Cosmic Dawn and Reionization with the Square Kilometre Array

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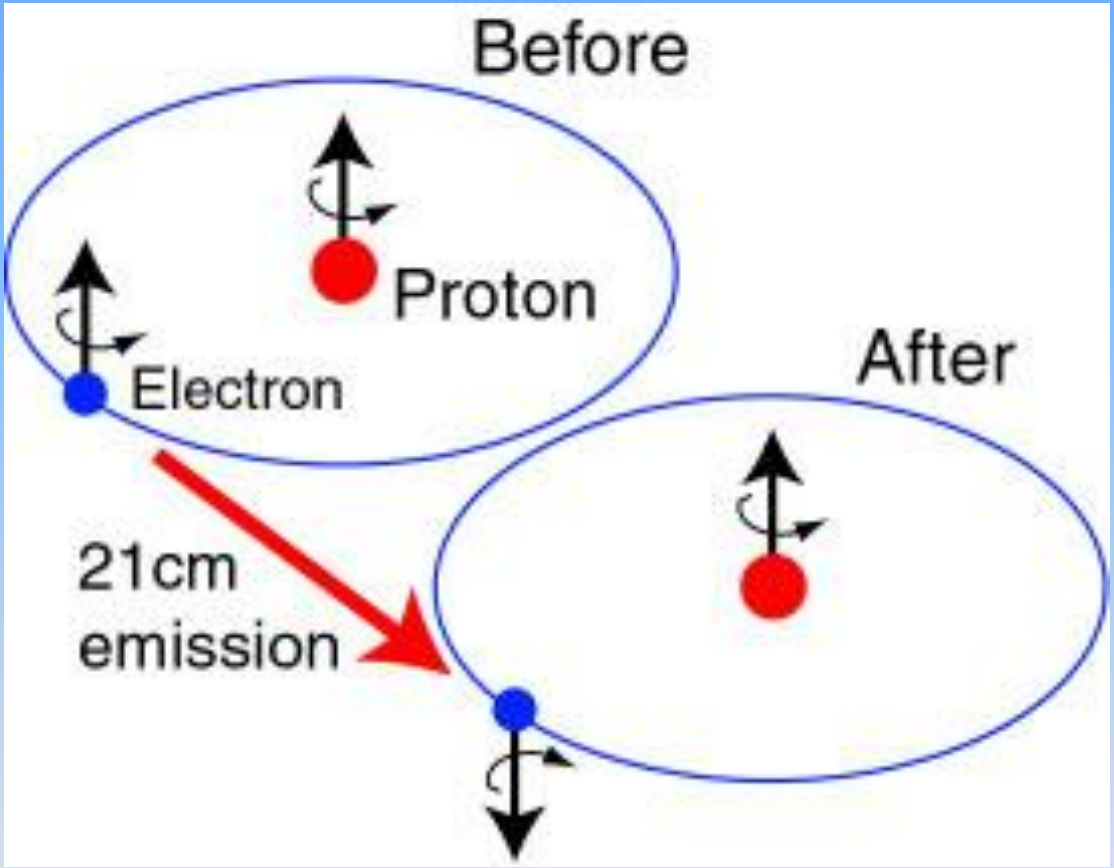
SKA SA & Rhodes University

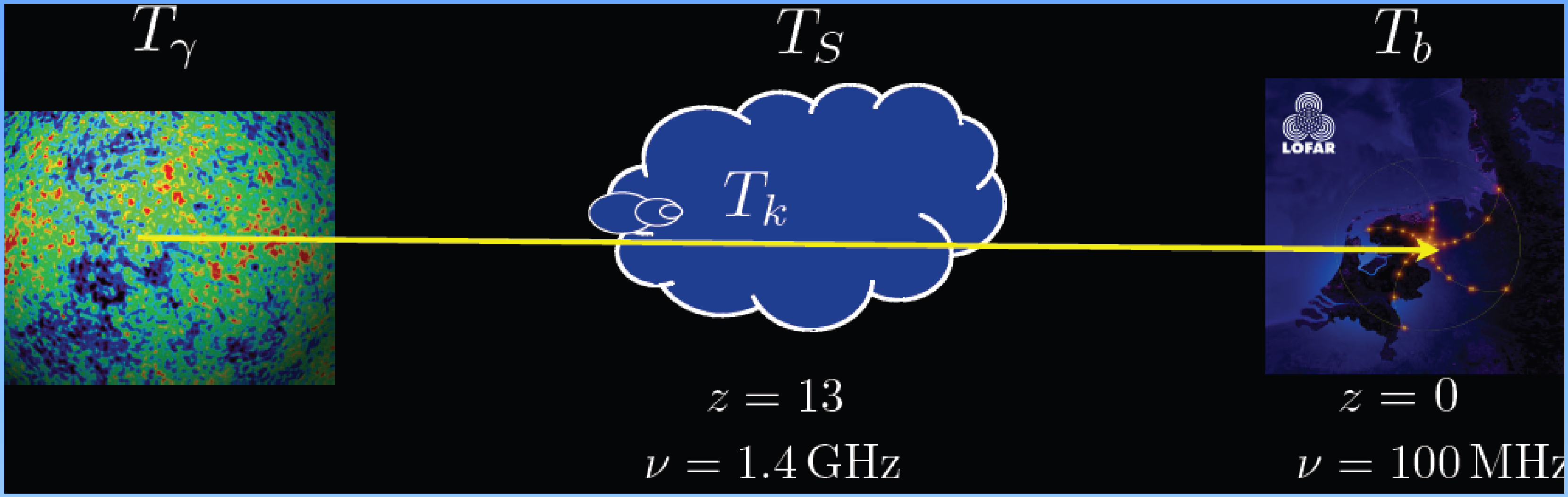
(for the HERA, LEDA and PAPER collaborations)

DIFA & OAB-INAF, May 16th 2016

21-cm cosmology



21-cm cosmology

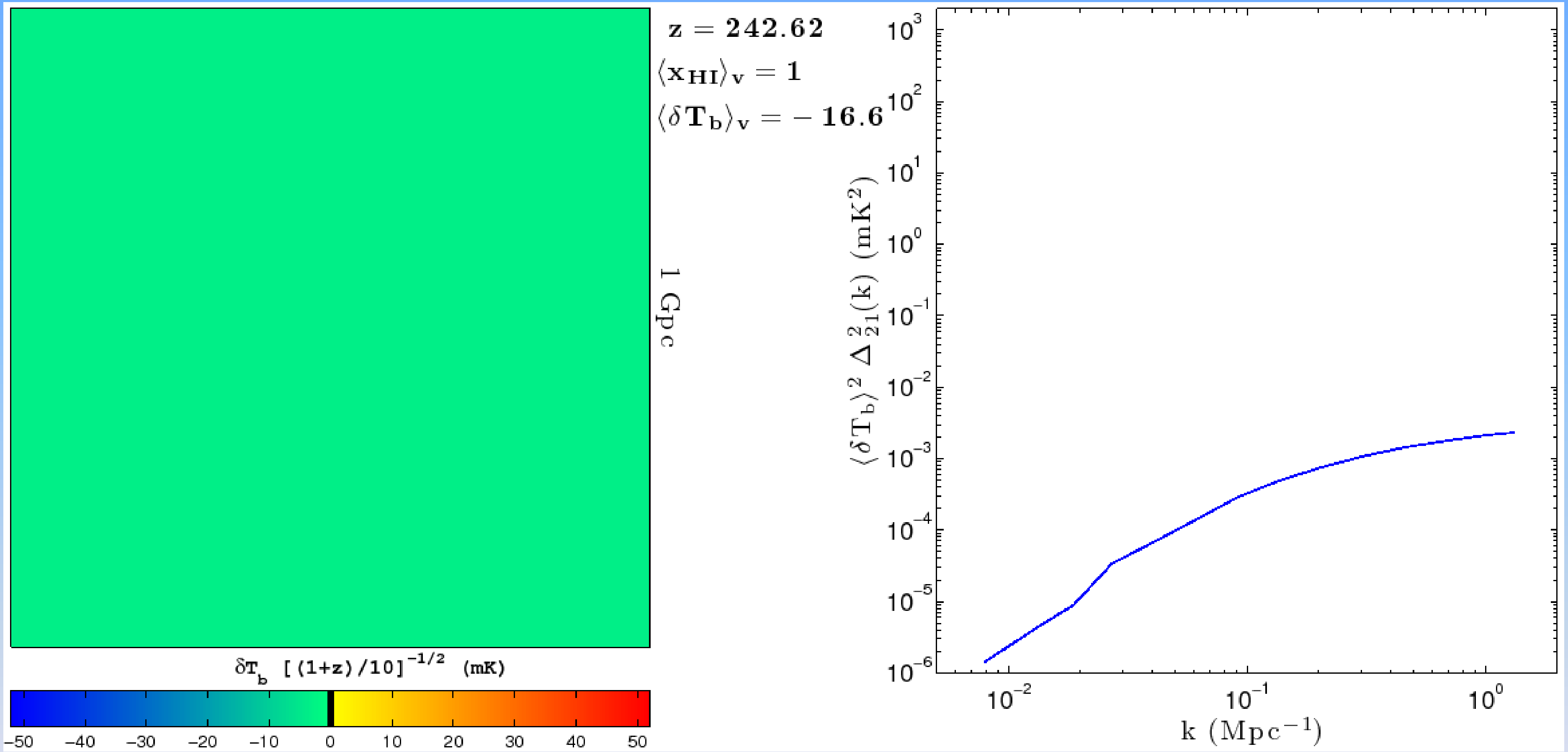


3 fundamental temperatures:

- T_γ: the CMB temperature;
- T_k: the gas (IGM) temperature;
- T_s: the spin temperature (sets the population of the hyperfine level with respect to the ground state)

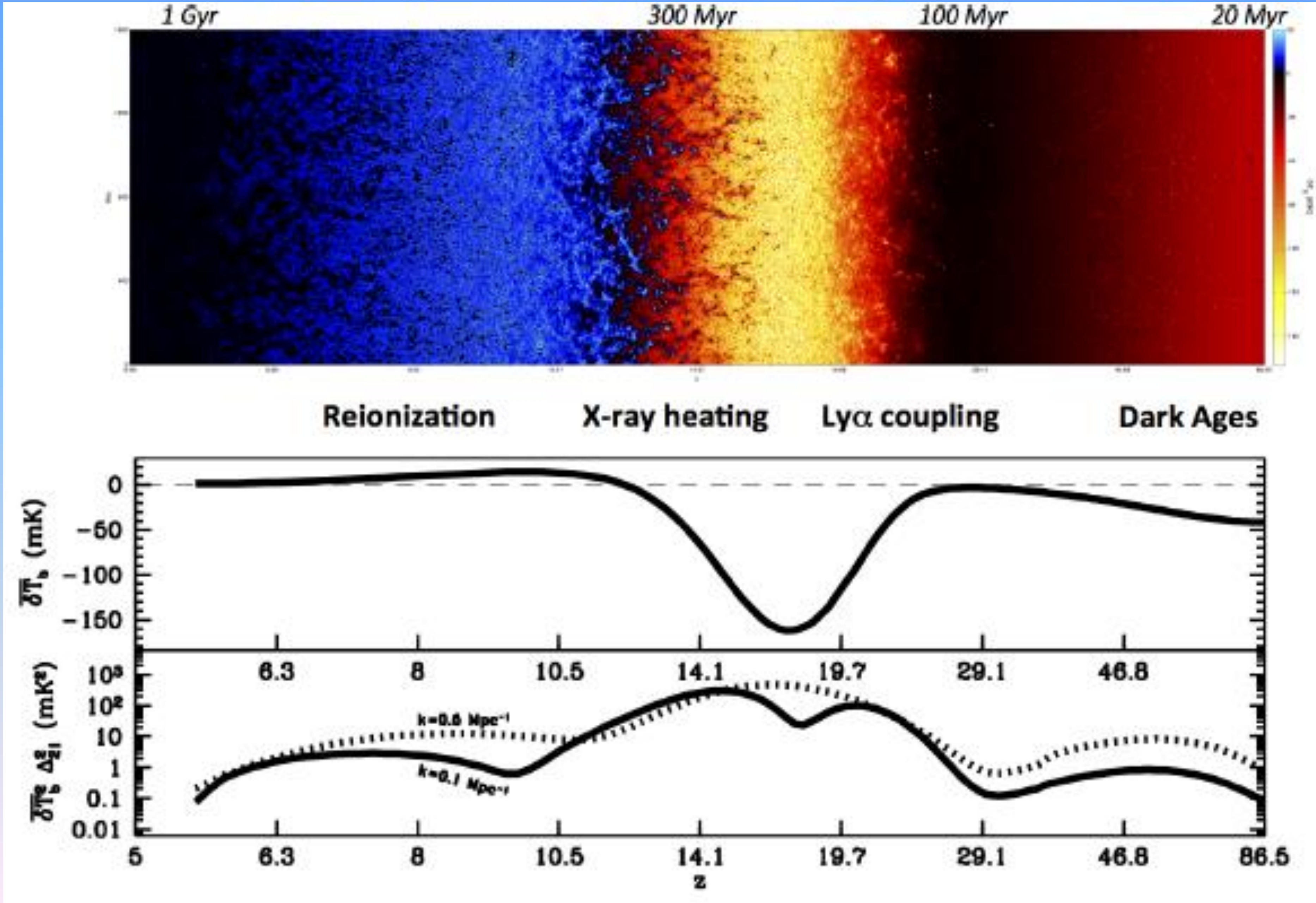
- the 21 cm line is observable when $T_s = T_k \neq T_\gamma$

Evolution of fluctuations



courtesy A. Mesinger

A few fundamental transitions



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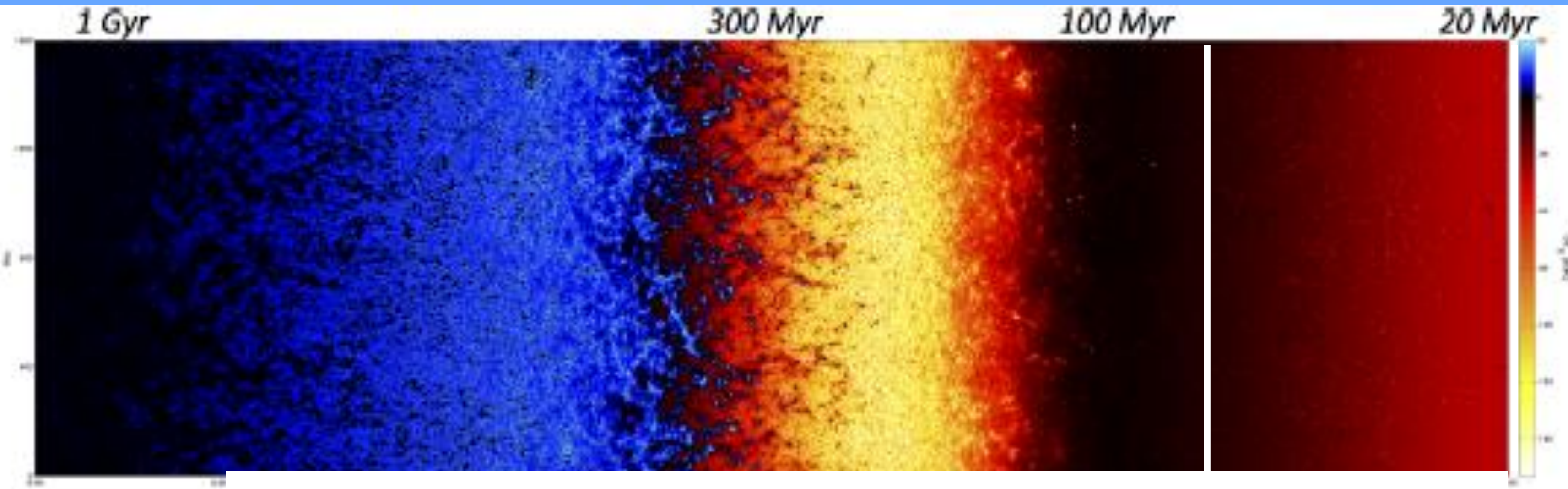
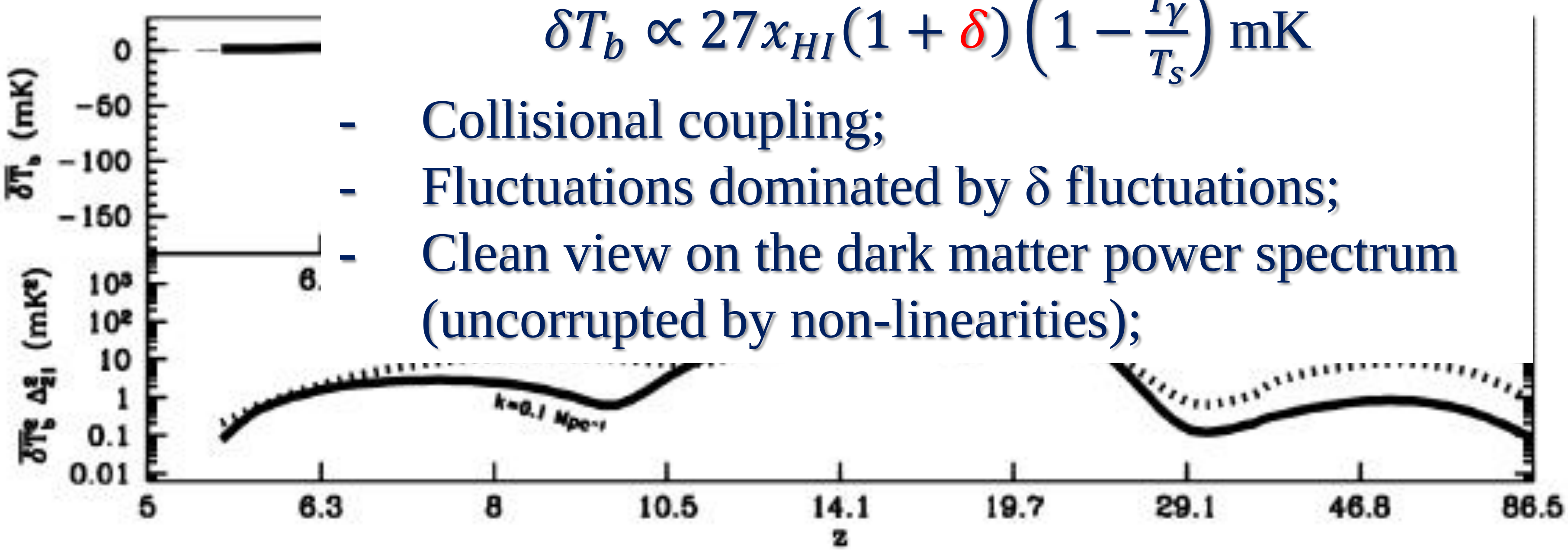


$$T_s = T_k < T_\gamma$$

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

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



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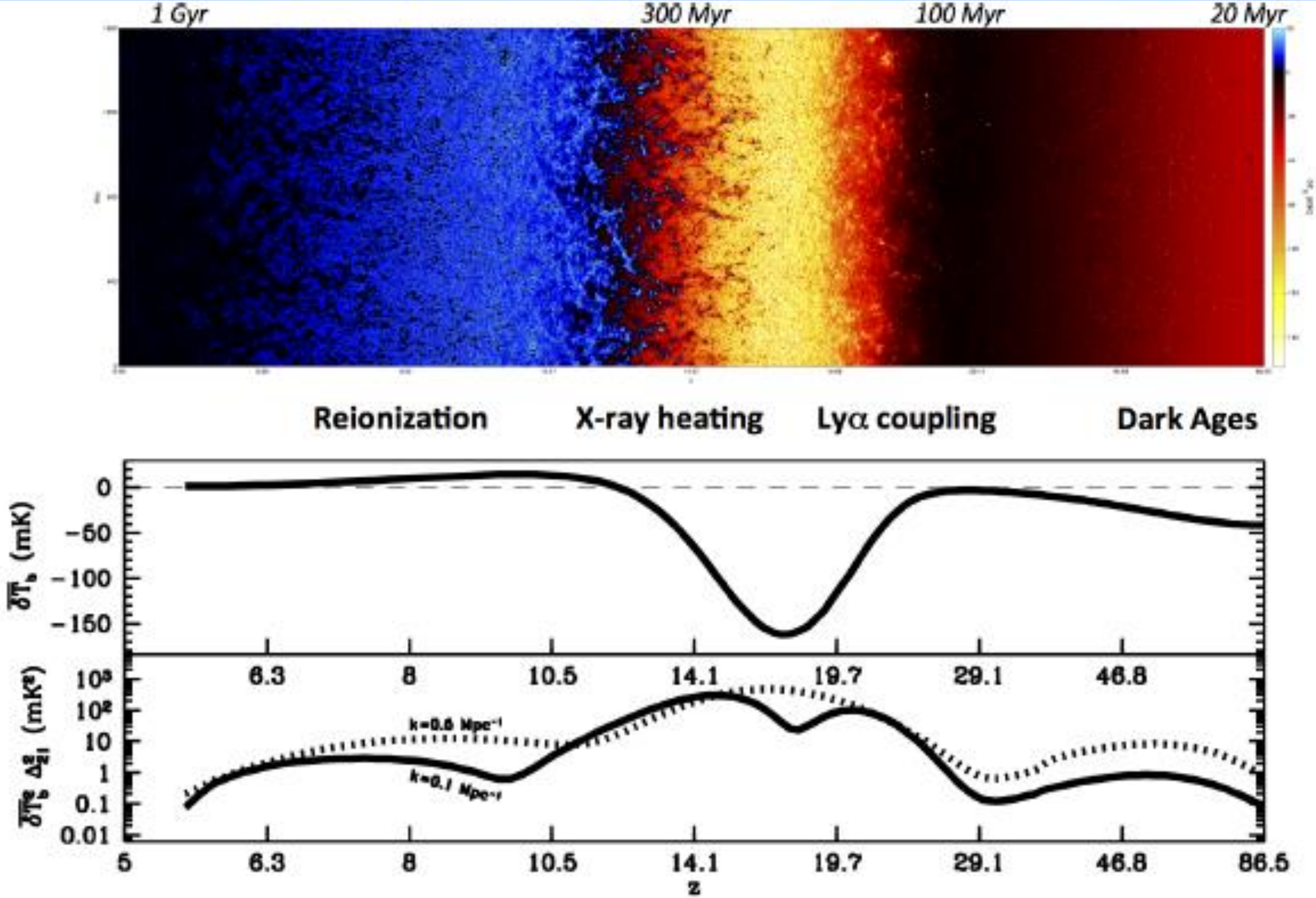

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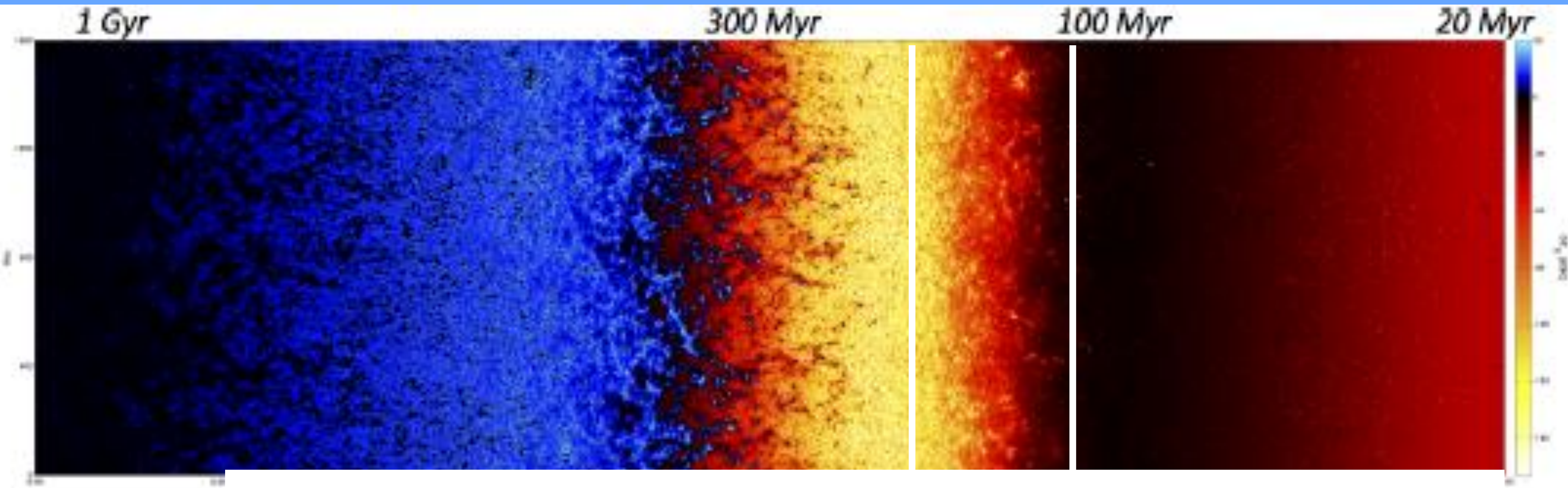
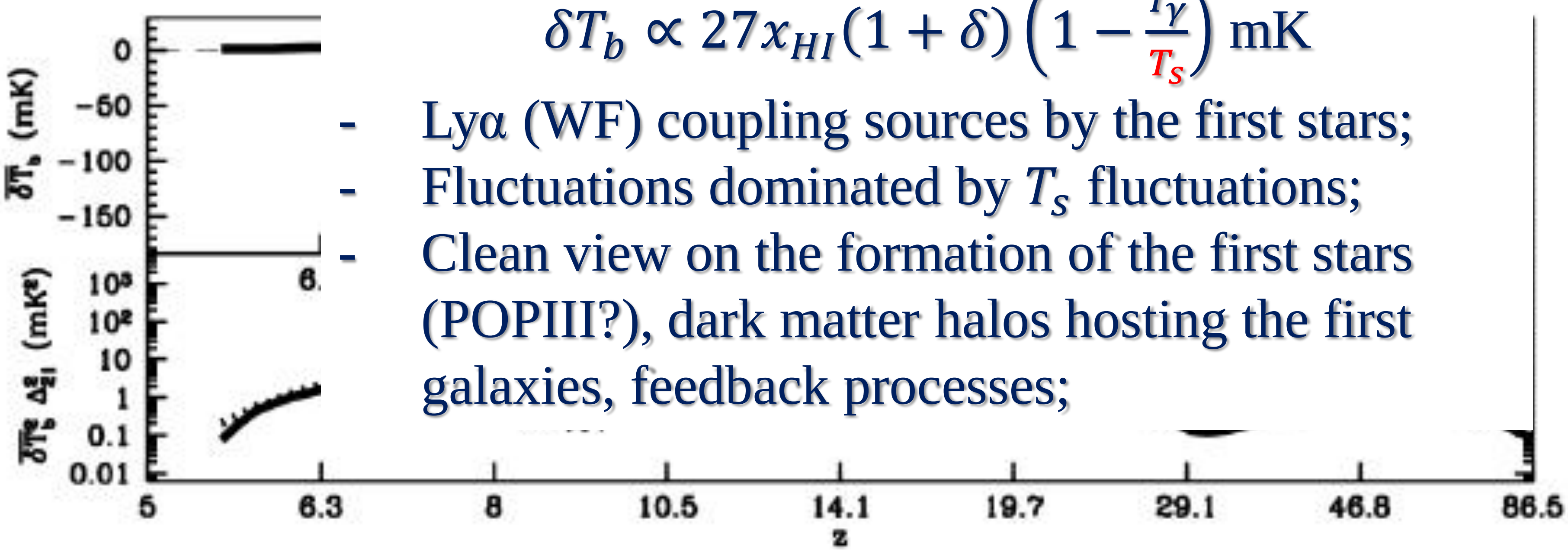


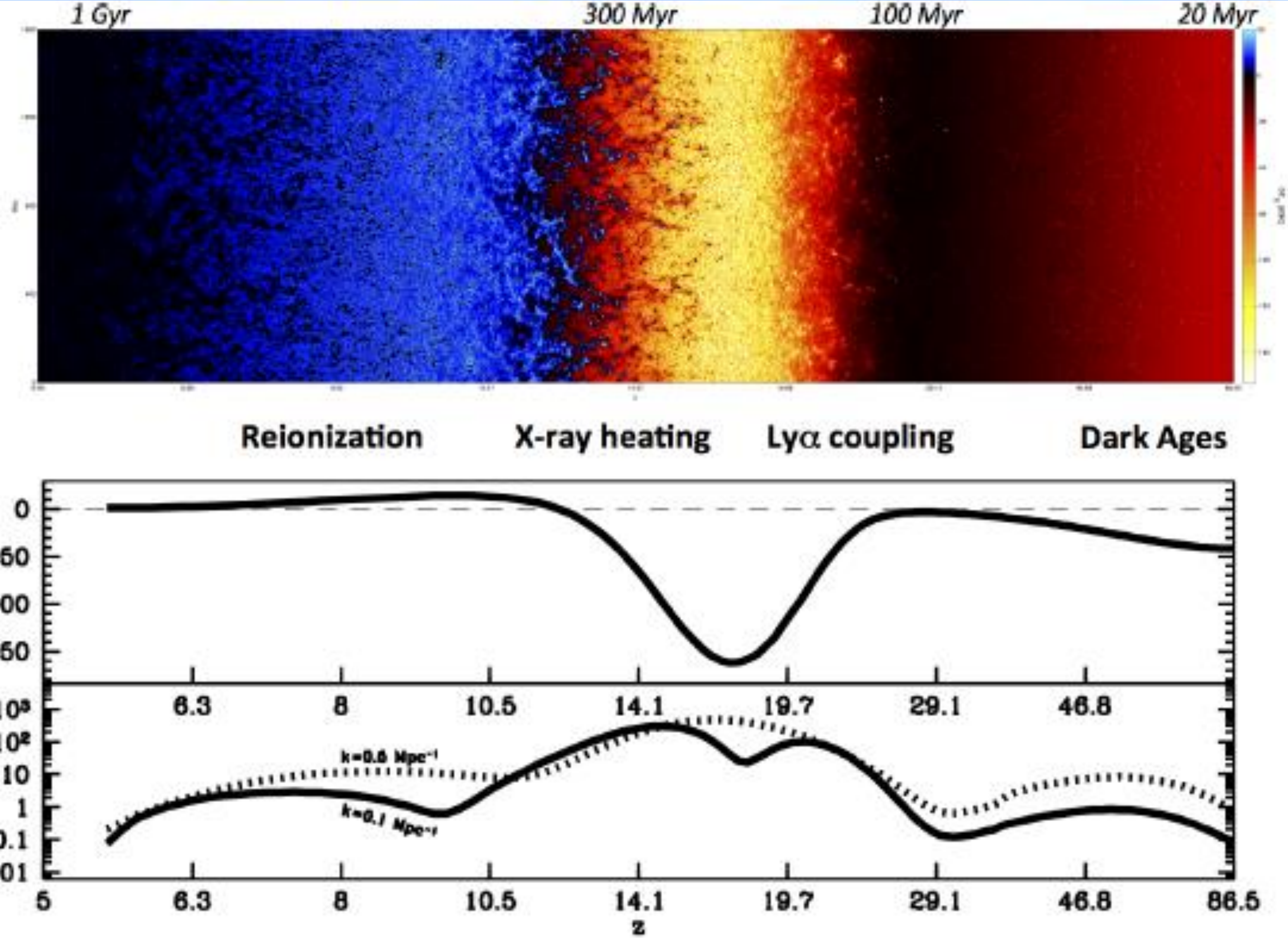
$$T_s = T_k < T_\gamma$$

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

- 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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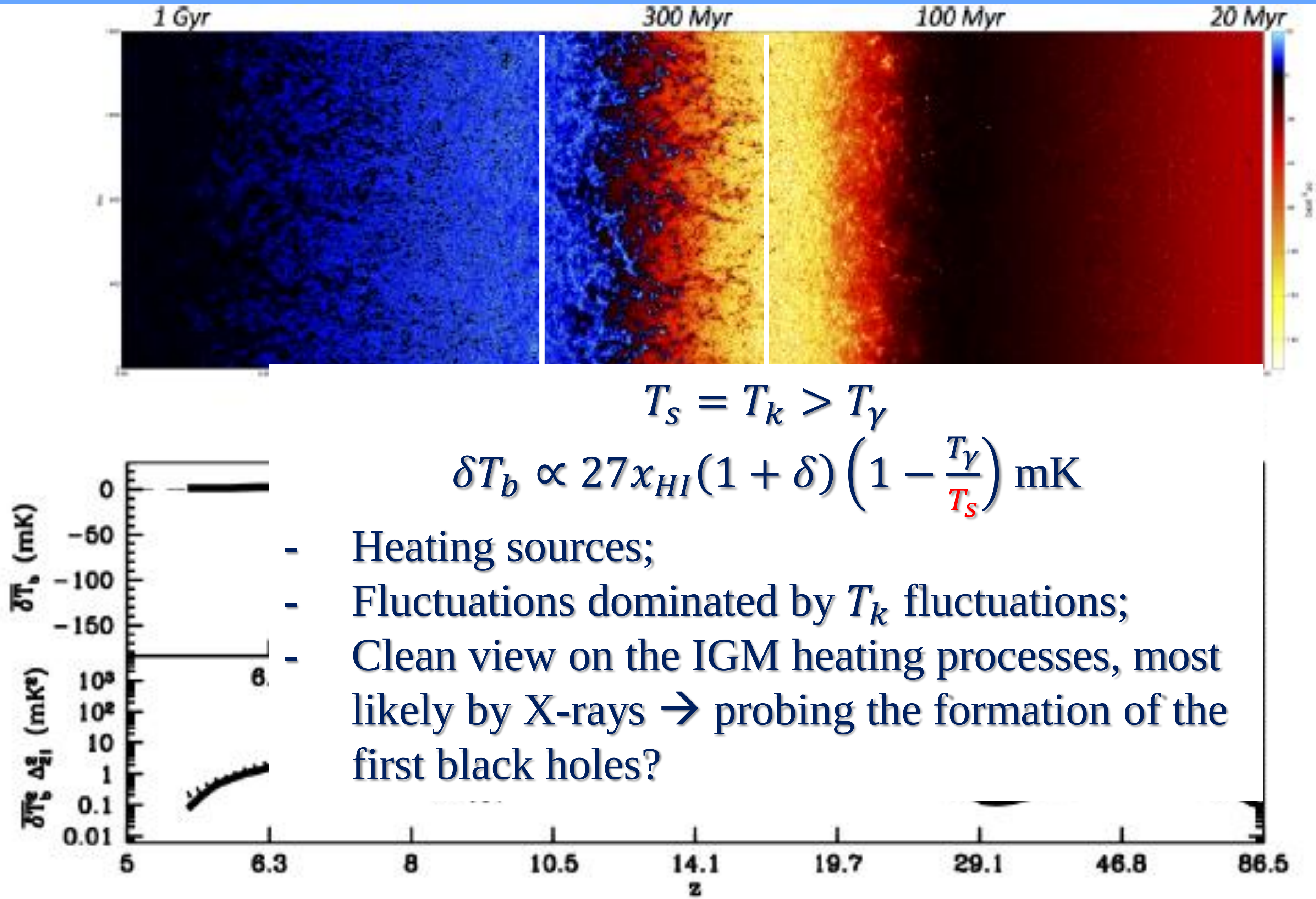
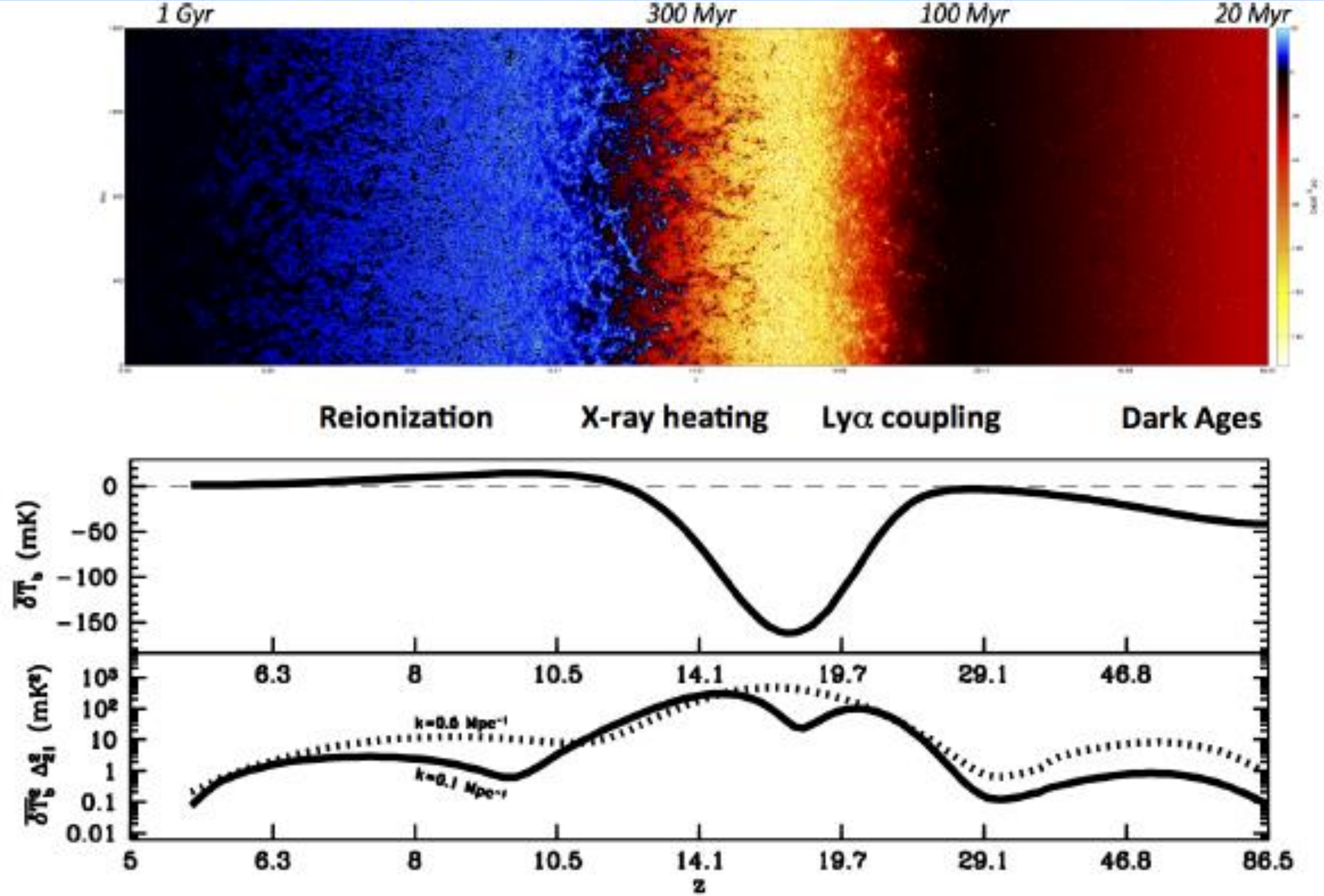


$$T_s = T_k > T_\gamma$$

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

- 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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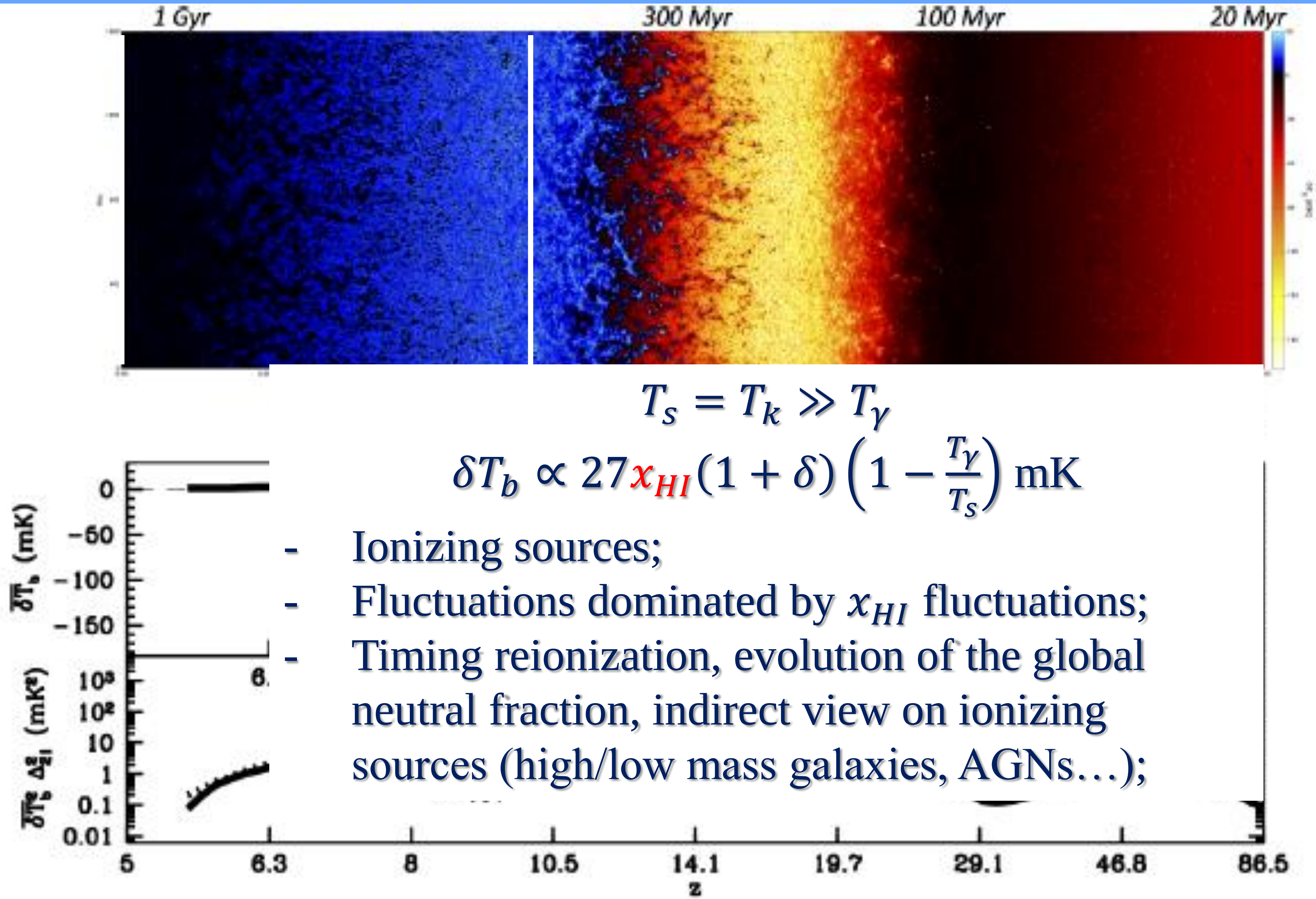
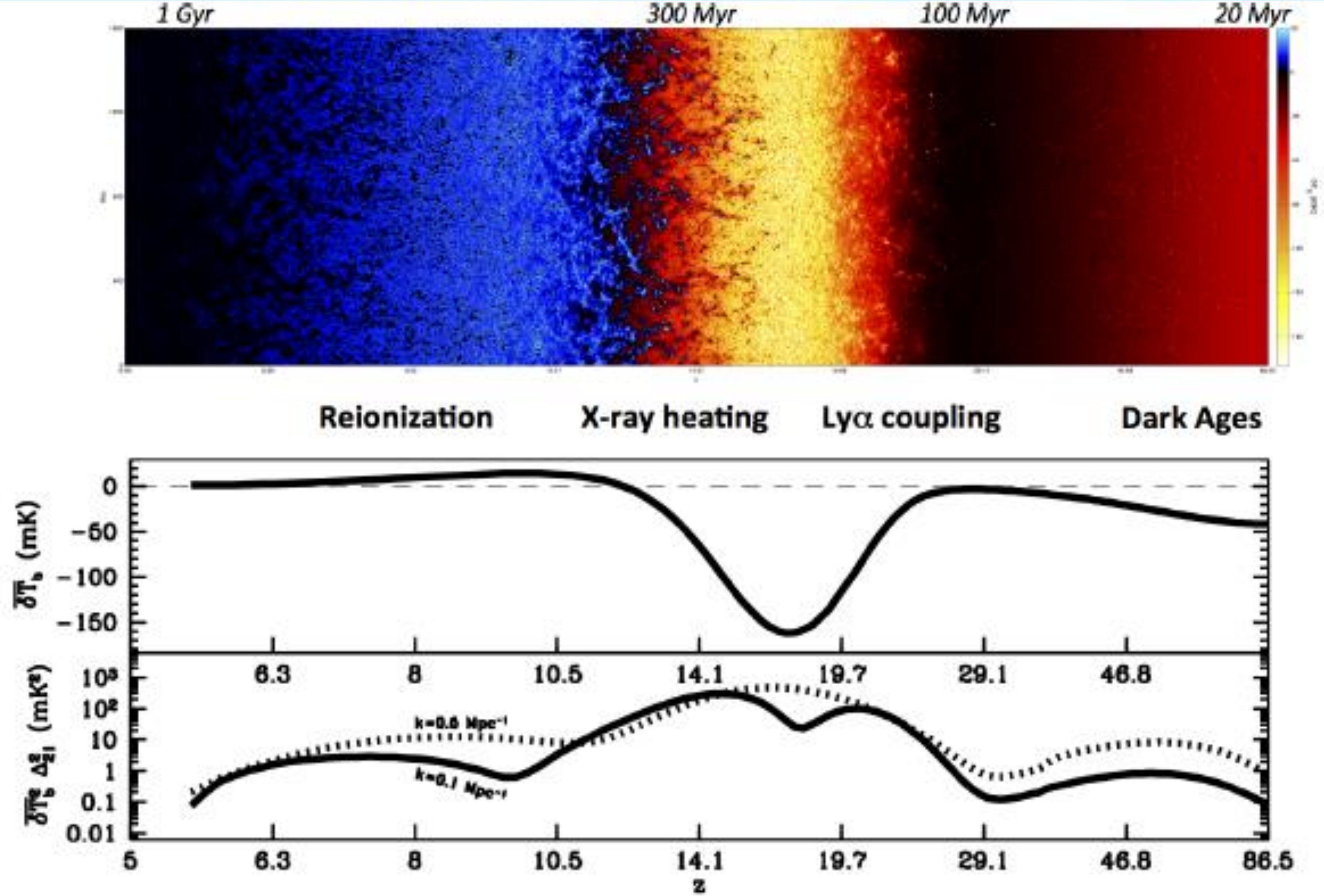


$$T_s = T_k \gg T_\gamma$$

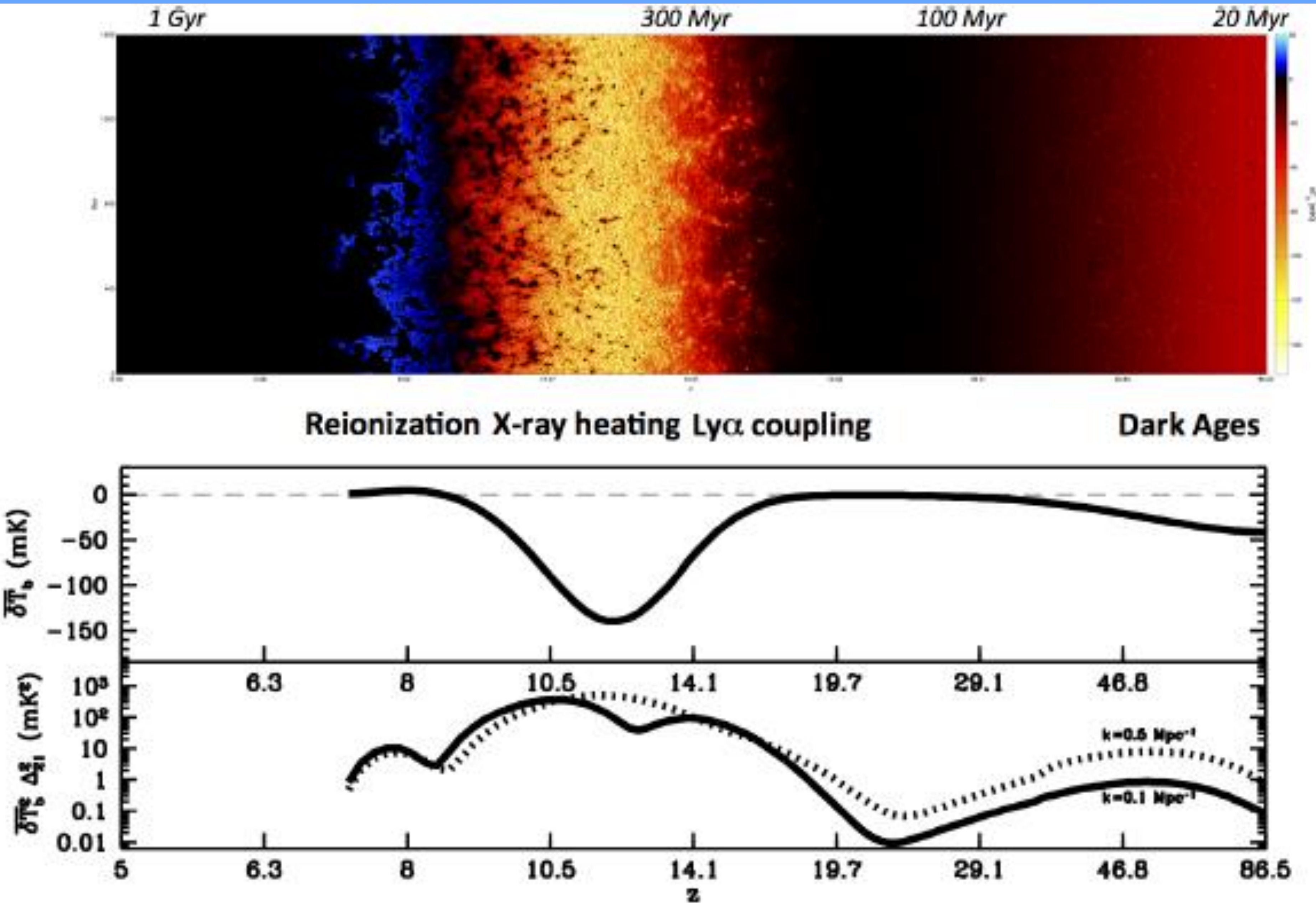
$$\delta T_b \propto 27 x_{HI} (1+\delta)\left(1 - \frac{T_\gamma}{T_s}\right)\,\mathrm{mK}$$

- 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…);

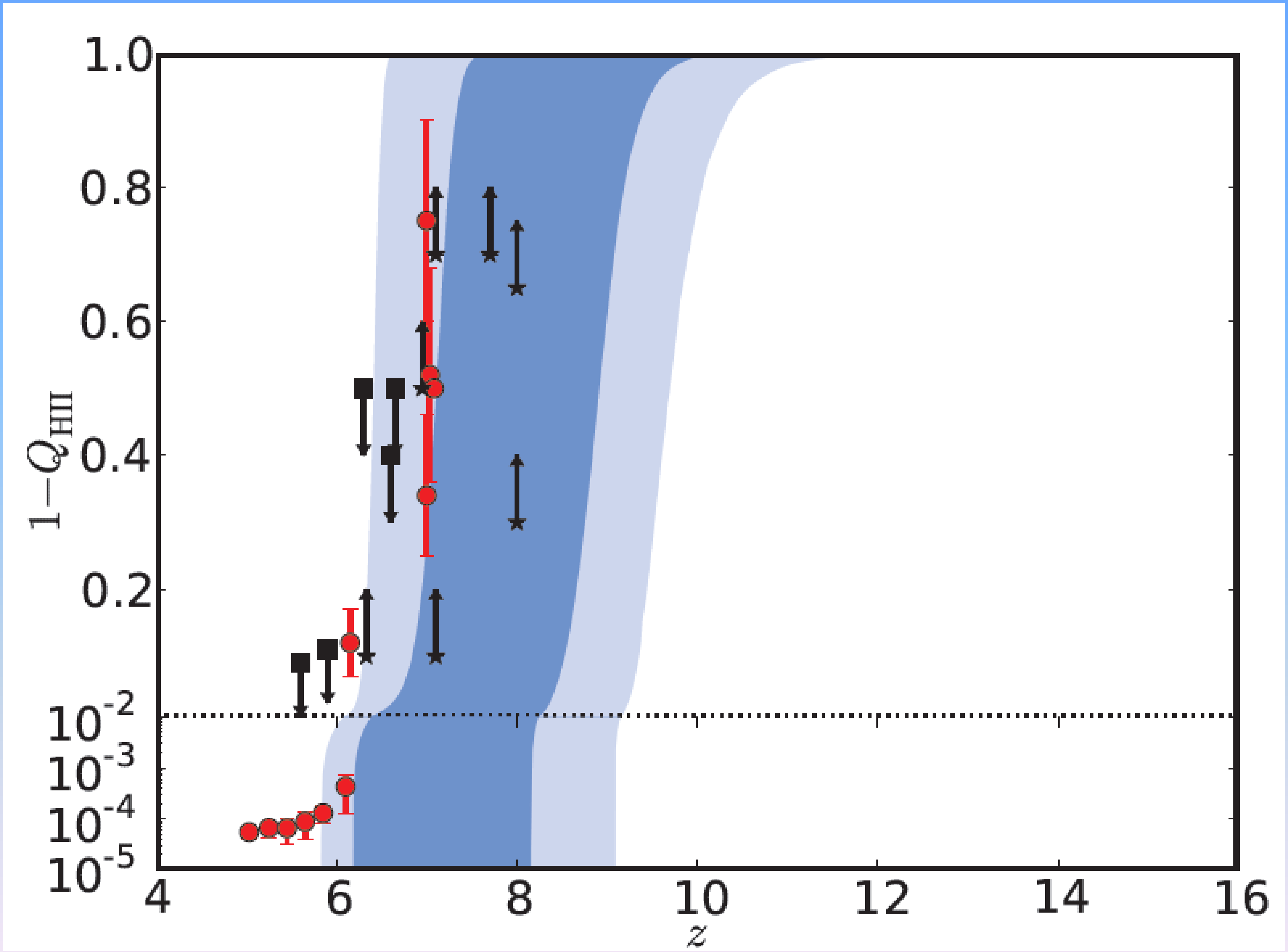
Evolution of fluctuations



Evolution of fluctuations

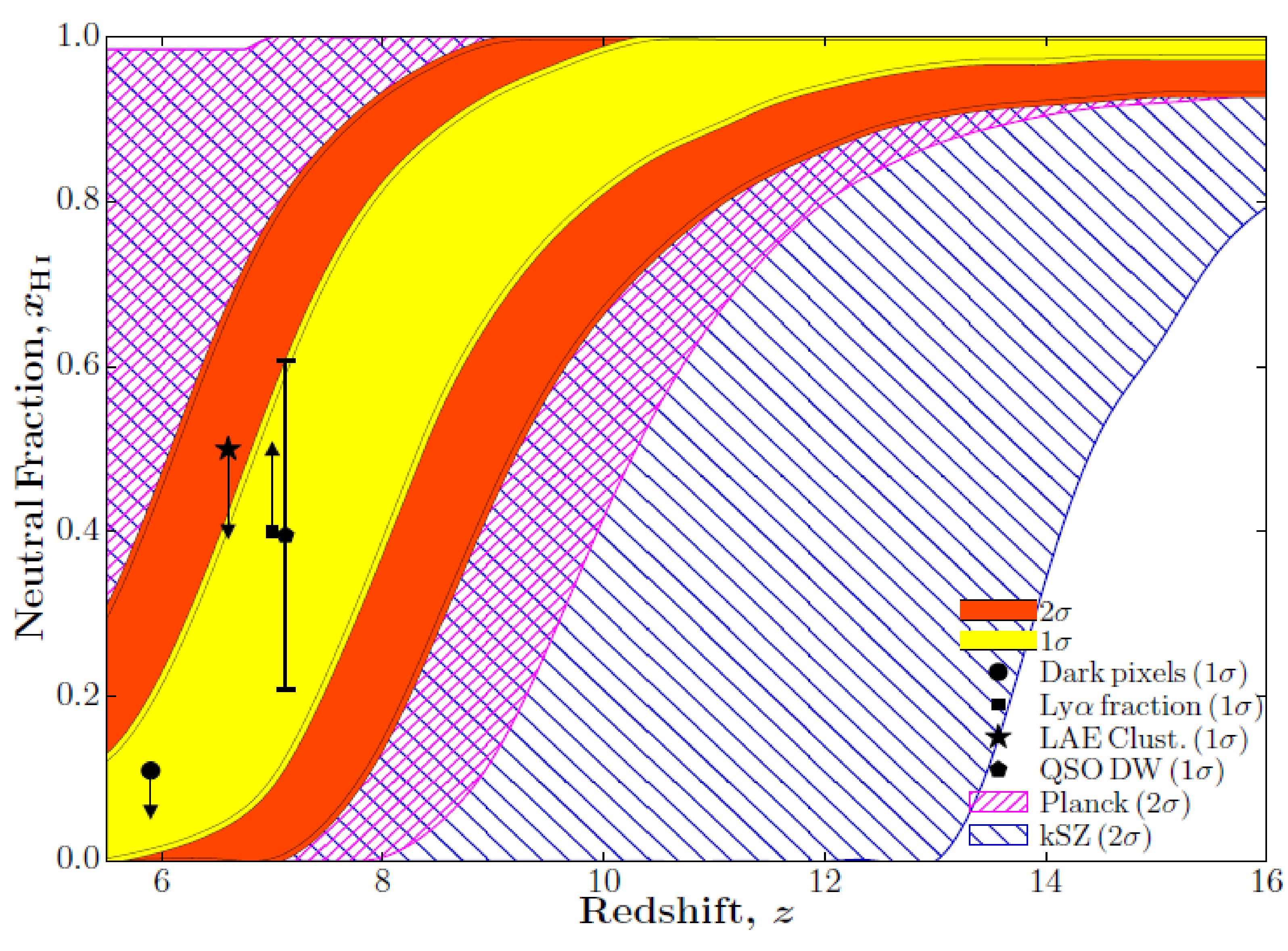


Current constraints on reionization



Planck Collaboration (2015)

Current constraints on reionization



Greig & Mesinger (2016)

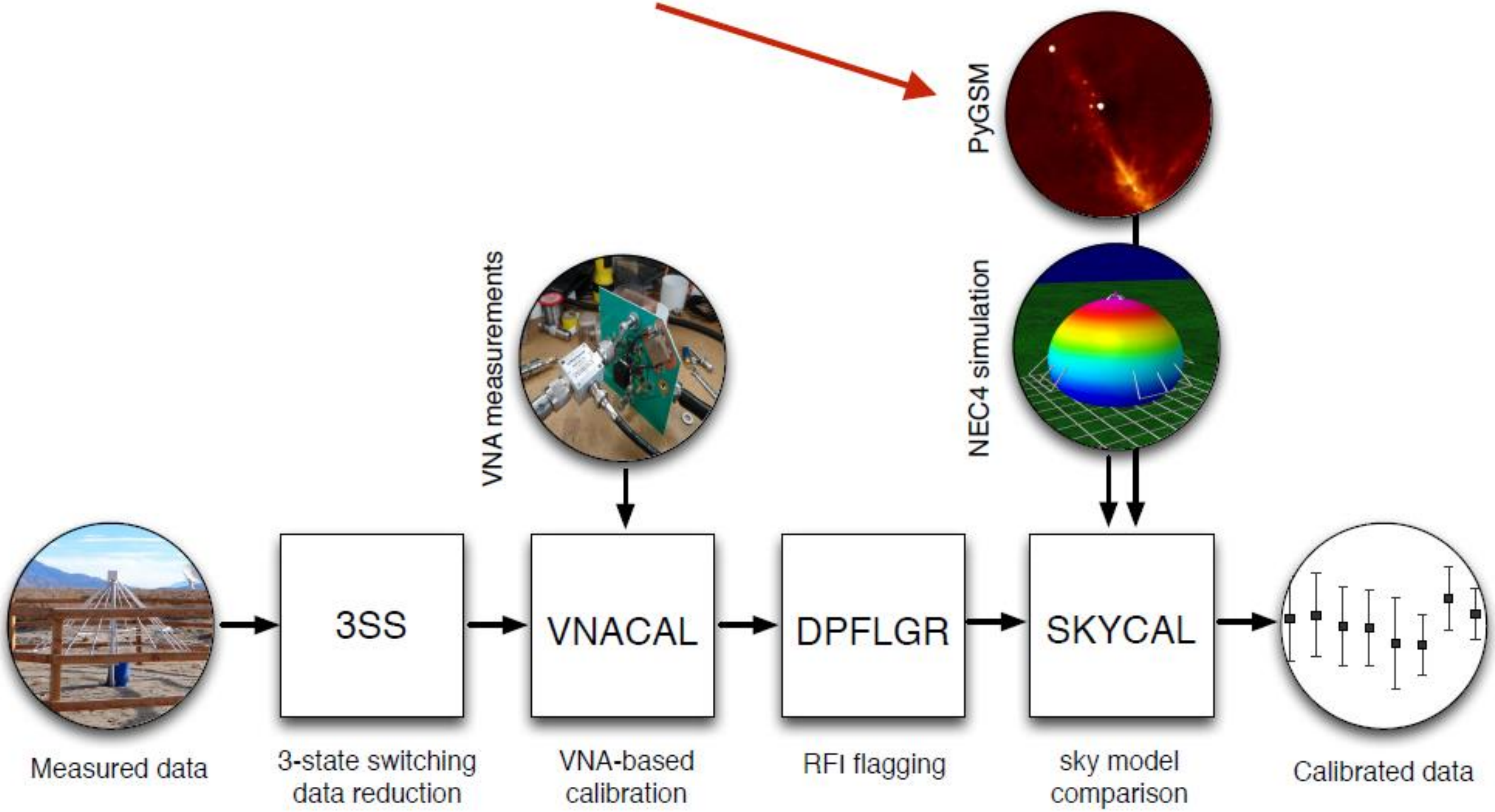
New constraints on the 21-cm emission at $13.2 < z < 27.4$

(GB et al., MNRAS, in press, arXiv:1606.06006)

- Large Aperture Experiment to detect the Dark Ages (LEDA)
- 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;

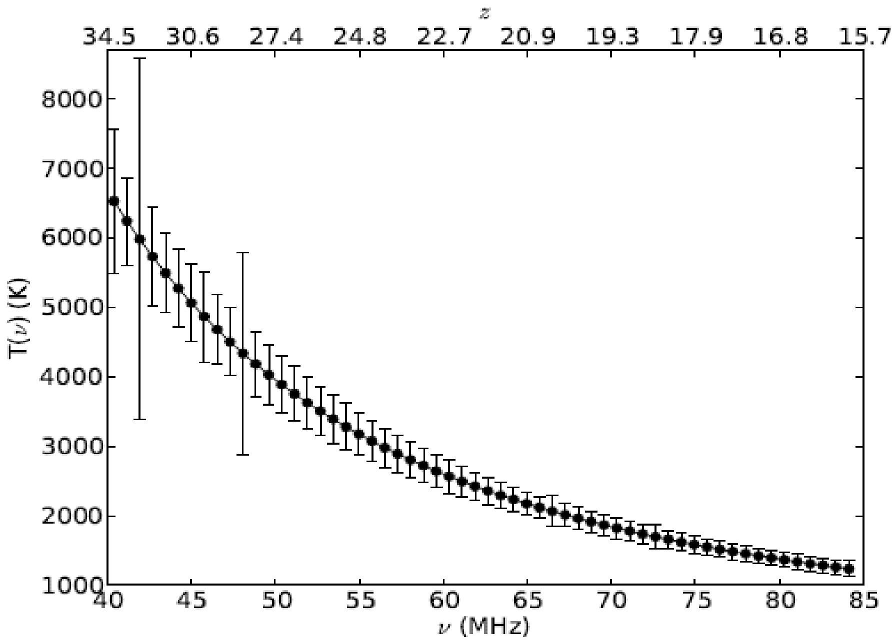
Current LEDA data flow & calibration

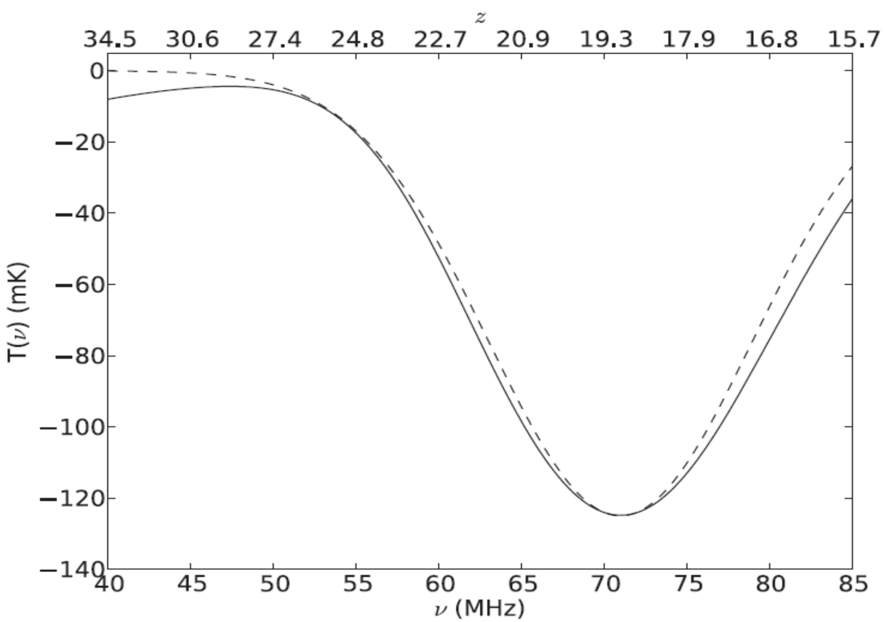
github.com/telegraphic/pygsm



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;
- reference 21-cm model

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

Bayes' theorem:

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

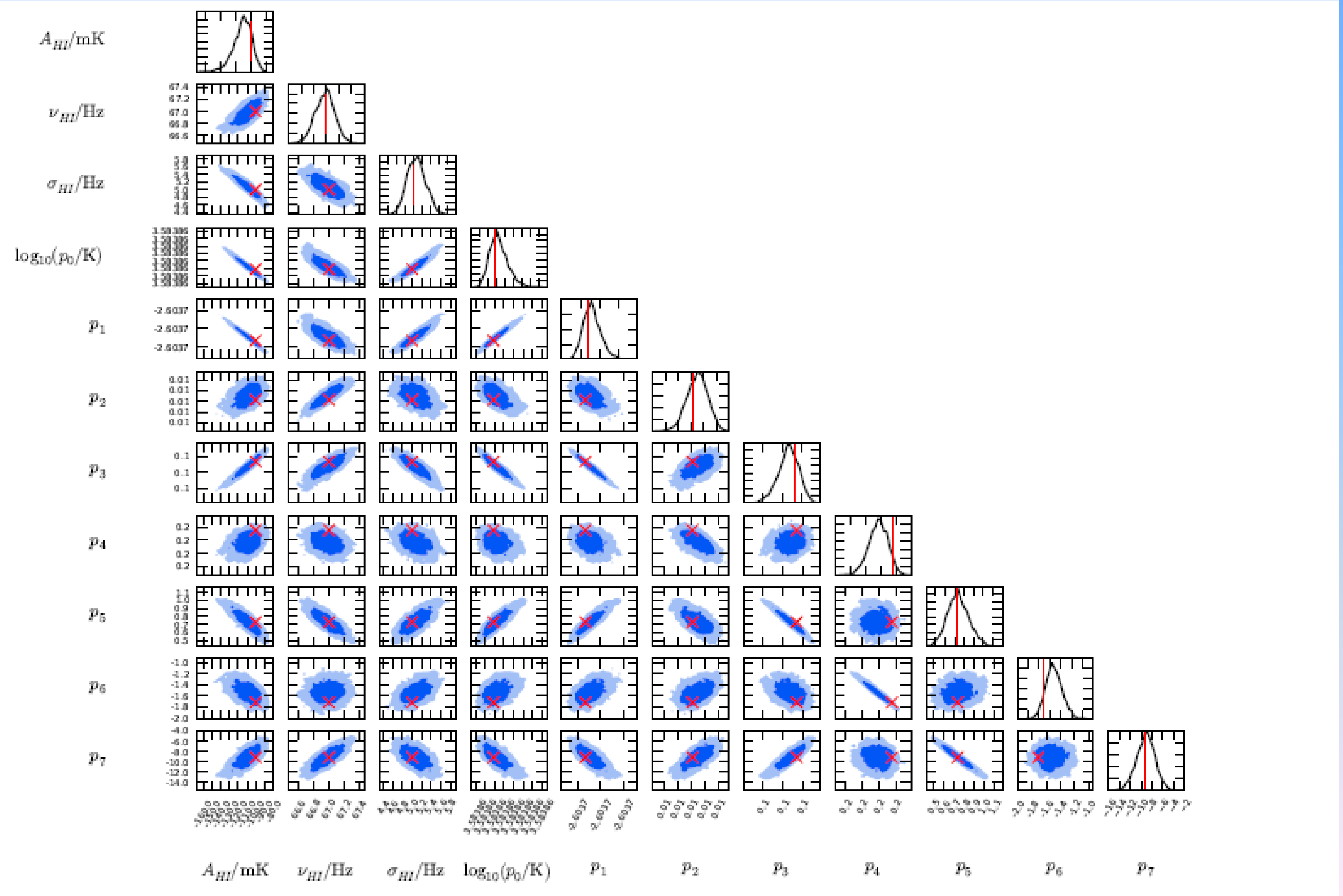
Likelihood:

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

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

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



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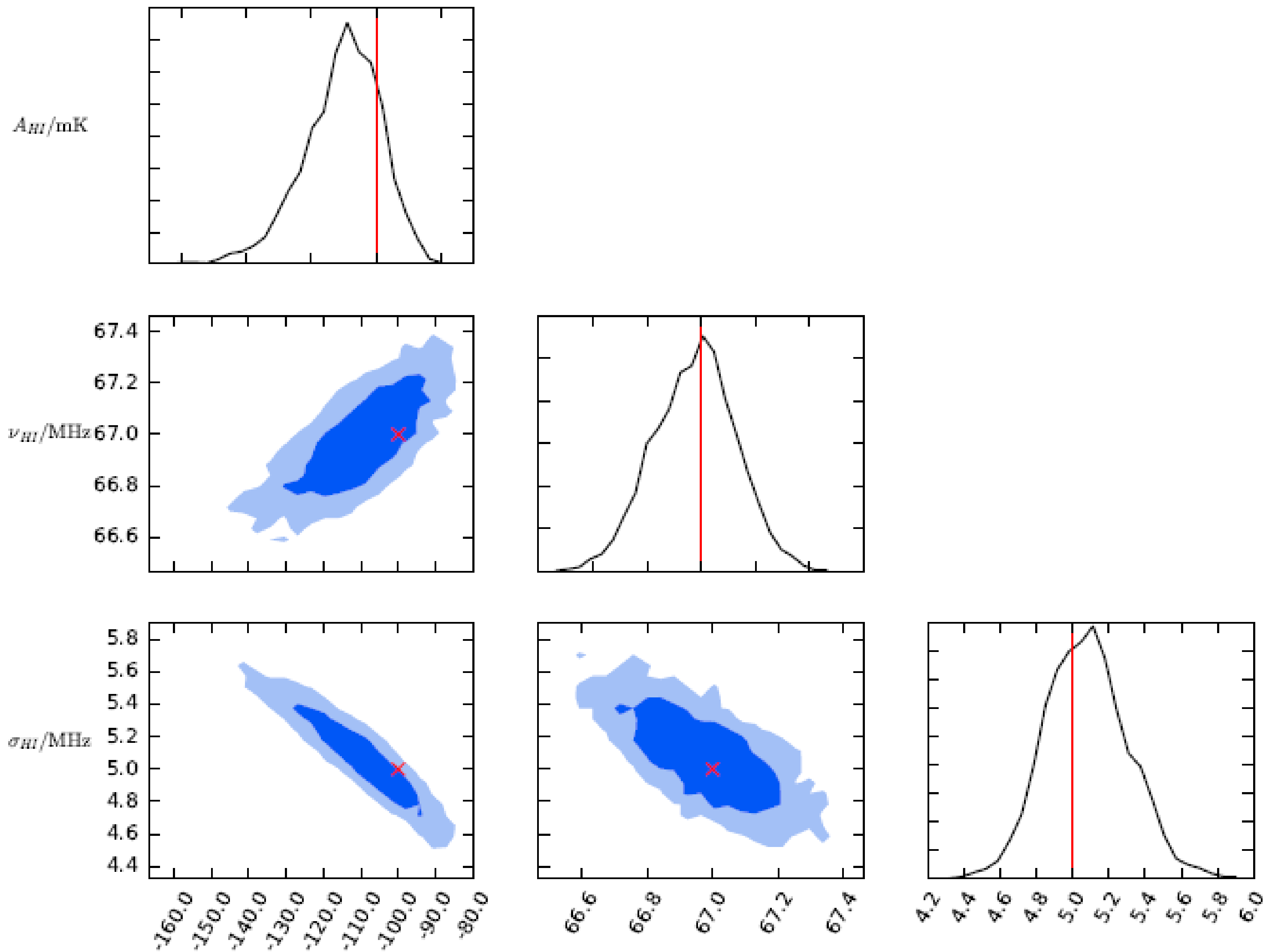
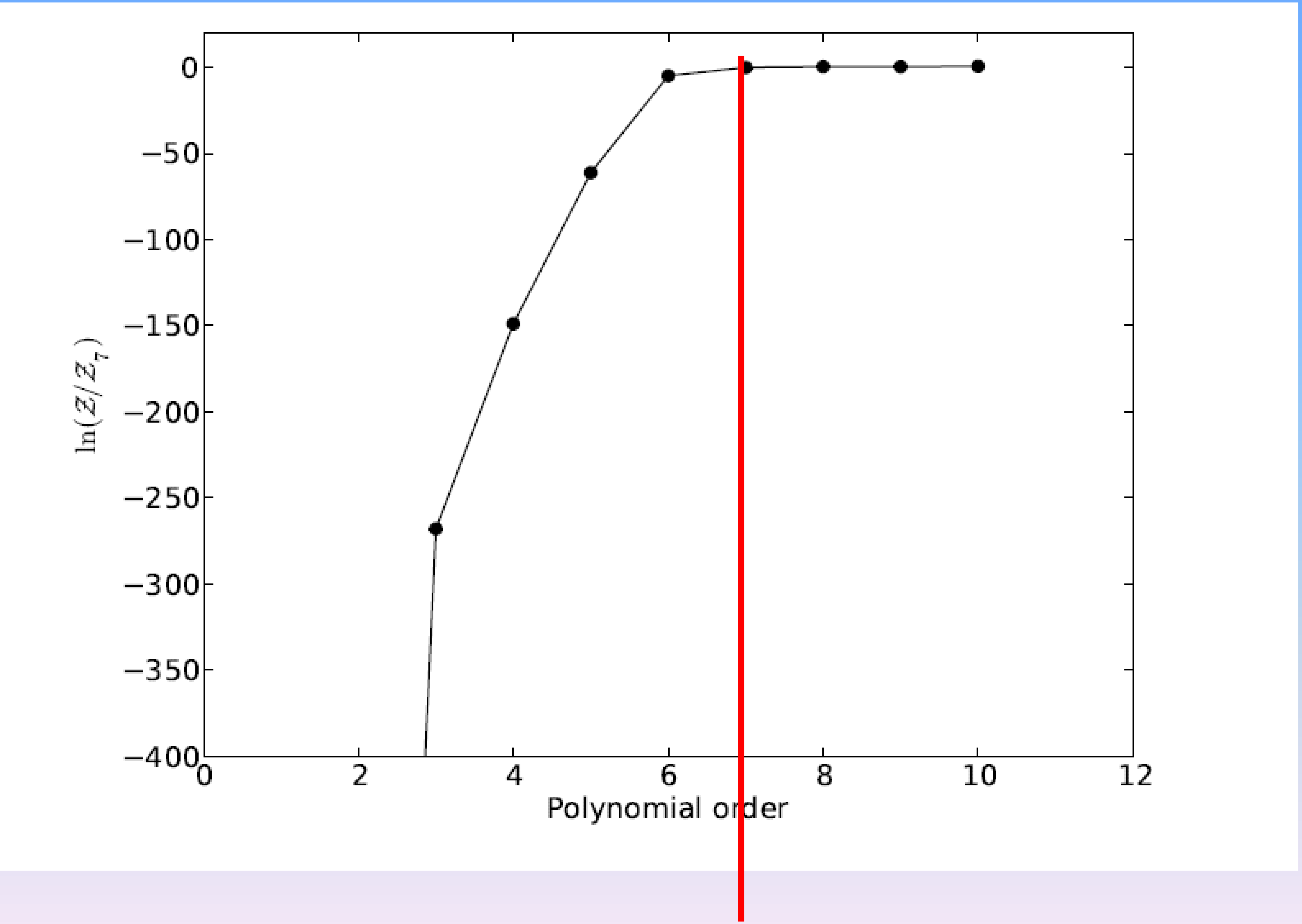
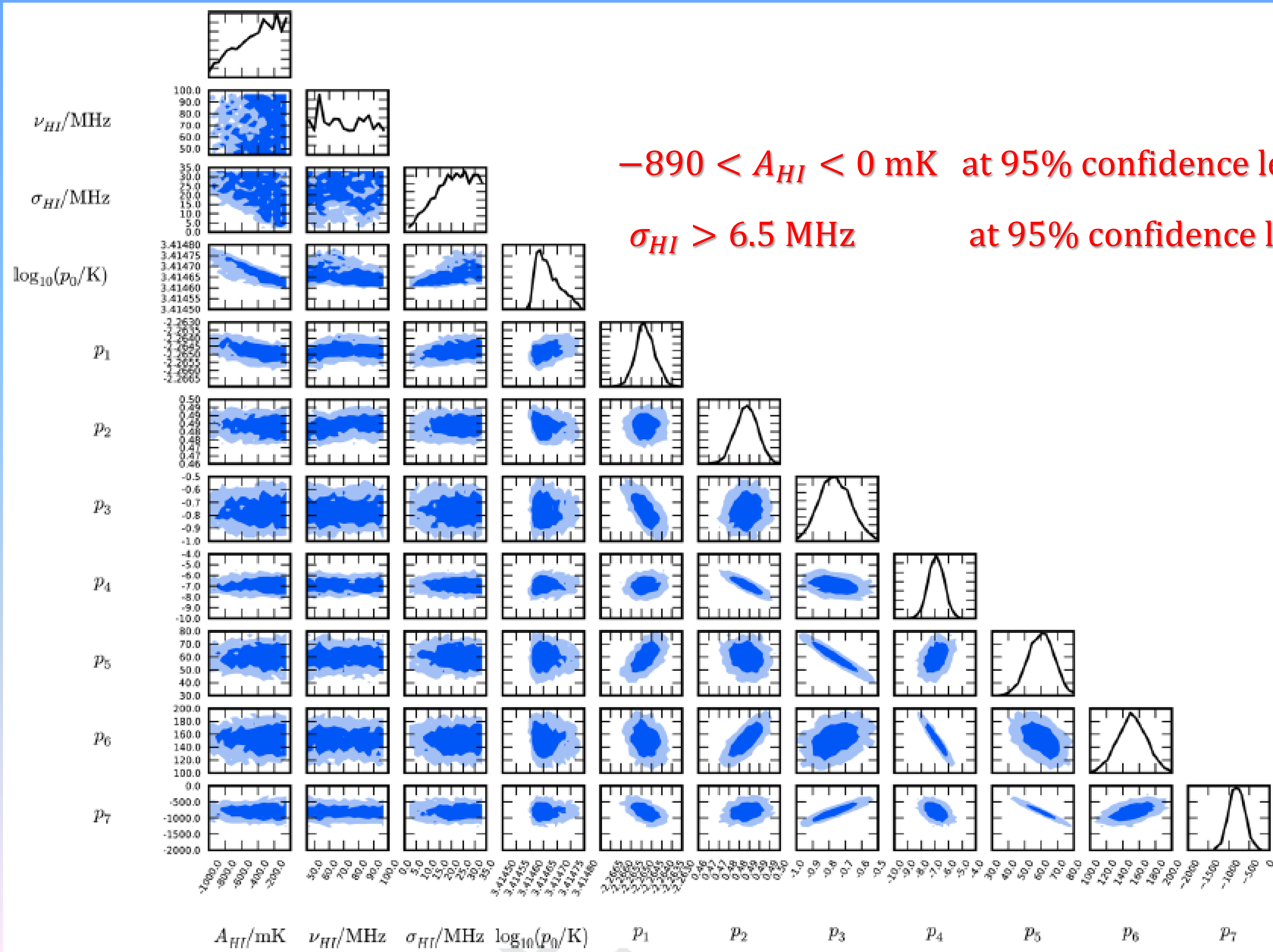


Application to data: evidence-based model selection



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 at 95% confidence level

$\sigma_{HI} > 6.5$ MHz at 95% confidence level

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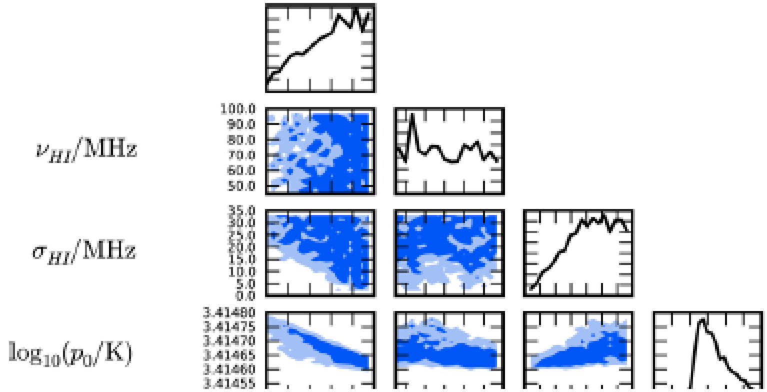

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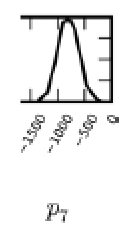
If we consider and extreme model with no heating and full Lyα coupling ($x_{HI} = 1, \delta = 1, T_s = T_k$):

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

$$A_{HI} \approx -380\ \mathrm{mK}\ @\ \mathrm{z} = 15.7$$

…

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

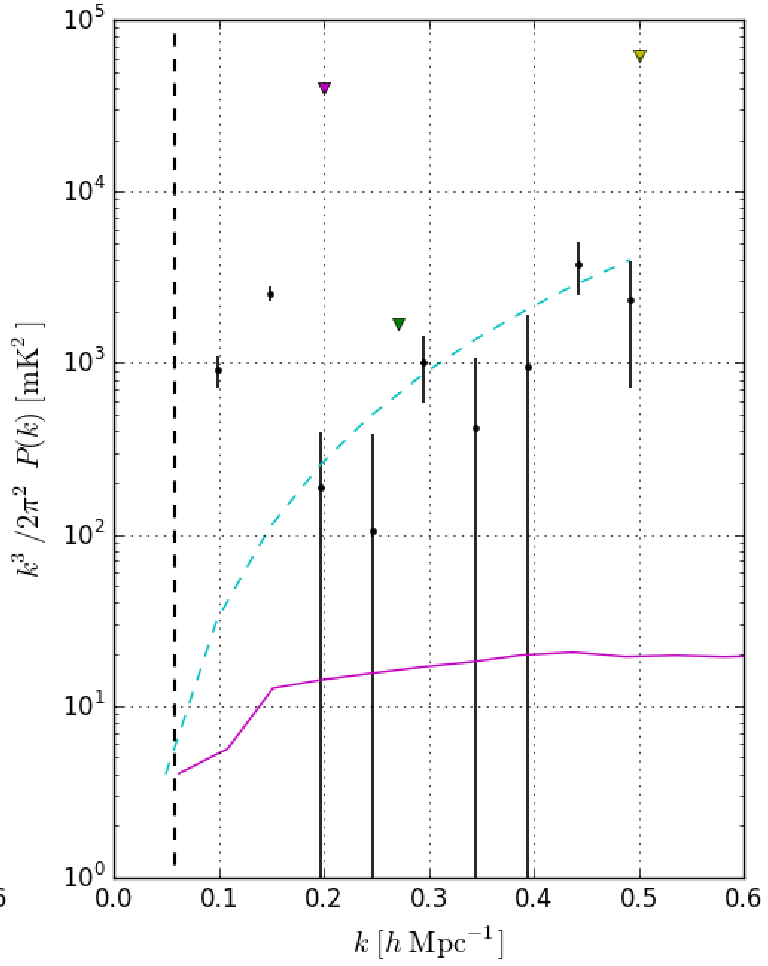


21-cm science with radio interferometers: upper limits from PAPER and a look to the future (HERA and SKA)

Upper limits on the 21 cm power spectrum at z = 8.4

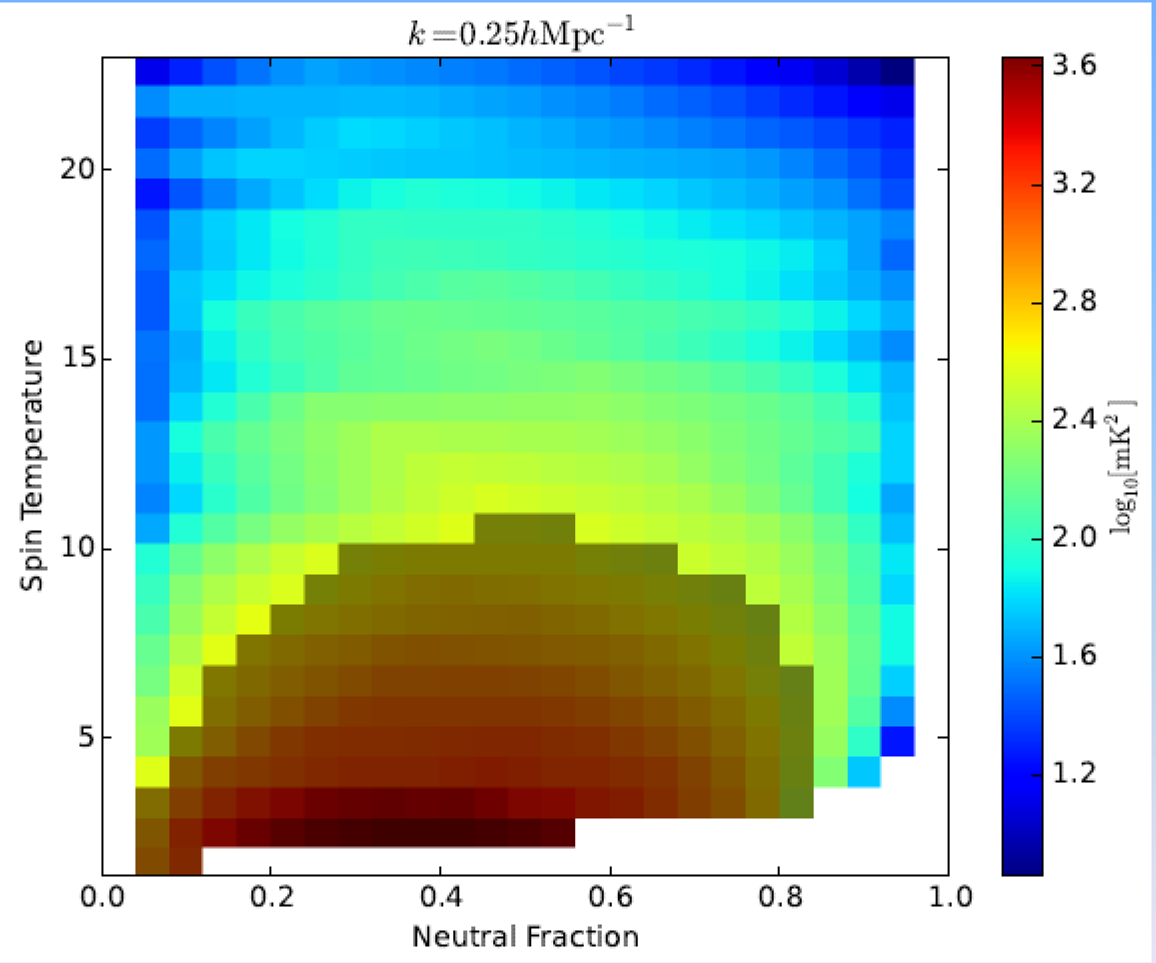
(Ali et al. 2015, Pober et al. 2015)

PAPER



(Ali et al. 2015)

Constrains on the IGM temperature at z = 8.4



- modeling using 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 $15\% < x_{HI} < 80\%$

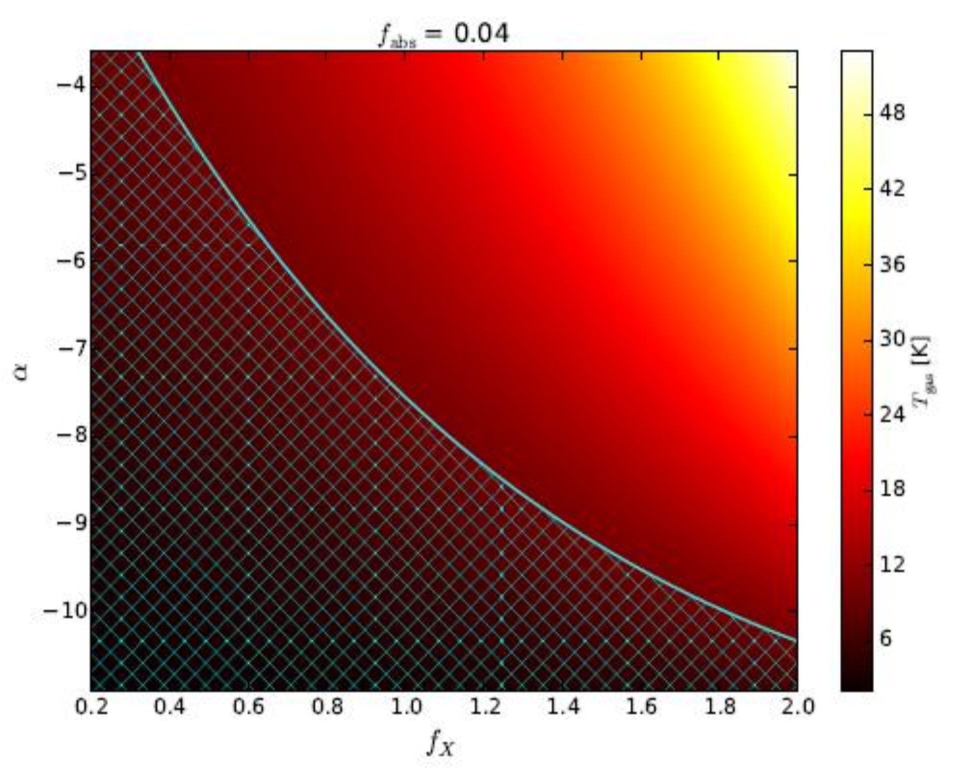
(Pober et al. 2015)

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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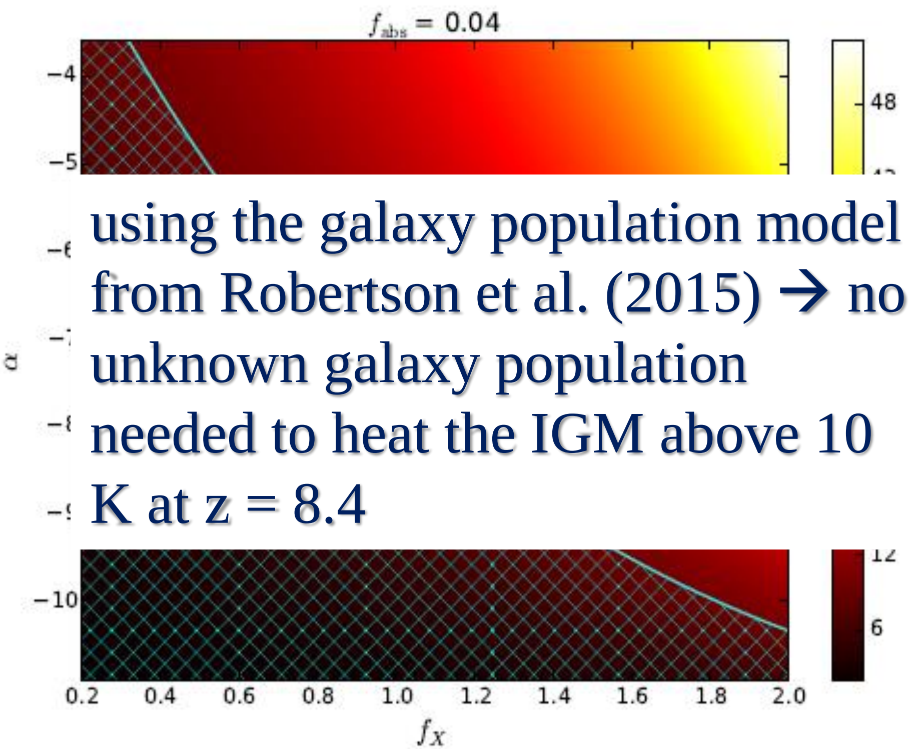
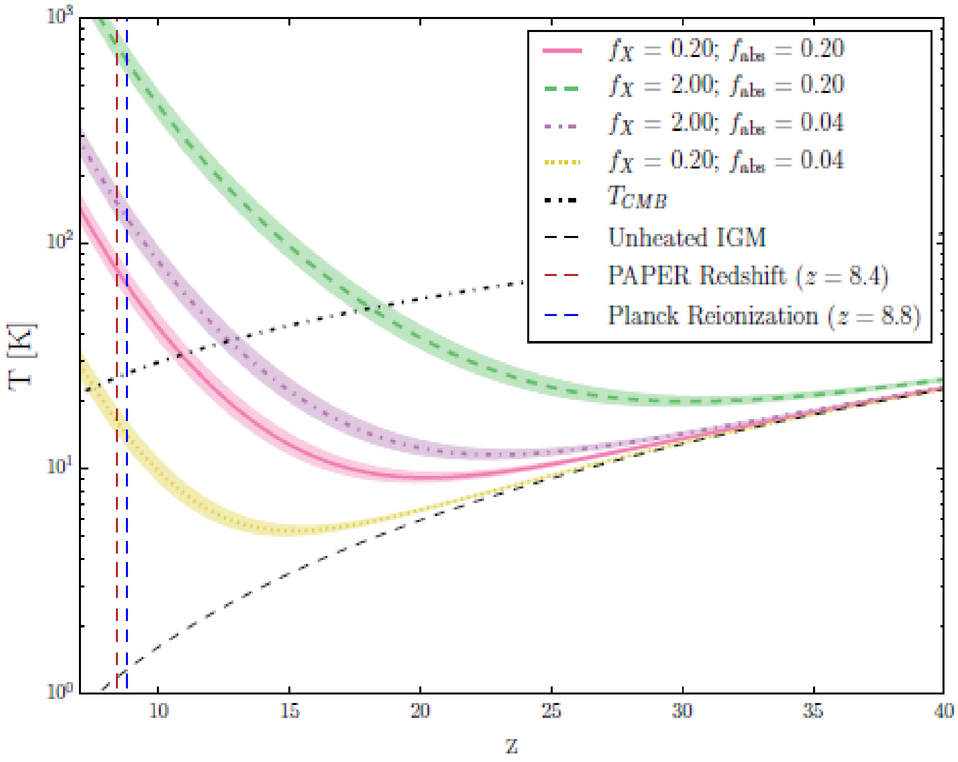


using the galaxy population model from Robertson et al. (2015) → no unknown galaxy population needed to heat the IGM above 10 K at z = 8.4



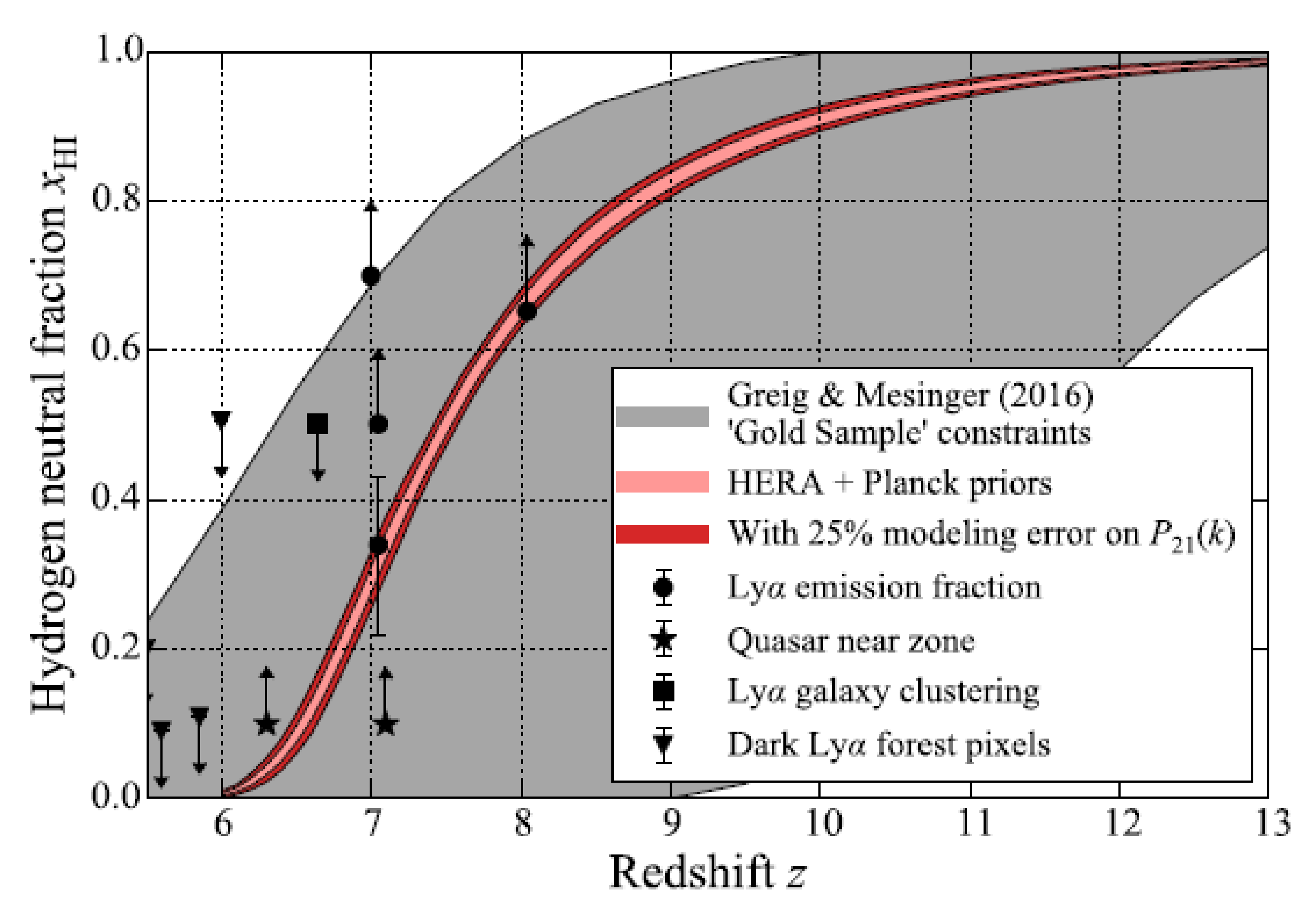
Looking at the future (1): the Hydrogen Epoch of Reionization Array (HERA)

(deBoer et al., arXiv:1606.07473)

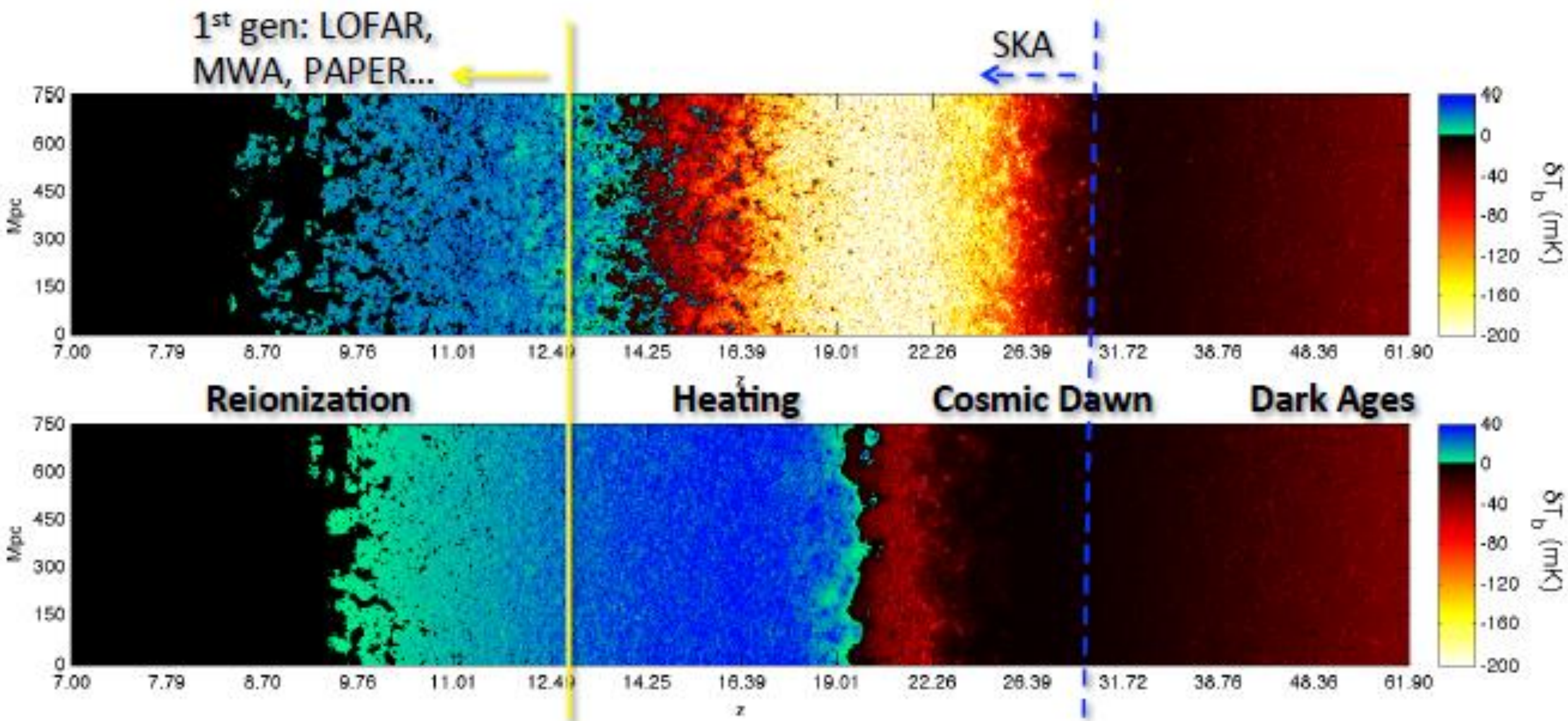
- ASU, Brown U., Cambridge U., MIT, NRAO, SKA-SA, SNS, UCB, UPenn, Uwashington (PIs: J.E. Aguirre, G. Bernardi, J.D. Bowman, C.L. Carilli, J.N. Hewitt, M.F. Morales, J.C. Pober, A.R. Parsons);
- 19 dishes on the ground, expandable to ~350 by the end of 2018-2019 (proposal under final NSF review);
- 100-200 MHz (possible extension to 50 MHz);
- Located at the SA SKA site;

First 19 dishes

Pinning down the Epoch of Reionization



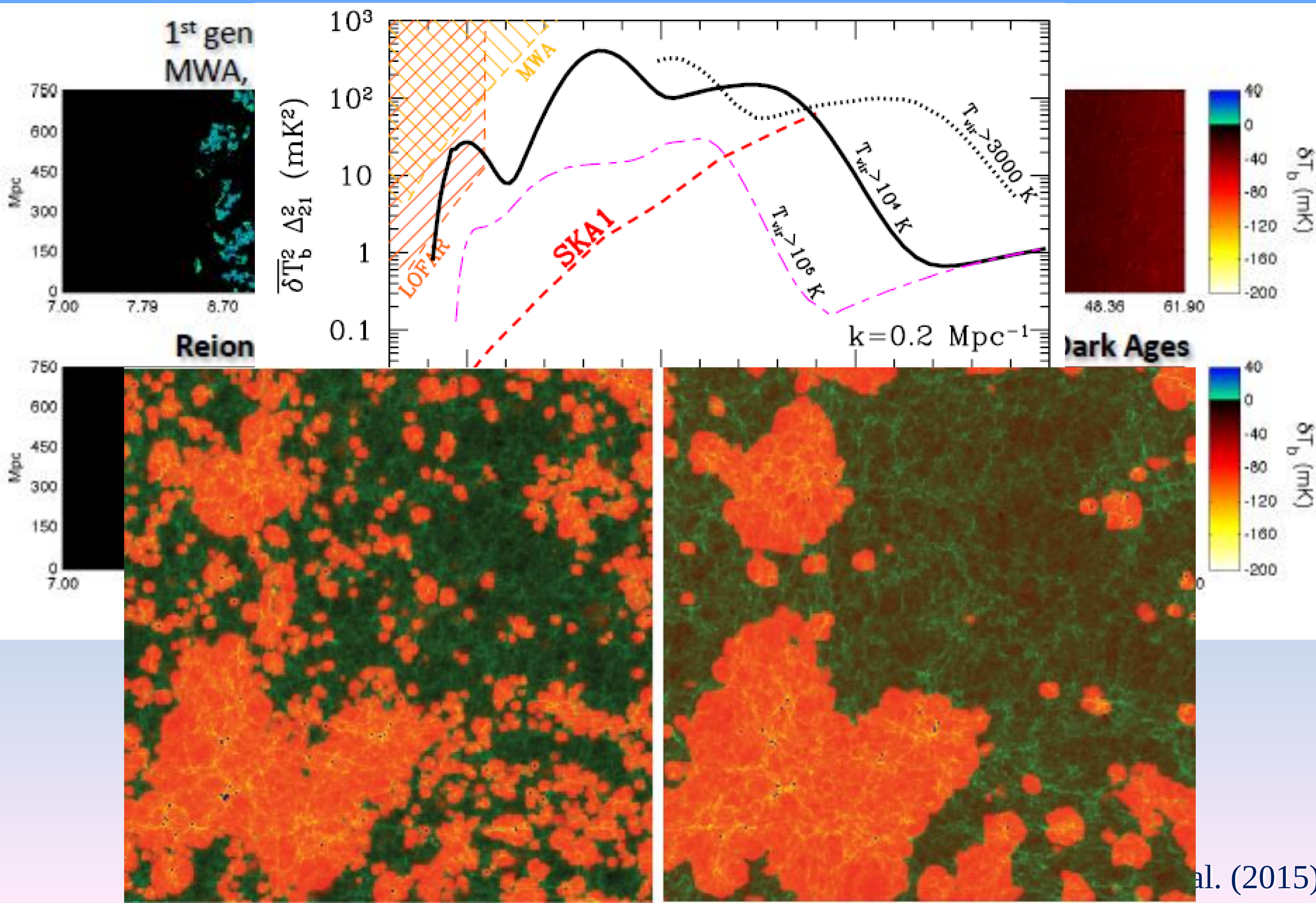
Looking at the future (2): the Square Kilometre Array (SKA)



- 21-cm power spectra at $6 < z < 30$, imaging HI bubbles at $6 < z < 12$;
- we are preparing the bid to become a KSP (fingers crossed) by 2018;

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

Looking at the future (2): the Square Kilometre Array (SKA)



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 the SKA becomes 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