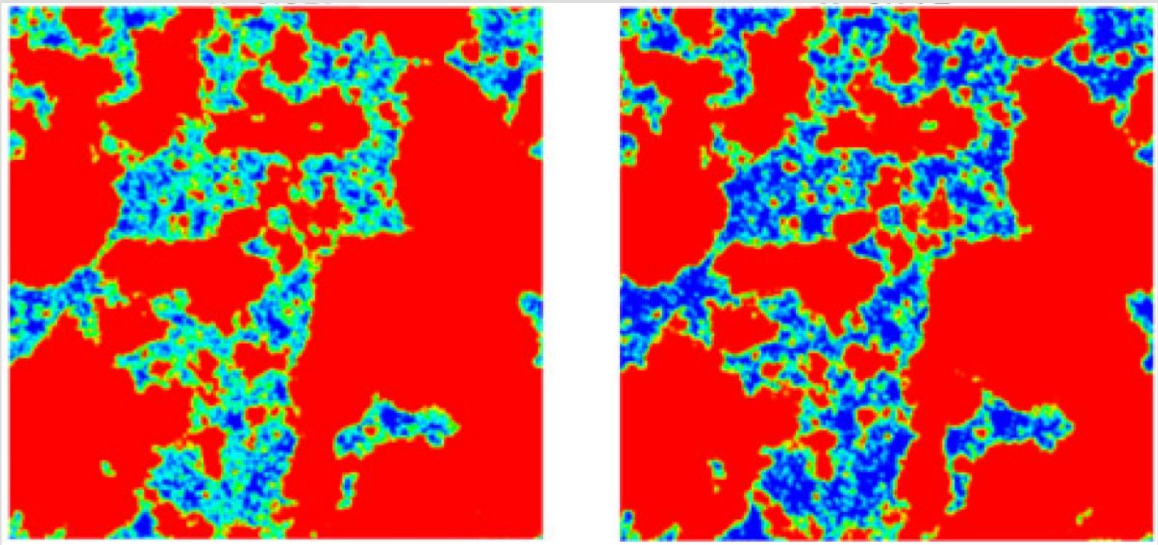
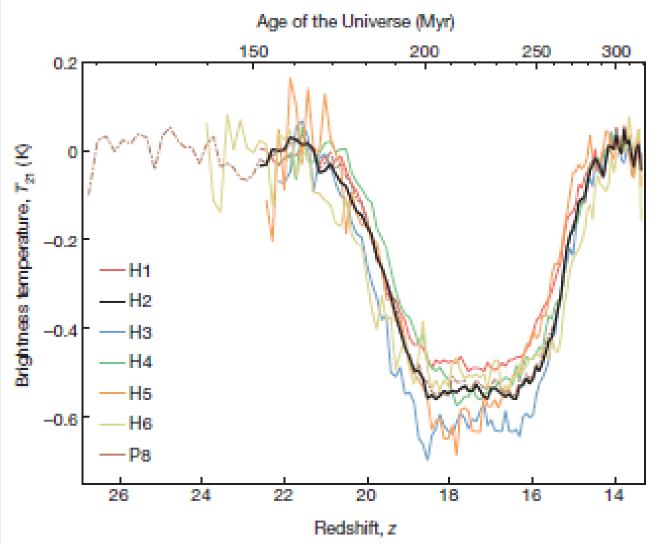
Variance in cosmic reionization scenarios and its impact on the baryon-dark matter scattering cross-section

Based on KA+2012 ApJL 756:16 and work in progress





Kyungjin Ahn (Chosun U, Korea)
COSMOLOGY, Quy Nhon, Vietnam
Aug 2019

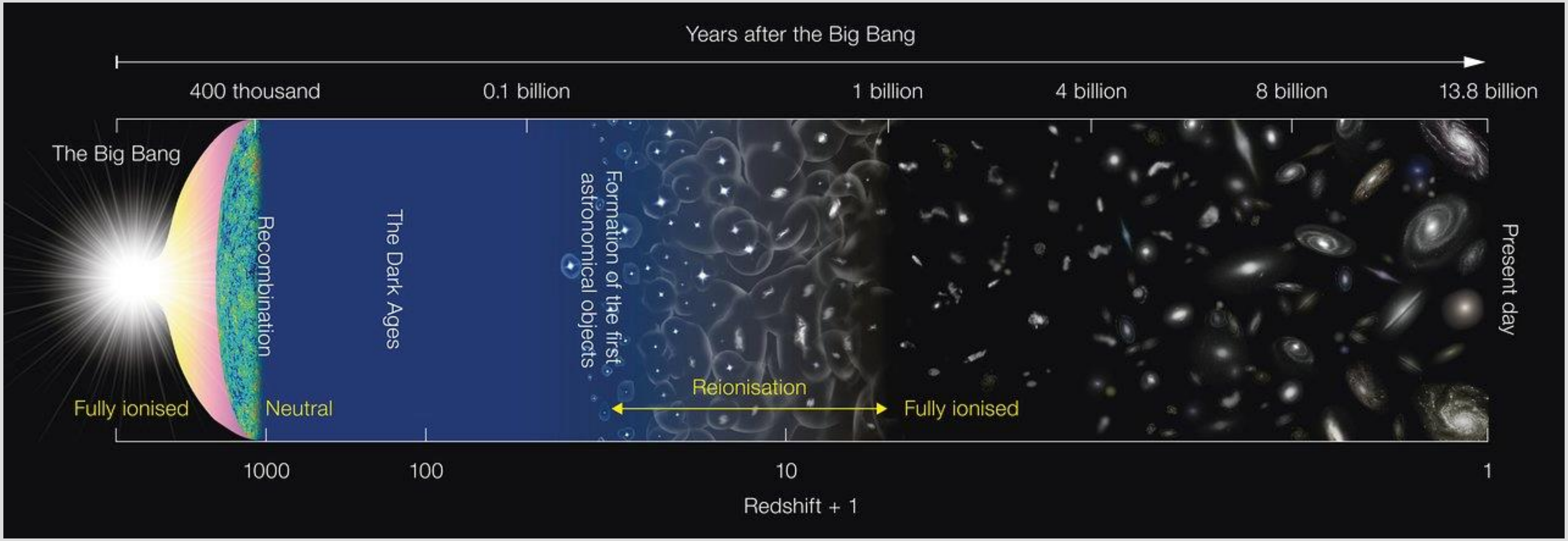
Outline

- Cosmic reionization in a nutshell
- Planck-favored reionization history
- EDGES result and interpretation
- More constraint on DM-baryon scattering from reionization (LiteBird!)

Cosmic Reionization in a nutshell

(and my favorite scenario)

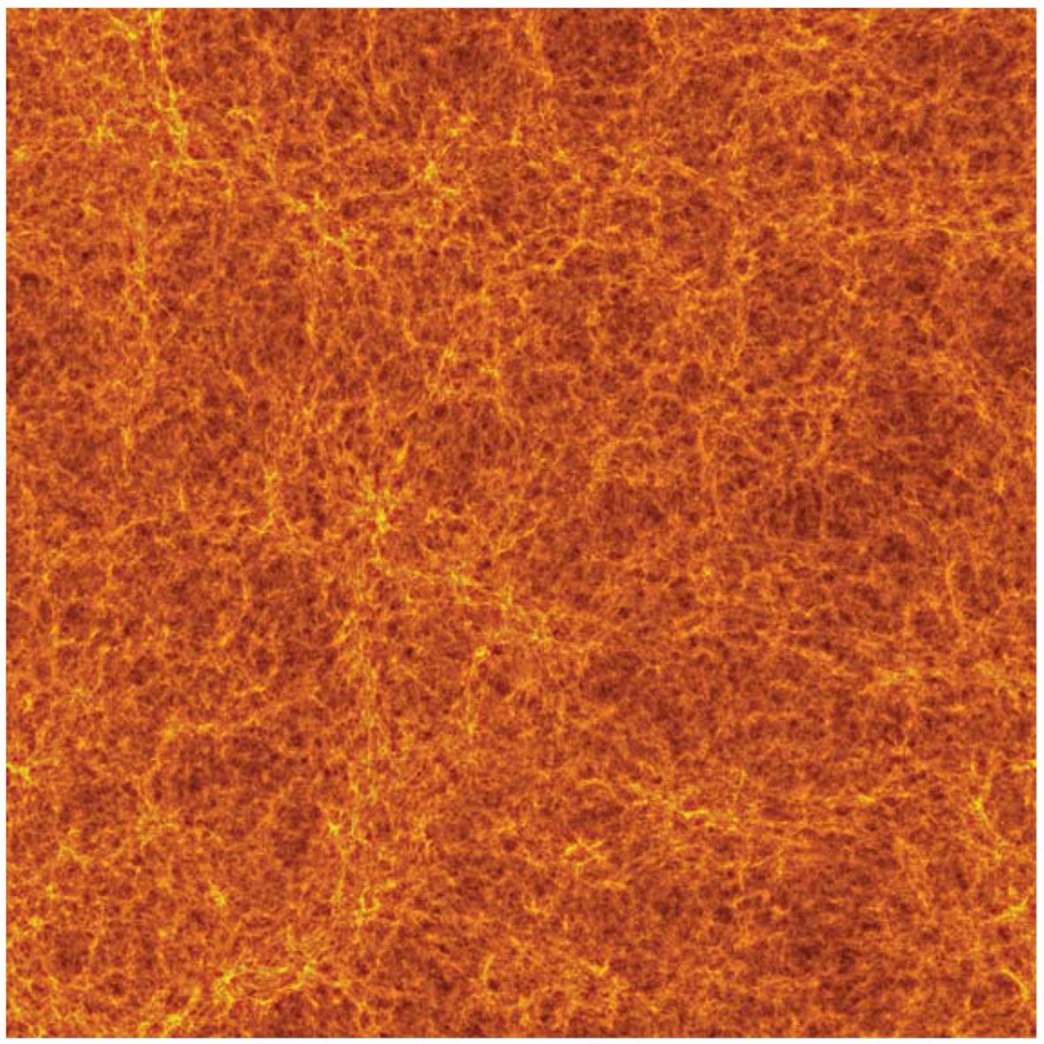
Evolution of the universe



credit: NAOJ

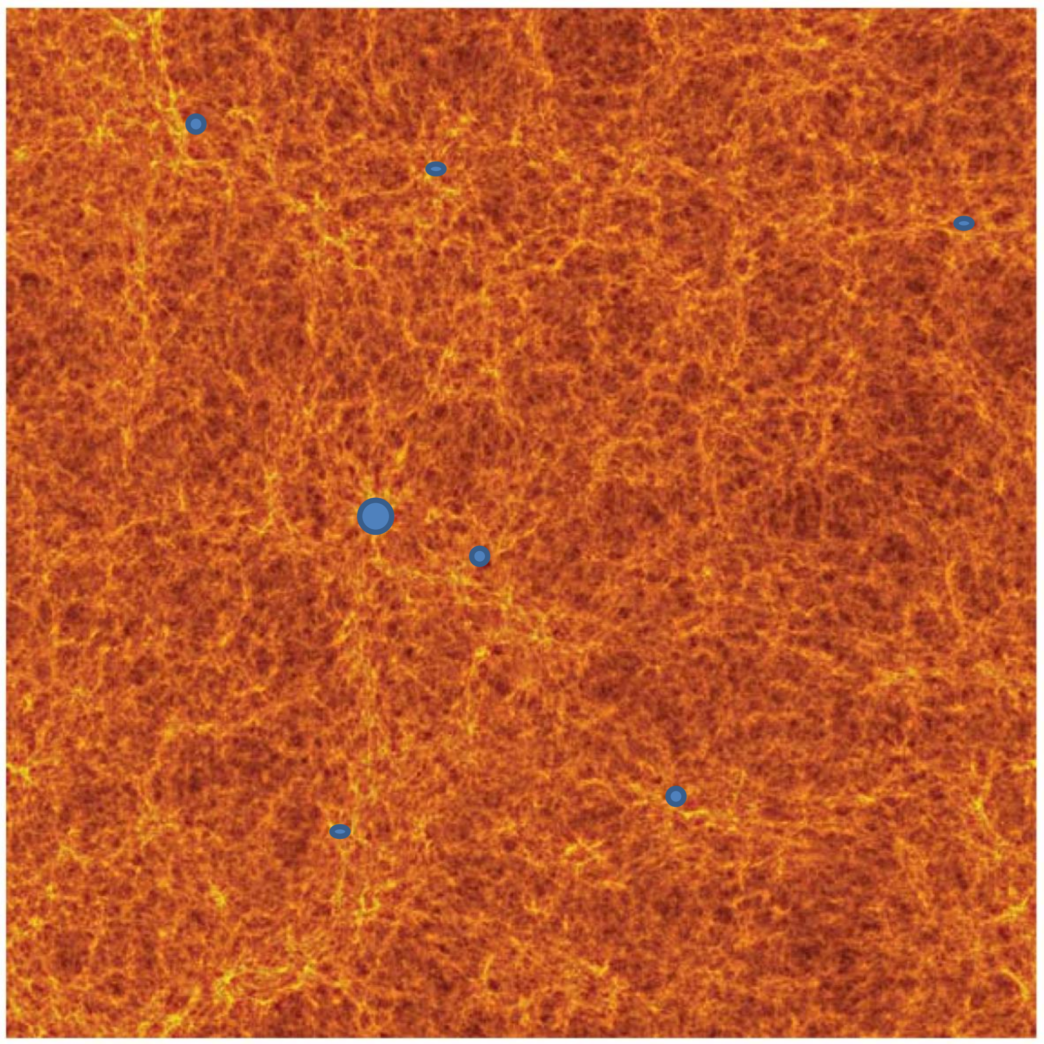
Simulation of Cosmic Reionization – 1. N-body(+hydro) simulation

density field



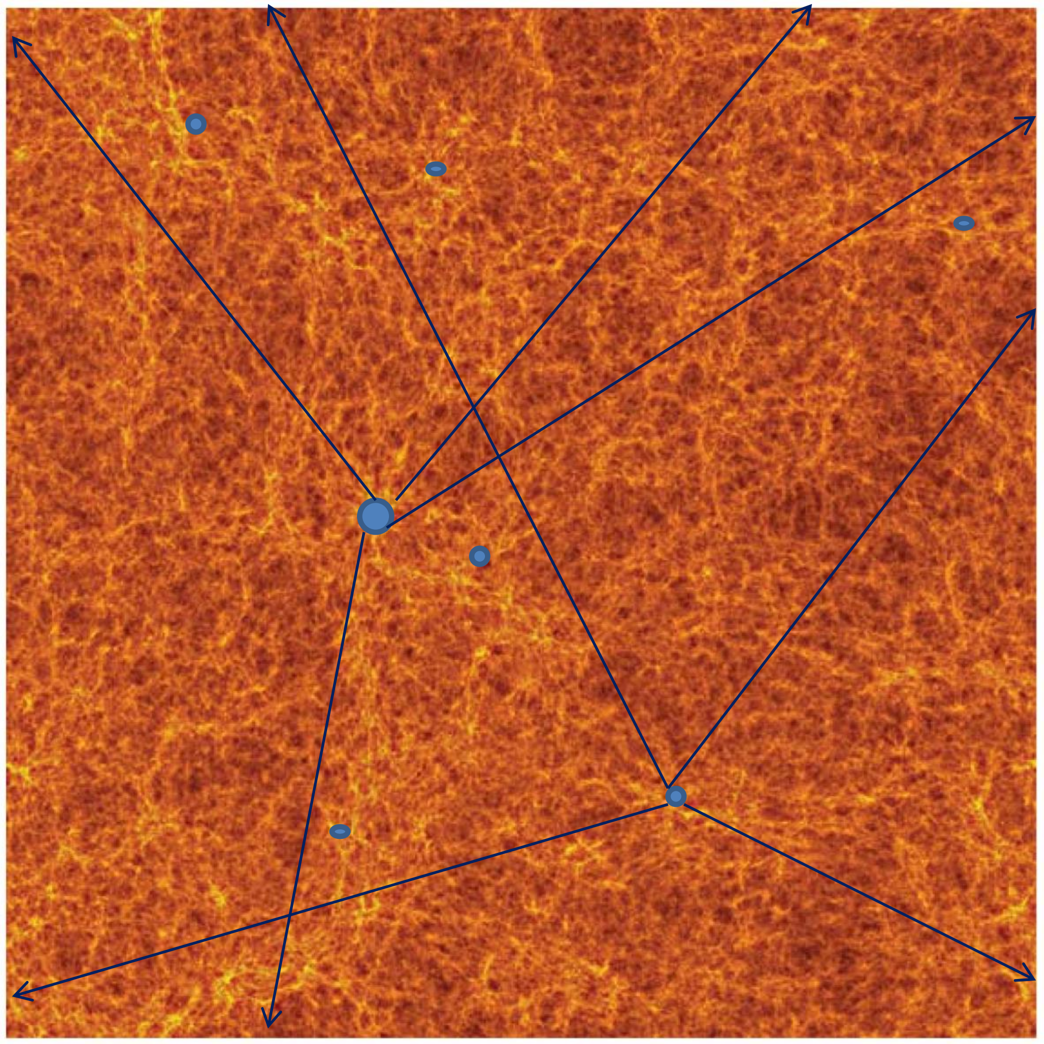
Simulation of Cosmic Reionization – 2. Halo Identification

Halo → Star → ionizing photon



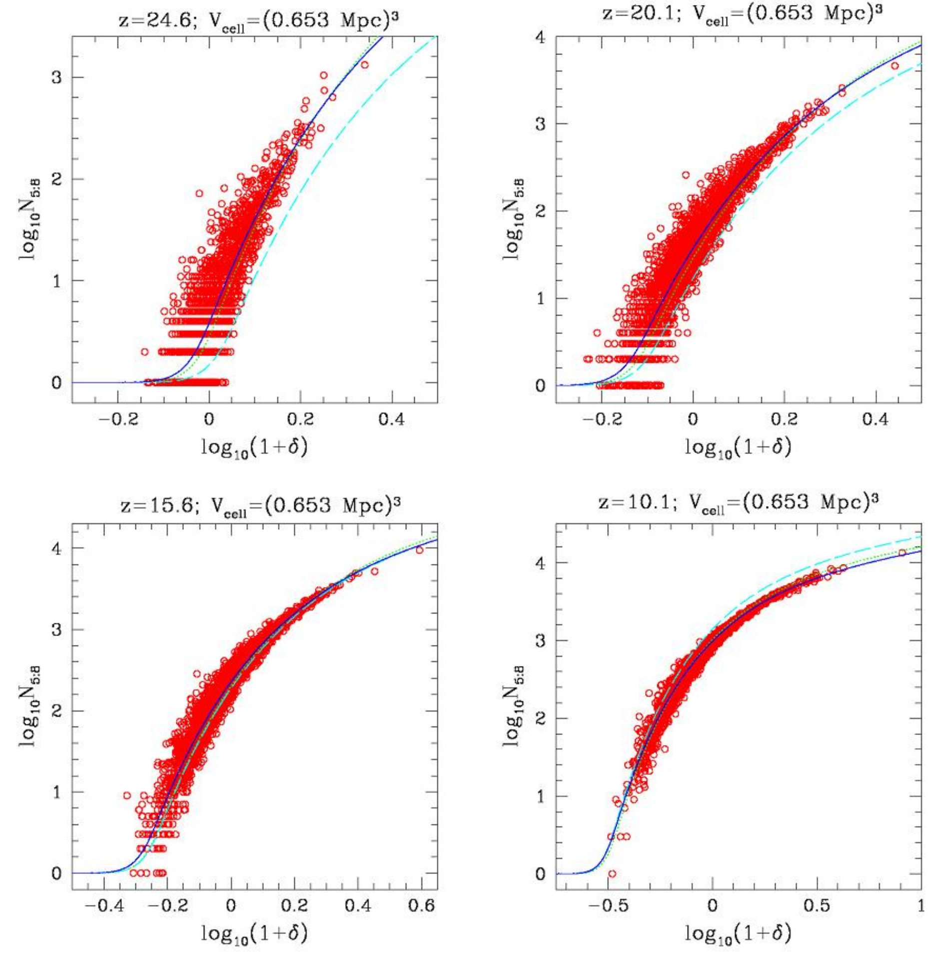
Simulation of Cosmic Reionization – 3. Ray tracing

- Draw rays into all directions from each source
- Along each ray, perform radiative transfer + chemistry calculation



What’s new?

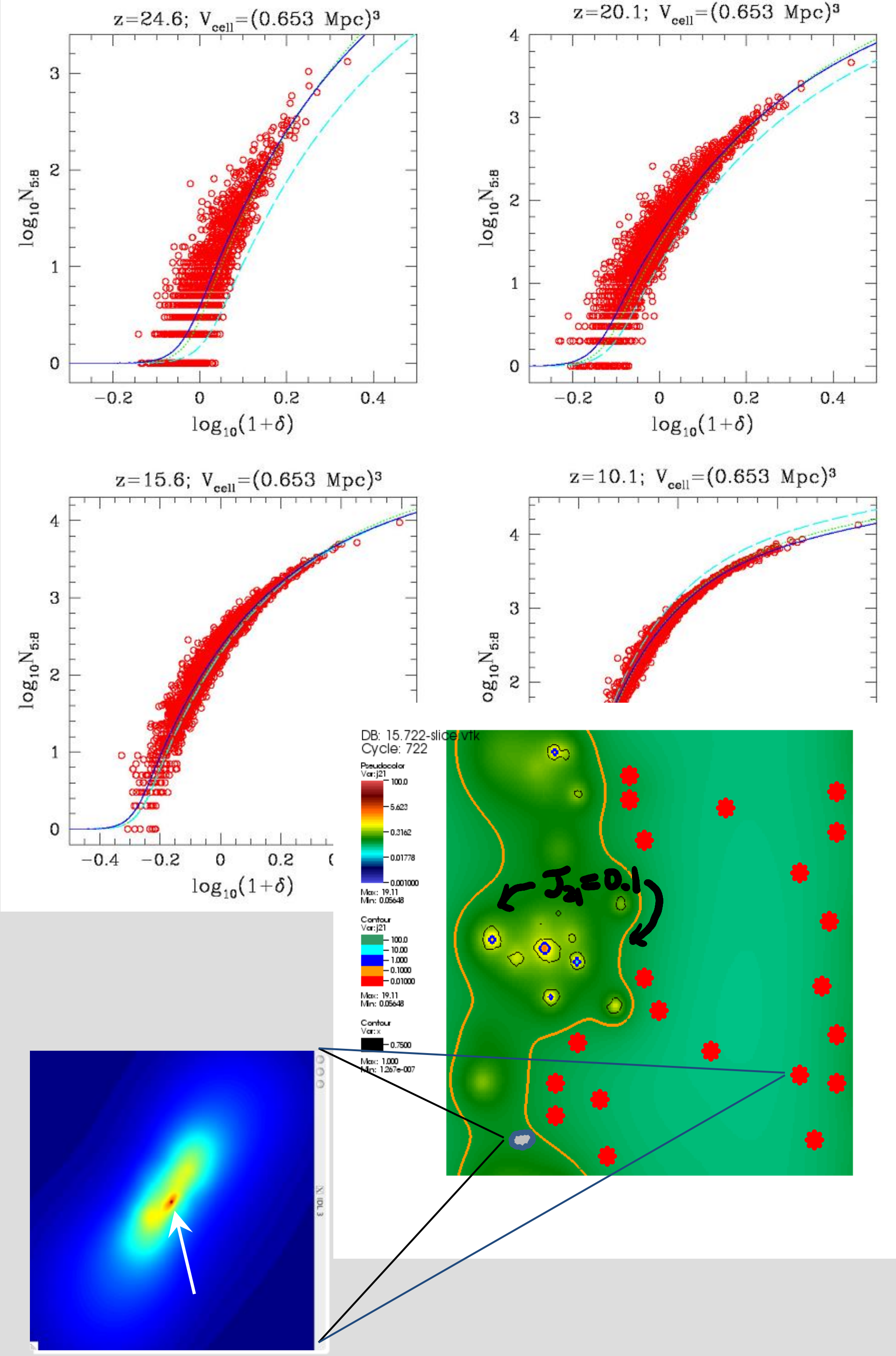
- Populating grid with minihalos (first stars!)
  - small-box (6.3/h Mpc) simulation resolving minihalos
  - correlation between density & minihalo population (KA, Iliev, Shapiro, Srisawat 2015)
  - put one Pop III star per minihalo



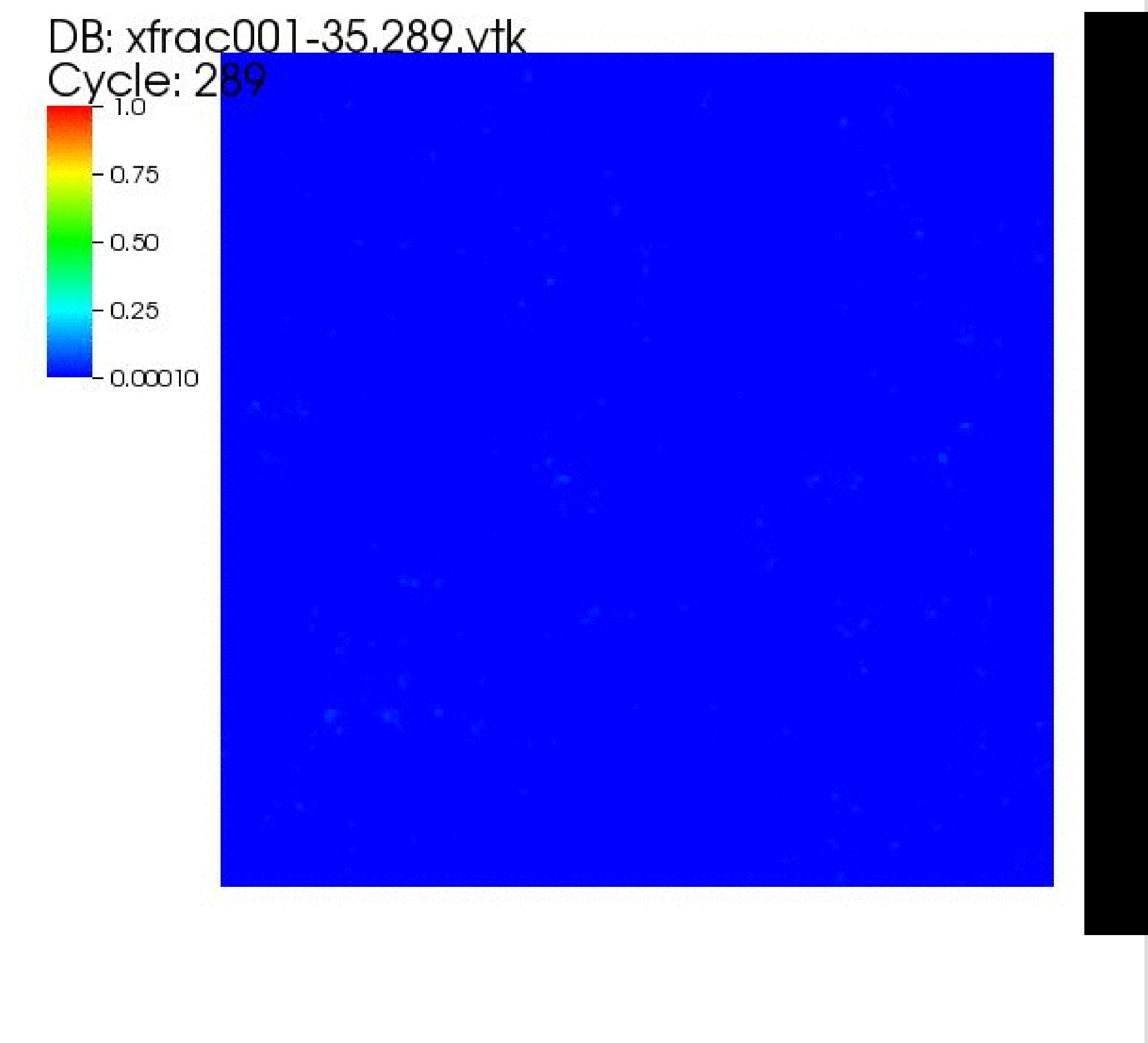
What’s new?

- Populating grid with minihalos (first stars!)
    - small-box (6.3/h Mpc) simulation resolving minihalos
    - correlation between density & minihalo population (KA, Iliev, Shapiro, Srisawat 2015)
    - put one Pop III star per minihalo

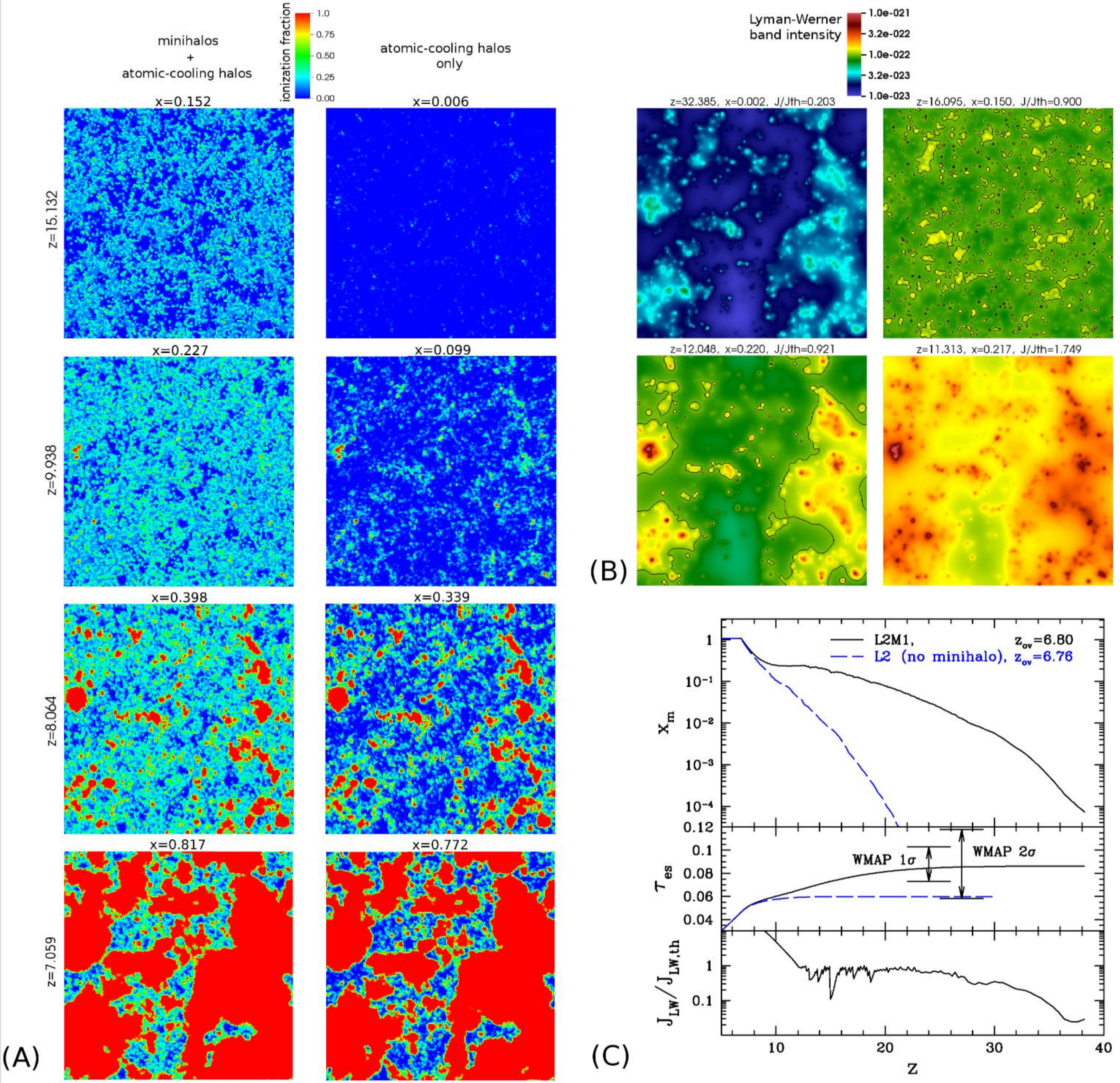
- Considering photo-dissociation of coolant
    - calculate transfer of Lyman-Werner Background (KA, Shapiro, Iliev, Mellema, Pen 2009)
    - remove first star from minihalos, if LW intensity over-critical



114/h Mpc, w/ Minihalo+ACH, M(Pop III star)=$300M_\odot$, $J_{LW,th}=0.1\times10^{-21}$ erg cm^{-2} s^{-1} sr^{-1}
(Ahn, Iliev, Shapiro, Mellema, Koda, Mao 2012)



With and Without Minihalo stars (first stars)



Planck-favored reionization history

(agreeing with my favorite scenario)

Some hint of early first star formation from Planck 2015

- First star formation epoch as expected by this work?

  (Miranda, Lidz, Heinrich, Hu 2017)

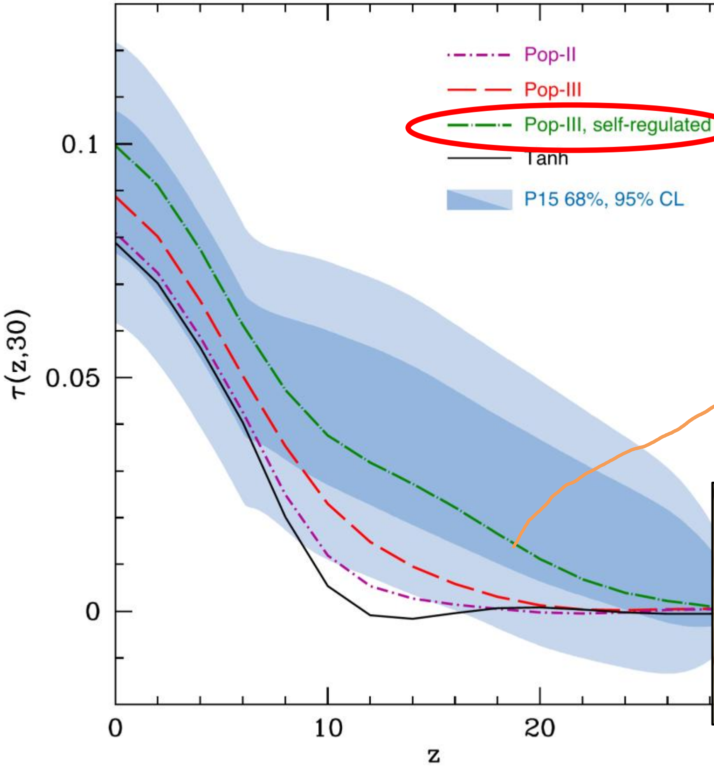
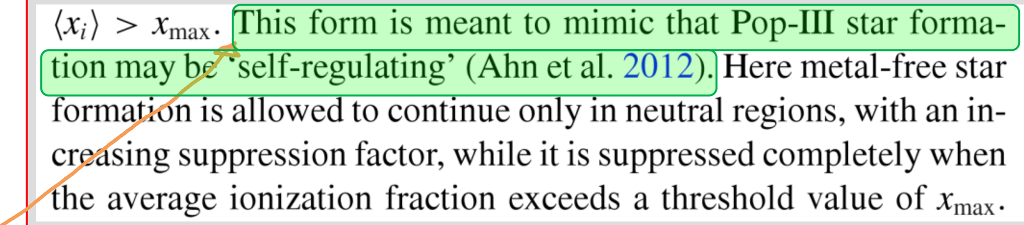
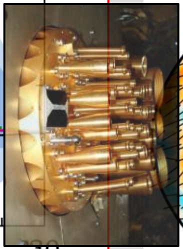
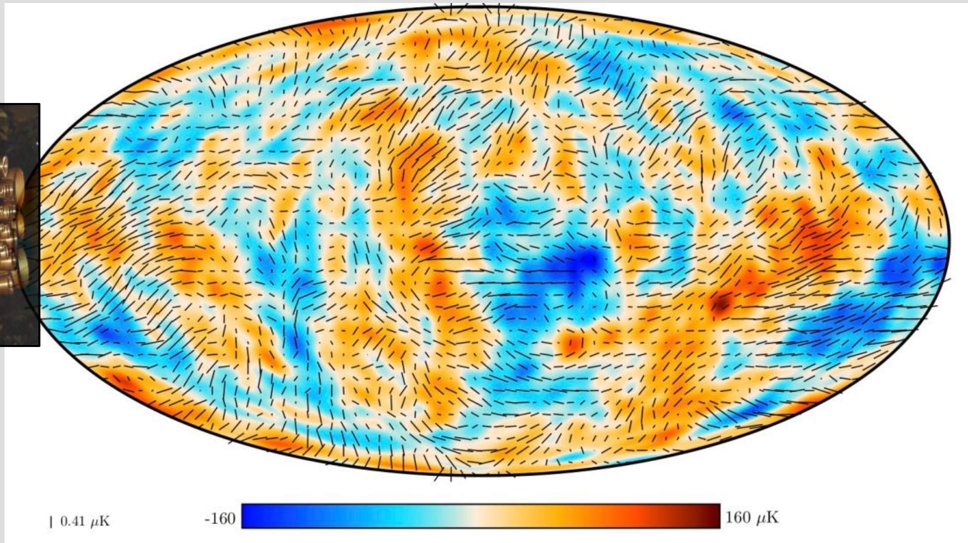


Figure 3. Cumulative optical depth $\tau(z, 30)$ in the *Planck* 2015 analysis. Blue shaded regions are the 68 per cent and 95 per cent constraints from the complete PC analysis. This is compared with the best-fitting models from Table 1: Tanh (black solid line), Pop-II only (purple dot-short-dashed line), additional Pop-III fiducial (red long-dashed line), additional Pop-III self-regulated (green dot–dashed line) models.



$\langle x_i \rangle > x_{\max}$. This form is meant to mimic that Pop-III star formation may be 'self-regulating' (Ahn et al. 2012). Here metal-free star formation is allowed to continue only in neutral regions, with an increasing suppression factor, while it is suppressed completely when the average ionization fraction exceeds a threshold value of $x_{\max}$.





Some hint? of early first star formation from Planck 2018

- TANH has a strong unphysical prior
- FlexKnot has some prior
- PCA (by Wayne Hu) allows any shape of reionization history
- Seems some high-z (z>15) tail is allowed.

???

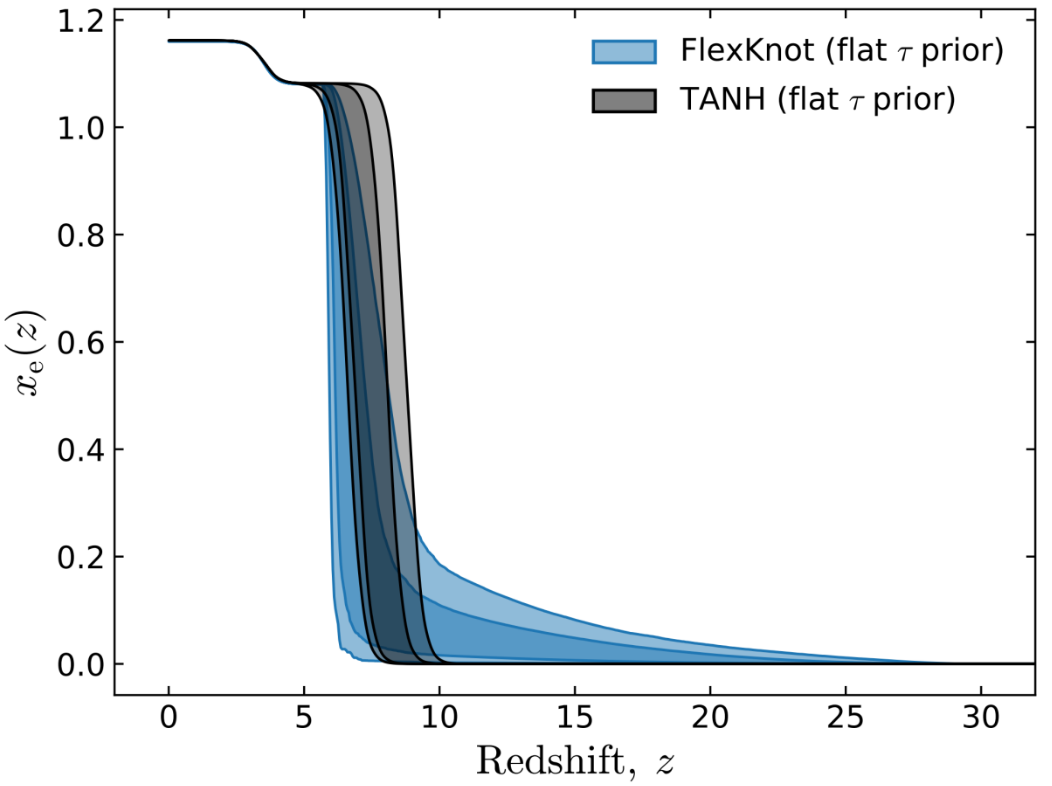


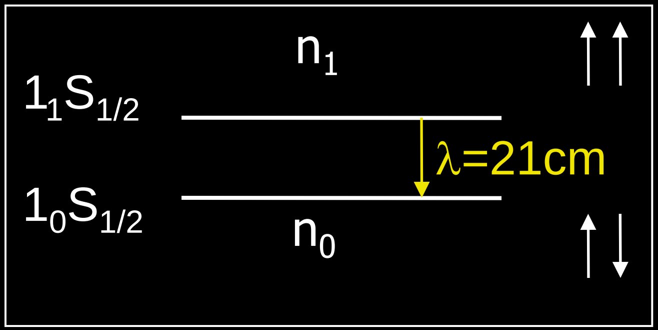
Fig. 45. Constraints on the free electron fraction, $x_\mathrm{e}(z)$, from lowE alone, with $A_\mathrm{s}e^{-2\tau}$ and other cosmological and instrumental parameters held fixed to their best-fit values from *Planck* TT,TE,EE, and with a flat prior on τ. The shaded bands are middle 68th and 95th percentiles (note that this does not correspond exactly to confidence intervals). The FlexKnot constraints show that any non-zero component of reionization above a redshift of about 15 is highly disfavoured.

EDGES result and interpretation

(with some excerpts from slides of J. Pritchard)

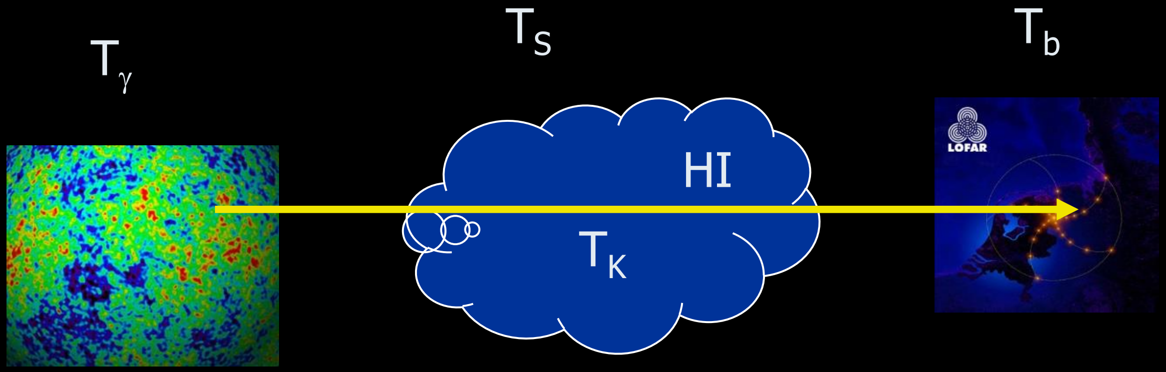
21 cm basics

- HI hyperfine structure



$n_1/n_0=3\exp(-h\nu_{21cm}/kT_s)$

- Use CMB backlight to probe 21cm transition



z=13
f_{21cm}=1.4 GHz

z=0
f_{obs}=100 MHz

- 3D mapping of HI possible - angles + frequency
- 21 cm brightness temperature

$$T_b = 27 x_{\rm HI}(1+\delta_b)\left(\frac{T_S-T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\right)^{1/2}\ {\rm mK}$$

- 21 cm spin temperature

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

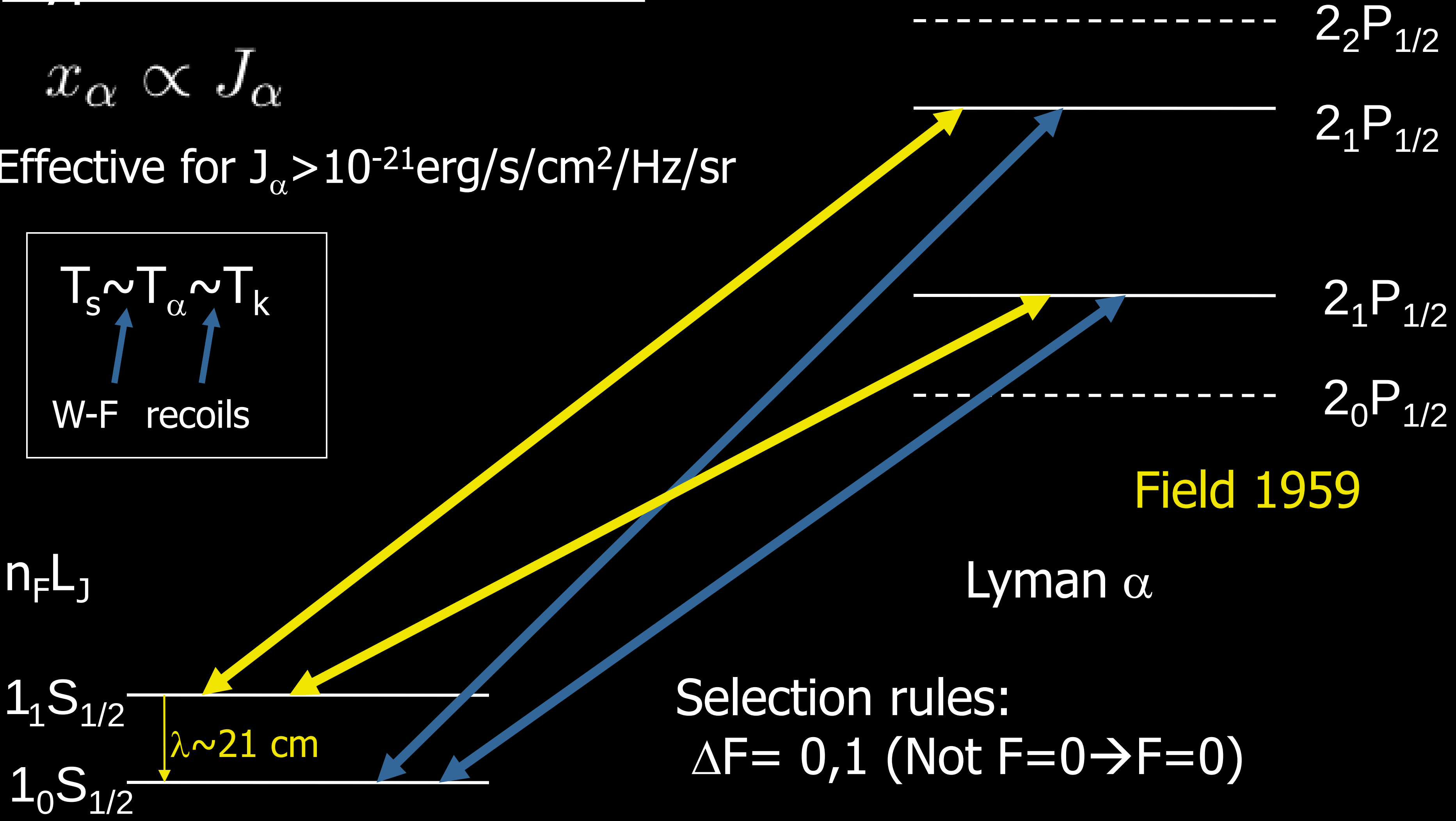
- Coupling mechanisms:
  - Radiative transitions (CMB)
  - Collisions
  - Wouthuysen-Field

Wouthuysen–Field effect

Hyperfine structure of HI

$x_\alpha \propto J_\alpha$

Effective for $J_\alpha > 10^{-21}$ erg/s/cm^2/Hz/sr



$T_s \sim T_\alpha \sim T_k$

W-F recoils

$2_2P_{1/2}$

$2_1P_{1/2}$

$2_1P_{1/2}$

$2_0P_{1/2}$

Field 1959

n_FL_J

Lyman α

$1_1S_{1/2}$

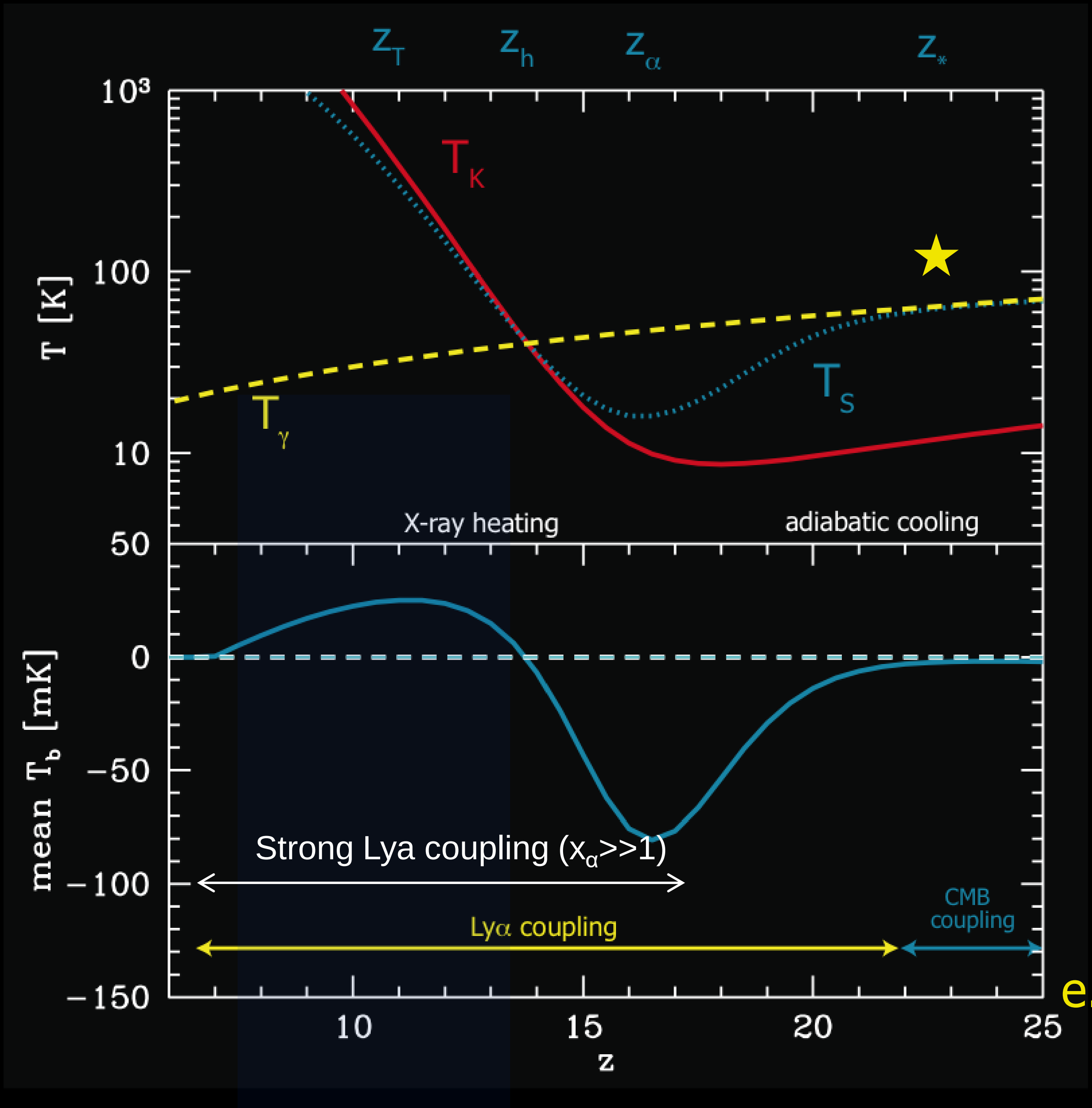
λ~21 cm

$1_0S_{1/2}$

Selection rules:

ΔF= 0,1 (Not F=0→F=0)

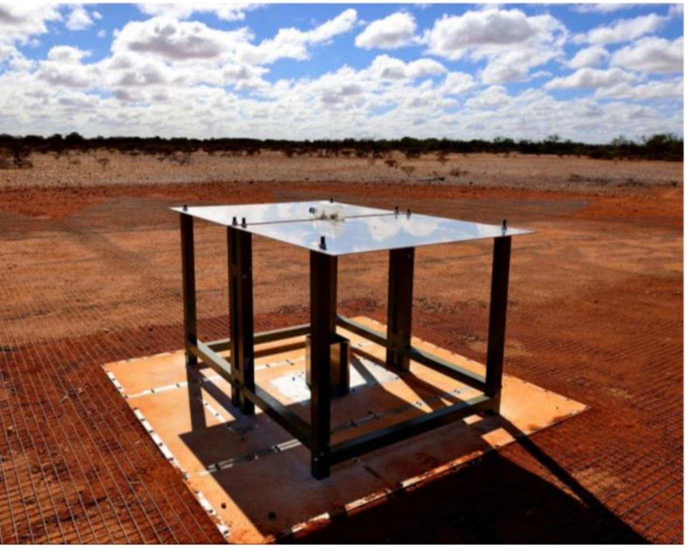
Global Thermal History



e.g. Furlanetto 2006

EDGES

Low-Band



50–100 MHz

60–160 MHz

Mid-Band

High-Band

100–200 MHz

Surprise

- EDGES successfully probed cosmic dawn (CD) and epoch of reionizaion (EoR)
  - First such detection, but expected, so not a surprise
- Surprise: absorption ($T_b < 0$) signal too strong to be possible in ΛCDM framework !

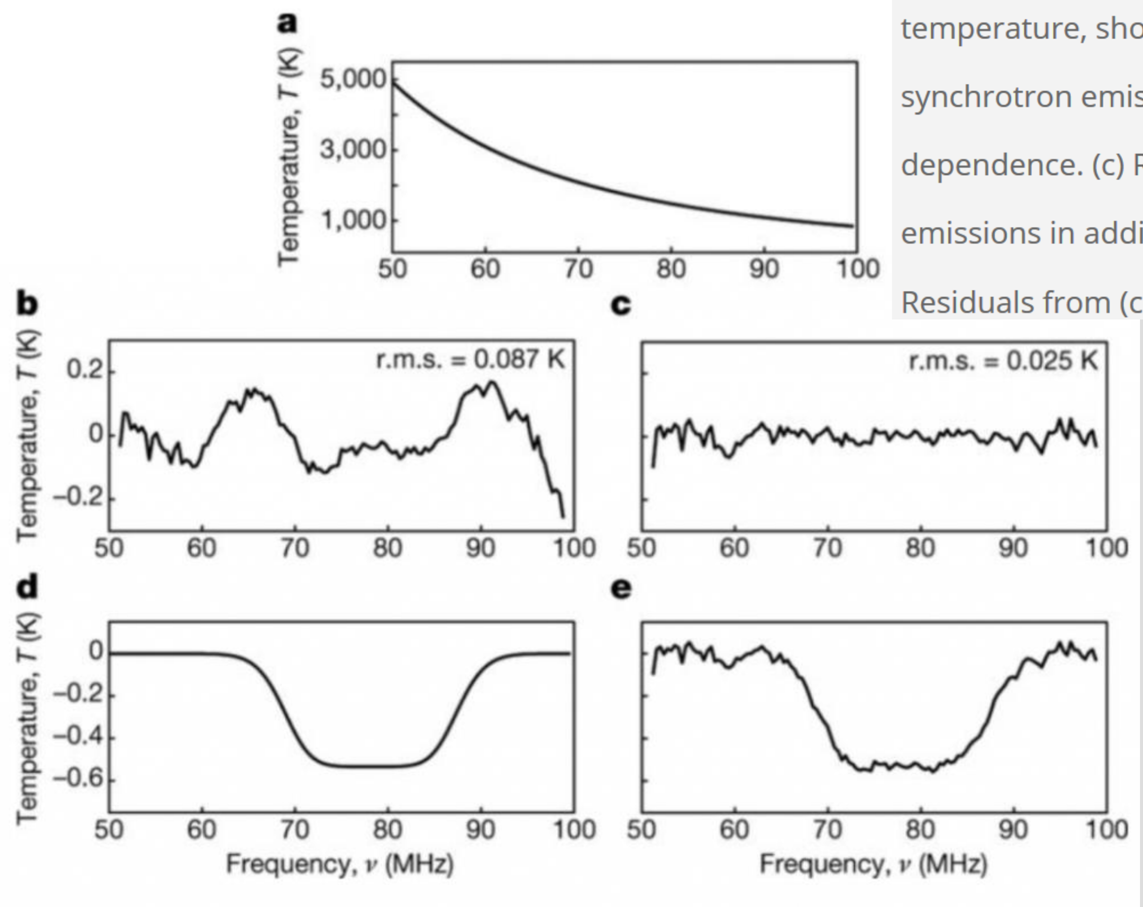


Figure 3: (a) The EDGES sky measurement in units of brightness temperature, showing the strong power-law spectrum due to galactic synchrotron emission. (b) Residuals after removing the power-law dependence. (c) Residuals after removing the power-law synchrotron emissions in addition to a model (d) of the 21cm absorption signal. (e) Residuals from (c) added to model in (d).

Resolution

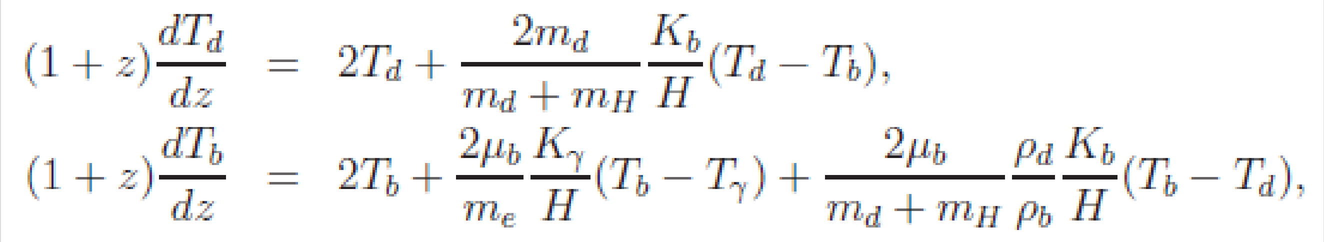
- Lower–than–normal T_s needed ($T_b \propto 1 - \frac{T_\gamma}{T_s}$)
  - From Wouthysen–Field effect, $T_s \sim T_k$
  - Lower–than–normal gas temperature T_k needed
  - Normal gas temperature: adiabatic cooling due to expansion
  - Cooling (by atoms) in intergalactic medium (IGM) extremely inefficient
  - So, need to find exotic cooling mechanism

- Suggestion
  - CDM – baryon interaction as cooling
  - Each "collision" drains thermal energy of gas (hot) and dumps it into CDM (cold)

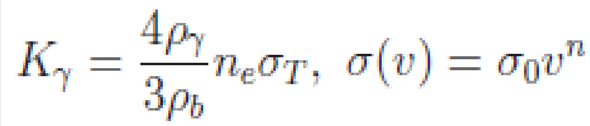
- Implication
  - CDM and baryon may be interacting

Resolution (Tashiro+ 2014, Barkana 2018 etc.)

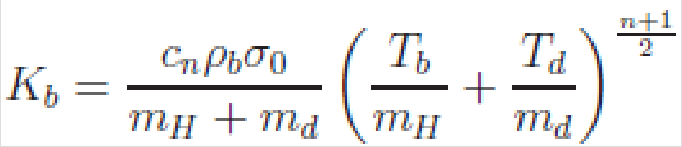
- Energy transfer bet. CDM and baryons (Tashiro+ PRD 2014, 90, 083522)



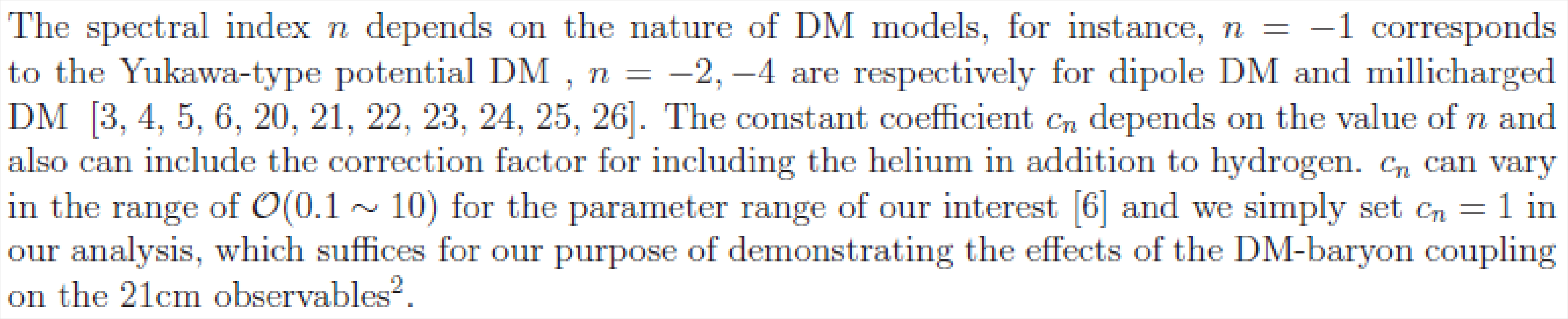
$$\begin{aligned}(1+z)\frac{dT_d}{dz} &= 2T_d + \frac{2m_d}{m_d+m_H}\frac{K_b}{H}(T_d-T_b),\\ (1+z)\frac{dT_b}{dz} &= 2T_b + \frac{2\mu_b}{m_e}\frac{K_\gamma}{H}(T_b-T_\gamma) + \frac{2\mu_b}{m_d+m_H}\frac{\rho_d}{\rho_b}\frac{K_b}{H}(T_b-T_d),\end{aligned}$$



$$K_\gamma = \frac{4\rho_\gamma}{3\rho_b}n_e\sigma_T,\ \sigma(v)=\sigma_0 v^n$$



$$K_b = \frac{c_n\rho_b\sigma_0}{m_H+m_d}\left(\frac{T_b}{m_H}+\frac{T_d}{m_d}\right)^{\frac{n+1}{2}}$$



The spectral index n depends on the nature of DM models, for instance, $n=-1$ corresponds to the Yukawa-type potential DM , $n=-2,-4$ are respectively for dipole DM and millicharged DM [3, 4, 5, 6, 20, 21, 22, 23, 24, 25, 26]. The constant coefficient c_n depends on the value of n and also can include the correction factor for including the helium in addition to hydrogen. c_n can vary in the range of $\mathcal{O}(0.1\sim 10)$ for the parameter range of our interest [6] and we simply set $c_n=1$ in our analysis, which suffices for our purpose of demonstrating the effects of the DM-baryon coupling on the 21cm observables[2].

Resolution (Tashiro+ 2014 etc.)

- DM should be light for this to work

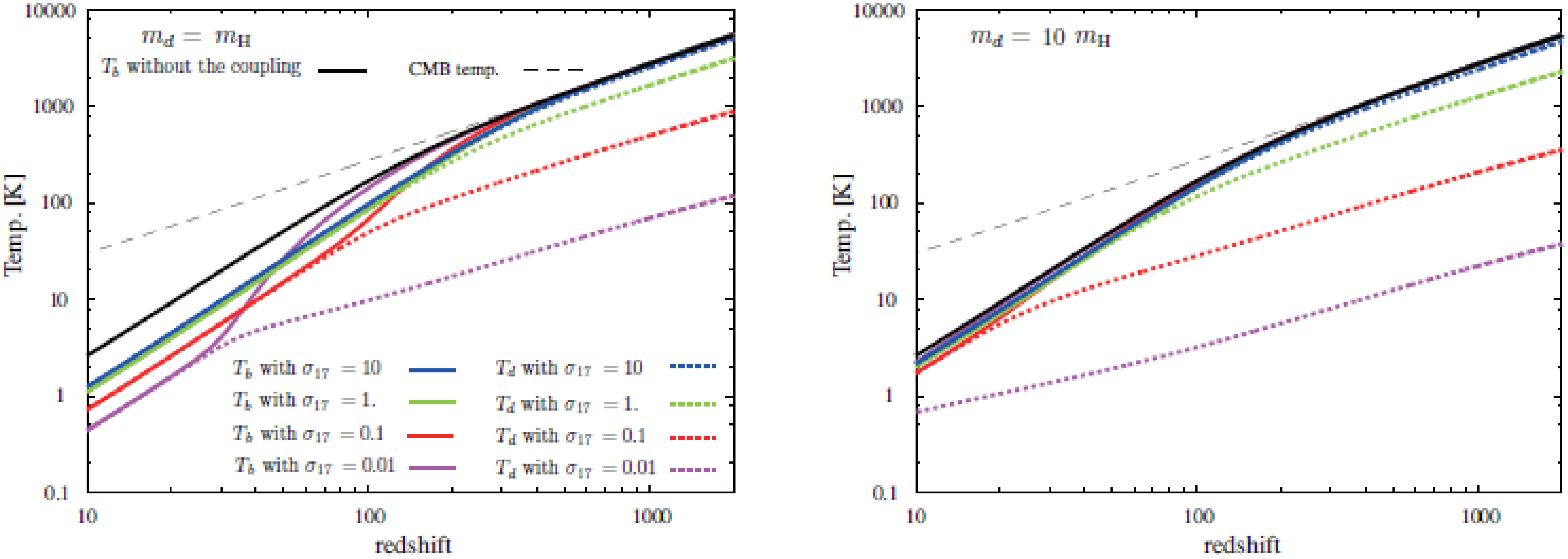


Figure 1: The baryon and dark matter temperature evolution for different values of DM-baryon coupling (the DM-baryon elastic scattering cross section is parameterized as $\sigma = \sigma_0 v^{-4}$, with $\sigma_0 = \sigma_{17} m_{\rm H} 10^{-17} {\rm cm}^2/{\rm g}$). We set $m_d = m_{\rm H}$ in the left panel and $m_d = 10 m_{\rm H}$ in the right panel. The solid and dotted lines represent the baryon and dark matter temperatures, respectively. The CMB temperature is plotted as the dashed line. The magenta, red, green and blue lines are for $\sigma_{17} = 0.01$, 0.1, 1.0 and 10 respectively. The black solid line shows the baryon temperature evolution without DM-baryon coupling ($\sigma_{17} = 0$).

Resolution (compation Nature paper by Barkana)

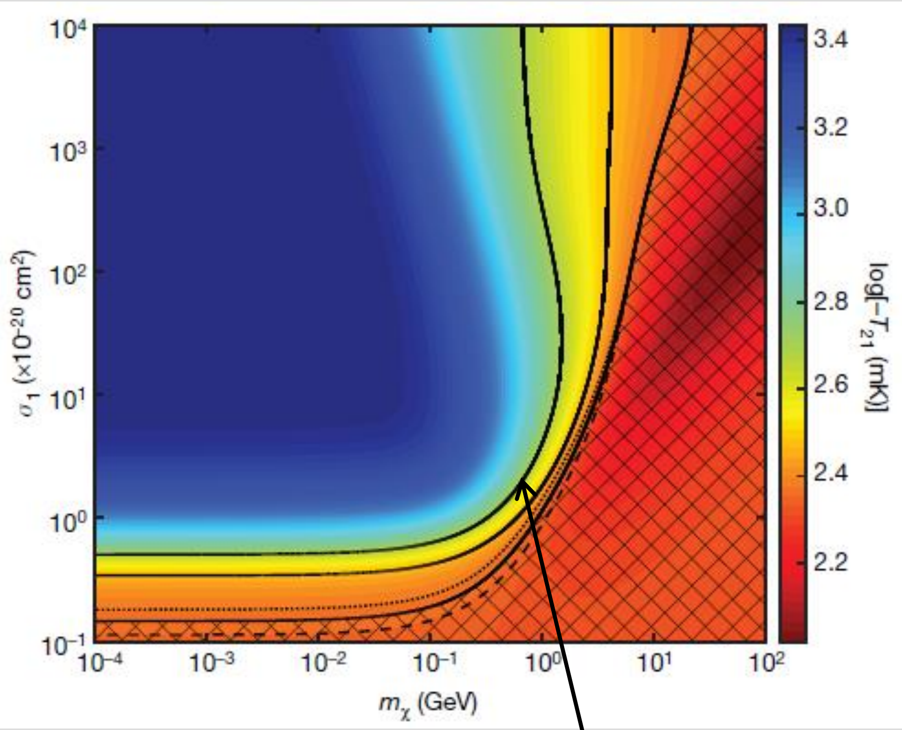


Figure 3 | Constraints on dark-matter properties using cosmic dawn observations. The minimum possible 21-cm brightness temperature T_{21} (expressed as the logarithm of its absolute value) is shown at $z = 17$ ($\nu = 78.9$ MHz), regardless of the astrophysical parameters used (that is, assuming saturated 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 $\sigma_1 > 1.5 \times 10^{-21}$ cm^2 (corresponding to $\sigma_c > 1.9 \times 10^{-43}$ 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 $\sigma_1 > 3.4 \times 10^{-21}$ cm^2 ($\sigma_c > 4.2 \times 10^{-43}$ cm^2) and $m_\chi < 4.3$ GeV; a brightness temperature of -500 mK implies $\sigma_1 > 5.0 \times 10^{-21}$ cm^2 ($\sigma_c > 6.2 \times 10^{-43}$ 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).

Favored region in green

More constraint on DM-baryon scattering from reionization (LiteBird!)

Combining reionization model

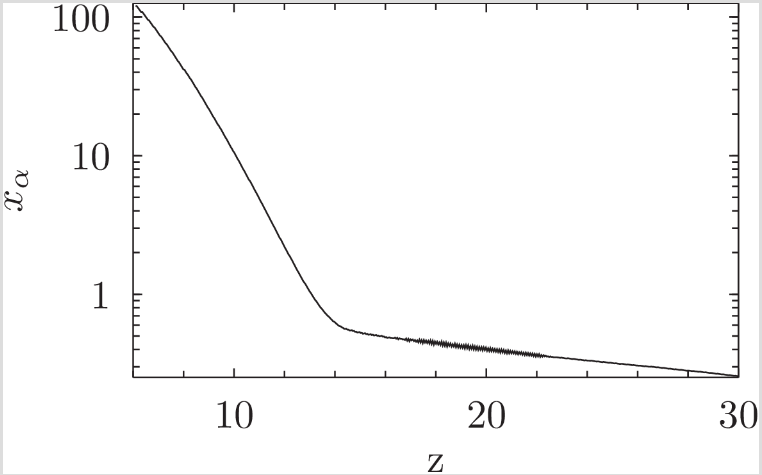
- Energy transfer bet. CDM and baryons

$$
\begin{aligned}
(1+z)\frac{dT_d}{dz} &= 2T_d + \frac{2m_d}{m_d+m_H}\frac{K_b}{H}(T_d - T_b),\\
(1+z)\frac{d\boxed{T_b}}{dz} &= 2T_b + \frac{2\mu_b}{m_e}\frac{K_\gamma}{H}(T_b - T_\gamma) + \frac{2\mu_b}{m_d+m_H}\frac{\rho_d}{\rho_b}\frac{K_b}{H}(T_b - T_d),
\end{aligned}
$$

$$K_\gamma = \frac{4\rho_\gamma}{3\rho_b} n_e \sigma_T, \ \ \sigma(v) = \sigma_0 v^n$$

$$K_b = \frac{c_n \rho_b \sigma_0}{m_H + m_d}\left(\frac{T_b}{m_H} + \frac{T_d}{m_d}\right)^{\frac{n+1}{2}}$$

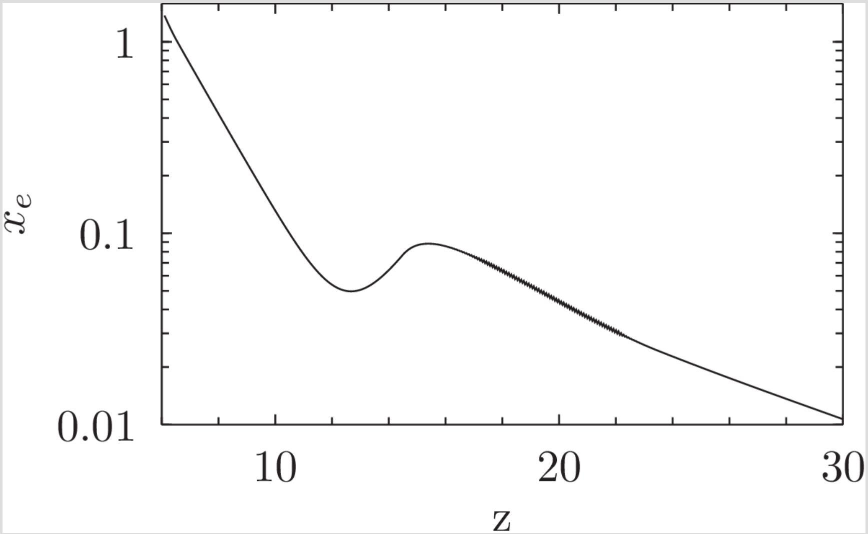
$$T_S^{-1} = \frac{1 + (\boxed{x_\alpha} + \cancel{x_c})T_b^{-1}}{1 + x_\alpha + \cancel{x_c}}$$

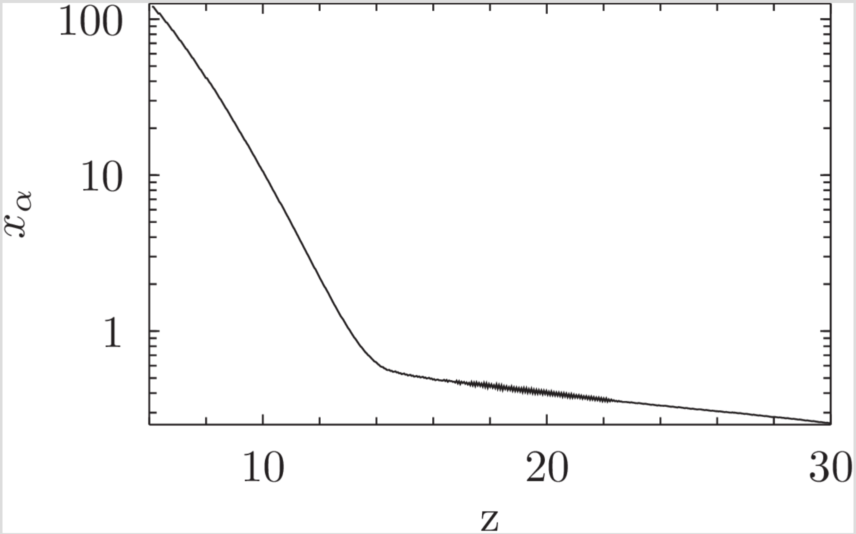


Weakly Planck-favored model has small x_α → z~17 is NOT strongly Lya-pumped. → weaker coupling Of T_s to T_b.

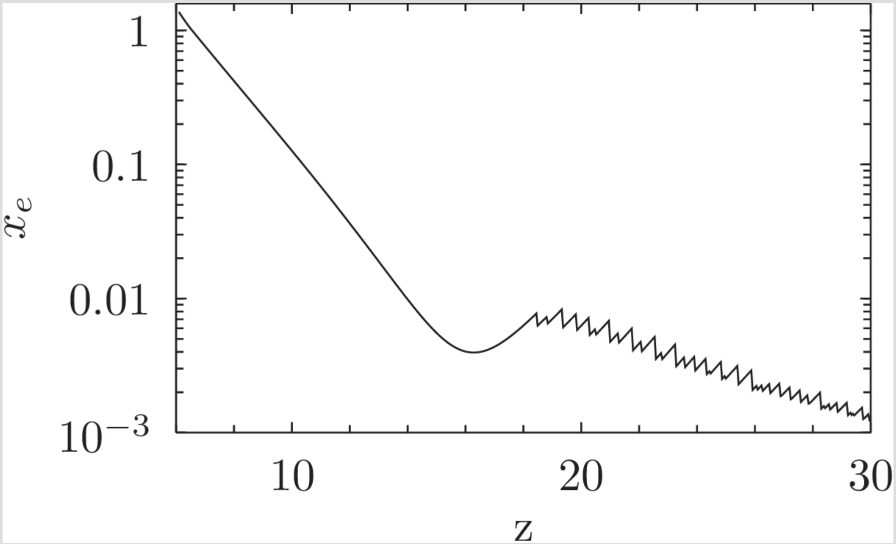
Combining reionization model

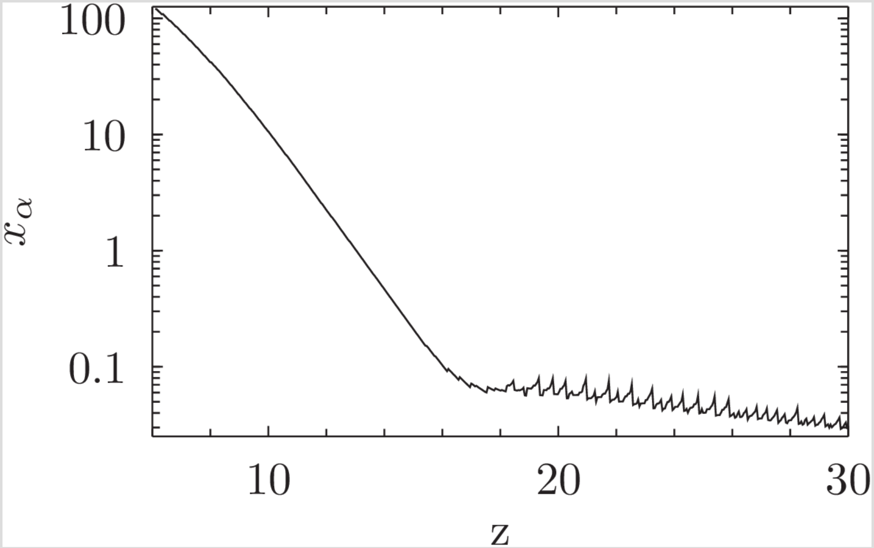
Case 1



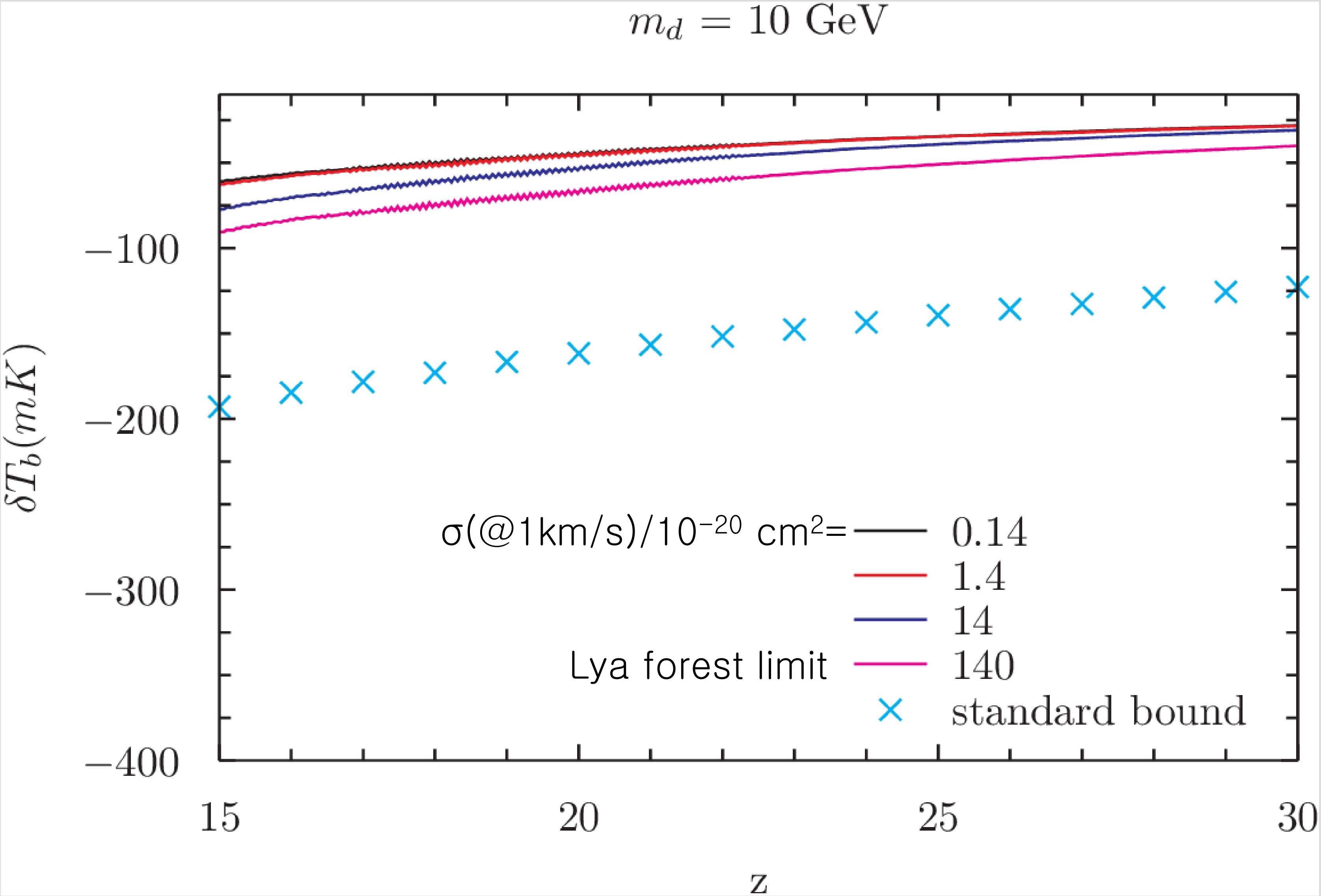


Case 2

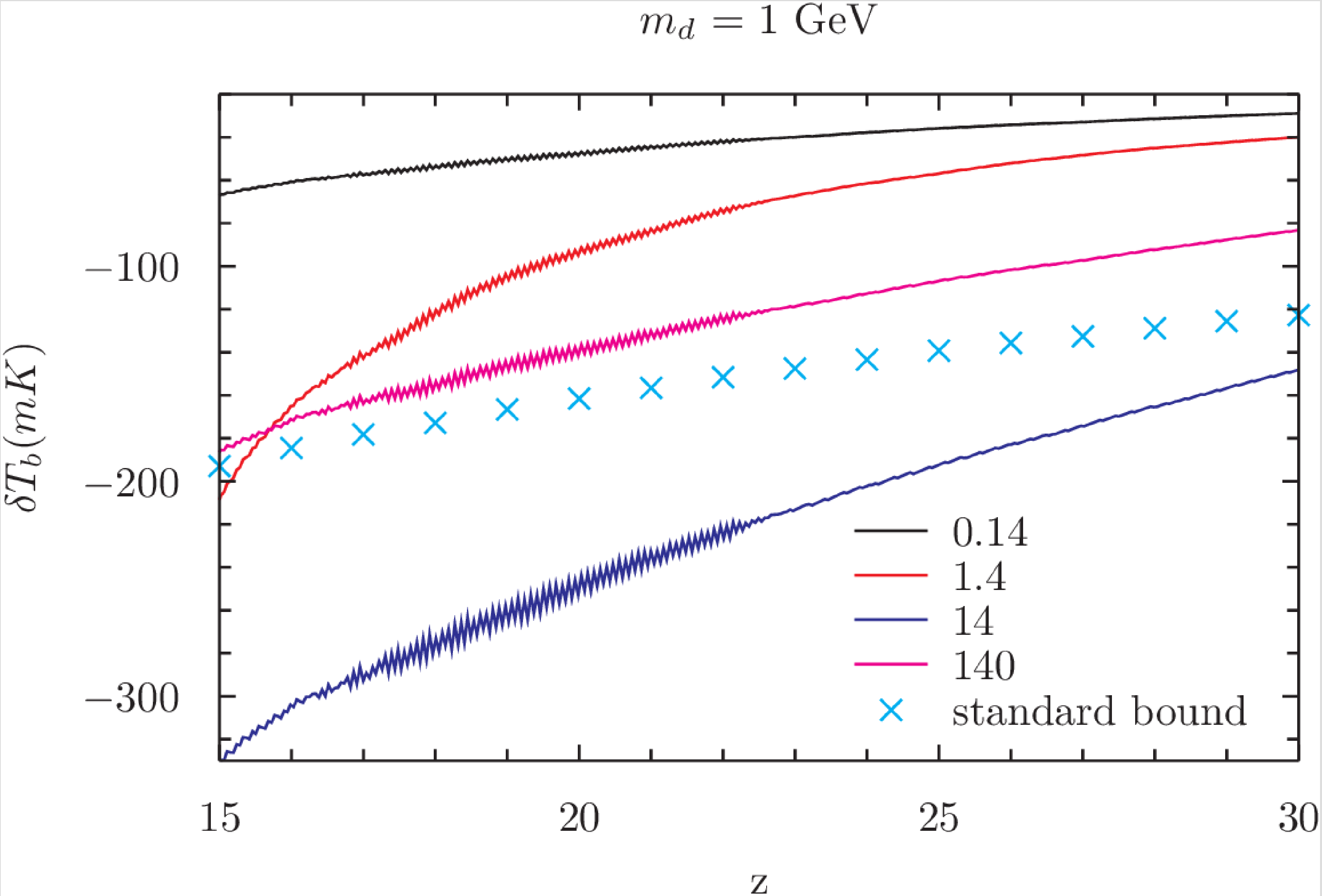




Case 1

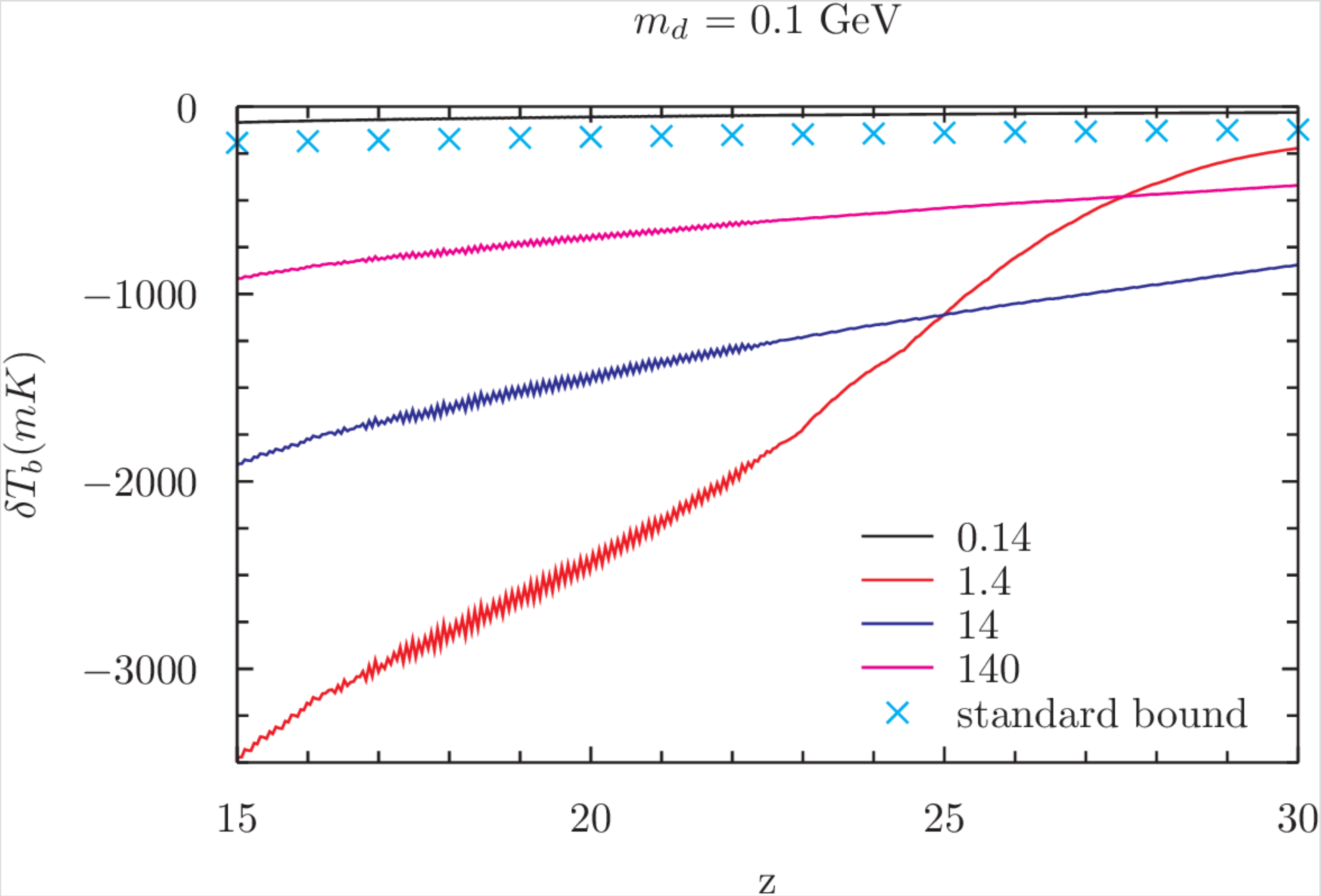

m_d = 10 GeV
$\delta T_b(mK)$
−100
−200
−300
−400
15
20
25
30
z
σ(@1km/s)/10^{-20} cm^2=
0.14
1.4
14
Lya forest limit
140
standard bound

Case 1



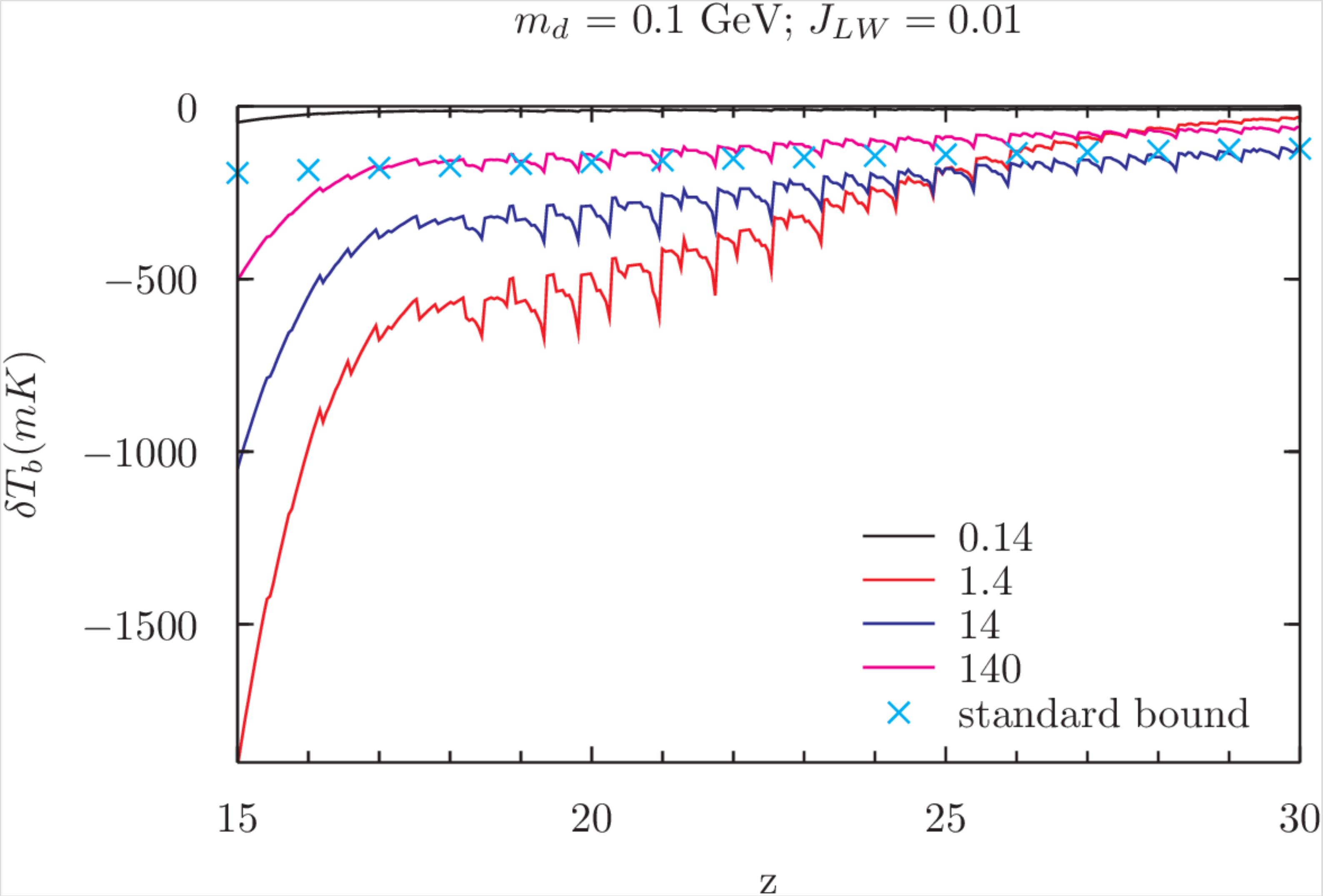
$m_d = 1$ GeV
$\delta T_b(mK)$
−100
−200
−300
15
20
25
30
z
0.14
1.4
14
140
standard bound

Case 1



m_d >~ 1 GeV dark matter excluded

Case 2



m_d >~ 0.2 GeV dark matter excluded

Lesson: Weaker the First Stars, smaller the DM mass

Should we believe EDGES result?

- parametric power-law fit: dangerous
  - We don't know too much about galactic foreground in EDGES band
  - Arman: EDGES data consistent with null result
  - Tuhin: currently monopole-only in the band and don't know foreground there

- Not much room with other cosmological calculations
  - BBN + CMB + 1987A + etc. → only tens of MeV, fractional charged DM allowed (Berlin+ 2018, PRL, 121, 011102)

- Signal-shape prior: dangerous
  - CMB: reionization history: tanh??
  - 21cm: symmetric well??
  - should allow generic signal
  - does not comply with regulated Pop-III scenario: should be long absorption trough before X-ray heating kicks in.

Summary

- Self-regulated Pop III star drives early reionization for long duration
- generates weak-Lya epoch (some caveat, if curious ask me)
- EDGES result suspicious, but even constraint on reionization history helps to narrow baryon-dark matter scattering cross section
- Successful (and reasonable) foreground removal necessary
- Pop-III regulated reionization with parameter J_{LW} a viable possibility with smooth 21cm dip