Brief introduction to Cosmology

From the Big-Bang to the Large-Scale Structures of the Universe

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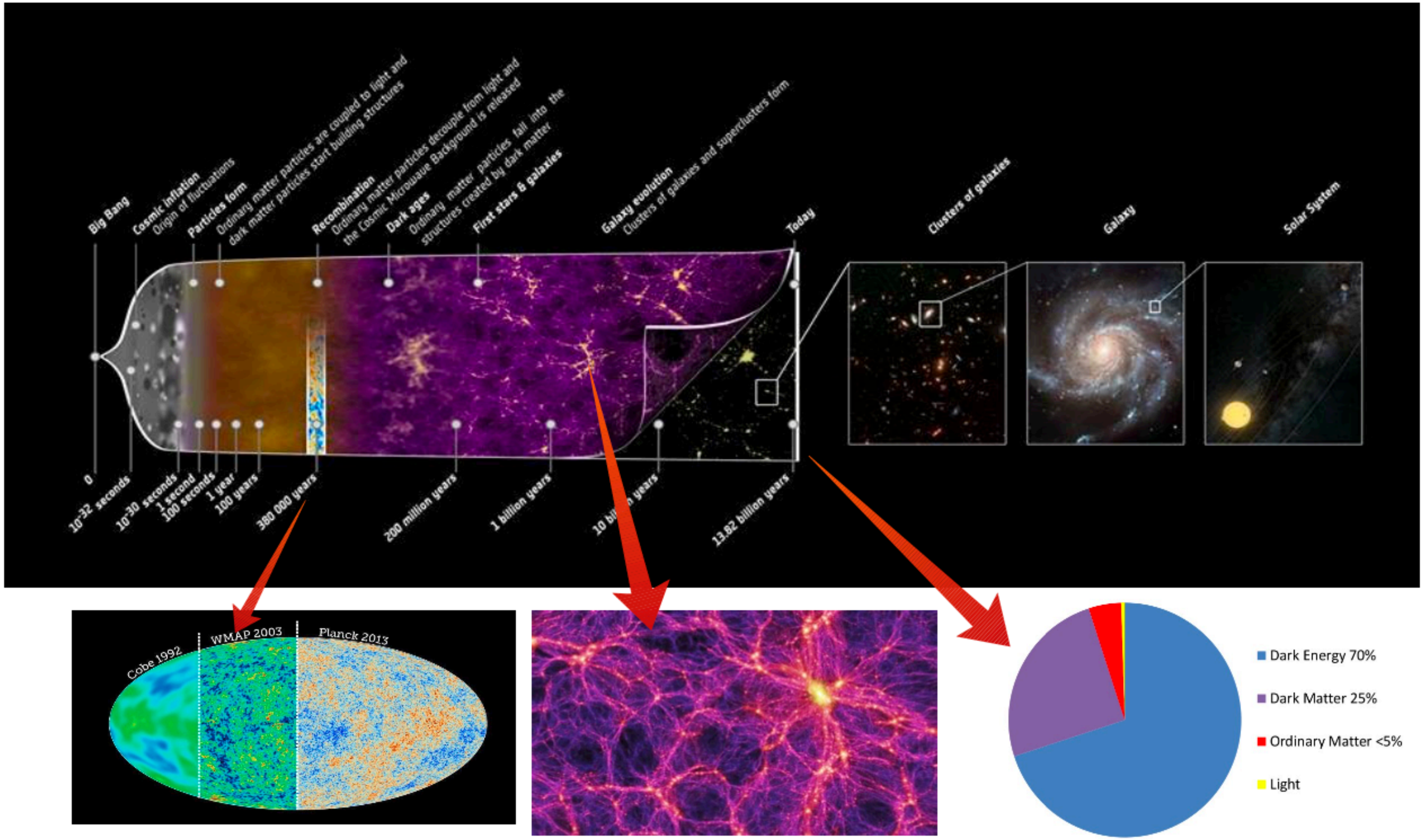
1. The history of our universe

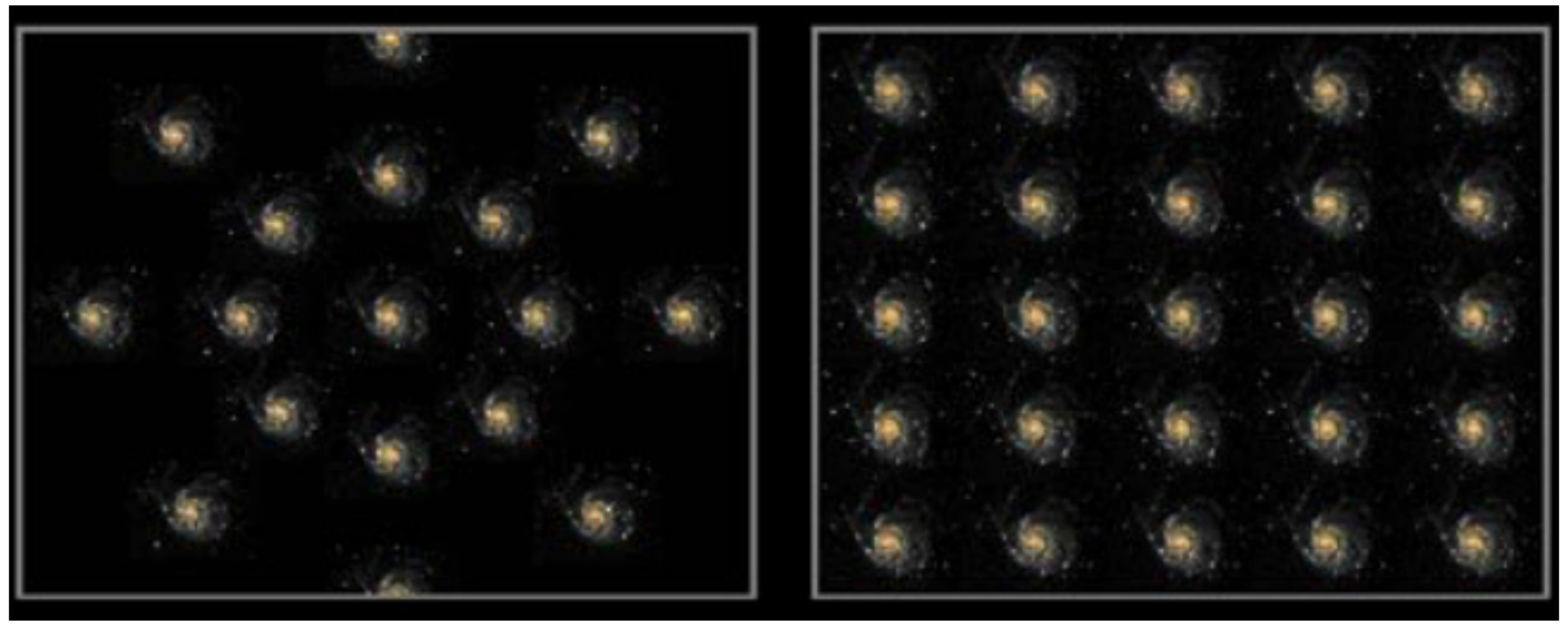


2. The cosmological principle

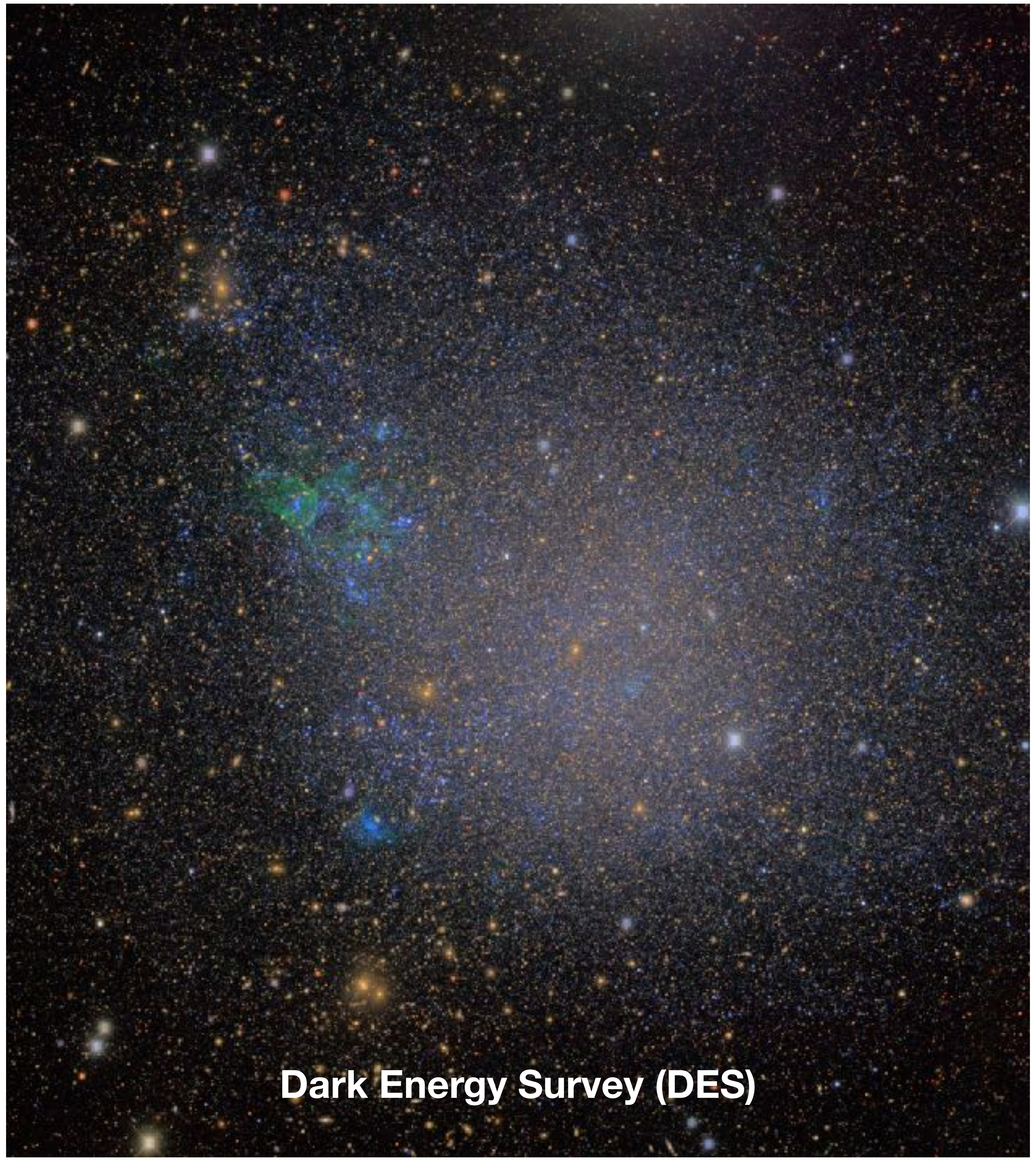
Our location in the Universe is not special

- Invariance under rotations (isotropy)
- Invariance under translations (homogeneity)

Aliens in Andromeda will observe the same universe



- The real universe: small asymmetries and fluctuations originated at the beginning of time.



3. The hot Big-Bang

Outline

- The Big Bang is the name for our physical model of the expanding universe.
- It makes specific predictions that can be tested through observations.
- Observational evidences:

1. **The expansion of the Universe:** explains the Hubble Law and the age of the Universe
2. **The Cosmic Microwave Background radiation (CMB):** relic blackbody radiation from the first light of the Universe
3. **Primordial Nucleosynthesis:** creation of the first particles and elements.

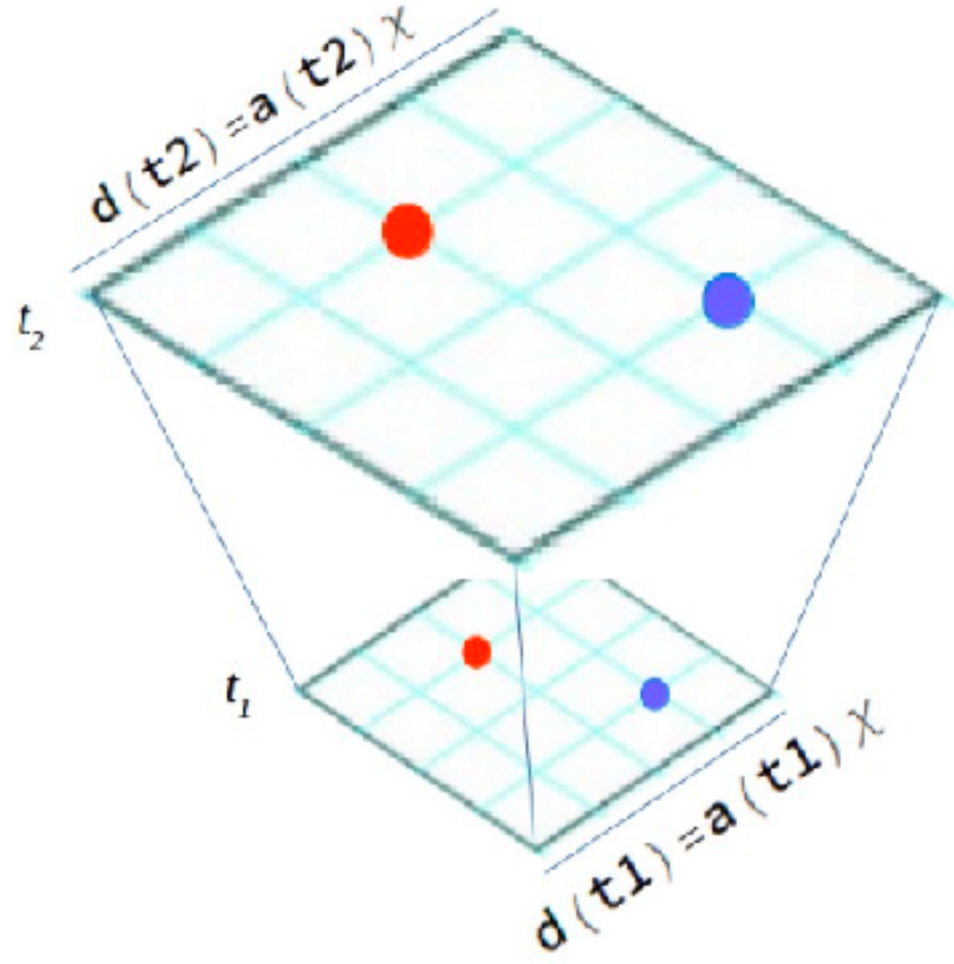
3. The hot Big-Bang

3.1. Expansion of the Universe

- The Universe is observed to be expanding today. The Hubble law.
- As the Universe expands, it cools. In the past it must have been smaller, denser and hotter than today.
- The initial state (very hot and dense) must have existed at some finite time in the past: **The Big Bang.** General Relativity.

- **How do we study the expansion of the Universe?**
  1. **Reference frame:**
     i) Fundamental observers, whose coordinates are not affected by the expansion
     ii) Comoving coordinate system (grid).
  2. **Physical distances:** change with the scale factor $d(t) = a(t)\,x$
  3. **Hubble parameter:** expansion rate (Friedmann equations) $H(t) := \dot{a}(t)/a(t)$
  4. **Hubble's law**

$$v_{rec} = \frac{\partial}{\partial t} d(t) = H(t) d(t)$$



3. The hot Big-Bang

Redshift

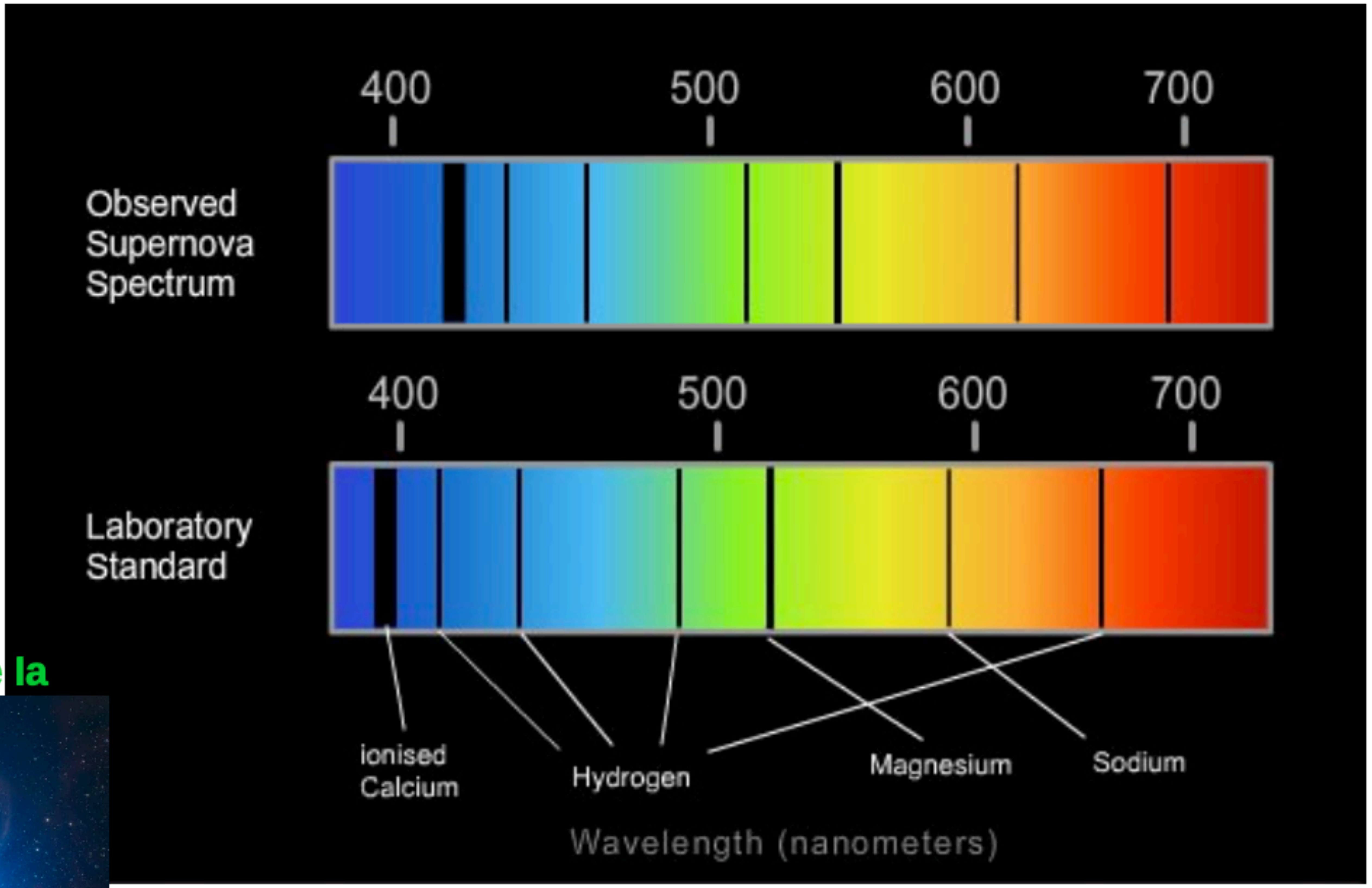
- The expansion of space also stretches light into longer and redder wavelengths.

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

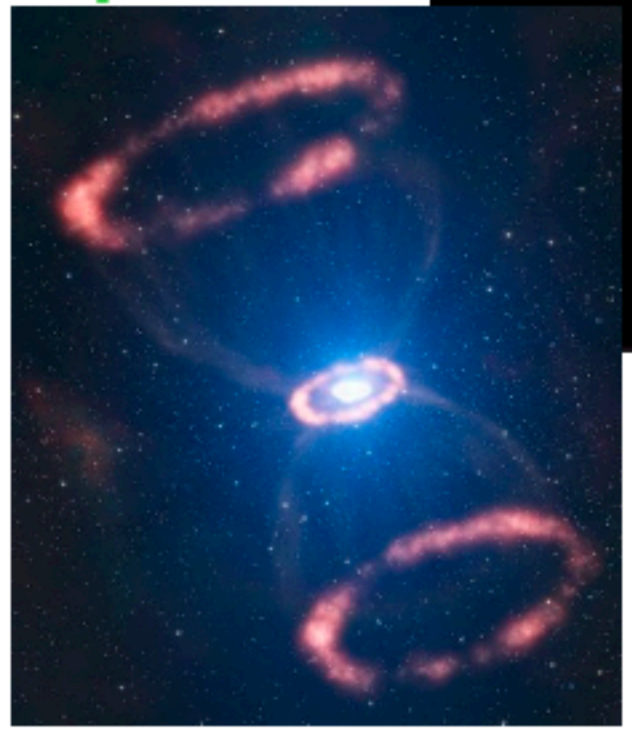
- The redshift of an object gets larger with increasing distance

Redshift-scale factor relation

$$1 + z = \frac{\lambda_{obs}}{\lambda_{em}} = \frac{a(t_0)}{a(t)}$$



Supernovae Ia



Redshift → Distances

Redshift → Time

Z=0 means "present time"

3. The hot Big-Bang

Density is destiny!

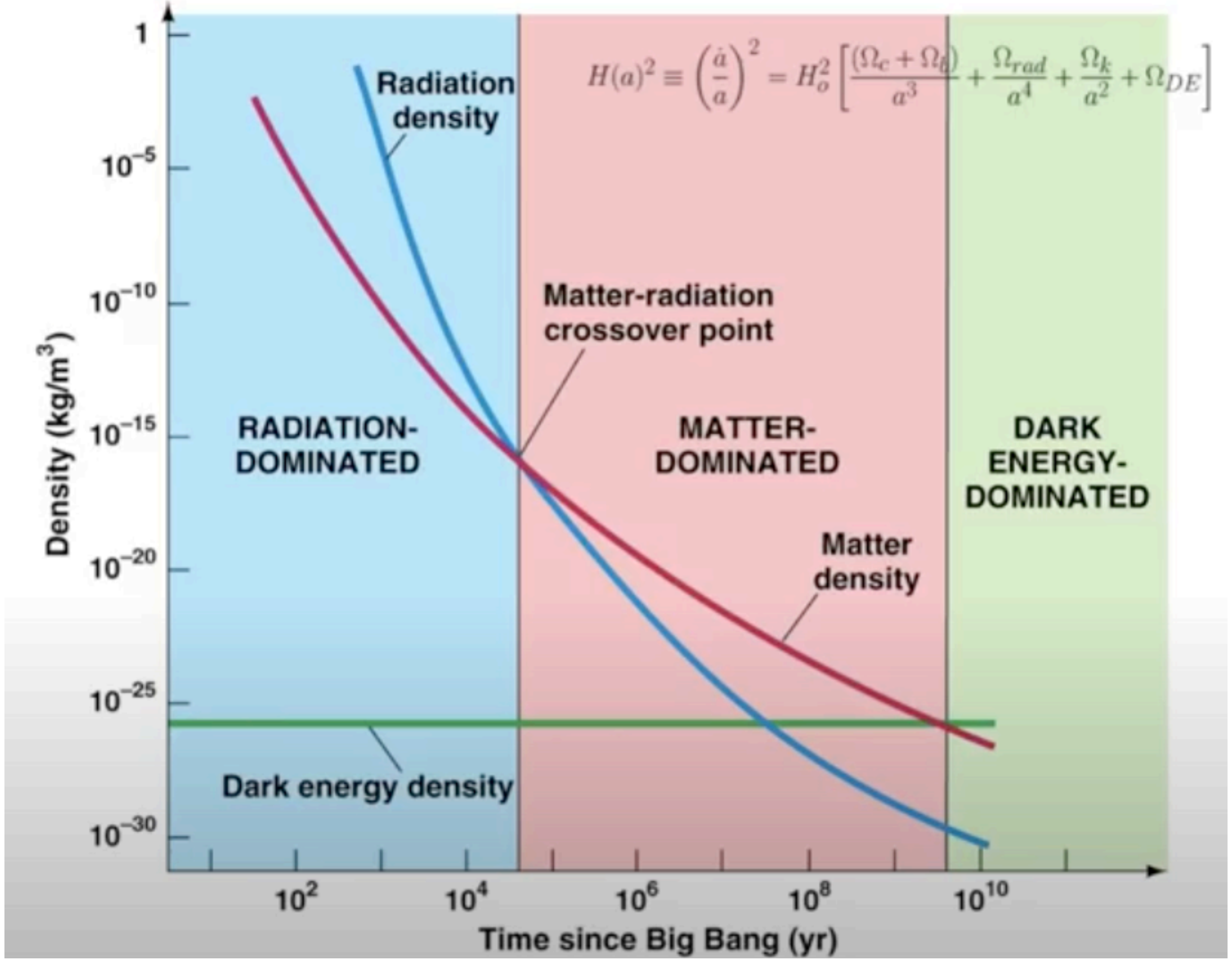
- Friedman equation ingredients:
  1. The Hubble constant
  2. Matter density: CDM + baryons
  3. Radiation
  4. Curvature or surface tension
  5. Dark energy

$$\Omega_x = \left(\frac{average\ density}{critical\ density} \right) = \frac{\rho_x(t)}{\rho_{c,0}}$$

$$\rho_{c,0} = \frac{3H_0^2}{8\pi G}\ (M_\odot / Mpc^3)$$

Matter:

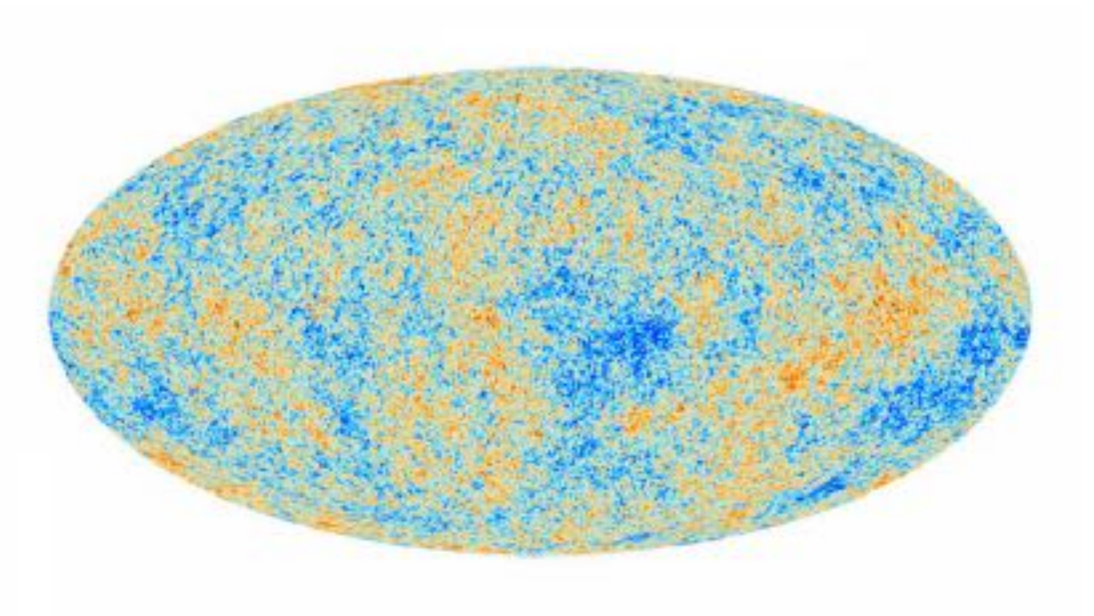
$$\Omega_m = \Omega_c + \Omega_b = \Omega_{m,0} a^{-3}$$



3. The hot Big-Bang

3.2. The Cosmic Microwave Background

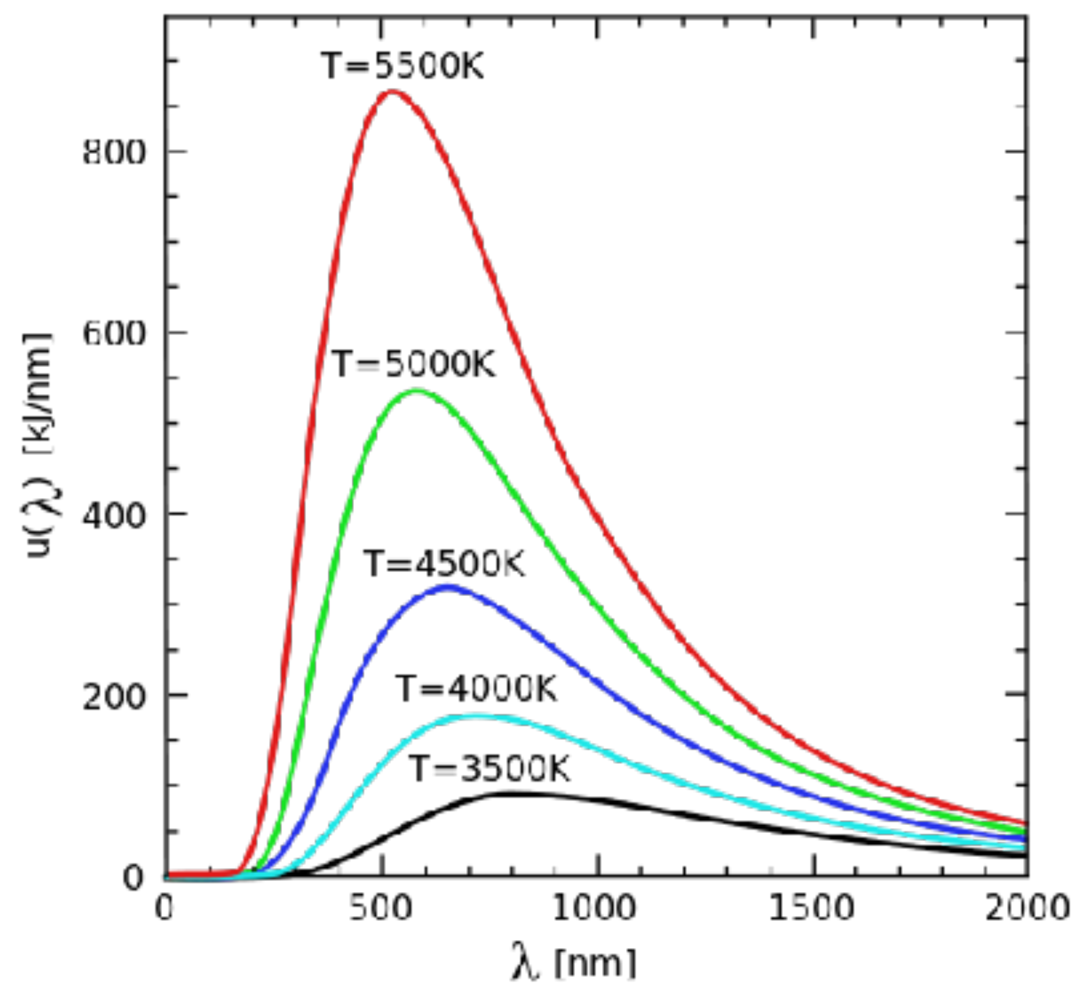
http://chrisnorth.github.io/planckapps/Simulator/#



- The CMB represent the **first light** of the Universe
- Before CMB
  - Photons could not cross the universe without hitting an electron (scattering)
  - Protons were pulled by electrons, so photons, electrons and protons had same temperature (thermal equilibrium)
  - Once the Universe was cold enough, photons and electrons decoupled (last scattering surface)
  - Light could finally travel freely! CMB!
- After CMB: CMB photons travelled towards us, stretching and reddening.

- **Most important elements**:
  i) The spectrum in any direction in the sky is an almost perfect blackbody
  ii) Mean temperature of that blackbody is $2.725 \pm 0.001K$.
  iii) Residual anisotropies in the temperature $\sim O(\mu K)$

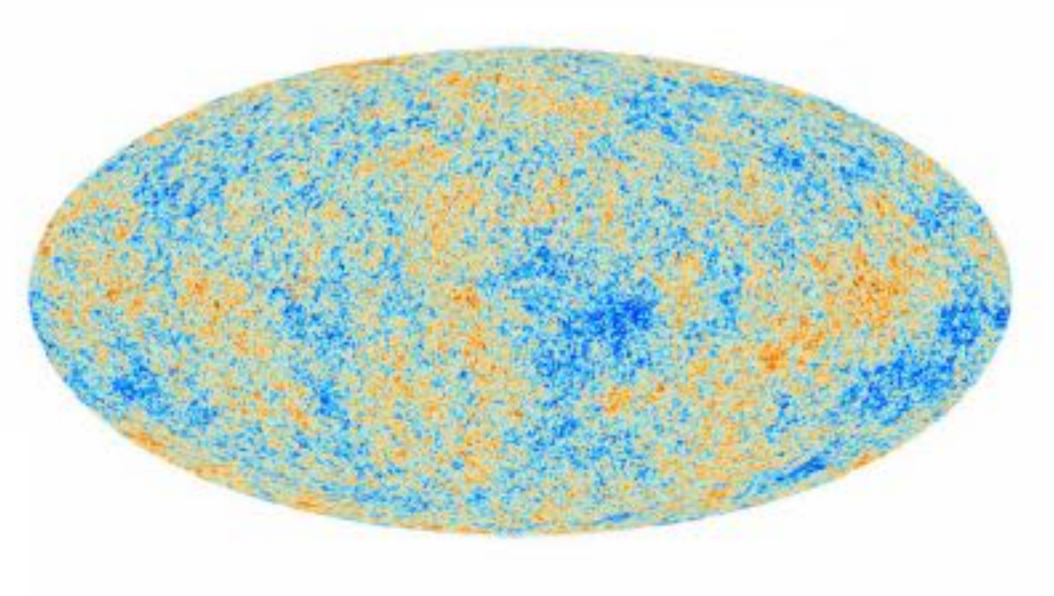
These small temperature fluctuations are seeds of the large-scale structure of the Universe



http://chrisnorth.github.io/planckapps/Simulator/#

3. The hot Big-Bang

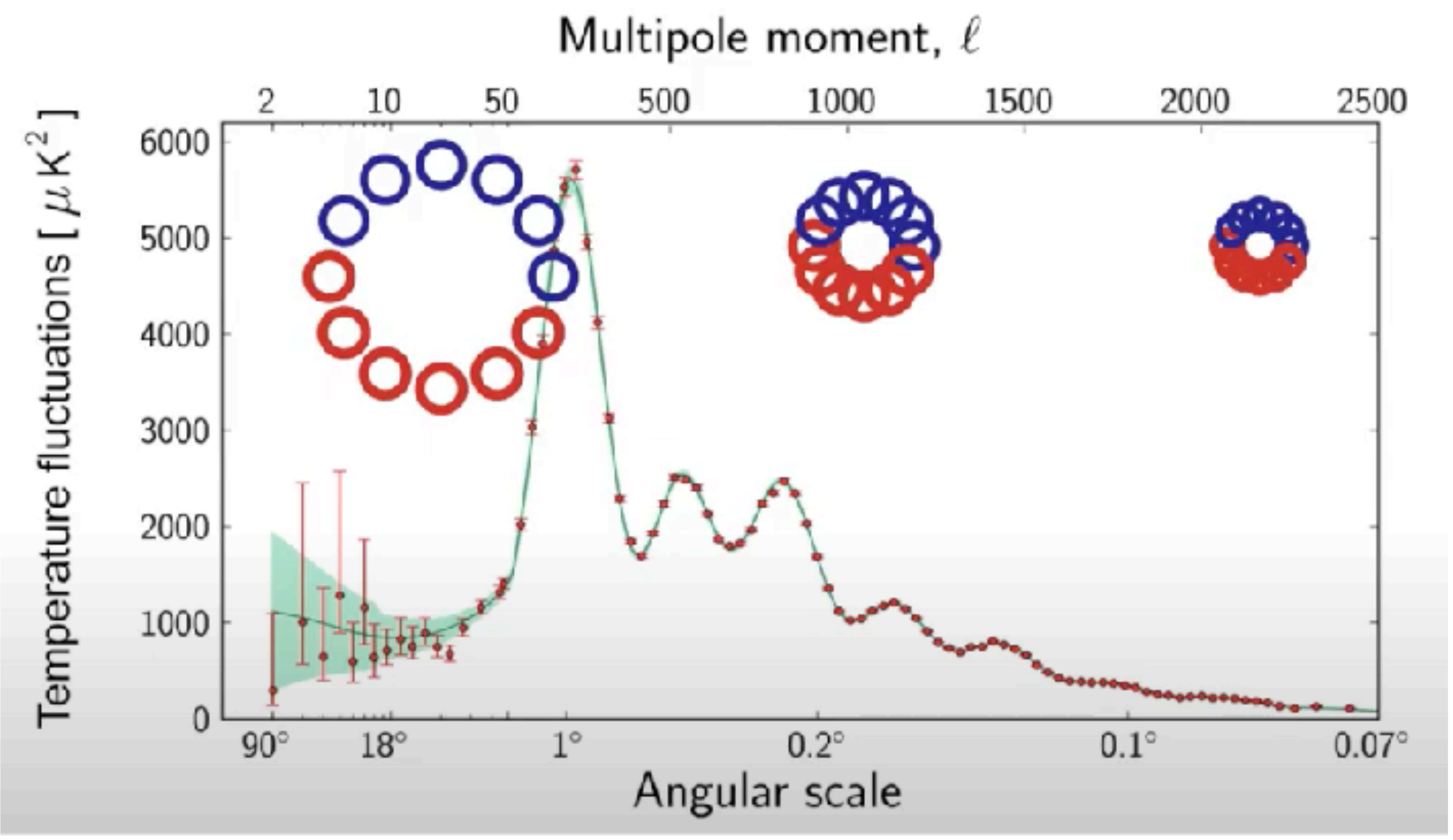
Baryon Acoustic Oscillations



- **CMB power spectrum:** correlations between points —> seeds of structures!!!
  - Angular scale and temperature fluctuations
  - The multipole moments are “ringing oscillations” on the surface of a sphere (spherical steel drum)

    The higher the “moment” the higher the “pitch” (shorter wavelength on the surface)

  - The different peaks are called “**acoustic oscillations**”
    - The first peak:
      - Angular scale: size of the Universe at the time of Last Scattering (when it became transparent to radiation)
      - Height: amount of baryonic matter in the Universe.
    - The ratio of the height of the 2nd and 3rd peaks shows the amount of baryonic to dark matter in the universe.
    - The tail shows the depth of the last scattering surface.



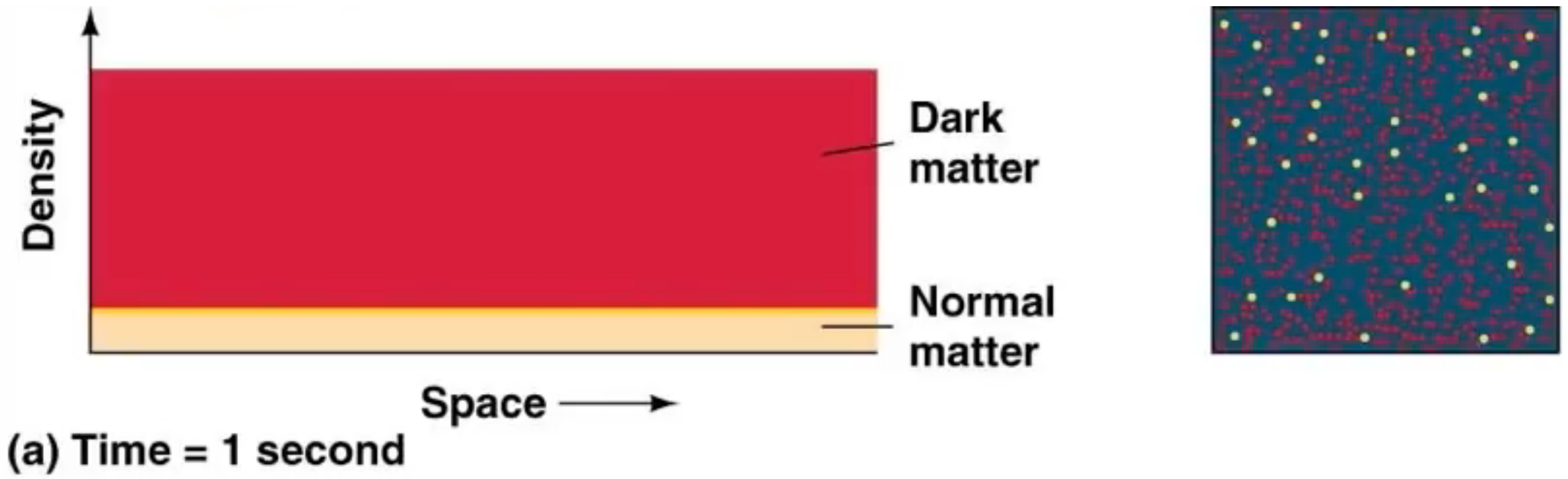
4. Large-scale structures

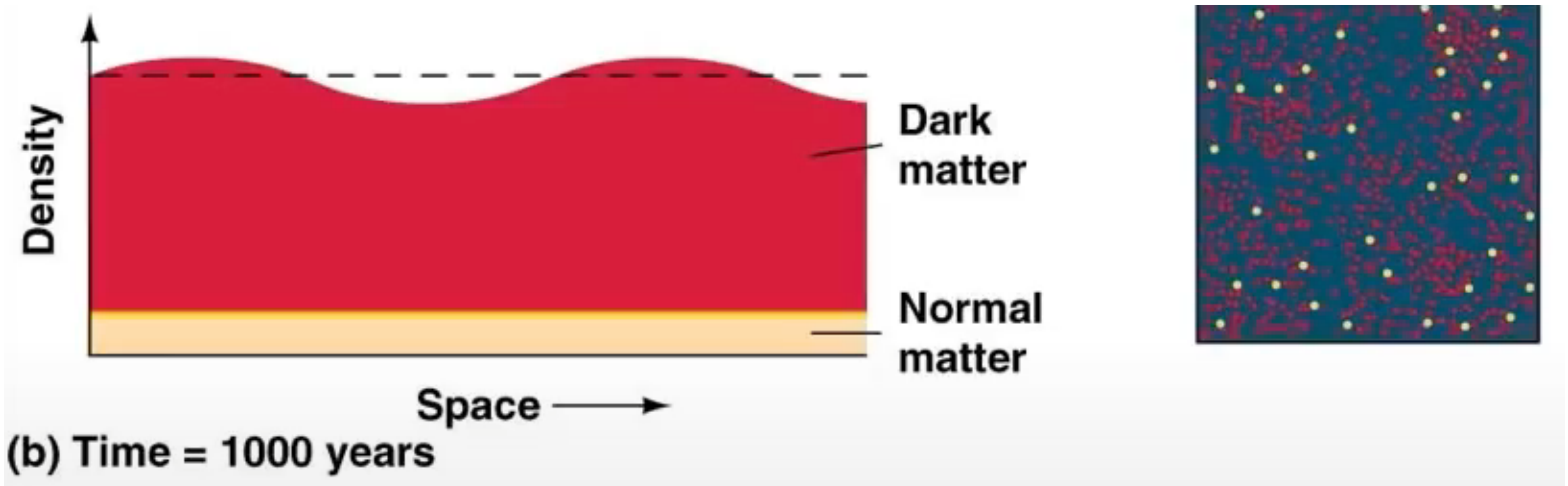
Formation of structures

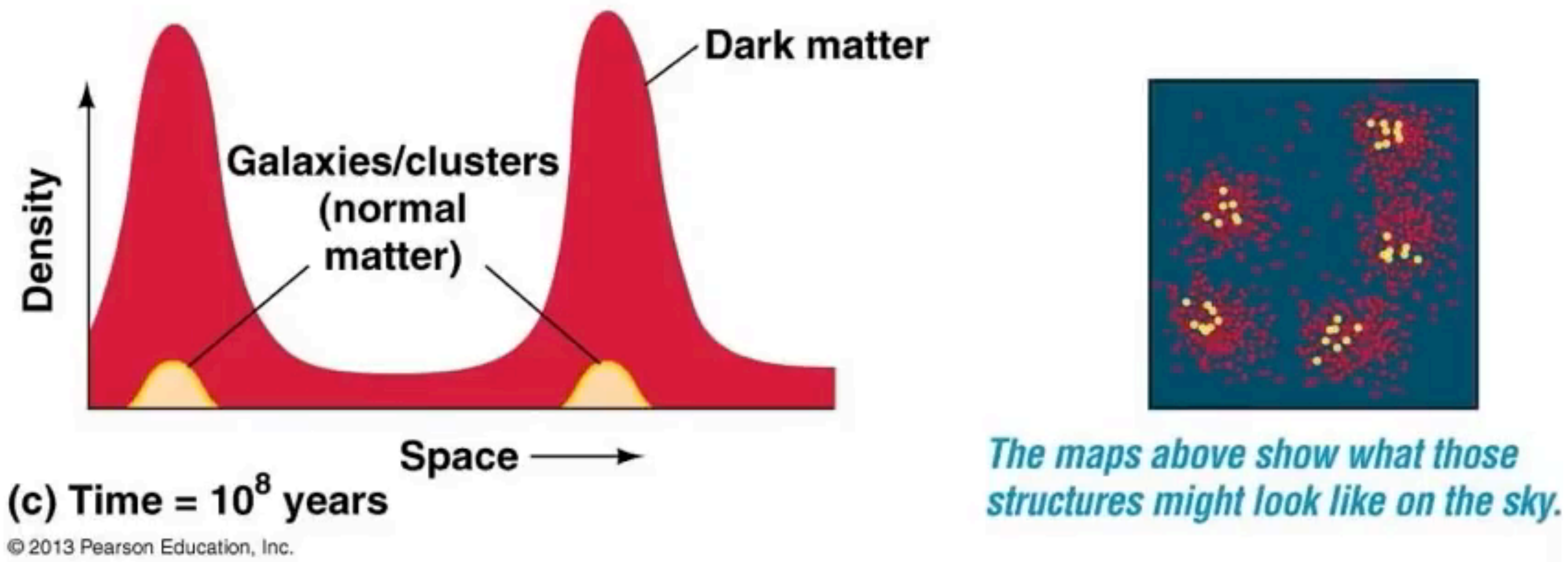
- Before decoupling (last scattering), radiation kept baryons from forming structures.
- This means, those structures would have started forming after last scattering.
- Dark matter started to cluster earlier because it does not interact with light.
- Galaxies could then form around dark matter clusters, attracted by their gravitational potential.

4. Large-scale structures

Growth of matter perturbations







Amplitude of perturbations

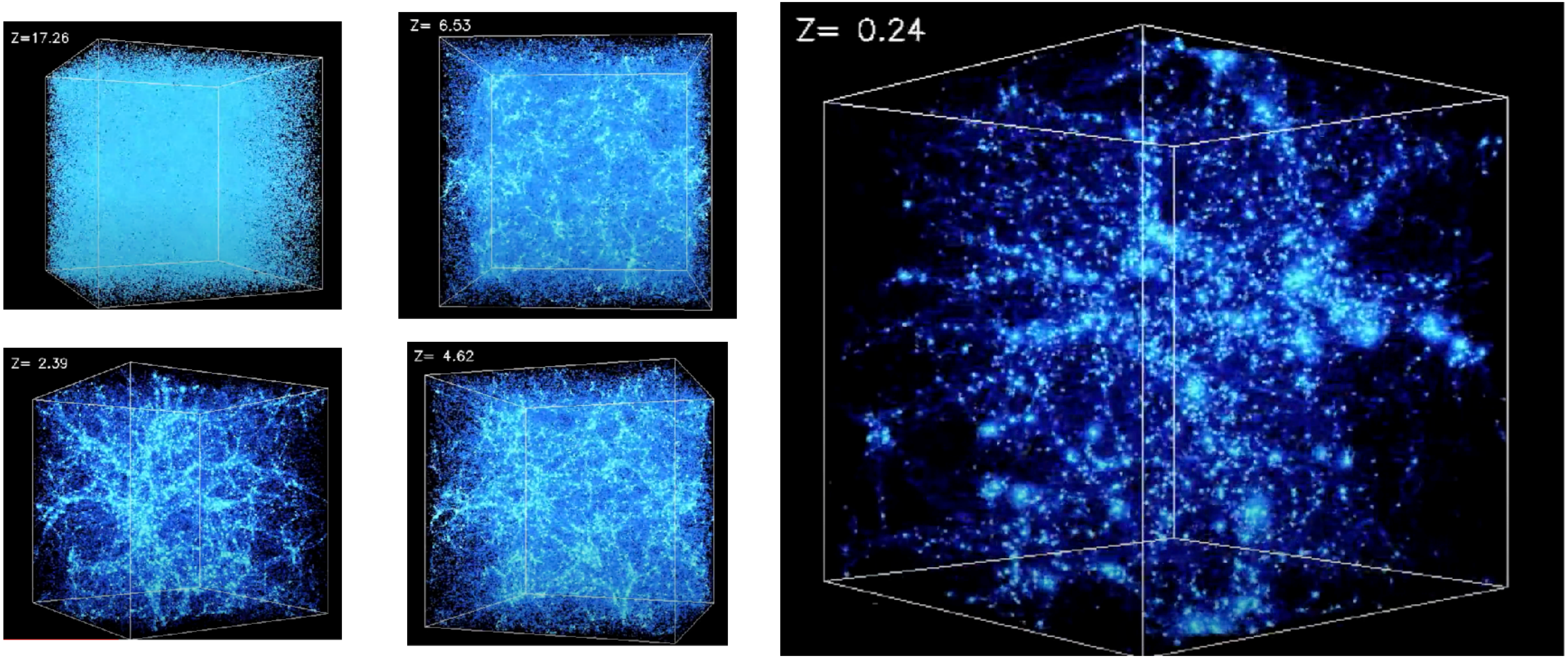
$$\sigma^2(M,z) = \frac{D^2(z)}{2\pi^2}\int k^2 P(k) W^2(kR)\, dk$$

- Growth function $D(z)$
- Dark matter power spectrum $P(k)$
- Wavenumber $k = 2\pi/r$
- Window function $W(kR)$
- Radius or scale R

4. Large-scale structures

http://cosmicweb.uchicago.edu/

Dark matter simulations



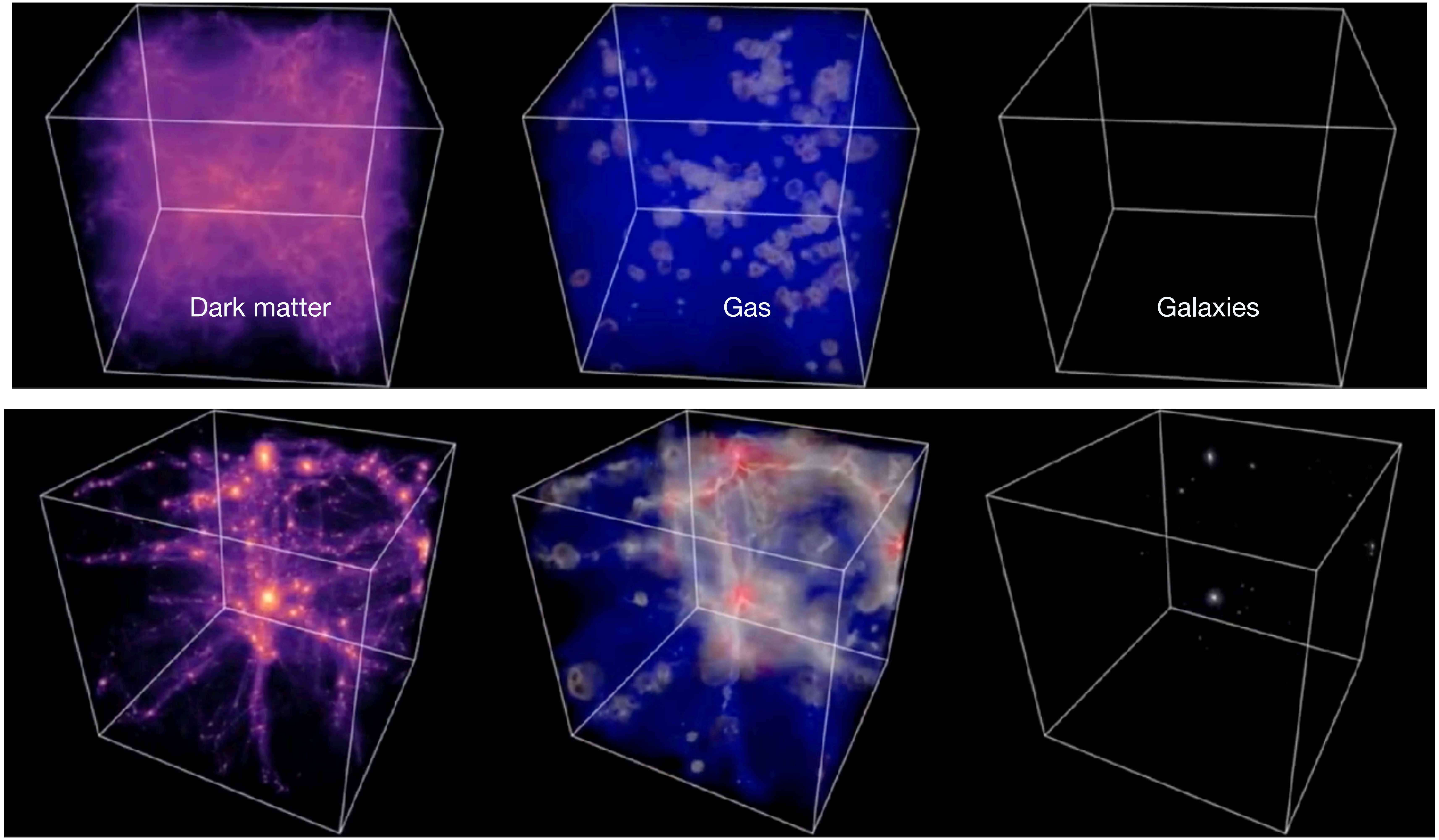
4. Large-scale structures

Dark matter and galaxies

Rob Crain https://vimeo.com/user4391791
EAGLE Simulation (U Durham)

Past

Present

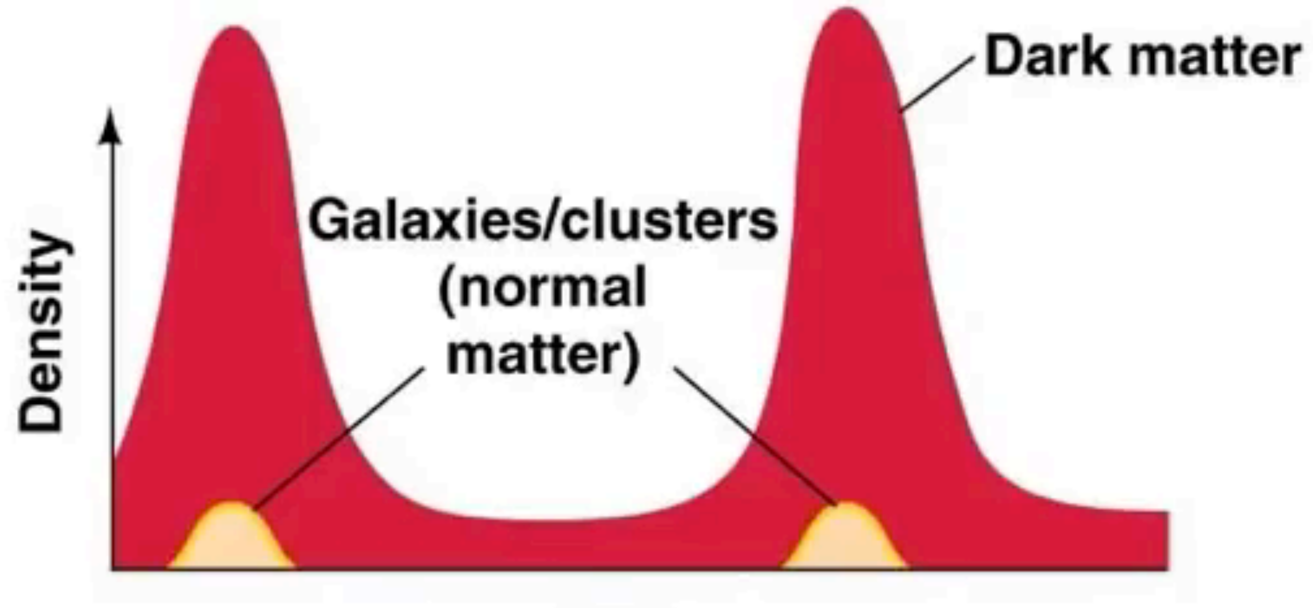


4. Large-scale structures

Dark matter power spectrum

$$\sigma^2(M,z) = \frac{D^2(z)}{2\pi^2}\int k^2 P(k) W^2(kR)dk$$

- The universe is a fluid made of components characterised by energy density ρ and pressure P
- Density: $\rho = background\ + fluctuations\ = \rho_0 + \delta\rho$
- Density contrast: $\delta = \dfrac{\rho - \rho_0}{\rho_0}$
- Dark matter: $\{\delta_m, P = 0\}$

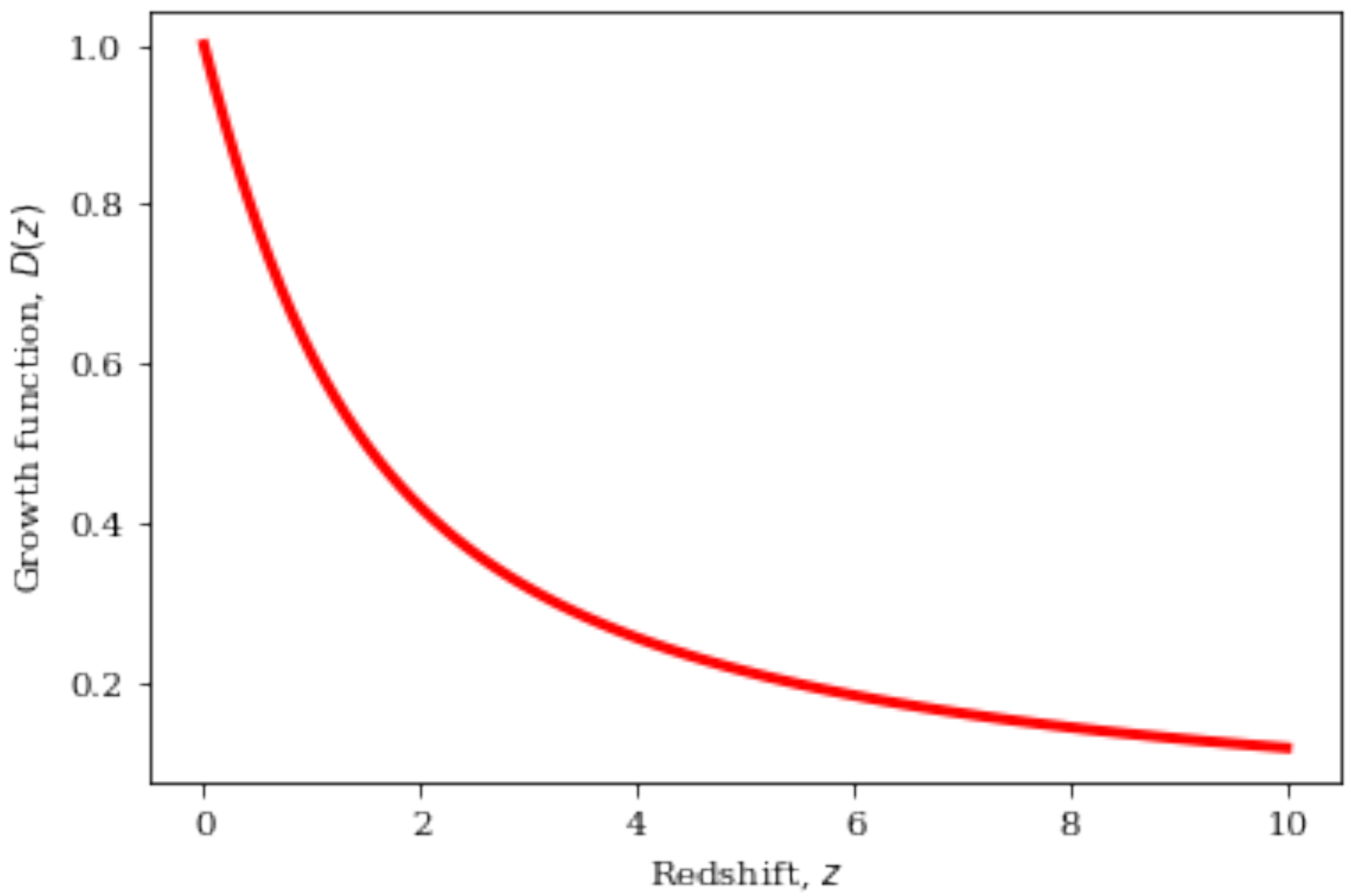


Density conservation	$\dot{\delta} + \nabla\cdot((1+\delta)\underline{v}) = 0$	[1]
Newton's law	$\dot{\underline{v}} + (\underline{v}\cdot\nabla)\underline{v} + 2H\underline{v} - \frac{1}{a^2}\nabla\Phi = 0$	[2]
Poisson's equation	$\frac{1}{a^2}\nabla^2\Phi = -\frac{3H^2}{2}\Omega_m\delta$	[3]

4. Large-scale structures

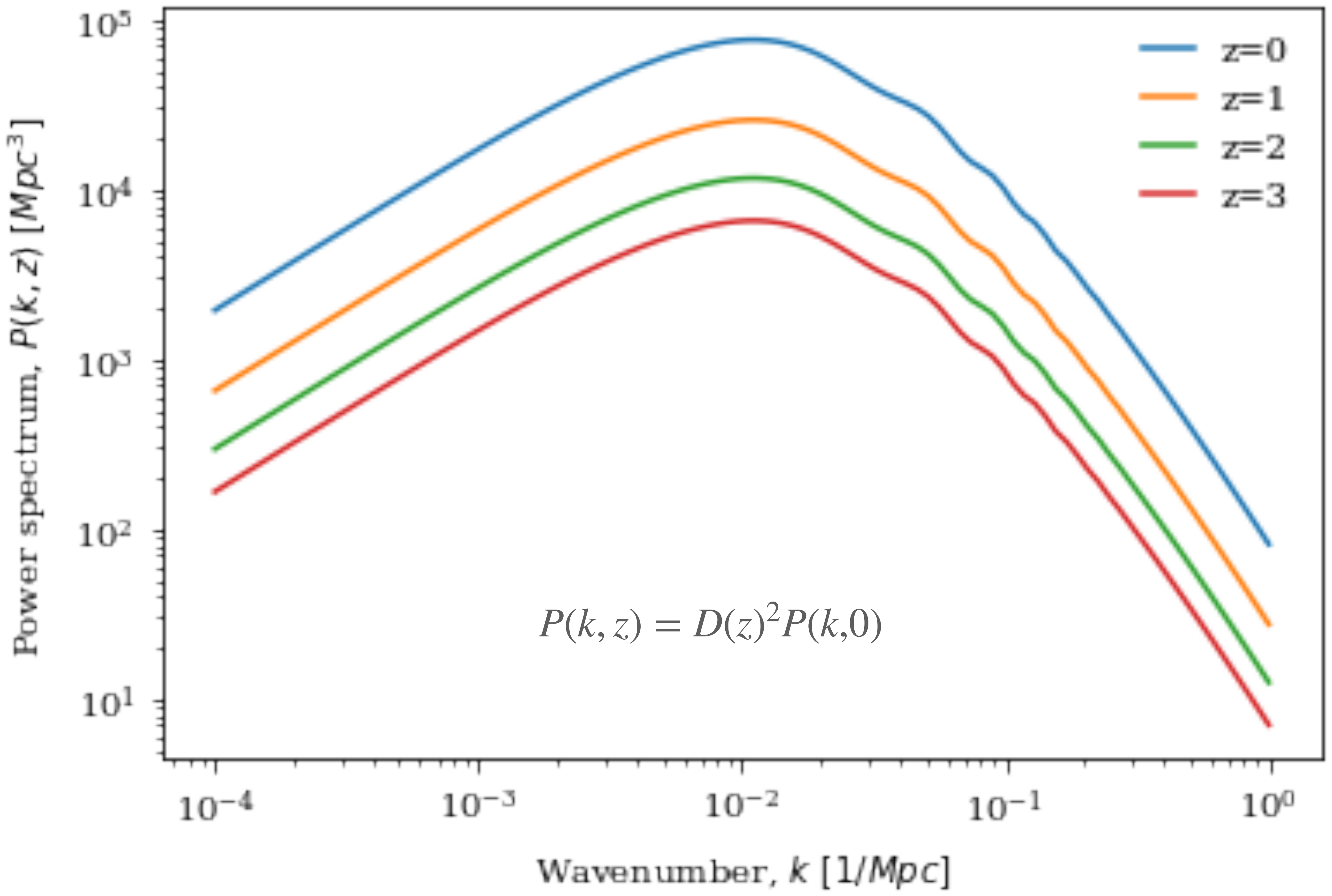
Using SkyPy functions

Dark matter power spectrum (Fourier space)



Dark matter density field

$$\delta(k, z) = D(z)\delta(k, z_{init})$$



Dark matter power spectrum

$$\langle \delta(\vec{k}_1, z)\delta^*(\vec{k}_2, z)\rangle := (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2) P(k, z)$$

5. The cosmological model

Ingredients

$$\Lambda CDM$$

- The (reduced) Hubble parameter H (h)
- Total matter density Ω_m
- Baryon density Ω_b
- Cosmological constant or dark energy Ω_{DE}
- And more parameters. Which?