`DM21cm`: a GPU-accelerated simulation of **dark matter energy injection** in the **Cosmic Dawn**

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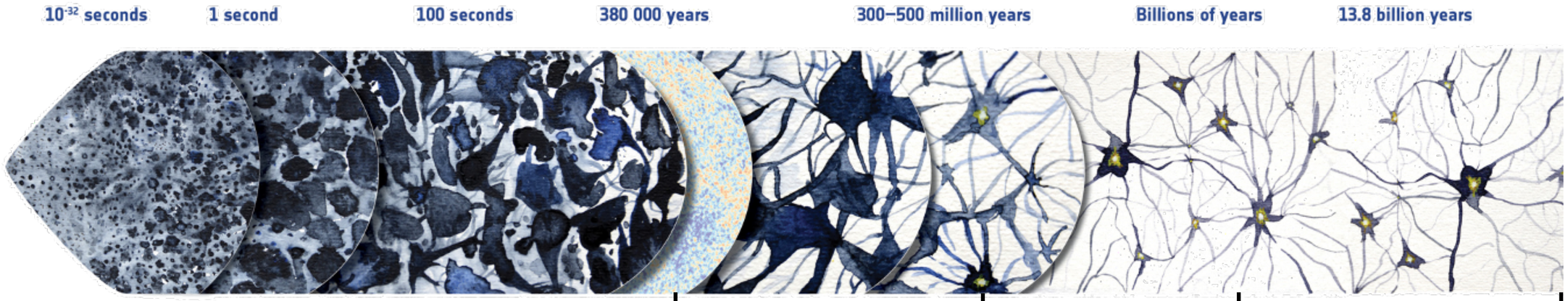
Based on work by **YS**, Joshua Foster, Hongwan Liu, Julian Muñoz, and Tracy Slatyer [2312.11608]

Dark matter & the early universe



Time

z=1100
CMB

translucent

z=30~15
Cosmic dawn

PopIII stars
(1st gen)

z=15~6
Reionization

PopII stars
(2nd gen)

z=0
Present day

PopI stars
(3rd gen)

Gravitational evidences of Dark Matter (DM)	CMB anisotropies			large scale structures		rotation curves bullet clusters galaxy clusters mass
Particle interactions of DM?	CMB anisotropies		21-cm line thermal/ionization history	Ly-α forest		X-ray/γ-ray observations

Outline

- I. Introduction: the Cosmic Dawn and 21-cm cosmology
- II. Our simulation: **`DM21cm`**
  - Energy deposition transfer functions from **`DarkHistory`**.
  - Modifies **`21cmFAST`**'s equation of motion.
  - Our custom photon propagation and energy deposition treatment.
- III. Signal of dark matter energy injection.

Part I: 21-cm cosmology

Hydrogen atom hyperfine transition emits the 21-cm line

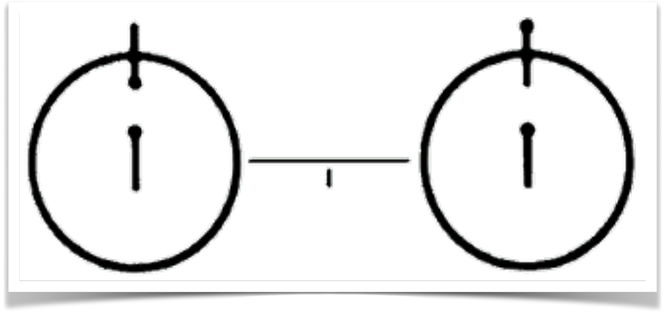
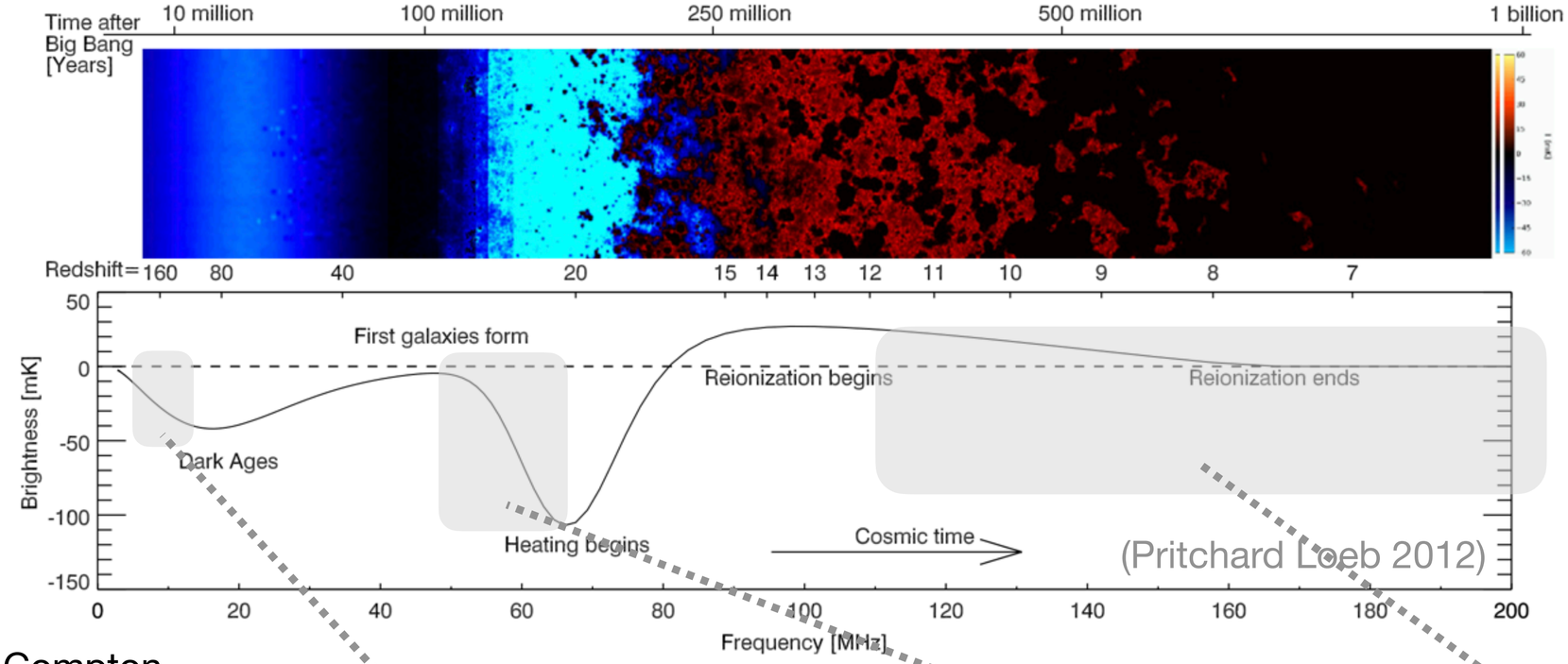
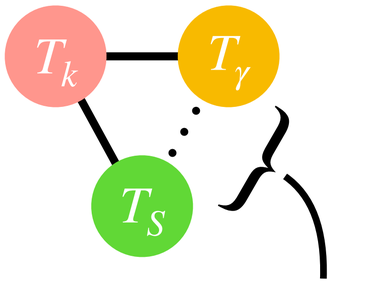


diagram on board the *Voyagers*

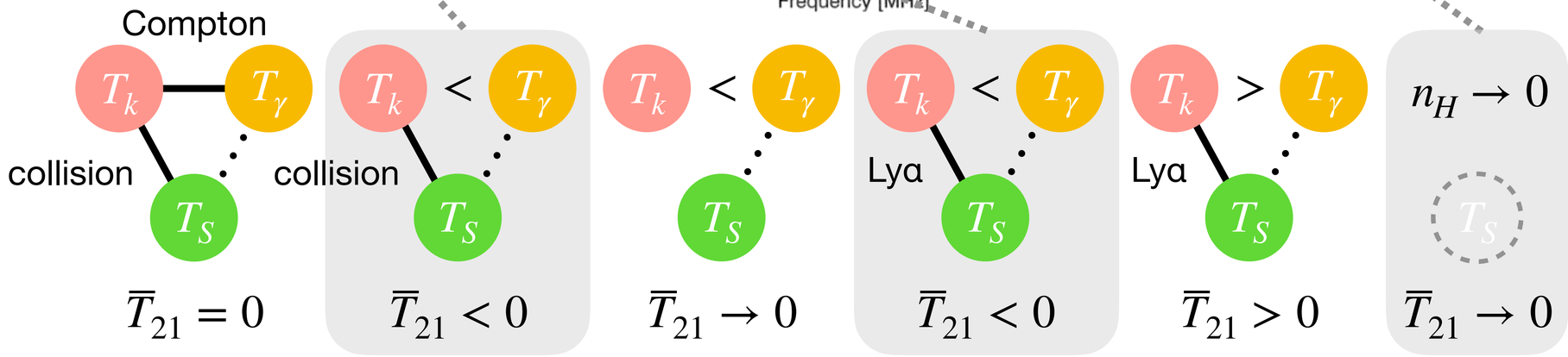
relative abundance → T_S



(Pritchard Loeb 2012)

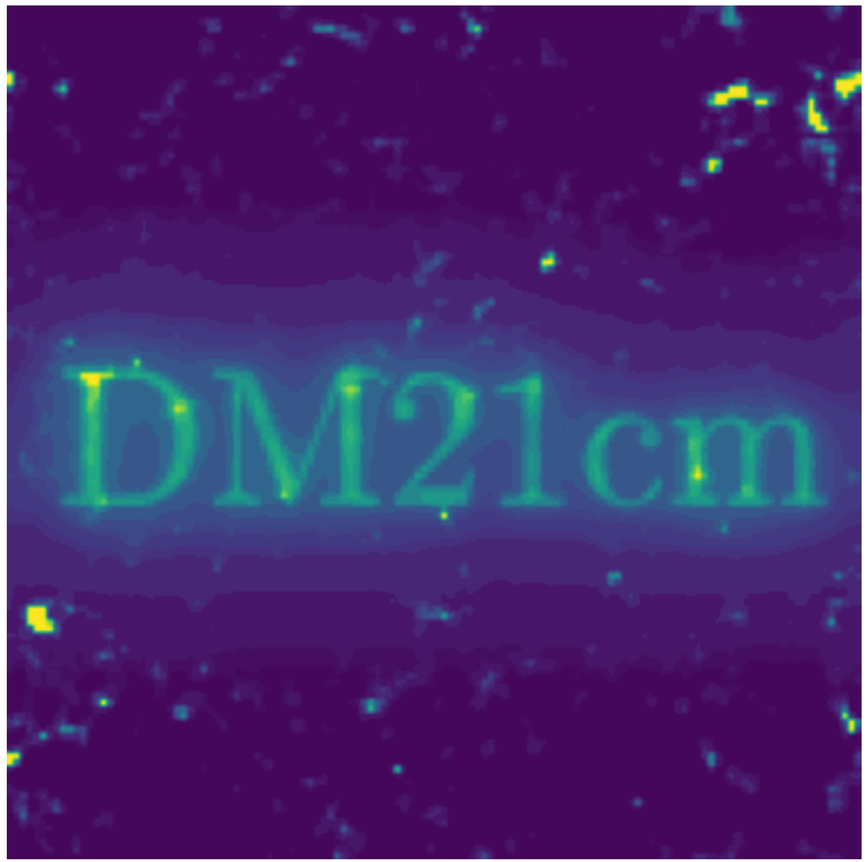


$$T_{21} \propto x_H (T_S - T_\gamma)/T_S$$



Part II: Our simulation **DM21cm**

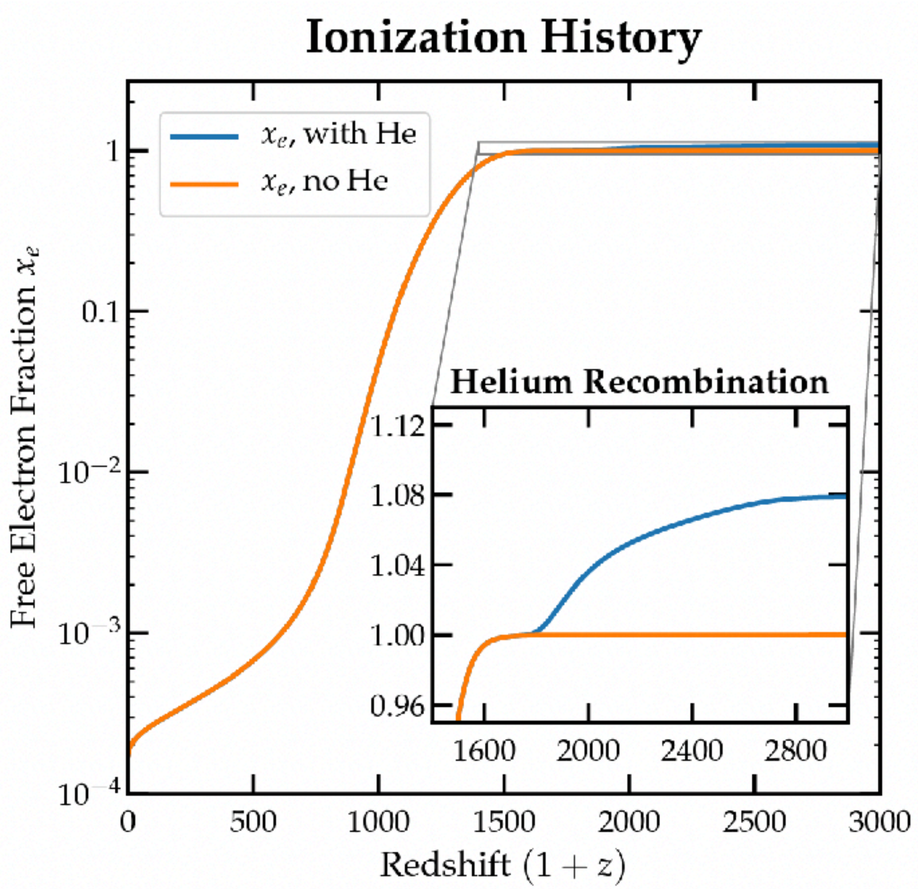
- Built on **21cmFAST**: Modify **21cmFAST**'s Euler step simulation. Defer astrophysics (UV, stellar X-ray, etc.) to **21cmFAST**.
- Use **DarkHistory** to initialize the universe before reionization, and pre-calculate energy deposition processes in a redshift step under various intergalactic medium (IGM) conditions.
- Compute the dark matter energy injection, propagation, and deposition using our new framework: **DM21cm**, which pass the modification terms to **21cmFAST**.



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).

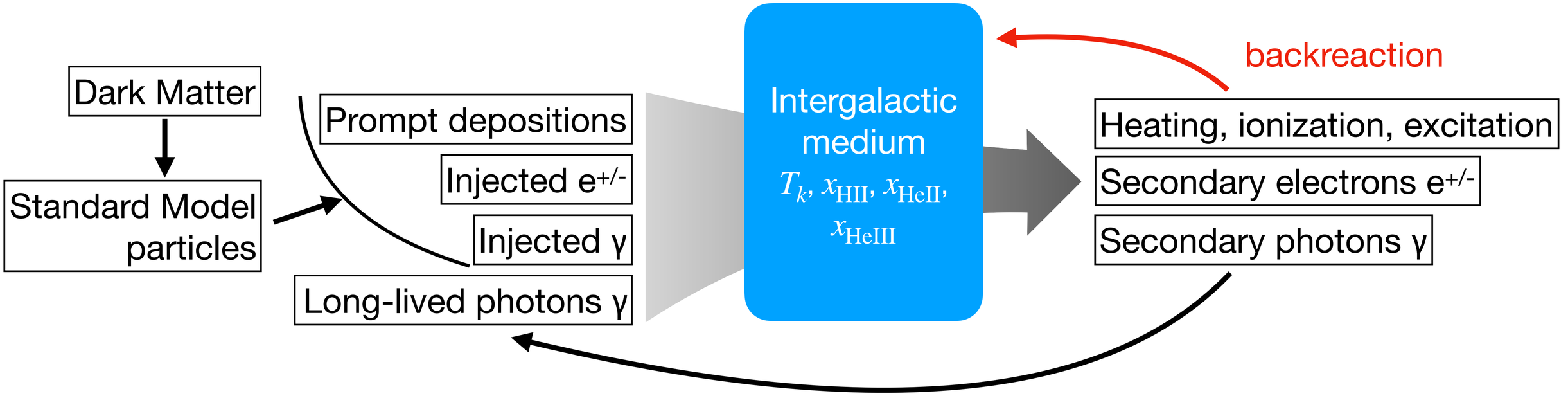


DarkHistory γ and $e^{+/-}$ processes

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

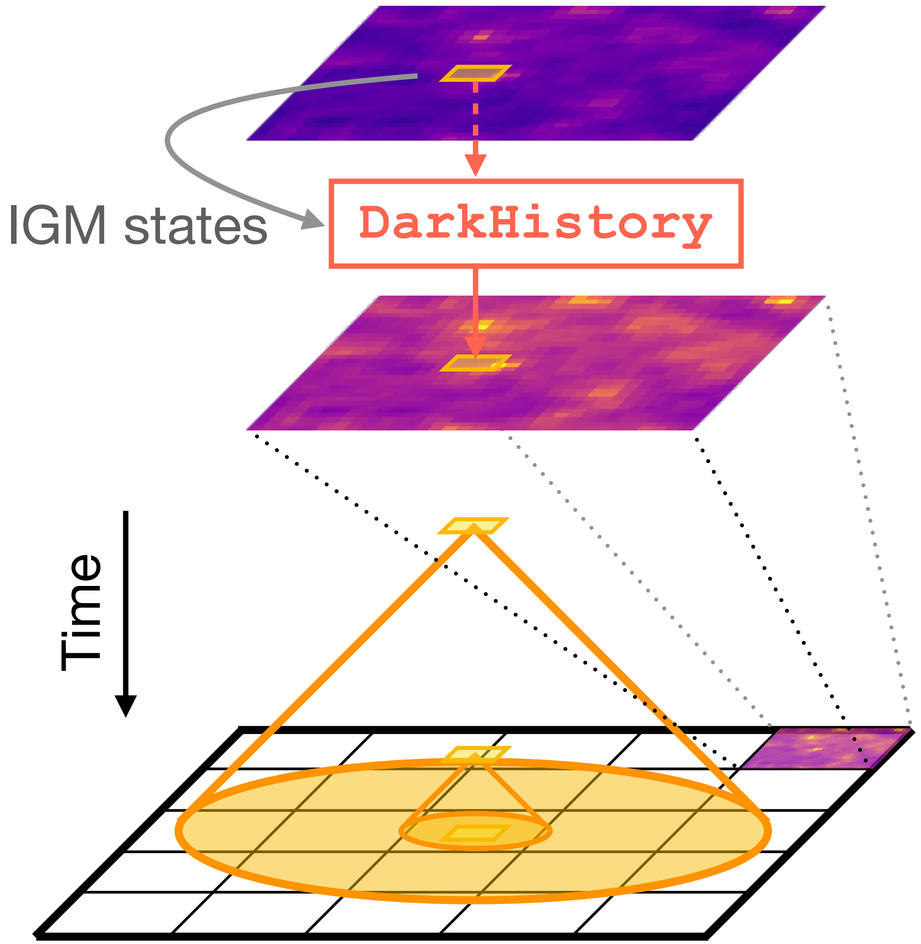
e^- :
- Inverse Compton scatter -> γ, e^-
- Heat, ionize, excite matter

e^+ :
- Annihilate with electrons -> γ, γ



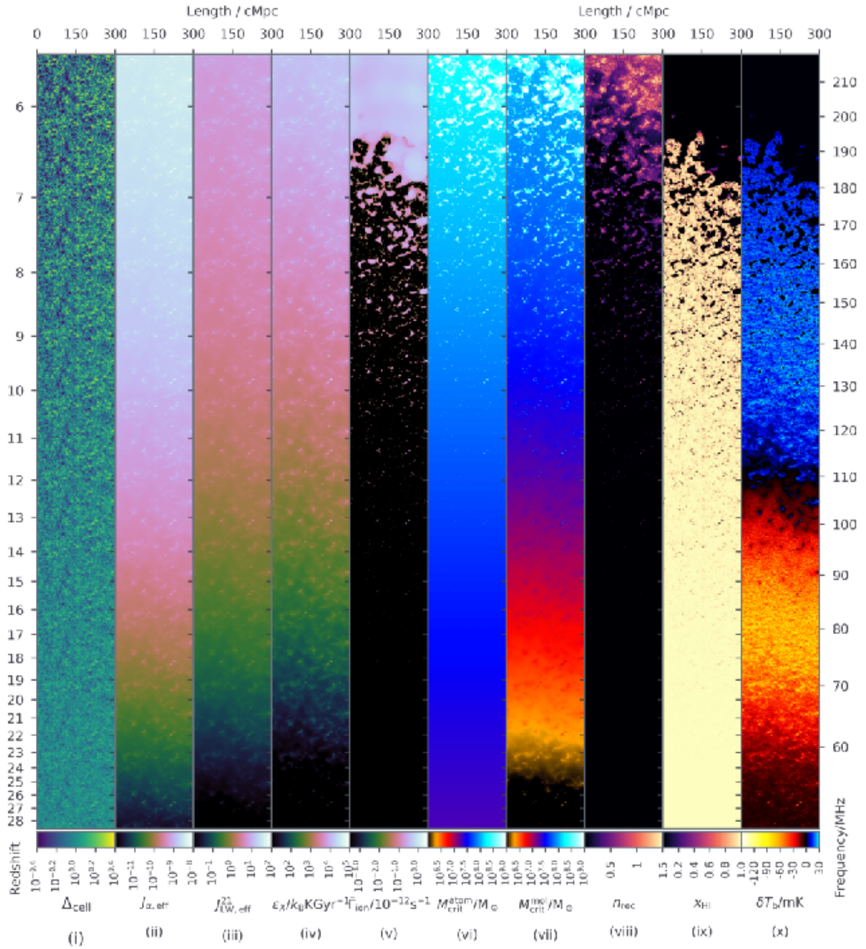
Plan for DM21cm

- 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?



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 $x_{\rm HII} = x_{\rm HeII} = x_e$, ($x_{\rm HeIII} = 0$)
  - matter/baryon overdensity $\delta_M = \delta_B$.



Modifying the EoM

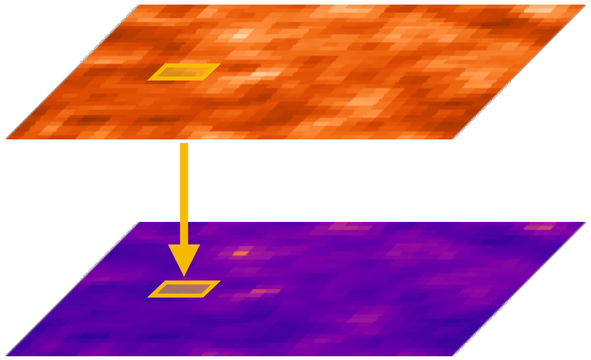
Dark matter (all injections) contributes the red terms:

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

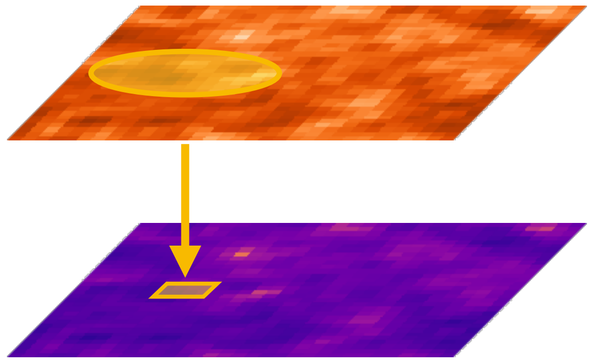
$$\frac{dT_k(z,\mathbf{x})}{dz} = \frac{2}{3k_B(1+x_e)}\frac{dt}{dz}\sum_p \epsilon_p + \frac{2T_k}{3n_A}\frac{dn_A}{dz} - \frac{T_k}{1+x_e}\frac{dx_e}{dz} + \frac{dT_k^{\rm DM}}{dz}$$

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

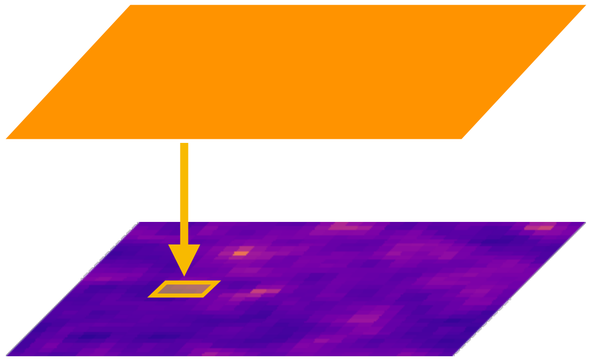
On-the-spot or bath depositions?



On-the-spot



X-rays



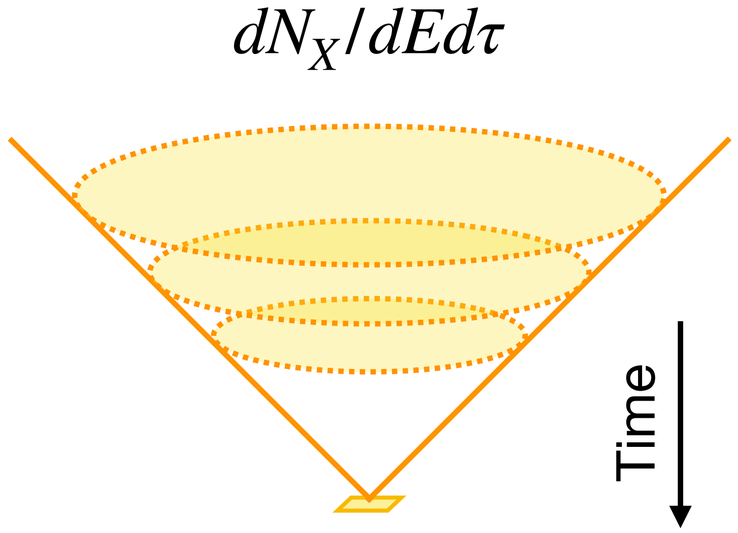
Bath

`DM21cm`'s X-ray treatment

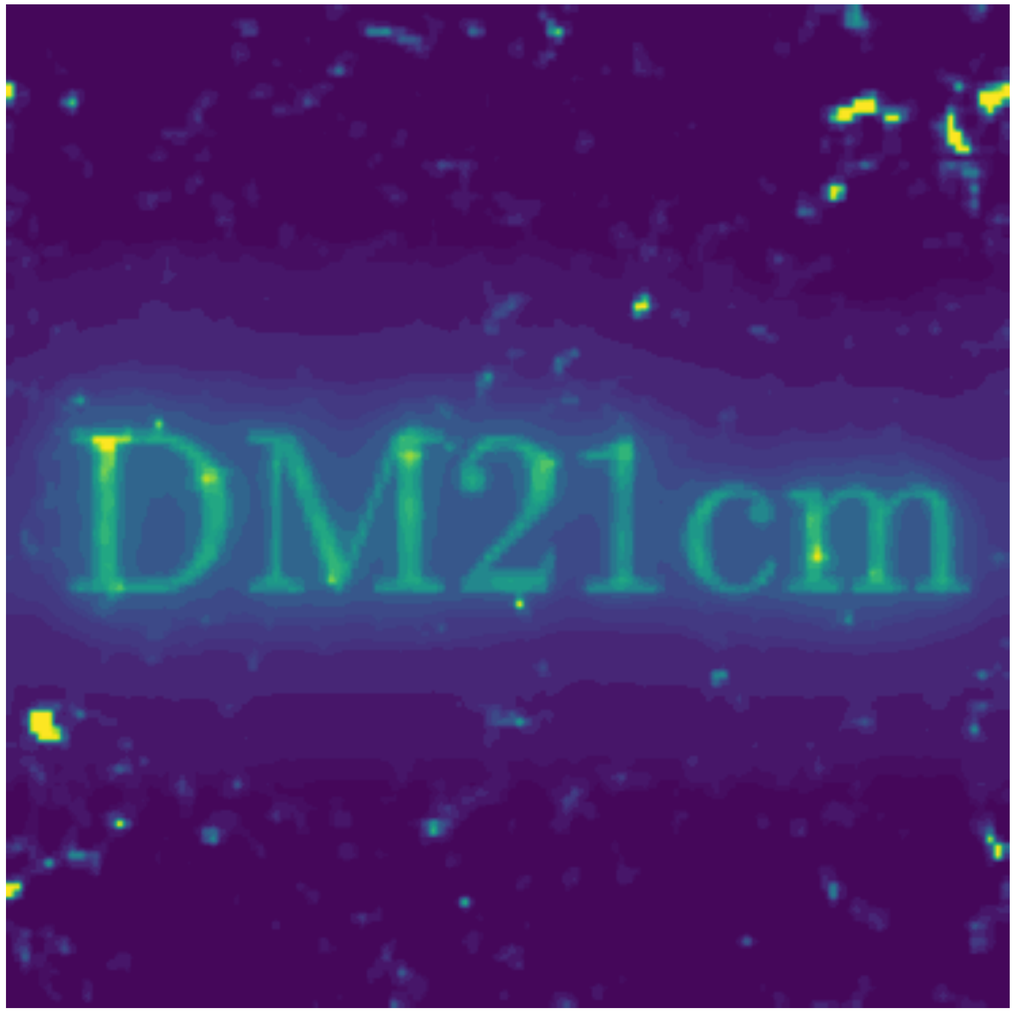
- No need for photon direction information.
- Integrate over shells of past lightcone.
- To keep memory manageable, we assumes the X-ray luminosity field can be separated into

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

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



X-ray in action



Expanding halo
of ionization
due to X-rays.

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)
```

GPU acceleration for interpolation and FFT

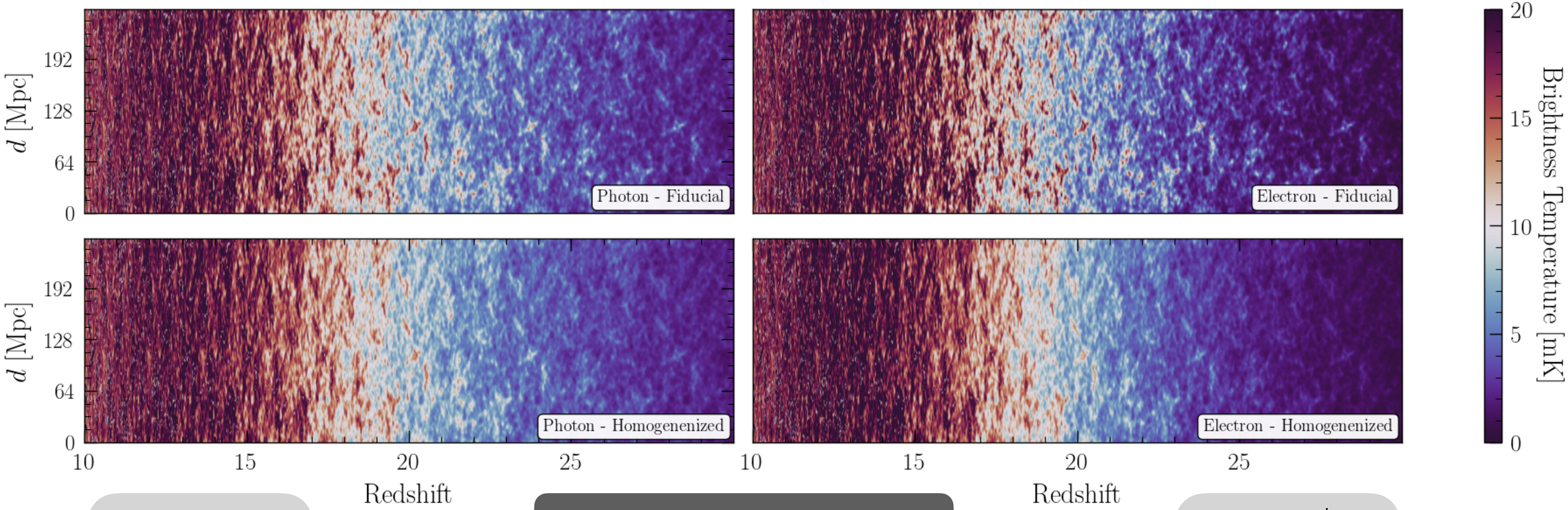
Interpolation:

Exec time (s) on	48CPU 32GB mem	48CPU A100 GPU
scipy (base)	3.997290 +/- 0.004115	4.304705 +/- 0.068191
jax (base)	0.506022 +/- 0.006346	0.010241 +/- 0.000188

Fast Fourier transform (FFT):

Exec time (ms) on	48CPU 32GB mem	48CPU A100 GPU
numpy (base)	371.69 +/- 0.54 inv 428.46 +/- 0.37	332.11 +/- 7.22 inv 401.51 +/- 11.05
jax (base)	107.25 +/- 0.38 inv 148.36 +/- 0.75	0.40423 +/- 0.00125 inv 0.57528 +/- 0.00157

Part III: T_{21} signal



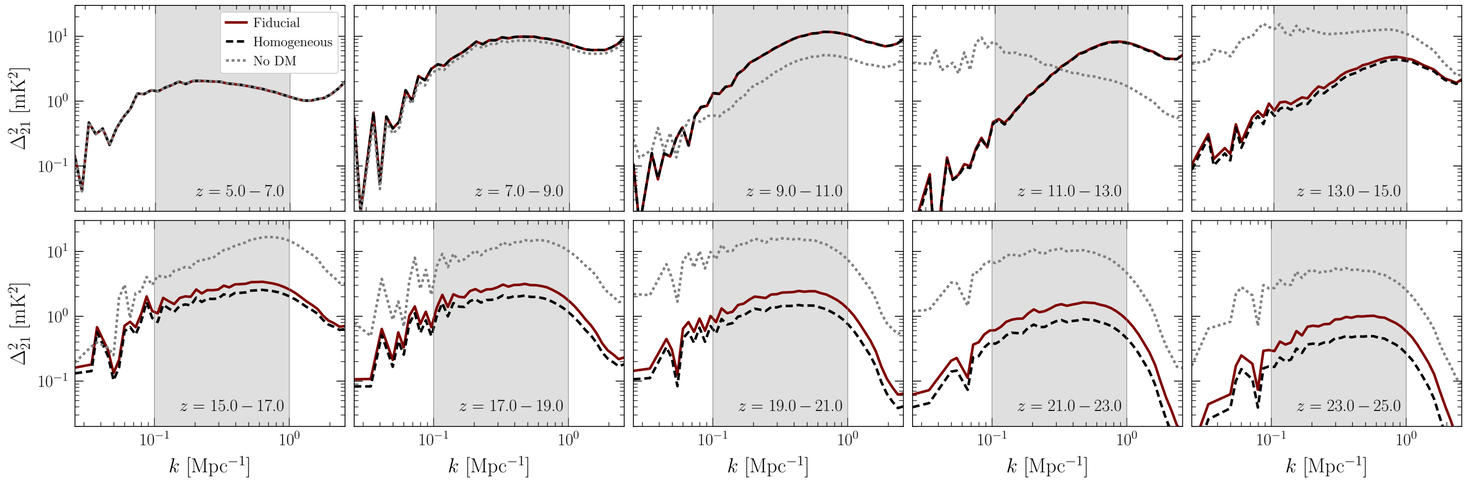
$\chi \to \gamma\gamma$
$m = 5$ keV
$\tau = 10^{26}$ s

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



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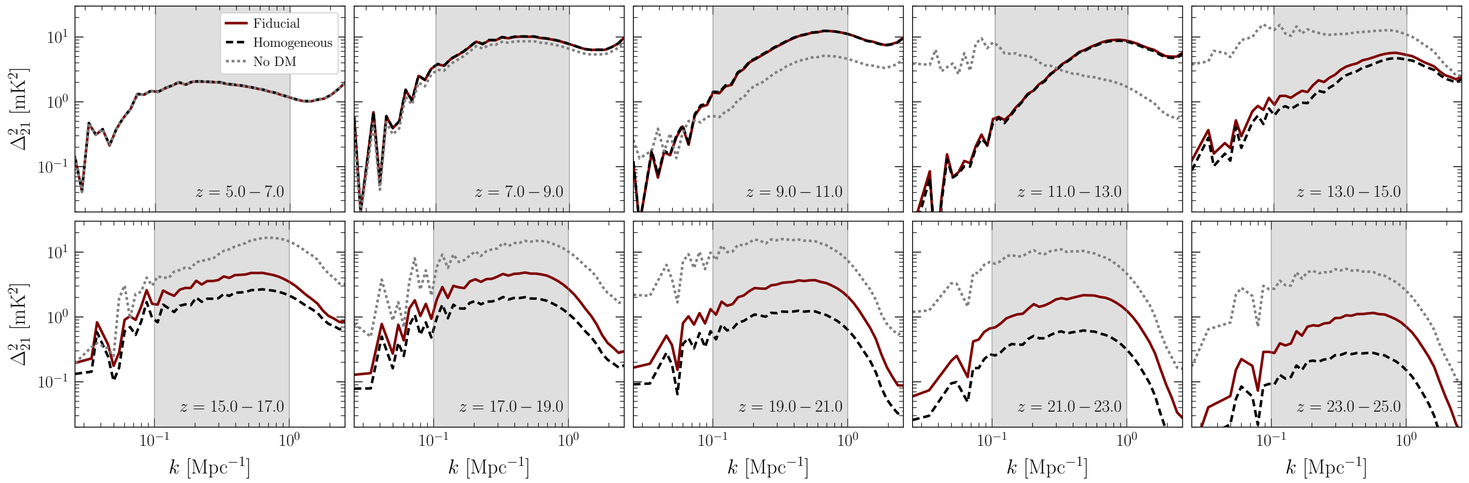
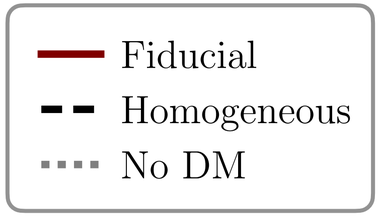
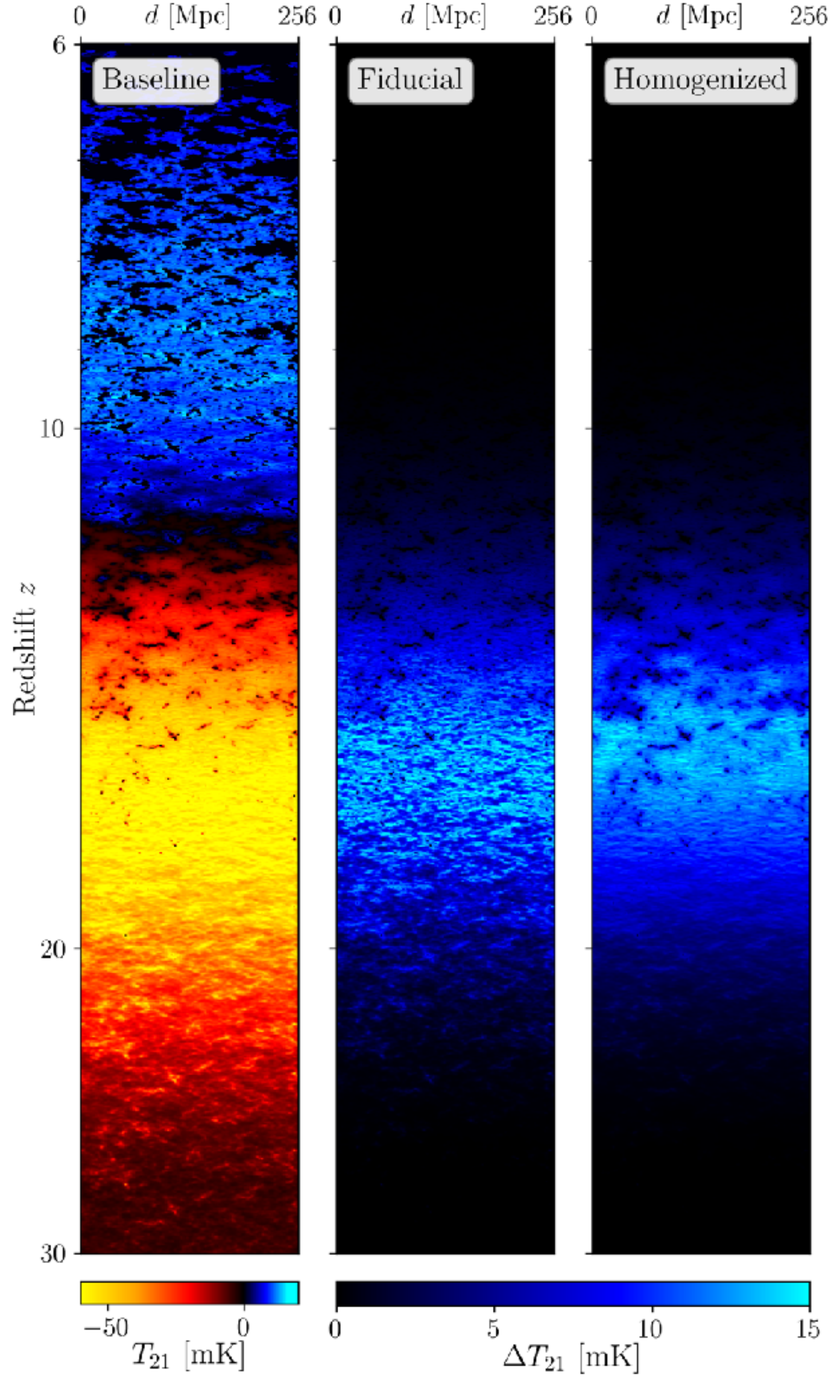
$\tau = 10^{25}$ s





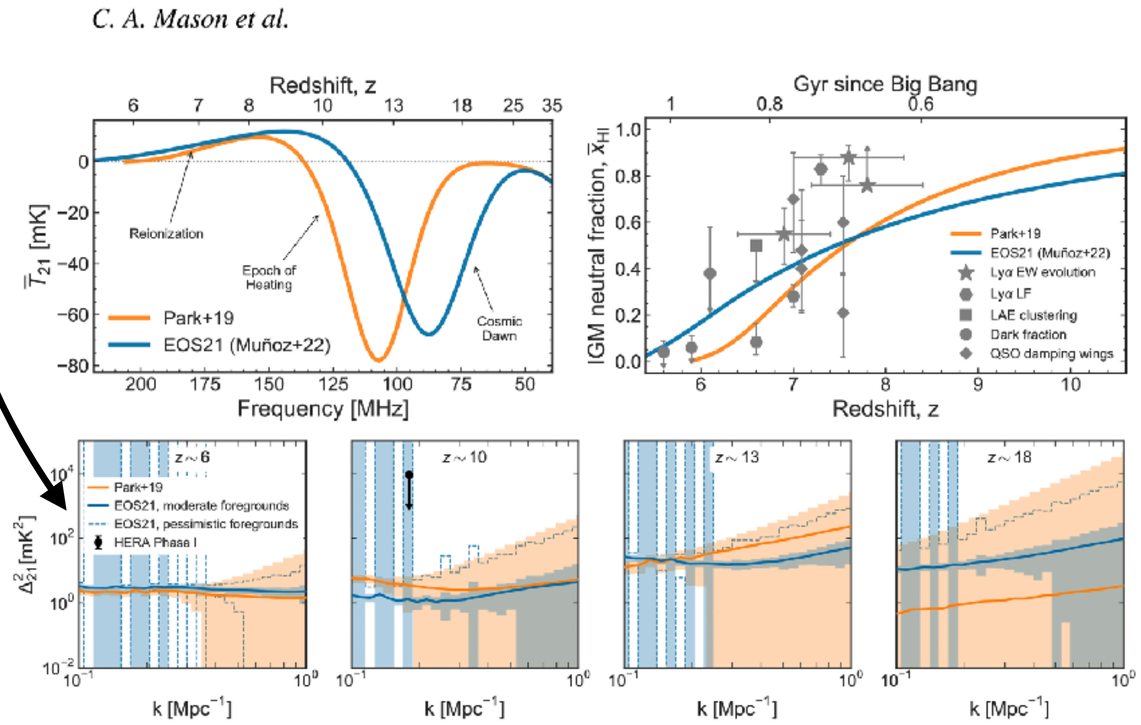
T_{21} signal: small signal limit

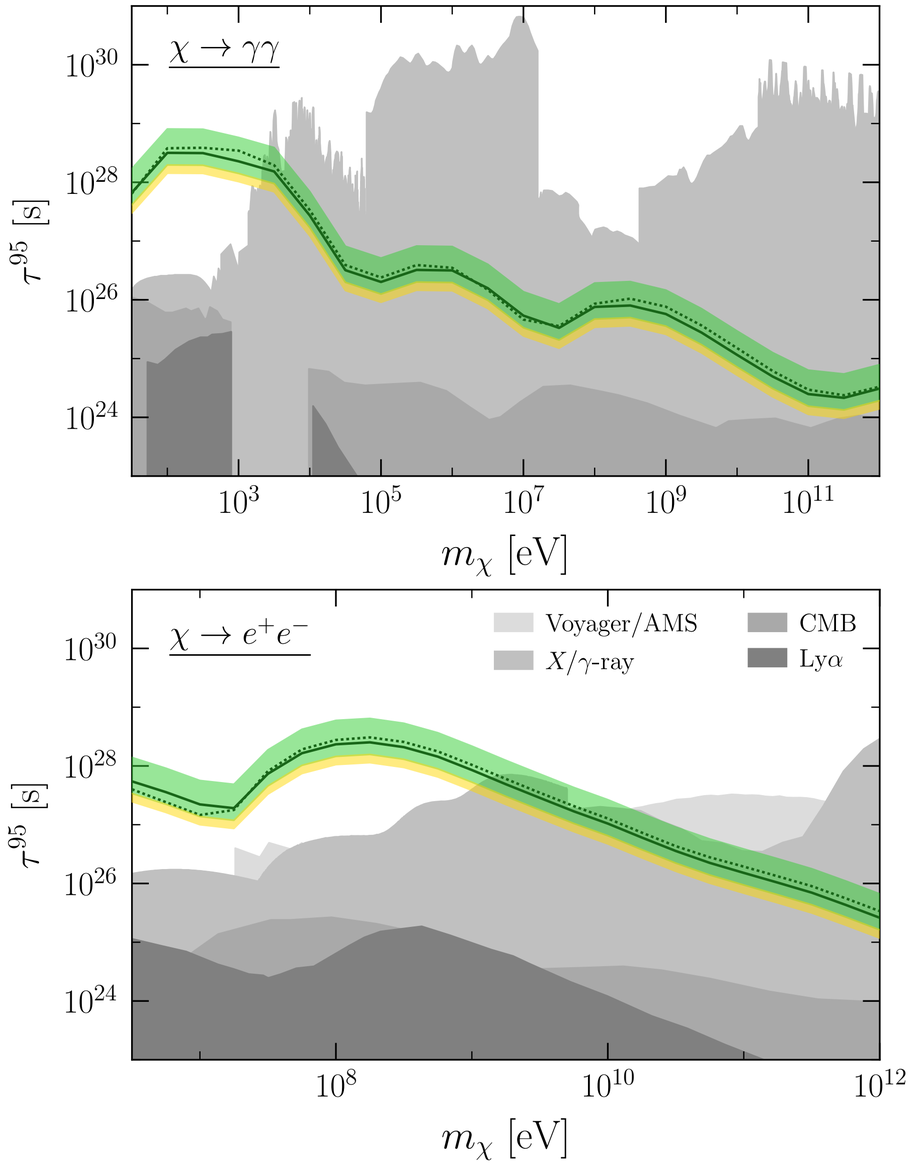
Small signal limit: universe to close to no-DM configuration. More relevant for observation forecasts.



Fisher information forecast of HERA sensitivity

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



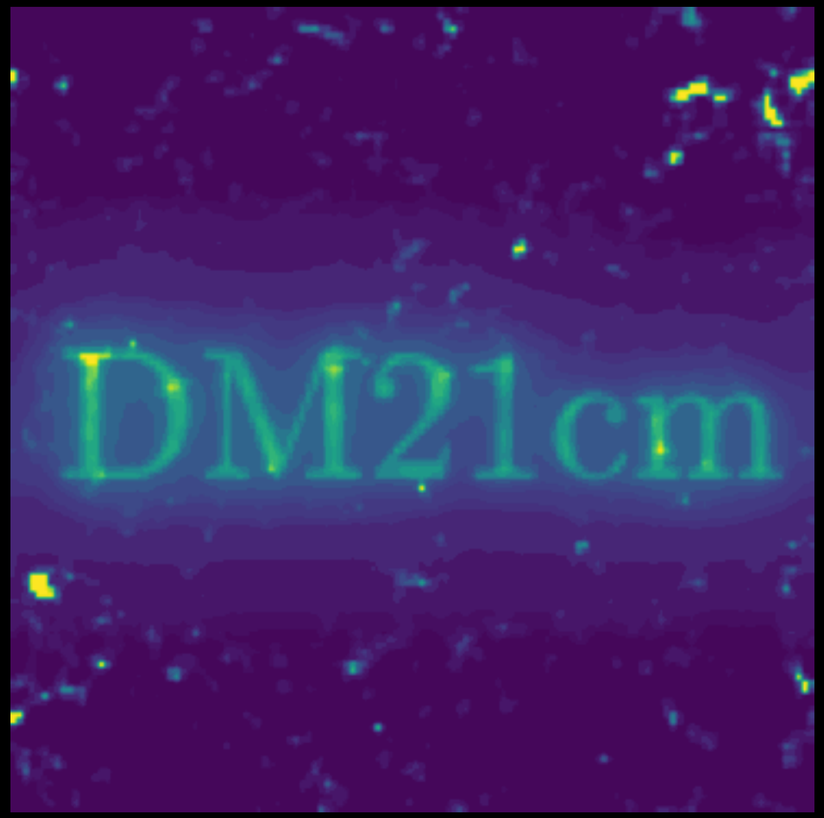


Summary

- We built **`DM21cm`**: a simulation for dark matter energy injection during reionization based on **`21cmFAST`** that self-consistently deposit energy into the IGM, and tracks long-lived propagating photons.

- We computed dark matter monochromatic decay signals, and HERA's sensitivity to this signal with a Fisher information forecast.

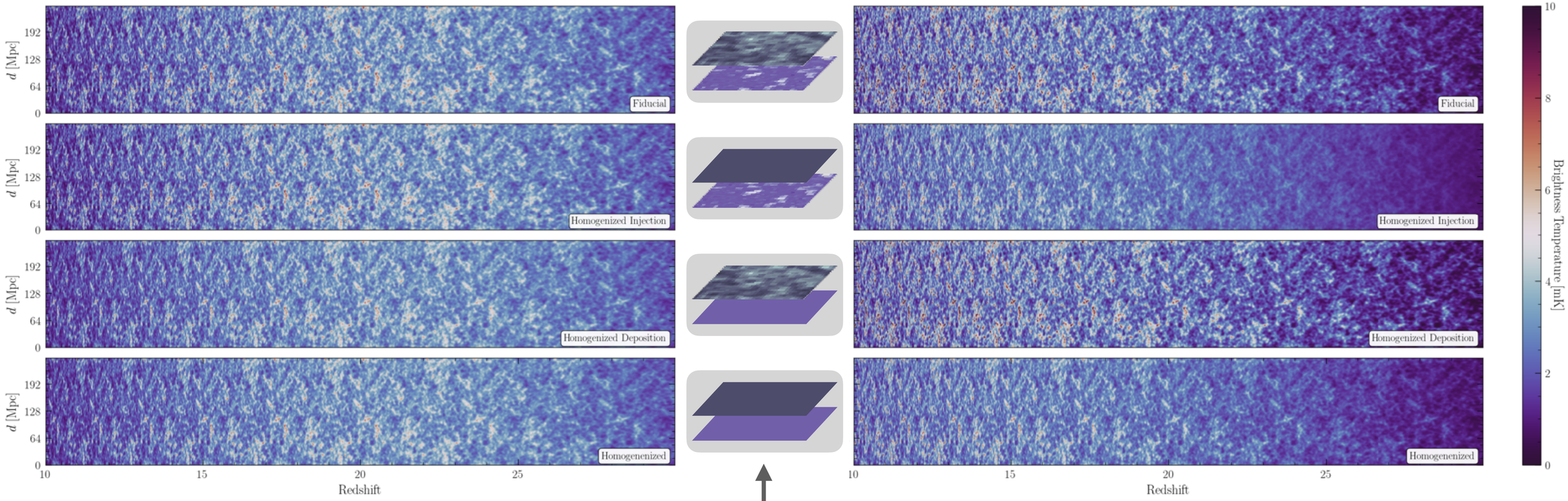
- Our analysis is made possible by GPUs, as running on CPUs would be forbiddingly hard. We have plans to accelerate the base **`21cmFAST`** code with GPUs as well.



Thank you!

Backup

T_{21} signal: homogeneous injection / deposition



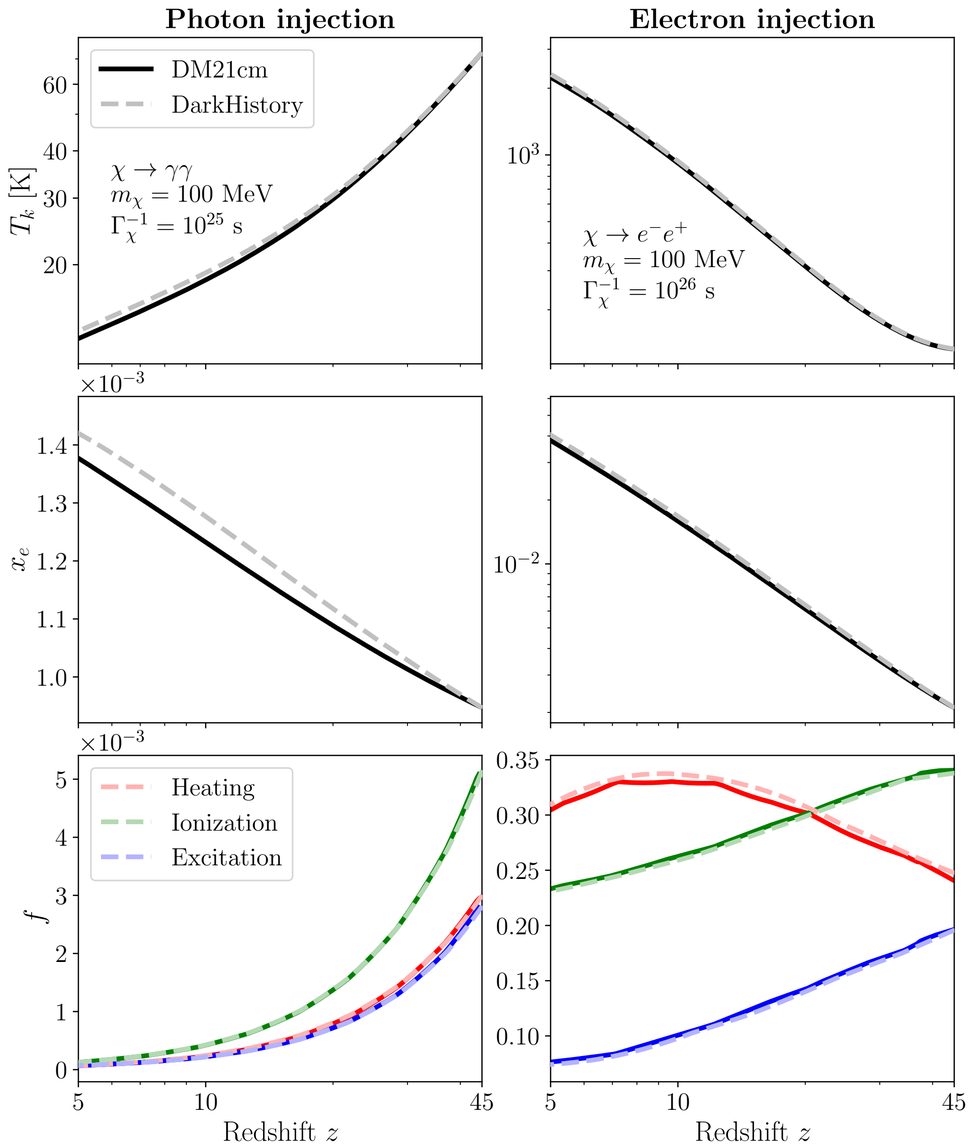
T_{21} signal for $\chi \to \gamma\gamma$, with $m = 5$ keV and $\tau = 10^{26}$ s

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

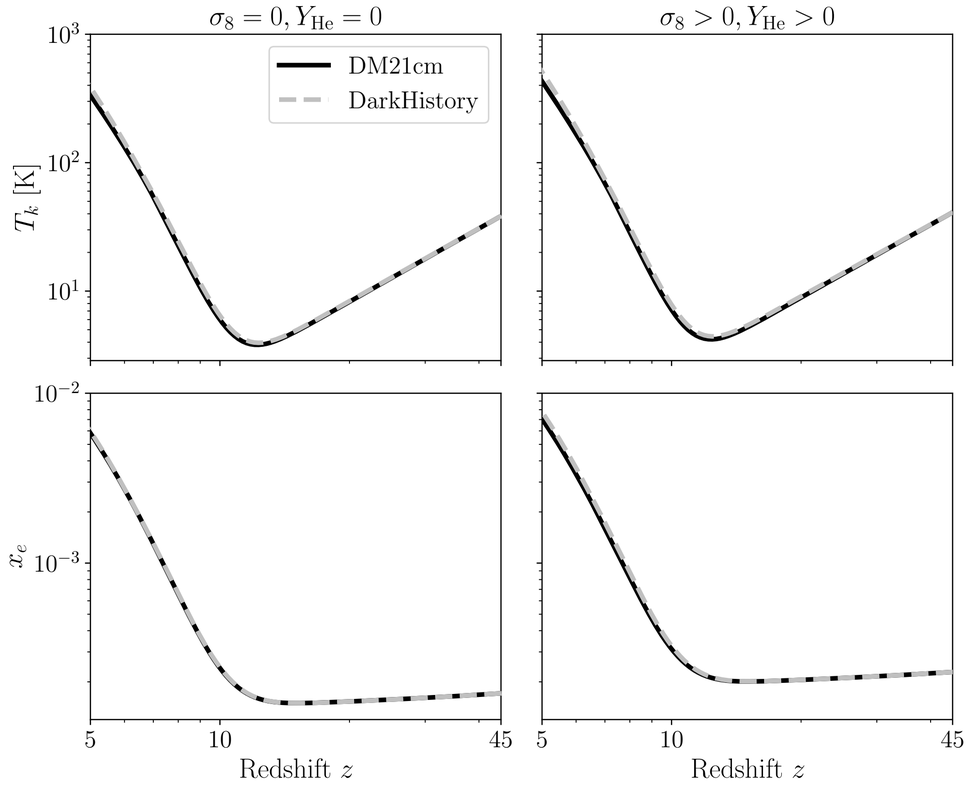
Injection $dE/dVdt$

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

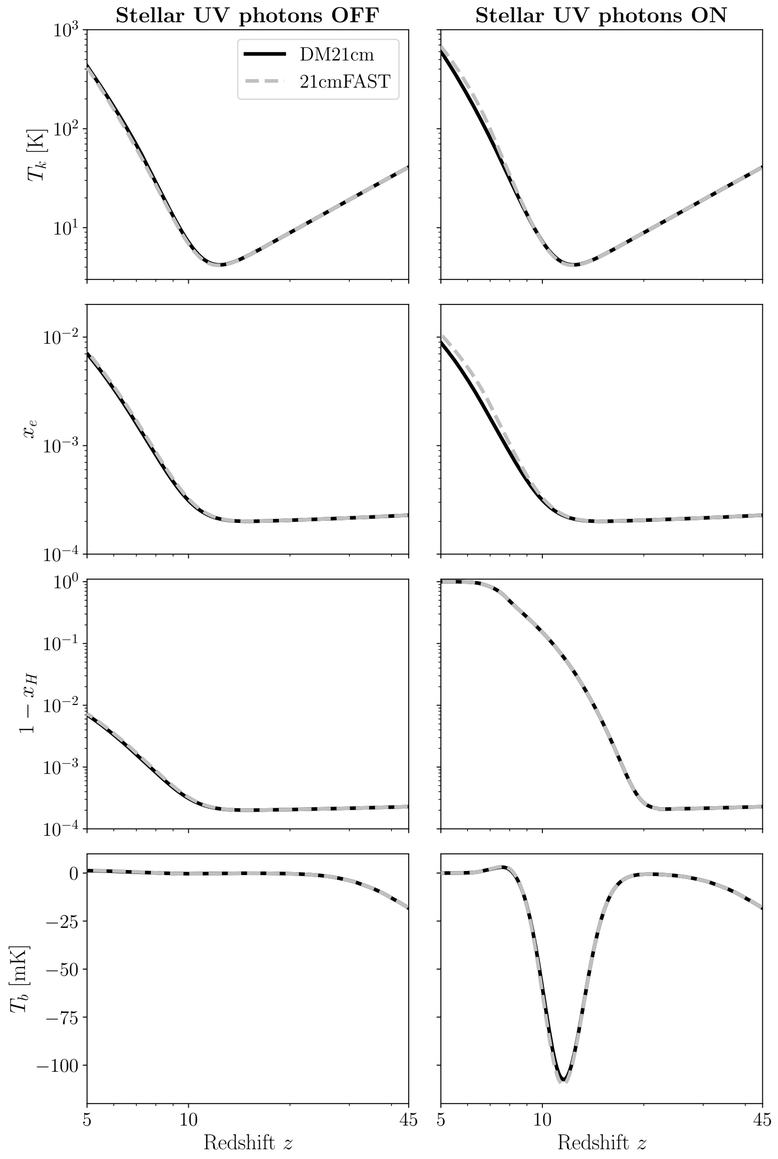
Cross check: DarkHistory and DM21cm

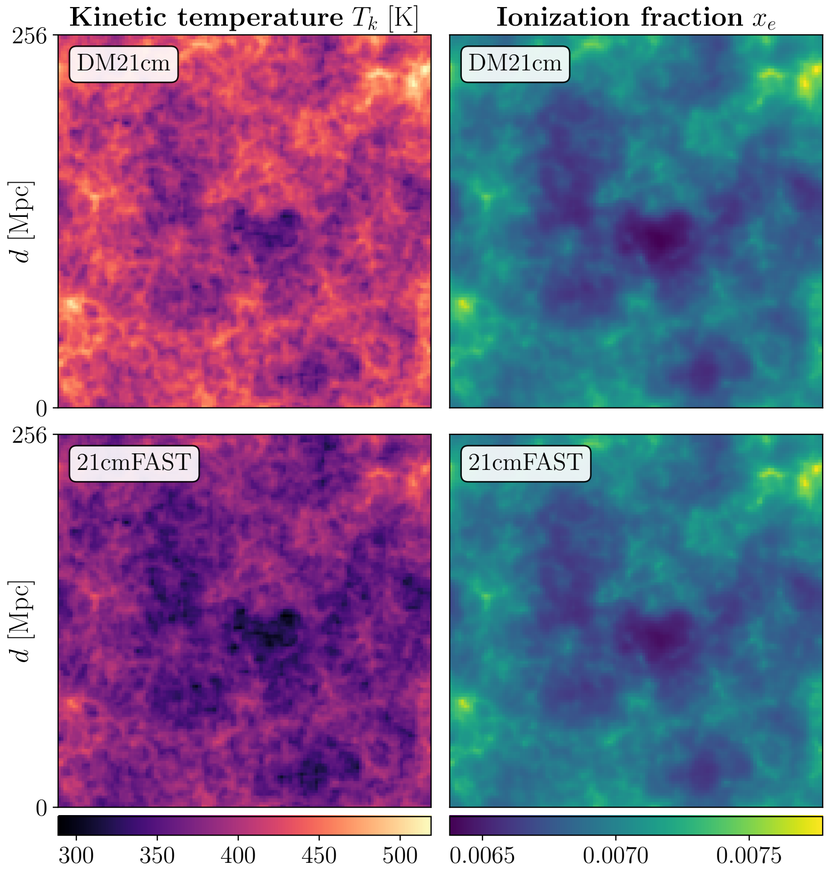


X-ray injection (Sheth-Torman HMF)



Cross check: 21cmFAST & DM21cm





spatiotemporal convergence