Constraints on the IGM temperature @ z > 6 from 21 cm observations

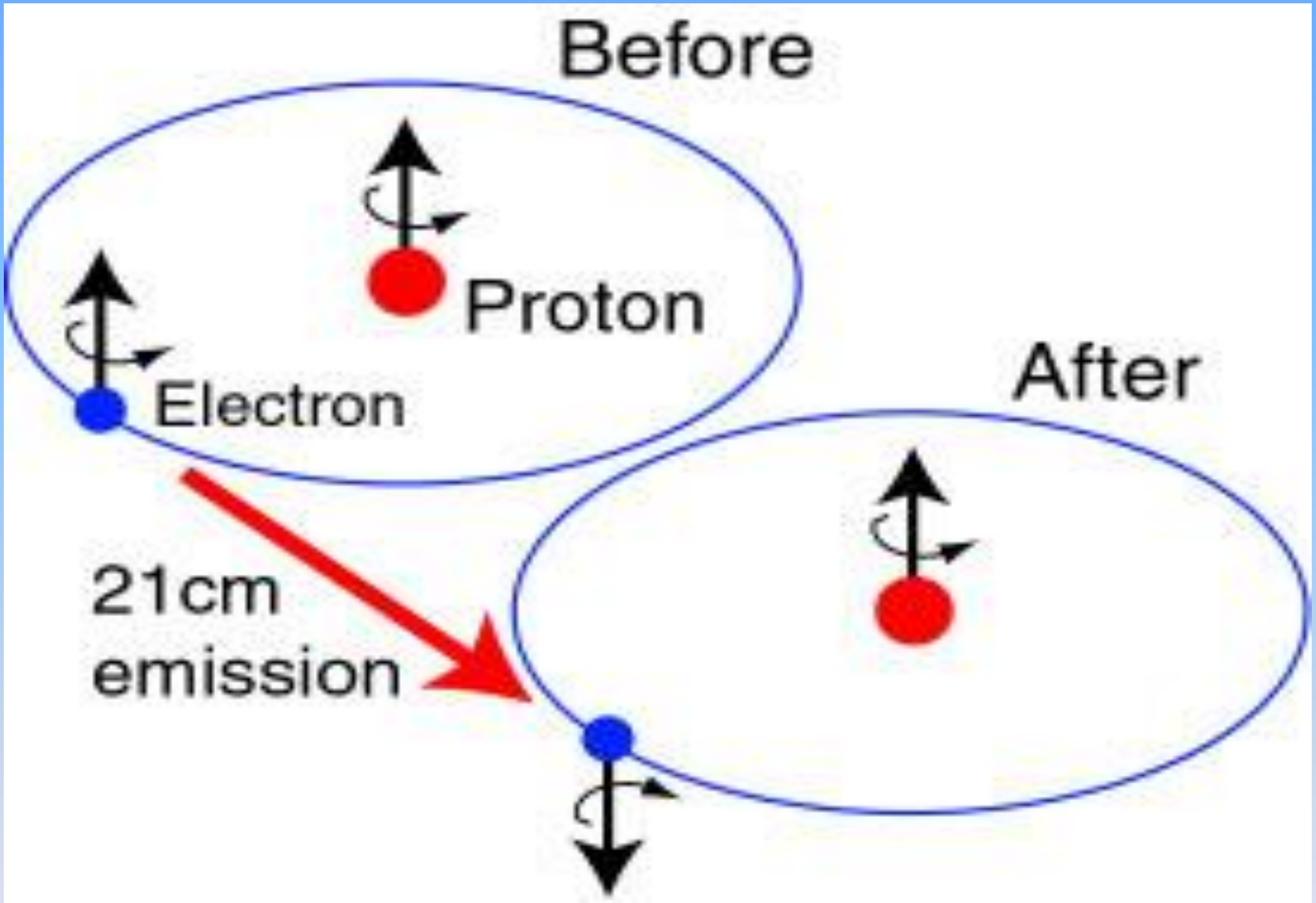
Gianni Bernardi

SKA SA & Rhodes University

(for the HERA, LEDA and PAPER collaborations)

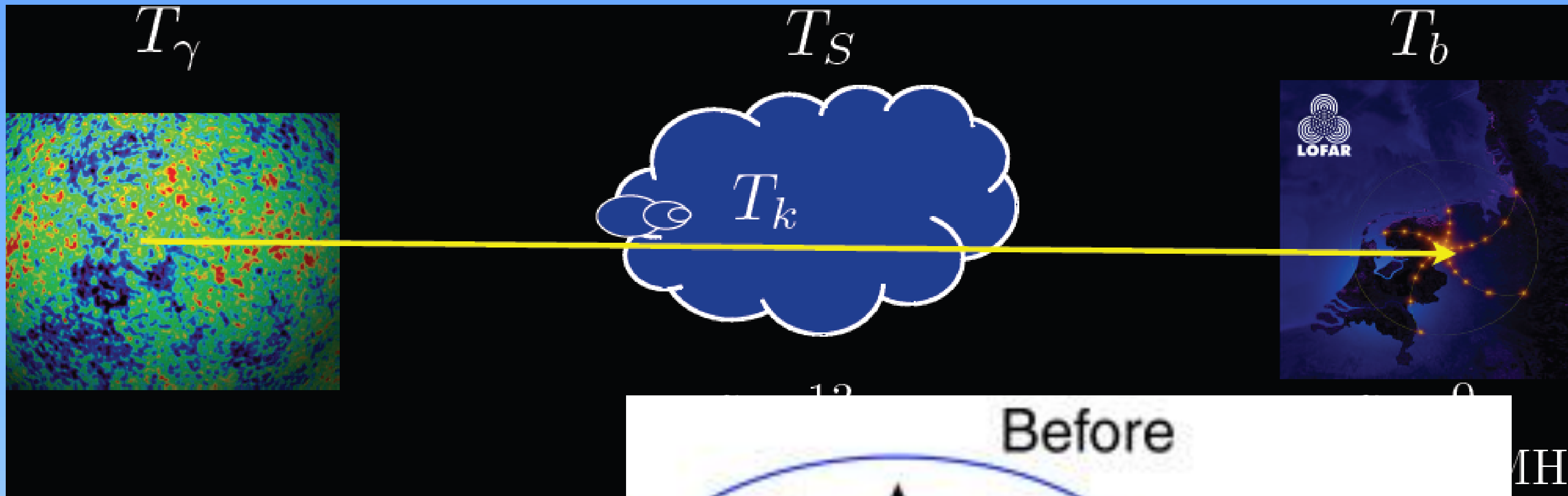
"Cosmology with 21cm Surveys, Cosmic Microwave Background and Large Scale Structure", Madrid, June 17th 2016

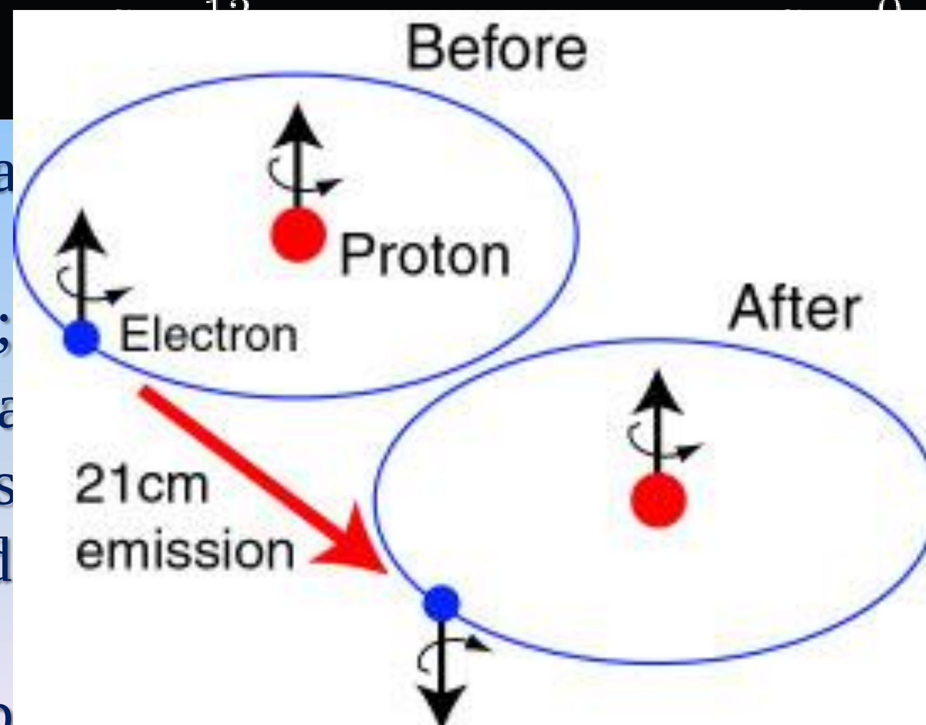
21 cm cosmology



1420 MHz (rest frame)

21 cm cosmology



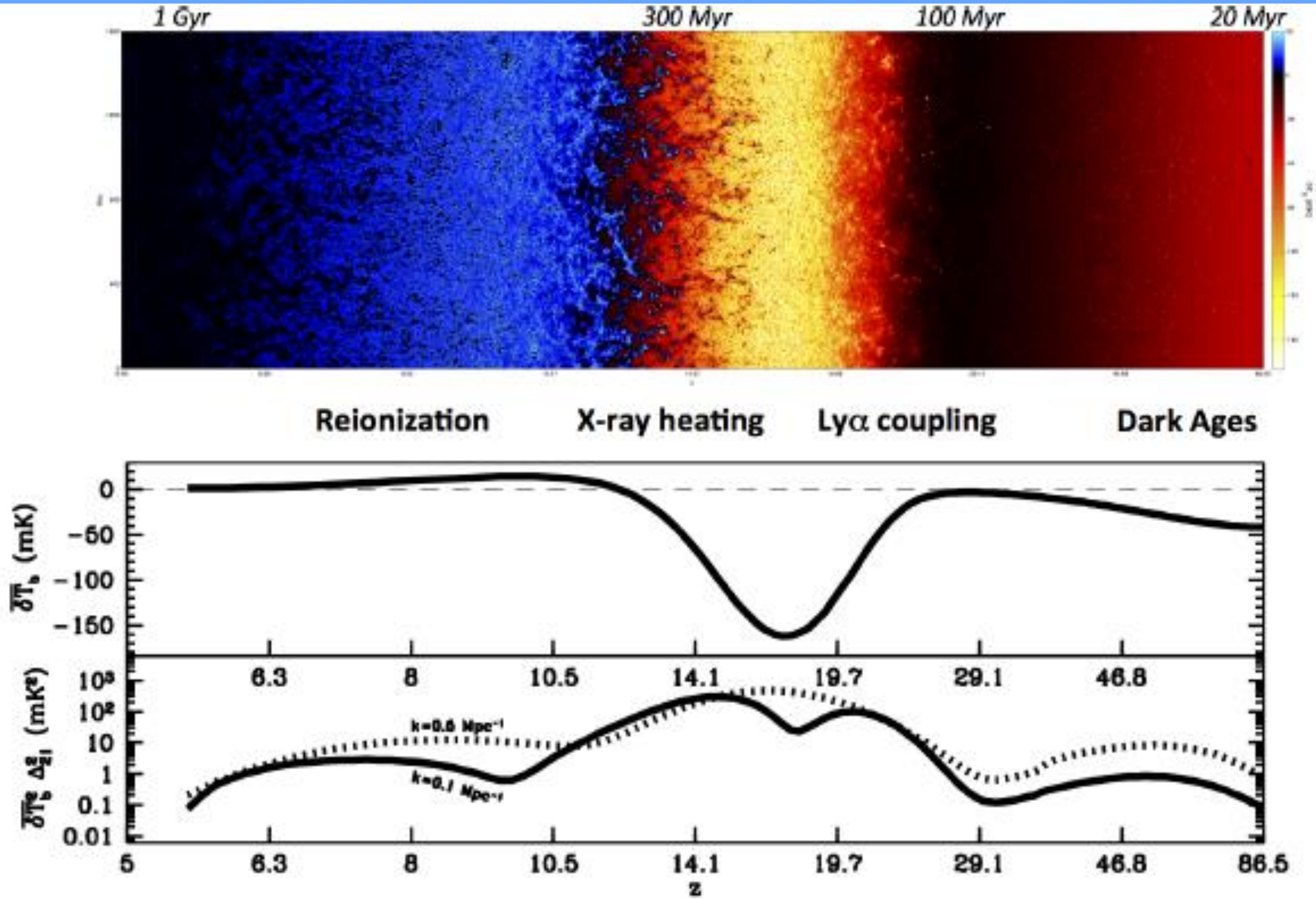


3 funda

- T_γ: the CMB temperature;
- T_k: the gas (IGM) tempera
- T_S: the spin temperature (s … evel
  with respect to the ground

- the 21 cm line is observab

A few fundamental transitions



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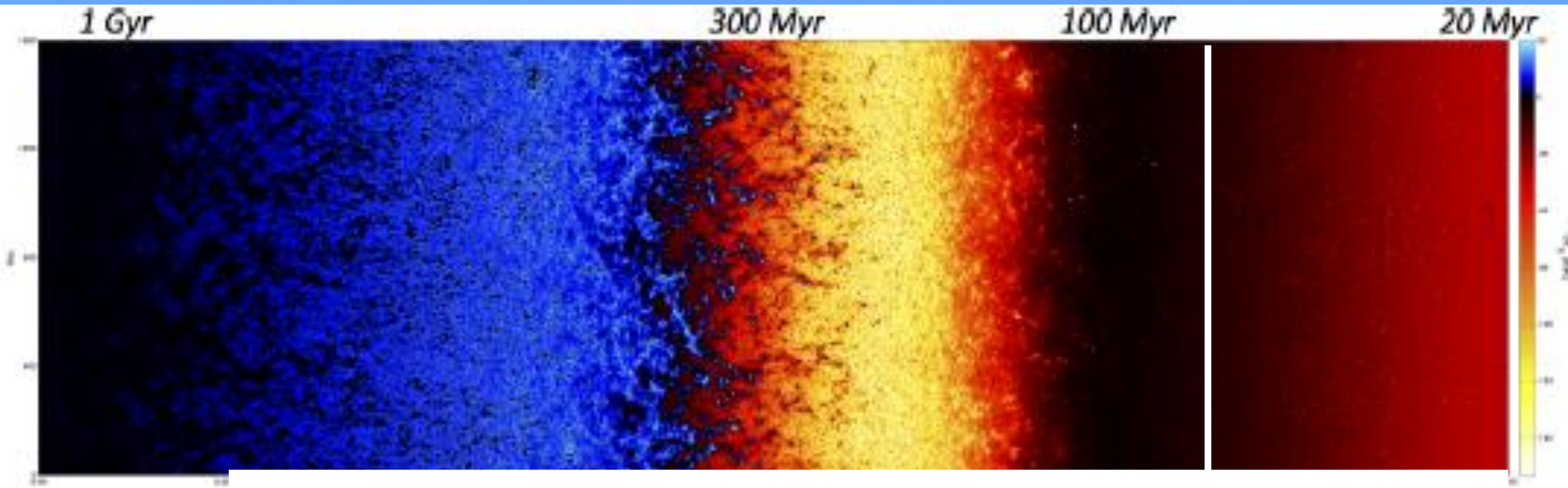
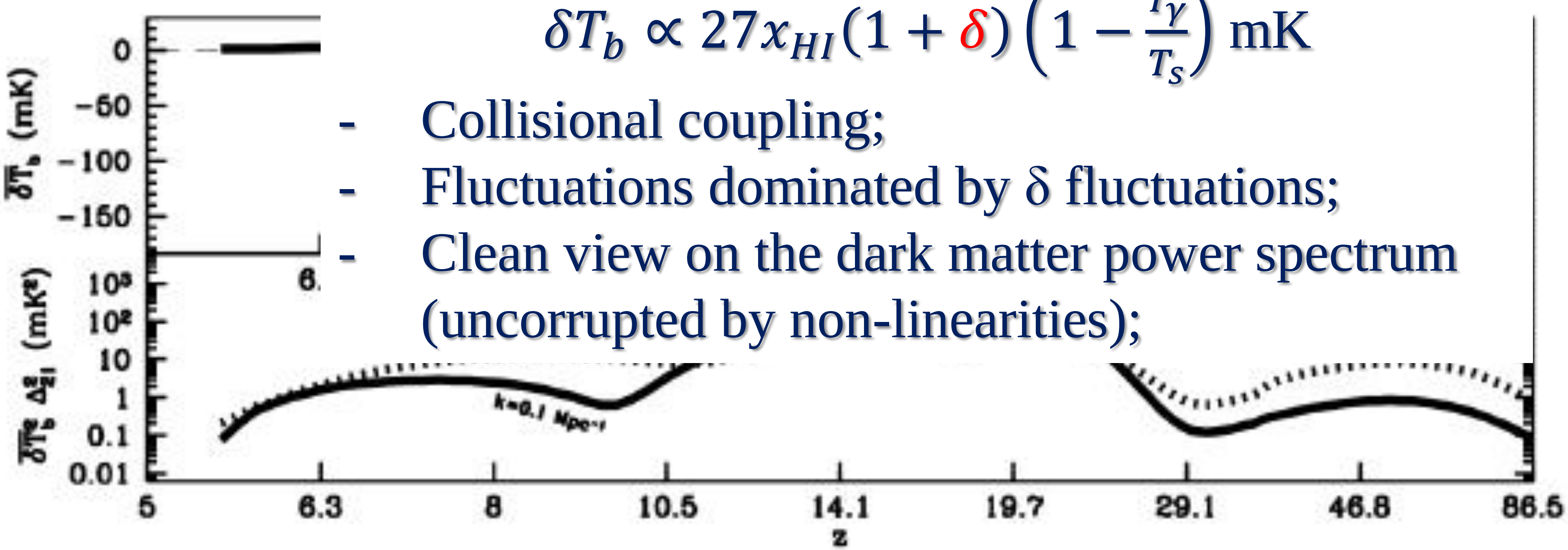


$$T_s = T_k < T_\gamma$$

$$\delta T_b \propto 27 x_{HI} (1 + \delta) \left(1 - \frac{T_\gamma}{T_S}\right) \text{ mK}$$

- Collisional coupling;
- Fluctuations dominated by δ fluctuations;
- Clean view on the dark matter power spectrum (uncorrupted by non-linearities);



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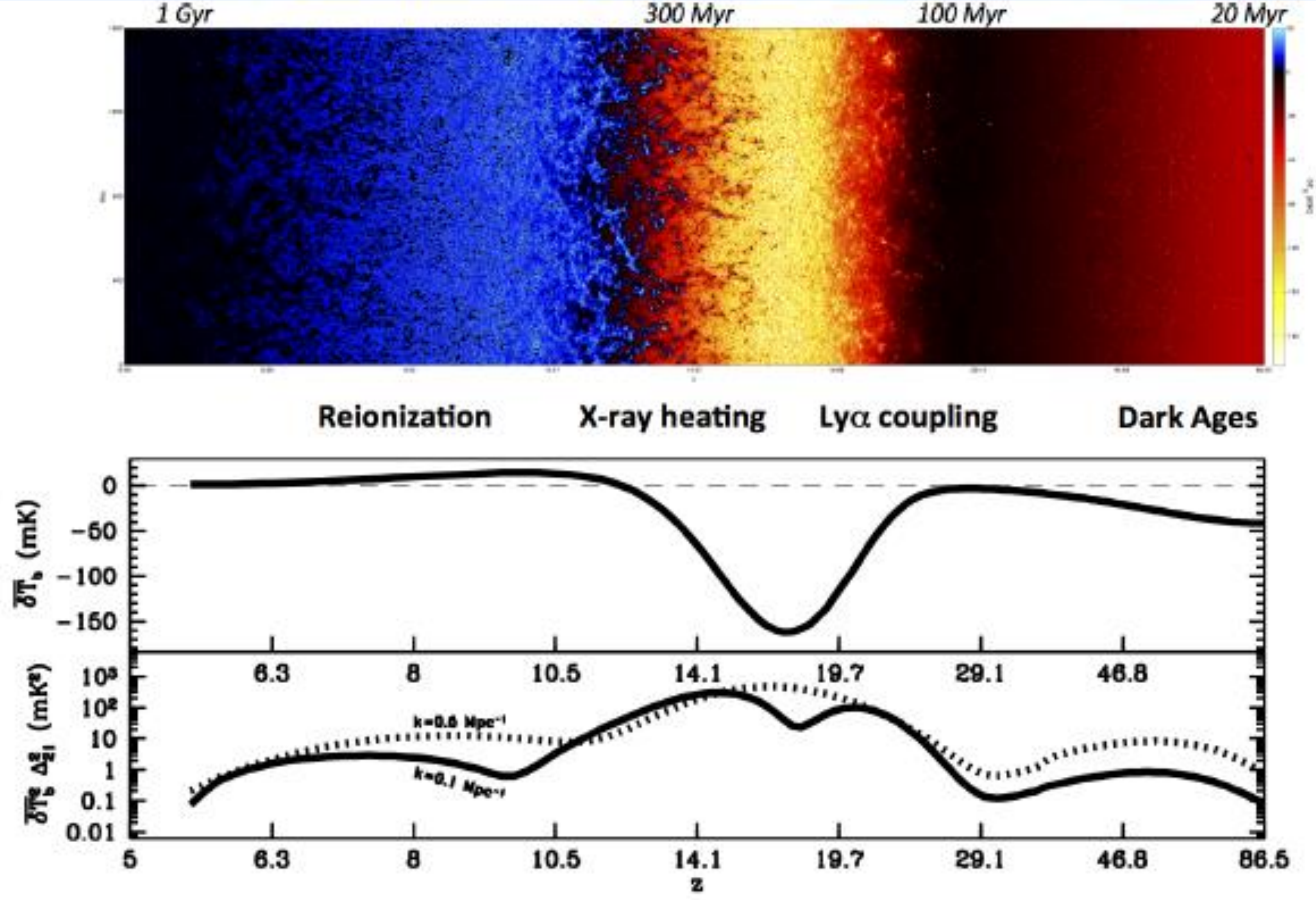

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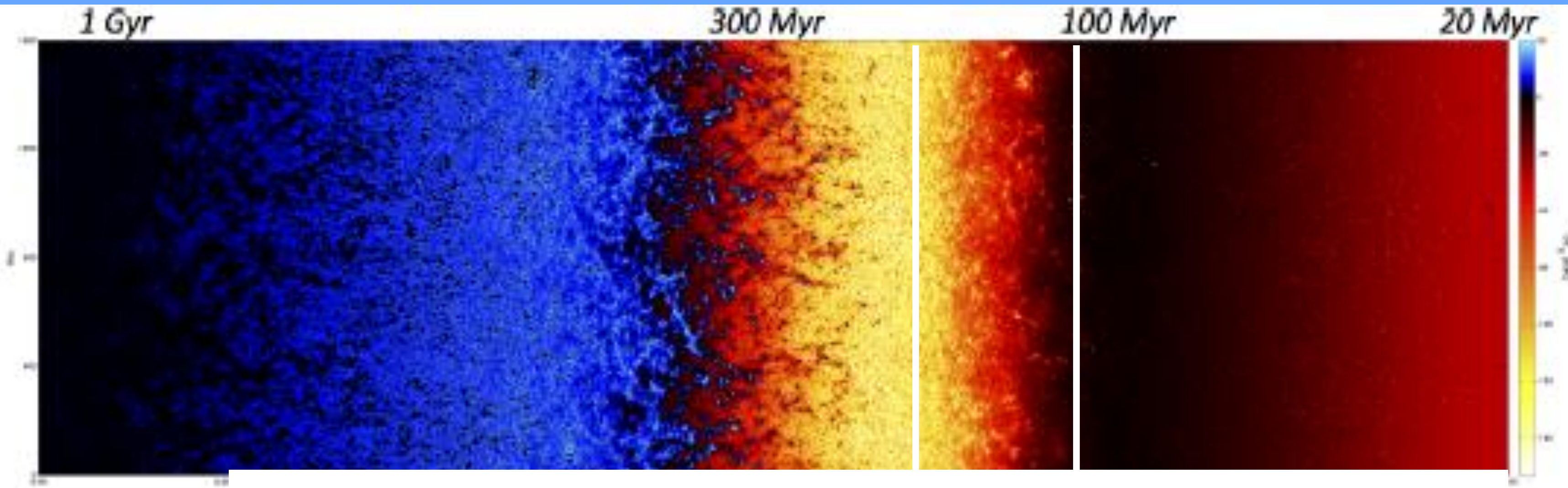
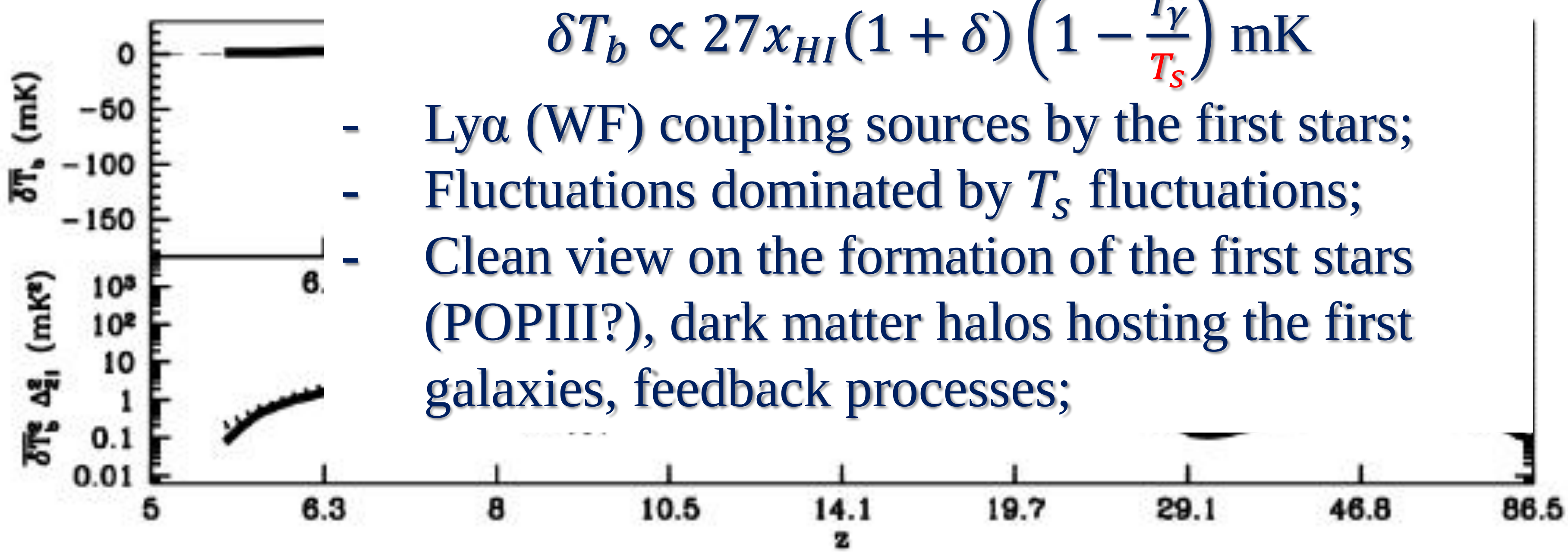


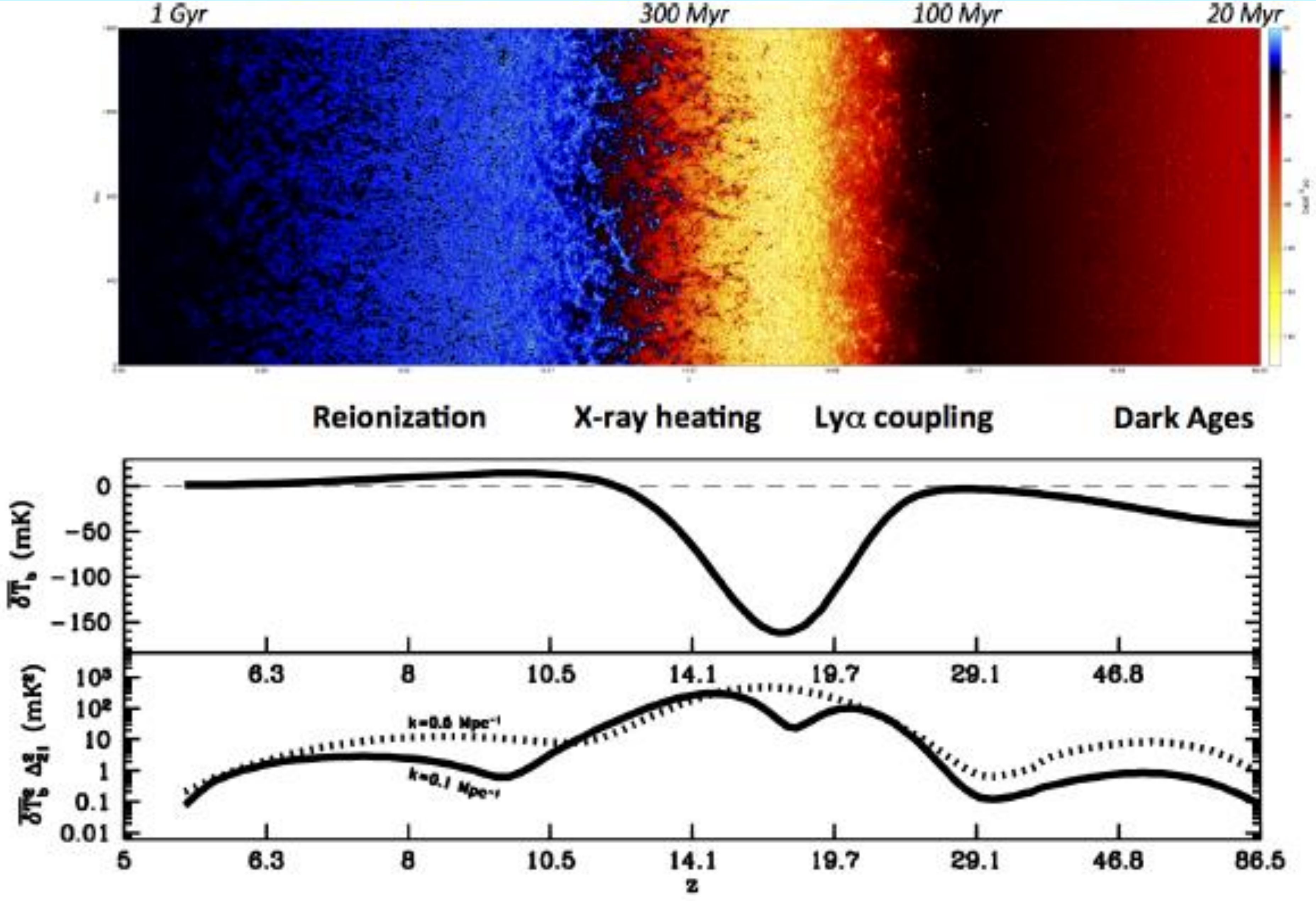
$$T_s = T_k < T_\gamma$$

$$\delta T_b \propto 27 x_{HI}(1+\delta)\left(1 - \frac{T_\gamma}{T_S}\right) \text{ mK}$$

- Lyα (WF) coupling sources by the first stars;
- Fluctuations dominated by T_s fluctuations;
- Clean view on the formation of the first stars (POPIII?), dark matter halos hosting the first galaxies, feedback processes;



Evolution of fluctuations



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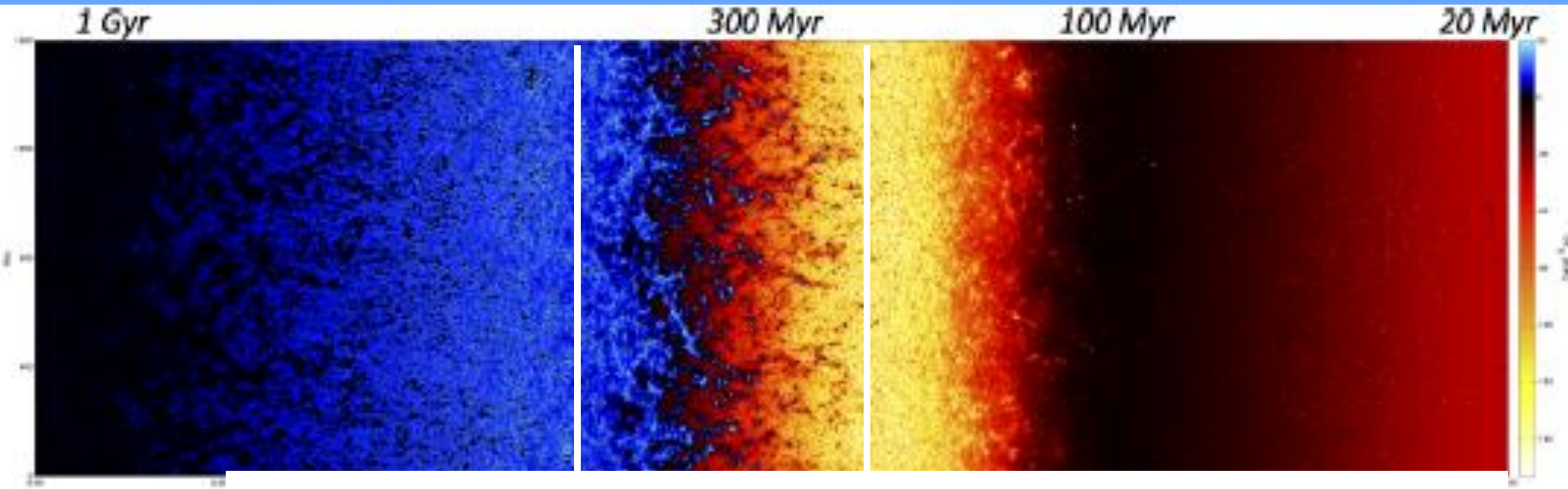
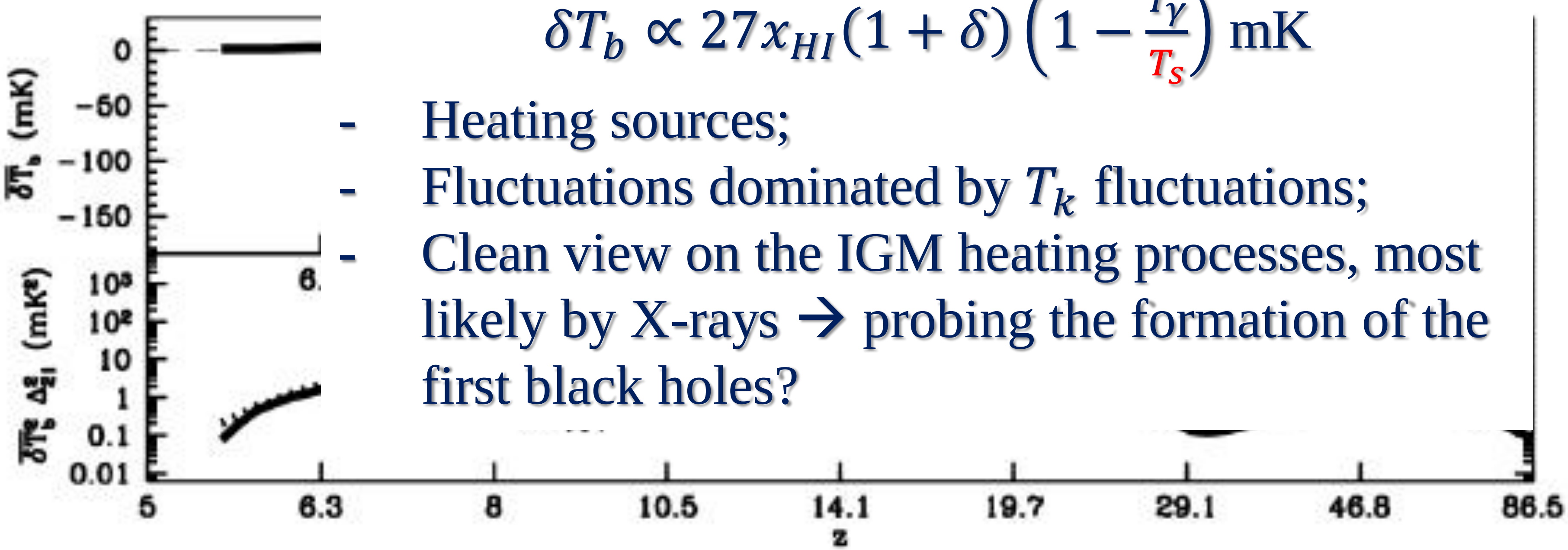


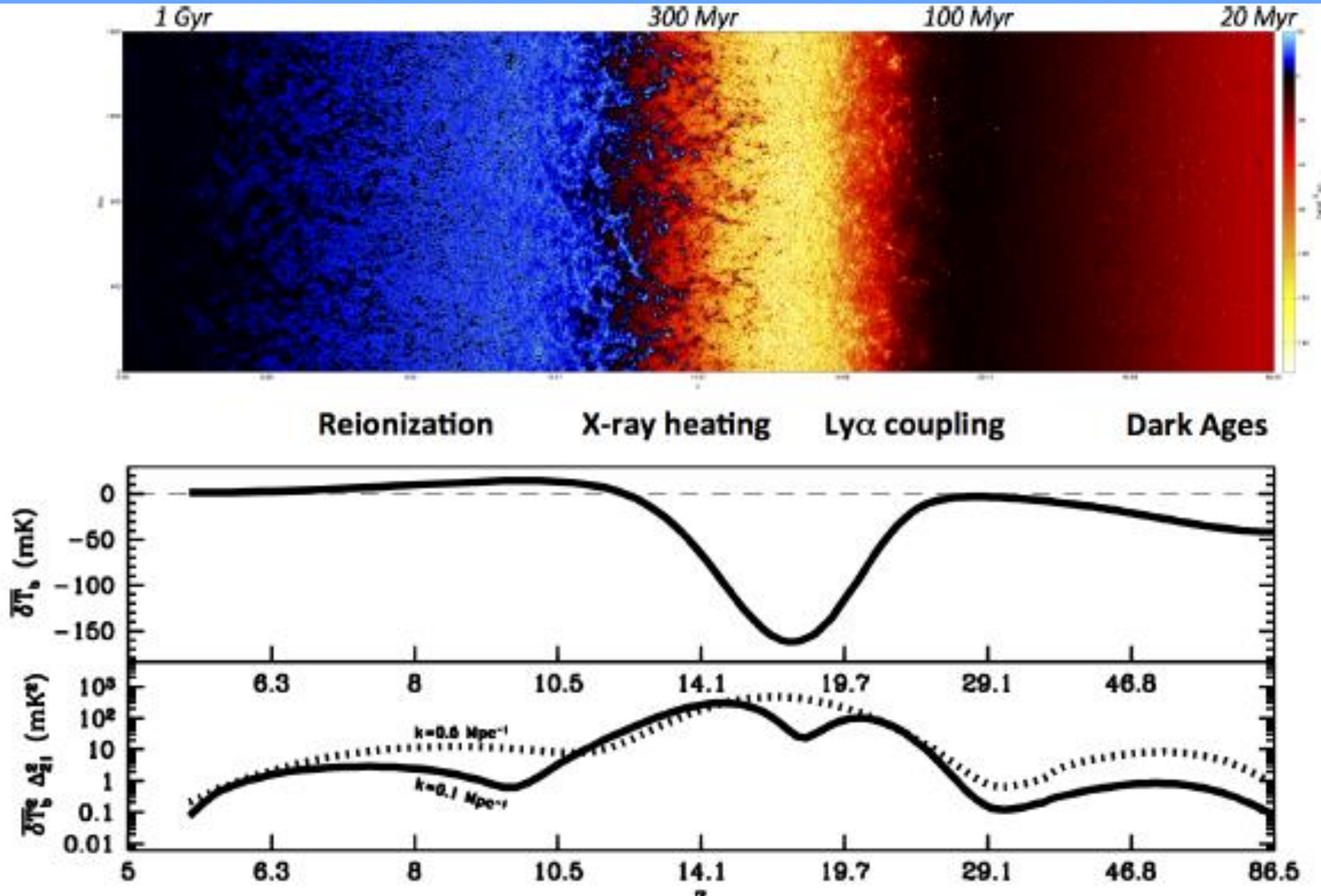
$$T_s = T_k > T_\gamma$$

$$\delta T_b \propto 27 x_{HI}(1+\delta)\left(1 - \frac{T_\gamma}{T_s}\right) \text{ mK}$$

- Heating sources;
- Fluctuations dominated by T_k fluctuations;
- Clean view on the IGM heating processes, most likely by X-rays → probing the formation of the first black holes?



Evolution of fluctuations



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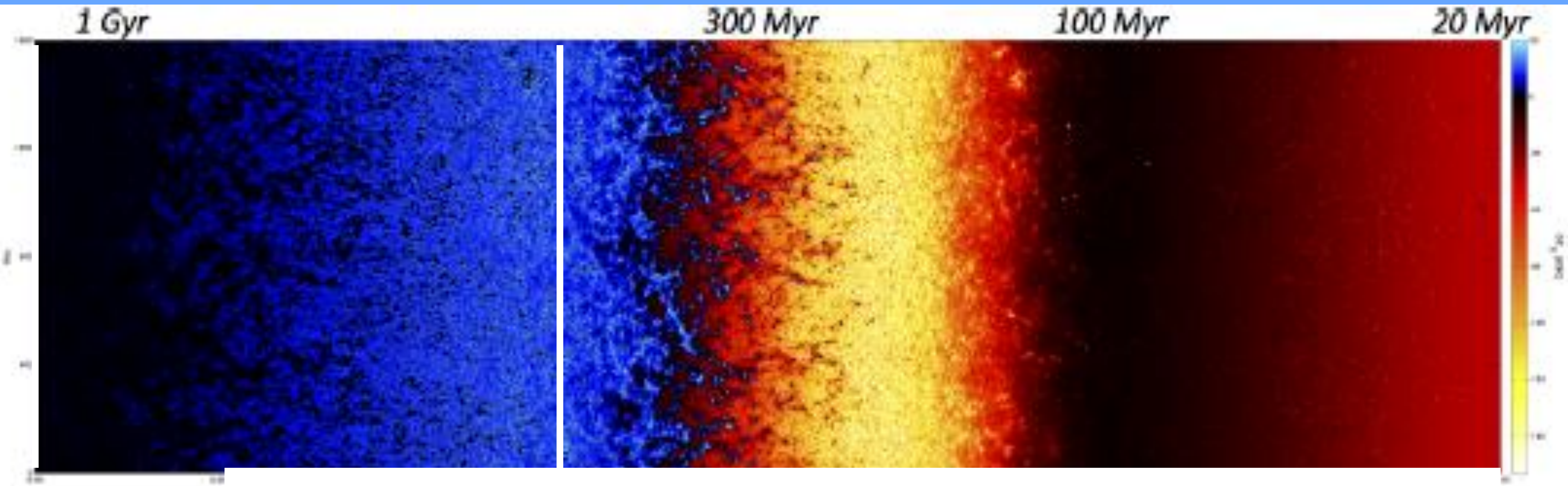
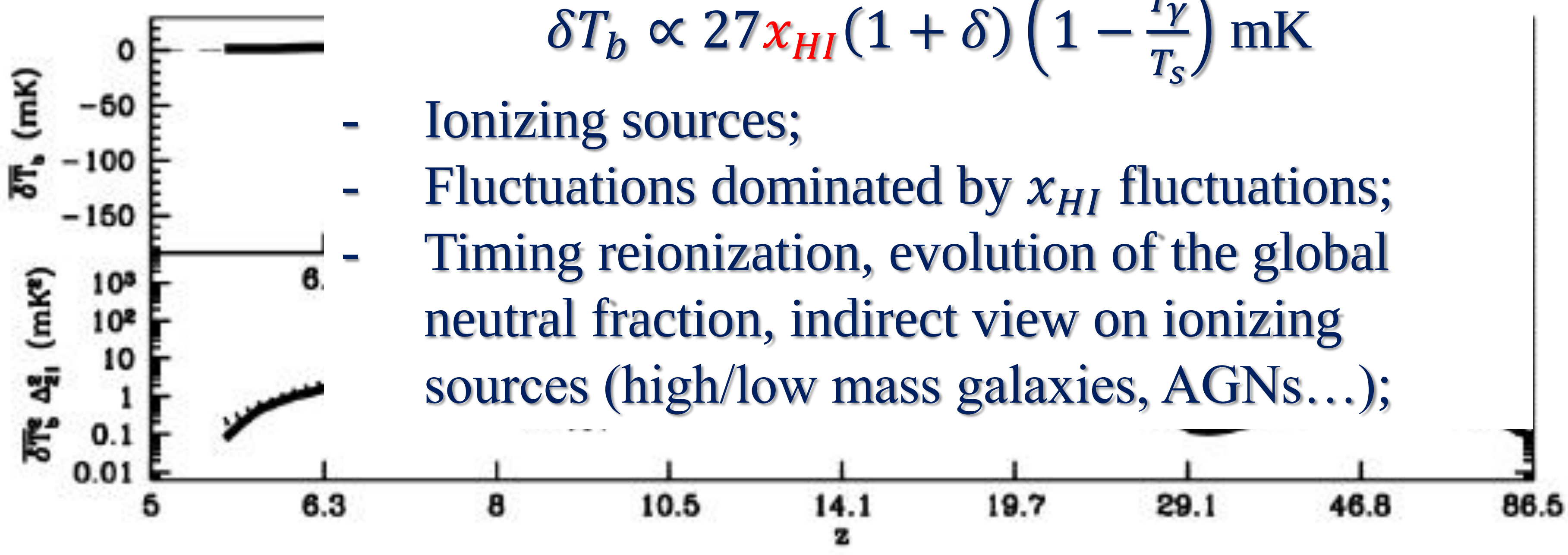


$$T_s = T_k \gg T_\gamma$$

$$\delta T_b \propto 27 x_{HI} (1+\delta)\left(1 - \frac{T_\gamma}{T_s}\right) \text{ mK}$$

- Ionizing sources;
- Fluctuations dominated by x_{HI} fluctuations;
- Timing reionization, evolution of the global neutral fraction, indirect view on ionizing sources (high/low mass galaxies, AGNs…);



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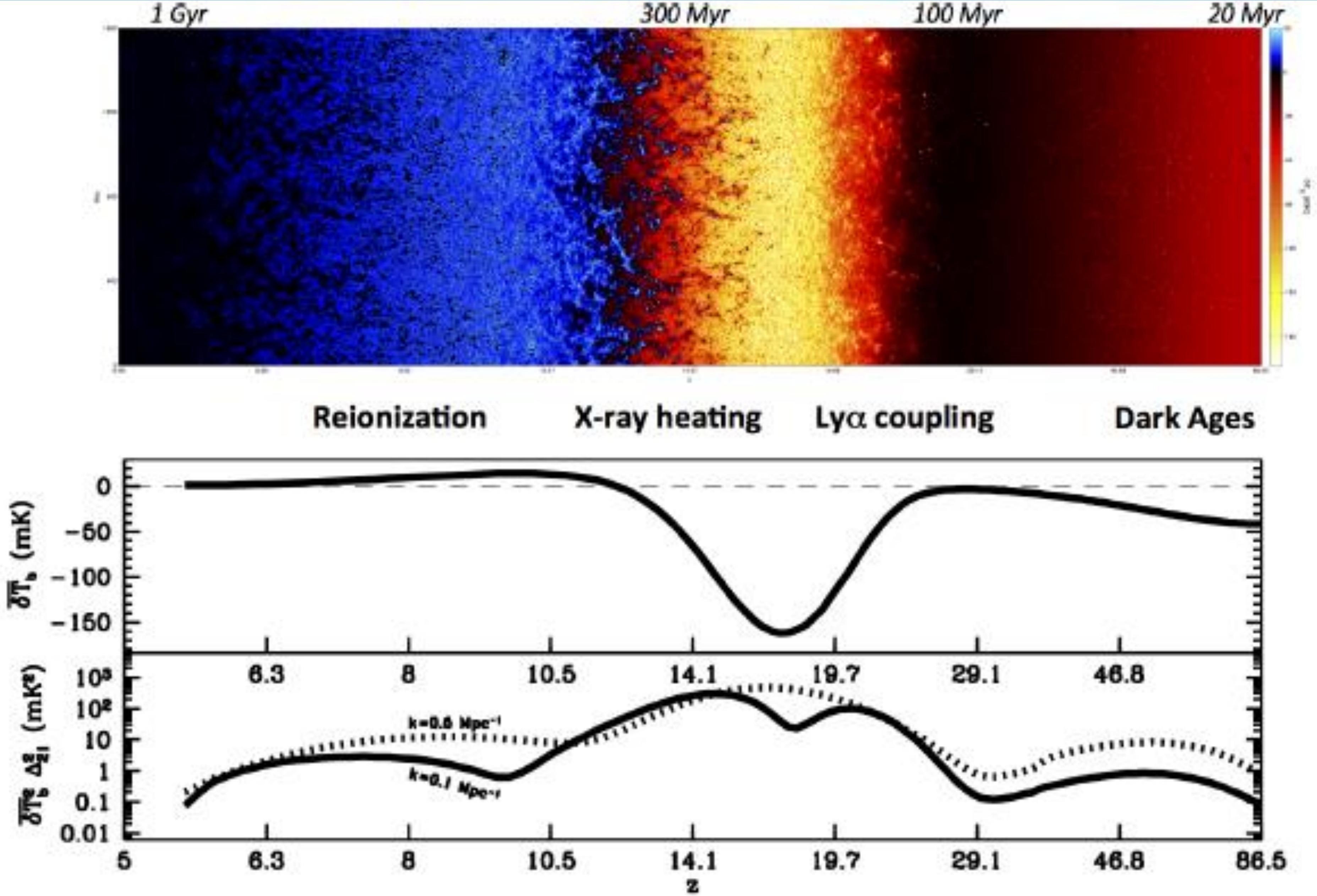
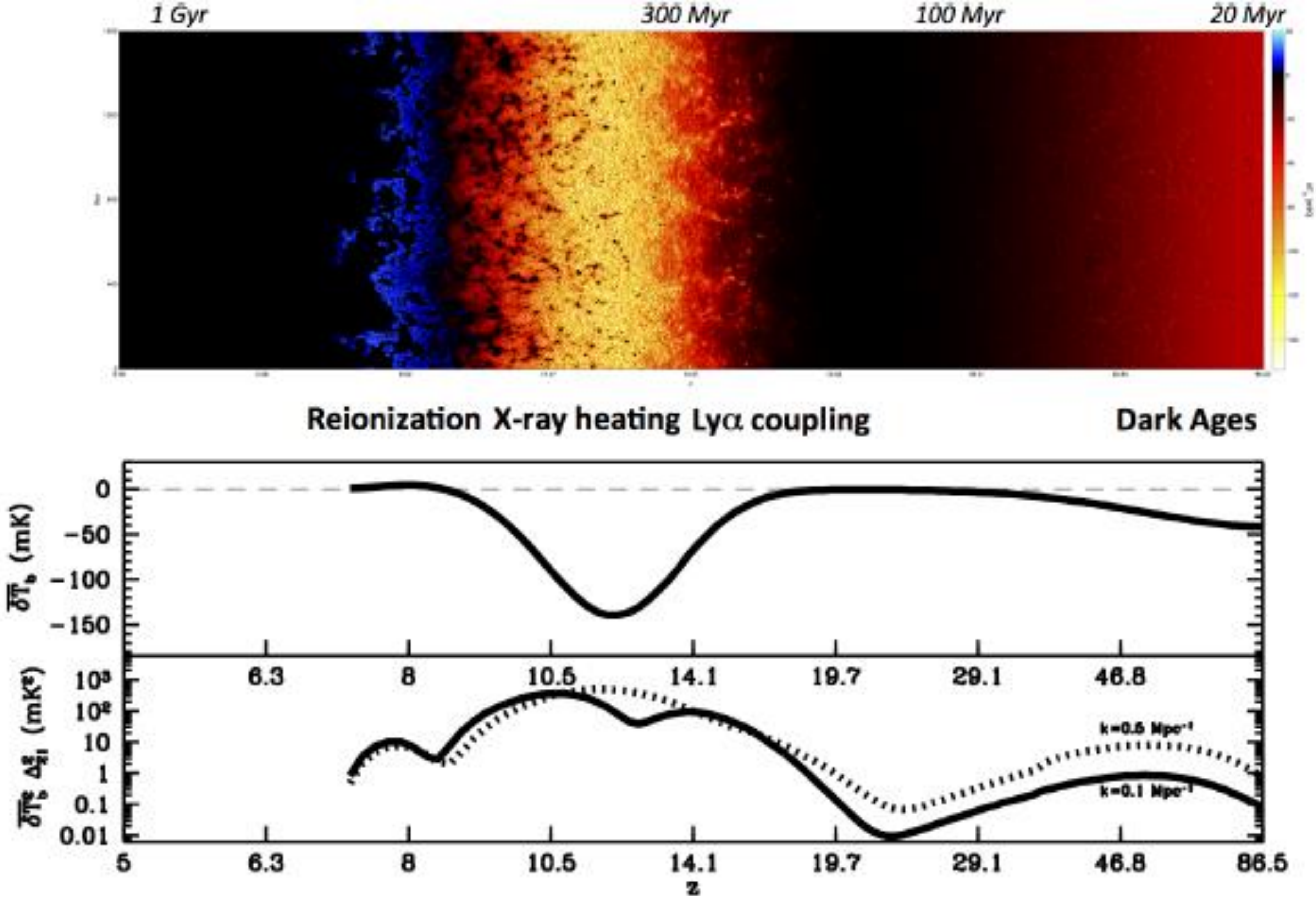
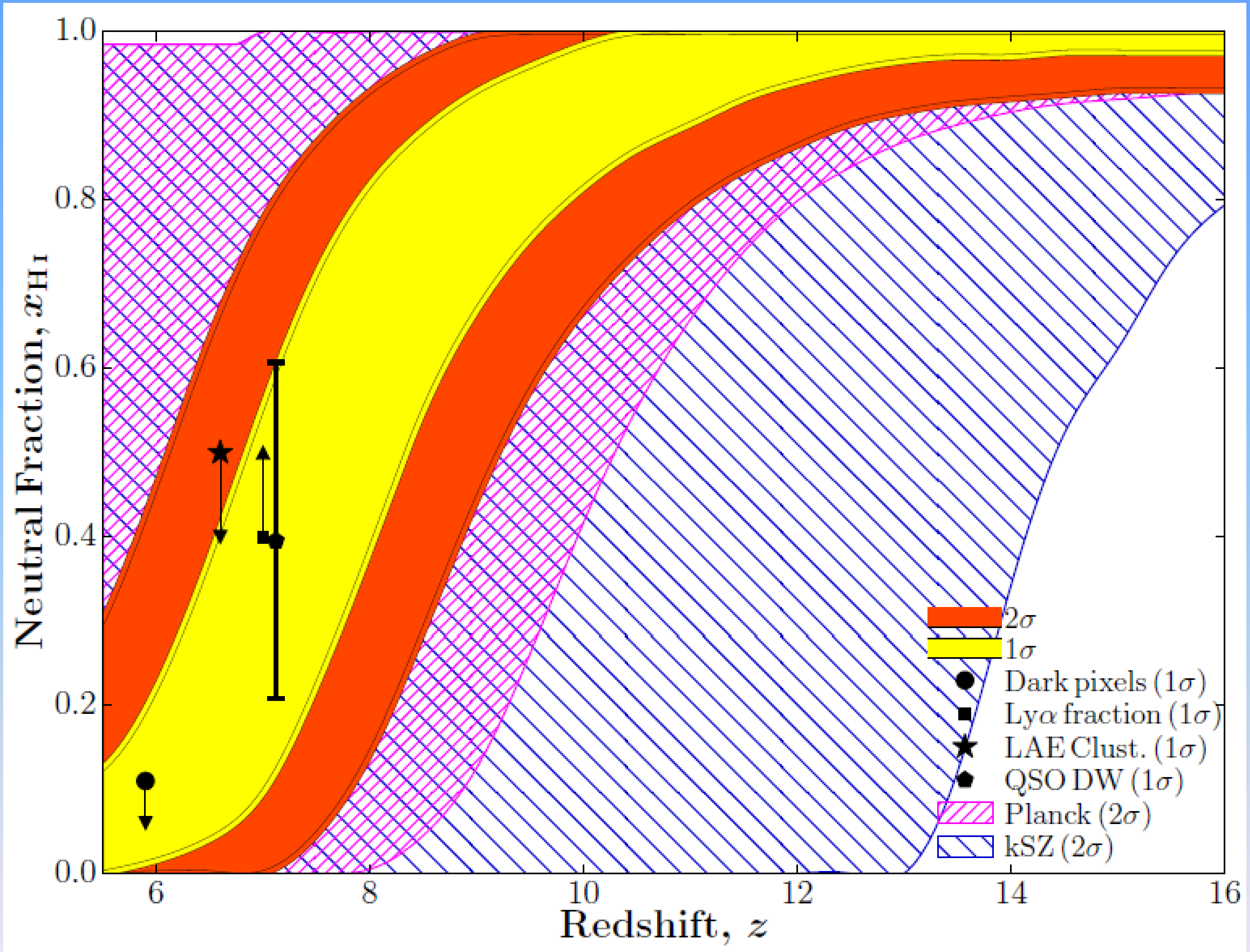


Evolution of fluctuations



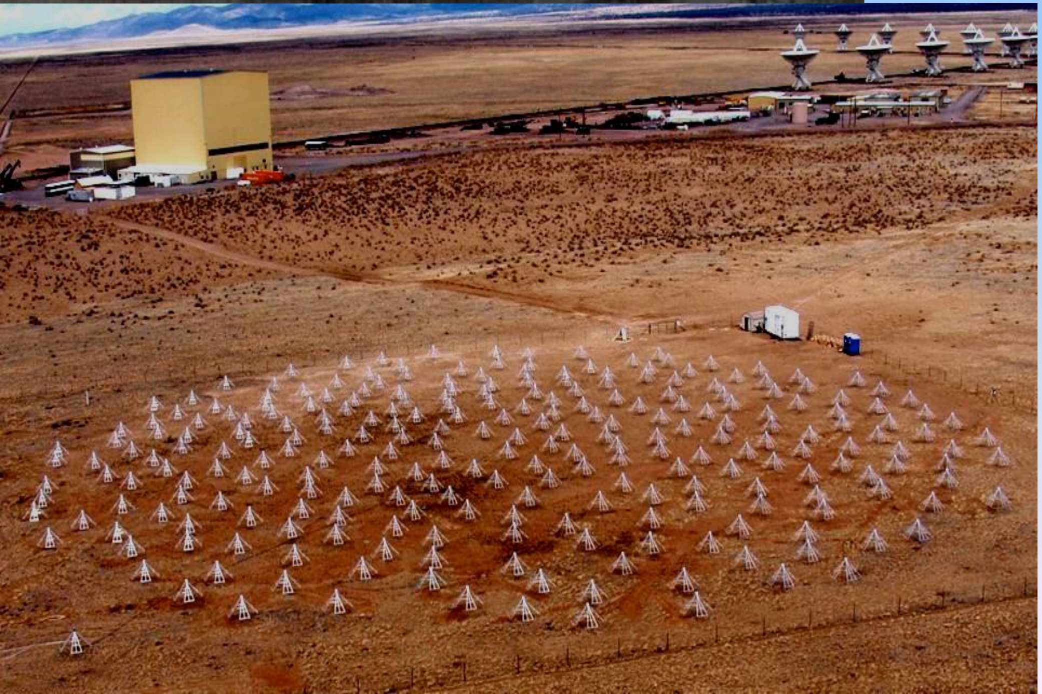
Current constraints on reionization



Greig & Mesinger (2016)

Bayesian constraints on the global 21 cm signal from the Cosmic Dawn from LEDA (Large aperture Experiment to detect the Dark Ages)

(GB et al., submitted)



- 20-90 MHz V-inverted dipoles;
- two 256-dipole stations (LWA, OVRO);
- 256 correlated inputs (dual pol, 60 MHz bandwidth) → low resolution interferometric array used to improve calibration (Bernardi, McQuinn & Greenhill 2015);
- 21cm global signal measurements from four isolated outriggers;

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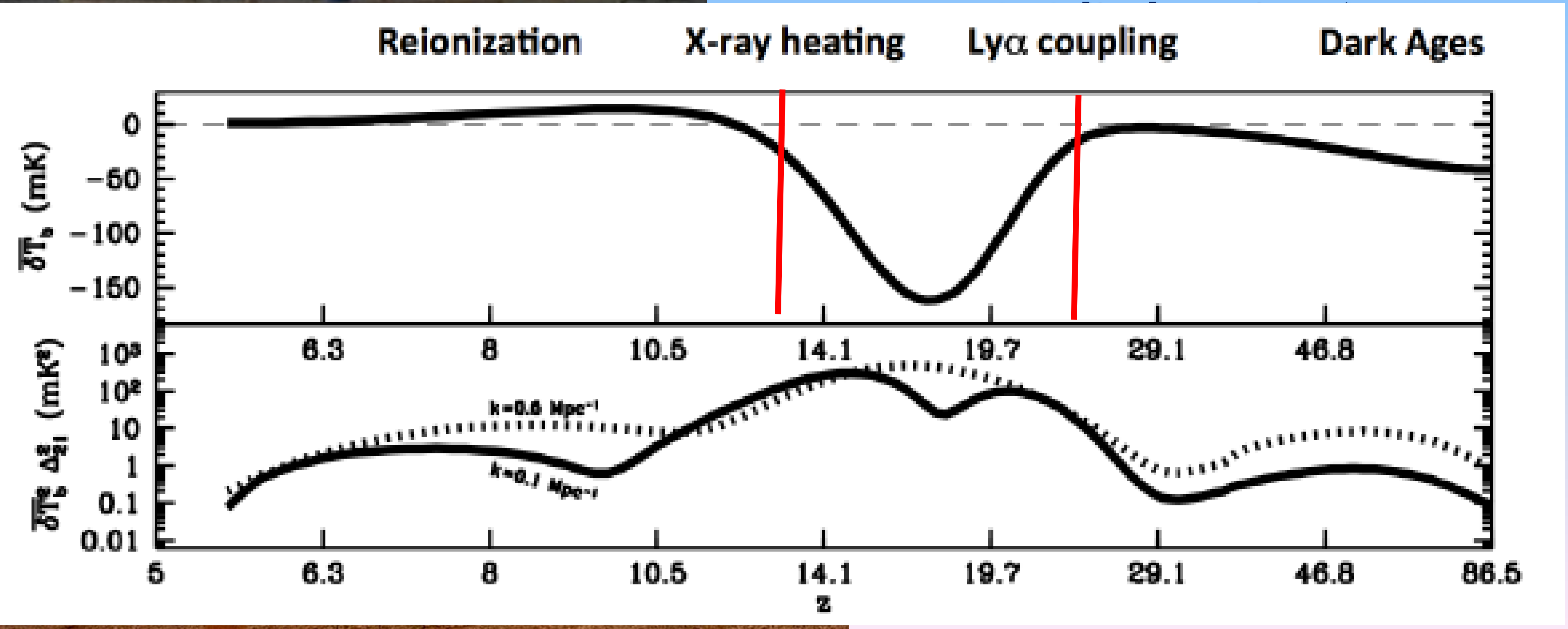
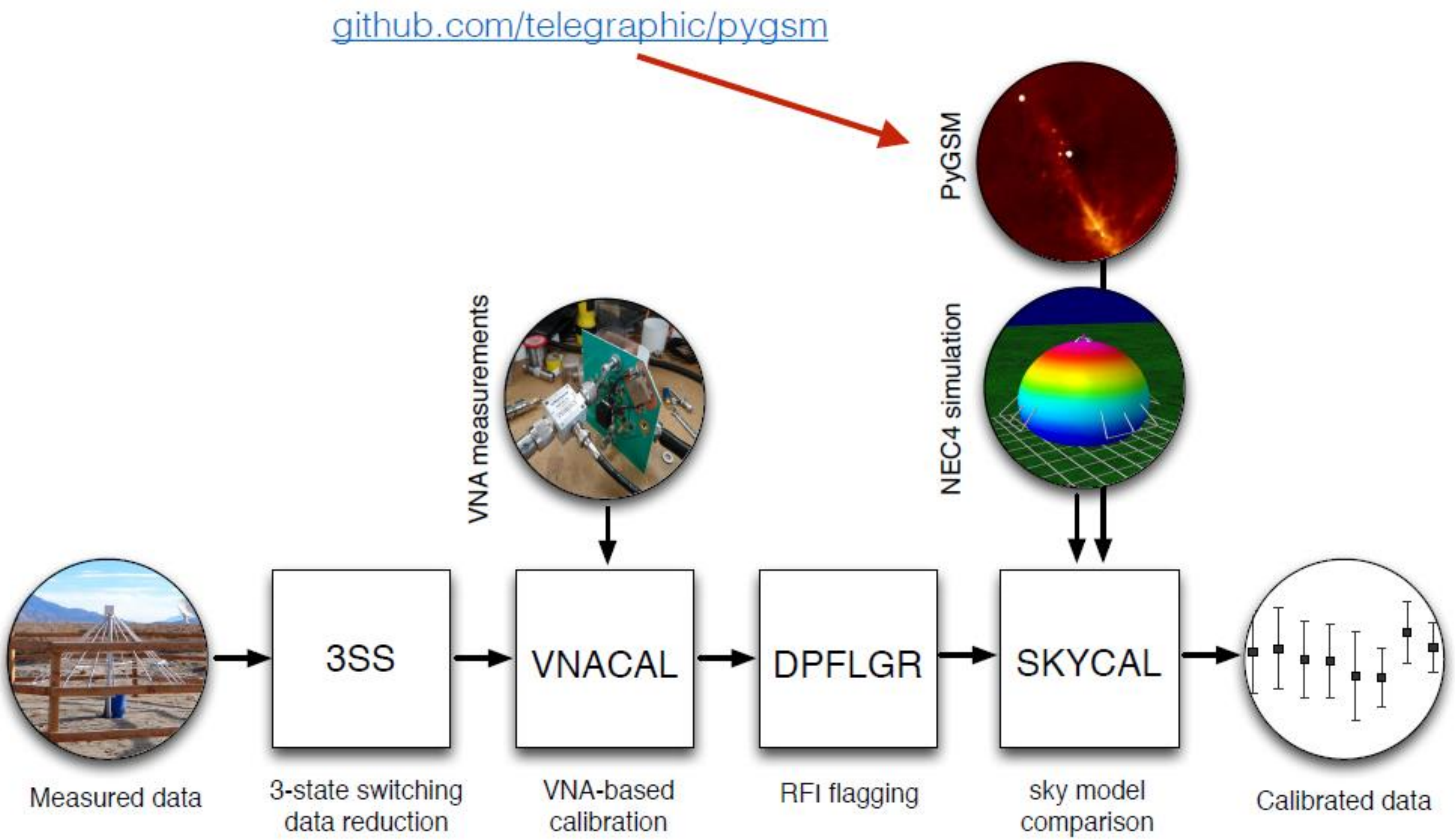
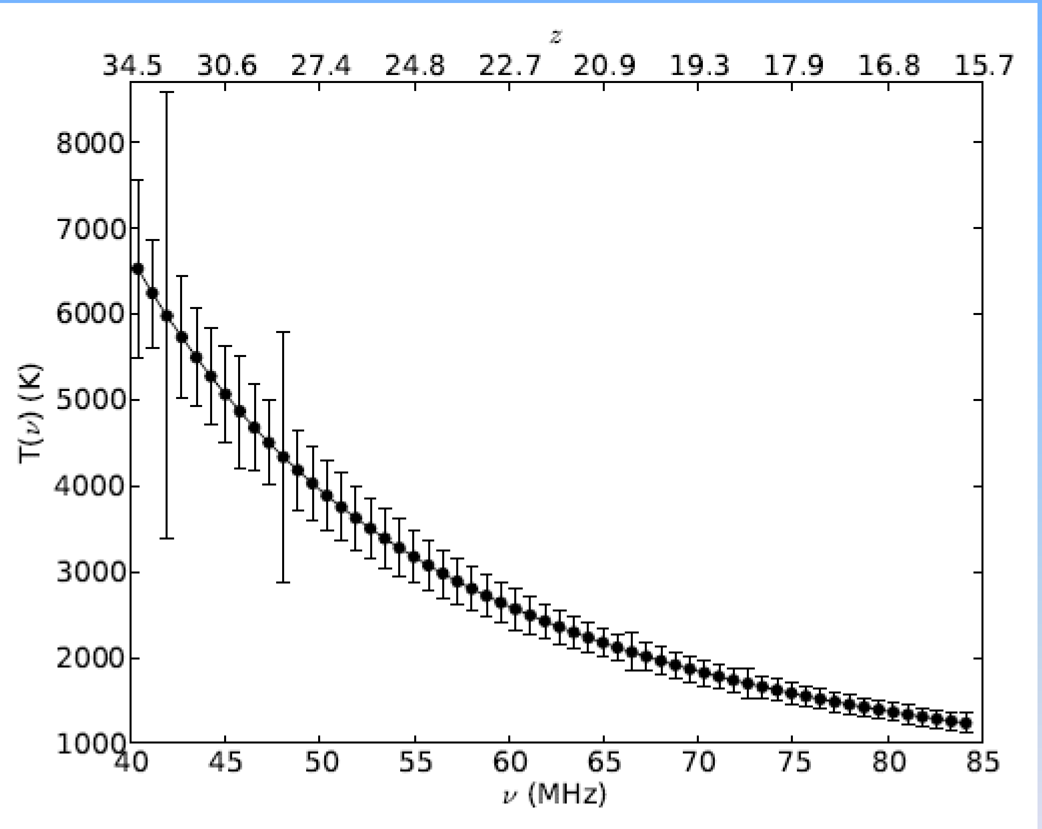


Current data flow & calibration



courtesy D. Price

Measured sky spectrum



- 2 hours on February 12 2016, 9.5 < LST < 11.5 (error bars inflated by 1000);
- ~1150 sec effective integration time;
- 40-85 MHz band, covered by 58, 768 kHz wide channels;
- three-state calibration switch + reflection coefficients corrections + sky model based calibration;

Bayesian signal extraction: joint fit for the global 21 cm and foreground signals

Bayes' theorem:

$$\mathcal{P}(\boldsymbol{\Theta}|\boldsymbol{D},\mathcal{H}) = \frac{\mathcal{L}(\boldsymbol{D}|\boldsymbol{\Theta},\mathcal{H})\Pi(\boldsymbol{\Theta}|\mathcal{H})}{\mathcal{Z}(\boldsymbol{D}|\mathcal{H})}$$

Likelihood:

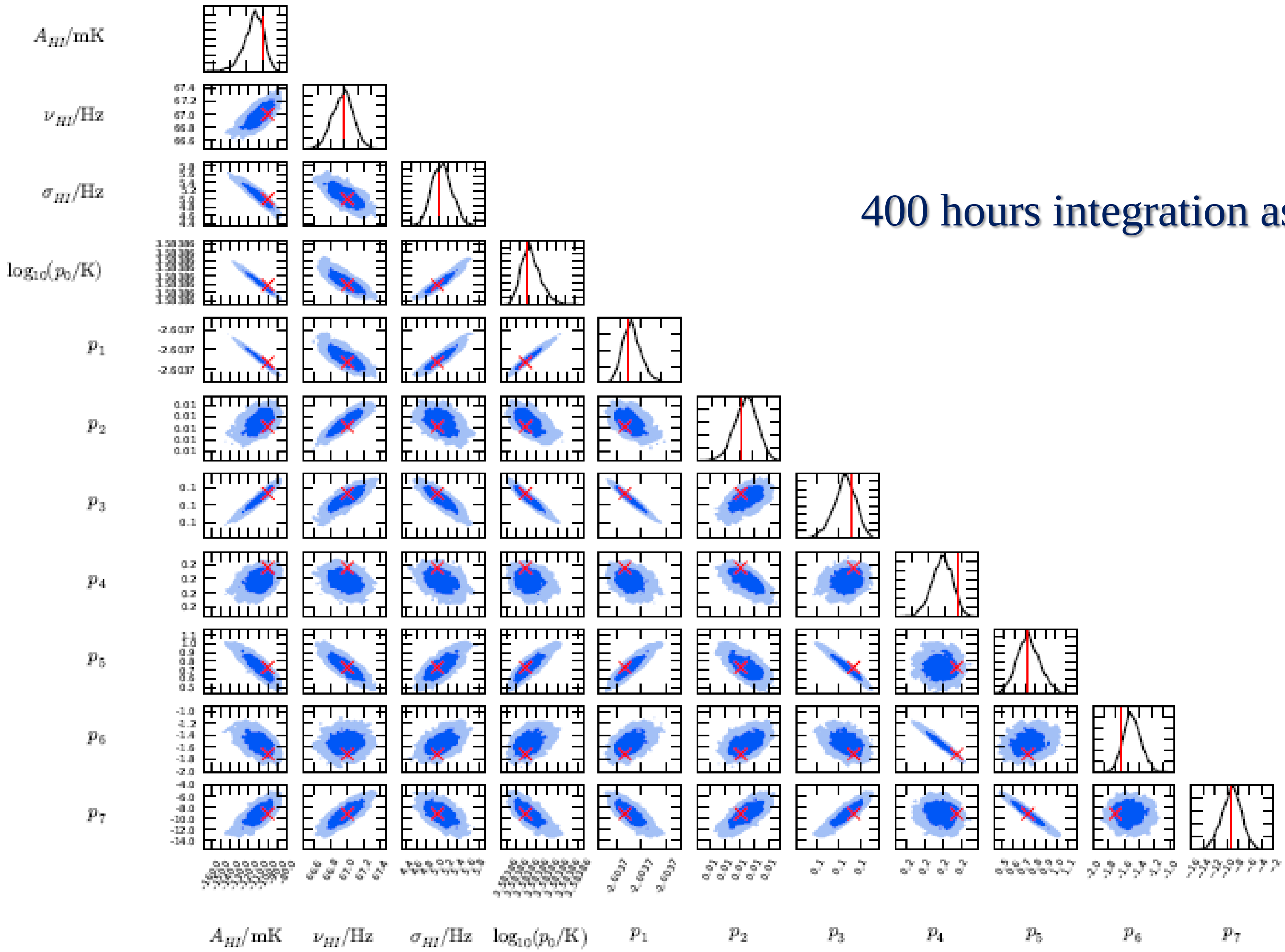
$$\mathcal{L}_j(T_{ant}(\nu)|\boldsymbol{\Theta}) = \frac{1}{\sqrt{2\pi\sigma^2(\nu)}} e^{-\frac{[T_{ant}(\nu)-T_m(\nu,\boldsymbol{\Theta})]^2}{2\sigma^2}}$$

$$\ln \mathcal{L}(\boldsymbol{T}_{ant}|\boldsymbol{\Theta}) = \sum_j \ln \mathcal{L}_j\left(T_{ant}(\nu_j)|\boldsymbol{\Theta}\right)$$

Chosen model:

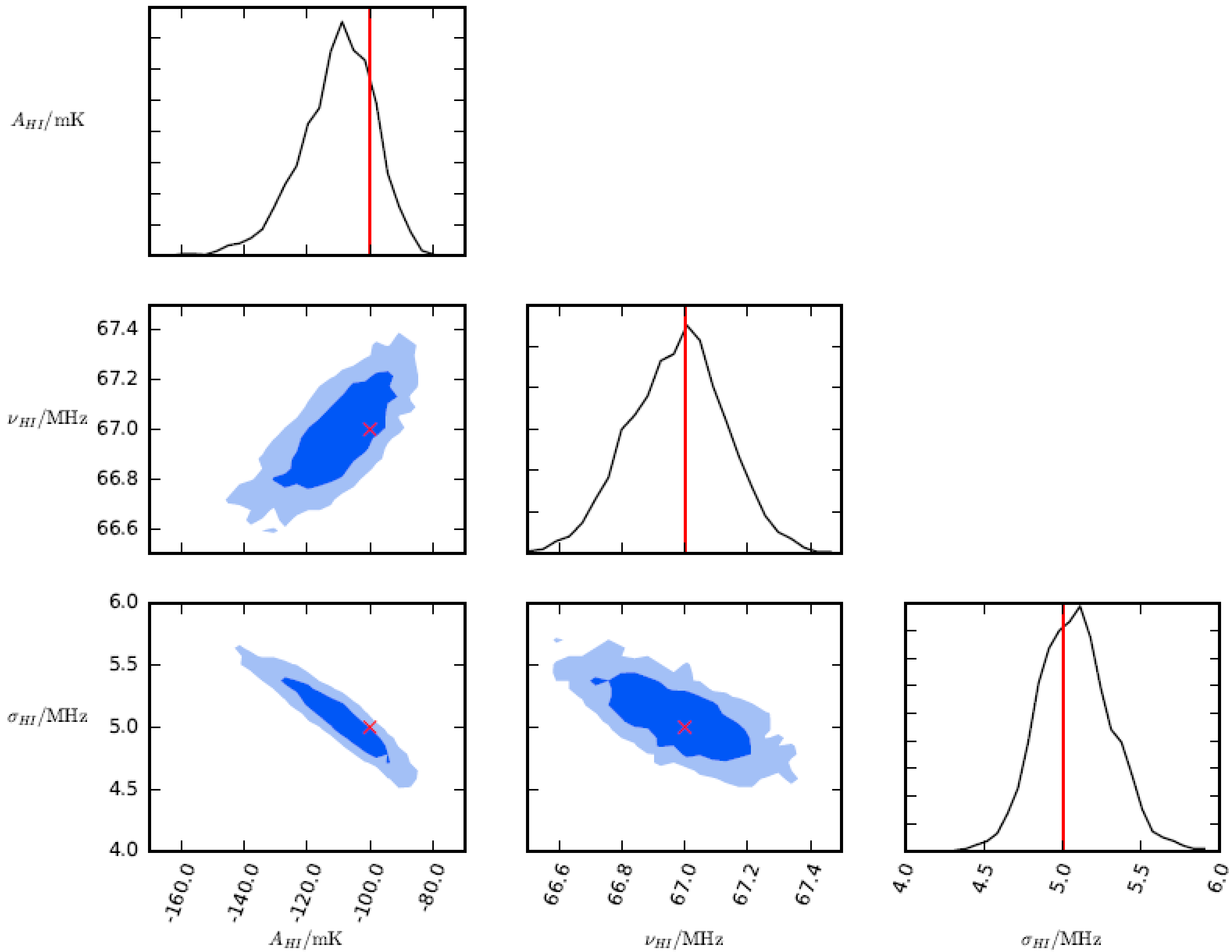
$$T_m(\nu_j) = T_f(\nu_j) + T_{HI}(\nu_j) = 10^{\sum_{n=0}^{N} p_n\left[\log\left(\frac{\nu_j}{\nu_0}\right)\right]^n} + A_{HI} e^{-\frac{(\nu_j-\nu_{HI})^2}{2\sigma_{HI}^2}}$$

Bayesian signal extraction: a simulated case

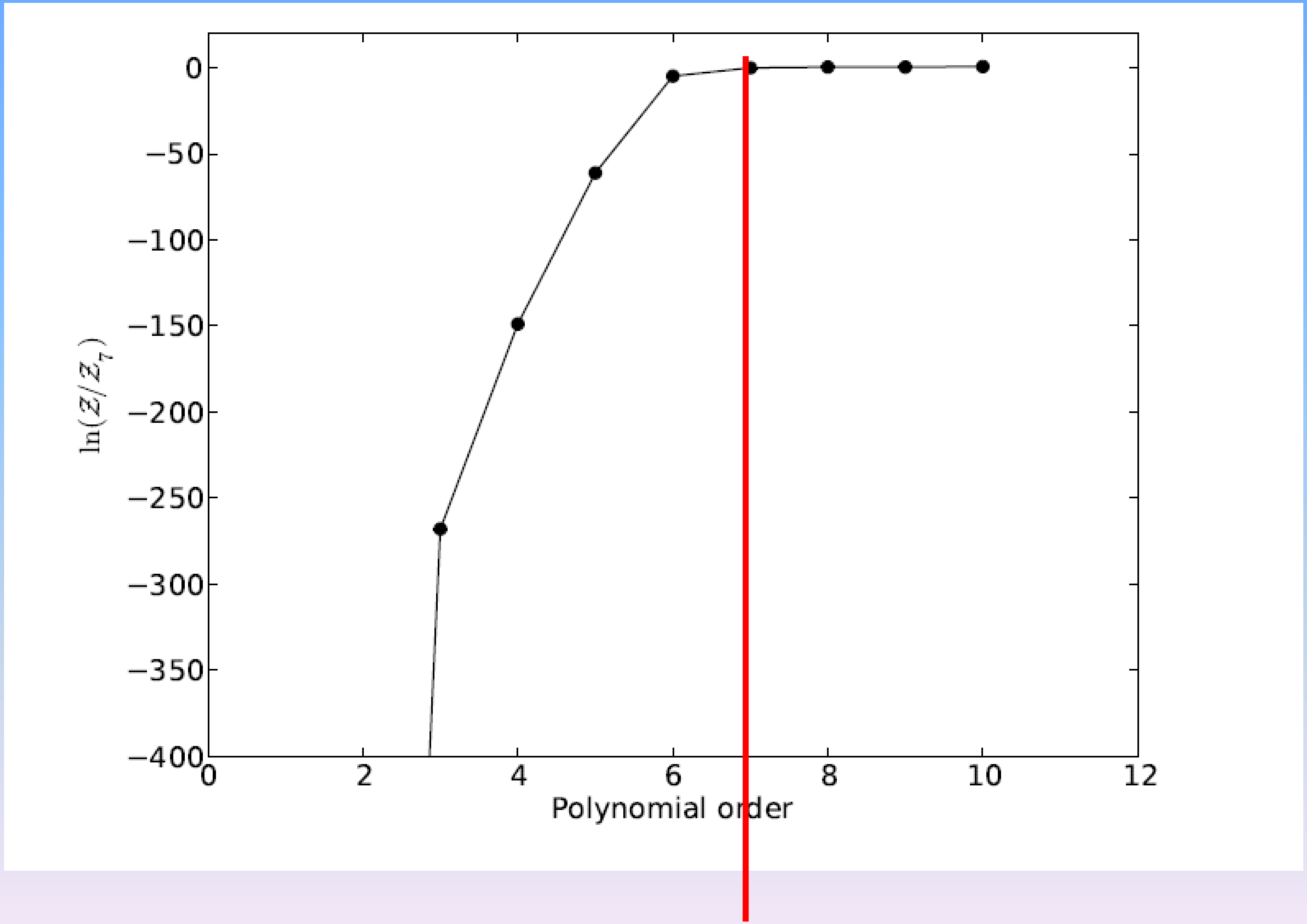


400 hours integration assumed

Bayesian signal extraction: a simulated case

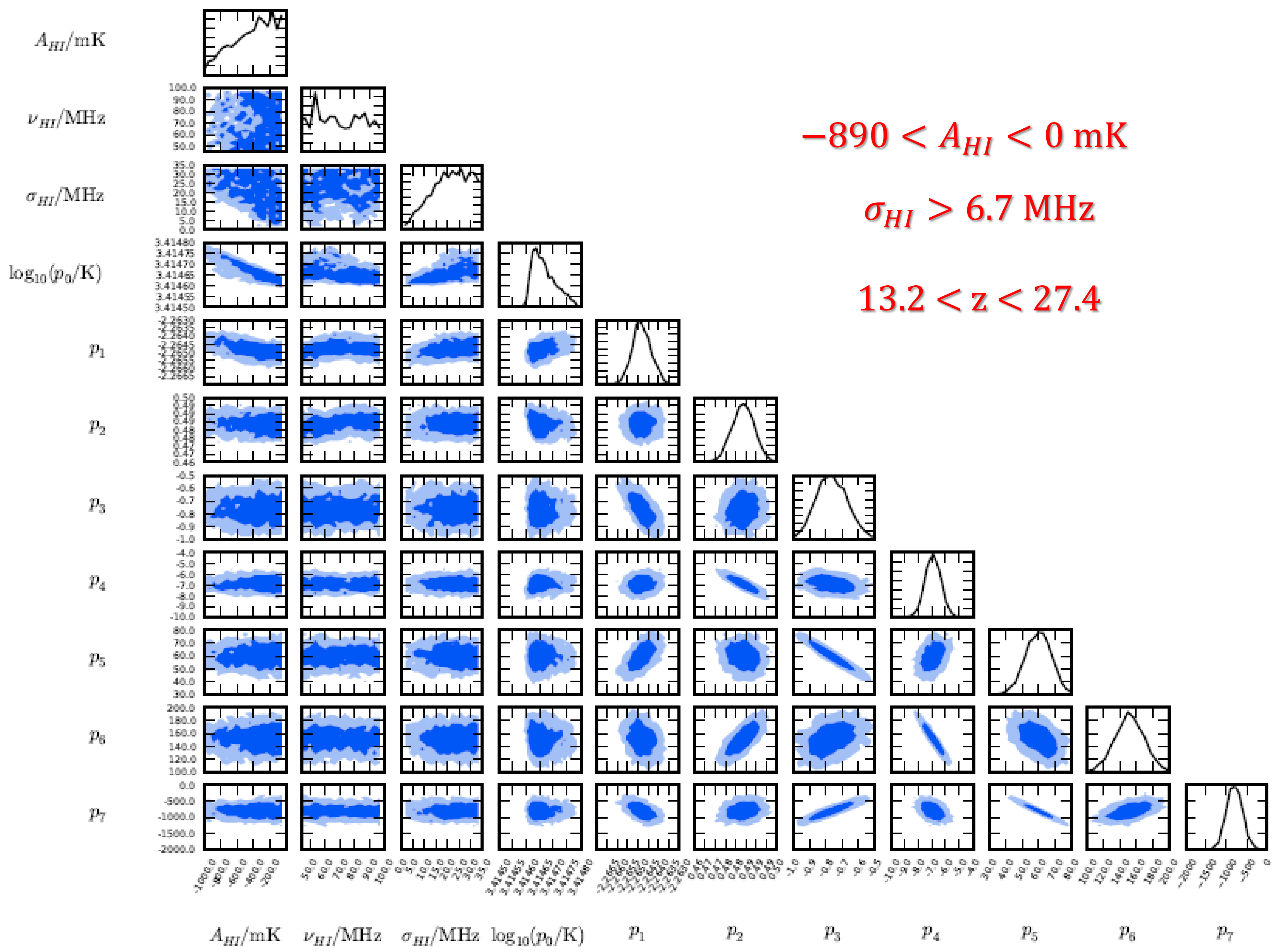


Application to data: evidence-based model selection



the evidence is maximum for a N=7 order polynomial foreground model

Upper limits on the 21 cm signal from the Cosmic Dawn



$-890 < A_{HI} < 0$ mK

$\sigma_{HI} > 6.7$ MHz

$13.2 < z < 27.4$

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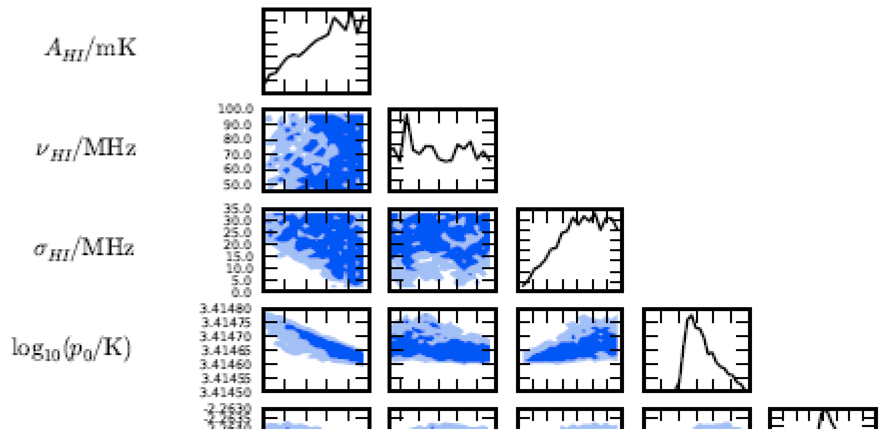

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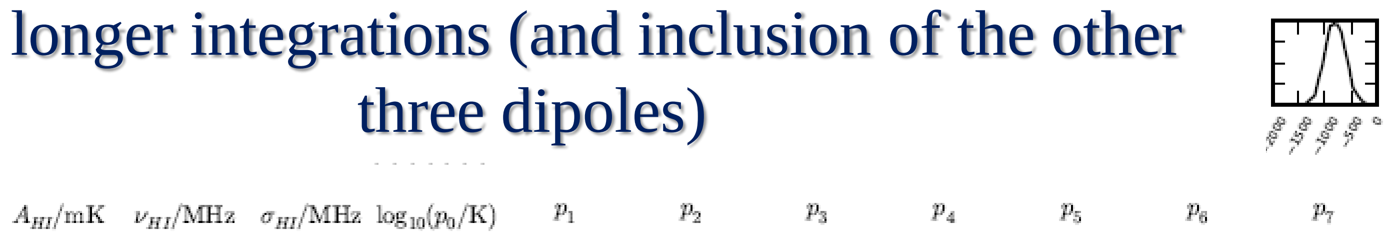
If we consider an extreme model with no heating and full Lyα coupling ($x_{HI} = 1, \delta = 1, T_s = T_k$):

$$A_{HI} \approx 27\left(1 - \frac{1+z_d}{1+z}\right)\sqrt{\frac{(1+z)}{10}\frac{0.15}{\Omega_m}\frac{\Omega_b h}{0.023}} \text{ mK}$$

$$A_{HI} \approx -300 \text{ mK @ z = 22.5}$$

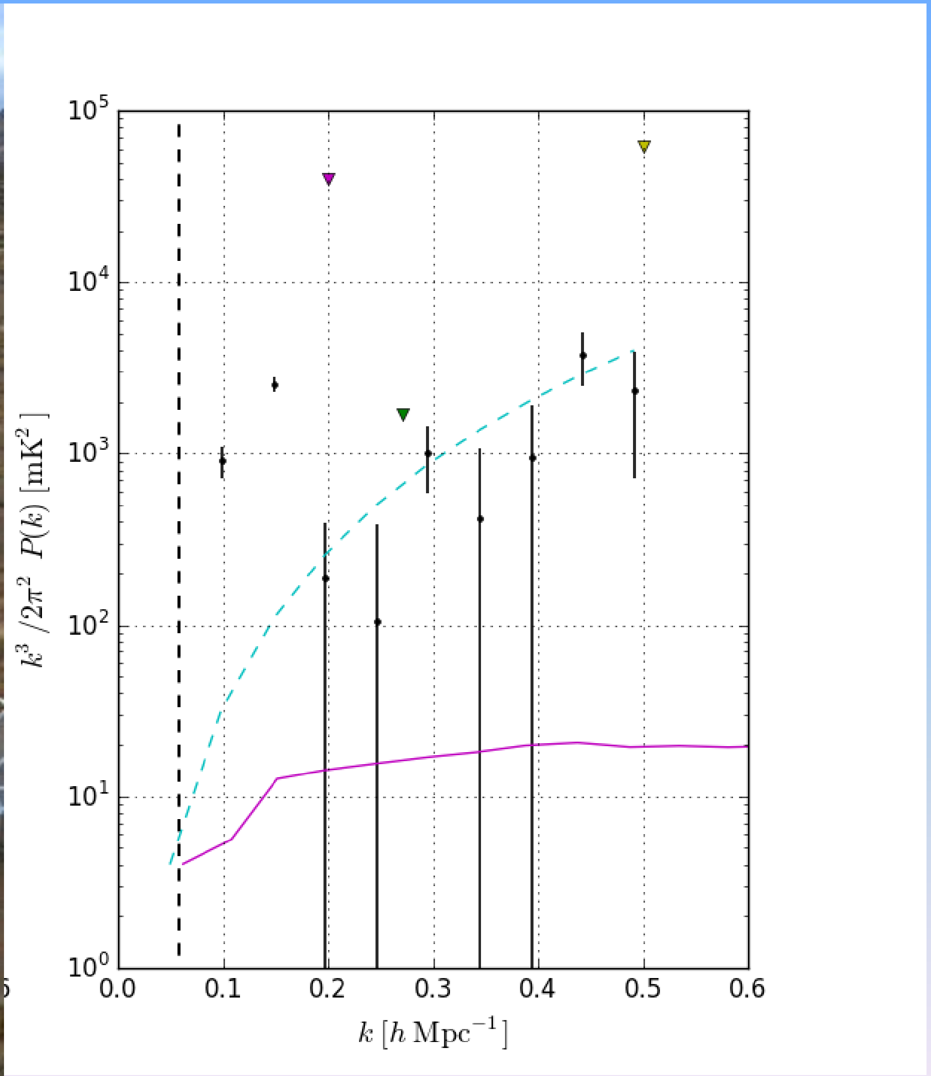
…

meaningful constrains on the IGM temperature coming with longer integrations (and inclusion of the other three dipoles)



PAPER upper limits on the 21 cm power spectrum @ z = 8.4

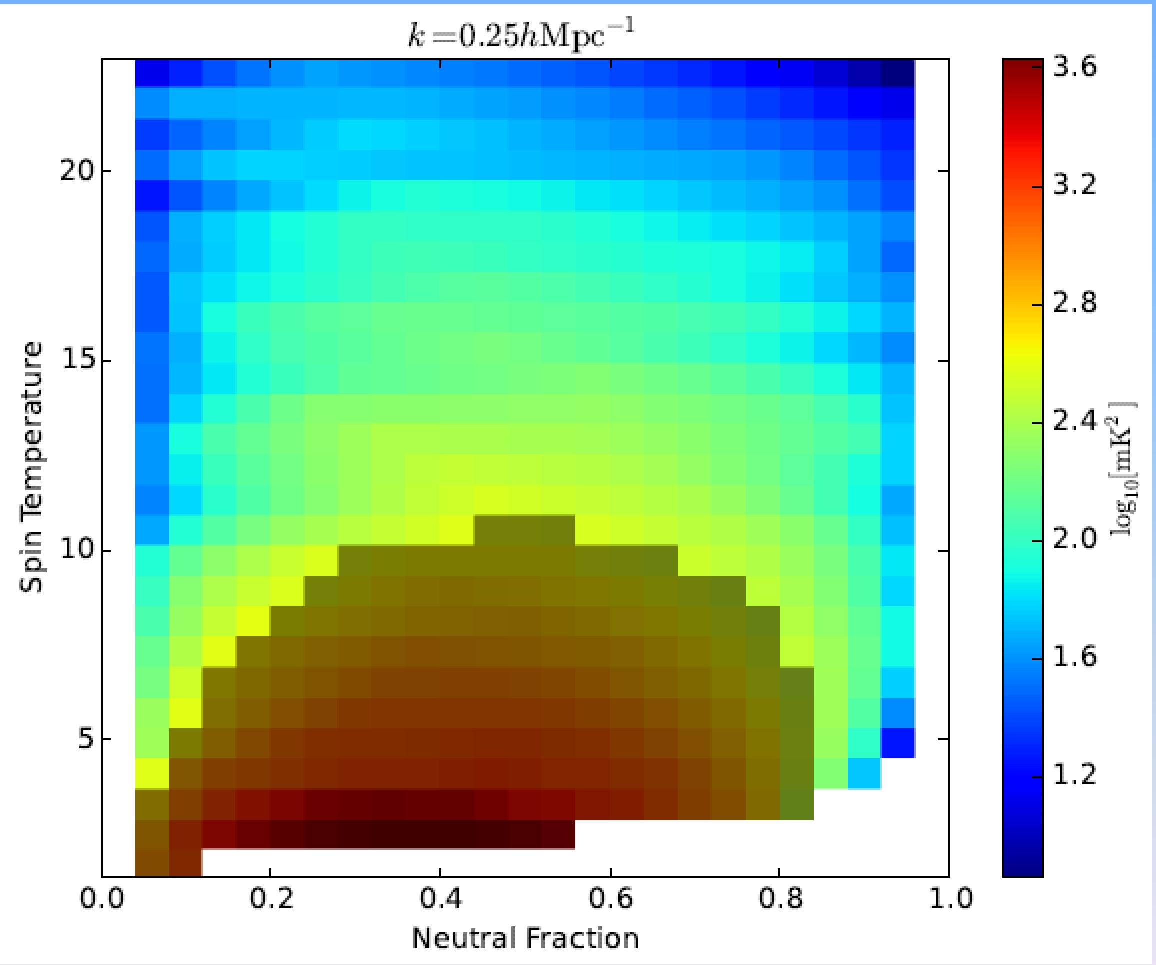
(Ali et al. 2015, Pober et al. 2015)



PAPER

(Ali et al. 2015)

Constrains on the IGM temperature at z = 8.4



- modeling performed with 21cmFAST;
- the X-ray emissivity ϵ_X is used as a single free parameter to determine the heating history;

$\delta T_s > 10$ K @ z = 8.4 for $15\% < x_{HI} < 80\%$

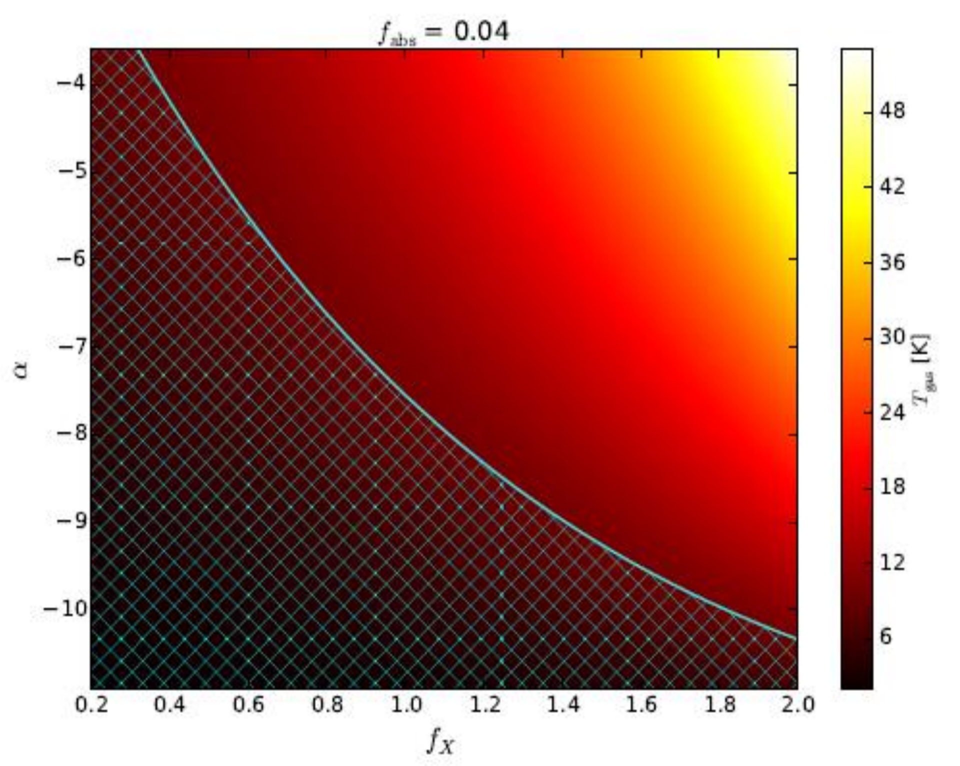
(Pober et al. 2015)

Constraints on physical models

The X-ray emissivity is parameterized as:

$$\epsilon_X \propto f_X f_{abs} \dot{\rho}_{SFR}$$

- f_X is the star formation rate/X ray luminosity correlation;
- f_{abs} is the fractional (X-ray) energy that heats the IGM;
- $\dot{\rho}_{SFR}$ is the star formation rate density, $\dot{\rho}_{SFR} \propto (1+z)^{\alpha}$



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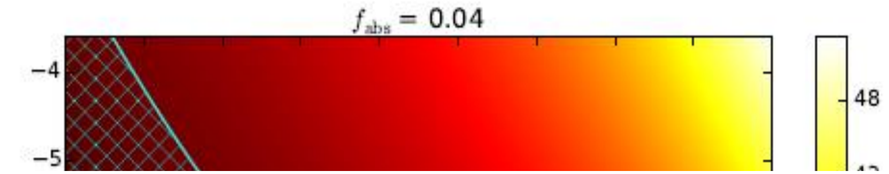
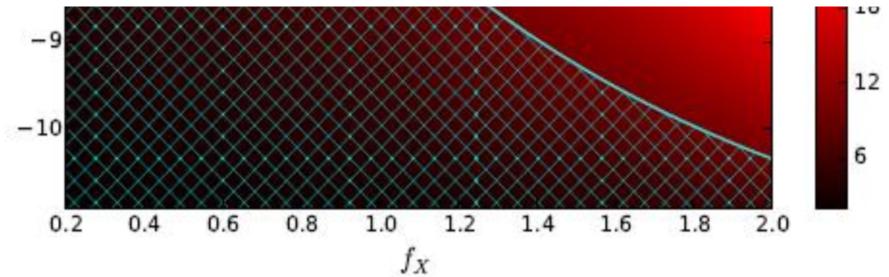
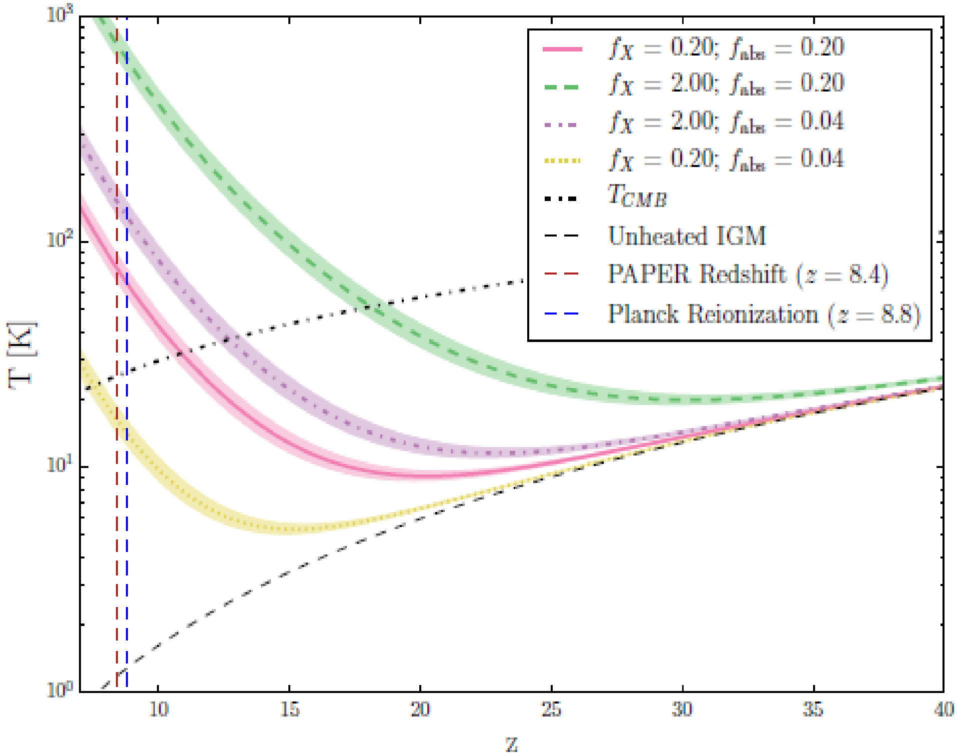


using the galaxy population model from Robertson et al. (2015) → no unknown galaxy population needed to heat the IGM above 10 K at z = 8.4





Looking at the future: the Hydrogen Epoch of Reionization Array (HERA)

(deBoer et al. 2016)

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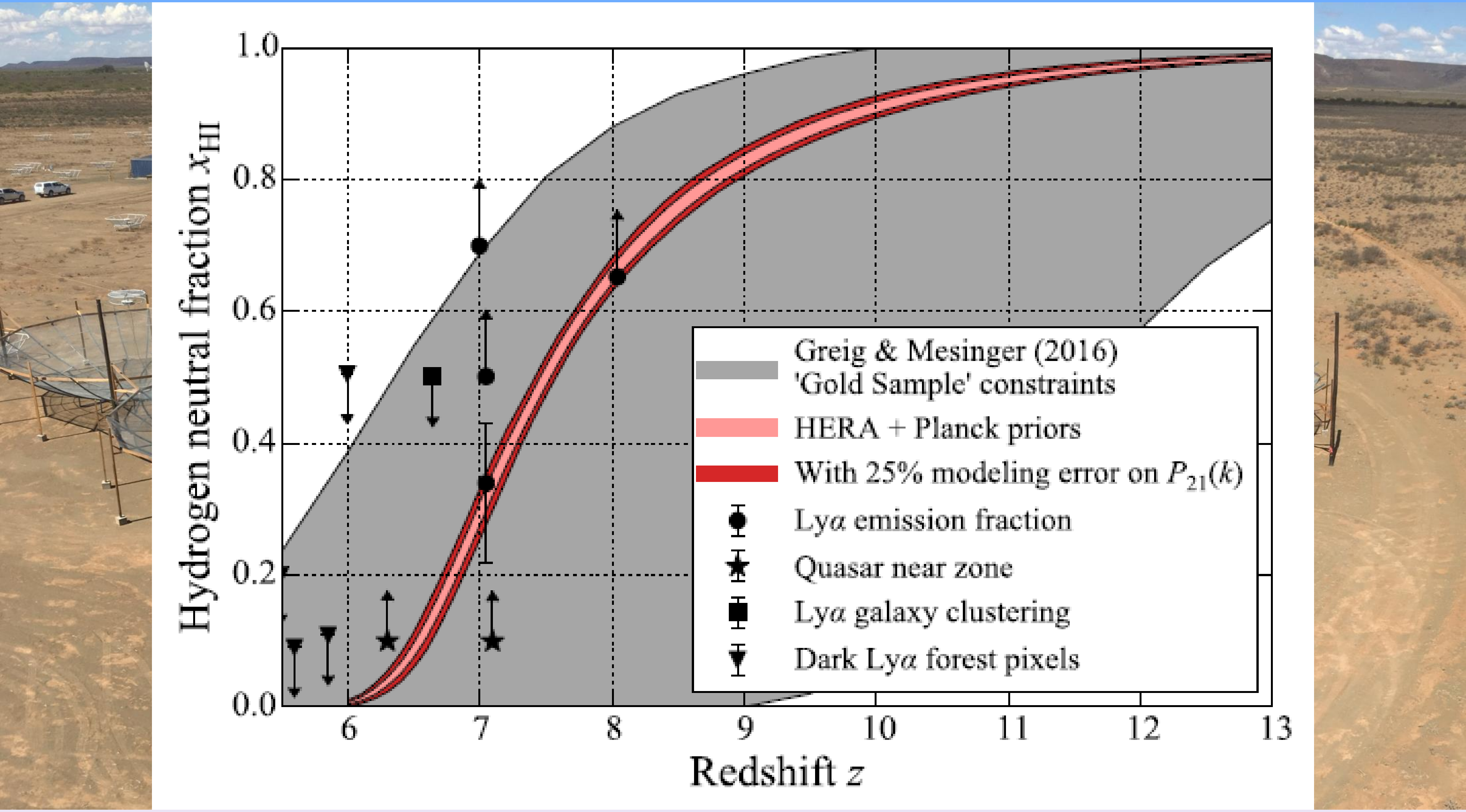

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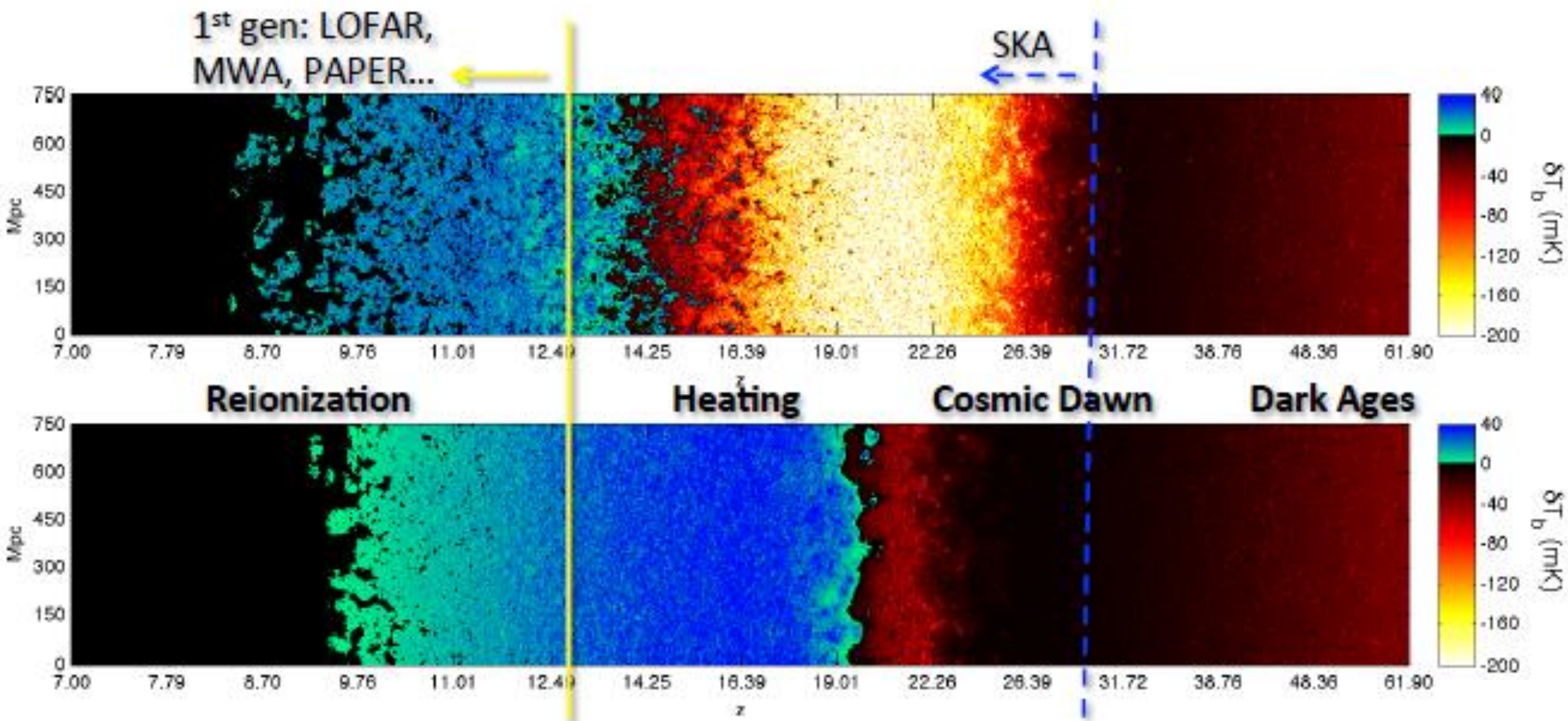
Looking at the future: the Square Kilometre Array (SKA)



Mesinger et al. (2015), Koopmans et al. (2015)

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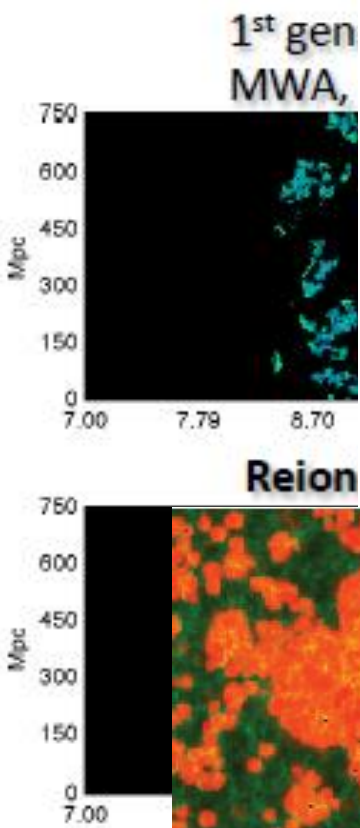

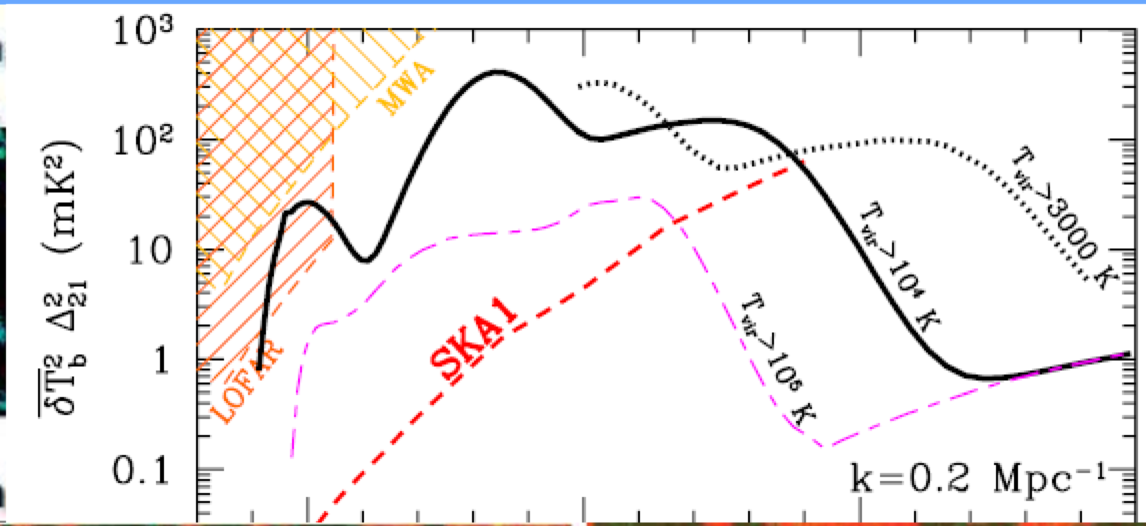

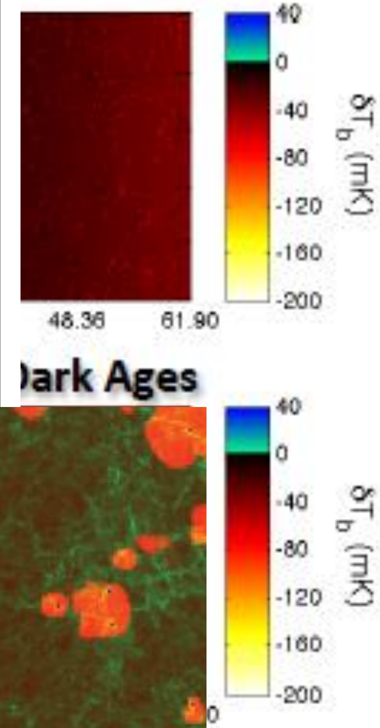

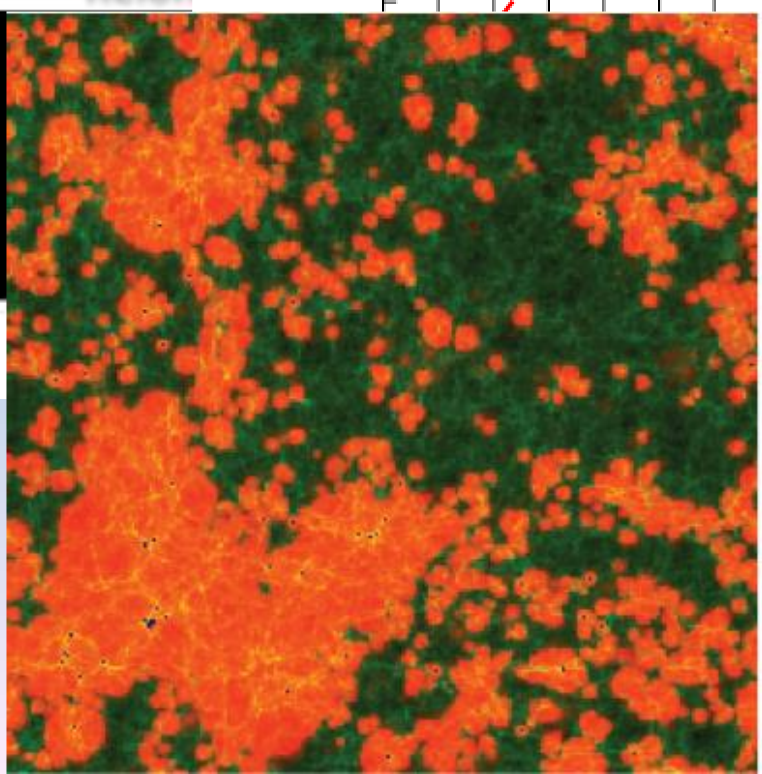

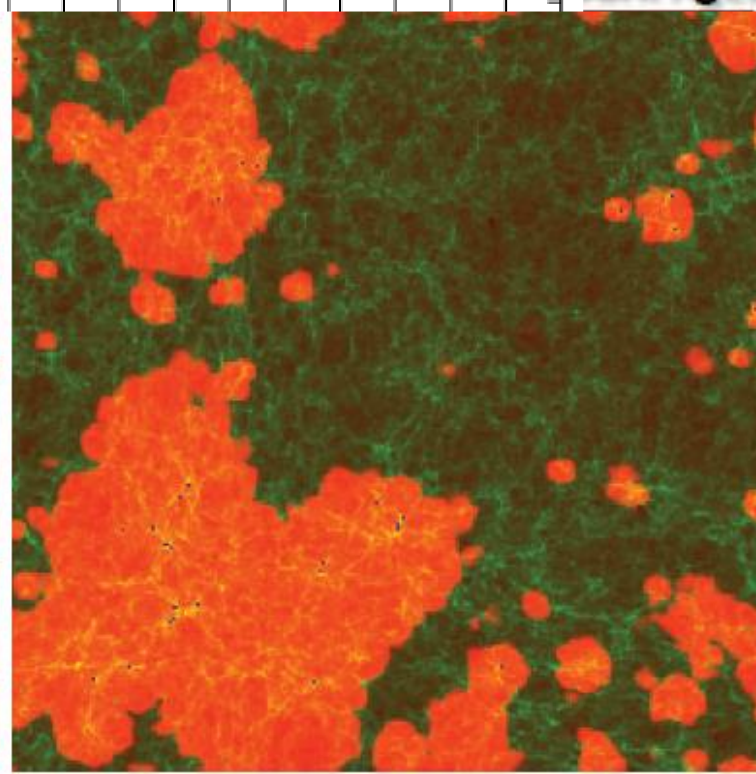

al. (2015)

Conclusions

- **The study of cosmic reionization (and beyond!) with the 21 cm line (21 cm cosmology) is becoming a mature field;**

- Global 21 cm experiment are delivering their first results (including EDGES) and they may offer the only probe of the thermal history of the IGM prior reionization until HERA/SKA become fully operational;

- Interferometric arrays are pushing down upper limits and are well placed to start constraining the reionization history (final observing season with PAPER; LOFAR and MWA to be continued);

- The most sensitive telescopes still have to come: MWA-expanded and HERA are under construction, the SKA later down the line → still a long story to be told!

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THANK YOU