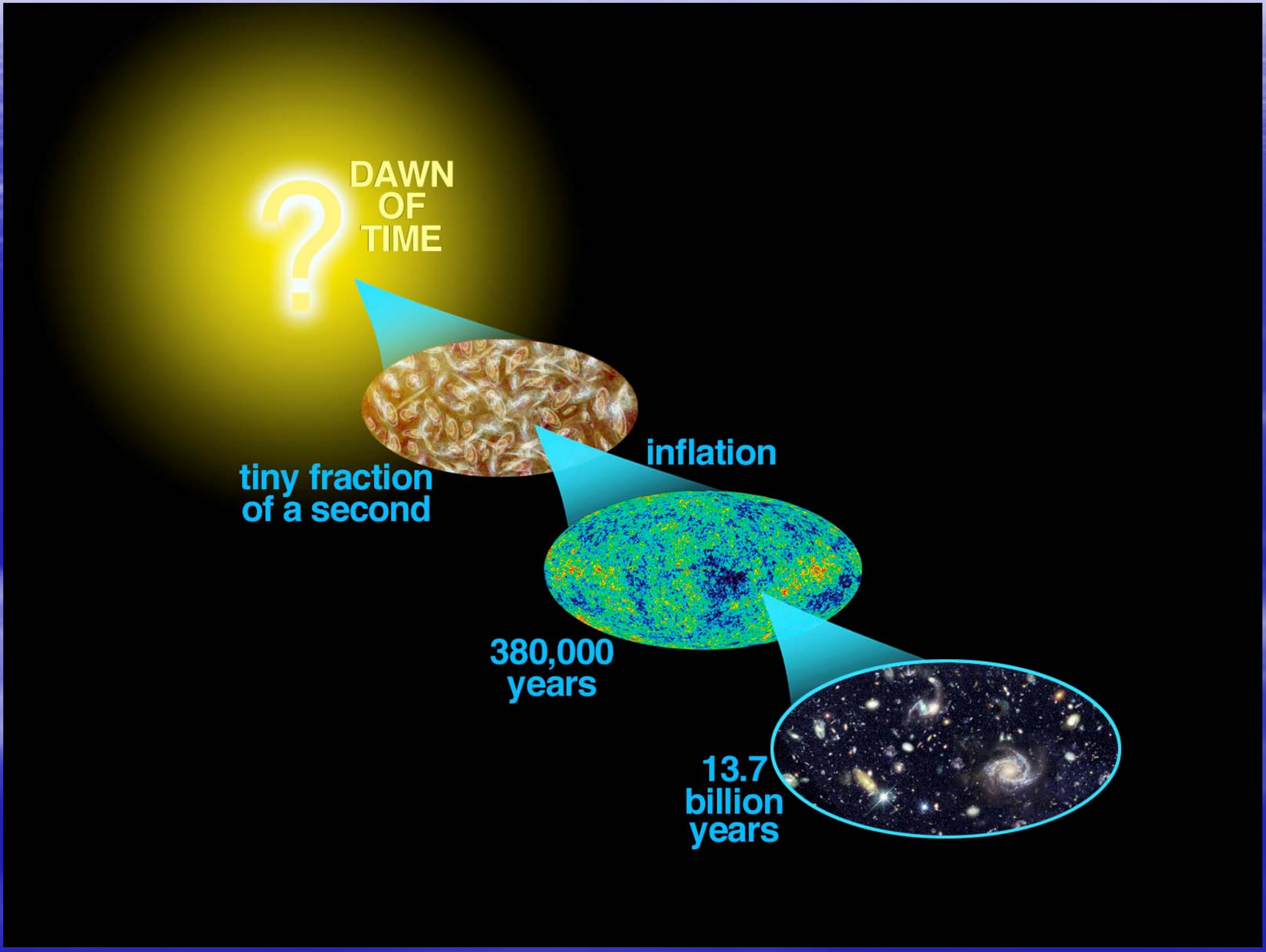
Lecture 12 Cosmology III



Unsolved issues in the standard model

- Horizon problem:
  – Why is the CMB so smooth?
- The flatness problem:
  – Why is Ω~1 ? Why is the universe flat ?
- The structure problem:
  – Where do the fluctuations in the CMB come from?
- The relic problem
  – Why aren't there magnetic monopoles, why is there more matter than antimatter?

Problem I: The horizon problem

- CMB: light emitted when the universe became transparent.
- Age of the Universe at that epoch: 400 000 yr
- The size of patches that can have influenced each other: < 400 000 lyr
- Those patches appear today under an angle of less than 1º
- Why is the CMB so smooth on scales larger 1º if those region never knew about each other?

Problem II: The flatness problem

- $\Lambda=0$: for most of its age, the universe looks either to be flat or to be empty
- $\Lambda>0$: for most of its age, the universe looks either to be flat or to be exponentially expanding
- Isn't it strange that we appear to live in that short period between those two extremes?
- Should we be surprised that the universe appears to be flat?

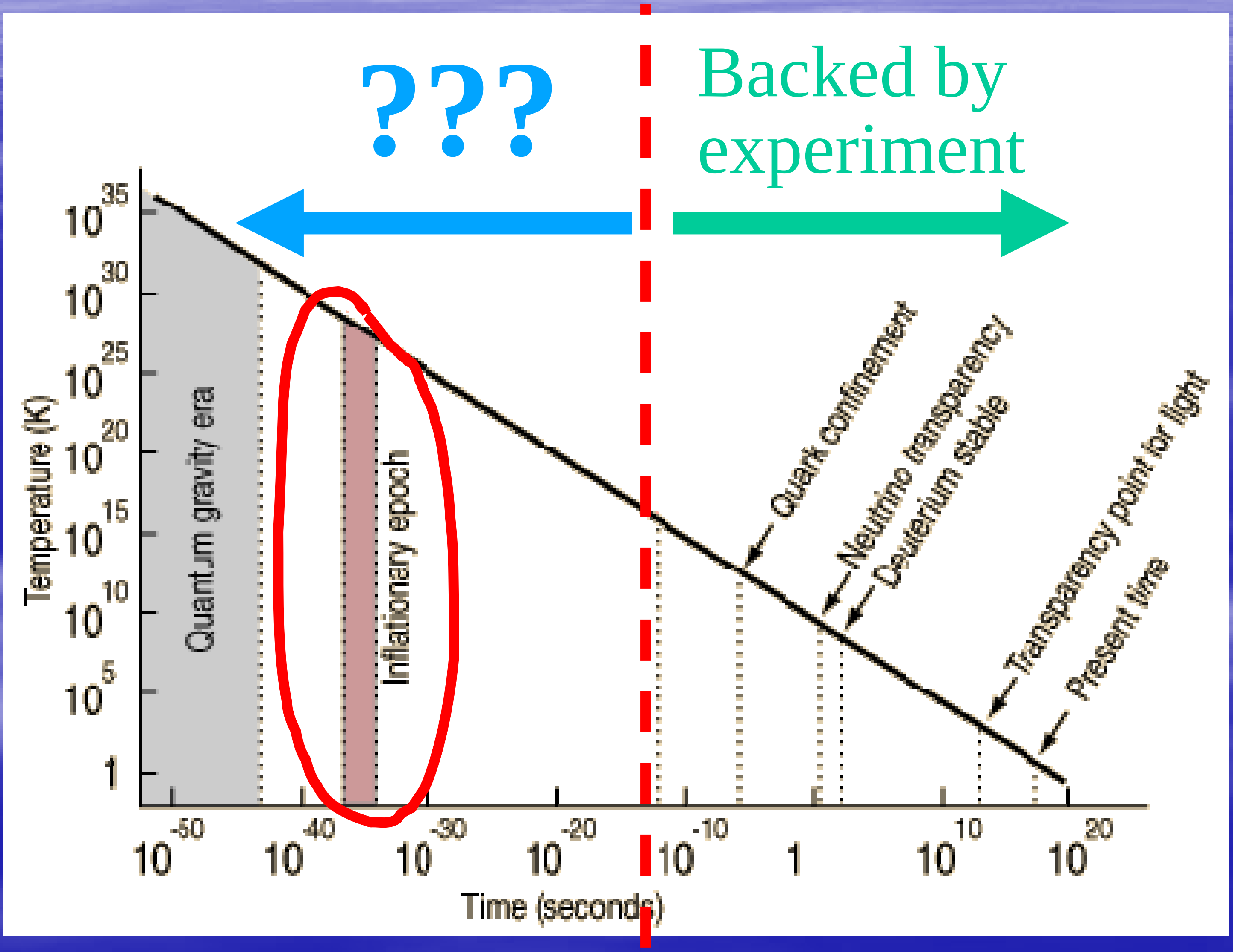
Problem III: Large scale structure

- Models like CDM nicely explain how the fluctuations we can observe in the CMB grew to form galaxies.
- They also can reproduce the observed large scale distribution of galaxies and clusters of galaxies.
- But why are there fluctuations in the first place?

Problem IV: The relic problem

- Modern cosmology is a very successful synergy of astrophysics and particle physics.
- Why are there so many photons in the universe (a billions times more than baryons)
- Why is there more matter than anti-matter ?
- Why aren’t there magnetic monopoles or any other relic particles?

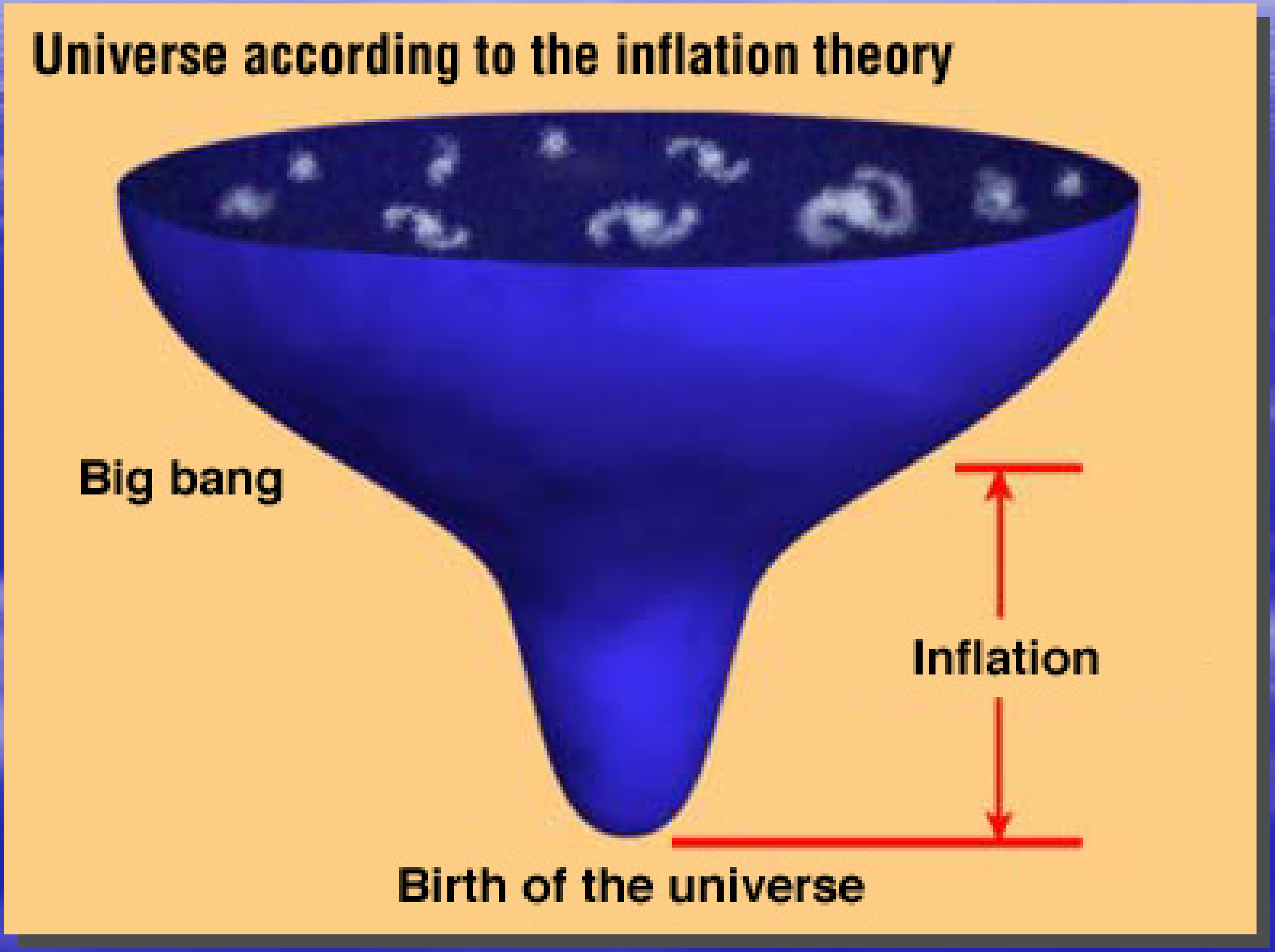
Timeline of the Universe



The concept of inflation

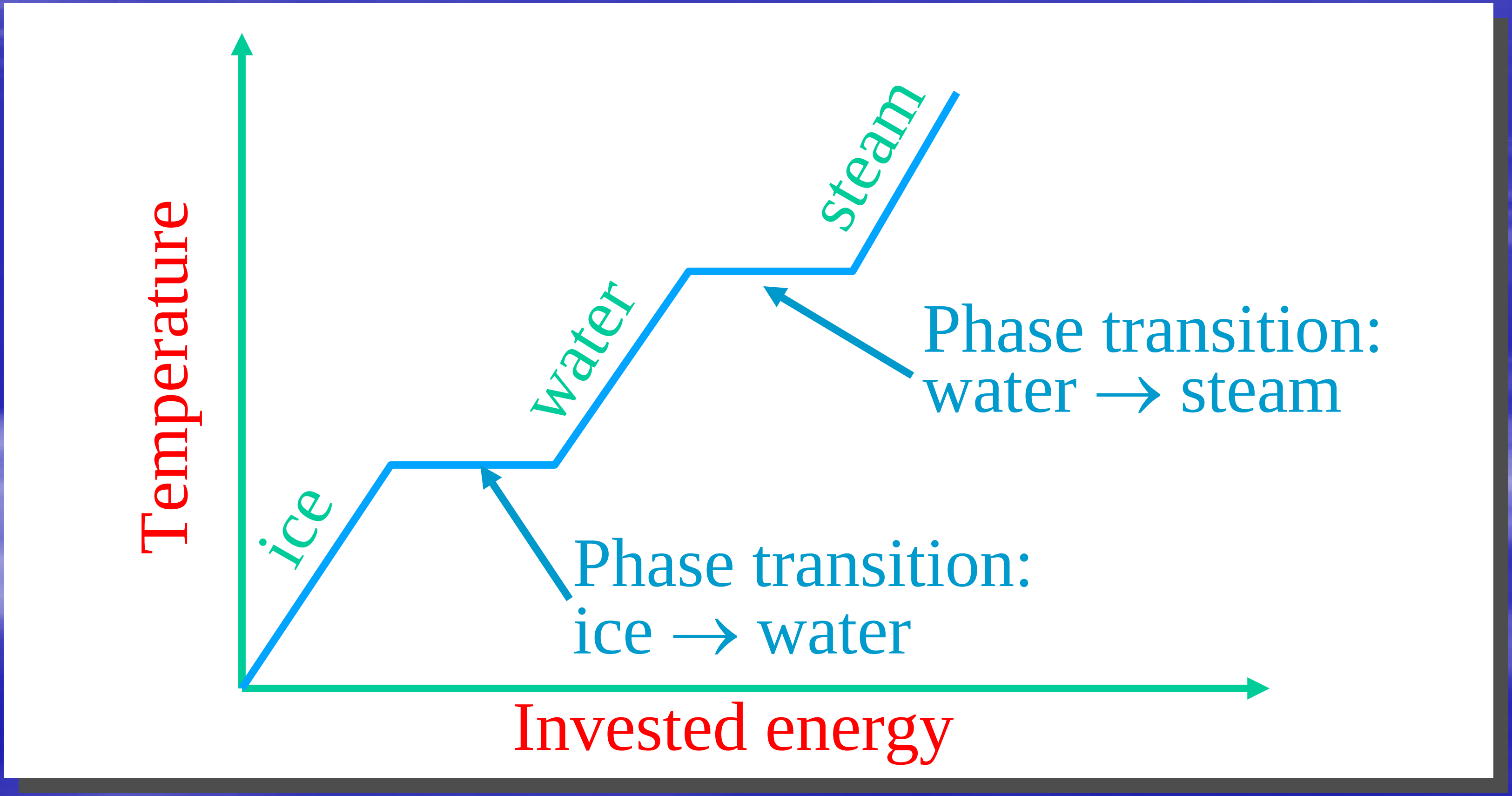
- The idea (A. Guth 1980): Shortly after the big bang, the universe went through a phase of rapid (exponential) expansion. In this phase the energy and thus the dynamics of the Universe was determined by term similar to the cosmological constant (vacuum energy).
  - Why should the Universe do that?
  - Why does it help?

The model of inflation



Phase transitions

- Example: ice → water → steam



Phase transitions in the early Universe

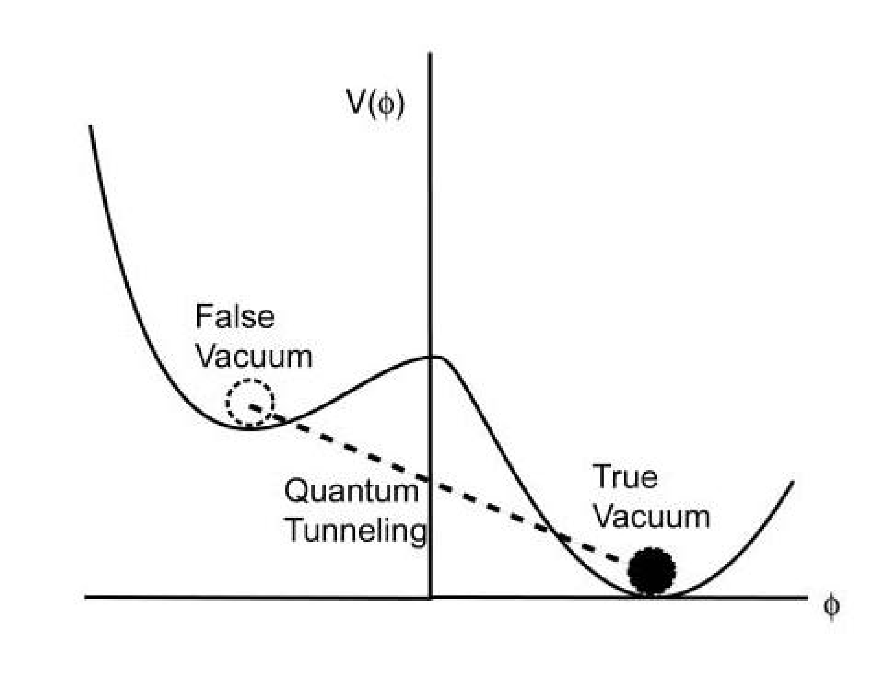
- Electroweak phase transition:
  As the temperature drops below ~ 10^{15}K, the electroweak force separates into electromagnetism and the weak nuclear force
  - $T > 10^{15}$K: electroweak force
  - $T < 10^{15}$K: electromagnetism, weak nuclear force
- but too moderate a phase transition to trigger inflation

Phase transitions in the early Universe

- GUT phase transition:
  As the temperature drops below ~ 10^{29}K, GUT force separates into the strong nuclear force and the electroweak force
  - T > 10^{29}K: GUT
  - T < 10^{29}K: electroweak force, strong nuclear force
- One of the candidates for inflation
- Other candidates: specifically designed inflaton fields

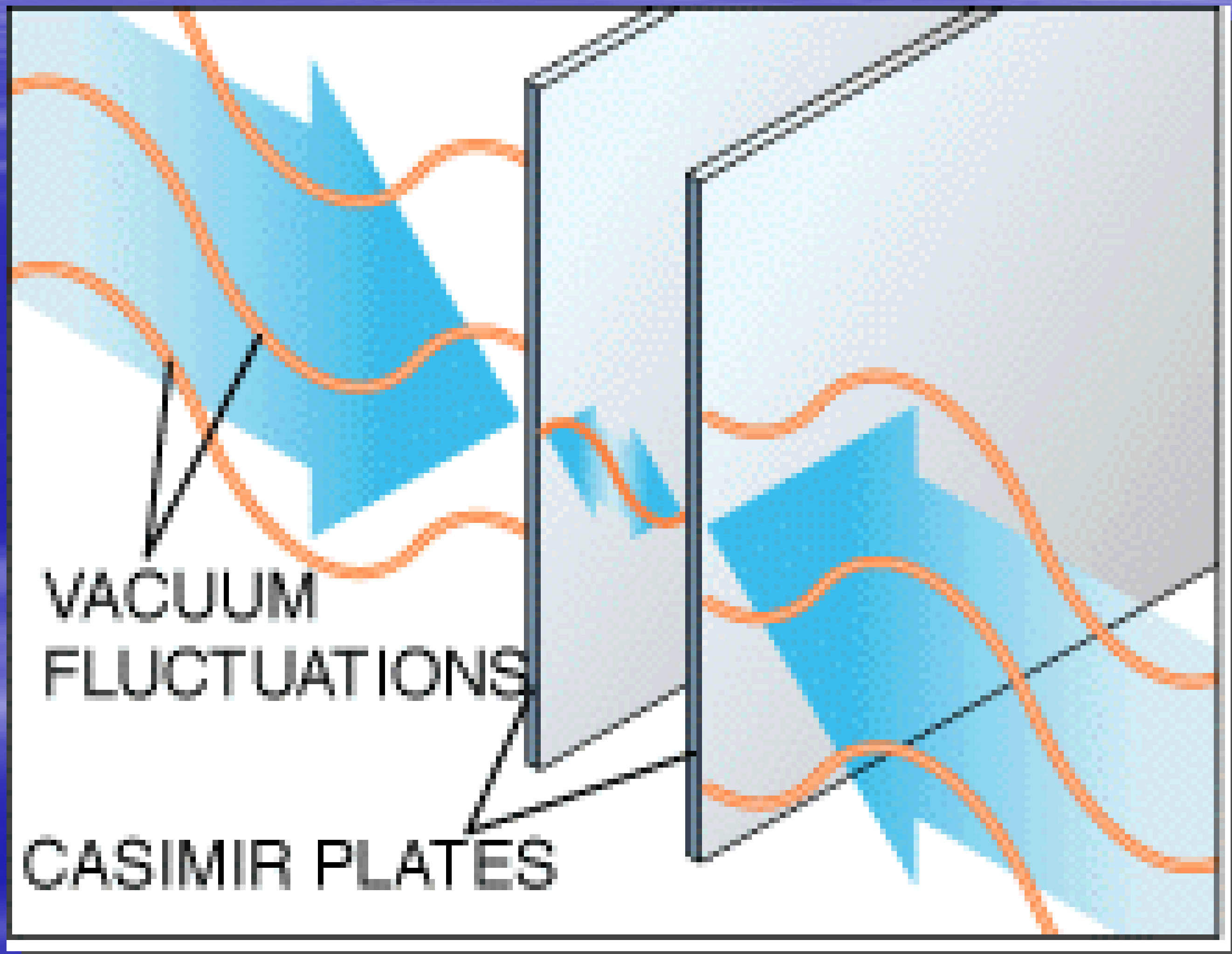
What happens in such a phase transition

- Universe in the state of false vacuum
- energy of Universe dominated by vacuum energy
- vacuum energy acts like a cosmological constant
- Universe expands exponentially

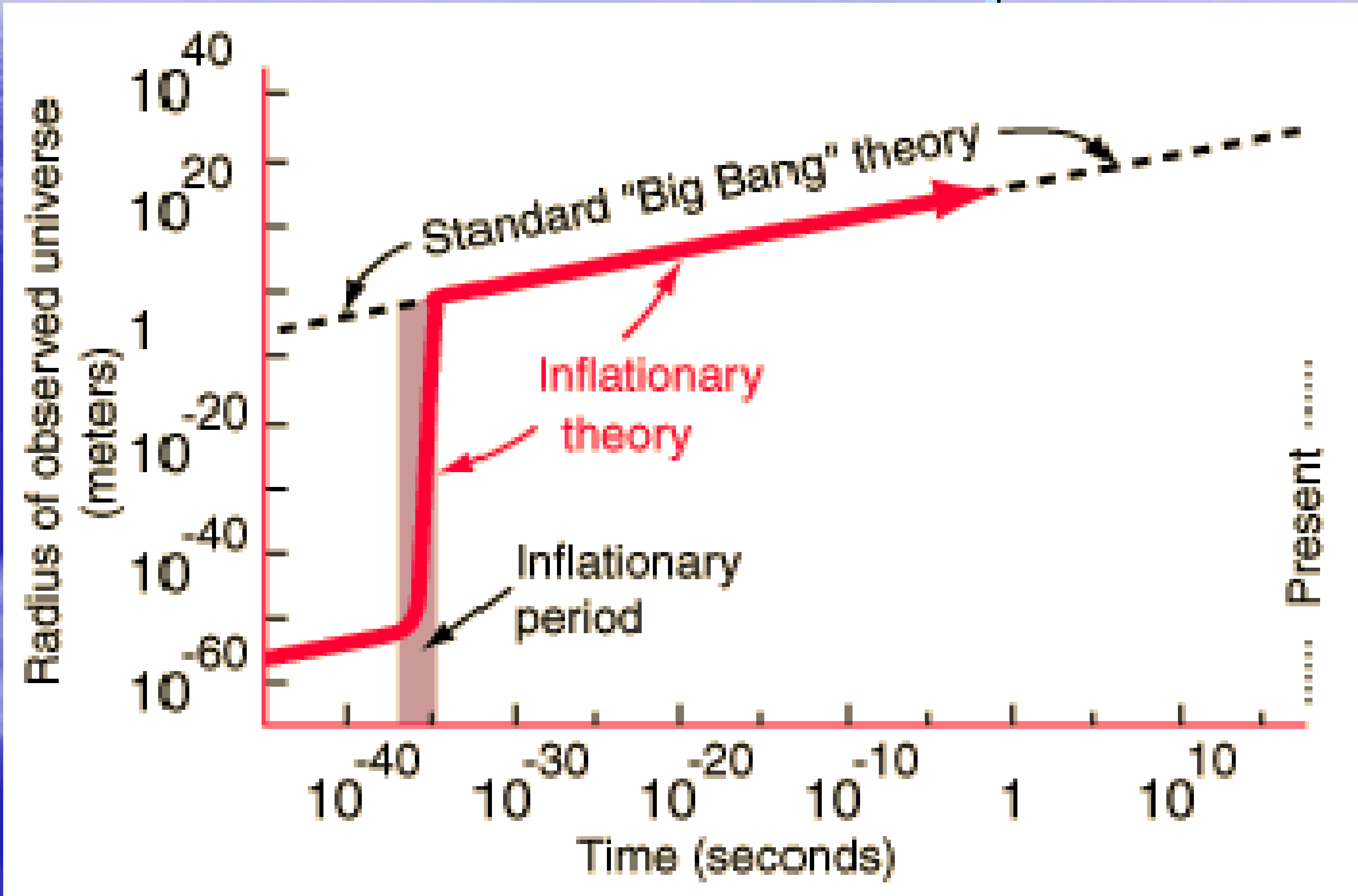


- Problem: how to gracefully exit inflation?

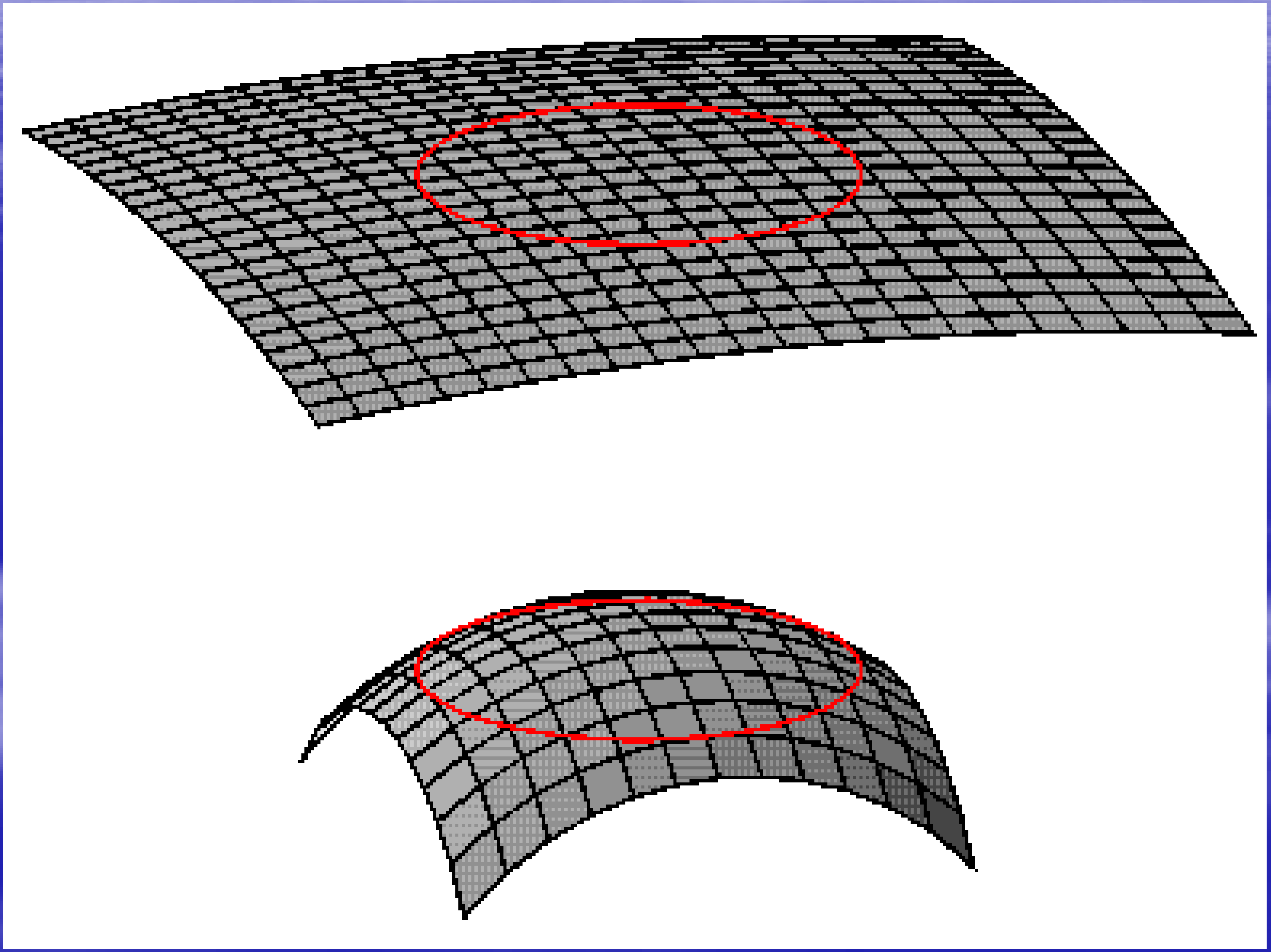
Manifestation of vacuum energy: the Casimir effect



Inflation and the horizon problem



Inflation and the flatness problem

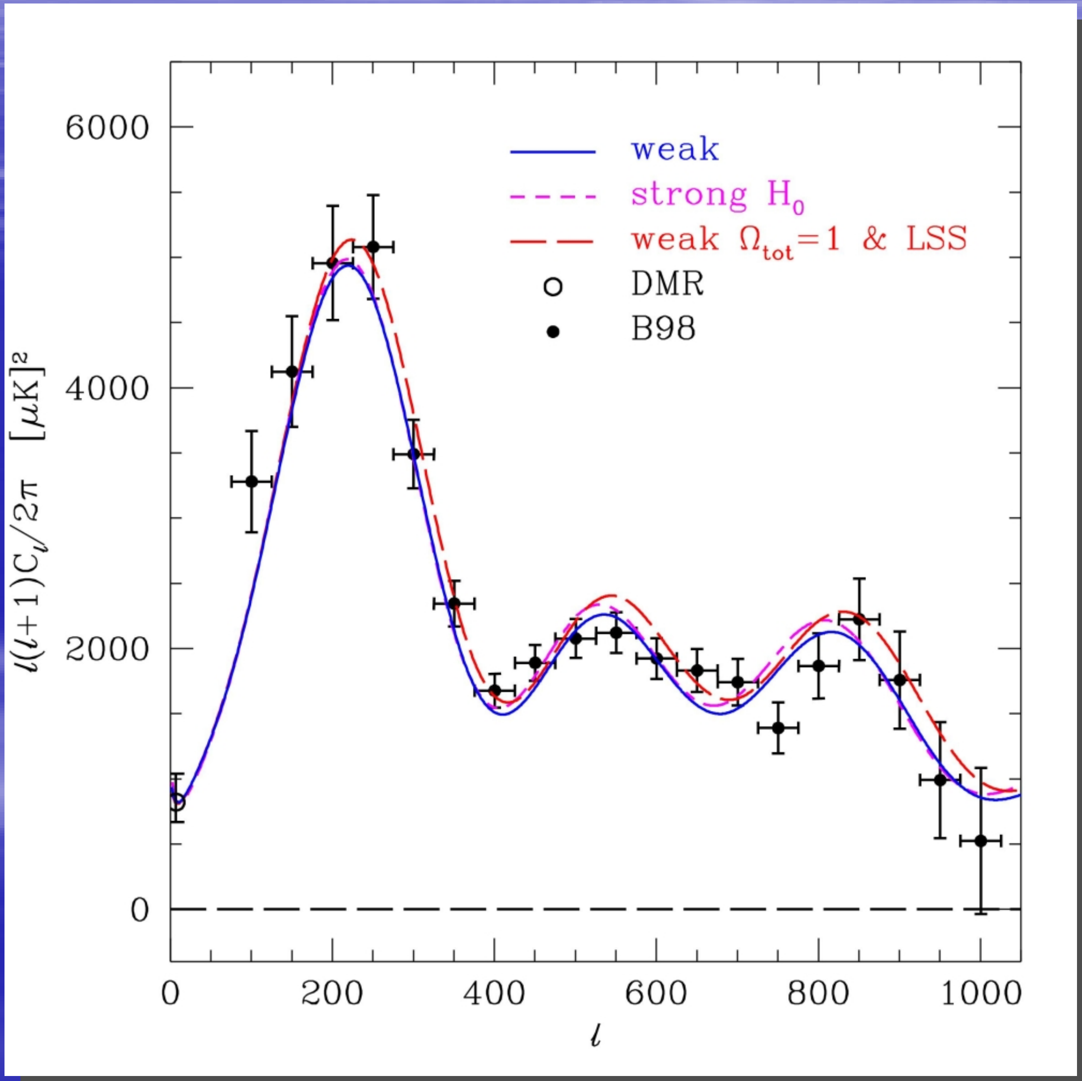


Inflation and the structure problem

- Before inflation: quantum fluctuations
- Inflation: amplifies quantum fluctuations to macroscopic scales
- After inflation: macroscopic fluctuations (as can be observed in the CMB radiation) provide the seeds from which galaxies form

How can we test inflation ?

- With the CMB
- 1st peak ⇒ universe resonates
- 2nd and 3rd peak ⇒ next overtones (harmonics)
- but in order to “hear” the overtones, all “bells” have to be ringing in phase.
- Inflation synchronizes the bells.
- Recent measurements of the 2nd and 3rd peaks is strongly in support of inflation

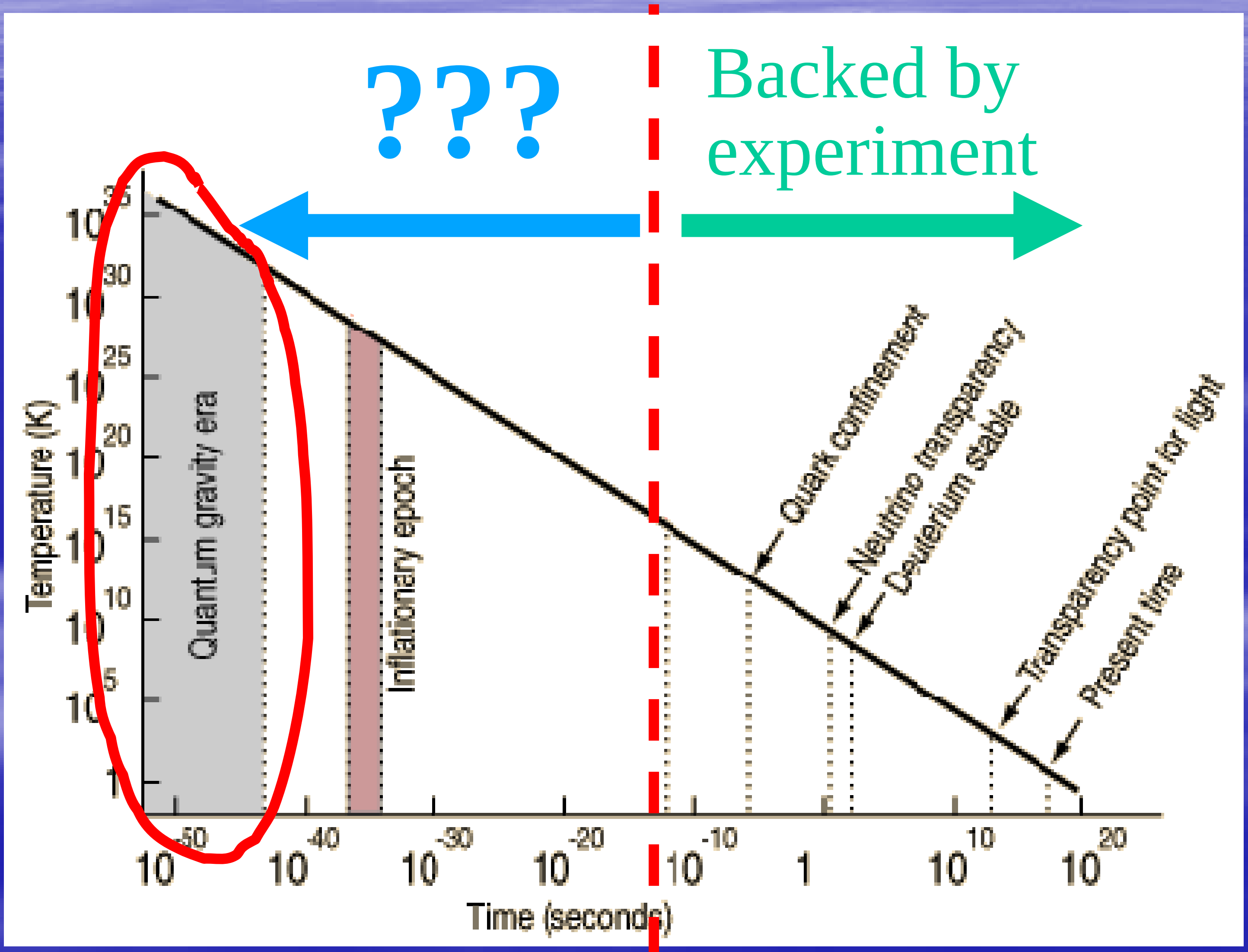


weak
strong H_0
weak $\Omega_{tot}=1$ & LSS
DMR
B98
6000
4000
2000
0
0
200
400
600
800
1000
$l(l+1)C_l/2\pi \quad [\mu K]^2$
l

Planck era

- $T > 10^{32}$K unification of GUT and gravity
- Particles:
  - ???
- Forces:
  - TOE?? (theory of everything, quantum gravity)
- The last frontier ...

Timeline of the Universe



Problems to be solved by quantum gravity

- Combination of quantum mechanics and general relativity
- Dealing with singularities in general relativity and particle physics
  - point-like elementary particles
  - black holes
  - the very early Universe
  - the “origin” of the Universe?

Physics around 1900

- Classical mechanics and electromagnetism were tremendously successful physical theories
- Deterministic world view
  - Supposed the initial conditions of all particles in the Universe are given
  - Using the laws of physics, the precise future state of the Universe at any time can be calculated (at least in principle)
- perception that **all** physics was almost completely known

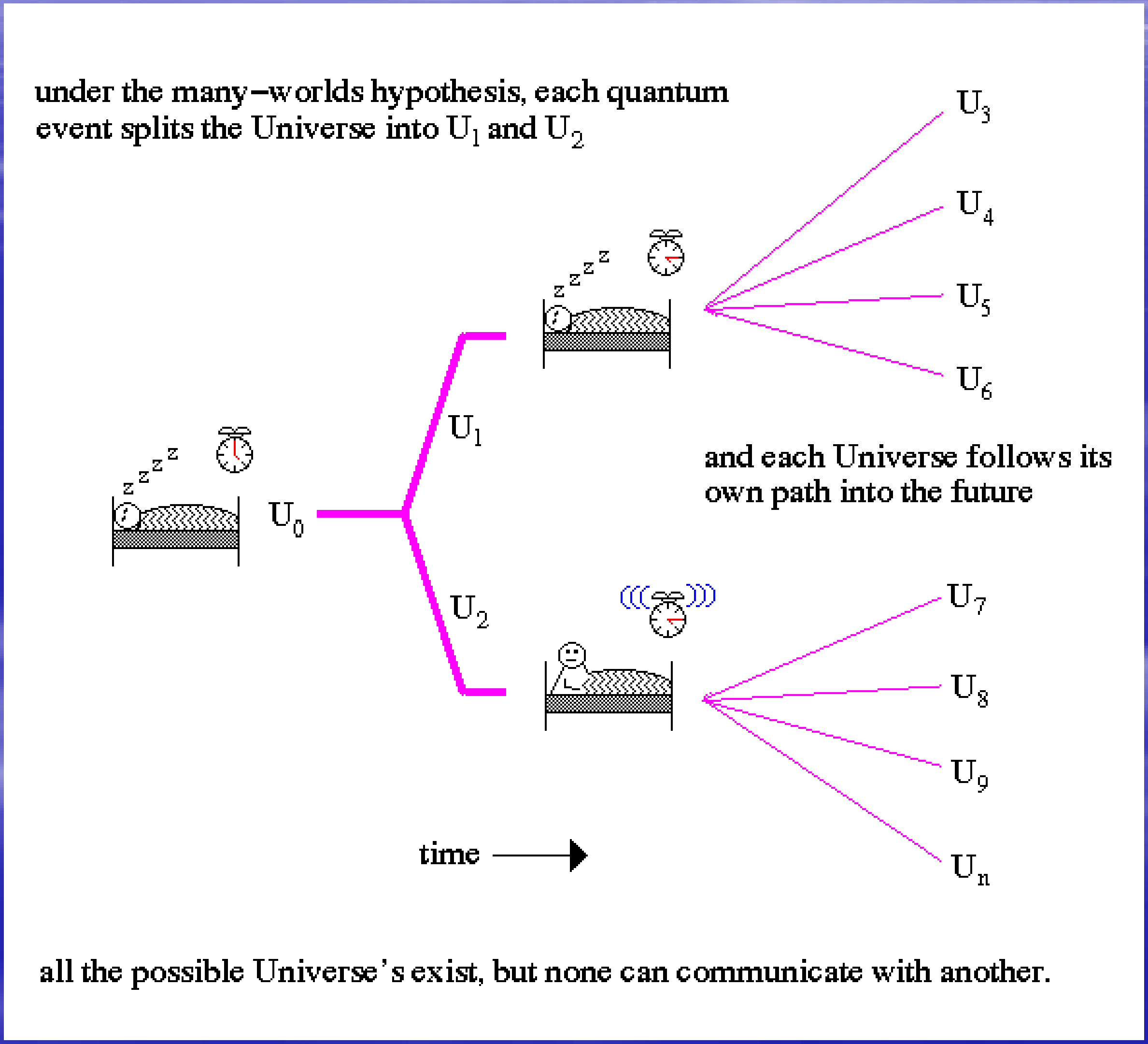
Some outstanding problems (~1900)

- Constancy of the speed of light
  - contradiction between classical mechanics and electrodynamics ⇒ special relativity
- Black body radiation
  - The observed energy distribution cannot be explained using the classical laws of physics ⇒ quantum physics
- Radioactivity
  - one cannot determine when a radioactive nucleus is going to decay
  - one can only specify probabilities
- Is light a particle or a wave ?

Quantum cosmology

- Task: calculate the wave function of the Universe
- Problem: observer is part of the system $\Rightarrow$ the Copenhagen interpretation cannot be applied
- Alternative: many-worlds interpretation
  - many universes exist, but mutually unobservable
  - all possible outcomes are realized
  - whenever a decision between two (or more) states has to be made, the universe splits into two (or more) branches

Many-worlds interpretation



Outstanding problems in cosmology

- What is the dark matter?
- What is the dark energy/cosmological constant?
- Quantum gravity/Cosmology
  - elementary particles are not points, but very small strings (loops) ($\sim 10^{-35}$ m)
  - oscillation modes of strings correspond to different particle types
  - there exist extra (compactified/wrapped) dimensions