宇宙論的観測で探る再電離

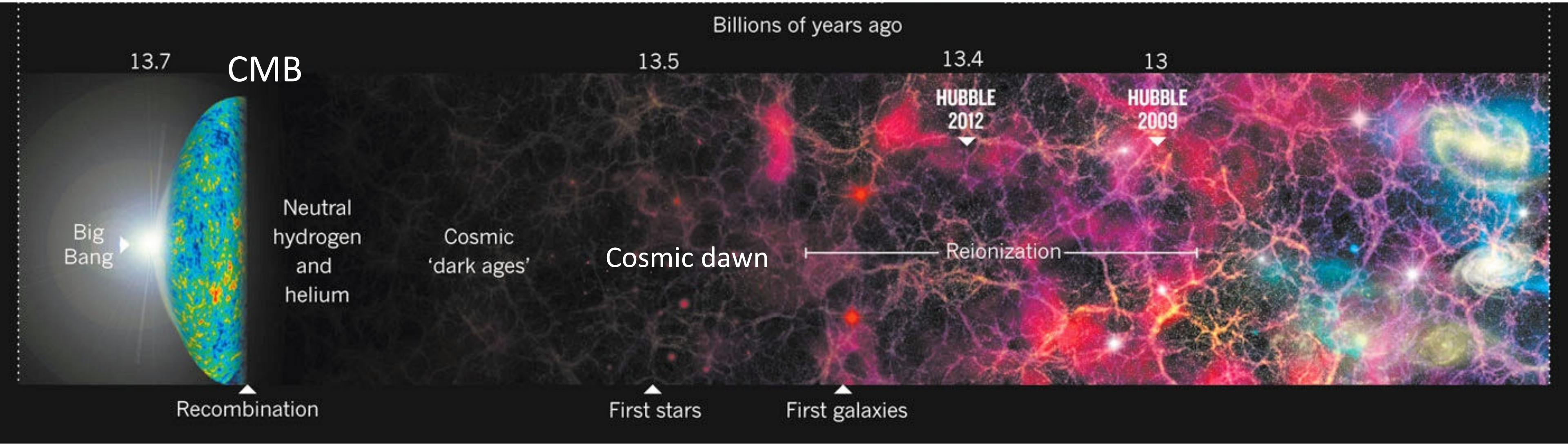
The history of baryonic component around the Epoch of Reionization

TASHIRO, Hiroyuki
（Nagoya Univ.）

初代星・初代銀河研究会2019 @名古屋大

Epoch of Reionization (EoR)

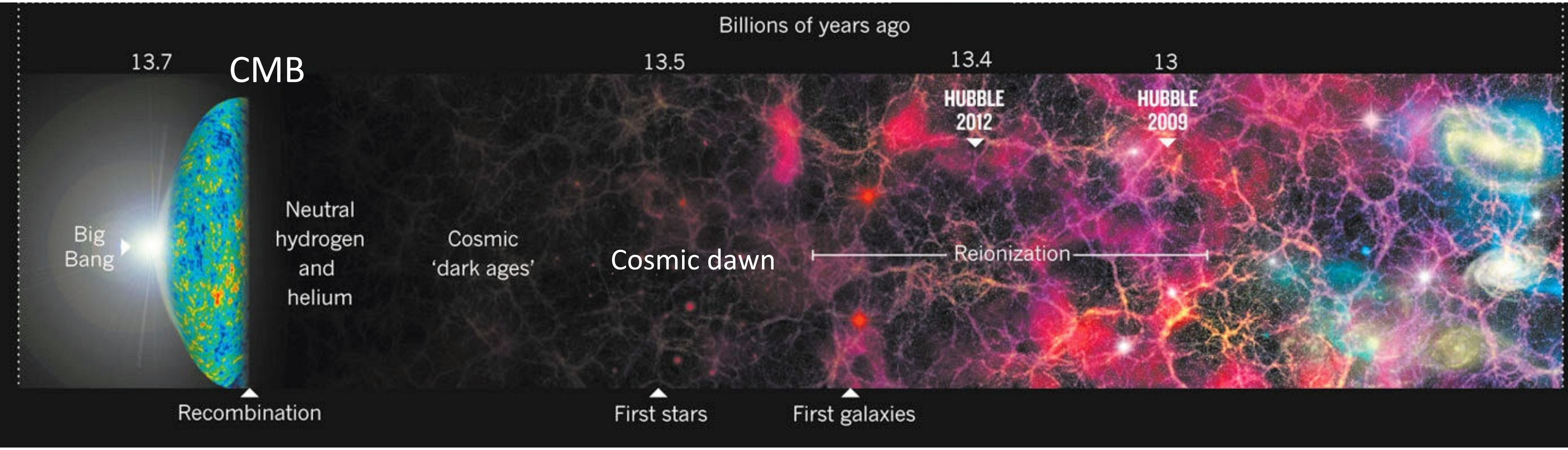
From Nature (Ncik Spenser)



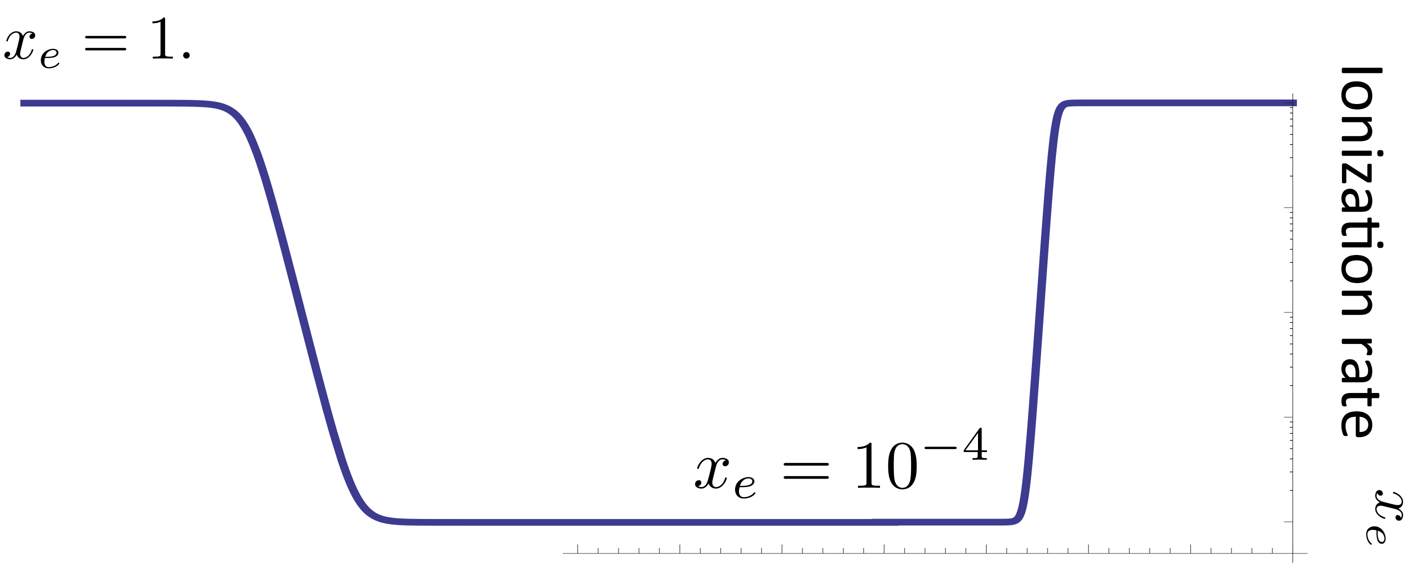
$z \sim 1000$ $z \sim 100$ $z \sim 10$ redshift

Epoch of Reionization (EoR)

From Nature (Ncik Spenser)

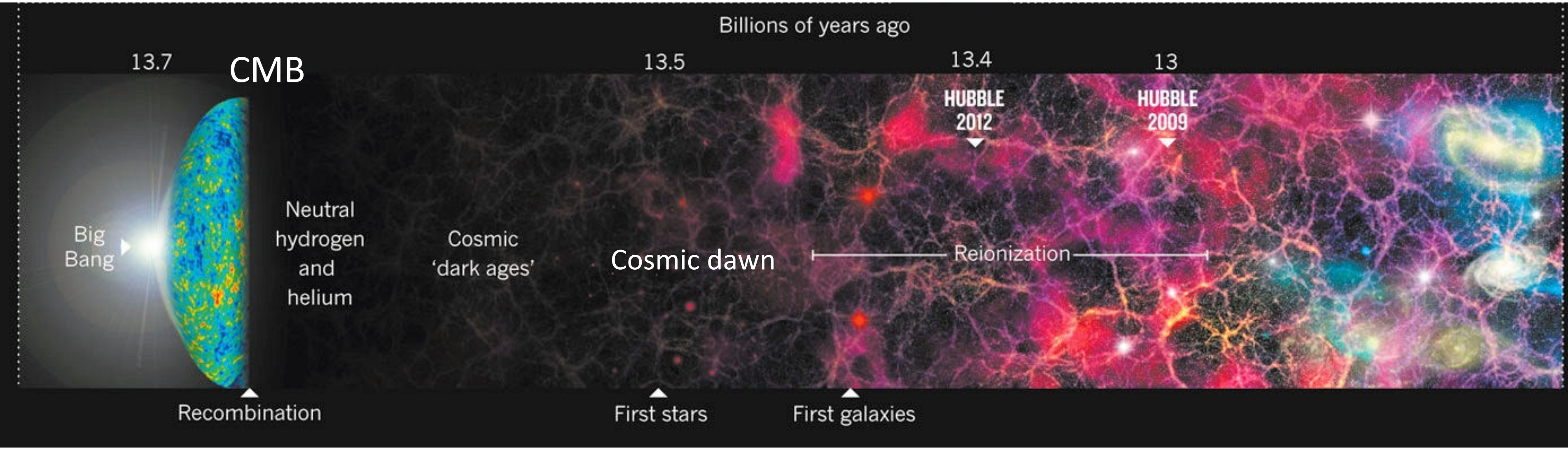


$z \sim 1000$ $z \sim 100$ $z \sim 10$ redshift

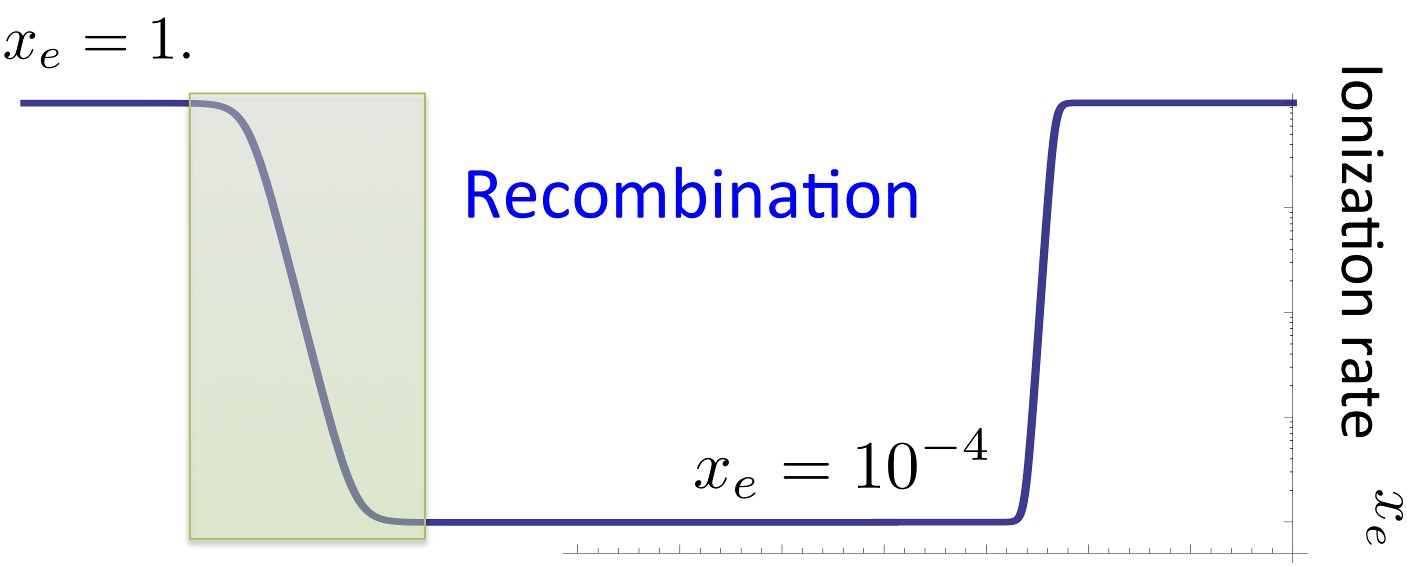


Epoch of Reionization (EoR)

From Nature (Ncik Spenser)

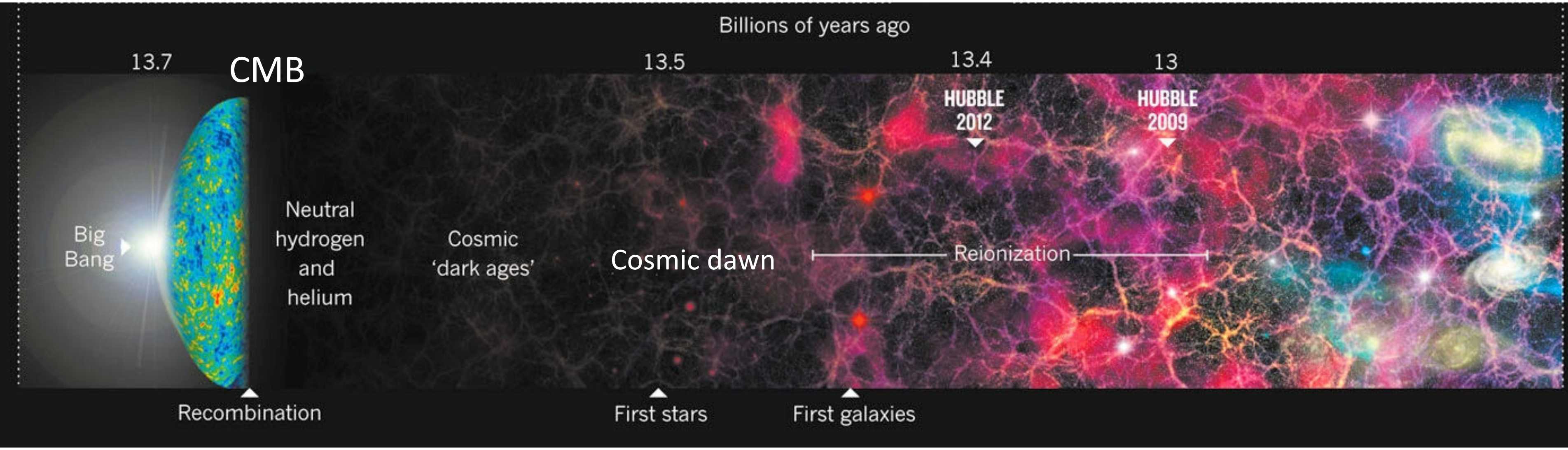


$z \sim 1000$ $z \sim 100$ $z \sim 10$ redshift

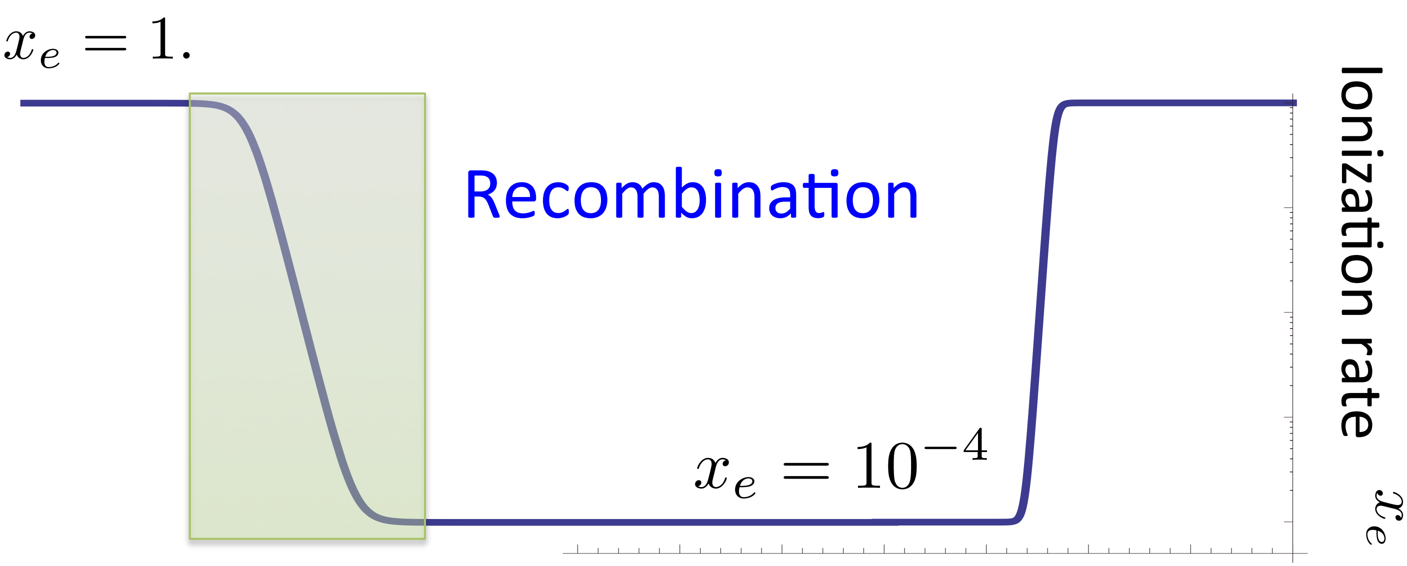


Epoch of Reionization (EoR)

From Nature (Ncik Spenser)

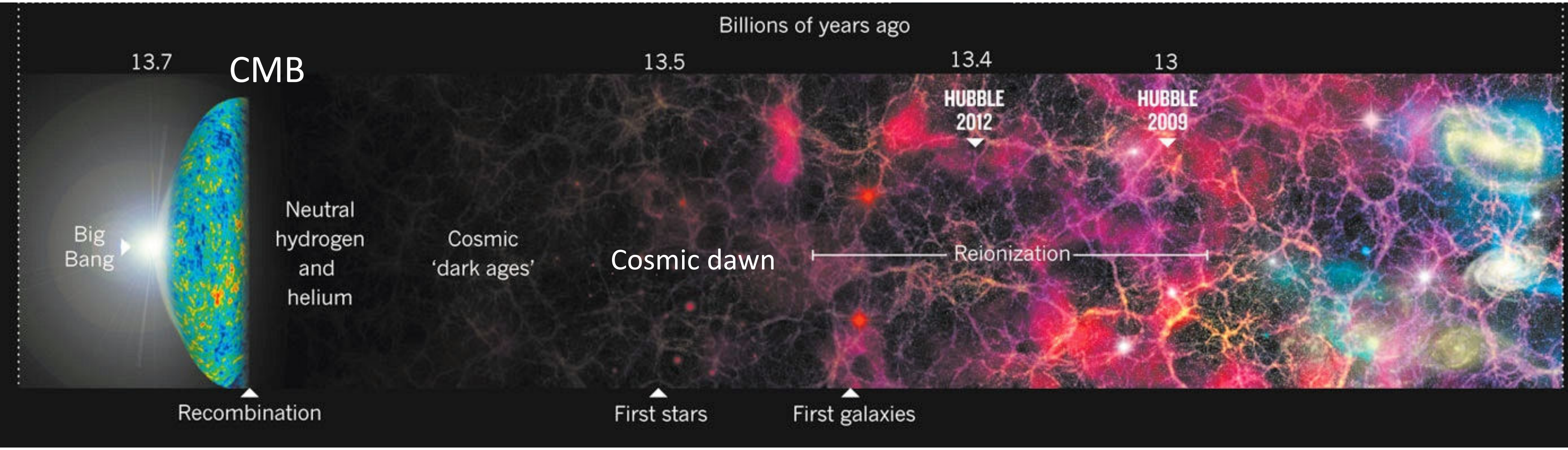


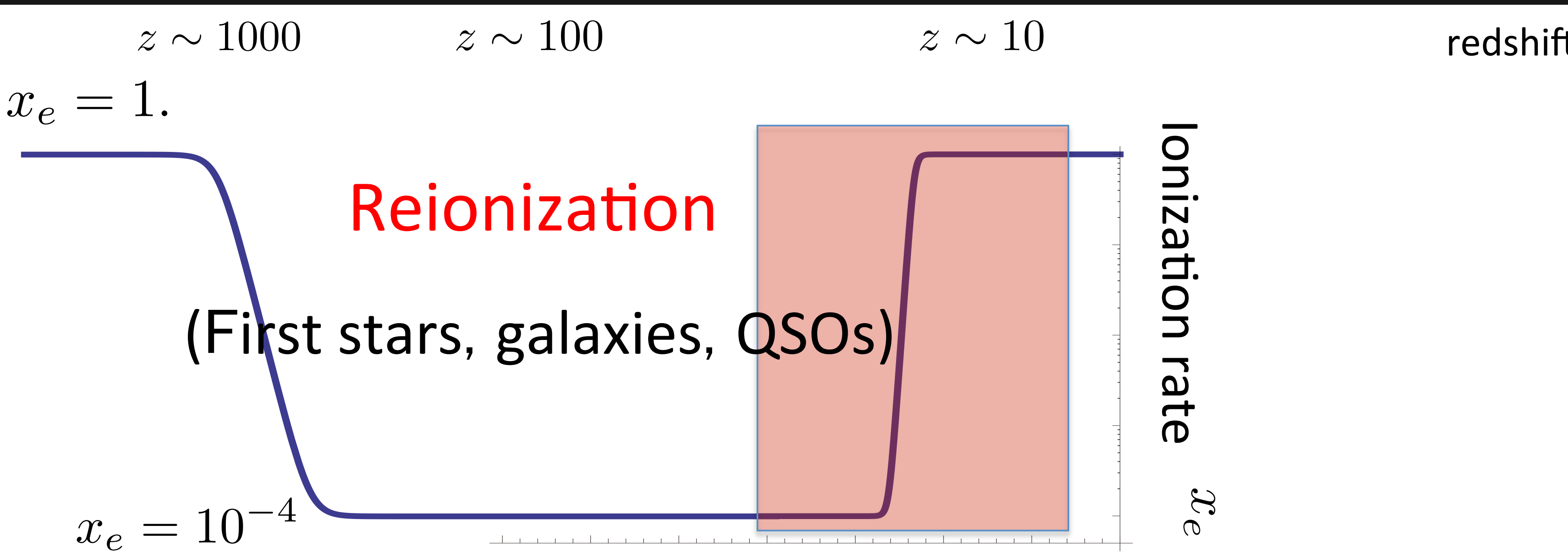
$z \sim 1000$ $z \sim 100$ $z \sim 10$ redshift



Epoch of Reionization (EoR)

From Nature (Ncik Spenser)





Observational constraints on the EoR

Several things we have learnt from the observations on the EoR

- CMB anisotropies
- Gunn-Peterson Troughs (high-z QSOs)
- High redshift galaxies (LAE)
- Gamma ray background

etc.

Observational constraints on the EoR

Several things we have learnt from the observations on the EoR

- CMB anisotropies

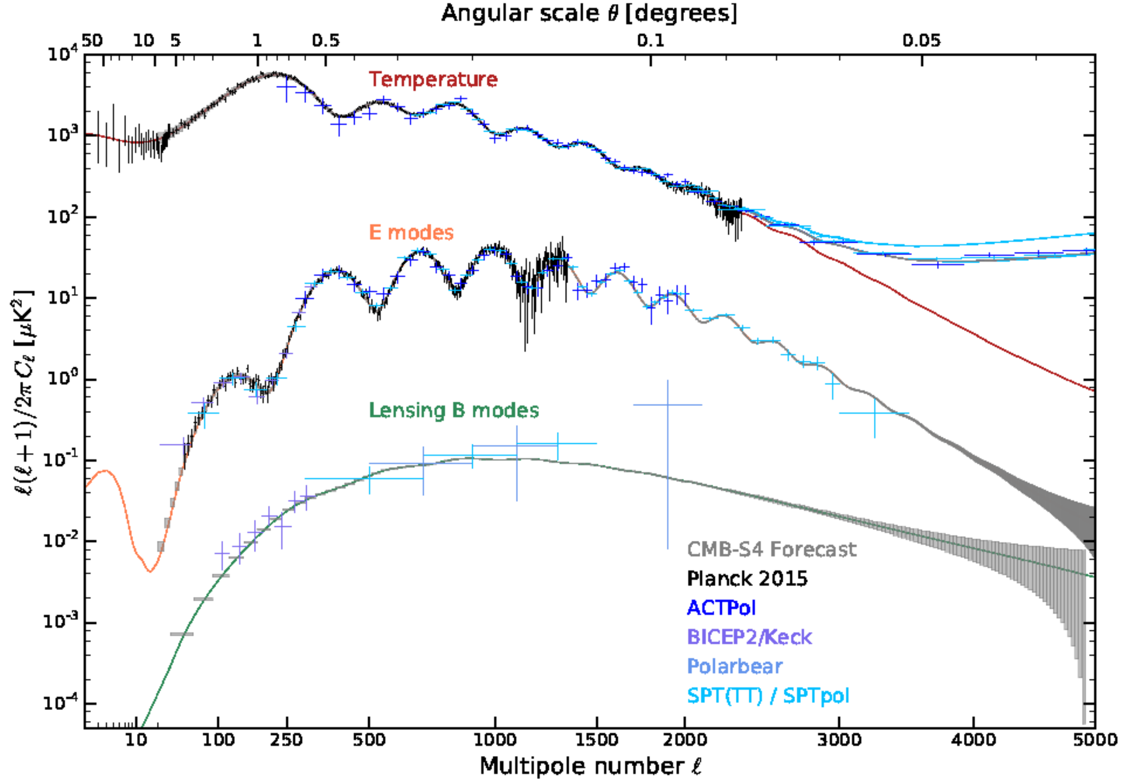
probe electrons

- Gunn-Peterson Troughs (high-z QSOs)
- High redshift galaxies (LAE)
- Gamma ray bursts

probe neutral hydrogen

etc.

CMB anisotropy



Base- ΛCDM cosmological parameters

$$(\Omega_b h^2,\ \Omega_c h^2,\ \theta_*,\ \tau,\ \ln(10^{10}A_s),\ n_s)$$

τ :Thomson scattering optical depth to reionization

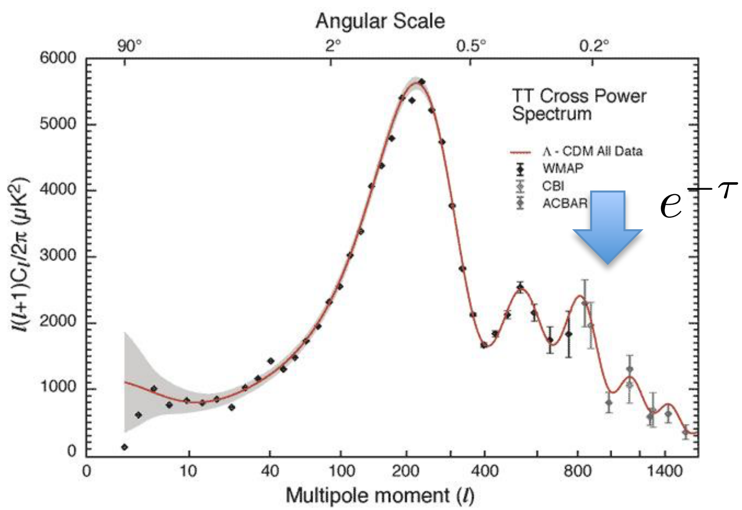
$$\tau = \sigma_T \int_{t_0}^{t_{\max}} c dt\ x_e(t) n_{\rm H}(t)$$

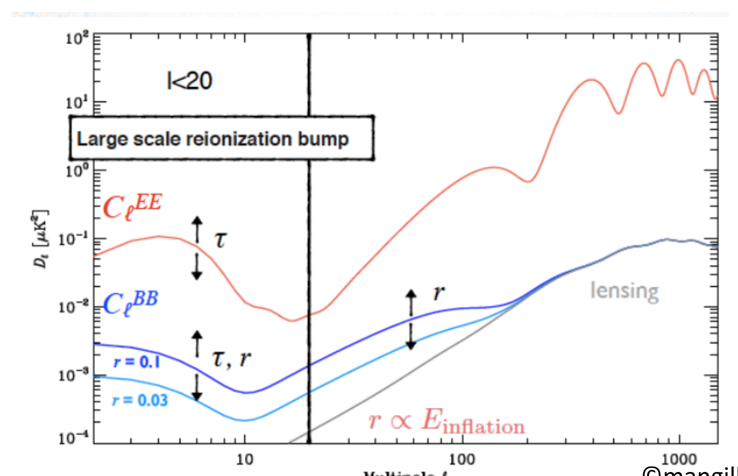
Impact of reionization on CMB anisotropies

Increase free electron density

⇨ Enhance the rate of scatterings (large τ)

- Scatterings suppress the anisotropic signals
- Scatterings make a bump on the CMB polarization





©mangilli

Reionization from CMB anisotropy

2018 Planck Best fit

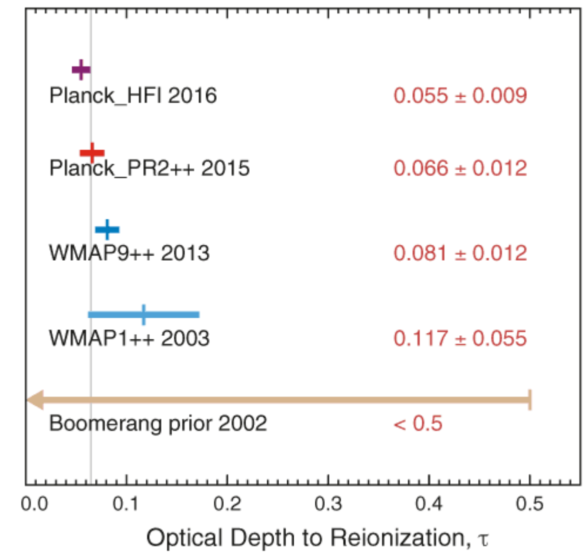
$$\tau = 0.0544^{+0.0070}_{-0.0081}$$

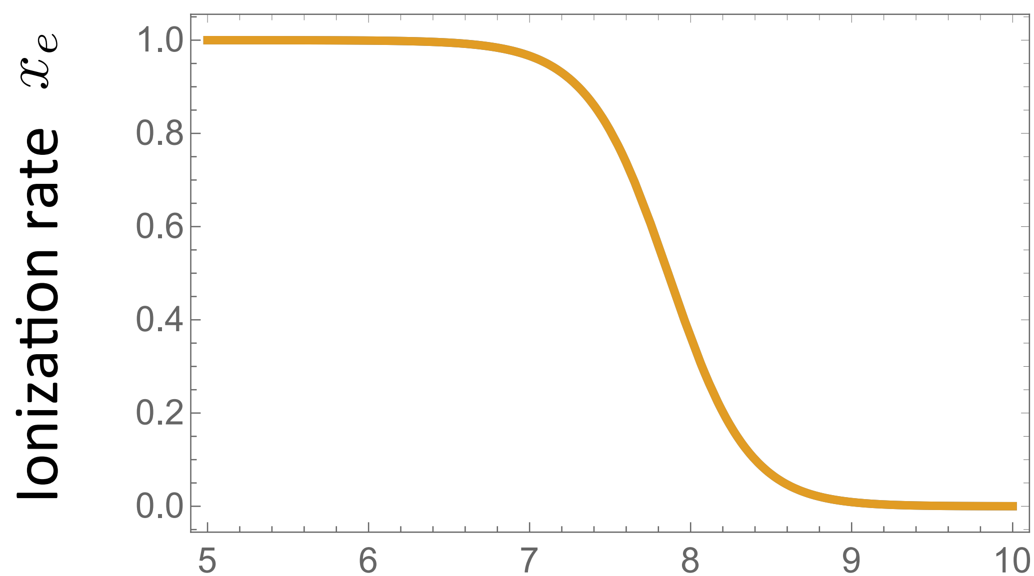
(68 %, TT,TE,EE+lowE).

$$z_{\rm re} = 7.68 \pm 0.79$$

mid-point redshift

NASA LAMBDA





Observational constraints on the EoR

Several things we have learnt from the observations on the EoR

- CMB anisotropies

- Gunn-Peterson Trough (high-z QSOs)
- High redshift galaxies (LAE)
- Gamma ray bursts

probe neutral hydrogen

etc.

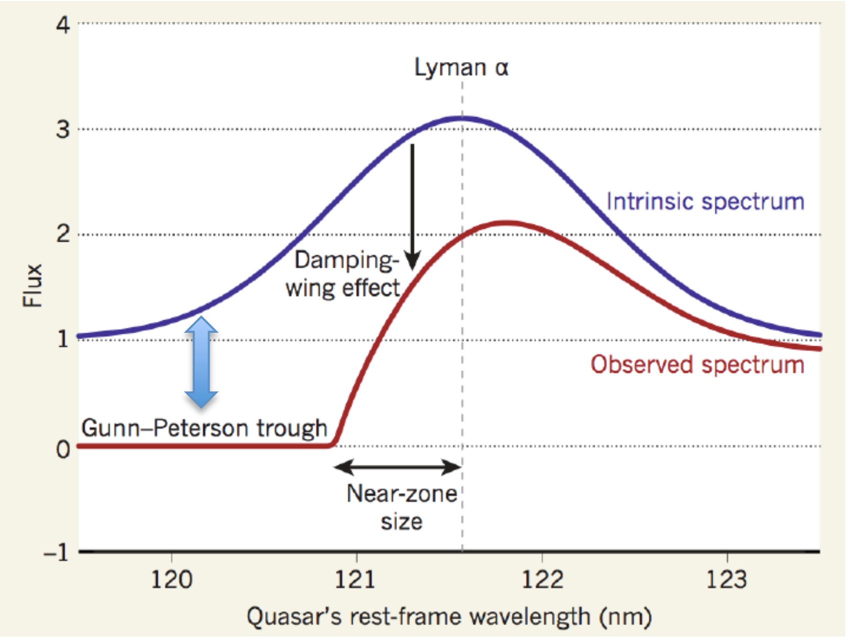
Gunn-Peterson Trough

Complete absorption by neutral hydrogen
along the line of sight on distant QSO spectrum

Optical depth of the absorption

$$\tau_{GP} \approx 4.3 \times 10^5 \left(\frac{n_{HI}}{n_H} \right)$$

Willott 2011



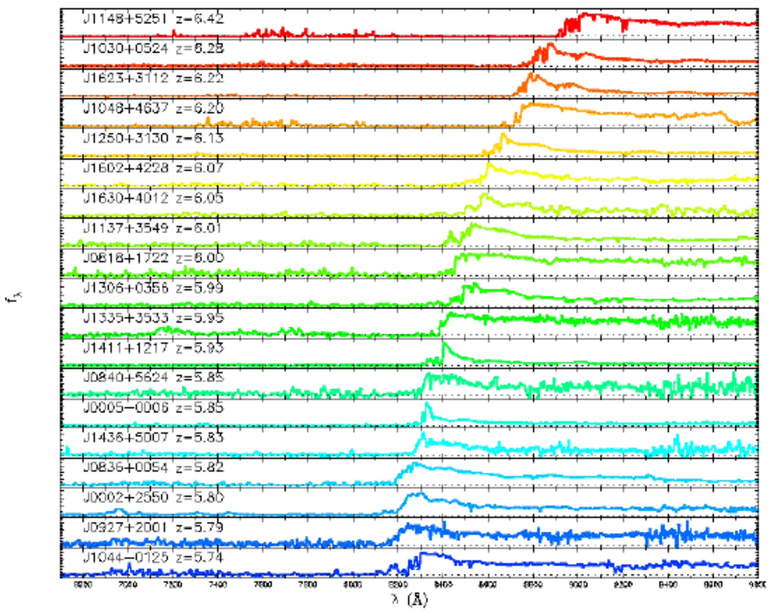
Measurements give the neutral fraction of hydrogen

Gunn-Peterson Trough

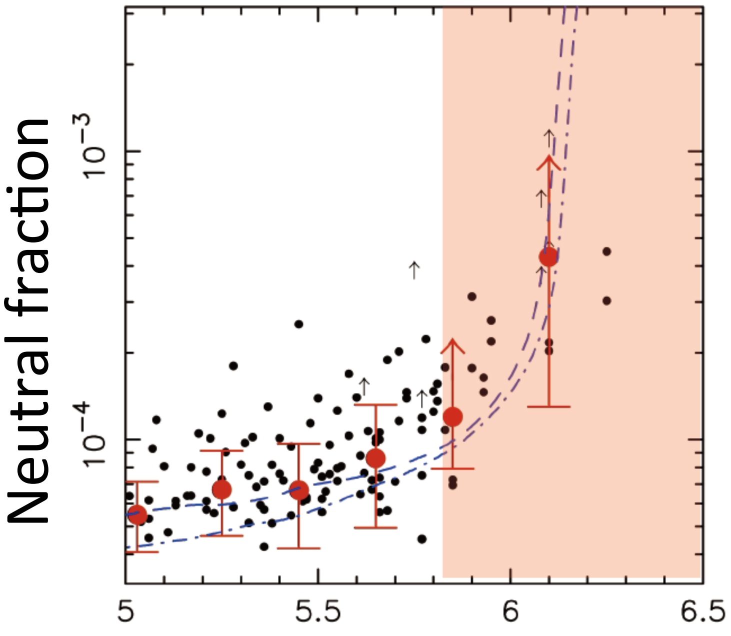
Gunn-Peterson trough measurement by SDSS QSO survey

Neutral fraction evolution between z=5 to 6.4

Fan et al. 2006



Fan et al. 2006



Observational constraints on the EoR

Several things we have learnt from the observations on the EoR

- CMB anisotropies

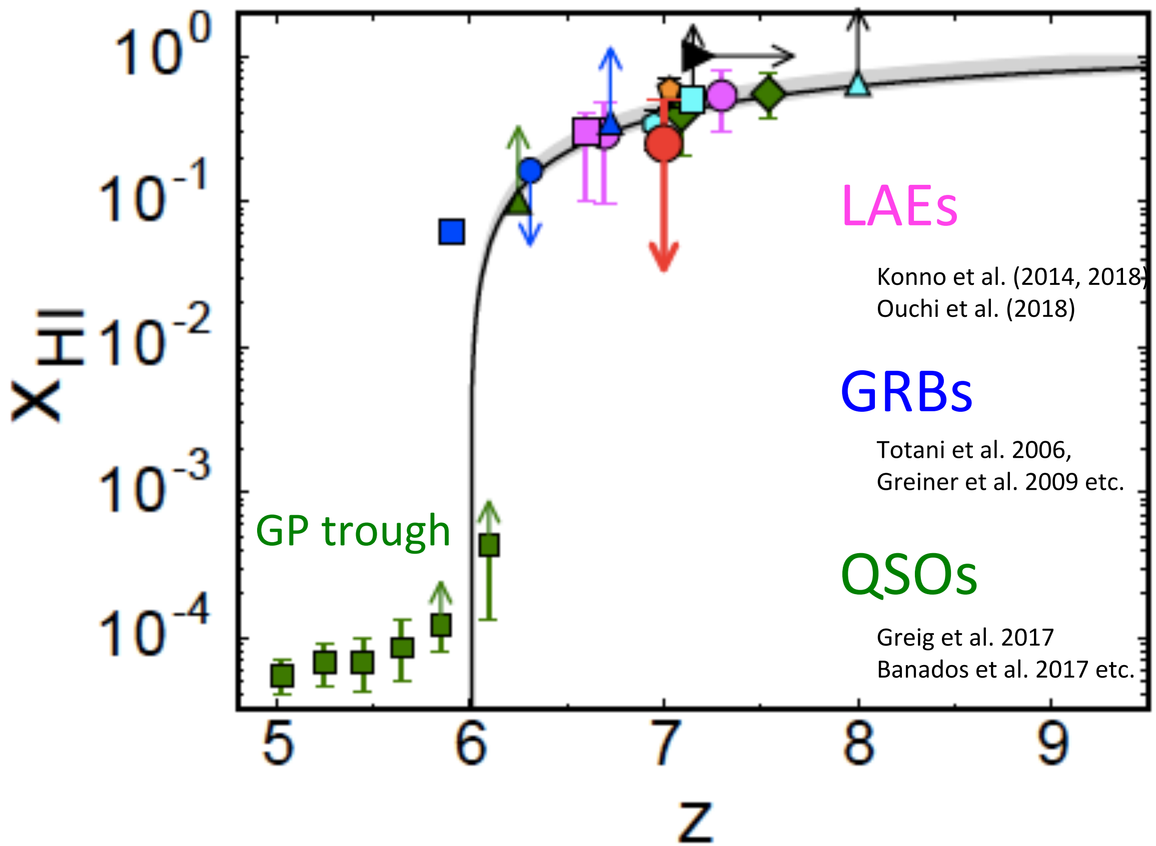
- Gunn-Peterson Trough (high-z QSOs)
- High redshift galaxies (LAE)
- Gamma ray bursts

probe neutral hydrogen

etc.

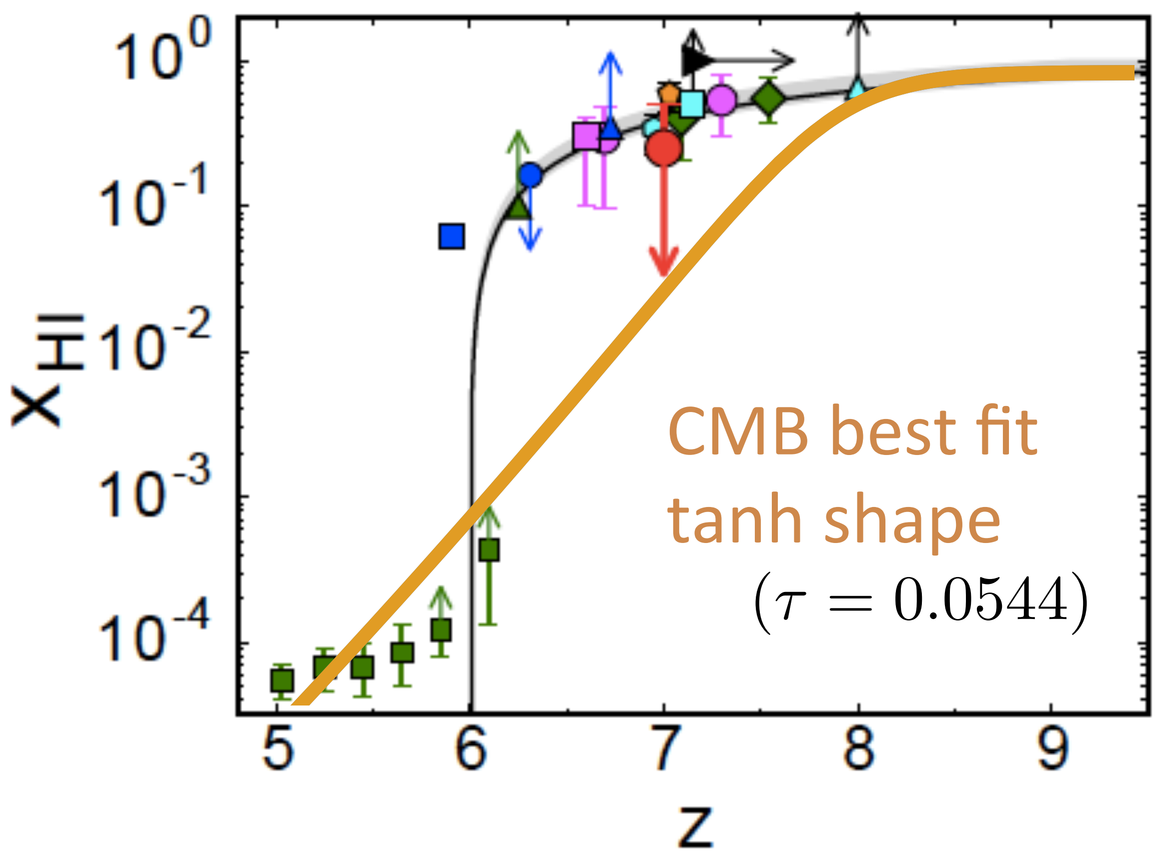
Neutral fraction evolution

Itoh et al. 2018

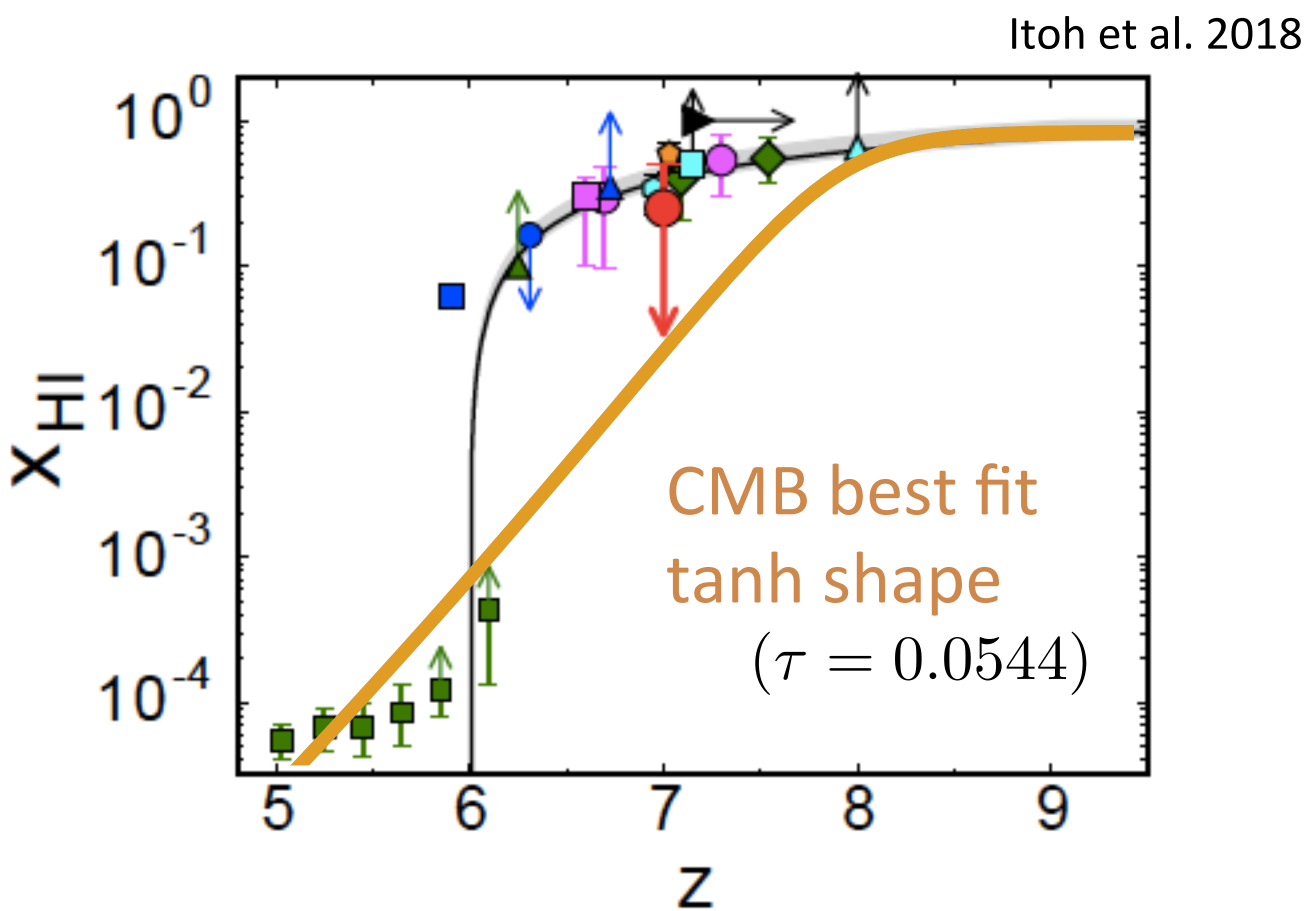


Neutral fraction evolution

Itoh et al. 2018

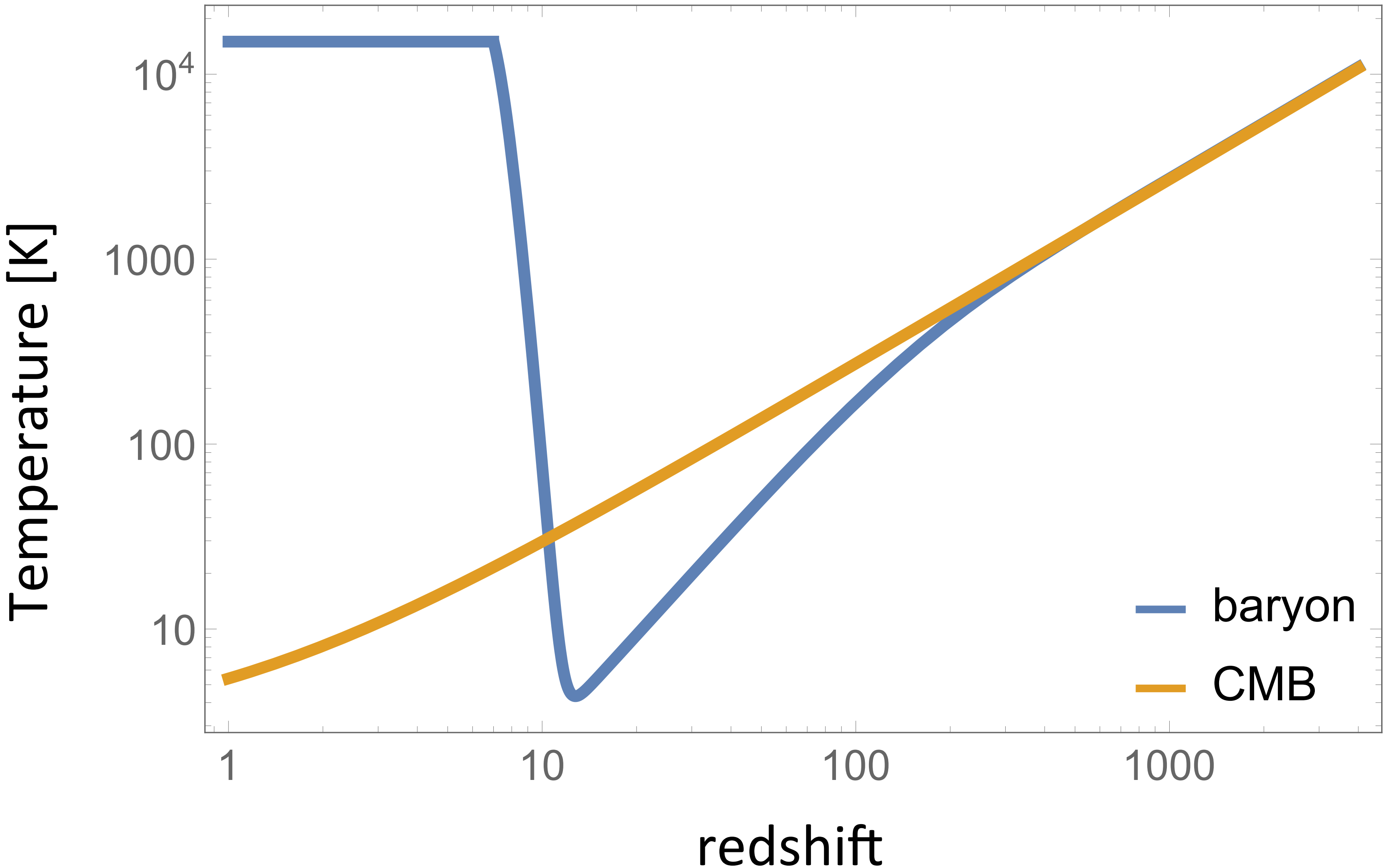


Neutral fraction evolution

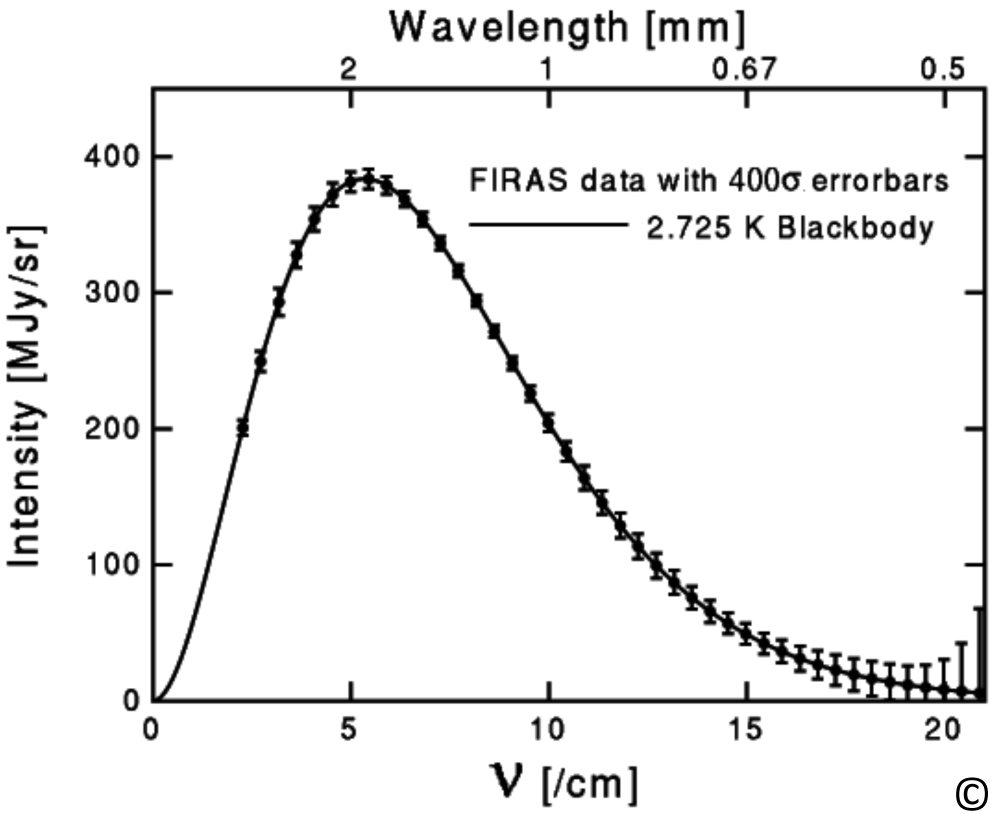


First stars, galaxies, QSOs in the early Universe

Thermal evolution of the Universe



CMB: 2.725 Blackbody spectrum

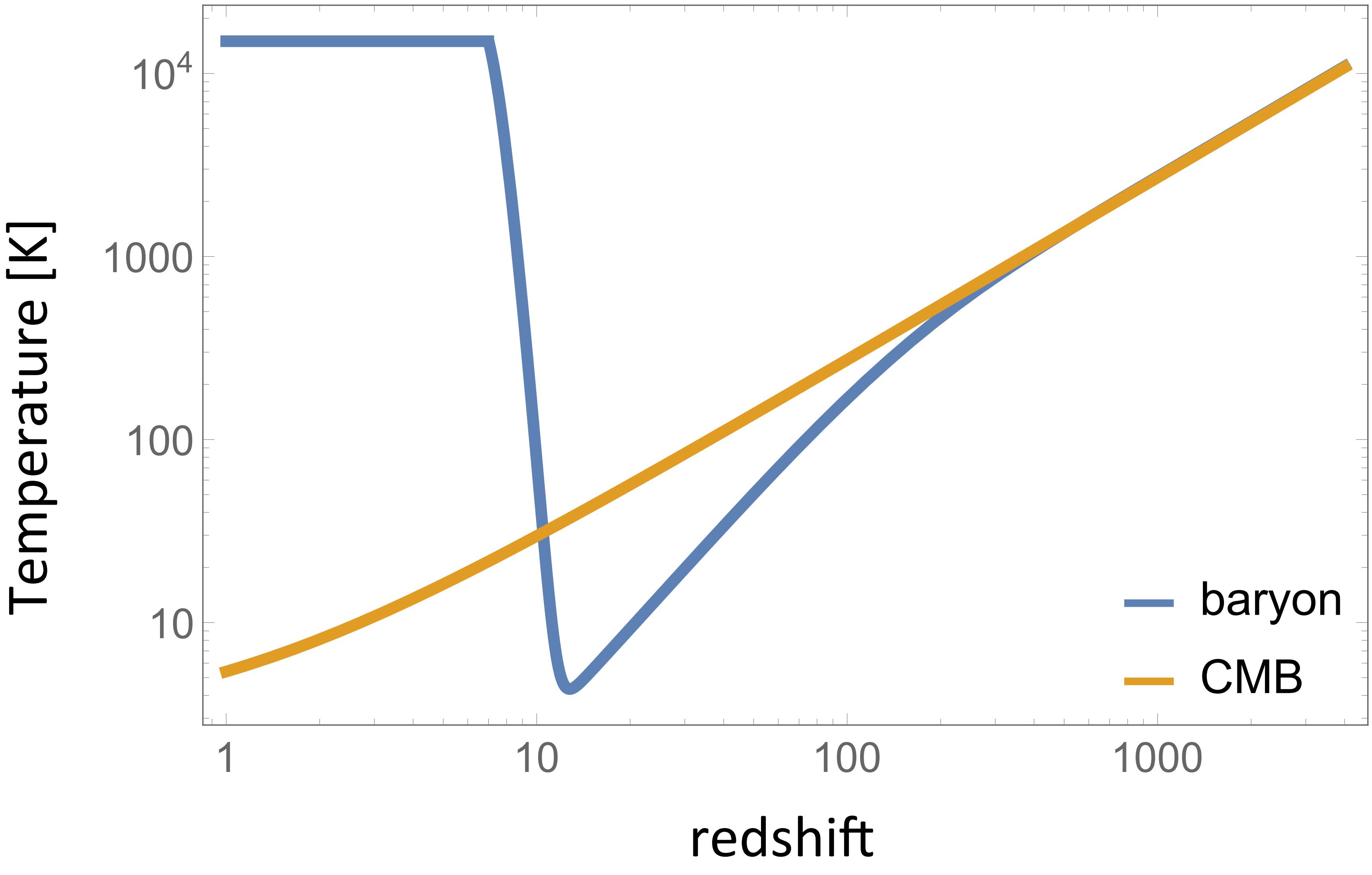


©E.L.Wright

Standard Big Bang model

$$T(z) = T_0(1+z), \quad T_0 = 2.725\mathrm{K}$$

Thermal evolution of the Universe



Baryon temperature evolution

$$\frac{dT}{dt} = -2HT - \frac{T}{n_{\rm tot}}\frac{dn_{\rm tot}}{dt} + \frac{2}{3k_B n_{\rm tot}}\frac{dQ}{dt}$$

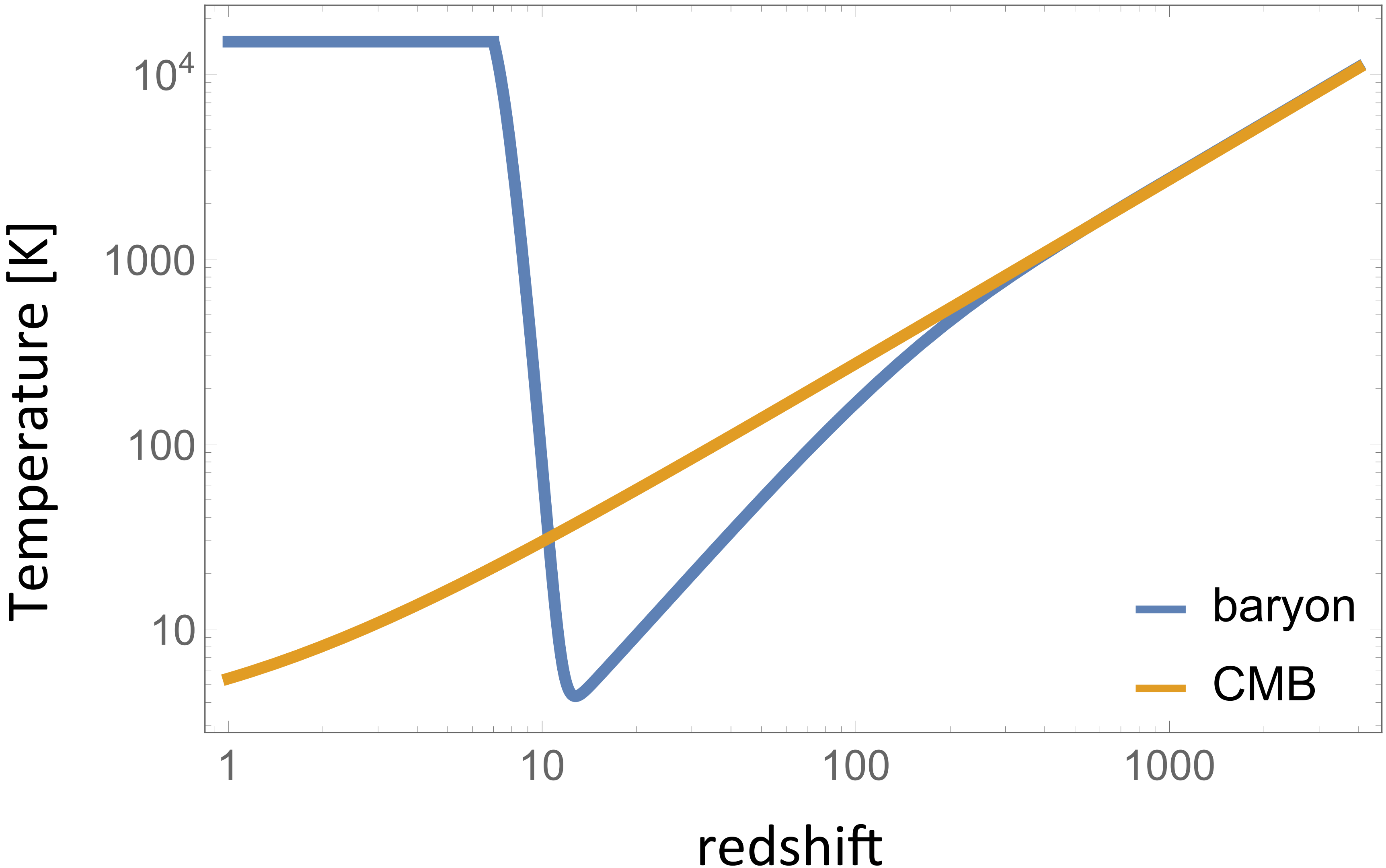
$n_{\rm tot}$: Total number of "baryonic particles" (including electrons)

Adiabatic evolution

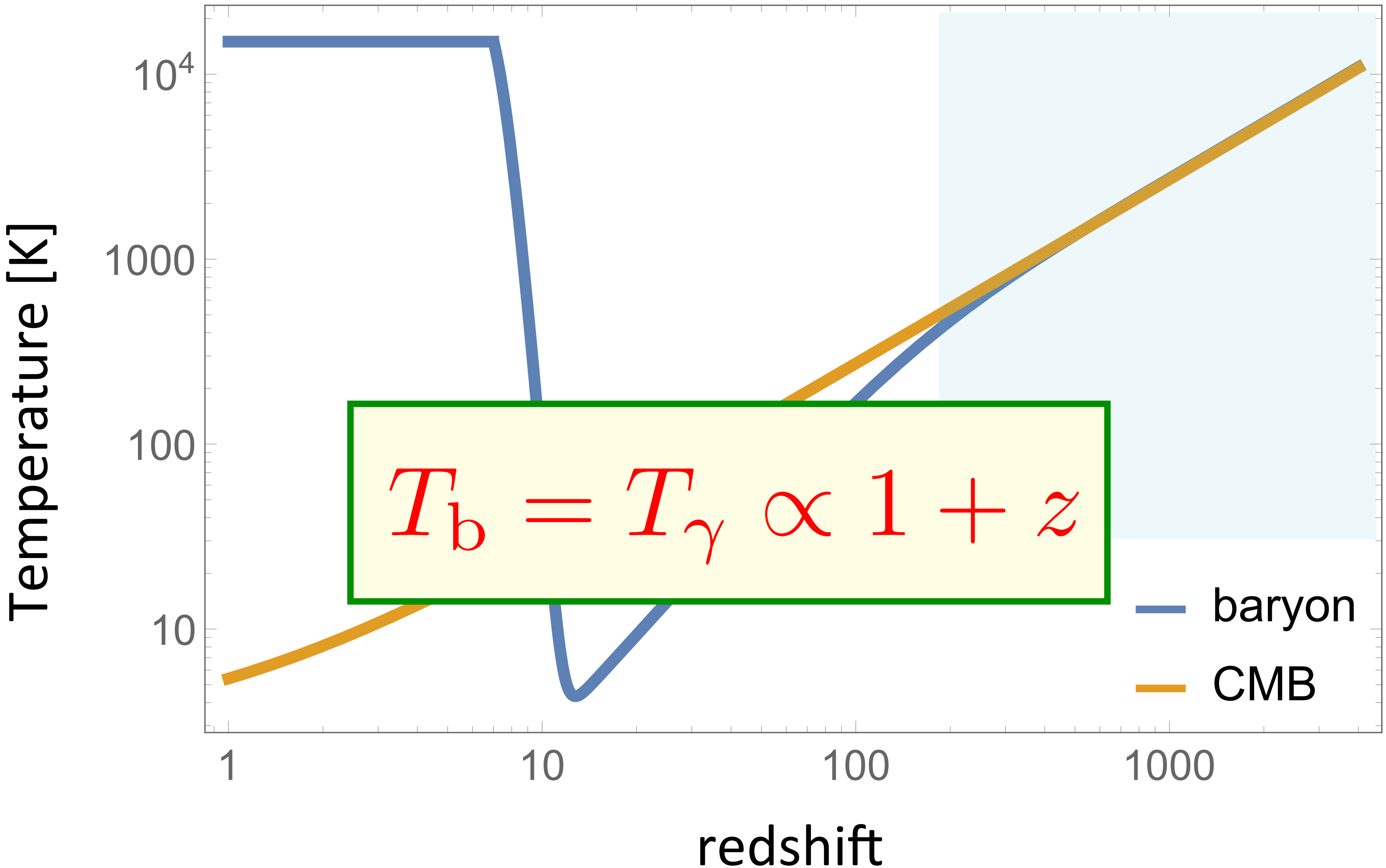
$$\frac{dT}{dt} = -2HT \quad \Rightarrow \quad T \propto (1+z)^2$$

Deviation from the adiabatic evolution tells us heating and cooling sources in the Universe

Thermal evolution of the Universe



Thermal evolution of the Universe



$$T_{\rm b} = T_\gamma \propto 1 + z$$

Baryon temperature evolution

$$\frac{dT}{dt} = -2HT - \frac{T}{n_{\rm tot}}\frac{dn_{\rm tot}}{dt} + \frac{2}{3k_B n_{\rm tot}}\frac{dQ}{dt}$$

$n_{\rm tot}$: Total number of "baryonic particles" (including electrons)

$$\frac{dQ}{dt} = C_{\rm Comp}(T_\gamma - T) + \left.\frac{dQ}{dt}\right|_{\rm heat} + \left.\frac{dQ}{dt}\right|_{\rm cool}$$

Baryon temperature evolution

$$\frac{dT}{dt} = -2HT - \frac{T}{n_{\rm tot}} \frac{dn_{\rm tot}}{dt} + \frac{2}{3k_B n_{\rm tot}} \frac{dQ}{dt}$$

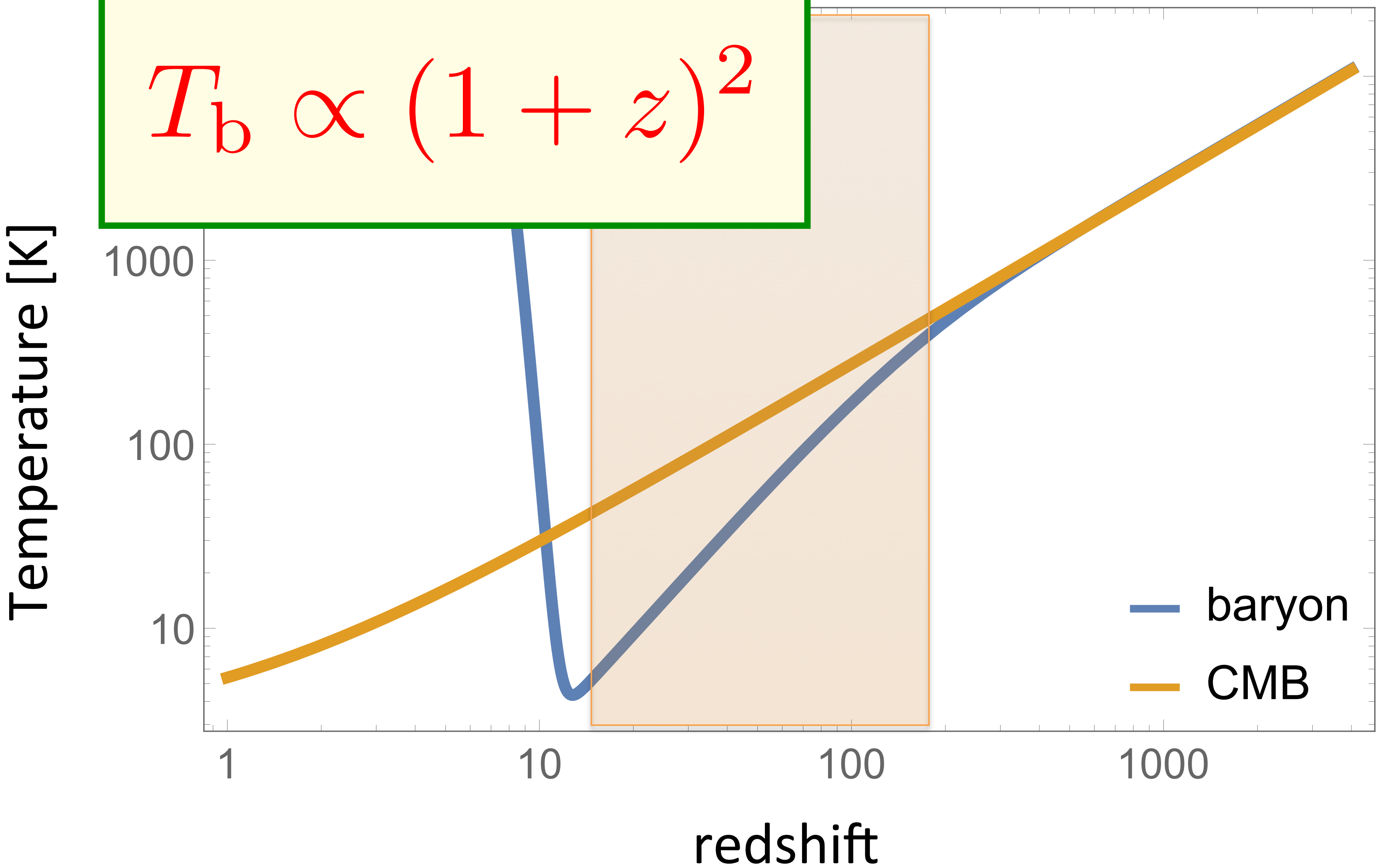
$n_{\rm tot}$: Total number of "baryonic particles" (including electrons)

$$\frac{dQ}{dt} = \underline{C_{\rm Comp}(T_\gamma - T)} + \left.\frac{dQ}{dt}\right|_{\rm heat} + \left.\frac{dQ}{dt}\right|_{\rm cool}$$

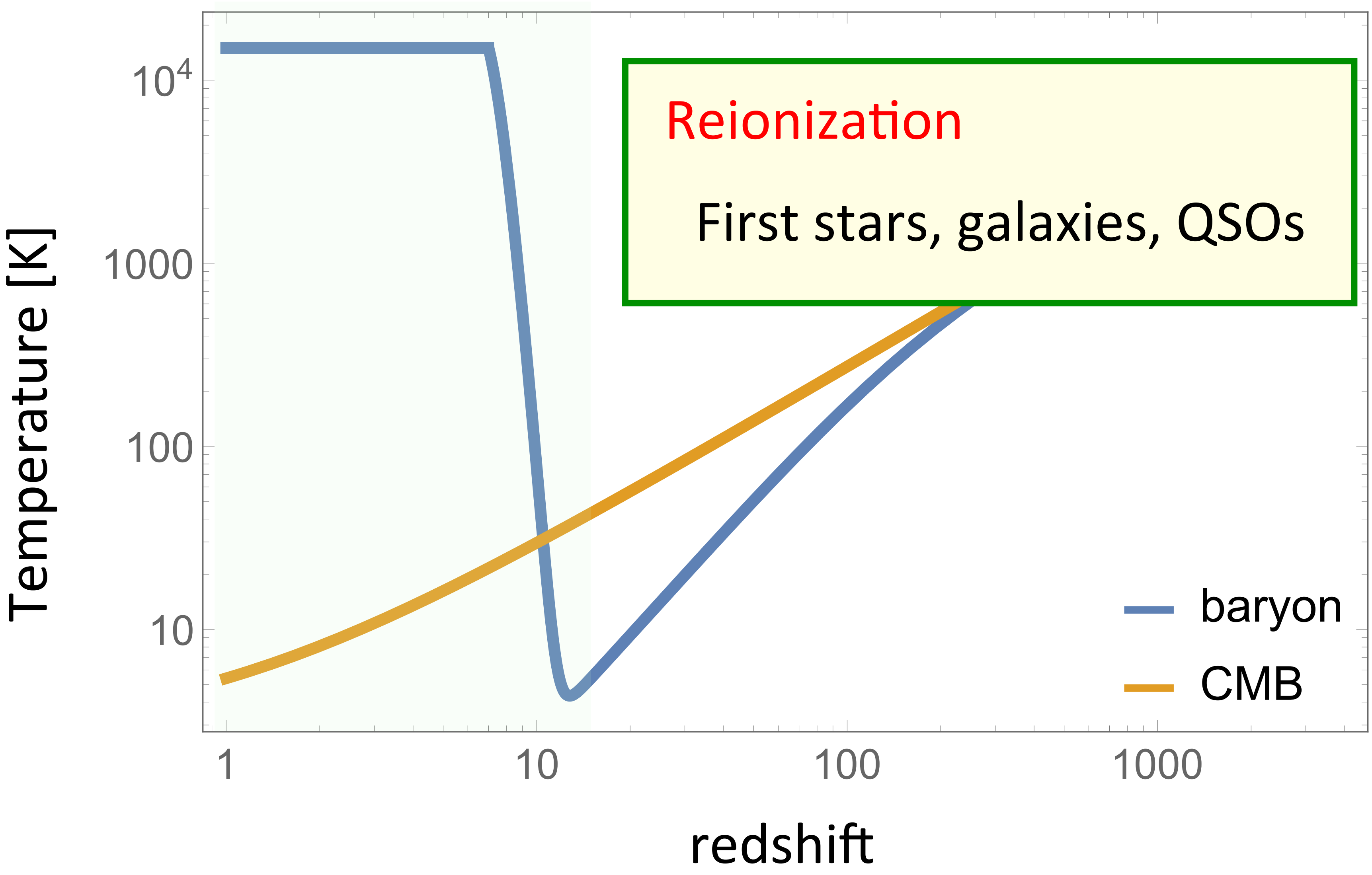
Effective Compton scattering in the early Universe → $T_{\rm b} = T_\gamma$

Thermal evolution of the Universe

$$T_{\rm b} \propto (1+z)^2$$



Thermal evolution of the Universe



Baryon temperature evolution

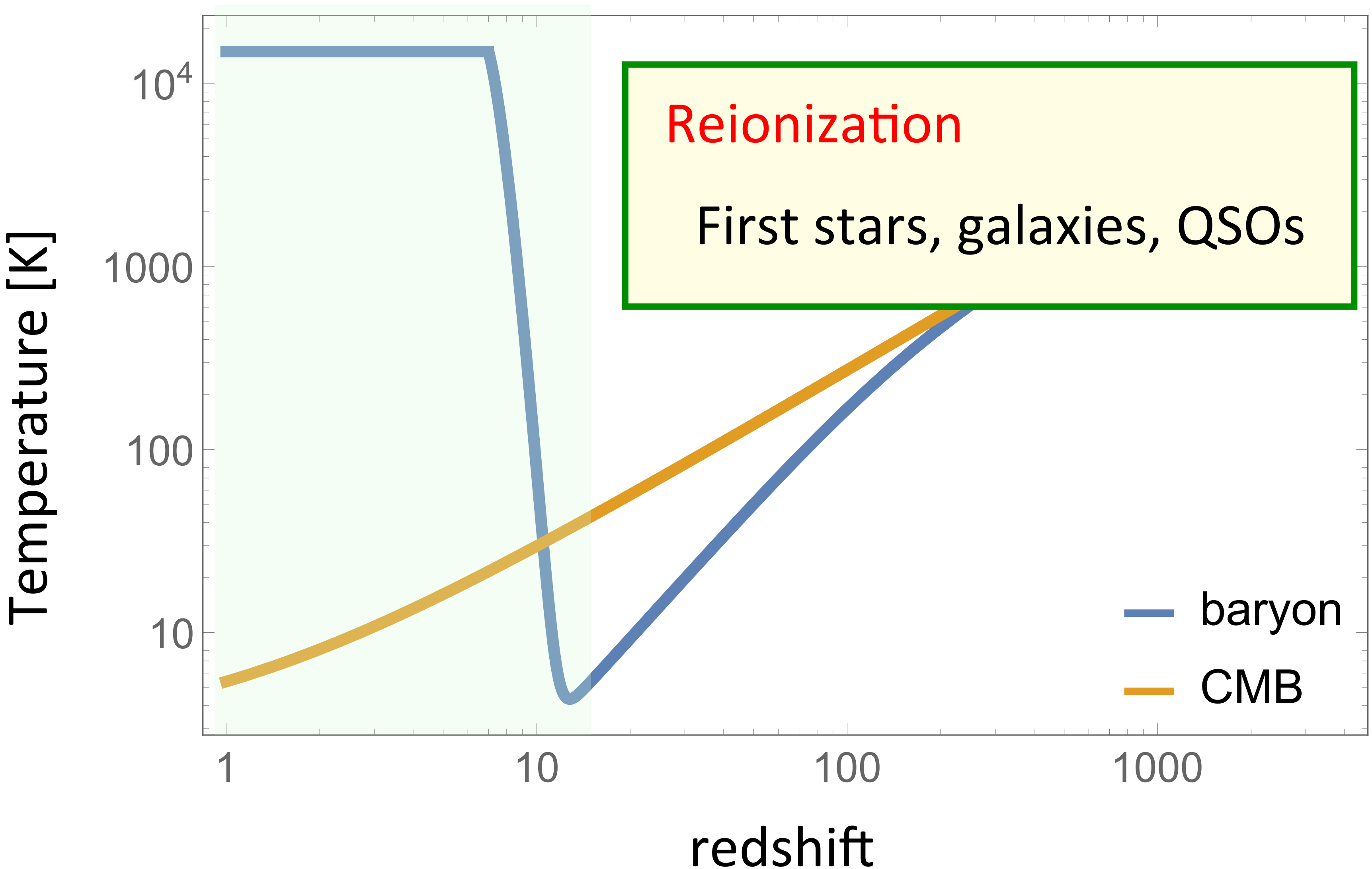
$$\frac{dT}{dt} = -2HT - \frac{T}{n_{\rm tot}}\frac{dn_{\rm tot}}{dt} + \frac{2}{3k_B n_{\rm tot}}\frac{dQ}{dt}$$

$$\frac{dQ}{dt} = C_{\rm Comp}(T_\gamma - T) + \left.\frac{dQ}{dt}\right|_{\rm heat} + \left.\frac{dQ}{dt}\right|_{\rm cool}$$

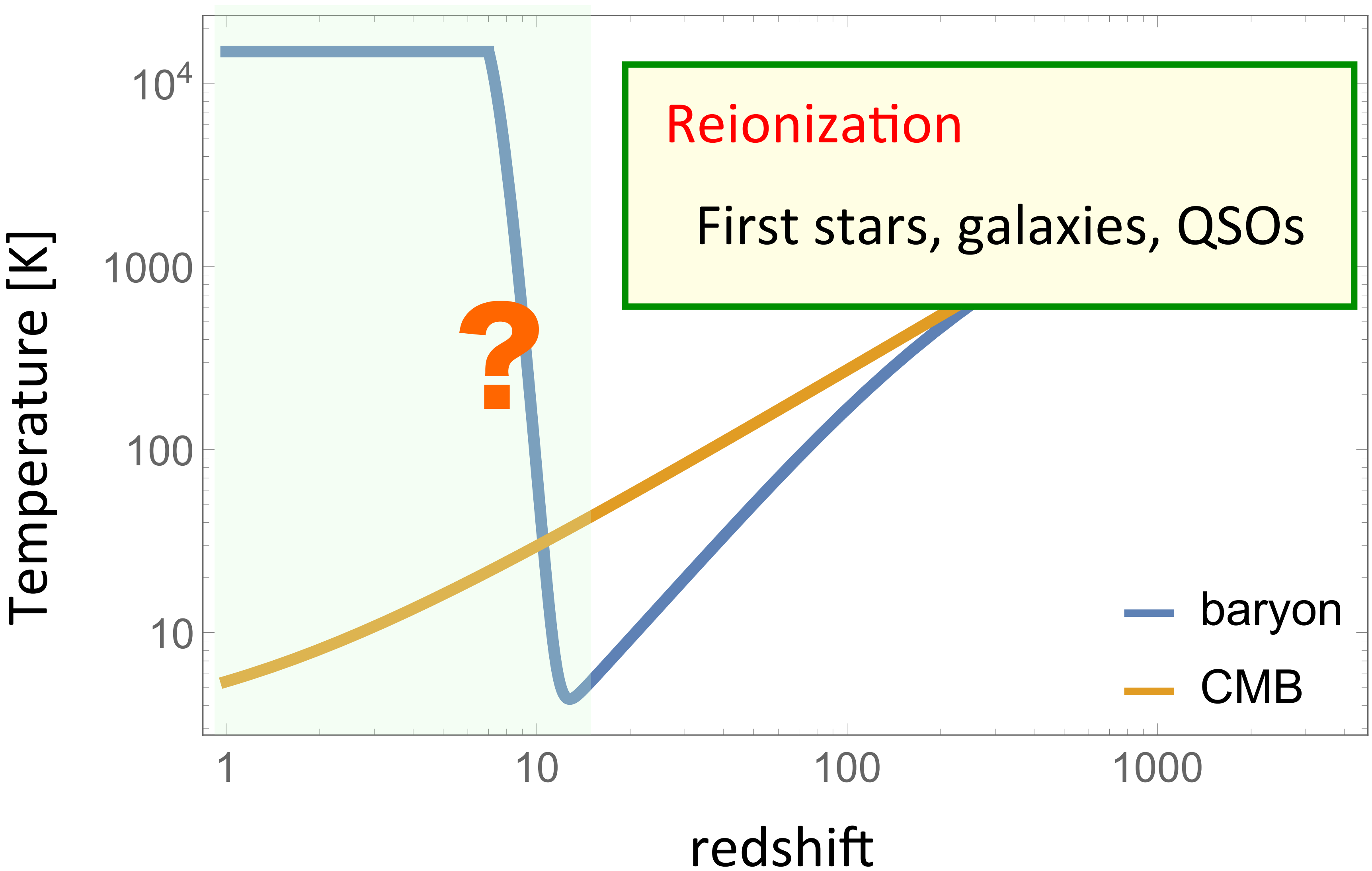
Reionization

First stars, galaxies, QSOs

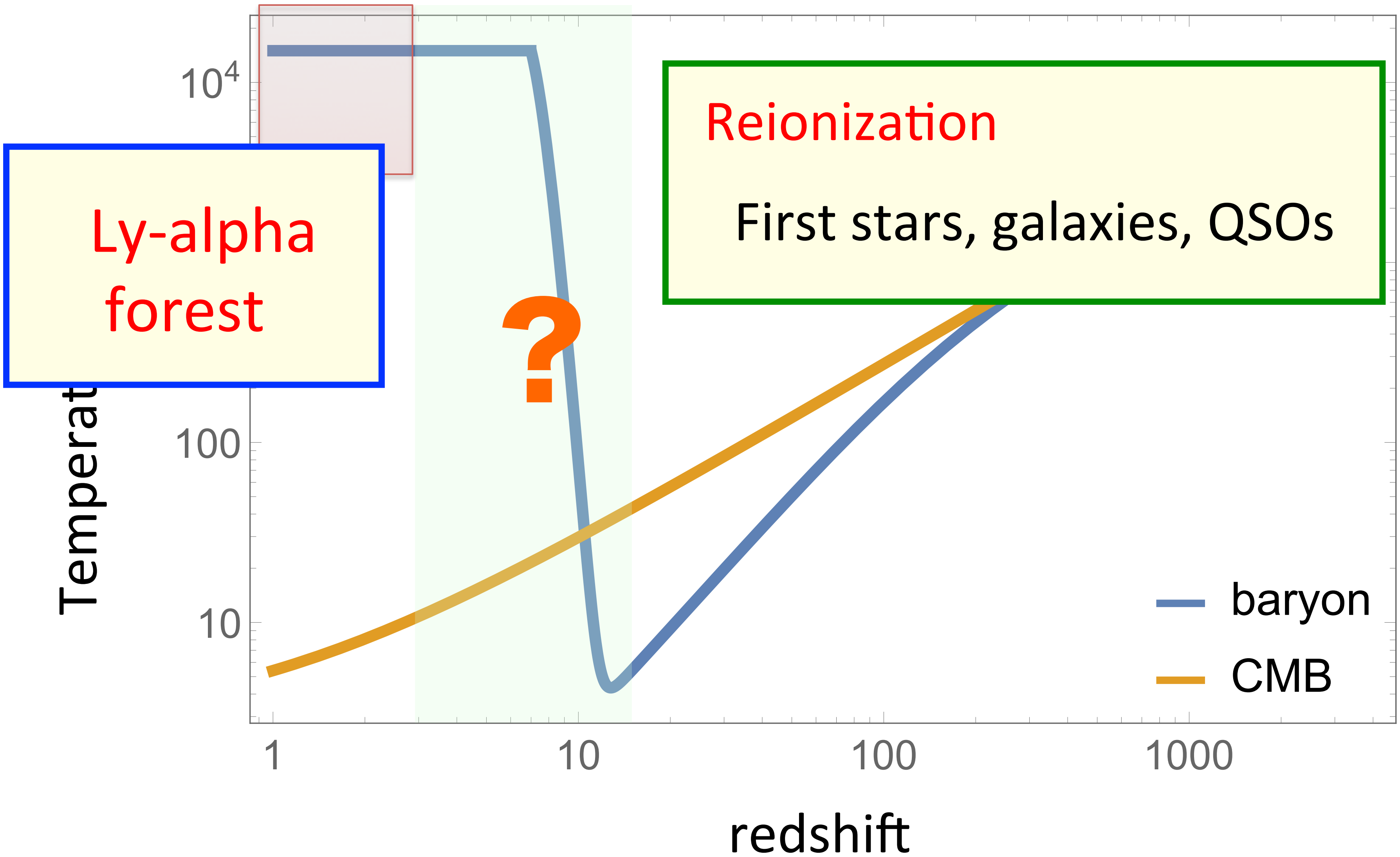
Thermal evolution of the Universe



Thermal evolution of the Universe

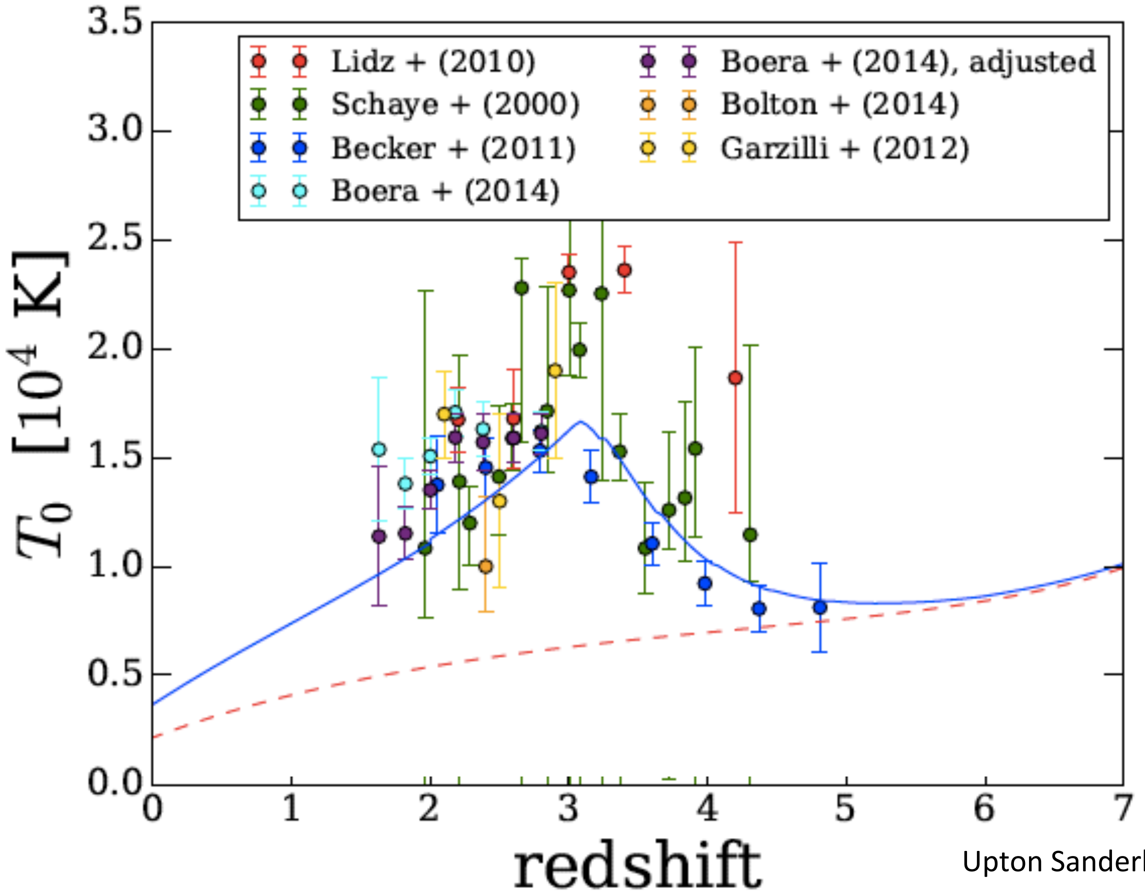


Thermal evolution of the Universe



IGM gas temperature evolution in lower redshifts

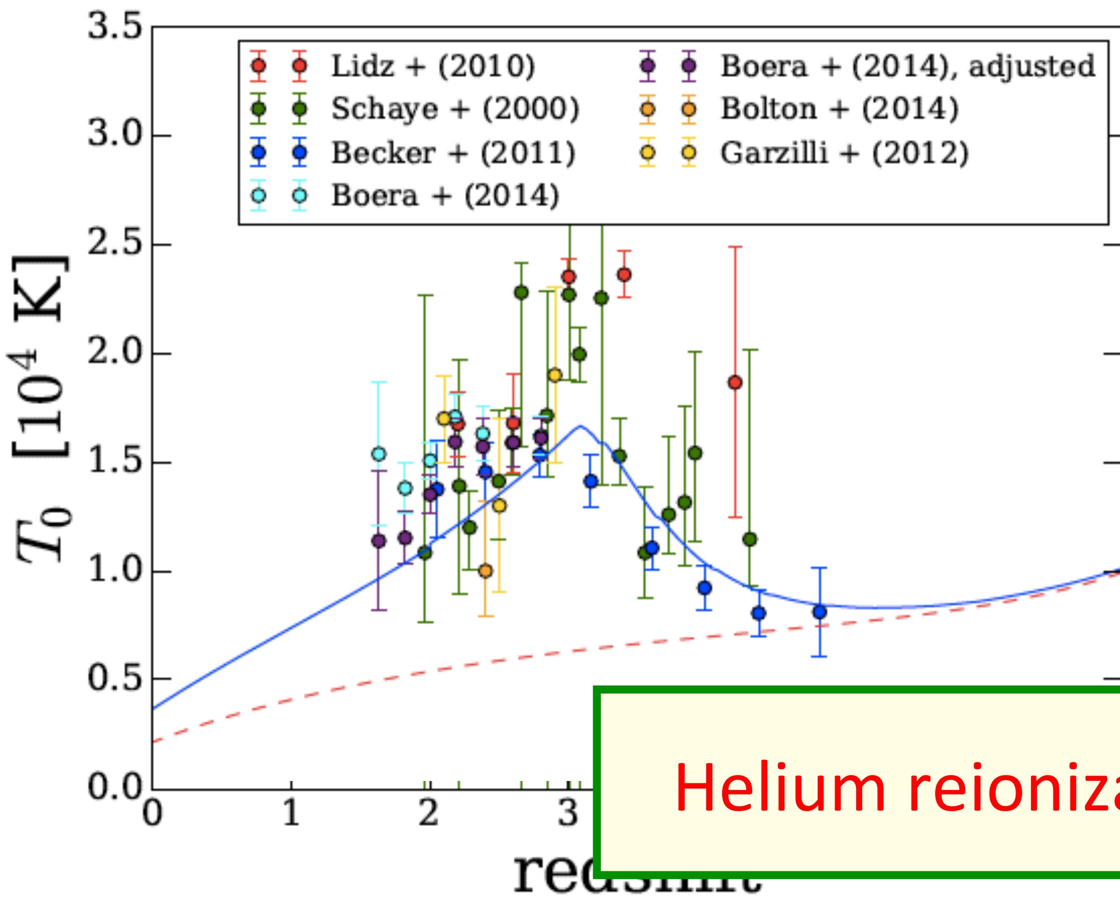
Width of Lyman-α feature provides the IGM temperature



Upton Sanderbek et al. 2016

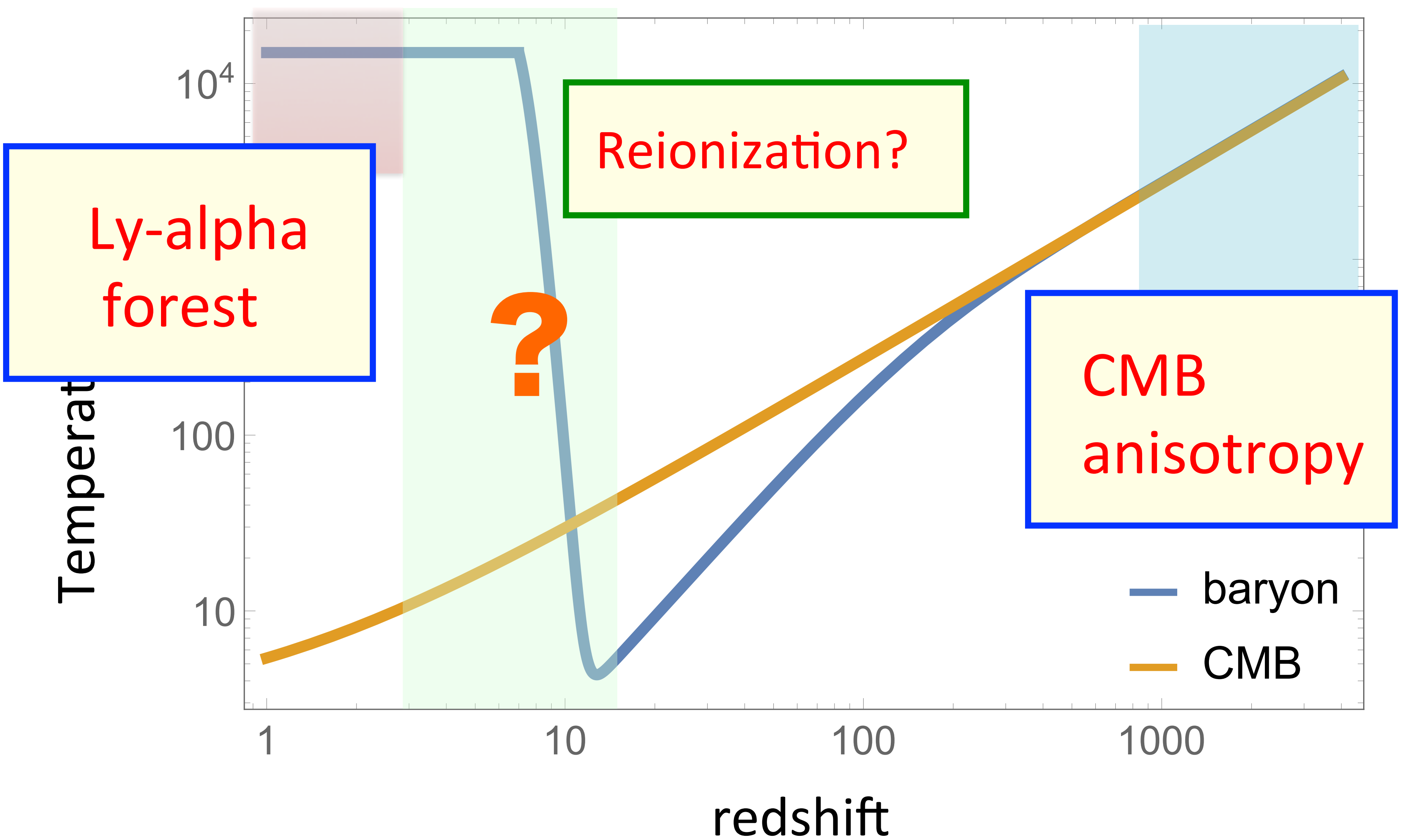
IGM gas temperature evolution in lower redshifts

Width of Lyman-α feature provides the IGM temperature

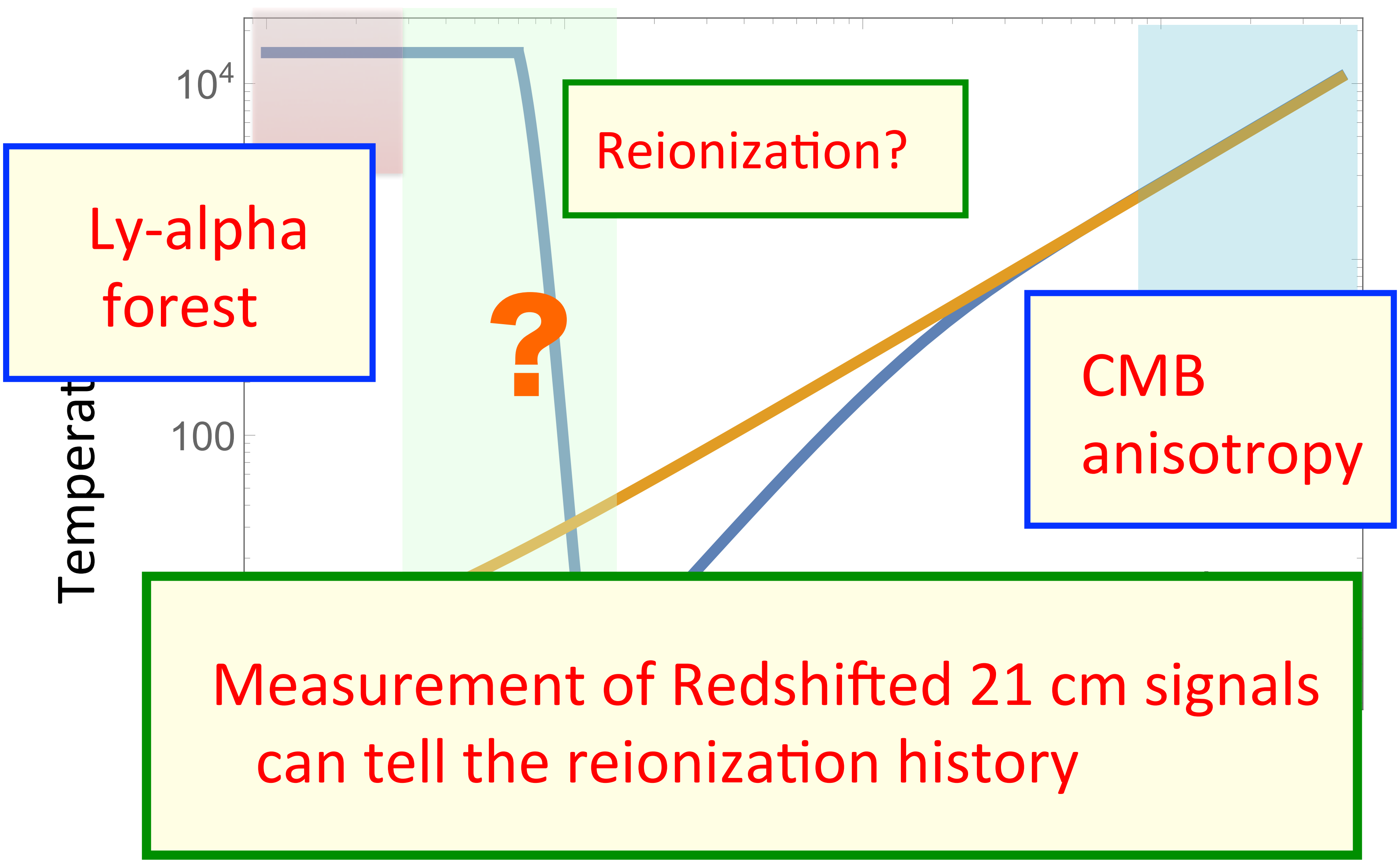


Helium reionization bump

Thermal evolution of the Universe



Thermal evolution of the Universe



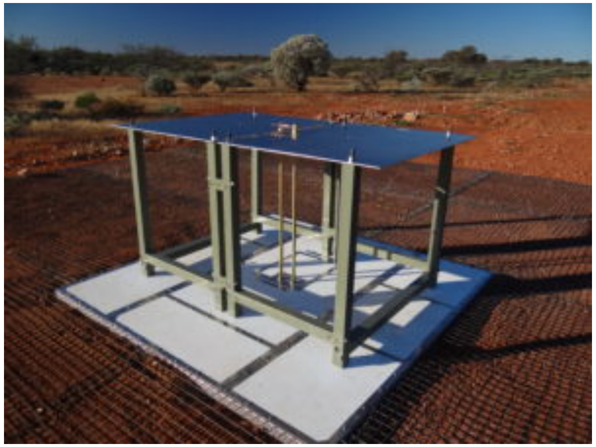
Letter

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

Judd D. Bowman, Alan E. E. Rogers, Raul A. Monsalve, Thomas J. Mozdzen & Nivedita Mahesh

Nature **555**, 67–70 (01 March 2018)
doi:10.1038/nature25792
Download Citation

Received: 13 September 2017
Accepted: 24 January 2018
Published online: 28 February 2018

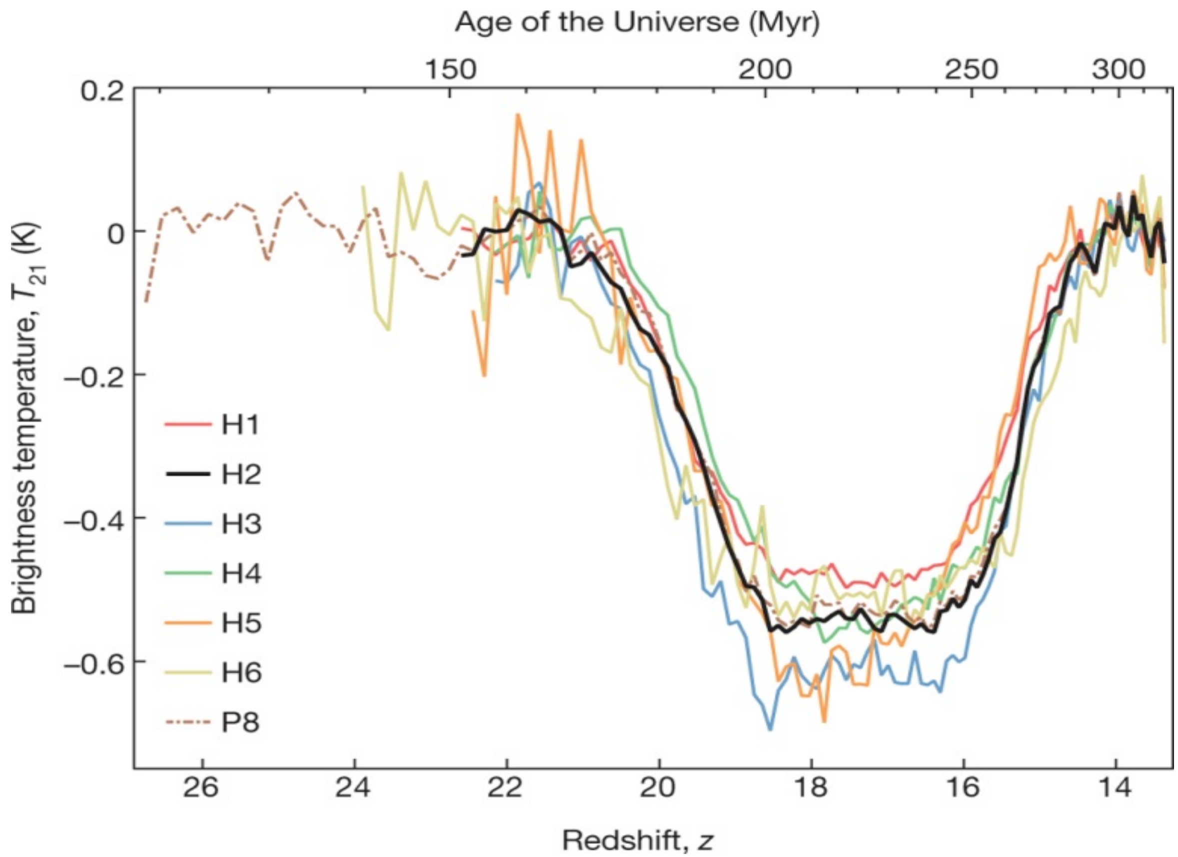


1. a low-band instrument sensitive to 50-100 MHz.

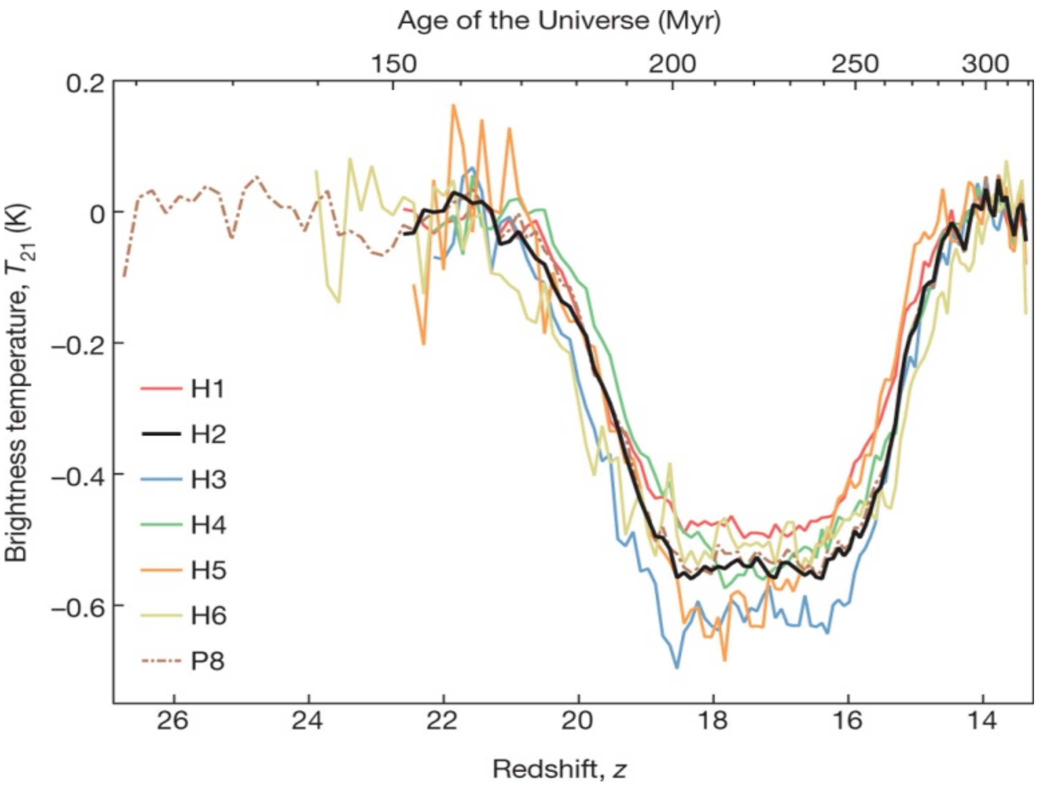
2. a high-band instrument sensitive to 100-200 MHz,

Experiment to Detect the Global EoR Signature (EDGES)

The EDGES team reported the detection of 21cm absorption signals from redshifts around 17



EDGES anomaly



EDGES result

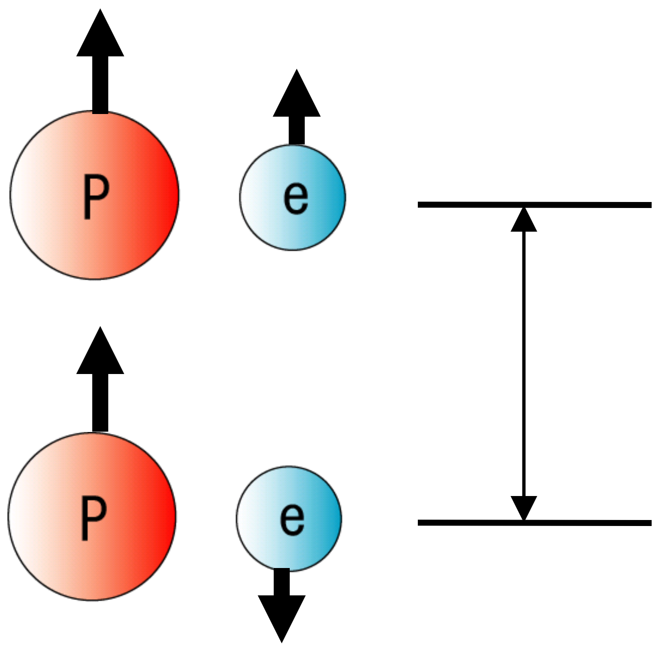
$$\frac{T_\gamma}{T_s} \approx \frac{T_\gamma}{T_K} \sim 15$$

Standard cosmological model (at most)

$$\frac{T_\gamma}{T_K} \sim 7$$

21cm line

The hyperfine structure of neutral hydrogen atom

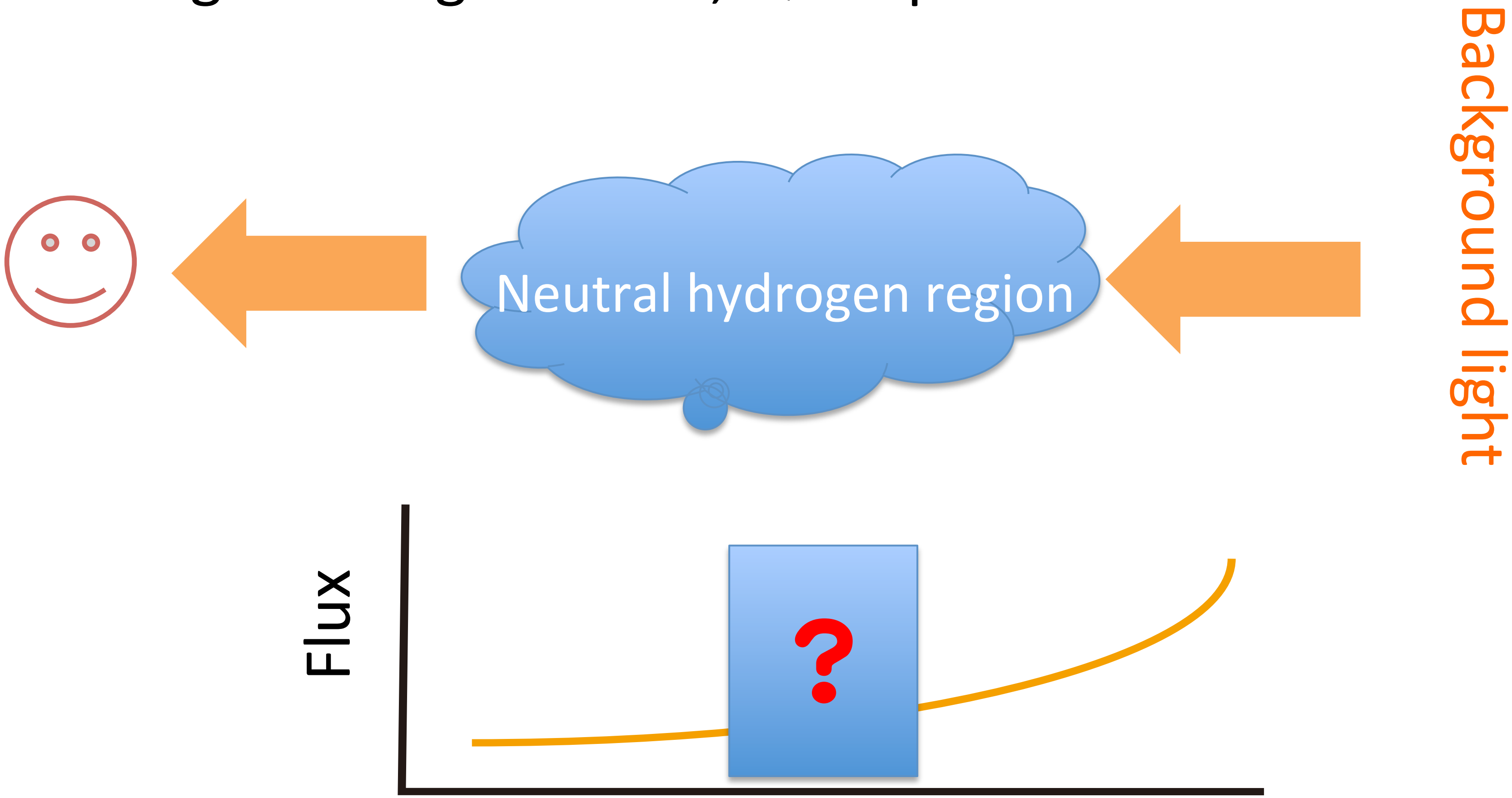


$$\Delta E = 5.9\ \ \mu\mathrm{eV},\ \ (\lambda = 21\mathrm{cm})$$

At the transition of these levels,
21 cm photon is emitted or absorbed.

Cosmological 21cm signal

Background light： CMB, QSO spectrum



Signal depends on hydrogen gas state

Differential Brightness temperature

$$\delta T_b(z) \approx 28 x_{\rm HI}(1+\delta)\left(1-\frac{T_\gamma(z)}{T_s(z)}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.025}\right)\ [\mathrm{mK}]$$

the population ratio between the excitation and ground states

$$\frac{n_1}{n_0} \equiv \left(\frac{g_1}{g_0}\right)\exp\left(-\frac{E_\star}{k_B T_s}\right).$$

Spin temperature

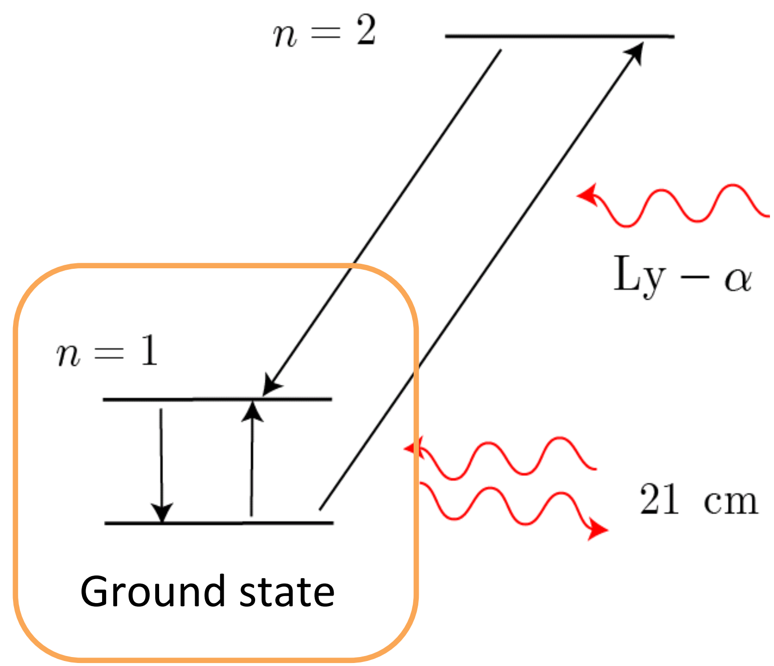
In the hyperfine structure $g_1 = 3, g_0 = 1$

$$E_\star = k_B T_\star, \quad T_\star = 0.0681\mathrm{K}$$

21 cm transition in cosmology

- Spontaneous emission
- Transition induced by CMB

  absorption and stimulated emission
- Transition induced by collisions
- Lyman alpha pumping



Hyper fine structure

Assuming the equilibrium balance of these effects,
Level population :

$$n_1\left(C_{10}+P_{10}+A_{10}+B_{10}I_{\mathrm{CMB}}\right)=n_0\left(C_{01}+P_{01}+B_{01}I_{\mathrm{CMB}}\right)$$

Spin temperature

$$T_s = \frac{T_\gamma + (y_\alpha + y_c)T_K}{1 + y_\alpha + y_c}$$

(Field 1975)

Spin temperature is determined by
the balance between gas and CMB temperature

Collision and Ly-a are not effective : $y_c \ll 1,\ y_\alpha \ll 1$

$$T_s \sim T_\gamma$$

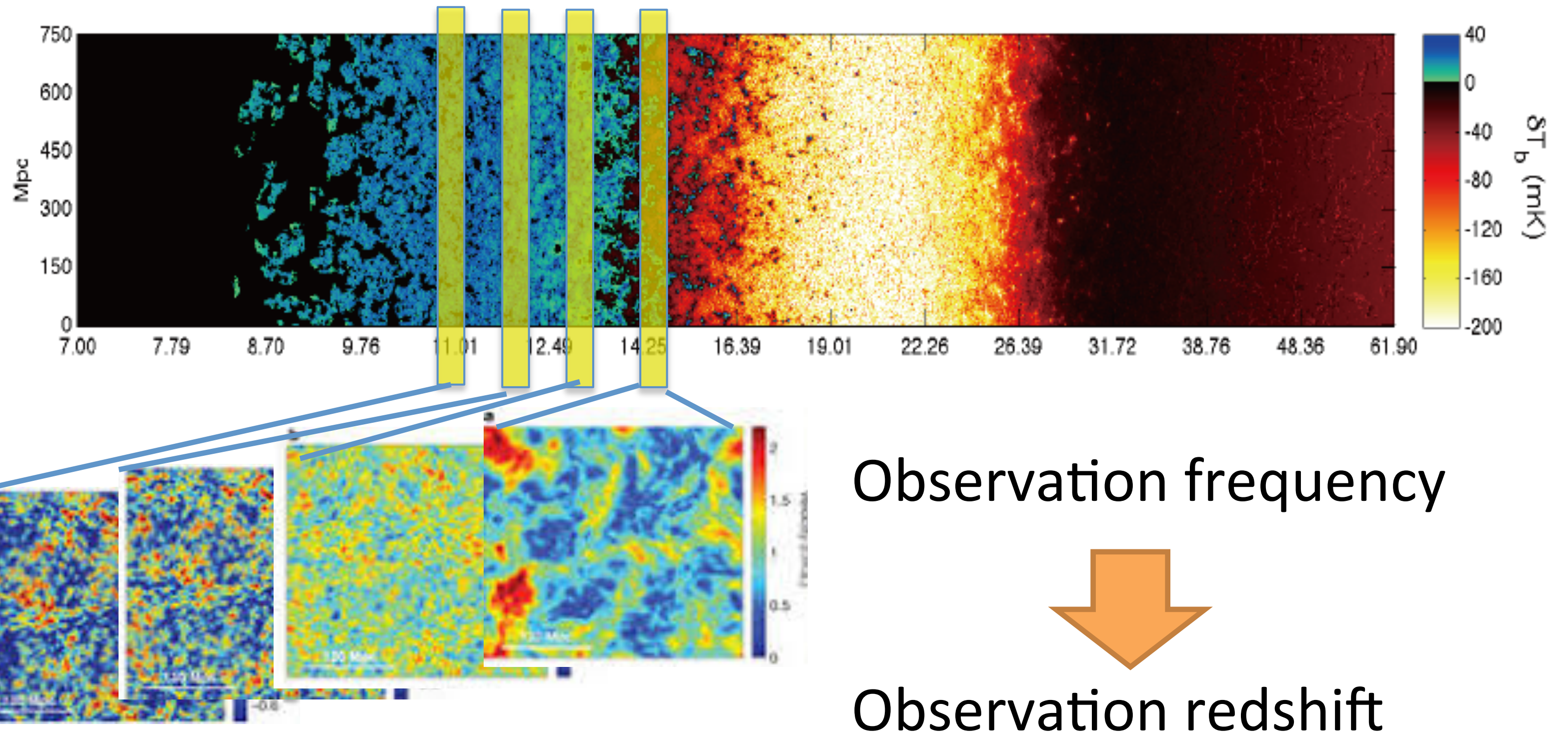
Collision or Ly-a is effective: $y_c \gg 1, \quad \text{or} \quad y_\alpha \gg 1$

$$T_s \sim T_{\rm K}$$

21 cm Tomography

- Line absorption (emission)

21 cm signals



Observation frequency

Observation redshift

$$\nu_{\rm obs} = 1440\ {\rm MHz}/(1+z)$$

Differential Brightness temperature

$$\delta T_b(z) \approx 28 x_{\rm HI}(1+\delta)\left(1-\frac{T_\gamma(z)}{T_s(z)}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.025}\right) \ [\rm mK]$$

the population ratio between the excitation and ground states

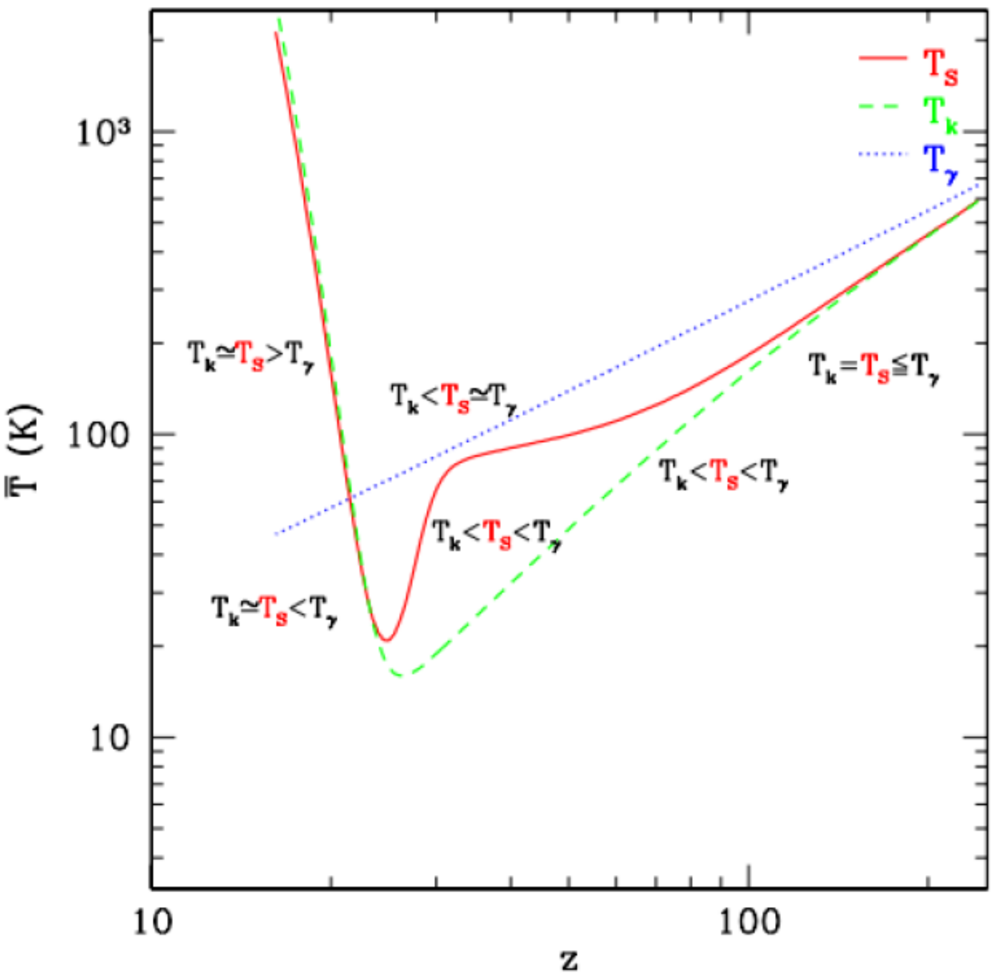
$$\frac{n_1}{n_0} \equiv \left(\frac{g_1}{g_0}\right)\exp\left(-\frac{E_\star}{k_B T_s}\right).$$

Spin temperature

In the hyperfine structure $g_1 = 3, g_0 = 1$

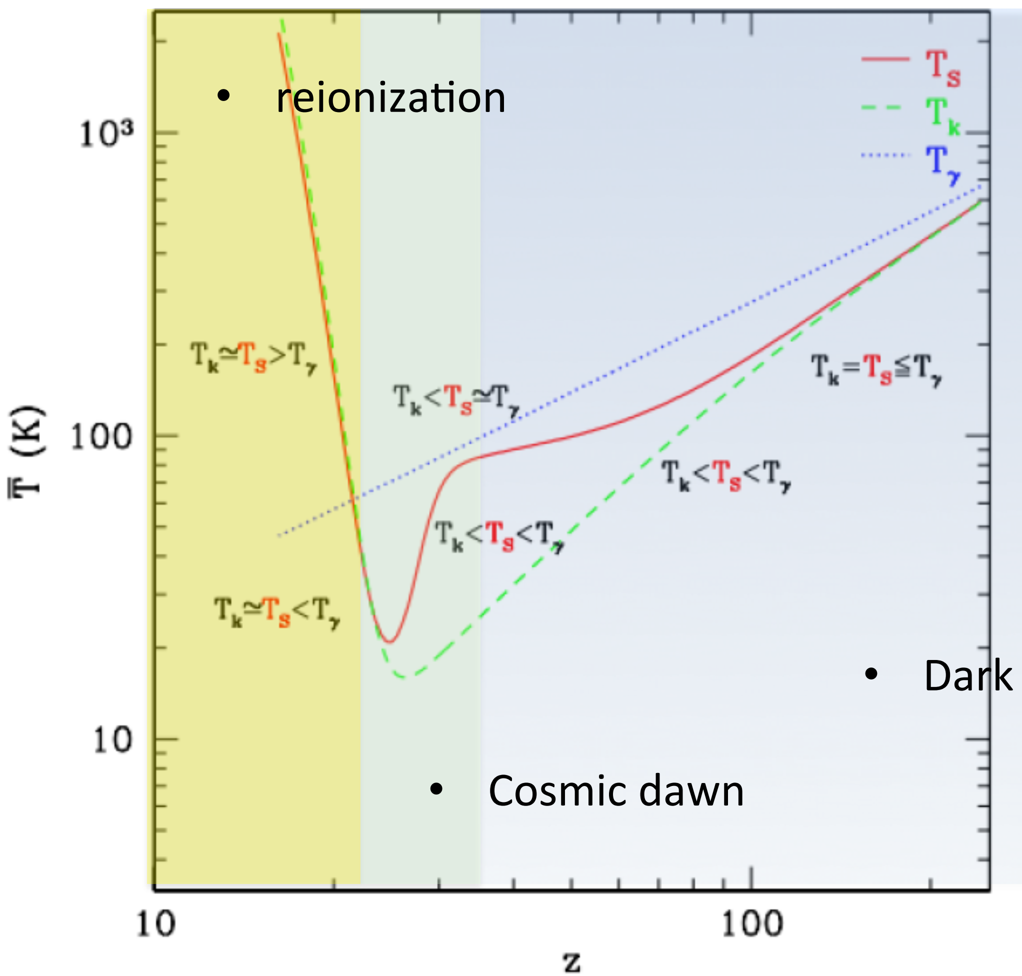
$$E_\star = k_B T_\star, \quad T_\star = 0.0681 \rm K$$

Global Spin temperature



$$T_s = \frac{T_\gamma + (y_\alpha + y_c)T_K}{1 + y_\alpha + y_c}$$

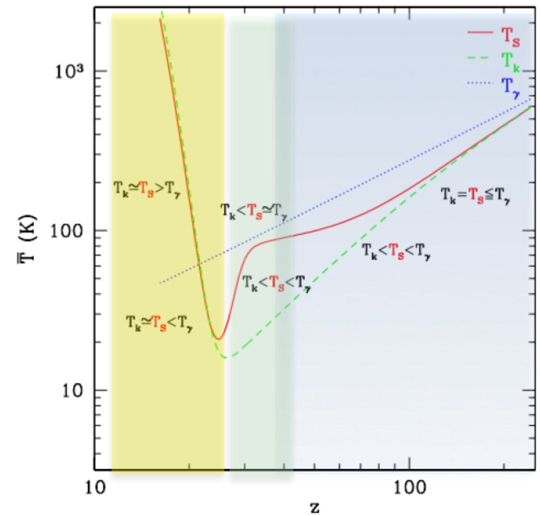
Global Spin temperature



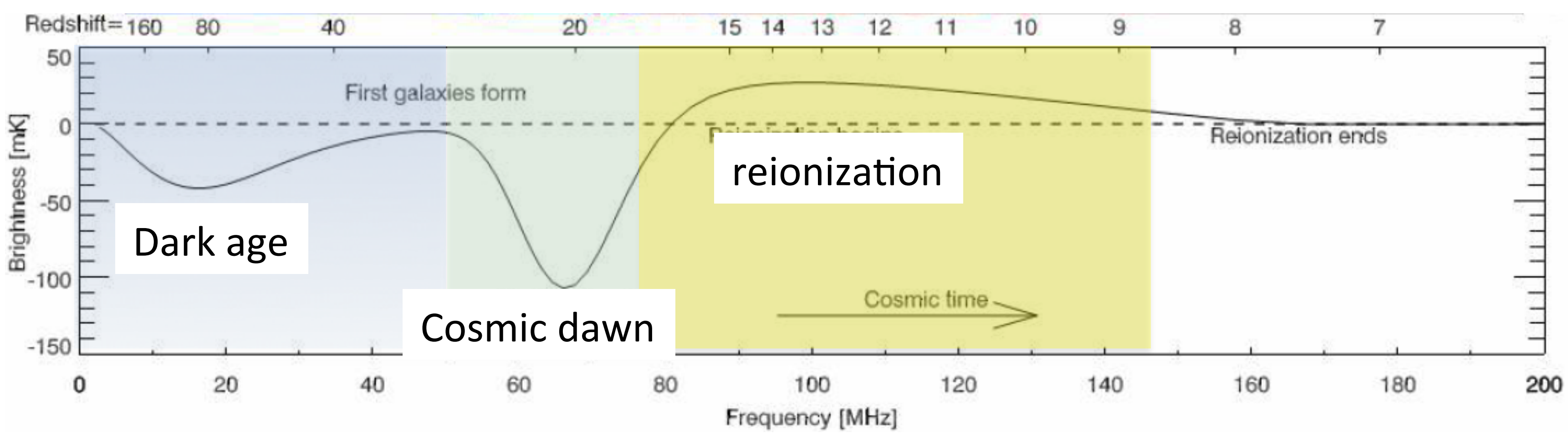
- reionization
- Cosmic dawn
- Dark age

Global 21cm signal

$$\delta T_b(\nu) \approx 28 x_{\rm HI} \left(1 - \frac{T_\gamma(z)}{T_s(z)}\right) \left(\frac{1+z}{10}\frac{0.15}{\Omega_m h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.025}\right) \; [\rm mK]$$

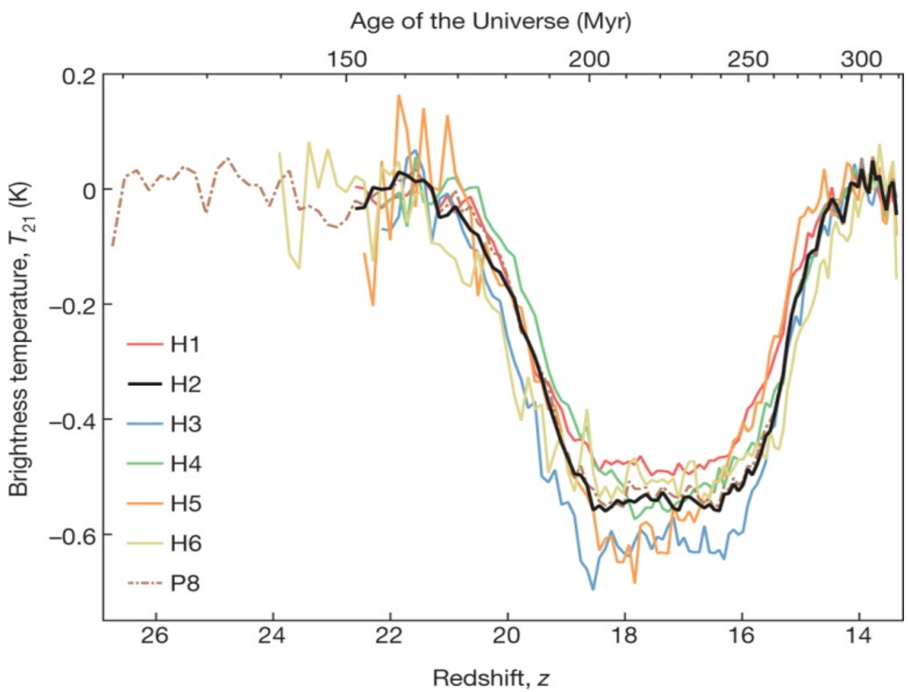


Global 21cm signal



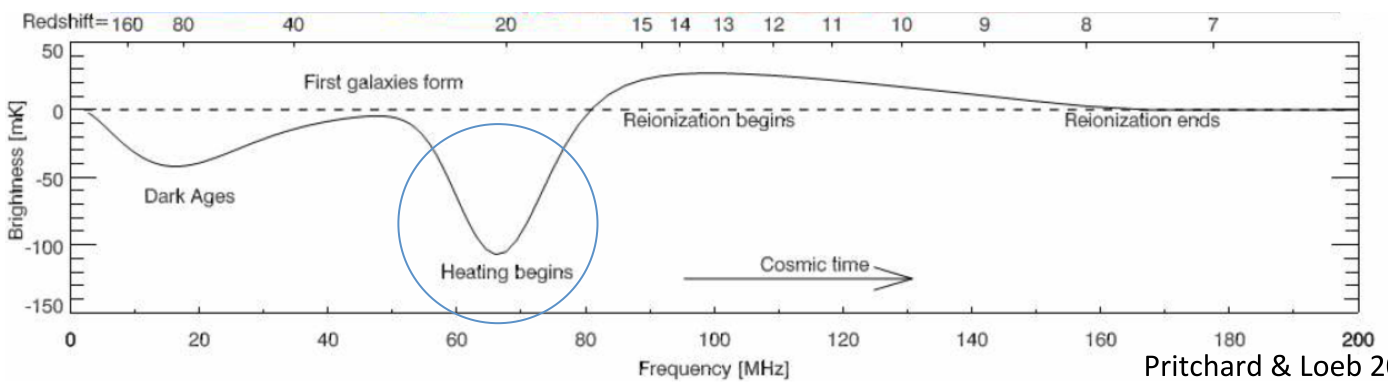
Pritchard & Loeb 2012

Experiment to Detect the Global EoR Signature (EDGES)



Best-fitting 21-cm absorption profiles for each hardware case

It seems that the spin temperature strongly couples with the gas temperature by Ly-a



Pritchard & Loeb 2012

EDGES anomaly

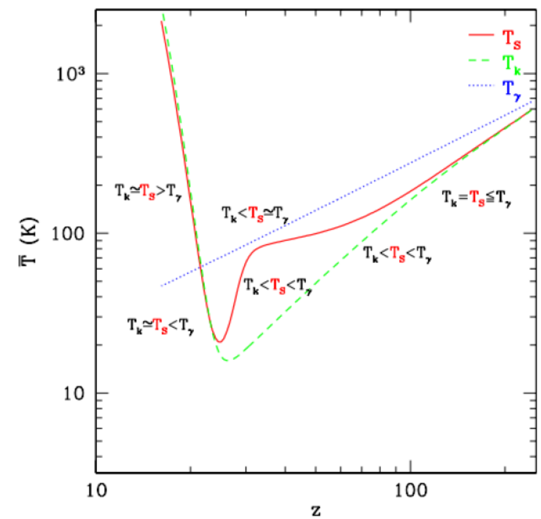
$$\delta T_b(\nu) \approx 28 x_{\rm HI} \left(1 - \frac{T_\gamma(z)}{T_s(z)}\right) \left(\frac{1+z}{10} \frac{0.15}{\Omega_m h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.025}\right) \ [\mathrm{mK}]$$

EDGES result

$$\frac{T_\gamma}{T_s} \approx \frac{T_\gamma}{T_K} \sim 15$$

Standard cosmological model
(at most)

$$\frac{T_\gamma}{T_K} \sim 7$$

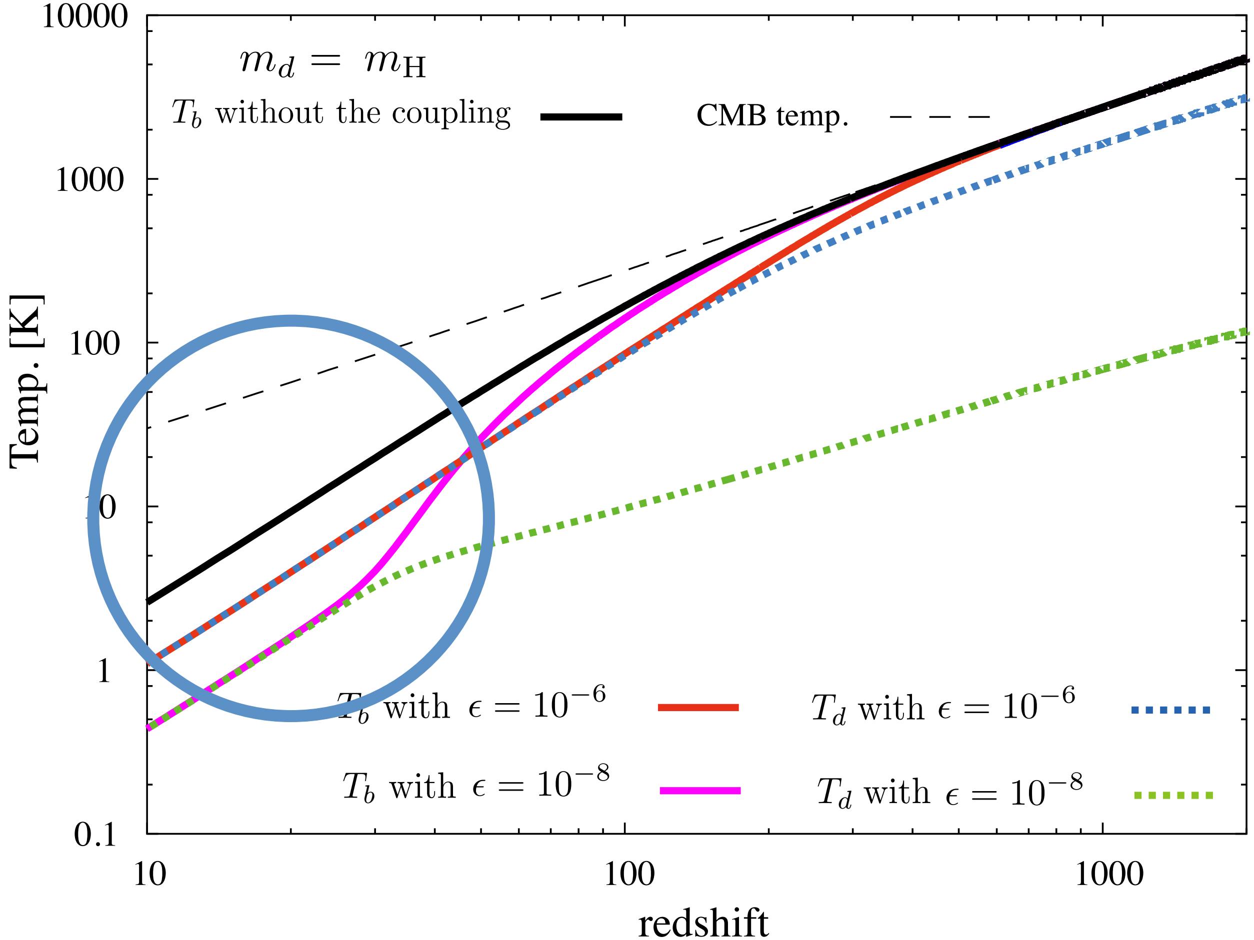


Baryon gas is cooler than
in the standard cosmological model?

DM-Baryon interaction can cool the baryon temperature

$$\frac{dQ}{dt} = C_{\rm b-d}(T_{\rm d} - T)$$

HT et al. 2014



Baryon-Dark matter coupling

- Redshifted 21cm signal

  HT et al. 2014, Brkana 2019…

- Small-scale power spectrum

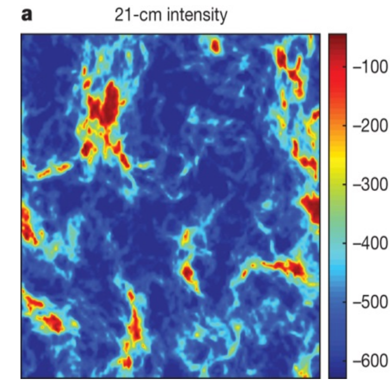
  Dvorkin et al. 2014, Ooba, HT et al. 2019

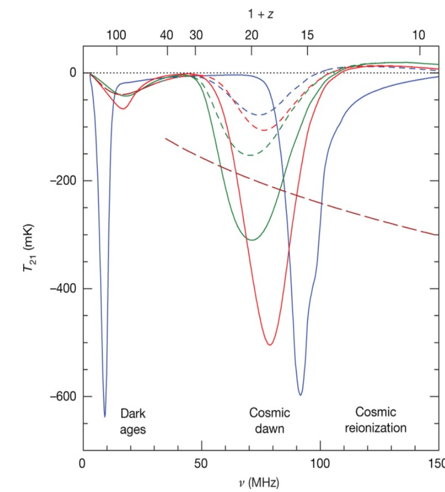
- First star formation

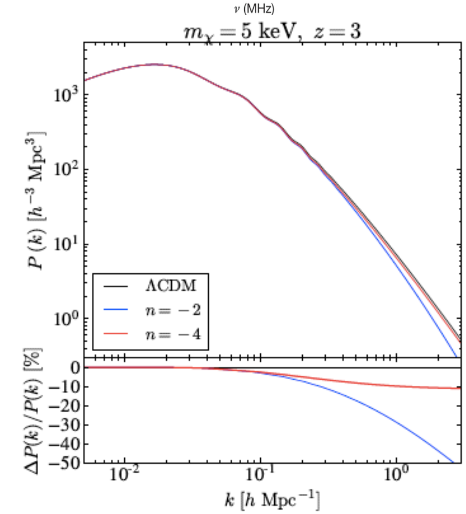
  Hirano & Bromm 2018

- Dark matter halo profile

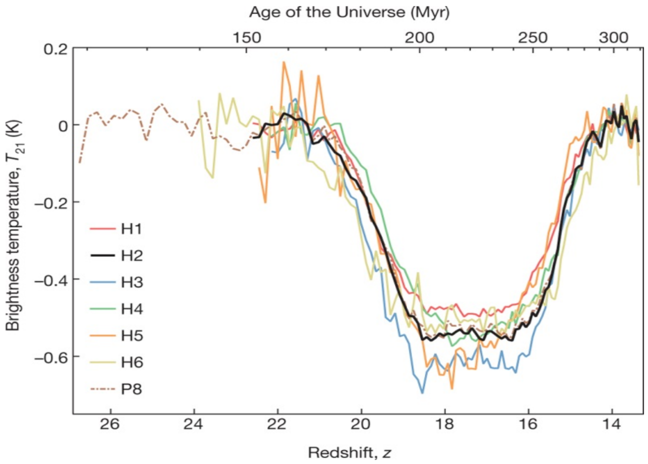
  Kadota, HT et al. 2016



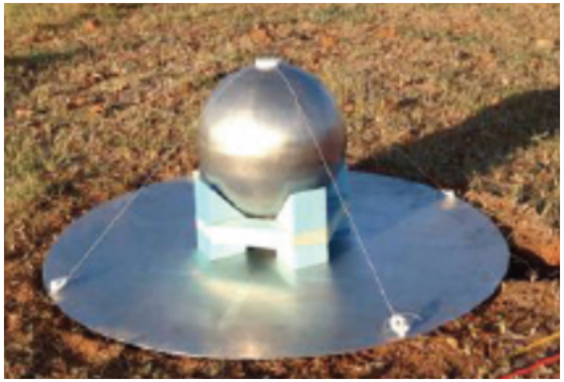




EDGES results

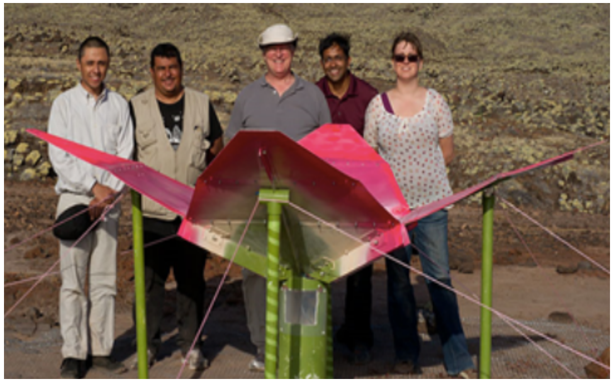


Need to be confirmed by other experiments !



SARAS

LEDA



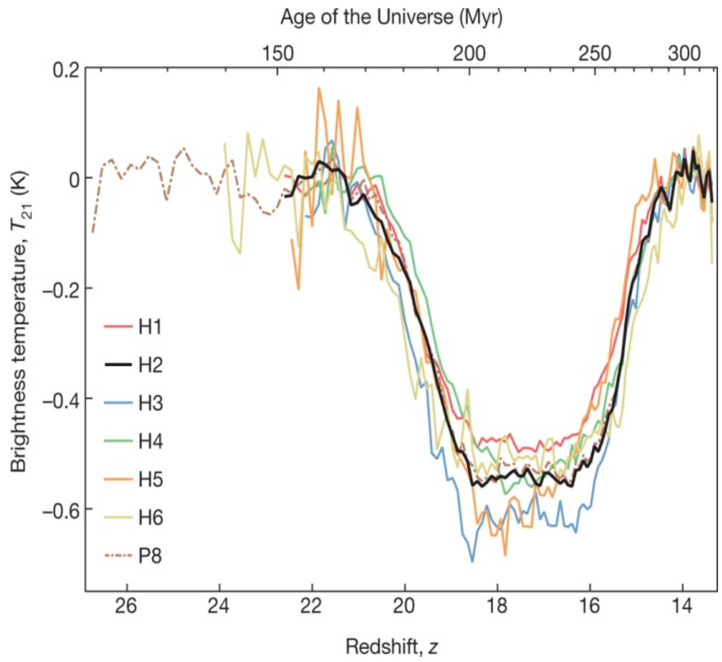
Sci-Hi

EDGES results

Global 21 cm Science

Absorption line signature $(T_{\rm gas} < T_\gamma)$

Ly-α photon production



- DM-Baryon coupling
- Primordial black holes
  (Clark et al. 2018, Hecktor et al. 2018)
- Primordial magnetic fields
  (Minoda, HT et al. 2019)
- Decaying / annihilating dark matter (Clark et al. 2018)
- Structure formation in the early universe (Yoshiura et al. 2018)

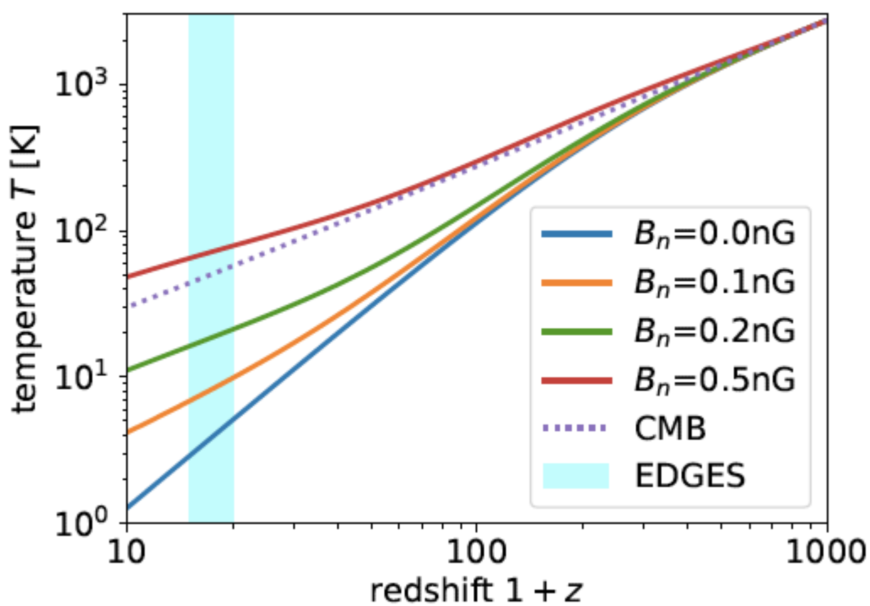
Primordial magnetic fields

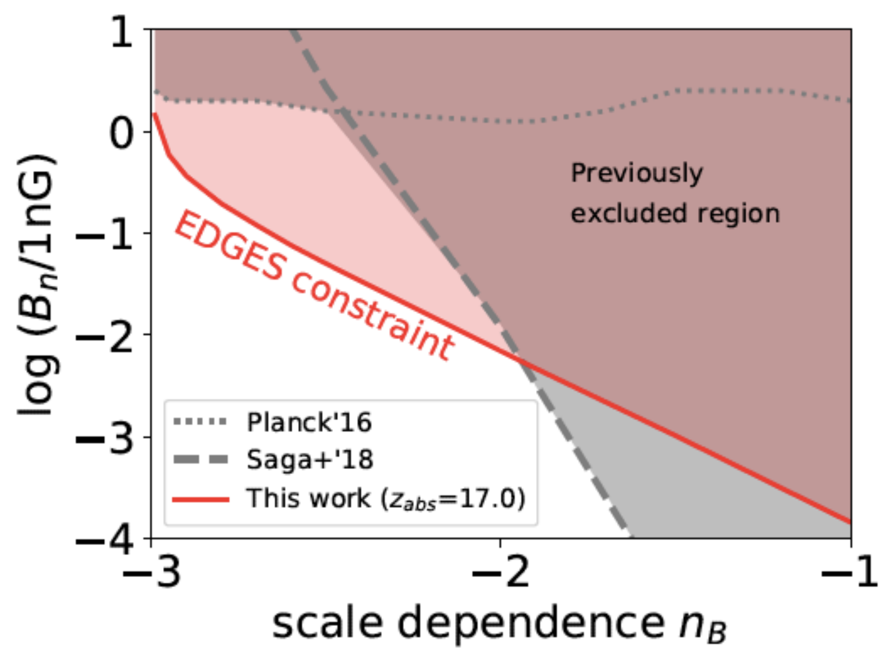
Minoda, HT, Takahashi 2019

Seed magnetic fields of magnetic fields in galaxy and galaxy clusters?

Additional heat source for the IGM gas

$$\left.\frac{dQ}{dt}\right|_{\rm heat} = \frac{|(\nabla \times \mathbf{B}) \times \mathbf{B}|^2}{16\pi^2 \xi \rho_{\rm b}^2} \frac{1 - x_{\rm e}}{x_{\rm e}}$$





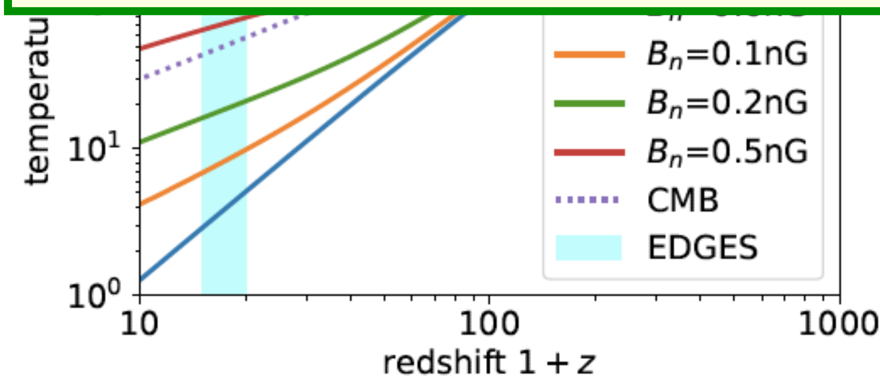
Primordial magnetic fields

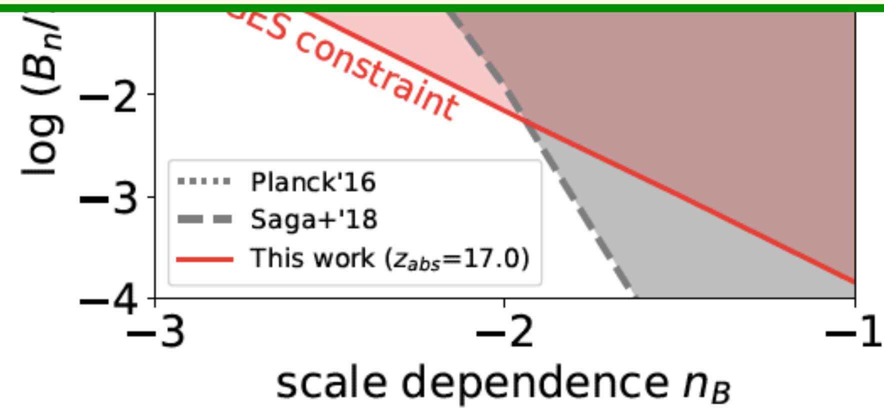
Seed magnetic fields of magnetic fields in galaxy and galaxy clusters?

Additional heat source for the IGM gas

$$\left.\frac{dQ}{dt}\right|_{\rm heat} = \frac{|(\nabla \times \mathbf{B}) \times \mathbf{B}|^2}{16\pi^2 \xi \rho_{\rm b}^2}\frac{1-x_{\rm e}}{x_{\rm e}}$$

Global 21 cm signal can provide constraints on the heating sources during the EoR





Summary

Reionization ⟷ First stars, First galaxies, QSO, etc.

- Ionization fraction evolution
- Thermal history

Global 21 cm signal measurement

- First result from EDGES experiment

21 cm fluctuation measurement

Signal image : First stars, galaxies, QSOs, SNe

Abe-san's talk

Statistical analysis : first star statistical property

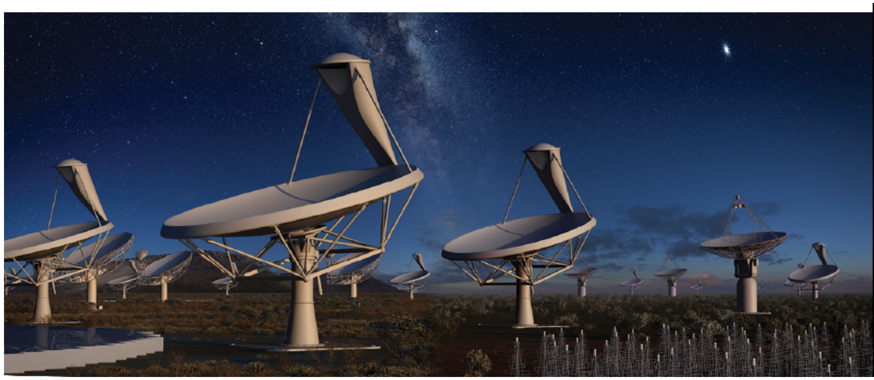
Tanaka-san's talk

application to cosmology

- Initial density fluctuations

Furugori-san's talk

SKA（Squqre Kilometer Array）



In the 2020's