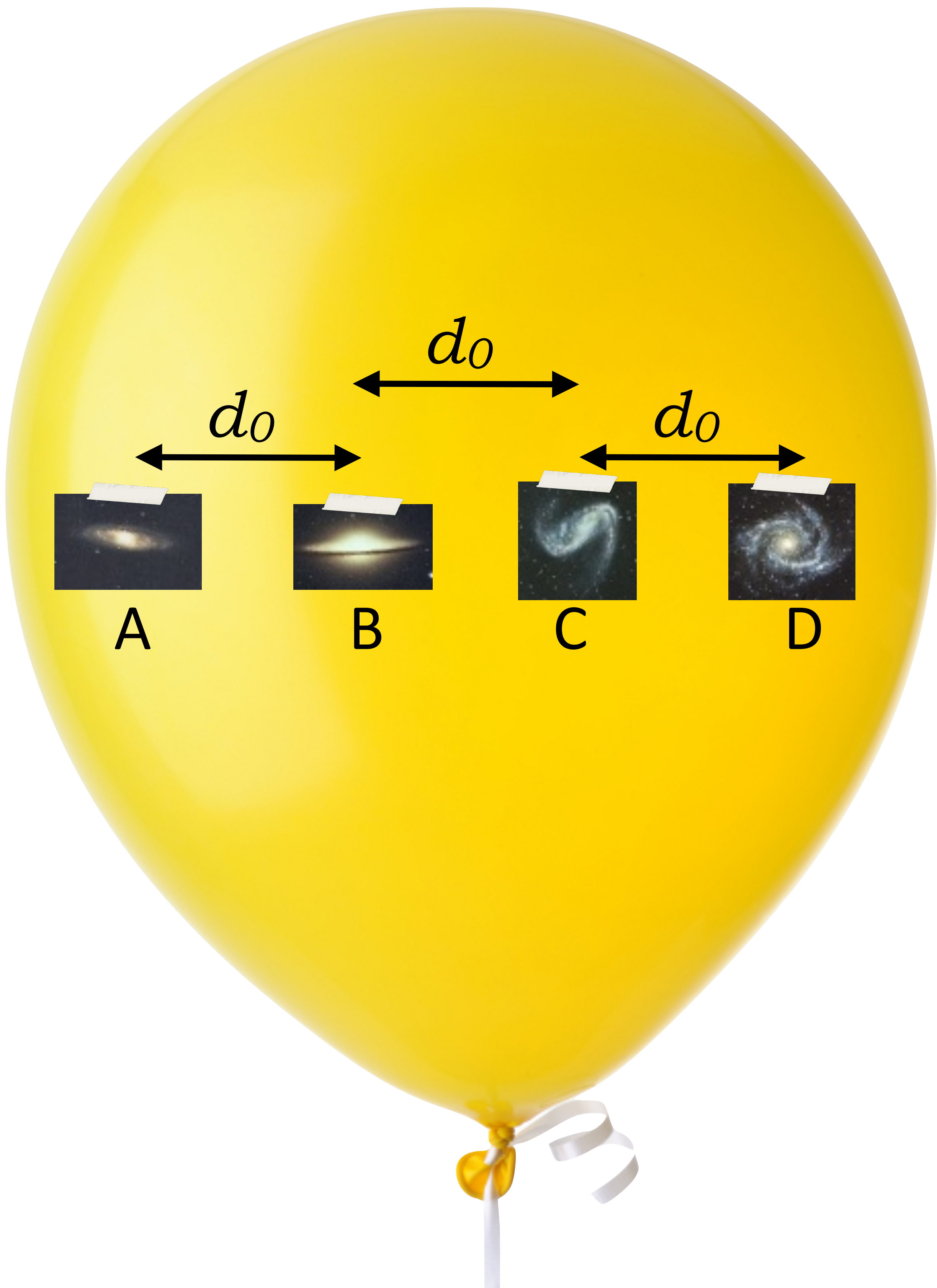
$$v = rH$$

It's a little tricky... Think Balloons.



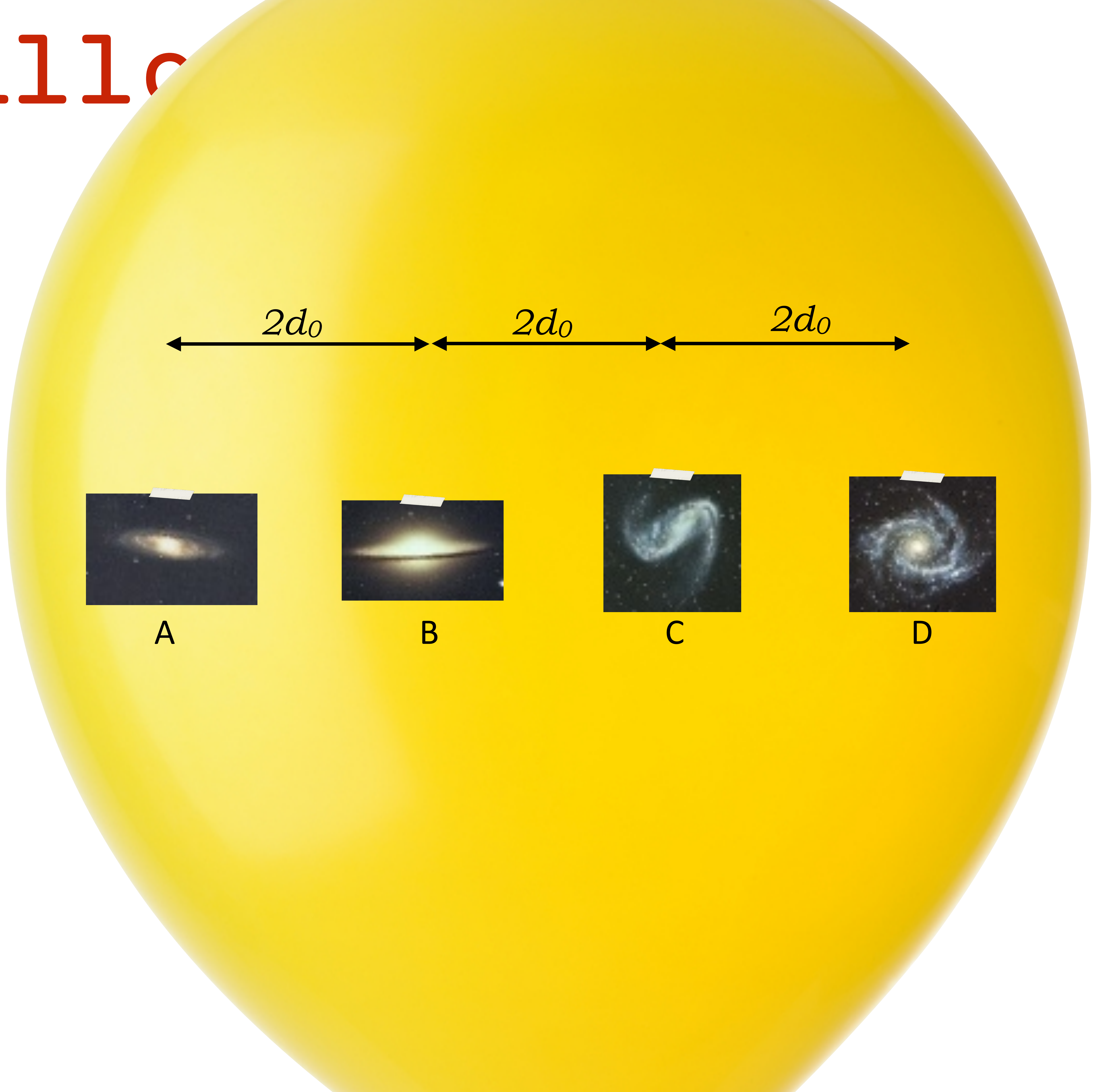
FROM LEAVITT'S CEPHEID VARIABLE RELATION

balloon world



Time 1

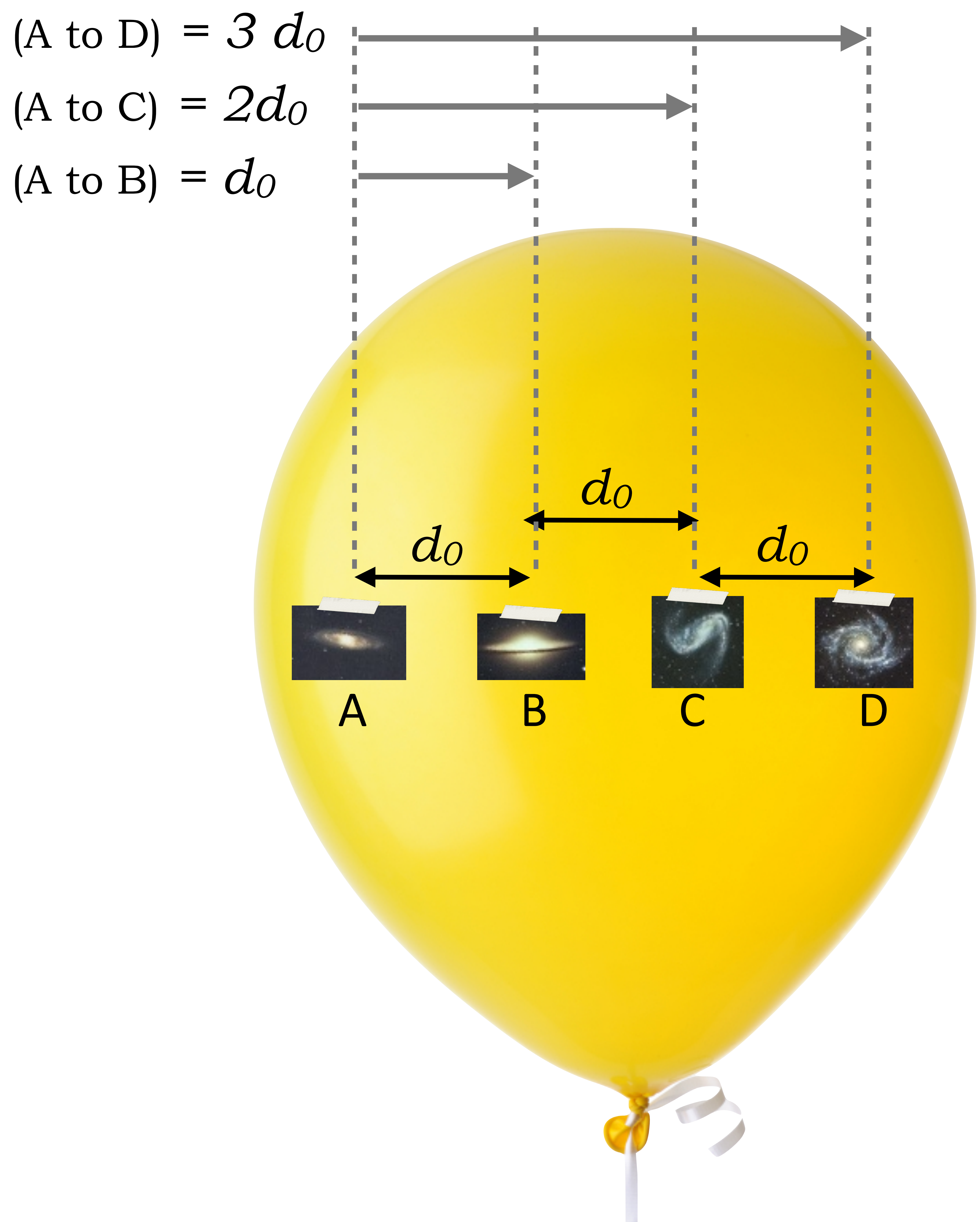
ballo



Time 2

Time 3

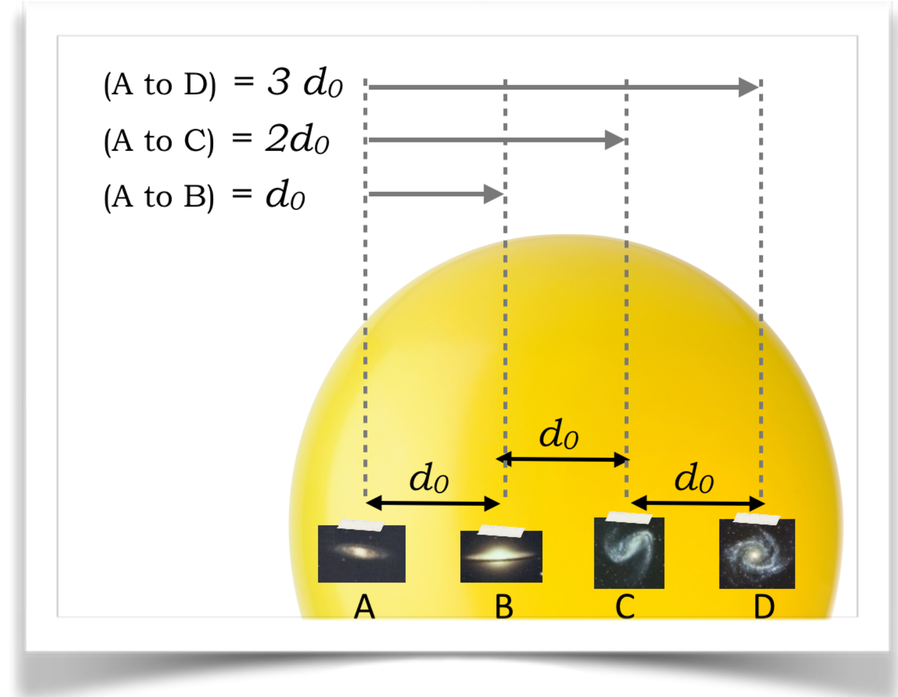
keep track of how far away everything is from Galaxy A



Going to calculate the speed at which **B and C** recede from **A** in
Time 1-2
and
Time 2-3

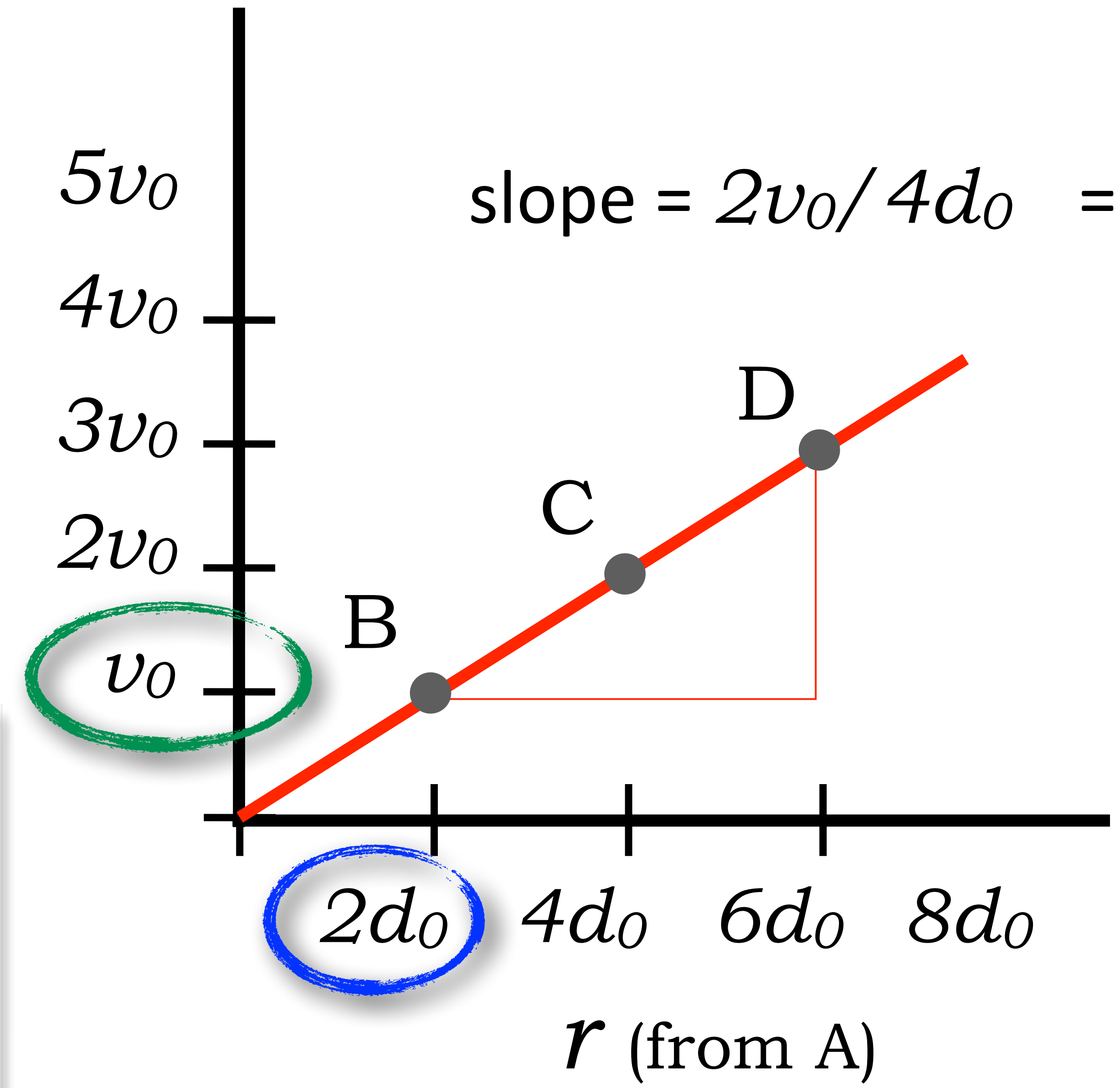
what we had

Time 1



distance, time 1	r = (A to B)= d_0	r = (A to C)= $2d_0$	r = (A to D)= $3d_0$
time 2, Δt later… distance, doubled	$r = 2d_0$	$r = 4d_0$	$r = 6d_0$
Δr, the difference:	Δr (A to B)	Δr (A to C)	Δr (A to D)
Δr between time 1 and 2 = Δt	$\Delta r = 2d_0 - d_0 = d_0$		
speed	$d_0/\Delta t = v_0$		

plot 'em up



slope = $2v_0/4d_0 = v_0/2d_0$

distance, time 1	r = (A to B)= d_0	r = (A to C)= $2d_0$	r = (A to D)= $3d_0$
distance, time 2	$r = 2d_0$	$r = 4d_0$	$r = 6d_0$
difference:	Δr (A to B)	Δr (A to C)	Δr (A to D)
Δr between time 1 and 2 = Δt	$\Delta r = 2d_0 - d_0 = d_0$	$\Delta r = 4d_0 - 2d_0 = 2d_0$	$\Delta r = 6d_0 - 3d_0 = 3d_0$
speed	$d_0/\Delta t = v_0$	$2d_0/\Delta t = 2v_0$	$3d_0/\Delta t = 3v_0$

$$v = (slope)r = \left(\frac{v_0}{2d_0}\right) r$$

suppose $r = 5\ d_0$?

what's v? $2.5\ v_0$

Also: look at the dimensions of that slope $\left(\frac{v_0}{2d_0}\right)$: $\frac{\text{velocity}}{\text{distance}} \sim \frac{\text{m/s}}{\text{m}} \sim \frac{1}{\text{time}}$

Hubble's Law

a **profound** discovery about the Universe

$$v = rH$$

relation alert: **Hubble's Law**

refers to:

$$v = rH$$

Speed of a galaxy is proportional to the distance away from any point.

example:

galaxy NGC1832 is 9.57 x 10^{20} km away, so Hubble's Law says it would be moving at v = 2150 km/s

original results:

$$1 \text{ light year} = c \times 1 \text{ year} = 9.5 \times 10^{15}\text{m}$$

H = 160 km/sMly

The outstanding feature, however, is the possibility that the velocity-distance relation may represent the de Sitter effect, and hence that numerical data may be introduced into discussions of the general curvature of space.

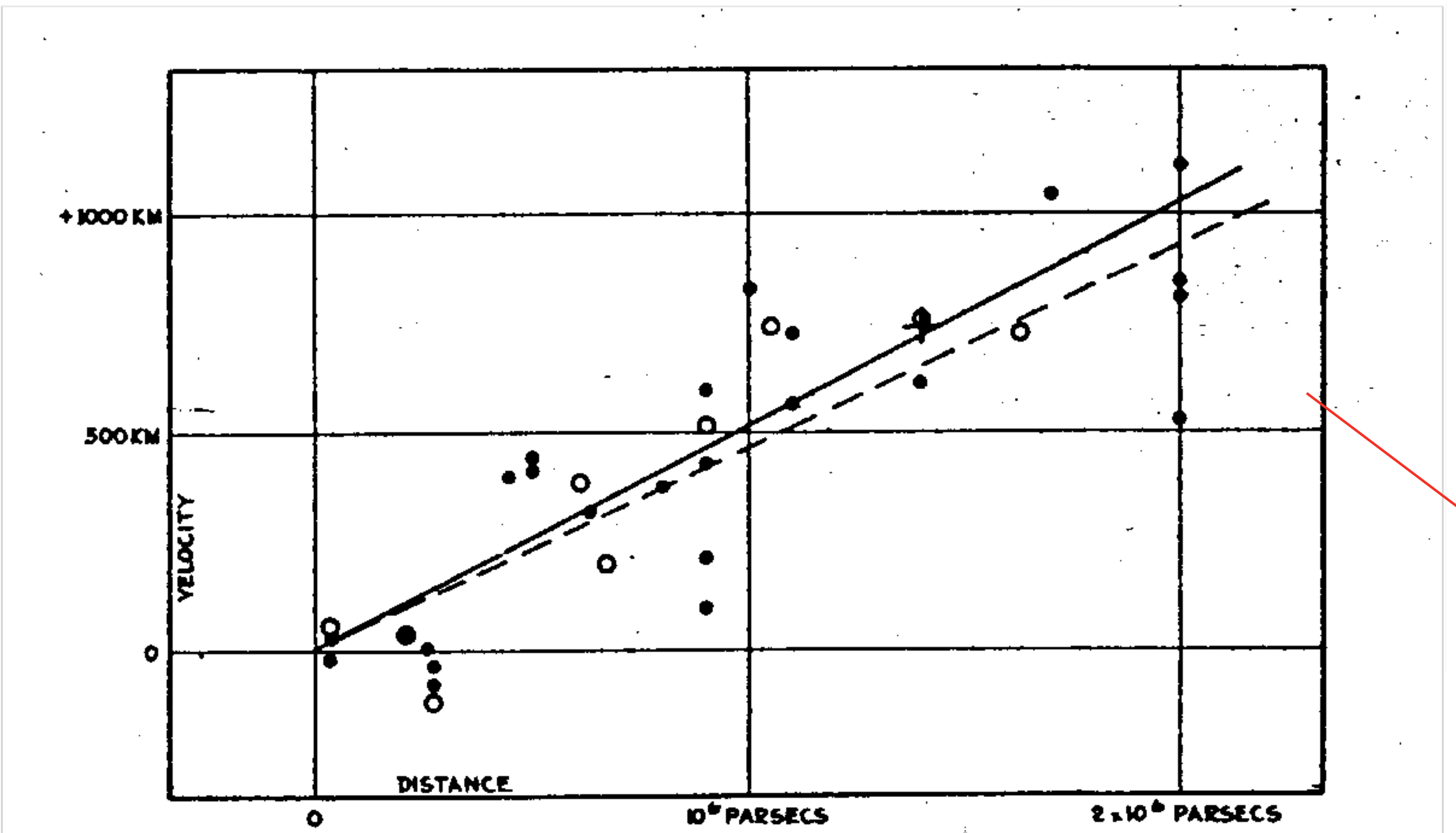
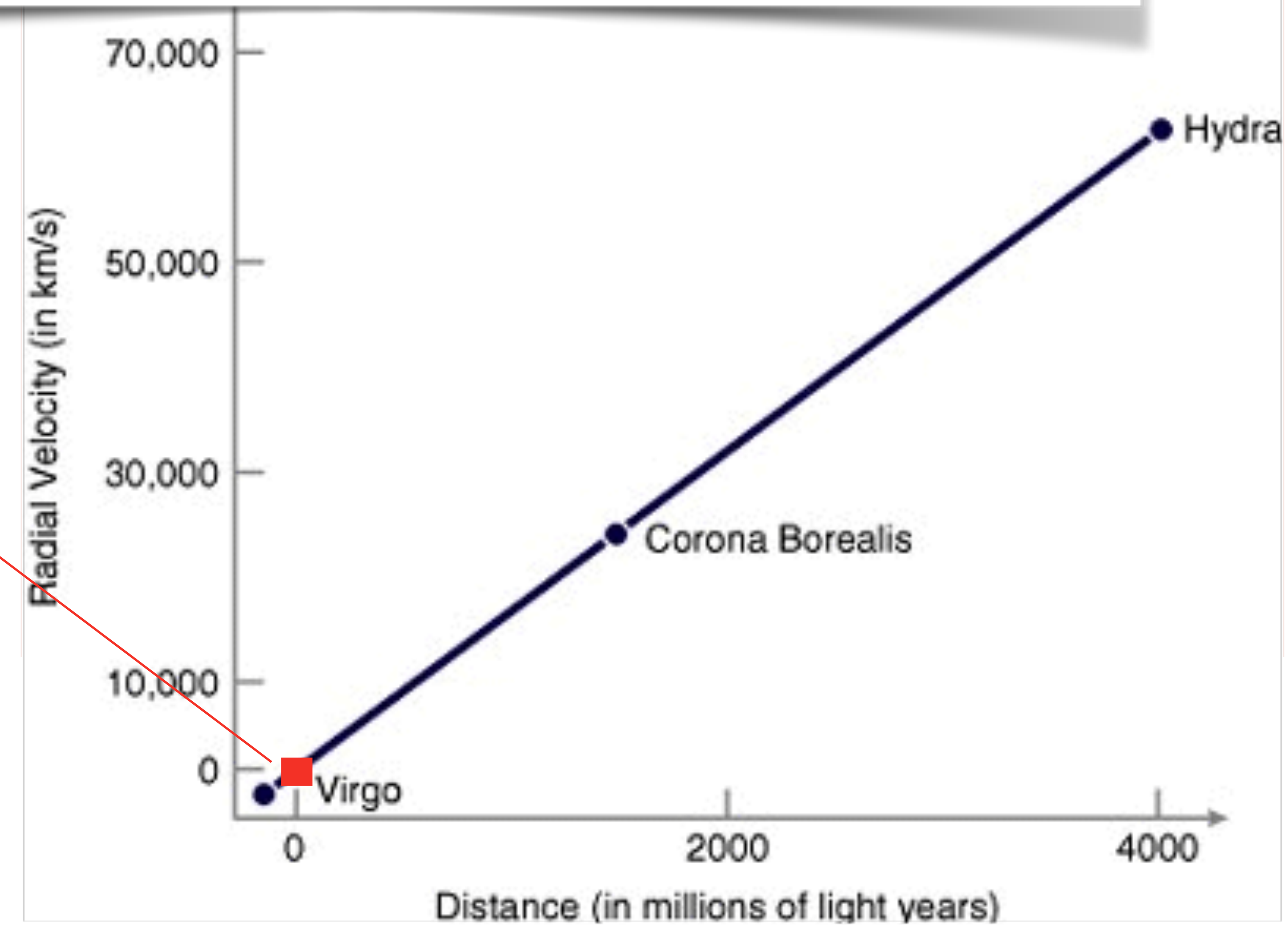


FIGURE 1



So, what does Hubble's Law mean?

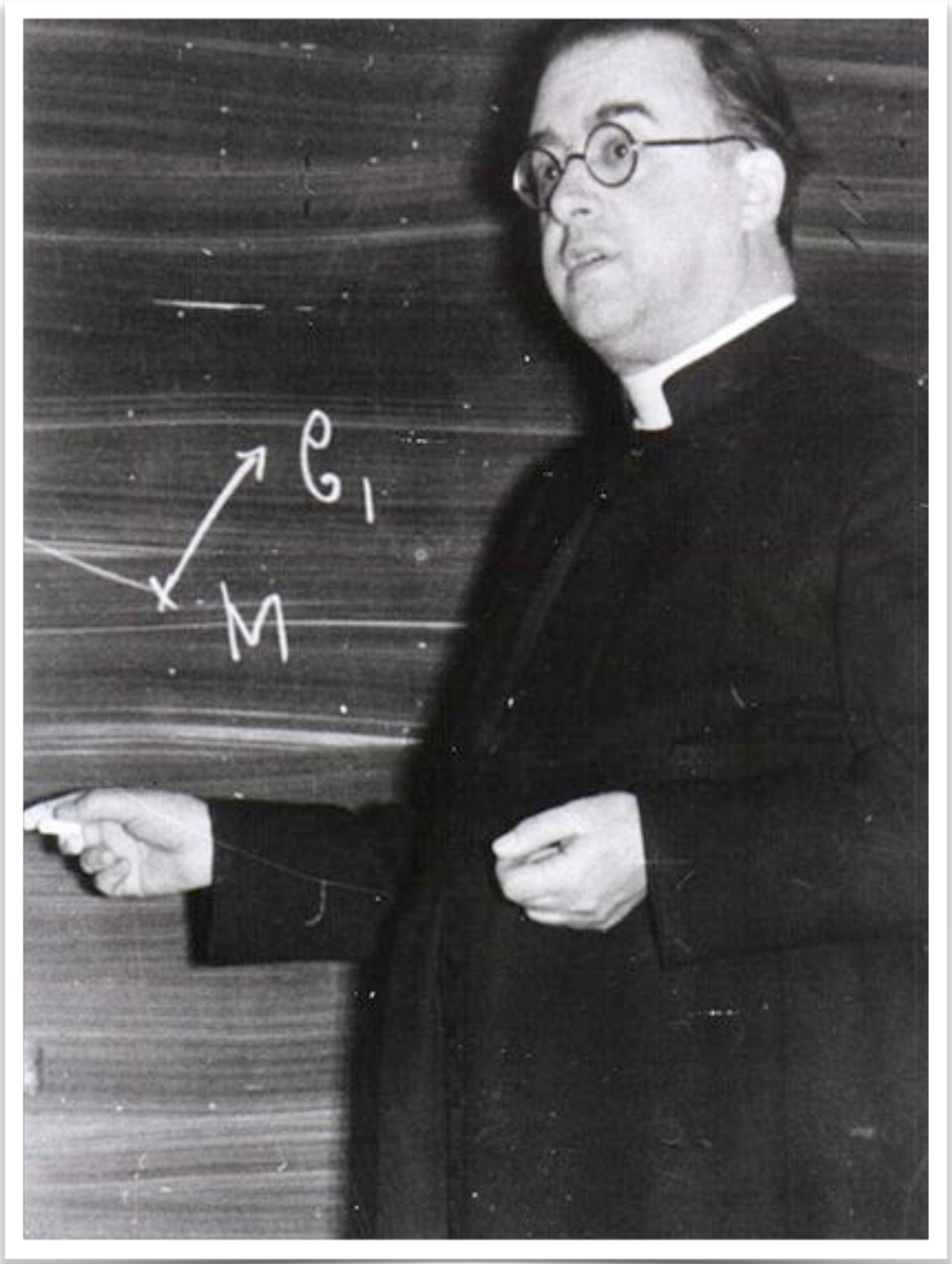
apart from the balloon…

$$v = rH$$

Georges Lemaître (1894-1966)

The father of the Big Bang

get it?



three kinds of education

war

seminary

physics

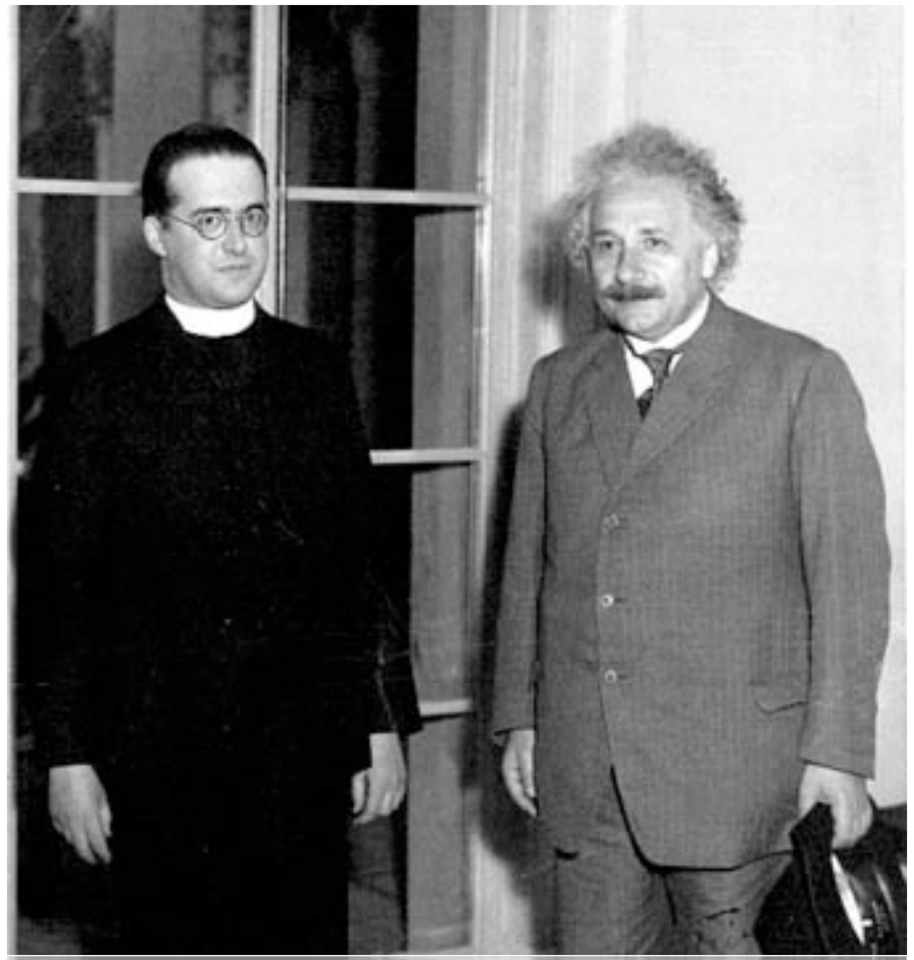
http://www.flickr.com/photos/miguelcalleja/sets/72157604962600986/detail/

1927

Lemaître’s model

published obscurely

he believed that General Relativity required an expanding universe



again, Einstein behaved badly

"Your math is correct, but your physics is abominable."

Again, Einstein lets his prejudices

get the better of him

he'd pay for that

In 1927 he published a solution

"A homogeneous Universe of constant mass and growing radius accounting for the radial velocity of extragalactic nebulae"

Solving $G = T$....with spacetime geometry set free

in an obscure Belgian journal

He predicted the H constant!

his model required the Universe
to be explicitly expanding

When Hubble's results were announced

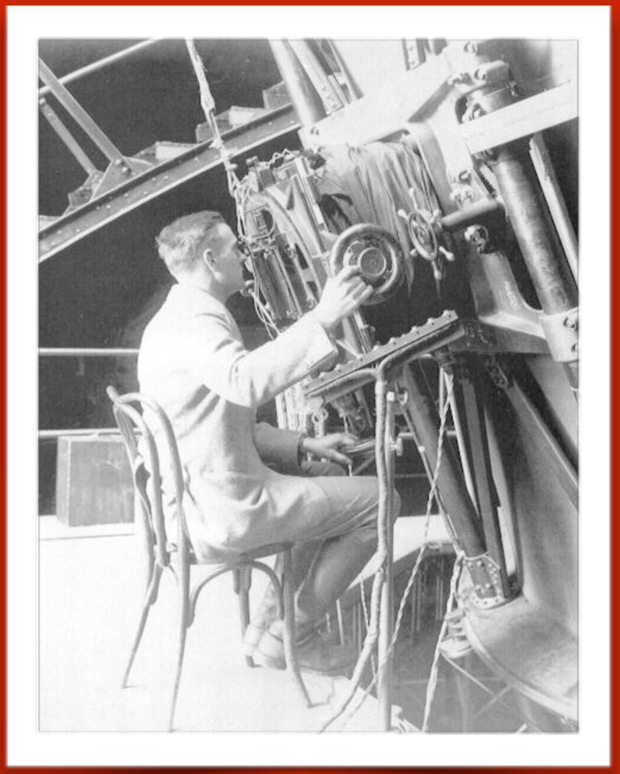
"brilliant"

he showed it to his old advisor, Sir Arthur Eddington who made it public in 1930:

The Lemaître-Eddington model:

constant size, with Einstein's value...and expands from there...

Lemaître was the first to realize that Hubble had demonstrated:



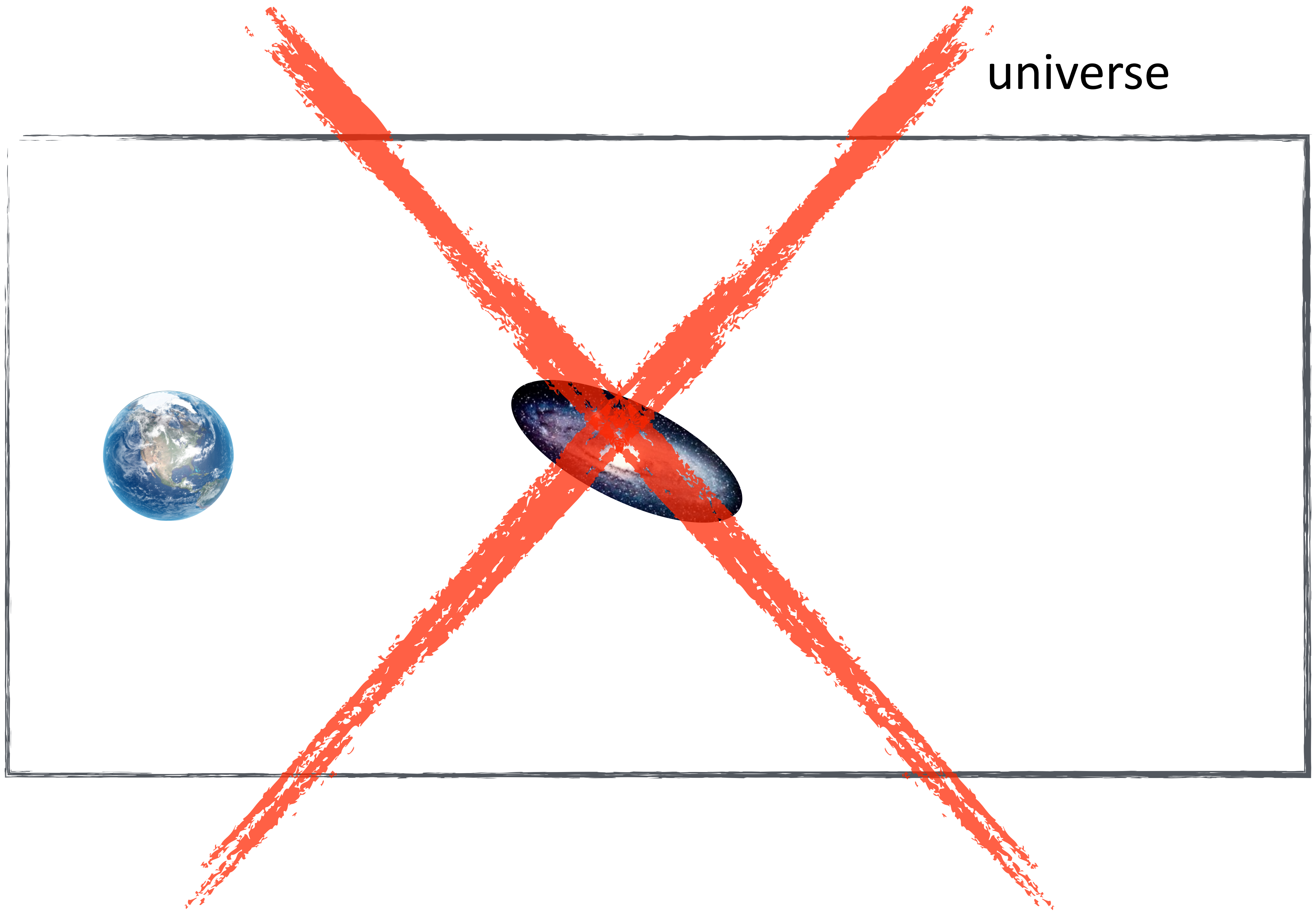
1. spacetime is stretching

The entire kit and caboodle is expanding

Here’s what it does NOT mean:

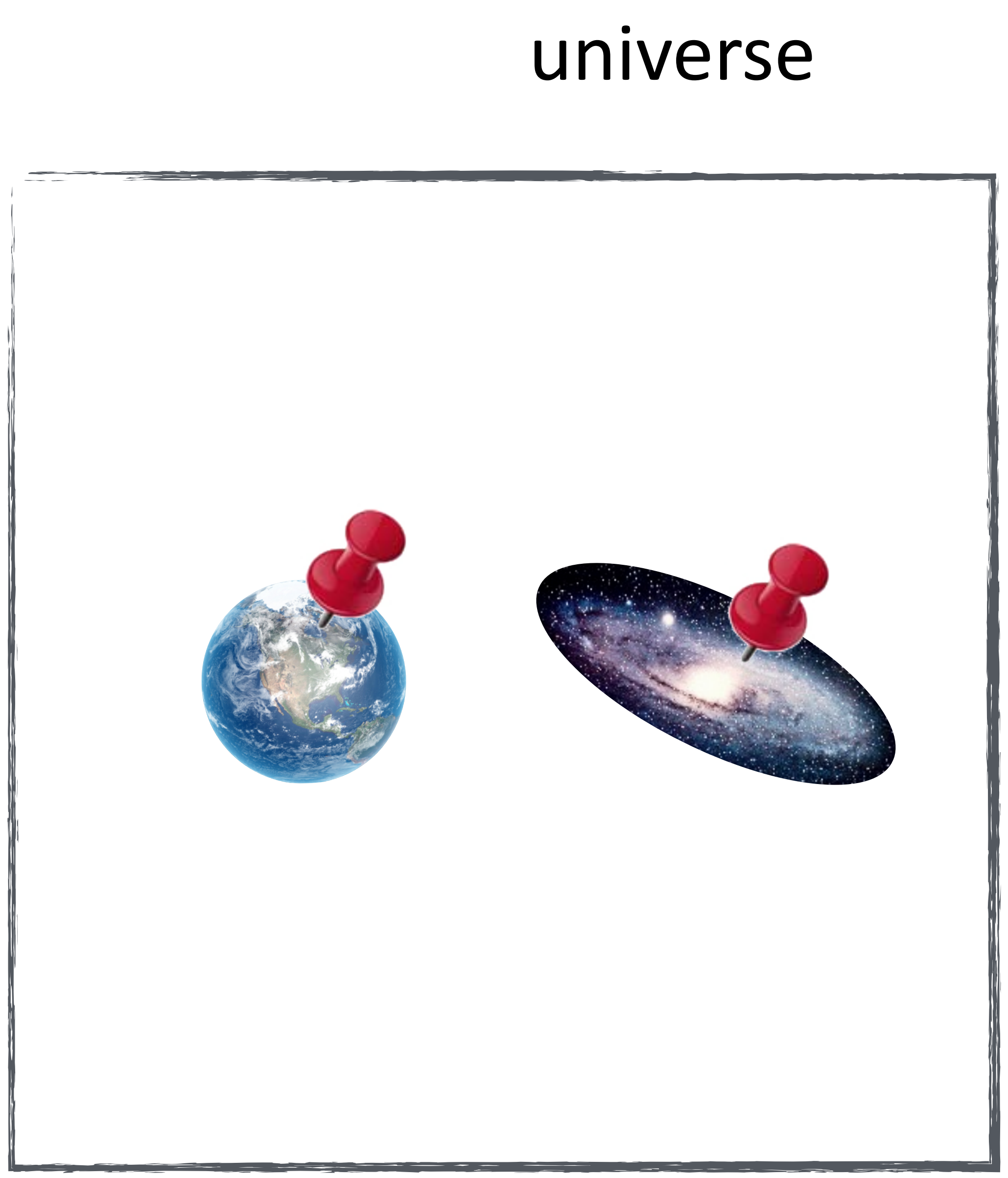
galaxies are not "moving away"

inside of the universe



what stretching DOES mean

is complicated!



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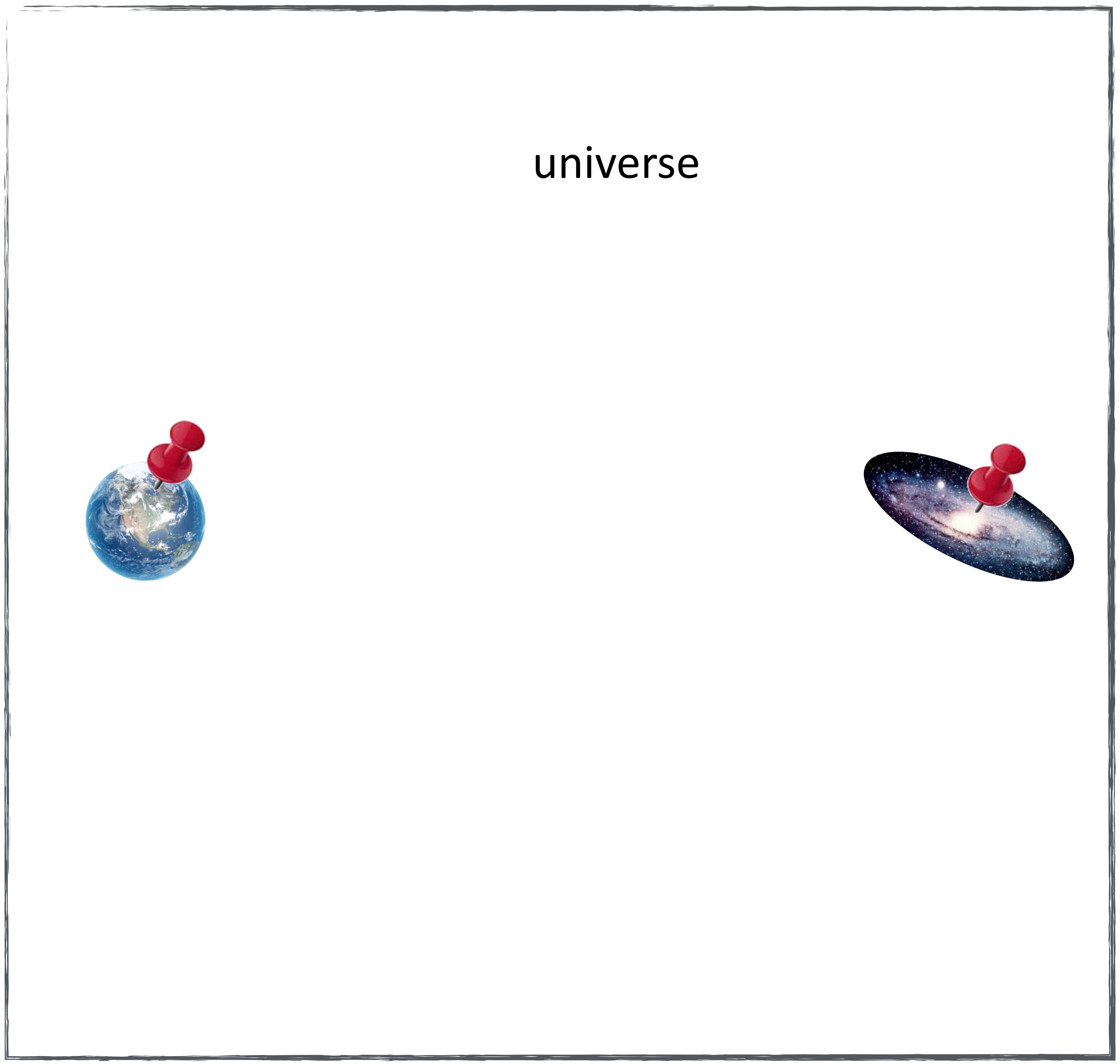

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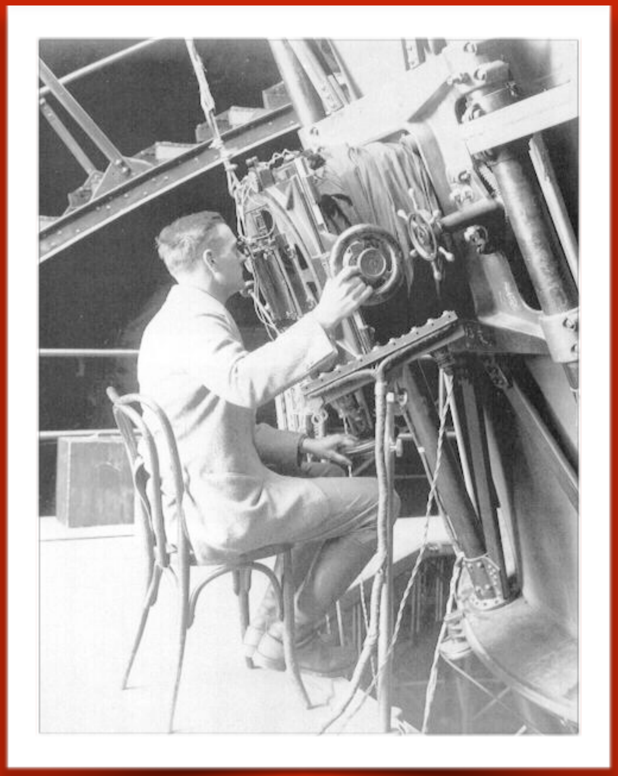
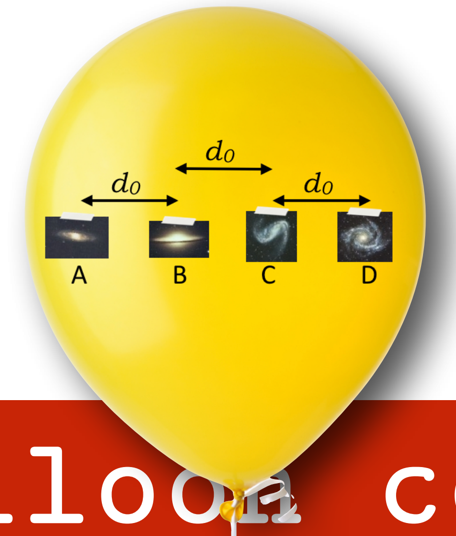


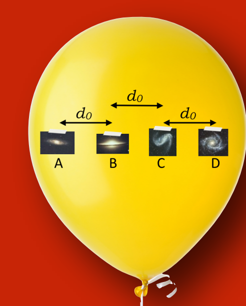
1. spacetime is stretching

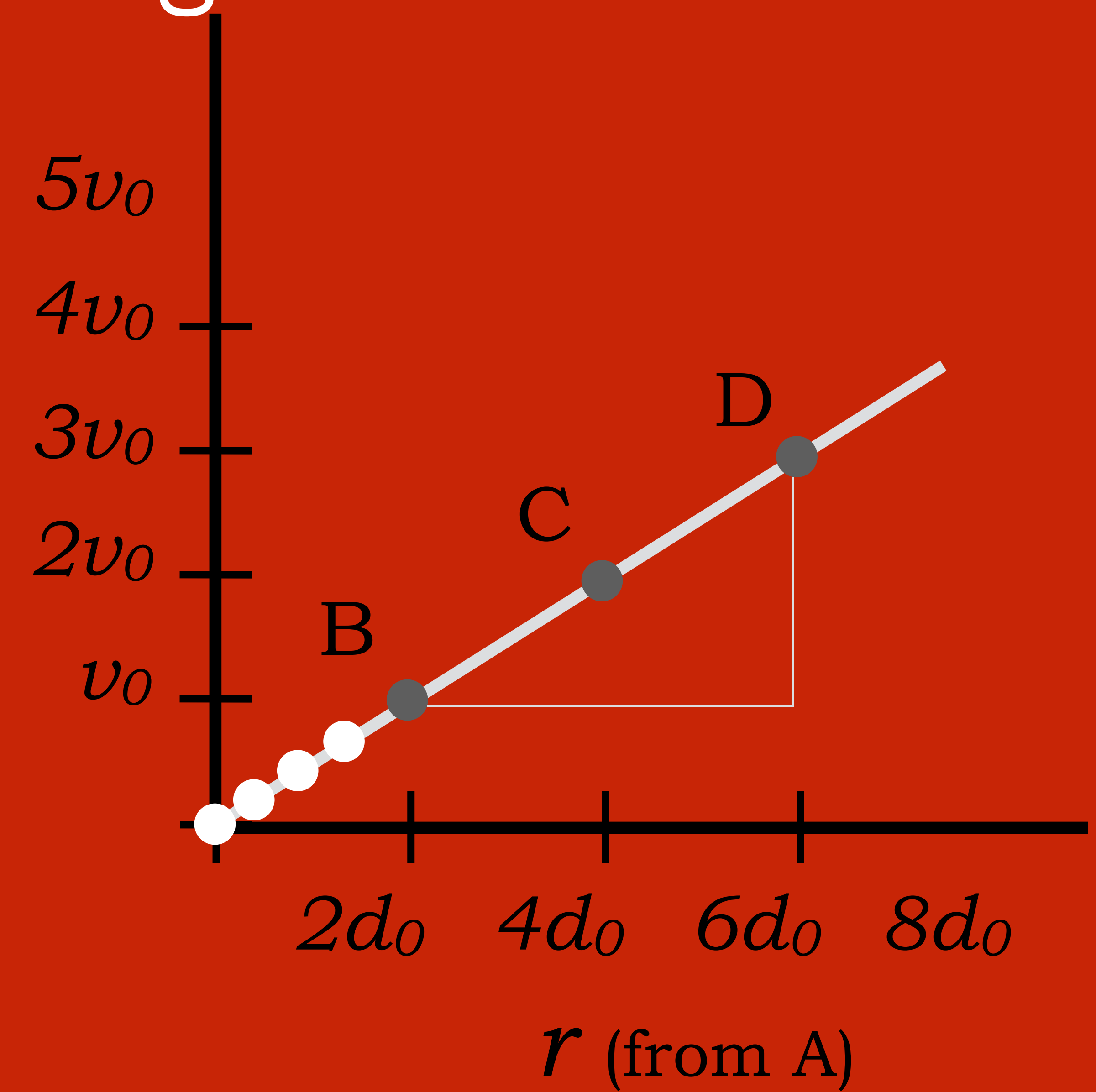
The entire kit and caboodle is expanding

2. But then he realized that the current Universe could have come from something smaller

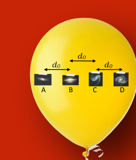


think about the balloon coming from a smaller size





and still smaller



and still smaller

until.

blink