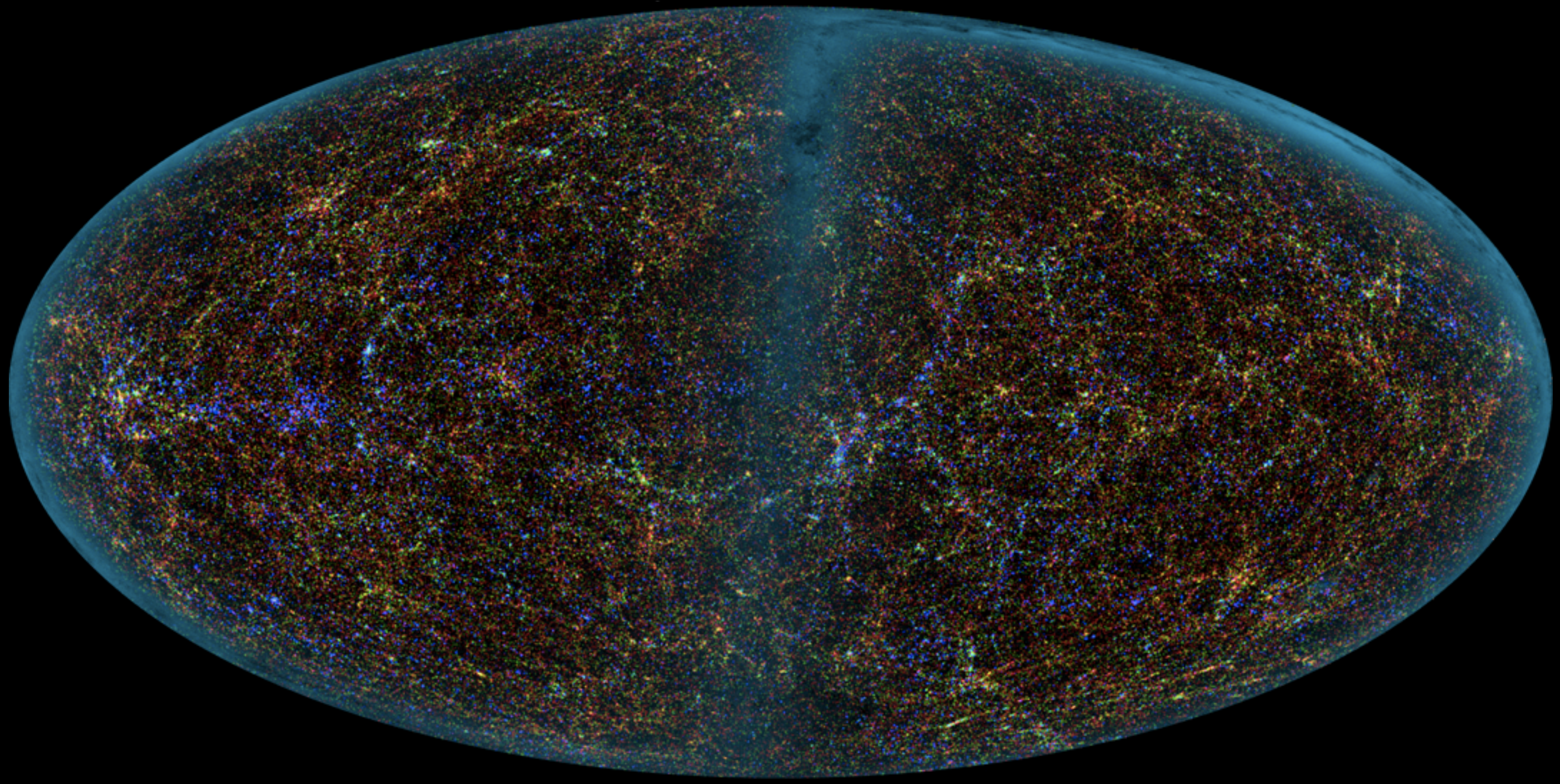
Cosmology

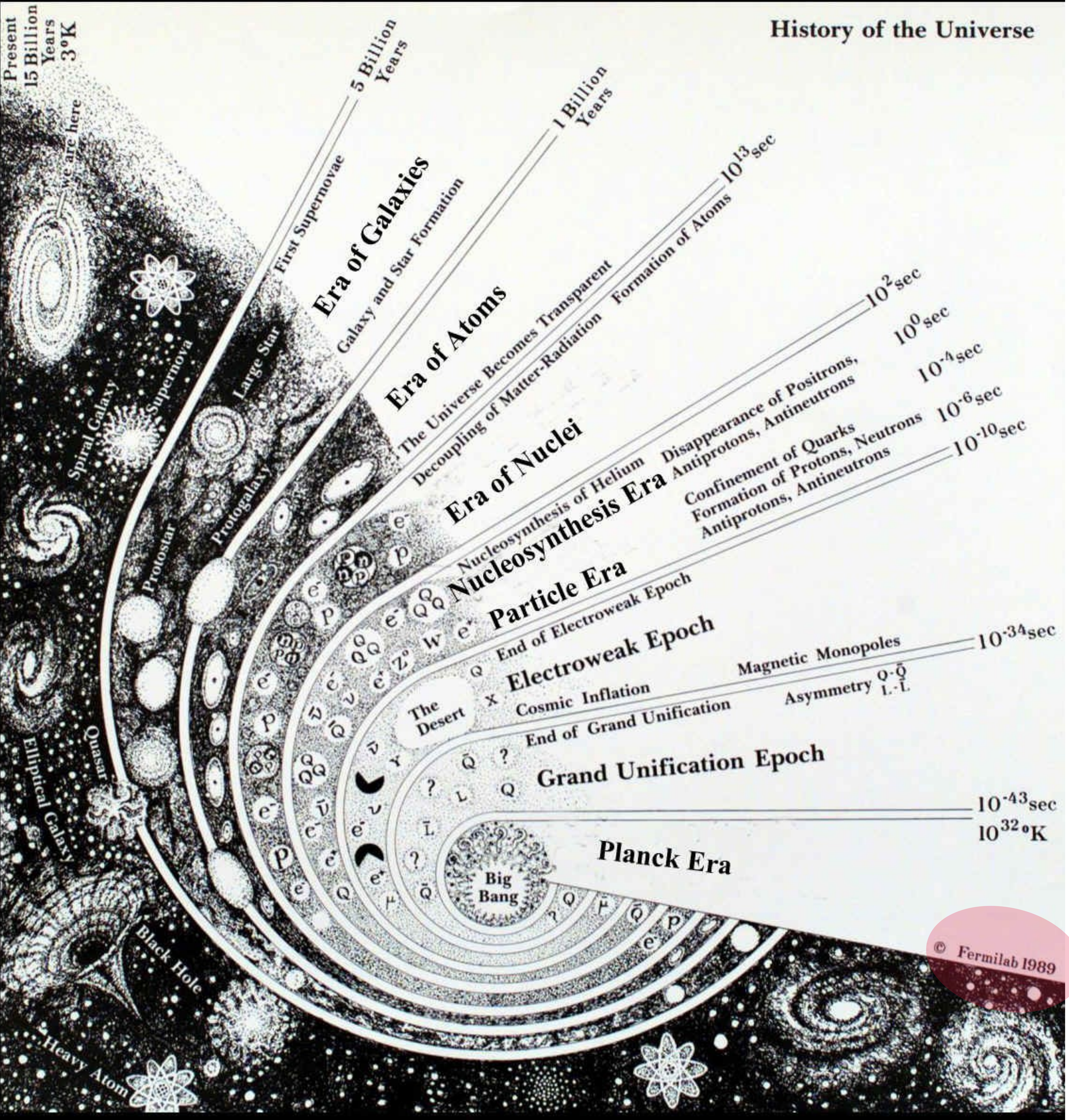
and Large Scale Structure



Today
Dark Ages
Cosmic Dawn

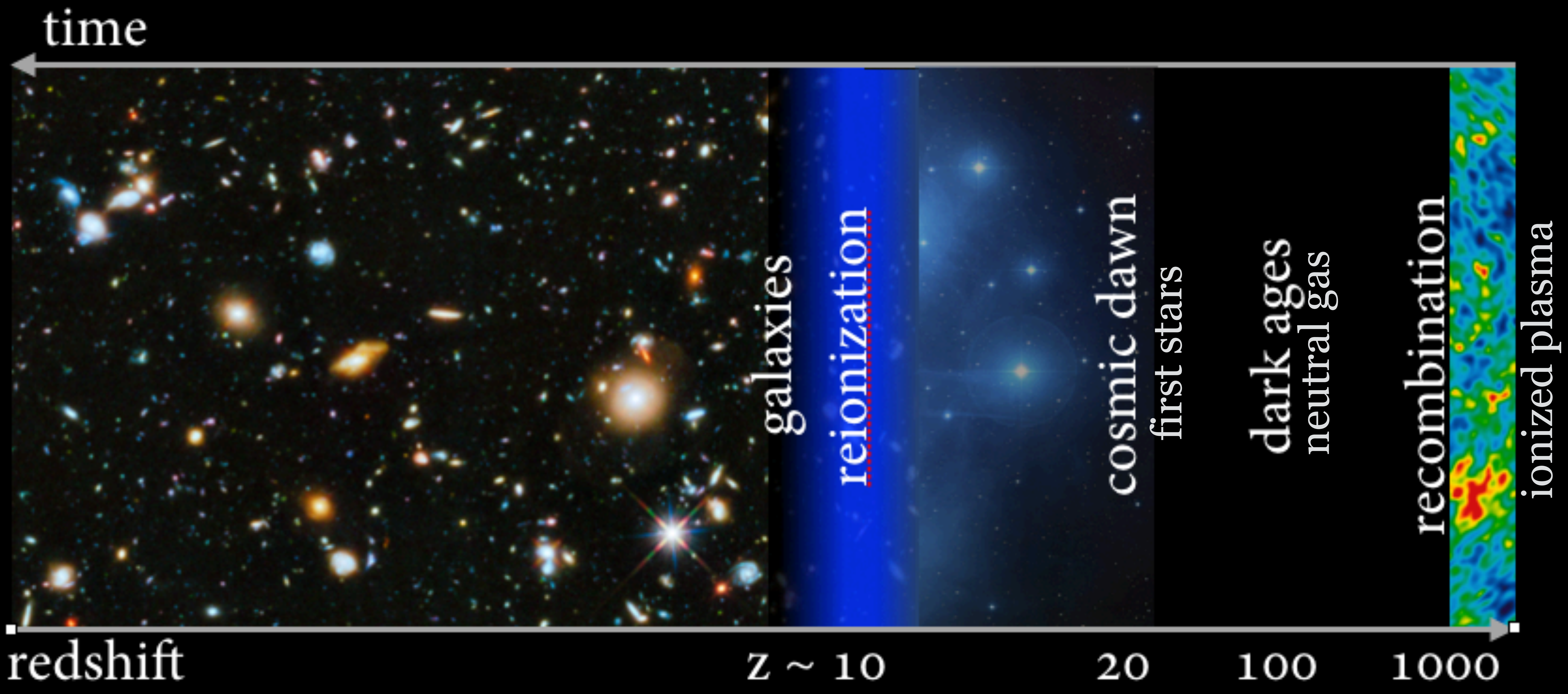
Bonus slides

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

Next frontier: 21 cm absorption at high redshift



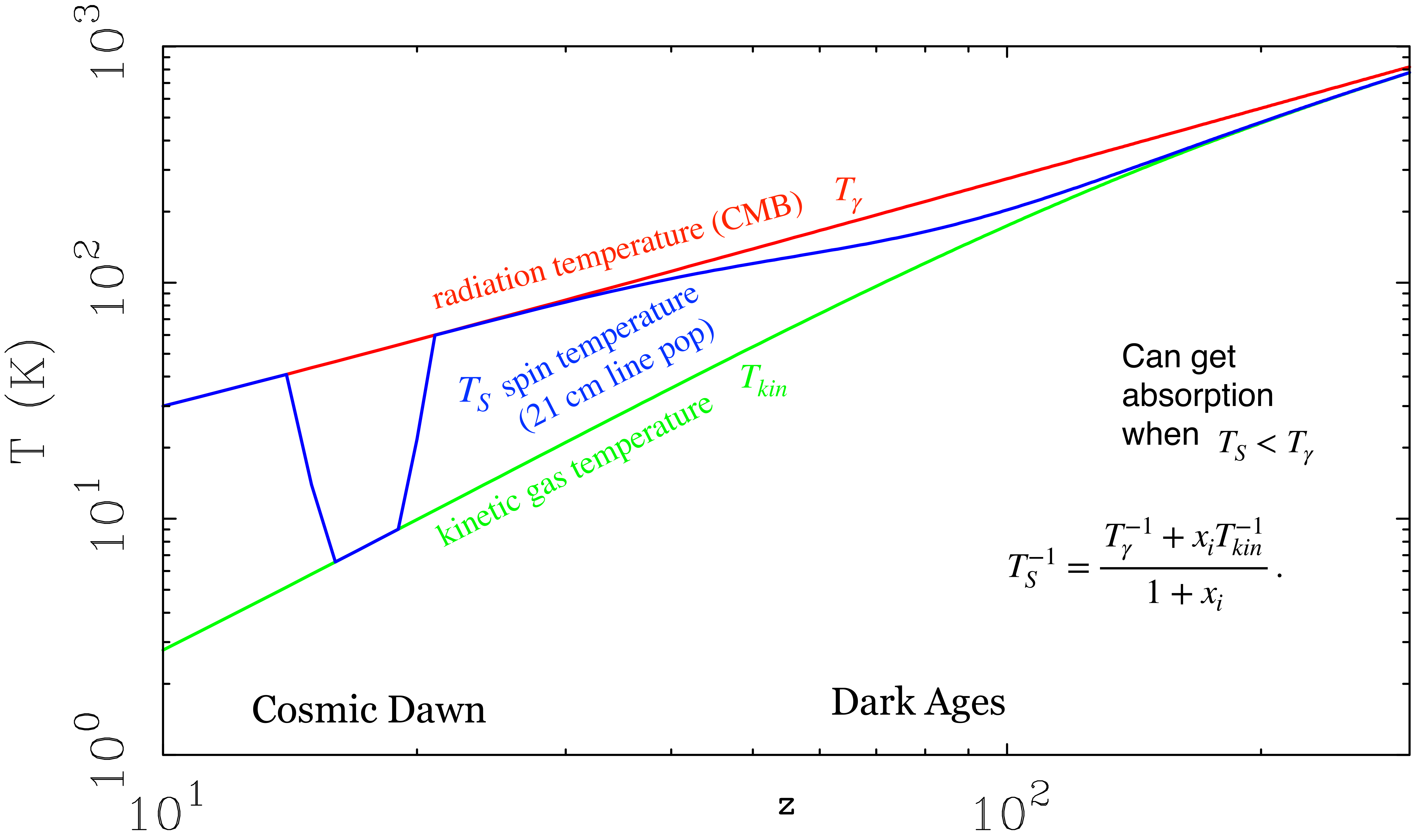
Radio wavelength photons traveling to us from the epoch of recombination can be absorbed by neutral gas during the dark ages and at cosmic dawn

Three Temperatures:

T_γ radiation temperature (CMB)

T_{kin} gas kinetic temperature (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

Different coupling mechanisms are relevant at different times.

$T_0 = 20$ mK

$\omega_b = \Omega_b h^2$

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

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 $T_S < T_\gamma$

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

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

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

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

Expansion history specifies path-length photons must traverse.

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

Emission and absorption of the atomic hydrogen 21 cm line in intergalactic space as a function of redshift/time/frequency

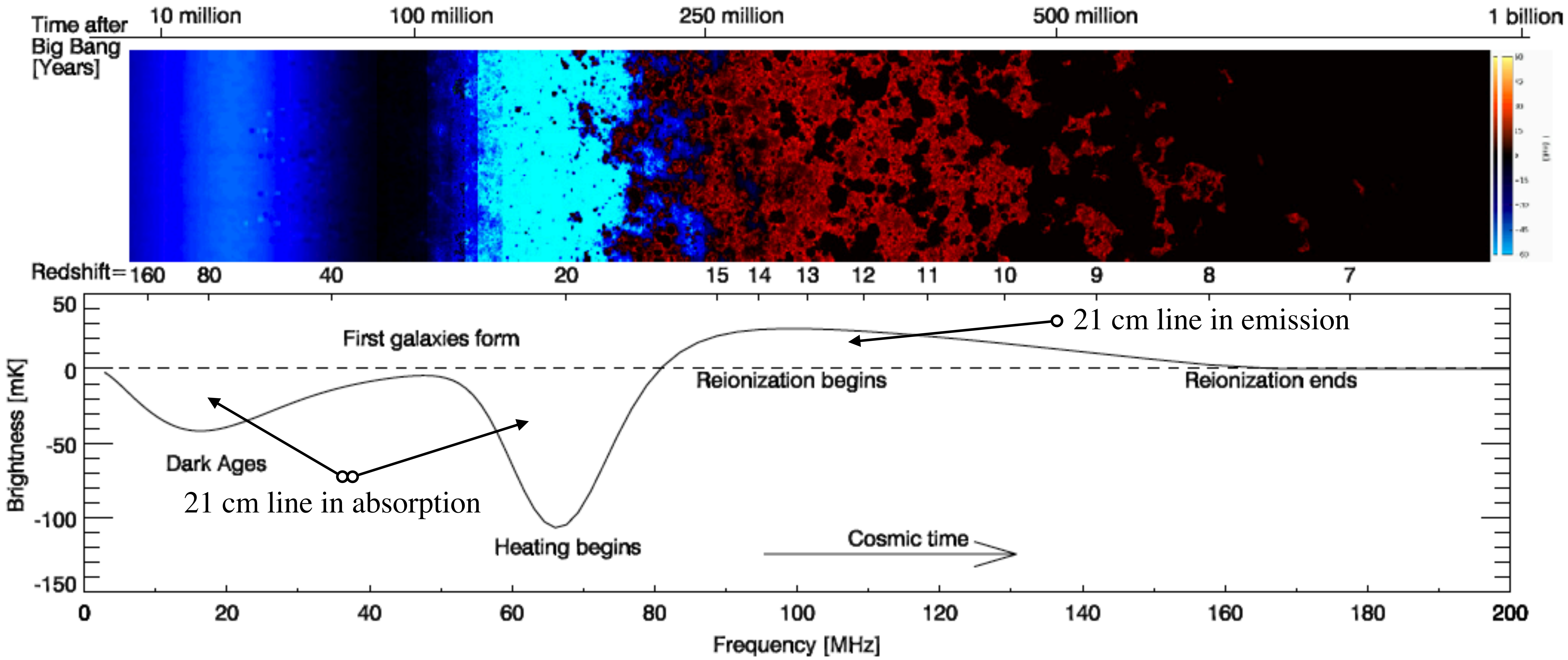


Figure 1. The 21 cm cosmic hydrogen signal. (*a*) Time evolution of fluctuations in the 21 cm brightness from just before the first stars formed through to the end of the reionization epoch. This evolution is pieced together from redshift slices through a simulated cosmic volume [1]. Coloration indicates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

<u>Coupling mechanism</u>

x_i {
- Dark ages: atomic collisions $z \approx 100$ — Hydrogen atoms knock each other around during the dark ages; redistribute 21 cm spin-flip levels
- Cosmic dawn: Lyman α photons (Wouthuysen-Field effect) $z \approx 20$

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

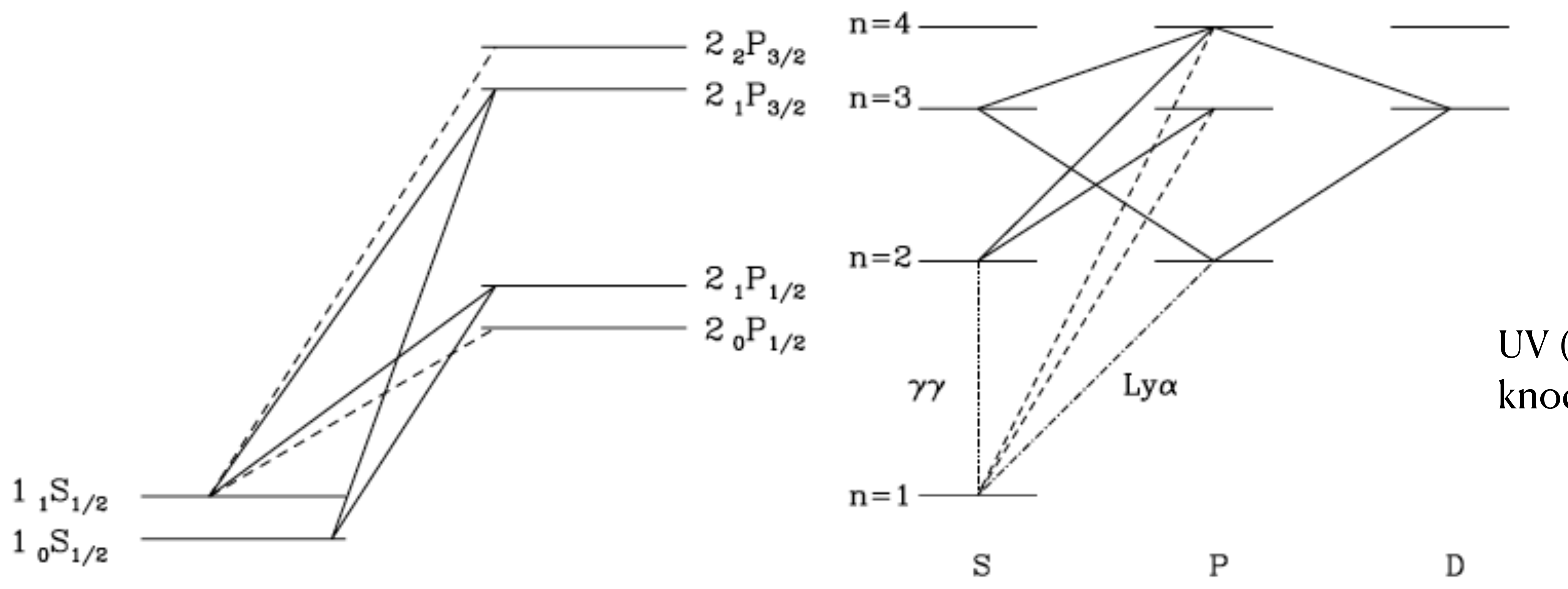


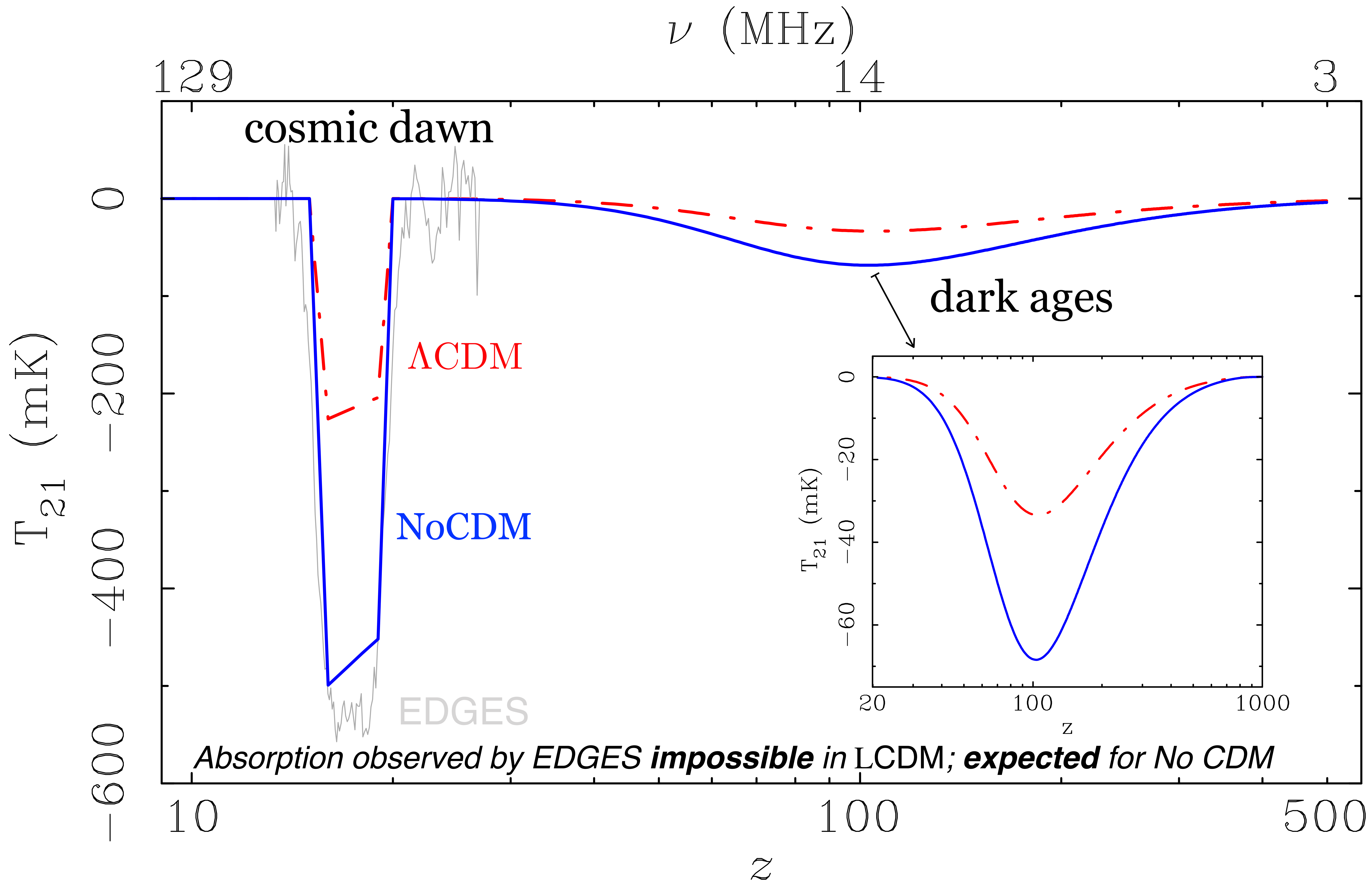
Figure 2. Left panel: hyperfine structure of the hydrogen atom and the transitions relevant for the Wouthuysen–Field effect [25]. Solid line transitions allow spin–flips, while dashed transitions are allowed but do not contribute to spin–flips. Right panel: illustration of how atomic cascades convert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

Wouthuysen-Field effect

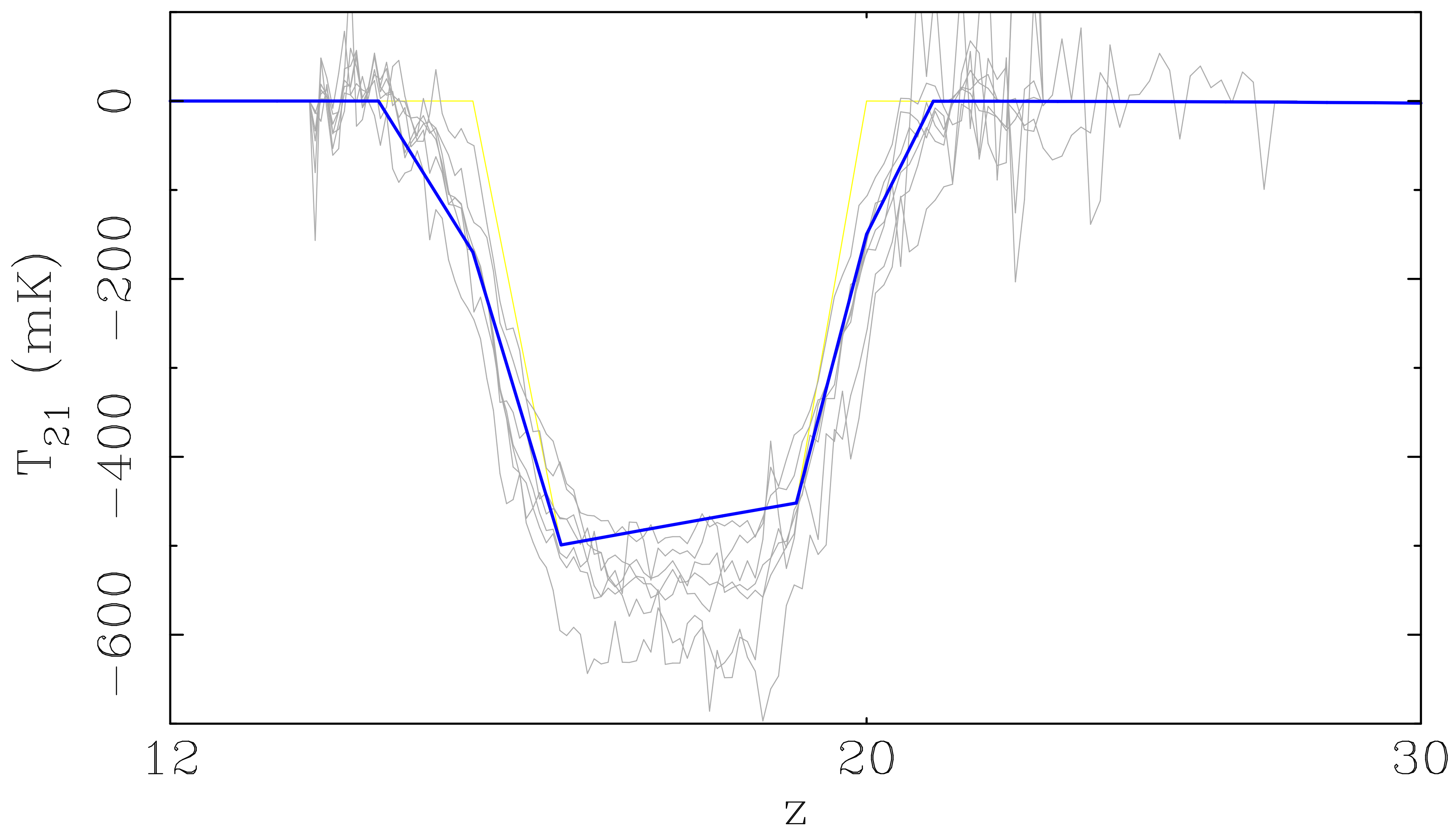
UV (Lyman α) photons from the first stars at cosmic dawn knock hydrogen around; redistribute 21 cm spin-flip levels

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

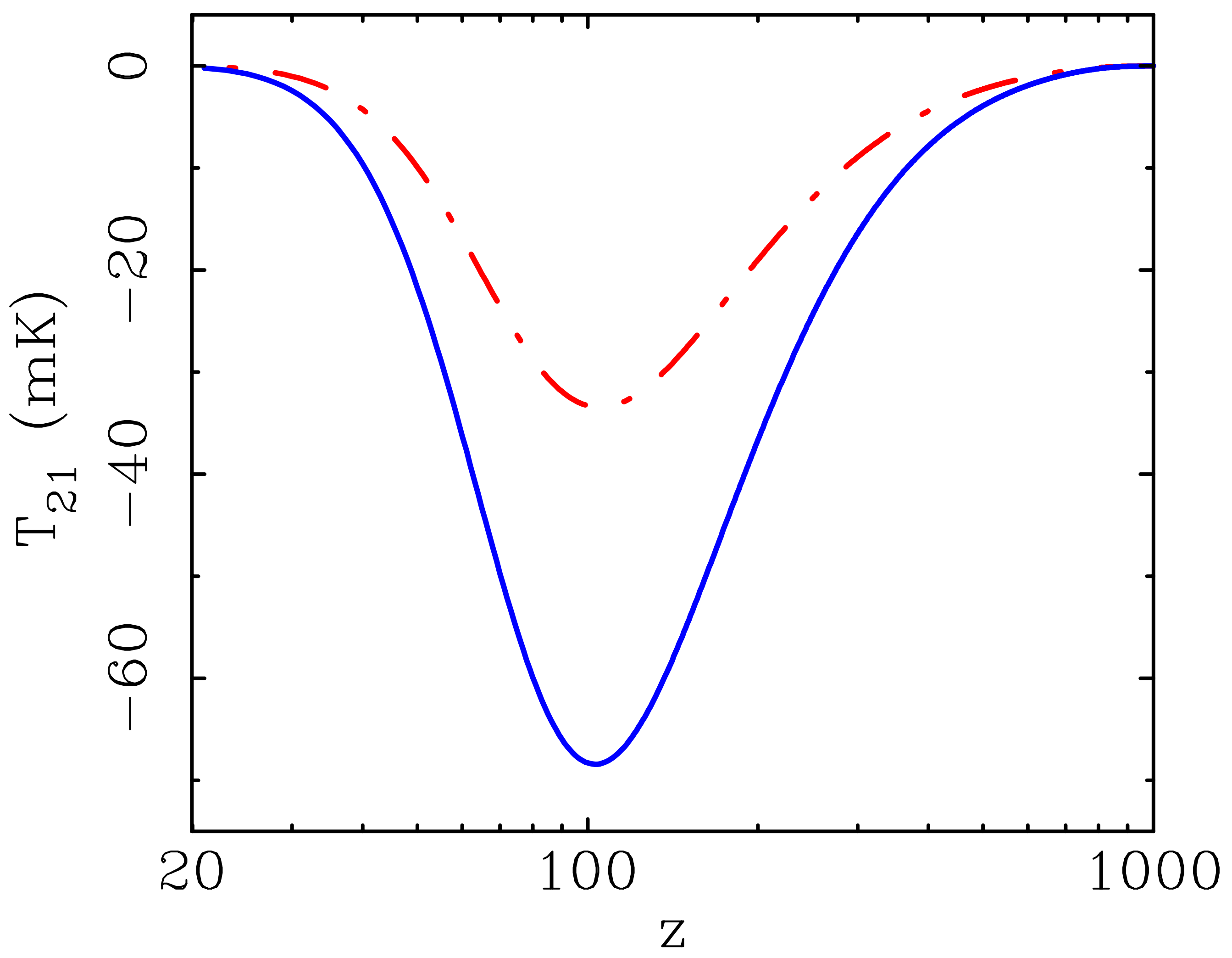
McGaugh, S.S. 2018, PRL, 121, 081305



Cosmic Dawn



Dark Ages



EDGES signal indicates

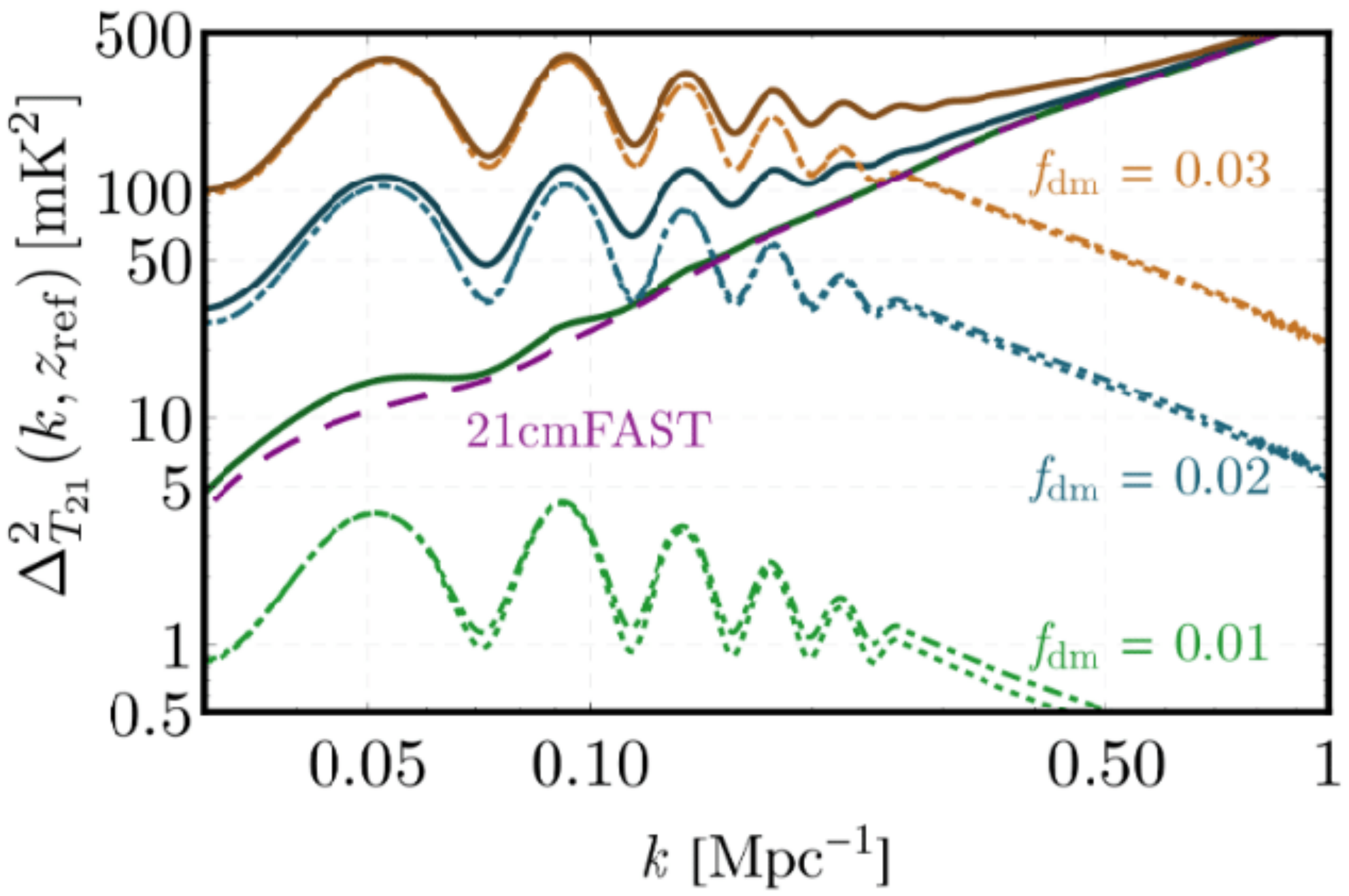
- rapid transition from CMB to gas T
  - Full off at z=21 to full on at z=19
  - Full on at z=16 to full off at z=14
  - anticipated by Sanders (1998); McGaugh (2004)
- maximum absorption too great for ΛCDM
- natural without CDM

(~50 Myr)

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

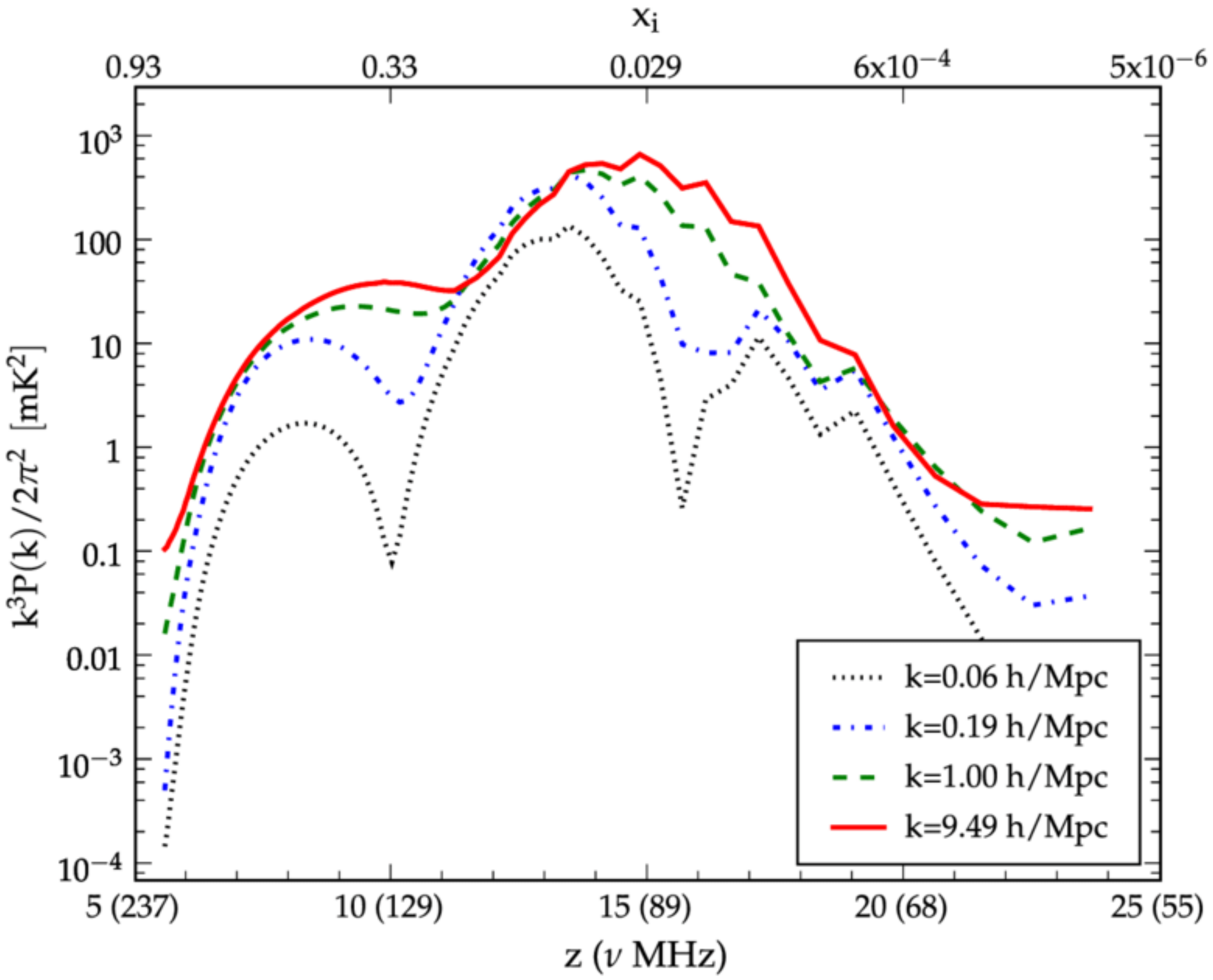
Can only be observed from space - frequency below 30 MHz <u>ionospheric cutoff</u>

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]



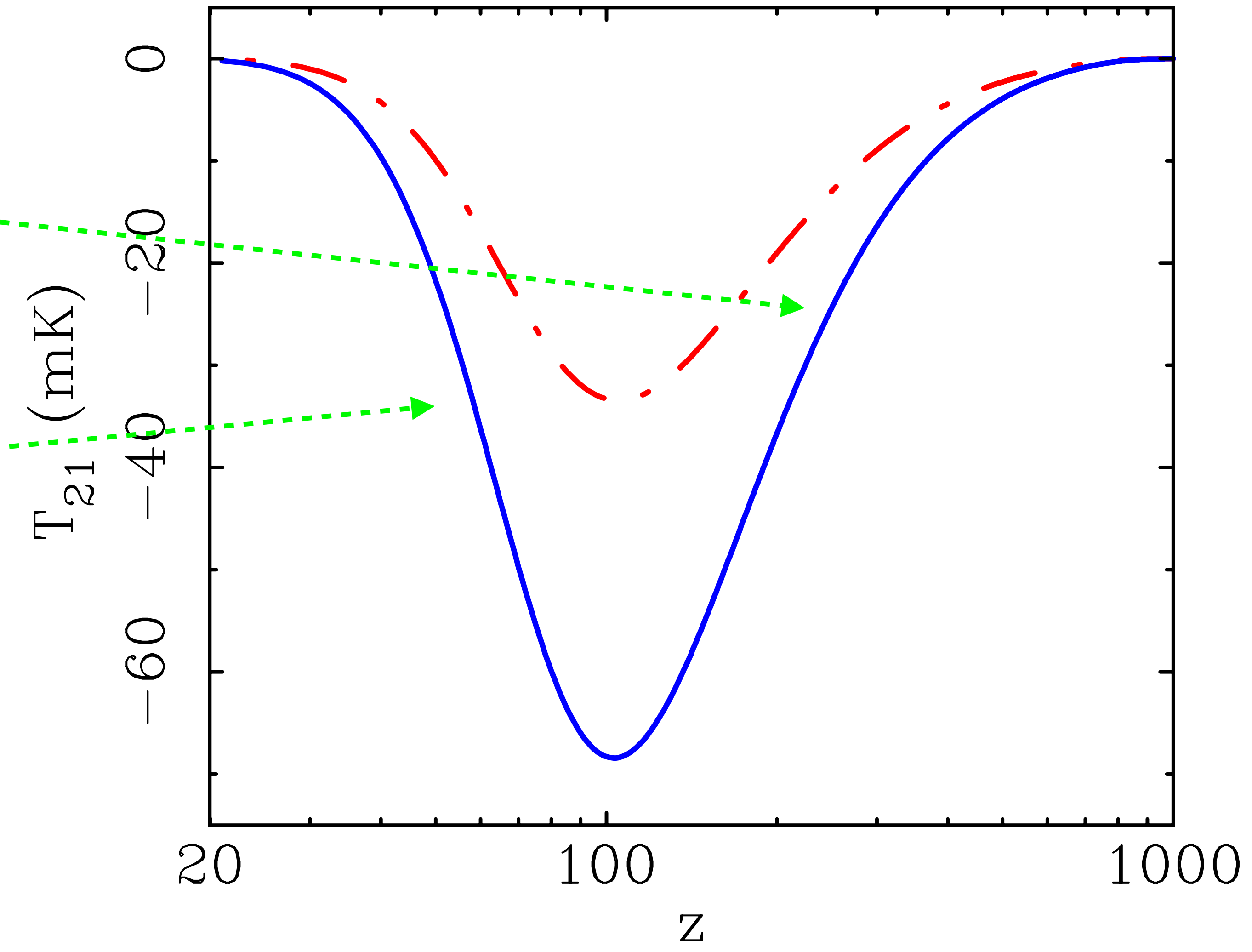
Evolution of four different k-modes of the spherically averaged 21cm power spectra (k 3 P(k)/(2π 2) or Δ 2 (k)) with redshift. The lowest k-mode clearly shows the three epochs of Ly-α fluctuations, heating fluctuations and ionization fluctuations. Figure 9 from Santos et al. (2008).

Power as a function of redshift (frequency)

Prediction for 21 cm power spectrum

- No CDM: Less power than LCDM at z ~ 150
  - baryon oscillations strong
- No CDM: 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 <u>ionospheric cutoff</u>