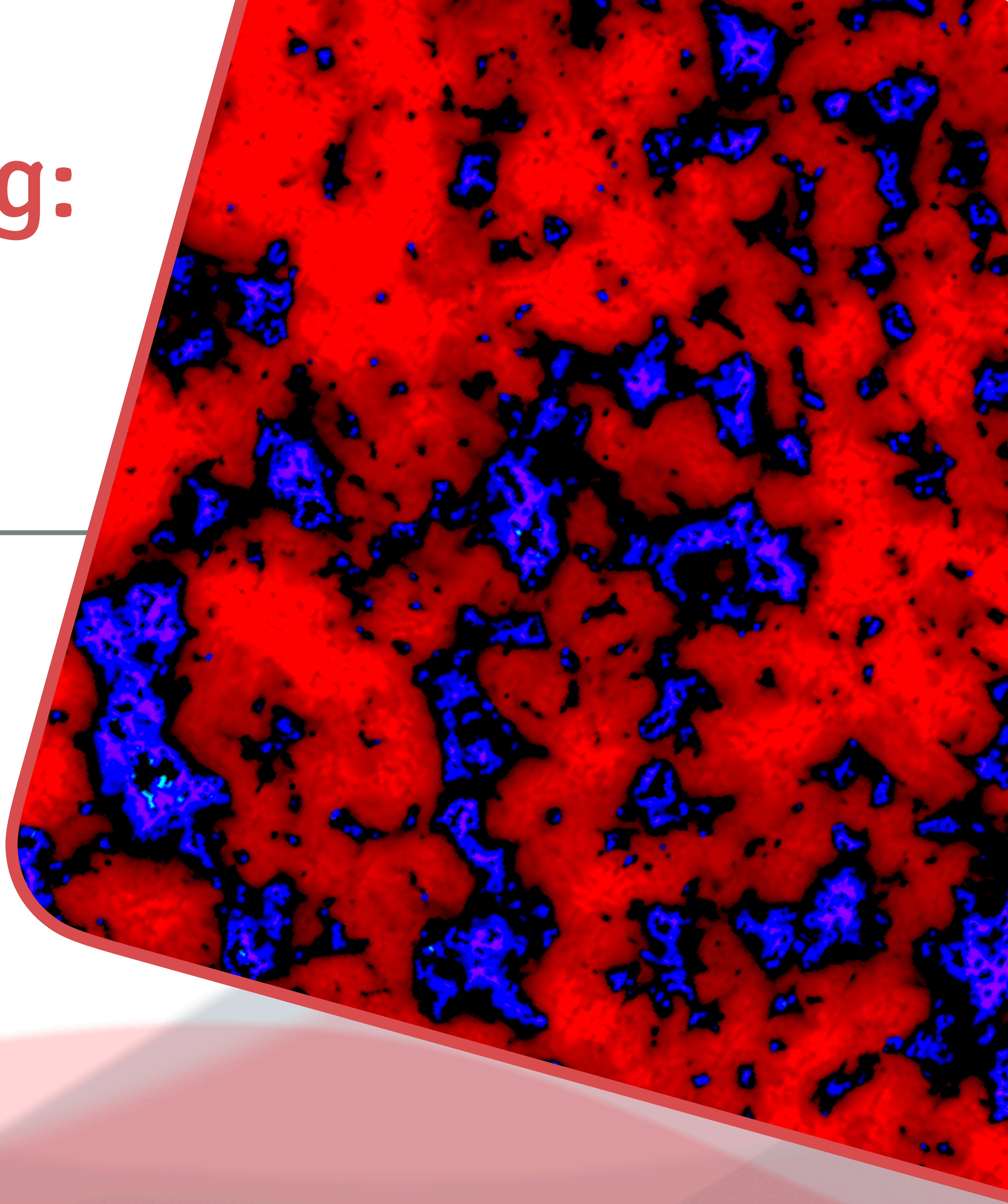
21cm and exotic heating: the example of dark matter decays

[based on arXiv:2308.16656]



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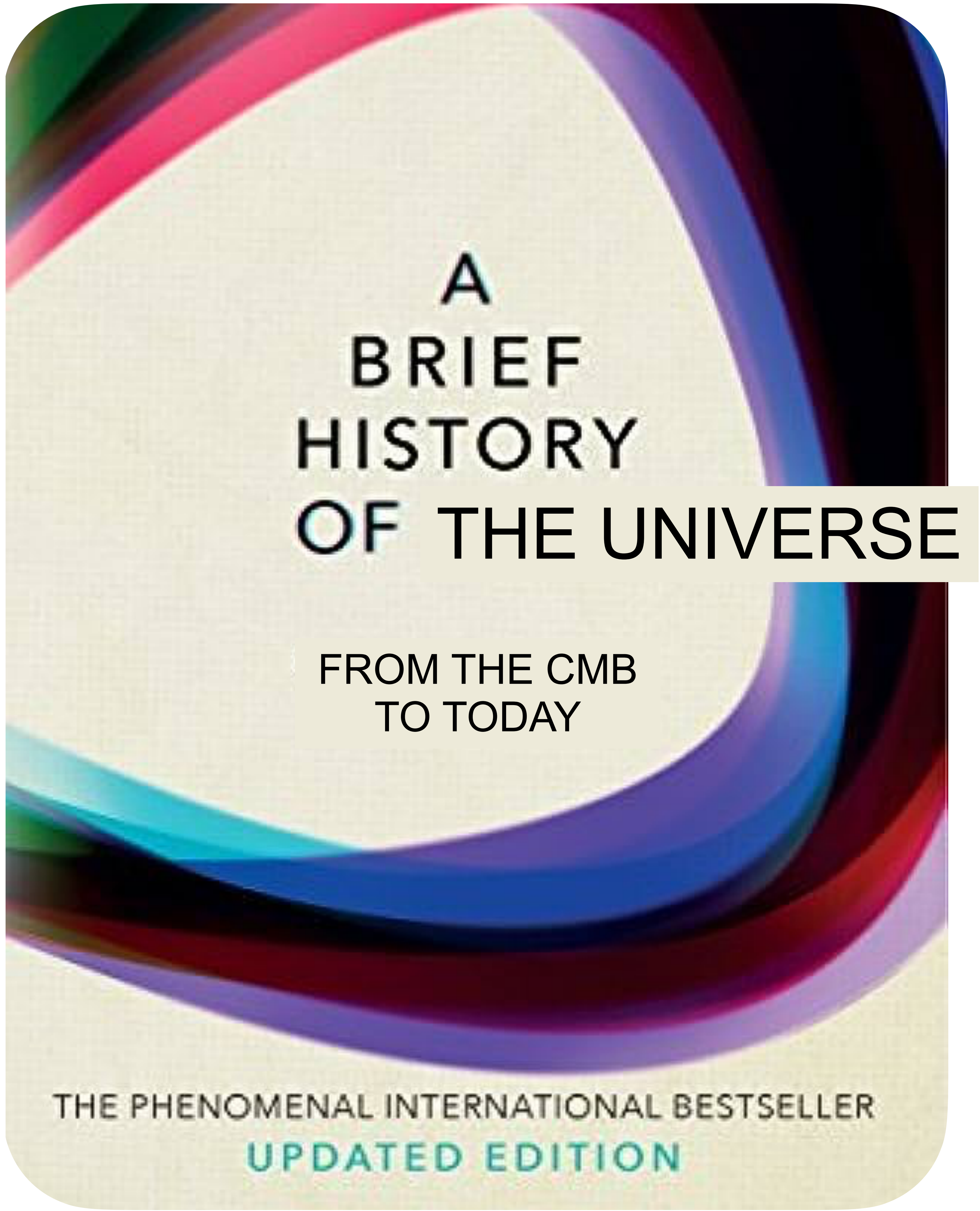
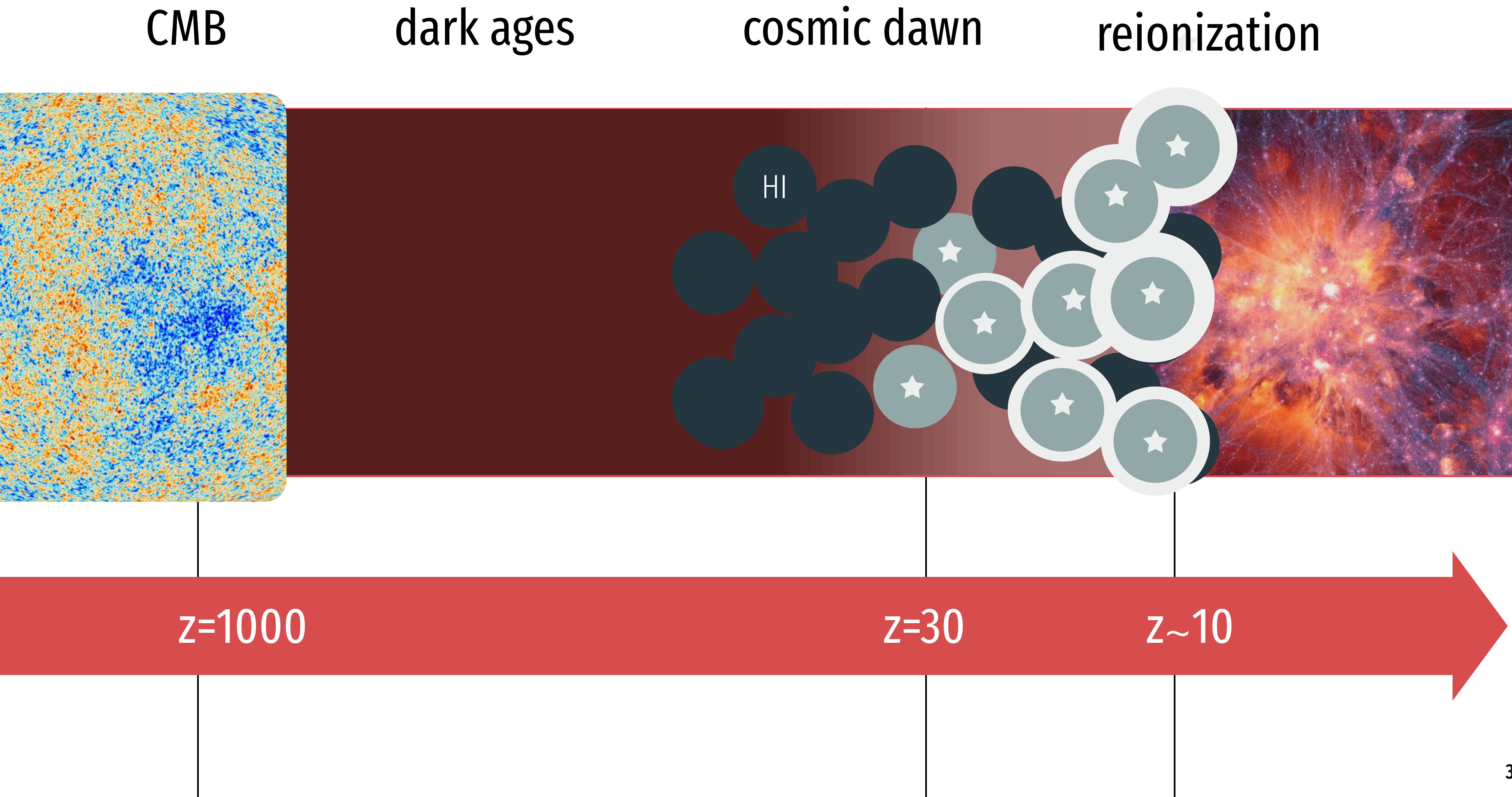
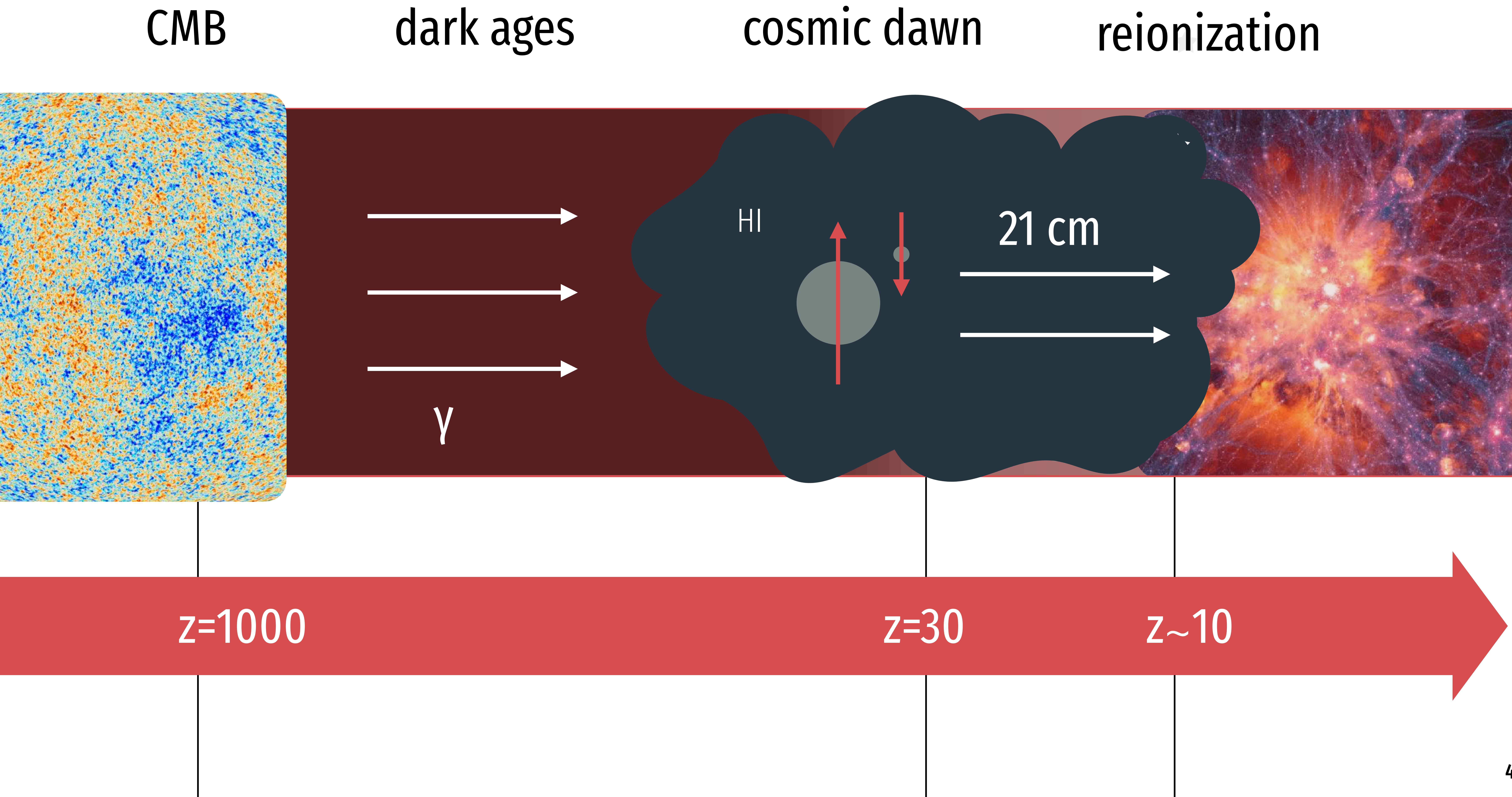
in collaboration with
Laura Lopez-Honorez (Université Libre de Bruxelles),
Andrei Mesinger (Scuola Normale Superiore di Pisa),
Yuxiang Qin (University of Melbourne)

Let's start with




CMB
dark ages
cosmic dawn
reionization
HI
z=1000
z=30
z~10


CMB
dark ages
cosmic dawn
reionization
γ
HI
21 cm
z=1000
z=30
z~10

[See review by Furlanetto et al. 2006]

*« **From a drop of water** [...] a logician could infer the possibility of an Atlantic or a Niagara **without having seen** or heard of one or the other. »*

Arthur Conan Doyle, A study in Scarlet

Can we say something on our Niagara, that is **BSM physics**, potentially leaving drops of water in the **21cm signal** ...

?

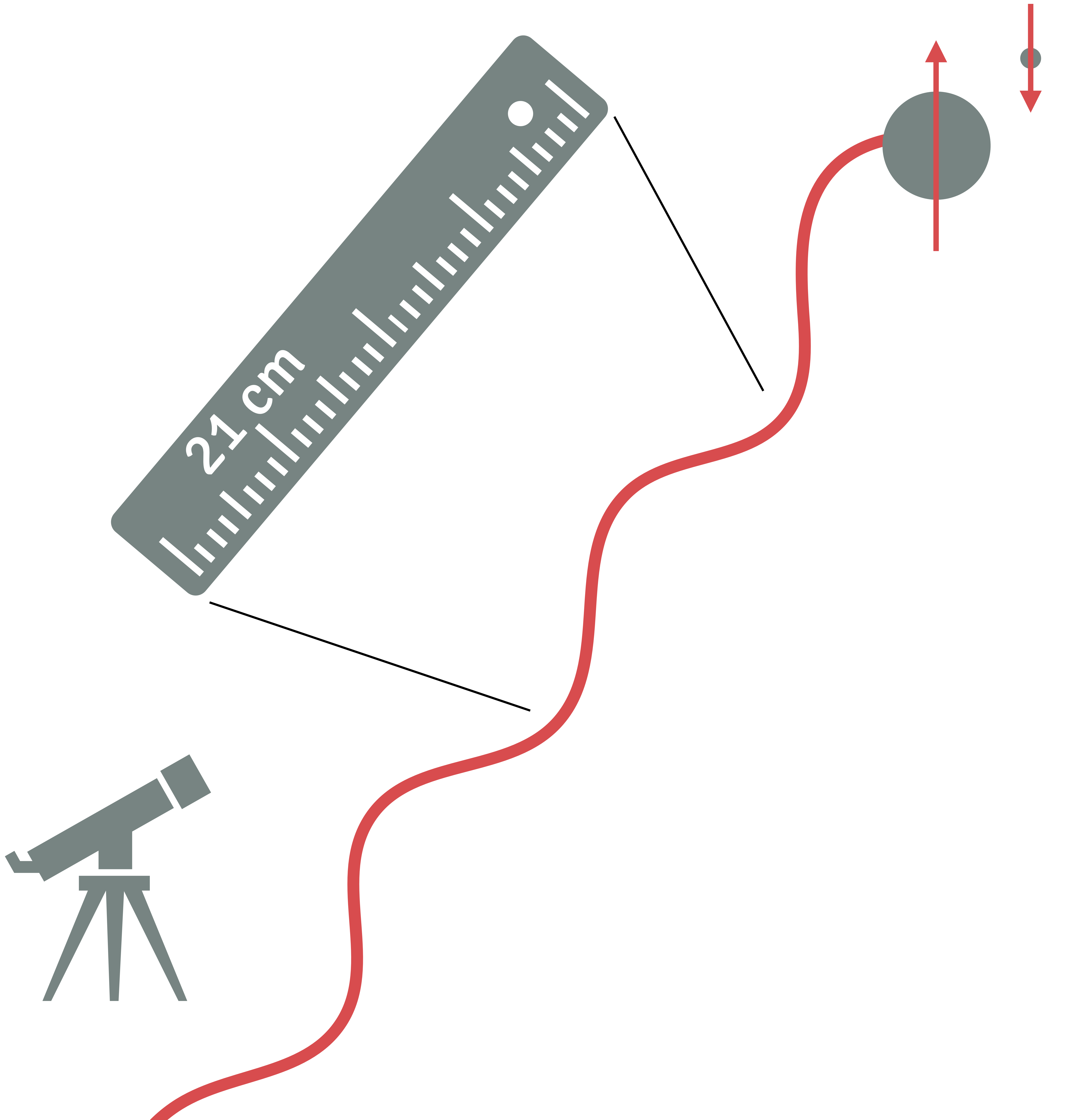
I. (Exotic) heating of the IGM

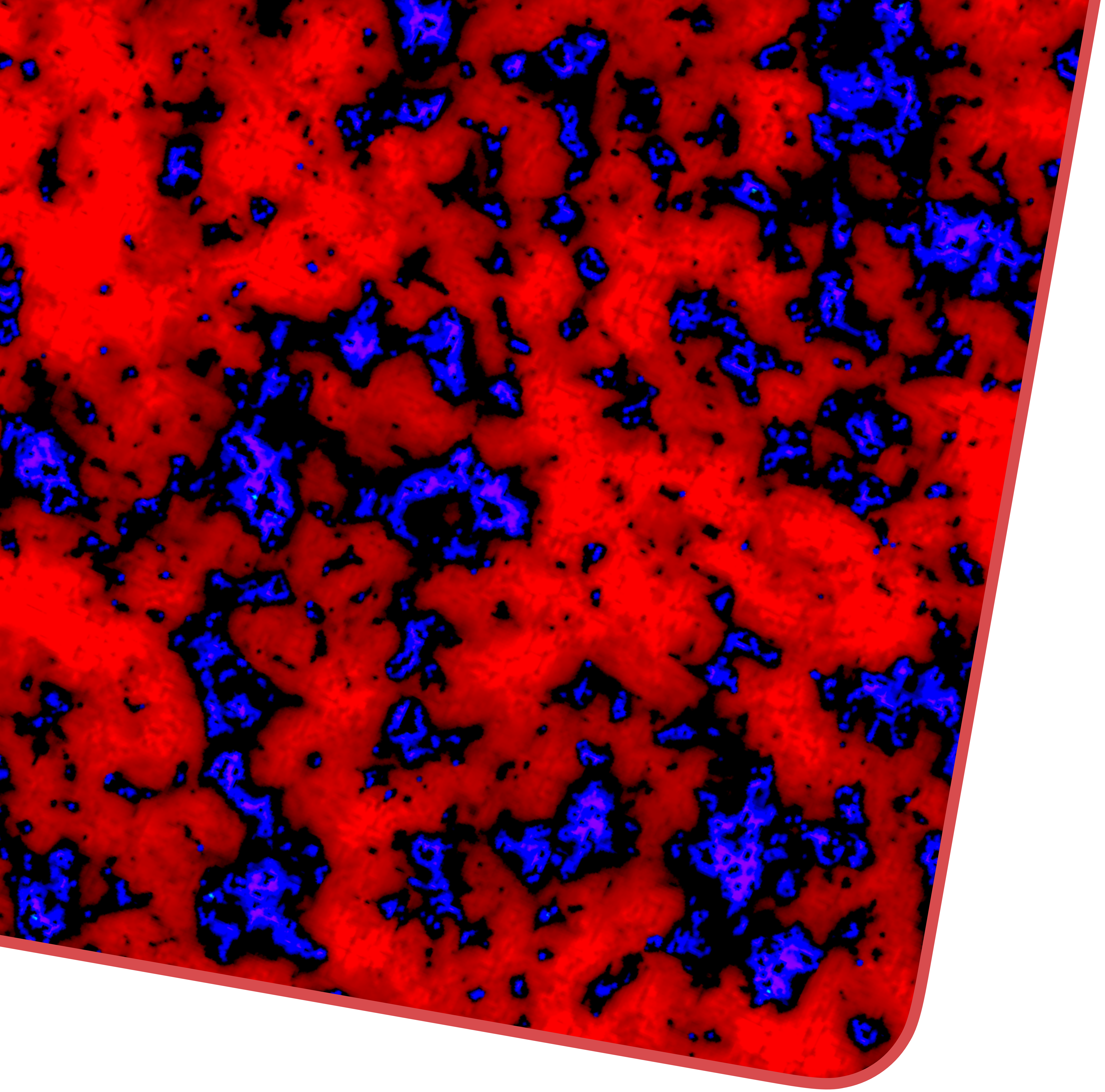
II. The example of dark matter decays

III. Fisher forecasts

I.

Heating of the IGM





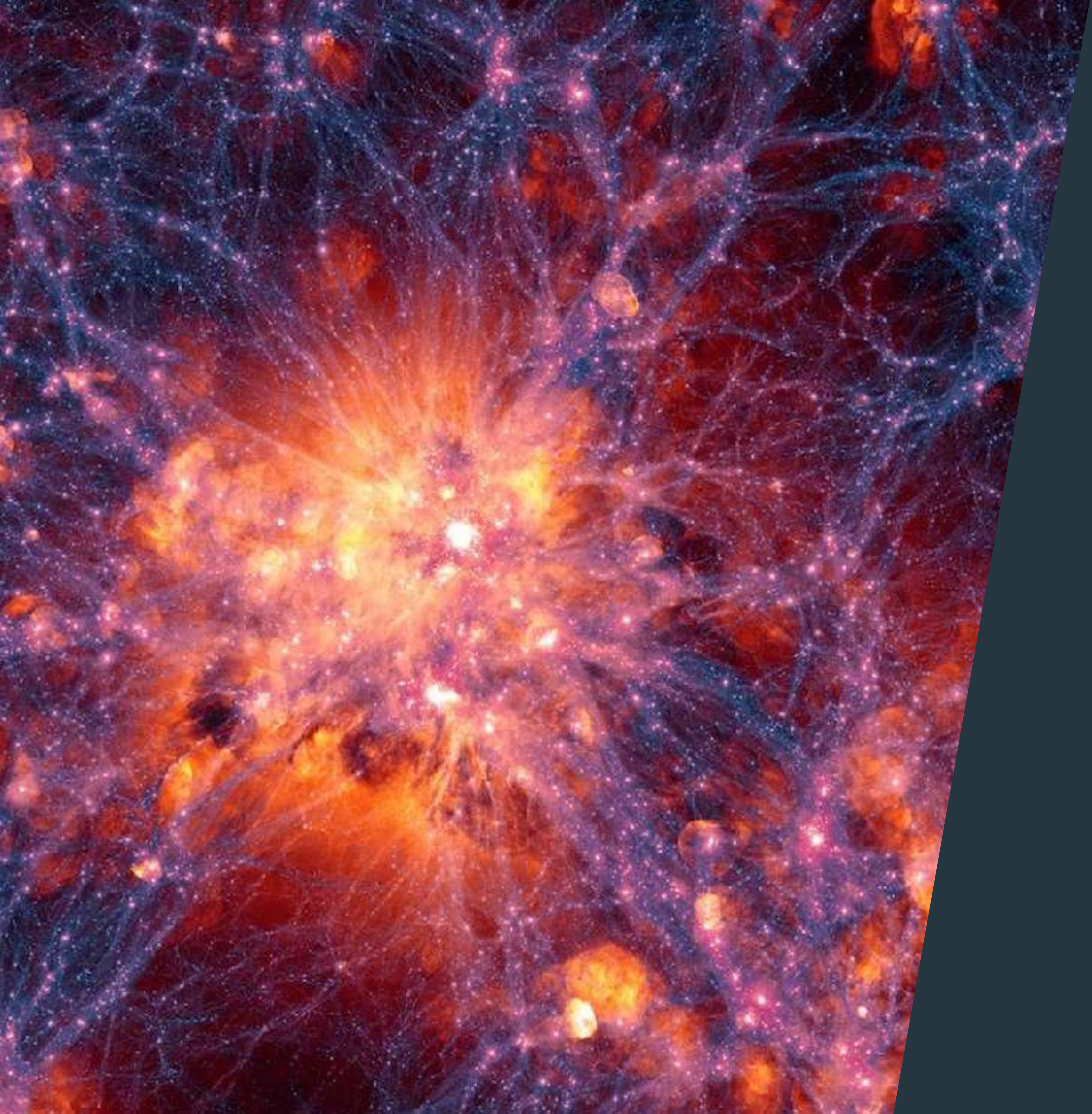
δT_b, the differential brightness temperature, depends on

(i)

the CMB temperature
(background light)

$$T_\gamma$$


T_γ



(ii)

$$T_{\mathrm{K}}$$

the kinetic temperature (of the IGM gaz)

Due to collisional and UV interactions within the neutral hydrogen gas changing the occupation number of the triplet and singlet state

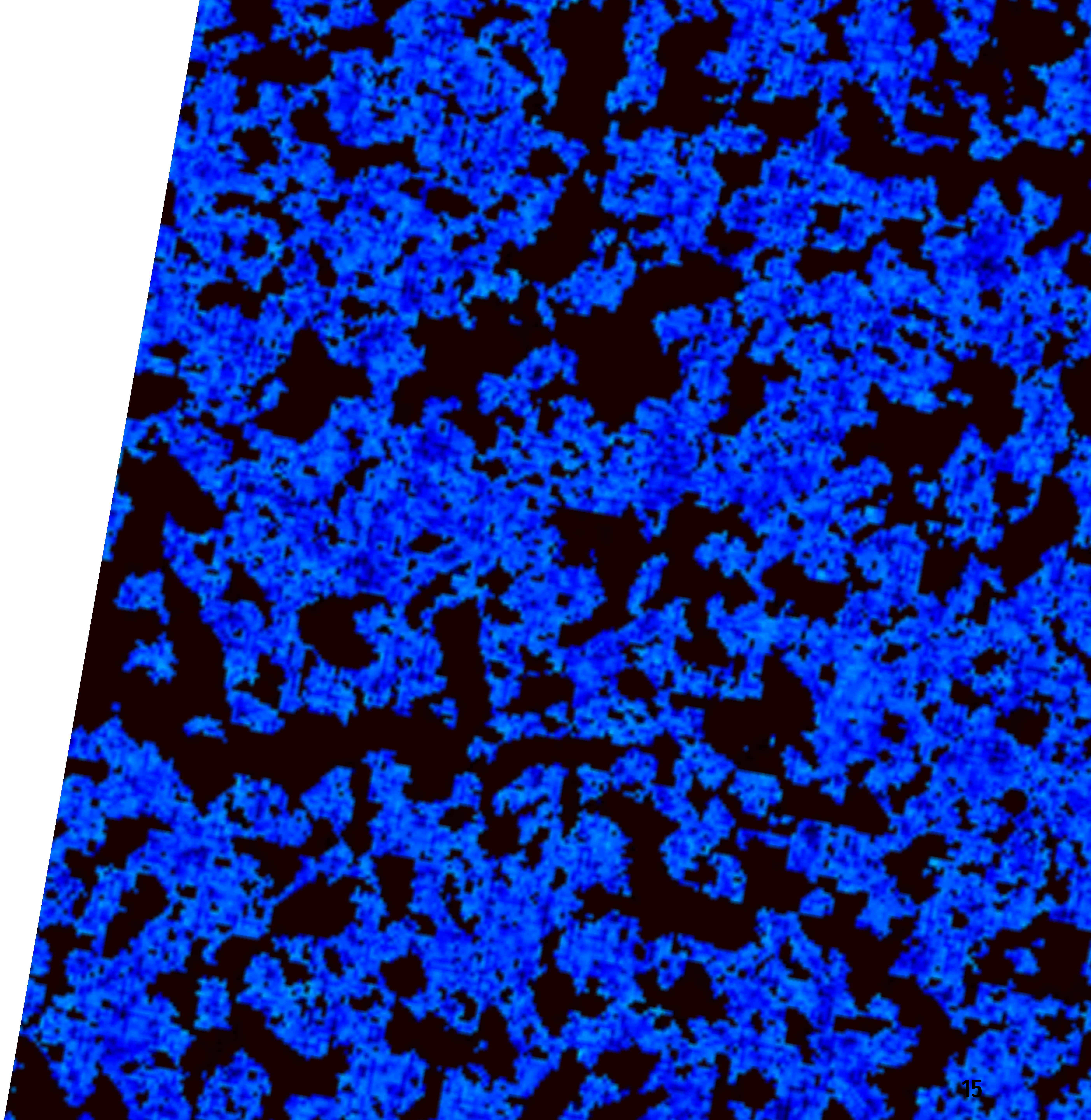

T_γ
T_K

(iii)

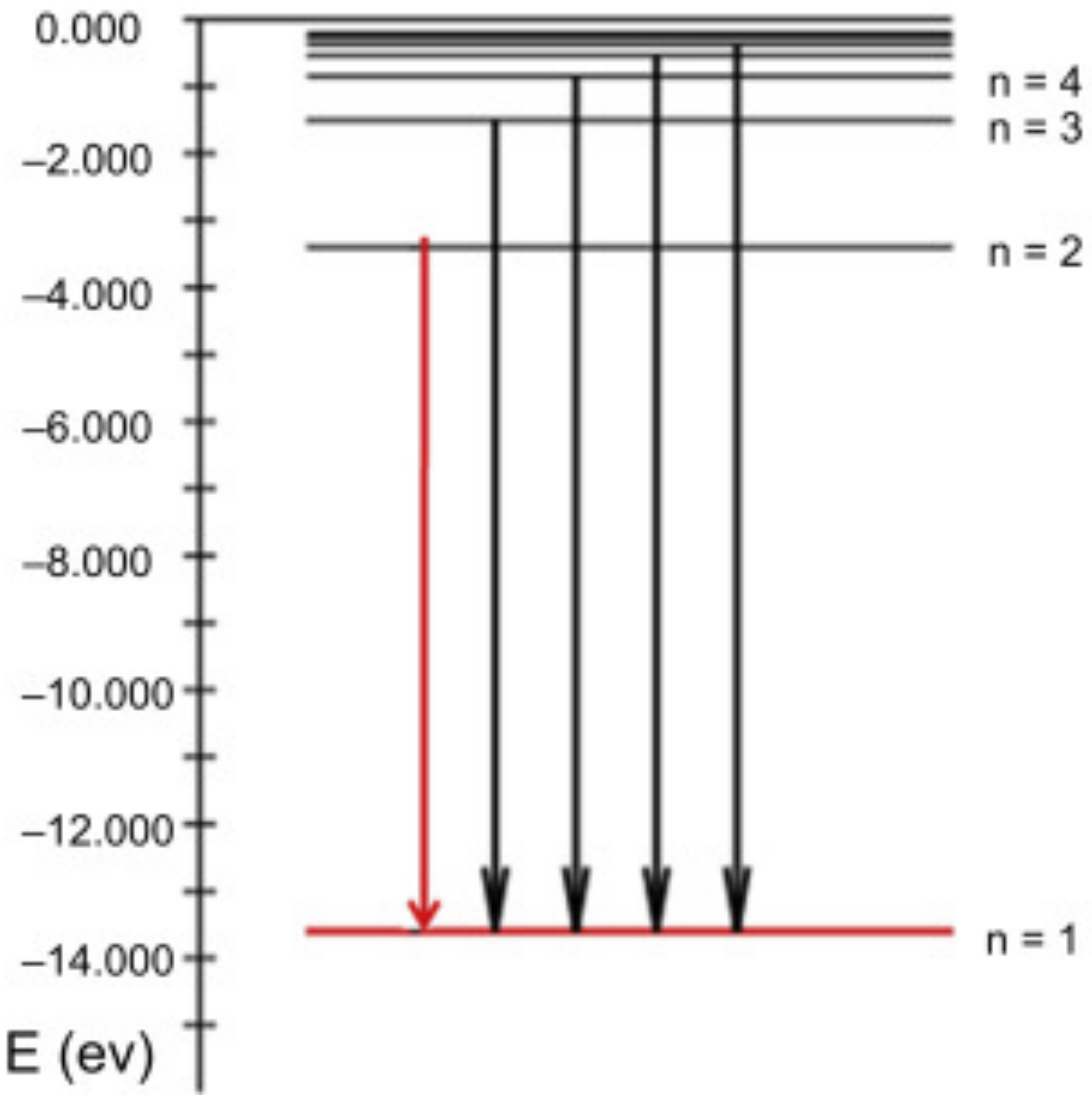
the ionized fraction of hydrogen

(here ~electron fraction)

x_e




T_γ
T_K
x_e



(iv)

the flux of Lyman-α photons exciting the neutral Hydrogen

J_α

… in short, it depends on the evolution of the IGM

$$\delta T_{\rm b} = f(T_\gamma, T_{\rm K}, x_e, J_\alpha, \ldots)$$

[See review by Furlanetto et al. 2006]

The « mostly neutral » IGM evolution is described by:

$$
\begin{cases}
\dfrac{\partial x_e(\boldsymbol{x}, t)}{\partial t} = \underbrace{\Lambda_{\text{ion}}(\boldsymbol{x}, t)}_{\text{ionisation rate}} - \text{recomb . rate} \\[2ex]
\dfrac{\partial T_{\text{K}}(\boldsymbol{x}, t)}{\partial t} = f(\boldsymbol{x}, t) \displaystyle\sum_{\beta} \underbrace{\epsilon^{\beta}_{\text{heat}}(\boldsymbol{x}, t)}_{\text{heating rates}} + \dots
\end{cases}
$$

ionisation rate

heating rates

… so, said differently, δT_b depends on:

$$\delta T_\mathrm{b} = f\left(T_\gamma, \Lambda_\mathrm{ion}, \left\{ \epsilon^\beta_\mathrm{heat} \right\}_\beta, J_\alpha, \dots \right)$$

1. the *standard* scenario

CMB background

X-ray photons
Lyman-α photons

CMB background

X-ray photons

Lyman-α photons

CMB background

X-ray photons

Lyman-α photons

The X-ray energy injection rate is

$$\epsilon^X_{\mathrm{inj}} = \sum_{i\in\{\mathrm{II},\mathrm{III}\}} \int \mathrm{d}M_\mathrm{h} \, \frac{\mathrm{d}n}{\mathrm{d}M_\mathrm{h}} f^i_{\mathrm{duty}}(M_\mathrm{h}) \; \dot{M}^i_\star(M_\mathrm{h}) \, \mathscr{L}^i_X$$

and depends on the

- *halo mass function*
- *star formation rate*
- *X-ray luminosity* $\propto L^i_X$

$$\epsilon^{X}_{\mathrm{inj}} = \sum_{i\in\{\mathrm{II},\mathrm{III}\}} \int \mathrm{d}M_{\mathrm{h}} \frac{\mathrm{d}n}{\mathrm{d}M_{\mathrm{h}}} f^{i}_{\mathrm{duty}}(M_{\mathrm{h}})\, \dot{M}^{i}_{\star}(M_{\mathrm{h}})\, \mathscr{L}^{i}_{X}$$

There are different population of stars

from molecular-cooling galaxies ('PopIII'-dominated)

$$\epsilon^{X}_{\mathrm{inj}} = \sum_{i\in\{\mathrm{II},\mathrm{III}\}} \int \mathrm{d}M_{\mathrm{h}} \frac{\mathrm{d}n}{\mathrm{d}M_{\mathrm{h}}} f^{i}_{\mathrm{duty}}(M_{\mathrm{h}})\, \dot{M}^{i}_{\star}(M_{\mathrm{h}})\, \mathscr{L}^{i}_{X}$$

There are different population of stars

from molecular-cooling galaxies ('PopIII'-dominated)

from atomic-cooling galaxies ('PopII'-dominated)

Deposition does

NOT happen

on the **spot**

ϵ^X_{inj} *deposited into*

- ϵ^X_{heat} *heat*
- Λ^X_{ion} *ionisation*
- J^X_α *Lyman-α flux*

CMB background

X-ray photons

Lyman-α photons

$\epsilon_{\mathrm{heat}}^{\mathrm{Compton}}$ $\epsilon_{\mathrm{heat}}^{X}$

heating rates

$\Lambda_{\mathrm{ion}}^{X}$

ionisation rate

J_{α}^{X} $J_{\alpha}^{\star}$

Lyman-α flux

The

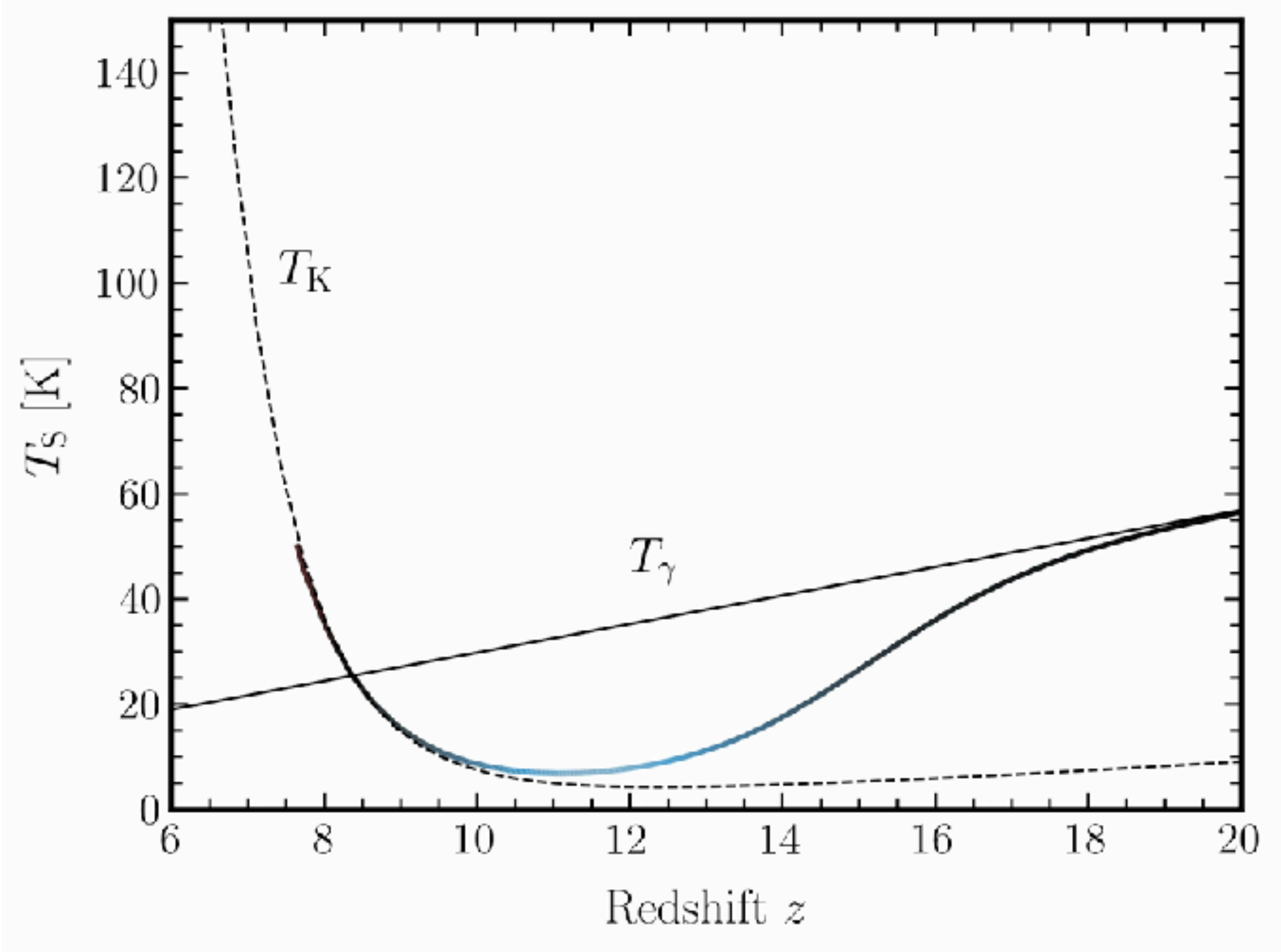
21cmFAST

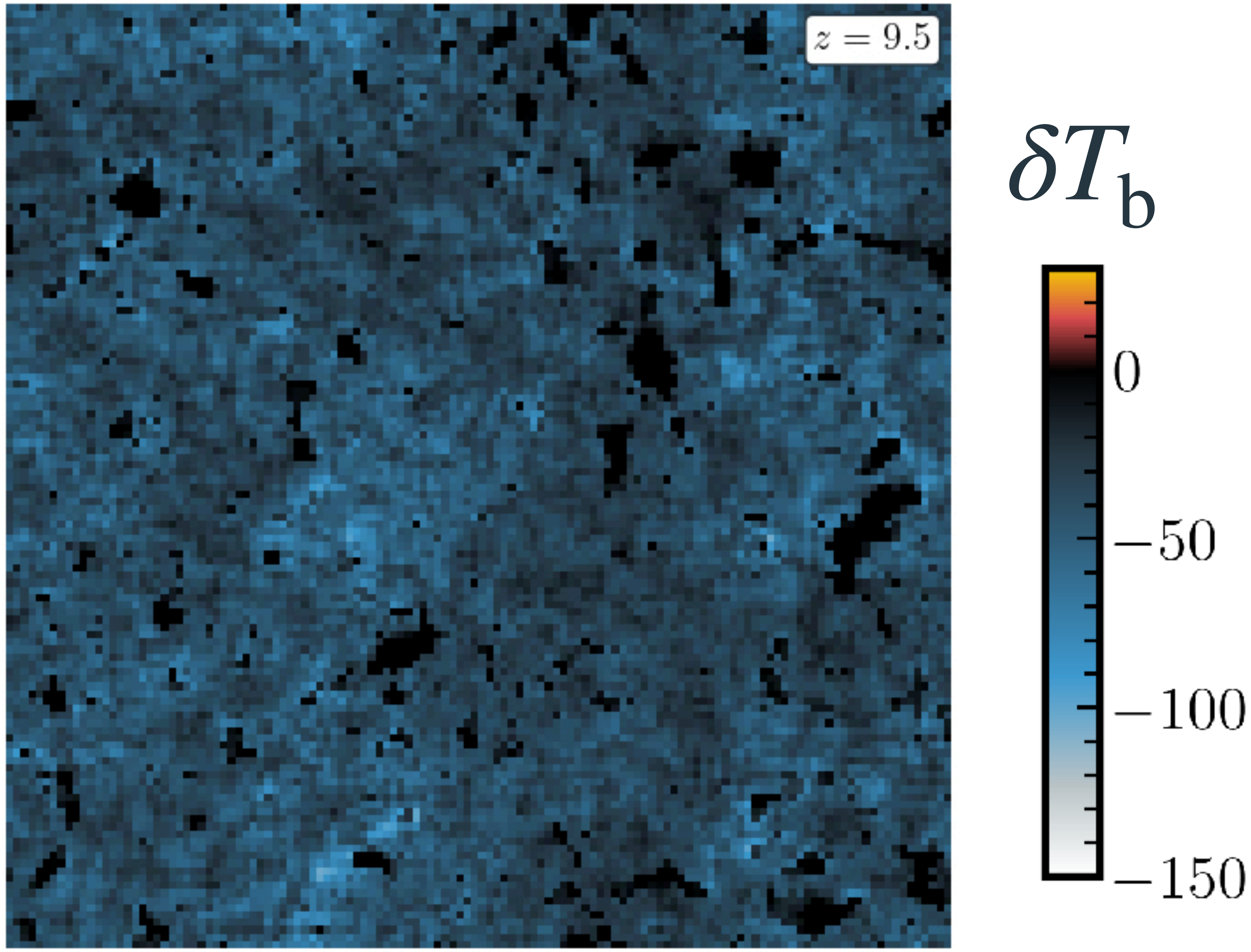
(Semi-analytical code to model the 21 cm signal)

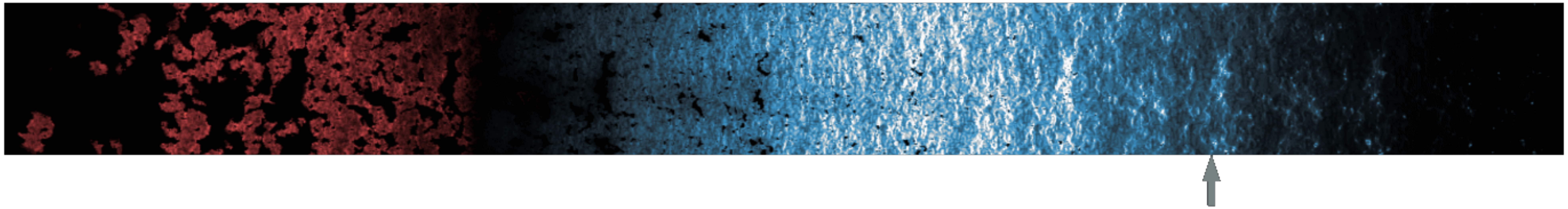
code

[Messinger et al. 2010, Messinger et al. 2007]

simulates the IGM

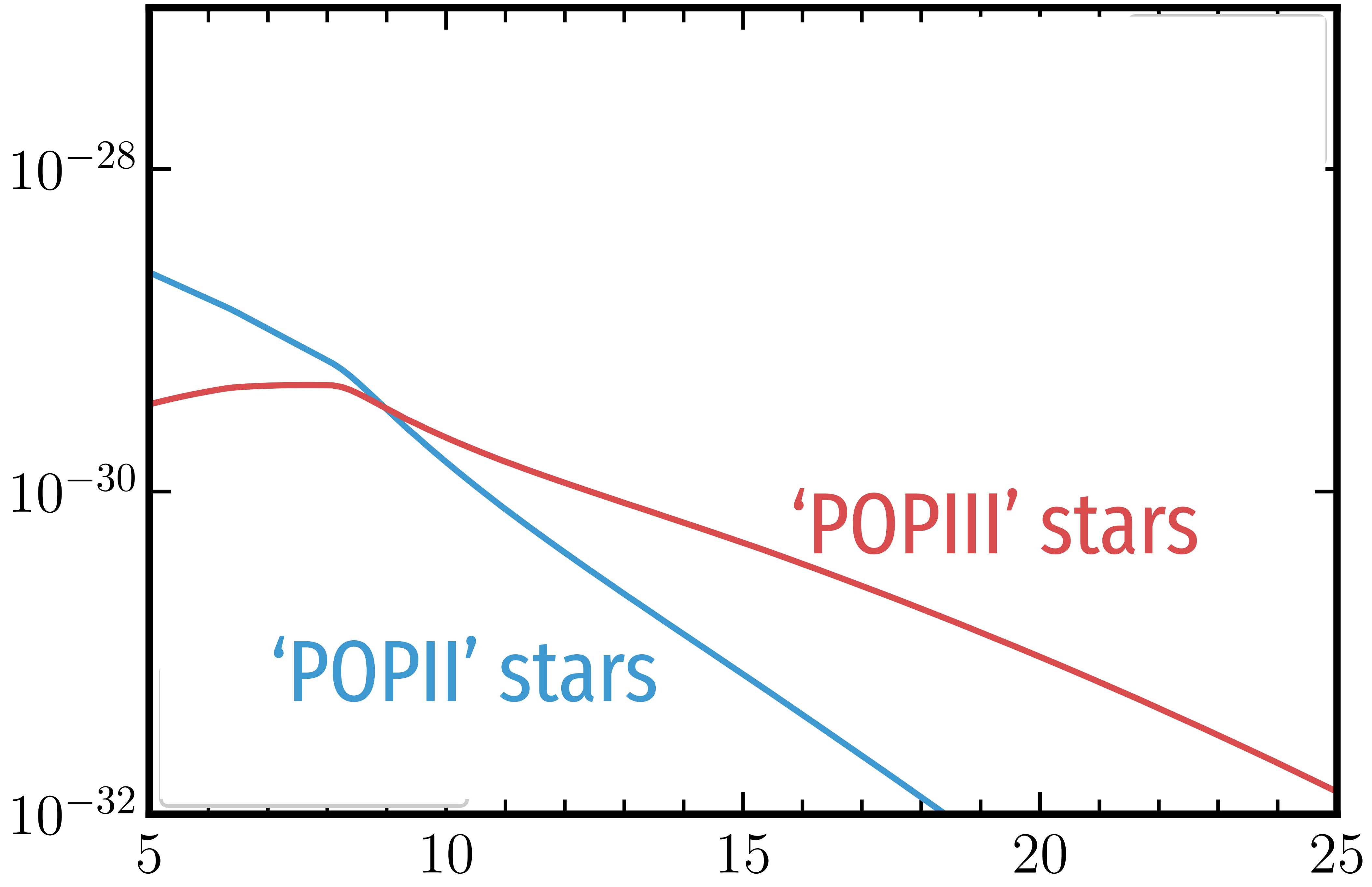






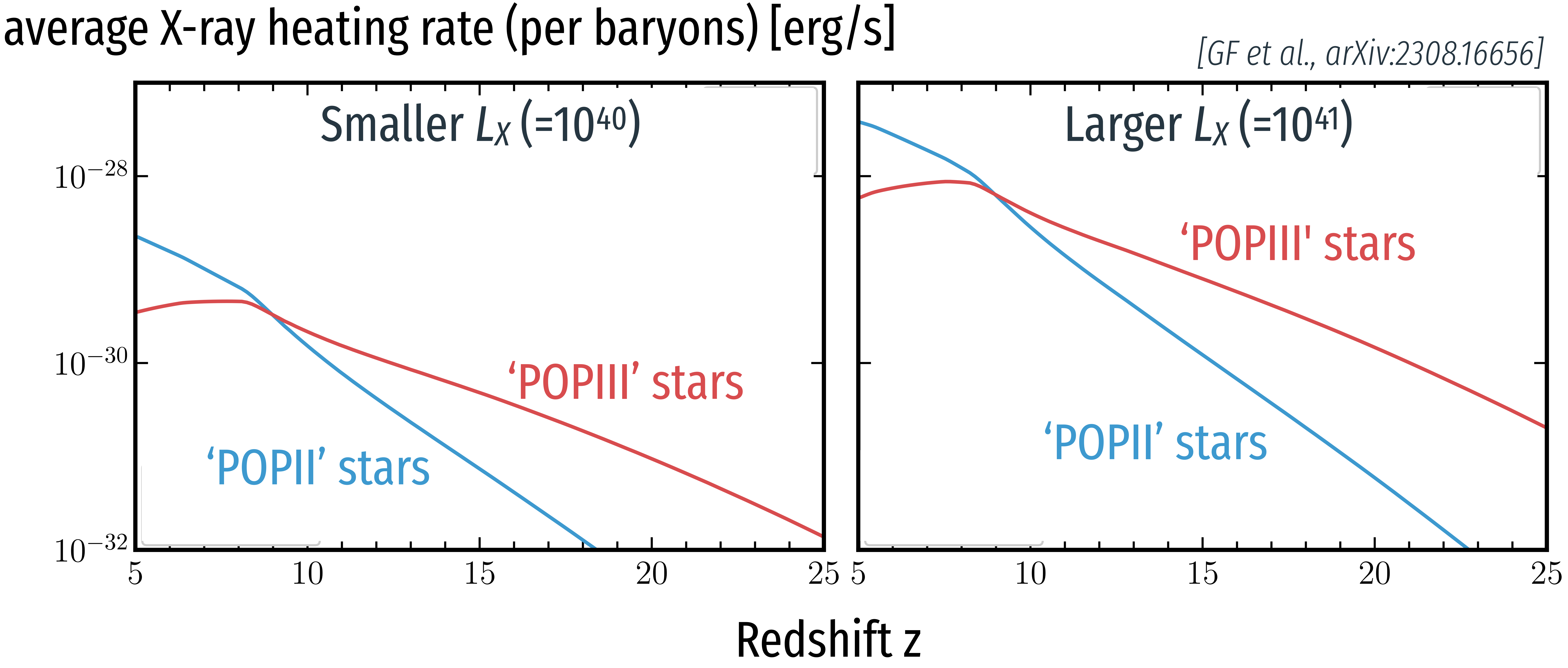
by computing, e.g.,
how strongly X rays heat the IGM

average X-ray heating rate (per baryons) [erg/s]



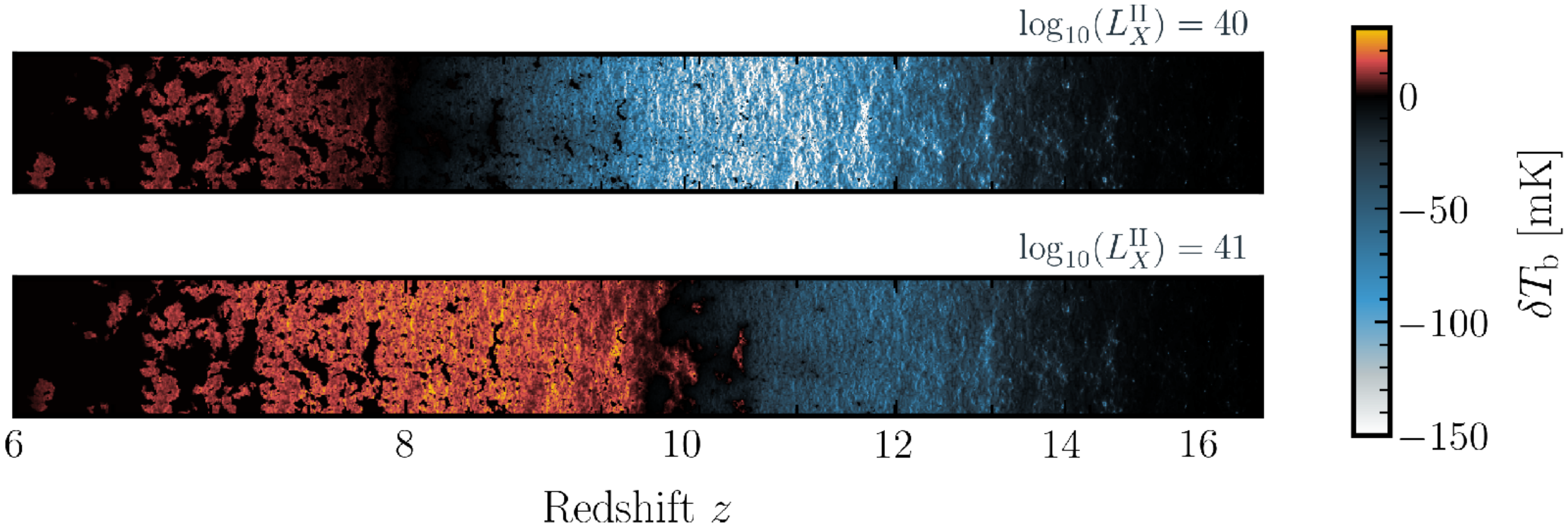
Redshift z

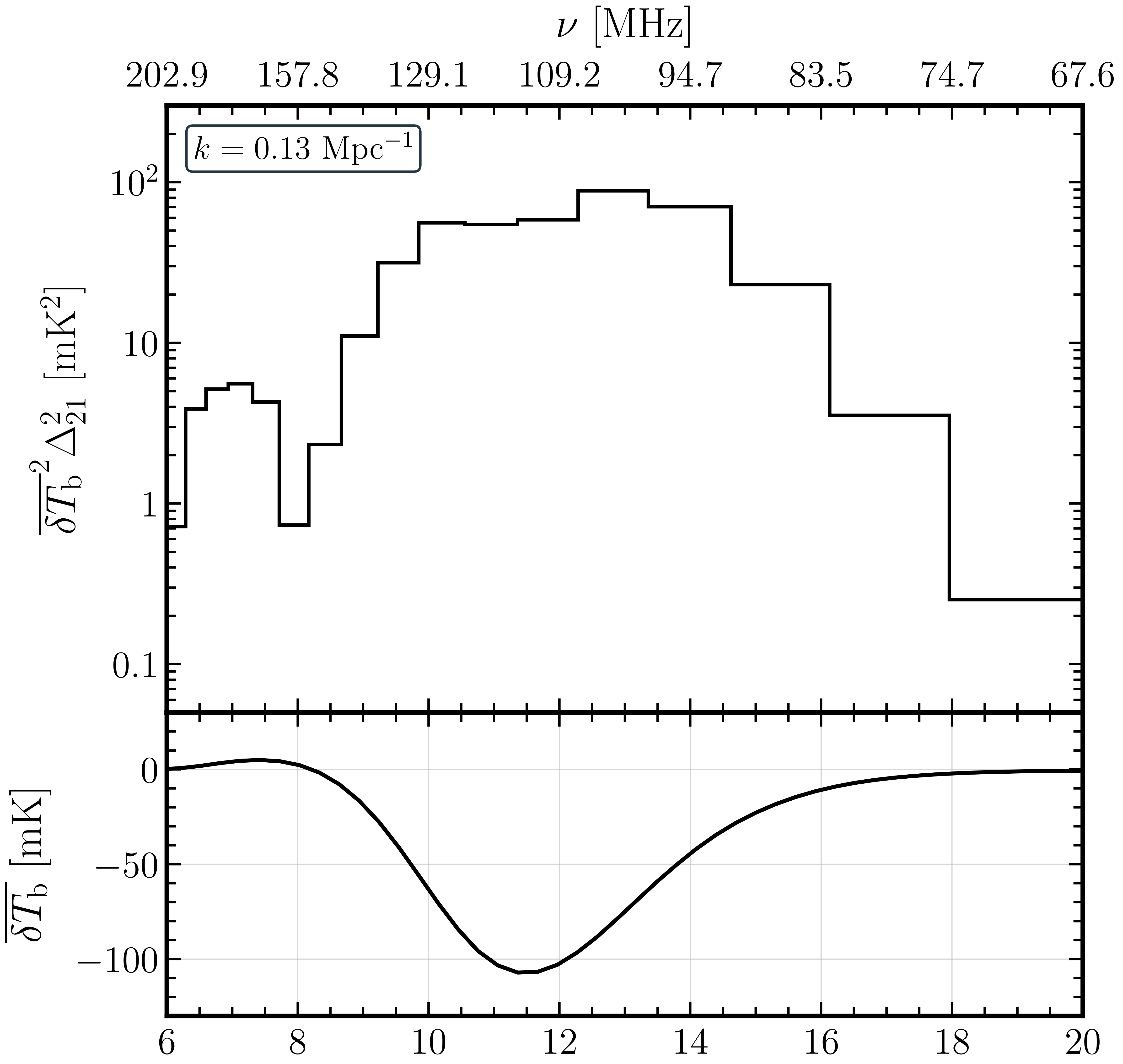
With 21cmFAST one can then compare different X-ray normalisation: L_X



[GF et al., arXiv:2308.16656]

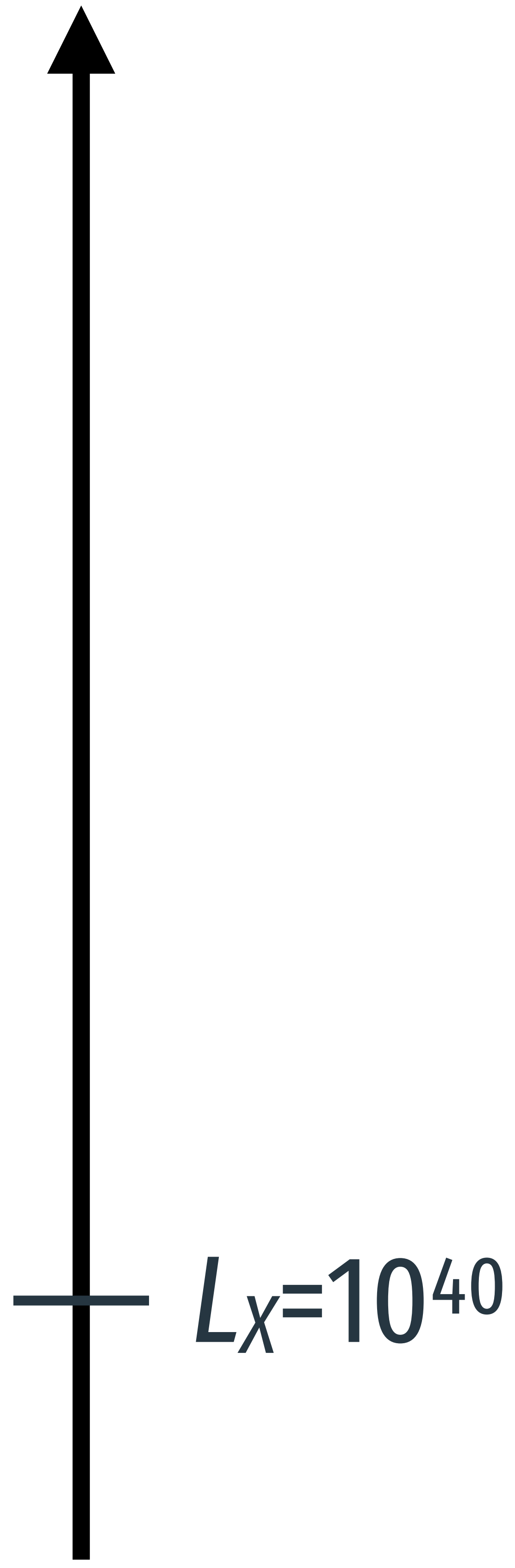
With 21cmFAST one can then compare different X-ray normalisation: L_X



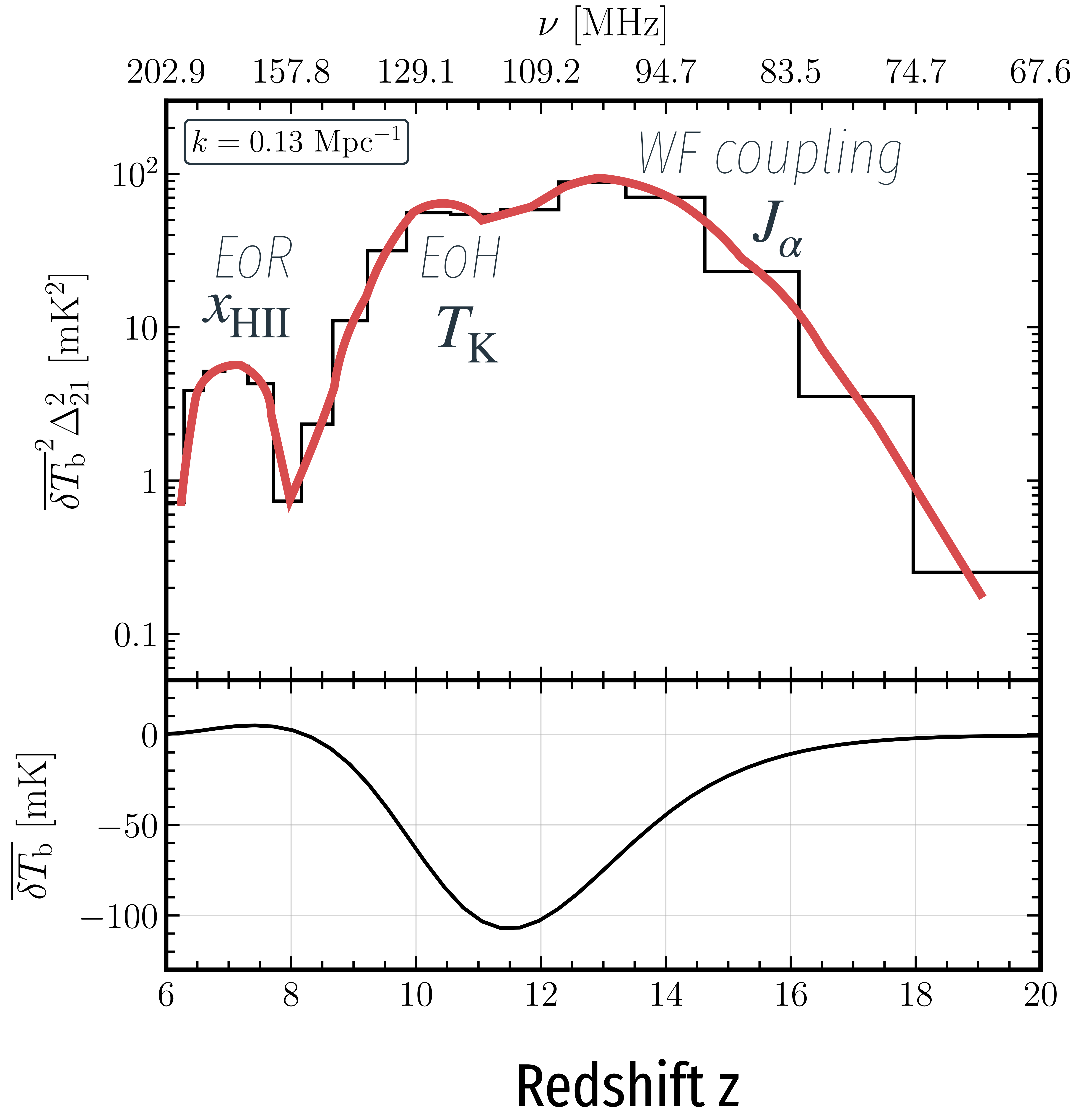


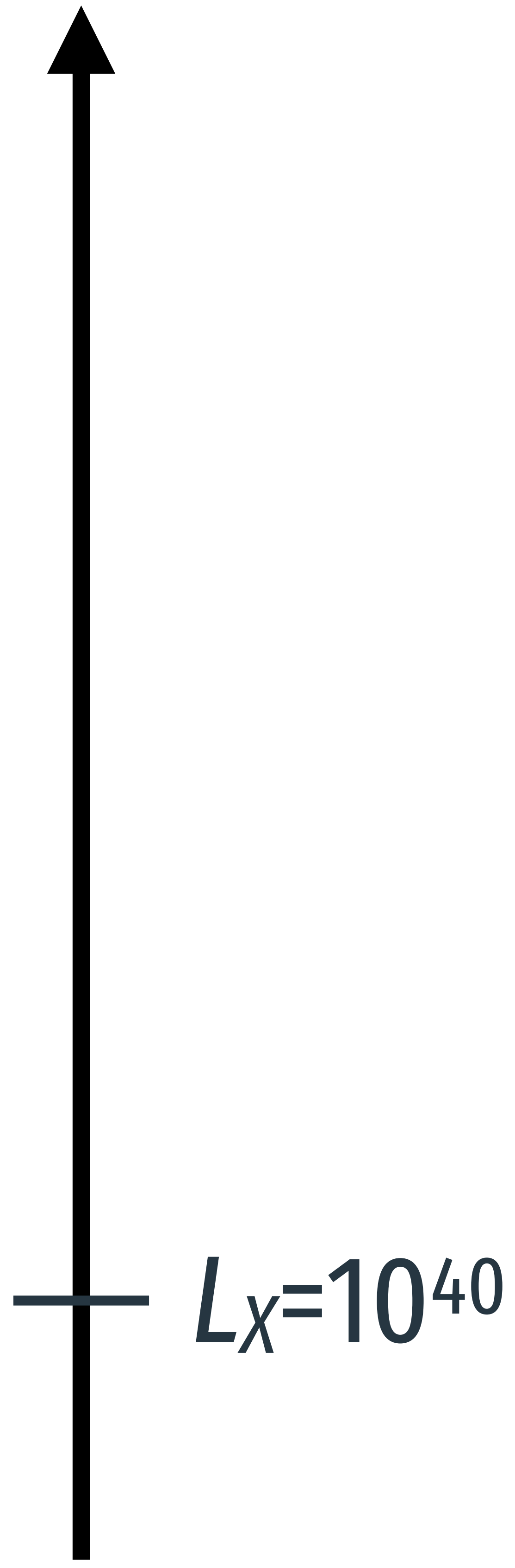
Redshift z

and evaluate the power spectrum



and evaluate the power spectrum





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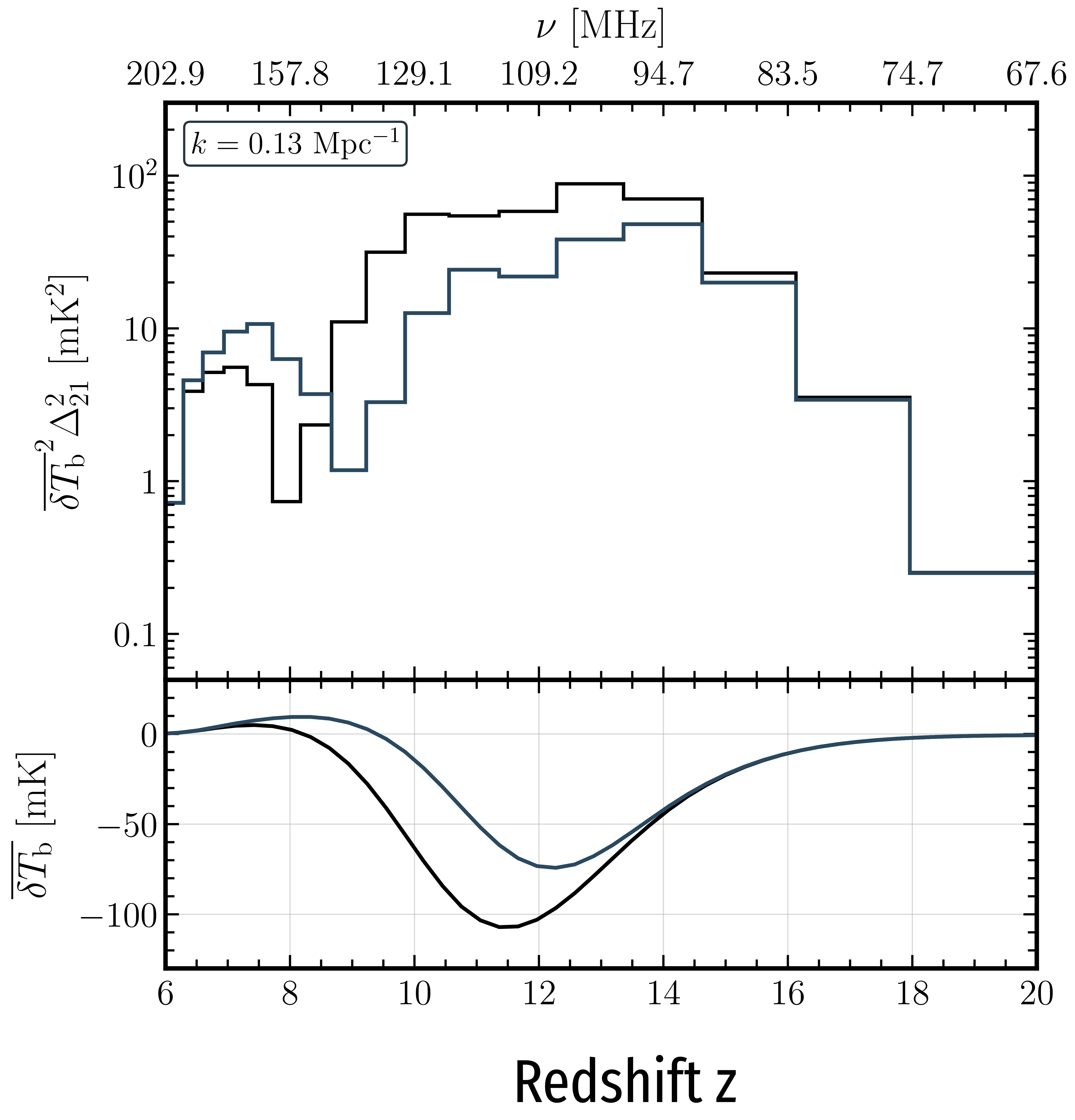

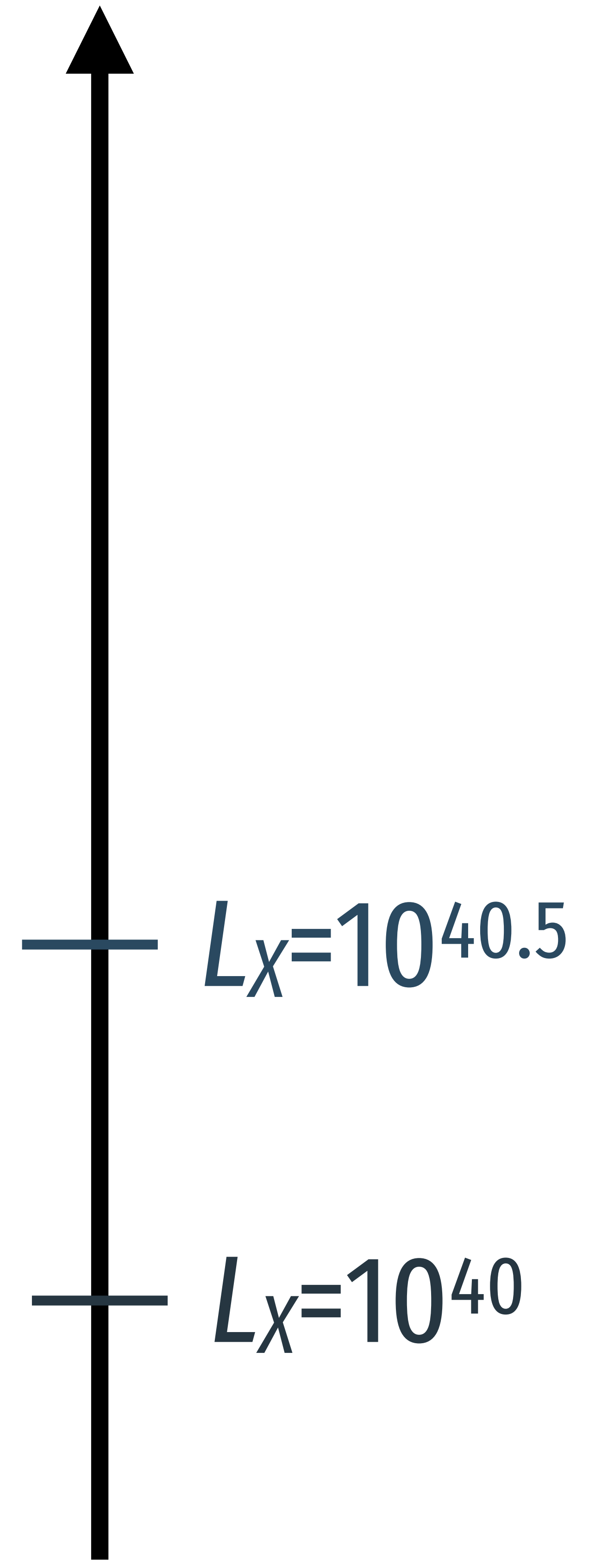

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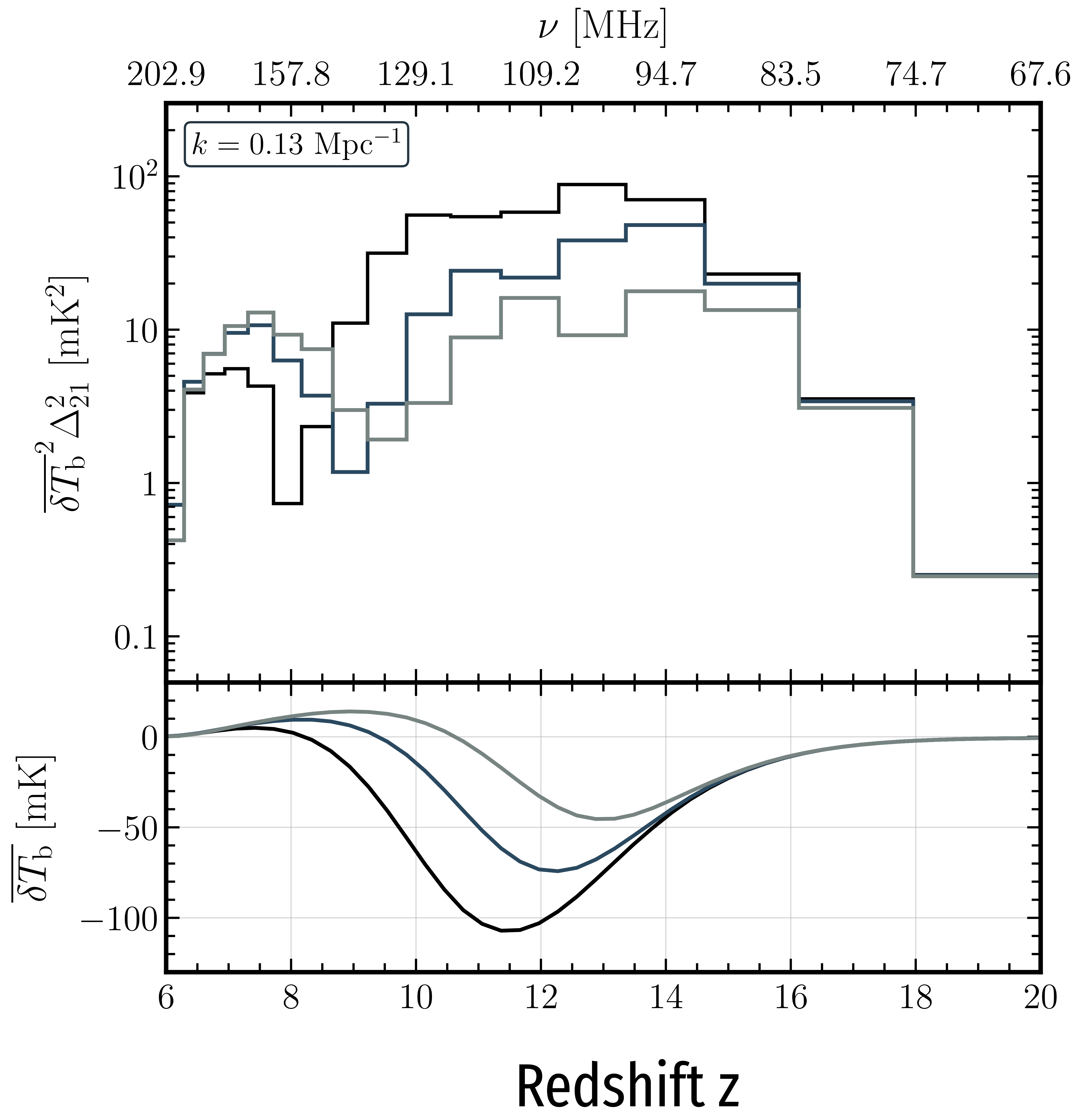
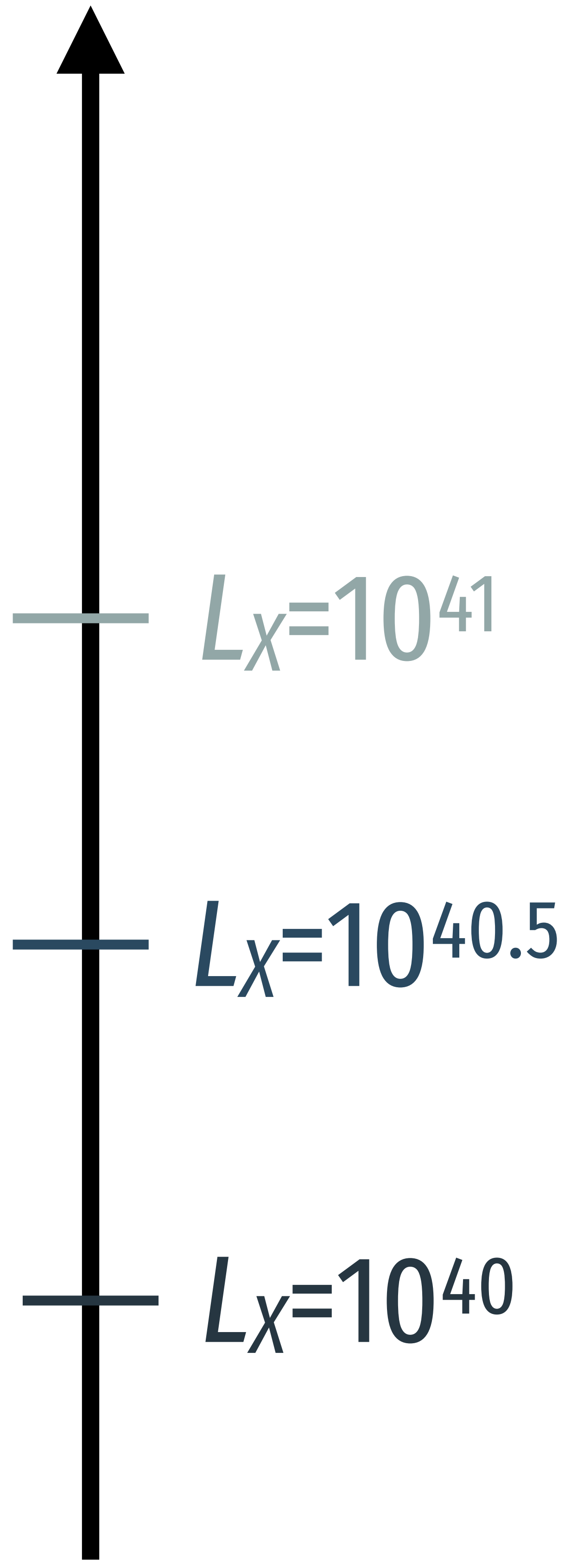
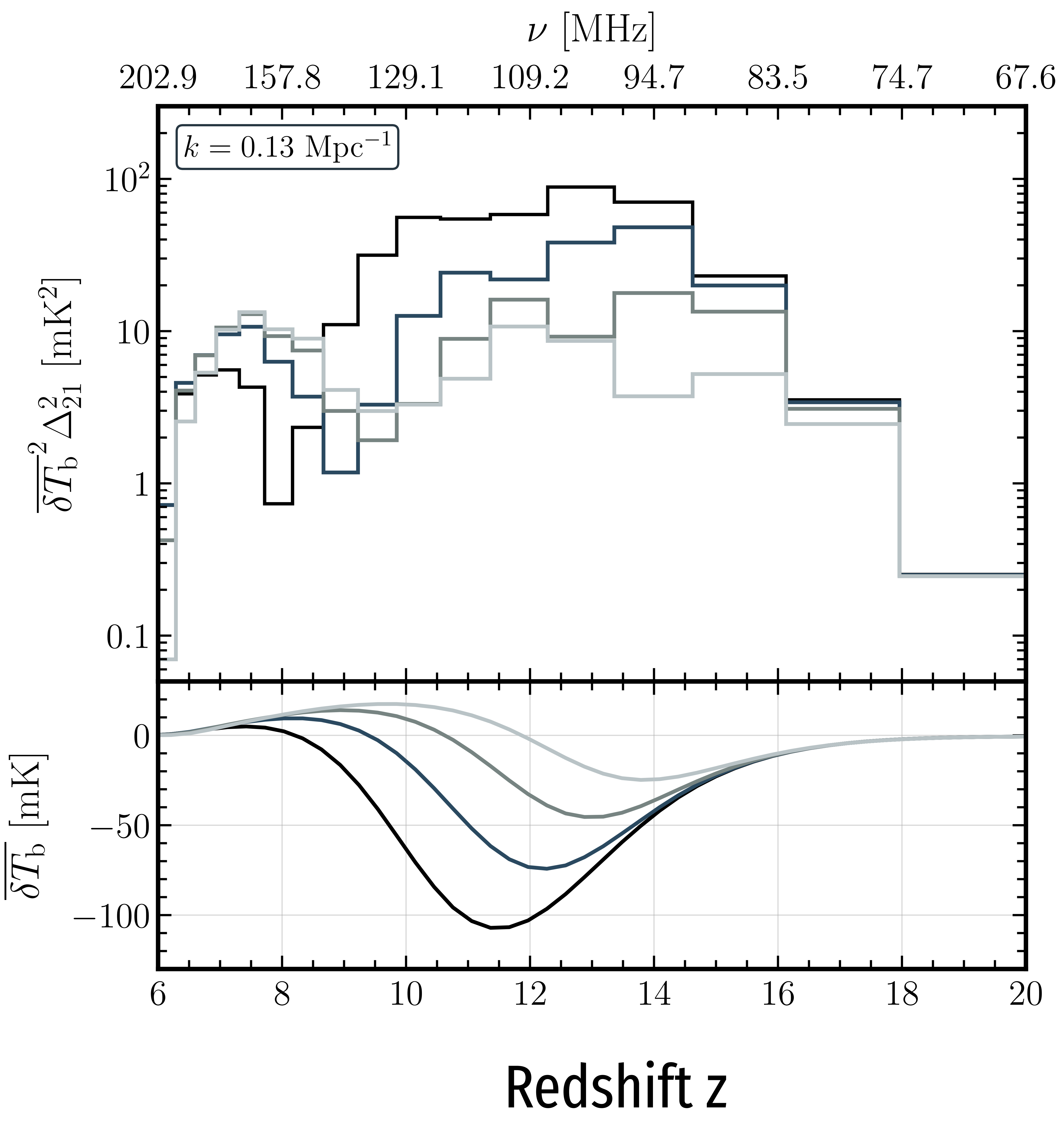
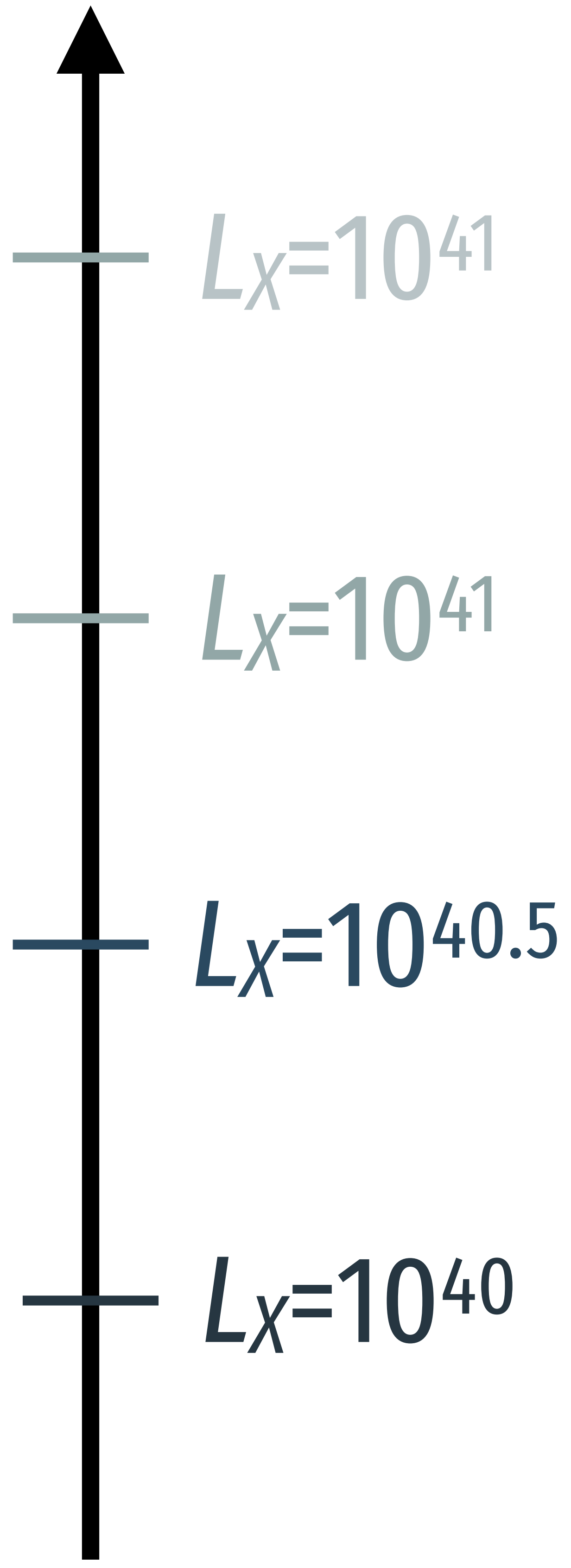
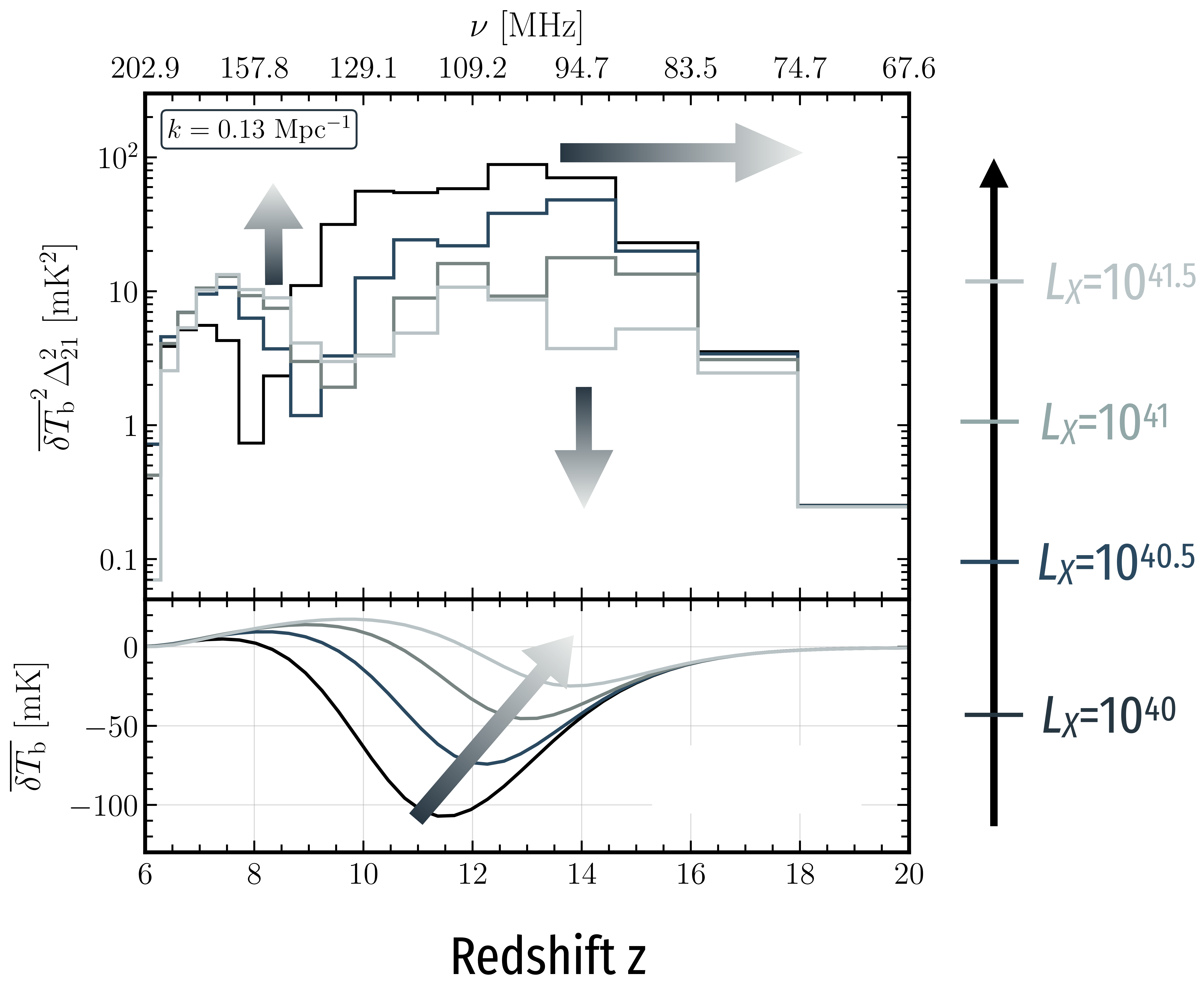


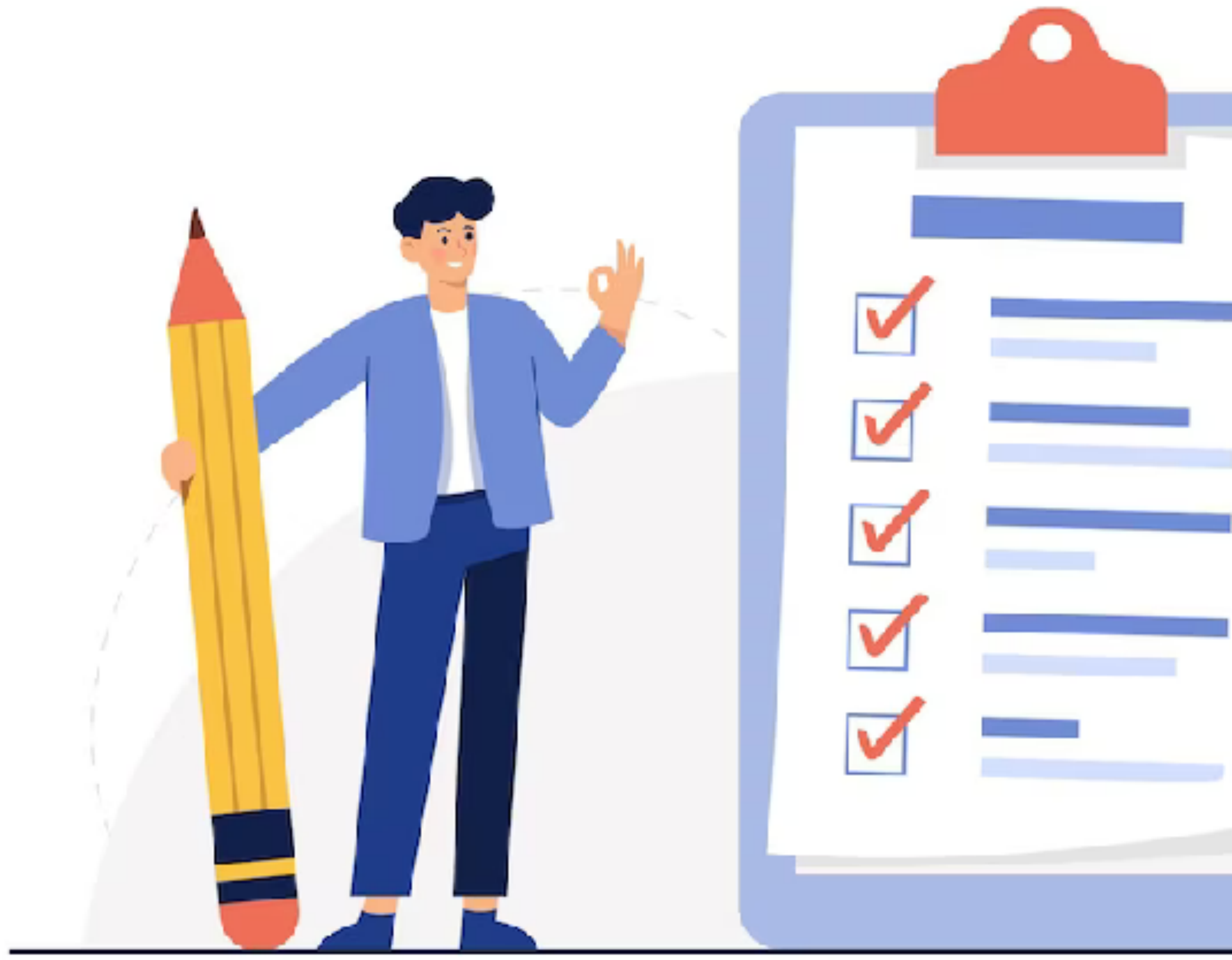


and evaluate the power spectrum









[freepik.com]

Higher L_X results in:

- earlier heating
- higher first peak
- lower second/third peaks

2. adding exotic sources

Let us assume that
exotic sources inject energy at a rate

$$\epsilon_{\text{inj}}^{\text{exo}}$$

This energy is similarly deposited into the IGM

$\epsilon_{\text{inj}}^{\text{exo}}$ *deposited into*

- $\epsilon_{\text{heat}}^{\text{exo}}$ *heat*
- $\Lambda_{\text{ion}}^{\text{exo}}$ *ionisation*
- J_{α}^{exo} *Lyman-α flux*

The total deposited energy is the sum

$$\left\{\begin{array}{l} \epsilon_{\mathrm{heat}} = \epsilon_{\mathrm{heat}}^{X} + \epsilon_{\mathrm{heat}}^{\mathrm{Compton}} + \epsilon_{\mathrm{heat}}^{\mathrm{exo}} \\ \\ \Lambda_{\mathrm{ion}} = \Lambda_{\mathrm{ion}}^{X} + \Lambda_{\mathrm{ion}}^{\mathrm{exo}} \\ \\ J_{\alpha} = J_{\alpha}^{X} + J_{\alpha}^{\star} + J_{\alpha}^{\mathrm{exo}} \end{array}\right.$$

For homogeneous injection we use DarkHistory

$\epsilon_{\rm inj}^{\rm exo}$ *deposited into*

- $\epsilon_{\rm heat}^{\rm exo}$ *heat*
- $\Lambda_{\rm ion}^{\rm exo}$ *ionisation*
- $J_{\alpha}^{\rm exo}$ *Lyman-α flux*

DarkHistory

[Liu et al. 2019, Sun et al. 2022]

I have created the

exo21cmFAST

(Semi-analytical code to model the 21 cm signal)

code that includes

exotic energy injection

[GF et al., arXiv:2308.16656]


DarkHistory
exo21cmFAST
21cmFAST

II.

The example of
dark matter decays

Our *Niagara*
is
decaying DM...

predicted in many
BSM models

Using 21 cm signal for DM searches is not a new idea

[Sekiguchi et al. 2014, Shimabukuro et al. 2014, Sitwell 2013 et al., Zurek et al. 2007, ...]

Constraining warm dark matter or the matter power spectrum

… even for **exotic** energy **injection**

(with the global signal)

[D’amico et al., 2018]
Constraining annihilation using the global signal

However,
we need the power spectrum
to really tell something

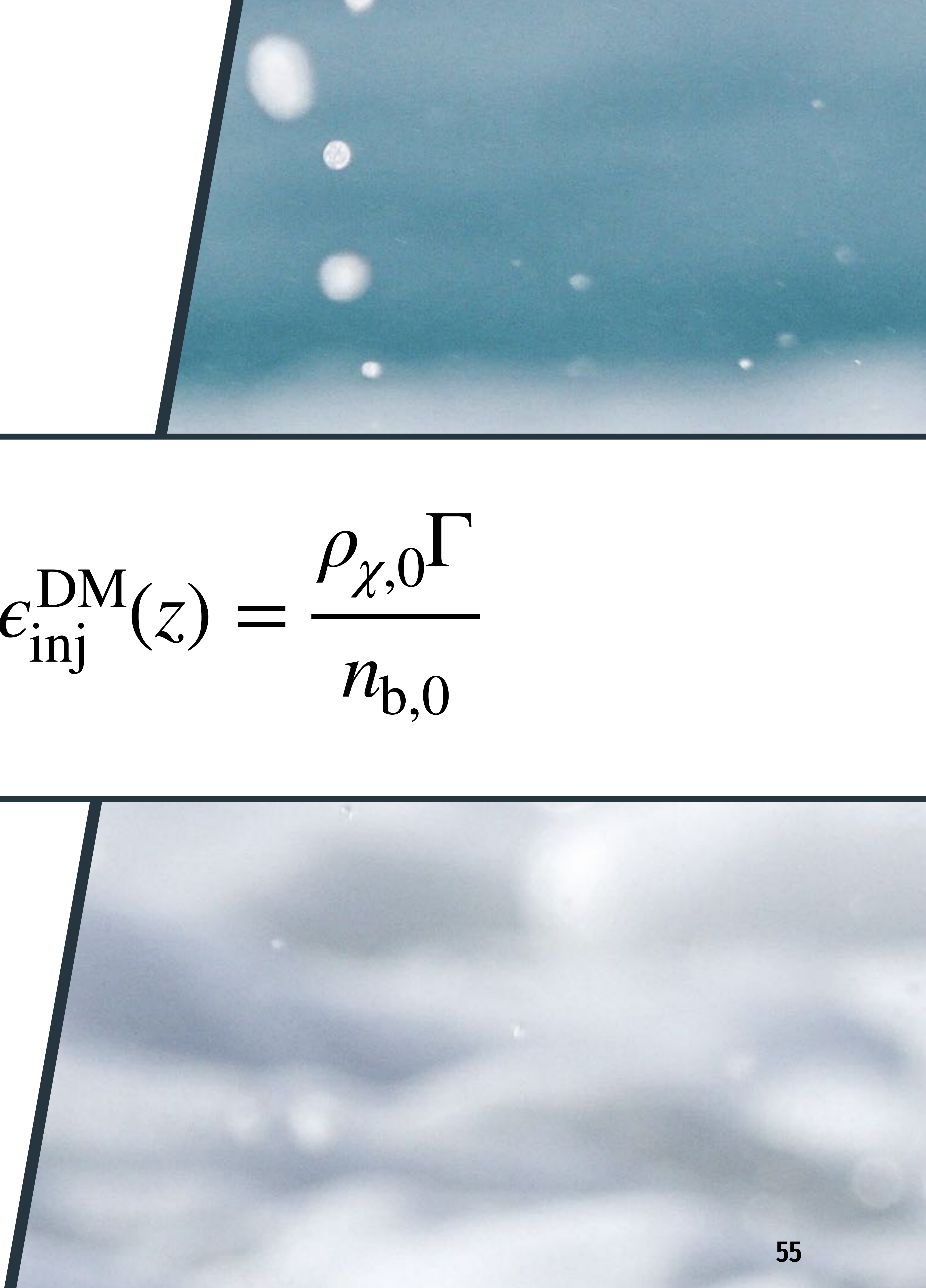
[Lopez-Honorez et al., 2016]
Difficult to disentangle dark matter
energy injection contributions from « astrophysics »

HERA (will try to) measure(s) the 21 cm power spectrum

… 21 cm signal should be **good probe** of DM decay because late time probe

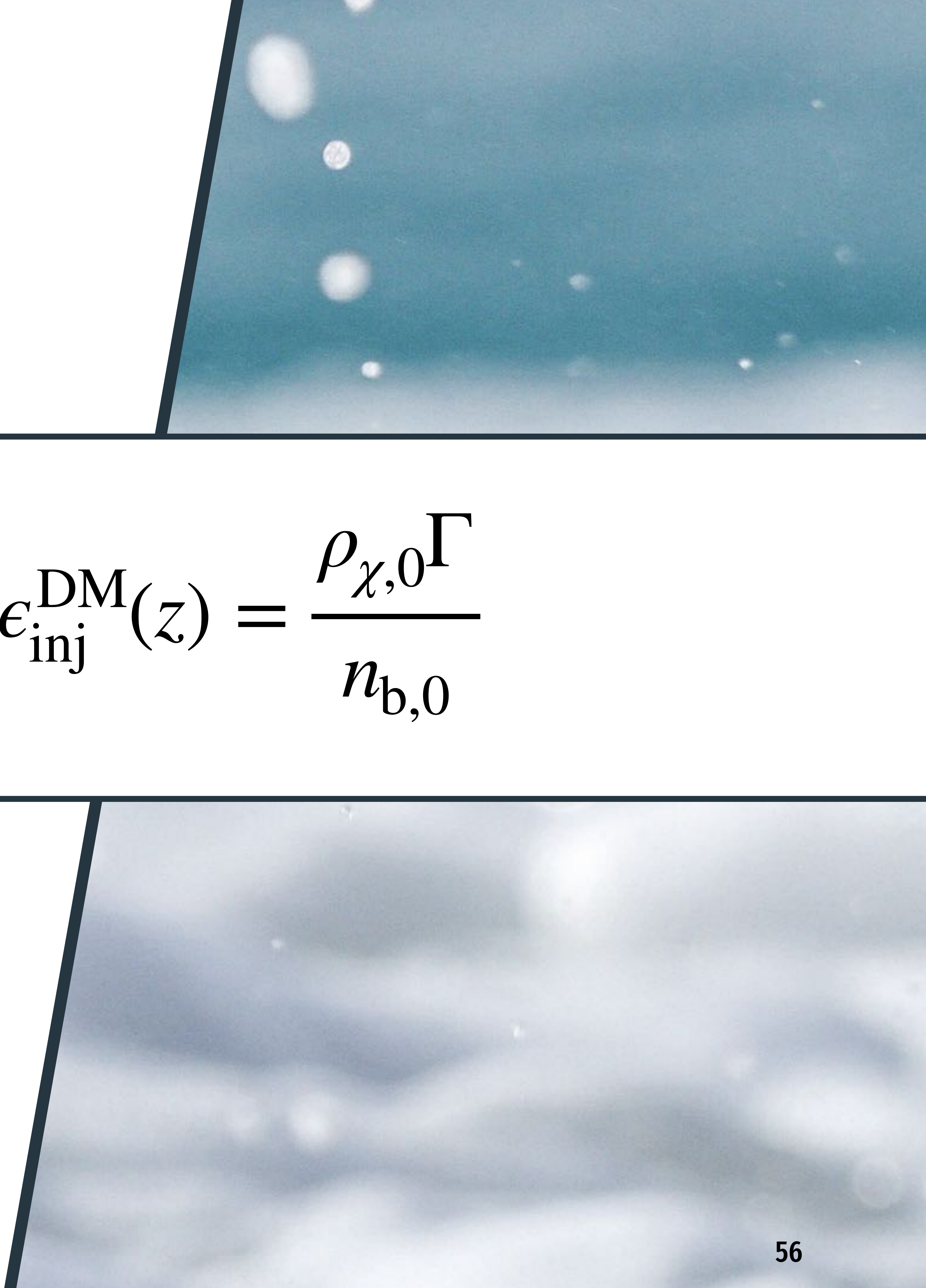
When **decaying** DM injects energy into the IGM at a **rate** *(per baryon)*

— in the form of photons and electrons showers —



$$\epsilon_{\rm inj}^{\rm DM}(z) = \frac{\rho_{\chi,0}\Gamma}{n_{\rm b,0}}$$

which mainly depends on the **decay rate**



$$\epsilon_{\mathrm{inj}}^{\mathrm{DM}}(z) = \frac{\rho_{\chi,0}\Gamma}{n_{\mathrm{b},0}}$$

Deposited heat and **injected** heat
are related by the **deposition fractions**

$$\epsilon_{\text{heat}}^{\text{DM}}(z, x_e) \equiv f_{\text{heat}}(z, x_e, m_\chi, p, \ldots)\epsilon_{\text{inj}}^{\text{DM}}(z)$$

The deposition fractions depend on

- the **DM mass**
- the **decay product** (electrons, quarks, ...)
- the ionization fraction

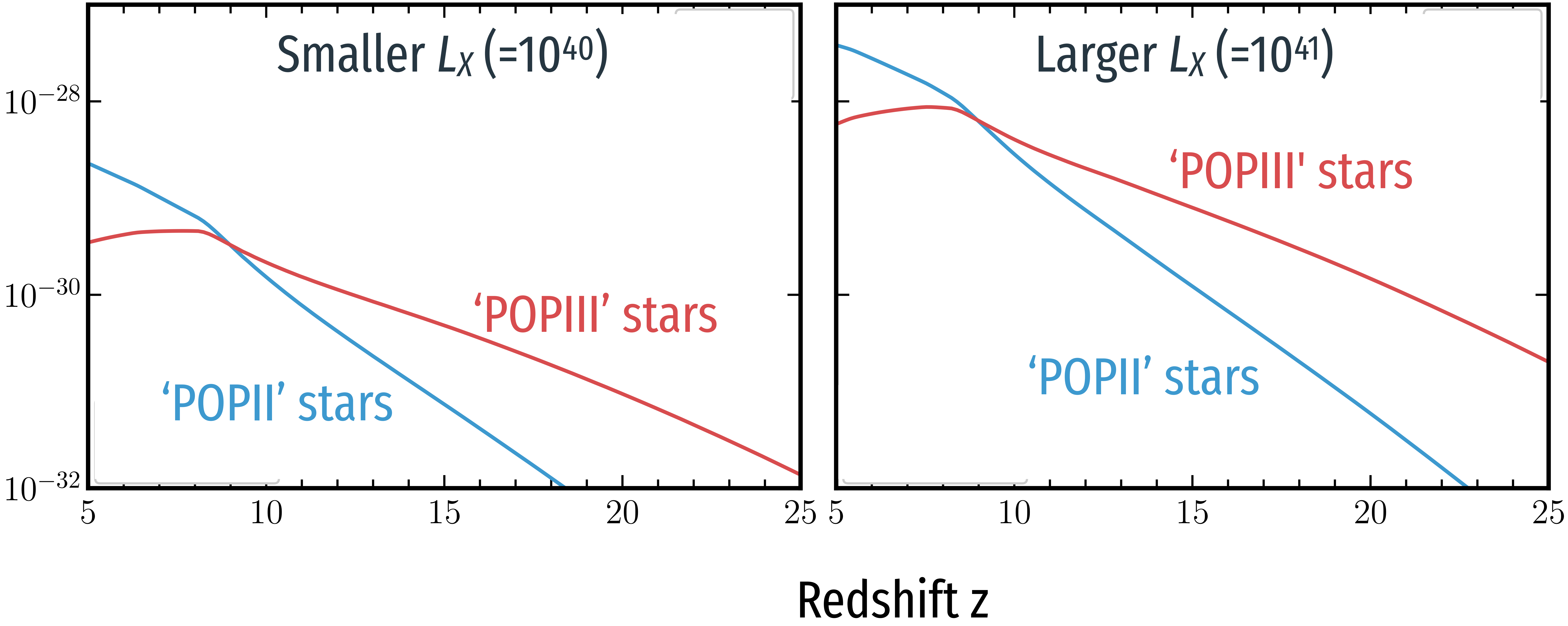
[Liu et al. 2019, Sun et al. 2022]

[Slatyer et al. 2009, Slatyer 2013, ...]

$$\epsilon_{\rm heat}^{\rm DM}(z, x_e) \equiv f_{\rm heat}(z, x_e, m_\chi, p, \ldots)\epsilon_{\rm inj}^{\rm DM}(z)$$

Coming back to the heating rates

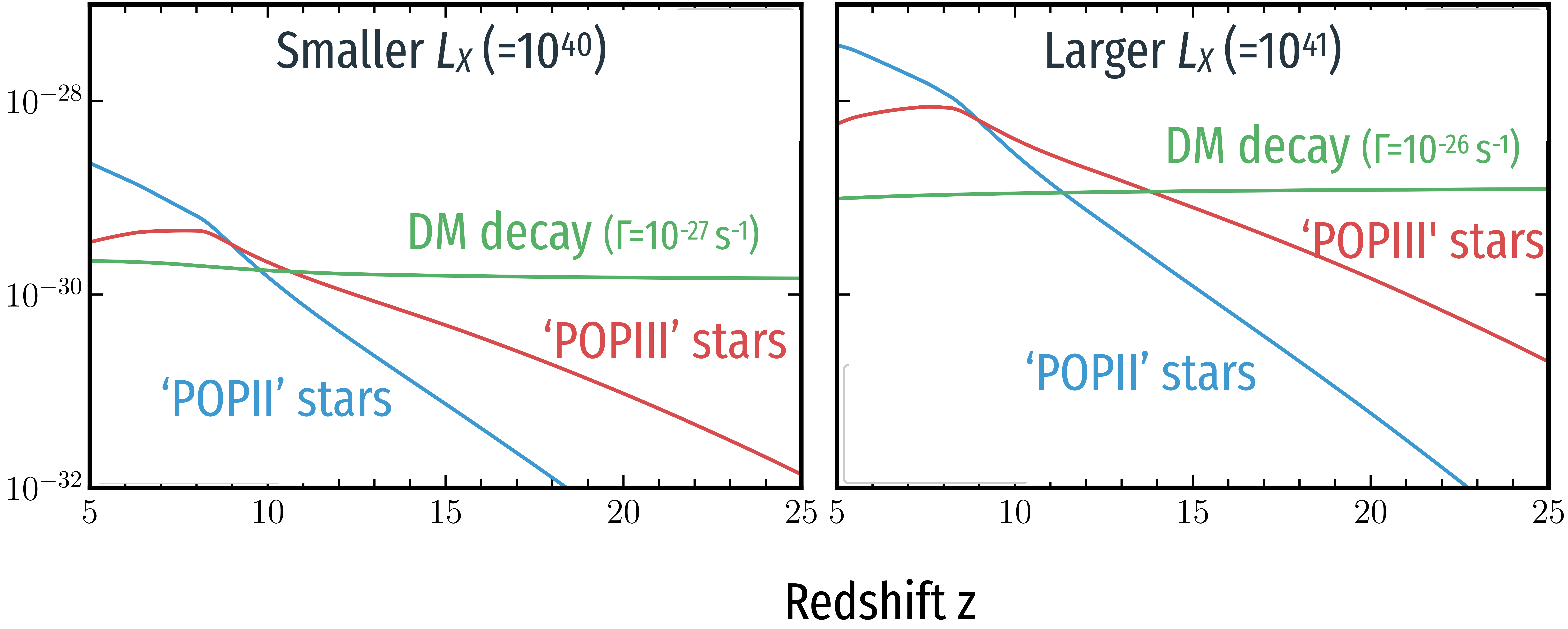
average X-ray & DM heating rate (per baryons) [erg/s]



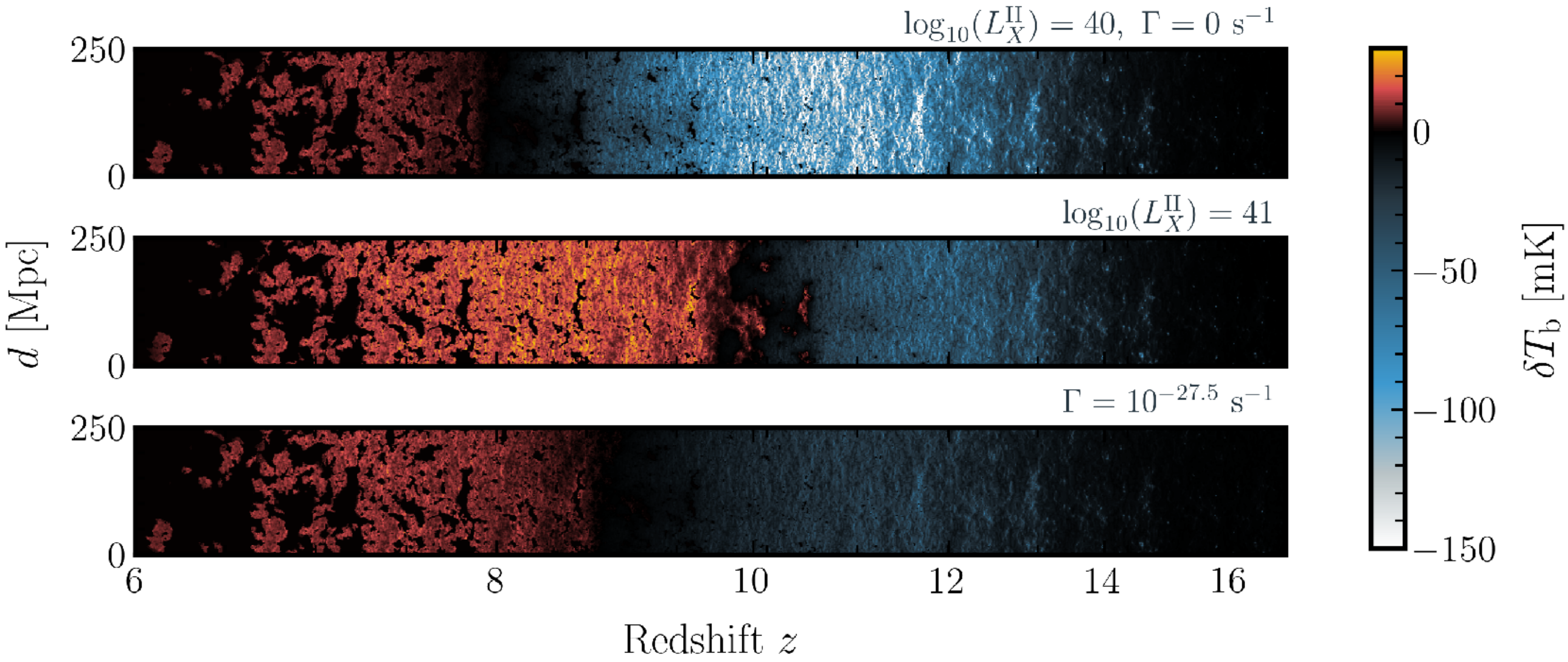
DM heating is roughly constant in time!

average X-ray & DM heating rate (per baryons) [erg/s]

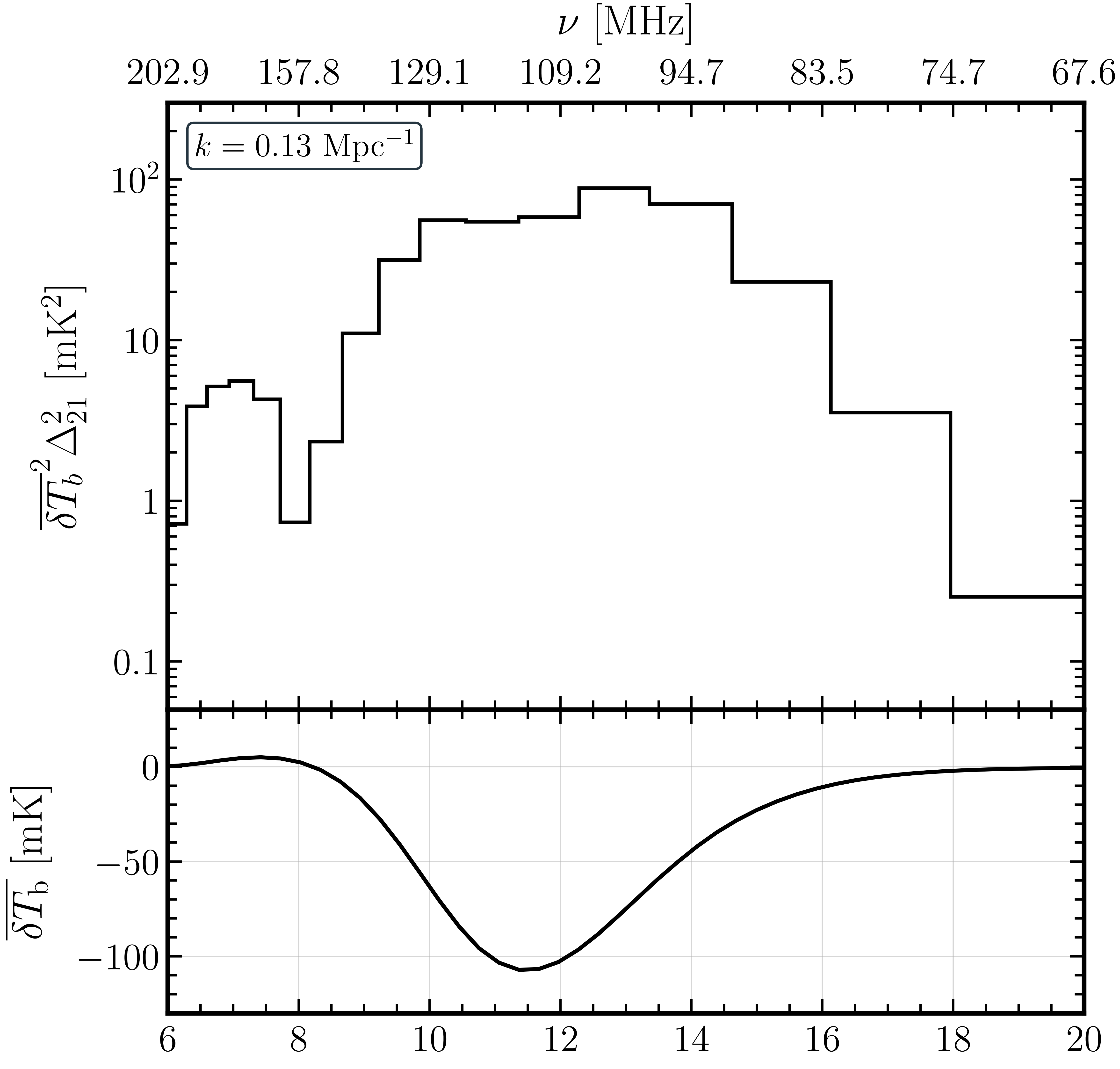
[GF et al., arXiv:2308.16656]



Which leads to a more homogeneous suppression of the perturbations



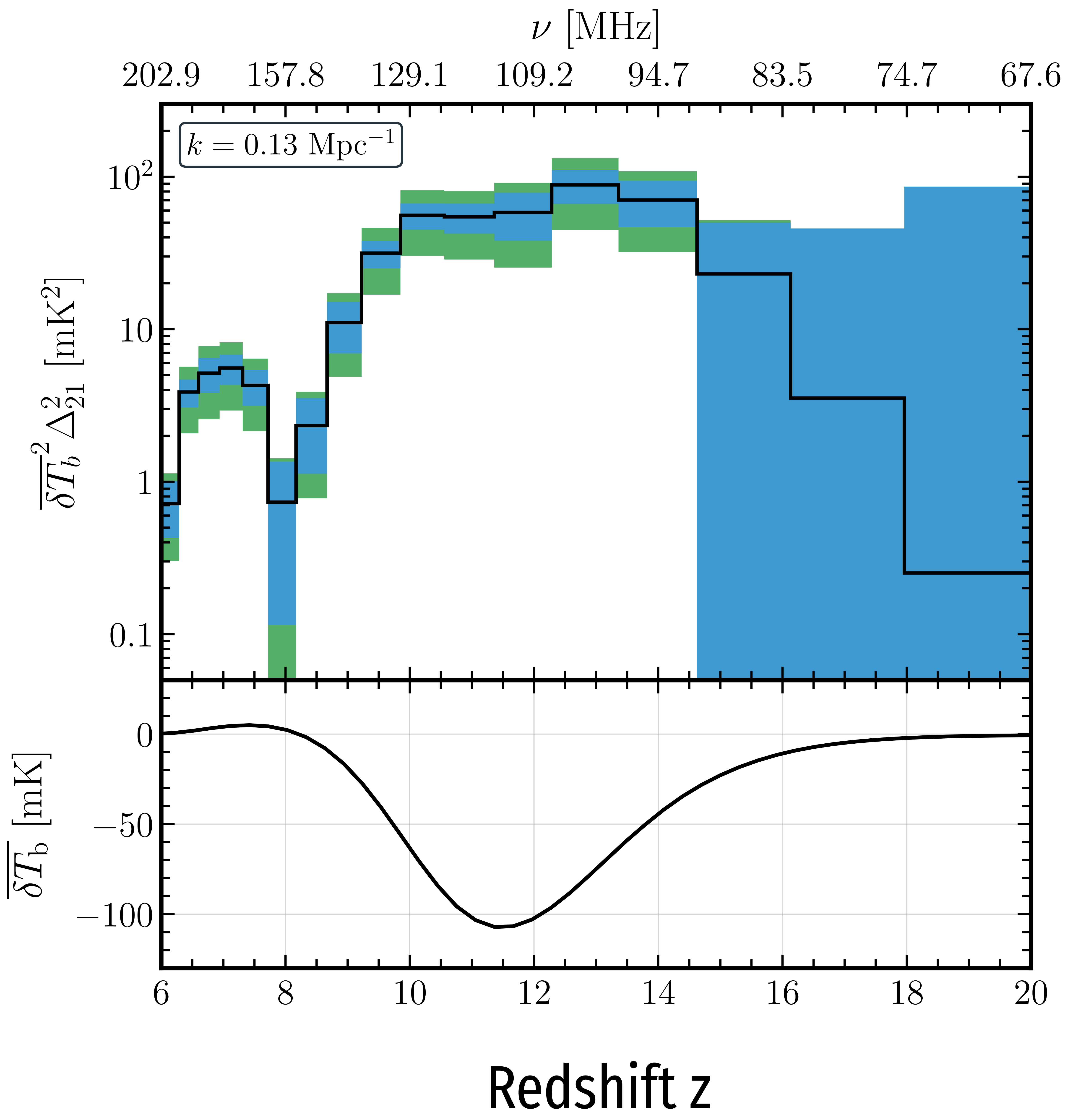
[GF et al., arXiv:2308.16656]



Redshift z

Let's also look at the impact on the (large scale) power spectrum

[GF et al., arXiv:2308.16656]

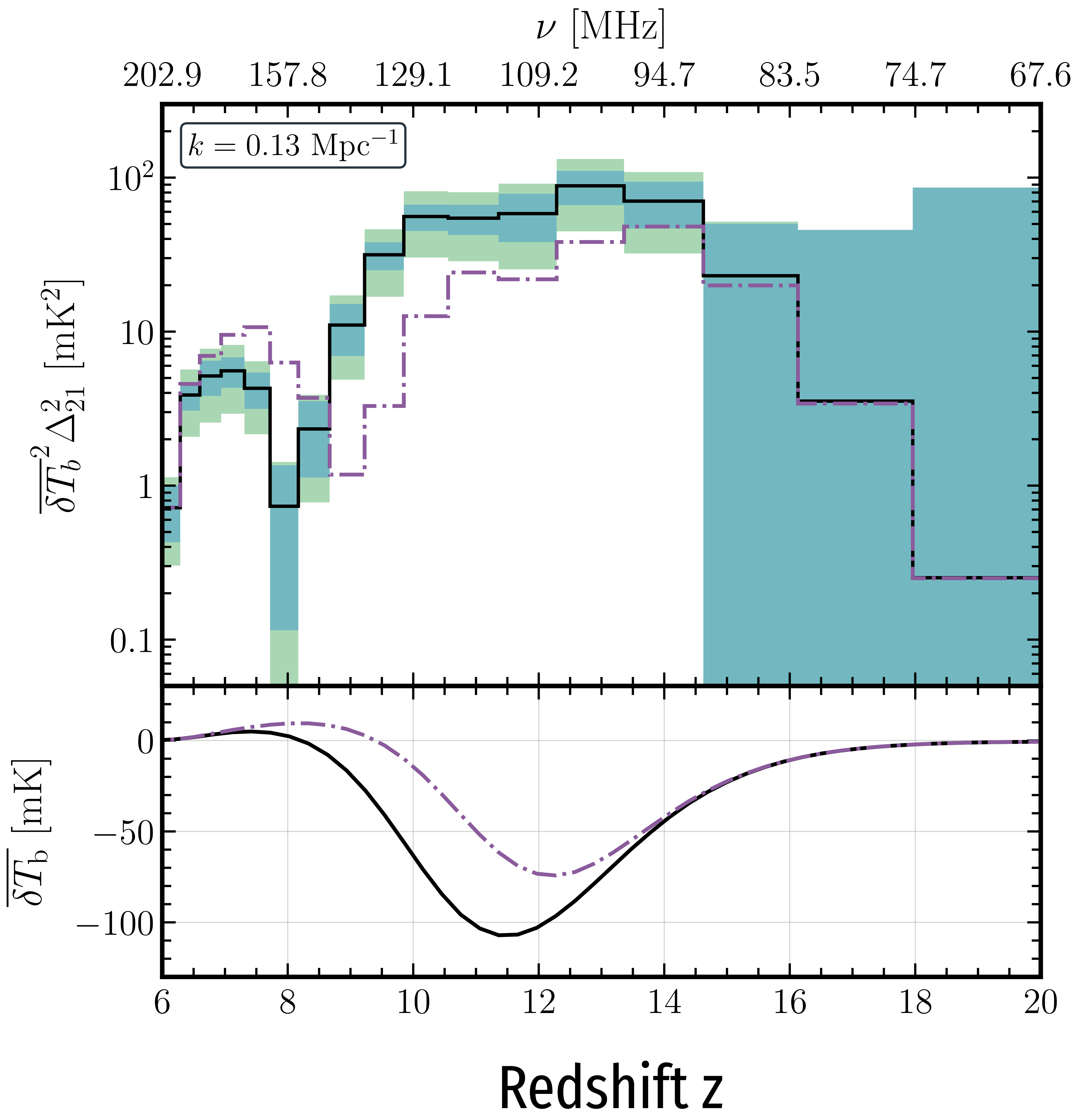


Firstly, we show the 2σ measurement error for the HERA telescope

(Using 21cmSense)

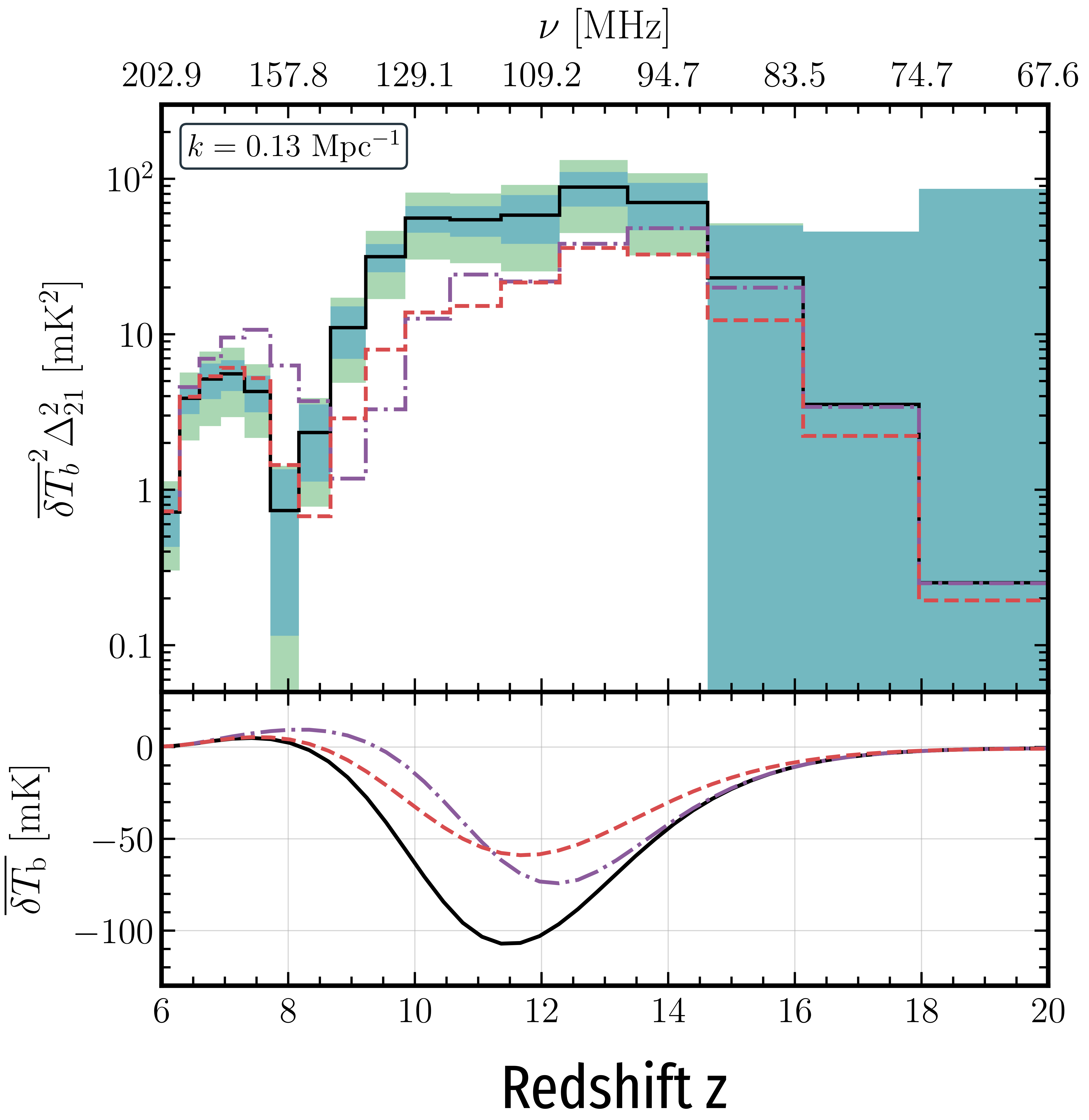
[Pober et al.]

[GF et al., arXiv:2308.16656]



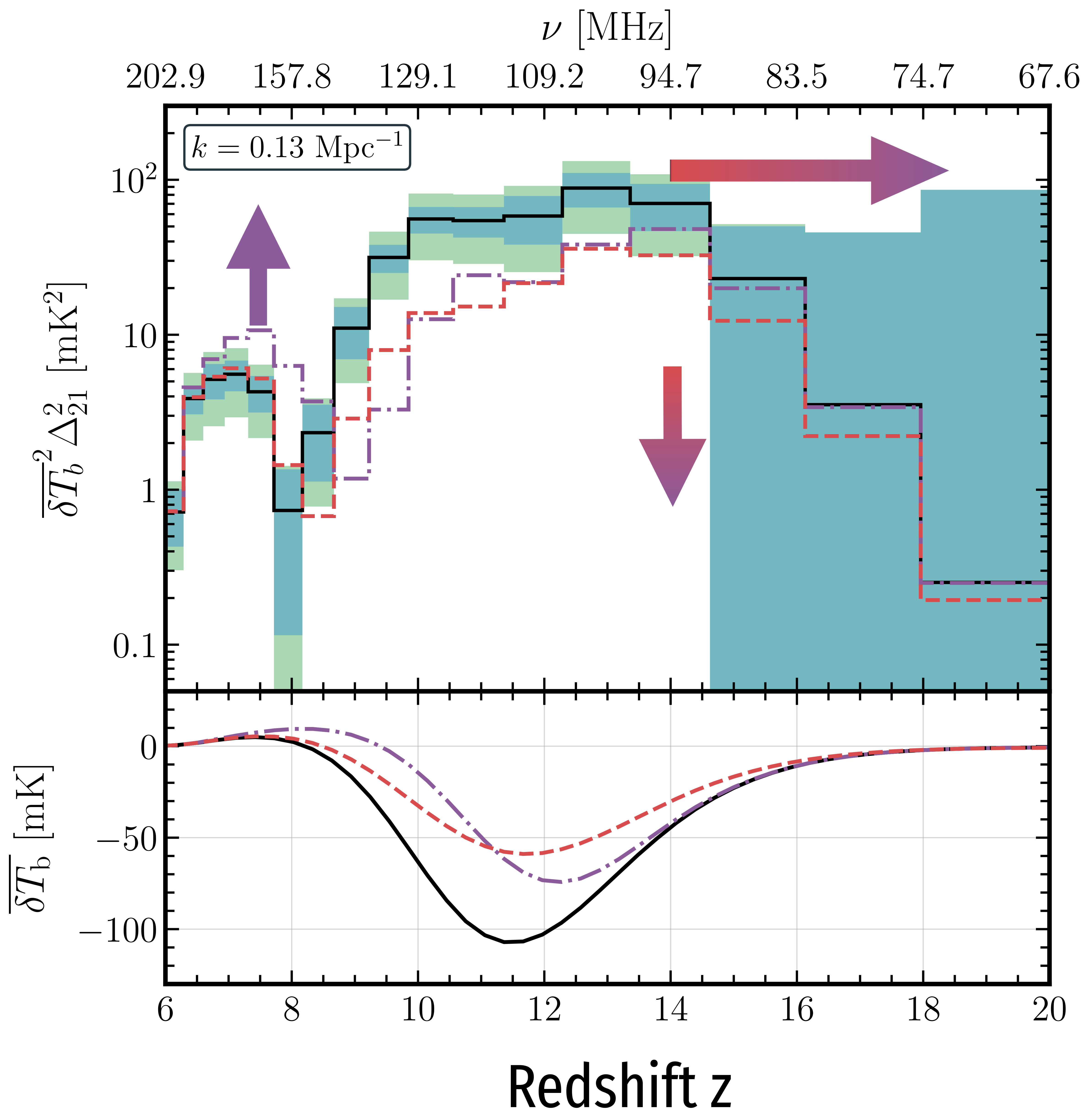
Secondly, we add the result obtained for a larger value of L_X (=10^{41})

[GF et al., arXiv:2308.16656]



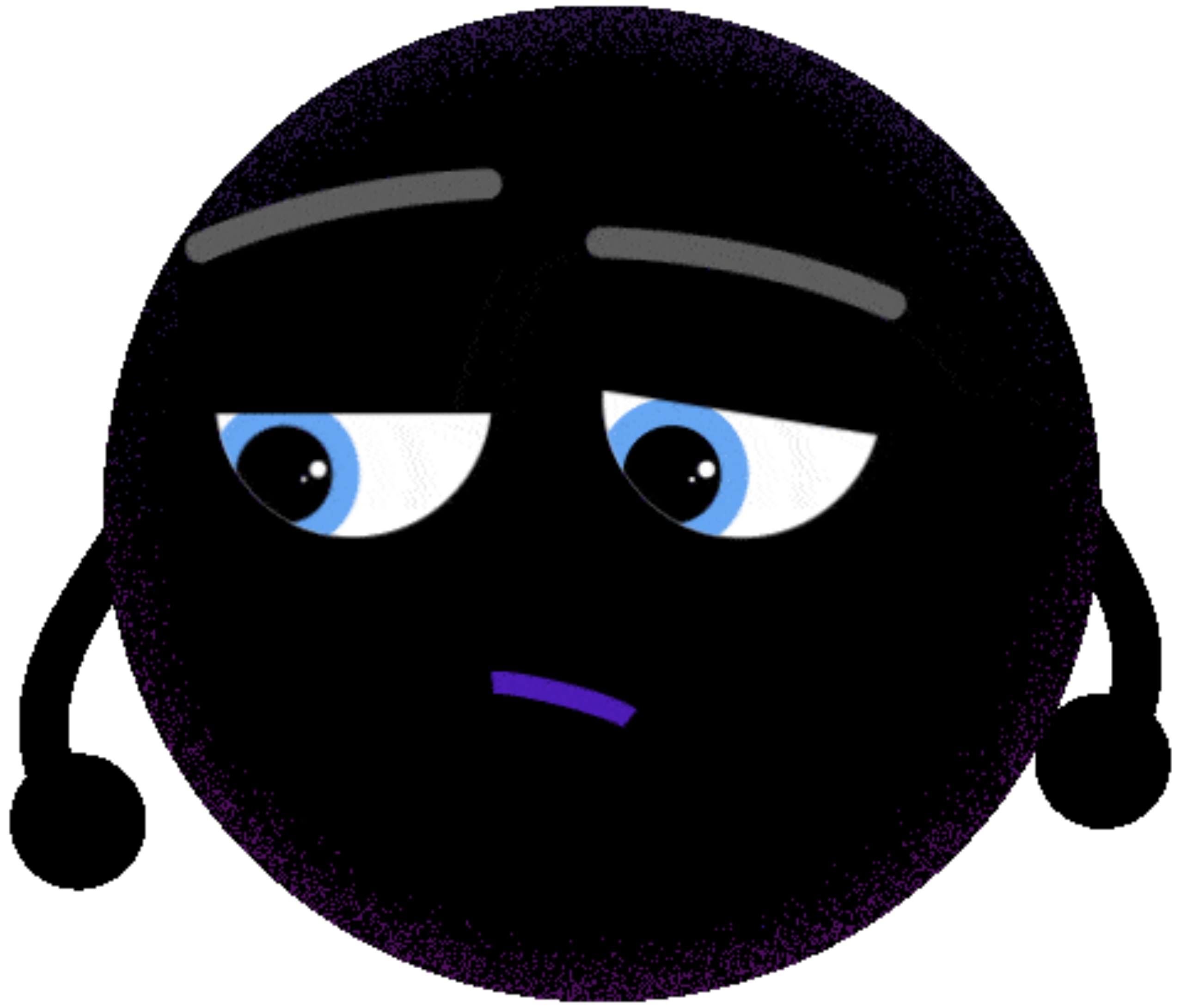
Thirdly, we add the result obtained for a larger value of Γ (=$10^{-27.5}$)

[GF et al., arXiv:2308.16656]



The imprint of DM decay is similar but still distinguishable from X-ray emissions

Intermezzo:
What about other exotic sources?



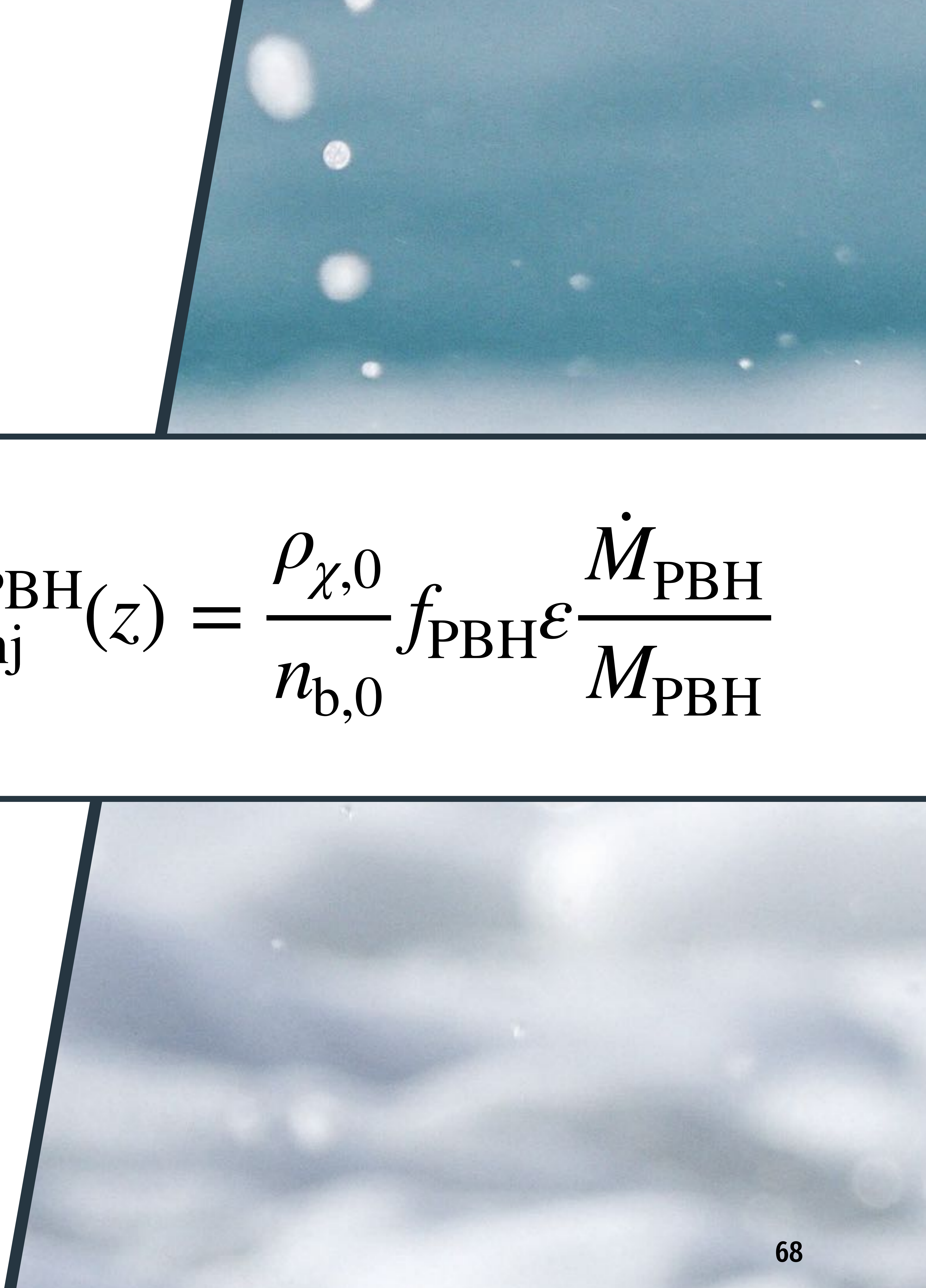
Typical teenager primordial black holes

[NASA's Goddard Space Flight Center]

Accreting PBH injects energy into the IGM at a rate

(per baryon)

— in the form of photons and electrons showers —



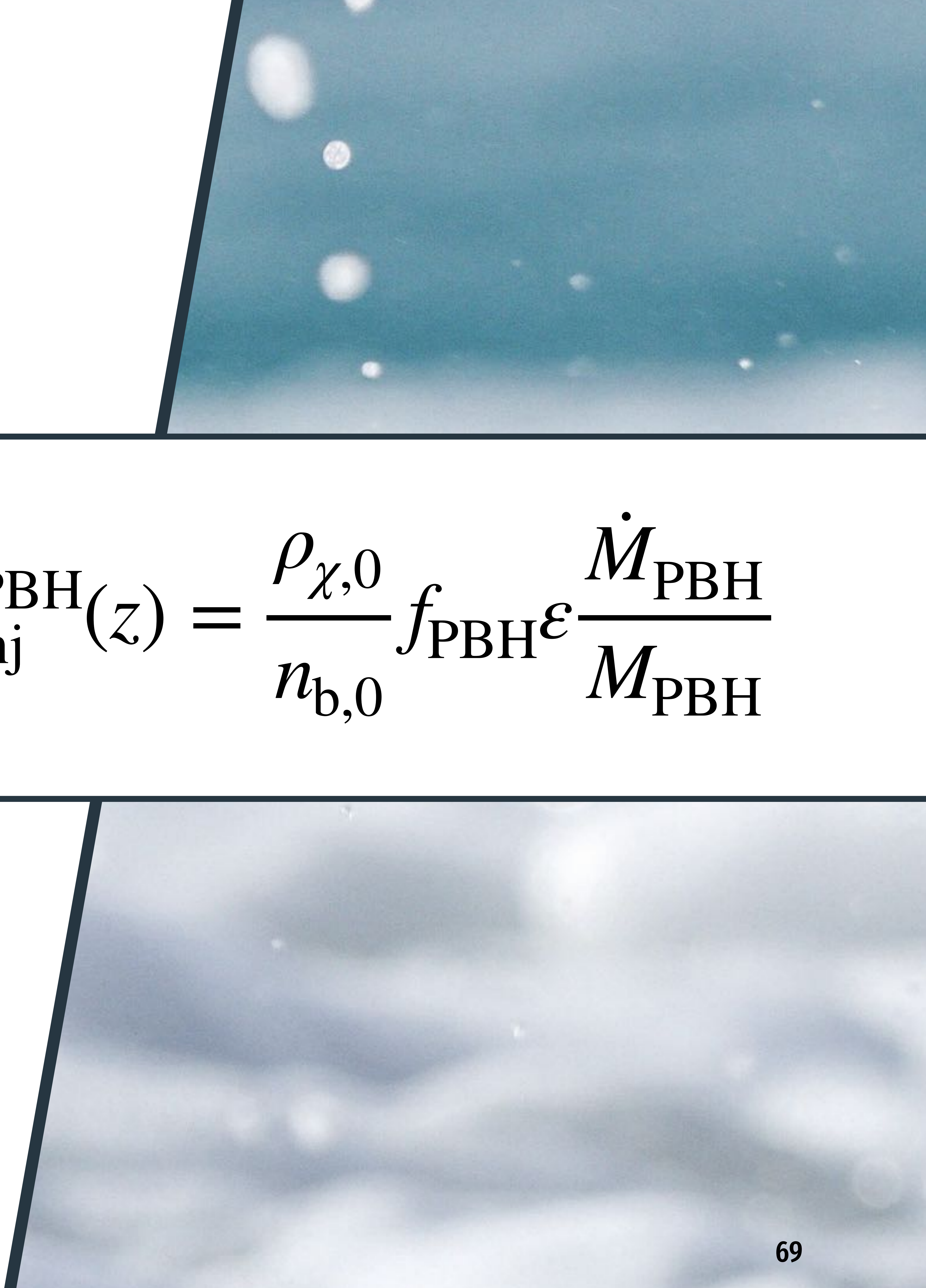
$$\epsilon_{\rm inj}^{\rm PBH}(z) = \frac{\rho_{\chi,0}}{n_{\rm b,0}} f_{\rm PBH}\, \varepsilon \frac{\dot{M}_{\rm PBH}}{M_{\rm PBH}}$$

The accretion rate and efficiency should be computed carefully

See [GF et al. arXiv:2212.07969]

$$\epsilon_{\rm inj}^{\rm PBH}(z) = \frac{\rho_{\chi,0}}{n_{\rm b,0}} f_{\rm PBH} \varepsilon \frac{\dot{M}_{\rm PBH}}{M_{\rm PBH}}$$

Other than that, similar treatment than for DM decay



III.

Fisher forecasts

Forecast HERA sensitivity to the DM decay rate Γ

at fixed DM mass and decay product

(and repeat for various DM decay masses)

Choose a fiducial model without DM decay (Γ=0)

and fixed
astrophysical parameters

By how much can we change Γ
without impacting
the astrophysical
parameter reconstruction?

We use my own

21cmCAST

(Automatic Fisher forecast tool for 21cmFAST results)

code

[GF et al. arXiv:2308.16656]

We perform 2 Fisher analyses:

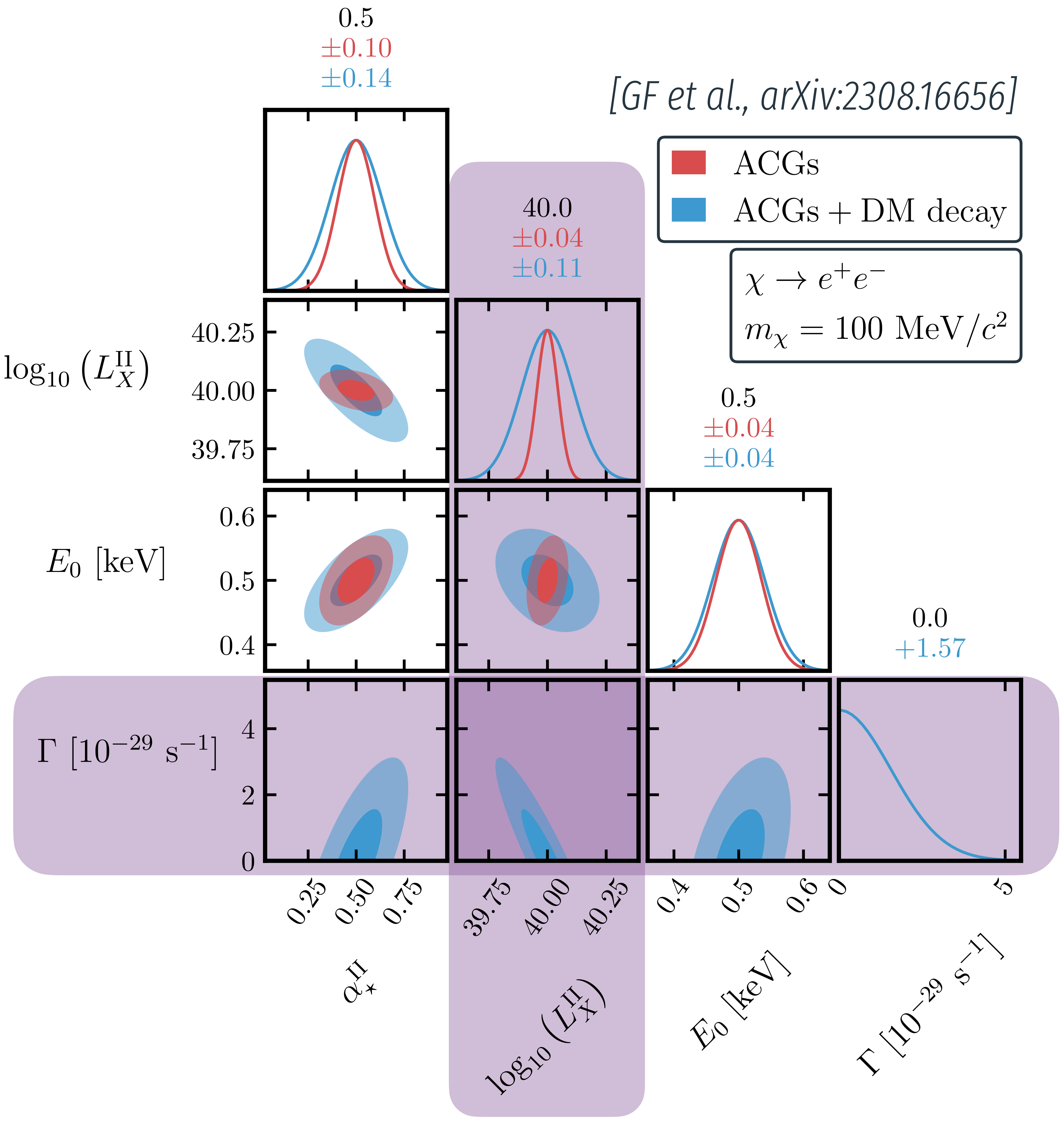
- with ACGs ('POPII' stars) only: **9 parameters**

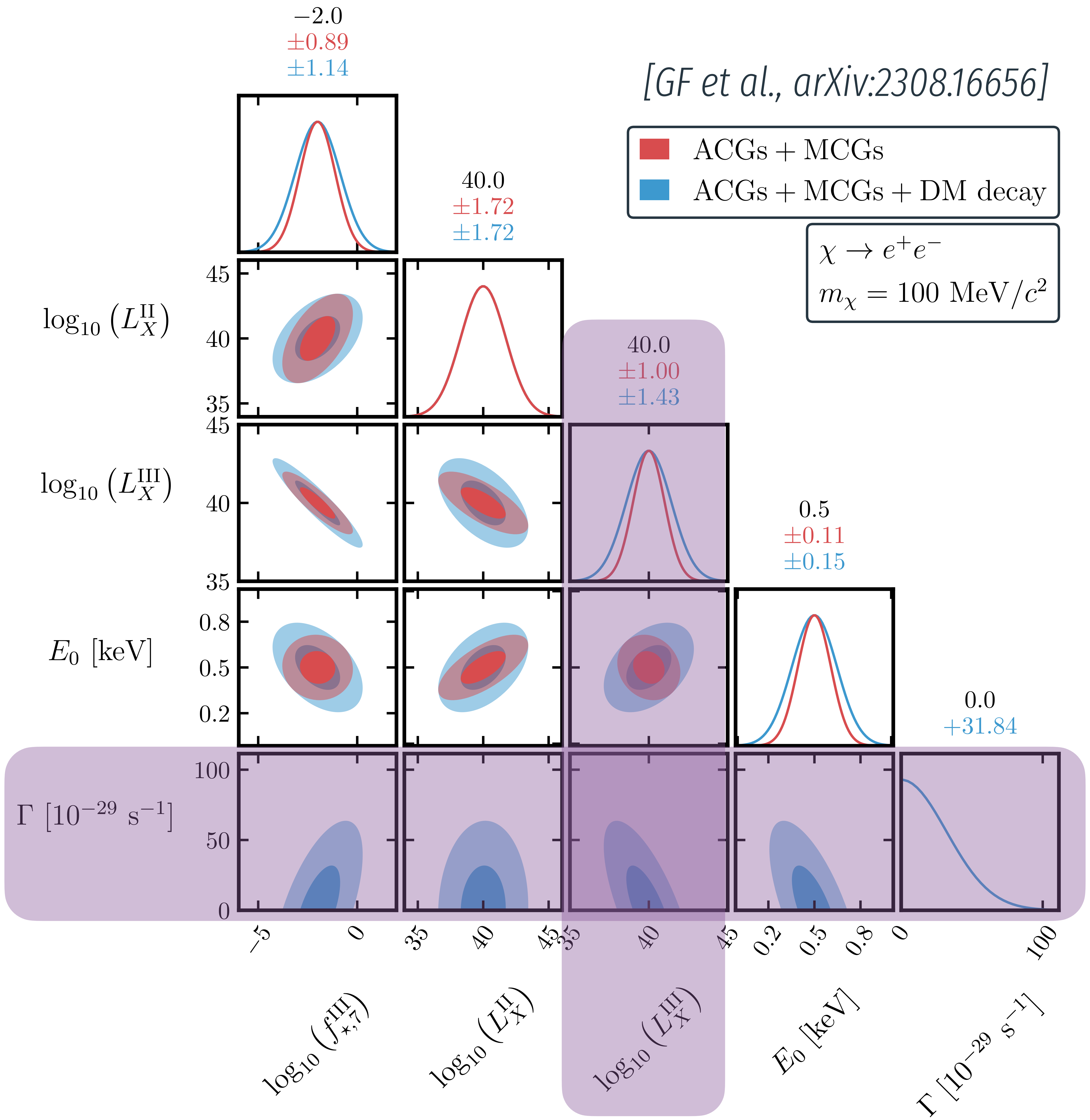
We perform 2 Fisher analyses:

- with ACGs (‘POPII’ stars) only: **9 parameters**
- with ACGs+MCGs (‘POPII+POPIII’ stars): **12 parameters)**

For a 100 MeV DM decaying into e^+e^-

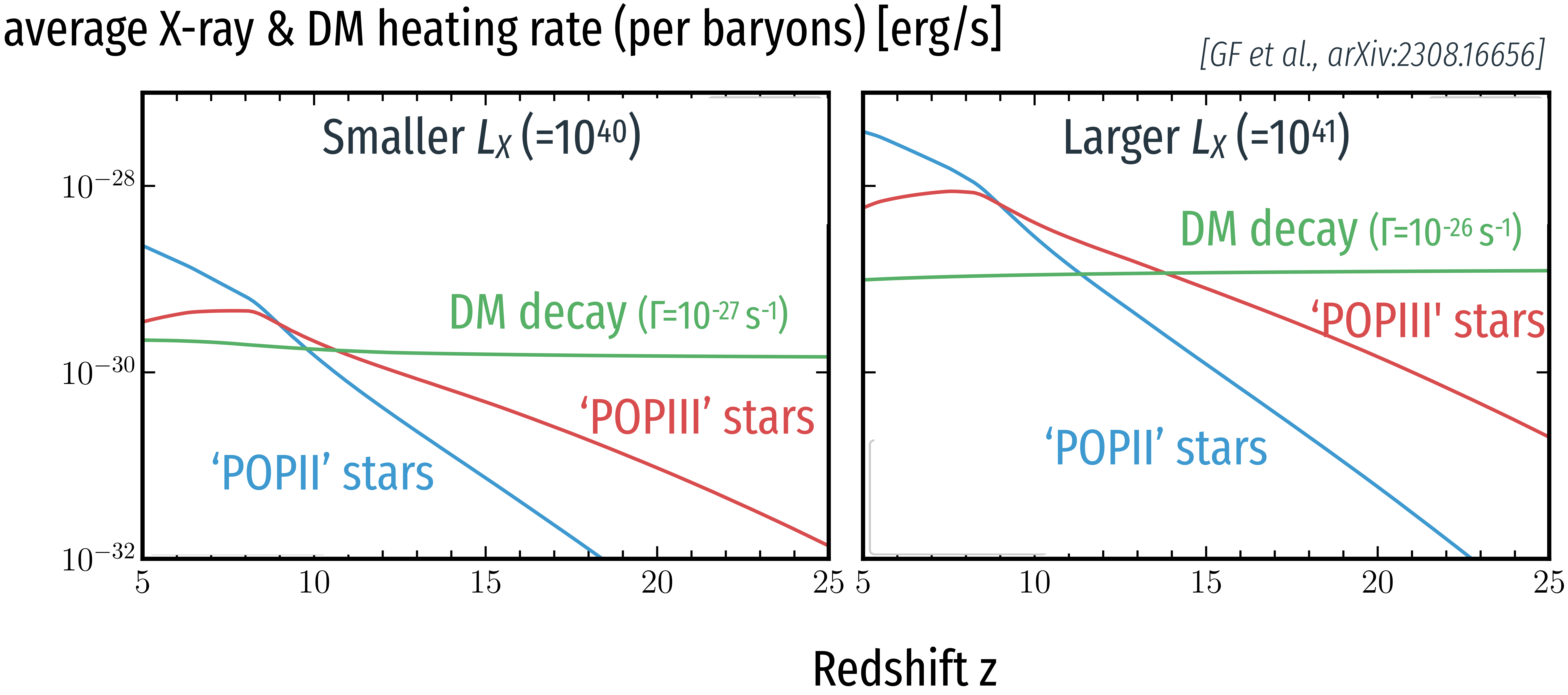
The DM decay rate is degenerate with the ACGs X-ray amplitude





The DM decay rate is more degenerate with the MCGs X-ray amplitude

DM heating is roughly constant in time!



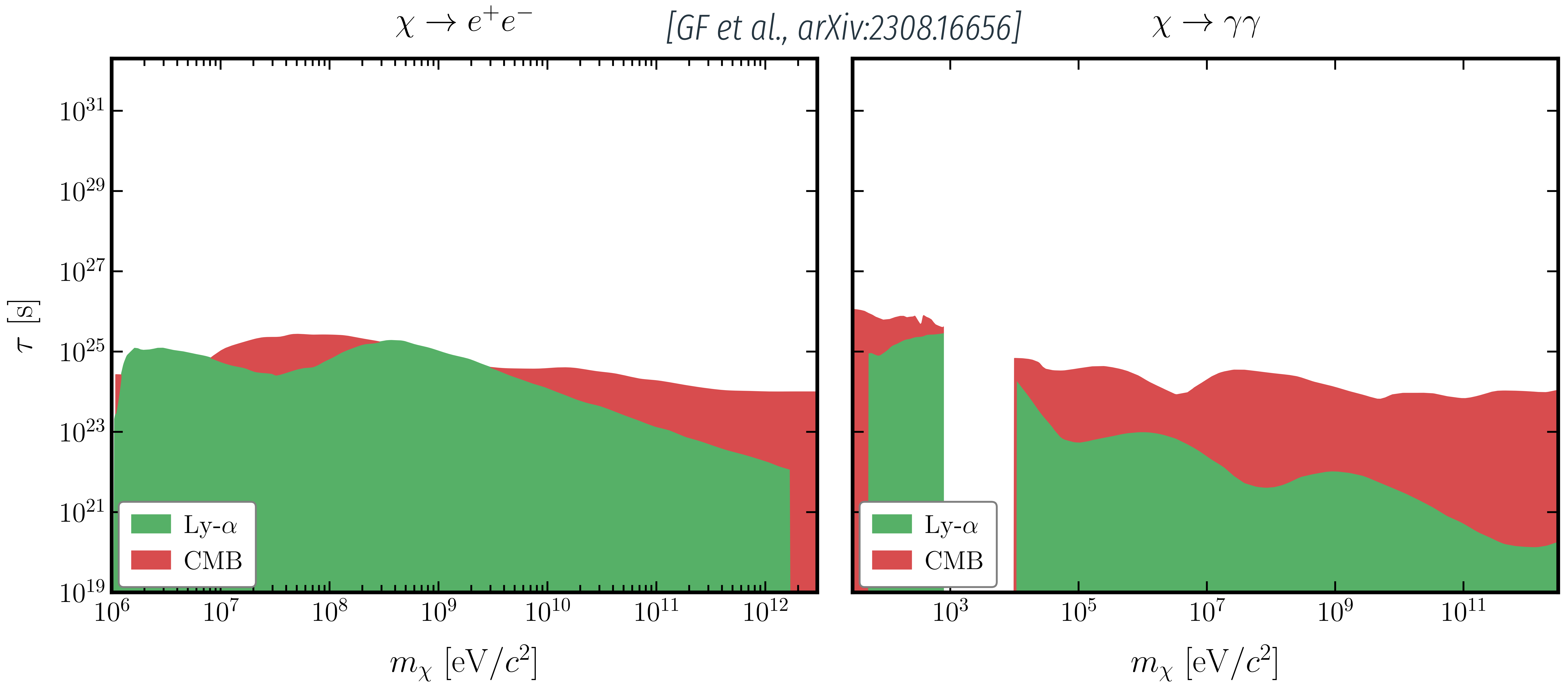

Stellar X-ray emission
DM decay
K.KAGEURA
JPN
otpbank
FRANCE

Repeating the analysis for different masses

We obtain our main result

Here is the sensitivity on $\tau = 1/\Gamma$ [s] for different DM masses and decay products

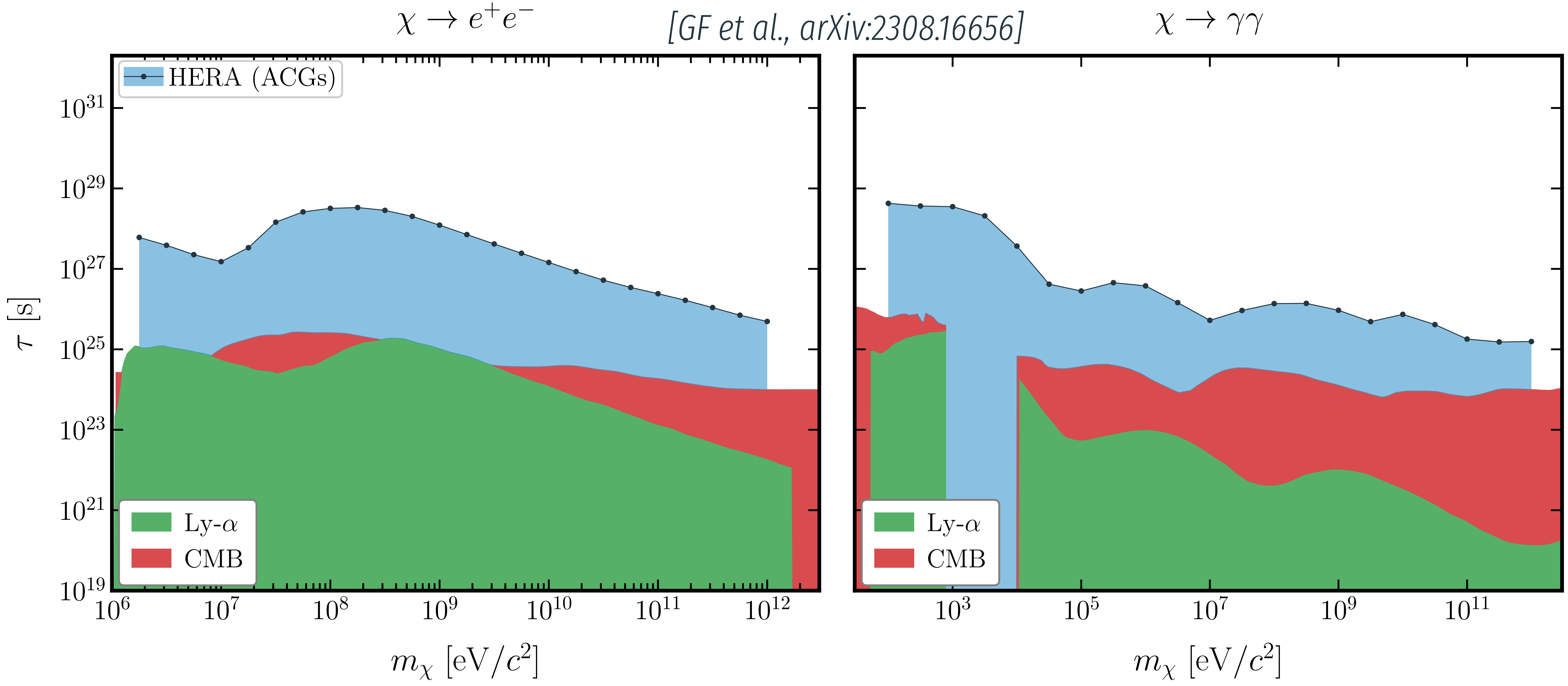
(compared to other probes)



Here is the sensitivity on $\tau = 1/\Gamma$ [s] for different DM masses and decay products

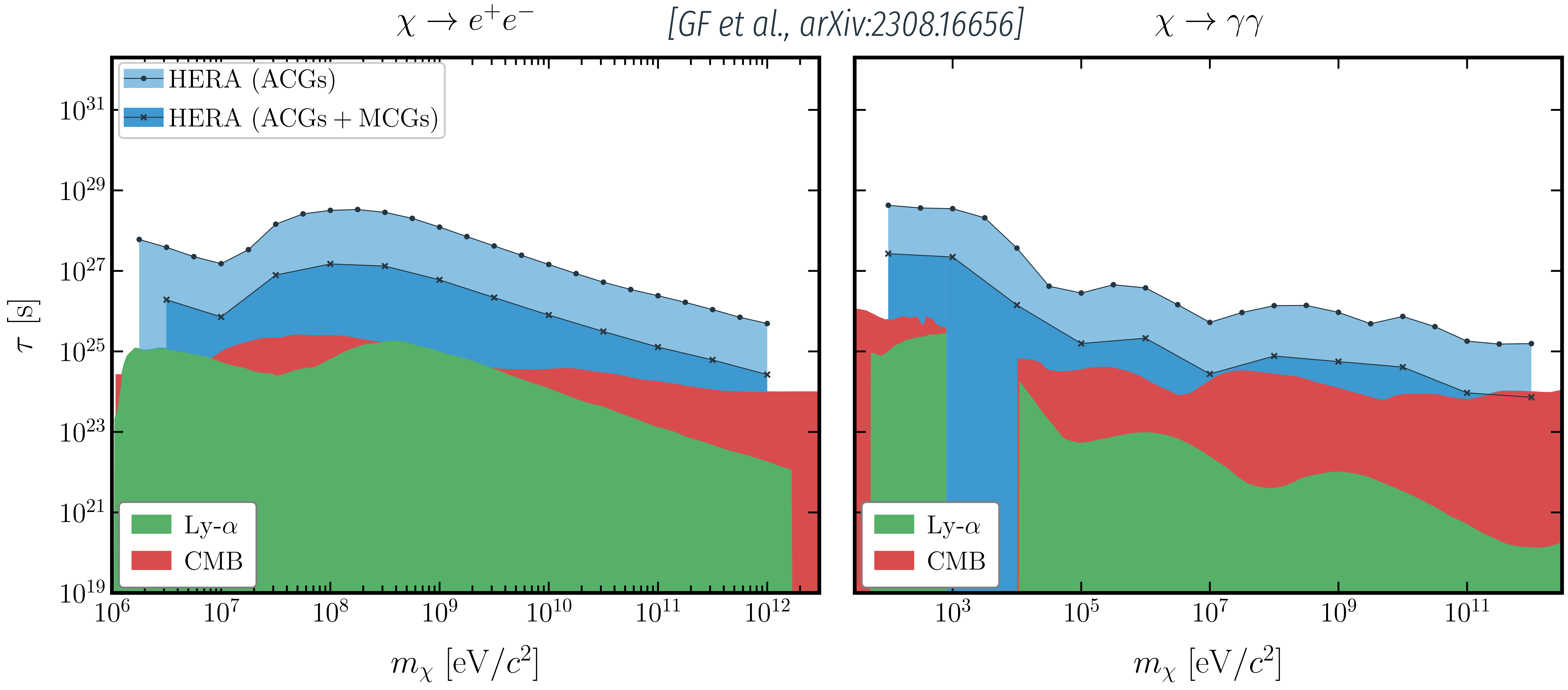
(compared to other probes)

[GF et al., arXiv:2308.16656]



Here is the sensitivity on $\tau = 1/\Gamma$ [s] for different DM masses and decay products

(compared to other probes)



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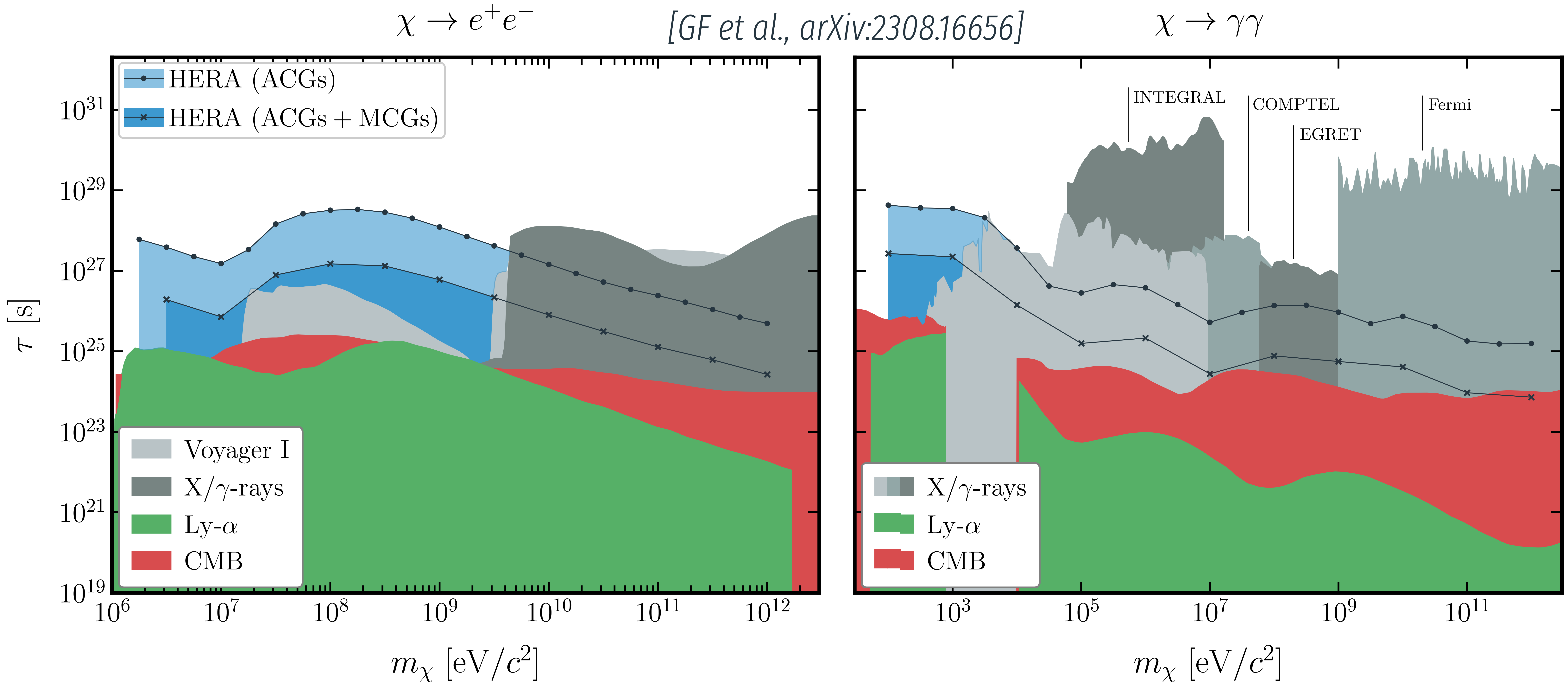


HERA may be

the best

(cosmological) probe

for DM decay

HERA could be competitive

< 2 GeV for e^+e^-

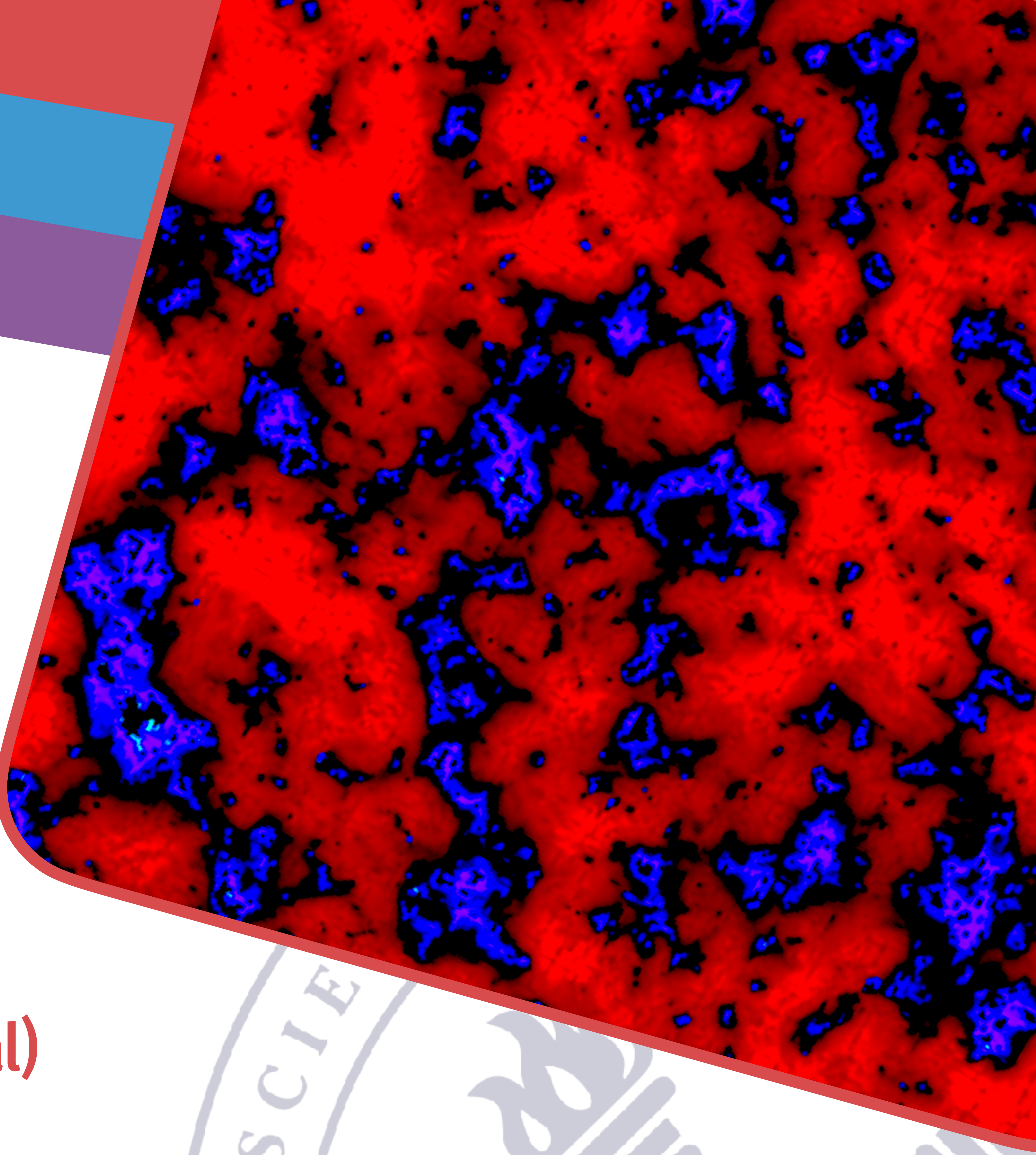
< few MeV for γ

Conclusions

- The 21 cm power spectrum can be an **excellent probe** of dark matter energy injection (in particular through decay)

- I have developed **exo21cmFAST** to numerically solve for the 21 cm power spectrum with exotic energy injection

- **HERA may become the best (cosmological) probe of DM decay**



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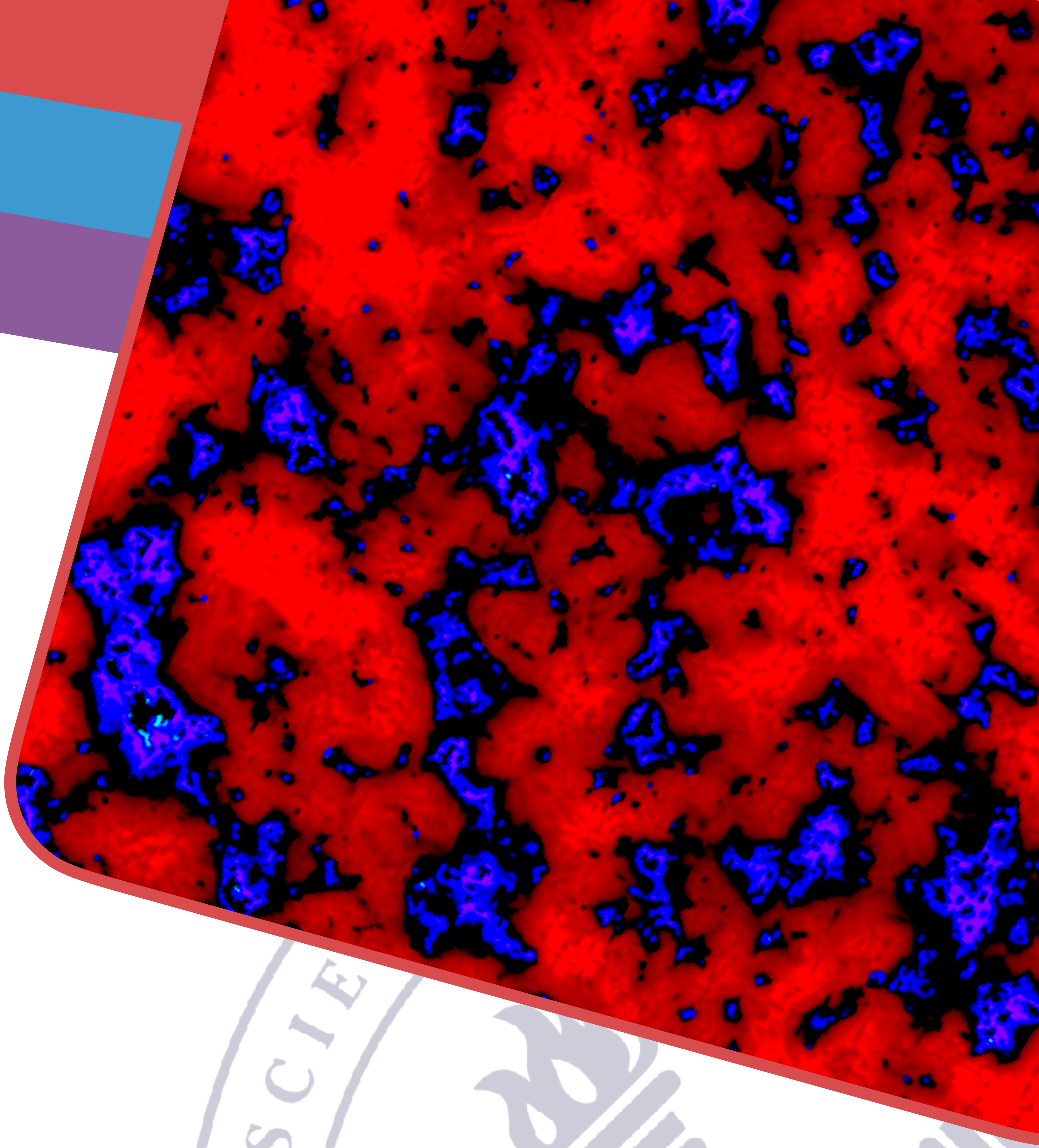
Conclusions



https://github.com/gaetanfacchinetti/exo21cmFAST

https://github.com/gaetanfacchinetti/21cmCAST

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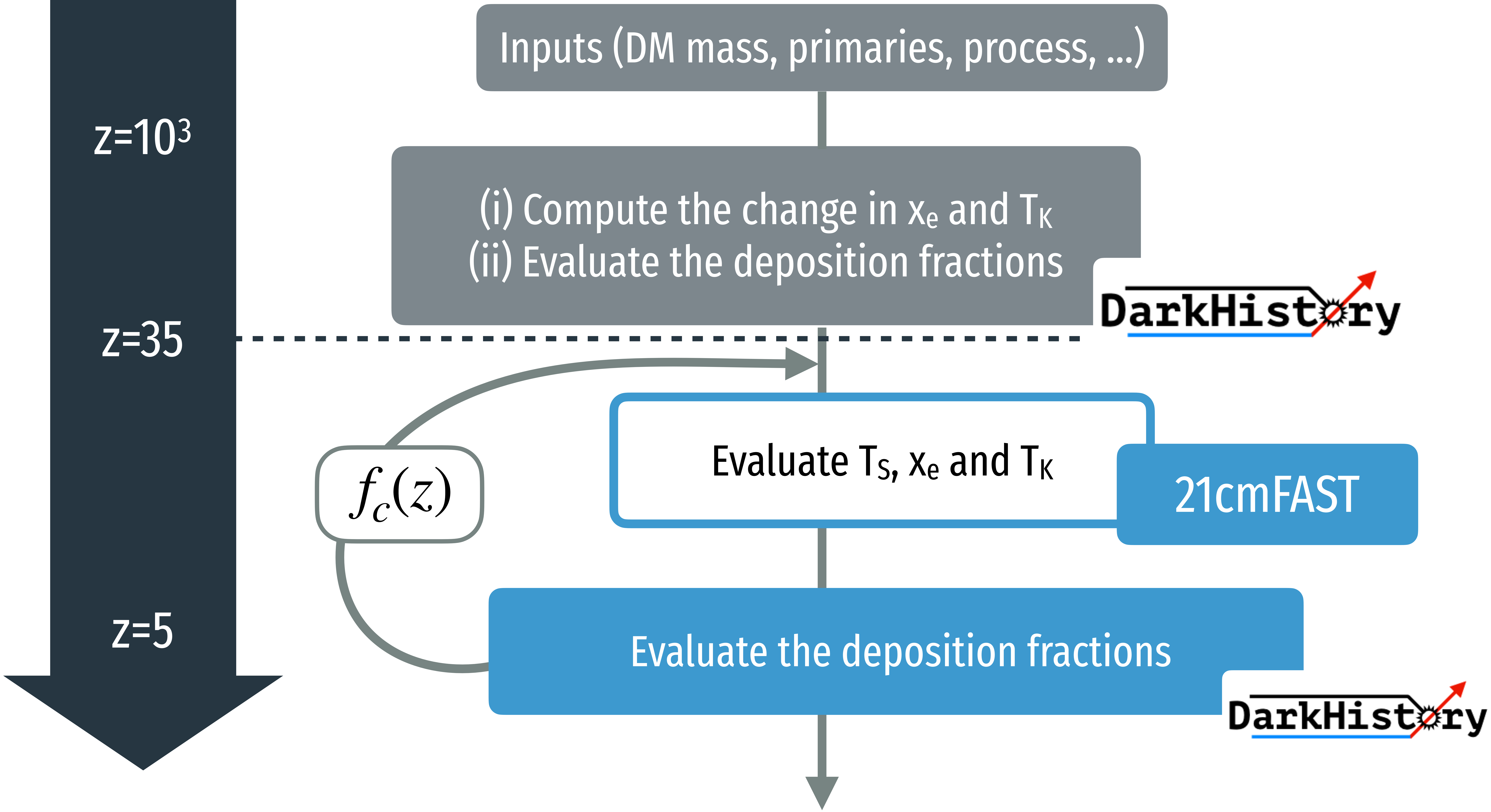
Back-up slides


z=10^3
z=35
z=5
Inputs (DM mass, primaries, process, ...)
(i) Compute the change in x_e and T_K
(ii) Evaluate the deposition fractions
DarkHistory
$f_c(z)$
Evaluate T_S, x_e and T_K
21cmFAST
Evaluate the deposition fractions
DarkHistory

Binned data + model

$$X = \{\overline{\delta T_\mathrm{b}}^2(z_i)\Delta^2_{21}(k_j, z_i)\}_{ij}$$

$$\boldsymbol{\theta} = \{\mathrm{astro\ params}, \Gamma\}$$

+

Covariance matrix of experimental noise (from 21cmSense)

$$C_X$$

Likelihood

$$\mathscr{L}(\boldsymbol{X} \,|\, \boldsymbol{\theta})$$

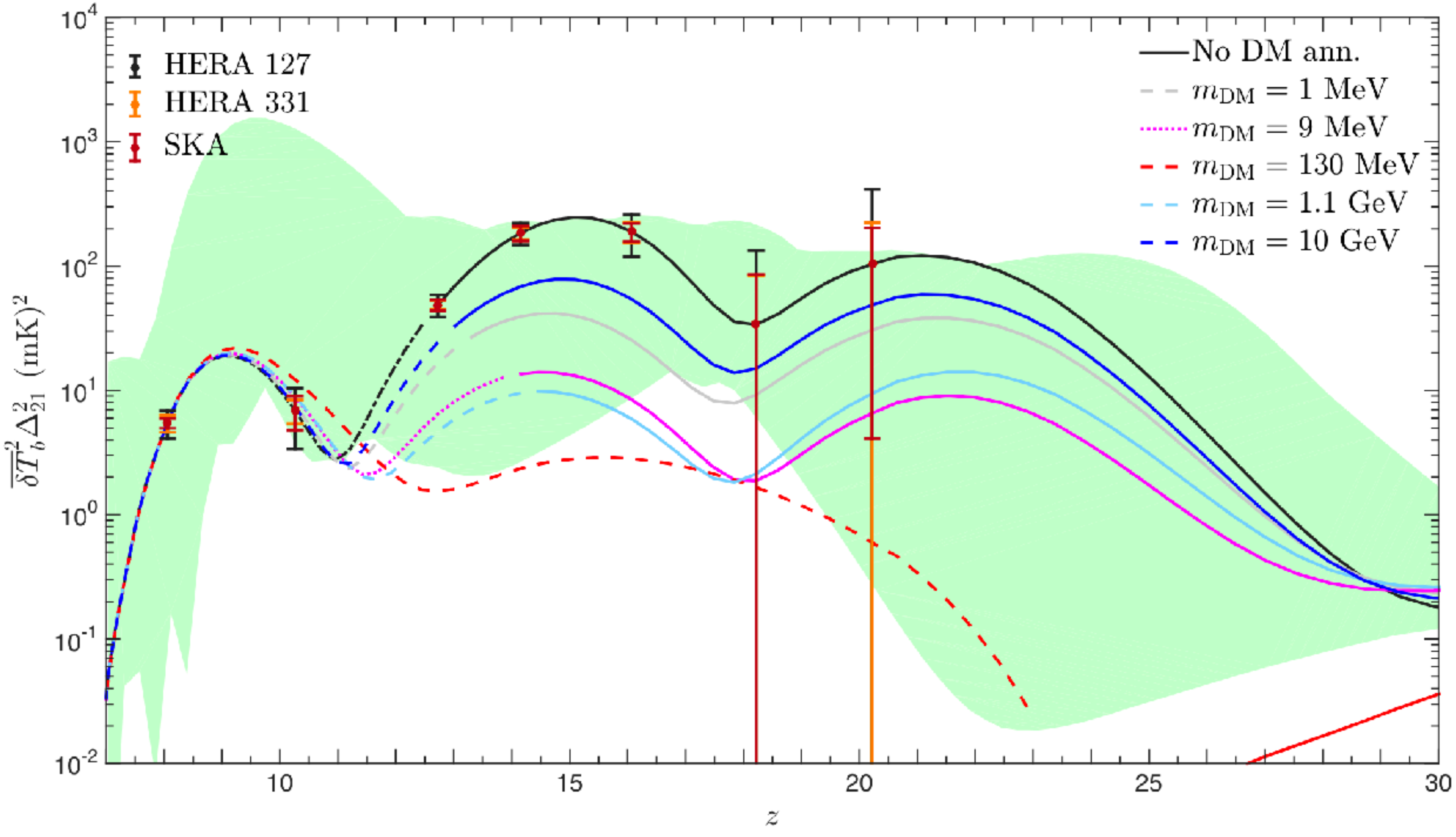
Fisher matrix

$$F_{ij} \equiv -\mathbb{E}_X\left[\frac{\partial^2}{\partial\theta_i\partial\theta_j}\ln\mathscr{L}(\boldsymbol{X}\,|\,\boldsymbol{\theta})\,\middle|\,\boldsymbol{\theta}\right]$$

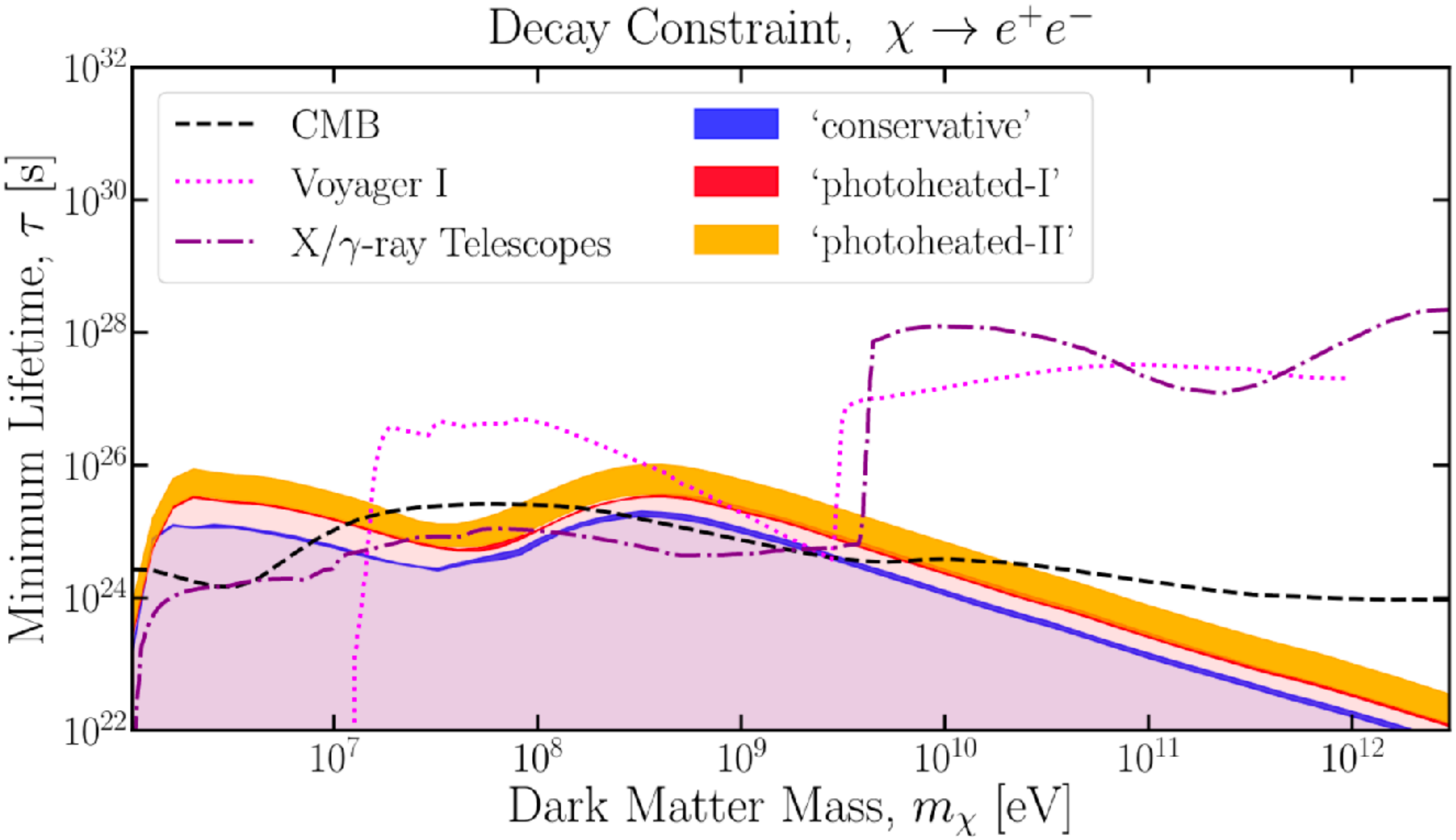
Covariance matrix estimate on the parameters

$$C_{ij} \geq (F^{-1})_{ij}$$

[Lopez-Honorez et al., 2016]



[Liu et al., 2021]



Solving the ionization history of the Universe we get:

$$f_c(z, x_e) \rightarrow f_c(z) = f_c[z, x_e(z)]$$

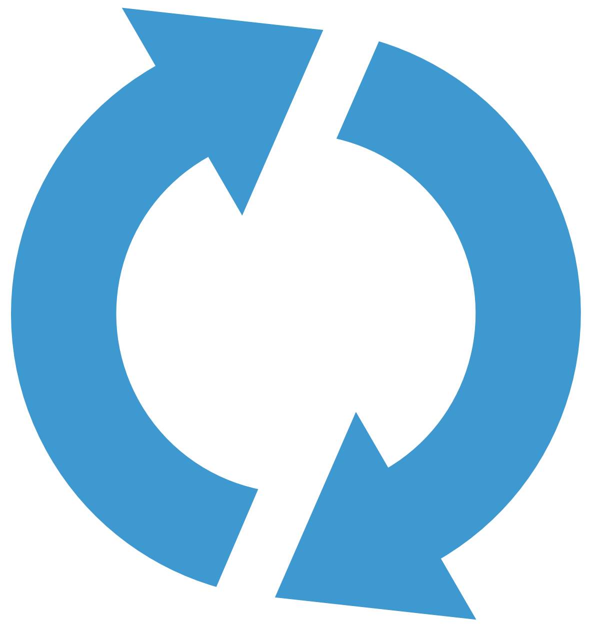
with

$$\frac{\partial x_e(\boldsymbol{x}, z)}{\partial z} = \lambda_{\text{ion}}(\boldsymbol{x}, z) - \text{recombination rate}$$

$$\frac{\partial T_{\text{k}}(\boldsymbol{x}, z)}{\partial z} = \frac{2}{3\, k_{\text{B}}} \frac{1}{1 + x_e(\boldsymbol{x}, z)} \epsilon_{\text{heat}}(\boldsymbol{x}, z) + \ldots$$

Accounts for **backreaction**

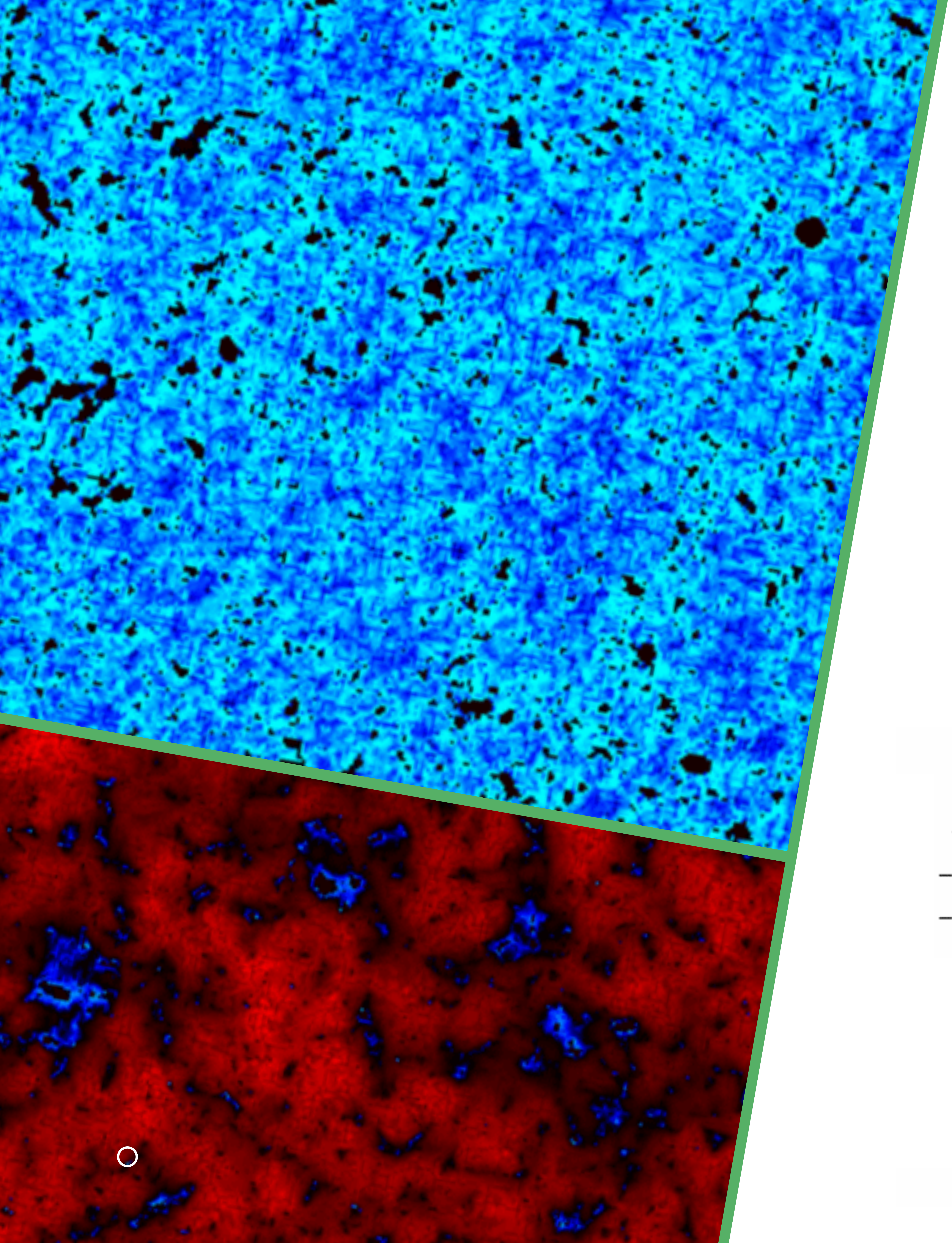
$f_c(z)$



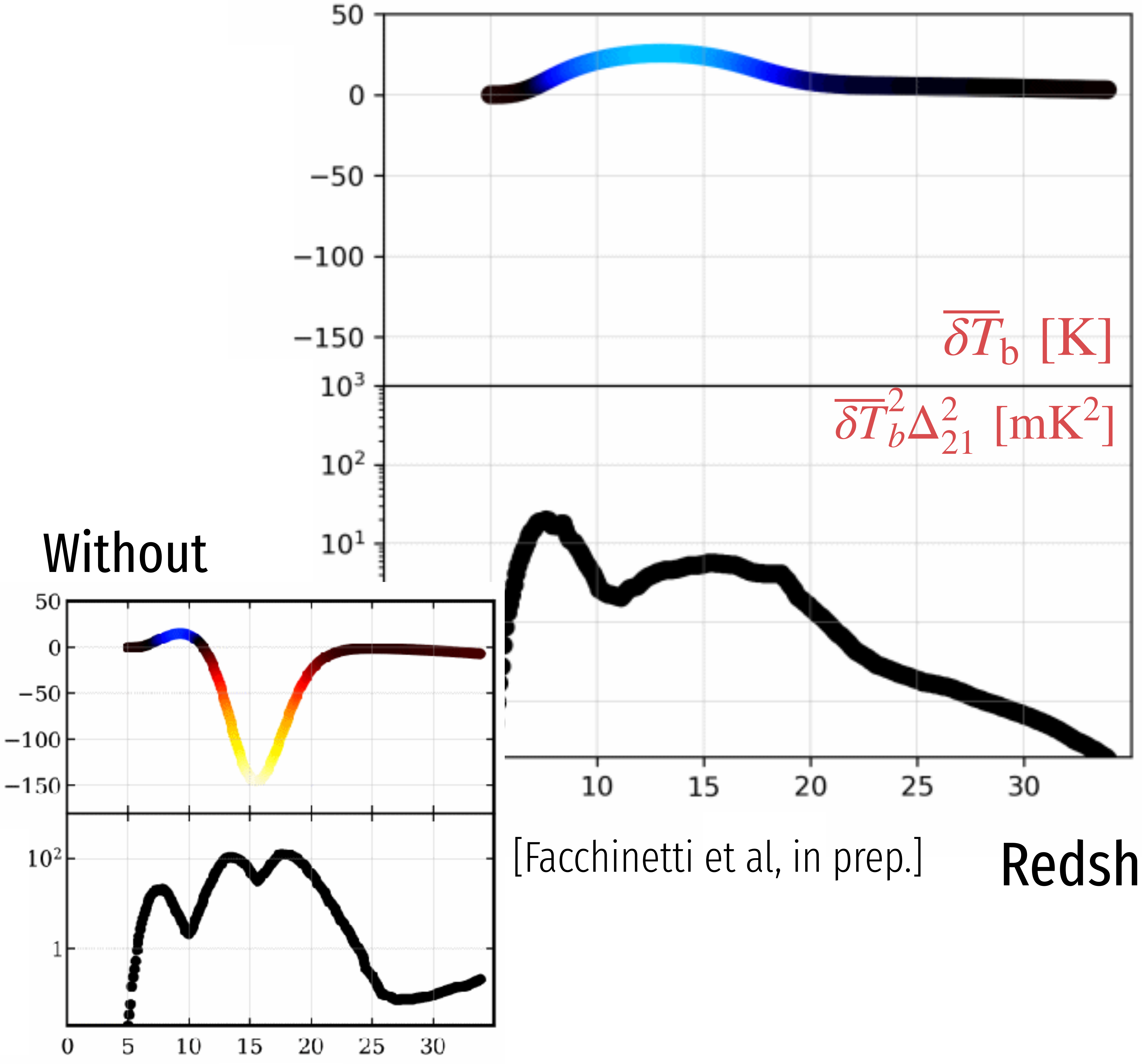
contributes to ionisation

impacts on how the energy is deposited

x_e



With DM energy injection $\chi \to e^+e^-$



[Facchinetti et al, in prep.]

Redshift

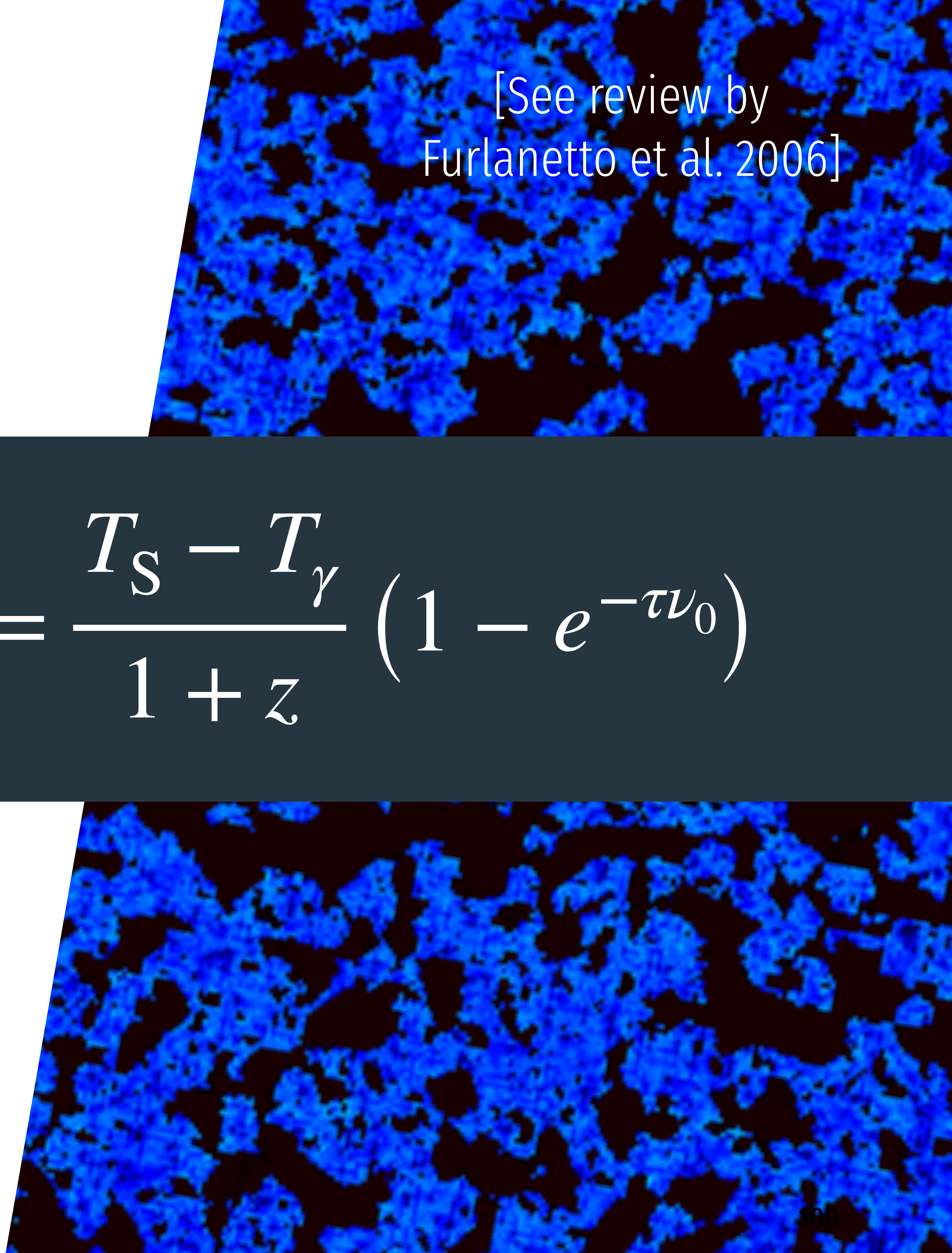
Radio telescopes

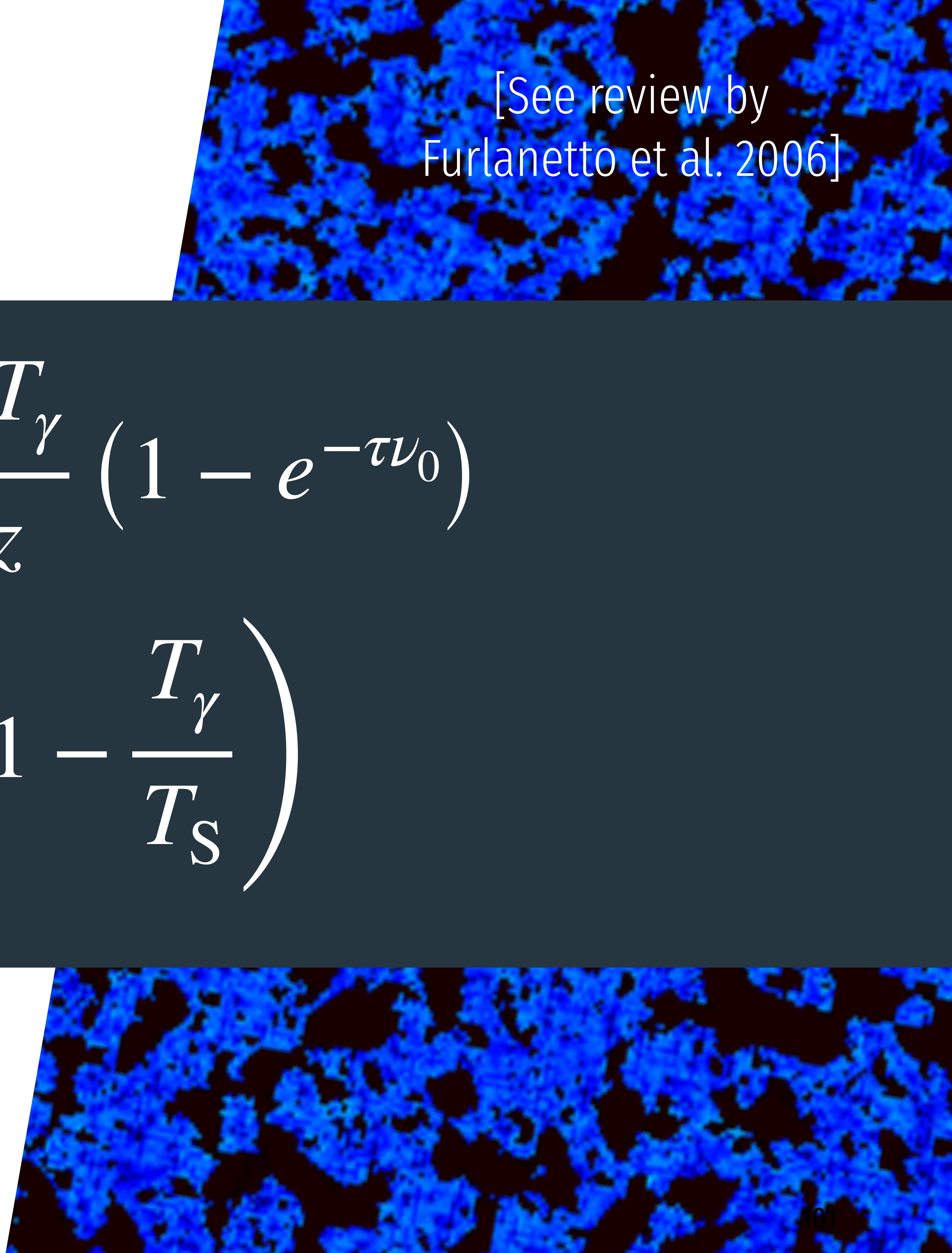
« see » the

differential

brightness temperature

$$\delta T_{\mathrm{b}} = \frac{T_{\mathrm{S}} - T_{\gamma}}{1+z}\left(1 - e^{-\tau_{\nu_0}}\right)$$



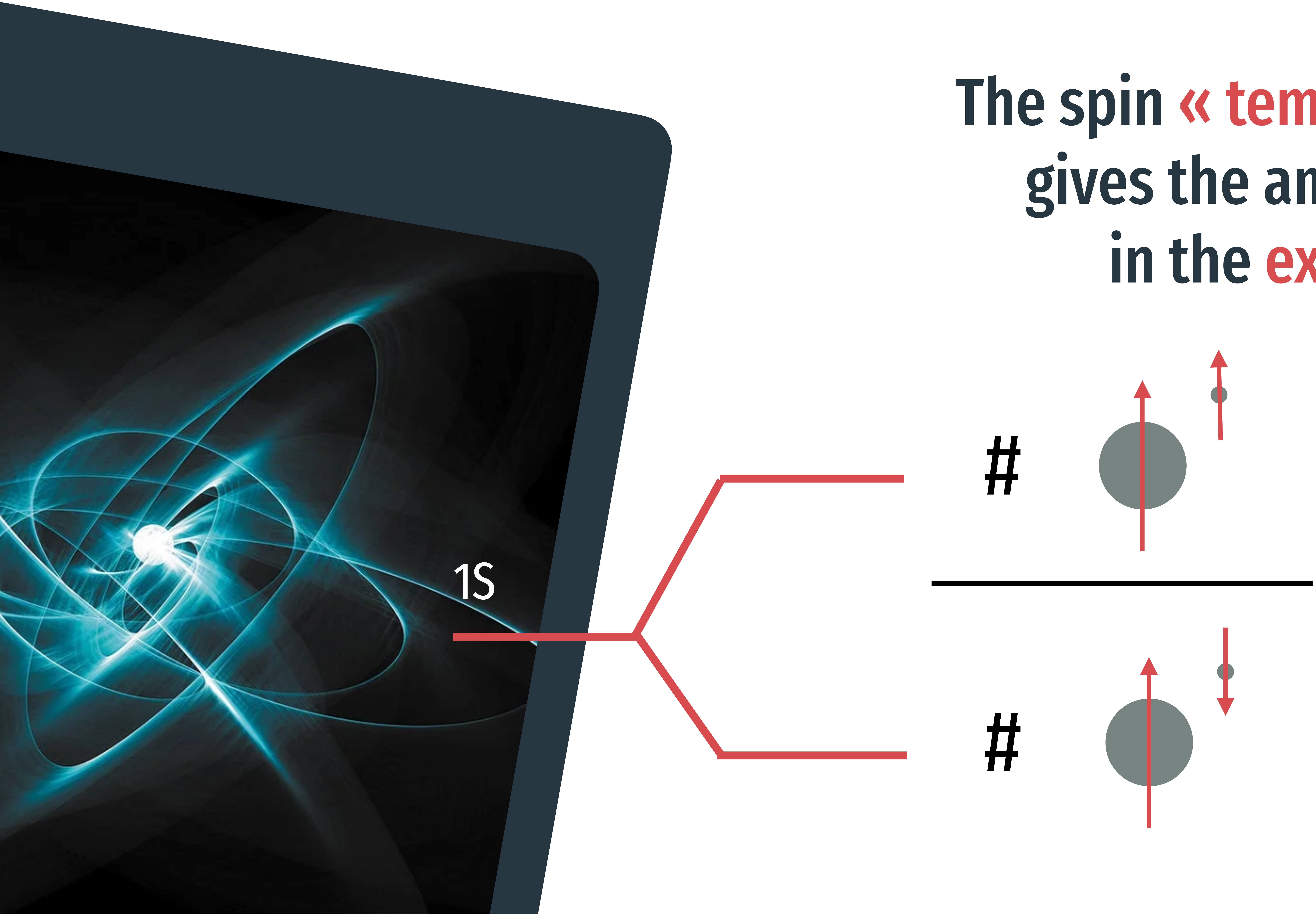


[See review by Furlanetto et al. 2006]

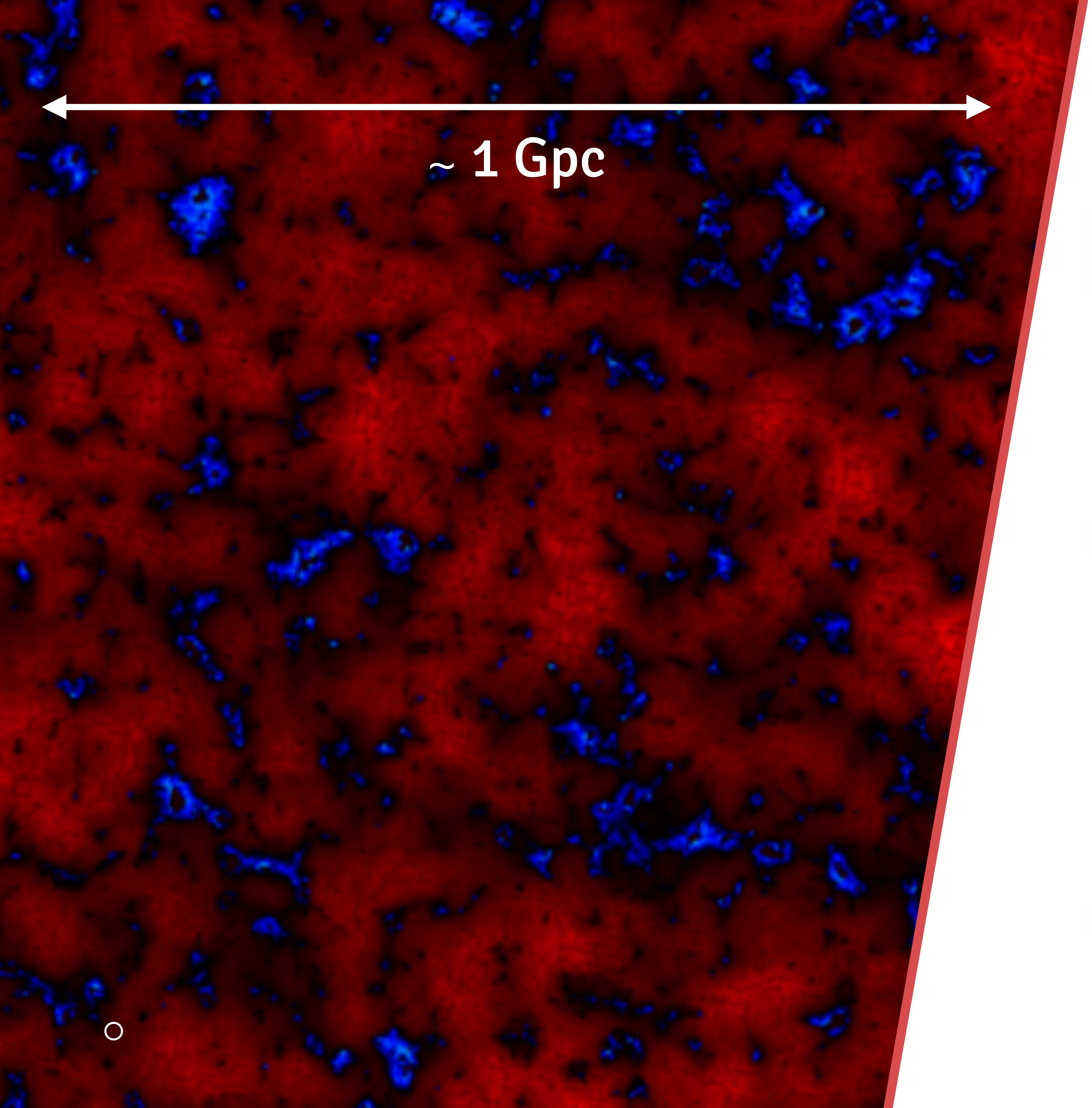
$$\delta T_{\mathrm{b}} = \frac{T_{\mathrm{S}} - T_{\gamma}}{1+z}\left(1 - e^{-\tau_{\nu_0}}\right)$$

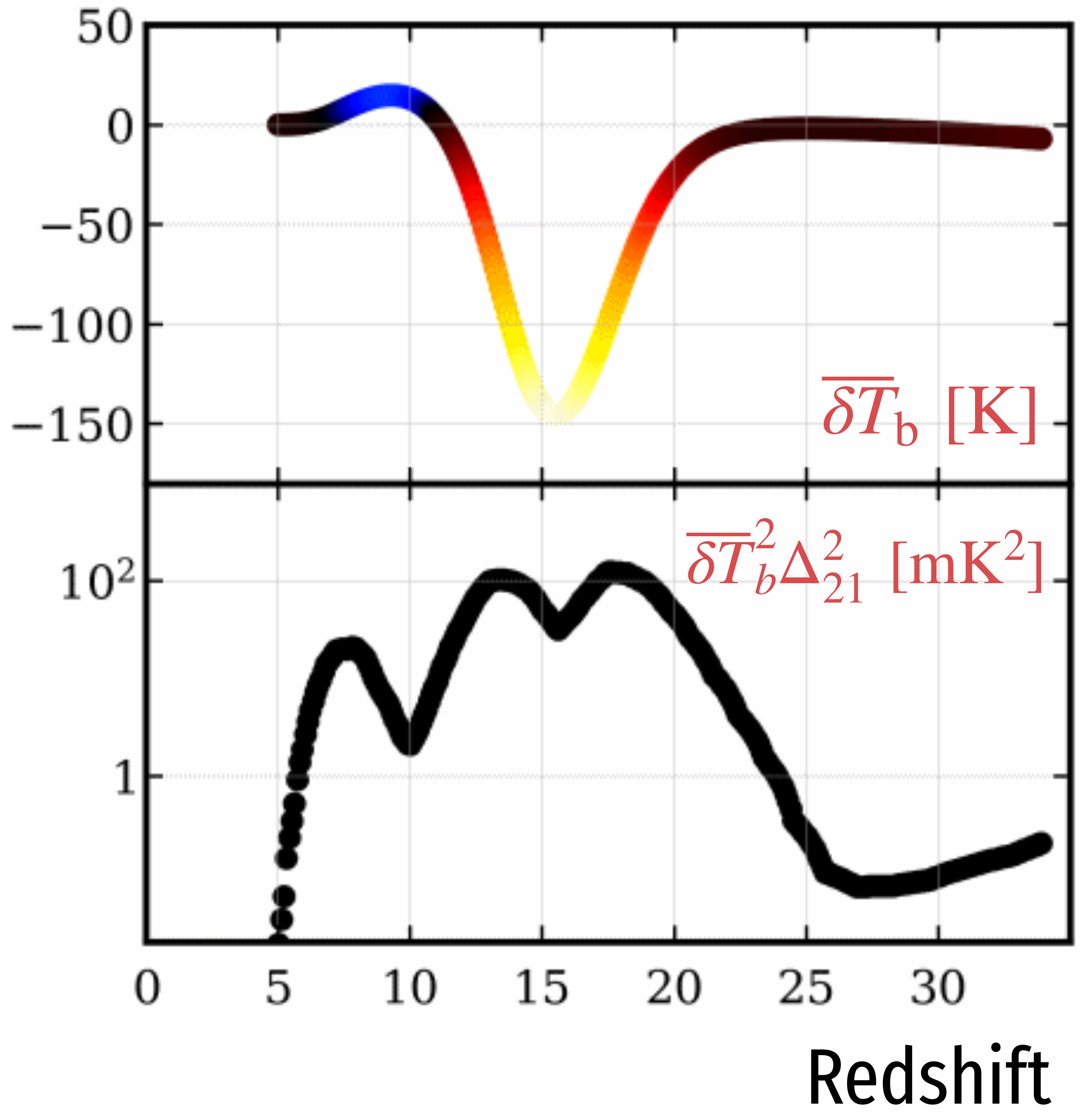
$$\propto x_{\mathrm{HI}}\left(1 - \frac{T_{\gamma}}{T_{\mathrm{S}}}\right)$$

The spin « temperature » gives the amount of HI in the excited state



$$\frac{\#}{\#} = 3e^{-\frac{T_\star}{T_S}}$$


~ 1 Gpc


50
0
−50
−100
−150
$\overline{\delta T}_b$ [K]
$\overline{\delta T}_b^2 \Delta_{21}^2$ [mK^2]
10^2
1
0
5
10
15
20
25
30
Redshift