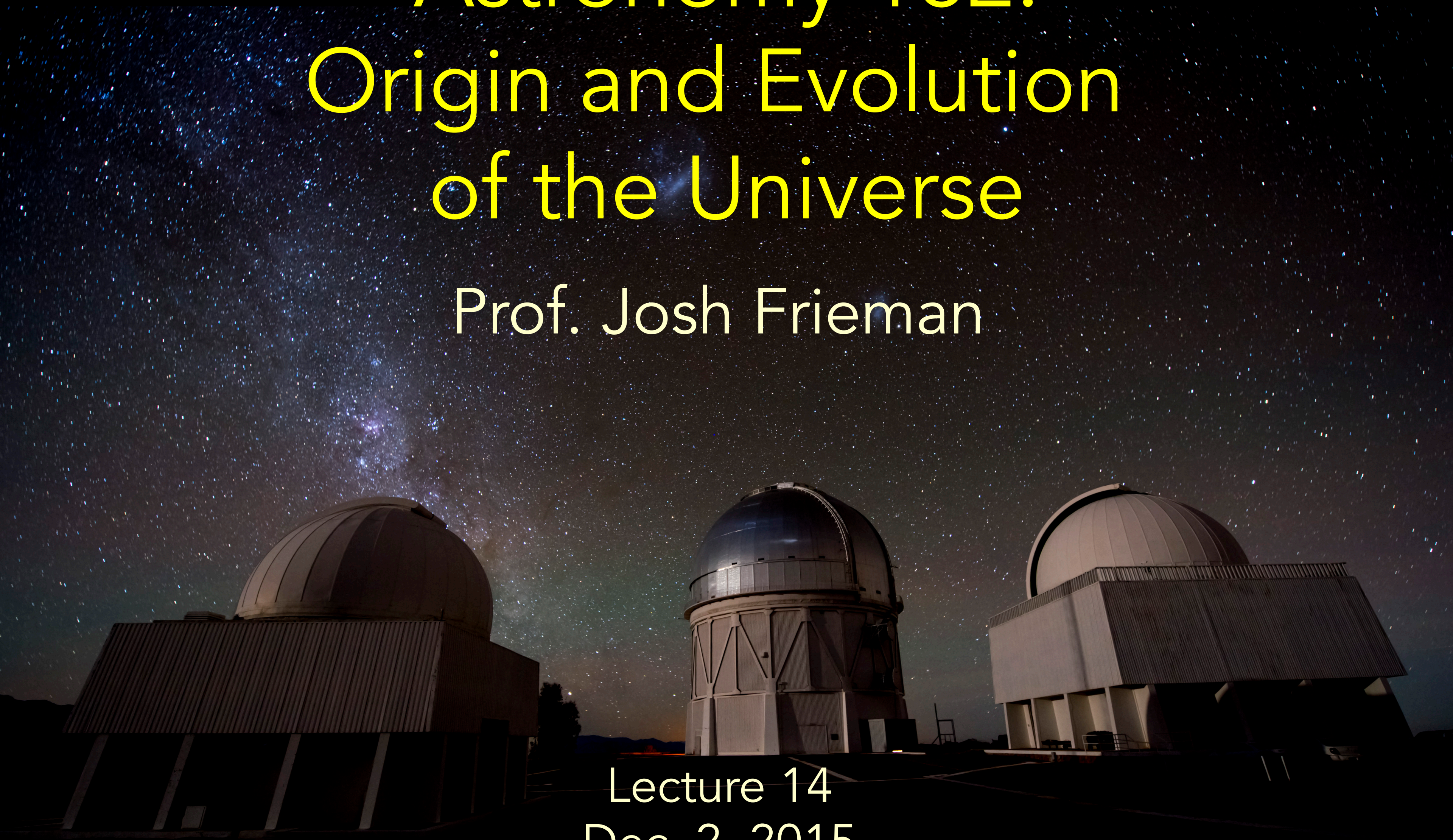
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 14
Dec. 2, 2015

Today

- The Inflationary Universe
  - Origin of Density Perturbations
  - Gravitational Waves
- Origin and Evolution of Structure in the Universe

Assignments

- Final project: choose a topic in cosmology from popular books or an article in the reputable press: Scientific American, NY Times, Astronomy Magazine, Discover, Science News,…write a 3-page essay in the style of a newspaper or magazine article in that theme, *in your own words*. Due this Friday (last class).

Some Possible Project Topics

- Recent Measurements of the Cosmic Expansion Rate
- 100th Anniversary of General Relativity
- Einstein's Views on the Cosmological Constant
- Evidence for Black Holes in the Universe
- Experiments searching for Dark Matter
- Cosmic Surveys constraining the nature of Dark Energy (DES, eBOSS, DESI, LSST, WFIRST, Euclid,…)
- Theories of Dark Energy
- Theories of Modified Gravity to explain Cosmic Acceleration
- Experiments Measuring the Cosmic Microwave Background (Planck, SPT, ACT, BICEP,…)
- (Testing) Theories of Primordial Inflation
- Computer Simulations of the formation and evolution of large-scale structure and galaxies

Cosmic History

- Going back in time from the present toward the Big Bang, we reach important epochs when relics were (likely) created:
  - H recombination/photon decoupling at t ~ 380,000 years (T~3000 deg).
  - Big Bang Nucleosynthesis at t~3 minutes (T~10^9 deg).
  - Weakly Interacting Massive Particles would have frozen out at t~10^{-10} sec (T~10^{15} deg).
  - Baryogenesis: creation of matter-antimatter asymmetry, at t~10^{-33} sec (T~10^{27} deg)
  - Inflation: just before Baryogenesis

Higgs Boson & Symmetry Breaking

Higgs Boson: spin-zero particle (scalar field) that breaks the electroweak symmetry and differentiates the electromagnetic from the weak interactions.

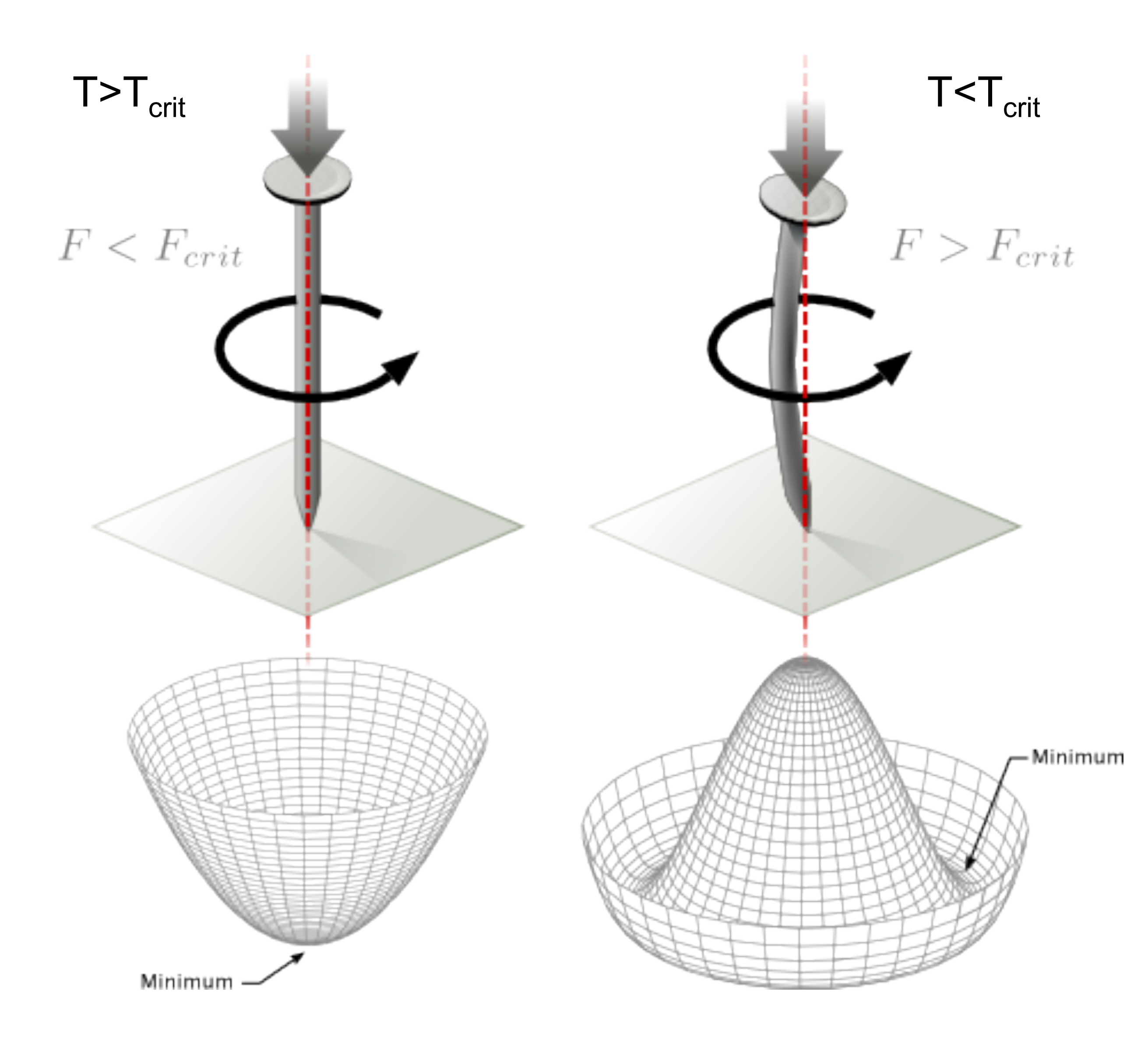
The Higgs interacts with and gives mass to the W and Z Bosons and to all other elementary matter particles, but leaves the photon massless. Can think of it as a kind of `medium' through which elementary particles move. It is a `field' (like an electromagnetic or gravitational field) but with the same value throughout all of space.

Like the photon of electromagnetism, the Higgs field has an associated particle, the Higgs boson, with a mass about 130 times the proton mass.

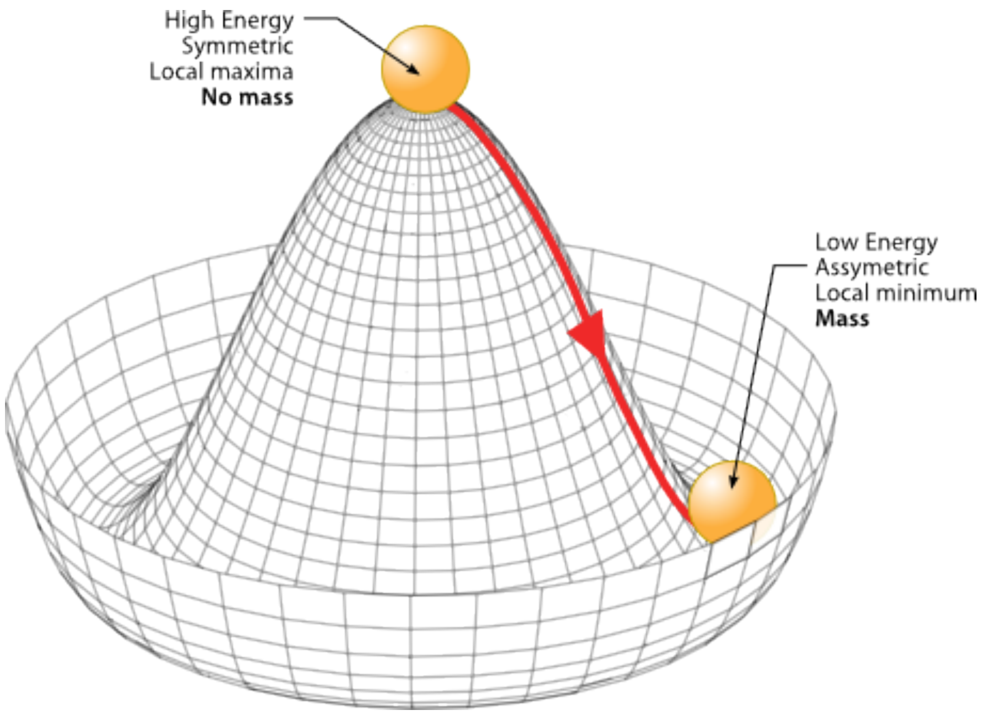
Symmetry Breaking Phase Transitions

- Although the electroweak symmetry is broken today (the weak and electromagnetic interactions look very different), the symmetry can be *restored* at high Temperature in the early Universe.
- As Universe expands and cools, at some point a *critical Temperature* is reached when the symmetry gets broken.
- This phase transition from a more symmetric to a less symmetric phase is analogous to the phase transition from liquid water to ice (T_c=0 deg C, 32 deg F).
- Above the critical temperature for electroweak symmetry breaking, $T_c \sim 10^{15}$ deg ($kT_c \sim 100$ GeV), $t \sim 10^{-10}$ sec, the Higgs field vanishes, and all the particles of the Standard Model are massless.

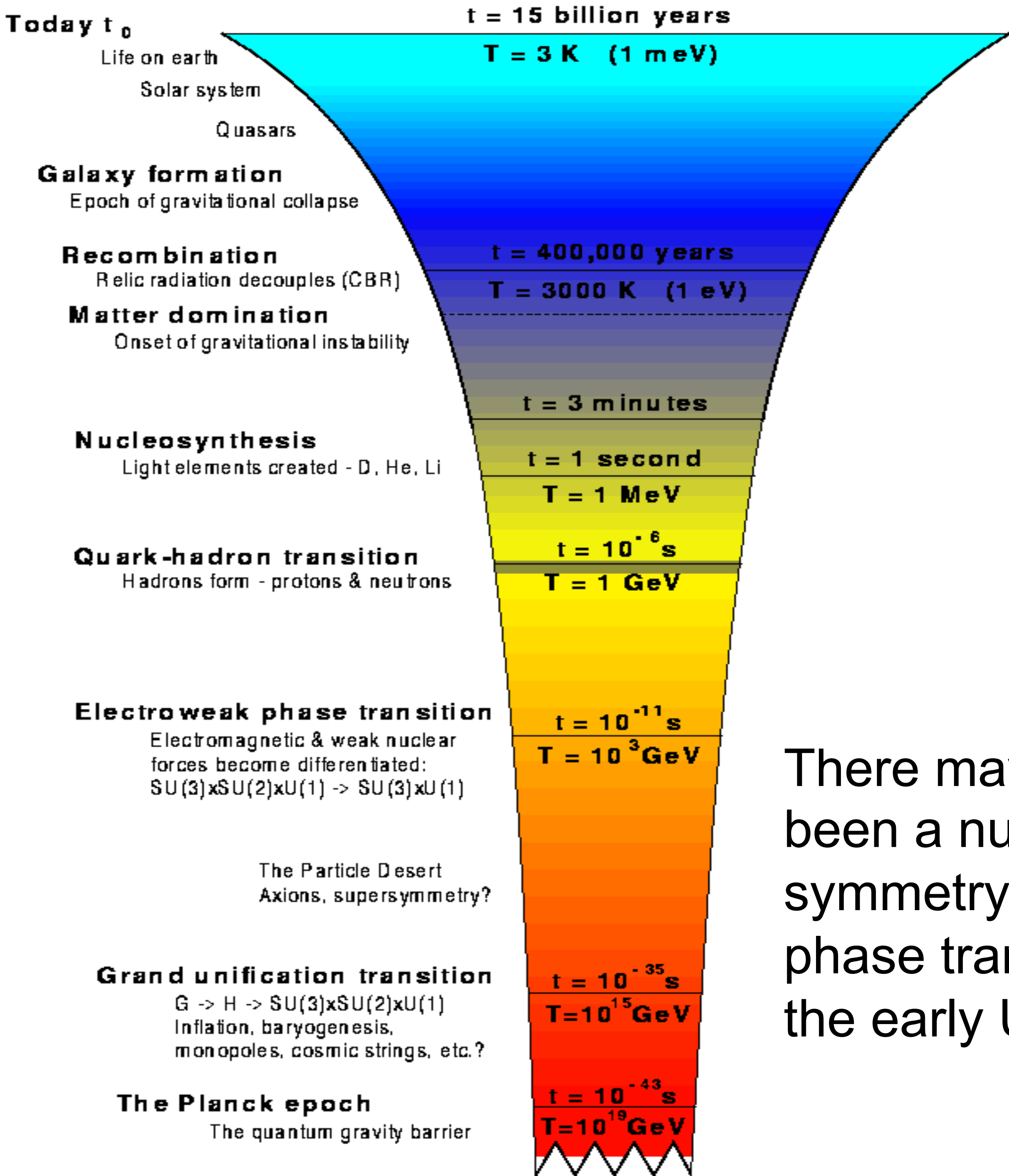
Symmetry Breaking



Higgs Potential Energy



Radius of the sombrero = amplitude of the Higgs field φ



There may have been a number of symmetry-breaking phase transitions in the early Universe.

The Inflationary Scenario

Alan Guth (1980): young cosmologist who was thinking about the cosmological consequences of symmetry-breaking Phase Transitions in the early Universe, associated with Grand Unified Theories. He realized that if a transition associated with a much heavier cousin of the Higgs field proceeded very slowly, it could have profound implications for cosmic evolution. He was motivated by several cosmological conundrums:

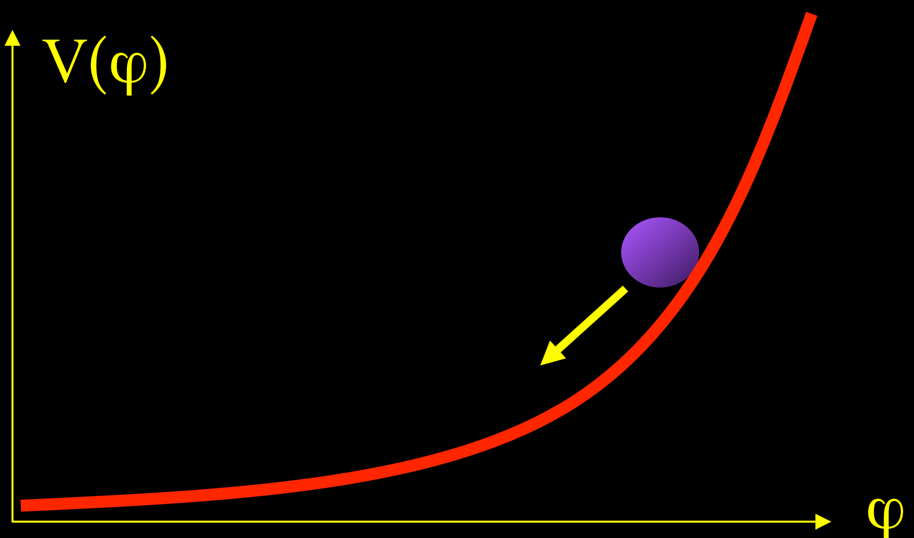
Horizon/homogeneity, flatness, and structure problems

Inflation in the Early Universe

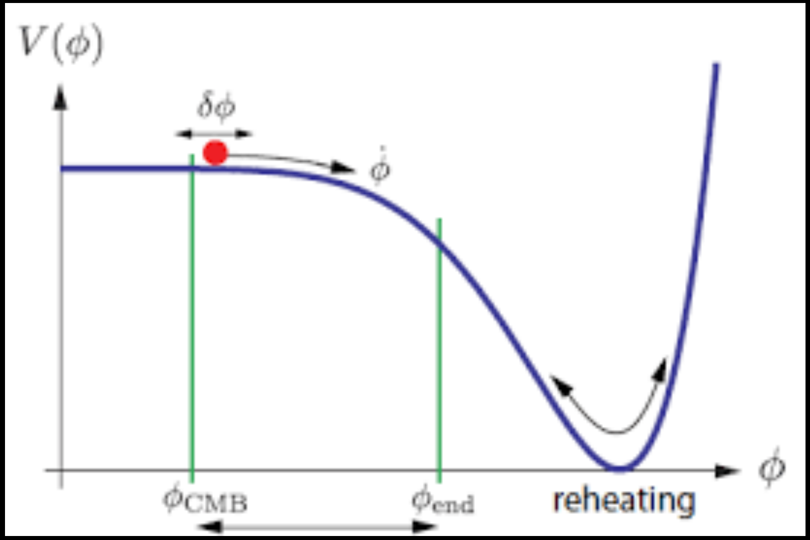
- A hypothetical epoch of rapid, *accelerated* expansion in the very early Universe, that occurred a tiny fraction of a second after the Big Bang.
- If this period of accelerated expansion lasts long enough, it effectively stretches inhomogeneity and spatial curvature to unobservably large scales, solving the horizon and flatness problems.
- In Guth's original model, inflation was driven by vacuum energy associated with a heavier cousin of the Higgs field.
- Today, inflation encompasses the more general idea of very early accelerated expansion, driven by a heavy scalar field (likely not a Higgs field) or by some other mechanism.

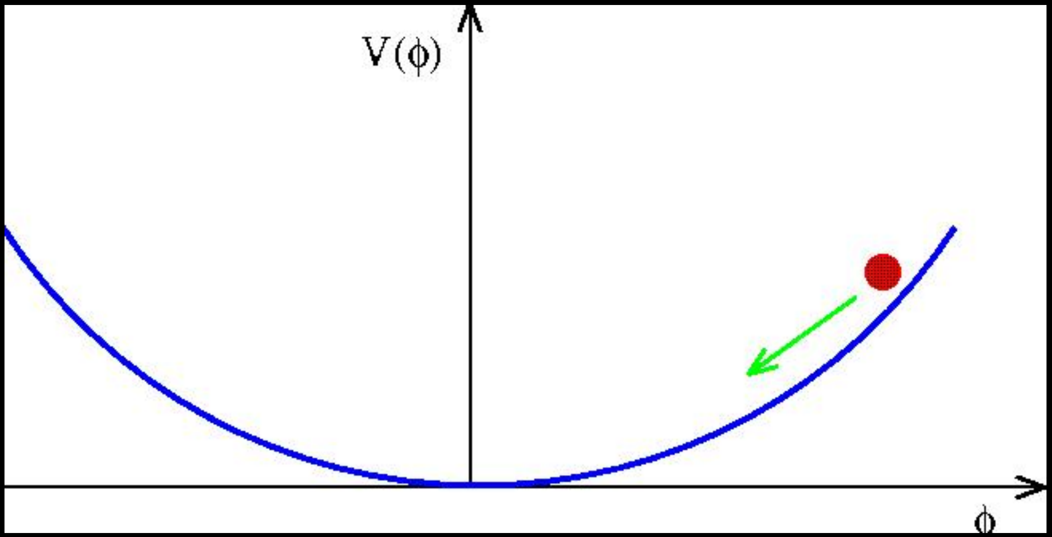
Scalar Field and Inflation

- Inflation could be driven by a very slowly rolling (evolving in time) scalar field: the *inflaton* φ.
- This field is likely many orders of magnitude heavier than the electroweak Higgs field.
- If the field evolves slowly enough, its potential energy dominates over its kinetic energy, causing negative pressure and leading to accelerated expansion: for scalar field, pressure = kinetic energy – potential energy



Models of Inflation





Models inspired by Symmetry breaking: Field evolves from small to large value

'Large field' Models

No consensus model at this time

Scalar Field and Expansion

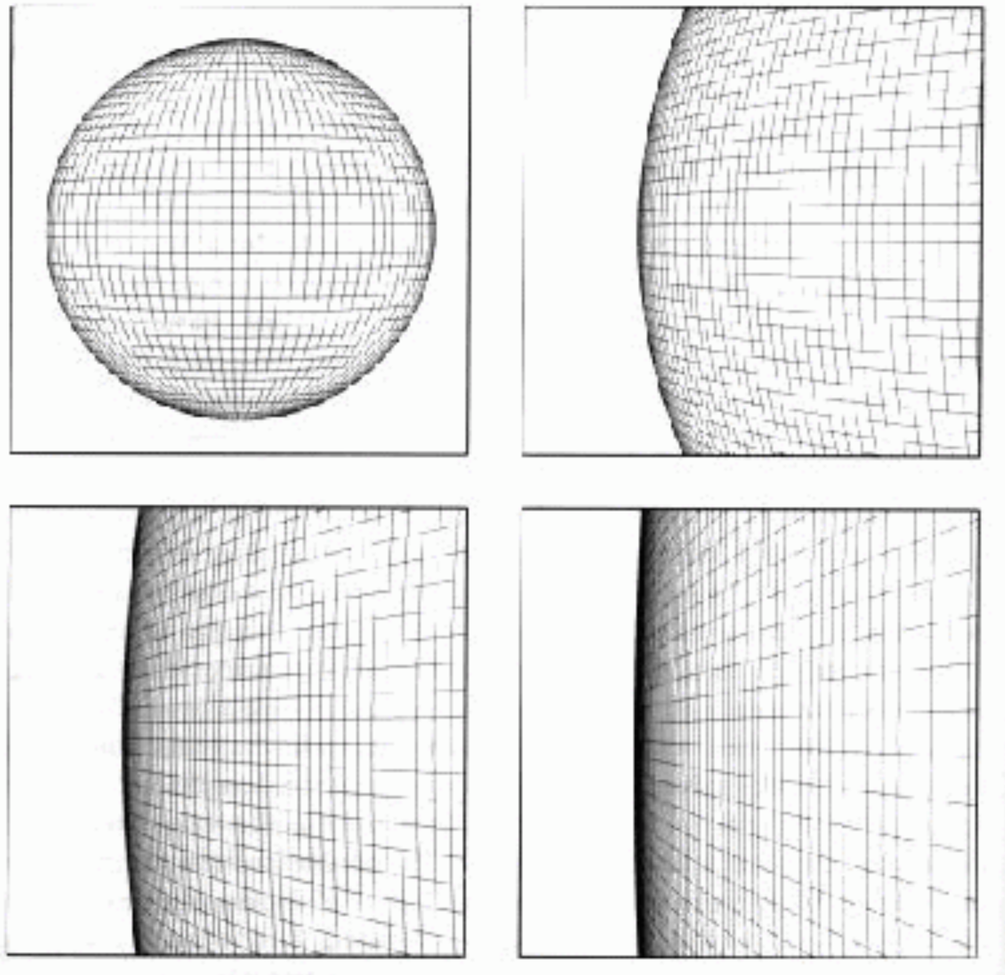
- For slowly rolling scalar field, $w = p_\varphi / \rho_\varphi \sim -1$, similar to vacuum energy, which drives accelerated expansion:

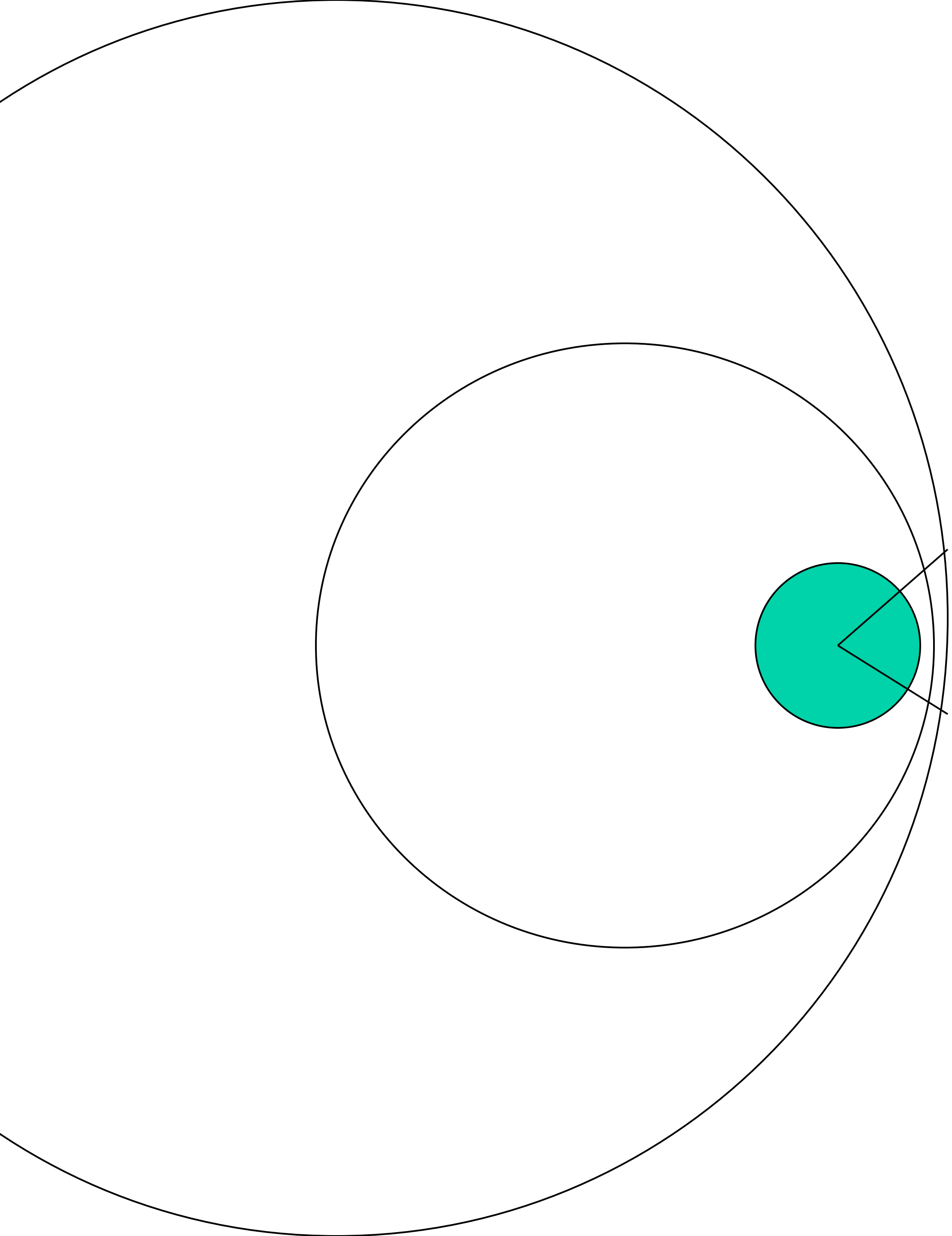
$$H^2 = \left(\frac{1}{a} \frac{\Delta a}{\Delta t} \right)^2 = \frac{8\pi G(\rho_{matter} + \rho_\varphi)}{3} - \frac{k}{a^2}$$

$$\frac{1}{a} \frac{\Delta}{\Delta t} \left(\frac{\Delta a}{\Delta t} \right) = -\frac{4\pi G}{3} (\rho_{matter} + \rho_\varphi + 3p_\varphi)$$

$$p_\varphi = w\rho_\varphi \text{ with } w \approx -1$$

Inflate to Flatness



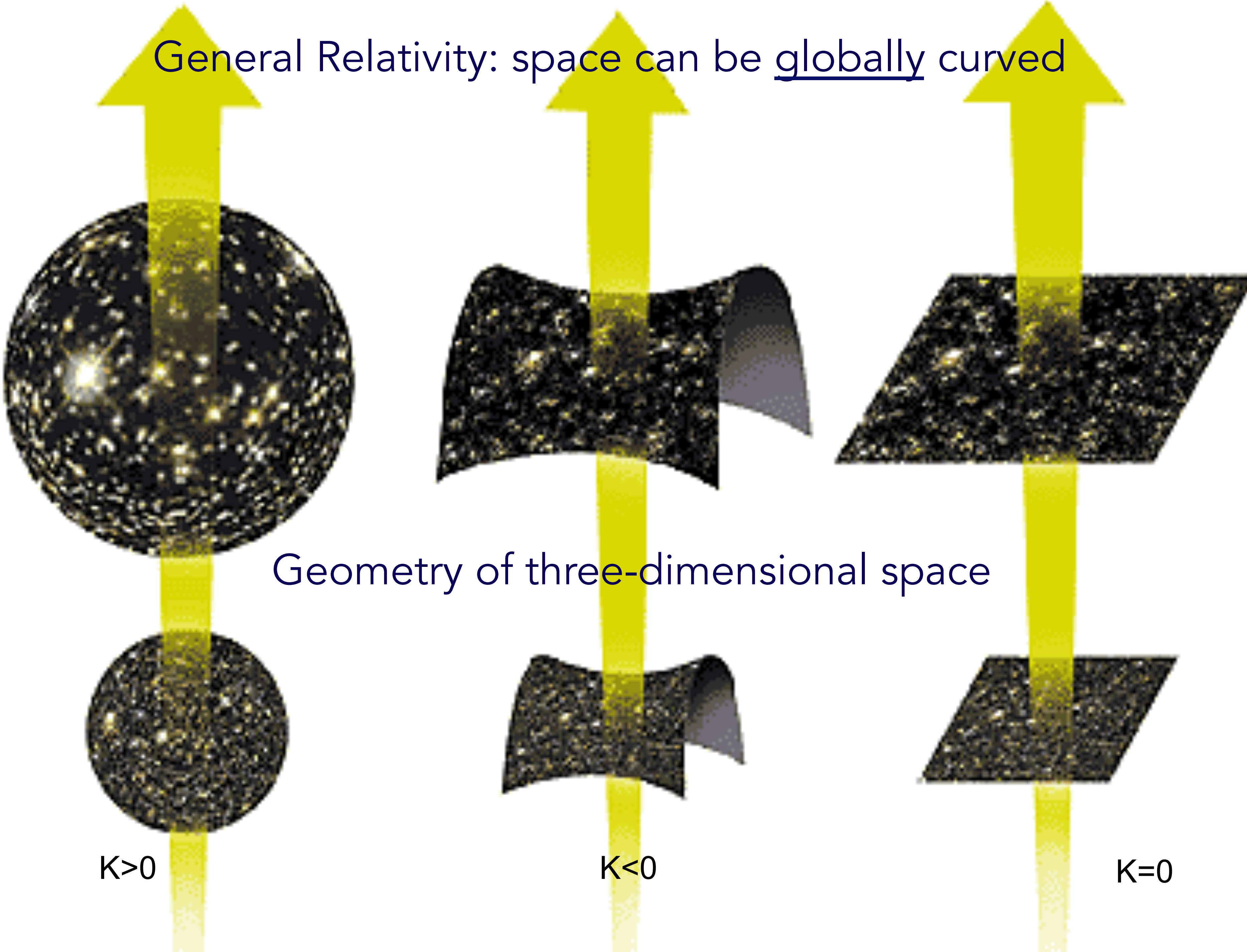


Solving the Flatness problem:

Since the Universe after inflation is much larger, the part we can see looks much flatter.

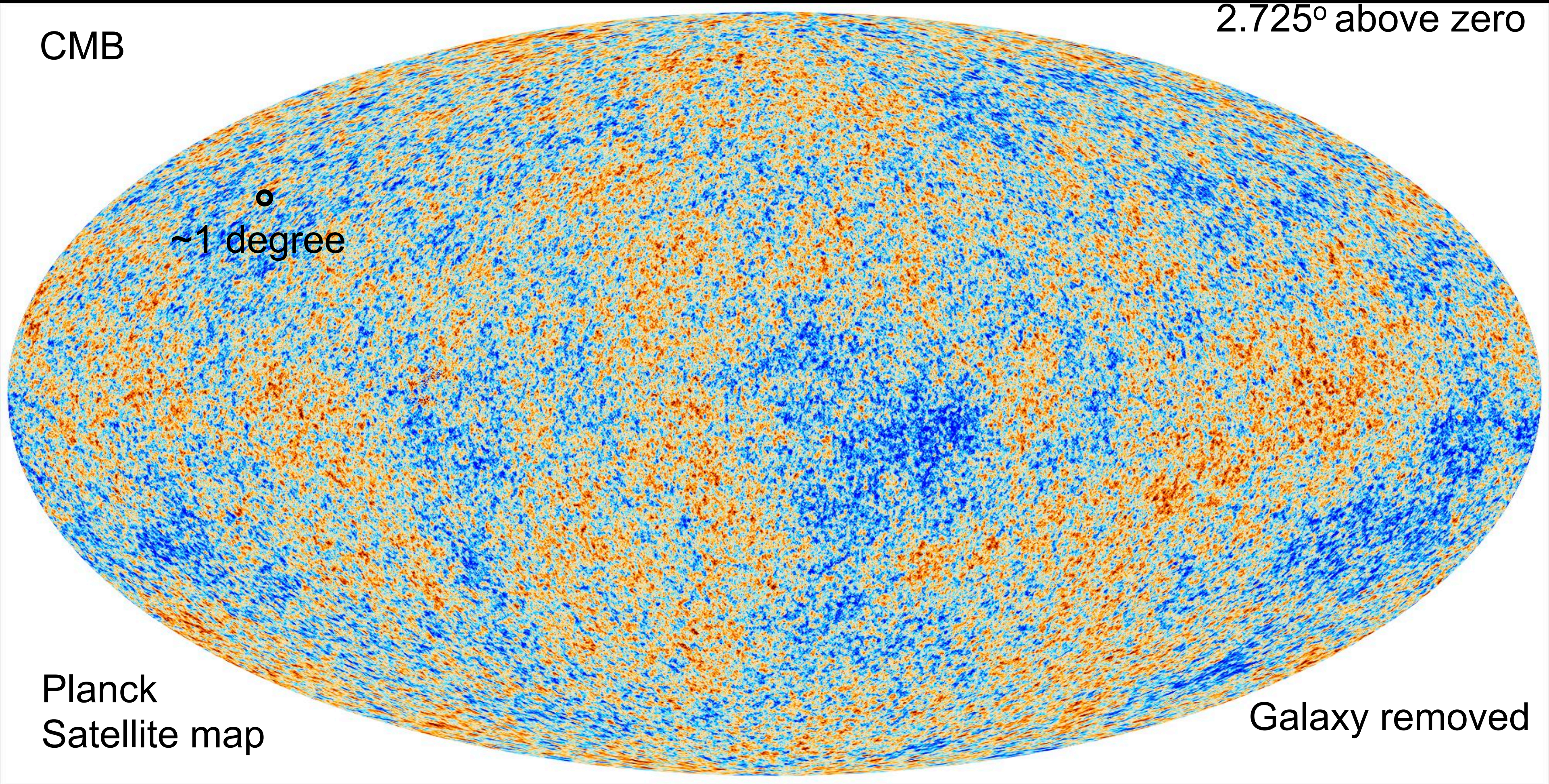
In fact, if inflation lasts longer than a minimal amount, the observable Universe should be indistinguishable from flat. This is in accord with CMB anisotropy measurements

General Relativity: space can be globally curved



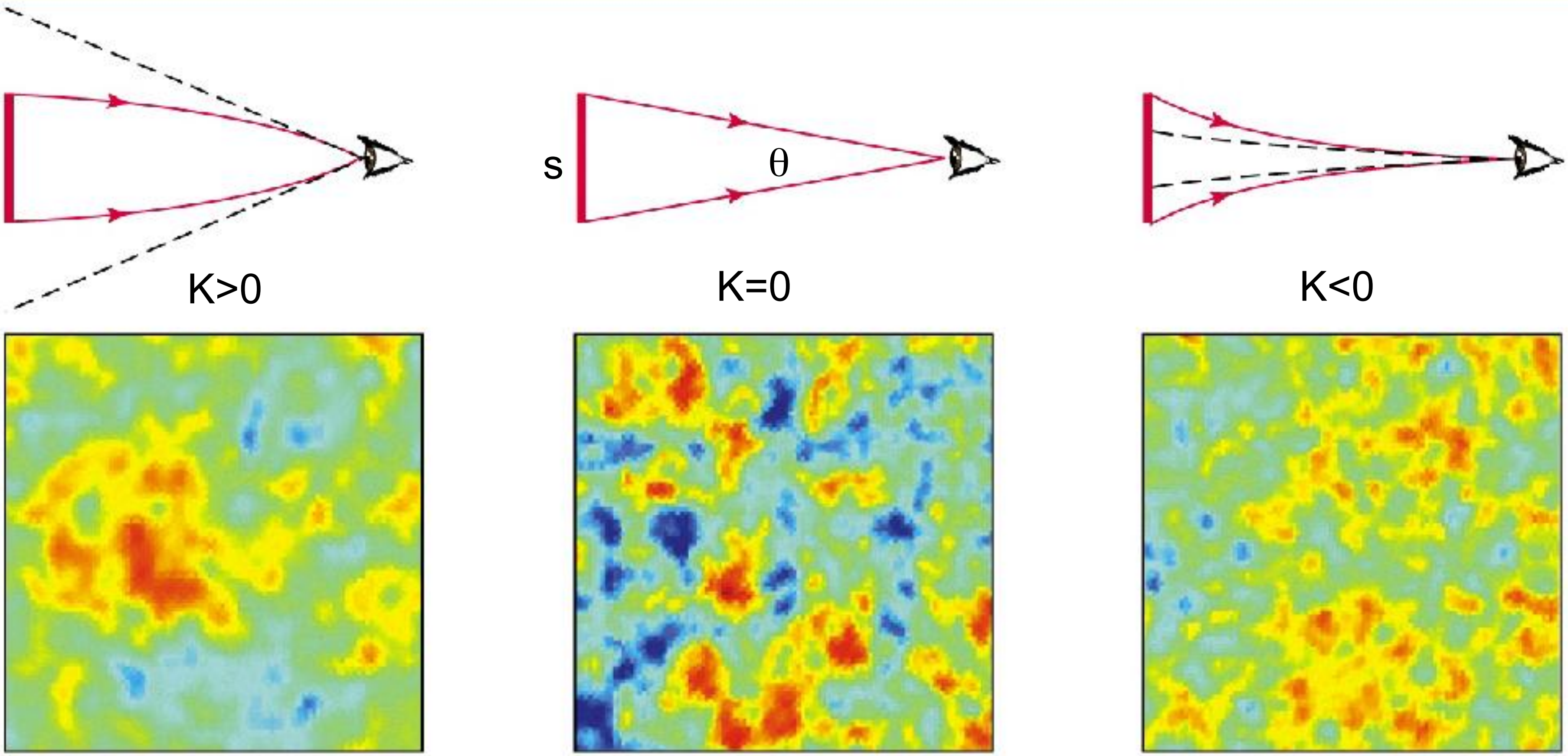
Geometry of three-dimensional space

Planck CMB Temperature Map



Hot and Cold spots differ in temperature by only ~10^{-5} degrees across the sky.

Seeing the Sound Horizon



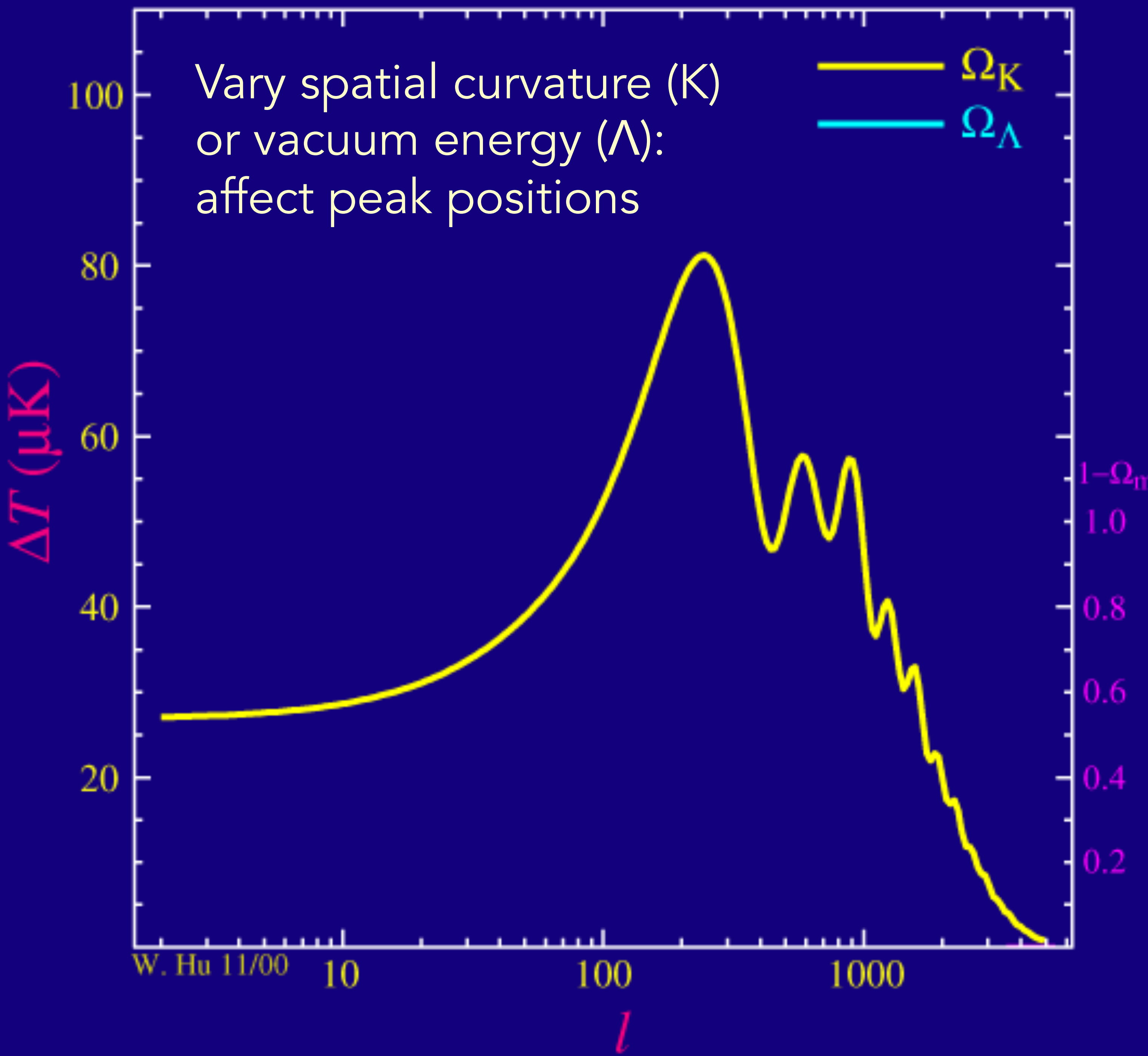
a If universe is closed, "hot spots" appear larger than actual size

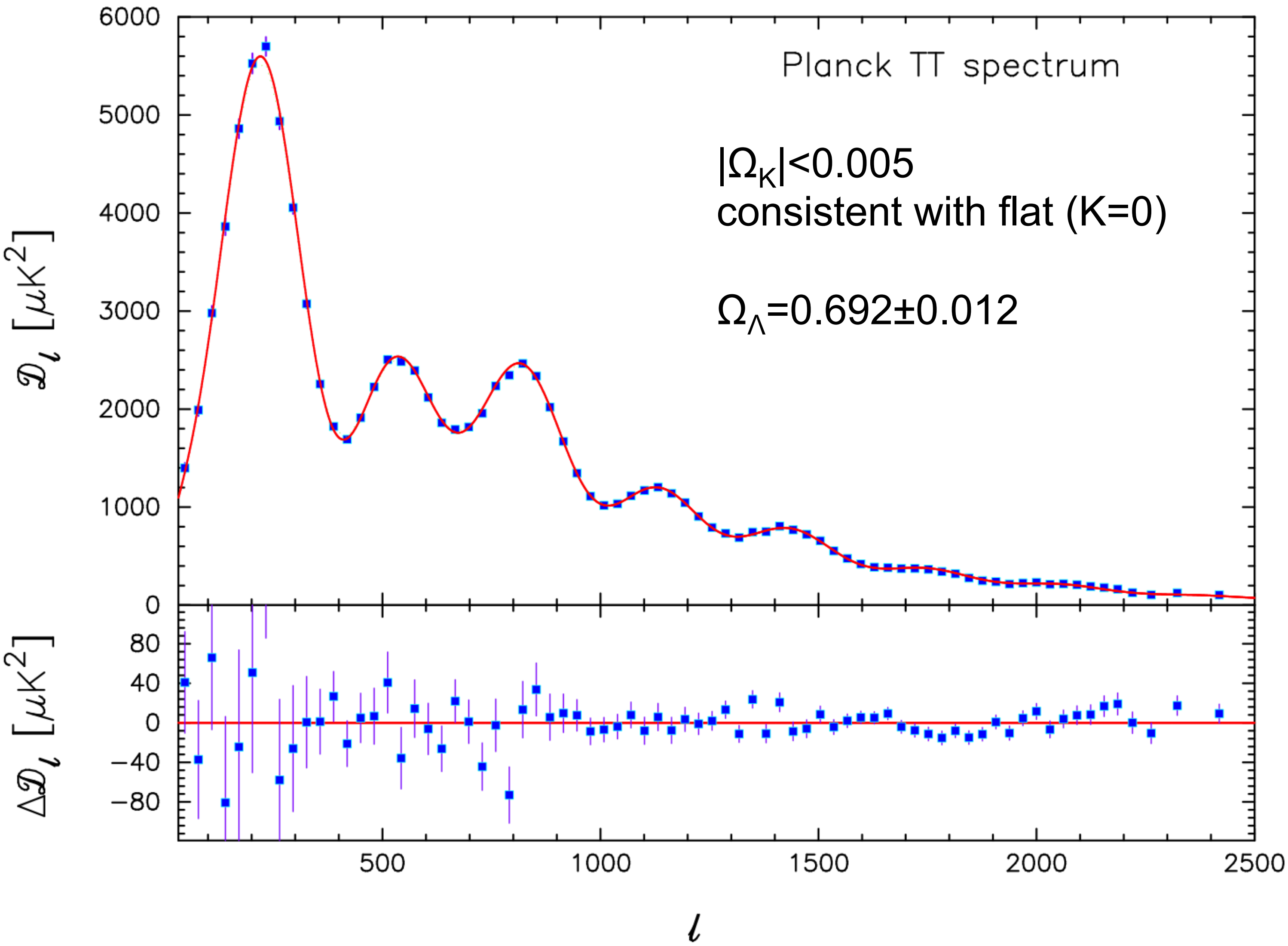
b If universe is flat, "hot spots" appear actual size

c If universe is open, "hot spots" appear smaller than actual size

CMB Maps tell us space is nearly flat

Vary spatial curvature (K)
or vacuum energy (Λ):
affect peak positions





Planck TT spectrum
$|\Omega_K|<0.005$
consistent with flat (K=0)
$\Omega_\Lambda=0.692\pm0.012$
$\mathcal{D}_\ell\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
ℓ
6000
5000
4000
3000
2000
1000
0
80
40
0
−40
−80
500
1000
1500
2000
2500

Minimal Duration of Inflation

How long should inflation last in order to solve the horizon and flatness problems?

For inflation occurring around the Grand Unification epoch, $t \sim 10^{-34}$ sec, the scale factor $a(t)$ should grow during inflation by at least a factor of $e^{60} \sim 10^{28}$.

This can happen rather quickly:

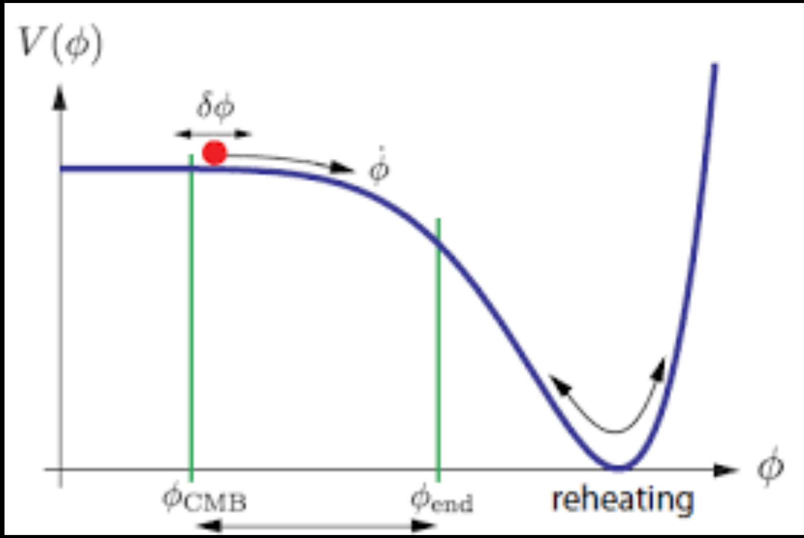
typically during inflation, $a(t) \sim e^{Ht}$

so this growth only requires 60 `expansion times':

e.g., from 10^{-35} seconds to 10^{-33} seconds

Note: during inflation, the Temperature and matter and radiation densities drop exponentially: the Universe becomes cold and empty

The End of Inflation: Reheating



When scalar field approaches the minimum of its potential, it speeds up and starts oscillating: large kinetic energy, no longer negative pressure, acceleration stops. Energy in oscillations leads to decay of the scalar field into lighter particles, reheating the cold, empty Universe to a hot, dense state again. This process must be efficient enough so baryogenesis, particle dark matter, and nucleosynthesis can occur at high Temperature. Inflation as Tabula Rasa.

Classical vs Quantum Mechanics

Suppose the Universe was a large pool table filled with billiard balls. In classical physics, if you know the positions x and momenta p (~velocities) of all the balls at any time, you can in principle predict their future positions and momenta with arbitrary precision.

Classical vs Quantum Mechanics

Suppose the Universe was a large pool table filled with billiard balls. In classical physics, if you know the positions x and momenta p (~velocities) of all the balls at any time, you can in principle predict their future positions and momenta with arbitrary precision.

In quantum mechanics, there is a *fundamental* uncertainty in how well you can simultaneously determine the position and momentum of a particle.

Heisenberg Uncertainty Principle

In quantum mechanics, there is a *fundamental* uncertainty in how well you can simultaneously determine the position x and momentum p of a particle:

Werner Heisenberg

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

Planck's constant

Quantum Mechanics

On macroscopic scales, this uncertainty is tiny: you don't need to know quantum mechanics to play billiards.

However, it implies that you cannot make infinitely precise predictions about the future positions and momenta of particles. Instead, you can predict the *probability* of a given particle having a specific position and momentum at some future time:
Schrodinger's equation describes how that probability evolves in time.

Erwin Schrodinger

Quantum Mechanics

The fact that quantum mechanics entails that only probabilistic statements can be made about the future is a fundamental shift in our understanding of physics (away from the classical, Newtonian view).

The role of probability in quantum mechanics differs from its role in, e.g., cards or dice. In those cases, there is no inherent uncertainty in the outcome—it is in principle knowable—and uncertainty just arises from our lack of complete knowledge of the system. In quantum mechanics, even with complete knowledge, one is limited to probabilistic statements due to the Uncertainty Principle.

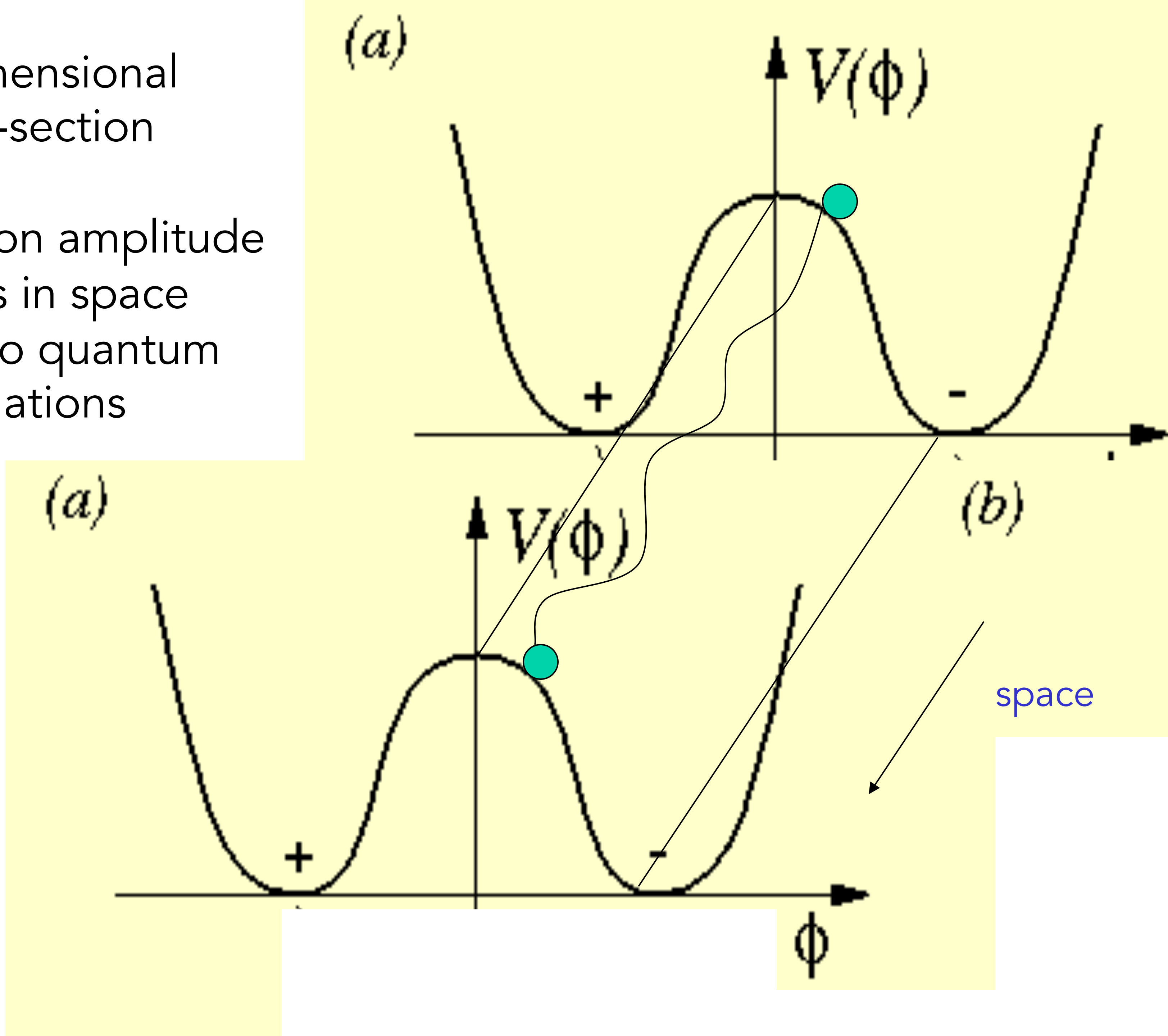
Quantum Fluctuations & Inflation

Classically, the inflaton scalar field can be homogeneous in space and roll down its potential at the same speed everywhere in the Universe: $\phi = \phi(t)$.

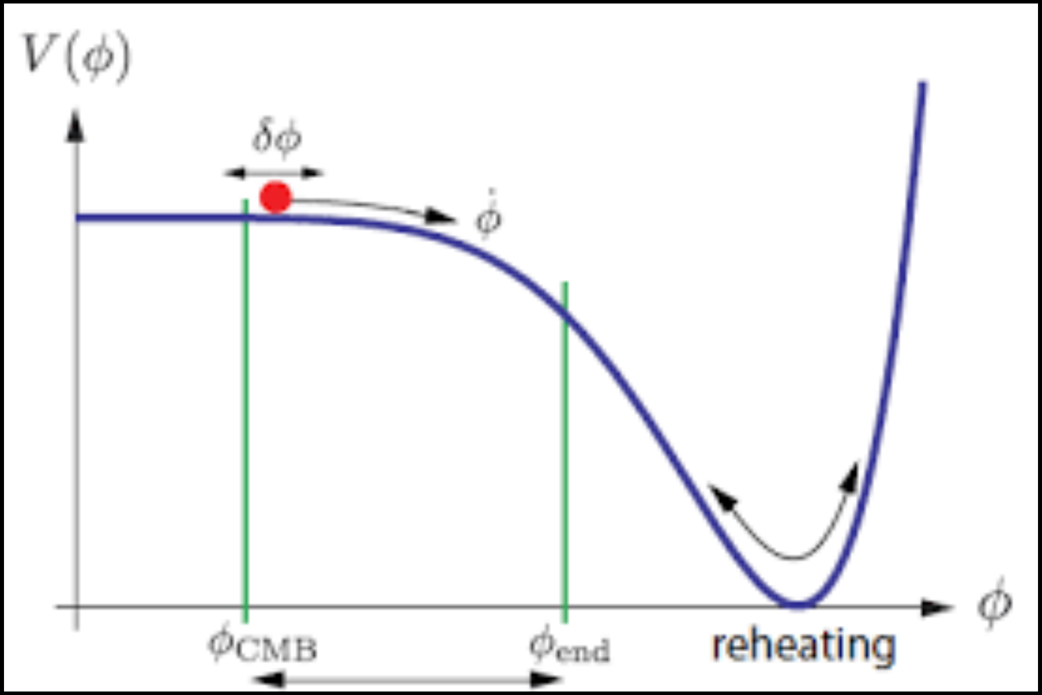
According to Quantum Mechanics, the amplitude (or rolling speed) of the field fluctuates: it differs from place to place by a small amount, $\phi = \phi(x,t)$. These quantum field fluctuations imply spatial fluctuations in the energy density of the Universe: points higher and lower on the potential hill $V(\phi)$.

1-dimensional
cross-section

Inflaton amplitude
varies in space
due to quantum
fluctuations



Quantum Fluctuations & Density Perturbations



Quantum Fluctuations & Density Perturbations

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During reheating, when ϕ decays, these fluctuations become spatial fluctuations in the density of all matter and radiation particles throughout the Universe.

The rapid expansion during inflation stretches these density fluctuations from submicroscopic scales to cosmological scales (by contrast, in everyday life, we don't notice quantum fluctuations since they're only significant on submicroscopic scales).

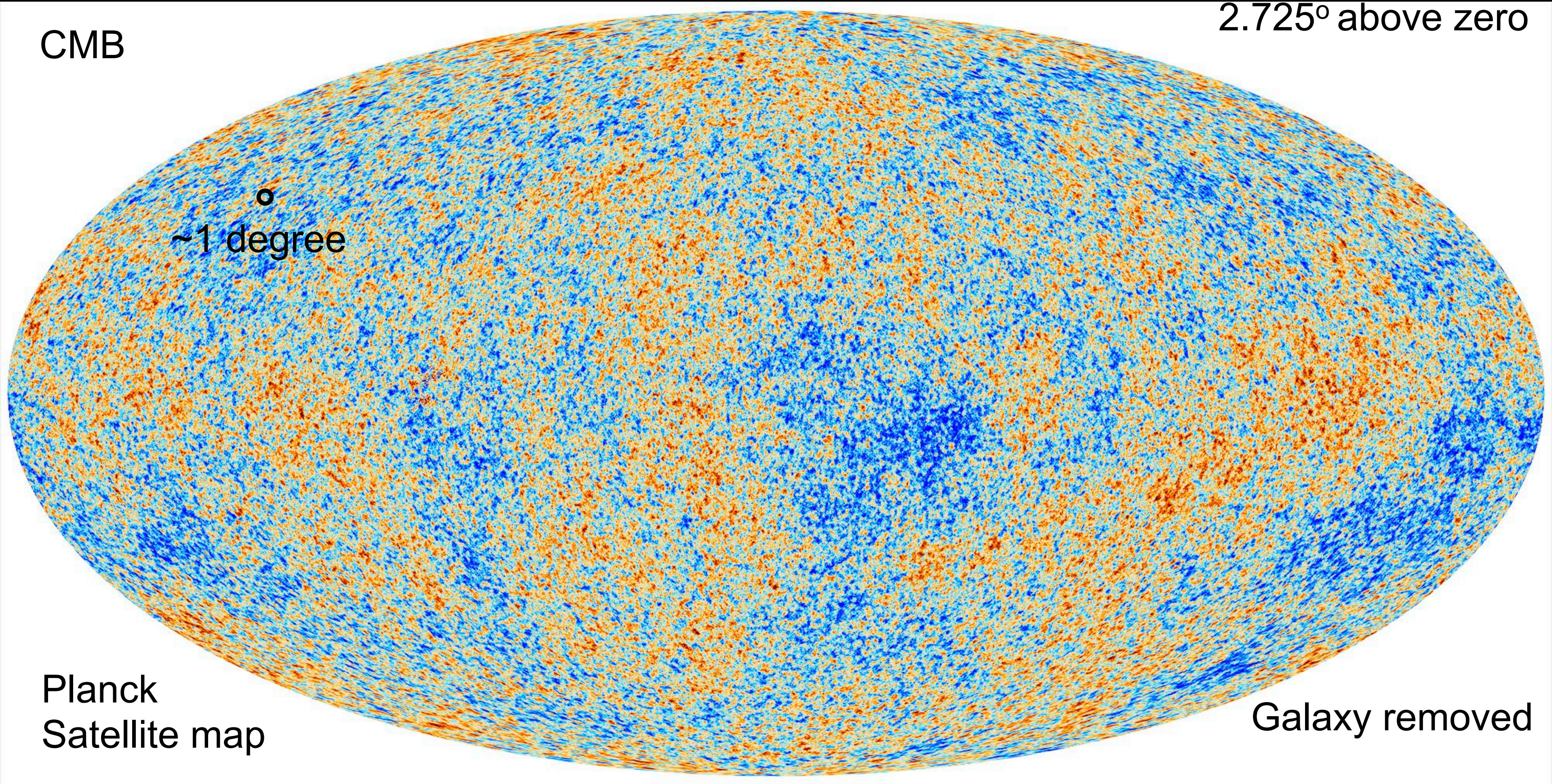
Inflation Density Perturbations & Cosmic Microwave Background

Quantum fluctuations of the inflaton field translate into spatial density fluctuations in all matter & radiation at the end of inflation.

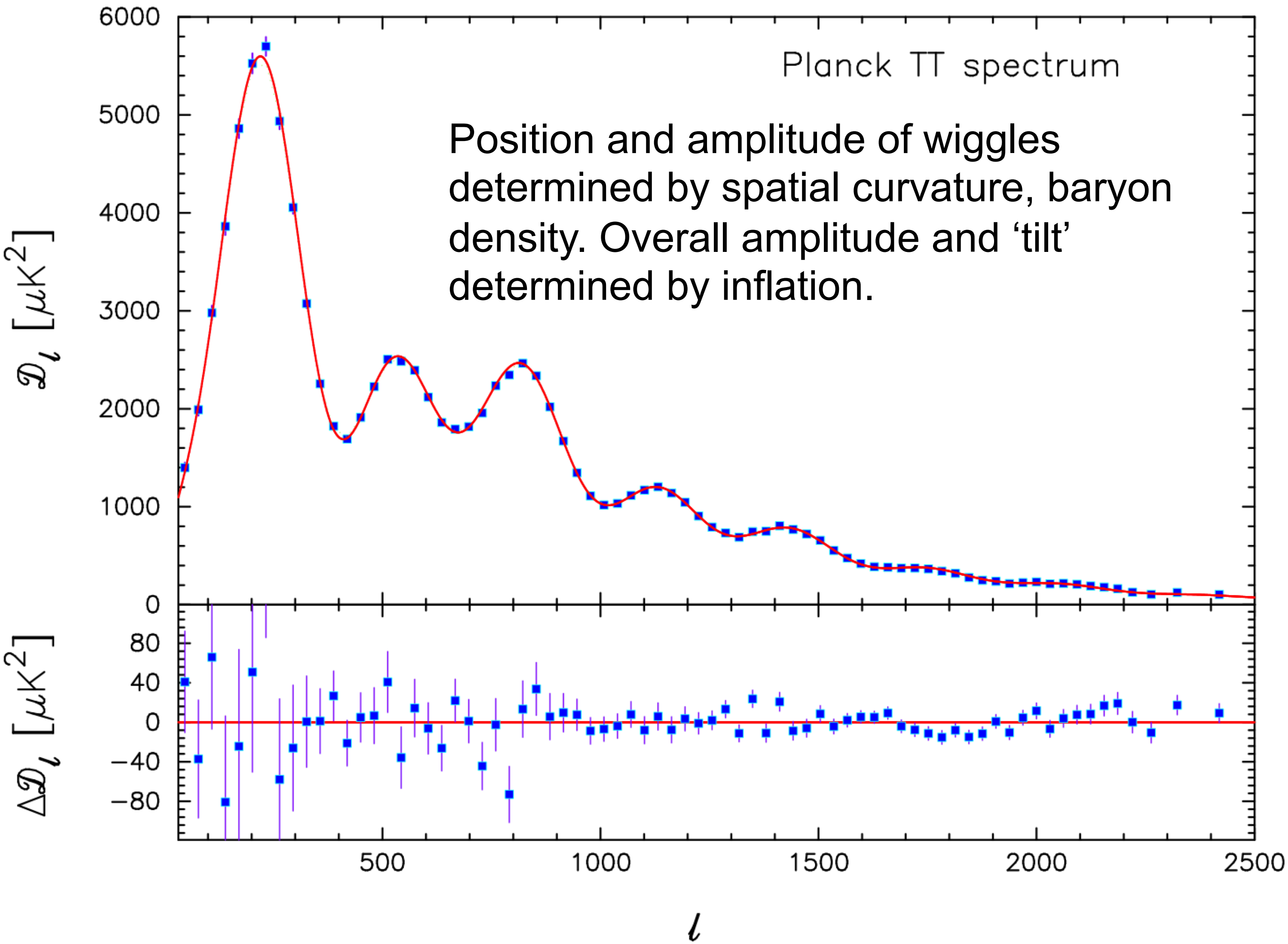
These fluctuations in energy density of radiation correspond to spatial fluctuations in the temperature of the Cosmic Microwave Background.

The pattern of hot and cold spots in the CMB mapped by WMAP, Planck, and other experiments agrees remarkably well with the predictions of inflation.

Planck CMB Temperature Map



Hot and Cold in CMB spots give a (filtered) picture of quantum fluctuations in the very early Universe.



Position and amplitude of wiggles determined by spatial curvature, baryon density. Overall amplitude and 'tilt' determined by inflation.

Gravity vs. Electromagnetism

- Maxwell:
  - Theory of Electromagnetism describes how electric charges create Electric Fields and how electric currents create Magnetic Fields.
  - Light explained as a travelling electromagnetic wave.
- Einstein:
  - General Relativity describes how mass-energy creates Gravitational Field (=Spacetime curvature).
  - Travelling gravitational waves (at the speed of light) also predicted by the theory: travelling distortions of spacetime

Gravity Waves from Inflation

Like all quantum fields, the gravitational field (the structure of spacetime) undergoes quantum fluctuations due to the Uncertainty Principle.

For the most part, these are only appreciable on submicroscopic lengthscales (the gravitational field of the Earth does not fluctuate wildly, fortunately for us). The Planck length ($\sim 10^{-43}$ cm) is the scale over which these spacetime fluctuations are expected to be large.

During inflation, however, these gravitational fluctuations are stretched from submicroscopic to astronomical scales (just as the fluctuations of the inflaton field itself). These long wavelength gravity fluctuations are gravitational waves.

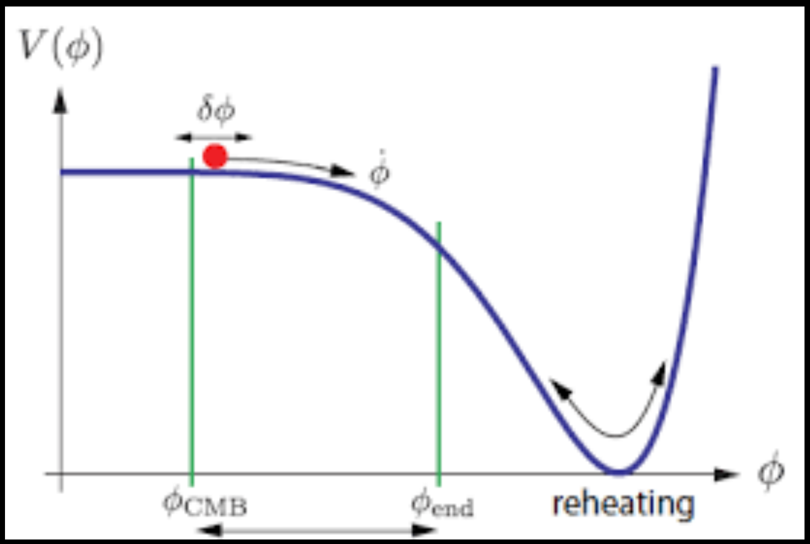
Gravity Waves from Inflation

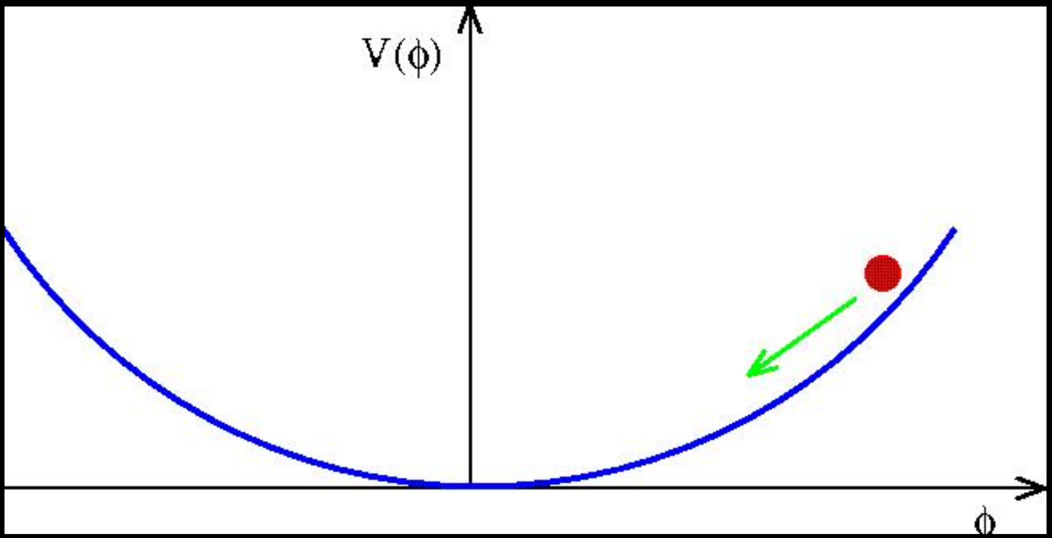
Gravity waves from inflation not expected to be seen in ground-based laser interferometer gravity wave detectors, such as Advanced LIGO, because they probe relatively short wavelength waves.

However, gravity waves from inflation would produce a distinctive signature in the Cosmic Microwave Background anisotropy.

CMB experiments at the South Pole, in Chile, and elsewhere are hunting for this signature of inflationary gravitational waves, which would be a smoking gun for inflation.

Gravity Waves can test models of Inflation





Models inspired by Symmetry breaking: Field evolves from small to large value. Expect little to no gravity wave signal.

'Large field' Models: typically expect detectable gravity wave signal in the CMB.

March 2014: BICEP2 experiment announces detection of inflation gravity waves in CMB polarization.

SCIENTIFIC AMERICAN™

Physics » News

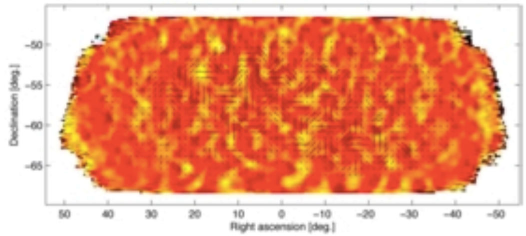
This article is from the In-Depth Report Cosmic Inflation and Big Bang Ripples

Gravitational Waves from Big Bang Detected

A curved signature in the cosmic microwave background light provides proof of inflation and spacetime ripples

By Clara Moskowitz | March 17, 2014

Physicists have found a long-predicted twist in light from the big bang that represents the first image of ripples in the universe called gravitational waves, researchers announced today. The finding is direct proof of the theory of inflation, the idea that the universe expanded extremely quickly in the first fraction of a nanosecond after it was born. What's more, the signal is coming through much more strongly than expected, ruling out a large class of inflation models and potentially pointing the way toward



Proof of gravitational waves created by cosmic inflation is shown here in this image of the cosmic microwave background radiation collected by the BICEP2 experiment at the South Pole. The proof comes in the form of a signature called B-mode polarization, a curling of the orientation, or polarization, of the light, denoted by the black lines on the image. The color indicates small temperature

"This is huge," says Marc Kamionkowski, professor of physics and astronomy at Johns Hopkins University, who was not involved in the discovery but who predicted back in 1997 how these gravitational wave imprints could be found. "It's not every day that you wake up and find out something completely new about the early universe. To me this is as Nobel Prize–worthy as it gets."

BICEP2 Collaboration

The Background Imaging of Cosmic Extragalactic Polarization 2 (BICEP2) experiment at the South Pole found a pattern called primordial B-mode polarization in the light left over from just after the big bang, known as the cosmic microwave background (CMB). This pattern, basically a curling in the polarization, or orientation, of the light, can be created only by gravitational waves produced by inflation. "It looks like a swirly pattern on the sky," says Chao-Lin Kuo, a physicist at Stanford University, who designed the BICEP2 detector. "We've found the smoking gun evidence for inflation and we've also produced the first image of gravitational waves across the sky."

January 2015: BICEP2+Planck joint analysis shows the BICEP signal was due to dust in our Milky Way, not inflation gravity waves.

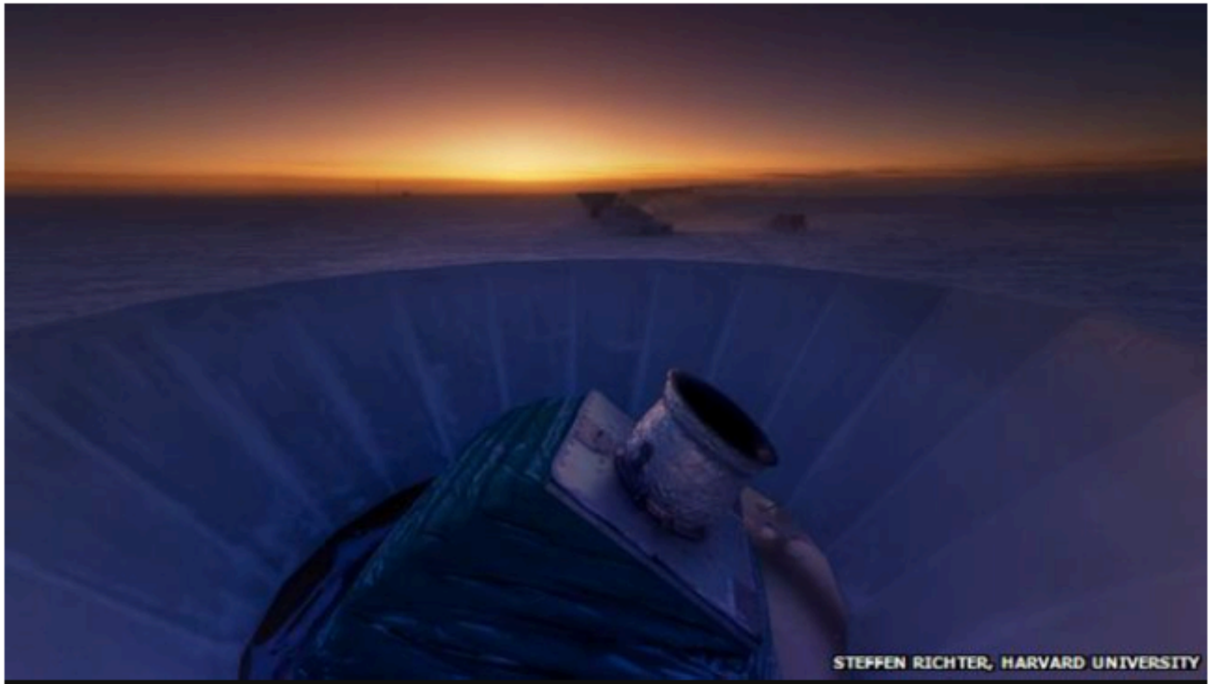
The hunt continues.

Science & Environment

Cosmic inflation: New study says BICEP claim was wrong

By Jonathan Amos
Science correspondent, BBC News

30 January 2015 | Science & Environment



The measurements were taken using the BICEP2 instrument at the South Pole Telescope facility

Scientists who claimed last year to have found a pattern in the sky left by the super-rapid expansion of space just fractions of a second after the Big Bang were mistaken.

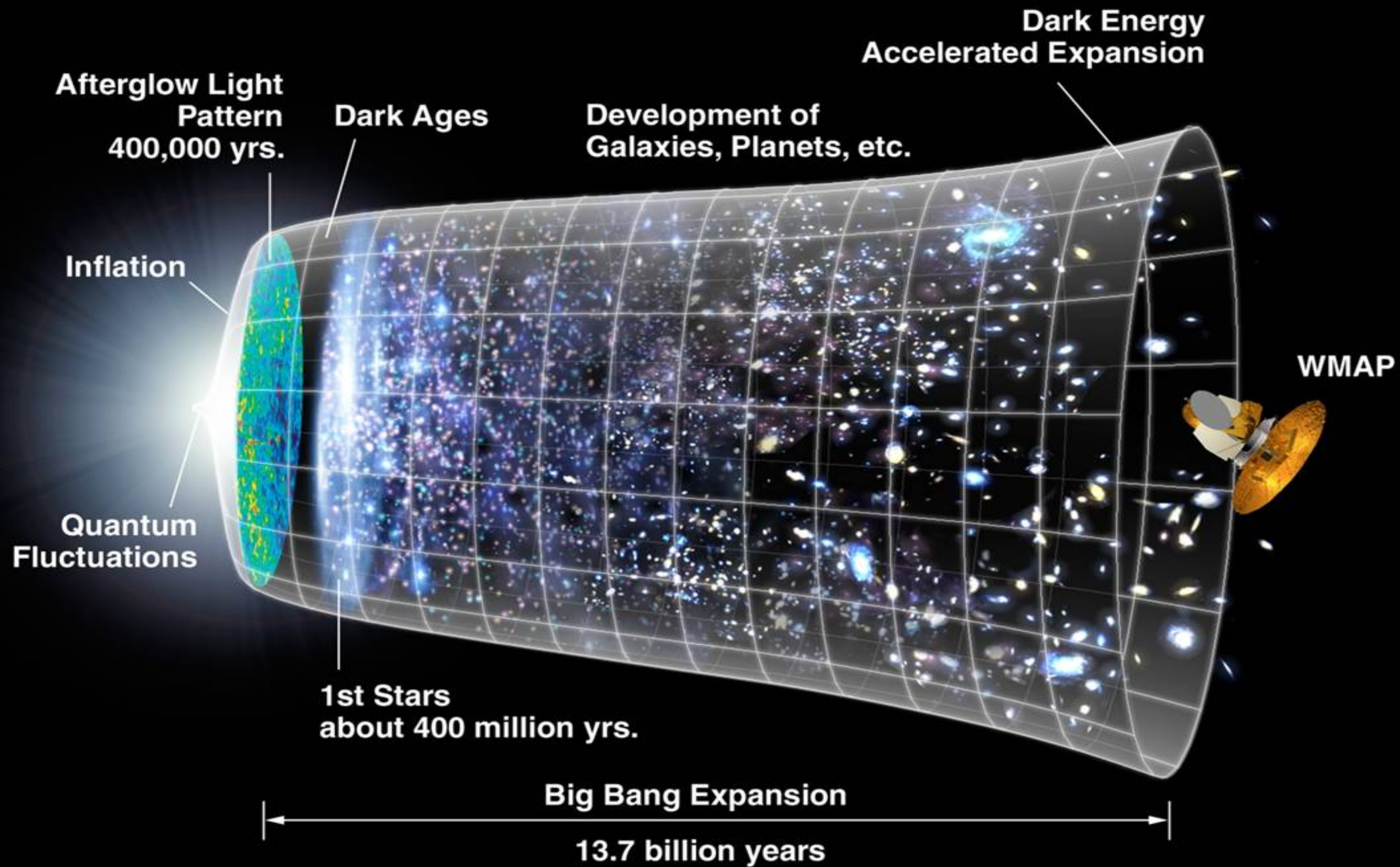
Inflation Density Perturbations & Large-scale Structure

Quantum fluctuations of the inflaton field translate into spatial density fluctuations in all matter & radiation at the end of inflation.

These fluctuations in energy density of radiation correspond to fluctuations in the temperature of the Cosmic Microwave Background, consistent with Planck, WMAP,…

These density perturbations subsequently grow in amplitude due to gravity: overdense regions become more dense, underdense regions less dense. Overdense regions eventually collapse (stop expanding) and form gravitationally bound systems: galaxies, clusters,… Pattern of large-scale structures we see is remarkably consistent with this scenario.

Brief History of the Universe



All the large-scale structure we see in the Universe (galaxies, cluster cosmic web) likely originated from inflation quantum fluctuations.

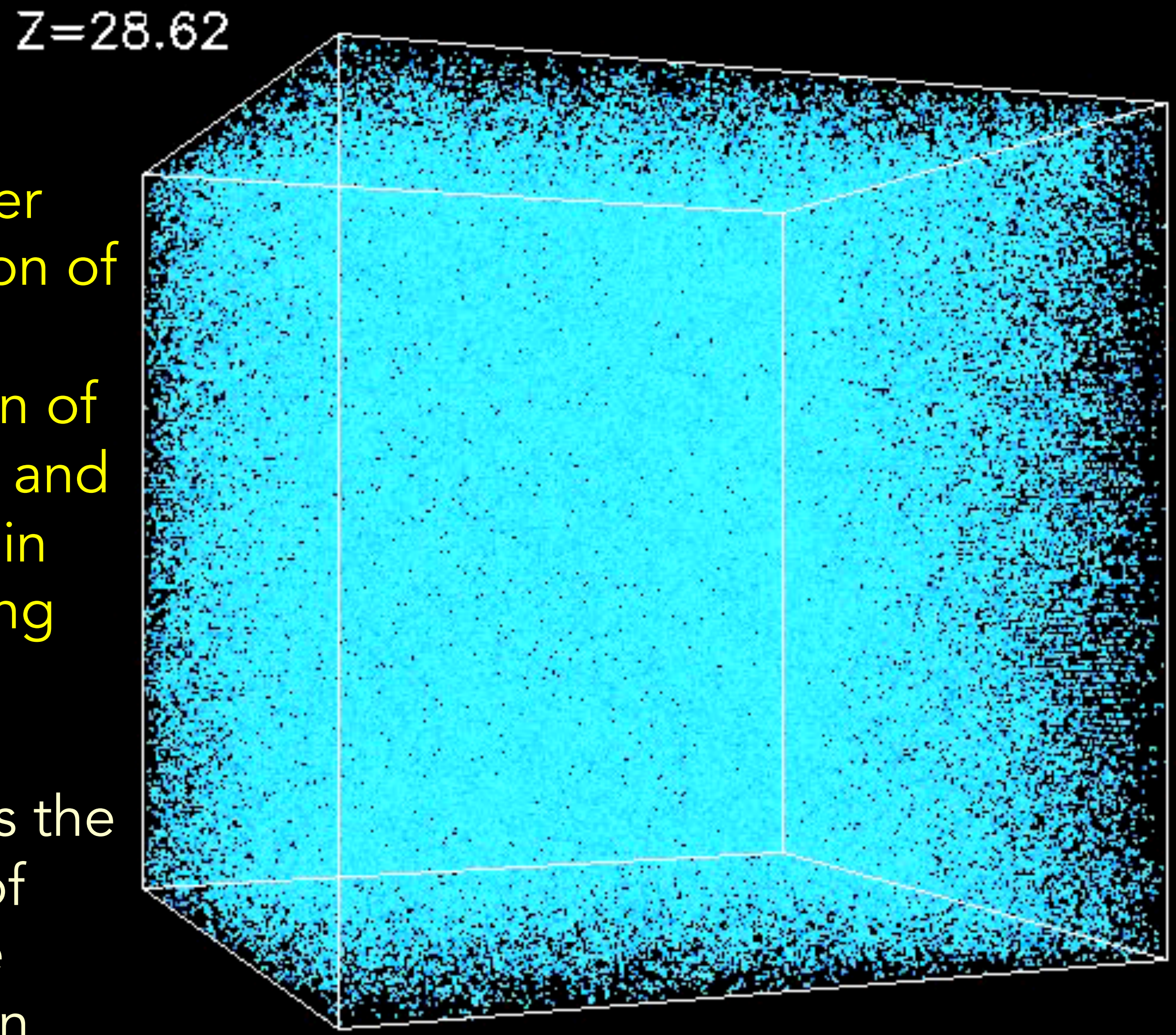
The Structure Formation Cookbook

1. Initial Conditions: Start with a Theory for the Origin of Density Perturbations in the Early Universe
   Your favorite Inflation model (constrained by CMB)

2. Cooking with Gravity: Growing Perturbations to Form Structure
   Set the Oven to Cold, Hot, or Warm Dark Matter
   Season with a few Baryons and add Dark Energy

3. Let Cool for 14 Billion years (simulate on a supercomputer)

4. Compare with CMB and galaxy surveys and adjust recipe as needed.



Computer Simulation of the formation of Galaxies and Clusters in Expanding Universe

Gravity is the engine of structure formation

Z=40.52

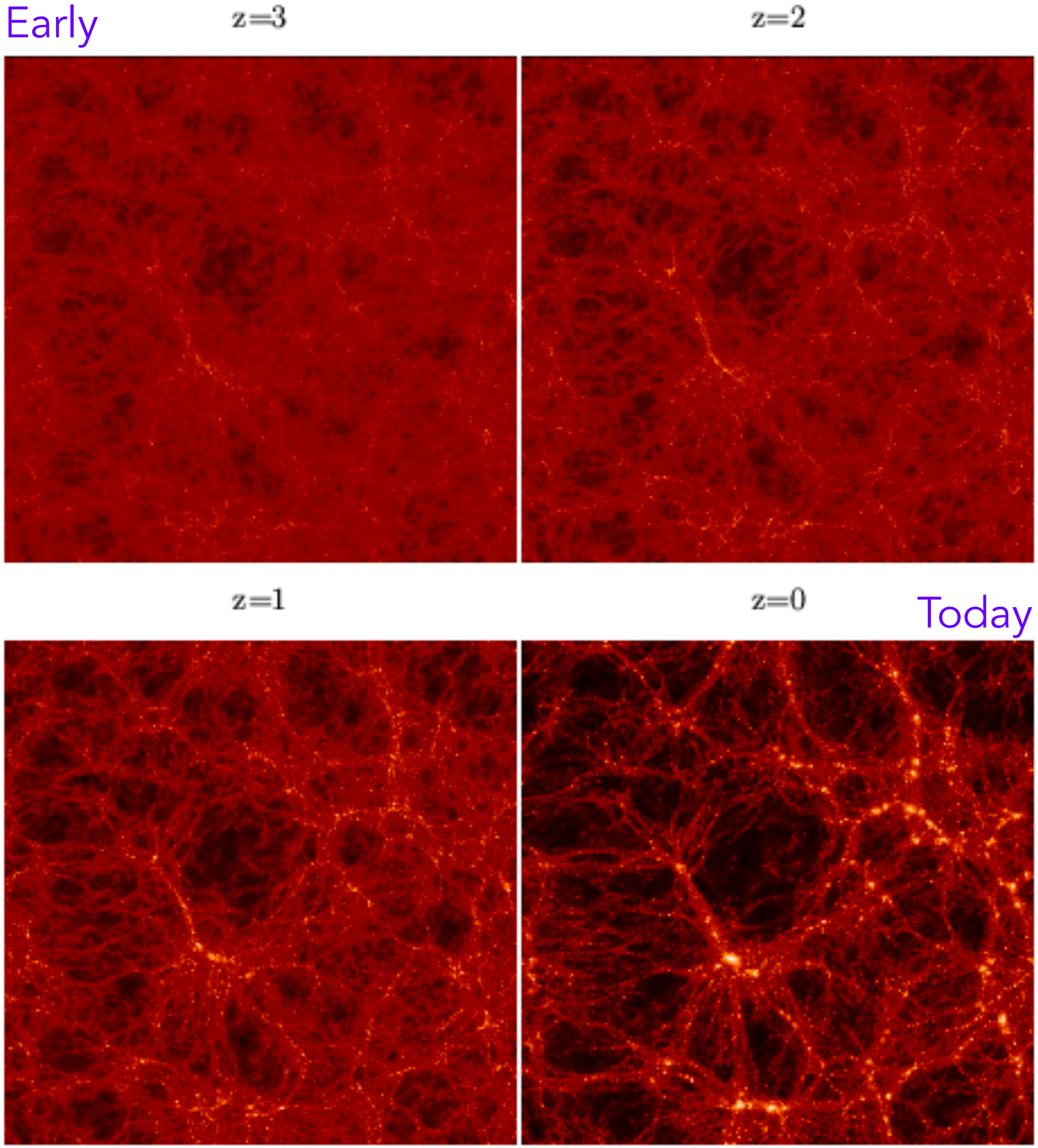
Formation of a (lumpy) halo of Dark Matter

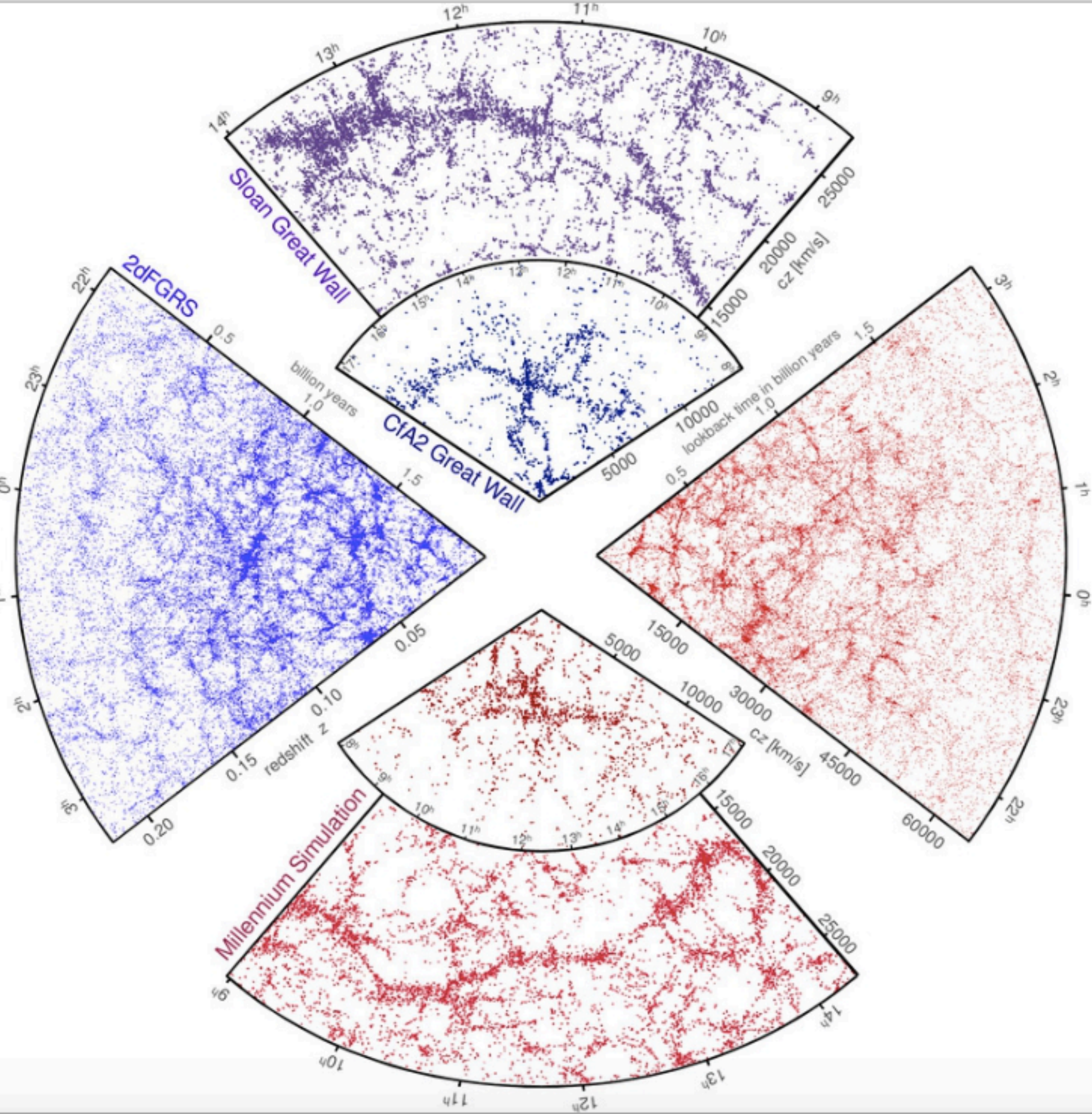
Kravtsov

Evolution of Structure in a <u>Simulated</u> Universe filled with Cold Dark Matter and Dark Energy

`The Cosmic Web'

Matches the structures seen in galaxy surveys





Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
billion years
lookback time in billion years
redshift z
cz [km/s]