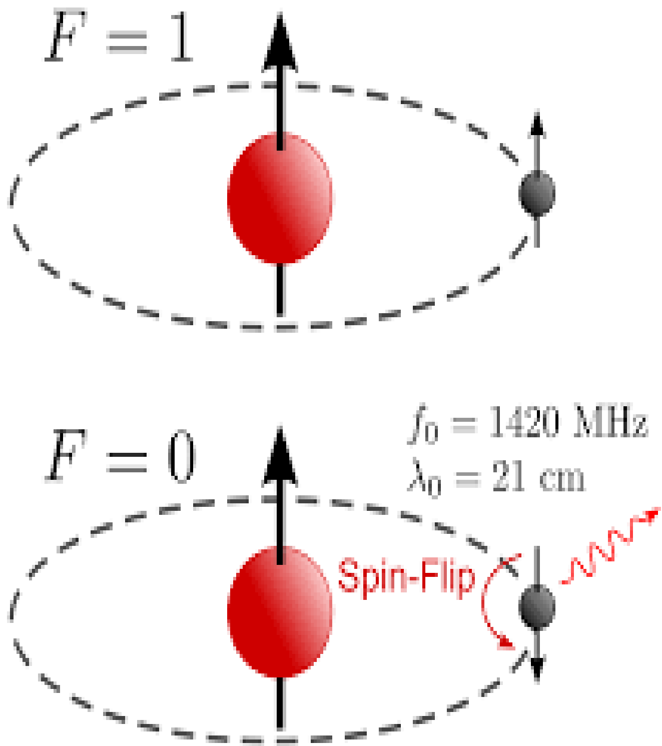
21-cm (observational) cosmology

Gianni Bernardi

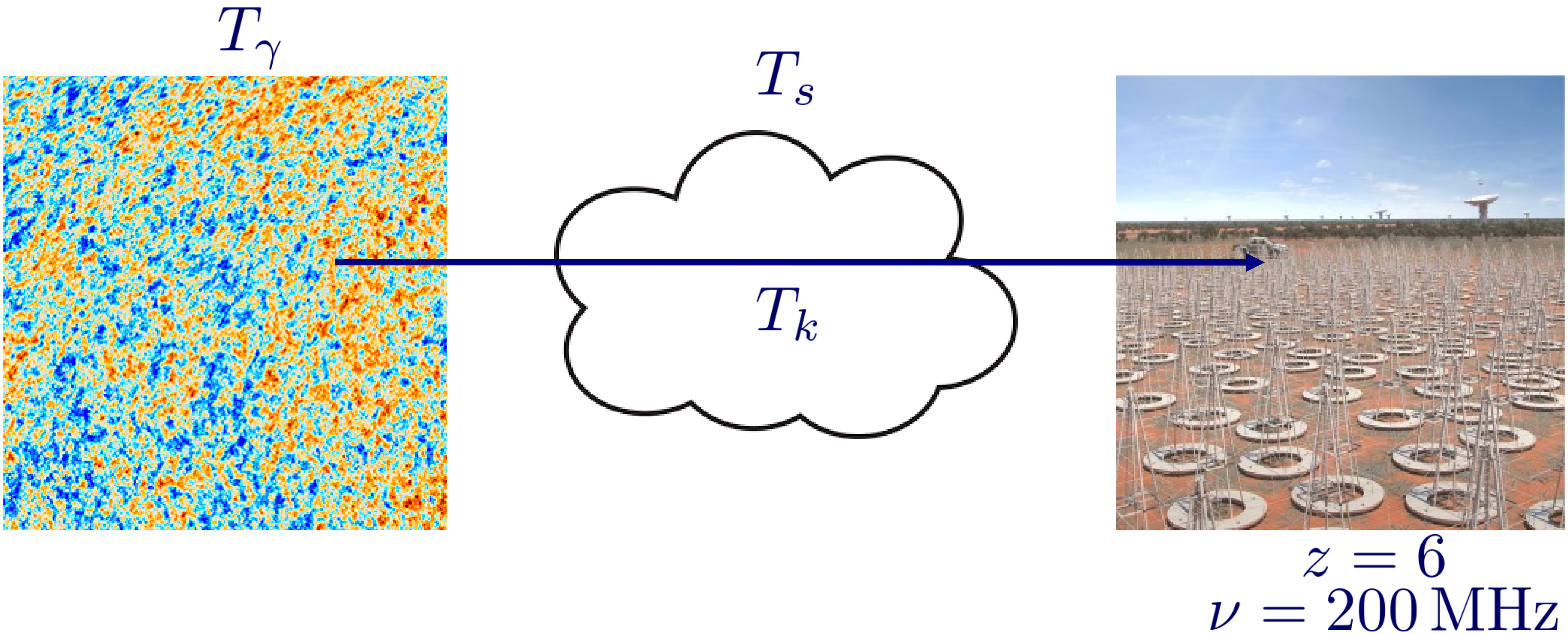
IRA-INAF & Rhodes University

JAC, Bologna, 1/3/2018

21-cm hyperfine transition from HI



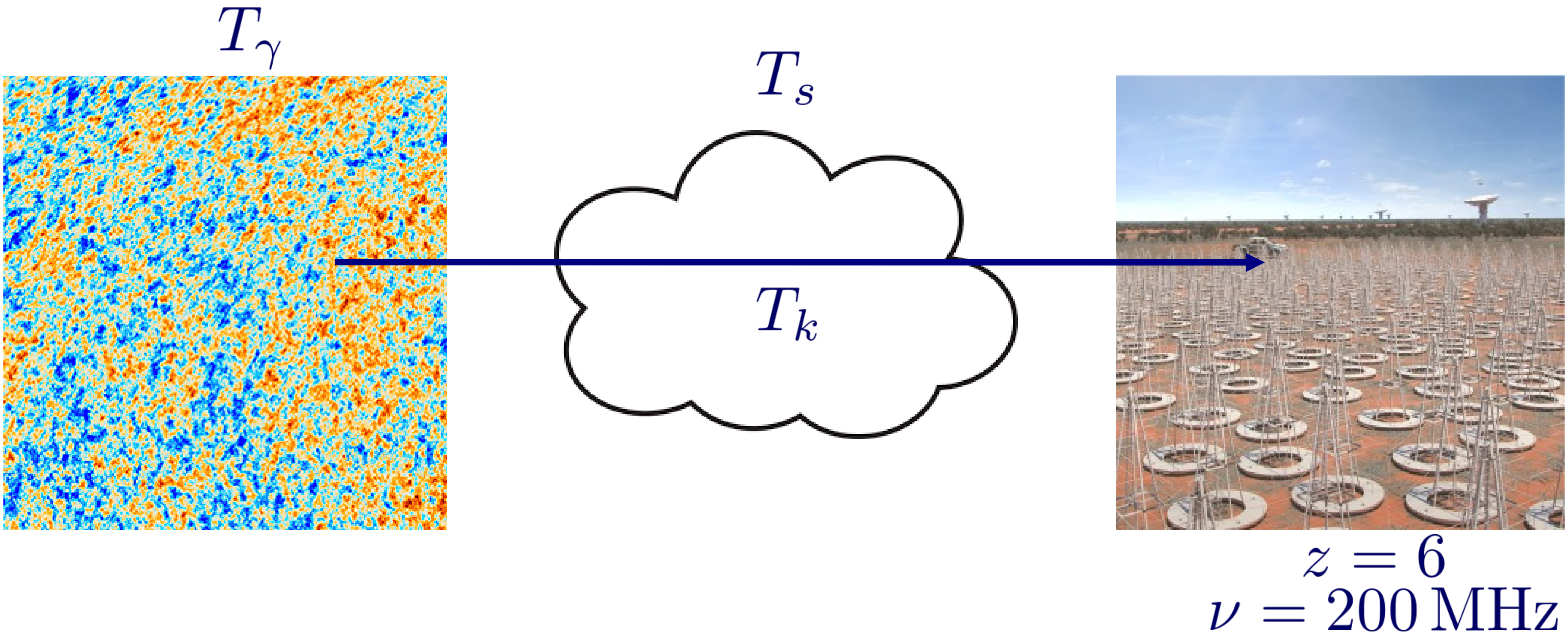
21-cm cosmology: a tale of three temperatures



- T_γ: the CMB temperature - scales as (1+z);
- T_k: the gas temperature;
- T_s: the spin temperature that sets the population in the hyperfine level →

$$\frac{n_1}{n_0} = 3e^{\frac{0.068\mathrm{K}}{T_s}}$$

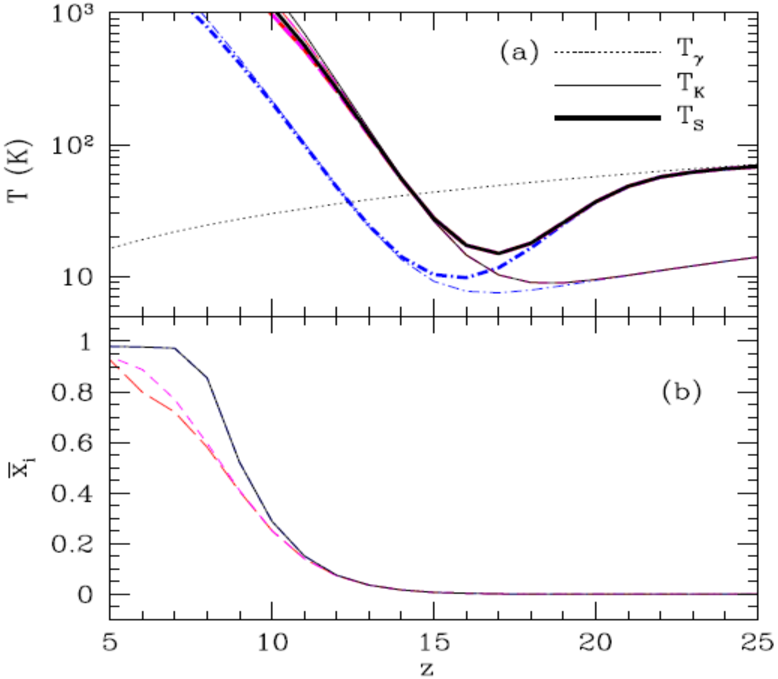
21-cm cosmology: a tale of three temperatures

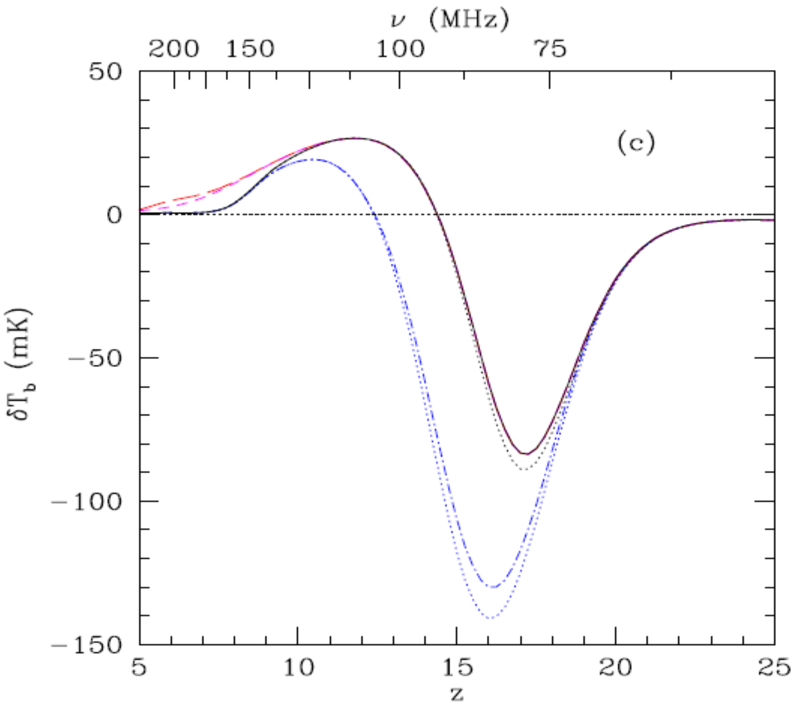


observable: $\delta T_b(z) \simeq 28 x_{\mathrm{HI}}(1+\delta)\left(1-\frac{T_\gamma}{T_s}\right)\sqrt{\frac{1+z}{10}\frac{0.15}{\Omega_m}}\,\frac{\Omega_b h}{0.0023}\ \mathrm{mK}$

the redshifted 21-cm is observable when $T_s(=T_k) \neq T_\gamma$

IGM thermal history and evolution of the 21-cm signal

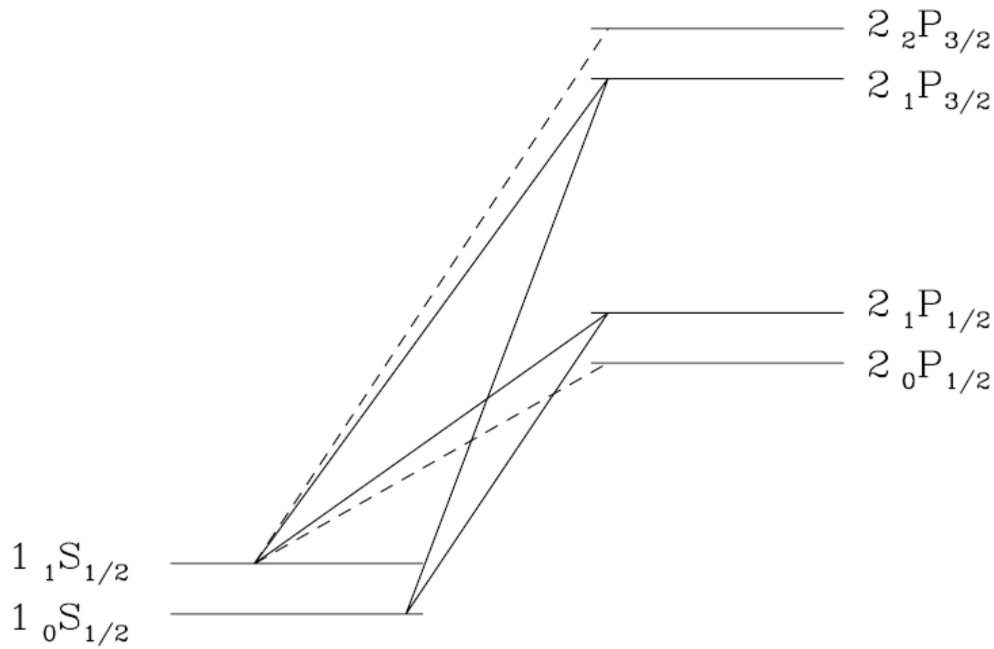




$$\delta T_b(z) \propto x_{\rm HI} \left(1 - \frac{T_\gamma}{T_s}\right) \ \mathrm{mK}$$

Furlanetto (2006)

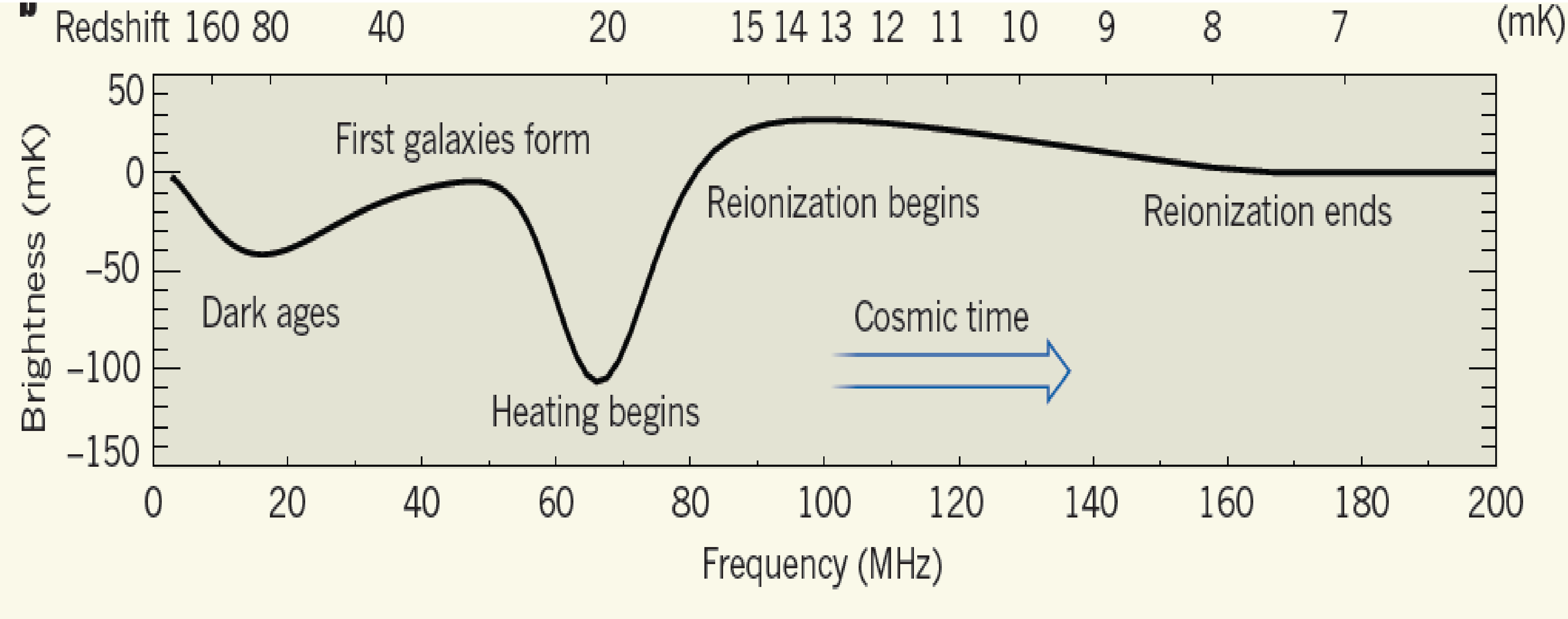
First luminous sources turn on 21-cm emission through the Wouthuysen-Field effect: resonant scattering of Lyα photons



due to the high IGM opacity,
the Wouthuysen-Field effect couples T_s to T_k (i.e. $T_s \rightarrow T_k$)
As the gas has cooled adiabatically below the CMB, the 21-cm is expected in absorption against the CMB

Wouthuysen (1957), Field (1958), Furlanetto, Oh & Briggs (2010)

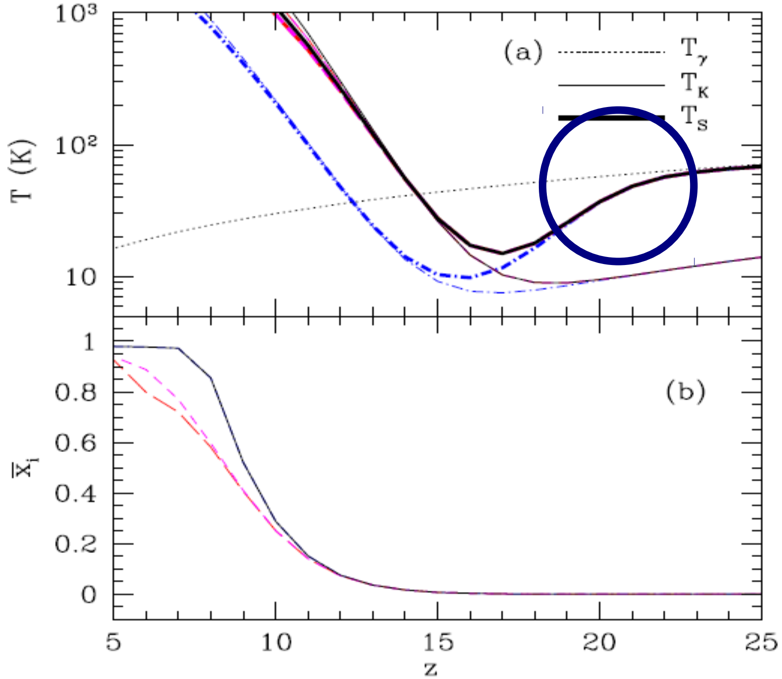
Evolution of the 21-cm signal

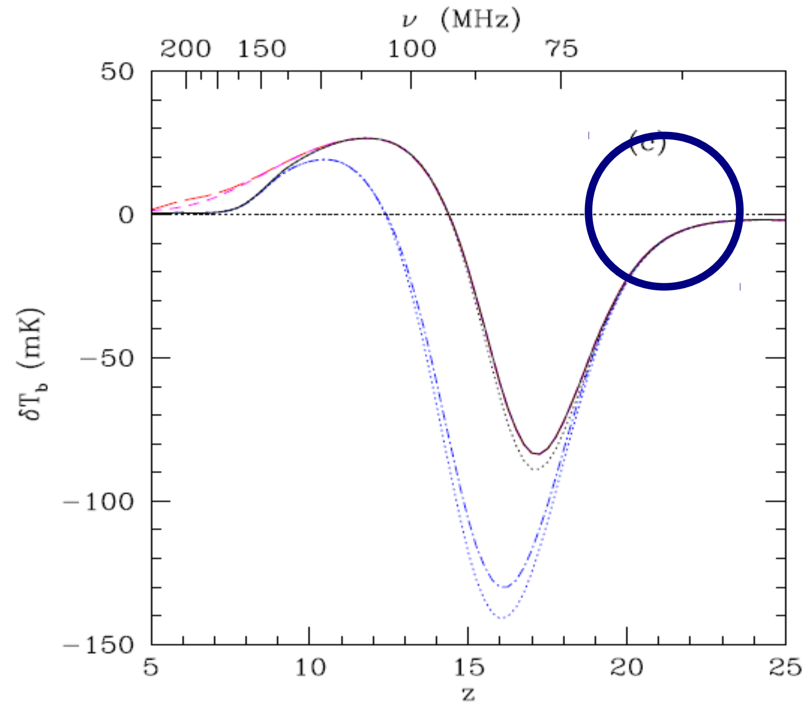


- First galaxies form ($20 < z < 35$): UV radiation from the first stars and galaxies “turn the 21-cm signal on”:
-

Pritchard & Loeb (2010)

IGM thermal history and evolution of the 21-cm signal

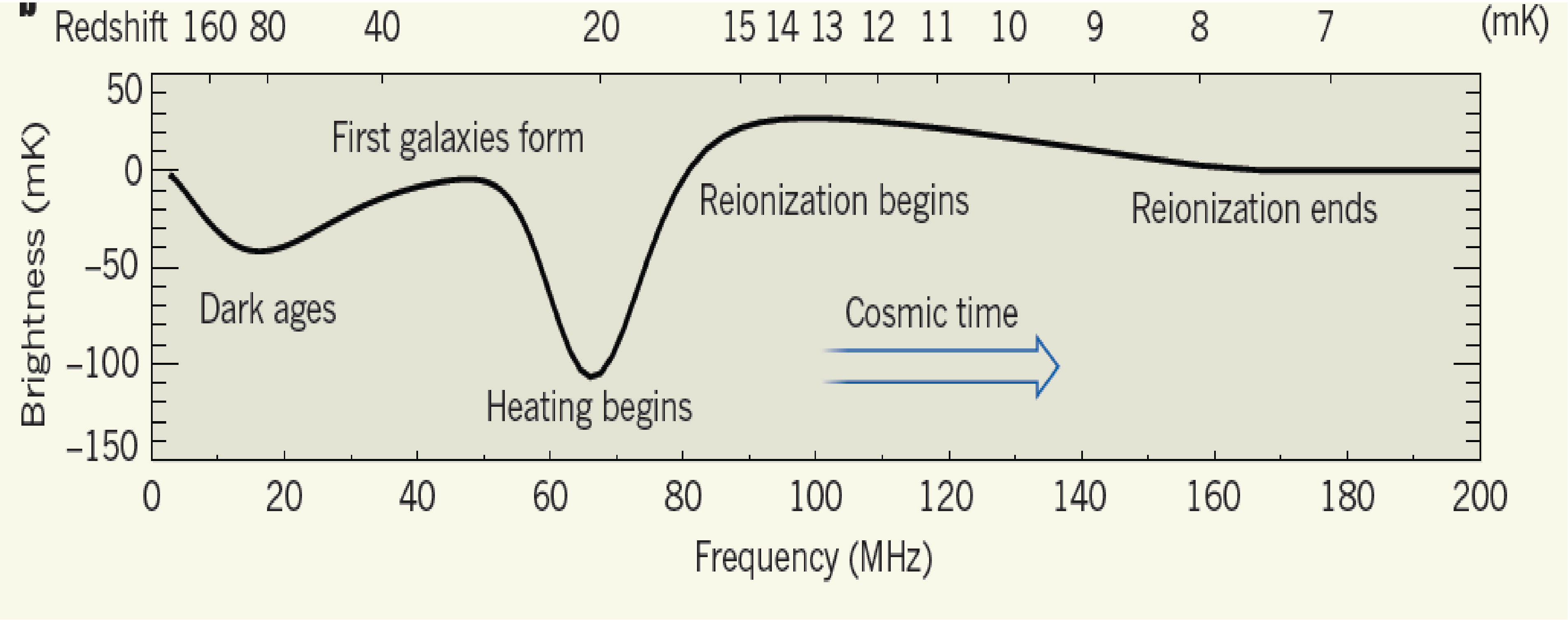




$$\delta T_b(z) \propto x_{\rm HI} \left(1 - \frac{T_\gamma}{T_s}\right) \ \mathrm{mK}$$

Furlanetto (2006)

Evolution of the 21-cm signal

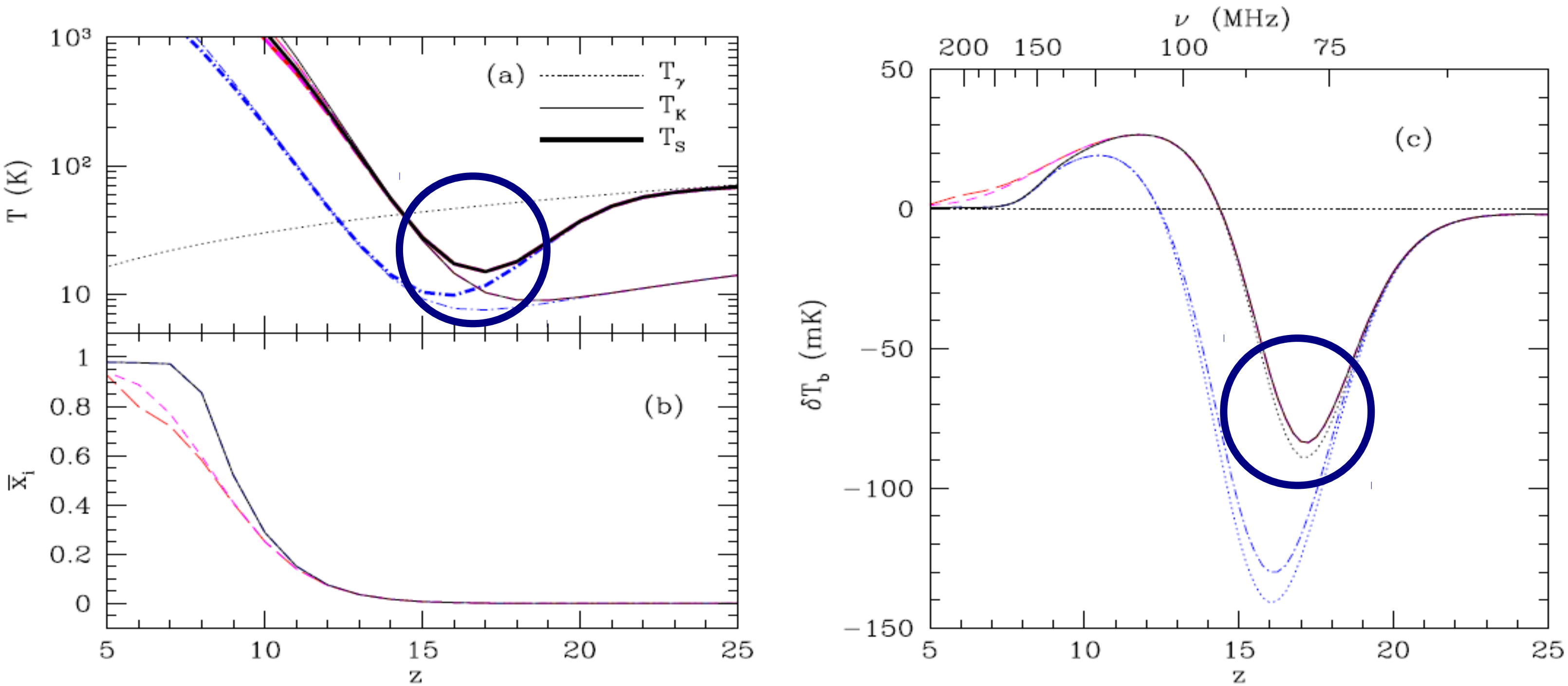


- First galaxies form (20 < z < 35): UV radiation from the first stars and galaxies "turn the 21-cm signal on":

- Heating begins (15 < z < 20): photons begins to heat the IGM (mostly X-ray photons produced in early X-ray binaries a/o SNR remnants);

Pritchard & Loeb (2010)

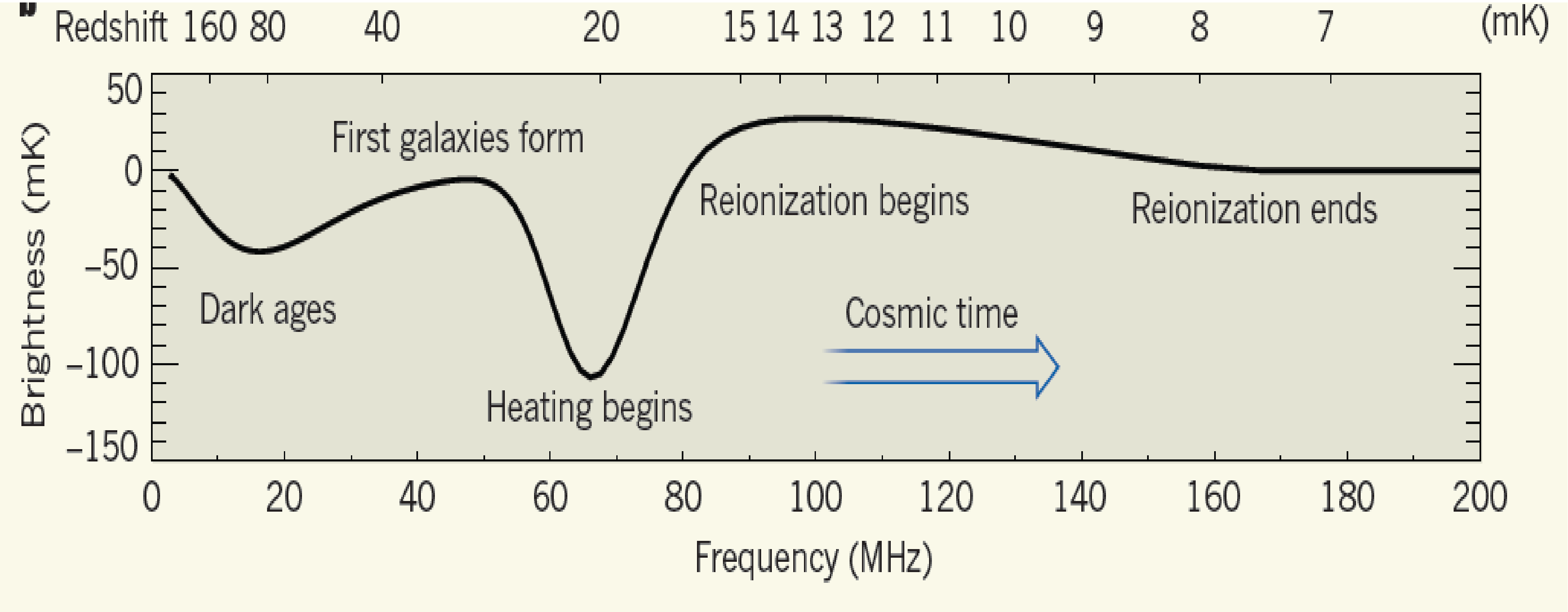
IGM thermal history and evolution of the 21-cm signal



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

Furlanetto (2006)

Evolution of the 21-cm signal

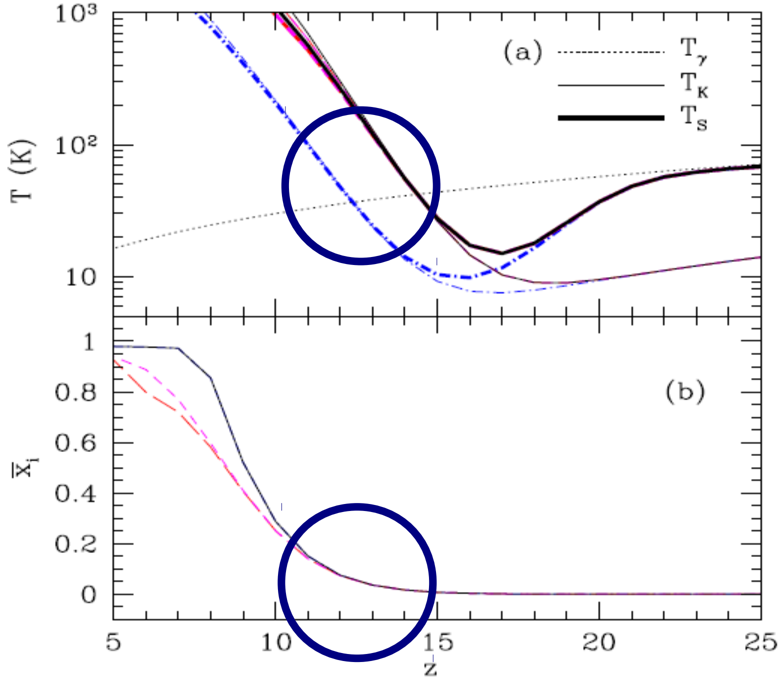


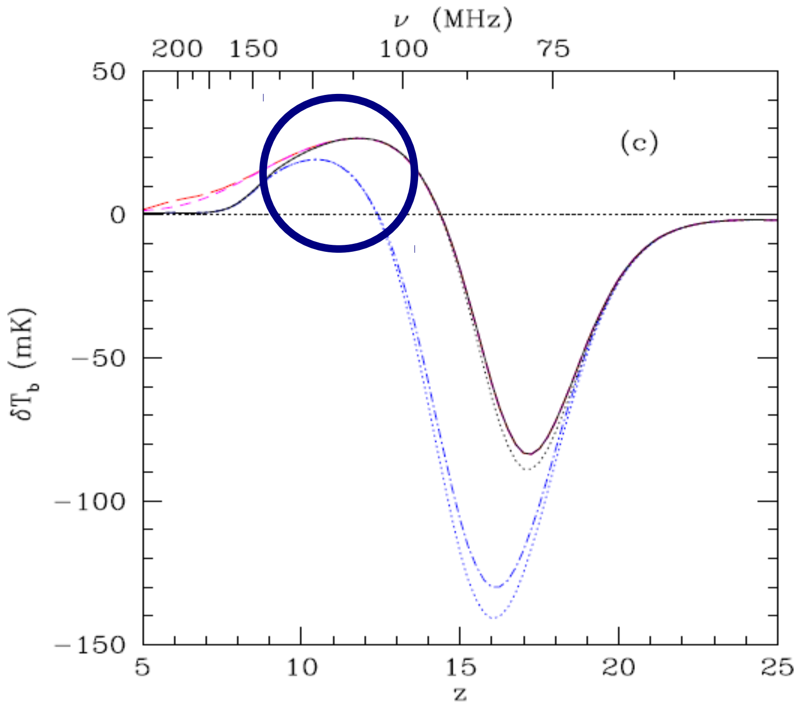
- First galaxies form (20 < z < 35): UV radiation from the first stars and galaxies "turn the 21-cm signal on":

- Heating begins (15 < z < 20): photons begins to heat the IGM (mostly X-ray photons produced in early X-ray binaries a/o SNR remnants);

- Reionization begins (12 < z < 18): persistent star formation in early galaxies → UV photons begin to escape host galaxies and ionize the surrounding IGM;

IGM thermal history and evolution of the 21-cm signal

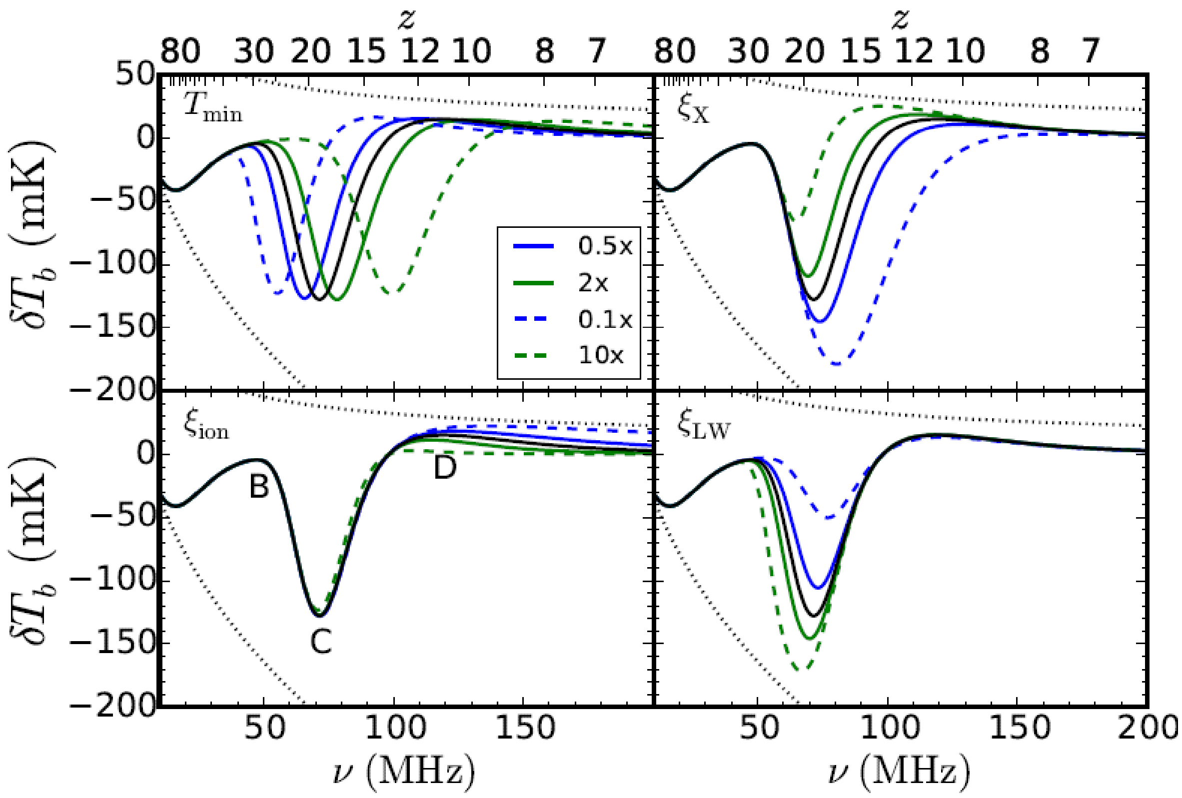




$$\delta T_b(z) \propto x_{\rm HI}\left(1-\frac{T_\gamma}{T_s}\right)\ \mathrm{mK}$$

Furlanetto (2006)

Exploring the parameter space



Mirocha et al. (2015)

All you need is... one dipole: LEDA

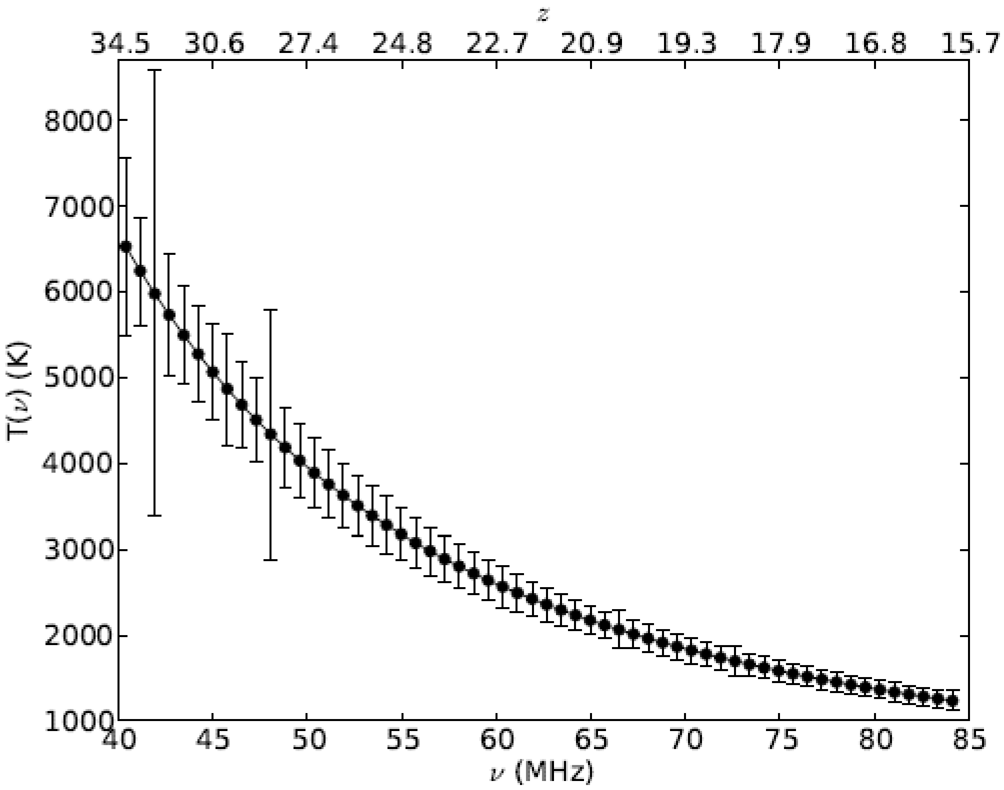
(Large-Aperture Experiment to detect the Dark Ages, PI: L. Greenhill)

20-90 MHz isolated V-inverted dipoles with custom designed front ends for radiometry → detection of the global 21-cm signal in the $15 < z < 30$ range (pre-reionization);

All you need is... one dipole: LEDA

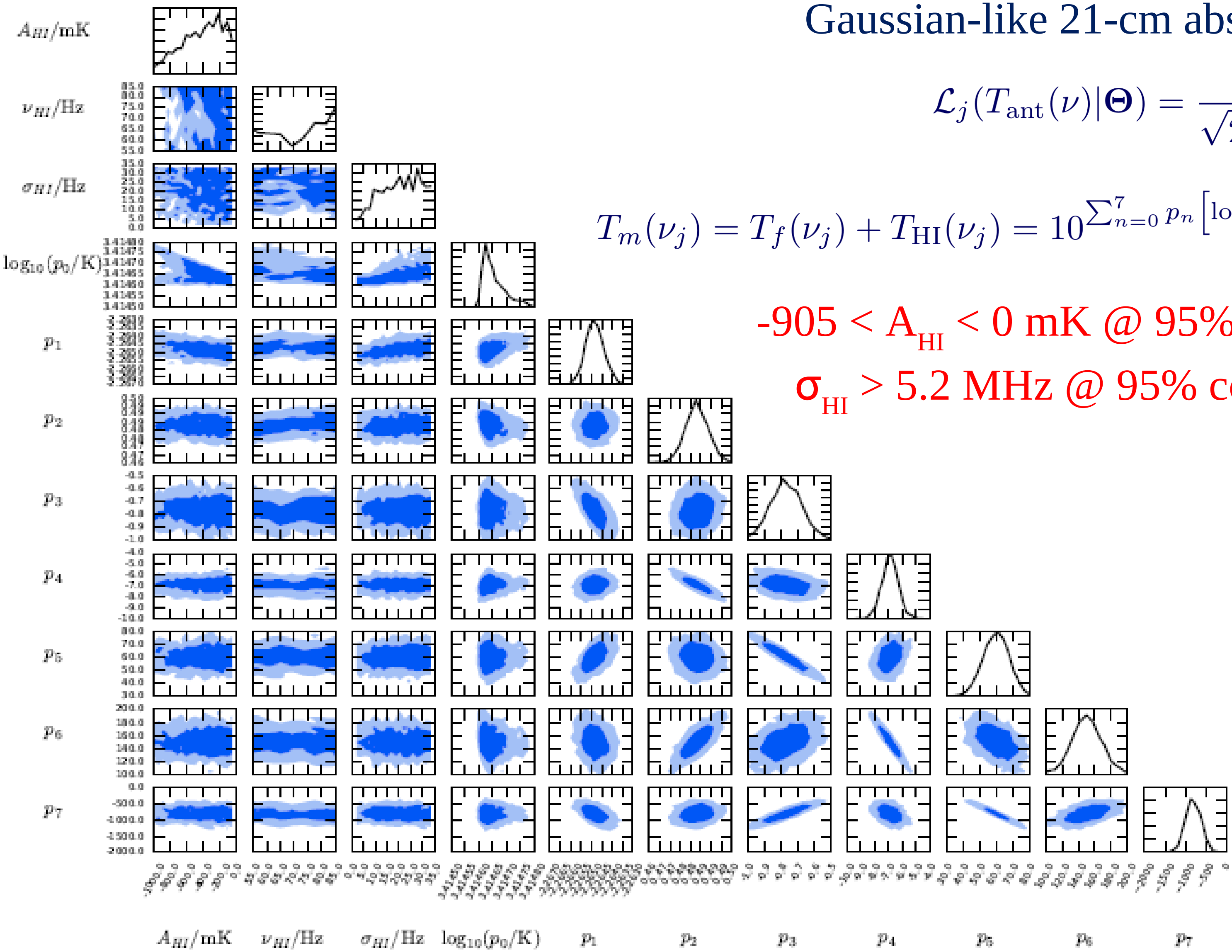
(Large-Aperture Experiment to detect the Dark Ages, PI: L. Greenhill)

20-90 MHz isolated V-inverted dipoles with custom designed front ends for radiometry → detection of the global 21-cm signal in the 15 < z < 30 range (pre-reionization);



GB et al. (2016)

Upper limits on the global 21-cm in the 16 < z < 35 range



Bayesian separation of foregrounds from a Gaussian-like 21-cm absorption signal:

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

$$T_m(\nu_j) = T_f(\nu_j) + T_{\rm HI}(\nu_j) = 10^{\sum_{n=0}^{7} p_n \left[\log \frac{\nu_j}{\nu_0}\right]^n} + A_{\rm HI} e^{-\frac{(\nu_j - \nu_{\rm HI})^2}{2\sigma_{\rm HI}^2}}$$

$-905 < A_{\rm HI} < 0$ mK @ 95% confidence level

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

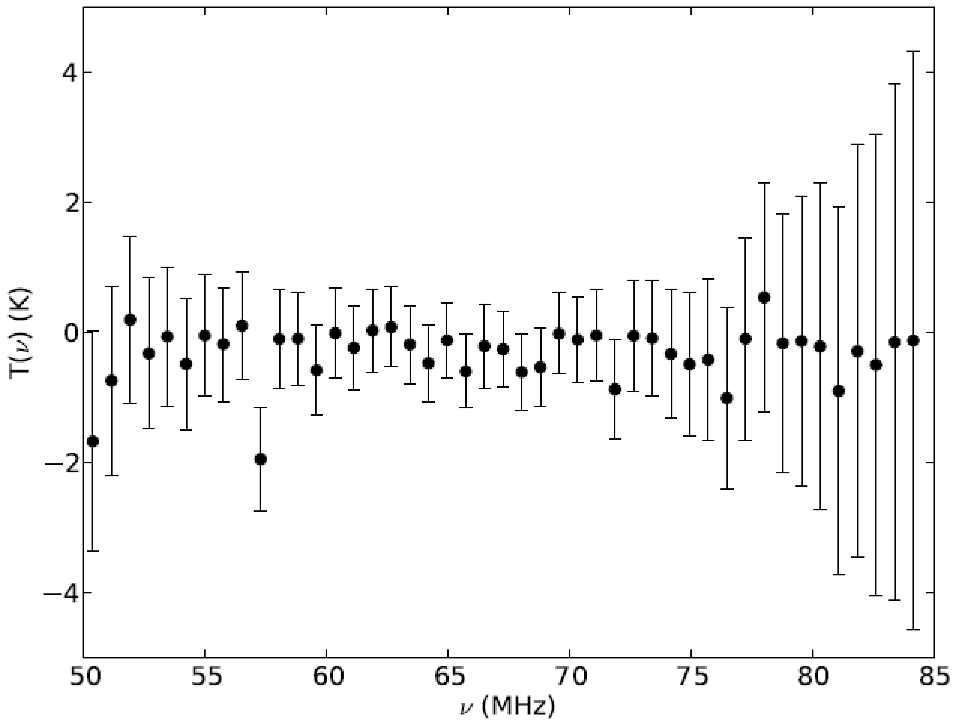
GB et al. (2016)

Upper limits on the global 21-cm in the 16 < z < 35 range

Bayesian separation of foregrounds from a Gaussian-like 21-cm absorption signal:

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

$$T_m(\nu_j) = T_f(\nu_j) + T_{\rm HI}(\nu_j) = 10^{\sum_{n=0}^{7} p_n \left[\log\frac{\nu_j}{\nu_0}\right]^n} + A_{\rm HI} e^{-\frac{(\nu_j-\nu_{\rm HI})^2}{2\sigma_{\rm HI}^2}}$$



GB et al. (2016)

Today, March 1st 2018

LETTER

doi:10.1038/nature25792

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]

After stars formed in the early Universe, their ultraviolet light is expected, eventually, to have penetrated the primordial hydrogen gas and altered the excitation state of its 21-centimetre hyperfine line. This alteration would cause the gas to absorb photons from the cosmic microwave background, producing a spectral distortion that should be observable today at radio frequencies of less than 200 megahertz[1]. Here we report the detection of a flattened absorption profile in the sky-averaged radio spectrum, which is centred at a frequency of 78 megahertz and has a best-fitting full-width at half-maximum of 19 megahertz and an amplitude of 0.5 kelvin. The profile is largely consistent with expectations for the 21-centimetre signal induced by early stars; however, the best-fitting amplitude of the profile is more than a factor of two greater than the largest predictions[2]. This discrepancy suggests that either the primordial gas was much colder than expected or the background radiation temperature was hotter than expected. Astrophysical phenomena (such as radiation from stars and stellar remnants) are unlikely to account for this discrepancy; of the proposed extensions to the standard model of cosmology and particle physics, only cooling of the gas as a result of interactions between dark matter and baryons seems to explain the observed amplitude[3]. The low-frequency edge of the observed profile indicates that stars existed and had produced a background of Lyman-α photons by 180 million years after the Big Bang. The high-frequency edge indicates that the gas was heated to above the radiation temperature less than 100 million years later.

Observations with the Experiment to Detect the Global Epoch of

The absorption profile is found by fitting the integrated spectrum with the foreground model and a model for the 21-cm signal simultaneously. The best-fitting 21-cm model yields a symmetric U-shaped absorption profile that is centred at a frequency of 78 ± 1 MHz and has a full-width at half-maximum of 19^{+4}_{-2} MHz, an amplitude of $0.5^{+0.5}_{-0.2}$ K and a flattening factor of $\tau = 7^{+5}_{-3}$ (where the bounds provide 99% confidence intervals including estimates of systematic uncertainties; see Methods for model definition). Uncertainties in the parameters of the fitted profile are estimated from statistical uncertainty in the model fits and from systematic differences between the various validation trials that were performed using observations from both instruments and several different data cuts. The 99% confidence intervals that we report are calculated as the outer bounds of (1) the marginalized statistical 99% confidence intervals from fits to the primary dataset and (2) the range of best-fitting values for each parameter across the validation trials. Fitting with both the foreground and 21-cm models lowers the residuals to an r.m.s. of 0.025 K. The fit shown in Fig. 1 has a signal-to-noise ratio of 37, calculated as the best-fitting amplitude of the profile divided by the statistical uncertainty of the amplitude fit, including the covariance between model parameters. Additional analyses of the

a

Today, March 1st 2018

LETTER

doi:10.1038/nature25792

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]

After stars formed in the early Universe, their ultraviolet light is expected, eventually, to have penetrated the primordial hydrogen gas and altered the excitation state of its 21-centimetre hyperfine line. This alteration would cause the gas to absorb photons from the cosmic microwave background, producing a spectral distortion that should be observable today at radio frequencies of less than 200 megahertz[1]. Here we report the detection of a flattened absorption profile in the sky-averaged radio spectrum, which is centred at a frequency of 78 megahertz and has a best-fitting full-width at half-maximum of 19 megahertz and an amplitude of 0.5 kelvin. The profile is largely consistent with expectations for the 21-centimetre signal induced by early stars; however, the best-fitting amplitude of the profile is more than a factor of two greater than the largest predictions[2]. This discrepancy suggests that either the primordial gas was much colder than expected or the background radiation temperature was hotter than expected. Astrophysical phenomena (such as radiation from stars and stellar remnants) are unlikely to account for this discrepancy; of the proposed extensions to the standard model of cosmology and particle physics, only cooling of the gas as a result of interactions between dark matter and baryons seems to explain the observed amplitude[3]. The low-frequency edge of the observed profile indicates that stars existed and had produced a background of Lyman-α photons by 180 million years after the Big Bang. The high-frequency edge indicates that the gas was heated to above the radiation temperature less than 100 million years later.

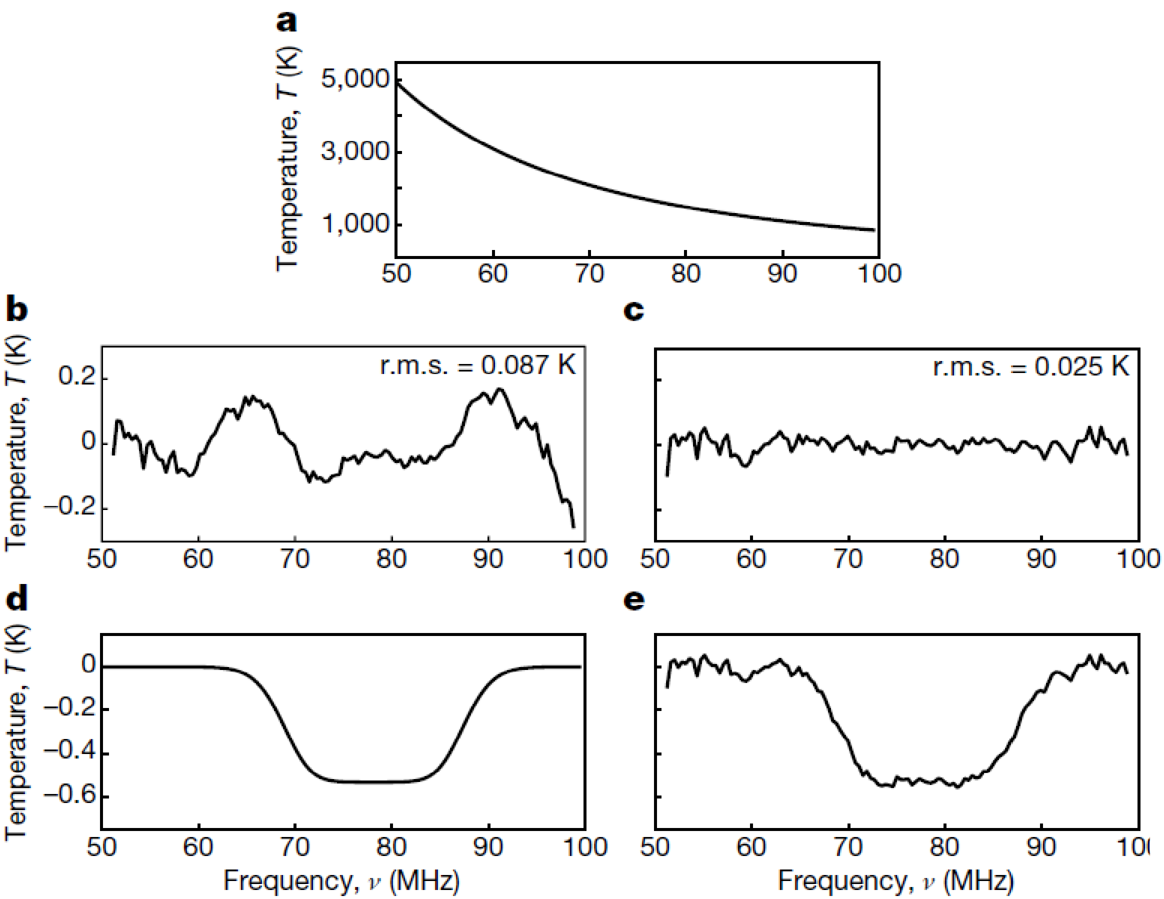
Observations with the Experiment to Detect the Global Epoch of

Shocking...

EDGES

courtesy J. Bowman

Global 21-cm signal detected from the Cosmic Dawn (pre-reionization)

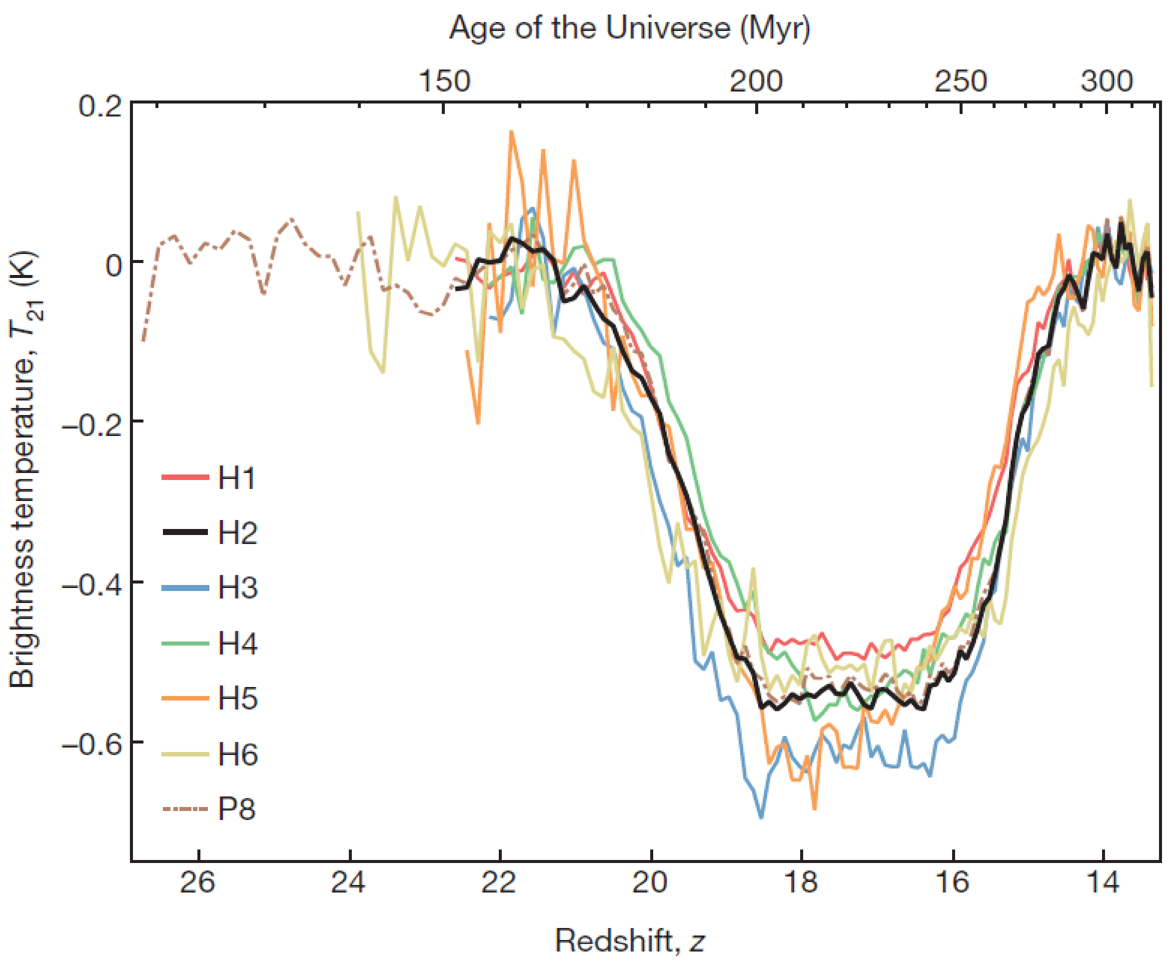


- 530 mK amplitude;
- 78.1 MHz centred (z ~ 17.2);
- 18.7 MHz width

  Δz ~ 4, 80 Myr);

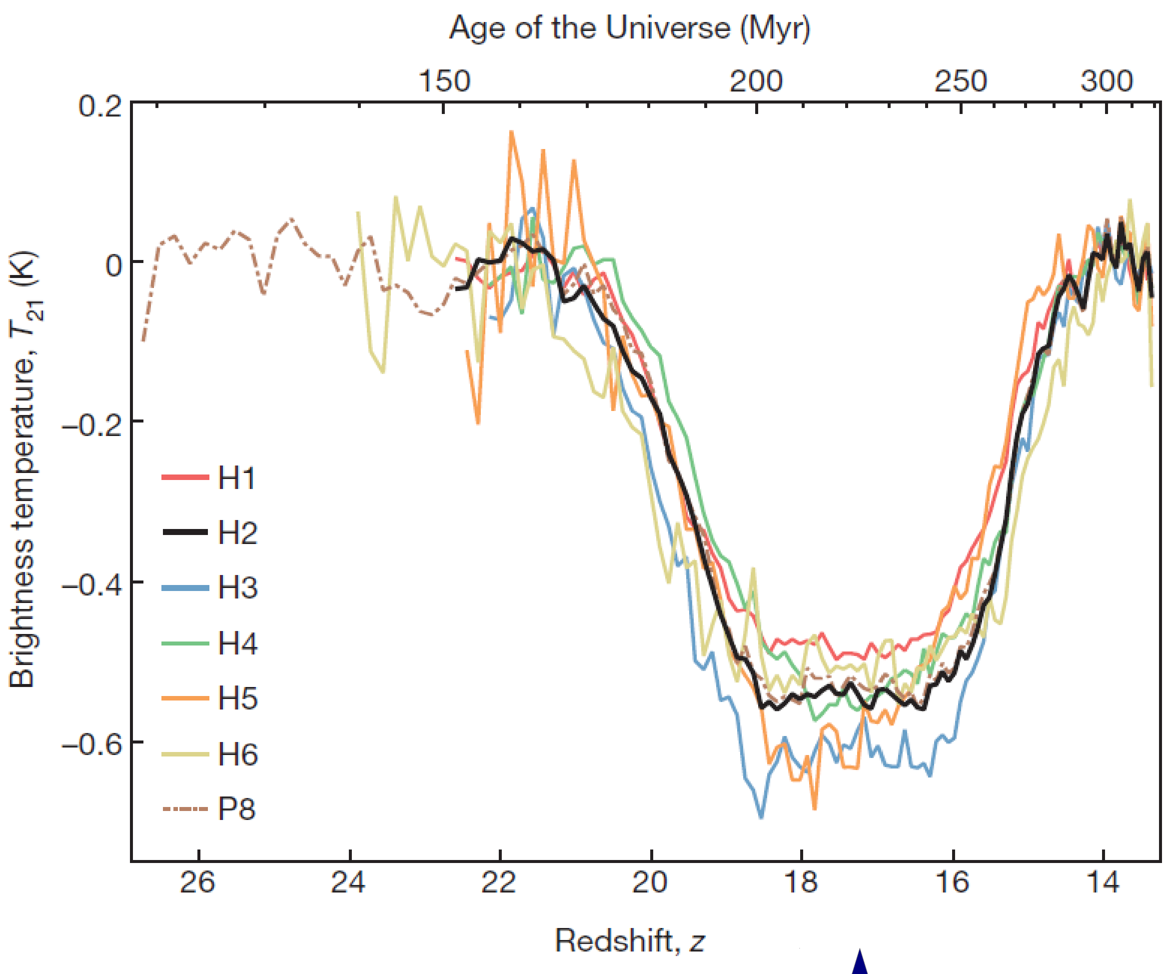
Bowman et al. (2018)

Why is it shocking?



Bowman et al. (2018)

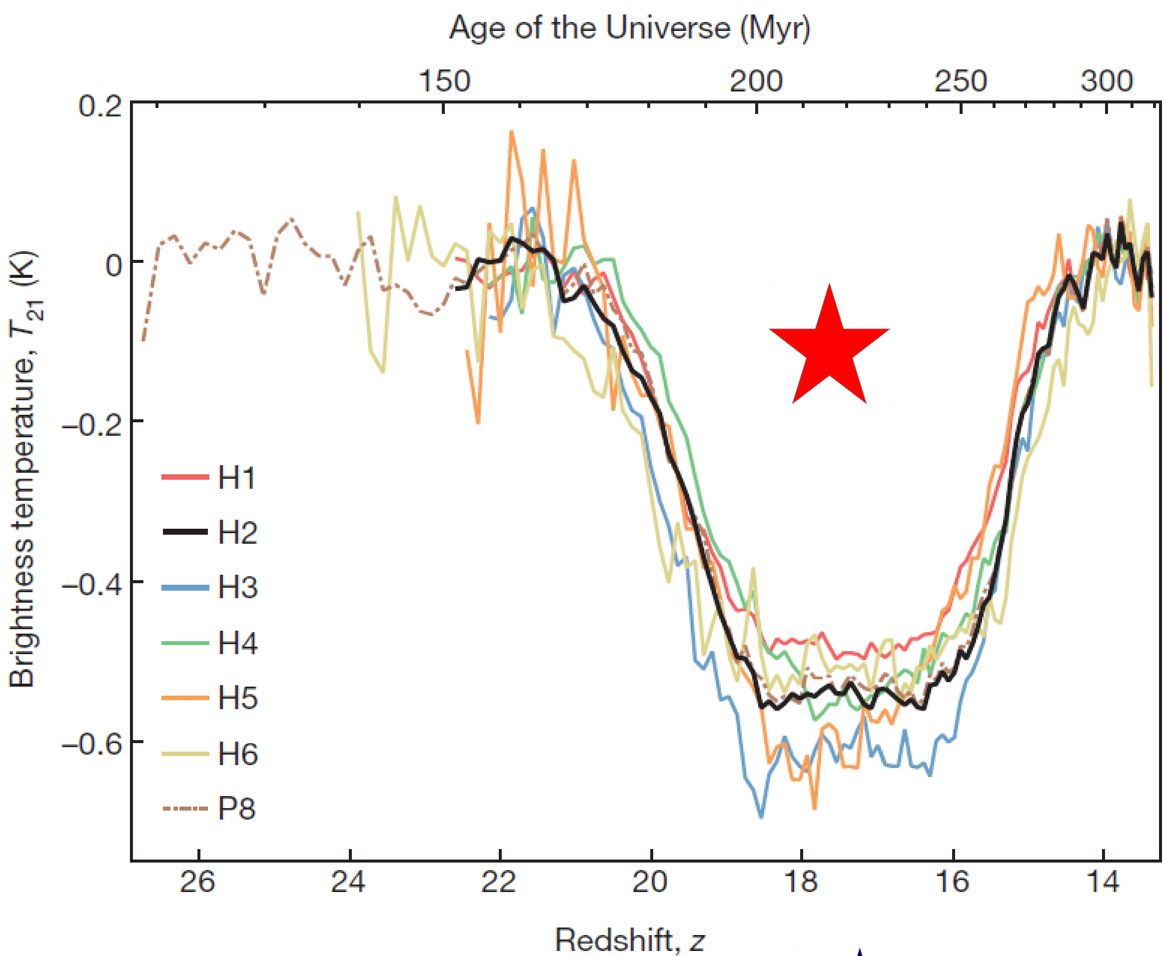
Why is it shocking?



GB et al. (2016)

Bowman et al. (2018)

Why is it shocking?

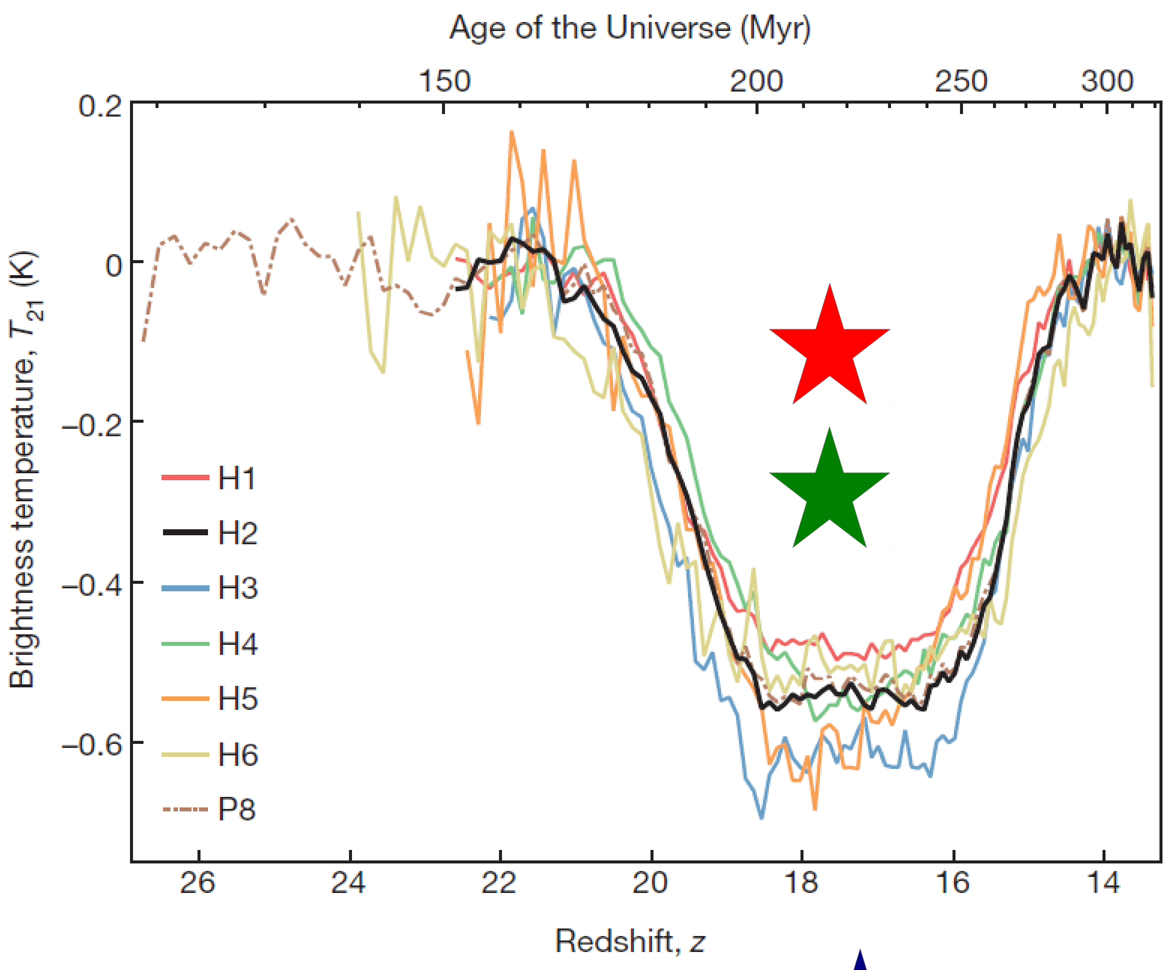


"Reference model" (a factor of ~ 5 fainter)

GB et al. (2016)

Bowman et al. (2018)

Why is it shocking?



"Reference model" (a factor of ~ 5 fainter)

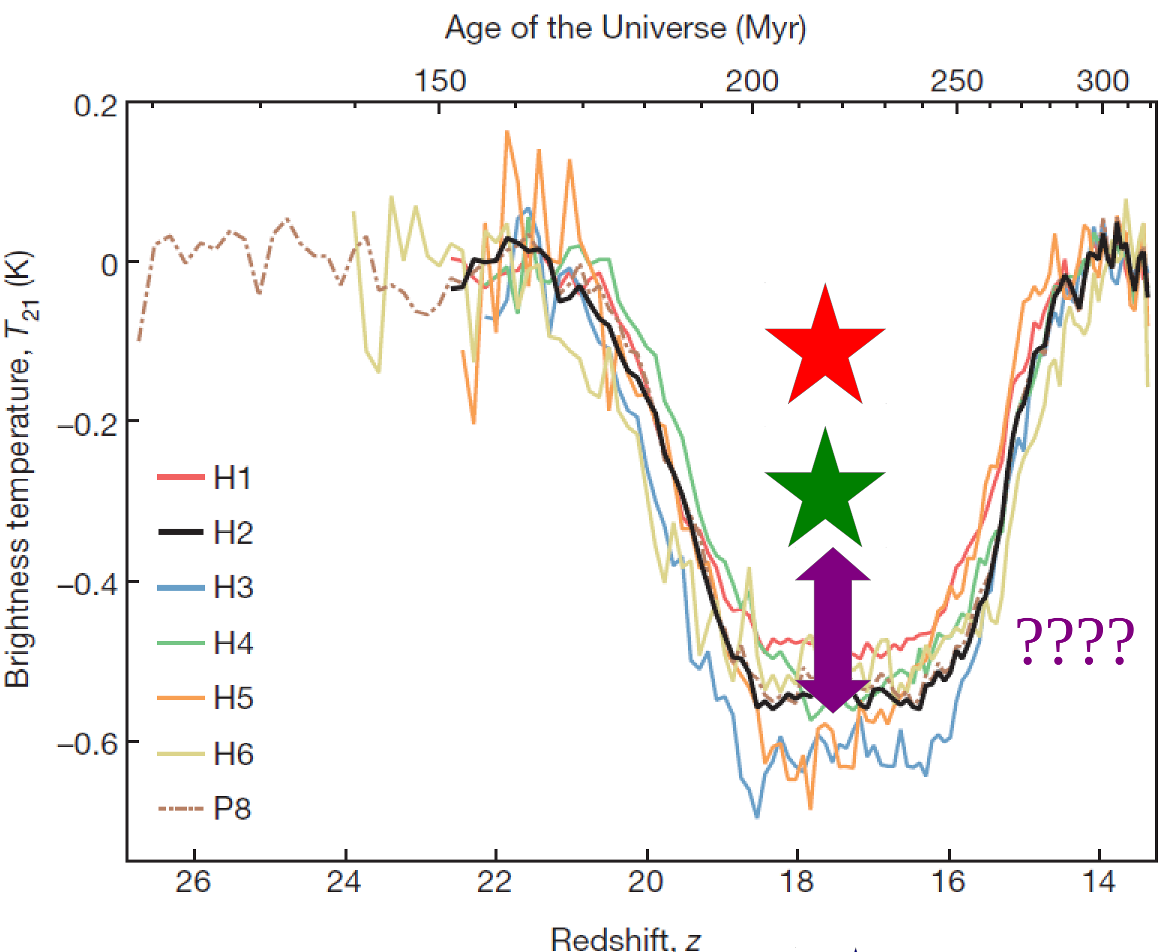
Most extreme model allowed by "standard, known" physics

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

GB et al. (2016)

Bowman et al. (2018)

Why is it shocking?



"Reference model" (a factor of ~ 5 fainter)

Most extreme model allowed by "standard, known" physics

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

GB et al. (2016)

Bowman et al. (2018)

Let's recap... if it is true:

- First start appeared at z ~ 20 when the Universe was ~ 170 Myr old,

  but...

- how can the gas have cooled faster than adiabatically and the signal be a factor of ~2 brighter than the most extreme model?

- one needs a background brighter than the CMB (e.g., Feng & Holder, 2018)... very unlikely;

- or

Today, March 1st 2018 (continued)

LETTER

doi:10.1038/nature25791

Possible interaction between baryons and dark-matter particles revealed by the first stars

Rennan Barkana[1]

The cosmic radio-frequency spectrum is expected to show a strong absorption signal corresponding to the 21-centimetre-wavelength transition of atomic hydrogen around redshift 20, which arises from Lyman-α radiation from some of the earliest stars[1–4]. By observing this 21-centimetre signal—either its sky-averaged spectrum[5] or maps of its fluctuations, obtained using radio interferometers[6,7]—we can obtain information about cosmic dawn, the era when the first astrophysical sources of light were formed. The recent detection of the global 21-centimetre spectrum[5] reveals a stronger absorption than the maximum predicted by existing models, at a confidence level of 3.8 standard deviations. Here we report that this absorption can be explained by the combination of radiation from the first stars and excess cooling of the cosmic gas induced by its interaction with dark matter[8–10]. Our analysis indicates that the spatial fluctuations of the 21-centimetre signal at cosmic dawn could be an order of magnitude larger than previously expected and that the dark-matter particle is no heavier than several proton masses, well below the commonly predicted mass of weakly interacting massive particles. Our analysis also confirms that dark matter is highly non-relativistic and at least moderately cold, and primordial velocities predicted by models of warm dark matter are potentially detectable. These results indicate that 21-centimetre cosmology can be used as a dark-matter probe.

An excess 21-cm absorption signal is a clear sign of scattering of bar-

Epoch of reionization Signature (EDGES) [5], which detected the signal's global spectrum from cosmic dawn and found an absorption peak at frequency $\nu = 78 \pm 1$ MHz ($z = 17.2$) with brightness temperature $T_{21} = -500^{+200}_{-500}$ mK; the uncertainties represent 99% confidence intervals and include both thermal and systematic noise. This absorption signal has passed robustness tests for variations in the hardware and processing configuration. If confirmed, this signal (which is 3.8σ below -209 mK, where σ is the standard deviation; the strongest possible absorption at this frequency under standard expectations) cannot be explained without a new dark-matter interaction, even if we take exotic astrophysics into account (see Methods). Indeed, $T_{21} = -300$ mK at $z = 17.2$ implies $T_{\rm gas} < 5.1$ K, whereas the lowest possible value in the standard scenario is 7.0 K. Basic thermodynamics suggests that it is easy to heat the cosmic gas but difficult to cool it. The extra cooling indicated by the data is possible only through the interaction of the baryons with something even colder.

The only known cosmic constituent that can be colder than the early cosmic gas is dark matter. The reason for this is that dark matter is assumed to interact with itself and with baryons mainly gravitationally, and so it is expected to decouple thermally in the very early Universe and cool down thereafter (very quickly if it is non-relativistic early on, as in the case of cold dark matter). Substantial electrodynamic or nuclear interactions of dark matter would be inconsistent with the observational successes of standard cosmology, including Big Bang

Today, March 1st 2018 (continued)

- The signal at z ~ 20 can be explained with the first stars;

- extra cooling can be provided by from baryon-dark matter scattering as dark matter decoupled earlier (i.e. it is colder):

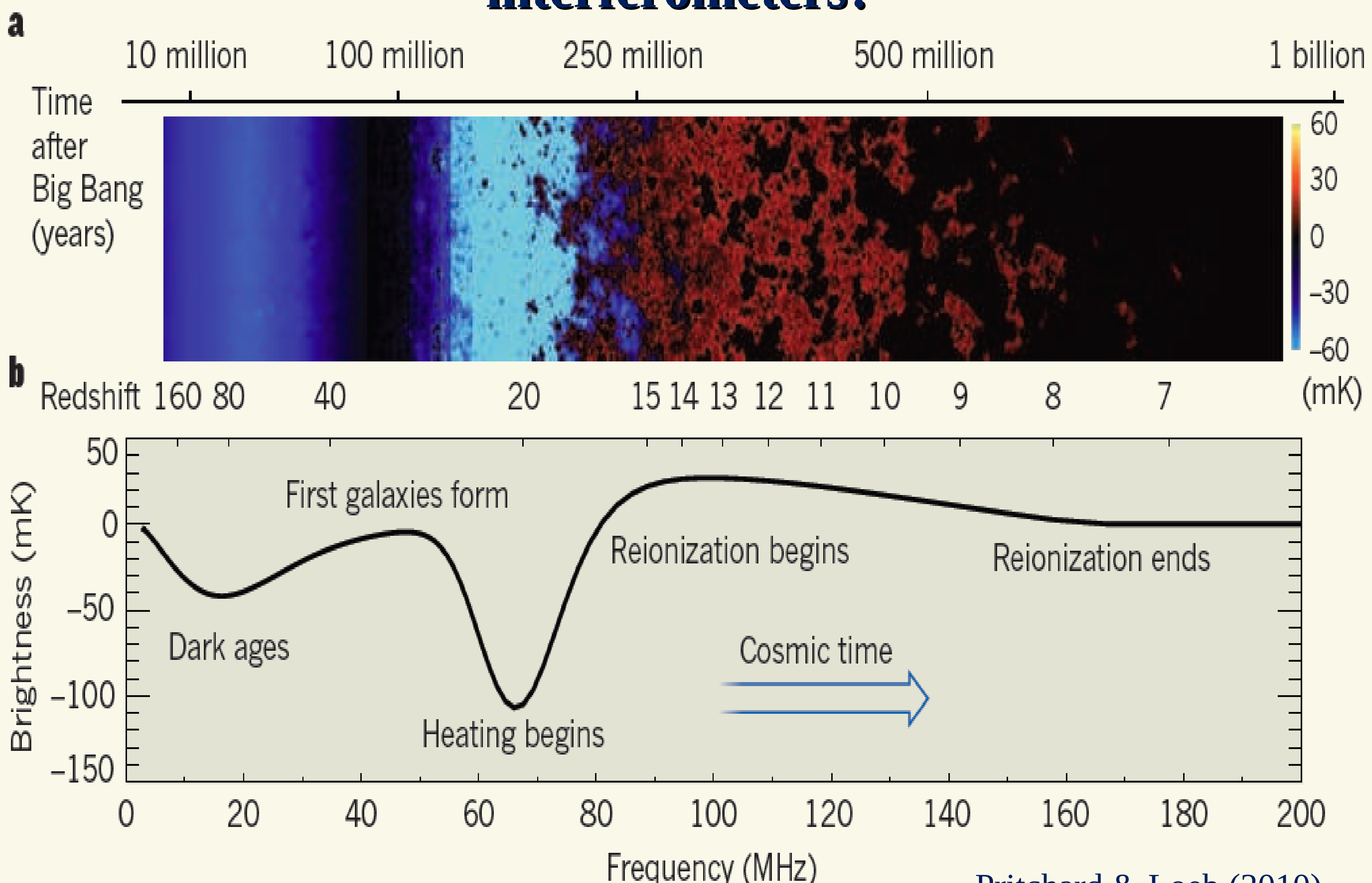
$$\sigma(v) = \sigma_1 \left(\frac{v}{1\,\mathrm{km\,s^{-1}}} \right)^{-4}$$

- the signal would constrain a light (< 4.3 GeV) and relatively cold (rms velocity < 16 km/s);

- the signal at 14 < z < 16 would be consistent with IGM heating (probably from X-rays?);

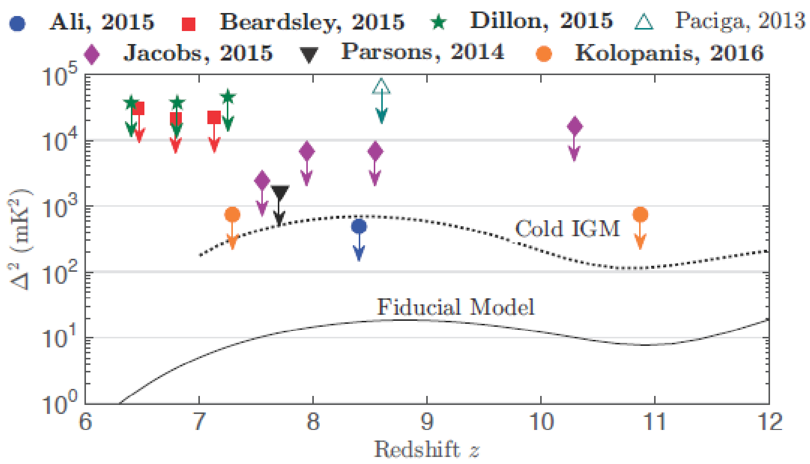
- rms signal fluctuations may now be 7 times stronger than anticipated...

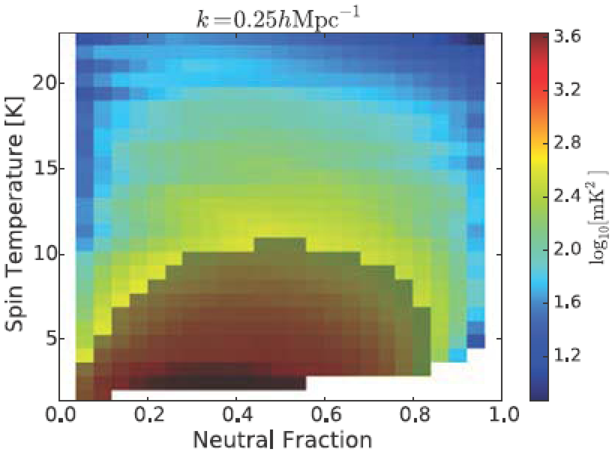
… another JAC to cover reionization and all the interferometers?

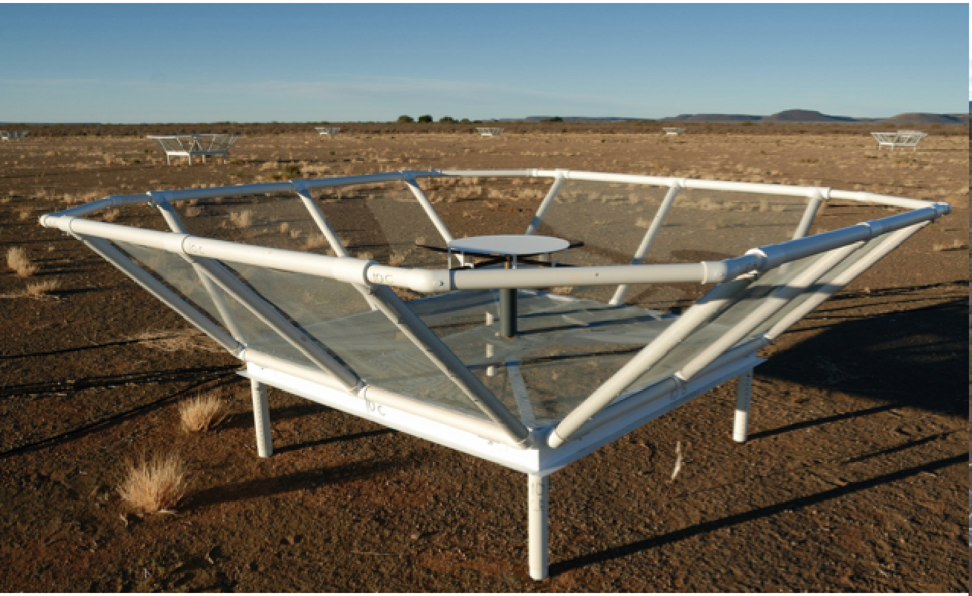


Pritchard & Loeb (2010)

Current status...





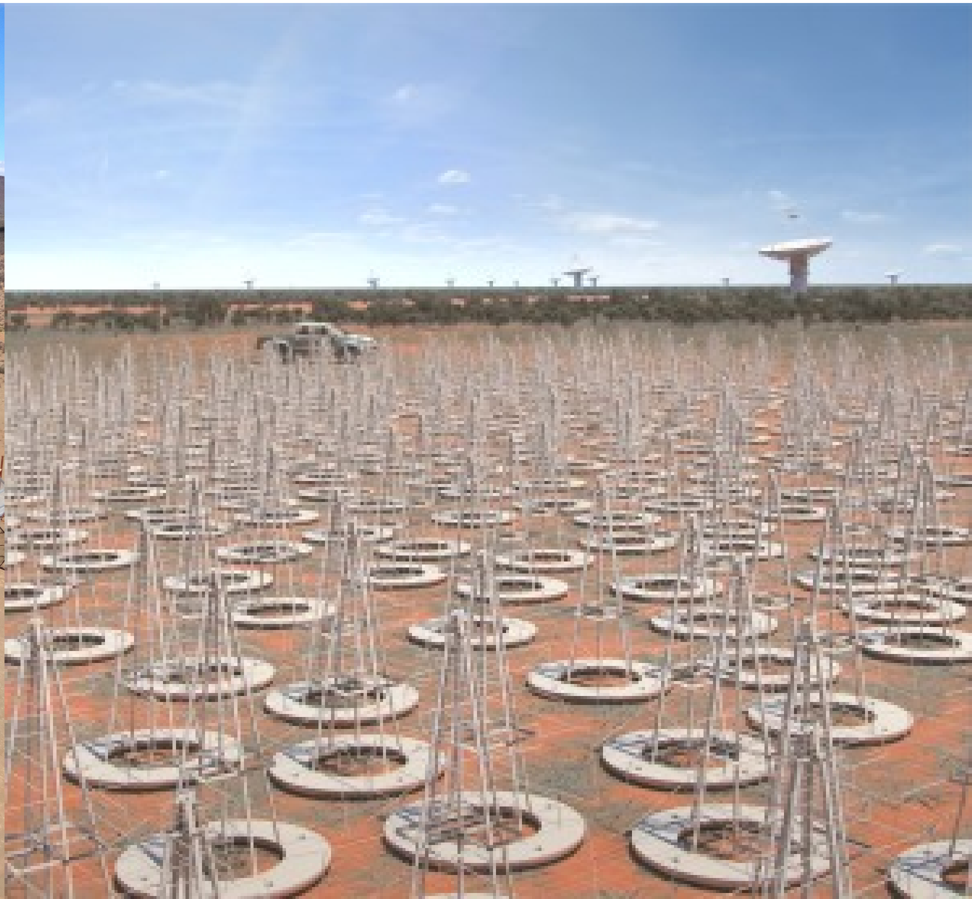


PAPER

… and future instruments

HERA
331 14m dishes in SA
70-200 MHz (pure 21-cm experiment)
Under construction now!
(50+ dishes on the ground)

SKA(low)
150000 dipoles
50-350 MHz
Imaging reionization and cosmic dawn?
2020+



Conclusions and future outlooks

- IRA has hired the wrong person – apologies, Tiziana;

- Today will go down in our history books: are we witnessing the detection of the 21-cm signal? Is it telling us something unexpected about fundamental physics?

- We have a ~1000 hours of LEDA to “finish” to analyze in order to confirm (or not) the EDGES results...

- If this is a detection (and not another BICEP2 event):
    - it remains shocking;
    - it boosts confidence in detecting reionization too;
    - it paves the way for future instrumentation: HERA and, later on the SKA;
    - 21-cm may lead to understand the formation and evolution of the first structures and much more...

- Let the party begin!

Conclusions and future outlooks

- IRA has hired the wrong person – apologies, Tiziana;

- Today will go down in our history books: are we witnessing the detection of the 21-cm signal? Is it telling us something unexpected about fundamental physics?

- We have a ~1000 hours of LEDA [illegible] to analyze in order to confirm (or not) the EDGES results...

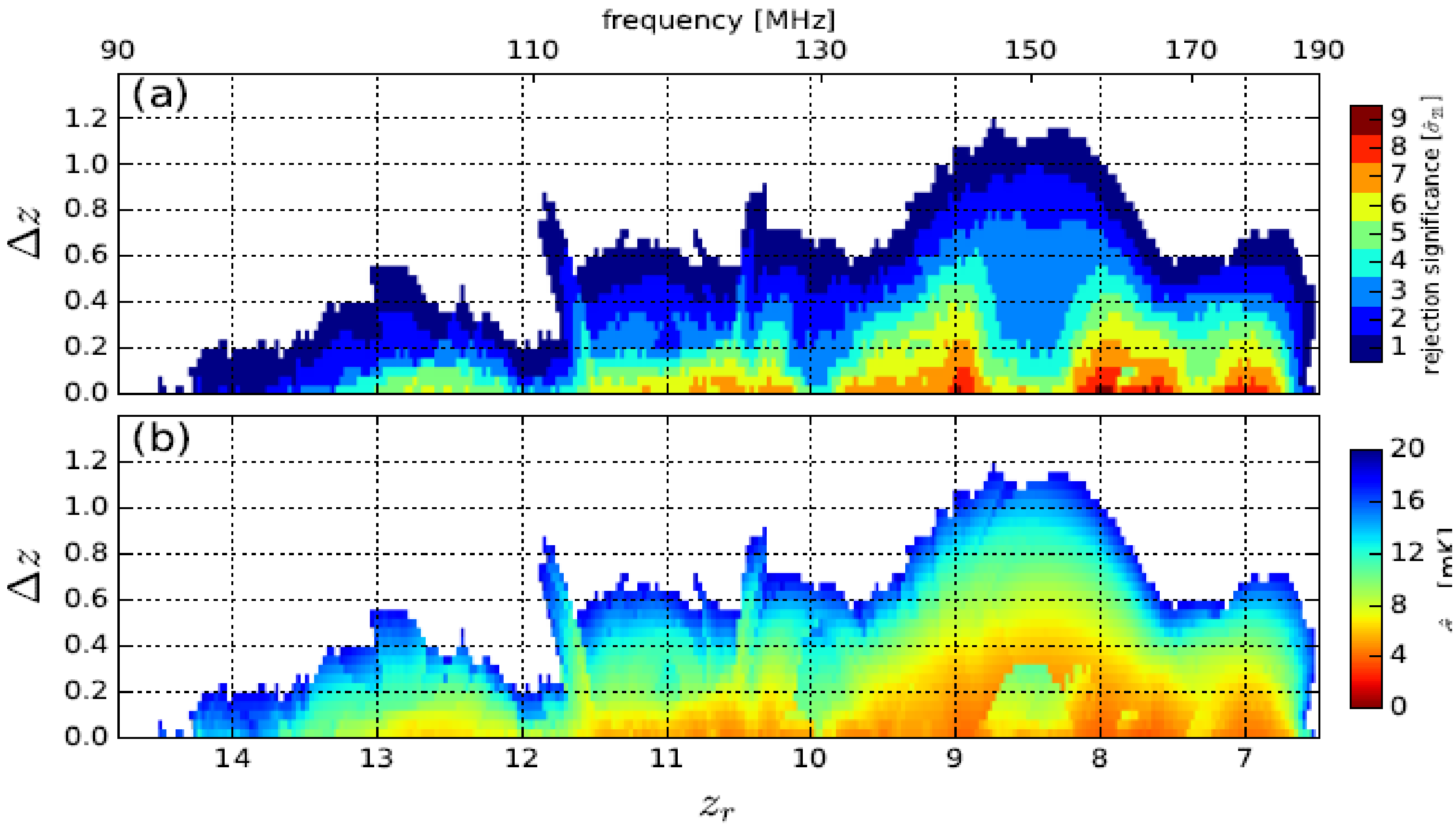
- If this is a detection (a[illegible]er BICEP2 event):
    - it remains shock[illegible]
    - it boosts confidenc[illegible] in detecting reionization too;
    - it paves the way for future instrumentation: HERA and, later on the SKA;
    - 21-cm may lead to understand the formation and evolution of the first structures and much more...

- Let the party begin!

Thank you

Backup slides

Reionization constraints from EDGES



Monsalve et al. (2017)

Dark Matter constraints

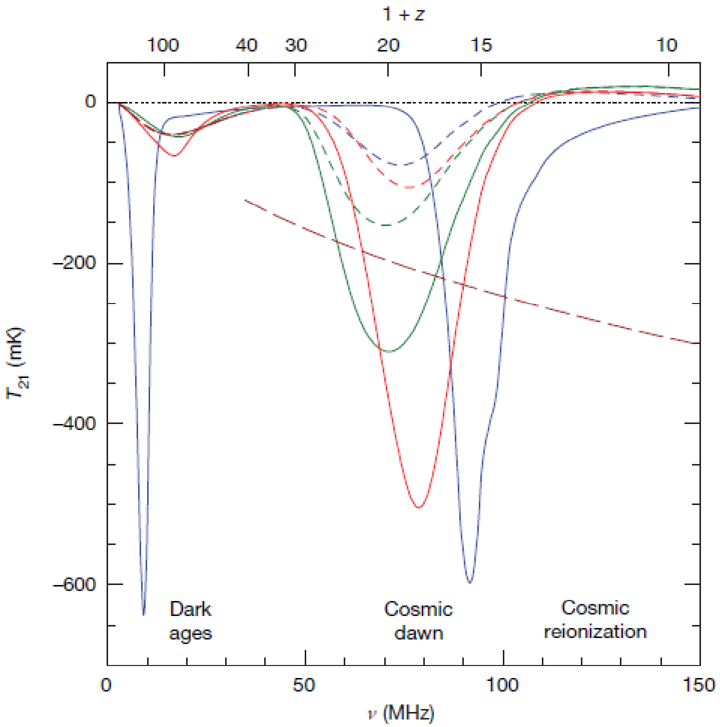


Figure 2 | Global 21-cm signal in models with baryon–dark matter scattering. The globally averaged 21-cm brightness temperature T_{21} (in millikelvin) is shown at an observed frequency ν (in megahertz), with the corresponding value of $1+z$ displayed at the top. We chart some of the space of possible 21-cm signals (see Methods for a discussion on their shapes) using three models (solid curves), with: $\sigma_1 = 8\times10^{-20}$ cm^2 and $m_\chi = 0.3$ GeV (red; roughly matching the most likely observed value[5] of the peak absorption); $\sigma_1 = 3\times10^{-19}$ cm^2 and $m_\chi = 2$ GeV (green); and $\sigma_1 = 1\times10^{-18}$ cm^2 and $m_\chi = 0.01$ GeV (blue). The astrophysical parameters assumed by these models are given in Methods. The corresponding 21-cm signals in the absence of baryon–dark matter scattering are shown as short-dashed curves. Also shown for comparison (brown long-dashed line) is the standard prediction for future dark ages measurements assuming no baryon–dark matter scattering for $\nu < 33$ MHz (matches all the short-dashed curves in this range) and the lowest global 21-cm signal at each redshift that is possible with no baryon–dark matter scattering, regardless of the astrophysical parameters used (for $\nu > 33$ MHz).

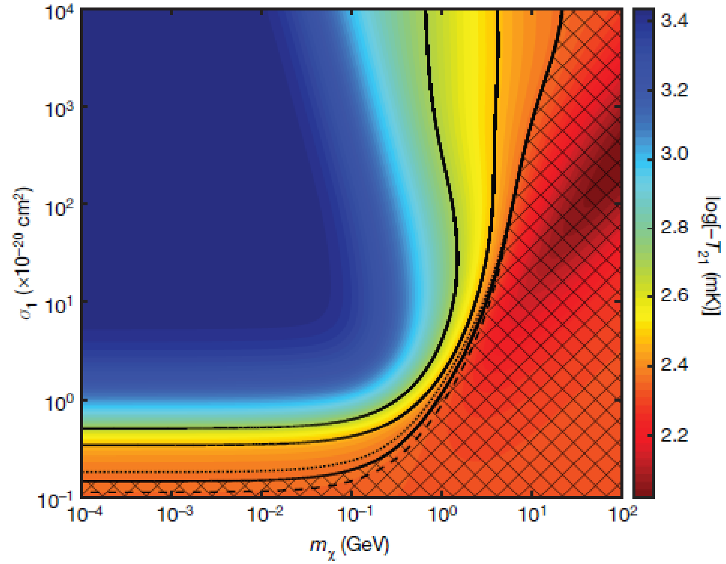


Figure 3 | Constraints on dark-matter properties using cosmic dawn observations. The minimum possible 21-cm brightness temperature T_{21} (expressed as the logarithm of its absolute value) is shown at $z = 17$ ($\nu = 78.9$ MHz), regardless of the astrophysical parameters used (that is, assuming saturated Lyman-α coupling and no X-ray heating), as a function of m_χ and σ_1 (equation (2)). Also shown (solid black curves) are contours corresponding to the following values of T_{21} (from right to left): −231 mK, which corresponds to 10% stronger absorption than the highest value obtained without baryon–dark matter scattering (−210 mK at $z = 17$, or 2.32 on the logarithmic scale); −300 mK, which is the minimal absorption depth in the data at a 99% confidence level; and −500 mK, the most likely absorption depth in the data. The hatched region is excluded if we assume absorption[5] by at least −231 mK at $z = 17$; this 3.5σ observational result implies $\sigma_1 > 1.5\times10^{-21}$ cm^2 (corresponding to $\sigma_c > 1.9\times10^{-43}$ cm^2 for $\sigma(v) \propto v^{-4}$) and $m_\chi < 23$ GeV. (Although any m_χ above a few gigaelectronvolts requires high σ_1, this parameter combination could be in conflict with other constraints; see Methods.) If we adopt the observed minimum absorption of $T_{21} = -300$ mK, then (again, regardless of astrophysics) the dark matter must satisfy $\sigma_1 > 3.4\times10^{-21}$ cm^2 ($\sigma_c > 4.2\times10^{-43}$ cm^2) and $m_\chi < 4.3$ GeV; a brightness temperature of −500 mK implies $\sigma_1 > 5.0\times10^{-21}$ cm^2 ($\sigma_c > 6.2\times10^{-43}$ cm^2) and $m_\chi < 1.5$ GeV. We also illustrate the redshift dependence of these limits via the corresponding 10% contours at $z = 14$ (dashed) and $z = 20$ (dotted).

Barkana (2018)