The Beginning & End of the Universe

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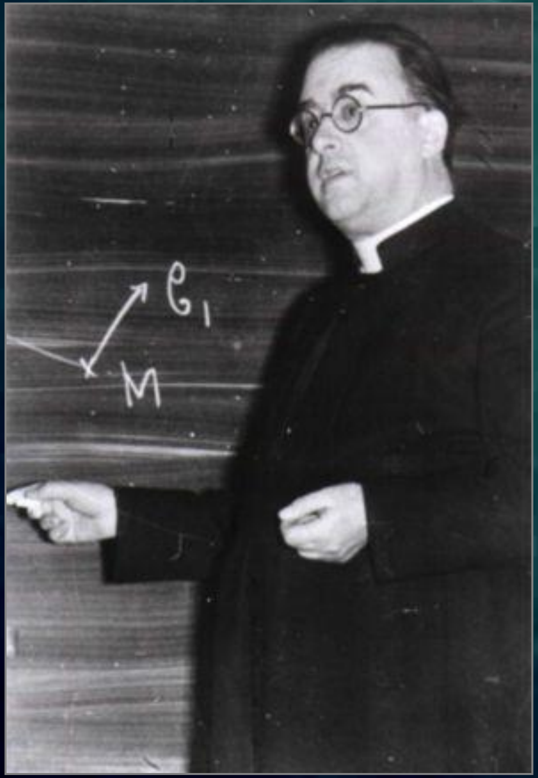
What is cosmology?



The evolution of the world can be compared to a display of fireworks that has just ended; some few red wisps, ashes and smoke. Standing on a cooled cinder, we see the slow fading of the suns, and we try to recall the vanishing brilliance of the origin of the worlds.

Father G. Lemaitre

Many cultures have similar questions…

- Has the cosmos existed forever or did it have a beginning? If so, how old is it?

Now we also want to know:

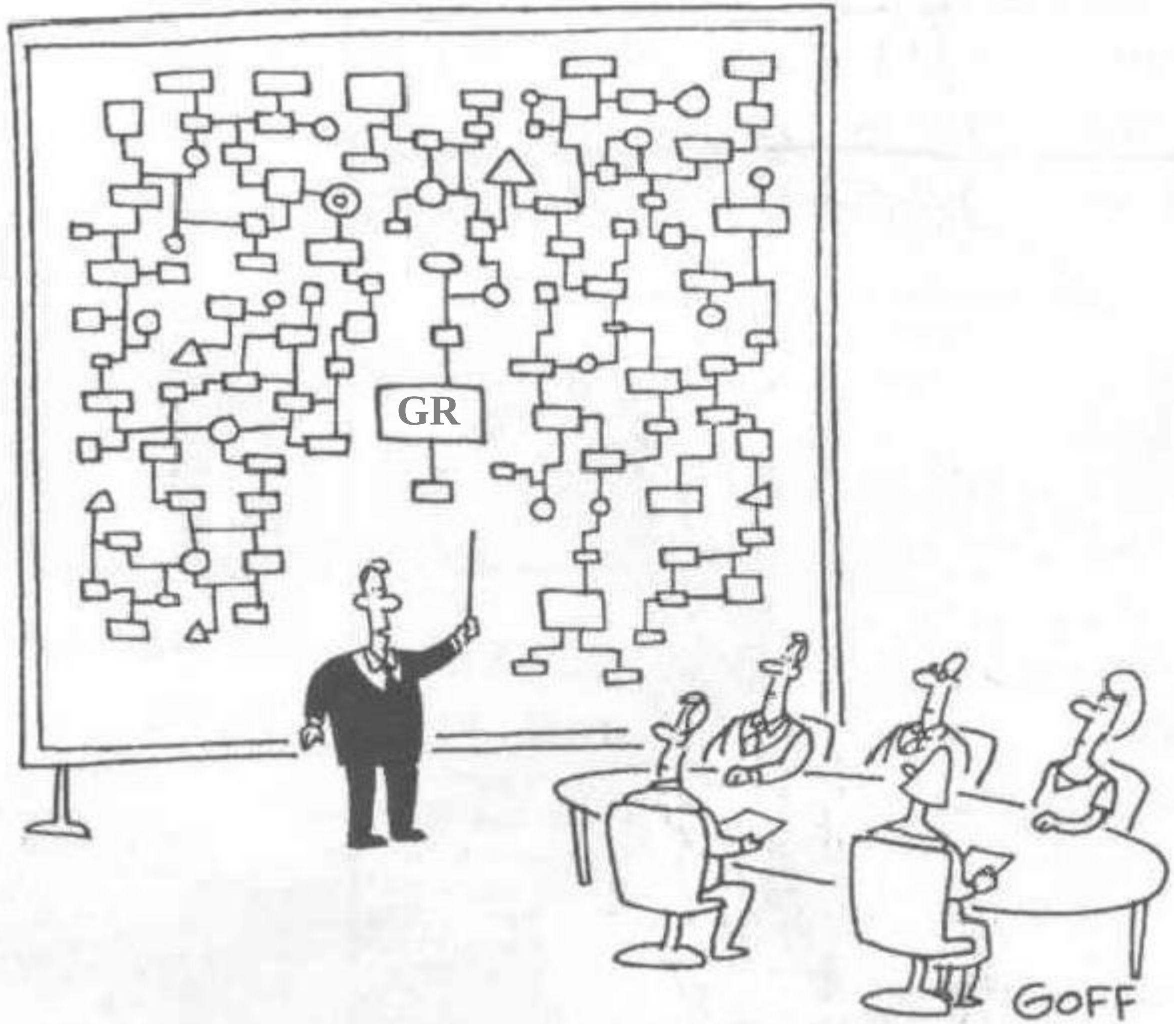
- What is the Universe made up of?
- Why is the Universe as we see it?
- What is our place in the Universe?

Einstein's theory of General Relativity…

- Einstein thought of gravity as curvature of space and time…

- Objects then travel on the shortest path in 4 dimensions…but when space is curved that isnt a straight line anymore…


Curvature…
$G_{\mu\nu} = 8\pi G T_{\mu\nu}$
Matter

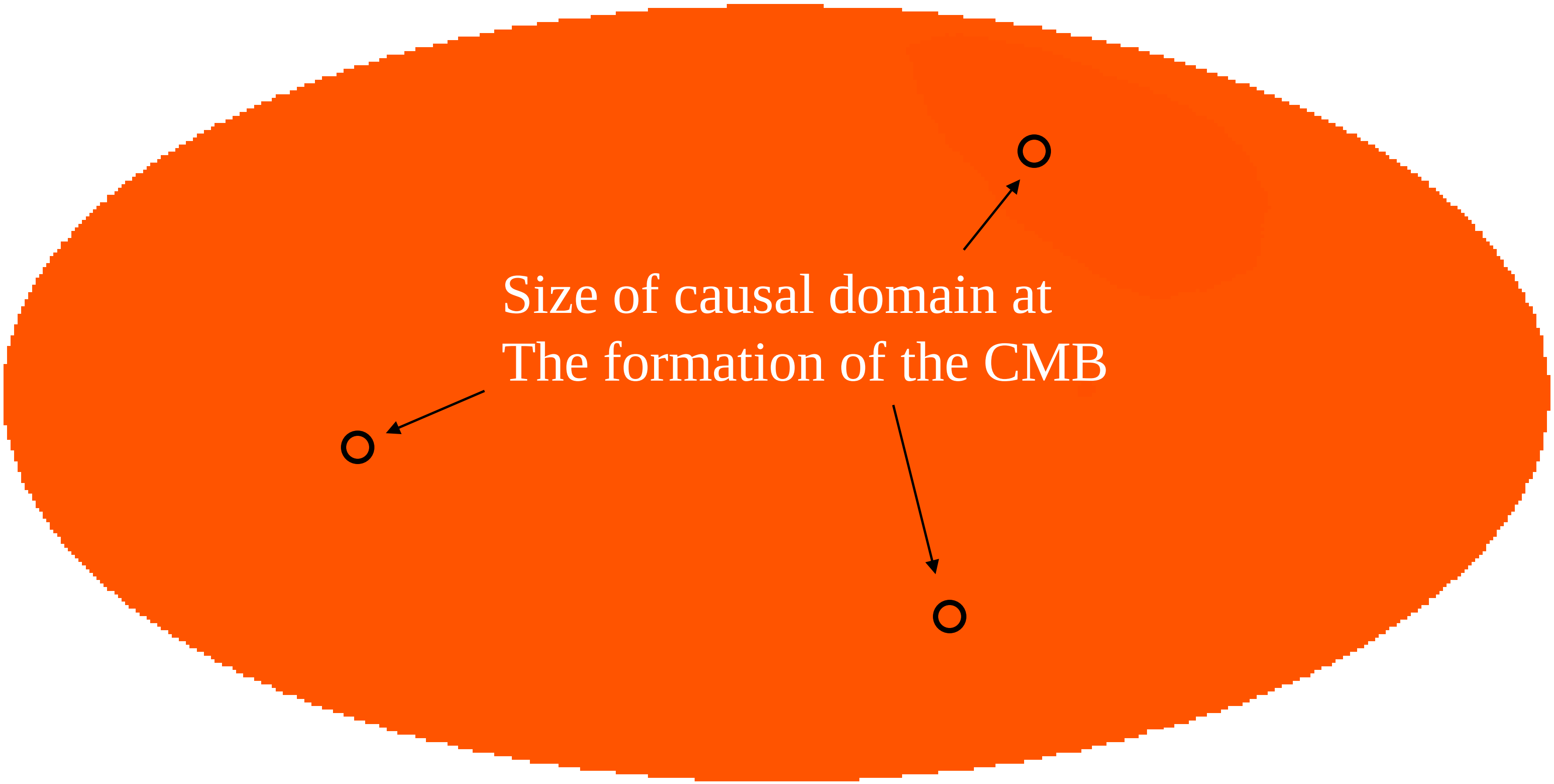


"AND THAT'S WHY I NEED A VACATION."

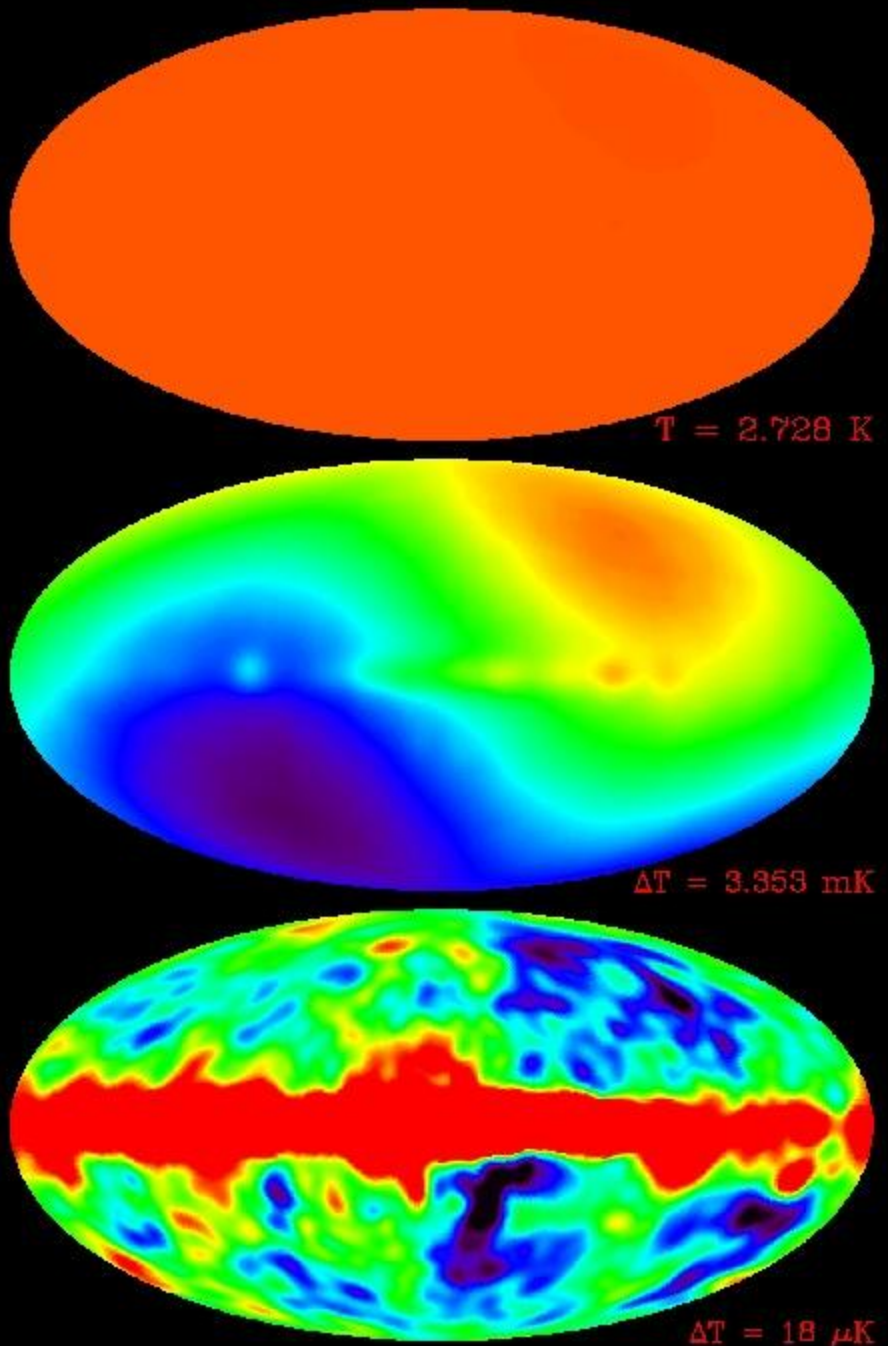
Our mysterious cosmos

- Our Universe is one of many mysteries…
- What happened in the first 10^{-30} seconds after the Big Bang?
- Are we somehow reliving the early universe today?

Cosmic Problem 1 : Isotropy



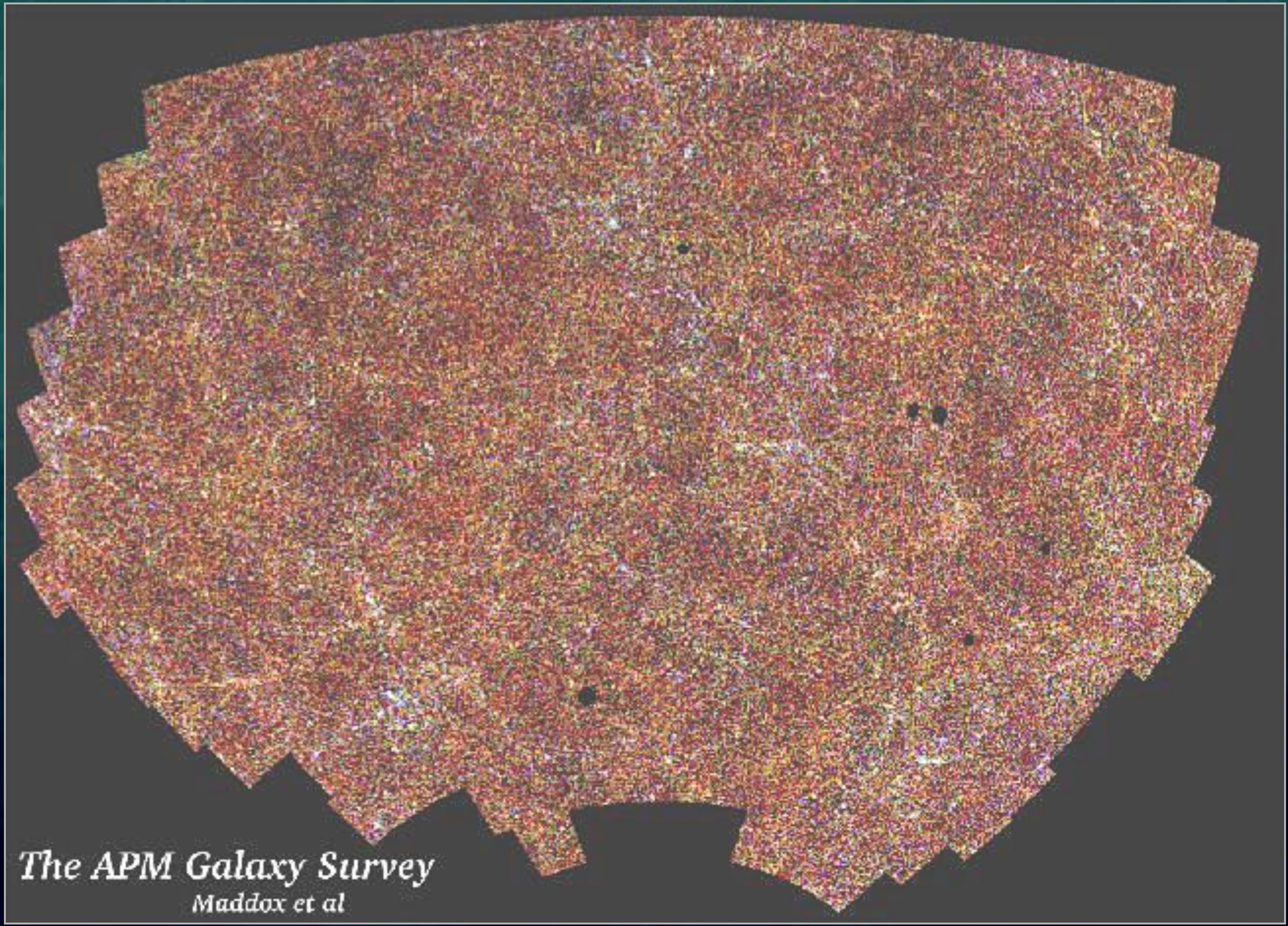
Evidence 1: CMB



$$\frac{\Delta T}{T} \approx 10^{-5}$$

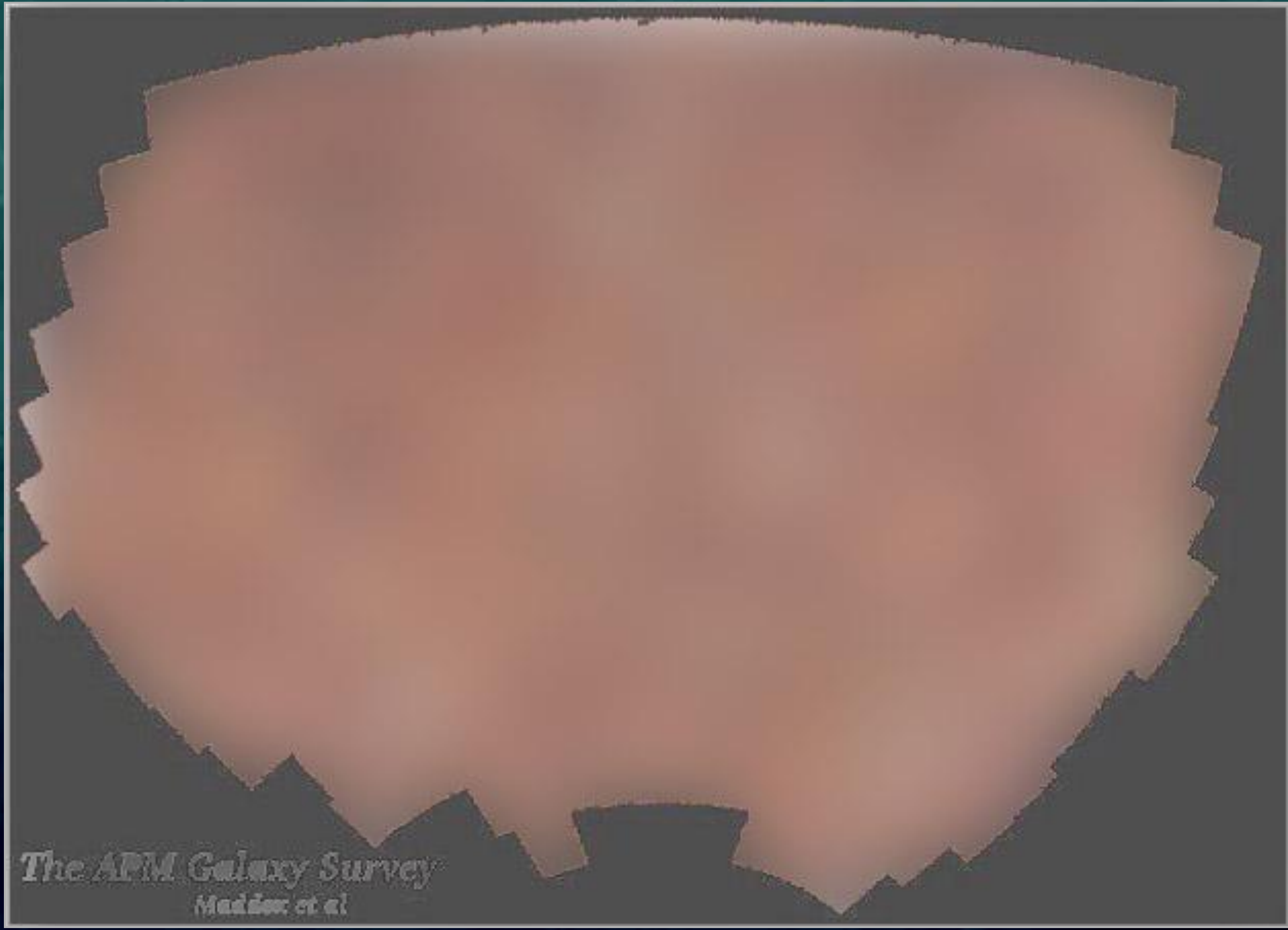
Evidence 2: 2d map of APM galaxies ($\sim 10^6$ of them)

Each point is a galaxy…



After smoothing, it looks about the same in each direction

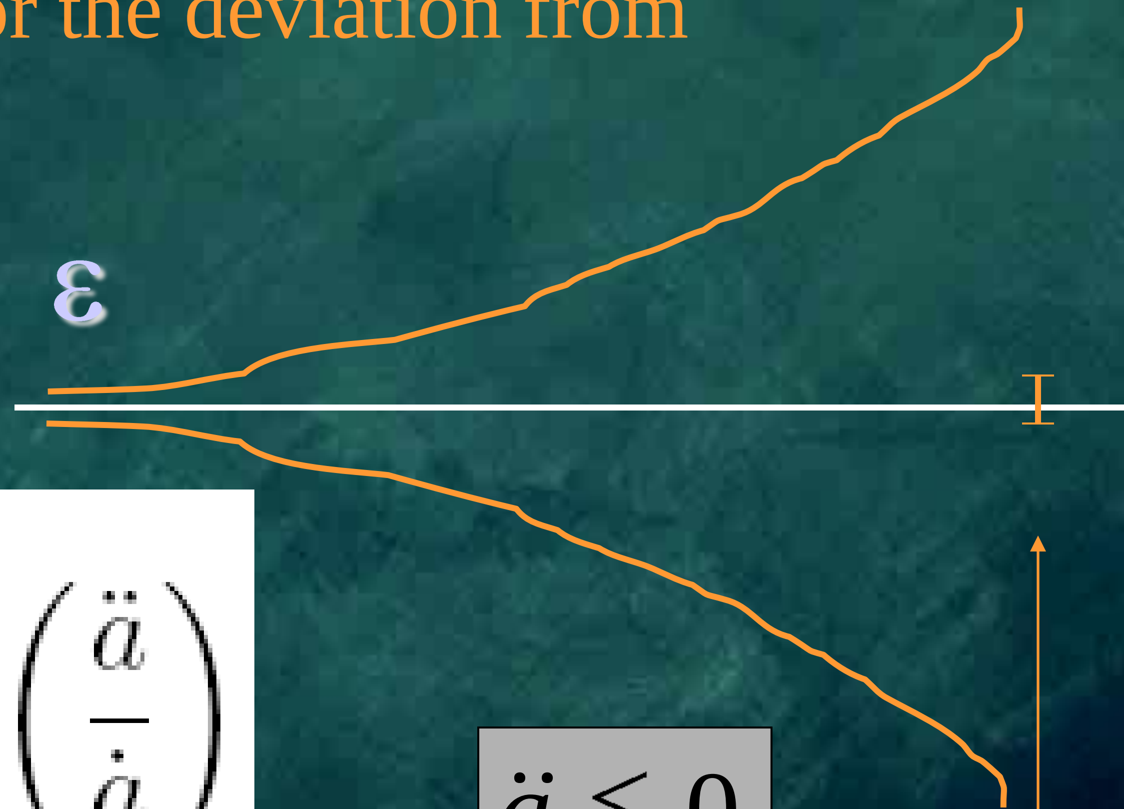
Angular Gaussian smoothing
of ~7% FWHM
(note edge effects)



Cosmic Problem 2: flatness

- We know that our universe is flat to within a few percent…
- But gravity makes space curve…So the flatness of the cosmos is is a mystery
- A typical universe should last much less than a second…not 15 billion years!
- Q: why?

- General relativity gives the following evolution law for the deviation from flatness…



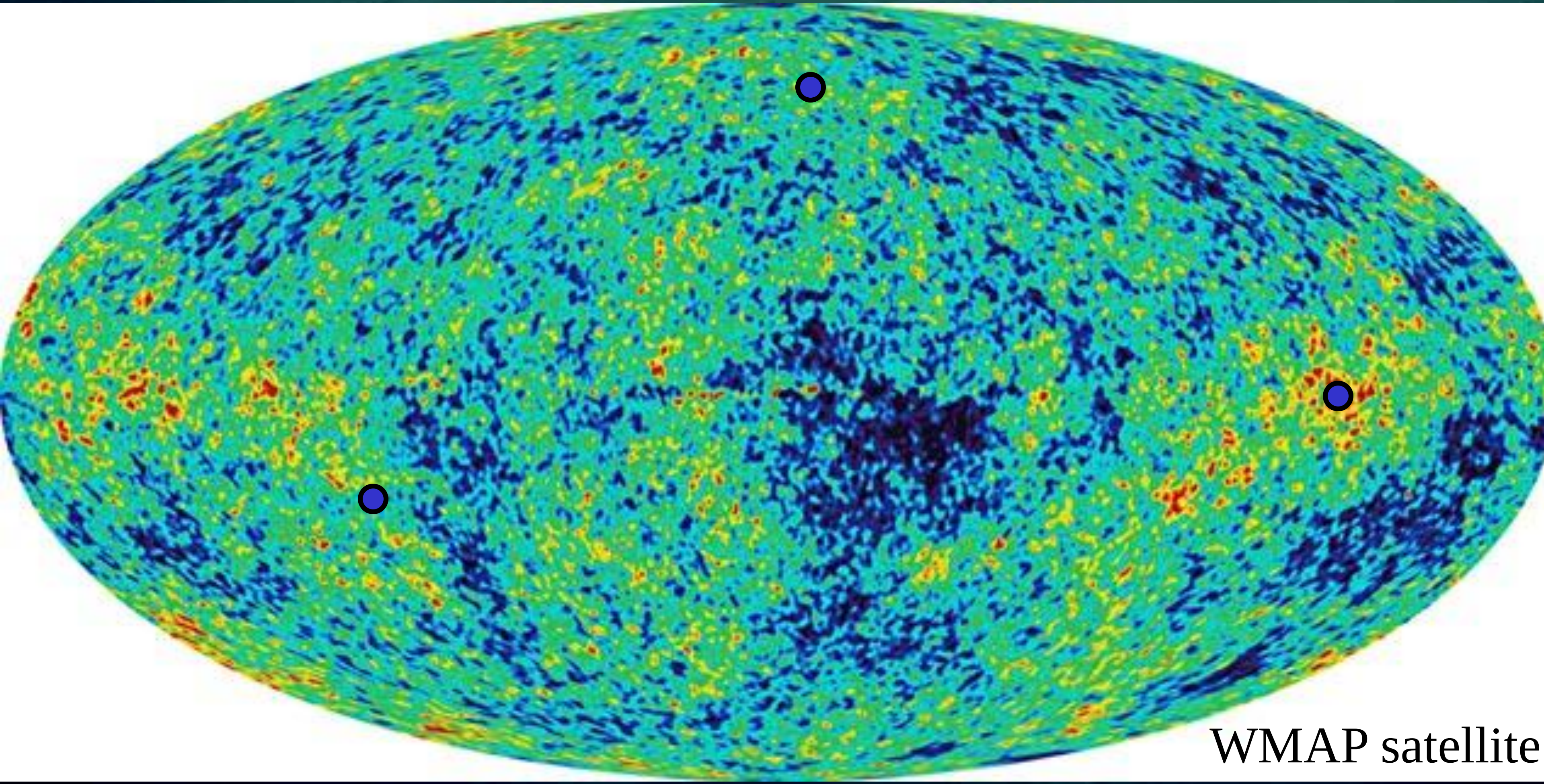
$$\dot{\epsilon} = -2\epsilon\left(\frac{\ddot{a}}{\dot{a}}\right)$$

$\ddot{a} < 0$

So if the universe is decelerating…the curvature grows…but today $\varepsilon \sim 0.01^{+0.02}_{-0.02}$

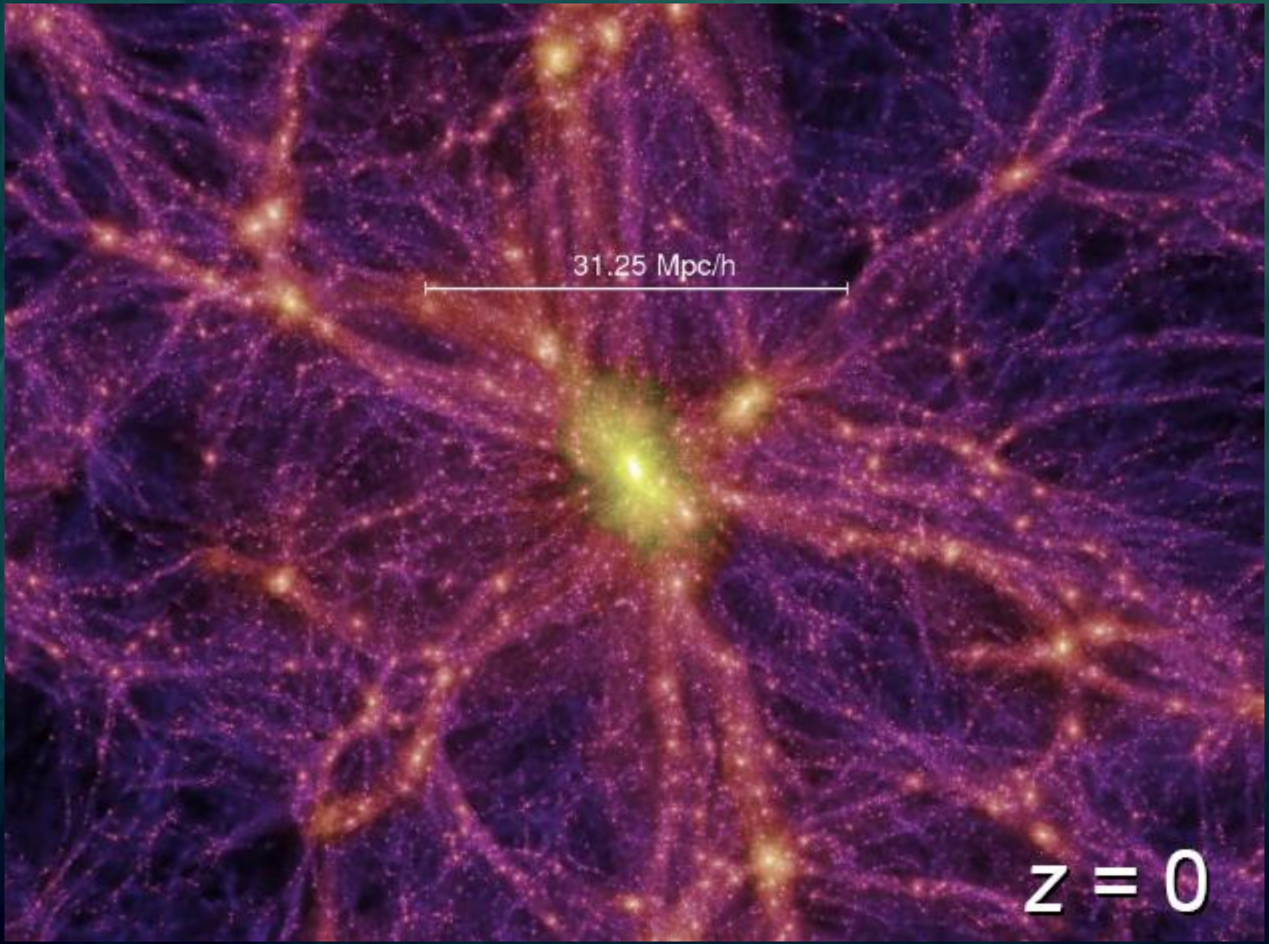

He
H

Cosmic Problem 3: fluctuations

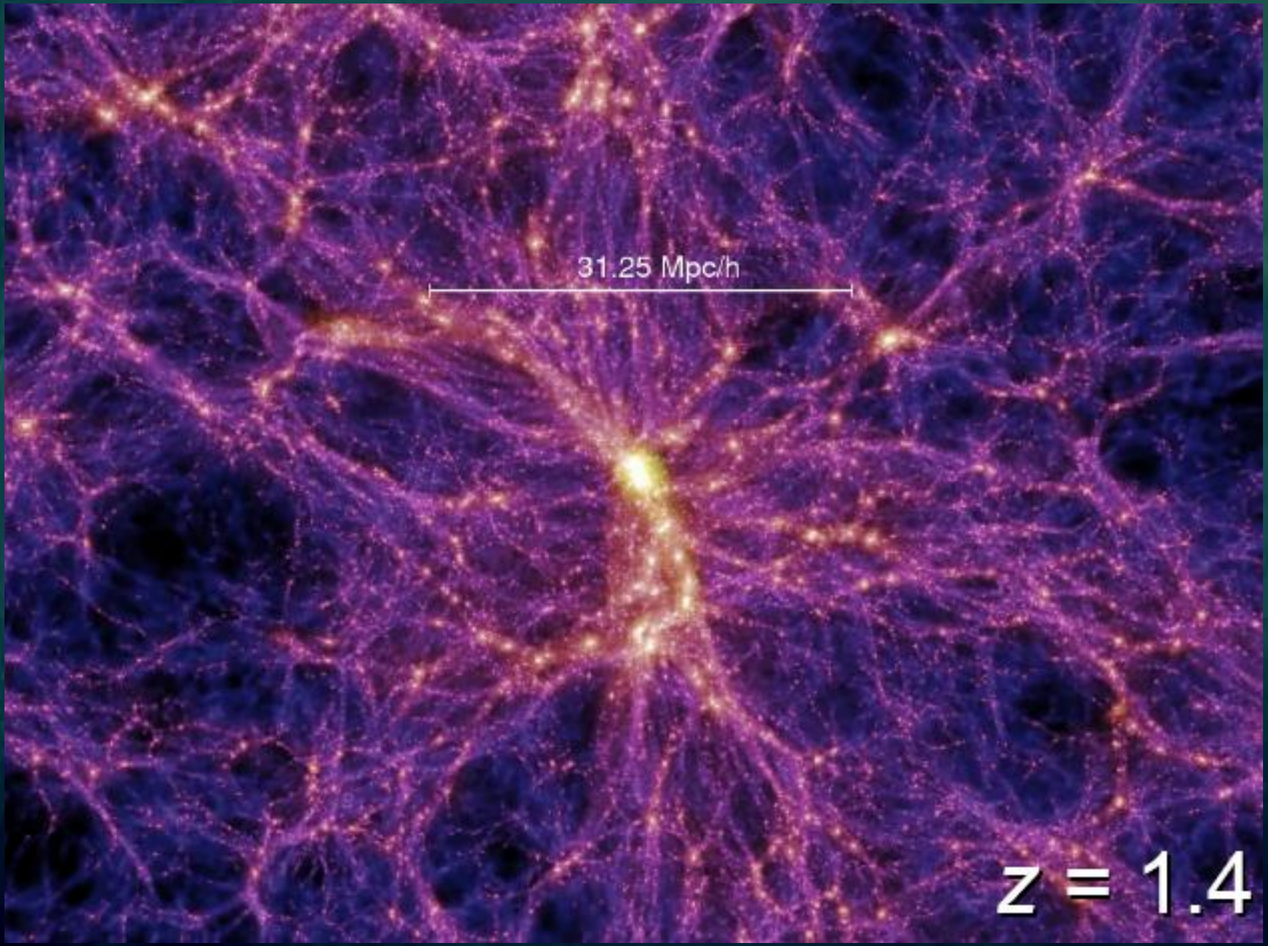


WMAP satellite

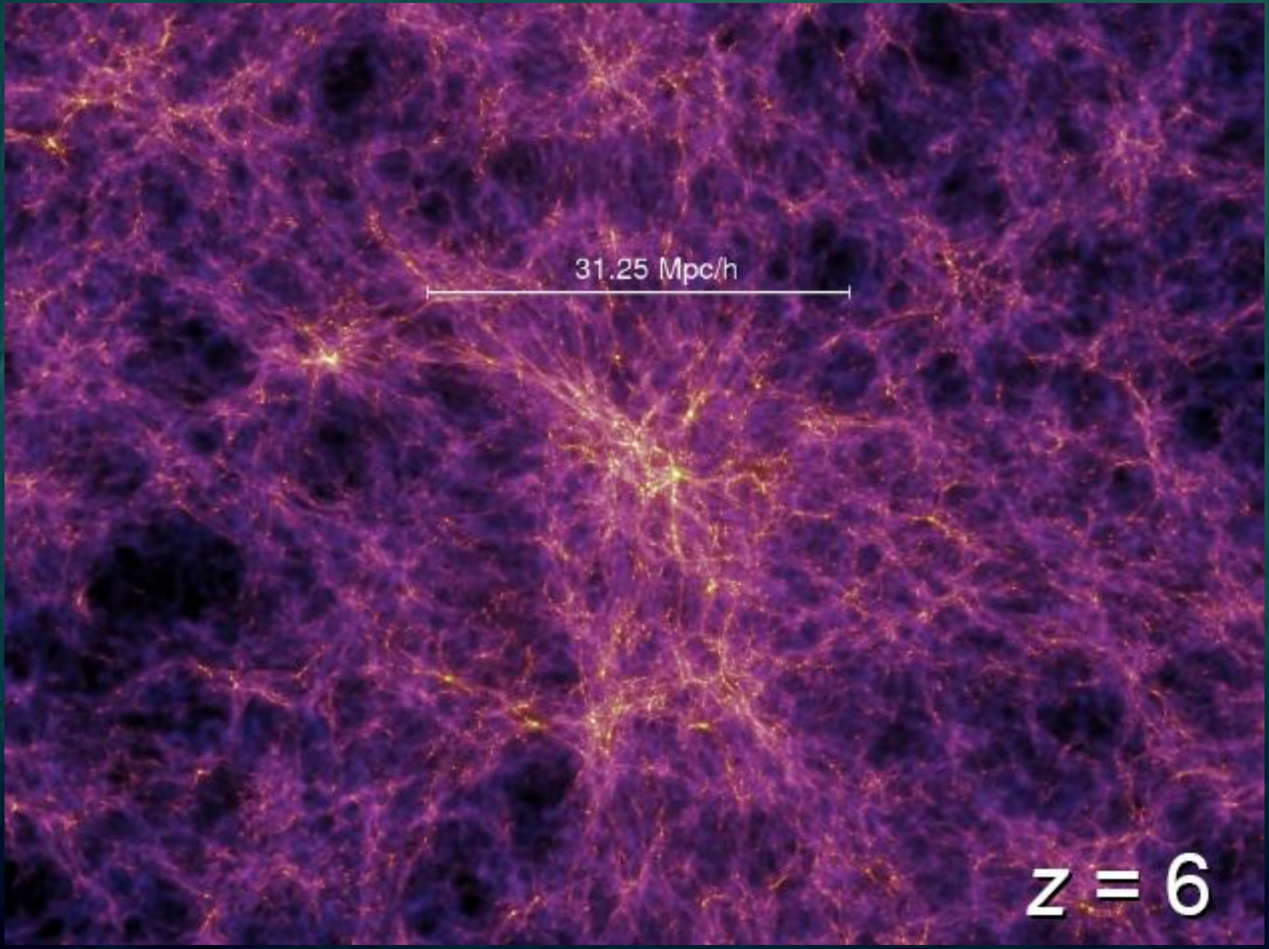
Growth of structure



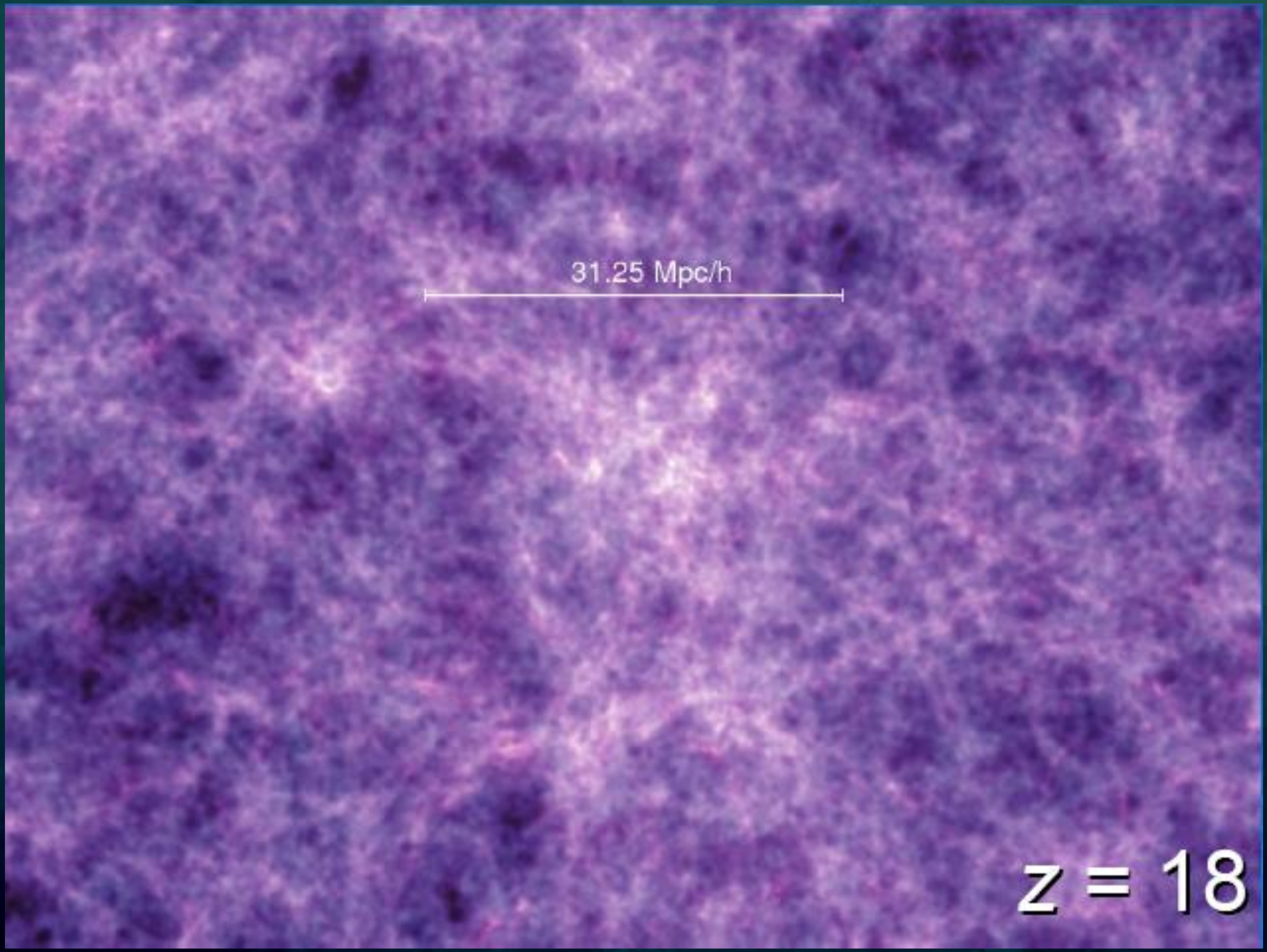
Growth of structure



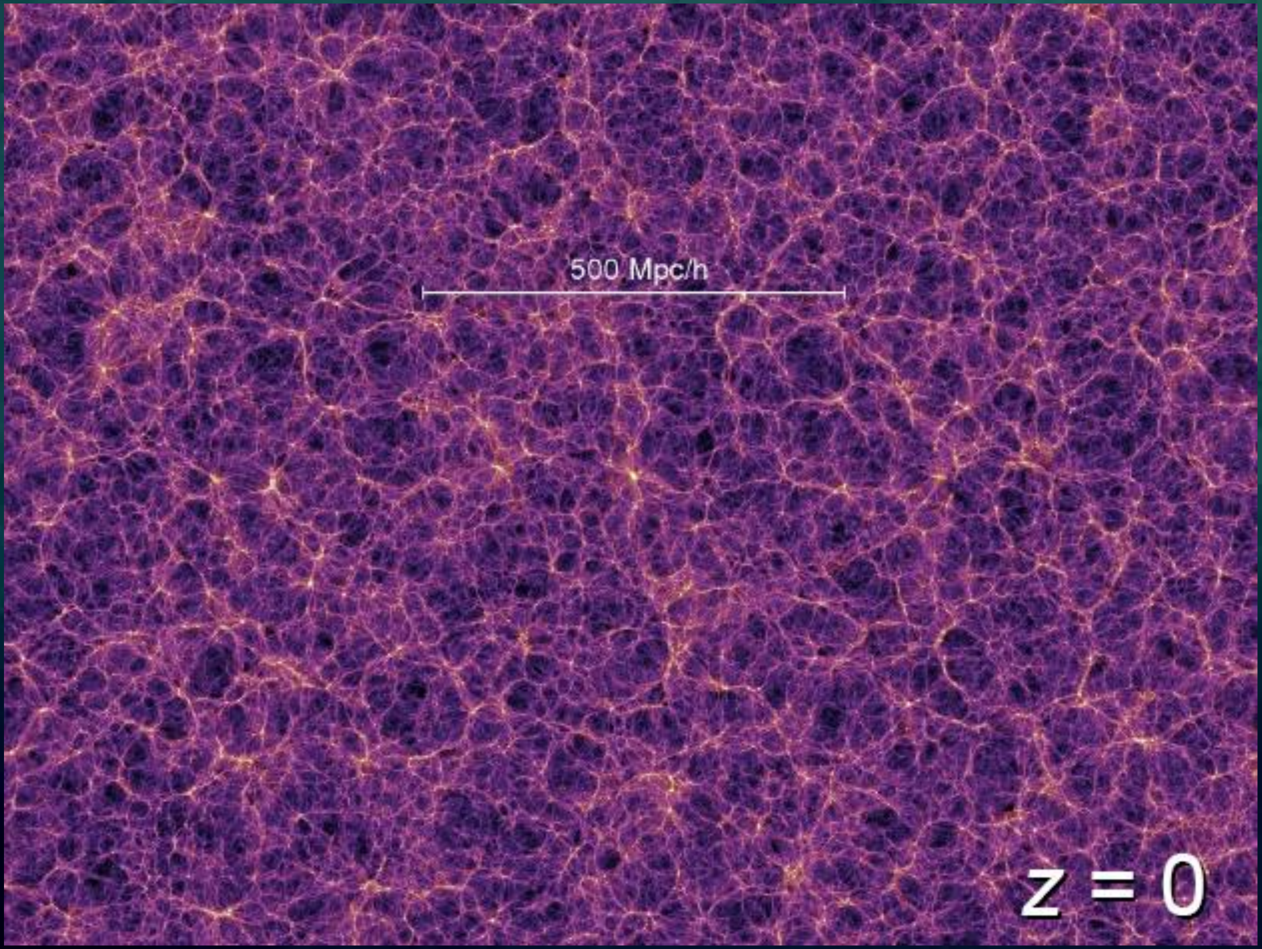
Growth of structure



Growth of structure

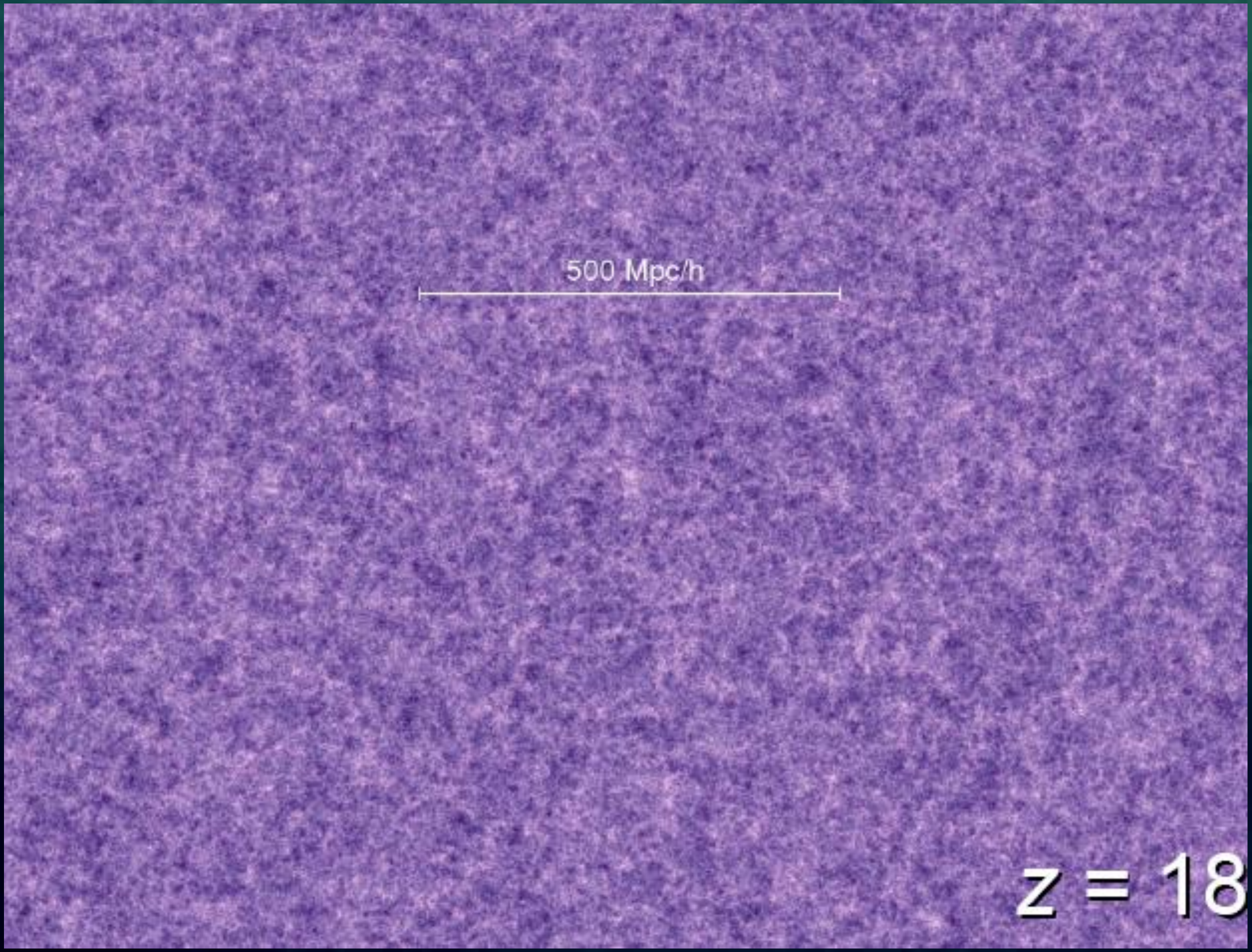


Evolution on the largest scales…



The millenium simulations – Springel *et al.* (2005)

Evolution on the largest scales…



Where do these tiny fluctuations come from?

Cosmic Problem 3: fluctuations

- If we look at the density fluctuations on large scales we notice that they are very special.
- The power spectrum of the fluctuations is almost perfectly flat (there is equal power on large and small scales = scale invariant)
- Put another way, fluctuations are very large scales are correlated…
- But these are on acausal scales…so we have another horizon problem!
- Very difficult to solve this in standard decelerating cosmology…

Cosmic Problem 4: the baryonic universe

- There must have been a tiny matter—anti-matter asymmetry in the early universe which yielded 1 proton per ~ 10^{10} photons today – why and how did this happen?

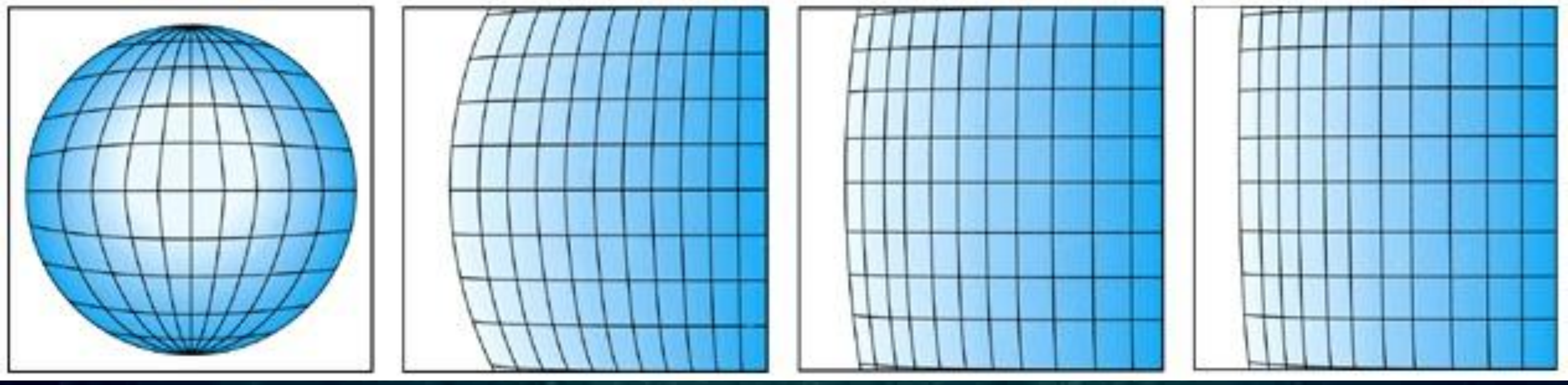
- We should expect no baryons at all…since they should have annihilated with an equal number of anti-baryons…

To get an asymmetry requires non-equilibrium physics and violation of CP and B conservation

Inflation – the solution?

- We already saw this equation…

Guth



- If the universe was accelerating it would become flat…

$$\ddot{a} > 0$$

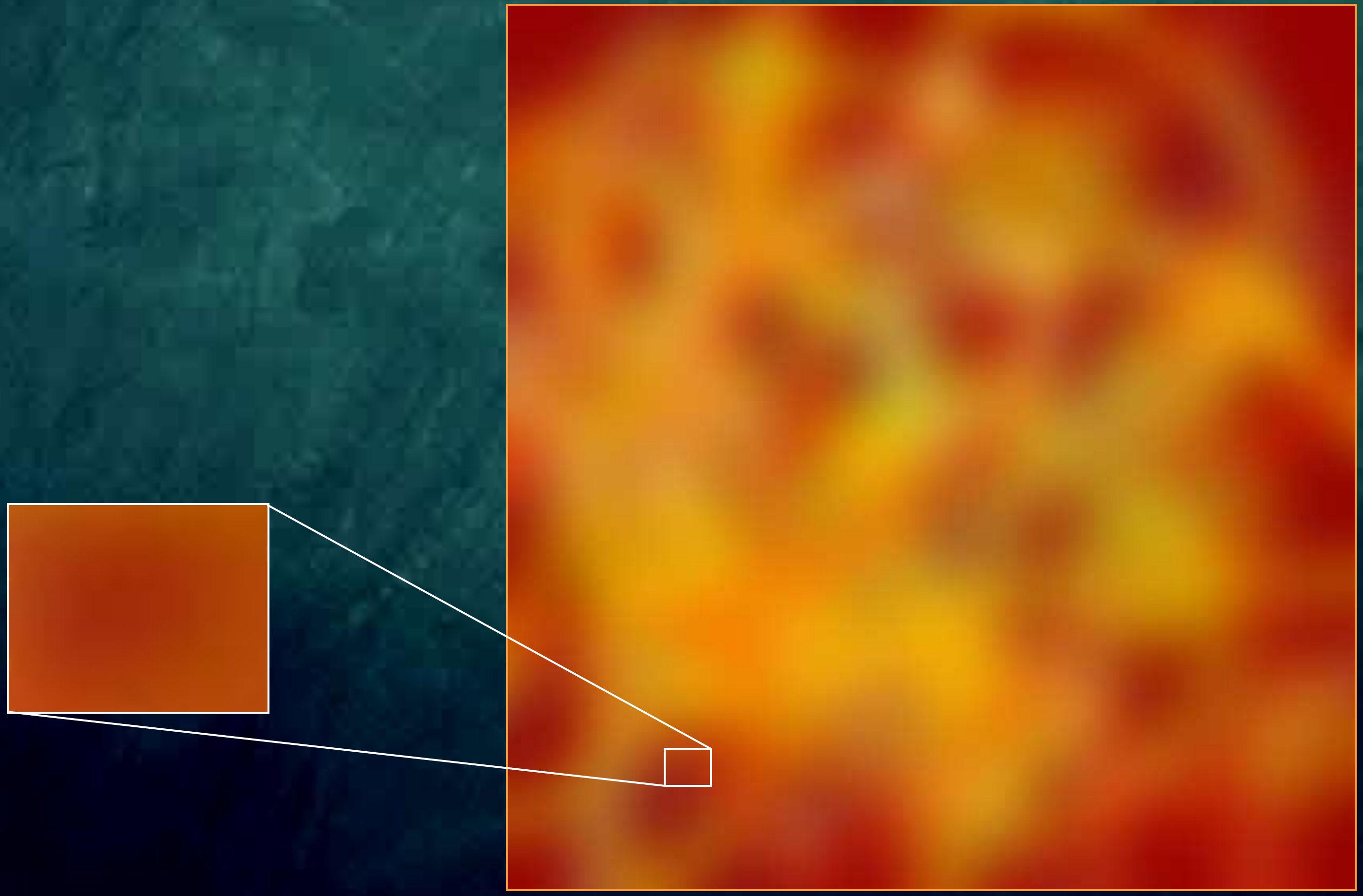
Acceleration…

Inflation

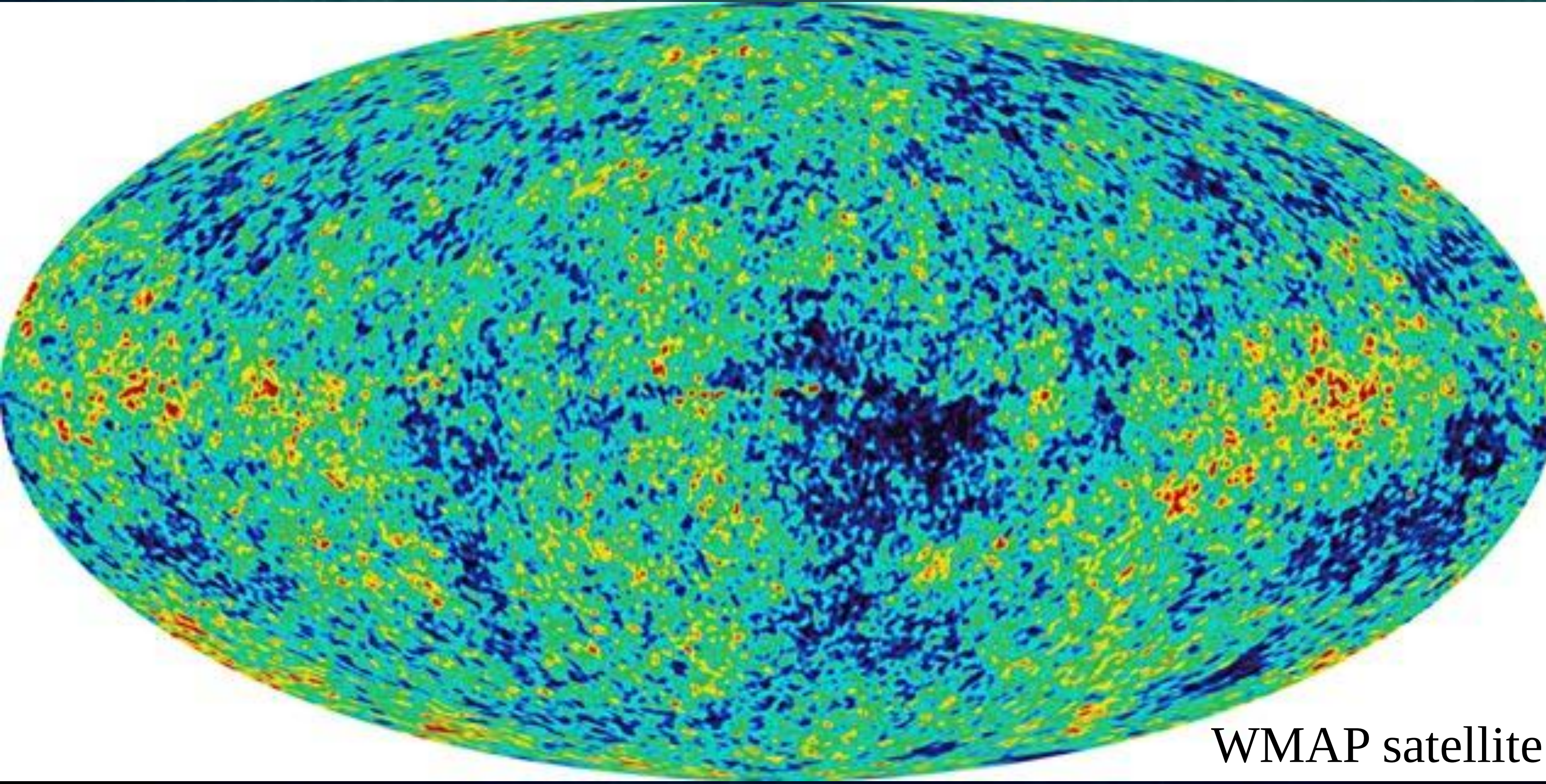
- Inflation begins around 10^{-33} seconds after the big bang and needs to expand the universe by about a factor of $> 10^{30}$ to solve the cosmological problems.

- In inflation, our entire observable universe is argued to come a region smaller than this:

Solving the isotropy problem…



What about the fluctuations that lead to galaxies?



WMAP satellite

What about the fluctuations that lead to galaxies?

- The Heisenberg uncertainty principle means the universe cannot be completely smooth…
- Otherwise all the particles in the cosmos would have zero momentum
- Hence, there must be small quantum fluctuations…
- It turns out that these provide the perfect seeds for galaxy formation and have the right fractal structure

Quantum fluctuations as seeds

- In an expanding spacetime our scalar field (the "inflaton") exhibits quantum fluctuations of size:
- k = wavenumber~1/L

$$\delta\phi(k) \approx \frac{H}{2\pi}\Big|_{k=aH}$$

$$H \equiv \frac{\dot{a}}{a}$$

- These quantum fluctuations are the seeds for galaxy formation in inflation and because H is almost constant, the spectrum is almost scale-invariant.

So how do we get inflation?

- The acceleration satisfies the Raychaudhuri equation:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i (\rho_i + 3p_i)$$

- The sum is over all different species of energy in the universe (matter, radiation, neutrinos, etc…) and here c=1.

So how do we get inflation?

- Hence acceleration requires…

$$(\rho + 3p/c^2) < 0$$

Energy density   Pressure

- But how do we get negative pressure?

So can we really believe in inflation?

- Unfortunately negative pressure this large is not possible with any known form of matter…

- It ***IS*** possible with scalar fields (such as the postulated Higgs boson)

Scalar fields as the source of acceleration…

- Denoted: ϕ (spin-0 particle)
- Evolution completely determined by $V(\phi)$
- Background Evolution: $$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = 0$$

Think of a ball rolling on a surface with shape $V(\phi)$ and friction Given by H

Scalar fields continued…

- They are perfect fluids with:

- Pressure:

$$p = \frac{\dot{\phi}^2}{2} - V(\phi)$$

- Energy density:

$$\rho = \frac{\dot{\phi}^2}{2} + V(\phi)$$

Kinetic Energy

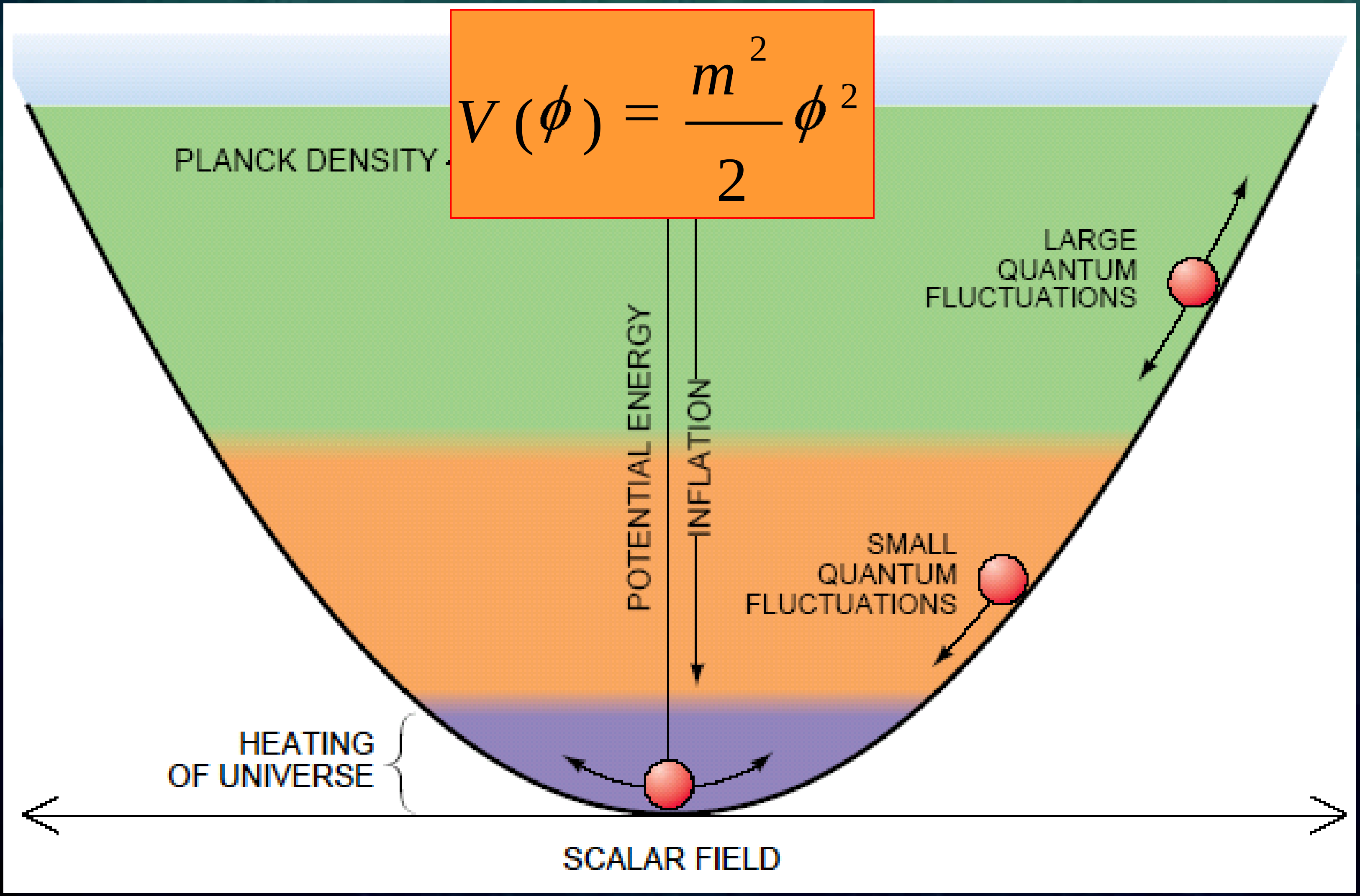
Potential Energy

- Acceleration needs a flat potential:

$$\rho + 3p < 0 \Rightarrow V(\phi) > \dot{\phi}^2$$

A simple potential for inflation

$$V(\phi) = \frac{m^2}{2}\phi^2$$



Chaotic inflation

- In chaotic inflation, we imagine that all possible values of ϕ occur as initial conditions..
- Only those regions with very large ϕ give inflation, but they dominate the future of the universe

Chaotic inflation continued…

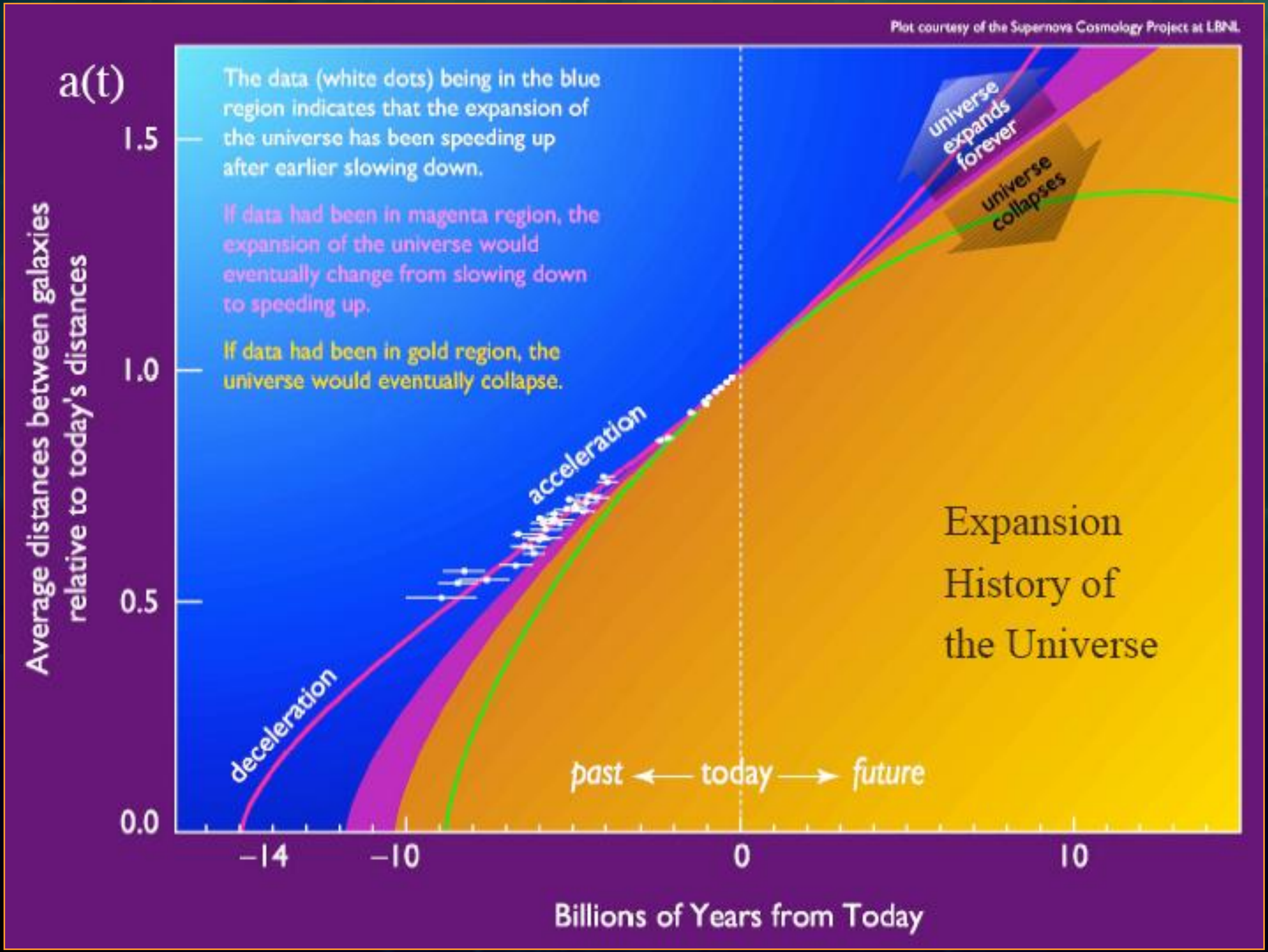
- The classical evolution is always down the potential but large quantum fluctuations can always go up the potential and start a new phase of inflation…
- In this model, the universe is always inflating somewhere…so it is known also as eternal inflation

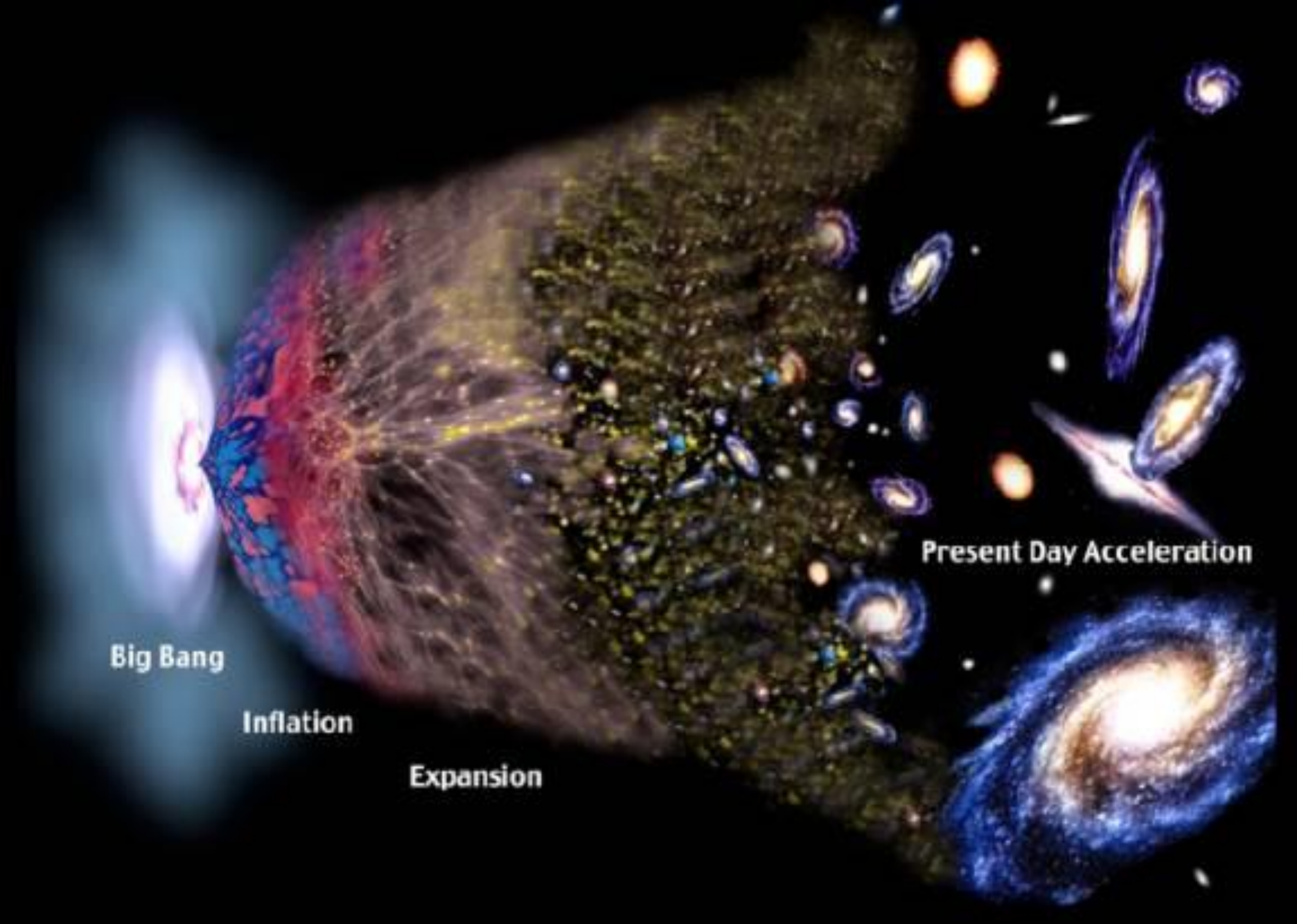
But can this be true?

- Does this sound like a fairy tale?
- Is there really any reason to believe in inflation?
- After all, we have never discovered a fundamental scalar field…

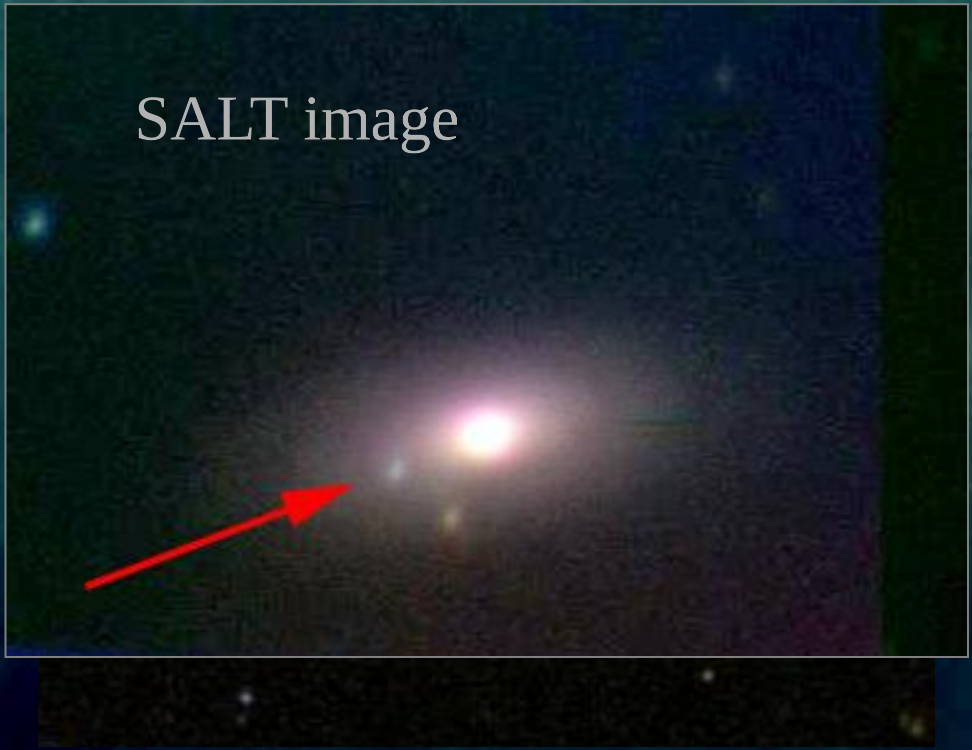
"The pink form is for accounting.
The blue form is for underwriting.
The yellow form is for the commissioner.
The green form is for the broker.
The white form is for the tooth fairy."

…there was no reason until 1998



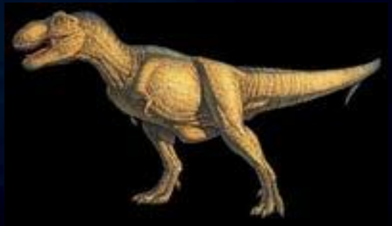

Big Bang
Inflation
Expansion
Present Day Acceleration

A death 250 million years ago…



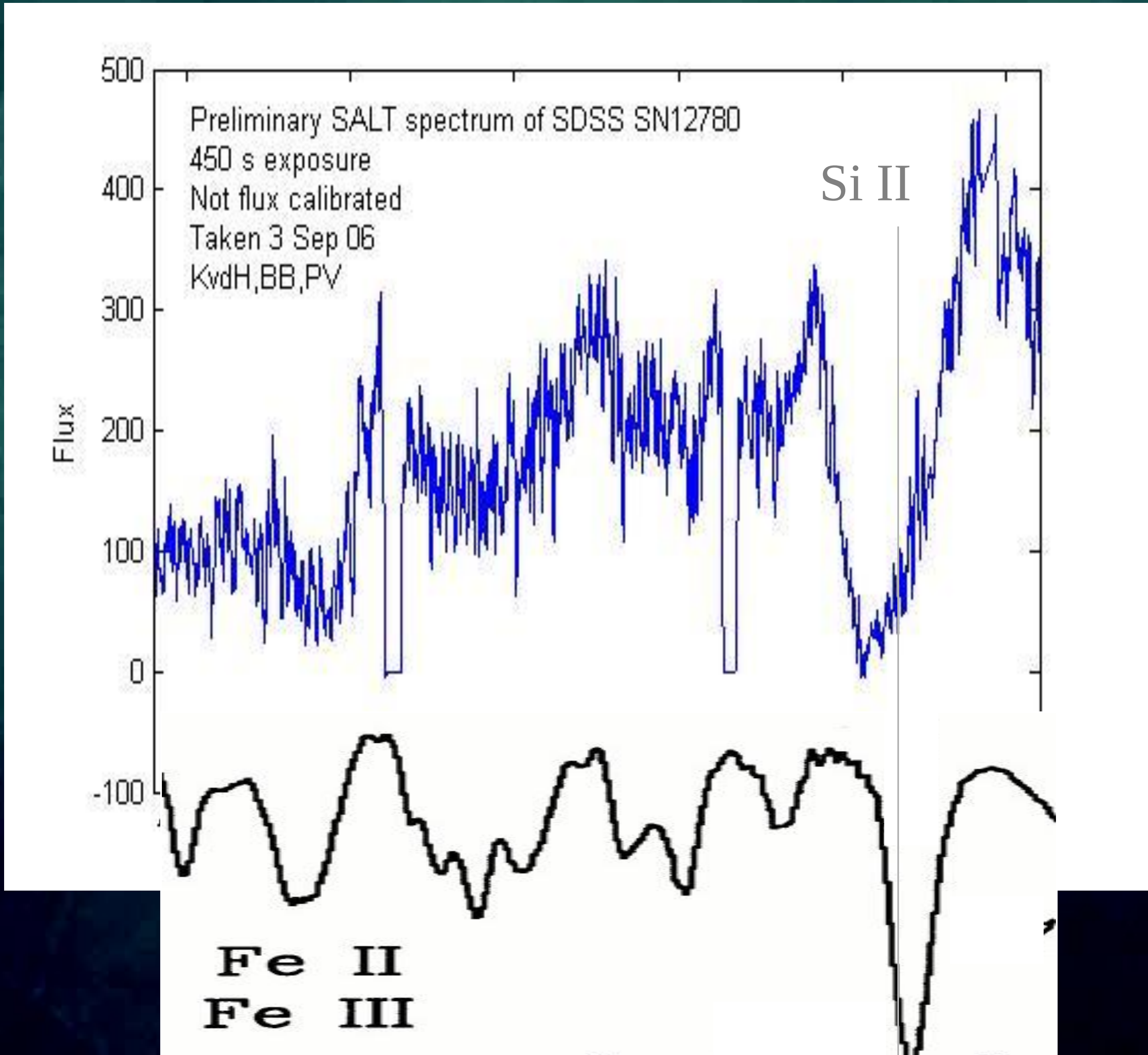
BB,
van der Heyden,
Vaisanen

But the news only reached us in 2006!



Our first SALT SNIa spectrum

- Part of the SDSS SN survey
- Redshift z=0.049
- *3 Sep ‘06*
- *vd Heyden et al, ‘06*



Now we know acceleration is possible…

- The universe **is** accelerating today…so it looks like we are in the early stages of a second inflationary phase…
- The problem is…we still don't know what the cause of the acceleration is…and whether this new inflation will last for ever.
- If the acceleration is speeding up, then the universe could end in a *big-rip singularity* where atoms are torn

Was Copernicus Wrong?

- The current acceleration of the universe requires that the universe be isotropic and homogeneous
- But if we are willing to live at the centre of a spherically symmetric universe then we may not need dark energy.
- So was Copernicus right or wrong? One of the most fundamental questions for modern cosmology to answer…

Tutorial questions

1. Convince yourself that the Hubble constant, H, really is almost constant during inflation (assume $p \sim -\rho$).

2. Assuming H is almost constant and assuming a very flat potential ($dV/d\phi$ very small) derive the future evolution of ϕ from some initial time when $\phi_0 = \phi\,(t_0)$ using the eq.

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV(\phi)}{d\phi} = 0$$

Basic Equations

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\sum_i \rho_i - \frac{k}{a^2}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\sum_i (\rho_i + 3p_i)$$

$$\dot{\rho} + 3H(\rho + p) = 0$$