

Reading: OpenStax, Chapter 29, Sections 29.1-29.6

Exam 3: Monday, November 23rd, 12-2 PM, Webex, 2 parallel sessions based on your recitation time, 30 questions from last third of the class, 10 more general questions

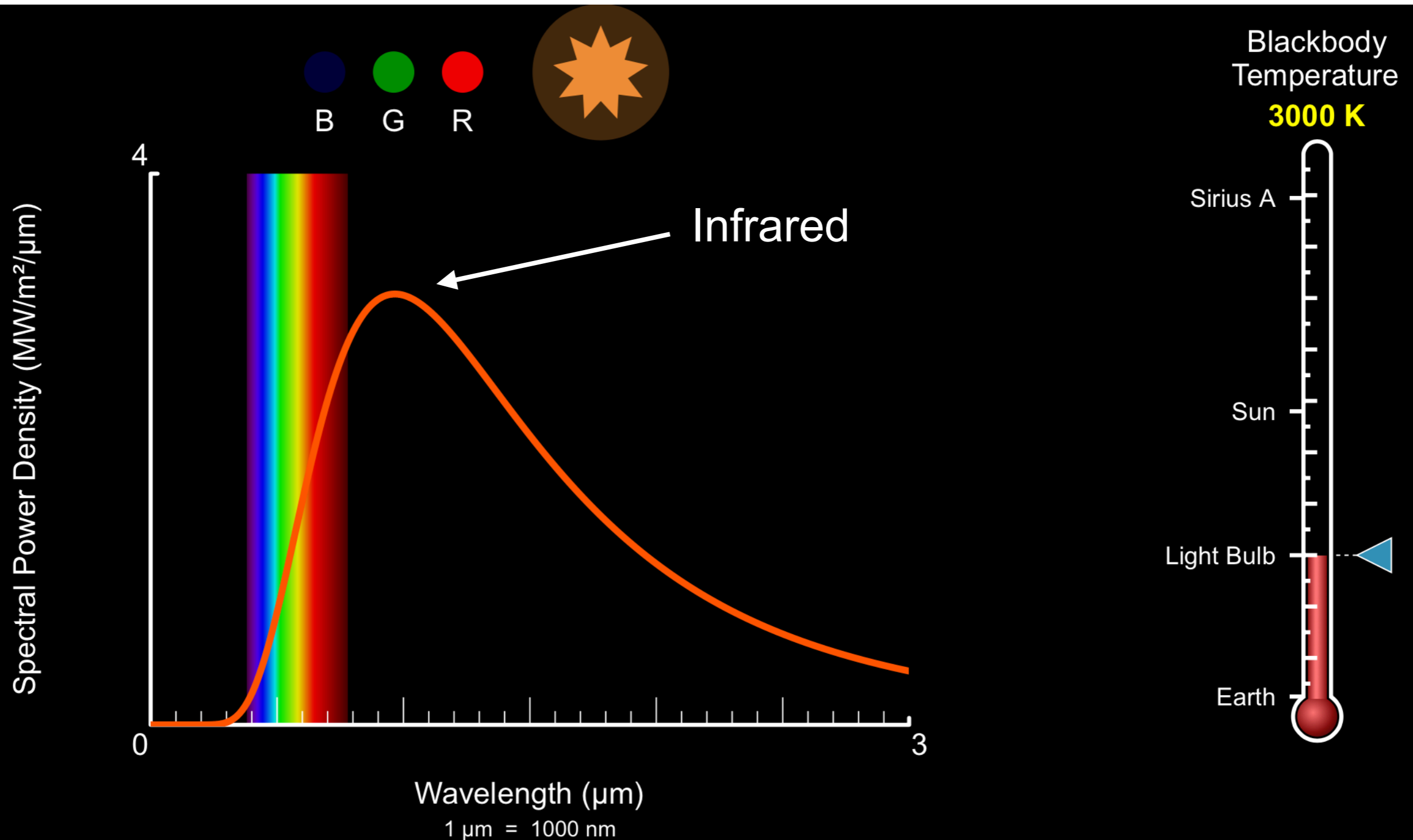
Previously: **Cosmology II - The Big Bang and its aftermath**

- Remnant radiation produces a cosmic microwave background
- Small density fluctuations needed to make galaxy clusters were present in the very early universe
- A very “Inflation” epoch is needed to make the post-Big Bang expanding universe look like what we see today

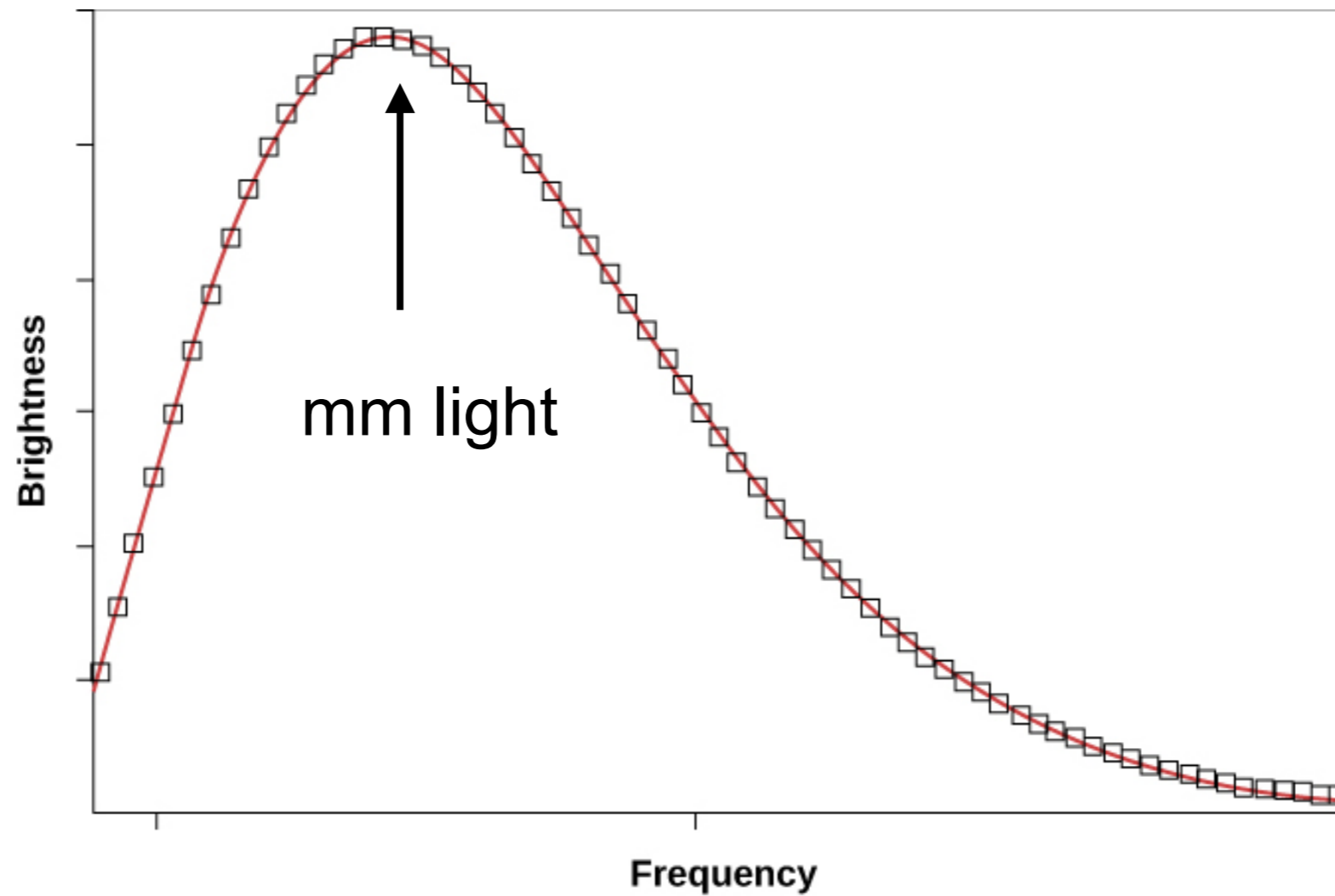
Today: **Cosmology III - The content of the Universe and its evolution**

- We live in a very flat Universe (as suggested by inflation and the CMB)
- Dark Matter (~30%) + Dark Energy (~70%) + ordinary matter (~ 5%)
- Expansion is now “accelerating” - dark matter joined by dark energy
- Possible alternative future Universes include Big Rip, Big Crunch, but most likely slowly expanding and cooling forever

(Review) At 380,000 years, Universe was a blackbody of $T = 3000\text{K}$



(Review) CMB observed by COBE is at a much lower temperature

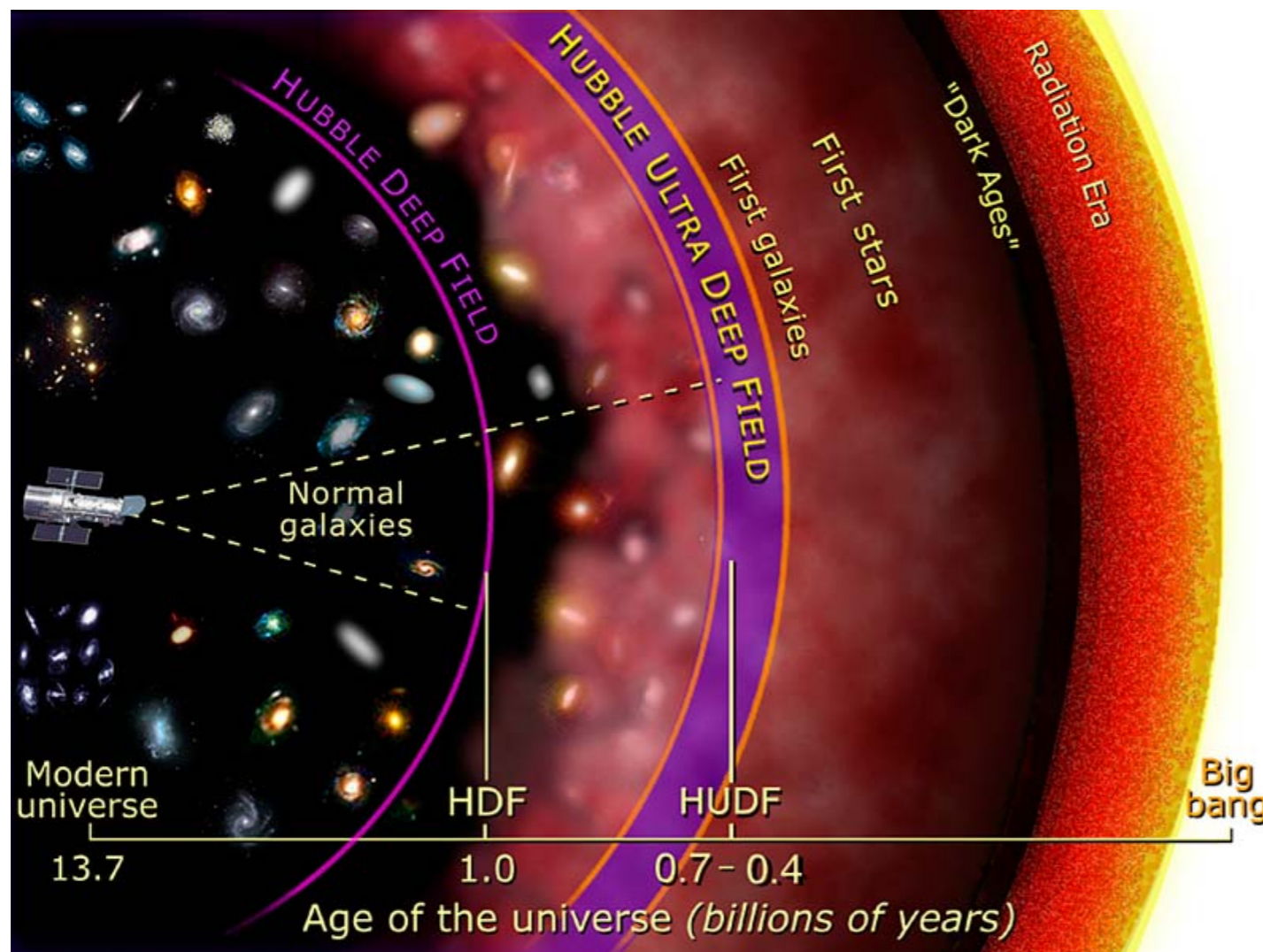


A quiz question! (Answer)

- *If the Universe was 3000 K (and emitted at infrared wavelengths) at 380,000 years of age, why is it now observed to be 2.73 K (microwave)?*

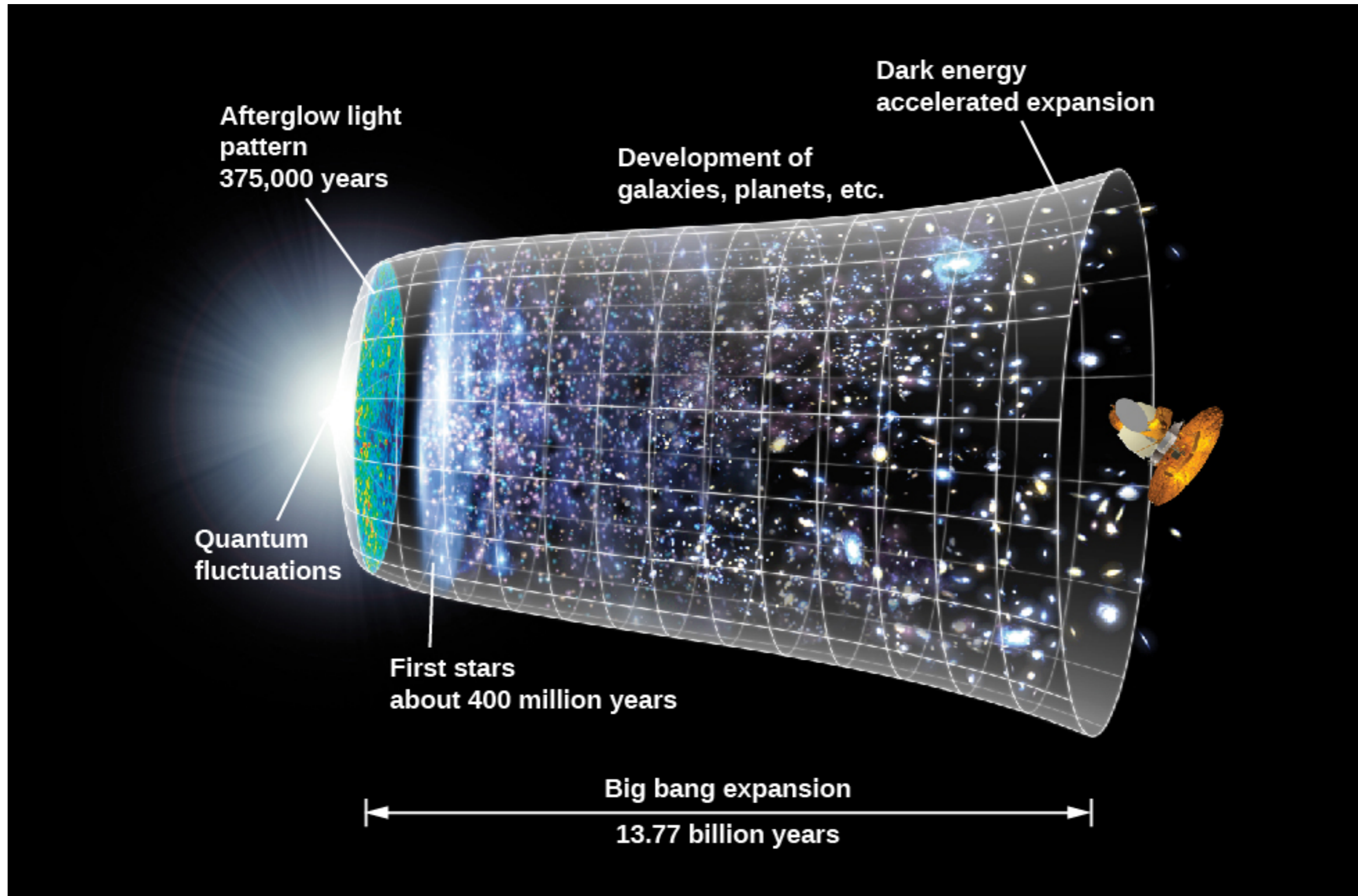
A quiz question! (Answer)

- *If the Universe was 3000 K (and emitted at infrared wavelengths) at 380,000 years of age, why is it now observed to be 2.73 K (microwave)?*



- Redshift increases with distance
- CMB is VERY far away (14 billion light years!)
- Its redshift will be sufficiently large to shift infrared light to microwave

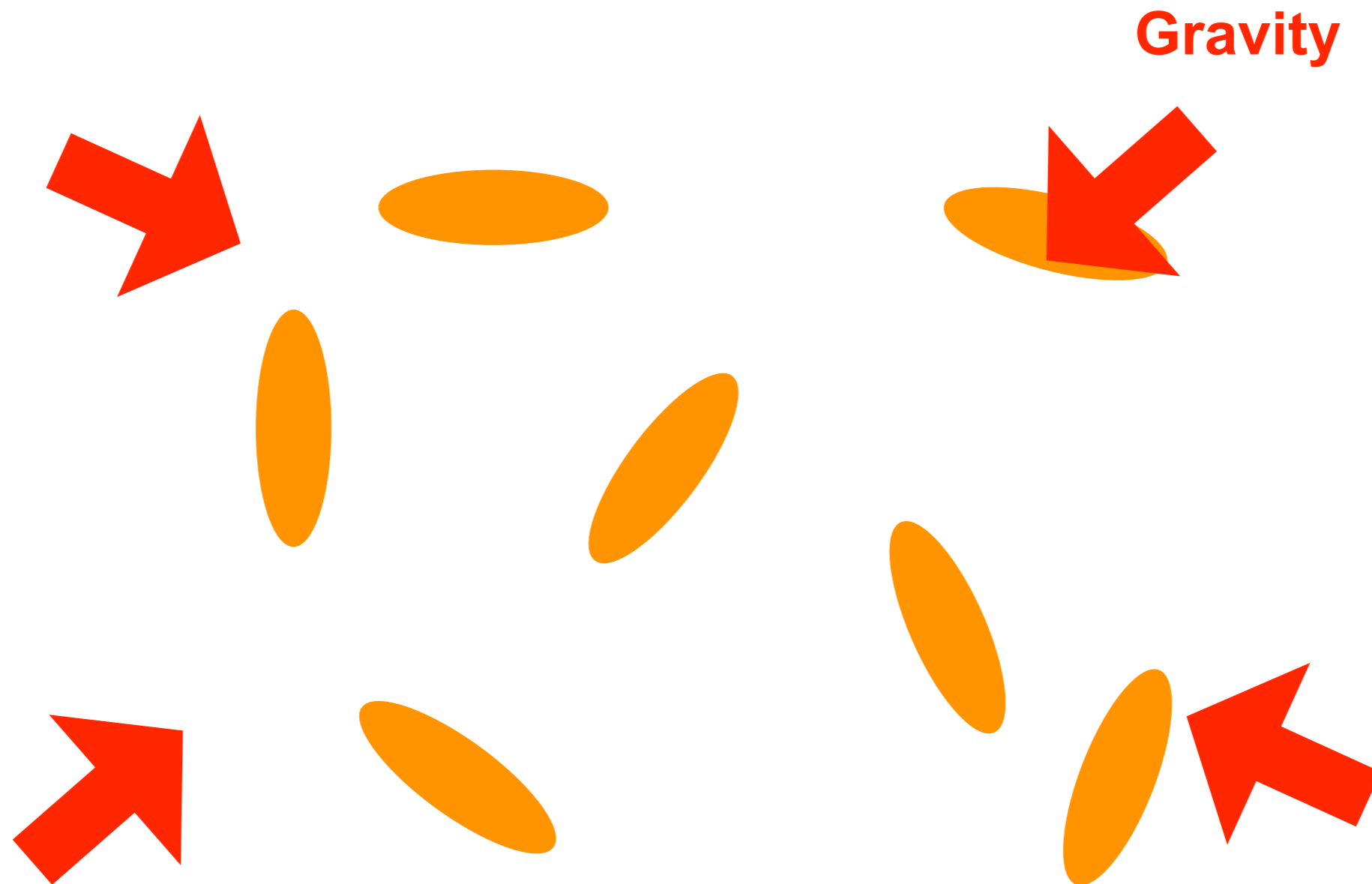
(Review) Summary so far



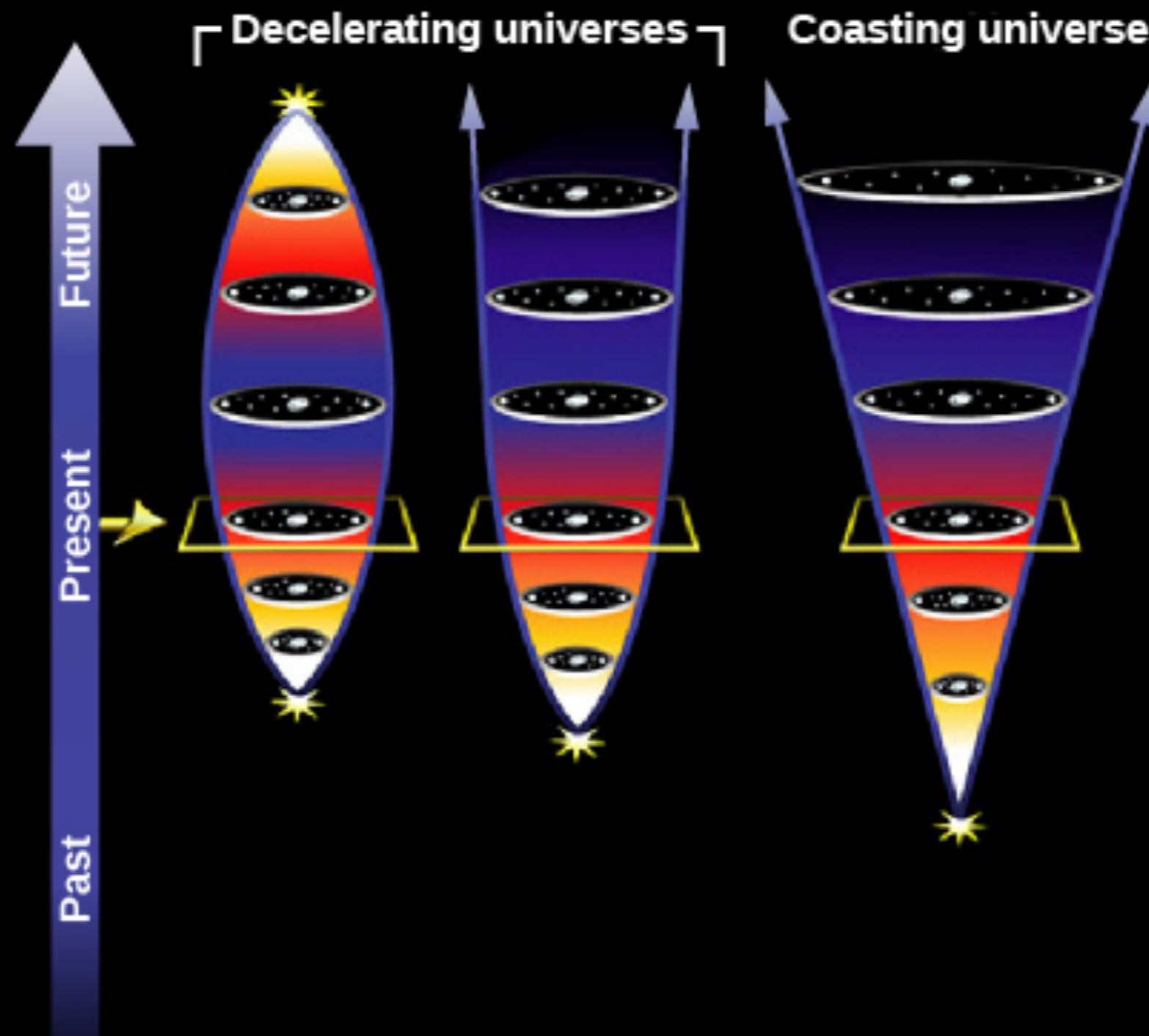
Will the Universe expand forever or will it eventually collapse?



Will the Universe expand forever or will it eventually collapse?



Whether the Universe reverses its expansion or continues to expand depends on the “density”



Whether the Universe reverses its expansion or continues to expand depends on the “density”

- is there enough **mass** for gravity to stop expansion?

- **critical density:**

$$\rho_{\text{crit}} \sim 9.1 \times 10^{-30} \text{ g/cm}^3$$

- **measured density: ρ**

- recast as $\Omega \equiv \rho / \rho_{\text{crit}}$

- if $\Omega < 1$: expansion **continues forever**: universe is “open”

- if $\Omega > 1$: expansion **reverses**: universe is “closed”

- **Open (infinite) Universe:**

- infinite volume no true edge

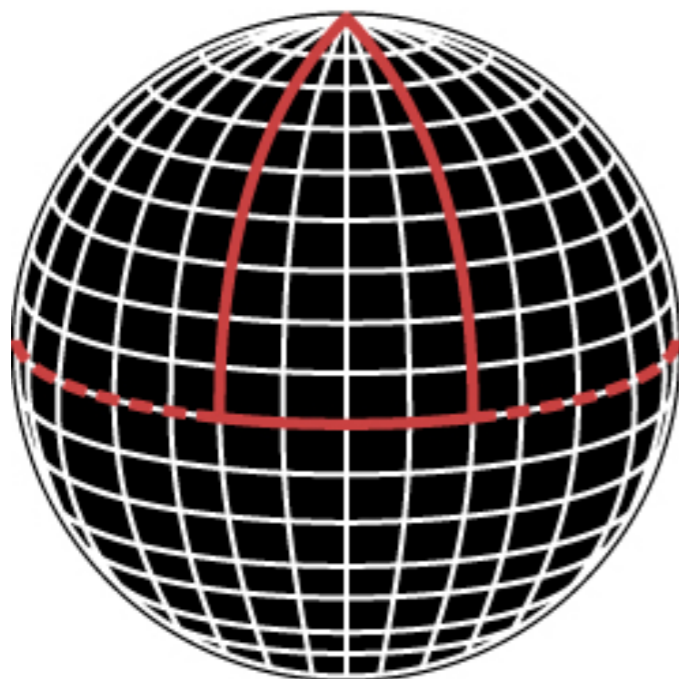
- **Closed (finite) Universe:**

- finite volume no true edge

- **Flat Universe:** density = critical density $\Omega = 1$

Three possible geometries for the Universe

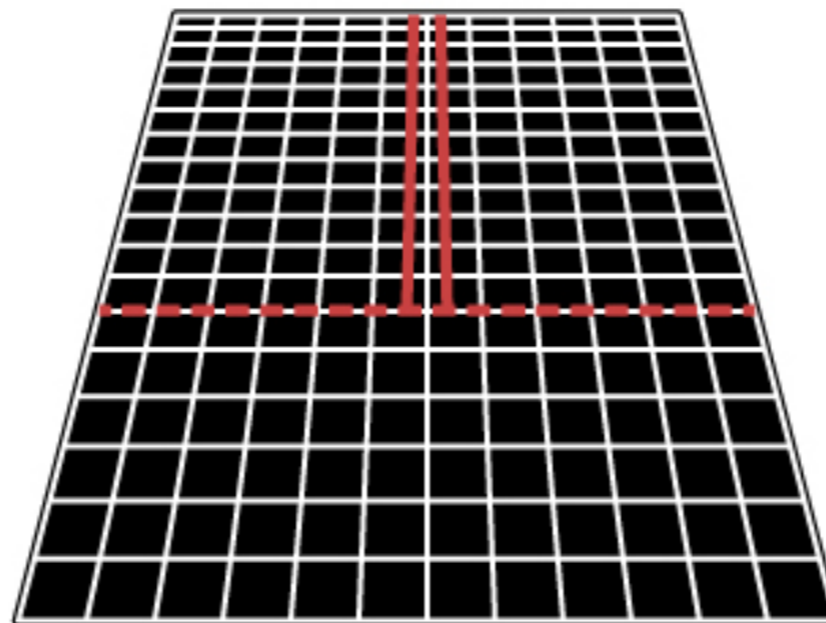
Spherical space



• Closed

$$\Omega > 1$$

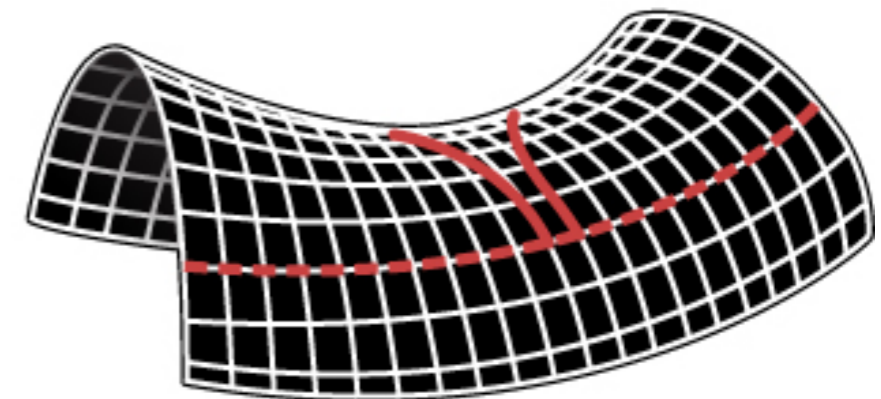
Flat space



• Flat

$$\Omega = 1$$

Hyperbolic space

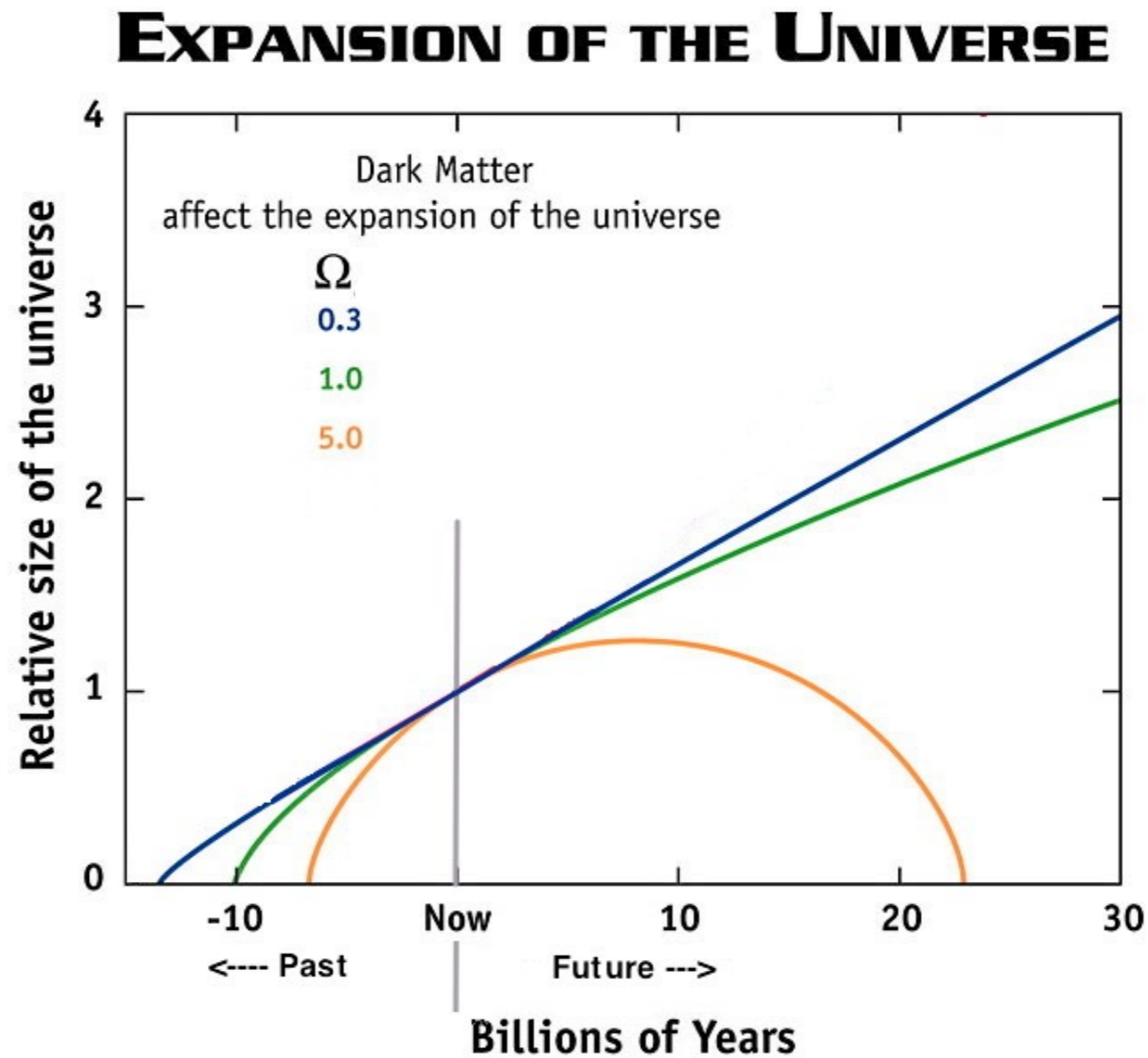


• Open

$$\Omega < 1$$

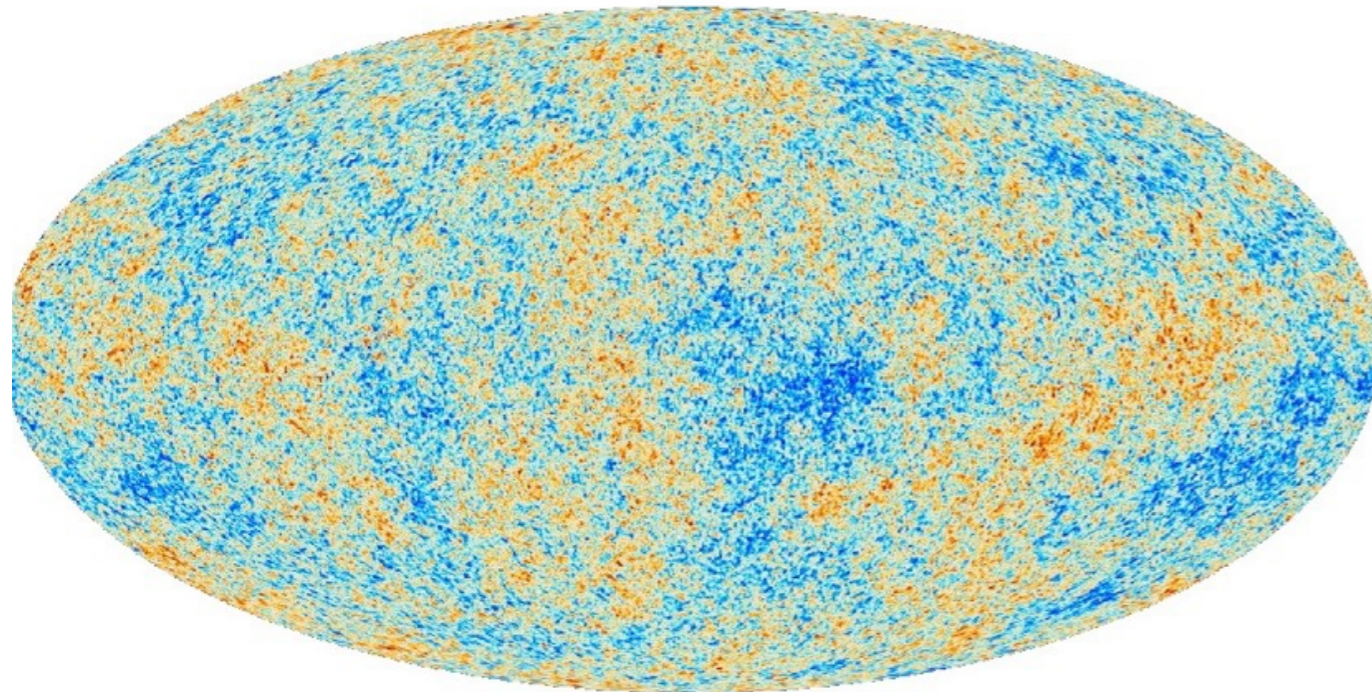
$$\Omega \equiv \rho / \rho_{\text{crit}}$$

How these different universes evolve



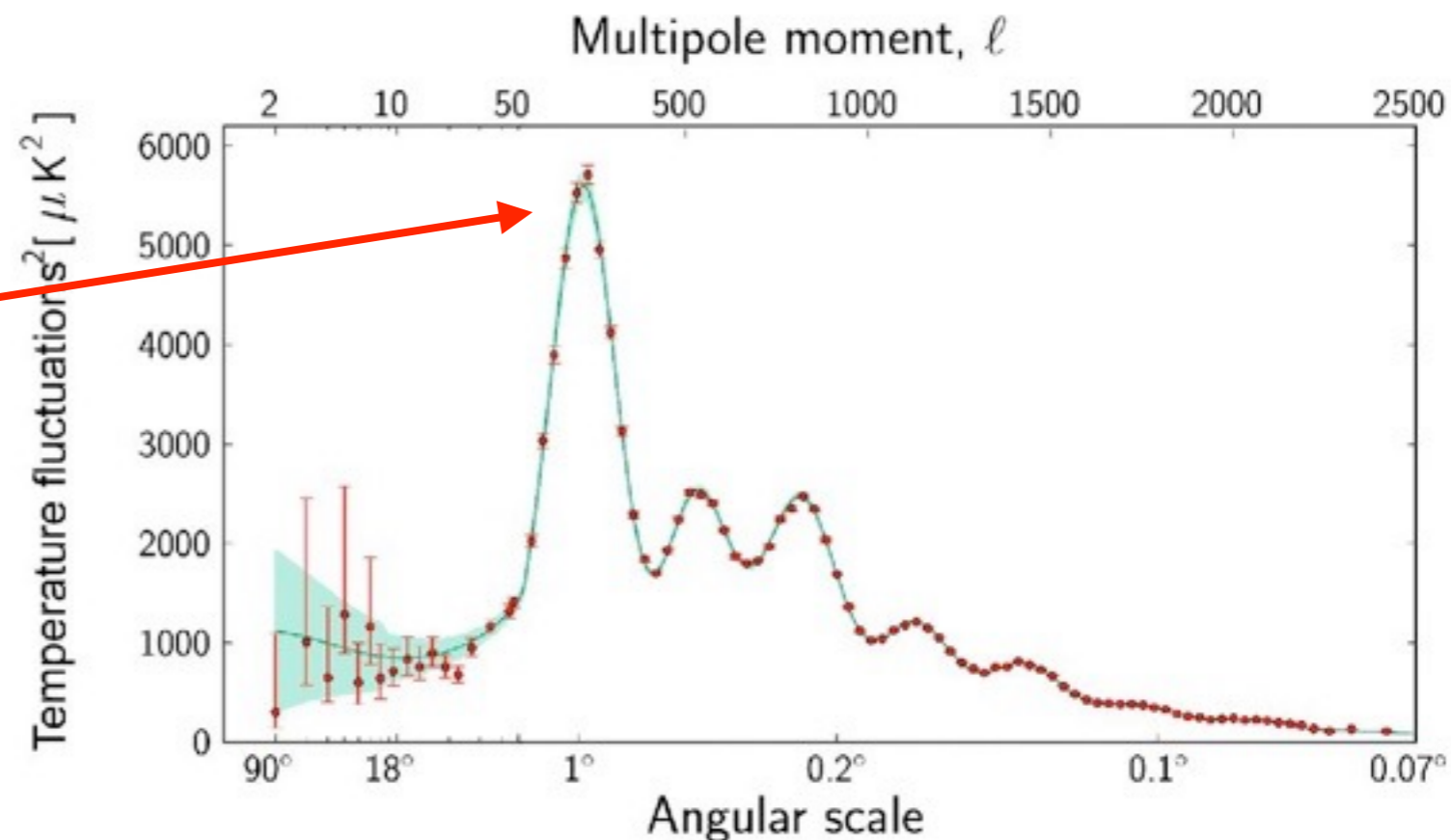
$$\Omega \equiv \rho / \rho_{\text{crit}}$$

Size of CMB fluctuations can tell us what type of Universe we live in

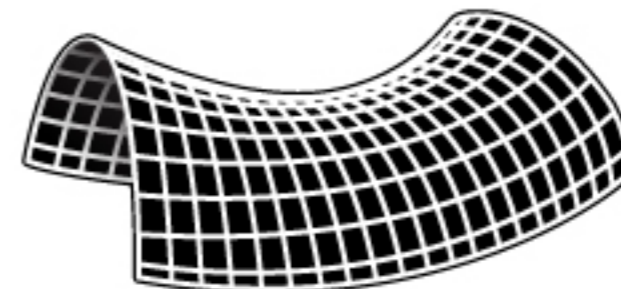
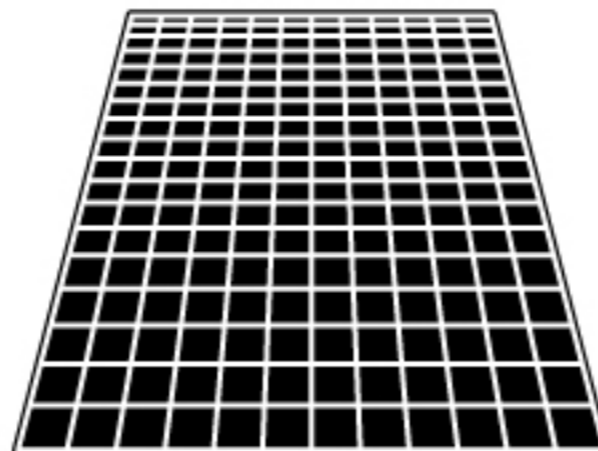
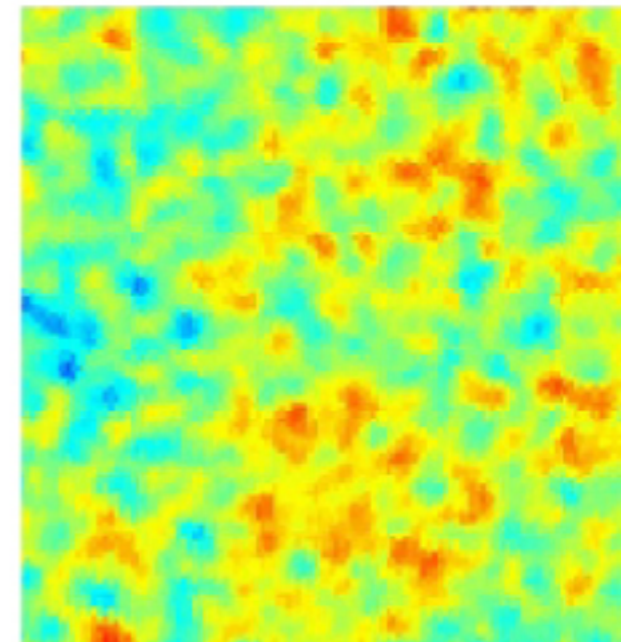
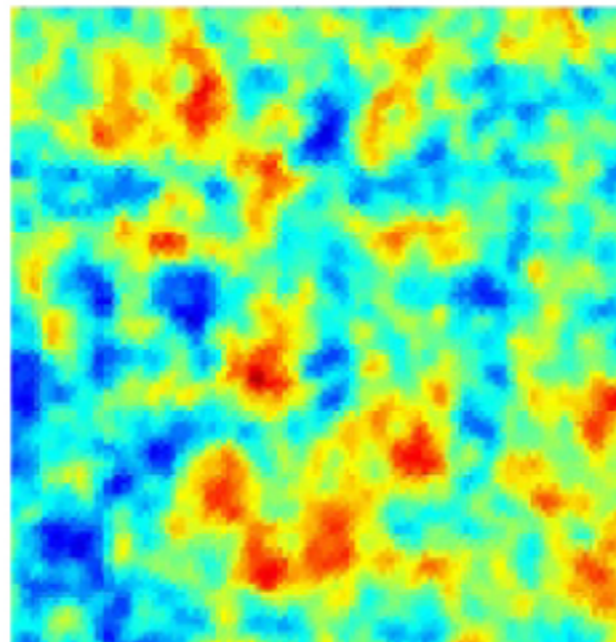
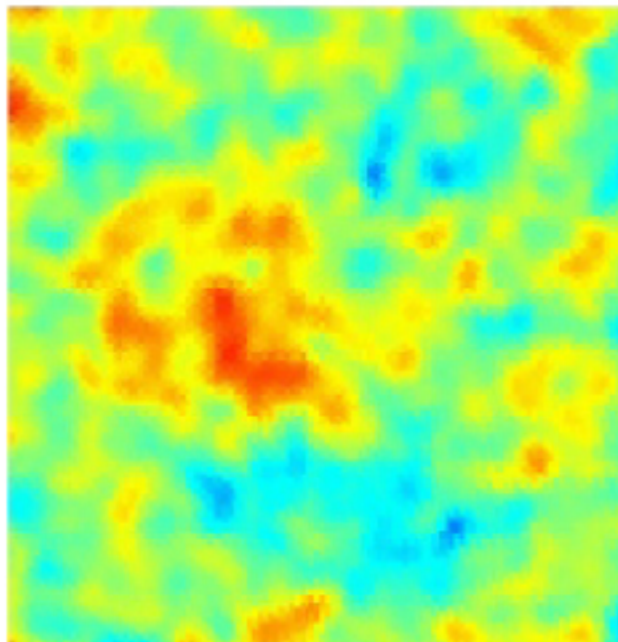
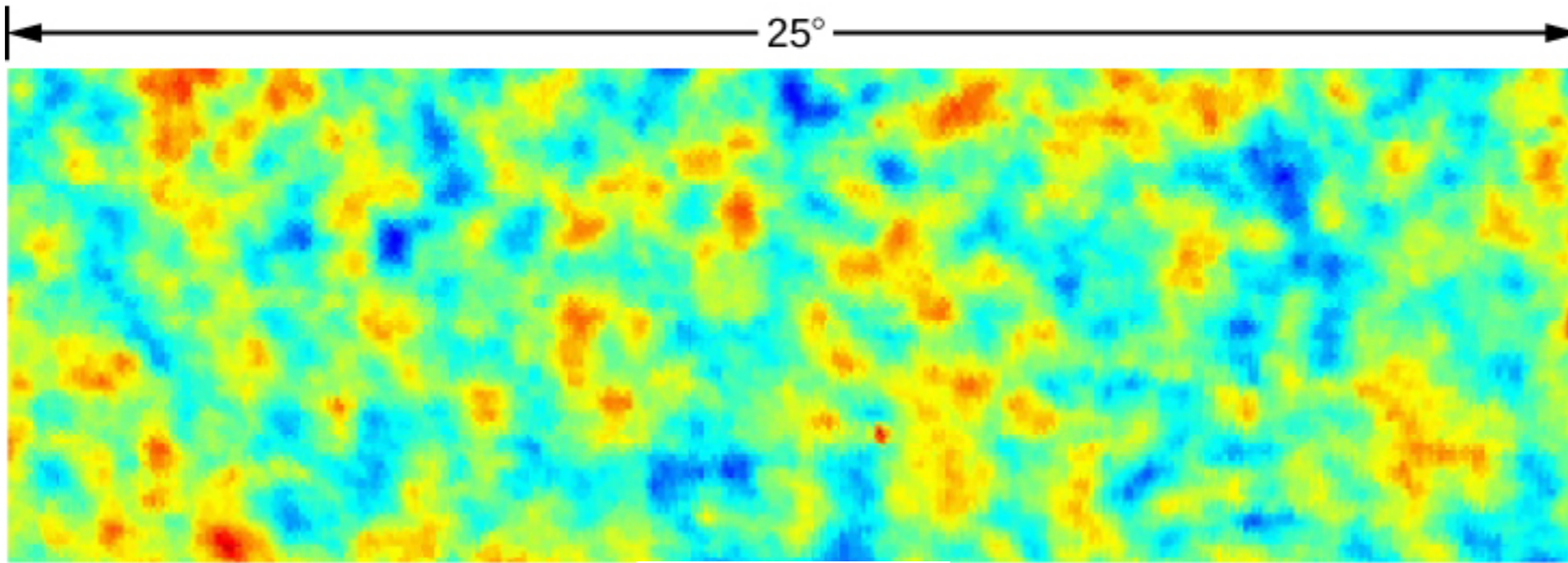


- The size of the cold and hot spots depends on the geometry of the Universe

- A size of $\sim 1^\circ$ means the Universe is flat!
- $\Omega = 1$

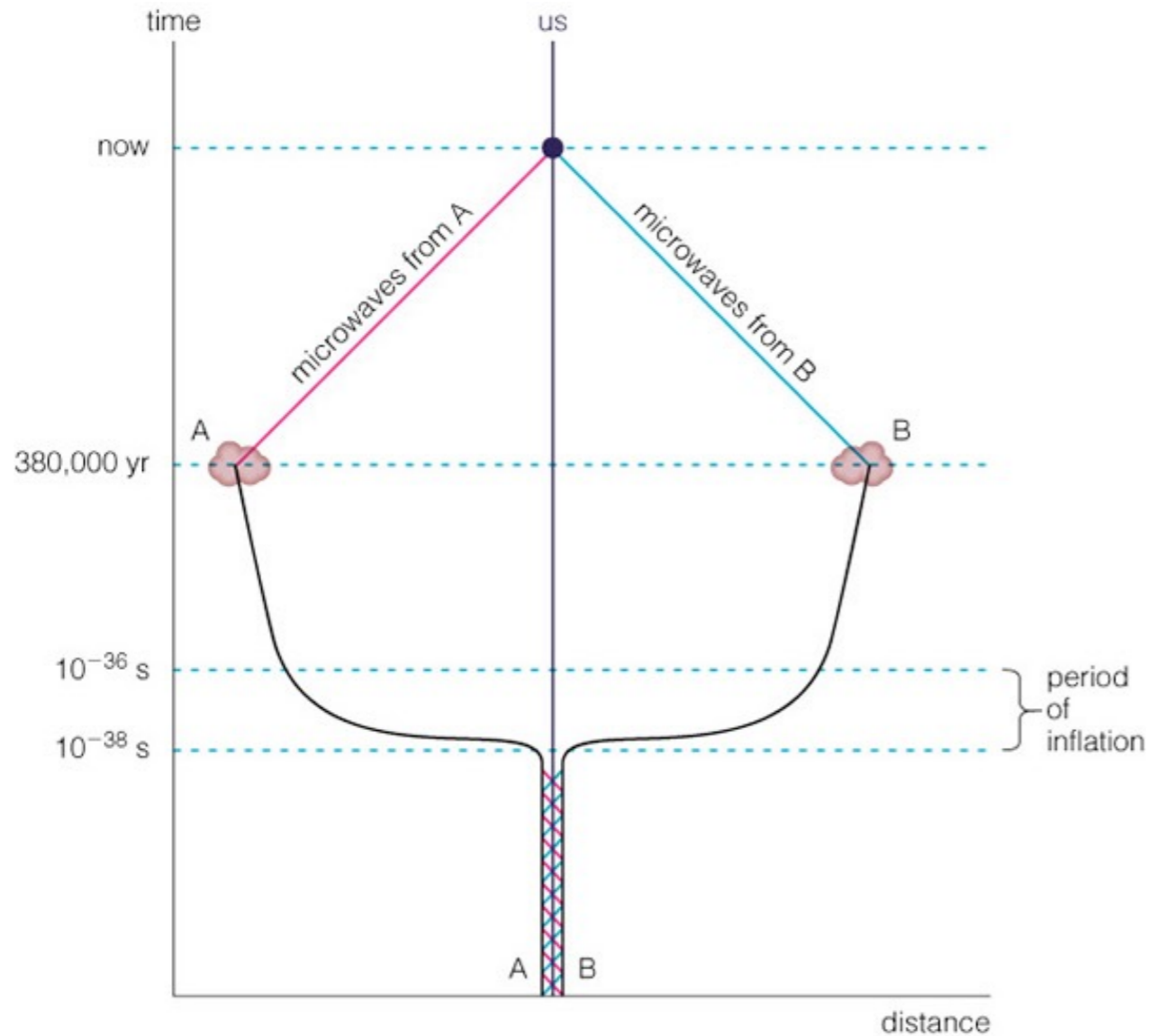


$$\Omega \equiv \rho / \rho_{\text{crit}}$$

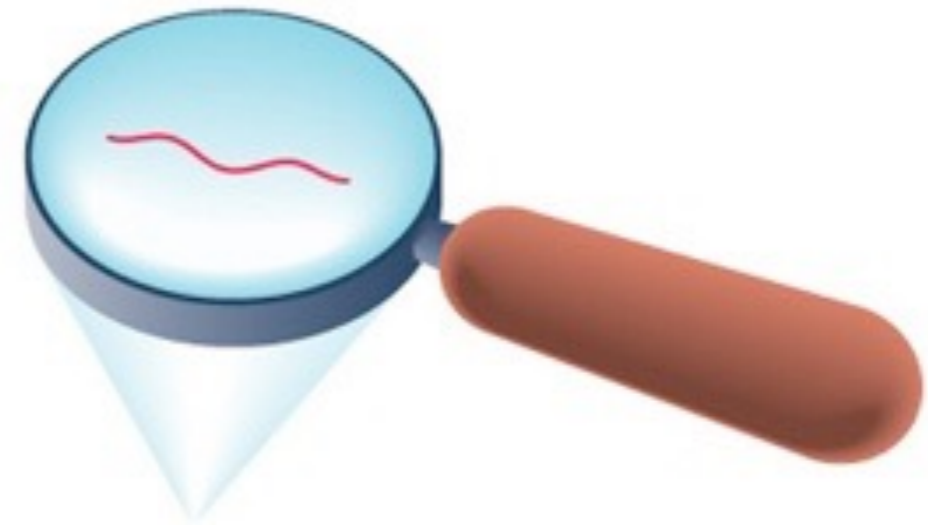


$$\Omega \equiv \rho / \rho_{\text{crit}}$$

Quick review of inflation



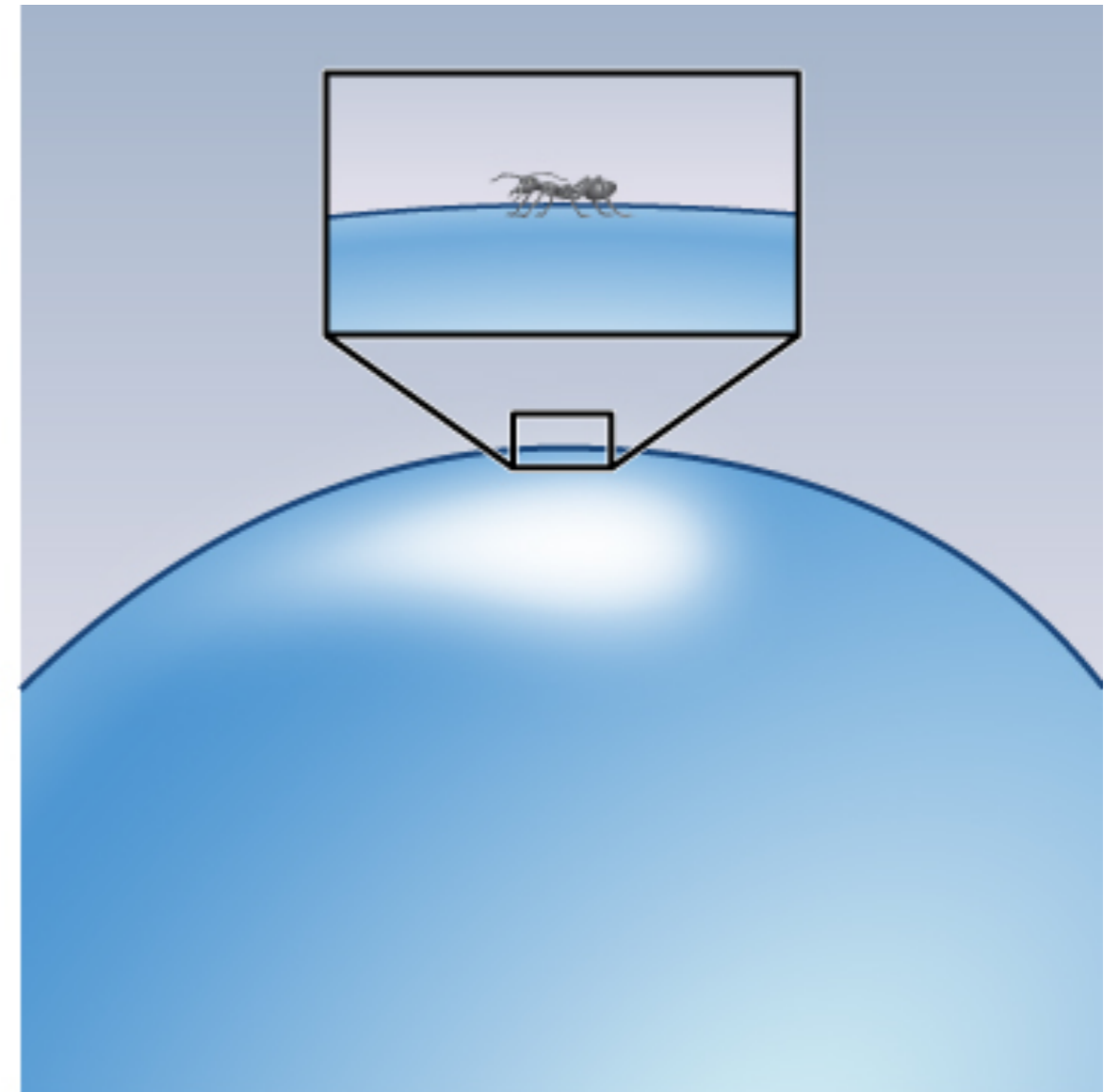
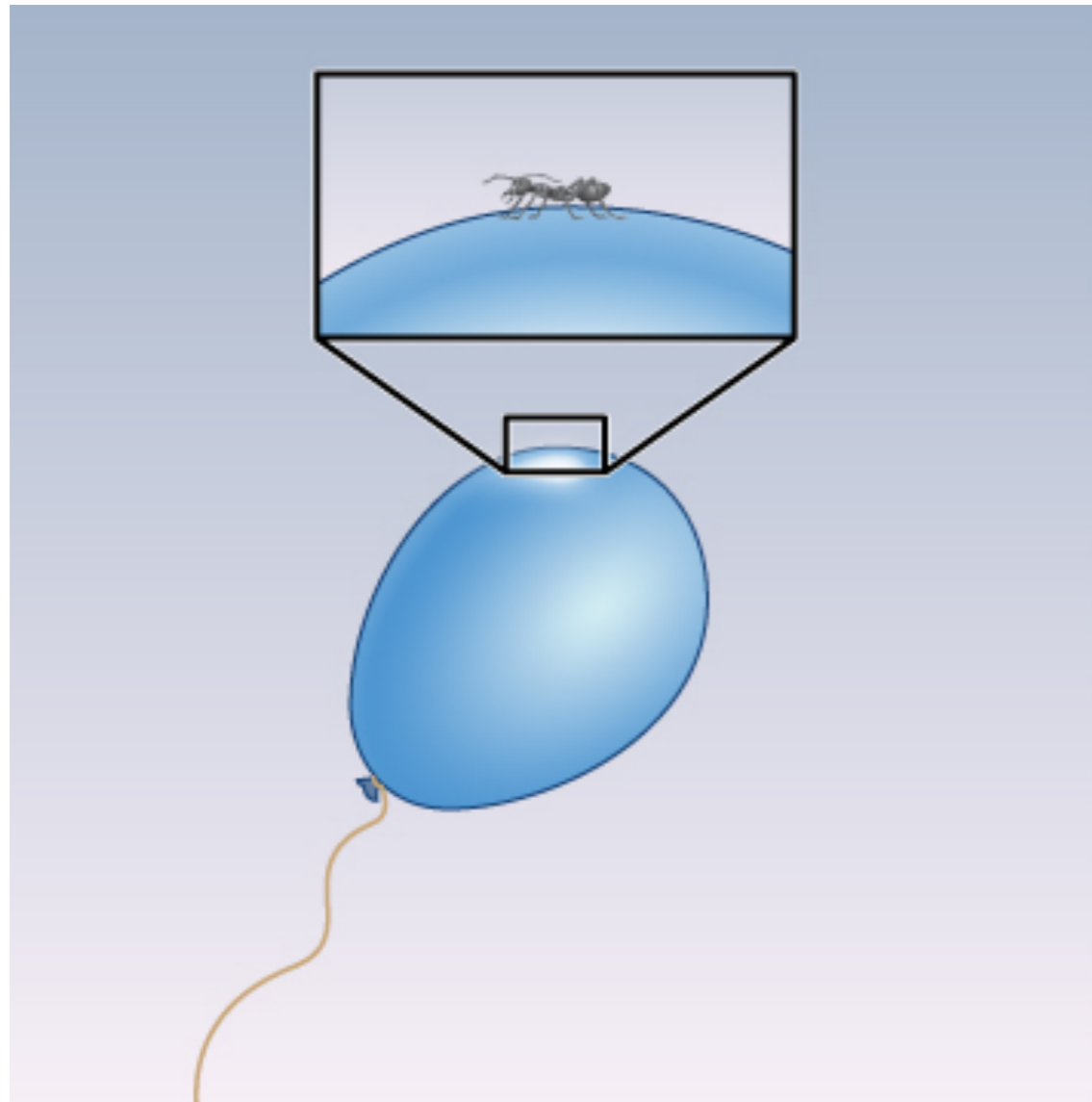
size of ripple before inflation = size of atomic nucleus



size of ripple after inflation = size of solar system

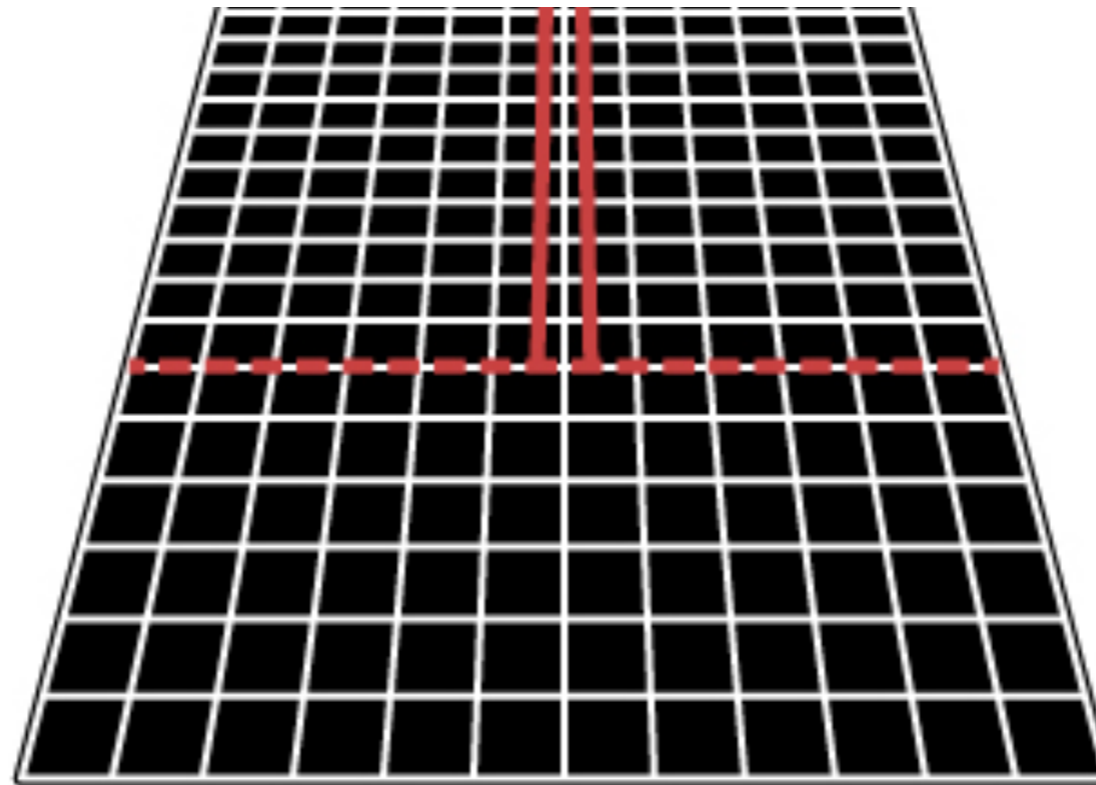


Inflation provides an explanation for this flatness



$$\Omega \equiv \rho/\rho_{\text{crit}}$$

Flat Universe



- Universe goes on forever — there is no physical edge (but still CMB represents an “observational edge”)
- $\Omega = 1$ implies that all matter and energy in the Universe must add up to equal a number VERY close to the critical density

$$\Omega \equiv \rho/\rho_{\text{crit}}$$

$$\Omega = \Omega_{\text{matter}} + \Omega_{\text{energy}}$$

Remember that $E = mc^2$



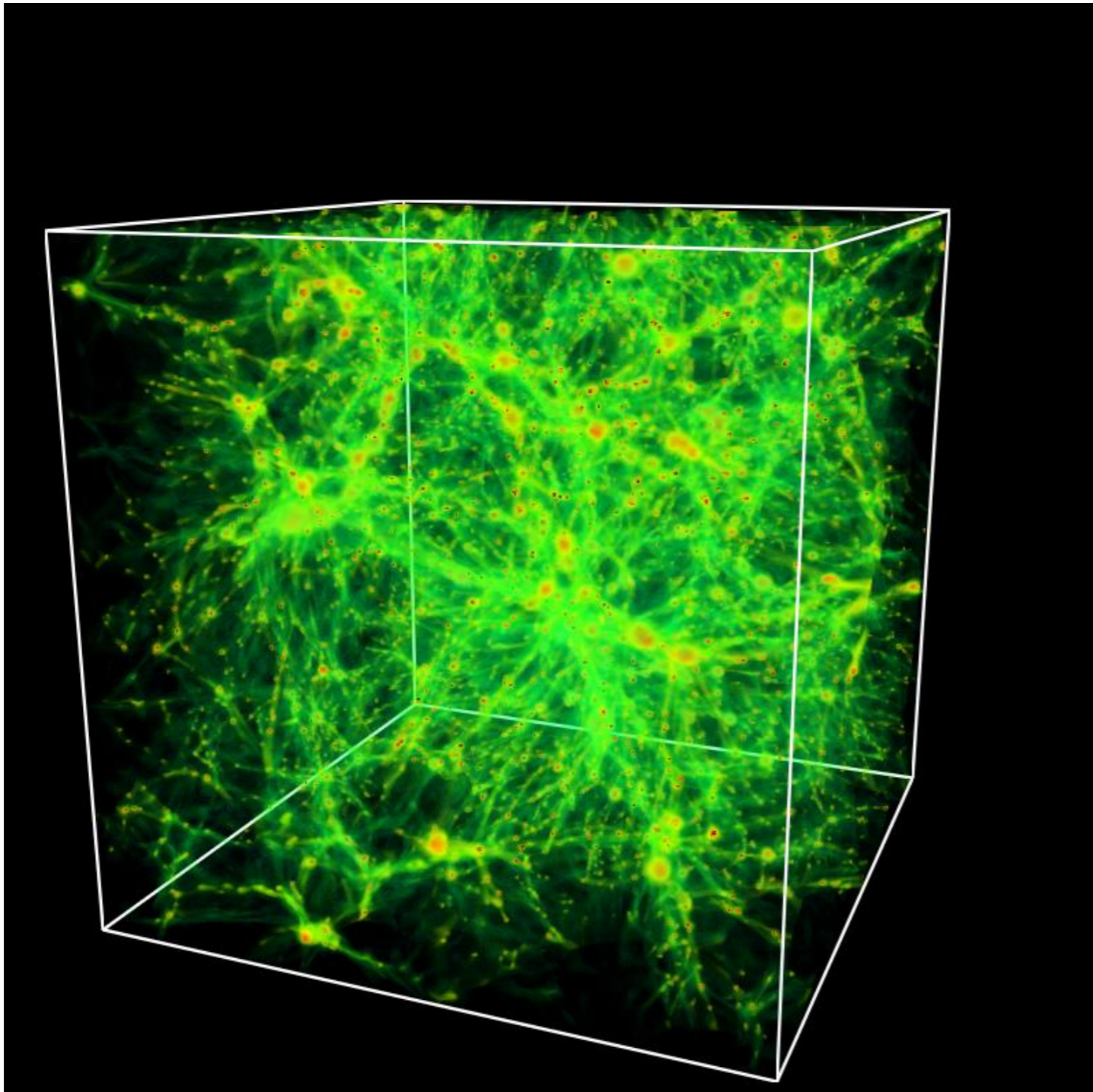
From Big Bang Nucleosynthesis, we know how much matter there should be

$$\Omega_{\text{matter}} < 0.1$$

- But if we add up all the luminous matter in stars and galaxies, we get

$$\Omega_{\text{luminous matter}} < 0.01$$

There is a LOT of mass in intergalactic (and interstellar) gas



- While the density of this gas is very low, the amount of space that it takes up is *tremendous*
- $\Omega_{\text{gas matter}} = 0.04$
- $\Omega_{\text{baryonic matter}} \approx 0.05$

All baryonic matter only makes up 5% of the total Universe!!!

Adding in dark matter...



- There is a lot of matter that we can't see (dark matter)
- $\Omega_{\text{baryonic matter}} = 0.05$
- $\Omega_{\text{dark matter}} = 0.27$

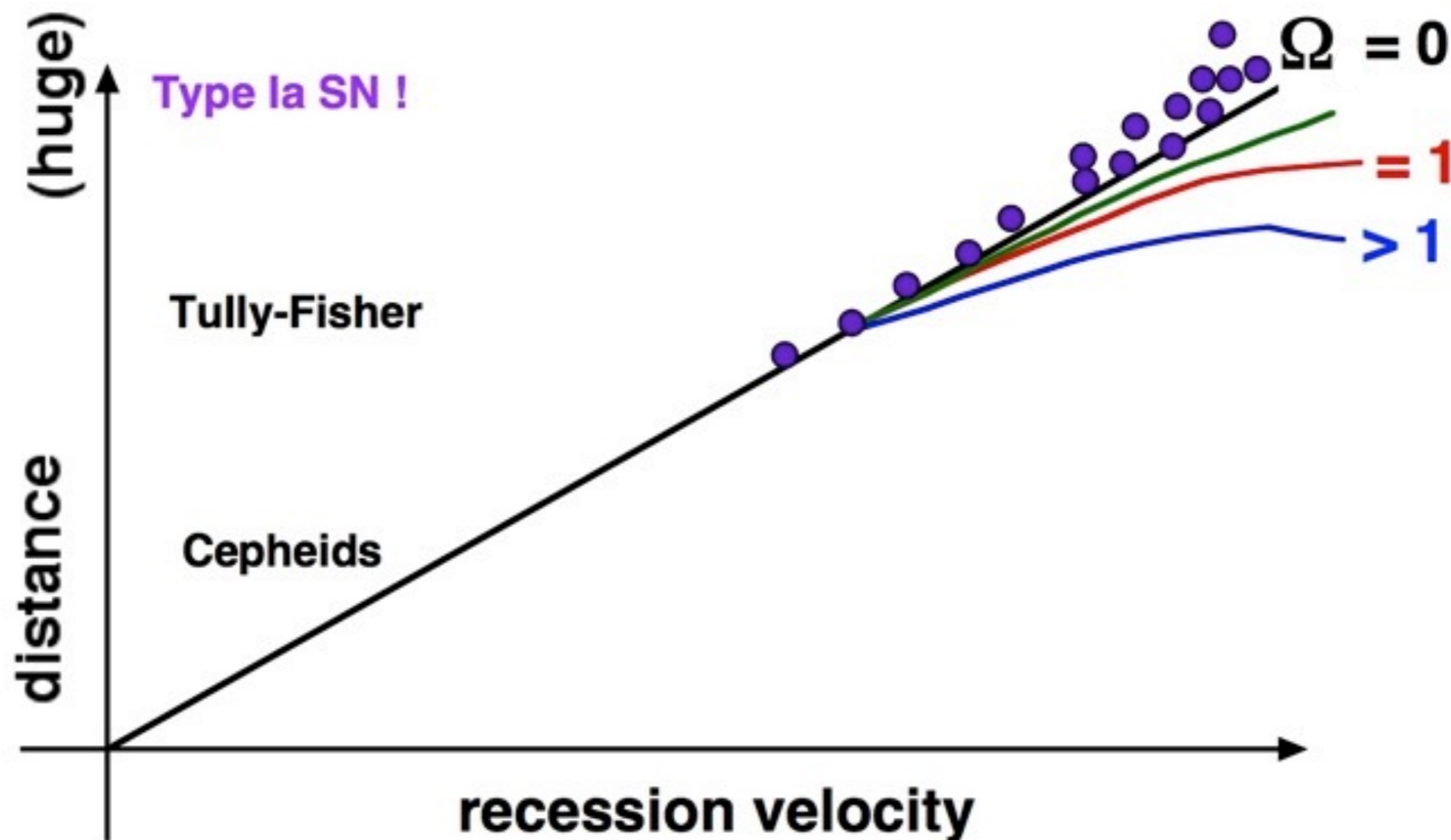
All matter is only ~32% of the critical density of the Universe, but $\Omega = 1$

For a long time, the fate of the Universe was unknown

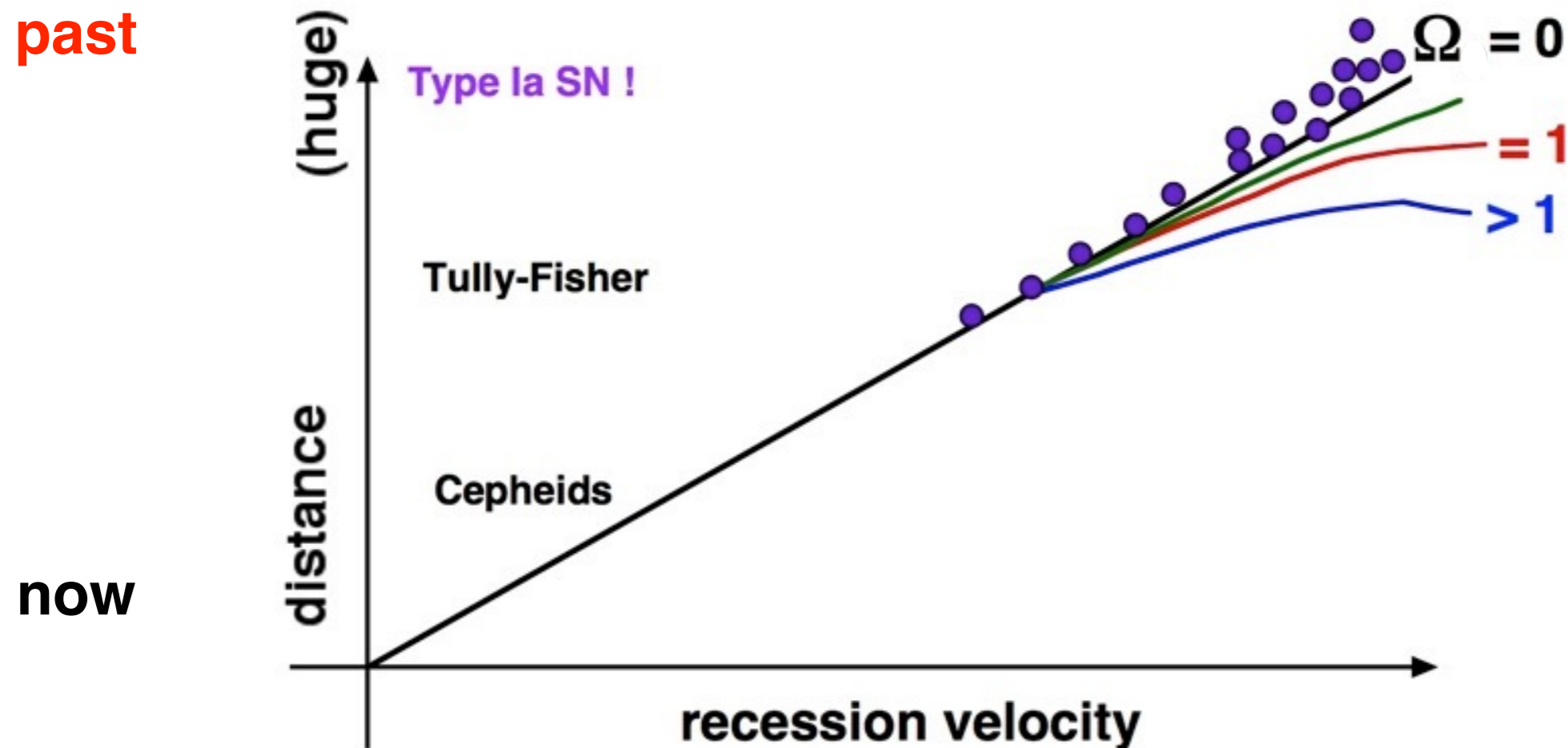
- Would there be a Big Crunch?
- Would the Universe just continue to expand forever?



In the late 1990s, a team set out to measure the Hubble constant



Type 1a Supernovae



- expansion in past was **slower** than any prediction
- universe has accelerated compared with expectations
- conclusion: Ω has a **non-gravity** part
- “**dark energy**” helping push the expansion (?)

Universe's expansion is *accelerating!*



Photo: Lawrence Berkeley National Lab

Saul Perlmutter



Photo: Belinda Pratten, Australian National University

Brian Schmidt



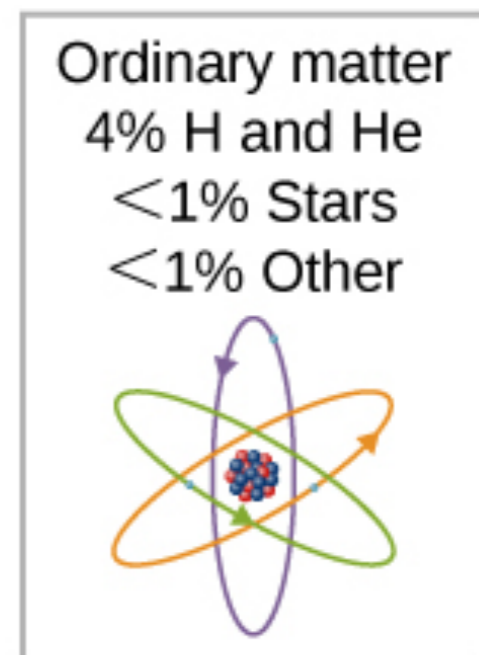
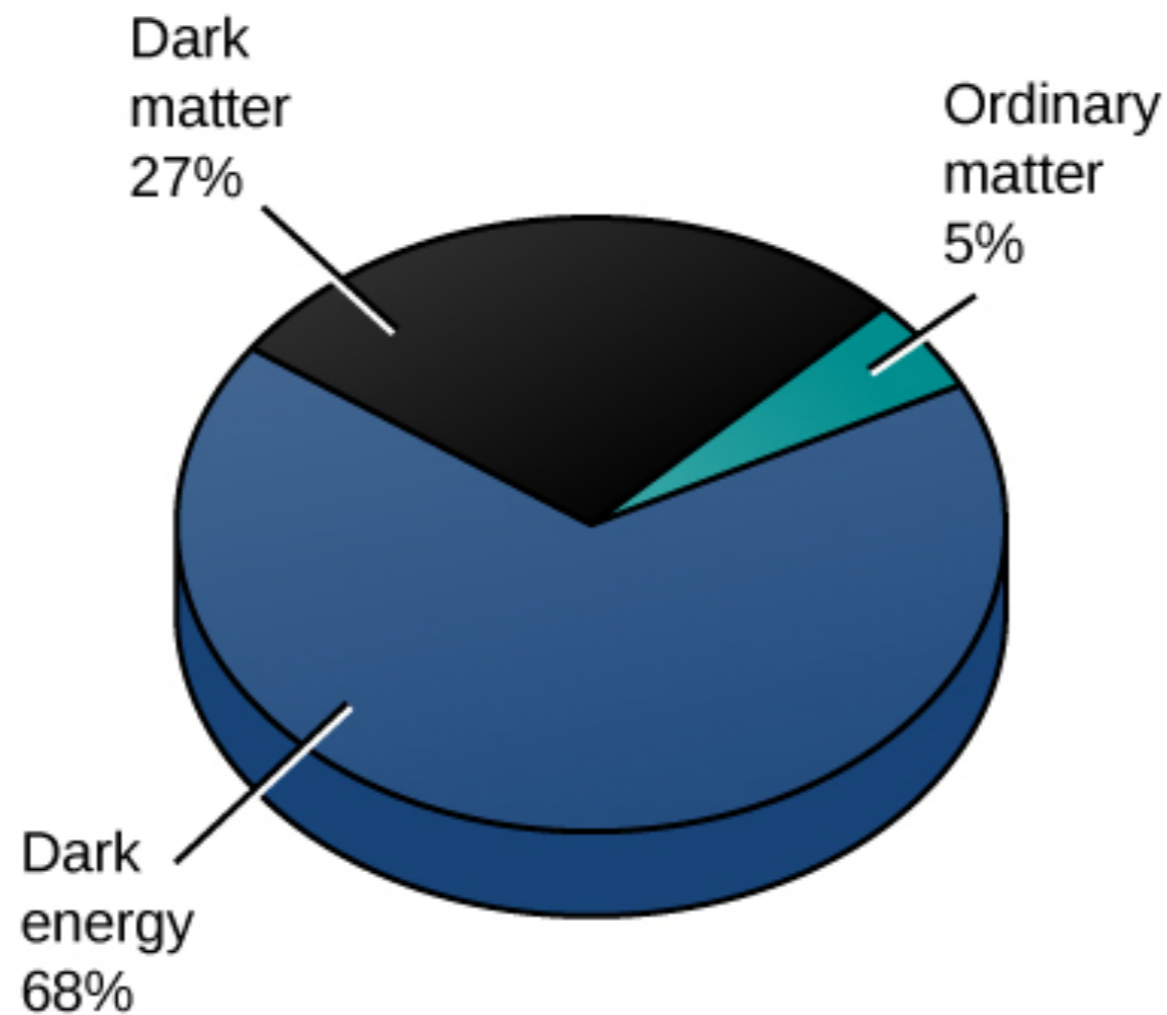
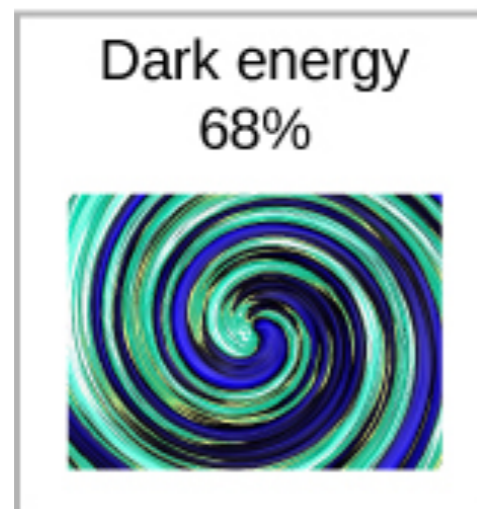
Photo: Scanpix/AFP

Adam Riess

2011 Nobel Prize in Physics

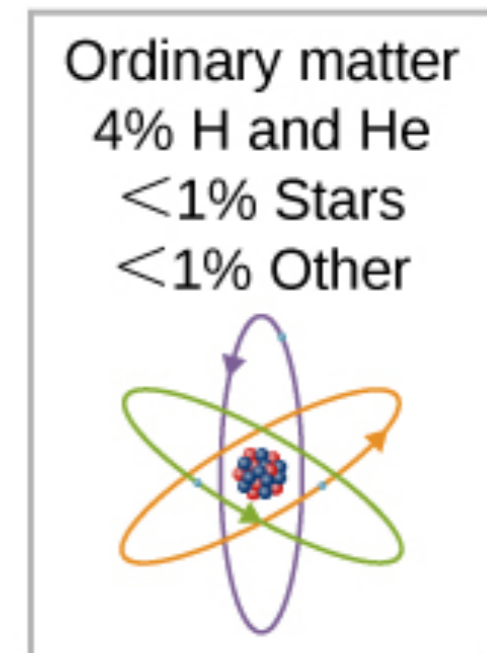
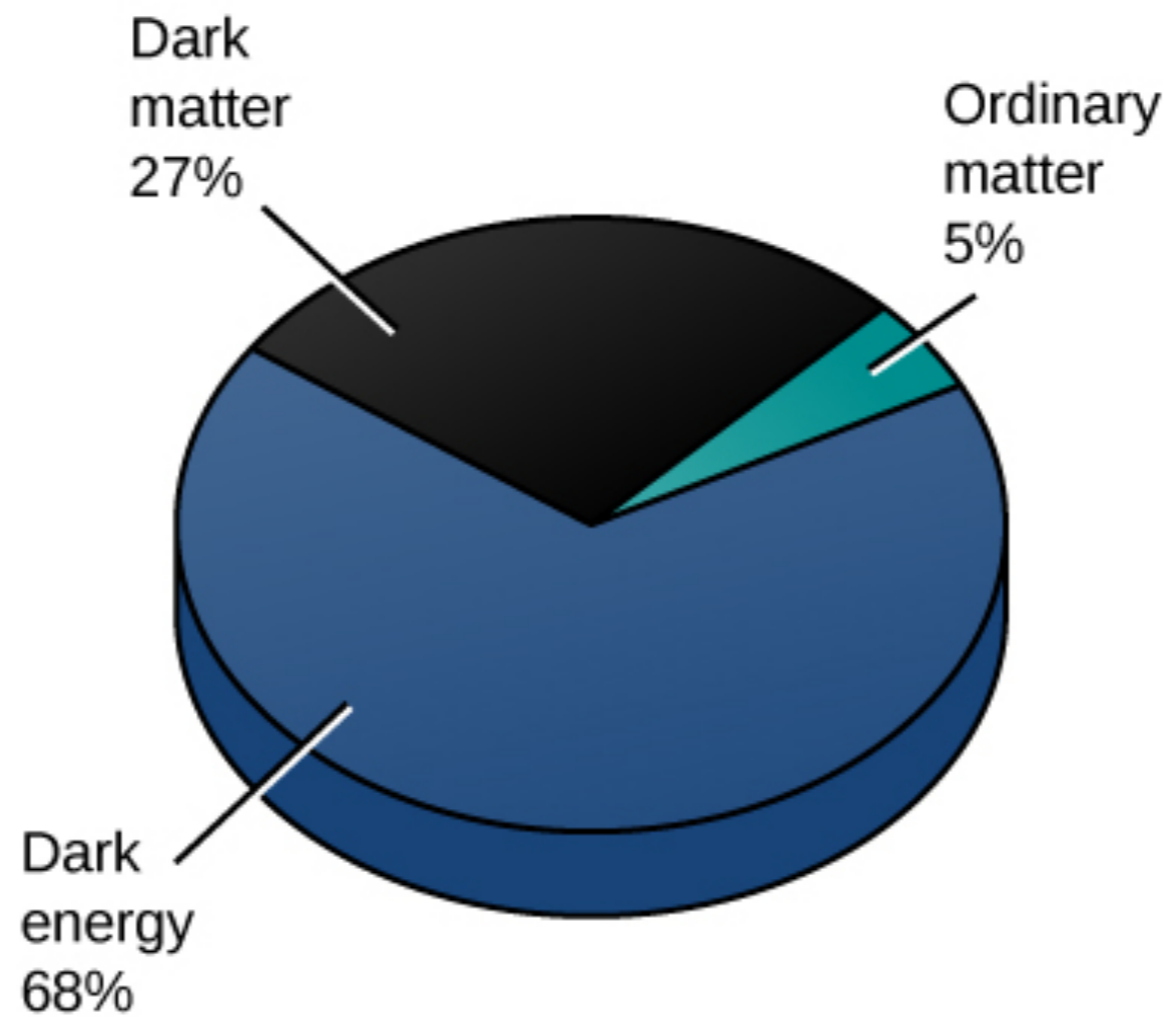
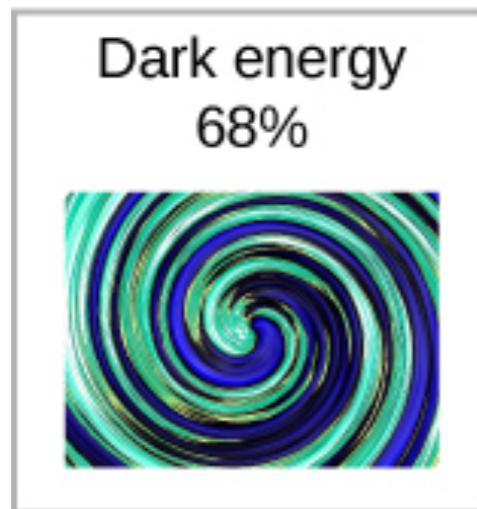
The rest of the mass/energy in the Universe is due to some anti-gravity type “stuff” called dark energy

Composition of the Universe



Everything that we can see only makes up 5% of the Universe!!!!

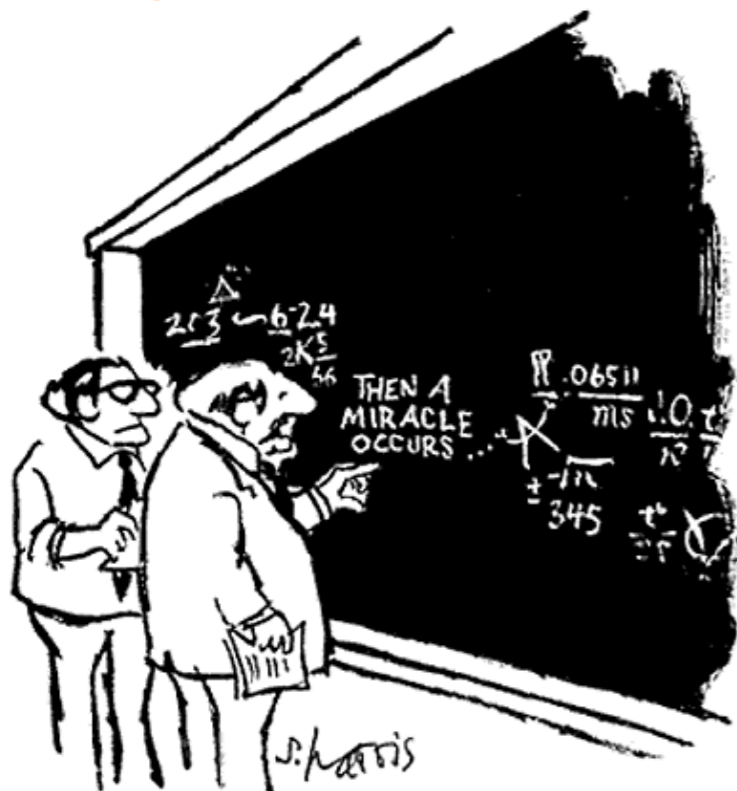
Composition of the Universe



So, what is this dark energy?

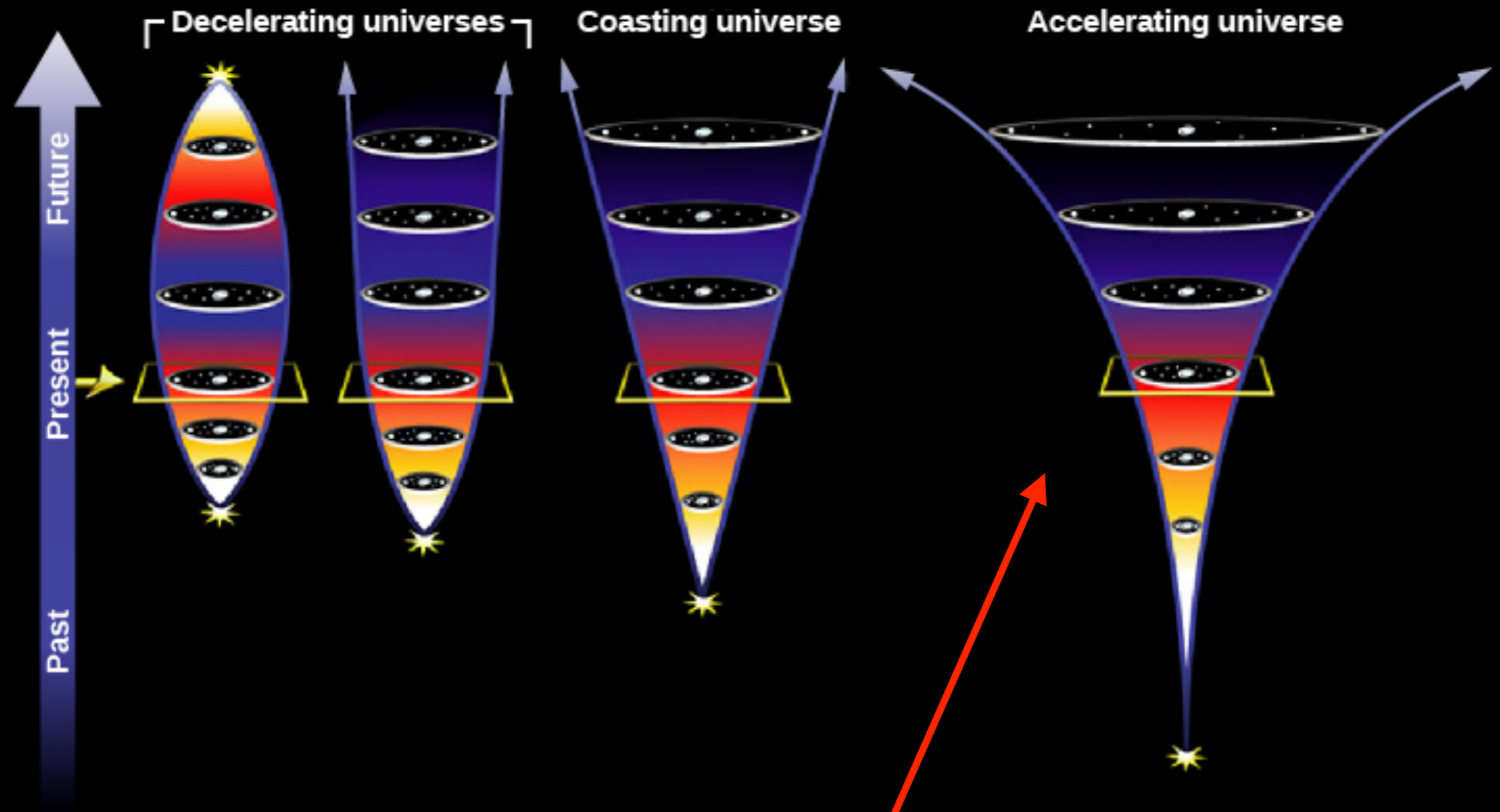
We don't yet know, but some possibilities...

- Empty space itself has its own form of energy: the cosmological constant!
- Quantum energy (particles continually forming and annihilating)
- Some new kind of energy fluid or field (yes, the vagueness of this statement reflects our lack of understanding!)
- Maybe our understanding of gravity (GR) isn't yet complete



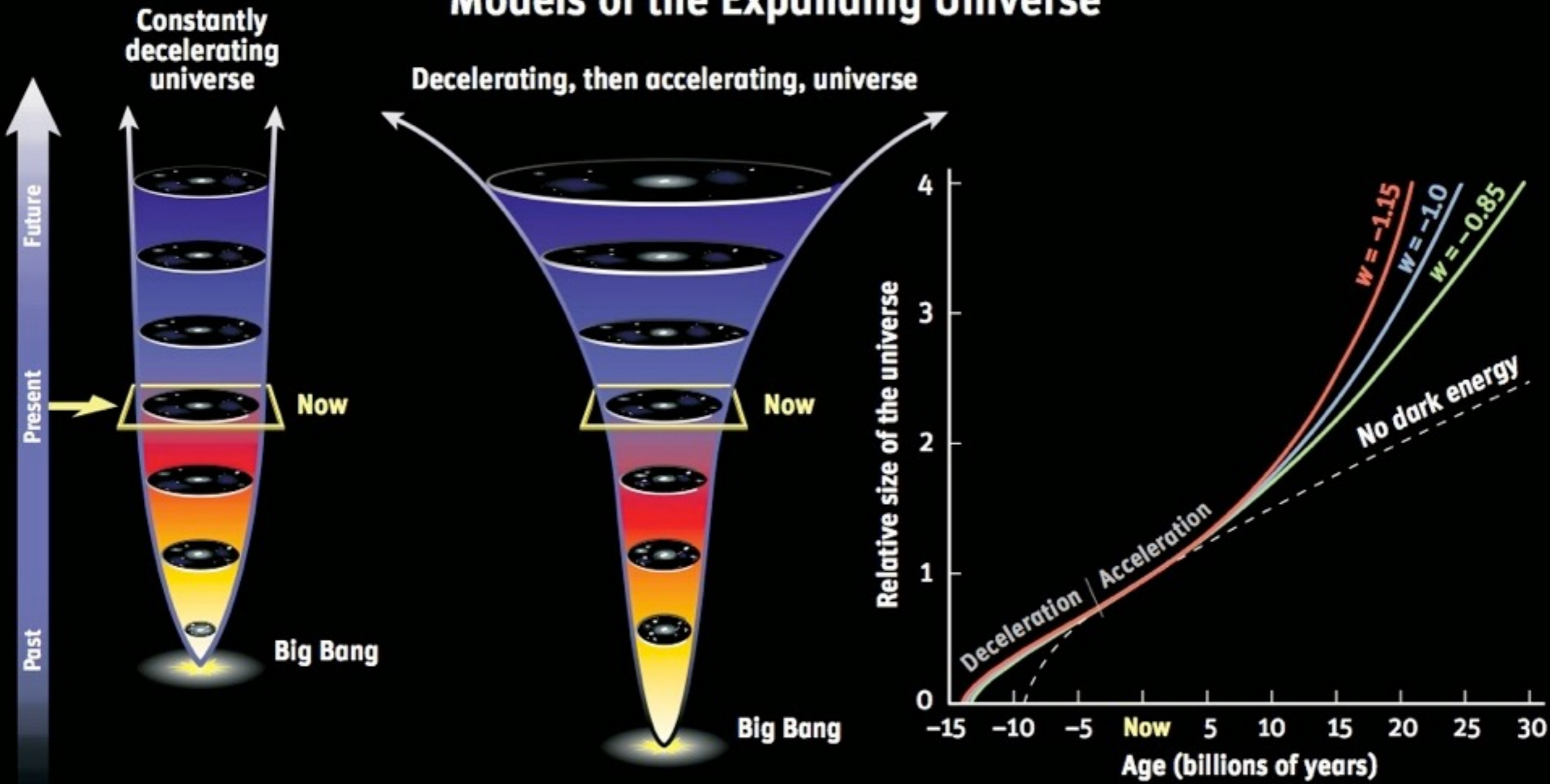
"I think you should be more explicit here in step two."

Models for evolution of the Universe

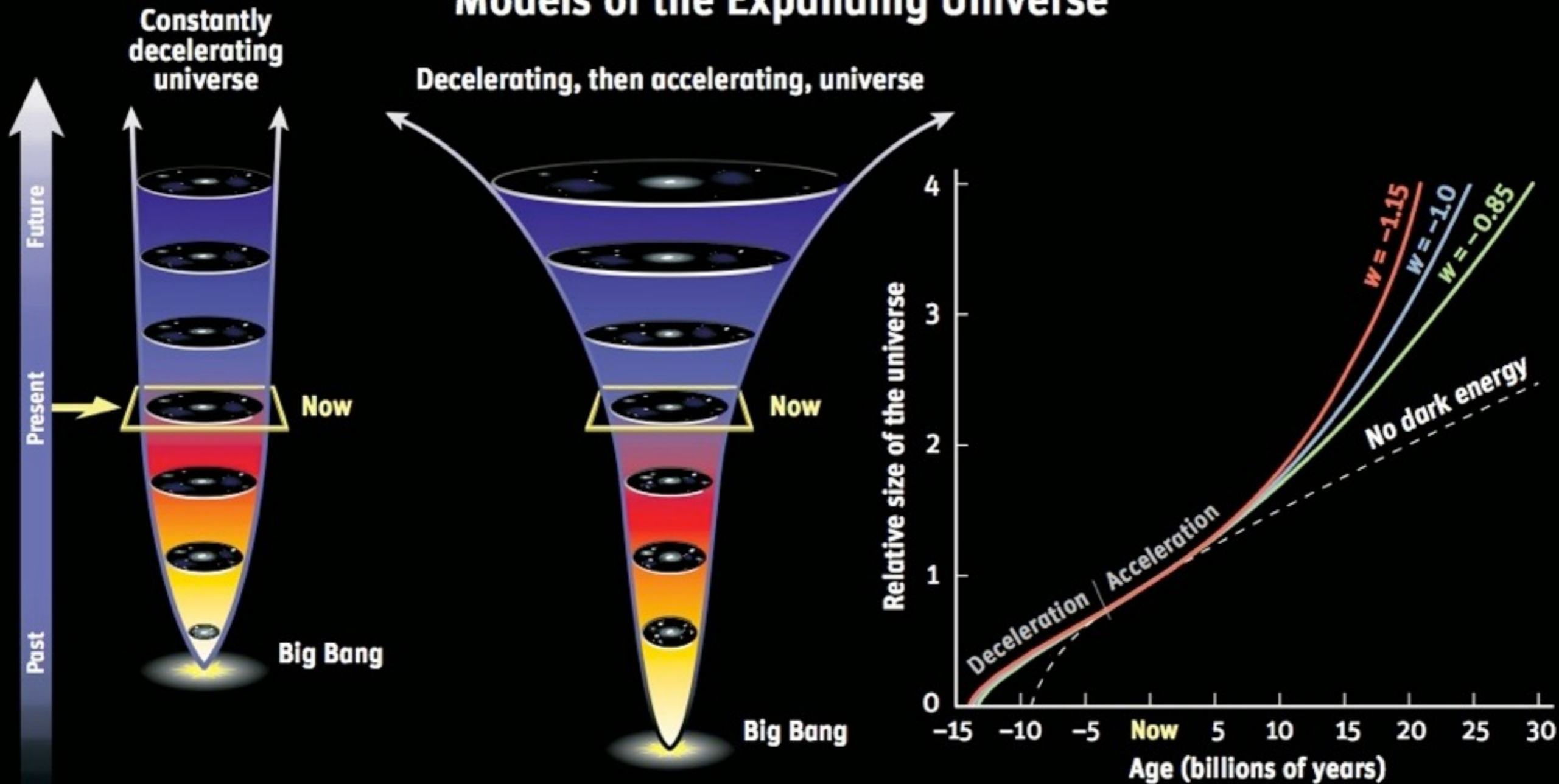


Appears to be the currently favored model

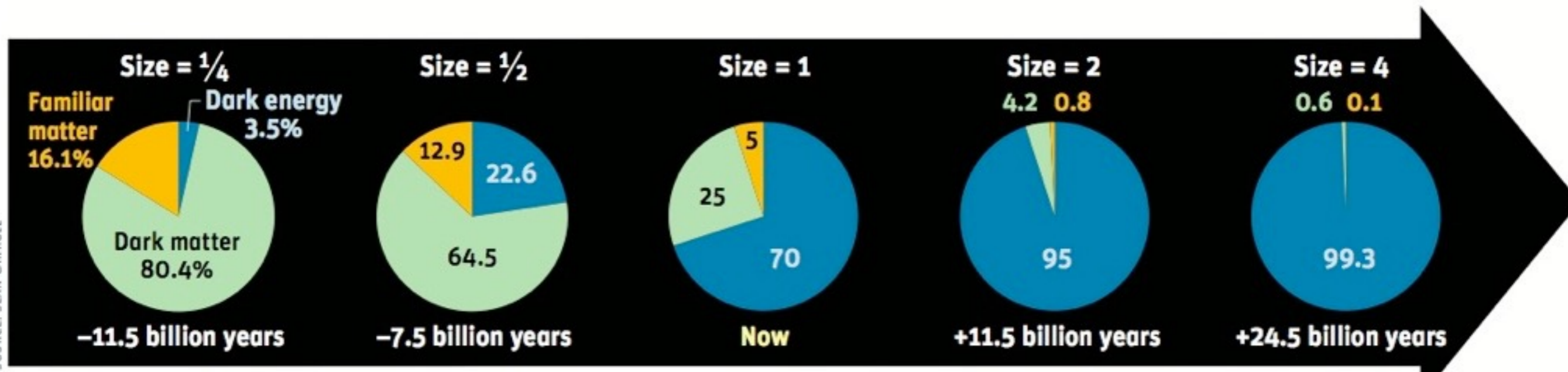
Models of the Expanding Universe



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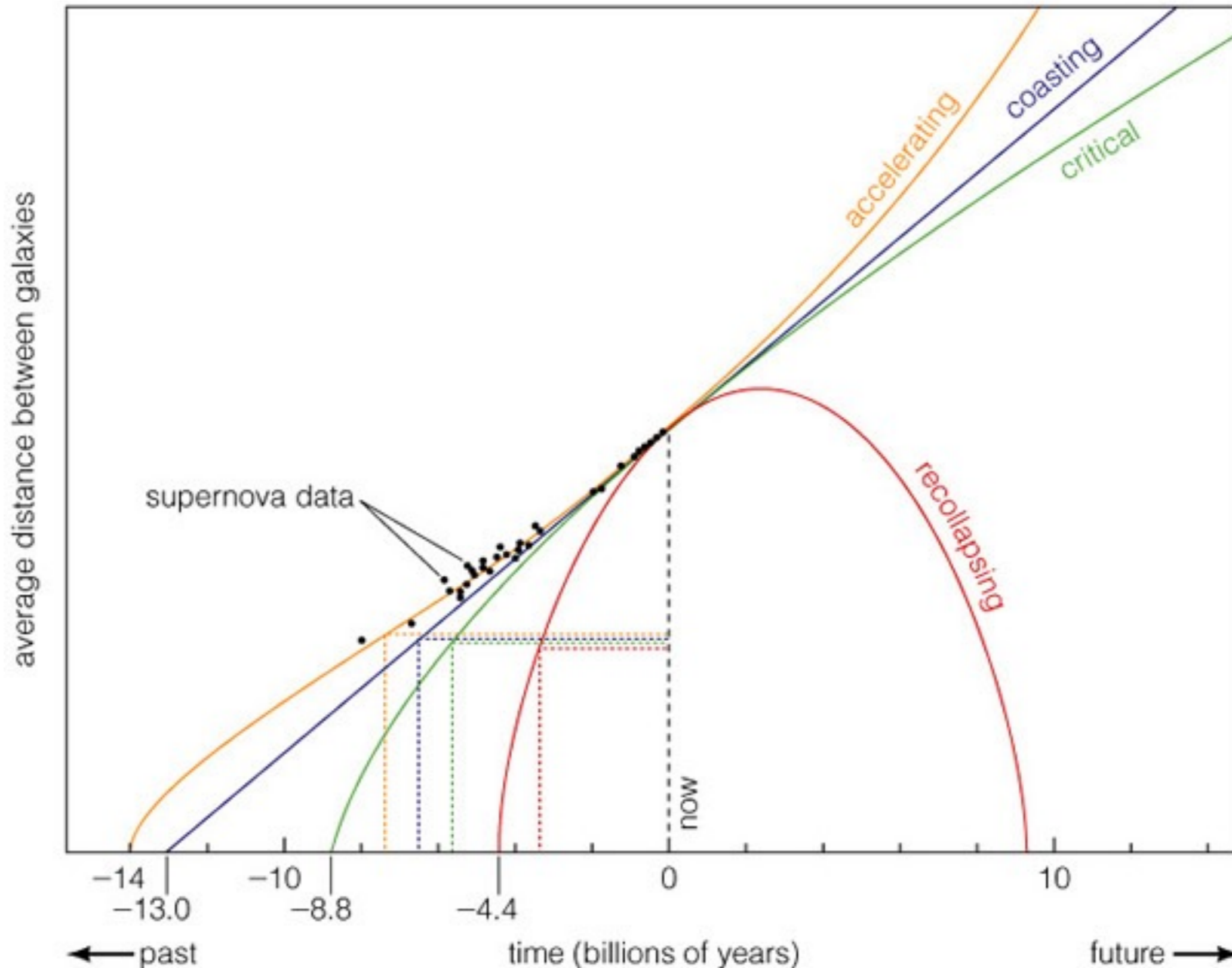


S&B: GREGG DINDERMAN. SOURCE: NASA / STSCI / SEAN CARROLL

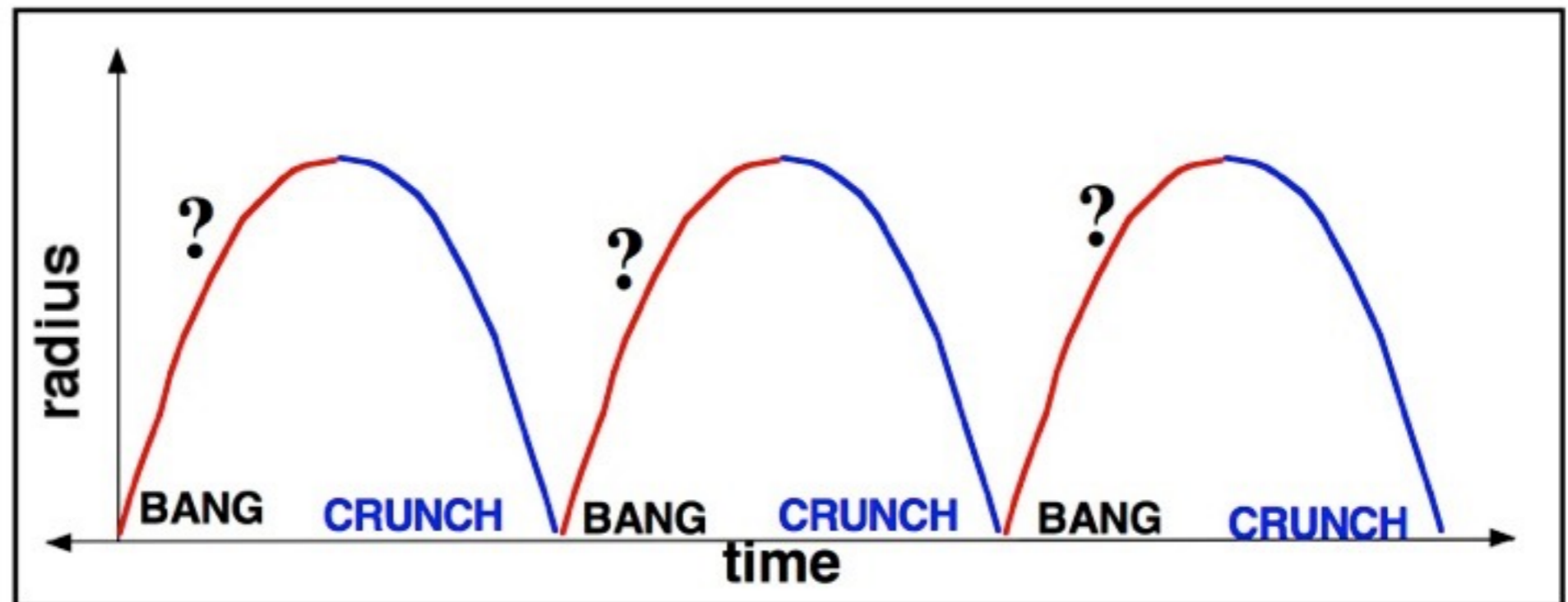
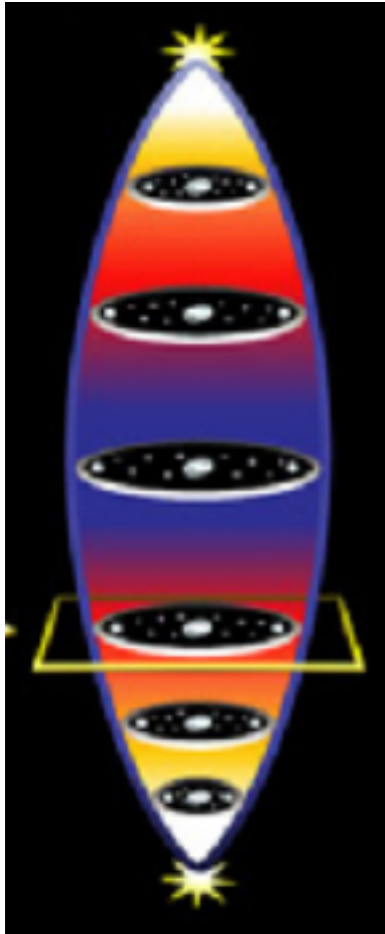


SOURCE: SEAN CARROLL

SN data only shows so much — maybe the Universe will surprise us yet again...



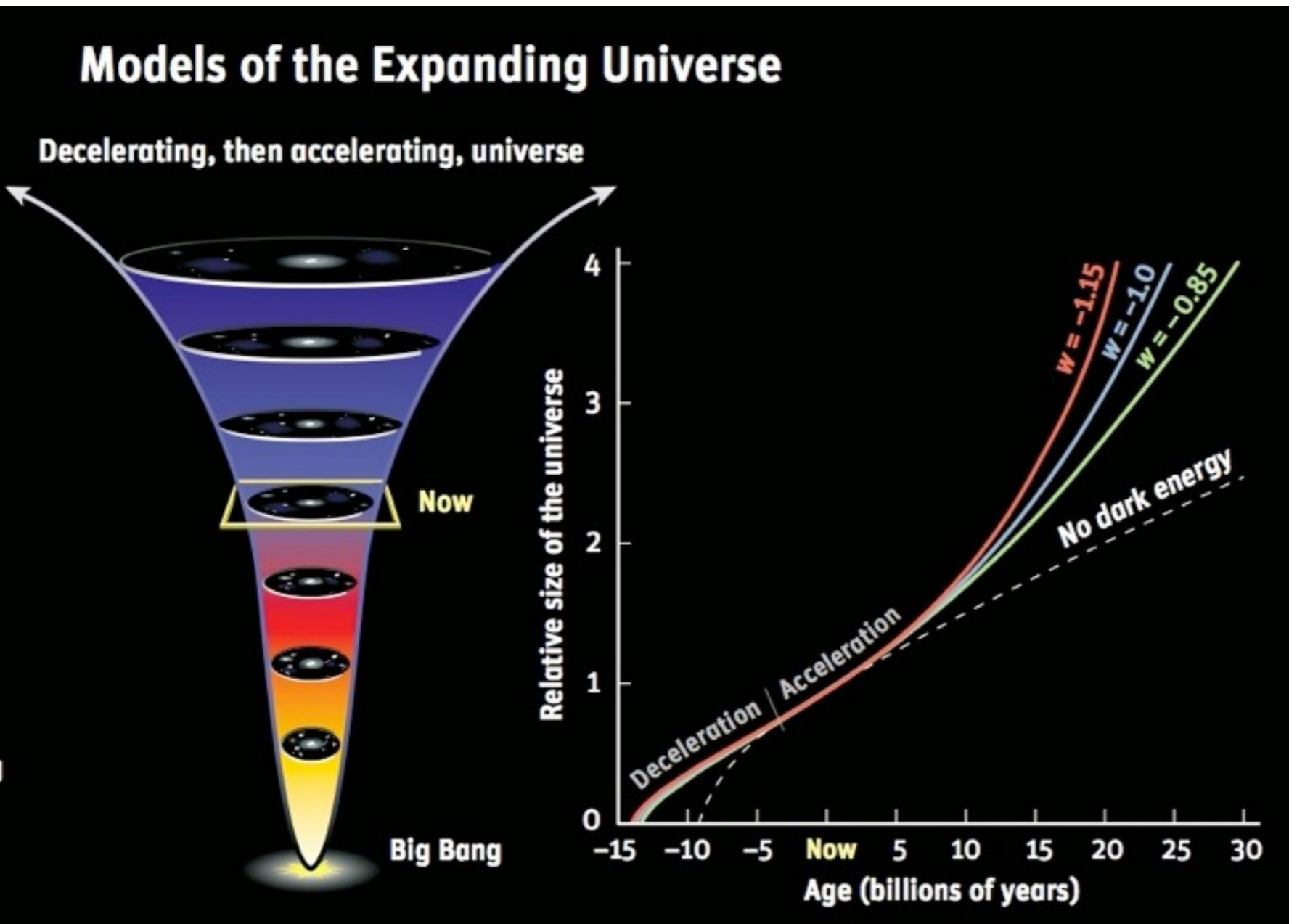
Alternate Universe possibilities



The “Oscillating” Universe

The Universe could oscillate between Big Bangs and Big Crunches

The Big Rip



- If $w < -1$, then as the Universe expands, the amount of dark energy per volume increases!
- Eventually, galaxies, stars, planets, and even atoms would be ripped apart!
- But current data suggests $w = -1$ (i.e., no Big Rip)

The most likely extrapolation (though still an extrapolation!)

- Clusters of galaxies will spread further apart over time
- All stars will eventually die (even the low mass ones that live for trillions of years)
- White dwarfs will cool into black dwarfs
- Pulsars will stop spinning and slowly cool down as well
- Black holes will consume the remainder of their gas and “shut off”
- Overall, things will slowly fade into darkness and cold (yikes!)
- But remember — this is still speculation! Science is always a progress report!

Final summary of Cosmology

