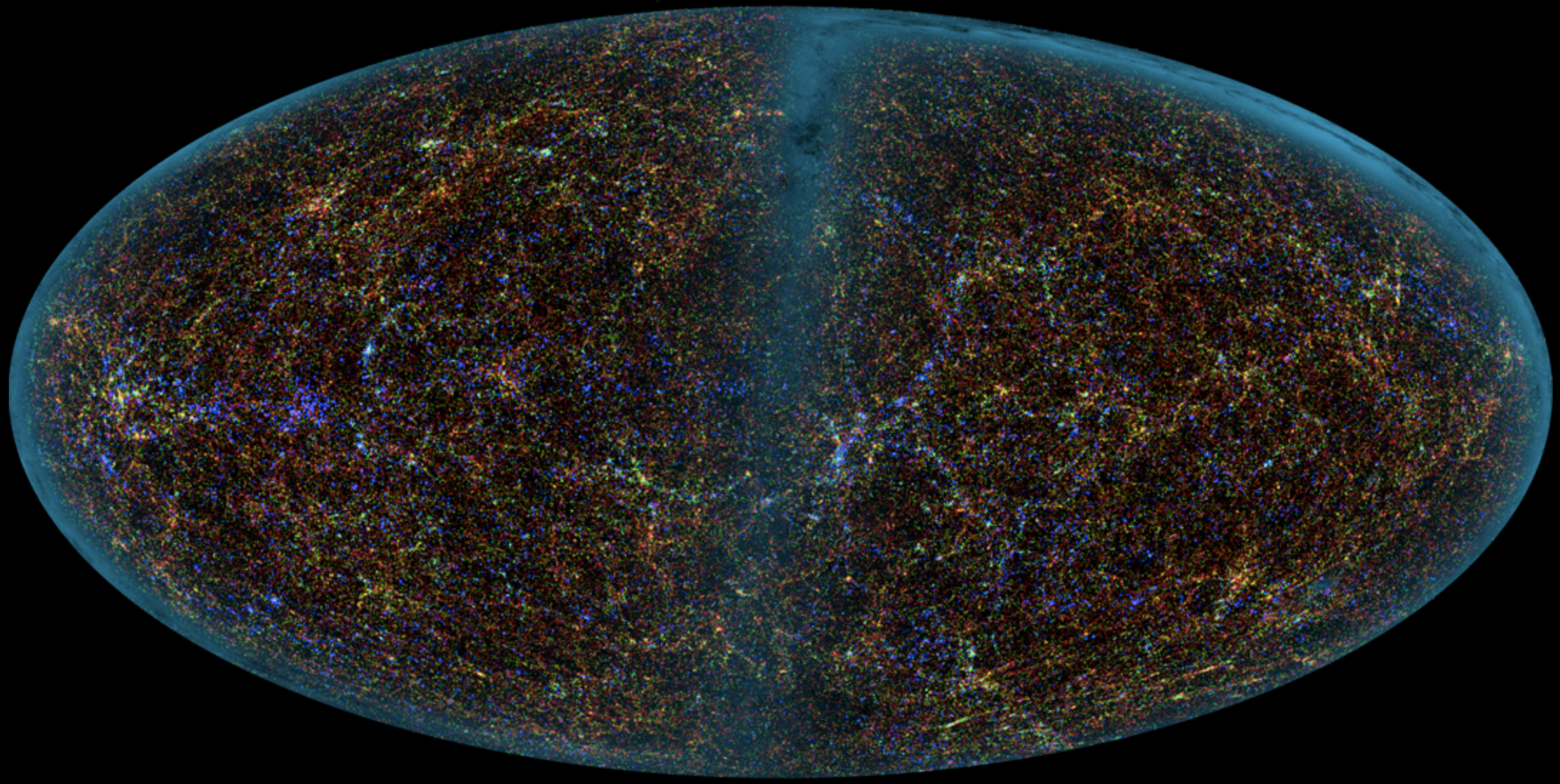
Cosmology

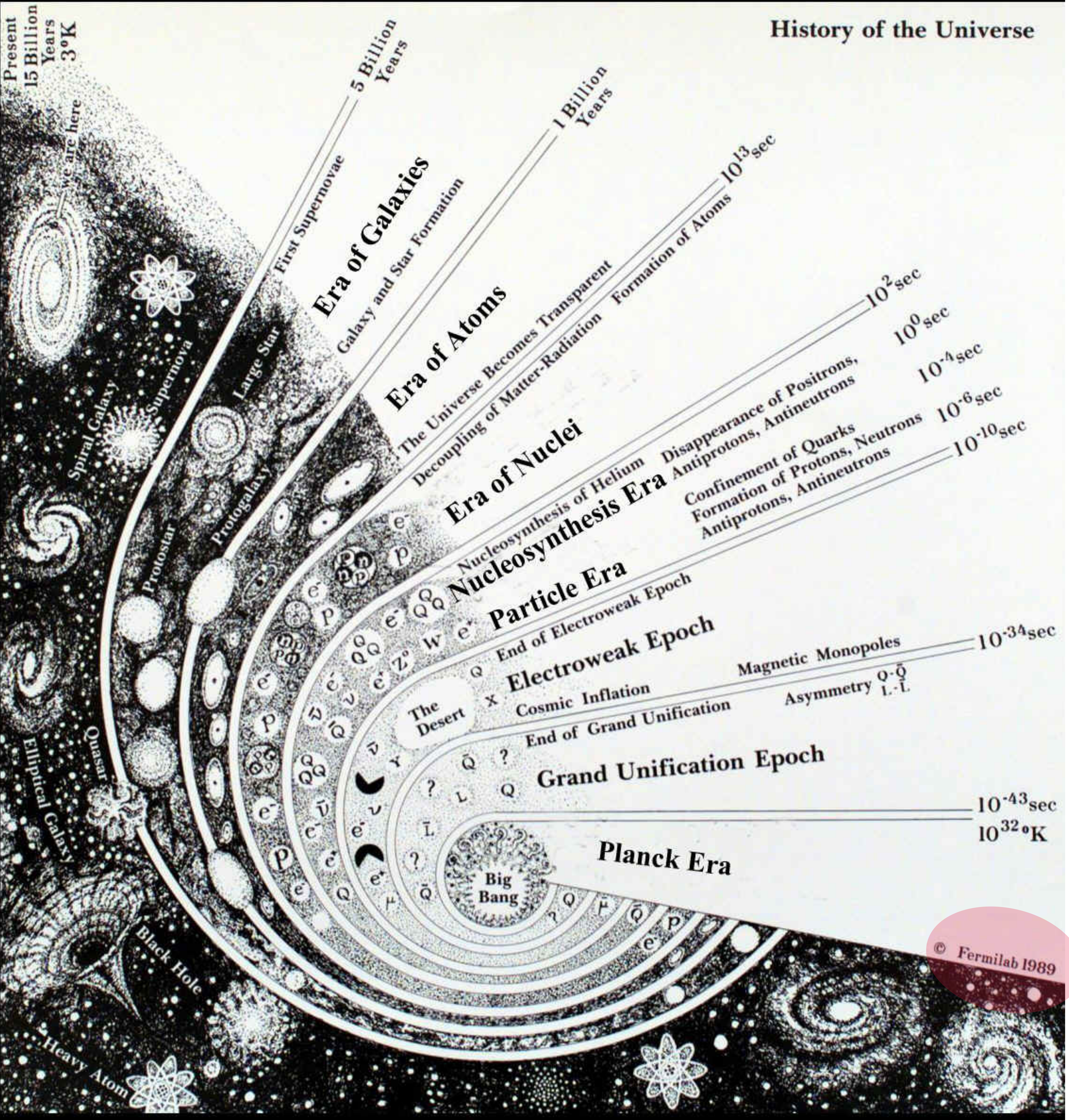
and Large Scale Structure



Today
Inflation
Dark Ages
History

11 November 2020

http://astroweb.case.edu/ssm/astr328/



Time	Event
$t \sim 10^{-43}$ s	Planck scale (*speculative*)
$t \sim 10^{-38}$ s	GUT scale (*speculative*)
$t \sim 10^{-35}$ s	Inflation (*speculative*)
$t \sim 10^{-12}$ s	Standard Model forces emerge
$t \sim 10^{-8}$ s	WIMPs decouple (*speculative*)
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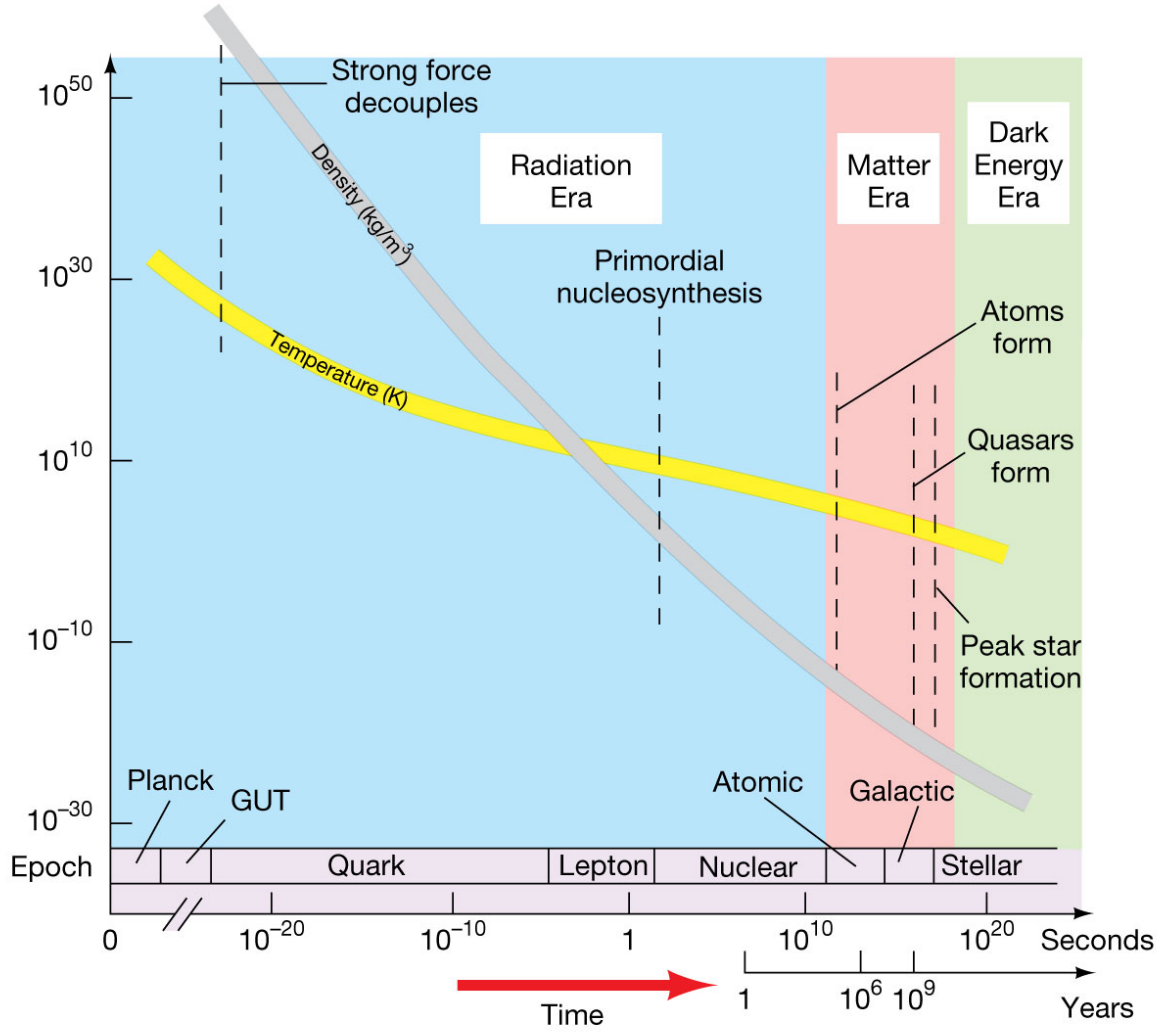


Time | Event

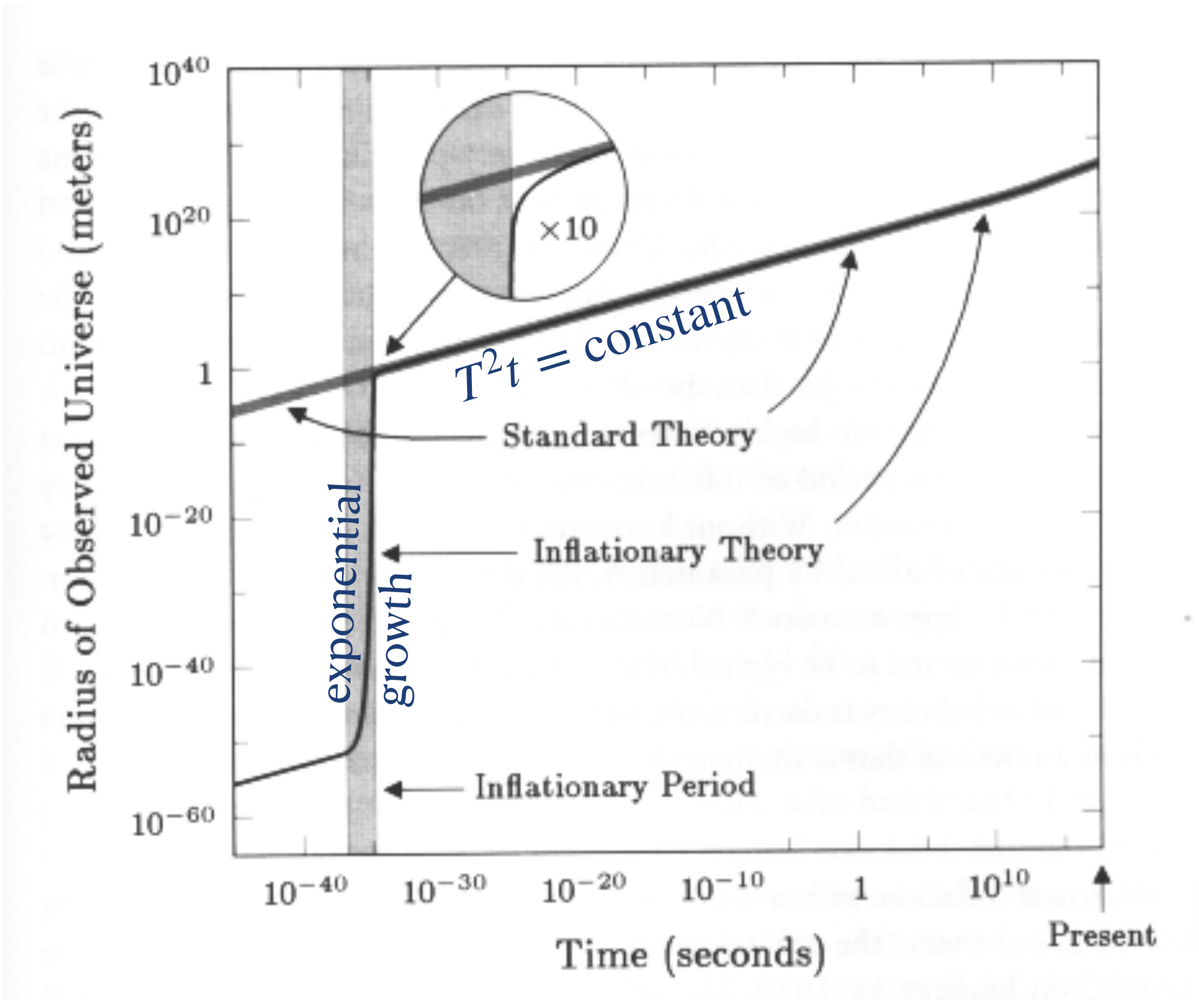
$t \sim 10^{-38}$ s GUT scale (*speculative*)

GUT stands for Grand Unified Theory; this is the hypothetical scale at which the strong nuclear force becomes indistinguishable from the electroweak force.

$t \sim 10^{-35}$ s Inflation (*speculative*)

Period of exponential growth: $a \sim e^{Ht}$

precedes radiation domination when $a \sim t^{1/2}$
so $T^2 t = \text{constant}$



Inflation

An epoch of early, exponential expansion $a \sim e^{H_I t}$

- Invoked to solve the
  - Flatness problem
  - Horizon problem
  - Magnetic monopole problem
- provides seeds for the formation of large scale structure

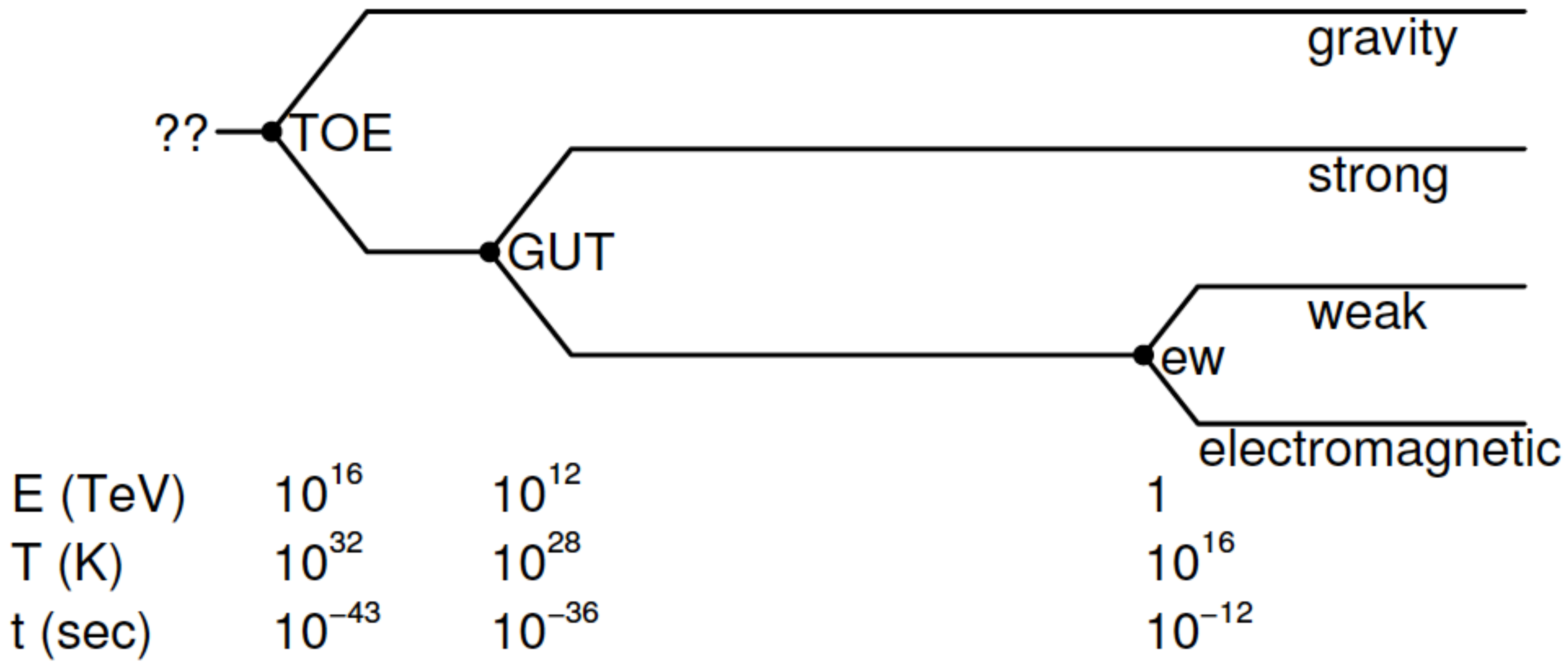


Figure 11.2: The energy, temperature, and time scales at which the different force unifications occur.

Inflation

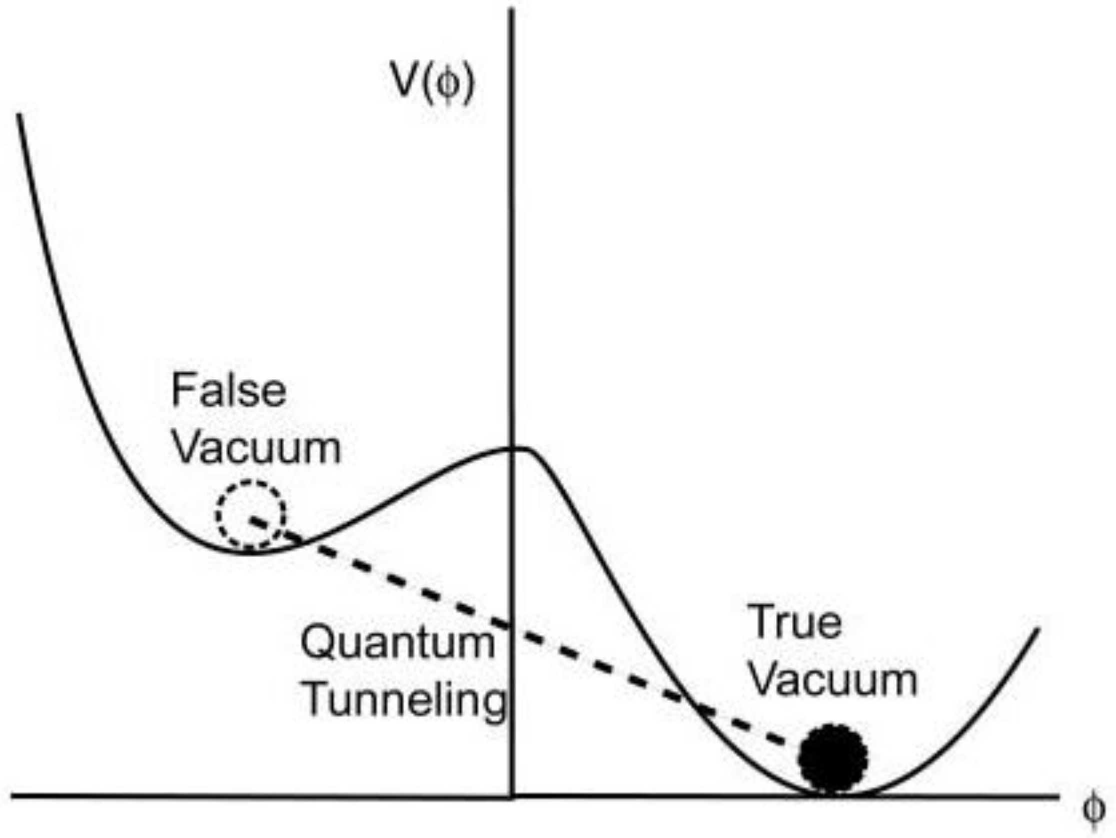
An epoch of early, exponential expansion

$$a \sim e^{H_I t}$$

Inflation emerged from the MIT "bag model" of dense nuclear matter, which has an *effective* equation of state $P = -\rho$ like what we now call dark energy. Solution of the Friedmann equation is the same, with

$$H_I = \sqrt{\frac{\Lambda_I}{3}}$$

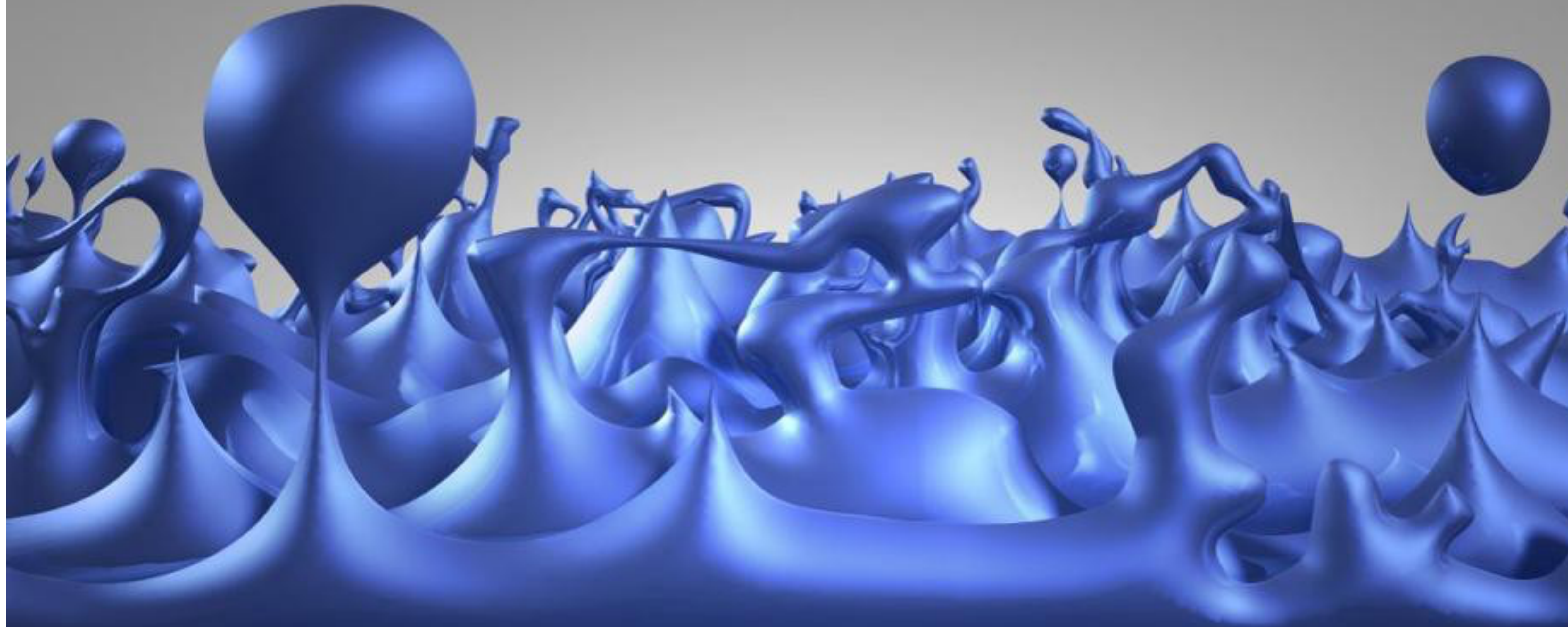
where the subscript *I* denotes Inflation. This early "energy of the vacuum" is much greater than the current dark energy.



"False" vacuum of Inflation $\varepsilon_{\Lambda_I} = \frac{c^2}{8\pi G}\Lambda_I \sim 10^{102}\ \mathrm{GeV\,cm^{-3}}$

Current vacuum energy density $\varepsilon_{\Lambda_0} \sim 3.4\ \mathrm{GeV\,cm^{-3}}$

Inflationary bubble emerging from the quantum foam of the false vacuum



Inflation

An epoch of early, exponential expansion

- Invoked to solve the
  - Magnetic monopole problem

Expect monopoles to emerge in the GUT symmetry breaking, but they've never been detected. This can be avoided if they're sufficiently massive that they freeze out very early, then a period of Inflation dilutes their numbers.

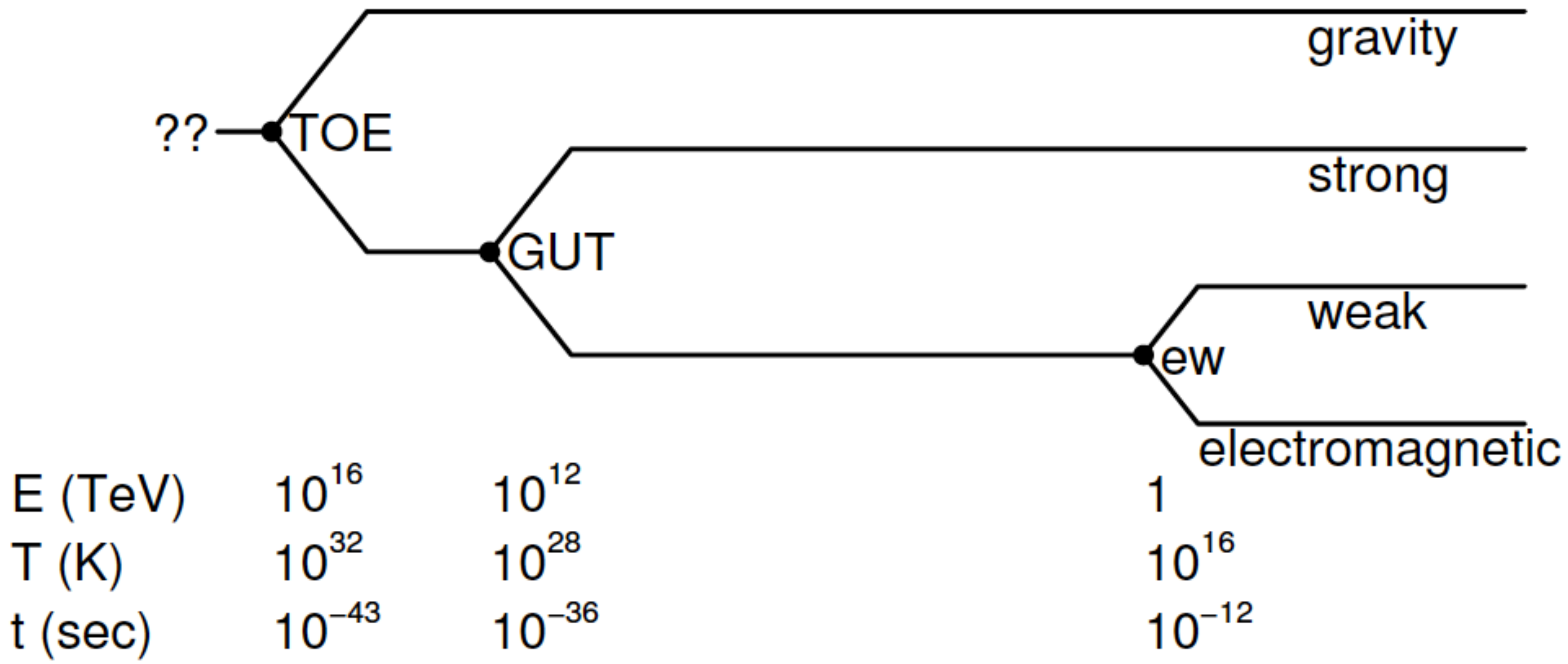
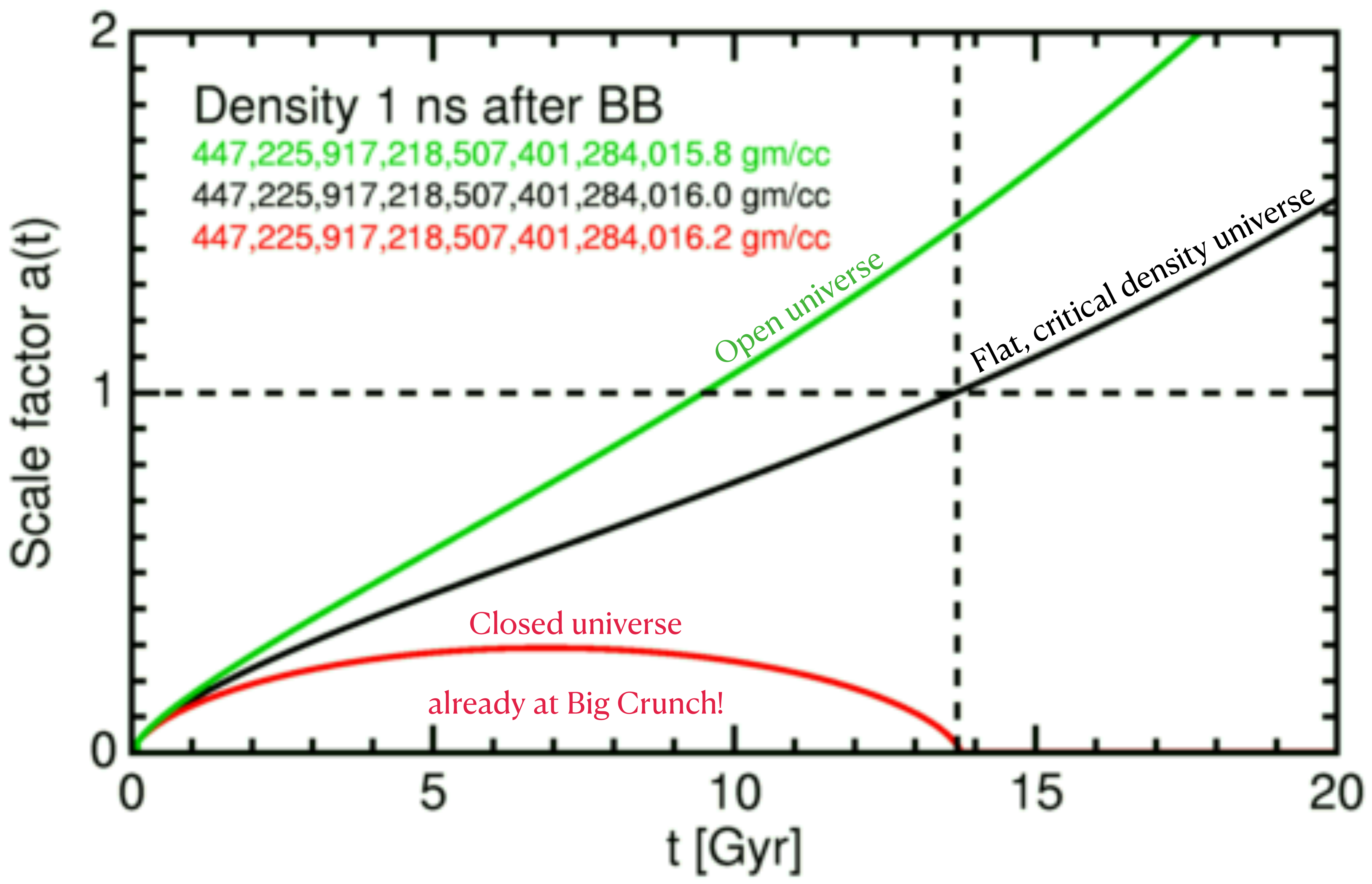


Figure 11.2: The energy, temperature, and time scales at which the different force unifications occur.

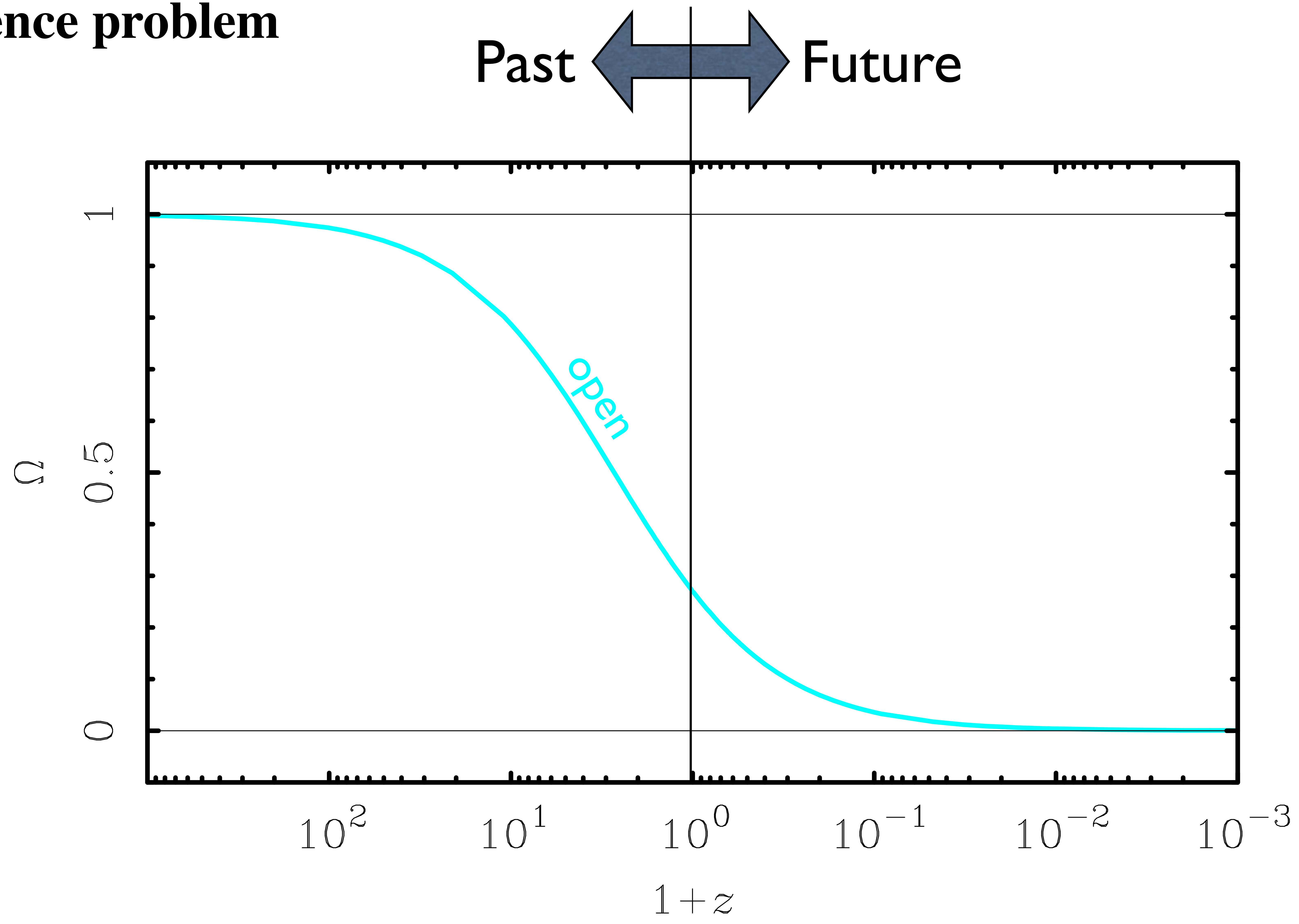
The flatness problem

Look at this figure (taken from Ned Wright's Cosmology Tutorial; see also the textbook of Kolb & Turner) this argument made Inflation fly in the ‘80s:
if the density of the universe had been ever so slightly non-critical 1 nanosecond after the big bang, we would have a drastically different universe:



How can this be? That we live in a universe anywhere near to $\Omega = 1$ but not exactly that is incredible fine-tuned - to a part in 10^{25} !
Hence we infer that some mechanism drove Omega to exactly one - **Inflation**.

The coincidence problem



Another way to look at it: how can $\Omega_m \approx 0.3$ today when it will spend all eternity asymptotically approaching $\Omega_m \to 0$?

The flatness/coincidence problem

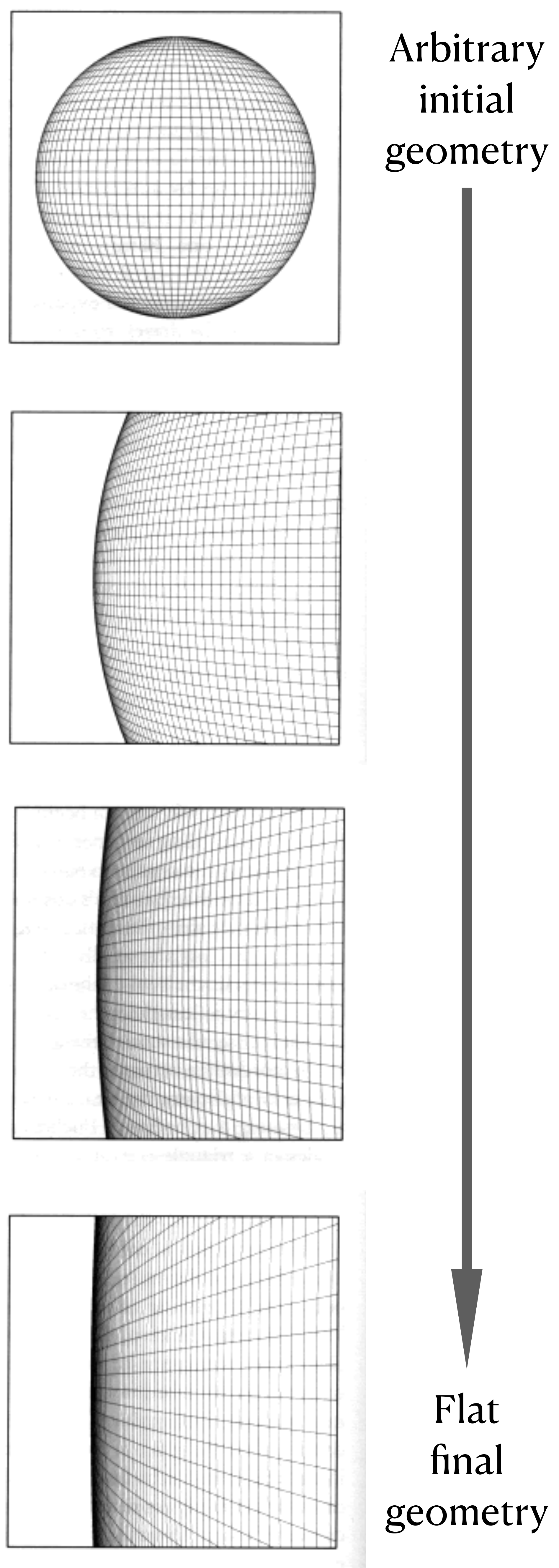
The Inflationary solution:

$$\Omega_k = 1 - \sum_{\text{not } k} \Omega = \left(\frac{c}{R_0 a(t) H(t)} \right)^2$$

During Inflation, $a(t) \sim e^{H_I t}$ with $H_I = \sqrt{\Lambda_I / 3}$ = constant, so $|\Omega_k| \rightarrow e^{-2H_I t}$

The initial condition is irrelevant; the exponential expansion drives the universe to be flat.

To get the observed flatness, $|\Omega_k| < 0.005$, requires that Inflation persists for > 60 e-foldings.



The Horizon (or Smoothness) Problem

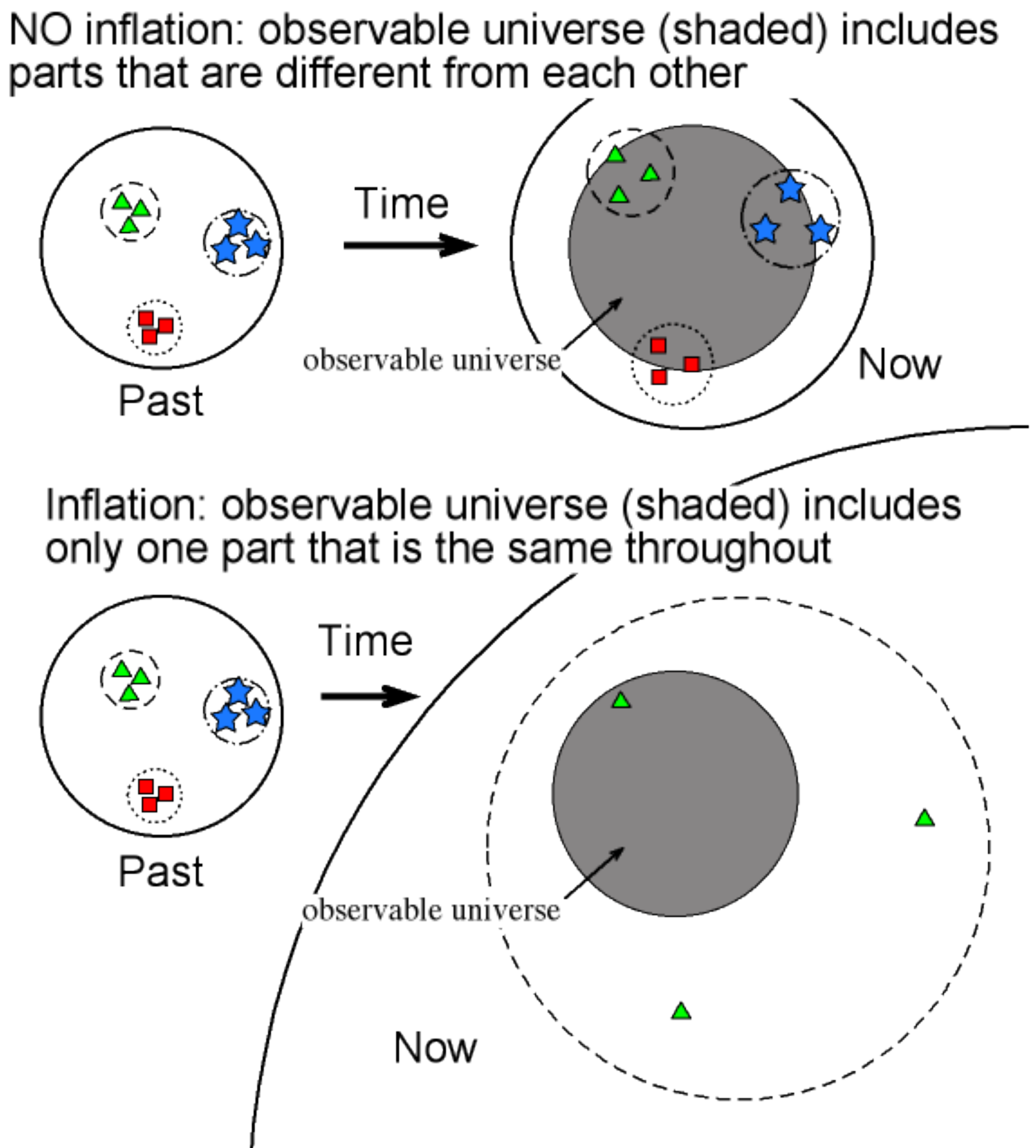
Looking at the microwave background, it is very smooth to 1 part in 10^5. Everywhere. But at the time of recombination, regions of the universe which are now separated by more than 2 degrees on the sky were never in causal contact.

Think about the horizon distance: $$d_h(t) = R(t) \int_0^t \frac{c\ dt}{R(t')}$$

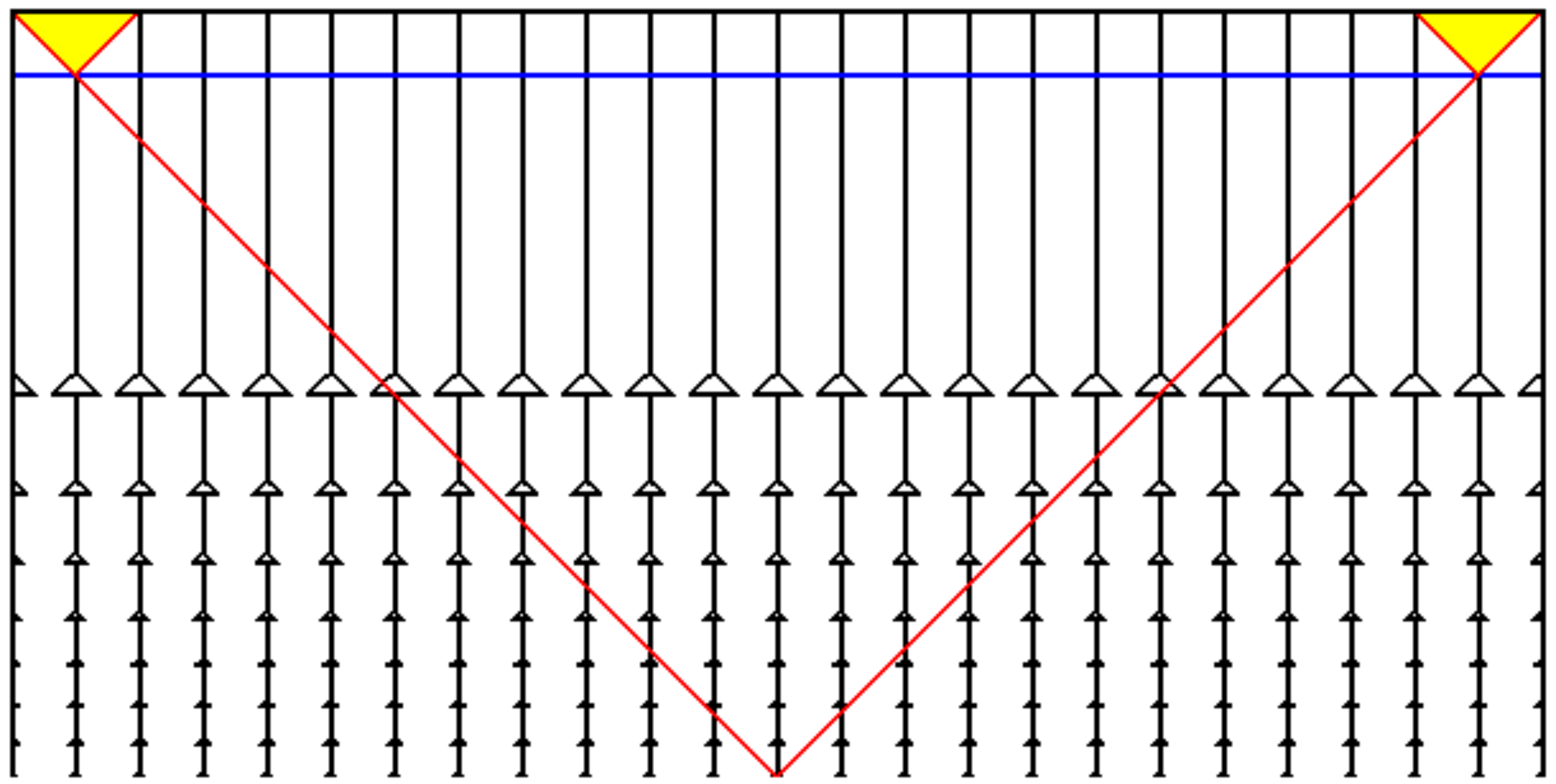
At the time of the CMB, the horizon scale was about 0.25 Mpc. The current horizon distance is ~ 14.6 Gpc, so the observable universe at a redshift of z=1100 was 14.6 Gpc/1100 ~ 13.2 Mpc in size - much larger than the horizon.

*How did regions out of causal contact **know** to all have the same temperature?*

Well, how about $T^2 t$ = constant

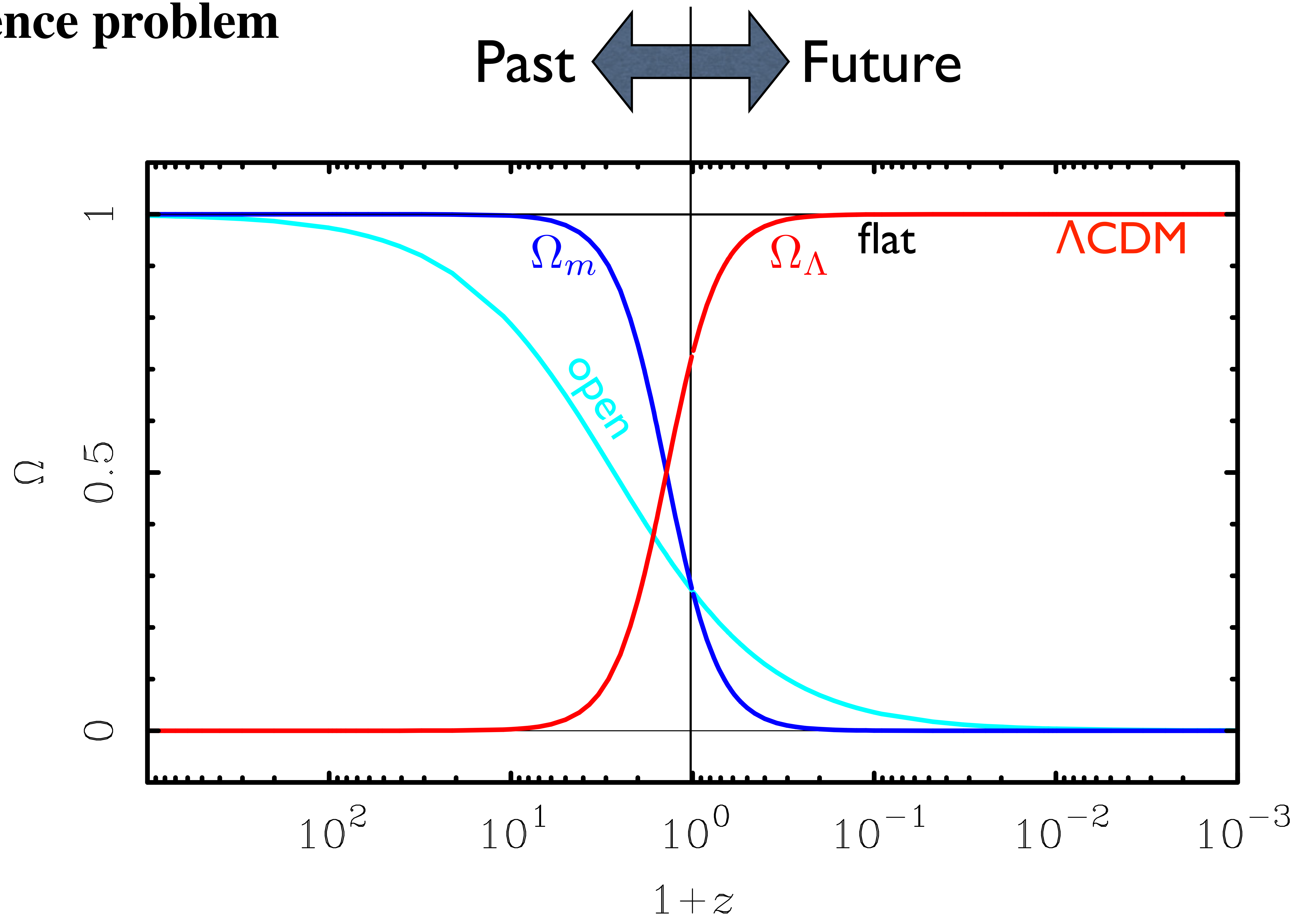


Yellow regions out of causal contact at recombination yet are observed to have the same temperature on the sky now



The conformal space-time diagram above has exaggerated this part even further by taking the redshift of recombination to be 1+z = 144, which occurs at the blue horizontal line. The yellow regions are the past lightcones of the events which are on our past lightcone at recombination. Any event that influences the temperature of the CMB that we see on the left side of the sky must be within the left-hand yellow region. Any event that affects the temperature of the CMB on the right side of the sky must be within the right-hand yellow region. These regions have no events in common, but the two temperatures are equal to better than 1 part in 10,000. How is this possible? This is known as the "horizon" problem in cosmology. (Image credit: Ned Wright).

The coincidence problem



The coincidence problem gets ***worse*** in LCDM. The geometry may be flat, but we still live at a special time when the universe transitions from matter domination to dark energy domination.

Inflation

An epoch of early, exponential expansion $a \sim e^{H_I t}$

- Invoked to solve the
  - Flatness problem **Coincidence problem not really solved**
  - Horizon problem $T^2 t =$ **constant, so is this really a problem?**
  - Magnetic monopole problem **Do monopoles even exist?**

Monopoles could be a figment of Grand Unified Theories that haven't panned out.

Graceful exit problem:
To get the observed flatness, $|\Omega_k| < 0.005$, requires that Inflation persists for > 60 e-foldings.
Why does it ever stop?

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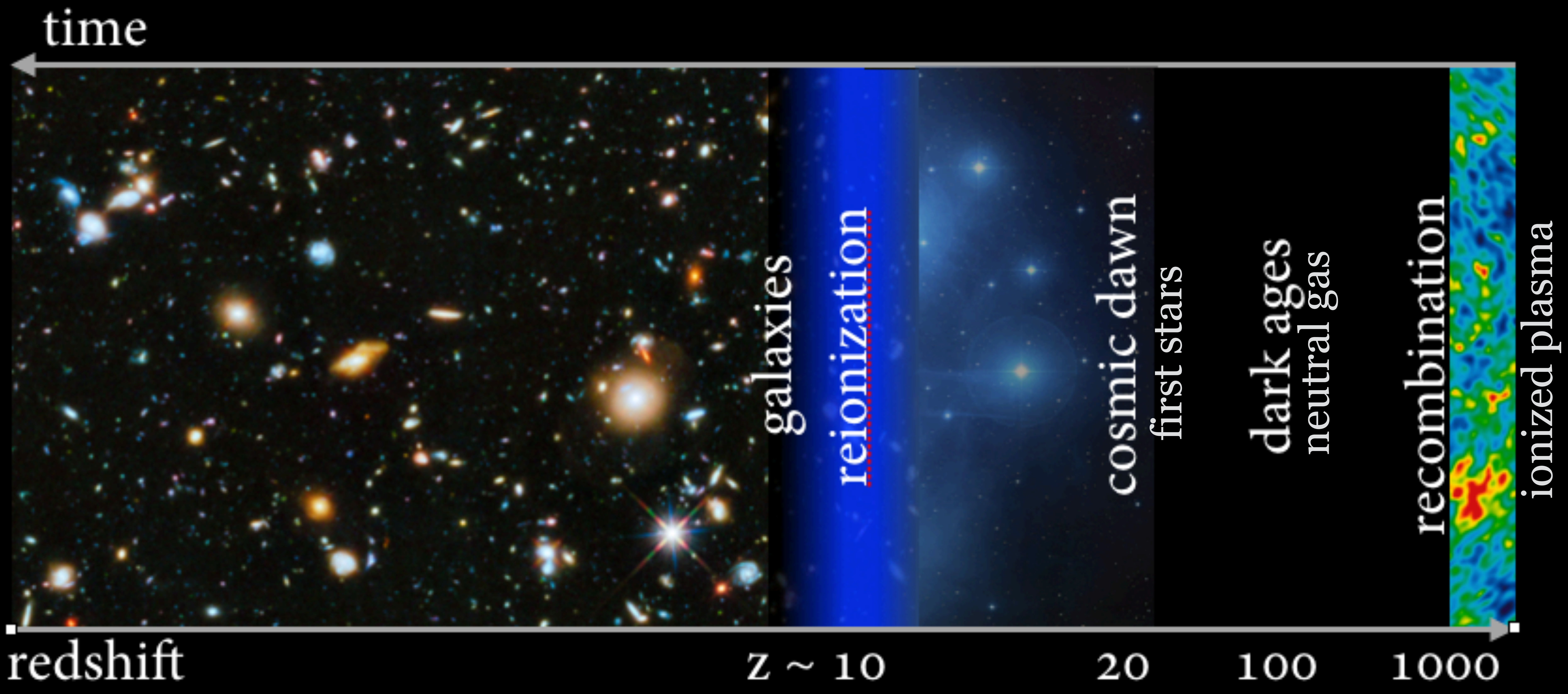
Next frontier: 21 cm absorption at high redshift



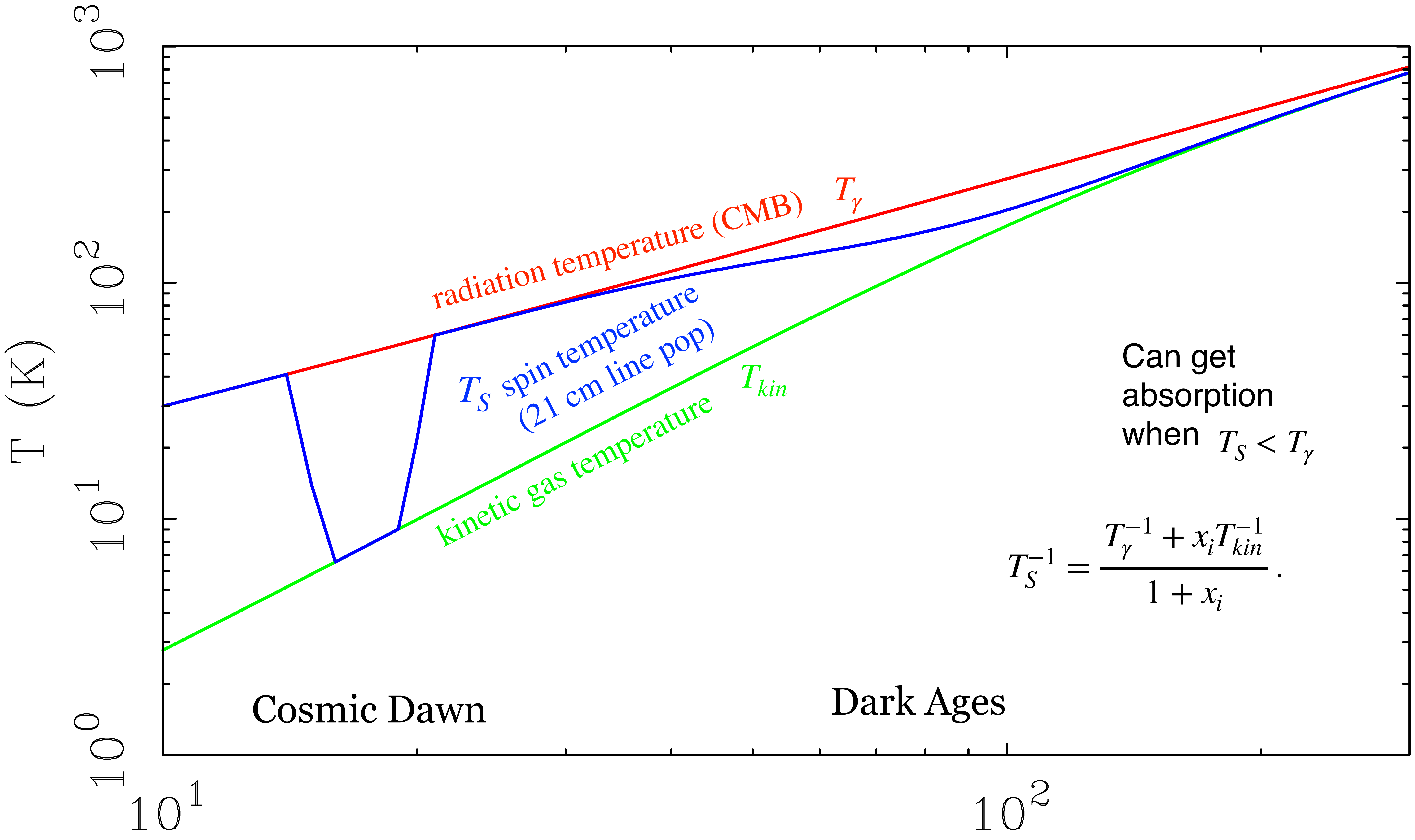
Radio wavelength photons traveling to us from the epoch of recombination can be absorbed by neutral gas during the dark ages and at cosmic dawn

Three Temperatures:

T_γ radiation temperature (CMB)

T_{kin} kinetic temperature (gas - what we normally think of as temperature)

T_S spin temperature (21 cm line - statistical distribution of levels in atomic hydrogen)



Prediction for 21 cm absorption at high redshift

Spin temperature bracketed by the radiation temperature and the kinetic gas temperature:

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_i T_{kin}^{-1}}{1 + x_i}.$$

x_i { Dark ages: atomic collisions; Cosmic dawn: Lyman **α** photons }

x_i couples the spin temperature to the kinetic gas temperature

$T_0 = 20$ mK

$\omega_b = \Omega_b h^2$

$f_b = \frac{\Omega_b}{\Omega_m}$

x_{HI} neutral hydrogen fraction ($x_{HI} \approx 1$ during the dark ages)

21 cm brightness temperature:

$$T_{21}(z) = T_0 \frac{x_{HI}}{\mathfrak{h}_z} \left[(1+z) f_b \left(\frac{\omega_b}{0.02} \right) \right]^{1/2} \left(1 - \frac{T_\gamma}{T_S} \right)$$

absorption when $T_S < T_\gamma$

$$\mathfrak{h}_z = \frac{H(z)}{\tilde{H}(z)}$$

$$H^2(z) = H_0^2[\Omega_\Lambda + \Omega_m(1+z)^3 + \Omega_r(1+z)^4 - \Omega_k(1+z)^2]$$

$$\tilde{H}(z) = H_0 \Omega_m^{1/2} (1+z)^{3/2}$$ → (This is an approximation)

Expansion history specifies path-length photons must traverse.

This usual approximation $\tilde{H}(z)$ may not suffice.

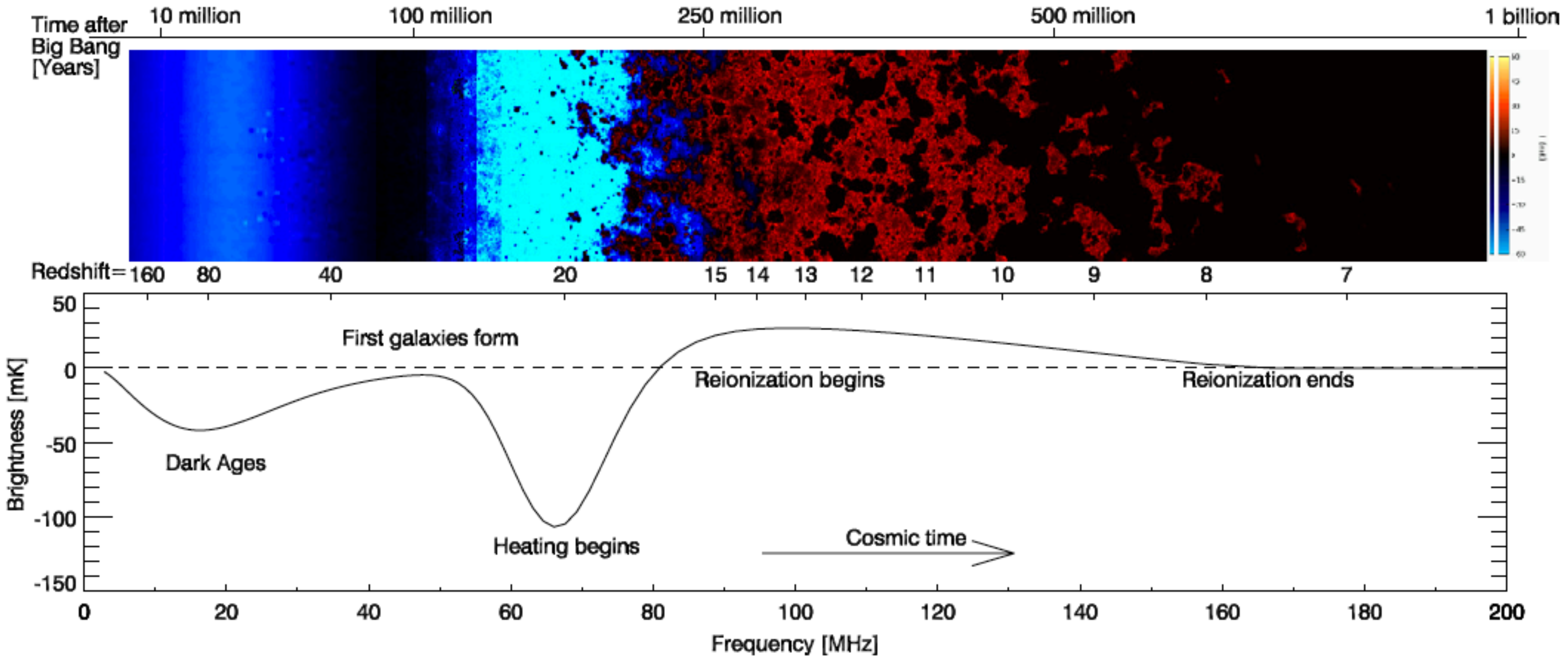


Figure 1. The 21 cm cosmic hydrogen signal. (*a*) Time evolution of fluctuations in the 21 cm brightness from just before the first stars formed through to the end of the reionization epoch. This evolution is pieced together from redshift slices through a simulated cosmic volume [1]. Coloration indicates the strength of the 21 cm brightness as it evolves through two absorption phases (purple and blue), separated by a period (black) where the excitation temperature of the 21 cm hydrogen transition decouples from the temperature of the hydrogen gas, before it transitions to emission (red) and finally disappears (black) owing to the ionization of the hydrogen gas. (*b*) Expected evolution of the sky-averaged 21 cm brightness from the 'Dark Ages' at redshift 200 to the end of reionization, sometime before redshift 6 (solid curve indicates the signal; dashed curve indicates $T_b = 0$). The frequency structure within this redshift range is driven by several physical processes, including the formation of the first galaxies and the heating and ionization of the hydrogen gas. There is considerable uncertainty in the exact form of this signal, arising from the unknown properties of the first galaxies. Reproduced with permission from [2]. Copyright 2010 Nature Publishing Group.

Atomic levels in atomic hydrogen

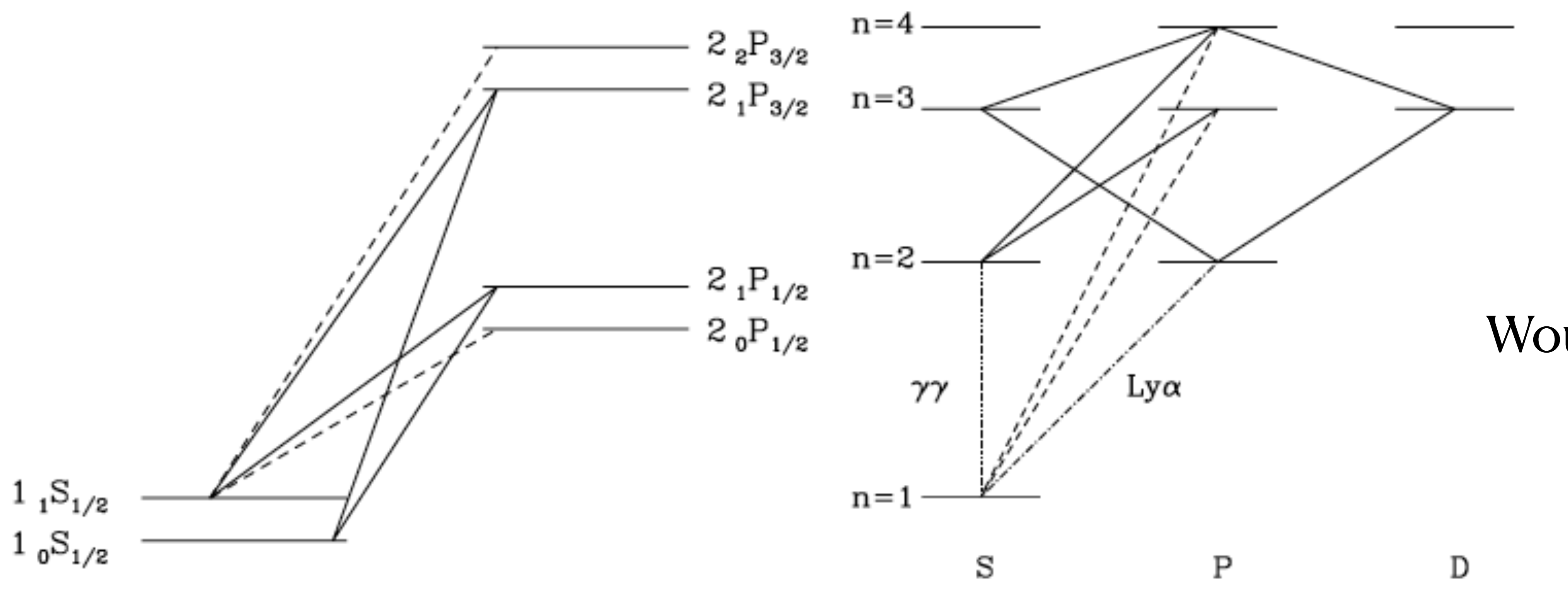
21 cm absorption should happen twice: once during the Dark Ages, then again at Cosmic Dawn.

Atomic collisions control the distribution of atomic levels during the dark ages.

Quixotically, Lyman alpha photons can cause a net “cooling” of the hyperfine transition via the Wouthuysen-Field effect, leading to 21 cm absorption of the cosmic background radiation.

x_i { Dark ages: atomic collisions
Cosmic dawn: Lyman α photons

Rep. Prog. Phys. **75** (2012) 086901 J R Pritchard and A Loeb

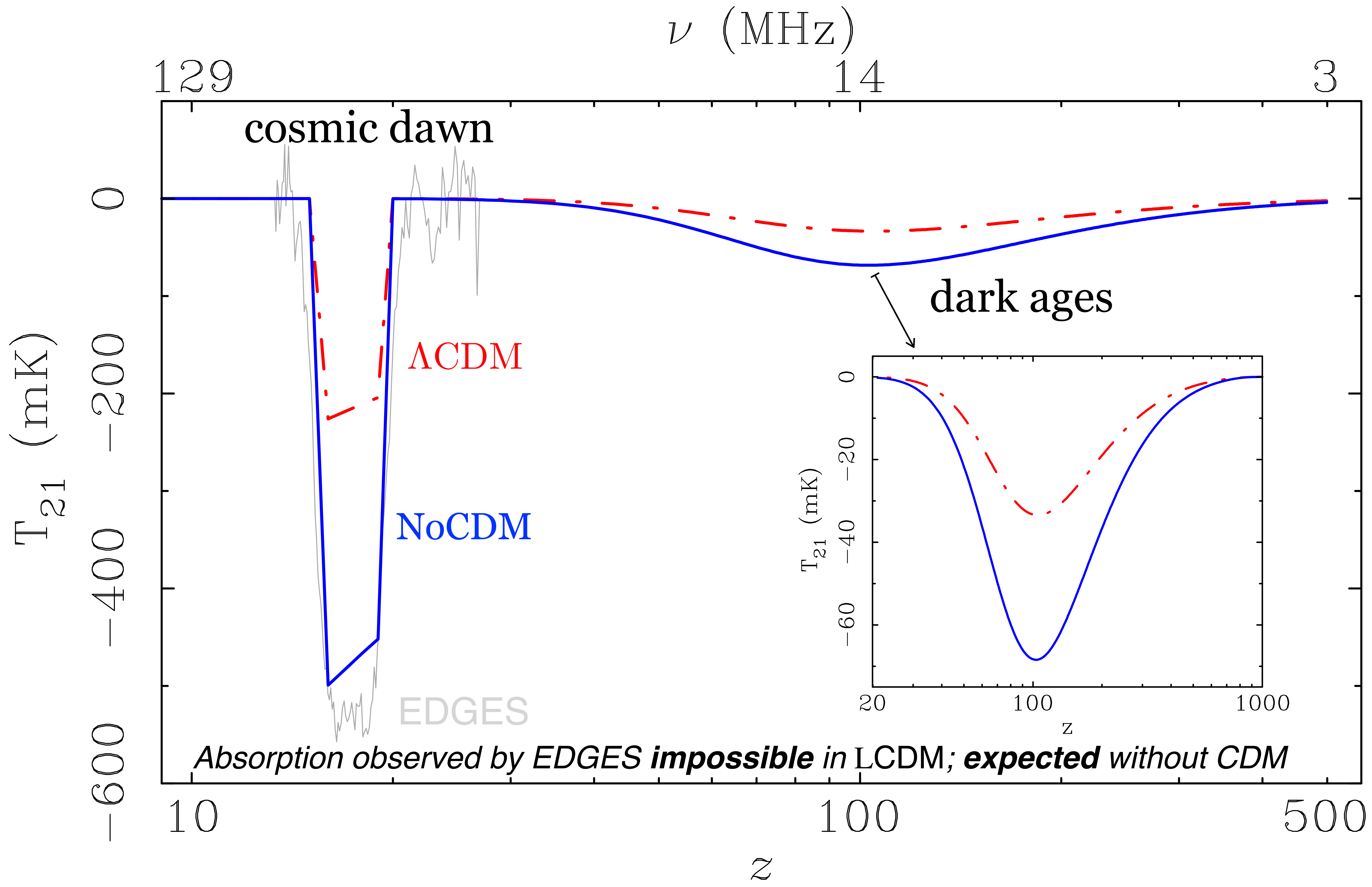


Wouthuysen-Field effect

Figure 2. Left panel: hyperfine structure of the hydrogen atom and the transitions relevant for the Wouthuysen–Field effect [25]. Solid line transitions allow spin–flips, while dashed transitions are allowed but do not contribute to spin–flips. Right panel: illustration of how atomic cascades convert Lyn photons into Lyα photons. Reproduced with permission from [25]. Copyright 2006 Wiley.

2004 model prediction for 21 cm absorption at high redshift

McGaugh, S.S. 2018, PRL, 121, 081305



“Cosmologists are often wrong, but never in doubt”

- Lev Landau

Cosmological parameters by decade

Quantity	“Standard CDM” SCDM 1988	“Concordance model” LCDM 1998	WMAP5 2008	Planck 2018
Ω_m	1	0.3	0.258±0.027	0.321 ± 0.013
Ω_Λ	0	0.7	0.742	0.670 ± 0.013
$\Omega_b h^2$	0.0125	0.015	0.02273 ±0.00062	0.02212 ±0.00022
H_o	50	70	71.9±2.7	66.88 ± 0.92
dark matter	CDM	CDM	CDM	CDM