hi

Day 18, 26.03.2019

Cosmology 4

2 days until opening day

Ray Brown week

housekeeping

Gotta come to class

- question about <u>anything</u>?
- I'll make a movie for 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

MasteringAstronomy:

- Homework #8 also in MasteringAstronomy
- Course ID: MABROCK41459;
- free code: WSSPCT-BLIDA-INANE-TOGUE-RIGOT-UNRWA

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 HW7 due	18	19 lecture	20	21 lecture	22	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

Honors project

Document #2 is uploaded

https://qstbb.pa.msu.edu/storage/QS&BB2019/Homework_Projects/honors_project_2019/

It assigns data files to each

Two due dates:

report on the day of the Final

text file of data by April 26

you'll see in document #2

Index of /storage/QS&BB2019/Homework_Projects/honors_project_2019

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ISP220_inspirationaltalk.pdf	2019-03-10 12:42	4.3M	Portable Document Format file
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MinervaInstructions2_2019_1.pdf	2019-03-22 15:50	122K	Portable Document Format file
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KEEP
CALM
AND
LET’S
REVIEW

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."

the dreaded

Cosmological Constant, Λ

geometry $G = T$ energy, pressure, mass

Wanted a spherical, static universe.
You can't always get what you want.

So he added a **slow-down** term...

$$G + \Lambda = T$$

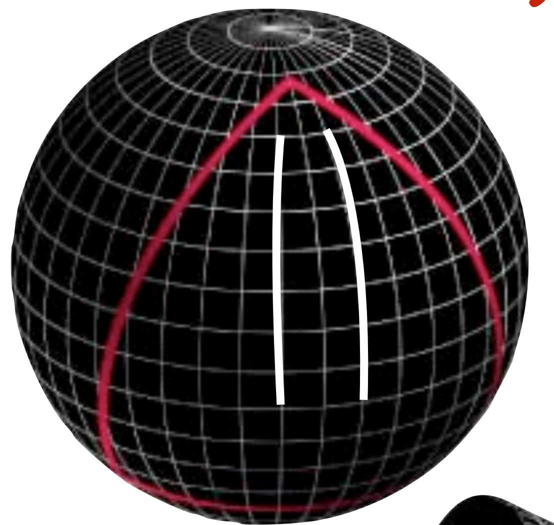
the "Cosmological Constant"

Makes the Universe static...not expanding or contracting

later: "My biggest blunder."

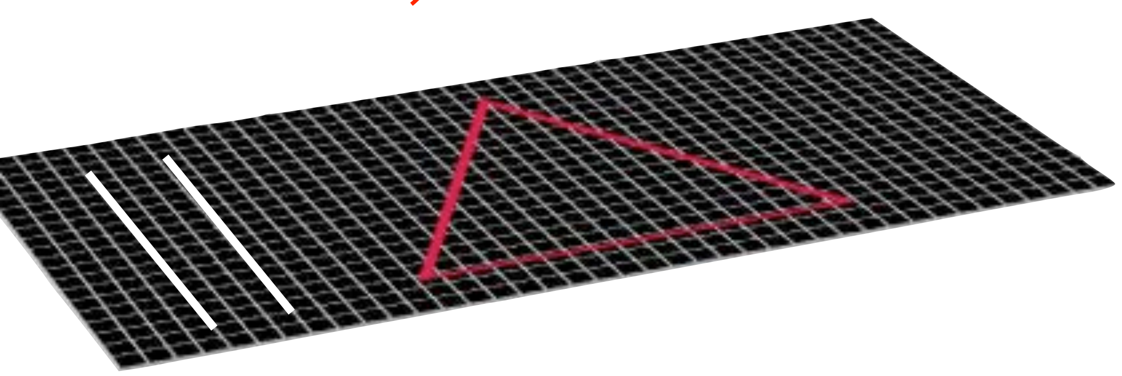
for 2 reasons: Hubble and instability

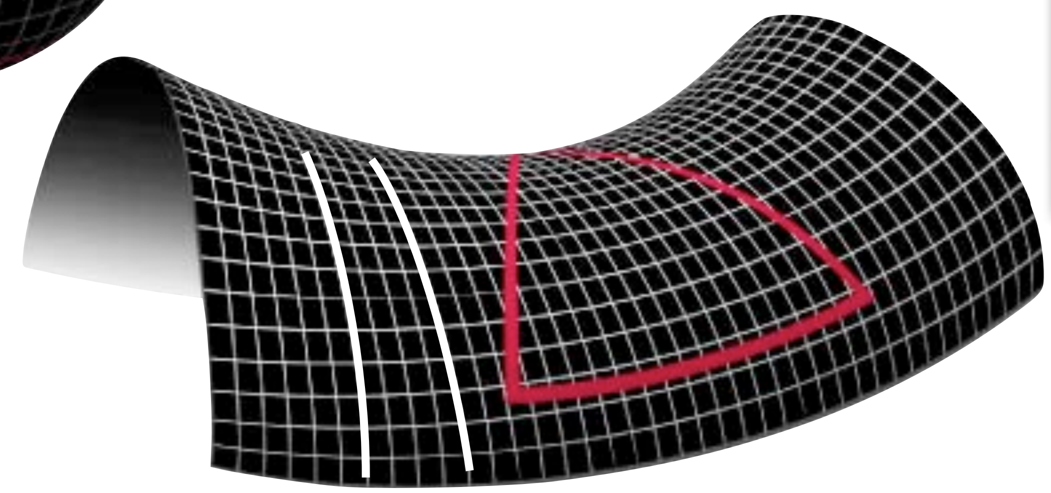
curvature, "k" - hypervolumes



$k = +1,$
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

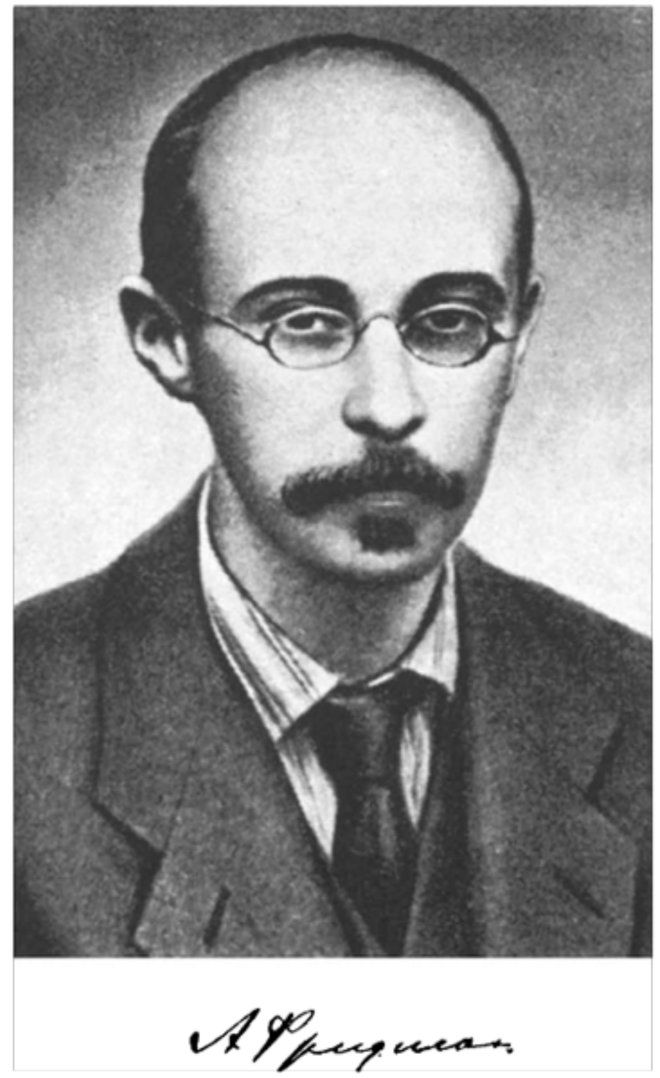
A mathematical fact:
These 3 are the only geometries that can be both homogeneous and isotropic

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"

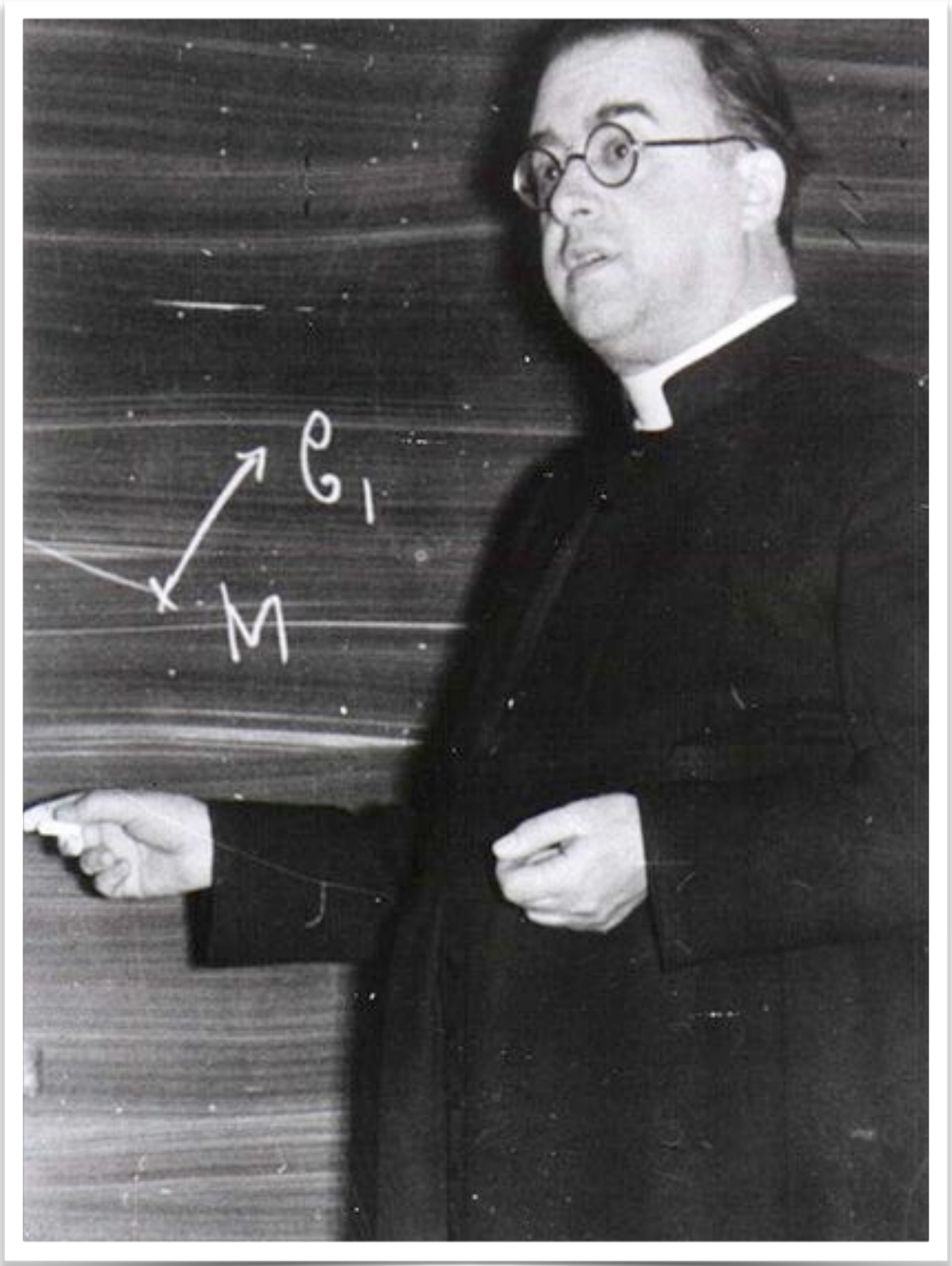
29 June 1922, submits paper "On the curvature of Space" to to *Zeitschrift für Physik*

Einstein didn't take it well.

Georges Lemaître (1894-1966)

Father of the Big Bang

I crack myself up.



In 1927 Lemaitre 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

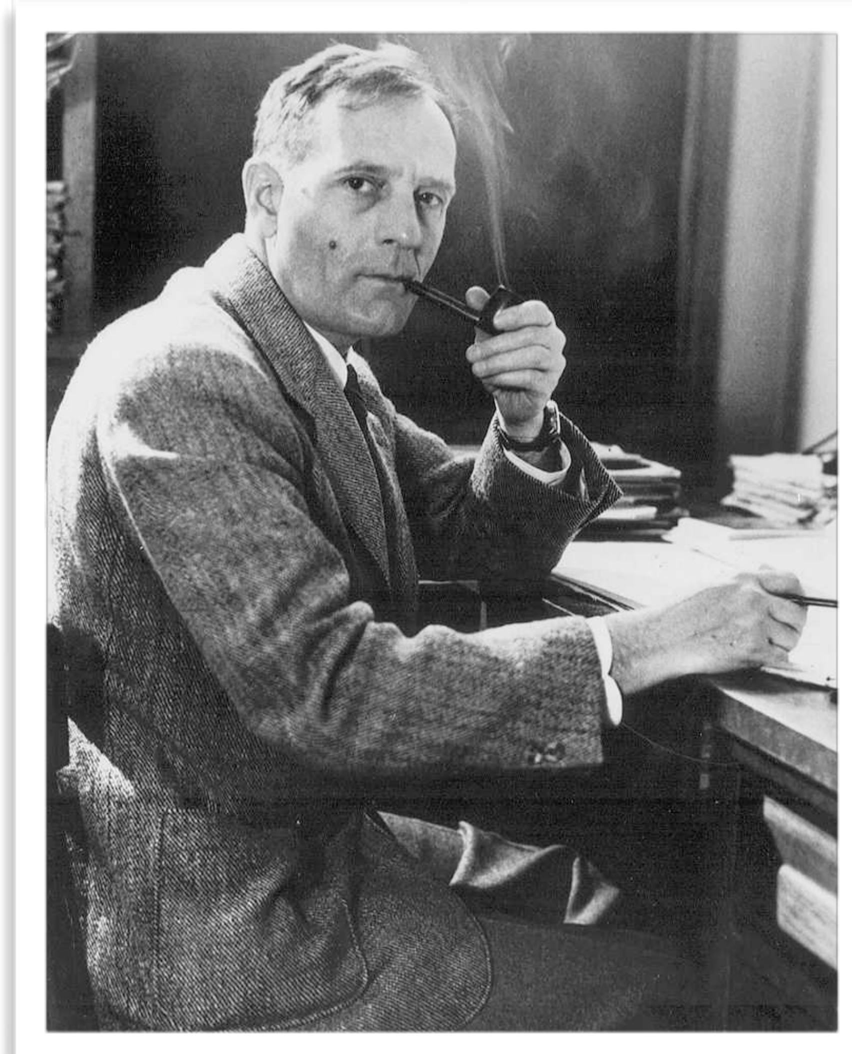
He predicted the existence of the Hubble constant!

Edwin Hubble 1889-1953

astronomer

discoverer of:

- the whole universe
- the expanding universe



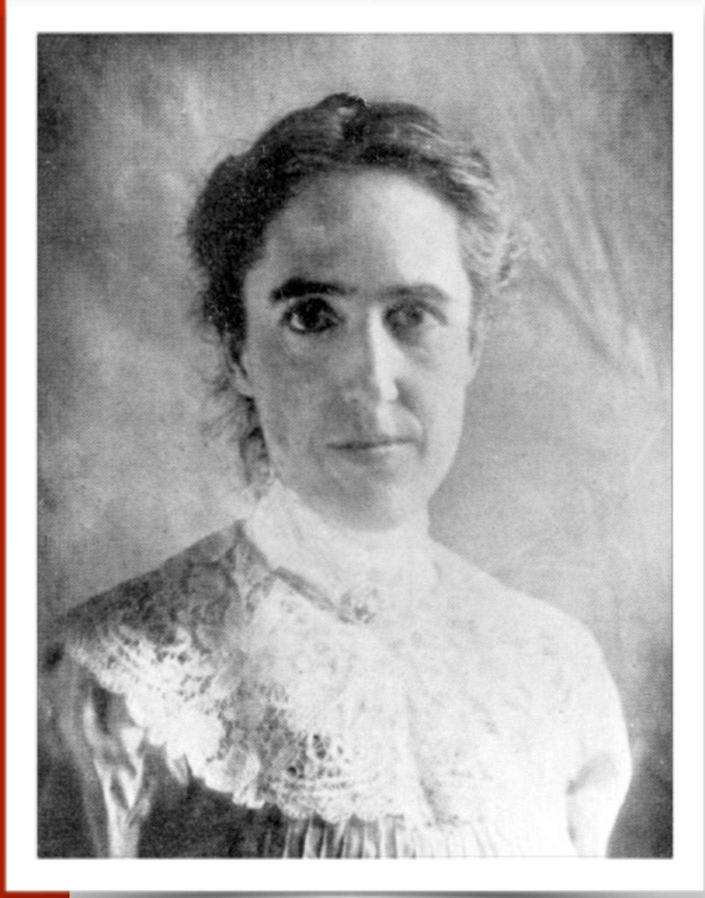
distances are hard to determine

Cepheid Variable stars: the clue to galactic distances

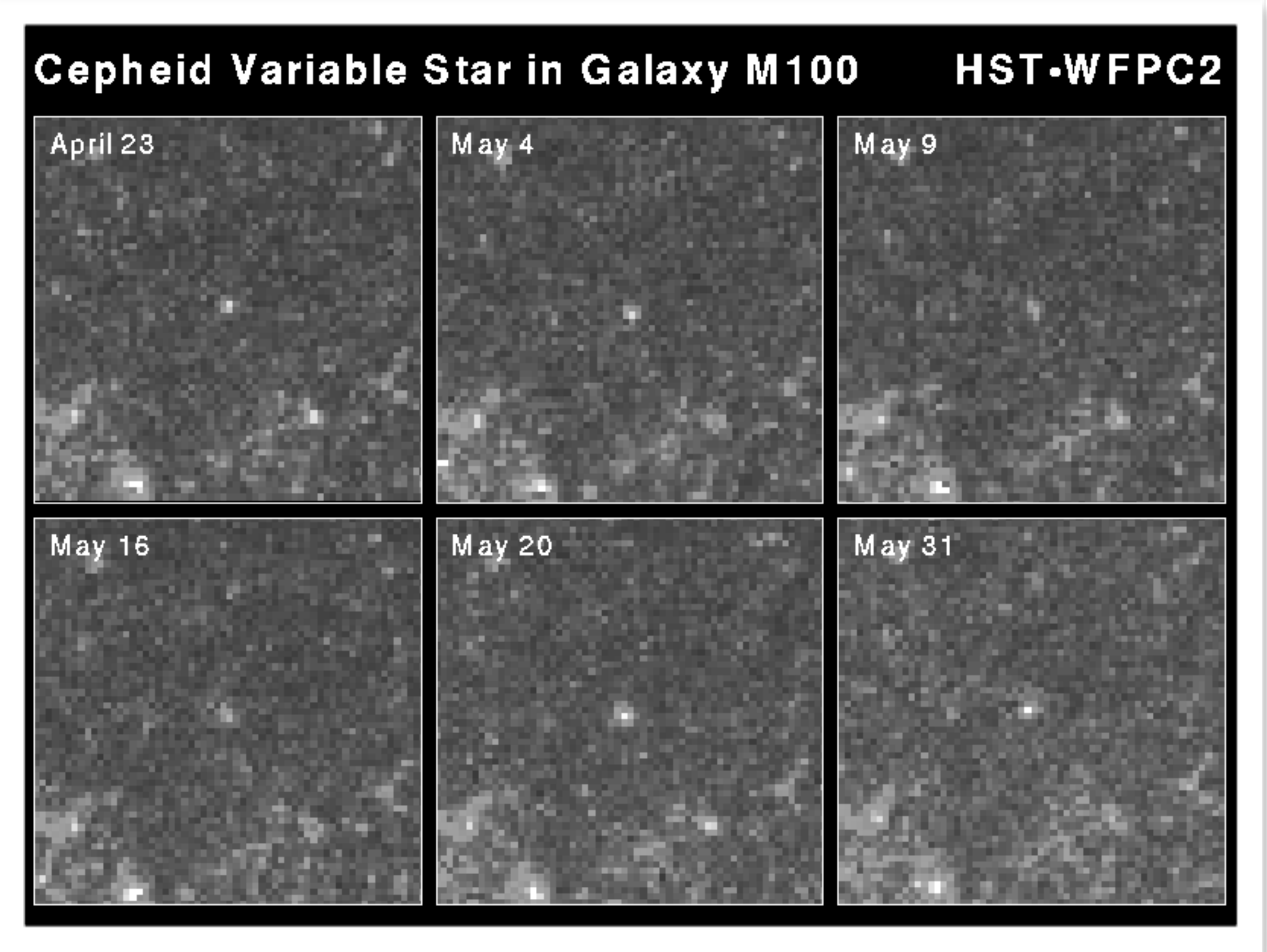
absolute brightness is related to their period

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

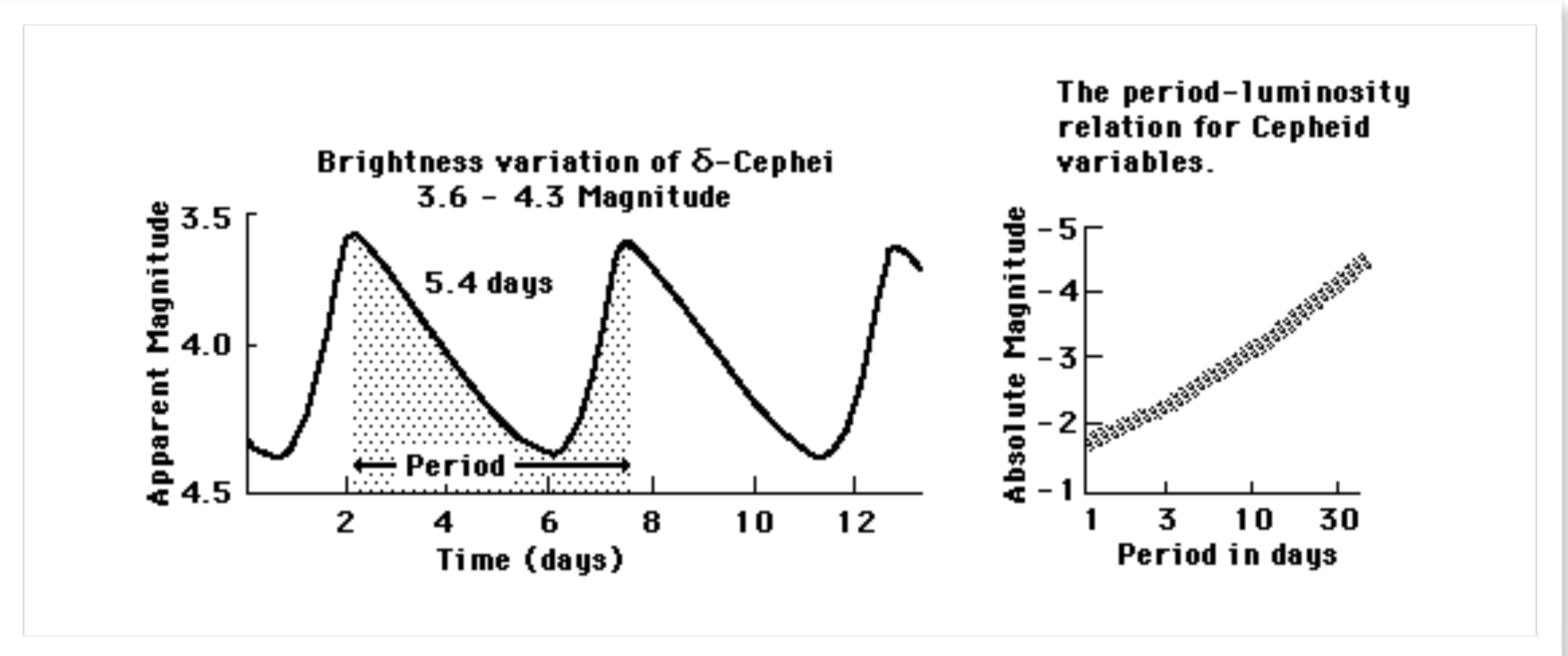
bootstrapping



discovered by Henrietta Leavitt at Harvard



1912



Cepheid Variable Stars

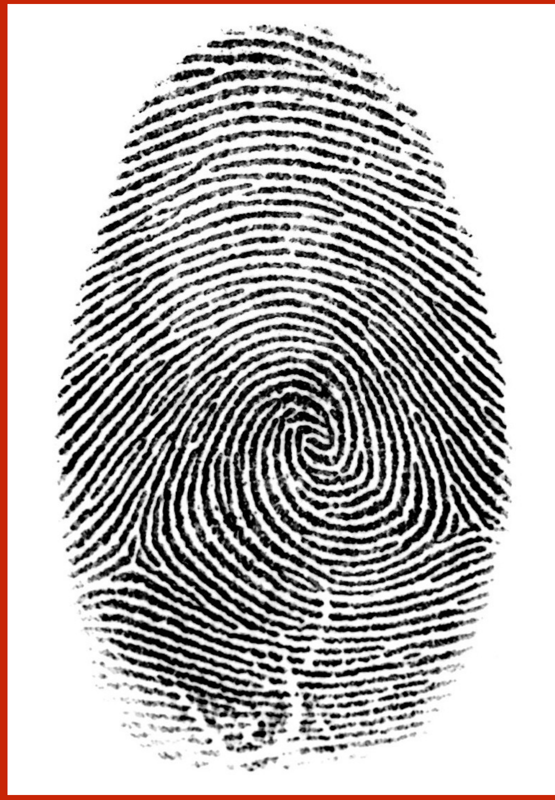
plus Leavitt’s analysis:

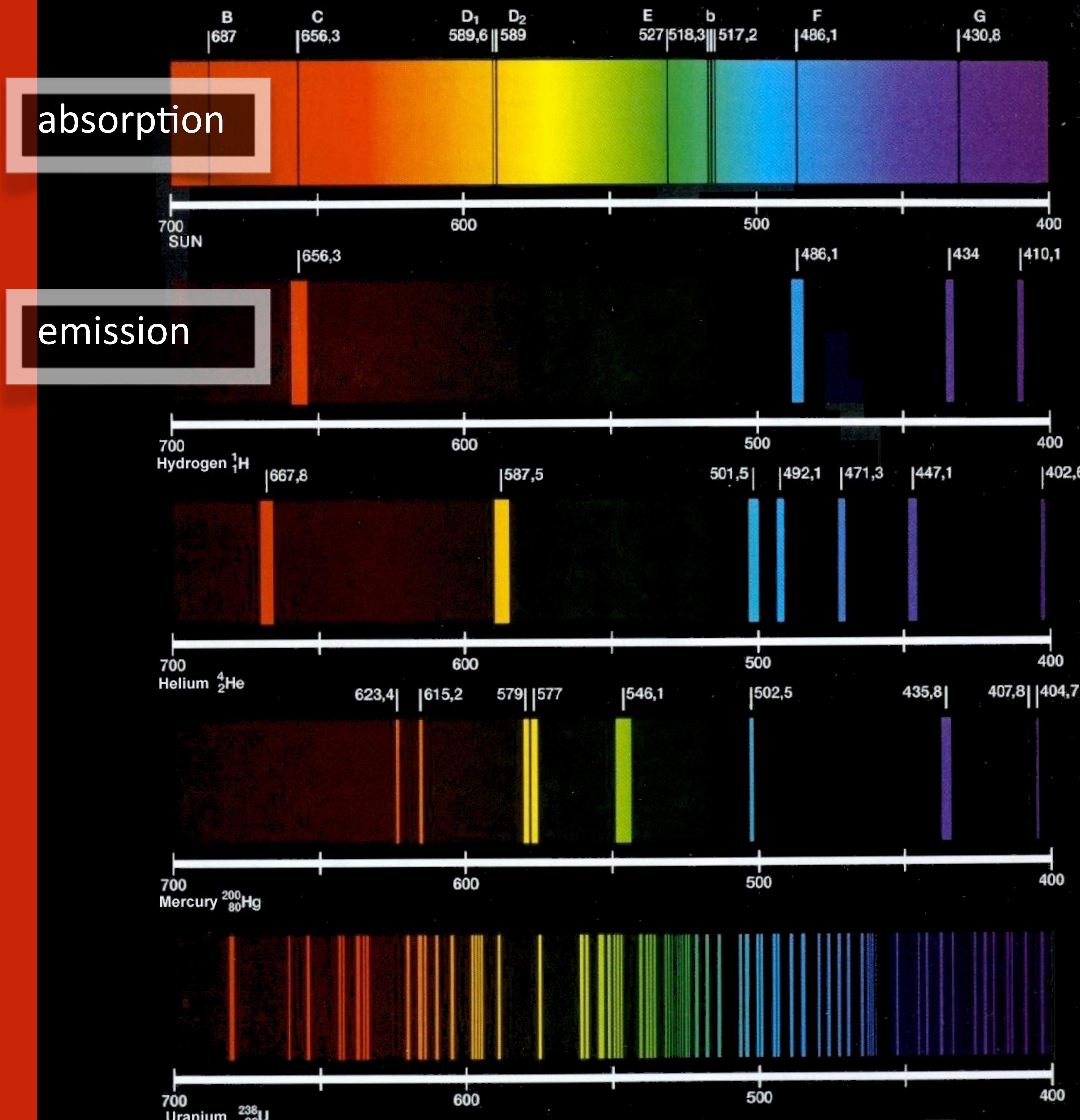
👉 **distance from Earth**

to galaxies that include Cepheid stars

atomic spectra

unique fingerprint of the atomic species





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

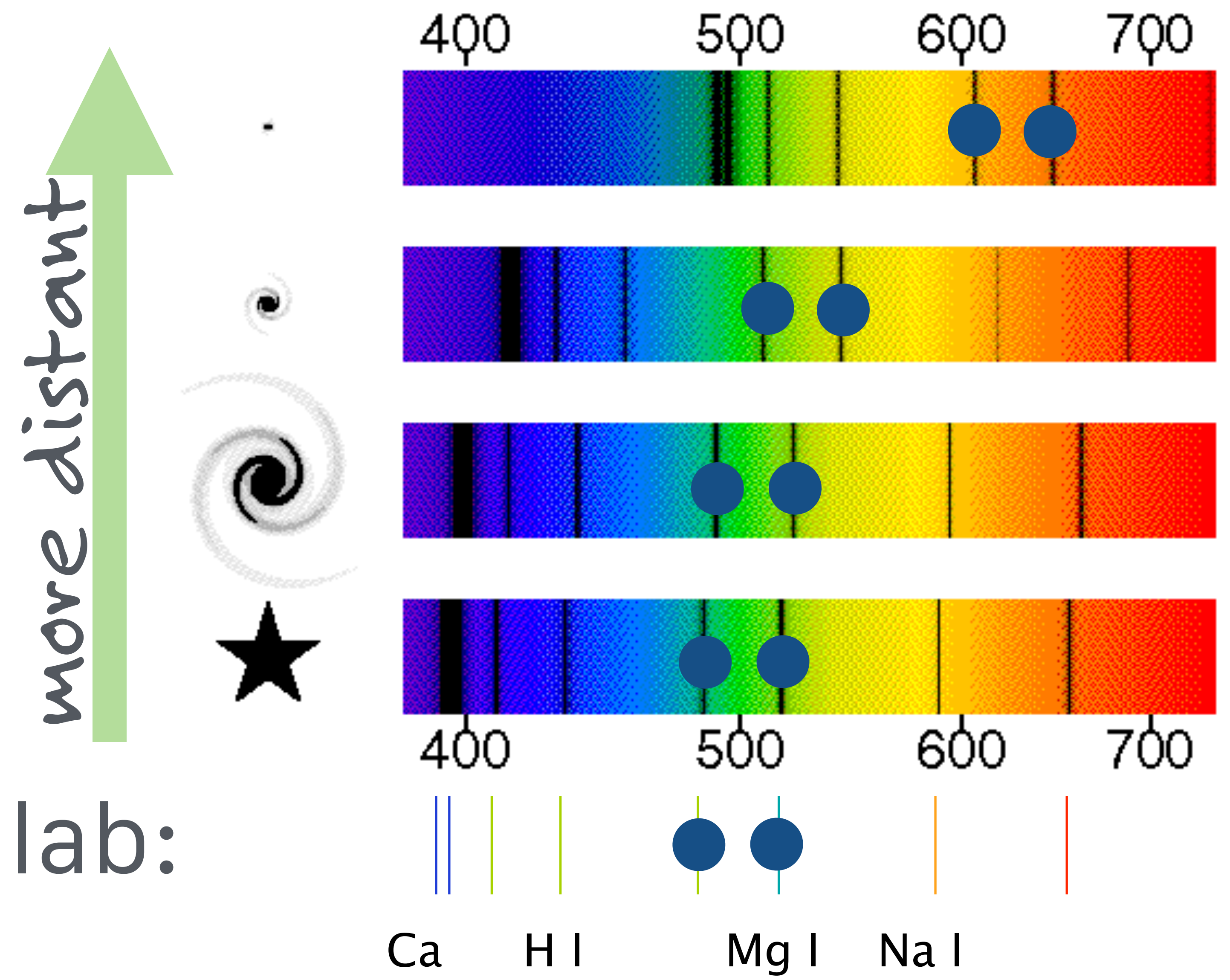
Hubble used

the finger-print tool of spectroscopy

His results:

Wavelengths from far-away sources appeared longer - “**redshifted**”

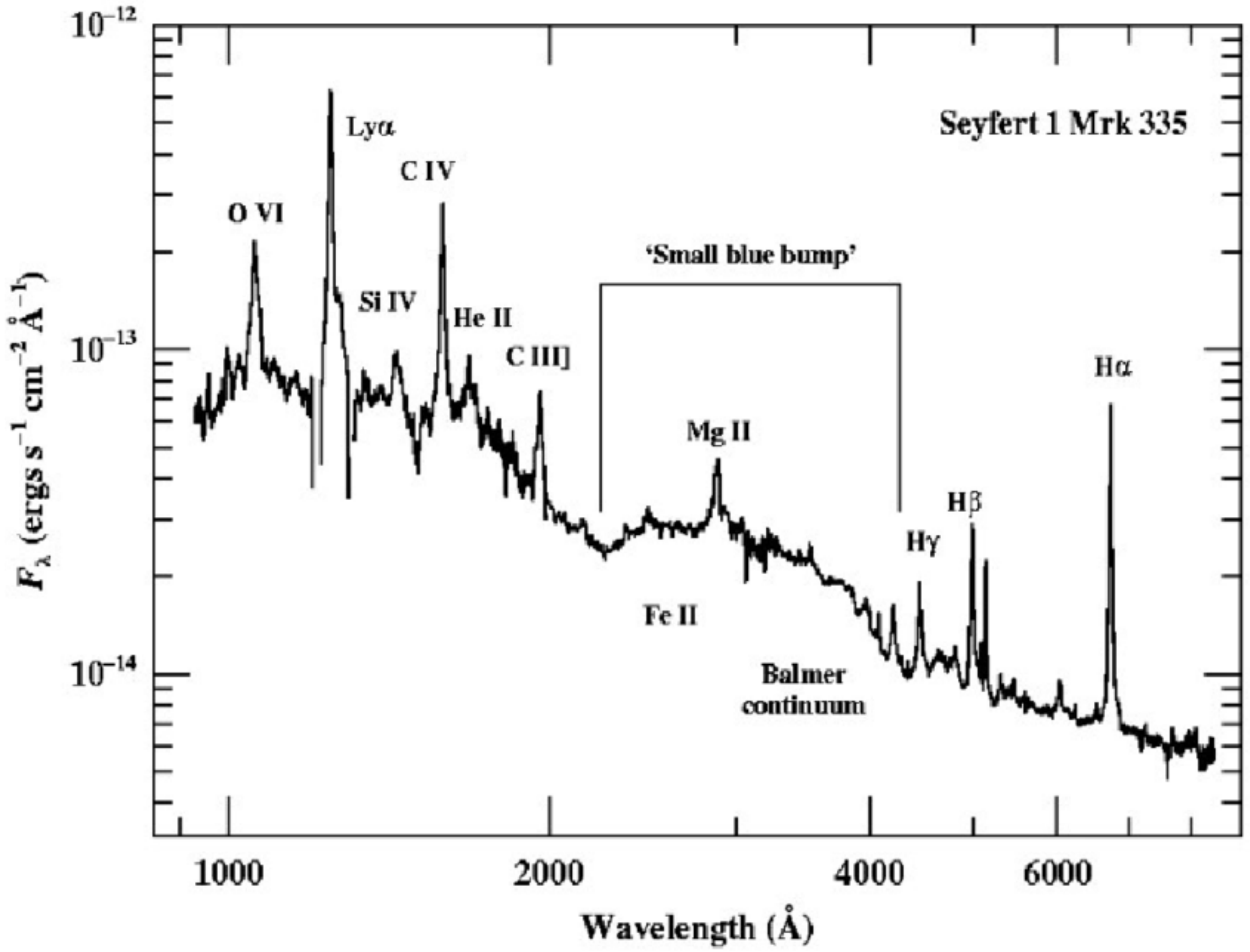
suggesting all of his galaxies seemed to be moving away from us…thinking “Doppler”

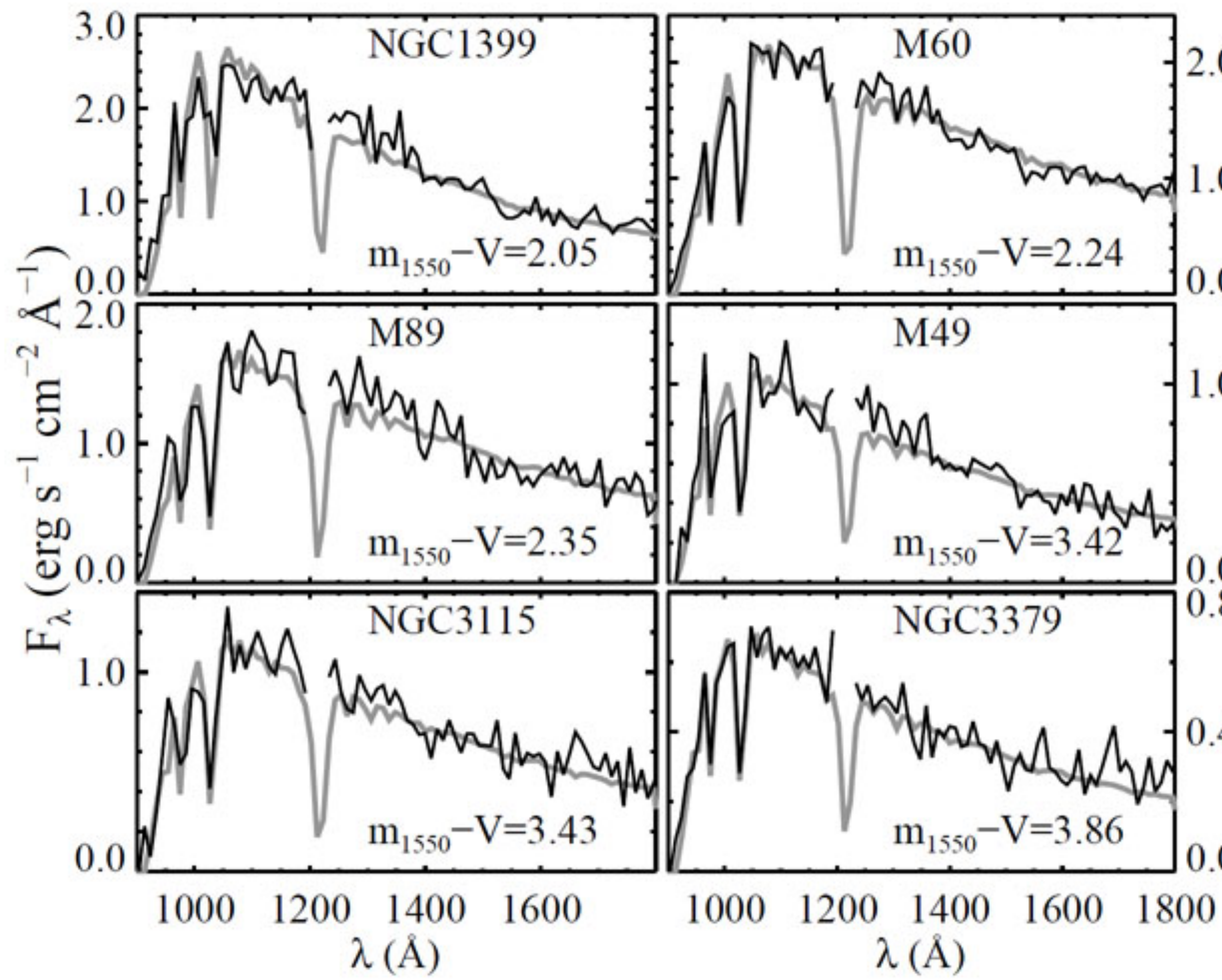


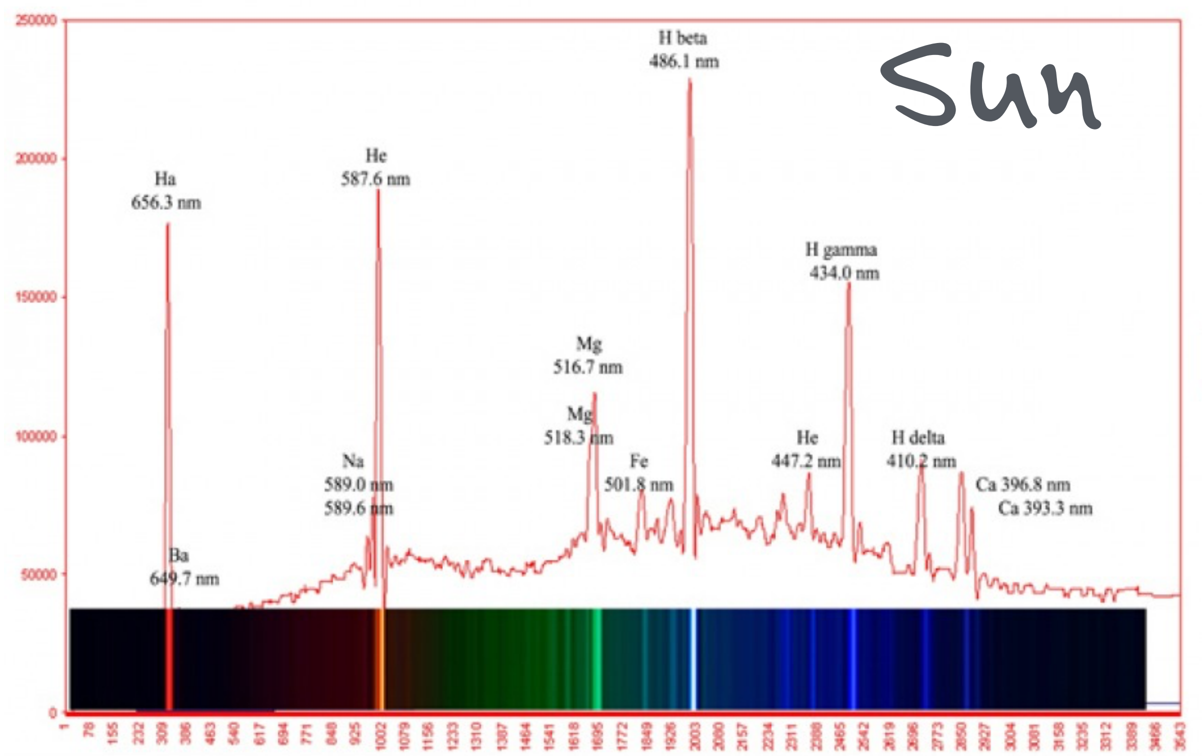
$$\frac{\lambda_O - \lambda_e}{\lambda_e} = \frac{v_e}{c}$$

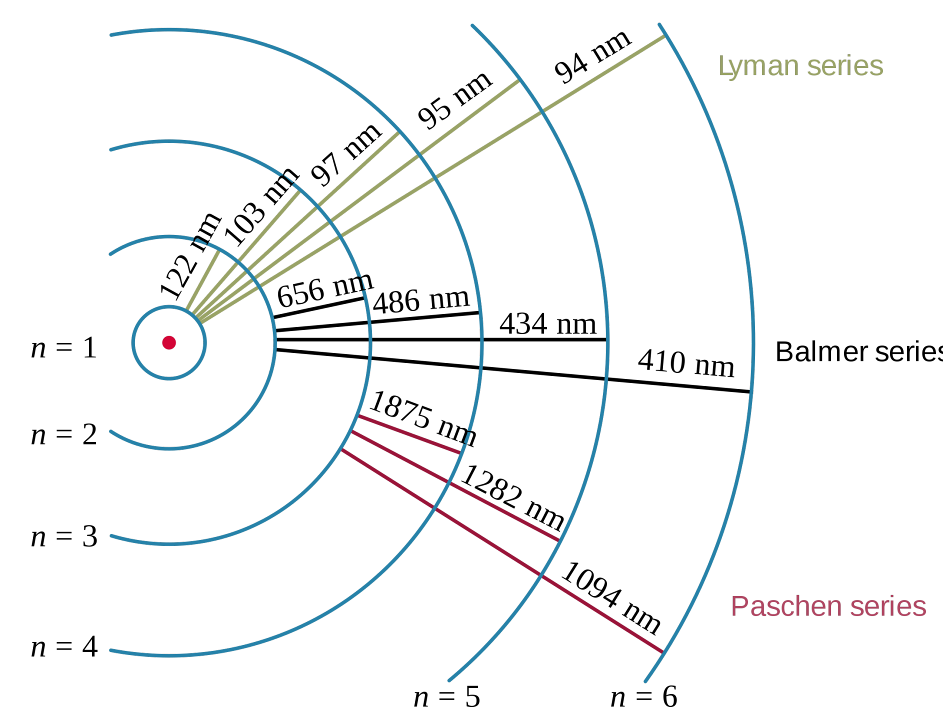
http://www.astro.ucla.edu/~wright/doppler.htm

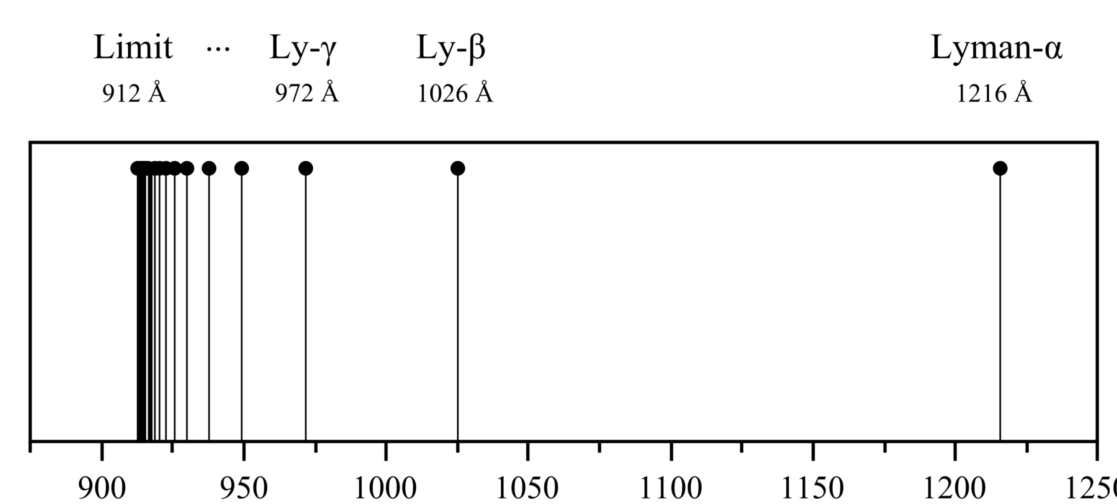
spectra examples











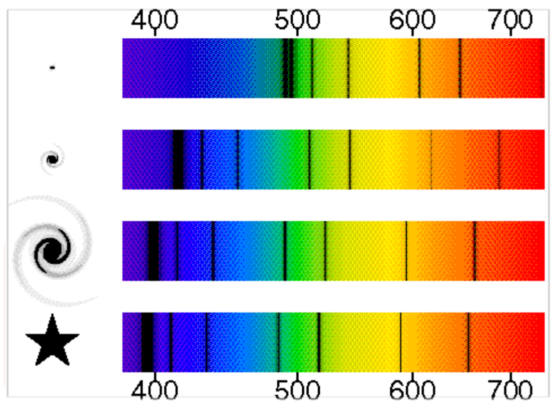
spectroscopy of stars and galaxies

plus Hubble's analysis:

👉 **speed of galaxies**

from Earth

Hubble's



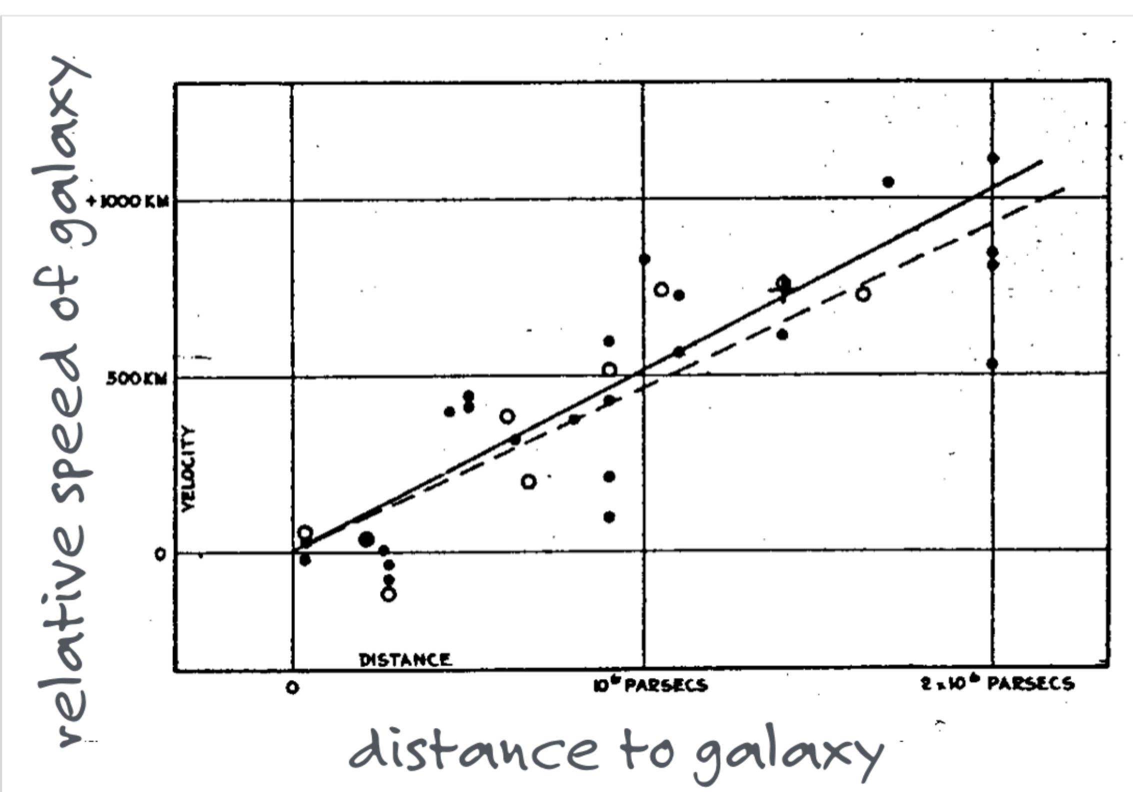
FROM PRESUMED DOPPLER-SHIFTED SPECTRA

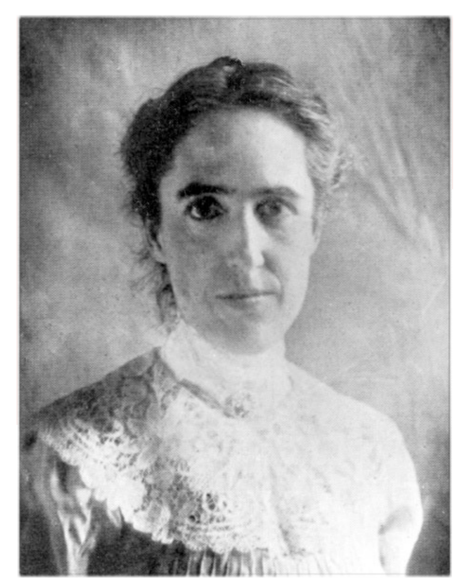
HUBBLE'S CONSTANT = 1/T

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

relation alert: **Hubble's Law**

refers to: $$v = rH$$

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

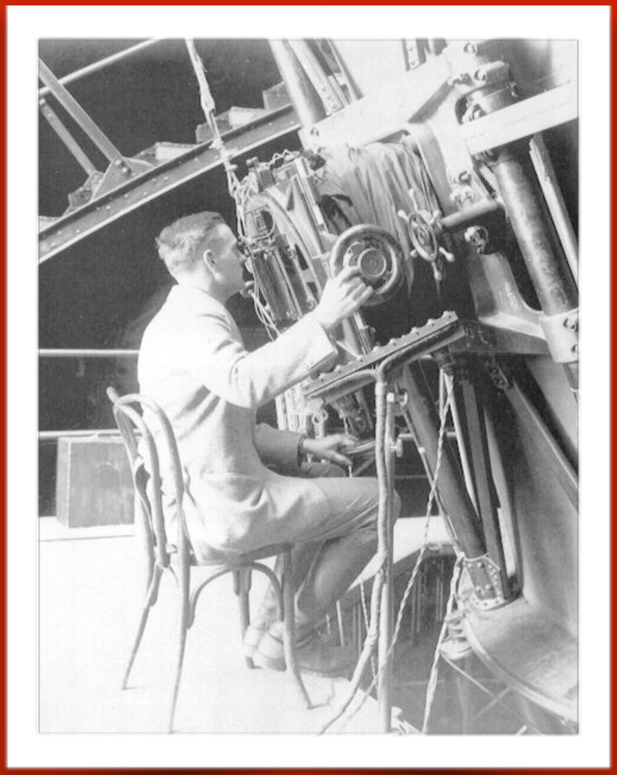
example:

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

Lemaître was the first to realize that Hubble had demonstrated:

1. spacetime is stretching

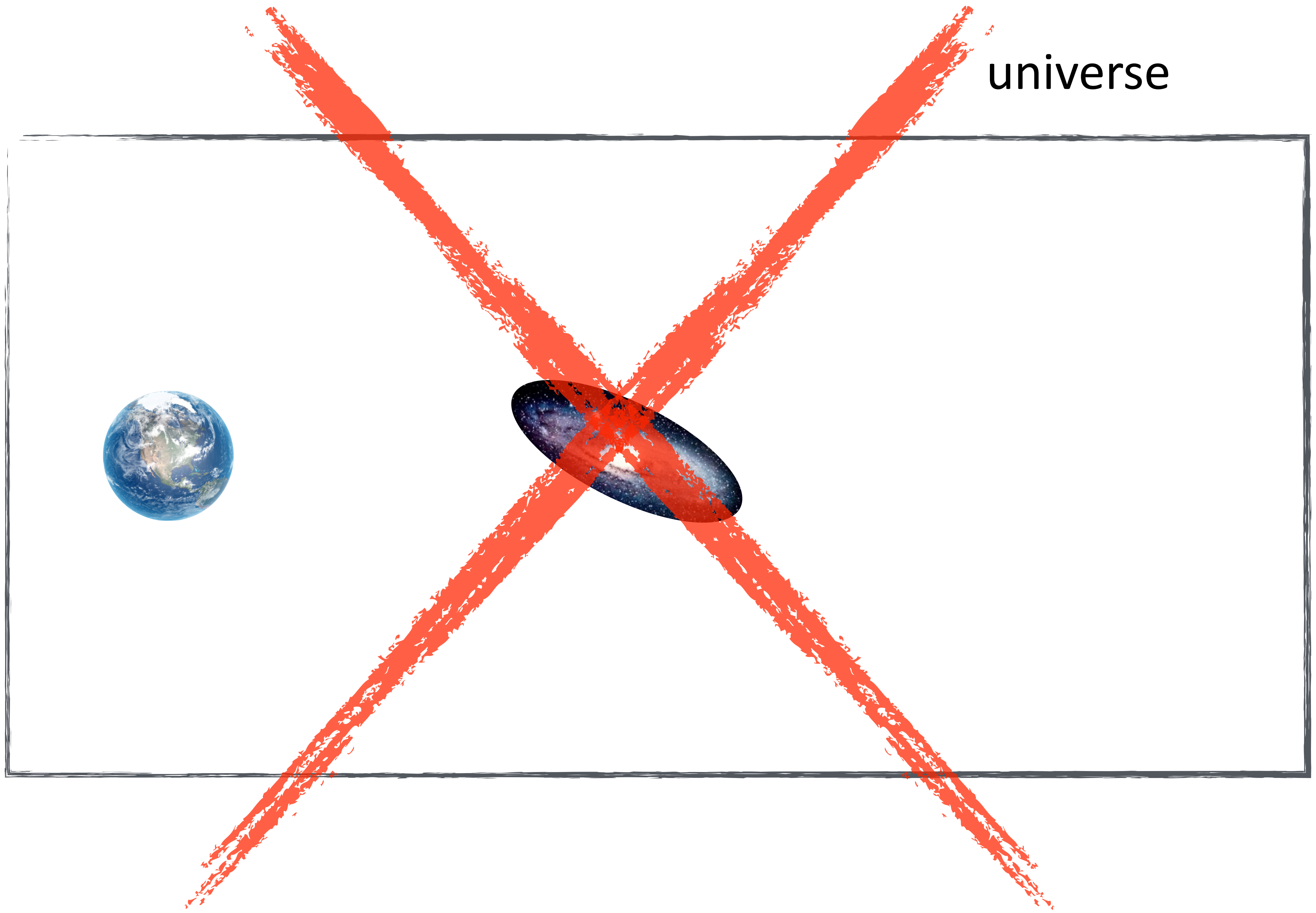
The entire kit and caboodle is expanding



Here’s what it does NOT mean:

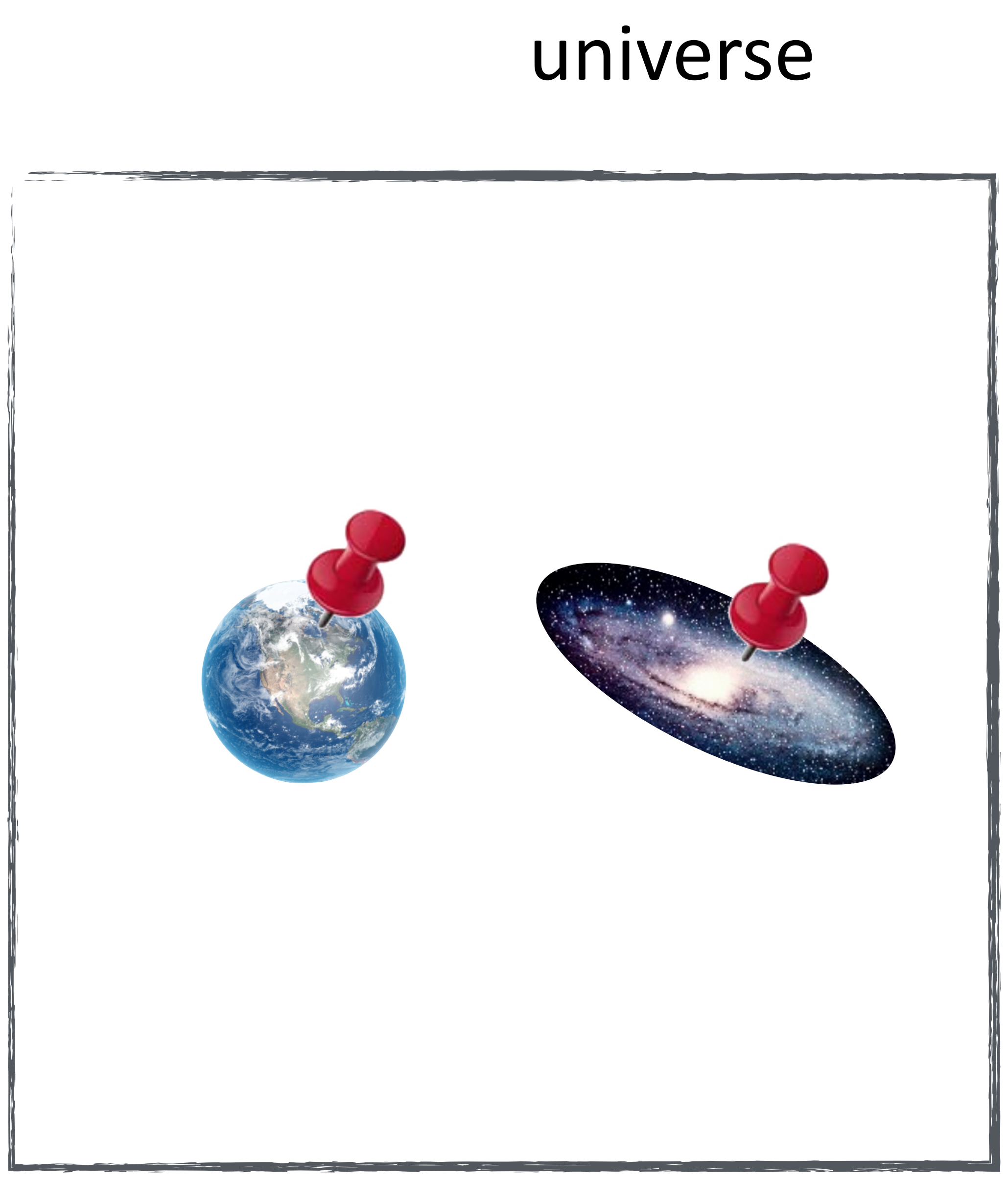
galaxies are not ‘‘‘moving away’’

inside of the universe

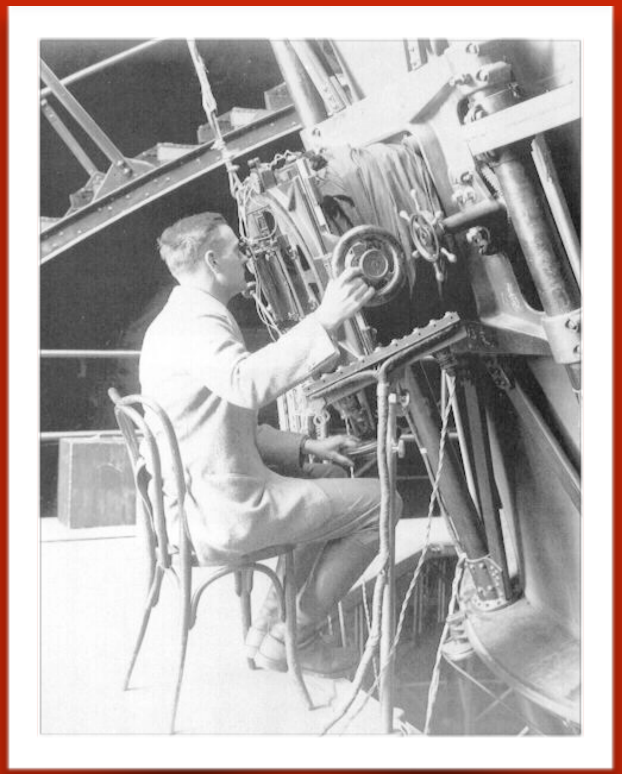


what stretching DOES mean

is complicated!



Lemaître was the first to realize that Hubble had demonstrated:



1. spacetime is stretching

The entire kit and caboodle is expanding

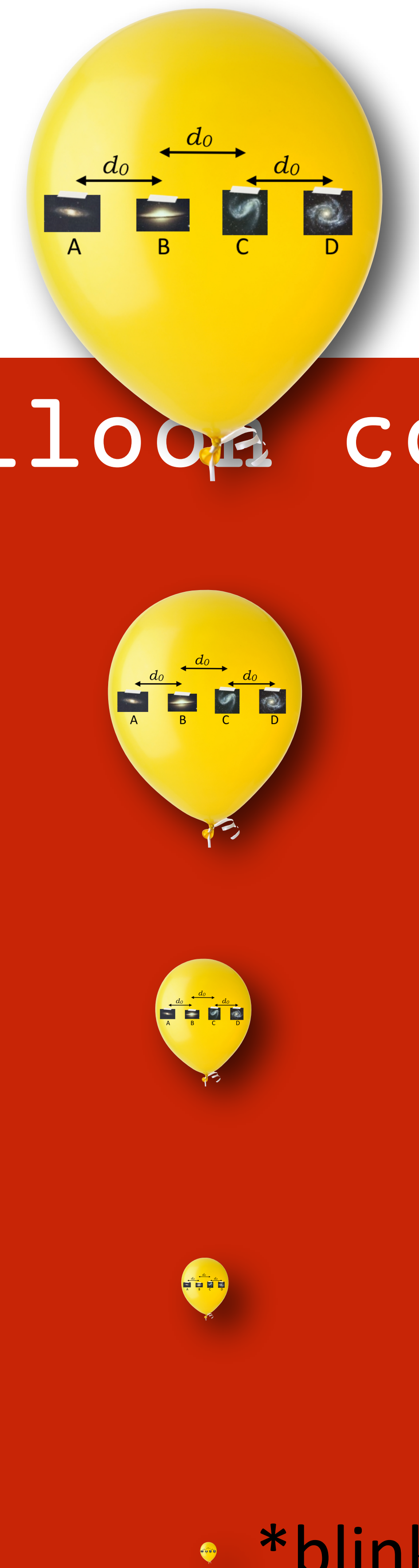
2. But then he realized that the current Universe could have come from something smaller

think about the balloon coming from a smaller size

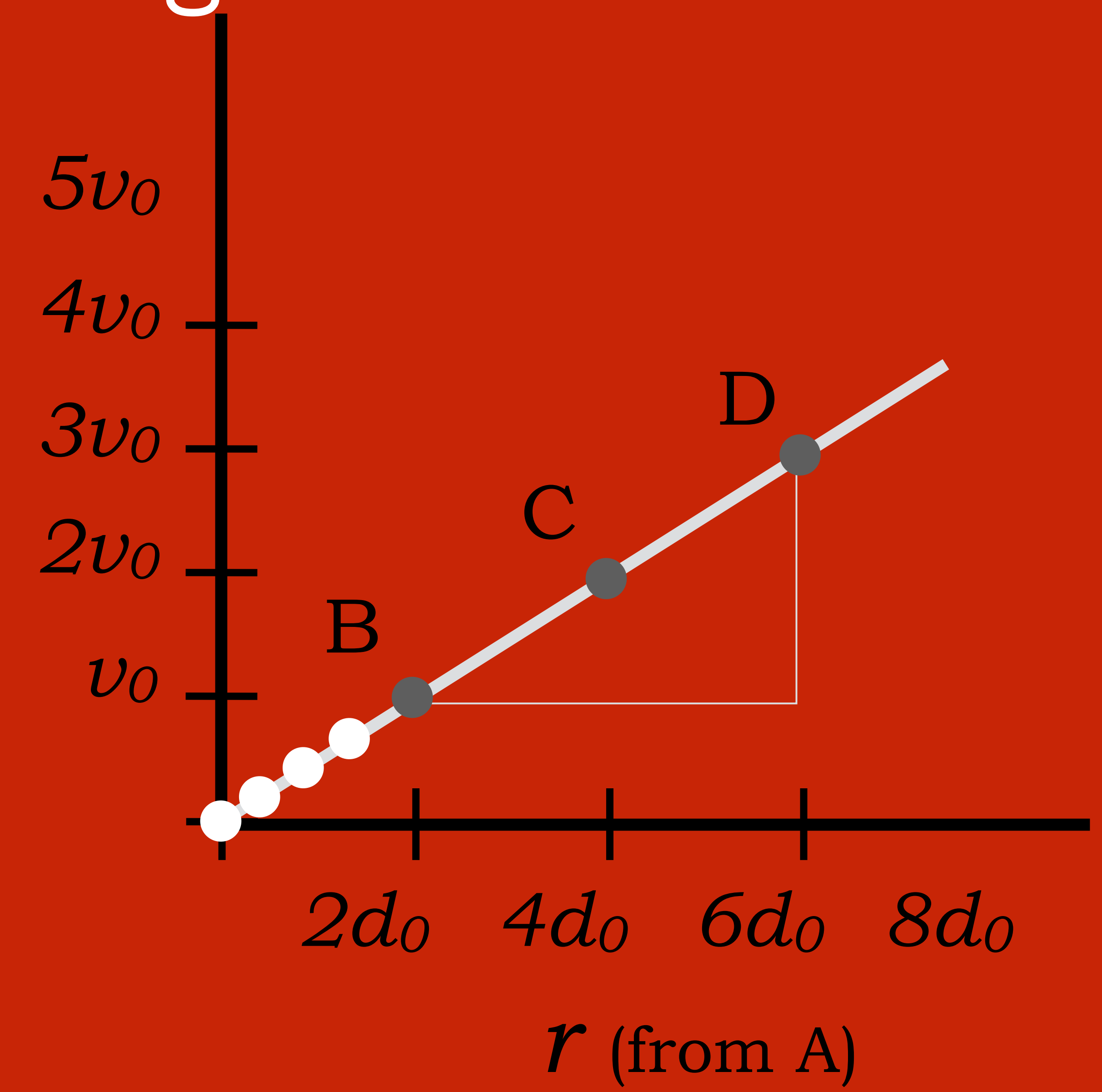
and still smaller

and still smaller

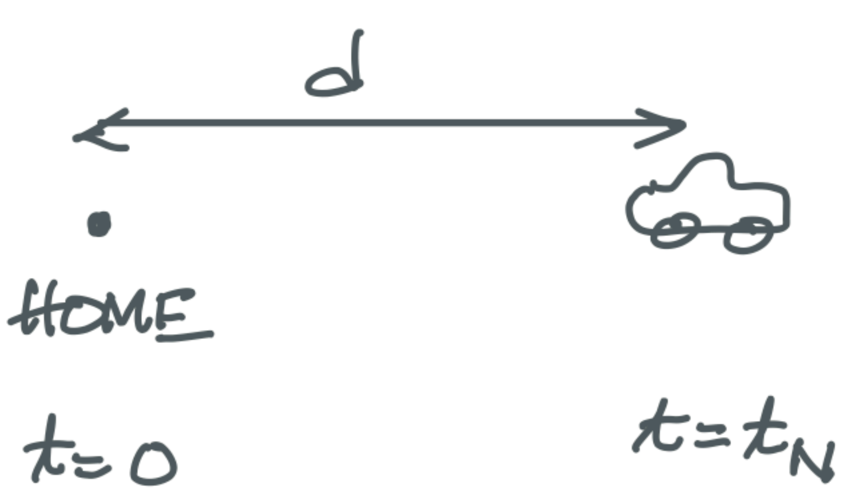
until.



blink



speed and distance!

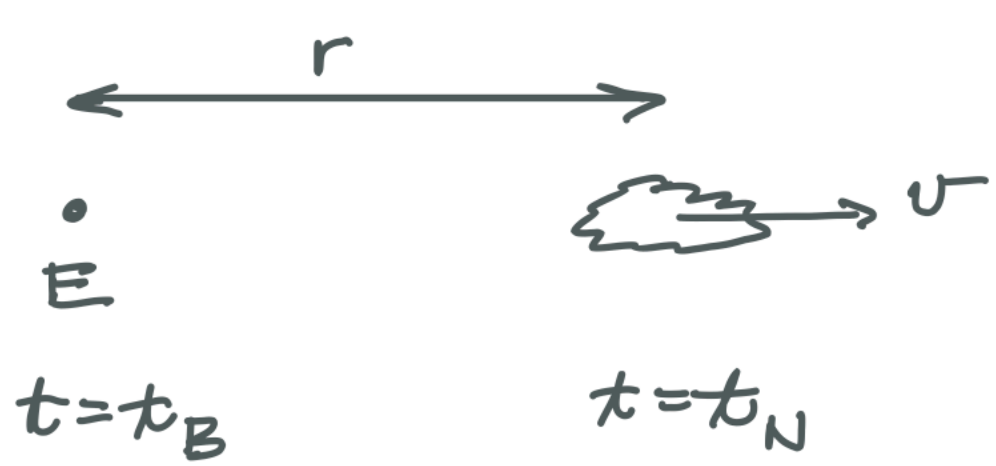


$d = 300\,\text{mi}$ & $v = 60\,\text{mph}$

how long? ... what's t_N?

$$v = \frac{\Delta d}{\Delta t} \Rightarrow \Delta t = \frac{\Delta d}{v}$$

$$= \frac{300\,\text{mi}}{60\,\text{mi/h}} = 5\,\text{h}$$



same thing:

$$\Delta t = t_N - t_B = \frac{r}{v}$$

BUT: HUBBLE'S LAW $v = Hr$

$$H = \frac{v}{r}$$

$$H^{-1} = \frac{r}{v}$$

Hubble Constant

critical measurable parameter in cosmology

a rough estimate of the age of the universe

Measuring the Hubble Constant is an important cottage industry in astronomy

current best result:

$H_0 = 67.66 \pm 0.42$ km/sec/Mpc

$H_0 = 2.2 \times 10^{-18}\ s^{-1} = 4.5 \times 10^{17}\ s = 14.5$ By*

The subscript "0" means: "Now"

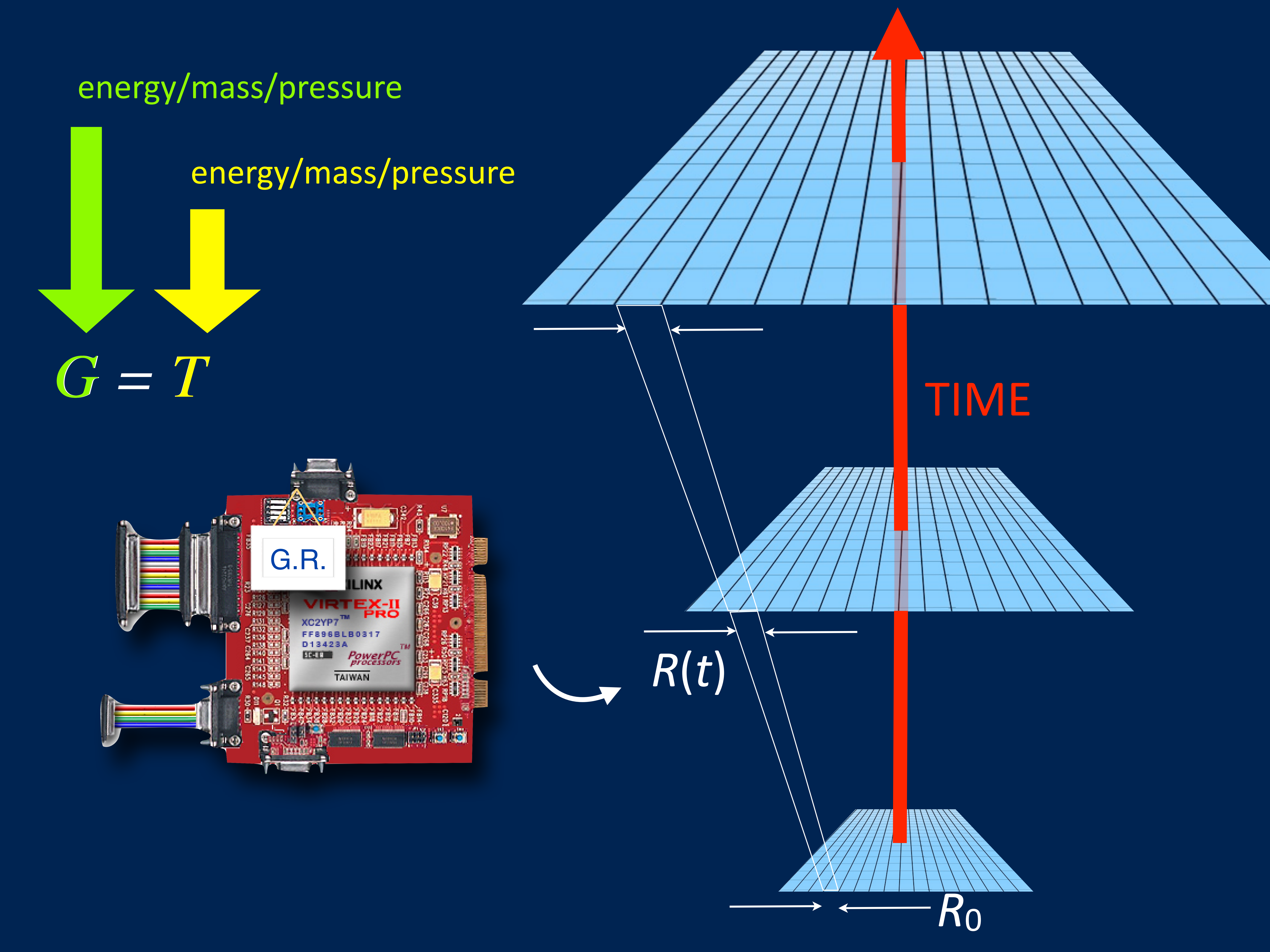
* first-pass: The inverse of the Hubble Constant isn't necessarily the age of the universe currently accepted value: 13.82 By

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

the expansion represented as

the "Scale Factor": $\mathrm{R}(t)$

the stretchiness of spacetime

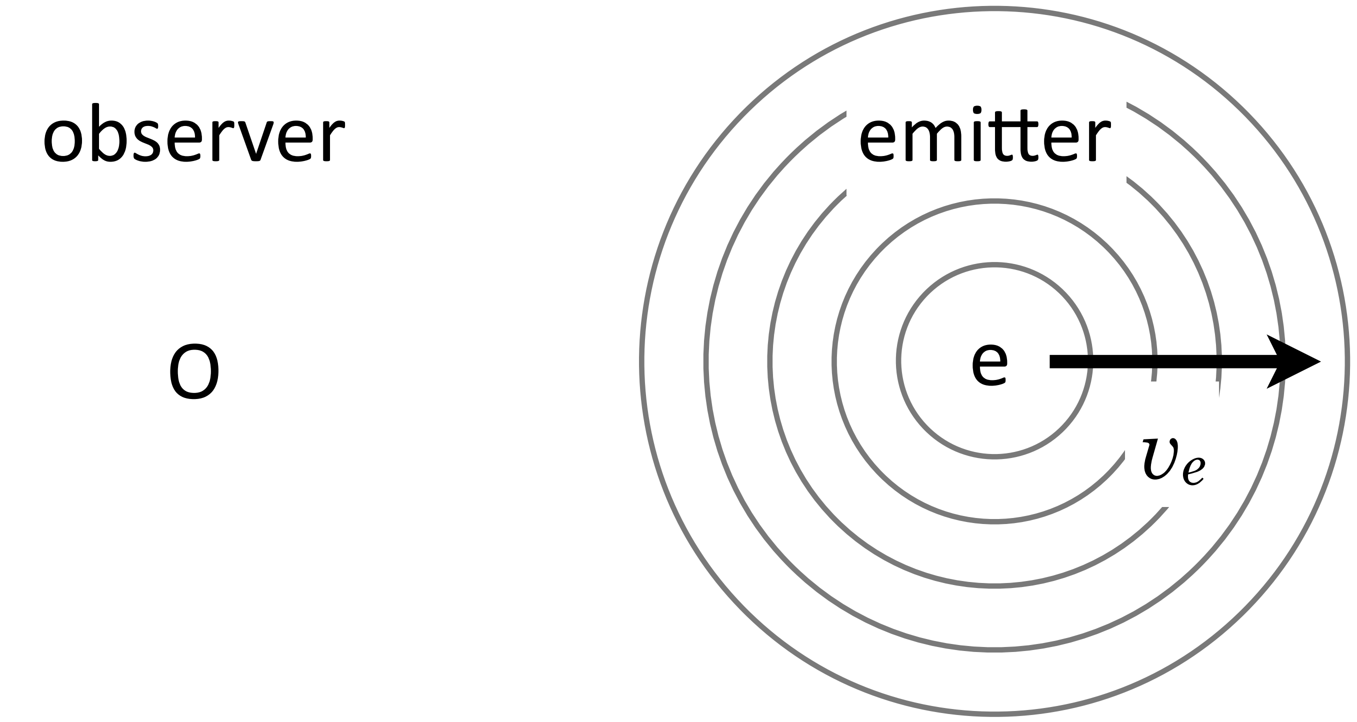

energy/mass/pressure
energy/mass/pressure
$G = T$
G.R.
XILINX
VIRTEX-II PRO
XC2YP7
FF896BLB0317
D13423A
PowerPC processors
TAIWAN
TIME
$R(t)$
R_0

modern data

characterized by the “red shift”

z: distance and recession velocity

red shift…5¢ version



"Relativistic Doppler shift"

$$z \equiv \frac{\Delta\lambda}{\lambda_e} = \frac{\lambda_O - \lambda_e}{\lambda_e}$$

z measures the stretchiness of space

z is called the "redshift"

related to the recession velocity: $$\frac{\lambda_O - \lambda_e}{\lambda_e} = \frac{v_e}{c}$$

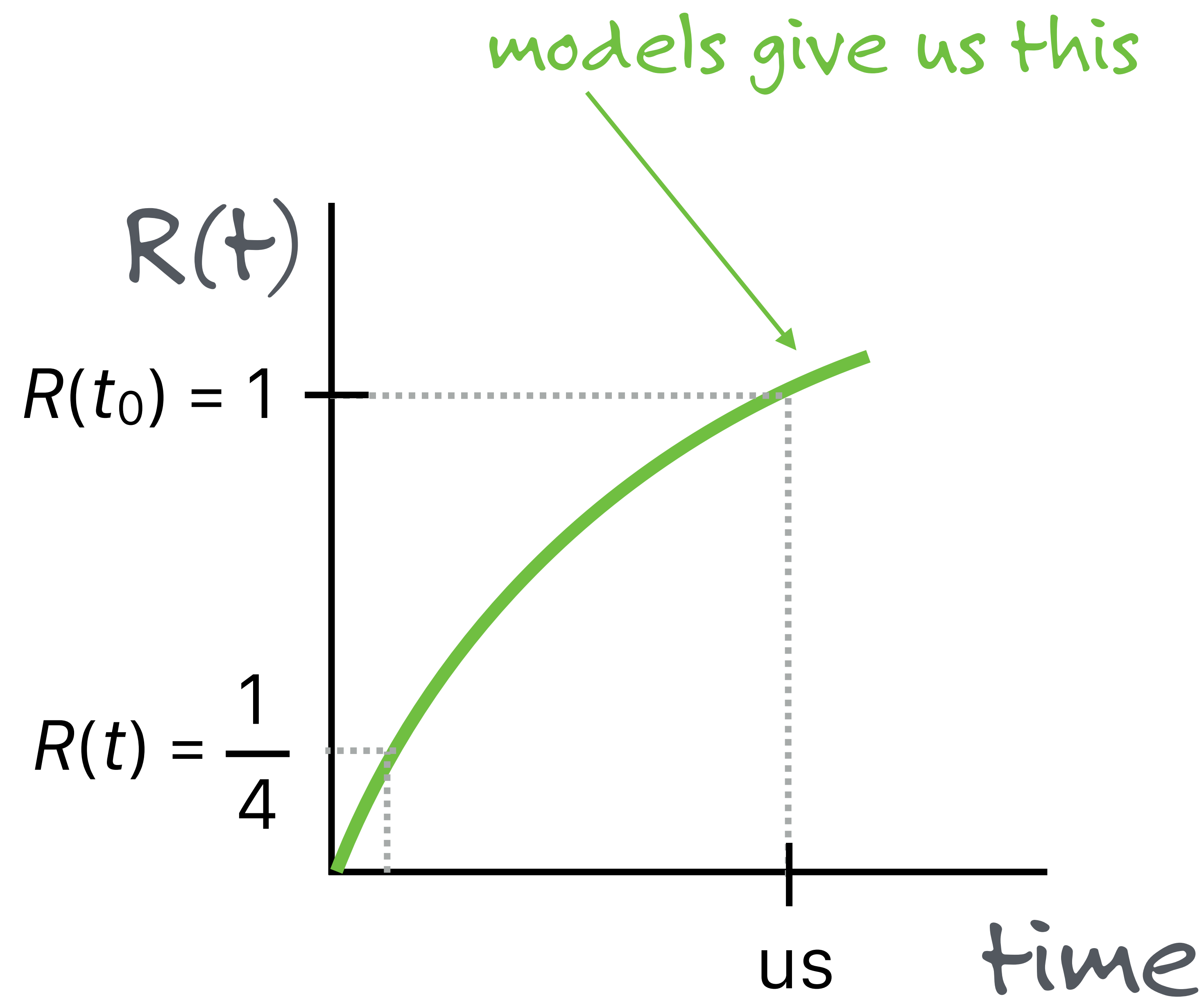
relativistically:

$$z = \sqrt{\frac{1+\beta}{1-\beta}} - 1 \qquad \beta = \frac{v_e}{v}$$

s t r e t c h i n e s s

$$z \equiv \frac{\Delta\lambda}{\lambda_e} = \frac{\lambda_O - \lambda_e}{\lambda_e} = \frac{\lambda_0}{\lambda_e} - \frac{\lambda_e}{\lambda_e}$$

$$\ldots \quad z + 1 = \underbrace{\frac{\lambda_0}{\lambda_e}}_{\text{measurable}} = \frac{R(t_0)}{R(t)}$$



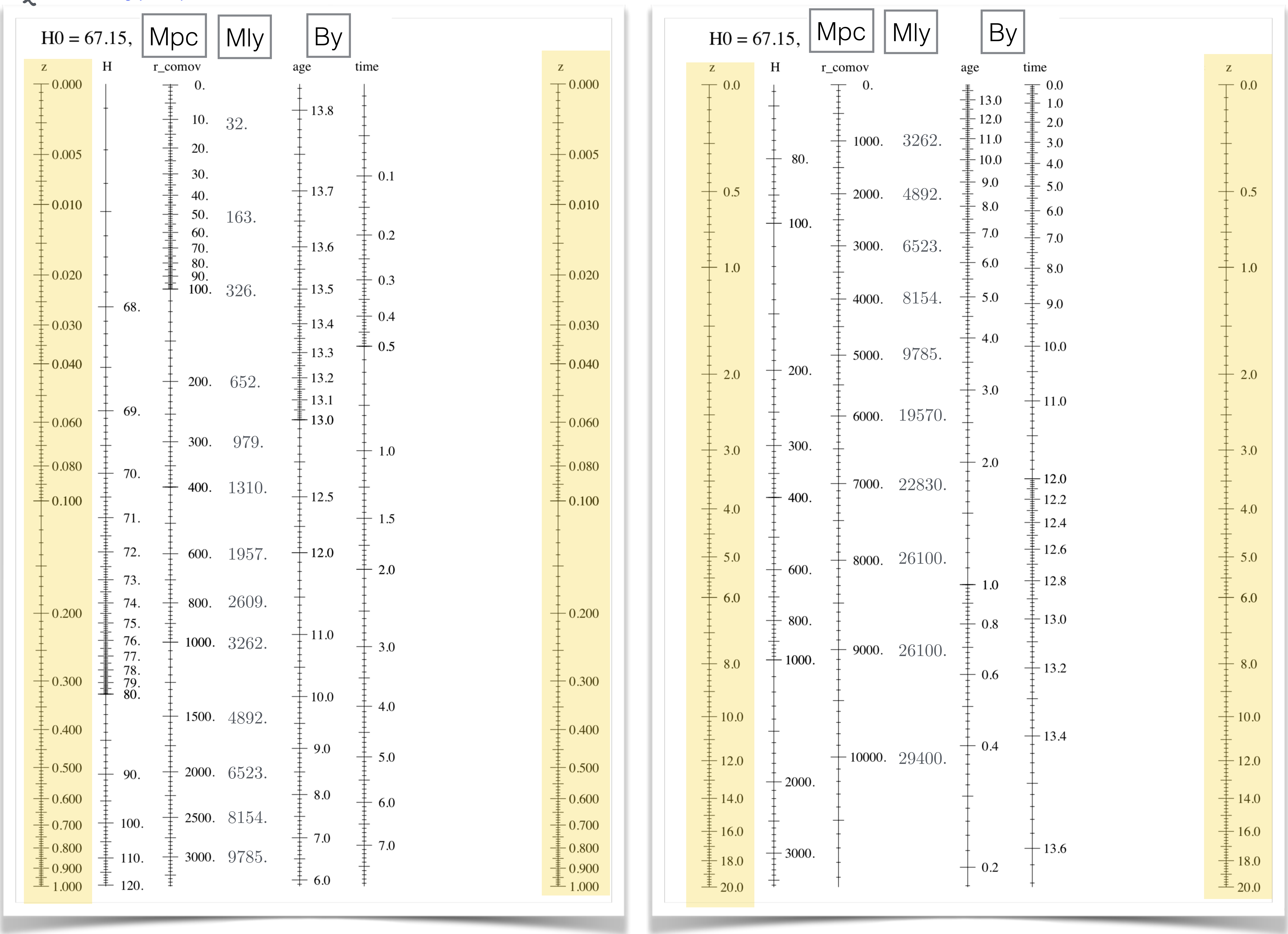
suppose light from a galaxy is observed
@ wavelength 4 times emitted

we'd say: it has a "redshift of 3"

from:

Paper-and-pencil cosmological calculator

Sergey V. Pilipenko



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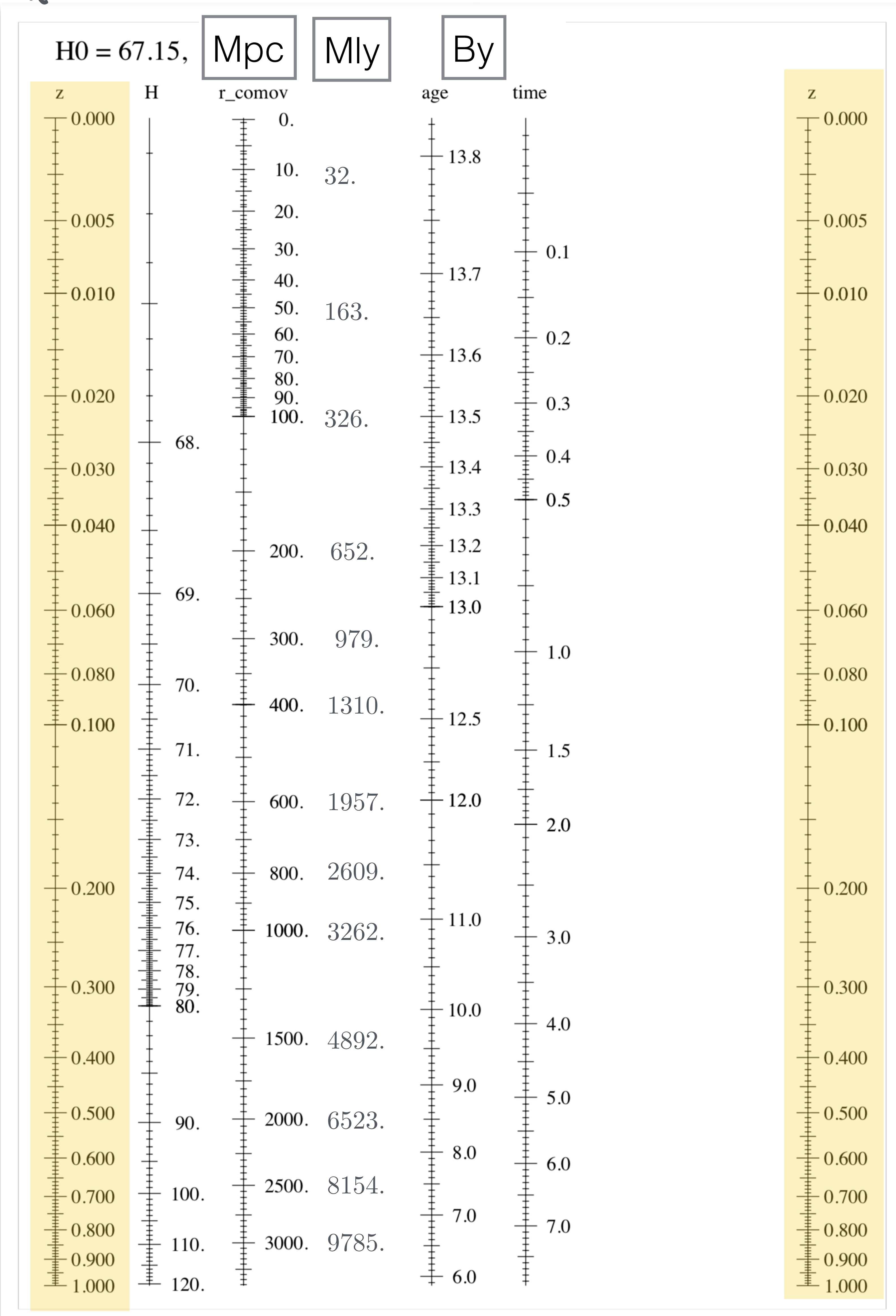
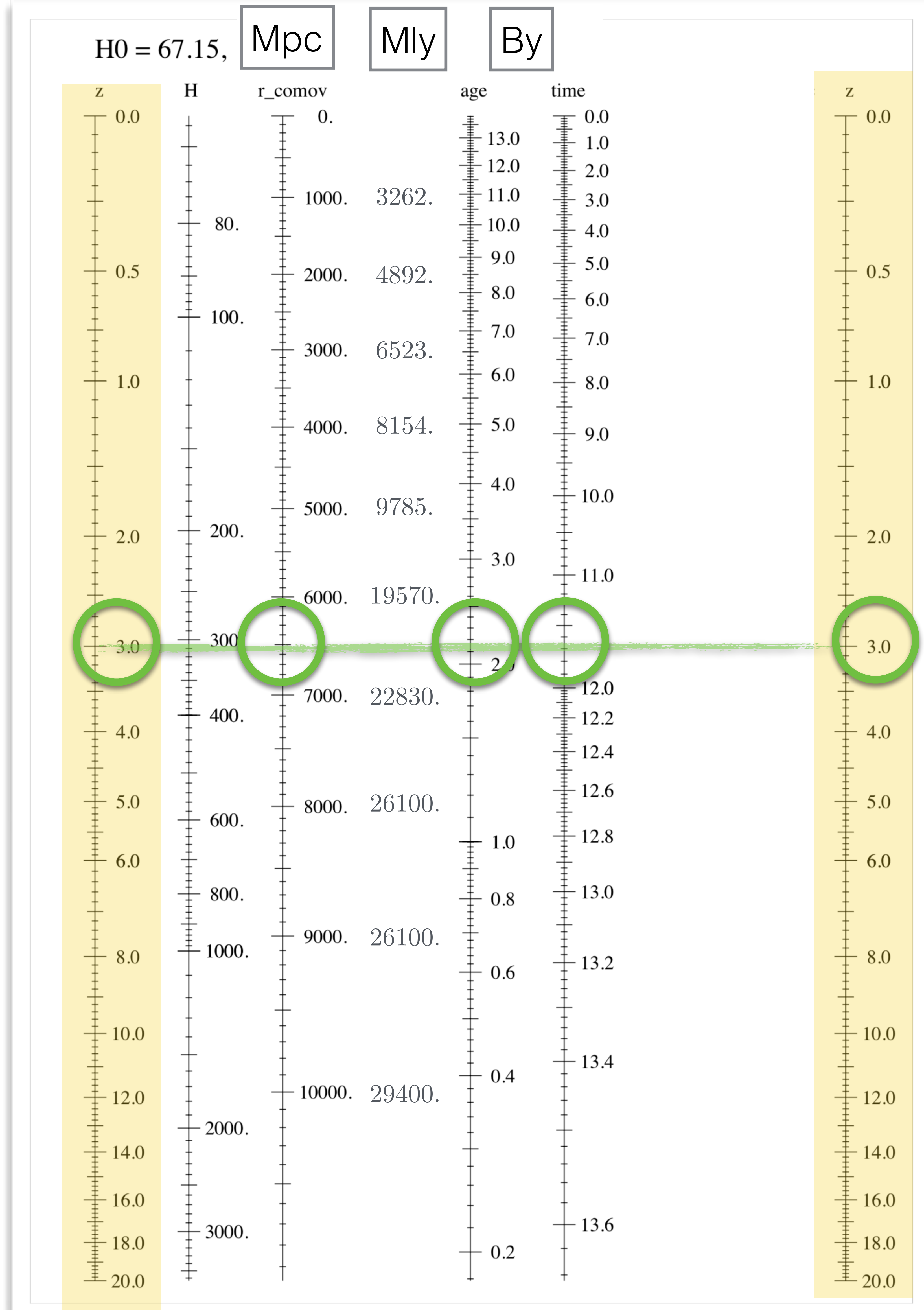
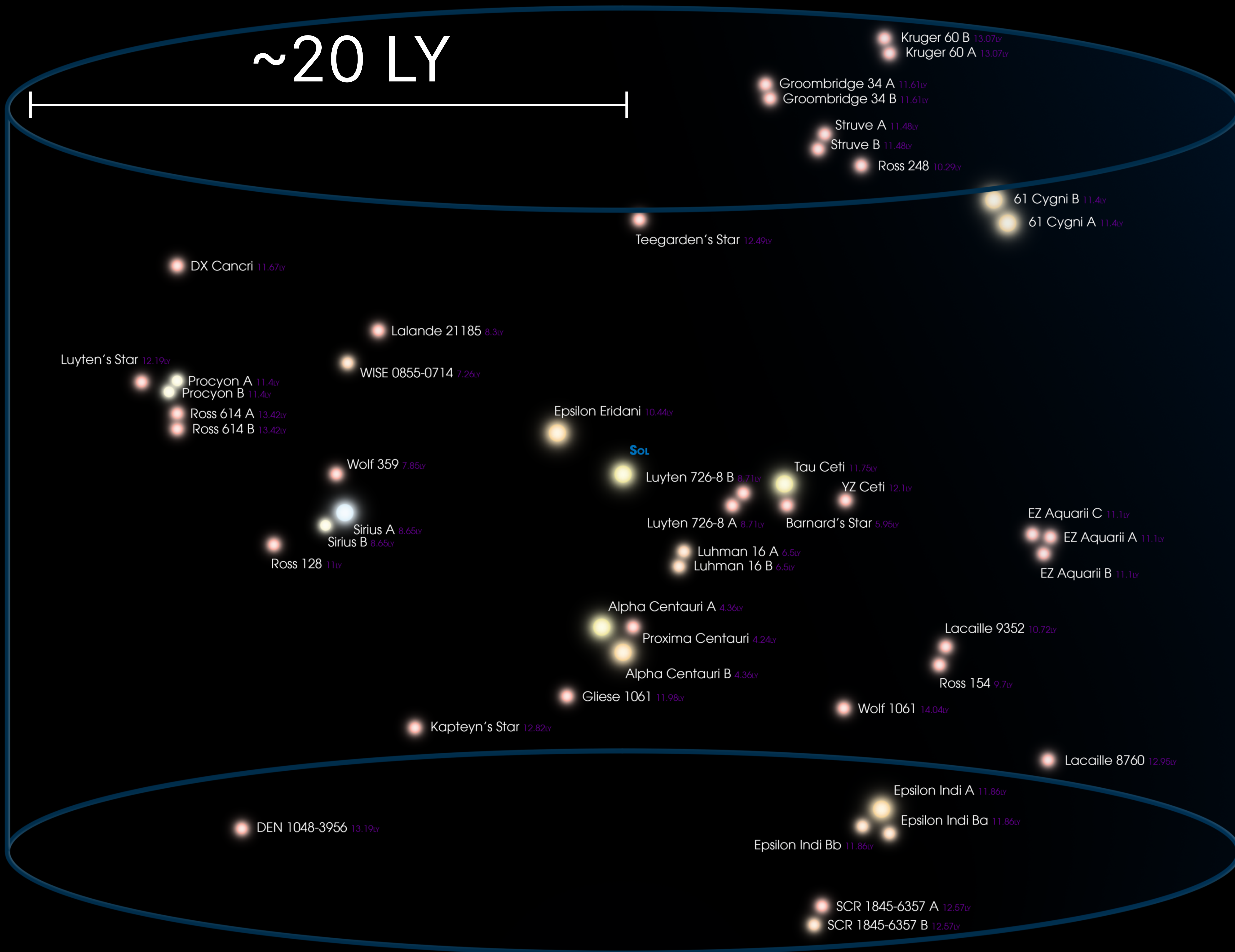
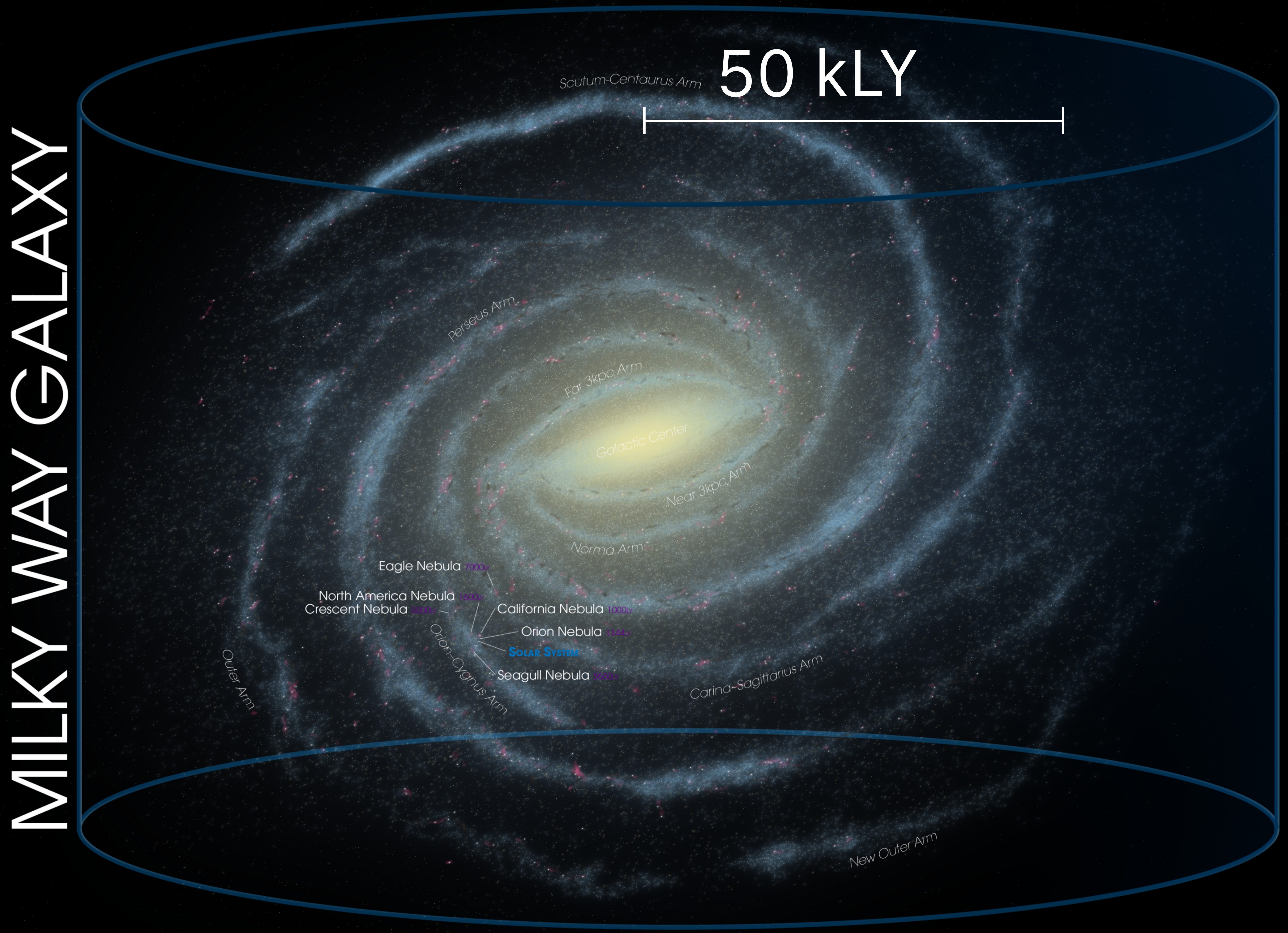




CLOSEST STARS

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50 kLY
Scutum-Centaurus Arm
Perseus Arm
Far 3kpc Arm
Galactic Center
Near 3kpc Arm
Norma Arm
Eagle Nebula
North America Nebula
Crescent Nebula
California Nebula
Orion Nebula
Solar System
Seagull Nebula
Orion-Cygnus Arm
Outer Arm
Carina-Sagittarius Arm
New Outer Arm

from:

Paper-and-pencil cosmological calculator

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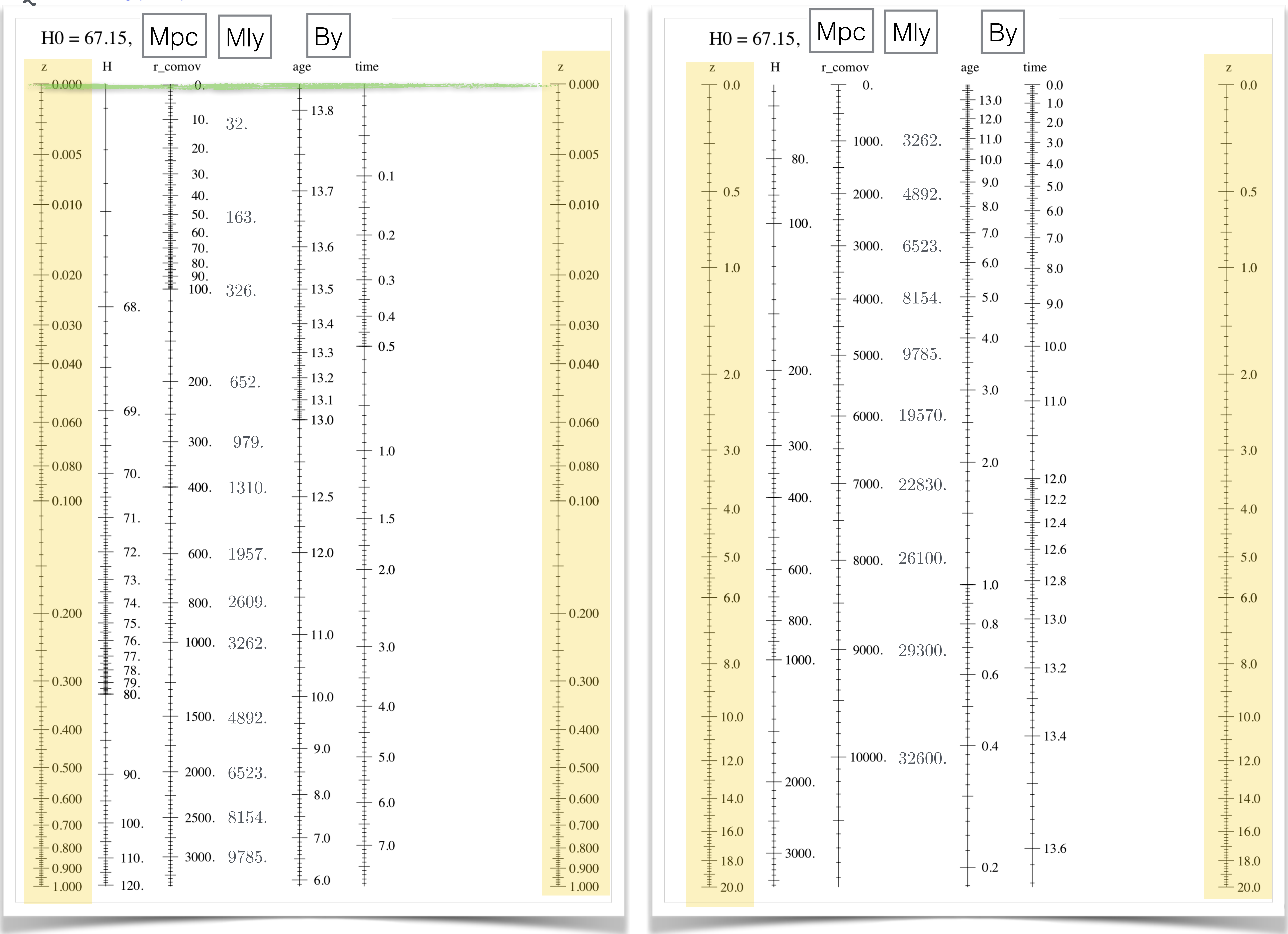

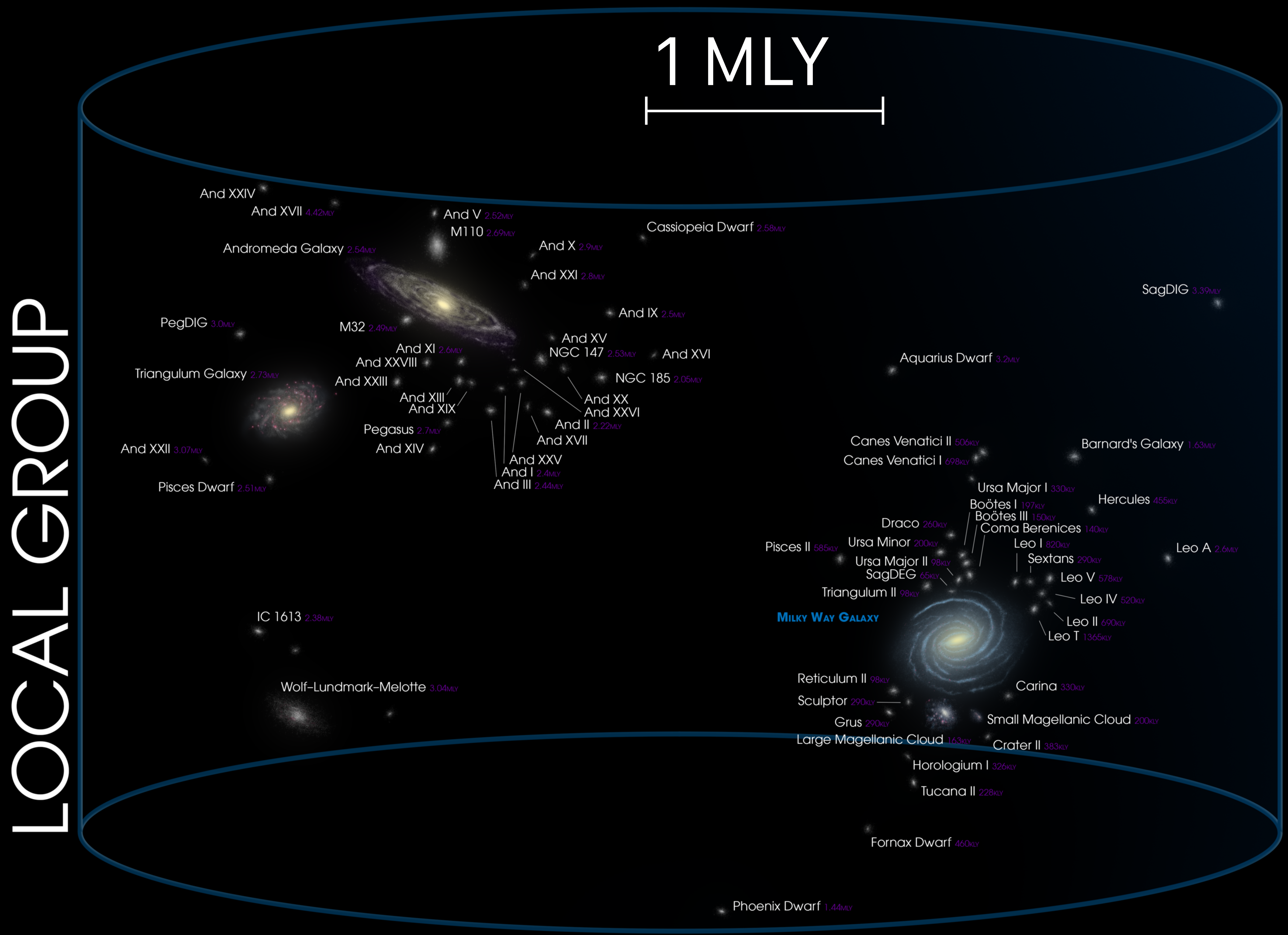

LOCAL GROUP
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And XXIV
And XVII 4.42MLY
And V 2.52MLY
M110 2.69MLY
Andromeda Galaxy 2.54MLY
Cassiopeia Dwarf 2.58MLY
And X 2.9MLY
And XXI 2.8MLY
And IX 2.5MLY
SagDIG 3.39MLY
PegDIG 3.0MLY
M32 2.49MLY
And XI 2.6MLY
And XXVIII
And XV
NGC 147 2.53MLY
And XVI
Aquarius Dwarf 3.2MLY
Triangulum Galaxy 2.73MLY
And XXIII
NGC 185 2.05MLY
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Pegasus 2.7MLY
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Canes Venatici I 698KLY
Barnard's Galaxy 1.63MLY
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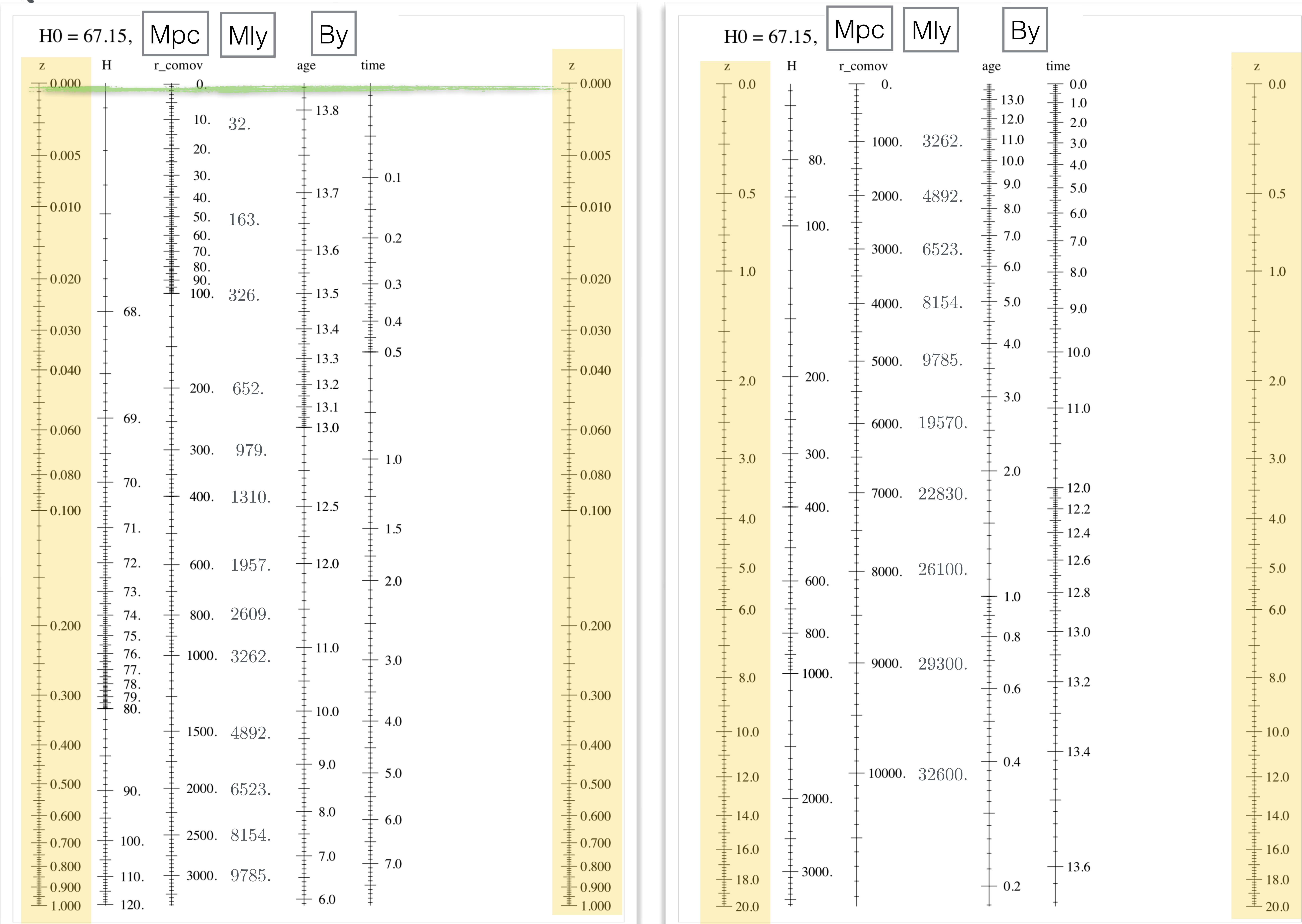
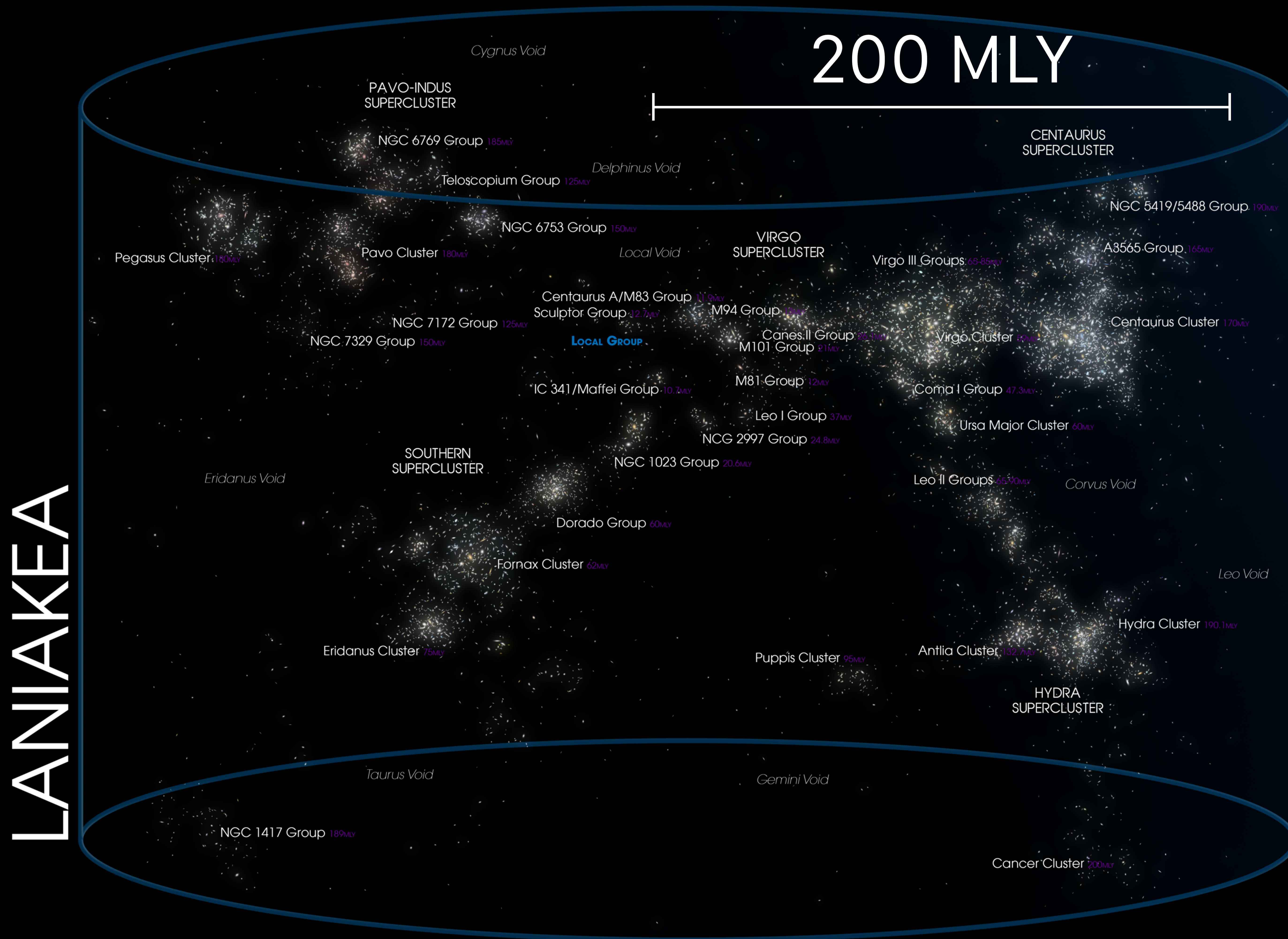
Leo V 578KLY
Triangulum II 98KLY
Leo IV 520KLY
IC 1613 2.38MLY
Milky Way Galaxy
Leo II 690KLY
Leo T 1365KLY
Wolf–Lundmark–Melotte 3.04MLY
Reticulum II 98KLY
Carina 330KLY
Sculptor 290KLY
Grus 290KLY
Small Magellanic Cloud 200KLY
Large Magellanic Cloud 163KLY
Crater II 383KLY
Horologium I 326KLY
Tucana II 228KLY
Fornax Dwarf 460KLY
Phoenix Dwarf 1.44MLY

from:

Paper-and-pencil cosmological calculator

Sergey V. Pilipenko

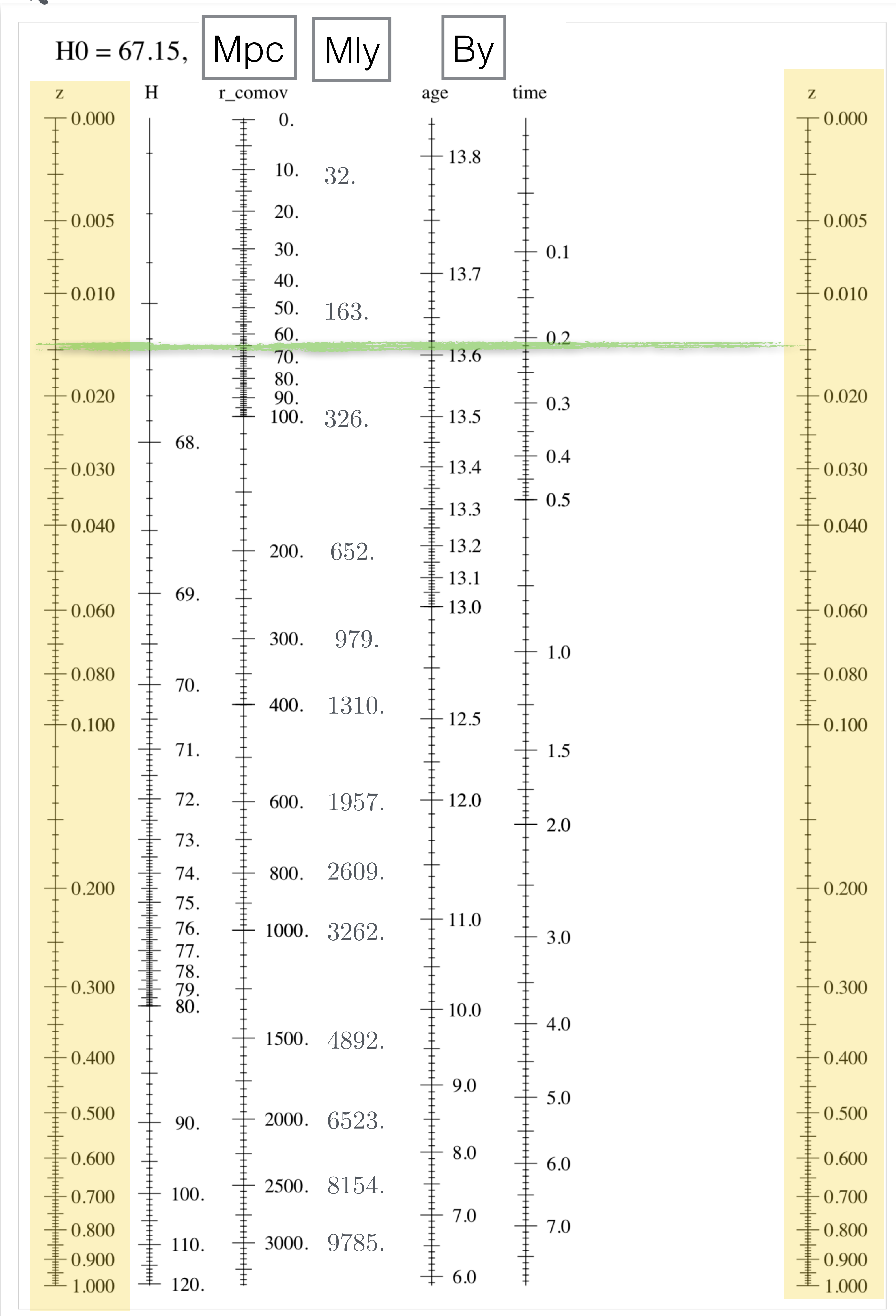


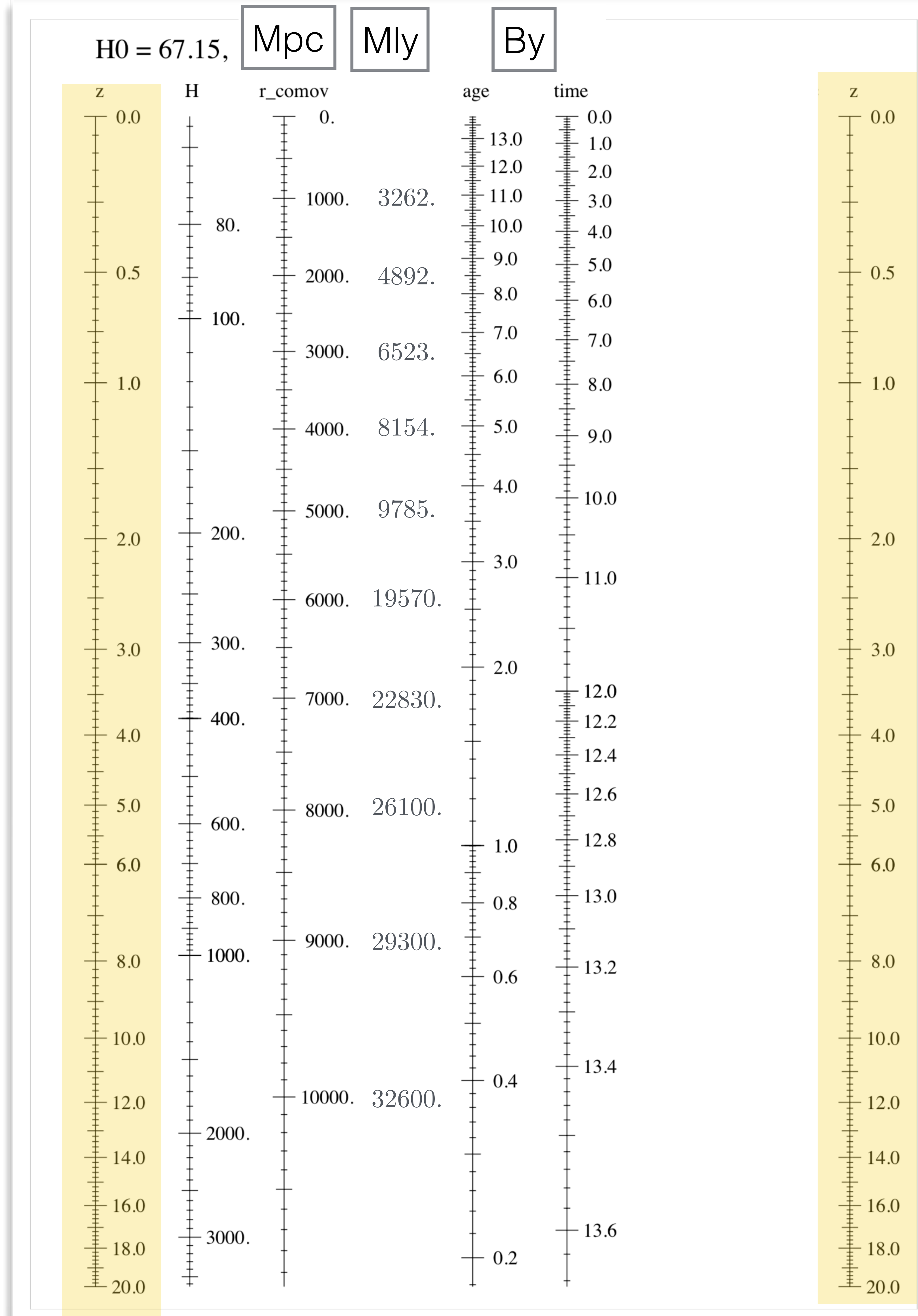

LANIAKEA
200 MLY
Cygnus Void
PAVO-INDUS SUPERCLUSTER
NGC 6769 Group
Teloscopium Group
Delphinus Void
CENTAURUS SUPERCLUSTER
NGC 5419/5488 Group
A3565 Group
NGC 6753 Group
Pegasus Cluster
Pavo Cluster
Local Void
VIRGO SUPERCLUSTER
Virgo III Groups
Centaurus A/M83 Group
Sculptor Group
M94 Group
NGC 7172 Group
NGC 7329 Group
Local Group
Canes II Group
M101 Group
Virgo Cluster
Centaurus Cluster
IC 341/Maffei Group
M81 Group
Coma I Group
Leo I Group
Ursa Major Cluster
NCG 2997 Group
NGC 1023 Group
SOUTHERN SUPERCLUSTER
Eridanus Void
Leo II Groups
Corvus Void
Dorado Group
Fornax Cluster
Leo Void
Hydra Cluster
Eridanus Cluster
Puppis Cluster
Antlia Cluster
HYDRA SUPERCLUSTER
Taurus Void
Gemini Void
NGC 1417 Group
Cancer Cluster

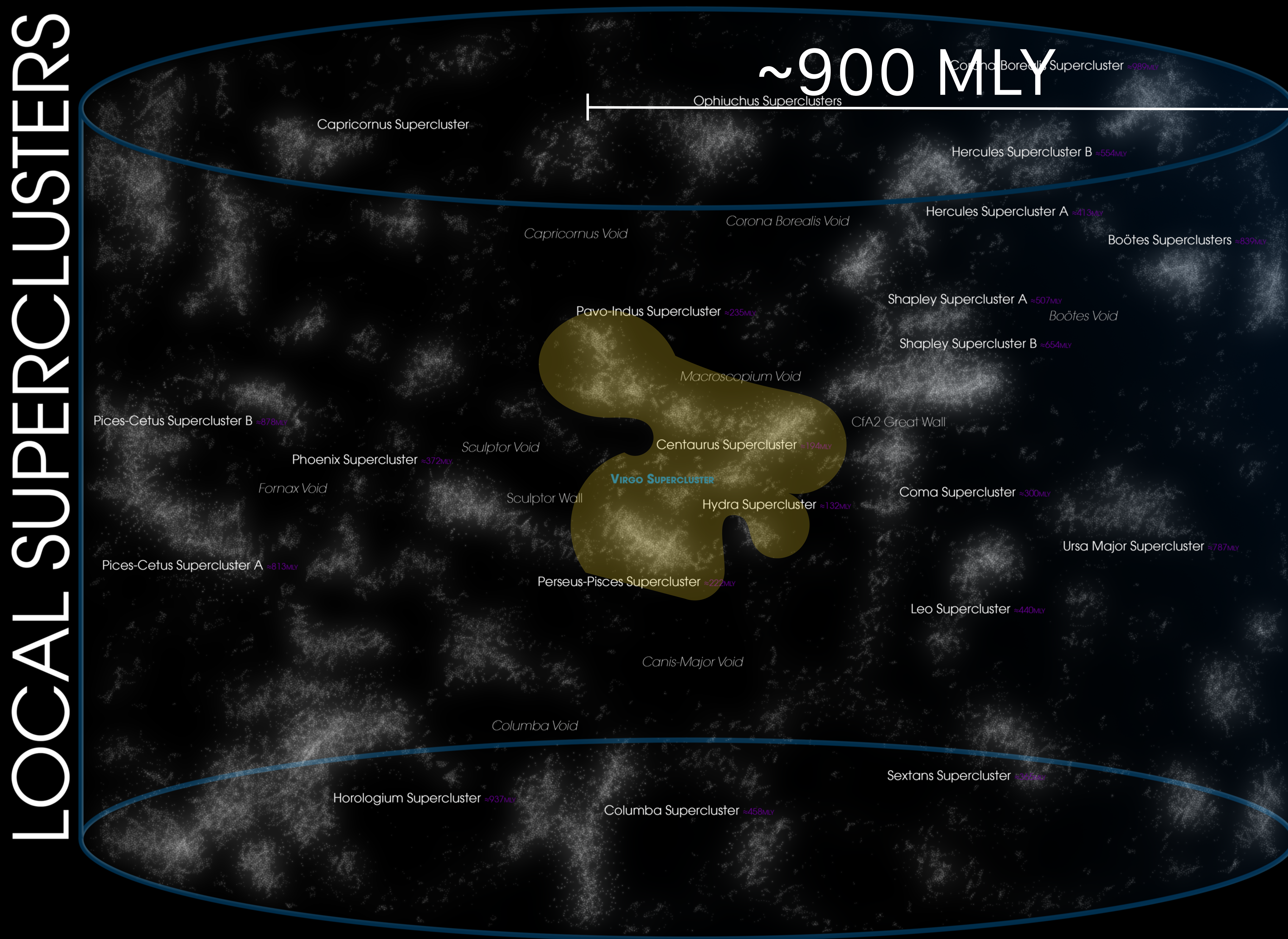
from:

Paper-and-pencil cosmological calculator

Sergey V. Pilipenko






LOCAL SUPERCLUSTERS
~900 MLY
Corona Borealis Supercluster ≈989MLY
Ophiuchus Superclusters
Capricornus Supercluster
Hercules Supercluster B ≈554MLY
Hercules Supercluster A ≈413MLY
Corona Borealis Void
Capricornus Void
Boötes Superclusters ≈839MLY
Shapley Supercluster A ≈507MLY
Boötes Void
Pavo-Indus Supercluster ≈235MLY
Shapley Supercluster B ≈654MLY
Macroscopium Void
Pices-Cetus Supercluster B ≈878MLY
CfA2 Great Wall
Sculptor Void
Centaurus Supercluster ≈194MLY
Phoenix Supercluster ≈372MLY
Virgo Supercluster
Fornax Void
Sculptor Wall
Hydra Supercluster ≈132MLY
Coma Supercluster ≈300MLY
Ursa Major Supercluster ≈787MLY
Pices-Cetus Supercluster A ≈813MLY
Perseus-Pisces Supercluster ≈222MLY
Leo Supercluster ≈440MLY
Canis-Major Void
Columba Void
Sextans Supercluster
Horologium Supercluster ≈937MLY
Columba Supercluster ≈458MLY

from:

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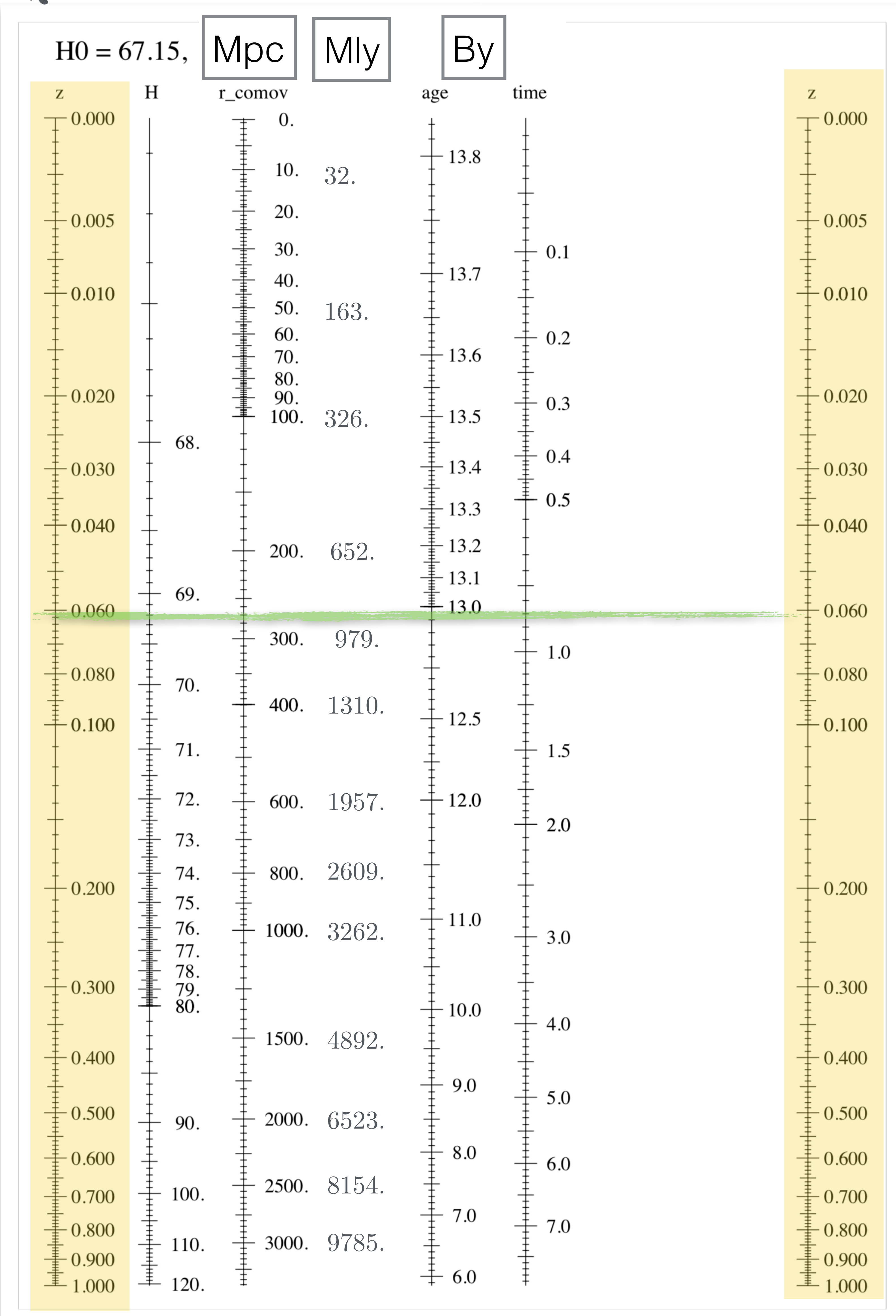
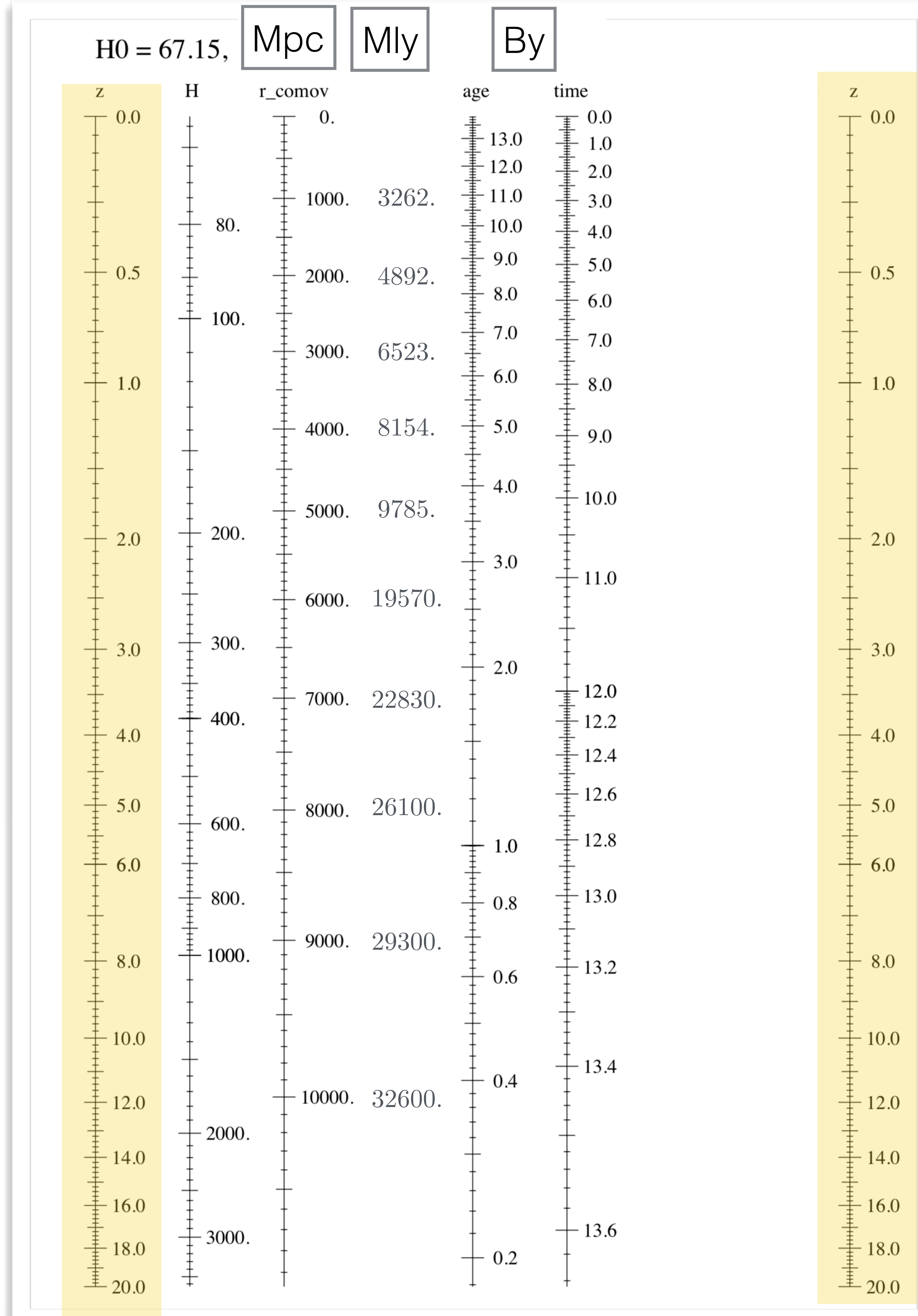
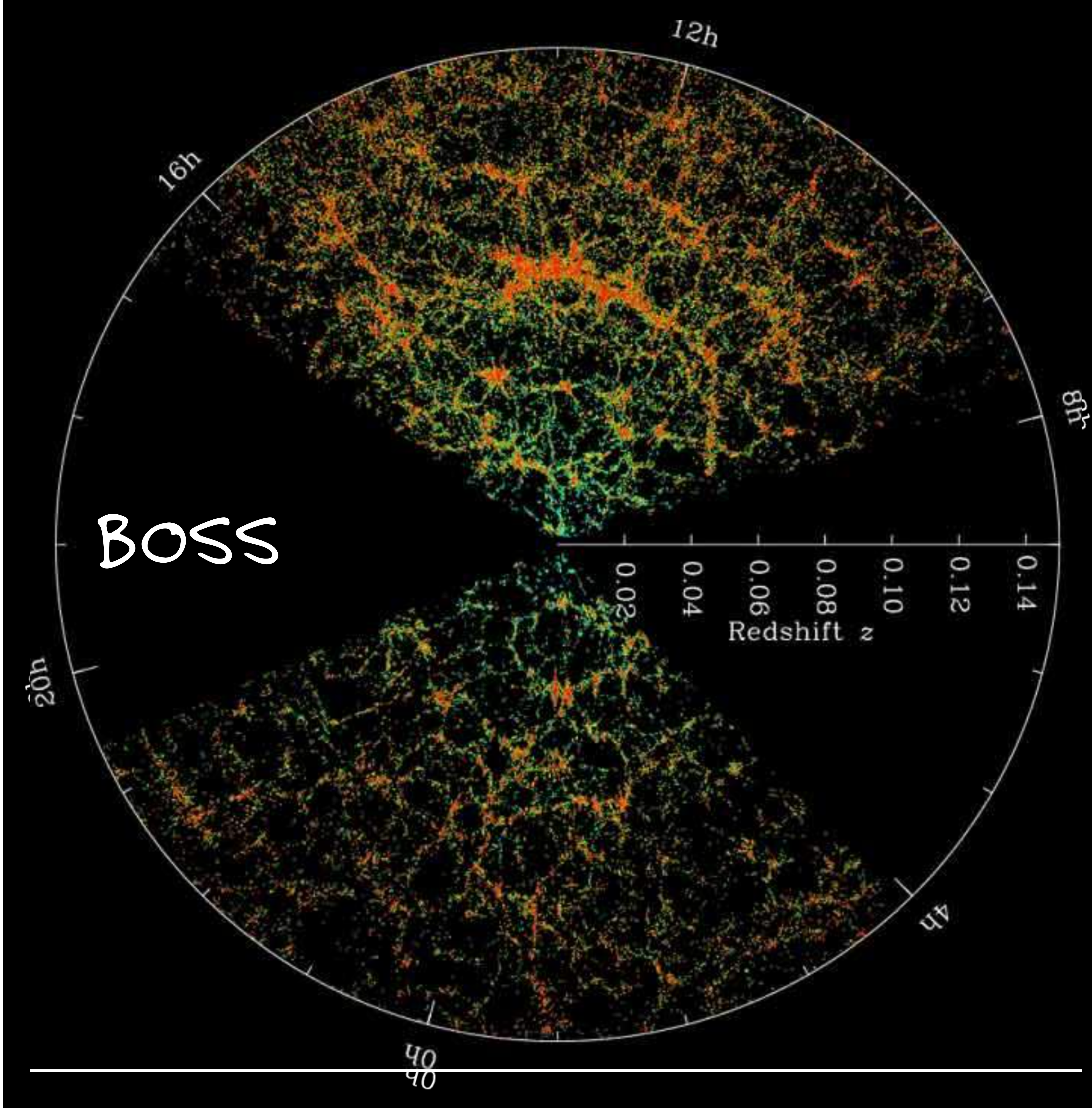




Sloan Digital Sky Survey

Apache Point, New Mexico



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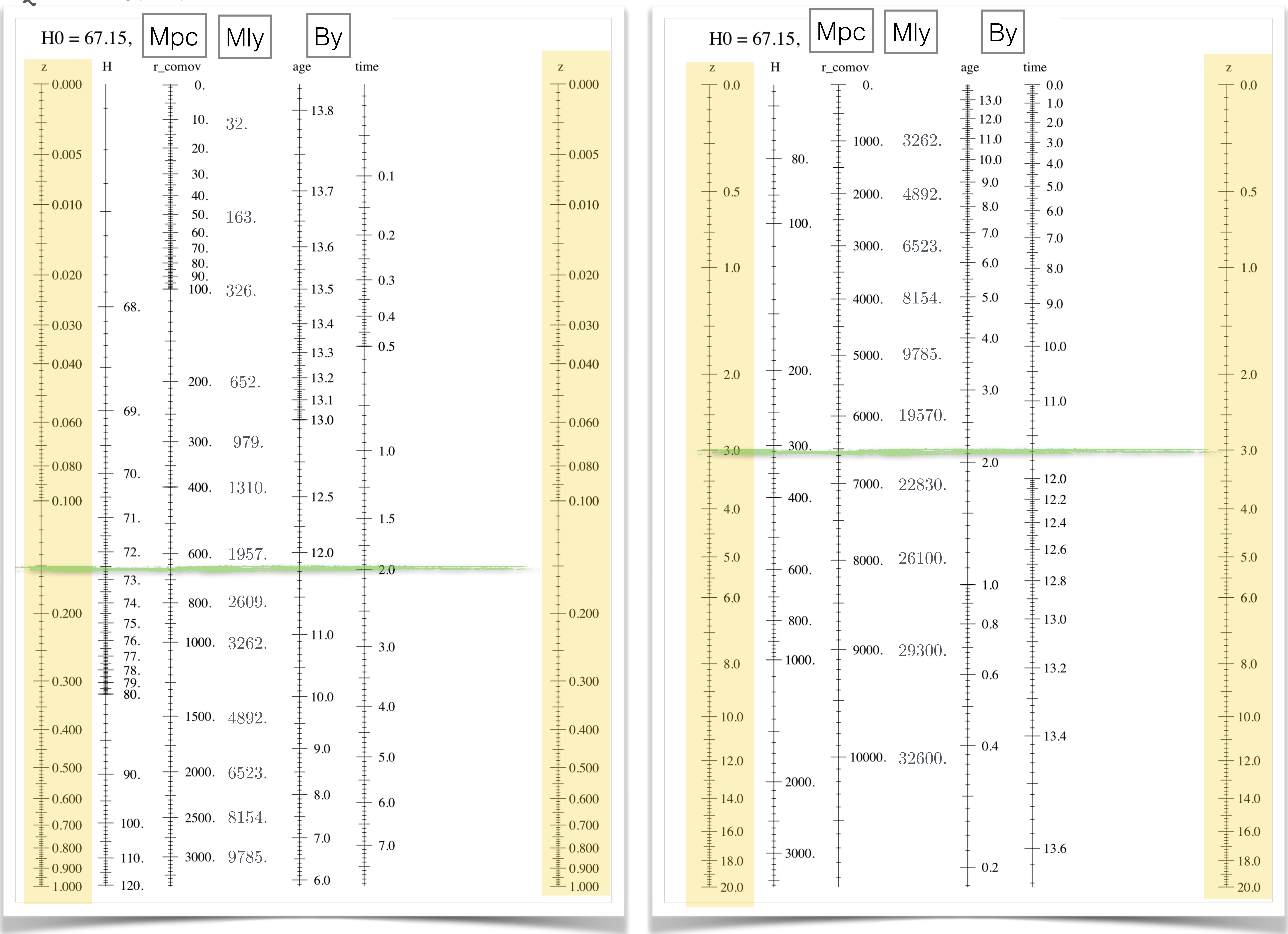


fly-through of original SDSS, z=0.1

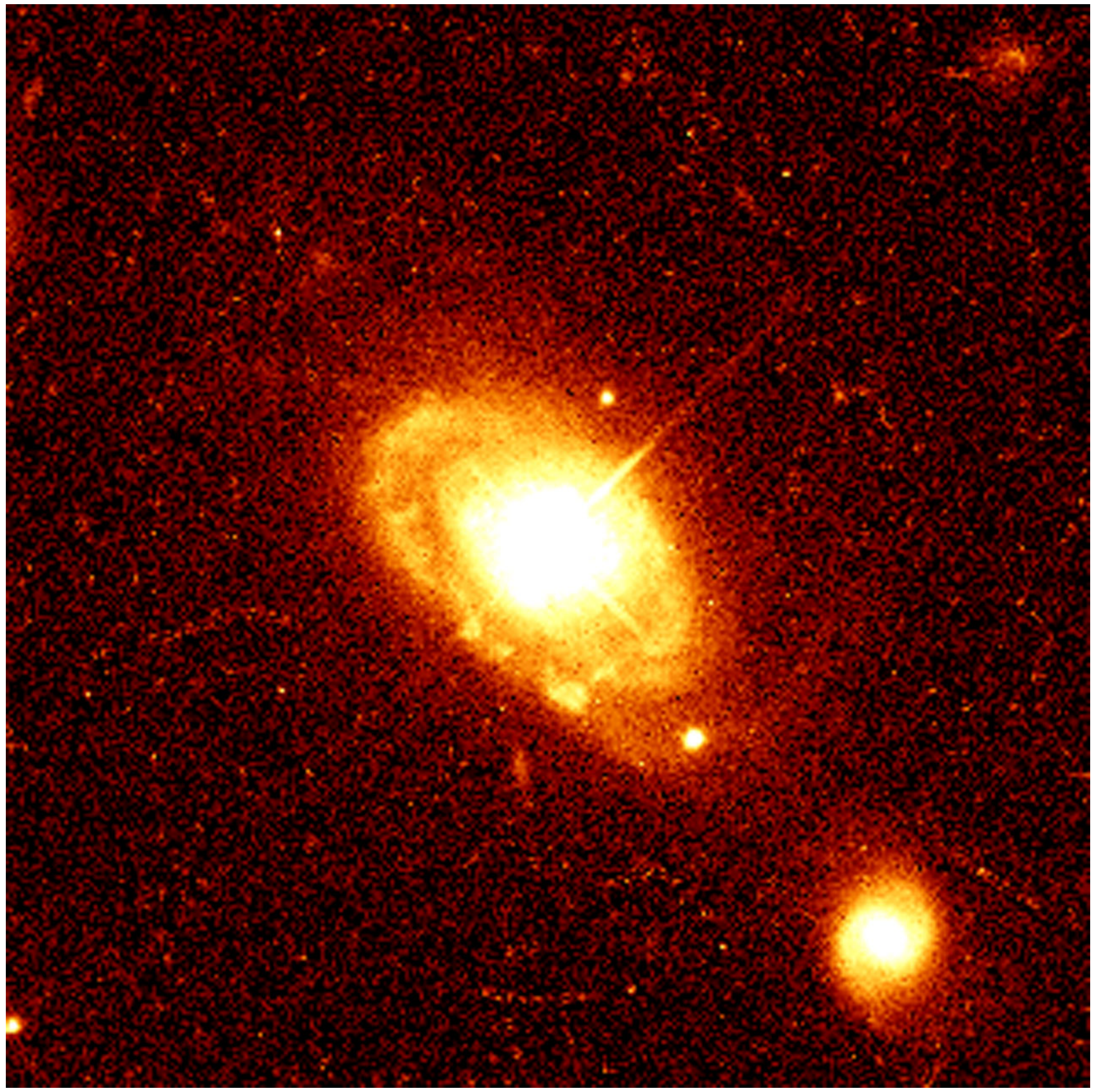
~ 1.4 BLy

‘‘quasars’’

“Quasi-stellar object”

very distant “AGN”…active galactic nucleus

extremely energetic black hole environment “radiation”

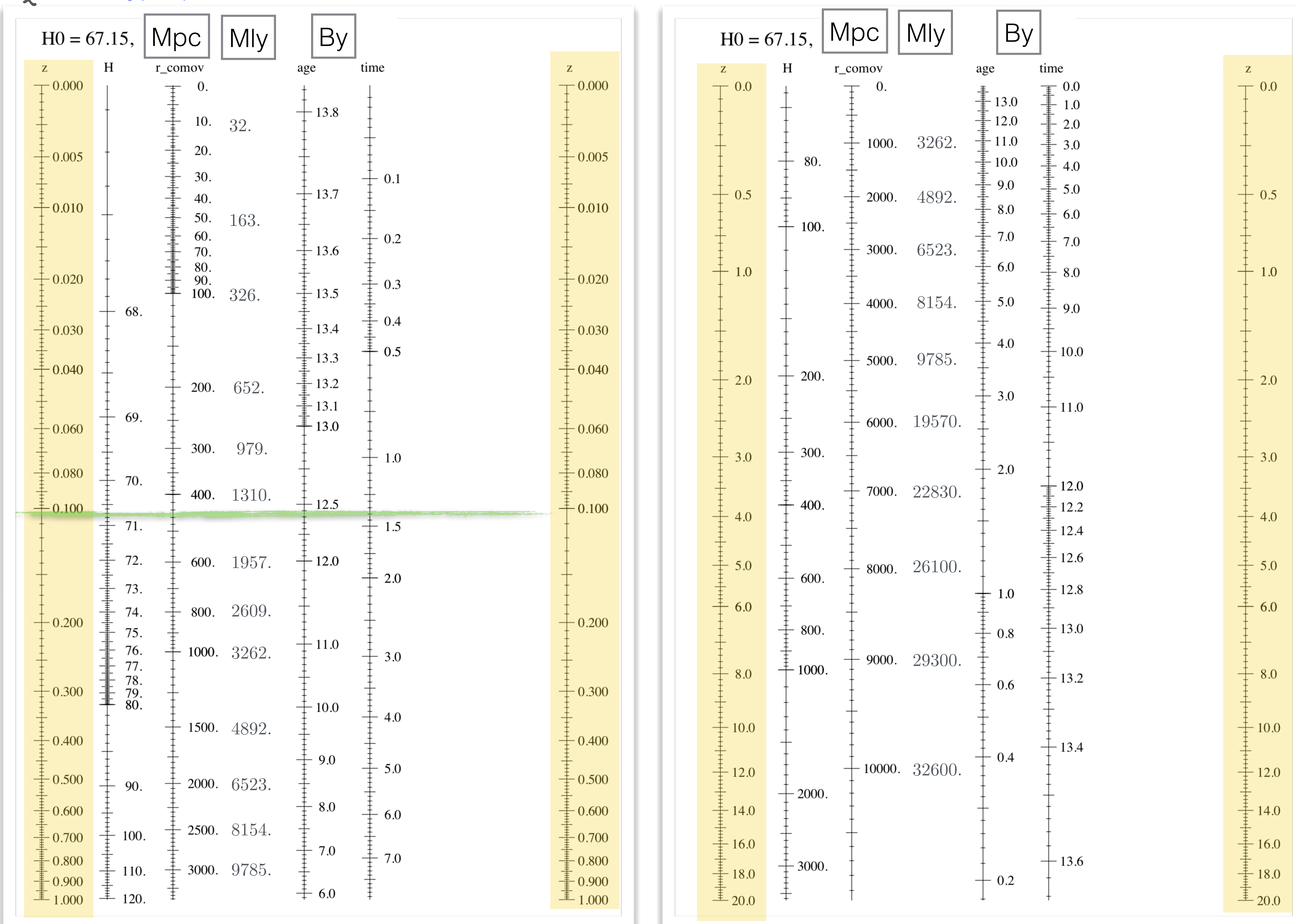


quasar PG 0052+251
1.4 BLy

from:

Paper-and-pencil cosmological calculator

Sergey V. Pilipenko



‘‘quasars’’

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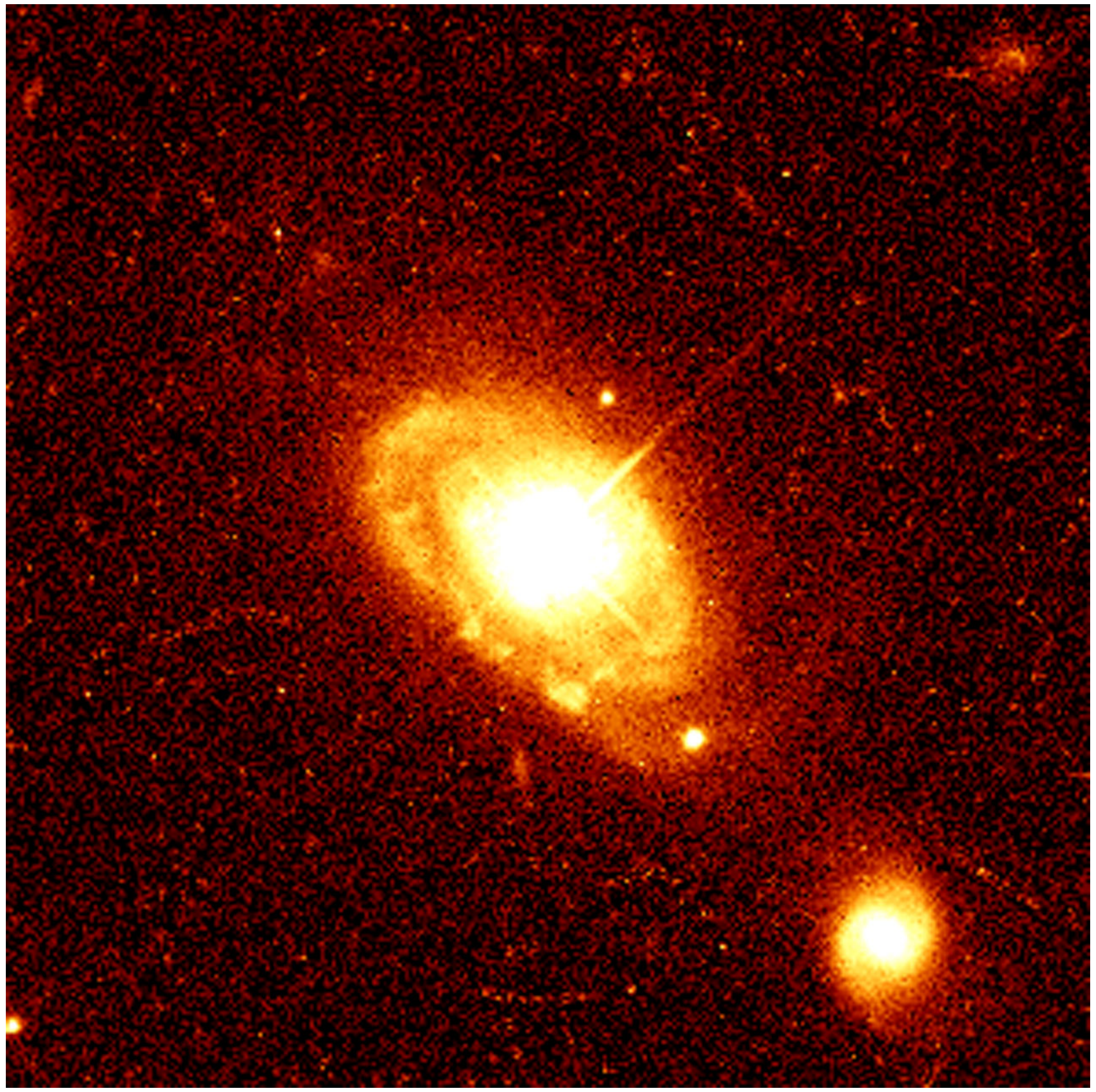


quasar PG 0052+251

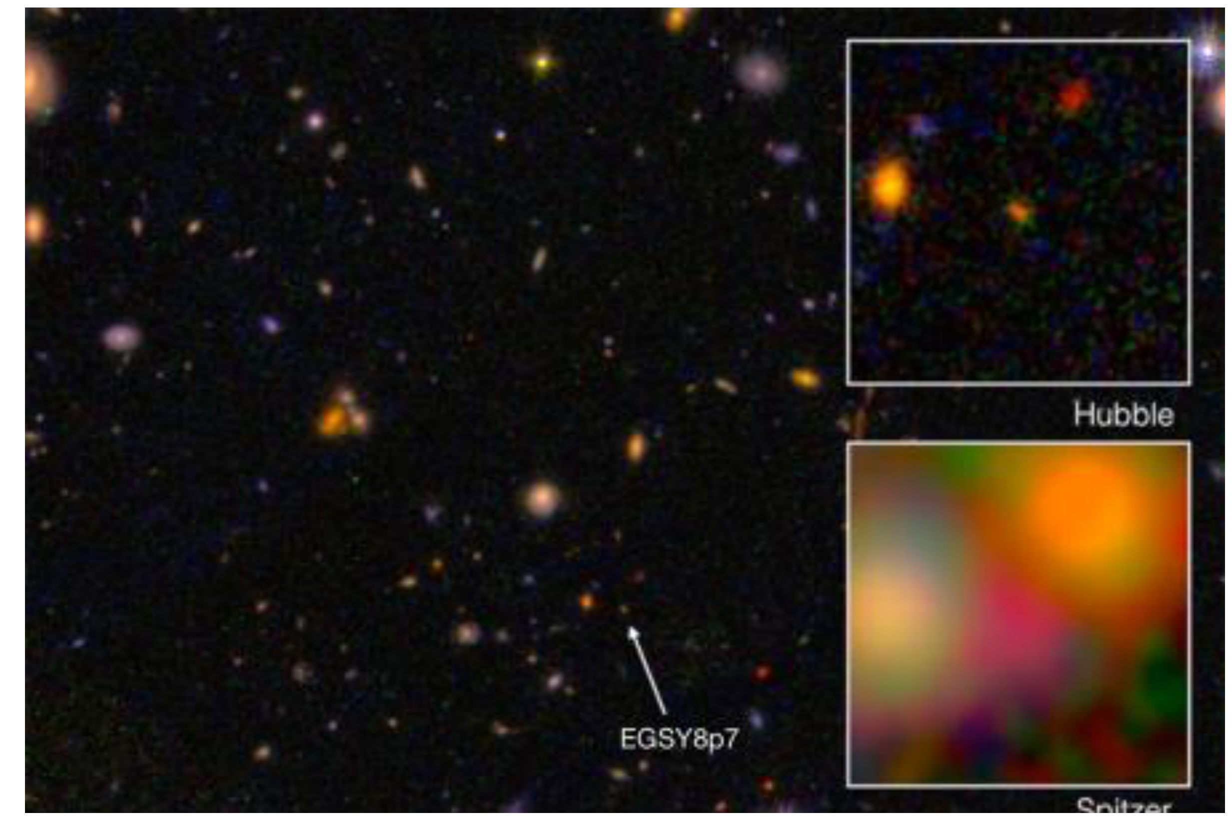
1.4 BLy

so, $z \sim 0.1$

h o w   l o w   c a n   y o u   g o

The record: September, 2015.

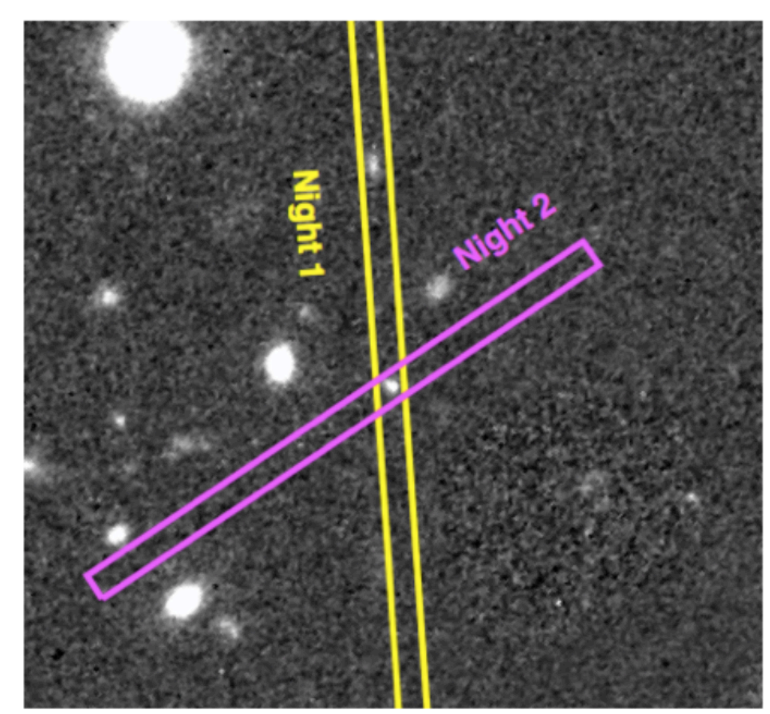
EGS8p7...$z = 8.68$

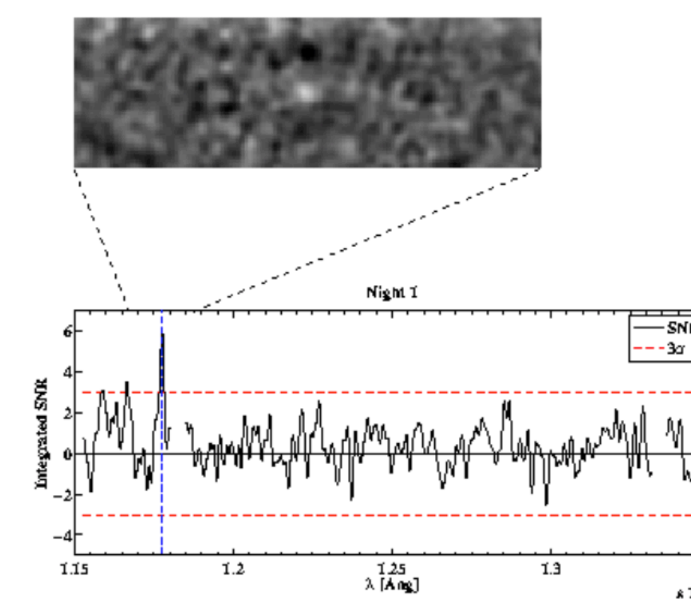


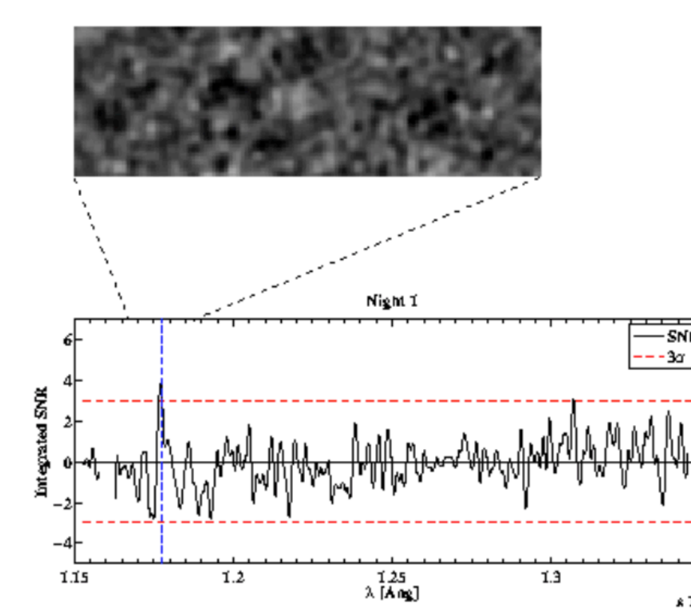
wavelength observed now

$$\frac{\lambda_0}{\lambda_e} = 1 + z = 1 + 8.68 = 9.68$$

wavelength emitted then



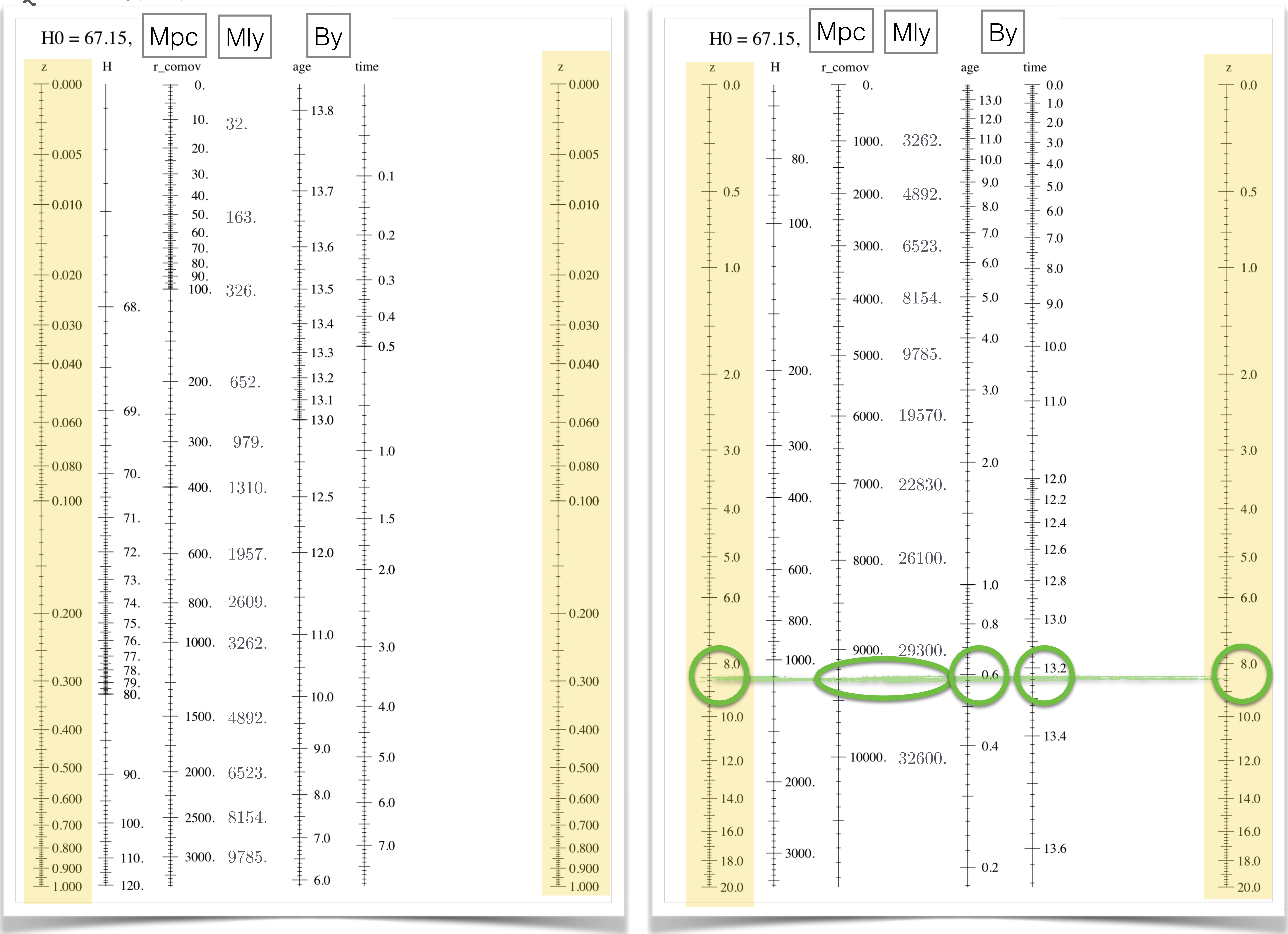




from:

Paper-and-pencil cosmological calculator

Sergey V. Pilipenko

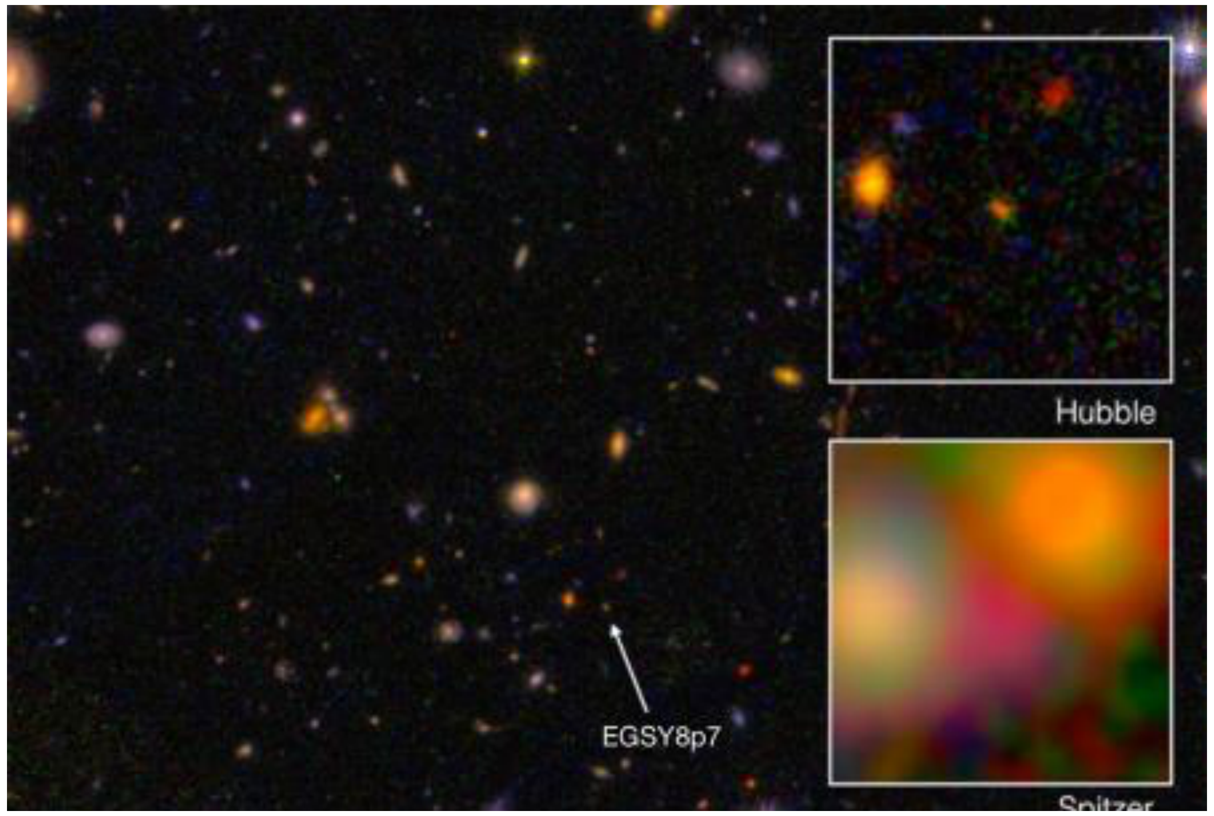


how low can you go

The record: September, 2015.

EGS8p7...z = 8.68

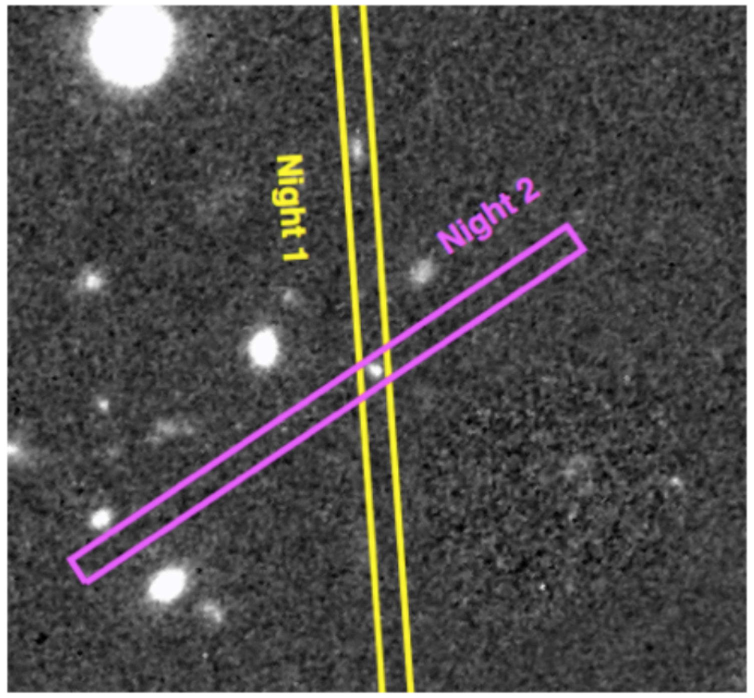
Light emitted 13.2 By ago

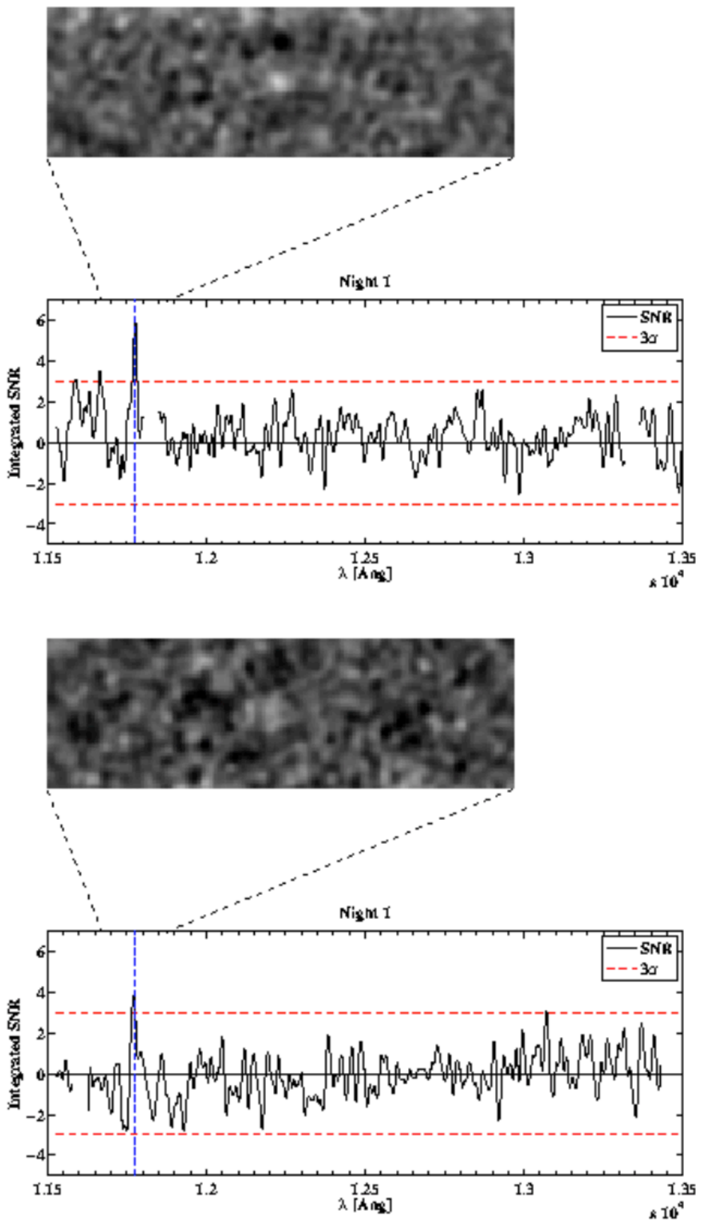


wavelength observed now

$$\frac{\lambda_0}{\lambda_e} = 1 + z = 1 + 8.68 = 9.68$$

wavelength emitted then





universe record-holder

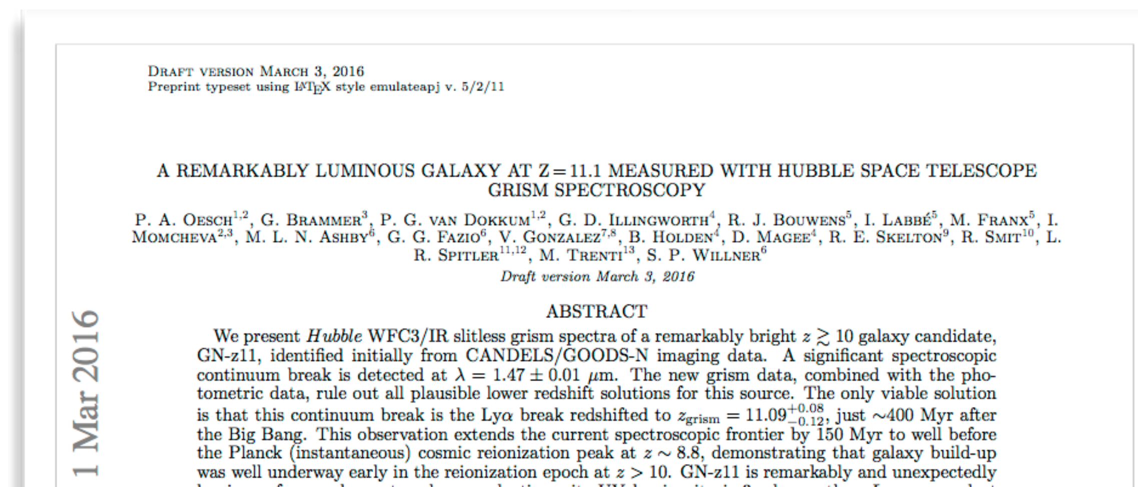
The record: March, 2016.

GN-z11...z = 11.1...

wavelength observed now

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

wavelength emitted then



Draft version March 3, 2016
Preprint typeset using LaTeX style emulateapj v. 5/2/11

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

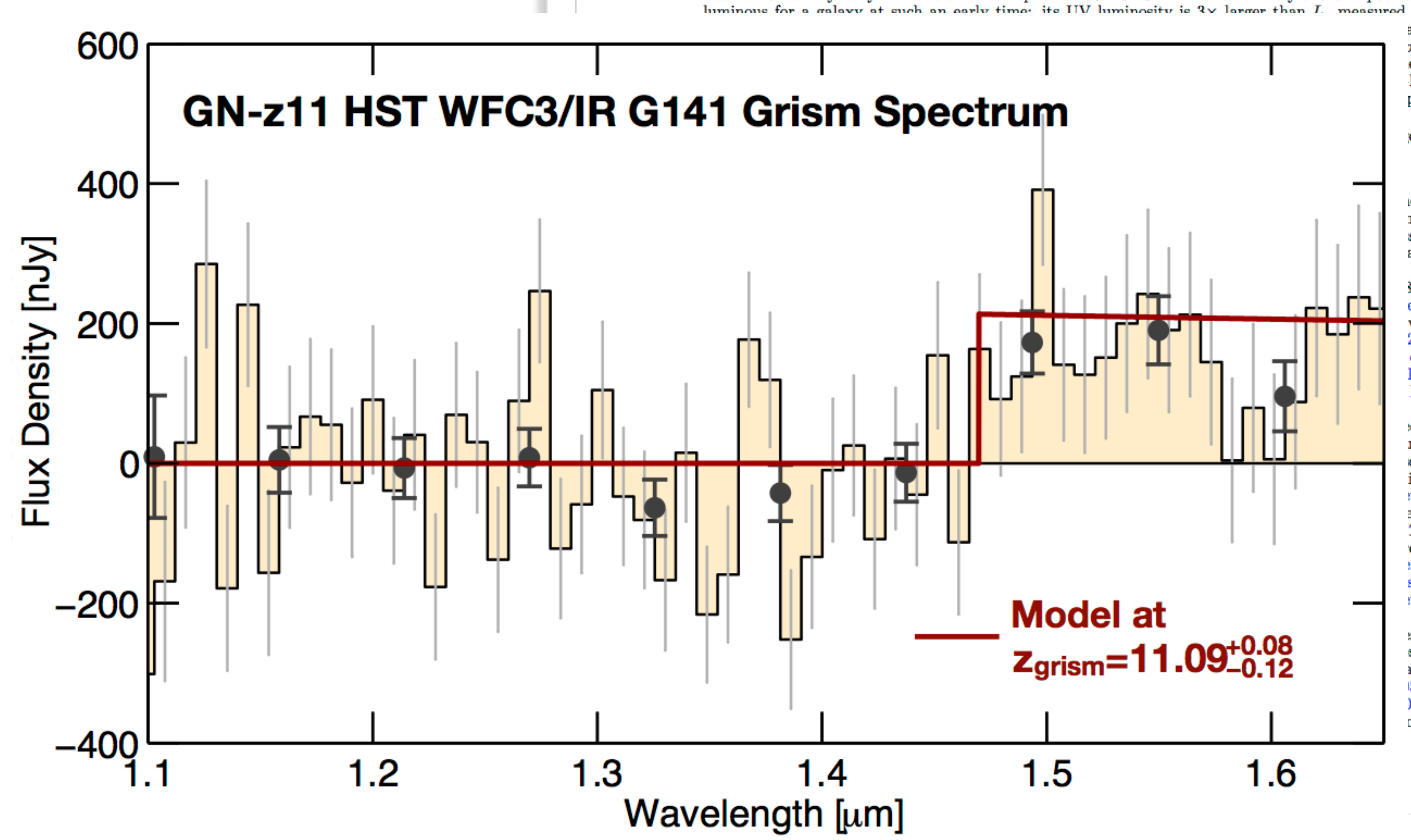
P. A. Oesch[1,2], G. Brammer[3], P. G. van Dokkum[1,2], G. D. Illingworth[4], R. J. Bouwens[5], I. Labbé[5], M. Franx[5], I. Momcheva[2,3], M. L. N. Ashby[6], G. G. Fazio[6], V. Gonzalez[7,8], B. Holden[4], D. Magee[4], R. E. Skelton[9], R. Smit[10], L. R. Spitler[11,12], M. Trenti[13], S. P. Willner[6]

Draft version March 3, 2016

1 Mar 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 $z_{\rm grism} = 11.09^{+0.08}_{-0.12}$, 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



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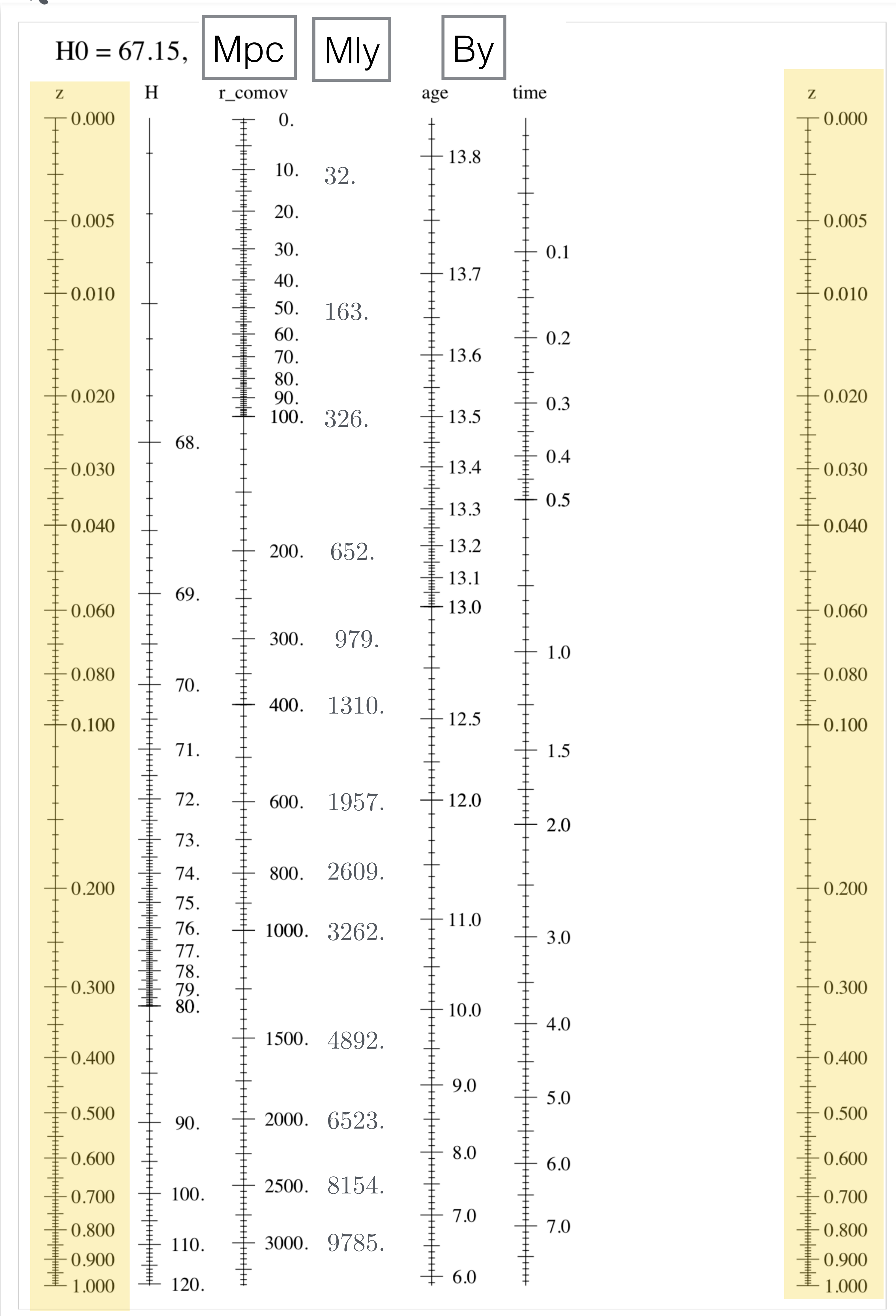
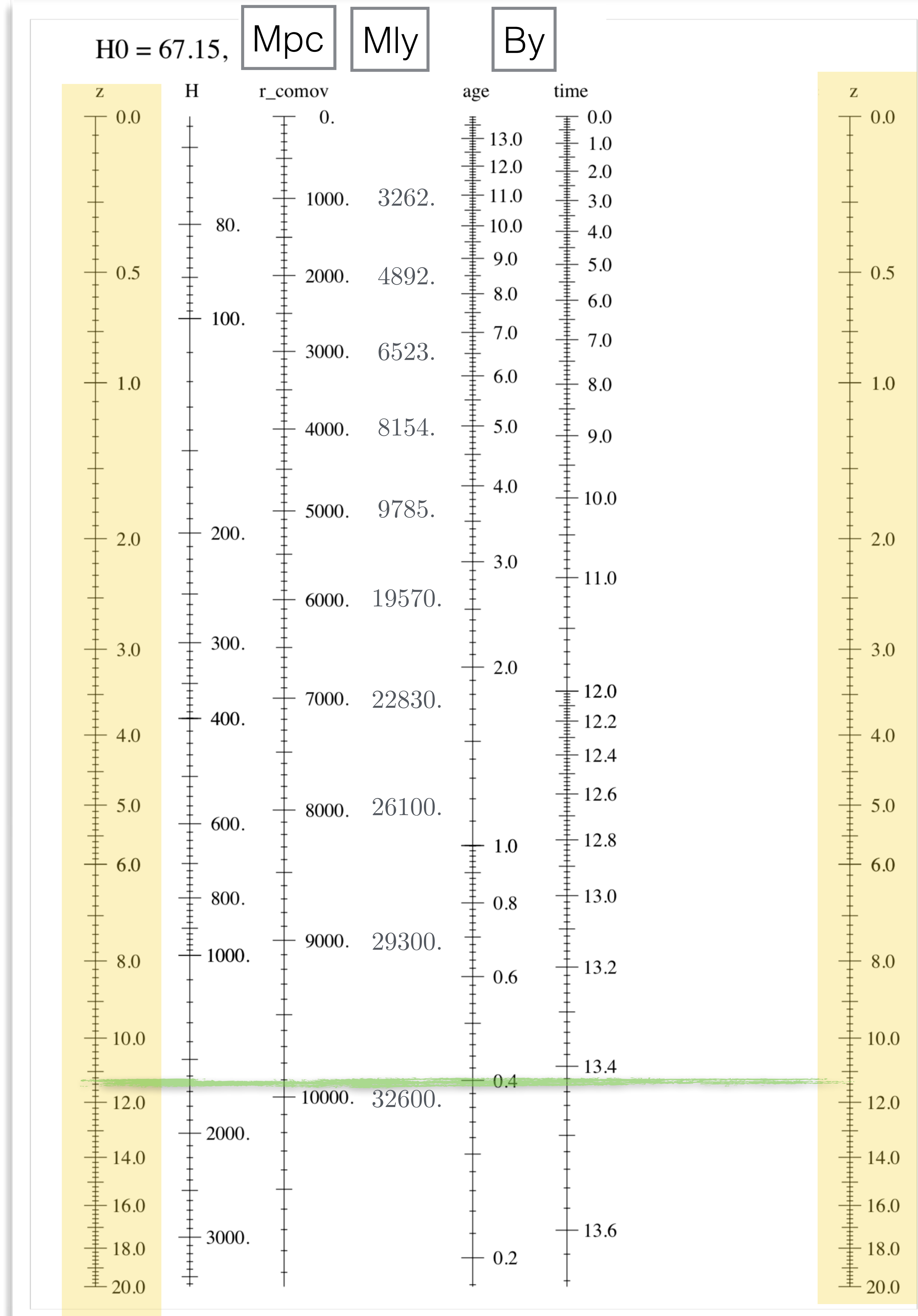
Paper-and-pencil cosmological calculator

Sergey V. Pilipenko





universe record-holder

The record: March, 2016.

GN-z11...z = 11.1...so $\beta = 0.986$!

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!

DRAFT VERSION MARCH 3, 2016
Preprint typeset using LaTeX style emulateapj v. 5/2/11

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

P. A. OESCH[1,2], G. BRAMMER[3], P. G. VAN DOKKUM[1,2], G. D. ILLINGWORTH[4], R. J. BOUWENS[5], I. LABBÉ[5], M. FRANX[5], I. MOMCHEVA[2,3], M. L. N. ASHBY[6], G. G. FAZIO[6], V. GONZALEZ[7,8], B. HOLDEN[4], D. MAGEE[4], R. E. SKELTON[9], R. SMIT[10], L. R. SPITLER[11,12], M. TRENTI[13], S. P. WILLNER[6]

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 $\lambda = 1.47 \pm 0.01\ \mu m$. 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 $z_{grism} = 11.09^{+0.08}_{-0.12}$, 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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[5] Leiden Observatory, Leiden University, NL-2300 RA Leiden, The Netherlands
[6] Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
[7] Departamento de Astronomia, Universidad de Chile, Casilla 36-D, Santiago, Chile
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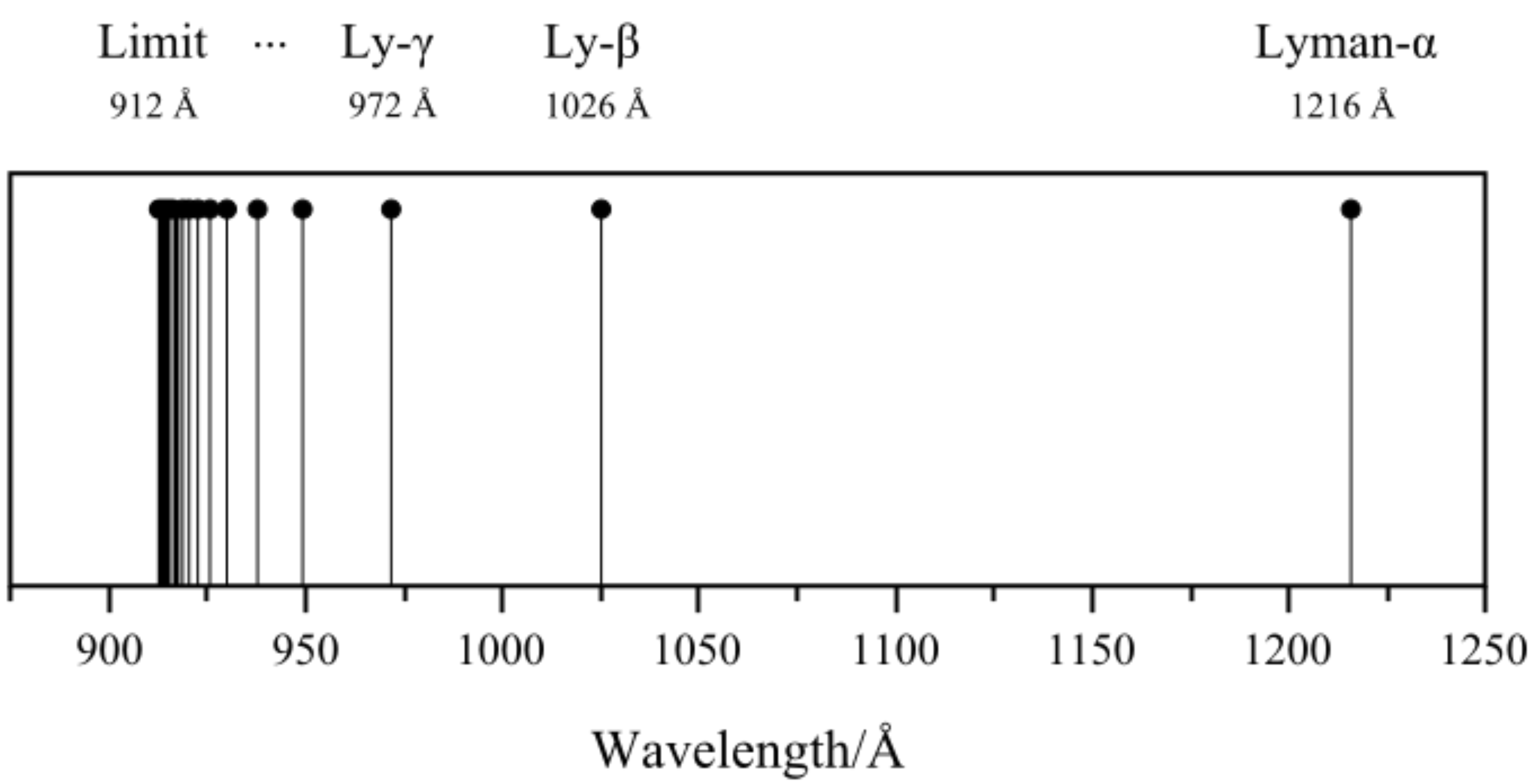
[9] South African Astronomical Observatory, P.O. Box 9, Observatory 7935, South Africa
[10] Department of Physics, Durham University, South Road, Durham DH1 3LE, UK
[11] Department of Physics and Astronomy, Faculty of Sciences, Macquarie University, Sydney, NSW 2109, Australia
[12] Australian Astronomical Observatory, P.O. Box 915, North Ryde, NSW 1670, Australia
[13] School of Physics, University of Melbourne, Parkville 3010, VIC, Australia

example quasar

J006.1240+39.2219



now you do it:

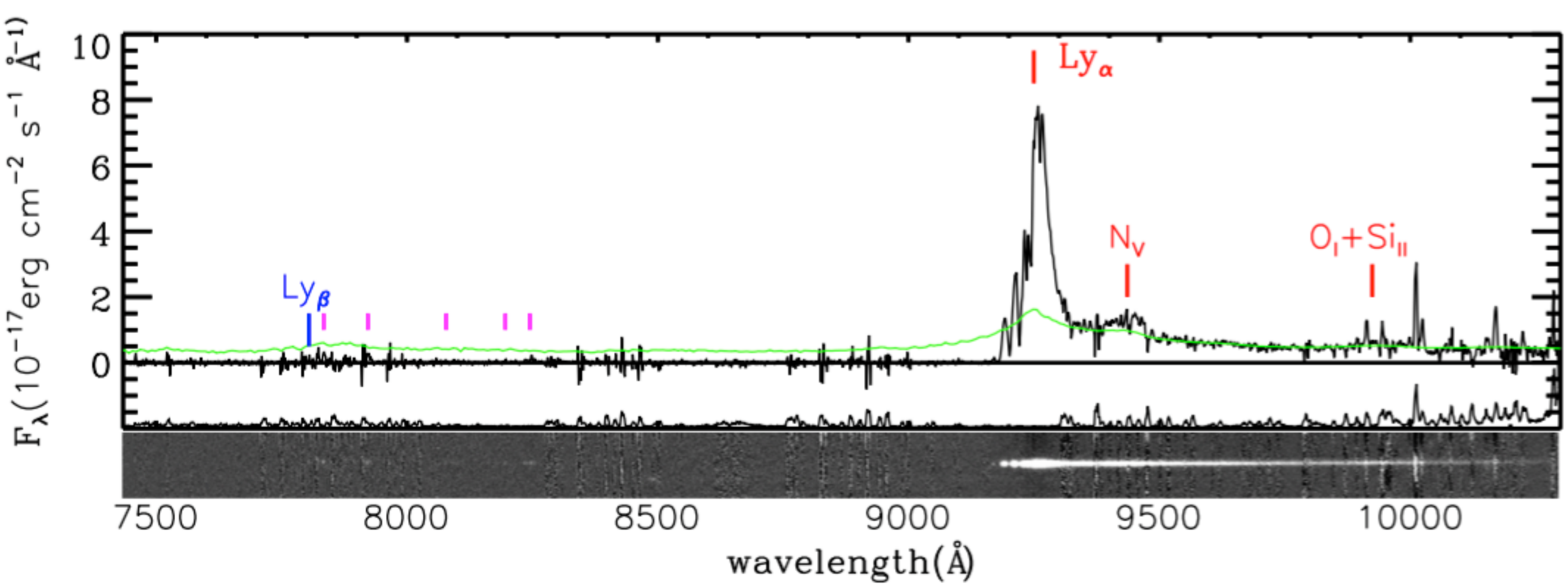
next Homework

what's the red shift?

what's the expansion factor?

how far away?

how old when it released the light?



The Friedman, Walker, Robertson models

Their model of cosmology is variously called the:

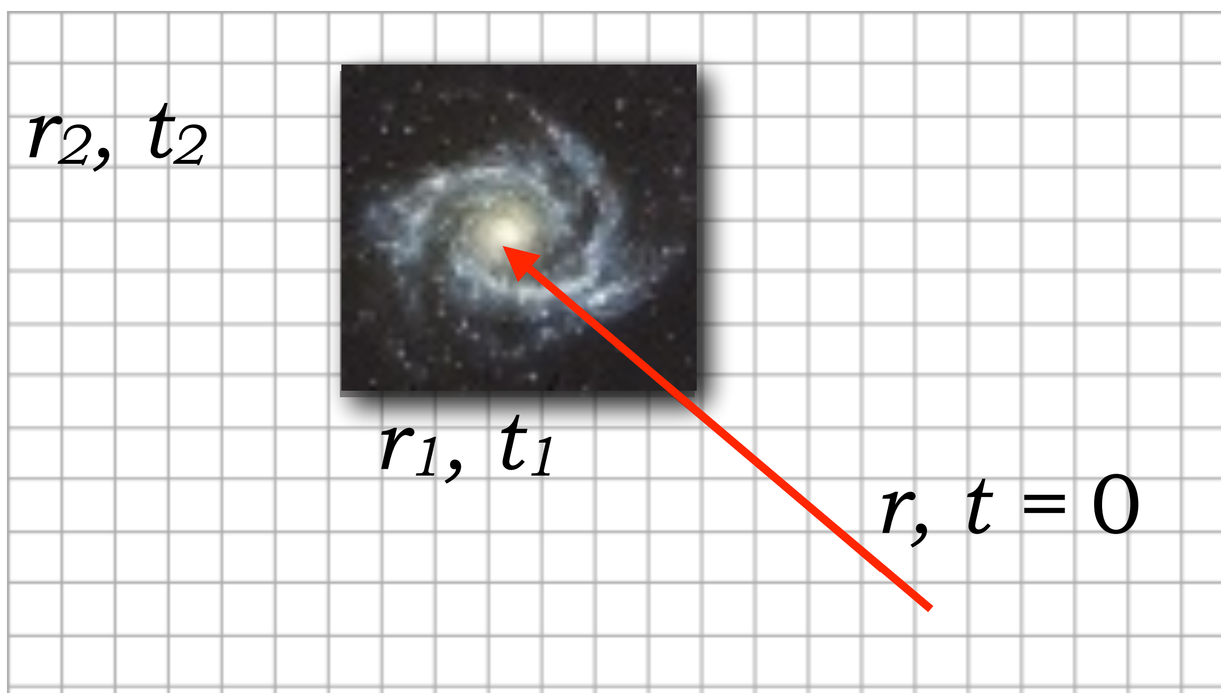
Friedman, Walker, Robertson (**FWR)** model

Friedman, Lemaitre, Walker, Robertson **FLWR** model

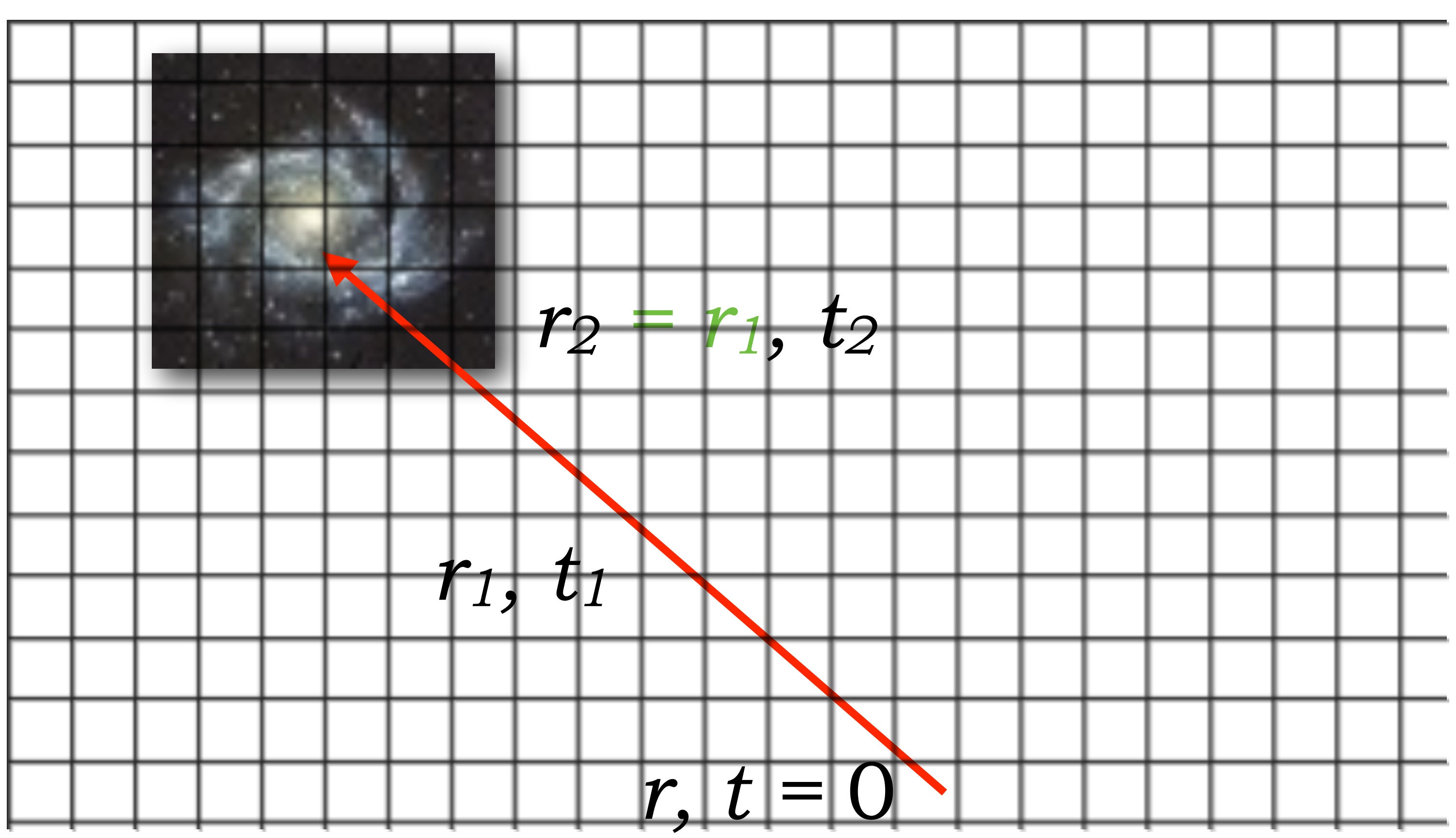
Standard Model of Cosmology

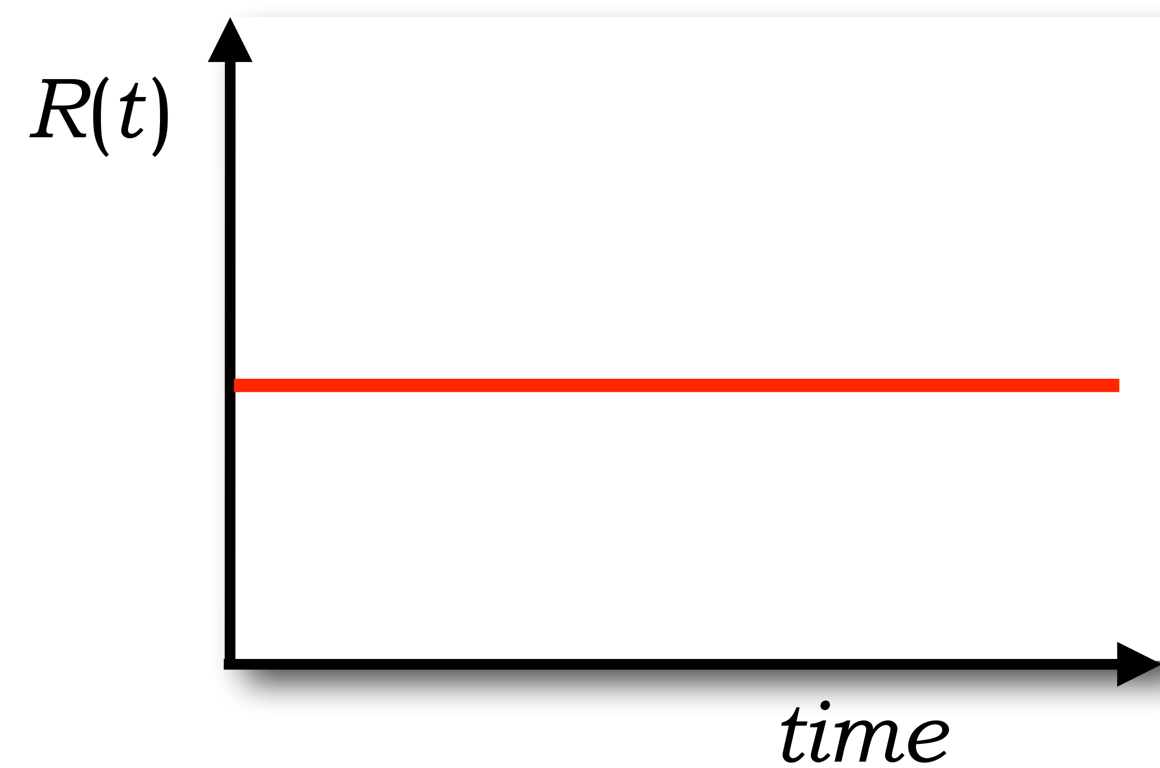
Einstein's original model

It's like...we can watch galaxies move away. Not really, but we can look at many galaxies at different distances...and model their expansions



What did Einstein say would be the case?





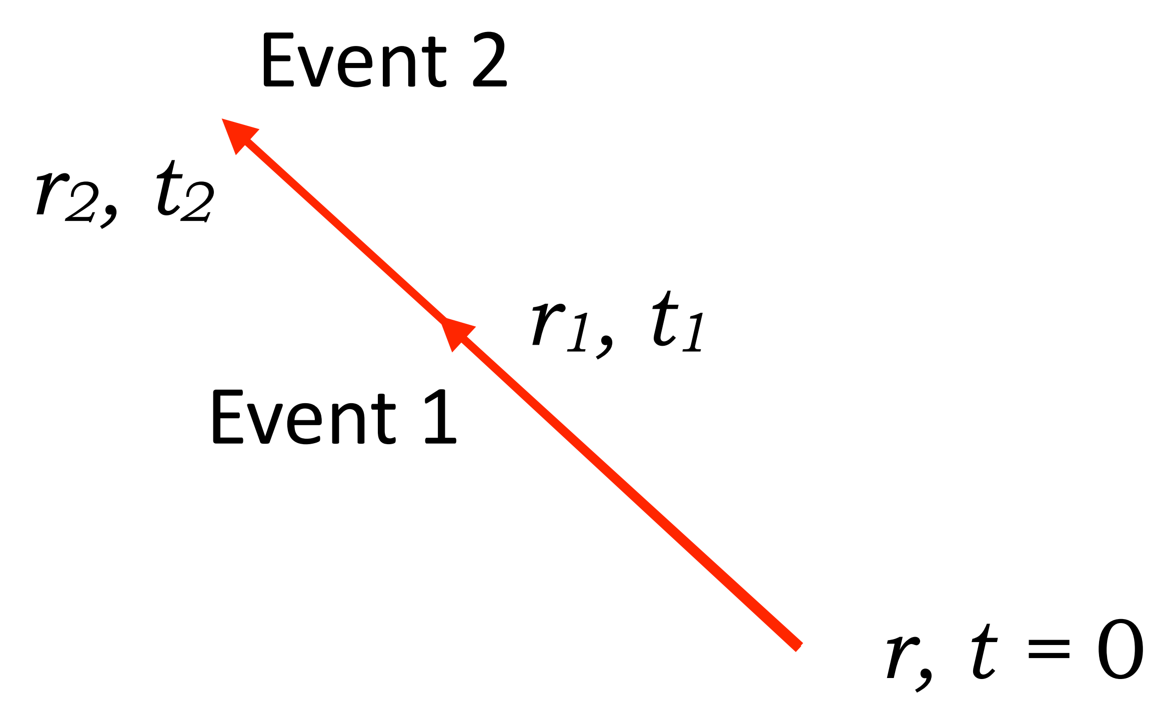
Static...for which he needed a particular value of the Cosmological Constant

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

the interval again - spacetime separation between two events.

In Special Relativity...which is flat spacetime:

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



In general:

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

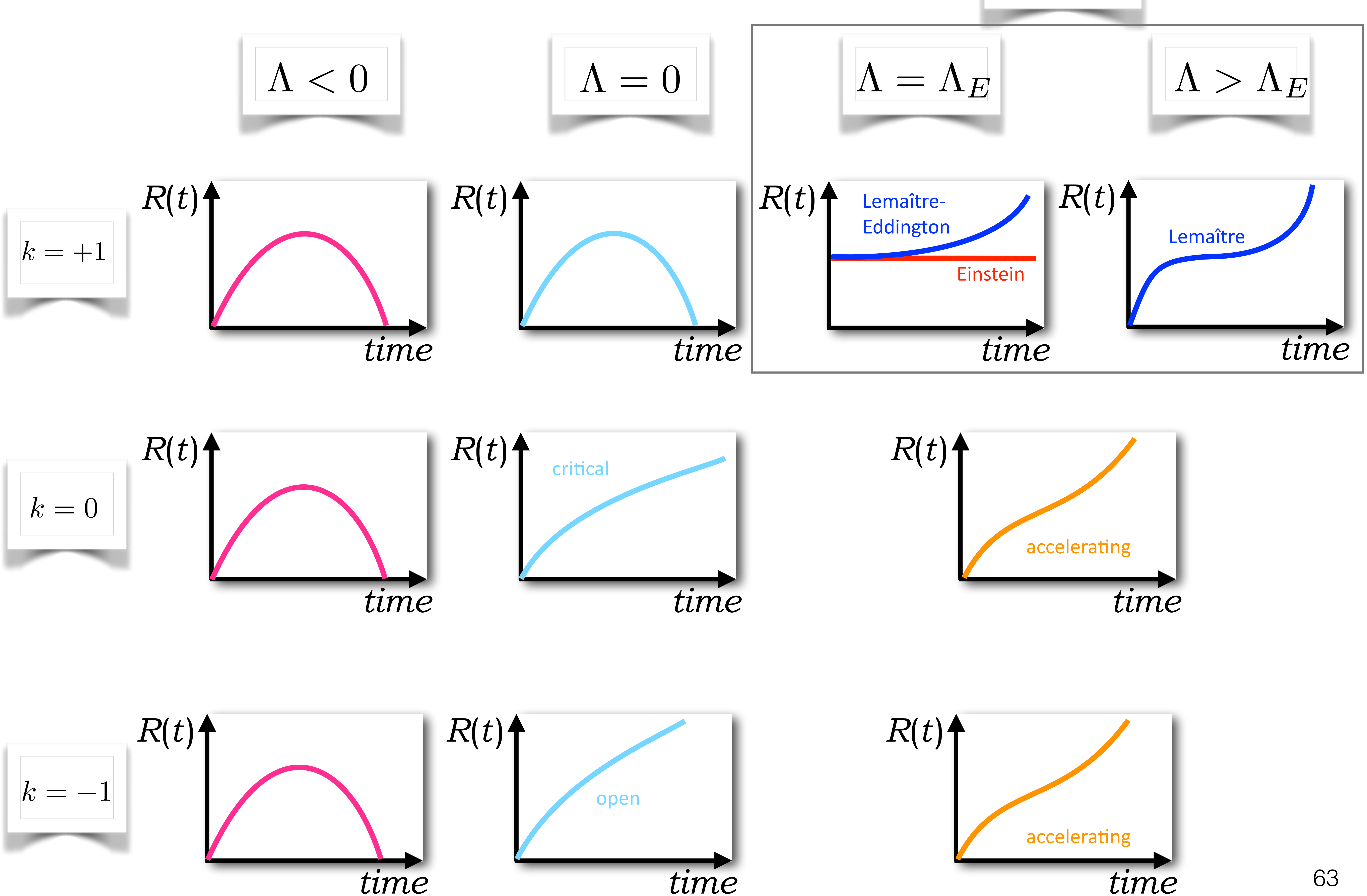
the time-dependent scale factor

For FLRW model, a parameterization:

$$\Delta s^2 = (c\Delta t)^2 - \frac{R^2(t)}{\left(1 + \frac{kr^2}{4}\right)^2}(\Delta r)^2$$

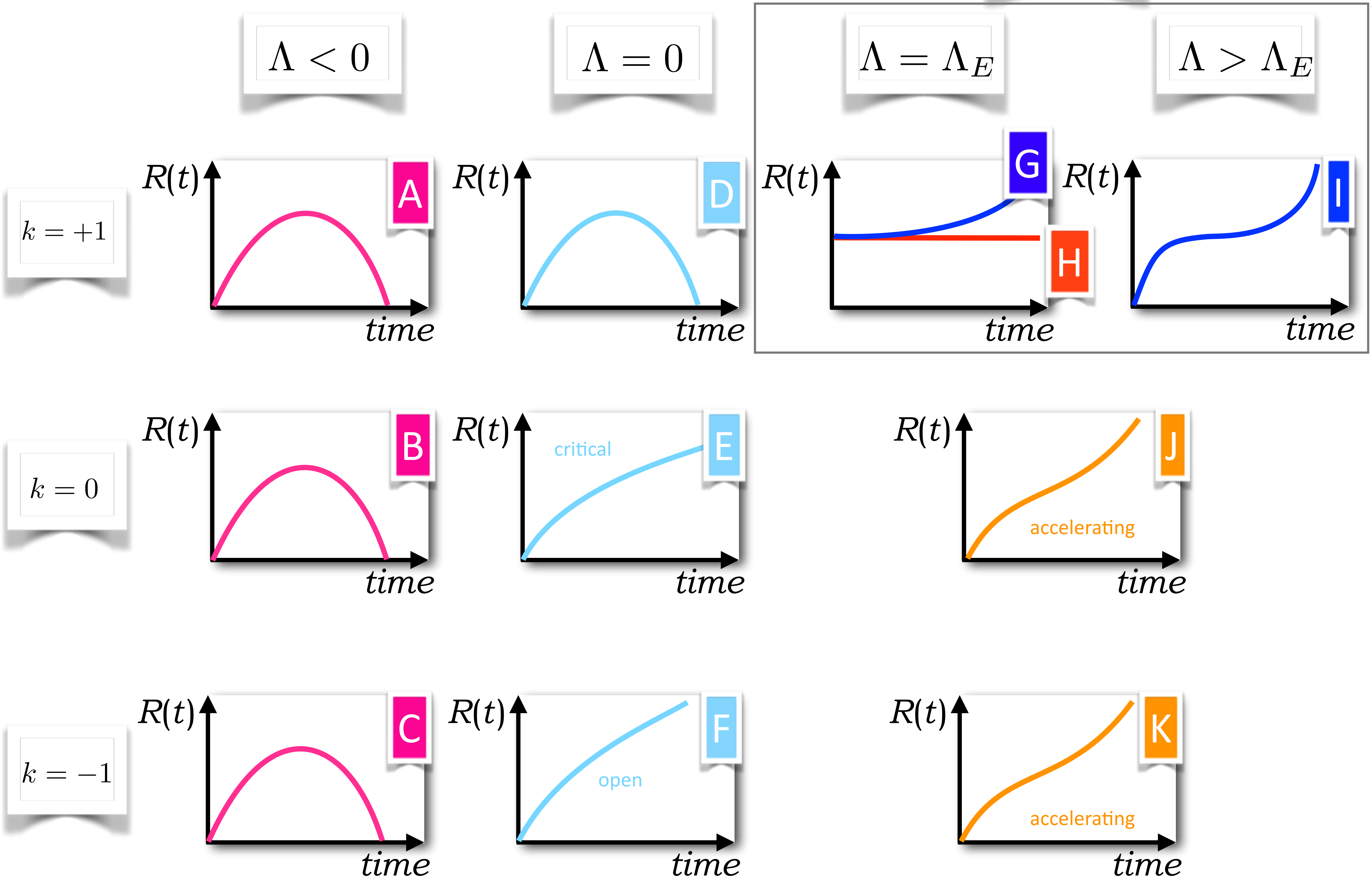
the curvature...

FLRW catalogue of Universes



FLRW catalogue of Universes

$\Lambda > 0$



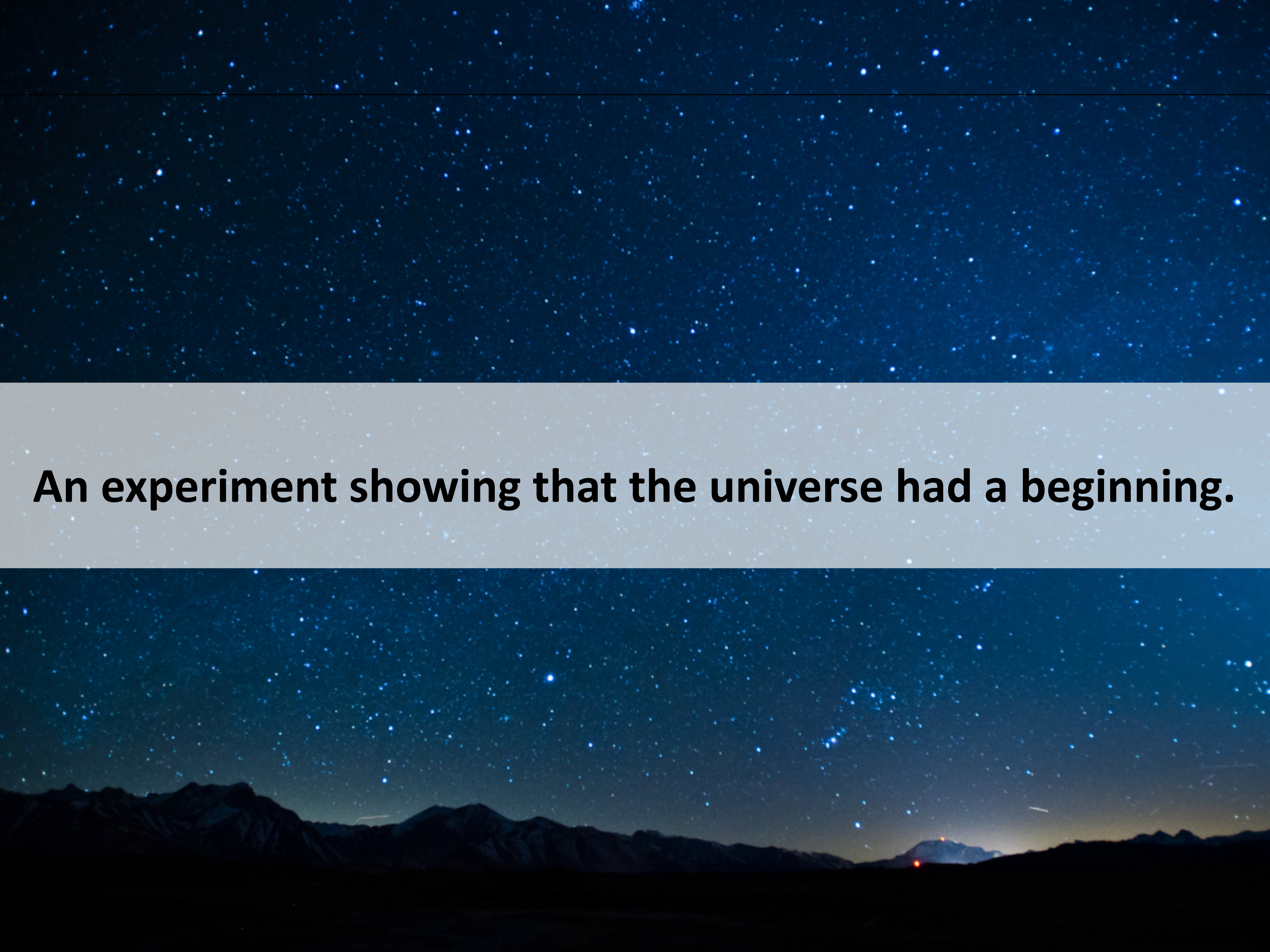
`which one is ours?`

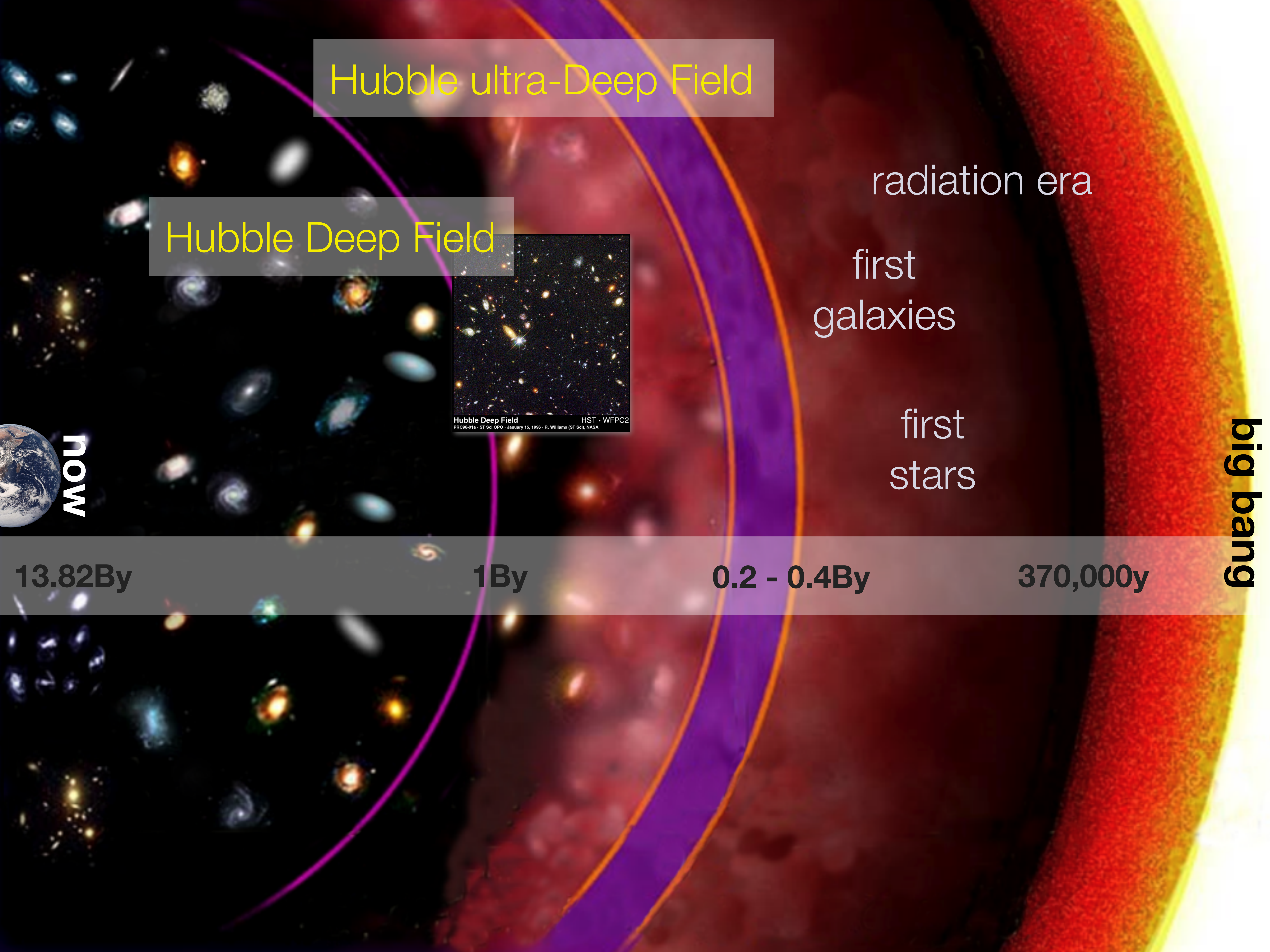
that’s the story of the last 3 decades

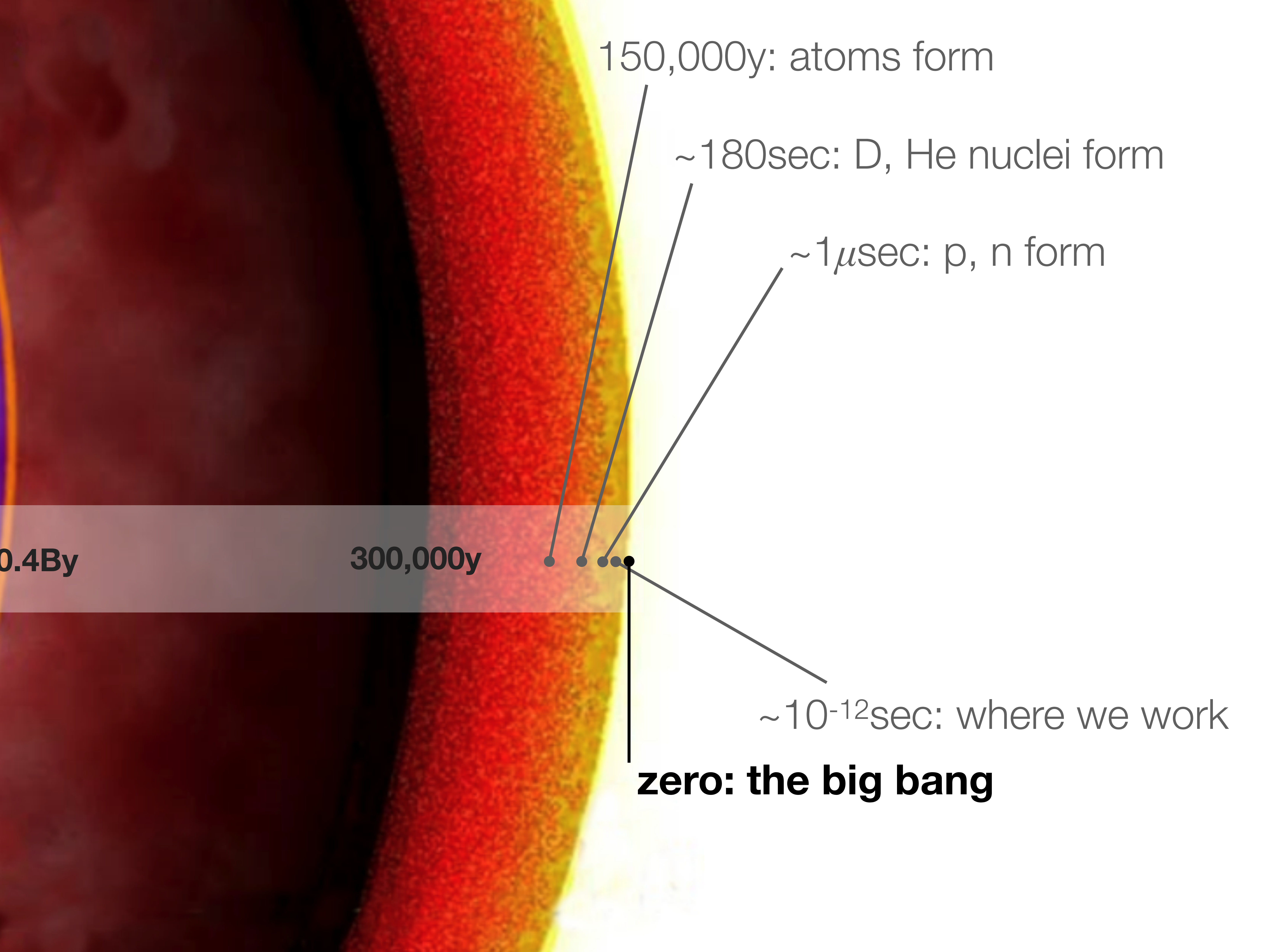
stay tuned

I see

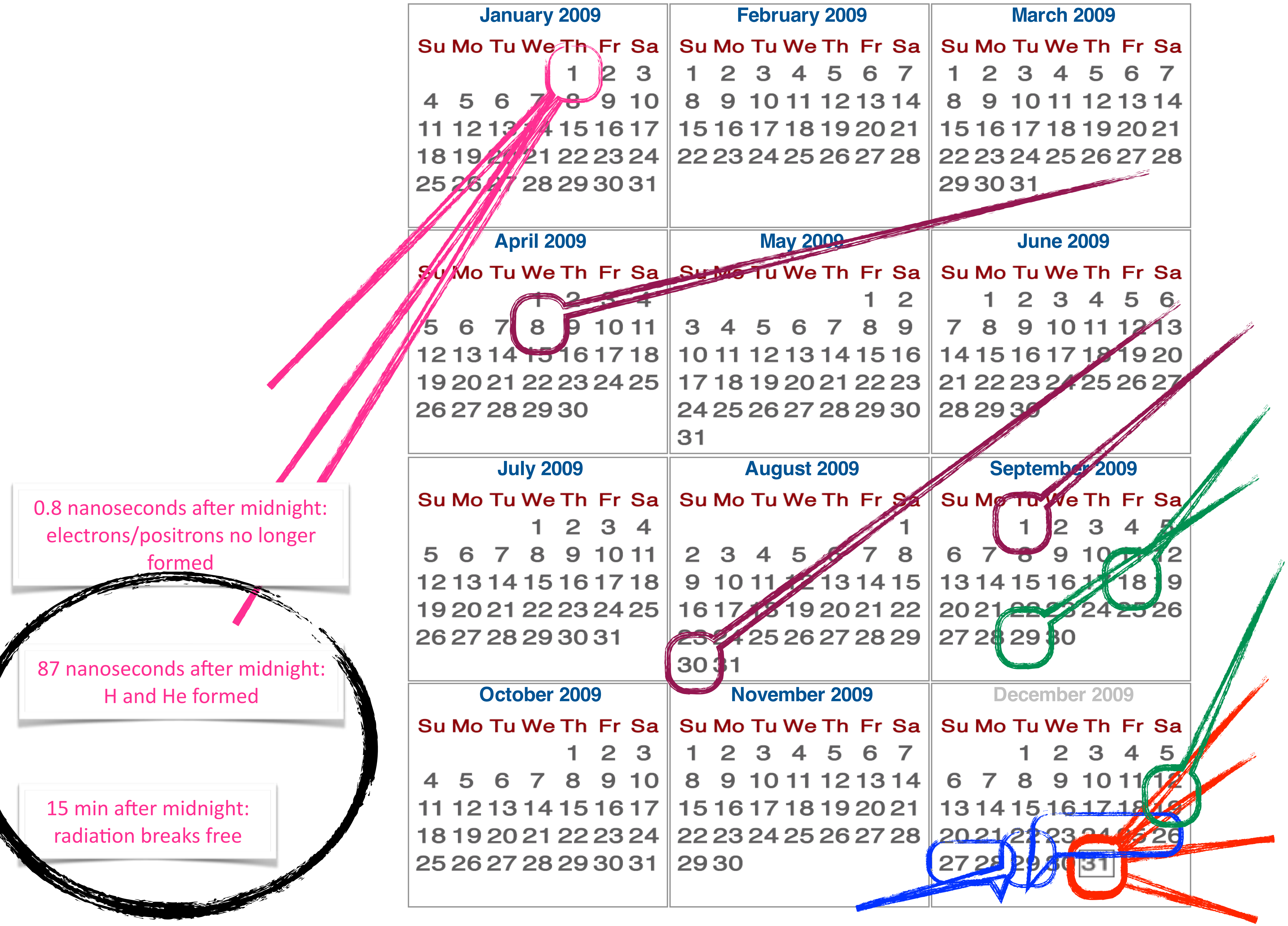
dead stars


An experiment showing that the universe had a beginning.


Hubble ultra-Deep Field
radiation era
Hubble Deep Field
first
galaxies
Hubble Deep Field
HST · WFPC2
first
stars
now
big bang
13.82By
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^{-12}sec: where we work
zero: the big bang

our cosmic calendar: 12 months = 13.8 By



0.8 nanoseconds after midnight: electrons/positrons no longer formed

87 nanoseconds after midnight: H and He formed

15 min after midnight: radiation breaks free

Milky Way disk

Sun

Earth

first cells

sponges

first plants

4.5 hr to midnight: early chimps

2.8 hr to midnight: australopithecus

14 min to midnight: neanderthal

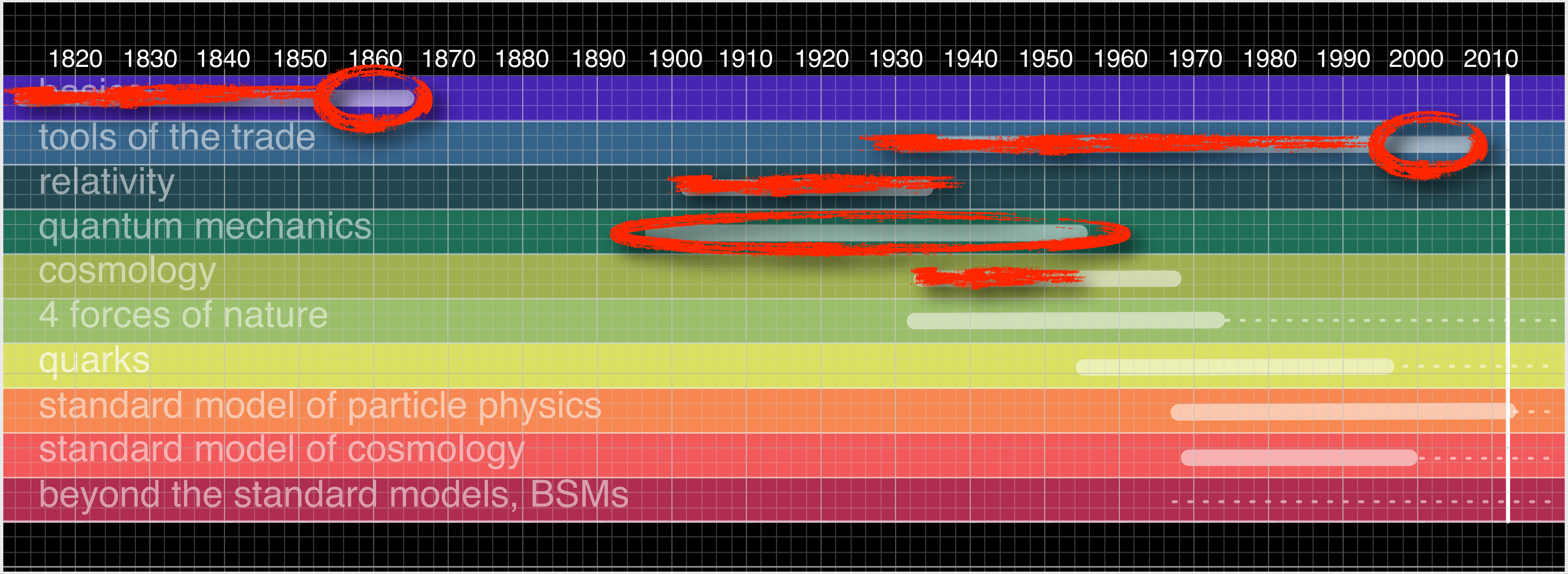
7 min to midnight: homosapiens

dinosaur extinction

dinosaurs

To take the story there

We need quantum mechanics and particle physics


1820 1830 1840 1850 1860 1870 1880 1890 1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000 2010
tools of the trade
relativity
quantum mechanics
cosmology
4 forces of nature
quarks
standard model of particle physics
standard model of cosmology
beyond the standard models, BSMs