Cosmology

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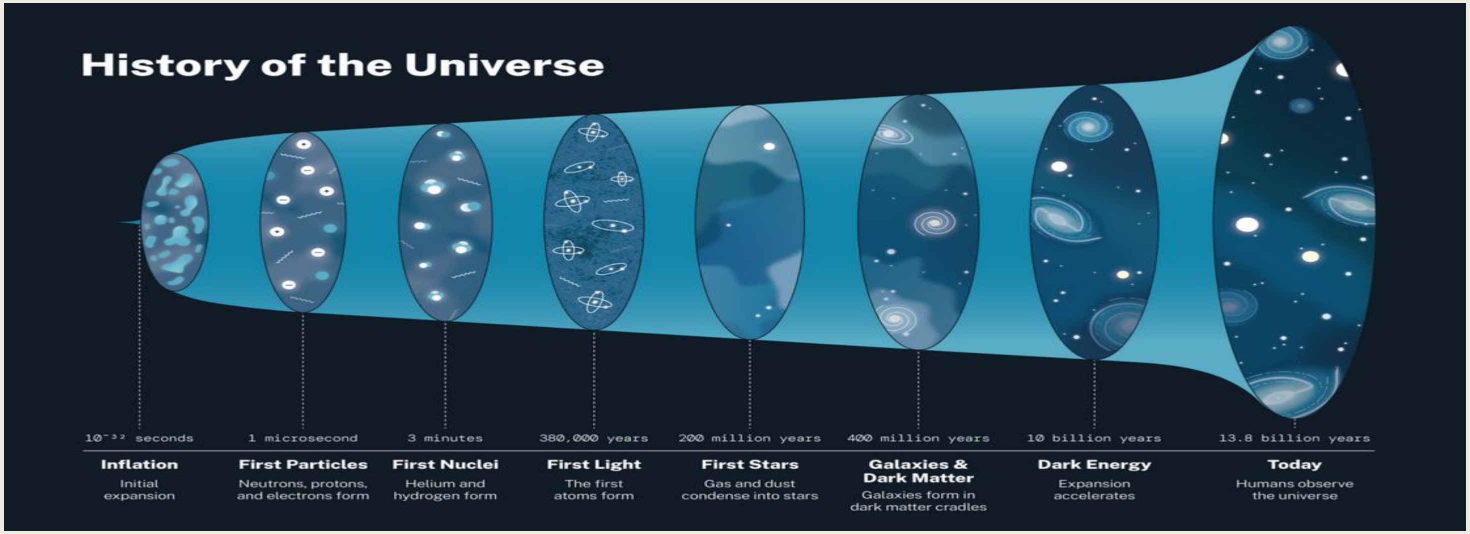
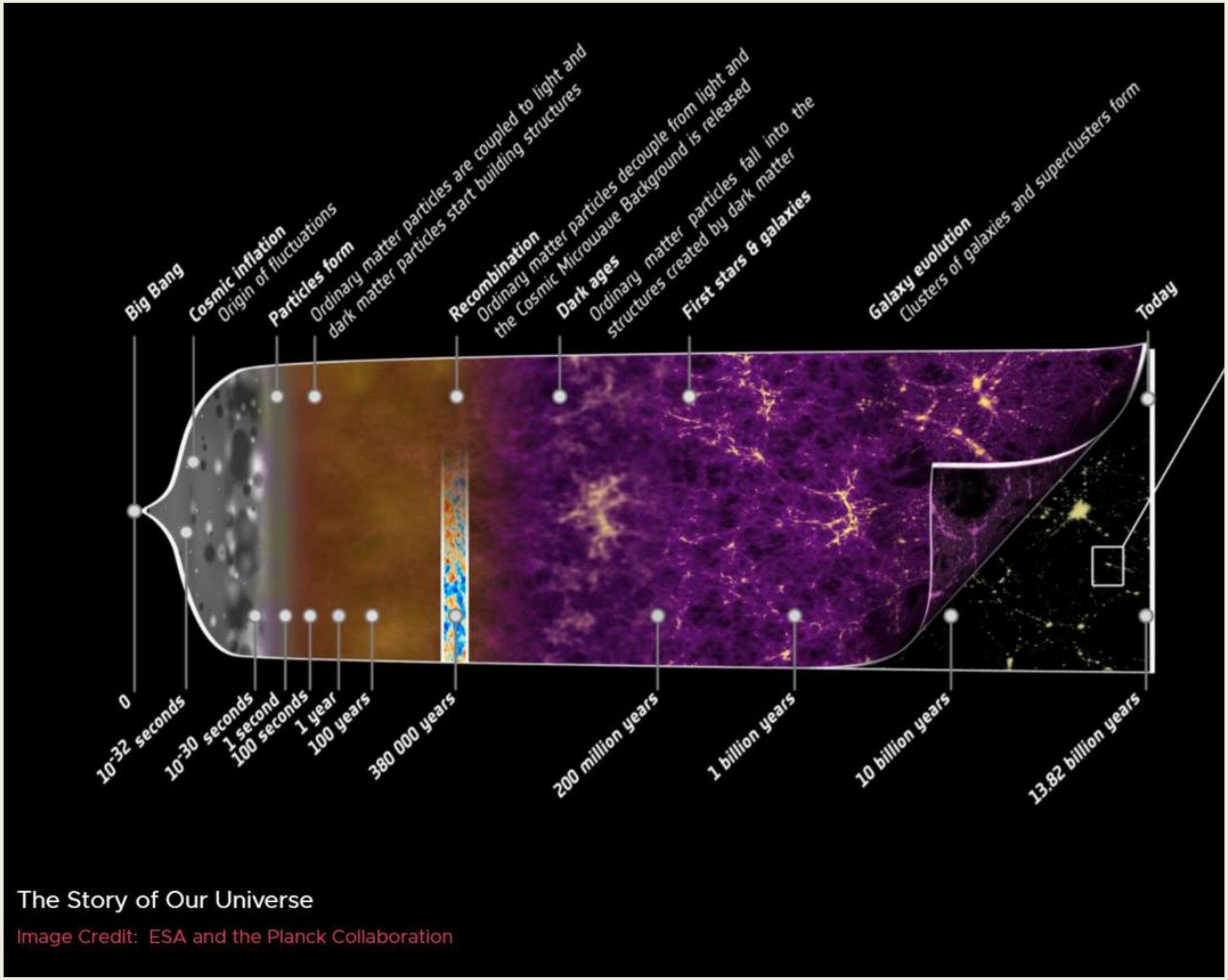
What we know so far – general picture I

Era/Epoch	Beginning	Ending	Note
Planck	0	10^{-43} sec	All four forces are unified
GUT	10^{-43} sec	10^{-36} sec	Strong, weak, and electromagnetic forces are unified
Inflation	10^{-36} sec	10^{-32} sec	Rapid expansion in a fraction of a second
Electroweak	10^{-32} sec	10^{-12} sec	Weak and electromagnetic forces are unified
Particle: Quark	10^{-12} sec	10^{-6} sec	Quarks forms
Particle: Hadron	10^{-6} sec	10^{-3} sec	Protons and Neutrons form
Particle: Lepton	1 sec	10 sec	Electrons (Leptons) form
Nucleosynthesis	3 sec (10^{-3} sec)	20 min (3 min)	Hydrogen and Helium Nuclei form
Photon	10 min	380,000 years	Energetic photons bounce around the universe
Recombination	≈240,000 years	380,000 years	Nuclei bond with electrons to form atoms
CMB		380,000 years	Light escapes and the universe becomes transparent
Dark Ages	≈400,000 years	½ to 1 billion years	Few stars to create light
Reionization	400 million years	1 billion years	Energetic photons knock electrons off atoms creating ions
Stars	100 to 250 million years		Stars form from hydrogen nuclei and atoms
Galaxies	½ to 1 billion years		Stars are pulled together into galaxies

Credit: https://www.fas37.org



What we know so far – general picture II



How do we know all that?

General Relativity Theory and Standard Model

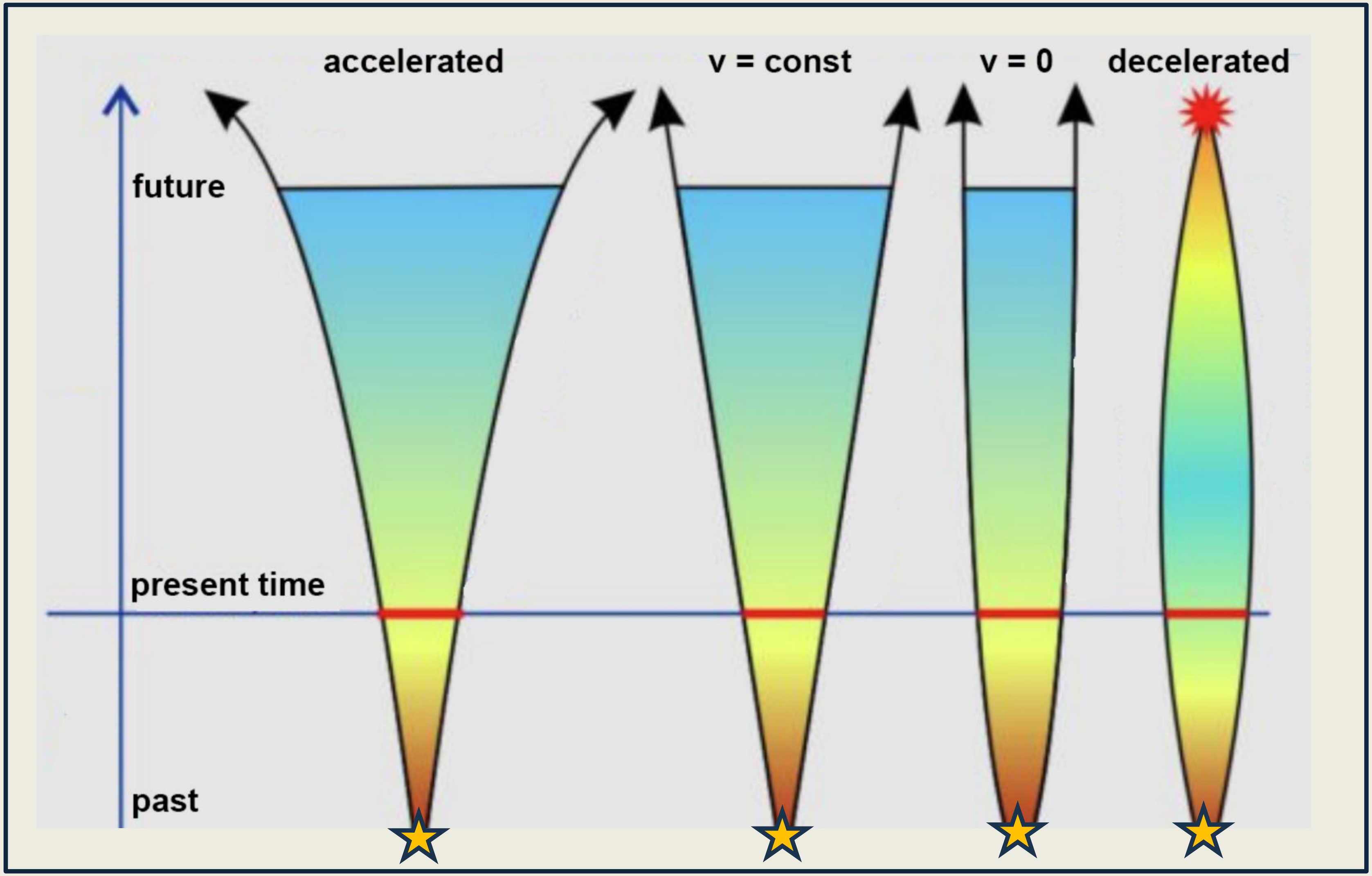
Einstein's equations

$$R_\mu^\nu - \frac{1}{2}\delta_\mu^\nu R = T_\mu^\nu$$

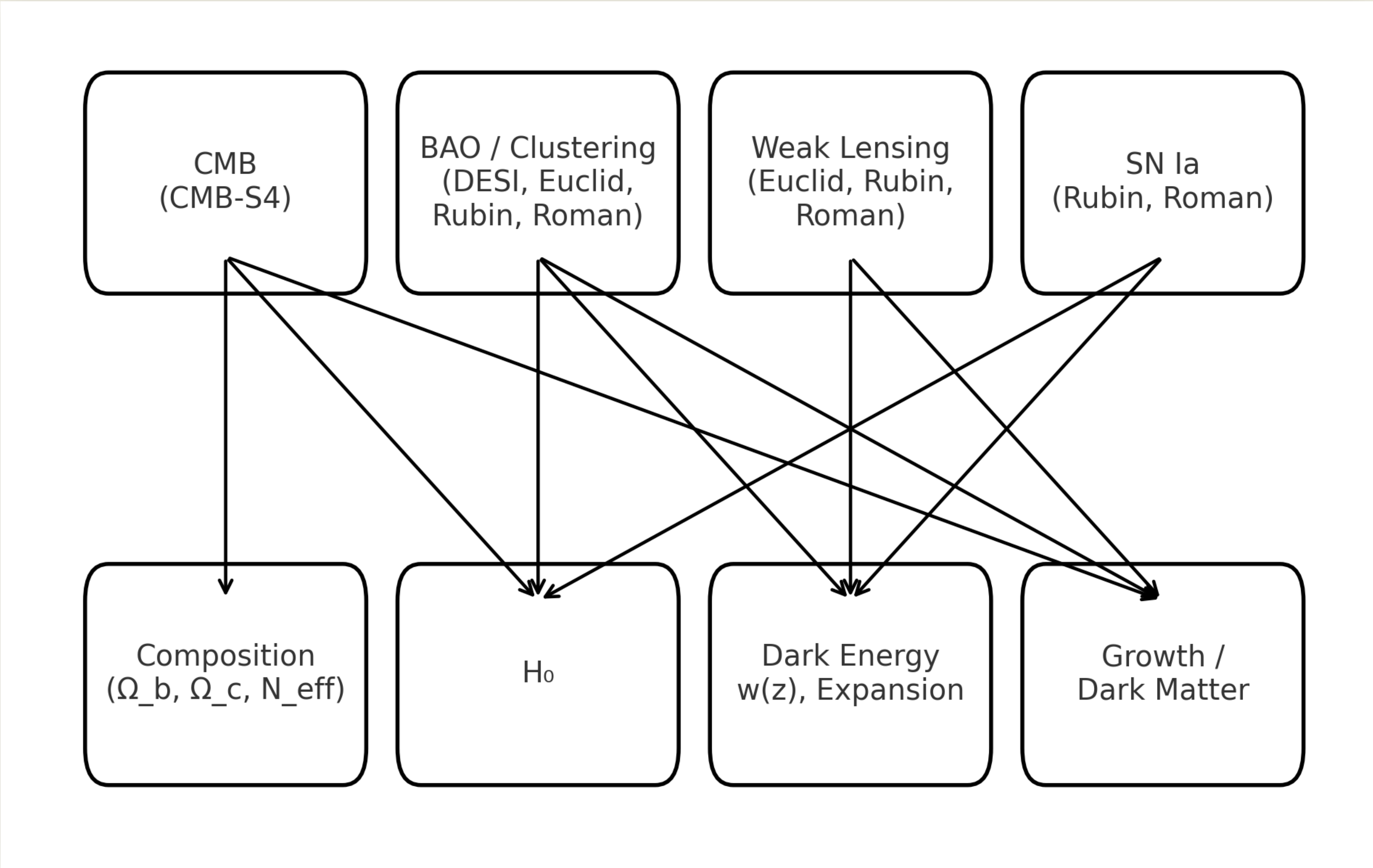
Geometry

Matter

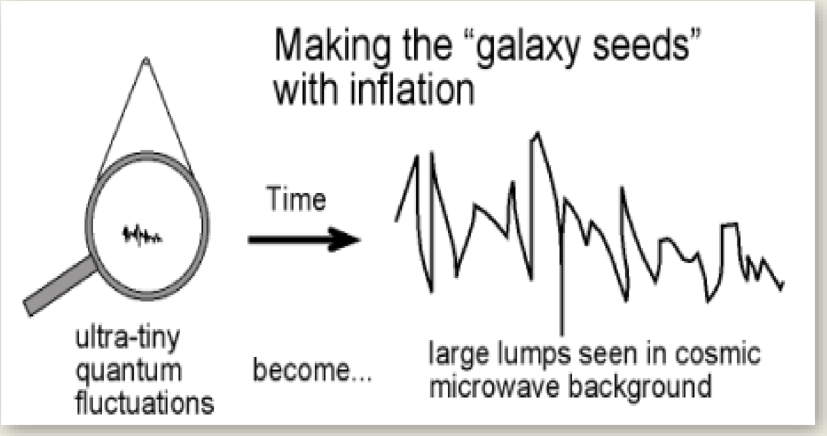
How do we know all that?

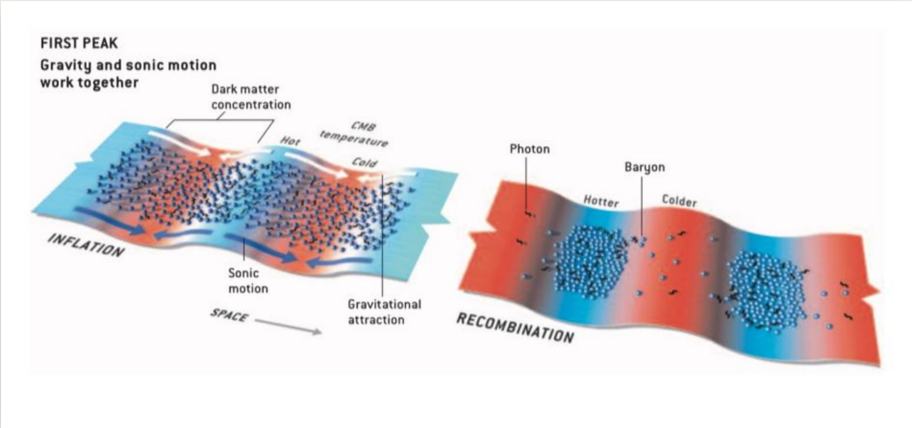


Big Five experiments

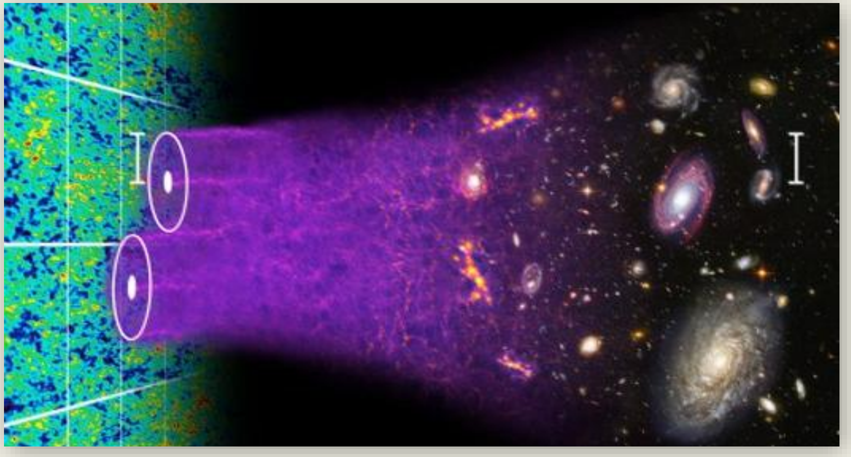


Cosmic Microwave Background Baryonic Acoustic Oscillations & Clustering

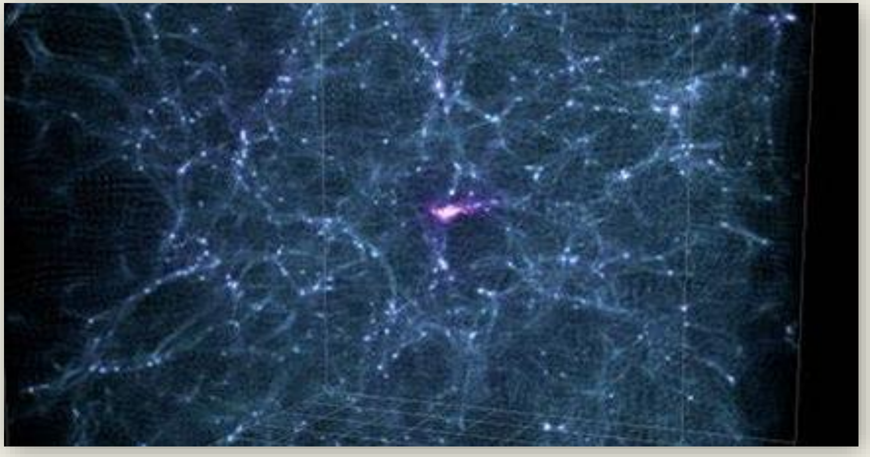




The number of galaxies should be correlated with each other on scales comparable to the sound horizon of the largest acoustic peaks (~150 Mpc comoving)



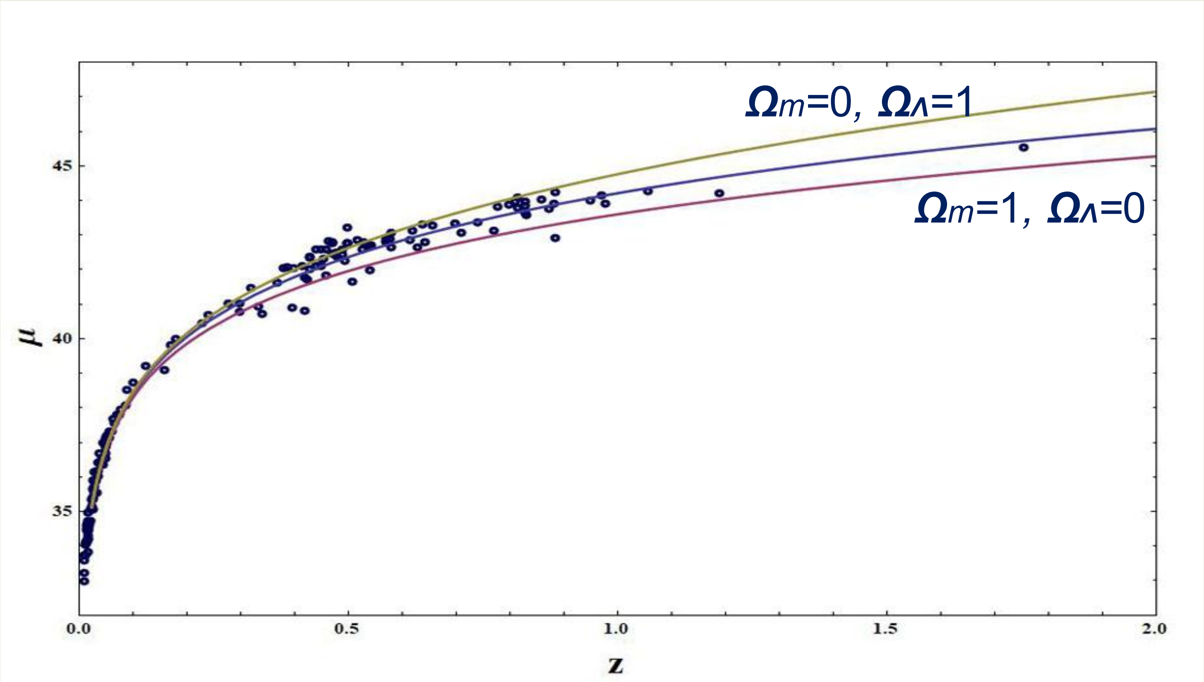
Credit: BOSS



Credit: DEUS

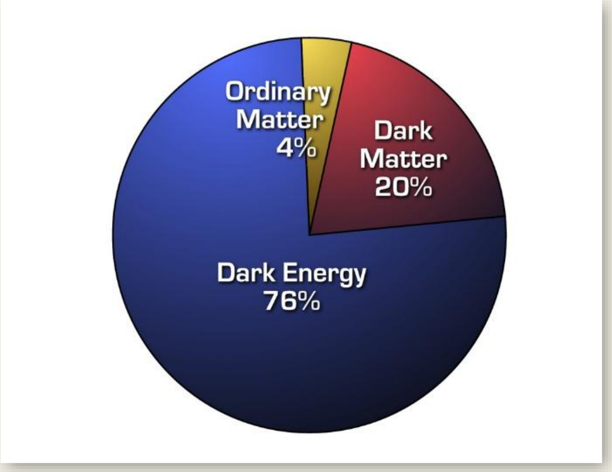
Super Novae 1a

The Type Ia a binary with white dwarf. This of supernova produces a consistent peak luminosity because of the fixed critical mass at which a white dwarf will explode. Their consistent peak luminosity allows these explosions to be used as standard candles to measure the distance to their host galaxies.



Best fit for Ω_m=0.29 and Ω_Λ=0.71

Cosmology Today: Parameters & Key Puzzles



Credit: https://euclid.caltech.edu/

ΛCDM is the standard cosmological model in which the universe is made of ordinary matter, cold dark matter, and a cosmological constant that drives accelerated expansion. It remains the simplest model that fits the majority of high-precision data extremely well. At the same time, persistent tensions in the Hubble constant and the growth of structure show that ΛCDM is under increasing pressure, and future measurements will test whether it needs to be extended or revised.

ΛCDM Best-Fit Parameters:

- $\Omega_m \approx 0.31$ • $\Omega_\Lambda \approx 0.69$
- $H_0 \approx 67.5$ km/s/Mpc (CMB+BAO)
- $\sigma_8 \approx 0.81$ • $S_8 \approx 0.83$ (CMB), ~0.77 (lensing)
- $n_s \approx 0.965$ • $N_{eff} \approx 3.0$
- $\Sigma m_\nu < 0.1$ eV (upper limit)

Unresolved Puzzles:

- H_0 tension: early-universe 67–68 vs. local 73 km/s/Mpc
- S_8 tension: weaker late-time structure growth than ΛCDM predicts
- Nature of dark energy (is $w = -1$? evolving?)
- Nature of dark matter (cold? warm? interacting?)
- Neutrino sector: mass scale & possible extra light species