21 cm absorption anomaly at cosmic dawn

new physics or systematics ?

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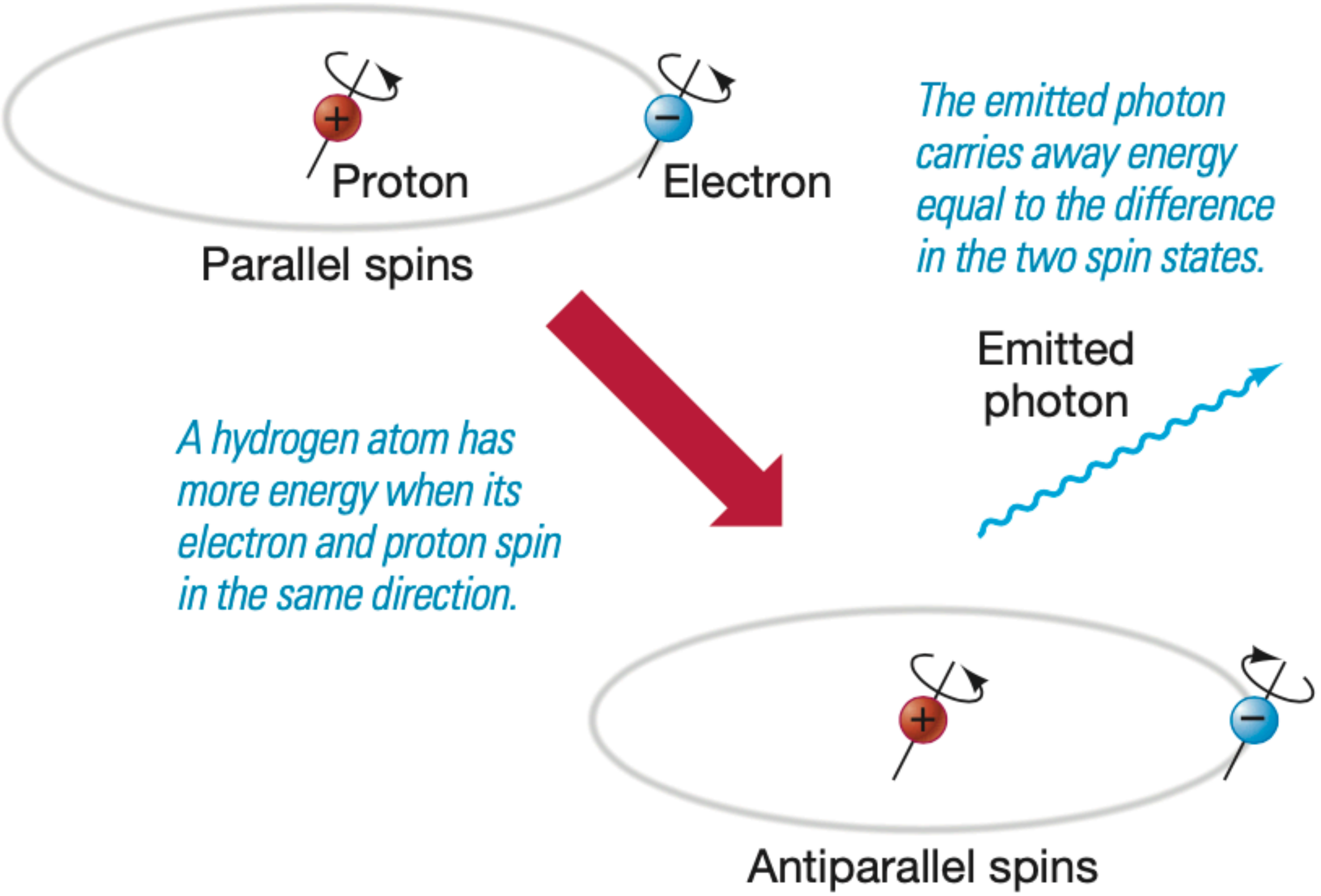
Supervisor: Yi Mao

22/04/2022

OUTLINE

- Background
- Experiment
- Theory
    - dark matter cooling
    - early radio excess
- Summary

Physics of the 21 cm line of atomic hydrogen



- How the 21 cm line of hydrogen produce?

  Hyperfine splitting of the 1S ground state due to interaction of magnetic moments of proton and electron.

$$\Delta E = 5.9 \times 10^{-6} eV$$

$$\lambda = 21.1 cm \ , \ \nu = 1420 MHz$$

- Spin temperature T_S

  Ratio between the number densities of hydrogen atoms in the two hyperfine levels.

$$\frac{n_1}{n_0} = \left(\frac{g_1}{g_0}\right) exp\left(-\frac{T_\star}{T_S}\right)$$

Physics of the 21 cm line of atomic hydrogen

- Three processes determine the spin temperature:

absorption/emission from/to the radio background, primarily CMB
$T_\gamma = T_{CMB}$

resonant scattering of $Ly\alpha$ photons
$(T_\alpha\ ,\ x_\alpha)\quad T_\alpha \rightarrow T_K$

collisions with other hydrogen atoms and with electrons
$(T_K\ ,\ x_c)$

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

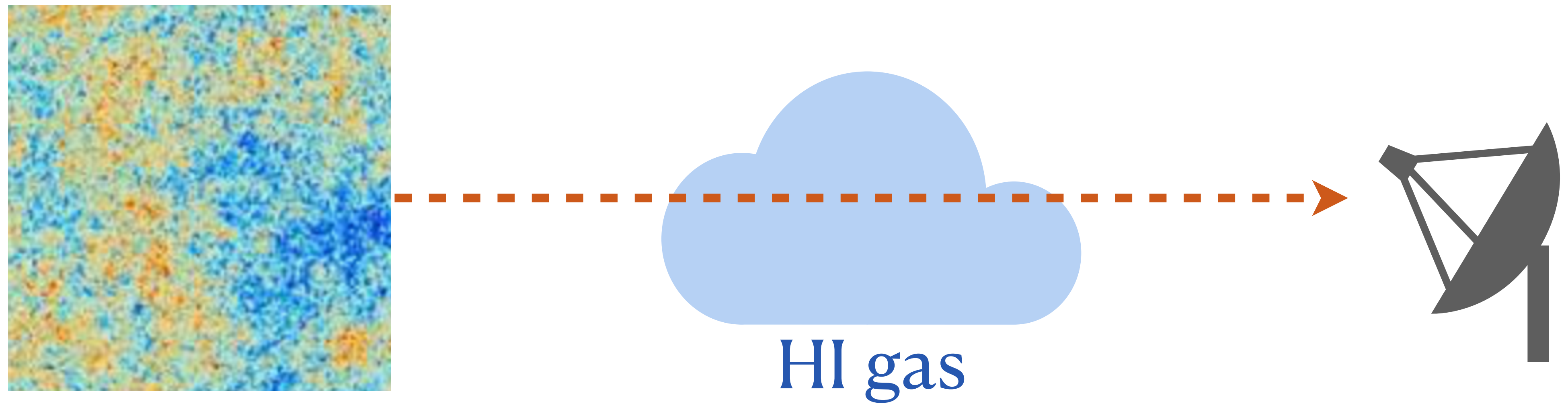
- when $x_{tot} \equiv x_c + x_\alpha \gtrsim 1$, T_S strongly couple to T_{gas}
- when $x_{tot} \ll 1$, T_S couple to T_γ

Physics of the 21 cm line of atomic hydrogen

○ How can we see the 21 cm line ?

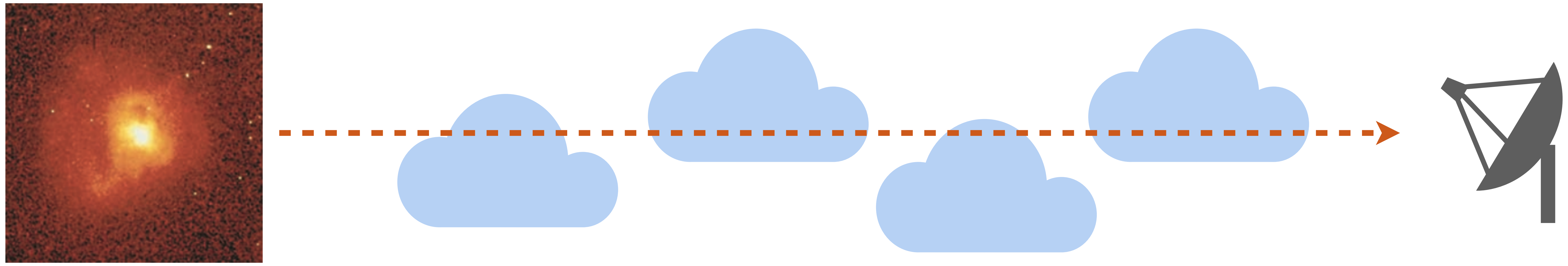
$$\delta T_b = \frac{T_S - T_\gamma}{1+z}\left(1 - e^{-\tau_\nu}\right)$$

- $T_S > T_\gamma$ emission signal
- $T_S < T_\gamma$ absorption signal
- $T_S = T_\gamma$ no signal



CMB
- **global 21 cm signature**
- 21 cm tomography
- intensity mapping

radio-loud point source
- 21 cm forest



Evolution of the global 21 cm signal

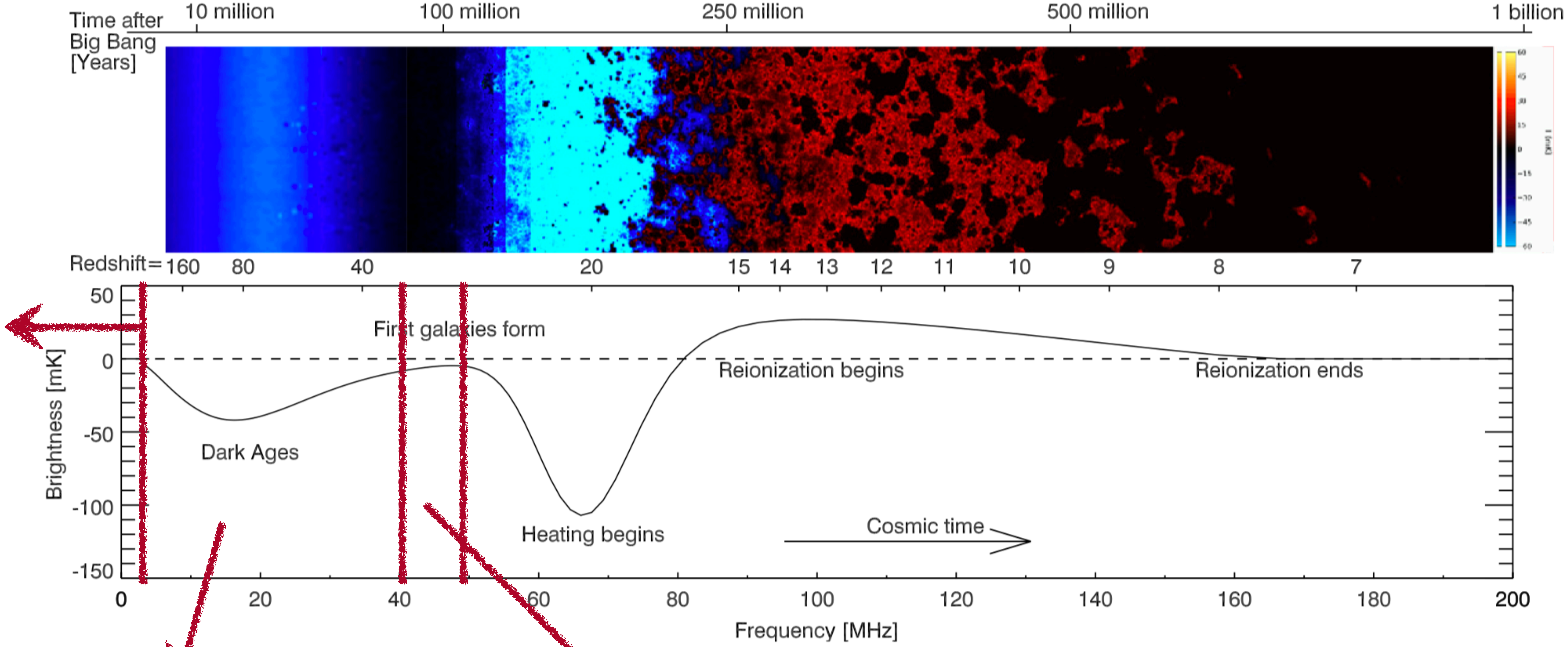
$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

$200 \lesssim z \lesssim 1100$:

gas couple to CMB $\rightarrow T_K = T_\gamma$

high gas density $\rightarrow T_S = T_\gamma$

$\rightarrow \bar{T}_b = 0$ no signal



$40 \lesssim z \lesssim 200$:

gas cools adiabatically $\rightarrow T_K \propto (1+z)^2 \rightarrow T_K < T_\gamma$

collisional coupling $\rightarrow T_S < T_\gamma$

$\rightarrow \bar{T}_b < 0$ early absorption signal

$z_\star \lesssim z \lesssim 40$:

expansion decrease gas density

→ collisional coupling becomes ineffective

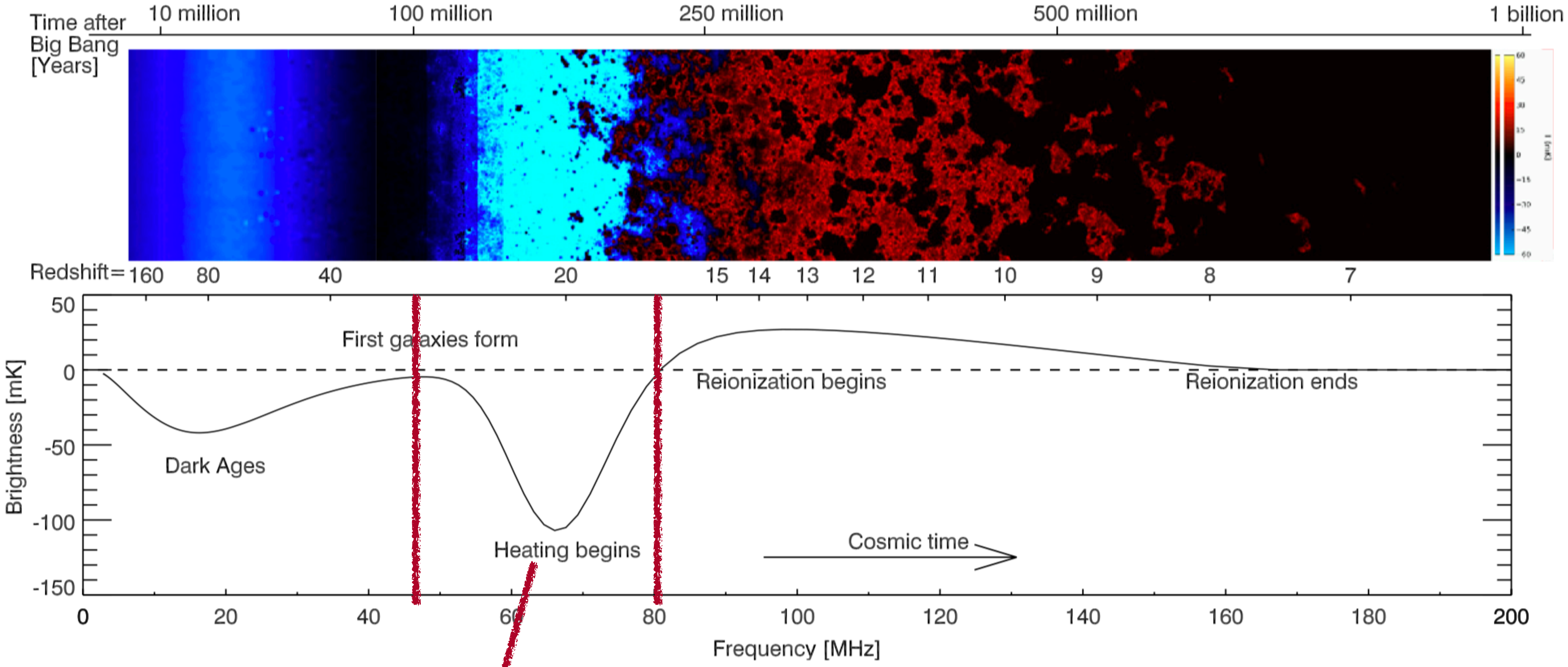
$\rightarrow T_S$ couple to CMB $\rightarrow T_S = T_\gamma$

$\rightarrow \bar{T}_b = 0$ absorption disappear

(Pritchard&Loeb 2012)

Evolution of the global 21 cm signal

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$



$z_\alpha \lesssim z \lesssim z_\star$:

when first source form → emit $Ly\alpha$ photons

in some regime, T_S couple to cold gas $\rightarrow T_S \sim T_K < T_\gamma$

$\rightarrow \bar{T}_b < 0$ absorption signal

at z_α, $Ly\alpha$ coupling saturate, $x_\alpha \gg 1$

$z_h \lesssim z \lesssim z_\alpha$:

→ significantly heating gas

→ T_K increase

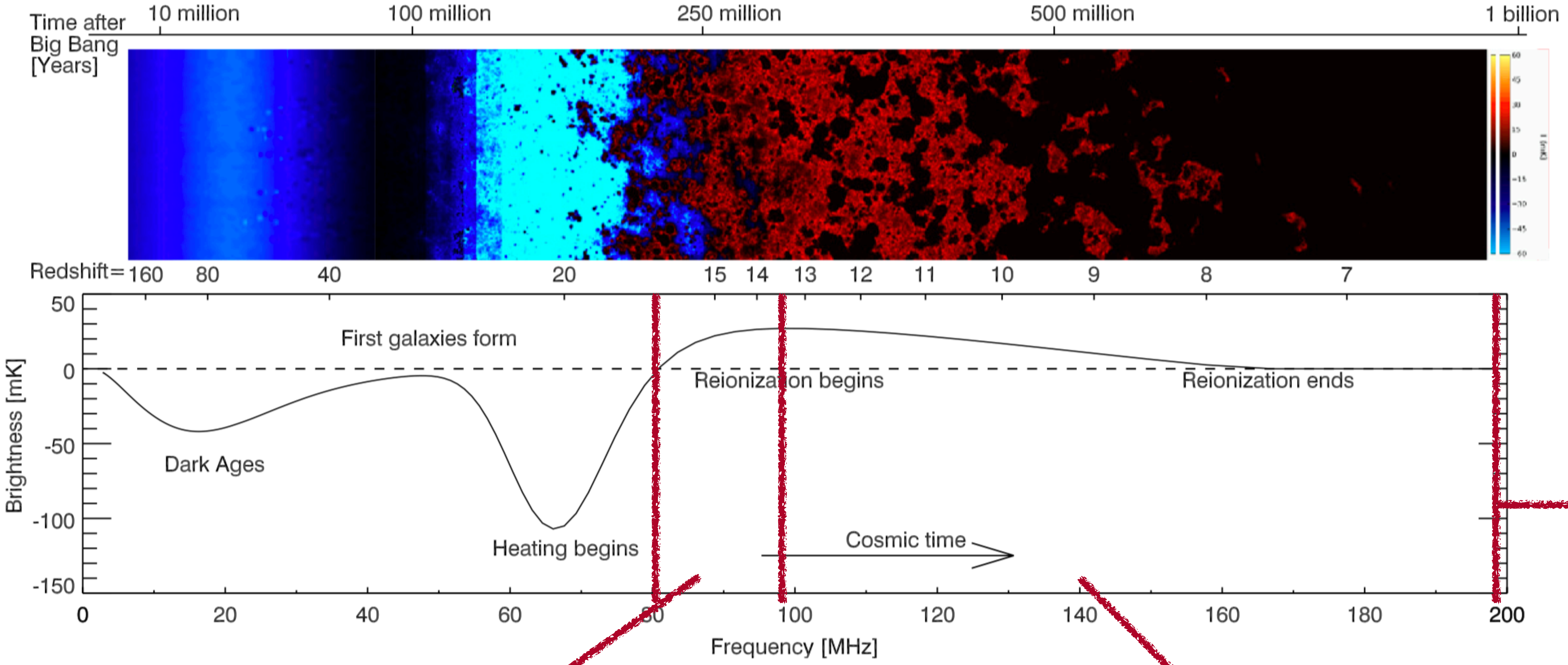
at z_h, heated gas everywhere,

$\bar{T}_K = T_\gamma \rightarrow$ global $\bar{T}_b = 0$

(Pritchard&Loeb 2012)

Evolution of the global 21 cm signal

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$



$z_T \lesssim z \lesssim z_h$:

heating continue → $T_K > T_\gamma$

→ $T_S \sim T_K \gg T_\gamma$

→ $\bar{T}_b > 0$ emission signal

$z_r \lesssim z \lesssim z_T$:

heating continue → $T_K \gg T_\gamma$

ionization and HII regions growth

→ emission signal decrease

$z \lesssim z_r$:

heating continue → $T_K \gg T_\gamma$

after reionization

→ signal from collapsed islands

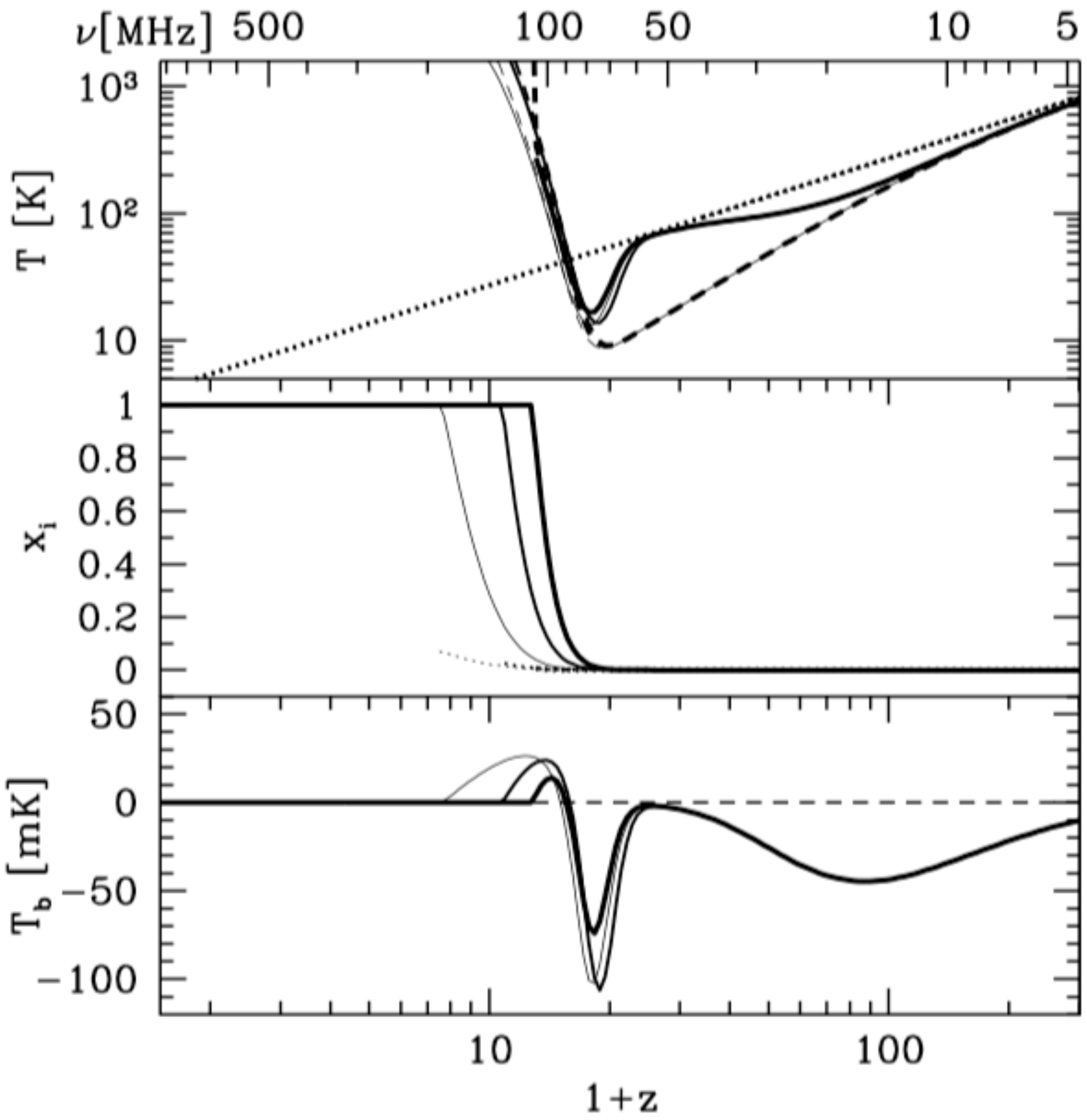
(Pritchard&Loeb 2012)

Why need to detect the global 21 cm signal ?

- In the evolution model, we need four parameters to describe the signal:
    - number of ionizing photons $N_{ion,IGM}$
    - $Ly\alpha$ emissivity f_α
    - X-ray emissivity f_X
    - star-formation efficiency $f_\star$

- basic emission and absorption feature
- highly uncertain when star formation begins

→ positions of turning points constrain the underlying astrophysics



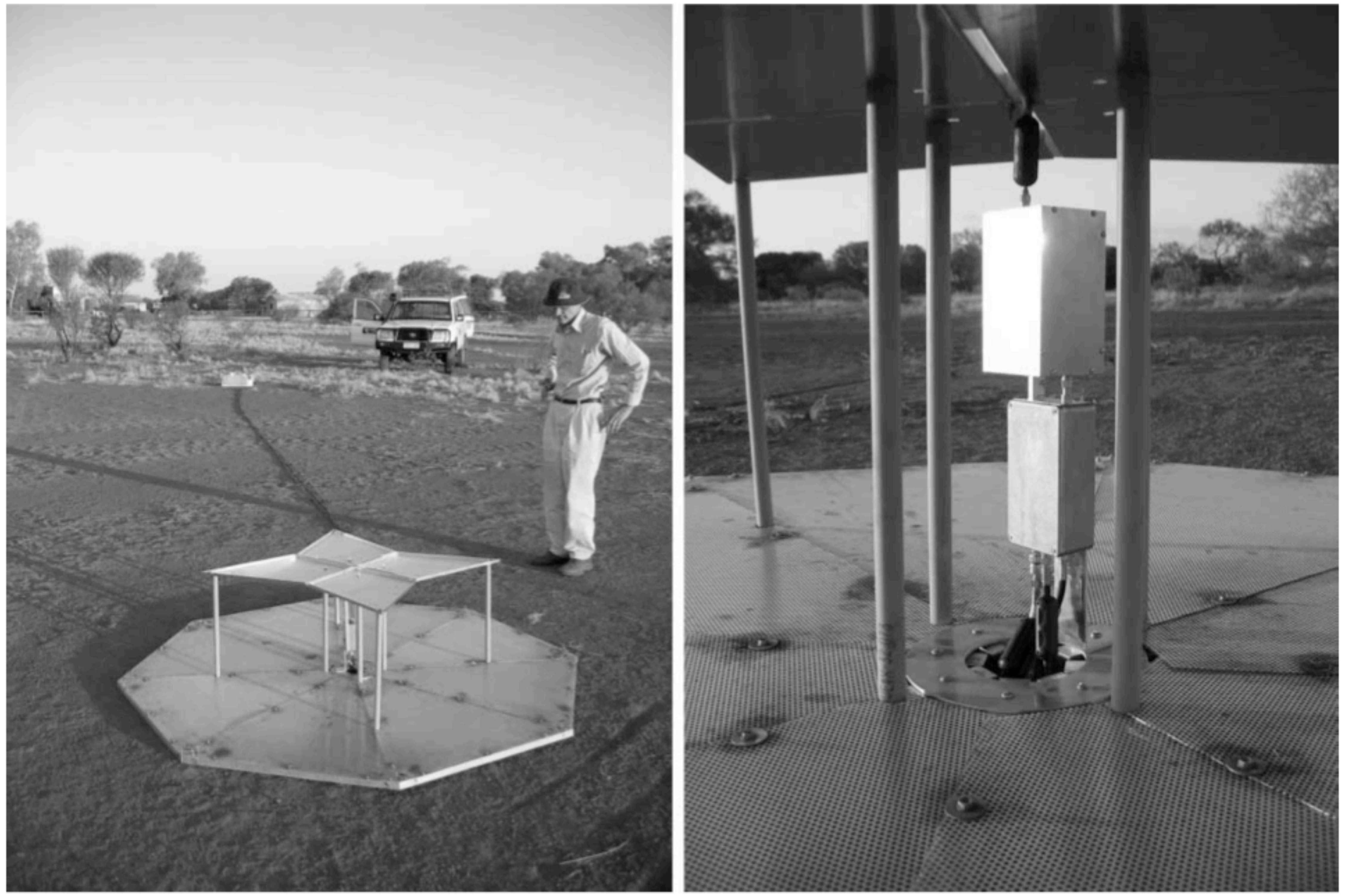
(Pritchard&Loeb 2008, 2012)

Detectability of the global signal with small numbers of dipoles

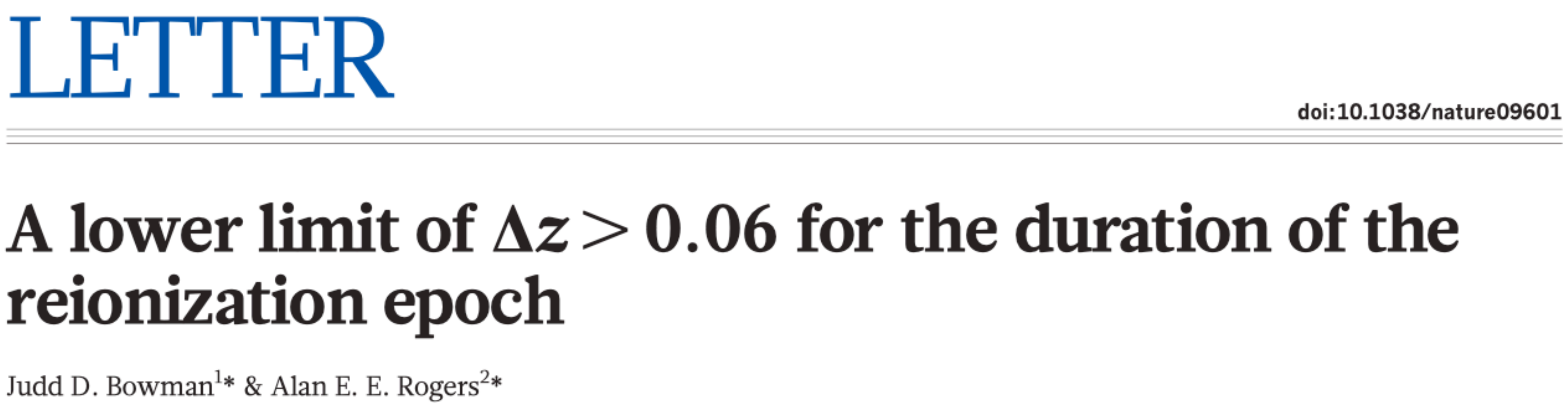
- Measurement does not need high angular resolution & need just a single dipole.
- Complication mainly come from galactic foreground removal, which are much larger than the desired signal.

COsmological Reionization Experiment (CORE)

Experiment to Detect the Reionization Step (EDGES)



EDGES high band detection



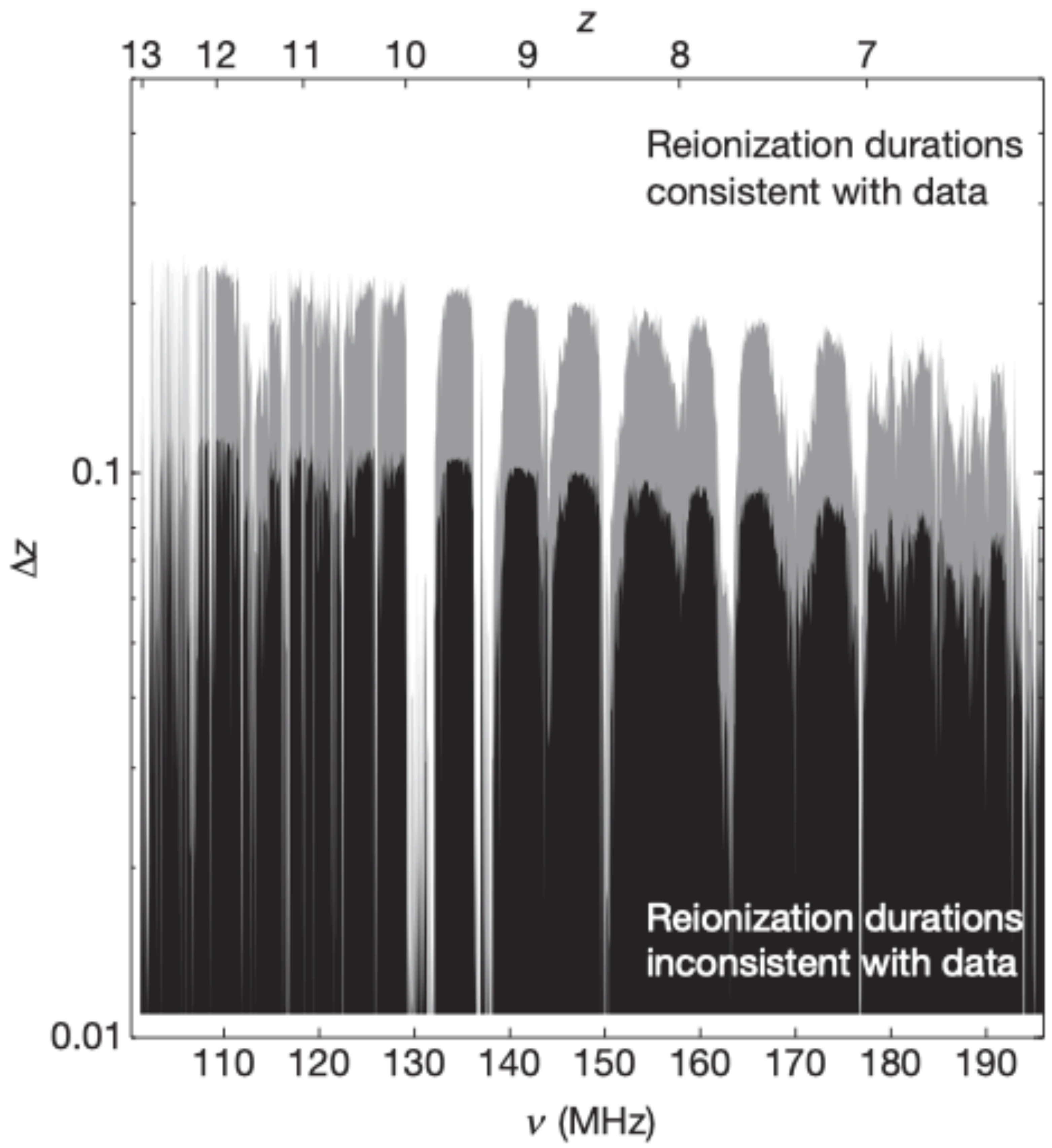
LETTER

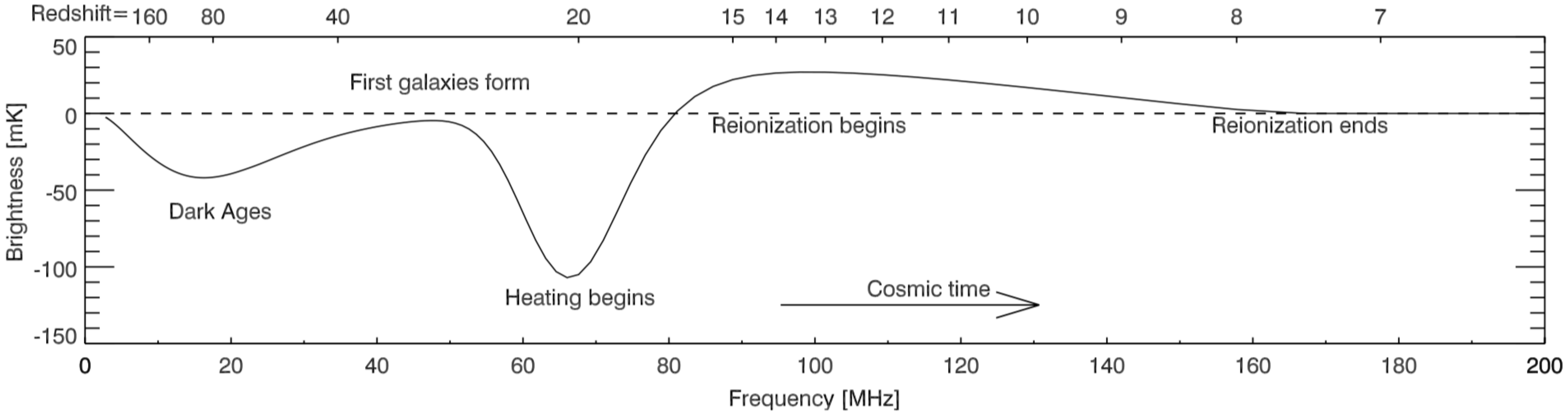
doi:10.1038/nature09601

A lower limit of $\Delta z > 0.06$ for the duration of the reionization epoch

Judd D. Bowman[1]* & Alan E. E. Rogers[2]*

- All-sky spectrum between 100 and 200 MHz ($6 < z < 13$)
- The experiment exclude a rapid reionization timescale of $\Delta z < 0.06$ at 95% confidence level.





(Bowman&Rogers 2010)

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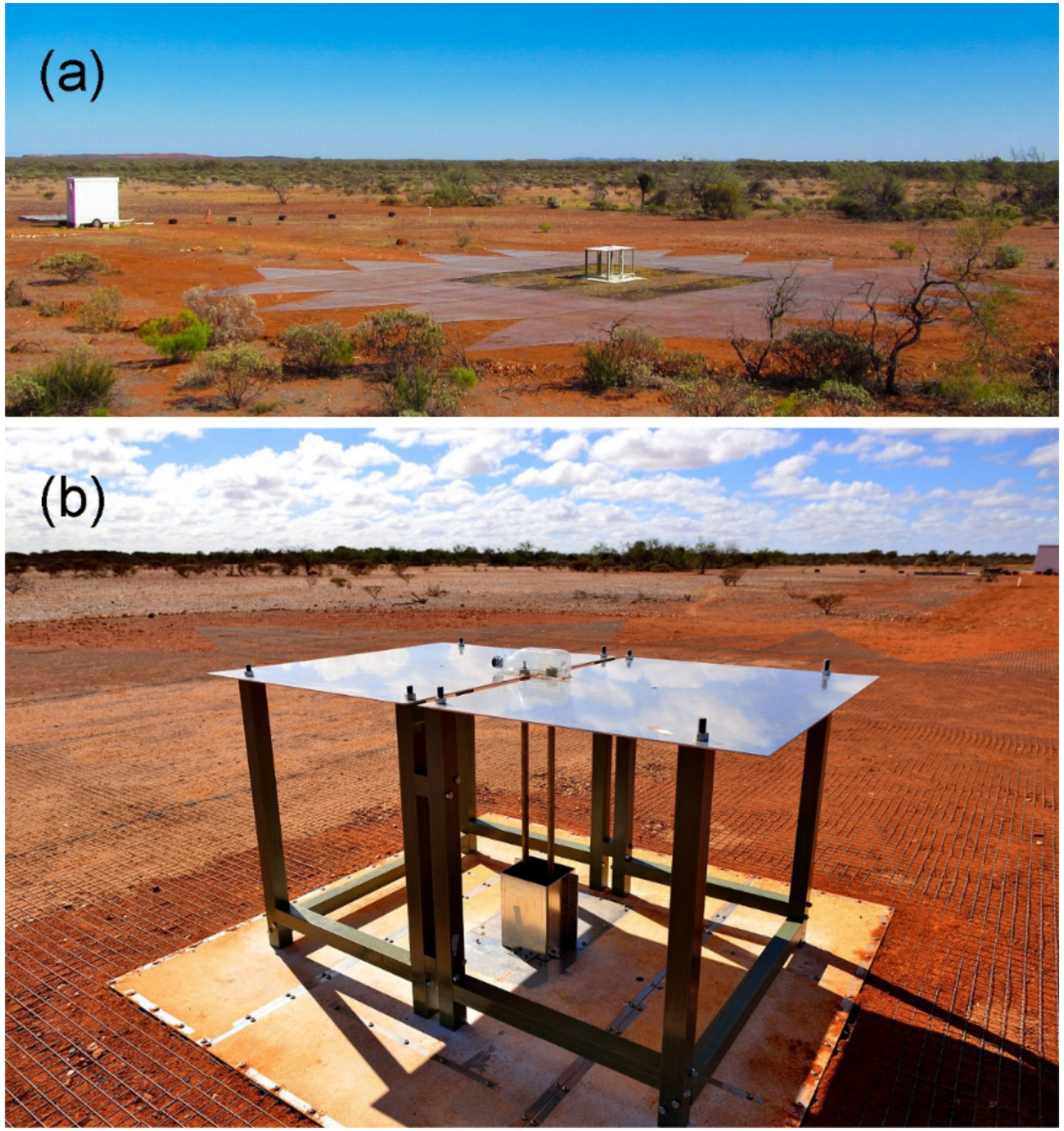
On the detection of a cosmic dawn signal in the radio background

Bowman et al. 2018 (Nature)

Singh et al. 2021 (Nature Astronomy)

EDGES low band instruments



It contains:

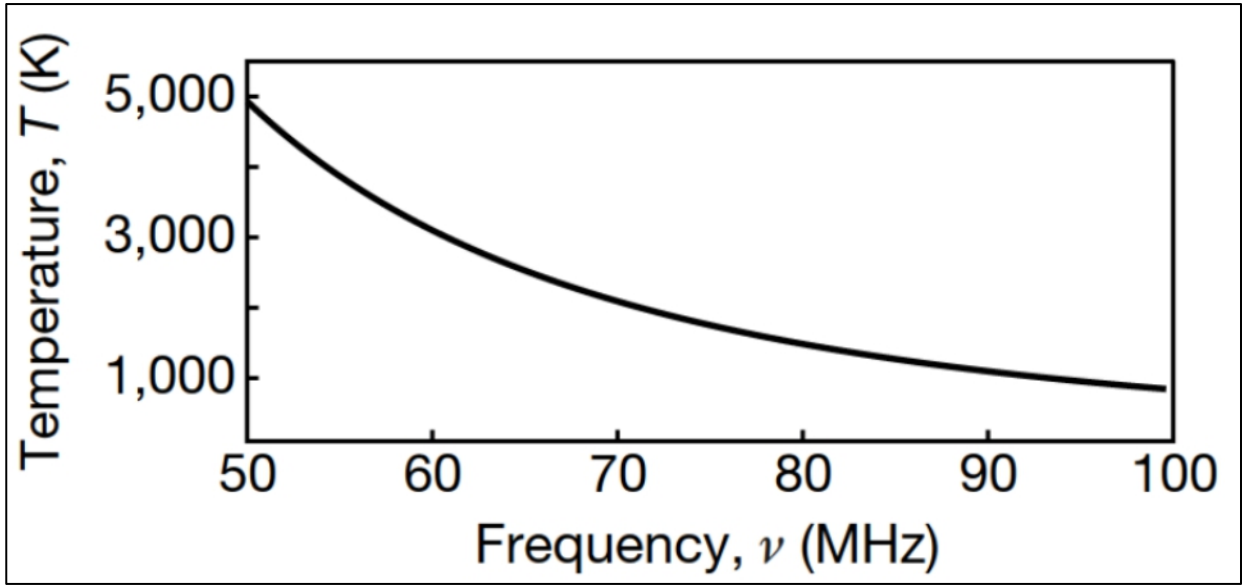
- The ground plane rests directly on the physical ground and consists of a 10x10 meter mesh, to reduce radio waves emitted by the ground.

- Dipole-like “blade” antenna consisting of two rectangular metal panels.

- Bracket, ground beneath receiver...

Band: 50–100 MHz (27 > z > 13)
Resolution: 6.1 kHz

EDGES low band detected spectrum



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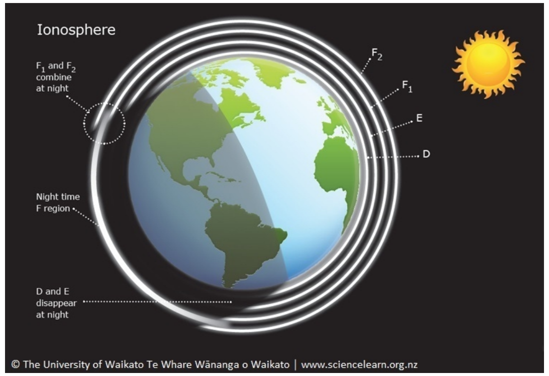

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Galactic synchrotron

Earth's ionosphere

Foreground modeling:

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

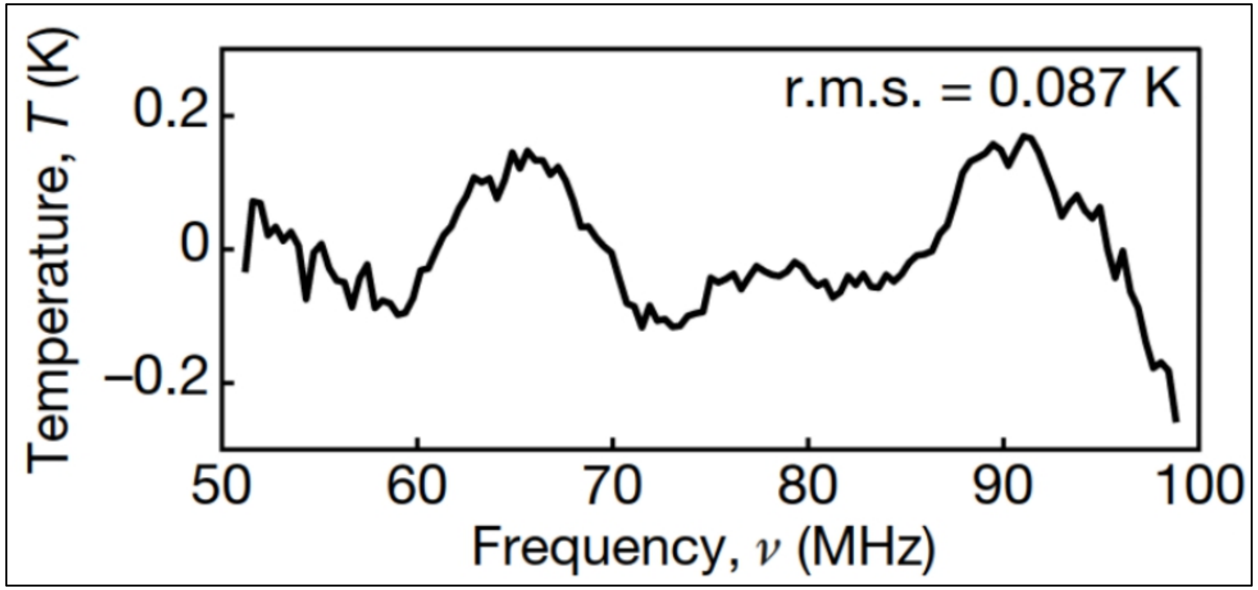
The five terms polynomial foreground model is physically motivated based on the known spectral properties of the Galactic synchrotron spectrum and Earth's ionosphere.

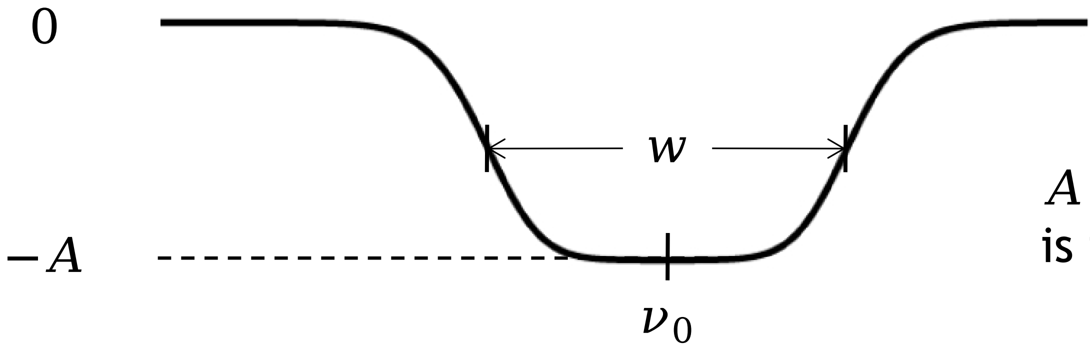
After foreground subtraction

Absorption profile modeling:

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

$$B = \frac{4(\nu-\nu_0)^2}{w^2}\log\left[-\frac{1}{\tau}\log\left(\frac{1+\mathrm{e}^{-\tau}}{2}\right)\right]$$

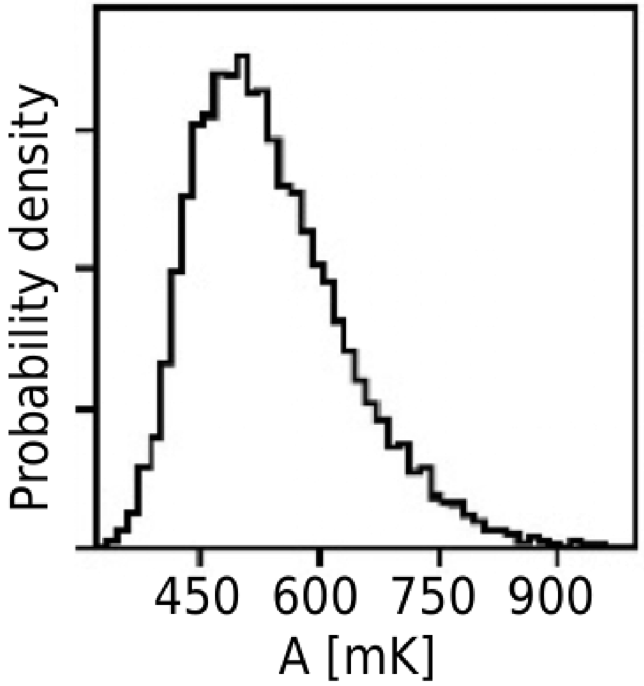


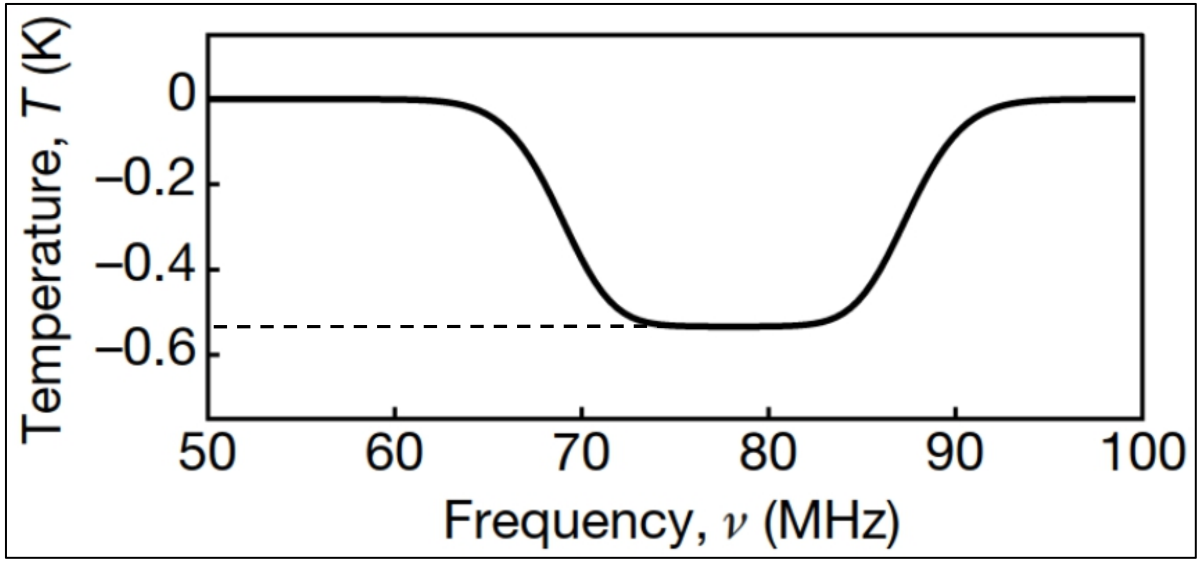


A is the absorption amplitude, ν_0 is the centre frequency, w is the full-width at half-maximum and τ is a flattening factor.

MCMC analysis result

The probability distribution of parameter A:

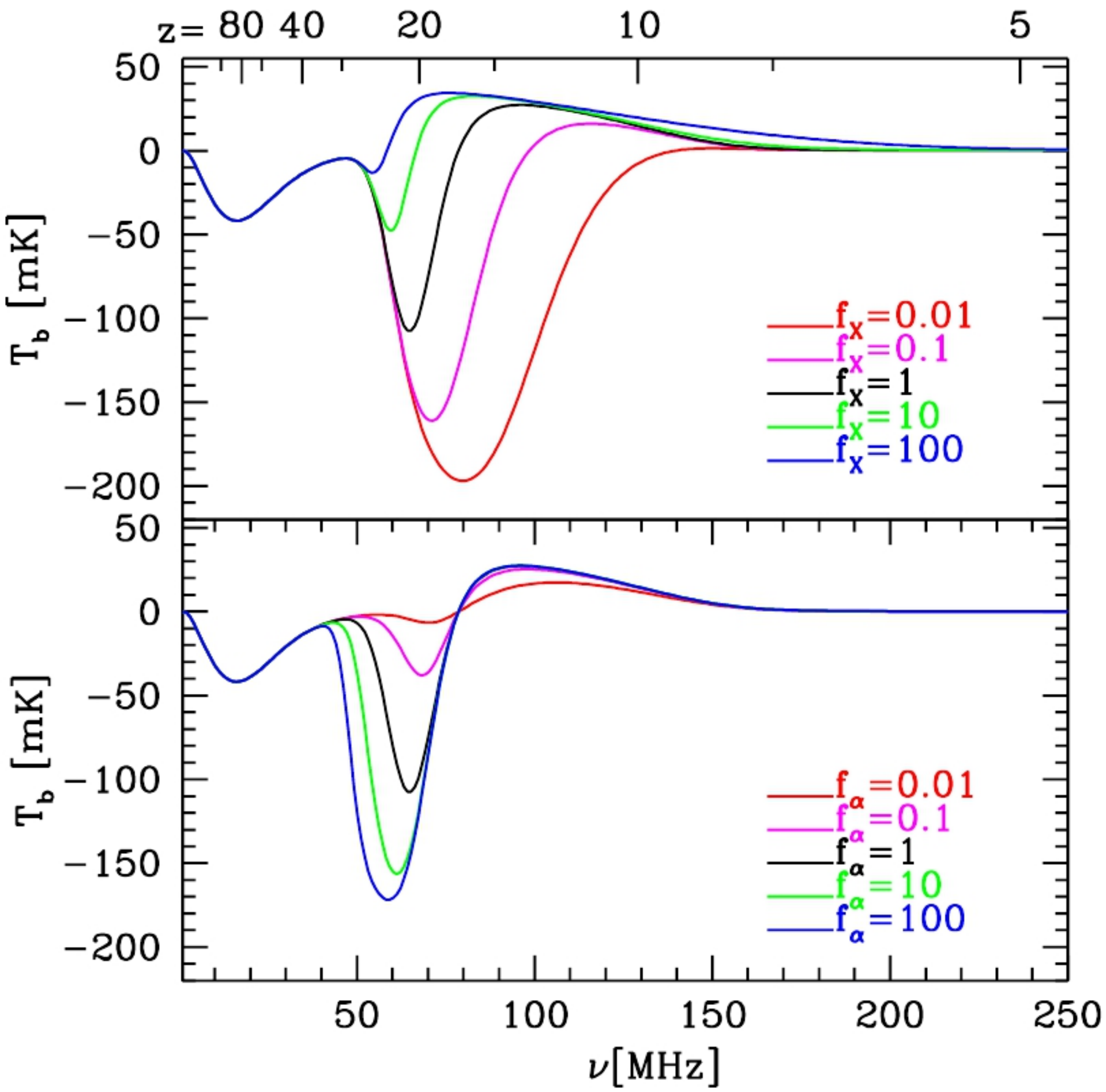




The best fit parameters for the absorption profile:

- ν_0 =78 ± 1 MHz (z ≈ 17)
- A ≈ 500 mK

Inconsistent with previous study



However, previous theoretical prediction gives 200 mK amplitude at most!

- There might be new physics.
- It is a false alarm.

SARAS 3 radio telescope

It contains:

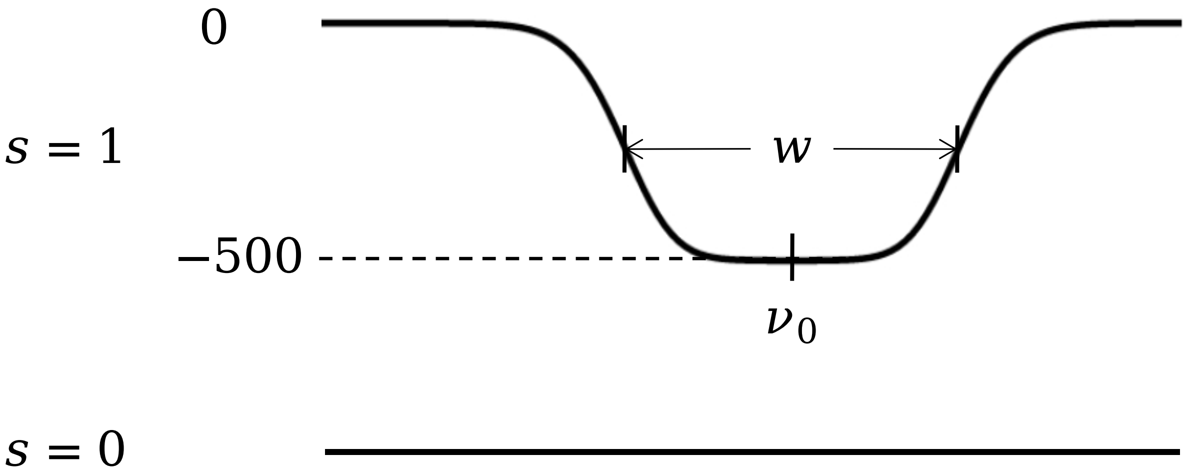
- A raft on water, to reduce (avoid) radio waves emitted by the ground beneath radio telescopes.
- Antenna...

Band: 3.75–87.5 MHz
Resolution: 61 kHz

Model foreground and absorbtion profile

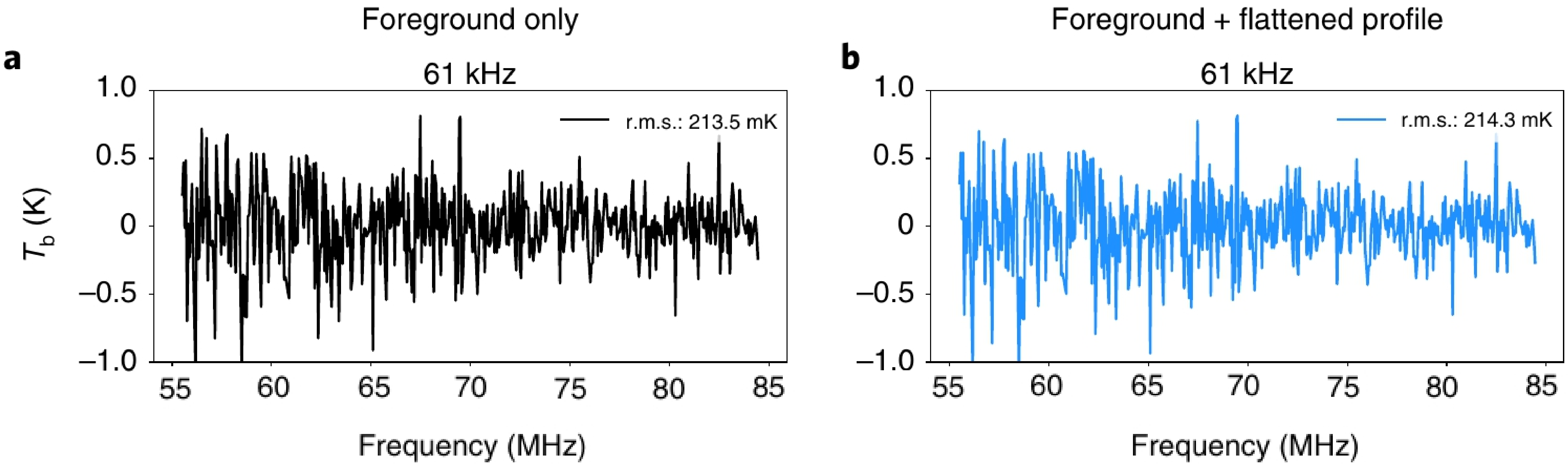
Modeling expression:

$$\log_{10}\{(T(\nu)/1\,\mathrm{K}) - s(T_{\mathrm{EDGES}}(\nu)/1\,\mathrm{K})\} = \sum_{i=0}^{i=6} a_i\,\Re(\log_{10}(\nu/1\,\mathrm{MHz}))^i$$



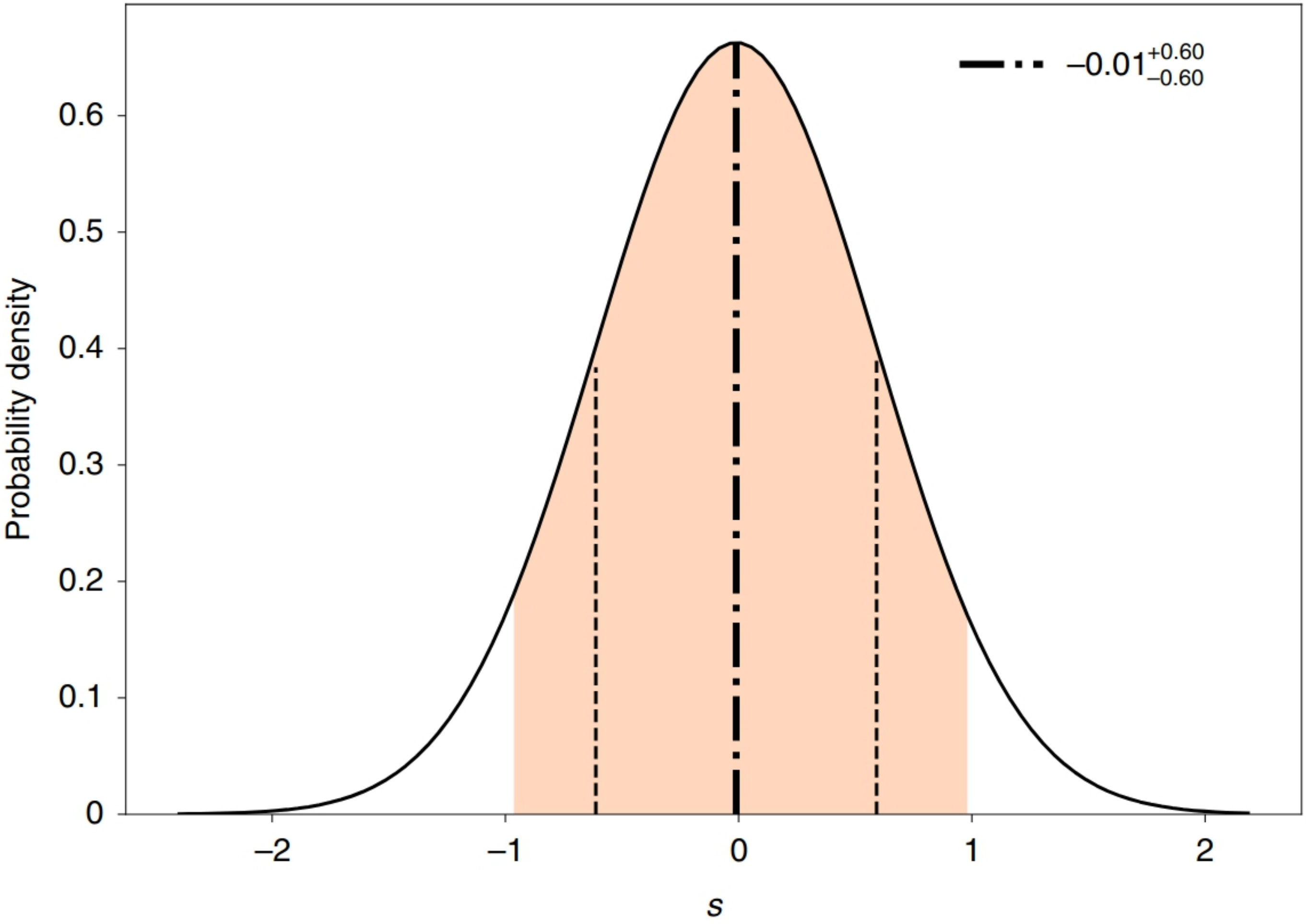
$T_{EDGES}(\nu)$ is the best-fitting profile that was found by EDGES and s is a multiplying scale factor for the profile. The $\Re$ operator linearly rescales values to be between −1 and +1. a_i are the coefficients of the sixth-order polynomial that models the foreground.

Foreground w/ & w/o flattened profile modeling



The outcome concluded by SARAS is opposite to EDGES!

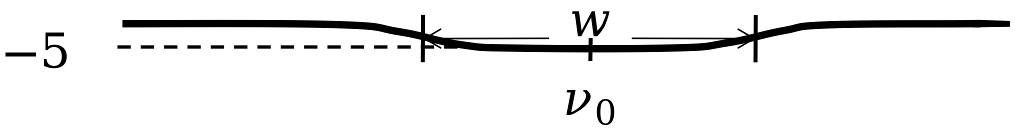
MCMC analysis result



The best fit parameters for the absorption profile:

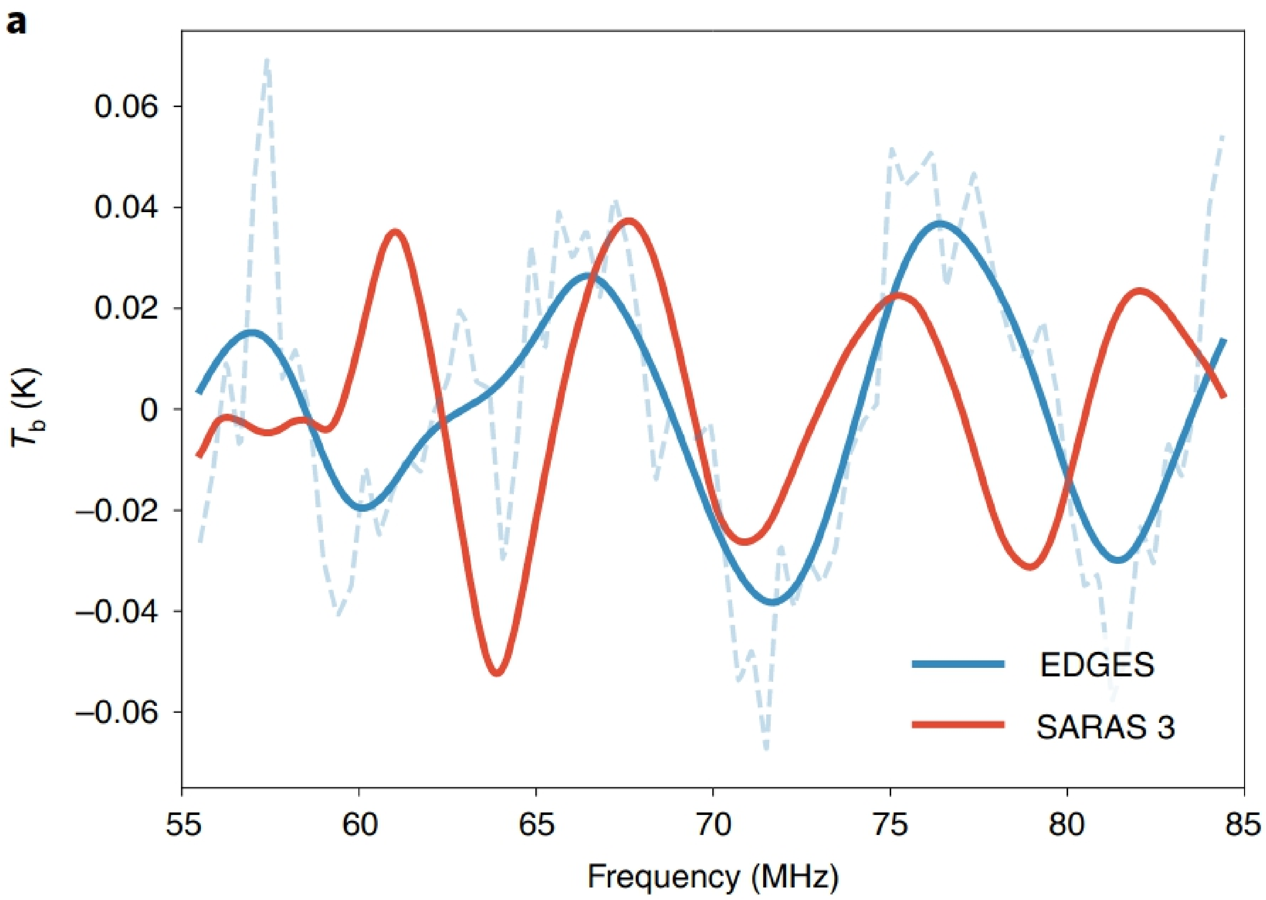
- $s \approx 0.01$

“The absorbtion profile found in EDGES is also in SARAS” is rejected (by 95.3%).



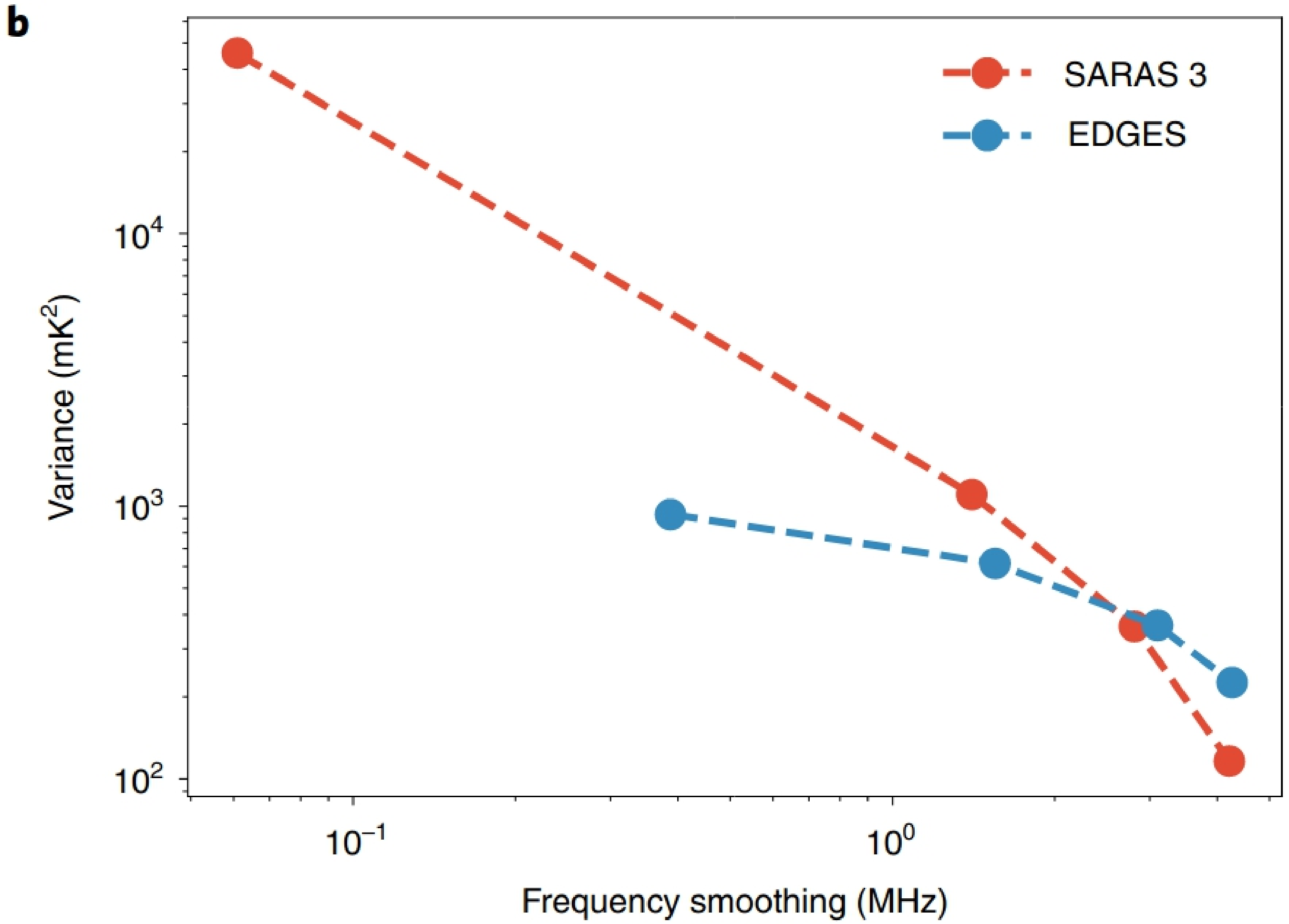
The outcome concluded by SARAS is opposite to EDGES!

Comparision on residuals from EDGES and SARAS



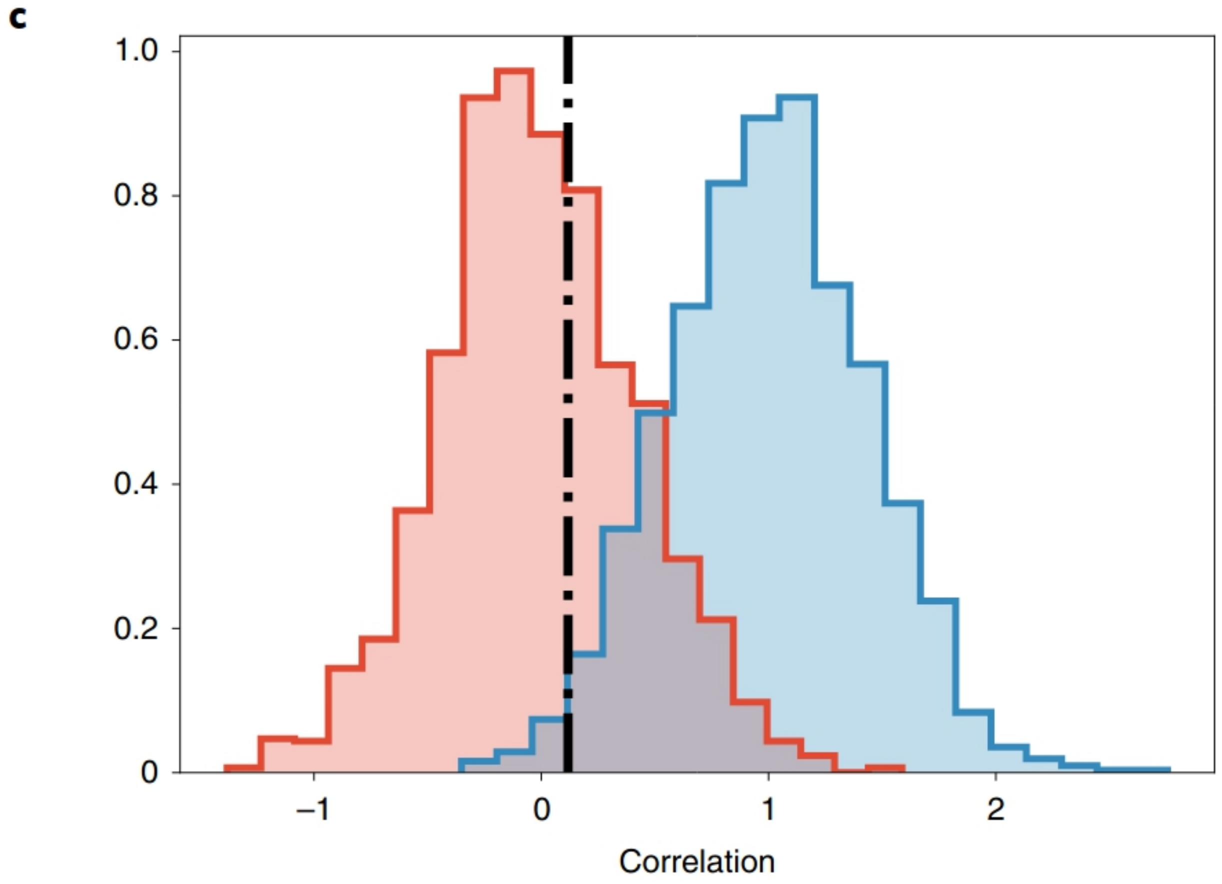
After substract all signals from the spectrum, the residual should be consistent with a Gaussian random noise.

Comparision on residuals from EDGES and SARAS



- Smooth the two spectrum to different length, the variance of EDGES spectrum decrease slower than SARAS 3 spectrum.
- The residual spectrum from the EDGES instrument has a distortion feature.

Comparision on residuals from EDGES and SARAS



Calculate the correlation:

$$\zeta = \frac{\mathbb{E}[SE]}{\mathbb{E}[E^2]}$$

S —— SARAS spectrum, E —— EDGES spectrum.

Simulations:

- Blue color is the correlation values between SARAS mock data w/o distortion & EDGES data
- Red color is the correlation values between SARAS mock data w/ distortion & EDGES data

Results:

- Smooth the two spectrum to different length, the variance of EDGES spectrum decrease slower than SARAS 3 spectrum.

The distortions in the EDGES spectrum are not present in the SARAS 3 spectrum.

But still we are not 100% percent confident to rule out EDGES experiments

Summary

- Two groups have done experiments to detect the 21 cm absorbtion line in the cosmic dawn.
- However, their results are not consistent.
- Currently, there is still no solid conclusions on whether the absorbtion line exists.

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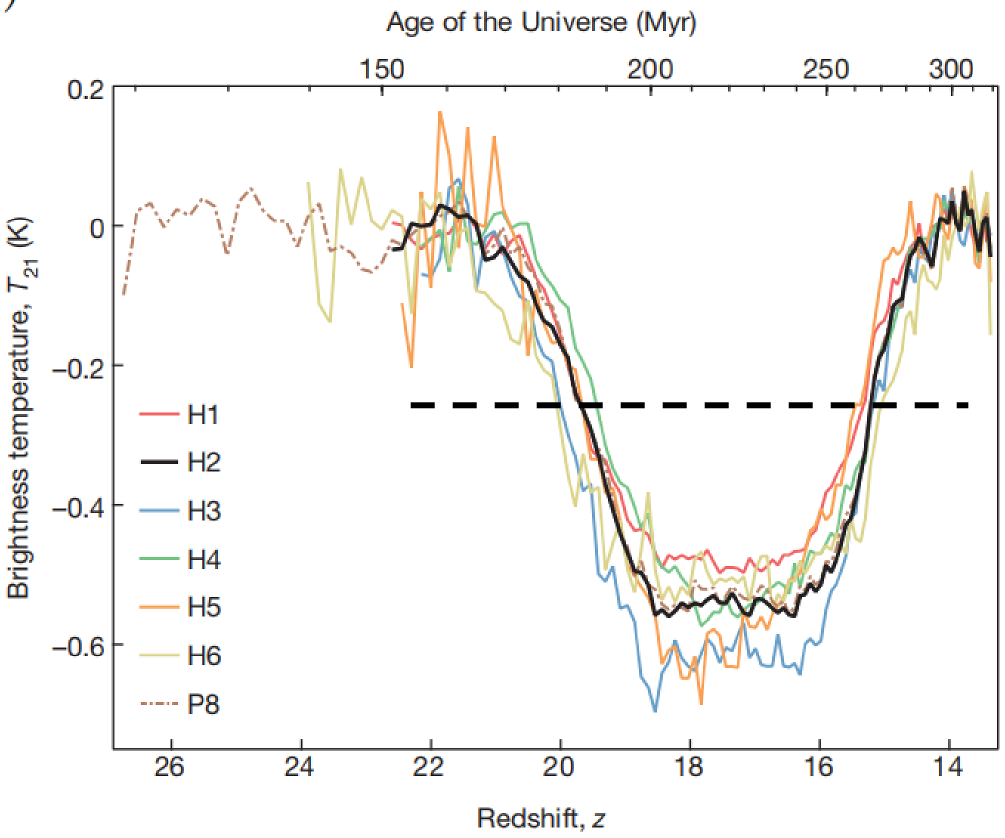
Possible Reasons

$$T_{21} = 26.8 x_{\mathrm{HI}} \frac{\rho_g}{\bar{\rho}_g} \left(\frac{\Omega_b h}{0.0327} \right) \left(\frac{\Omega_m}{0.307} \right)^{-1/2} \left(\frac{1+z}{10} \right)^{1/2} \left(\frac{T_S - T_{\mathrm{CMB}}}{T_S} \right)$$

T_s: spin temperature of hydrogen at z

T_{CMB} = background temperature T_{bkg}



T_{21} lower than expected ⇒ lower T_s

higher T_{bkg}

⇒ Interact with something colder: Dark Matter

Bowman+ 2018, Barkana+ 2018

Baryon-Dark Matter Scattering

Cross section of a Coulomb-like force:

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

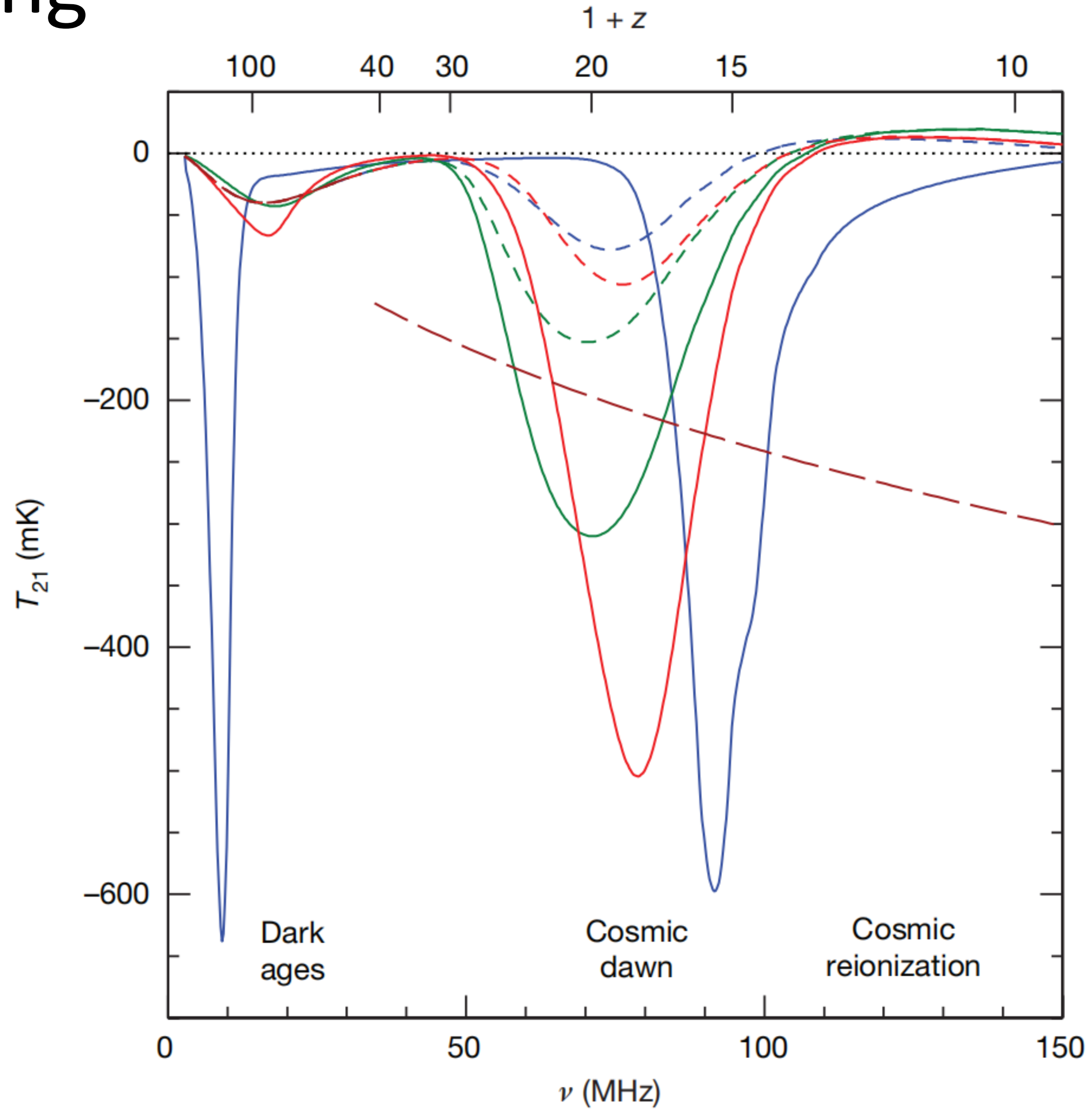
Largest at cosmic dawn

Green: $\sigma_1 = 3 \times 10^{-19}\ \mathrm{cm}^2, m_\chi = 2\ \mathrm{GeV}$

Red: $\sigma_1 = 8 \times 10^{-20}\ \mathrm{cm}^2, m_\chi = 0.3\ \mathrm{GeV}$

Blue: $\sigma_1 = 1 \times 10^{-18}\ \mathrm{cm}^2, m_\chi = 0.01\ \mathrm{GeV}$

Dashed: without Baryon-Dark Matter Scattering



Barkana+ 2018

Constrain the Properties of Dark Matter

Solid lines (at z = 17) (from left to right):

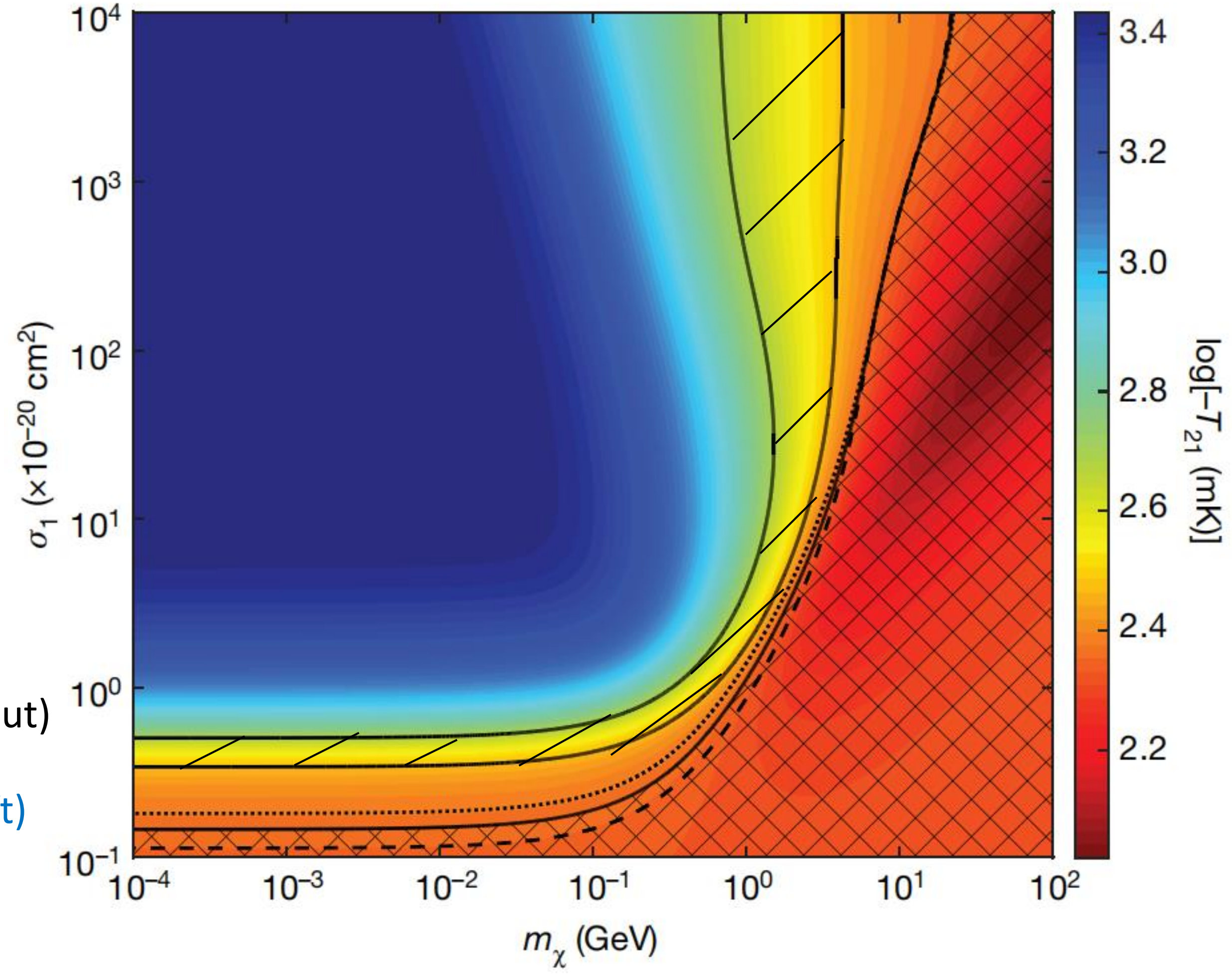
- \- 500 mK (observed depth)
- \- 300 mK (99% confidence level)
- \- 231 mK (10% lower than - 210 mK)

Dashed: z = 14, Dotted: z = 20

$m_\chi < 4.3\ \mathrm{GeV} \ll \sim 100\ \mathrm{GeV}$ (WIMP)

$\sigma_1 > 3.4 \times 10^{-21}\ \mathrm{cm}^2$?

- A new mediator particle (the 5th force) (ruled out)
- Millicharged dark matter (little parameter space left)



Barkana+ 2018

Constraints on the Millicharged Dark Matter:

1. CMB: Kinematic Decoupling

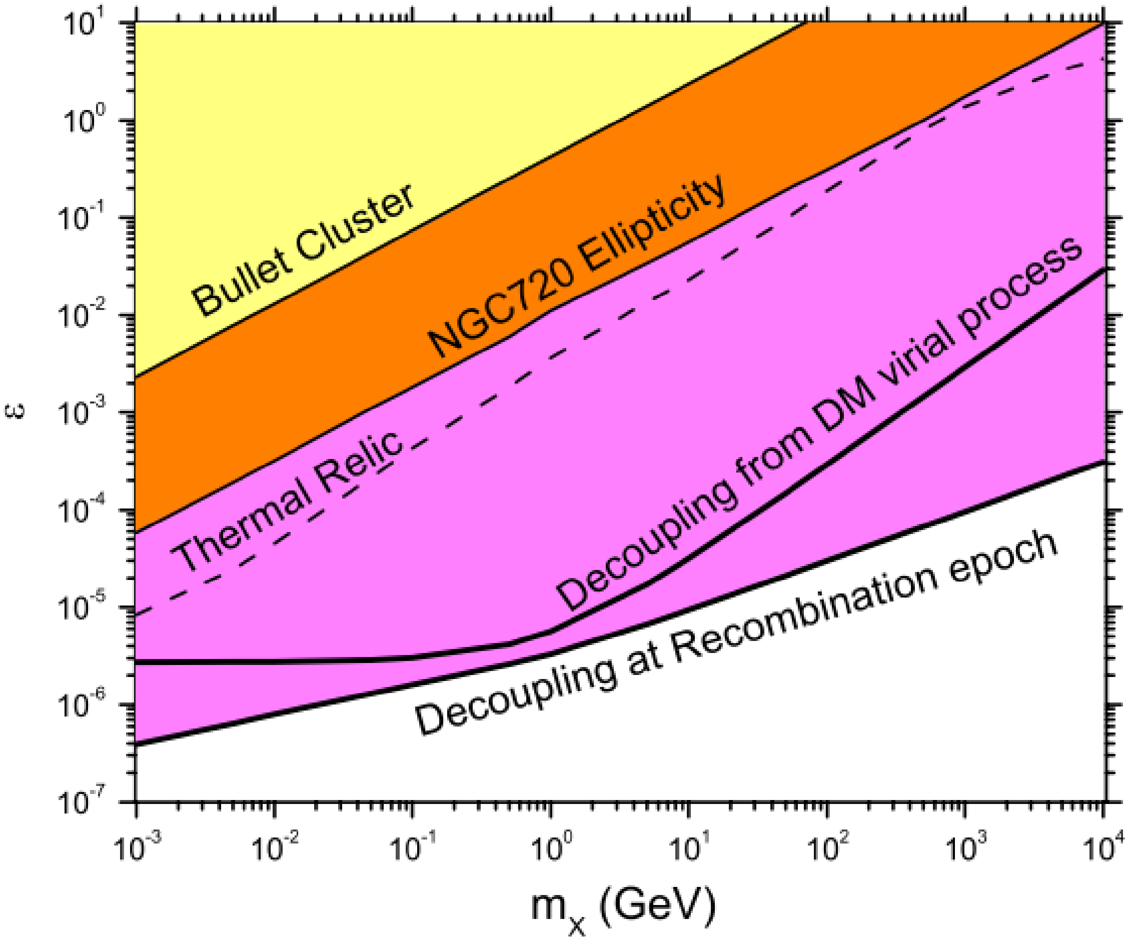
Momentum transfer rate:

$$\Gamma_p = \sum_{B=e,p} \frac{8\sqrt{2\pi} n_b \alpha_{\rm em}^2 \epsilon^2 \mu_b^{1/2}}{3 m_X T^{3/2}} \ln\left[\frac{3T\lambda_D}{\epsilon\alpha_{\rm em}}\right].$$

Constraint: Dark matter should not be coupled with photon-baryon at recombination epoch

Relaxation time > Hubble time at z = 17

$$\Gamma_p^{-1}(T_R) > t_R,$$



McDermott+ 2011

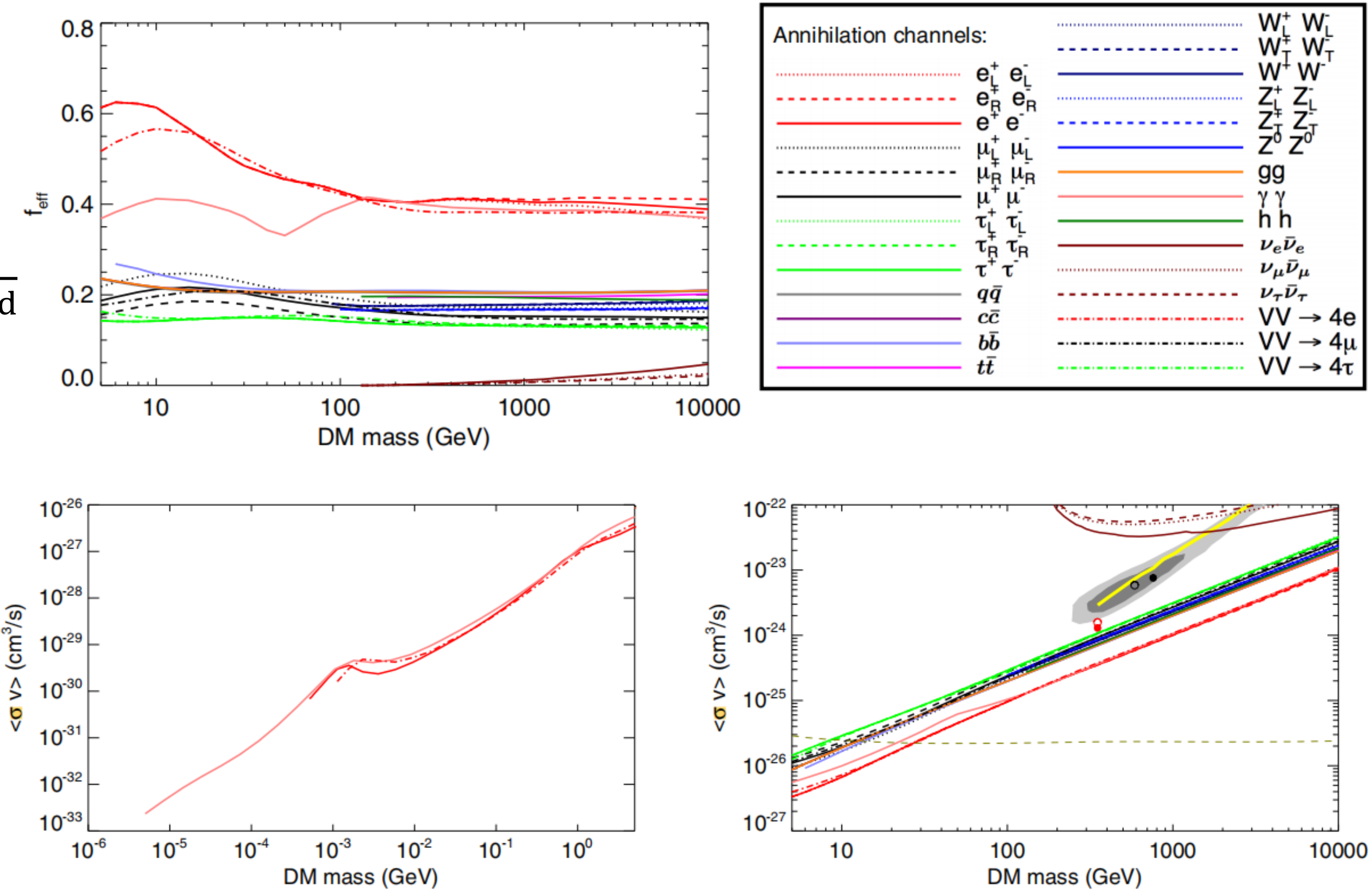
Constraints on the Millicharged Dark Matter:

2. CMB: Annihilation of Dark Matter

Efficiency factor:

$$f_{\mathrm{eff}} = \frac{\text{power deposited to gas}}{\text{annihilation power injected}}$$

Annihilation with different mass and cross sections will have different f_{eff}



Slatyer+ 2016

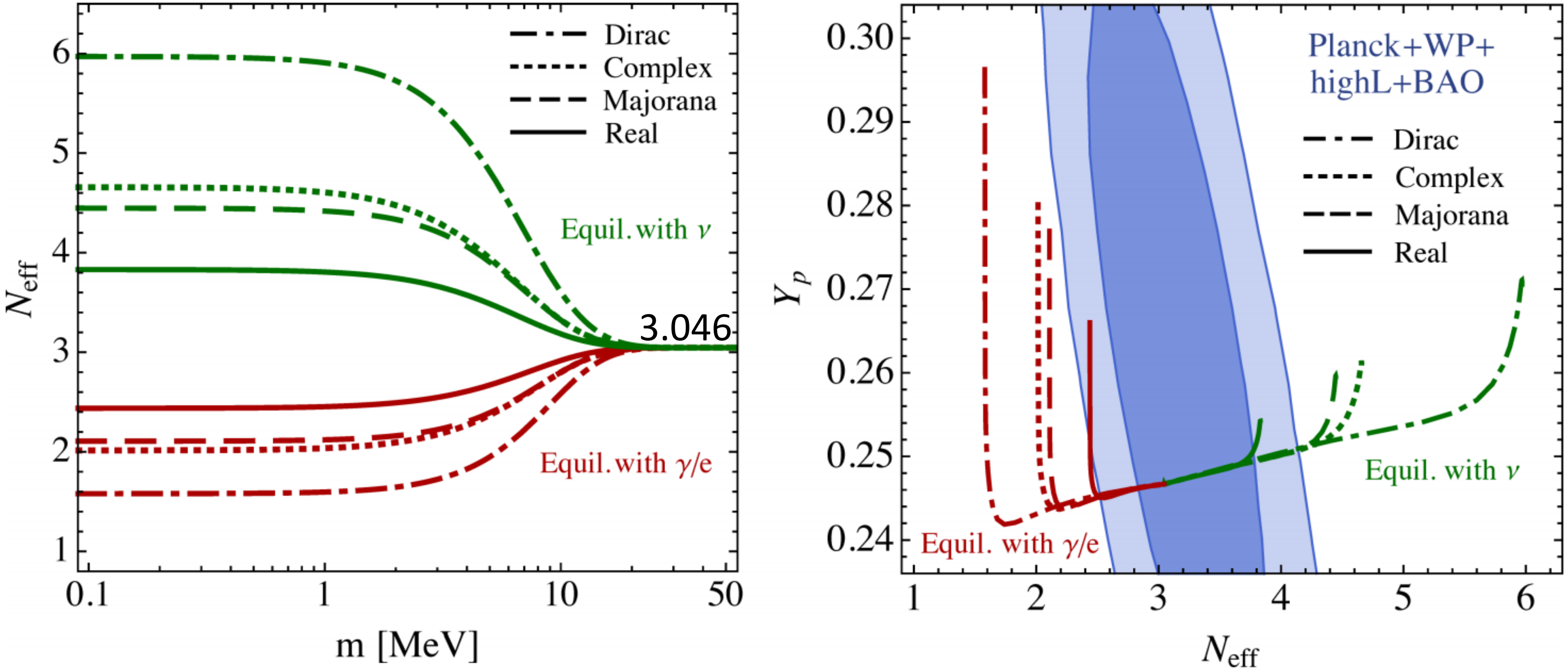
Constraints on the Millicharged Dark Matter:

3. Big Bang Neucleosynthesis

When DM become non-relativistic and decouple,

it will change the effective number of neutrinos

$$N_{\rm eff} = \left(\frac{4}{11}\right)^{-4/3}\left(\frac{T_\nu}{T_\gamma}\right)^4\left[N_\nu + \sum_{i=1}^{n}\frac{g_i}{2}I\left(\frac{m_i}{T_\nu}\right)\right]$$



Boehm+ 2013

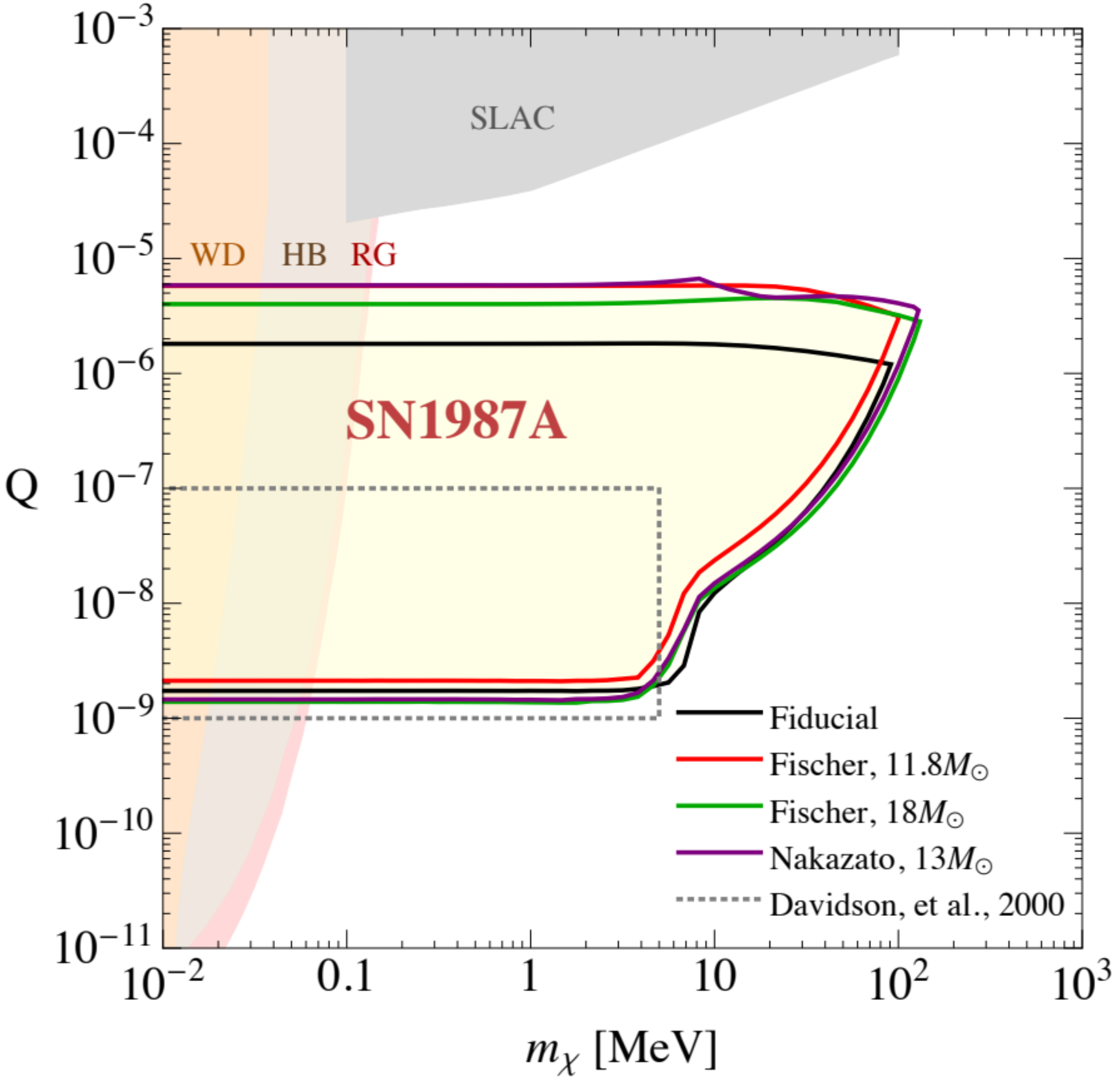
Constraints on the Millicharged Dark Matter:

4. Supernova 1987A

Baryon-dark matter scattering:

- an additional efficient channel of energy flow
- shorter cooling time of the supernova

$$\langle Q/\rho \rangle \lesssim 10^{19}\ \mathrm{erg\ g^{-1}\ s^{-1}},$$

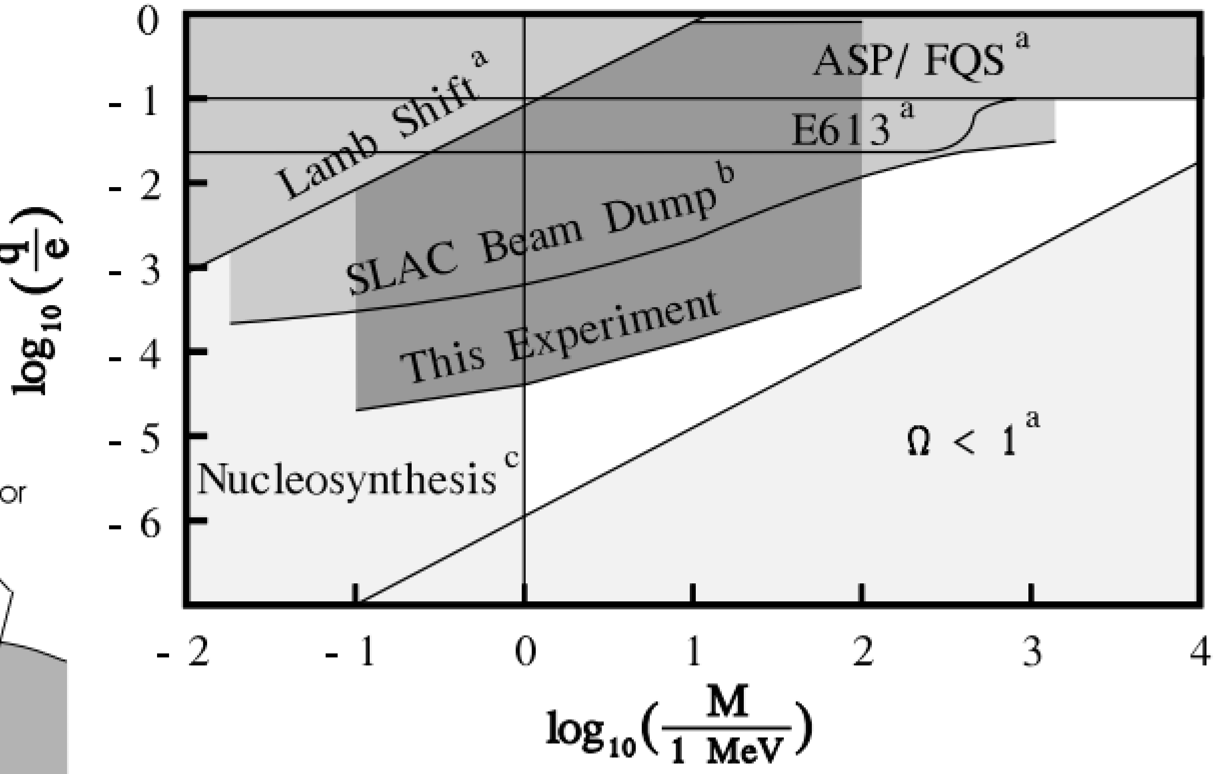


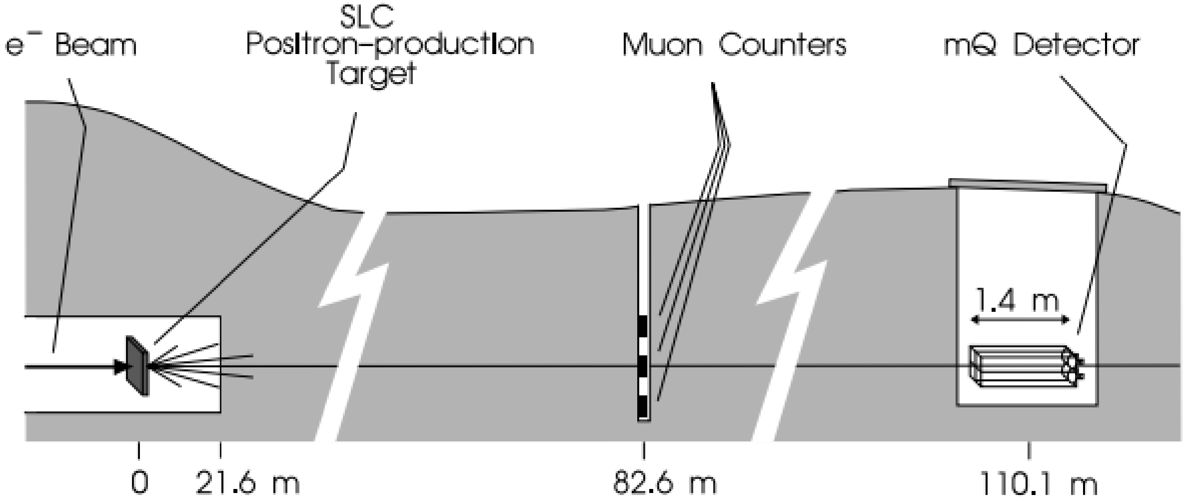
Davidson+ 2000, Chang+ 2018

Constraints on the Millicharged Dark Matter:

5. The SLAC Experiment

- Positron production
- Ordinary charged particles (including muons) are ranged out in less than 90 m.





Prinz+ 1998

Summary

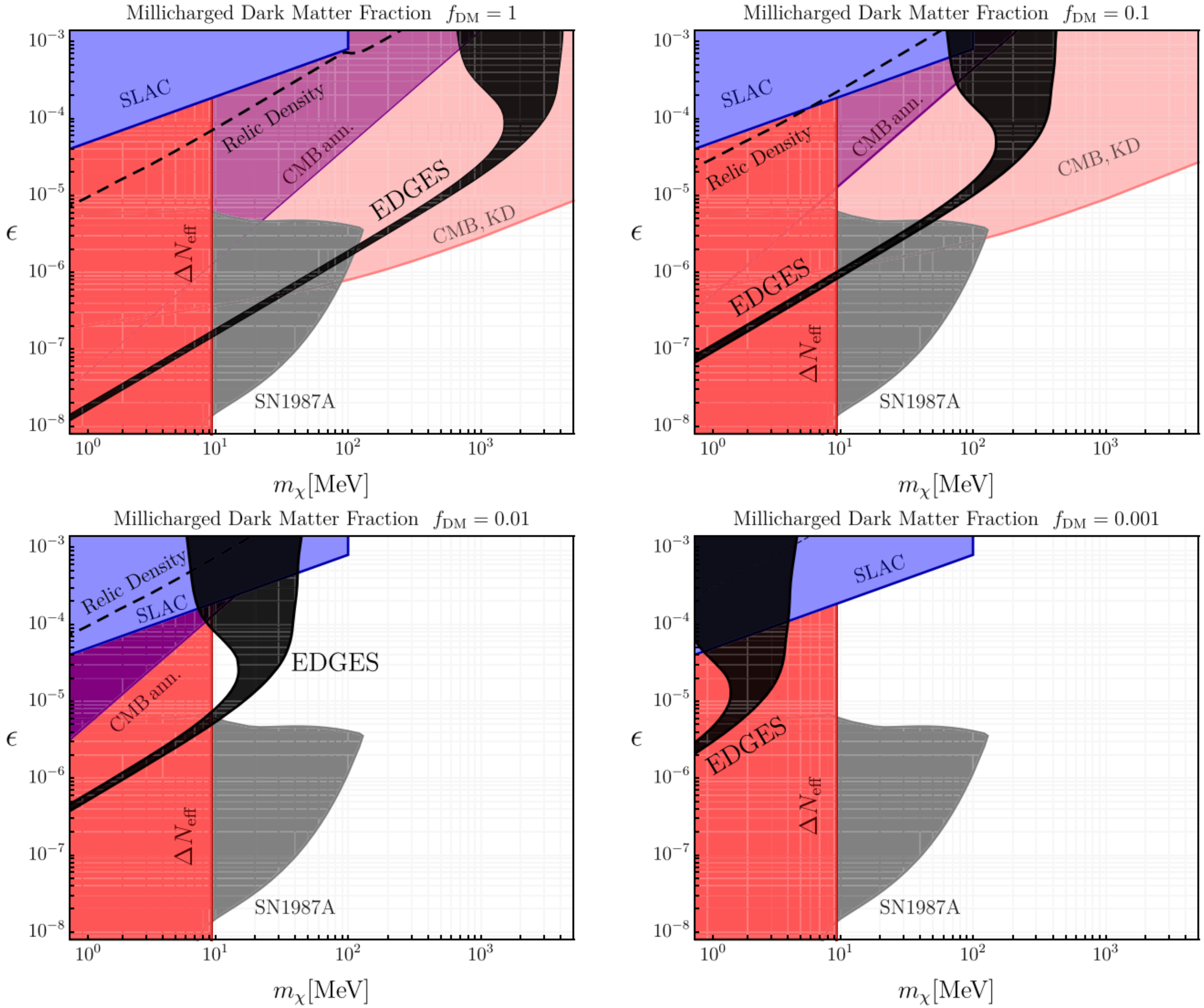
$f_{\rm DM}$: $\sim 0.3\% - 2\%$

m_χ: $10 - 80$ MeV

e_χ/e: $10^{-6} - 10^{-4}$

Future experiments:

M^3 Phase1, NA64μ, M^3 Phase2



Berlin+ 2018

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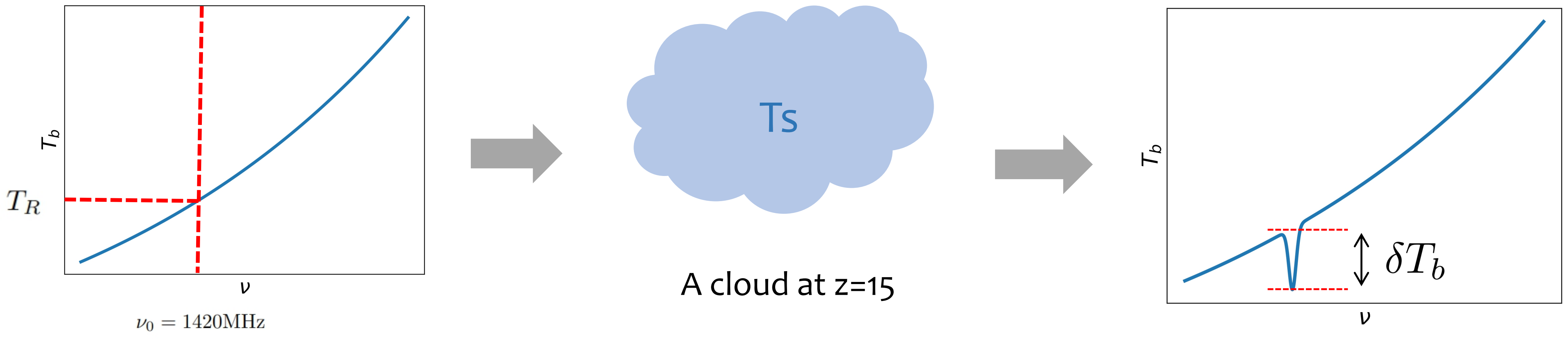
Excess radiation at cosmic dawn

Feng & Holder 2018

Fialkov & Barkana 2019

Physical picture of 21cm adsorption



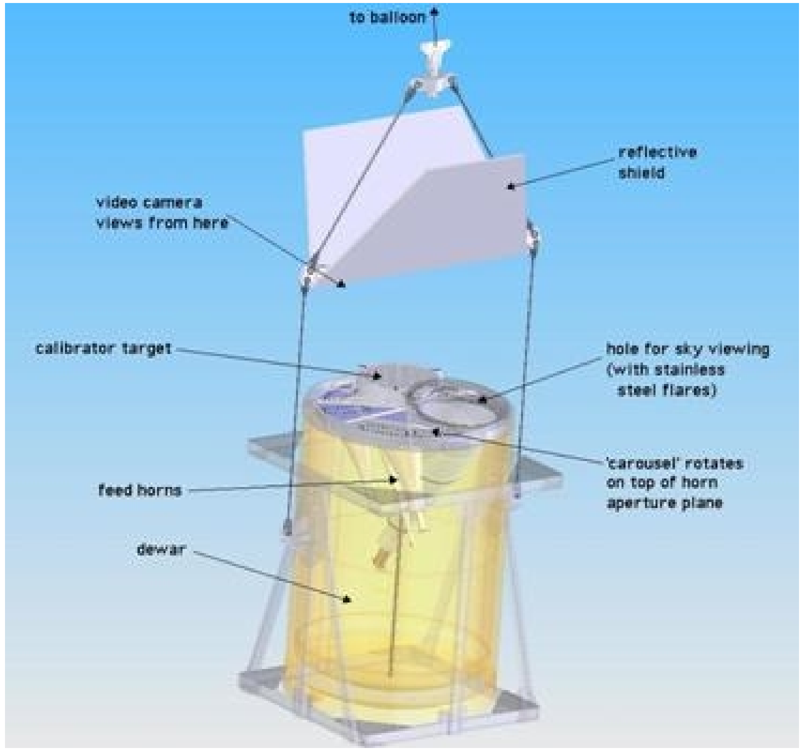
A cloud at z=15

Effect1: Larger Tr

$$\delta T_b = 27 x_{\rm HI}\left(1 - \frac{T_r}{T_{\rm s}}\right)\sqrt{\frac{1+z}{10}\frac{0.15}{\Omega_m h^2}}\left(\frac{\Omega_b h^2}{0.023}\right)(\text{mK})$$

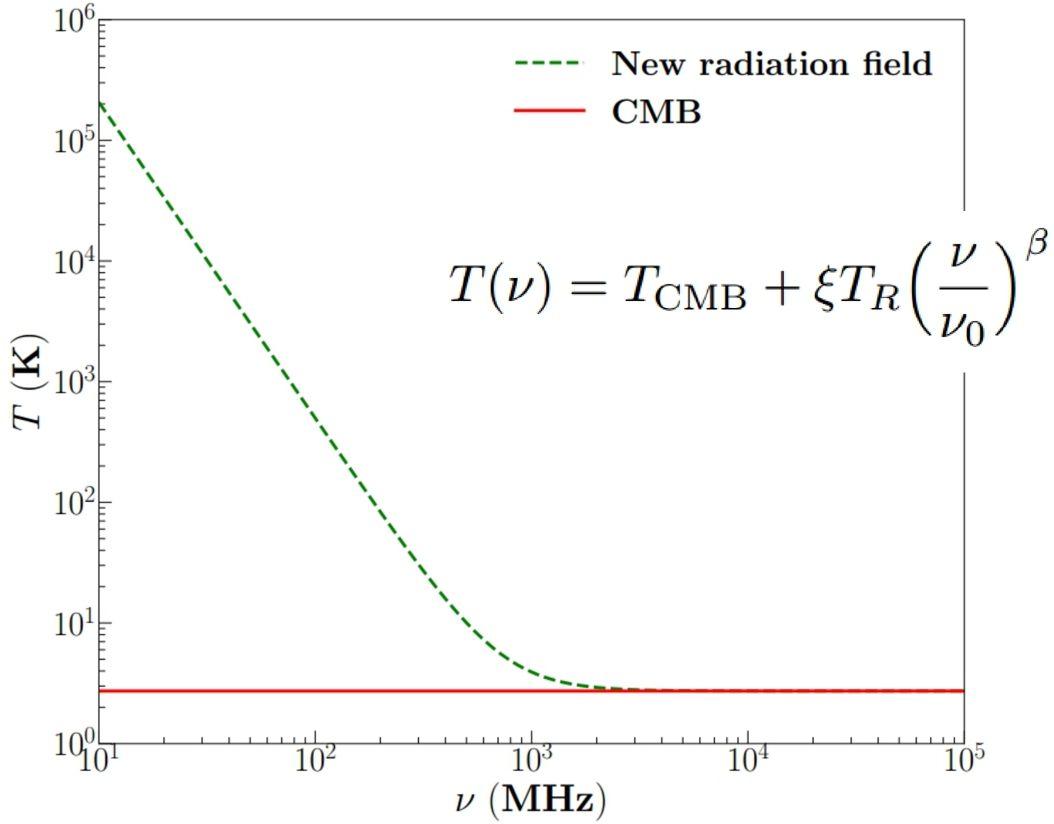
Effect2: change Ts

Radio excess ~100MHz 🤔



ARCADE 2 instrument

Maybe part of it comes from early universe?

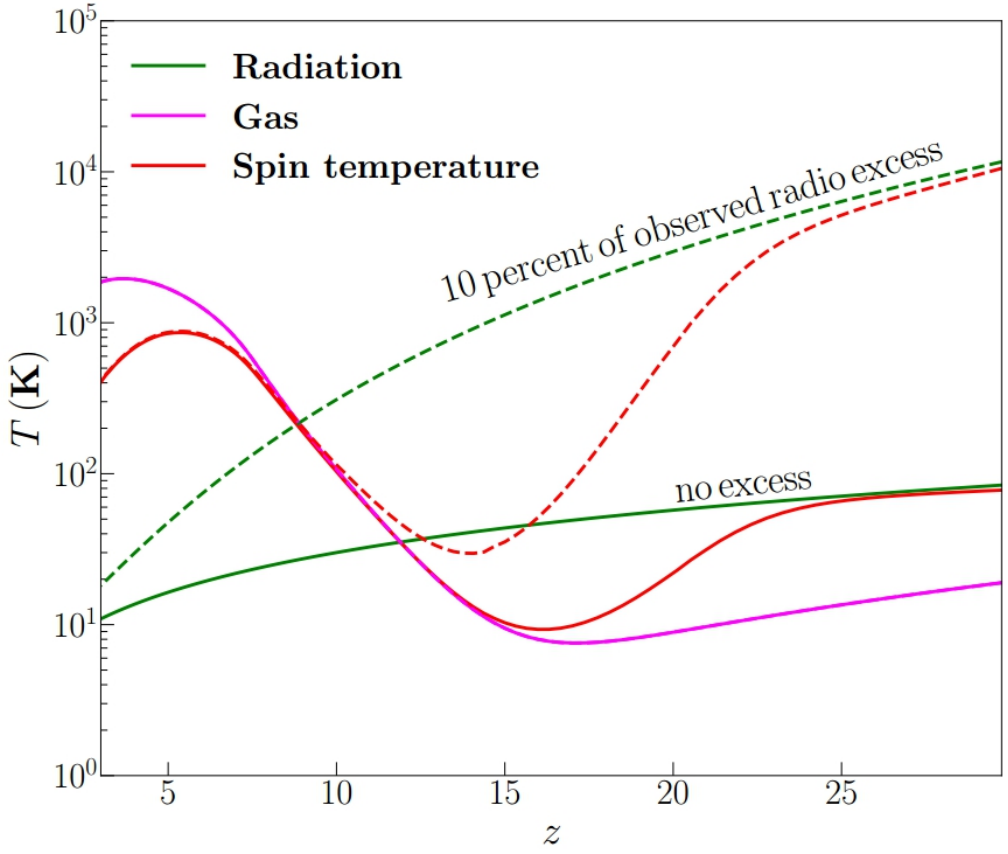


$$T(\nu) = T_{\mathrm{CMB}} + \xi T_R \left(\frac{\nu}{\nu_0}\right)^{\beta}$$

Detected radio excess by ARCADE 2

Coupling between Ts, Tr, TK

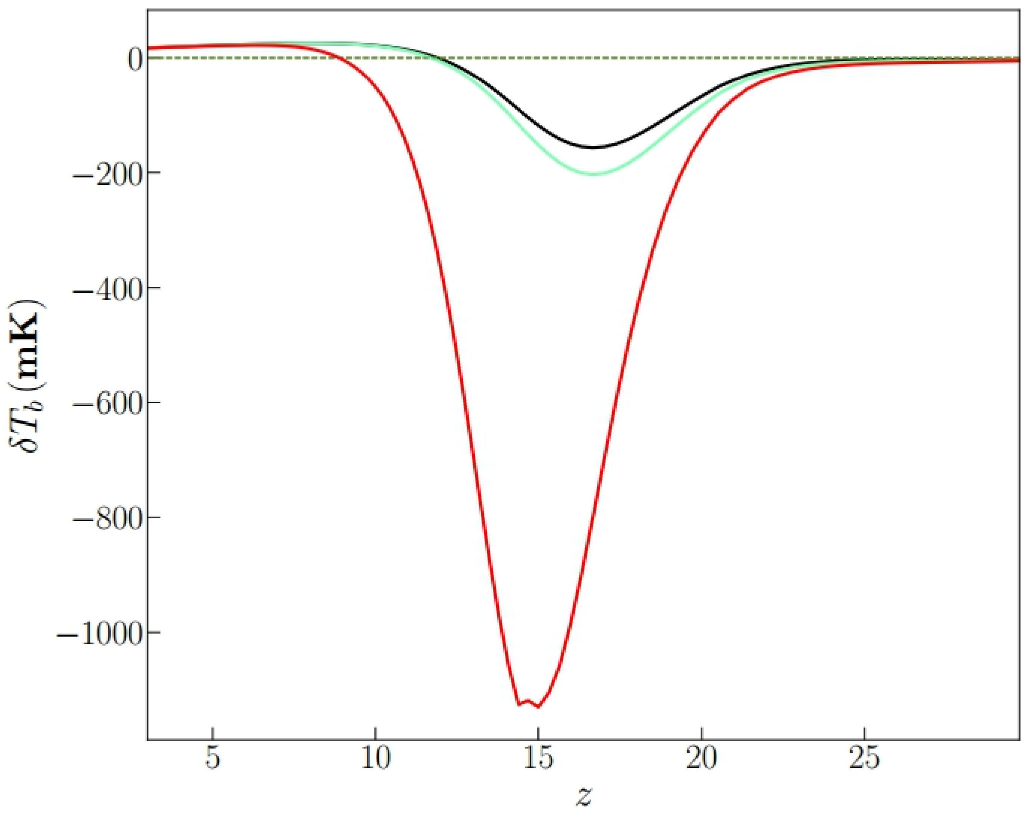
$$T_s^{-1} = \frac{T_r^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

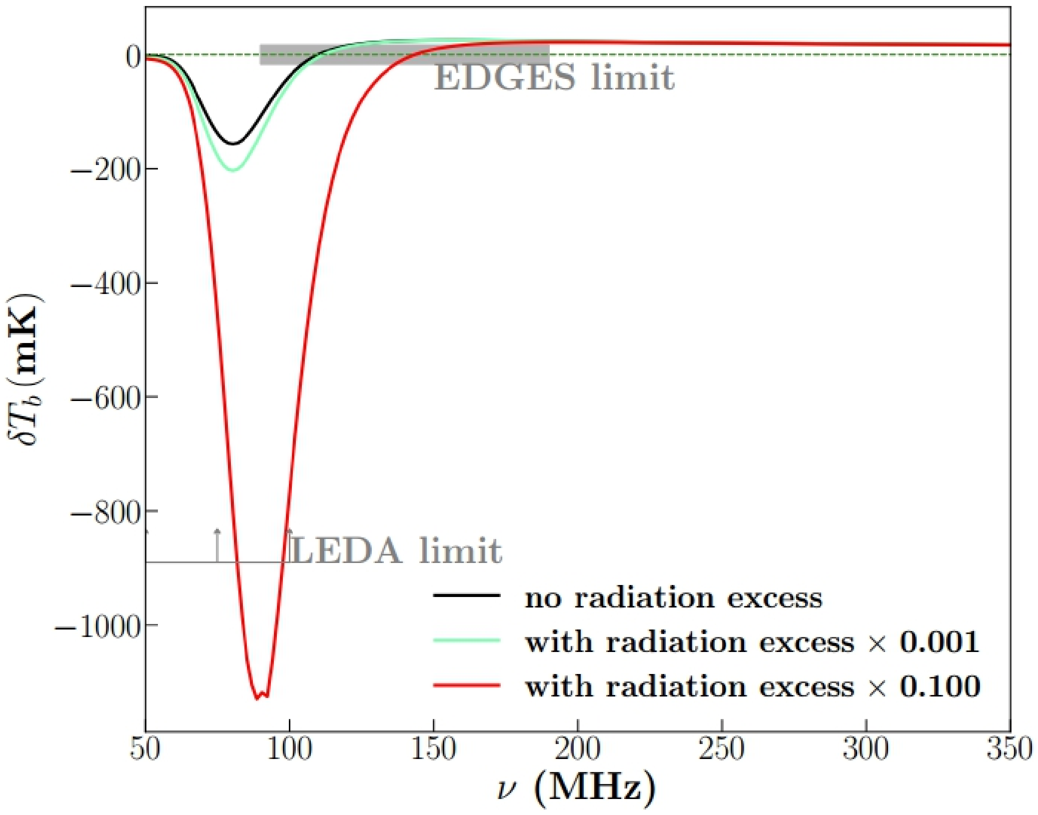


With gas:
1. WFE: xa
Wouthuysen-Field effect
2. Collision: xc

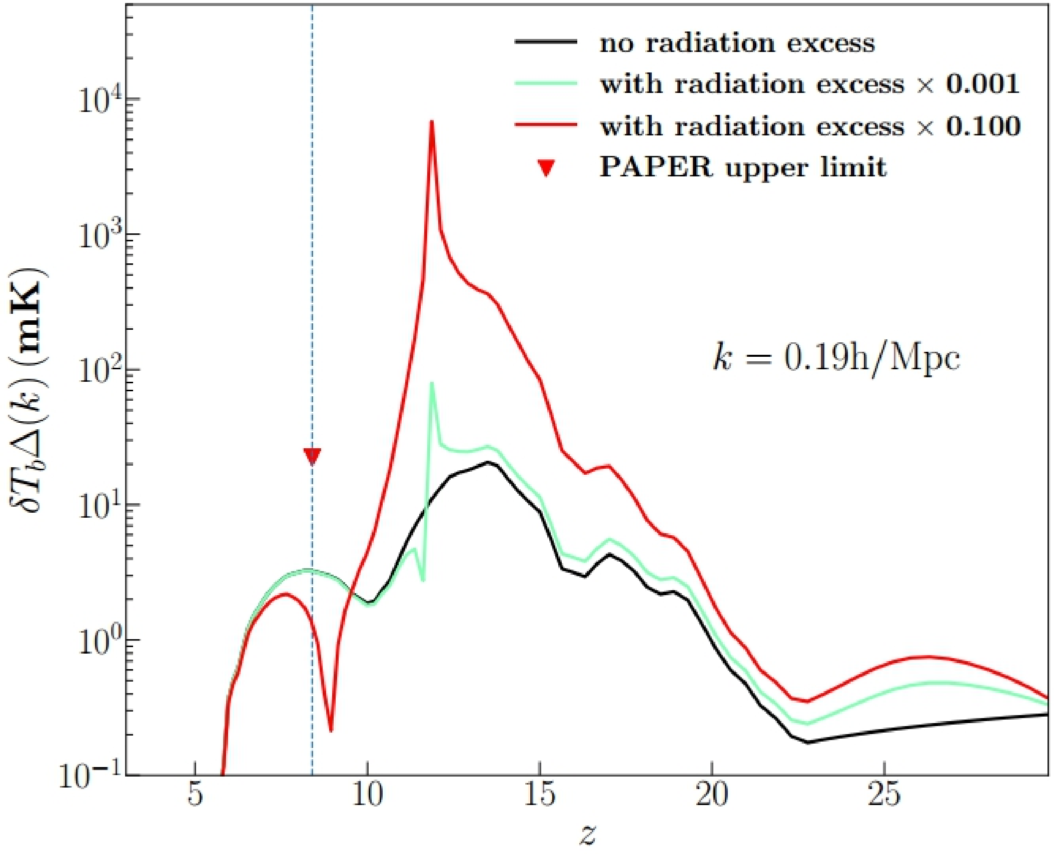
xa, xc is related with Tr

21cm adsorption feature





21cm fluctuations



Prospect:
Radio array (interferometers): fluctuations
HERA: the Hydrogen Epoch of Reionization Array
LWA: Long Wavelength Array (Expanding)
SKA: Square Kilometre Array

Defect of this explanation:

Still naive (e.g. modelling of the radio excess source)

Summary

- 21cm signal (both adsorption, emission) traces HI distribution and contains rich information about early universe.
- Recent attempt to detect global signal between z=~13-22 shows a stronger adsorption feature than expectation, which requires explanation.
    - Observation: False detection?
    - Theory:
        - Dark matter cooling?
        - Early radio excess beyond CMB?
    - Still under debate
- Future observation (e.g. HERA, SKA) may help to answer.