Probing **Dark Matter Energy Injection** in the Cosmic Dawn with the **21-cm Power Spectrum**

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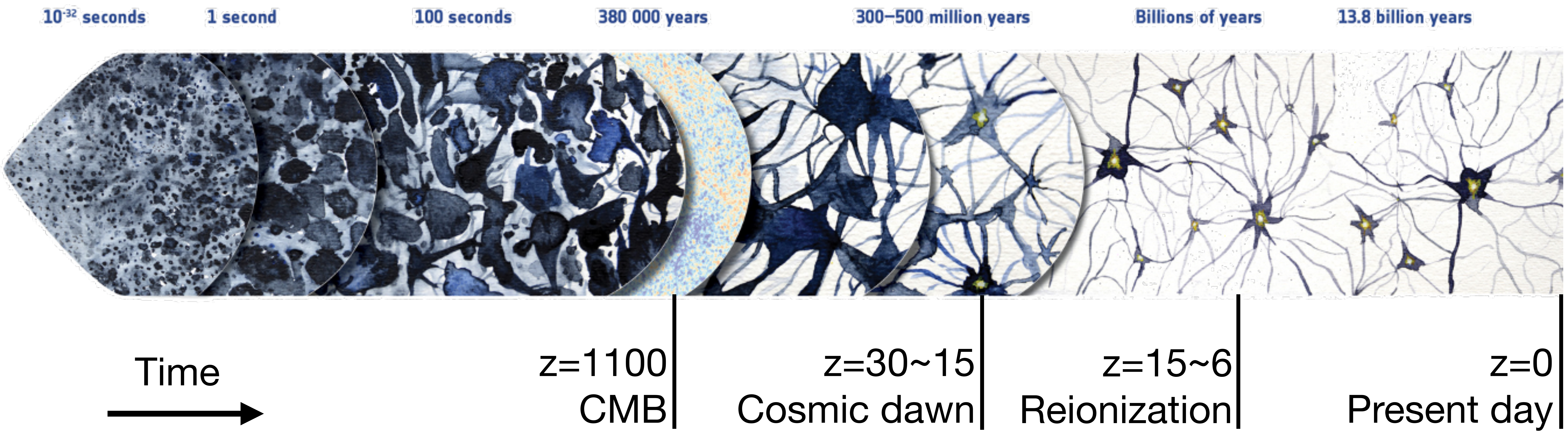
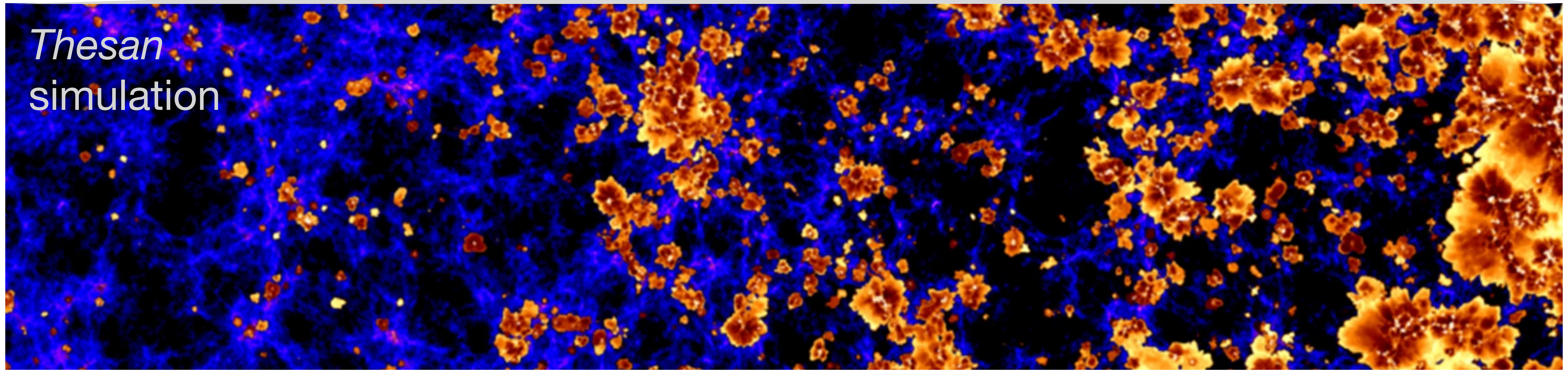
Based on work by **YS**, Joshua Foster, Hongwan Liu, Julian Muñoz, and Tracy Slatyer [2312.11608] and *in prep.*

DPF-Pheno 2024



The first stars produce X-ray and UV, heating and reionizing the universe.



So can dark matter and other exotic energy injection!

Energy injection changes IGM thermal and ionization states, radiation field states…

Observable: the 21-cm line

Hydrogen atom's hyperfine transition emits the 21-cm line

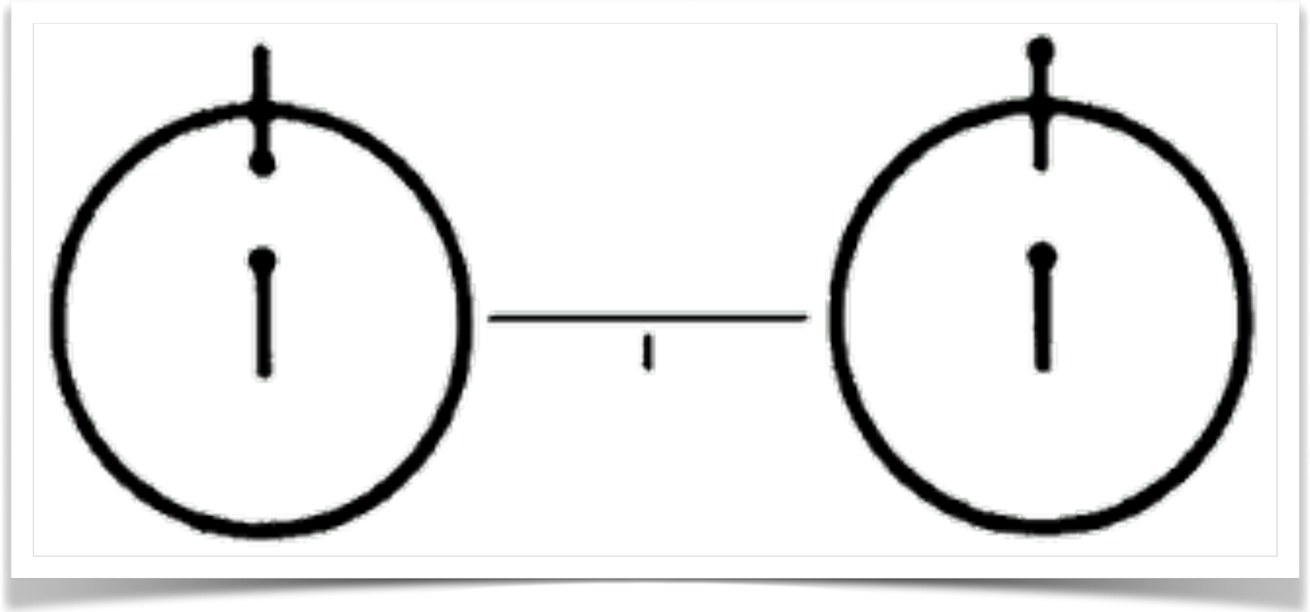
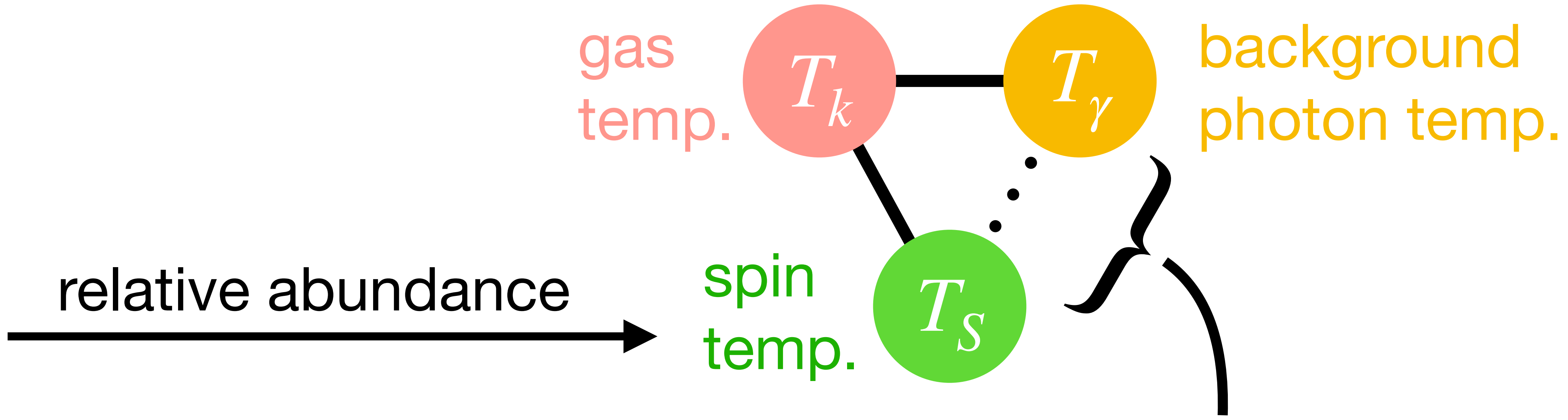
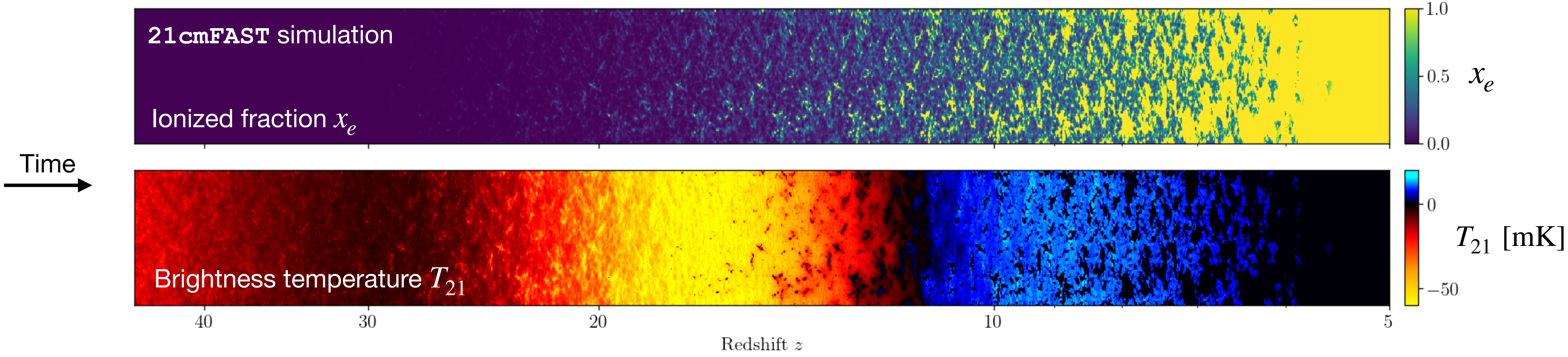


diagram on board the *Voyagers*

Emission / absorption depends on difference between T_S and background T_γ



$$T_{21} \propto x_H (T_S - T_\gamma)/T_S$$

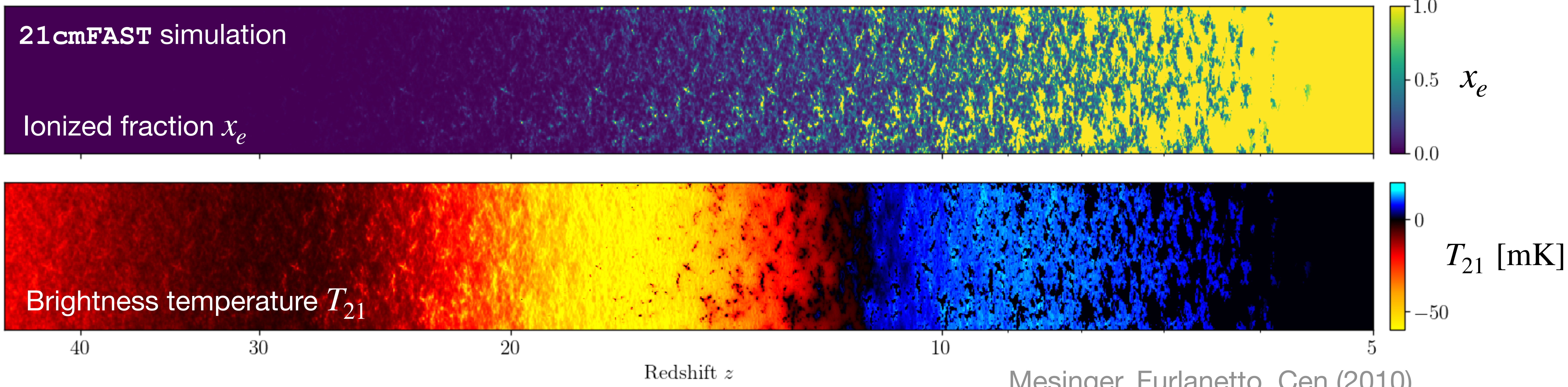


DM21cm: A new simulation

A **python** code package for dark matter energy injection in a homogeneous universe (from before the CMB to reionization)
https://github.com/hongwanliu/DarkHistory

Liu, Ridgway, Slatyer (2019)

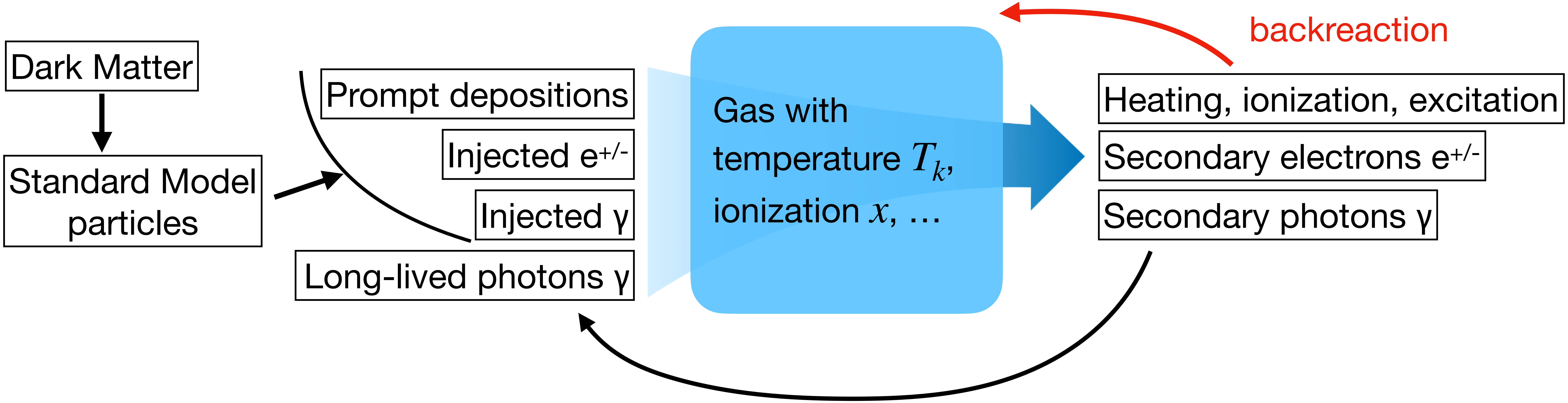
energy injection



Mesinger, Furlanetto, Cen (2010)

DM21cm: A new simulation

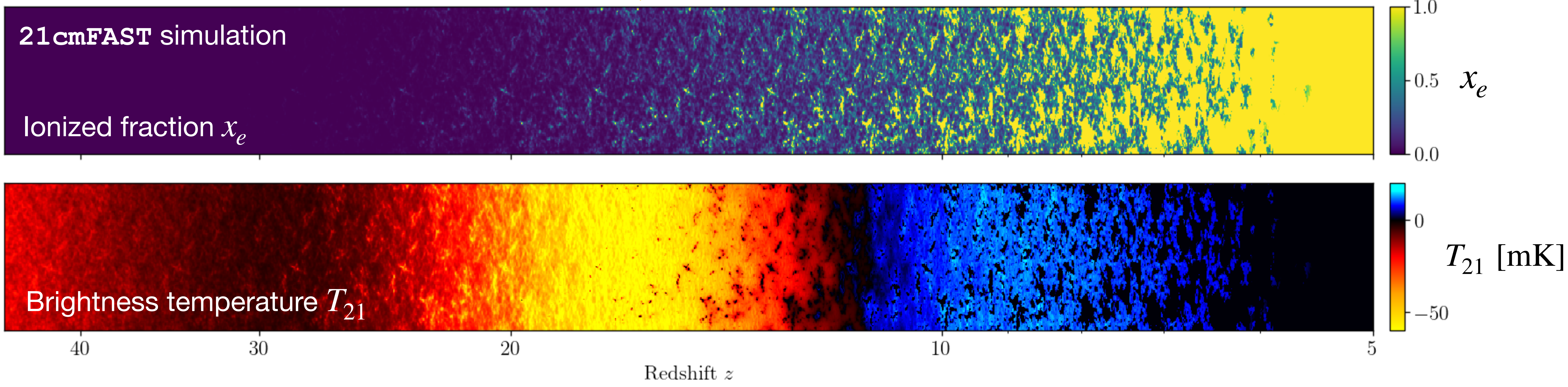
DarkHistory γ and $e^{+/-}$ processes



DM21cm: A new simulation

DarkHistory evolves the IGM thermal state and radiation in a homogeneous universe.

energy injection



DM21cm: A new simulation

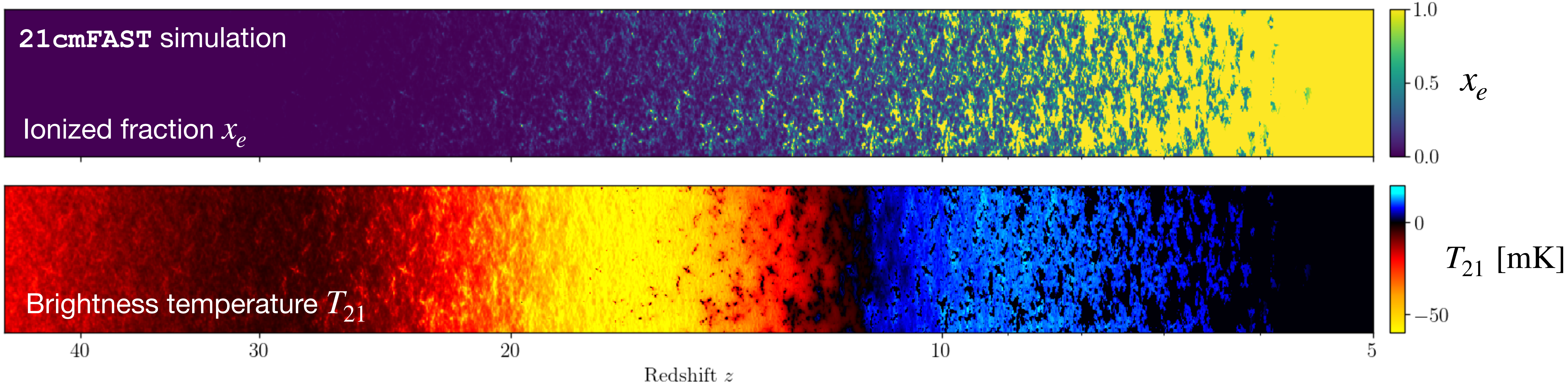
21cmFAST evolves the IGM thermal state in a reionizing, inhomogeneous universe:

$$\frac{dx_e(z,\mathbf{x})}{dz} = \frac{dt}{dz}\left[\Lambda_{\rm ion} - \alpha_A C x_e^2 n_A f_{\rm H}\right] + \frac{dx_e^{\rm DM}}{dz}$$

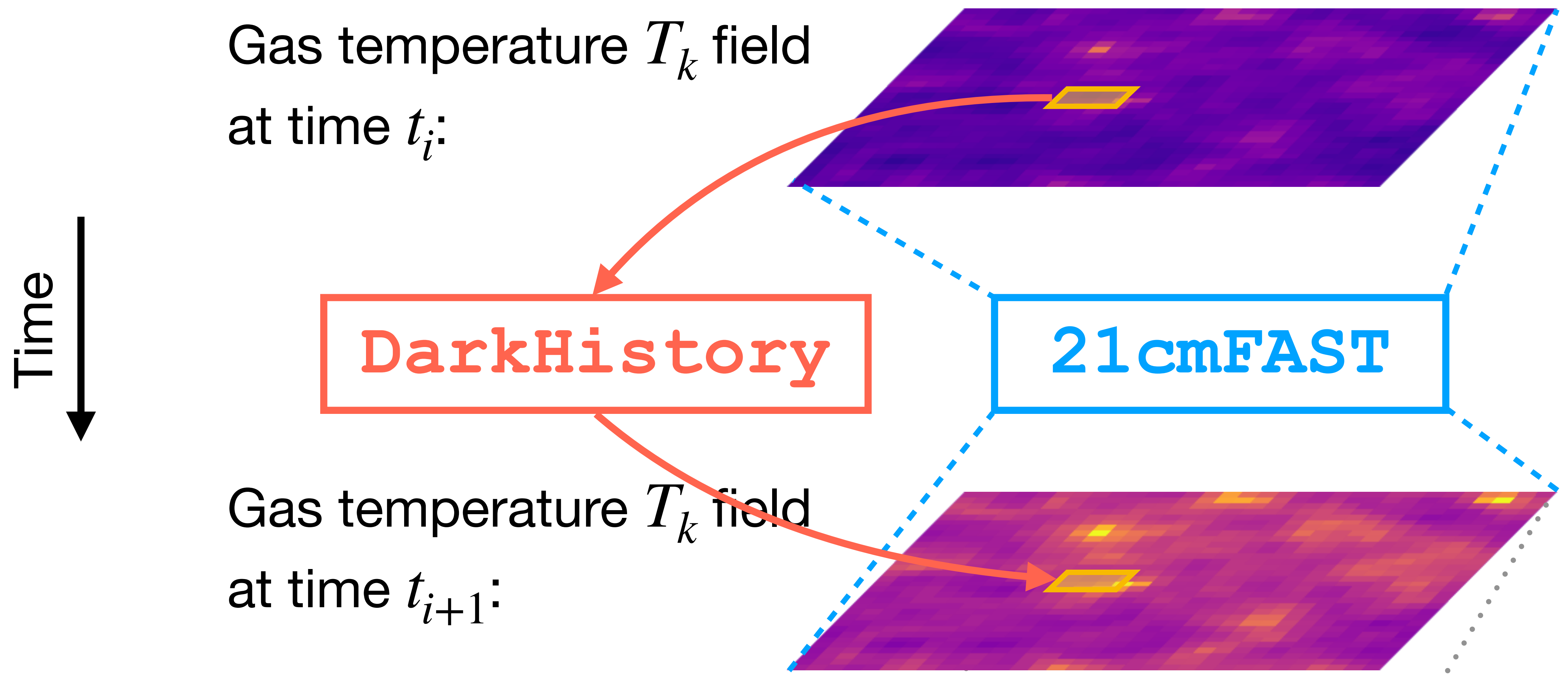
$$\frac{dT_k(z,\mathbf{x})}{dz} = \frac{2}{3k_B(1+x_e)}\frac{dt}{dz}\sum_p \epsilon_p + \frac{2T_k}{3n_A}\frac{dn_A}{dz} - \frac{T_k}{1+x_e}\frac{dx_e}{dz} + \frac{dT_k^{\rm DM}}{dz}$$

$$J_\alpha \to J_\alpha + J_\alpha^{\rm DM}$$

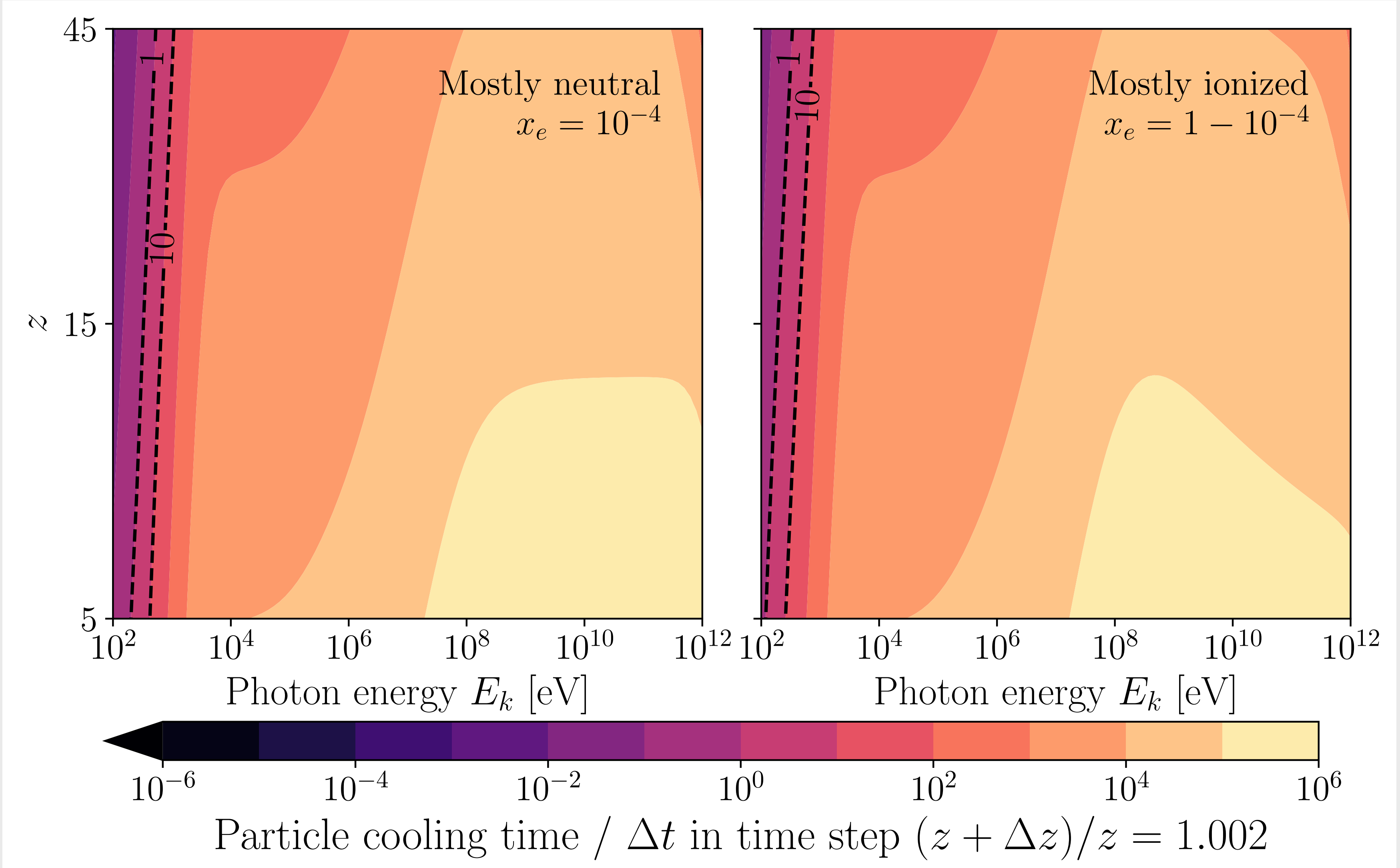
exotic energy injection terms



Adding DarkHistory to 21cmFAST



Photon transparency:

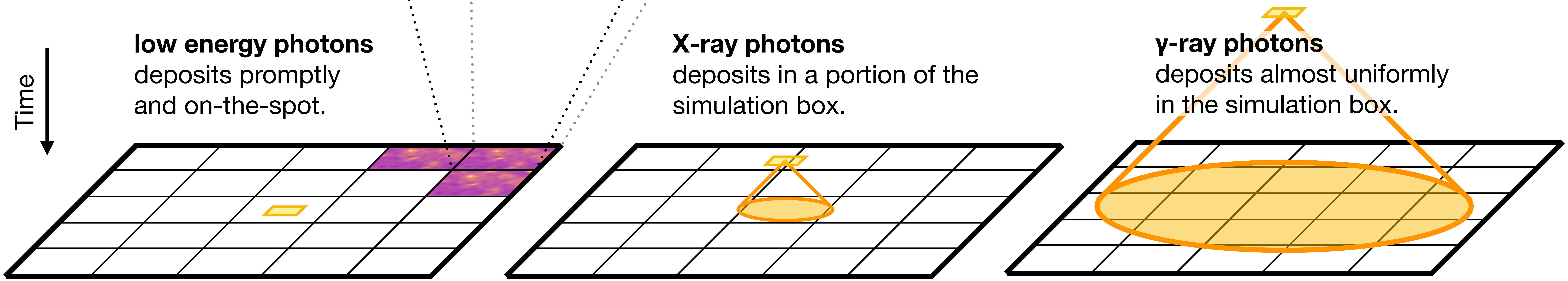


Photons can be treated in 3 regimes:

low energy photons
deposits promptly
and on-the-spot.

X-ray photons
deposits in a portion of the
simulation box.

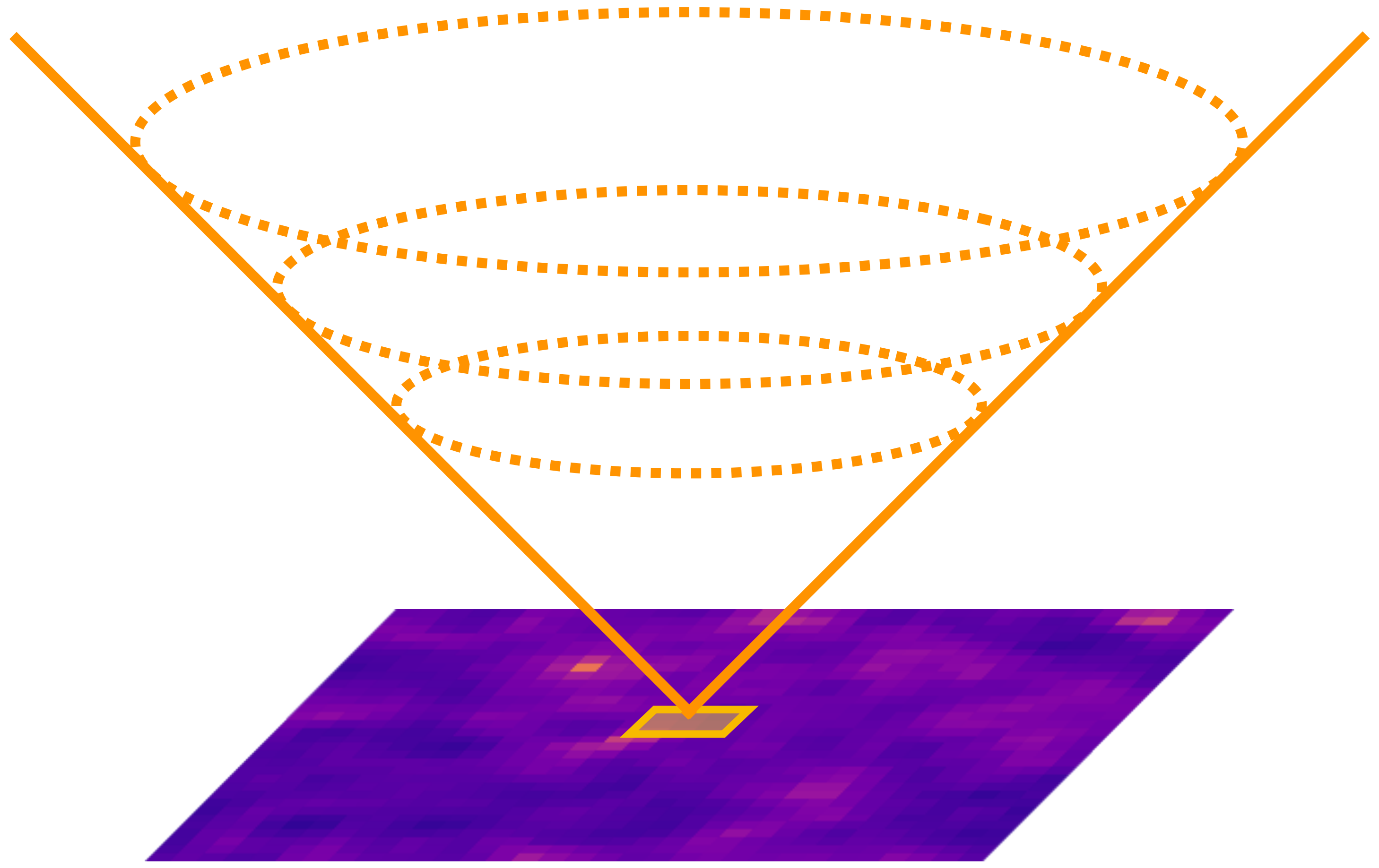
γ-ray photons
deposits almost uniformly
in the simulation box.



Universe simulated with periodic BC box

X-ray photon treatment

From the receiving site, need to look back along the lightcone.



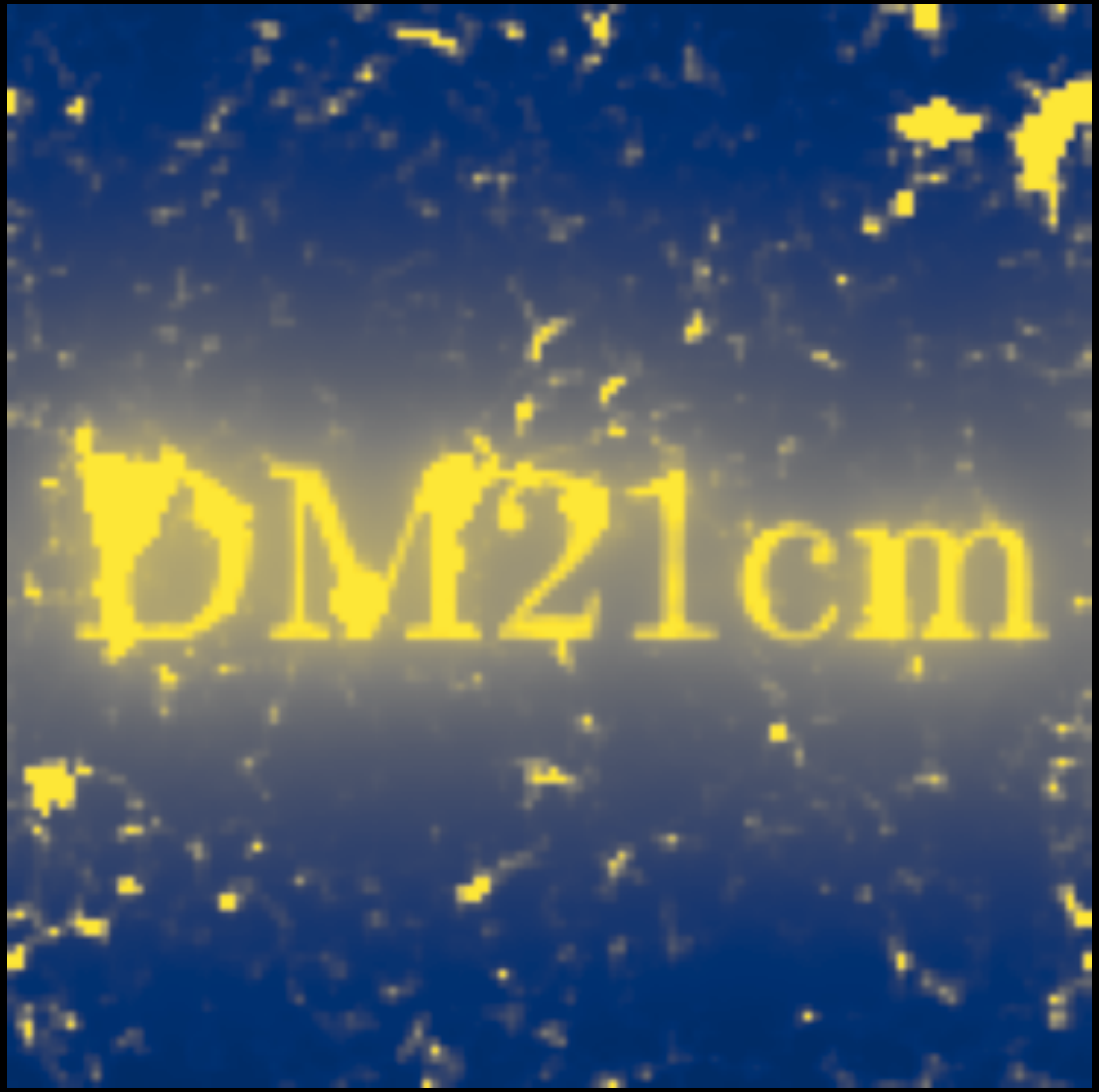
Need to perform convolution of *X*-ray luminosity with spherical filters.

$$\frac{dN_X}{dEd\tau}(z_i, \vec{x}x, E\,|\,z_e)$$

Use GPU to accelerate convolution & interpolation. Greatly speeds up run time.

* Not actual GPU used

X-ray deposition in action



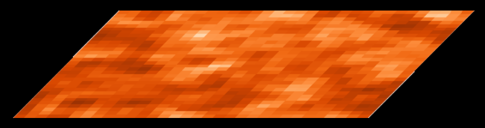
DM21cm works with your favorite model!

```python
class CustomInjection:
    """Handles DarkHistory and DM21cm."""

    def __init__(self):
        pass

    def inj_rate(self, z):
        pass # [1 / pcm^3 s]

    def inj_power(self, z):
        pass # [eV / pcm^3 s]

    def inj_phot_spec(self, z, **kwargs):
        pass # [1 / eV pcm^3 s]

    def inj_elec_spec(self, z, **kwargs):
        pass # [1 / eV pcm^3 s]

    def inj_phot_spec_box(self, z, **kwargs):
        pass # [1 / eV pcm^3 s] [1]

    def inj_elec_spec_box(self, z, **kwargs):
        pass # [1 / eV pcm^3 s] [1]
```

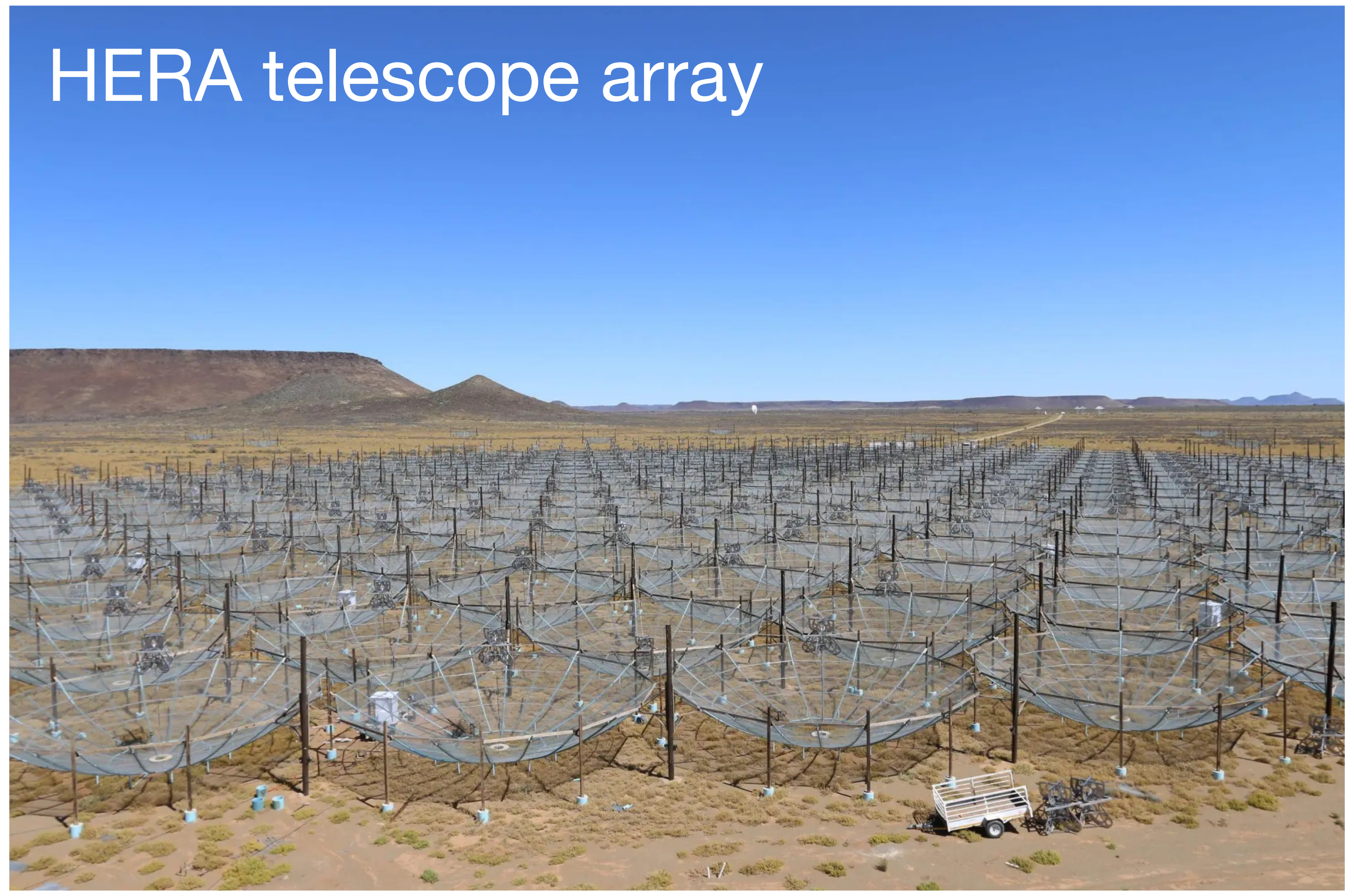
Github:
github.com/yitiansun/DM21cm

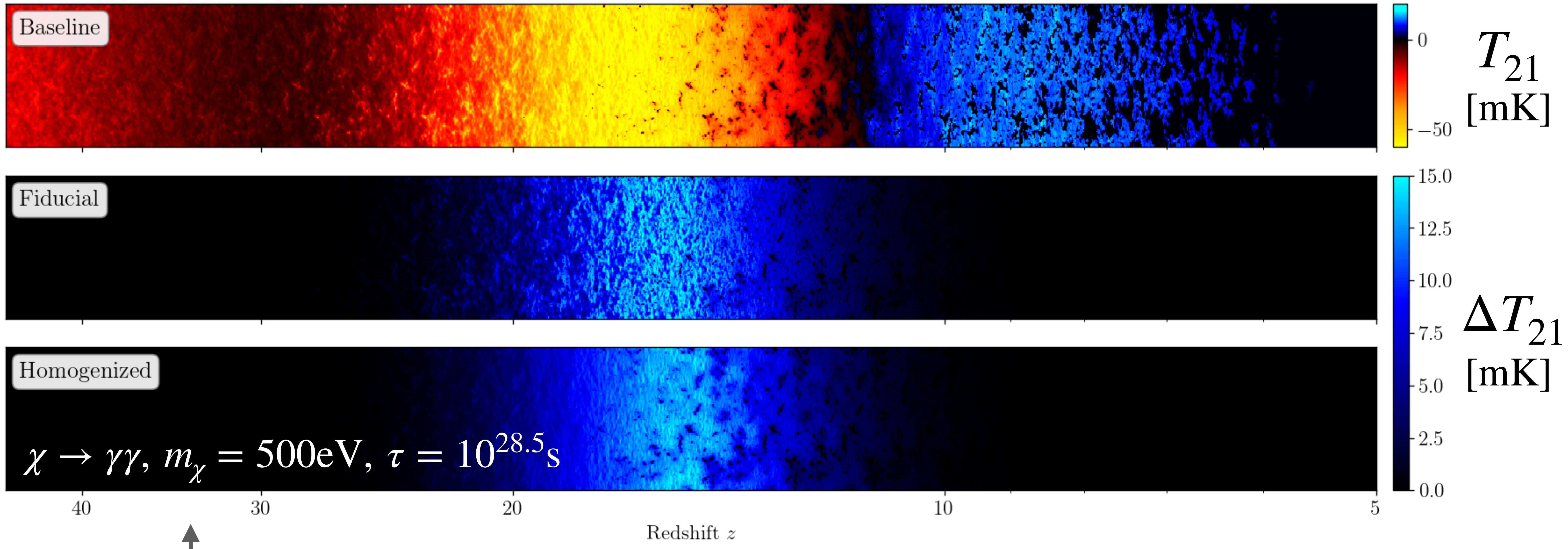
Examples:
github.com/yitiansun/DM21cm/blob/main/examples

Homogeneous rates 

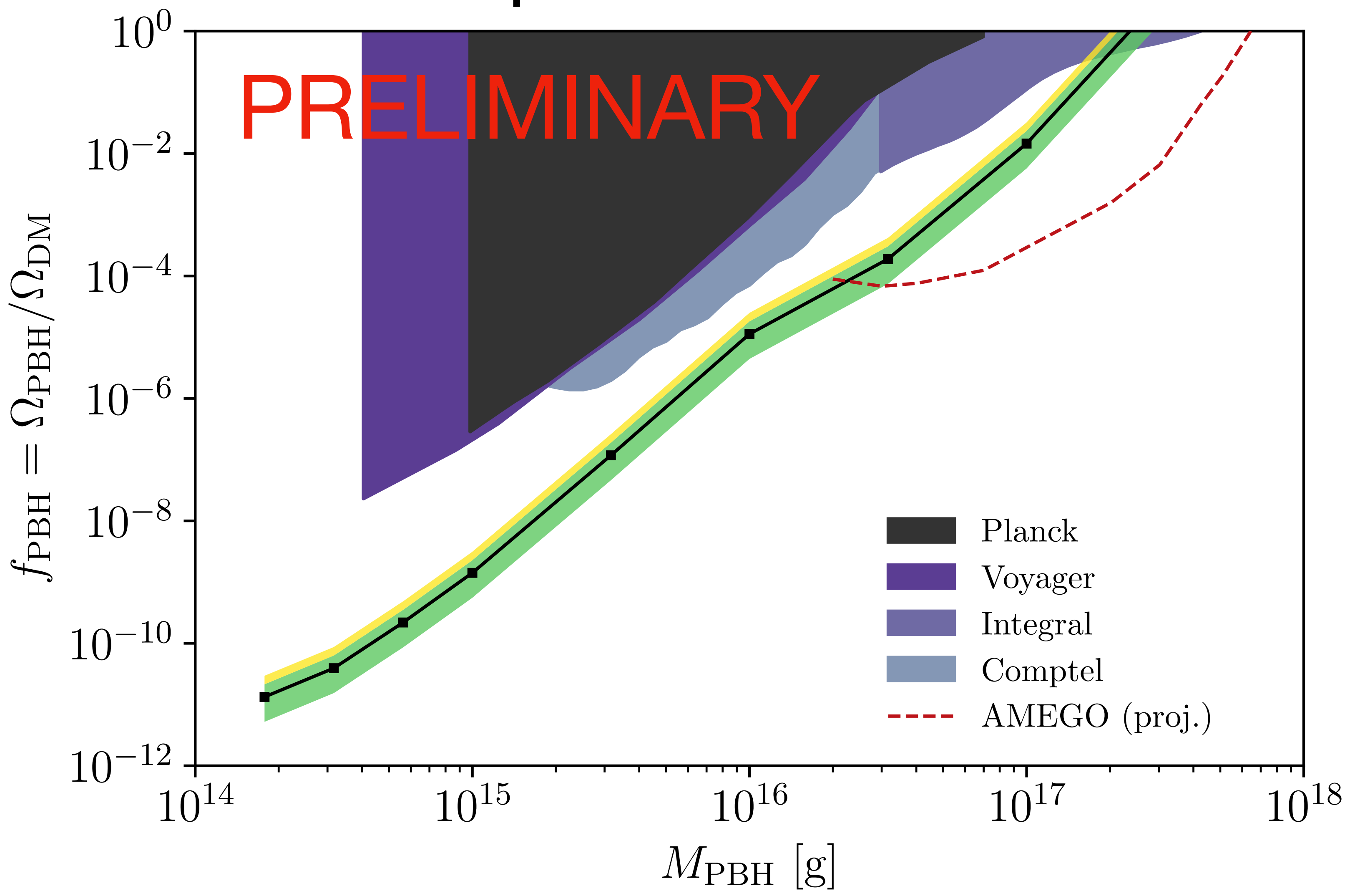
Inhomogeneous rates 

HERA limits projections on decays

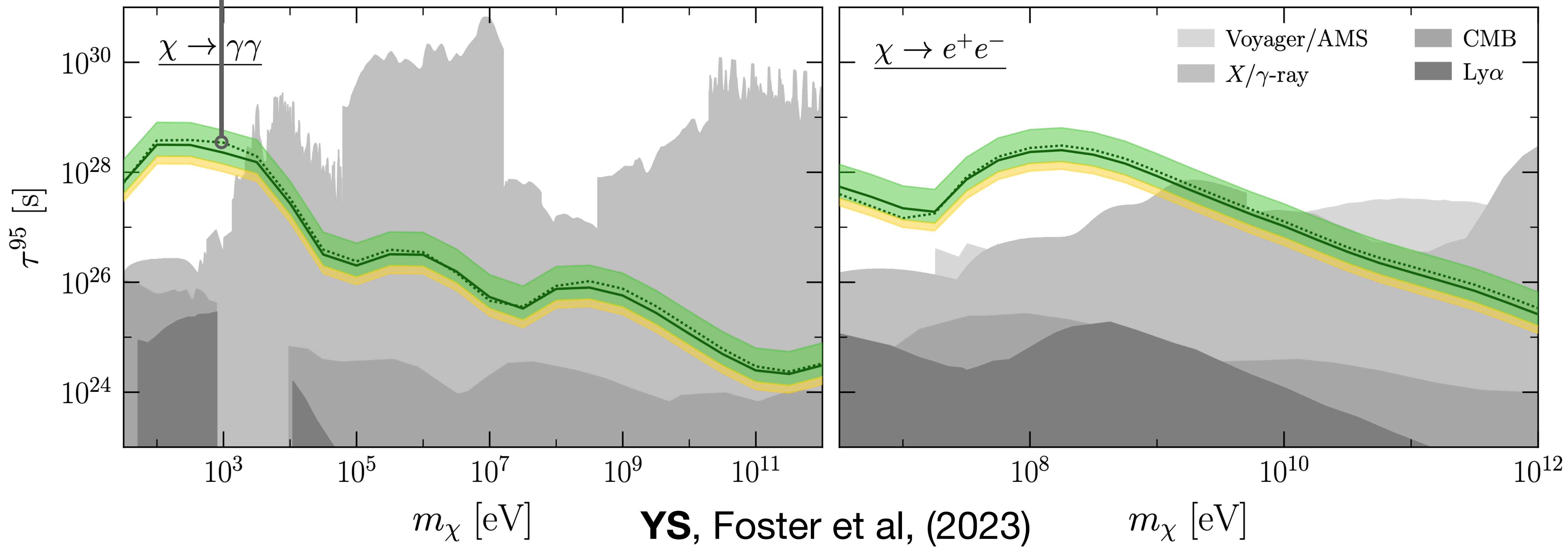




PBH evaporation limits



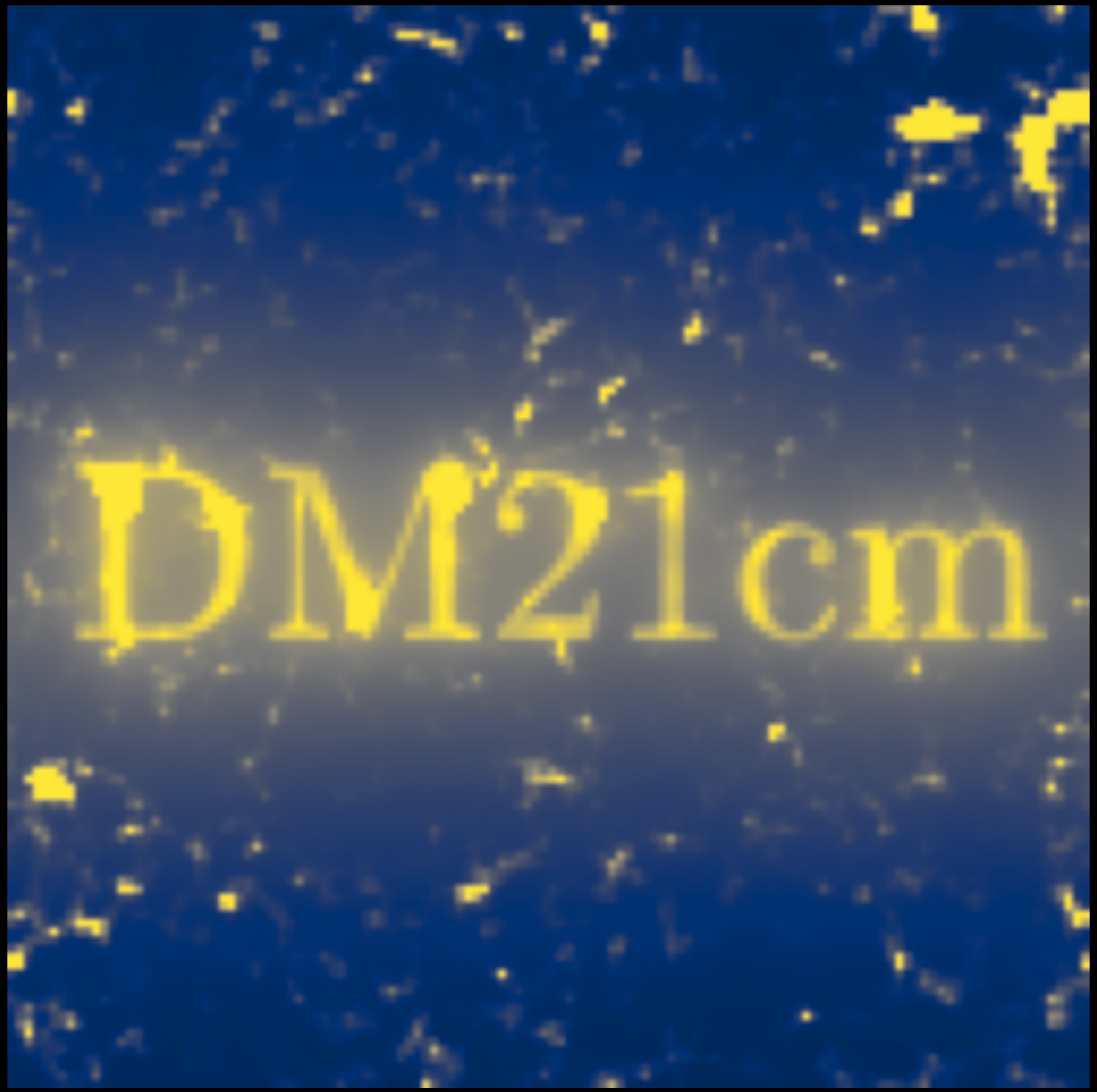
DM monochromatic decays



YS, Foster et al, (2023)

Summary

- We built **`DM21cm`**: a simulation for dark matter energy injection during reionization.
- It self-consistently deposit energy into the IGM, and tracks propagating photons.
- We forecast HERA's sensitivity on DM decays. Stay tuned for more.
- Many avenues for future improvements.



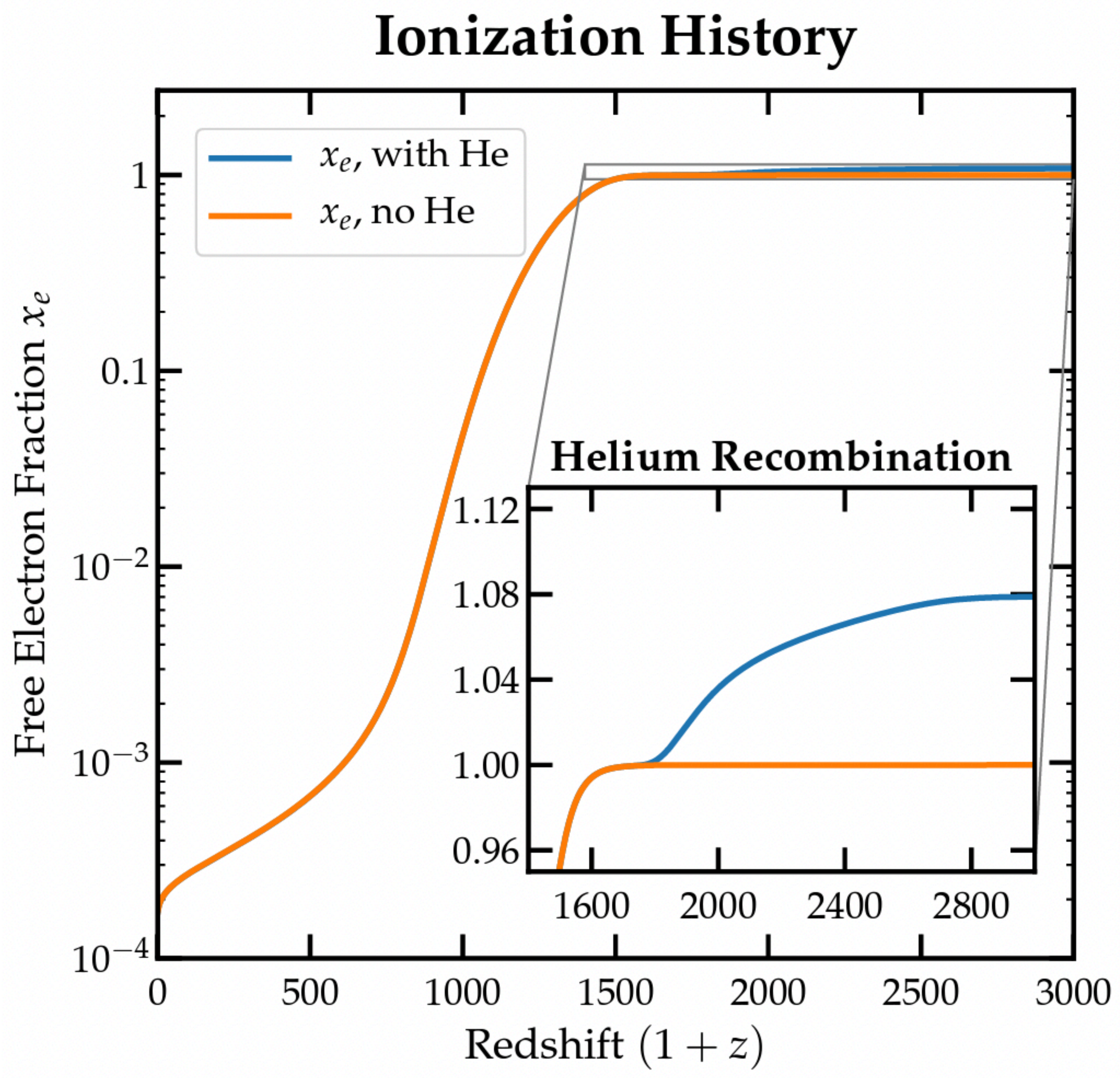
Thank you!

Backup slides

DarkHistory

A **python** code package available at https://github.com/hongwanliu/DarkHistory

- In a homogeneous universe, calculates exotic energy injection and deposition from before CMB (z=3000) to reionization (given reionization model).
- Handles injected photons and electrons from 10^{-4} eV to 10^{12} eV kinetic energy.
- Self-consistently modifies IGM temperature, ionization (backreaction).
- Tracks propagating photons as a photon bath.



Liu, Ridgway, Slatyer (2019)

DarkHistory γ and $e^{+/-}$ processes

γ :

- Compton scatter -> γ, e^-
- Pair produce -> e^+, e^-
- Heat, ionize, excite matter
- Just redshift

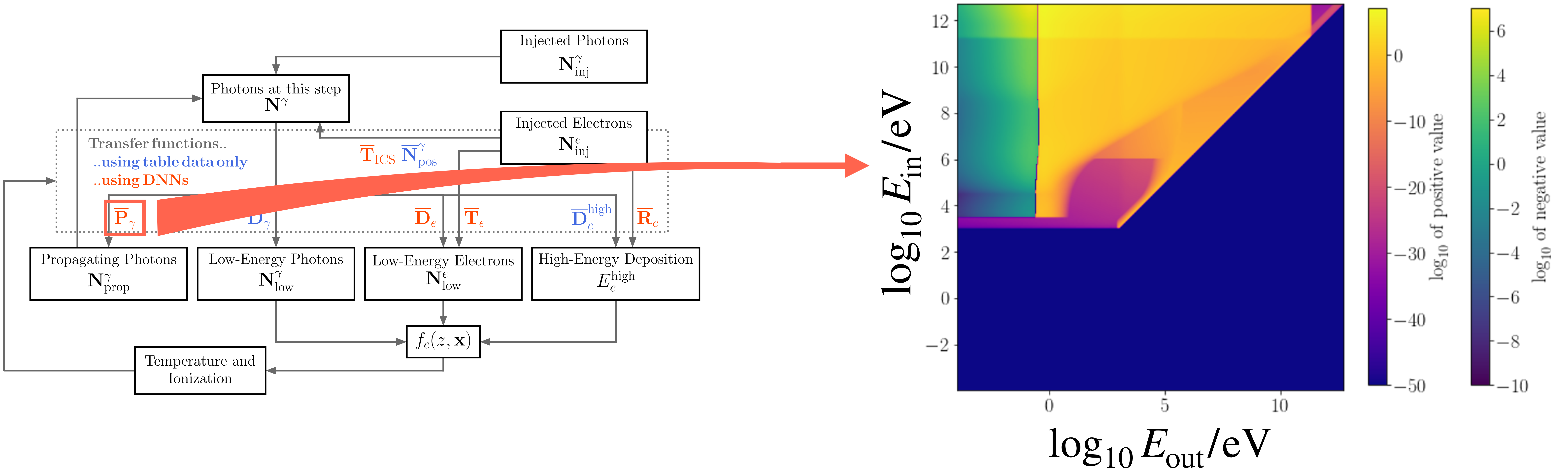
e^- :

- Inverse Compton scatter -> γ, e^-
- Heat, ionize, excite matter

e^+ :

- Annihilate with electrons -> γ, γ

DarkHistory particle transfer functions



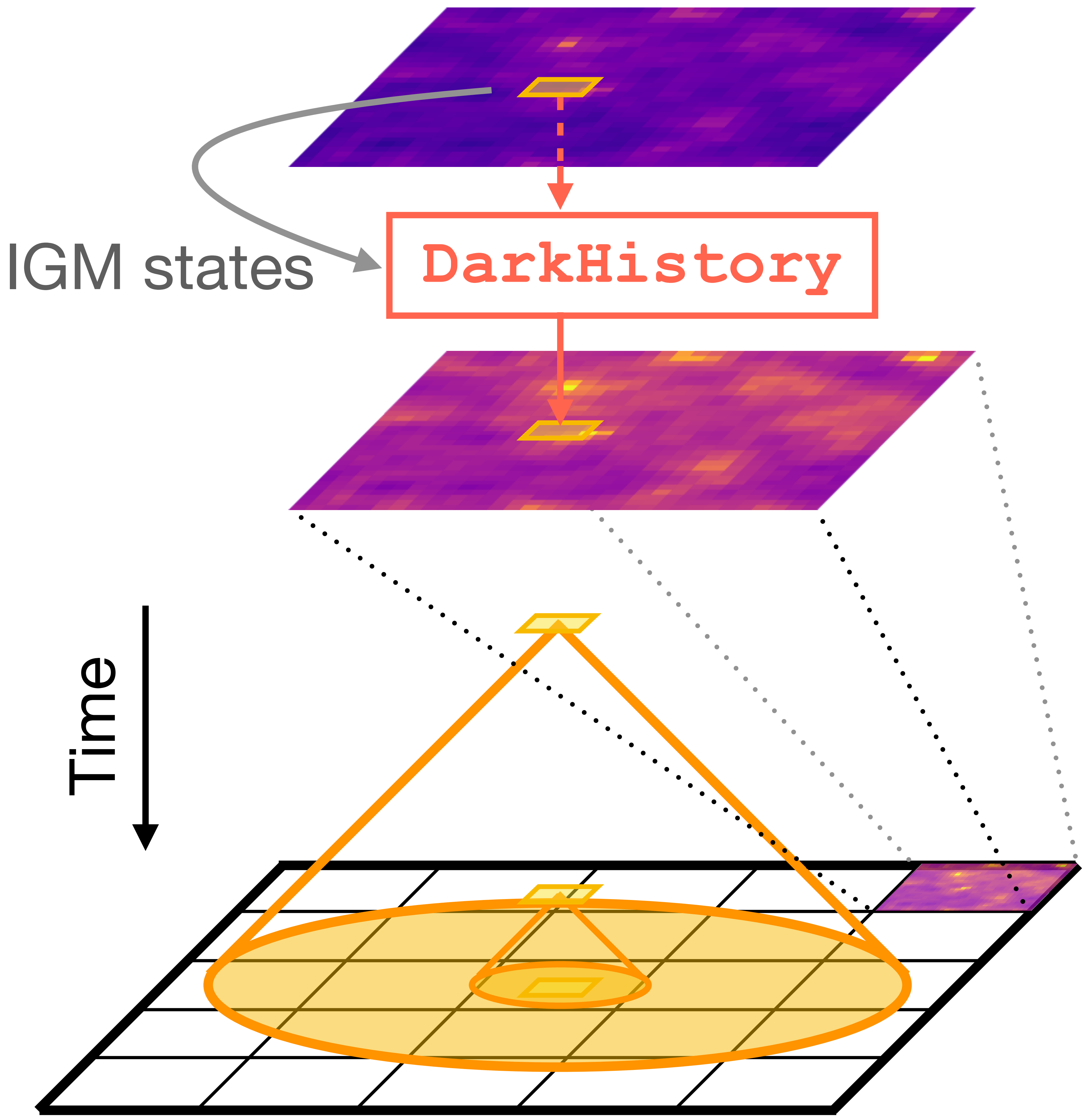
Can dependent on: **YS**, Slatyer (2022)

- $T_{\rm CMB}$
- Ionization levels $x_{\rm HII}$, $x_{\rm HeII}$, $x_{\rm HeIII}$, …
- Local gas overdensity $\delta_{\rm B}$ (new!)

- Transfer functions encode all the physical processes for **`DarkHistory`**.
- Similar ones are generated for energy deposition in **`DM21cm`**.

Plan for **DM21cm**

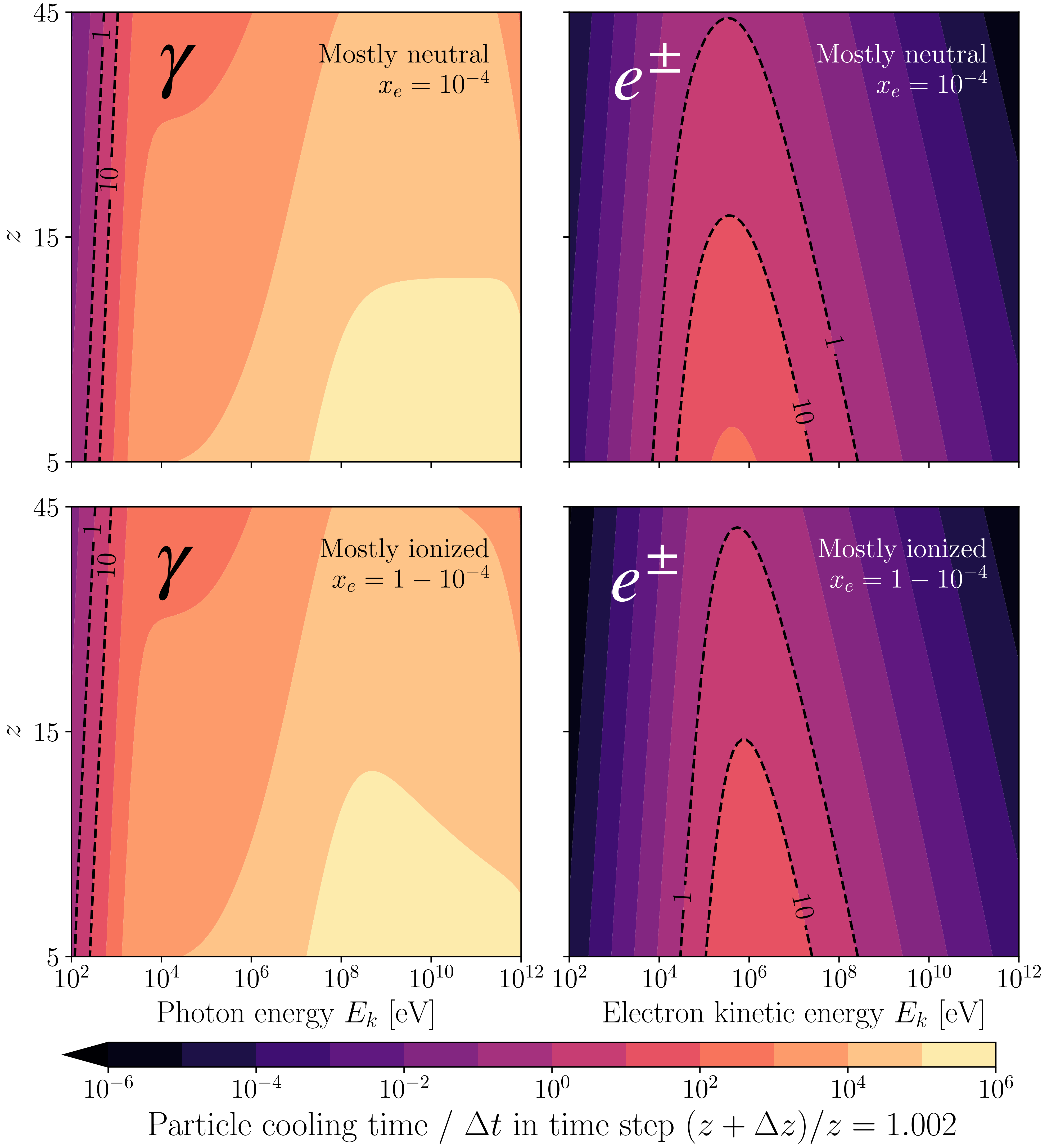
- In order to calculate 21-cm line signal, we need spatially resolved simulations.
- Naively, we can
    - track states of the universe in a periodic box.
    - track long-lived photon intensity field (very expensive!)
- If we don't want to do radiative transfer, we can
    - notice that some photons deposit energy very quickly, while others travel for a long time / space relative to time step / box size.
    - long-lived photons saturate the box quickly, but deposit energy over long period of time. Can model as a homogeneous isotropic bath.
    - What about particles in between?



Transparency window

Photons:

- High energy photons free stream and are long-lived.
- Lowering the energy to ~ keV, opacity quickly turns on as photoionization becomes efficient.
- Low energy photons from 10.2-100 eV ionize/excite IGM efficiently.
- Lower energy photons free stream.



Electrons:

- Do not propagate, as trace amount (10^{-20}G) of the IG magnetic field confines them. Deposit energy on-the-spot.
- We assume they promptly deposit as well. In cases where our constraints are not the strongest, this is a good approximation.
- Future work can account for long-lived localized electrons.

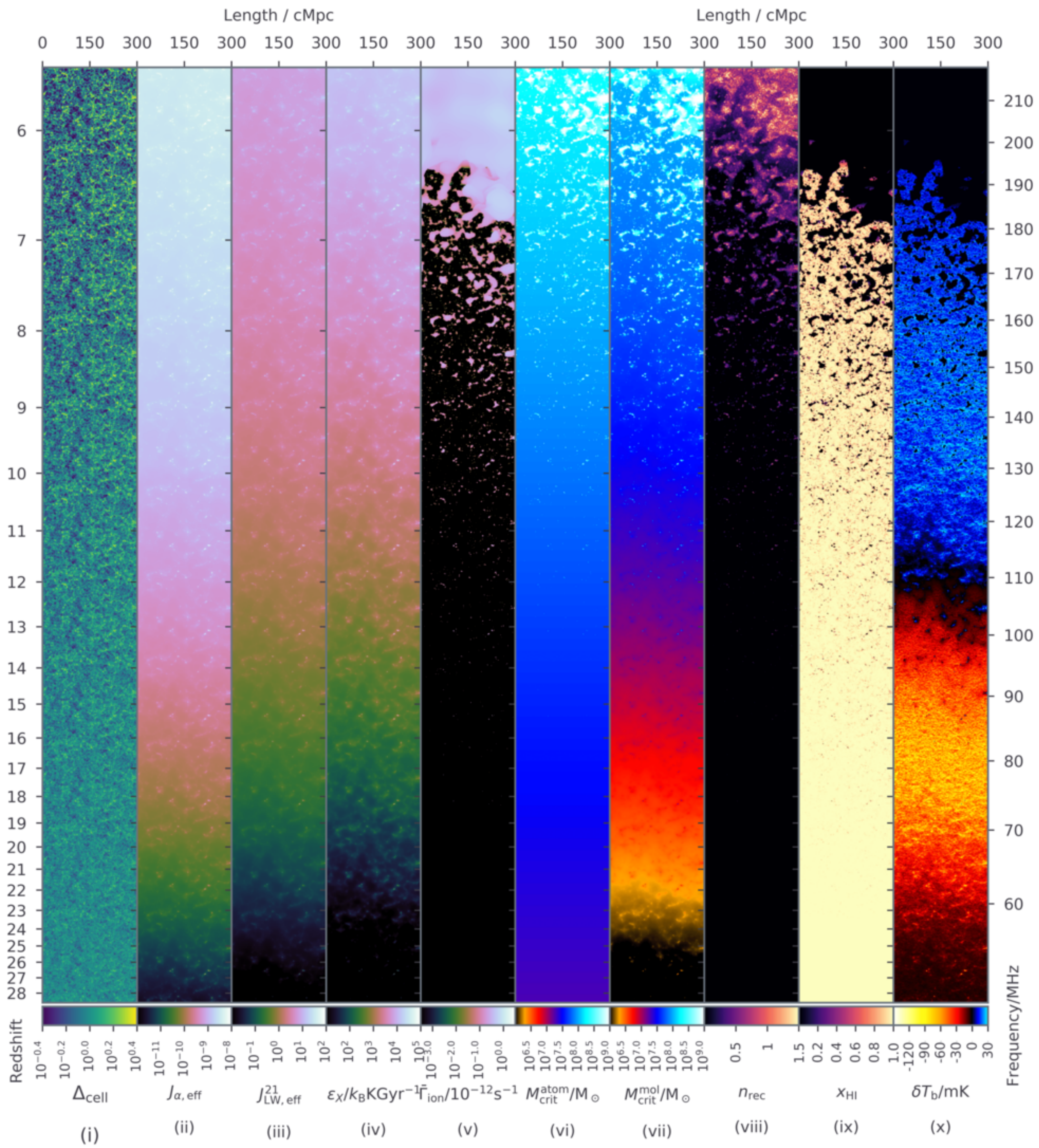
21cmFAST overview

- simulates the reionizing universe in a periodic box.
- typical run ~ (128 cell * 2 Mpc/cell)^3.
- tracks IGM temperature T_k, IGM ionization level $x_{\rm HII} = x_{\rm HeII} = x_e$, ($x_{\rm HeIII} = 0$), overdensity $\delta_M = \delta_B$.
- EoM:

$$\frac{dx_e(z,\mathbf{x})}{dz} = \frac{dt}{dz}\left[\Lambda_{\rm ion} - \alpha_A C x_e^2 n_A f_{\rm H}\right]$$

$$\frac{dT_k(z,\mathbf{x})}{dz} = \frac{2}{3k_B(1+x_e)}\frac{dt}{dz}\sum_p \epsilon_p + \frac{2T_k}{3n_A}\frac{dn_A}{dz} - \frac{T_k}{1+x_e}\frac{dx_e}{dz}$$

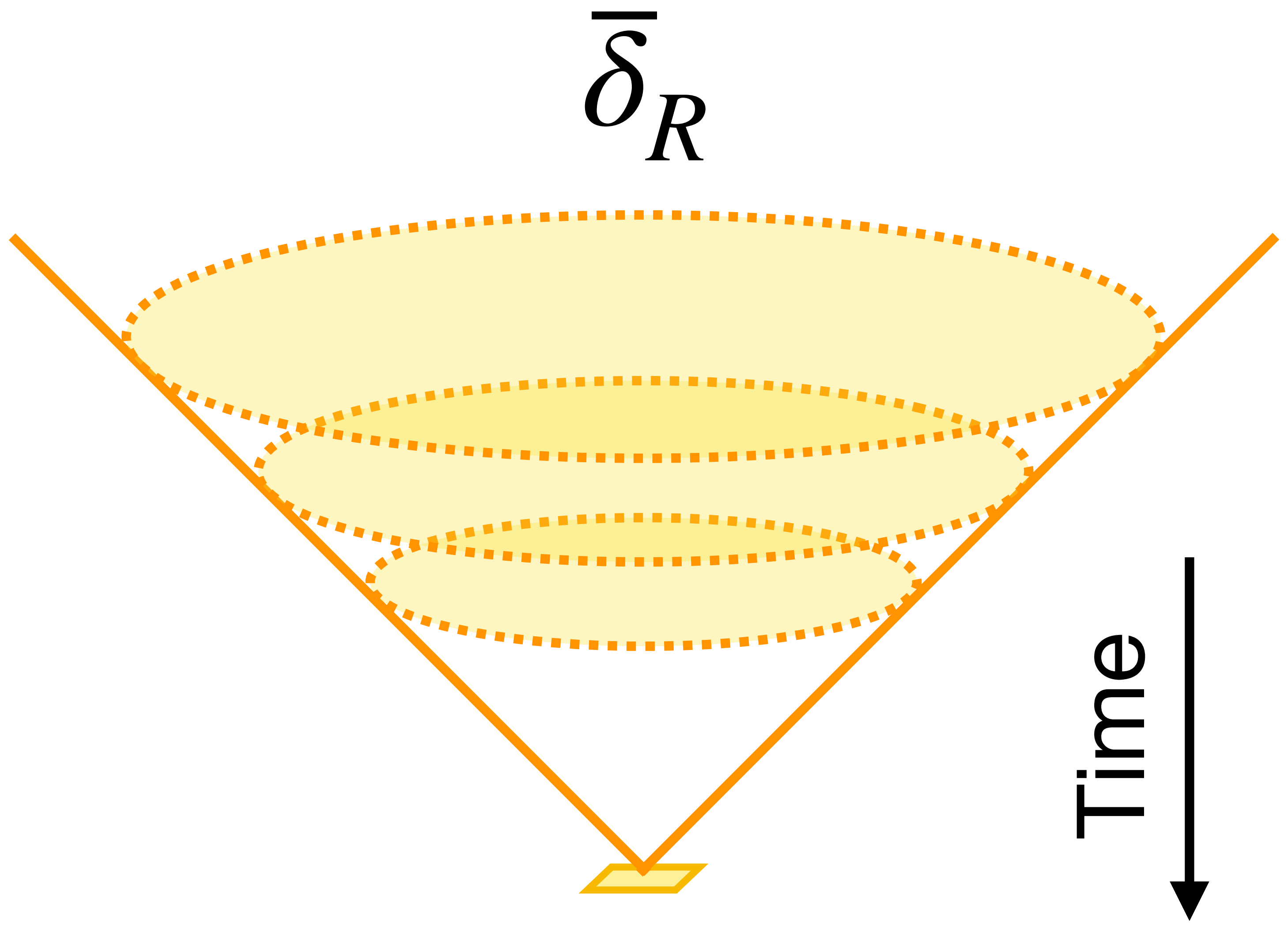
- construct lightcone for T_{21} after a typical simulation run from z~45 to z~5.



Murray, Greig, Mesinger, Muñoz, Qin, Park, Watkinson (2020)

21cmFAST's X-ray treatment

- **21cmFAST** calculates astrophysical X-ray from the first stars. The luminosity is proportional to the star formation rate density (SFRD).
- It uses past overdensity δ, calculates $\bar{\delta}_R$, use the Press-Schechter formalism to calculate $f_{\rm collapse}(\vec{x}, z)$, normalize with Sheth-Tormen $\bar{f}_{\rm collapse}(z)$, then calculate SFRD.
- integrates over frequencies: assumes a power law spectrum to simplify redshifting.
- uses ON/OFF attenuation in the frequency domain.

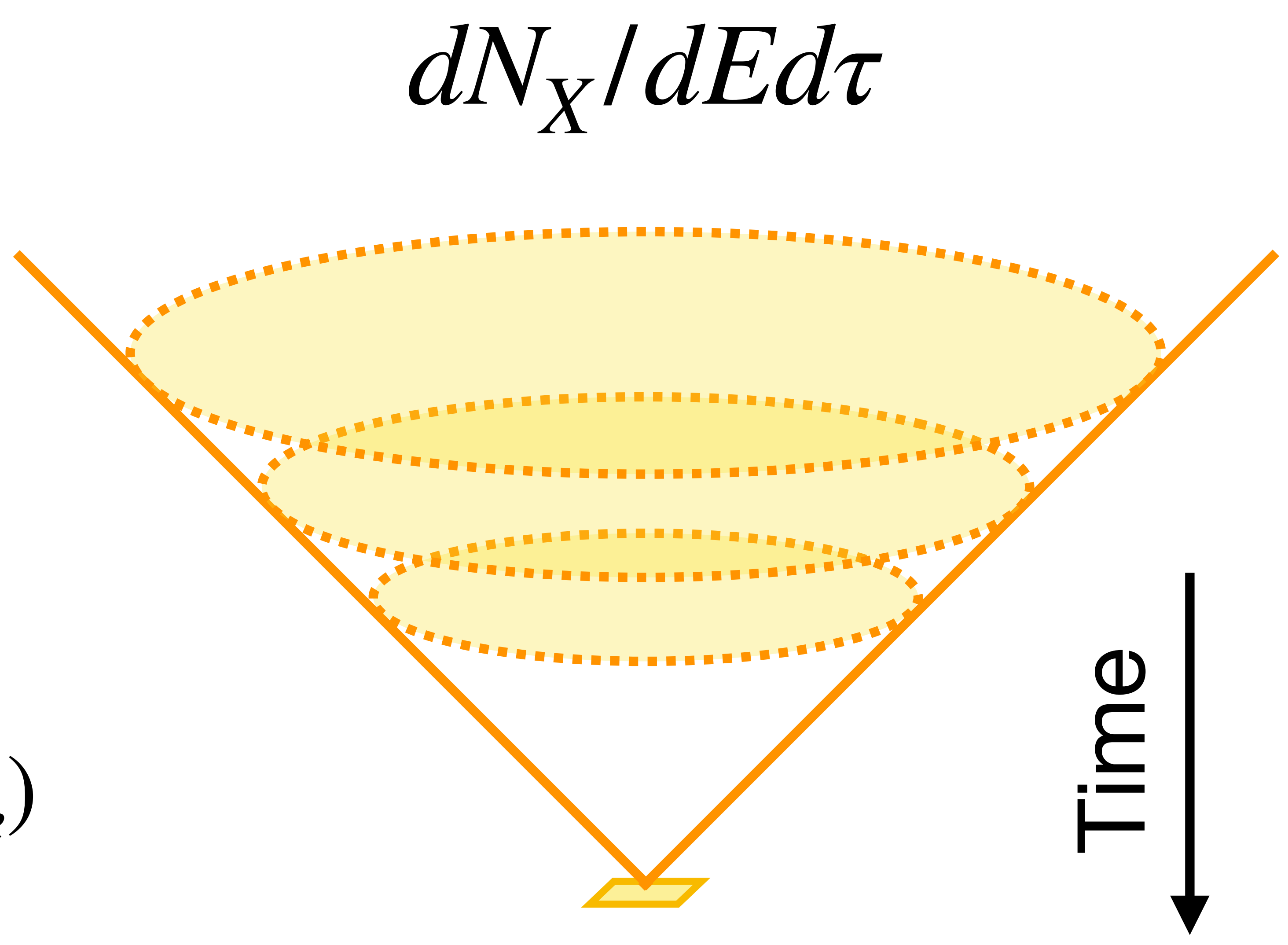


`DM21cm`'s X-ray treatment

- We would like a more physical method. We take inspiration from **`21cmFAST`**.
- No need for photon direction information: sources are usually isotropic, and there's almost no scattering in the X-ray regime. We only need the shell averaging.
- To keep memory manageable, we assumes the X-ray luminosity field can be separated into

$$\frac{dN_X}{dEd\tau}(z_i, \vec{x}x, E\,|\,z_e) \approx \frac{dN_X}{dEd\tau}(z_i, E\,|\,z_e)\,\tilde{\epsilon}_X(\vec{x}\,|\,z_e)$$

- We physically attenuate and redshift $dN_X/dEd\tau$.
- Each previous shell has a different X-ray spectrum; their deposition happens in serial. This is enabled by faster computation of FFT and interpolation on GPUs by a factor of ~ 100.

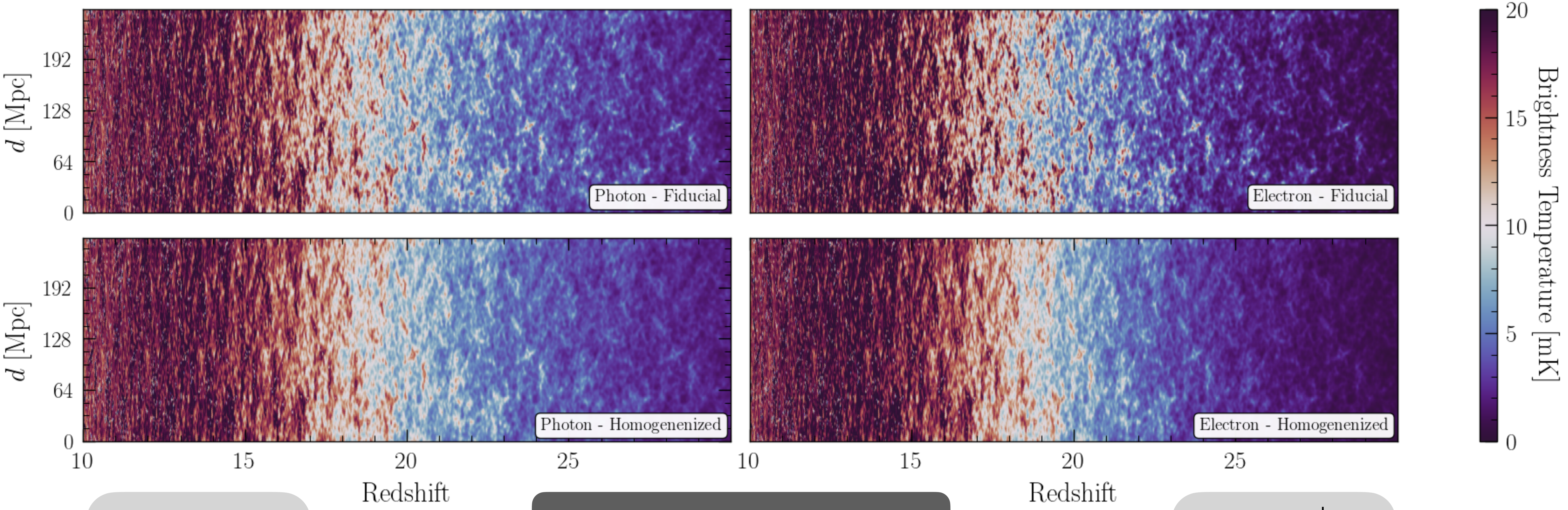


Aside: computational performance

- Few lines of code in the main evolve function, very readable.
- GPU-enabled with **`JAX`**, FFTs, interpolations can be faster by a factor of 100 than running on 16-core CPU. (Although automatic differentiation may be hard.)
- Deposition precision constrained by size of transfer function tables from **`DarkHistory`** and the memory of GPUs. Can easily replace with neural networks (**YS** et al 2022). Necessary for additional dimensions in the table.

```
for i_state, state in enumerate(xray_cache.states):
    if state.isinbath:
        continue # skip states that are already in bath
    if i_state not in inds_chosen_shells:
        accumulated_shell_spec += state.spectrum
        continue

    smoothed_rel_eng_box = xray_cache.get_smoothed_box(state, z_current)
    xray_spec = state.spectrum + accumulated_shell_spec
    tfs.inject_phot(xray_spec, inject_type='xray', weight_box=smoothed_rel_eng_box)

    accumulated_shell_spec *= 0.

profiler.record('xray')

#--- bath and homogeneous portion of xray ---
tfs.inject_phot(phot_bath_spec, inject_type='bath')

#--- dark matter (on-the-spot) ---
tfs.inject_from_dm(dm_params, inj_per_Bavg_box)
```

T_{21} signal: large signal limit



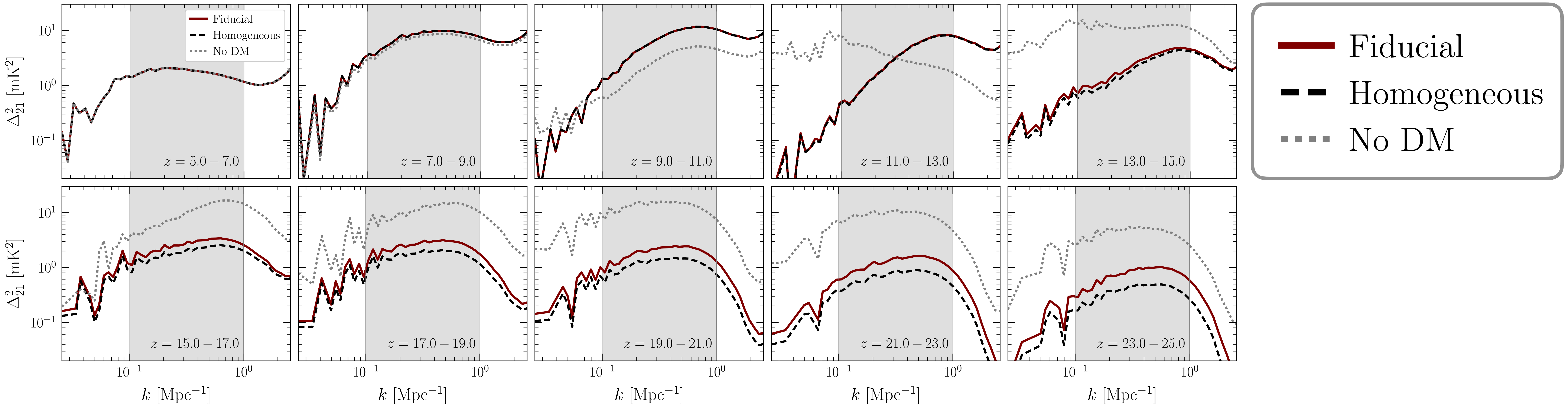
$\chi \to \gamma\gamma$
$m = 5$ keV
$\tau = 10^{26}$ s

Large signal limit: DM injection is the dominant energy contribution.

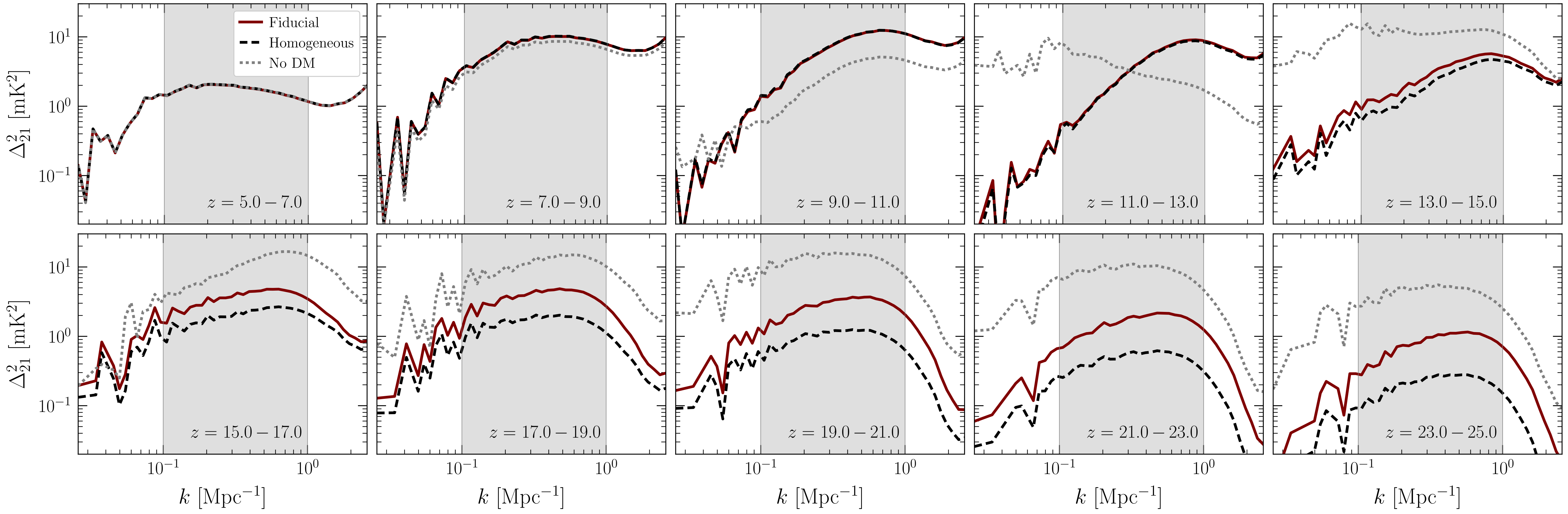
$\chi \to e^- e^+$
$m = 10$ MeV
$\tau = 10^{25}$ s

T_{21} power spectrum

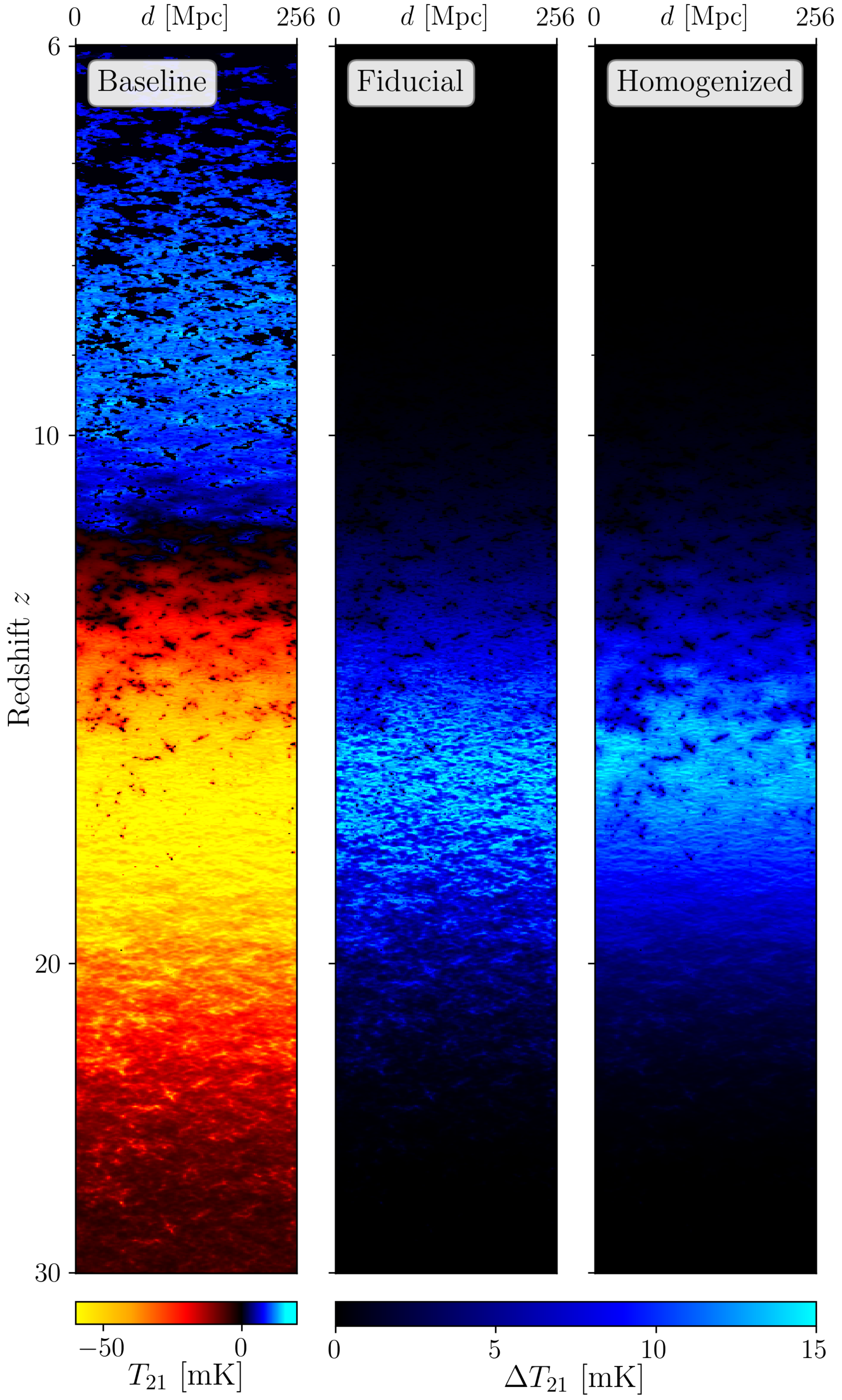
$\chi \to \gamma\gamma$
$m = 5$ keV
$\tau = 10^{26}$ s



$\chi \to e^- e^+$
$m = 10$ MeV
$\tau = 10^{25}$ s



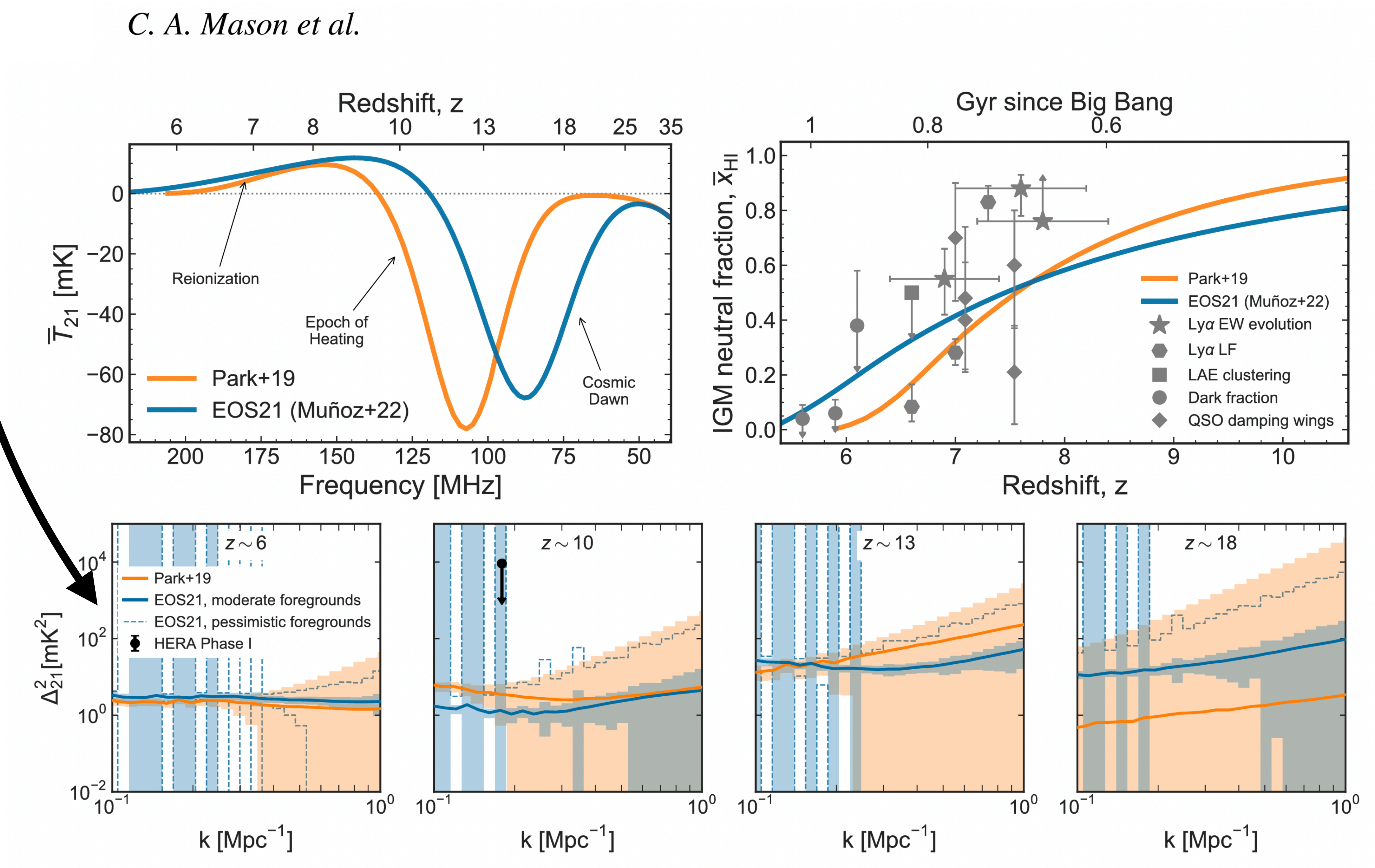
T_{21} signal: small signal limit

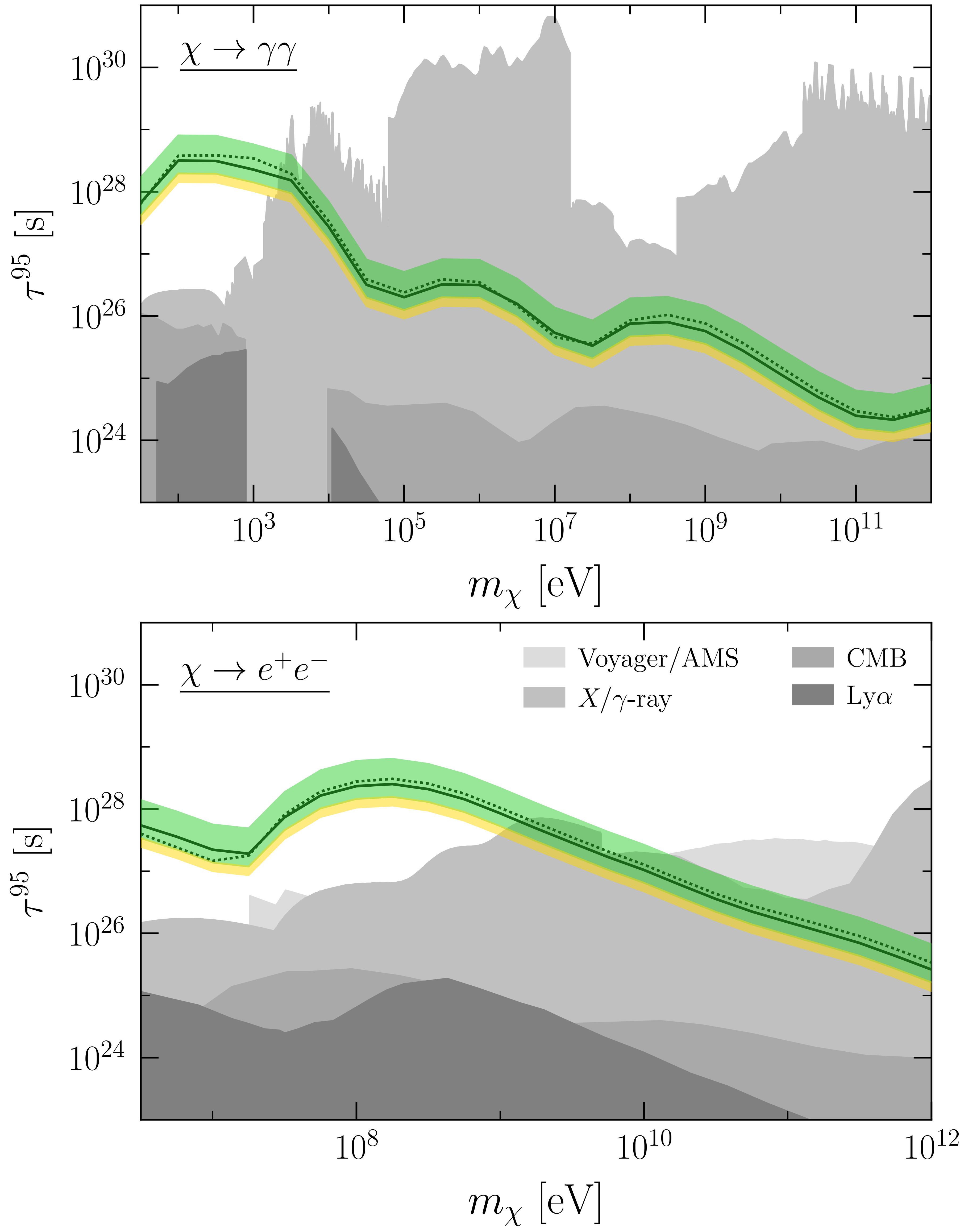


Small signal limit: universe to close to no-DM configuration. More relevant for observation forecasts.

Fisher information forecast of HERA sensitivity

We use **21cmfish** and assume its fiducial power spectrum Δ^2_{21} noise model for HERA:



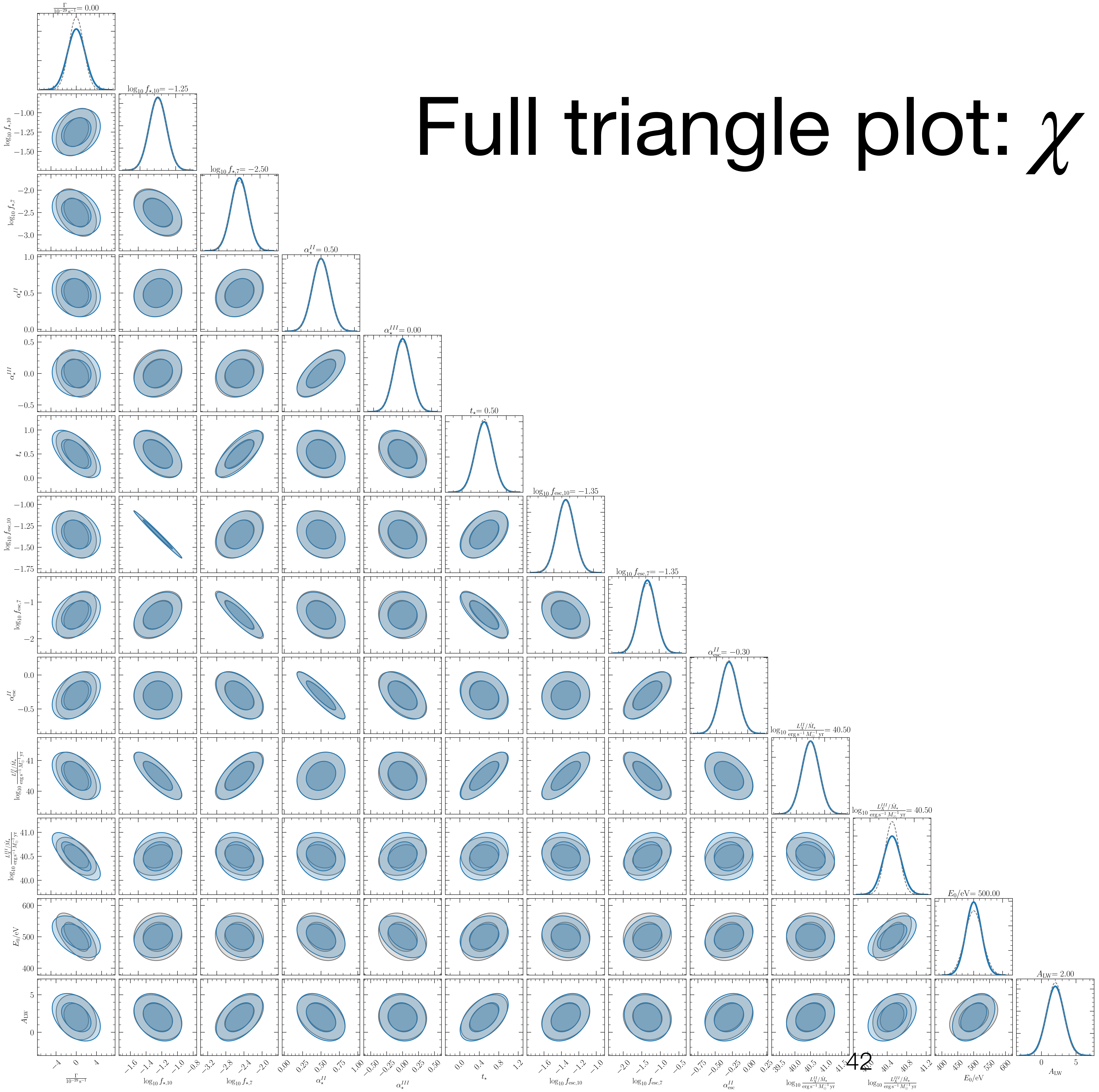


Degeneracy with astrophysical parameters

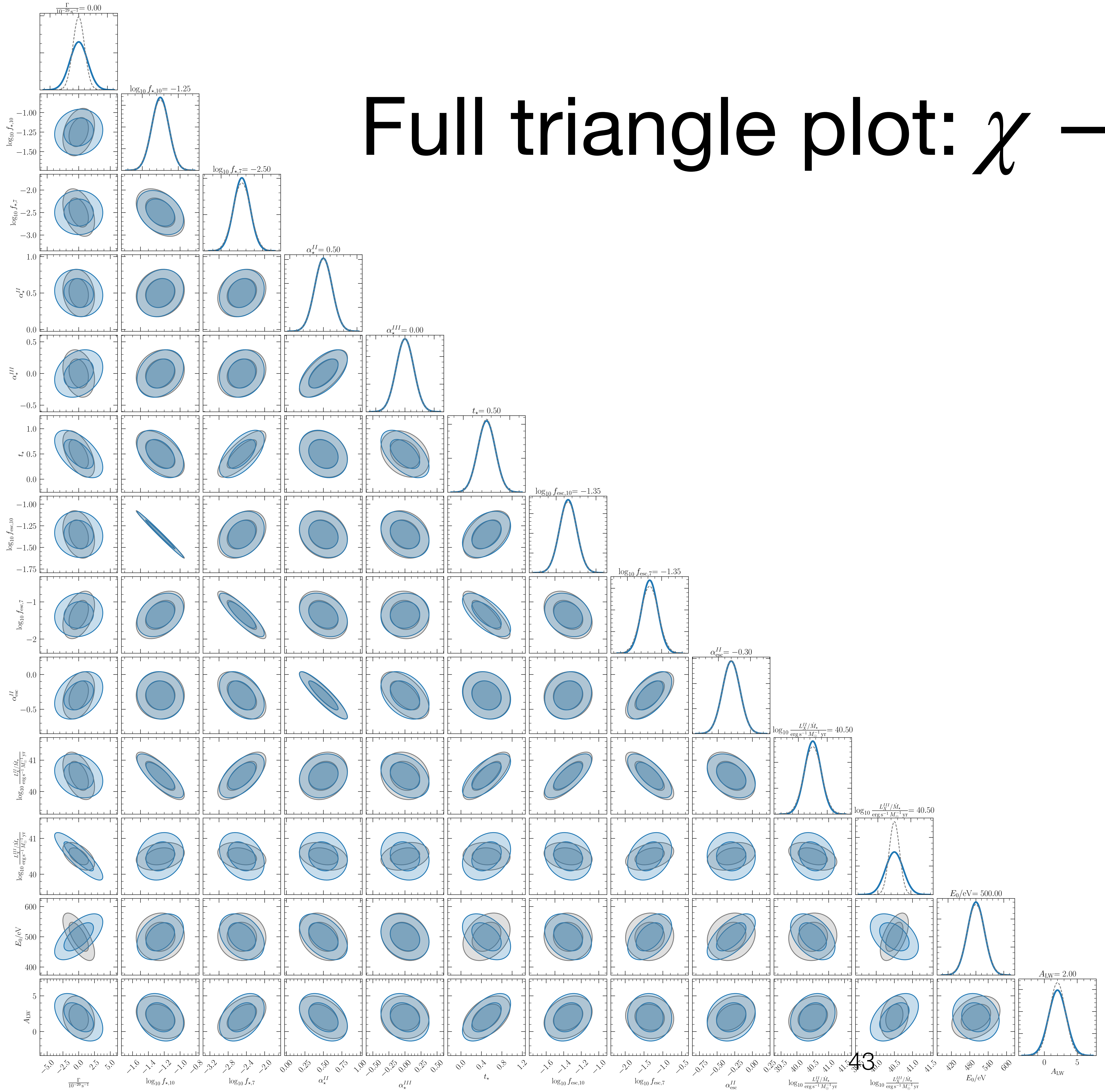
$t_\star H^{-1}$ is the characteristic star formation rate (SFR) timescale.

$L_X^{\mathrm{II/III}}/\dot{M}_\star$ is X-ray luminosity per SFR for PopII/III stars.

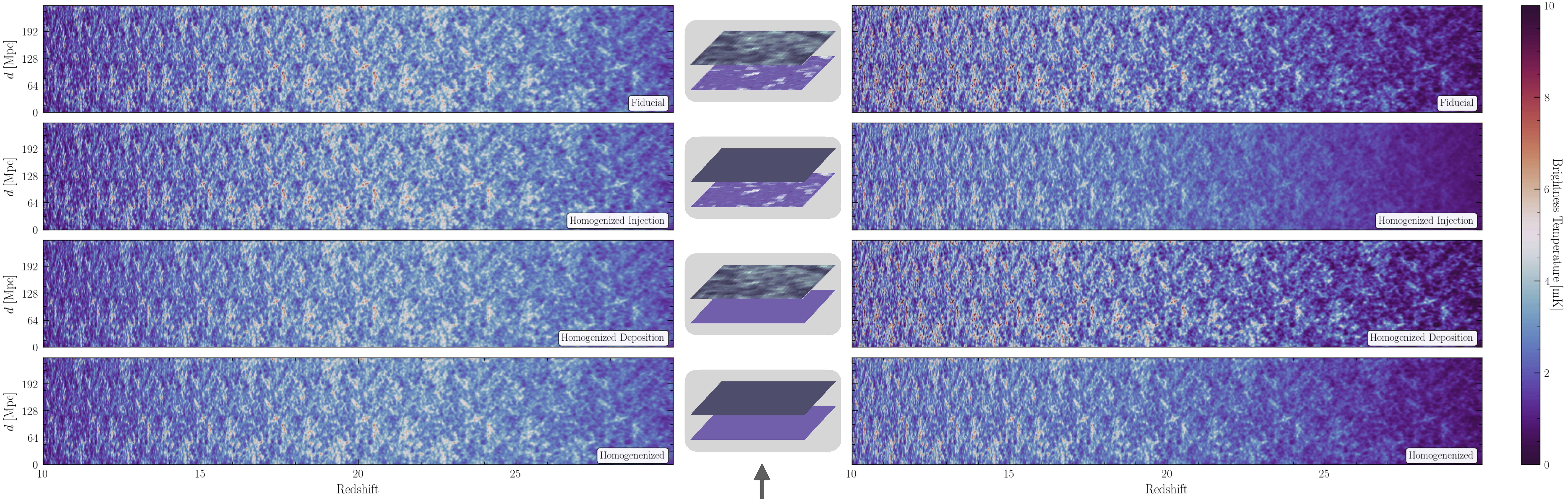
Full triangle plot: $\chi \rightarrow \gamma\gamma$



Full triangle plot: $\chi \to e^+e^-$



T_{21} signal: homogeneous injection / deposition



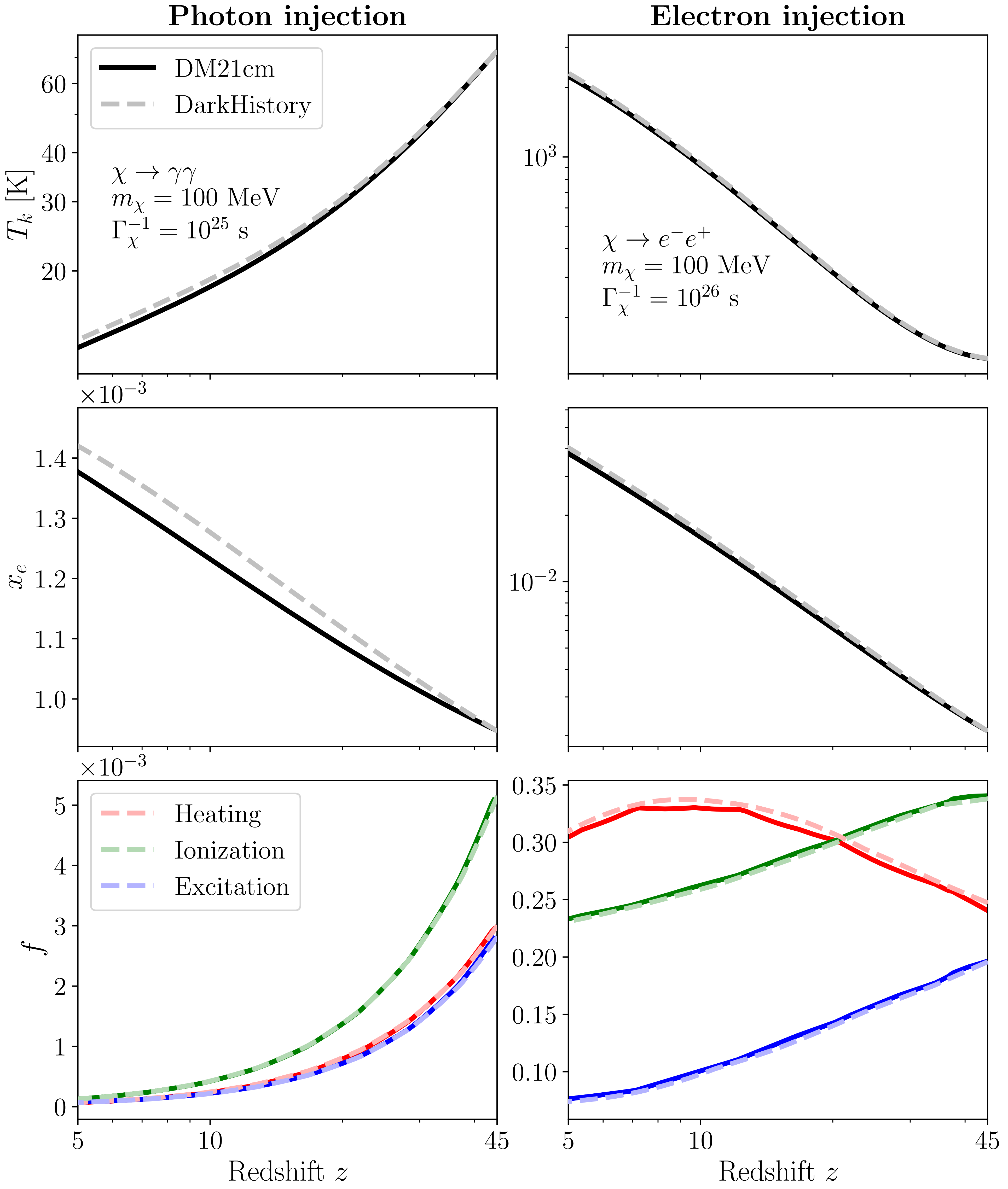
T_{21} signal for $\chi \rightarrow \gamma\gamma$, with $m = 5$ keV and $\tau = 10^{26}$ s

T_{21} signal for $\chi \rightarrow e^-e^+$, with $m = 10$ MeV and $\tau = 10^{25}$ s

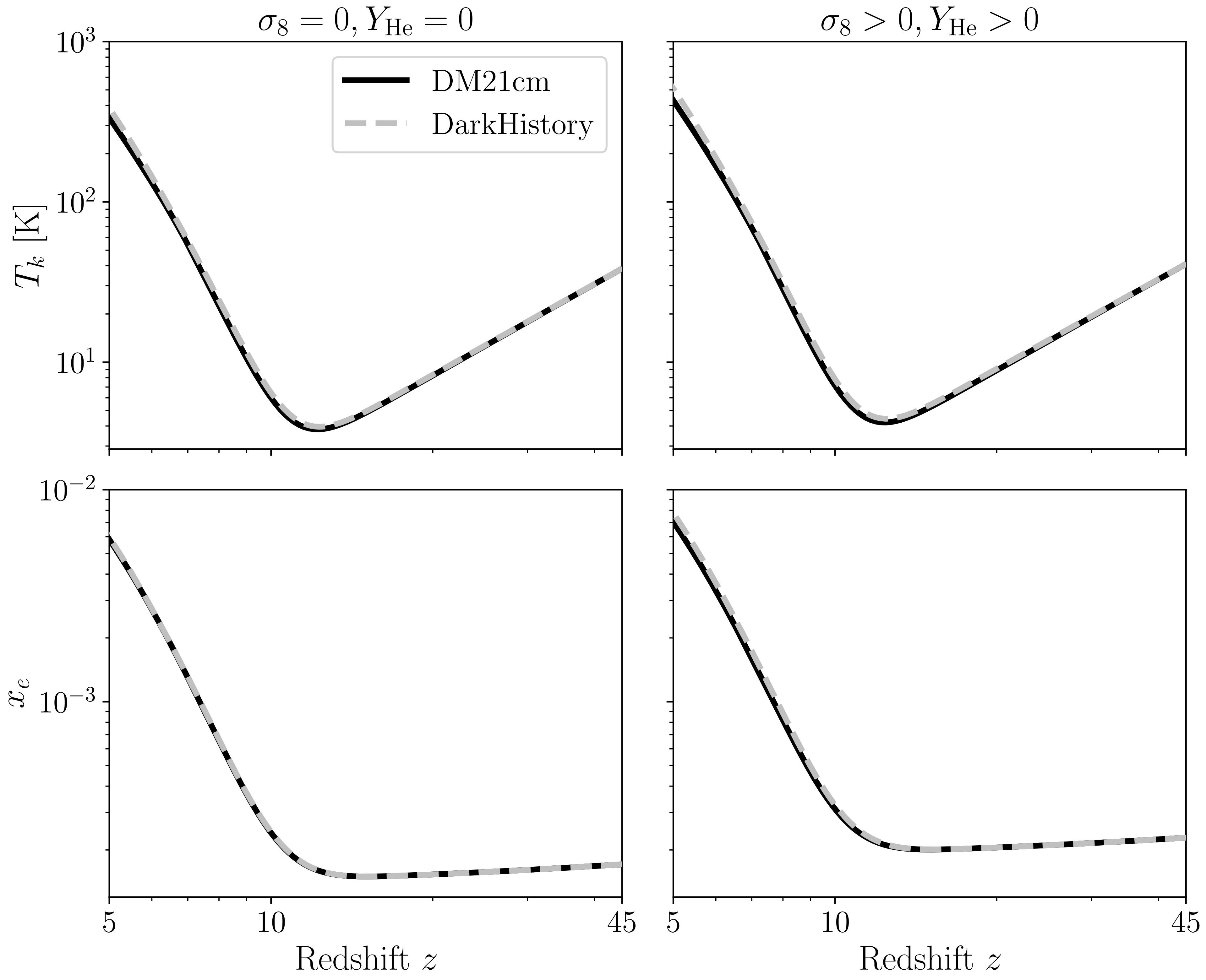
Injection $dE/dVdt$

Deposition $f_c(T_k, x, \delta)$

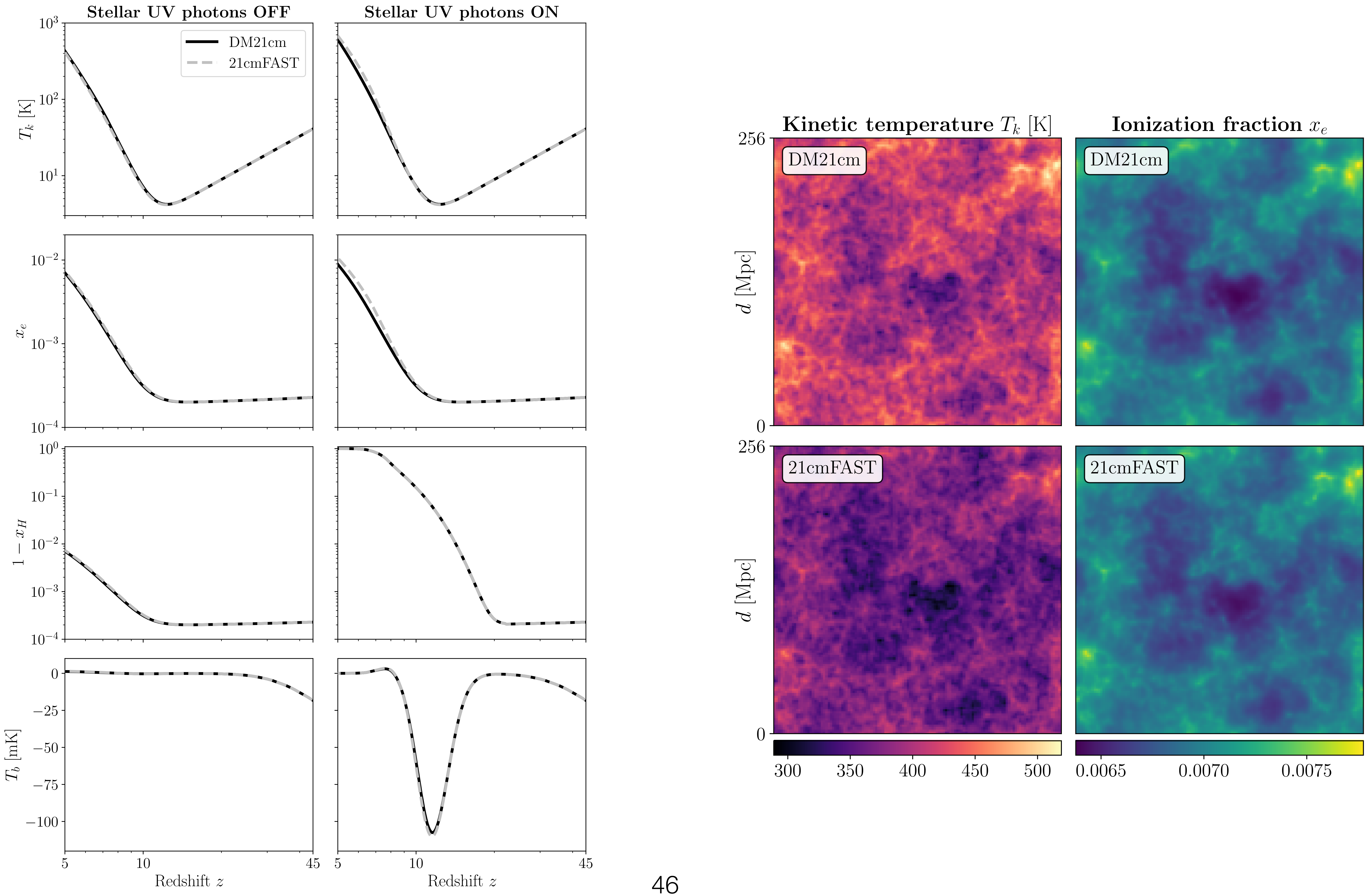
Cross check: **DarkHistory** and **DM21cm**



X-ray injection (Sheth-Torman HMF)



Cross check: 21cmFAST & DM21cm



spatiotemporal convergence