hi

Day 21, 29.03.2018: opening day

Cosmology 4.2

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

Instructions available same place later today

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”

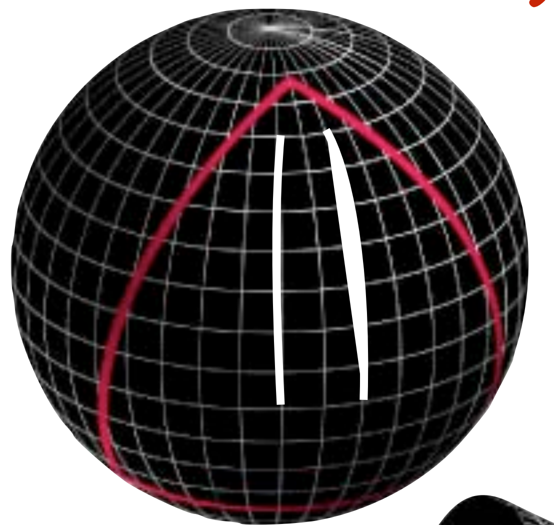
Black Holes

let Brian Greene explain

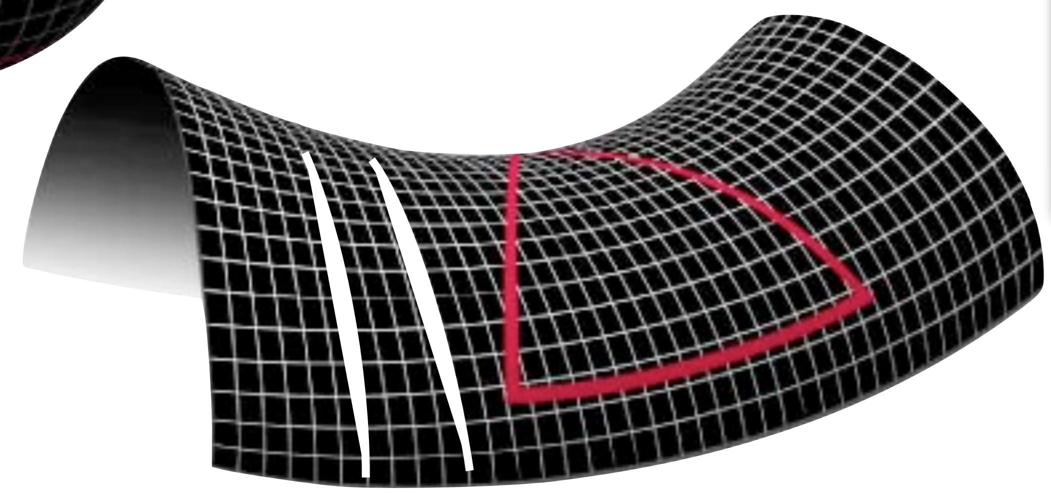
Brian was on campus last spring…did you go?

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

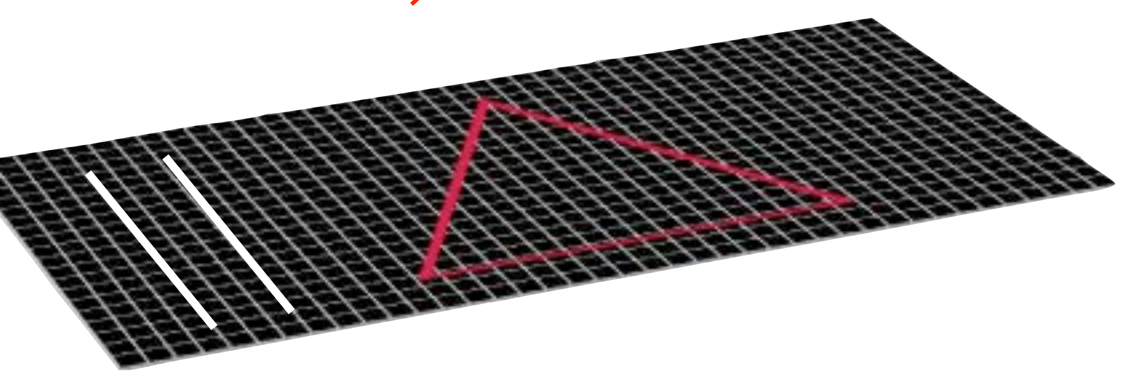
curvature, ‘‘k’’ - hypervolumes



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



$k = 0,$ no curvature
infinite, unbounded



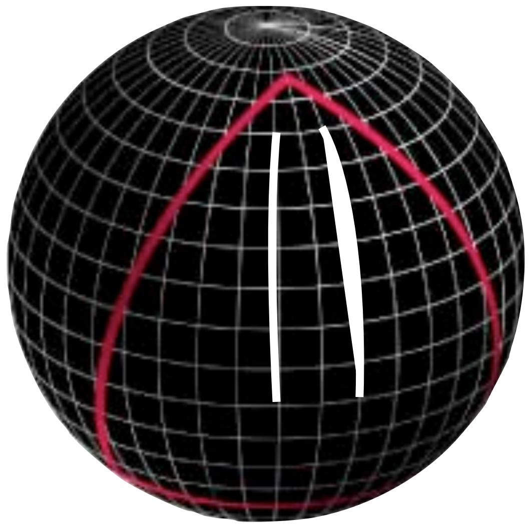
$k = -1,$ negative curvature
infinite, unbounded

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

Einstein wanted:

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



what he got was

a universe solution that was expanding or contracting

He mucked with his beloved equation.

‘‘Cosmological Constant’’

geometry of spacetime ↔ mass-energy, pressure, & momentum

$$\overbrace{G}^{\text{geometry of spacetime}} = \overbrace{T}^{\text{mass-energy, pressure, \& momentum}}$$

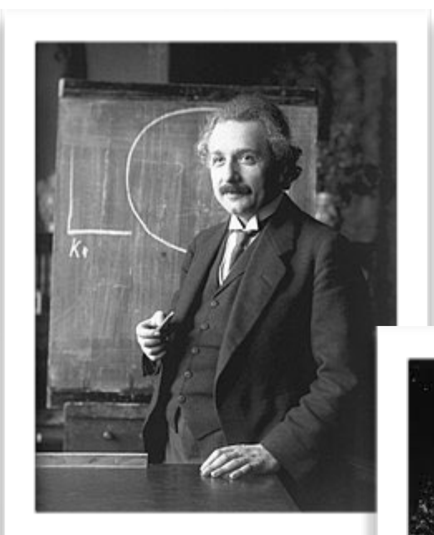
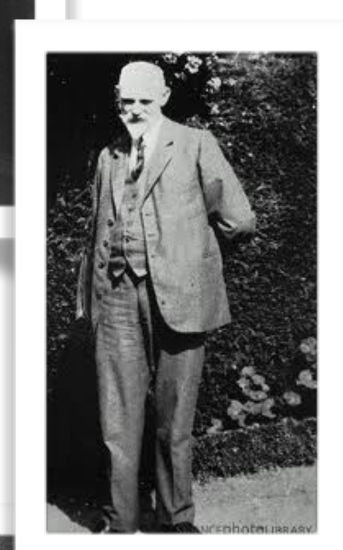
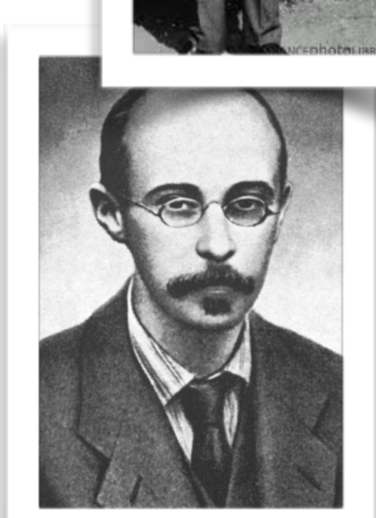
leads to an expanding or contracting spacetime: not stable

$$G + \Lambda = T$$

later:
“My biggest blunder.”

cosmological constant: stops the expansion

solutions to GR

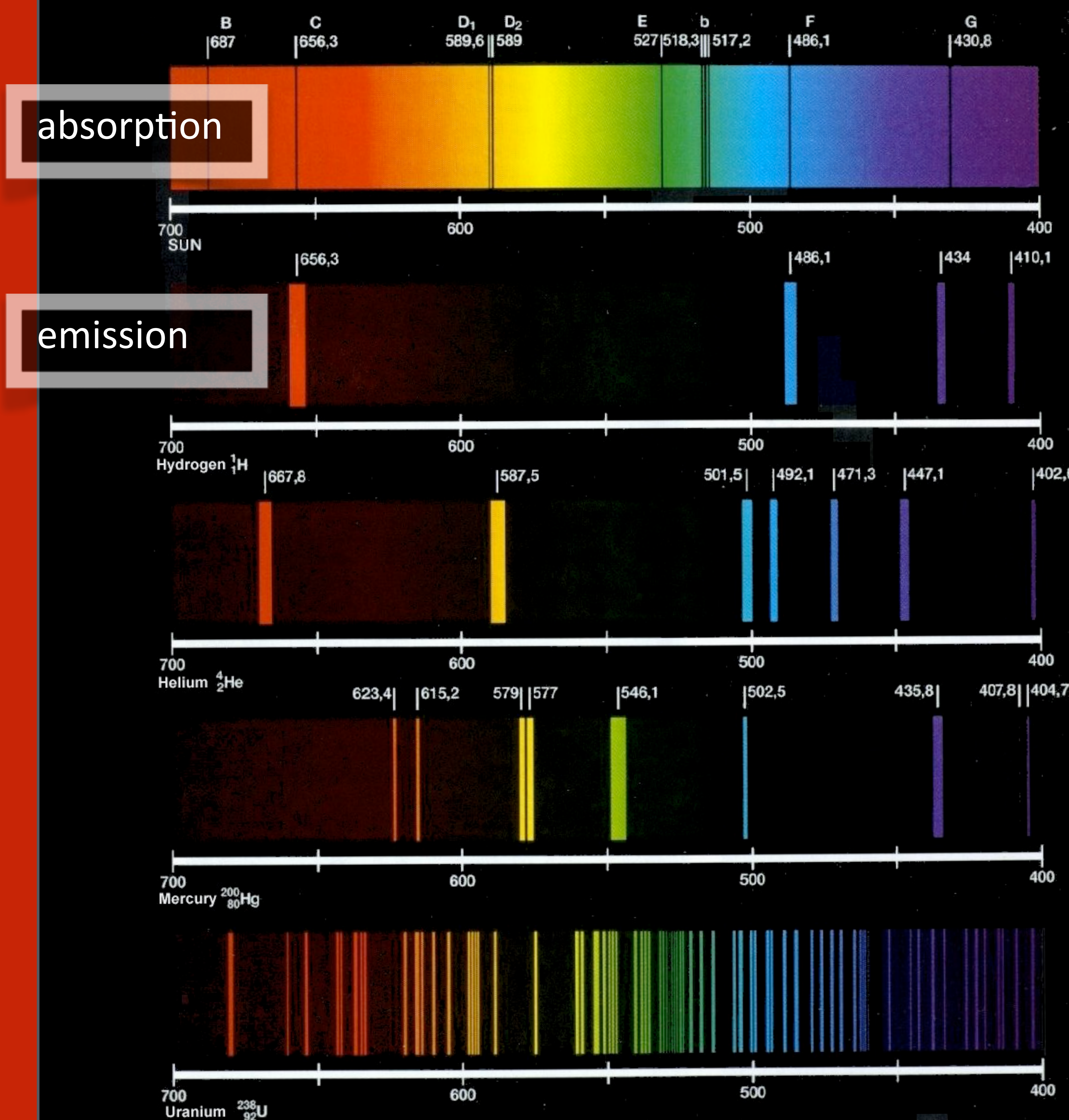




Einstein's: with and without Λ

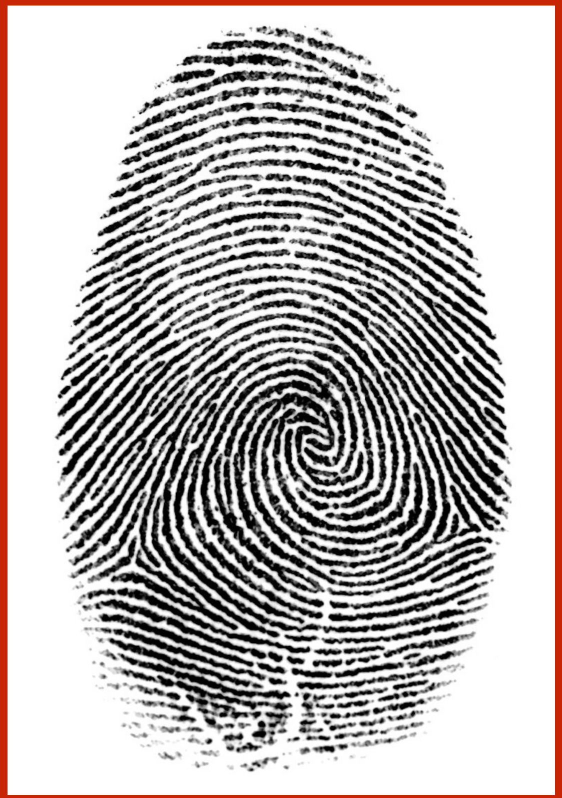
deSitter's: no mass, but a dynamic spacetime

Friedman's: whole mathematical classes of solutions

atomic spectra

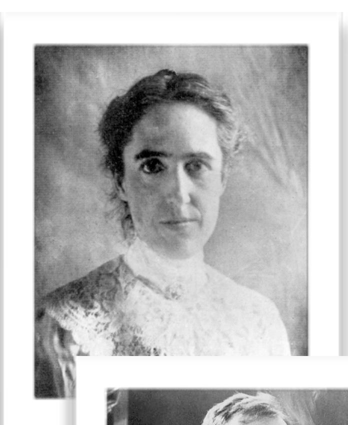


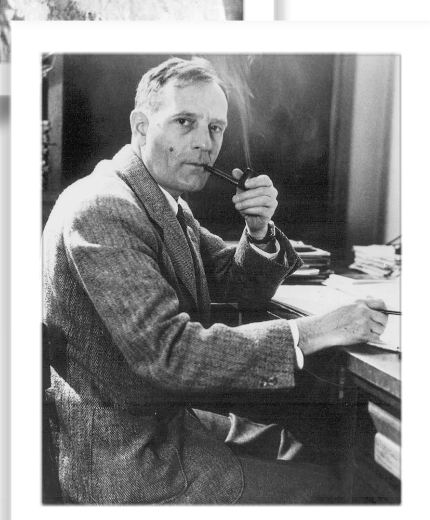
unique fingerprint of the atomic species



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

Edwin Hubble





Took Leavitt's variable stars technique: **distance**

Took spectroscopic measurements: **speed**

found a surprise

Hubble used

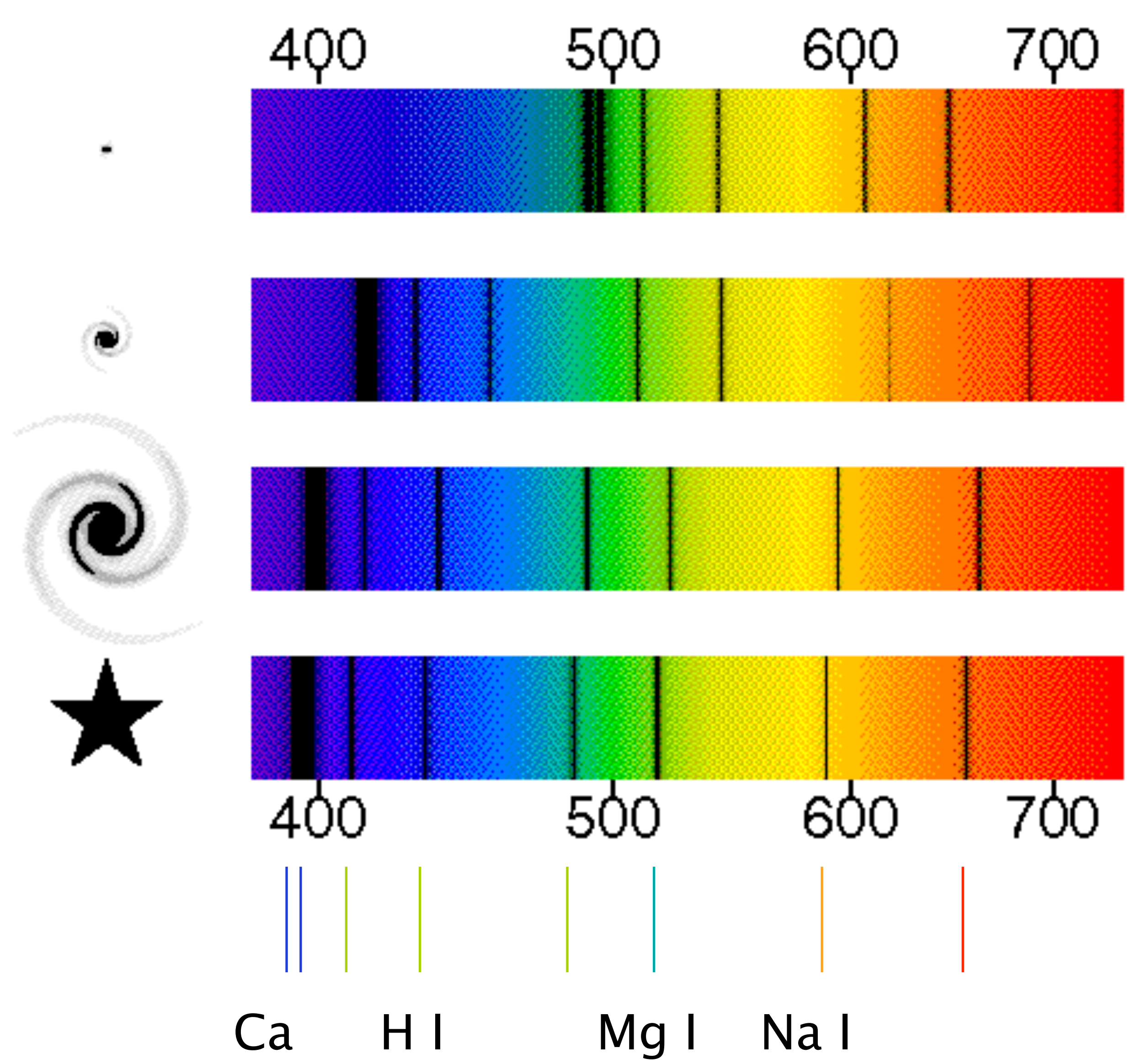
the finger-print tool of spectroscopy

plus

the distance determination tool of Cepheid Variables

His results:

Wavelengths of most galaxies shifted to longer - “**redshifted**”



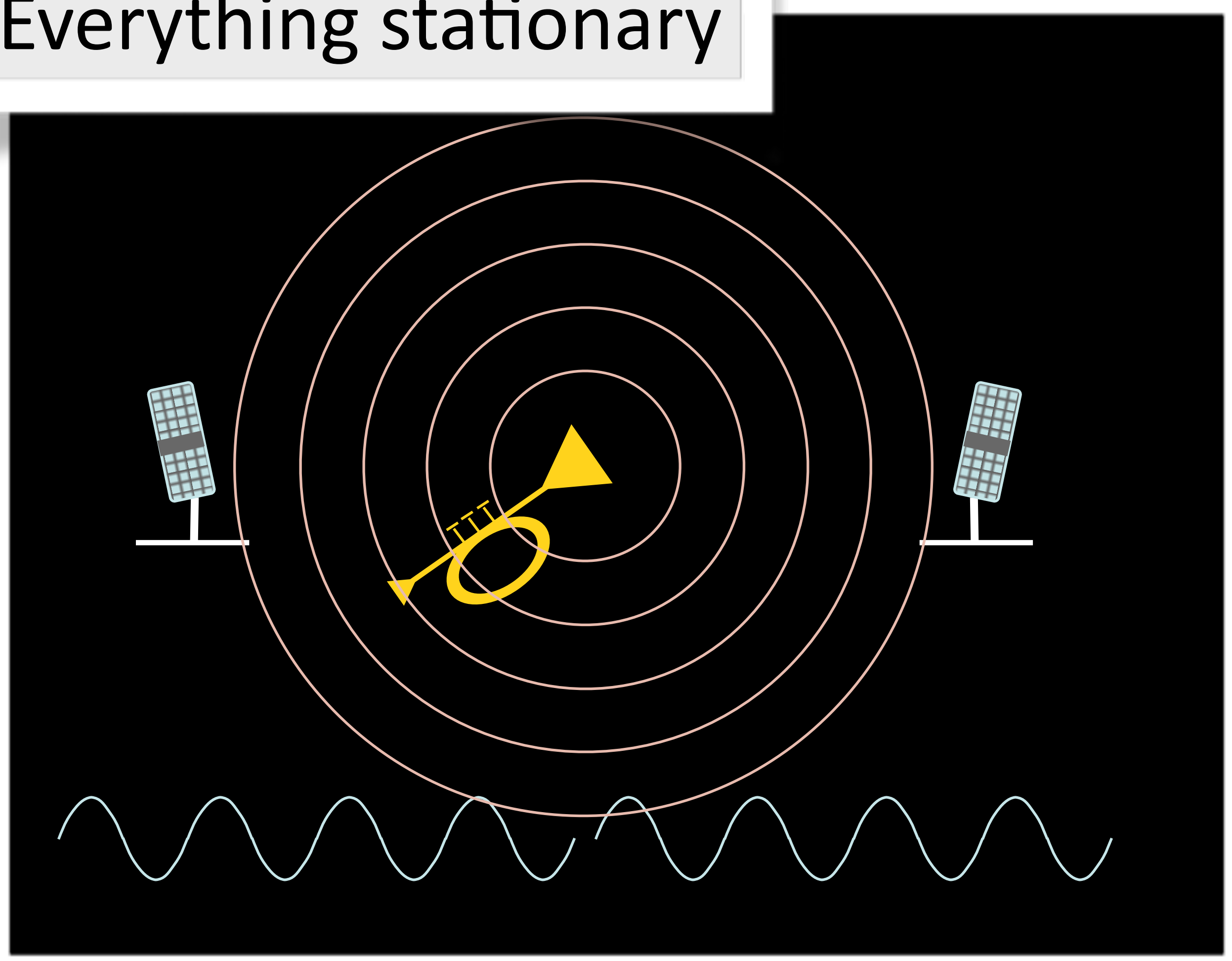
http://www.astro.ucla.edu/~wright/doppler.htm

a little doppler'll do 'ya

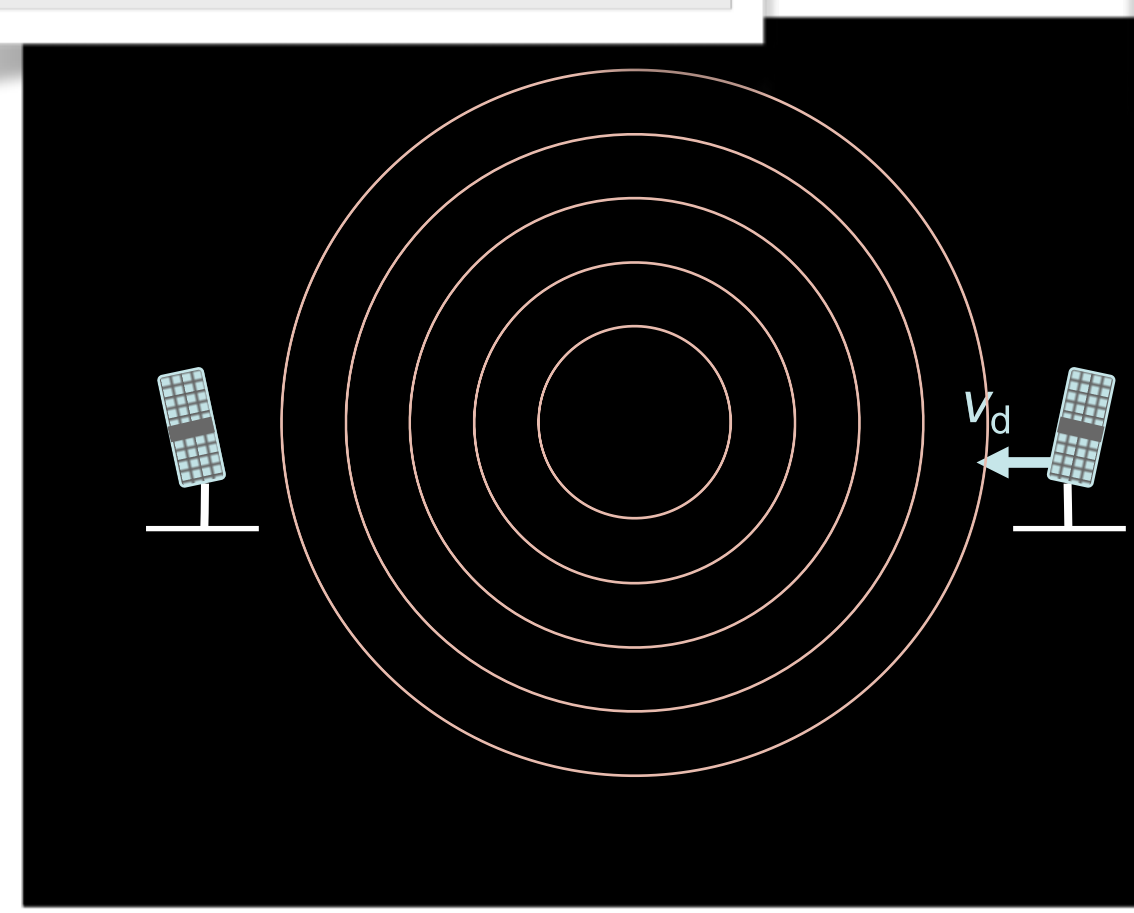
The Doppler Effect

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

Everything stationary

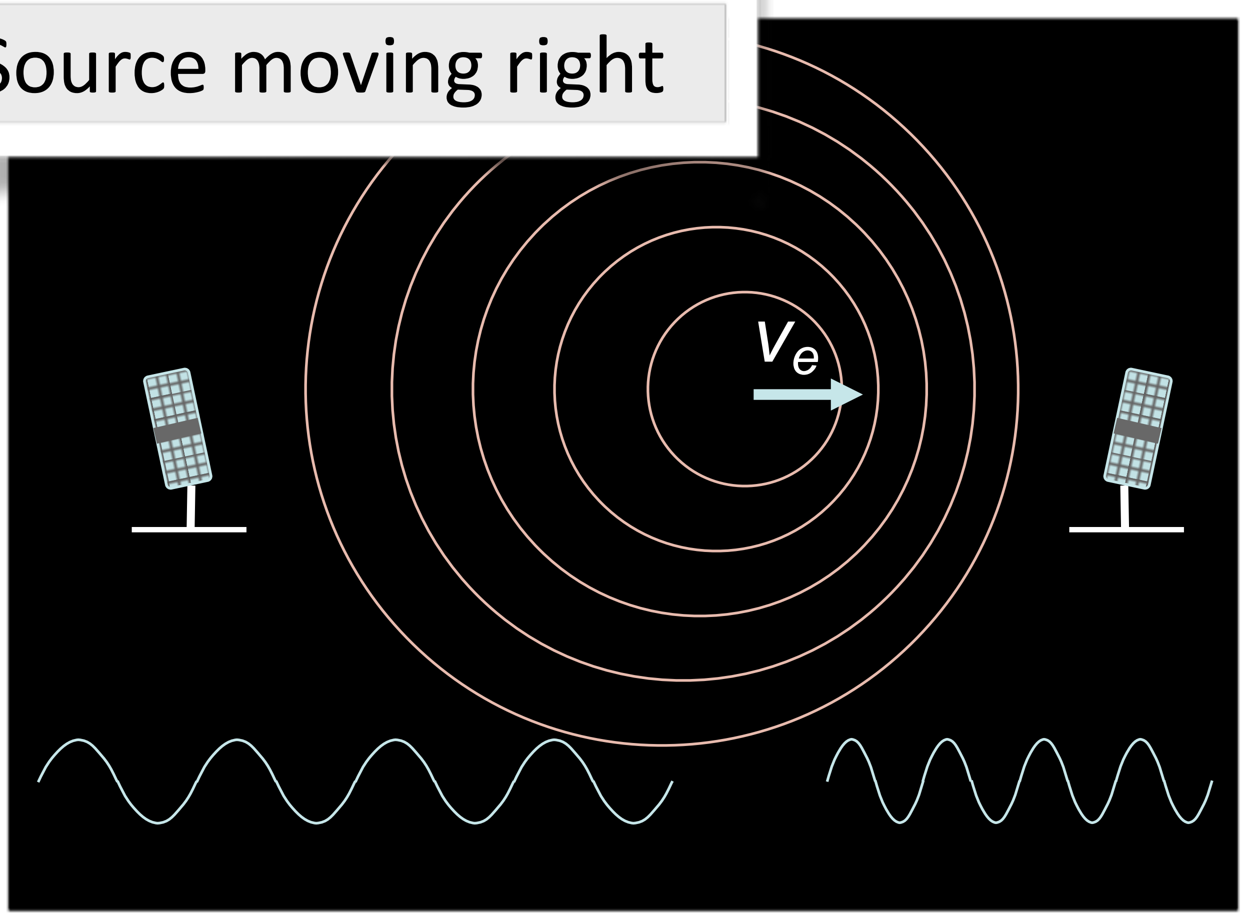


Receiver moving left



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

Source moving right



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

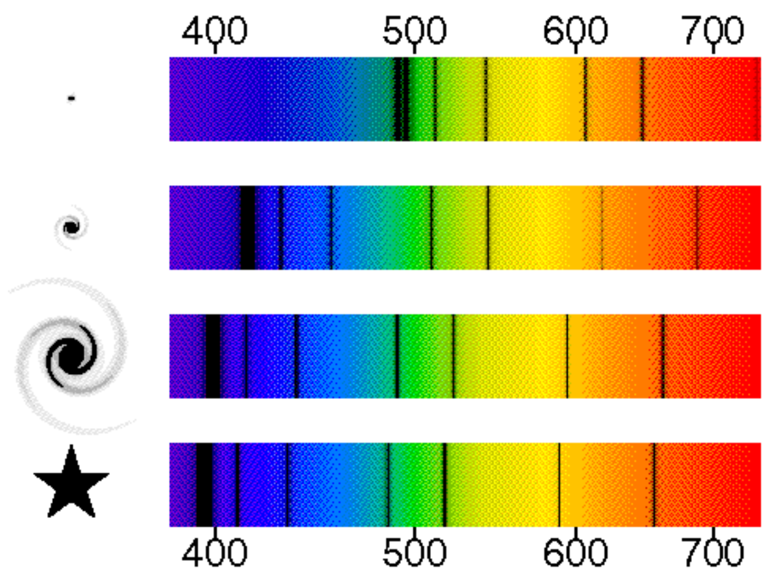
Sound moving away from L...**pitch goes down for L. lower pitch, longer wavelengths**

Hubble's remarkable conclusion:

all of the galaxies are moving away from us.

1929: a stunning quantitative conclusion

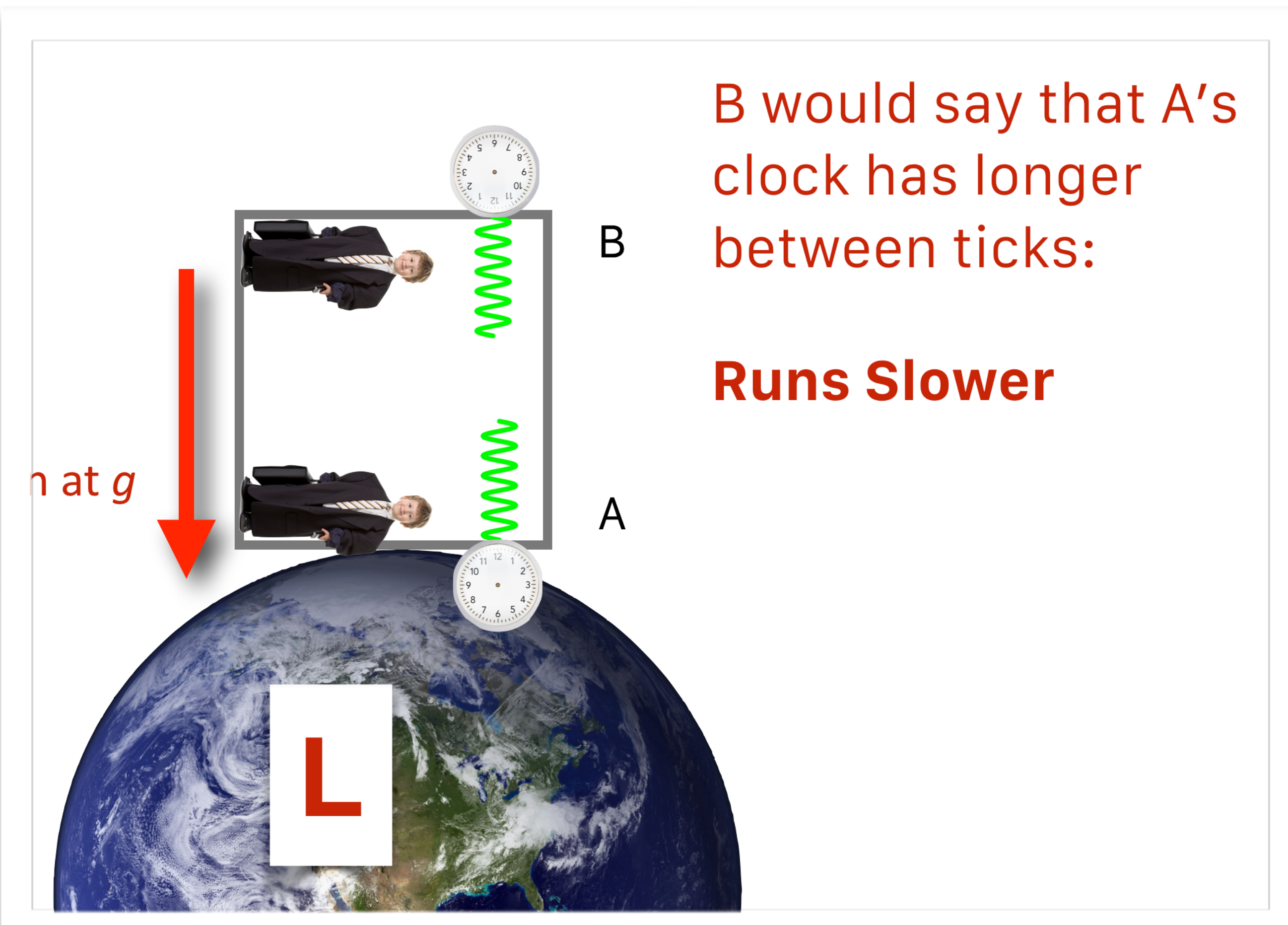
But the actual reason is even more stunning.

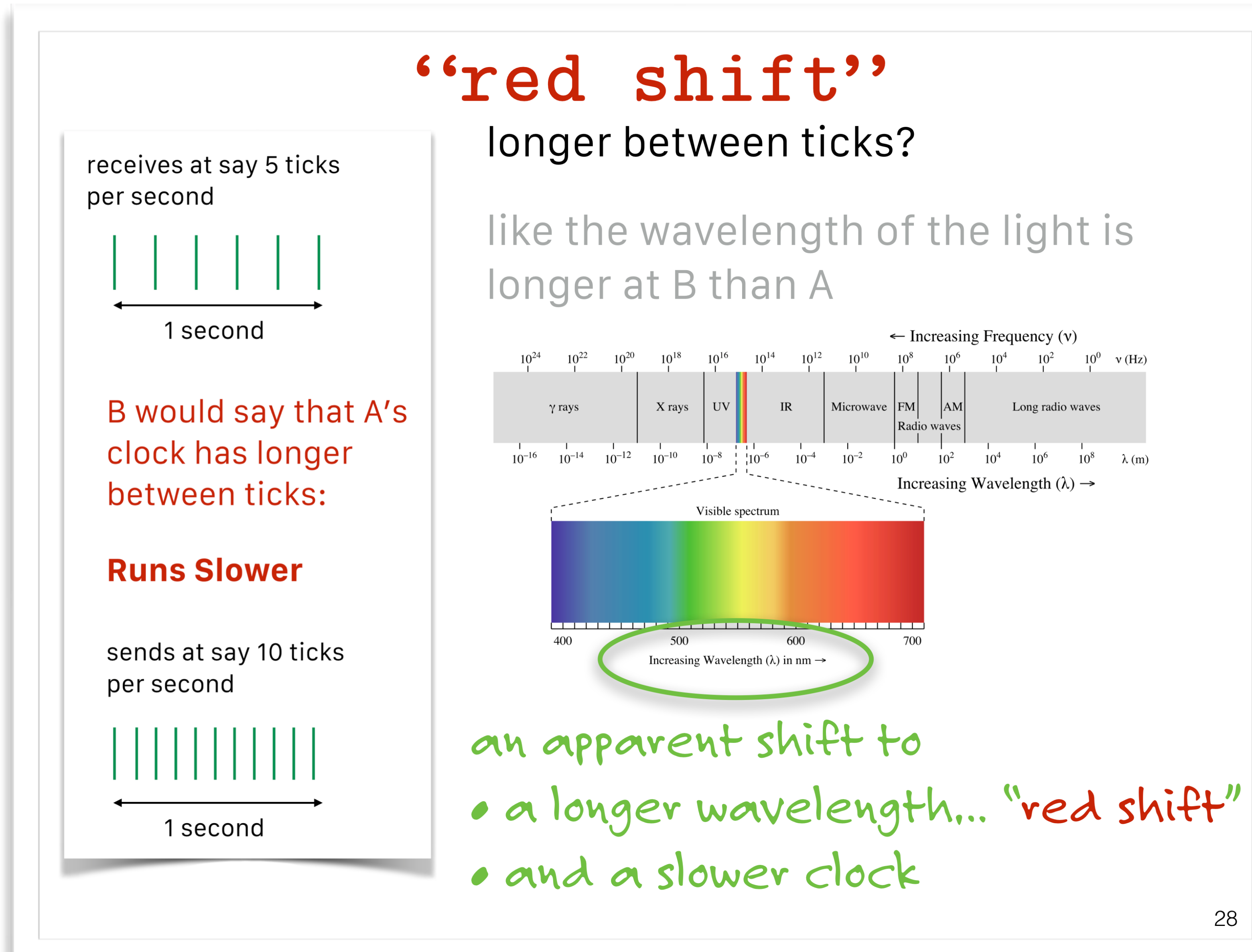


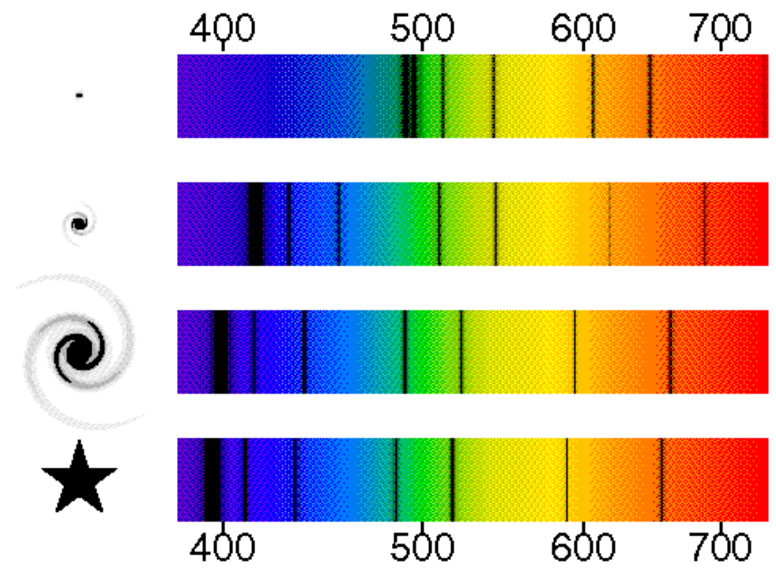
this is not that.

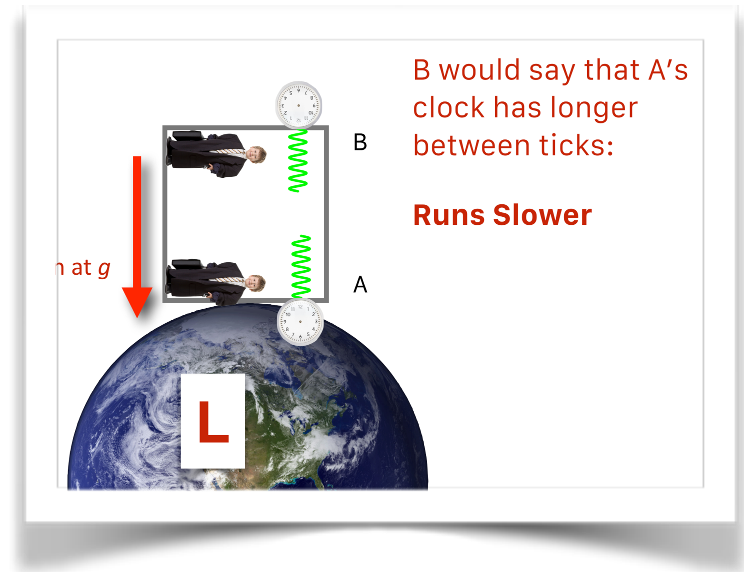
but Hubble presumed that it was

remember the Gravitational Red Shift?



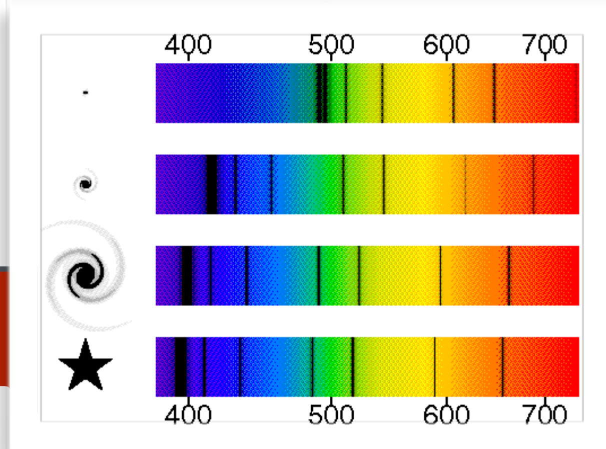






well, this is not that either!

Hubble's



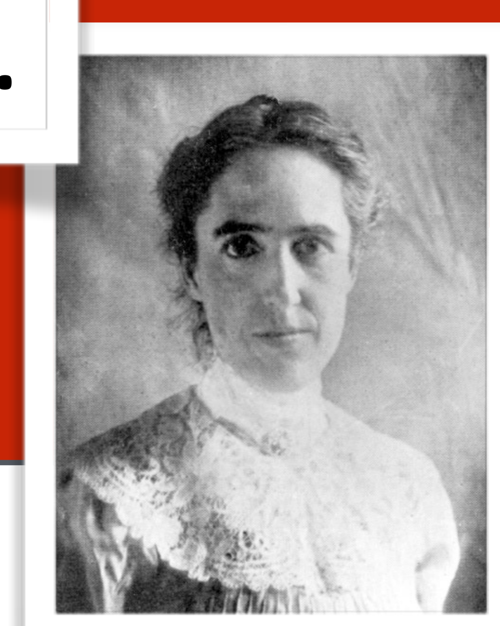
FROM PRESUMED DOPPLER-SHIFTED SPECTRA

HUBBLE'S CONSTANT = 1/T

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

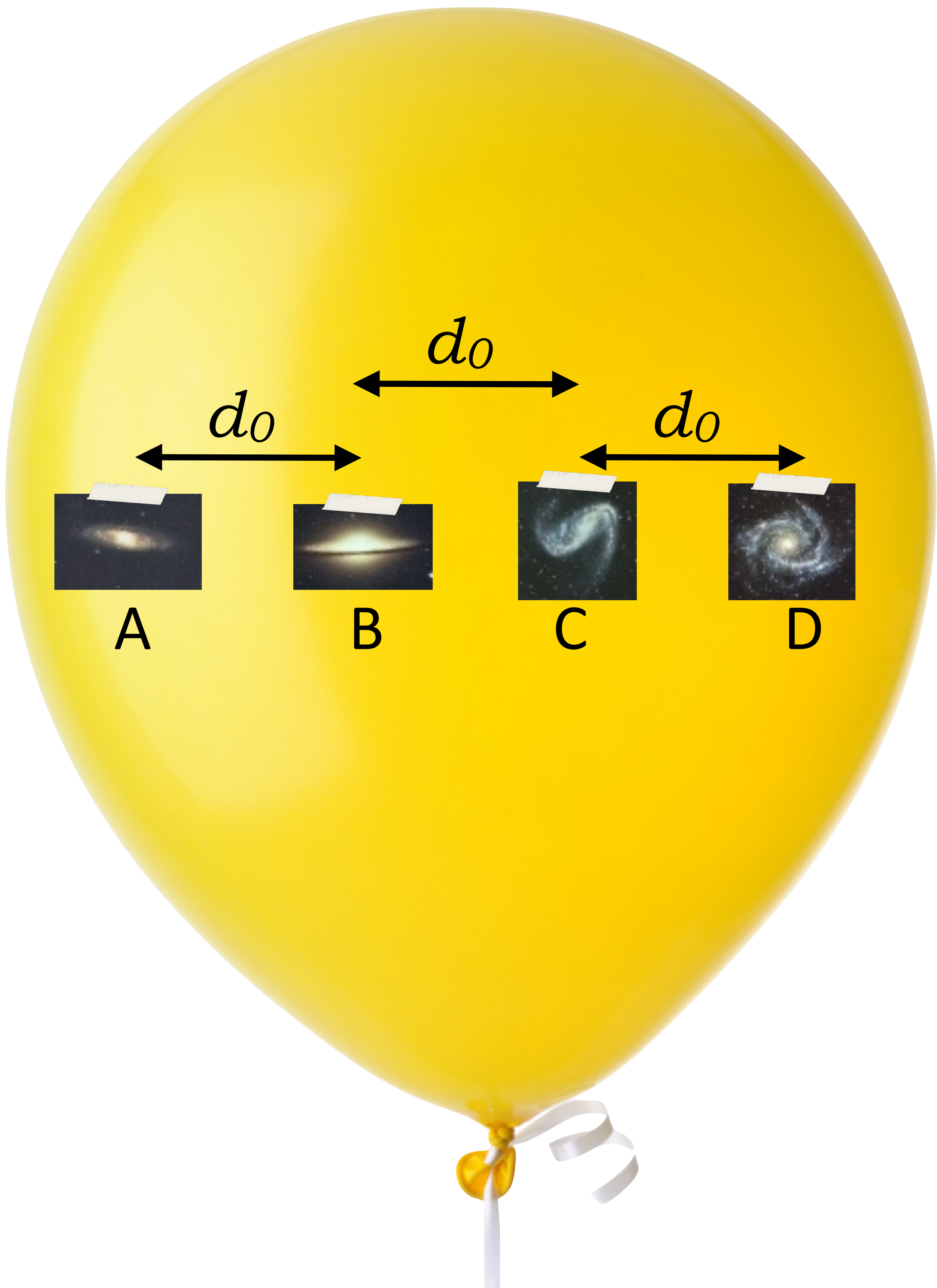
$$v = rH$$

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



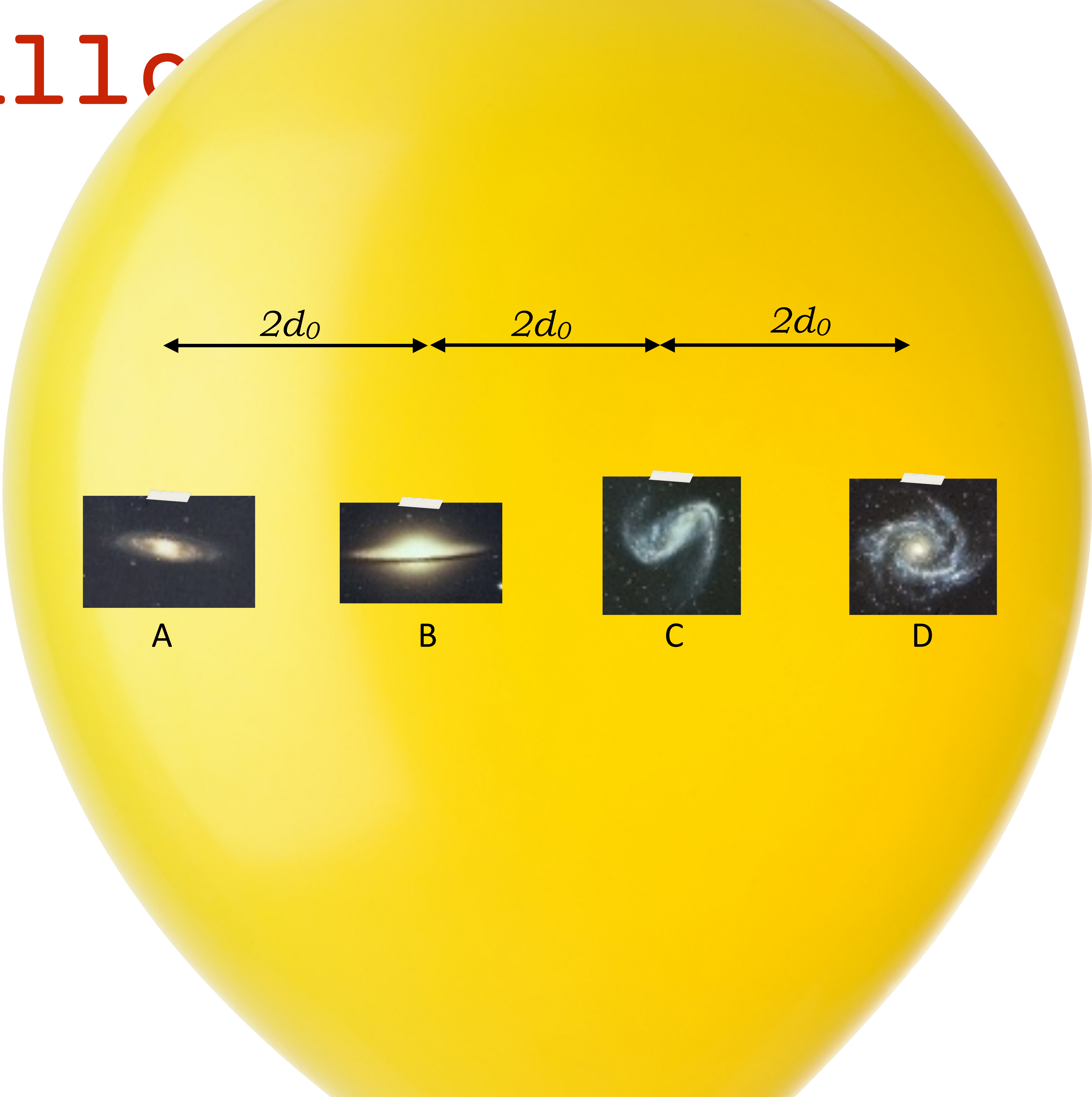
FROM LEAVITT'S CEPHEID VARIABLE RELATION

balloon world



Time 1

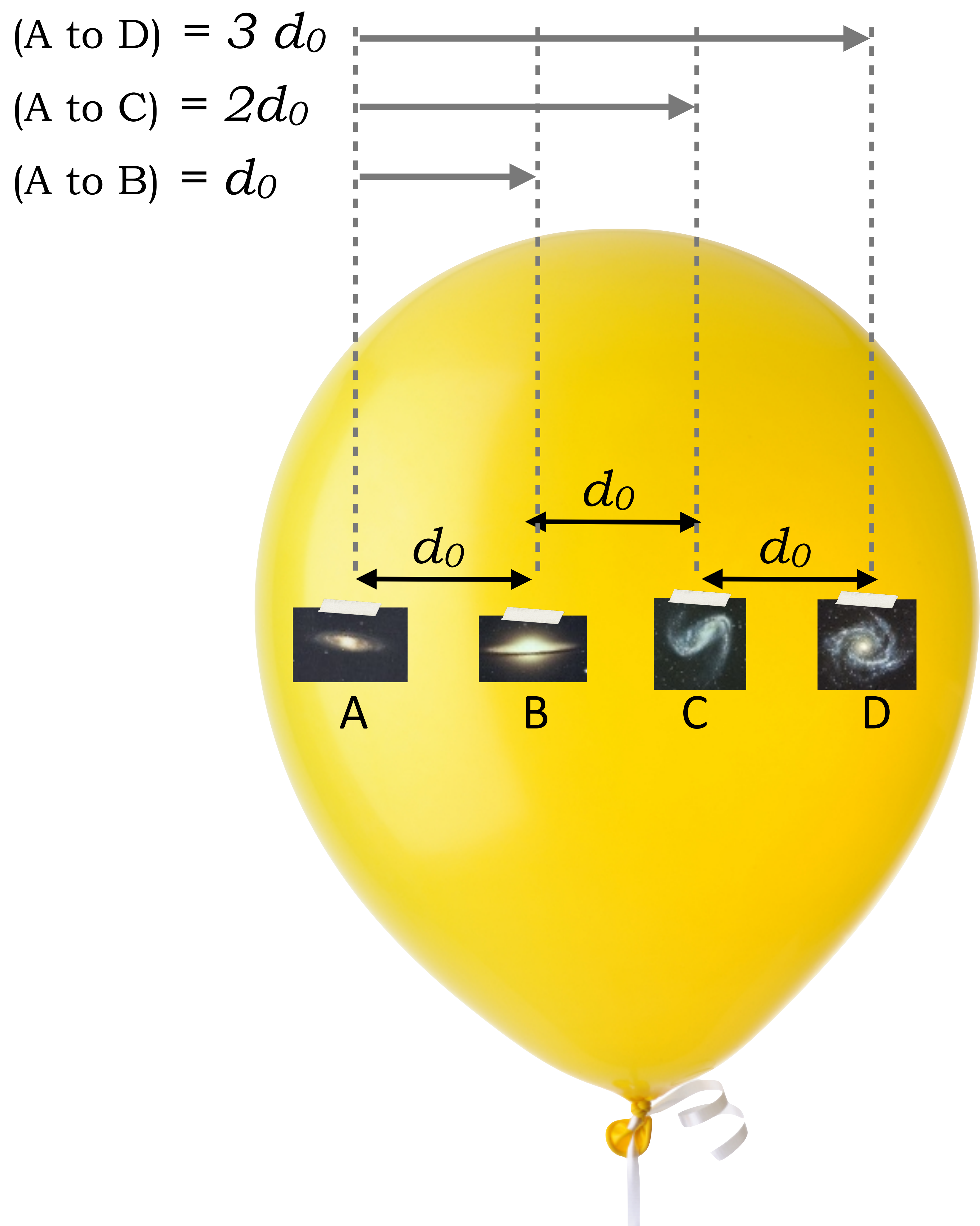
ballo



Time 2

Time 3

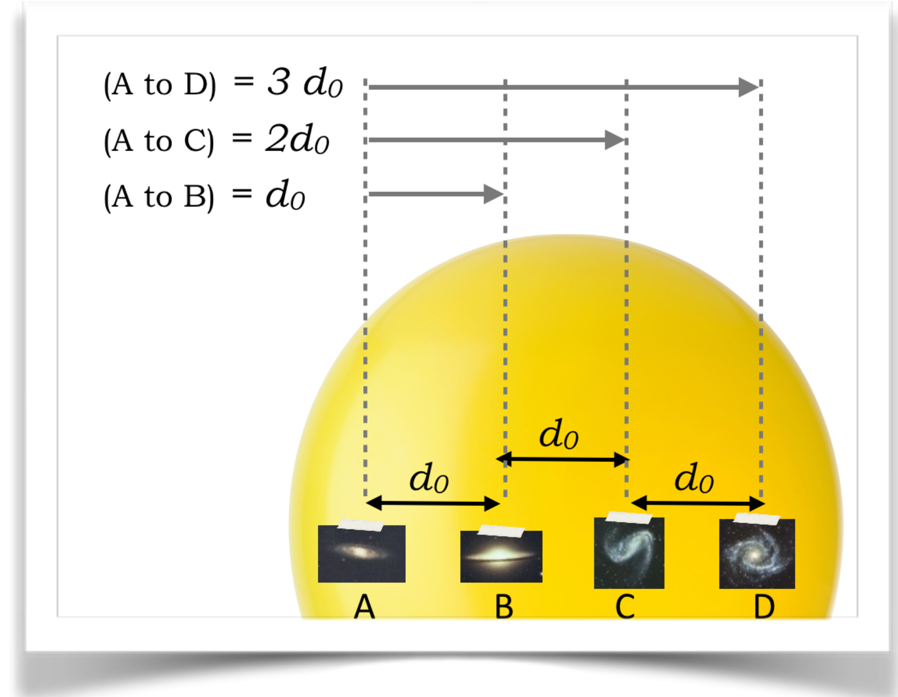
keep track of how far away everything is from Galaxy A



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

what we had

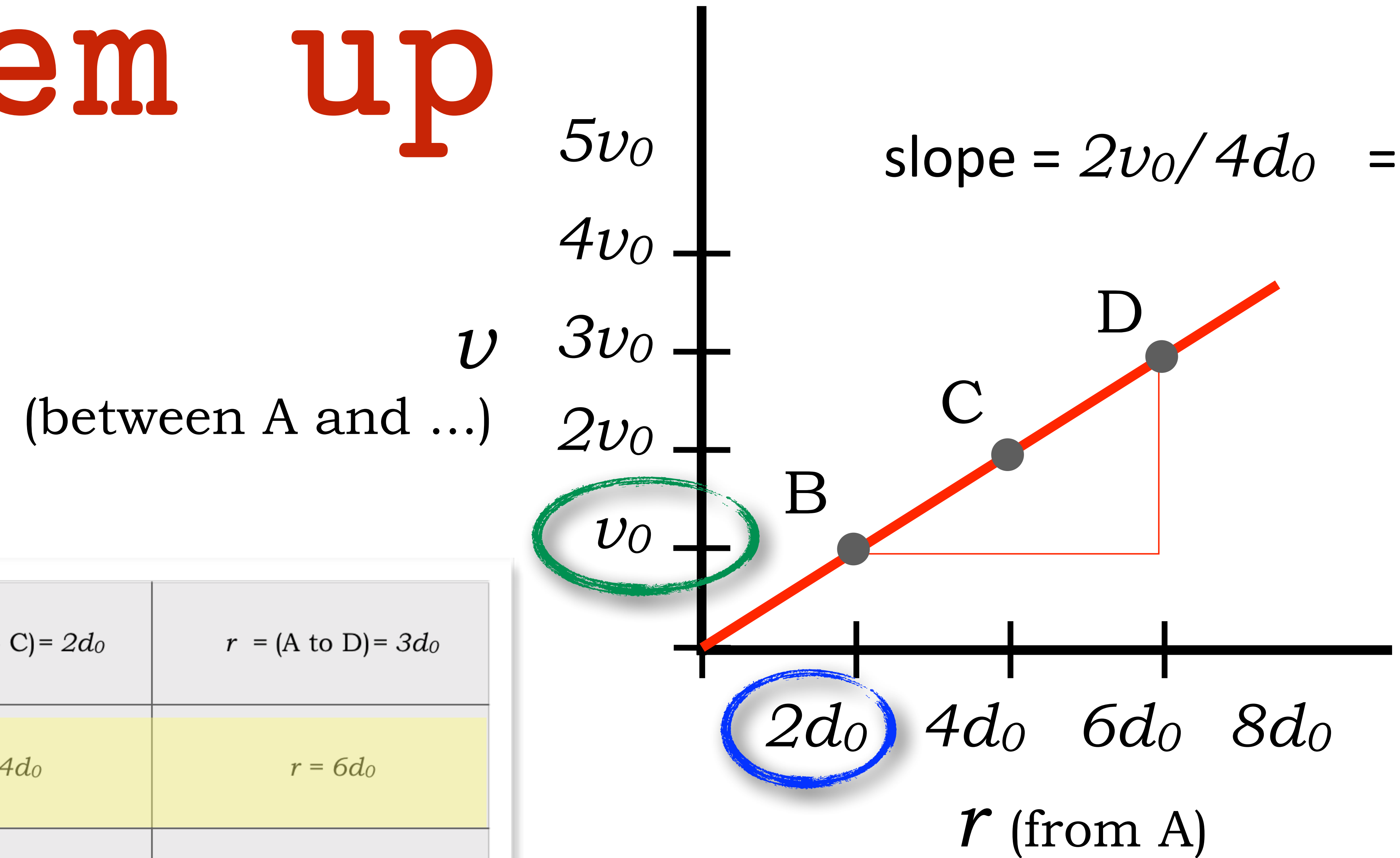
Time 1



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	$d_0/\Delta t = v_0$	$2d_0/\Delta t = 2v_0$	$3d_0/\Delta t = 3v_0$

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

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.

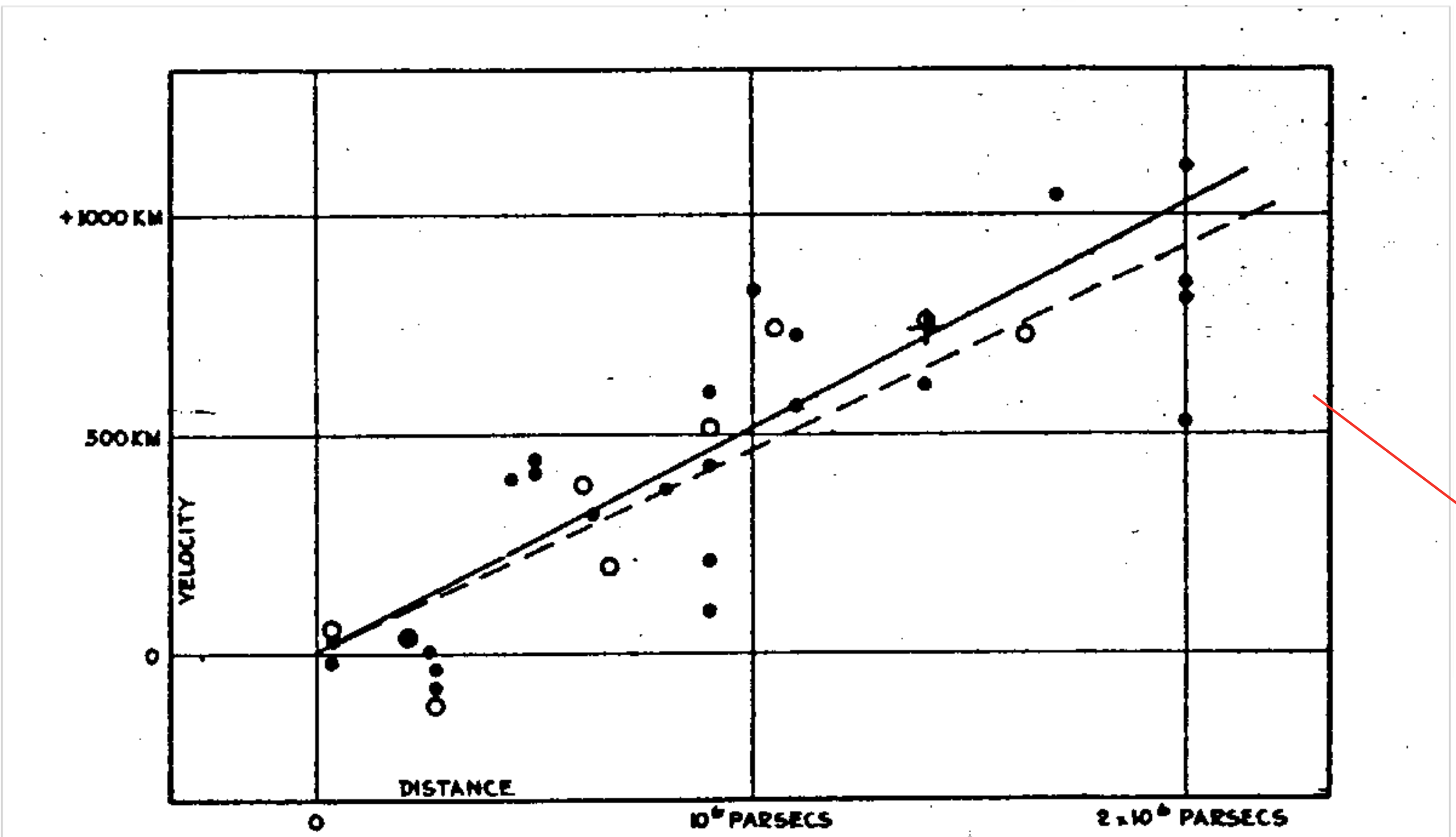
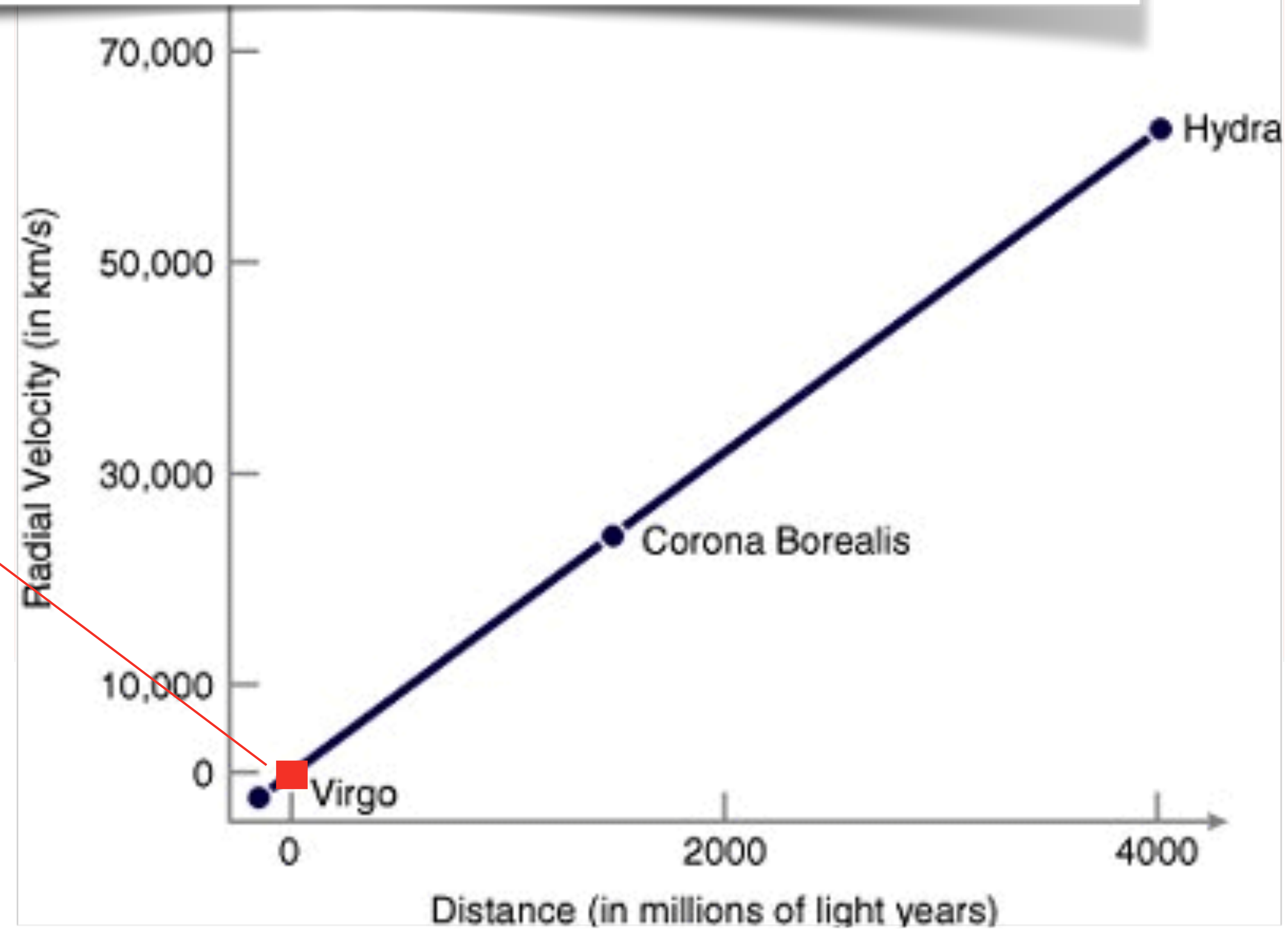


FIGURE 1



So, what does Hubble's Law mean?

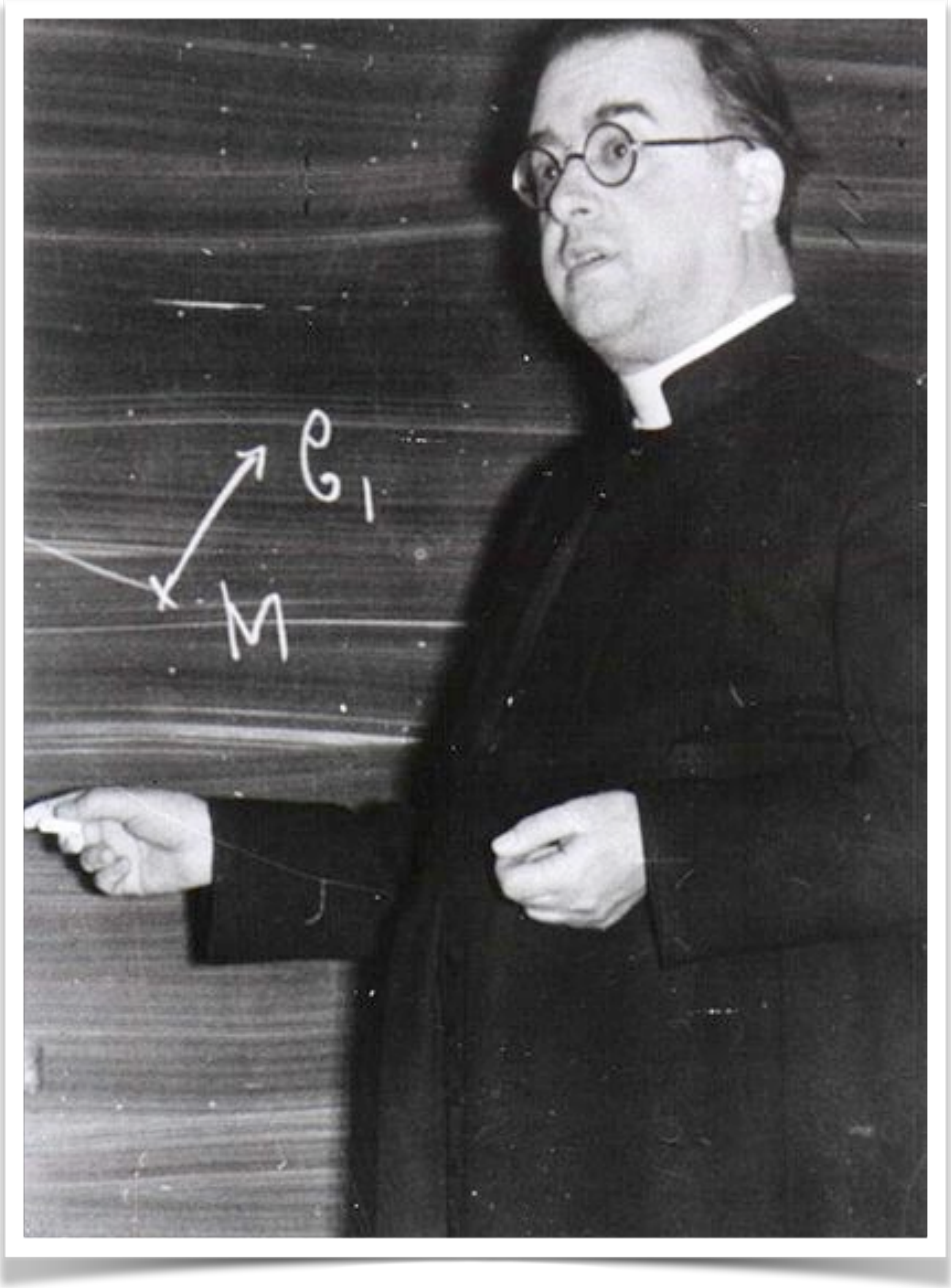
apart from the balloon…

$$v = rH$$

Georges Lemaître (1894-1966)

The father of the Big Bang

get it?



three kinds of education

war

seminary

physics

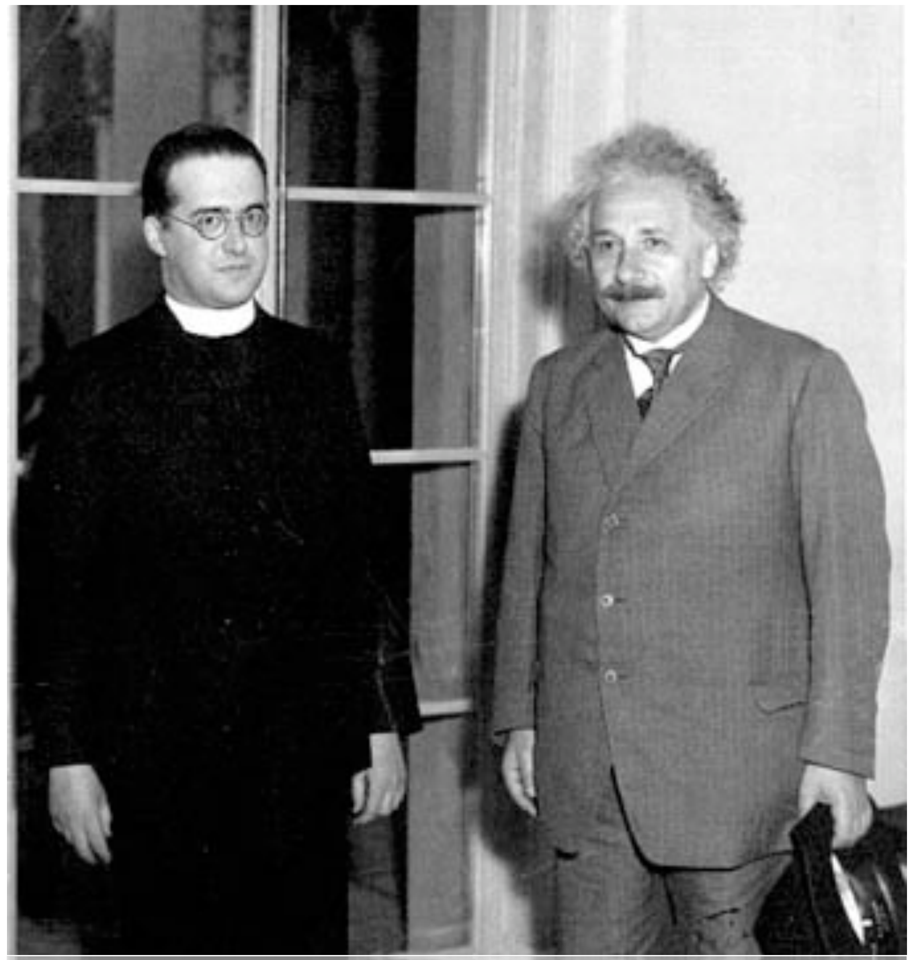
http://www.flickr.com/photos/miguelcalleja/sets/72157604962600986/detail/

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

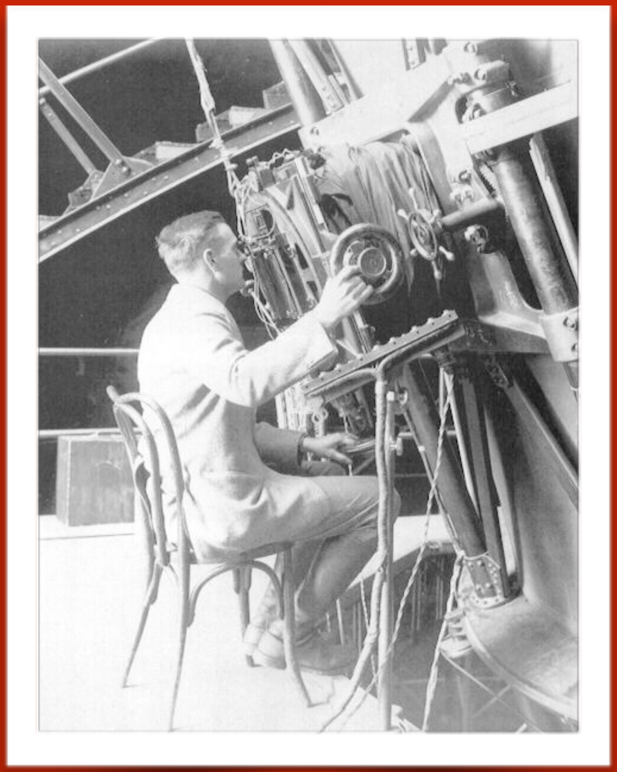
"brilliant"

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:



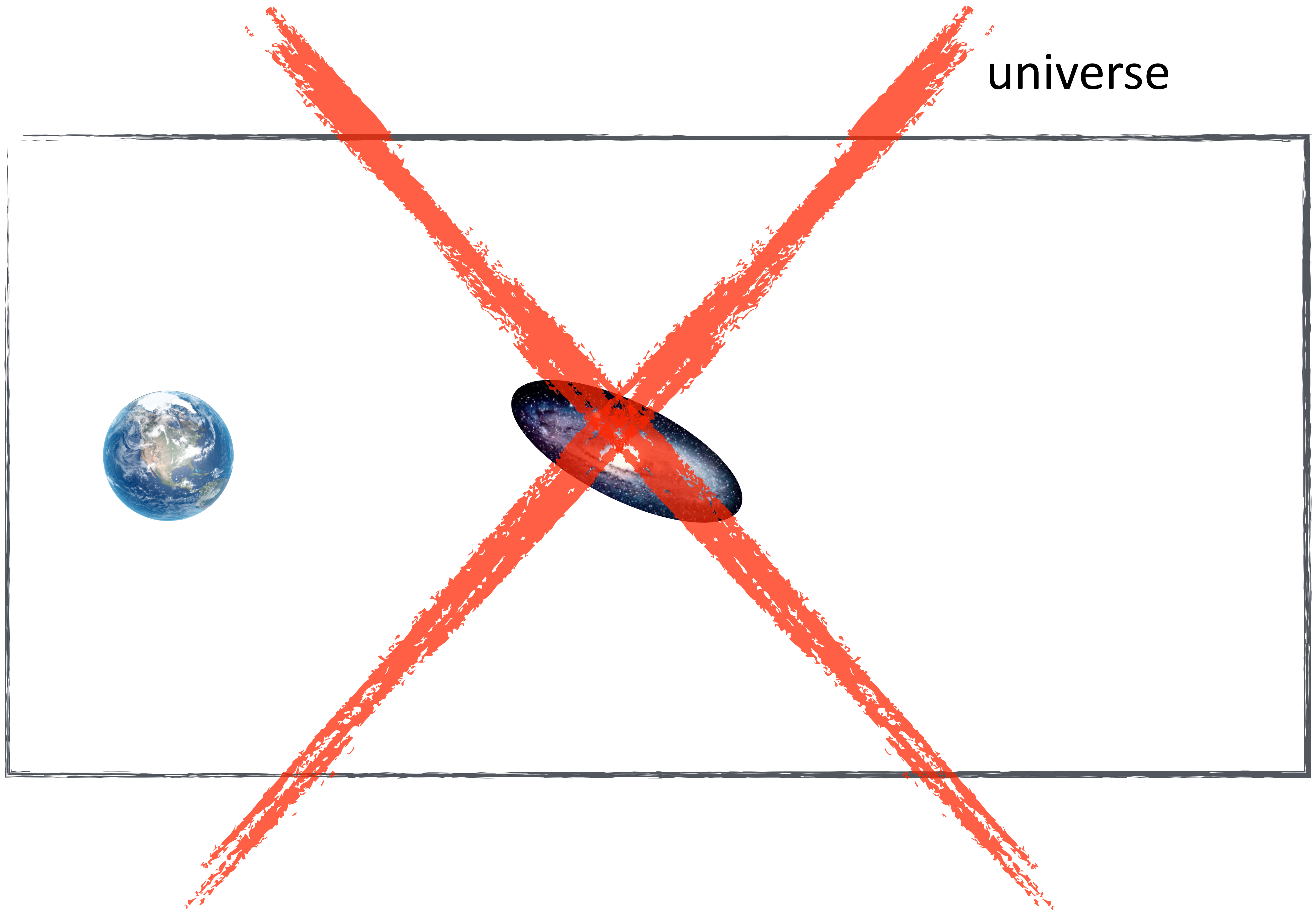
1. spacetime is stretching

The entire kit and caboodle is expanding

Here’s what it does NOT mean:

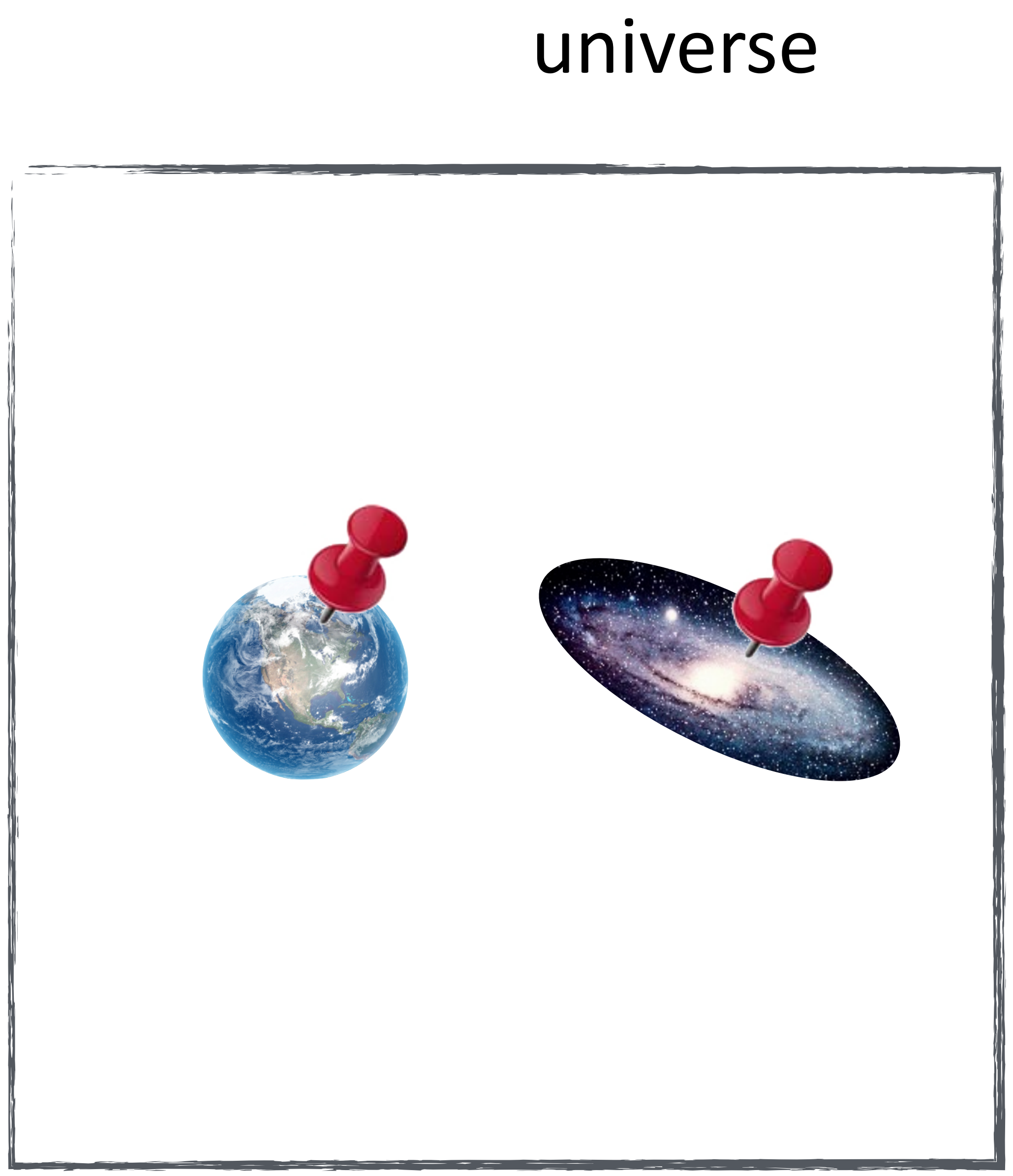
galaxies are not “‘moving away”’

inside of the universe

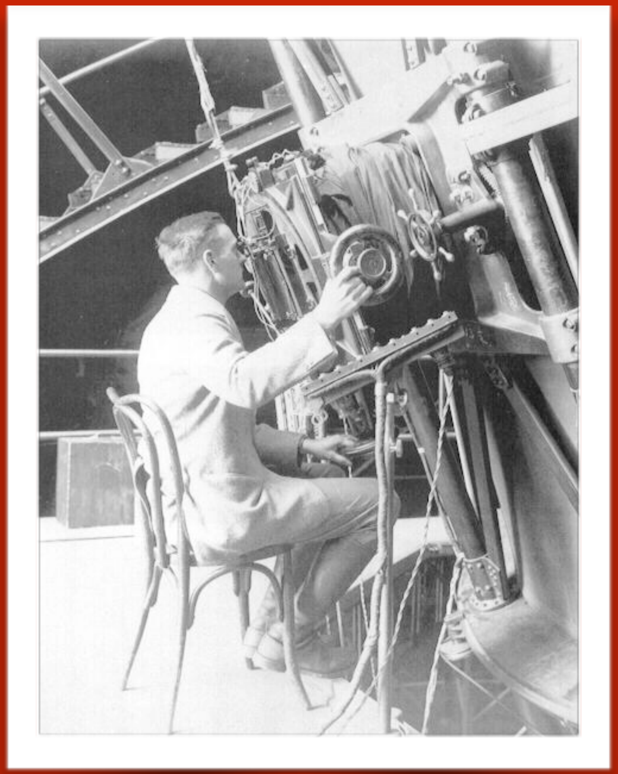


what stretching DOES mean

is complicated!



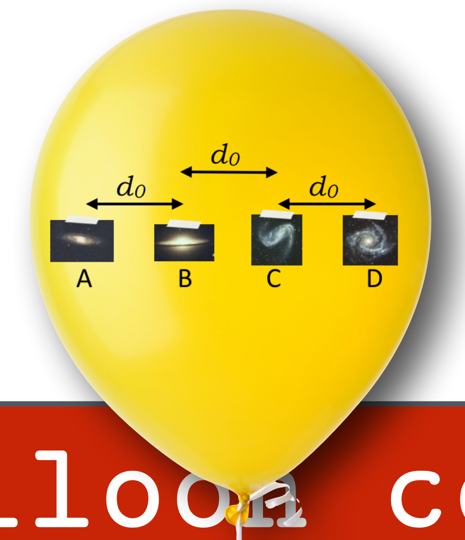
Lemaître was the first to realize that Hubble had demonstrated:



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



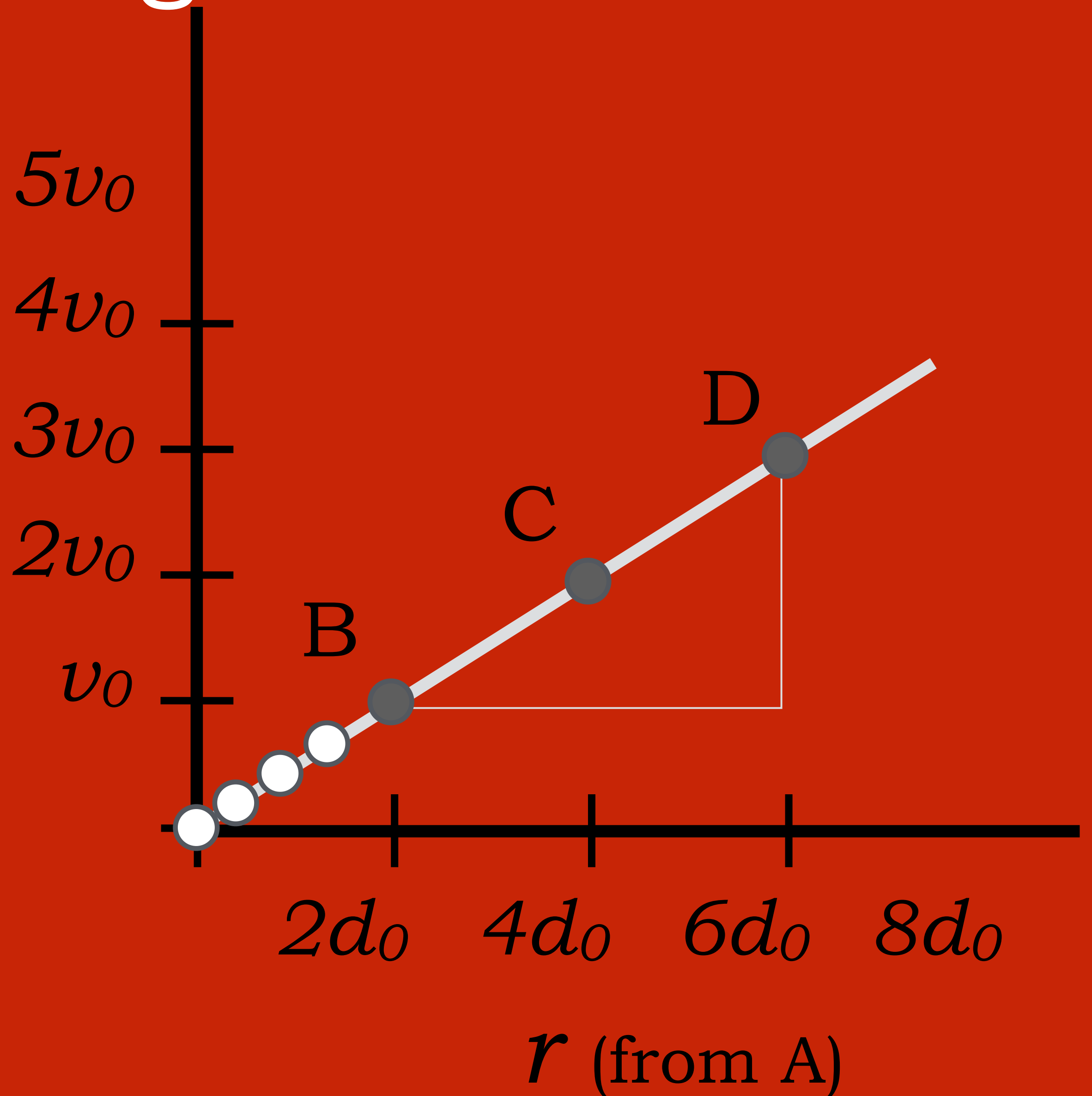
think about the balloon coming from a smaller size

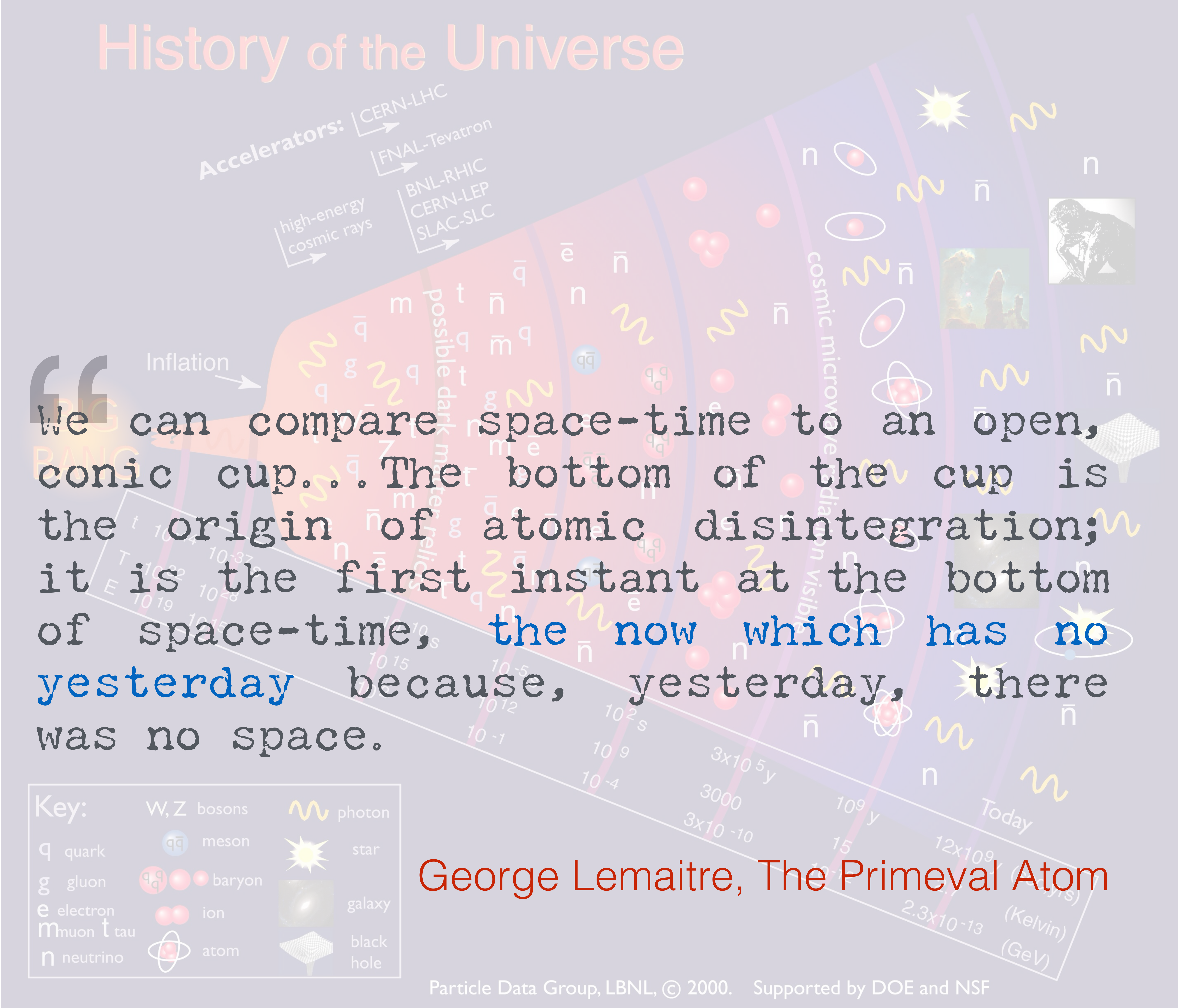
and still smaller

and still smaller

until.

blink





“We can compare space-time to an open, conic cup. . .The bottom of the cup is the origin of atomic disintegration; it is the first instant at the bottom of space-time, the now which has no yesterday because, yesterday, there was no space.

George Lemaitre, The Primeval Atom

Lemaître envisioned

A “primeval atom”

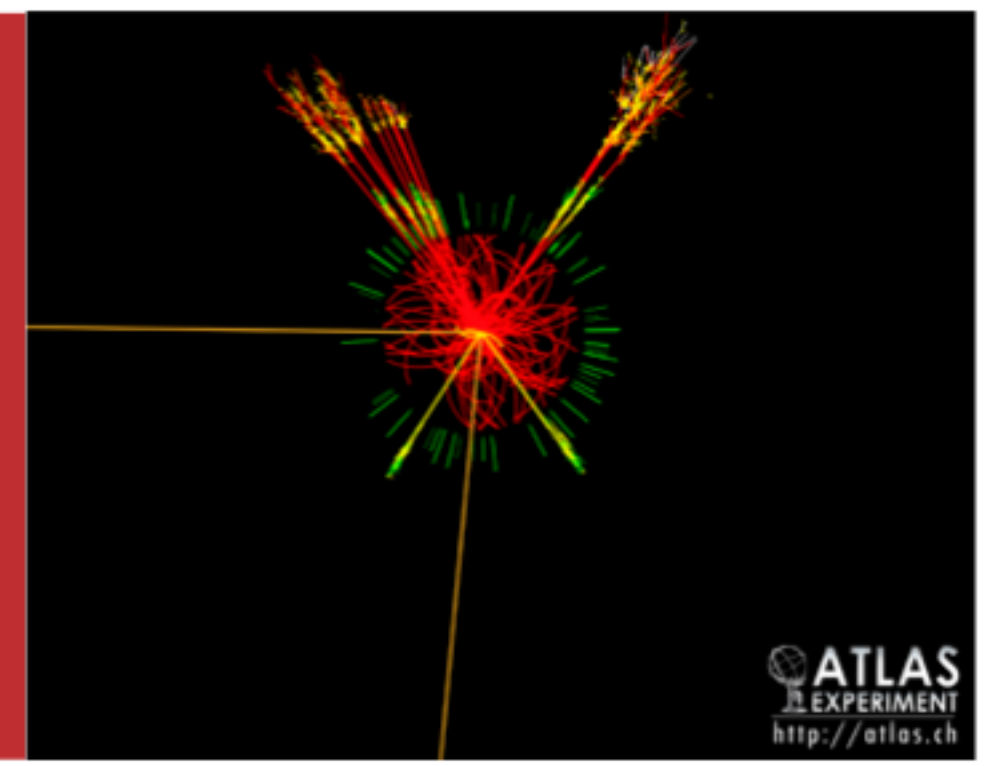
it was the heady times of quantum mechanics and early nuclear physics

He envisioned a fissioning of a big, big nucleus

QUARKS, SPACETIME, and the BIG BANG

spring term 2012

A simulated Higgs Boson event as it might appear inside of the ATLAS detector at the Large Hadron Collider.



think about this.

a Catholic Priest-Theoretical Physicist

envisioning the beginning of the Universe...a “creation story”?

Sir Arthur Eddington states that, philosophically, the notion of the beginning of the present order of Nature is repugnant...I would rather be inclined to think that the present state of quantum theory suggests a beginning of the world very different from the present order of Nature.

"

Lemaître: Nature

comment May 9, 1931

Was his theology in the way of his science?

No.

He was explicit in his separation

And, the respect that his colleagues held for him

did not result in accusations of him pushing his religion into Cosmology

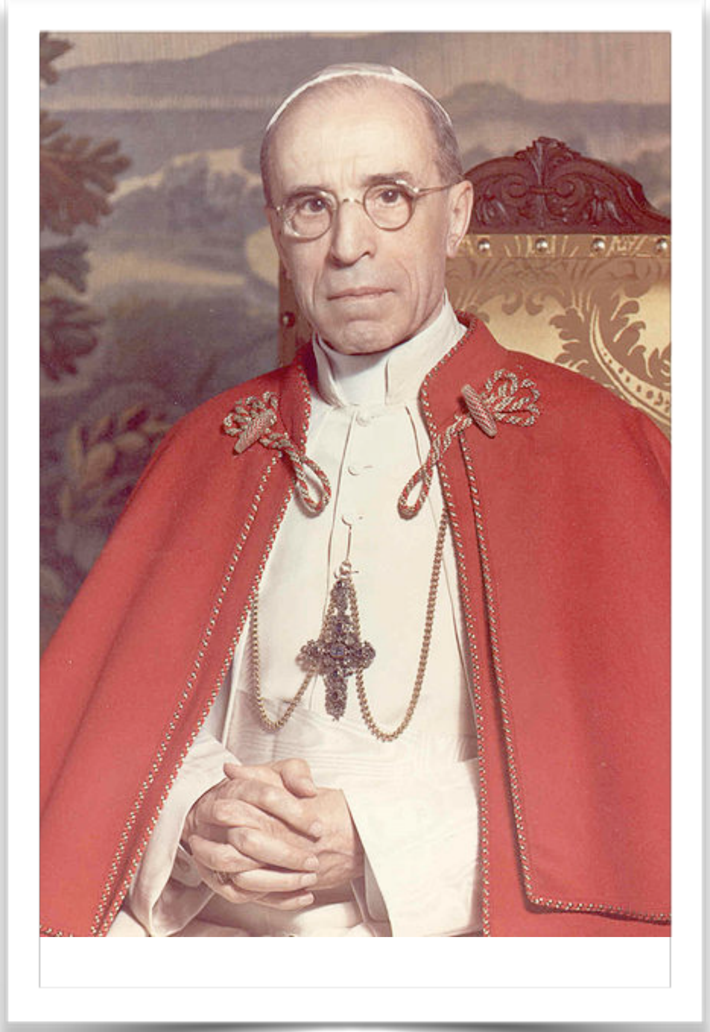
undercut

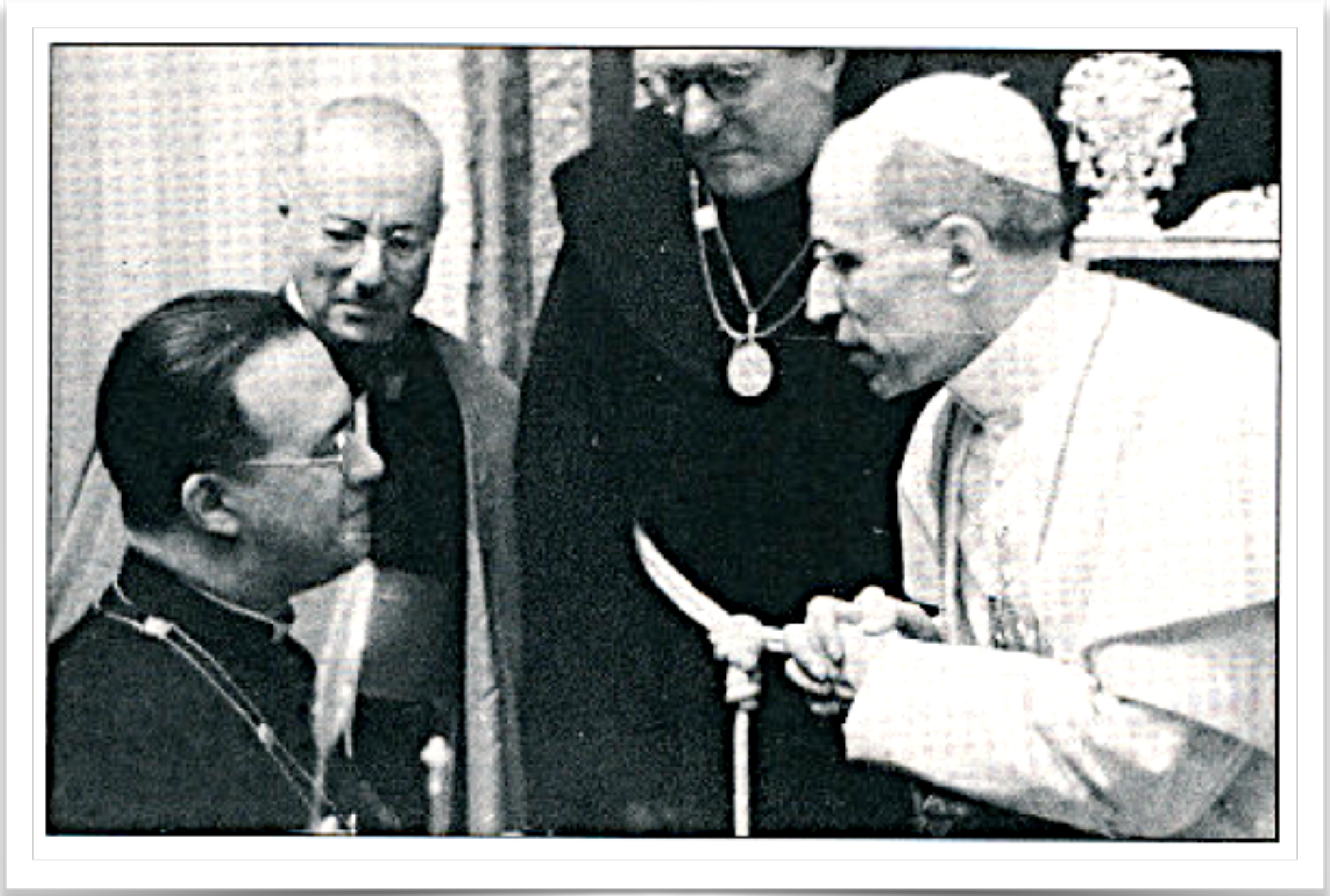
Lemaître had been very careful

to not mix religion and science

Imagine his panic

when 1951 "Study Week" the Pious XIII made a statement:





. . . contemporary science, with one sweep back across the centuries, has succeeded in bearing witness to the august instant of the primordial Fiat Lux, which along with the matter there burst forth from nothing a sea of light and radiation . . . Thus, with that concreteness which is characteristic of physical proofs, modern science has confirmed the contingency of the universe and also the well-founded deduction to the epoch when the world came forth from the hands of the creator.

Pious XIII, Un'Ora,1951

Whoa. Lemaître was stunned.

Science and religion to him: two completely different paths

As far as I can see, such a theory remains entirely outside any metaphysical or religious question. It leaves the materialist free to deny any transcendent Being.

We may speak of this event as of a beginning. I do not say a creation.

Physically it is a beginning in the sense that if something happened before, it has no observable influence on the behavior of our universe, as any feature of matter before this beginning has been completely lost by the extreme contraction at the theoretical zero.

Any preexistence of the universe has a metaphysical character. Physically, everything happens as if the theoretical zero was really a beginning.

The question if it was really a beginning or rather a creation, something started from nothing, is a philosophical question which cannot be settled by physical or astronomical considerations.

Lemaître

WWII was hard on Belgium

after the war, Lemaître did not go back to first-principle cosmology

but he pioneered scientific computing on cosmological parameters before anyone in the 1950's

Like Copernicus

Within days of his death, Lemaître learned of Penzias and Wilson's discovery of the cosmic microwave background

an important confirmation of the Big Bang model

June 20, 1966

a big ‘‘uh oh’’

almost immediately after Hubble’s measurement

original results:

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

H = 160 km/cMly = 1.68 x 10^{-17} s^{-1} $\Rightarrow \frac{1}{H} = 2 \times 10^9 \text{years}$

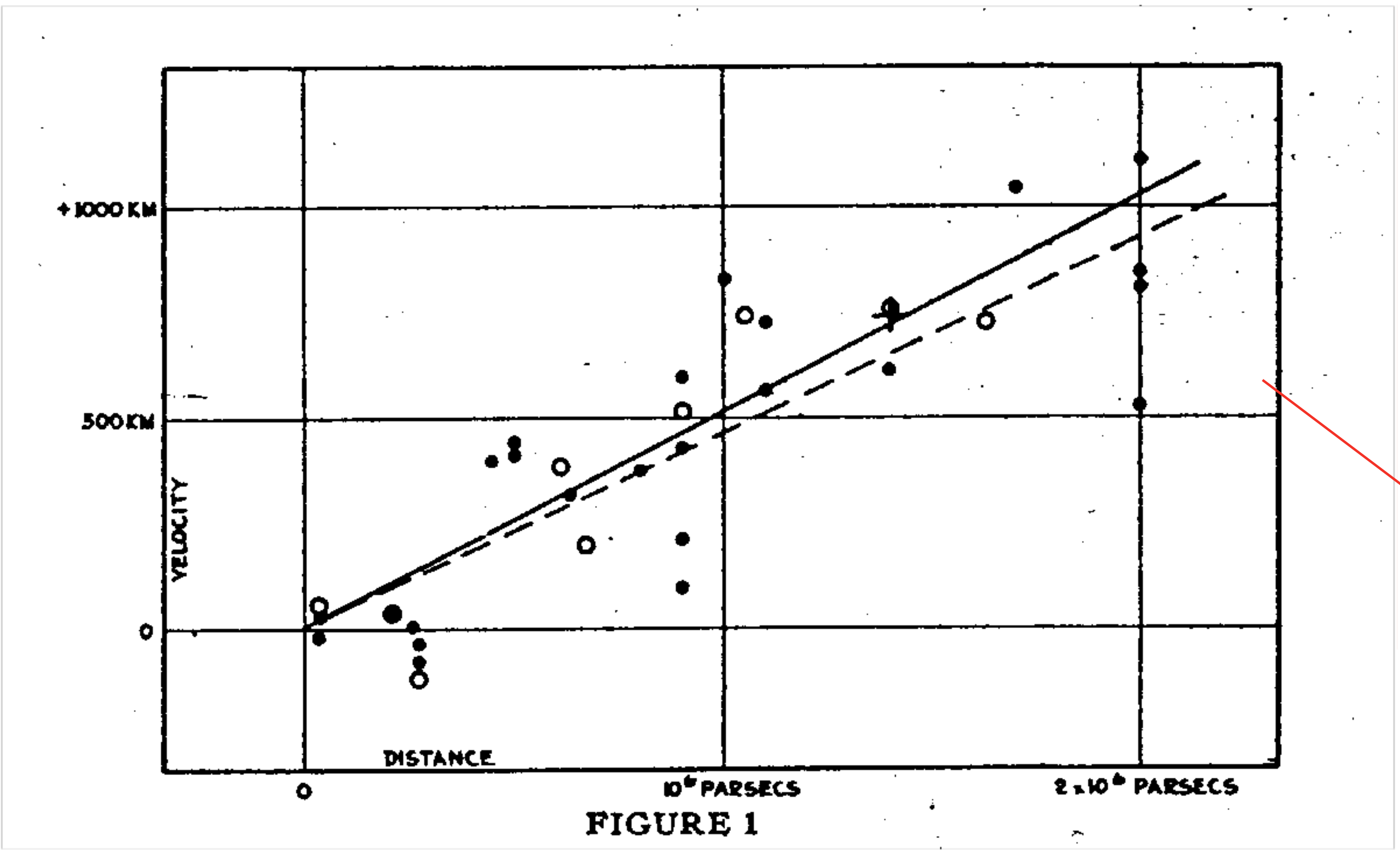
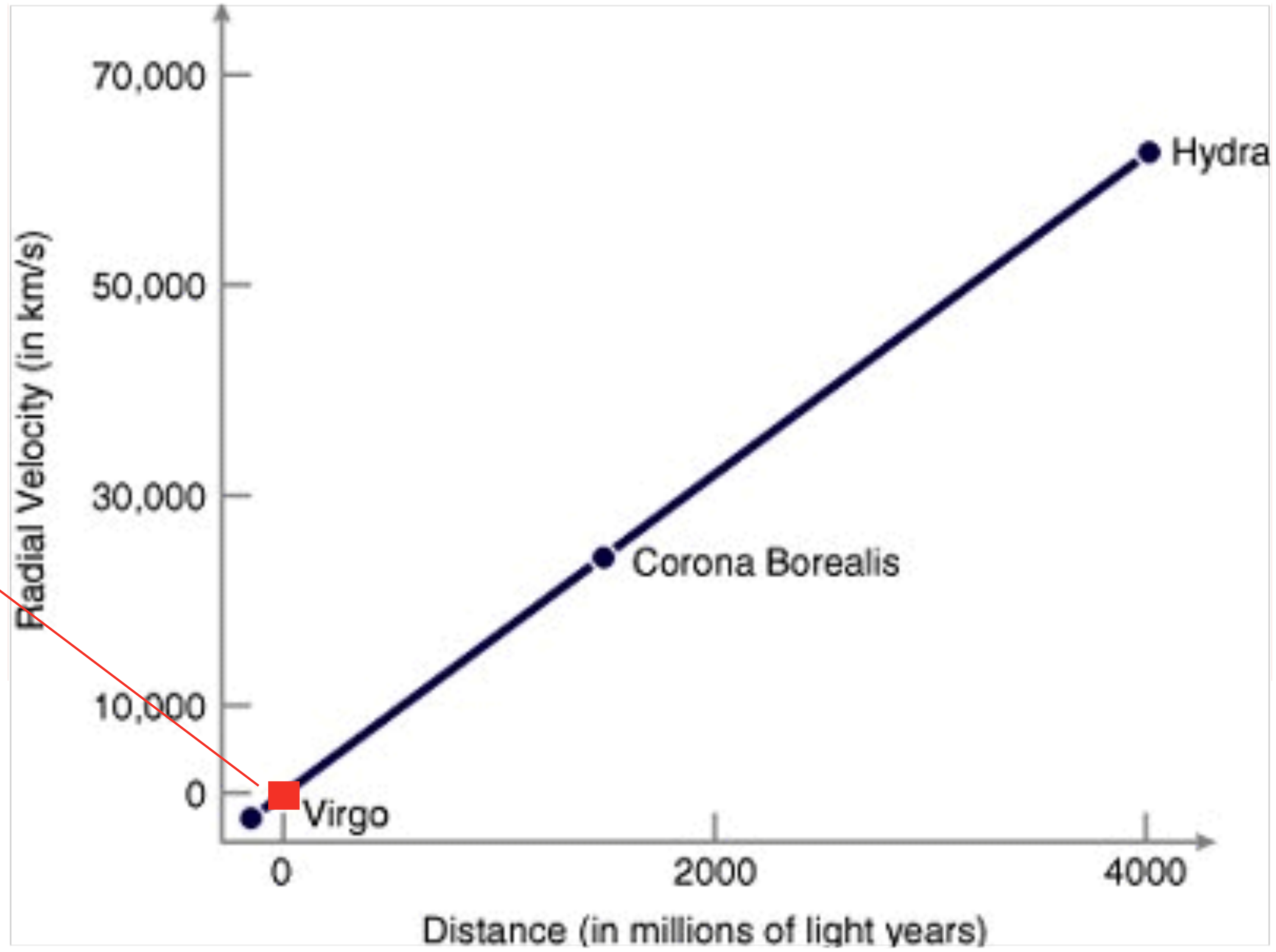


FIGURE 1



oops.

geologists already understood that the Earth was >3 By old.

That required some work!

Refinements found a number of assumptions in need of updating

for example…there are 2 kinds of Cepheid Variable stars, and other issues

This is the beginning of quantitative Cosmology.

Measuring the Hubble Constant is an important cottage industry in astronomy

current best result:

H_0 = 69.3 ± 0.8 km/sec/Mpc

$H_0 = 2.25 \times 10^{-18}\ s^{-1}$

1 megaparsec (Mpc) = 10^6 parsec = 3.26×10^6 light years = 3.086×10^{16} m

some cautionary comments

The Hubble Constant isn't constant.

H_0 = 67.8 ± 0.9 km/sec/Mpc

H_0 = 2.26 x 10^{-18} s^{-1}

The subscript "0" means: "Now"

The inverse of the Hubble Constant isn't necessarily

the age of the universe

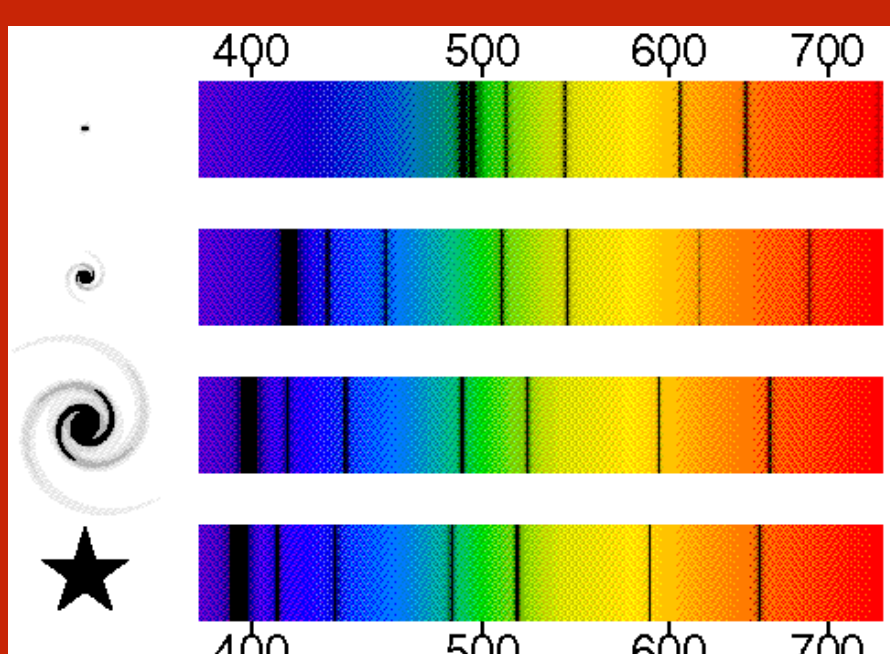
H_0^{-1} = 4.42 x 10^{17} s = 14.2 By

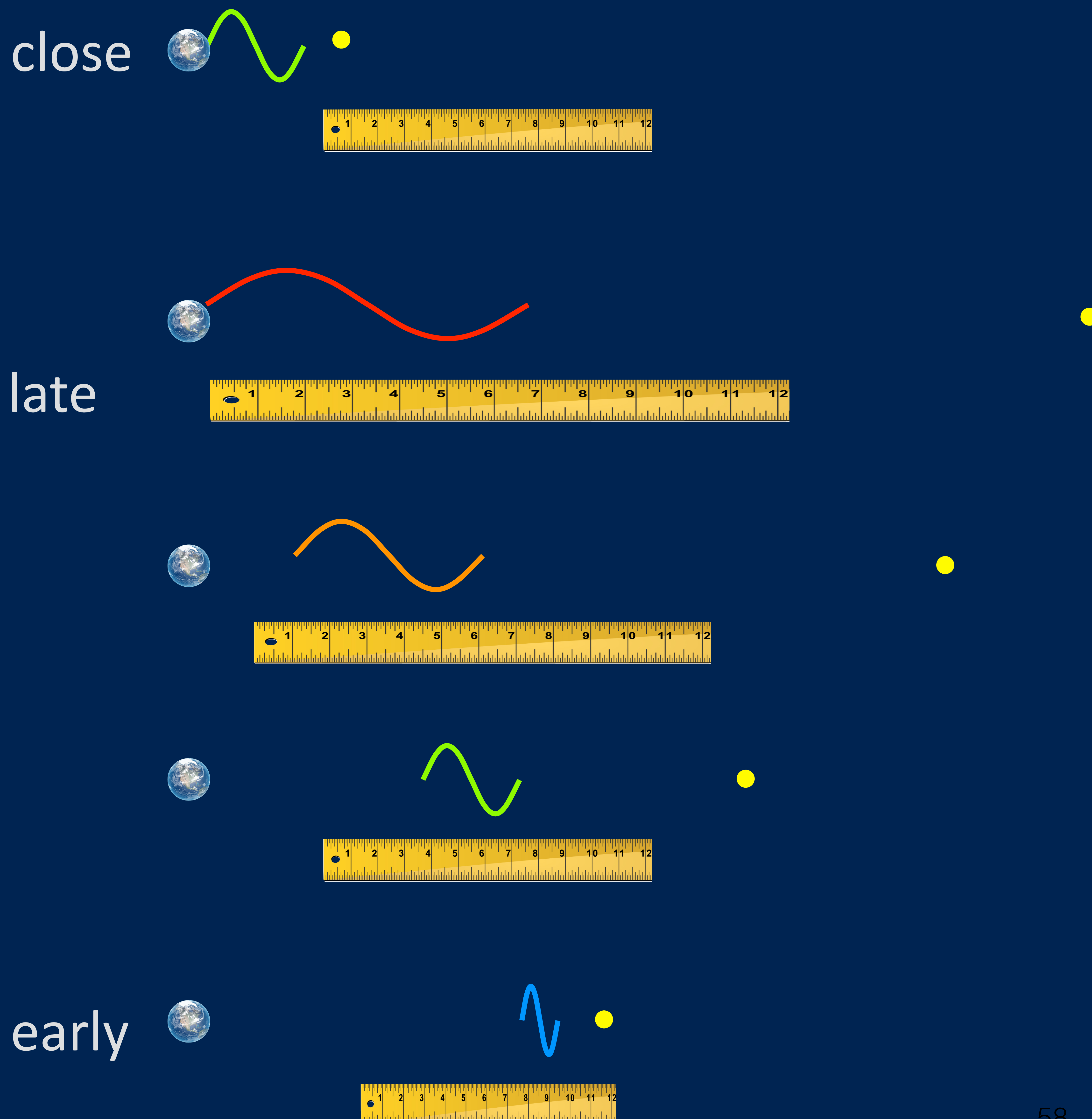
(stay tuned)

the “red shift”

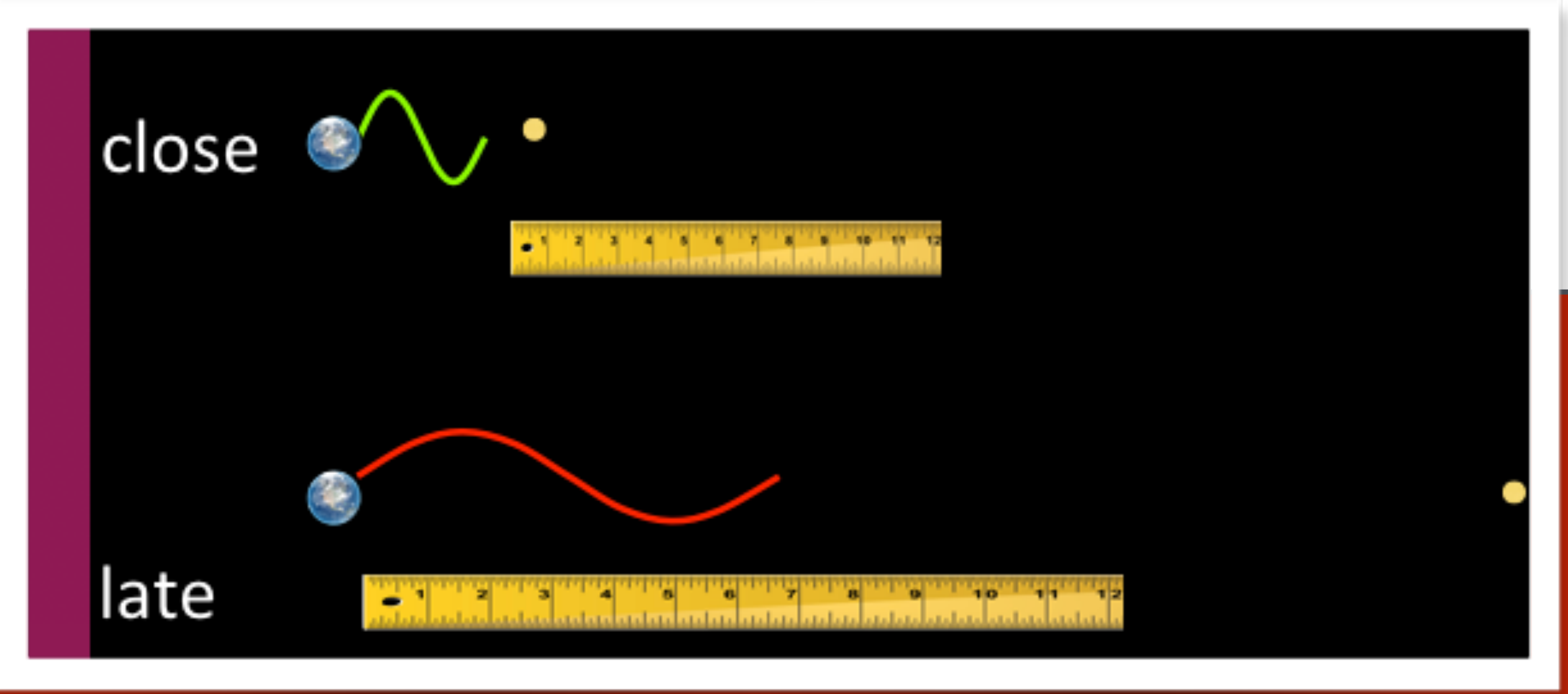
isn’t a Doppler velocity

it’s geometry





The further away a galaxy is:



the more red-shifted its spectrum will be

and the faster it will appear to be receding

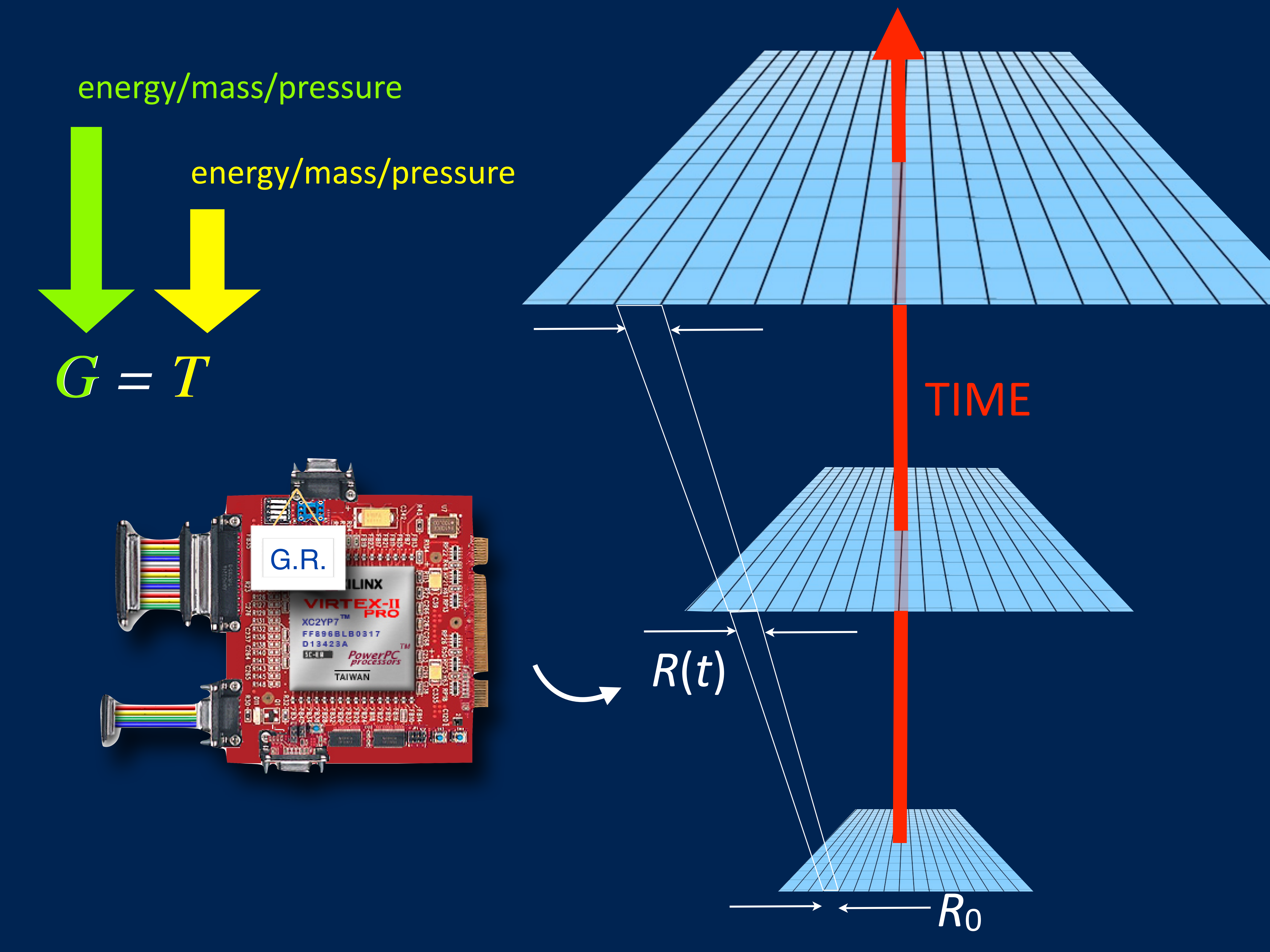
$$v = rH$$

the older it will actually be

and the younger it will appear to be!

here’s how this is described

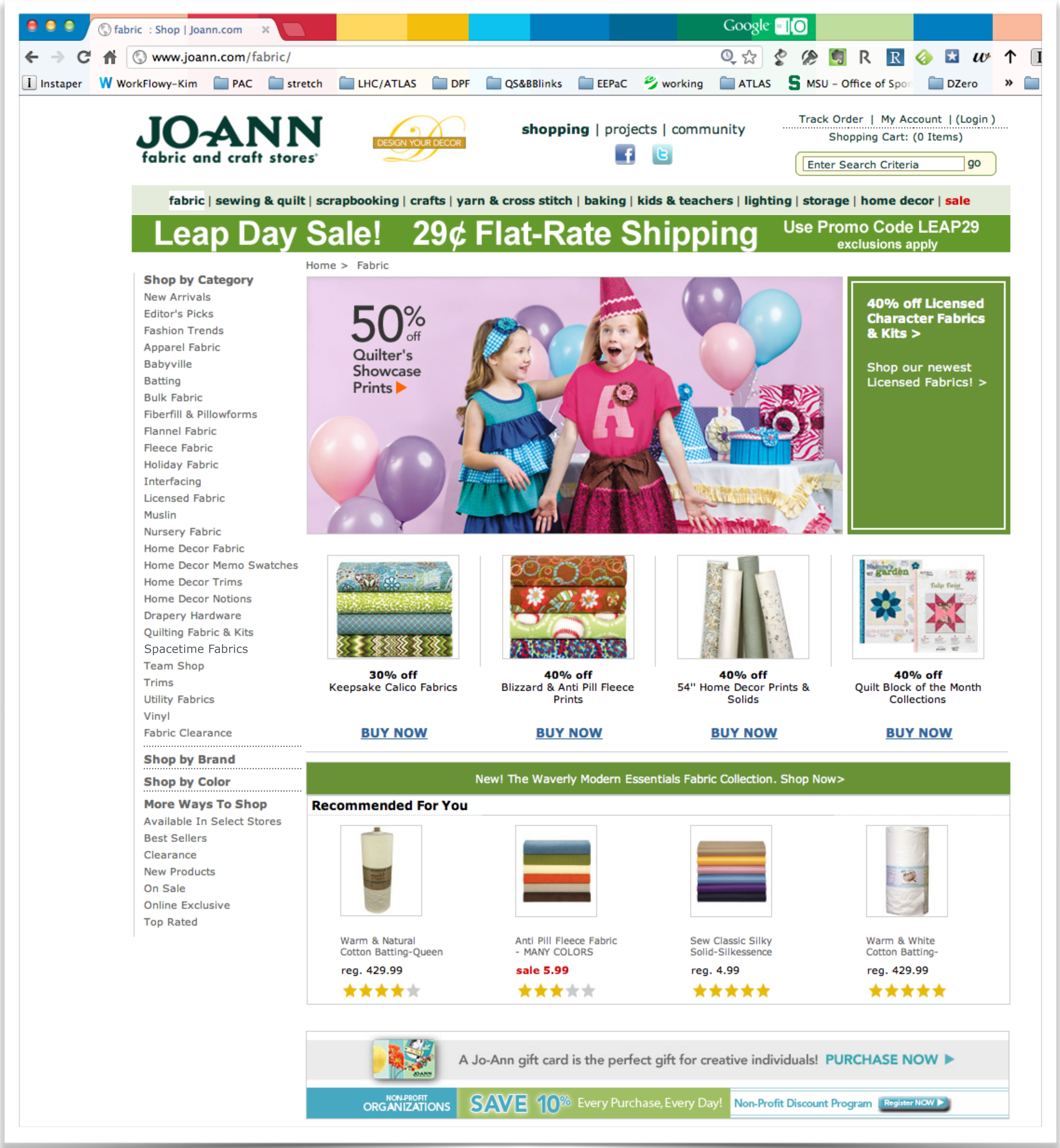
a little technical, but you can do it!


energy/mass/pressure
energy/mass/pressure
G = T
G.R.
VIRTEX-II PRO
XC2YP7
PowerPC processors
TAIWAN
TIME
R(t)
R0

Then a spiritual moment occurs.

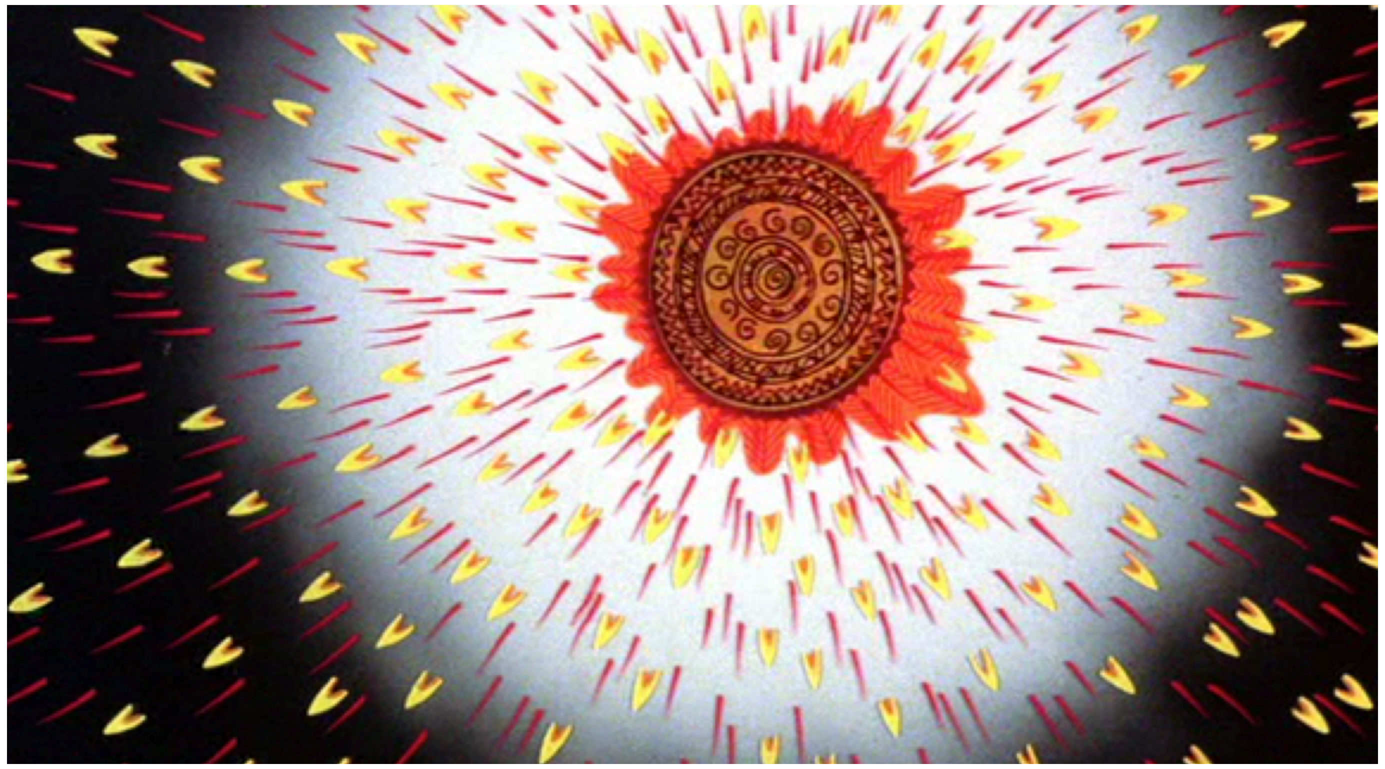
involving spandex.

fabric of spacetime



So, we need 4 deities:

dark specter from power rangers from space



lord firth watership down

Arceus from Pokémon

fujin from Mortal Kombat

universe record-holder

The record: last March.

GN-z11 $\beta = 0.986$!

Light emitted 13.4 By ago

wavelength observed now

$$\frac{\lambda_0}{\lambda_e} = 1 + z = 1 + 11.1 = 12.1$$

wavelength emitted then

So the universe has expanded a factor of 12.1 since GN-z11 sent its light our way!

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arXiv:1603.00461v1 [astro-ph.GA] 1 Mar 2016

A REMARKABLY LUMINOUS GALAXY AT Z = 11.1 MEASURED WITH HUBBLE SPACE TELESCOPE GRISM SPECTROSCOPY

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Draft version March 3, 2016

ABSTRACT

We present *Hubble* WFC3/IR slitless grism spectra of a remarkably bright $z \gtrsim 10$ galaxy candidate, GN-z11, identified initially from CANDELS/GOODS-N imaging data. A significant spectroscopic continuum break is detected at $\lambda = 1.47 \pm 0.01$ μm. The new grism data, combined with the photometric data, rule out all plausible lower redshift solutions for this source. The only viable solution is that this continuum break is the Lyα break redshifted to $z_{\mathrm{grism}} = 11.09^{+0.08}_{-0.12}$, just ~400 Myr after the Big Bang. This observation extends the current spectroscopic frontier by 150 Myr to well before the Planck (instantaneous) cosmic reionization peak at $z \sim 8.8$, demonstrating that galaxy build-up was well underway early in the reionization epoch at $z > 10$. GN-z11 is remarkably and unexpectedly luminous for a galaxy at such an early time: its UV luminosity is 3× larger than L_* measured at $z \sim 6 - 8$. The *Spitzer* IRAC detections up to 4.5 μm of this galaxy are consistent with a stellar mass of $\sim 10^9$ $M_\odot$. This spectroscopic redshift measurement suggests that the *James Webb Space Telescope* (*JWST*) will be able to similarly and easily confirm such sources at $z > 10$ and characterize their physical properties through detailed spectroscopy. Furthermore, WFIRST, with its wide-field near-IR imaging, would find large numbers of similar galaxies and contribute greatly to *JWST*'s spectroscopy, if it is launched early enough to overlap with *JWST*.

Subject headings: galaxies: high-redshift — galaxies: formation — galaxies: evolution — dark ages, reionization, first stars

1. INTRODUCTION

The first billion years are a crucial epoch in cosmic history. This is when the first stars and galaxies formed and the universe underwent a major phase transition from a neutral to an ionized state. Our understanding of galaxies in this early phase of the universe has been revolutionized over the last few years thanks to the very sensitive WFC3/IR camera onboard the Hubble Space Telescope (*HST*) in combination with ultra-deep *Spitzer*/IRAC imaging. WFC3/IR has pushed the observational horizon of galaxies to the beginning of the cosmic reionization epoch at $z \sim 9 - 11$, less than 500 Myr from the Big Bang. Several large extragalactic surveys have now resulted in the identification of a large sample of more than 800 galaxies at $z \sim 7 - 8$ (Bouwens et al. 2015b; McLure et al. 2013; Finkelstein et al. 2015; Bradley et al. 2014; Schmidt et al. 2014) and even a small sample of $z \sim 9 - 11$ candidates (Oesch et al. 2013, 2014, 2015a; Ellis et al. 2013; Zheng et al. 2012; Coe et al. 2013; Zitrin et al. 2014; Bouwens et al. 2015a; McLeod et al. 2015; Ishigaki et al. 2015; Infante et al. 2015; Kawamata et al. 2015; Calvi et al. 2016).

Spectroscopic confirmations of very high-redshift candidates remain limited, however. The primary spectral feature accessible from the ground for these sources, the Lyα line, is likely attenuated by the surrounding neutral hydrogen for all $z > 6$ galaxies (Schenker et al. 2012; Treu et al. 2013; Pentericci et al. 2014). Therefore, despite the large number of candidates from *HST* imaging, only a handful of galaxies in the epoch of reionization have confirmed redshifts to date (Vanzella et al. 2011; Ono et al. 2012; Shibuya et al. 2012; Finkelstein et al. 2013; Oesch et al. 2015b; Roberts-Borsani et al. 2015; Zitrin et al. 2015).

Given the low success rate of Lyα searches, a viable alternative approach is to search for a spectroscopic confirmation of the UV continuum spectral break (see e.g. Dow-Hygelund et al. 2005; Malhotra et al. 2005; Vanzella et al. 2009; Rhoads et al. 2013; Watson et al. 2015; Pirzkal et al. 2015). This break is expected owing to the near-

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What's R(t)?

The "scale factor"

the stretchiness of spacetime

The Friedman, Walker, Robertson models

Friedman's and Lemaître's work was expanded on by Howard P Robertson and Arthur G Walker in 1936

They found exact solutions to the Einstein equations, using the Friedman techniques.

Their model of cosmology is variously called the:

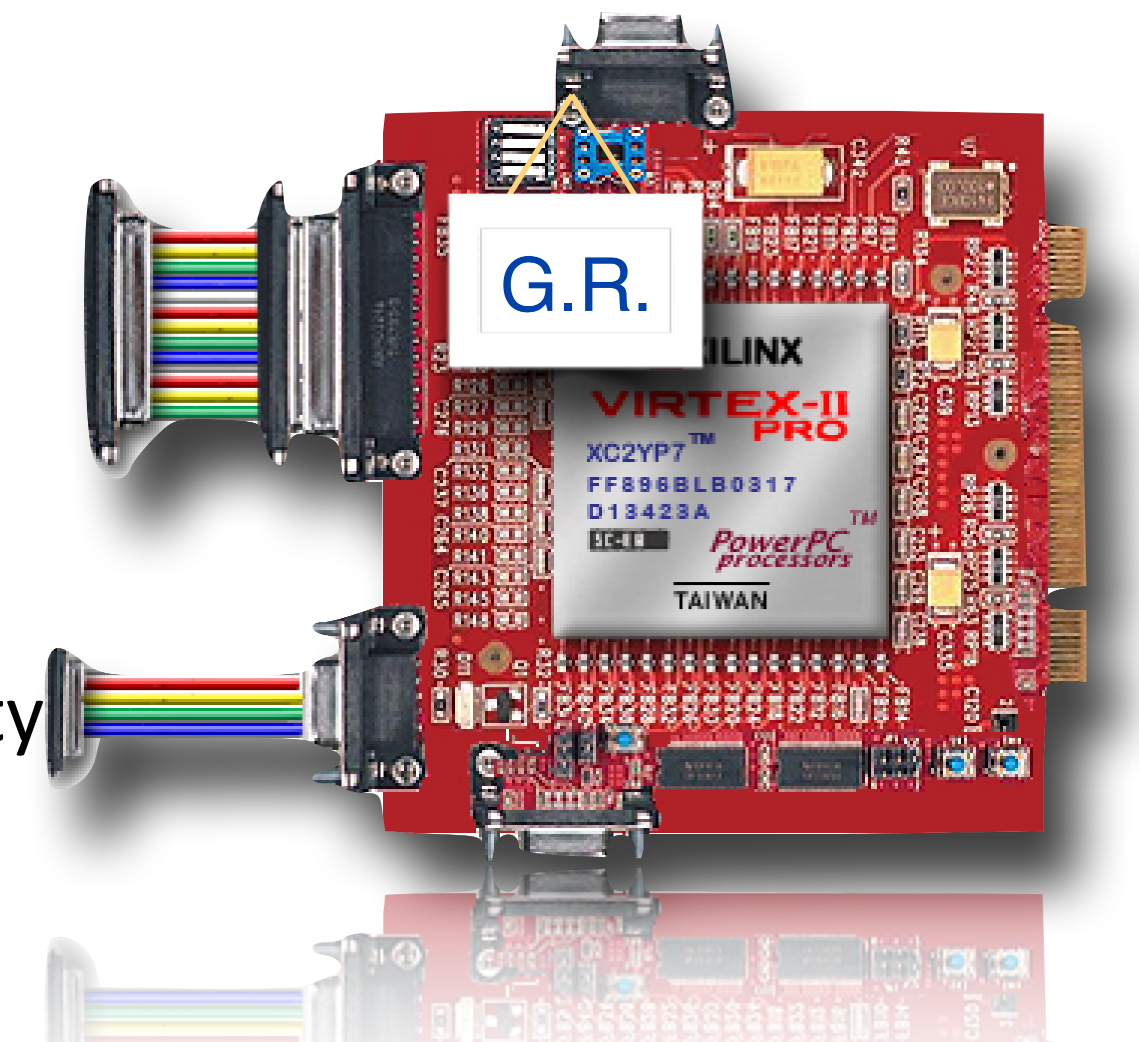
FWR model

FLWR model

Standard Model of Cosmology

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

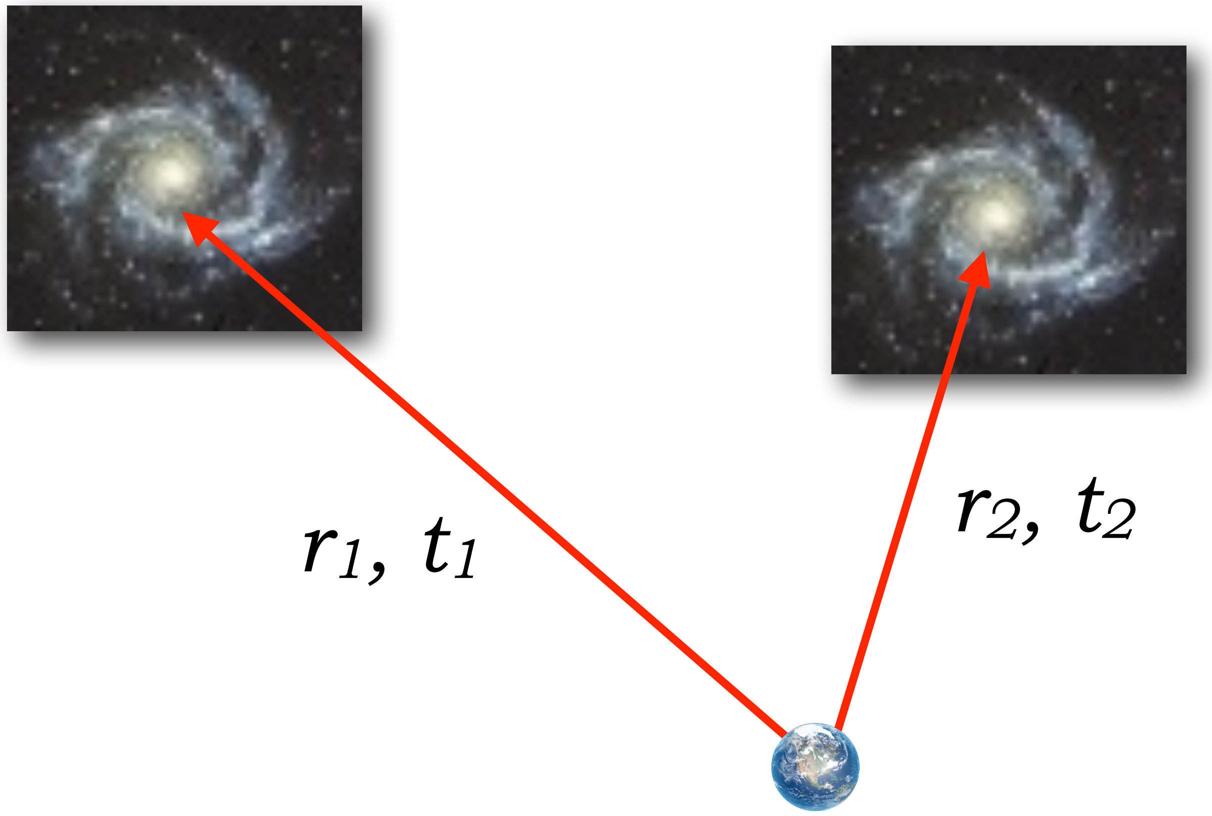
varying assumptions, k, density



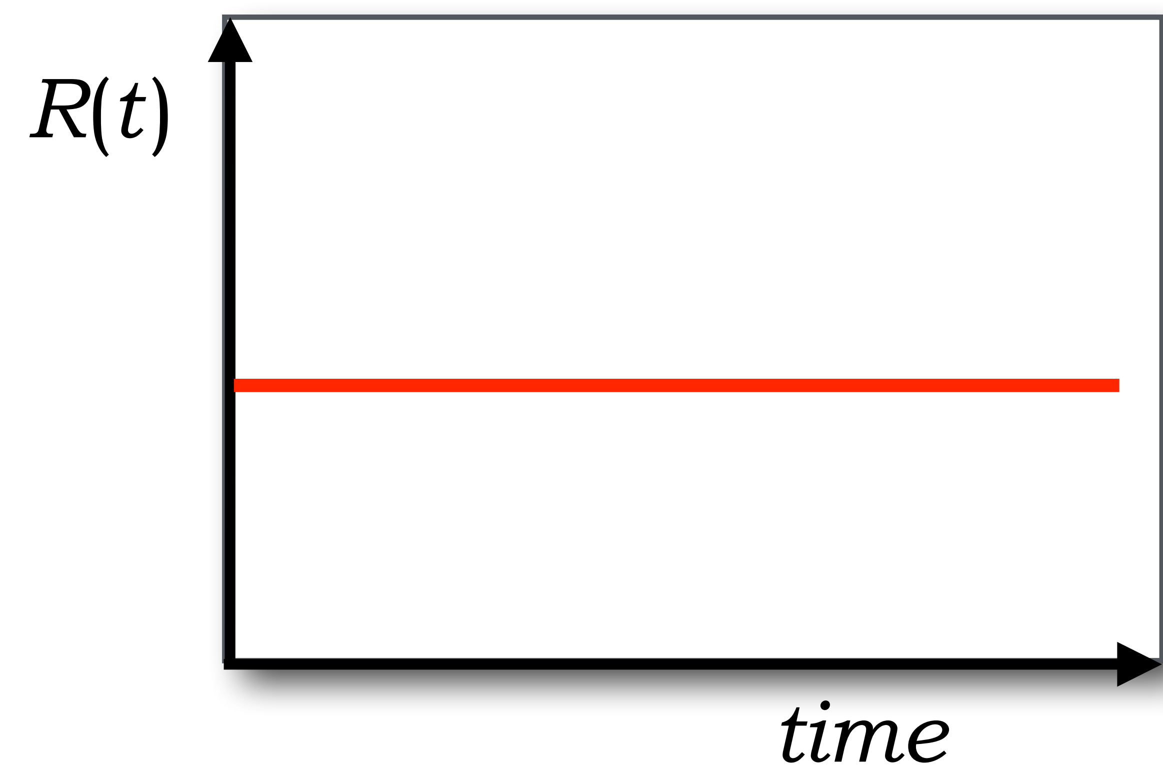
can catalogue the behavior of R

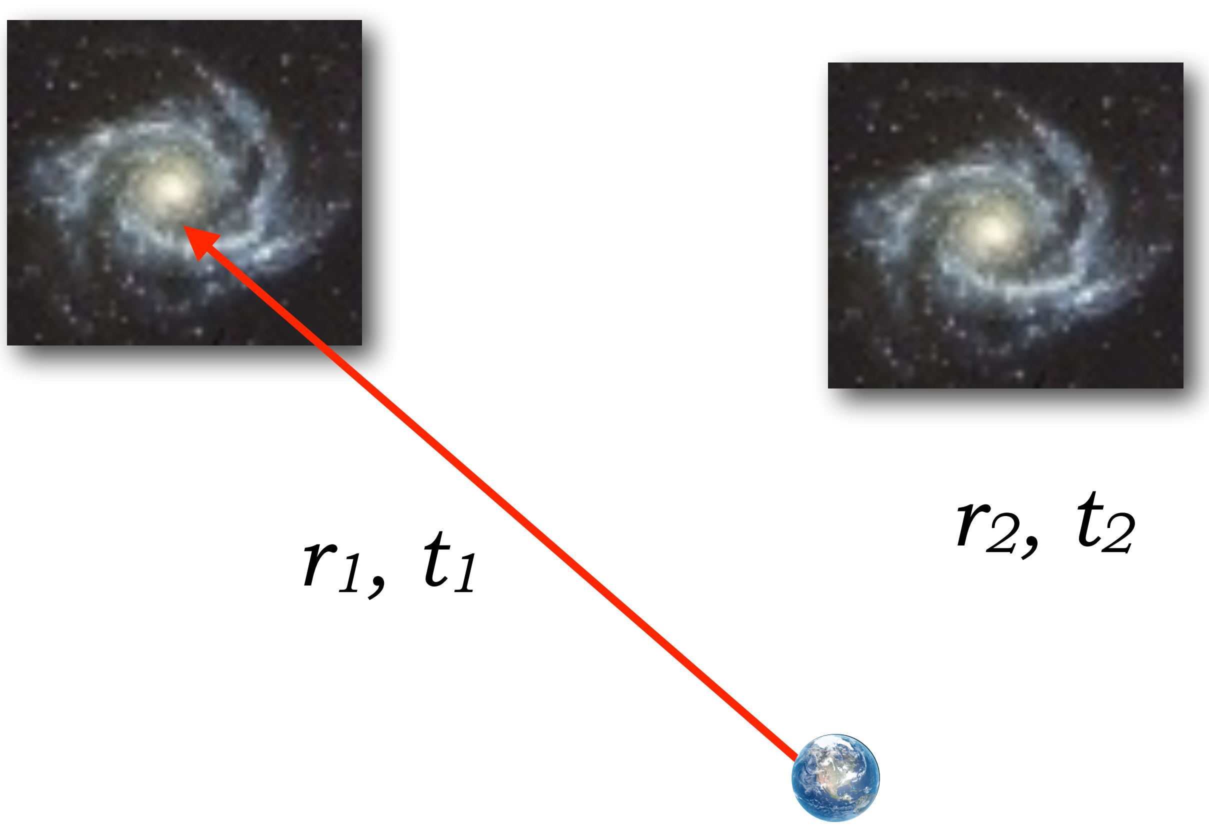
for different choices of the Cosmological Constant and k

Einstein's original model



What did Einstein say would be the case?

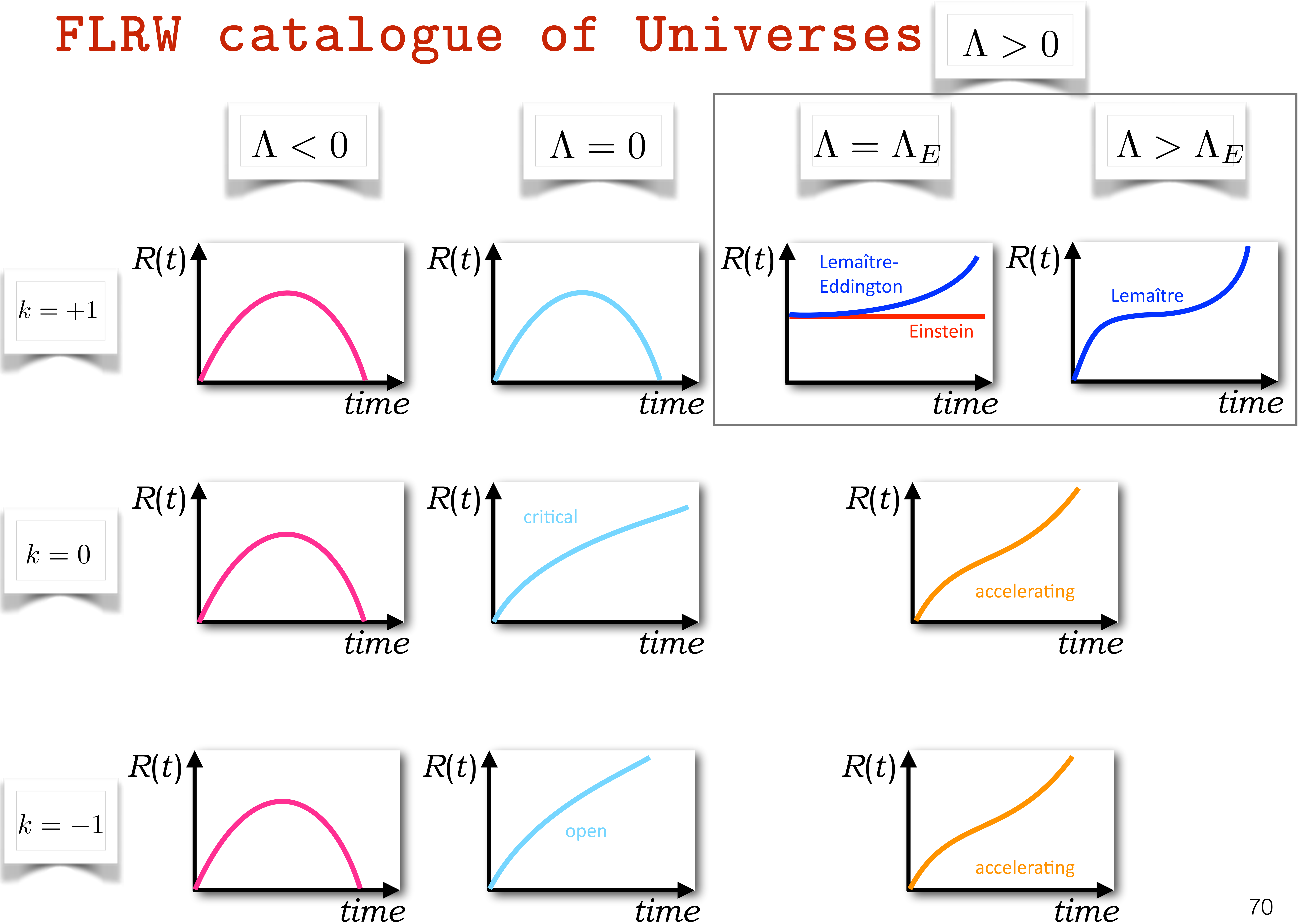




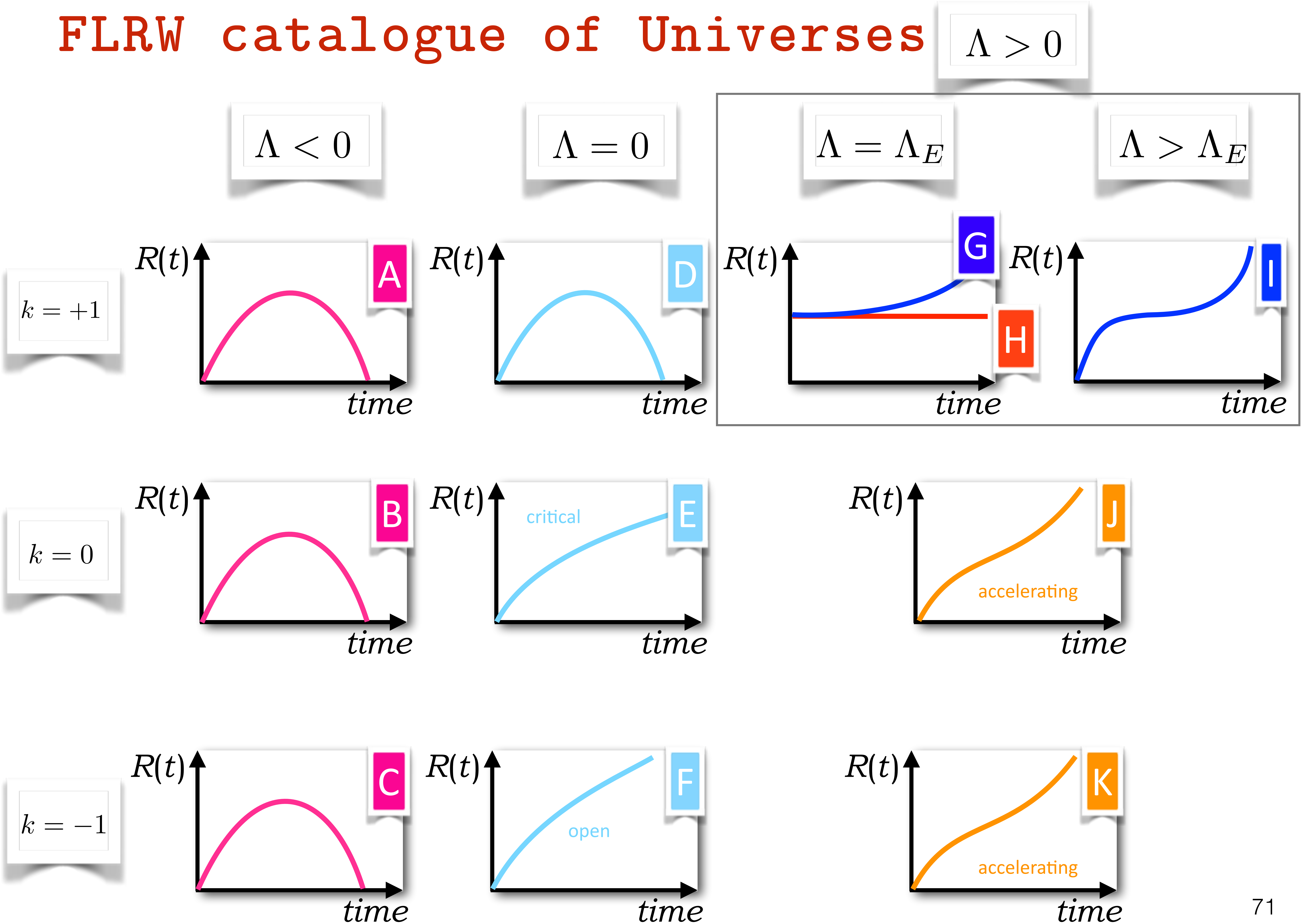
Static...for which he needed a particular value of the Cosmological Constant

$$\Lambda_E = \frac{4\pi G\rho}{c^2}$$

FLRW catalogue of Universes



FLRW catalogue of Universes



which one is ours?

that’s the story of the last 3 decades

stay tuned

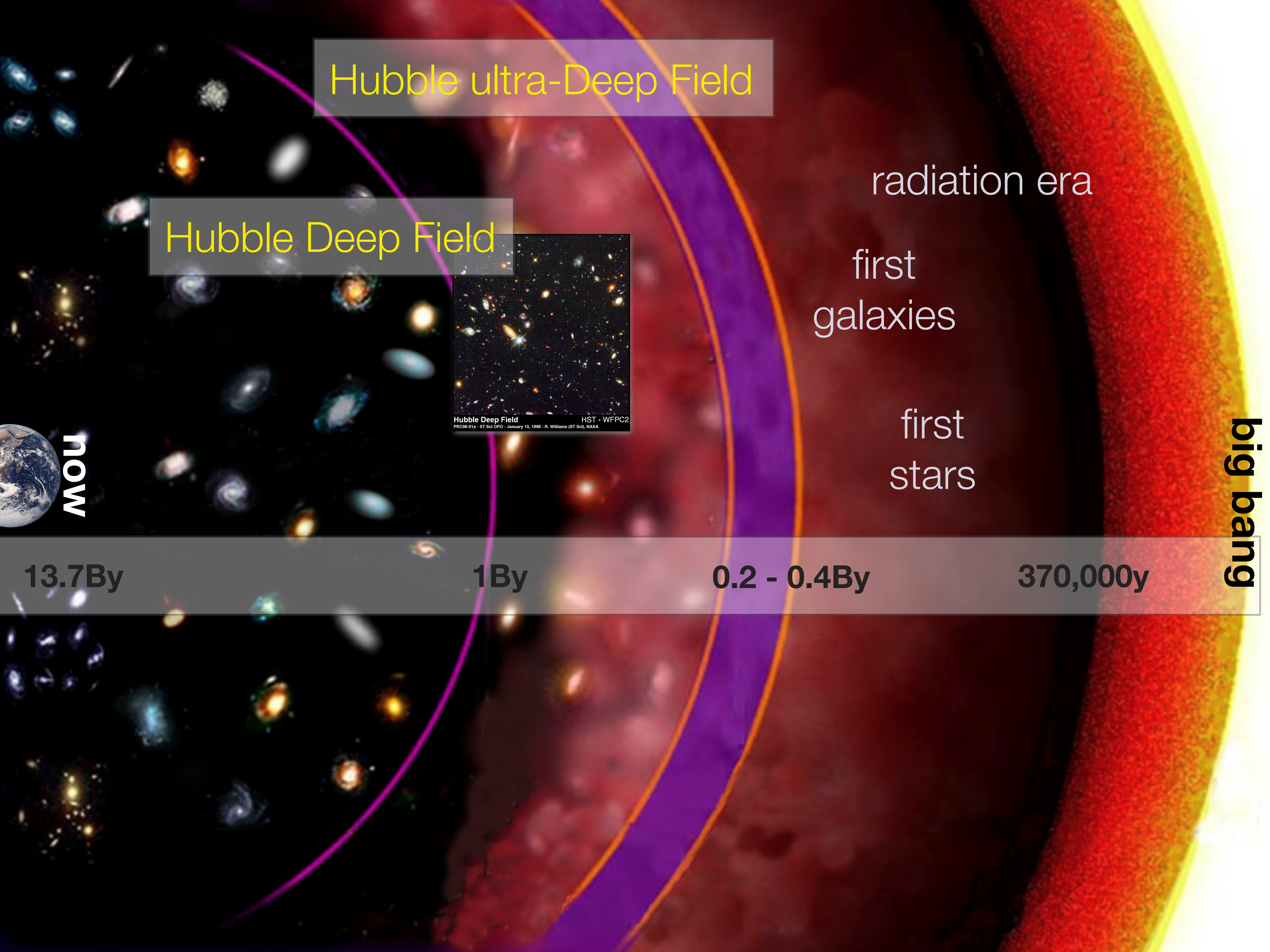
a broad timeline

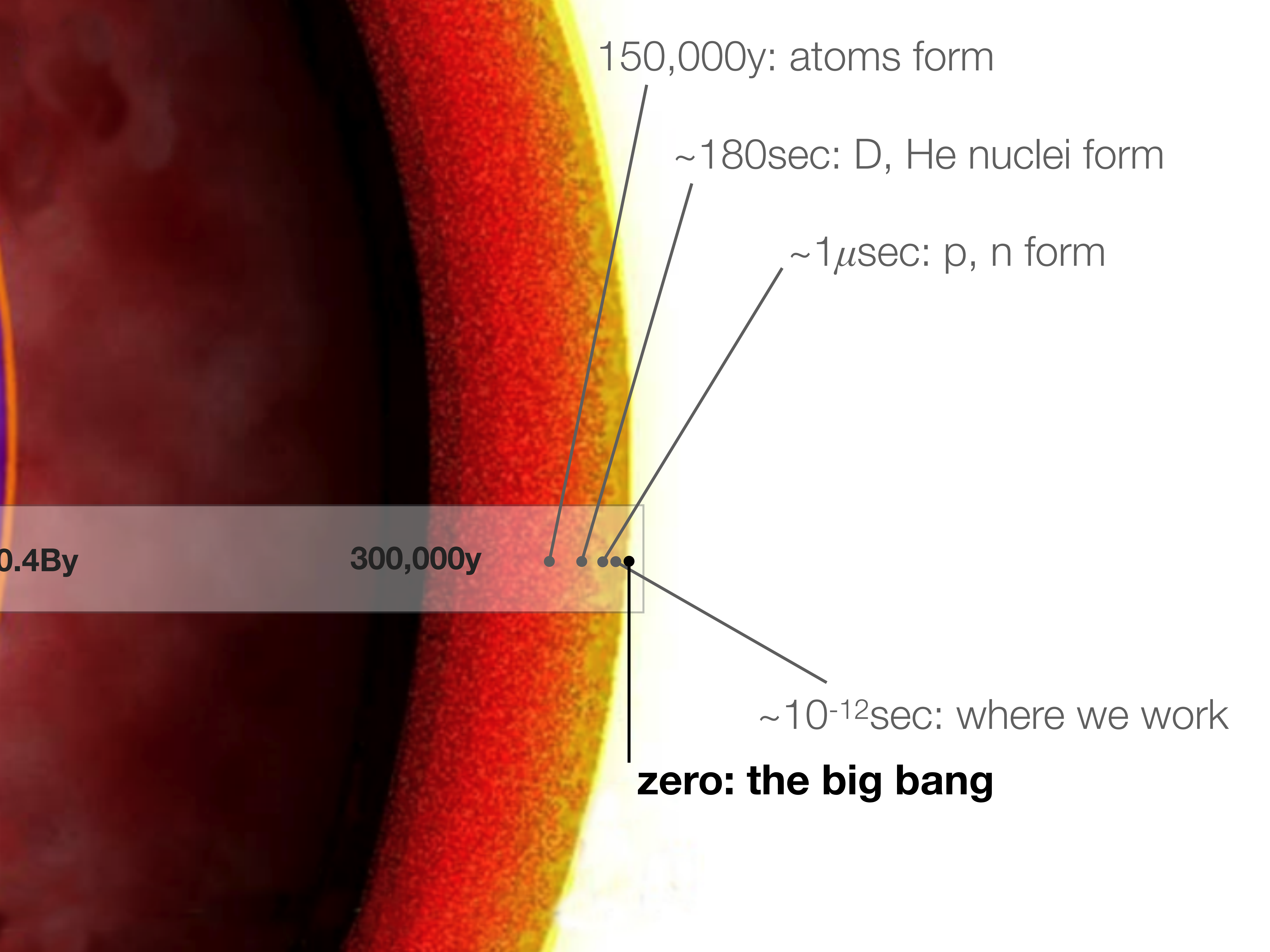
a telescope

is a time-machine

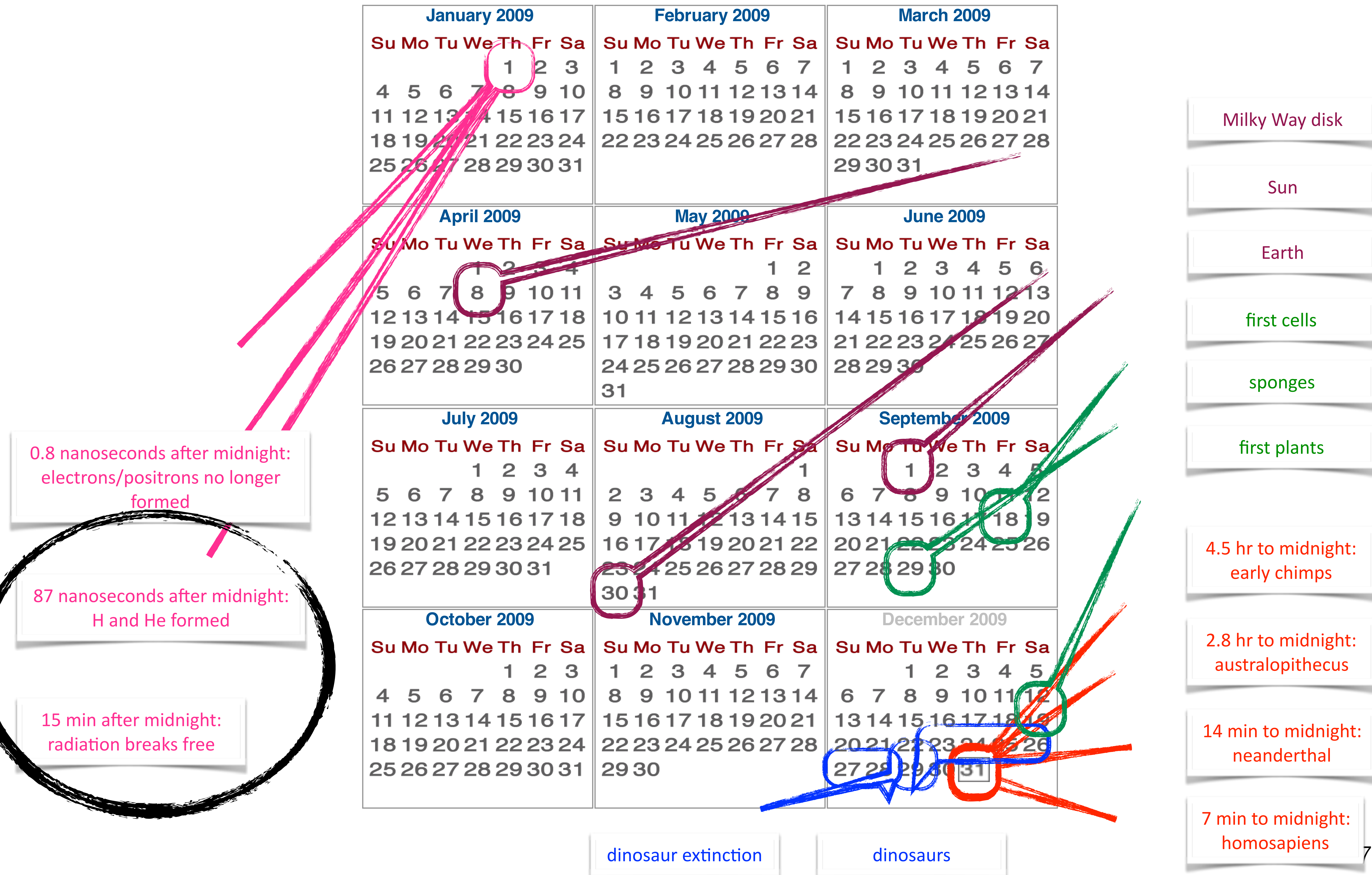
the furthest away, the fastest

the fastest, the newer we see it, the older is now is


Hubble ultra-Deep Field
radiation era
Hubble Deep Field
first
galaxies
Hubble Deep Field
HST · WFPC2
first
stars
now
big bang
13.7By
1By
0.2 - 0.4By
370,000y


150,000y: atoms form
~180sec: D, He nuclei form
~1μsec: p, n form
0.4By
300,000y
~10-12sec: where we work
zero: the big bang

our cosmic calendar: 12 months = 13.8 By



To take the story there

We need quantum mechanics and particle physics