Simulating the EOR with self-consistent growth of galaxies

Master's thesis presentation

ETH Zürich, University of Zürich

Simulating the Epoch of Reionization

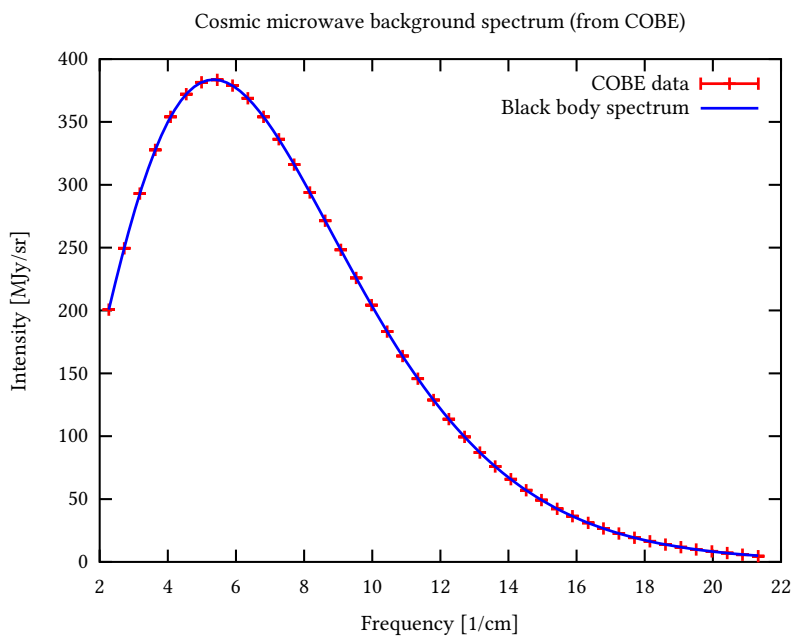
- The Epoch of Reionization
- The 21-cm signal
- Expression the 21-cm signal
- The current state of simulations
- Matrix
- Contained
- Four columns
- Two columns

The Epoch of Reionization

- Marks the universe's last major phase transition: from neutral to ionized hydrogen.
- Shapes the large-scale structure of the intergalactic medium (IGM).
- Is strongly linked to the formation and growth of the first galaxies and black holes.
- Sets the stage for many observables: CMB secondary anisotropies, 21-cm signal, high-z galaxy surveys.

The 21-cm signal

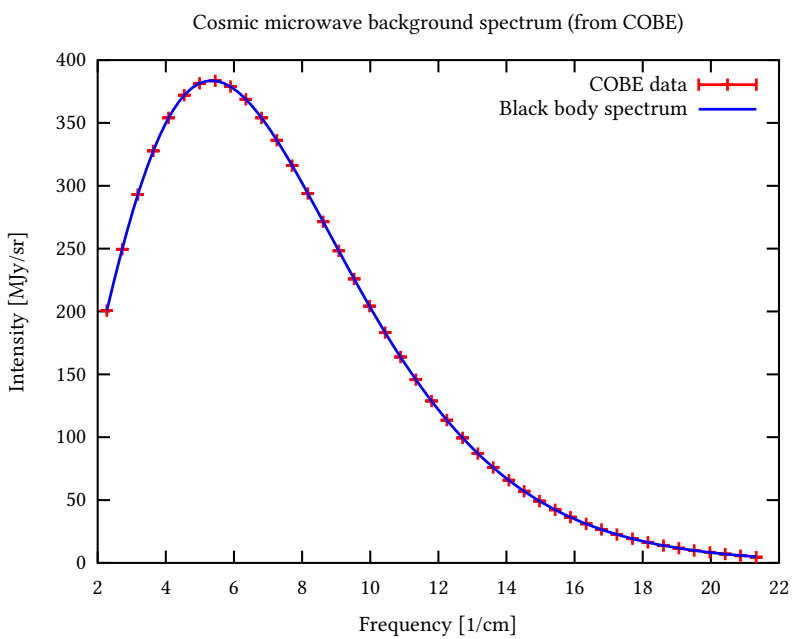
The brigthtness temperature describes the difference between the CMB temperature and the spin temperature of neutral hydrogen



from [1]

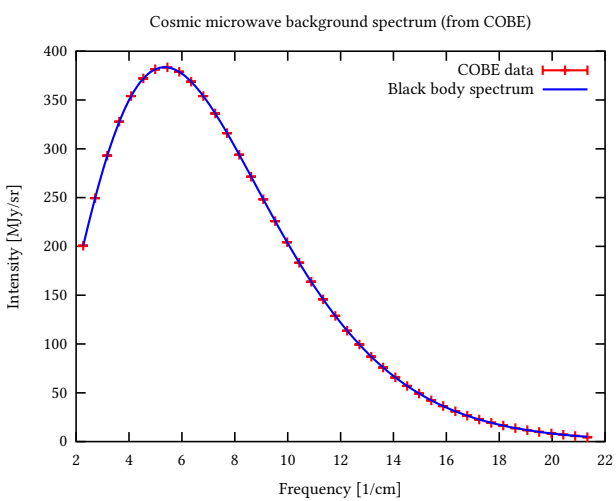
The 21-cm signal

The brigthtness temperature describes the difference between the CMB temperature and the spin temperature of neutral hydrogen

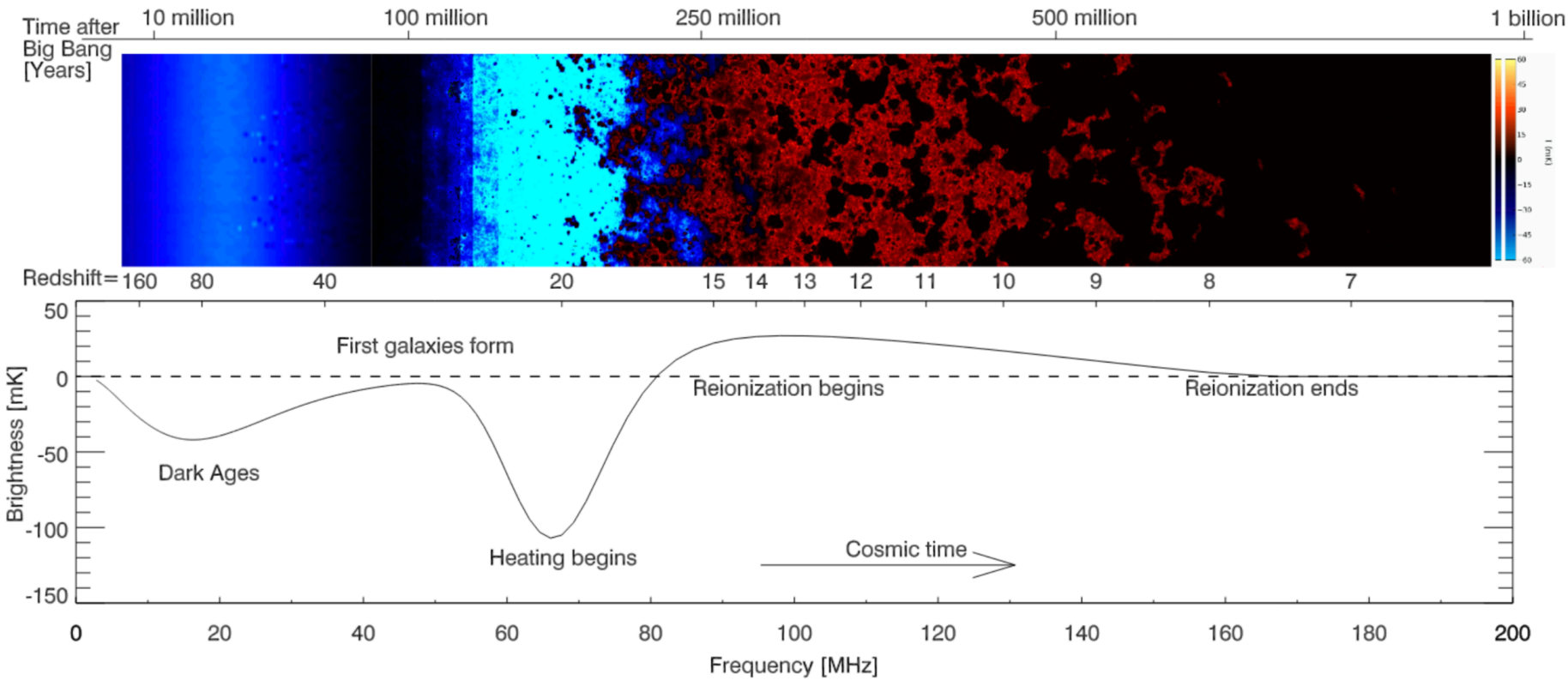


from [1]

Removing the contribution from the black body spectrum of the CMB yields the explicit 21-cm signal:



The 21-cm signal



from [2]

Expression the 21-cm signal

Expressing the brightness temperature (e.g [2]):

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

- further modulation by *RSD*

The current state of simulations

Traditional approaches:

$\rightarrow$ slow and big

$\rightarrow$ radiative transfer

The current state of simulations

Traditional approaches:

$\rightarrow$ slow and big

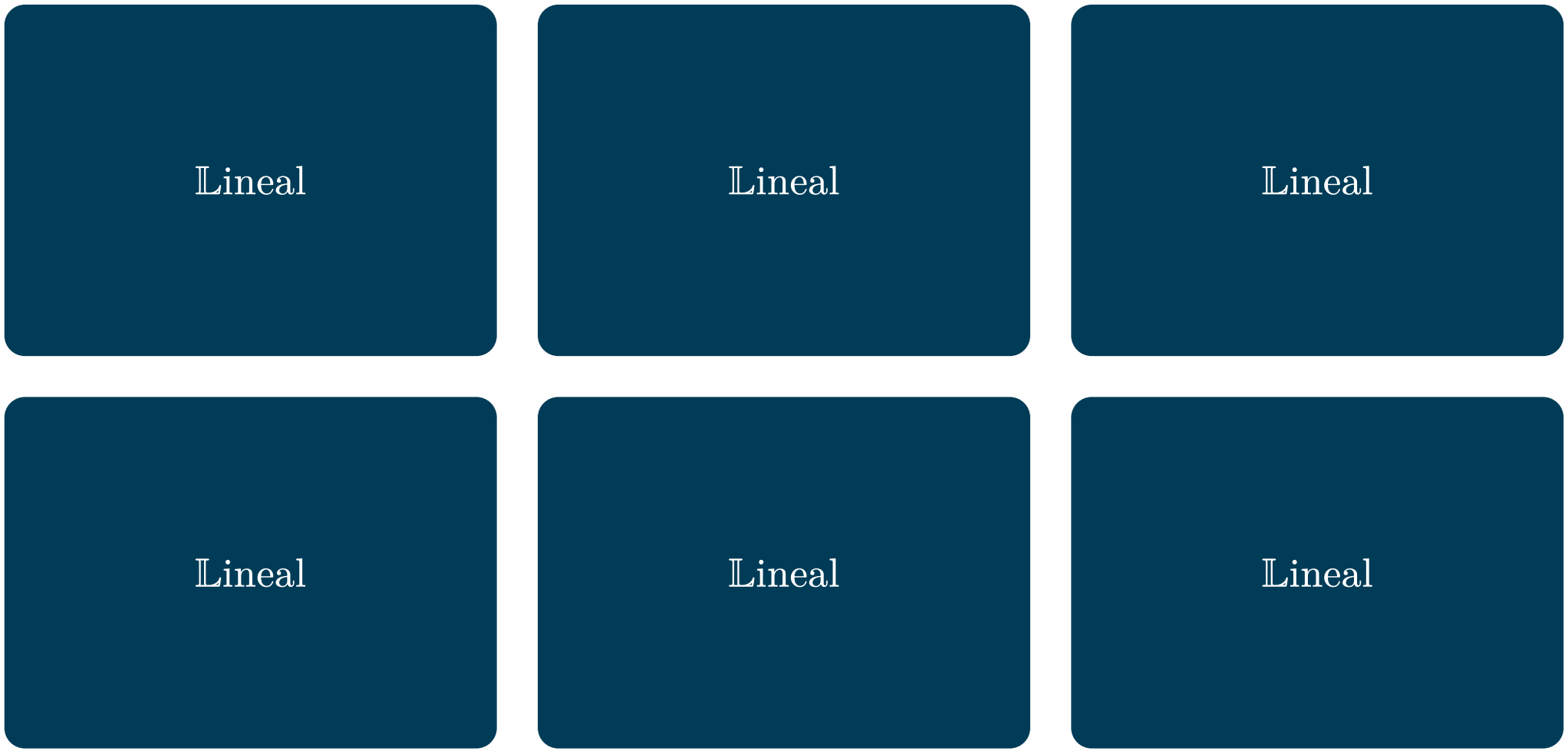
$\rightarrow$ radiative transfer

$\Longrightarrow$ semi-numerical approaches such as `BEoRN` [3]

- fast
- flexible

$\Rightarrow$ repeatable

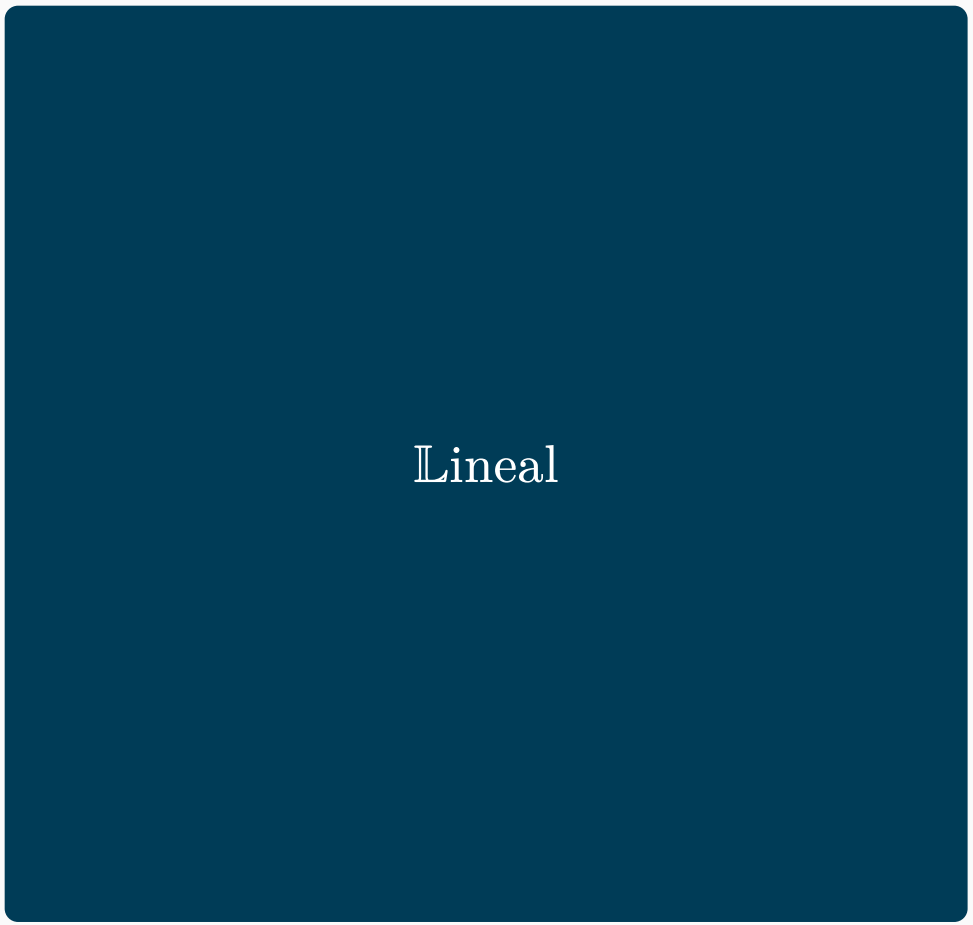
Matrix



Contained

- Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do.
- Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore.

- Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aeque doleamus.



Four columns

Lineal

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aeque doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut postea variari voluptas distinguique possit, augeri amplificarique non possit. At.

Lineal

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aeque doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem.

Lineal

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aeque doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut postea variari voluptas distinguique possit, augeri amplificarique non possit. At etiam Athenis, ut e patre audiebam facete et urbane Stoicos irridente, statua est in quo.

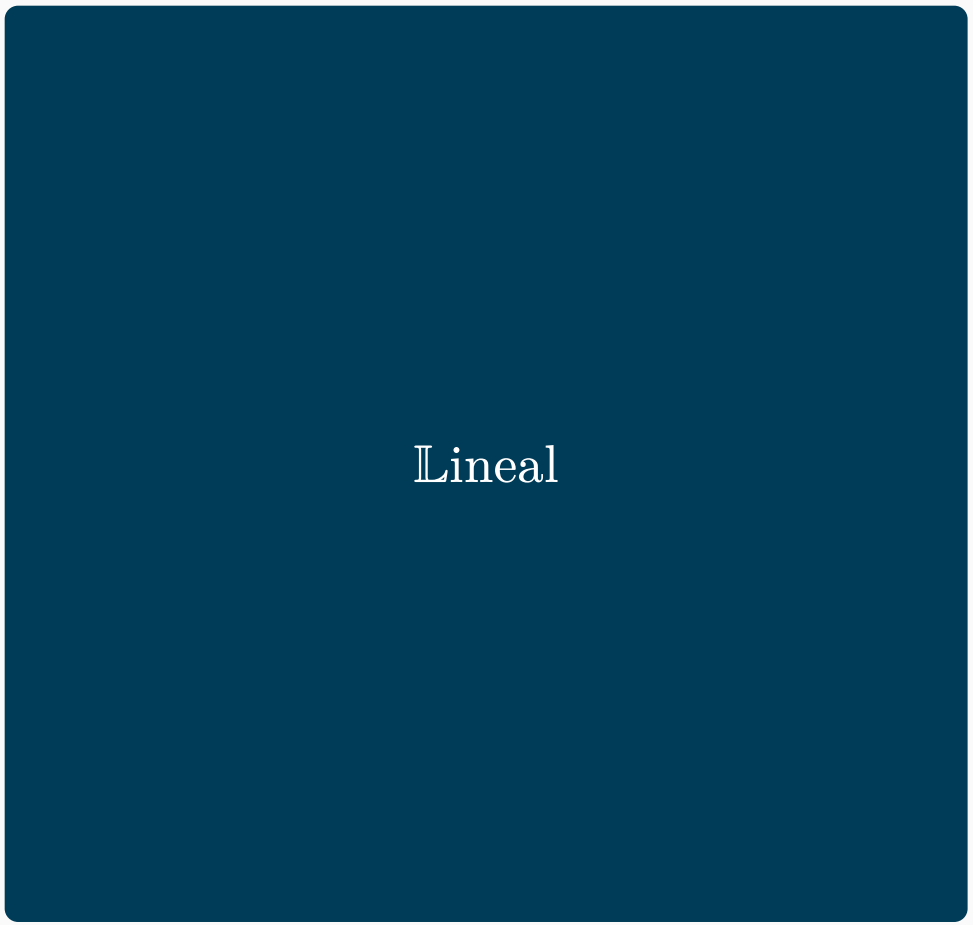
Lineal

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aeque doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut.

Two columns

- Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do.
- Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore.

- Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aeque doleamus.



The halo model of reionization

Following [4], [5]:

Following [4], [5]:

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

Following [4], [5]:

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

$$\frac{3}{2} \cdot \frac{\mathrm{d}\rho_h(r \mid M, z)}{\mathrm{d}z} = \frac{3\rho_h(r \mid M, z)}{1+z} - \frac{\rho_{\mathrm{xray}}(r \mid M, z)}{k_B(1+z)H(z)}$$

Following [4], [5]:

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

$$\frac{3}{2} \cdot \frac{\mathrm{d}\rho_h(r \mid M, z)}{\mathrm{d}z} = \frac{3\rho_h(r \mid M, z)}{1+z} - \frac{\rho_{\mathrm{xray}}(r \mid M, z)}{k_B(1+z)H(z)}$$

$$\frac{\mathrm{d}V_b}{\mathrm{d}t} = \frac{\dot{N}_{\mathrm{ion}(t)}}{\overline{n}_H^0} - \alpha_B \cdot \frac{C}{a^3} \cdot \overline{n}_H^0 \cdot V_b$$

Revisiting the 21cm signal

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

Revisiting the 21cm signal

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

from $x_{\rm HII}$

Revisiting the 21cm signal

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

from $x_{\rm HII}$

From ρ_α

Revisiting the 21cm signal

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

from $x_{\rm HII}$

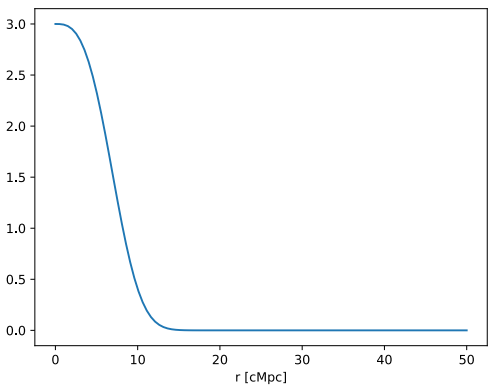
From ρ_α

From $\rho_{\rm h}$

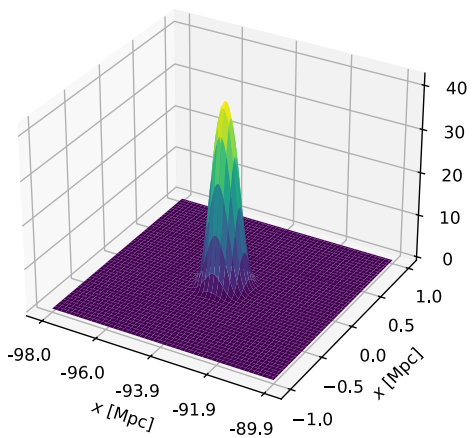
BEoRN

- Procedure
- Postprocessing

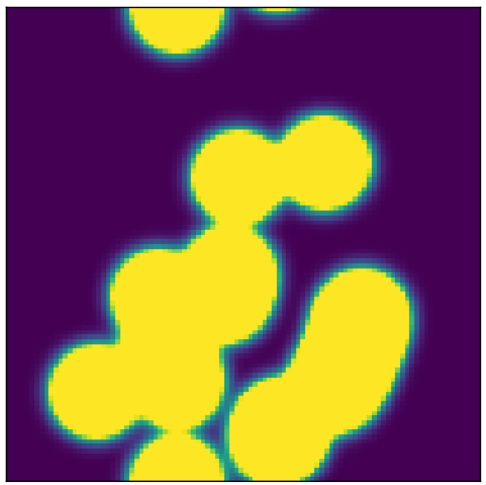
Procedure



$\Longrightarrow$



$\Longrightarrow$



1-d profile

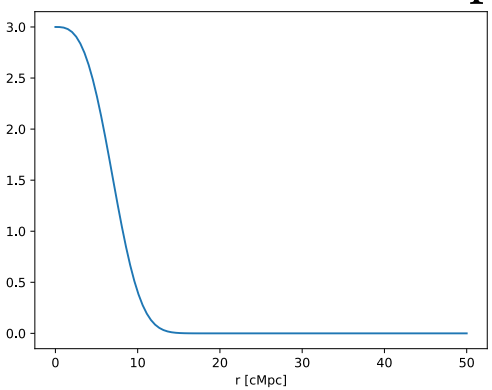
3-d kernel

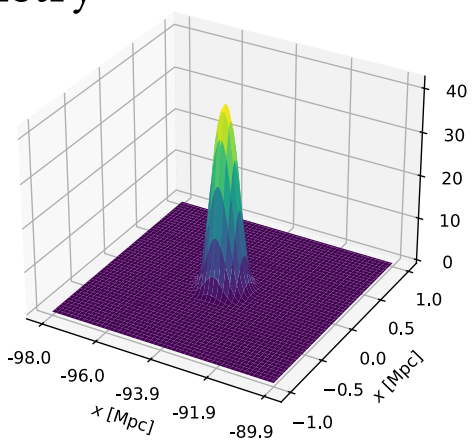
(localized)

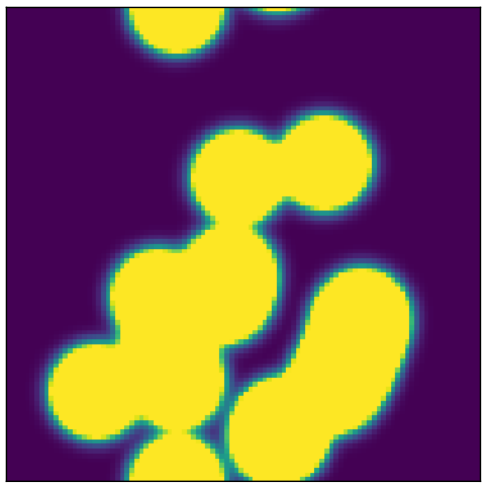
3-d contribution on a grid

Procedure

spherical symmetry







1-d profile

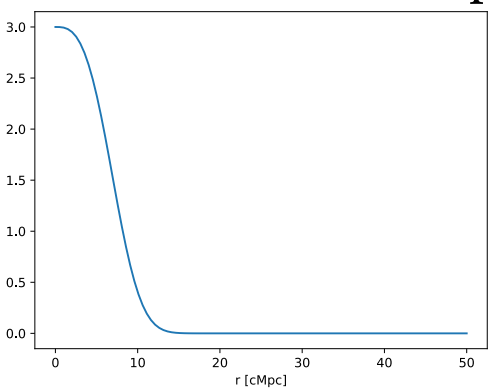
3-d kernel

(localized)

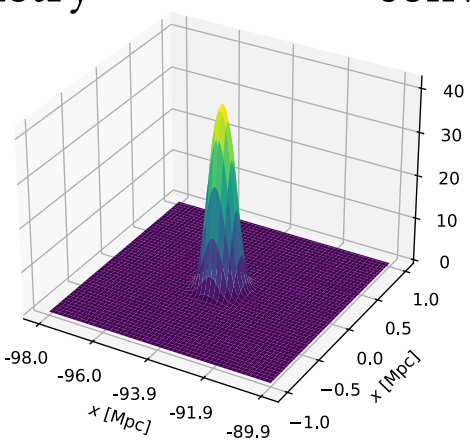
3-d contribution on a grid

Procedure

spherical symmetry



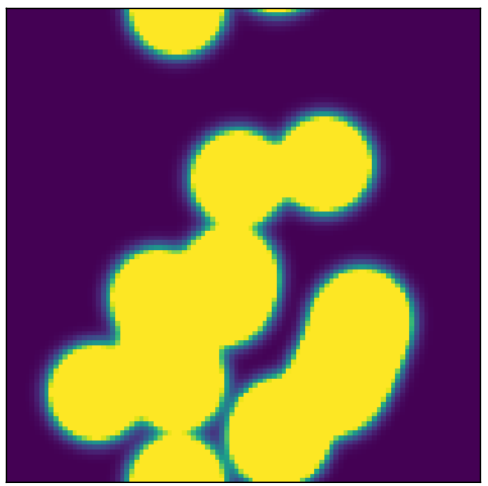
1-d profile



3-d kernel

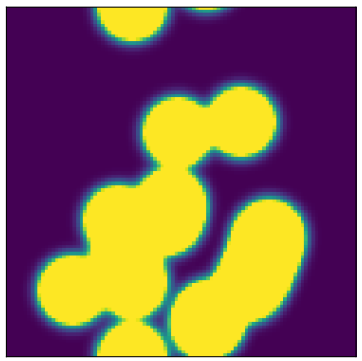
(localized)

convolution (fft)

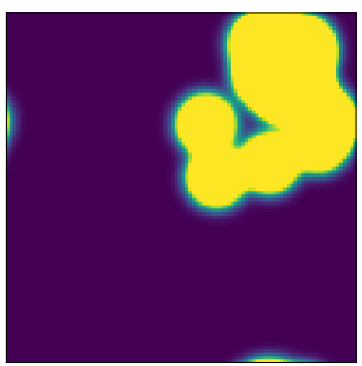


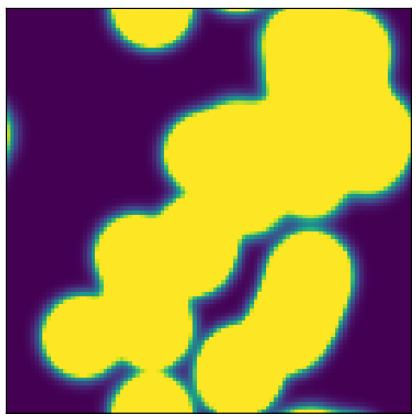
3-d contribution on a grid

Procedure



Multiple contributions $\Longrightarrow$





$\Longrightarrow$ *Postprocessing*

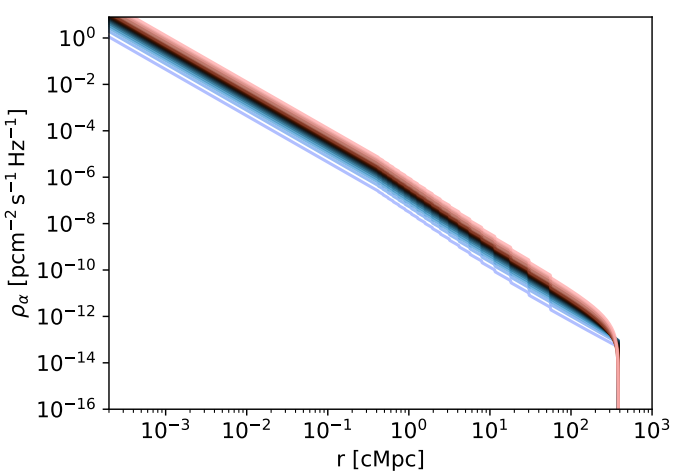
(overlaps, normalization, ...)

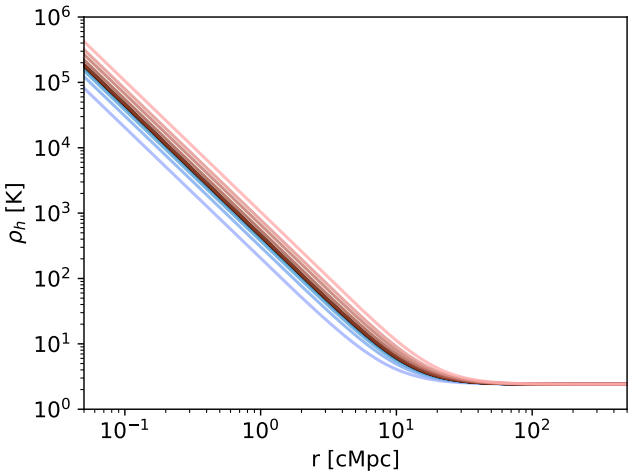
Postprocessing

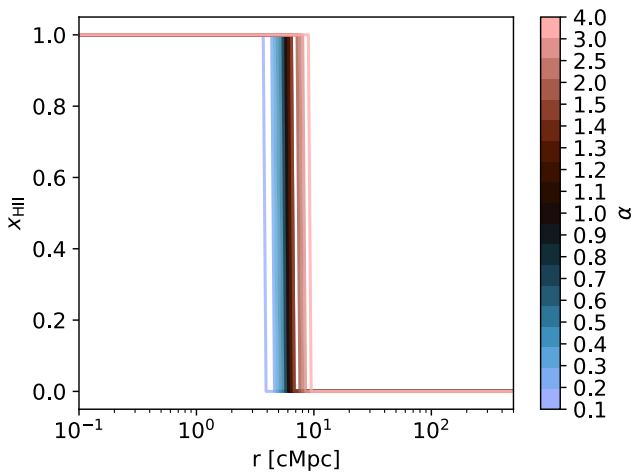
Halo growth

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

Effect on the flux profiles

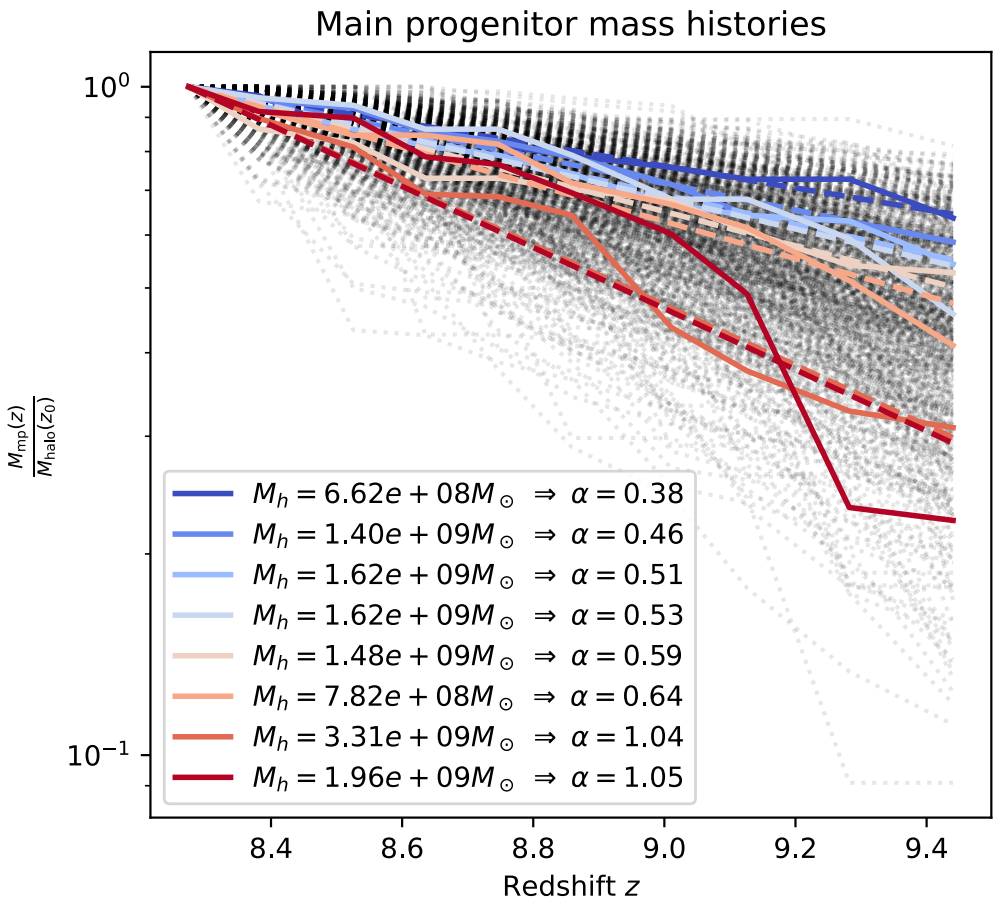


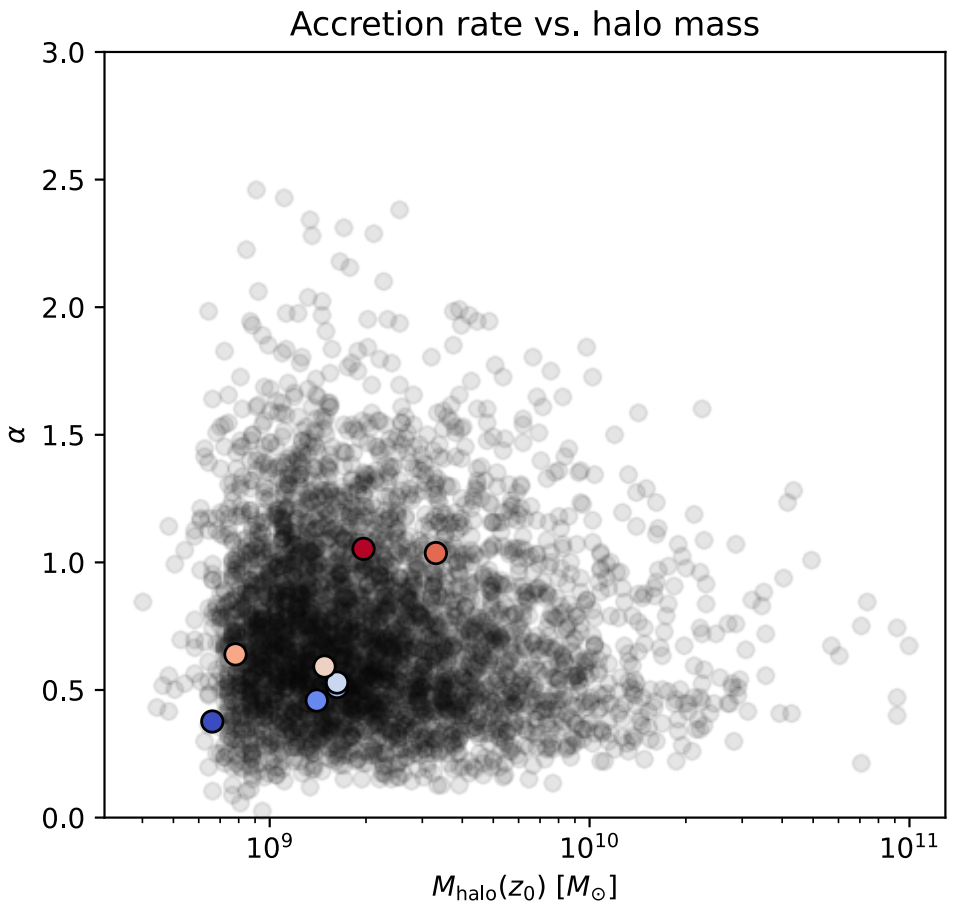




Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aeque doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut.

Inferring growth from THESAN data





Inferring growth from THESAN data

validation

Implementation

— Simplified usage

Simplified usage

/beorn.py

```python
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
```

Simplified usage


```
# 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()
```

Simplified usage

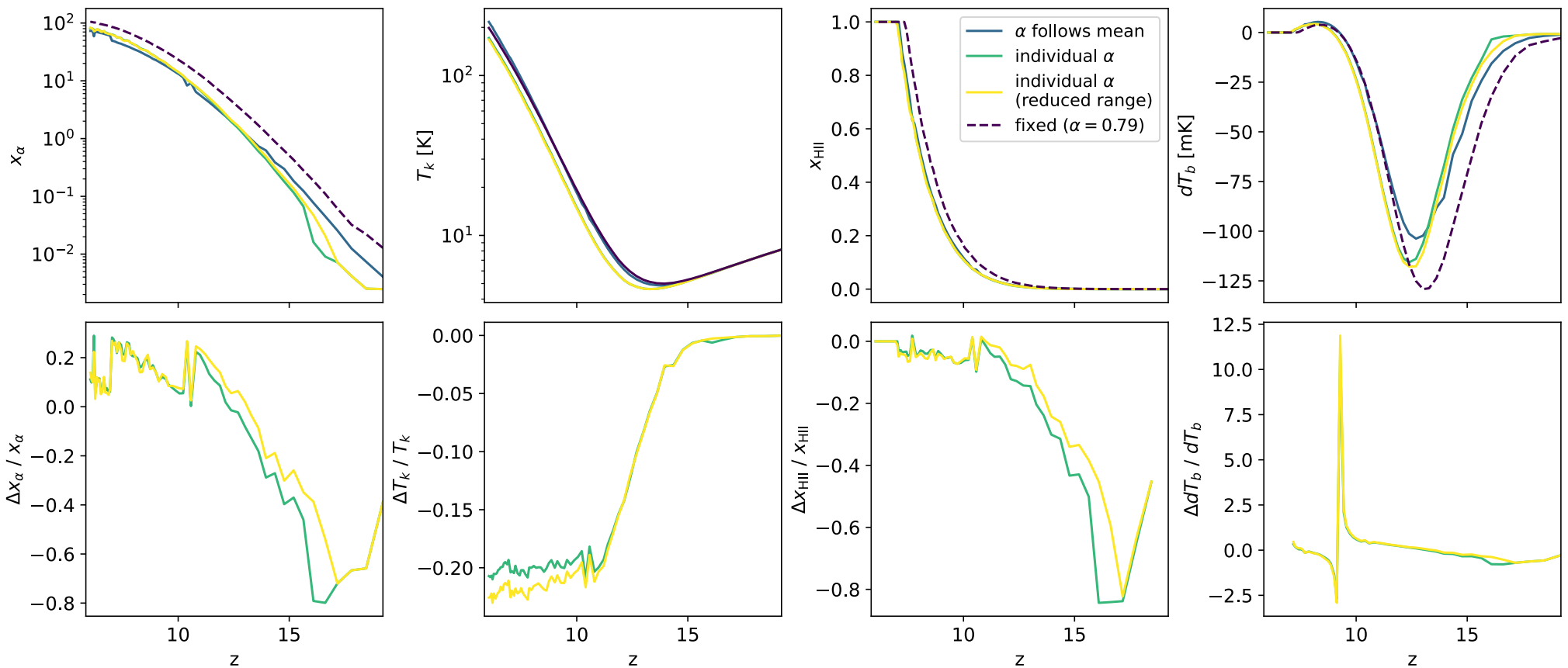

```
## Full 3D painting of the radiation profiles over the specified redshifts
painter = beorn.painting.Painter(
    parameters,
    loader = loader,
    cache_handler = cache_handler,
    output_handler = output_handler
)

grid = painter.paint_full(profiles)
```

Results

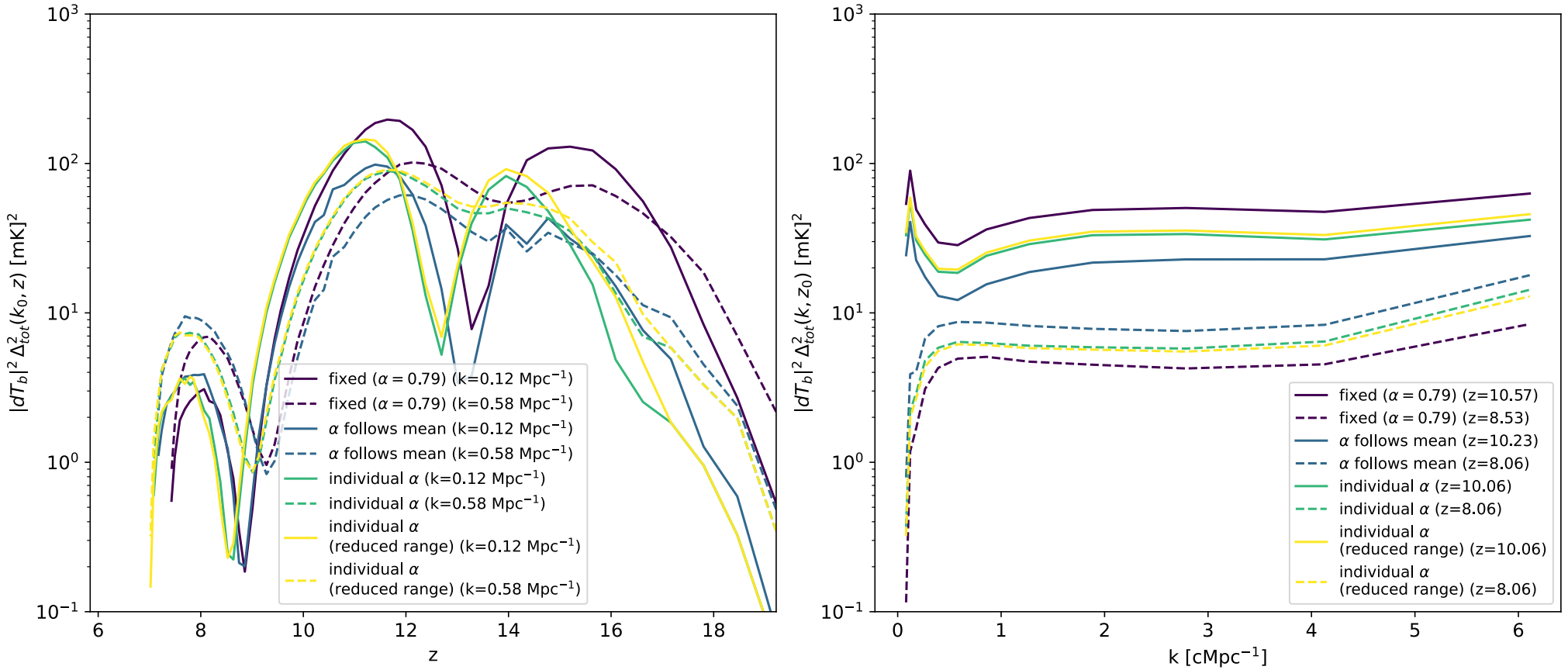
- Map outputs
- Signals

Map outputs

Signals


α follows mean
individual α
individual α (reduced range)
fixed (α = 0.79)
x_α
T_k [K]
x_{HII}
dT_b [mK]
$\Delta x_\alpha / x_\alpha$
$\Delta T_k / T_k$
$\Delta x_{HII} / x_{HII}$
$\Delta dT_b / dT_b$
z

Signals


$|dT_b|^2\,\Delta^2_{tot}(k_0, z)$ [mK]^2
z
fixed ($\alpha = 0.79$) (k=0.12 Mpc^{-1})
fixed ($\alpha = 0.79$) (k=0.58 Mpc^{-1})
α follows mean (k=0.12 Mpc^{-1})
α follows mean (k=0.58 Mpc^{-1})
individual α (k=0.12 Mpc^{-1})
individual α (k=0.58 Mpc^{-1})
individual α (reduced range) (k=0.12 Mpc^{-1})
individual α (reduced range) (k=0.58 Mpc^{-1})
$|dT_b|^2\,\Delta^2_{tot}(k, z_0)$ [mK]^2
k [cMpc^{-1}]
fixed ($\alpha = 0.79$) (z=10.57)
fixed ($\alpha = 0.79$) (z=8.53)
α follows mean (z=10.23)
α follows mean (z=8.06)
individual α (z=10.06)
individual α (z=8.06)
individual α (reduced range) (z=10.06)
individual α (reduced range) (z=8.06)

End

— Thank you for your attention

Bibliography

[1] "CMB spectrum." [Online]. Available: https://commons.wikimedia.org/wiki/File:Cmbr.svg

[2] J. R. Pritchard and A. Loeb, "21 cm cosmology in the 21st century," *Reports on Progress in Physics*, vol. 75, no. 8, p. 86901, Aug. 2012, doi: 10.1088/0034-4885/75/8/086901.

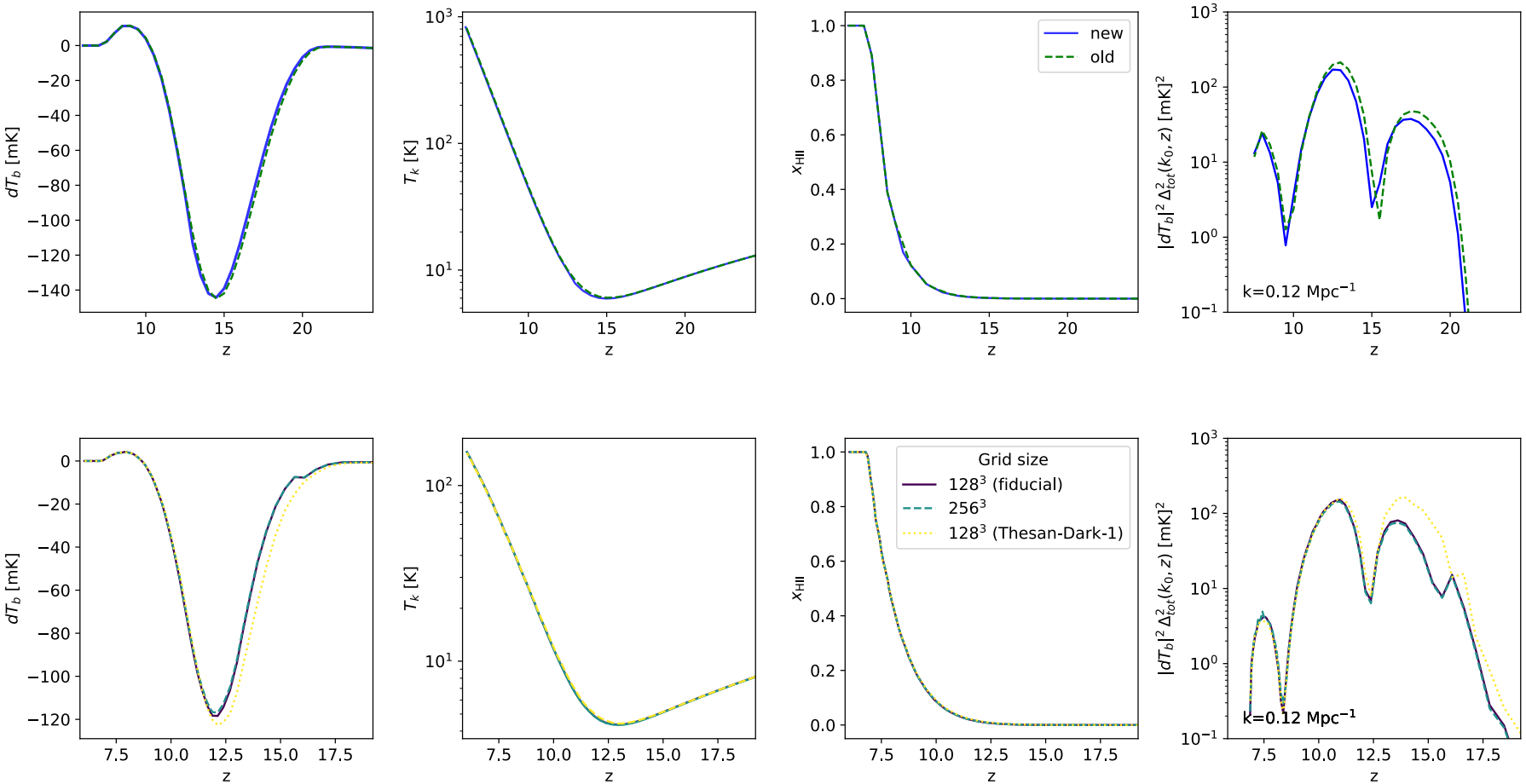
[3] T. Schaeffer, S. K. Giri, and A. Schneider, "<scp>beorn</scp>: a fast and flexible framework to simulate the epoch of reionization and cosmic dawn," *Monthly Notices of the Royal Astronomical Society*, vol. 526, no. 2, pp. 2942–2959, Sep. 2023, doi: 10.1093/mnras/stad2937.

[4] 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.

Bibliography

[5] A. Schneider, T. Schaeffer, and S. K. Giri, “Cosmological forecast of the 21-cm power spectrum using the halo model of reionization.” [Online]. Available: https://arxiv.org/abs/2302.06626

Validation


dT_b [mK]
T_k [K]
x_{HII}
$|dT_b|^2\,\Delta^2_{tot}(k_0, z)$ [mK]^2
z
new
old
k=0.12 Mpc^{-1}
Grid size
128^3 (fiducial)
256^3
128^3 (Thesan-Dark-1)

This is a backup slide Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aeque doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut.

Another backup slide

Lorem ipsum dolor sit amet, consectetur adipiscing elit, sed do eiusmod tempor incididunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim aeque doleamus animo, cum corpore dolemus, fieri tamen permagna accessio potest, si aliquod aeternum et infinitum impendere malum nobis opinemur. Quod idem licet transferre in voluptatem, ut.