Cosmology: Observing the Epoch of Reionization and Beyond

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"The study of the EoR and Dark Ages at long (redshifted 21-cm) wavelengths could be a strong science driver for space/moon missions."

- Formation of the first stars, galaxies, BHs/AGN, etc.
- Cosmology (the power spectrum and evolution of DM) + Cosmography
- Fundamental Physics (DM properties, non-Gaussianity from inflation, etc.)

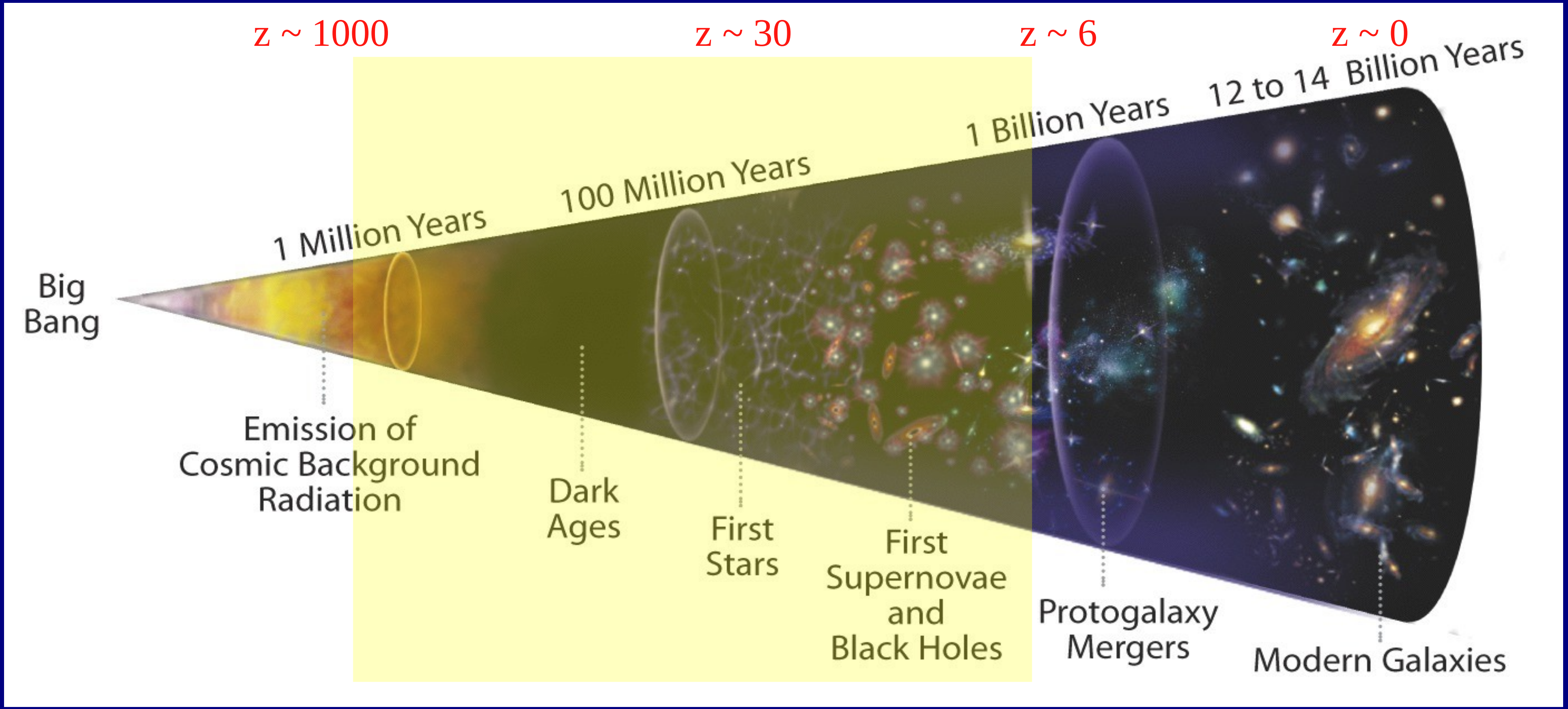
"Such studies are (in principle) much easier from space or on the moon!"

Overview

- Brief history of the Universe.
- Reionization of the Universe.
- Hydrogen as a tracer and ongoing EoR 21-cm detection projects.
- The "Dark Ages" & Cosmology
- Why going into space and to the moon?

A Brief History of the Universe:

The Dark Ages and the Epoch of Reionization



A Brief History of the Universe

The epoch between recombination (z~1100) and the first visible stars/quasars (z~6) is one of the least explored epochs in the history of the Universe!

Dark Ages:

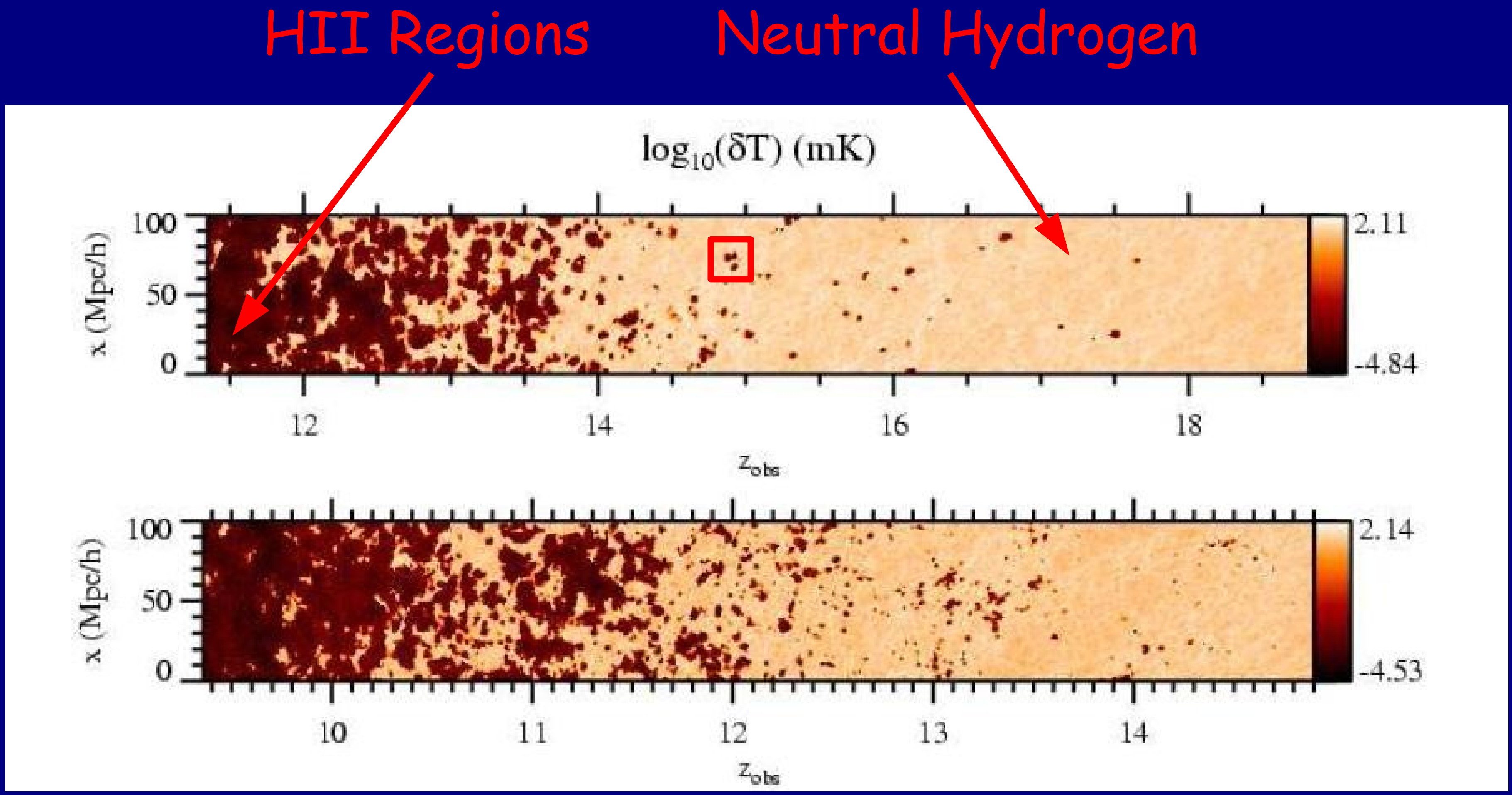
- HI traces dark matter and thus probes cosmology.
  (e.g. power-spectra, DM properties, cosmography, etc).

Reionization:

- The first non-linear objects form and radiate.
  (e.g. stars, galaxies, BHs, AGN, etc.)
- Feedback from these objects changes the IGM.
  (eg. heating/ionizing HI, metals, shocks, etc).
- The Universe reionizes and becomes transparent.
  (first galaxies, stars, etc. become visible)

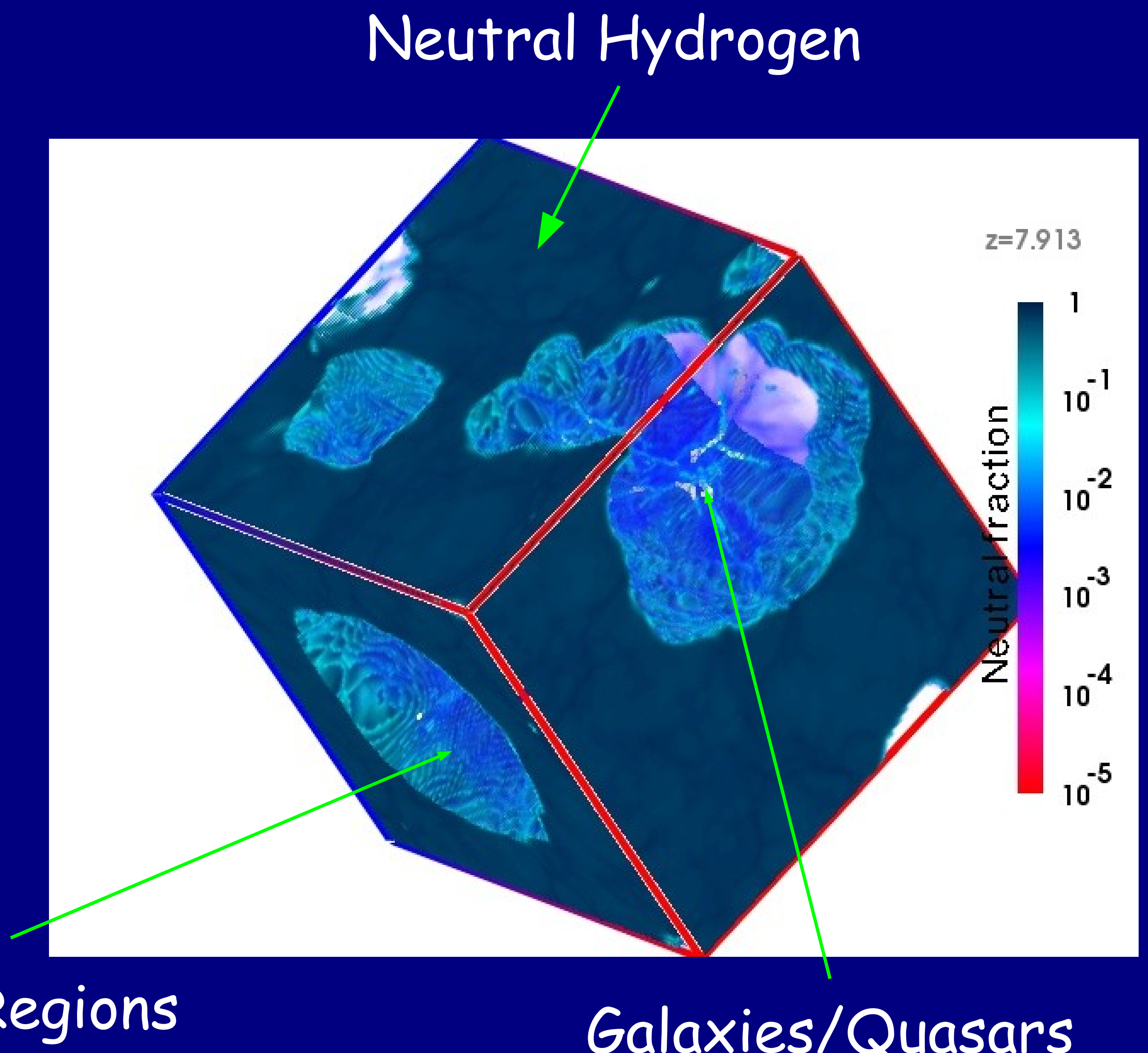
Reionization of the Universe

After the "Dark Ages", the first stars & quasars ionize neutral Hydrogen during the "Epoch of Reionization" and make the Universe transparent.



(Mellema et al. 2006)

Reionization of the Universe

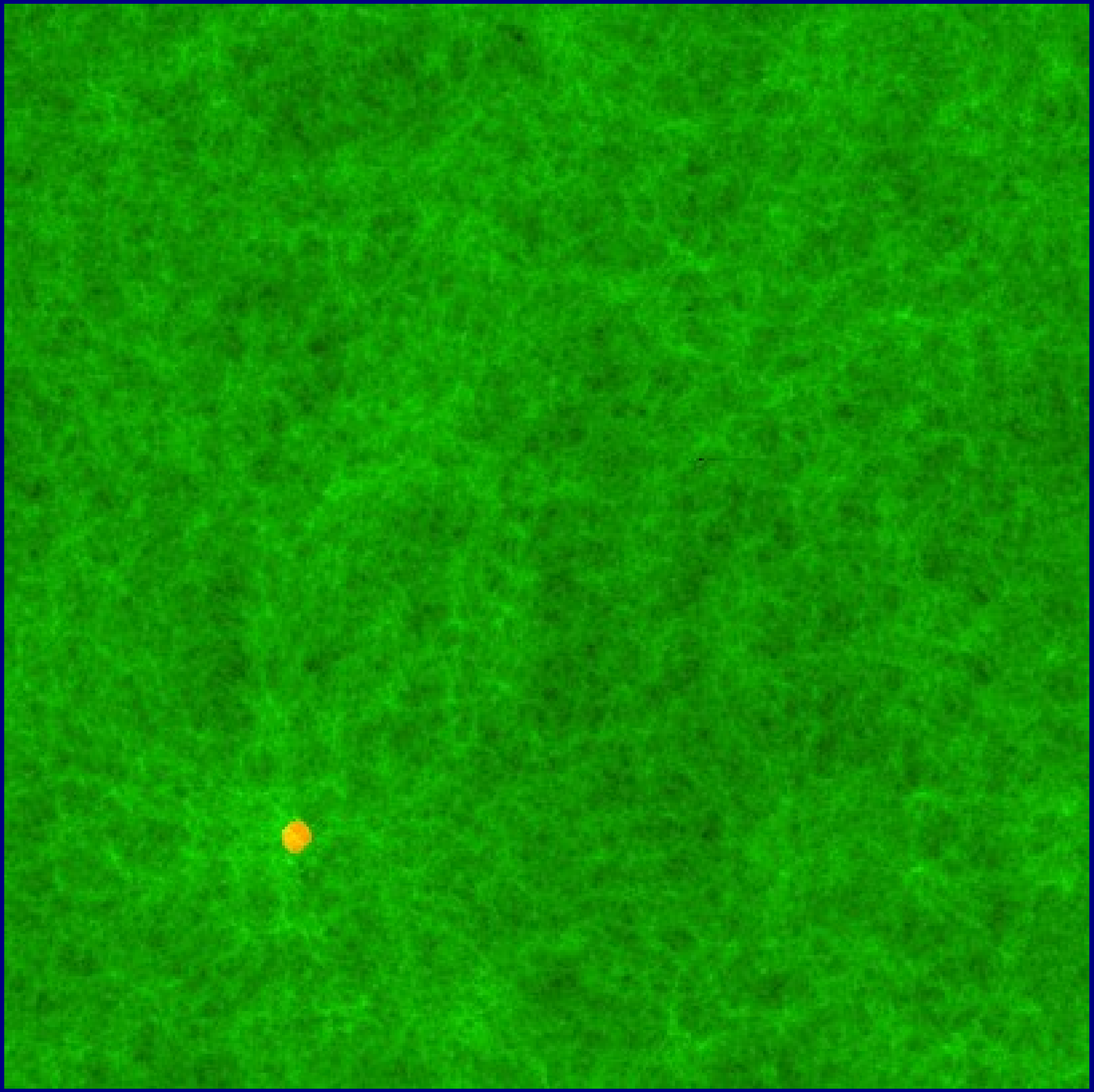


(from Gnedin)

Reionization of the Universe

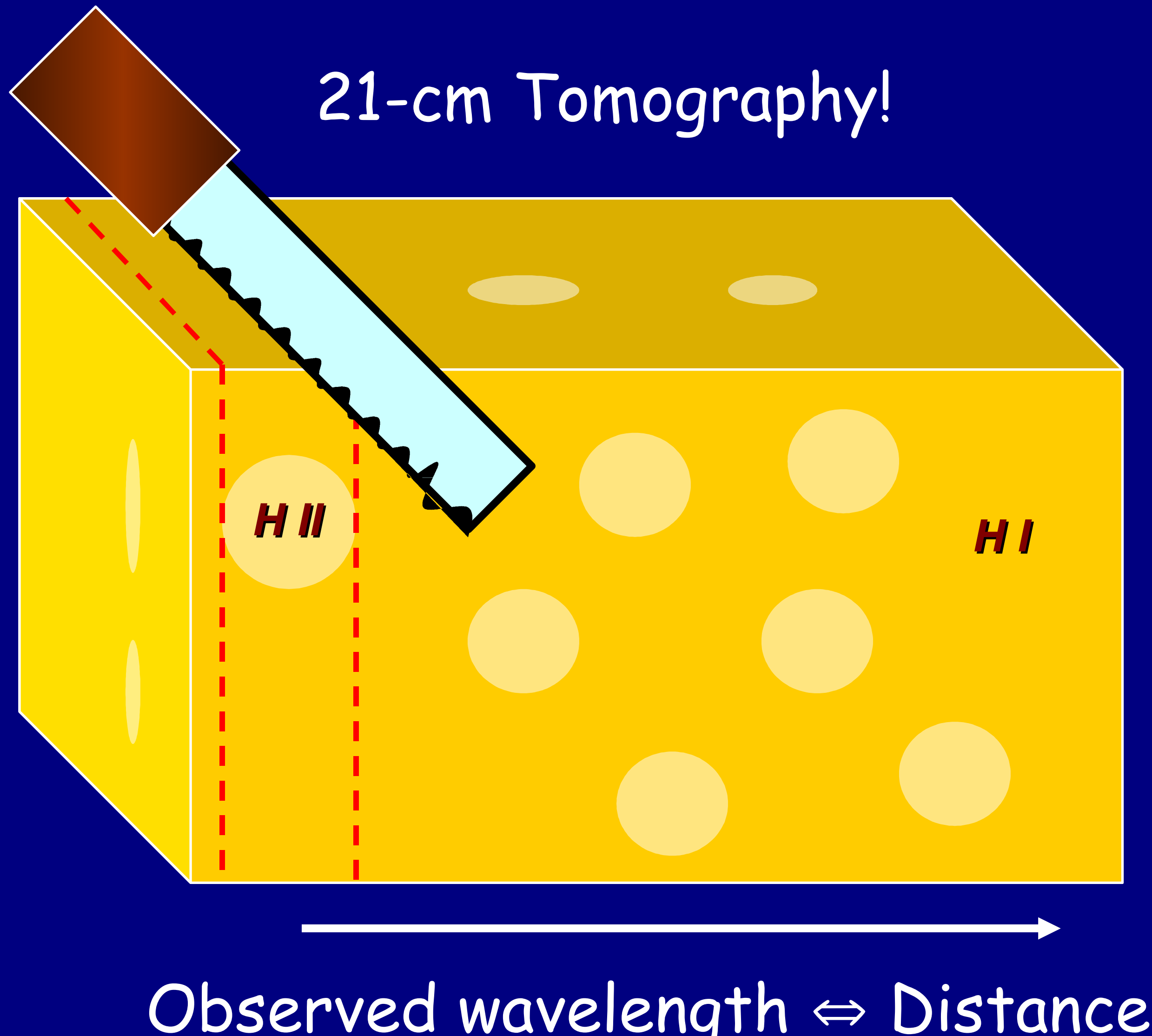
(from Mellema)

- Sources of radiation form in the highest density regions
- Sources ionize the HI in their surrounding
- "Bubbles" overlap, accelerating ionization until reionization is completed



35/h Mpc

Why use Hydrogen as a Probe of the EoR and Dark Ages?



(from Loeb)

The brightness temperature of the 21 cm hyperfine transition

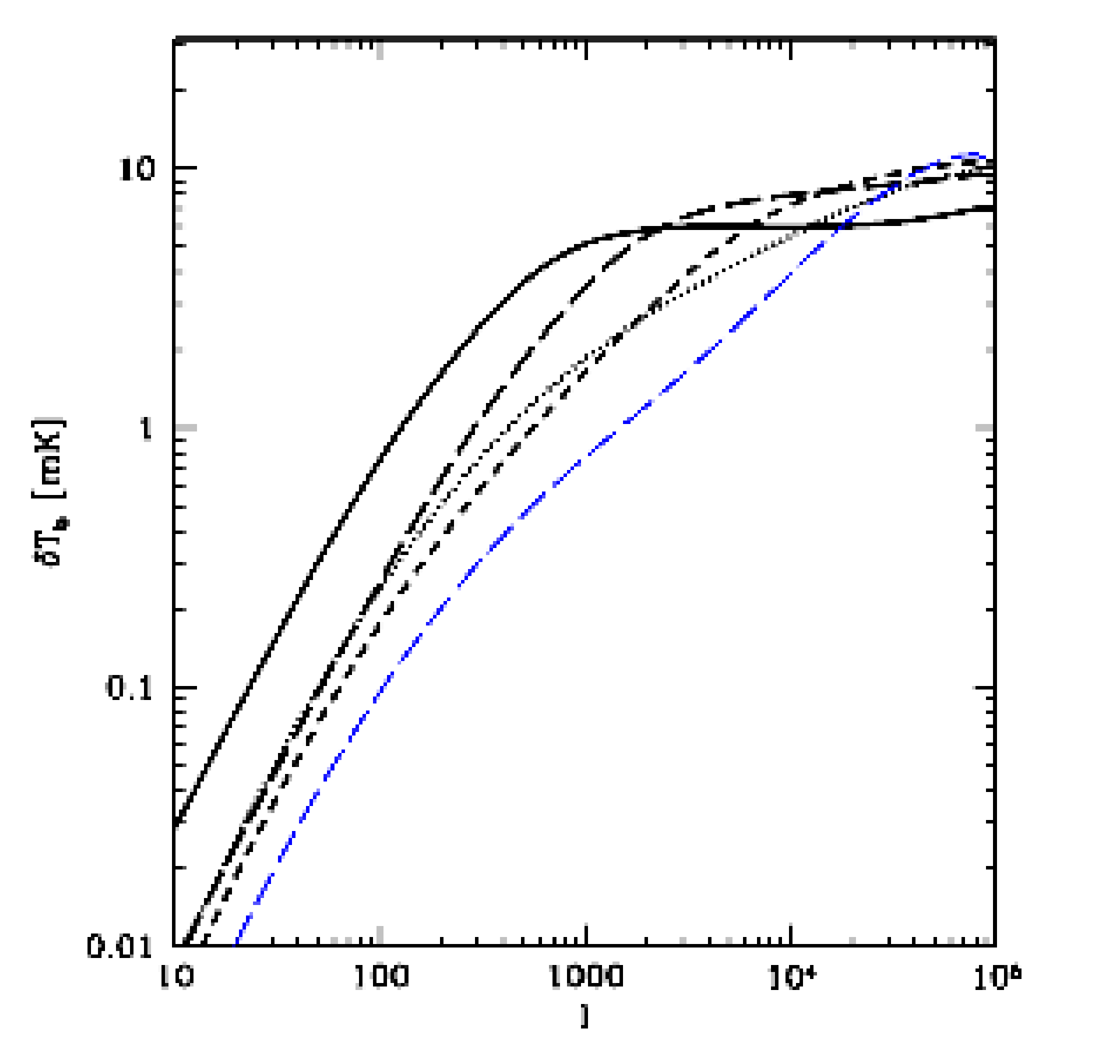
Expected 21-cm signal

$$\delta T(\nu) \approx 16\text{mK}\,(1+\delta)x_{HI}\,\frac{T_s - T_{CMB}}{T_s}\,\frac{\Omega_b h^2}{0.02}\left[\frac{0.15}{\Omega_m h^2}\,\frac{1+z}{10}\right]^{1/2}\left(\frac{0.7}{h}\right)$$

Note that the foregrounds are T~400K at ~2m wavelengths (i.e. z~10)!

21-cm Angular Power Spectrum

Power spectrum evolves and can reveal the nature of the sources and relevant physics



- evolution:
  - dotted: z=18, x_H = 0.96
  - short-dashed: z=15, x_H=0.81
  - long-dashed: z=13, x_H=0.52
  - solid: z=12, x_H=0.26
- feature grows, moves during reionization
- l = 20,000 ~ Θ = 1′
- l = 2,000 ~ Θ = 10′
- blue: HII around sources

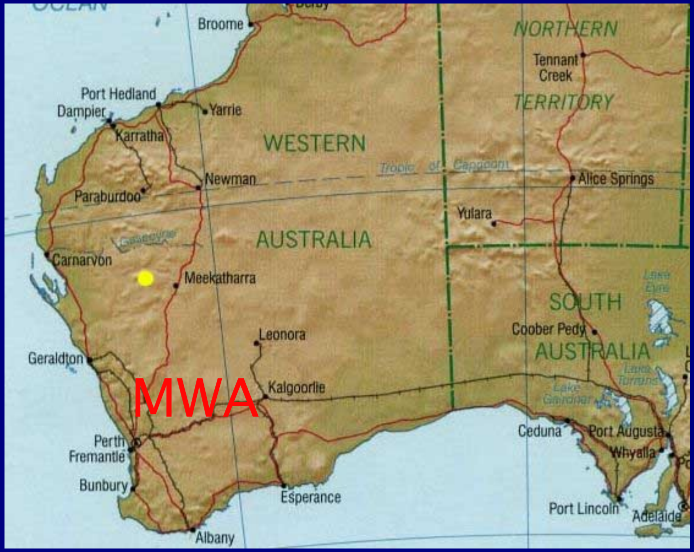
Observing the EoR in Neutral Hydrogen: Ongoing Projects

First generation projects:
LOFAR, 21CMA, MWA

- interferometers
- clustered dipoles
- typical baseline: a few km
- collecting area: $10^{4\text{-}5}$ m^2

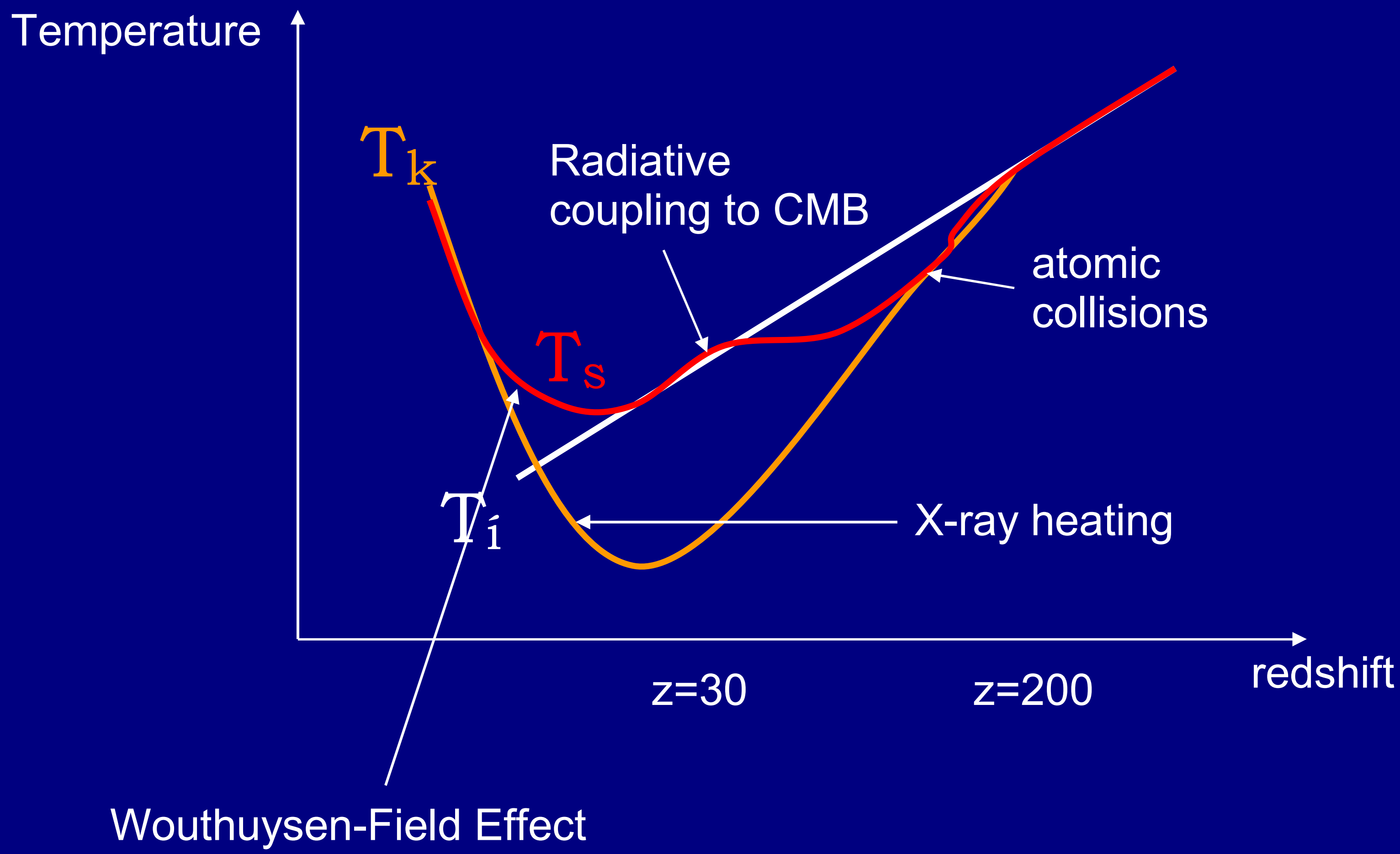
Using existing telescopes:
VLA, GMRT

More to come:
FAST, MWA5000, SKA



What happed before the EoR?
The “Dark Ages”

The Thermal History of Hydrogen



(from Loeb)

The Thermal History of Hydrogen

Thermal Epochs:

Dark Ages:

$z = 200 - 30$: $T_k < T_s < T_{cmb}$ - HI in absorption

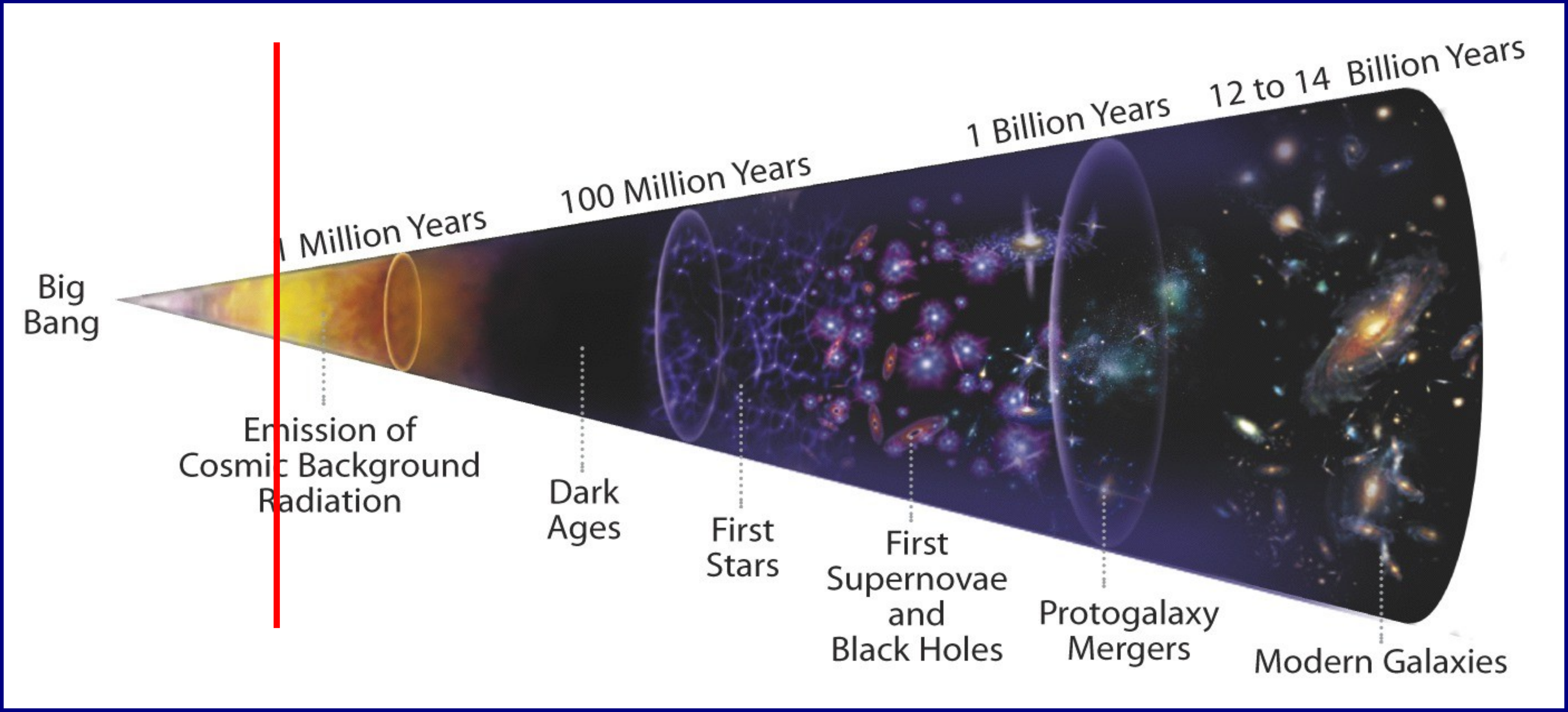
$z = 30 - 20$: $T_k > T_{cmb}$ - HI in emission

Epoch of Reionization:

$z = 20 - 6$: $T_k > T_{cmb}$ - HI reionizes

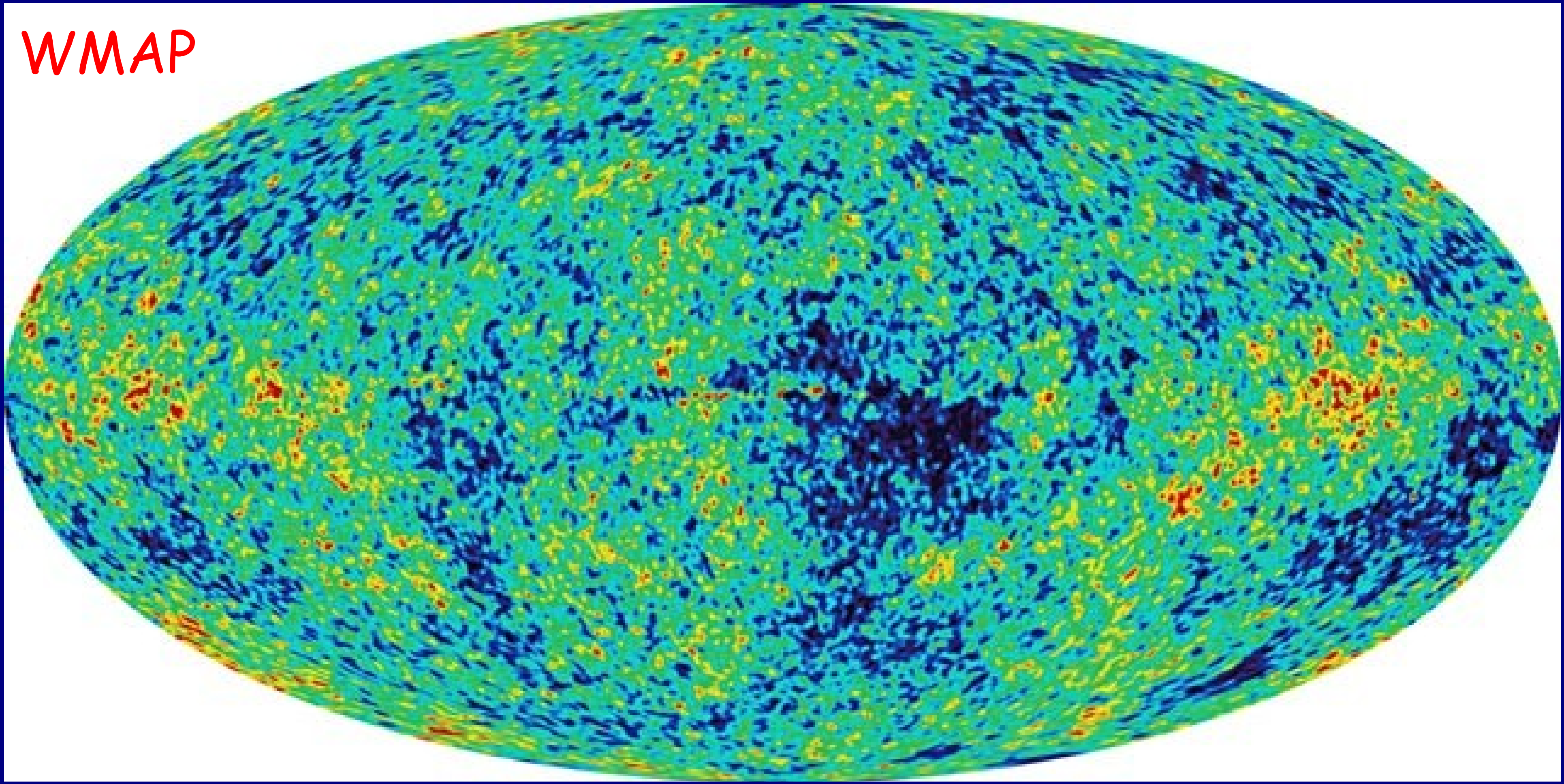
Why study the "Dark Ages"?

CMB is a single snapshot.

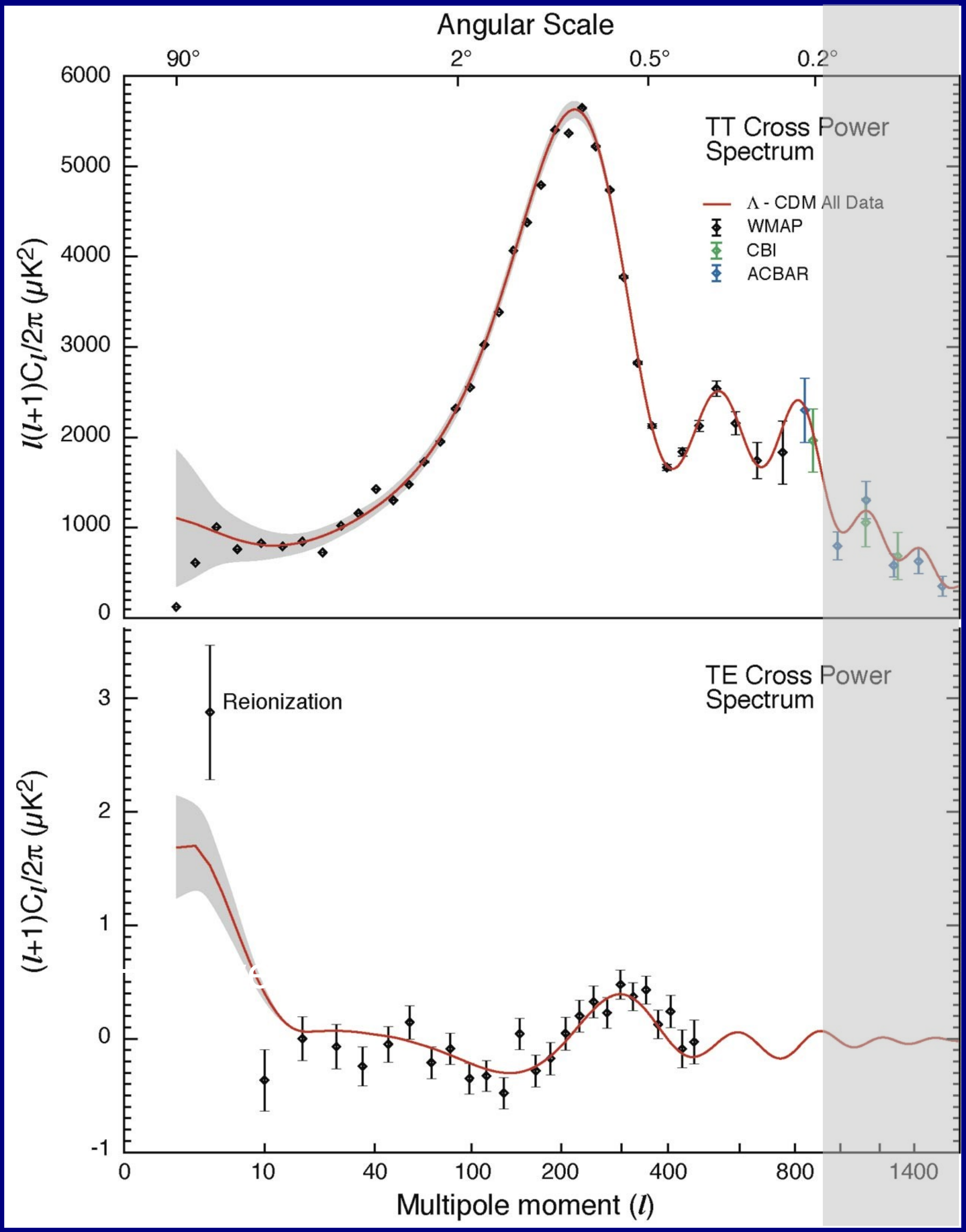


Why study the "Dark Ages"?

CMB is a single snapshot of the Universe at z~1100

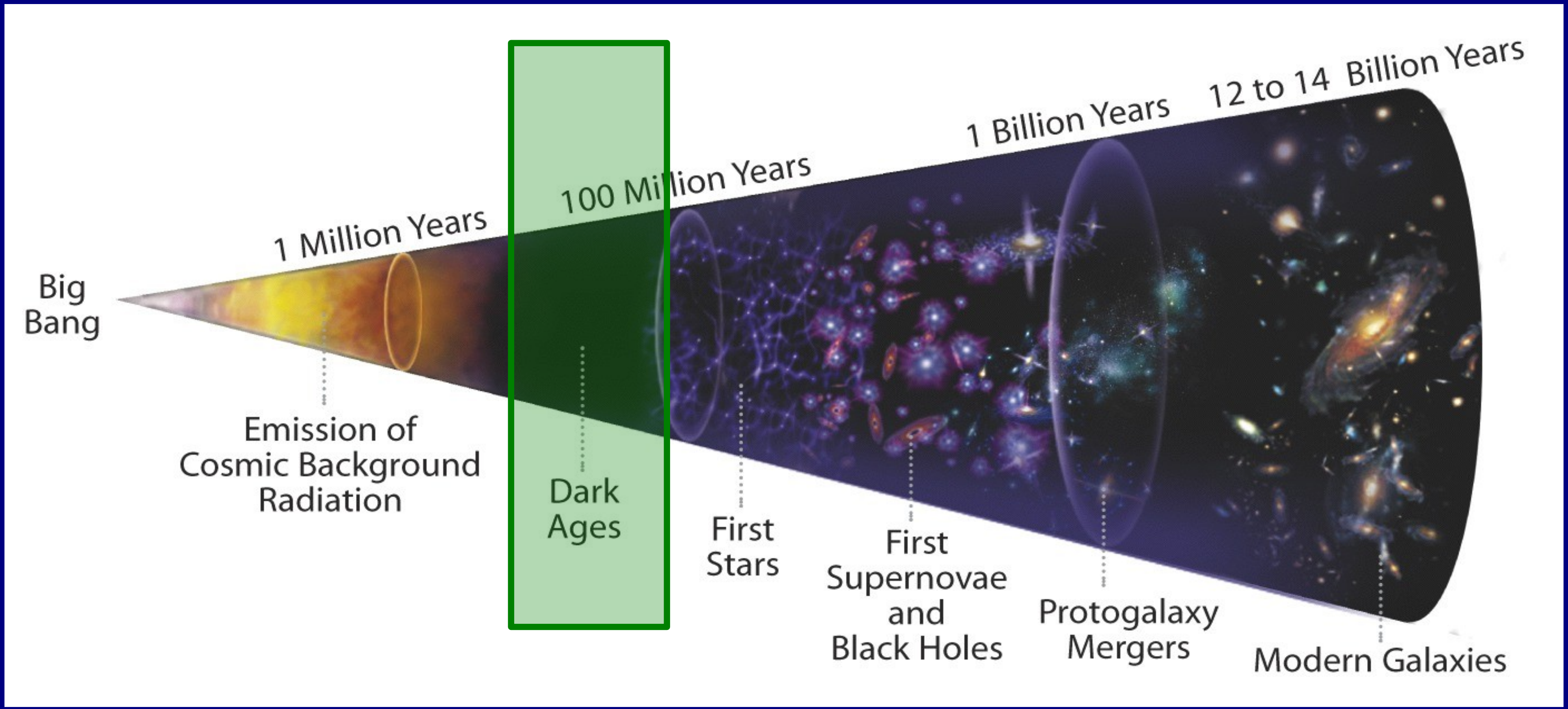


WMAP Power Spectrum



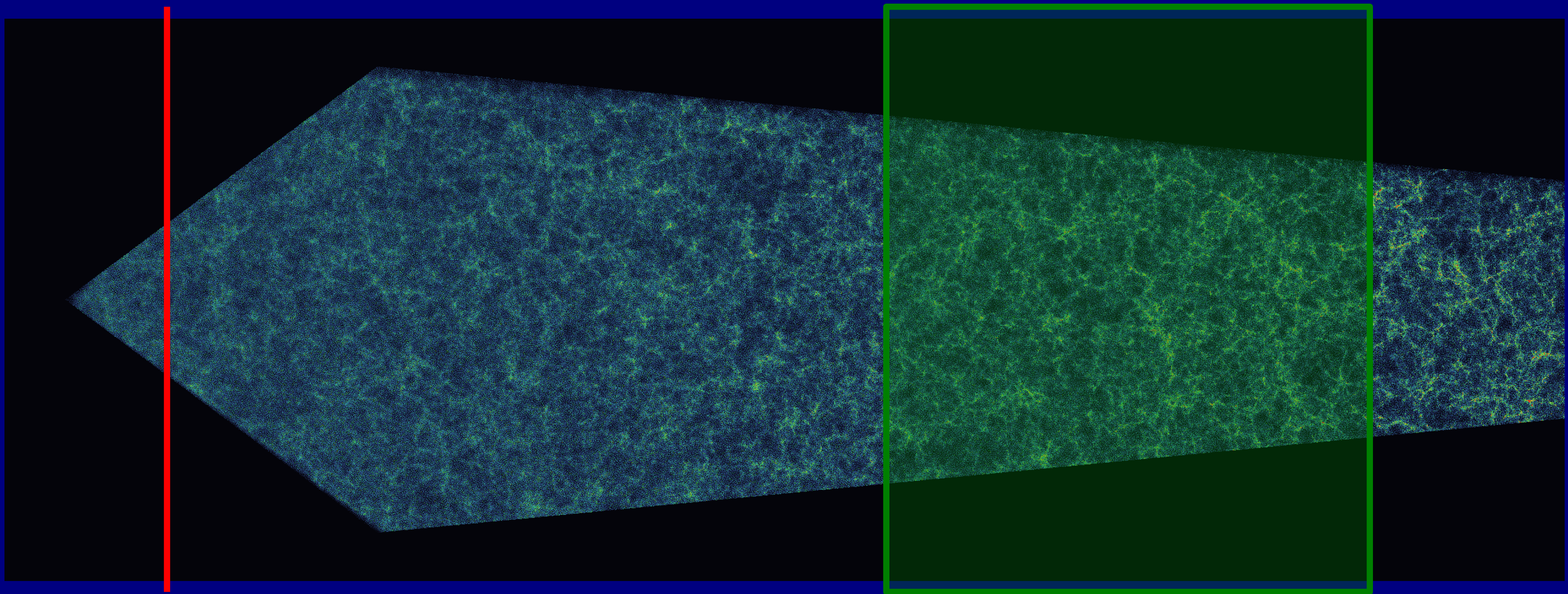
- Spectacular agreement with "vanilla" ΛCDM cosmological model.
- Cross-correlation of polarisation with scalar amplitudes of power spectrum gives optical depth of reionization
- However, power-spectrum cuts exp. off a l>1000 (Silk damping). Hence small-scale power can not be studied!

Why study the "Dark Ages"?



The DM power-spectrum can be traced!

Why study the "Dark Ages"?

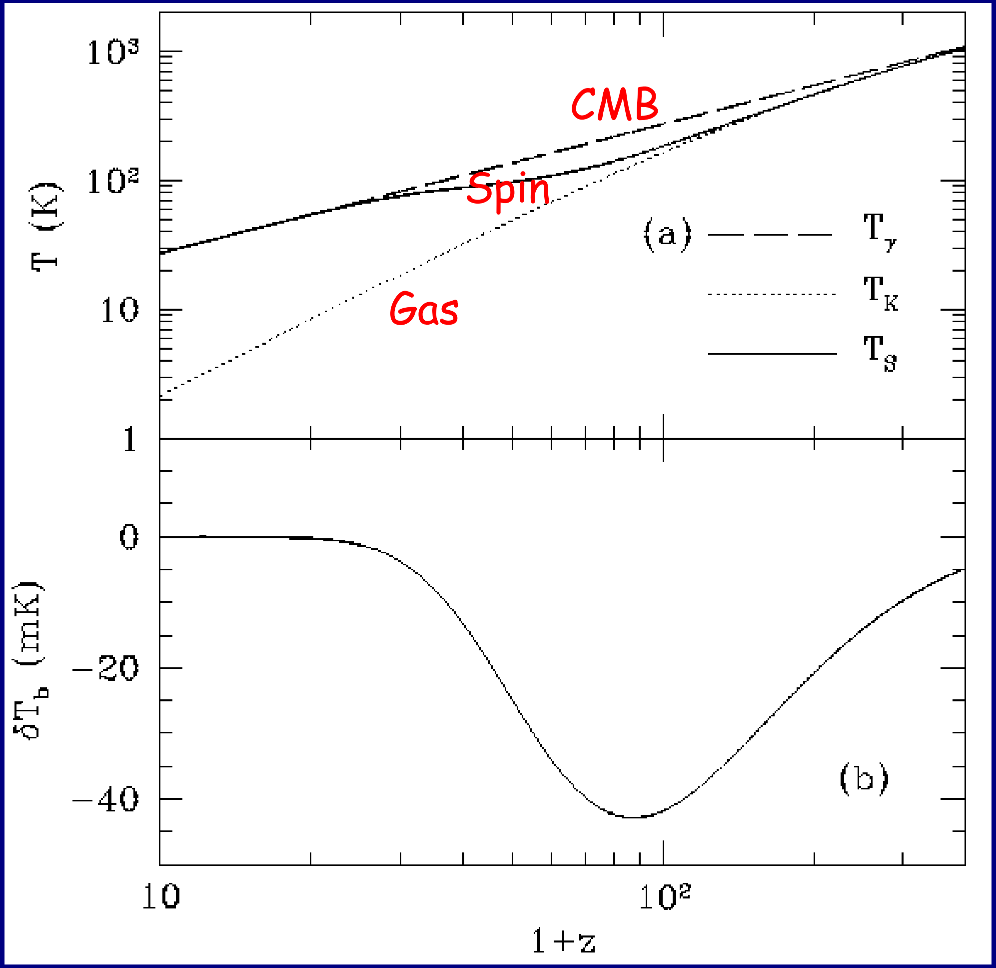


Single Snapshot

Evolution of the power-spectrum can be probed through redshifted 21-cm

Why study the "Dark Ages"?

In the dark ages hydrogen is still neutral

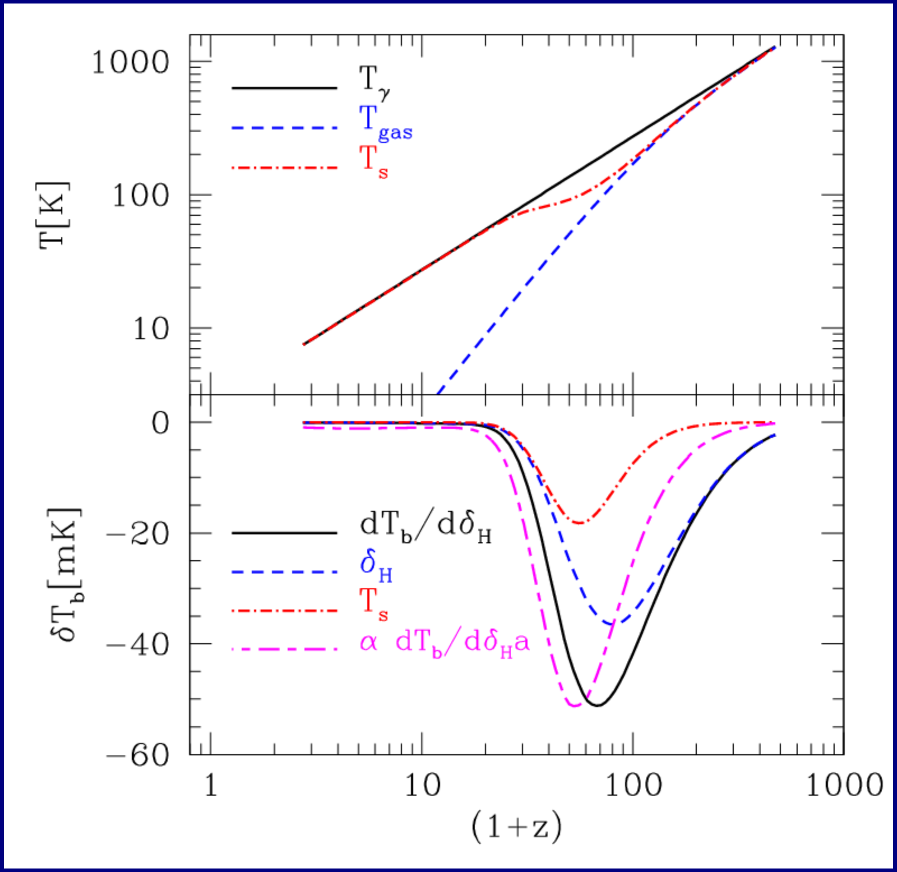


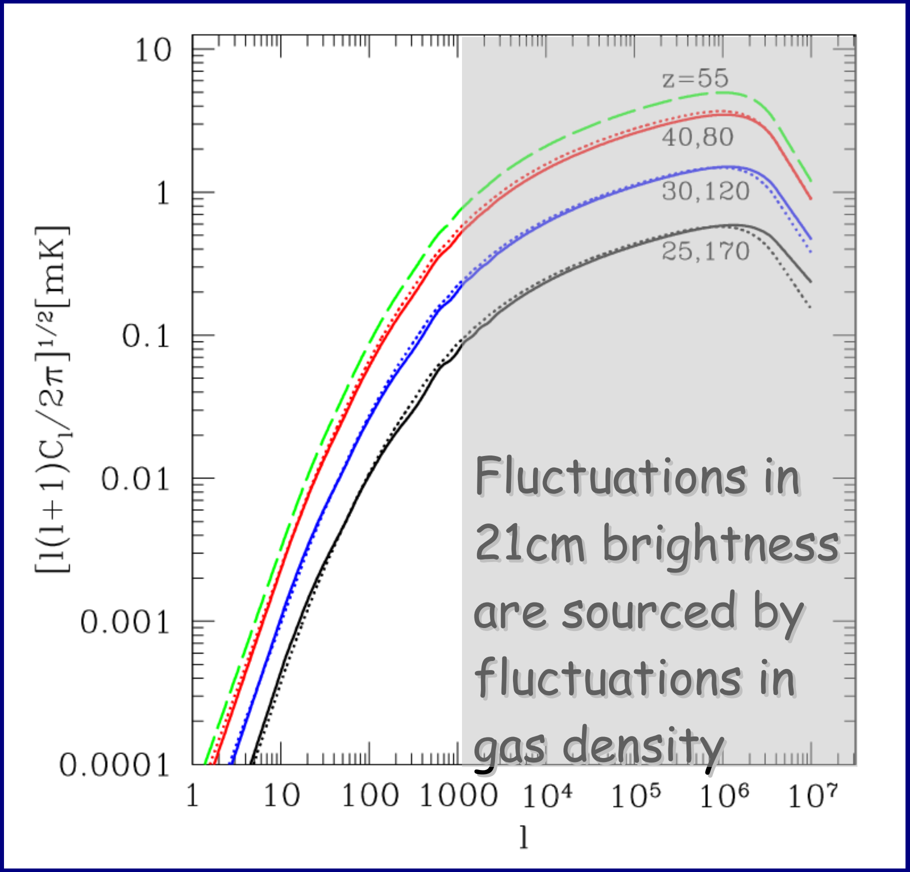
Furlanetto et al. (2006)

- "Simple" physics in the linear regime
- Fluctuations directly trace matter power spectrum (Loeb & Zaldarriaga 2004)
  - 3D dataset
  - Small-scale power

Why study the “Dark Ages”?

Small scale power and evolution can be probed!





(Loeb & Zaldarriaga, Phys. Rev. Lett., 2004; Scott & Rees, MNRAS, 1990)

Why study the “Dark Ages”?

In summary:

- The DM+Baryonic physics is still simple!
- Study of the DA allows direct detection and study of the evolution of the DM power-spectrum
- The large number of independent modes in the DA ($\sim 10^{16}$ versus 10^{7} for the CMB) allows precission cosmology and better tests of non-Gaussianity (related to inflation).

Difficulties Observing the EoR and Dark Ages

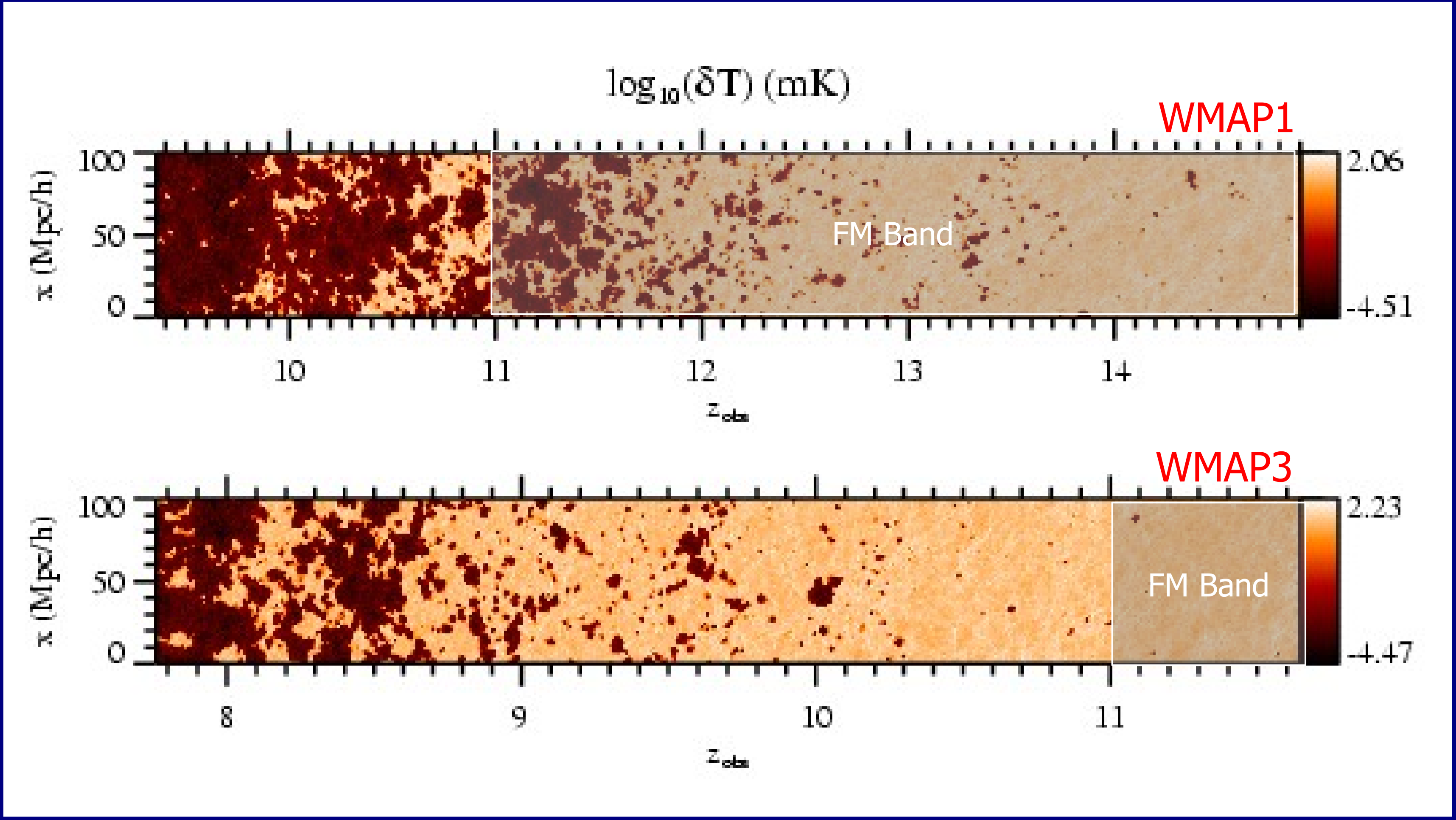
Far less problematic on the moon!

- RFI mitigation
- Ionospheric transients

- Galactic foreground (polarized; possibly the most difficult to overcome).
- Extra-galactic foregrounds.
- Instrumental response (calibration)
- Signal Extraction (DR~10^{5-6})

Difficulties Observing the EoR and Dark Ages

New WMAP3 results suggest EoR might happen a lower z, this also implies that the dark ages are within reach!



Why go in to space or to the moon?

"Whereas the EoR can be probed from the ground, increasing interference and ionospheric phase fluctuations make it much harder to probe the dark ages without going into space!"

Conclusions

- Reionization plus the Dark-Ages is one of the l(e)ast explored epochs of the Universe: Important for star/galaxy formation, cosmology and fundamental physics (inflation) studies.

- Redshifted 21-cm emission/absorption allows on to probe this epoch at $z>6$ ($\lambda>1.5$m) and do a tomographic study of the distribution of neutral hydrogen (in space & time).

- Ground-based projects (e.g. LOFAR, 21CMA, MWA) are ongoing but are limited by the ionosphere and RFI (as well as Galactic foreground, etc.). This will becomes worse with time!

- A LOFAR in space/on the moon would overcome most calibration issues (e.g. ionosphere, RFI, calibration stability, etc.)


LOFAR on the moon?