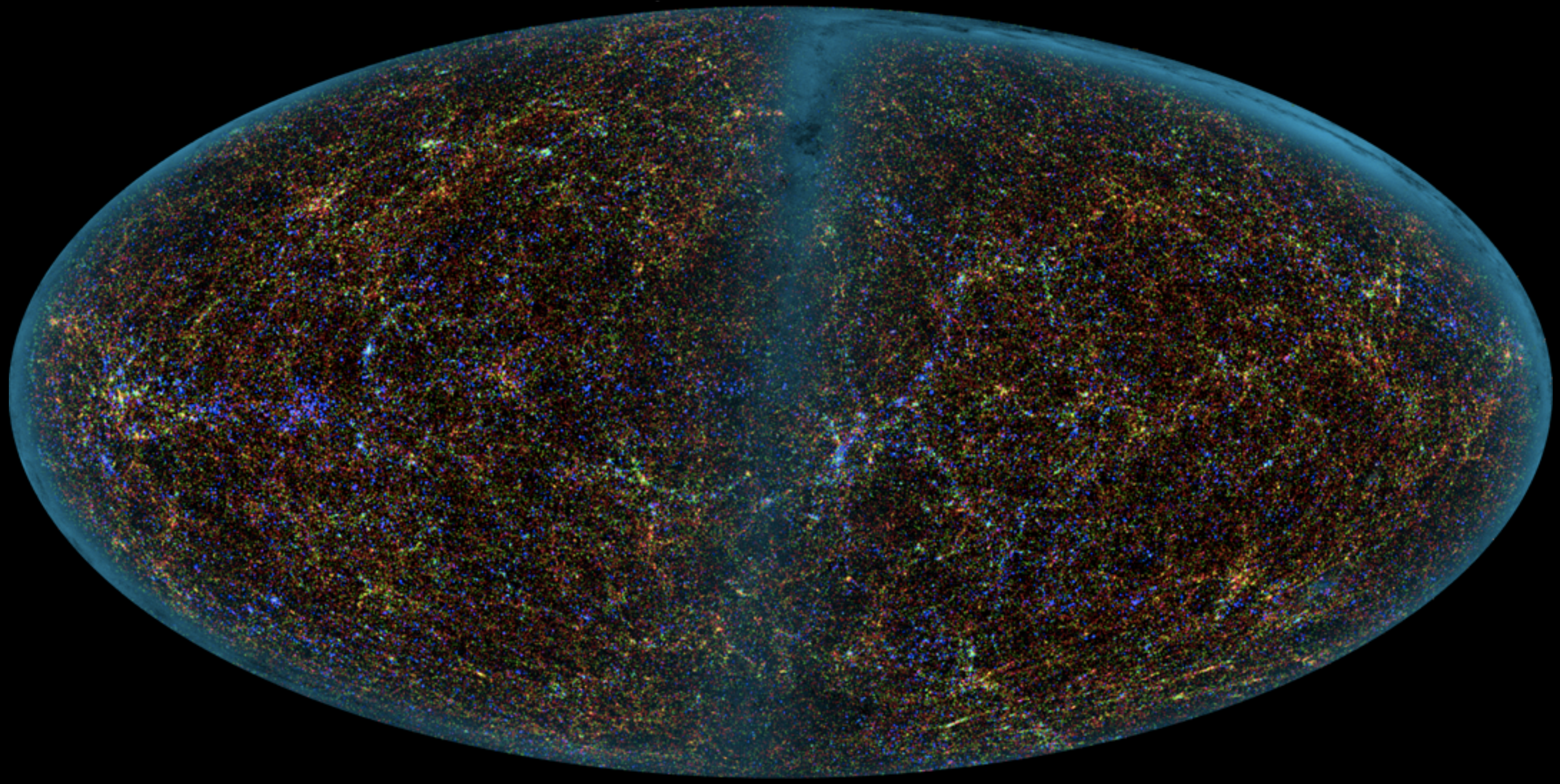
Cosmology

and Large Scale Structure



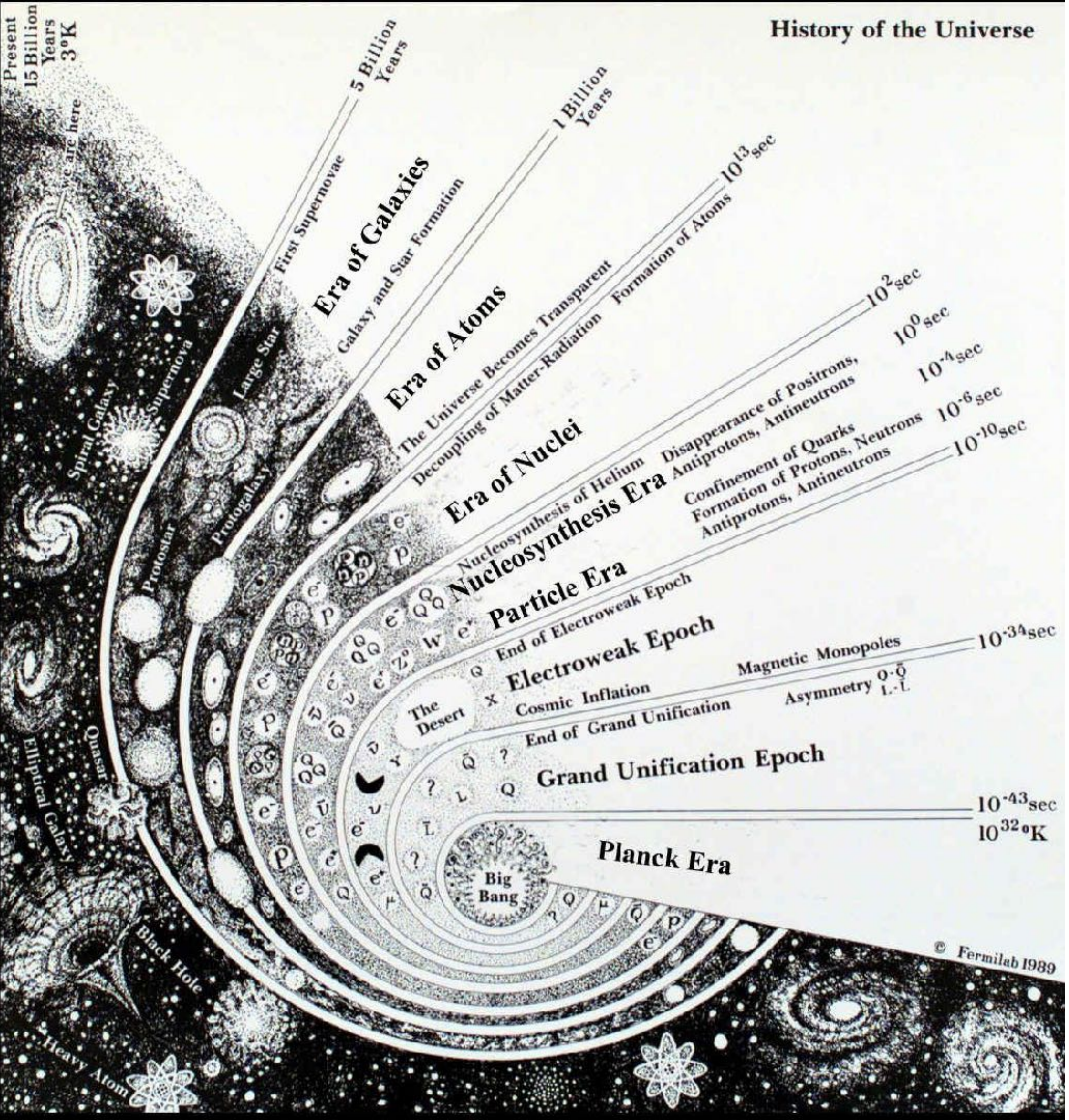
Today
Cosmic Dawn
Inflation

Homework 5 due

Project presentations when we return from Thanksgiving break

26 November 2024

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*)
$t \sim 10^{-5}$ s	quarks condense into baryons (*baryogenesis*)
$t \sim 10^{-4}$ s	proton-antiproton annihilation ends
$t \sim 1$ s	neutrinos decouple
$t \sim 4$ s	electron-positron annihilation ends
$t \sim 10^{2}$ s	Big Bang Nucleosynthesis
$t \sim 10^{5}$ yr	Matter-radiation equality
$t \sim 4 \times 10^{5}$ yr	Atoms form, CMB emerges
$t \sim 5 \times 10^{6}$ yr	Gas temperature decouples from radiation
$t \sim 10^{7}$ yr	Dark Ages
$t \sim 5 \times 10^{8}$ yr	Cosmic dawn (first stars)
$t \sim 10^{9}$ yr	Galaxies form
$t \sim 4 \times 10^{9}$ yr	Peak star formation
$t \sim 9 \times 10^{9}$ yr	Sun forms
$t \sim 13 \times 10^{9}$ yr	Life on earth

Kirchoff's Laws

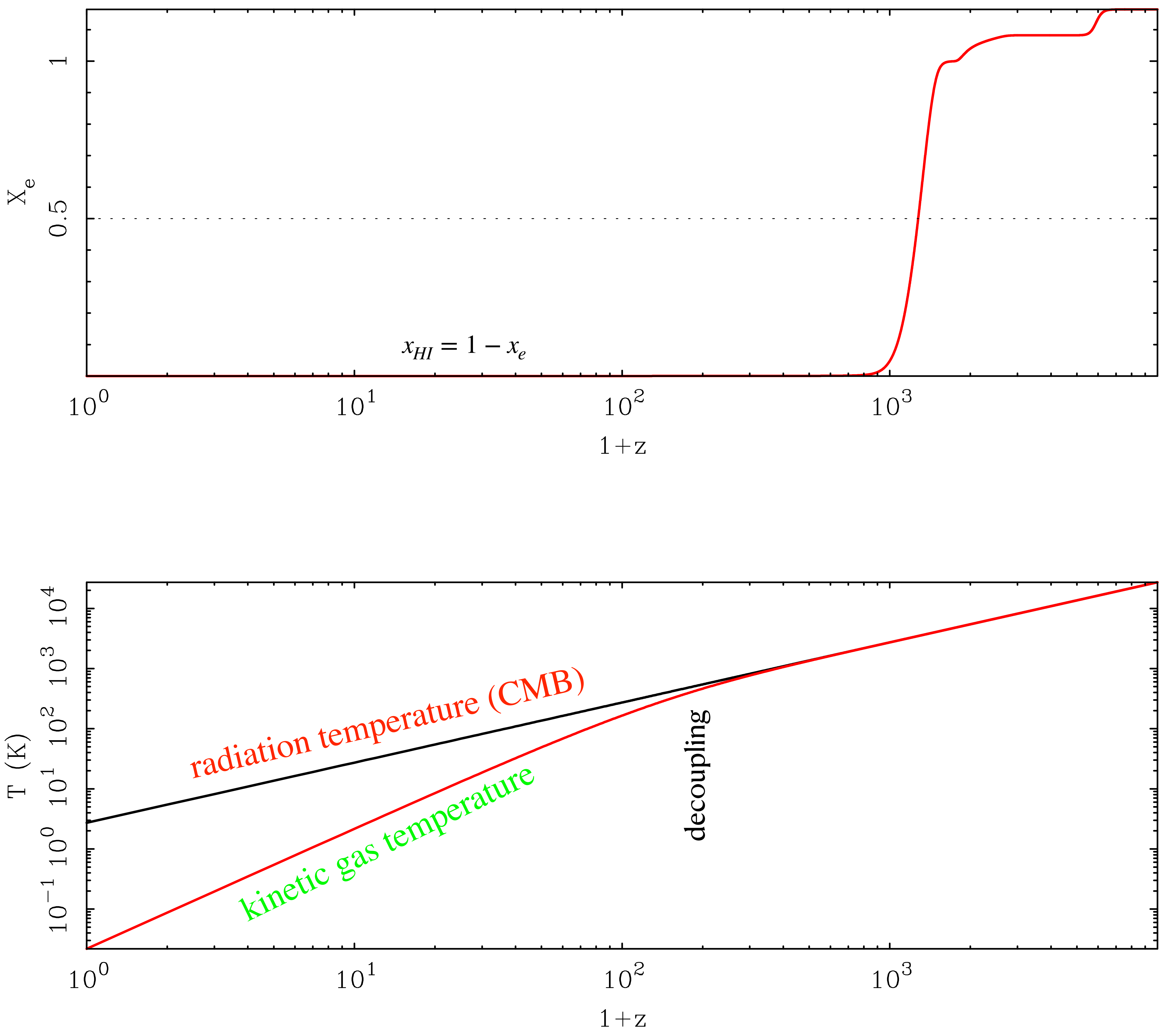
- Hot, dense objects emit a
  - **continuous spectrum** e.g., a light bulb
    - light of all colors & wavelengths
    - follows thermal (blackbody) distribution
    - obeys Wien's & Steffan-Boltzmann Laws.

$$I_\nu(\nu, T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{k_B T}} - 1}$$

Wien $\lambda_p T = 2.9 \times 10^6\ \mathrm{nm\,K}$

Steffan-Boltzmann $L = 4\pi R^2 \sigma_{SB} T^4$

- Hot, diffuse gas emits light only at specific wavelengths.
  - **emission line spectrum** e.g., a neon light, nebula
- A cool gas obscuring a continuum source will absorb specific wavelengths
  - **absorption line spectrum** e.g., stellar atmosphere



x_e
0.5
1
$x_{HI} = 1 - x_e$
10^0
10^1
10^2
10^3
1+z
T (K)
10^{-1}
10^0
10^1
10^2
10^3
10^4
radiation temperature (CMB)
kinetic gas temperature
decoupling
10^0
10^1
10^2
10^3
1+z

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

$\omega_b = \Omega_b h^2$

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

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

21 cm brightness temperature:

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

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.

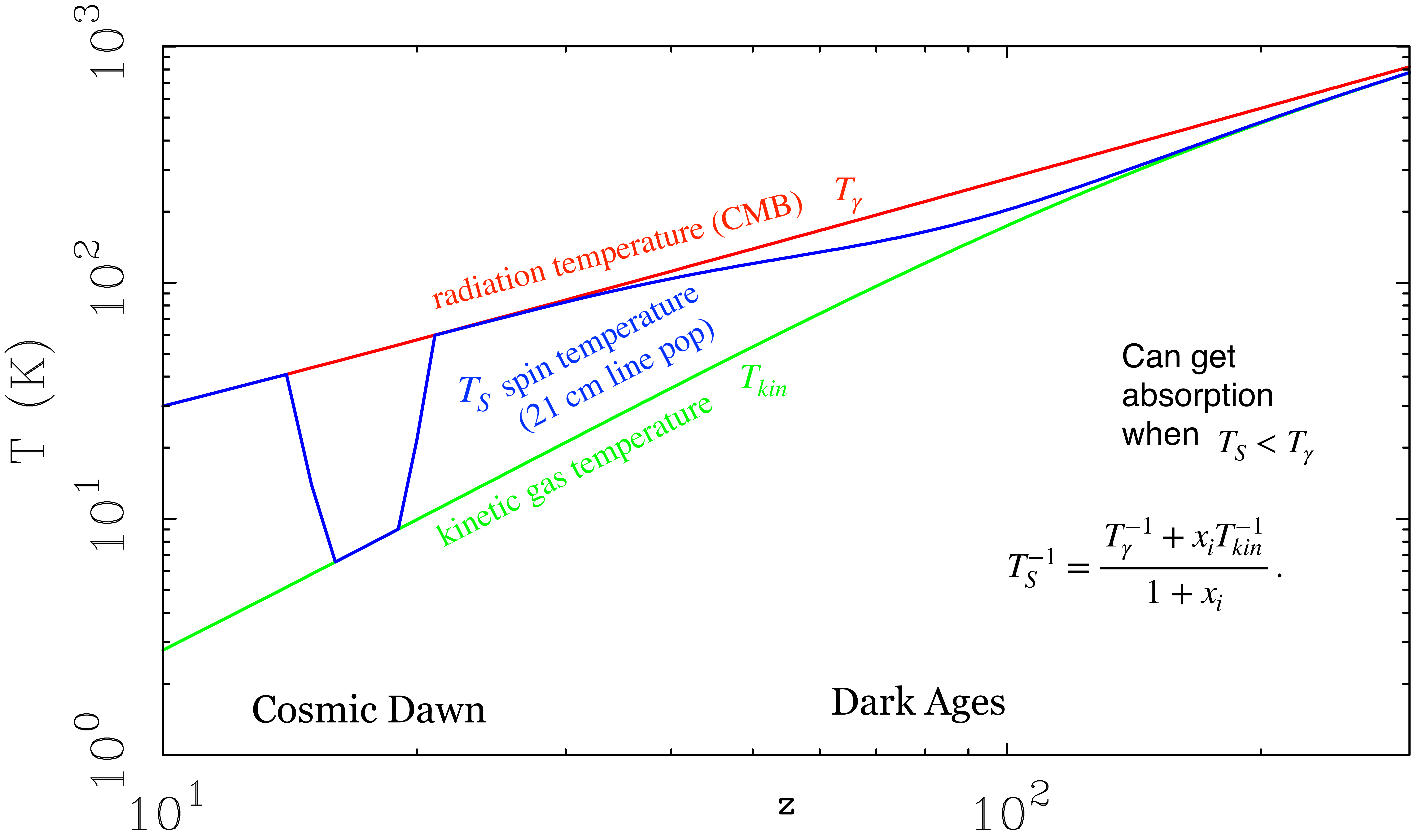
This usual approximation $\tilde{H}(z)$ may not suffice.

Three Temperatures:

T_γ radiation temperature (the energy of the relic radiation field that is now the CMB)

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

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



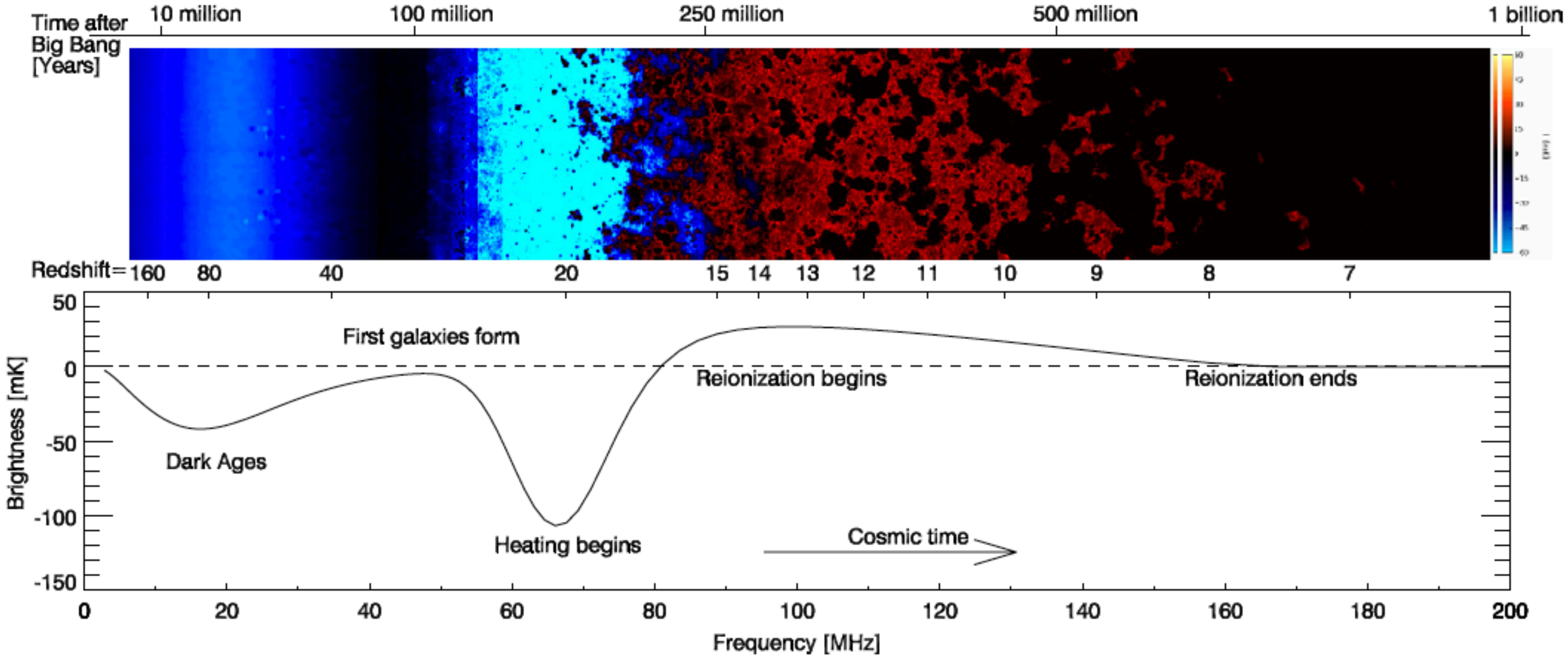


Figure 1. The 21 cm cosmic hydrogen signal. (*a*) Time evolution of fluctuations in the 21 cm brightness from just before the first stars formed through to the end of the reionization epoch. This evolution is pieced together from redshift slices through a simulated cosmic volume [1]. Coloration indicates 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

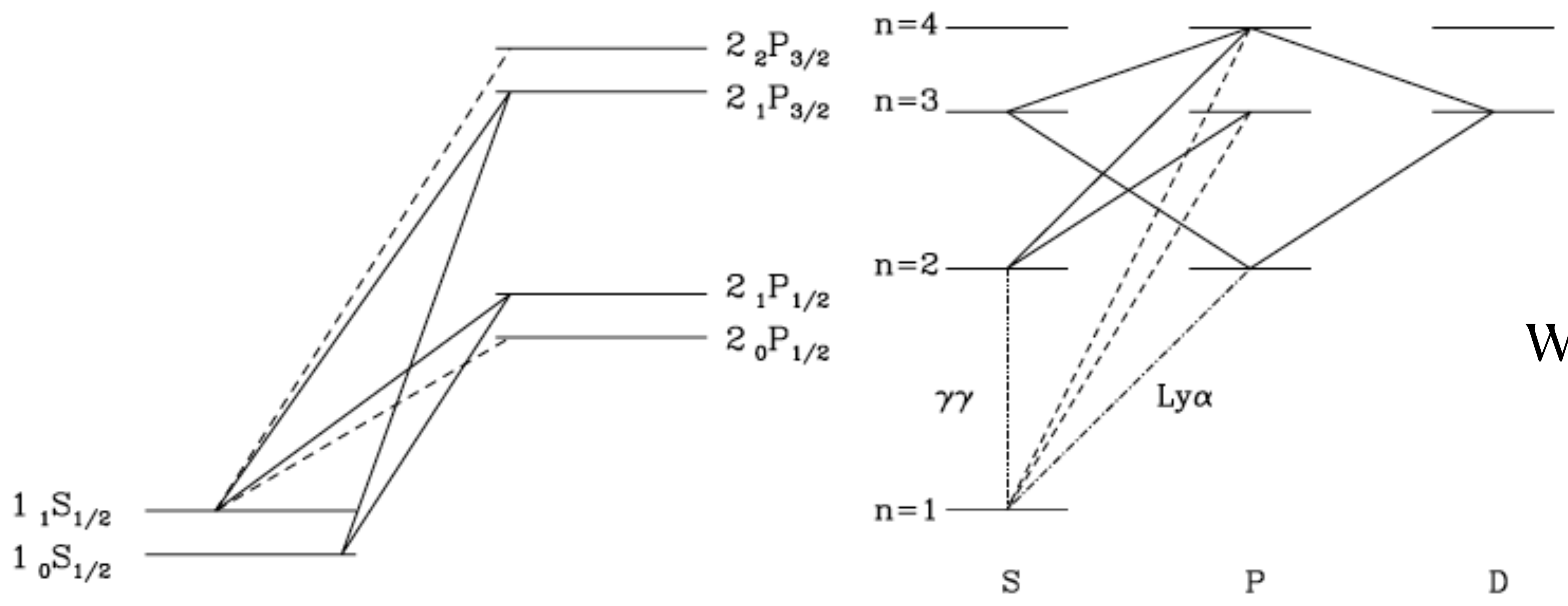
21 cm absorption should happen twice: once during the Dark Ages, then again at Cosmic Dawn.

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

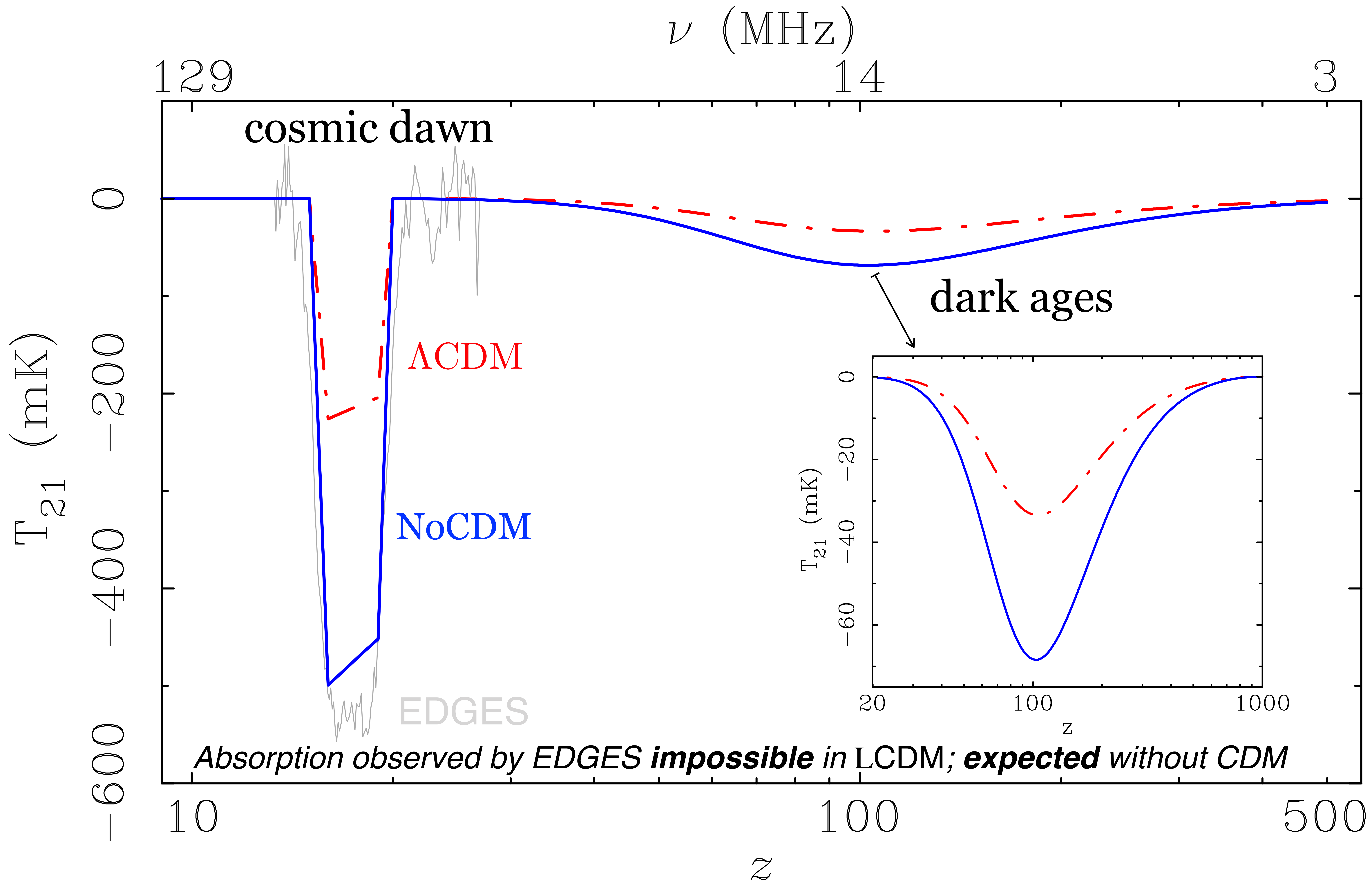


Wouthuysen-Field effect

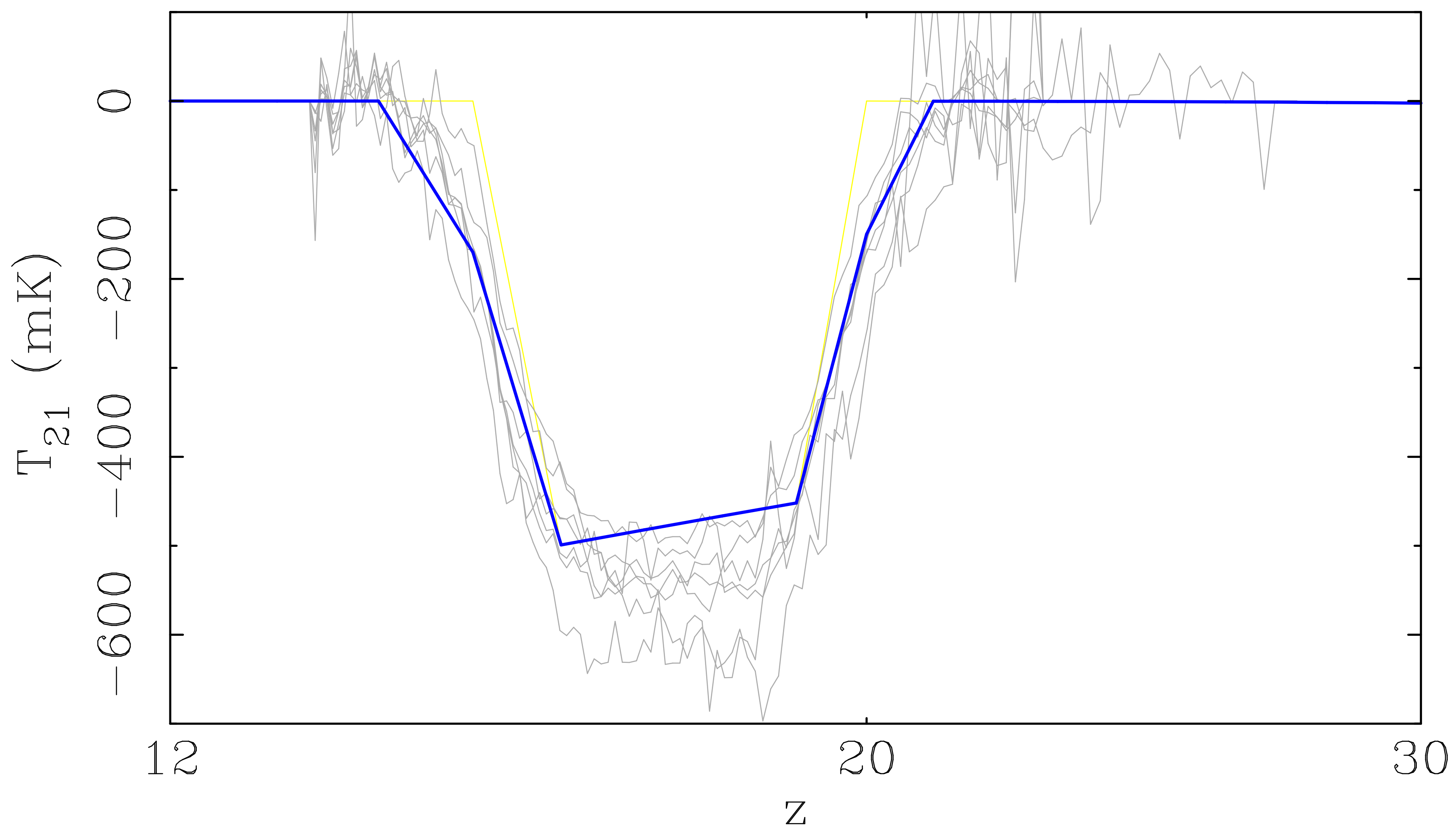
Figure 2. Left panel: hyperfine structure of the hydrogen atom and the transitions relevant for the Wouthuysen–Field effect [25]. Solid line transitions allow spin–flips, while dashed transitions are allowed but do not contribute to spin–flips. Right panel: illustration of how atomic cascades convert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

LCDM & No CDM model prediction for 21 cm absorption at high redshift

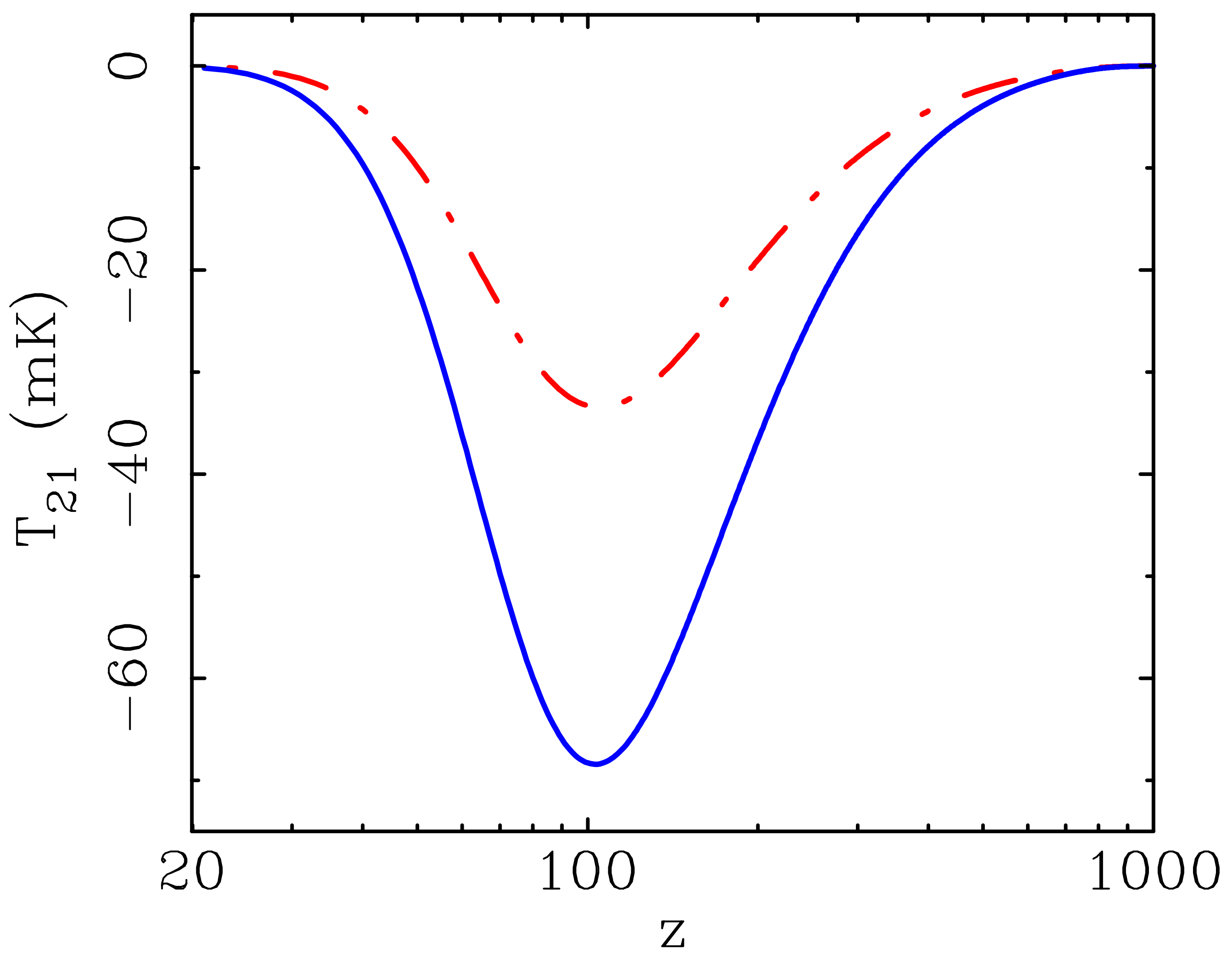
McGaugh 2018, PRL, 121, 081305



Cosmic Dawn



Dark Ages



EDGES signal indicates

- rapid transition from CMB to gas T
  - Full off at z=21 to full on at z=19
  - Full on at z=16 to full off at z=14
  - anticipated by Sanders (1998); McGaugh (2004)
- maximum absorption too great for ΛCDM
- natural without CDM

(~50 Myr)

Purely collisional coupling in neutral IGM - very clean prediction - just atomic physics in an expanding universe

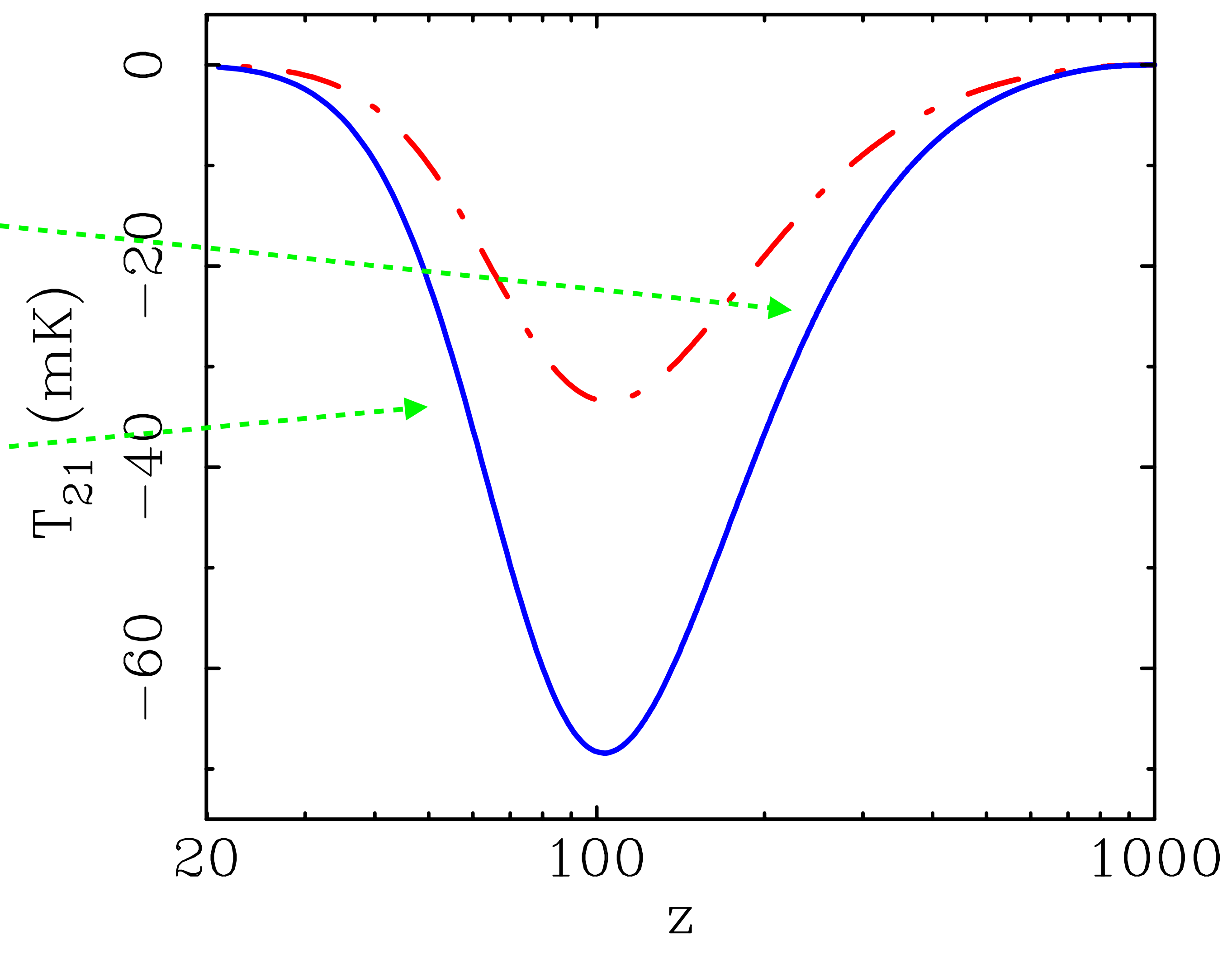
Can only be observed from space - frequency below 30 MHz ionospheric cutoff

Prediction for 21 cm power spectrum

- Less power than LCDM at z ~ 150
  - baryon oscillations strong

- More power than LCDM at z ~ 50
  - baryon oscillations will suffer mode mixing from non-linear growth, smoothing out power spectrum

Dark Ages

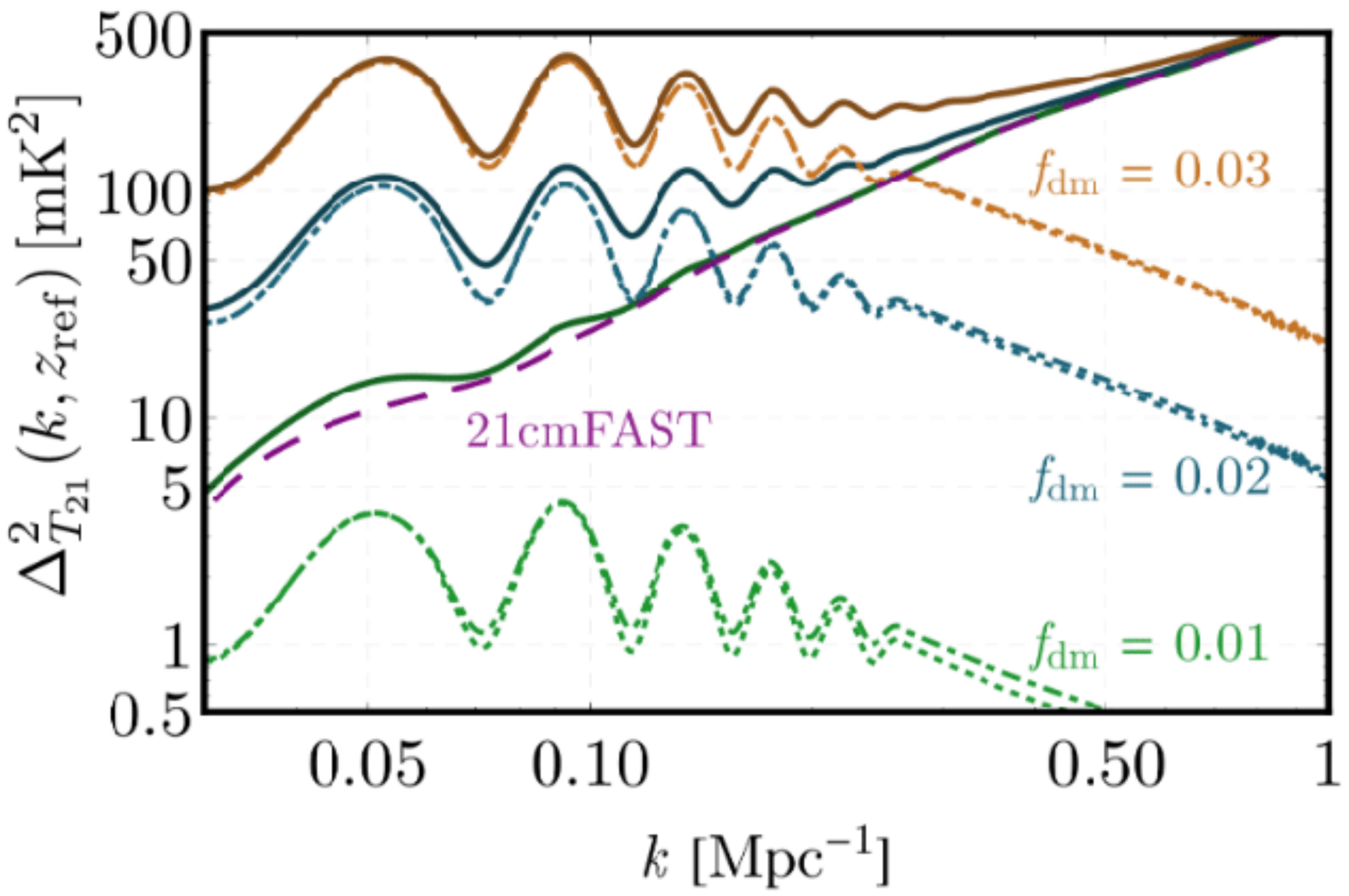


21 cm tomography will be like having the CMB over and over again at a series of redshifts from z ~ 15 to z ~ 200

Purely collisional coupling in neutral IGM -
very clean prediction -
just atomic physics in an expanding universe

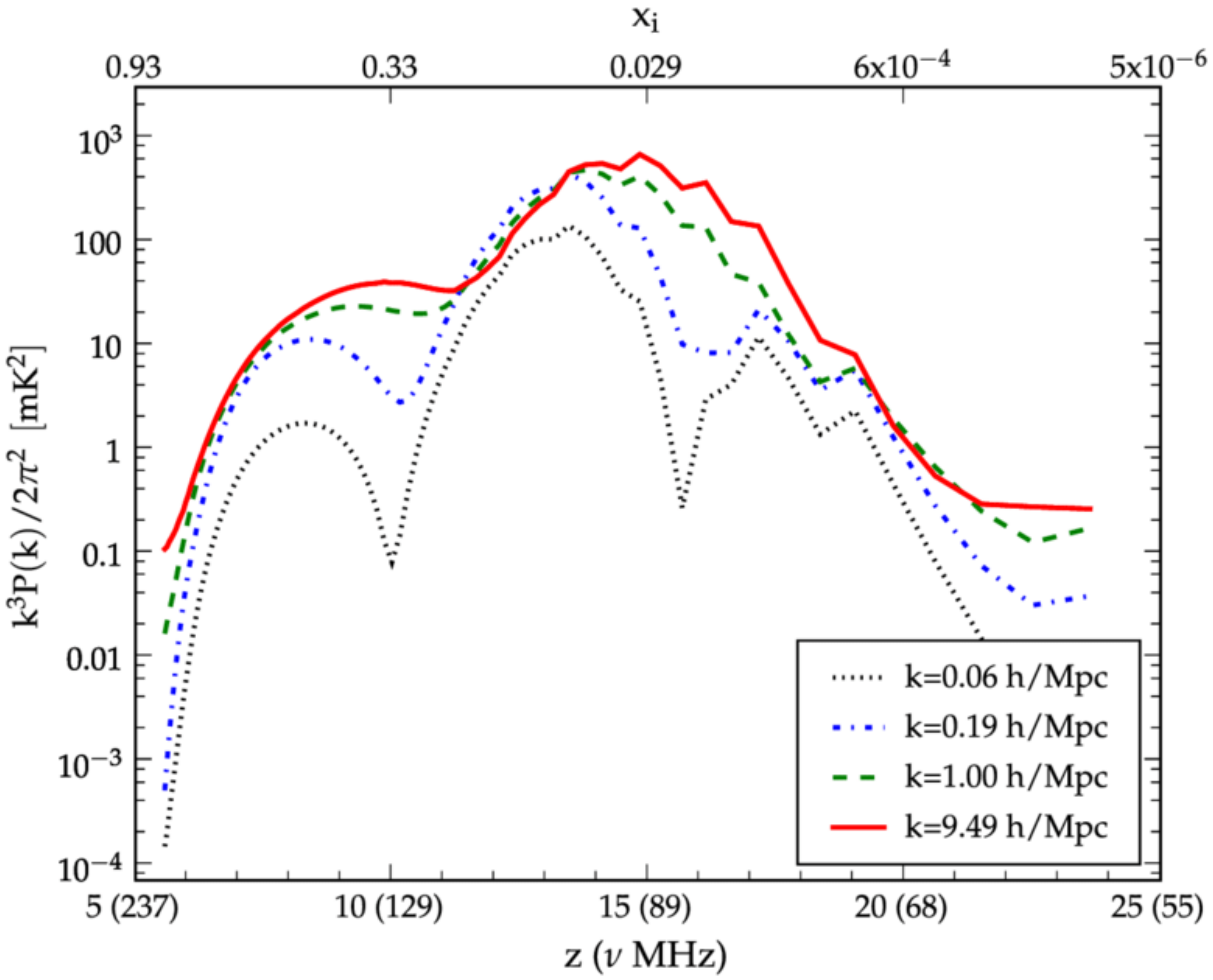
Can only be observed from space - frequency below 30 MHz ionospheric cutoff

A bright future for long-wavelength radio astronomy:
We should be able to measure the power spectrum in 21cm absorption — at many redshifts!



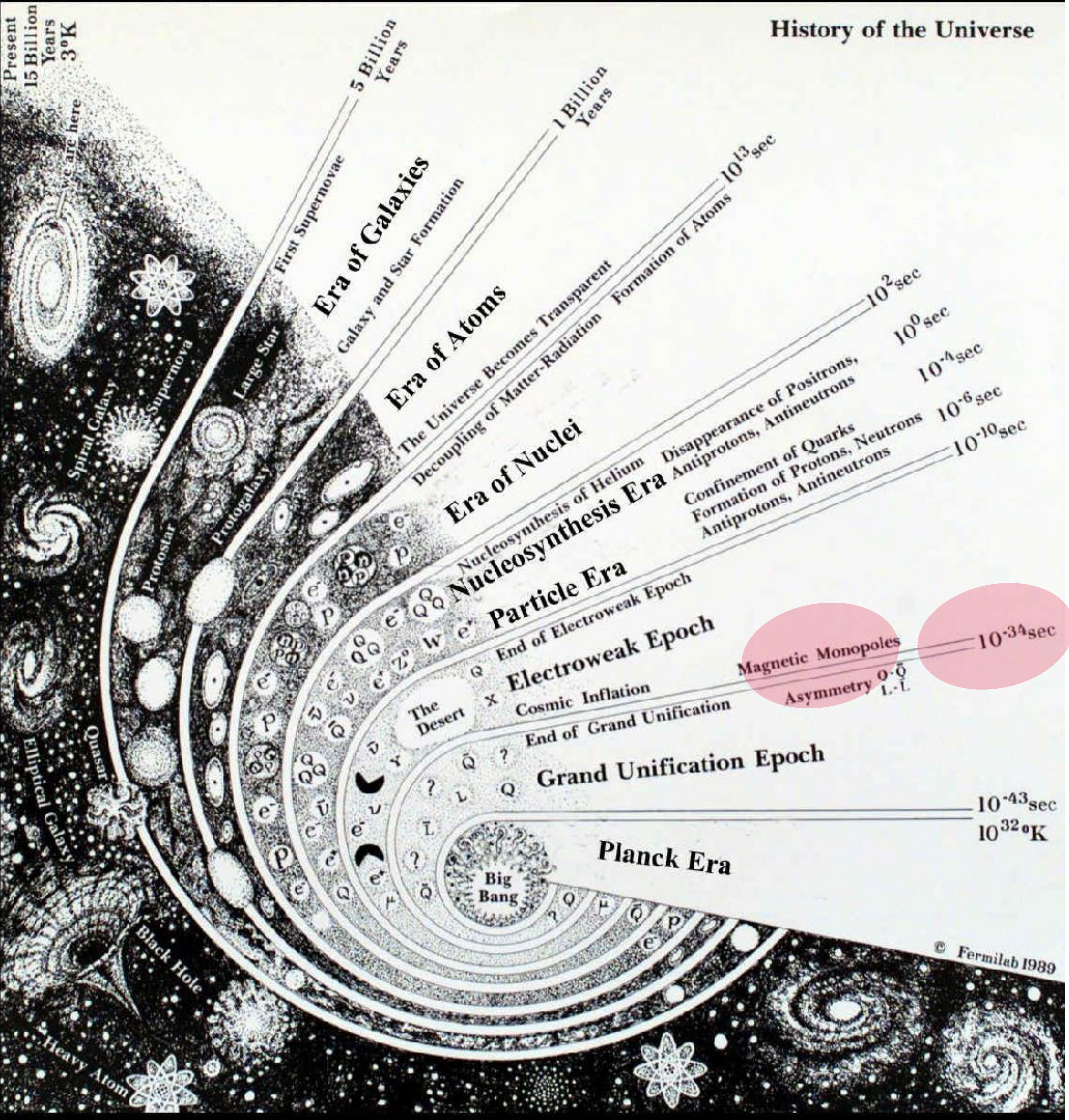
The 21-cm power spectrum can distinguish between different exotic physics scenarios during the Dark Ages. In these models, a fraction f_{dm} of the dark matter is assumed to have a small charge; the oscillations in the power spectrum arise from the large-scale streaming of baryons relative to dark matter. The solid curves are the total power for each value of f_{dm}, after linearly adding the dash-dotted lines, showing the contributions from dark matter-baryon scattering, to the standard cosmological model (labeled "21cmFAST"). Figure from Muñoz et al. (2018).

Power as a function of scale
[the usual depiction with wavenumber]



Evolution of four different k-modes of the spherically averaged 21cm power spectra (k 3 P(k)/(2π 2) or Δ 2 (k)) with redshift. The lowest k-mode clearly shows the three epochs of Ly-α fluctuations, heating fluctuations and ionization fluctuations. Figure 9 from Santos et al. (2008).

Power as a function of redshift (frequency)



Time	Event

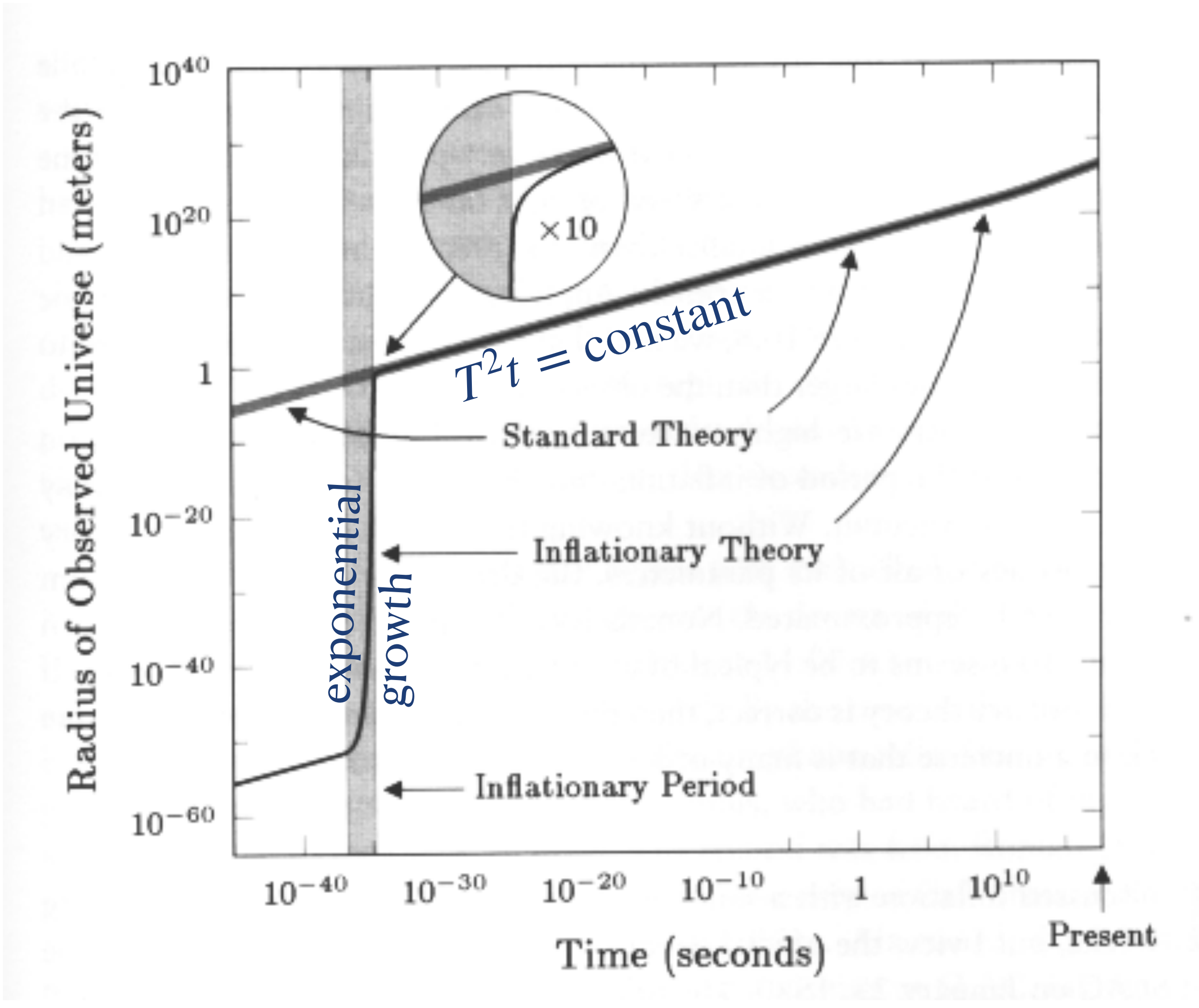
$t \sim 10^{-38}$ s   GUT scale (*speculative*)

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: $a \sim e^{Ht}$

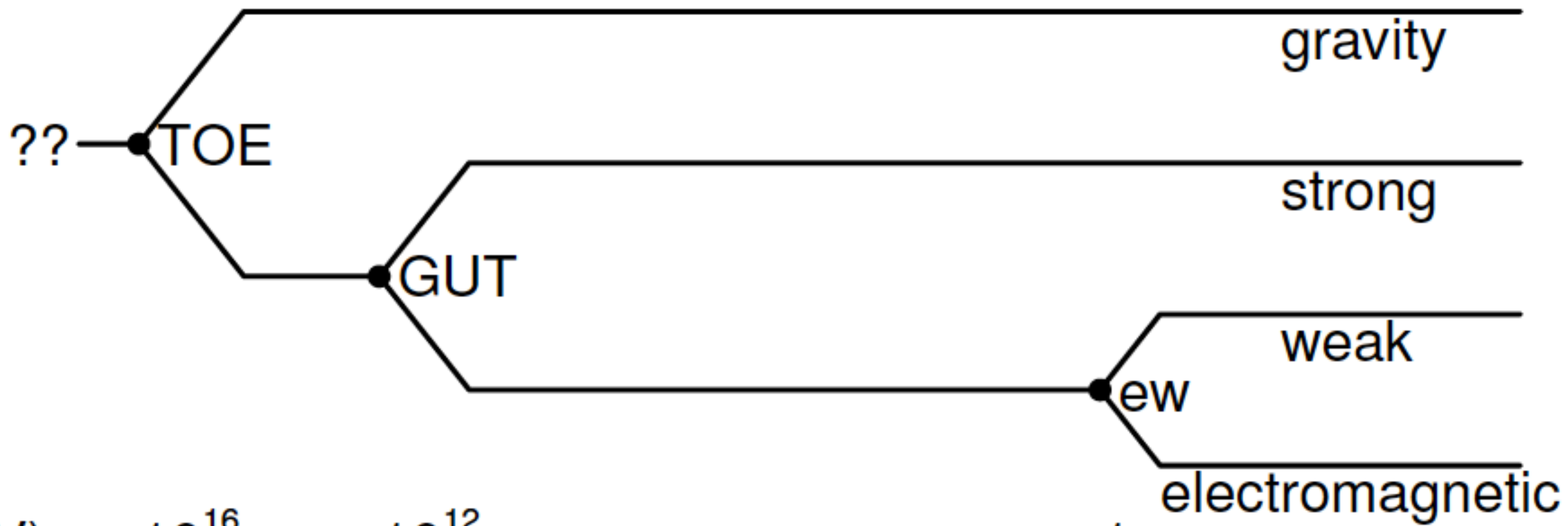
precedes radiation domination when $a \sim t^{1/2}$
so $T^2\, t = \text{constant}$



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



E (TeV)	10^{16}	10^{12}	1
T (K)	10^{32}	10^{28}	10^{16}
t (sec)	10^{-43}	10^{-36}	10^{-12}

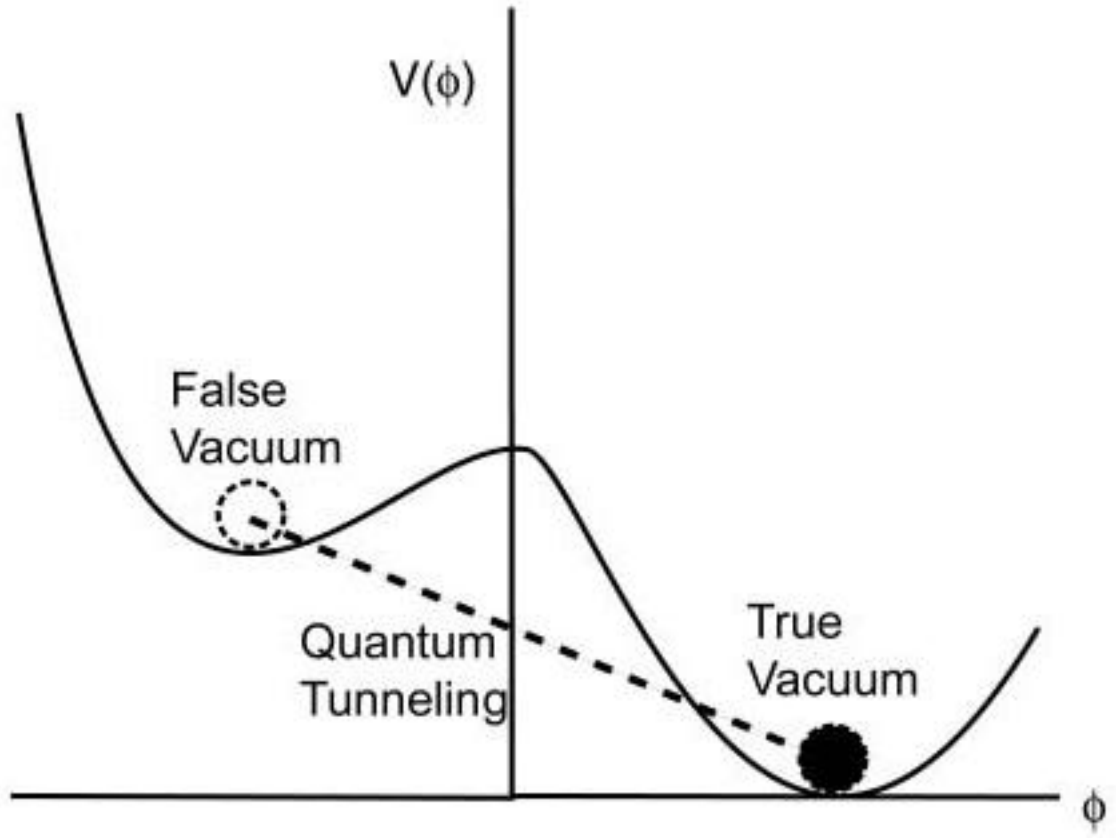
Figure 11.2: The energy, temperature, and time scales at which the different force unifications occur.

GUT = Grand Unified Theory
TOE = Theory of Everything

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

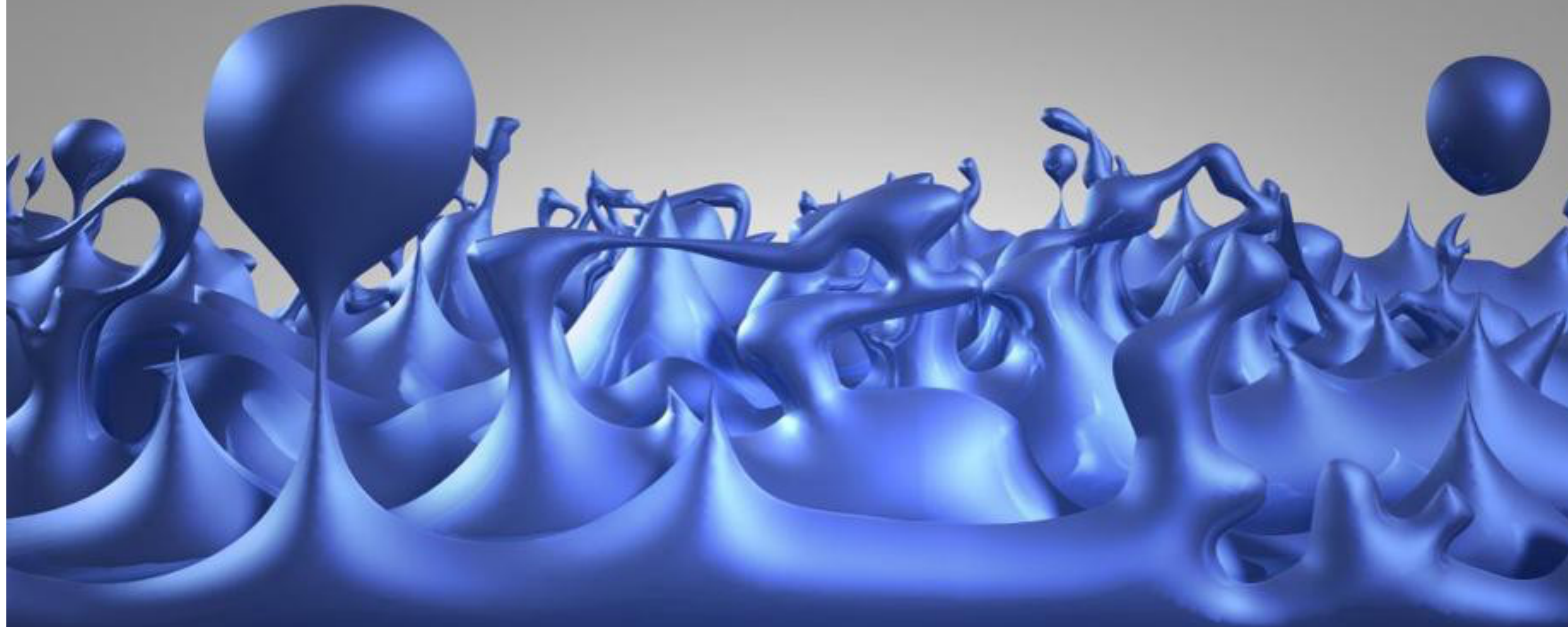
$$H_I = \sqrt{\frac{\Lambda_I}{3}}$$

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

"False" vacuum of Inflation $\varepsilon_{\Lambda_I} = \frac{c^2}{8\pi G}\Lambda_I \sim 10^{120}\ \mathrm{GeV\,cm^{-3}}$

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.

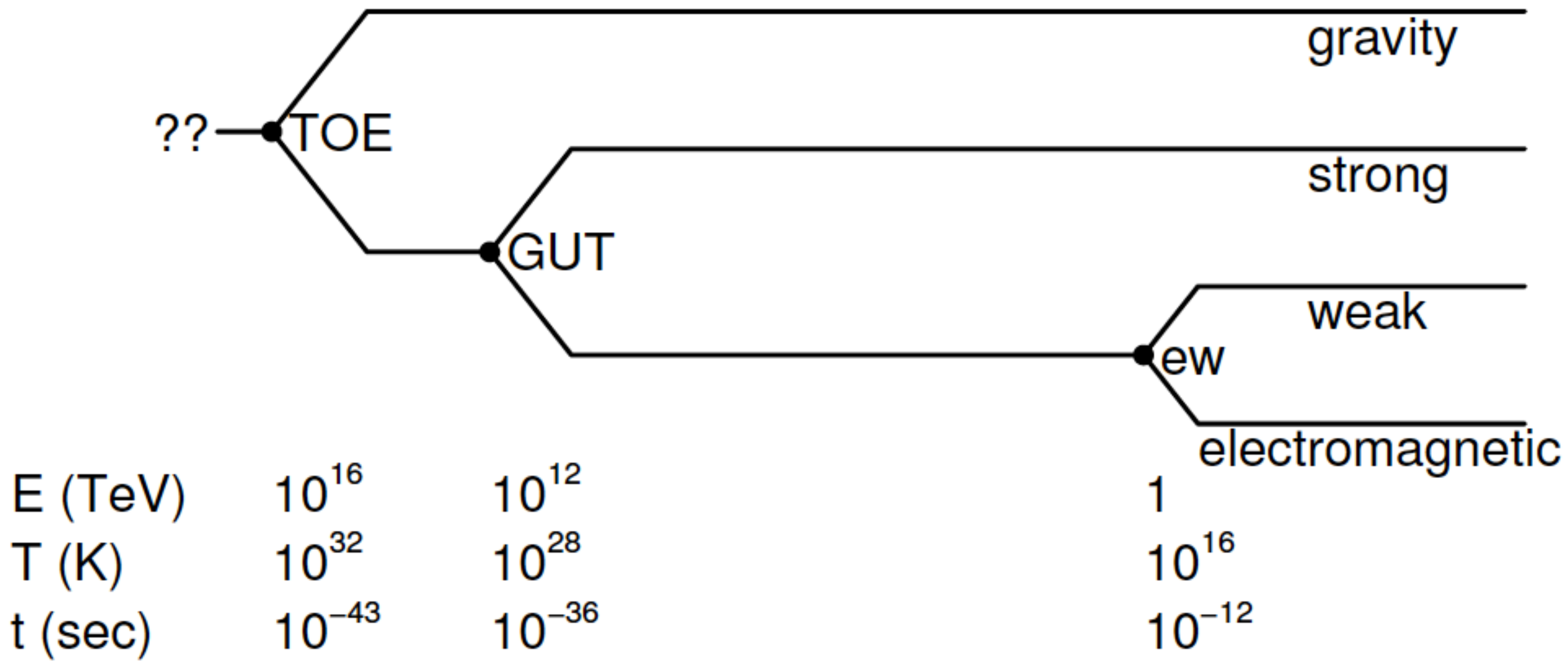


Figure 11.2: The energy, temperature, and time scales at which the different force unifications occur.

Motivating Inflation

See Ryden, chapter 10
see also Ned Wright's cosmology tutorial
https://www.astro.ucla.edu/~wright/cosmo_04.htm

Two observations, in particular, are extremely puzzling under the Big Bang model.

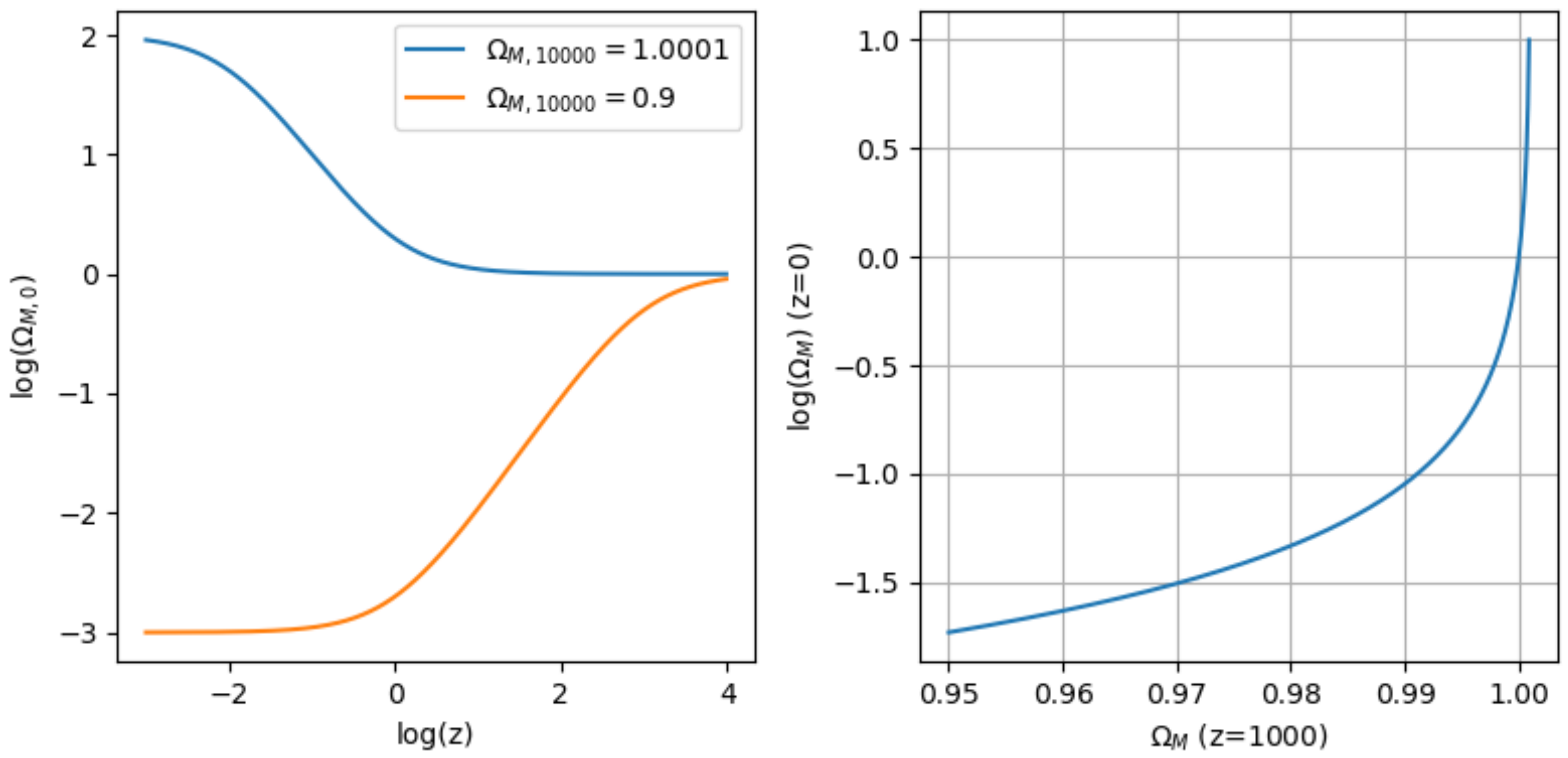
The flatness (or coincidence) problem
Why is $\Omega_{m_0} \approx 1$? Why not 106? Why not 42? Why not 0.0021034011031?
The density of the Universe changes with time, as the Universe expands. So Omega$_M$, the ratio of the actual density to the critical density also changes:

$$\Omega(z) = \Omega_0 \left[\frac{1+z}{1+\Omega_0 z}\right]$$

(Strictly speaking, this holds only for a matter dominated universe. But it's only recently that dark energy has started affecting the expansion of the universe, so early on the universe behaved like a matter dominated universe....)

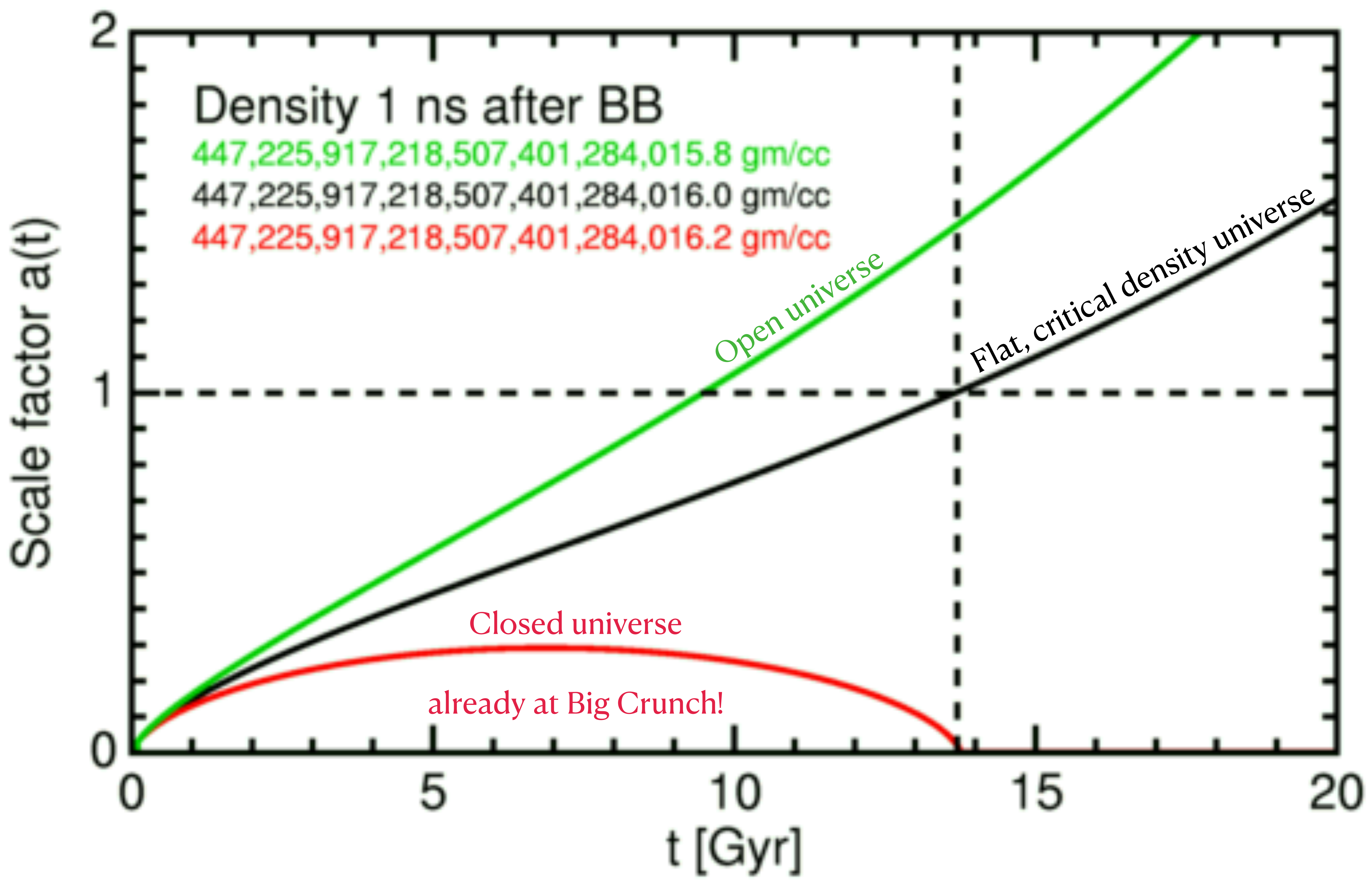
Let's look at two examples.
- At a redshift of z=10,000 (ie when the universe was 10^4 times smaller than now), it had a density parameter of 1.0001
- At a redshift of z=10,000, it had a density parameter of 0.9

In the universe that is slightly over-dense at z=10^4, the density parameter today (at z=0) would be 100. In the universe that is slightly under-dense at early times, we ought to measure a density parameter today of 0.001. Omega very quickly diverges from 1, unless it is exactly equal to 1.



The flatness problem

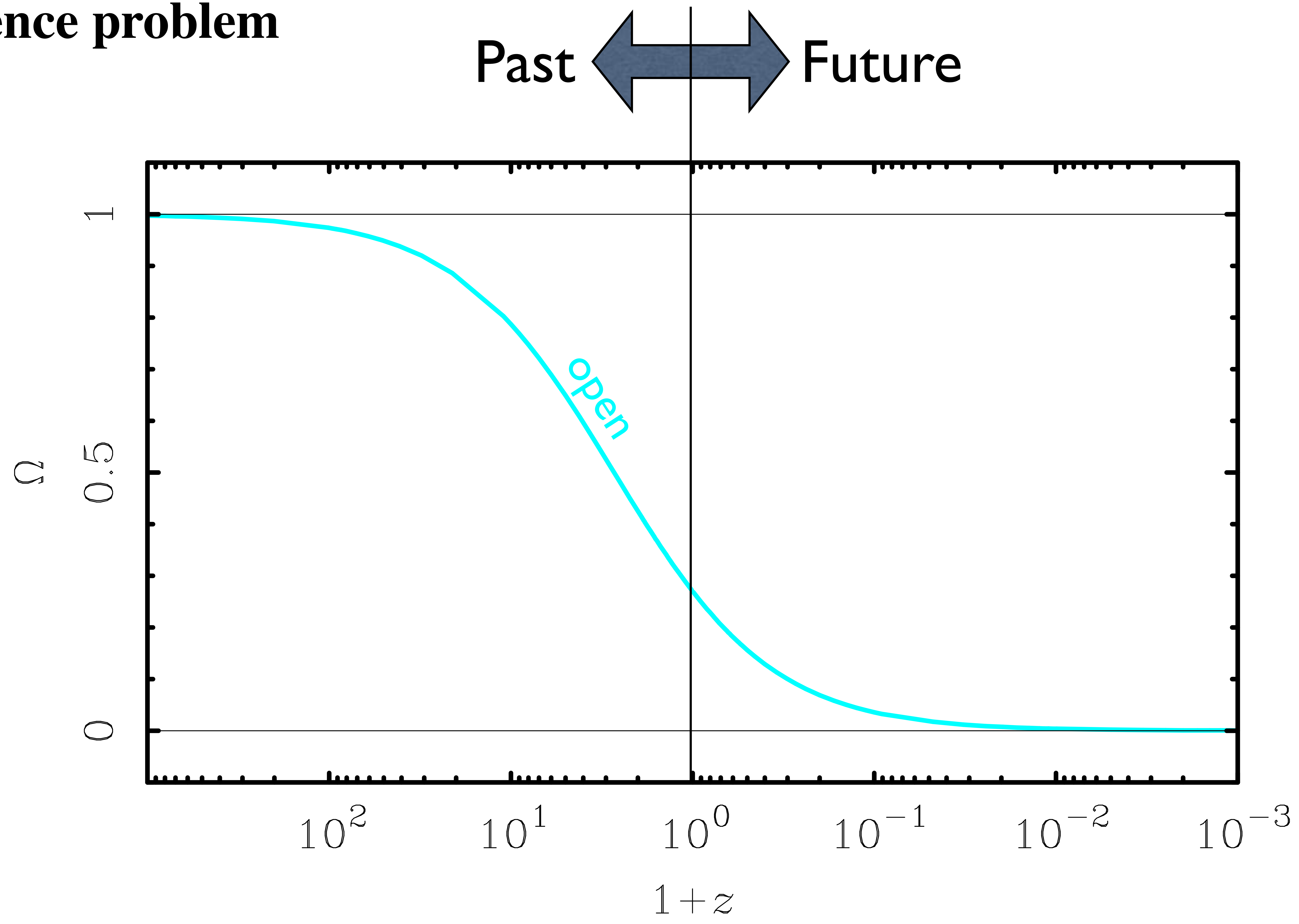
Look at this figure (taken from Ned Wright's Cosmology Tutorial; see also the textbook of Kolb & Turner) this argument made Inflation fly in the '80s:
if the density of the universe had been ever so slightly non-critical 1 nanosecond after the big bang, we would have a drastically different universe:



Why 1 ns?

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

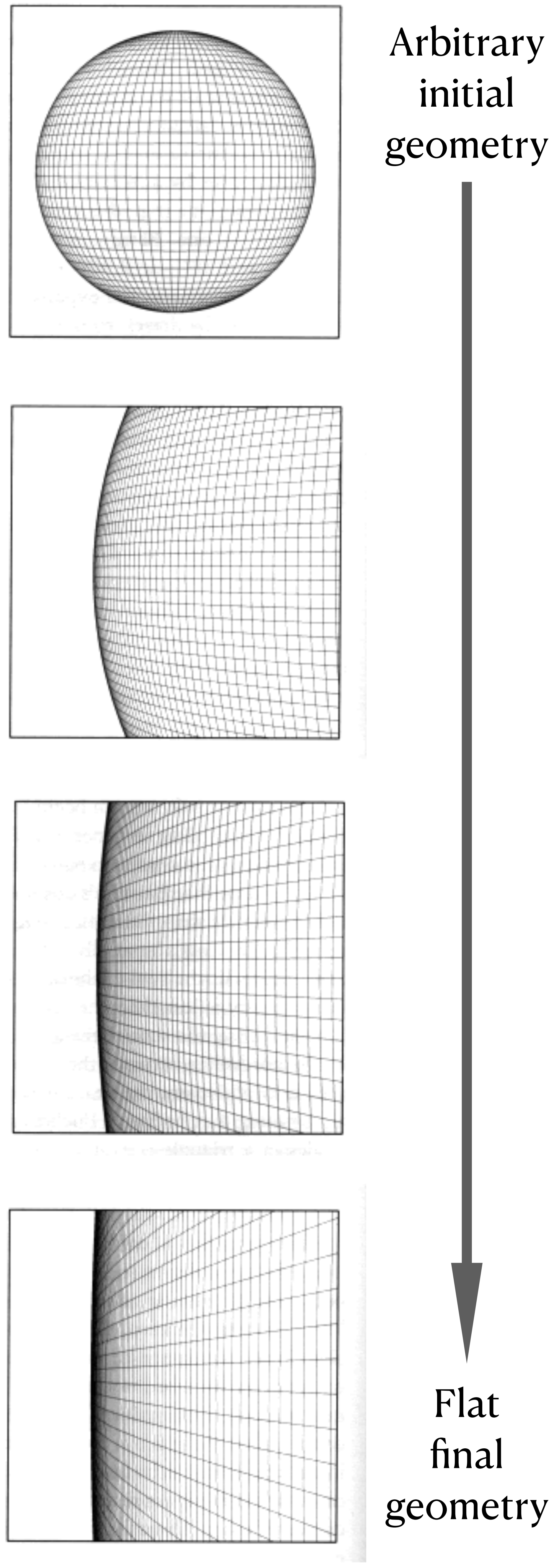
The Inflationary solution:

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

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

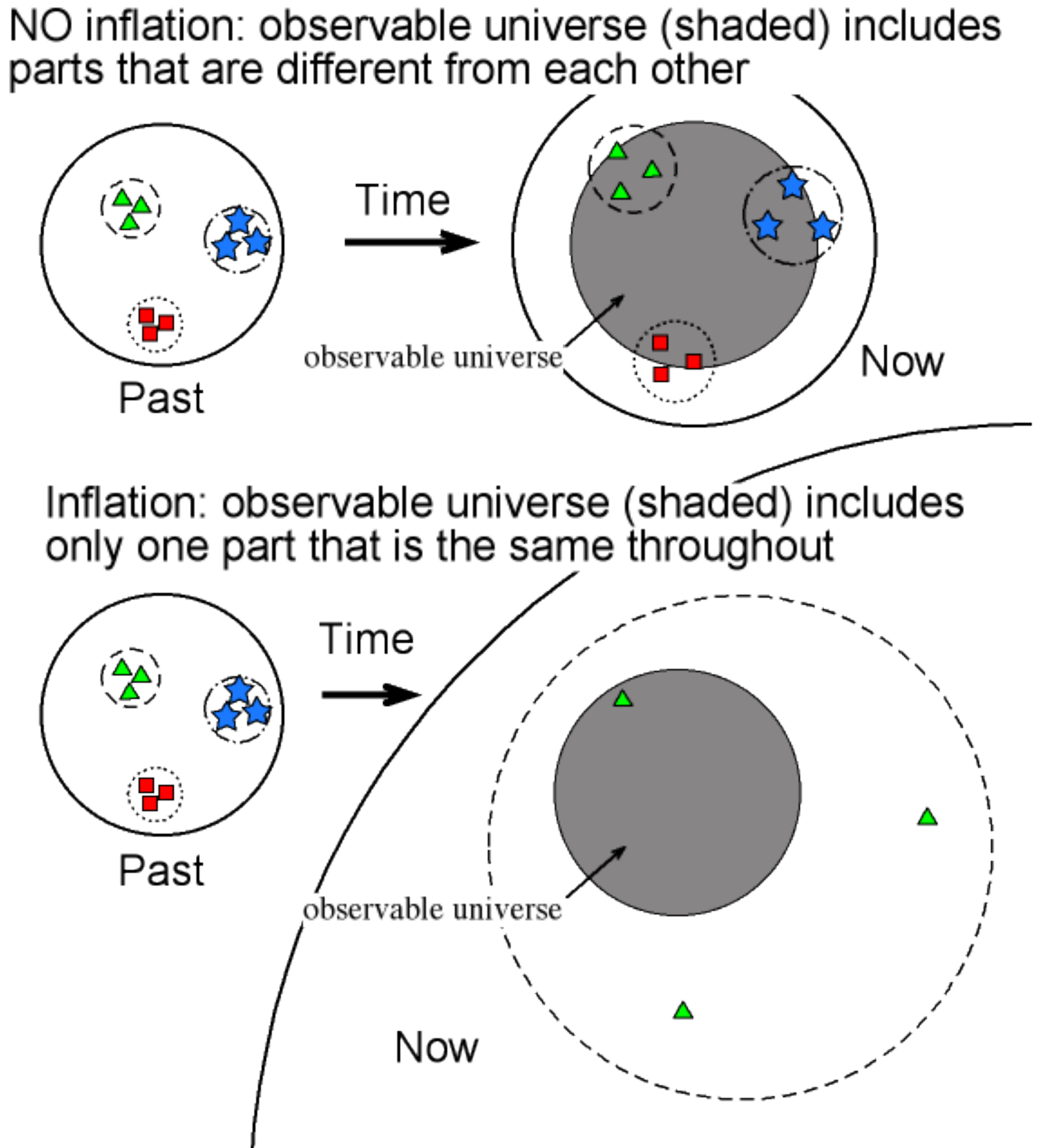
Looking at the microwave background, it is very smooth to 1 part in 10^5. Everywhere. But at the time of recombination, regions of the universe which are now separated by more than 2 degrees on the sky were never in causal contact.

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

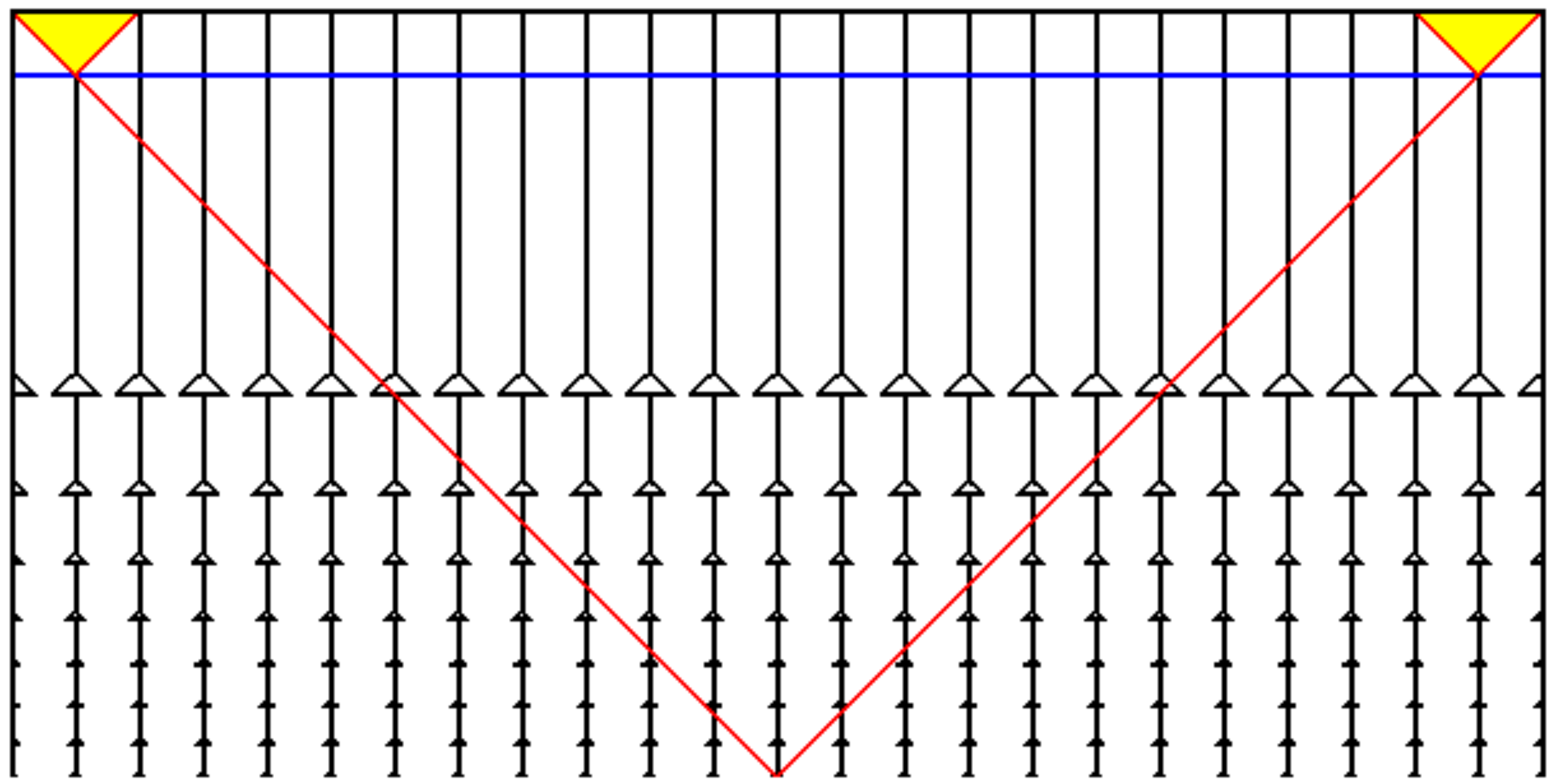
At the time of the CMB, the horizon scale was about 0.25 Mpc. The current horizon distance is ~ 14.6 Gpc, so the observable universe at a redshift of z=1100 was 14.6 Gpc/1100 ~ 13.2 Mpc in size - much larger than the horizon.

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

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

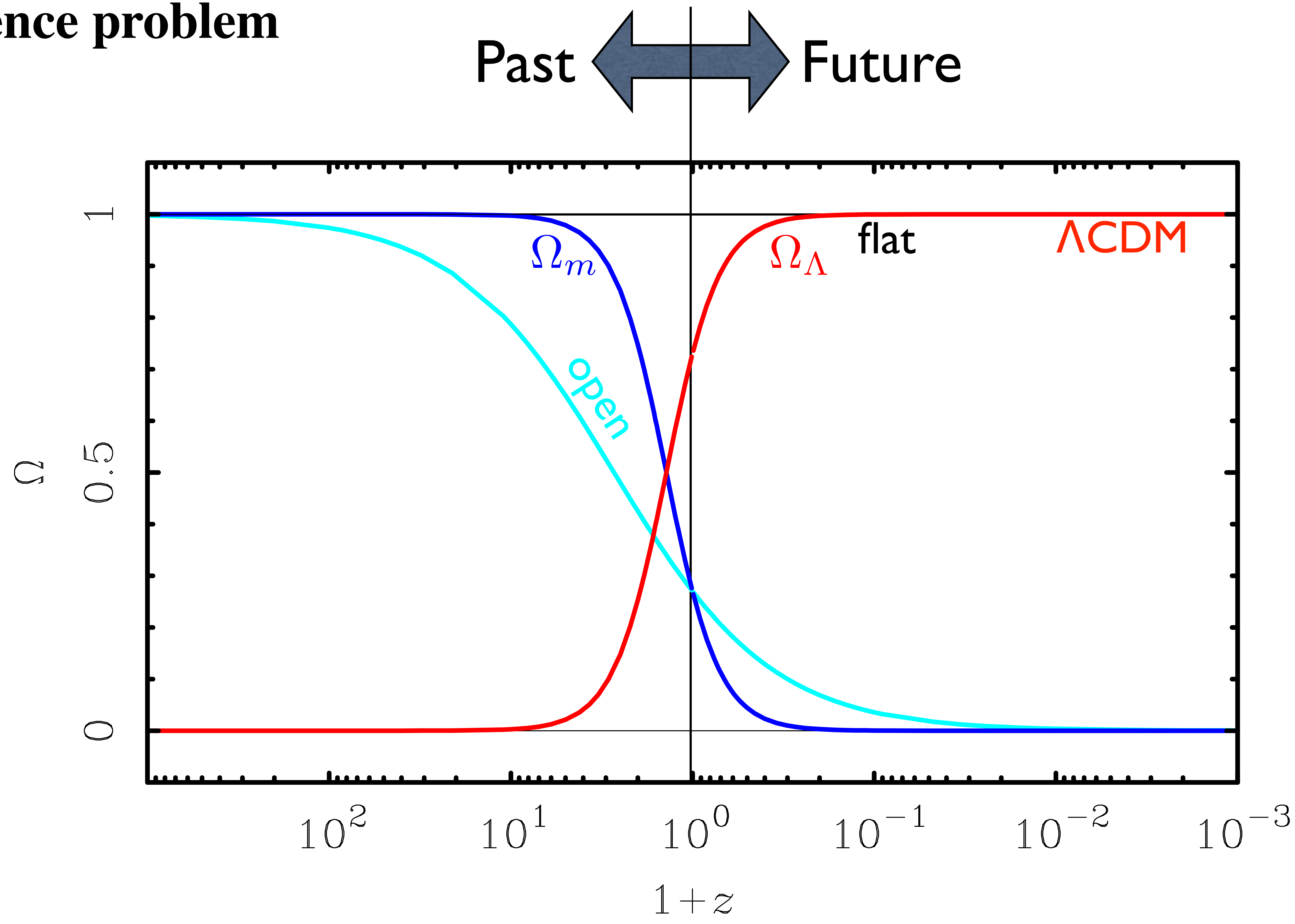


Yellow regions out of causal contact at recombination yet are observed to have the same temperature on the sky now



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:

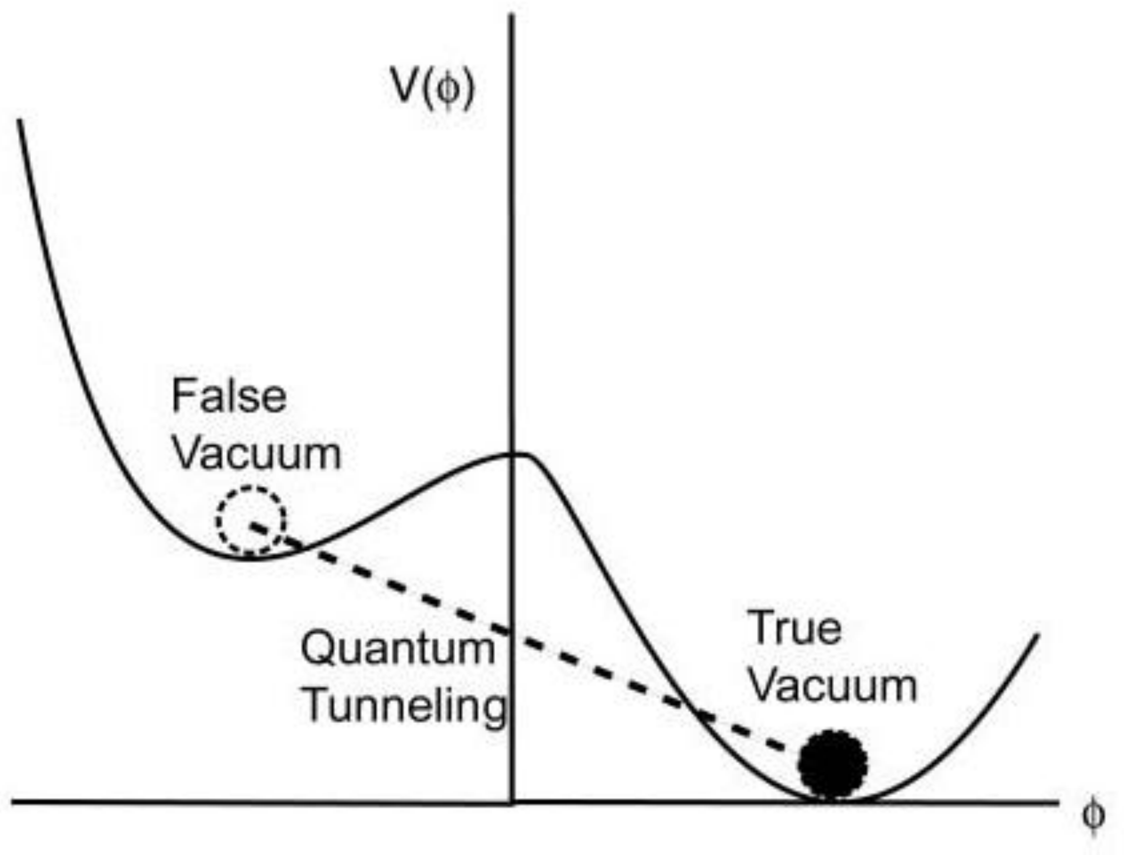
To get the observed flatness, $|\Omega_k| < 0.005$, requires that Inflation persists for > 60 e-foldings.
Why does it ever stop?

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?

The graceful exit problem was solved by slow-roll Inflation (Albrecht & Steinhardt 1982)



old inflation

$$V_T(\varphi) = (2A - B)\sigma^2\varphi^2 - A\varphi^4 + B\varphi^4 \ln(\varphi^2/\sigma^2) + 18(T^4/\pi^2)\int_0^\infty dx\, x^2 \ln\{1 - \exp[-(x^2 + 25g^2\varphi^2/8T^2)^{1/2}]\}, \quad (1)$$

where the adjoint Higgs field, Φ, has been reexpressed as $\varphi(1,1,1,-\frac{3}{2},-\frac{3}{2})$ (the fundamental Higgs field will be irrelevant for this discussion); g is the gauge coupling constant; σ is chosen to be 4.5×10^{14} GeV; $B = 5625g^4/1024\pi^2$; and A is a free parameter. Equation (1) includes the one-loop quantum and thermal corrections to the effective potential. For a CW model, the coefficient of the quadratic term, $2A - B$, is set equal to zero and the Higgs mass is $m_{CW} = 2.7\times 10^{14}$ GeV. We will also present results for non-CW models in which $2A - B$ is small and therefore the Higgs mass, m_H, is such that $\Delta_H \equiv (m_H^2 - m_{CW}^2)/m_{CW}^2$ is small.

As for more general GUT models, the process of the first-order phase transition from the SU(5) *symmetric* phase to the SU(3)⊗SU(2)⊗U(1) *symmetry-breaking* phase for the CW model can be understood by studying the shape of the effective potential as a function of the scalar field for various values of the temperature, as shown in Fig. 1. For temperatures above the critical temperature (T_{GUT}) for the transition, the symmetric phase ($\varphi = 0$) is the global stable minimum of the effective potential. At $T = T_{GUT}$, the symmetric phase and the symmetry-breaking phase have equal energy densities. As the temperature drops below T_{GUT}, the symmetric phase becomes *metastable*—it has a higher-energy density than *stable* symmetry-breaking phase but a potential barrier prevents it from becoming unstable.

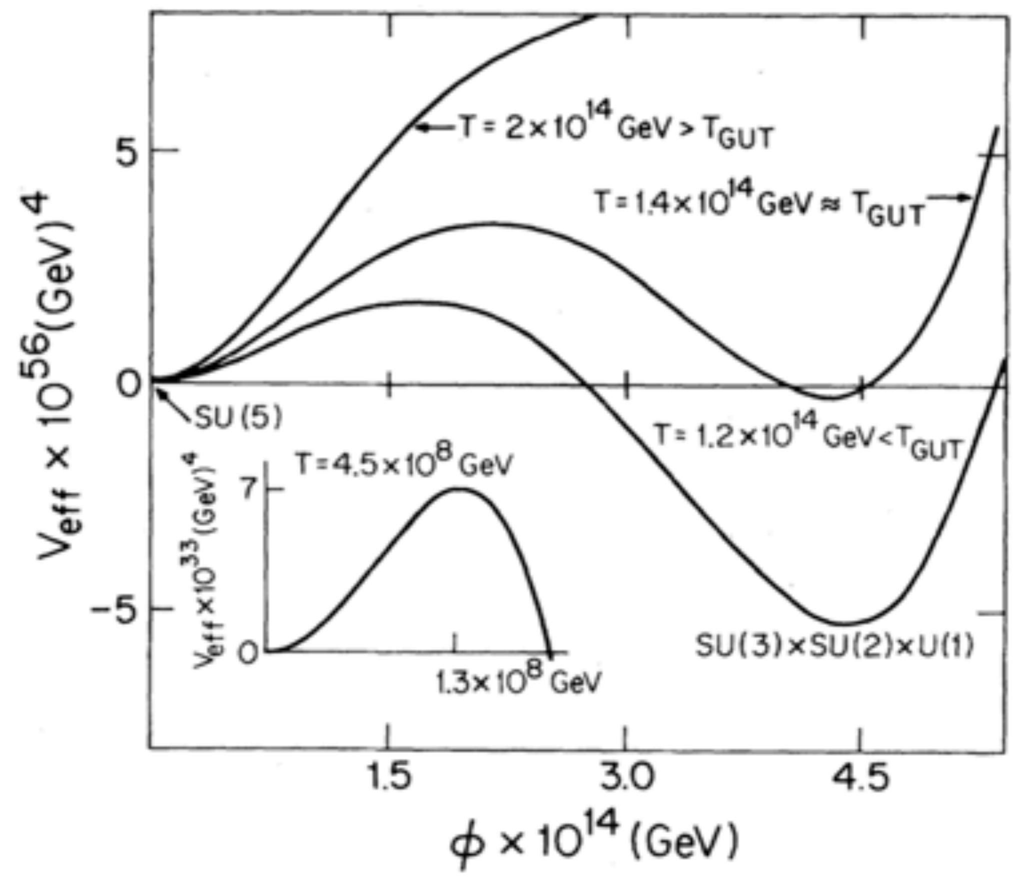


FIG. 1. Effective potential vs φ for various values of T.

new inflation

See Guth & Steinhardt (1984): http://astroweb.case.edu/ssm/USNA287/InflationGuthSteinhardt.html