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

Speakers: Yitian Sun

Collection: Dark Matter, First Light

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Abstract: The 21-cm signal provides a novel avenue to measure the thermal state of the universe during cosmic dawn and reionization, and thus a probe of exotic energy injection such as those from decaying or annihilating dark matter (DM). These DM processes are inherently inhomogeneous: both decay and annihilation are density dependent, and furthermore the fraction of injected energy that is deposited at each point depends on the gas ionization and density, leading to further inhomogeneities in absorption and propagation.

In this talk, I will present a new framework for modeling the impact of spatially inhomogeneous energy injection and deposition, accounting for ionization and baryon density dependence, as well as the attenuation of propagating photons. Our simulation code, DM21cm, is the first complete inhomogeneous treatment of the effects on the 21-cm power spectrum under exotic energy injection. With our pipeline, I will present the sensitivity forecast of the upcoming HERA 21-cm power spectrum measurements to DM decays to photons and electron/positron pairs.

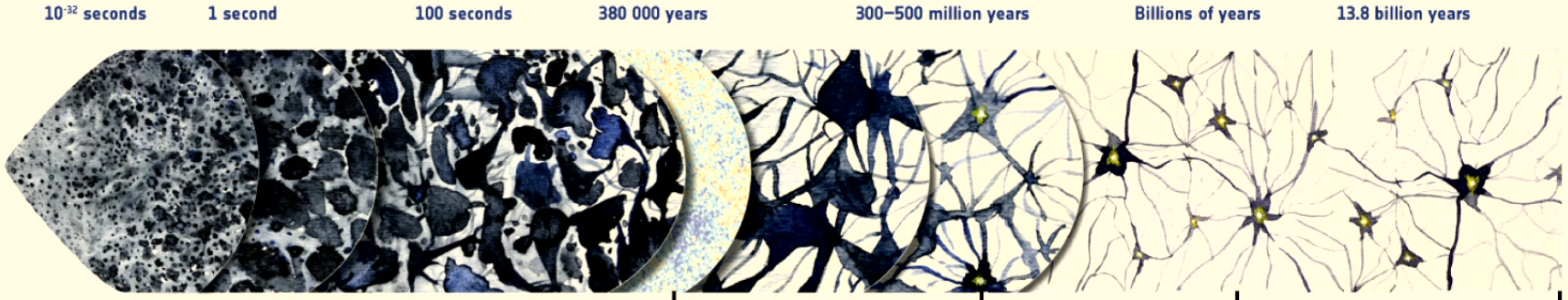
Probing **Dark Matter Energy Injection** in the Cosmic Dawn with the **21-cm Power Spectrum**

Yitian Sun

The NSF Institute for Artificial Intelligence and Fundamental Interactions

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 | z=15~6 Reionization | z=0 Present day

PopIII stars (1st gen) | PopII stars (2nd gen) | 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

first stars | 21-cm line | Ly-α forest | X-ray/γ-ray observations

thermal/ionization history

Outline

- I. Introduction: the 21-cm line observable
- II. Our dark matter energy injection 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

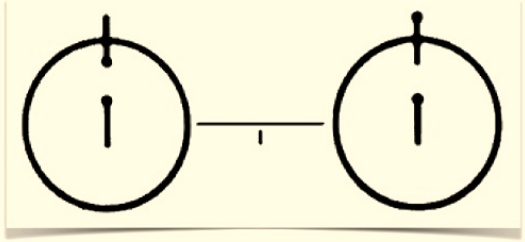
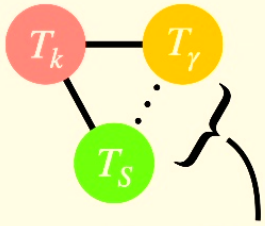
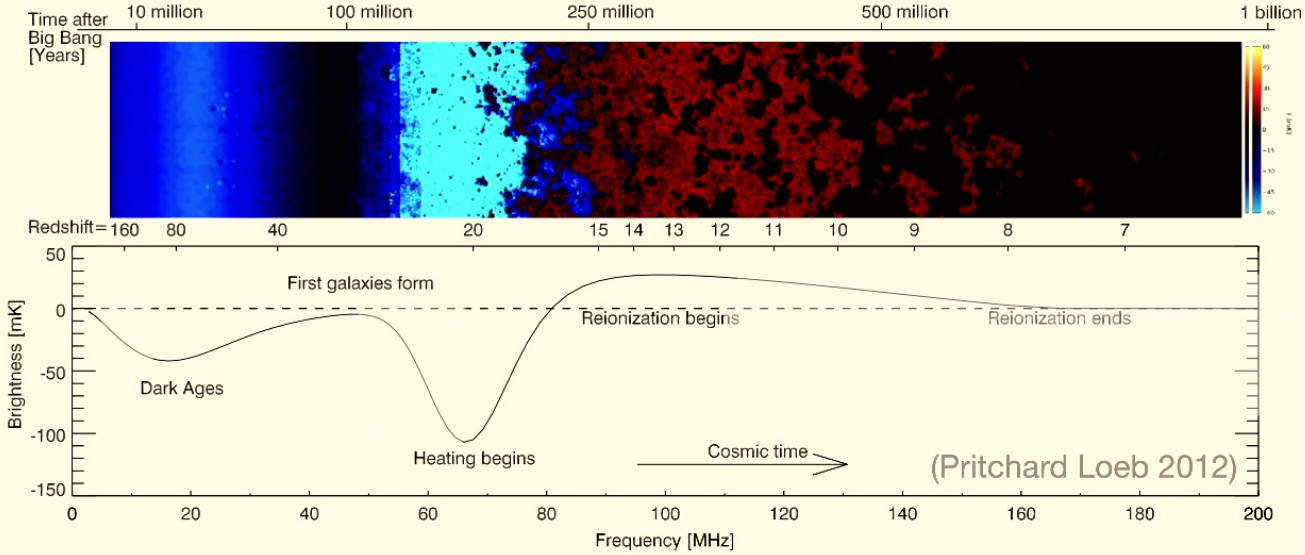


diagram on board the *Voyagers*

relative abundance $\rightarrow T_S$

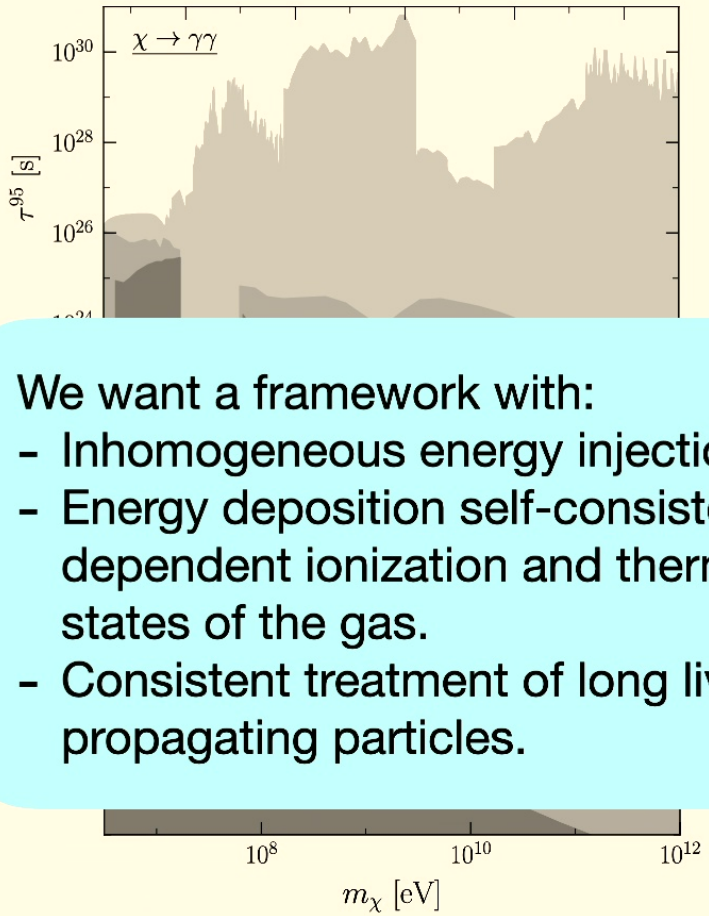


$$T_{21} \propto x_H (T_S - T_\gamma)/T_S$$



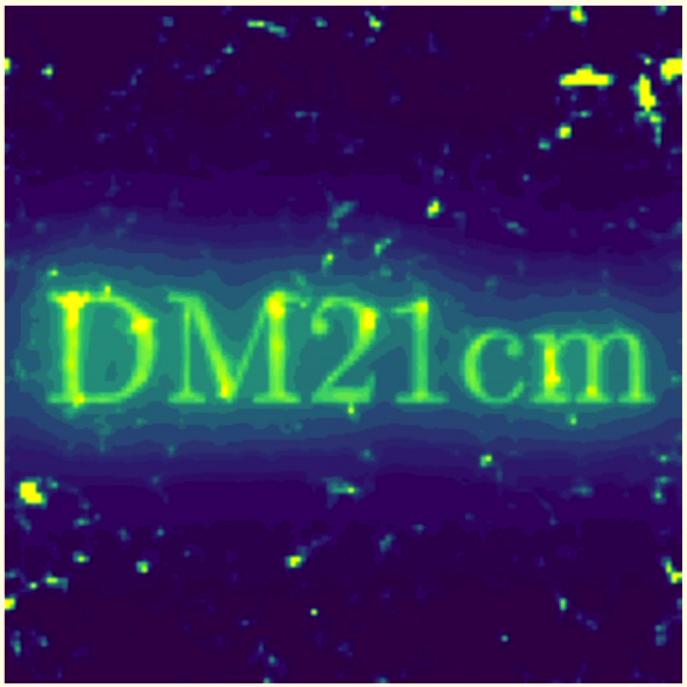
DM decay/annihilation constraints

- X-ray and γ-ray observations: line signals, present day universe.
- CMB: LOS integrated information.
- Lyman-α: Hard to pass through neutral hydrogen. LOS information.
- 21-cm line: 3D information. Sensitive to total energy injection. Direct access to ionization and thermal state.
  - Previous works have been using simplified deposition models and/or homogeneous energy injection. *e.g.* (Facchinetti *et al* 2023)



We want a framework with:
- Inhomogeneous energy injection.
- Energy deposition self-consistently dependent ionization and thermal states of the gas.
- Consistent treatment of long lived propagating particles.

Part II: Our simulation **DM21cm**



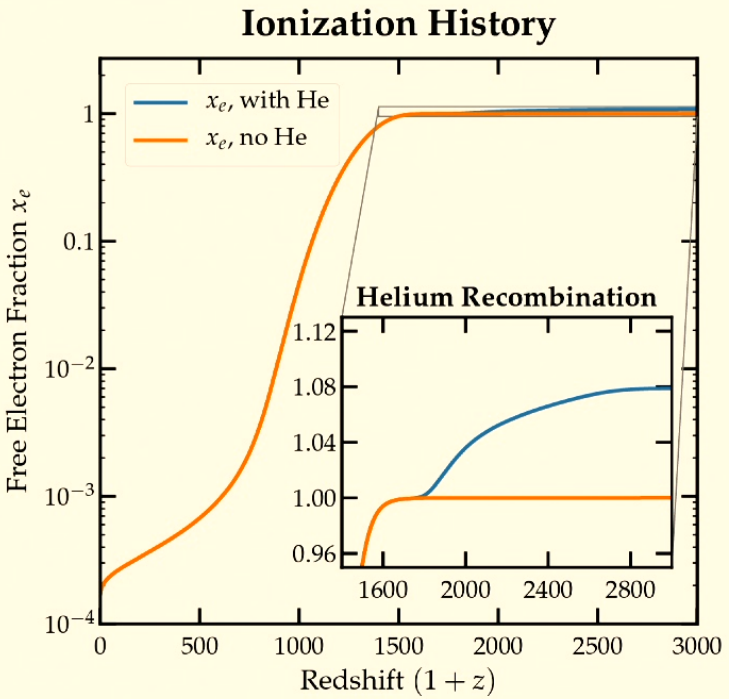
Part II: Our simulation **DM21cm**

- 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).
- 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.



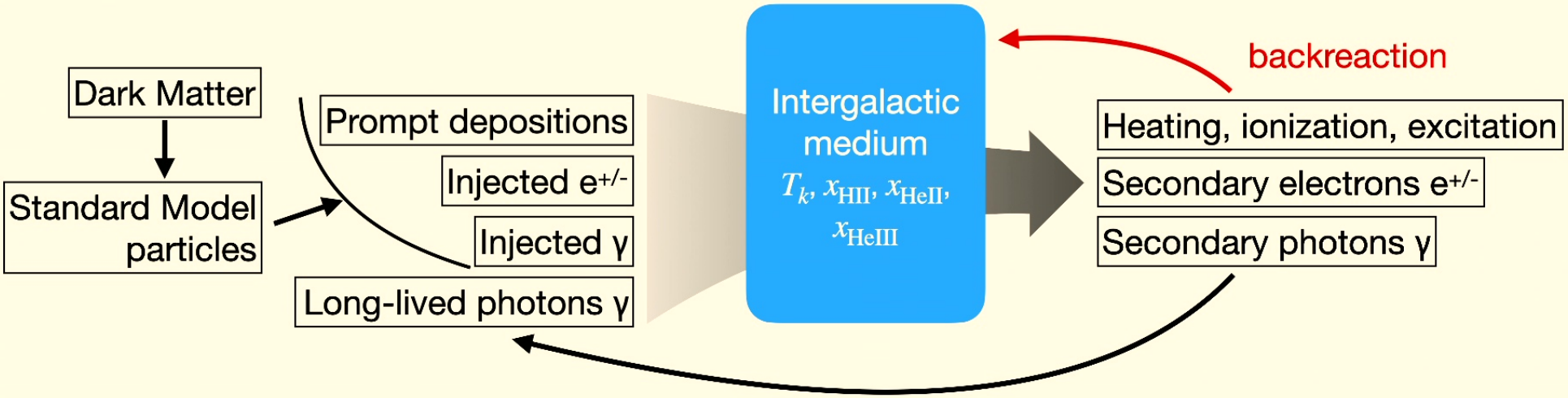
Liu, Ridgway, Slatyer (2019)

DarkHistory γ and $e^{+/-}$ processes

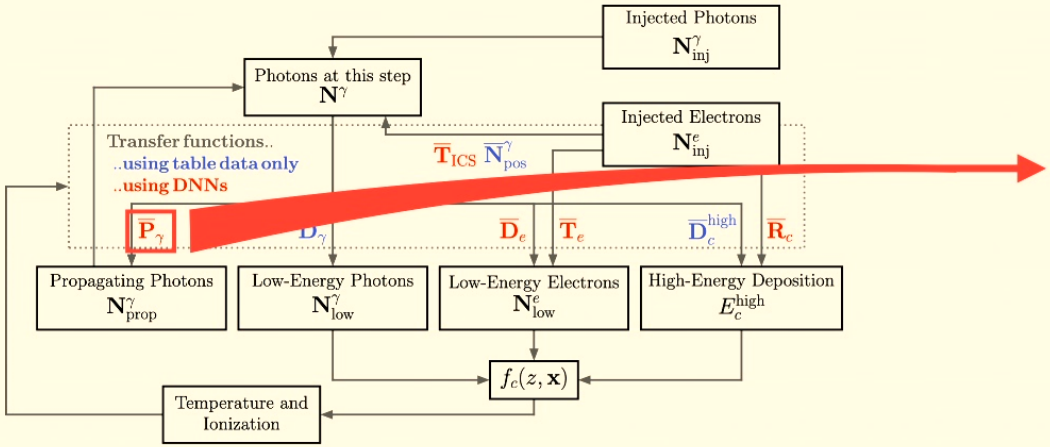
γ :
- Compton scatter -> γ, e^-
- Pair produce -> e^+, e^-
- Heat, ionize, excite matter
- Just redshift

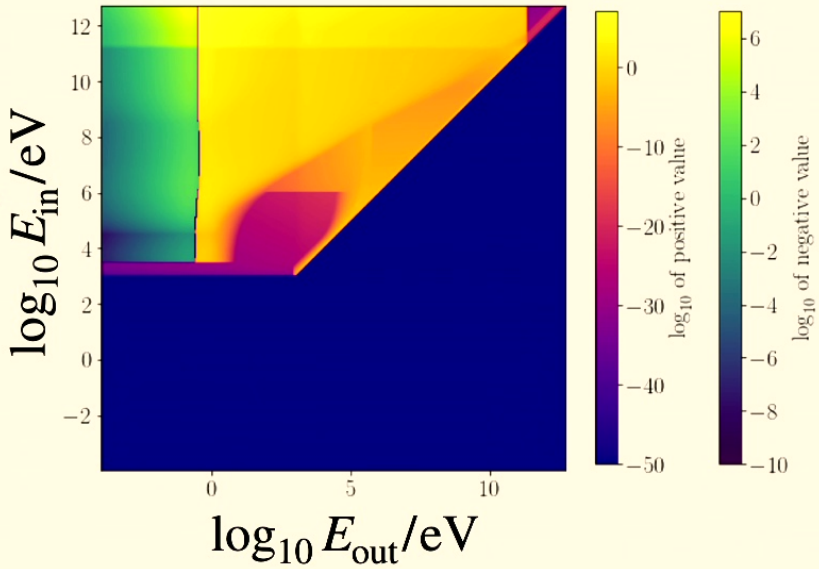
e^- :
- Inverse Compton scatter -> γ, e^-
- Heat, ionize, excite matter

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



DarkHistory particle transfer functions



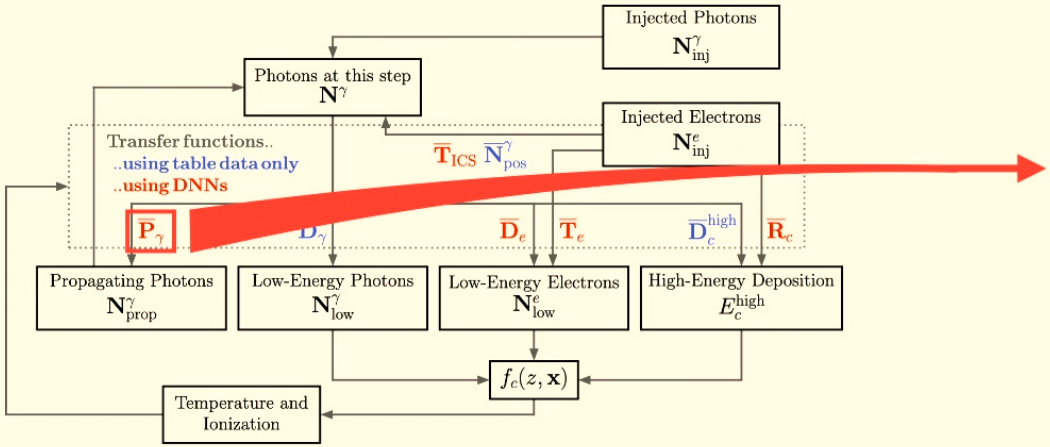


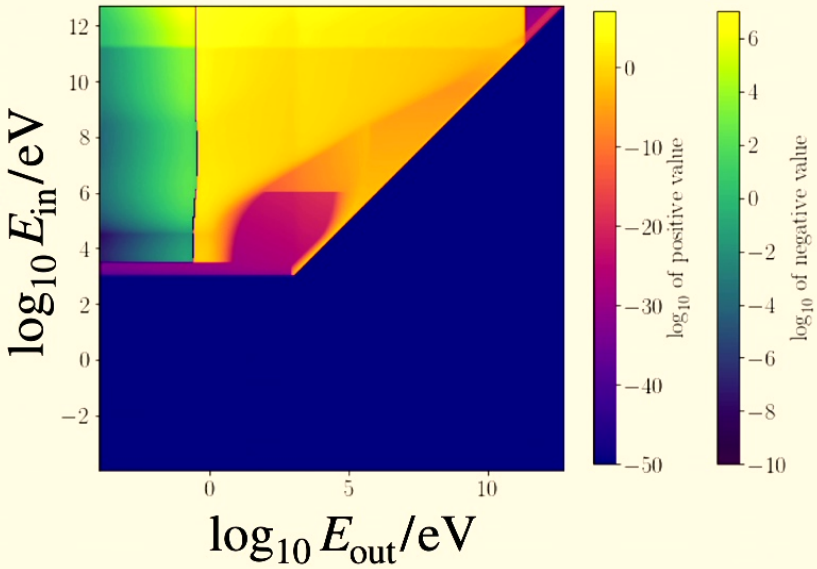
- Transfer functions encode all the physical processes for **`DarkHistory`**.
- Similar ones are generated for energy deposition in **`DM21cm`**.

Can dependent on:

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

DarkHistory particle transfer functions





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

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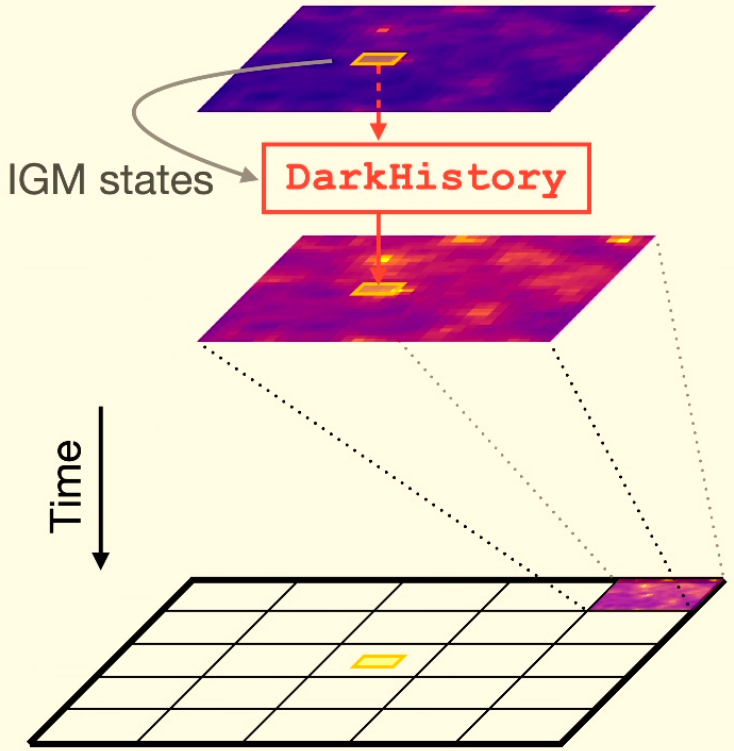
Plan for DM21cm

- 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.



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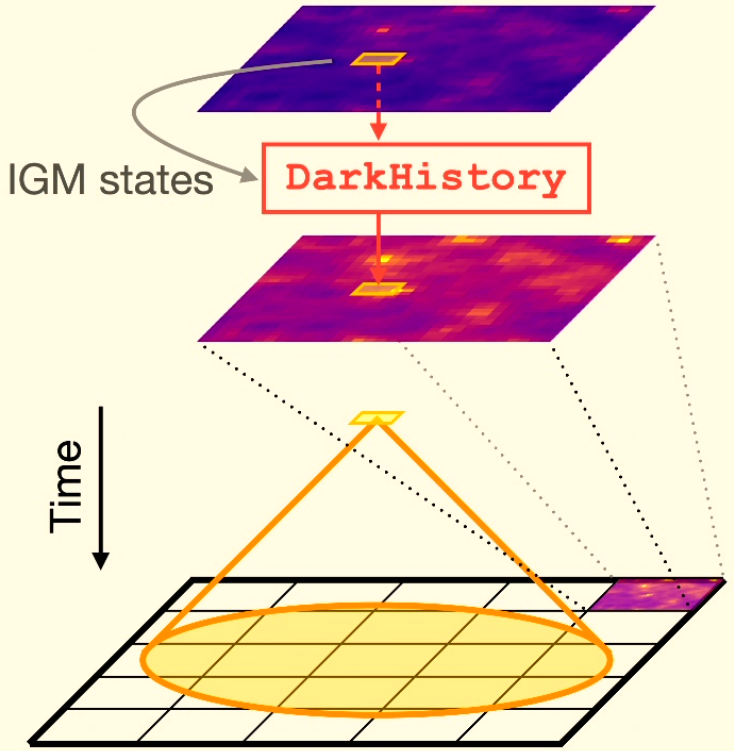
  - long-lived photons saturate the box quickly, but deposit energy over long period of time. Can model as a homogeneous isotropic bath.



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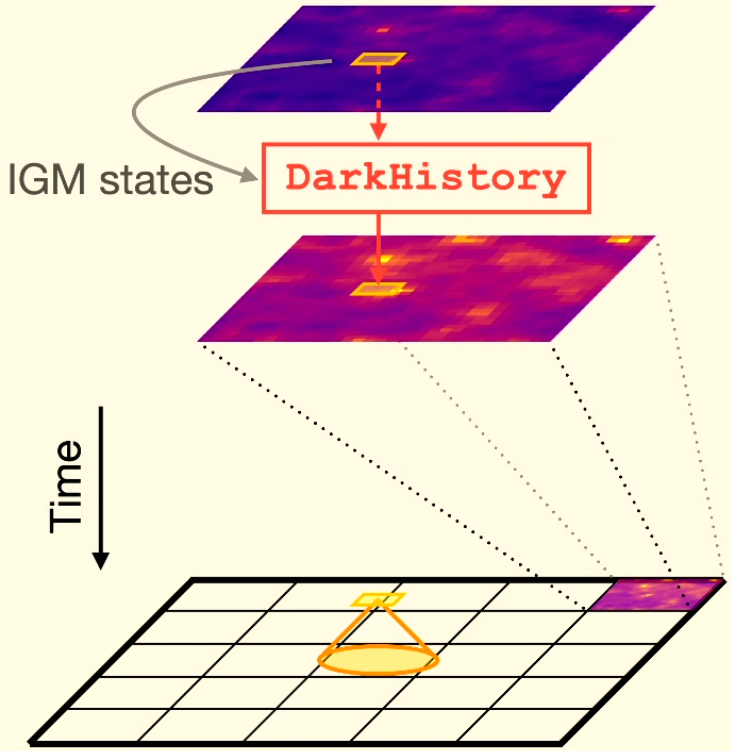
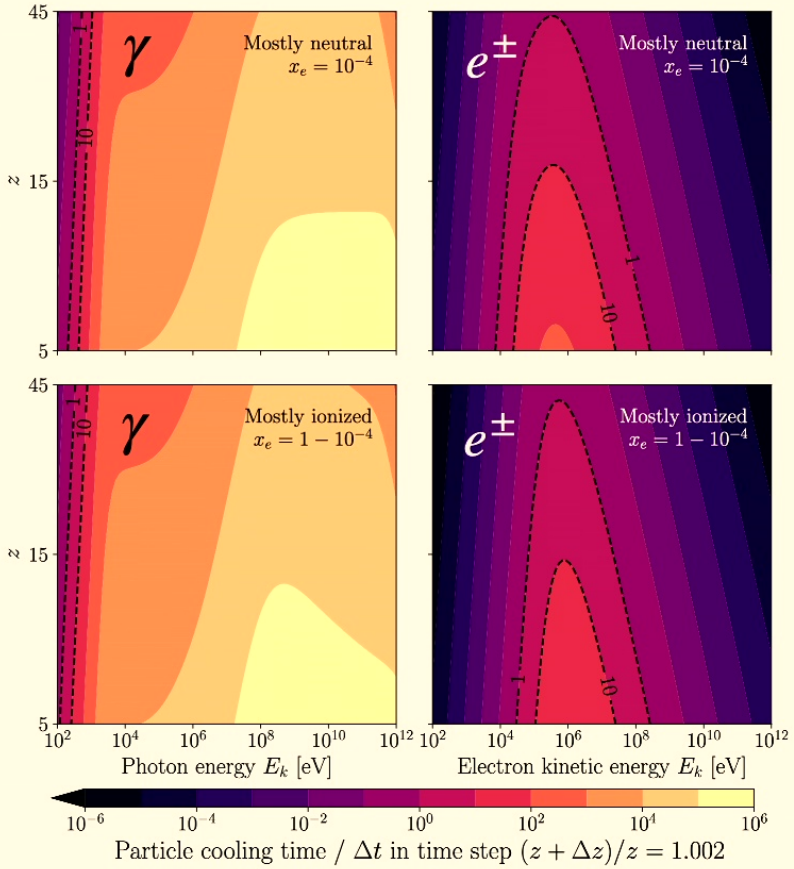
  - What about particles in between?



Transparency window

Photons:

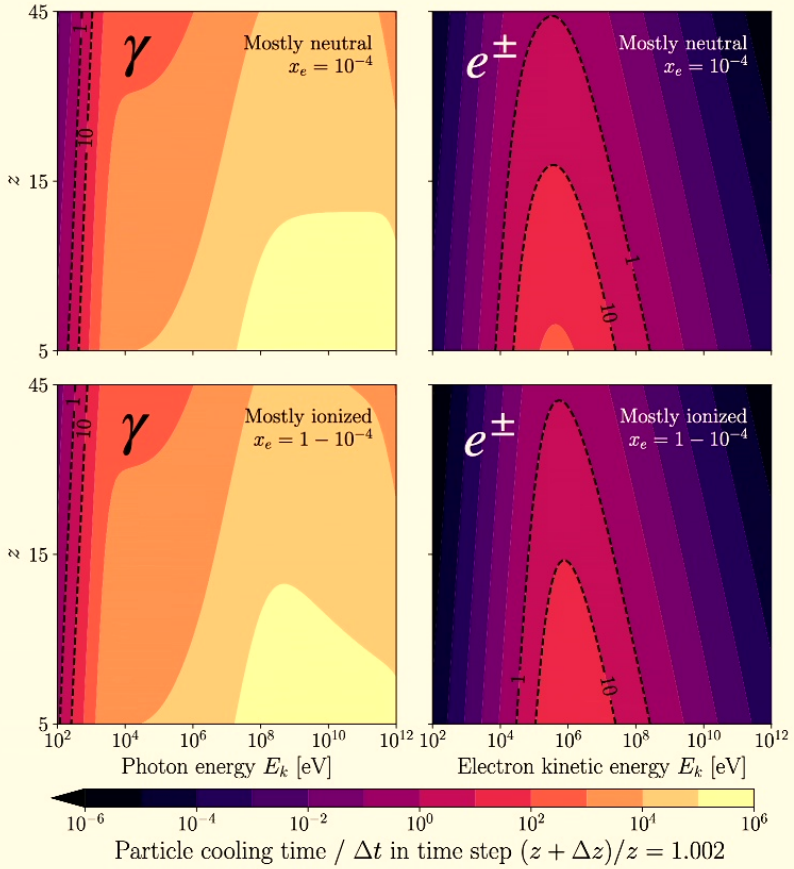
- High energy photons free stream and are long-lived.



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.



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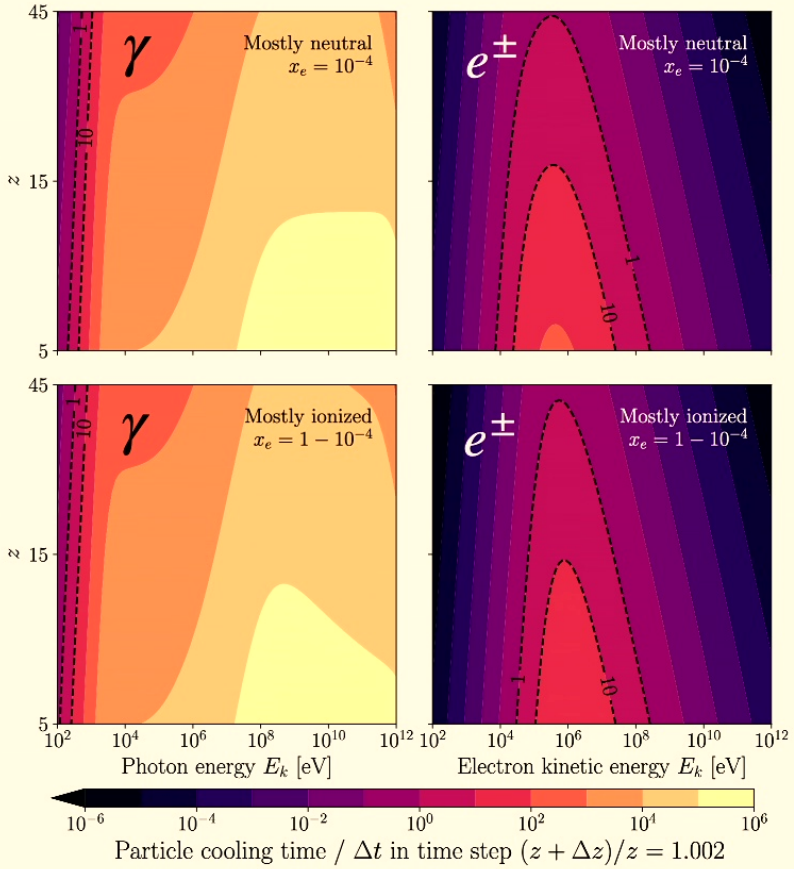
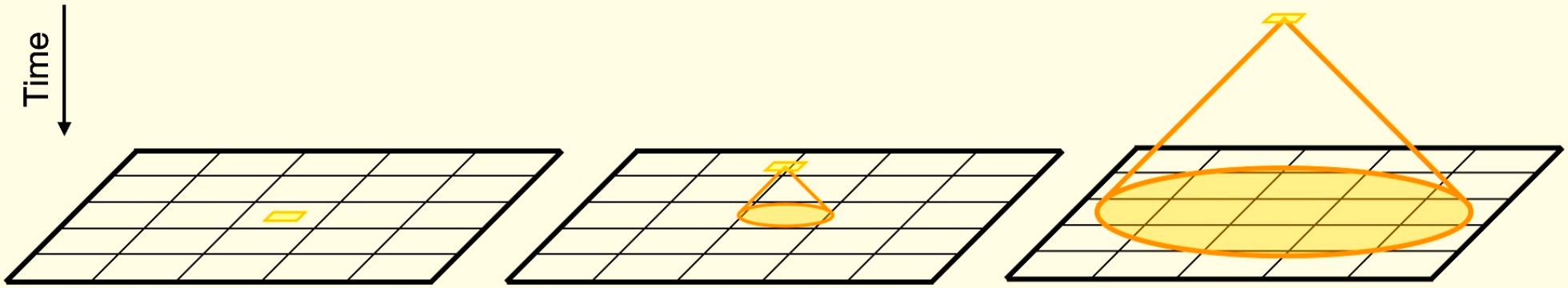


Electrons:

- 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.

Photons: 3 regimes



low energy photons
(10.2 to ~100 eV)
deposits promptly and
on-the-spot (OTS).

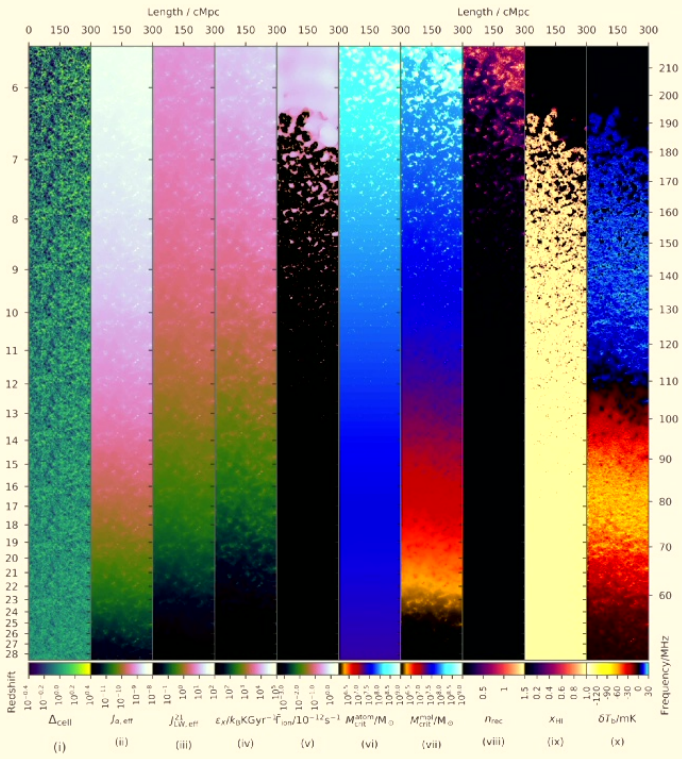
X-ray photons
(~100 eV to ~10 keV)
deposits in a portion of
the simulation box.

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:

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

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



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

On-the-spot and bath depositions

Can be implemented in a straightforward manner.

On-the-spot Bath

Modifying the EoM

Dark matter (all injections) contributes the red terms:

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

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

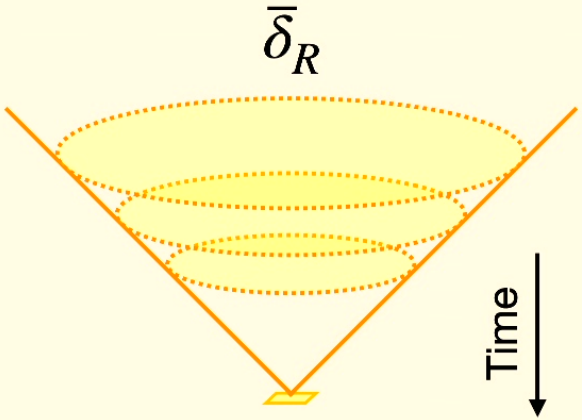
$$J_\alpha \to J_\alpha + J_\alpha^{\rm DM}$$

Ly-α modifies the coupling of T_k to the color temperature T_α.

$$T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_k^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_c + x_\alpha} \qquad x_\alpha \propto J_\alpha/(1+z)$$

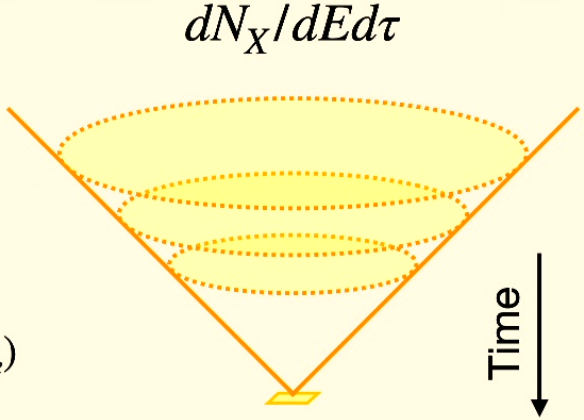
`21cmFAST`'s X-ray treatment

- **`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 $\overline{\delta}_R$, 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.

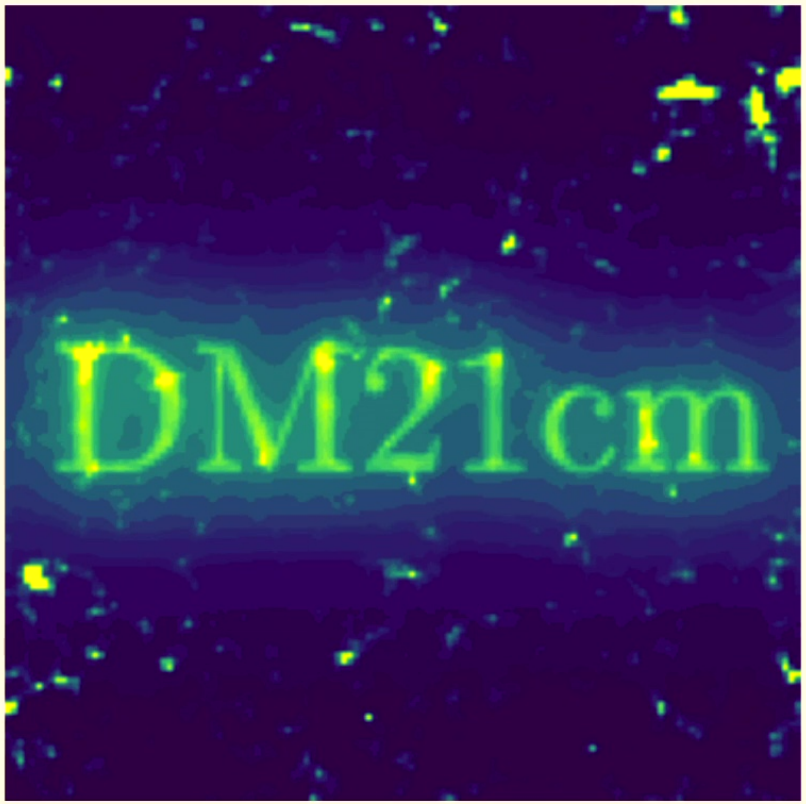


`DM21cm`'s X-ray treatment

- 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.



X-ray in action



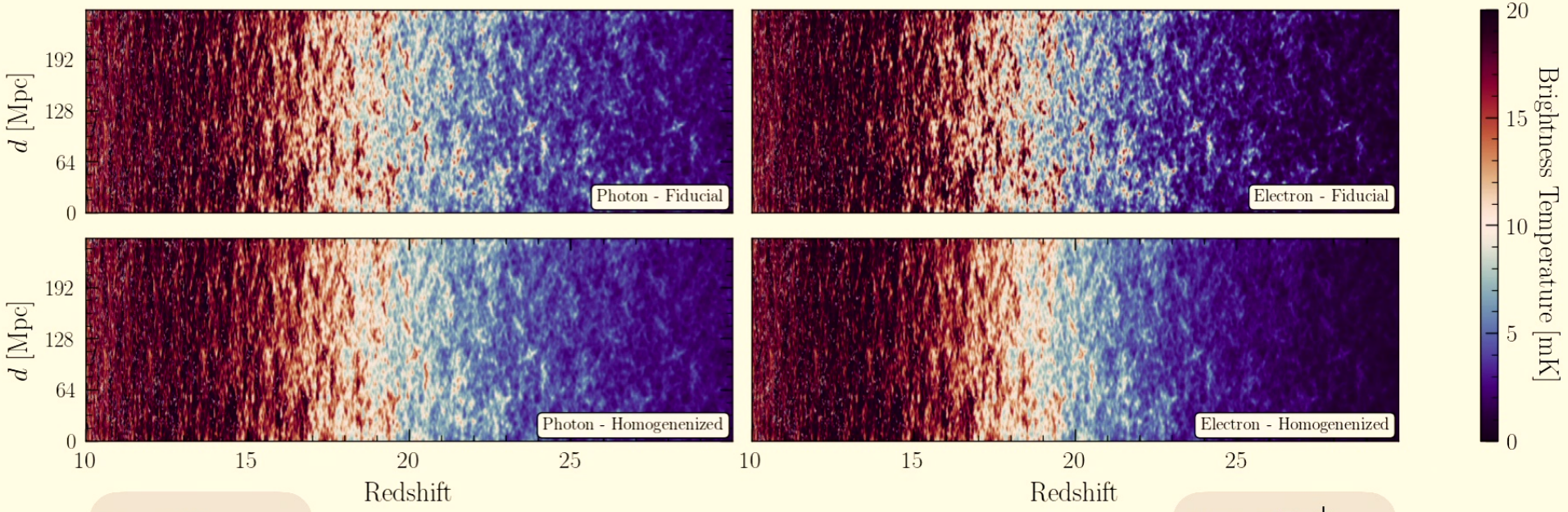
Expanding halo
of ionization
due to X-rays.

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)
```

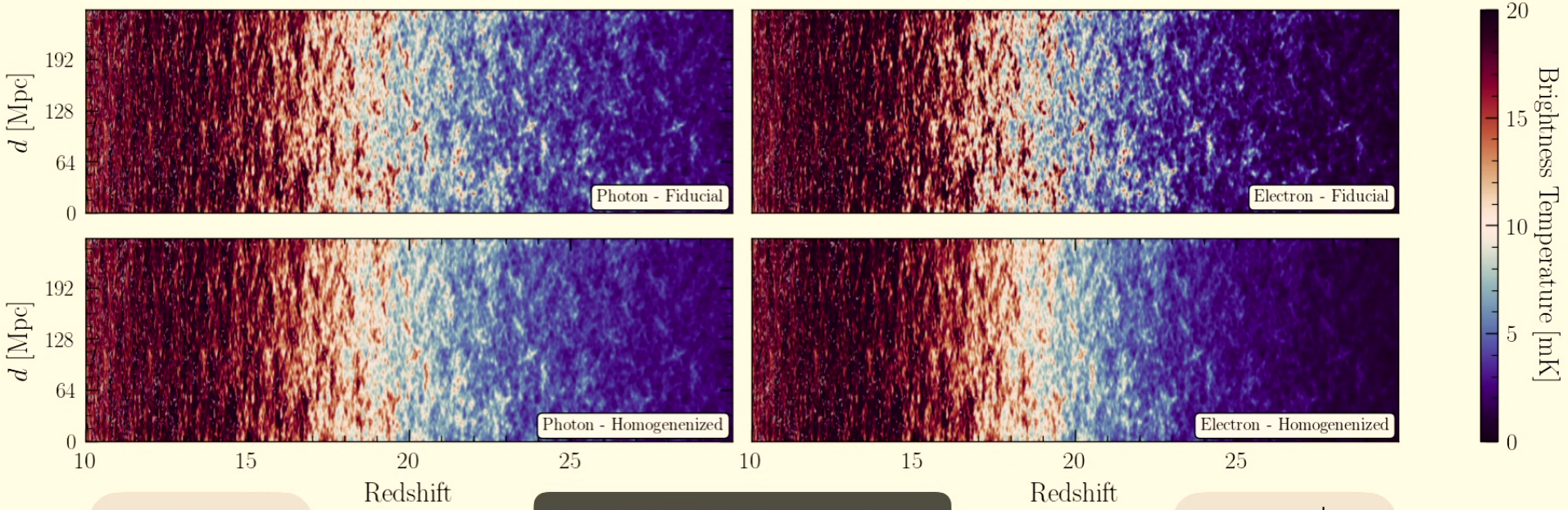
T_{21} signal: large signal limit



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

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

T_{21} signal: large signal limit



$\chi \to \gamma\gamma$
$m = 5$ keV
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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
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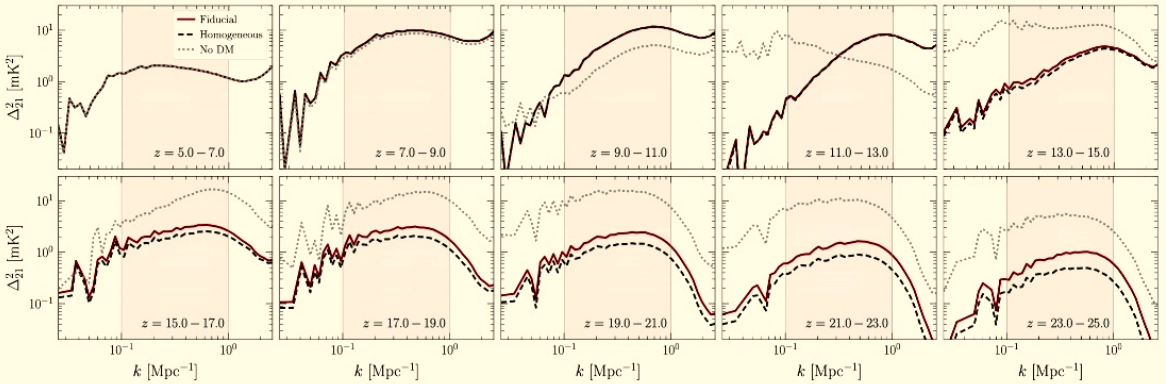

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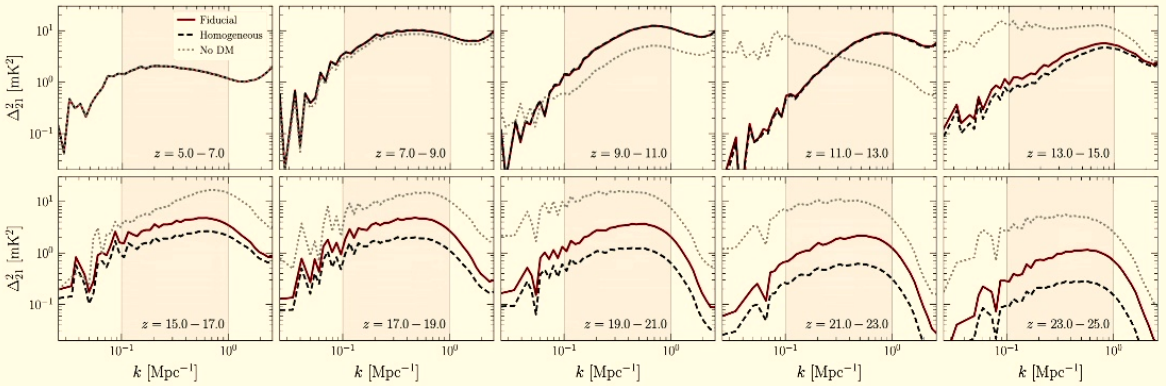
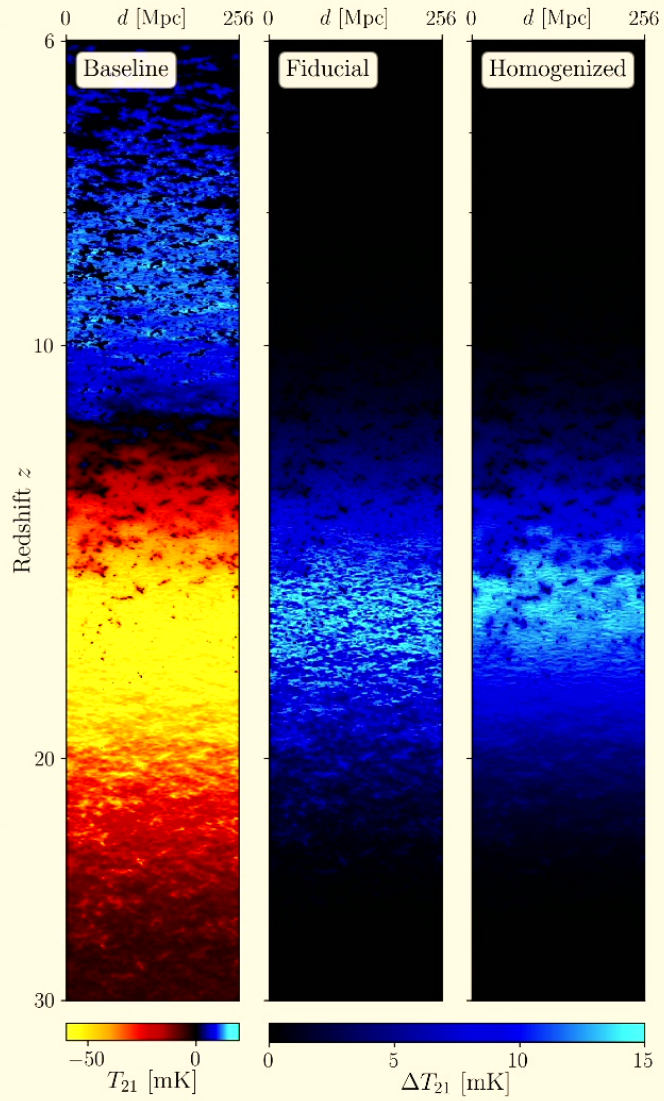


Fiducial
Homogeneous
No DM

T_{21} signal: small signal limit



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

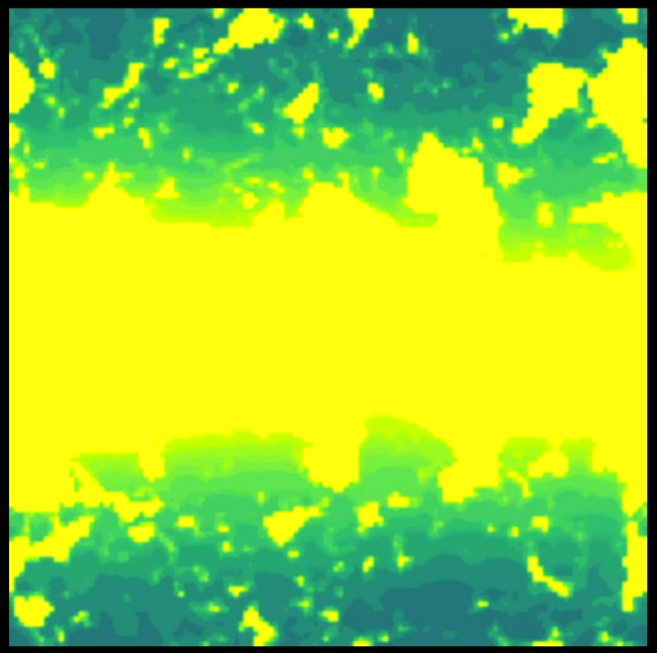
Inhomogeneous rates

Summary

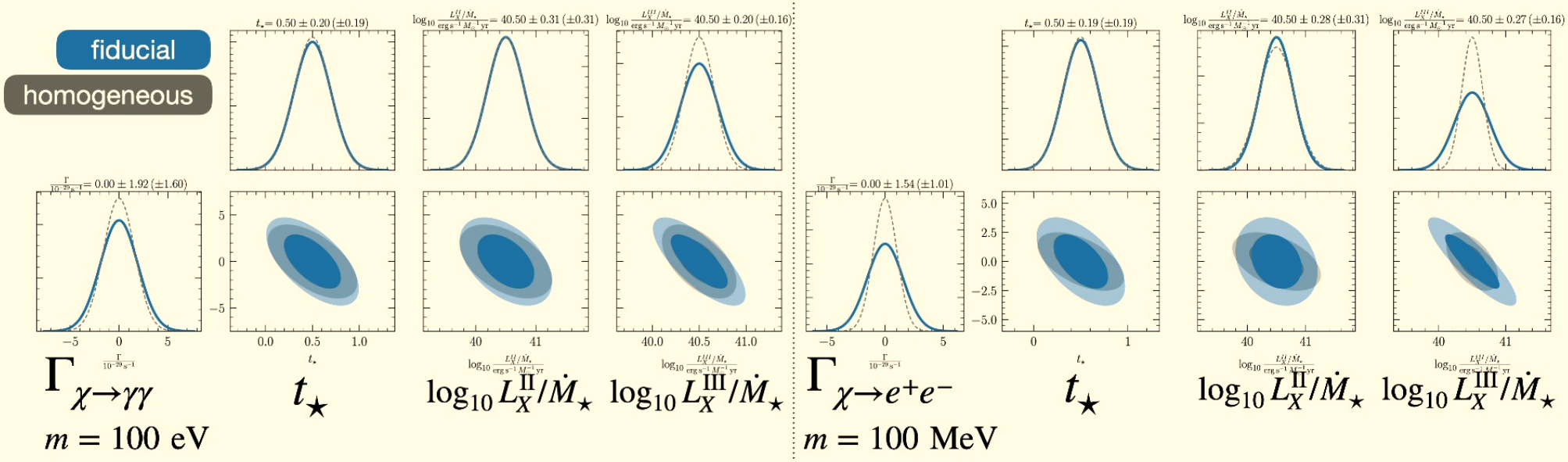
- We built **`DM21cm`**: a simulation for dark matter energy injection during reionization based on **`21cmFAST`** that self-consistently deposit energy into the IGM, and tracks long-lived propagating photons.

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

- Many avenues for future improvements, in the simulation itself, subgrid models 😇, initial conditions… stay tuned + happy to chat



Degeneracy with astrophysical parameters



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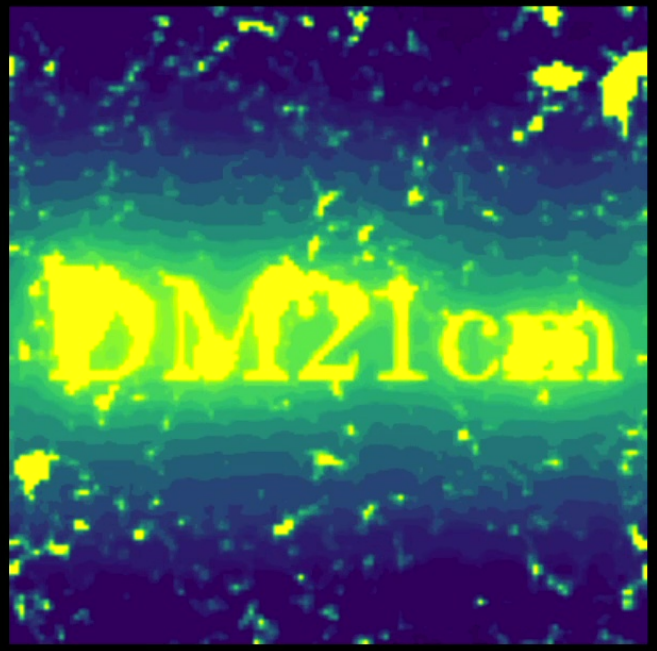
- We computed dark matter monochromatic decay signals, and HERA's sensitivity to this signal with a Fisher information forecast.

- Many avenues for future improvements, in the simulation itself, subgrid models 😇, initial conditions… stay tuned + happy to chat



T_{21} signal: small signal limit