NCTS SSP Lectures 2026 —Observational Cosmology

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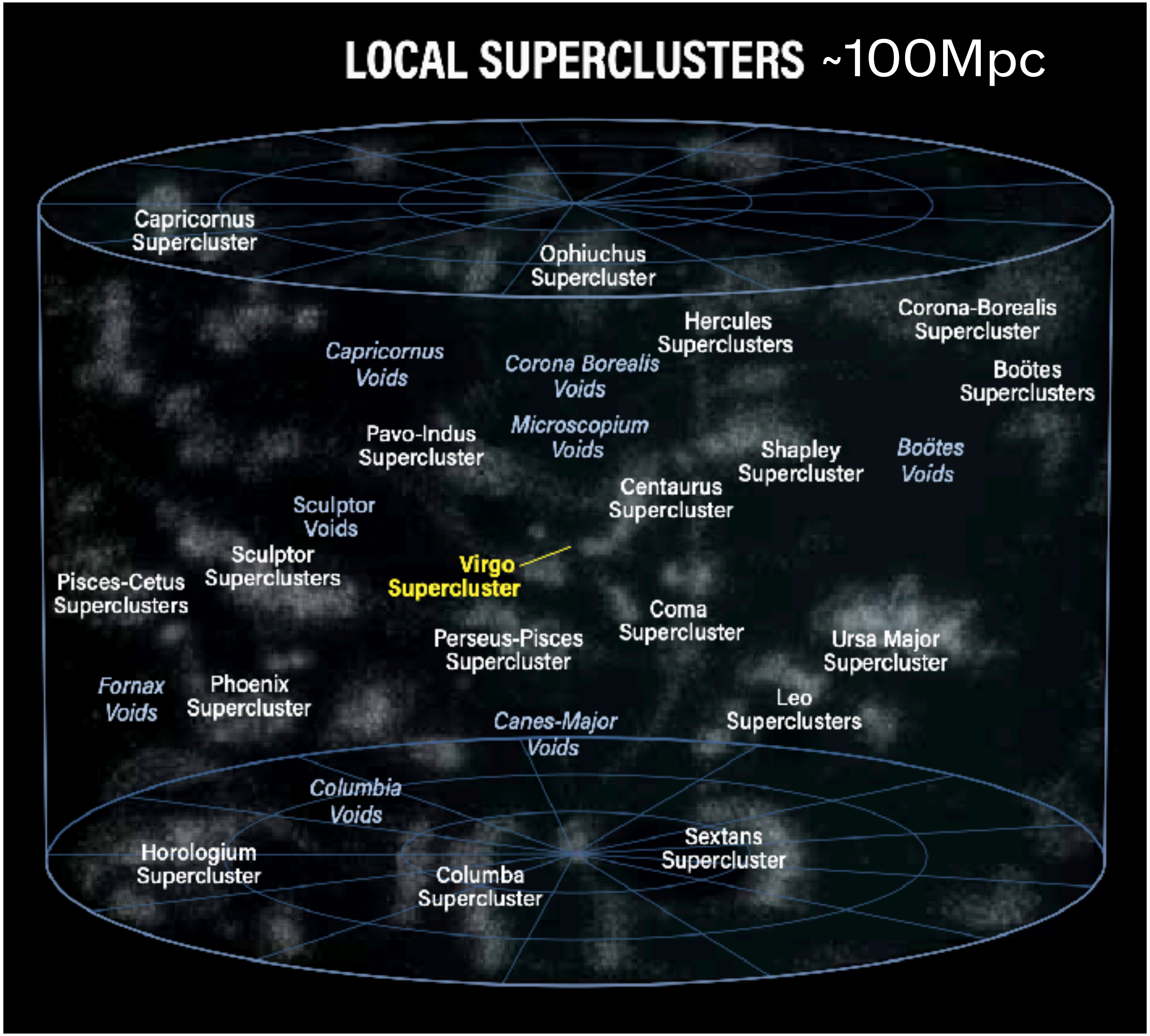
Some questions cosmologists are interested:

- What is the Universe made of?
- What is its spatial curvature?
- Did it have a beginning time/ origin in the past?
- What is the end of the Universe?
- To understand the origin, evolution, structure, and ultimate fate of the universe.

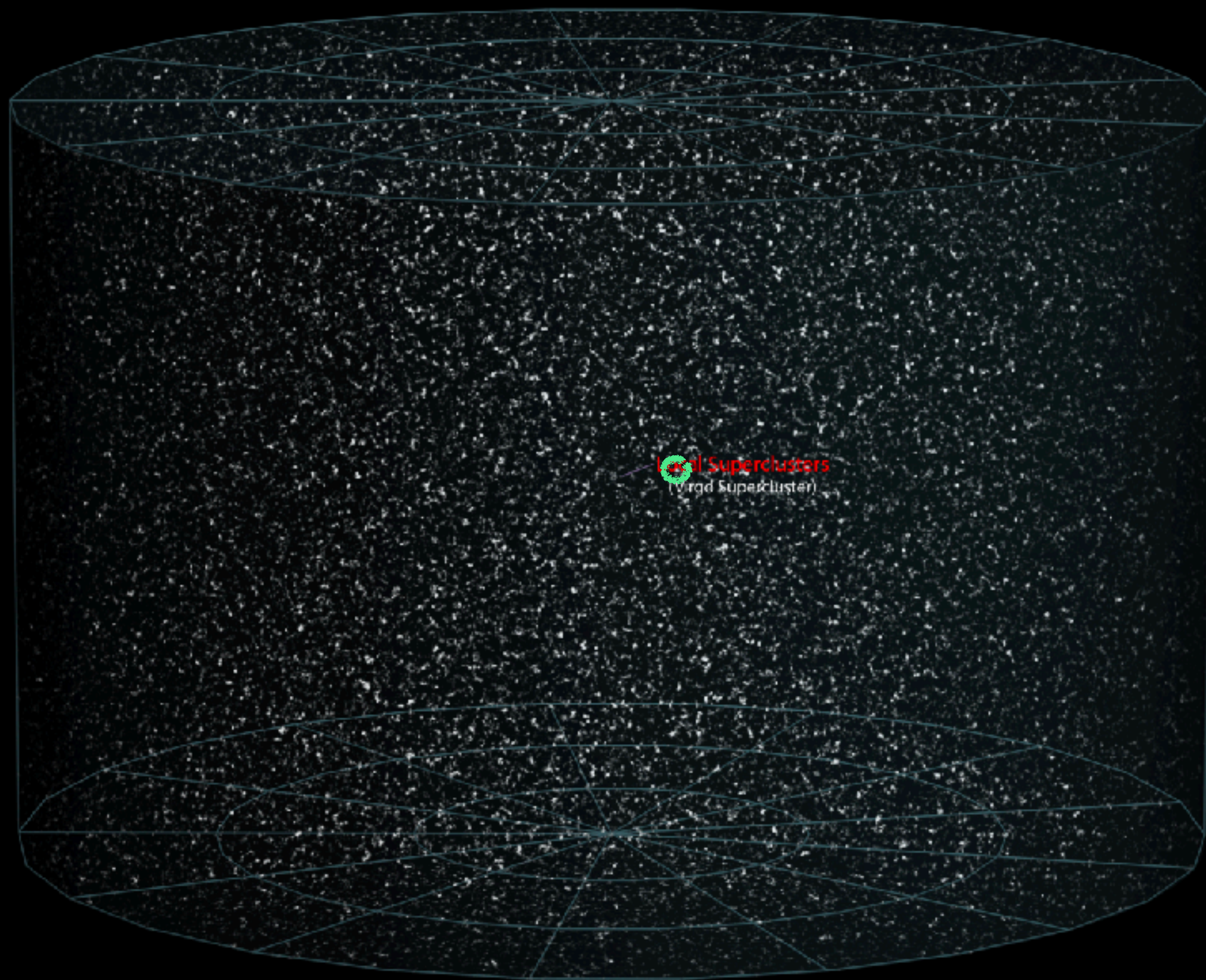
Modern Cosmology

- Foundational assumptions in cosmology:
  Cosmological Principle
  —On large scale, the Universe is isotropic and homogeneous
- 1. Homogeneity: the Universe looks the same from any location on large scale.
  —> There are no preferred locations or centers in the universe.
- 2. Isotropy: the Universe appears the same in all directions when observed from any point.
  —>There is no preferred direction in the universe on large scales.



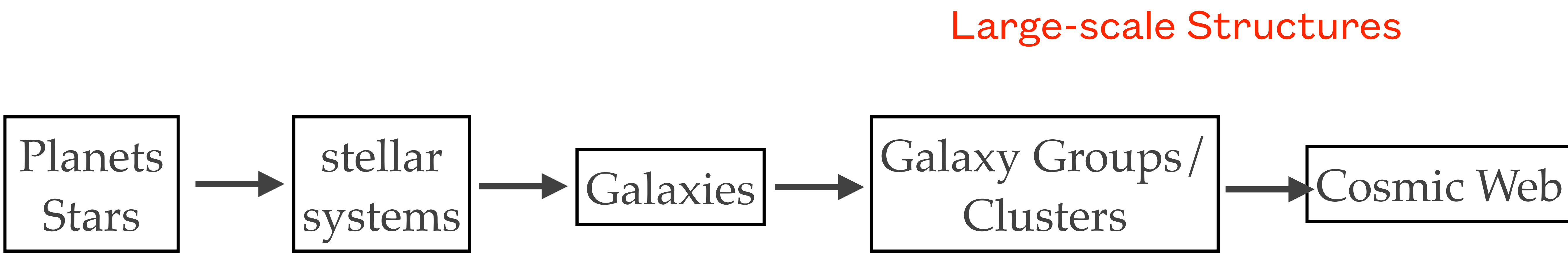
Composed by overdense region (filaments & galaxy clusters) and under-dense region (voids); average density ~ the universe as a whole

OBSERVABLE UNIVERSE



Many galaxy clusters form the large-scale structure of our universe.

Cosmological Principle



At small scales, the distribution of cosmic matter is not uniform;
Only at large scales >100Mpc, it conforms to the principles of cosmology.

We are not in a special location within the universe; the universe has no center point.

Hubble Law: Expansion

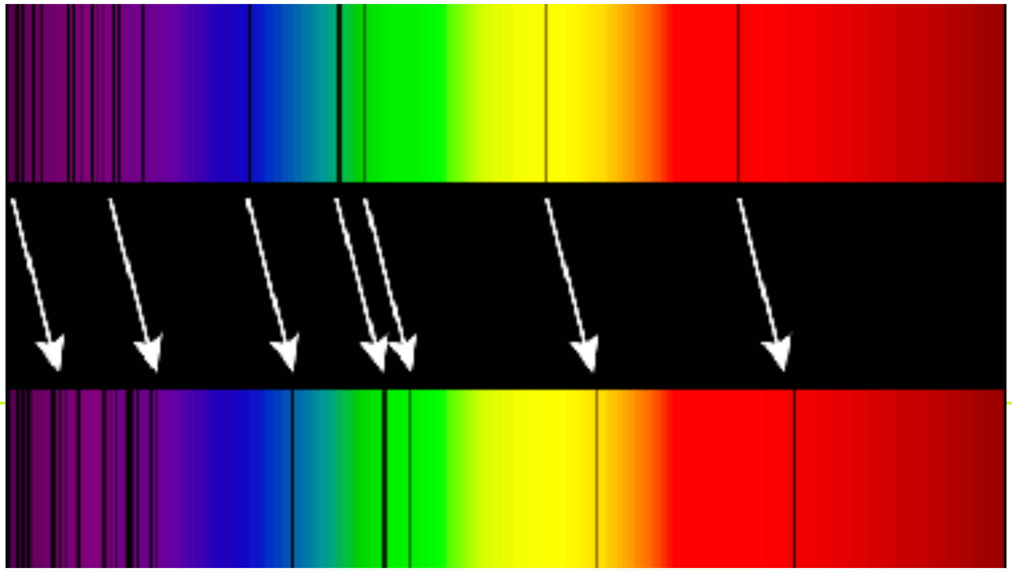
- In the early 20th century, Edwin Hubble discovered that galaxies are all moving away from the Milky Way at high speeds, and the farther galaxies are, the faster they are moving away.

- The Doppler effect: When there is relative motion between the source of waves and the observer, the wavelength observed by the observer differs from that emitted by the source.

- Galaxies have a set of absorption and emission line in their spectra;
  — If the light source is moving away from the observer, it results in a redshift.
  — If the light source is moving towards the observer, it produces a blueshift.

$$z \equiv \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

Cosmological redshift



Hubble's Law: Expansion

- Hubble found that $z = \frac{H_0}{c} r$, where H_0 is the Hubble constant
- With z=v/c, where v is the radial velocity of the source
- Hubble's Law: $v=H_0 D$,
  where H_0 represents the rate of cosmic expansion. The speed at which a galaxy recedes from us is directly proportional to its distance.
- From recent studies, $H_0 \sim 70\ \mathrm{kms^{-1}Mpc^{-1}}$
  —> For every increase of 1 Megaparsec (Mpc), the velocity increases by 70 km/s.
- Cosmological principles+Hubble's Law

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Any galaxies would see distant galaxy moves away from them

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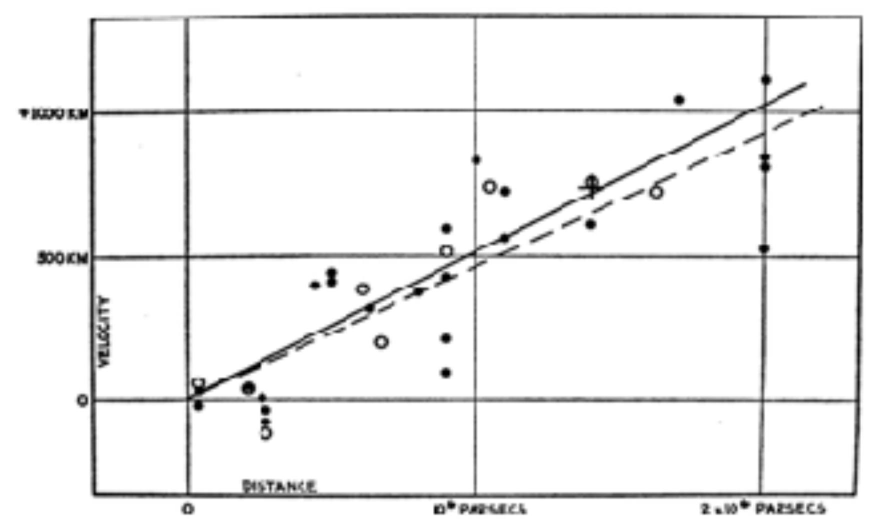
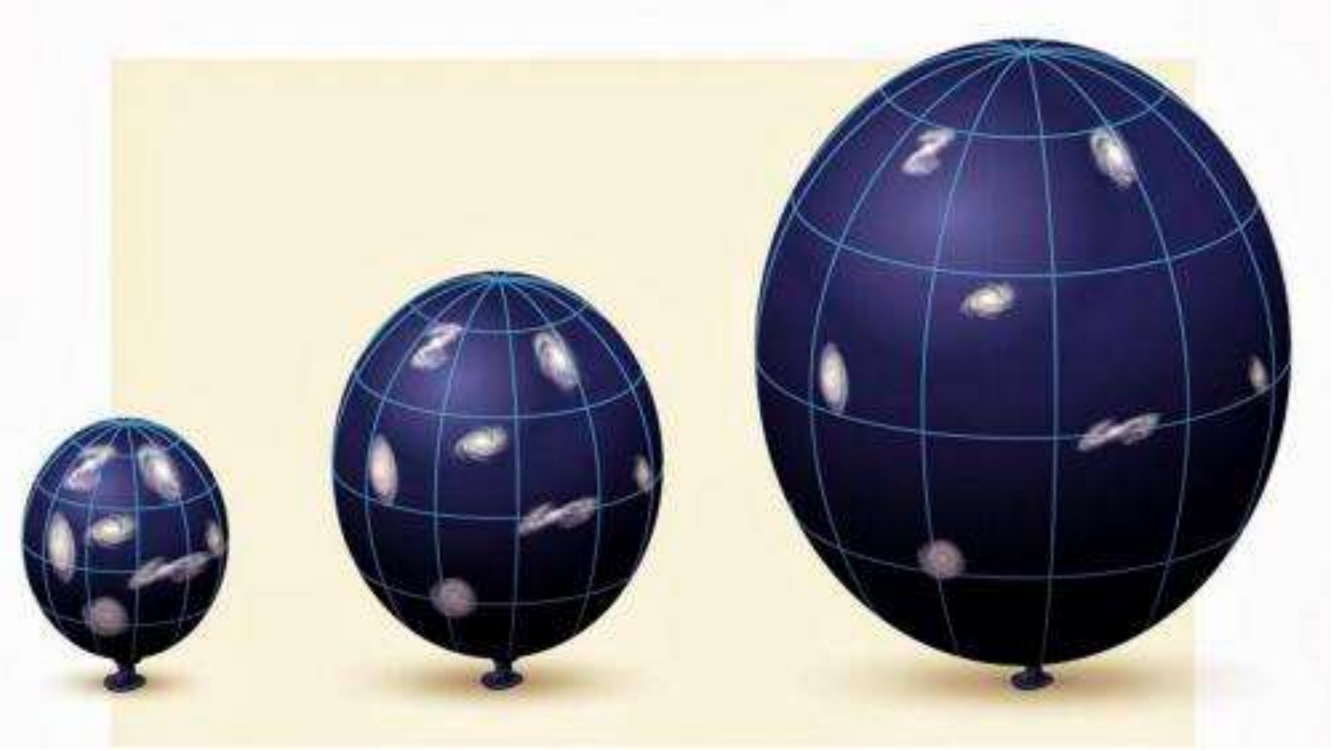
Universe is expanding!



Hubble 1929, Proc. Nat. Acad. Sci., 15, 168

Hubble's Law: Expansion

- In the distant past everything in the Universe was much closer together —> Big Bang: Universe form from a beginning
- Big Bang model:
  —> average density decreases, the mean distance between galaxies increases
  —> observational evidence: CMB



The expanding Raisin cake

https://www.youtube.com/watch?v=-xrg8Ikanf8

Cosmological redshift

- As the Universe expands, photon wavelengths are stretched, causing the spectra of distant galaxies to be redshifted.

$$z \equiv \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$

- As the Universe expands, the wavelength of a photon stretches in proportion to the cosmic scale factor a(t):

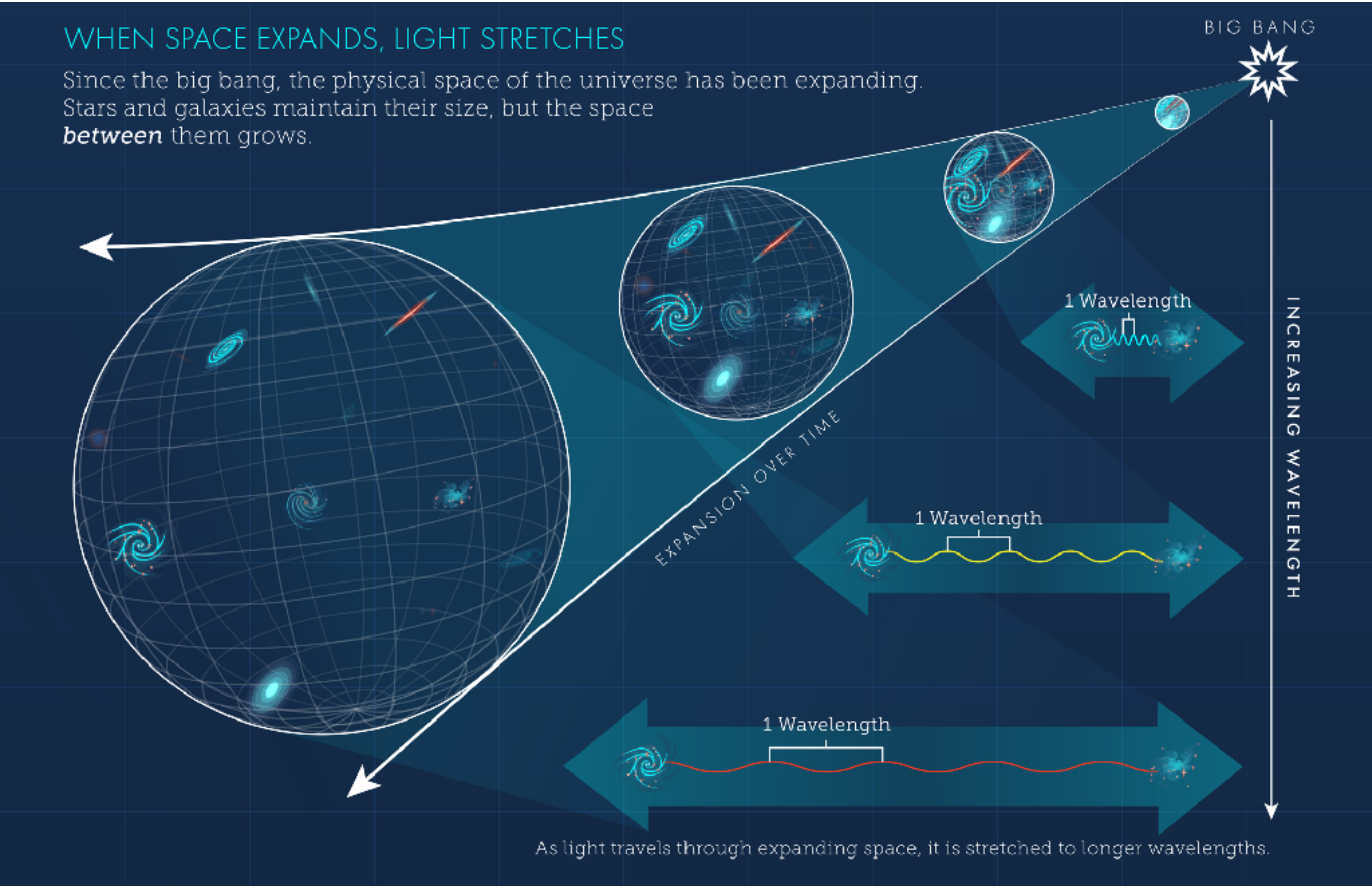
$$\lambda \propto a(t).$$

The relative size of the Universe:

$$d(t) = a(t)\,\chi$$

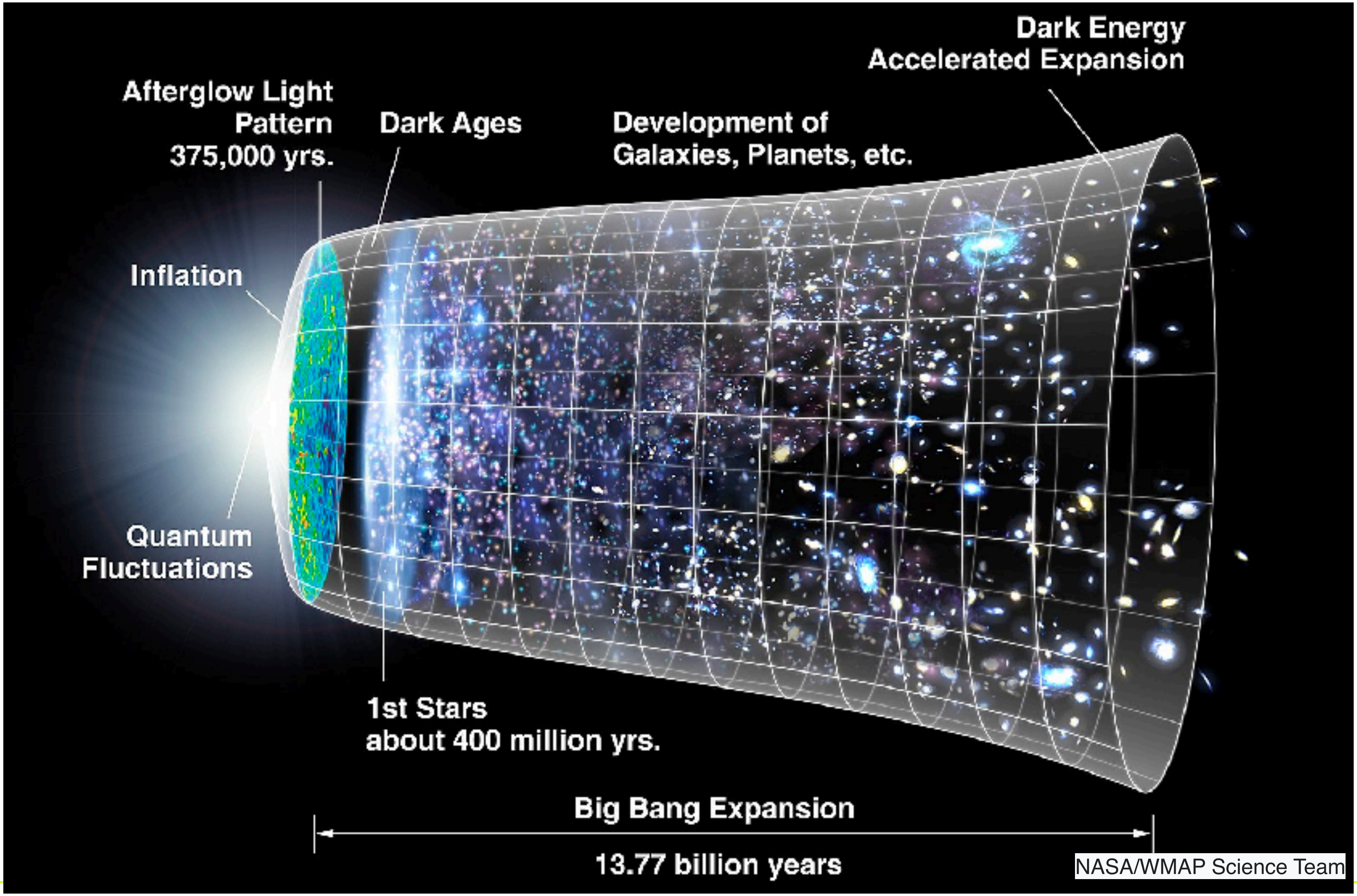
- The observed redshift directly measures how much the Universe has expanded since the photon was emitted:

$$1 + z = \frac{a_0}{a_{\rm emit}}.$$



Credit: NASA, ESA, Leah Hustak (STScI) https://science.nasa.gov/mission/hubble/science/science-behind-the-discoveries/hubble-cosmological-redshift/

Evolution of the Universe



FLRW models

- Friedmann–Lemaître–Robertson–Walker (FLRW) model

$$ds^2 = -c^2 dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta\, d\phi^2)\right].$$

a(t):expansion of the Universe;
k: geometry of space, k=0: flat; k>0: closed; k<0: open

- Friedmann equations:

Matter, radiation

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}.$$

Expansion rate Curvature Dark energy

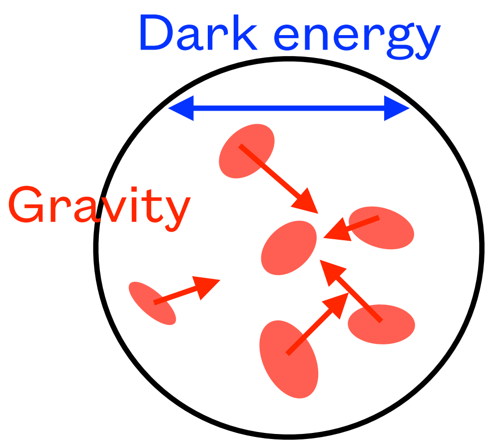
$$H^2(a) = H_0^2\left[\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda\right]$$

Density parameter: $\Omega_i = \frac{\rho_i}{\rho_c}$

$$\Omega_m + \Omega_r + \Omega_\Lambda + \Omega_k = 1.$$

Lambda CDM Universe

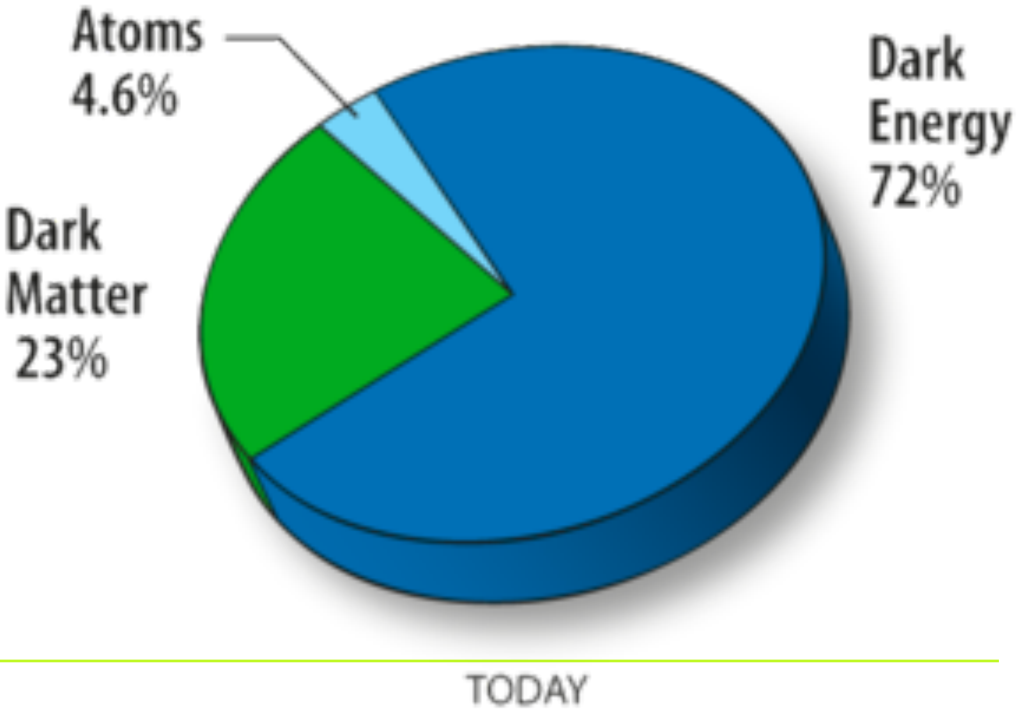
- Composition: Dark Energy, Dark Matter, Normal matter



- What determine the dynamical evolution of the Universe?
  -Expansion vs contraction;
  -Dark energy vs matter density (gravity)

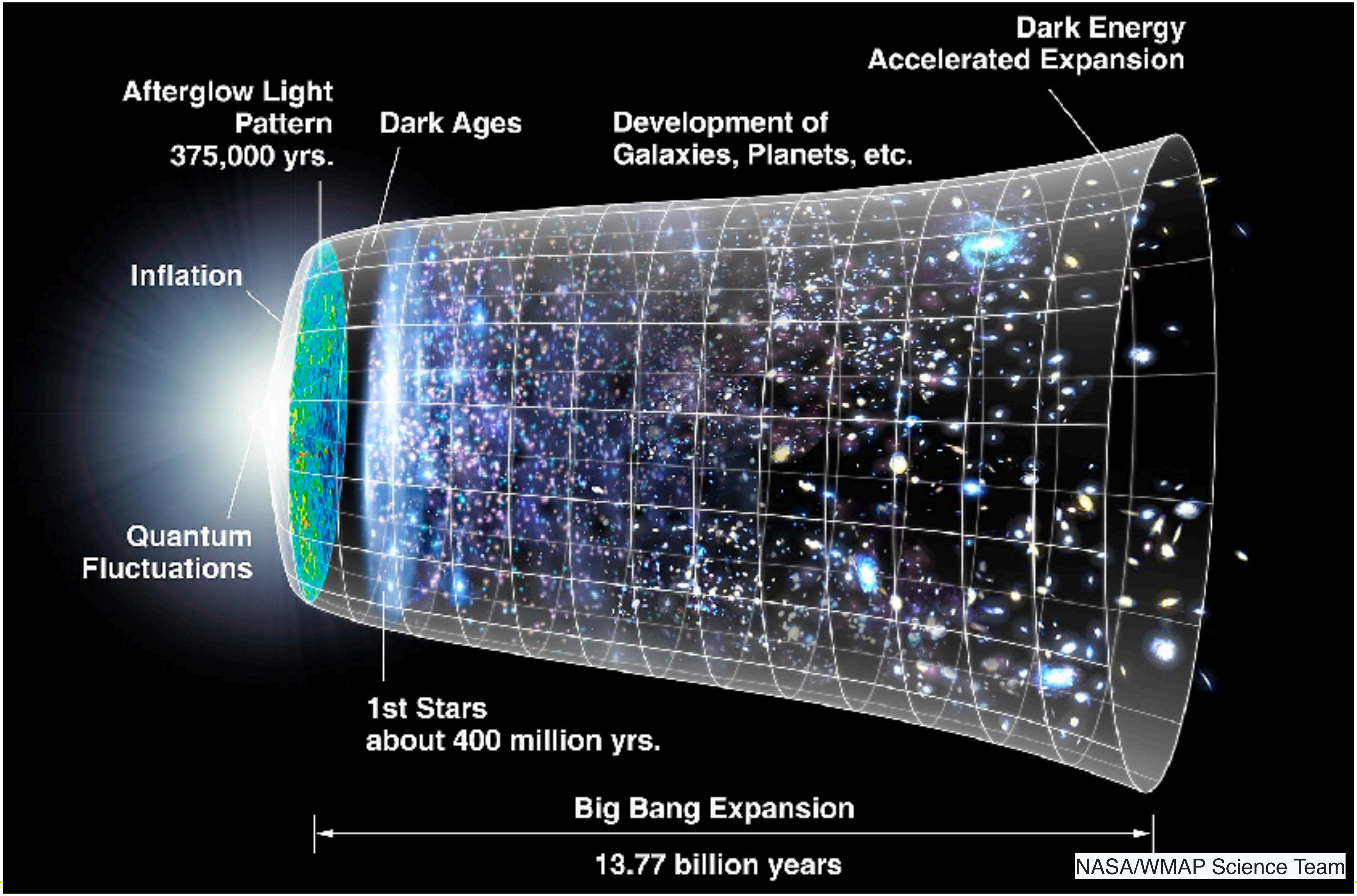
- The amount of energy density determines the curvature and expansion of the Universe

- Energy density changes with time —> causing different evolution stage of the Universe



- Current standard model: ΛCDM
  - Λ: cosmological constant, which is associated with dark energy—accelerating expansion
  - CDM: cold dark matter, "cold" refers to slow-moving, a form of matter that interacts only weakly with regular matter and radiation

Evolution of the Universe



NASA/WMAP Science Team

Expansion of the Universe

- Three different stages:
  - The Big Bang
  - Inflation
  - Decelerating expansion
  - Accelerating expansion

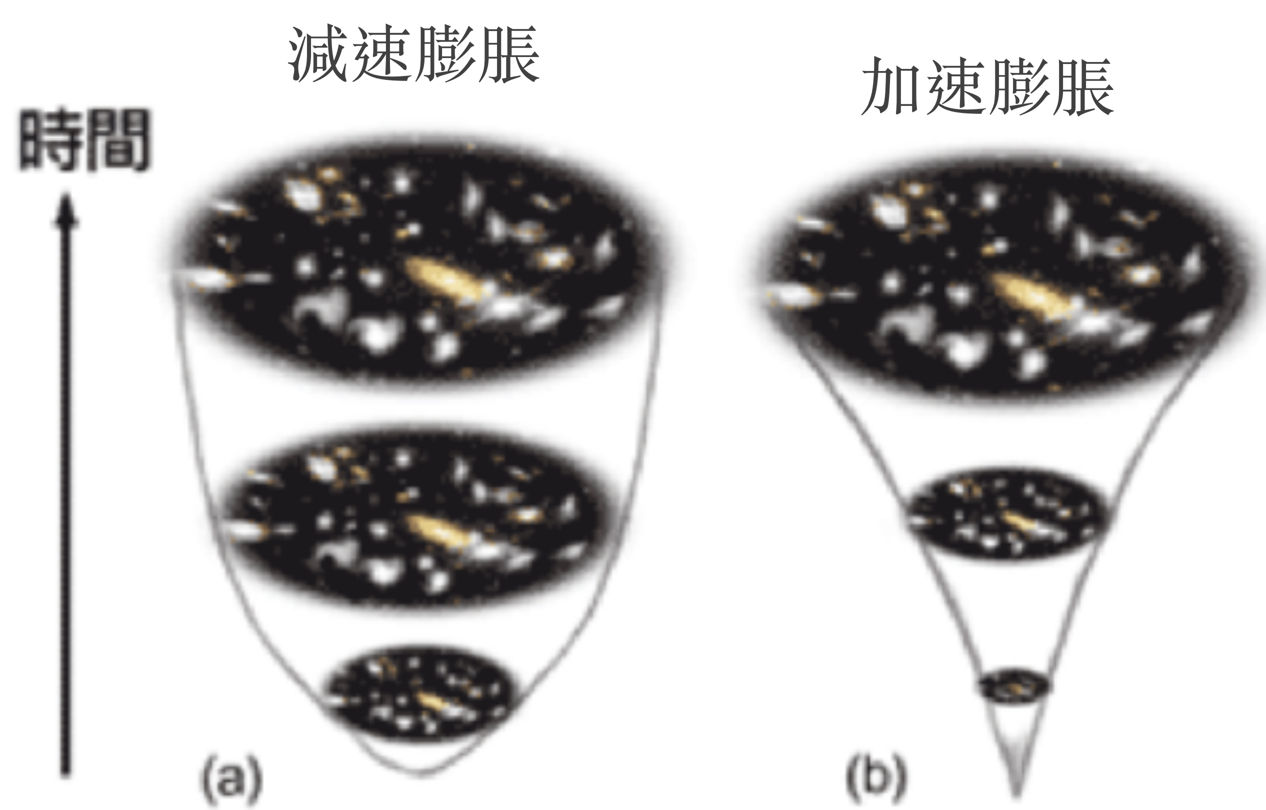
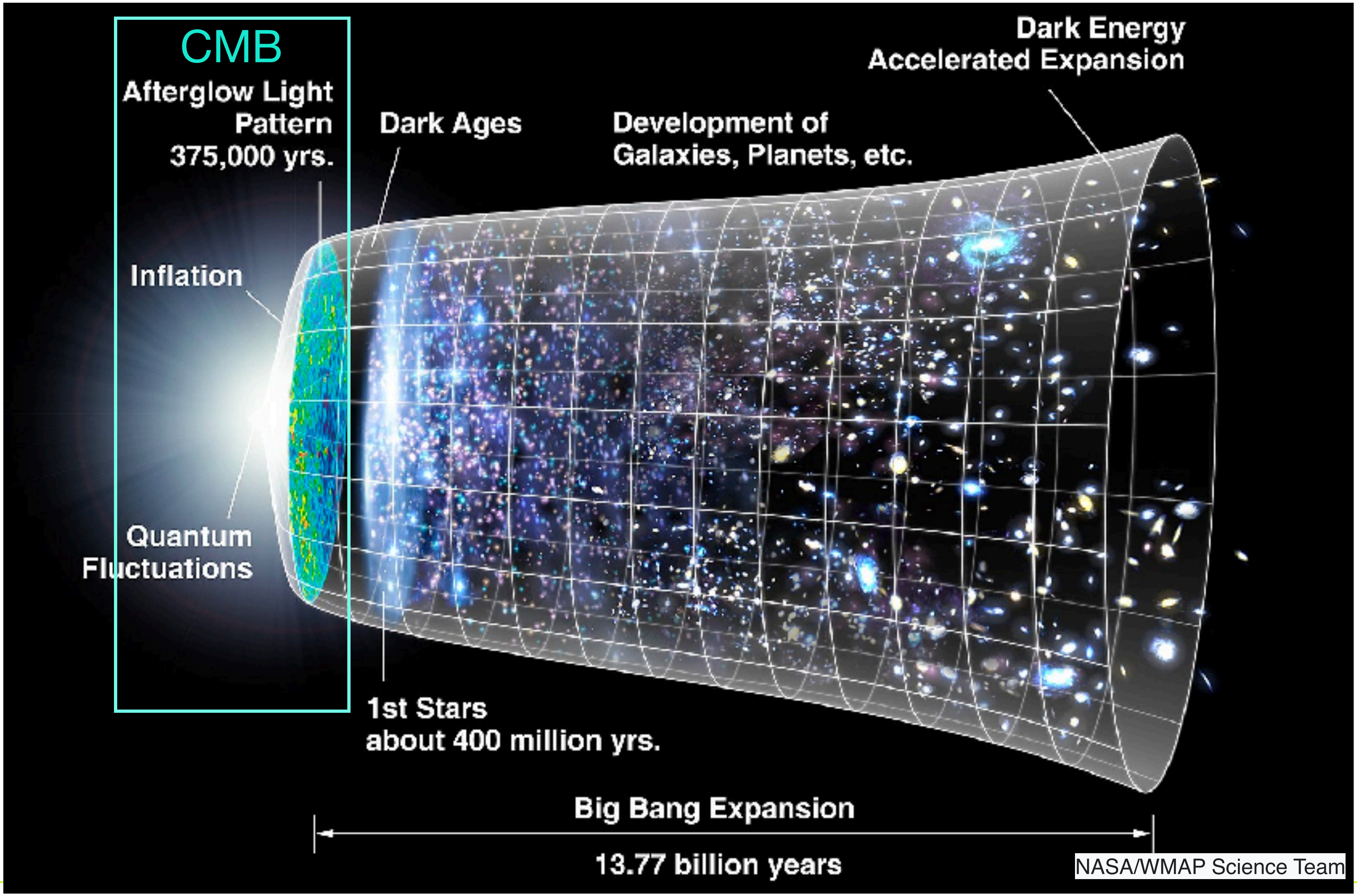


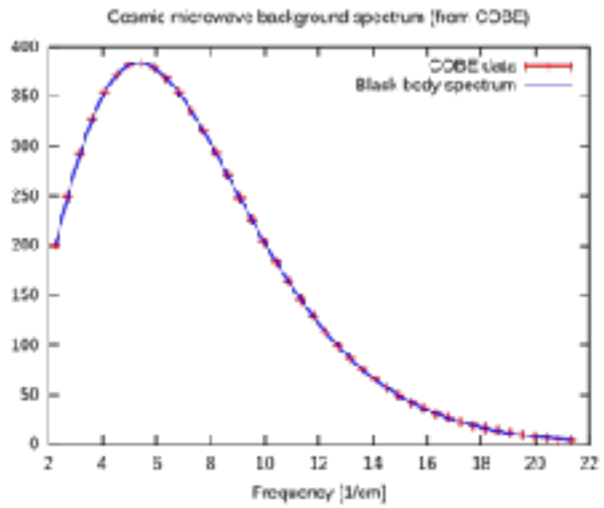
Image Credit: https://www.phy.cuhk.edu.hk/phyworld/articles/univexpand/univexpand.html

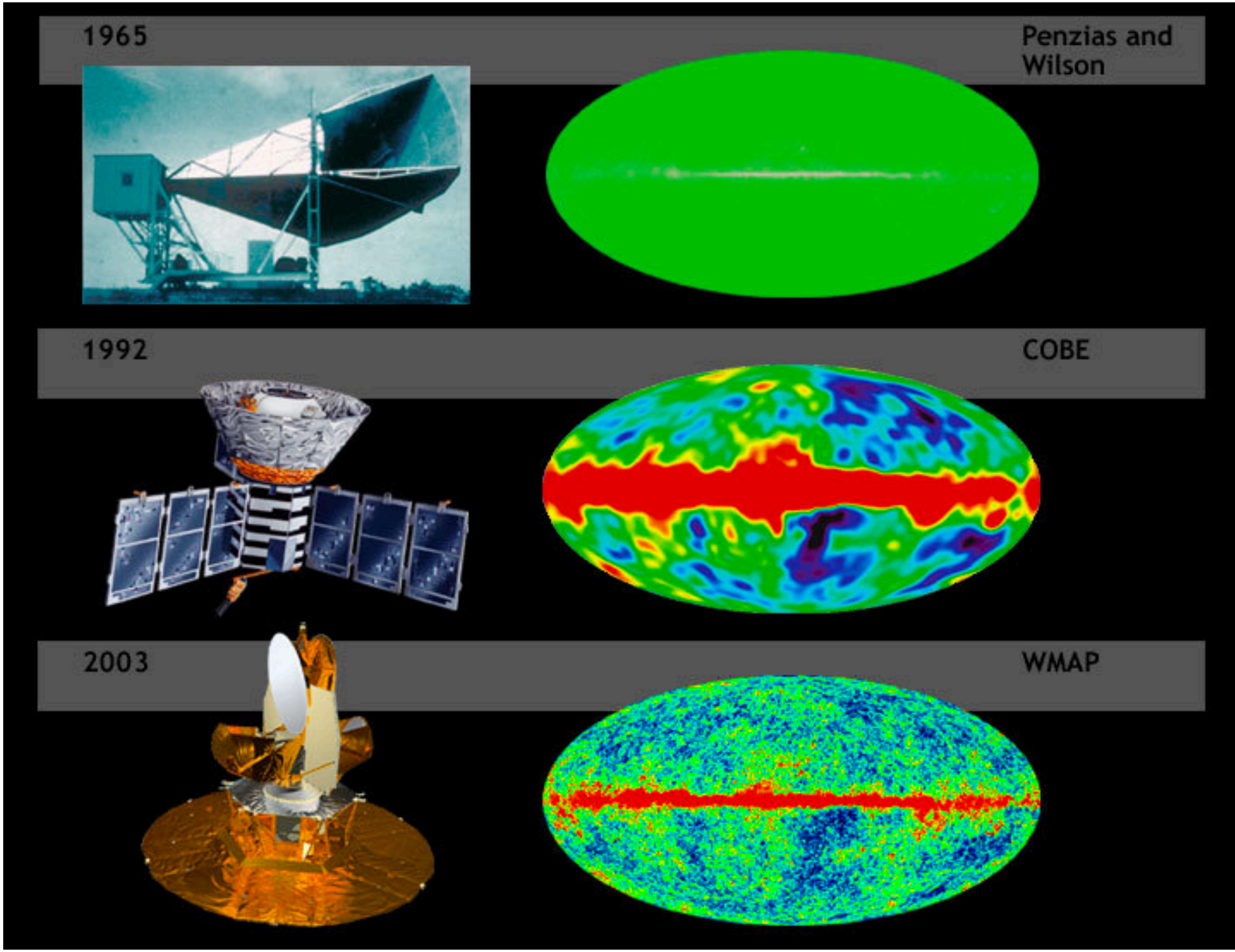
Evolution of the Universe



Blackbody radiation; isotropy

$$T_{\mathrm{CMB}} = 2.725\,\mathrm{K}.$$

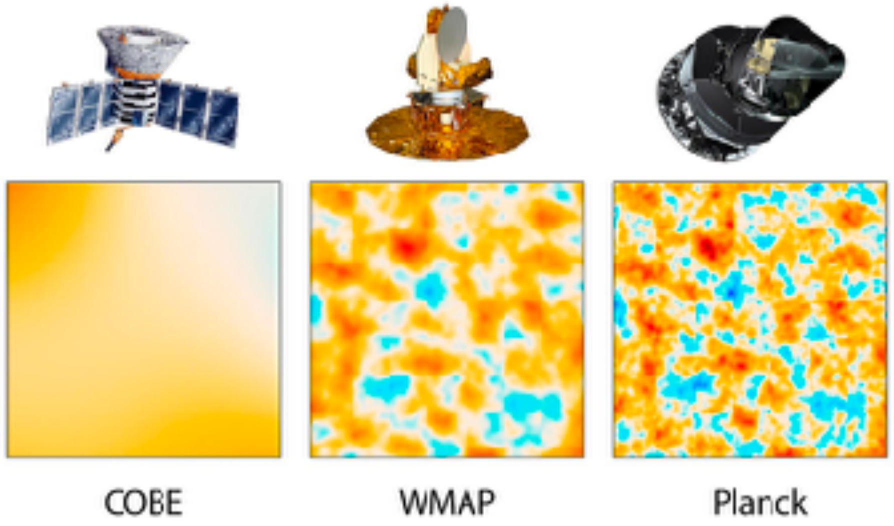




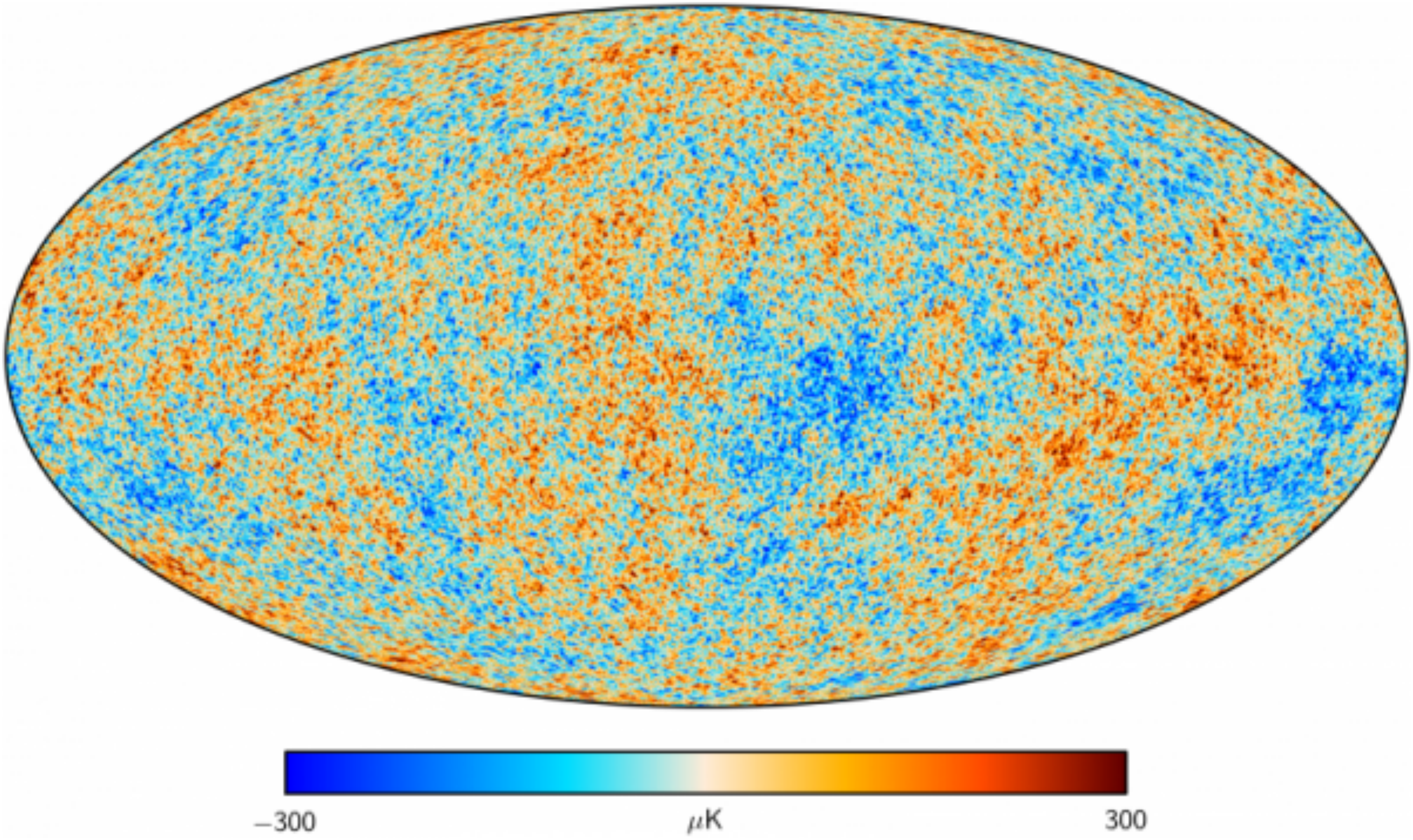
Credit:https://map.gsfc.nasa.gov/m_ig/030644/030644.html

FULL-SKY CMB

- Homogeneous and isotropic
- Tiny anisotropies ($\Delta T/T \sim 10^{-5}$)



(Image credit: NASA/JPL-Caltech/

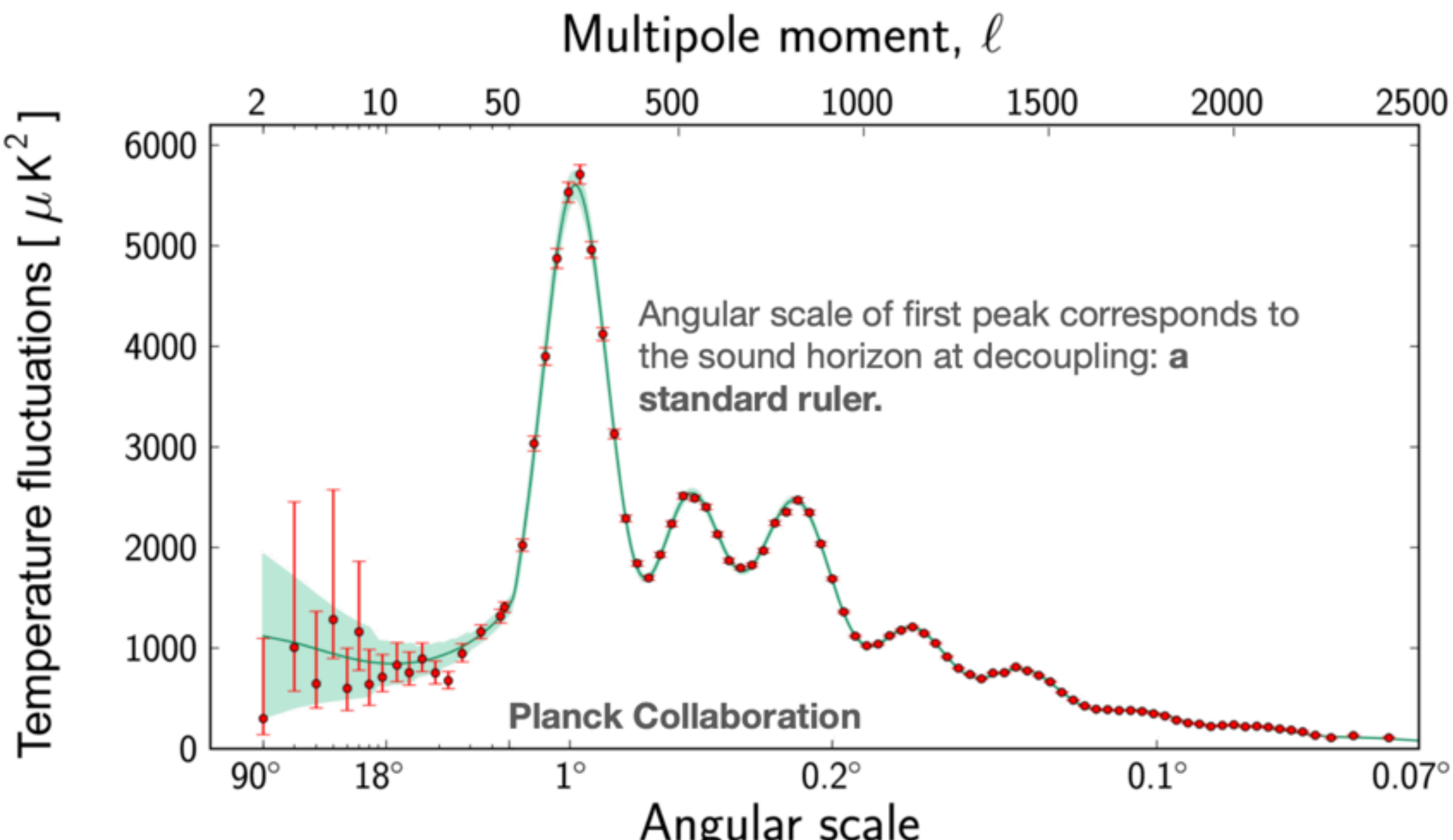


Credit: ESA/Planck Collaboration

- Decompose the CMB sky map into spherical harmonics:

$$\Delta T(\theta, \phi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta, \phi). \quad \text{with power spectrum:} \quad C_\ell = \langle |a_{\ell m}|^2 \rangle.$$

- The positions and amplitudes of the acoustic peaks provide valuable information about the composition of the Universe.



Credit: ESA/Planck Collaboration

Baryon Acoustic Oscillation (BAO)

- Sound waves in the photon–baryon fluid before recombination, driven by the competition between gravity (compression) and radiation pressure (expansion)
- The oscillations freeze out at recombination
- This scale is imprinted in the large-scale distribution of galaxies and halos, and appears as a peak in the two-point correlation function.
- BAO as a Standard Ruler: measuring its apparent size at different redshifts probes the expansion history of the Universe.
- One of the most powerful probes of dark energy.

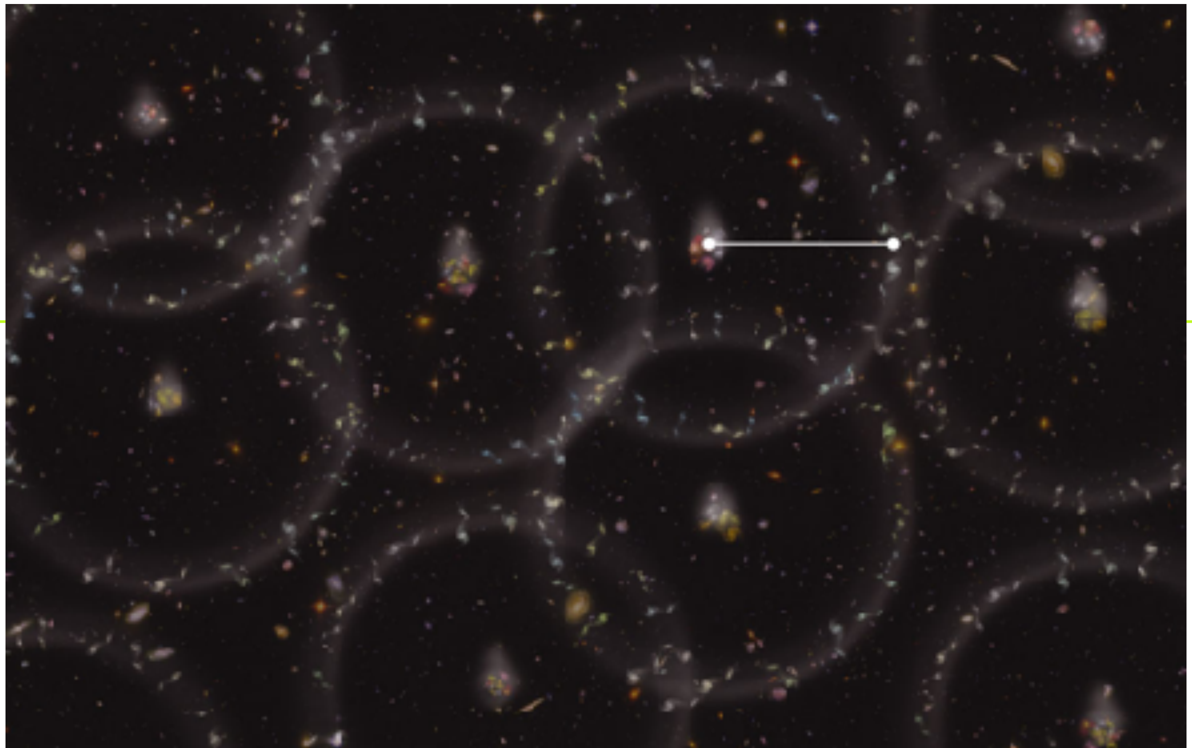
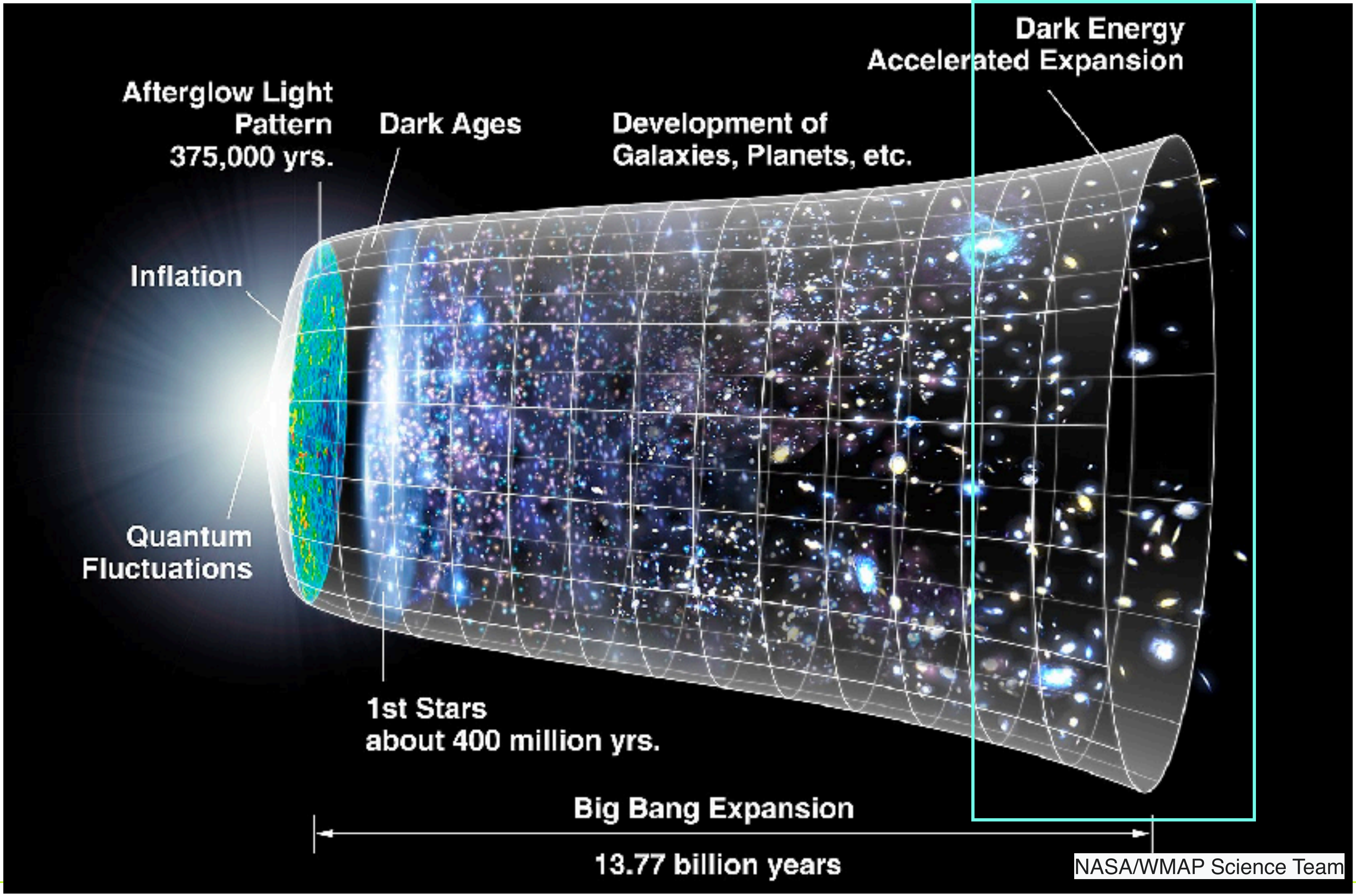


Illustration Credit: Zosia Rostomian (LBNL), SDSS-III, BOSS

Evolution of the Universe



Dark Energy

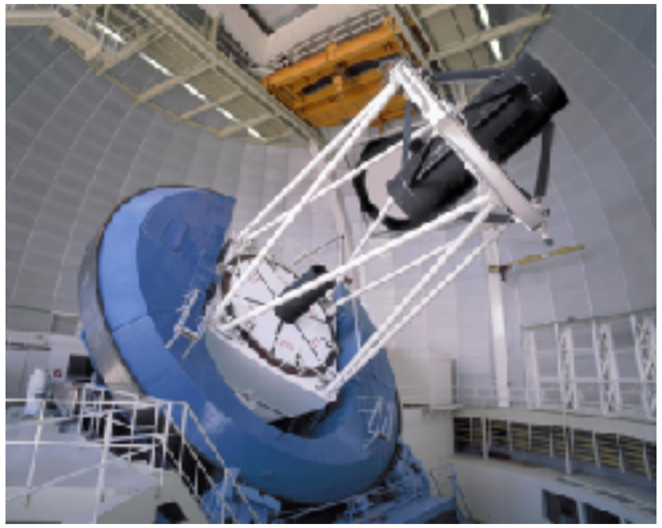
- Contributes about 70% of the energy density today
- Negative pressure —> drives the accelerated expansion of the Universe
- Discovered through observations of distant Type Ia supernovae (1998)
- Cosmological constant: Λ with equation of state: $w = \frac{p}{\rho c^2} = -1$
- Time-evolving dark energy with w≠−1?

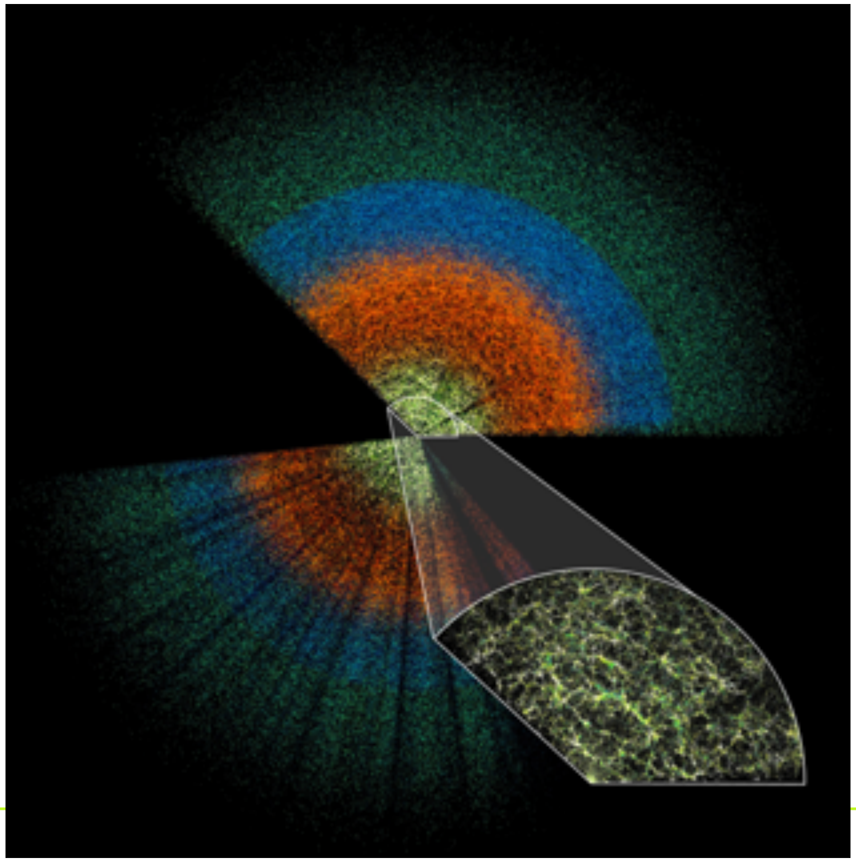
$$w(a) = w_0 + w_a(1 - a),$$

- Testing DE model: Next-generation cosmological surveys, e.g. galaxy redshift survey

Dark Energy Spectroscopic Instrument (DESI)

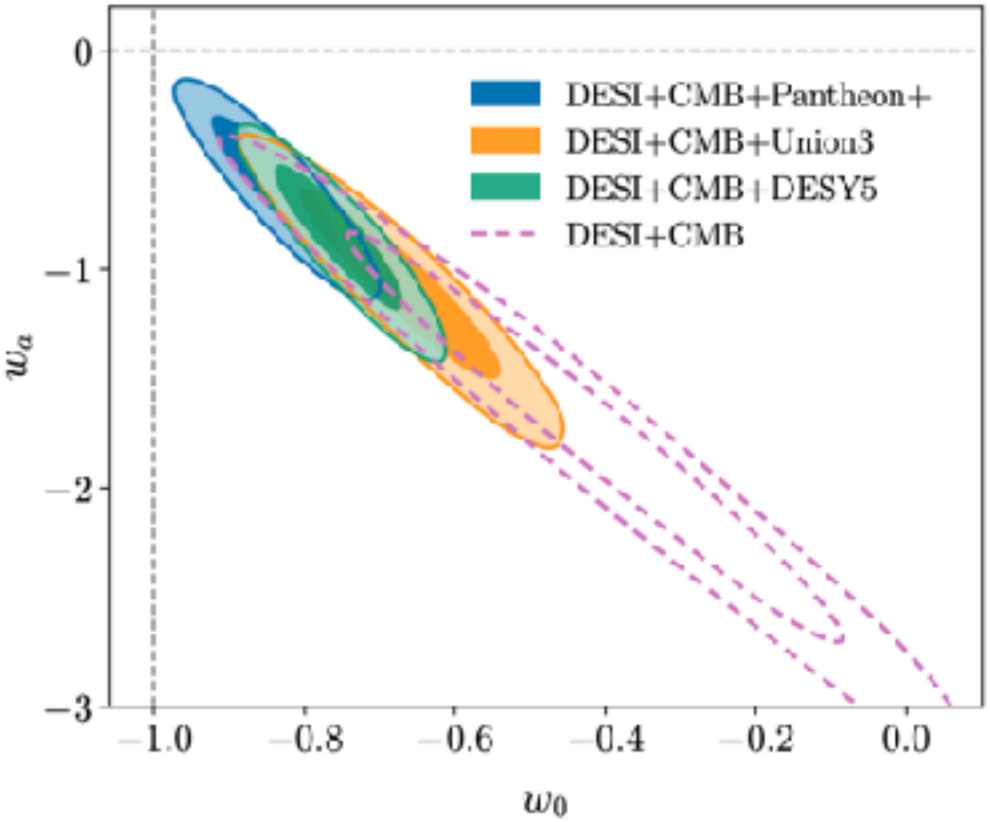
- Located on the 4-meter Mayall Telescope in Arizona.
- Measures the spectra and redshifts of millions of galaxies and quasars.
- Constructs the largest three-dimensional map of the Universe





Credit: DESI Collaboration/DOE/KPNO/NOIRLab/NSF/AURA/C. Lamman

DESI DR2 Results



DESI Collaboration et al. (2025)

What is Dark Matter?

N**ot ordinary matter** (atoms, stars, gas), doesn't emit, absorb or reflect light.

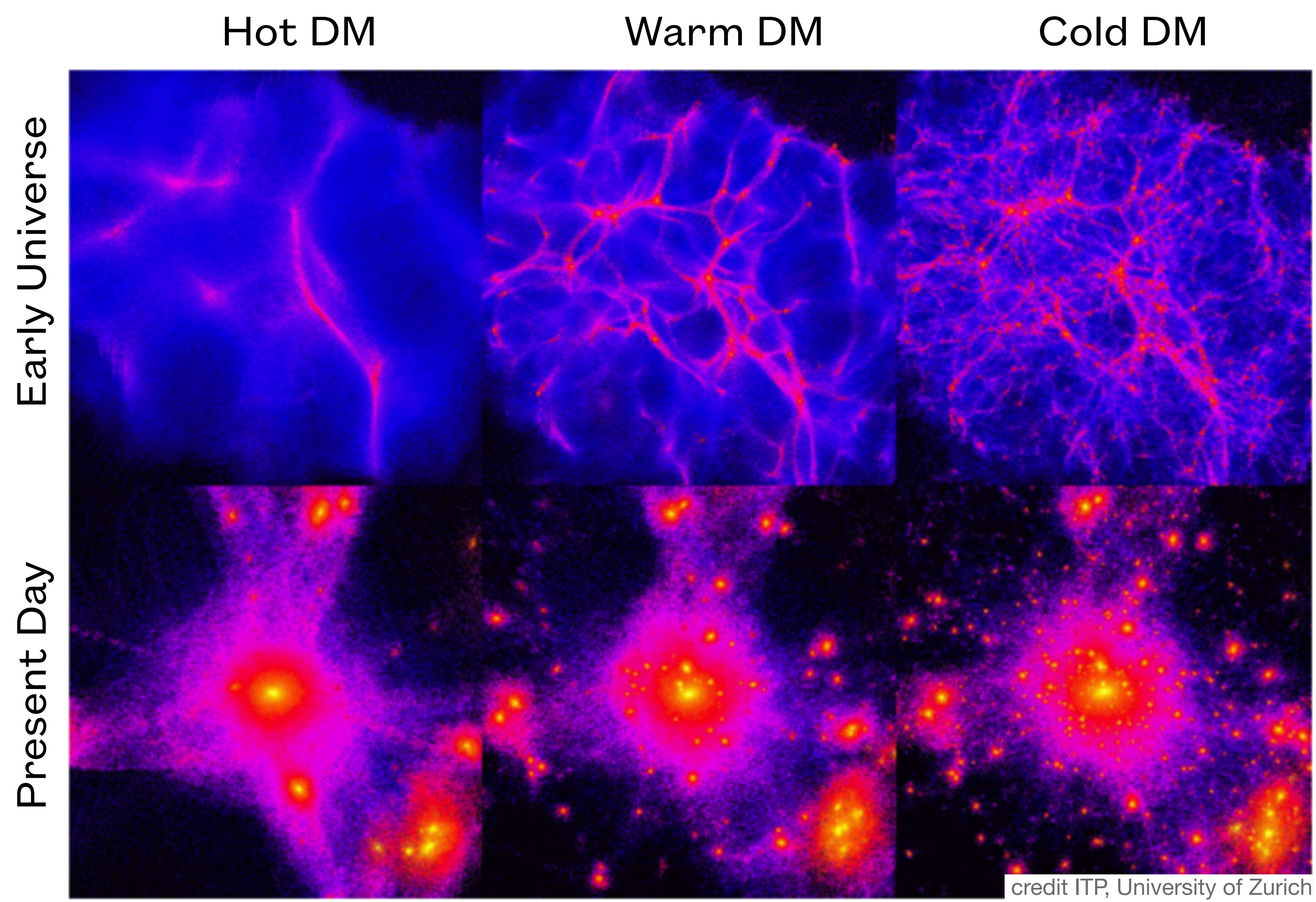
What we know about it

- **Massive** — It exerts gravity.
- **Invisible** — Does not emit or scatter light.
- **Non-baryonic** — Not made of protons, neutrons, electrons.
- **Cold** (in most models) — Dark matter particles are slow-moving compared to the speed of light, which helps in galaxy formation.

How to detect them?
→ Two Frontiers: Particle Physics and Astronomy

—Collider Searches
—Search for high-energy particles from **dark matter annihilation or decay.**

—Gravitational Signatures

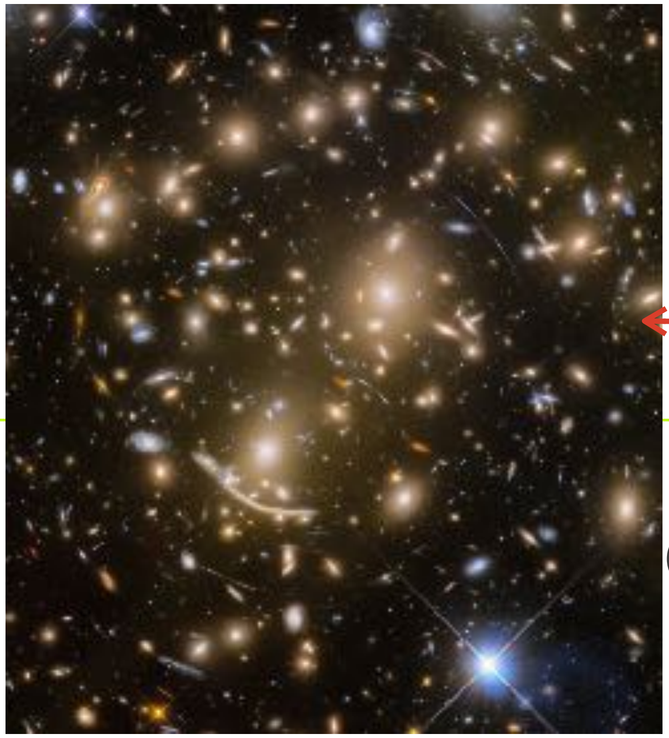


- Top-down structure formation: largest structures form first

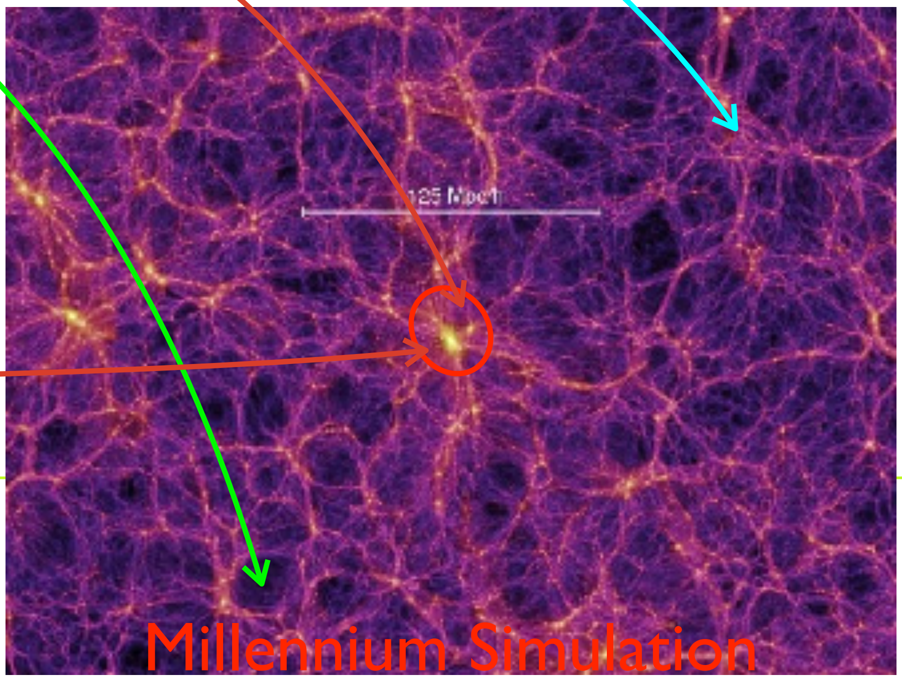
- Bottom-up structure formation
- More small-scales objects compare with HDM

Non-linear Gravitational Growth

- Non-linear regime: $\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}} \gtrsim 1$
- Numerical Simulations
- (cosmic web):
  filament structures
  Node: galaxy clusters
  voids: empty region



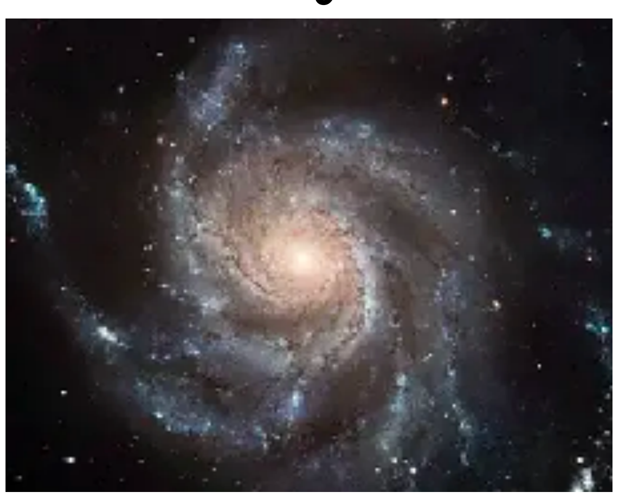
Galaxy cluster



Galaxy Clusters

- The most massive objects in the Universe
- —> consists of hundreds to thousands of galaxies and hot gas bound by gravity
  —>consists of 85% dark matter, 10% hot gas and 5% stars
  —>ideal laboratory for studying the dark Universe and testing the cosmological models

Galaxy

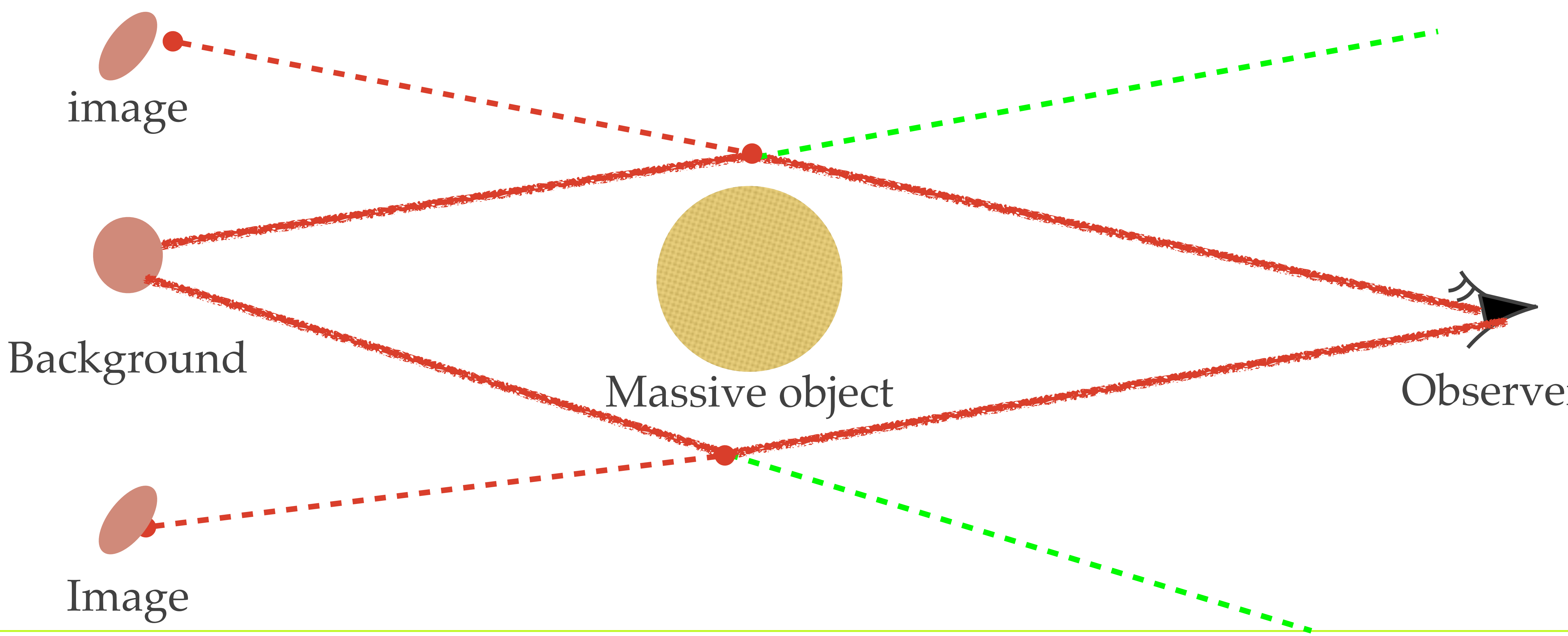


Galaxy cluster

Galaxy Cluster

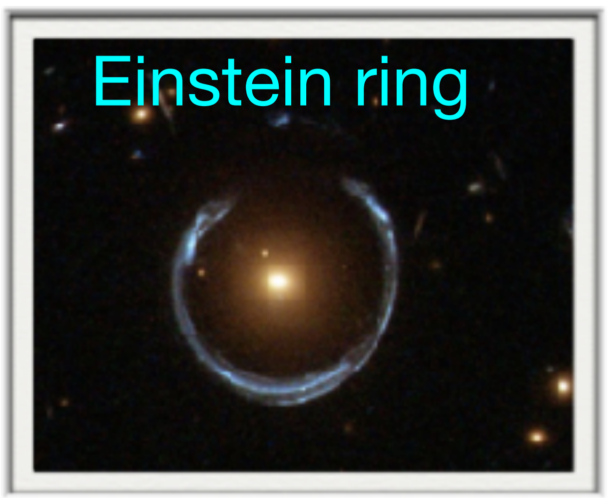
Gravitational Lensing 重力透鏡

- A natural telescope in our Universe
- According to Einstein's General Relativity, the presence of mass and energy in the universe can distort the space-time
- Light travels through the distorted space-time —> the bending of light paths



Strong Gravitational Lensing

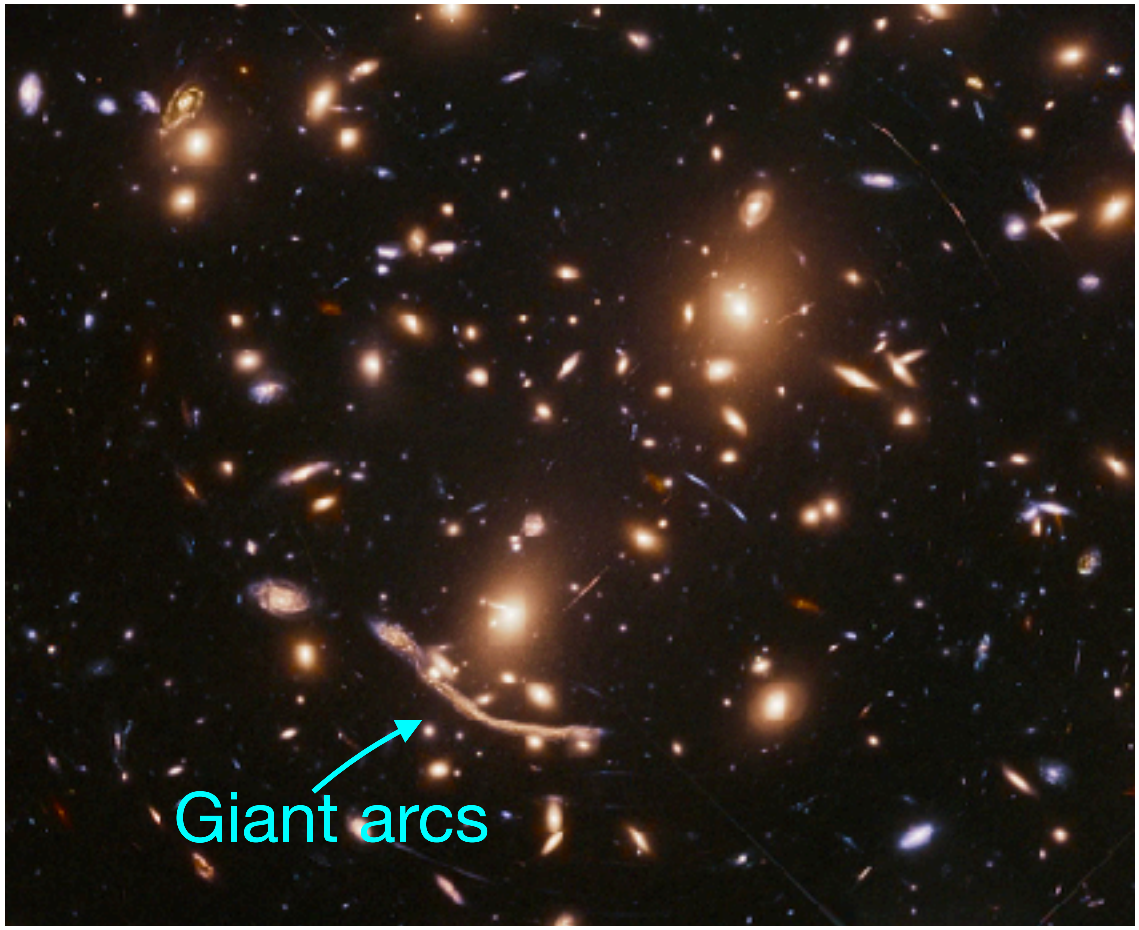
- Multiple images of the background appear, giant arcs, Einstein rings
- Dark Matter Mass in the core region

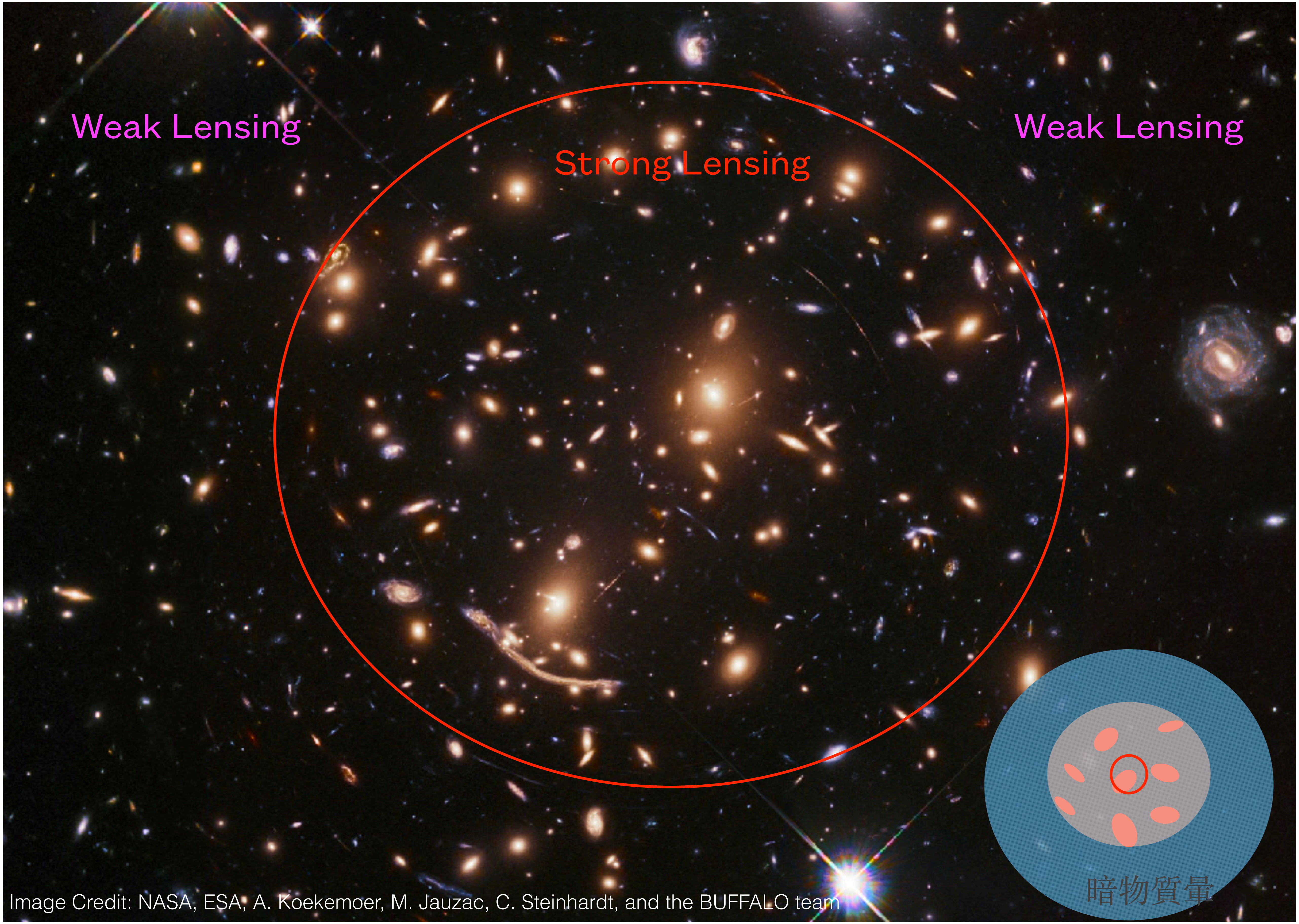


Galaxy-Galaxy Lenses

Galaxy-QSO Lenses

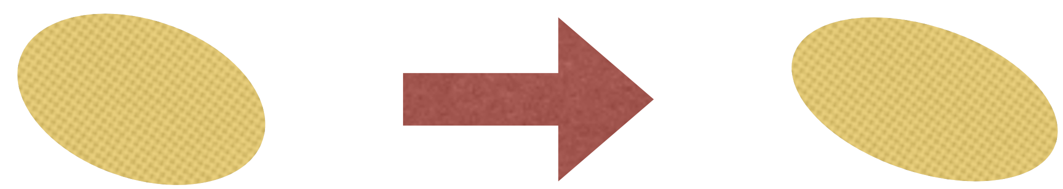
Galaxy-Cluster Lenses

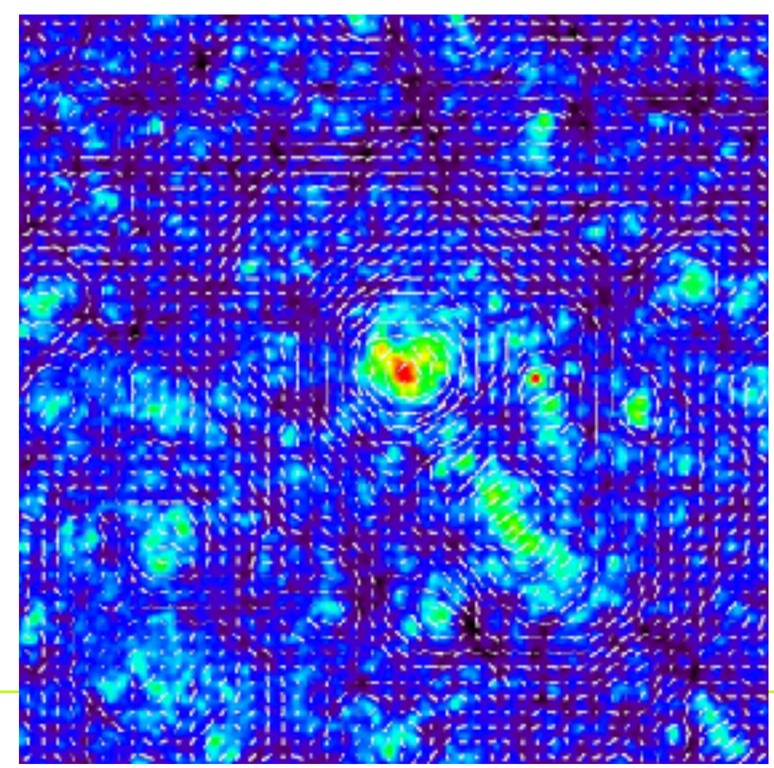



Weak Lensing
Strong Lensing
Weak Lensing
暗物質量
Image Credit: NASA, ESA, A. Koekemoer, M. Jauzac, C. Steinhardt, and the BUFFALO team

Weak Gravitational Lensing

- Occurs in low-density regions, causing a tiny distortion of background images.
- Important to detect the dark matter distribution in large-scale
- Very difficult to detect for a single source because of noise
- Need to measure statistically; Need a lot of background galaxies

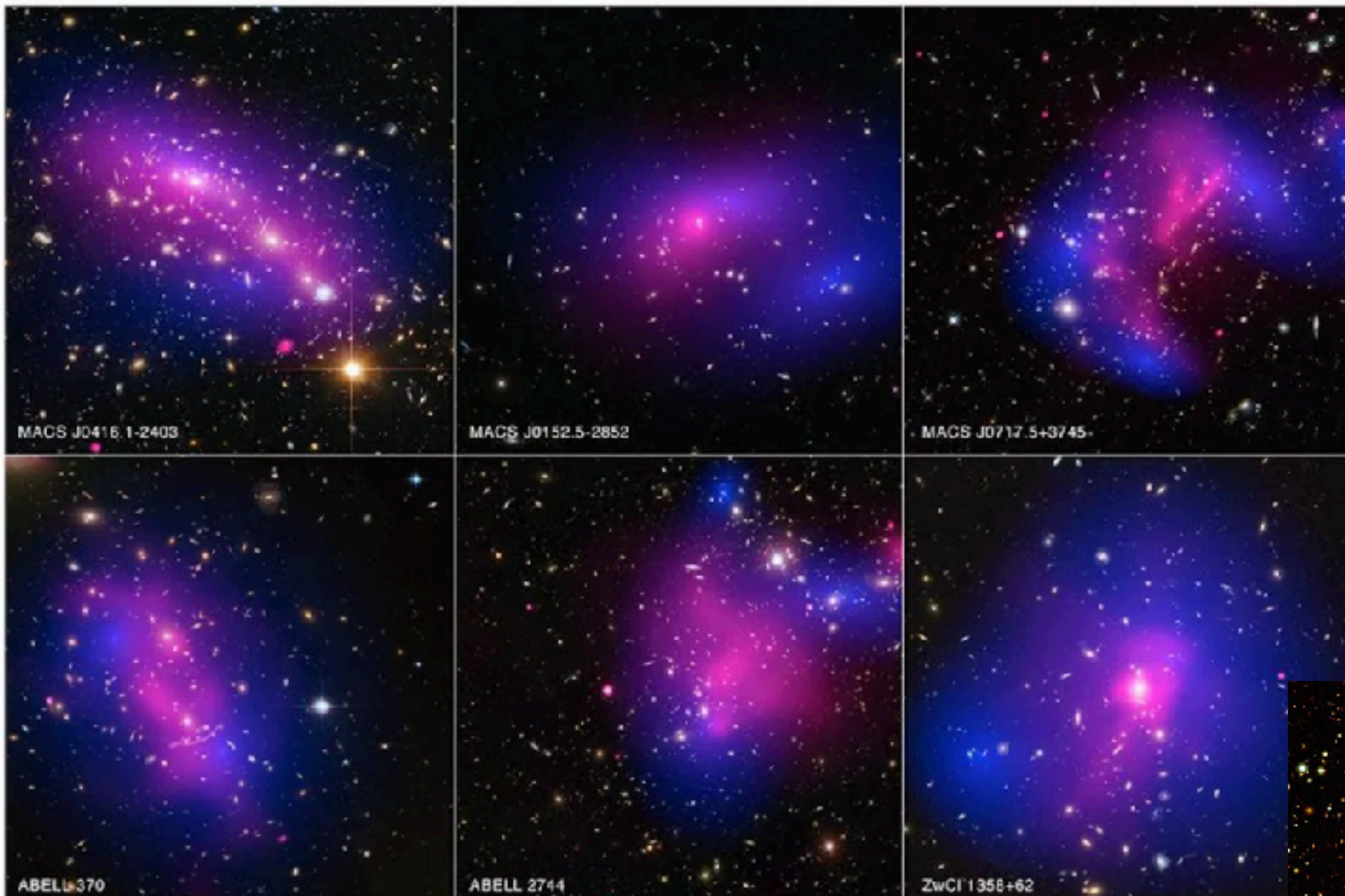




Color : projected mass distribution
White bars : shear

Dark Matter Distribution in Galaxy Cluster

—> cluster mass

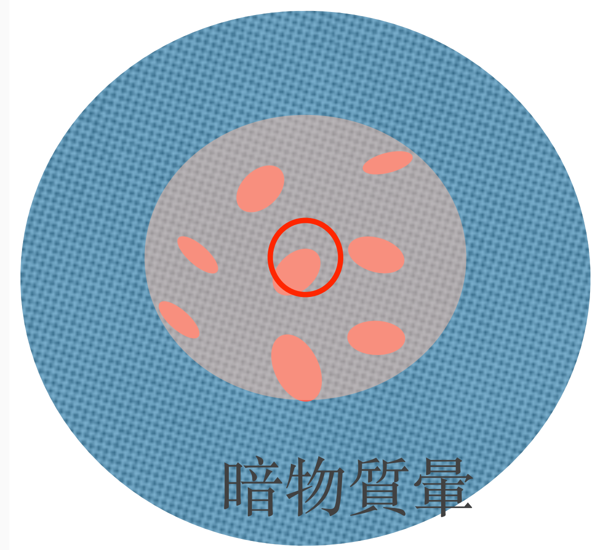


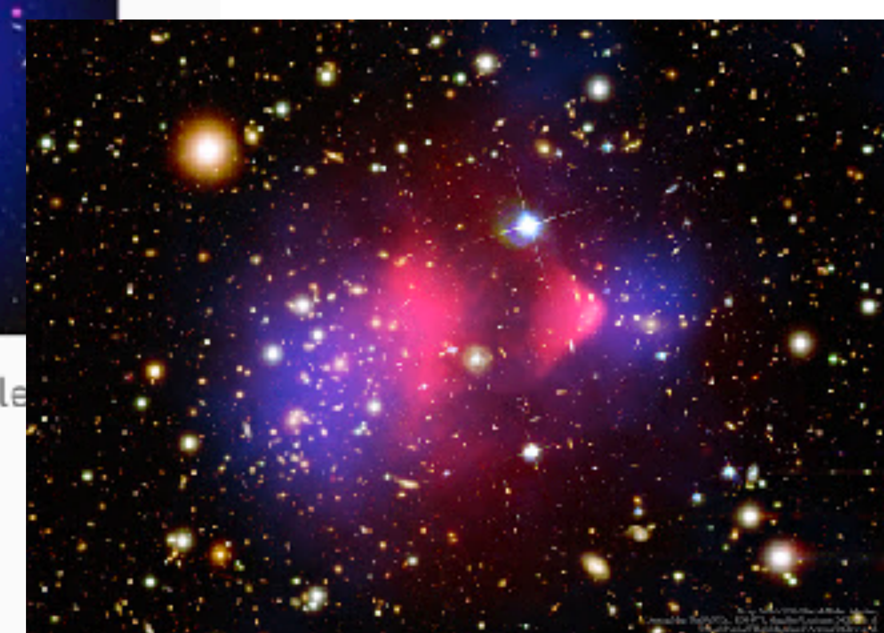
The X-ray (pink) and overall matter (blue) maps of various colliding galaxy clusters show a cle

[+] X-RAY: NASA/CXC/ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, SWITZERLAND/D.HARVEY NASA/CXC/DURHAM UNIV/R.MASSEY; OPTICAL/LENSING MAP: NASA, ESA, D. HARVEY (ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, SWITZERLAND) AND R. MASSEY (DURHAM UNIVERSITY, UK)

Pink: X-ray gas

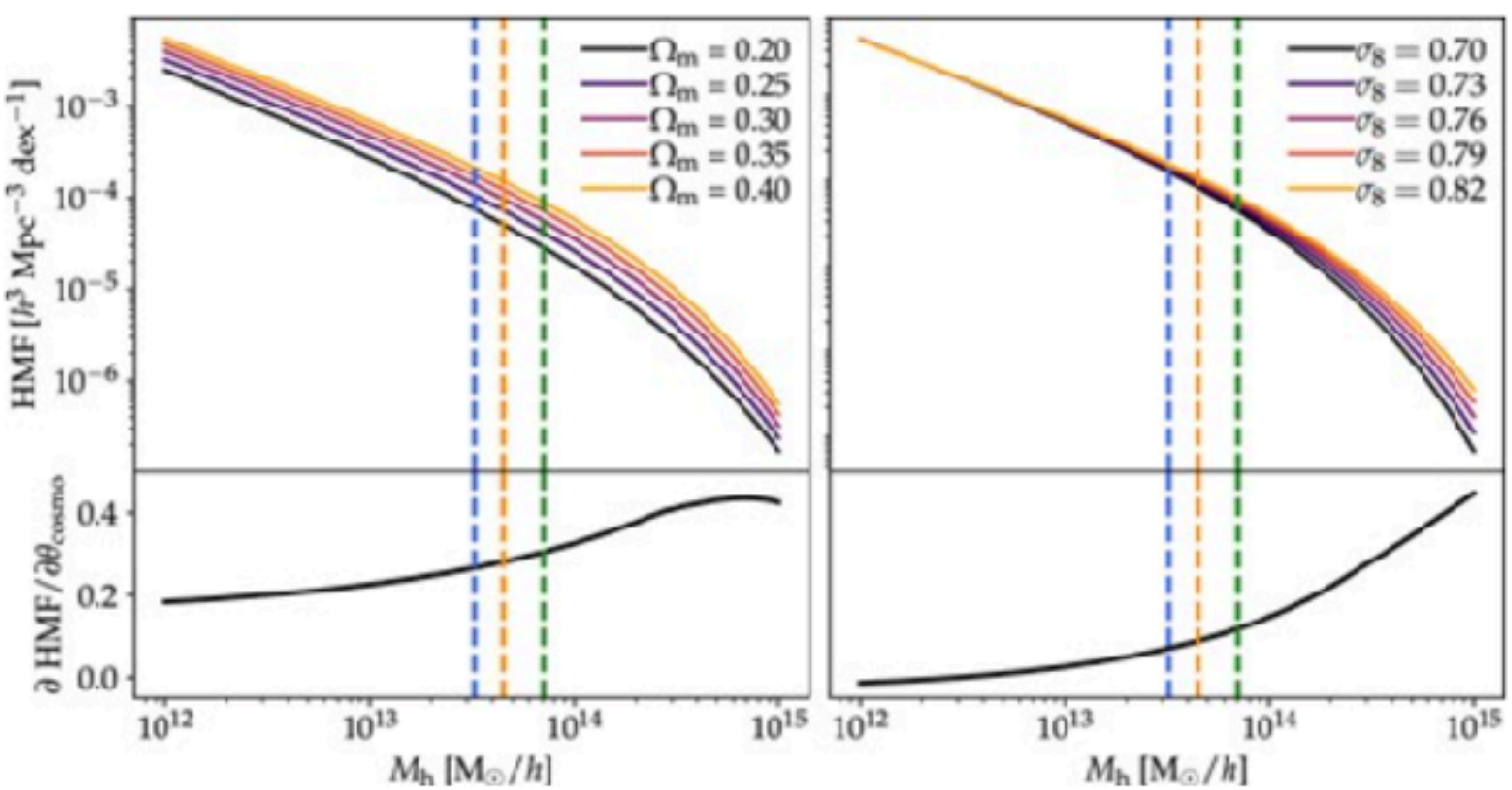
Blue: dark matter





Clusters as a cosmological probe

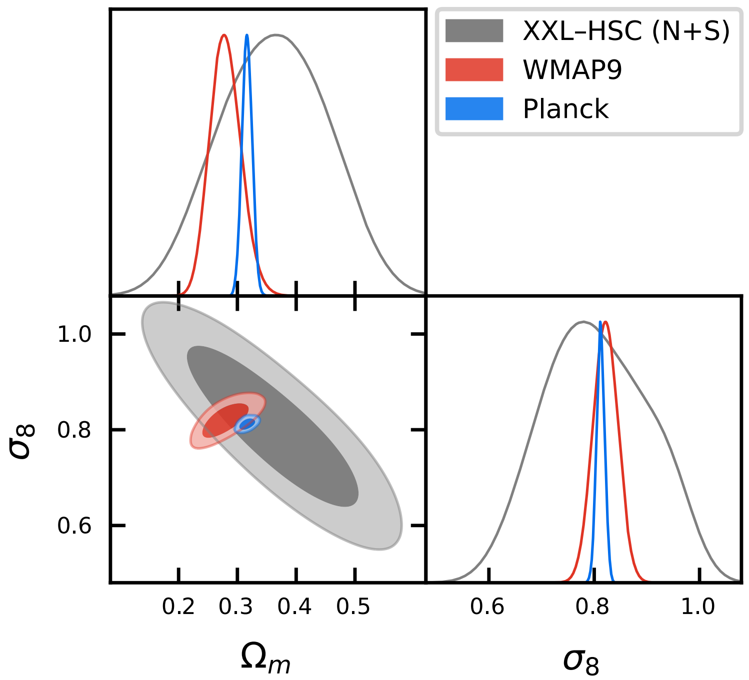
- Locate at high-mass end of HMF
- The abundance of massive clusters is exponentially sensitive to cosmological parameters.
- Higher σ8 → more massive clusters
- Higher Ωm → more structure growth → more clusters
- What we need: number counts of GC + their accurate mass measurement (incl. DM)



Xhakaj et al. 2023

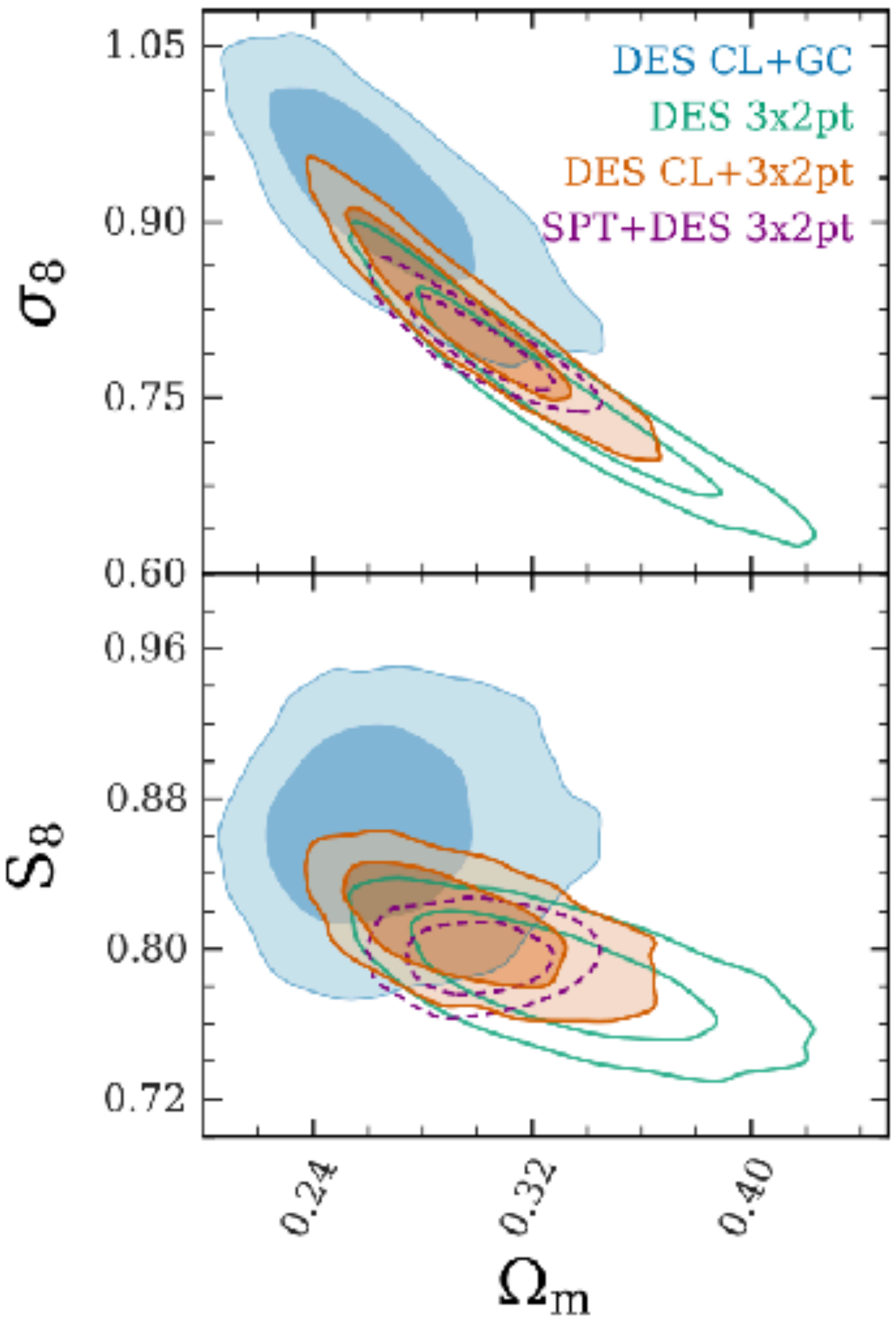
Cluster Cosmology Inference

- Weak gravitational lensing provides an unbiased calibration of cluster masses.
- Modern surveys such as DES, SPT, and Planck have measured cosmological parameters using galaxy clusters.
- Cluster cosmology provides an independent test of the standard ΛCDM model.



Tam et al. (2026)

DESI Y3 results

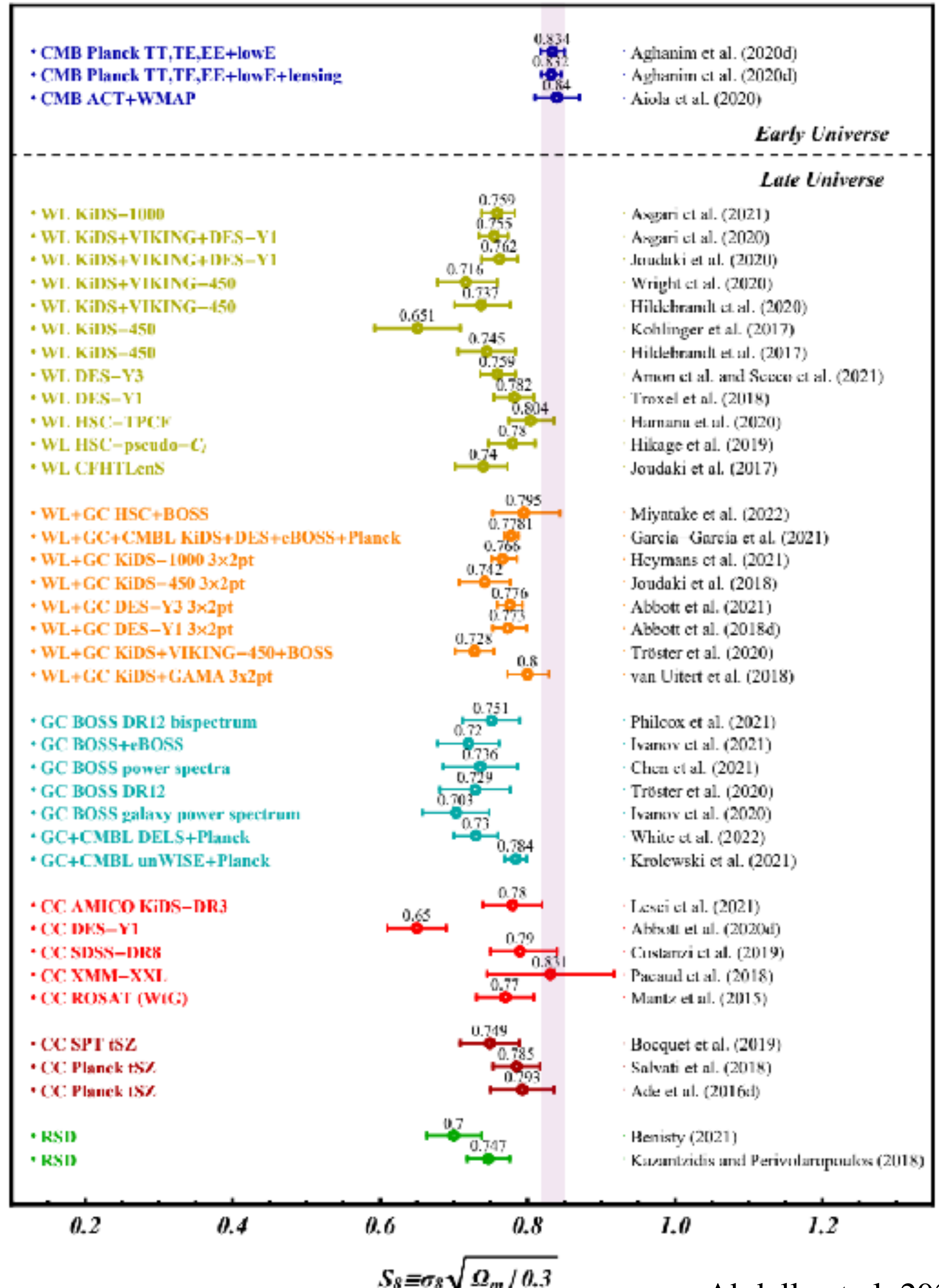


DESI Collaboration et al. (2025)

S_8 tension

$$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$$

- Early-Universe measurements (CMB) and late-Universe measurements do not perfectly agree on the S8.
- Weak lensing and galaxy clusters often favor lower S8 values than Planck.
- Different probes suffer from different observational and astrophysical systematics.
- The origin of the S8 tension remains unclear.
- Future surveys (DESI, Euclid, Rubin, Roman) will provide much tighter constraints on the growth of structure.



Abdalla et al. 2022

The Hubble Tension

- H_0: Measures the present-day expansion rate of the Universe.

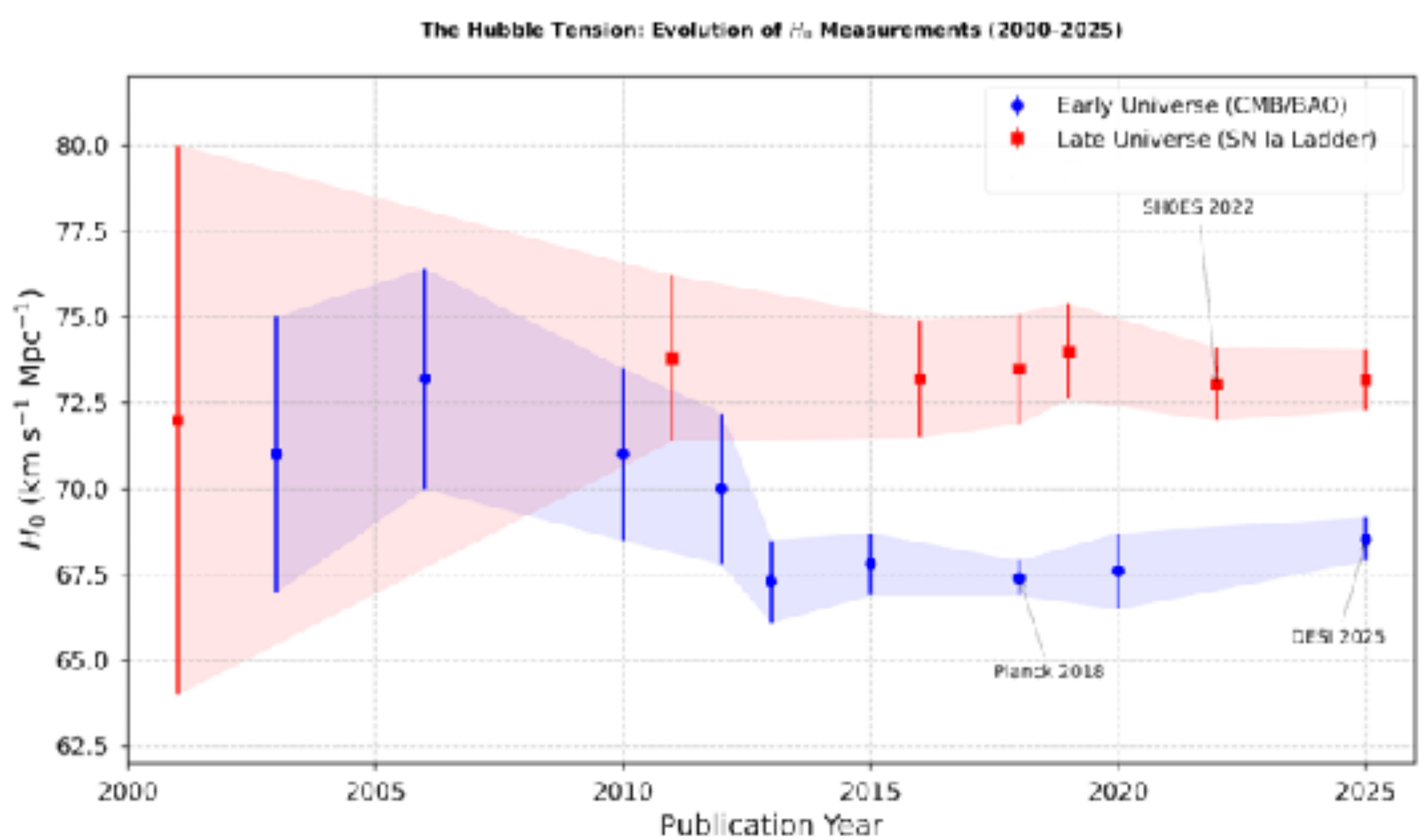
$$H_0 \equiv \left(\frac{\dot{a}}{a}\right)_{t=t_0}$$

- Two Independent Measurements:

—Early Universe (CMB): Planck Collaboration—$H0 \approx 67\ \mathrm{km s^{-1} Mpc^{-1}}$

—Late Universe (Distance Ladder): e.g. Cepheids + Type Ia Supernovae (SH0ES), Strong-lensing time delays (H0LiCOW / TDCOSMO)

$$H0 \approx 73\ \mathrm{km s^{-1} Mpc^{-1}}$$



https://beuke.org/hubble-tension/

Challenge in ΛCDM

- Nature of DM: different DM models
- Nature of DE: time evolving EOS?
- Small-Scale Challenges: Core-cusp problem; Missing satellites problem; Too-big-to-fail problem
- The Hubble Tension
- The S_8 Tension