Reionization of the Universe

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HETG Journal Club
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An absorption profile centred at 78 megahertz in the sky-averaged spectrum

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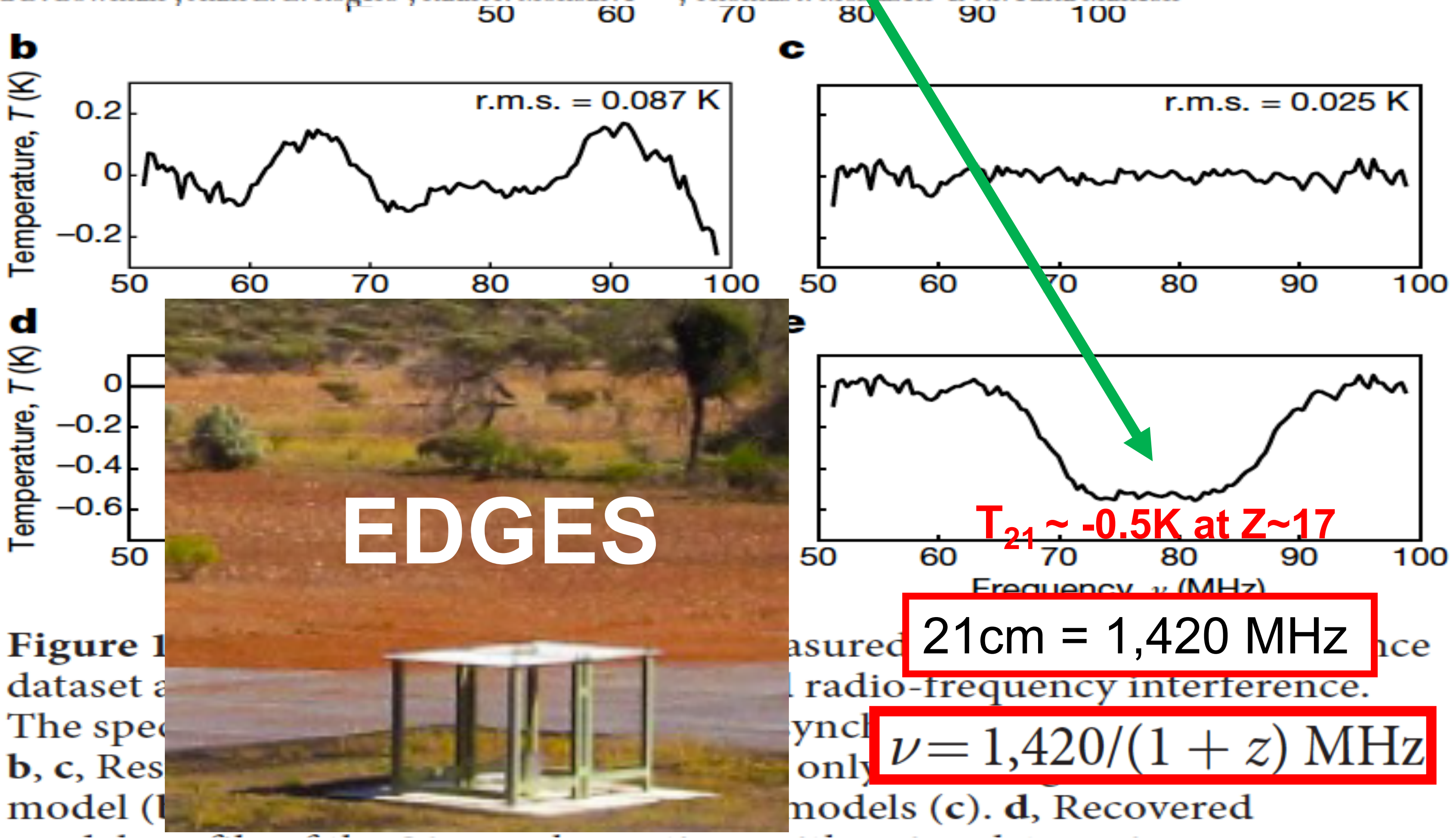


T_{21} ~ -0.5K at Z~17

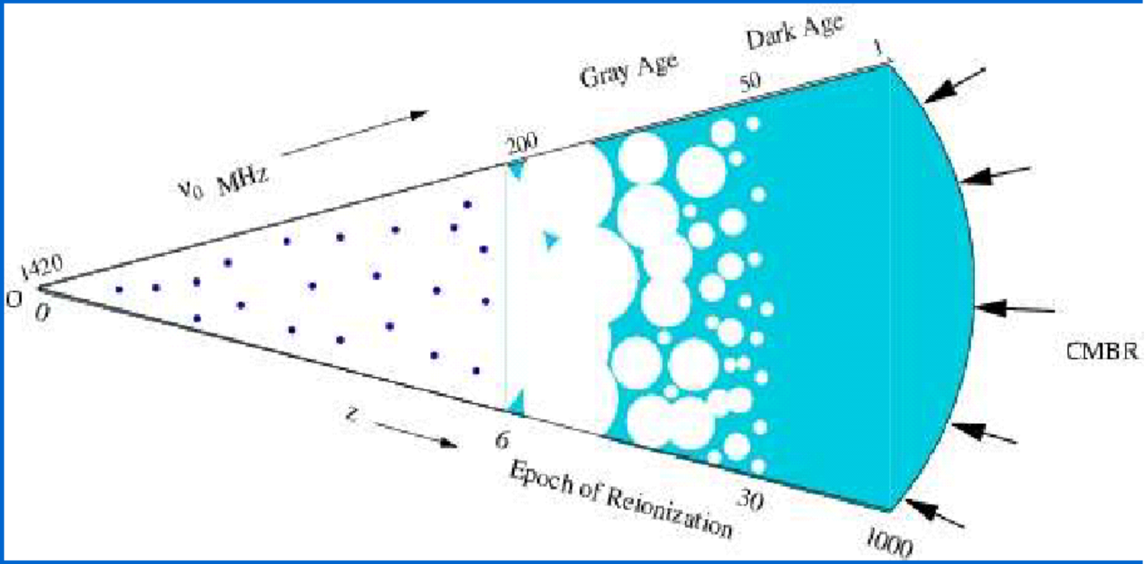
21cm = 1,420 MHz

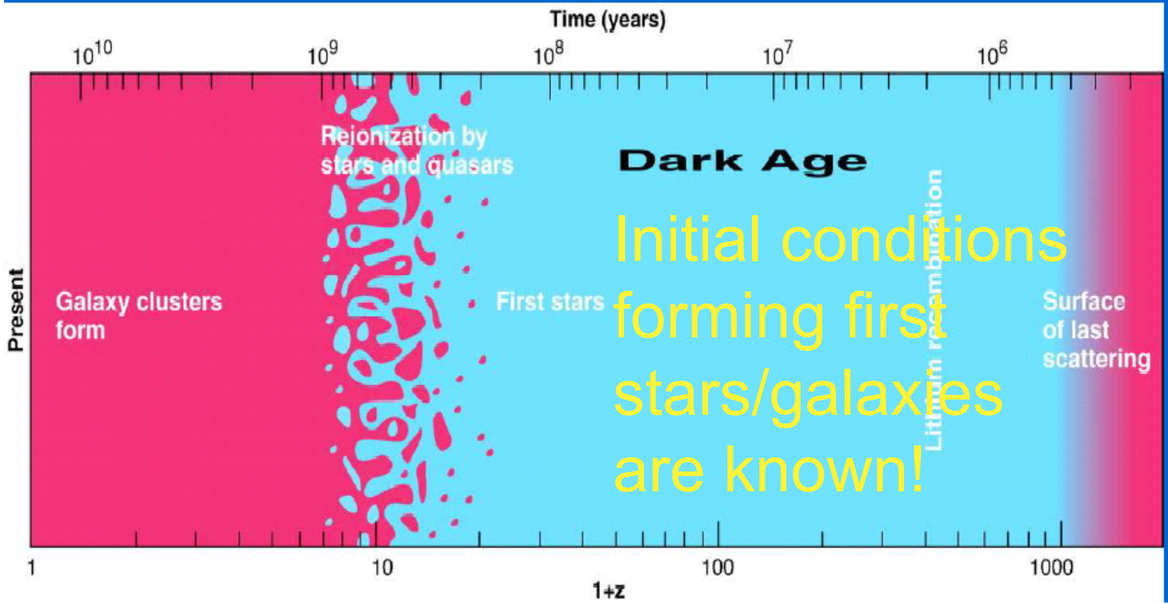
$\nu = 1{,}420/(1 + z)$ MHz

Figure 1 … asured … nce dataset a… radio-frequency interference. The spe… ynch… **b**, **c**, Res… only model (… models (**c**). **d**, Recovered

What are the Cosmic Dark Ages?

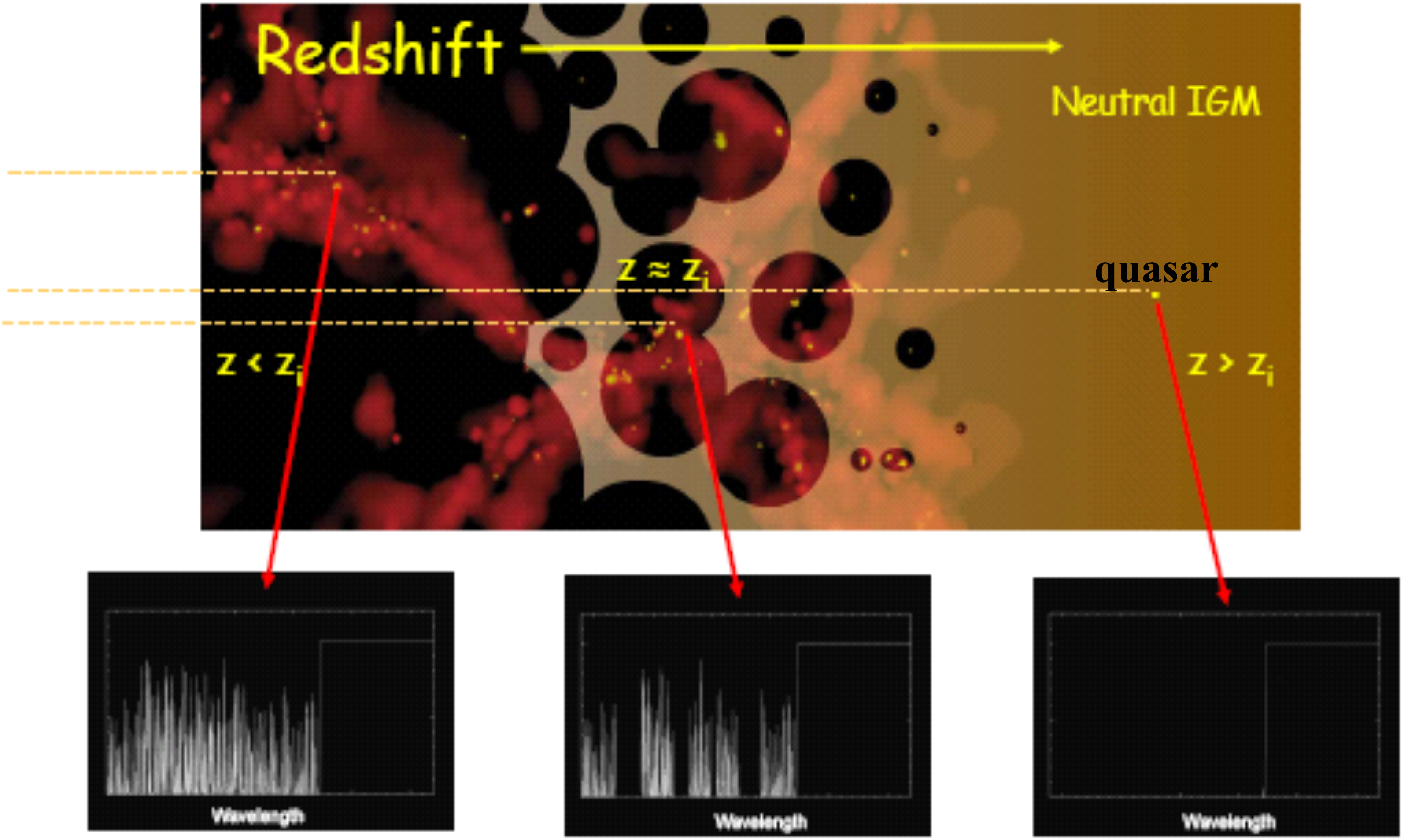
The Cartoons:





Initial conditions forming first stars/galaxies are known!

Lyman-✓ Absorption of Quasar



Lyman Forest Absorption

Patchy Absorption

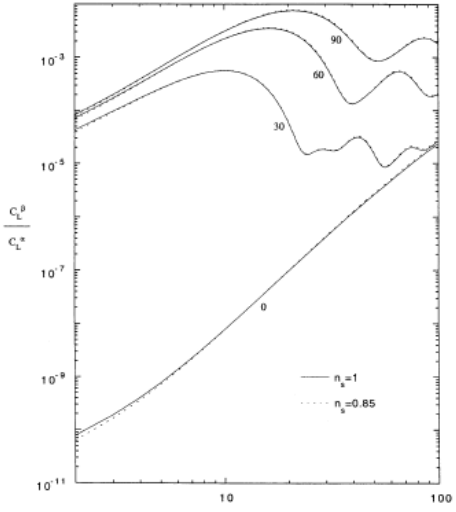
Black Gunn-Peterson trough

Courtesy of A. Ferrara

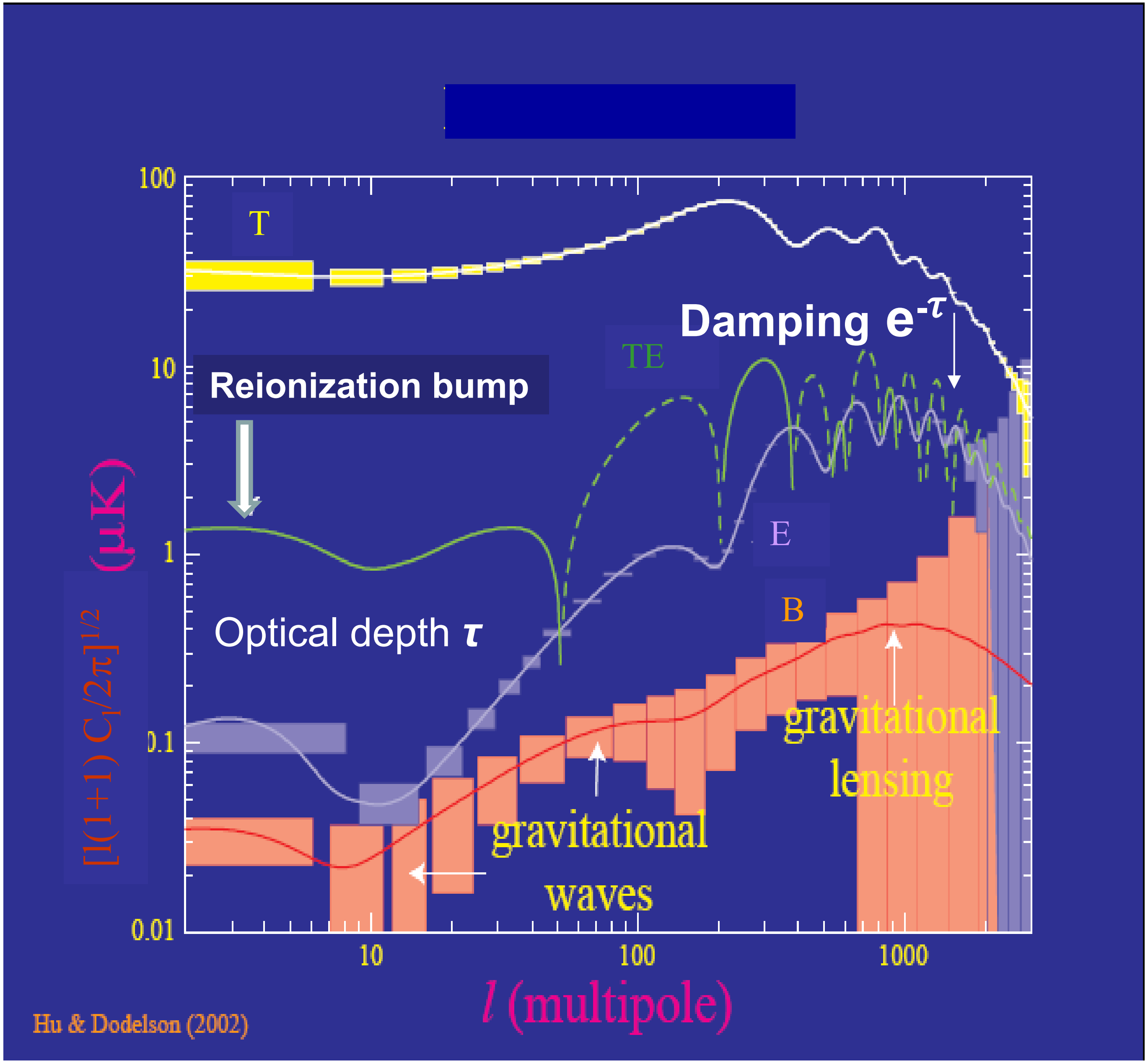
Precision measurements of reionization made by CMB experiments

Theoretical prediction of the reionization

Optical depth τ (from z=0 to the last scattering surface at z=1090)



Ng&Ng ApJ 96



Reionization bump

Optical depth τ

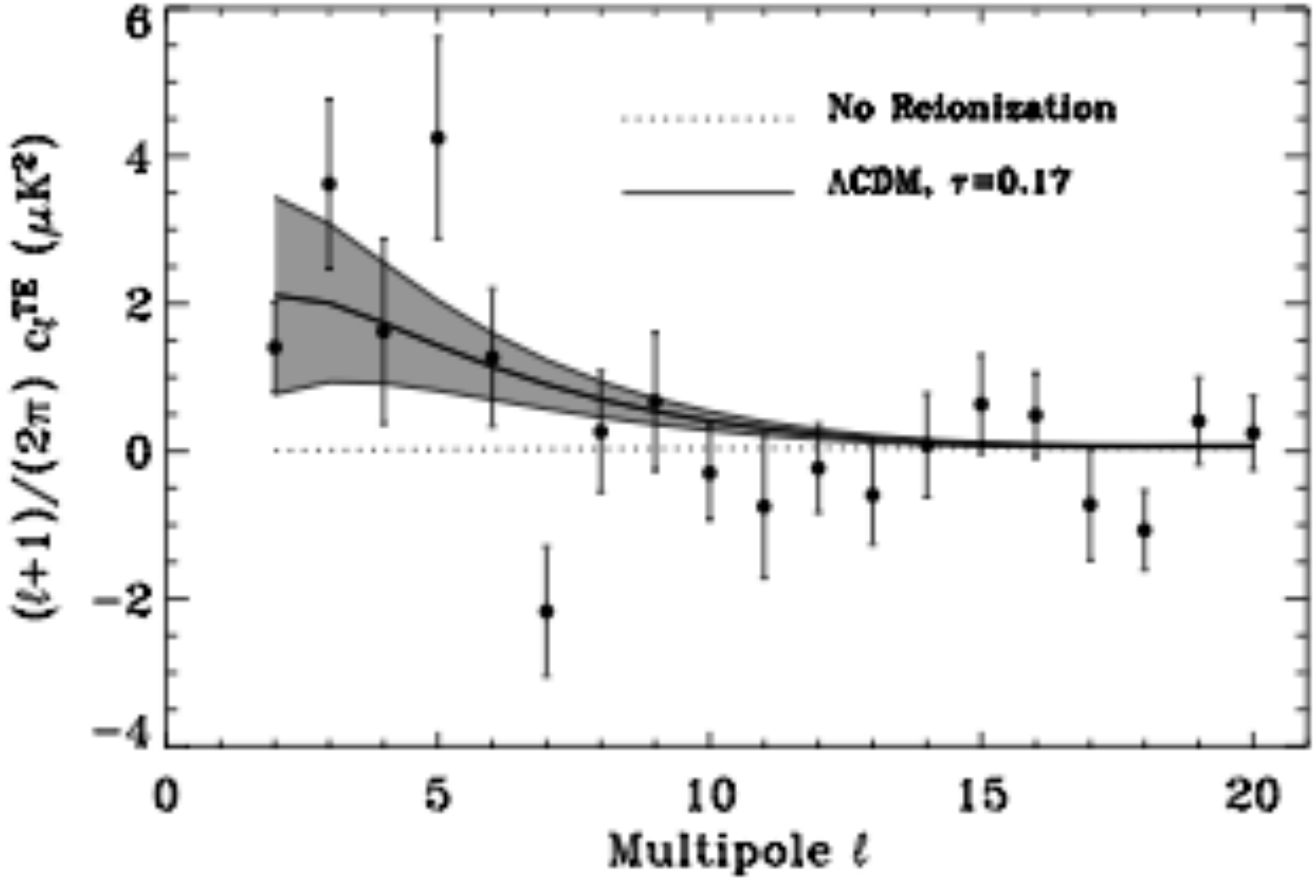
Damping $e^{-\tau}$

Hu & Dodelson (2002)

FIRST-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP*)[1] OBSERVATIONS: TEMPERATURE-POLARIZATION CORRELATION

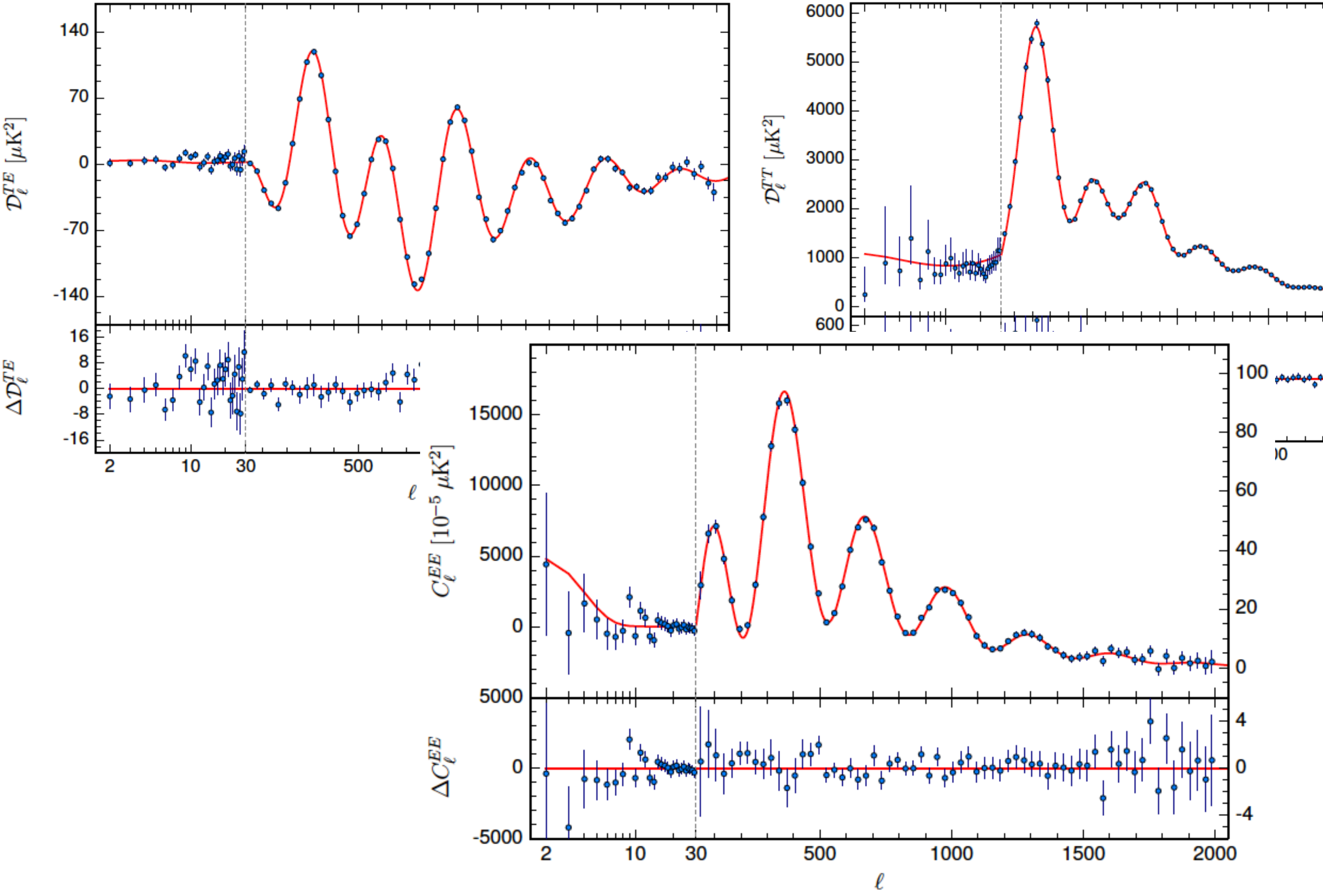
A. Kogut,[2] D. N. Spergel,[3] C. Barnes,[4] C. L. Bennett,[2] M. Halpern,[5] G. Hinshaw,[2] N. Jarosik,[4]
M. Limon,[2,4,6] S. S. Meyer,[7] L. Page,[3] G. S. Tucker,[2,6,8] E. Wollack,[2] and E. L. Wright[9]

Received 2003 February 11; accepted 2003 May 20



$Z_{reionization}$ ~ 20 (too big to be true?)

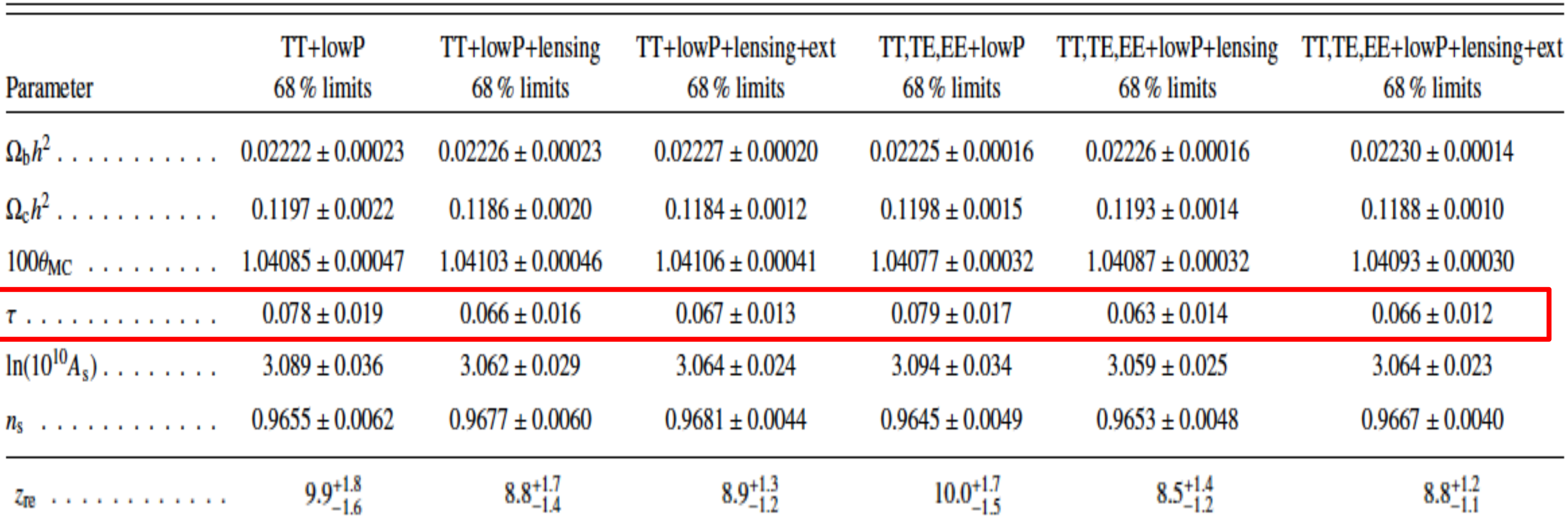
Planck CMB Power Spectra 2015



Best-fit 6-parameter ΛCDM model 2015

Density perturbation (scalar)

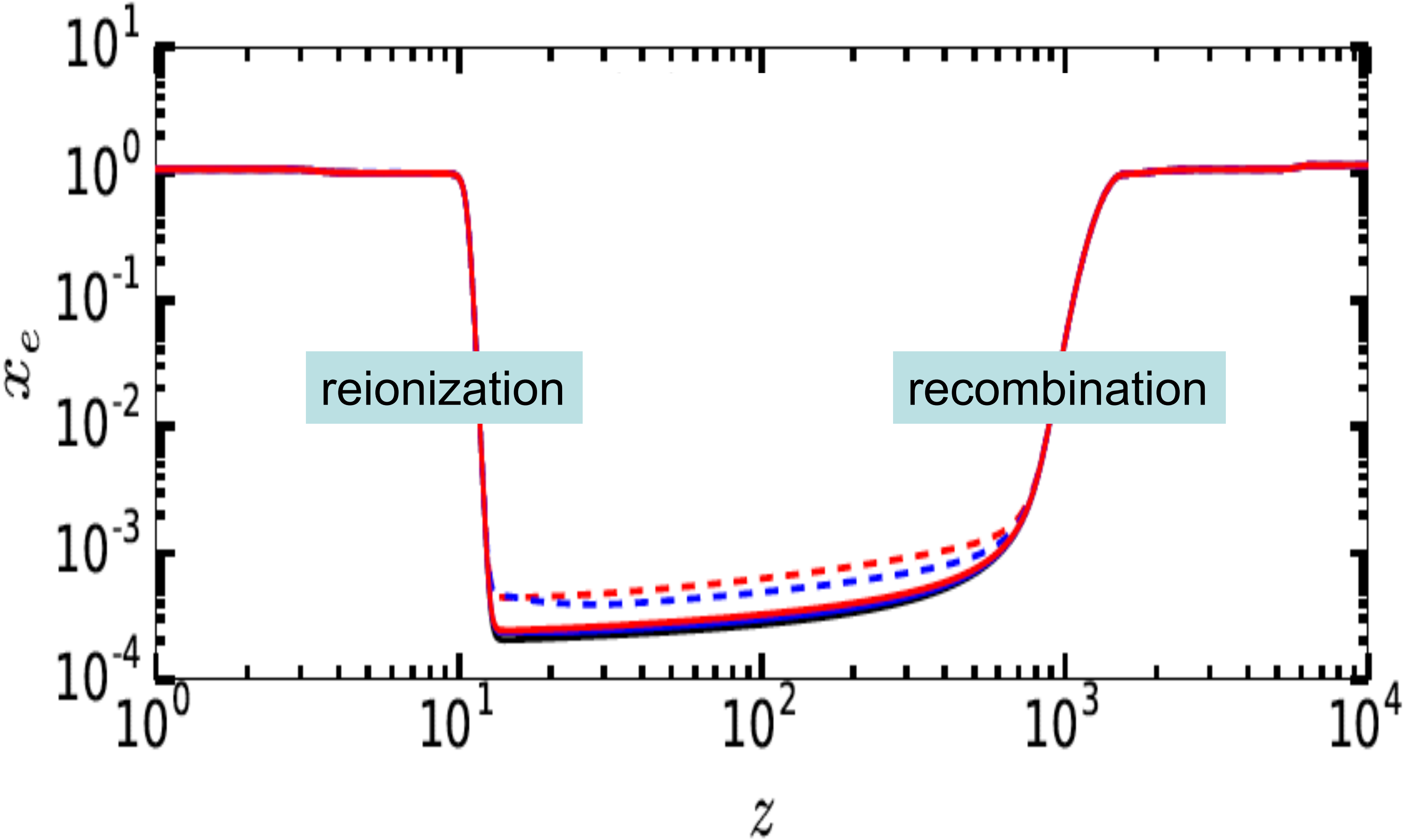
Spectral index $$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1}$$



Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$

- The 5 parameters determine the initial conditions for the formation of first stars/galaxies
- The optical depth τ (from z=0 to the last scattering surface at z=1090) constrains the process of reionization by first stars/galaxies

History of the ionization fraction of hydrogen atom



reionization

recombination

TIARA Reionization Workshop

February 13-14, 2006
TIARA, 8F General Building II, National Tsing Hua University, Hsinchu, Taiwan

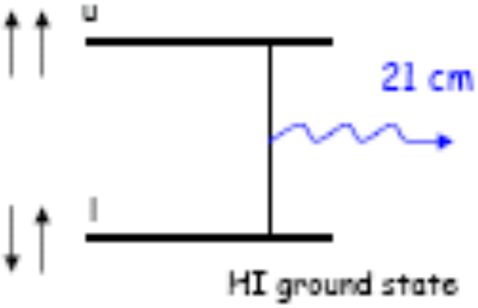
Program

2/16 (Thu.)	12:00 - 13:00	Benedetta Ciardi	Reionization theory and observations
2/20 (Mon.)	10:30 - 11:30	Asantha Cooray	21cm background
2/21 (Tue.)	10:30 - 11:30	Tom Theuns	TBD
2/23 (Thu.)	10:30 - 11:30	Tirthankar Roy Choudhury	Observational Constraints on Reionization Models
2/23 (Thu.)	12:30 - 13:30	Andrea Ferrara	First stars & the cosmic dawn
2/24 (Fri.)	10:30 - 11:30	Christopher Hirata	Excitation & de-excitation of the 21cm line
2/27 (Mon.)	10:30 - 11:30	Shiv Sethi	Primordial Magnetic Fields and Reionization of the Universe
2/28 (Tue.)	10:30 - 11:30	Tzu Ching Chang	Halo Mergers and Bubble Growth during Reionization
3/02 (Thu.)	10:30 - 11:30	Ilian Iliev	Large-scale simulations of reionization
3/01 (Wed.)	10:30 - 11:30	Garrelt Mellema	21cm predictions for the epoch of reionization

Contact Webmaster: web@asiaa.sinica.edu.tw
Last Updated: 2015-08-05

Atomic Hydrogen (HI) 21cm Emission

Hyperfine splitting



(1420 MHz)

n=1

Spin temperature

The two states ↑↓ and ↑↑ can be described by a Boltzmann relation:

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-h\nu_{10}/kT_s}$$

↓

statistical weights

T_s → spin temperature

$$\frac{h\nu_{10}}{k} \simeq 0.07\,K$$

↓

$$\frac{n_1}{n_0} = 3\left(1 - \frac{0.07K}{T_s}\right) \simeq 3$$

$T_s \gg 0.07K$

Radiative transfer:

$$I_\nu = I_\nu(T_{CMB})\, e^{-\tau_\nu} + I_\nu(T_s)\,(1-e^{-\tau_\nu})$$

to be seen against CMB

$$\delta I_\nu = I_\nu - I_\nu(T_{CMB}) = \left(I_\nu(T_{CMB}) - I_\nu(T_s)\right)(1-e^{-\tau_\nu})$$

< 0 → absorption

> 0 → emission

τ_ν depends on n_{HI}/T_s

With all the proper factors in:

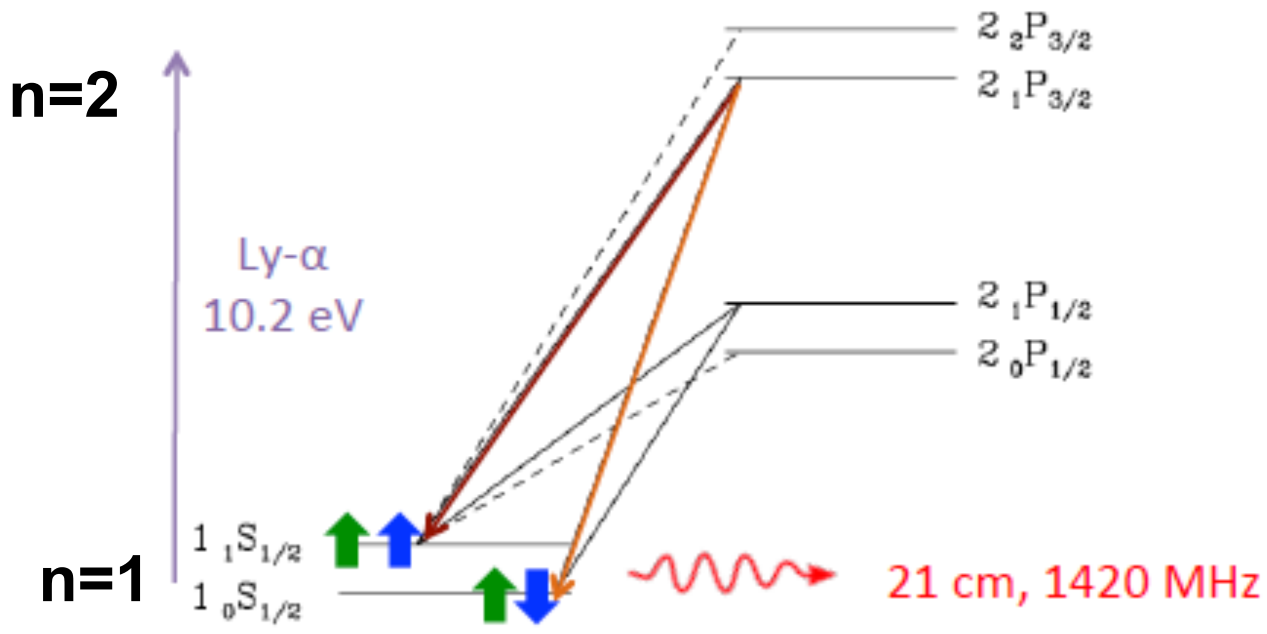
$$T_{21}(z) \approx 0.023\ \mathrm{K} \times x_{\mathrm{HI}}(z) \left[\left(\frac{0.15}{\Omega_{\mathrm{m}}}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}} \left(\frac{\Omega_{\mathrm{b}} h}{0.02}\right)\left[1-\frac{T_{\mathrm{R}}(z)}{T_{\mathrm{S}}(z)}\right]$$

$T_R \sim T_{CMB}$

where x_{HI} is the fraction of neutral hydrogen, Ω_{m} and Ω_{b} are the matter and baryon densities, respectively, in units of the critical density for a flat universe, h is the Hubble constant in units of $100\,\mathrm{km\ s^{-1}\ Mpc^{-1}}$,

Wouthuysen-Field Effect

how to populate the “u” and “l” states



Color temperature of ambient Ly-α radiation

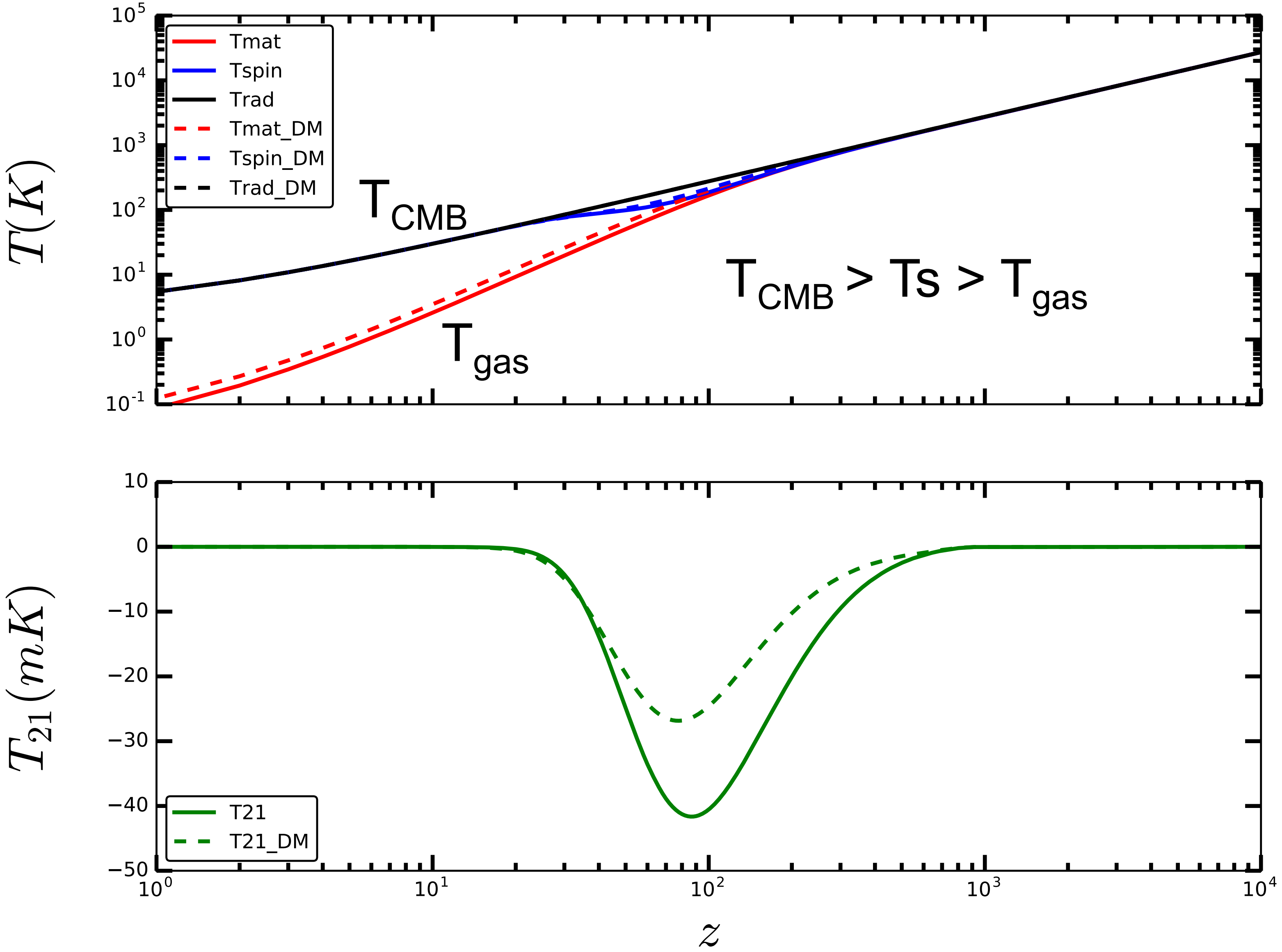
Gas temperature

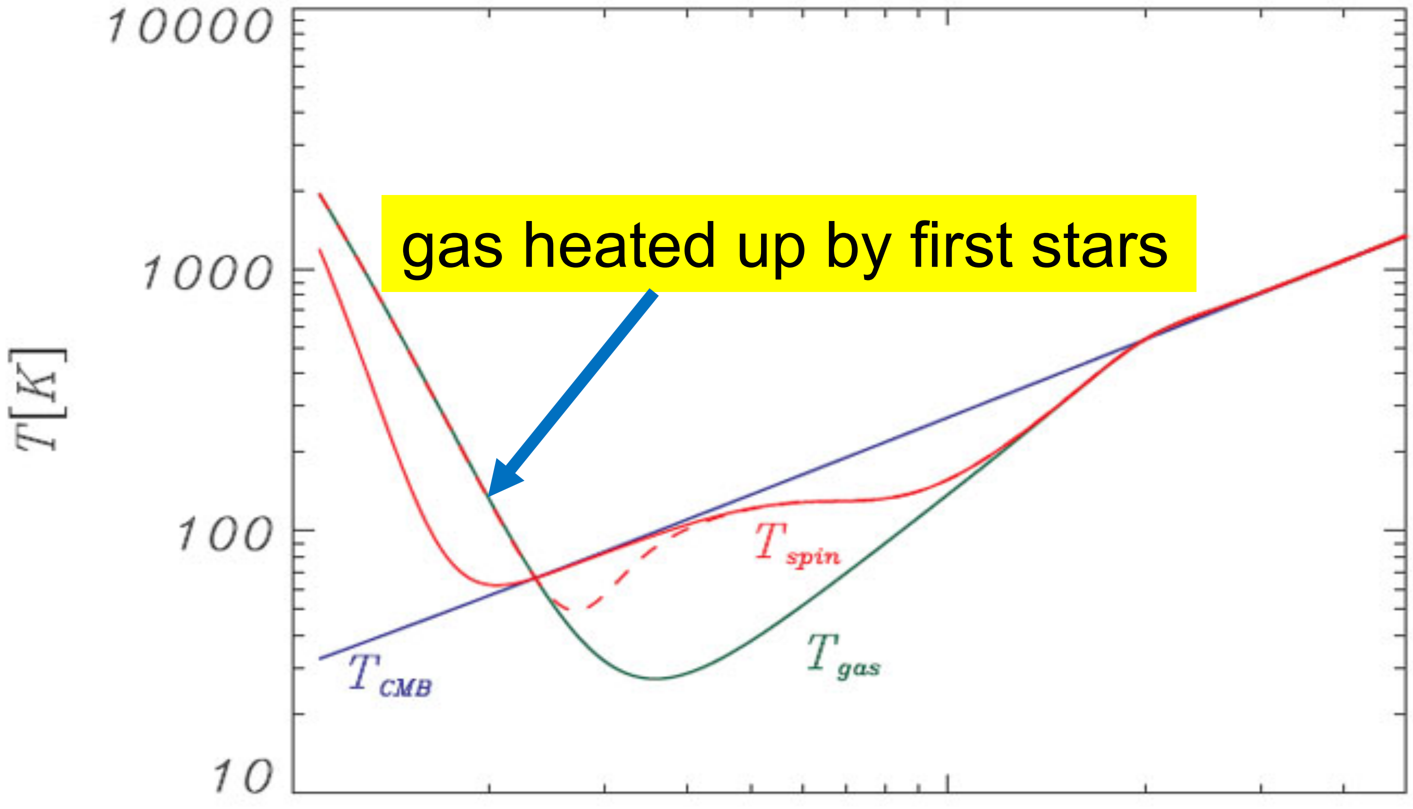
$$T_s^{-1} = \frac{T_{\mathrm{CMB}}^{-1} + y_\alpha T_\alpha^{-1} + y_c T_k^{-1}}{1 + y_\alpha + y_c}$$

Gas collision pumping efficiency

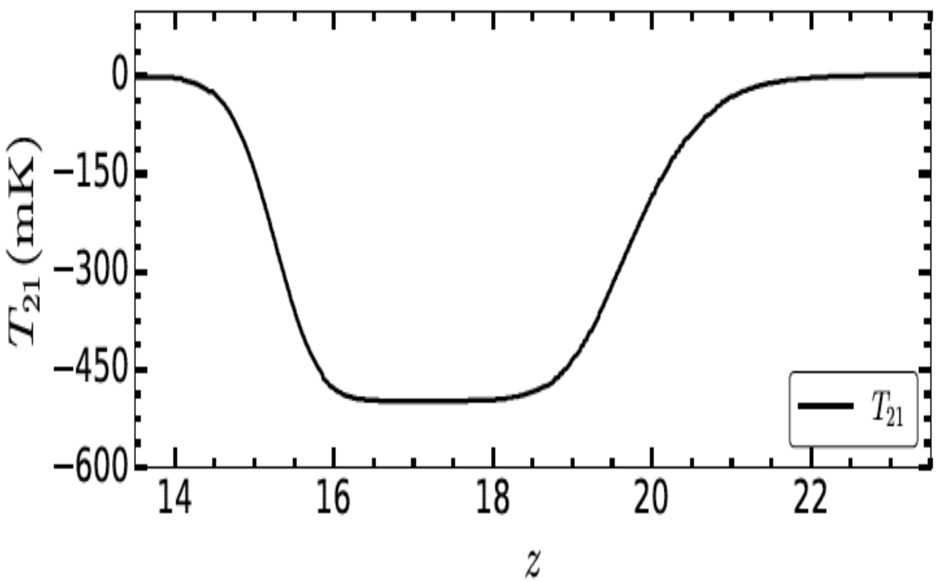
Ly-α pumping efficiency

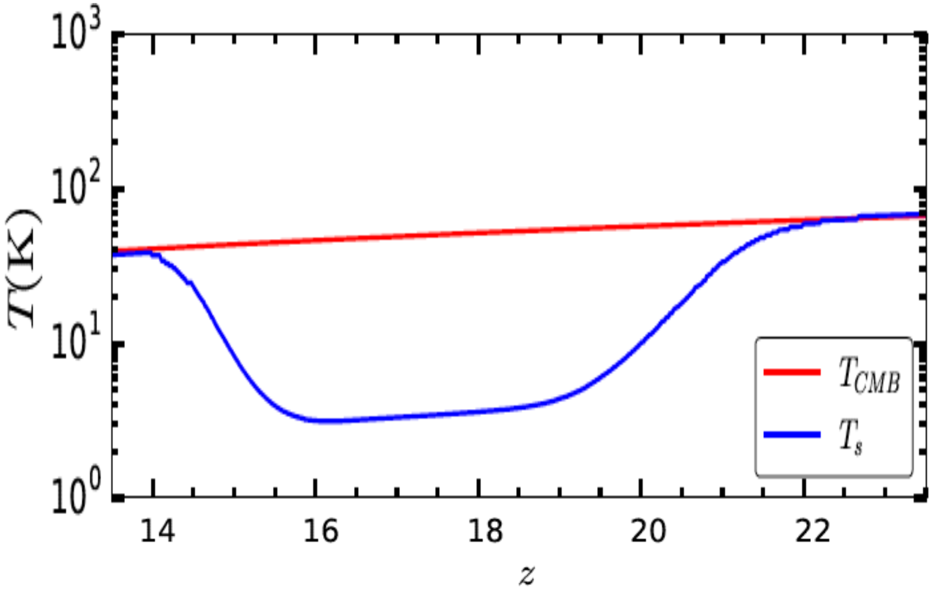
Temperatures versus redshift without first stars





gas heated up by first stars



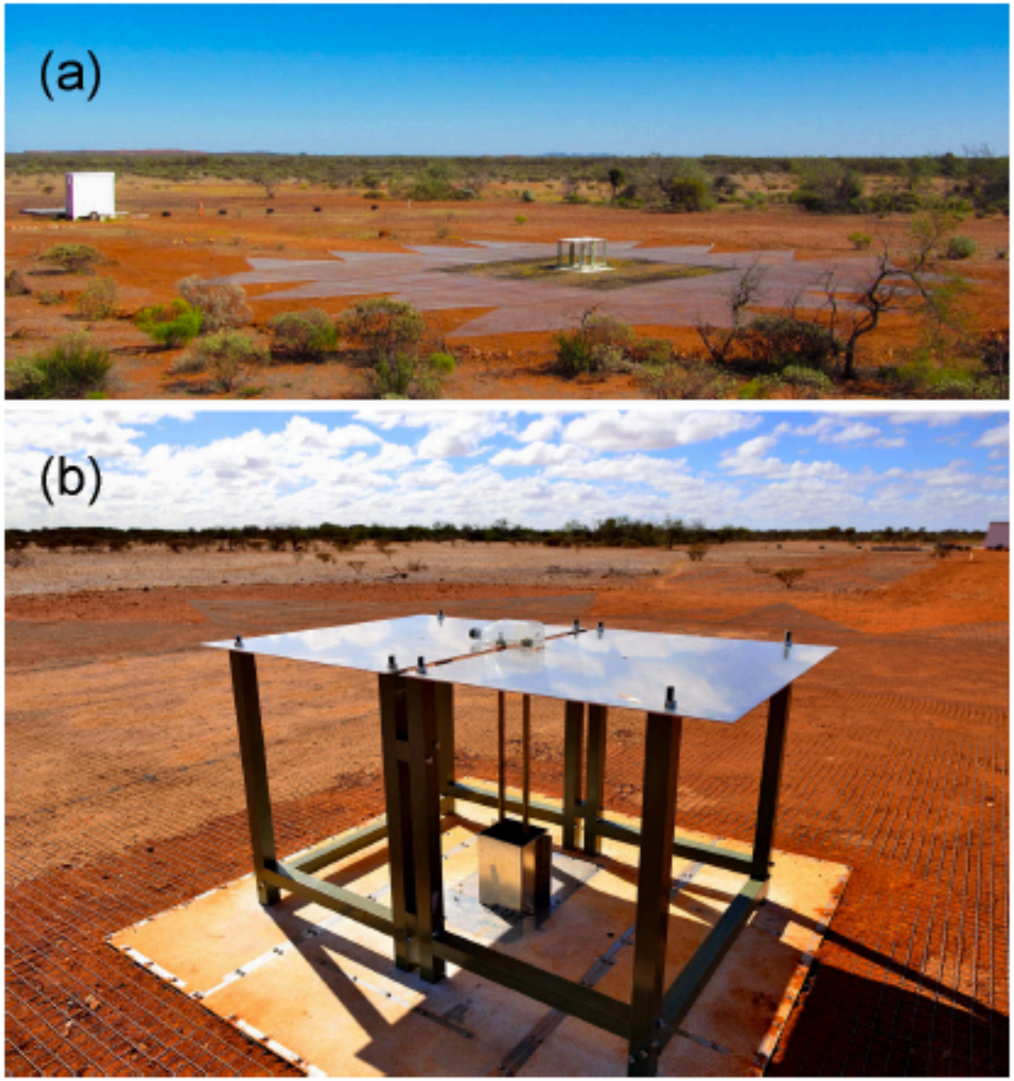


An absorption profile centred at 78 megahertz in the sky-averaged spectrum

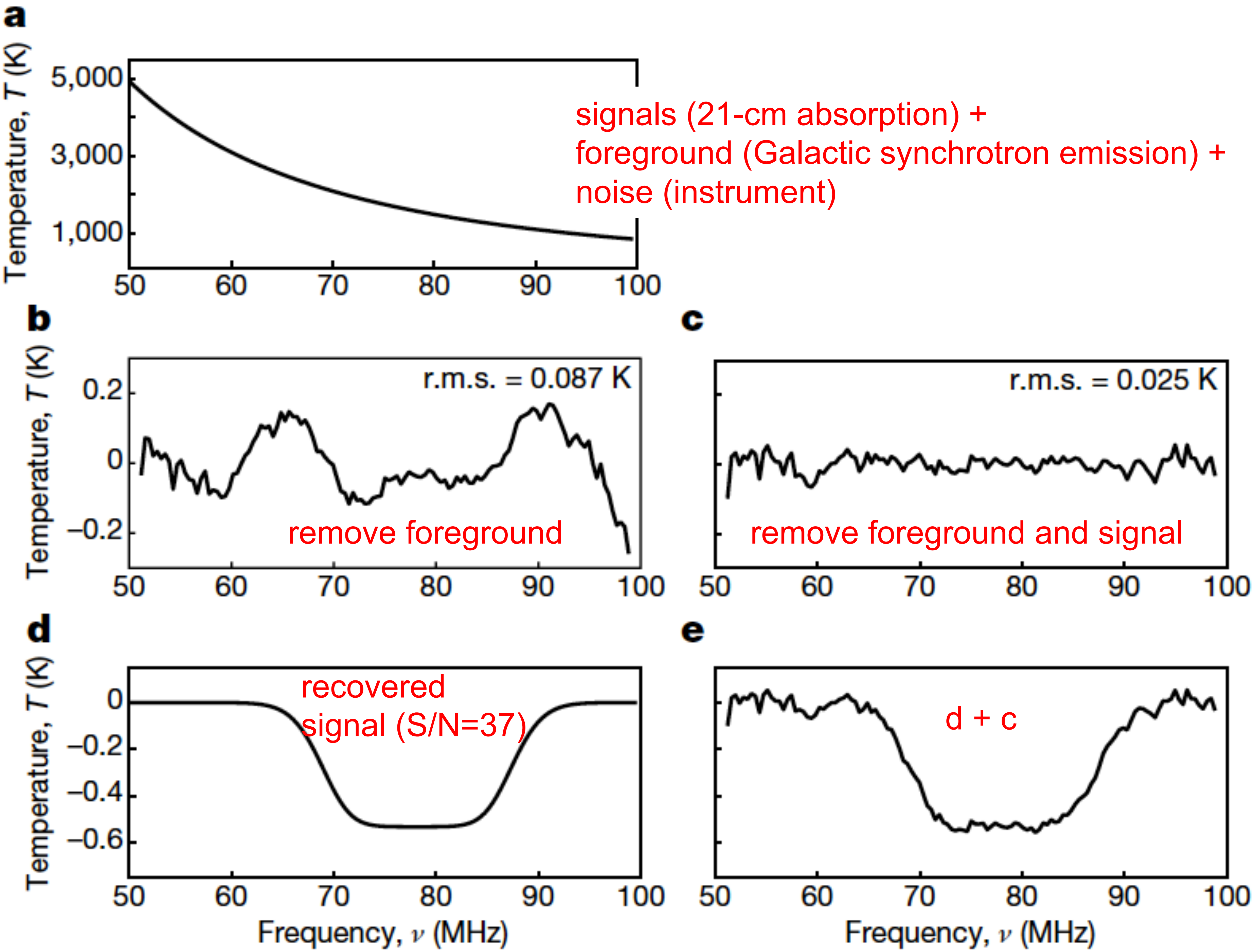
Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]

Experiment to
Detect the
Global
Epoch of reionization
Signature

@ Western Australia



Extended Data Figure 2 | Low-band antennas. a, The low-1 antenna with the 30 m × 30 m mesh ground plane. The darker inner square is the original 10 m × 10 m mesh. The control hut is 50 m from the antenna. **b,** A close view of the low-2 antenna. The two elevated metal panels form the dipole-based antenna and are supported by fibreglass legs. The balun consists of the two vertical brass tubes in the middle of the antenna. The balun shield is the shoebox-sized metal shroud around the bottom of the balun. The receiver is under the white metal platform and is not visible.



signals (21-cm absorption) +
foreground (Galactic synchrotron emission) +
noise (instrument)

remove foreground

remove foreground and signal

recovered
signal (S/N=37)

d + c

Parameter Estimation

- 5 terms Polynomial foreground model (galactic synchrotron + ionosphere):

$$T_{\mathrm{F}}(\nu) \approx a_0\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2.5} + a_1\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2.5}\log\left(\frac{\nu}{\nu_{\mathrm{c}}}\right) + a_2\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2.5}\left[\log\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)\right]^2 + a_3\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-4.5} + a_4\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2}$$

(5 parameters)

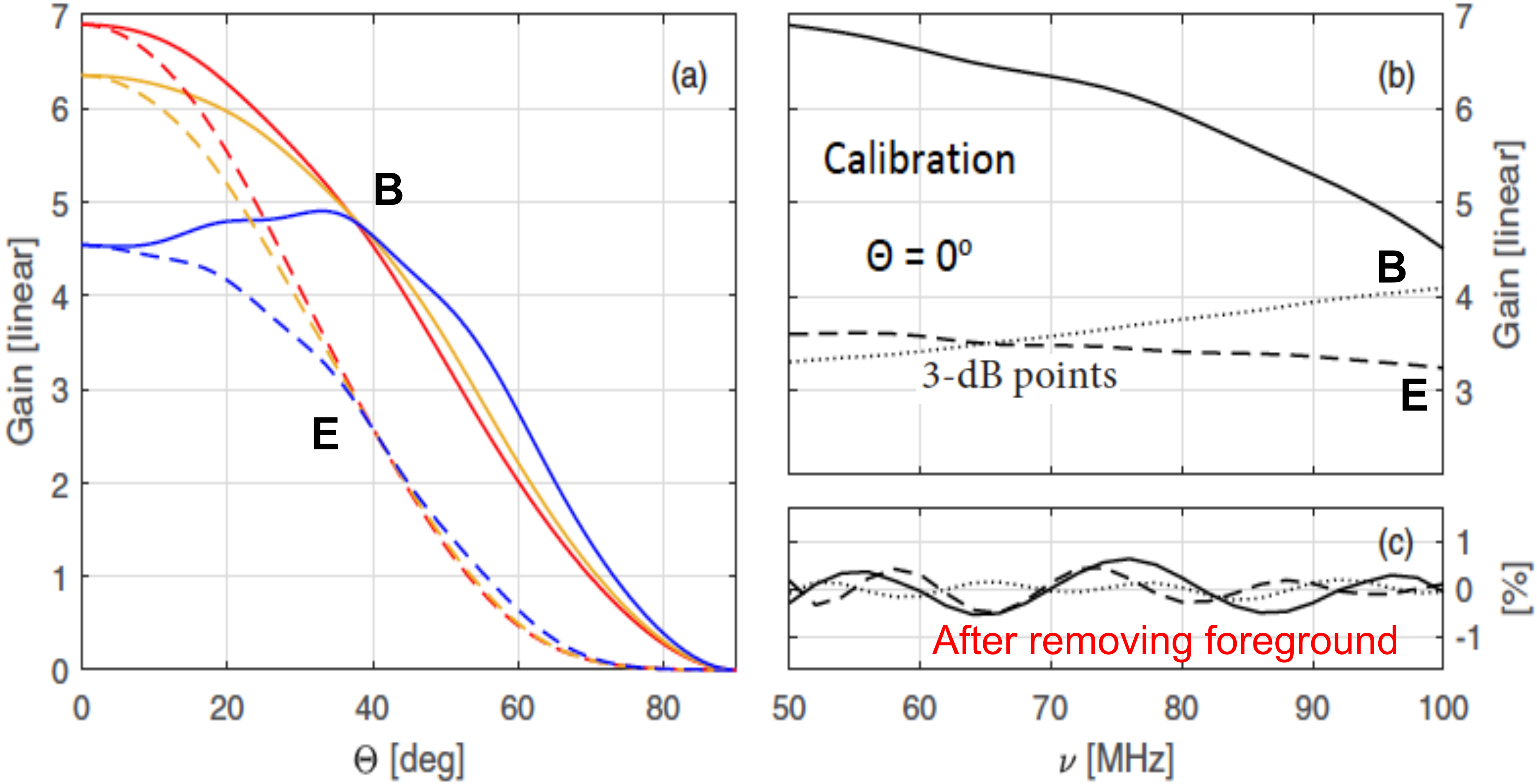
- 21-cm absorption profile:

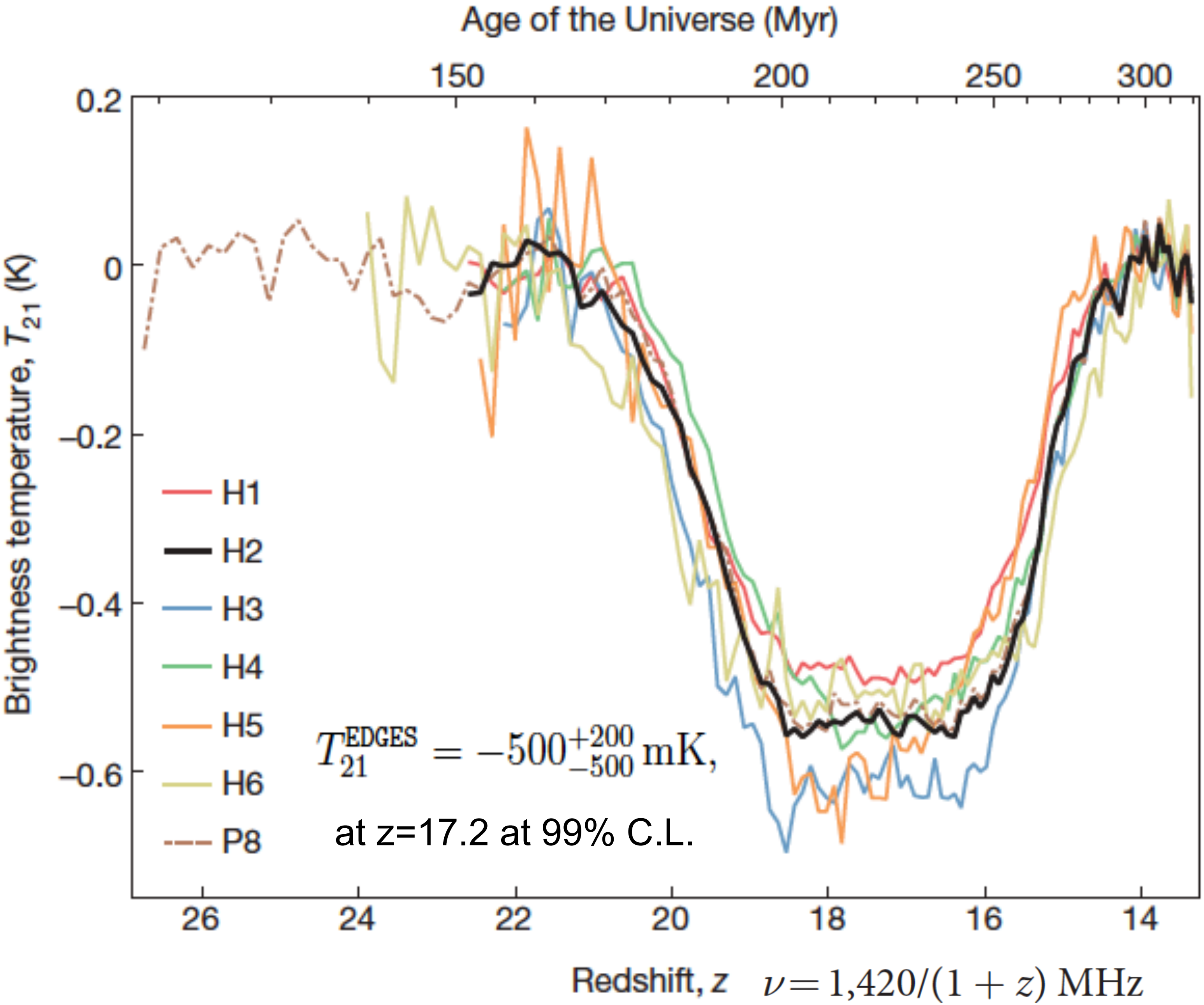
$$T_{21}(\nu) = -A\left(\frac{1 - \mathrm{e}^{-\tau \mathrm{e}^{B}}}{1 - \mathrm{e}^{-\tau}}\right)$$

(3 parameters)

Antenna Beam Model

- λ/D ~ resolution → ν dependent (Fig. a).
- The beam of their detector is frequency-dependent (Fig. b).
- Telescope may receive more or less synchrotron signals at particular frequency (Fig. c).



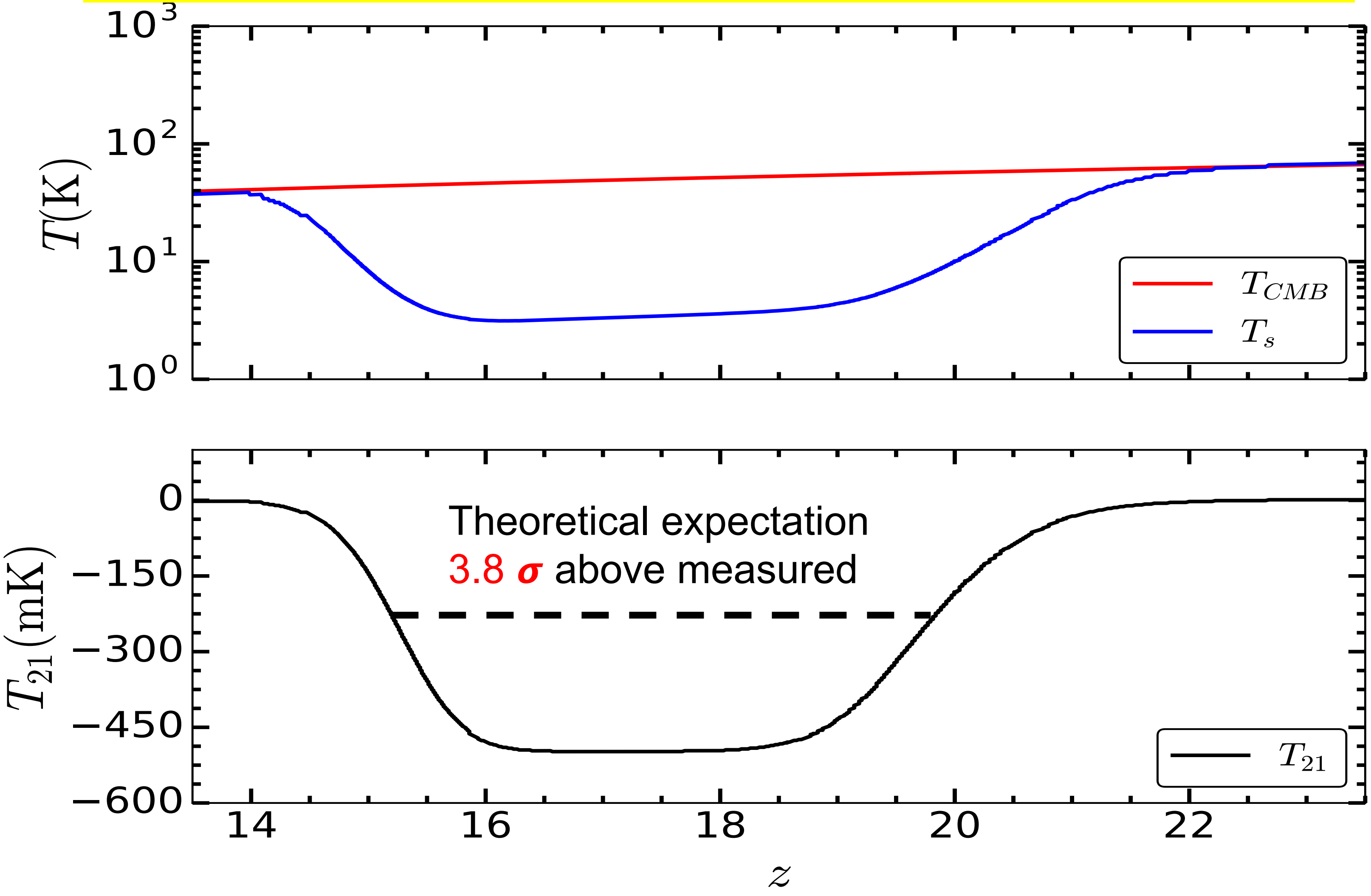


$$T_{21}^{\mathrm{EDGES}} = -500^{+200}_{-500}\,\mathrm{mK},$$

at z=17.2 at 99% C.L.

Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.

EDGES 21-cm absorption signal



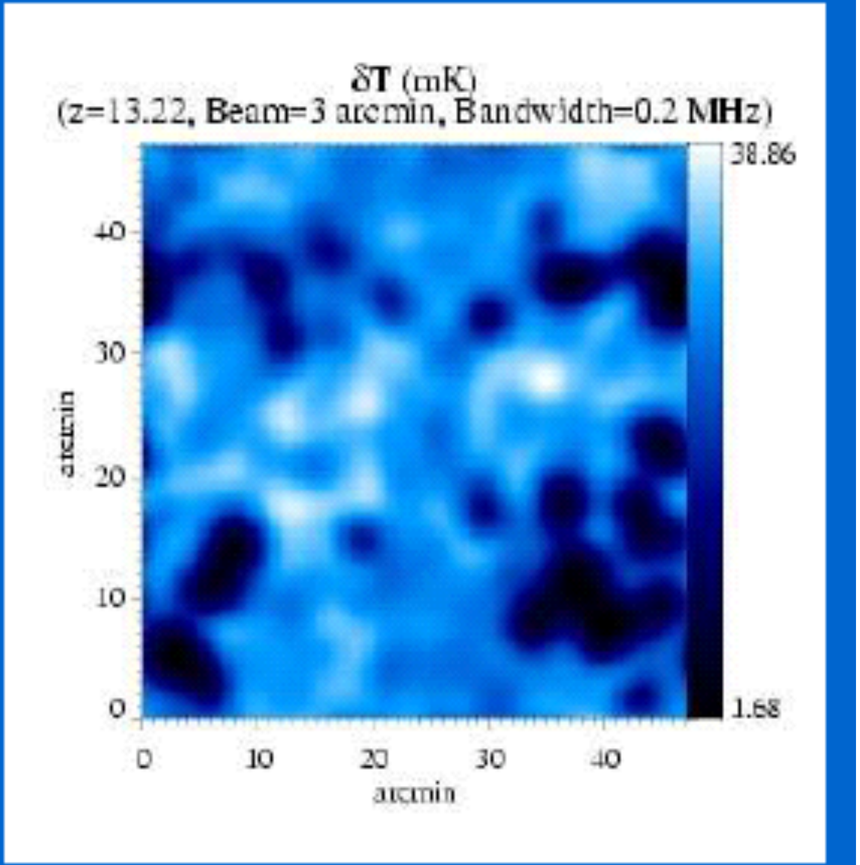
Theoretical expectation
3.8 **σ** above measured

$$T_{21}(z) \approx 0.023\ \mathrm{K} \times x_{\mathrm{HI}}(z) \left[\left(\frac{0.15}{\Omega_{\mathrm{m}}} \right) \left(\frac{1+z}{10} \right) \right]^{\frac{1}{2}} \left(\frac{\Omega_{\mathrm{b}} h}{0.02} \right) \left[1 - \frac{T_{\mathrm{R}}(z)}{T_{\mathrm{S}}(z)} \right]$$

Predictions for 21-cm Observations

- The large box and high resolution allow for the first detailed predictions of the 21-cm reionization signal for LOFAR, PAST, or SKA.
- Currently we assume Ly-α pumped IGM (T_{gas}) $T_S >> T_{CMB}$.

(21-cm emission)



21-cm Angular Power Spectrum

$$T^s(\hat{\boldsymbol{n}},\ \nu_0) = \int dr\, W_{\nu_0}(r) T_{21}(\hat{\boldsymbol{n}},\ r),$$

$$\langle \tilde{T}_{21}(\boldsymbol{k},\ \nu_1)\tilde{T}_{21}(\boldsymbol{k}',\ \nu_2)\rangle = (2\pi)^3\delta^{\mathrm{D}}(\boldsymbol{k}+\boldsymbol{k}')P_{21}(k,\ \nu_1,\ \nu_2),$$

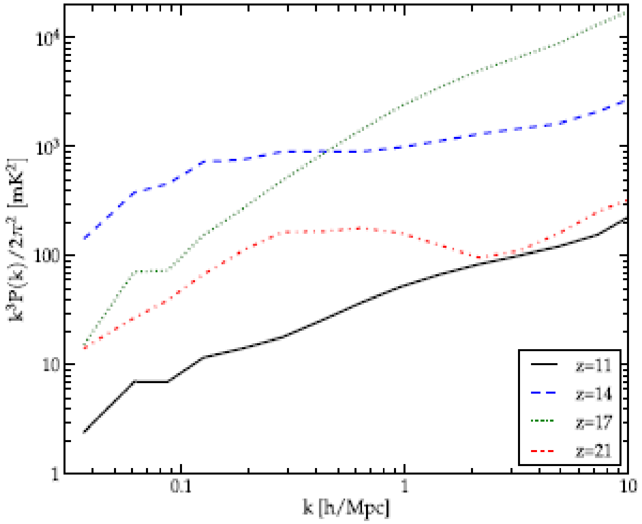
$$T_{21}(\hat{\boldsymbol{n}},\ r) \equiv T_{21}(\boldsymbol{r},\ \nu) = \int [d^3k/(2\pi)^3]\tilde{T}_{21}(\boldsymbol{k},\ \nu)e^{i\boldsymbol{k}\cdot\boldsymbol{r}}.$$

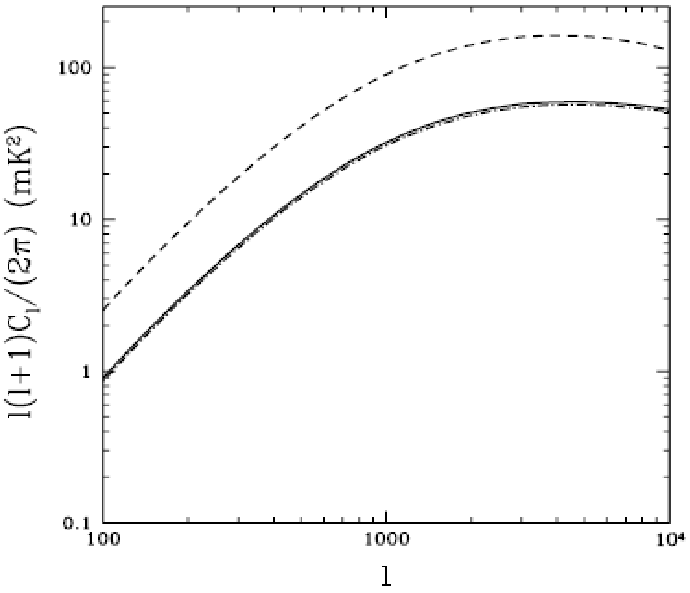
$$a^s_{lm}(\nu_0) = \int d\hat{\boldsymbol{n}}\, Y^*_{lm}(\hat{\boldsymbol{n}}) T^s(\hat{\boldsymbol{n}},\ \nu_0),$$

$$\begin{aligned}\langle a^s_{lm}(\nu_1)a^{s*}_{lm}(\nu_2)\rangle &= C^s_l(\nu_1,\ \nu_2)\\ &= \frac{2}{\pi}\int k^2\, dk\, P_{21}(k,\ \nu_1,\ \nu_2) I^{\nu_1}_l(k) I^{\nu_2}_l(k),\end{aligned}$$

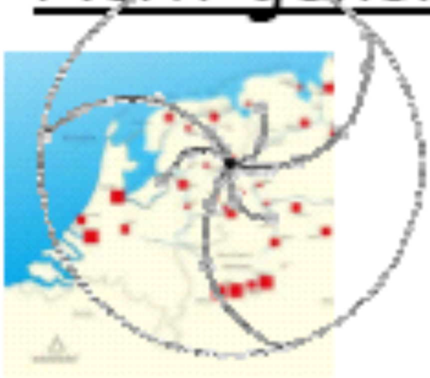
$$I^{\nu}_l(k) = \int dr\, W_\nu(r) j_l(kr),$$

$$\boxed{e^{i\boldsymbol{k}\cdot\boldsymbol{r}} = 4\pi\sum_{lm} i^l j_l(kr) Y^m_l(\hat{\boldsymbol{n}}) Y^{m*}_l(\hat{\boldsymbol{k}}).}$$





On-going and Next generation of radio telescopes



LOFAR: Low Frequency ARray; Netherlands
www.lofar.org

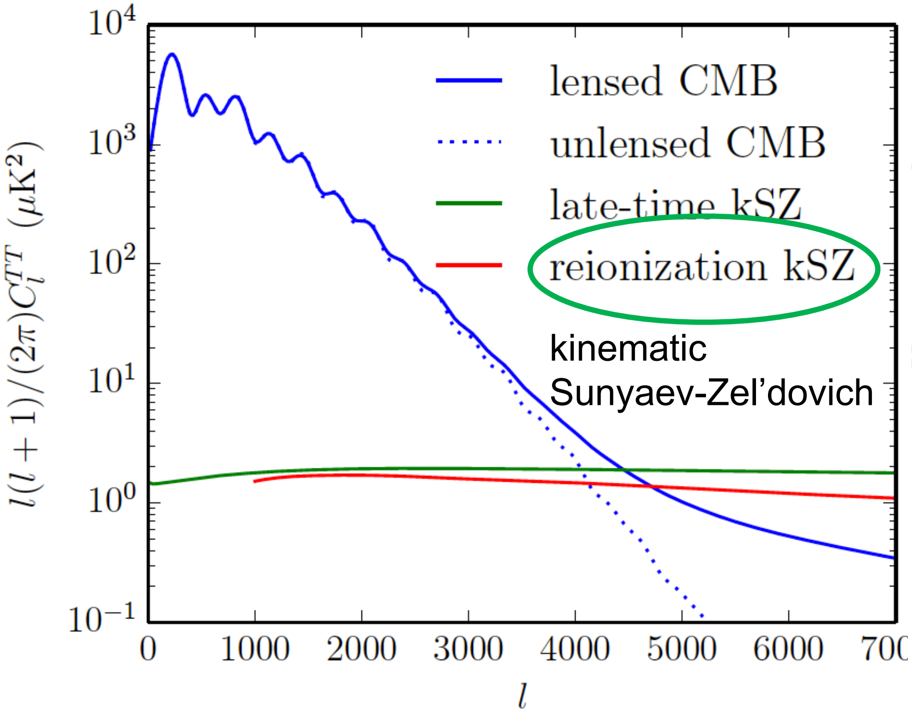
? PAST: Primeval Structure Telescope; China
web.phys.cmu.edu/~past

MWA: Mileura Widefield Array; Australia
space.mit.edu/RADIO/research/mwa.html

SKA: Square Kilometre Array
www.skatelescope.org

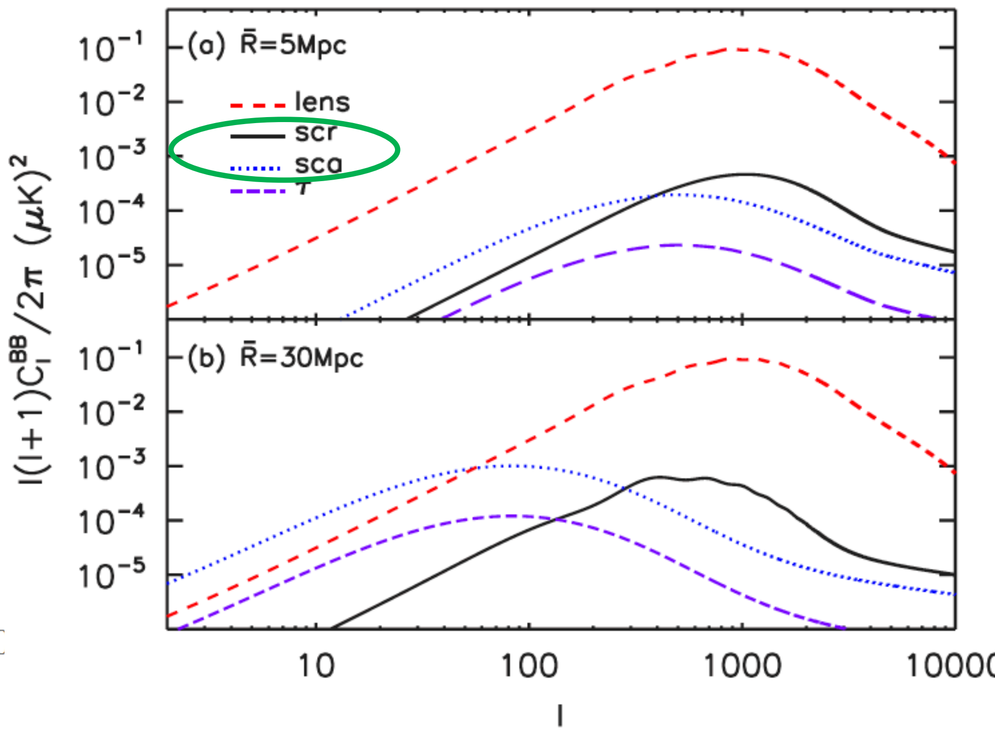
Secondary CMB anisotropy and B-mode polarization due to patchy reionization

Smith, Ferraro 16



kinematic Sunyaev-Zel'dovich

Dvorkin, Hu, Smith 09



Can be correlated to 21-cm sky fluctuations

lens – lensing of E-mode polarization
scr – screening of E-mode polarization
sca – scattering of quadrupole anisotropy

Guo-Chin Liu et al. 2001

Extended sources: CMB versus 21cm

- λ_{max}= 1cm
- $l_{\text{pol. peak}}$ = 1000
- Shortest baseline = 160 cm
- Biggest dish size = 160 cm (increase sensitivity)
- FoV=1/160
- Single-dish focal plane array to increase FoV

- λ_{max}= 210 cm (z=10)
- l_{peak} = 4000
- Shortest baseline = 1.34 km
- Dish size = 2.1 m (say, determined by budget)
- FoV=1/10
- Dipole or phased array to increase FoV

CMB Milestones

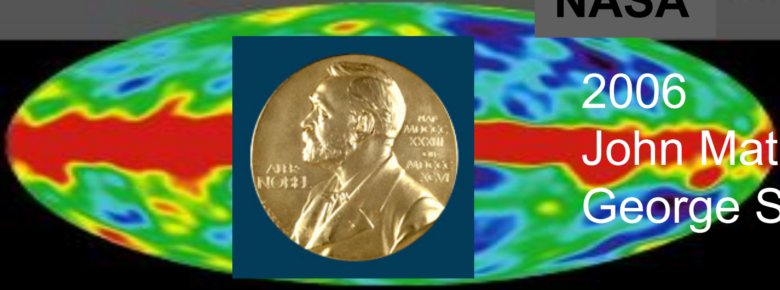
1965

AT&T Bell Penzias and Wilson

1978
Arno Penzias
Robert Wilson

1992

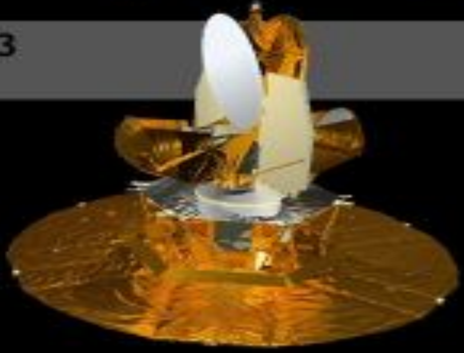
NASA COBE

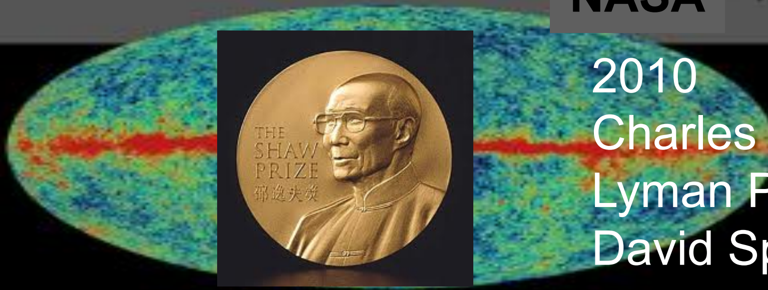


2006
John Mather
George Smoot

2003

NASA WMAP

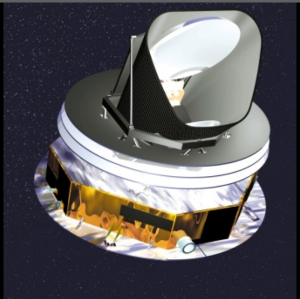


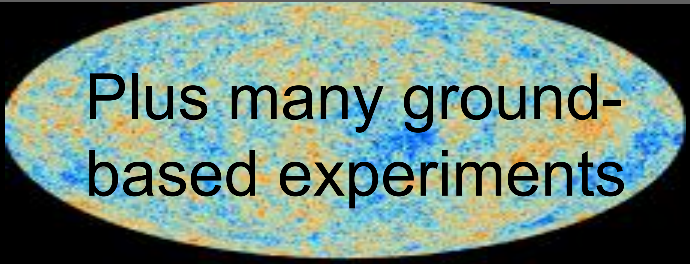


2010
Charles Bennett
Lyman Page
David Spergel

2013

ESA Planck





Plus many ground-based experiments