Epoch of Reionization and Cosmic Dawn with the redshifted 21-cm line

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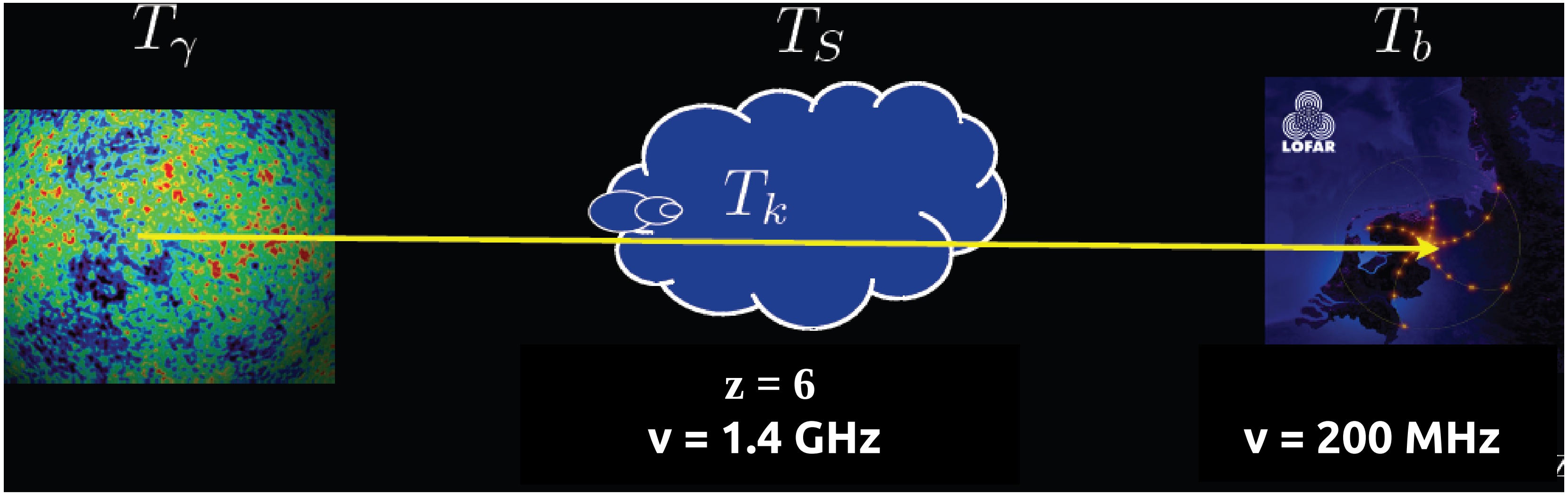
(thanks to the HERA, LEDA and PAPER collaborations)

“Cosmology with Large Surveys”, Durban, November 19-25, 2016

21 cm cosmology

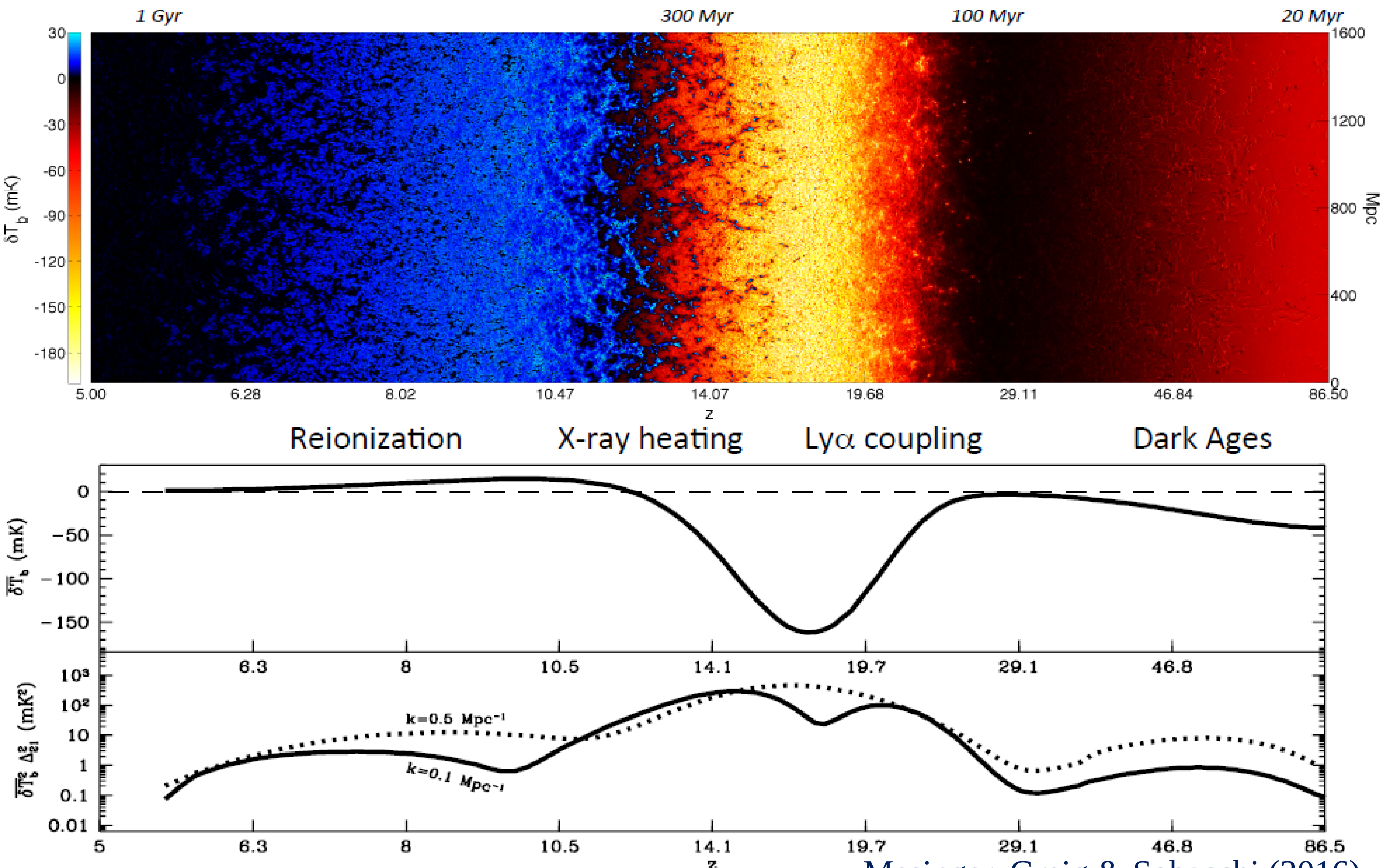


3 fundamental temperatures:

- 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)

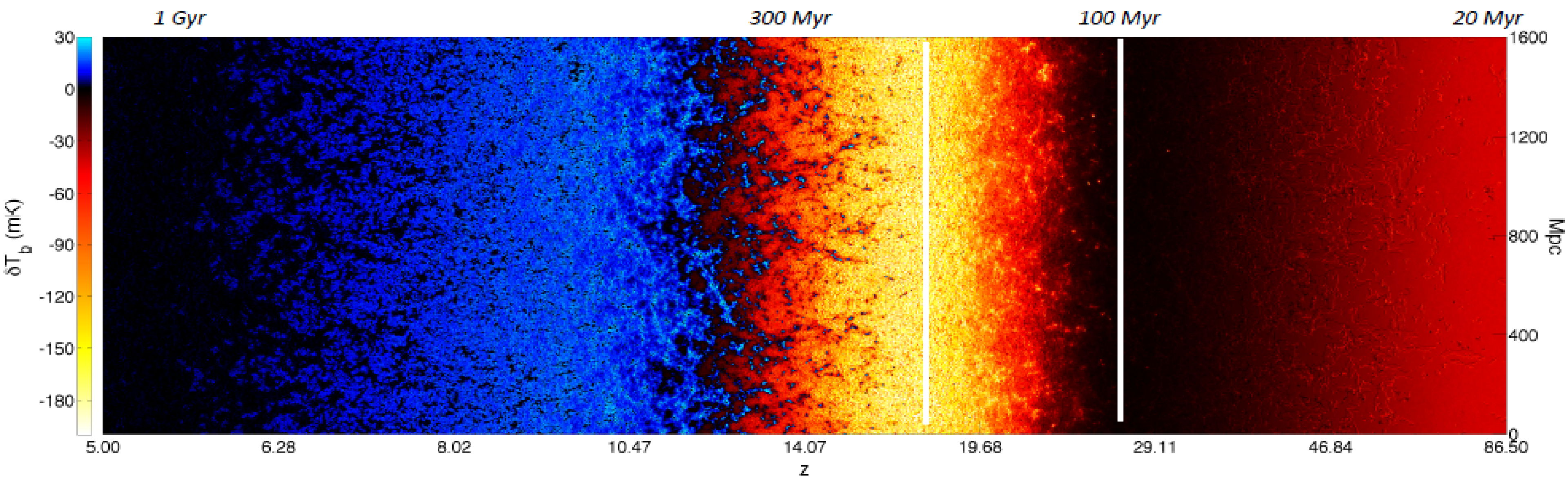
- the 21 cm line is observable when $T_s = T_k \neq T_\gamma$

A few fundamental transitions

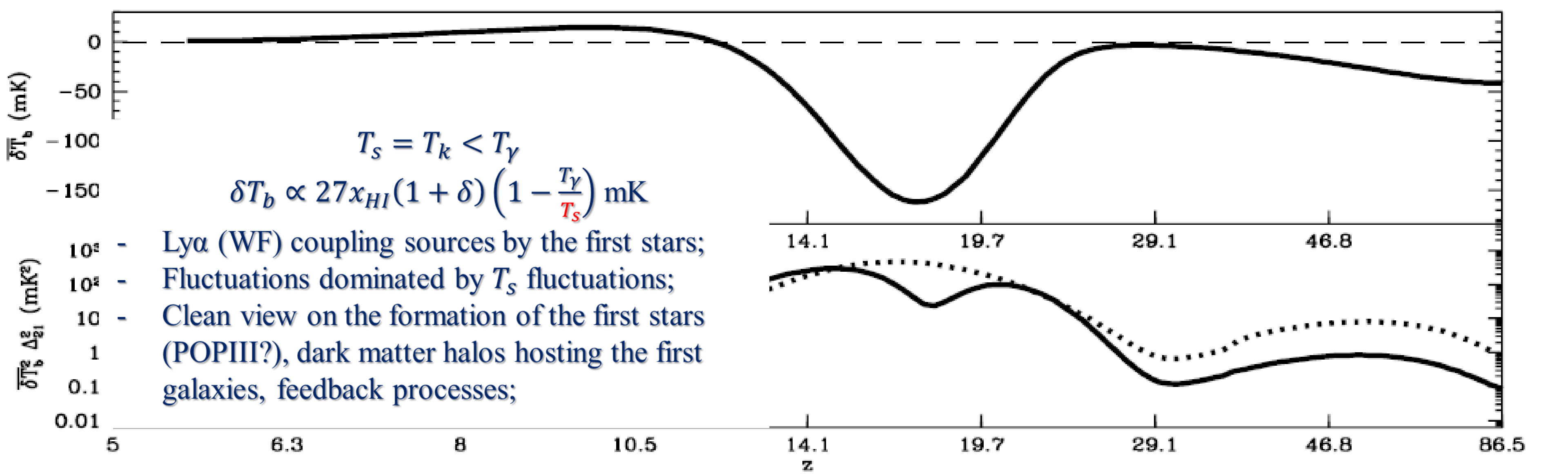


Mesinger, Greig & Sobacchi (2016)

A few fundamental transitions



Reionization X-ray heating Lyα coupling Dark Ages

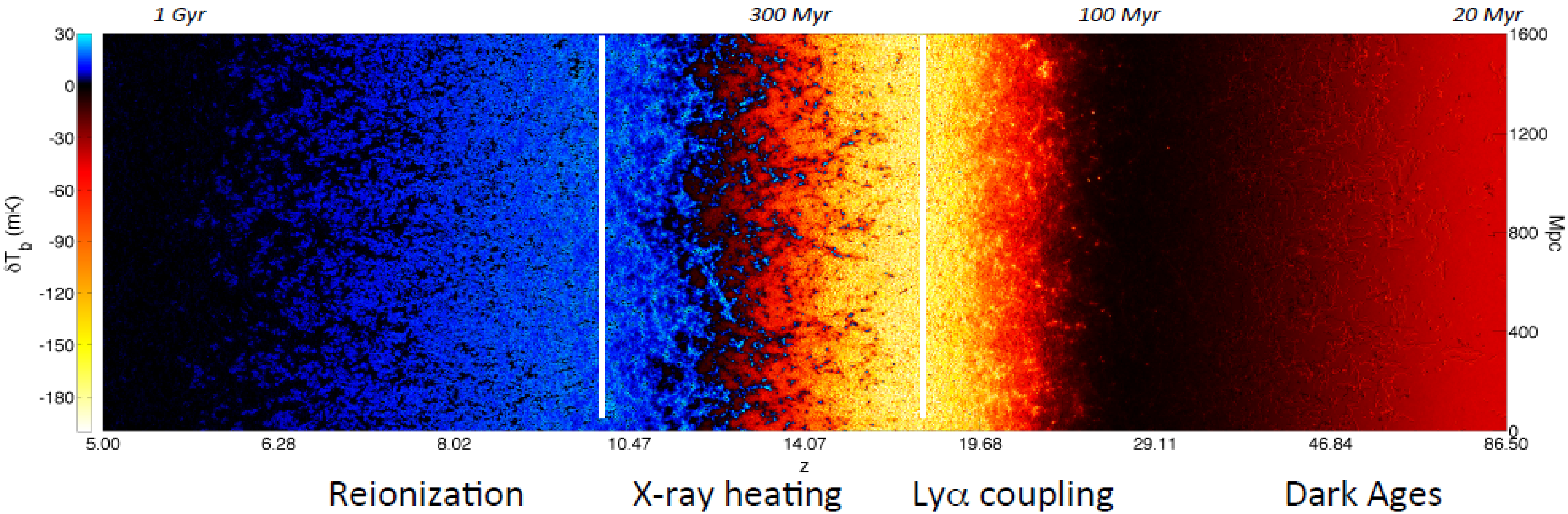


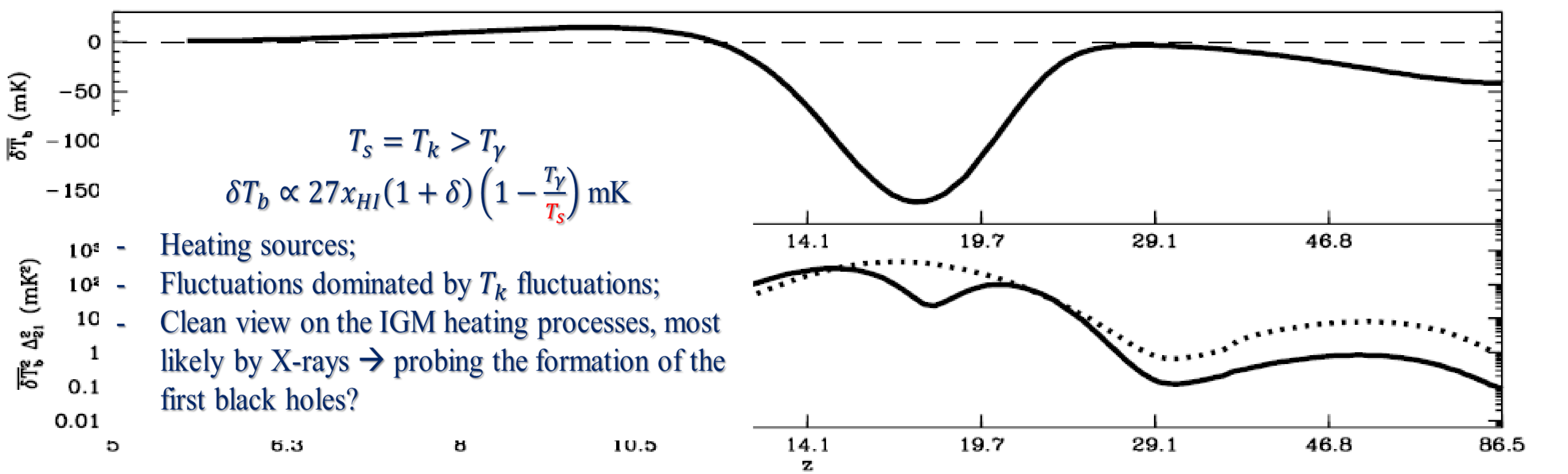
$$T_S = T_k < T_\gamma$$

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

- 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;

A few fundamental transitions



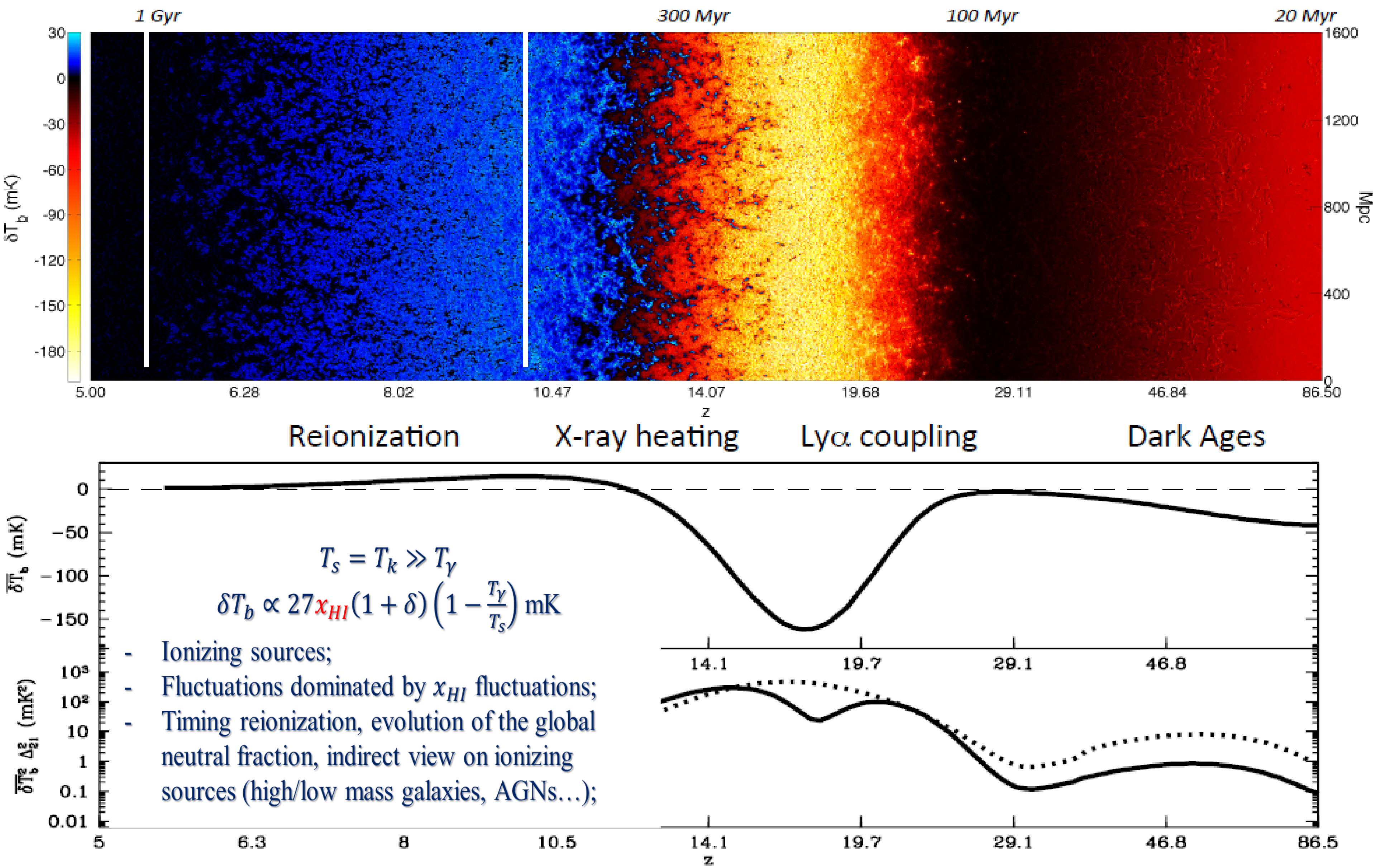


$$T_S = T_k > T_\gamma$$

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

- 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?

A few fundamental transitions

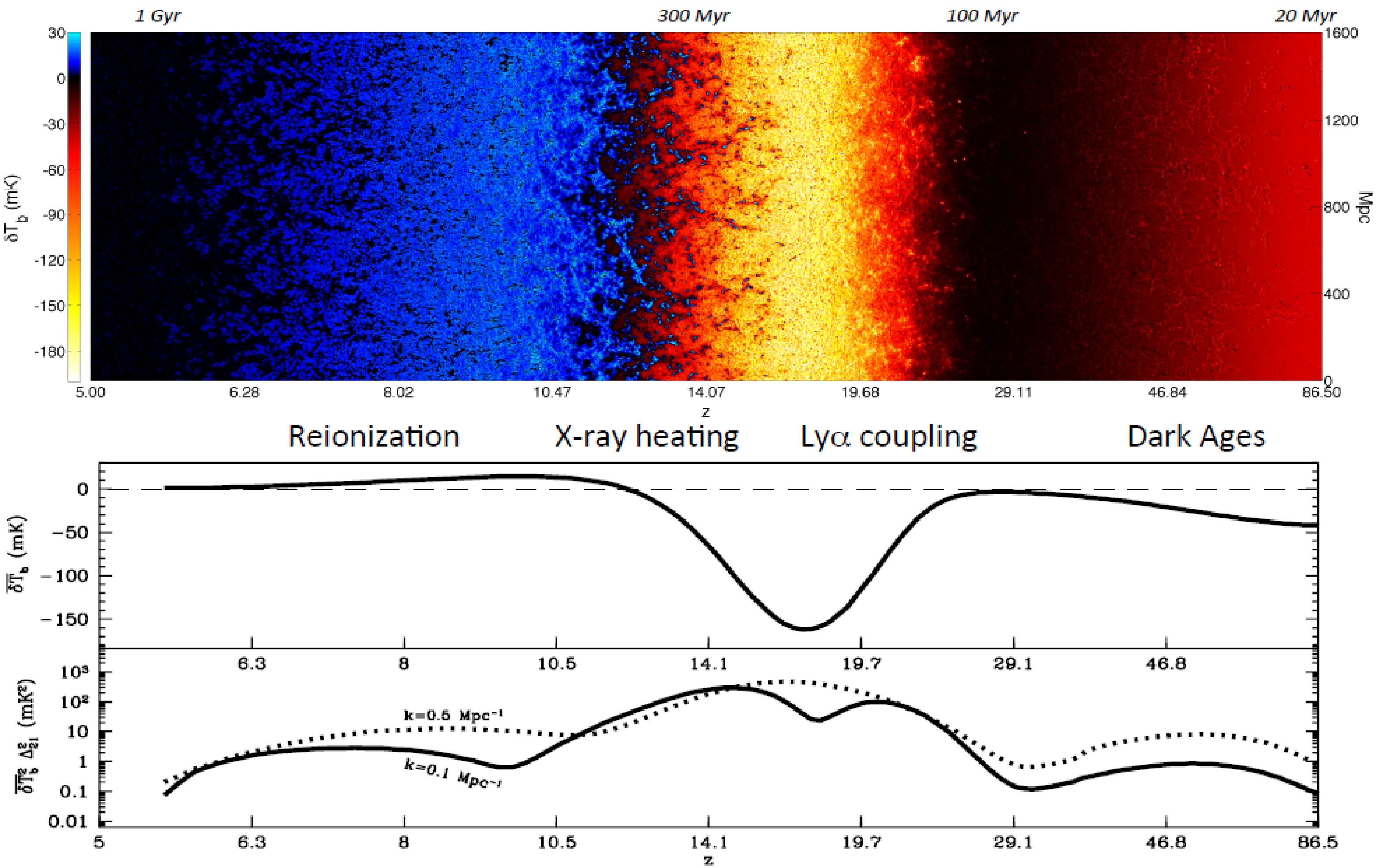


$$T_S = T_k \gg T_\gamma$$

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

- 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…);

A few fundamental transitions



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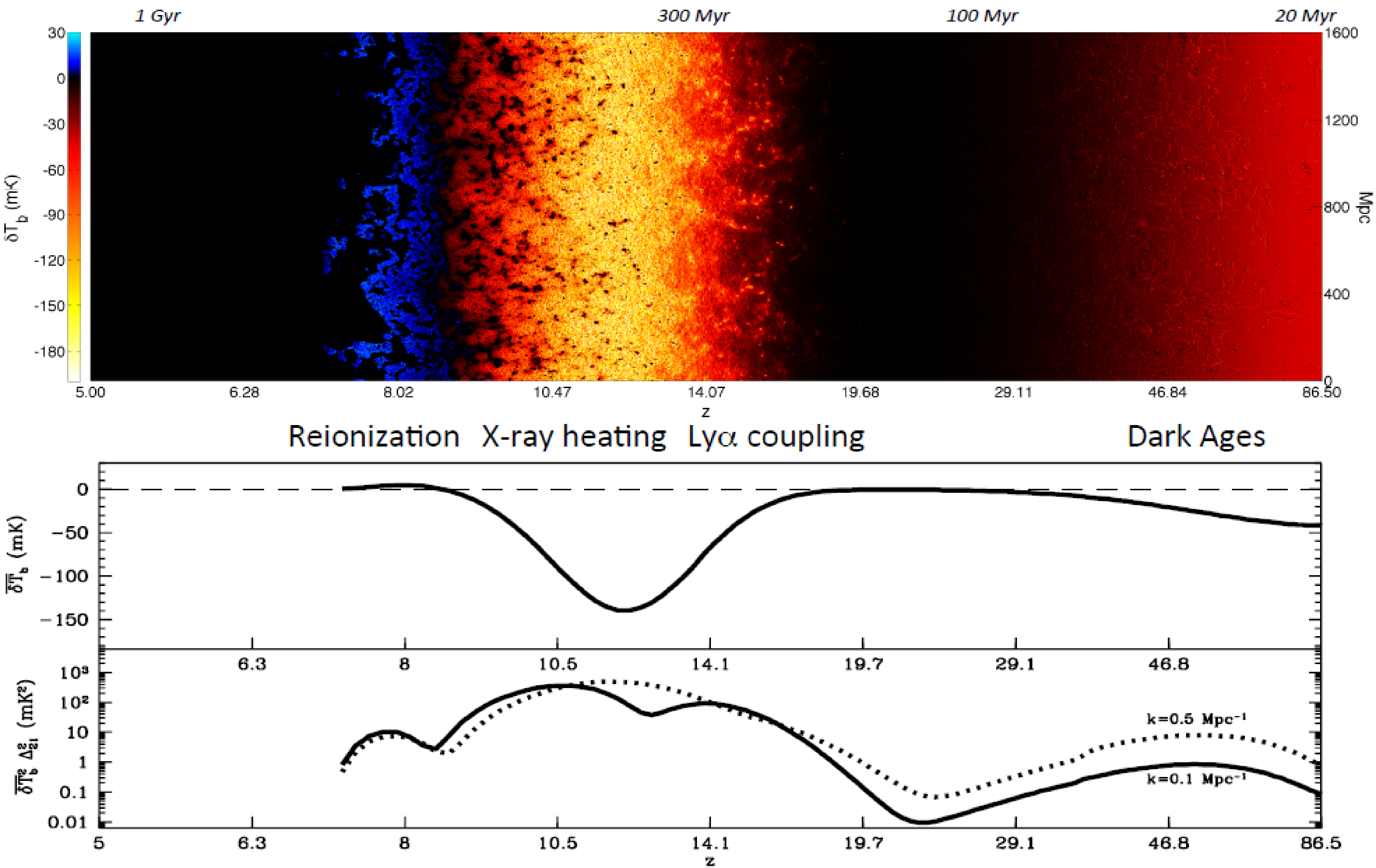
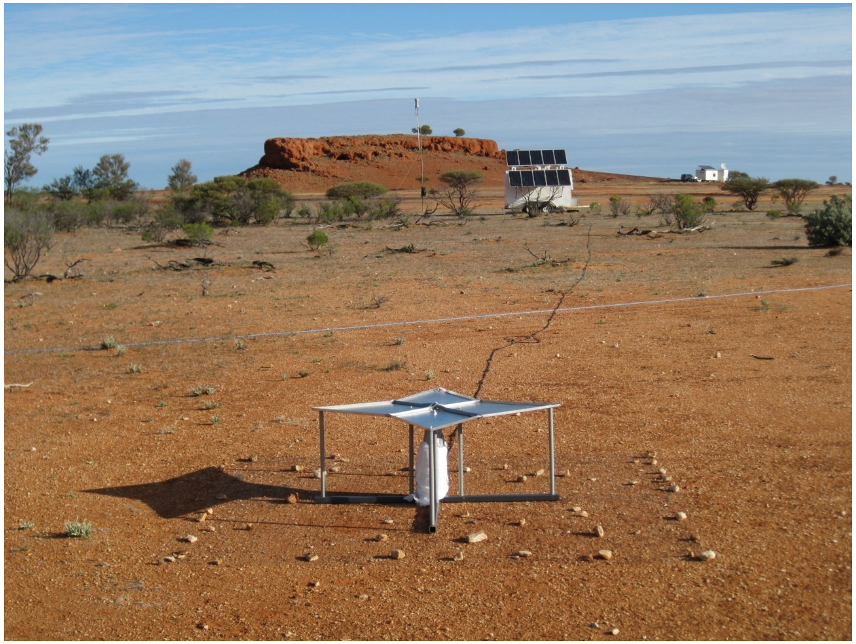


21 cm observables

Global signal



- No spatial information: average emission as a function of redshift;
- Requires separation from much brighter foregrounds;
- Requires very accurate calibration;

Fluctuations

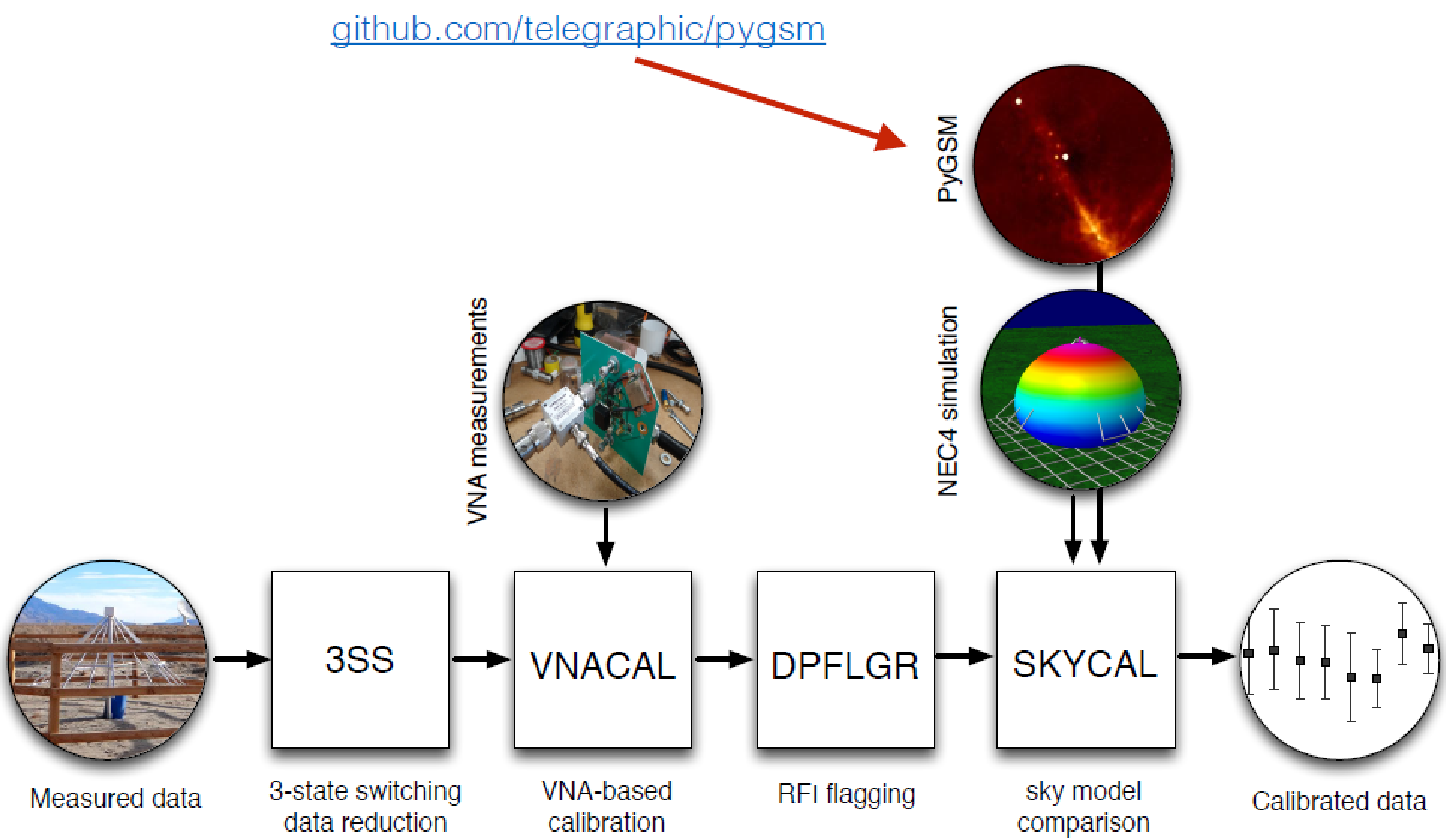
- Two dimensional slices as a function of redishift (or 3D power spectra);
- Requires separation from much brighter foregrounds;
- Requires very accurate calibration;
- Requires large collecting areas to achieve the necessary sensitivity

Bayesian constraints on the global 21 cm signal from the Cosmic Dawn

(GB et al. 2016)

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

Current LEDA data flow & calibration



courtesy D. Price

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:

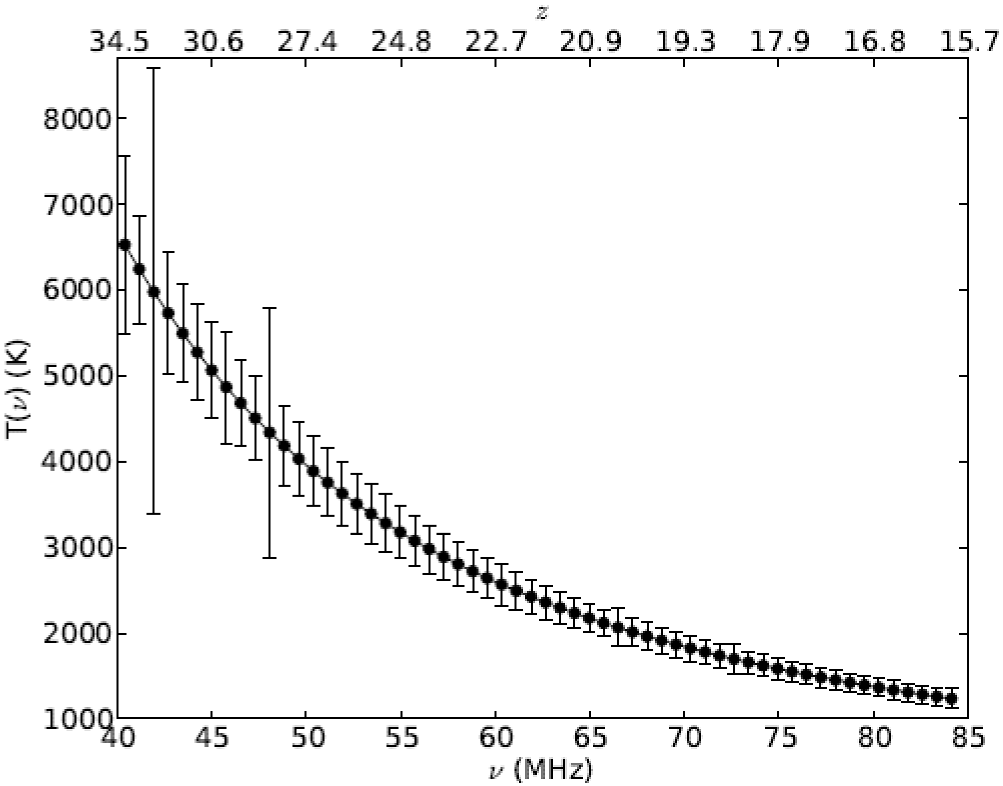
$$\mathcal{L}_j(T_{ant}(\nu)|\boldsymbol{\Theta}) = \frac{1}{\sqrt{2\pi\sigma^2(\nu)}} e^{-\frac{[T_{ant}(\nu)-T_m(\nu,\boldsymbol{\Theta})]^2}{2\sigma^2}}$$

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

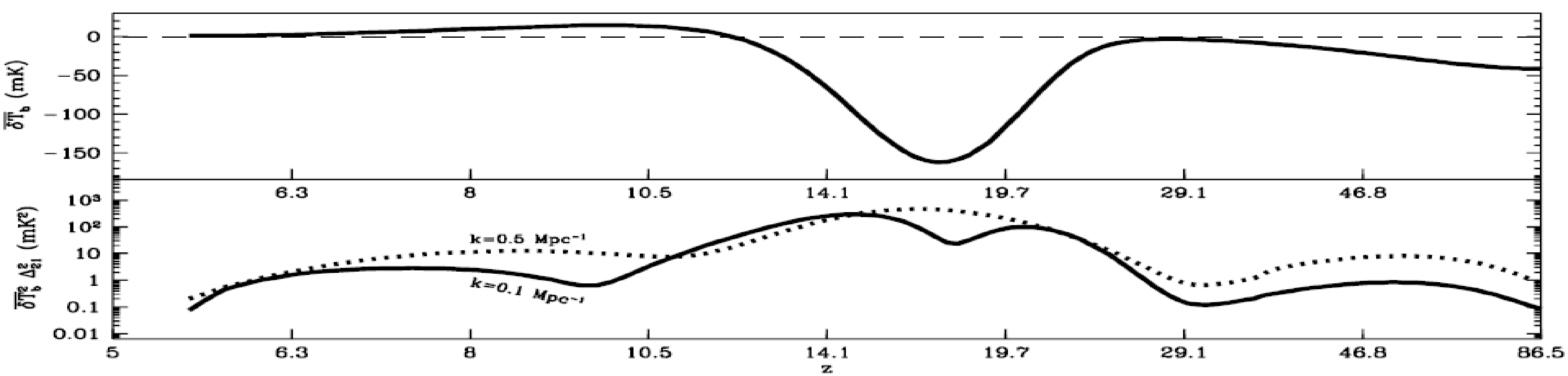
Chosen model:

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

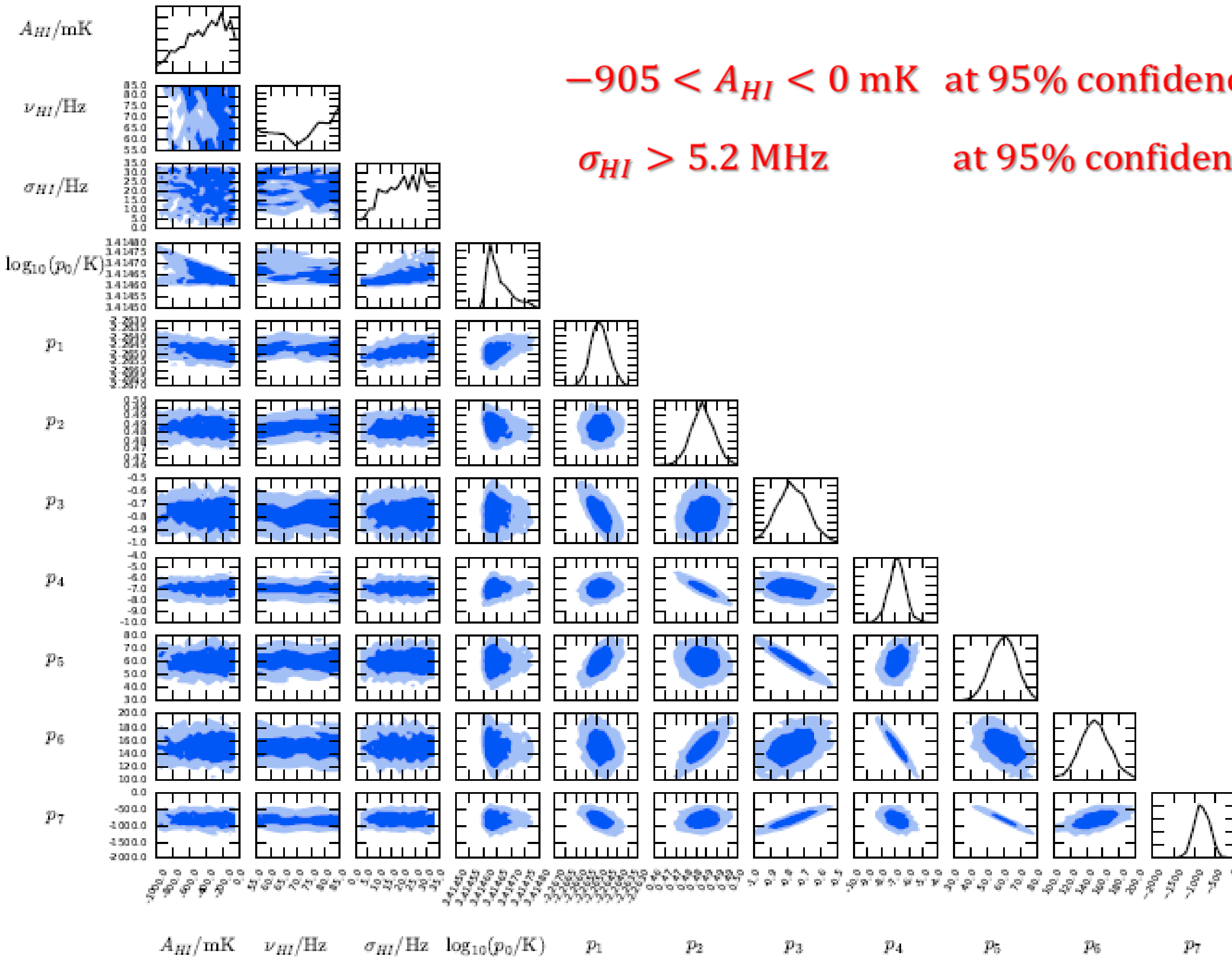
Measured sky spectrum



- 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;



Upper limits on the Cosmic Dawn



$-905 < A_{HI} < 0$ mK at 95% confidence level

$\sigma_{HI} > 5.2$ MHz at 95% confidence level

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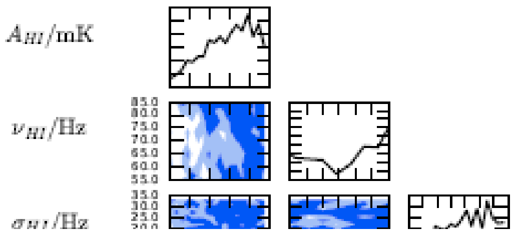

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If we consider and extreme model with no heating and full Lyα coupling ($x_{HI} = 1, \delta = 1, T_s = T_k$):

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

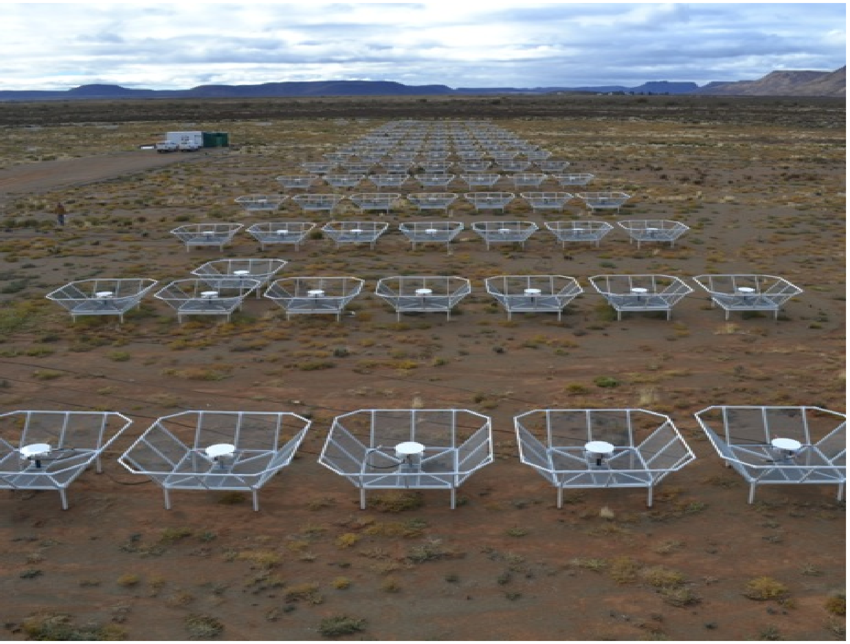
$$A_{HI} \approx -300 \text{ mK @ z} = 22.5$$

…

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

A_{HI}/mK ν_{HI}/Hz σ_{HI}/Hz $\log_{10}(p_0/\mathrm{K})$ p_1 p_2 p_3 p_4 p_5 p_6 p_7

PAPER highlights: redundancy and avoidance



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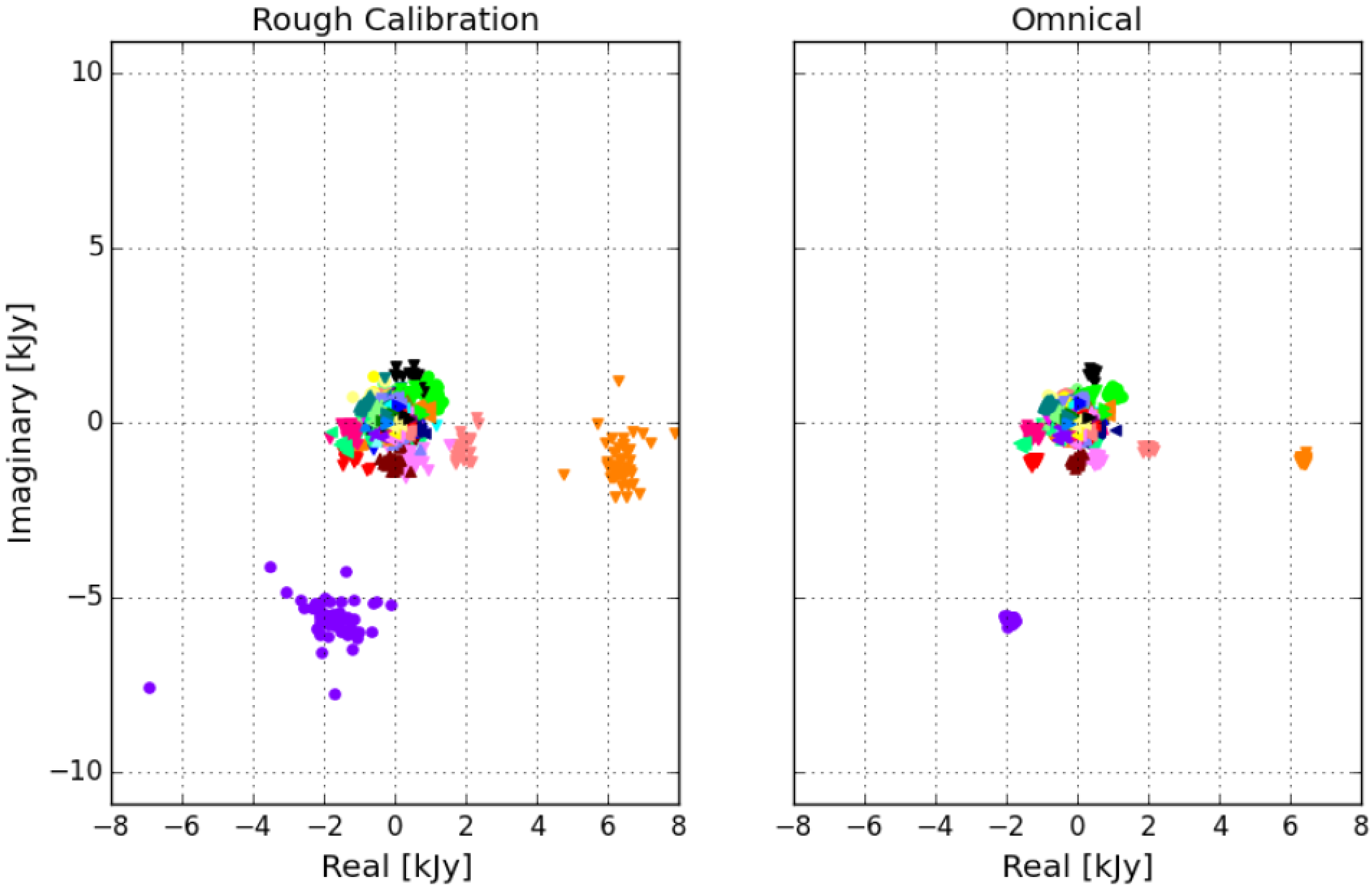
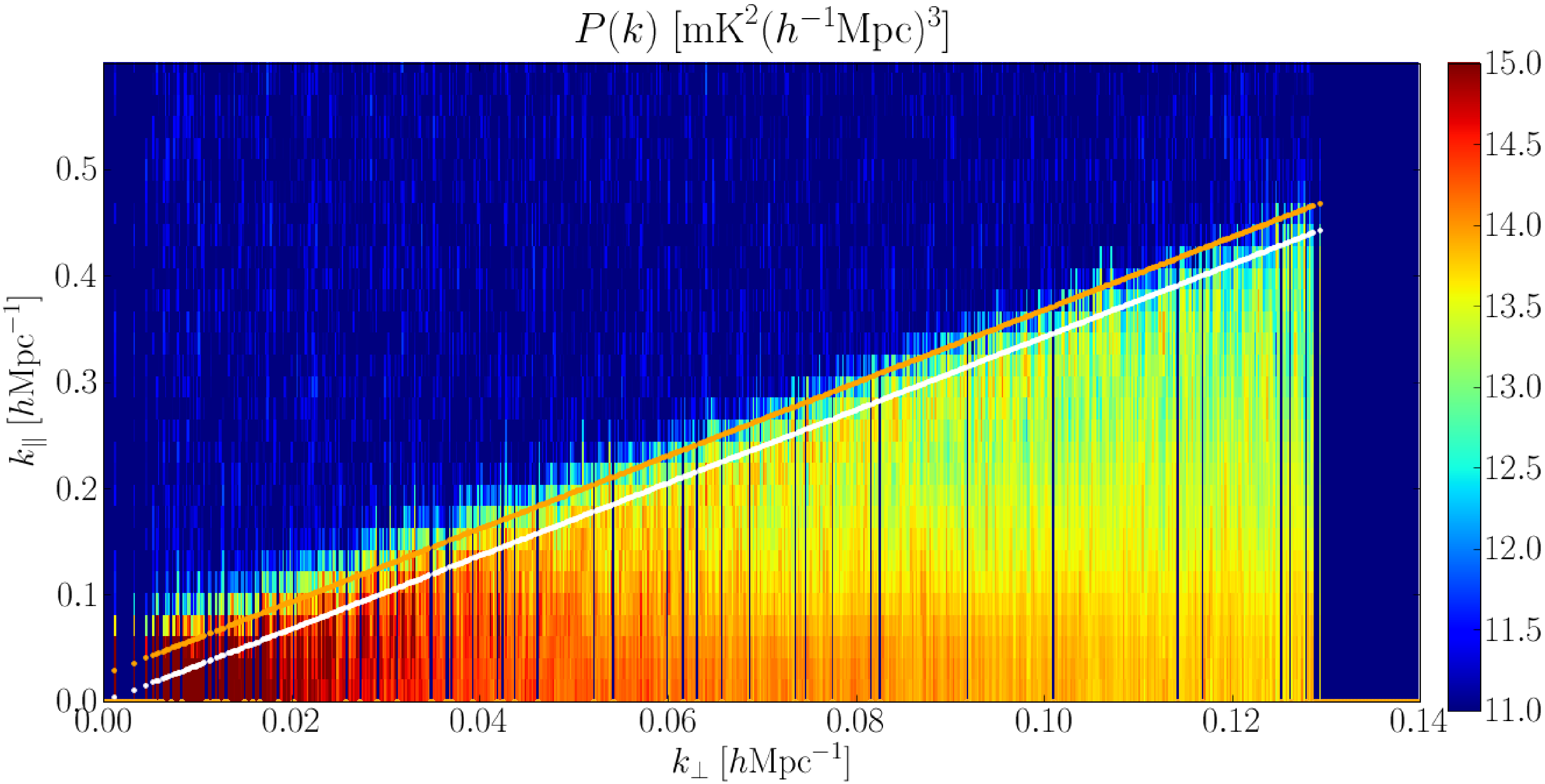


Ali et al. (2015)

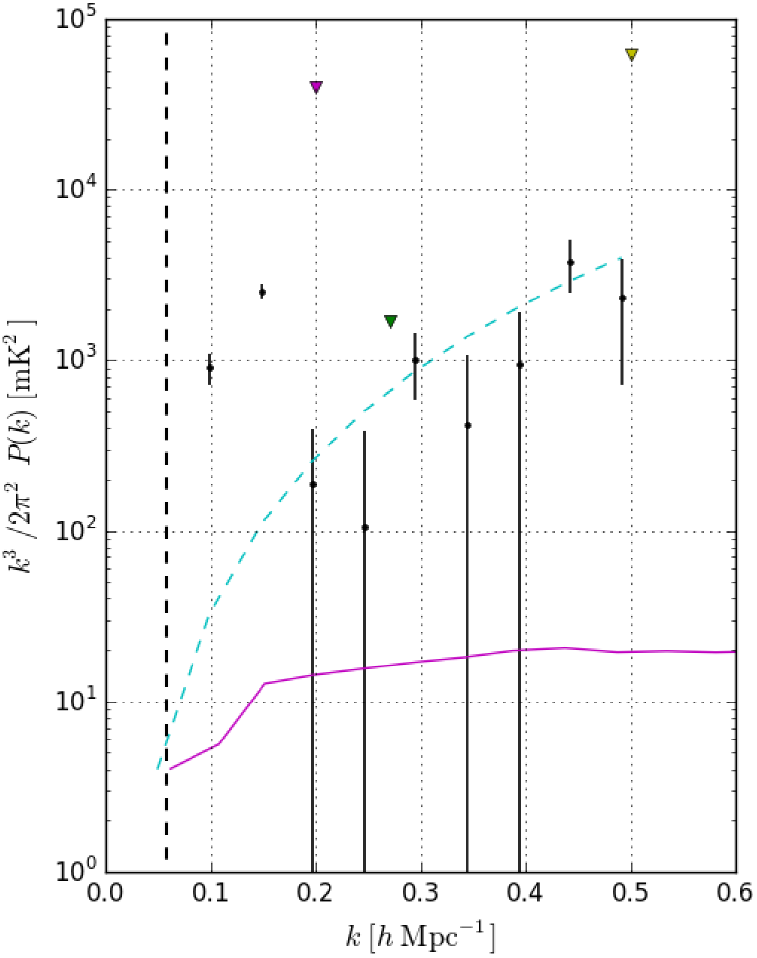
PAPER highlights: redundancy and avoidance



Pober et al. (2013)

Constraints on the IGM temperature at z = 8.4

(Ali, Parsons, …, GB et al. 2015; Pober, Ali, …, GB et al. 2015)



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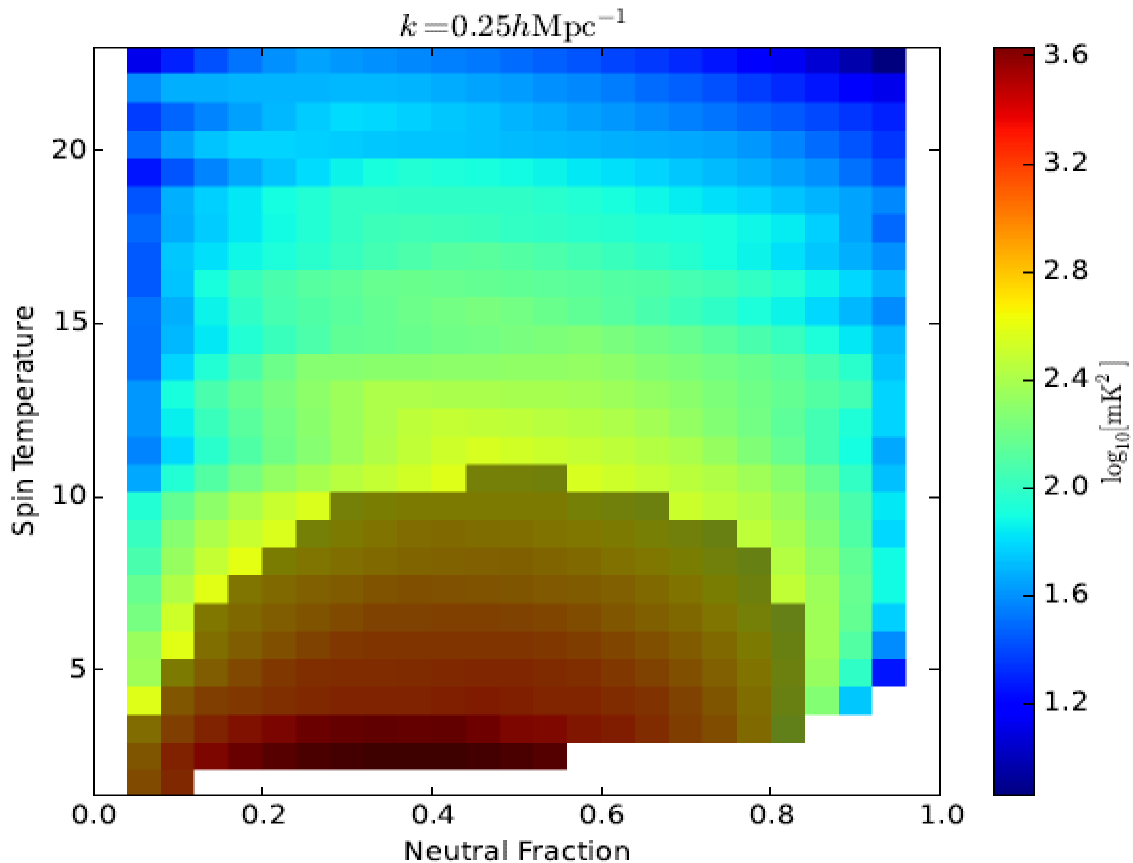

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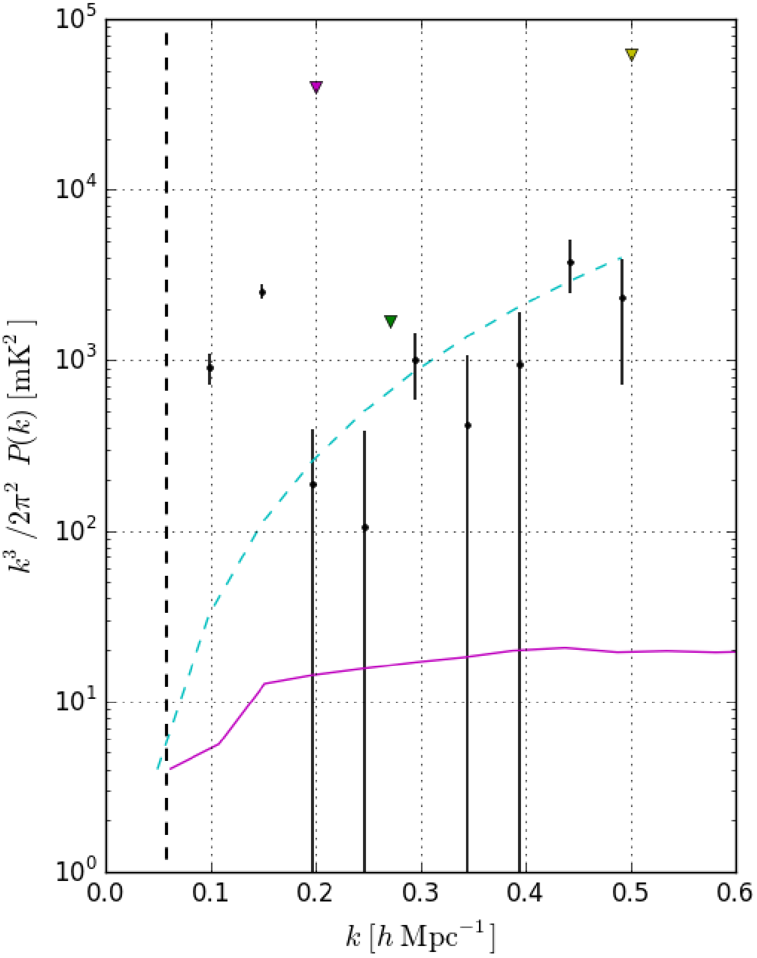

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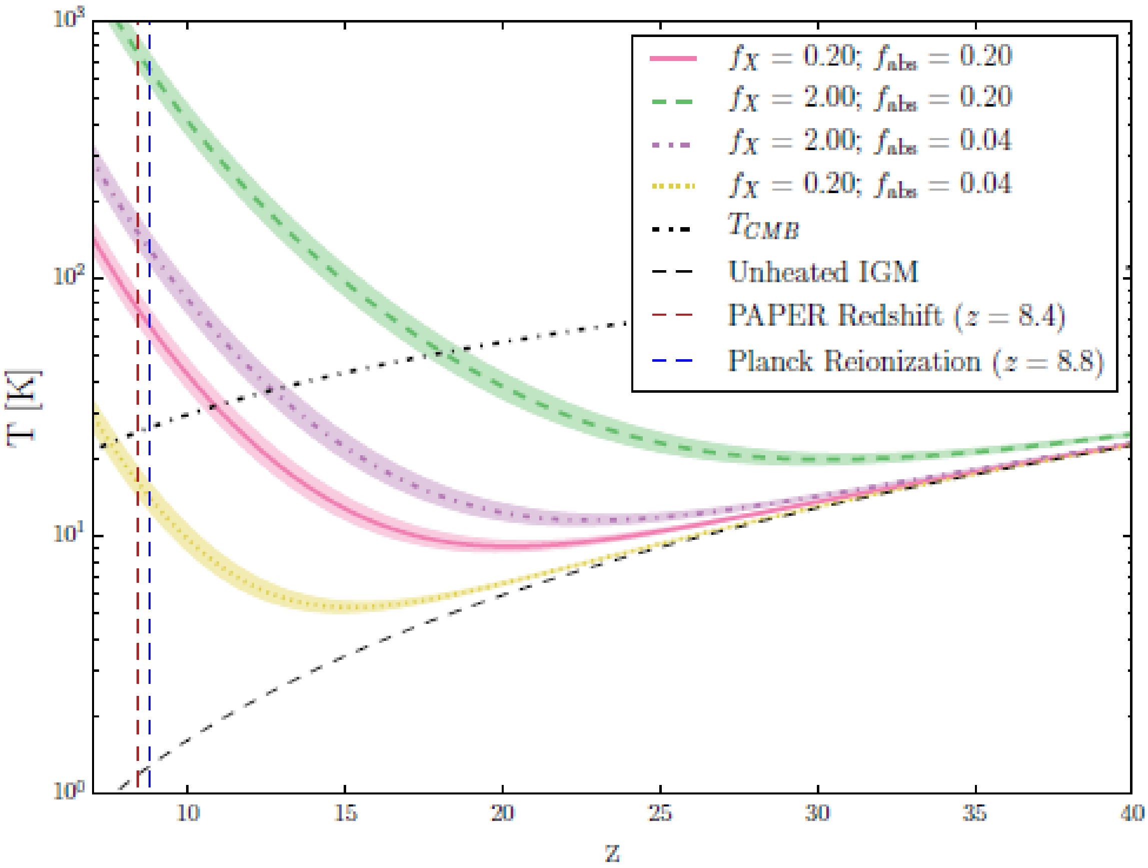


Hydrogen Epoch of Reionization Array
(deBoer et al. 2016)

- Arizona State University;
- Cambridge University;
- National Radio Astronomy Observatory;
- Massachusetts Institute of Technology;
- Scuola Normale Superiore;
- Square Kilometre Array South Africa;
- *University of California Berkeley*;
- University of California Los Angeles;
- University of Pennsylvania;
- University of Washington;

- University of KwaZulu Natal;
- University of Western Cape;

HERA science goals

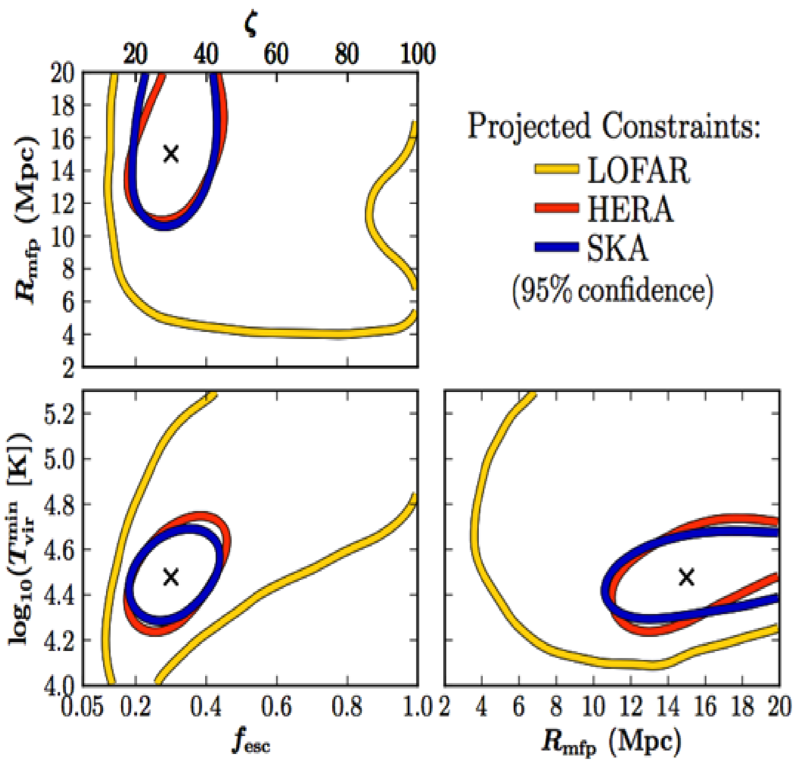
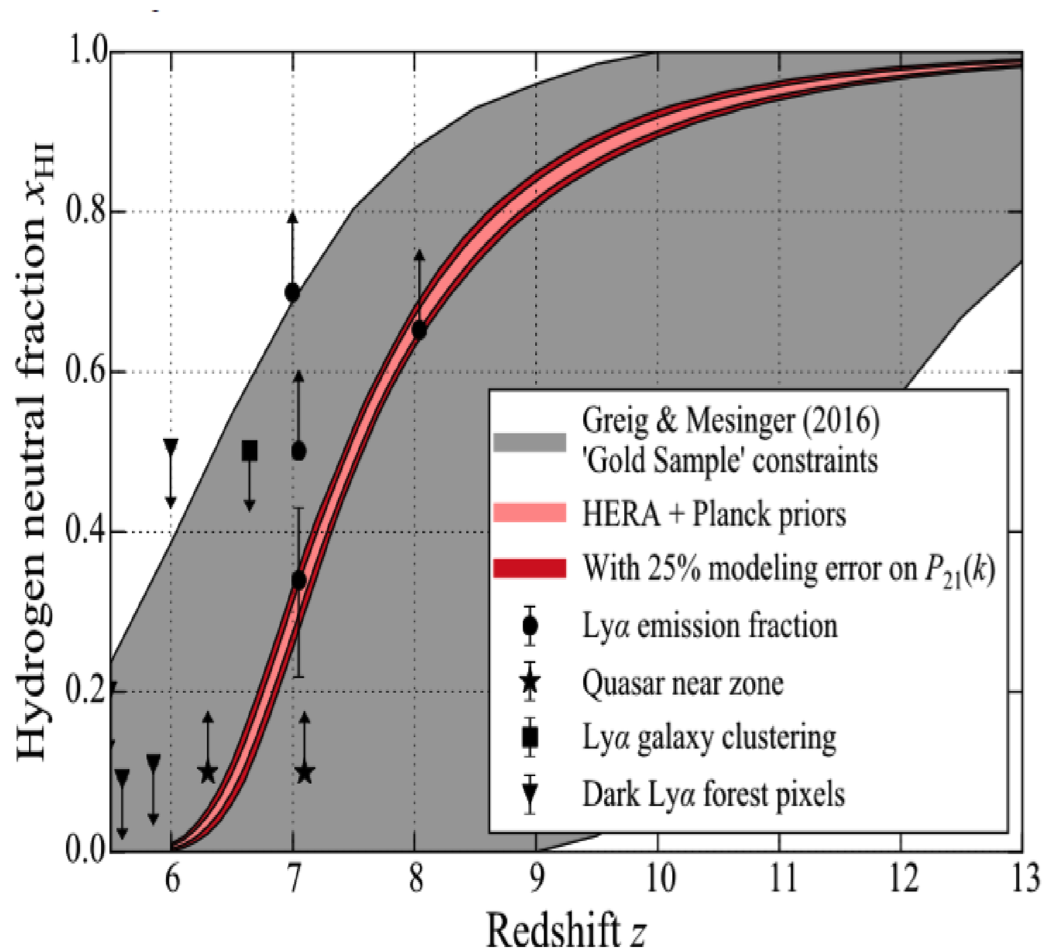


Fig. 4.— Projected likelihood contours from an MCMC analysis for astrophysical parameters of reionization. Model parameters are $T_{\rm vir}^{\rm min}$ (minimum virial temperature of ionizing galaxies); $R_{\rm mfp}$ (mean free path of ionizing photons in HII regions); and ζ_0 (ionizing efficiency of galaxies). Also shown are constraints on the derived ionizing escape fraction, $f_{\rm esc}$.



Current status

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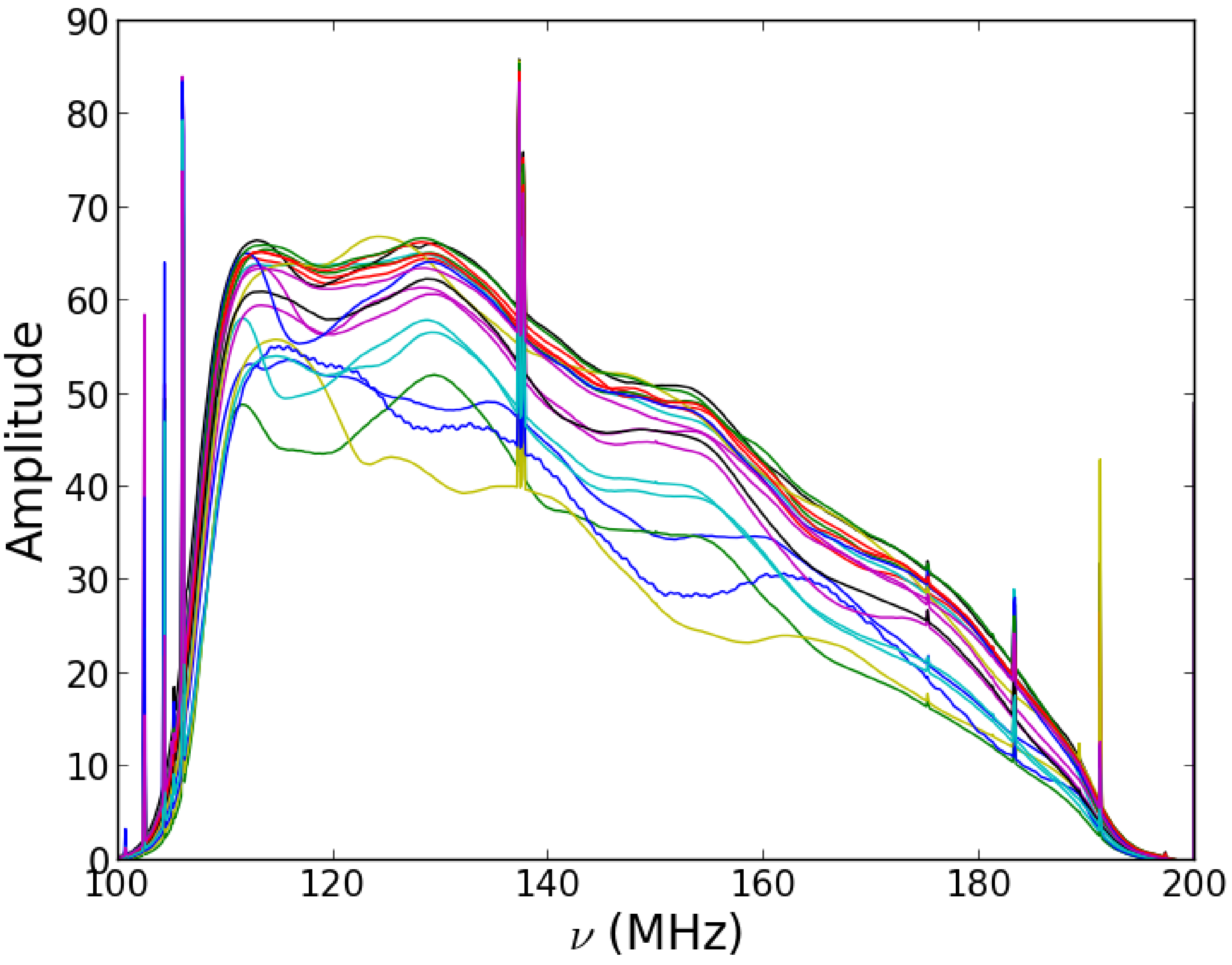

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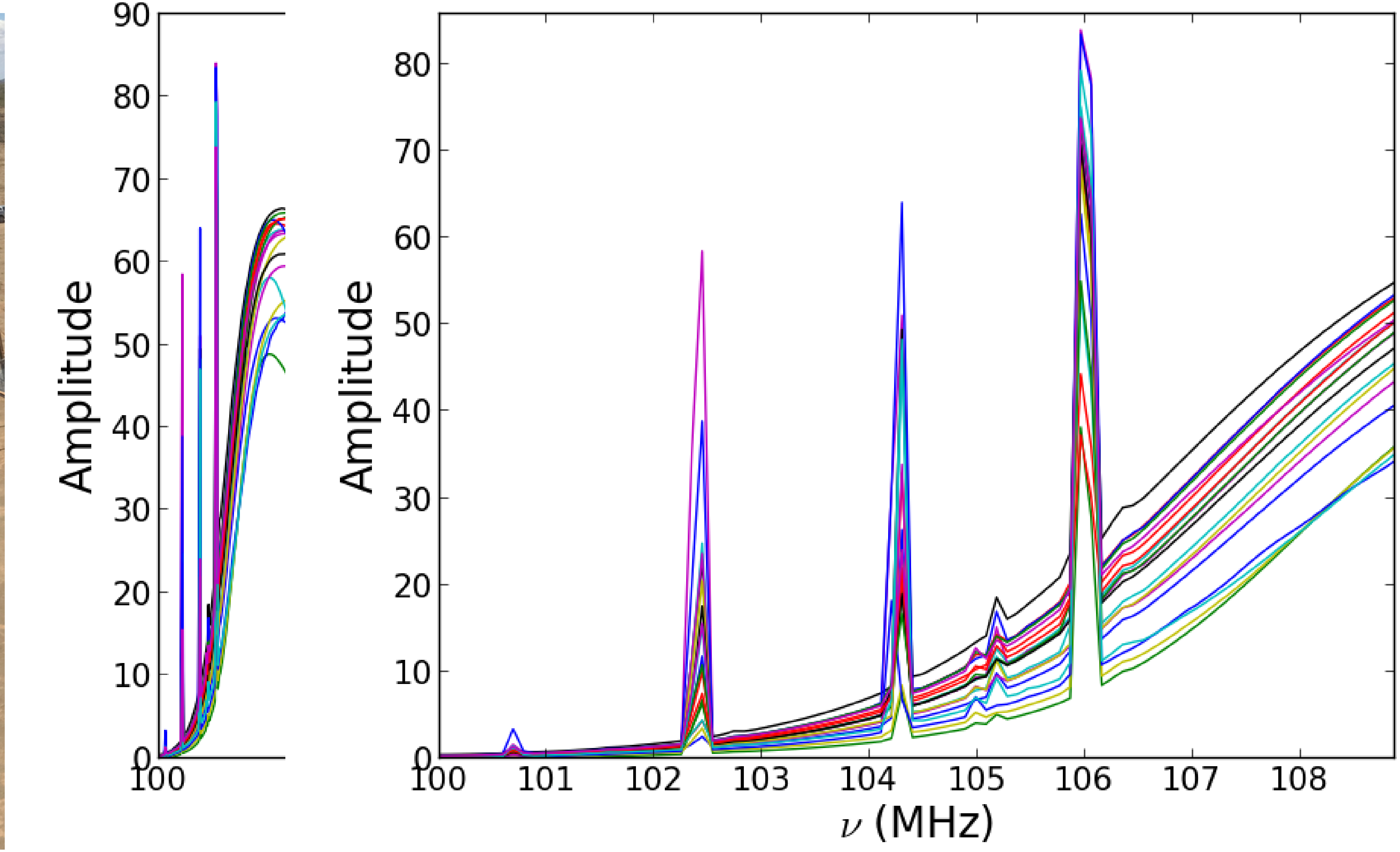

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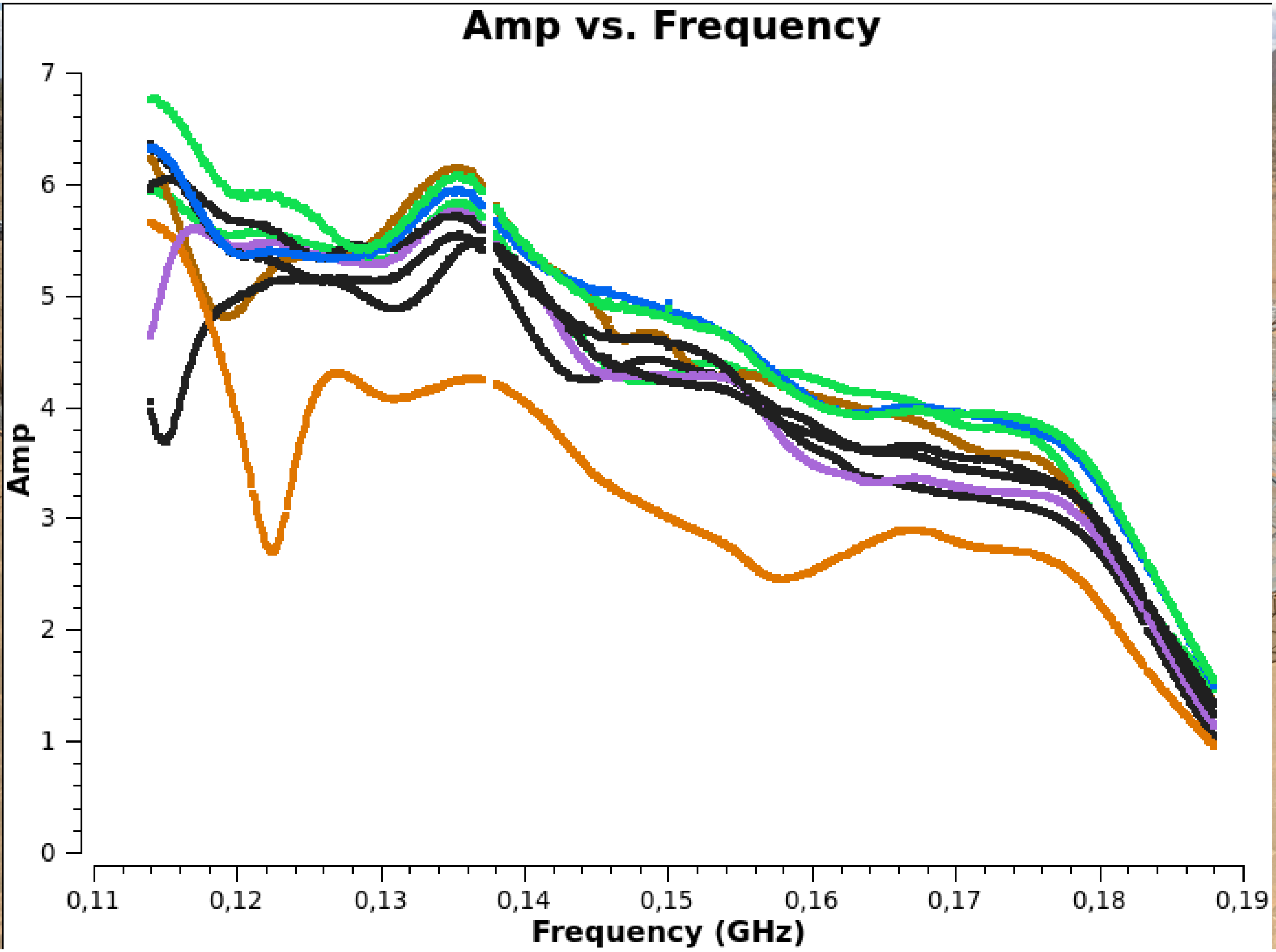

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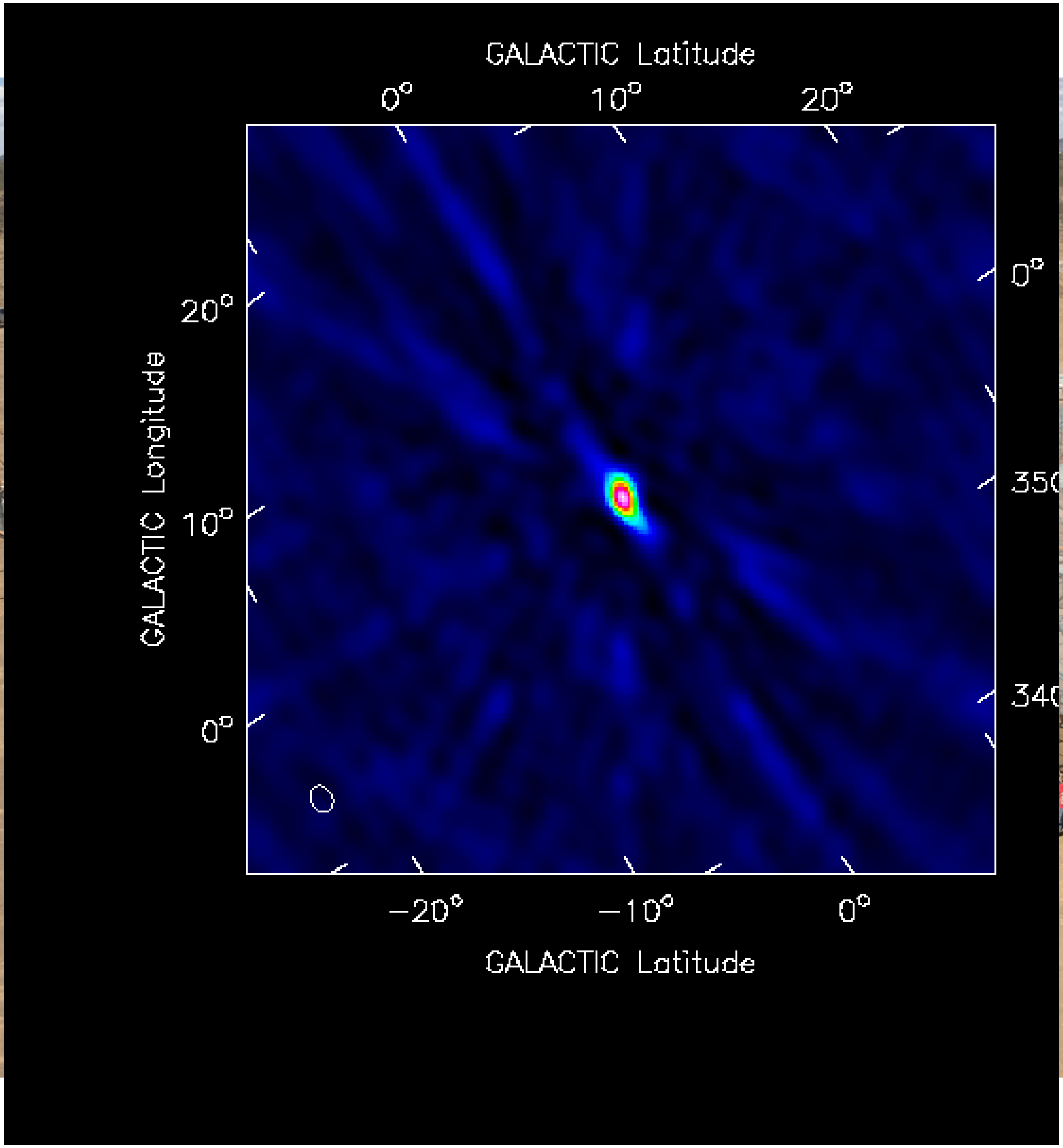

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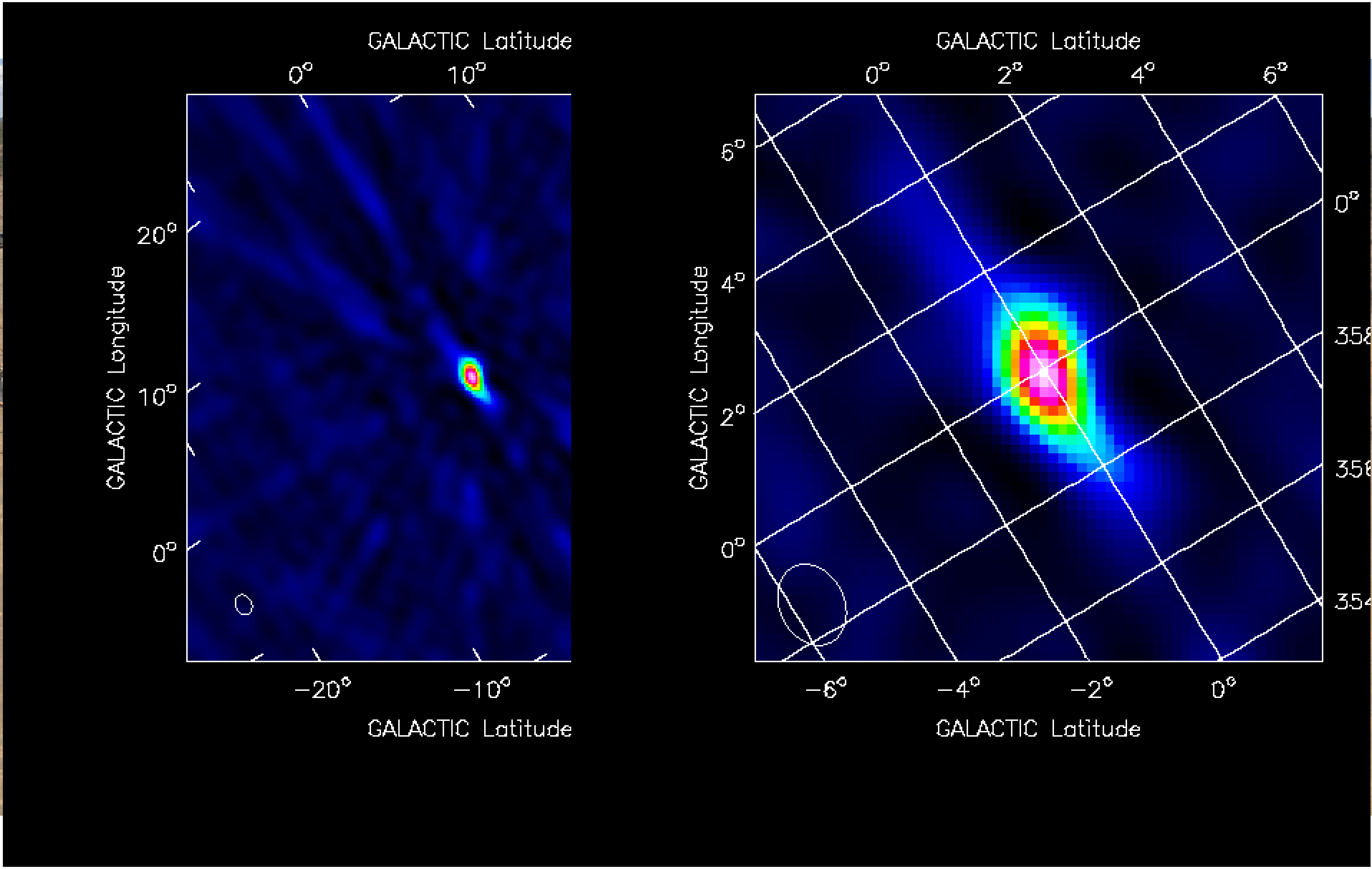
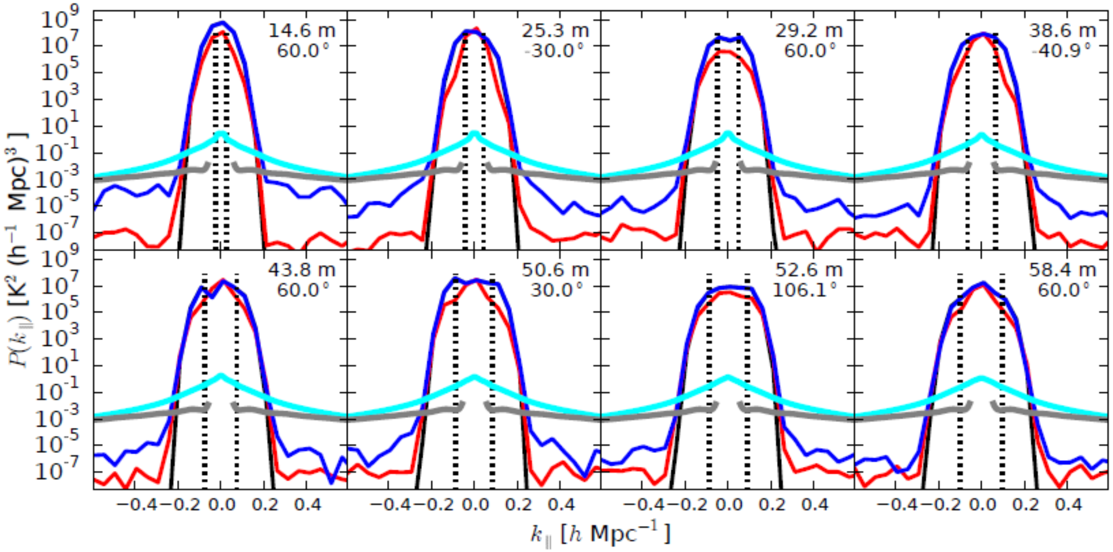
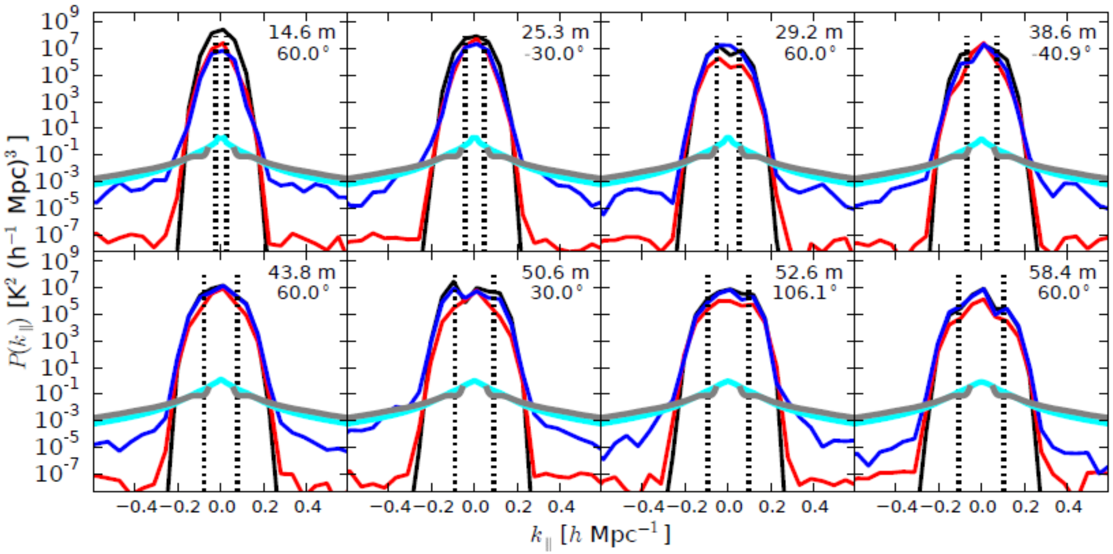


Characterizing the instrumental response



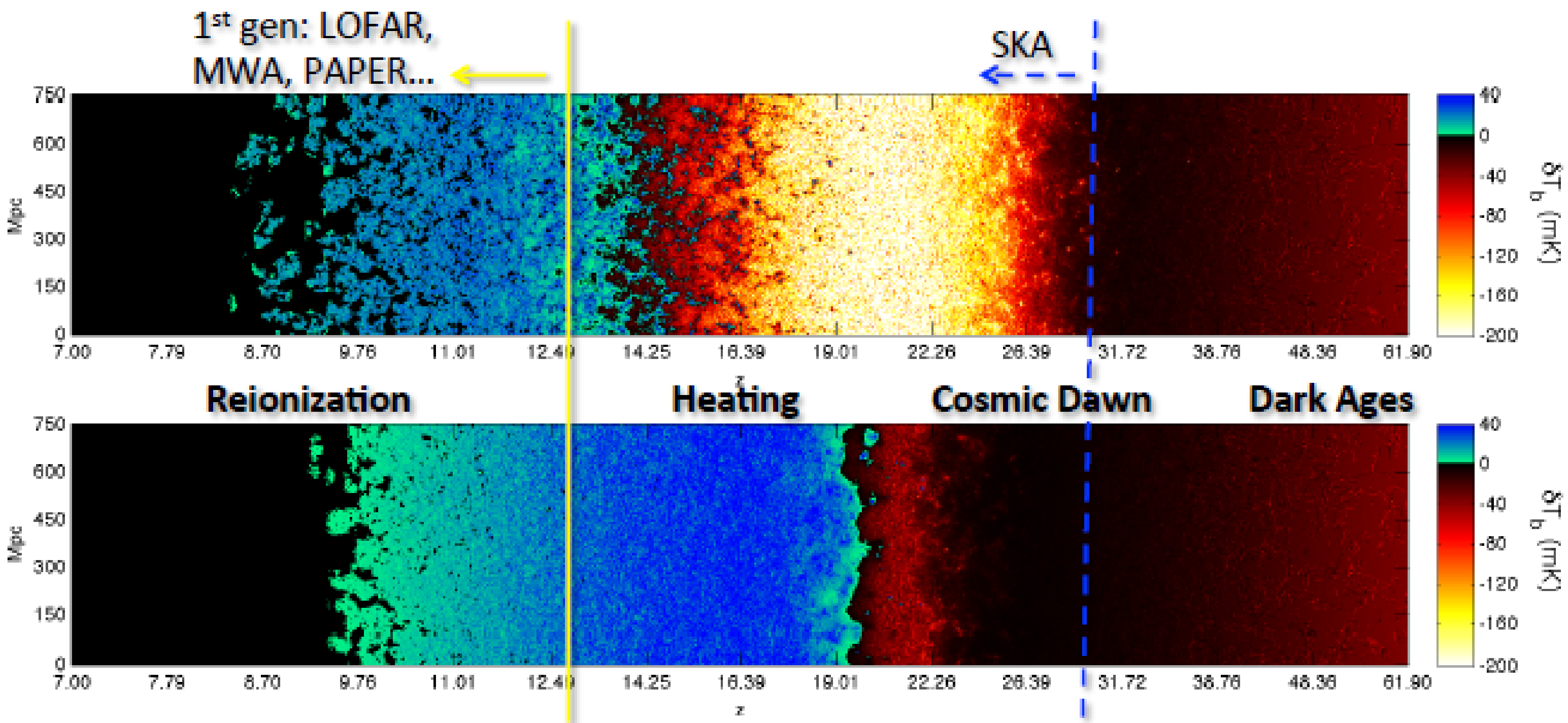
(a) 150 MHz subband ($z \approx 8.47$)



(b) 170 MHz subband ($z \approx 7.36$)

Thyagarajan et al. (2016)
(see also
Ewall-Wice et al. 2016,
Neben et al. 2016)

The future: SKA



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

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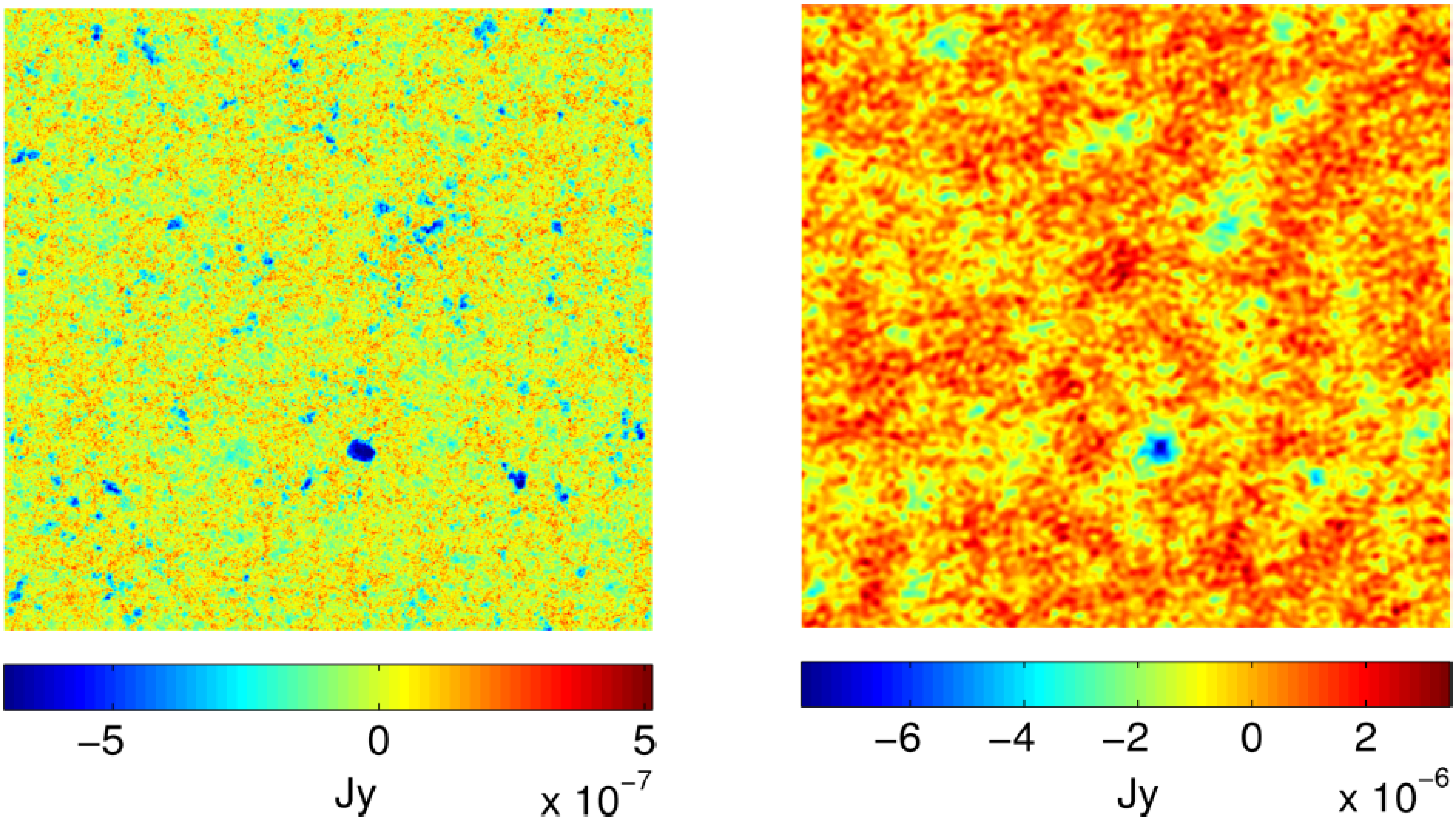

see Koopmans et al. (2015), Mesinger et al. (2015), Mellema et al. (2015)

Conclusions

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

- Global 21 cm experiment are delivering their first upper limits 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, HERA coming online);

- The most sensitive telescope still has to come online: the SKA will be capable of imaging reionization and observing the first luminous sources up to z ~ 30. Still a long story to be told!

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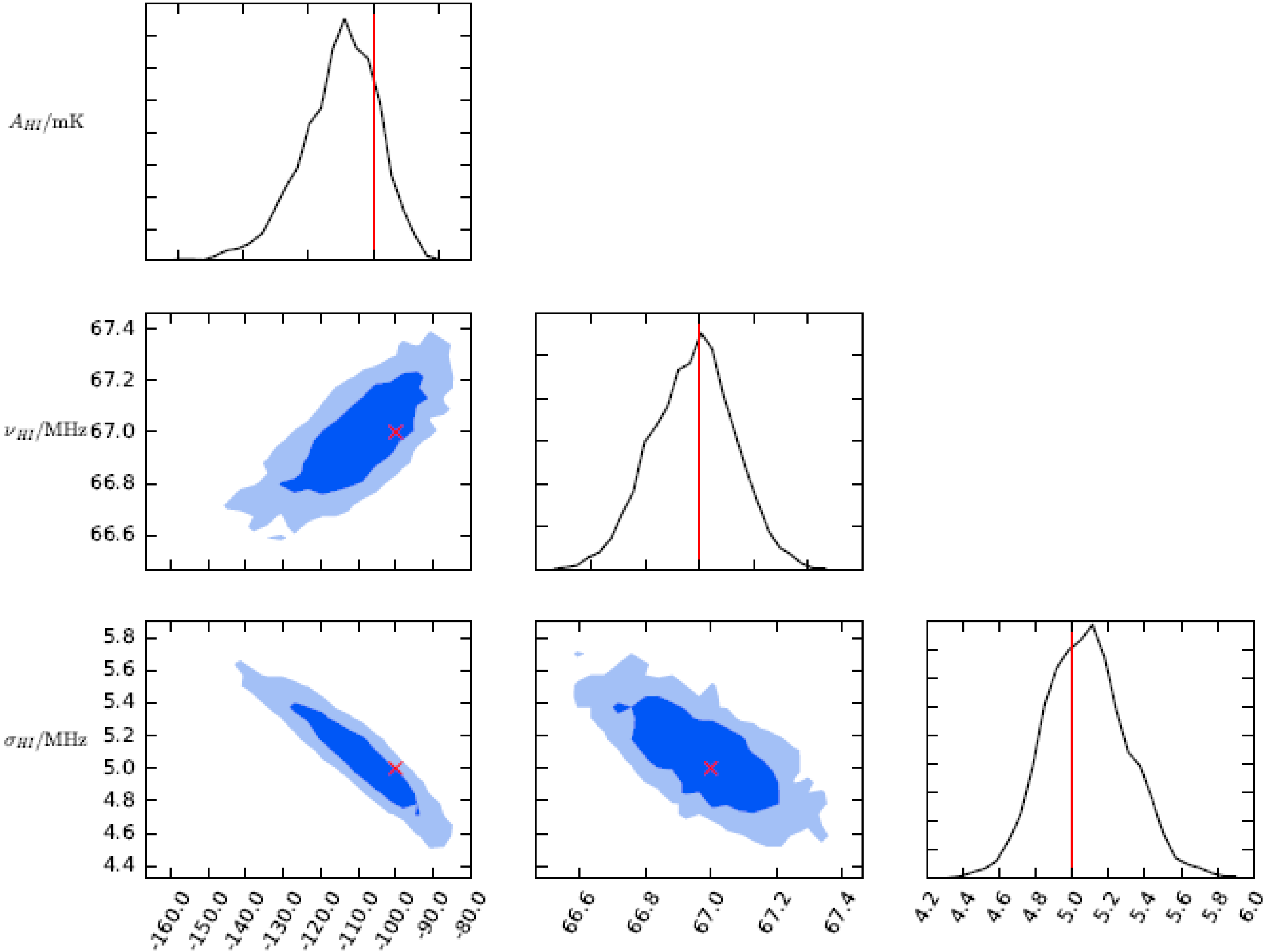
THANK YOU

Back up slides

Bayesian signal extraction: a simulated case



Current status