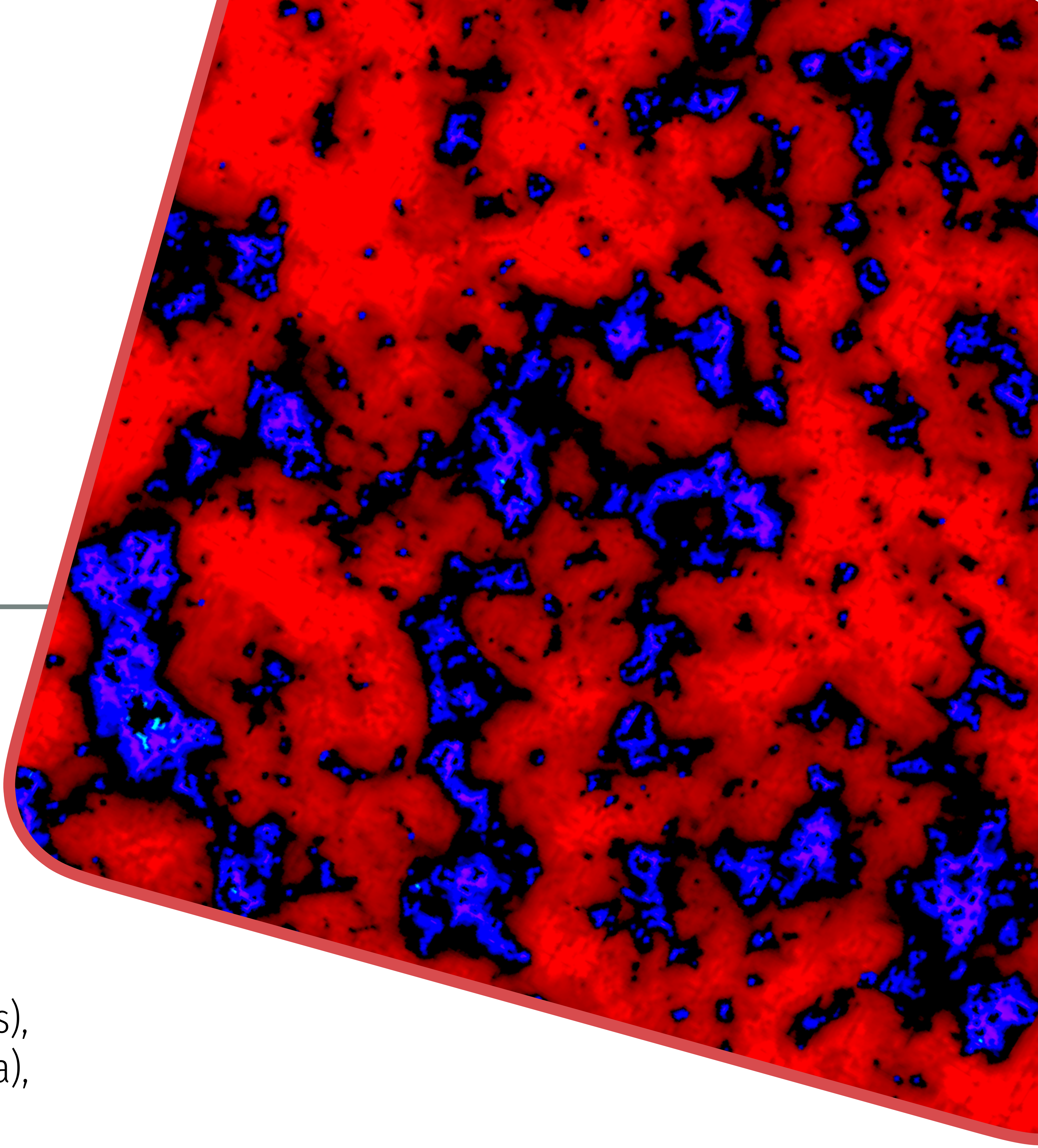
# Probing dark matter
## energy injection
## with the
# 21 cm power spectrum



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Credit: Tom Gauld (for NEW SCIENTIST)

# Importance of 21 cm physics for dark matter searches has been studied

[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

# also for exotic energy injection

[D'amico et al 2018]
Constraining annihilation using the global signal

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

# Goal

## get a clear prospective sensitivity of the upcoming 21cm observations to dark matter energy injection

I.

21 CM PHYSICS

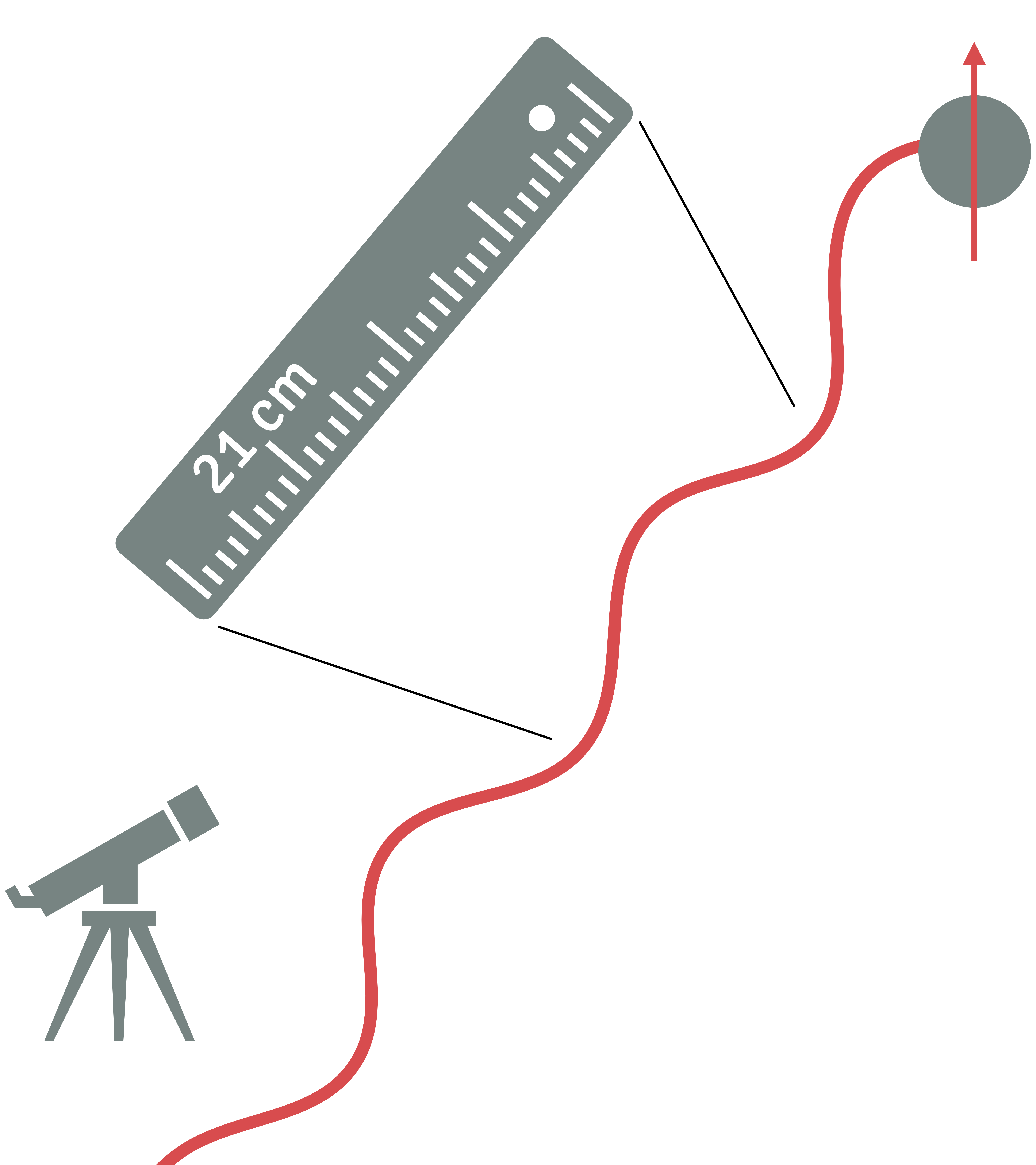
II.

21 CM AS A PROBE FOR DARK MATTER

III.

DARK MATTER ENERGY INJECTION ON THE 21CM SIGNAL

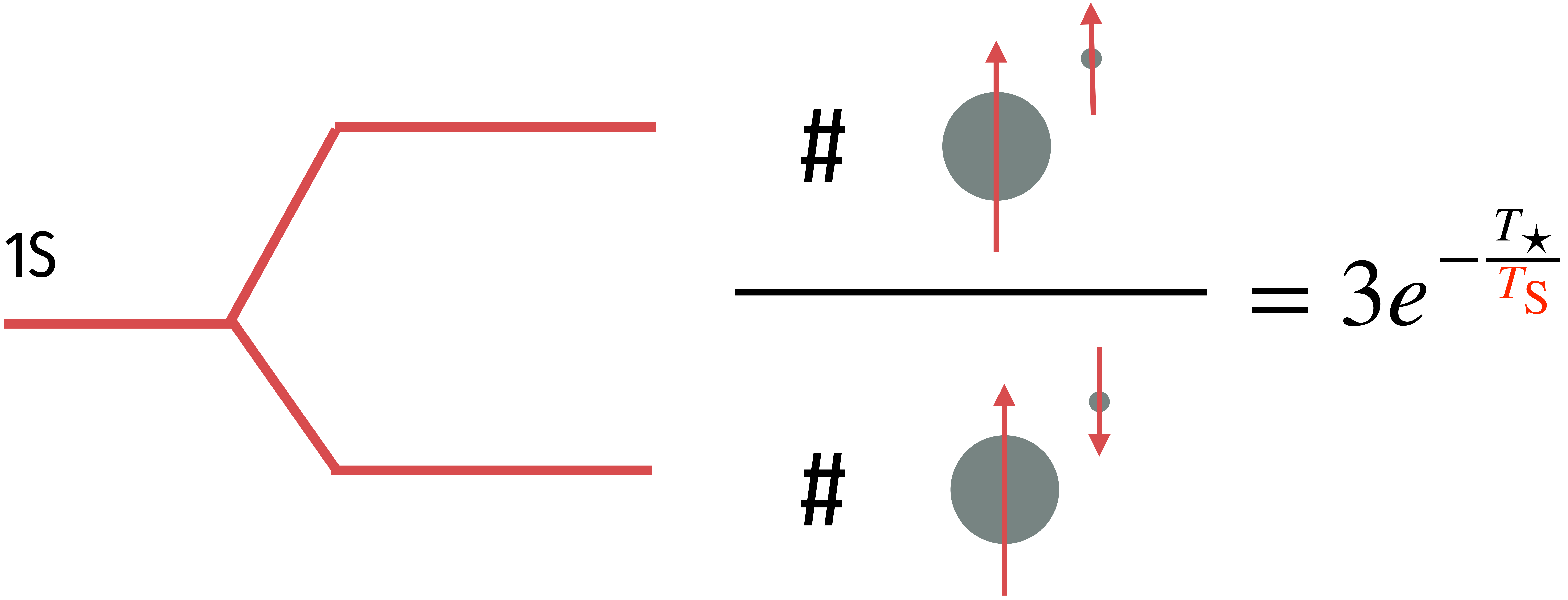
# 21 CM PHYSICS




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


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

# Amount of neutral Hydrogen HI
# in the excited state
# is quantified by the spin « temperature »



# The spin « temperature » is a function of two real temperatures

[See review by Furlanetto et al. 2006]

**The CMB temperature (background)**

$$T_\gamma$$

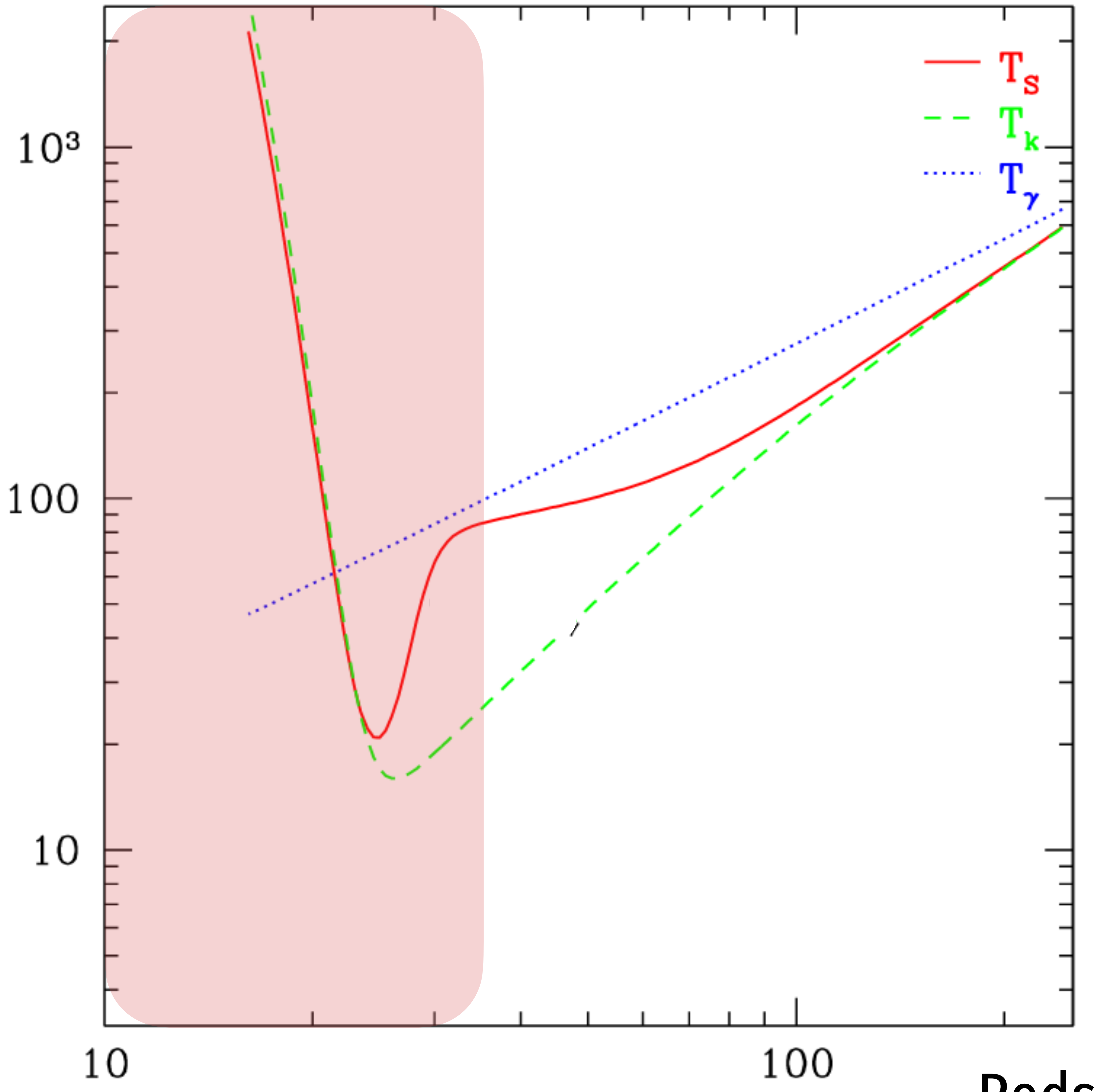
$$T_\mathrm{K}$$

**The kinetic temperature (of the IGM gaz)**

Due to collisional and UV interactions within the neutral hydrogen gaz

Mean temperature

From [Mesinger et al. 2010]




Redshift

# Instruments have access to **differential brightness temperature**

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

$$\delta T_{\rm b} \simeq 9 h x_{\rm HI}(1+\delta)\left(\frac{H}{\partial_r v_r + H}\right)\left(1 - \frac{T_{\gamma}}{T_{\rm S}}\right)\sqrt{1+z}\,\frac{\Omega_{\rm b}}{\Omega_{\rm dm}^{1/2}}$$

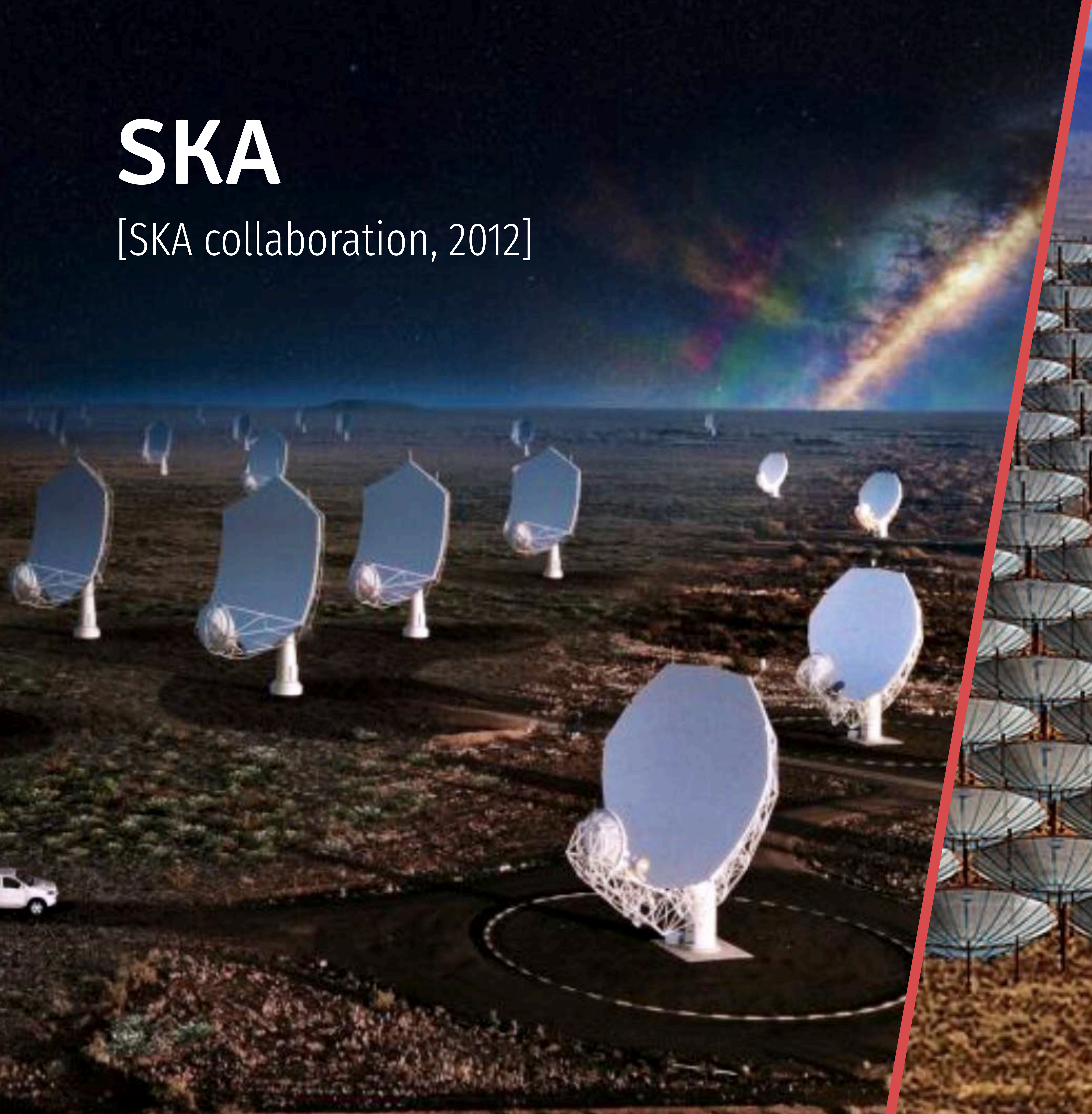
[See review by Furlanetto et al. 2006]

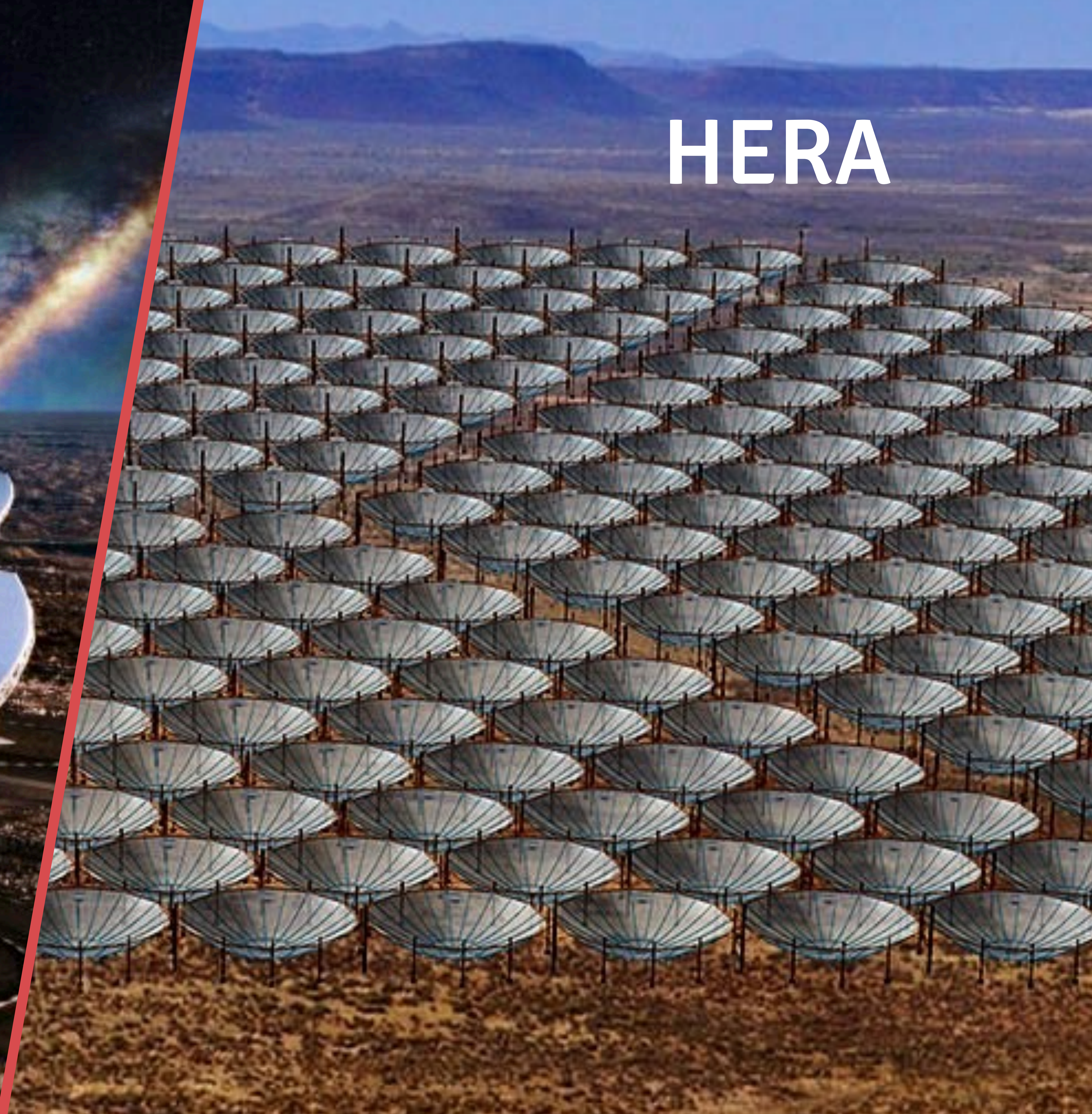
# and next gen. radio-interferometers will measure its **power spectrum**

(More information and easier to reject foreground)

$$\delta_{\mathrm{D}}\left(\mathbf{k}-\mathbf{k}'\right)\Delta^2_{21}(k,z) \equiv \frac{k^3}{16\pi^5}\left\langle \delta_{21}(\mathbf{k},z)\delta^*_{21}(\mathbf{k}',z)\right\rangle$$

$$\delta_{21}(\mathbf{k},z) \equiv \frac{\hat{\delta T}_{\mathrm{b}}(\mathbf{k},z)}{\overline{\delta T_b}(z)} - 1$$

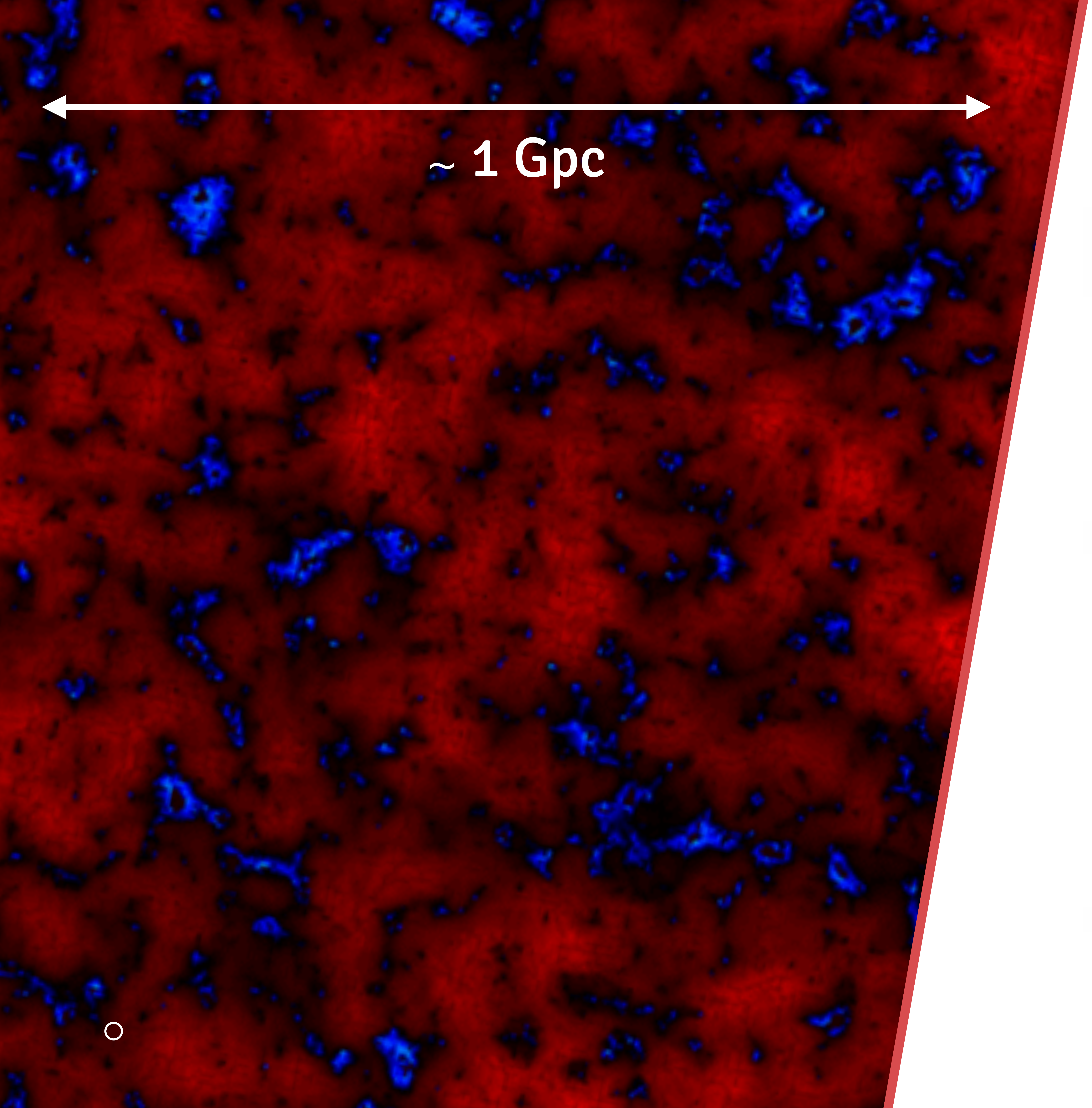

SKA
[SKA collaboration, 2012]

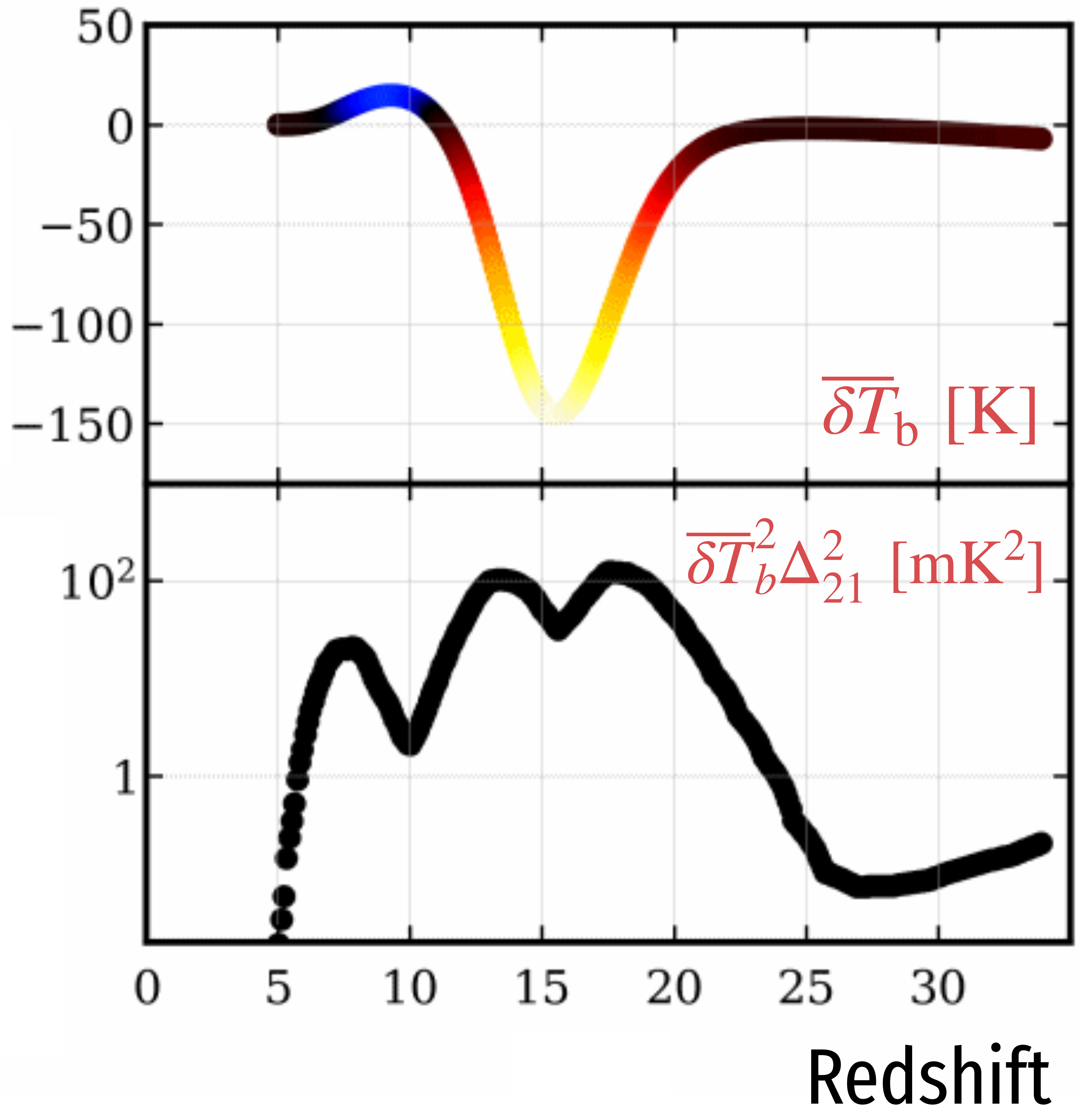

HERA

# Semi-analytical tool to predict the 21 cm signal

## 21cmFAST

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


~ 1 Gpc


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

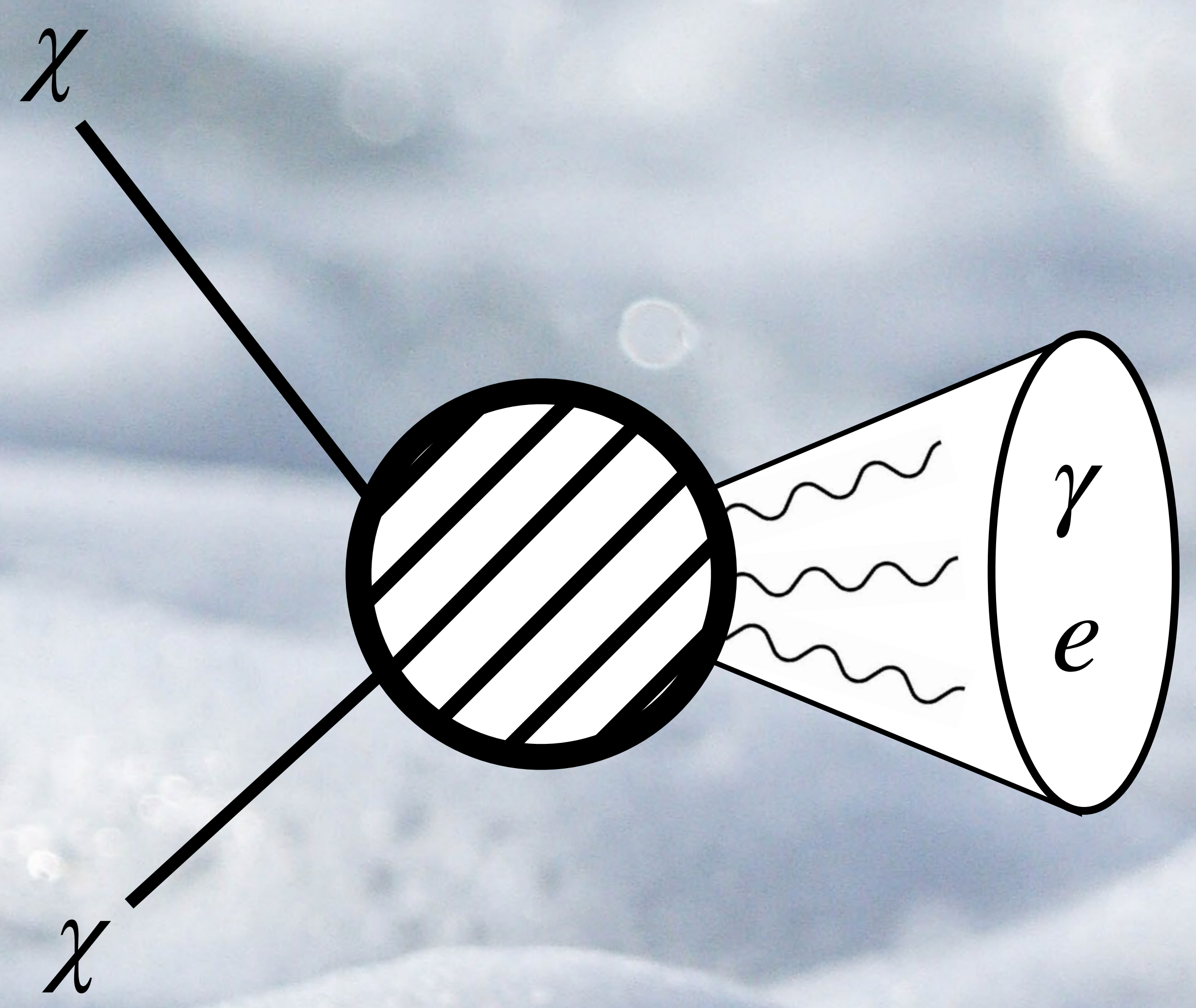
# 21cmFAST

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

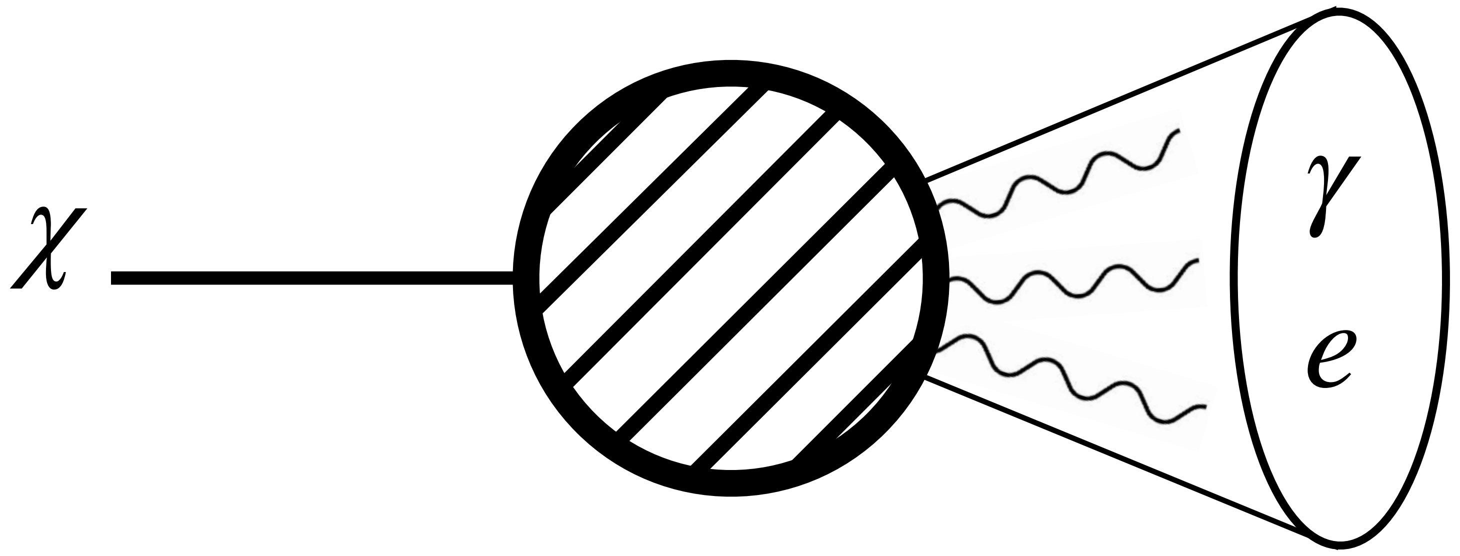
A tool to predict the 21 cm signal

## 21CM AS A PROBE FOR DARK MATTER

# Annihilation




# Decay



# Consider the **energy injected** by a **smooth** DM distribution

(by baryon number and Hubble time)

$$E_{\rm inj}(z) \equiv \frac{1}{n_{\rm b}(z)H(z)} \left( \frac{\mathrm{d}E}{\mathrm{d}t\mathrm{dV}} \right)^{\rm smooth}_{\rm inj}$$

[Lopez-Honorez et al. 2016]

## Annihilation

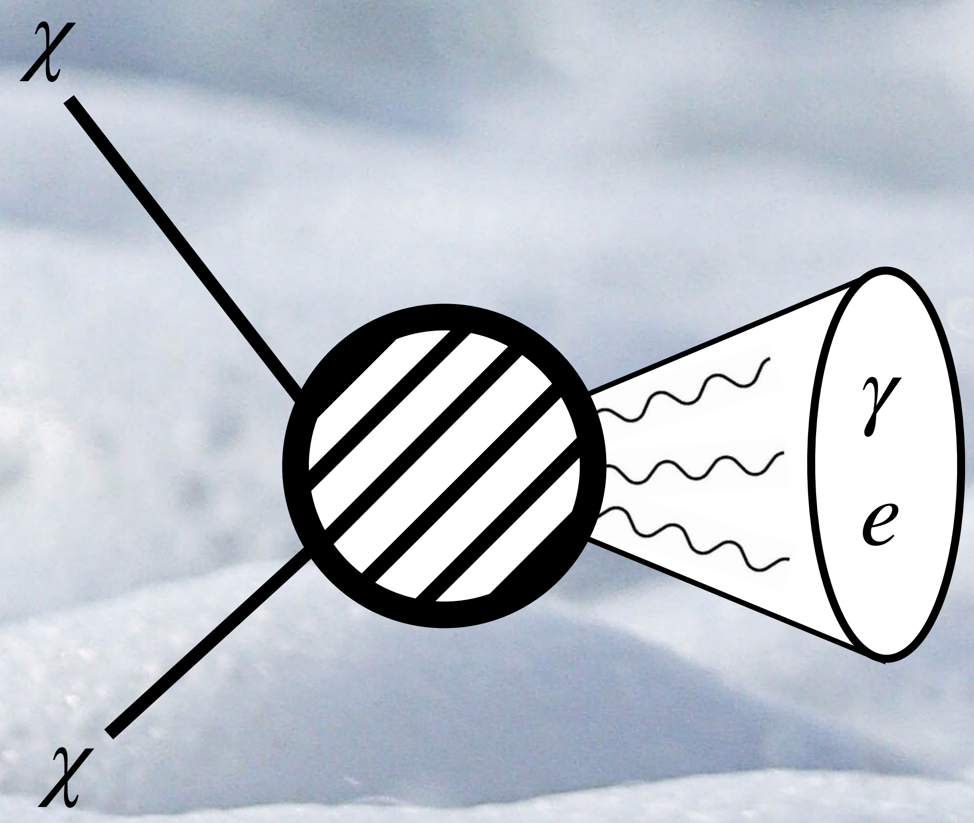
$$E_{\rm inj}(z) = \frac{(1+z)^3}{H(z)} \frac{\rho_{\chi,0}^2}{n_{\rm b,0}} \frac{\langle \sigma v \rangle}{m_\chi}$$

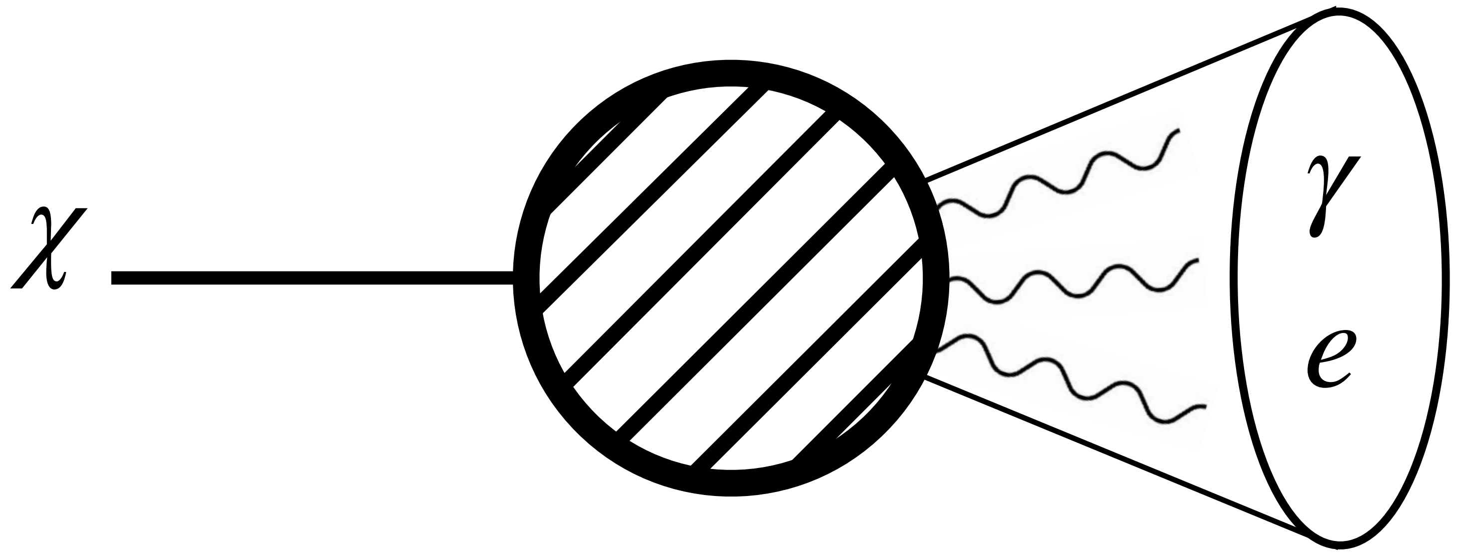
## Decay

$$E_{\rm inj}(z) = \frac{\rho_{\chi,0}}{n_{\rm b,0}} \frac{1}{\tau_\chi H(z)}$$

# Annihilation

$$\frac{\langle \sigma v \rangle}{m_\chi} \sim \frac{5 \times 10^{-22}\ \mathrm{cm^3 s^{-1}}}{(1+z)^{3/2}\ \mathrm{GeV}} \left( \frac{\delta E}{\mathrm{eV}} \right)$$




# Decay

$$\tau_\chi \sim \frac{10^{27}\ \mathrm{s}}{(1+z)^{3/2}} \left( \frac{\mathrm{eV}}{\delta E} \right)$$

$\delta E \sim$ sensitivity in energy

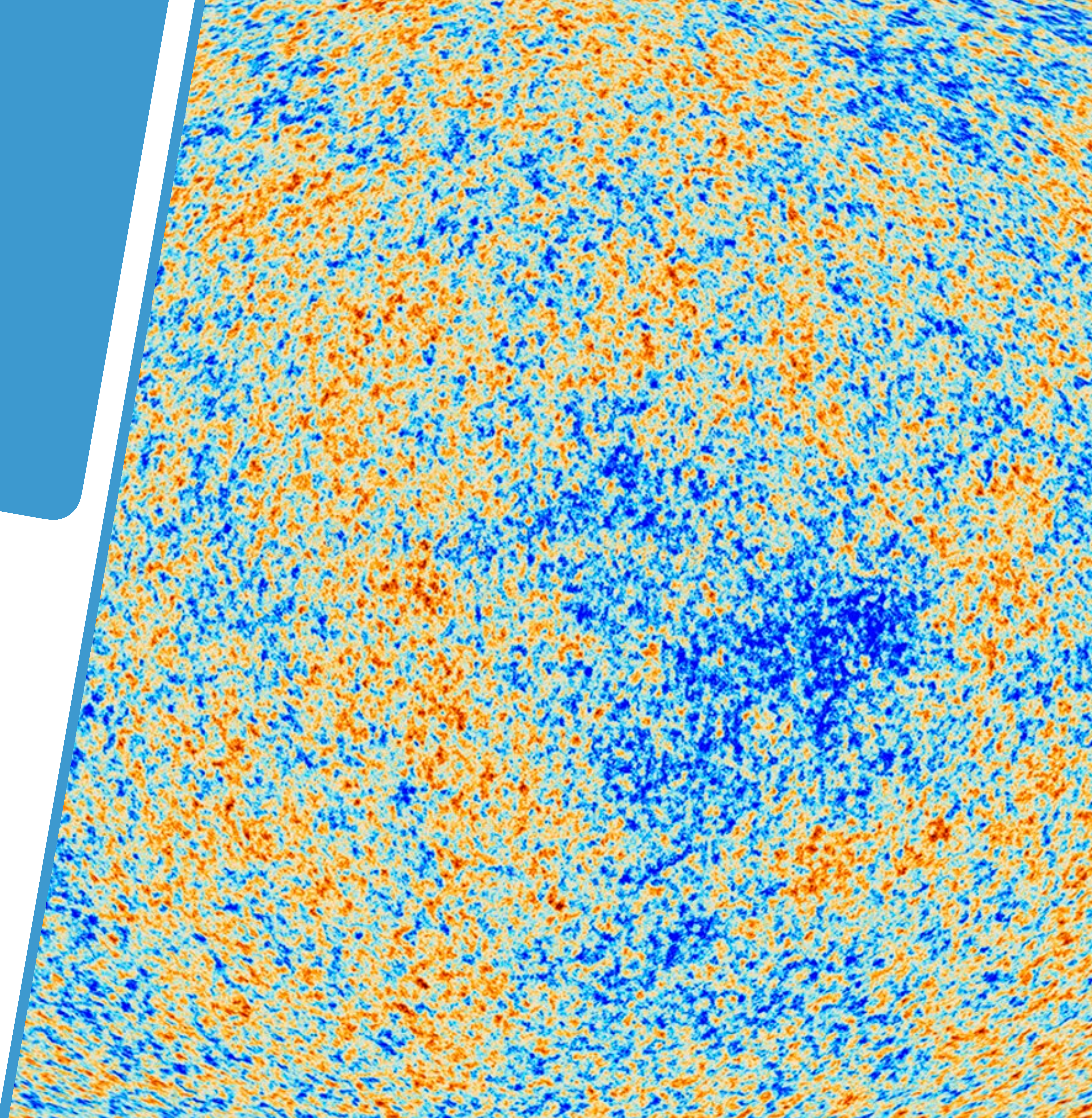
# CMB sensitivity

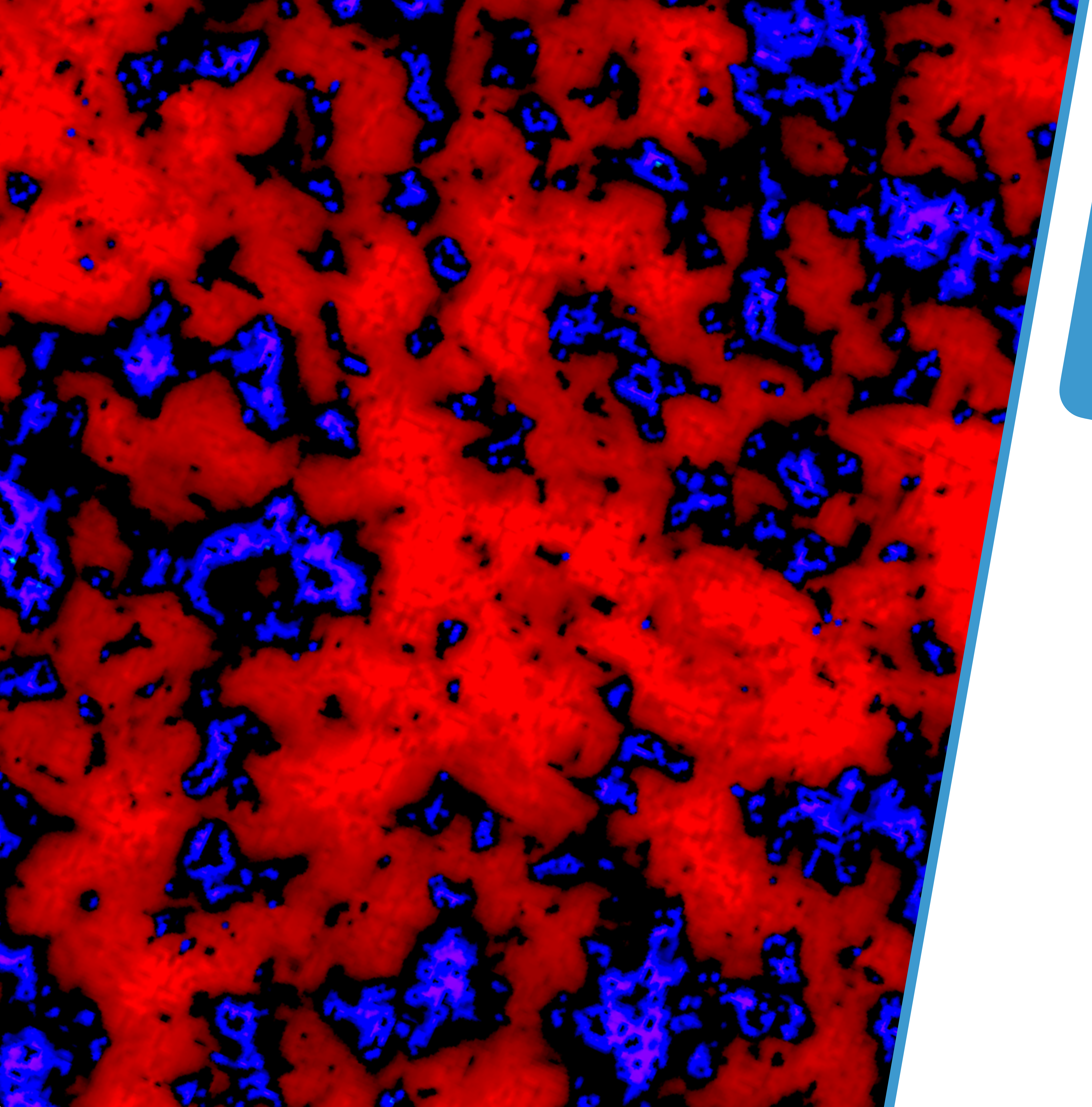
$$\delta E \sim 10^{-3} \times E_{\text{ion}}$$

$$\delta E \sim 10^{-2}\ \text{eV}$$

$$@\ z \sim 10^{3}$$

From T. Slatyer lectures series
Georges Lemaître Chair, UCL/CP3, May 2022





# 21 cm sensitivity

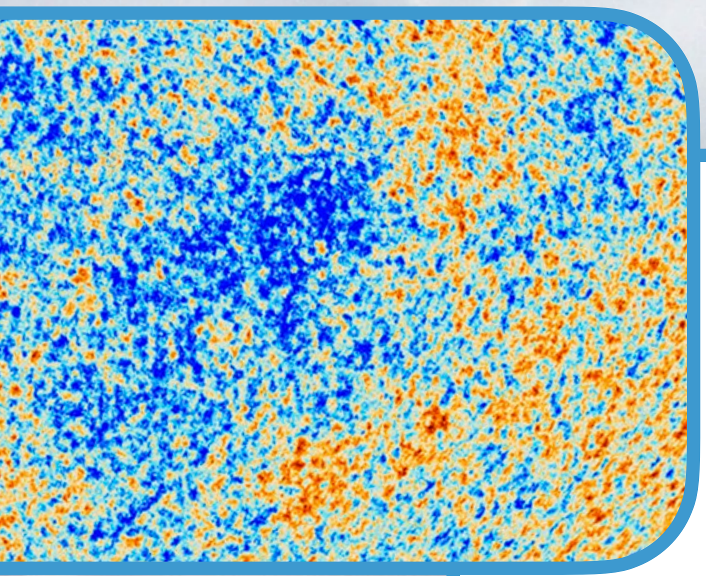
$$\delta E \sim T_{\mathrm{K}}$$

$$\delta E \sim 10^{-3}\ \mathrm{eV}$$

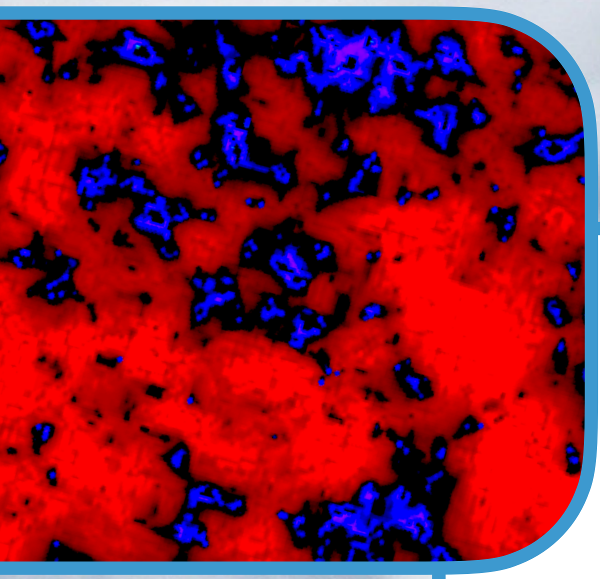
$$@\ \ z \sim 20$$

From T. Slatyer lectures series
Georges Lemaître Chair, UCL/CP3, May 2022

# Annihilation



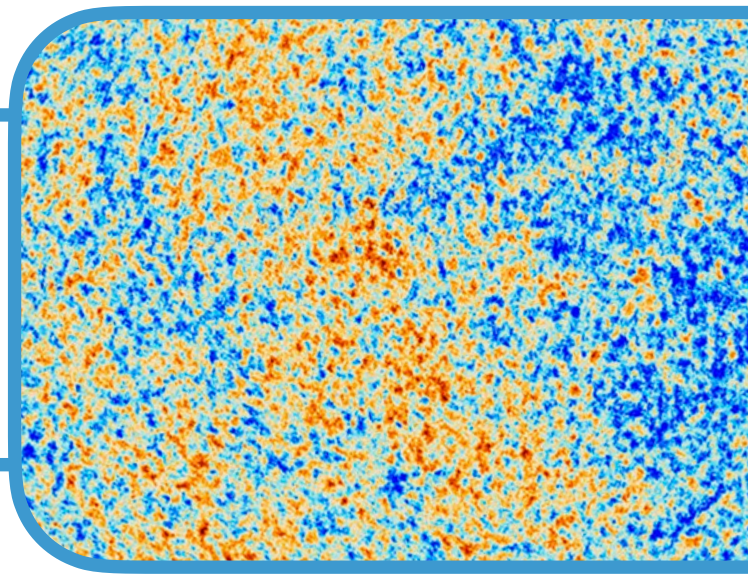
$$\frac{\langle \sigma v \rangle}{m_\chi} \sim 10^{-29} \ \frac{\mathrm{cm^3 s^{-1}}}{\mathrm{GeV}}$$



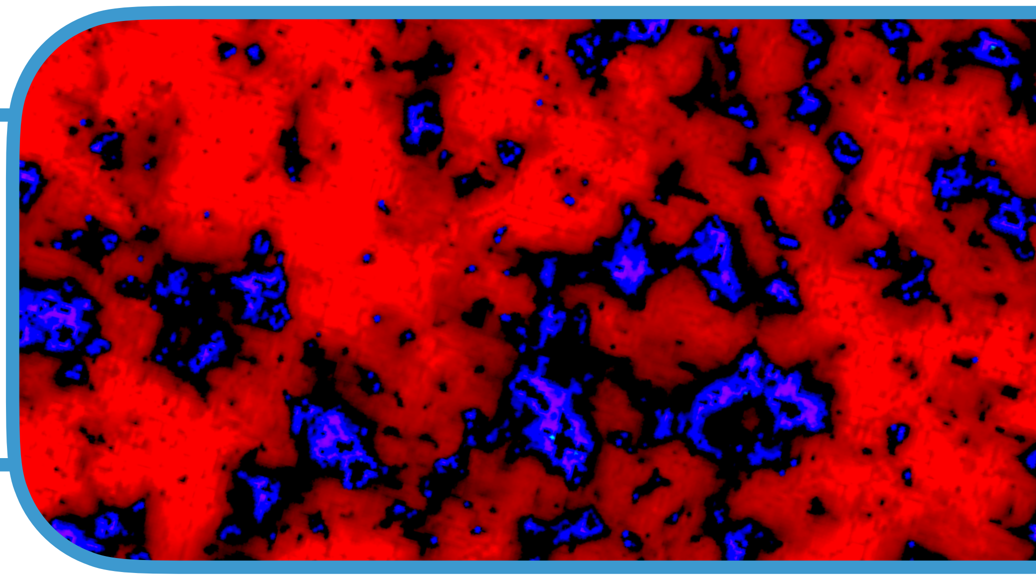
$$\frac{\langle \sigma v \rangle}{m_\chi} \sim 10^{-26} \ \frac{\mathrm{cm^3 s^{-1}}}{\mathrm{GeV}} [\mathscr{B}(z)]$$

# Decay

$$\tau_\chi \sim 10^{25}\ \mathrm{s}$$



$$\tau_\chi \sim 10^{28}\ \mathrm{s}$$



$$\tau_\chi \sim 10^{28}\,\mathrm{s}$$

# In practice it is a bit more **complicated**

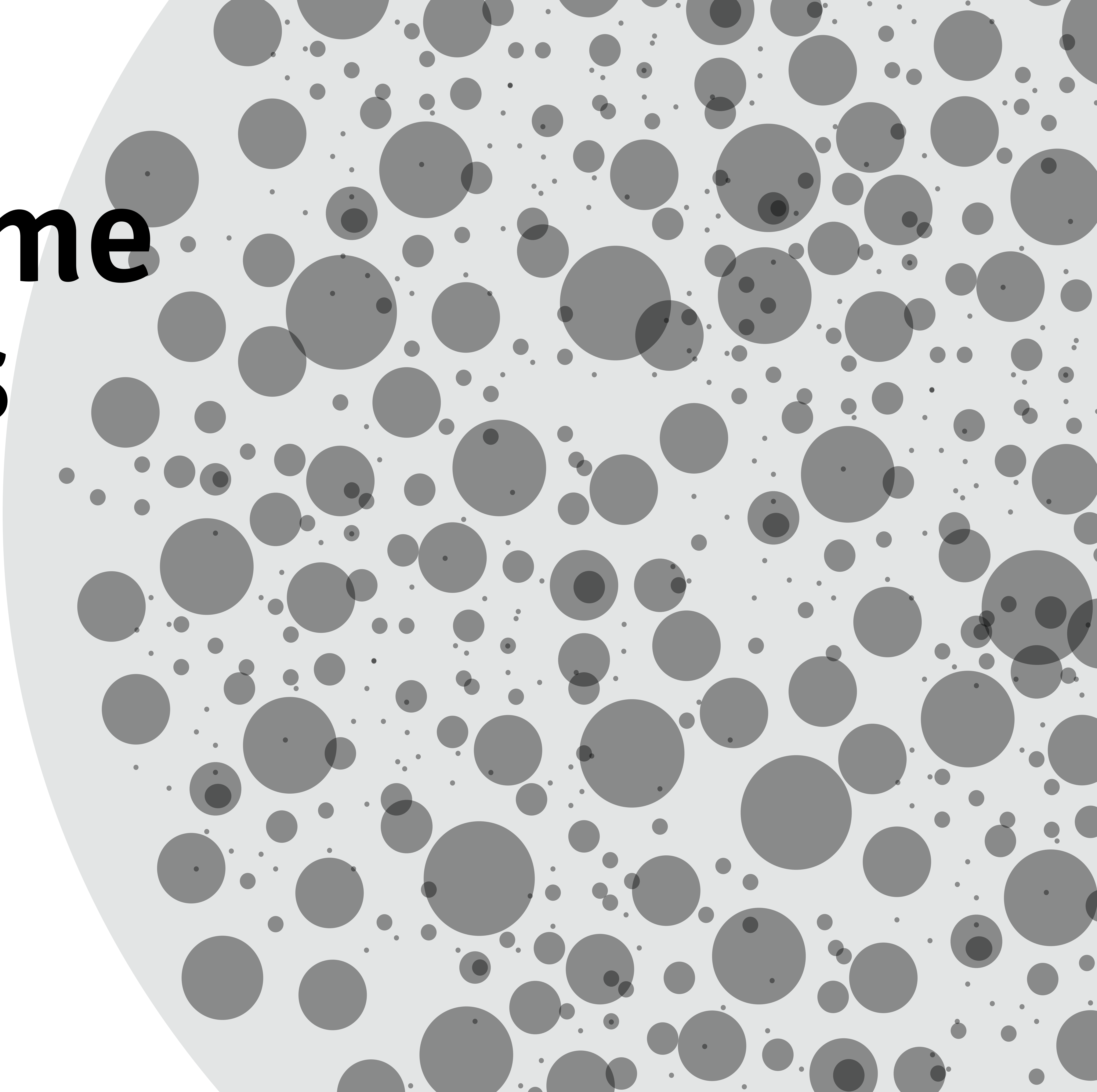
[Slatyer et al. 2009, Slatyer 2013, ....]

Deposition does **NOT** happen **on the spot**

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

# The late-time Universe is clumpy

$$\rho_\chi = \rho_{\rm smooth} + \sum_{i=1}^{N_{\rm h}} \rho_i$$



# We need the **deposited energy**

## for a non-smooth DM distribution

Computed from the deposition fractions

$$E_{\mathrm{dep,c}}(z, \mathbf{X}) \equiv f_c(z, \mathbf{X}) E_{\mathrm{inj}}(z)$$

c = heat, ionization, excitation

# We need the deposited energy

## for a non-smooth DM distribution

Computed from the deposition fractions

$$E_{\mathrm{dep,c}}(z, \mathbf{X}) \equiv f_c(z, \mathbf{X}) E_{\mathrm{inj}}(z)$$

$$\mathbf{X} = (x_{\mathrm{HII}}, x_{\mathrm{HeII}}, x_{\mathrm{HeIII}}) \sim x_e$$

# Deposition fraction can depend on the halo boost factor and more

$$f_c(z, \mathbf{X}) = f_c[z, \mathbf{X}, \mathscr{B}(z), \text{primaries}, m_\chi, \ldots]$$

$$\mathscr{B}(z) = \begin{cases} \dfrac{1}{\rho_{\chi,0}^2 (1+z)^3} \displaystyle\int \mathrm{d}M \frac{\partial n(M,z)}{\partial M} \int \rho^2(r) \mathrm{d}^3\vec{r} & \text{(annihilation)} \\ 1 & \text{(decay)} \end{cases}$$

# They can be computed with

# DarkHistory

Solves the ionization history of the Universe,
propagate the non deposited photon spectrum,
use sophisticated interpolation tables for energy deposition

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

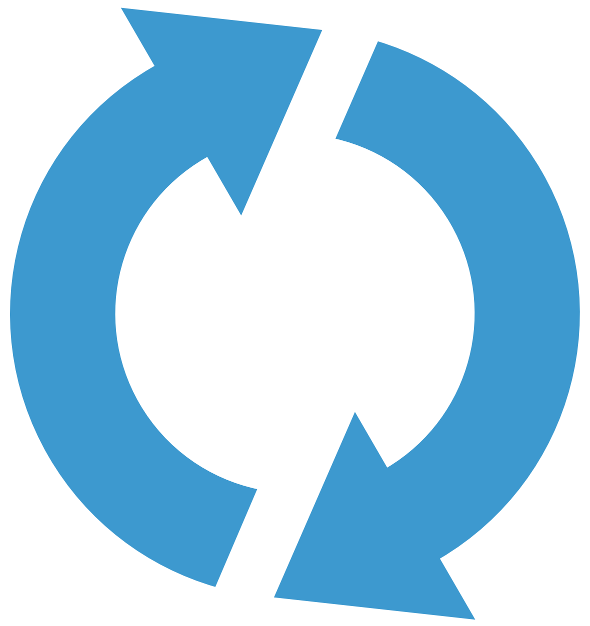
# Solving the ionization history of the Universe we get:

$$f_c(z, \mathbf{X}) \to f_c(z) = f_c[z, \mathbf{X}(z)]$$

with
$$\begin{cases} \dfrac{\mathrm{d}\mathbf{X}}{\mathrm{d}z} = \mathbf{g}_X[T_\mathrm{K}, \mathbf{X}] \\ \dfrac{\mathrm{d}T_\mathrm{K}}{\mathrm{d}z} = g_T[T_\mathrm{K}, \mathbf{X}] \end{cases}$$

# Accounts for backreaction

$f_c(z)$



contributes to ionisation

impacts on how the energy is deposited

$\mathbf{X}$

# Accounts for **backreaction**

$$\frac{\mathrm{d}T_\mathrm{K}}{\mathrm{d}z} = \left.\frac{\mathrm{d}T_\mathrm{K}}{\mathrm{d}z}\right|_\mathrm{astro} + \frac{\mathrm{d}t}{\mathrm{d}z}\frac{2f_\mathrm{heat}HE_\mathrm{inj}}{3k_\mathrm{B}(1+x_e)}$$

For annihilating DM (10 GeV, ~ $10^{-26}$ $cm^3/s$)

deposited energy

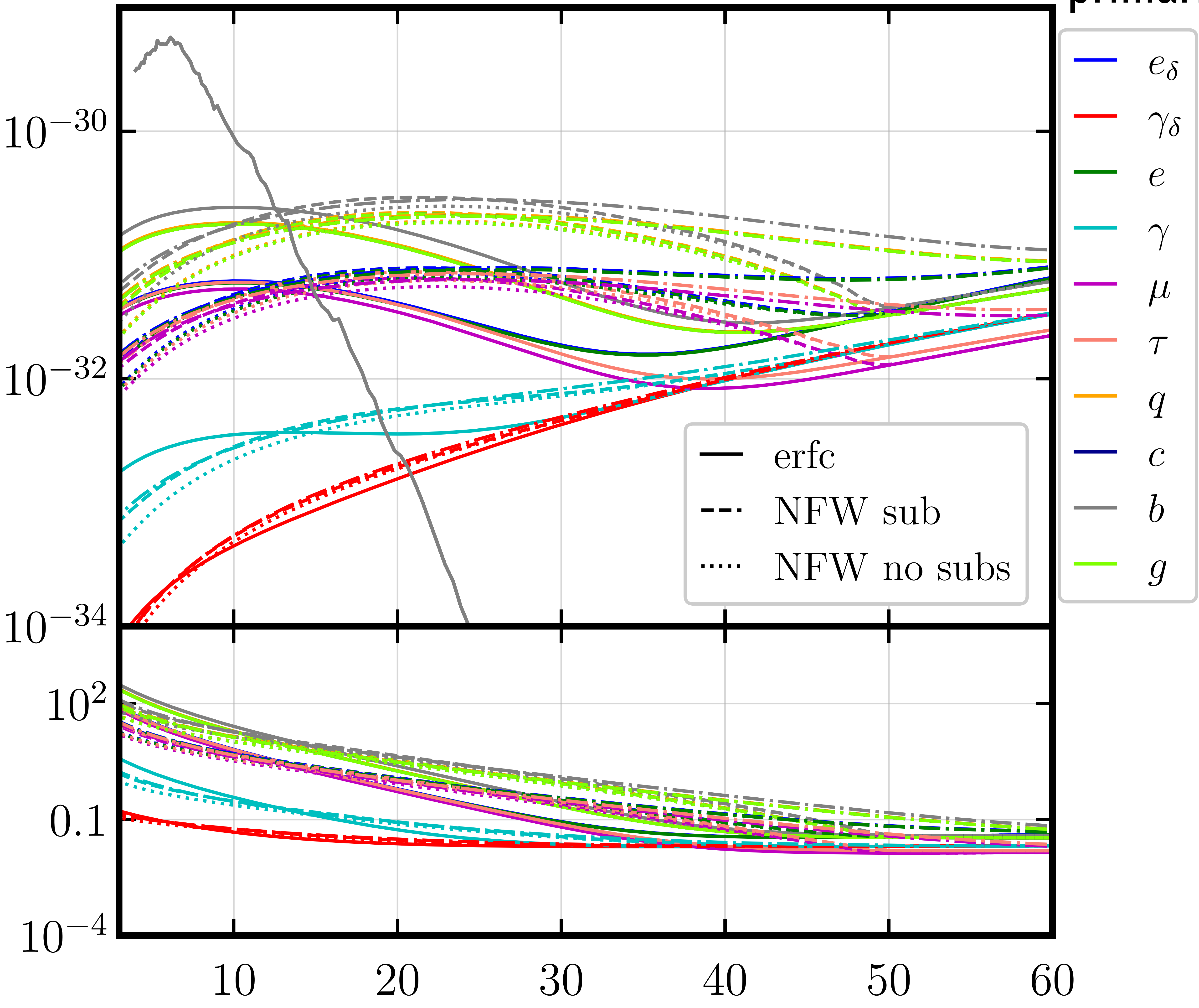
$H(z)E_{\text{dep, heat}}(z)$

[erg/s]

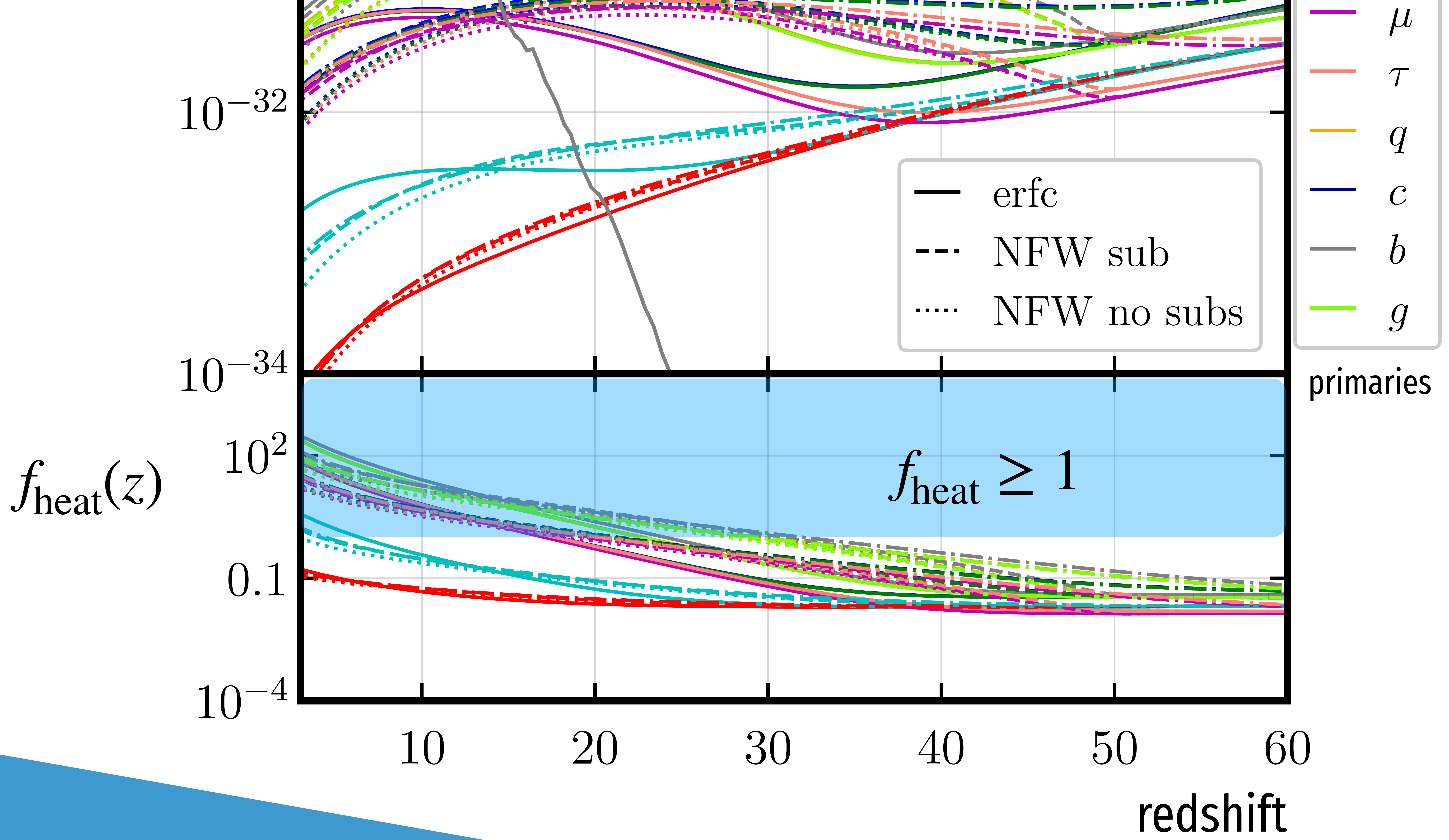
deposition fraction

$f_{\text{heat}}(z)$

primaries




redshift



$10^{-32}$
$10^{-34}$
$10^{2}$
0.1
$10^{-4}$
$f_{\rm heat}(z)$
$f_{\rm heat} \geq 1$
erfc
NFW sub
NFW no subs
$\mu$
$\tau$
$q$
$c$
$b$
$g$
primaries
10
20
30
40
50
60
redshift

DarkHistory

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

# A tool to evaluate exotic energy injection in the IGM

DARK MATTER
ENERGY INJECTION
ON THE 21CM SIGNAL

DarkHistory

# 21cmFAST

DarkHistory

# 21cmFAST


DarkHistory
exo21cmFAST
21cmFAST
depositphotos

# How does **exo21cmFAST** work?

$z=10^3$

$z=35$

$z=5$

Inputs (DM mass, primaries, process, ...)

$z=10^3$

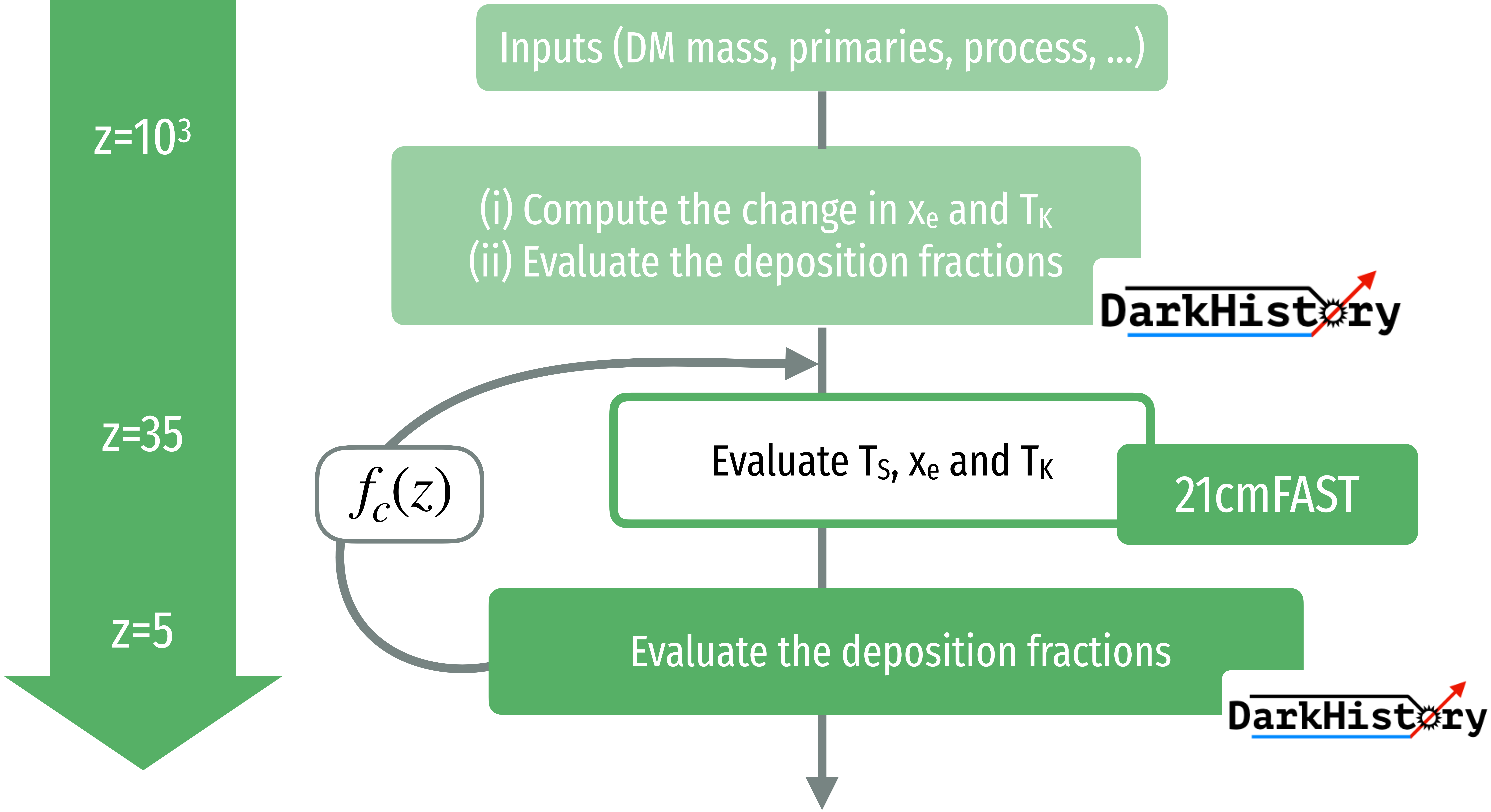
$z=35$

$z=5$

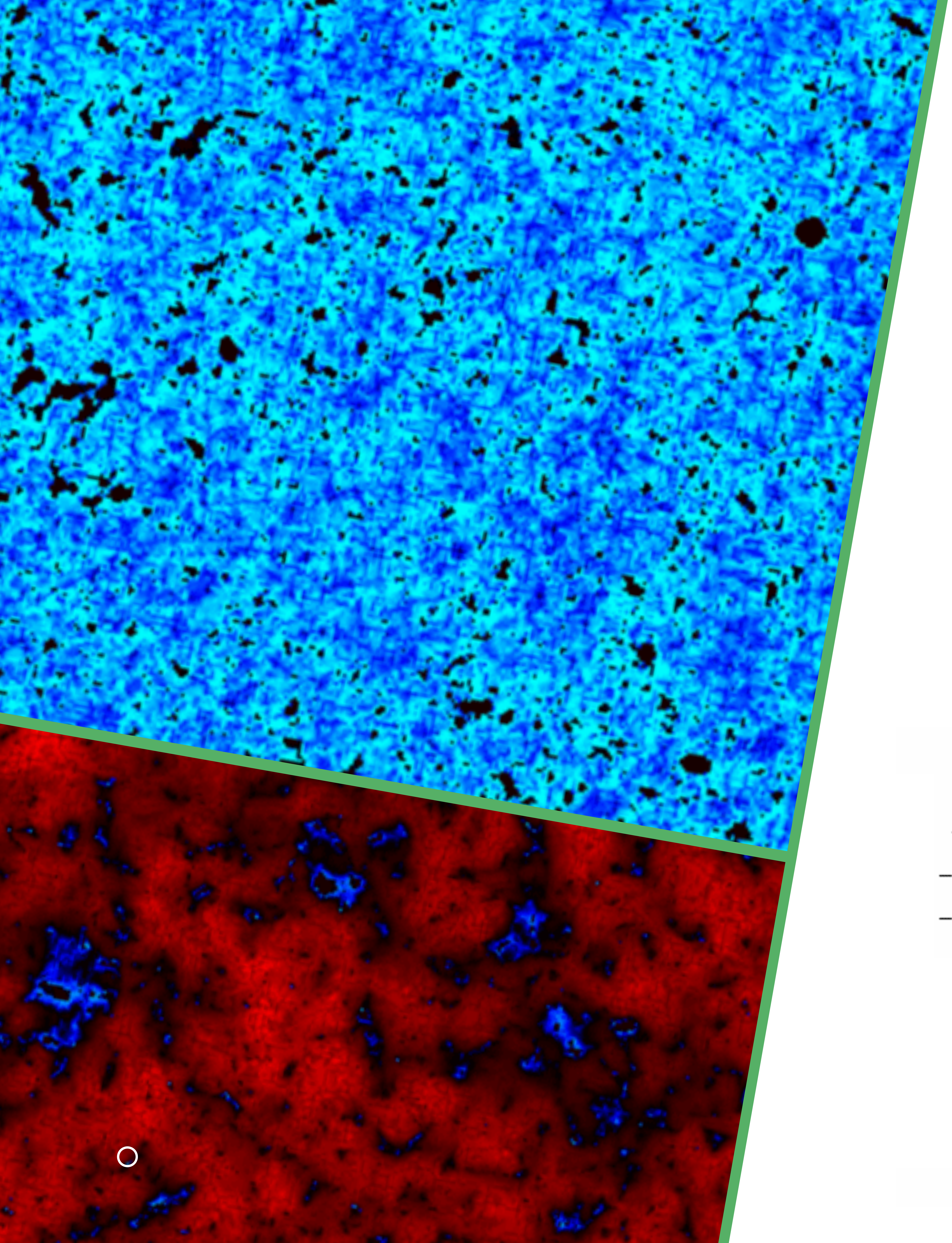
Inputs (DM mass, primaries, process, ...)

(i) Compute the change in $x_e$ and $T_K$
(ii) Evaluate the deposition fractions

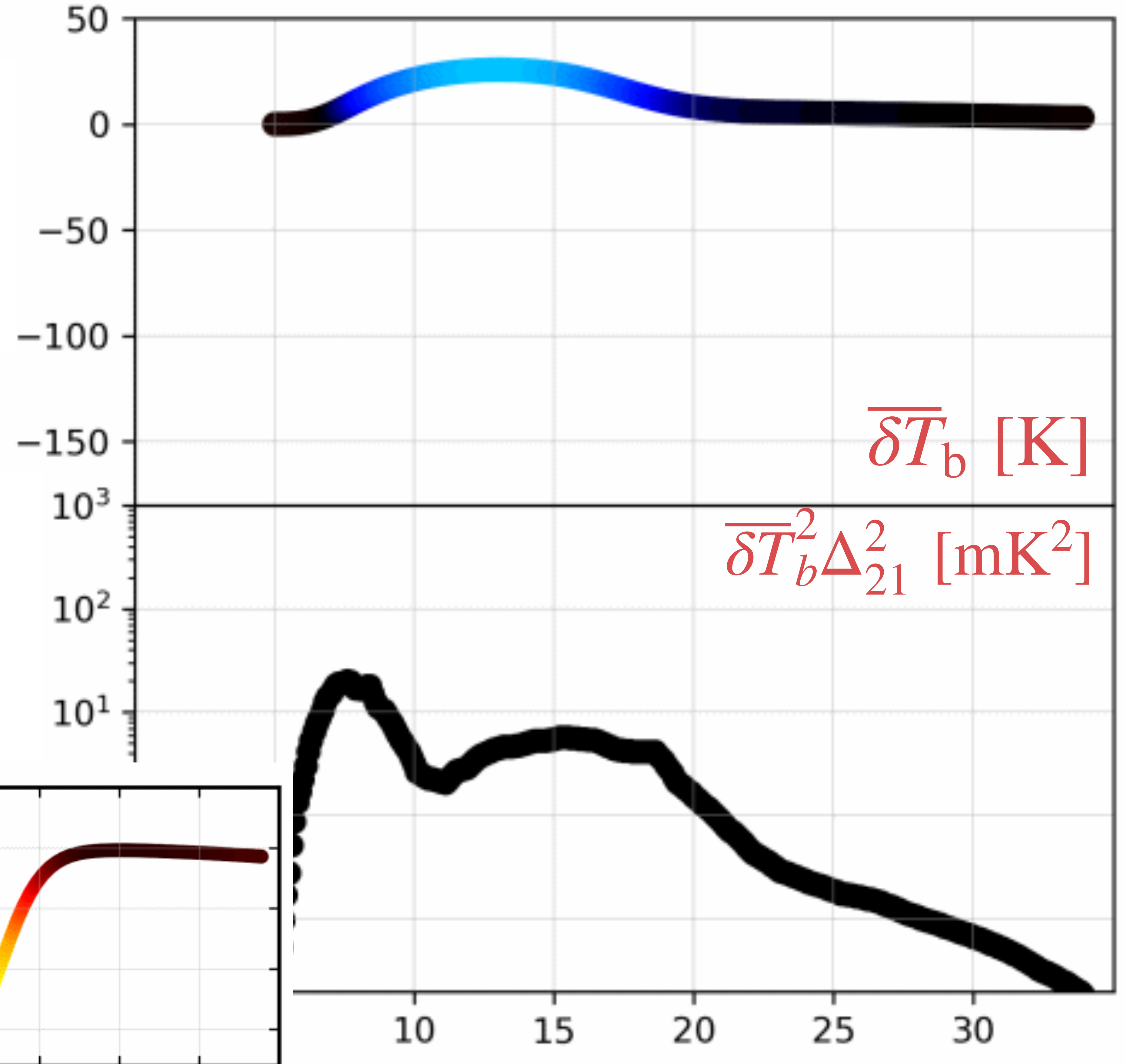
DarkHistory



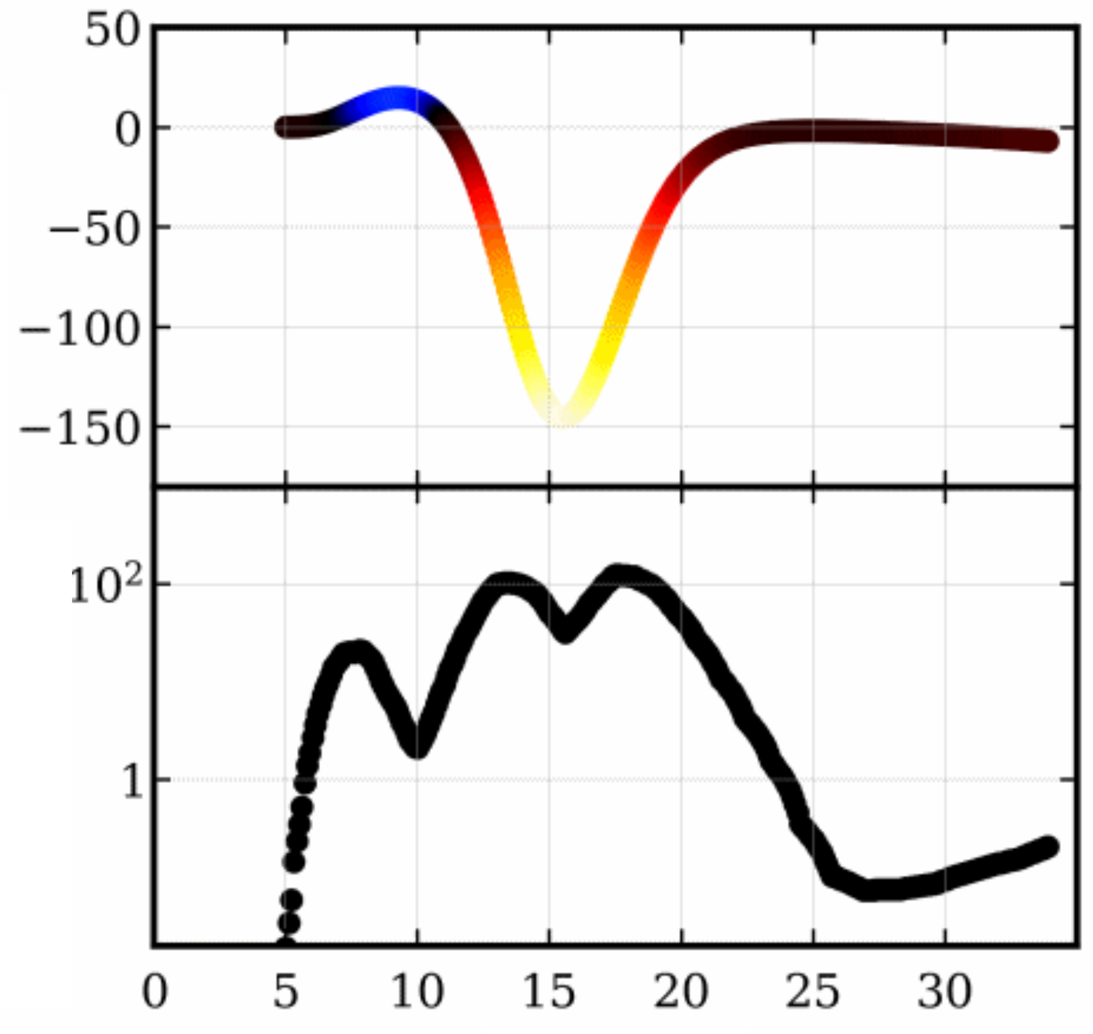
z=10³
z=35
z=5
Inputs (DM mass, primaries, process, ...)
(i) Compute the change in xe and TK
(ii) Evaluate the deposition fractions
DarkHistory
$f_c(z)$
Evaluate TS, xe and TK
21cmFAST
Evaluate the deposition fractions
DarkHistory



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




Without



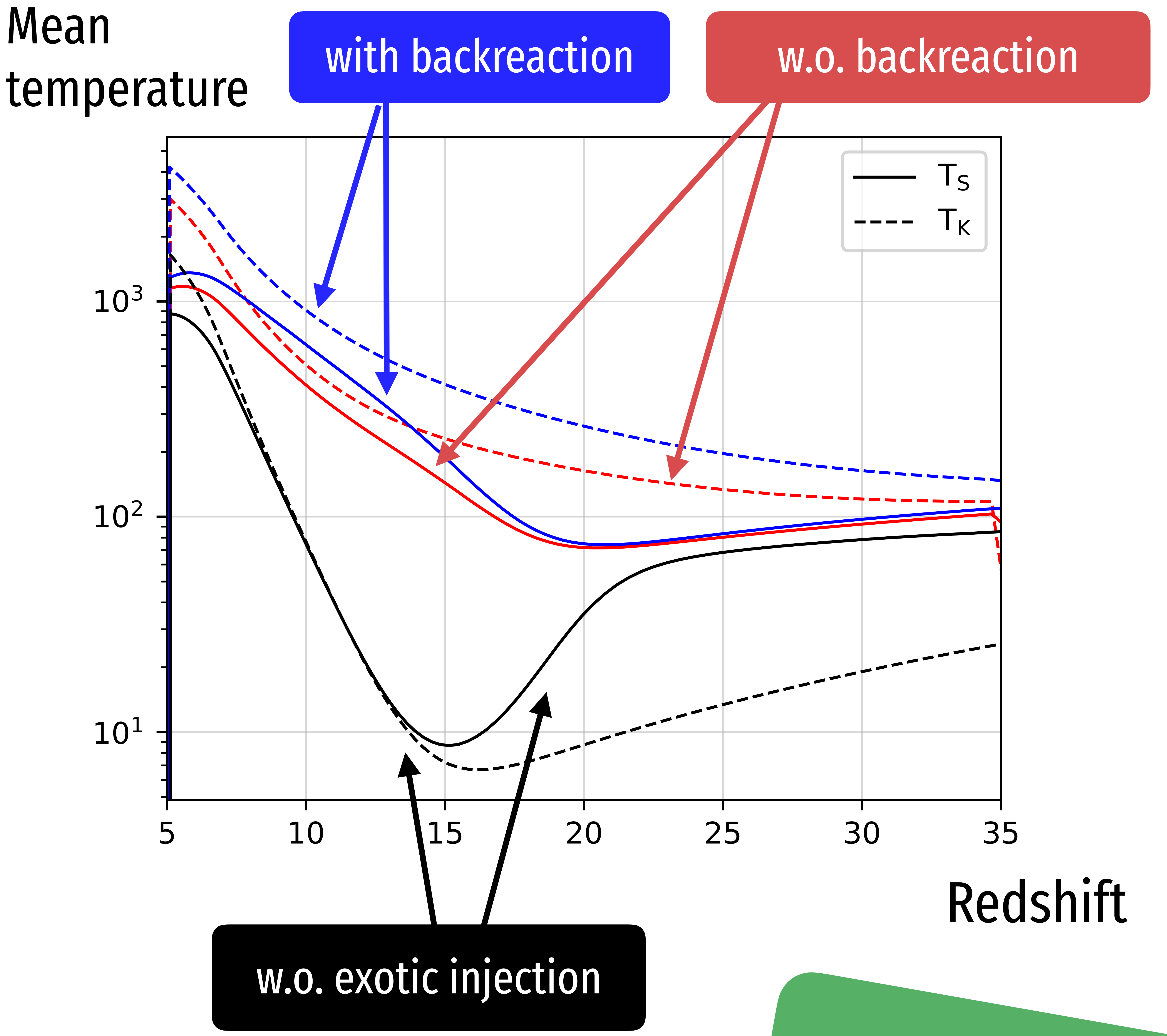

[Facchinetti et al, in prep.]

Redshift

$$f_c(z) = f_c[z, \mathbf{X}(z)]$$

$$f_c(z) = f_c[z, \mathbf{X}_{\mathrm{std}}(z)]$$

$$\mathbf{X}(z) \neq \mathbf{X}_{\mathrm{std}}(z)$$



# exo21cmFAST

[Facchinetti et al. in prep]

A tool to predict the 21 cm signal with exotic energy injection in the IGM

# There are some « caveats »:

21cmFAST is not fast enough to include backreaction generically in a MCMC

use templates

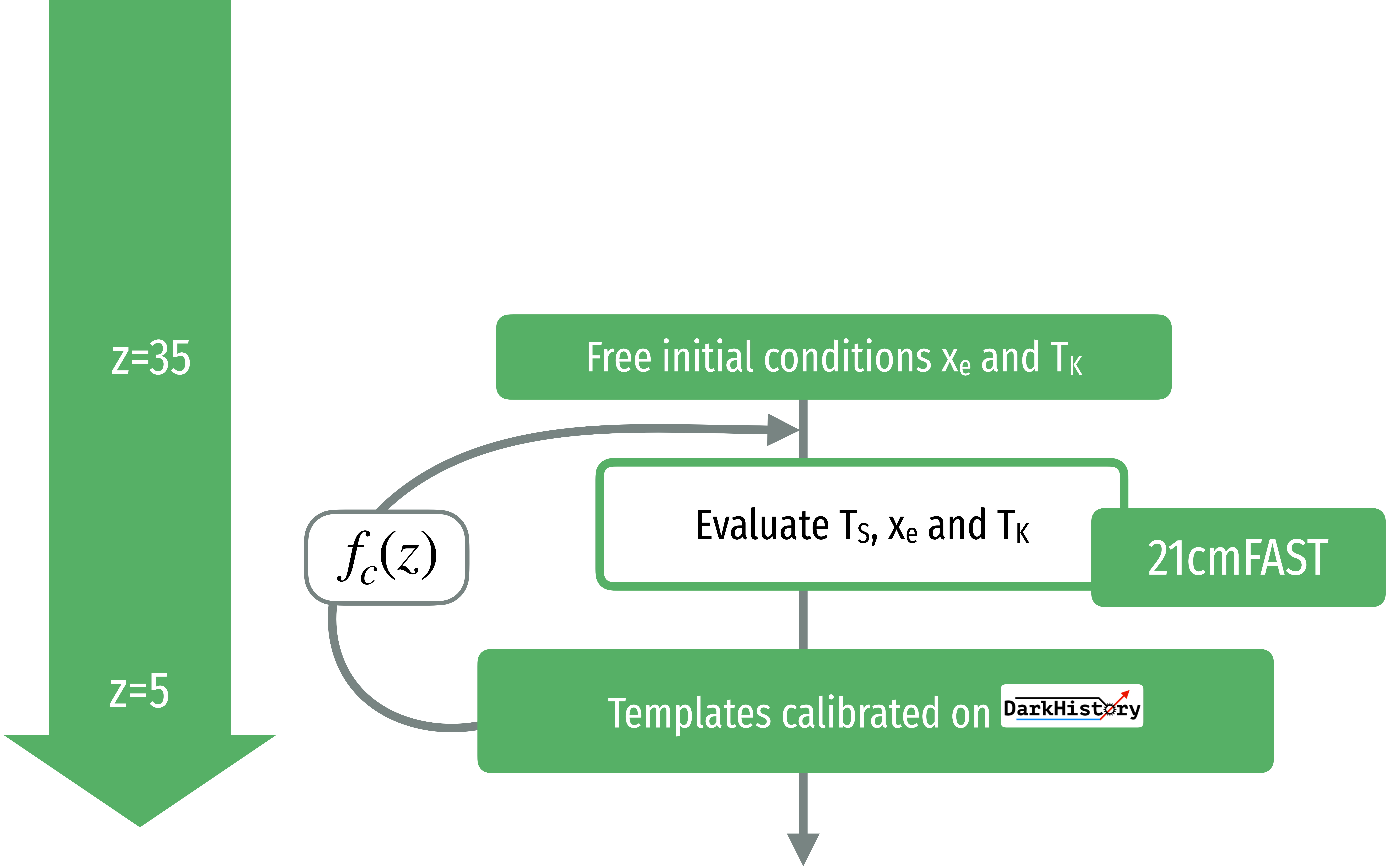
work on a specific case

We do not include spatial and density dependencies in the deposition fractions

(Future work by DarkHistory developers)

# Let us focus on decaying dark matter

# How to perform a MCMC with 21 cm power spectrum sensitivity?


z=35
z=5
Free initial conditions $x_e$ and $T_K$
$f_c(z)$
Evaluate $T_S$, $x_e$ and $T_K$
21cmFAST
Templates calibrated on DarkHistory

# Our template analysis in 7 steps

# 1 We run a sample of > 1000 cases

with DarkHistory
(without backreation)

$$f_c(z) = f_c[z, \mathbf{X}_{\rm std}(z)]$$

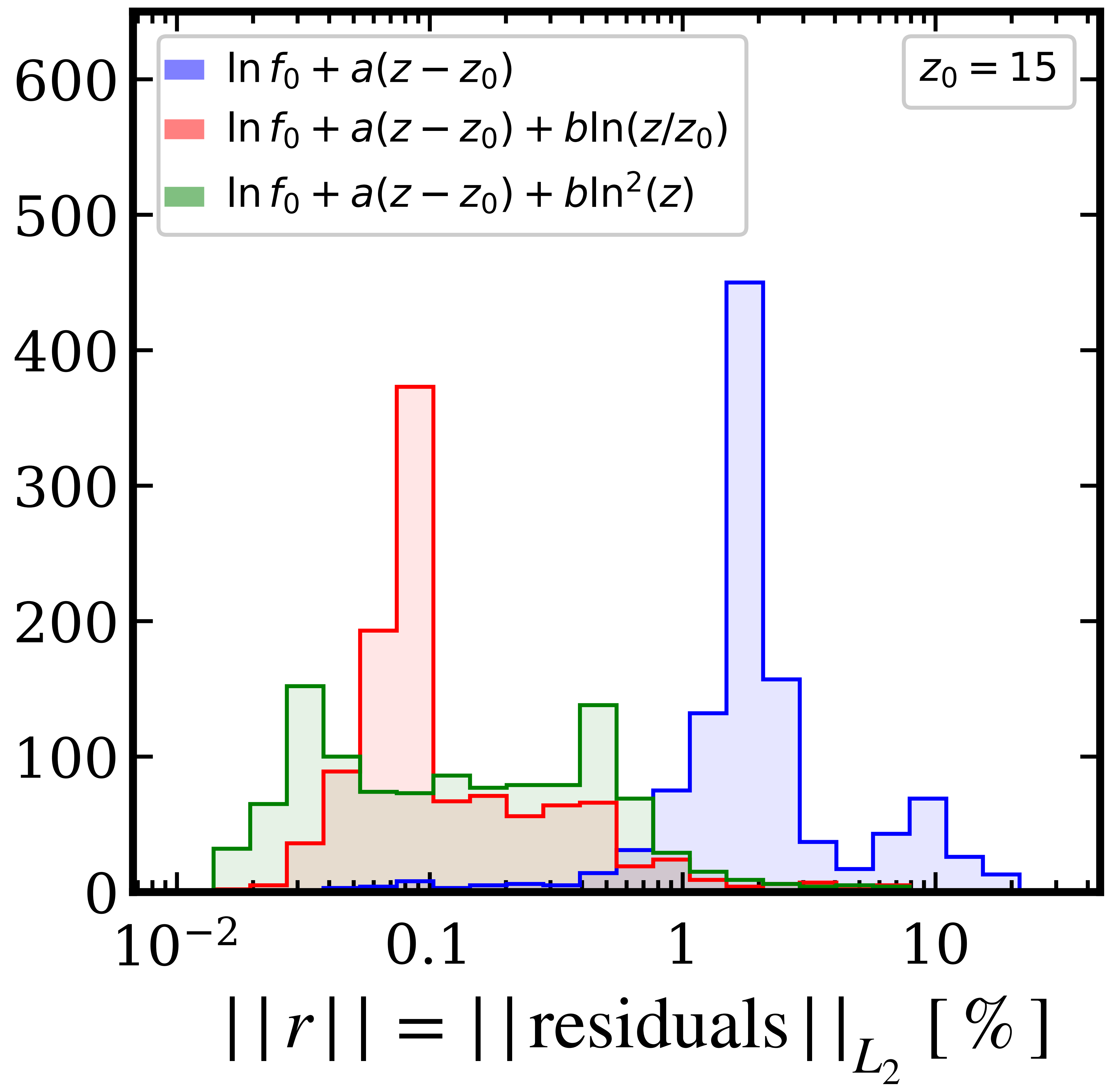
$$\mathbf{X}(z) \neq \mathbf{X}_{\rm std}(z)$$

# 2 We find a good template to fit $f_{heat}$

(dominant source of exotic energy inj.)

$$f_{\rm heat}(z) = f_0 e^{-a(z-z_0)} \left(\frac{z}{z_0}\right)^b$$

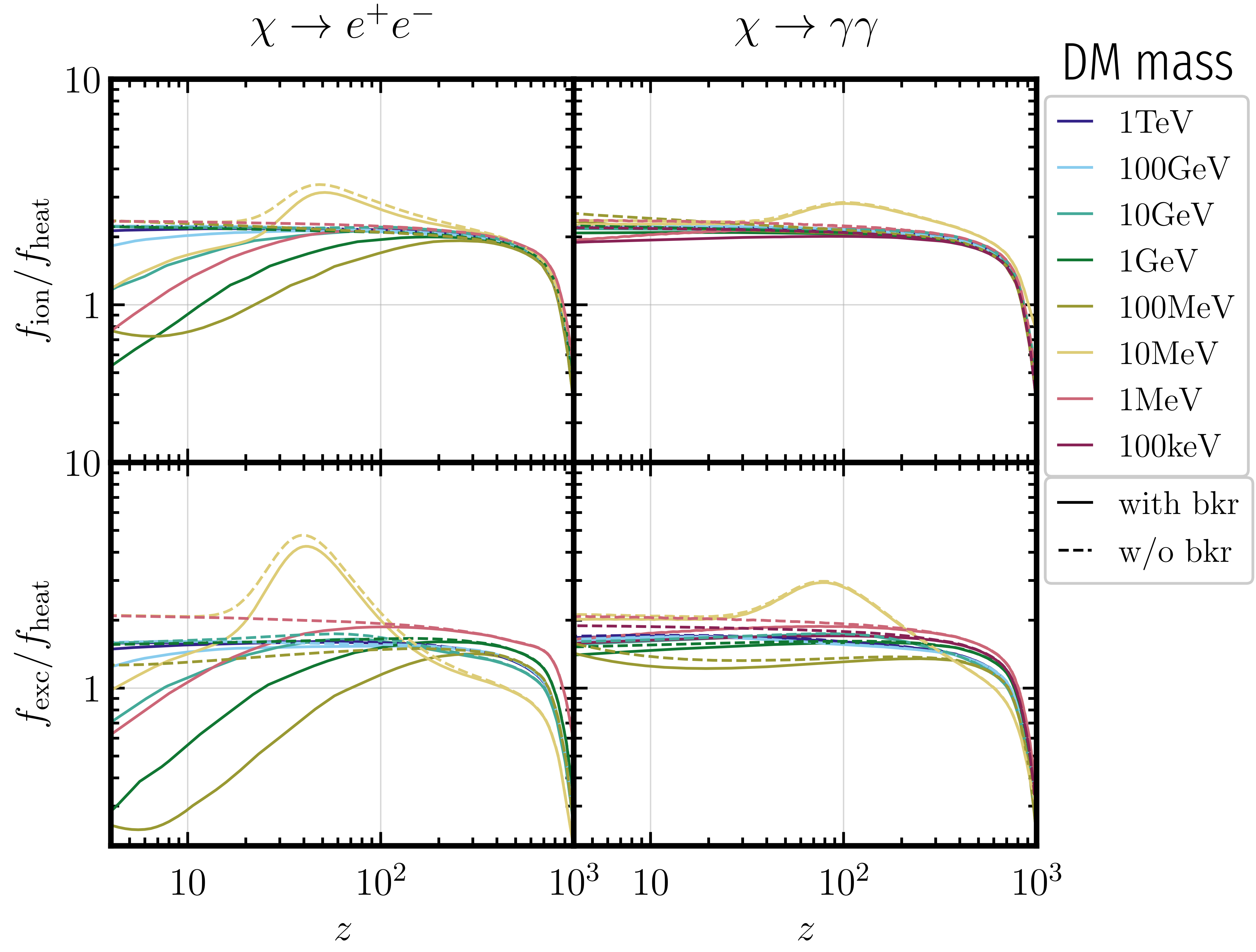
[Facchinetti et al, in prep.]



# 3 We evaluate $f_{ion}$ and $f_{exc}$ from $f_{heat}$

$$f_{ion}(z) \propto f_{heat}(z)$$
$$f_{exc}(z) \propto f_{heat}(z)$$

[Facchinetti et al, in prep.]

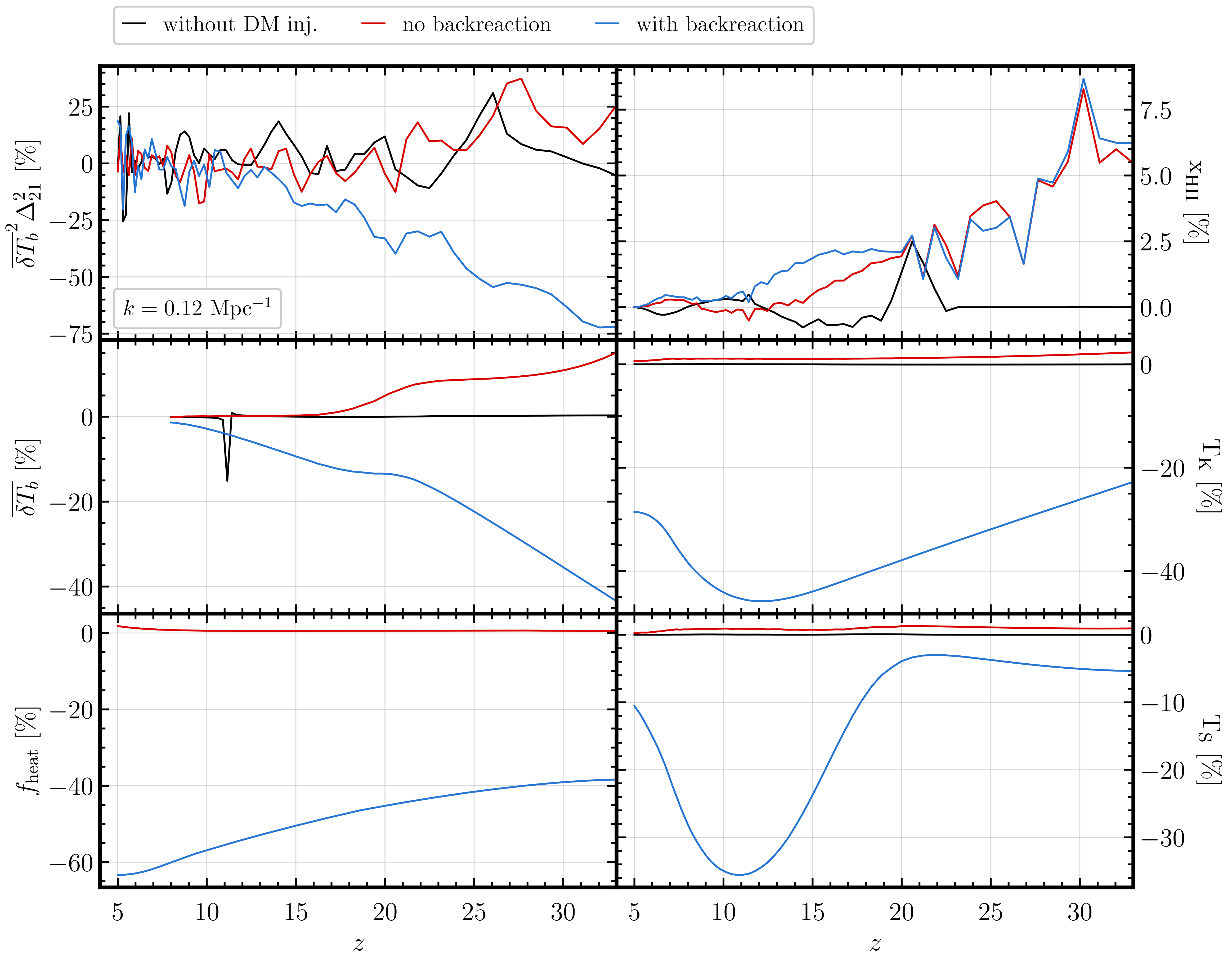


# 4 We check the accuracy of the method

$$f_{\text{heat}}(z) = f_0 e^{-a(z-z_0)} \left(\frac{z}{z_0}\right)^b$$

Residuals

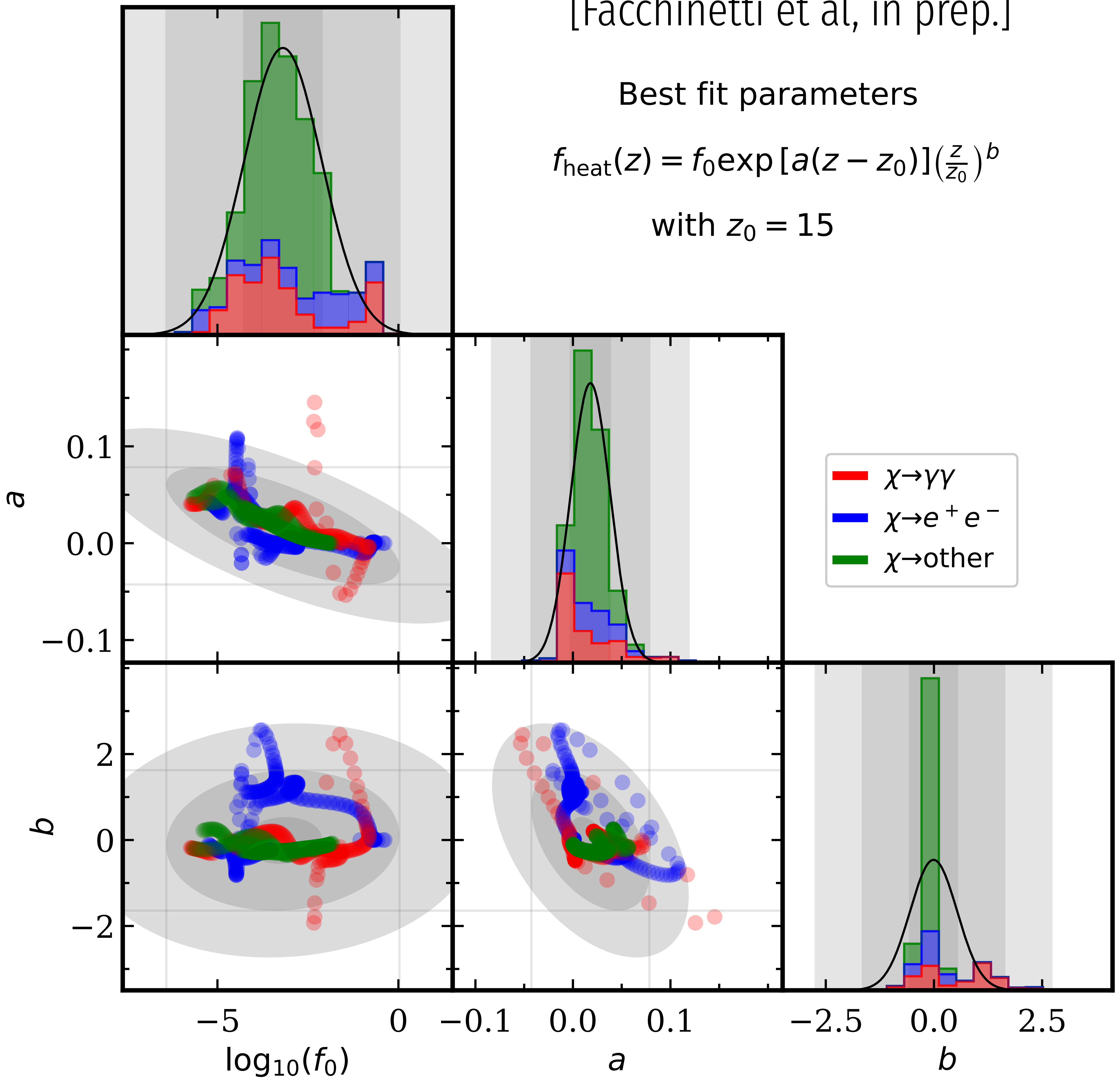
[Facchinetti et al, in prep.]



# 5 We find the distribution of best fit

$$f_{\rm heat}(z) = f_0 e^{-a(z-z_0)} \left(\frac{z}{z_0}\right)^b$$

[Facchinetti et al, in prep.]



# 6 We perform a MCMC with 21CMMC

New parameters to vary:

$$[\tau_\chi, f_0, a, b, x_e(z=35), T_\mathrm{K}(z=35)]$$

Plots coming soon ...

# 7 We map back the results to any model

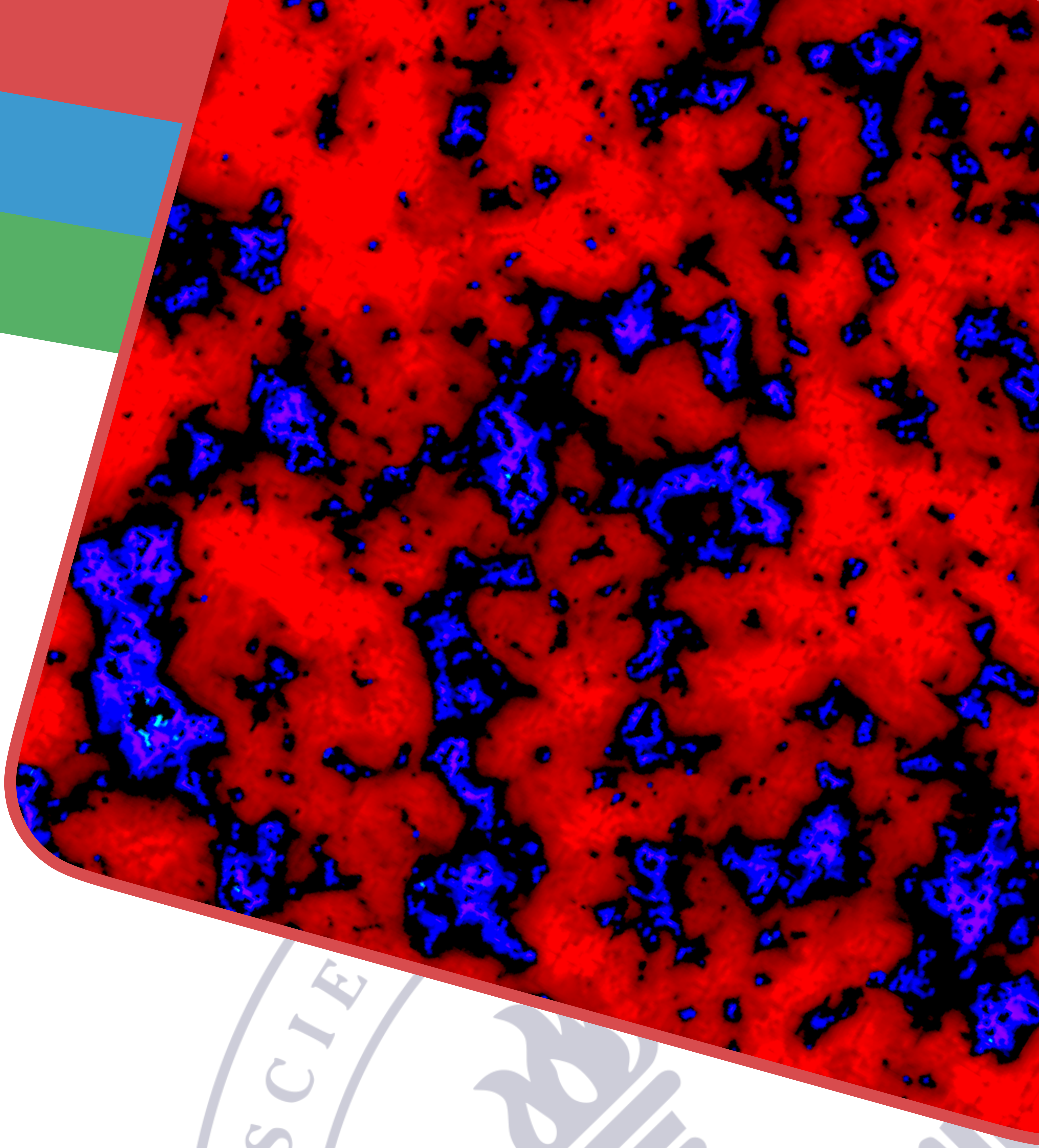
$$[\tau_\chi, f_0, a, b, x_e(z=35), T_\mathrm{K}(z=35)]$$

Neural network

$$[\tau_\chi, m_\chi, \mathrm{primaries}]$$

# Conclusions

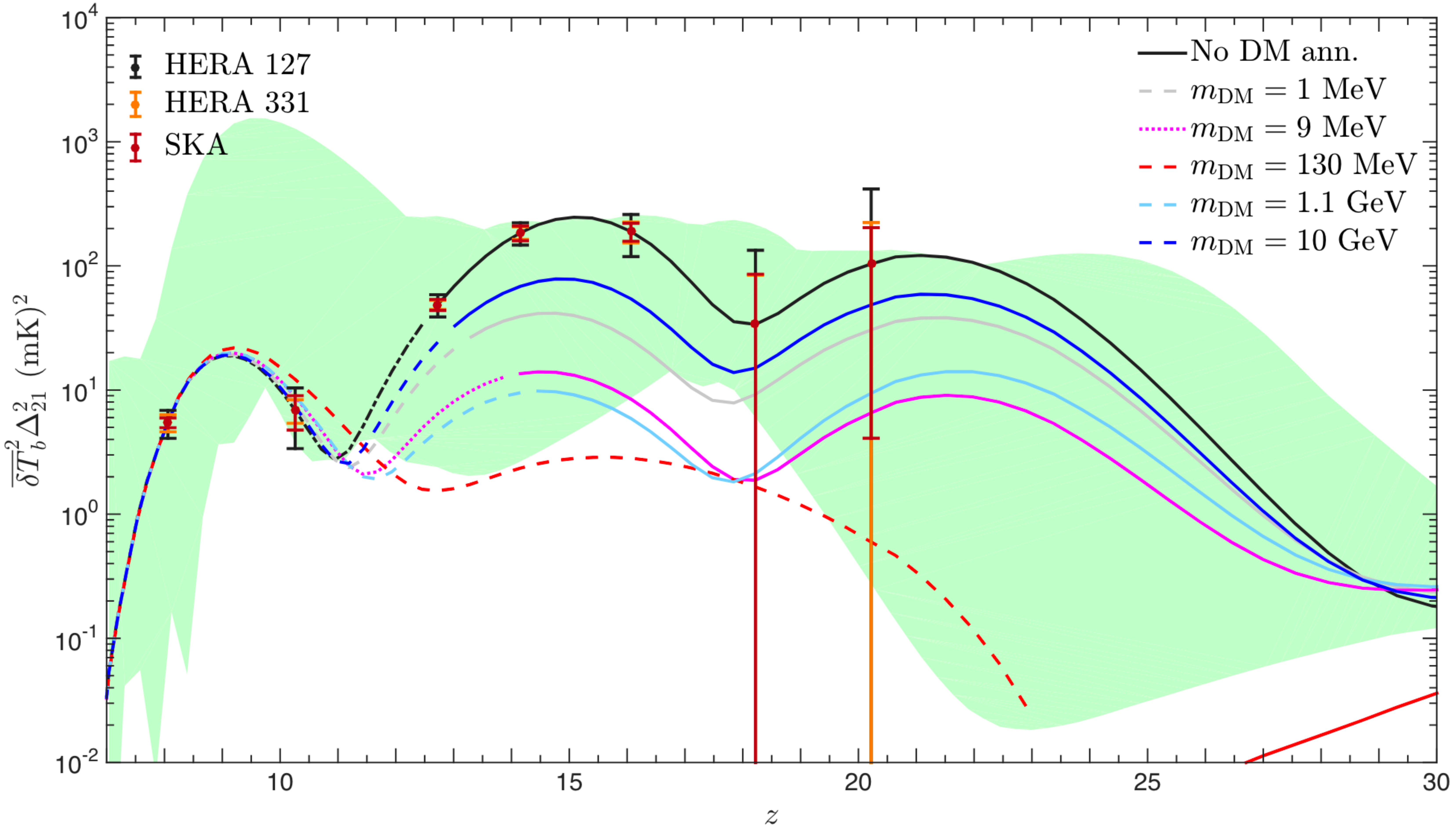
- The 21 cm power spectrum can be an excellent probe of dark matter energy injection (in particular through decay)
- We have developed exo21cmFAST to numerically solve for the 21 cm power spectrum with exotic energy injection
- **We are now evaluating the sensitivity of upcoming instruments (STAY TUNED!)**



gaetan.facchinetti@ulb.be

# Back-up slides

[Lopez-Honorez et al. 2016]



[Liu et al. 2021]