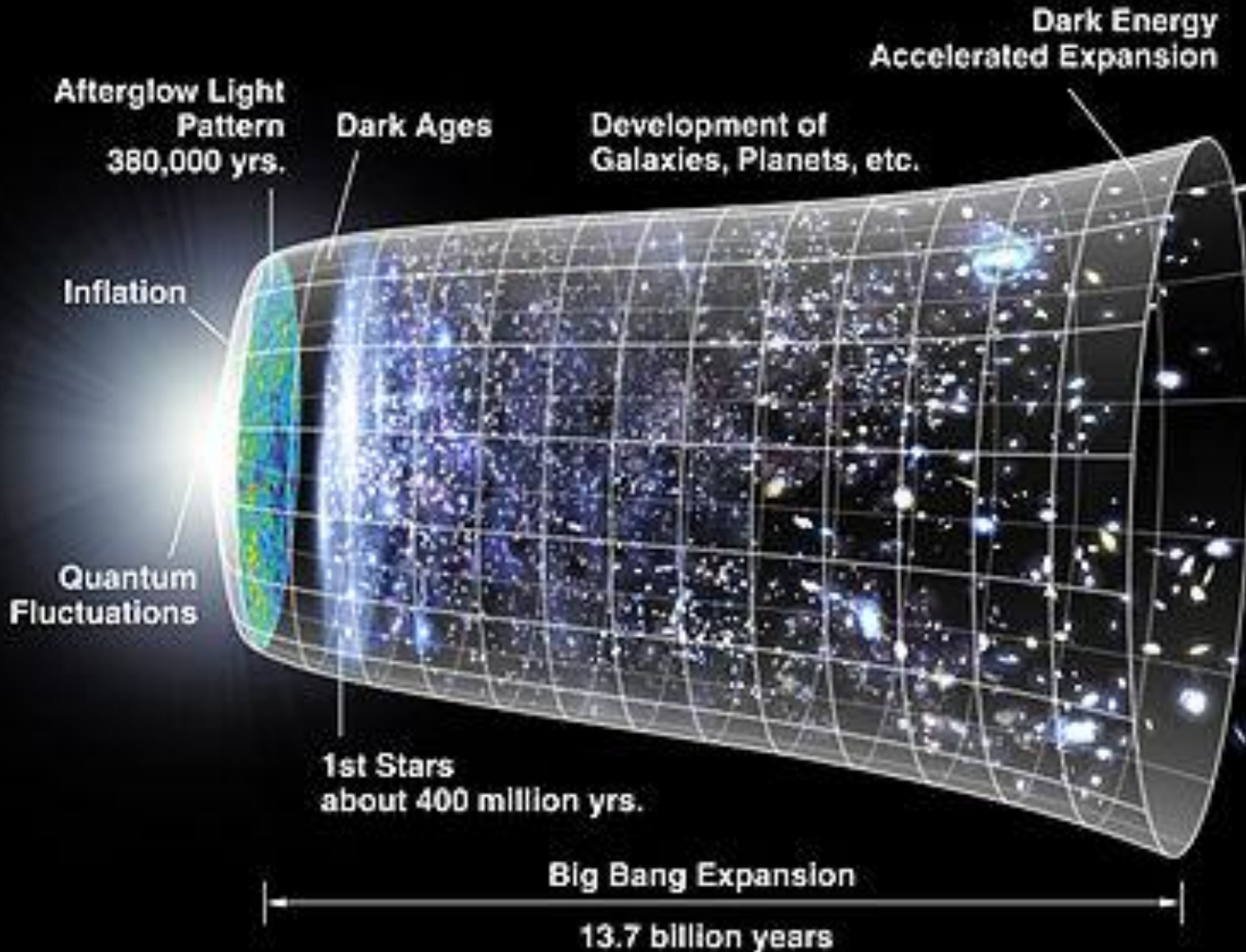


# Cosmology and the Big Bang

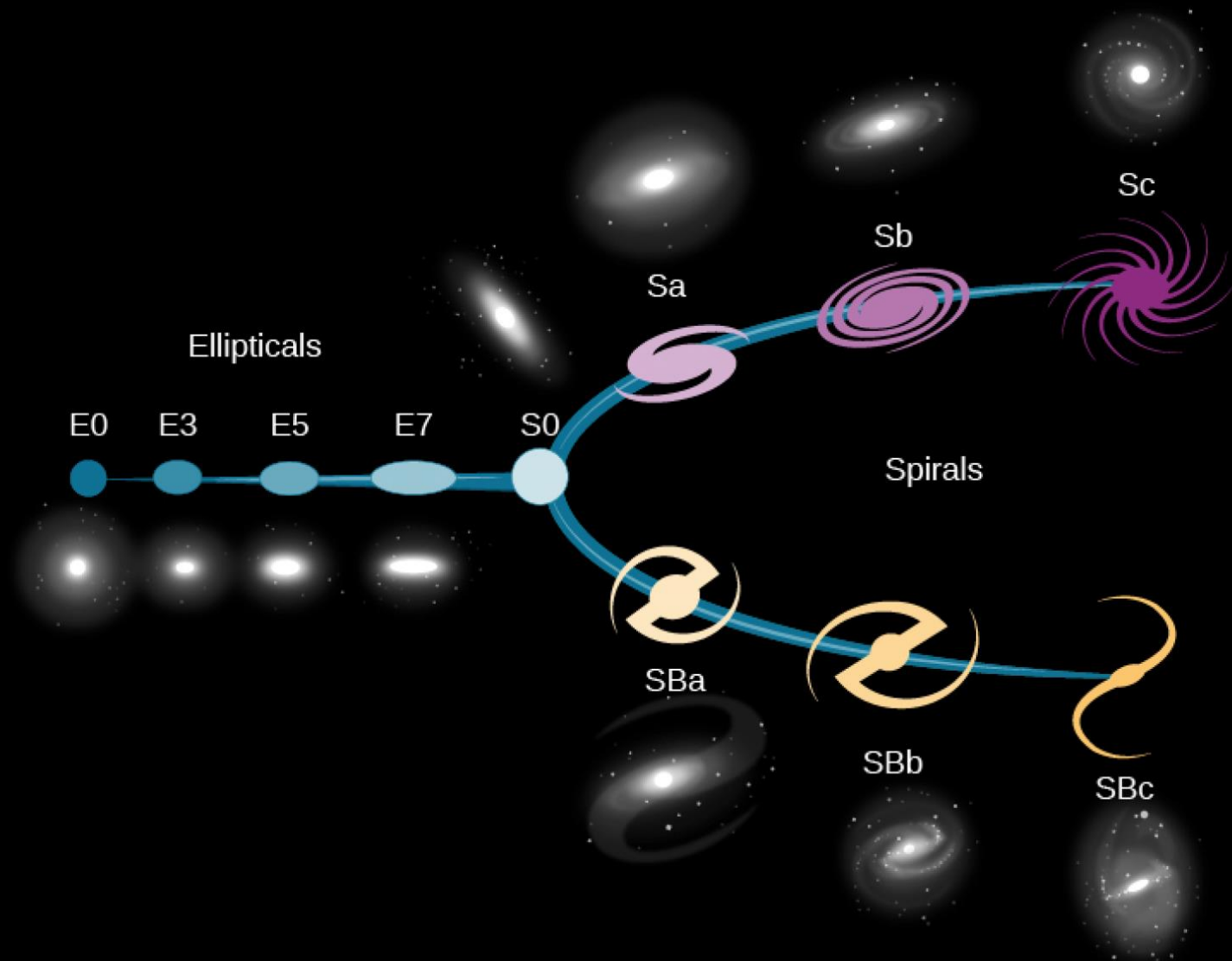


# Homeworks and projects

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- Oral Project 1: grades circulated
  - Homework due next week
    - Hand-written, turn in at the beginning of class
    - Questions?
  - Oral project 2: Citizen Science
    - Written and oral presentations
    - Due in late May (with automatic extension into early June)
  - Remember sunset photos
  - One more homework coming
-

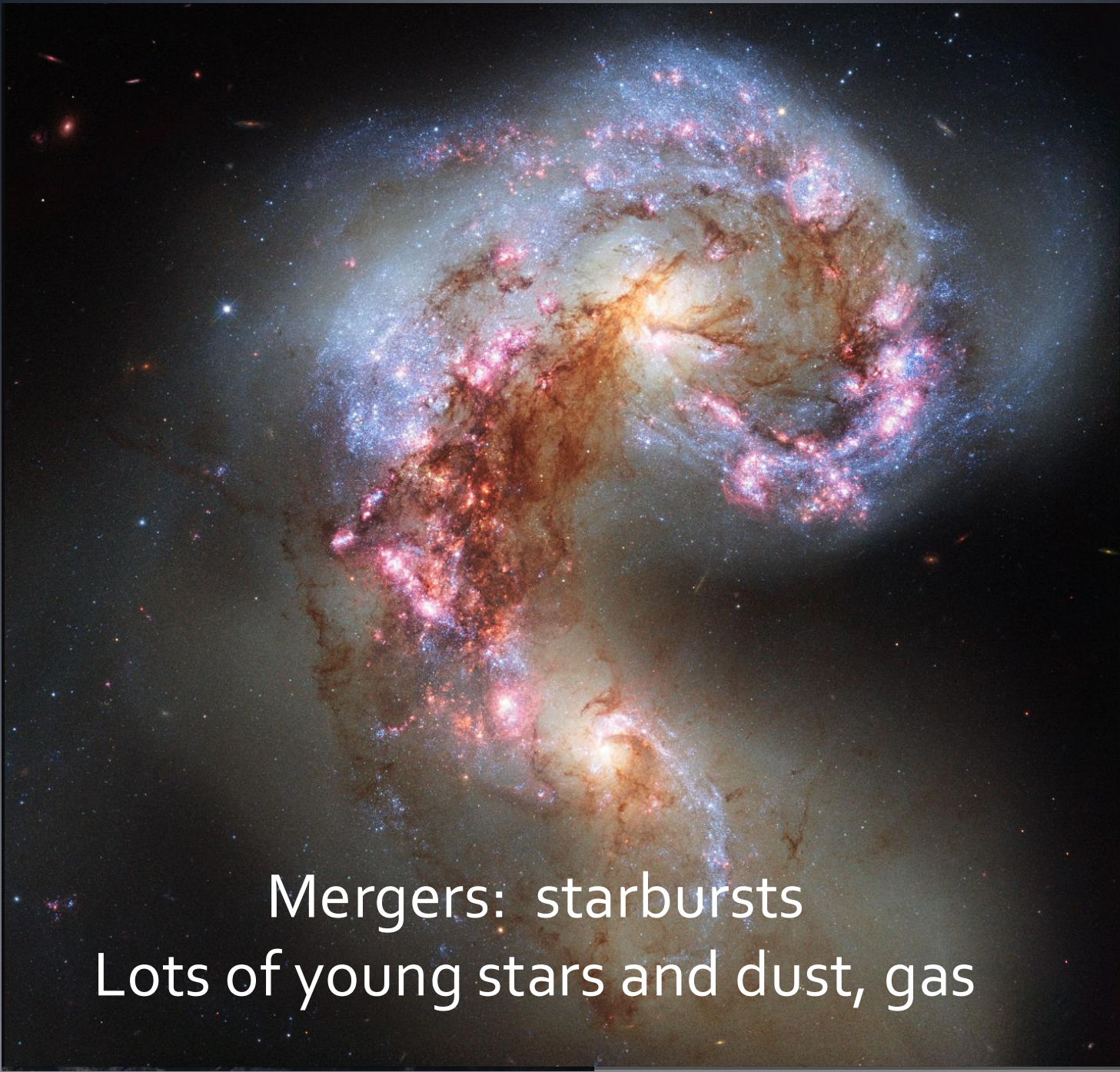
# Galaxies and their supermassive black holes





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

Spirals:  
Gas accumulates in spiral  
density waves;  
star formation

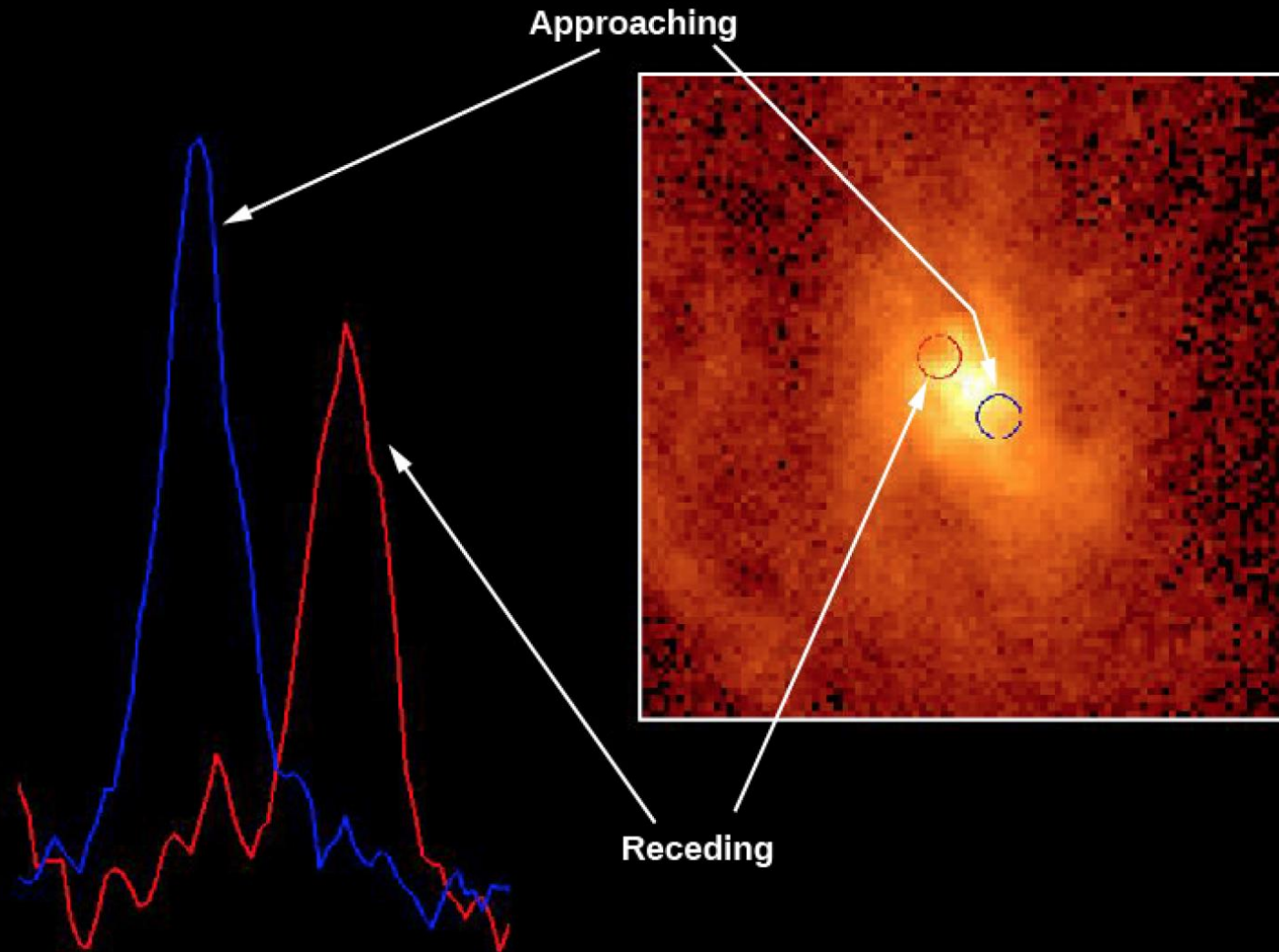


Mergers: starbursts  
Lots of young stars and dust, gas

## Characteristics of the Different Types of Galaxies

Characteristic	Spirals	Ellipticals	Irregulars
Mass ( $M_{\text{Sun}}$ )	$10^9$ 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 ( $L_{\text{Sun}}$ )	$10^8$ to $10^{11}$	$10^6$ to $10^{11}$	$10^7$ to $2 \times 10^9$
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





# Little red dots at high redshift

EIGER 4741



EIGER 4396



EIGER 18026



EIGER 4784



EIGER 7426



EIGER 9209



# The distance ladder!

## How to measure distances?

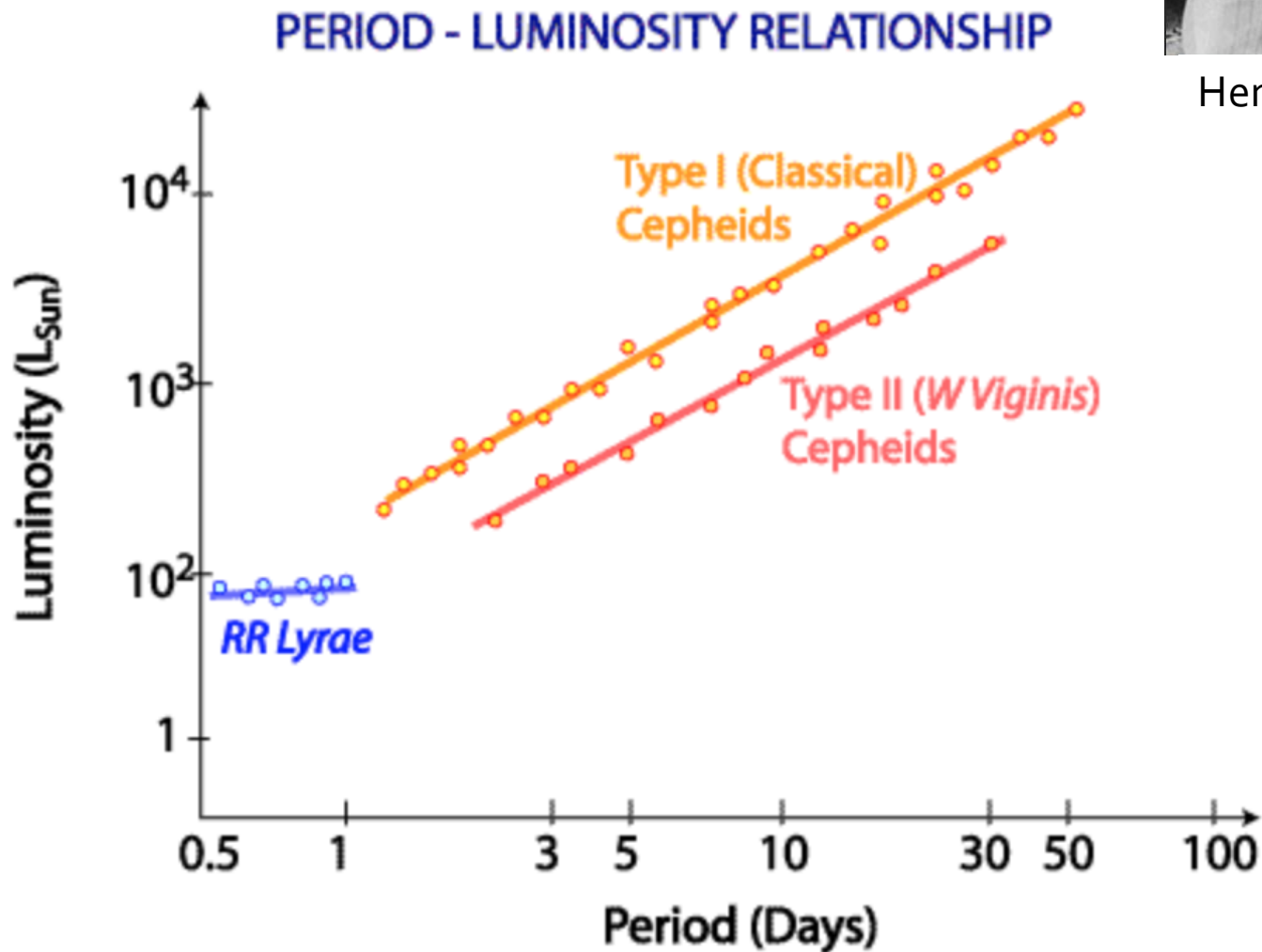
### Some Methods for Estimating Distance to Galaxies

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

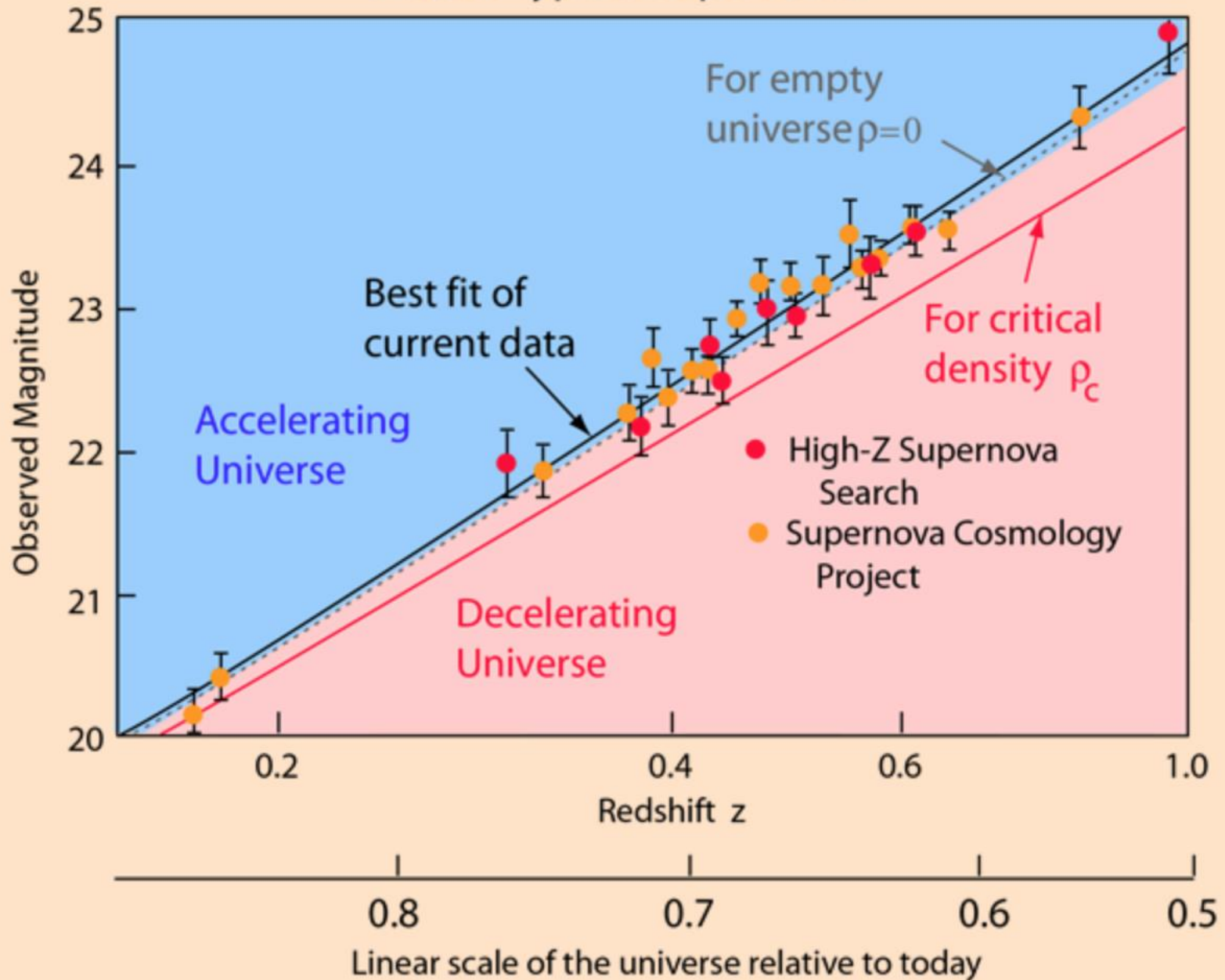
# Nearby galaxies: use variable stars!



Henrietta Leavitt

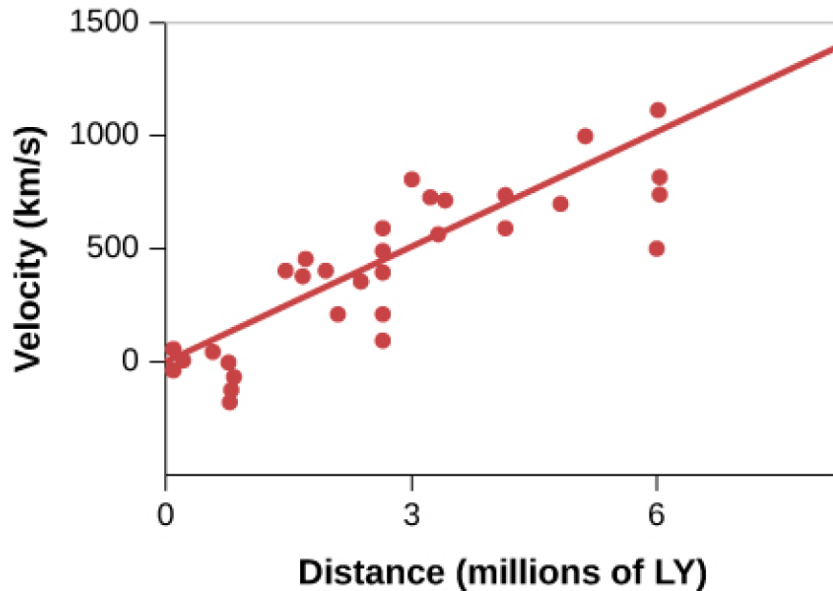


# Distant Type Ia Supernovae

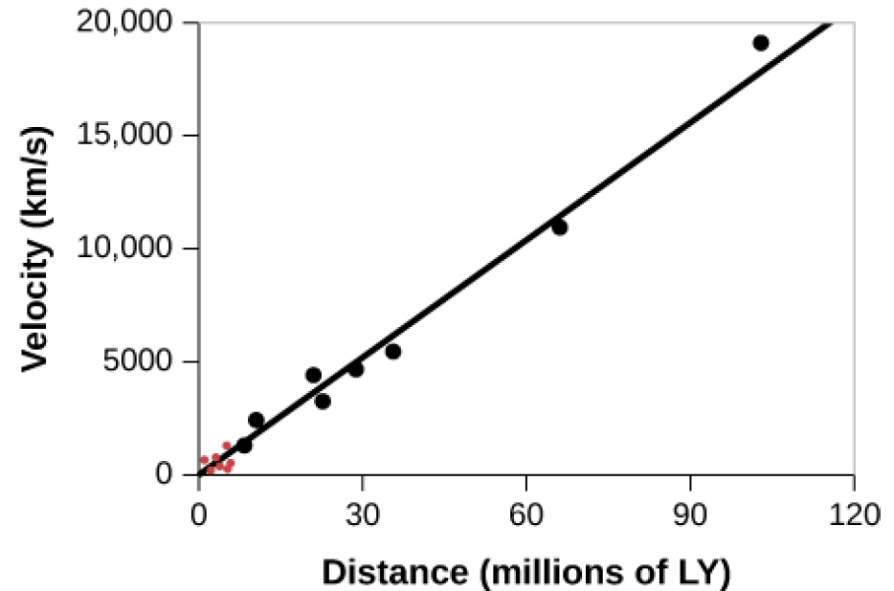


Hubble's Law: distance proportional to redshift  
Redshift: spectrum of light shifted to red  
(going away from us)

Hubble's Data (1929)



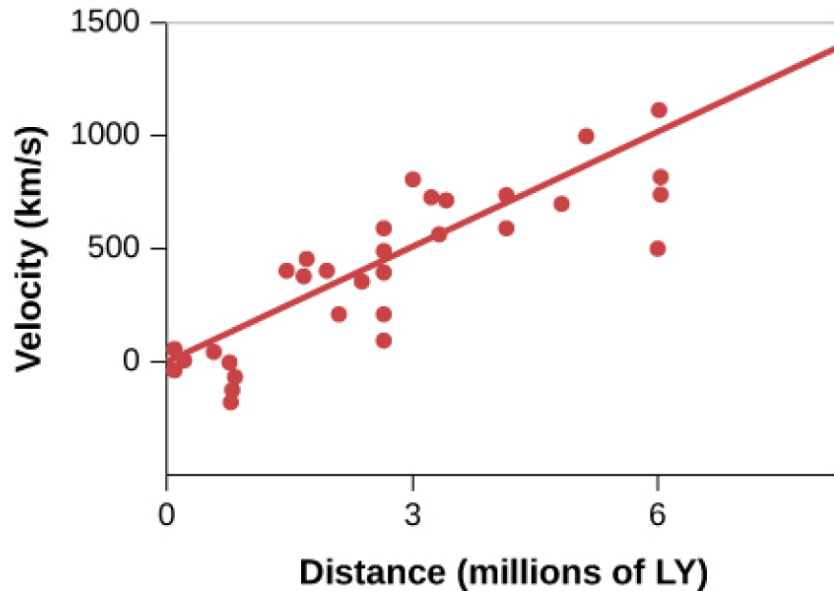
Hubble and Humason (1931)



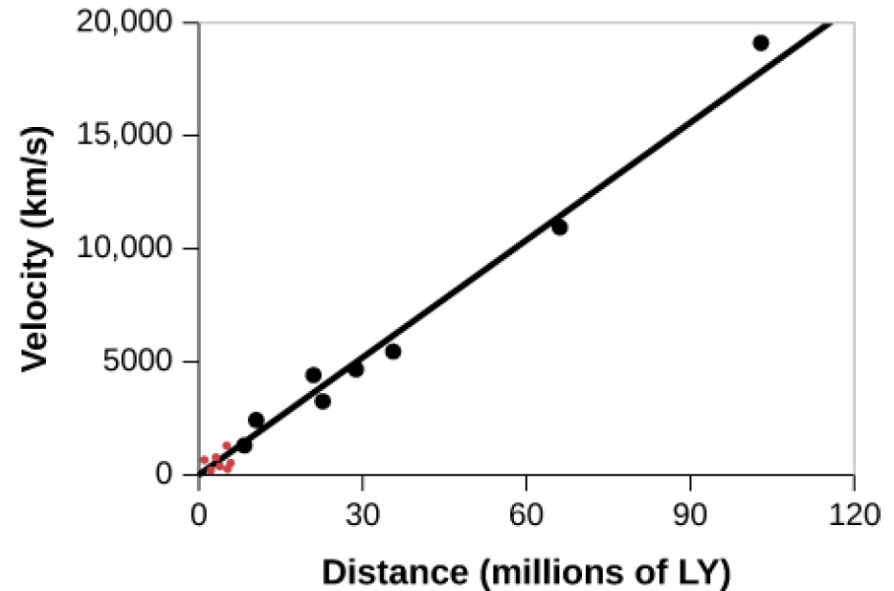
$$V = H \times d$$

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

Hubble's Data (1929)

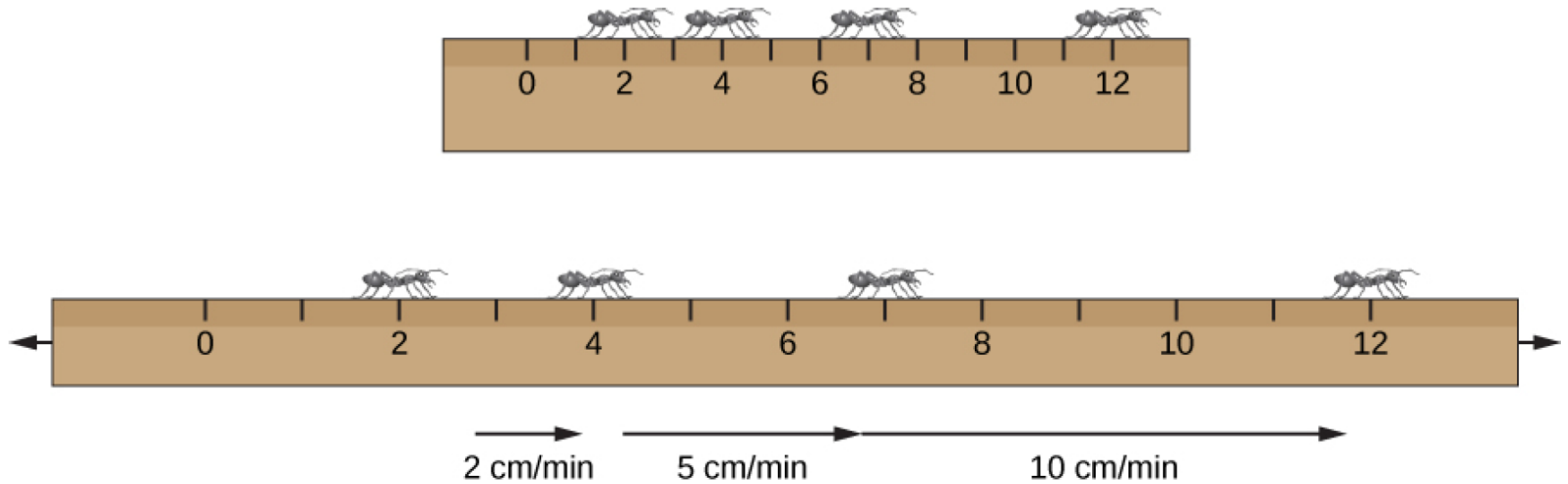


Hubble and Humason (1931)

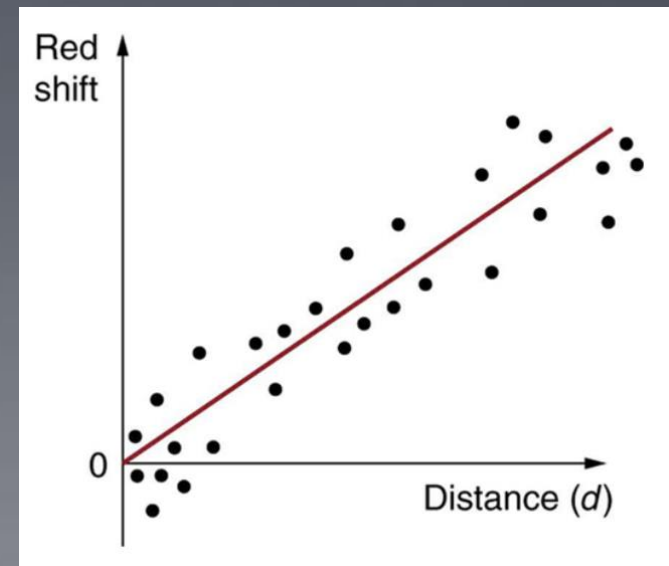


$$V = H \times d$$

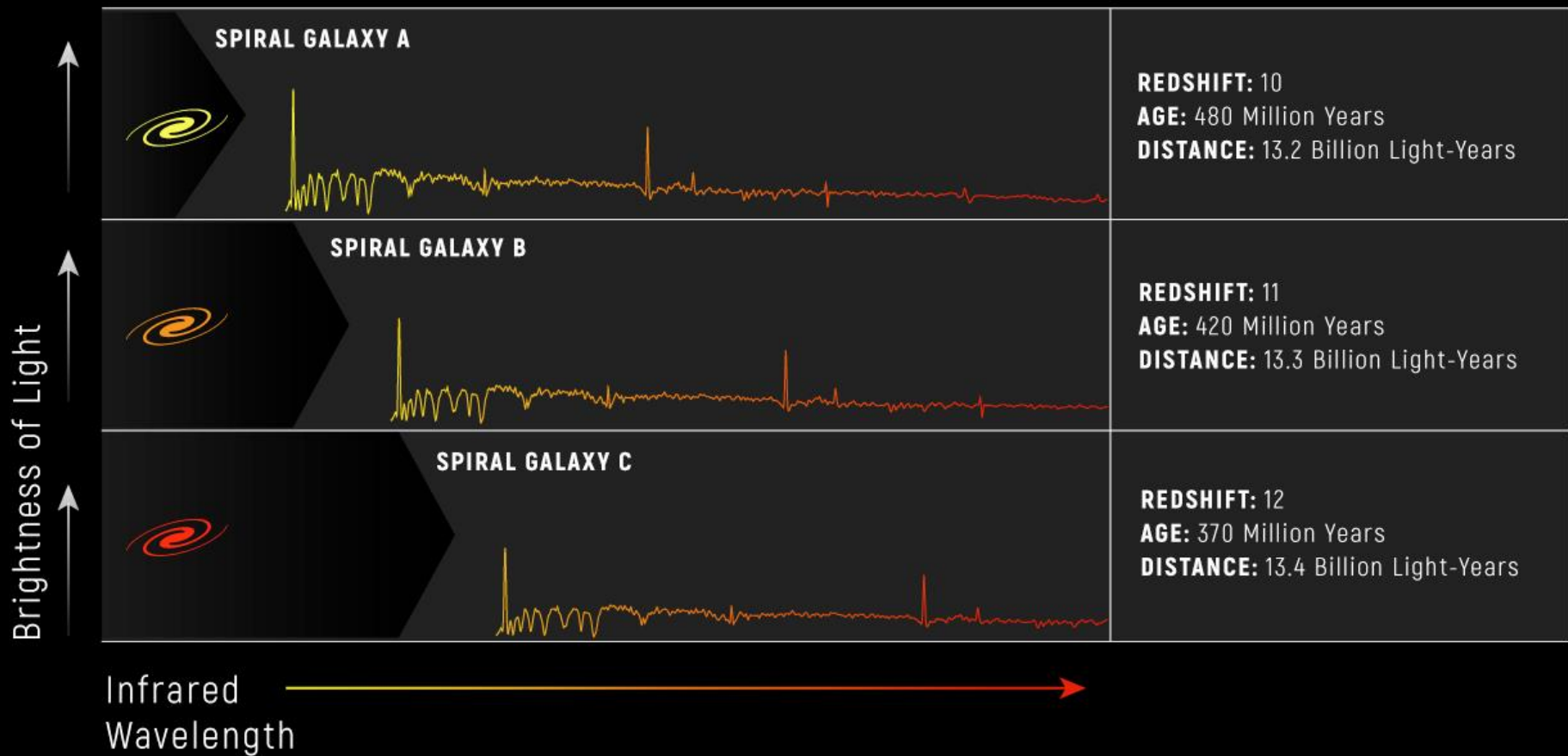
# Expansion of universe and redshift



Redshift: 3D maps of a 2D sky



# Searching for galaxies: redshift and wavelength



# Redshift formula

---

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

# Light travel time: distance ~ time

---

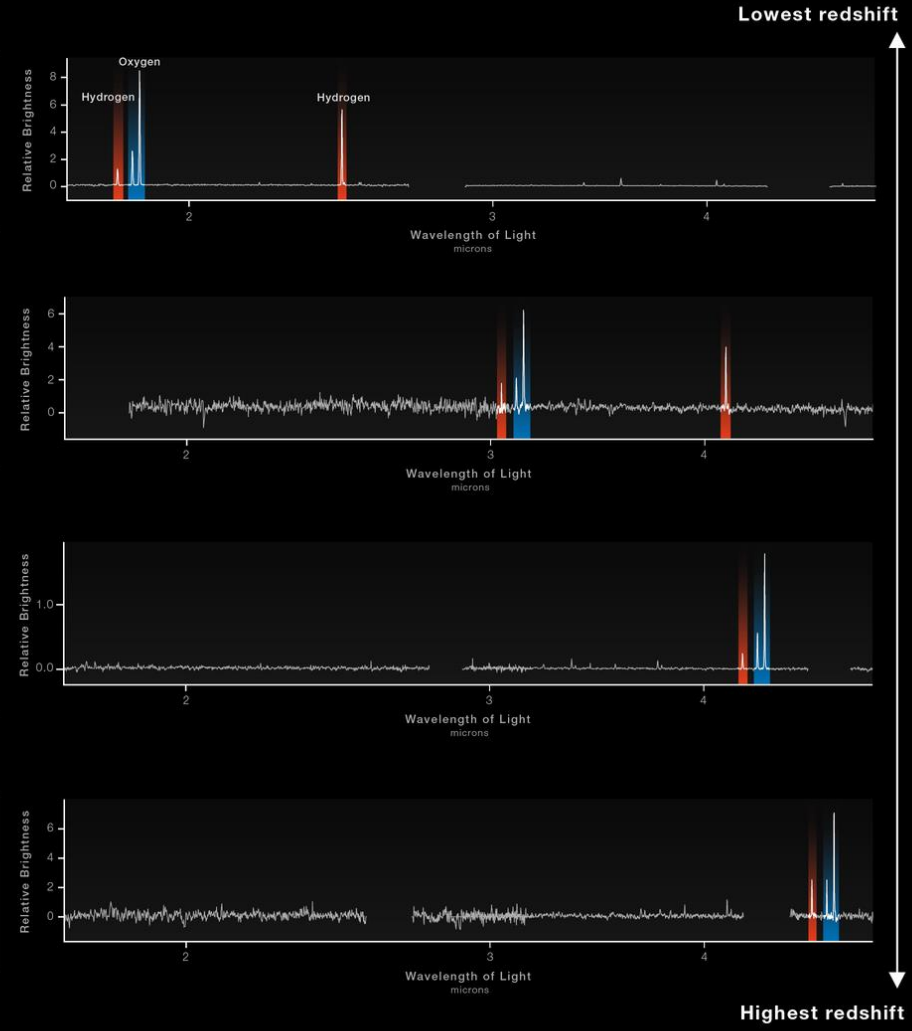
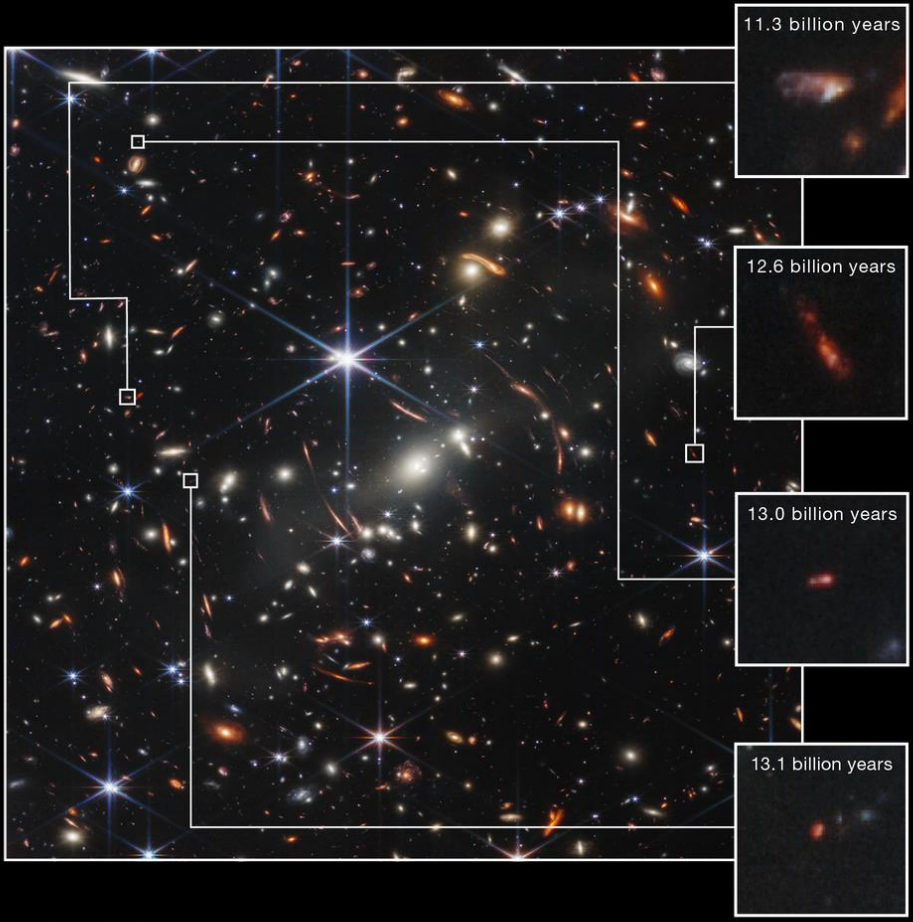
- Most distant: 13.5 billion light years
    - Current distance: ~50 billion light years (no longer visible)
  - When we observe the most distant objects, we are observing the universe when it was young!
-

GALAXY CLUSTER SMACS 0723

# WEBB SPECTRA IDENTIFY GALAXIES IN THE VERY EARLY UNIVERSE

NIRCam Imaging

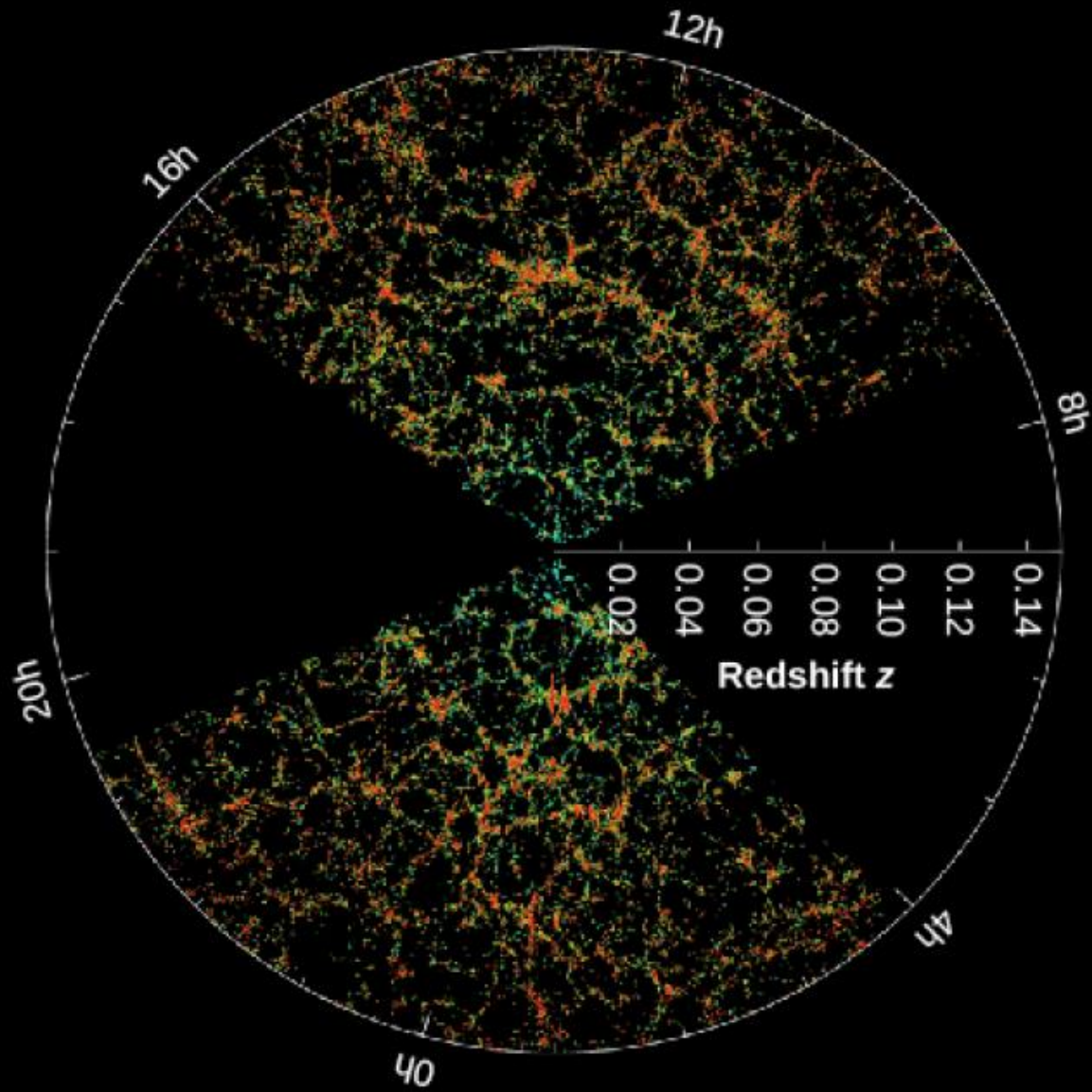
NIRSpec Microshutter Array Spectroscopy



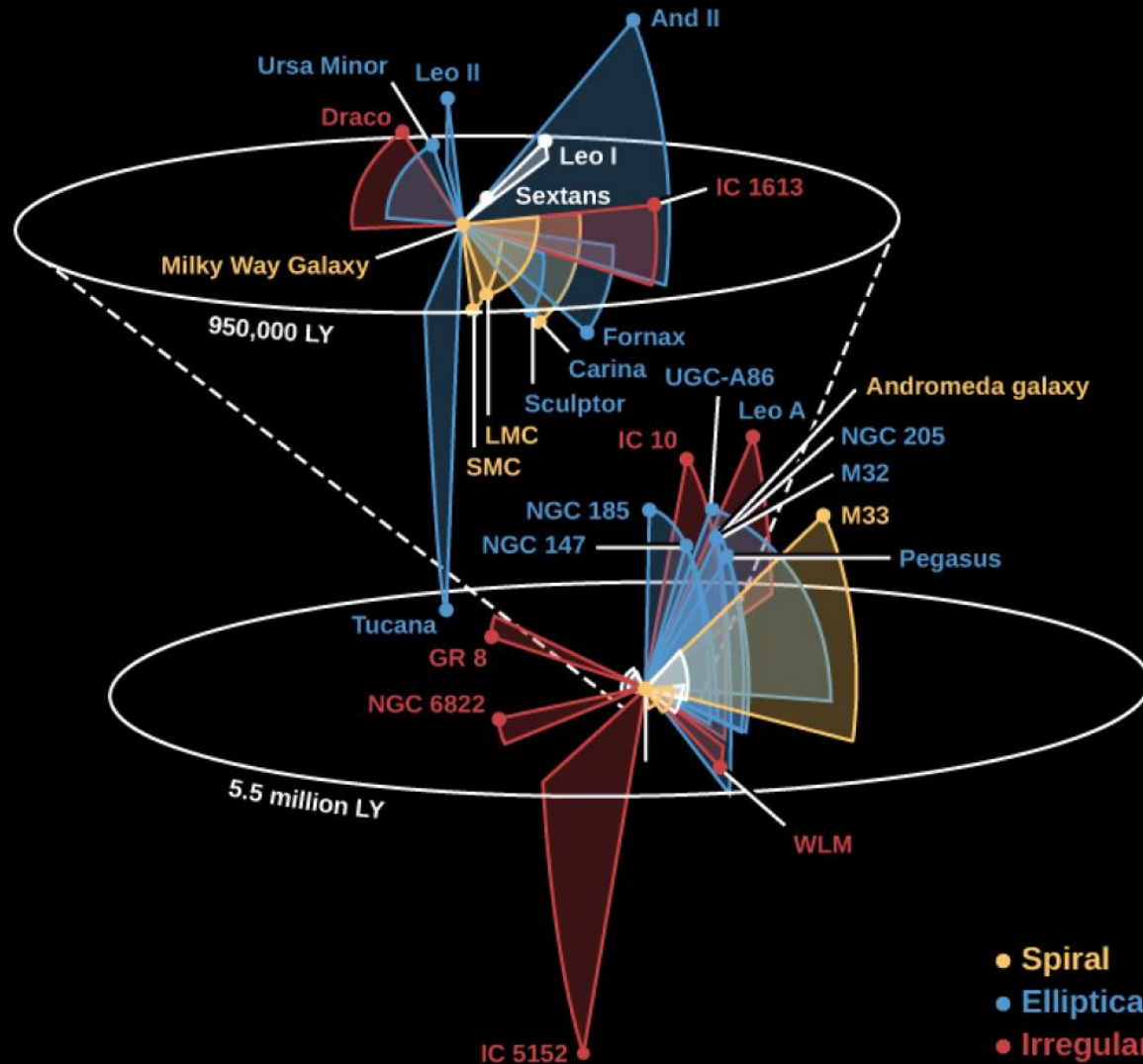
Most distant astronomical objects with spectroscopic redshift determinations

Image ⇄	Name ⇄	Redshift (z) ⇄	Light travel distance <sup>s</sup> (Gly) <sup>[4][5][6][7]</sup> ⇄	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. <sup>[8]</sup>
	JADES-GS-z14-1	$z = 13.90^{+0.17}_{-0.17}$			Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec. <sup>[9]</sup>
	JADES-GS-z13-0	$z = 13.20^{+0.04}_{-0.07}$	13.576 <sup>[4]</sup> / 13.596 <sup>[5]</sup> / 13.474 <sup>[6]</sup> / 13.473 <sup>[7]</sup>	33.6	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec. <sup>[10]</sup>
	UNCOVER-z13	$z = 13.079^{+0.014}_{-0.001}$	13.51	32.56 <sup>†</sup>	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec. <sup>[11]</sup>
	JADES-GS-z12-0	$z = 12.63^{+0.24}_{-0.08}$	13.556 <sup>[4]</sup> / 13.576 <sup>[5]</sup> / 13.454 <sup>[6]</sup> / 13.453 <sup>[7]</sup>	32.34 <sup>†</sup>	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRCam <sup>[10]</sup> and JWST/NIRSpec, <sup>[12]</sup> and CIII] line emission with JWST/NIRSpec. <sup>[12]</sup> 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 <sup>†</sup>	Galaxy	Lyman-break galaxy, detection of the Lyman break with JWST/NIRSpec. <sup>[11]</sup>

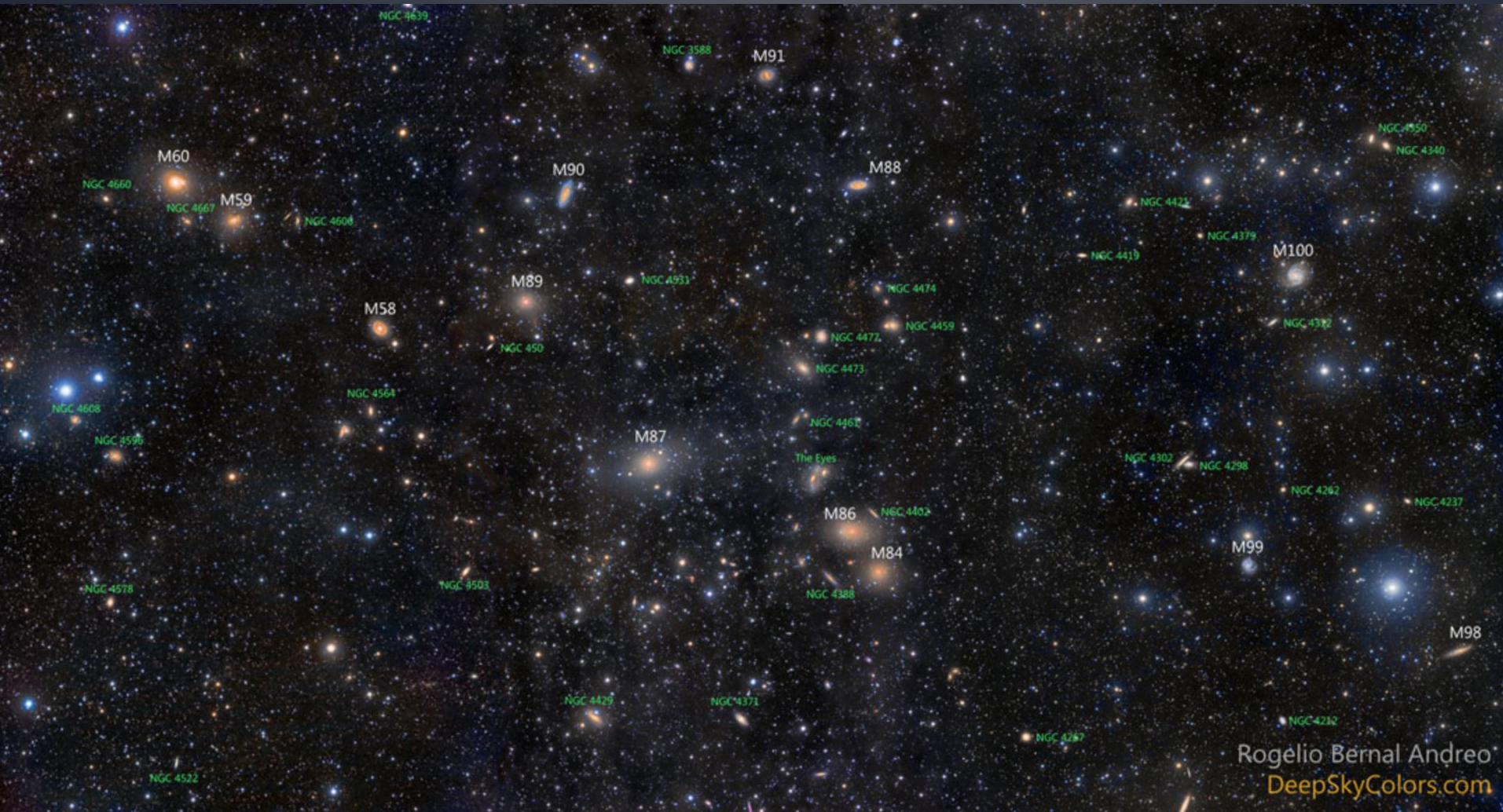
# 3D map of the universe: clusters and voids



# Galaxies cluster together: Local Group

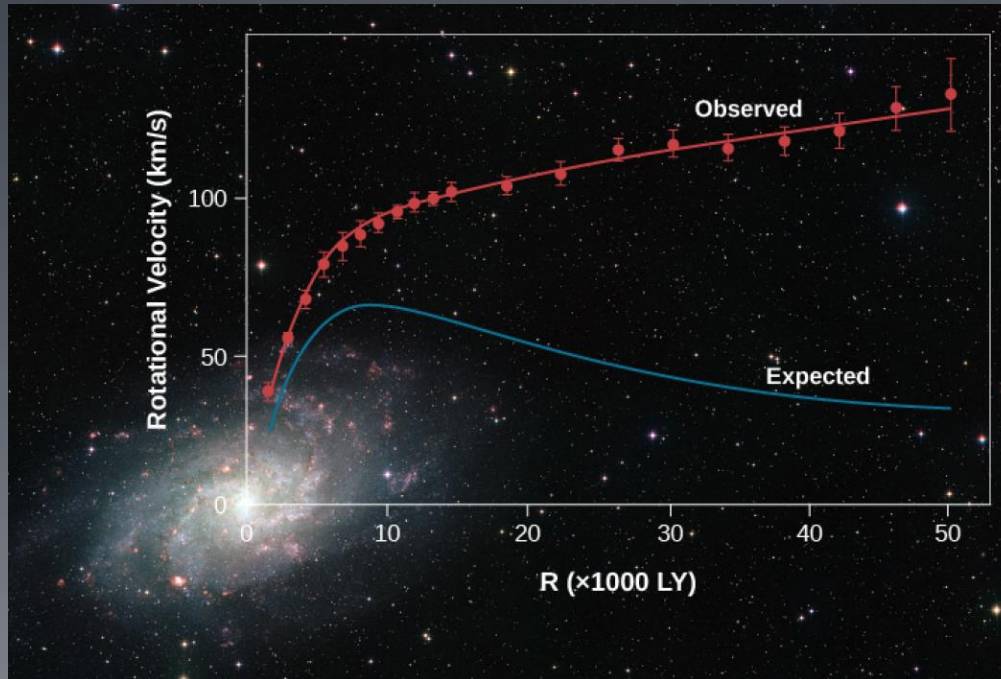


# Virgo Cluster

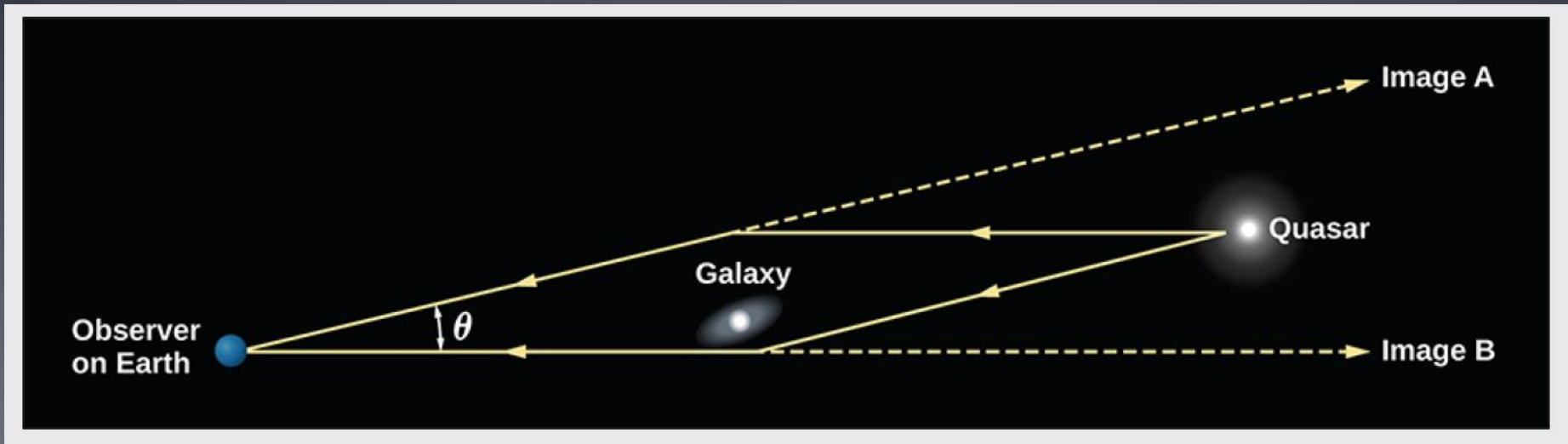


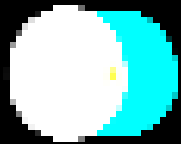
# How massive are galaxies?

- Rotation curves
- Gravitational lensing

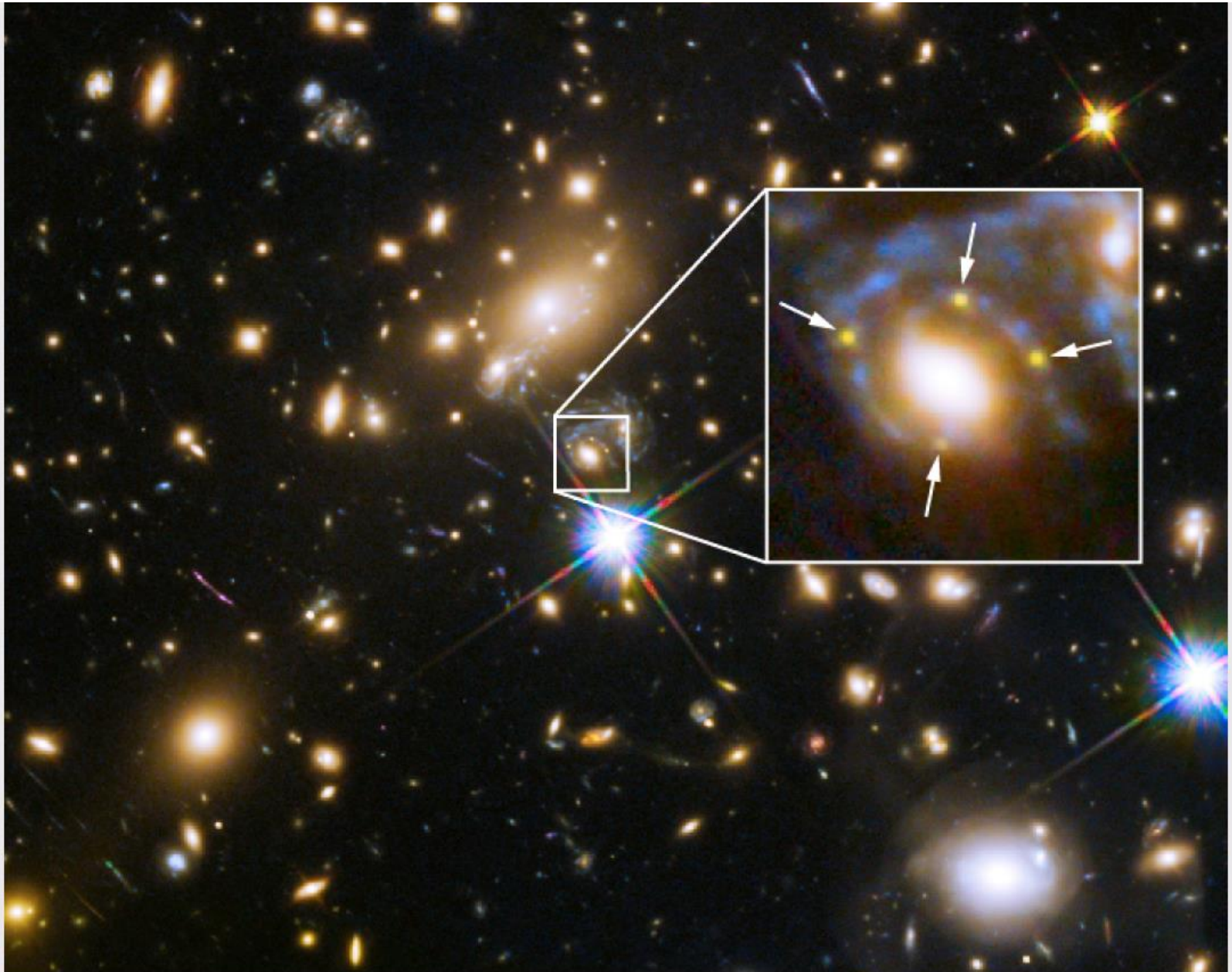


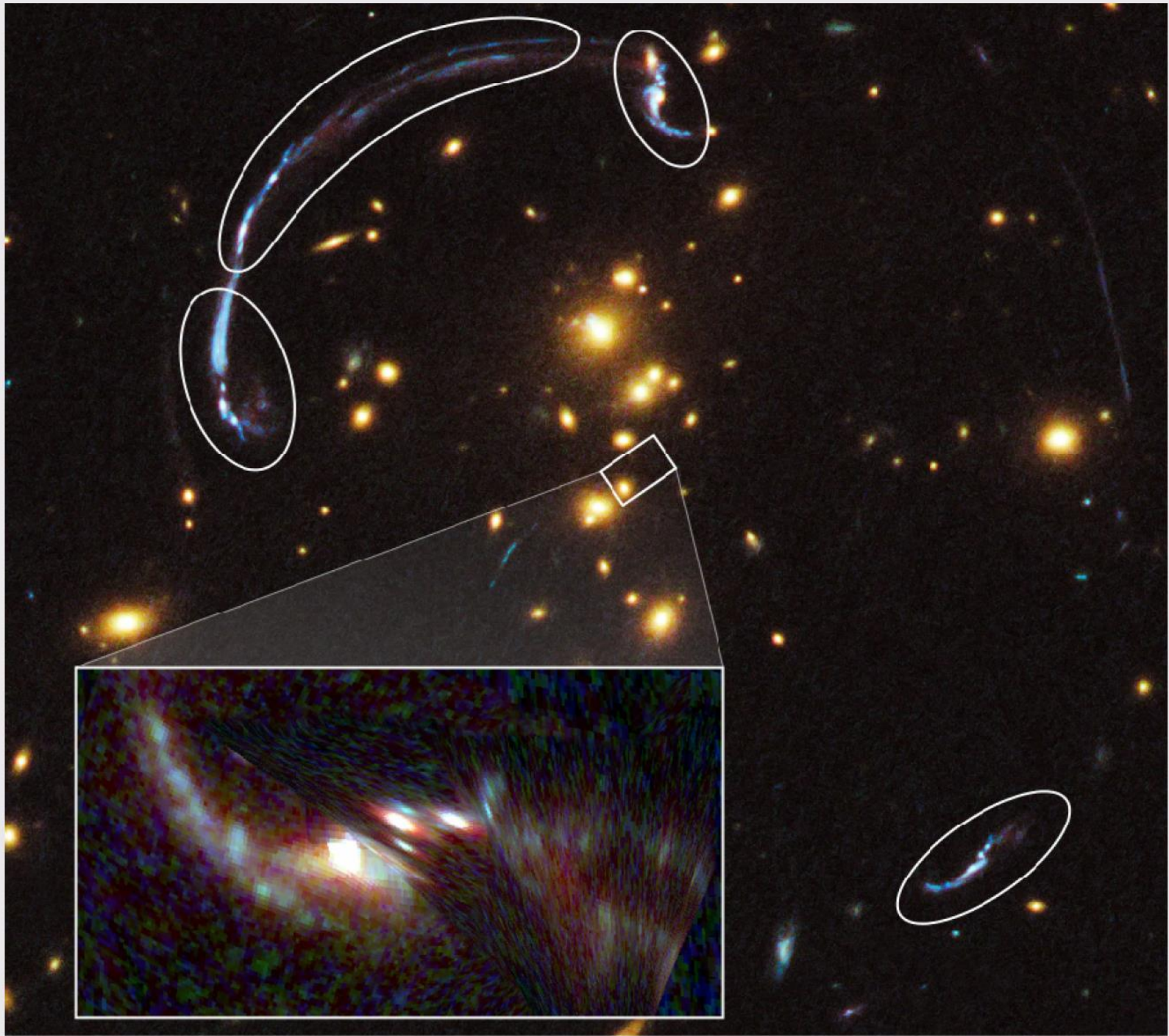
# Masses and dark matter: gravitational lensing



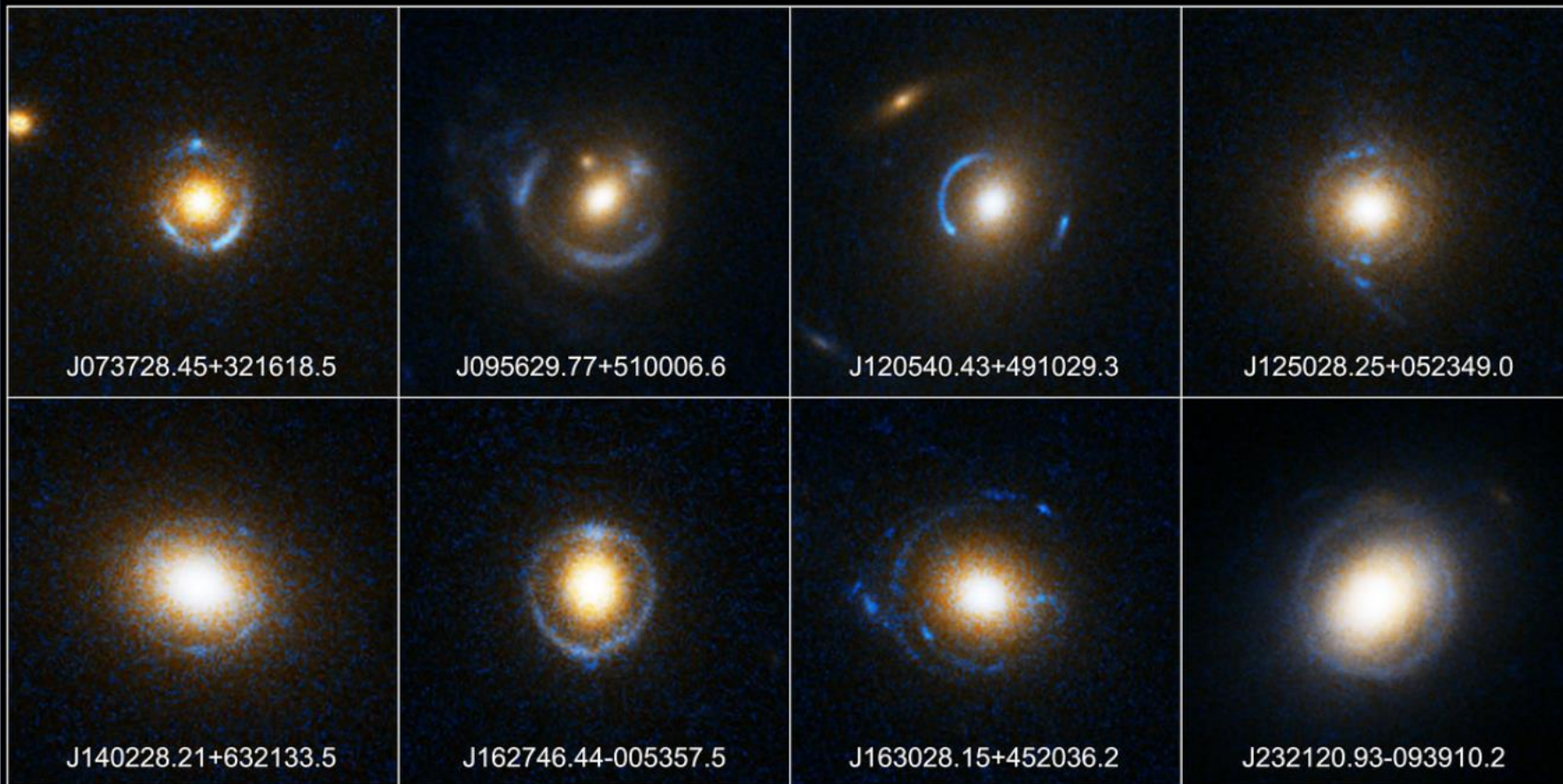


# Gravitational lensing

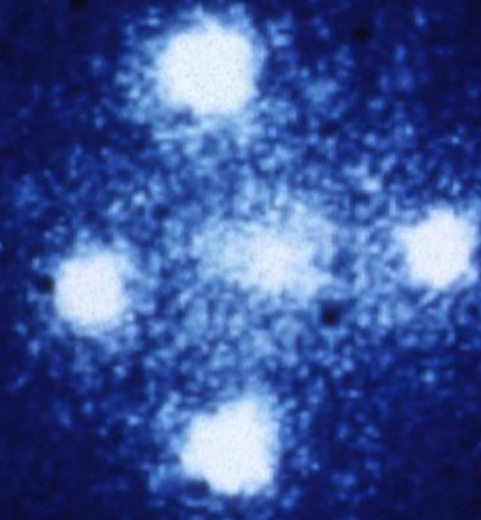


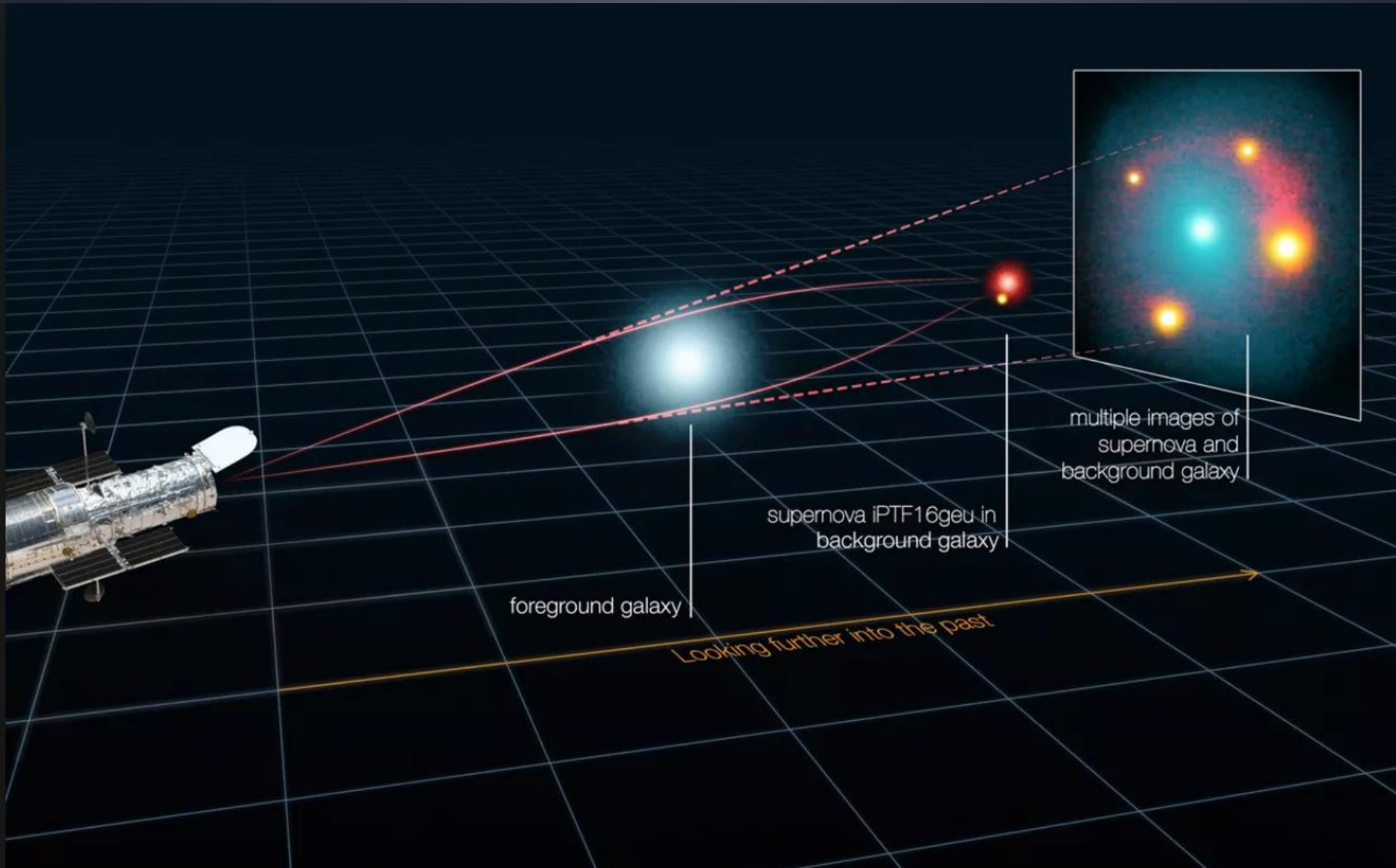




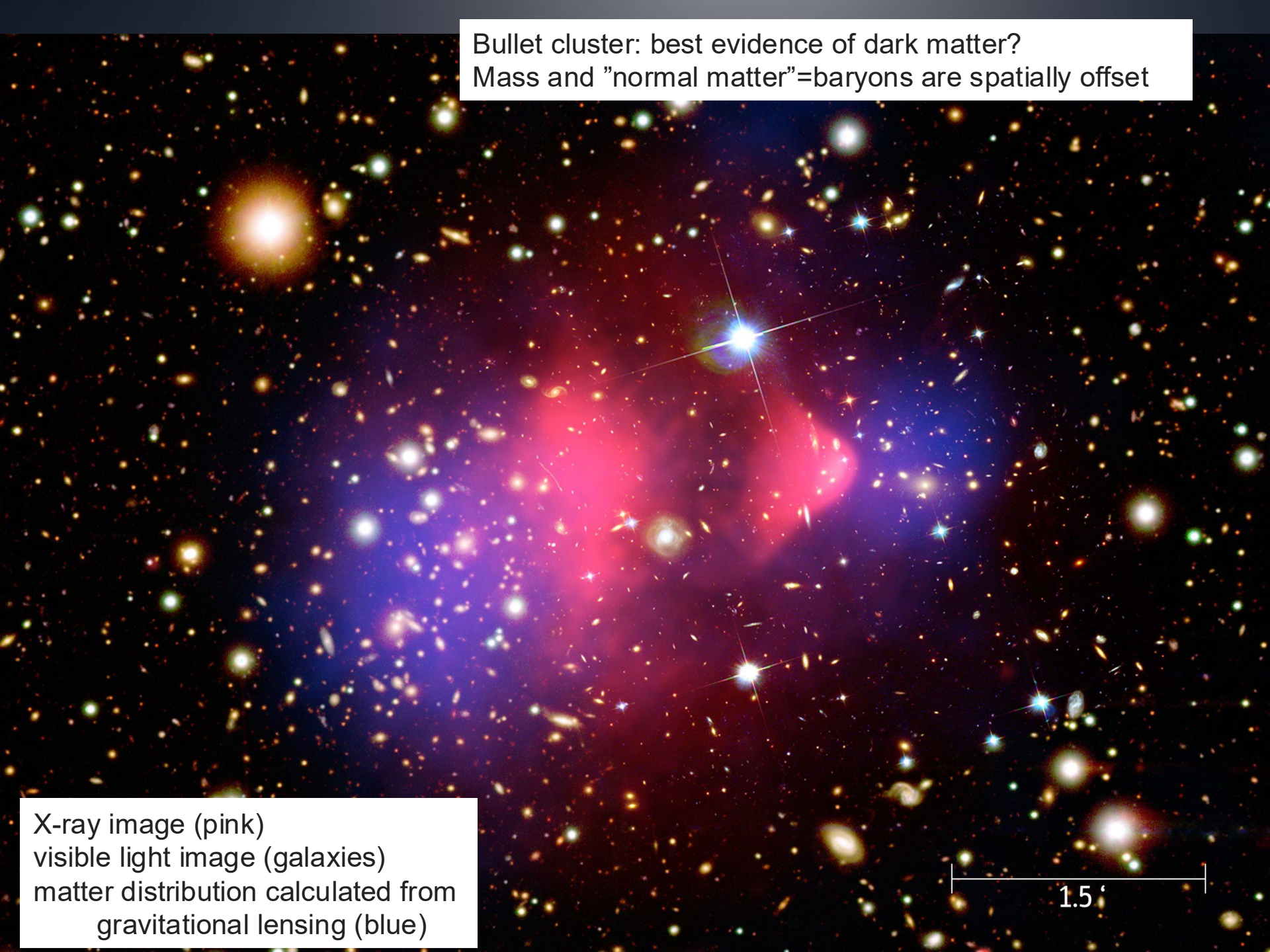


**Einstein Ring Gravitational Lenses**  
*Hubble Space Telescope • Advanced Camera for Surveys*





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)

1.5'

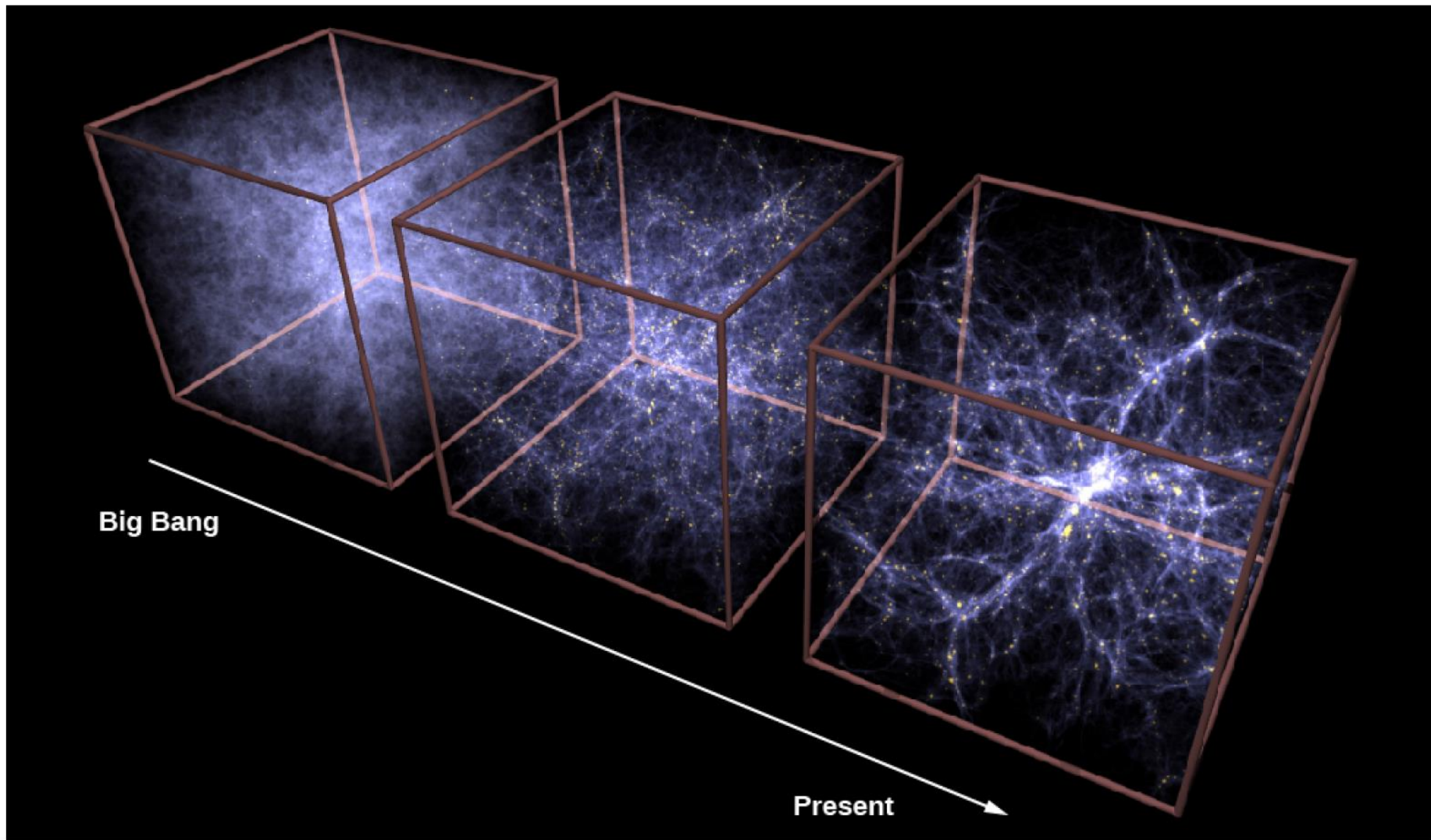
# What is the universe made of

---

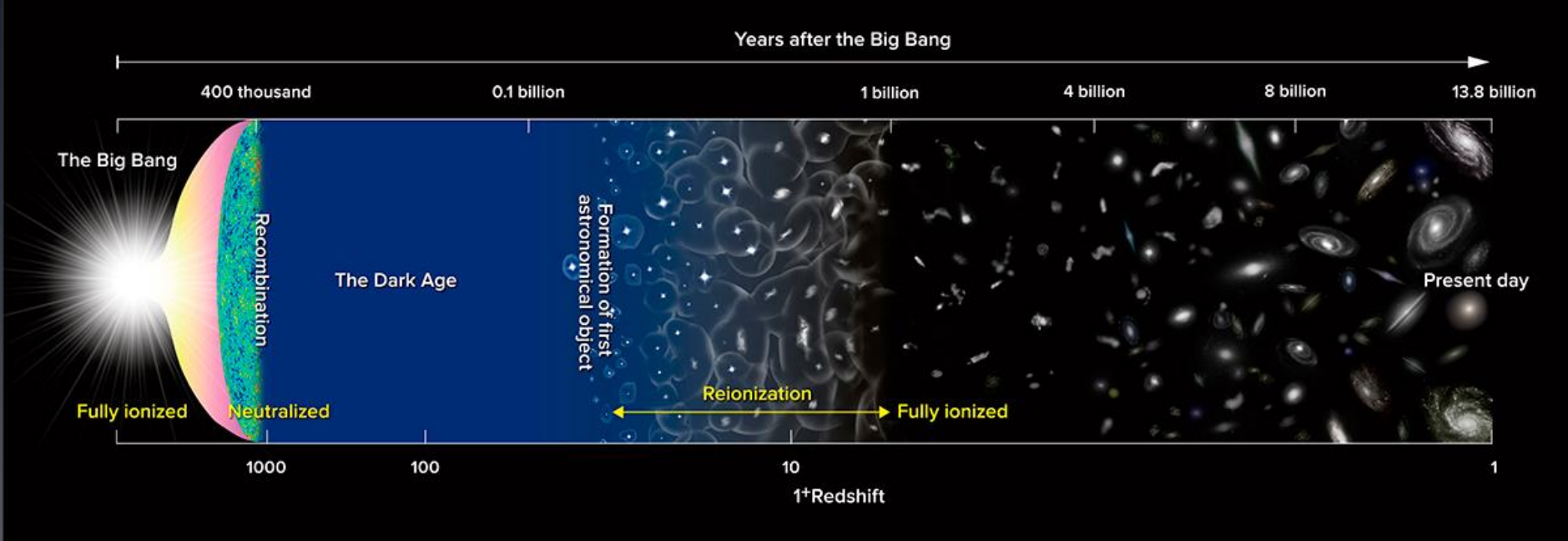
- “normal” matter: 25% of total mass
- 75% of mass: dark matter
  - “cold” dark matter
- Evidence for dark matter:
  - galactic rotation curves
  - gravitational lensing
  - the bullet cluster
  - Cosmological simulations (to be discussed): cold dark matter

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

---







# Size of the universe?

---

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

# Olbers Paradox

---

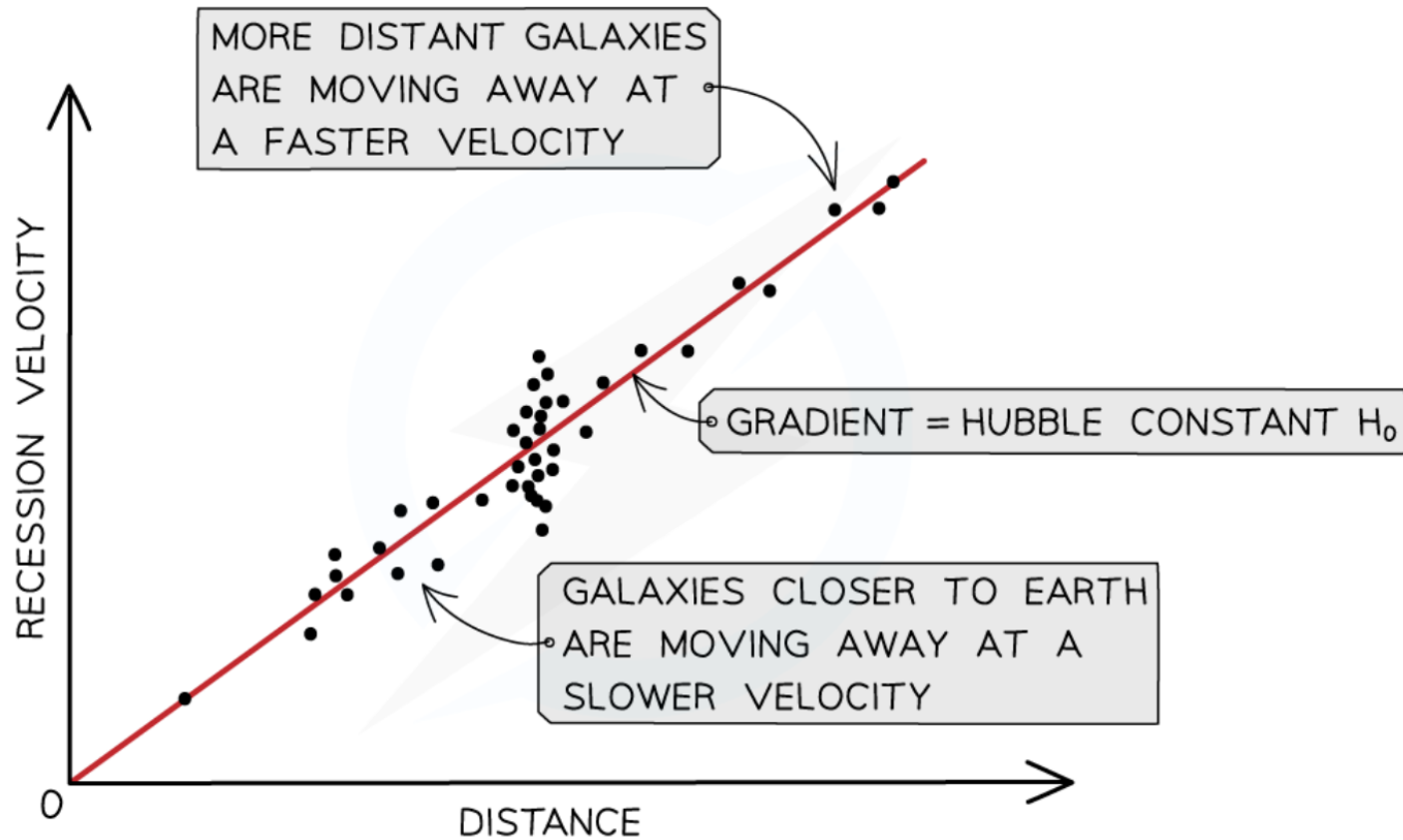
- Why is the sky dark at night?
- If the universe is
  - infinite in size
  - infinite in age
  - filled with stars
- then as we look out into a larger volume, number of stars increases. The entire sky would be as bright as a star

One of the assumptions must be wrong

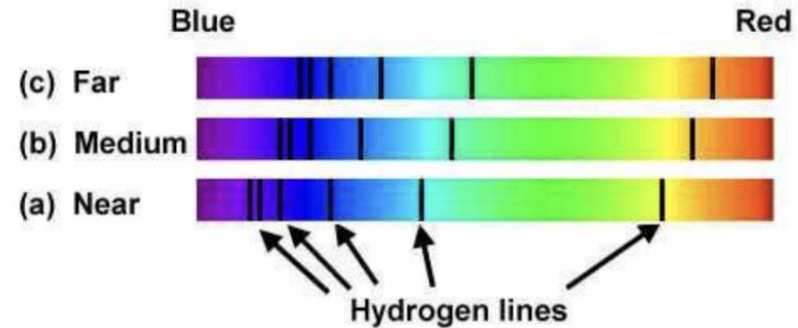
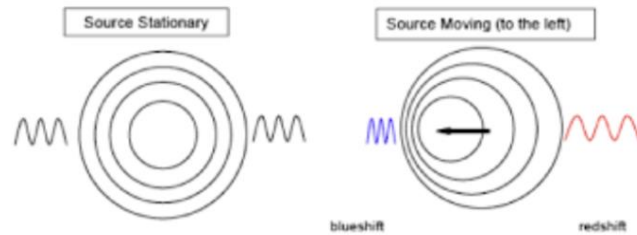
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# Solution: Universe is expanding

Graph of Hubble's Law

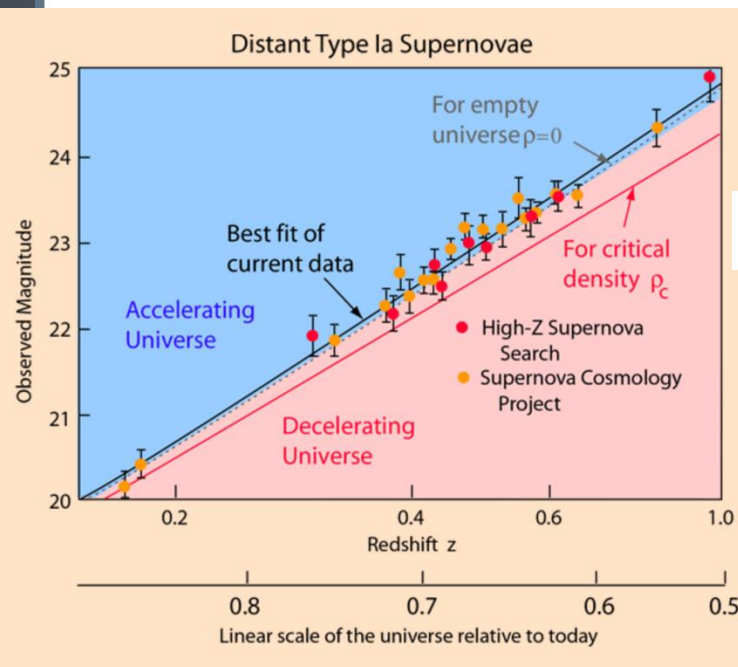


# Solution: Universe is expanding



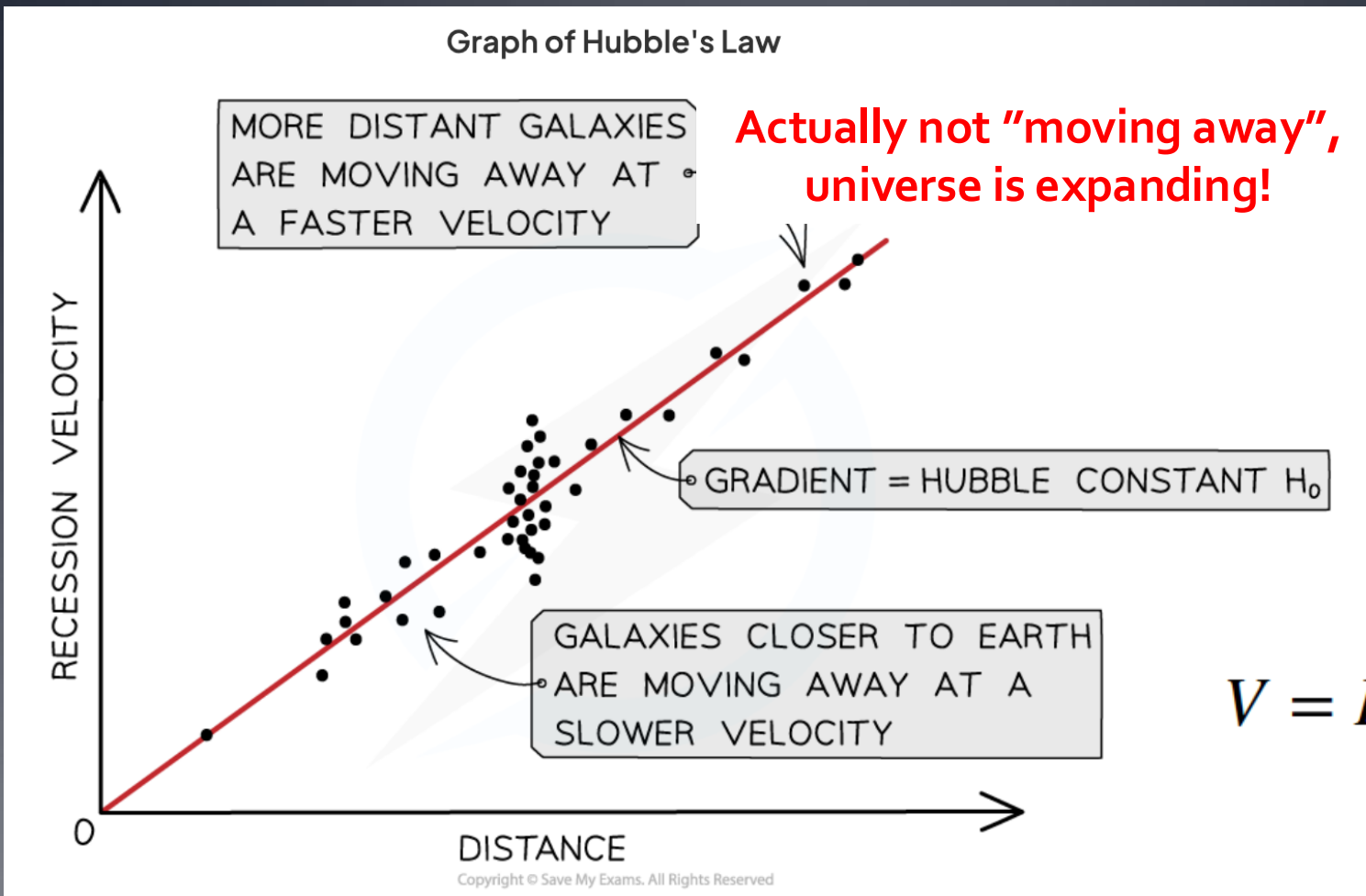
y-axis: redshift

x-axis: distance



$$V = H \times d$$

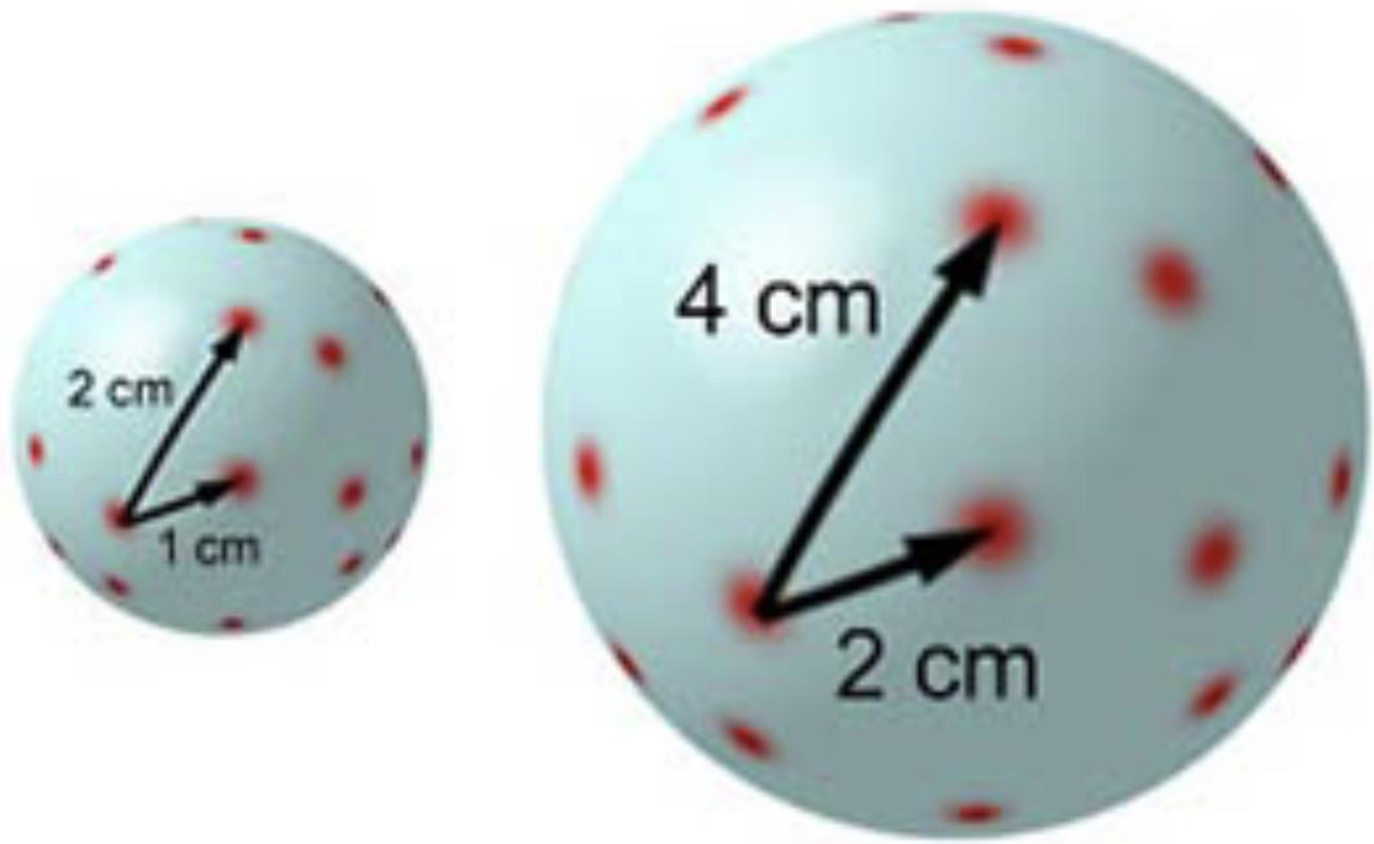
# Solution: Universe is expanding



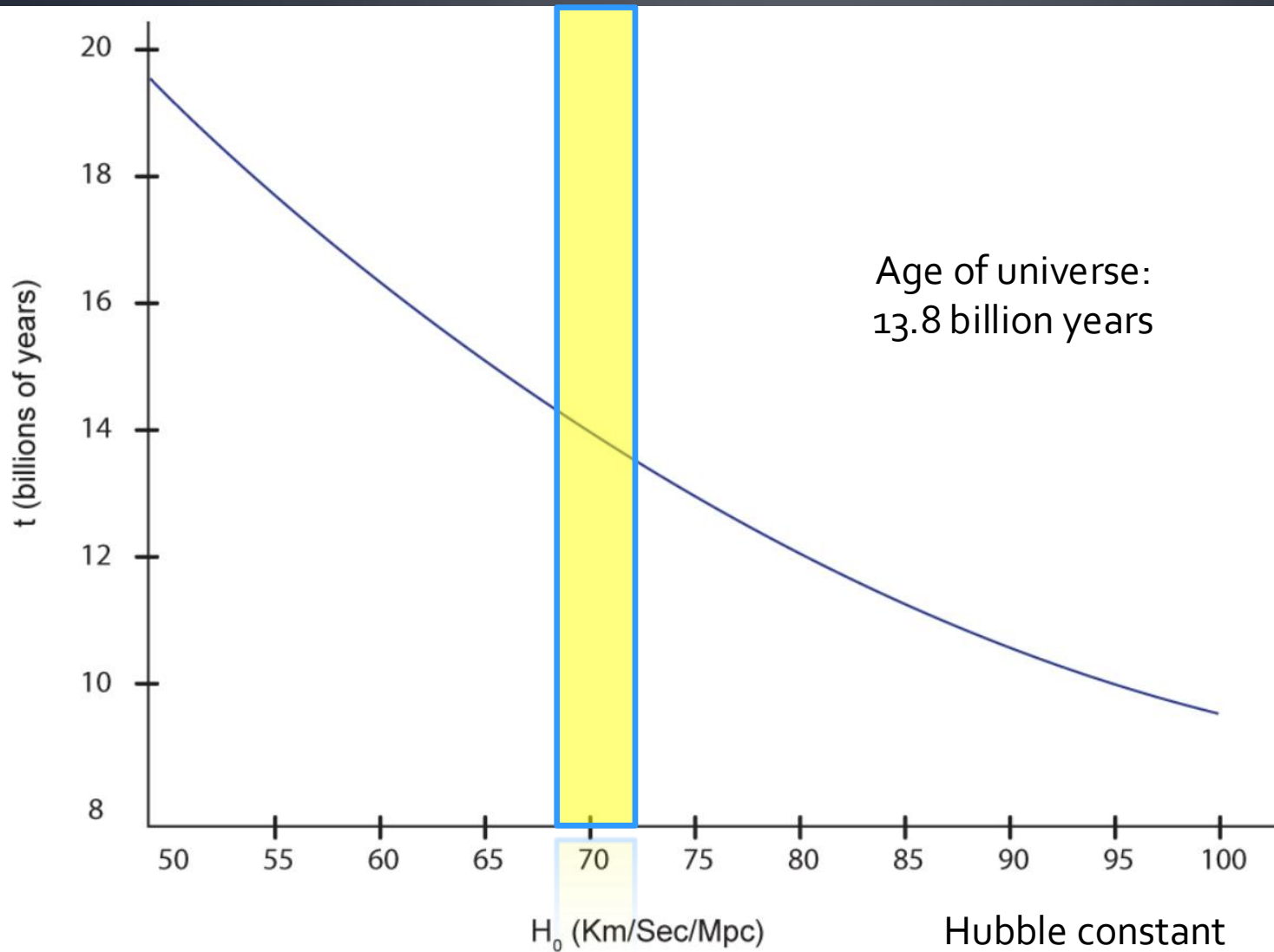
$$V = H \times d$$

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

# Solution: Universe is expanding



# Age of the universe



# Big Bang!

---

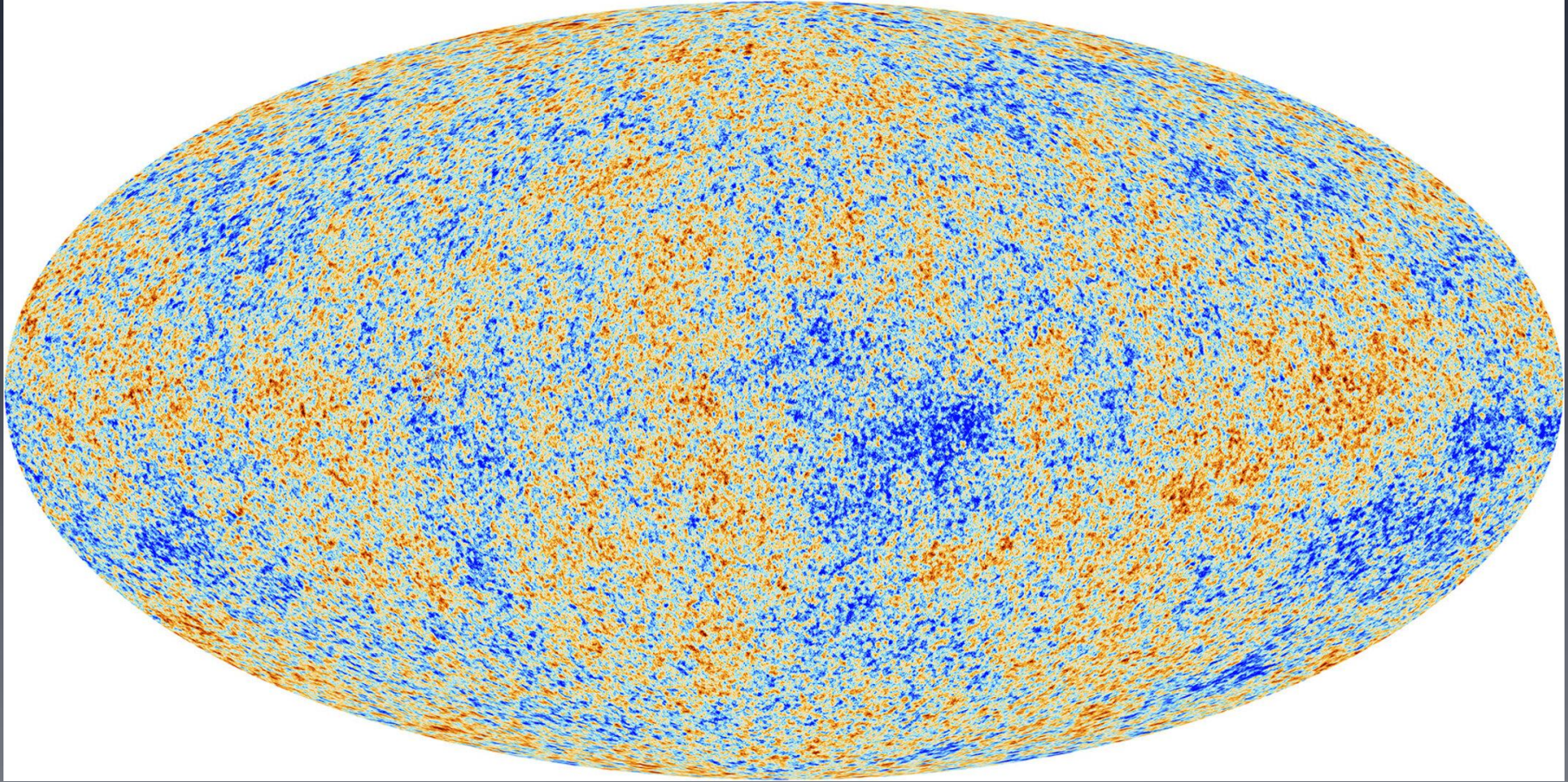
- Extrapolate back to explosion of space-time: 13.8 billion years ago
  - All universe in same place
-

# Evidence for the Big Bang

---

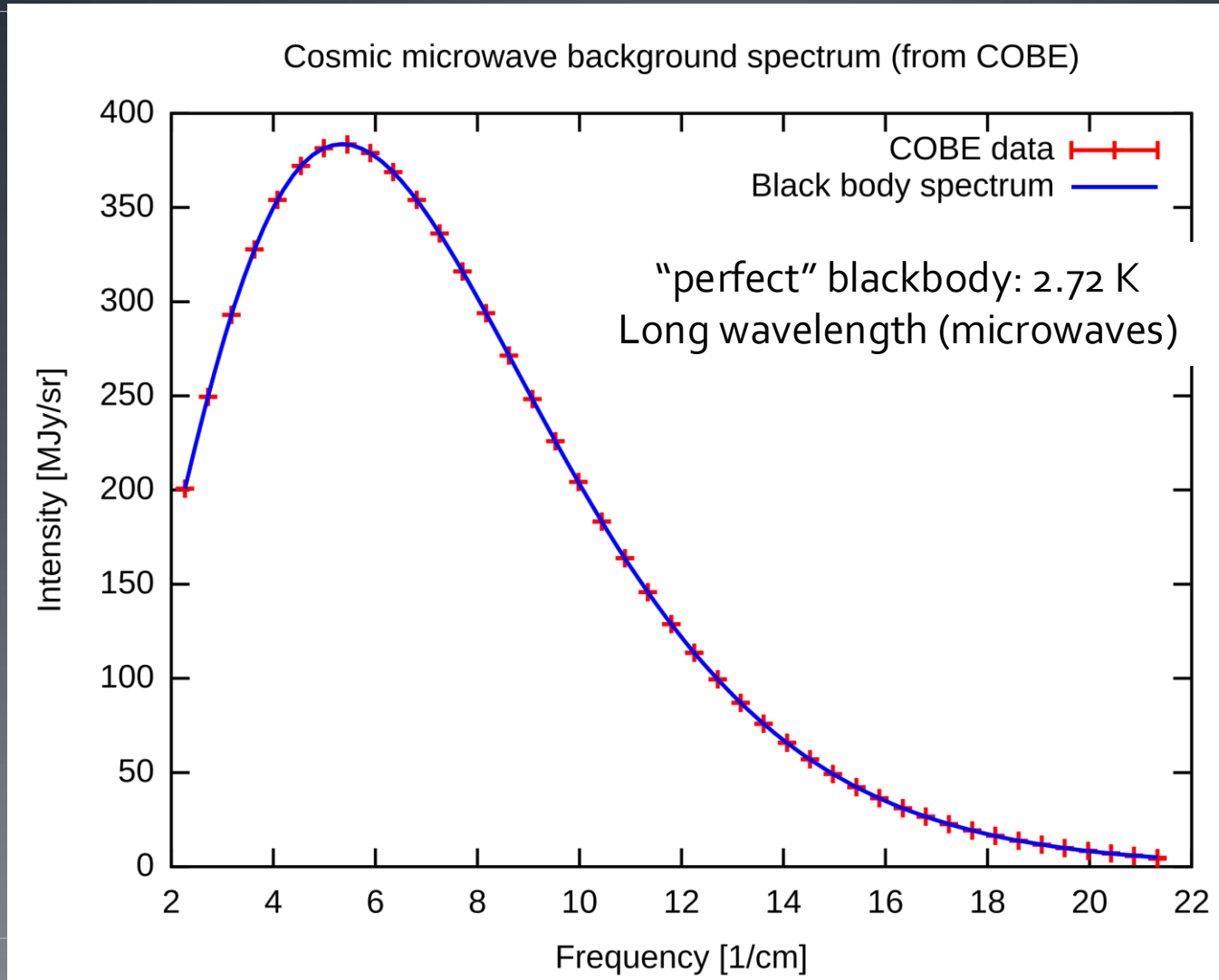
- Cosmic expansion (Hubble's law)
  - Cosmic Microwave Background
  - D, He<sup>3</sup>, Li elemental abundances
  - Galaxy evolution
-

# Cosmic microwave background



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

# Cosmic microwave background

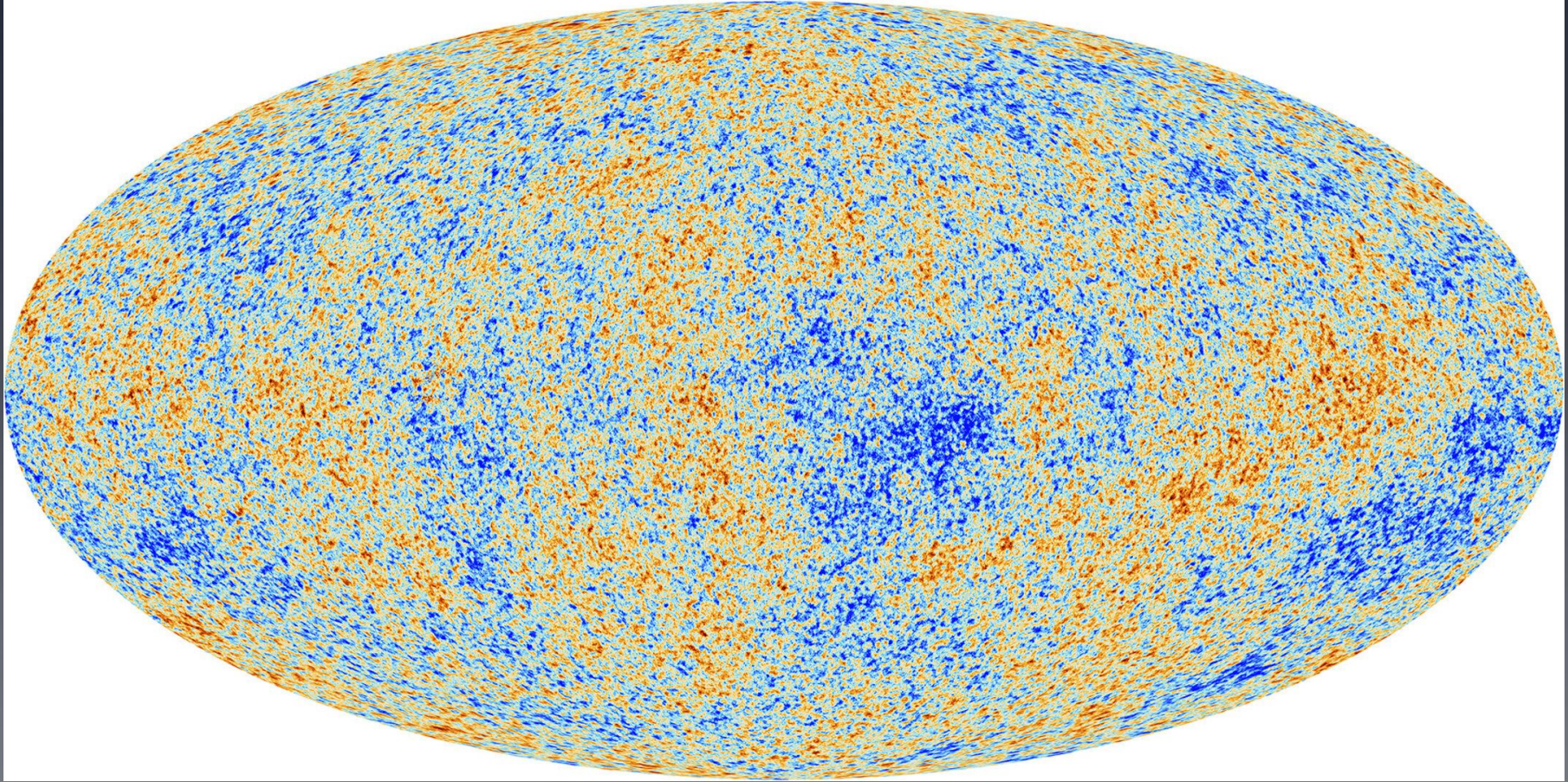


# Cosmic microwave background

---

- 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
    - $T_r = 2.725 \text{ K} \times (1 + z)$ ;  $z \sim 1,100$
-

# 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)

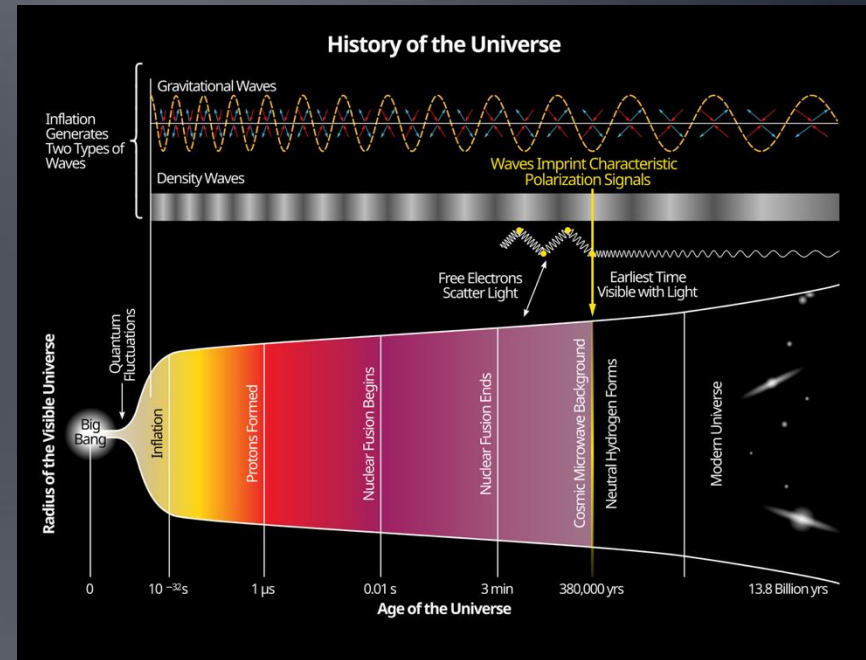
- 10-1000 s: nucleosynthesis (H, He, plus D, He-3, Li-7)

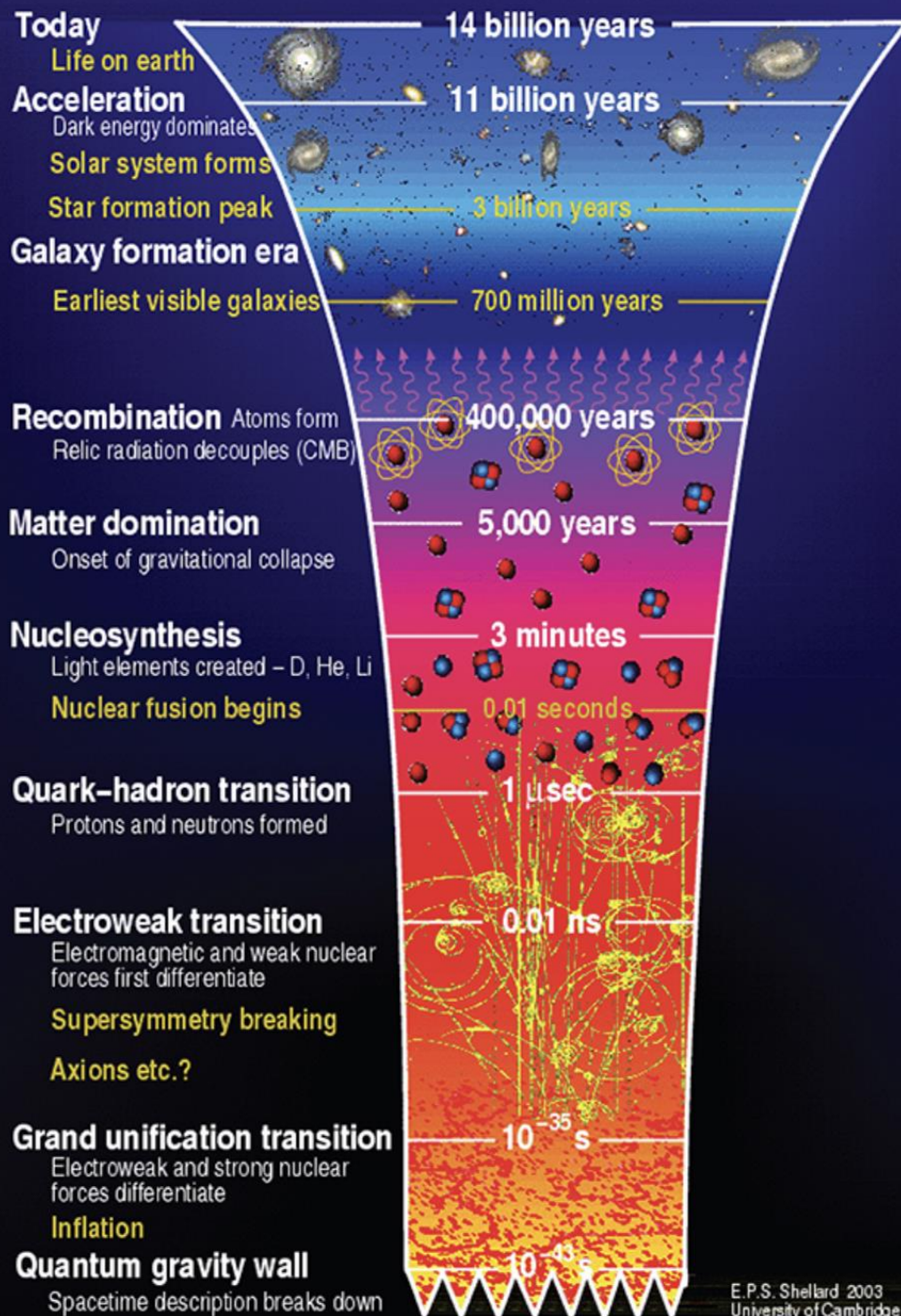
- Photon epoch: 10 s – recombination (T cools from  $10^9$  K to 4000 K)

- Recombination:  $p+e^- \Rightarrow$  neutral H

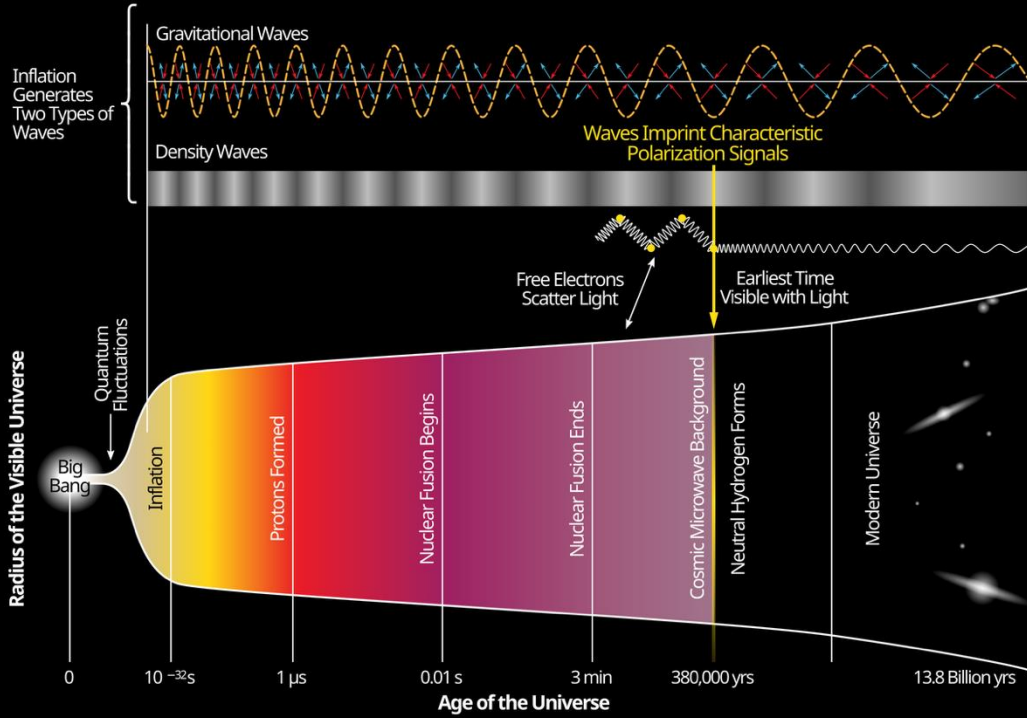
- Dark ages: recombination until the first stars

- First stars/galaxy formation: 300-400 Myr



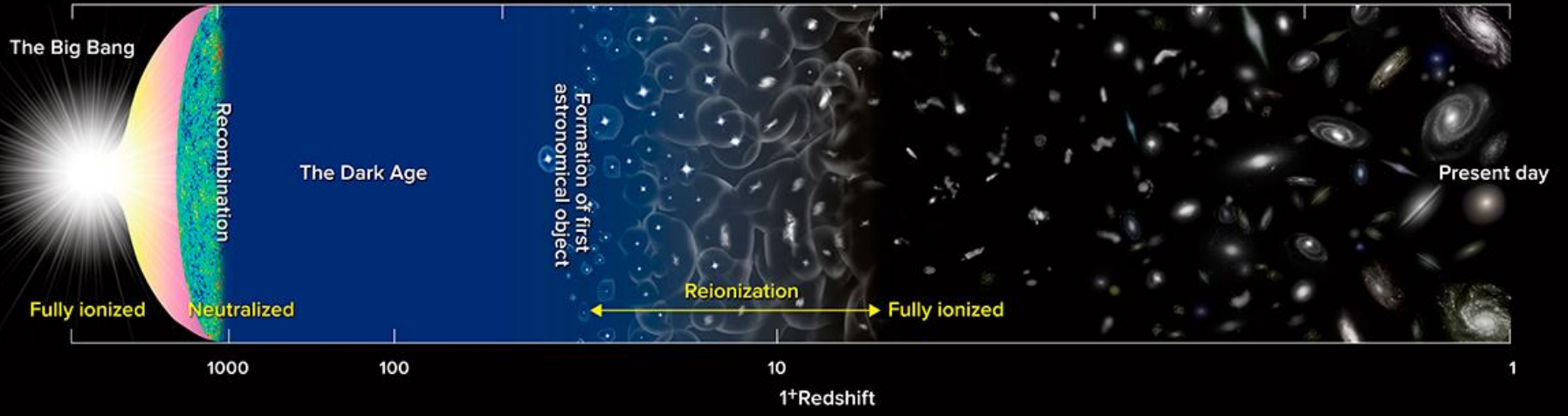


# History of the Universe

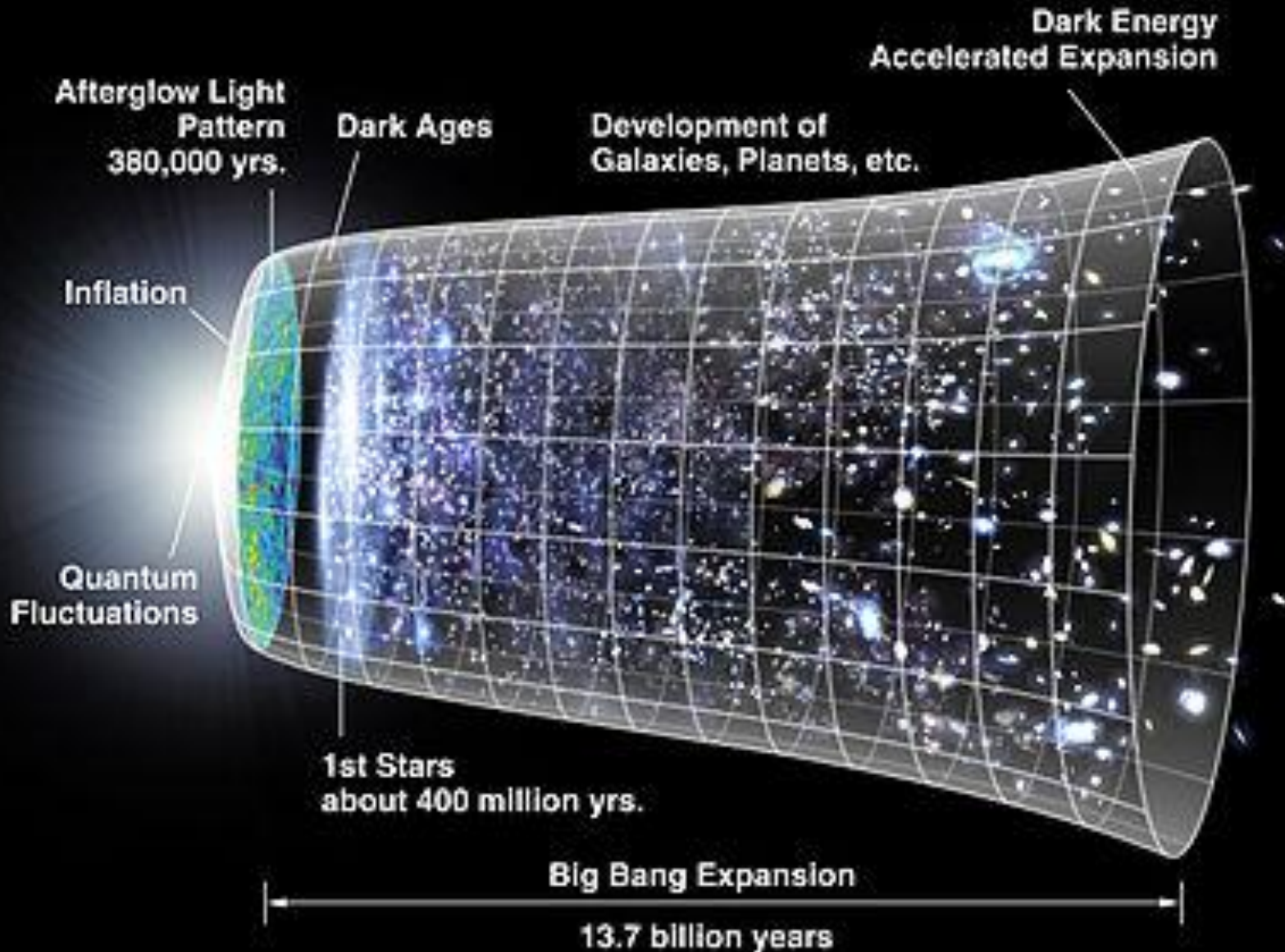


1g

400 thousand, 0.1 billion, 1 billion, 4 billion, 8 billion, 13.8 billion

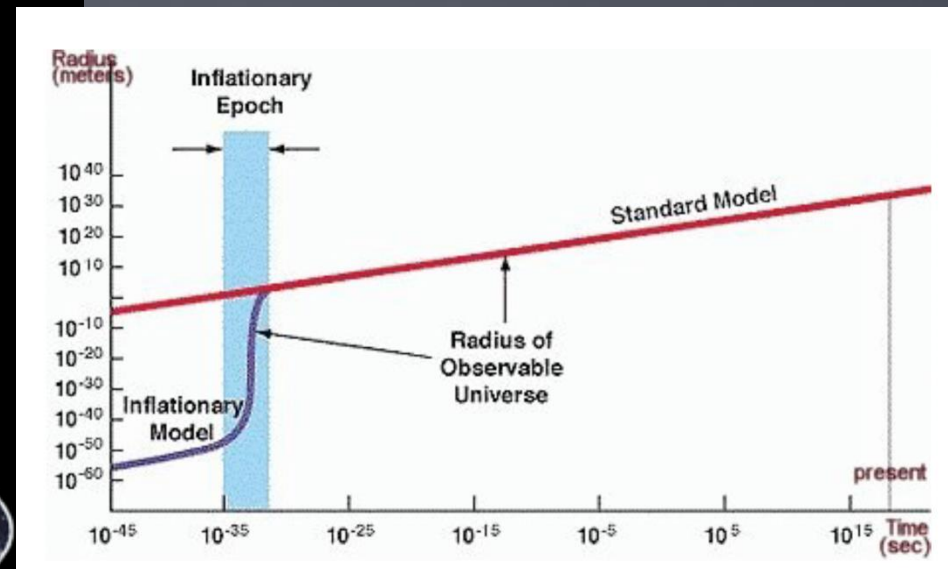
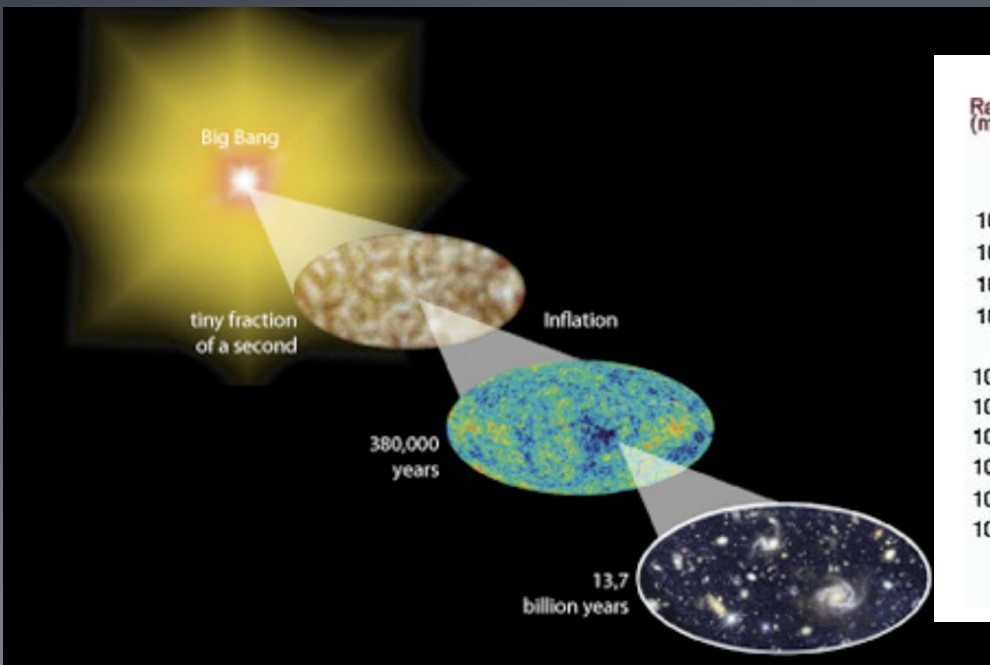


# Cosmology in a single plot

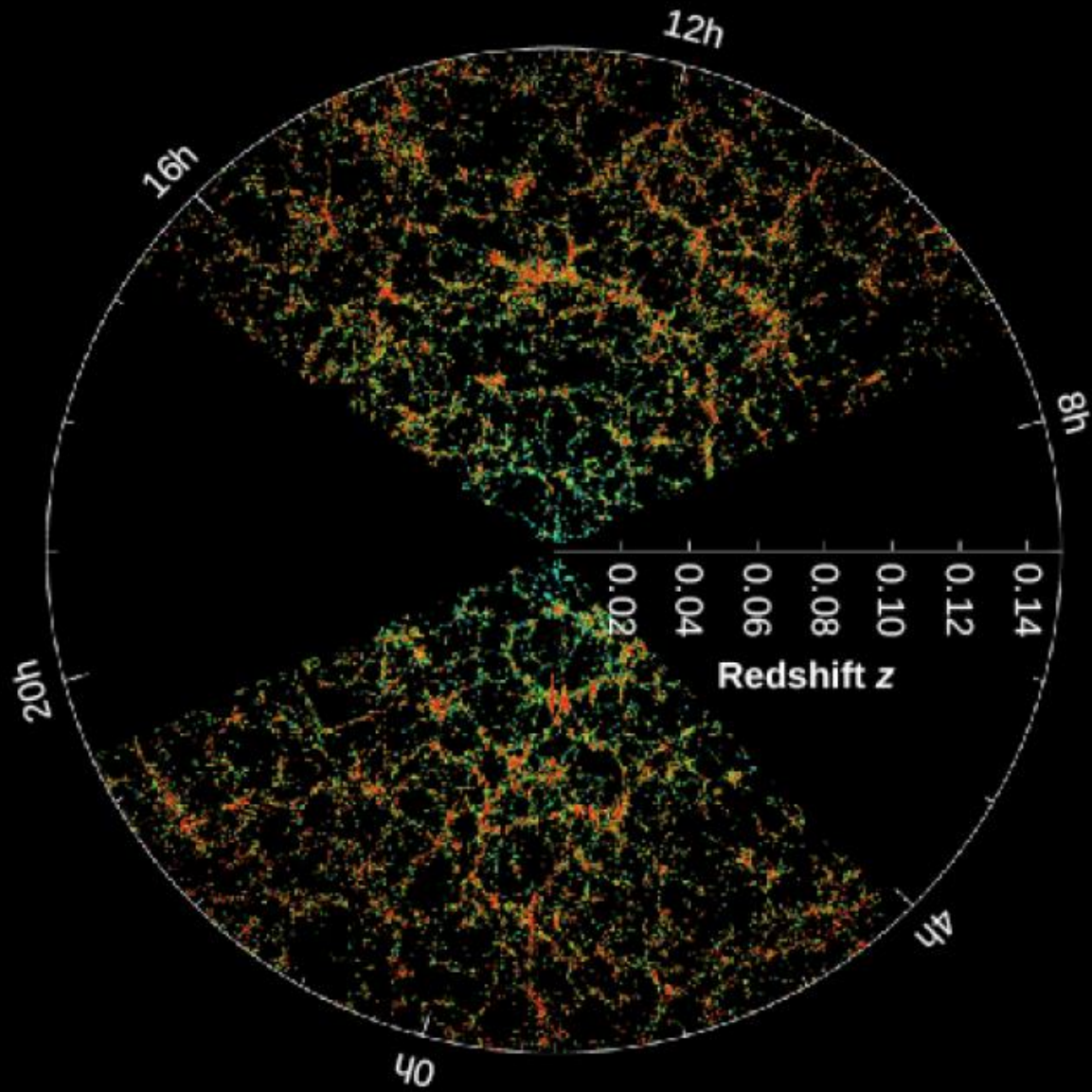


# Inflation: from $10^{-36}$ to $10^{-32}$ s

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

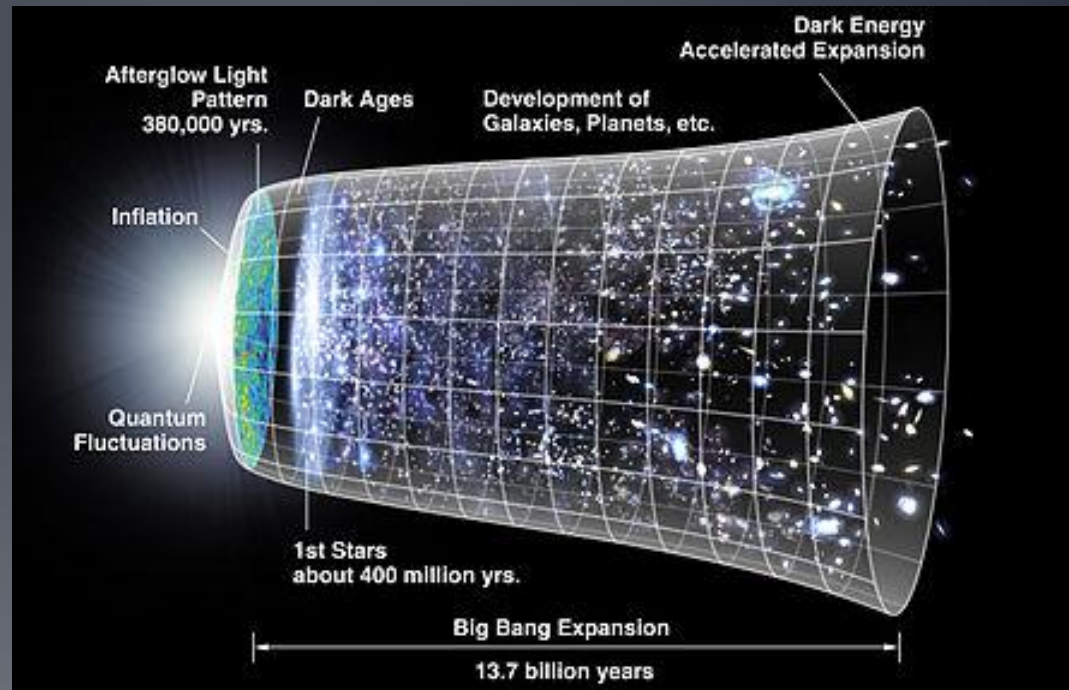


# 3D map of the universe: clusters and voids



# 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



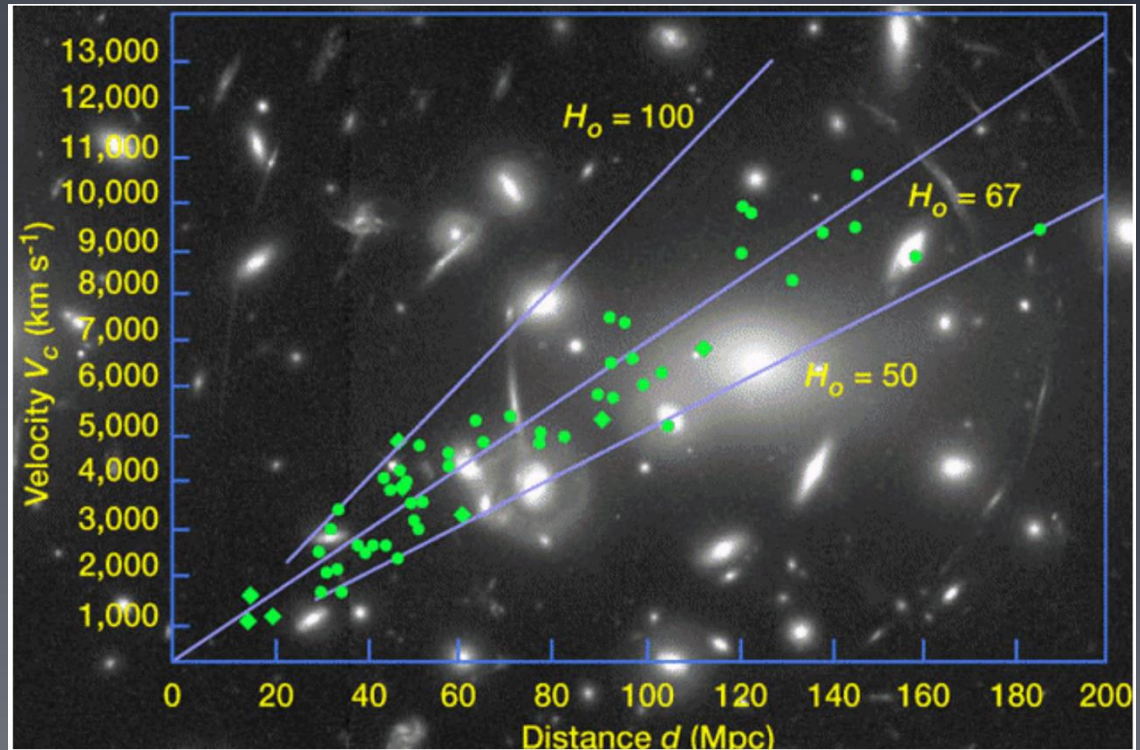
# Evidence for Big Bang

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

# Evidence for Big Bang

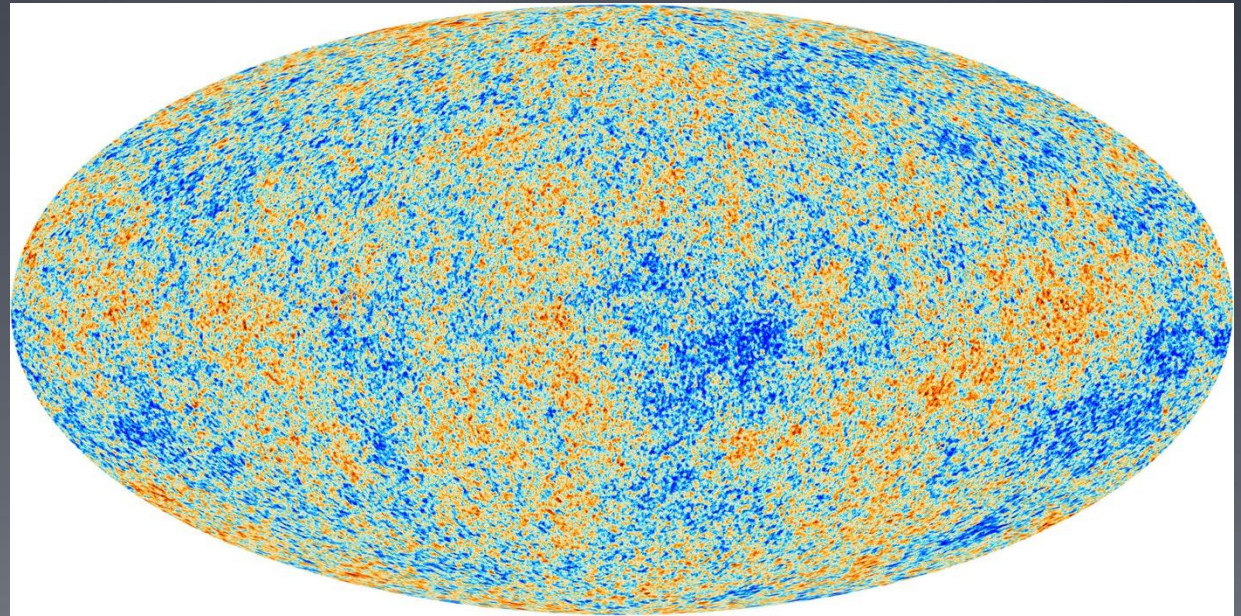
- Cosmic Expansion/Hubble's Law
- Cosmic Microwave Background
- Abundances of light elements
- Evolution of galaxy structures



# Evidence for Big Bang

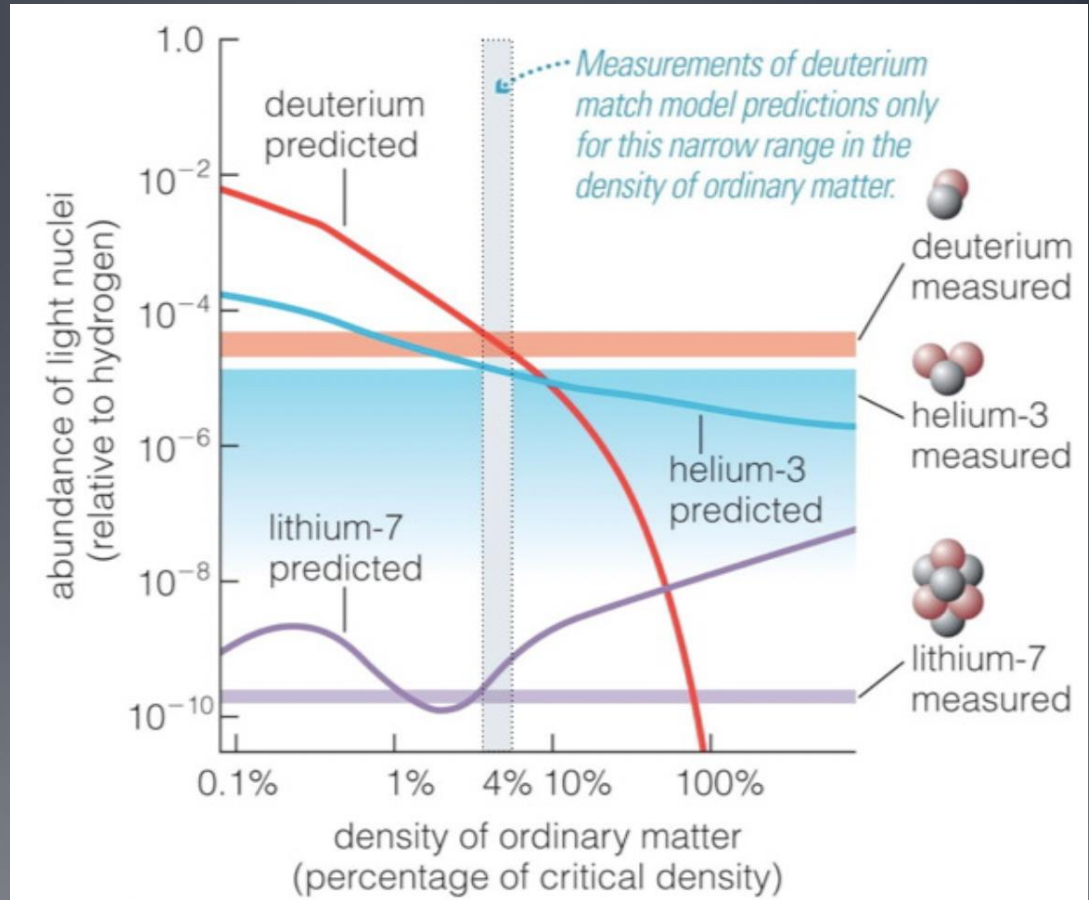
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- Cosmic Expansion/Hubble's Law
- **Cosmic Microwave Background**
- Abundances of light elements
- Evolution of galaxy structures



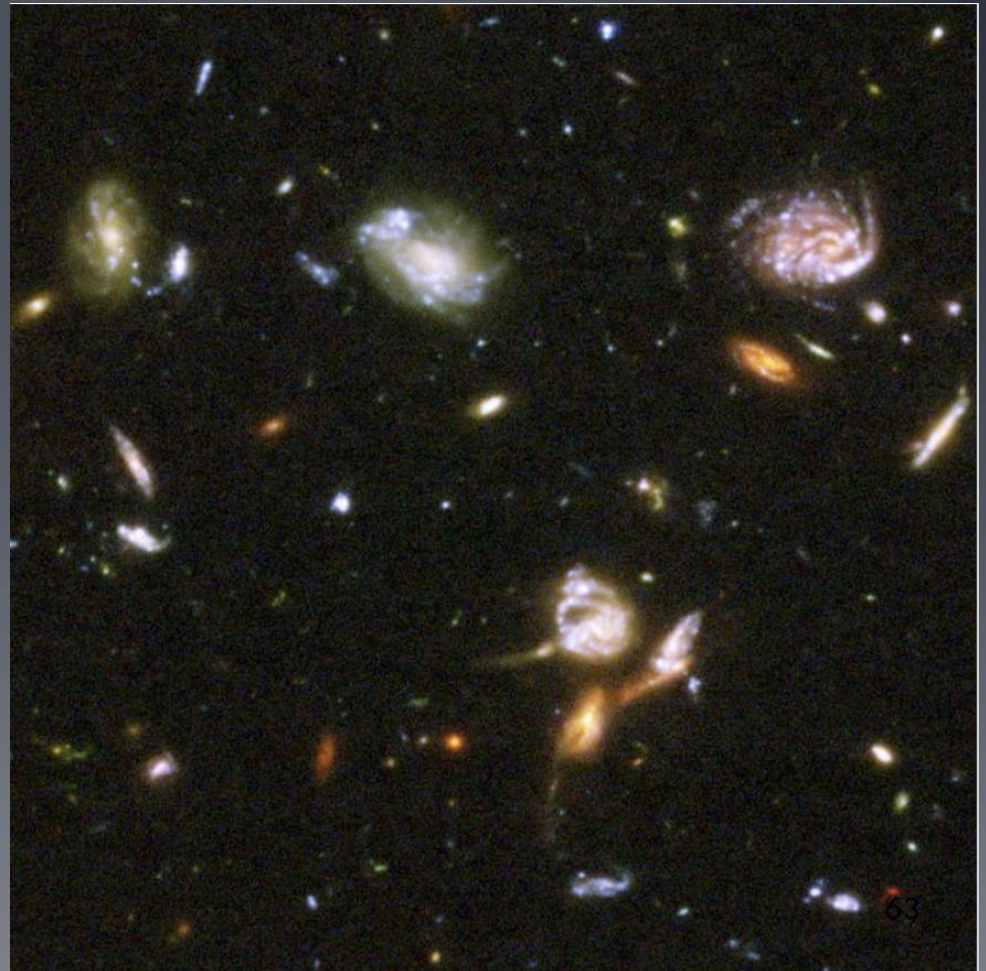
# Evidence for Big Bang

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

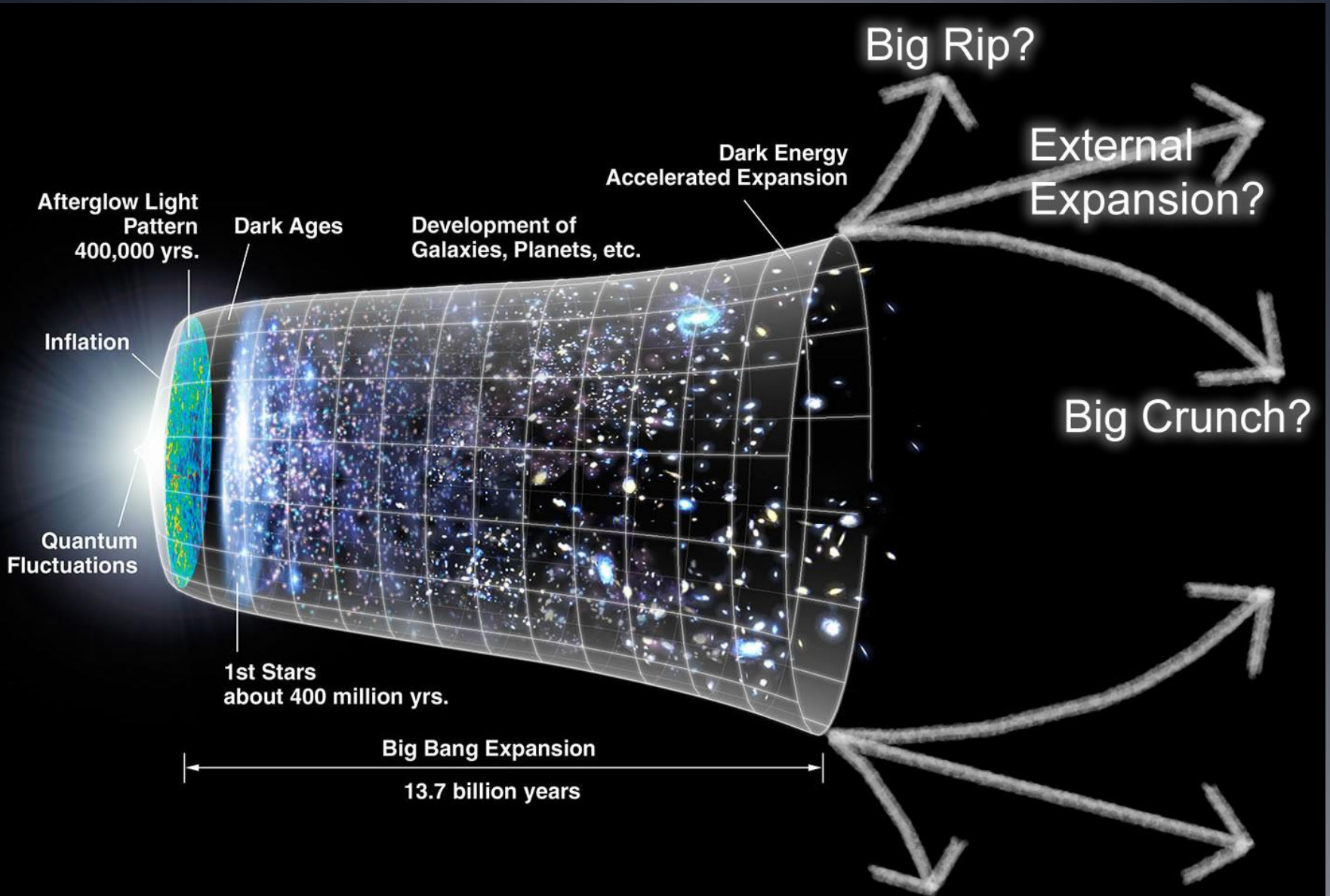


# Evidence for Big Bang

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



# 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?

---

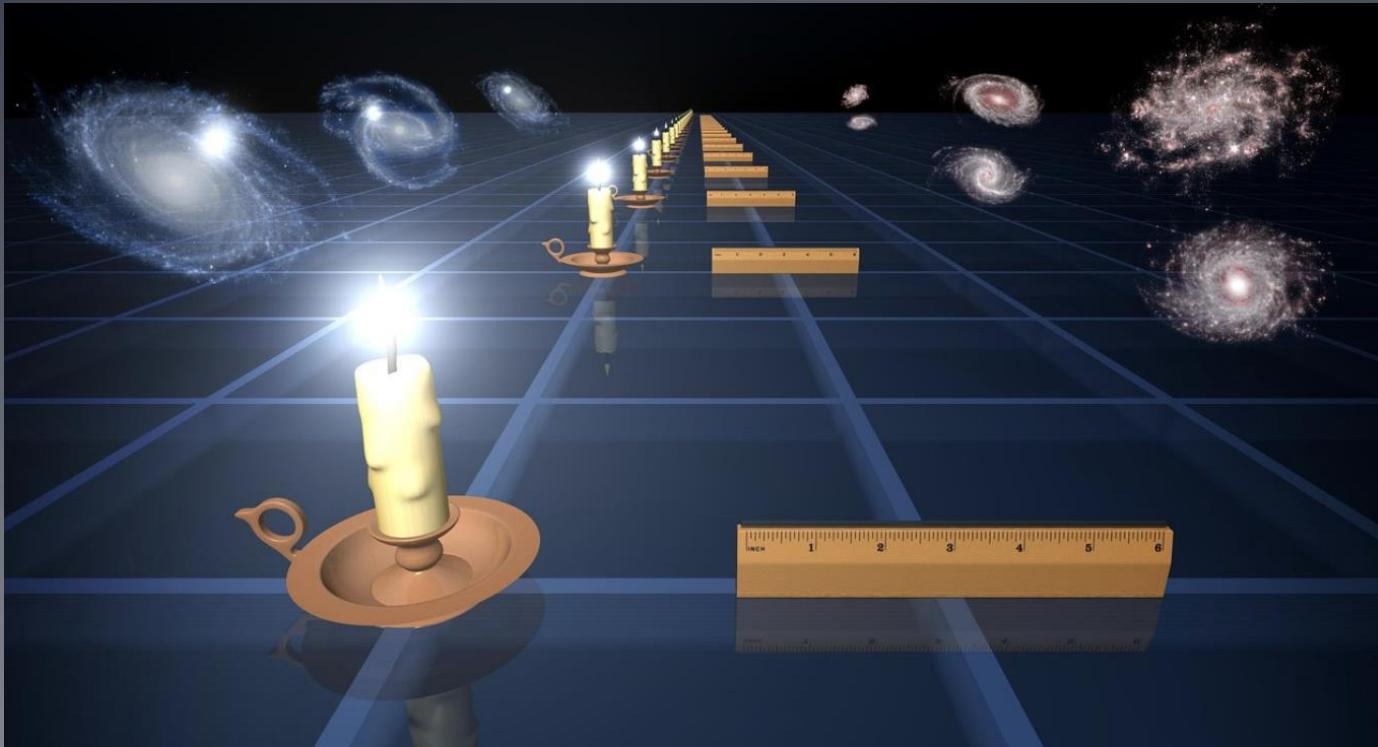
- Universe is accelerating
- Can gravity (long-distance) overcome the acceleration?

How do we measure mass?

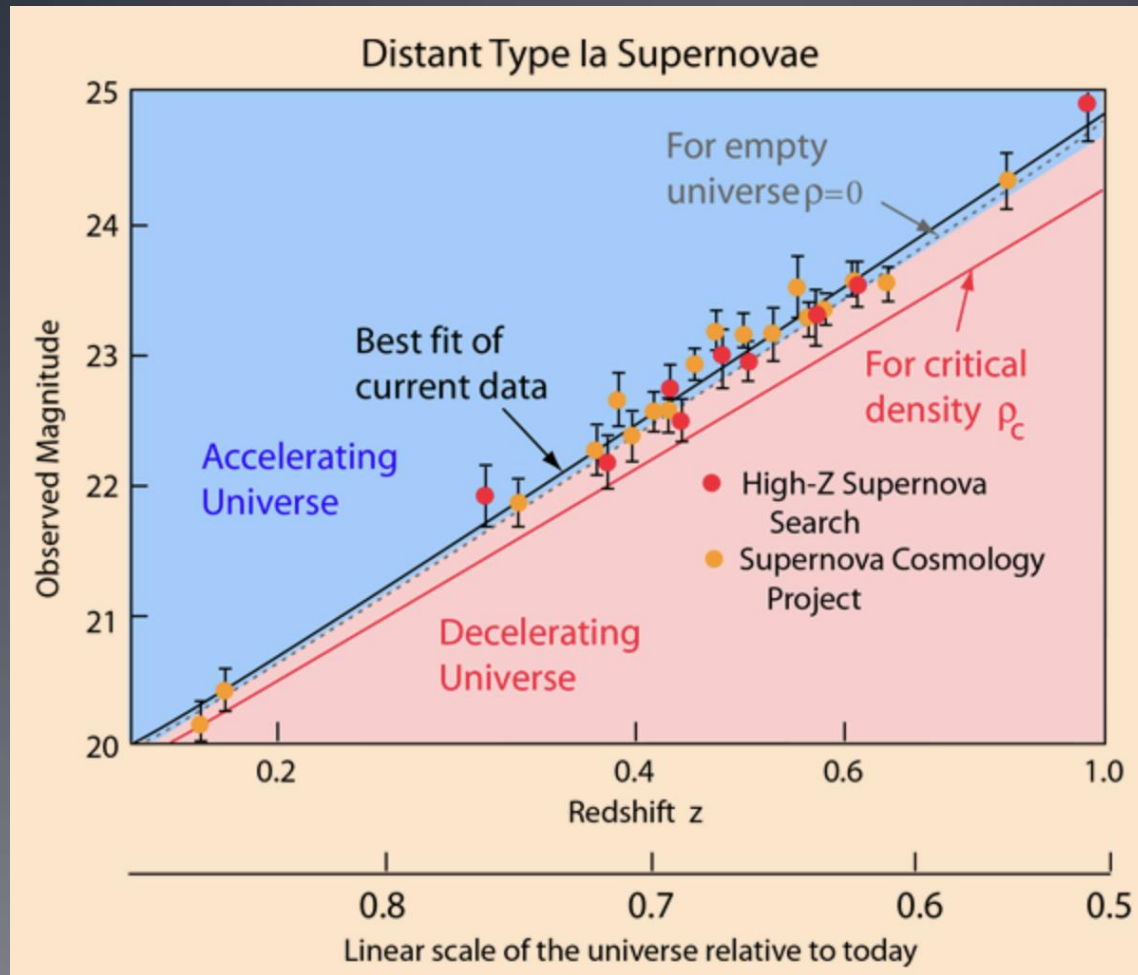
- Starlight (mass in stars, gas)
  - Galactic rotation curves
  - Gravitational lensing
-

# Type 1a supernova as standard candles

- White dwarf explosions
- Over  $1.4 M_{\text{sun}}$  (Chandrasekhar mass)
- Always same luminosity (after corrections)

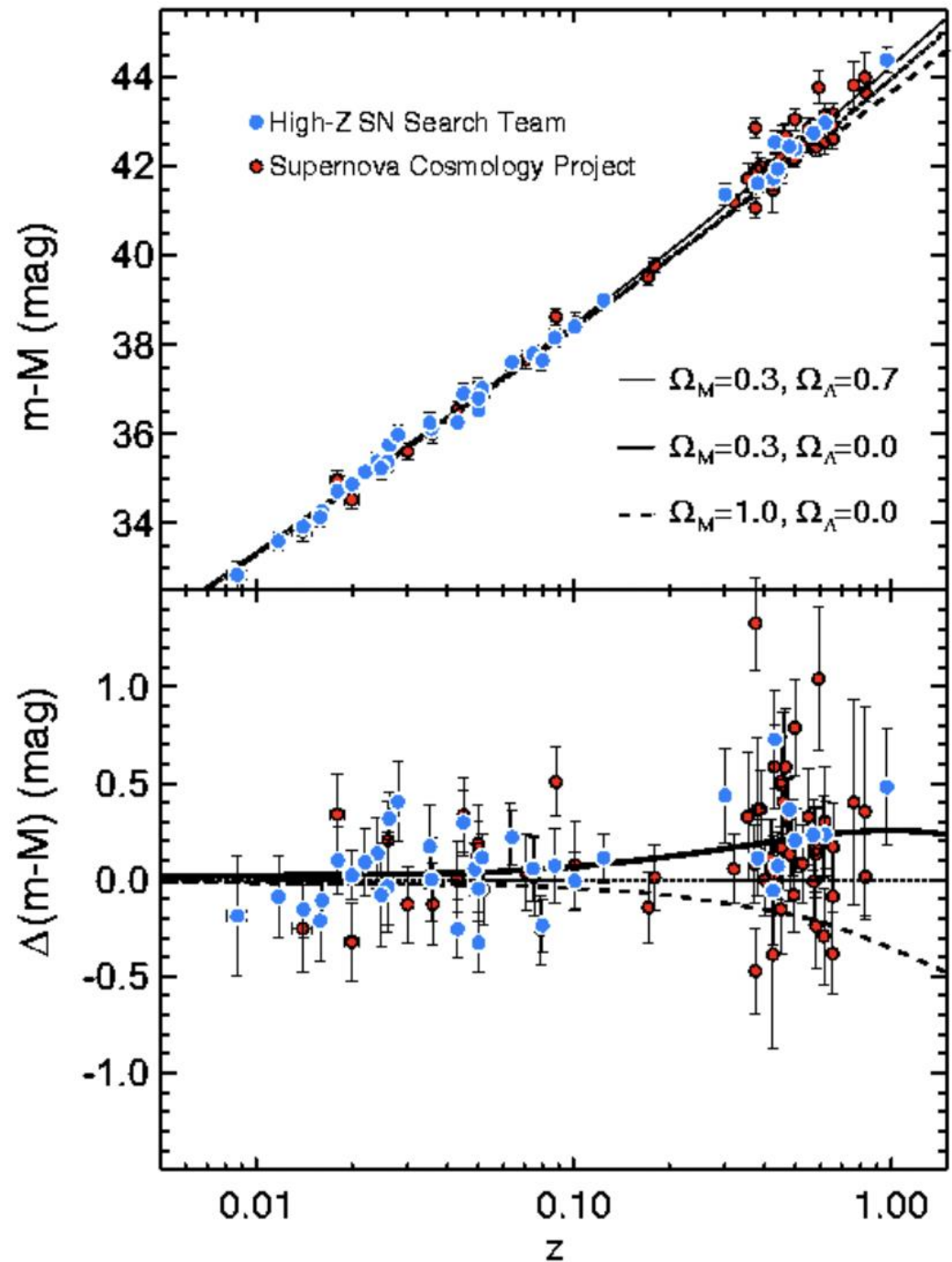


# Type 1a Supernova: expansion of universe is accelerating!



Type Ia  
Supernova:  
expansion of  
universe is  
accelerating!

Einstein's  
"cosmological  
constant"

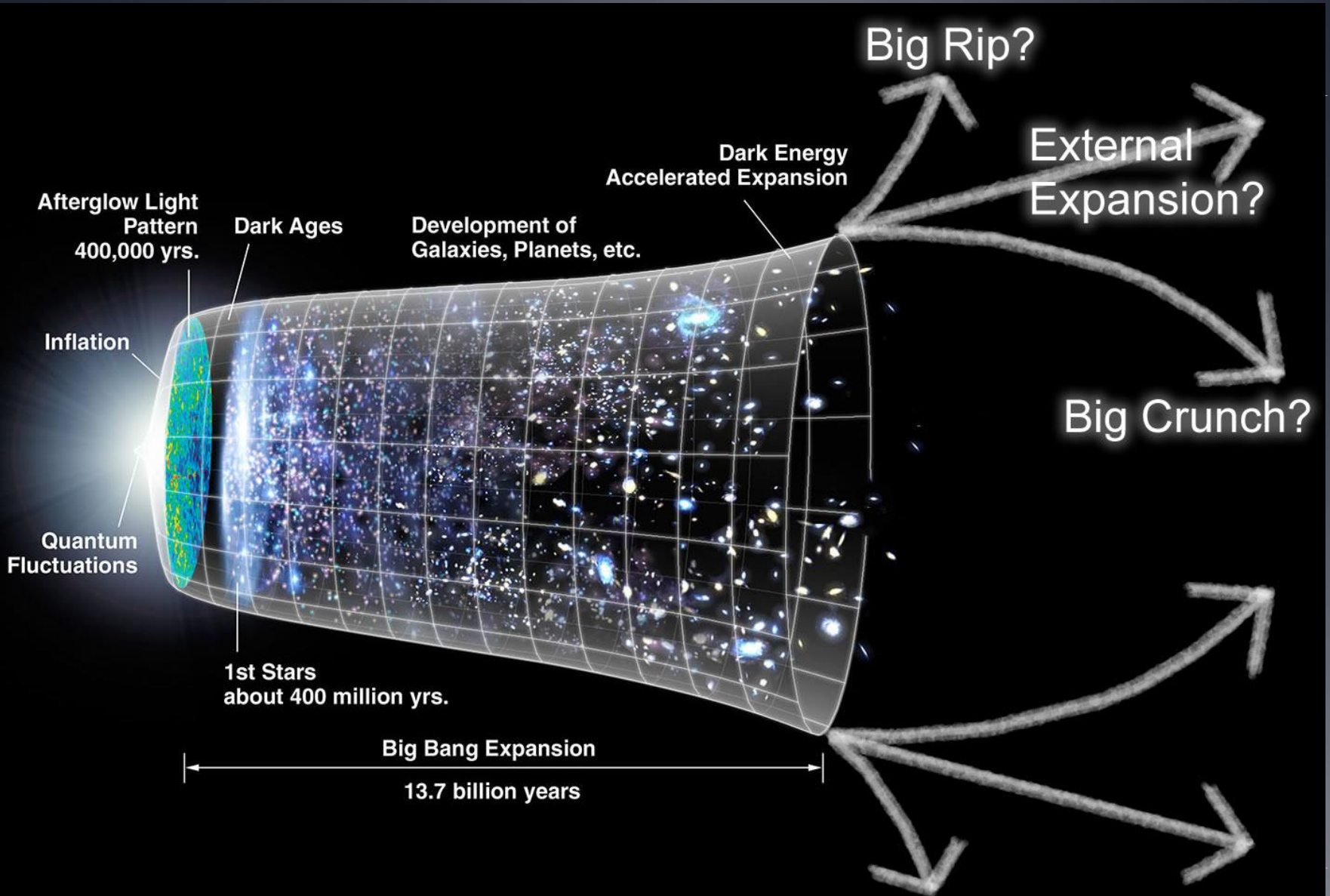


# Dark (vacuum) energy

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- 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
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# Big Rip



# 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