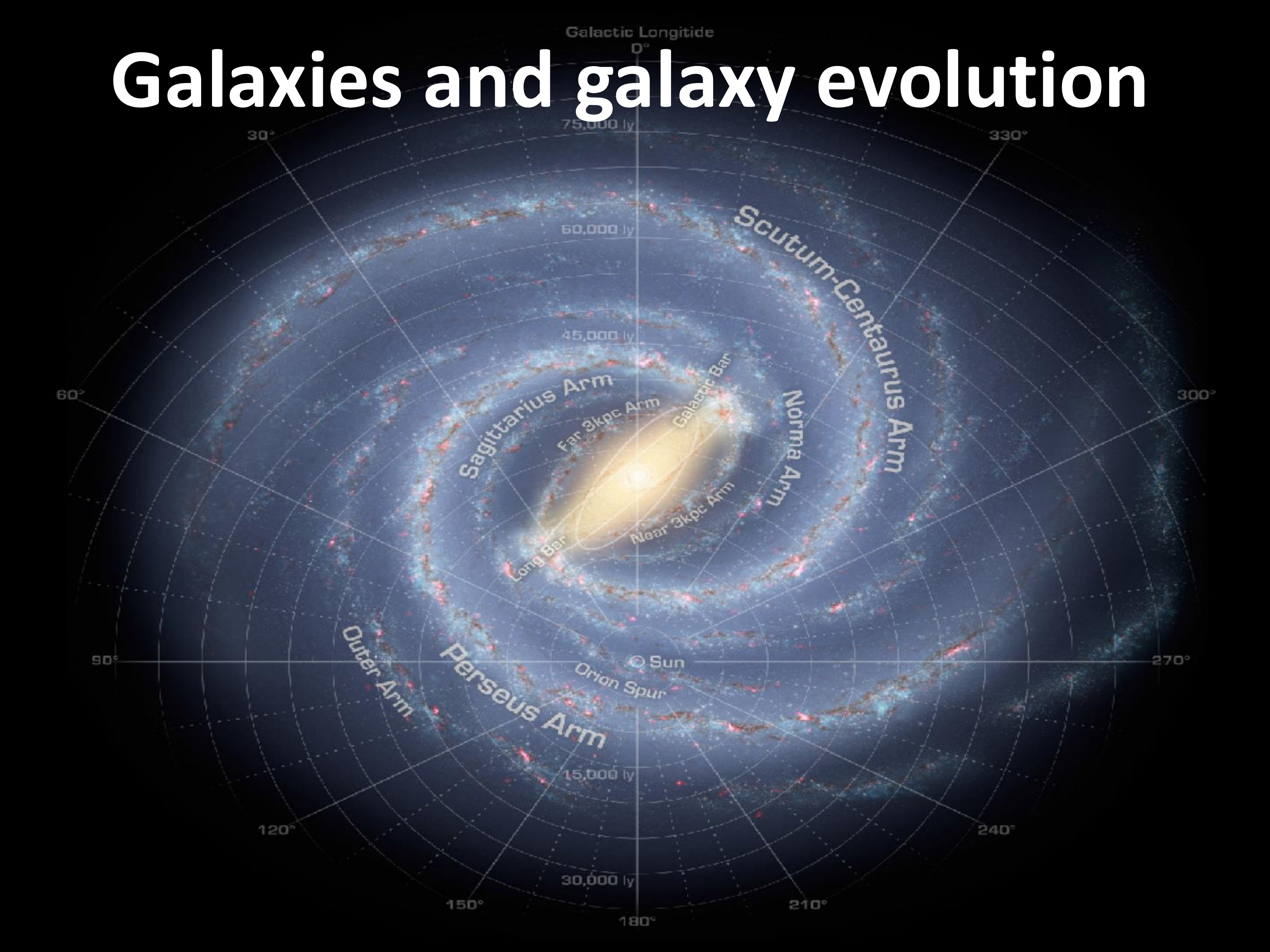
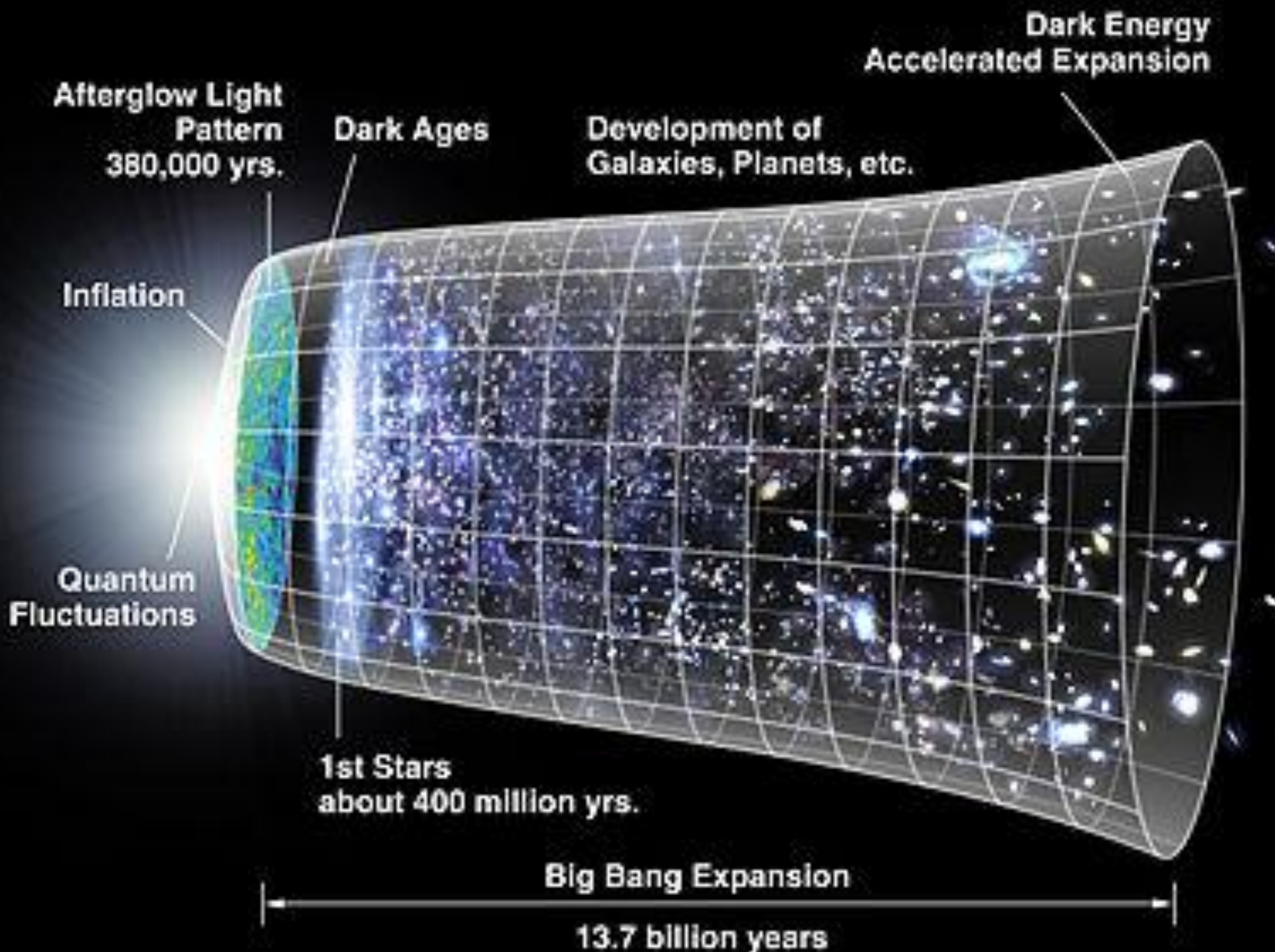
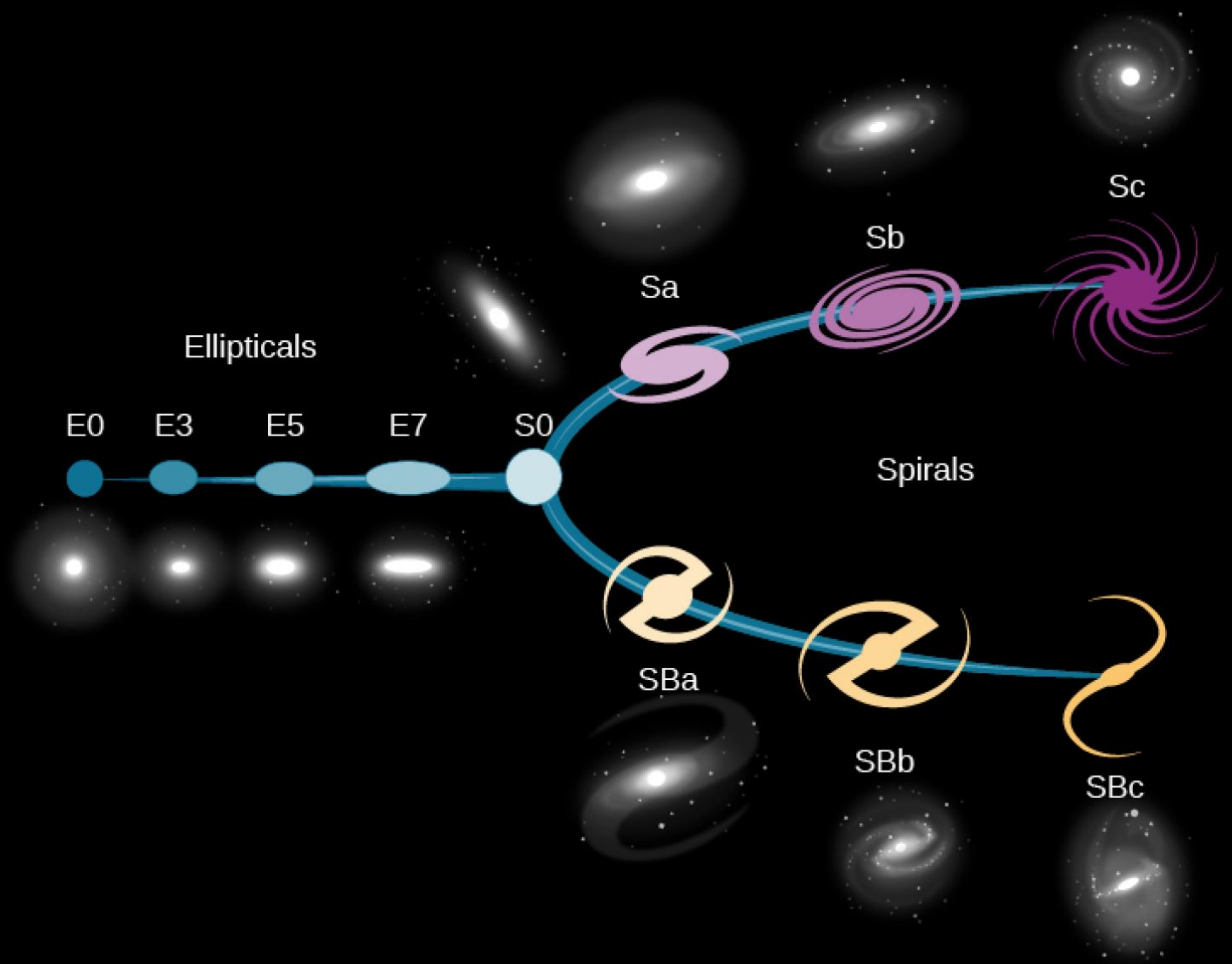
Galaxies and galaxy evolution



Cosmology in a single plot

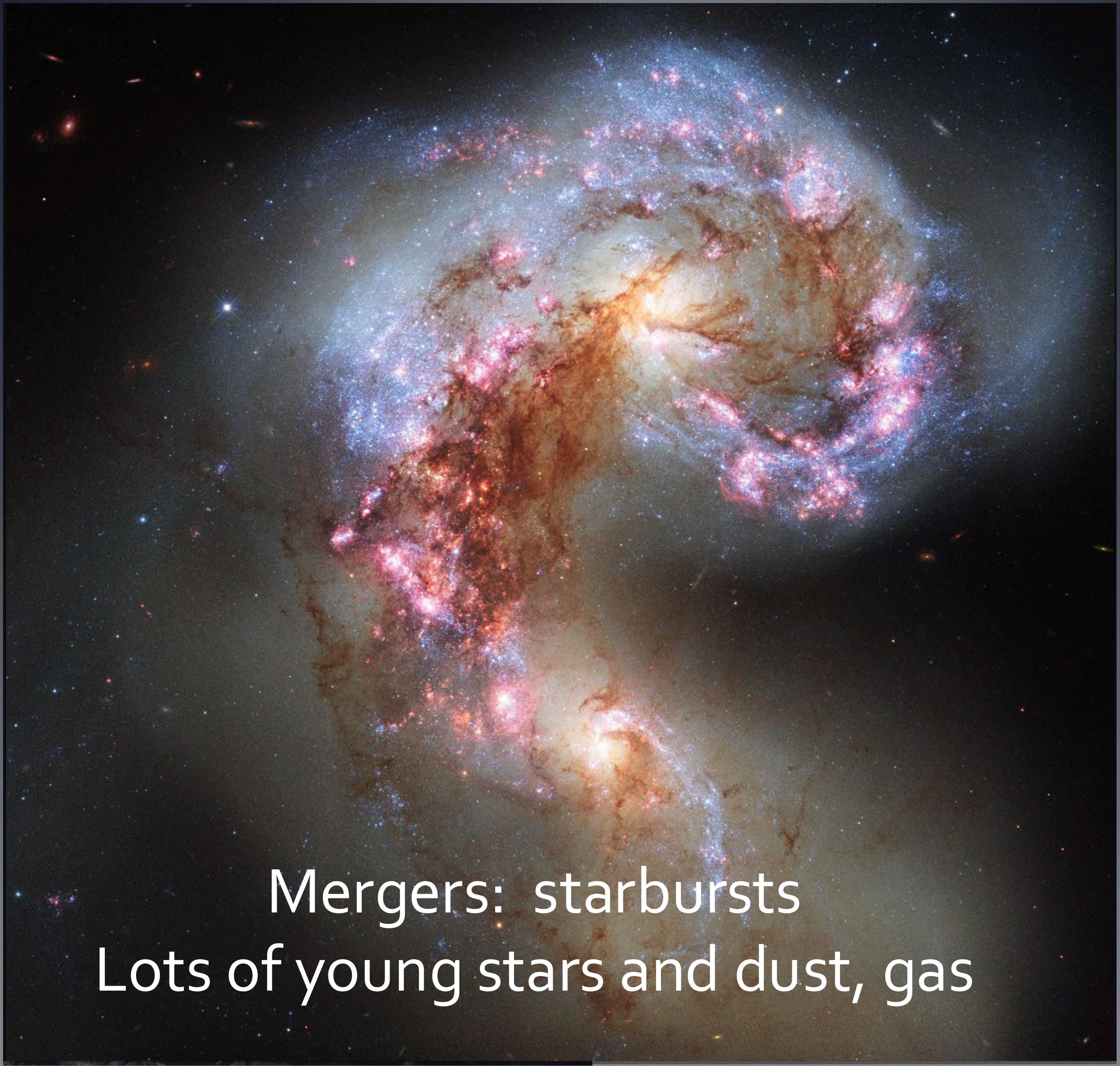


Galaxies and their supermassive black holes



Elliptical: red and dead
No dust/gas, no star formation

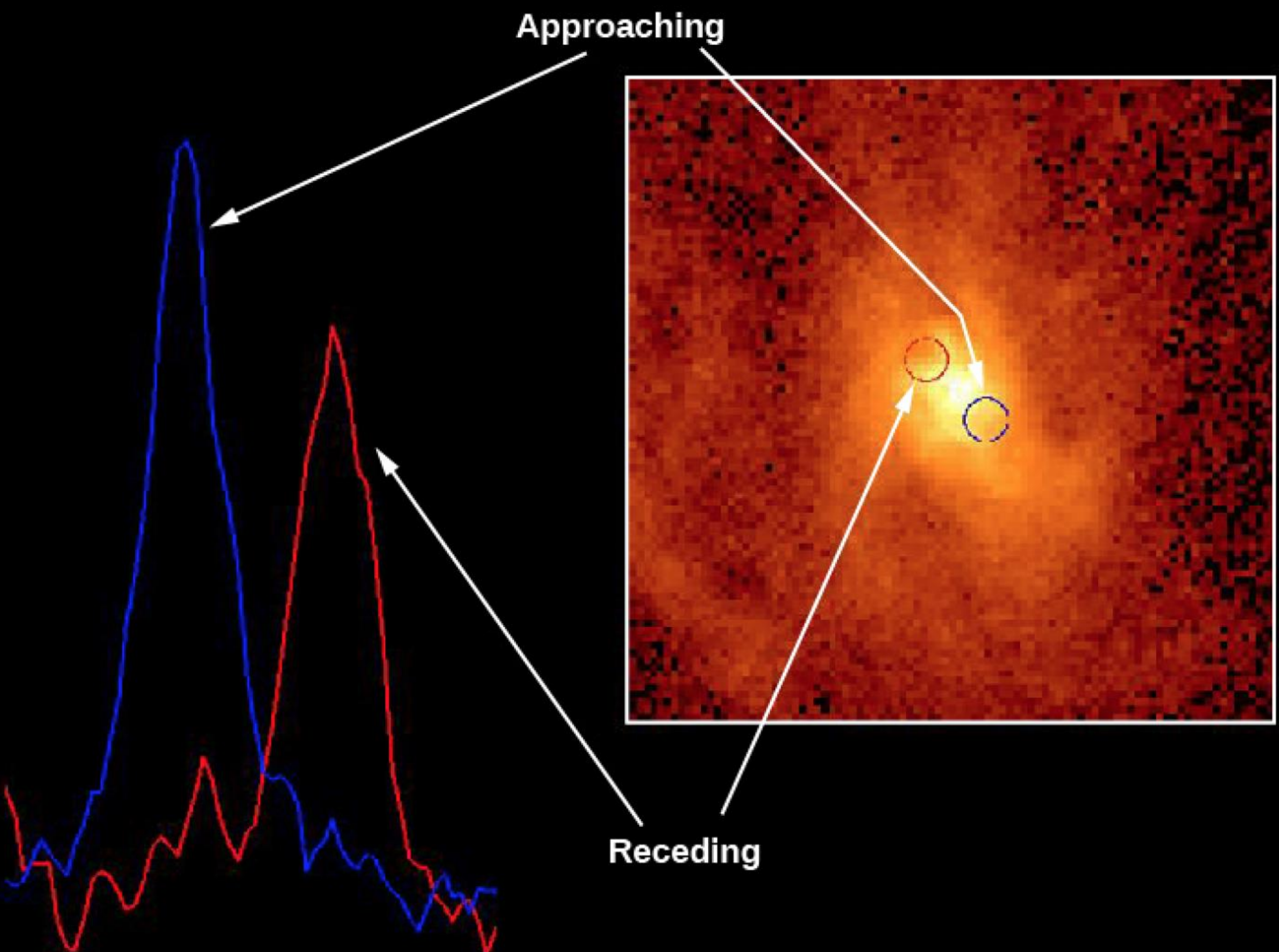
Spirals:
Gas accumulates in spiral density waves;
star formation


Mergers: starbursts
Lots of young stars and dust, gas

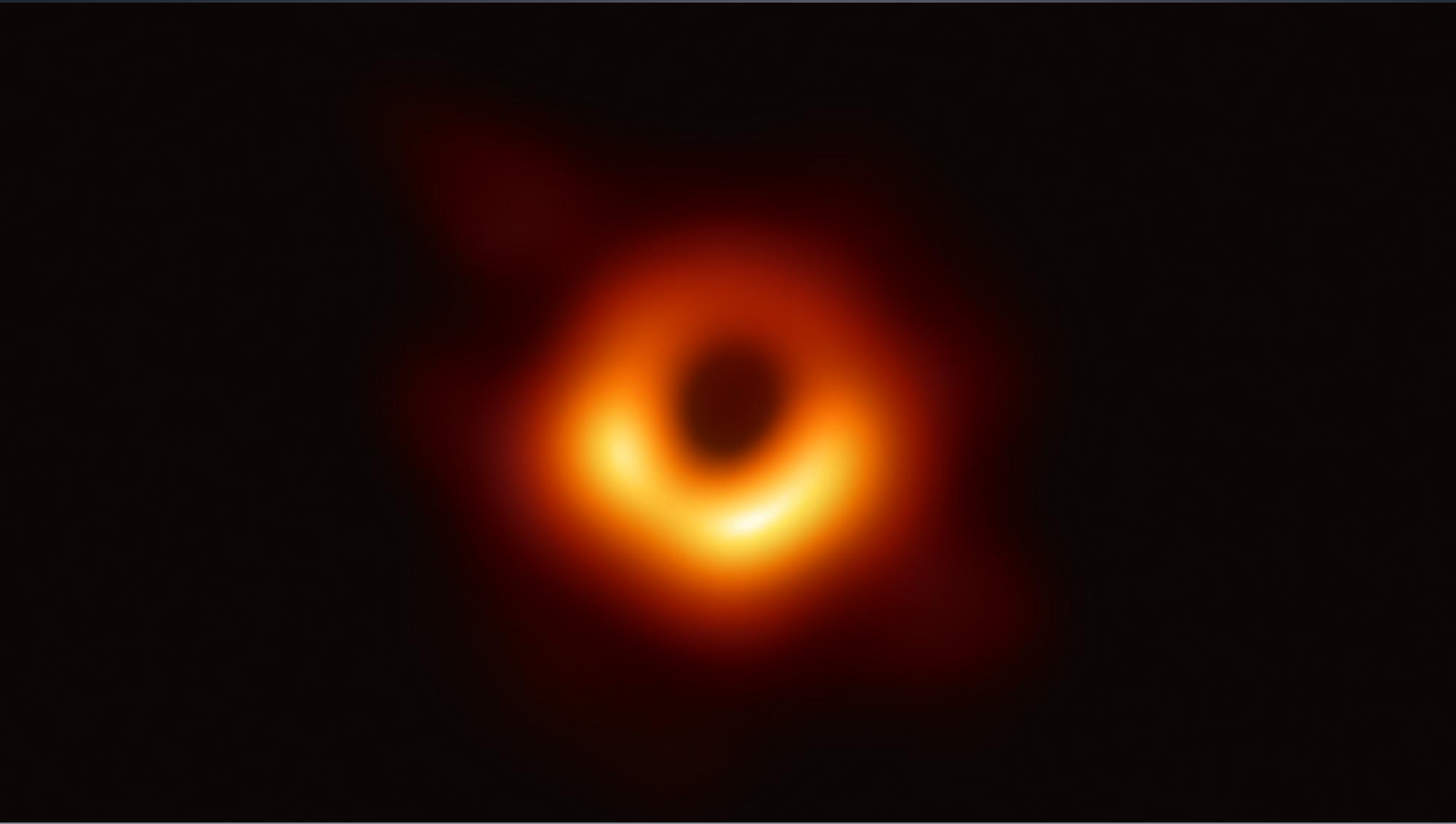
Characteristics of the Different Types of Galaxies

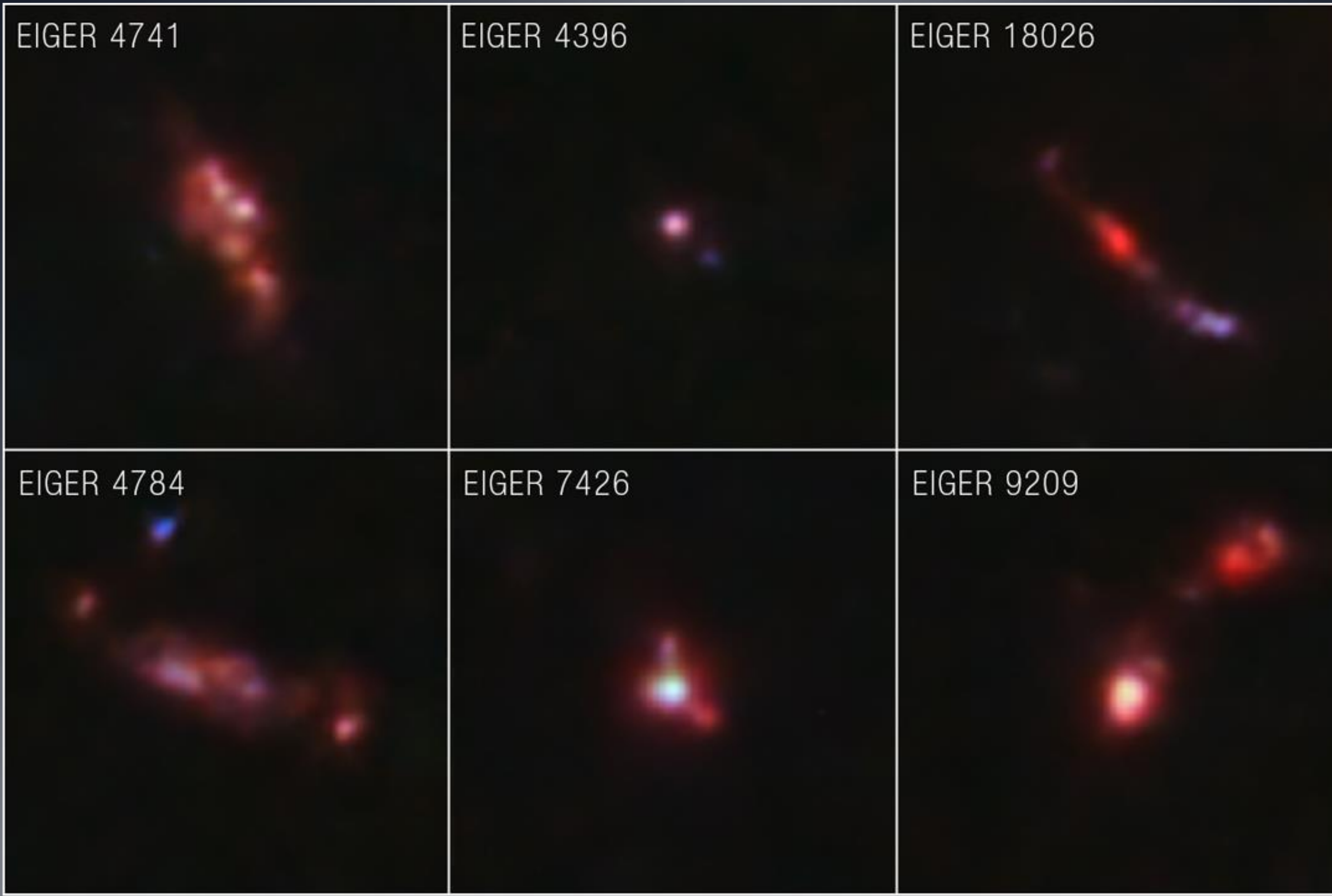
Characteristic	Spirals	Ellipticals	Irregulars
Mass (M_{Sun})	10^9 to 10^{12}	10^5 to 10^{13}	10^8 to 10^{11}
Diameter (thousands of light-years)	15 to 150	3 to >700	3 to 30
Luminosity (L_{Sun})	10^8 to 10^{11}	10^6 to 10^{11}	10^7 to 2×10^9
Populations of stars	Old and young	Old	Old and young
Interstellar matter	Gas and dust	Almost no dust; little gas	Much gas; some have little dust, some much dust
Mass-to-light ratio in the visible part	2 to 10	10 to 20	1 to 10
Mass-to-light ratio for total galaxy	100	100	?

Mass of black hole from velocity shifts



First "image" of a black hole
Supermassive black hole of M87



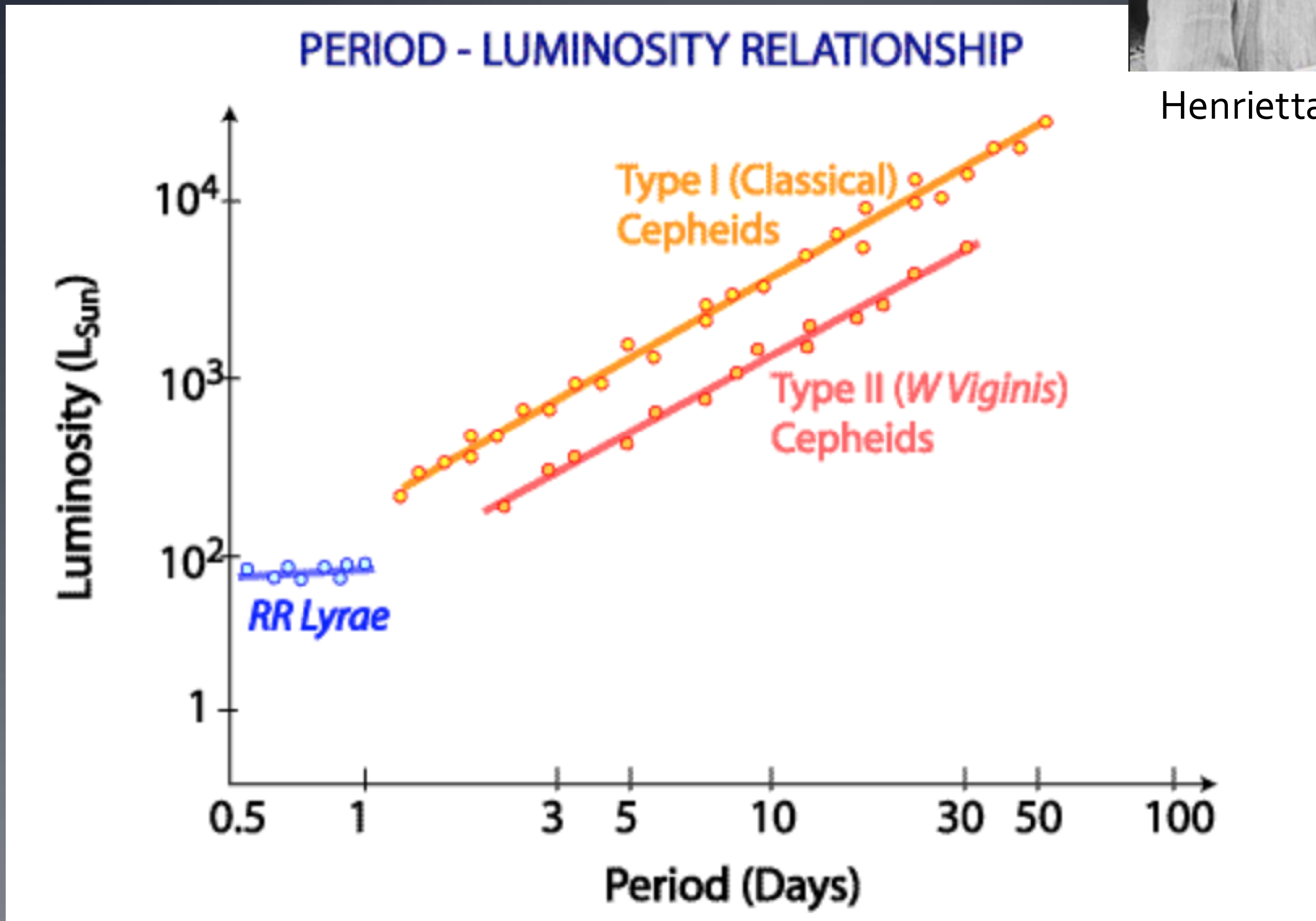

EIGER 4741
EIGER 4396
EIGER 18026
EIGER 4784
EIGER 7426
EIGER 9209

The distance ladder!
How to measure distances?

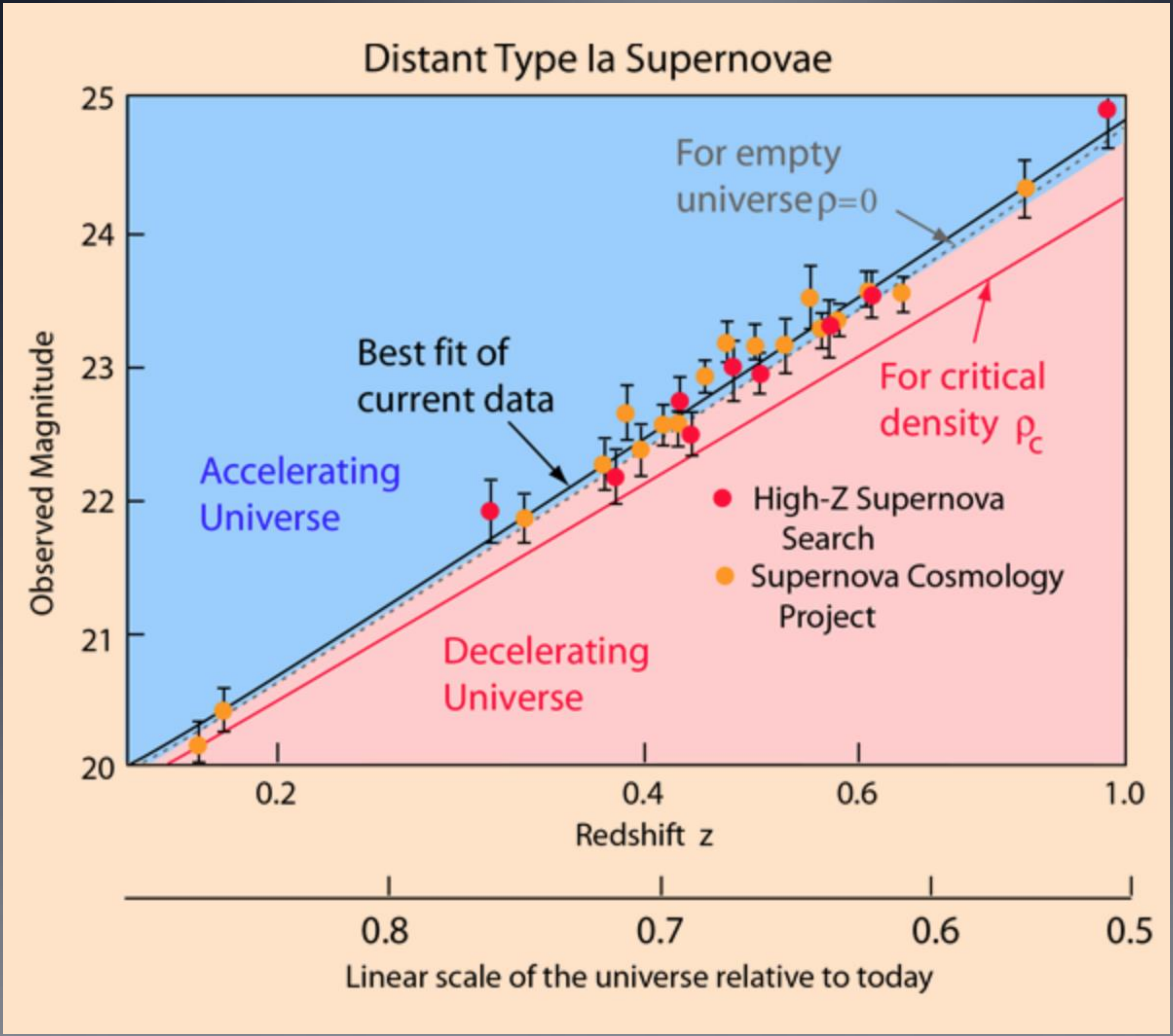
Some Methods for Estimating Distance to Galaxies

Method	Galaxy Type	Approximate Distance Range (millions of light-years)
Planetary nebulae	All	0–70
Cepheid variables	Spiral, irregulars	0–110
Tully-Fisher relation	Spiral	0–300
Type Ia supernovae	All	0–11,000
Redshifts (Hubble's law)	All	300–13,000

Nearby galaxies: use variable stars!

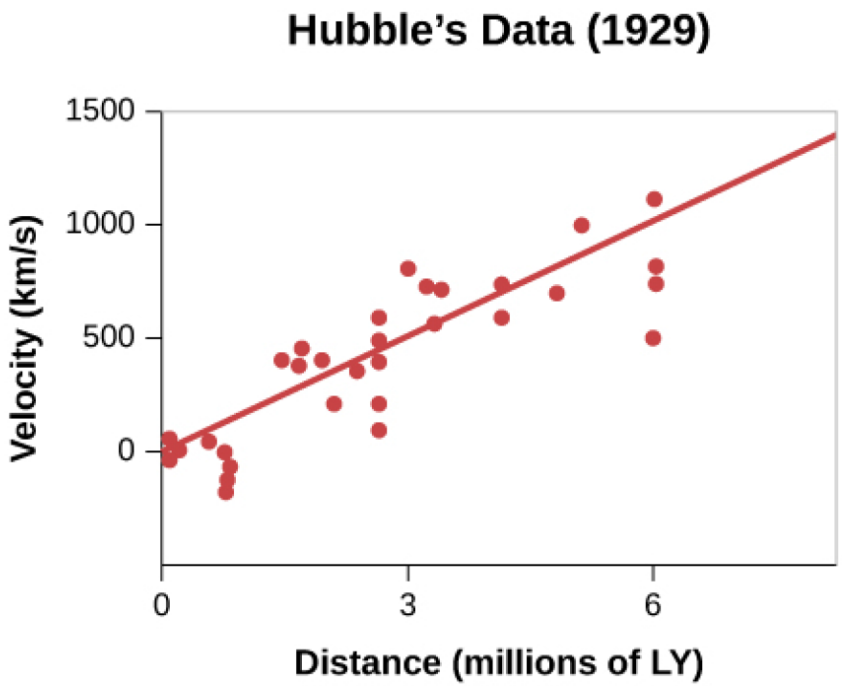


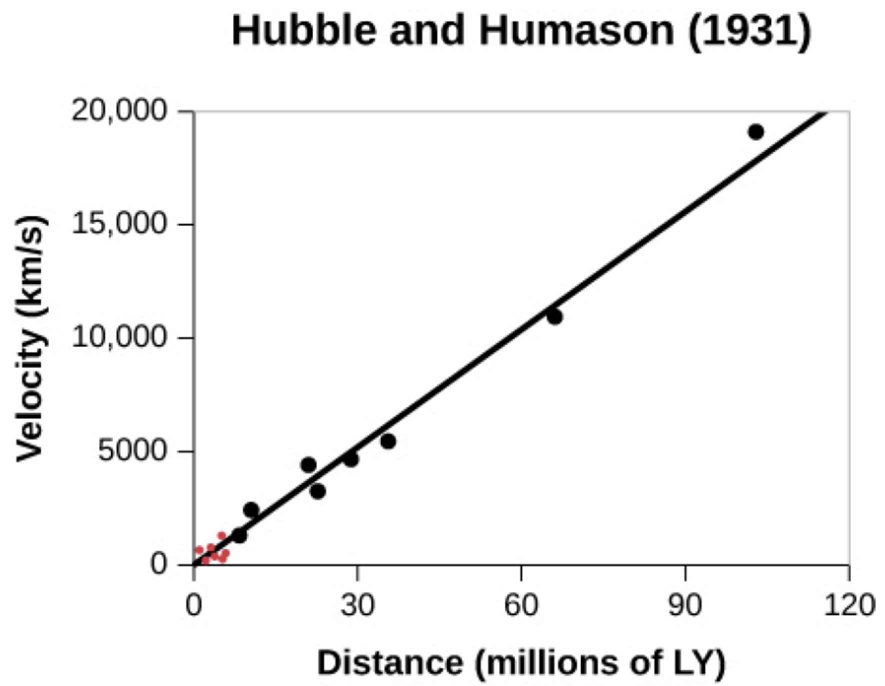
Henrietta Leavitt



Distant Type Ia Supernovae
25
24
23
22
21
20
Observed Magnitude
For empty universe ρ=0
Best fit of current data
For critical density ρ_c
Accelerating Universe
Decelerating Universe
High-Z Supernova Search
Supernova Cosmology Project
0.2
0.4
0.6
1.0
Redshift z
0.8
0.7
0.6
0.5
Linear scale of the universe relative to today

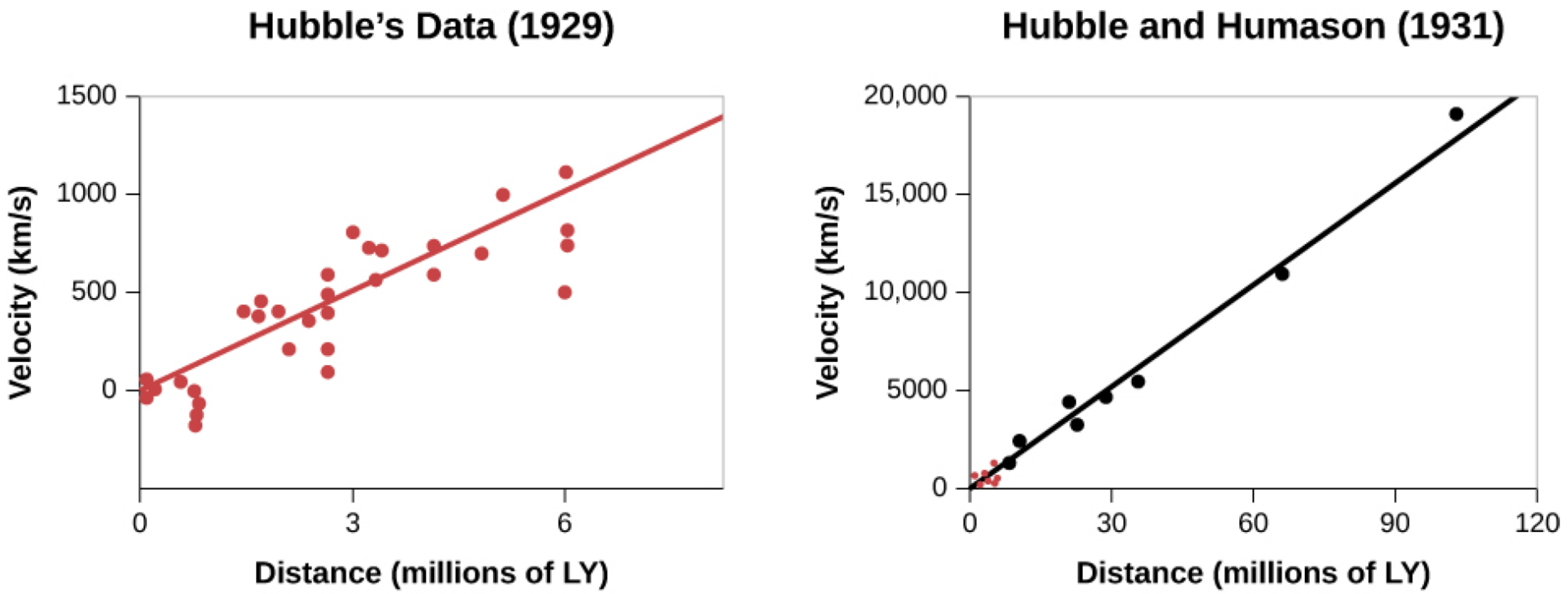
Hubble's Law: distance proportional to redshift
Redshift: spectrum of light shifted to red
(going away from us)





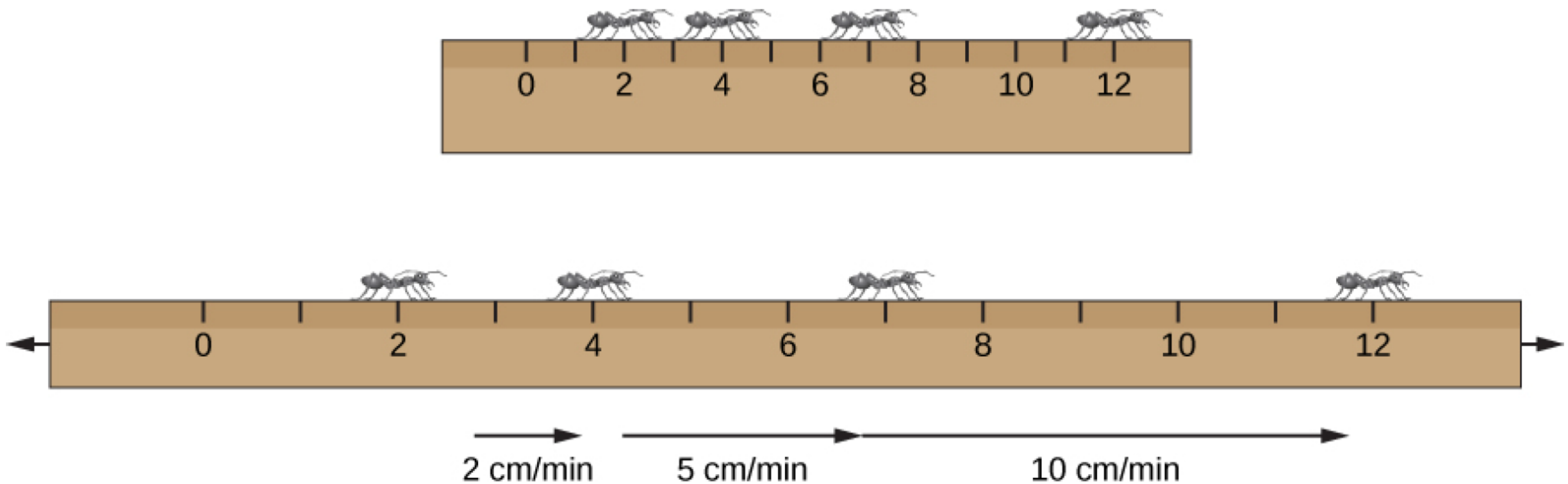
$$V = H \times d$$

When we look at larger distances, we are looking into the past!

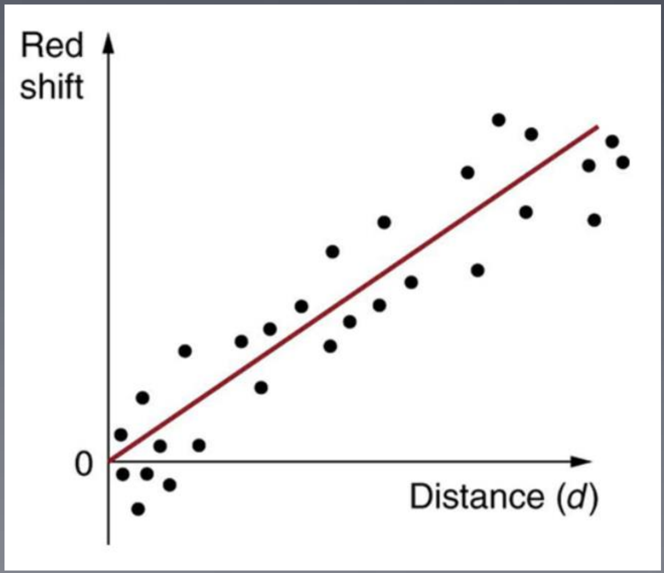


$$V = H \times d$$

Expansion of universe and redshift



Redshift: 3D maps of a 2D sky



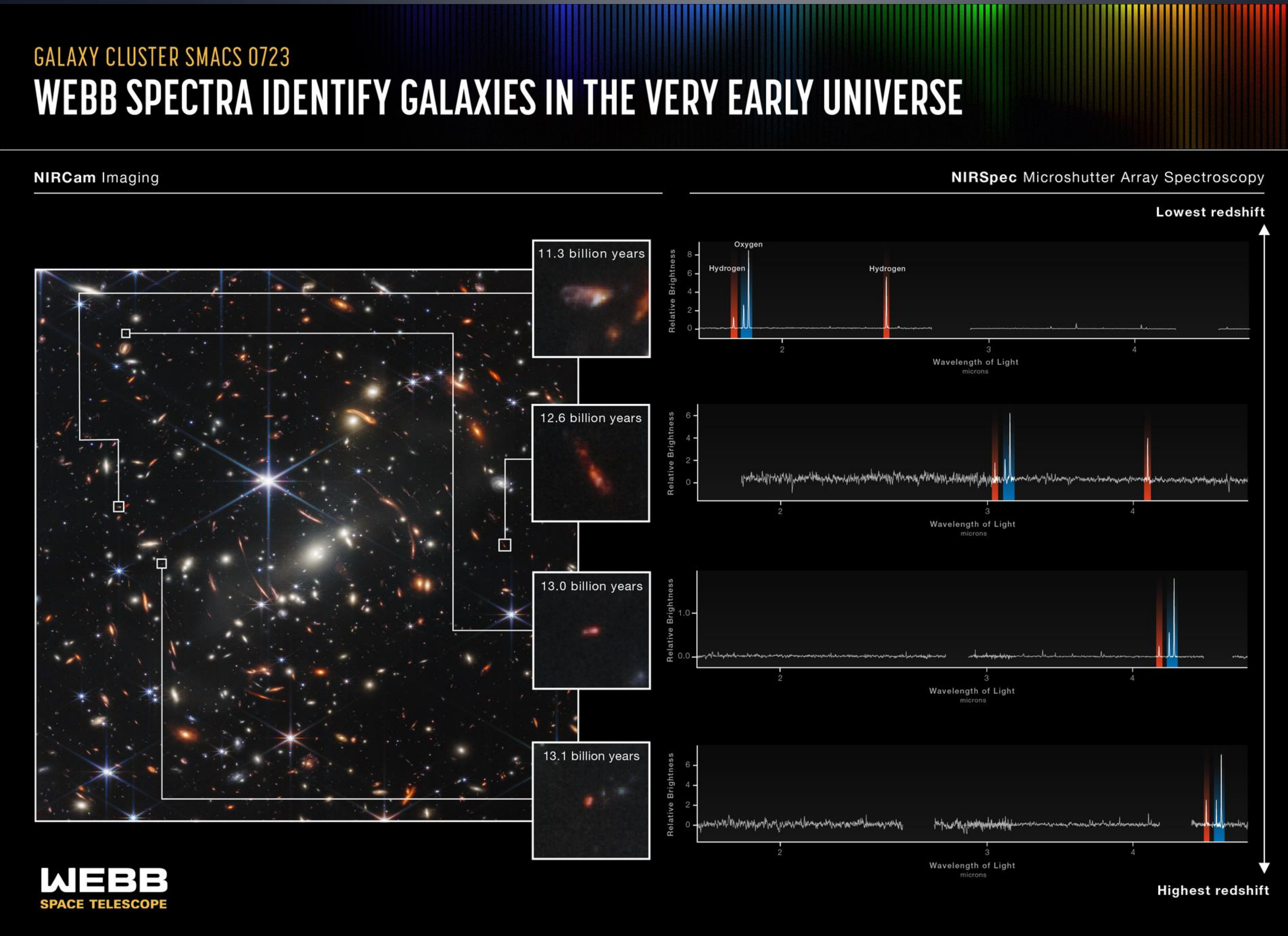
Searching for galaxies: redshift and wavelength

Redshift formula

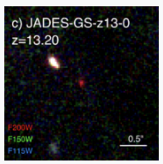
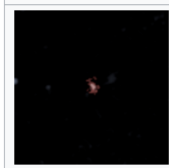
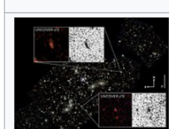
- Redshift $z = \Delta\lambda/\lambda = v/c$ (if $v << c$)
- $v = H_0 d$, H_0 is Hubble constant
- $D = z\, c/H_0$
- Age of universe: $1/H_0$

Light travel time: distance ~ time

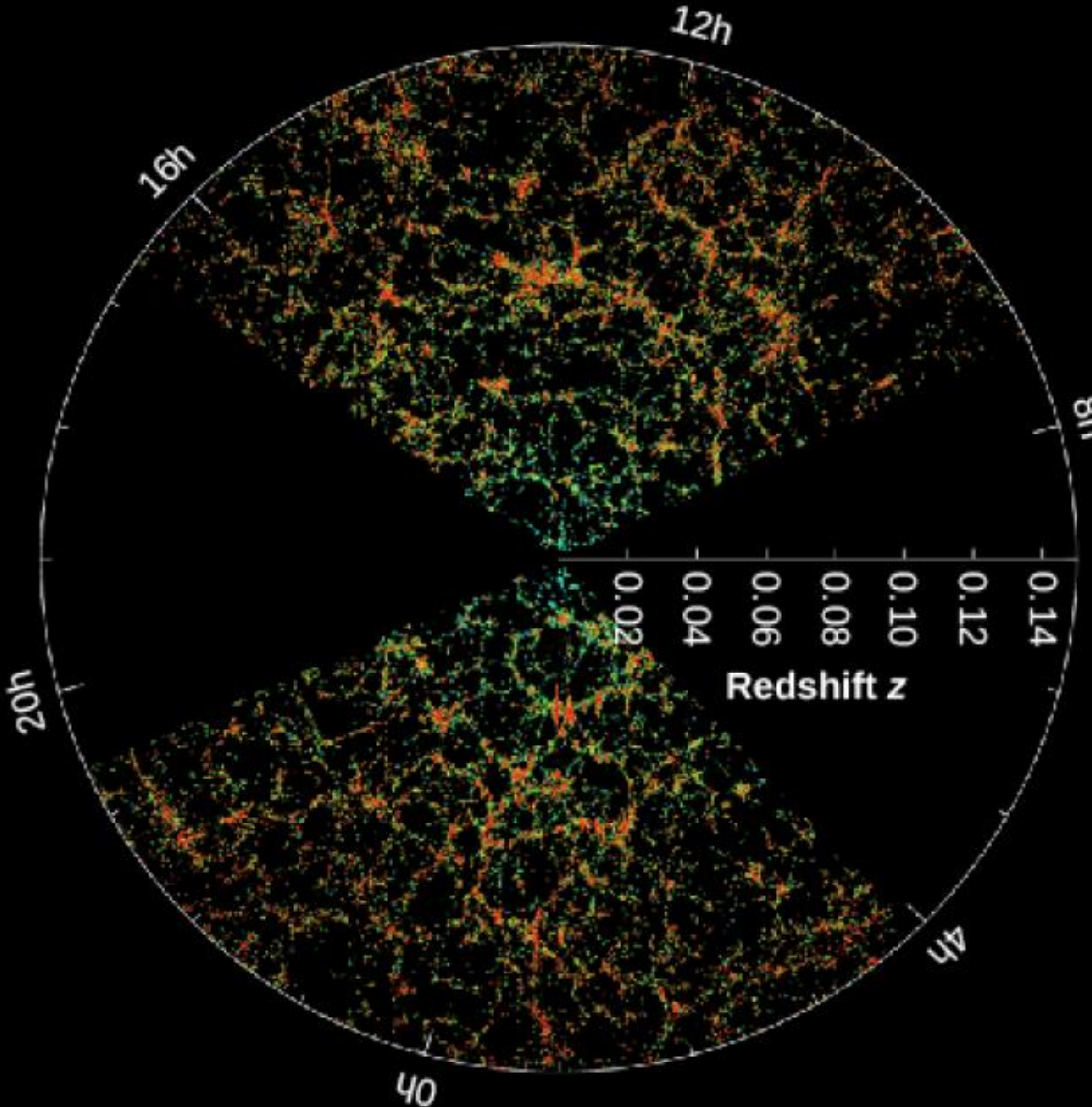
- Most distant: 13.5 billion light years
  - Current distance: ~50 billion light years (no longer visible)
- When we observe the most distant objects, we are observing the universe when it was young!


GALAXY CLUSTER SMACS 0723
WEBB SPECTRA IDENTIFY GALAXIES IN THE VERY EARLY UNIVERSE
NIRCam Imaging
NIRSpec Microshutter Array Spectroscopy
Lowest redshift
11.3 billion years
12.6 billion years
13.0 billion years
13.1 billion years
Oxygen
Hydrogen
Hydrogen
Relative Brightness
Wavelength of Light
microns
Highest redshift
WEBB
SPACE TELESCOPE

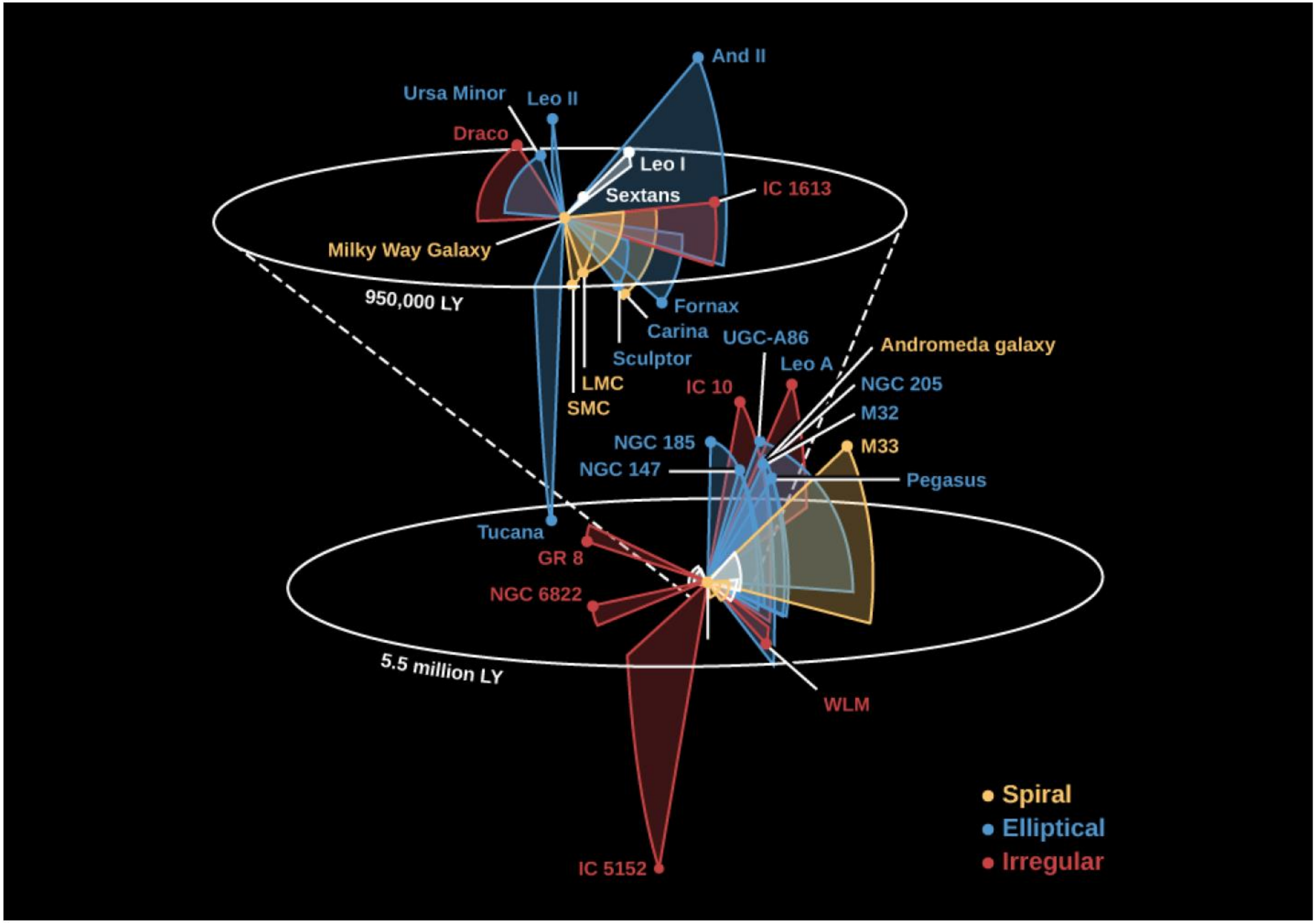
Most distant astronomical objects with spectroscopic redshift determinations

Image	Name	Redshift (z)	Light travel distance§ (Gly)[4][5][6][7]	Proper distance (Gly)	Type	Notes
	JADES-GS-z14-0	$z = 14.32^{+0.08}_{-0.20}$			Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec.[8]
	JADES-GS-z14-1	$z = 13.90^{+0.17}_{-0.17}$			Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec.[9]
	JADES-GS-z13-0	$z = 13.20^{+0.04}_{-0.07}$	13.576[4] / 13.596[5] / 13.474[6] / 13.473[7]	33.6	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec.[10]
	UNCOVER-z13	$z = 13.079^{+0.014}_{-0.001}$	13.51	32.56†	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec.[11]
	JADES-GS-z12-0	$z = 12.63^{+0.24}_{-0.08}$	13.556[4] / 13.576[5] / 13.454[6] / 13.453[7]	32.34†	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRCam [10] and JWST/NIRSpec,[12] and CIII] line emission with JWST/NIRSpec.[12] Most distant spectroscopic redshift from emission lines; most distant detection of non-primordial elements (C, O, Ne).
	UNCOVER-z12	$z = 12.393^{+0.004}_{-0.001}$	13.48	32.21†	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec.[11]

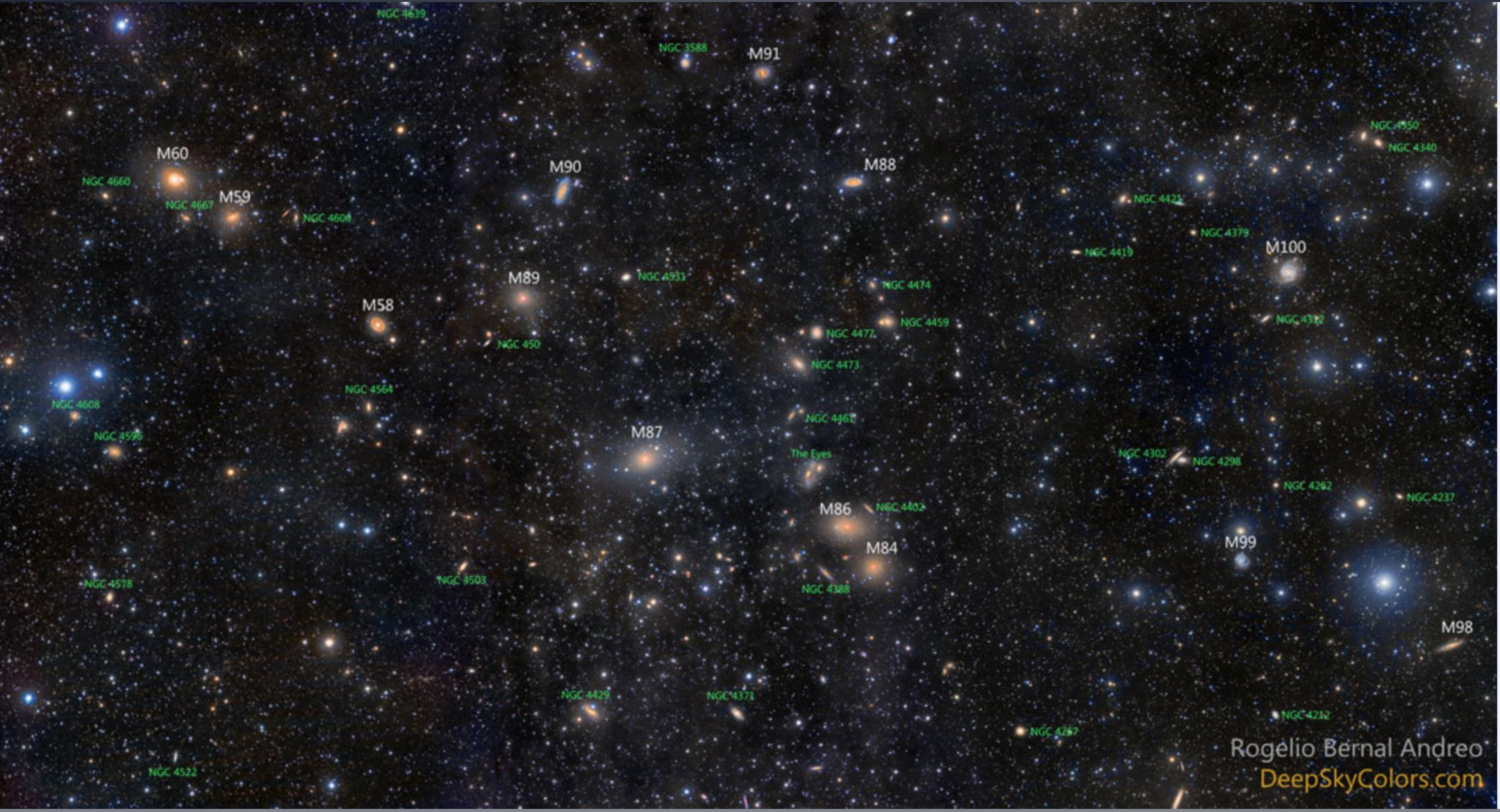
3D map of the universe: clusters and voids



Galaxies cluster together: Local Group

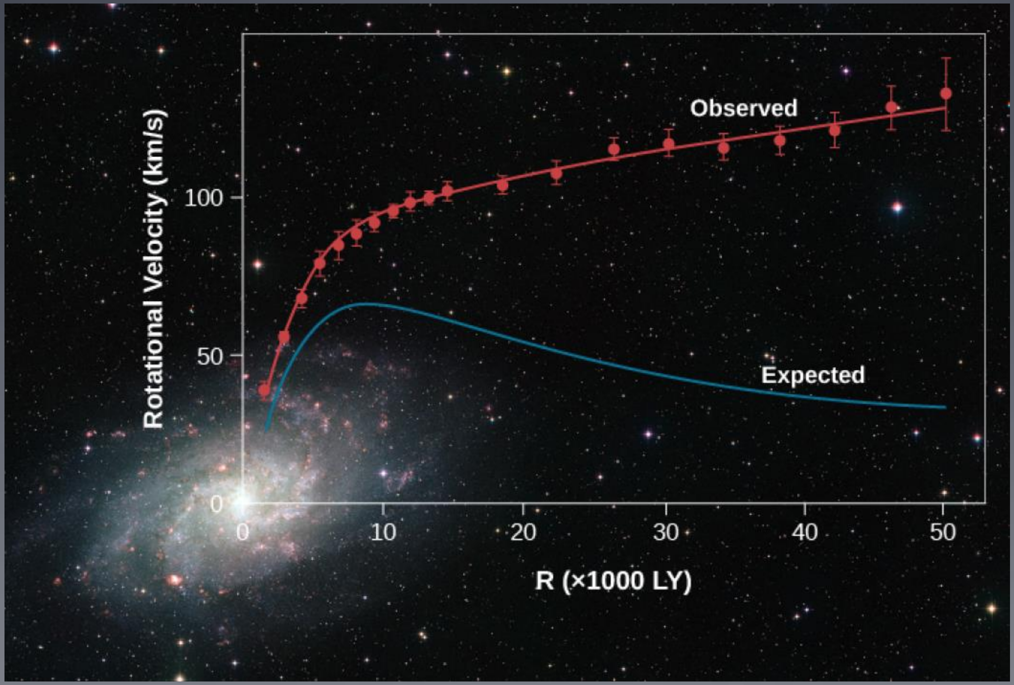


Virgo Cluster

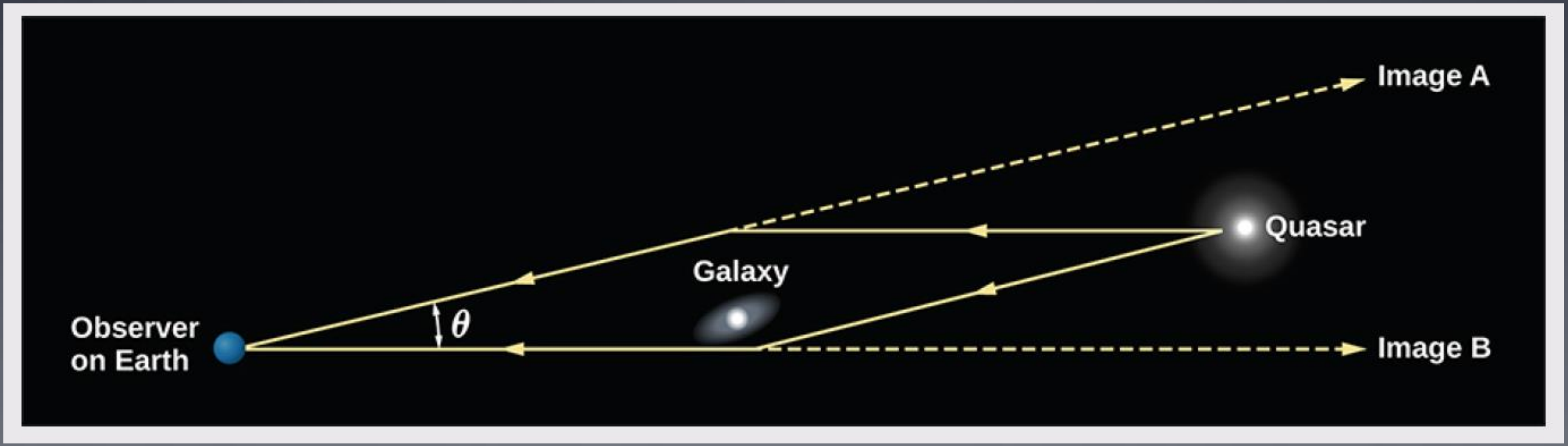


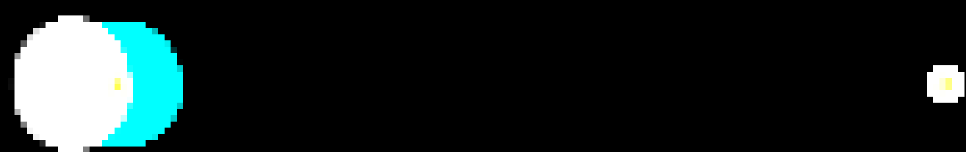
How massive are galaxies?

- Rotation curves
- Gravitational lensing

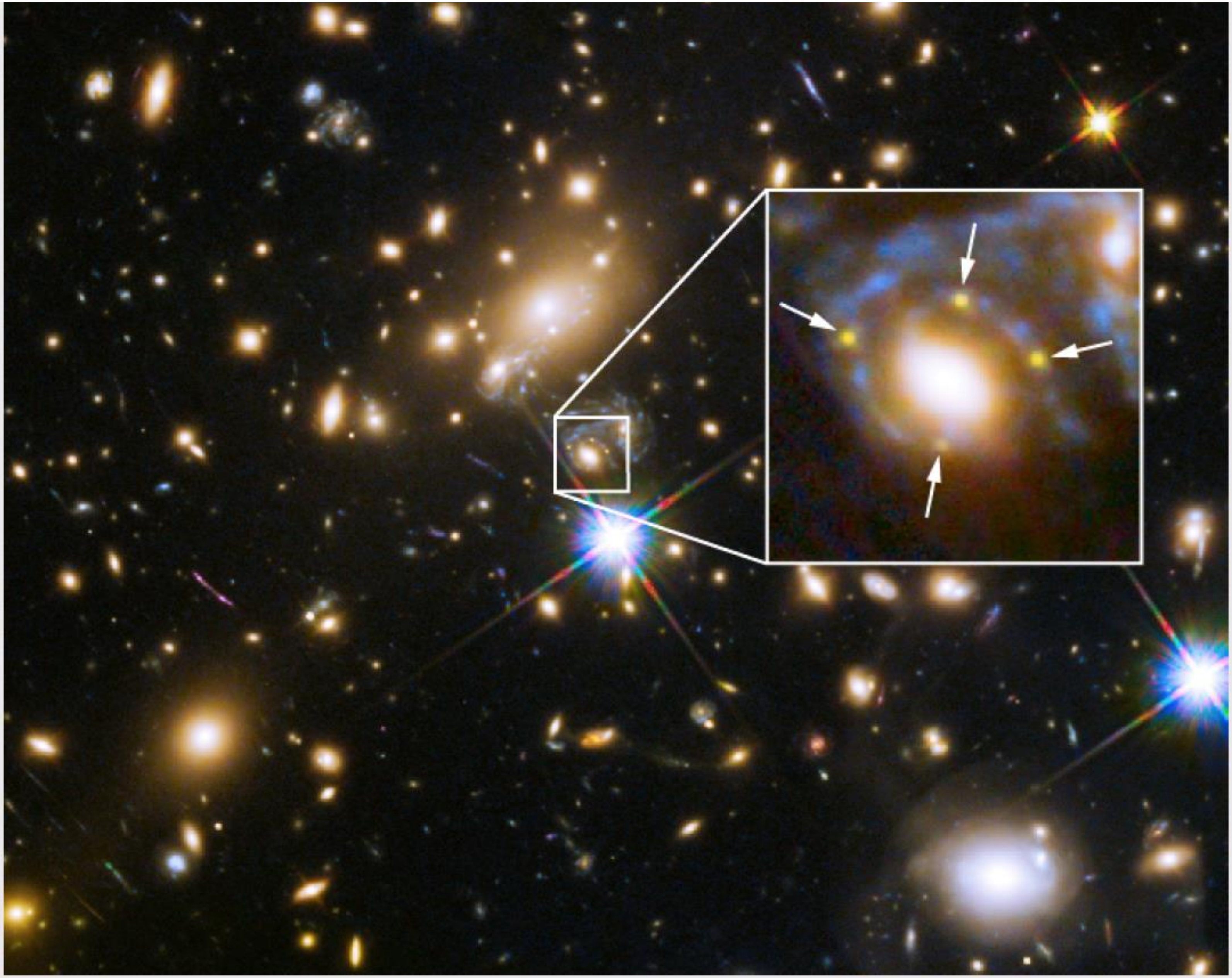


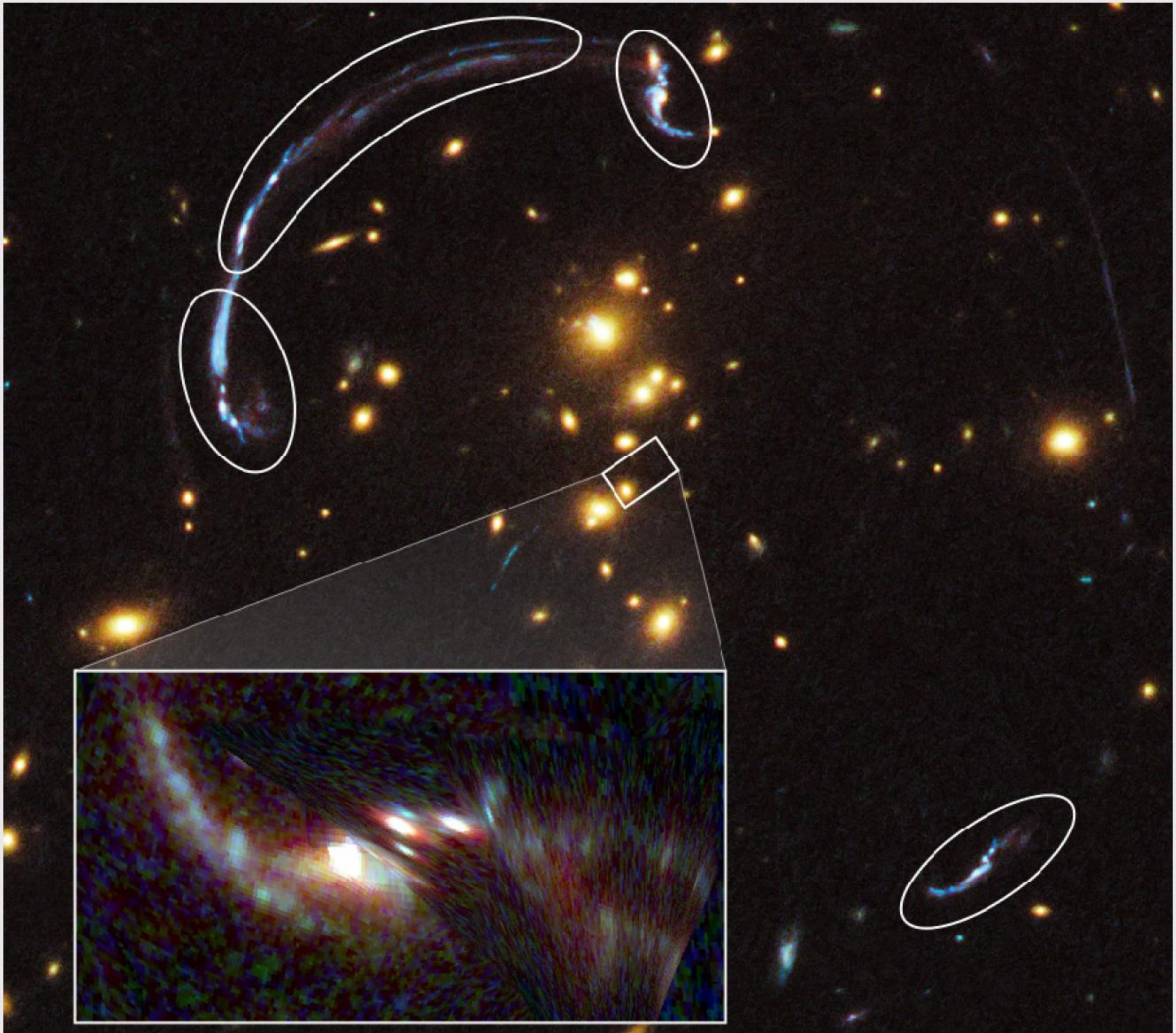
Masses and dark matter: gravitational lensing

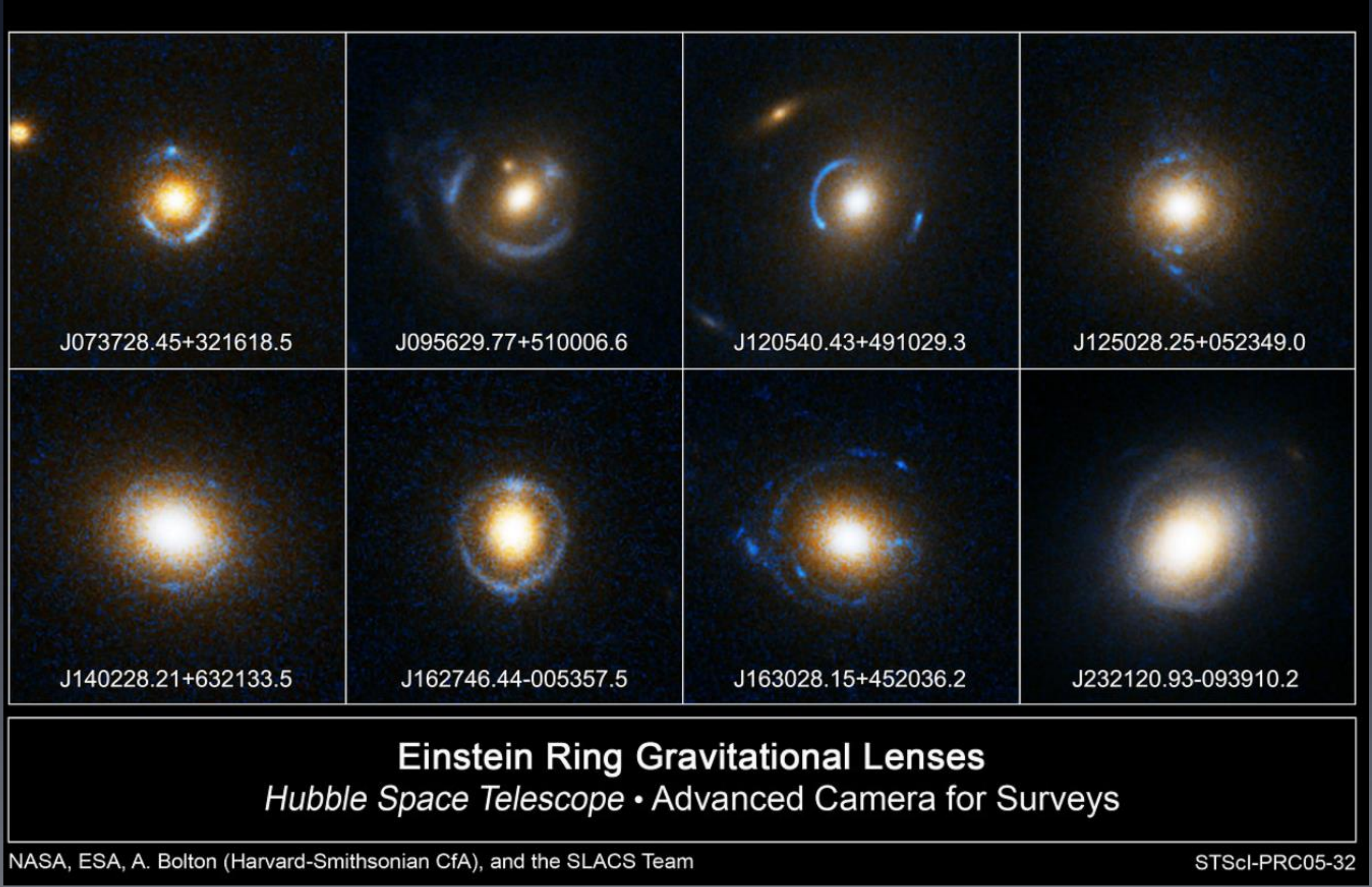


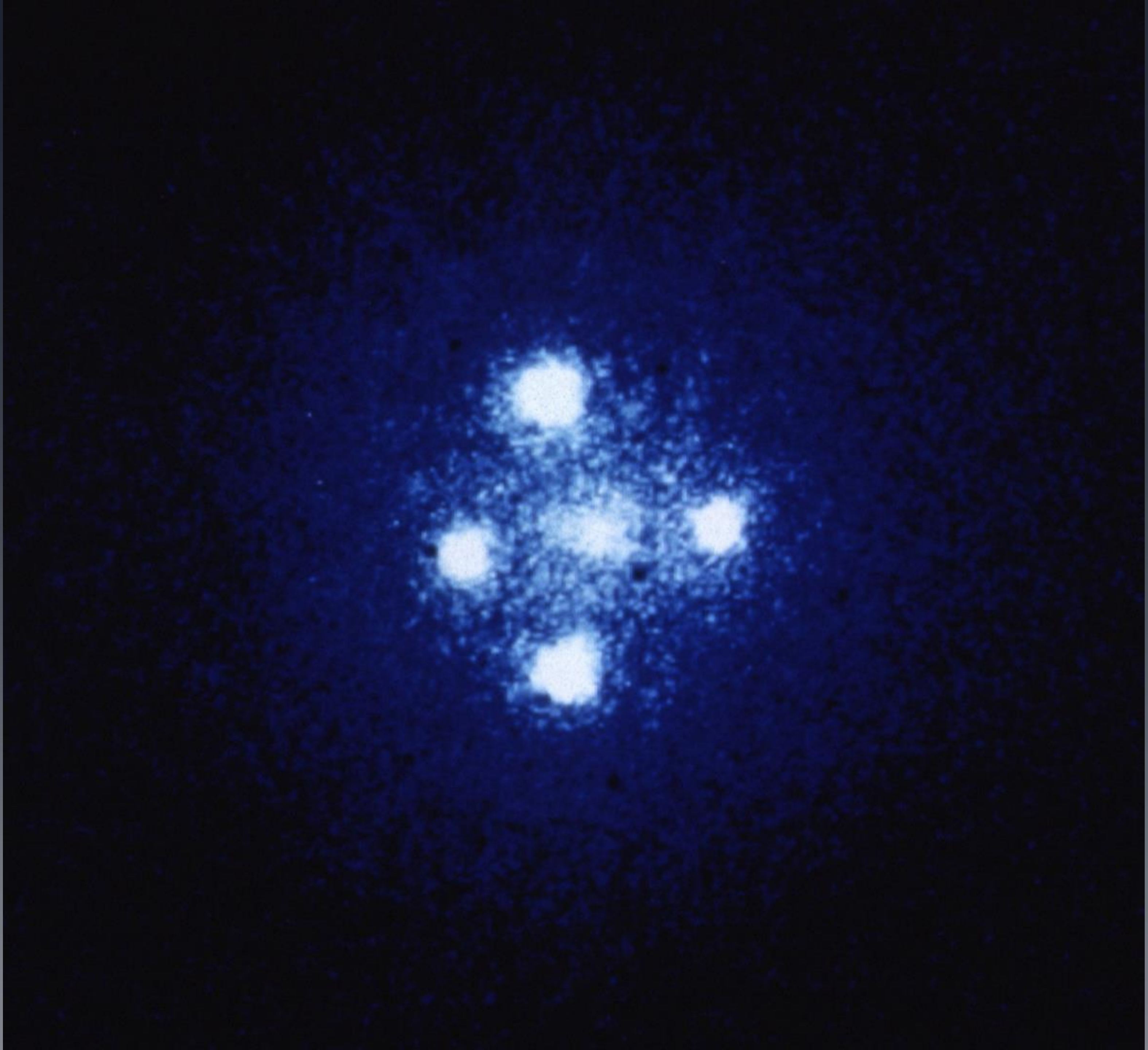


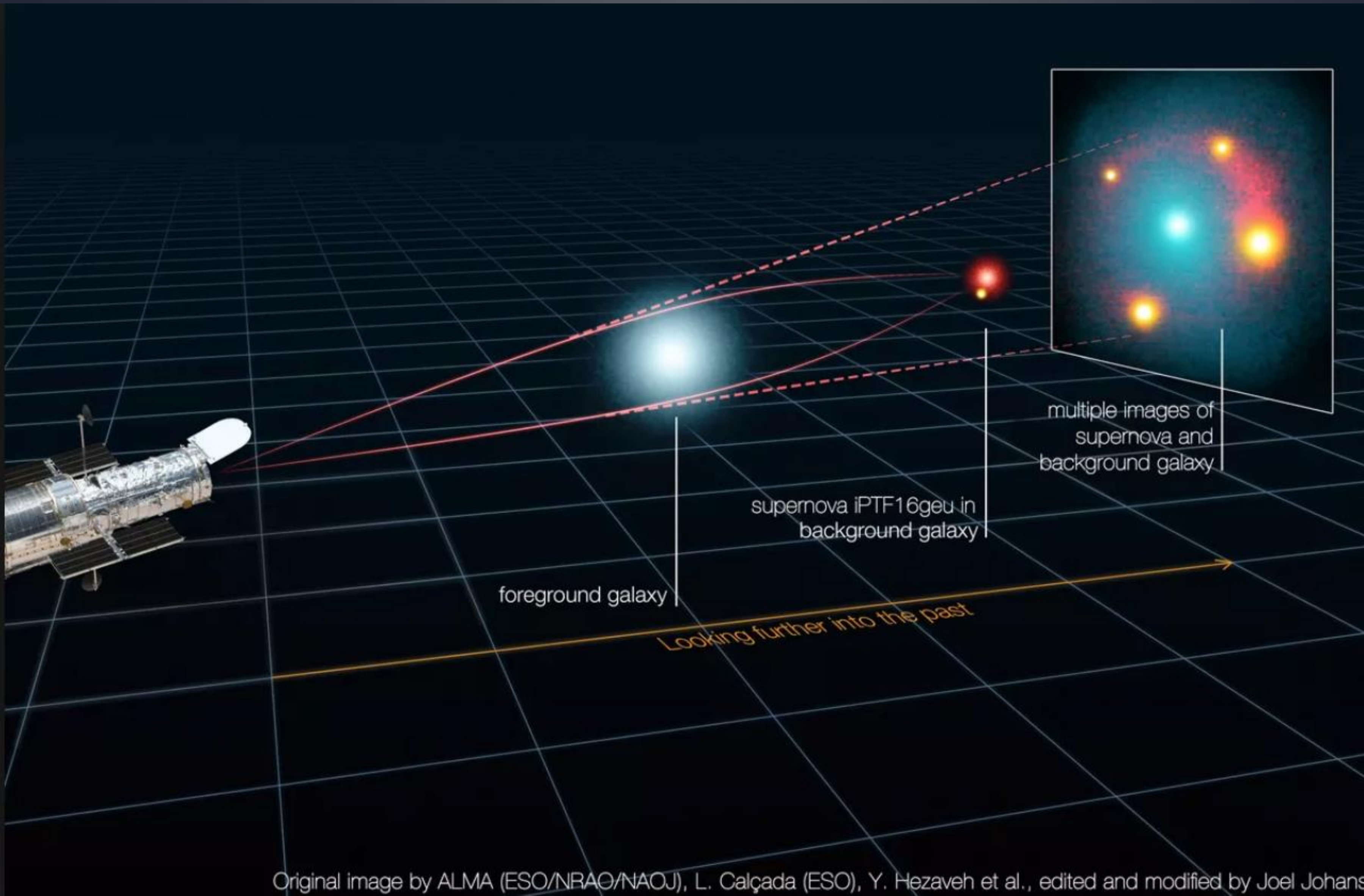
Gravitational lensing



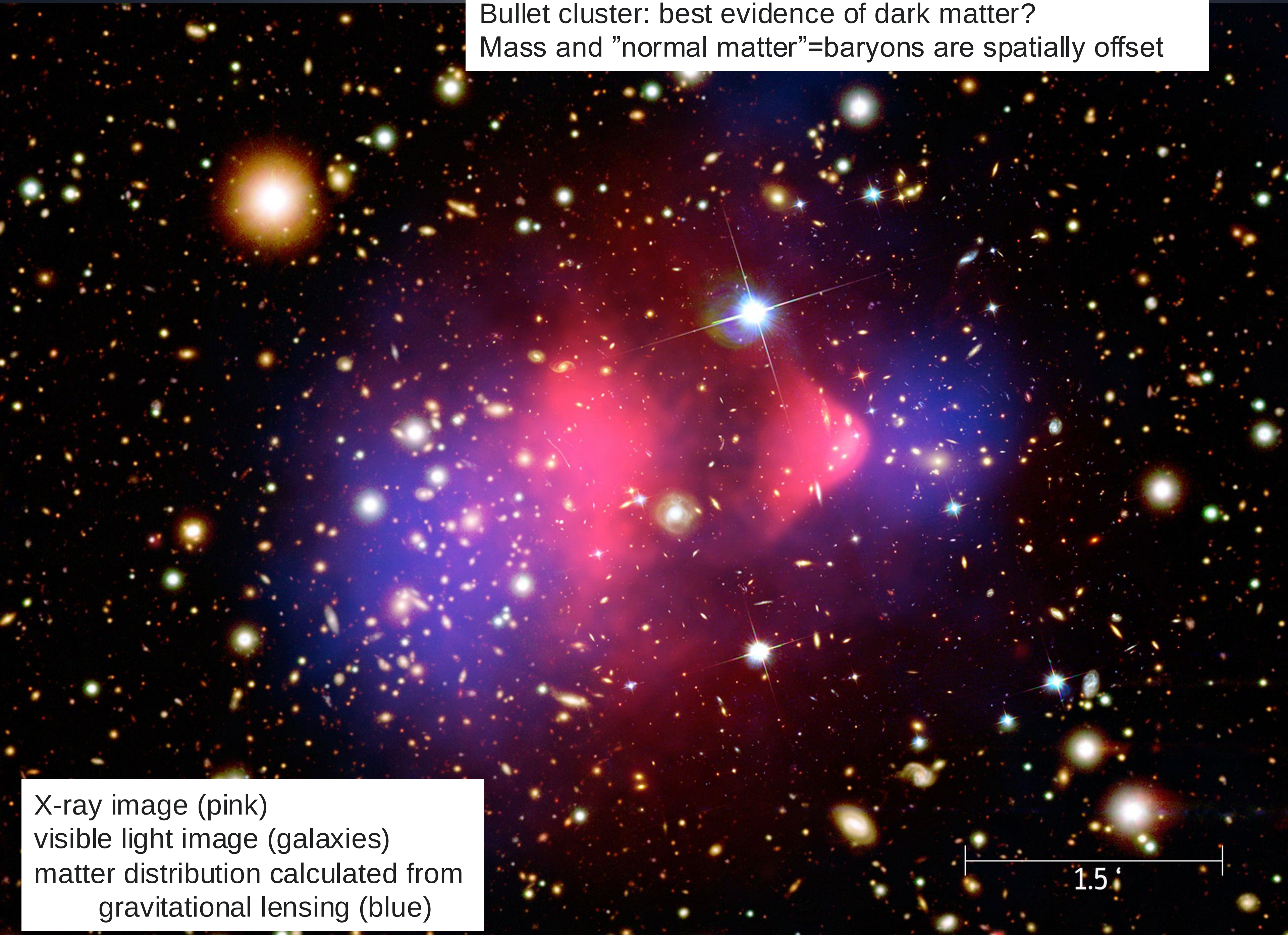



J073728.45+321618.5
J095629.77+510006.6
J120540.43+491029.3
J125028.25+052349.0
J140228.21+632133.5
J162746.44-005357.5
J163028.15+452036.2
J232120.93-093910.2
Einstein Ring Gravitational Lenses
Hubble Space Telescope • Advanced Camera for Surveys
NASA, ESA, A. Bolton (Harvard-Smithsonian CfA), and the SLACS Team
STScI-PRC05-32




multiple images of
supernova and
background galaxy
supernova iPTF16geu in
background galaxy
foreground galaxy
Looking further into the past
Original image by ALMA (ESO/NRAO/NAOJ), L. Calçada (ESO), Y. Hezaveh et al., edited and modified by Joel Johans

Bullet cluster: best evidence of dark matter?
Mass and ”normal matter”=baryons are spatially offset

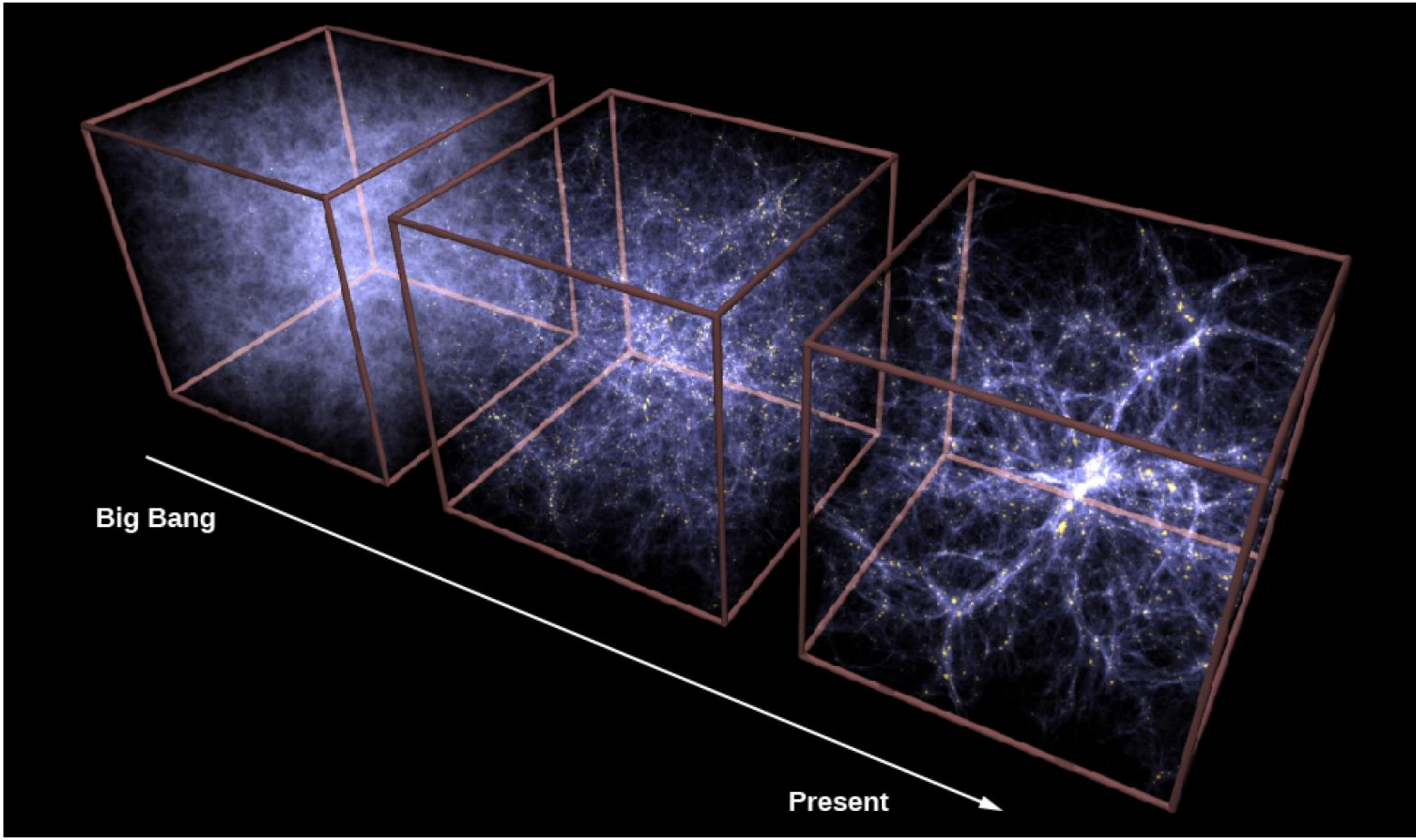


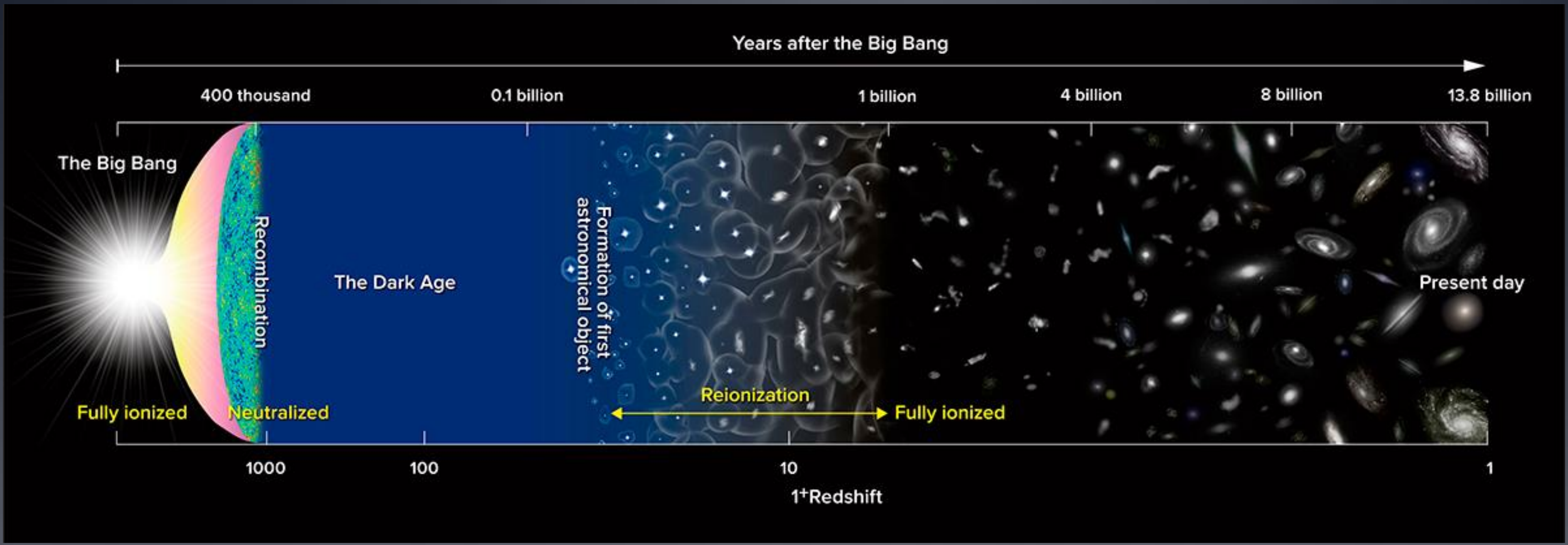
X-ray image (pink)
visible light image (galaxies)
matter distribution calculated from
gravitational lensing (blue)

What is the universe made of

- “normal” matter: 25% of total mass
- 75% of mass: dark matter
  - “cold” dark matter

But cosmology: dark (vacuum) energy is 75% of energy density of the universe


Big Bang
Present



Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Present day
Reionization
Fully ionized
Neutralized
Fully ionized
1000
100
10
1
1+Redshift

Size of the universe?

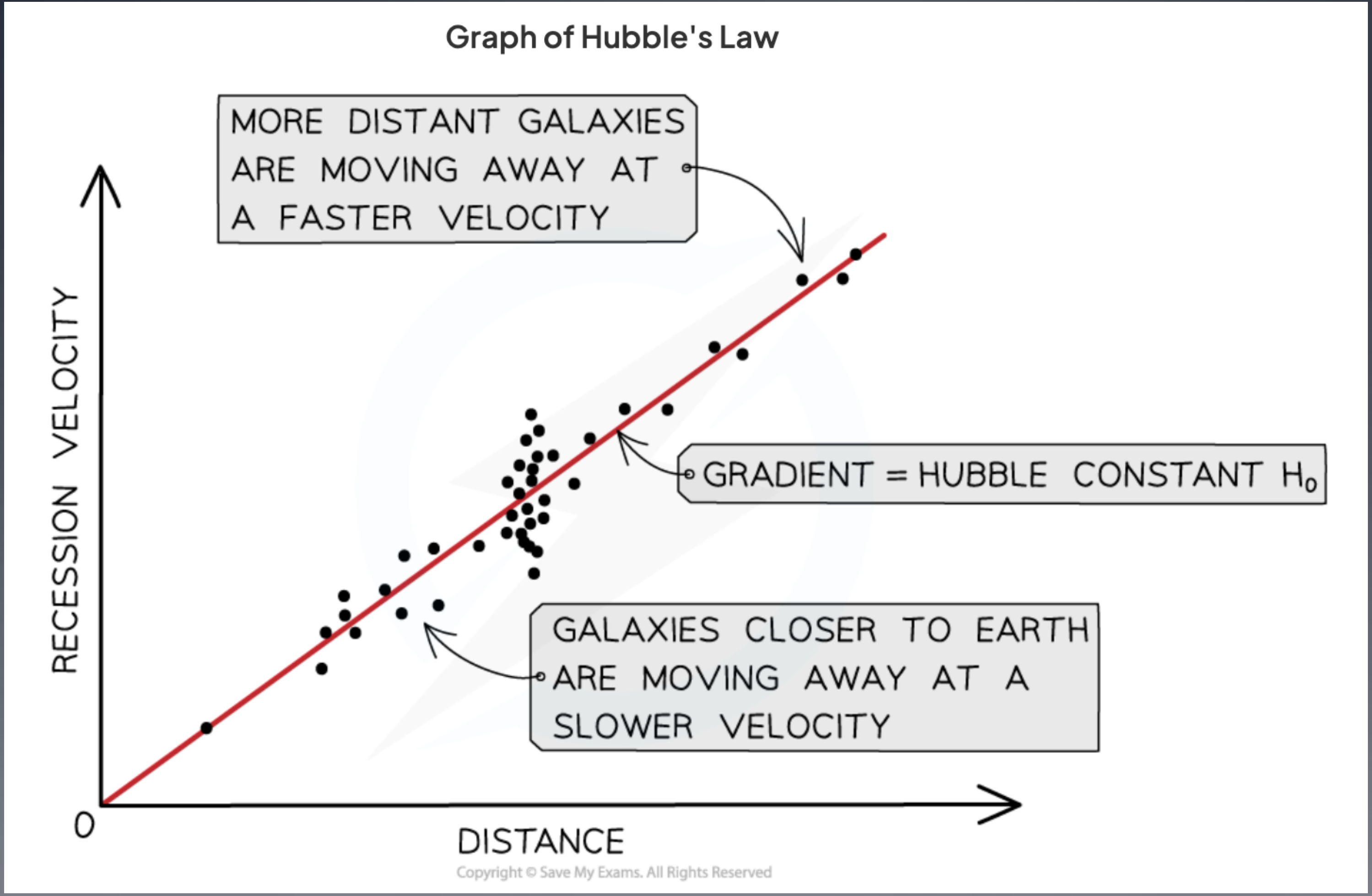
- Does the universe have a beginning? Or an edge in time?
- Or is the universe infinite?

Olbers Paradox

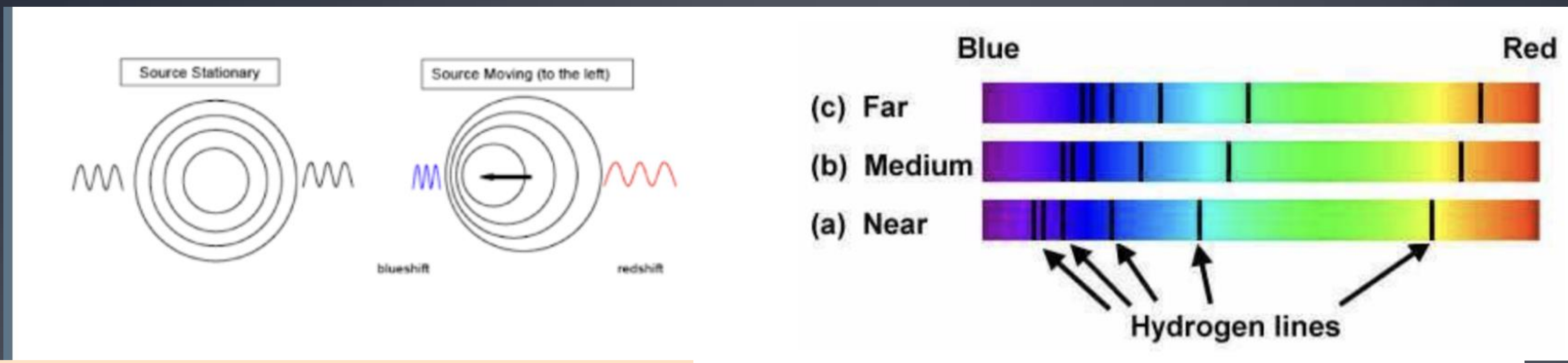
- Why is the sky dark at night?
- If the universe is
  - infinite in size
  - infinite in age
  - filled with stars
- then as we look out into a larger volume, number of stars increases. The entire sky would be as bright as a star

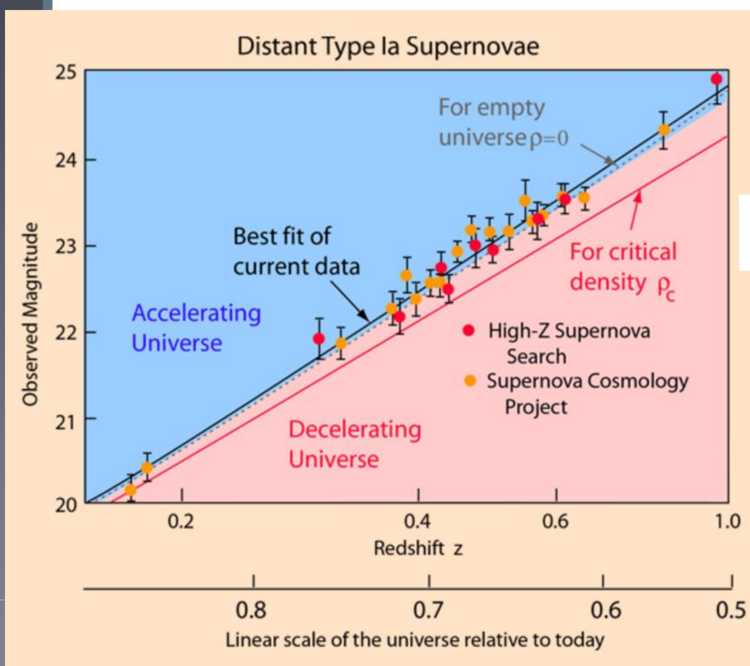
One of the assumptions must be wrong

Solution: Universe is expanding



Solution: Universe is expanding



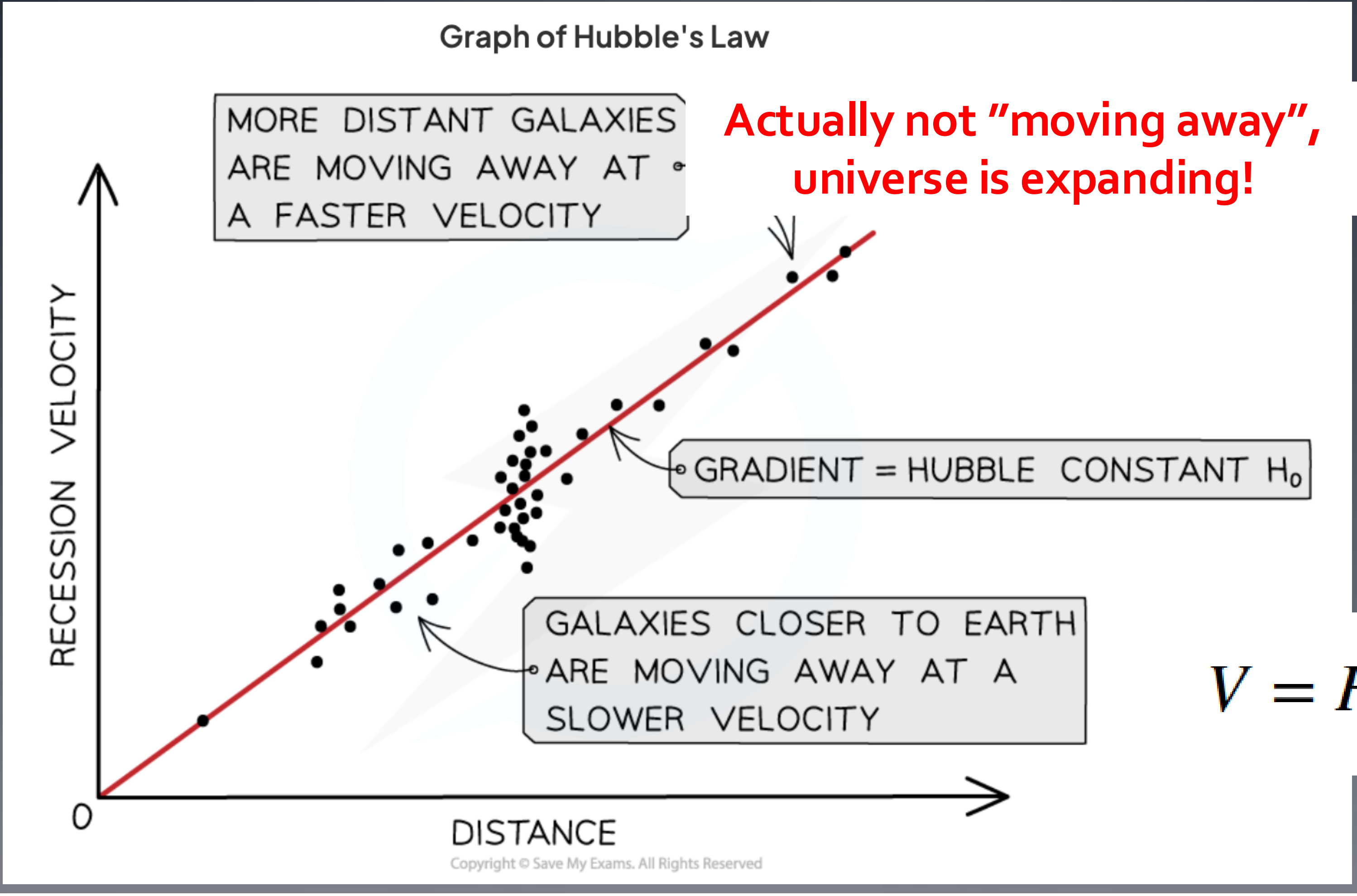


y-axis: redshift

x-axis: distance

$$V = H \times d$$

Solution: Universe is expanding

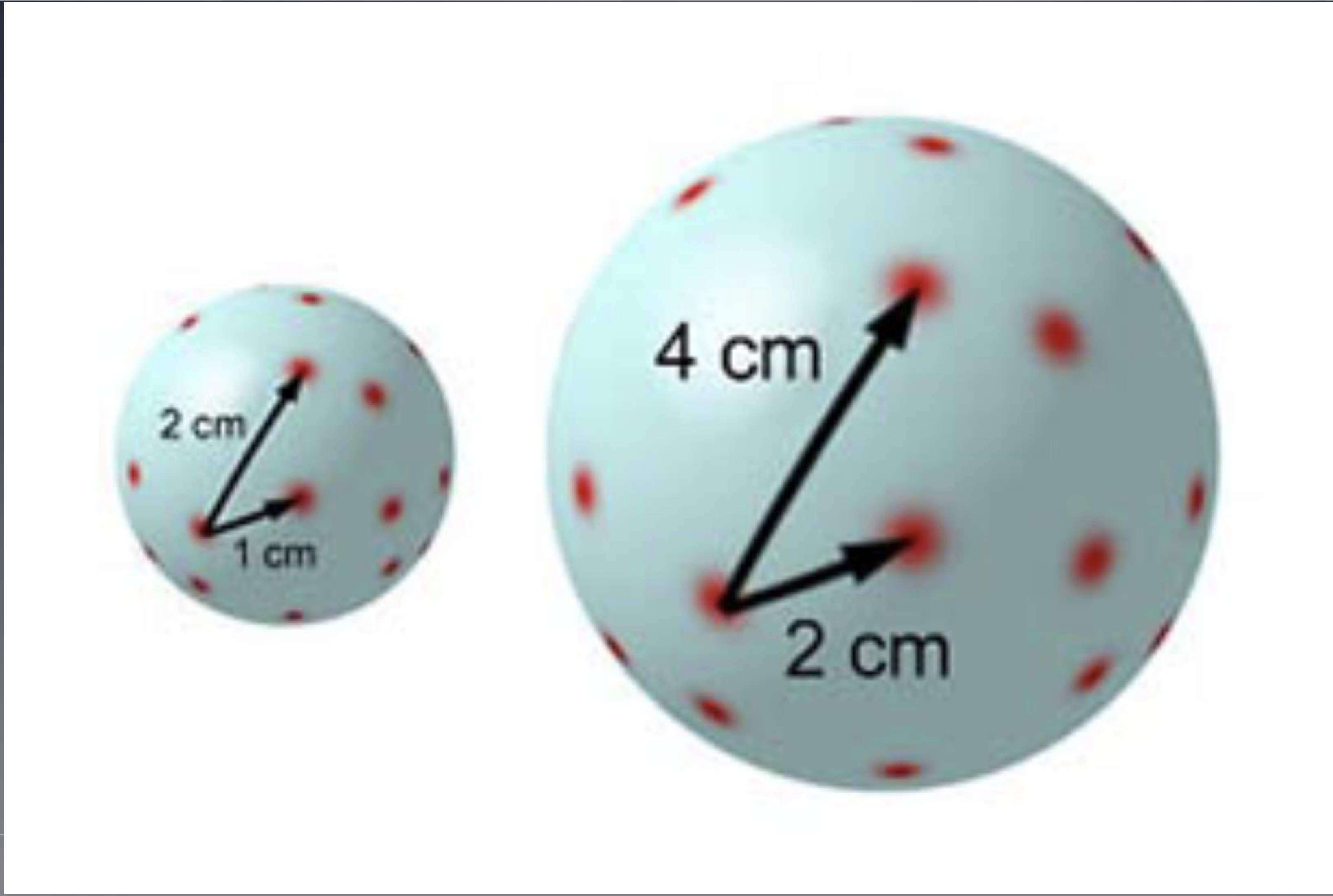


Actually not "moving away", universe is expanding!

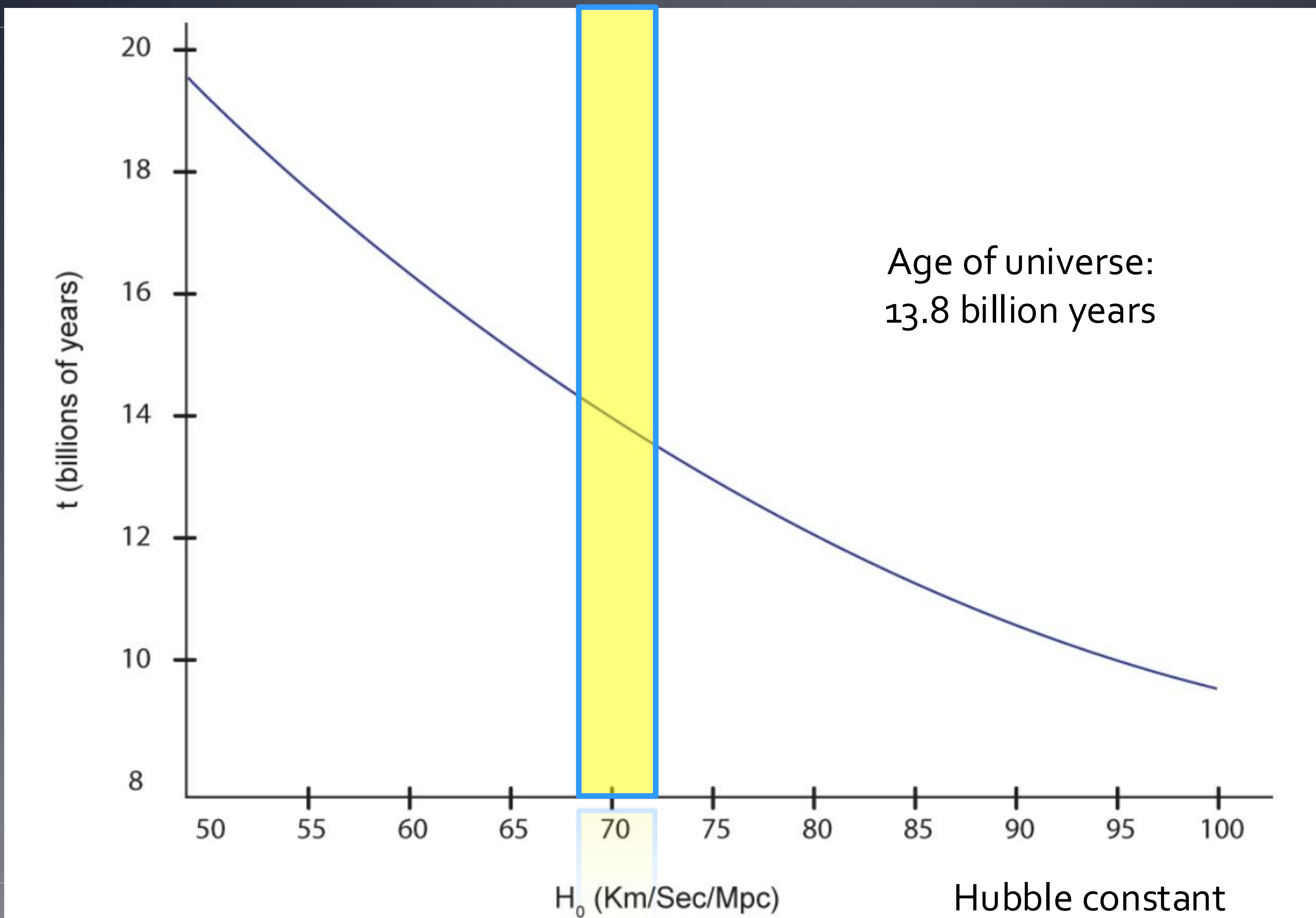
$$V = H \times d$$

Are we in a special place? If not, then universe is expanding everywhere!

Solution: Universe is expanding



Age of the universe



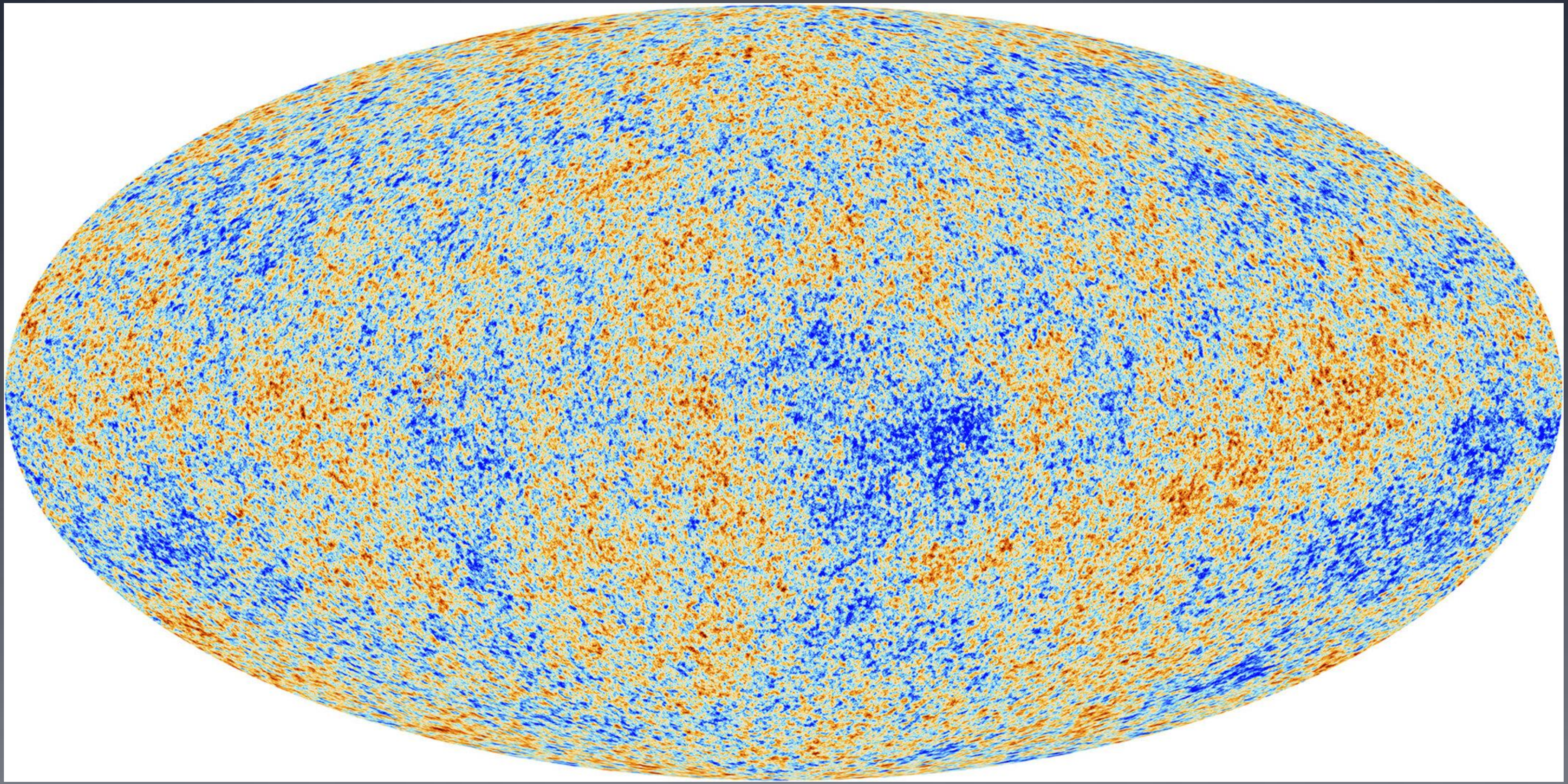
Big Bang!

- Exrapolate back to explosion of space-time: 13.8 billion years ago
- All universe in same place

Evidence for the Big Bang

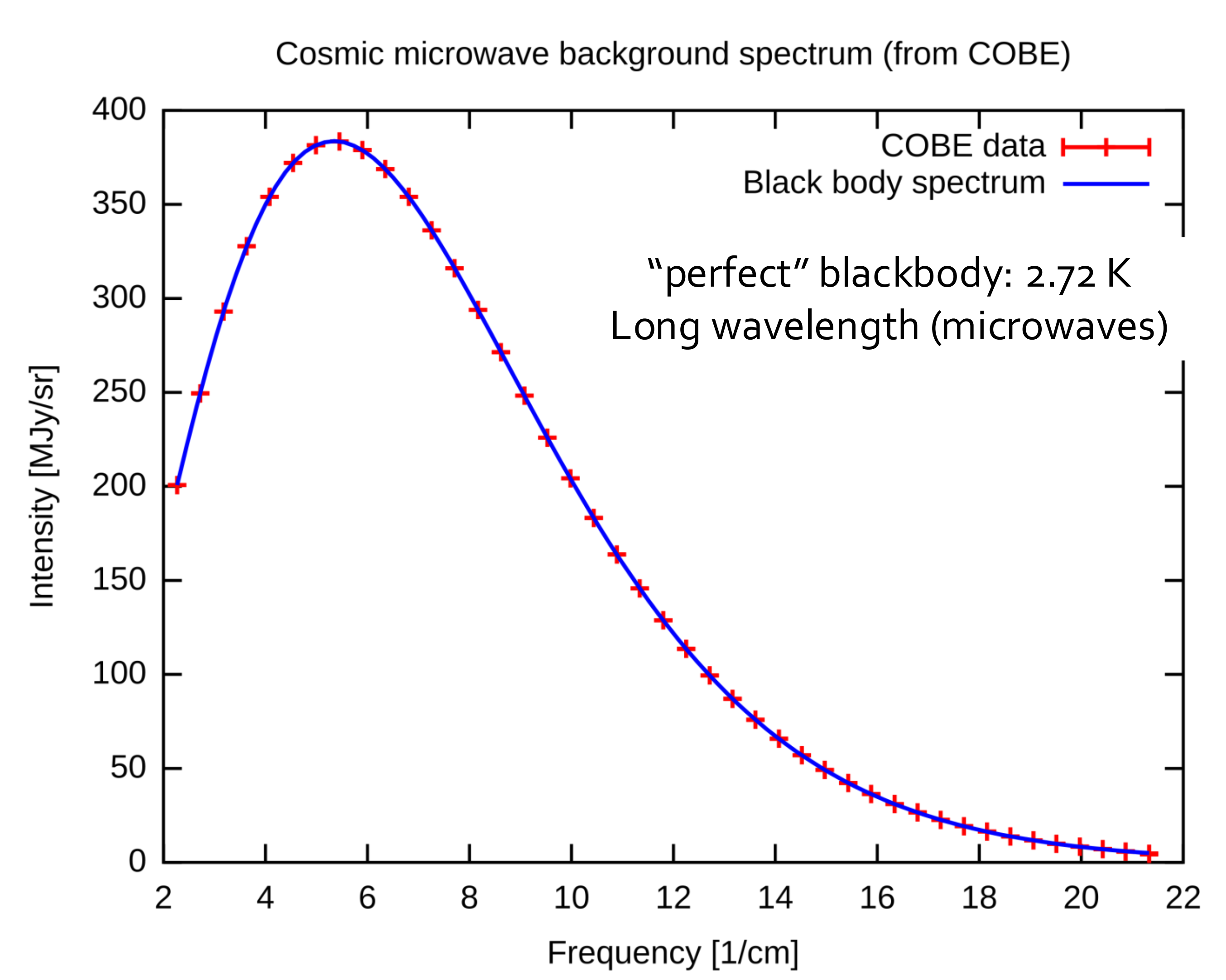
- Cosmic expansion (Hubble's law)
- Cosmic Microwave Background
- D, He3 Li elemental abundances
- Galaxy evolution

Cosmic microwave background



Initially discovered by Penzias & Wilson
Near-uniform microwave background (smooth to 1 part in 10^4)

Cosmic microwave background

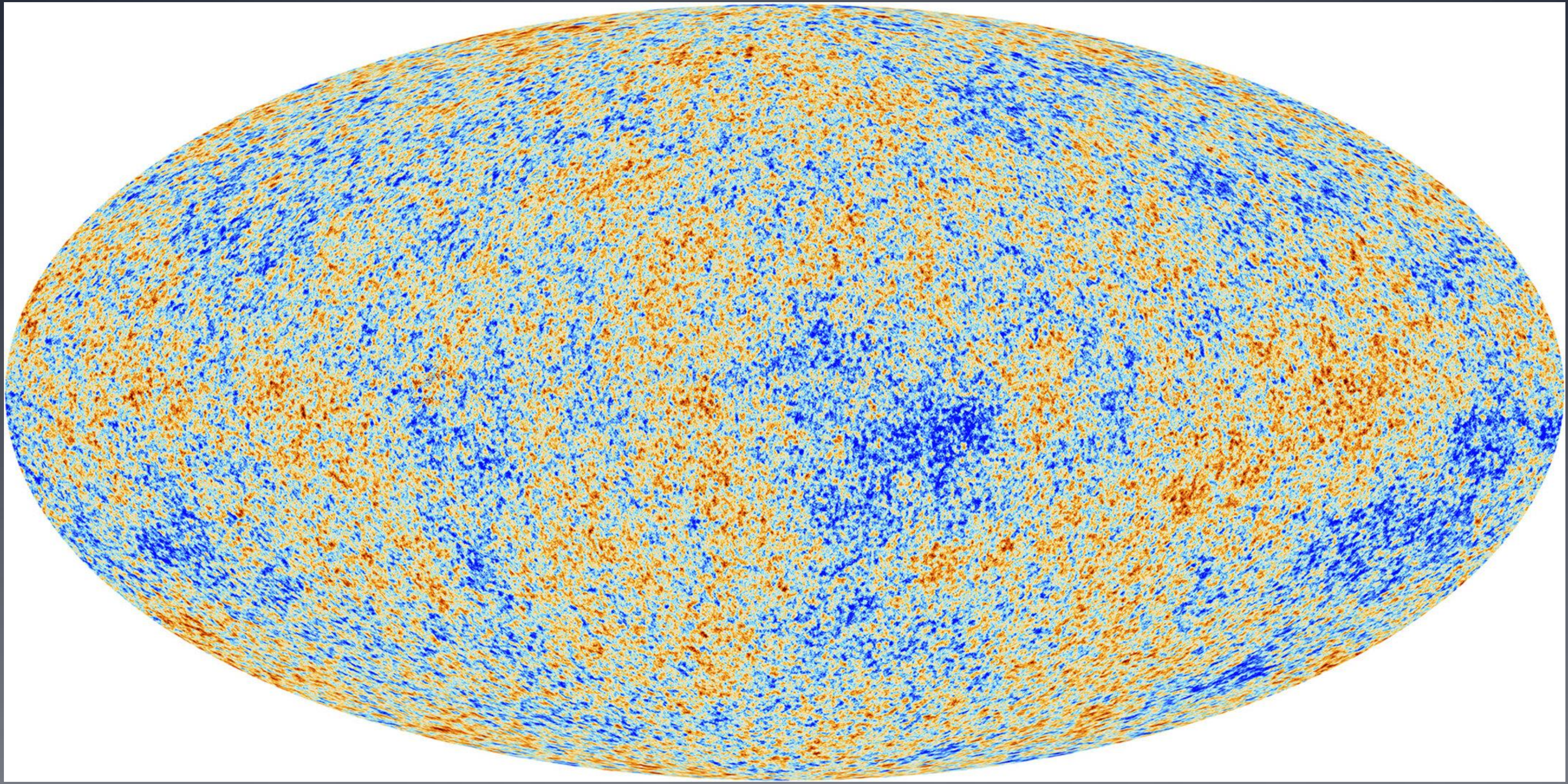


"perfect" blackbody: 2.72 K
Long wavelength (microwaves)

Cosmic microwave background

- Early universe was hot and fully ionized!
- Electrons absorb photons: no photons could escape
- Universe cools, electrons+protons => atoms
  - Recombination
  - Occurs at 3000 K
- We see photons from surface of last scattering
  - 4000 K redshifted to 2.72 K
  - Universe was 380,000 years old
  - $T_r = 2.725 \text{ K} \times (1 + z)$; z~1,100

Cosmic microwave background

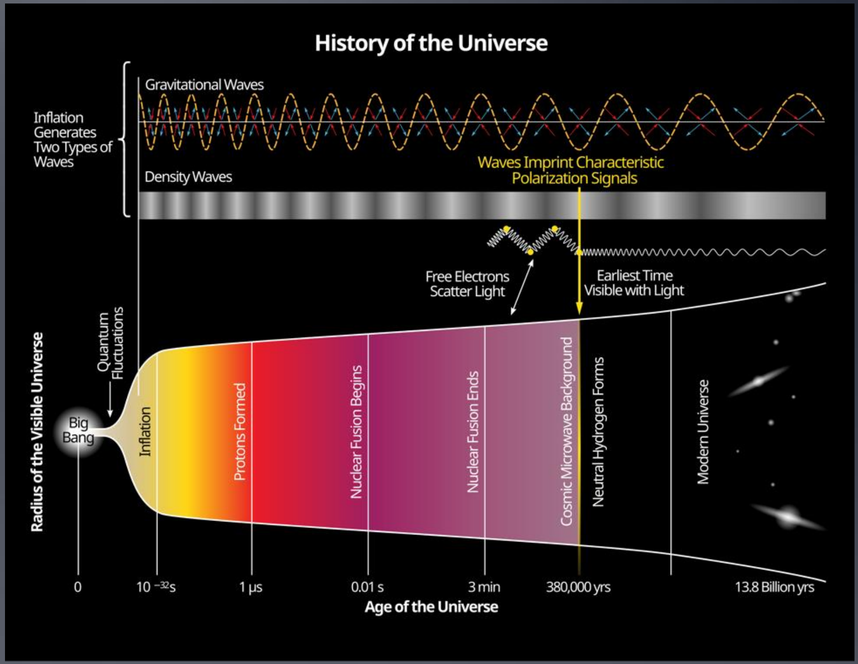


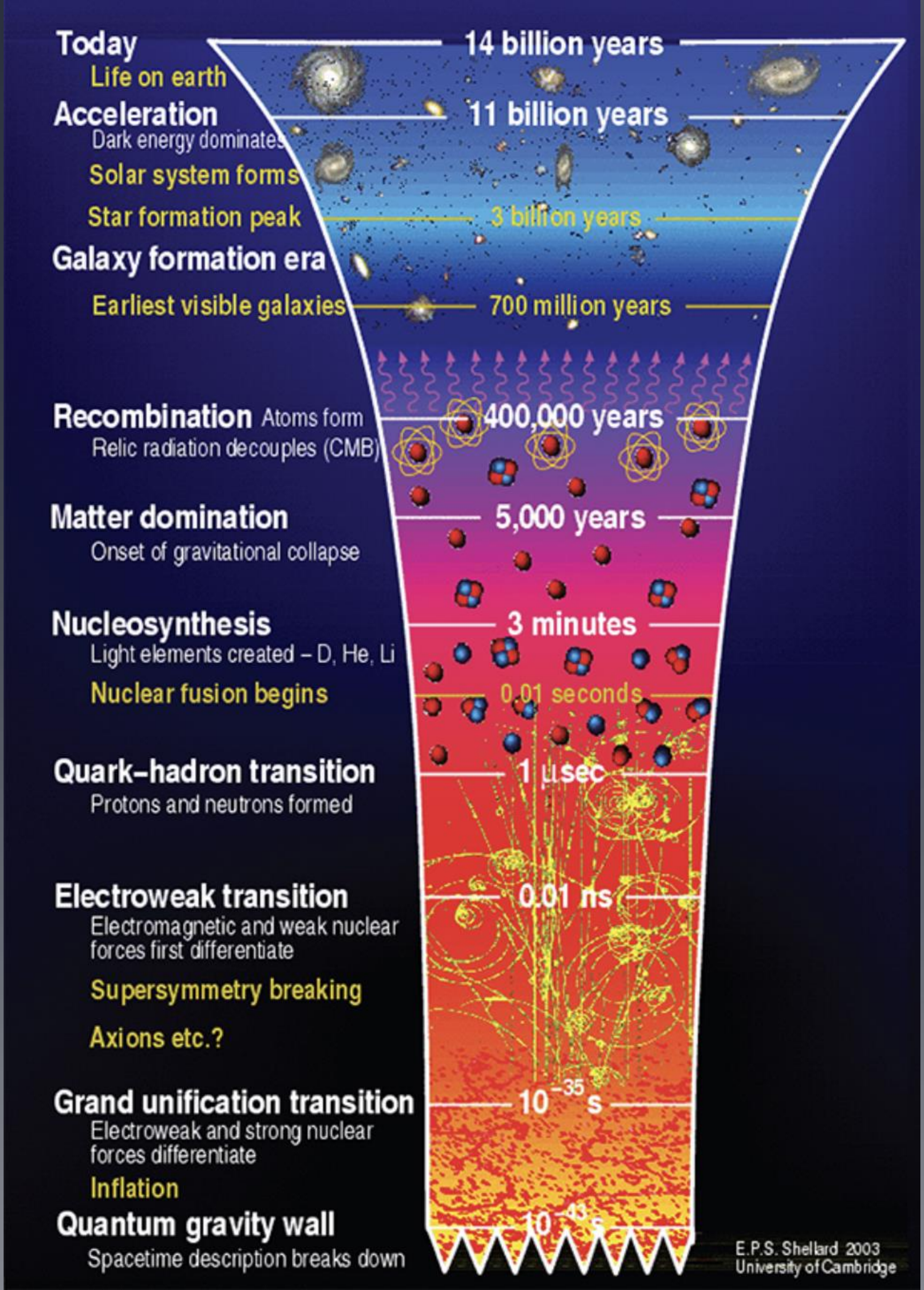
Near-uniform microwave background (smooth to 1 part in 10^4)

But not perfect: anisotropies!

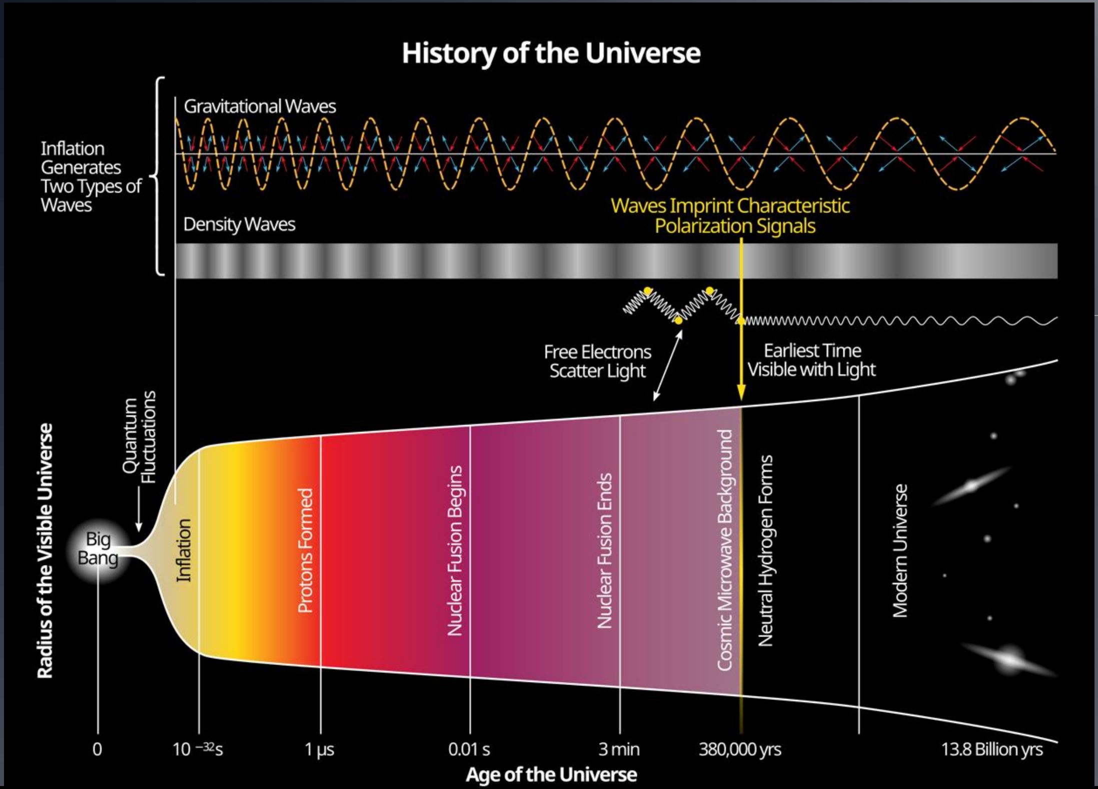
History of Universe

- Planck epoch: 1e-43 s; $T=10^{32}$ K;
  - universe was energy
  - universe was smaller than a proton
- Universe expands as cools
- Inflation: from 10^{-36} to 10^{-32} s
  - the universe expands by a factor of 10^{78}!
  - Quantum fluctuations expand
  - All structures from those fluctuations
- 10^{-12} to 10^{-5} s: quark soup!
- 0.01 s: protons/anti-proton annihilation
  - Excess of particles (1 in 30 million)
- 10-1000 s: nucleosynthesis (H, He, plus D, He-3, Li-7)
- Photon epoch: 10 s – recombination (T cools from 10^9 K to 4000 K)
- Recombination: p+e- => neutral H
- Dark ages: recombination until the first stars
- First stars/galaxy formation: 300-400 Myr

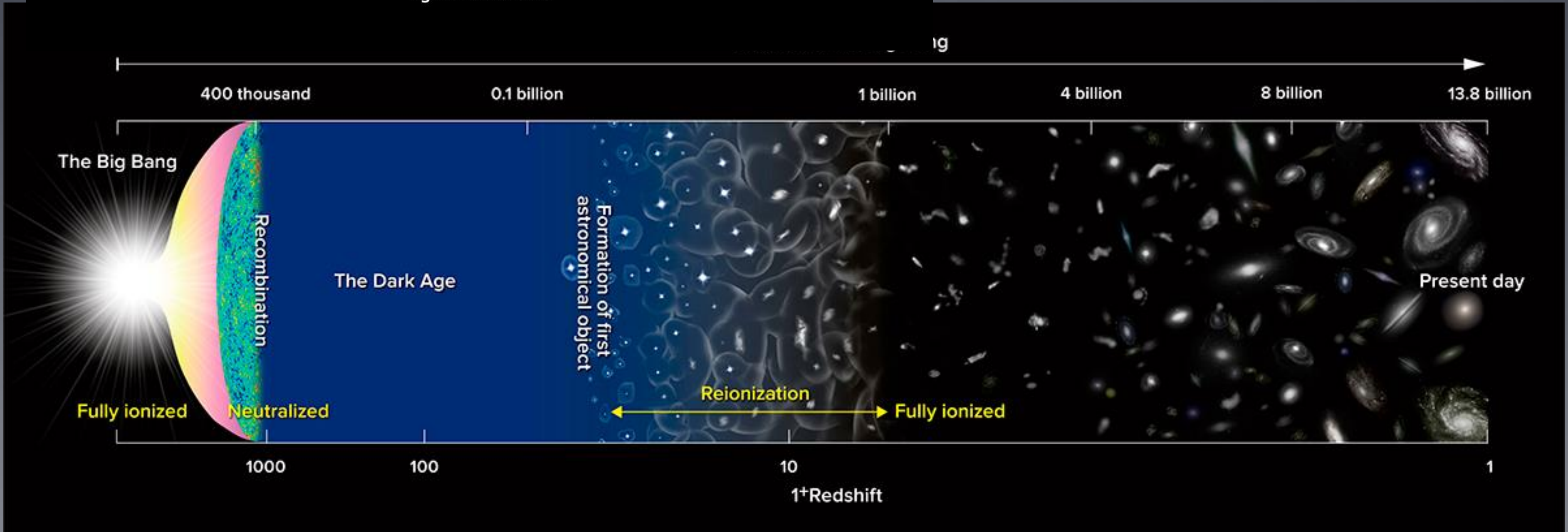




Today
Life on earth
Acceleration
Dark energy dominates
Solar system forms
Star formation peak
Galaxy formation era
Earliest visible galaxies
Recombination Atoms form
Relic radiation decouples (CMB)
Matter domination
Onset of gravitational collapse
Nucleosynthesis
Light elements created – D, He, Li
Nuclear fusion begins
Quark–hadron transition
Protons and neutrons formed
Electroweak transition
Electromagnetic and weak nuclear forces first differentiate
Supersymmetry breaking
Axions etc.?
Grand unification transition
Electroweak and strong nuclear forces differentiate
Inflation
Quantum gravity wall
Spacetime description breaks down
14 billion years
11 billion years
3 billion years
700 million years
400,000 years
5,000 years
3 minutes
0.01 seconds
1 µsec
0.01 ns
10^{-35} s
10^{-43} s
E.P.S. Shellard 2003
University of Cambridge

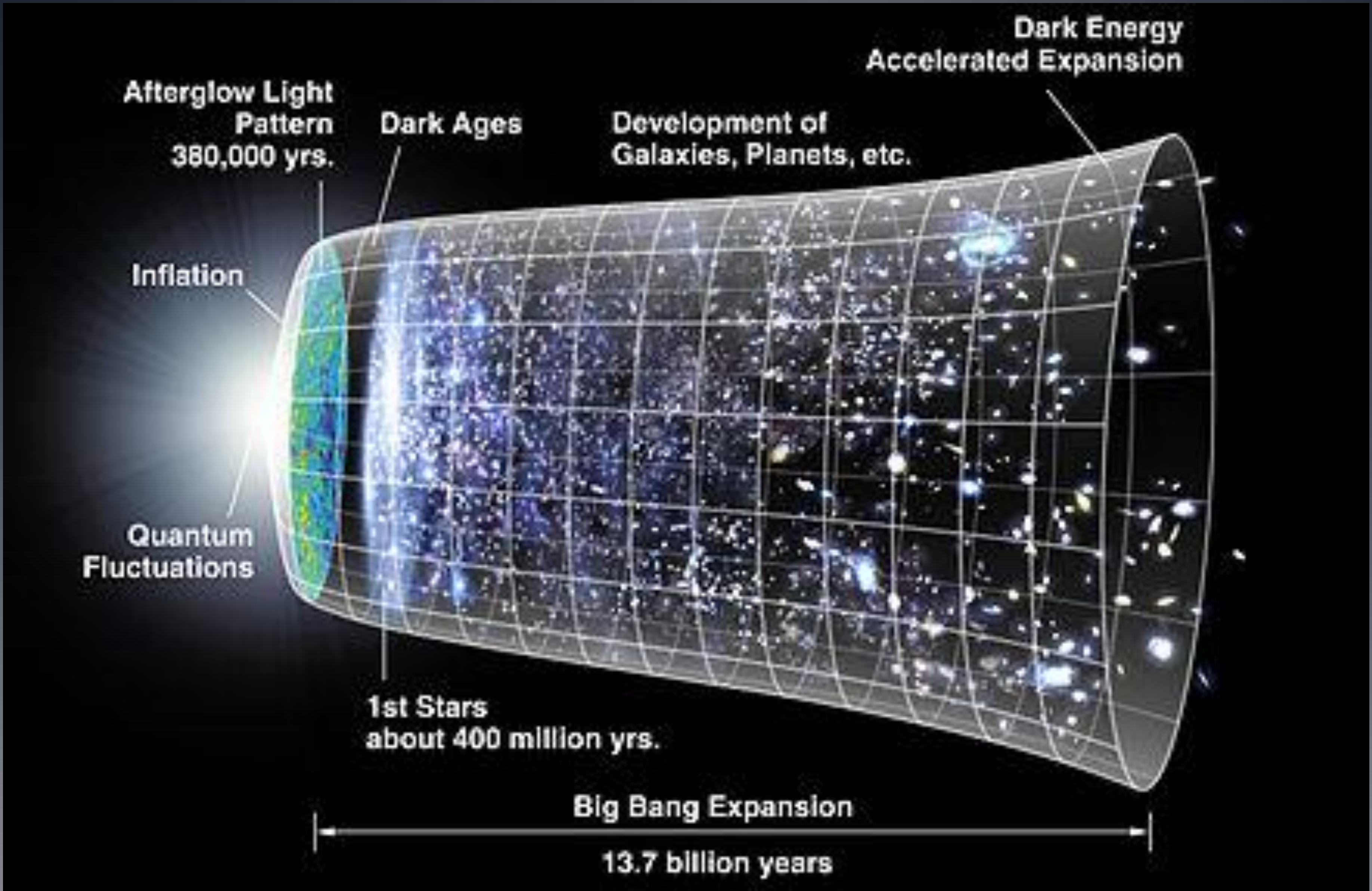


History of the Universe
Gravitational Waves
Inflation Generates Two Types of Waves
Density Waves
Waves Imprint Characteristic Polarization Signals
Free Electrons Scatter Light
Earliest Time Visible with Light
Radius of the Visible Universe
Quantum Fluctuations
Big Bang
Inflation
Protons Formed
Nuclear Fusion Begins
Nuclear Fusion Ends
Cosmic Microwave Background
Neutral Hydrogen Forms
Modern Universe
0
10 −32s
1 µs
0.01 s
3 min
380,000 yrs
13.8 Billion yrs
Age of the Universe



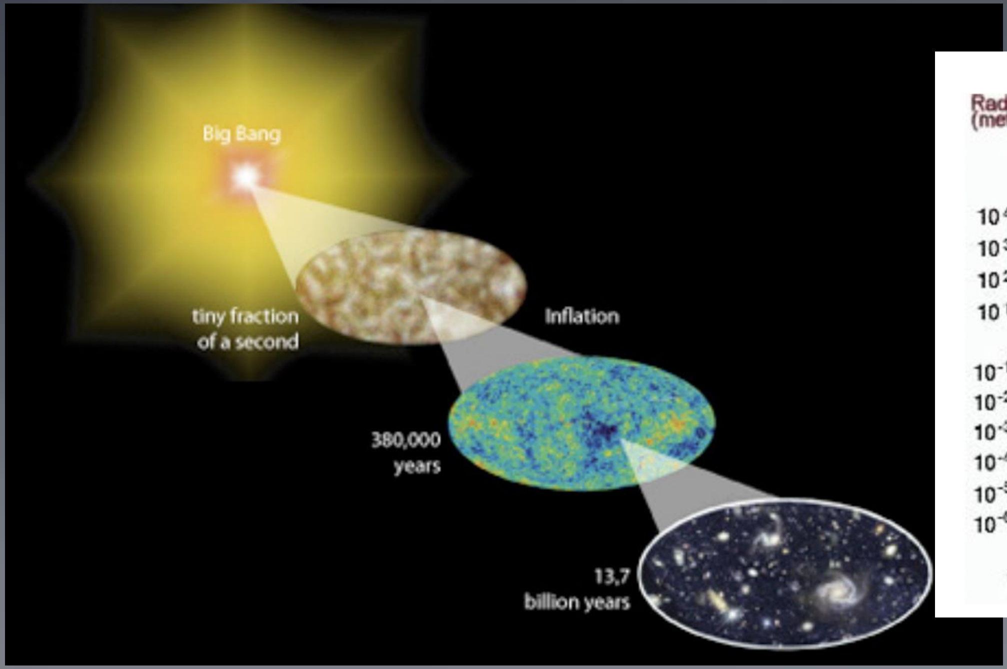
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Present day
Fully ionized
Neutralized
Reionization
Fully ionized
1000
100
10
1
1+Redshift

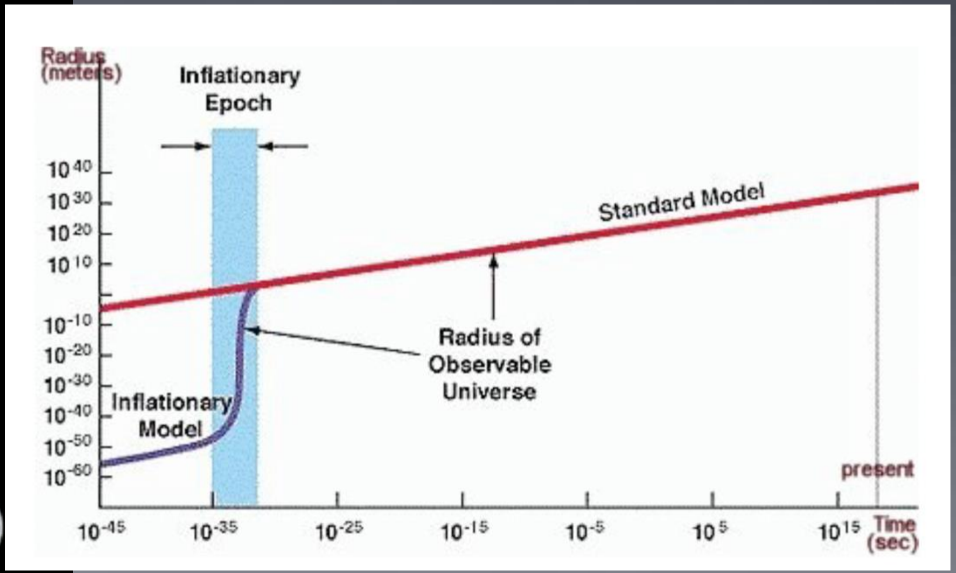
Cosmology in a single plot



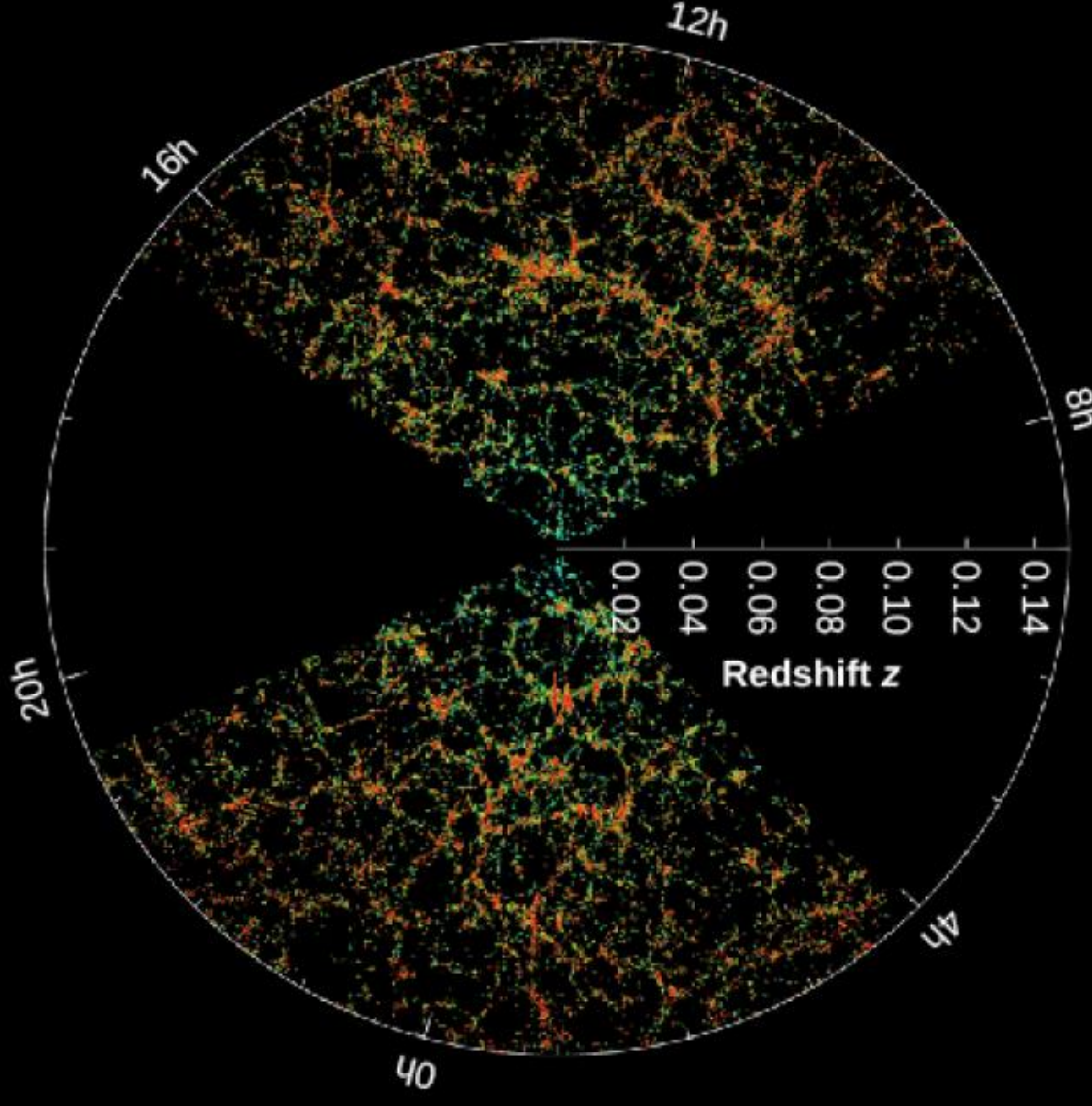
Inflation: from 10^{-36} to 10^{-32} s

- The universe expands by a factor of 10^{78}!
- All irregularities get smoothed out
- Tiny quantum fluctuations grow to become galaxy clusters



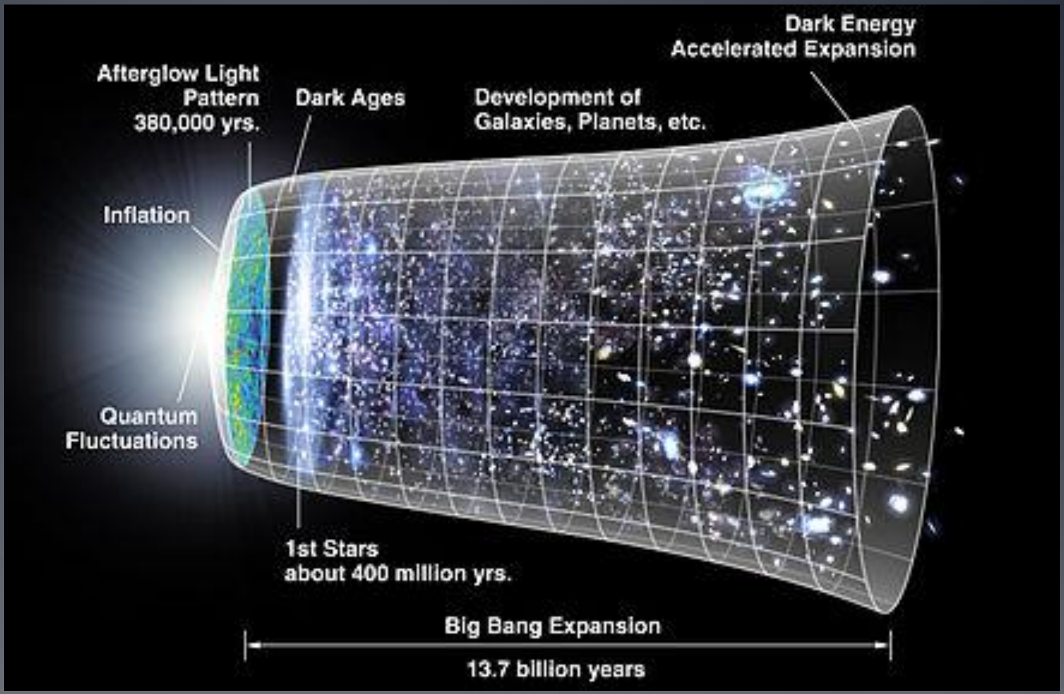


3D map of the universe: clusters and voids



First stars after dark ages

- Only H and He
- Can only form massive stars
  - From models
- 100-1000 Msun
  - Burn H quickly
- Quickly seed universe with heavier elements



- Searches for first stars:
  - low "metallicity" stars in Milky Way
  - Very bright stars in early universe

Evidence for Big Bang

- Cosmic Expansion/Hubble's Law
- Cosmic Microwave Background
- Abundances of light elements
- Evolution of galaxy structures

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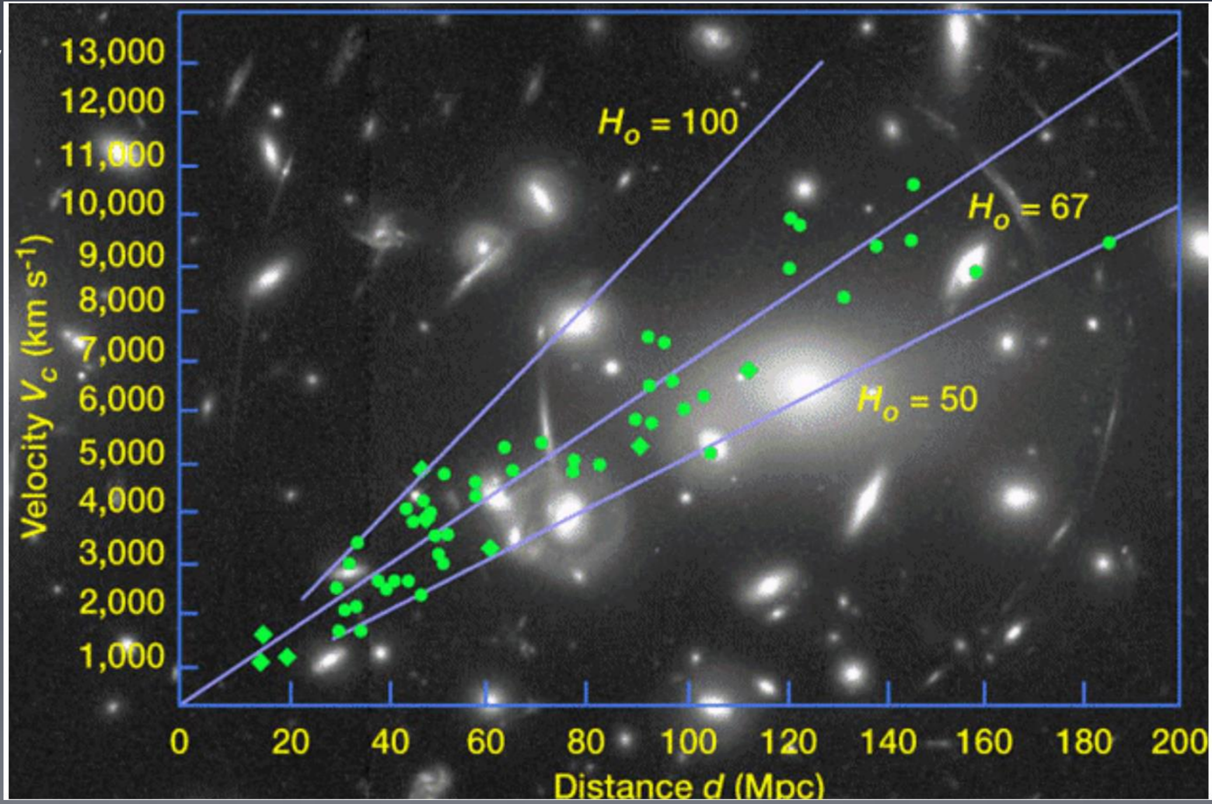

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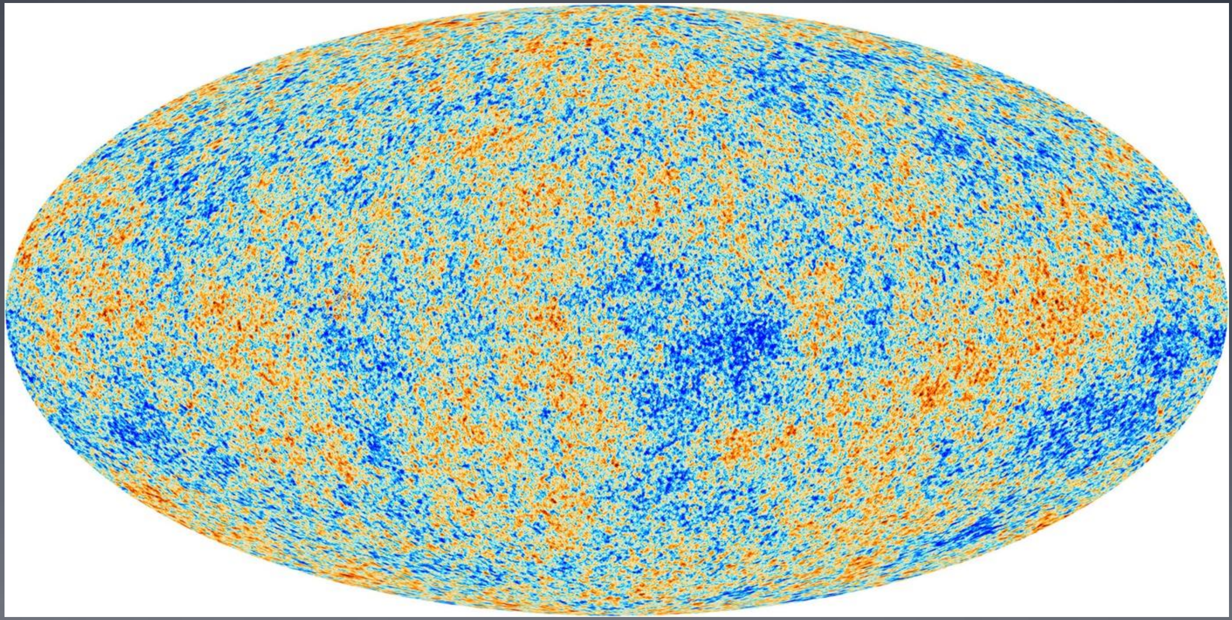

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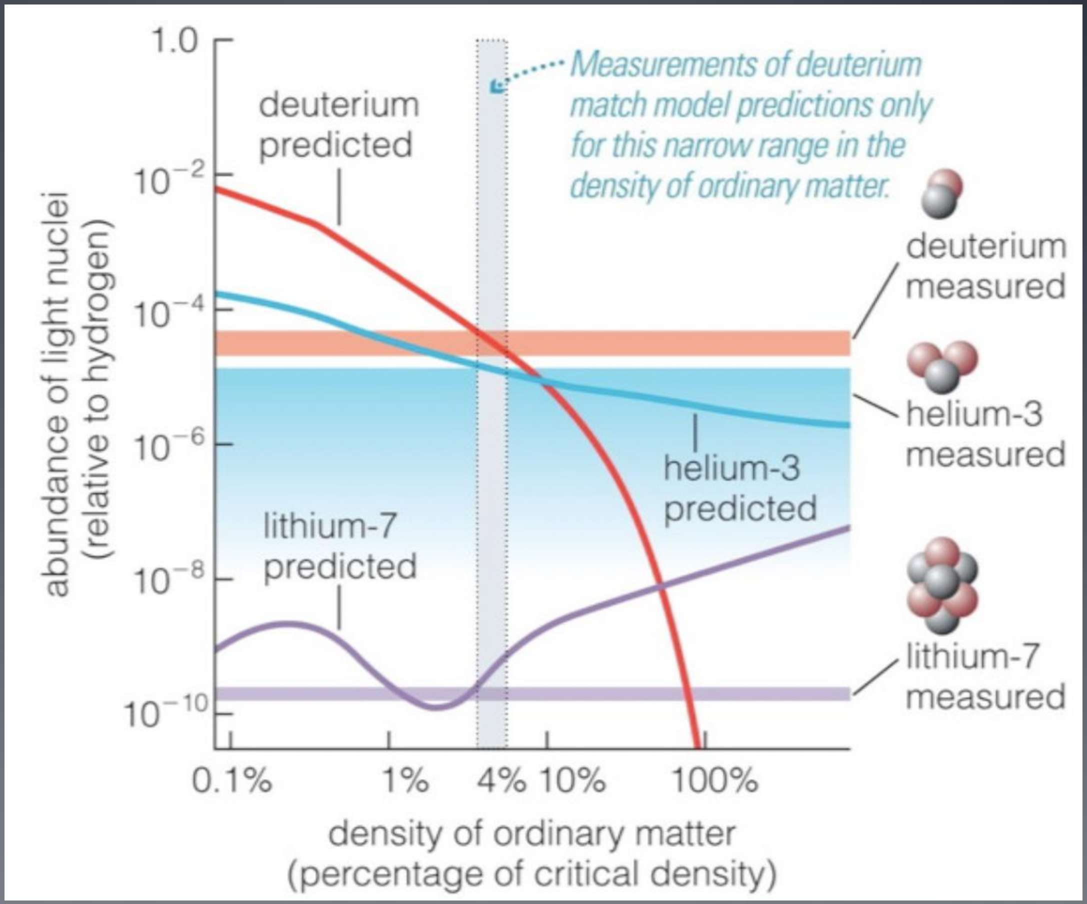

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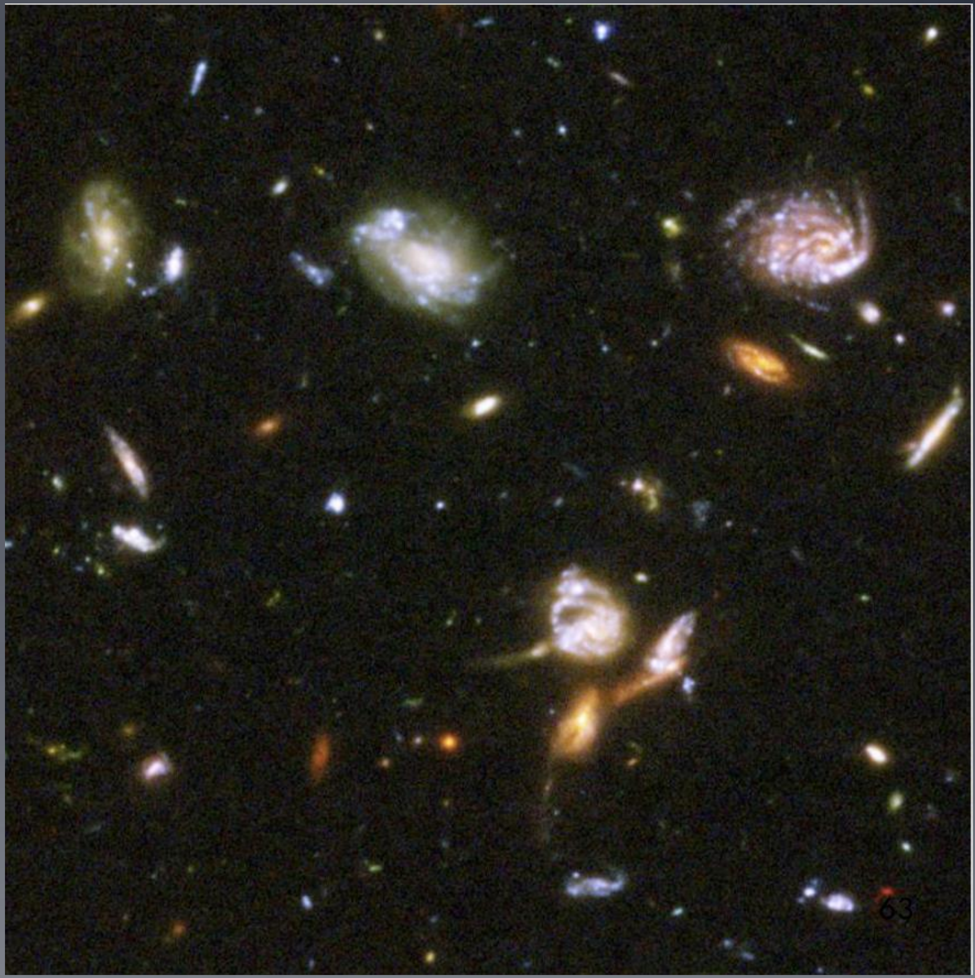
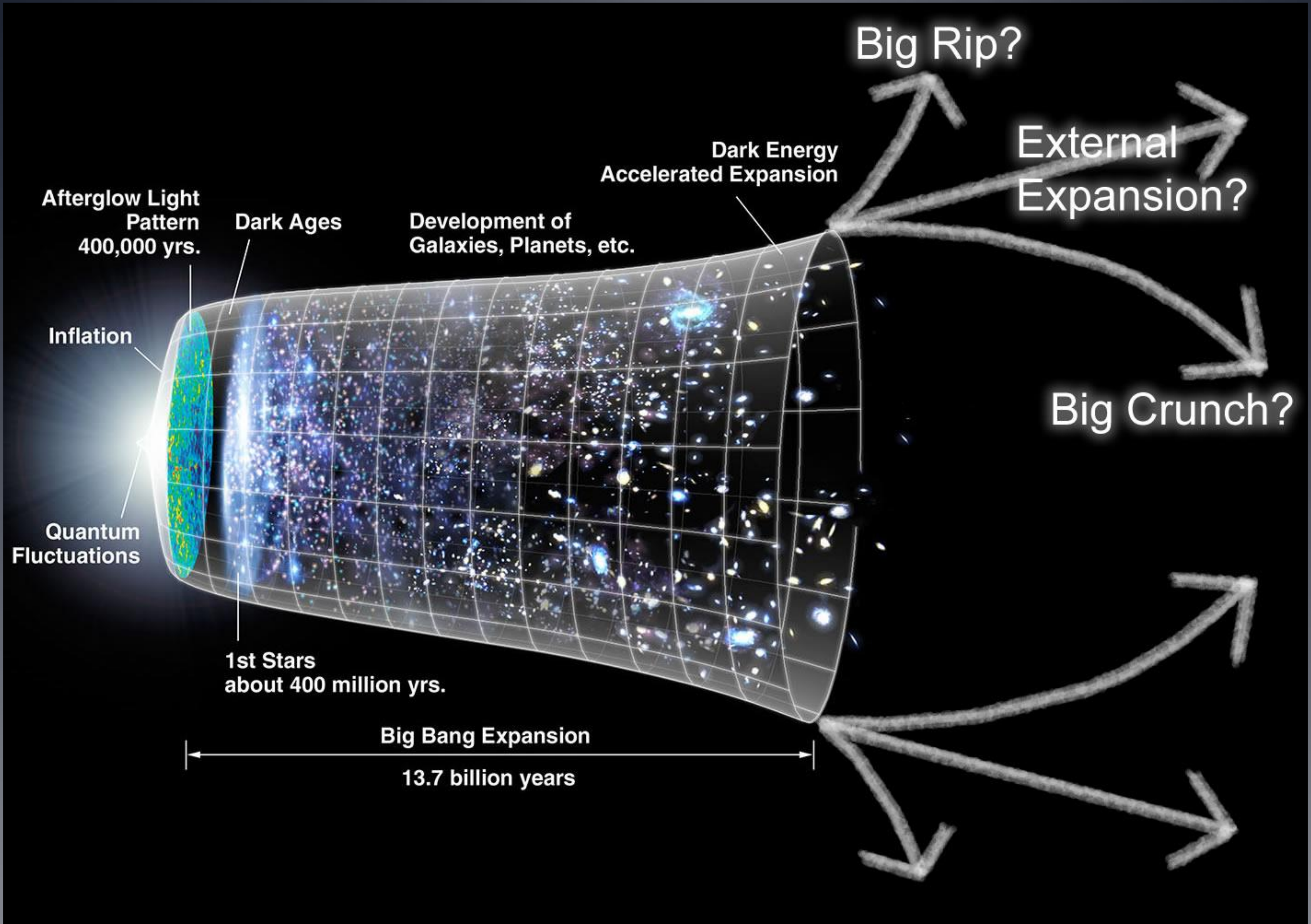


Cosmological Future: the fate of the universe?



Is there enough mass to overcome expansion?

- Universe is accelerating
- Can gravity (long-distance) overcome the acceleration?

Is there enough mass to overcome expansion?

- Universe is accelerating
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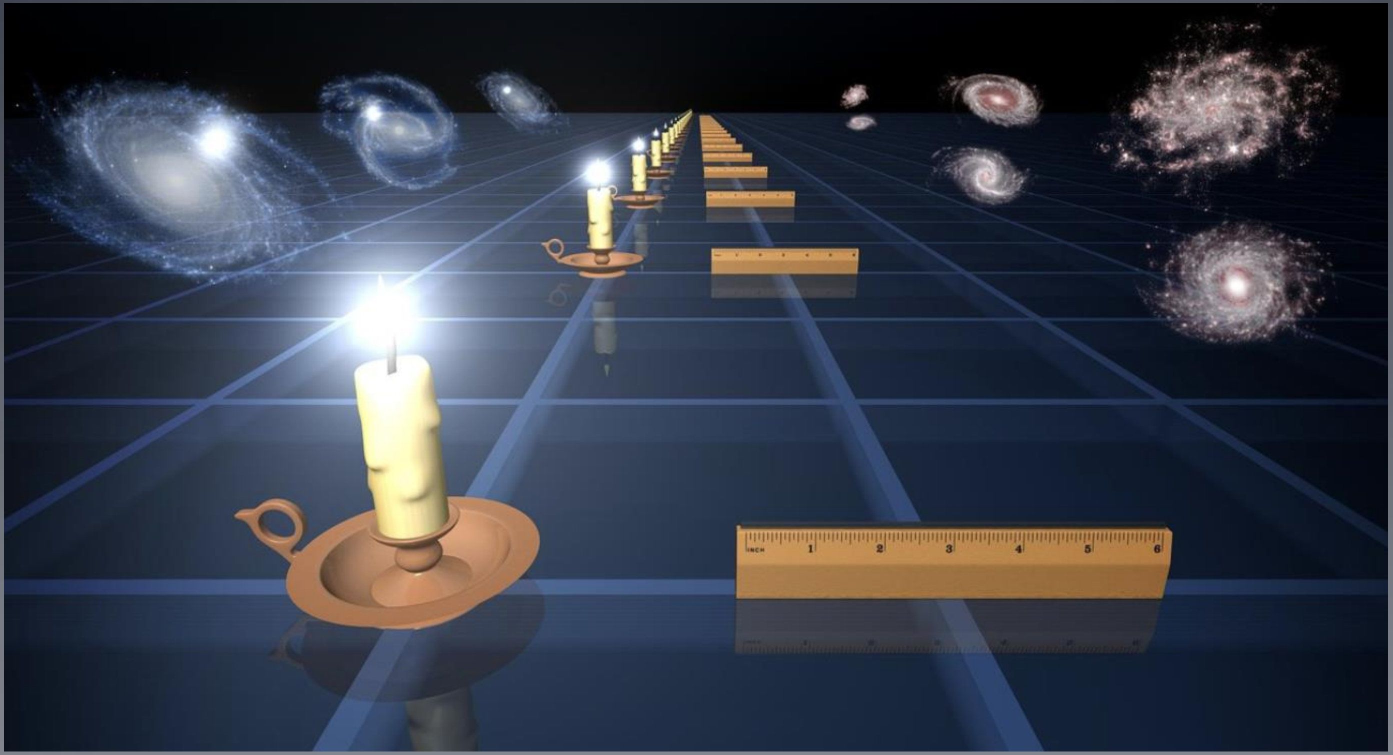
How do we measure mass?

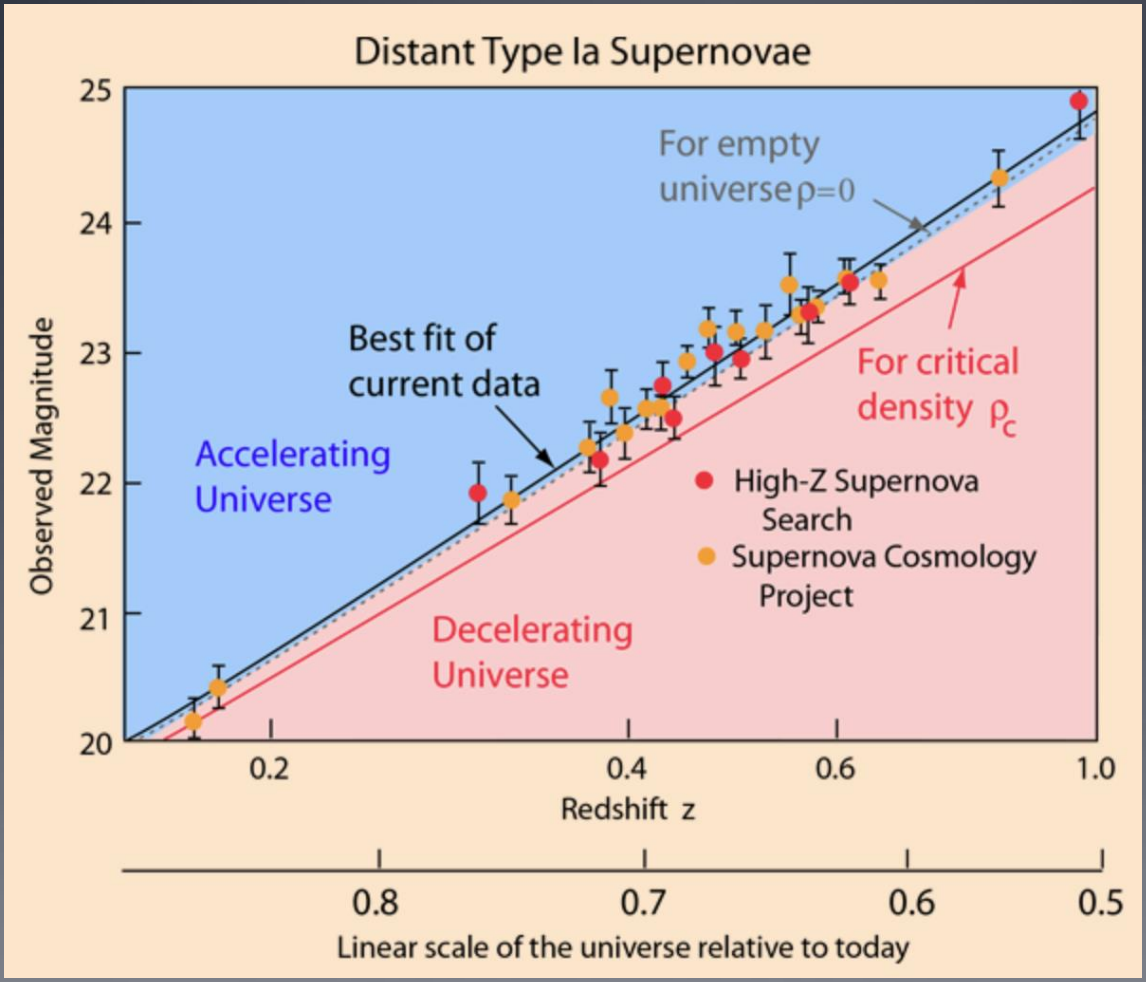
- Starlight (mass in stars, gas)
- Galactic rotation curves
- Gravitational lensing

Type 1a supernova as standard candles

- White dwarf explosions
- Over 1.4 Msun (Chandrasaekher mass)
- Always same luminosity (after corrections)

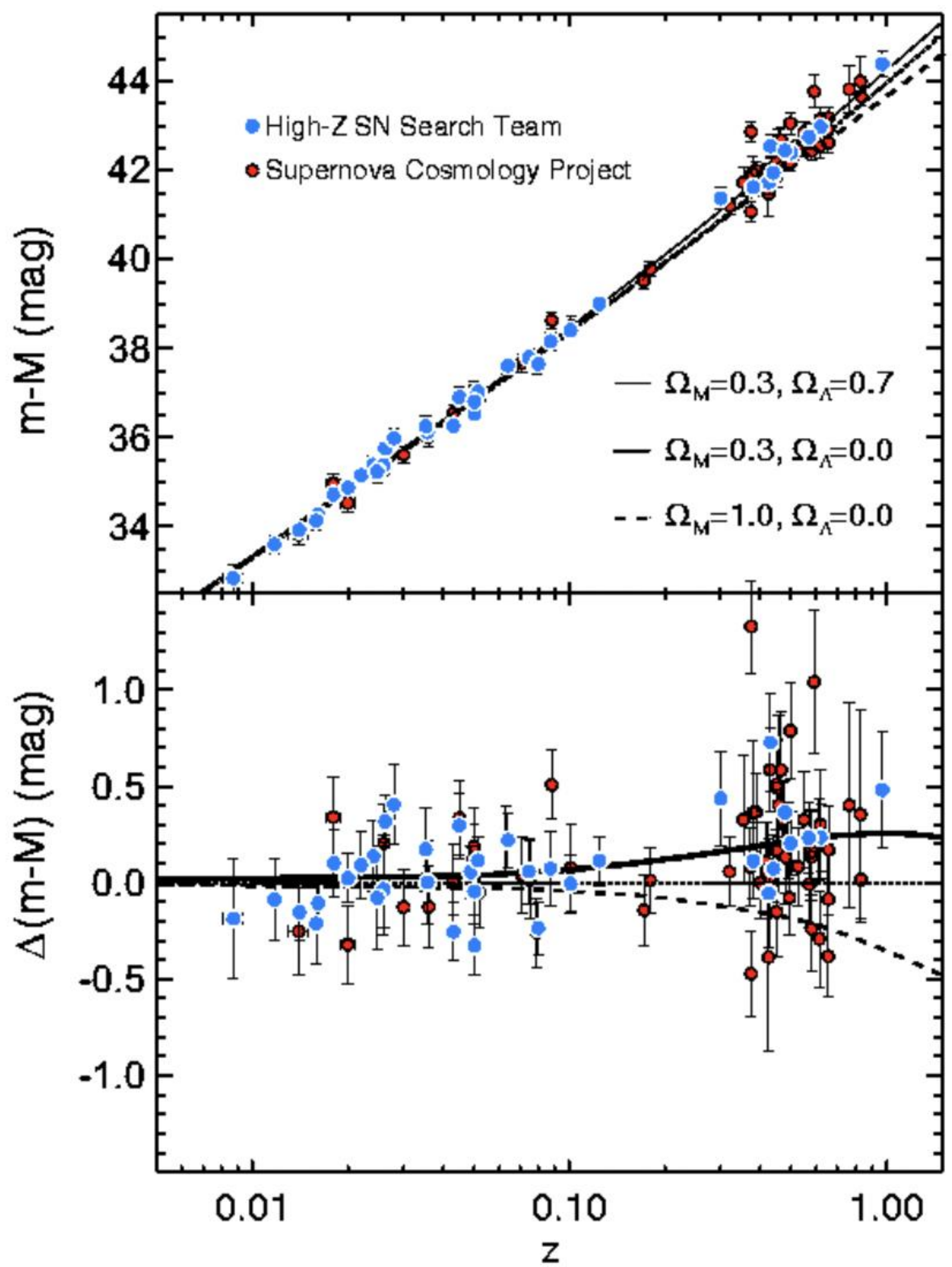


Type 1a Supernova: expansion of universe is accelerating!



Type 1a Supernova: expansion of universe is accelerating!

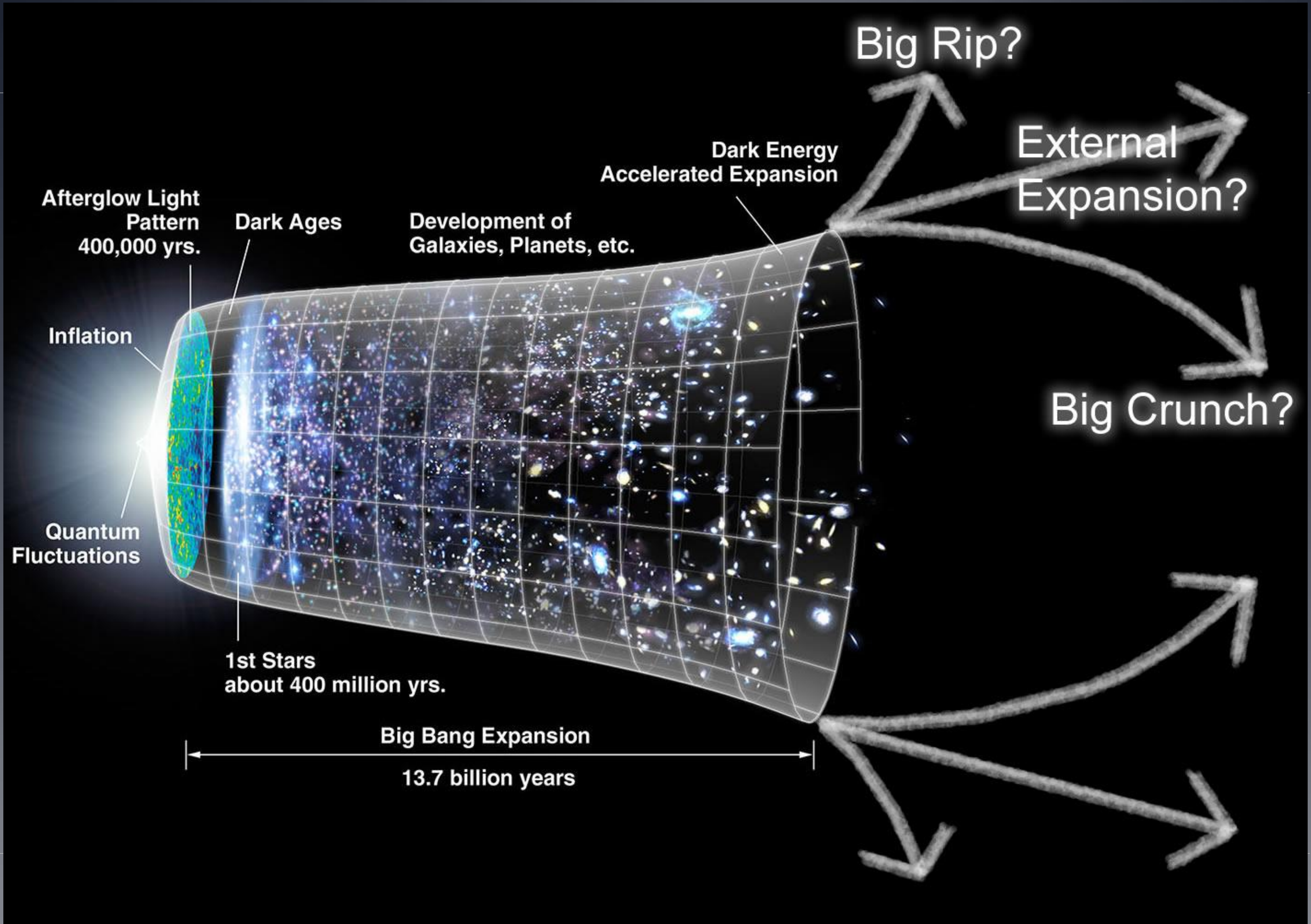
Einstein's "cosmological constant"



Dark (vacuum) energy

- Some vacuum energy leads to the expansion of the universe accelerating!
- Current model for universe: "Lambda CDM"
  - Lambda: acceleration of universe (dark energy)
  - CDM: cold dark matter

Big Rip


Big Rip?
External
Expansion?
Big Crunch?
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Big Rip (Big Chill/Heat Death): the far-future of the universe

If expansion continues to accelerate

-13.8 billion years: Big Bang
-5 billion years: Sun formed
2 billion years: people better leave Earth
5 billion years: sun evolves off main sequence
4-8 billion years: Andromeda Galaxy, Milky Way merge
100-1,000 billion years: Local Group galaxies merge
150 billion years: galaxies beyond local subcluster will pass beyond cosmological horizon (no causal interactions)
800 billion years: stars burn out, little star formation; luminosities diminish
2 trillion years: galaxies outside local supercluster not detectable
1-100 trillion years: star formation ends
1e20 years: galaxies ripped apart; stars flung out or eaten by black holes
1e50 years: protons decay, normal matter no longer exists
1e70 years: black holes evaporate
1e100 years: supermassive black holes evaporate
1e1000 years to eternity: dark era, heat death