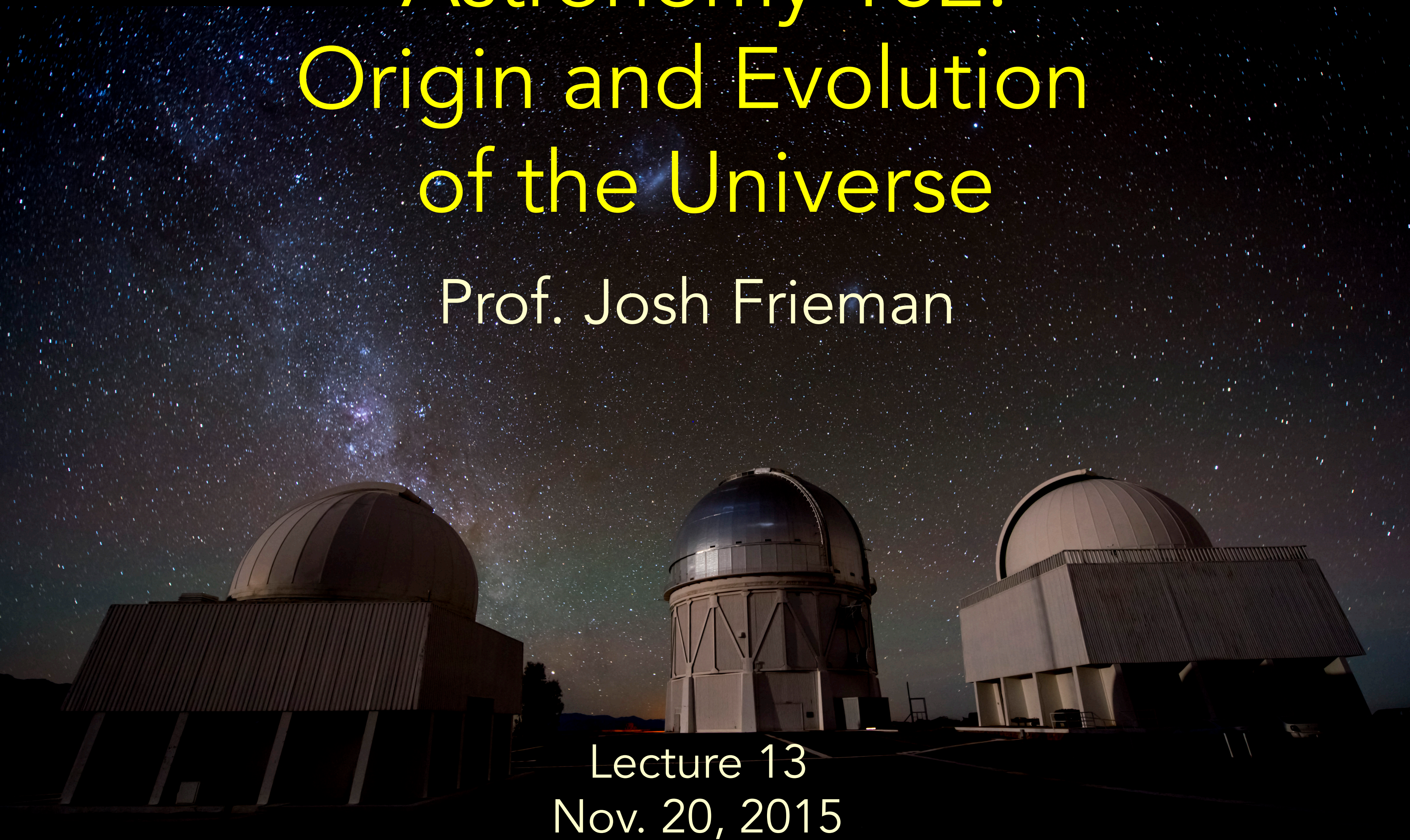
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 13
Nov. 20, 2015

Today

- Particle Physics & the Early Universe
  - Baryogenesis
  - The Inflationary Scenario

Assignments

- Today: Essay 4 due on HH, Chapter 12.
- 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*.

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

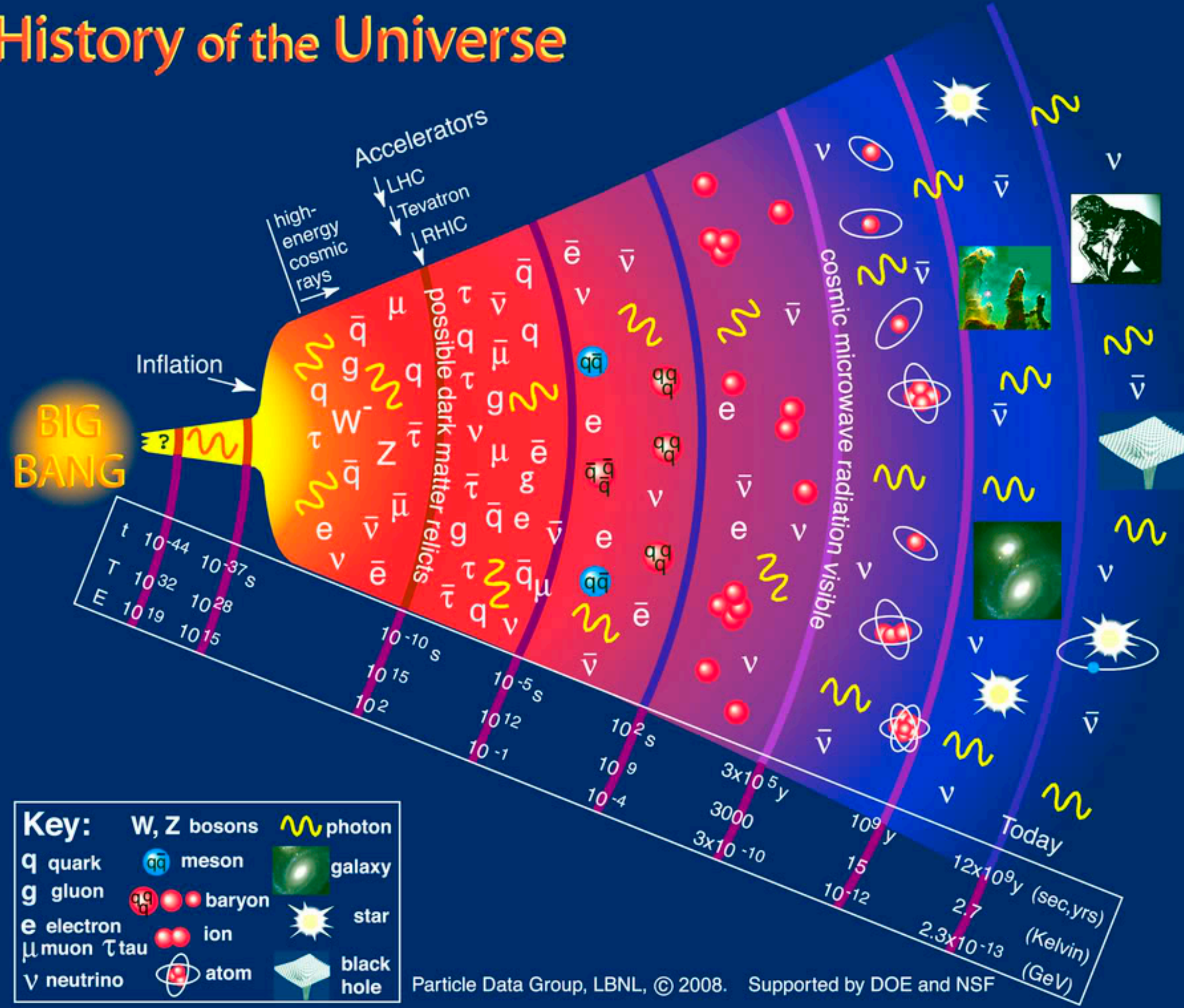
Cosmic History

- Going back in time from the present toward the Big Bang, first important epoch we reached was H recombination/photon decoupling at t ~ 380,000 years (T ~ 3000 deg).

- Continuing back, the next major epoch was that of Big Bang Nucleosynthesis, at t ~ 3 minutes (T ~ 10^9 deg).

- Earlier still, Weakly Interacting Massive Particles, prime candidates for cold dark matter, would have frozen out at $t \sim 10^{-10}$ sec ($T \sim 10^{15}$ deg).

History of the Universe



Symmetry & Unification

well-tested

1800's: electricity & magnetism given a unified description in Maxwell's theory of Electromagnetism
1930's: Initial Theory of Weak Interactions (Fermi)
1960's: Electromagnetic & weak interactions unified in electroweak theory (Glashow, Weinberg, Salam)
1970's: Theory of Strong Interactions (QCD)
1970's: Standard Model of Particle Physics

speculative

1970's: Electroweak & strong interactions unified in Grand Unified Theories (GUTs)
1980's-20??: Unify electroweak, strong, and gravitational interactions in Superstring Theory

Unification of Forces

<table>
<tr><th>Strong</th><th>Electromagnetic</th><th>Weak</th><th>Gravity</th></tr>
<tr><td>hadrons: p, n;
pions: $\pi^{\pm}, \pi^{0}$;
(QCD: quarks, gluons)</td><td>charged particles:
e^{-}, μ^{-}, τ^{-};
$p; \pi^{\pm}$</td><td>p, n, π; e, μ, τ;,
neutrinos:
ν_e, ν_μ, ν_τ</td><td>all particles (always attractive)</td></tr>
<tr><td>nuclear binding; energy in stars</td><td>atoms, crystals, molecules; light; chemical energy</td><td>decays: $n \to pe^{-}\bar{\nu}_e$; element synthesis</td><td>weight; binding of solar system, stars, galaxies</td></tr>
<tr><td></td><td>$\leftarrow$ $E + B$ $\rightarrow$
(Maxwell)</td><td></td><td></td></tr>
<tr><td>$\leftarrow$ QCD $\rightarrow$</td><td colspan="2">$\leftarrow$ Electroweak $(SU(2) \times U(1))$ $\rightarrow$</td><td></td></tr>
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</table>

Unification of Forces

Strong	Electromagnetic	Weak	Gravity
hadrons: p, n; pions: $\pi^{\pm}, \pi^{0}$; (QCD: quarks, gluons)	charged particles: e^{-}, μ^{-}, τ^{-}; p; $\pi^{\pm}$	p, n, π; e, μ, τ;, neutrinos: ν_e, ν_μ, ν_τ	all particles (always attractive)
nuclear binding; energy in stars	atoms, crystals, molecules; light; chemical energy	decays: $n \rightarrow pe^{-}\bar{\nu}_e$; element synthesis	weight; binding of solar system, stars, galaxies
	$\leftarrow \quad E + B \quad \rightarrow$ (Maxwell)		
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The Standard Model

Logarithmic view of Cosmic History

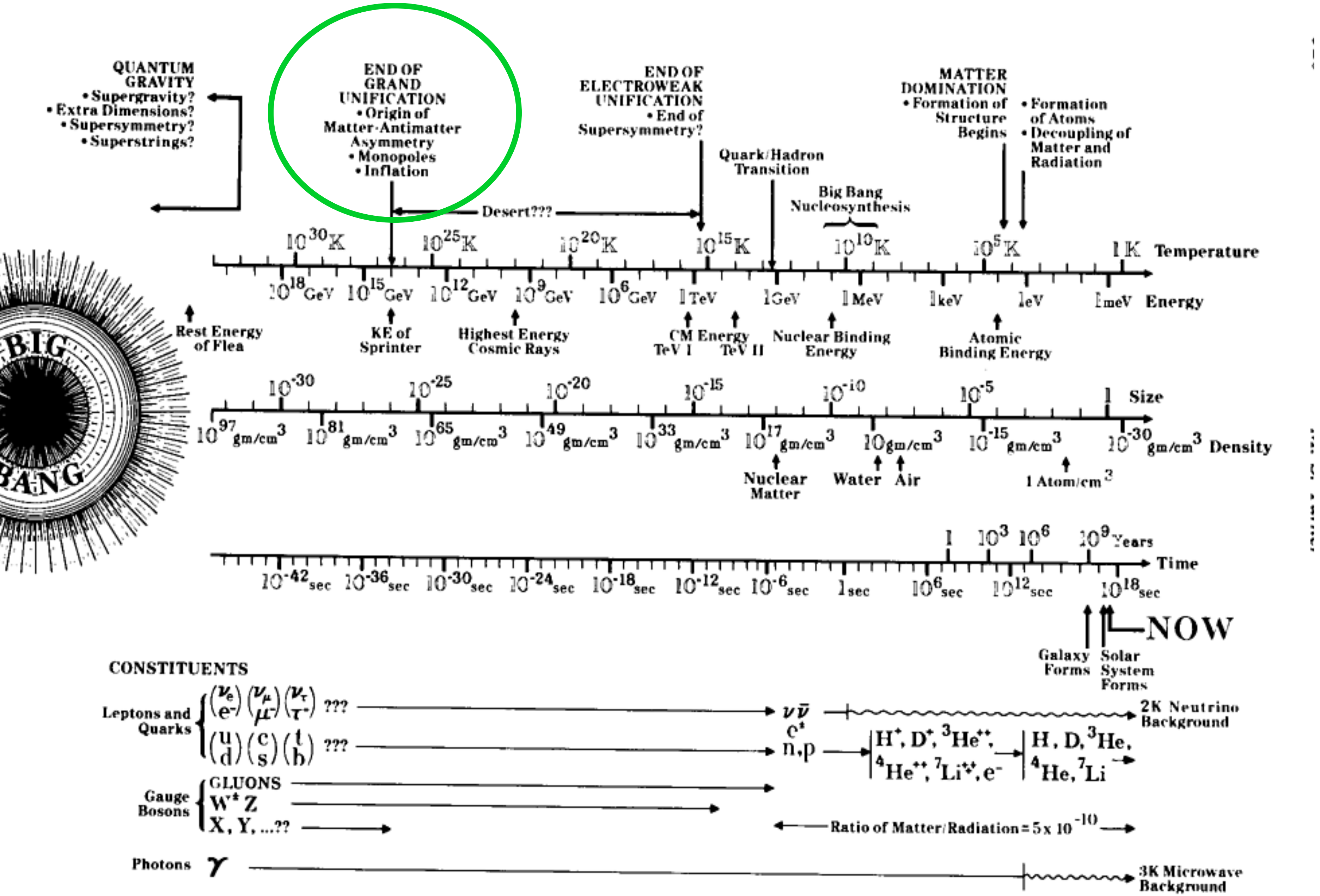


Fig. 1.5.

The Baryon Asymmetry

Beyond the electroweak scale (maximum energies reached in present particle accelerators), laws of physics become increasingly speculative. We can gain clues about these laws from the early Universe relics they should produce.

BBN & CMB: there is roughly 1 baryon for every two billion photons in the Universe.

There are approximately *zero* anti-baryons for every two billion photons. (Substantial amount of anti-matter would lead to annihilations with matter, which we do not observe.)

Conclude that the (baryonic) Universe is essentially composed of matter, not anti-matter: there is a Baryon Asymmetry.

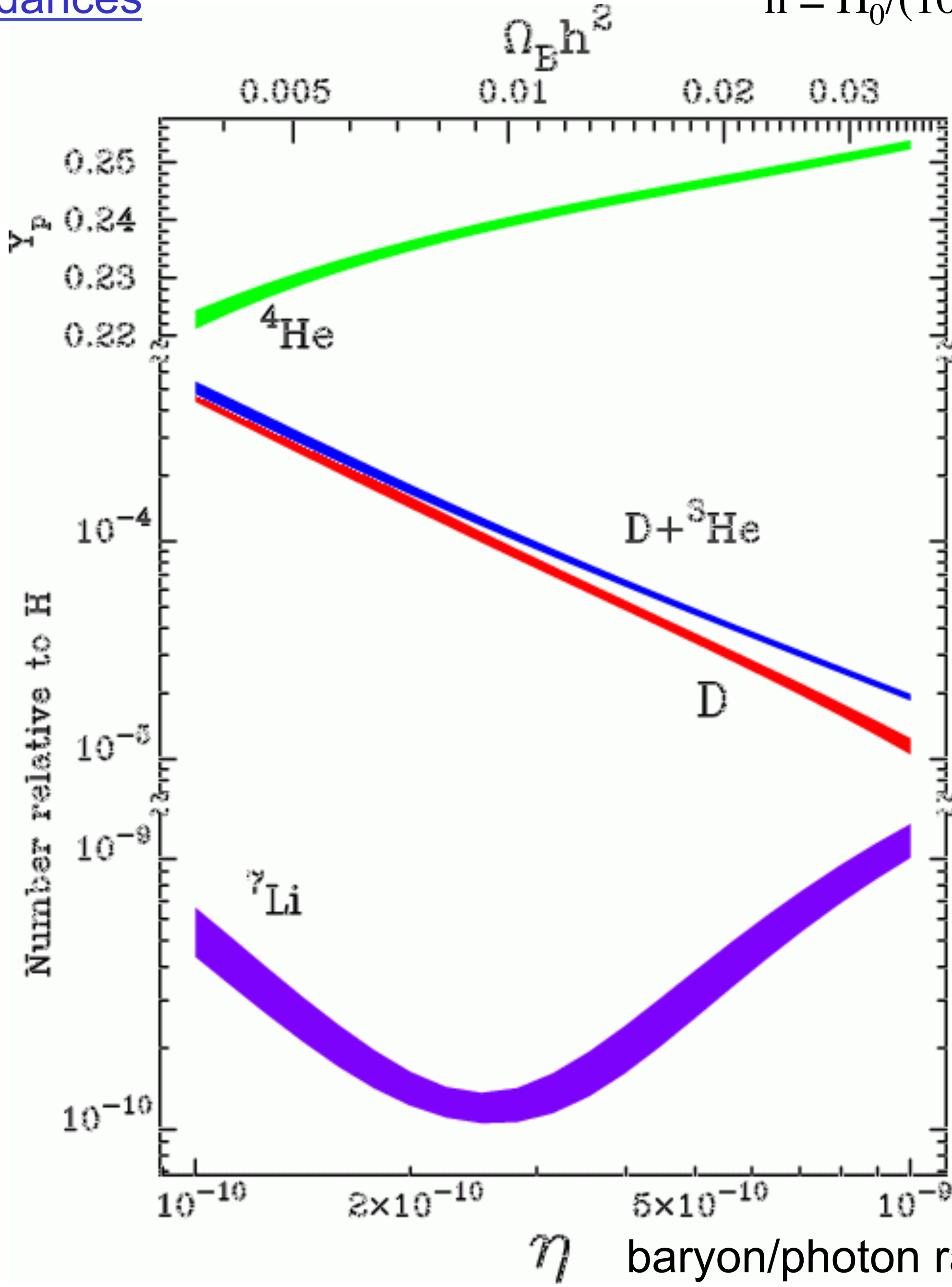
BBN predicted abundances

h = H_0/(100 km/sec/Mpc)

Fraction of baryonic mass in He^4

Deuterium to Hydrogen ratio

Lithium to Hydrogen ratio

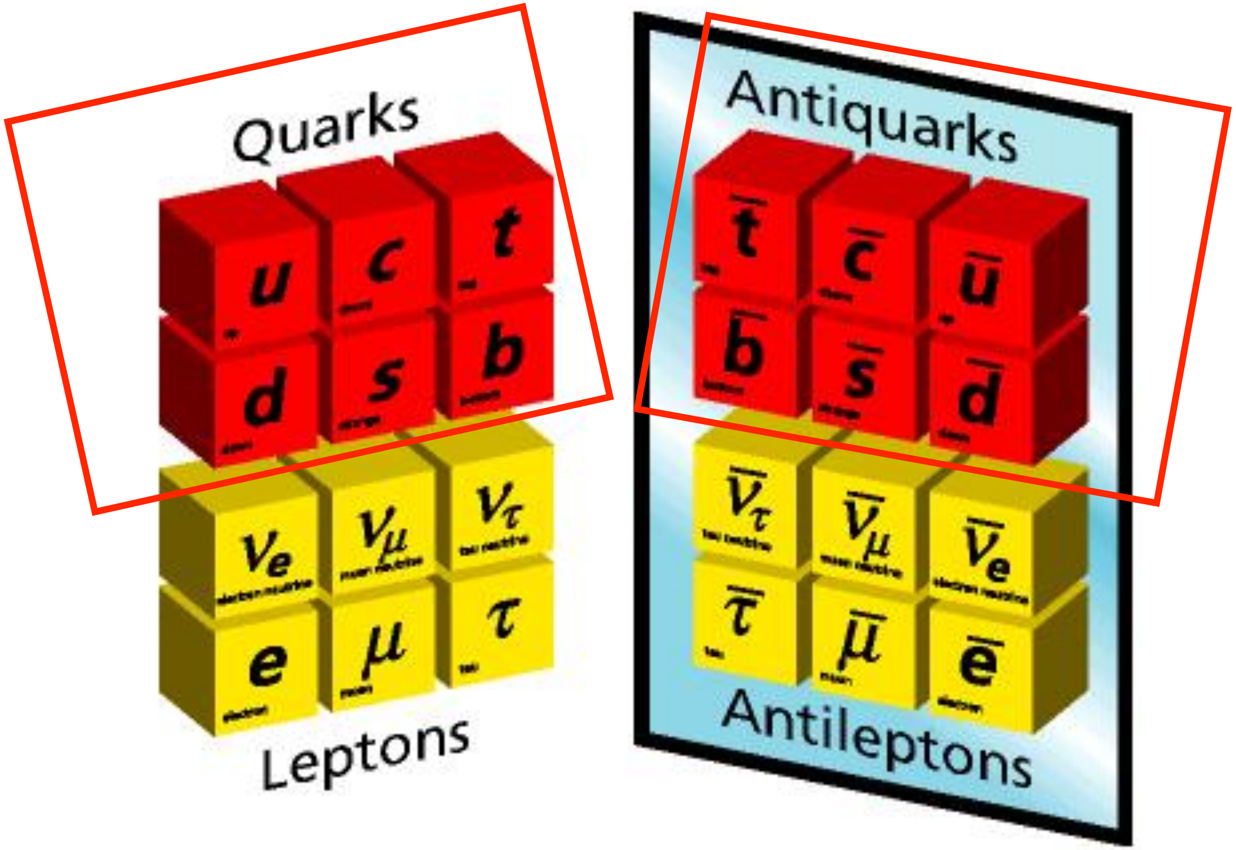


baryon/photon ratio

CMB+BBN: One baryon for every 2 billion CMB photons in the Universe

Particles & Anti-Particles

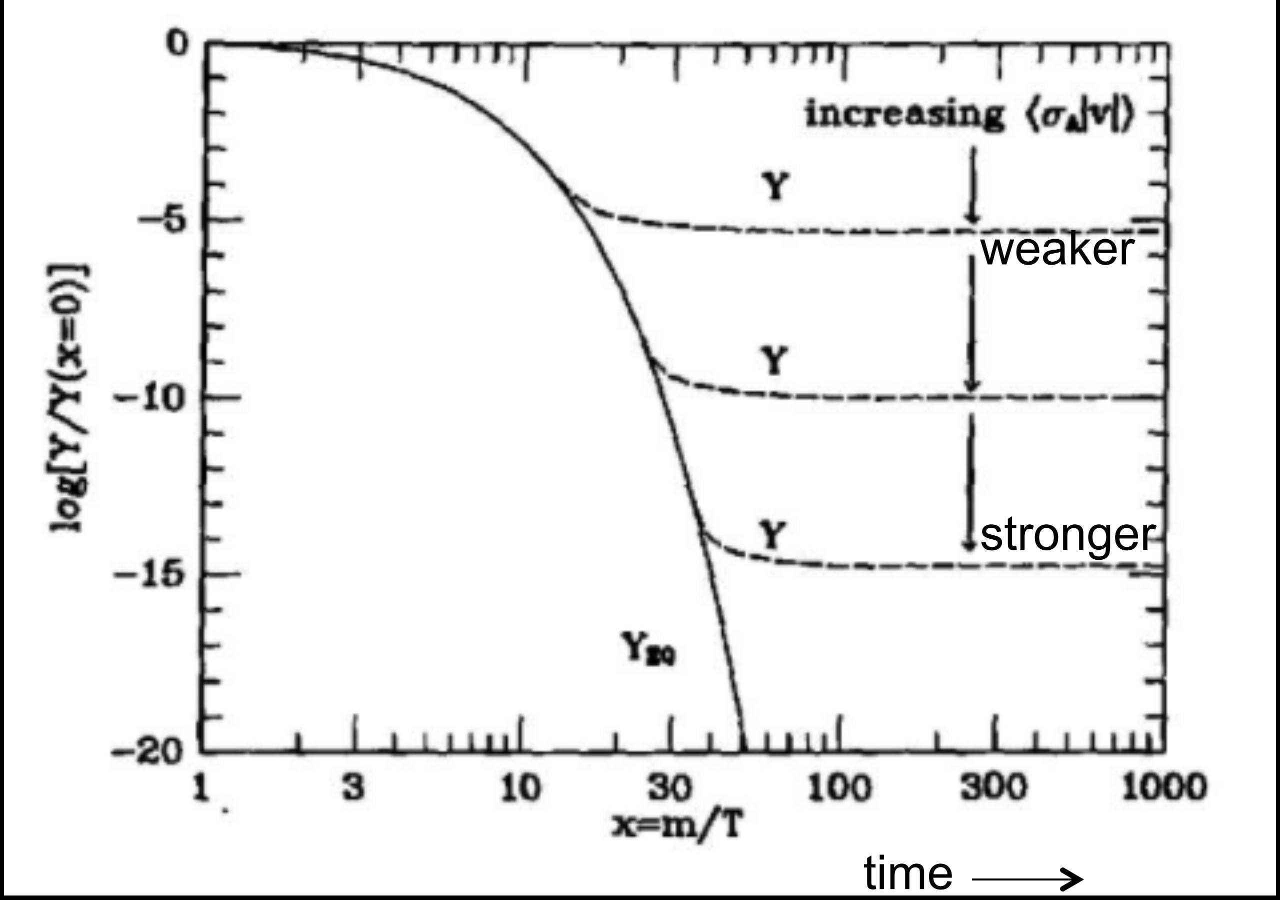
Baryons (positive Baryon Number)



Anti-Baryons (negative Baryon Number)

Baryon/Anti-Baryon Annihilation

Baryon abundance relative to photons



Baryon annihilation rate is strong: relic abundance would be <<1 per 2 billion photons if there were equal numbers of baryons and anti-baryons in the early Universe.

Baryogenesis

The Universe is matter-antimatter *asymmetric*, but the known laws of physics described by the Standard Model are (for the most part) *symmetric* between matter & antimatter. If this were absolutely true, we would expect equal amounts of matter & antimatter to be present in the early Universe. If that were the case, however, the matter & antimatter would have annihilated each other, leaving the Universe nearly empty of baryons.

Baryogenesis: we need to explain two facts:

1. Our (baryonic) Universe is made of something rather than nothing; why is there 1 baryon for every two billion photons? i.e., why are we here?

2. That something is matter, not anti-matter.

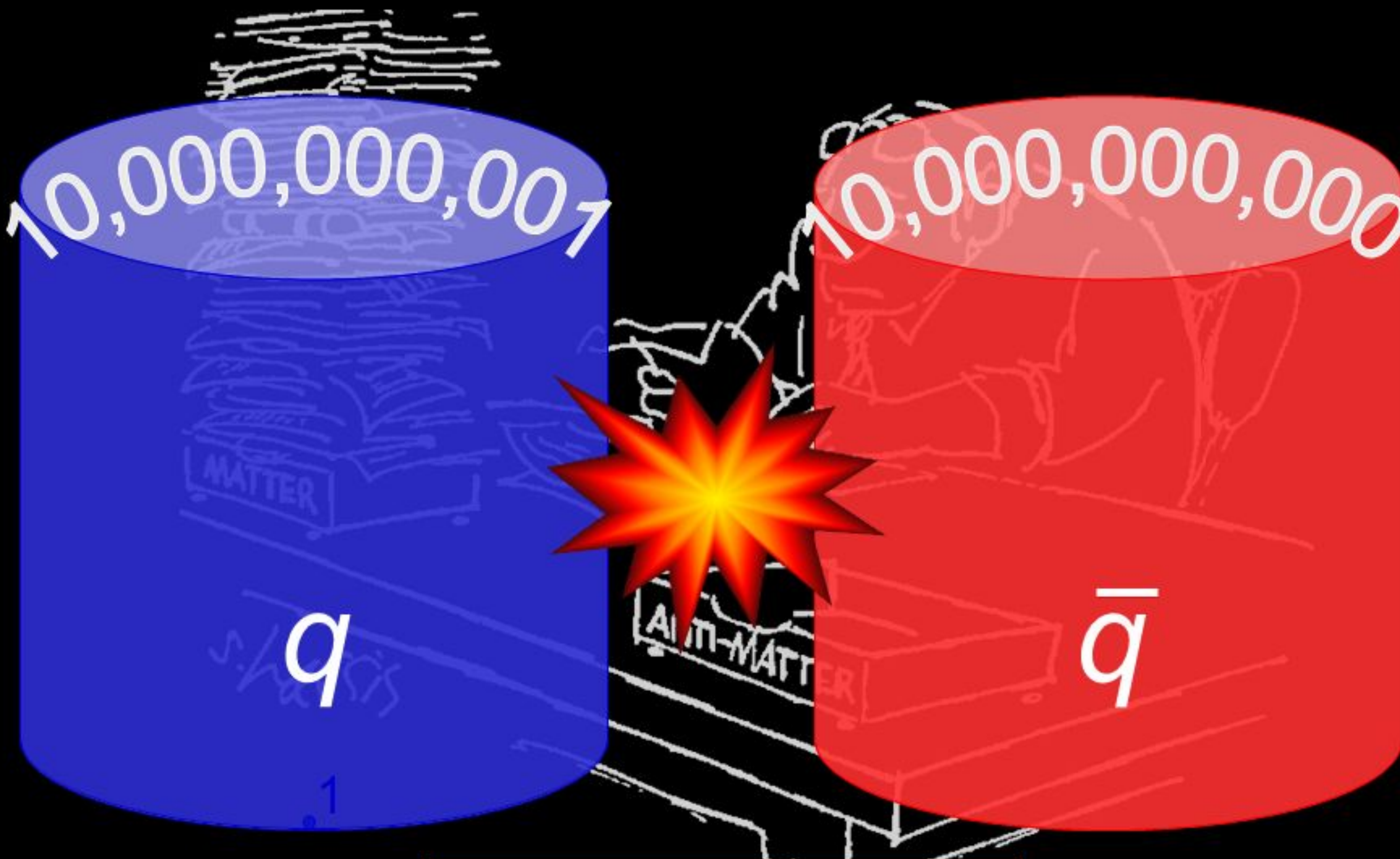

MATTER
ANTI-MATTER
s.harris

Baryogenesis: Requirements

In fact, the needed Matter-antimatter asymmetry is small. When the Universe was much hotter than the baryon mass, there were roughly equal numbers of baryons, antibaryons, and photons.

Consider a volume in the early Universe that contained 2 billion baryons, 2 billion anti-baryons, and 2 billion photons. We need some *physical mechanism* that will create just 1 extra baryon in this volume, so that once the matter & anti-matter particles annihilate, the Universe is left with 1 baryon per 2 billion photons, as observed.

Matter-Antimatter Asymmetry



Baryogenesis: Ingredients

- 1967: Andrei Sakharov (Soviet physicist, human rights and arms control advocate, developer of Soviet nuclear weapons) worked out the 3 key ingredients for this to happen:
  - Interactions between particles that violate Conservation of Baryon Number, provided in late 1970's by Grand Unified Theories
  - Violation of C (charge) and CP (charge+parity) symmetries.
  - Departure from thermal equilibrium, provided by rapid expansion of the early Universe

Conclusion: early Universe + particle physics provide what's needed. The observed baryon asymmetry of 1 part in 10^9 can be produced in early decays of supermassive particles in GUTs with slight preference for decaying into baryons.

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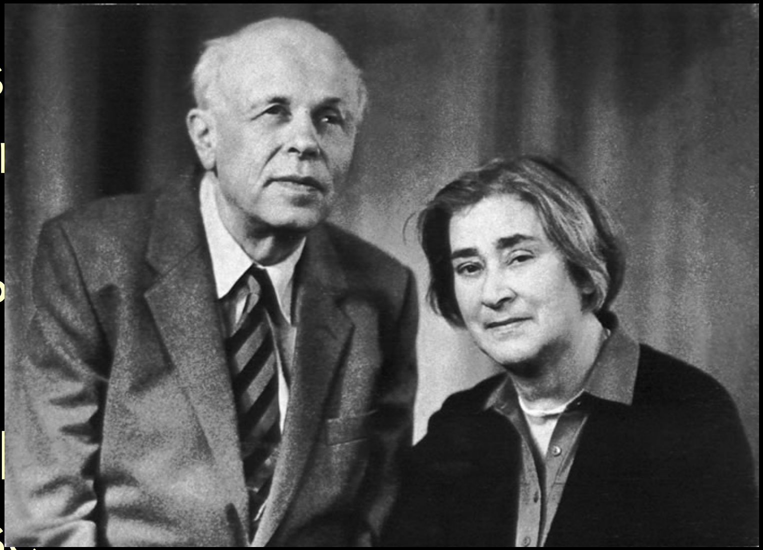

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Proton Decay

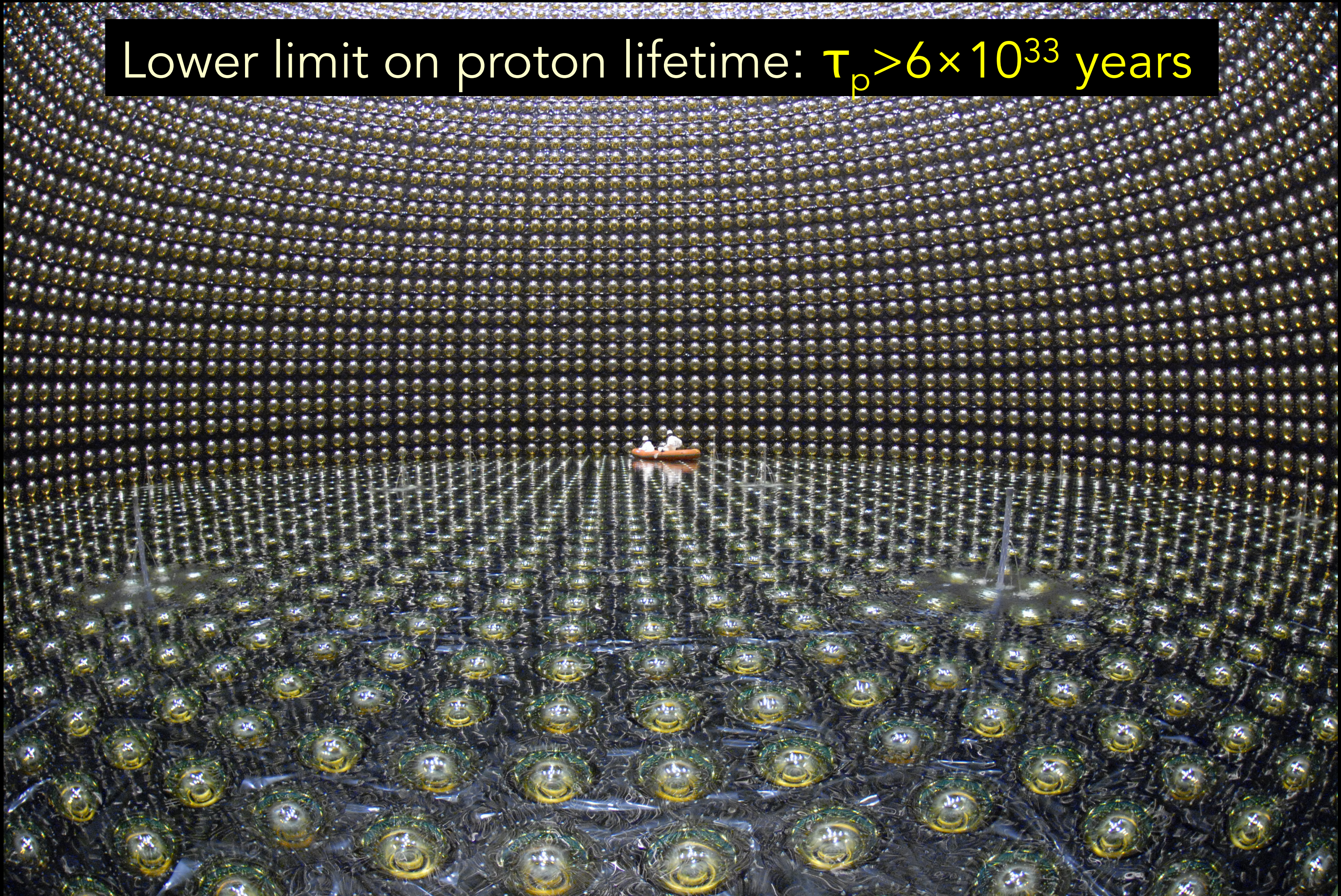
The proton (composed of 3 quarks), is the lightest particle that carries non-zero baryon number. (We're ignoring quarks themselves here, since they're always confined inside baryons and mesons.)

If baryon number is conserved → the proton is stable

If baryon number is not conserved[$] → the proton can decay*

[$]as needed for baryogenesis to occur
*but with a lifetime much longer than the age of the Universe. So far has not been detected in large-scale experiments: this constrains Grand Unified Theory models.

SuperKamiokande Experiment (Japan)



Spontaneous Symmetry Breaking

Symmetries of a theory may not be manifest in Nature: they can be broken.

Everyday Examples:

• Pencil balanced on its end is rotationally symmetric, looks the same from any angle. But when it falls, it must do so in a particular direction, thus breaking the rotational symmetry.

• People sitting at a round table must choose which glass to drink from, the one on their left or their right. Each is possible: initially, the system is left-right symmetric. However, once someone chooses, the symmetry is broken.

Higgs Boson & Symmetry Breaking

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

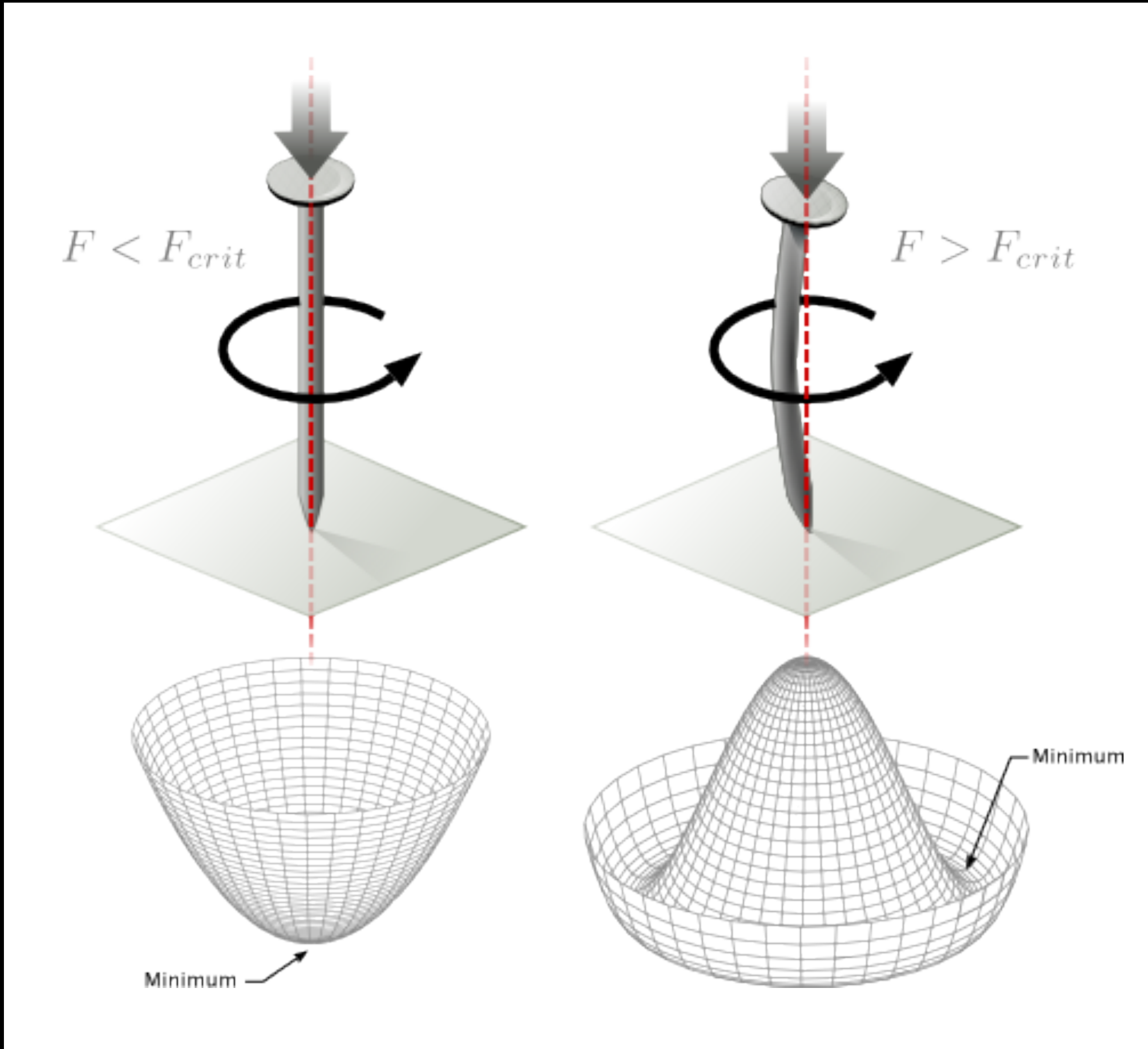
The Higgs interacts with and gives mass to the W and Z Bosons and to all other elementary matter particles, but leaves the photon massless. Can think of it as a kind of `medium' through which elementary particles move. It is a `field' (like an electromagnetic or gravitational field) but with the same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

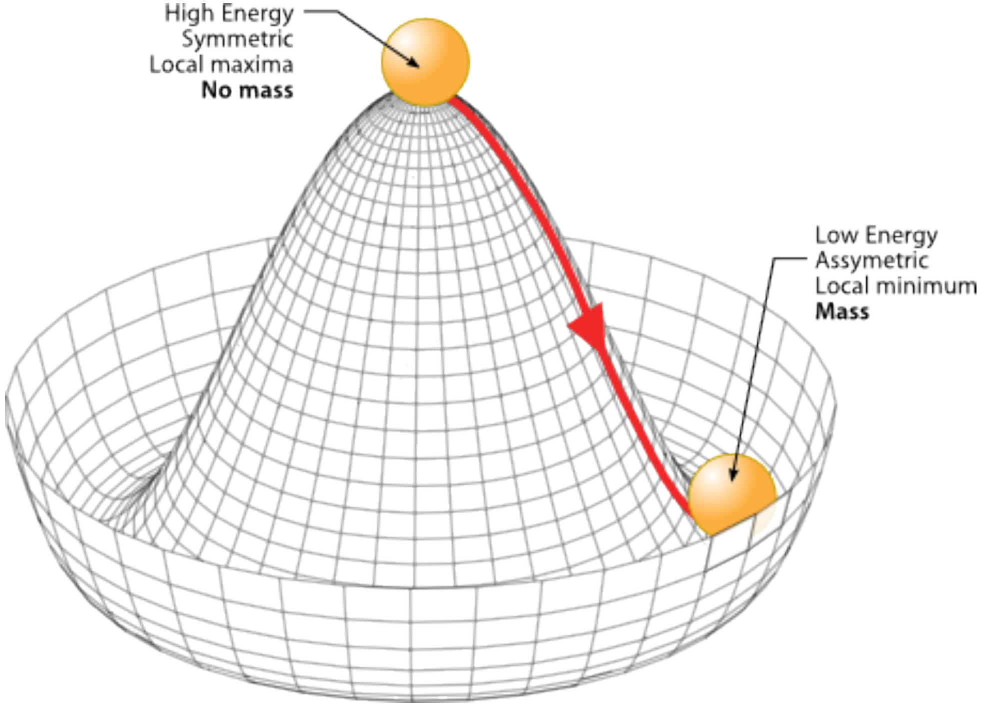
Symmetry Breaking Phase Transitions

- 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

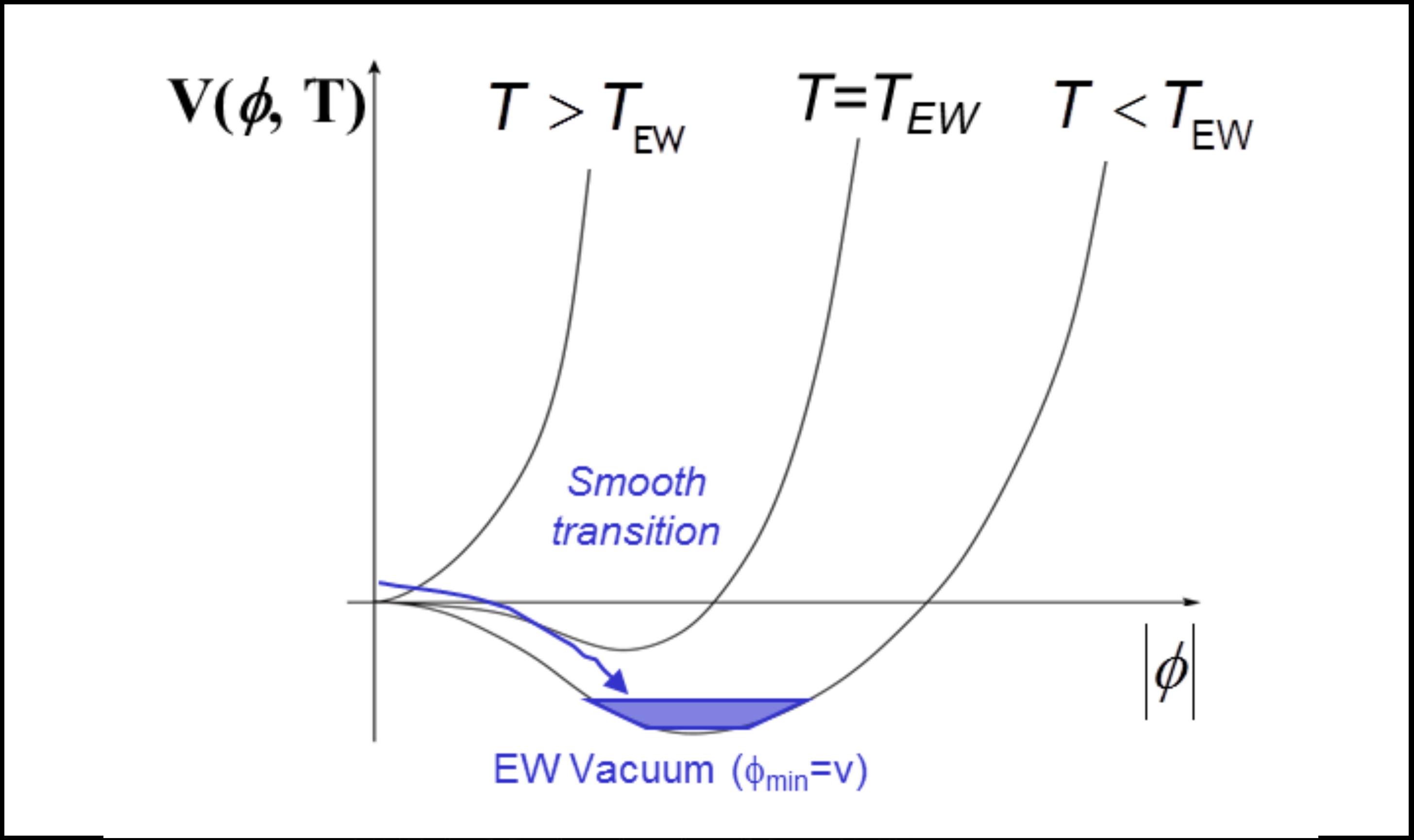


Higgs Potential Energy



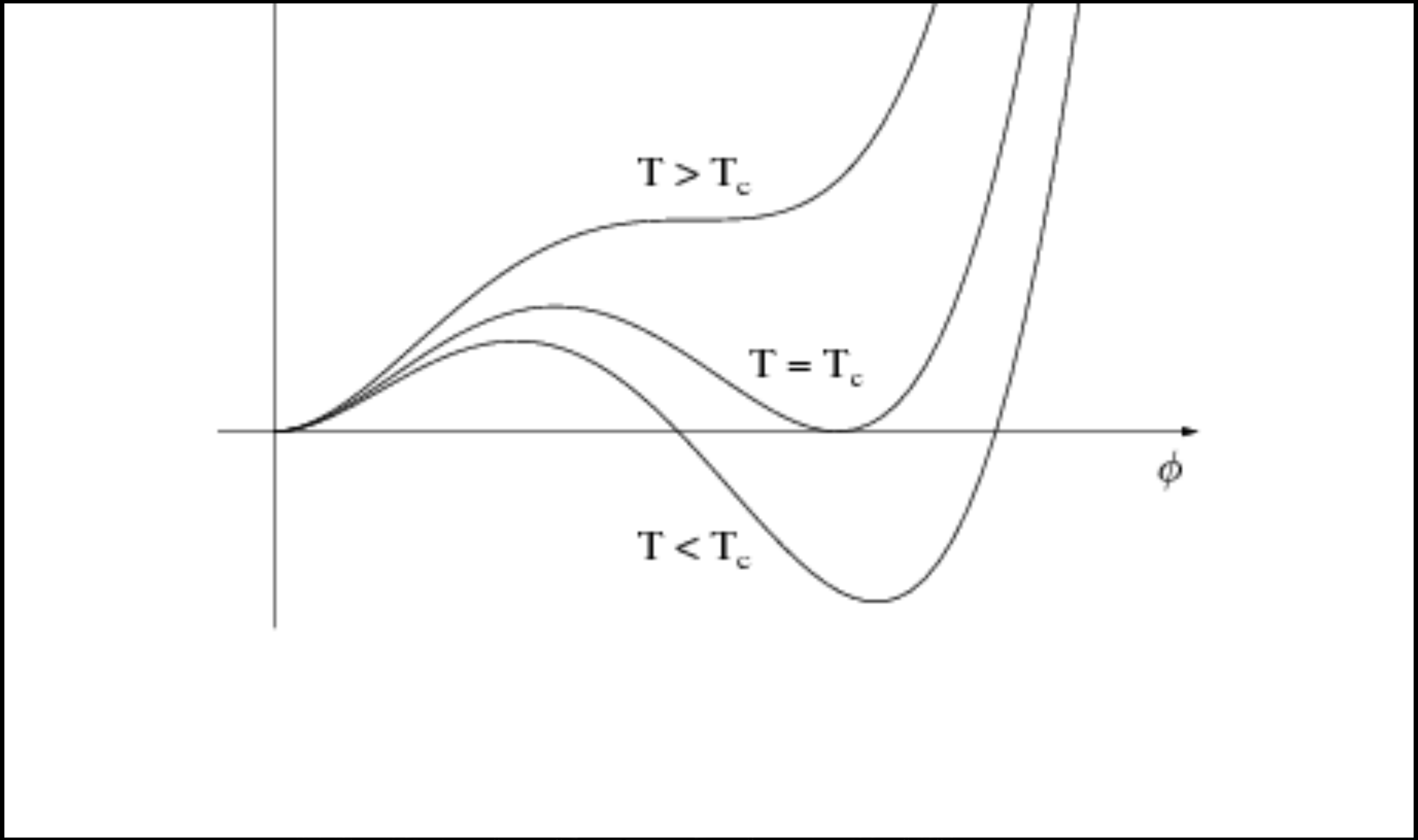
Radius of the sombrero = amplitude of the Higgs field φ

Higgs Potential Energy

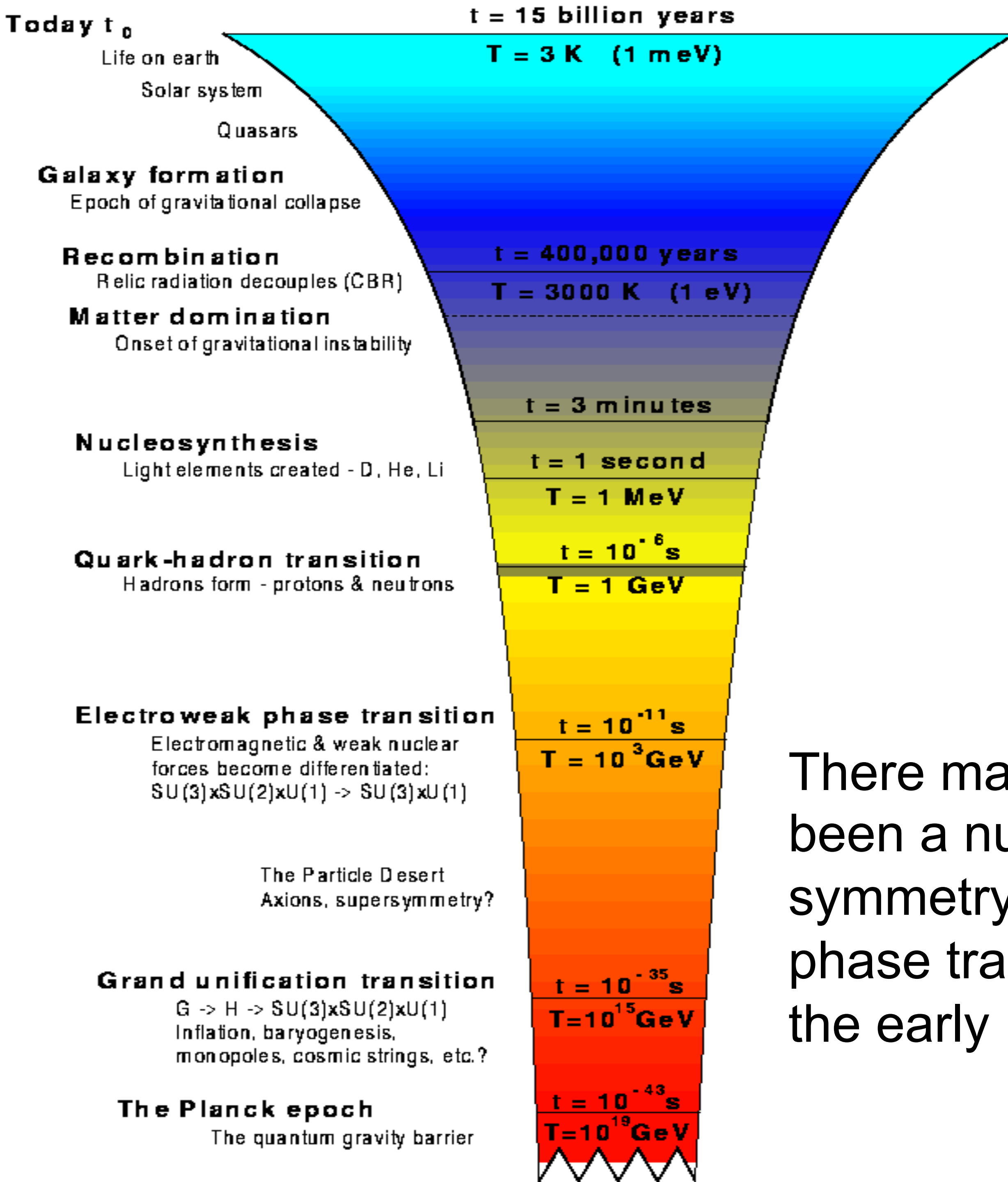


For $T>T_c$, Higgs field $\varphi \rightarrow 0$ (lowest energy state): particles massless
For $T<T_c$, Higgs evolves to non-zero value: particles gain mass

Higgs Potential Energy



In some models, there may be an energy barrier that prevents the field from immediately relaxing to its new lowest energy state. It may get trapped in a metastable state and later quantum-tunnel to the true ground state.



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

The Inflationary Scenario

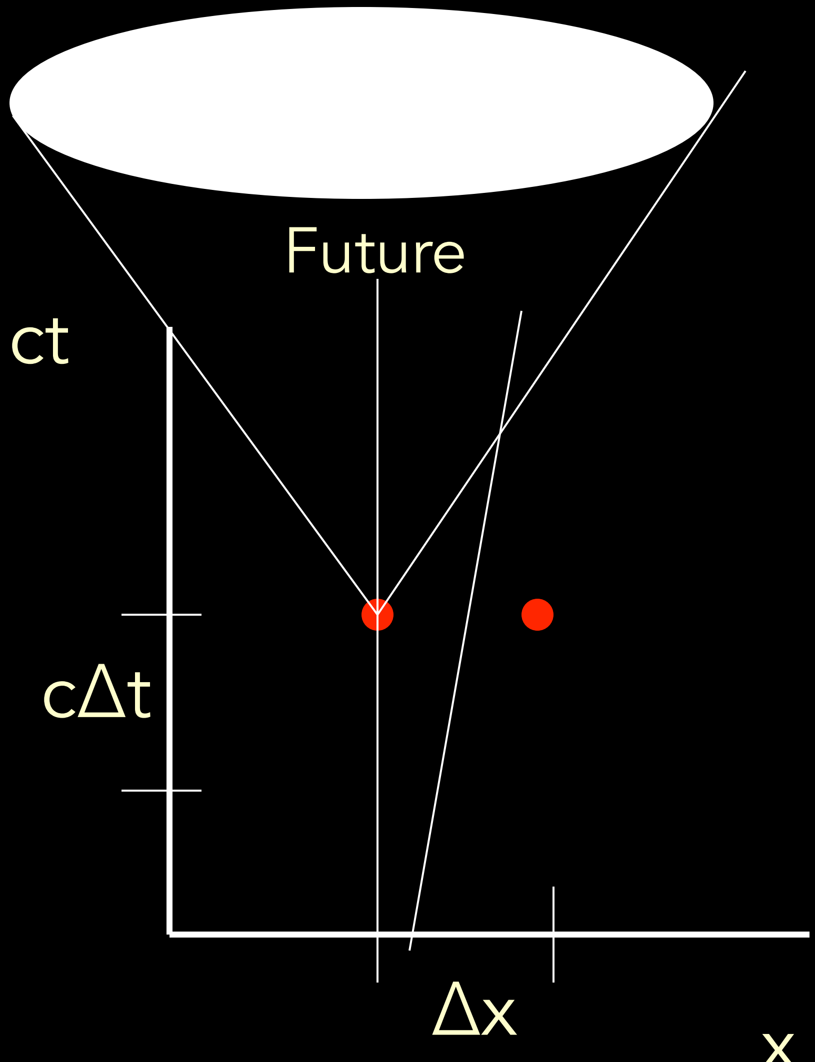
Alan Guth (1980): young cosmologist who was thinking about the cosmological consequences of symmetry-breaking Phase Transitions in the early Universe. He realized that if a transition proceeded very slowly, it could have profound implications for cosmic evolution. He was motivated by several cosmological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

Horizon/homogeneity, flatness, and structure problems

Why is the Universe homogeneous, isotropic, and nearly flat? These are not *robust* features of the standard Big Bang cosmology.

How can large-scale structure form without violating causality?

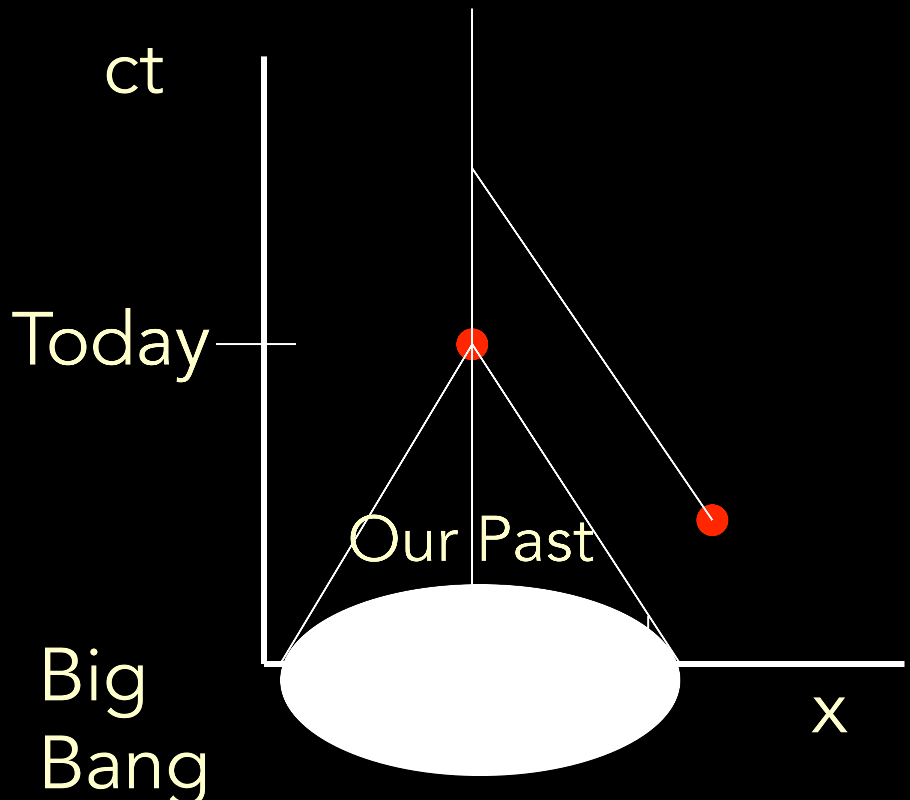
Spacetime



Light rays are always at 45 deg in spacetime coordinates

The causal future of an event lies inside the forward ‘light cone’ since nothing travels faster than light.

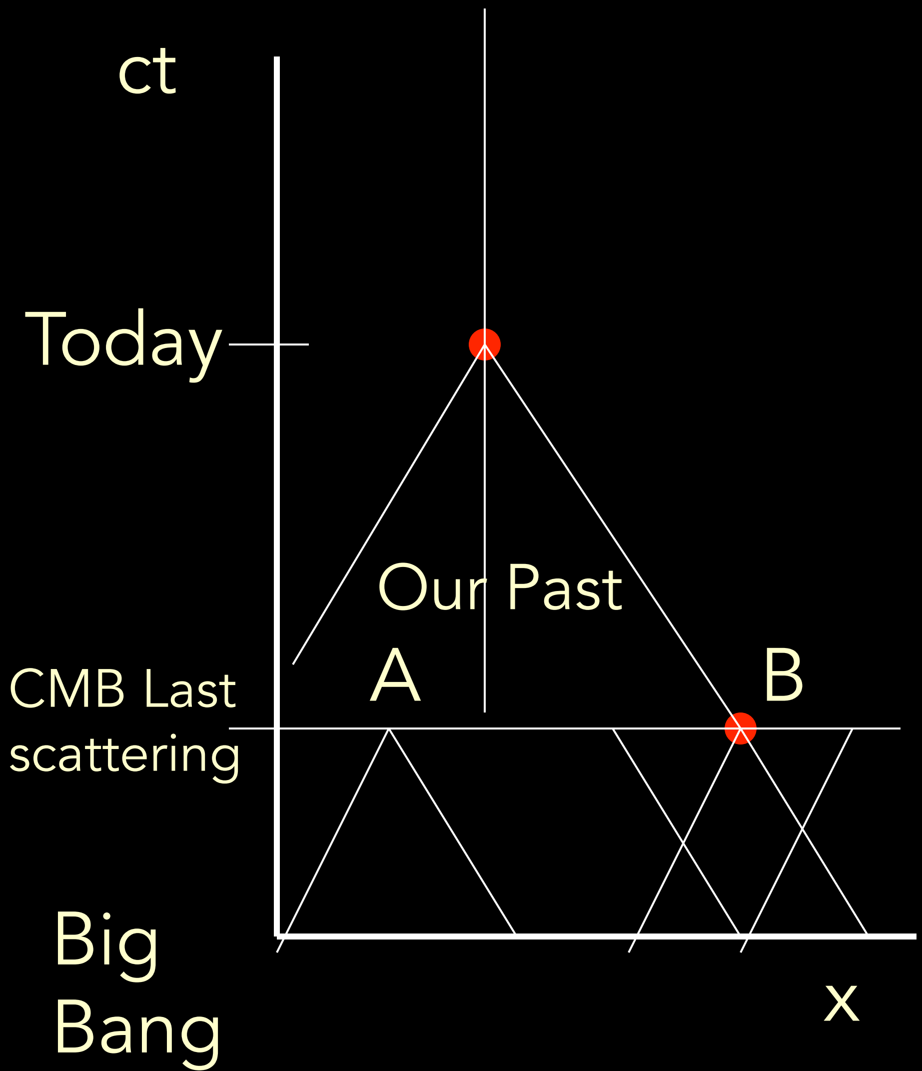
Causal Structure of Spacetime



Light rays are always at 45 deg in spacetime coordinates

The causal past of an event lies inside the past ‘light cone’ since nothing travels faster than light. It defines our *horizon*: volume of space of events we can be influenced by.

Causal Structure of Spacetime



A and B are points on the CMB surface of last scattering that we see in our maps of CMB temperature. But if those points are separated by more than ~2 degrees on the sky, then they were not yet in causal contact: outside each other's light cones.

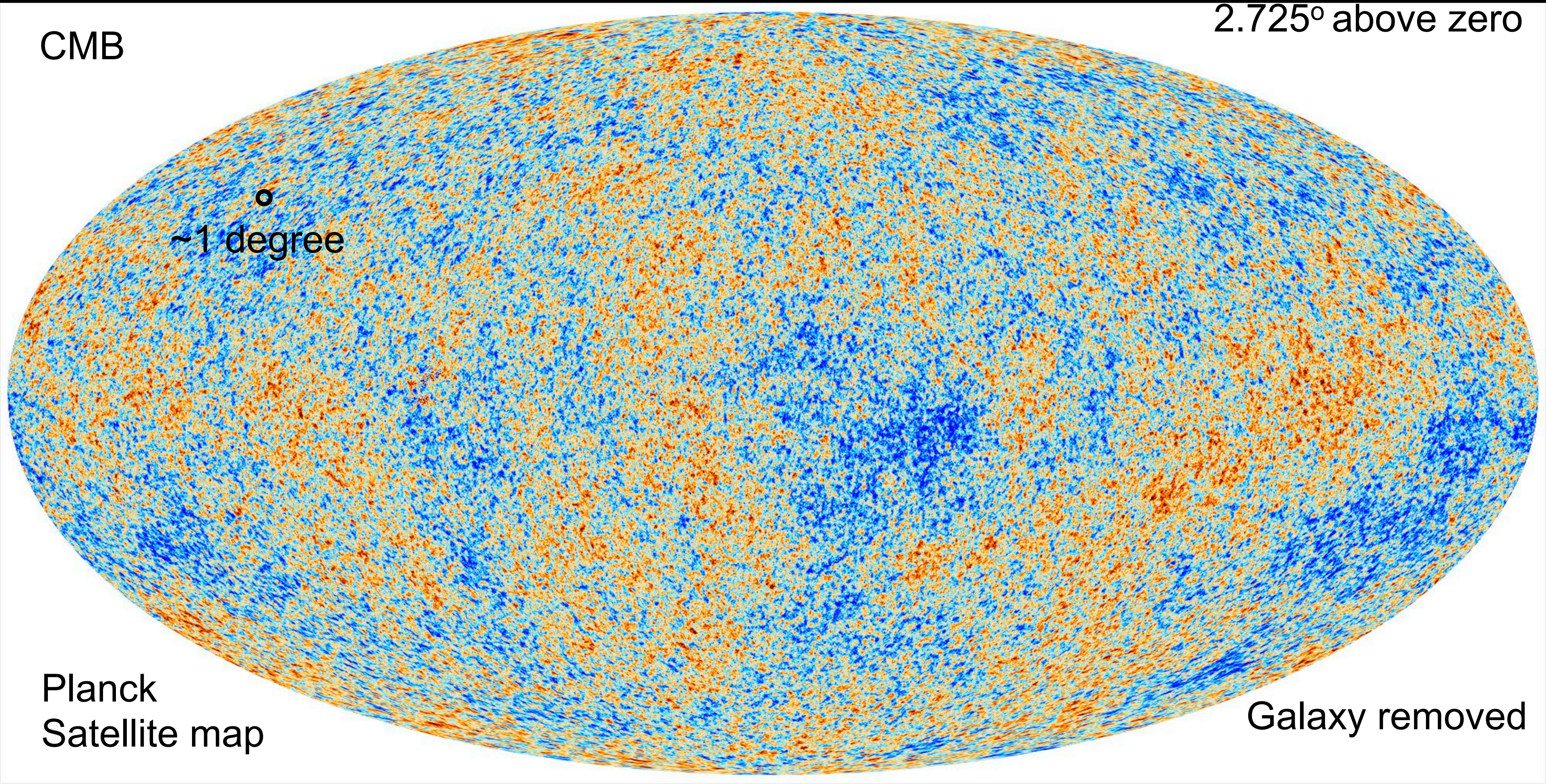
Horizons & the CMB

Cosmic Microwave Background radiation maps show that the temperature at the time of last scattering, t~380,000 years, was isotropic to 1 part in 10^5 over the whole sky.

This is a puzzle: different regions of the CMB separated by more than 1 degree or so in angle were, at the time of Photon decoupling/last scattering outside each other's horizon, not yet in causal contact. There's no reason these causally disconnected regions should have been at the same Temperature! No physical process acting since the Big Bang could have established this uniformity if it wasn't there at the beginning.

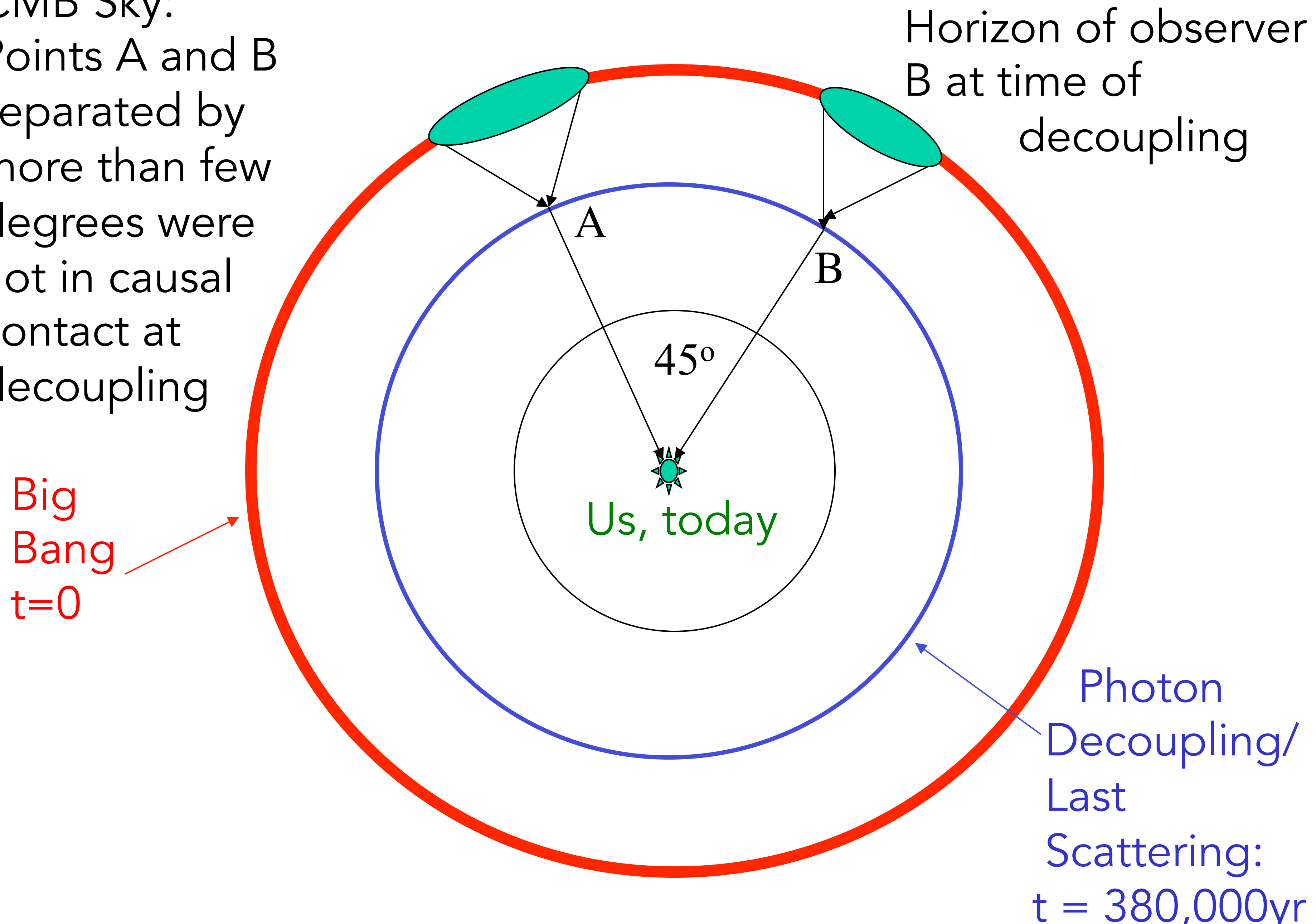
Why then does the Universe appear isotropic & homogeneous on large scales? HORIZON PROBLEM

Planck CMB Temperature Map



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

CMB Sky:
Points A and B separated by more than few degrees were not in causal contact at decoupling

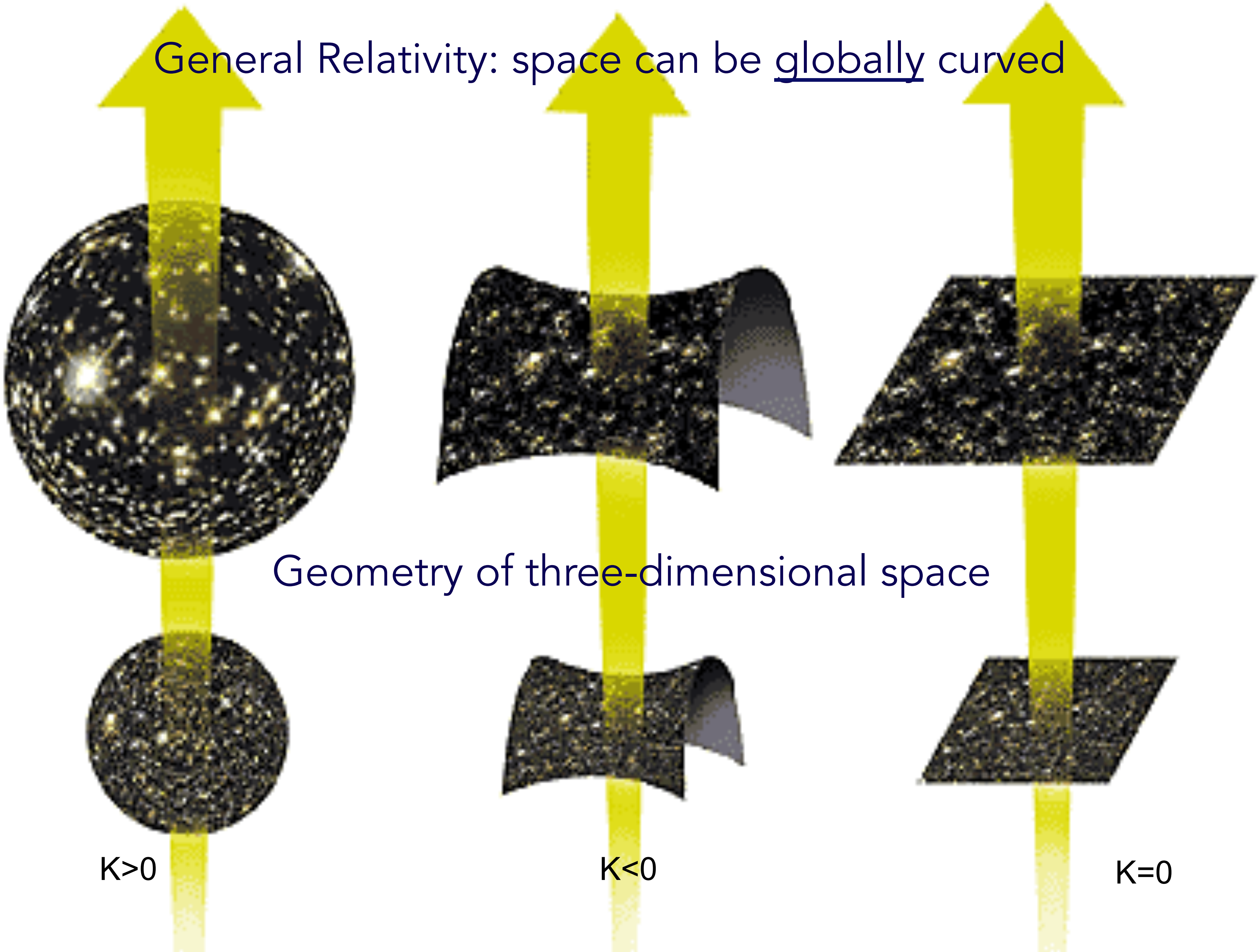


Structure/Causality Problem

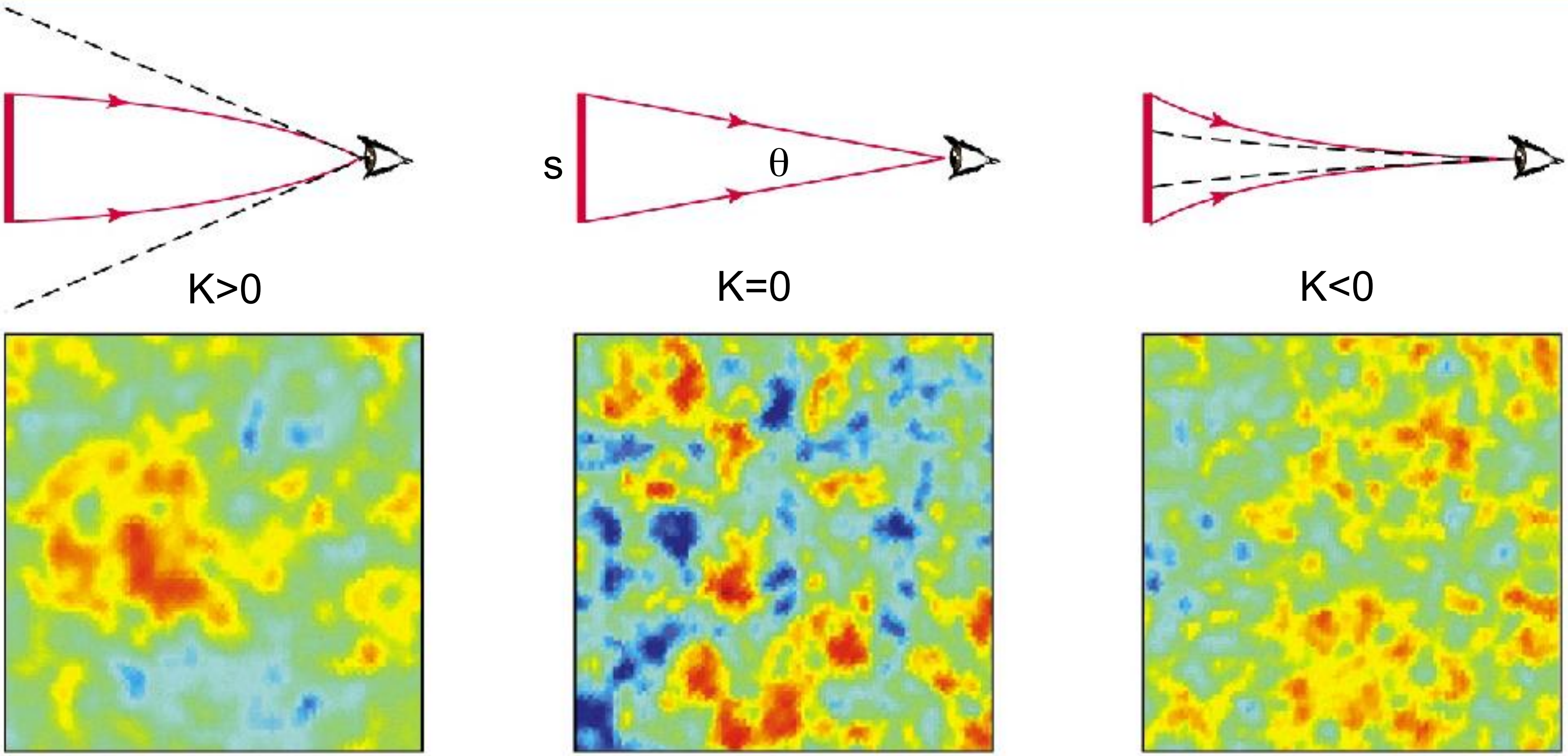
Another symptom of the Horizon problem:

The Large-scale structures we see today in galaxy surveys (e.g., clusters of galaxies) were, at early times, larger than the horizon. Thus, the seeds for structure (density perturbations which were amplified by gravity into galaxies, etc) could not have been made causally unless you wait until very late times (and we have no theory of how to form such seeds at late times).

General Relativity: space can be globally curved



Seeing the Sound Horizon

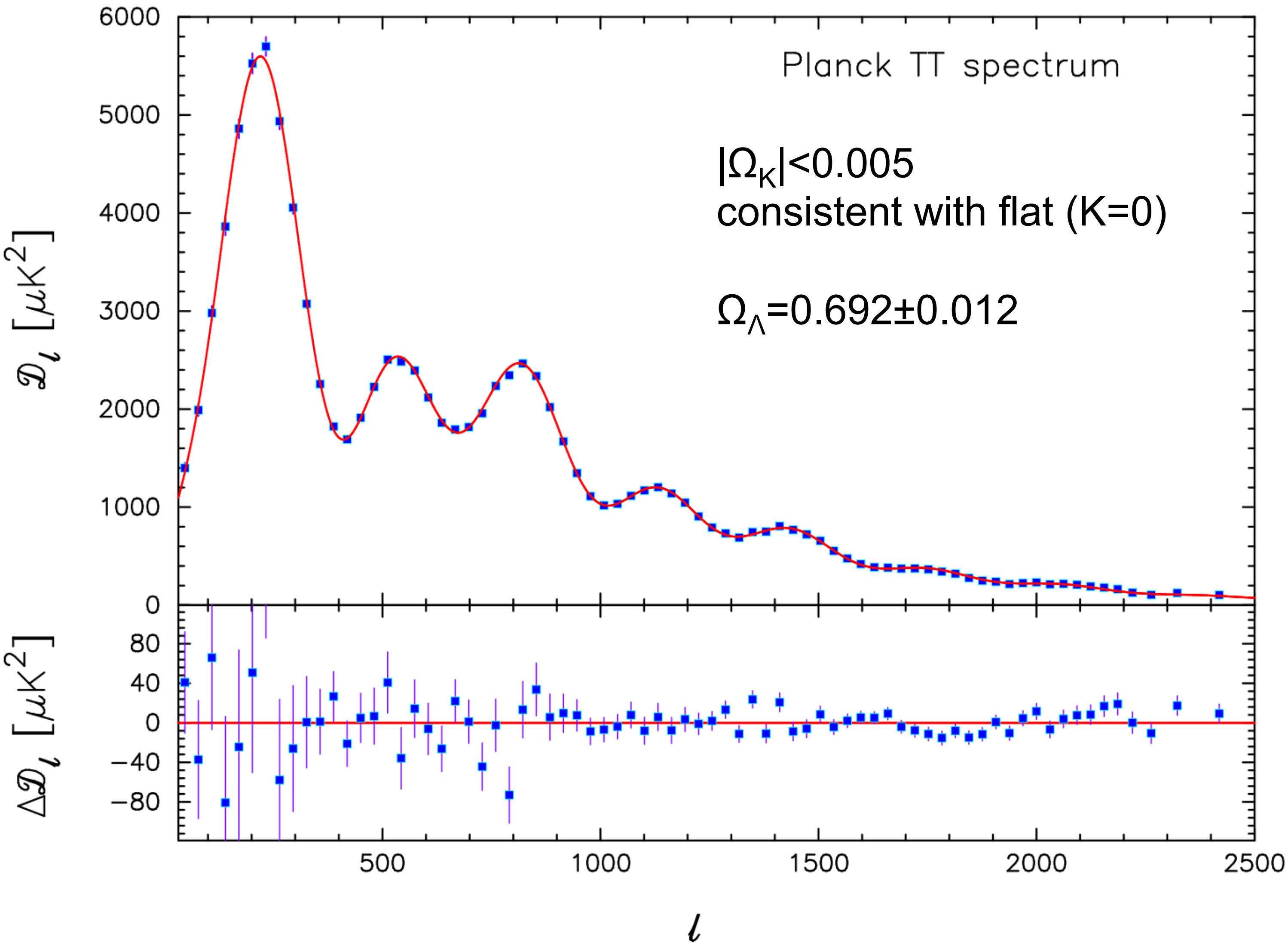


a If universe is closed, "hot spots" appear larger than actual size

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


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

Flatness Problem

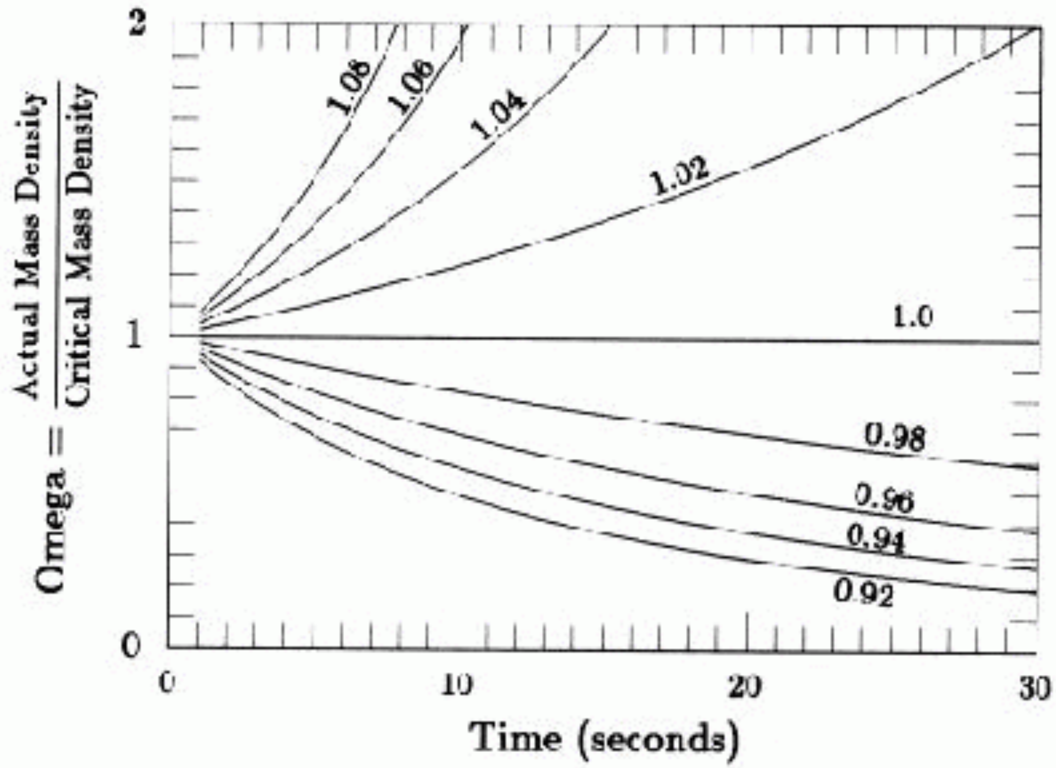
CMB observations indicate that the observable Universe (within our present horizon) is remarkably flat: $\Omega = 1$

As the Universe evolves, the spatial (3D) curvature generally becomes <u>more</u> important with time:

Saddle universe (K<0) rapidly becomes empty.
Spherical universe (K>0) should rapidly recollapse.

Natural timescale for this `rapid' evolution is the Planck time, $t_{Planck} = L_{Planck}/c \sim 10^{-43}$ seconds! But our Universe still appears flat $10^{17}$ sec $\sim 10^{60}$ Planck times after the Big Bang. The Universe must have been `fine tuned' to be very precisely flat at the Planck time for it still to be nearly flat today.

Flatness or Ω Problem



Near-flatness is an unstable property of the Universe

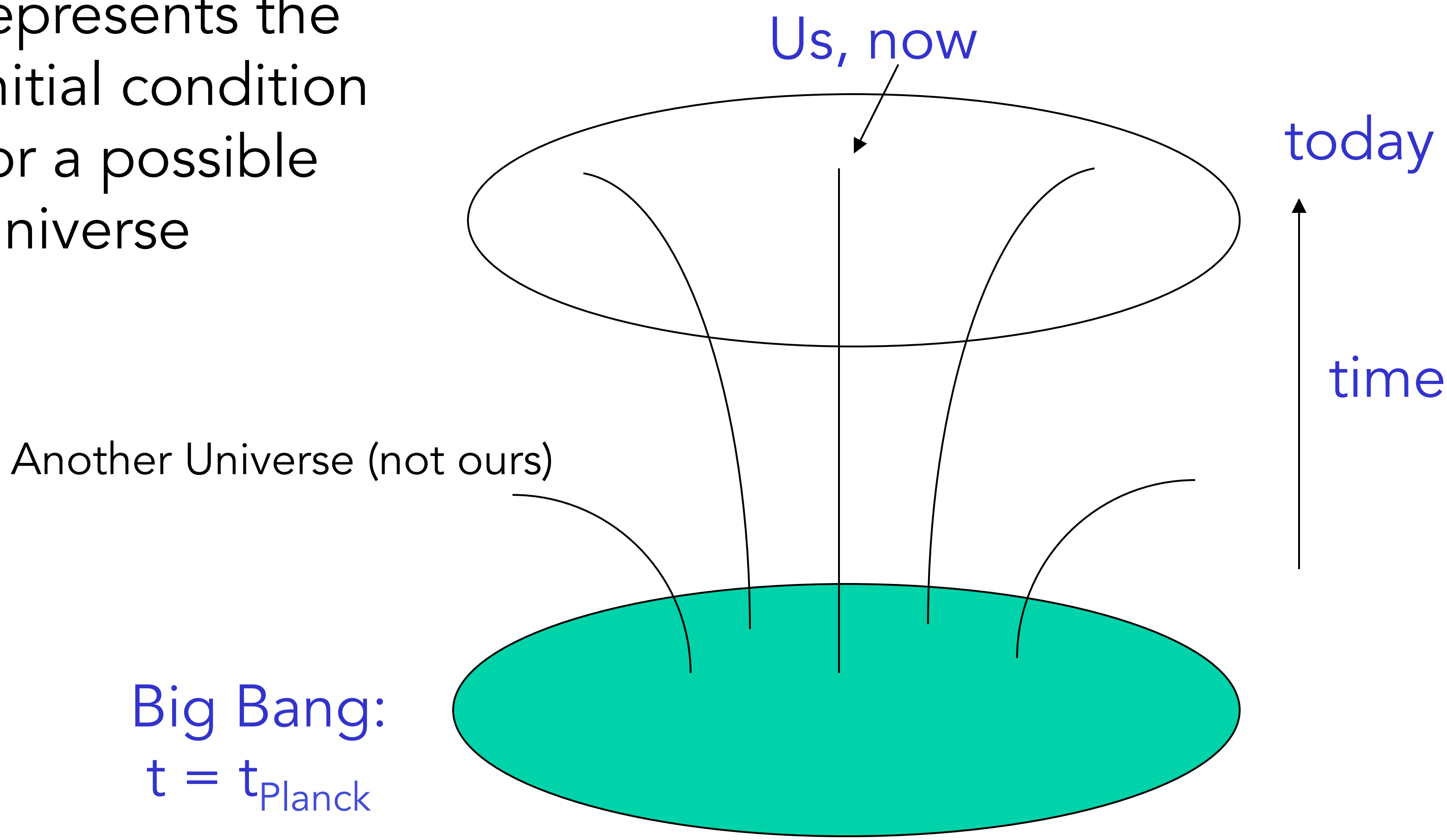
Problems of Initial Conditions

Neither flatness nor homogeneity are `robust' features of the standard cosmological model: they are unstable conditions. If the early Universe had been slightly more curved or inhomogeneous, then it would look much different today.

The present state of the observable Universe appears to depend sensitively on the initial state. If we consider an `ensemble' of Universes at the Planck time, only a tiny fraction of them would evolve to a state that looks like our Universe today. Our observed Universe is in some (hard to quantify) sense very improbable.

`God' may not play dice, but perhaps S/He throws darts...

Each point in the green dart board represents the initial condition for a possible Universe



Most Universes look less & less like ours does as they age;
God must have been extremely lucky or smart to have made our Universe.

Possible Solutions

1. That's the way it is: we're just lucky.

2. A Theory of Everything might constrain the possible conditions at the Planck time to be flat and nearly homogeneous and with the small-amplitude density perturbations needed to form large-scale structure.

3. Dynamical solution: perhaps the early Universe evolved in a different way, due to a Phase Transition:

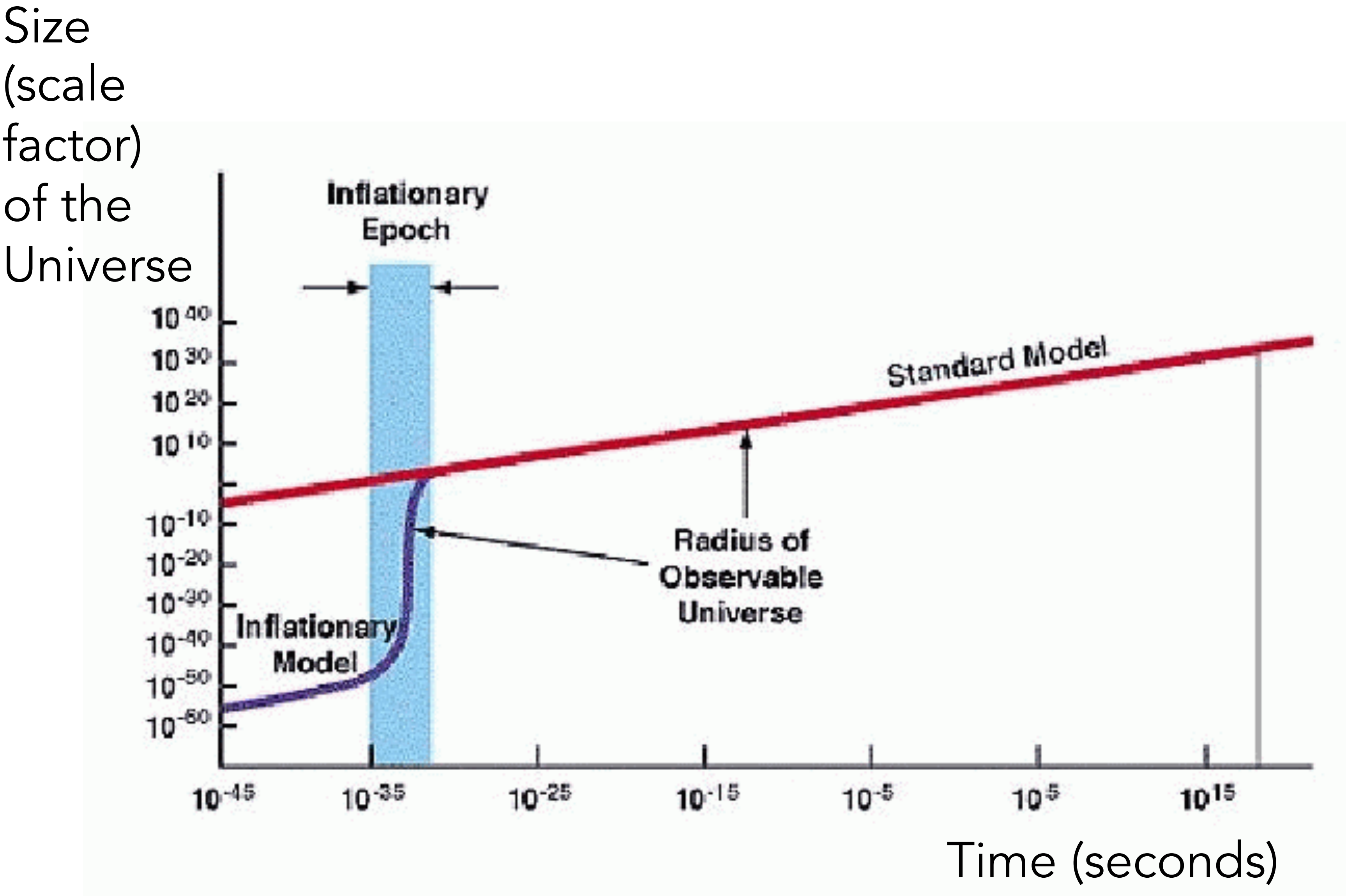
INFLATION

Hint

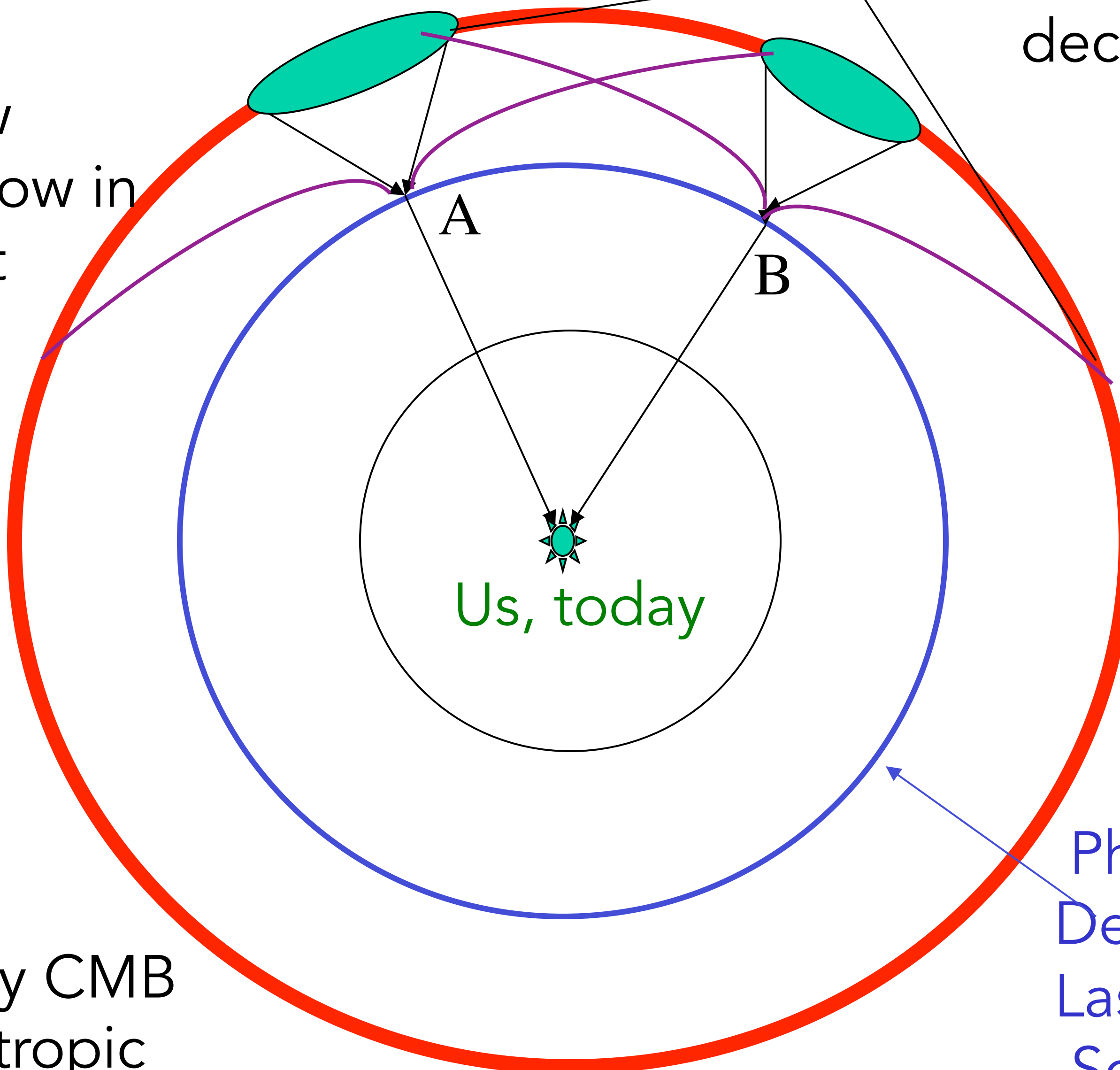
These puzzles of the standard Big Bang model all rest on the assumption that the Universe has been dominated by matter and radiation and thus that the expansion in the early Universe was always decelerating (slowing down) due to gravity.

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 this model, a Universe with our observed properties becomes an 'attractor' of cosmic evolution, rather than an unstable point: our Universe appears more likely.
- This very early acceleration phase is different from the current epoch of cosmic acceleration that set in several billion years ago. We think the Universe has gone through (at least) two epochs of acceleration.

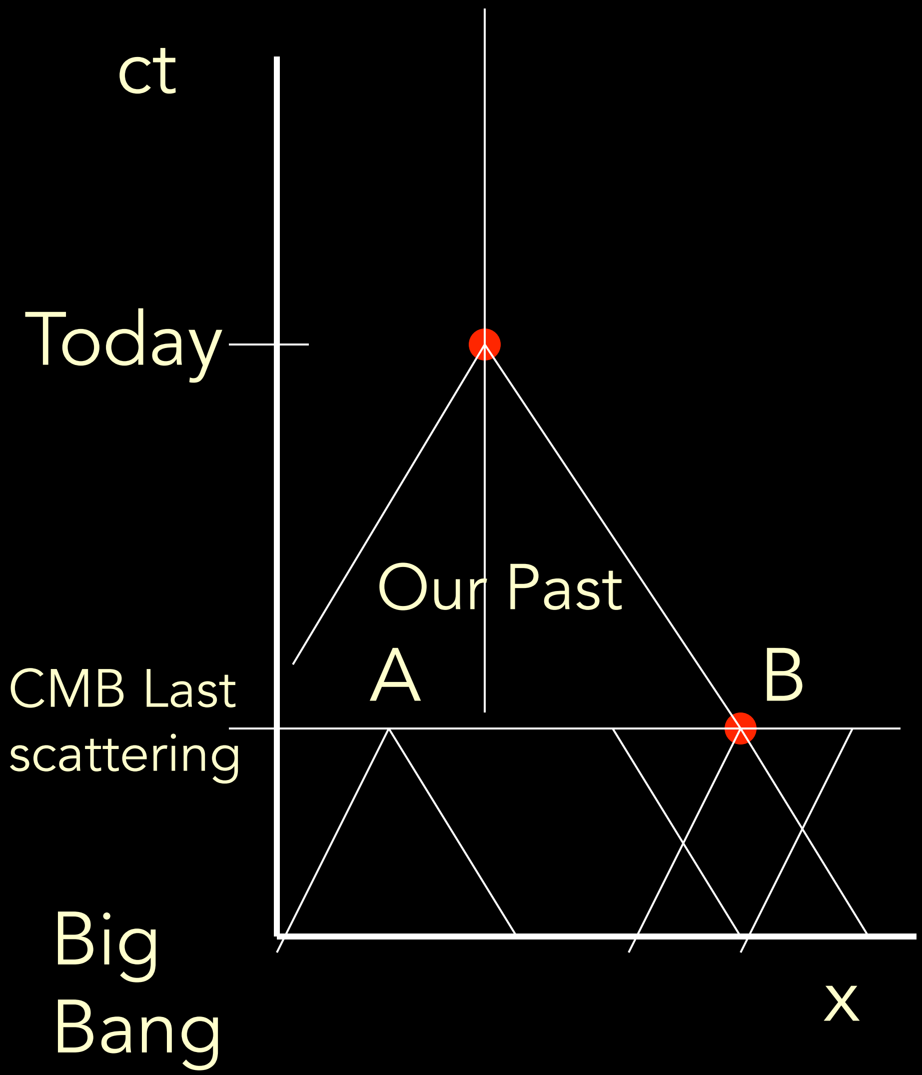

Size (scale factor) of the Universe
Inflationary Epoch
Standard Model
Radius of Observable Universe
Inflationary Model
10 40
10 30
10 20
10 10
10-10
10-20
10-30
10-40
10-50
10-60
10-45
10-35
10-25
10-15
10-5
10 5
10 15
Time (seconds)

CMB Sky:
Points A and B separated by more than few degrees are now in causal contact at decoupling



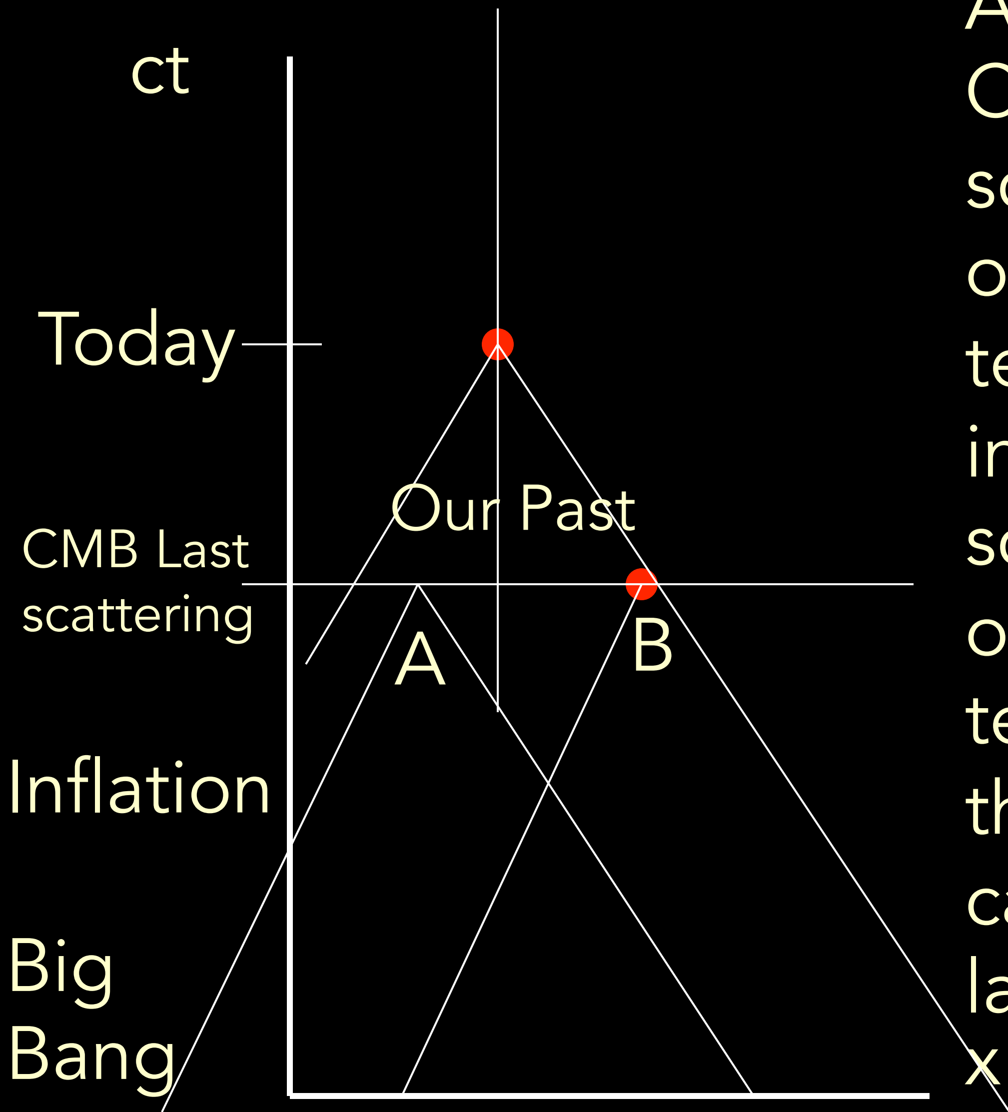
Explains why CMB appears isotropic

Causal Structure of Spacetime



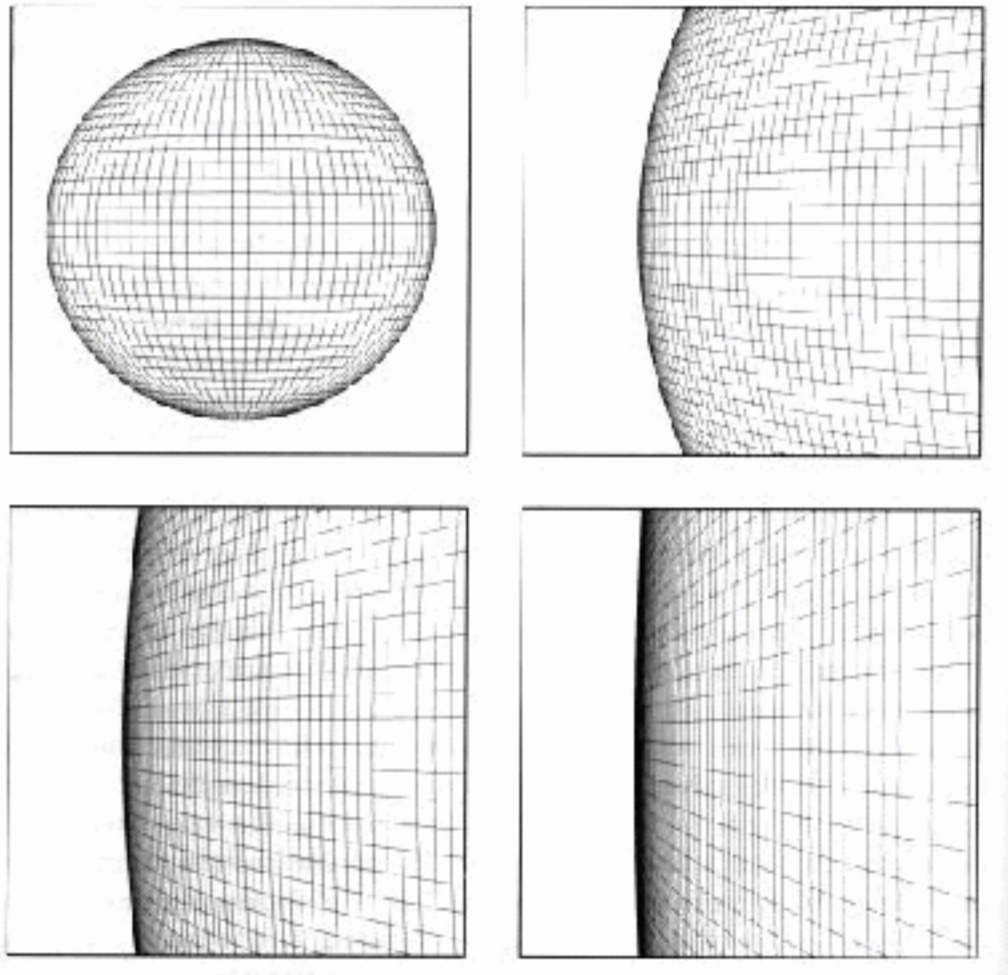
A and B are points on the CMB surface of last scattering that we see in our maps of CMB temperature. But if those points are separated by more than ~2 degrees on the sky, then they were not yet in causal contact: outside each other's light cones.

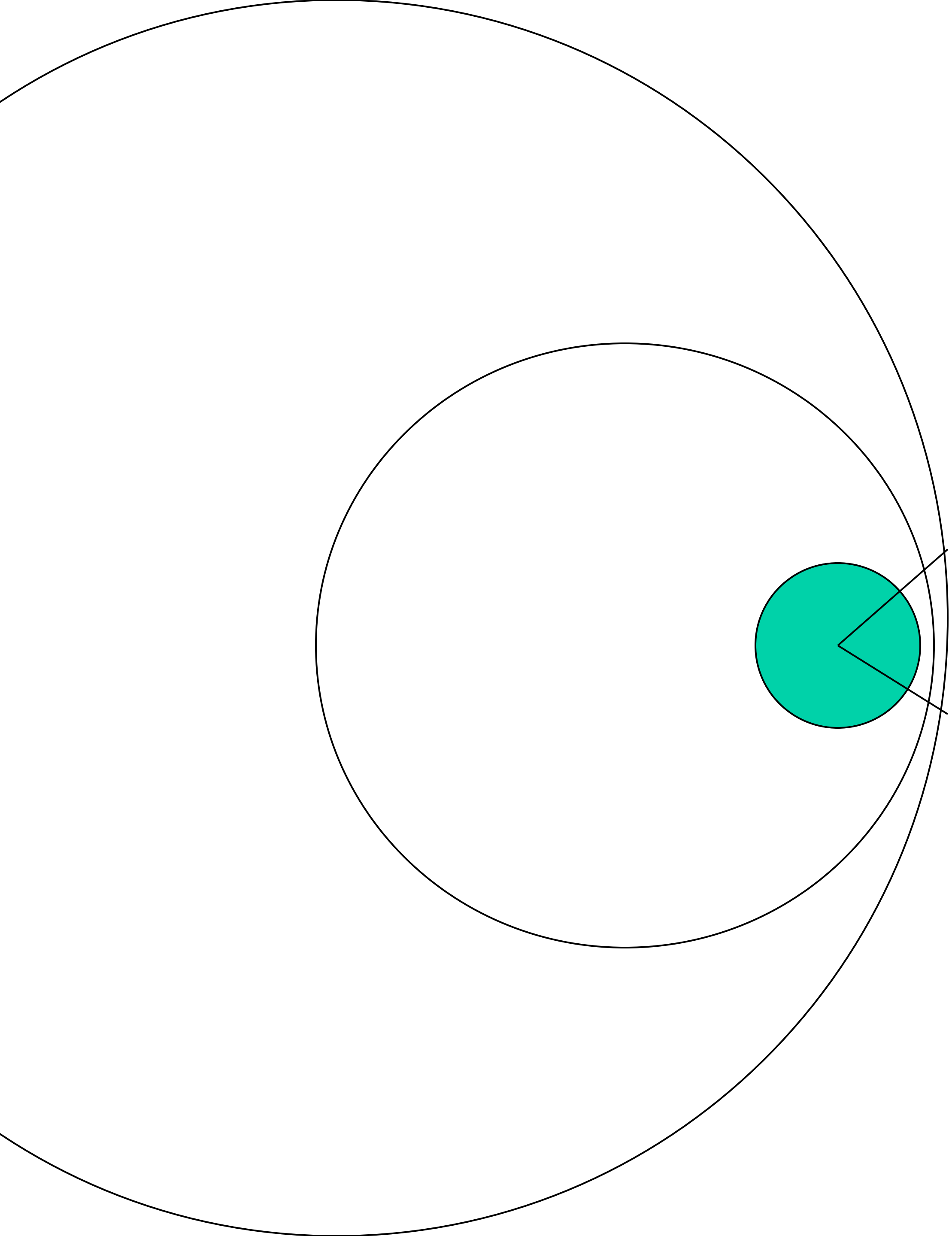
Causal Structure of Spacetime with Inflation



A and B are points on the CMB surface of last scattering that we see in our maps of CMB temperature. With inflation, CMB last scattering effectively occurs much ‘later’ in terms of the relative size of the Universe: A, B were in causal contact at time of last scattering.

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 the CMB anisotropy measurements

Minimal Duration of Inflation

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

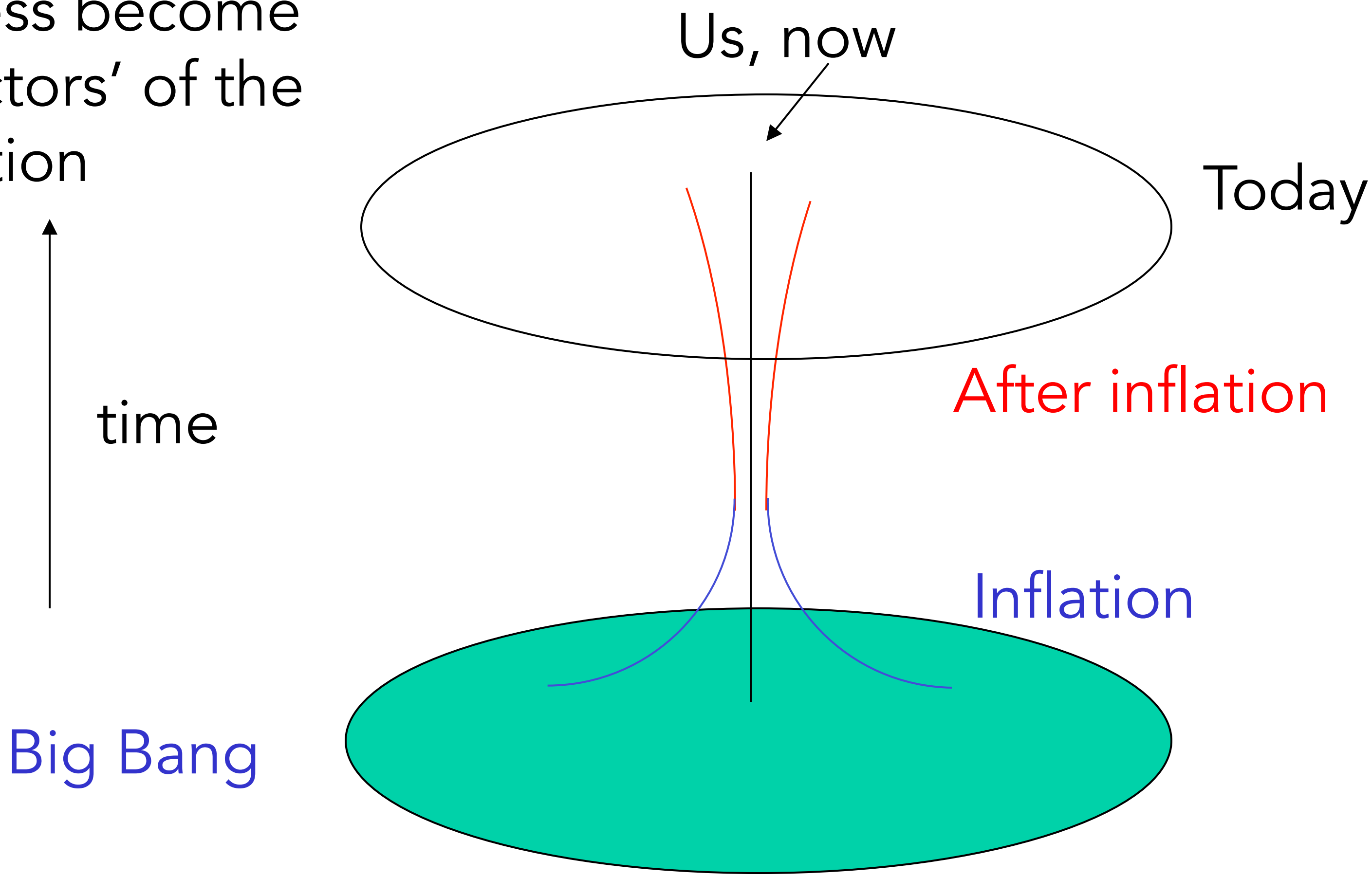
For inflation occurring around the Grand Unification epoch, the scale factor $a(t)$ should grow during inflation by at least a factor of $e^{60} \sim 10^{28}$.

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 particle density drop exponentially: the Universe becomes cold and empty)

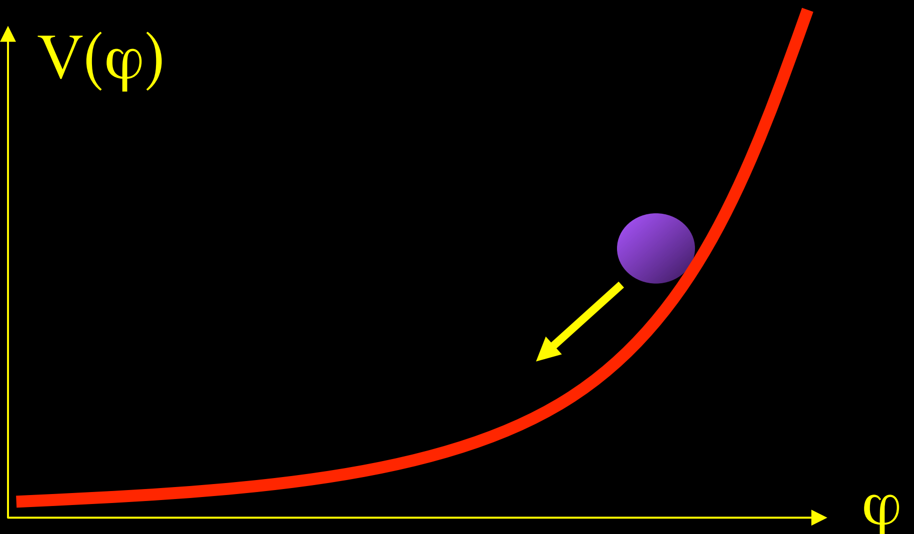
During inflation, Homogeneity & Flatness become `attractors' of the evolution



Inflation increases the set of initial Universes that end up looking like our Universe today: God could have been lousy at darts.

Scalar Field and Inflation

- Inflation could be driven by a very slowly rolling (evolving in time) scalar field: the *inflaton*.
- 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.



Dark Energy and Expansion

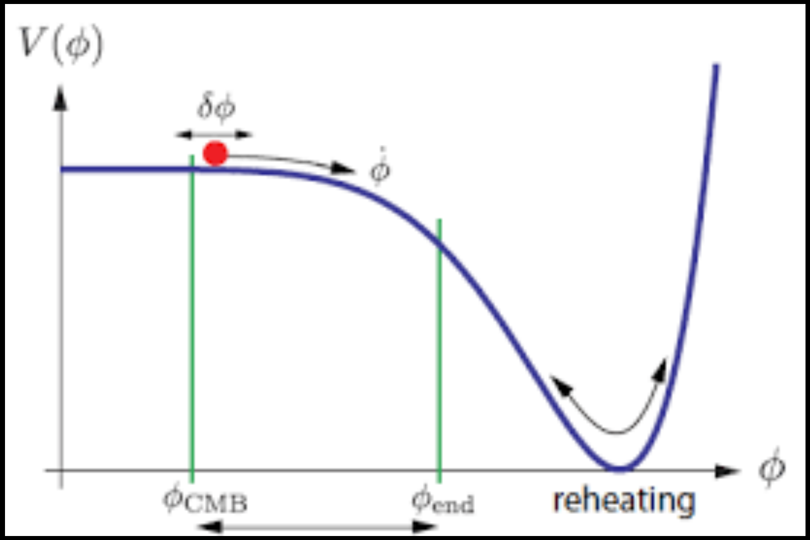
- Dark Energy (DE): more general concept than vacuum energy. Any form of mass-energy with sufficiently negative pressure, $p_{DE} < -\rho_{DE}/3$.
- If $w = p_{DE}/\rho_{DE} = -1$, i.e., vacuum energy, then ρ_{DE}=constant in time, but for other values of w the DE density evolves in time.

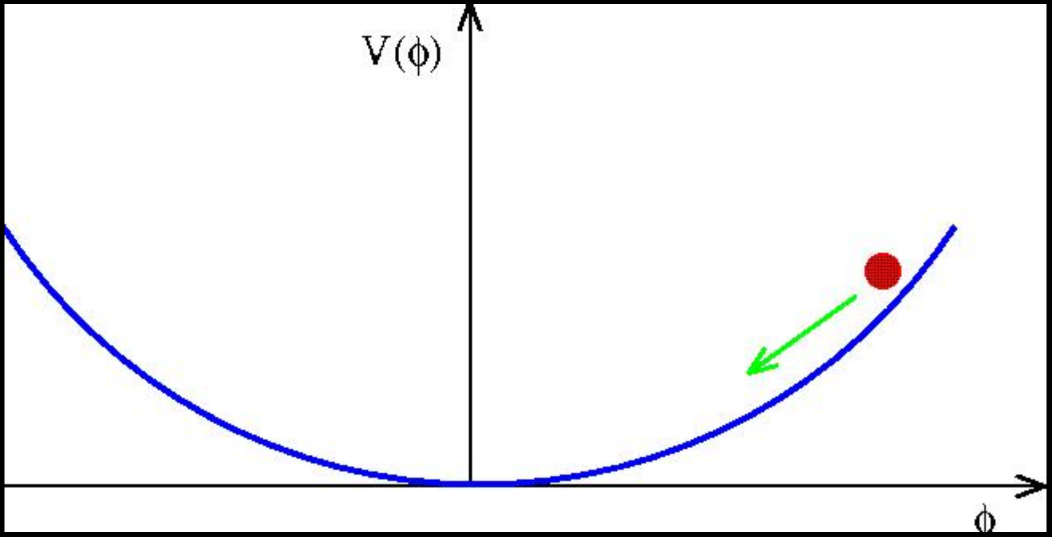
$$H^2 = \left(\frac{1}{a} \frac{\Delta a}{\Delta t} \right)^2 = \frac{8\pi G(\rho_{matter} + \rho_{DE})}{3} - \frac{k}{a^2}$$

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

$$p_{DE} = w\rho_{DE} \text{ with } w < -1/3$$

Models of Inflation



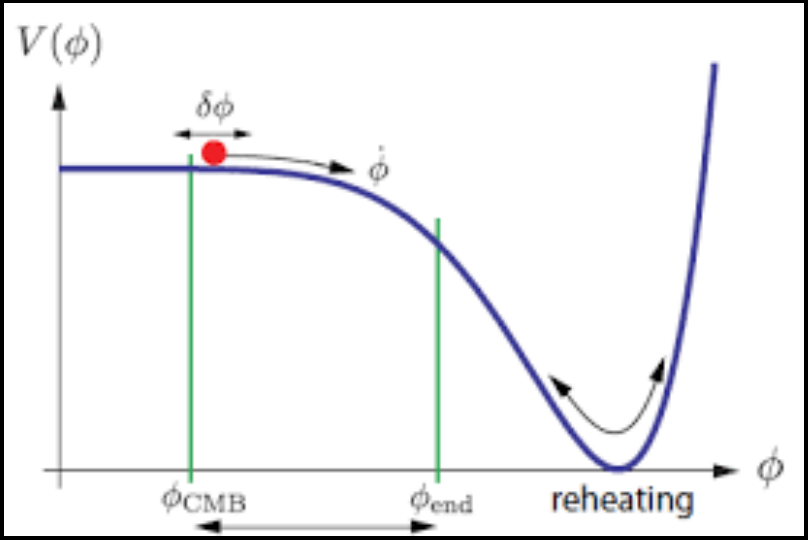


Models inspired by Symmetry breaking: Field evolves from small to large value

'Large field' Models

No consensus model at this time

The End of Inflation: Reheating



When scalar field approaches the minimum of its potential, it speeds up and starts oscillating. The energy in these oscillations leads to decay of the scalar field into other, lighter particles, repopulating and 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.