

Cosmology

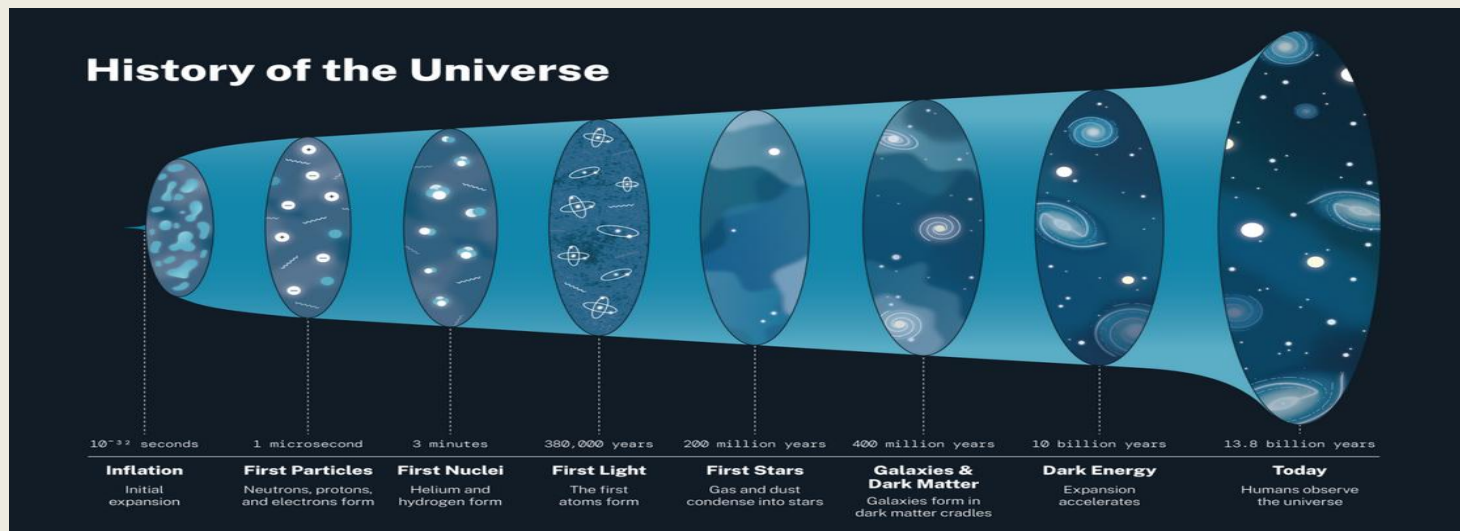
A deep space photograph of a galaxy cluster. The background is a dark, star-filled sky. In the center, there is a bright, yellowish-white core, likely the center of a galaxy or a dense cluster of galaxies. Surrounding this core are various structures: a prominent blue filament extends from the left towards the center, and a reddish-brown filament extends from the center towards the right. The overall image has a grainy, high-resolution appearance typical of astronomical observations.

Elena Koptieva, UIUC Physics, 2025

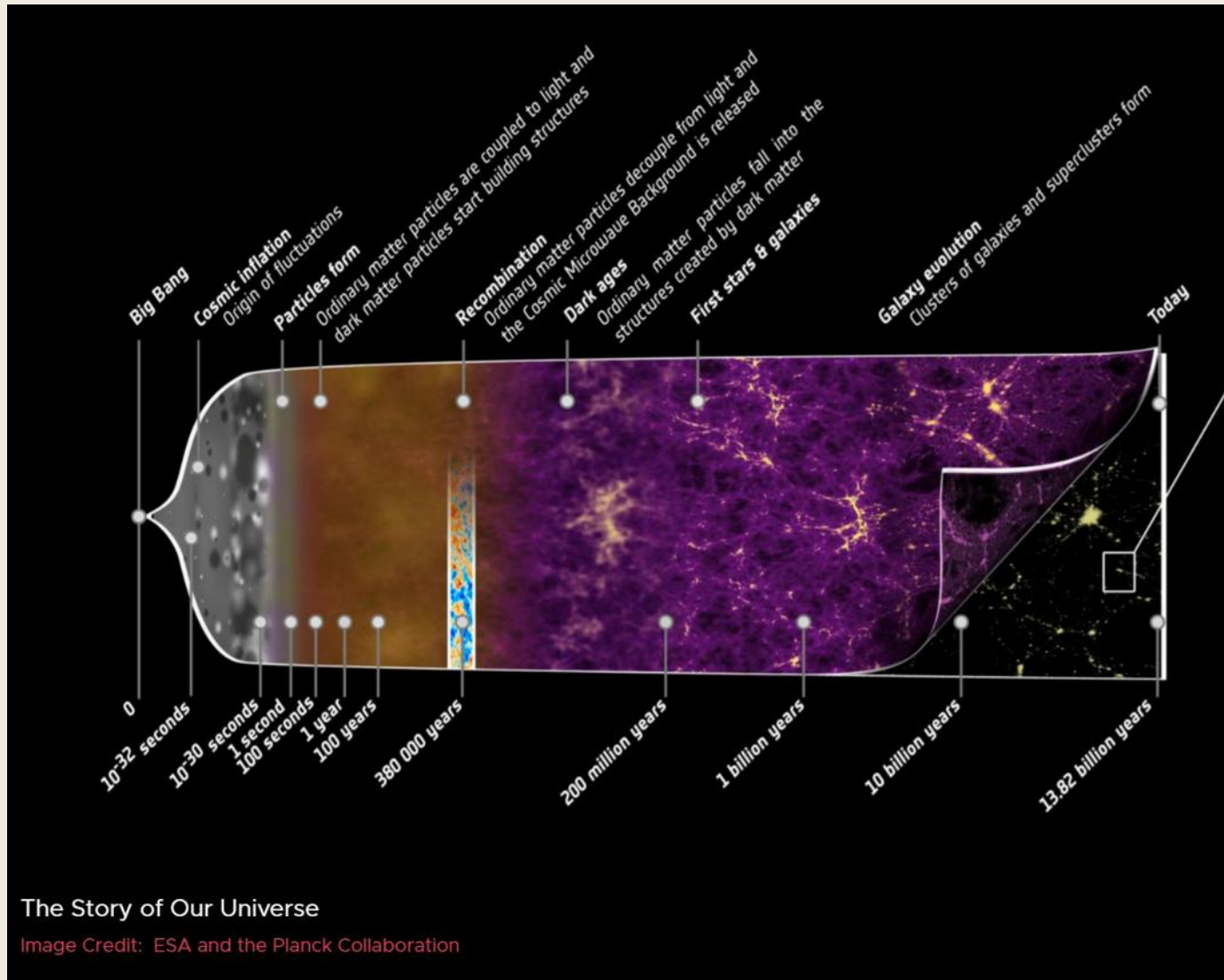
What we know so far – general picture I

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	$\approx 240,000$ years	380,000 years	Nuclei bond with electrons to form atoms
CMB		380,000 years	Light escapes and the universe <u>becomes</u> transparent
Dark Ages	$\approx 400,000$ years	$\frac{1}{2}$ 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	$\frac{1}{2}$ 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?

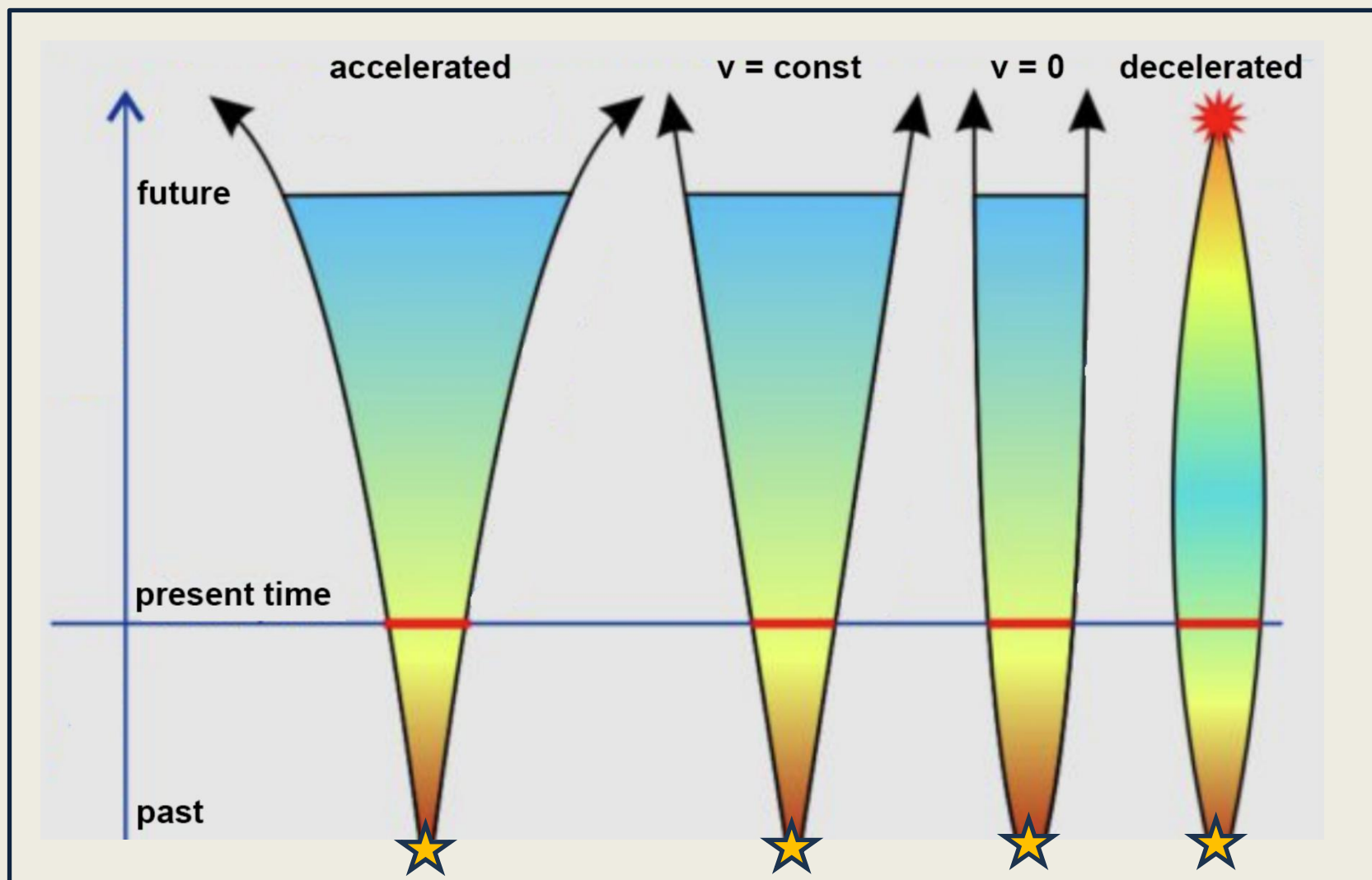
General Relativity Theory and Standard Model

Einstein's equations

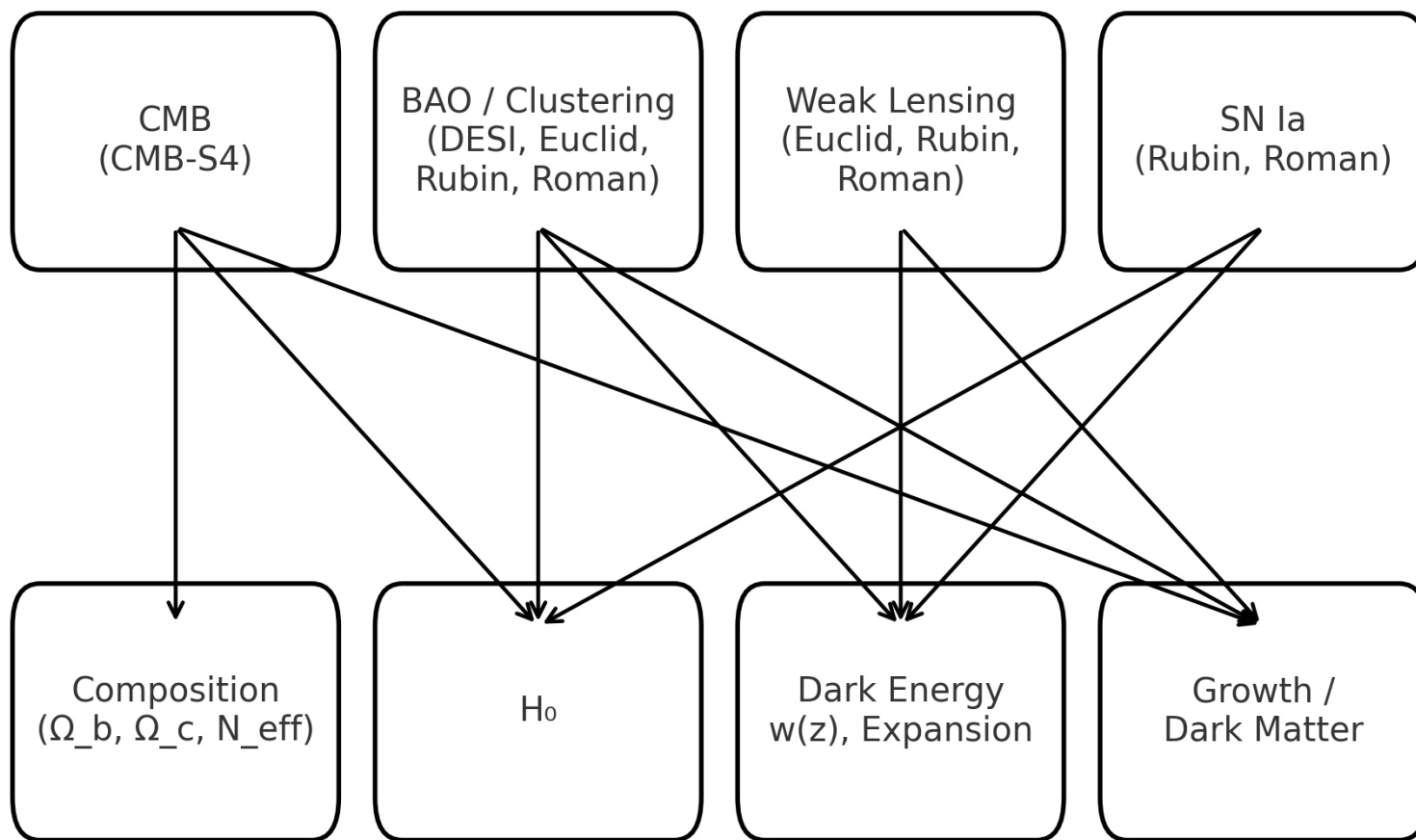
$$\underbrace{R^\nu_\mu - \frac{1}{2} \delta^\nu_\mu R}_{\text{Geometry}} = \underbrace{T^\nu_\mu}_{\text{Matter}}$$

The diagram illustrates Einstein's field equations. The left side of the equation, $R^\nu_\mu - \frac{1}{2} \delta^\nu_\mu R$, is bracketed in red and labeled "Geometry" with a red arrow pointing to it. The right side, T^ν_μ , is also bracketed in red and labeled "Matter" with a red arrow pointing to it. The equation shows that the geometry of spacetime is determined by the distribution of matter and energy.

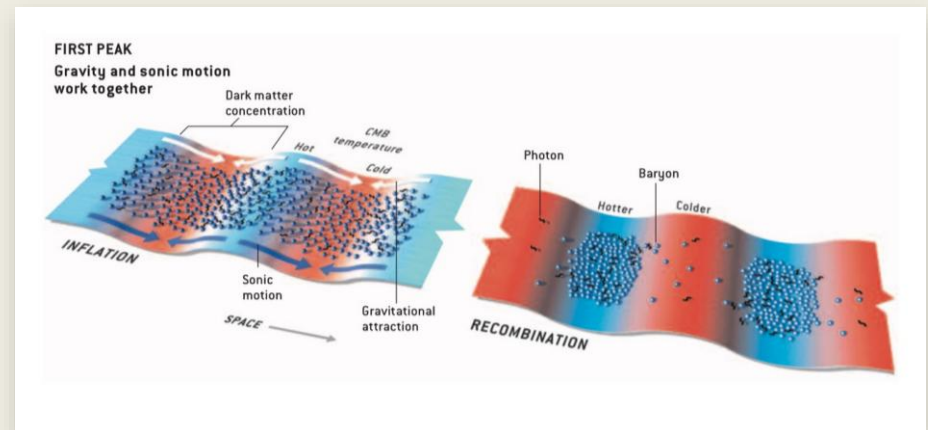
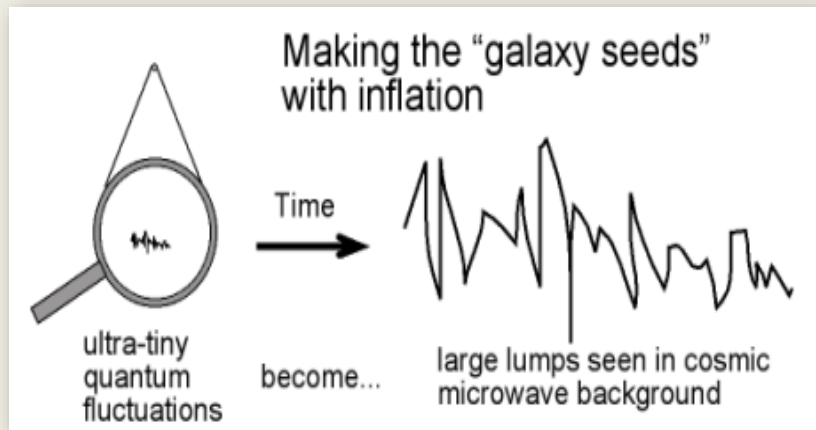
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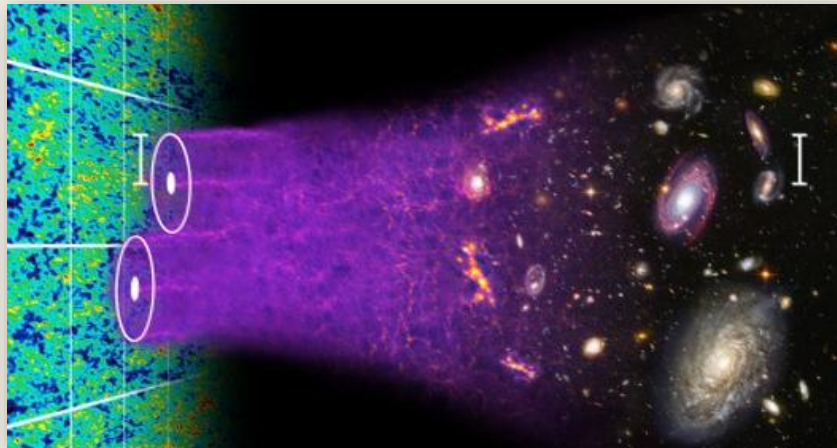
Big Five experiments



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)



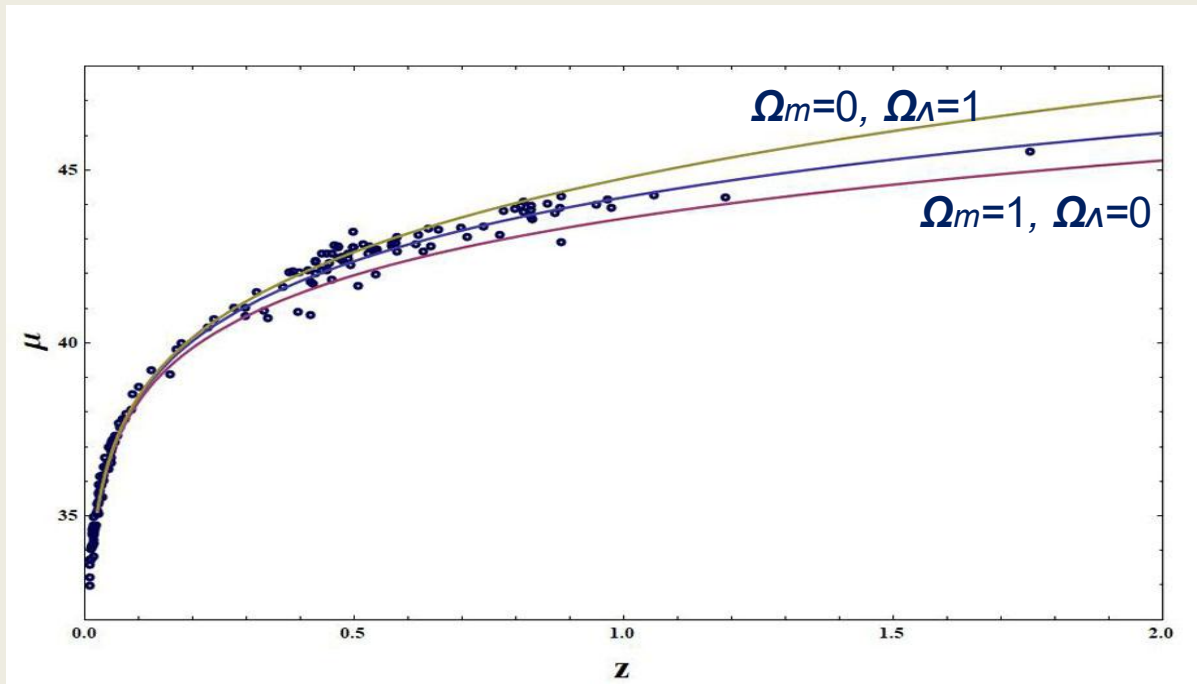
Credit: BOSS



Credit: DEUS

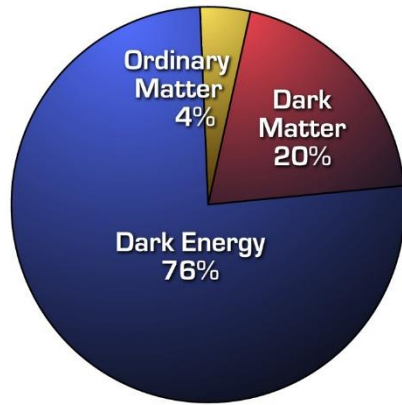
Super Novae 1a

The Type Ia supernova is a binary system with a white dwarf. This type 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 $\Omega_m=0.29$ and $\Omega_\Lambda=0.71$

Cosmology Today: Parameters & Key Puzzles



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

Λ CDM 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 Λ CDM is under increasing pressure, and future measurements will test whether it needs to be extended or revised.

Λ CDM 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)
- $n_s \approx 0.965$
- $N_{\text{eff}} \approx 3.0$
- $\Sigma m_\nu < 0.1$ 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 Λ CDM predicts
- Nature of dark energy (is $w = -1$? evolving?)
- Nature of dark matter (cold? warm? interacting?)
- Neutrino sector: mass scale & possible extra light species