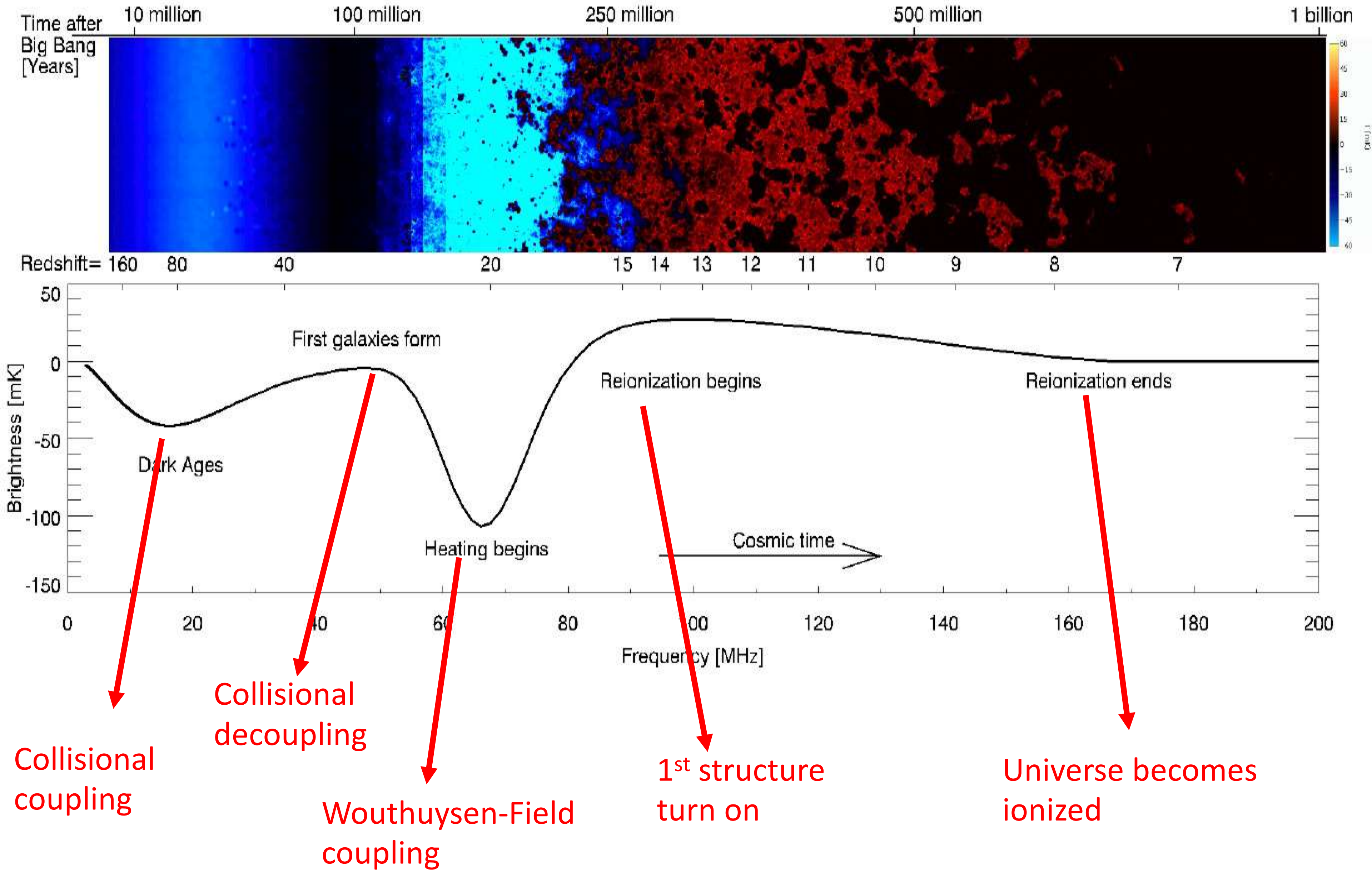
Probing dark matter and primordial black hole signals during Epoch of Reionization

Yin-Zhe Ma

University of KwaZulu-Natal, South Africa

→ (Sep/2023) Stellenbosch University, South Africa


Time after Big Bang [Years]
10 million
100 million
250 million
500 million
1 billion
Redshift= 160 80 40 20 15 14 13 12 11 10 9 8 7
Brightness [mK]
50
0
-50
-100
-150
First galaxies form
Dark Ages
Heating begins
Reionization begins
Reionization ends
Cosmic time
0 20 40 60 80 100 120 140 160 180 200
Frequency [MHz]
Collisional coupling
Collisional decoupling
Wouthuysen-Field coupling
1st structure turn on
Universe becomes ionized

- Constraints on decaying dark matter
- Constraints on Primordial black holes
- (Prospective) Constraints on warm dark matter

(1) Heating IGM (also affecting 21-cm transition from absorption to emission)

(2) Spatial fluctuation

J. Cang, X. Chen, S. Clark, B. Dutta, Y. Gao, M. Liu, A. Mesinger, K. Sigurdson, M. Sitwell, L. Strigari, Y. Xu, B. Yue, Z. Zhang

- Constraints on decaying dark matter
- Constraints on Primordial black holes
- (Prospective) Constraints on warm dark matter

Sitwell, Mesinger, **YZM**, Sigurdson, 2013, MNRAS

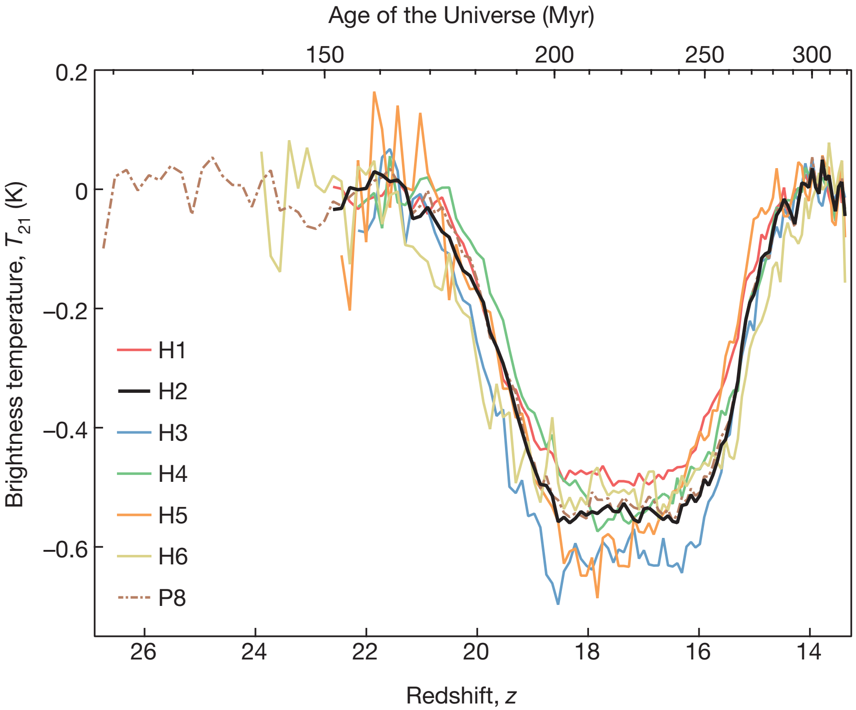
Clark, Dutta, Gao, **YZM**, Strigari, 2018, Phys. Rev. D

Cang, Gao, **YZM**, 2020, Phys. Rev. D.

Cang, Gao, **YZM**, 2021, JCAP

Zhang, Yue, Xu, **YZM**, Chen, Liu, 2023, Phys. Rev. D

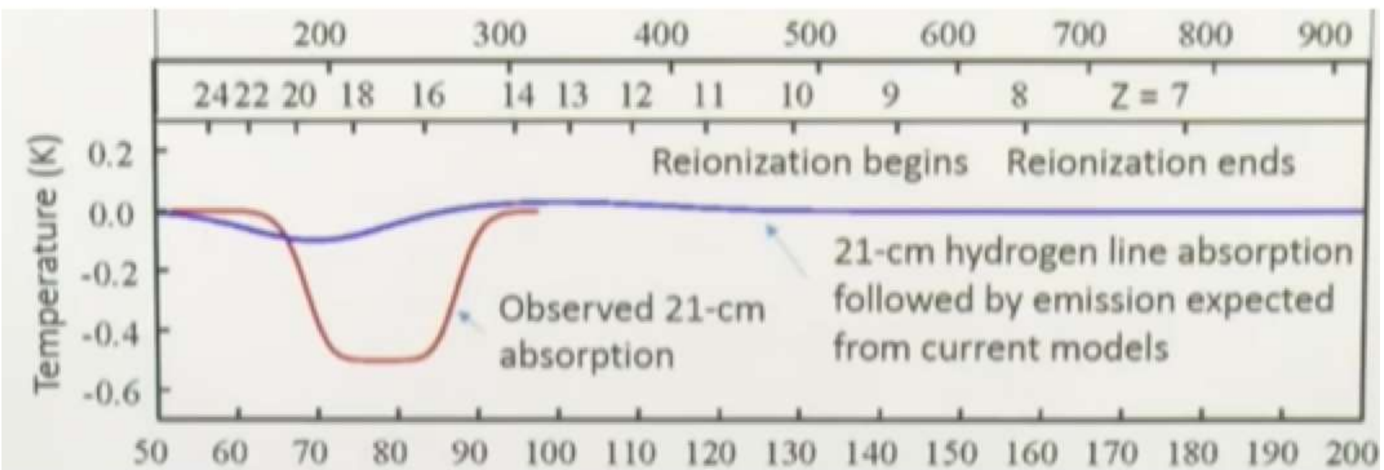
Cang, **YZM**, Gao, 2023, ApJ



EDGES Results 2018, J. Bowman et al., 2018 Nature

$$\nu = 78 \pm 1 \text{ MHz}$$
$$T = -0.5^{+0.2}_{-0.5}\text{K}$$

Time after the big bang in millions of years



Frequency [MHz]

- $\mathrm{DM} \to \gamma\gamma$
- $\mathrm{DM} \to e^+e^-$
- $\mathrm{DM} \to \mu^+\mu^-$
- $\mathrm{DM} \to b\bar{b}$

$$f_c(m_{\mathrm{DM}}, z) = \frac{\sum_s \int f_c(E, z, s) E (\mathrm{d}N/\mathrm{d}E)_s \mathrm{d}E}{\sum_s \int E (\mathrm{d}N/\mathrm{d}E)_s \mathrm{d}E}$$

$$I_{X_\mathrm{i}}(z) = \frac{f_\mathrm{i}(E, z)}{n_\mathrm{H}(z) E_\mathrm{i}} \frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t},$$

$$I_{X_\alpha}(z) = (1 - C) \frac{f_\alpha(E, z)}{n_\mathrm{H}(z) E_\alpha} \frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t},$$

$$K_\mathrm{h}(z) = \frac{f_\mathrm{h}(E, z)}{n_\mathrm{H}(z)} \frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}$$

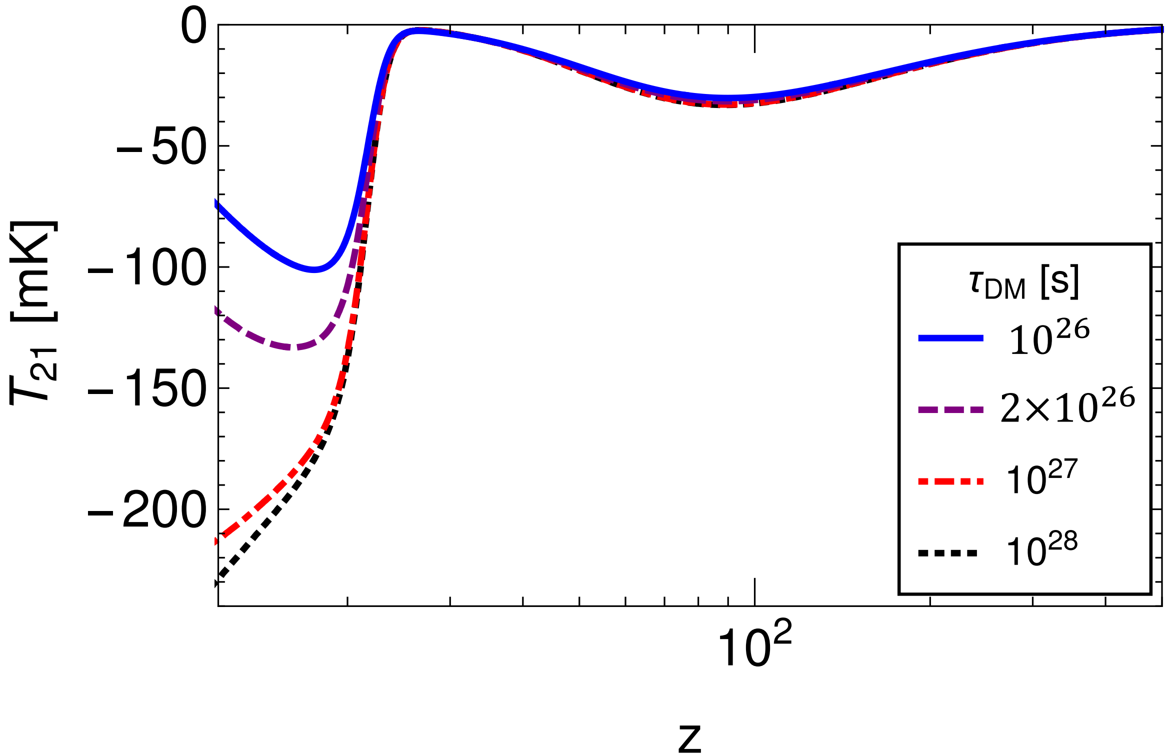
$$C = \frac{1 + K\Lambda_{2s,1s} n_\mathrm{H}(1 + x_\mathrm{e})}{1 + K\Lambda_{2s,1s} n_\mathrm{H}(1 - x_\mathrm{e}) + K\beta_\mathrm{B} n_\mathrm{H}(1 - x_\mathrm{e})}$$

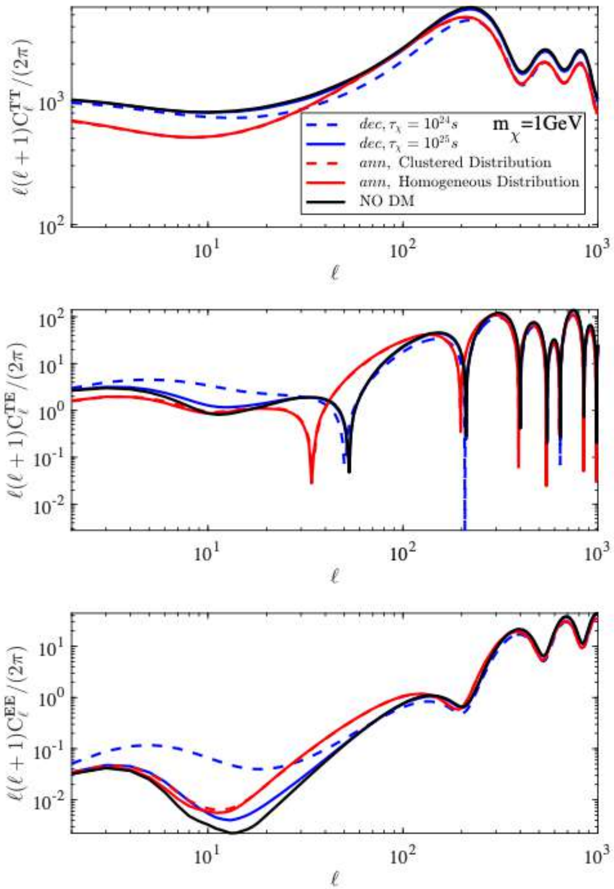
$$\left(\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)^{\mathrm{dec}}_{\mathrm{INJ}} = \Gamma_\chi \Omega_\chi (1 + z)^3 \rho_\mathrm{c},$$

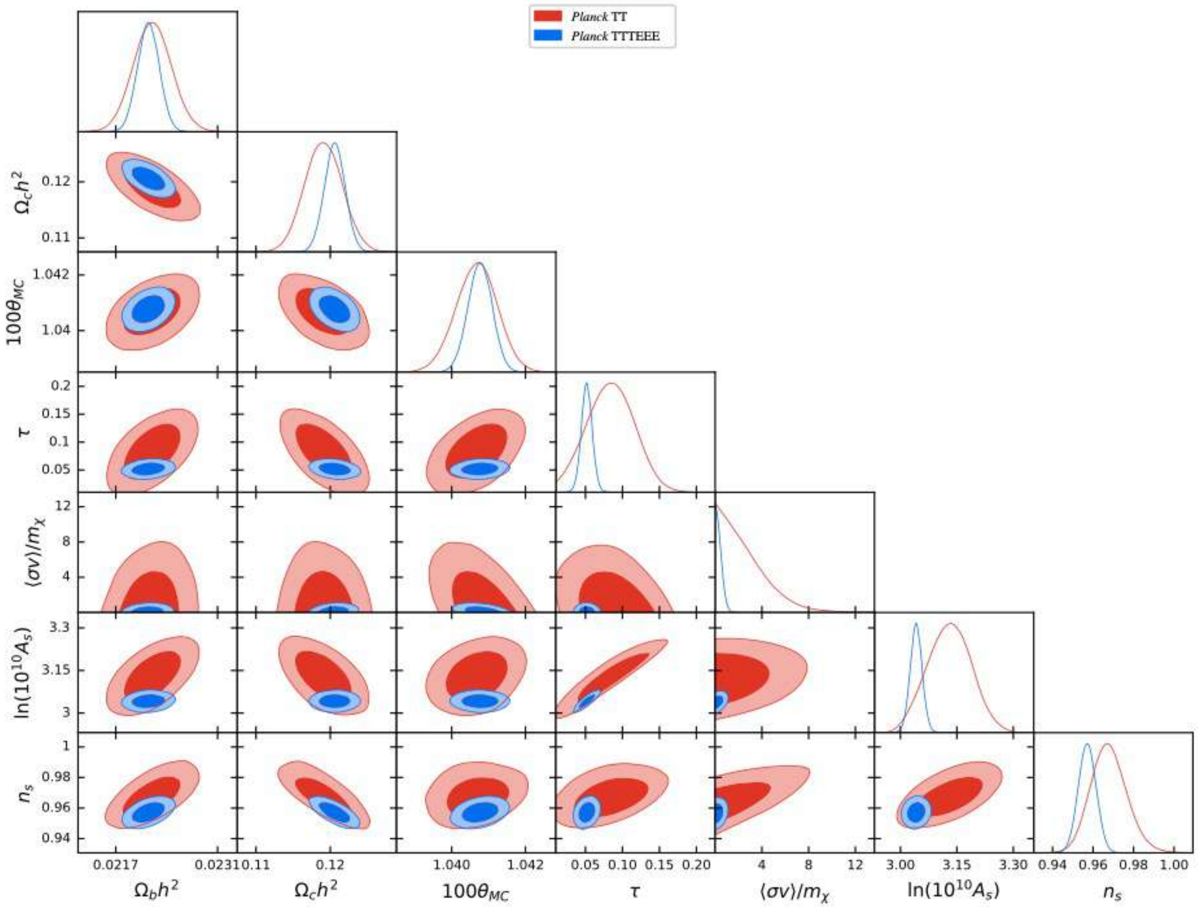
$$\left(\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)^{\mathrm{ann}}_{\mathrm{INJ}} = \frac{\langle \sigma v \rangle}{m_\chi} \Omega_\chi^2 (1 + z)^6 \rho_\mathrm{c}^2$$

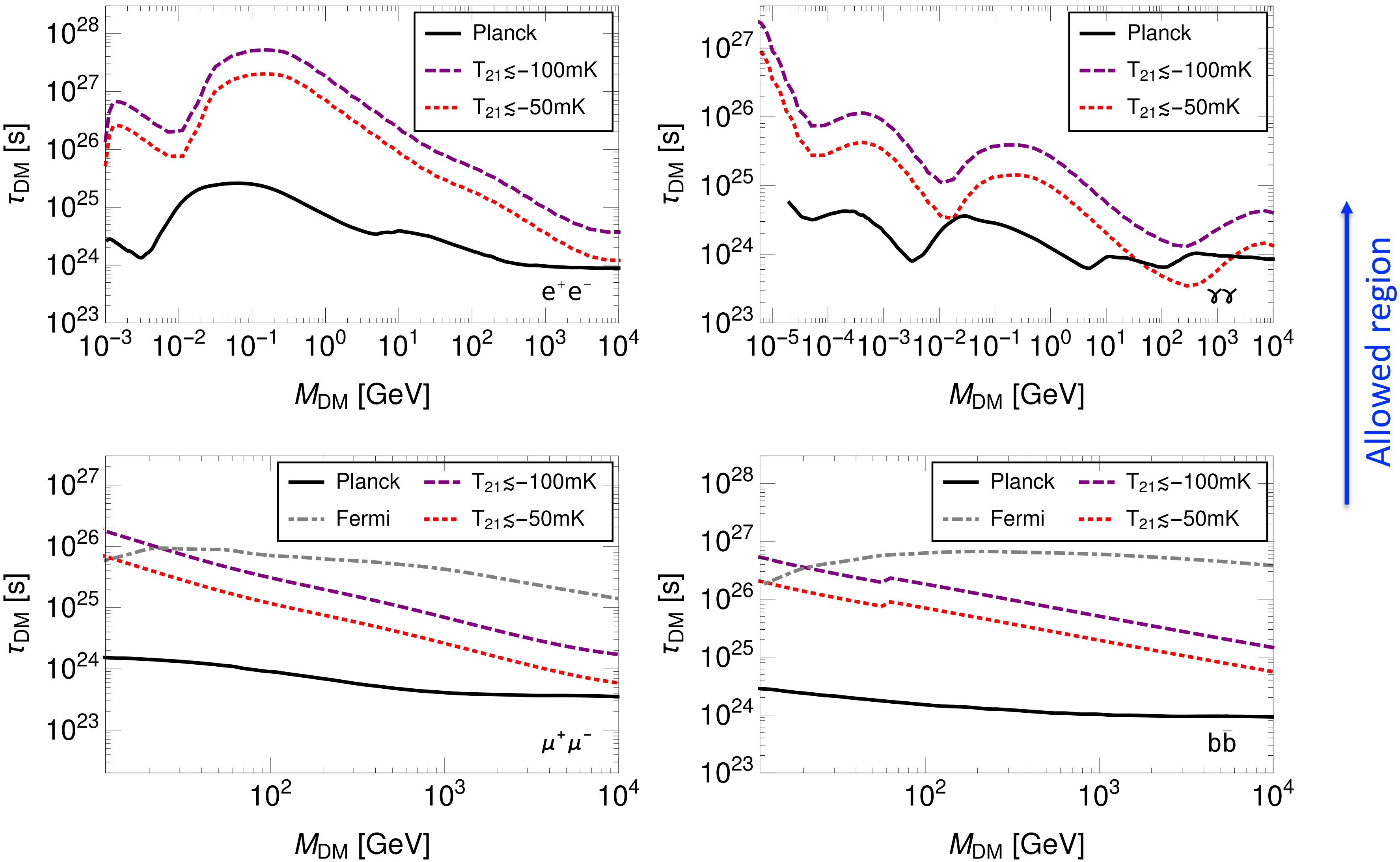
$$\frac{\mathrm{d}x_{\mathrm{e}}}{\mathrm{d}z} = \left.\frac{\mathrm{d}x_{\mathrm{e}}}{\mathrm{d}z}\right|_{\mathrm{orig}} - \frac{1}{(1+z)H(z)}[I_{\mathrm{X_i}}(z) + I_{\mathrm{X_\alpha}}(z)],$$

$$\frac{\mathrm{d}T_{\mathrm{G}}}{\mathrm{d}z} = \left.\frac{\mathrm{d}T_{\mathrm{G}}}{\mathrm{d}z}\right|_{\mathrm{orig}} - \frac{2}{3k_{\mathrm{B}}(1+z)H(z)}\frac{K_{\mathrm{h}}}{1+f_{\mathrm{He}}+x_{\mathrm{e}}}$$




$\ell(\ell+1)C_\ell^{TT}/(2\pi)$
$dec, \tau_\chi = 10^{24}s$
$dec, \tau_\chi = 10^{25}s$
ann, Clustered Distribution
ann, Homogeneous Distribution
NO DM
m_χ=1GeV
ℓ
$\ell(\ell+1)C_\ell^{TE}/(2\pi)$
ℓ
$\ell(\ell+1)C_\ell^{EE}/(2\pi)$
ℓ


Planck TT
Planck TTTEEE
$\Omega_b h^2$
$\Omega_c h^2$
$100\theta_{MC}$
τ
$\langle\sigma v\rangle/m_\chi$
$\ln(10^{10}A_s)$
n_s



Planck
T21≲−100mK
T21≲−50mK
e⁺e⁻
τDM [s]
MDM [GeV]
Planck
T21≲−100mK
T21≲−50mK
γγ
τDM [s]
MDM [GeV]
Planck
T21≲−100mK
Fermi
T21≲−50mK
μ⁺μ⁻
τDM [s]
MDM [GeV]
Planck
T21≲−100mK
Fermi
T21≲−50mK
bb̄
τDM [s]
MDM [GeV]
Allowed region

- Constraints on decaying dark matter
- Constraints on Primordial black holes
- (Prospective) Constraints on warm dark matter

Sitwell, Mesinger, **YZM**, Sigurdson, 2013, MNRAS

Clark, Dutta, Gao, **YZM**, Strigari, 2018, Phys. Rev. D

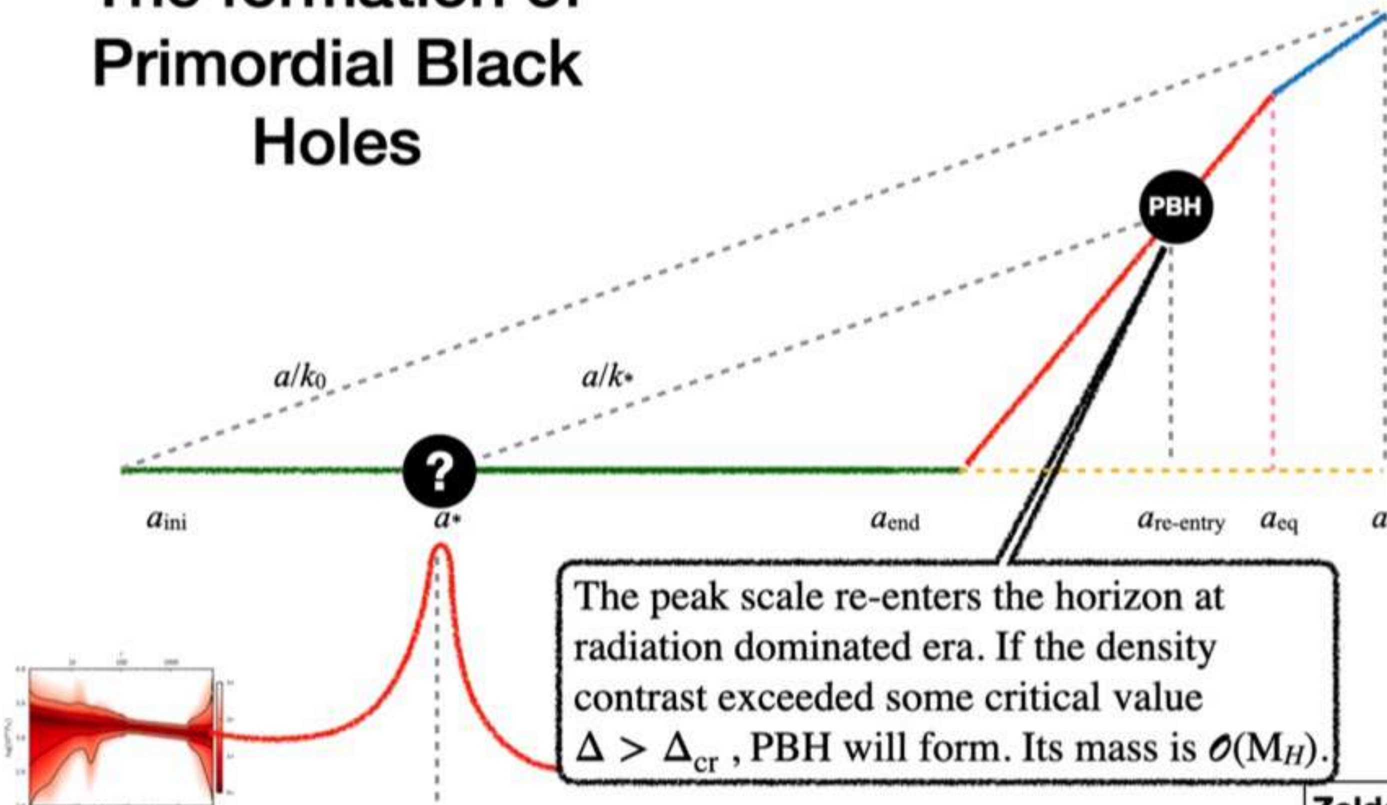
Cang, Gao, **YZM**, 2020, Phys. Rev. D.

Cang, Gao, **YZM**, 2021, JCAP

Zhang, Yue, Xu, **YZM**, Chen, Liu, 2023, Phys. Rev. D

Cang, **YZM**, Gao, 2023, ApJ

The formation of Primordial Black Holes



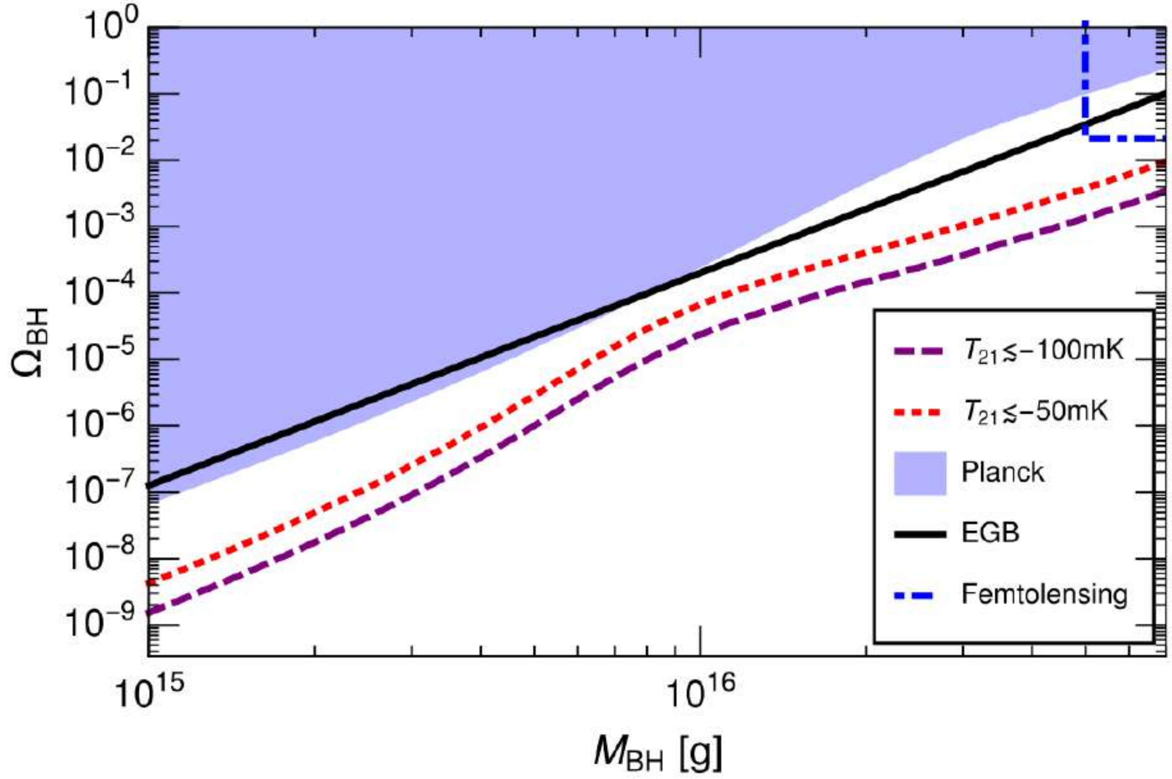
$k_* = Ha_*$

$$\mathcal{P}_\mathcal{R} = A_s\left(\frac{k}{k_*}\right)^{n_s-1}\left[1 + \frac{A}{\sqrt{2\pi\sigma^2}}e^{-\left(\ln\frac{k}{k_*}\right)^2/2\sigma^2}\right]$$

Zeldovich & Novikov 1966;
Hawking 1971;
Carr & Hawking 1974

$$\dot{M}_{\rm BH} = -5.34 \times 10^{25} \left(\sum_i \phi_i \right) M_{\rm BH}^{-2} \ \ {\rm g^3 s^{-1}}$$

$$\frac{{\rm d}E}{{\rm d}V{\rm d}t} = \sum_{i=\gamma,e^{\pm}} \phi_i \cdot \frac{\dot{M}_{\rm BH}}{M_{\rm BH}} \rho_{\rm c,0} \Omega_{\rm BH} (1+z)^3$$



Cang, Gao, **YZM**, 2021, JCAP

Zhang, Yue, Xu, **YZM**, Chen, Liu, 2023, Phys. Rev. D

Cang, **YZM**, Gao, 2023, ApJ

- Constraints on decaying dark matter
- Constraints on Primordial black holes
- (Prospective) Constraints on warm dark matter

Sitwell, Mesinger, **YZM**, Sigurdson, 2013, MNRAS
Clark, Dutta, Gao, **YZM**, Strigari, 2018, Phys. Rev. D
Cang, Gao, **YZM**, 2020, Phys. Rev. D.
Cang, Gao, **YZM**, 2021, JCAP
Zhang, Yue, Xu, **YZM**, Chen, Liu, 2023, Phys. Rev. D
Cang, **YZM**, Gao, 2023, ApJ

Global 21cm experiments

LEDA
30 – 88 MHz
Owens Valley

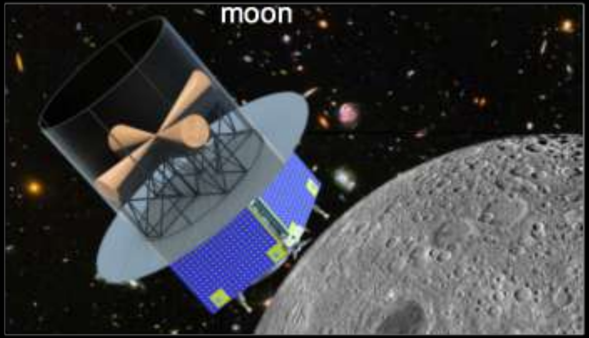
SARAS (2)
87.5 – 175 MHz
Gauribidanur Obs., India

BIGHORNS
50 – 200 MHz
Western
Australia

ALBATROS
2—80 MHz

EDGES
50 – 100, 100 – 200 MHz
Murchison Radio Obs.

DARE
40 – 120 MHz
Dark side of the
moon



Hyperion

HERA

MWA

LOFAR

SKA-LOW

What is the current constraint on warm dark matter mass from IGM?

- Lyman alpha forest: (Viel+ 2006; 2008; Irsic+ 2017; Baur+ 2017; Enzi+, 2021):

$$m_X > 1 - 3\ \mathrm{keV}$$

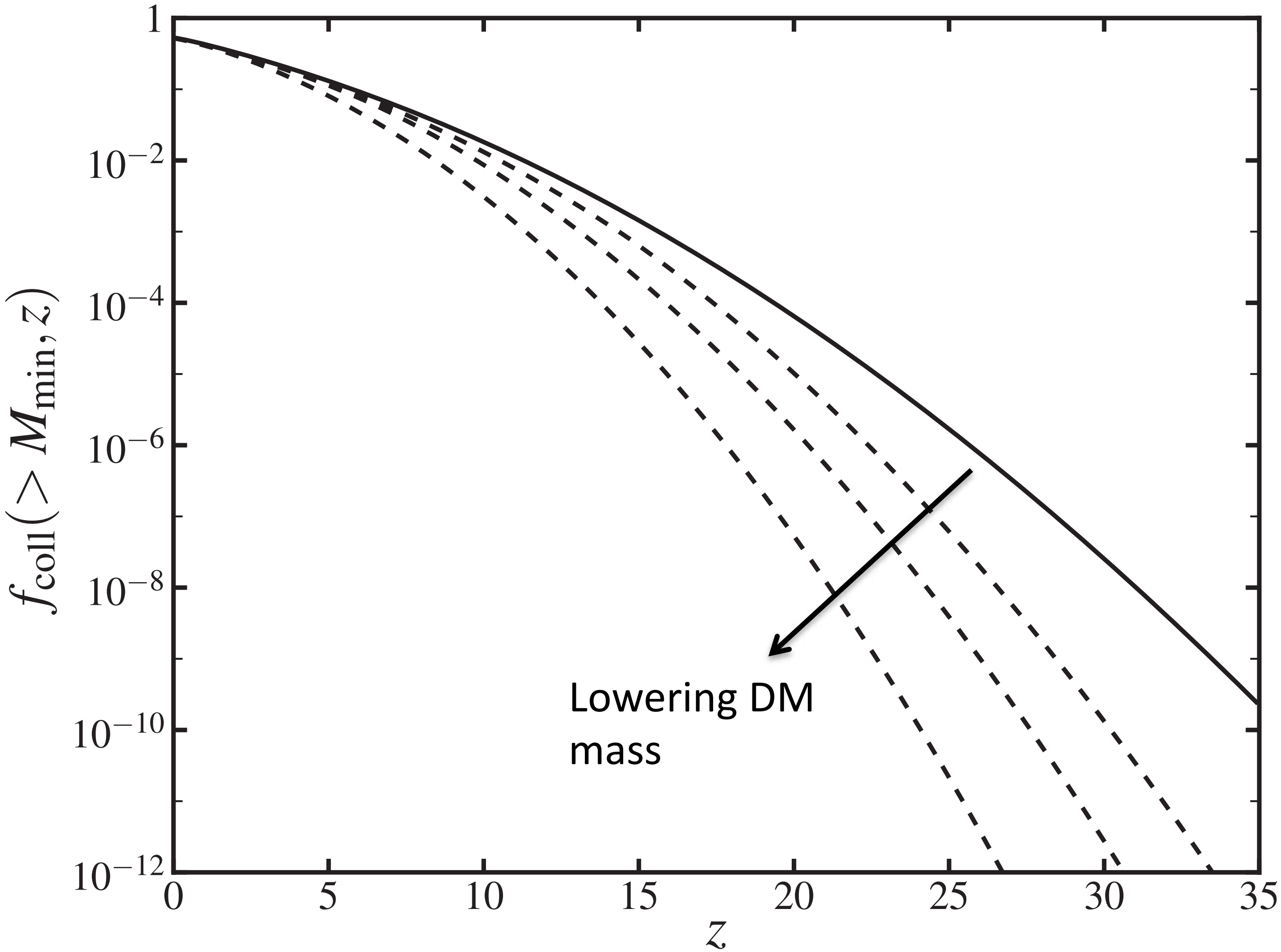
- Reionization occurring by $z \sim 6$ (Barkana+2011; Lopez-Honorez et al. 2017):

$$m_X > 1\ \mathrm{keV}$$

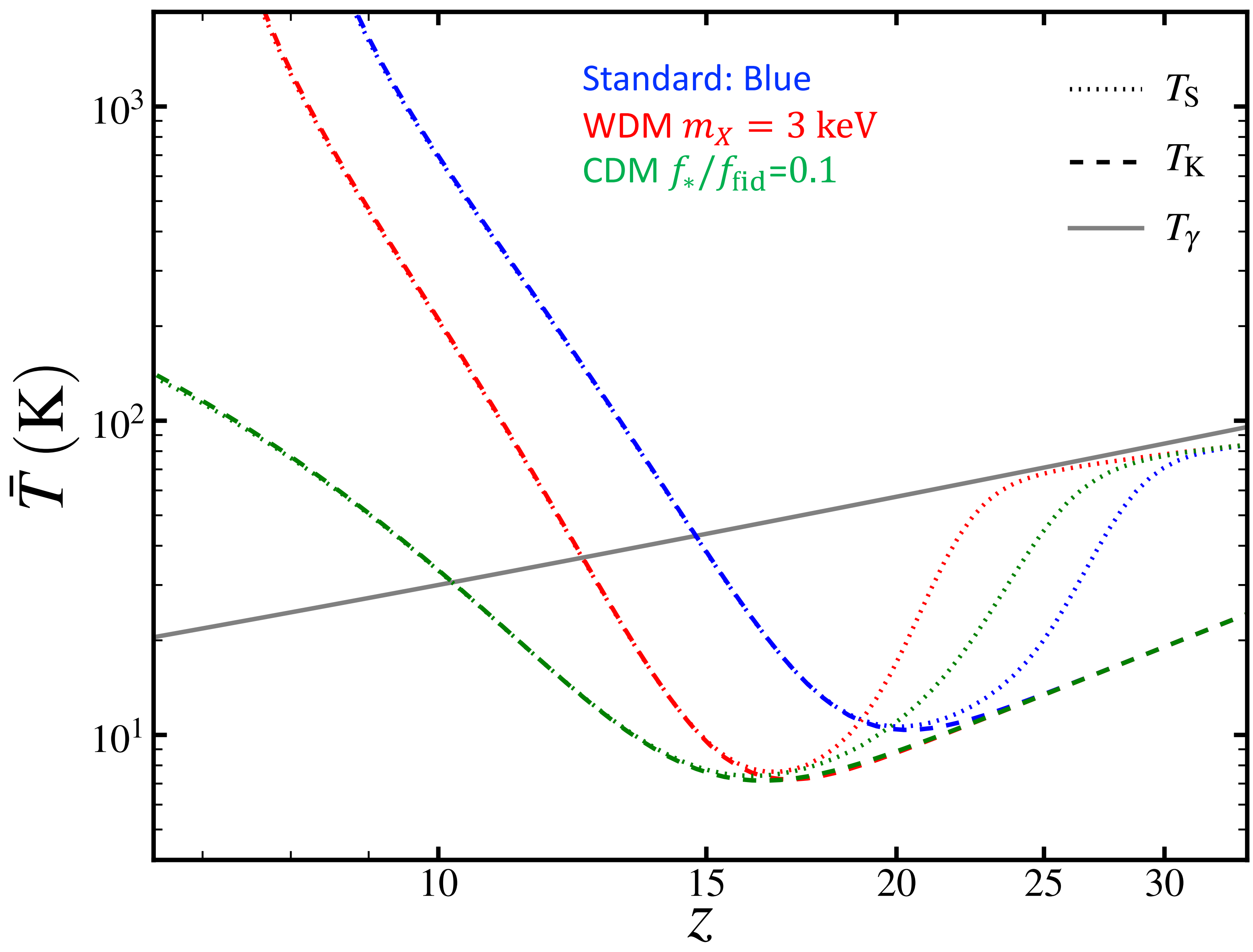
- Reproducing stellar mass function and Tully-Fisher relation: (Kang+2013):

$$m_X > 0.75\ \mathrm{keV}$$

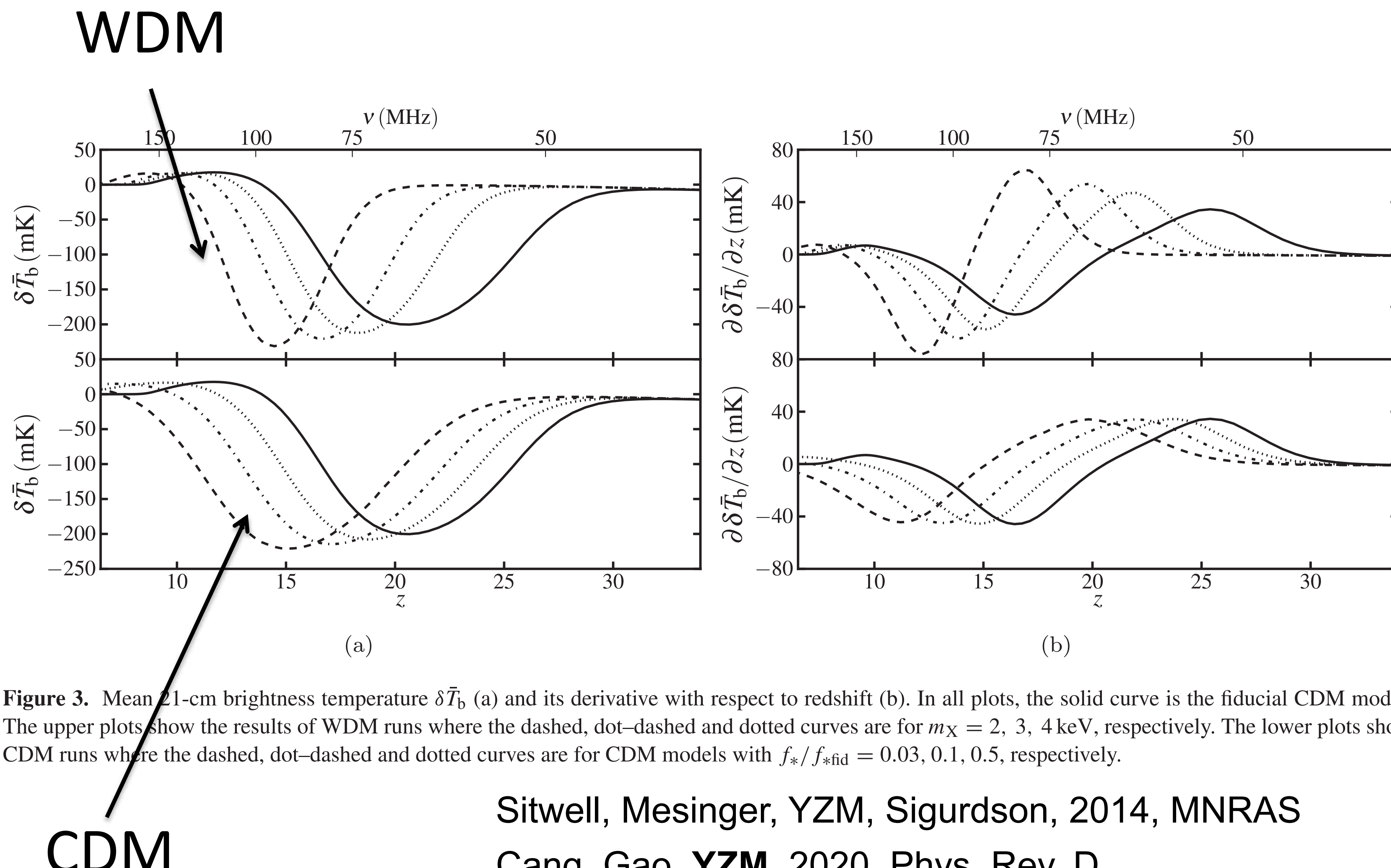
Dark matter effect on collapse fraction



($M_{\rm min} \sim 10^7 \rm M_\odot$)



Standard: Blue
WDM $m_X = 3$ keV
CDM $f_*/f_{\rm fid}$=0.1
$T_{\rm S}$
$T_{\rm K}$
T_γ
$\bar{T}$ (K)
10^1
10^2
10^3
10
15
20
25
30
z



(a)

(b)

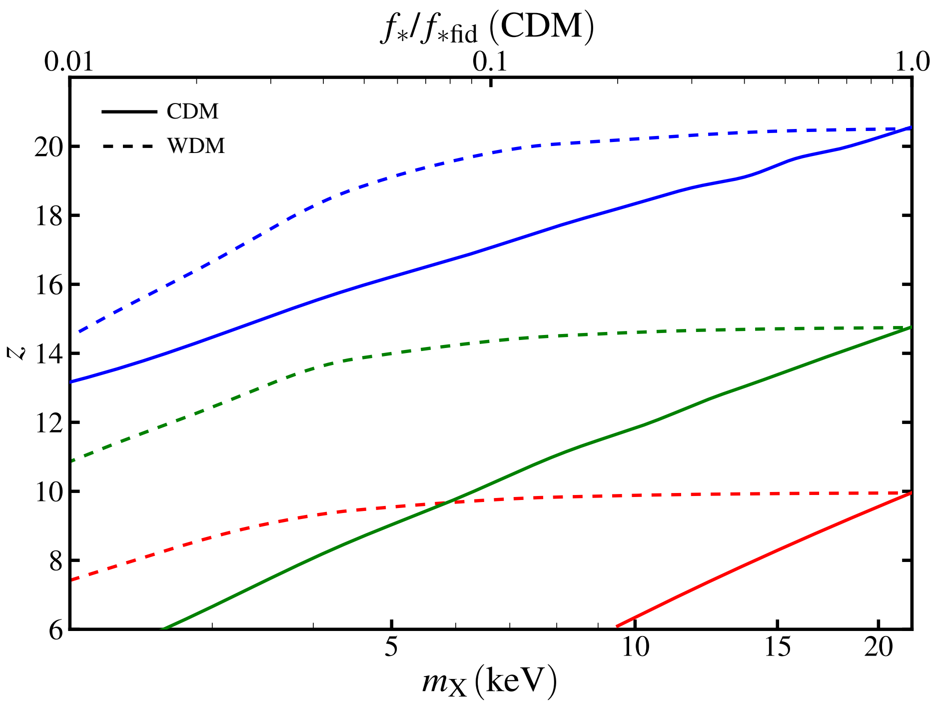
Figure 3. Mean 21-cm brightness temperature $\delta\bar{T}_{\rm b}$ (a) and its derivative with respect to redshift (b). In all plots, the solid curve is the fiducial CDM model. The upper plots show the results of WDM runs where the dashed, dot–dashed and dotted curves are for $m_{\rm X} = 2,\ 3,\ 4\,{\rm keV}$, respectively. The lower plots show CDM runs where the dashed, dot–dashed and dotted curves are for CDM models with $f_*/f_{*{\rm fid}} = 0.03, 0.1, 0.5$, respectively.

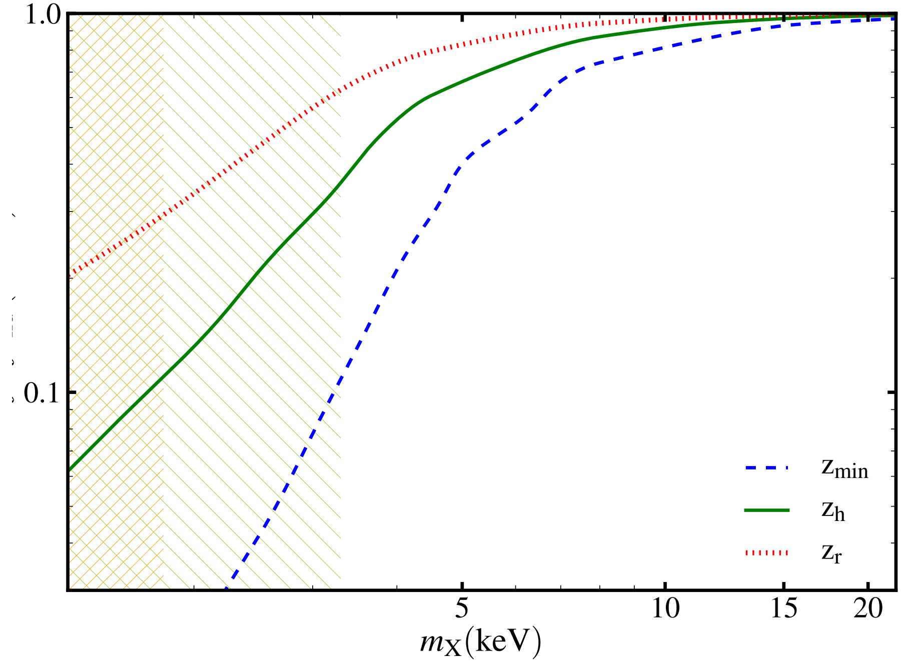
Sitwell, Mesinger, YZM, Sigurdson, 2014, MNRAS

Cang, Gao, **YZM**, 2020, Phys. Rev. D.

Cang, Gao, **YZM**, 2021, JCAP

Sitwell, Mesinger, Ma, Sigurdson, 2014, MNRAS



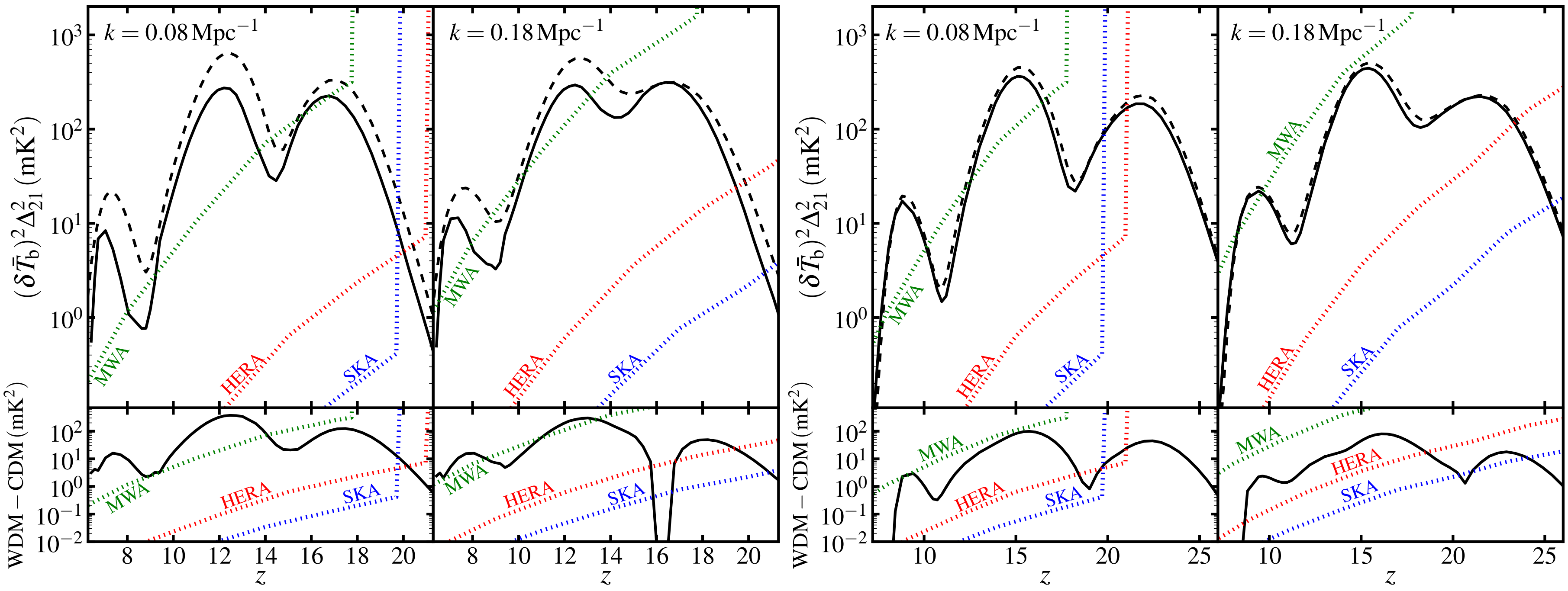


$$z_{\rm e}(f_*|{\rm CDM}) = z_{\rm e}(m_X|{\rm CDM})$$

For $m_X > 5\ \mathrm{keV}$, star formation efficiency is degenerated with WDM. For low mass, the two are not degenerated.

This is observable by the high-redshift measurement such as square kilometer array.

Forecast: comparing with future observations



- In light of EDGES-like detection of global 21-cm measurement, we reach:

○ $\tau_{DM} > 10^{26}$s for DM decays into $\gamma\gamma, \mu^+\mu^-, b\bar{b}$; and $\tau_{DM} > 10^{27}$s for DM decays into e^+e^-, stronger than Planck results.

○ PBH Hawking radiation can produce radiation as an energy injection into IGM. The EDGES constraint for PBH abundance is stronger than Planck.

- WDM has a particular feature of power spectrum comparing to CDM. The future MWA, HERA and SKA is sensitive to the warm dark matter with mass in the regime of 1—10 keV through power spectrum and global signal.