

Simulating the EOR with self-consistent growth of galaxies

Master's thesis presentation

ETH Zürich, University of Zürich

Simulating the Epoch of Reionization

BEoRN

Halo growth

Adaptations

Results

Conclusion

End

References

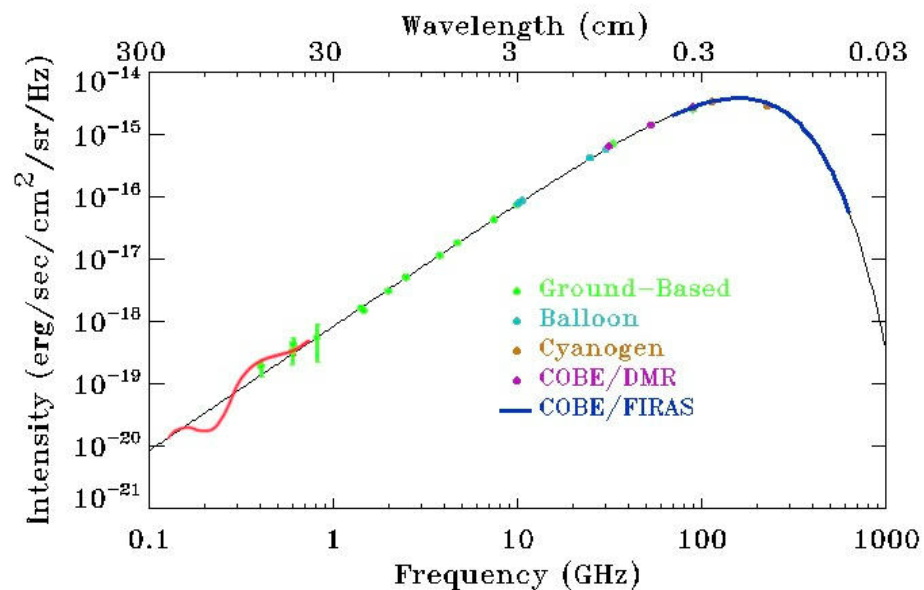
Simulating the Epoch of Reionization

- The 21-cm signal
- Expression the 21-cm signal [1], [2]
- The current state of simulations

The 21-cm signal

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The *brightness temperature* describes the intensity of the 21-cm line

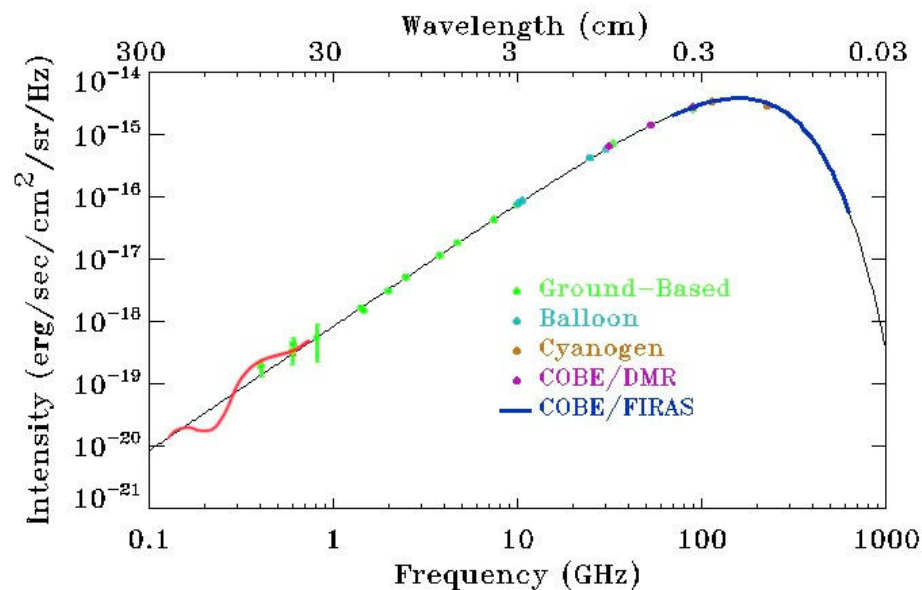


from [3]

The 21-cm signal

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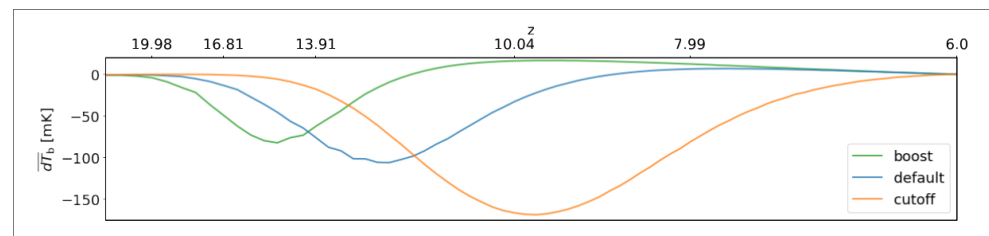


from [3]

remove contribution from the BB spectrum

differential brightness temperature

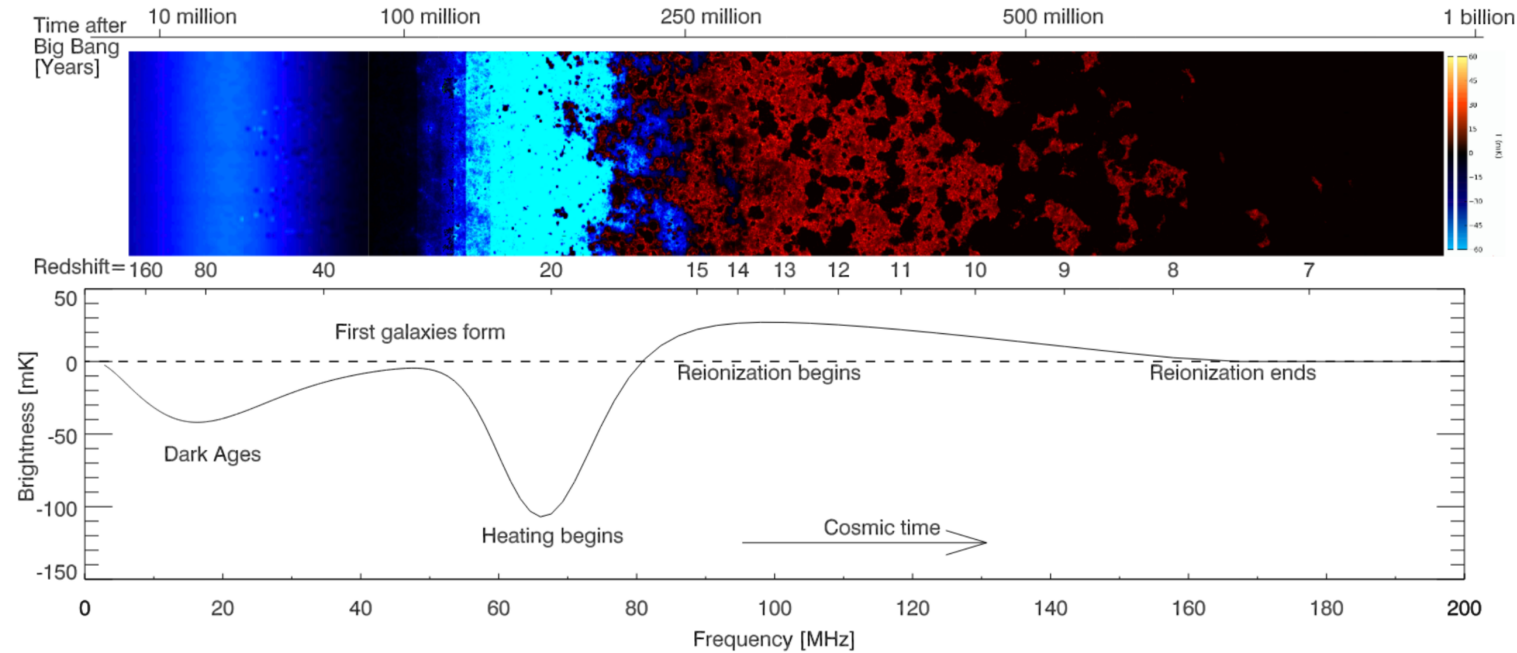
⇒ the actual reionization signal



from [4]

Expression the 21-cm signal [1], [2]

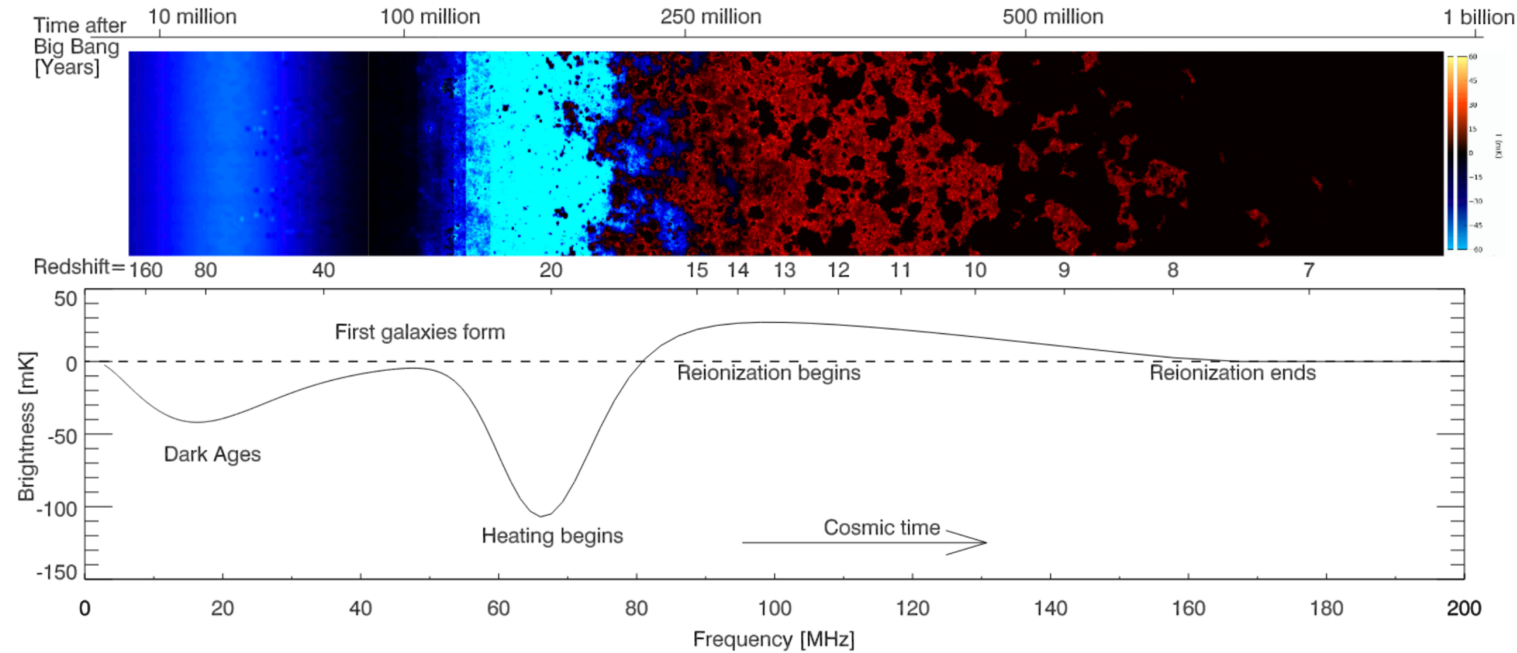
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Simulating the EOR with self-consistent growth of galaxies

Expression the 21-cm signal [1], [2]

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$$dT_b(\mathbf{x}, z) \simeq T_0(z) \cdot x_{\text{HI}}(\mathbf{x}, z) \cdot (1 + \delta_b(\mathbf{x}, z)) \cdot \frac{x_\alpha(\mathbf{x}, z)}{1 + x_\alpha(\mathbf{x}, z)} \cdot \left(\frac{1 - T_{\text{CMB}}(z)}{T_{\text{gas}}(\mathbf{x}, z)} \right)$$

Traditional approaches

- need to cover large dynamic range
- hydrodynamics & radiative transfer
- hard to scale
- ⇒ no reproducibility

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Semi-numerical approaches

- such as BEO RN [4], 21cmFAST [5]
- approximative treatment
- prediction of global signals
- scalable + efficient
- ⇒ reproducible and flexible

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BEoRN

- The halo model of reionization
- Revisiting the 21cm signal
- The “painting” procedure
- Postprocessing
- Maps
- Signal

Following [6], [7], the halo model describes (derivation):

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$$\rho_{\alpha}(r \mid M, z) = \frac{(1+z)^2}{4\pi r^2} \cdot \sum_{n=2}^{n_m} f_n \cdot \varepsilon_{\alpha}(\nu') \cdot f_{\star} \cdot \dot{M}(z' \mid M, z)$$

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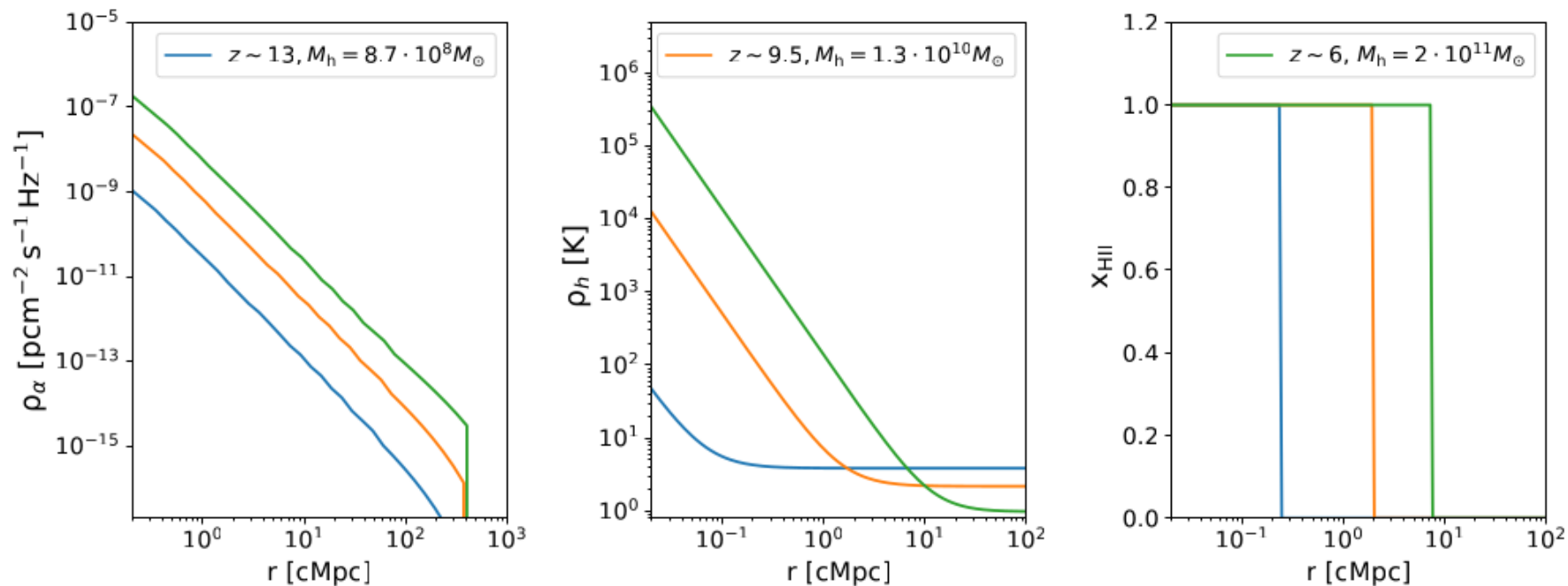
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$$\frac{dV_b}{dt} = \frac{\dot{N}_{\text{ion}}(t)}{\bar{n}_H^0} - \alpha_B \cdot \frac{C}{a^3} \cdot \bar{n}_H^0 \cdot V_b$$

The halo model of reionization

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Visually:



(from [4])

$$dT_b(\boldsymbol{x}, z) \simeq T_0(z) \cdot x_{\text{HI}}(\boldsymbol{x}, z) \cdot (1 + \delta_b(\boldsymbol{x}, z)) \cdot \frac{x_\alpha(\boldsymbol{x}, z)}{1 + x_\alpha(\boldsymbol{x}, z)} \cdot \left(\frac{1 - T_{\text{CMB}}(z)}{T_{\text{gas}}(\boldsymbol{x}, z)} \right)$$

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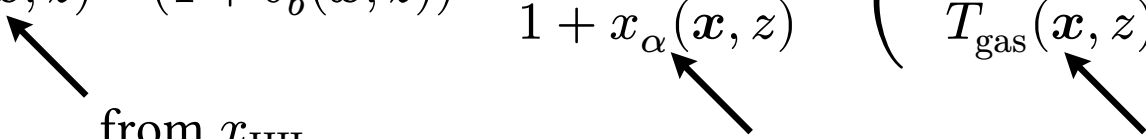
from x_{HII}

$$dT_b(\boldsymbol{x}, z) \simeq T_0(z) \cdot x_{\text{HI}}(\boldsymbol{x}, z) \cdot (1 + \delta_b(\boldsymbol{x}, z)) \cdot \frac{x_\alpha(\boldsymbol{x}, z)}{1 + x_\alpha(\boldsymbol{x}, z)} \cdot \left(\frac{1 - T_{\text{CMB}}(z)}{T_{\text{gas}}(\boldsymbol{x}, z)} \right)$$



from x_{HII} from ρ_α

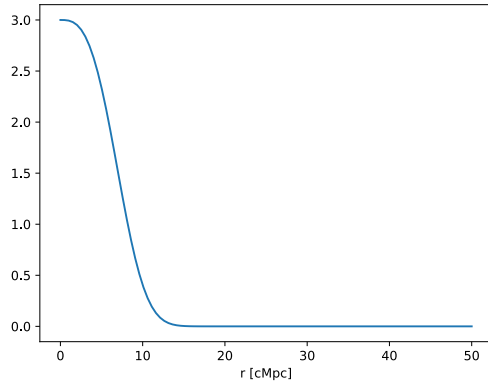
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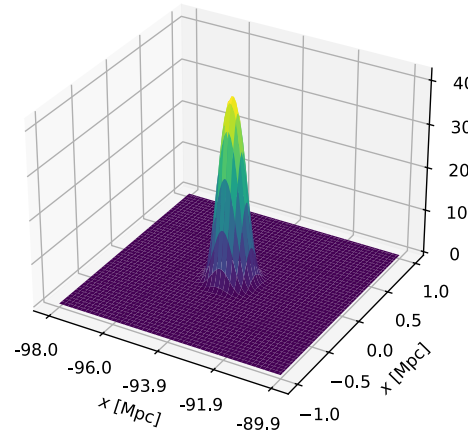
from x_{HII} from ρ_α from ρ_h

The “painting” procedure

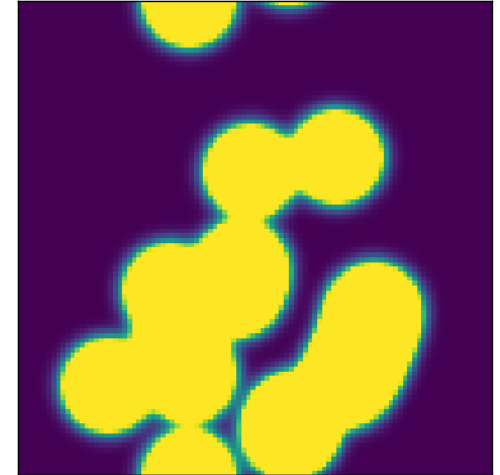
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1-d profile



3-d kernel
(localized)

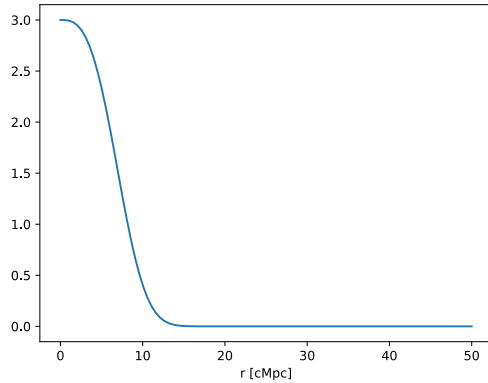


3-d contribution on a
grid

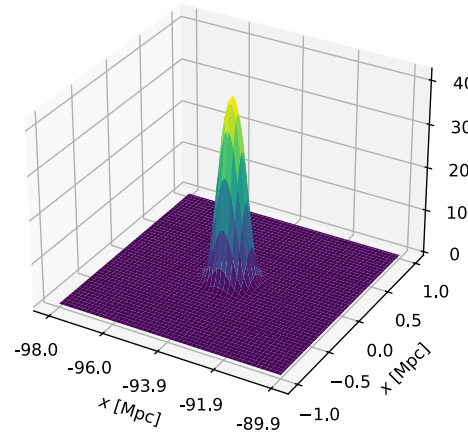
The “painting” procedure

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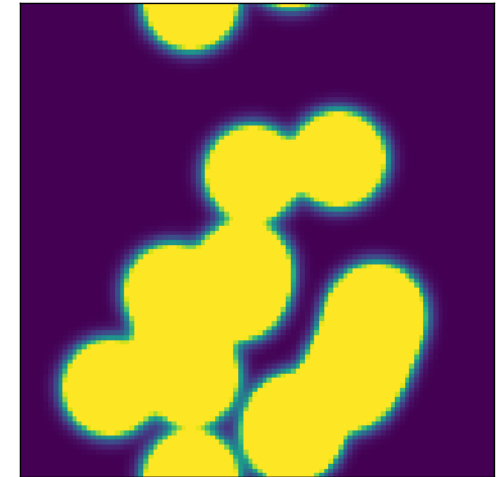
spherical symmetry



1-d profile



3-d kernel
(localized)

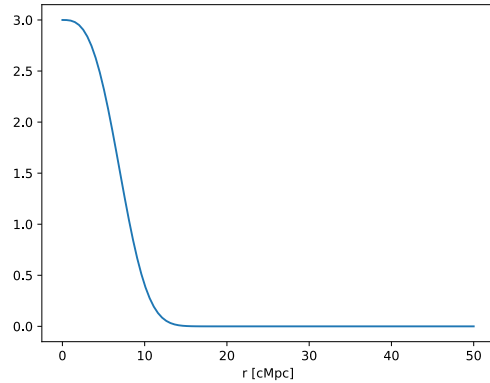


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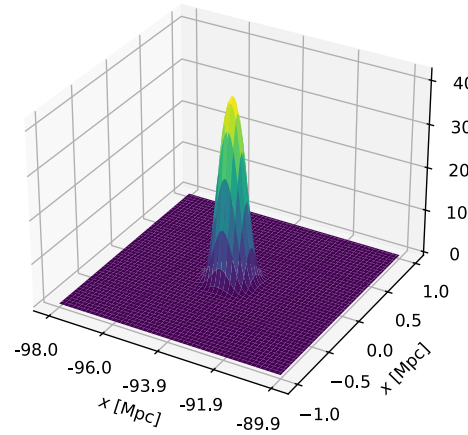
The “painting” procedure

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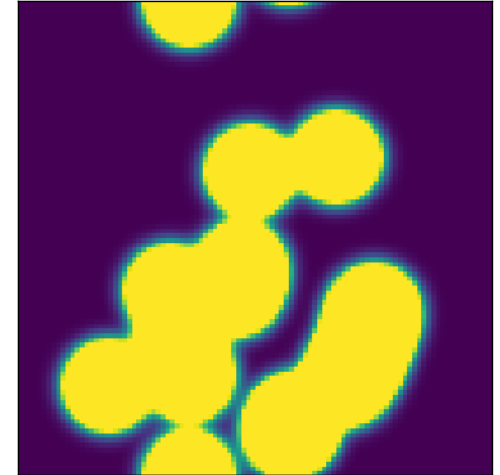


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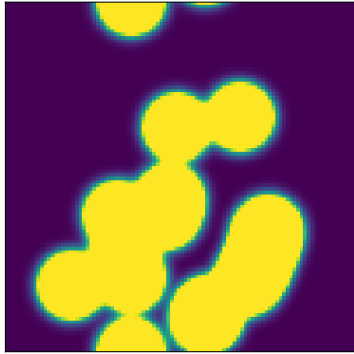
convolution (FFT)



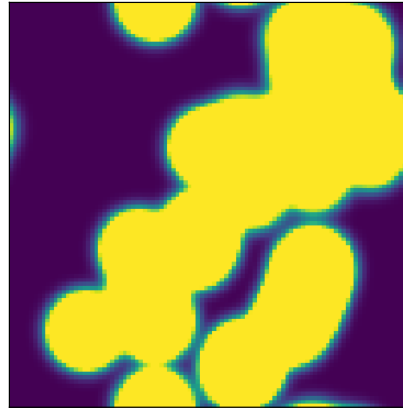
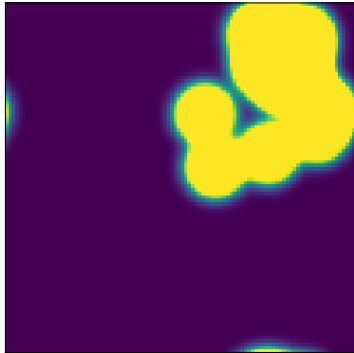
3-d contribution on a
grid

The “painting” procedure

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Multiple contributions $\Rightarrow$

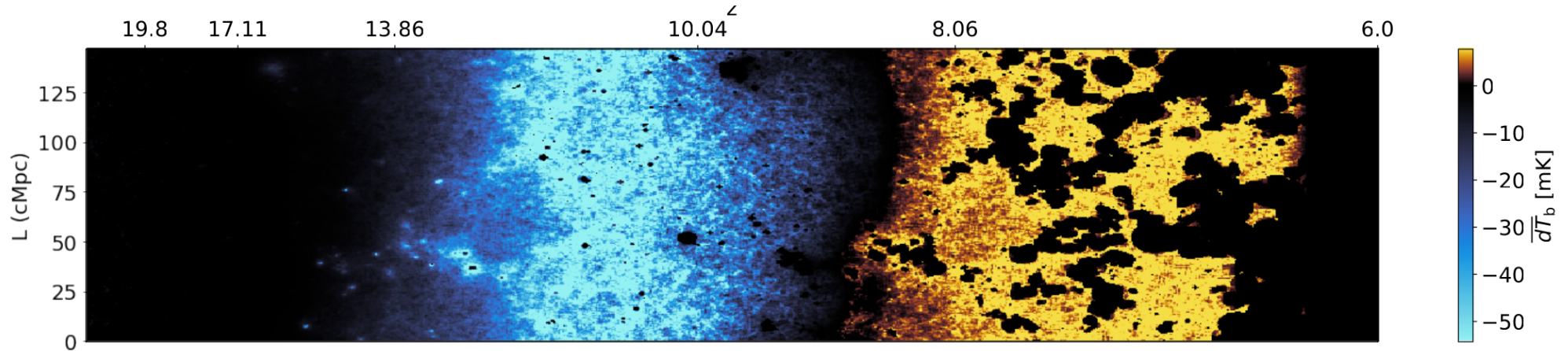


$\Rightarrow$ *Postprocessing*
(overlaps, normalization, ...)

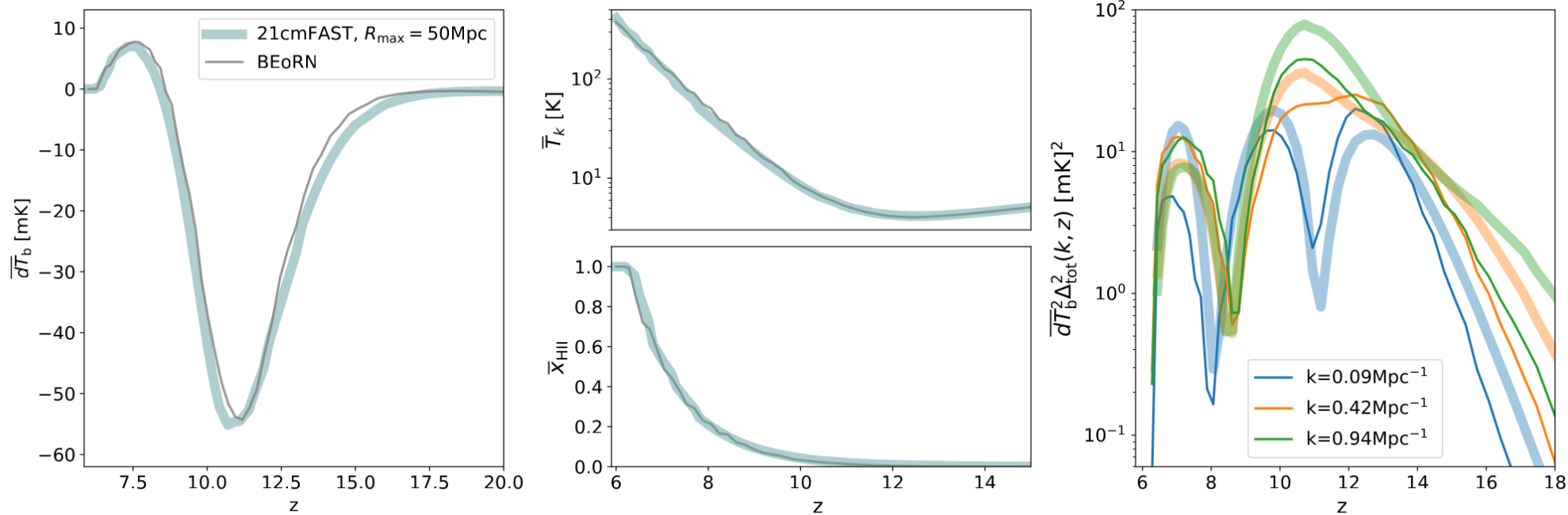
- ionization overlaps
- corrections due to RSD
- computation of derived quantities
- summary statistics

Through the redshifting of photons, the brightness temperature across redshift slices will be measured in a frequency band

⇒ representation as a lightcone



from [4]



from [4]

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Halo growth

- Motivation
- Effect on the flux profiles
- Inferring growth from THESAN data

Crucial dependence on the **star formation rate**

- assumed to be directly linked to halo growth rate $\dot{M}$:

$$\dot{M}_\star = f_\star(M_h) \cdot \dot{M}_h$$

- growth according to the exponential model:

$$M_h(z) = M_h(z_0) \cdot \exp[-\alpha(z - z_0)]$$

with $\alpha = \frac{\dot{M}_h}{M_h}$ the *specific growth rate*

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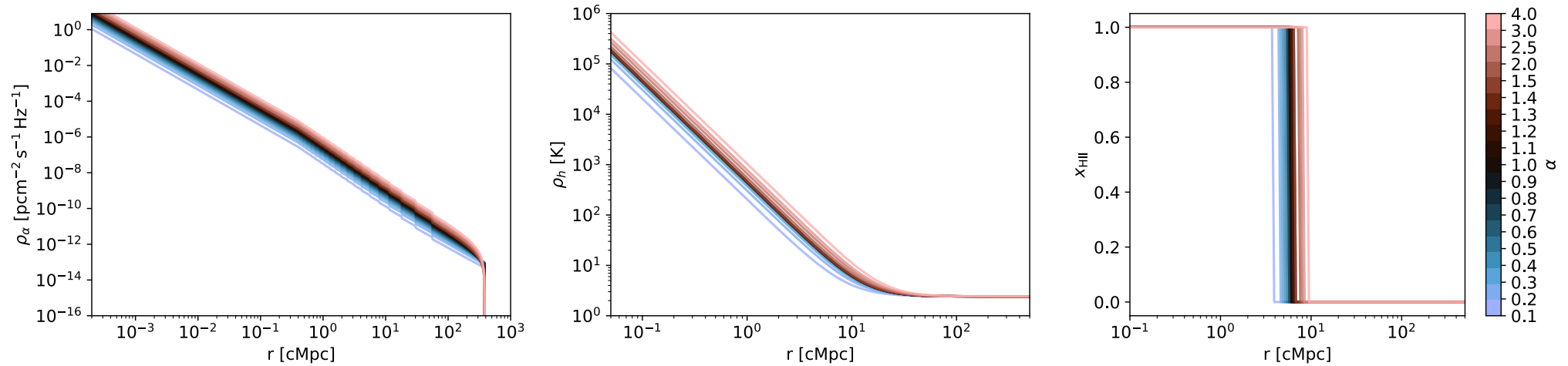
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→ inaccurate when applied to all halos
→ **inconsistent** with the N-body output
→ how to implement **consistent** growth?

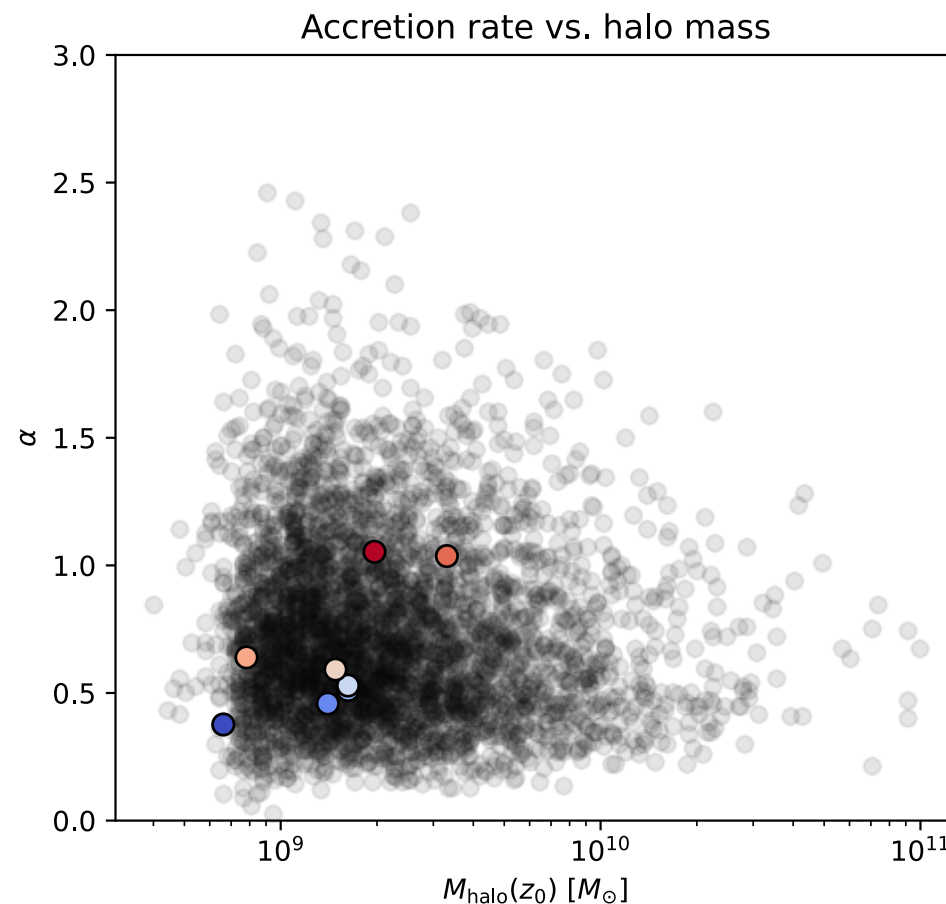
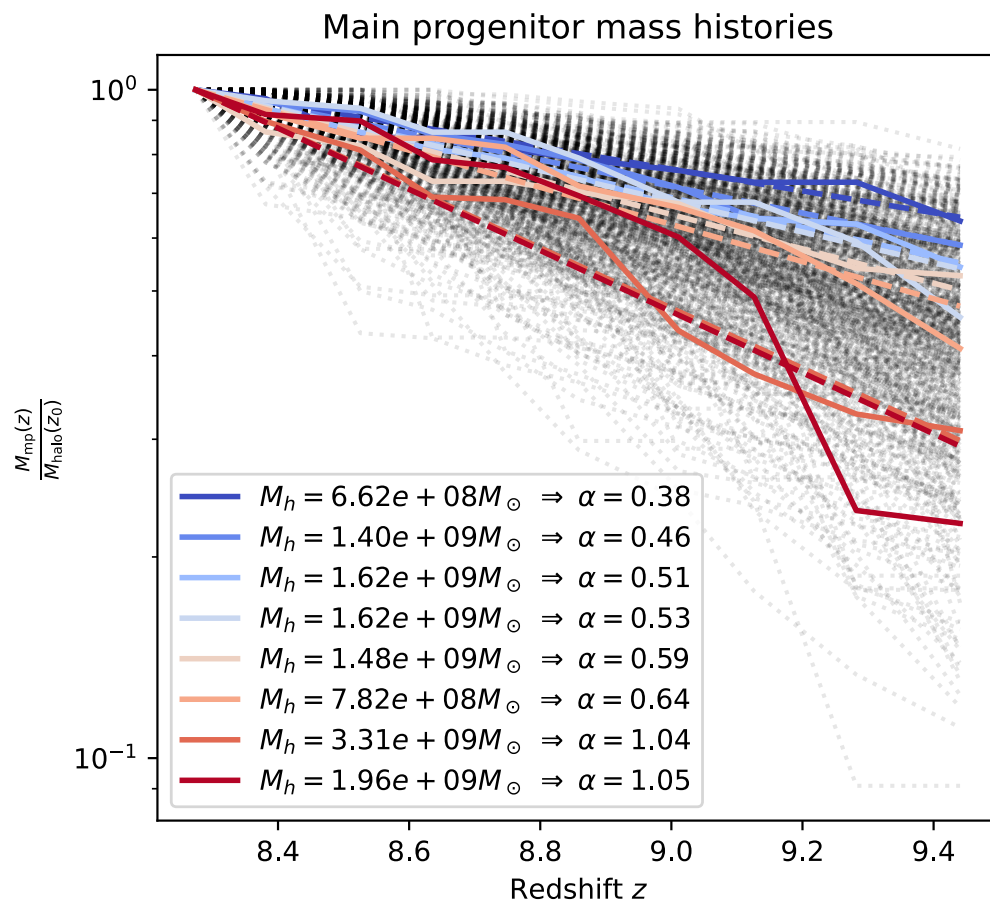


$$M_h = 6.08 \cdot 10^{11} M_\odot \text{ (fixed)}$$

$\Rightarrow$ correction up to $\times 5$

- already includes precomputed merger trees [8]
- follow main progenitor branch back in time
- fit the exponential model to main progenitor branch
- use **individual growth** to select profile
- **self-consistent** treatment of halo growth leveraging the snapshots

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Adaptations

- Central changes
- Simplified usage

- profile generation taking into account halo growth rate
- reading merger trees + inferring growth rates
- parallel painting across multiple halo bins
- performance and ease of use

- profile generation taking into account halo growth rate
- reading merger trees + inferring growth rates
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- performance and ease of use

→ Validated 

 /beorn.py

```
from pathlib import Path
import beorn

current_directory = Path(".")
## Setup the parameters
parameters_file = current_directory / "parameters.yaml"
parameters =
beorn.structs.Parameters.from_yaml(parameters_file)
# sample format:
# parameters.solver.redshifts = [6, 20]
# parameters.simulation.file_root = ... / "Thesan-Dark-1"

## Handling of the io
# this will interface with the input simulation
loader = beorn.load_input_data.ThesanLoader(
    parameters,
    is_high_res = True
)

cache_handler = beorn.io.Handler(current_directory /
"cache")
```

```
output_handler = beorn.io.Handler(current_directory /
"output")
# handlers can also manage logs for us:
# output_handler.save_logs(parameters)

## Computation of the radiation profiles
solver =
beorn.radiation_profiles.ProfileSolver(parameters)
profiles = solver.solve()

## Full 3D painting of the radiation profiles over the
specified redshifts
painter = beorn.painting.Painter(
    parameters,
    loader = loader,
    cache_handler = cache_handler,
    output_handler = output_handler
)

grid = painter.paint_full(profiles)
# Done!
```

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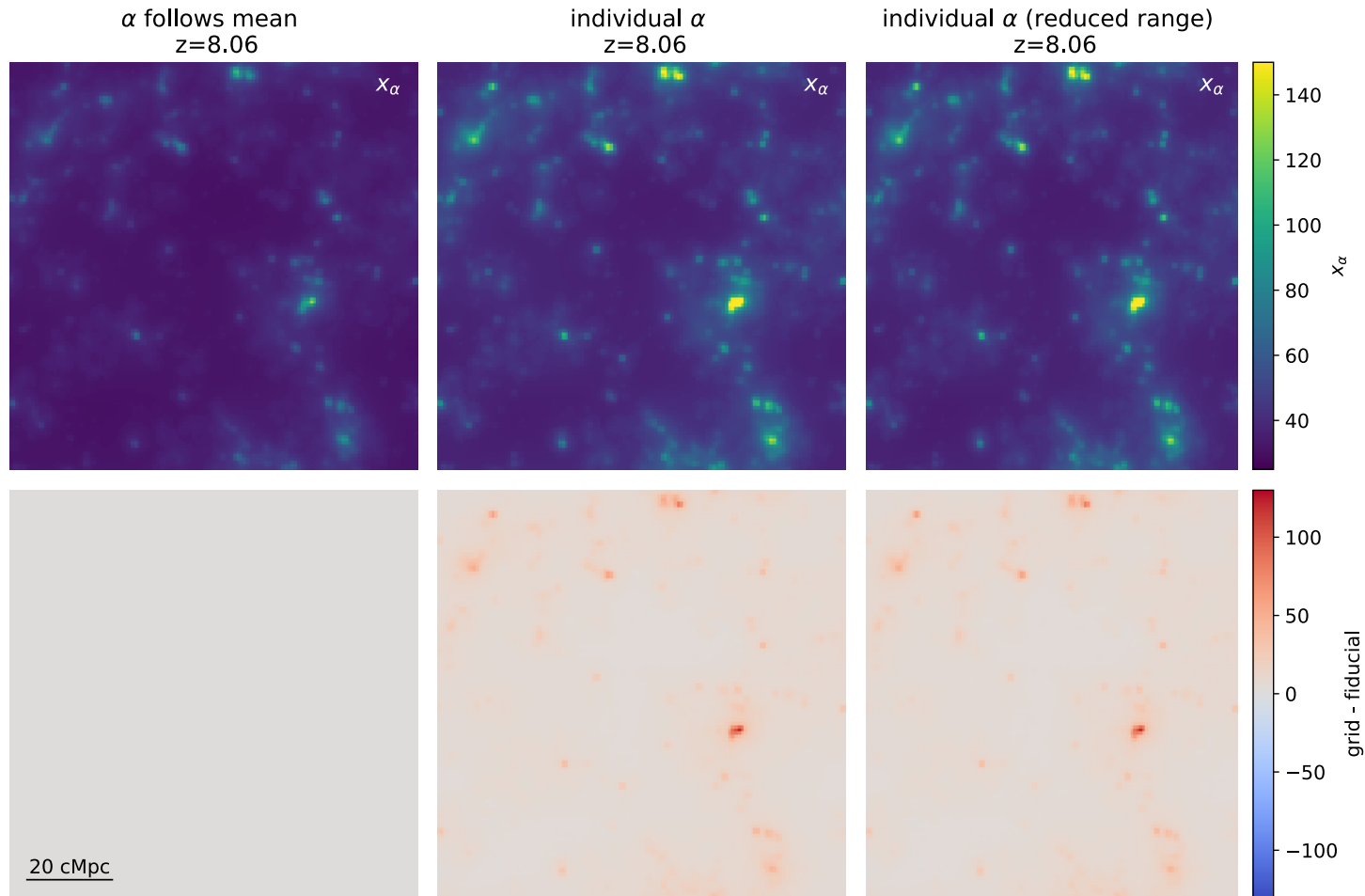
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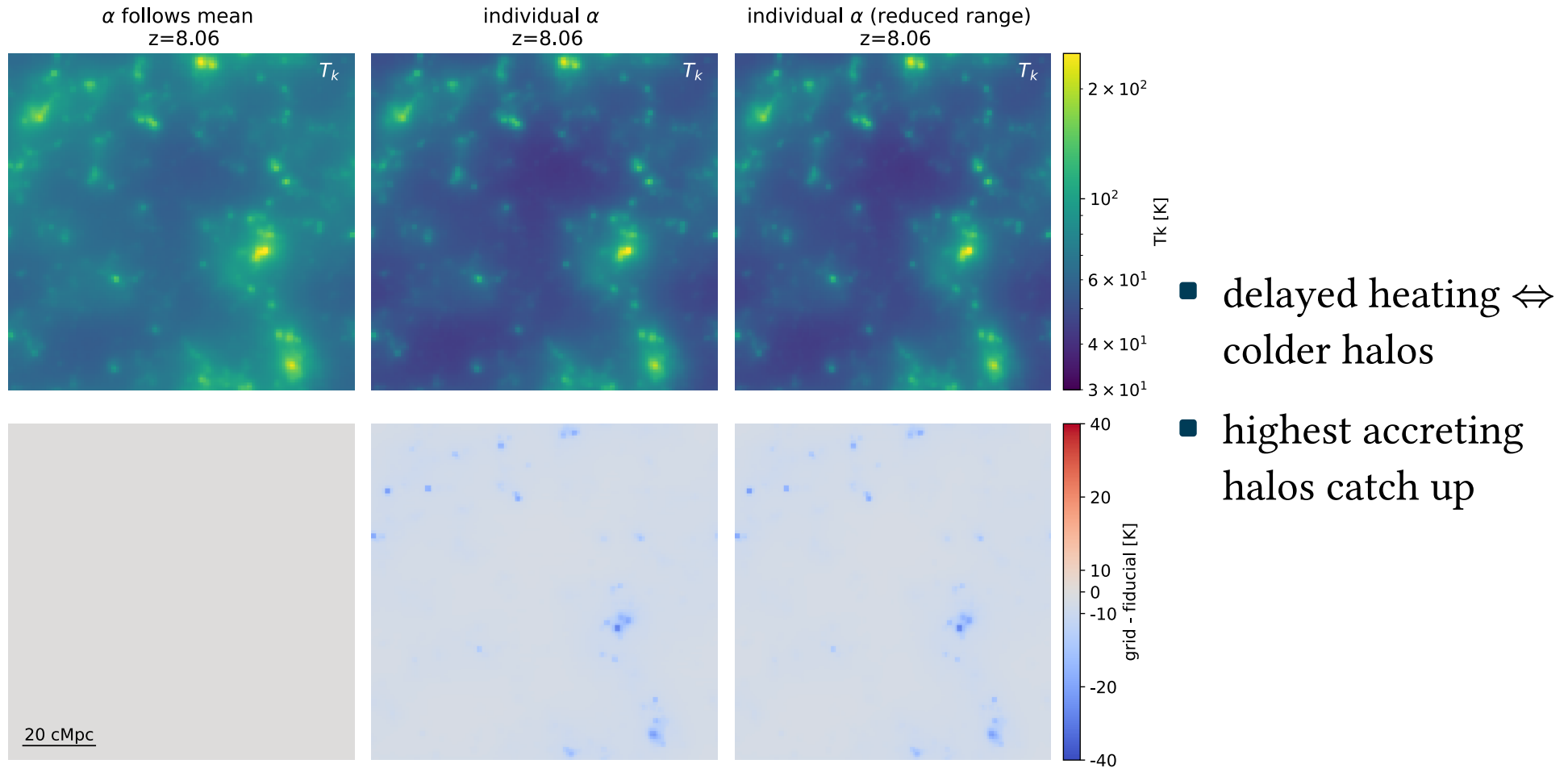
- Map outputs
- Signals



- stronger coupling in dense regions
- nearly no effect in voids

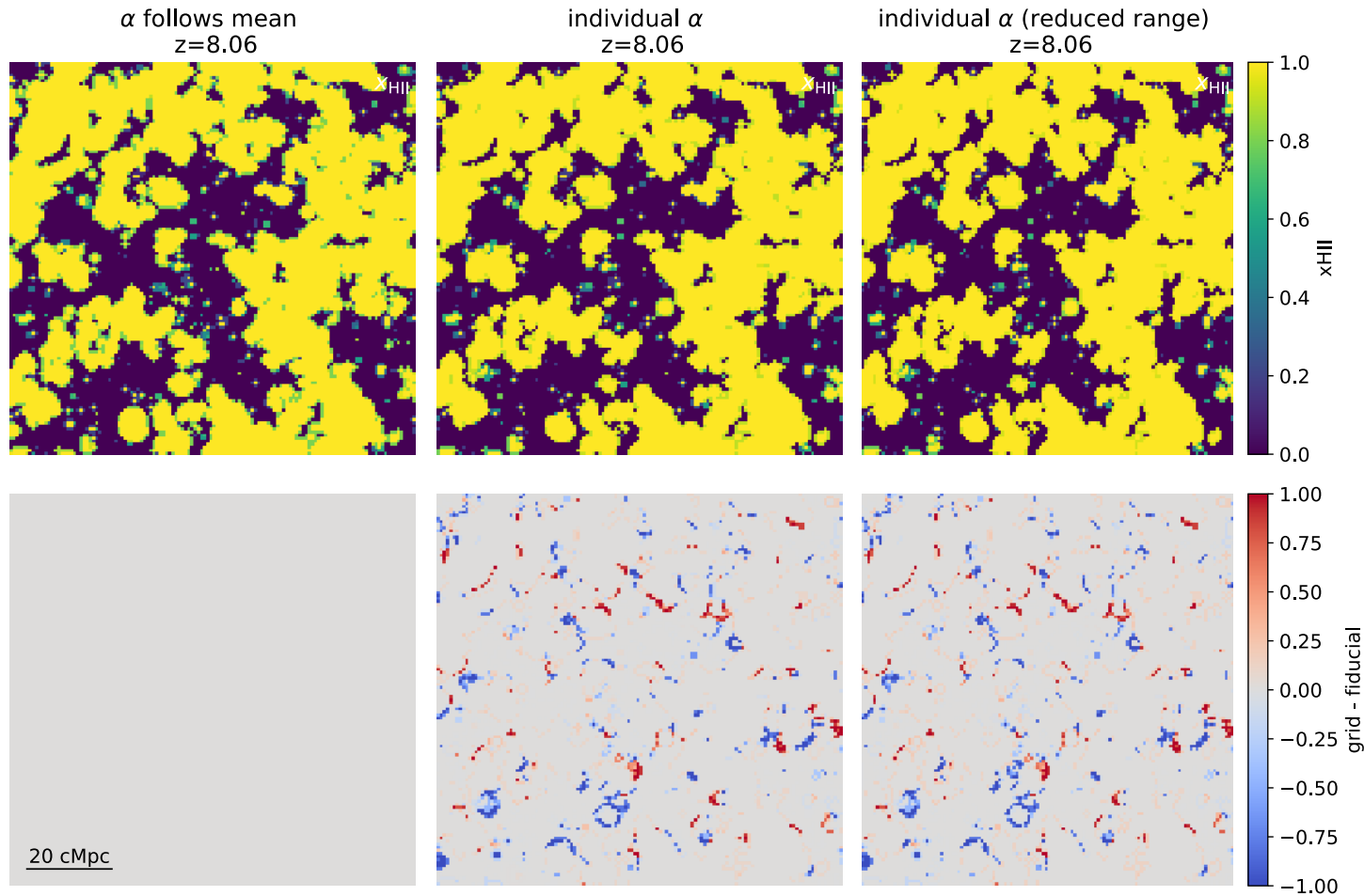
Map outputs

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Map outputs

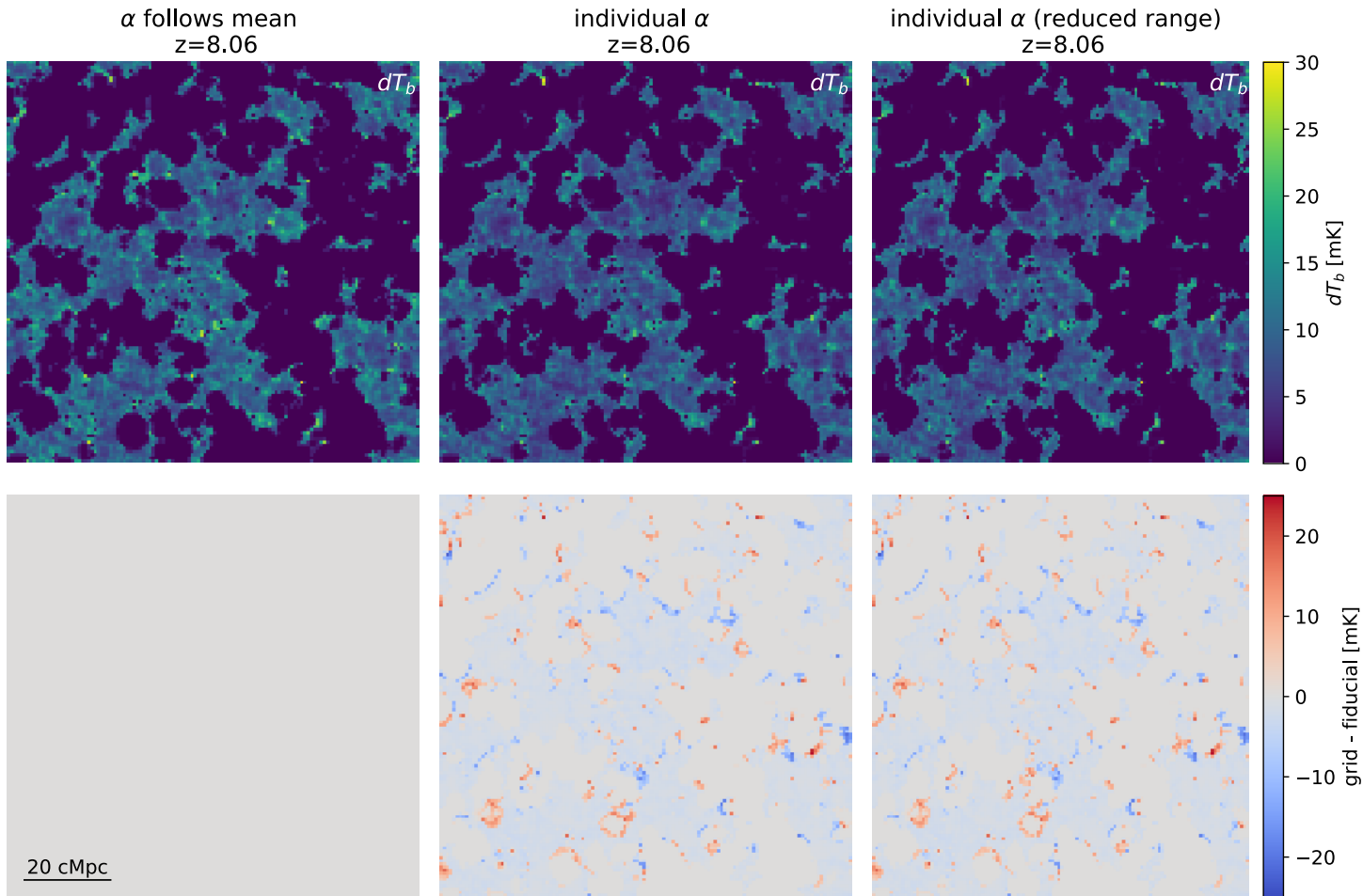
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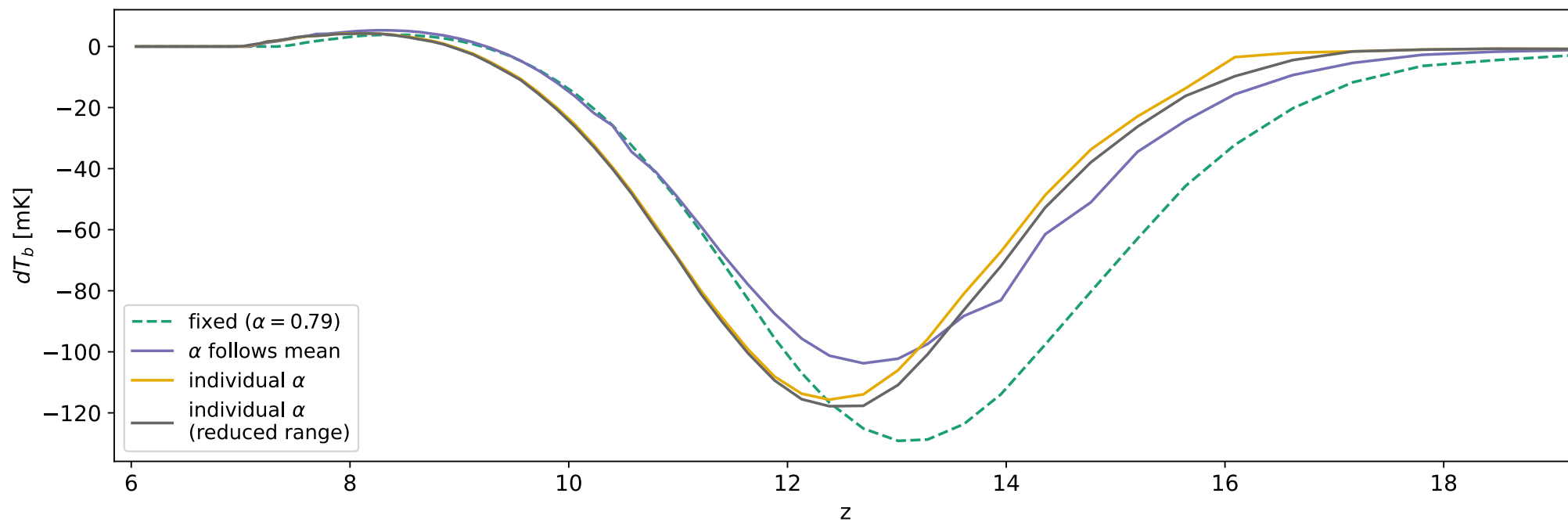
- high contrast due to sharp cutoffs
- clearly increased dynamic range

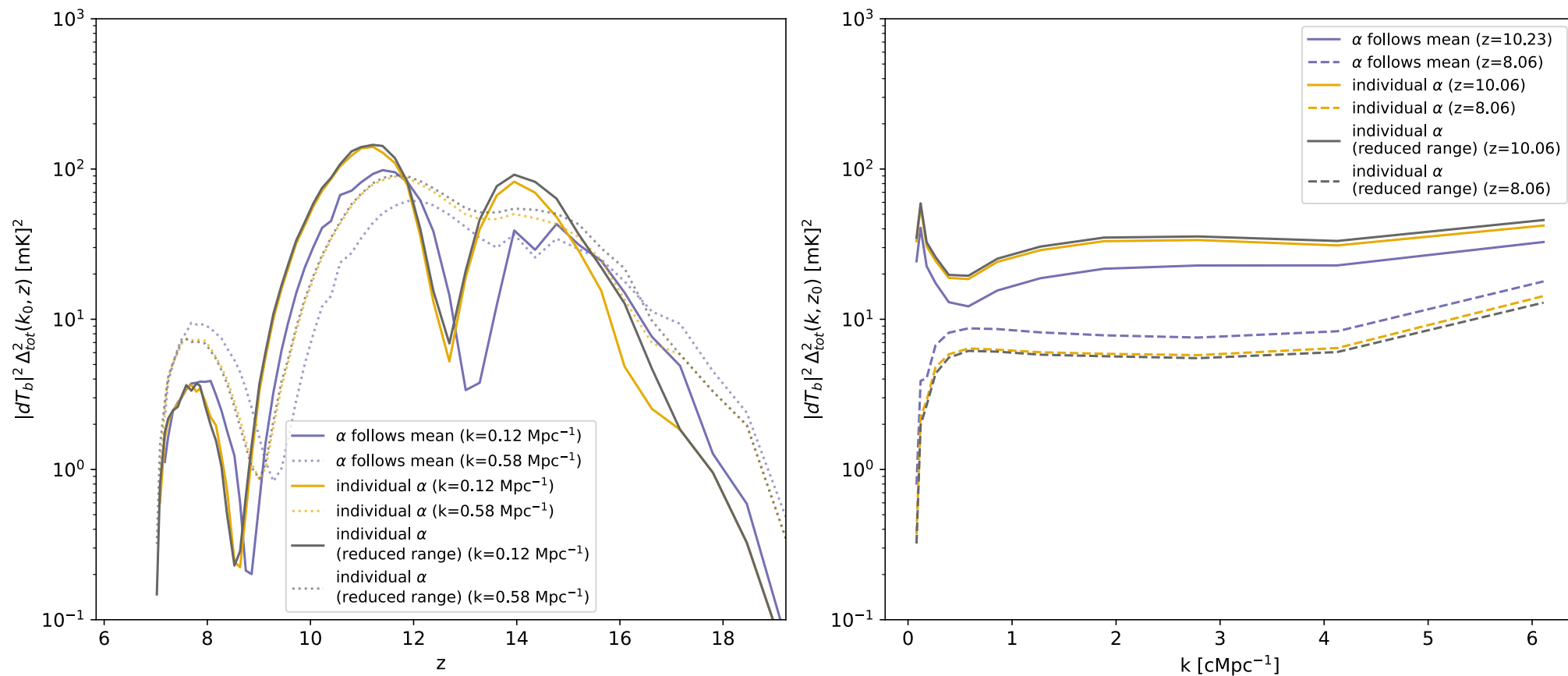
Map outputs

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- richer structures due to combined effects
- clear distinction between “foreground” and “background” effects





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Conclusion

- Summary
- Outlook

- BEO RN a semi-numerical tool to simulate the 21-cm signal
 - uses the *halo model of reionization*
 - describes sources in terms of their host DM halo
 - $\Rightarrow$ central dependence on halo growth
- more accurate treatment of **individual** mass accretion
 - leads to significant changes to reionization history
 - map-level fluctuations
- BEO RN python package: <https://github.com/cosmic-reionization/beorn>
 - simulation-agnostic
 - easier to use
 - fully parallelized

- further validation
- investigation + parameterization of stochasticity
- application to larger volumes

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— Thank you for your attention

References

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- [2] S. R. Furlanetto, S. Peng Oh, and F. H. Briggs, “Cosmology at low frequencies: The 21cm transition and the high-redshift Universe,” *Physics Reports*, vol. 433, no. 4–6, pp. 181–301, Oct. 2006, doi: 10.1016/j.physrep.2006.08.002.
- [3] “CMB spectrum.” [Online]. Available: https://asd.gsfc.nasa.gov/archive/arcade/cmb_intensity.html
- [4] T. Schaeffer, S. K. Giri, and A. Schneider, “<scp>beorn</scp>: a fast and flexible framework to simulate the epoch of reionization and cosmic dawn,” *Monthly Notices of the Royal Astronomical Society*, vol. 526, no. 2, pp. 2942–2959, Sep. 2023, doi: 10.1093/mnras/stad2937.

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- [5] A. Schneider, S. K. Giri, and J. Mirocha, “Halo model approach for the 21-cm power spectrum at cosmic dawn,” *Physical Review D*, vol. 103, no. 8, Apr. 2021, doi: 10.1103/physrevd.103.083025.
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- [7] V. Springel *et al.*, “Simulations of the formation, evolution and clustering of galaxies and quasars,” *Nature*, vol. 435, no. 7042, pp. 629–636, Jun. 2005, doi: 10.1038/nature03597.
- [8]

$$\rho_{\alpha}(r \mid M, z) = \frac{(1+z)^2}{4\pi r^2} \cdot \sum_{n=2}^{n_m} f_n \cdot \varepsilon_{\alpha}(\nu') \cdot f_{\star} \cdot \dot{M}(z' \mid M, z)$$

with the lookback redshift z' so $\nu' = \nu \cdot (1+z')/(1+z)$

$\Rightarrow$ coupling coefficient

$$x_{\alpha}(r \mid M, z) = \frac{1.81 \cdot 10^{11}}{1+z} \cdot S_{\alpha}(z) \cdot \rho_{\alpha}(r \mid M, z)$$

with a suppression factor $S_{\alpha}(z)$

$$\rho_{\text{xray}}(r \mid M, z) = \frac{1}{r^2} \sum_i f_i f_{X,h} \cdot \int_{\nu_{\text{th}}^i}^{\infty} d\nu (\nu - \nu_{\text{th}}^i) h_P \sigma_i(\nu) e^{-\tau_\nu} f_\star \dot{M}(z' \mid M, z)$$
$$\Rightarrow \frac{3}{2} \cdot \frac{d\rho_h(r \mid M, z)}{dz} = \frac{3\rho_h(r \mid M, z)}{1+z} - \frac{\rho_{\text{xray}}(r \mid M, z)}{k_B(1+z)H(z)}$$

with the Boltzmann constant k_B and $H(z)$ is the Hubble parameter

The comoving ionized volume around a source of ionizing photons satisfies the differential equation

$$\frac{dV}{dt} = \frac{\dot{N}_{\text{ion}}(t)}{\bar{n}_H^0} - \alpha_B \cdot \frac{C}{a^3} \cdot \bar{n}_H^0 \cdot V$$

bubble radius $R_b = \sqrt[3]{\frac{3}{4\pi} V(M, z)}$ and using the Heaviside step function θ_H :

$$x_{\text{HII}}(r \mid M, z) = \theta_H \left[R_b(M, z) - r \right]$$

