

# Announcements

SEIs!

Quiz 3 Friday.

Lab Monday optional: review for Quiz 3.

Lab Tuesday optional: review for Quiz 3.

Lecture today, Wednesday, next Monday.

Final Labs Monday & Tuesday next week.

## Quiz 3

How do we measure distances to galaxies?

What is an RR Lyrae or Cepheid? P-L relation?

What was the Great Debate?

What is a spheroid? Pop III, Pop II, Pop I?

Do galaxies run into each other? Why?

List some properties of supermassive black holes?

What is a galaxy cluster?

What is the evidence for the Big Bang?

What are the principal postulates and implications of Special Relativity?

What is Omega, and what does its value mean?

What is the evidence for Dark Matter? Dark Energy?

# We know less about dark energy than dark matter.

“Extra” energy density that does not dilute. **Not** like normal energy!

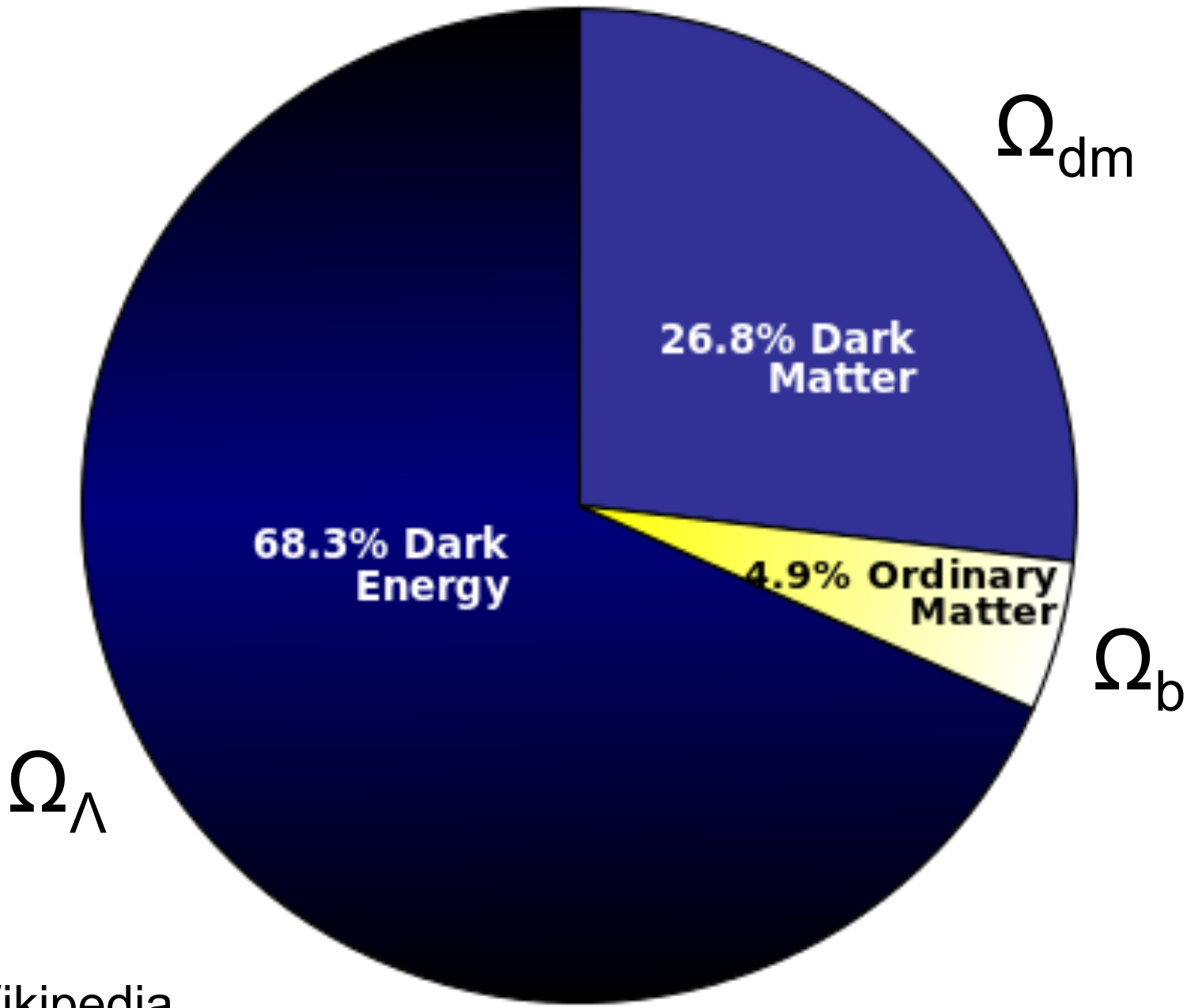
**Cosmological Constant ( $\Lambda$ ):**

- Vacuum energy component whose density is constant over cosmic history
- Problem: theories predict  $10^{100}$  times too high...

**Generic Dark Energy**

- Could vary in density over cosmic time
- Candidates include exotic particle physics objects like scalar fields, quintessence, phantom energy...

Why doesn't it affect things here?  $\Omega_{\Lambda} = 0.7!$



Wikipedia

# Maybe Dark Matter & Dark Energy don't exist at all!

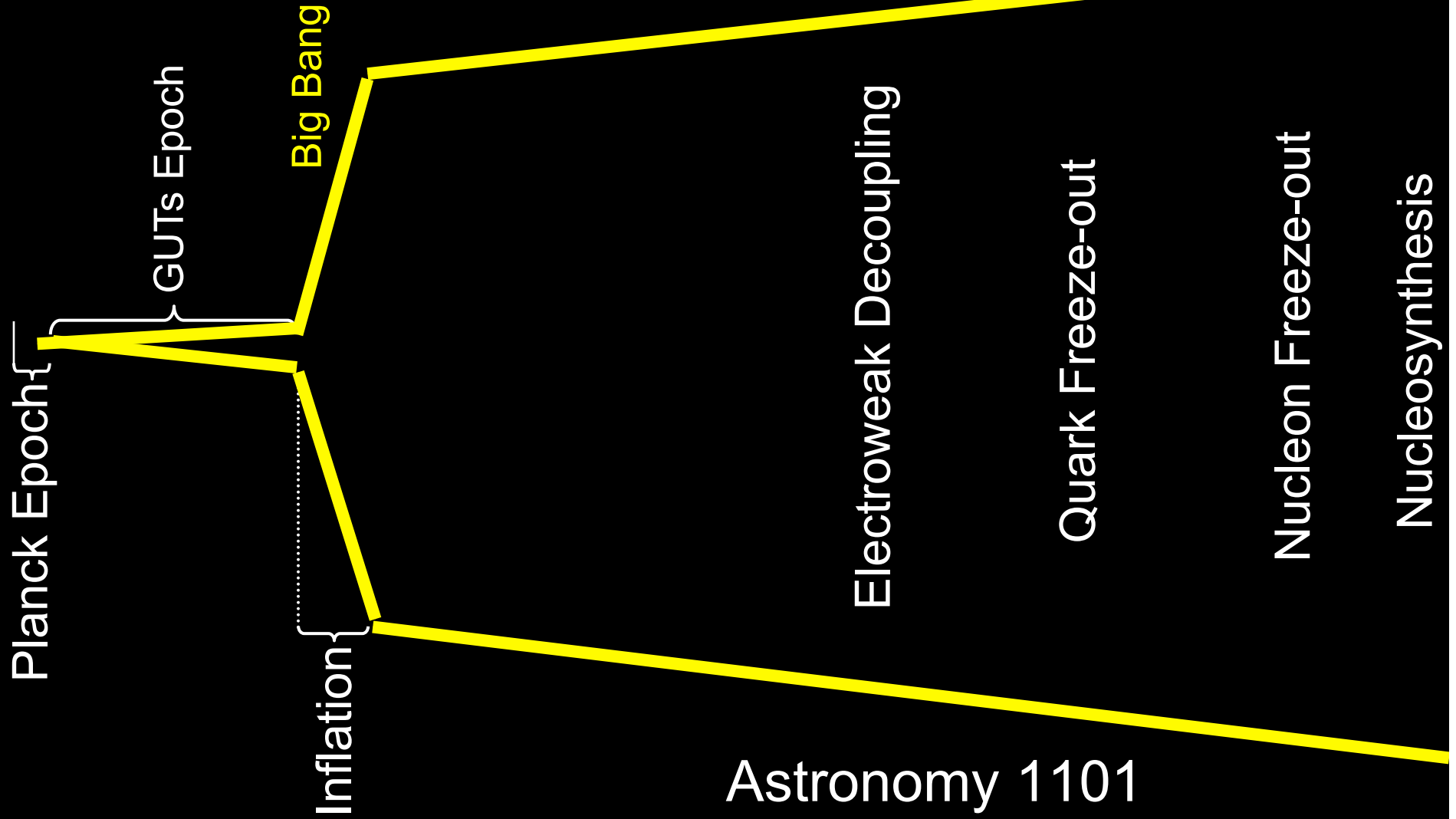
Is our theory of gravity *wrong* on large scales?

MoND: Modified Newtonian Dynamics

Major Problems:

- None of the alternative theories of gravity have survived key tests of detailed predictions.
- Hard to reconcile these theories with the observed gravitational lensing.

# *The First Three Minutes*



# Key Ideas:

## Physics of the Early Universe

- Informed by experimental & theoretical physics
- Later stages confirmed by observations

## The Cosmic Timeline:

- Unification of forces around time of the Big Bang
- Separation of forces as the Universe cools
- Inflation explains smoothness & flatness
- Emergence of matter starting at  $t = 10^{-6}$  sec
- Recombination & emergence of visible Universe

# The Big Bang's Hot Past

## The Universe Today:

- Low density, dark, and very cold (2.7 K)
- Continues to expand

## ~14 Gyr Ago:

- Universe was smaller, denser, & hotter
- Opaque and filled with photons

How far back can we go in cosmic history?

# Binding Energy

## Binding Energy:

- Energy needed to unbind (break up) matter.

## Binding Temperature:

- Temperature equivalent to the binding energy
- Matter at this temperature “melts” (unbinds)

## Examples:

- Molecules melt into atoms at  $T \sim 1000 \text{ K}$
- Atoms melt into free electrons/nuclei at  $T \sim 3000\text{-}10000\text{K}$
- Nuclei melt into free neutrons & protons at  $T \sim 10 \text{ Billion K}$
- Protons & Neutrons melt into quarks  $T \sim 10 \text{ Trillion K}$

# Fundamental Forces of Nature

## Gravitation:

- Long-Range Force, weakest in Nature

## Electromagnetic Force:

- Long-Range,  $10^{39}$  x stronger than gravity

## Weak Nuclear Force:

- Range  $\sim 10^{-17}$  meters,  $10^{28}$  x gravity

## Strong Nuclear Force:

- Range  $\sim 10^{-15}$  meters,  $10^{41}$  x gravity

# Unification of Forces

In the 19th century electrical and magnetic phenomena were considered separate.

- 1820: Orsted noticed that his compass deflected from magnetic north when the electric current from a battery was switched on.
- Work by Faraday, Maxwell, Hertz, and others proved that electricity and magnetism were two components of “electromagnetism,” a single force.
- **Unification.**

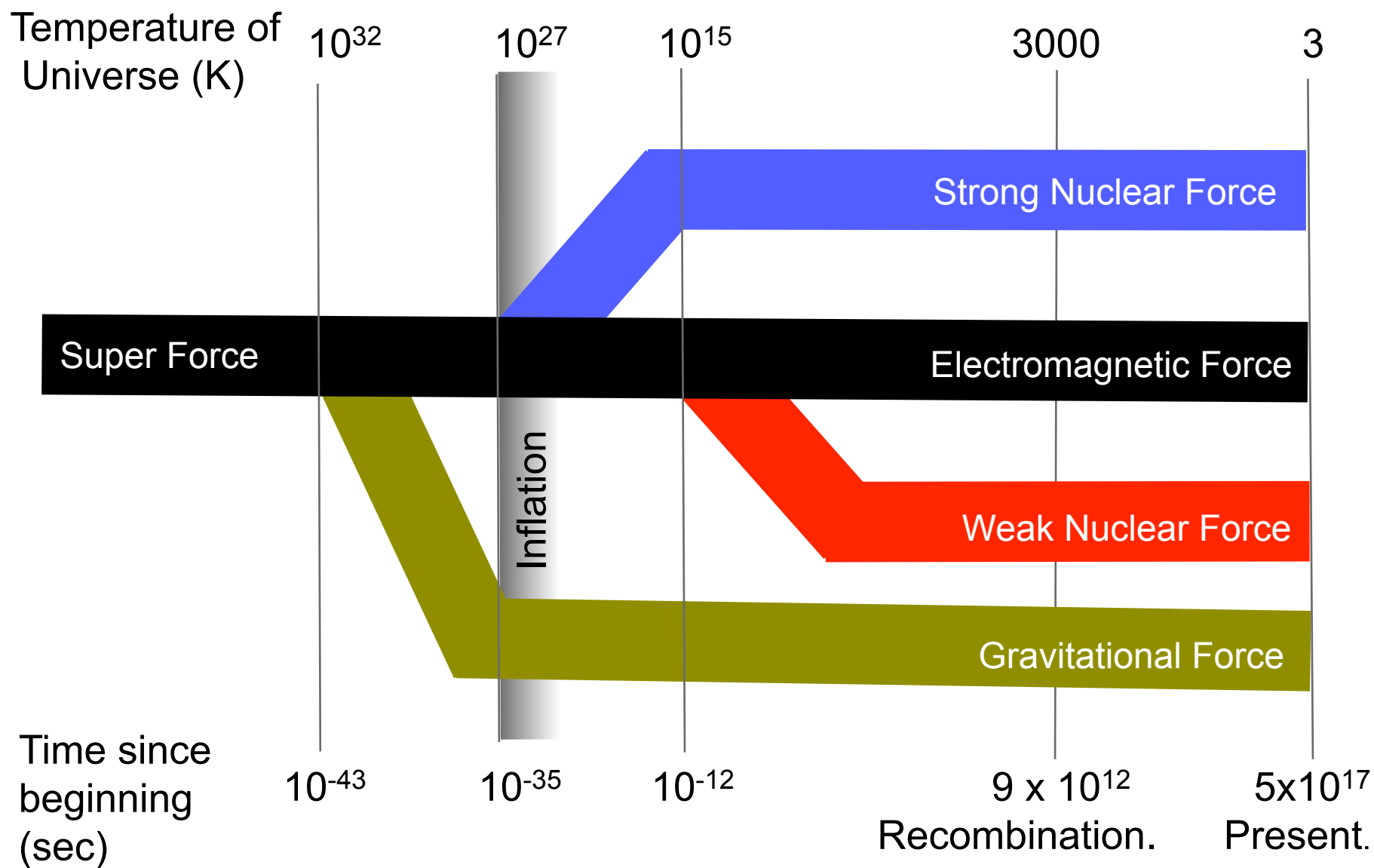
Can the other fundamental forces of nature be unified?

**Yes.** Electromagnetism and the Weak Nuclear Force were combined in the 20th century into “Electroweak.”

Predicted at temperature of  $10^{15}$  K. Verified in particle accelerator experiments. Nobel prize to Weinberg, Salam, Glashow 1979.

Can the other fundamental forces of nature be unified?

# Unification of the Forces



# The Cosmic Timeline

Physics gives us a framework to describe the Big Bang from the earliest phases to the present:

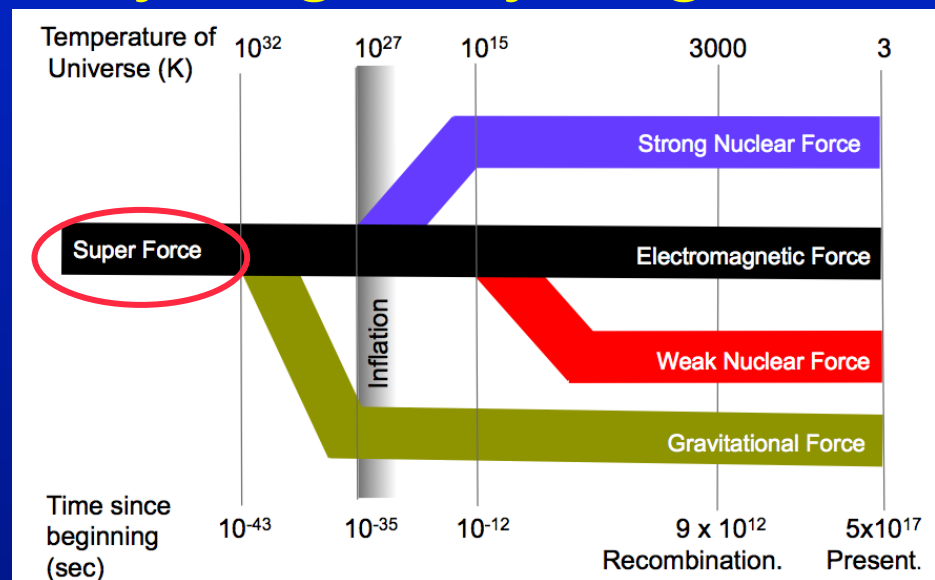
- Particle accelerators probe matter at states similar to some of these early phases.
- Theoretical physics formulating descriptions of the interplay of forces & particles.
- Astronomers look for evidence in the present Universe (e.g., Cosmic Background, amounts of primordial deuterium & helium) to verify this picture.

# The Planck Epoch

$t < 10^{-43}$  sec:

- All 4 forces unified into a single Superforce
- 1 force rules all of physics

Few details, as we as do not yet have a quantum theory of gravity to guide us (strings?).

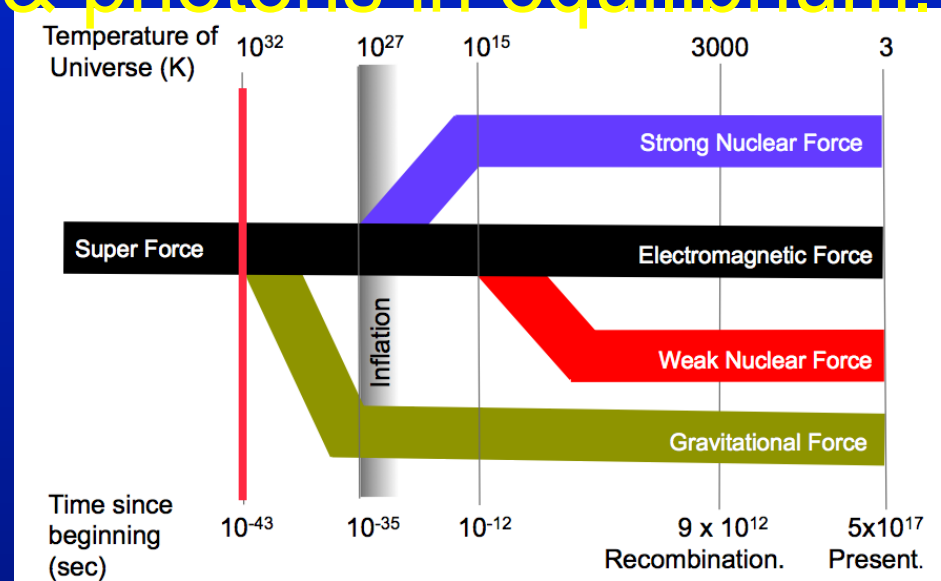


# The Grand Unification Epoch

At  $t = 10^{-43}$  sec,  $T = 10^{32}$  K (???):

- Gravity separates from the Superforce
- Strong & Electroweak Forces still unified.

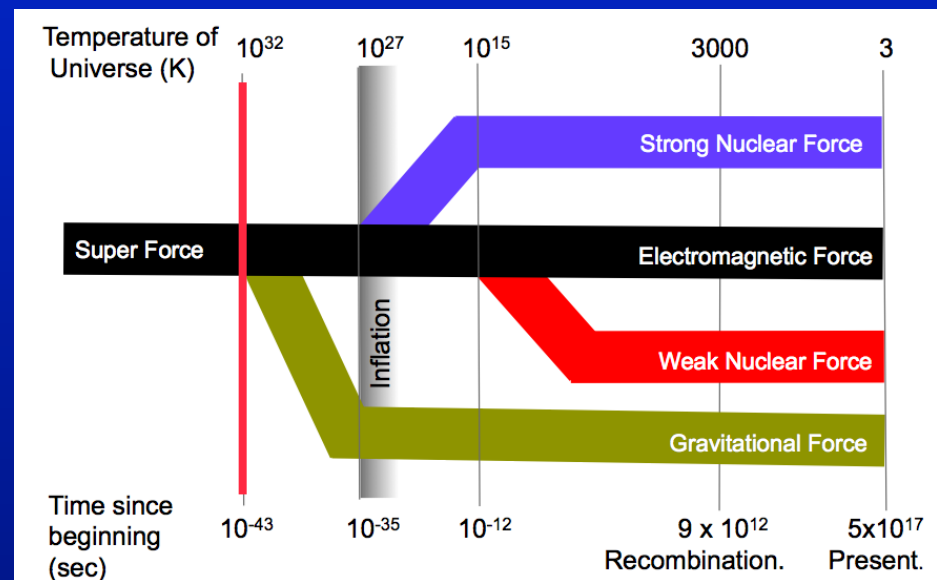
The Universe is a hot, dense soup of quarks, antiquarks & photons in equilibrium.



# The Grand Unification Epoch

A problem: In such a Universe there should be huge fluctuations in the Temperature and in the structure of spacetime on all scales because of quantum mechanics. Yet, we see a smooth Universe, of nearly uniform Temperature. Isotropic, homogeneous?

“Flatness problem” (also, “Horizon Problem”)

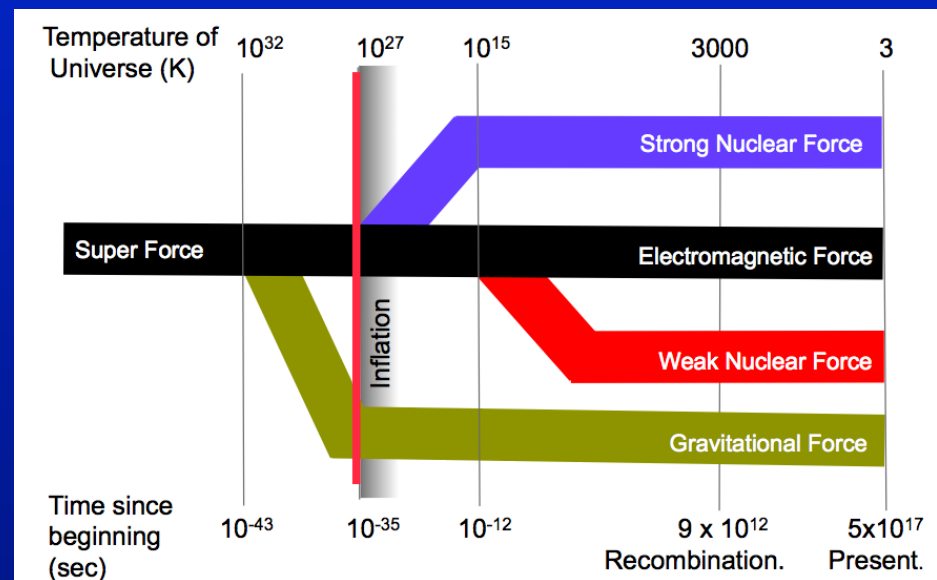


# The Inflationary Epoch (Guth 1980)

At  $t = 10^{-35}$  sec,  $T=10^{27}$  K:

- Strong force separates from GUT force
- EM & Weak forces still unified

The rapid separation of the forces **triggers** a rapid “inflation” of the Universe.



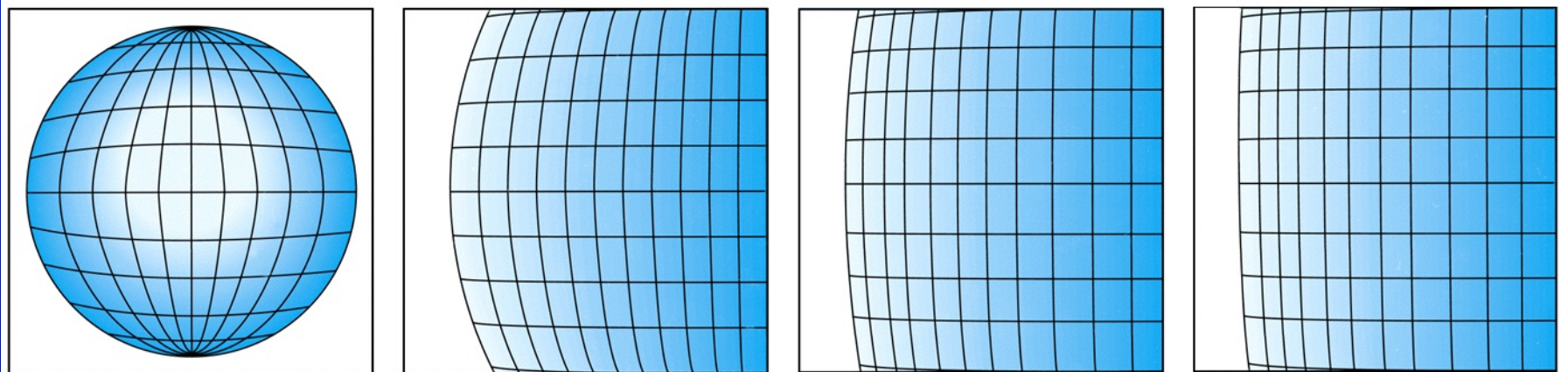
# The Inflationary Universe

Universe grows exponentially by  $\sim 10^{30-43}$   
between  $10^{-35}$  &  $10^{-33}$  sec:

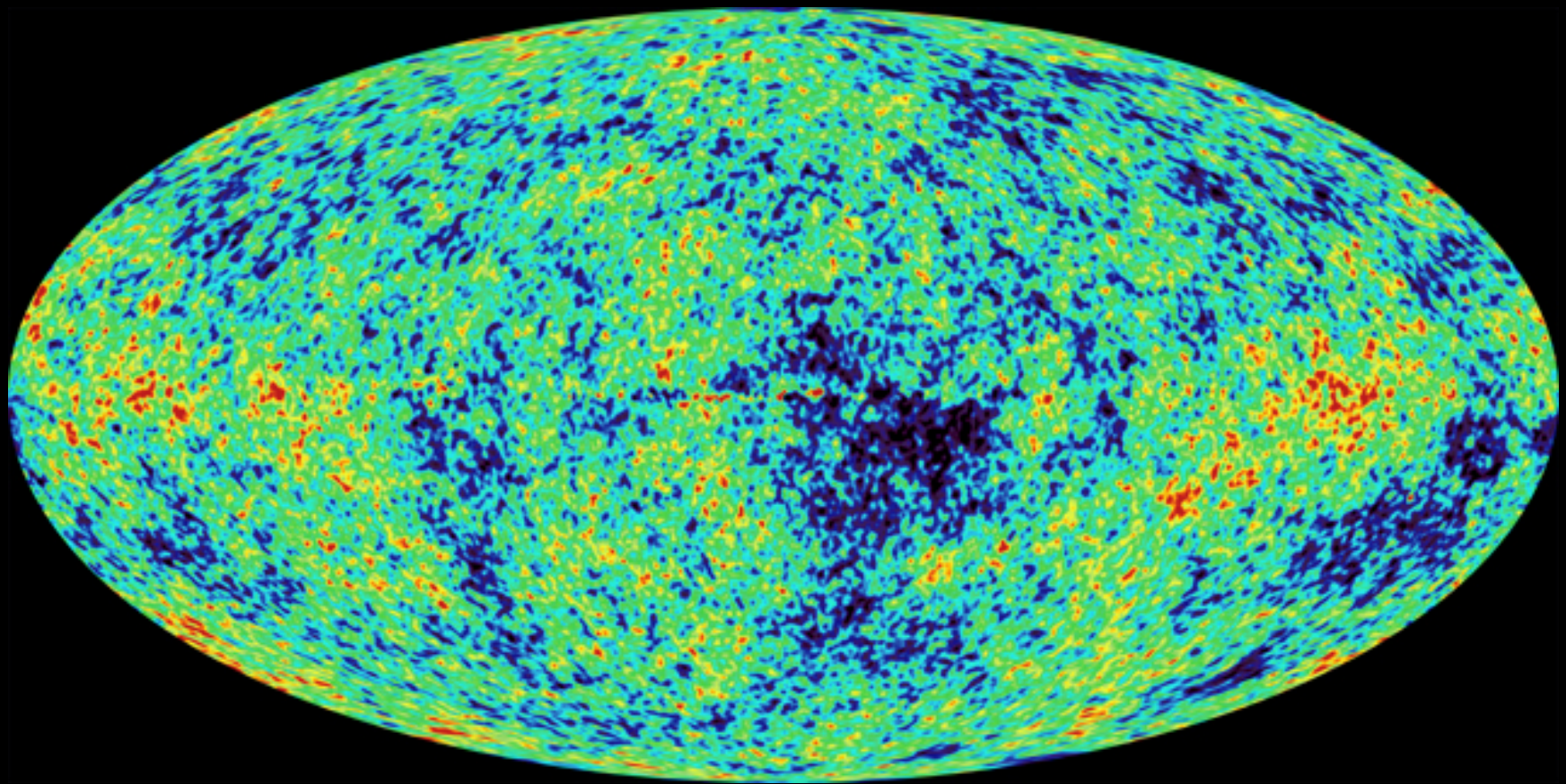
- Expansion slows down to normal afterwards

**Explains smoothness & flatness on large scales**

- Cosmic Background is smooth to 1 part in  $10^5$
- Observations suggest that space is flat, not curved.



# *Almost Perfectly Smooth: How?*



1 part  $10^5$  roughness

# The Inflationary Universe

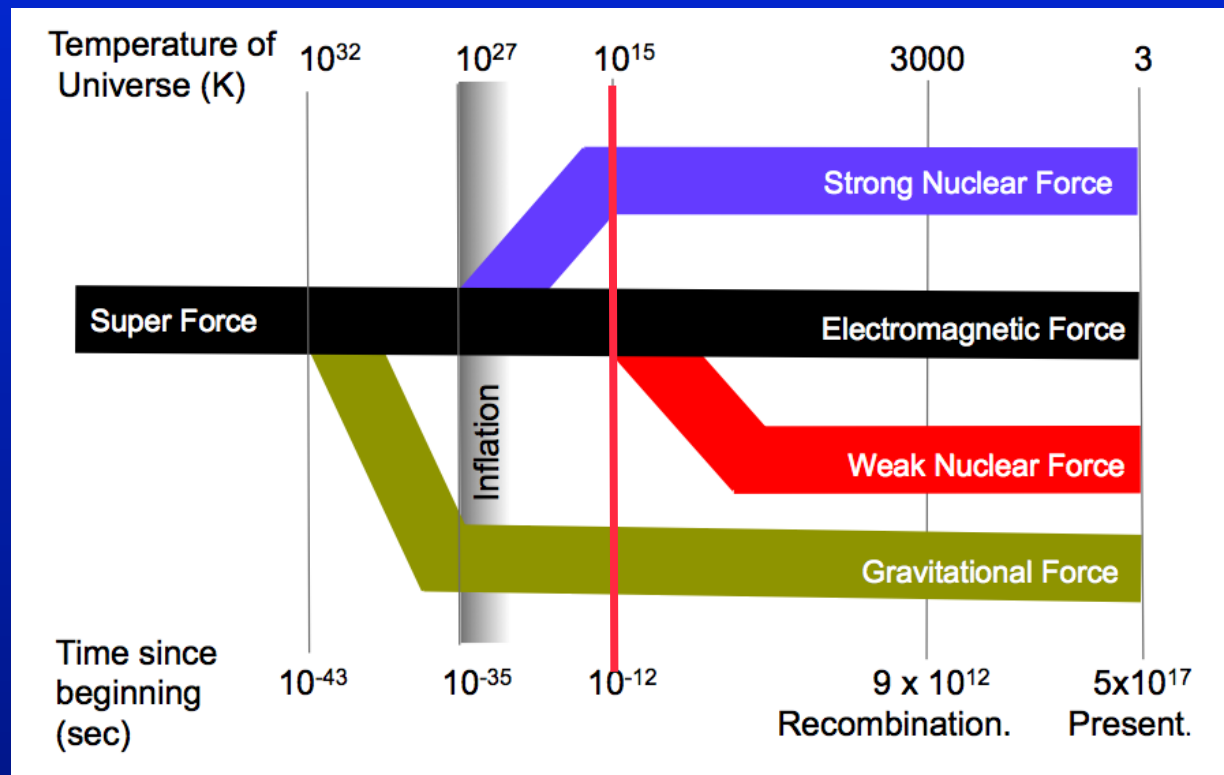
Universe grows exponentially by a factor of  $\sim 10^{43}$  between  $10^{-36}$  &  $10^{-34}$  seconds.

The little prince on a small planet!

# Four Forces at Last!

At  $t = 10^{-12}$  sec,  $T=10^{15}$  K:

- Electroweak separates into EM & Weak forces
- All forces are now separate

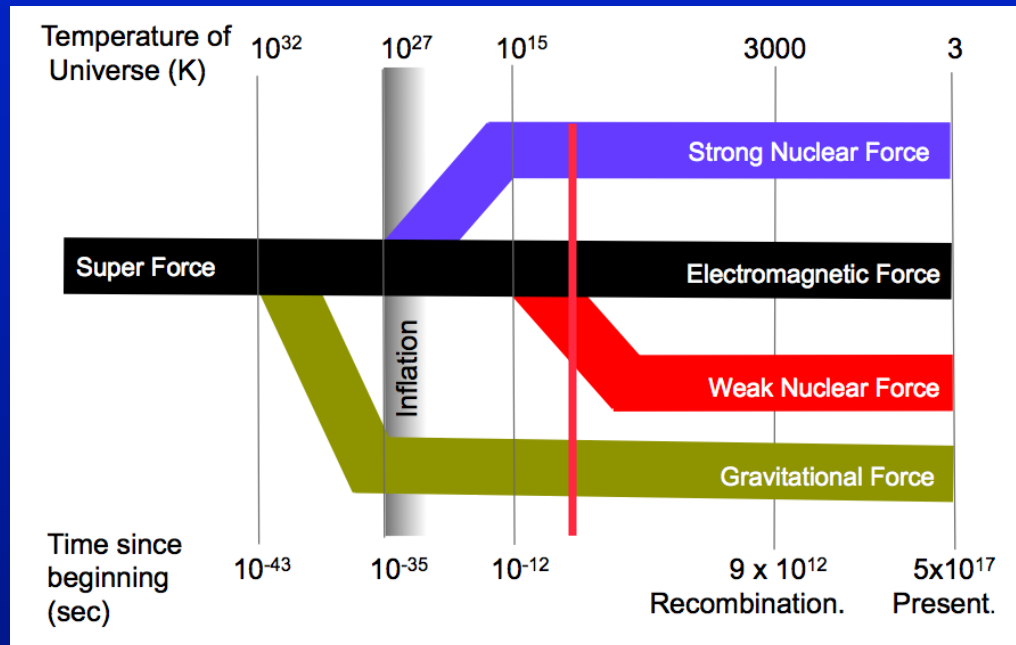


# Quark “Freeze-out”: nucleons!

$t = 10^{-6}$  sec,  $T = 10^{13}$  K (binding energy of p's & n's!)

- Free quarks combine into hadrons (primarily protons & neutrons)
- particle-antiparticle pairs & photons in equilibrium

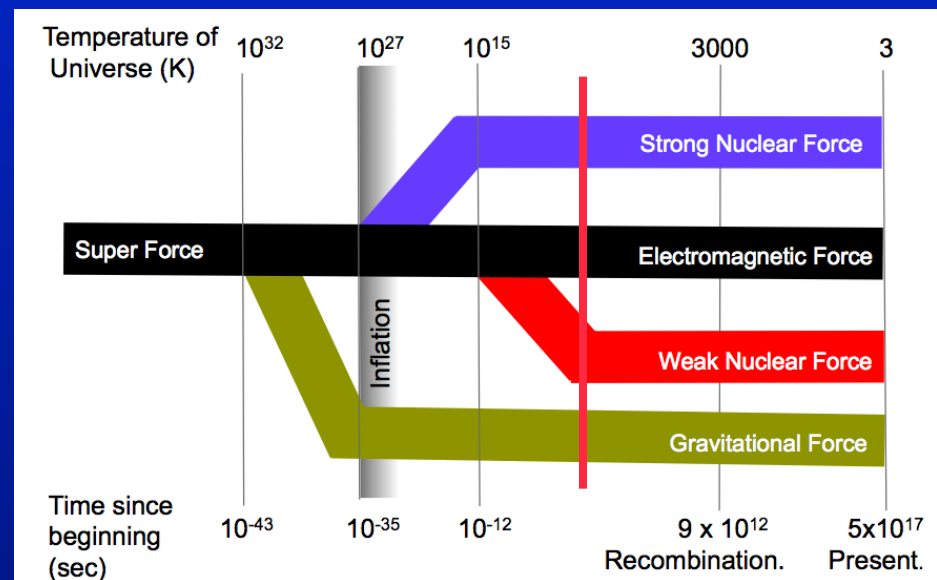
Matter as we understand it begins to emerge.



# Neutrino Decoupling (like recombination!!)

At  $t = 1$  sec,  $T=10^{10}$  K

- Neutrinos decouple from matter and stream out into space. For  $t < 1$ s universe is opaque to neutrinos. Forms a *Cosmic Neutrino Background* (predicted, but not yet observable)



# The Epoch of Nucleosynthesis

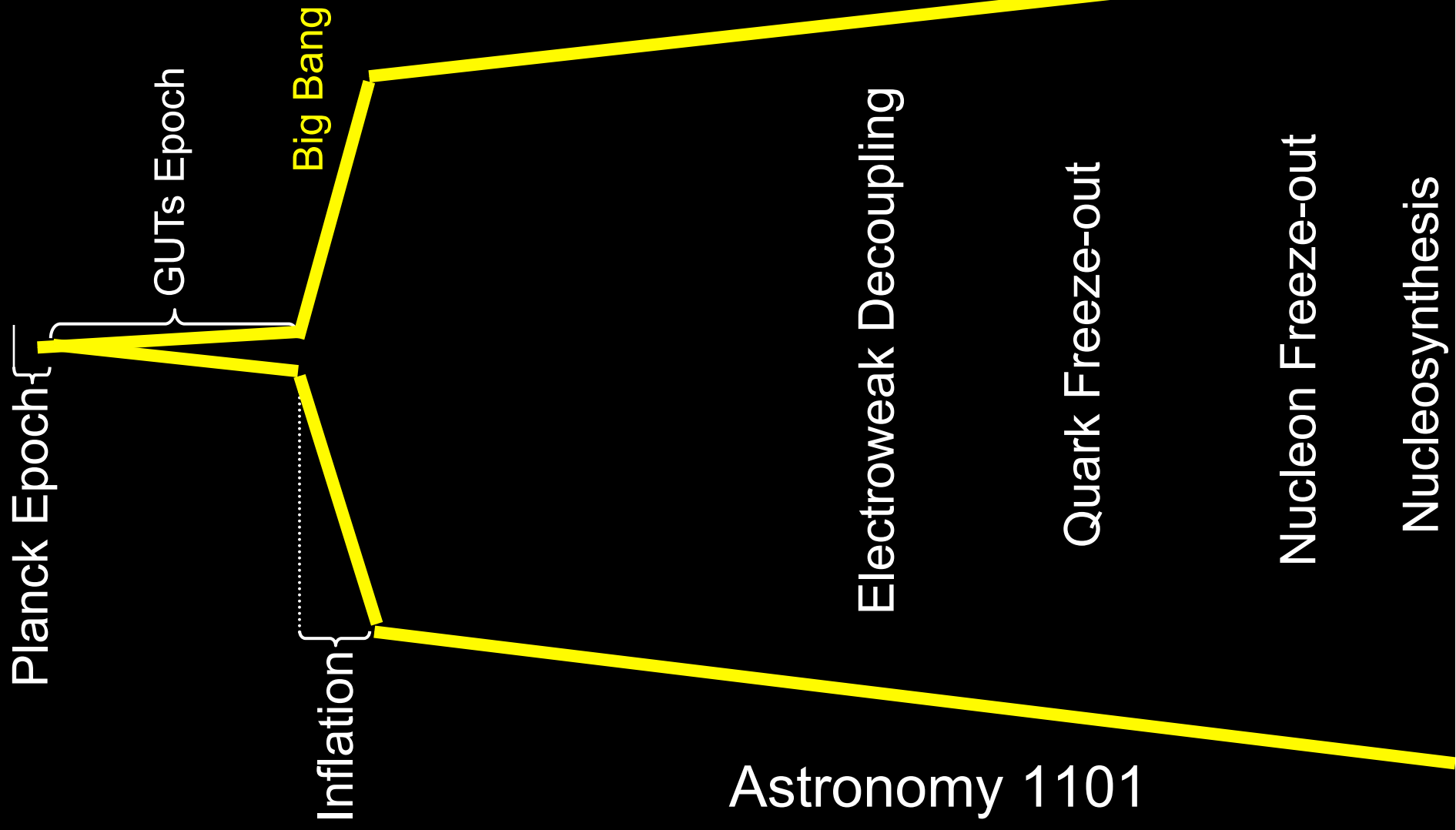
At  $t = 3$  minutes,  $T = 10^9$  K (binding energy of nuclei!)

Fusion of protons & remaining free neutrons:

- Formation of  ${}^2\text{H}$  (Deuterium) &  ${}^4\text{He}$
- End up with  $\sim 75\%$  H,  $25\%$  He
- Traces of D, Li, Be, B

We cannot observe this epoch directly, but we can measure the *products* of primordial nucleosynthesis in old stars.

*3 minutes.*



Astronomy 1101

# The Epoch of Recombination

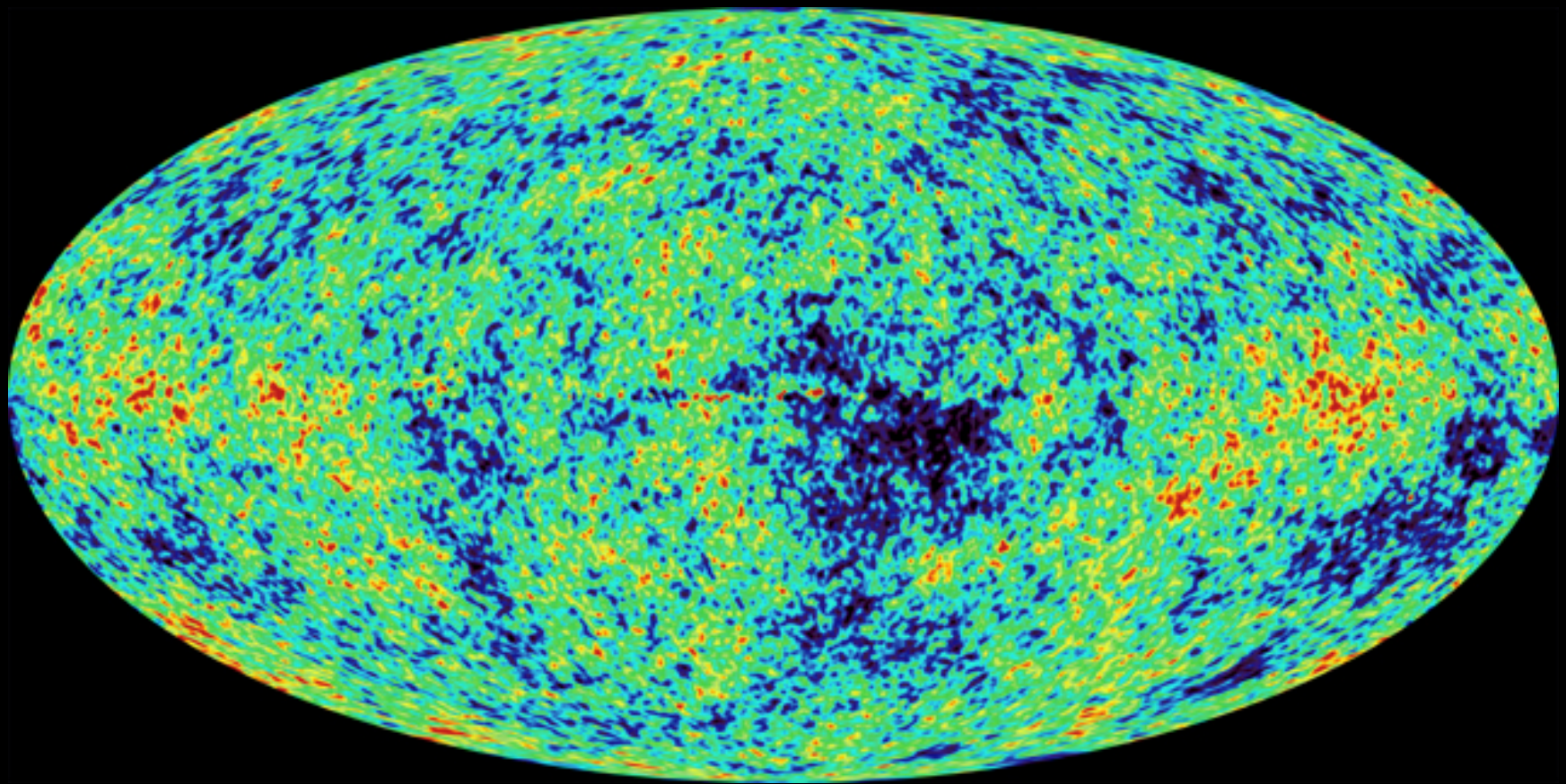
At  $t=300,000$  yr,  $T=3000$  K (binding energy of electrons to atoms!)

Electrons & nuclei combine into neutral atoms

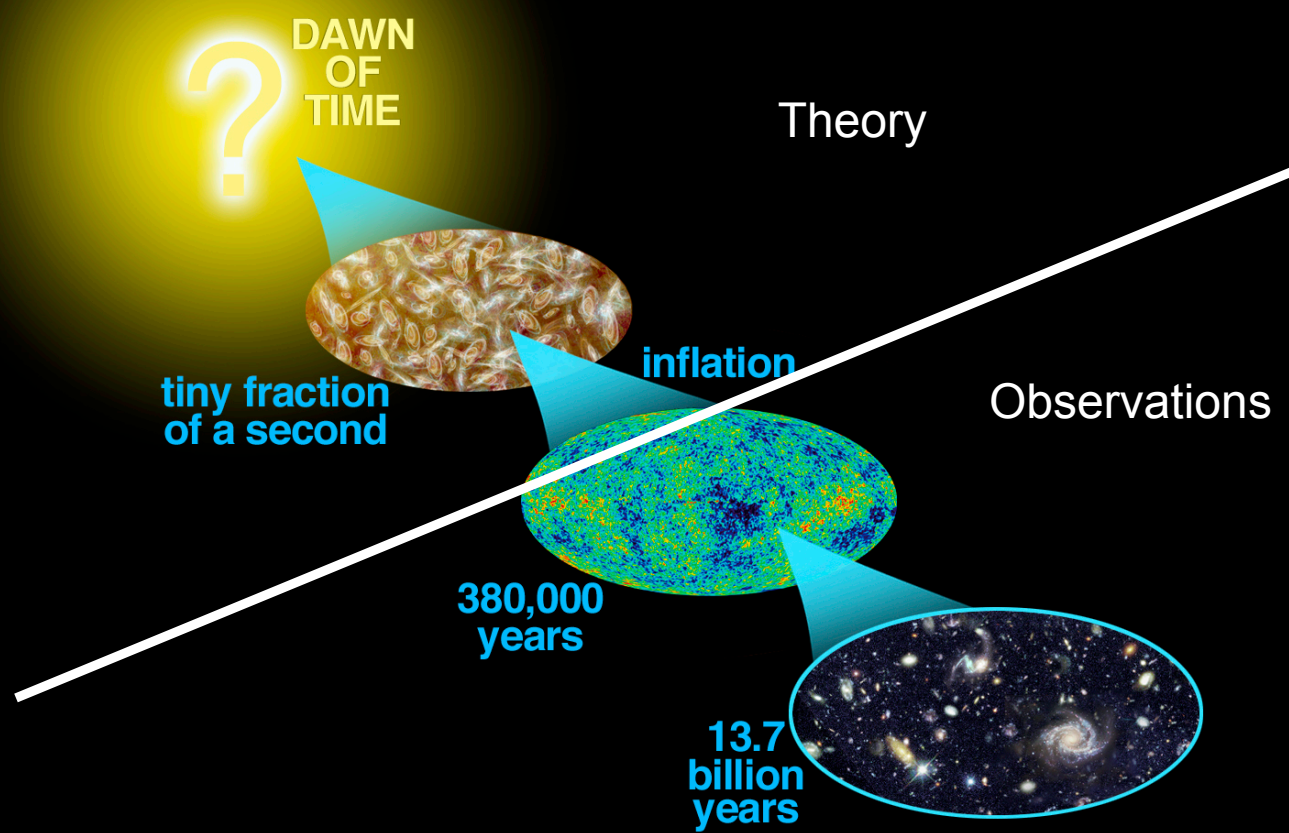
- Universe becomes transparent.
- Origin of the **Cosmic Background Radiation**

**The earliest epoch we can observe *directly*.**

# *WMAP* Cosmic Microwave Background map



1 part  $10^5$  roughness



Source: NASA/WMAP Science Team

# What about the *very* Beginning?

Our physics can not yet probe earlier than the end of the Planck Epoch ( $t=10^{-43}$  seconds).

The current frontier is before the Electroweak Epoch ( $t=10^{-12}$  seconds), and the inflationary epoch.

This will be the astrophysics of the 21<sup>st</sup> Century (or maybe the 22<sup>nd</sup>...)