Sterrewacht Leiden

Origins & Evolution of the Universe
an introduction to cosmology – Fall 2014

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http://www.strw.leidenuniv.nl/~hoekstra/TEACHING/OEU/OEU.html

The Hot Big Bang

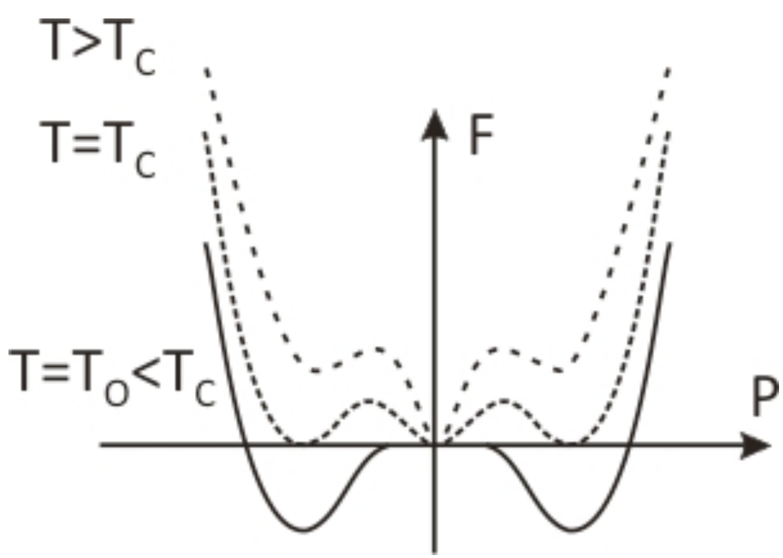
If cosmological nucleosynthesis is the correct explanation for the observed light-element abundances, the Universe must have gone through a phase where $T>10^{12}$K.

Going back in time, all particles that make up the Universe become relativistic and we can model it as a perfect ultra-relativistic gas of non-degenerate particles in thermal equilibrium.

Era of phase transitions

Phase transitions: rearrangement of the microphysics in which a particular symmetry is created or destroyed.

- location of particles: freezing, melting, evaporation
- orientation of particles: ferromagnetism



$F = U - T \times S$

Example of first order transition

Kibble mechanism

After each phase transition the effective physics changes

Phase transitions can leave defects if different regions pick a different state

Kibble mechanism: different horizon-sized volume choose their ground states independently; this creates seeds of defects, one per few horizon volumes

As the Universe expands and cools the fields decay to their ground stats over most of space, but trapped energy domains remain as defects: ***this is a generic prediction***!

Topological defects

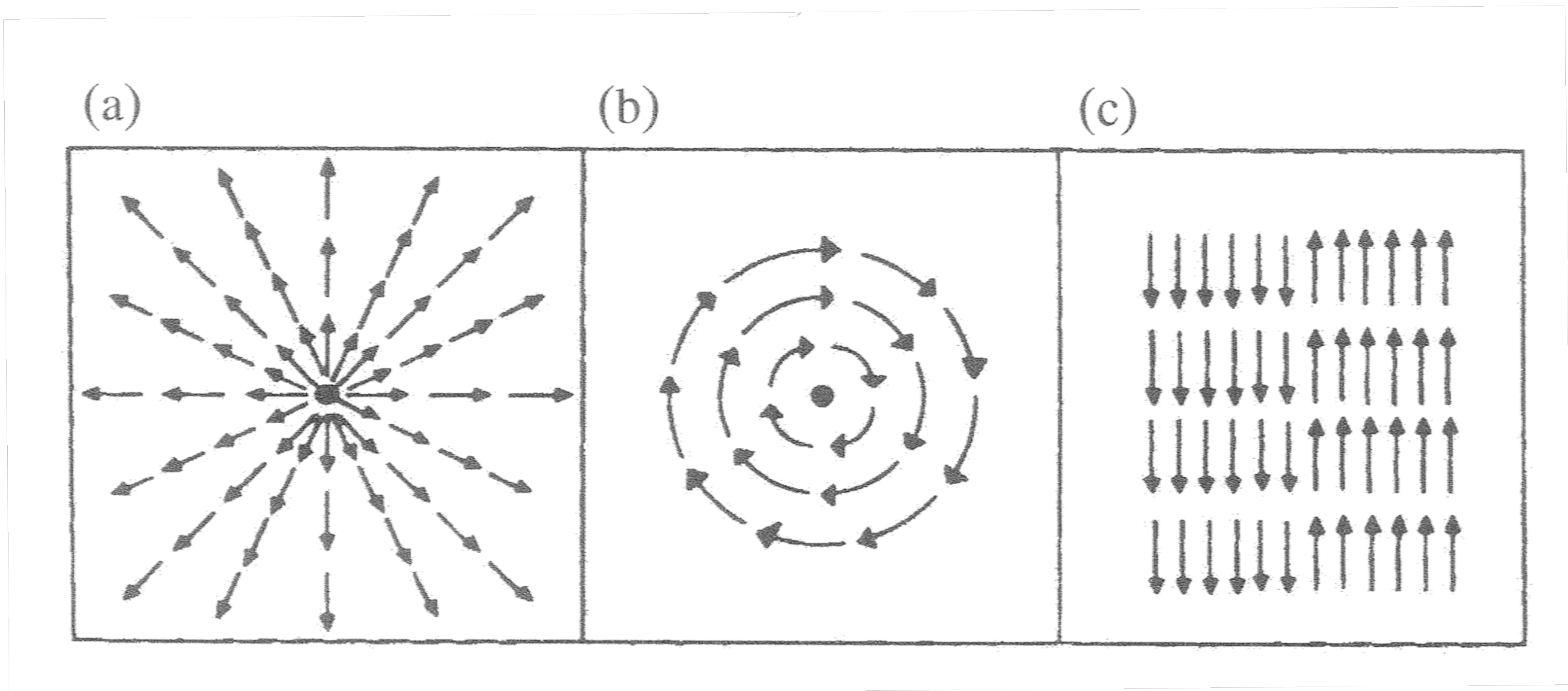
Monopole (point defect): defects that form when a spherical symmetry is broken, are predicted to have magnetic charge.

Cosmic string (line defect): one-dimensional lines that form when an axial or cylindrical symmetry is broken

Domain wall (surface defect): two-dimensional membranes that form when a discrete symmetry is broken at a phase transition.

Textures (higher dimensional defects): form when larger, more complicated symmetries are completely broken. They are not as localized as the other defects, and are unstable.

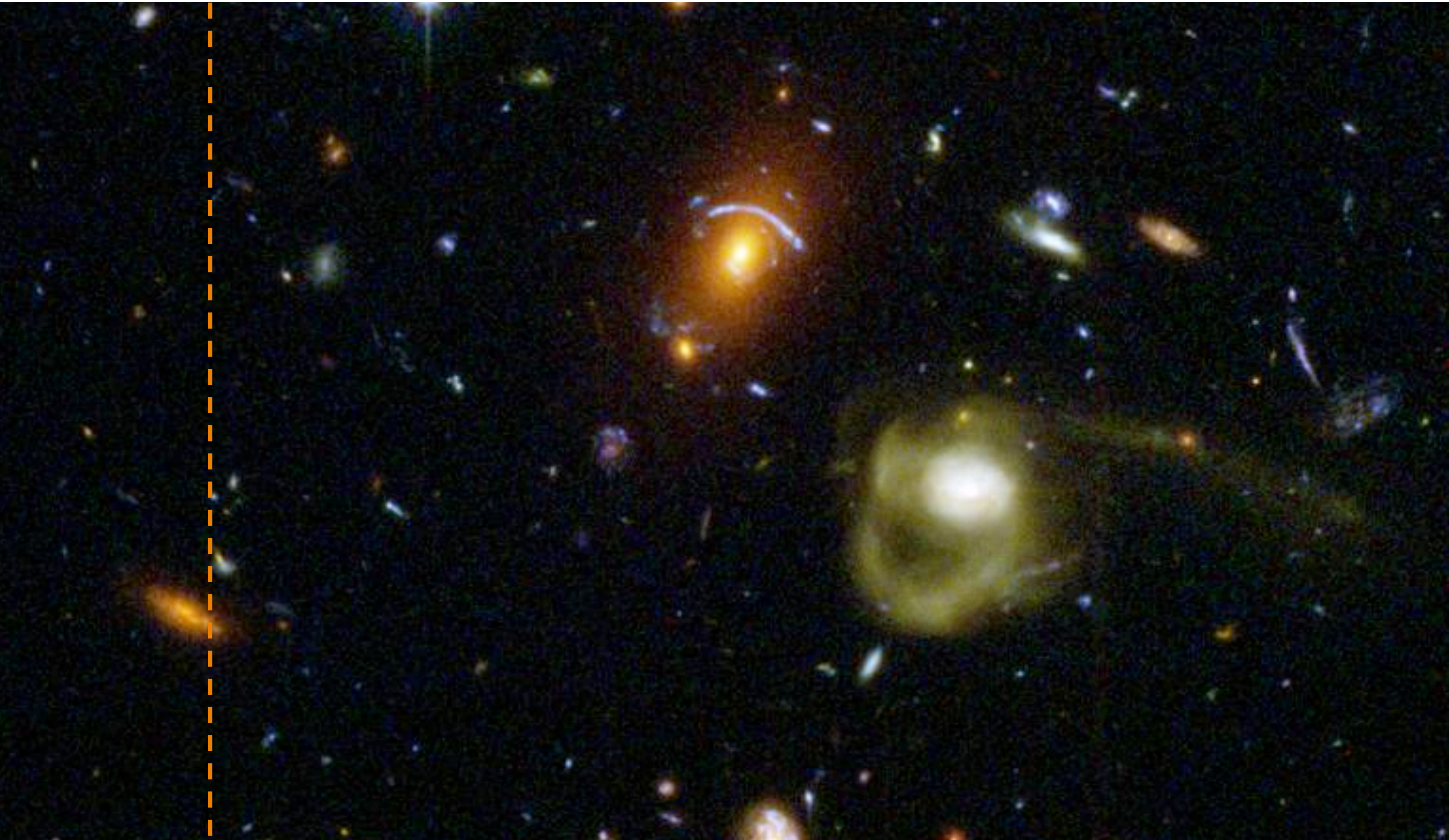
Topological defects



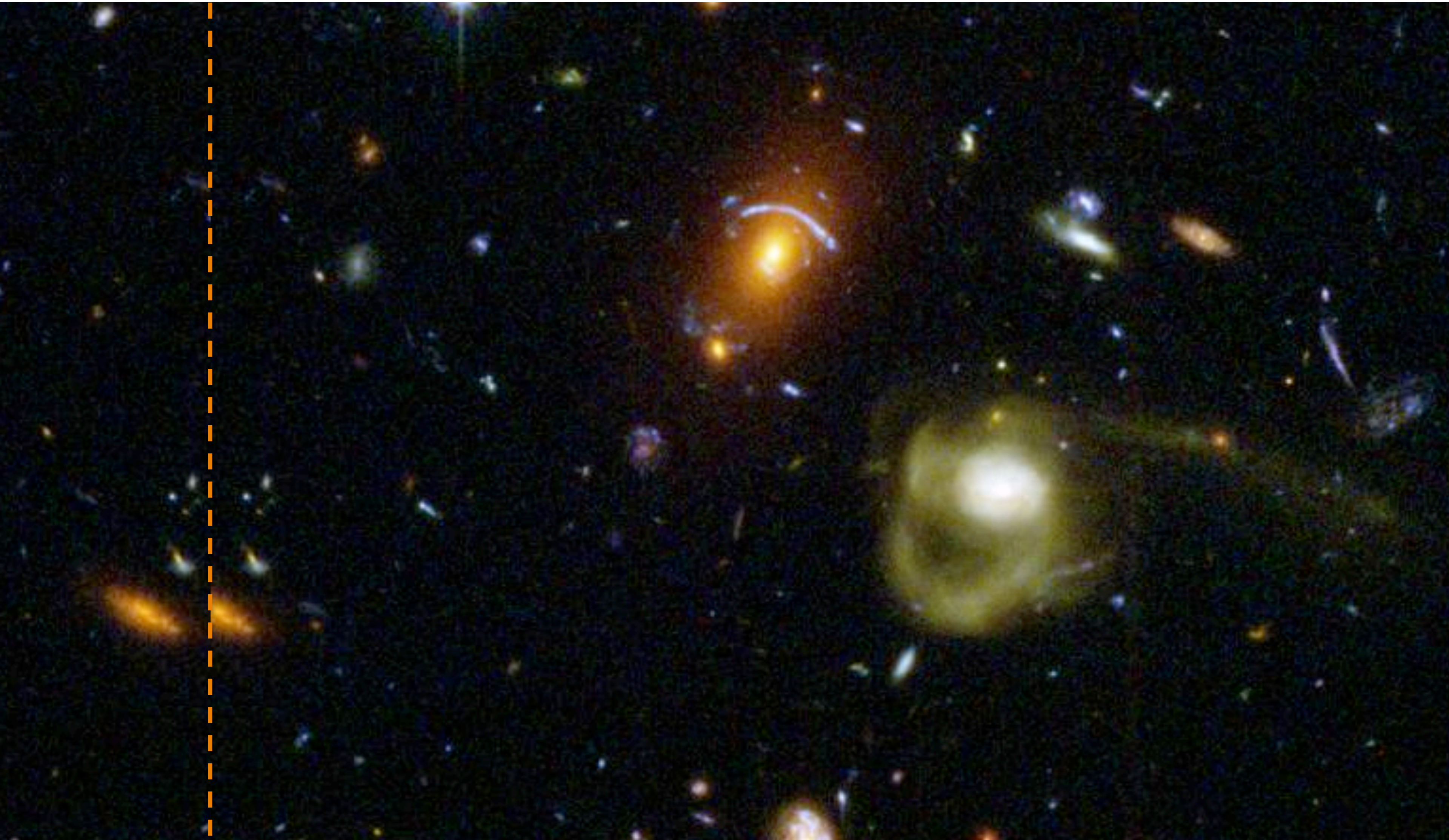
monopole string domain wall

From: Coles & Lucchin (2002)

Effect of a cosmic string

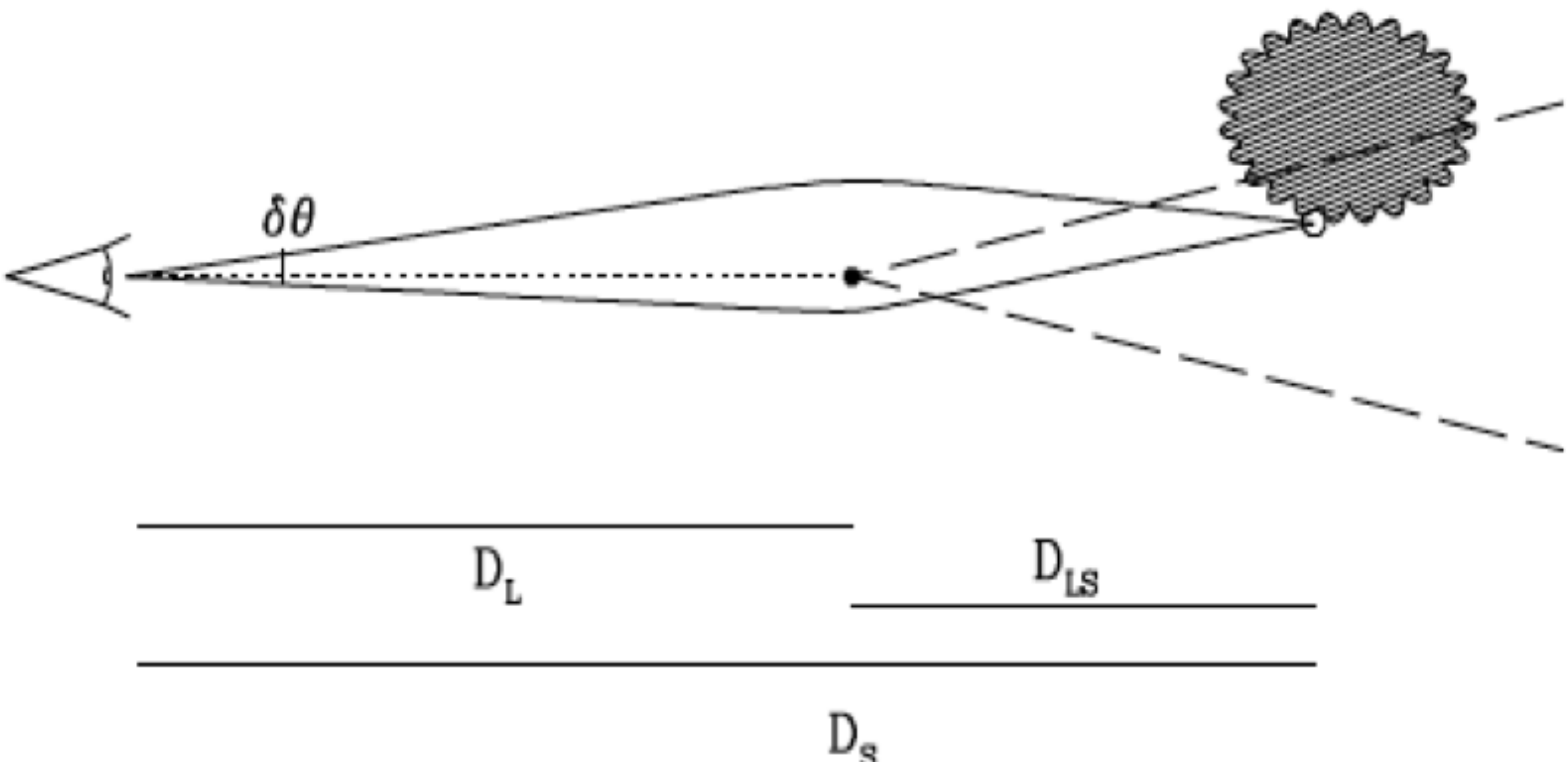


Effect of a cosmic string



Effect of a cosmic string

Cosmic strings split images - angle of splitting proportional to mass/unit length.



Phase transitions of the Universe

Between $T \approx 10^{19}$ and 10^{15} GeV, quantum gravity effect decrease in importance and interactions are described by a GUT. Baryon number is not conserved in GUTs, so no asymmetry between matter and antimatter.

Near $T \approx 10^{15}$ GeV ($t = 10^{-37}$s) the GUT symmetry breaks leading into the situation described by the standard model of particles; the GUT phase transition typically results in the formation of magnetic monopoles.

For typical GUTs:
- particle mass: $m_M \approx 10^{16}$GeV
- number density: $n_M > 10^{-10} n_\gamma$.

$\Longrightarrow \Omega_{monopole} > m_M/m_p \Omega_{bar} \approx 10^{16}$.

This does not match observations: **the monopole problem**

Phase transitions of the Universe

A GUT that unifies the elektroweak interactions with the strong interactions puts leptons and hadrons on the same footing and thus allows processes that do not conserve baryon number: source of matter/anti-matter asymmetry.

As the temperature falls below $T_{GUT} \approx 10^{15}$ GeV the unification of the strong and elektroweak interactions no longer holds. Towards the end of this period (10^{-11}s) the Universe is filled with an ideal gas op leptons and antileptons, the four vector bosons, quarks and anti-quarks.

The horizon is 1cm and contains $\approx 10^{19}$ particles!

Phase transitions of the Universe

At T_{EW}≈100 GeV elektro-weak symmetry is broken and we have separate elektromagnetic and weak forces. All the leptons acquire mass.

When the temperature drops to T_{QH}≈200-300 MeV (10^{-5}s) we have the final phase transition and the strong interaction leads to the confinement of quarks into hadrons: the quark-hadron phase

The horizon is 1km in size

Successes of the Big Bang model

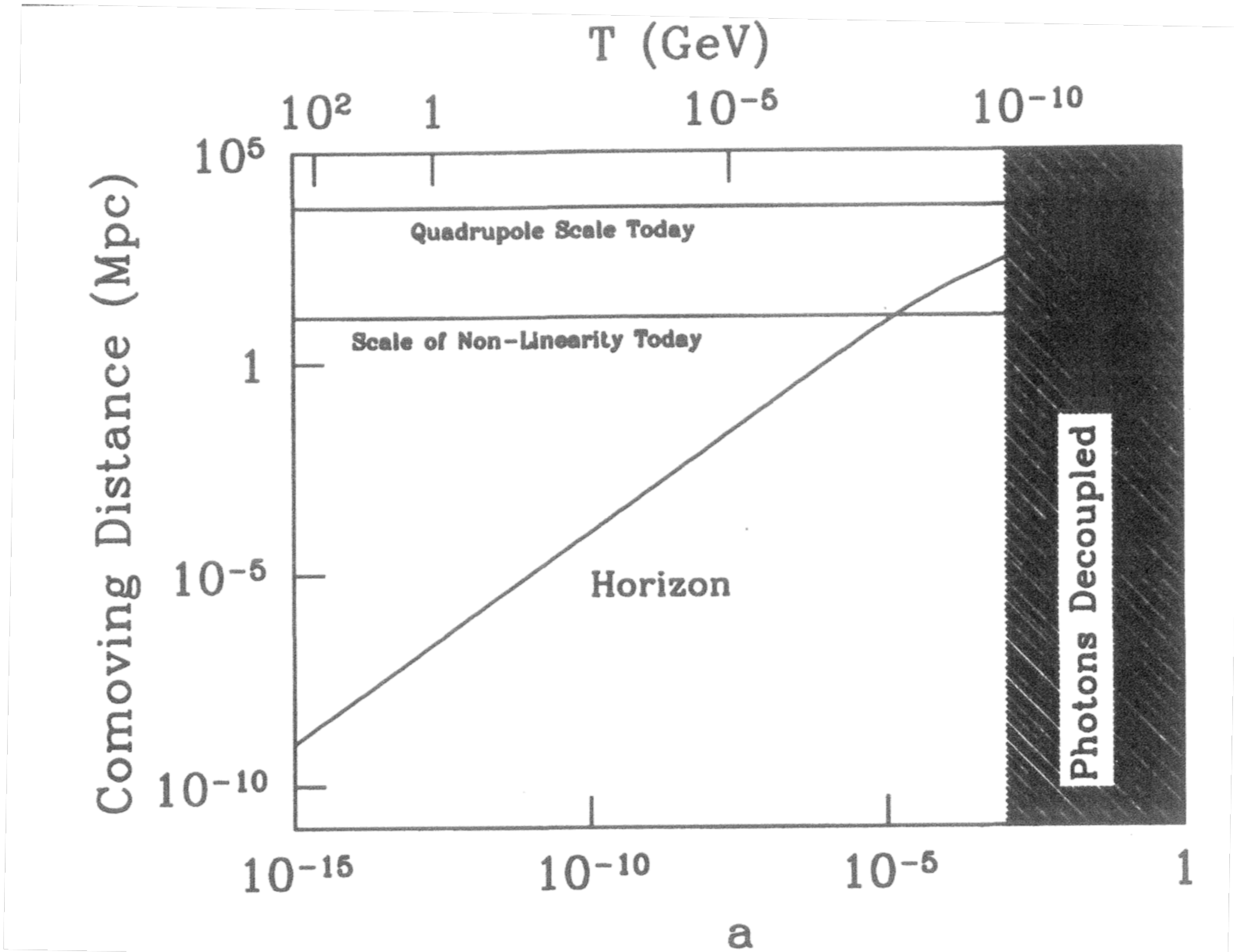
- Correctly predicts the abundances of light elements
- Explains the CMB as relic of the hot initial phase
- Naturally accounts for the expansion of the Universe
- Provides a framework to understand the formation of cosmic structure.

There are also several problems (some of which can be addressed by incorporating "new physics")

Problems with the Big Bang model

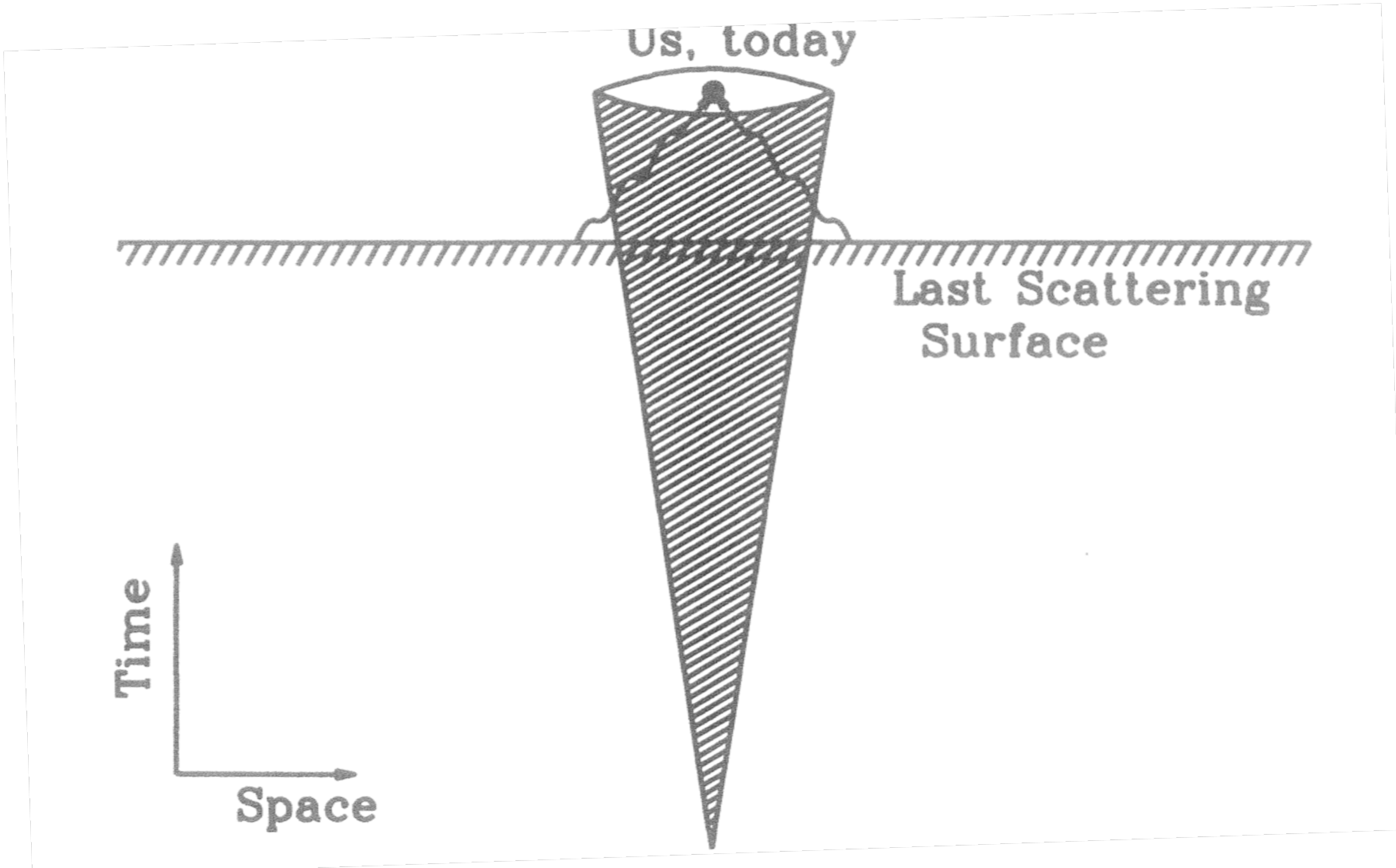
- Origin of the Universe
- The horizon problem
- The flatness problem
- Origin of the baryon asymmetry
- Monopole problem
- Origin of primordial density fluctuations
- Nature of dark matter
- Nature of dark energy

Horizon problem



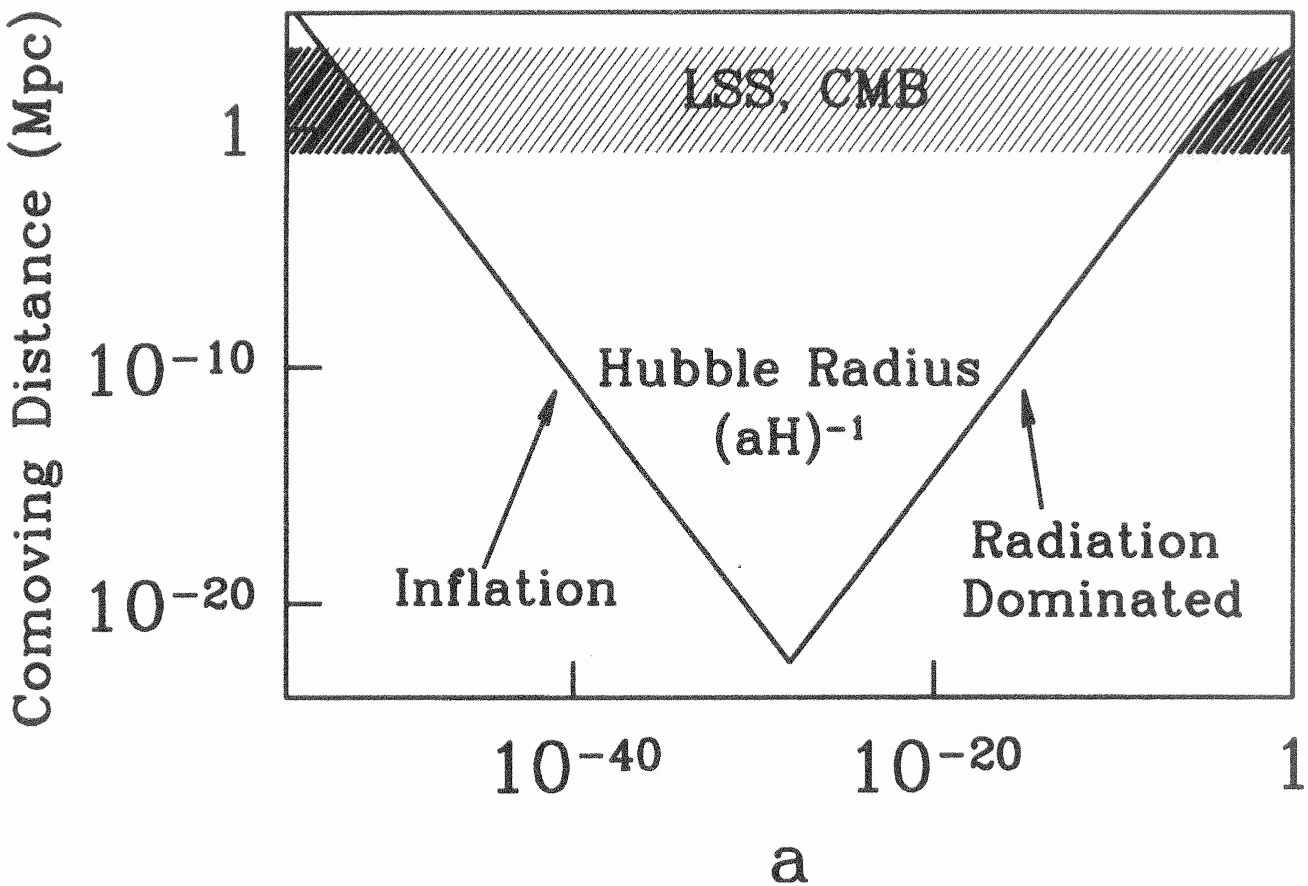
Dodelson (2003)

Horizon problem



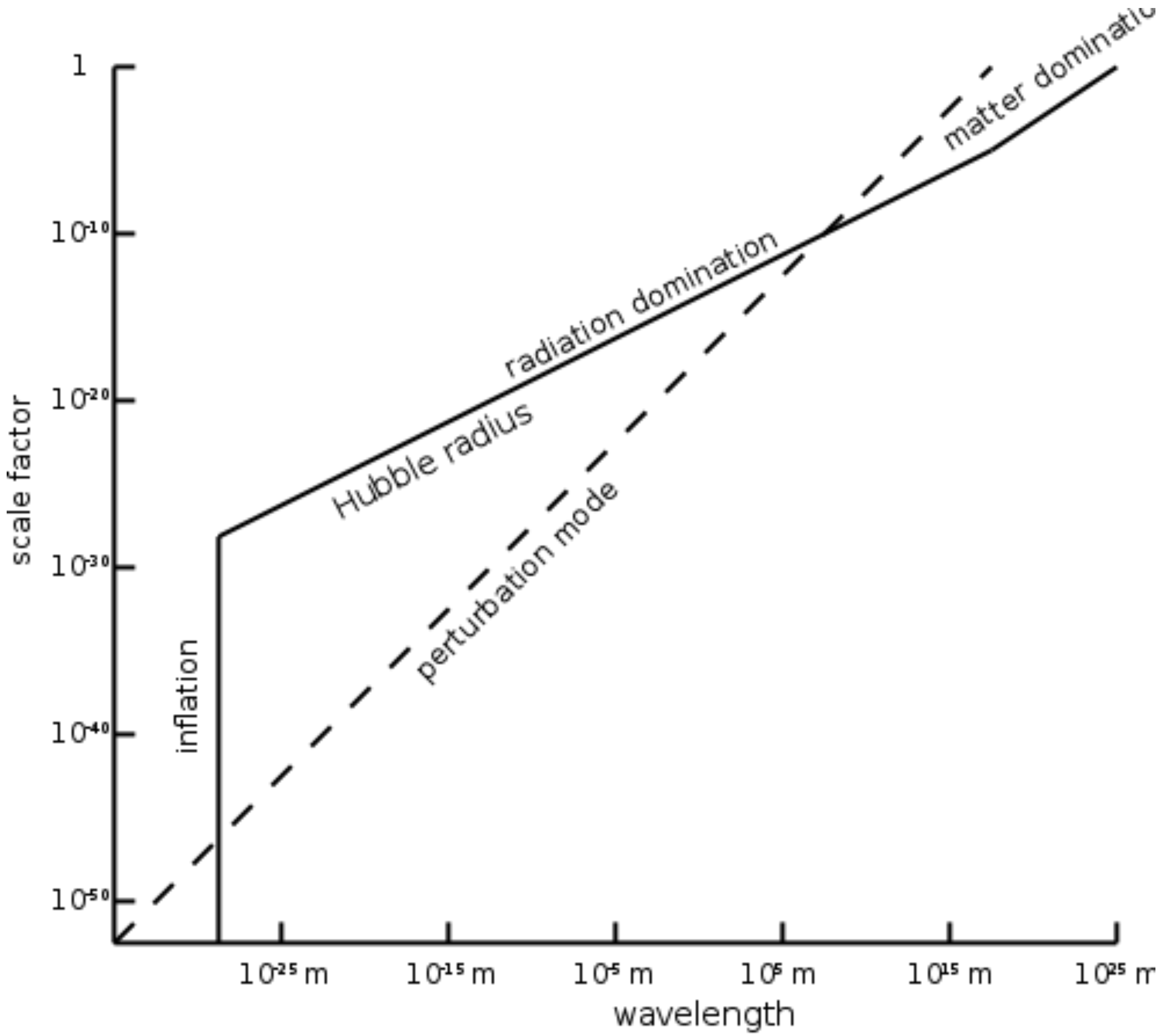
Dodelson (2003)

Inflation



Dodelson (2003)

Inflation



1
10^{-10}
10^{-20}
10^{-30}
10^{-40}
10^{-50}
scale factor
inflation
Hubble radius
radiation domination
perturbation mode
10^{-25} m
10^{-15} m
10^{-5} m
10^{5} m
10^{15} m
wavelength

Inflation

We need a period of accelerated expansion

This can solve the flatness, horizon and monopole problem in an elegant fashion

It can also explain the origin of the density fluctuations.

Inflation models

The behavior of the model depends on the potential (or vice versa)

- **Old inflation**: first-order transition (potential barrier) does not work
- **New inflation**: second-order transition, with a slow-roll phase; suffers from fine-tuning the model
- **Chaotic inflation**: the scalar field varies from place-to-place; inflation occurs if conditions are favorable and "take-over" the Universe
- **Stochastic inflation**: many instances of chaotic inflation spawning new macro-universe; the multi-verse may also solve the cosmological constant problem.

In the end we lack a solid connection to particle physics. This is needed to really make progress.