Tools21cm: a user-friendly package to create mock SKA observations of the epoch of reionization

University of Zurich[UZH]

Sambit K. Giri

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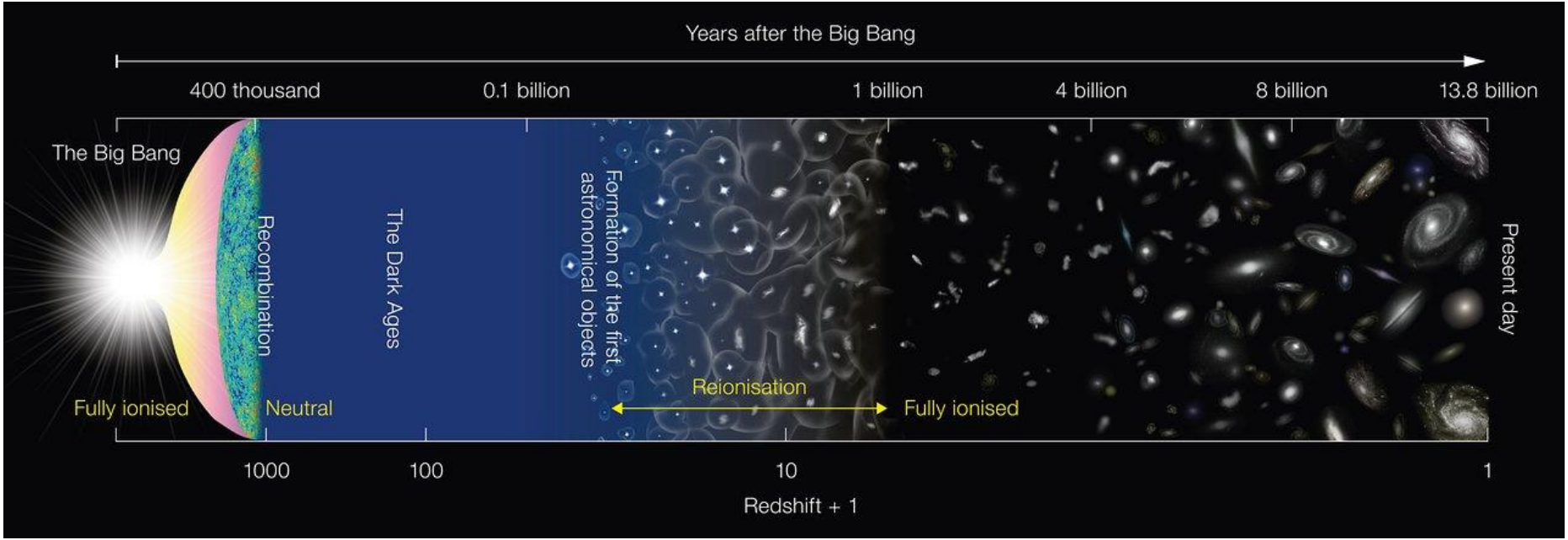
Collaborators

- Garrelt Mellema (Stockholm University)
- Raghunath Ghara (Technion)
- Michele Bianco (EPFL)
- Illian T. Iliev (Sussex university)
- Hannah E. Ross (Lawrence Berkeley National Lab)
- Hannes Jensen (Stockholm University, formerly)

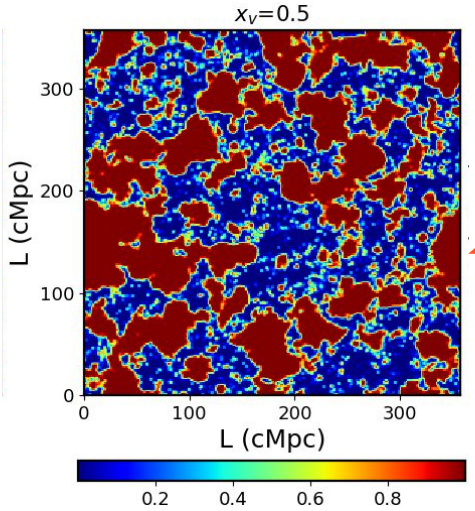
Timeline of the Universe

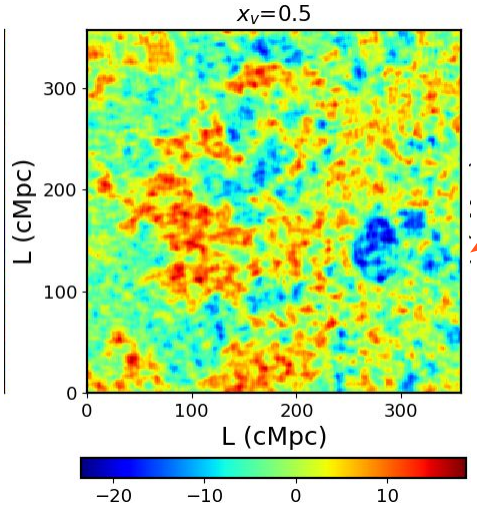


~100 MHz ~200 MHz

Credit: NAOJ

Tools21cm





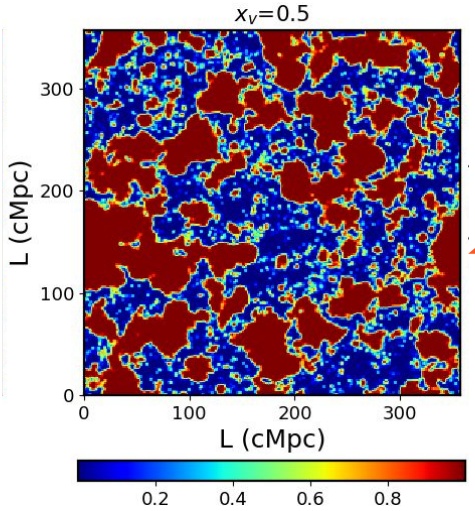
Simulations

Theoretical 21-cm signal

Mock 21-cm signal

- Power spectrum
- Position-dependent power spectrum
- Size distributions
- Betti numbers
- ....

Tools21cm



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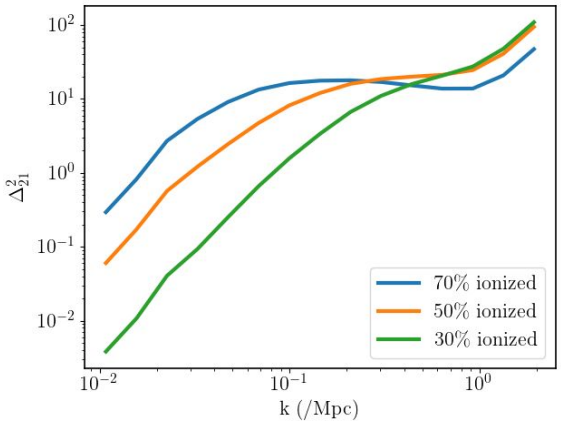

- Power spectrum
- Position-dependent power spectrum
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Tools21cm

JOSS 10.21105/joss.02363

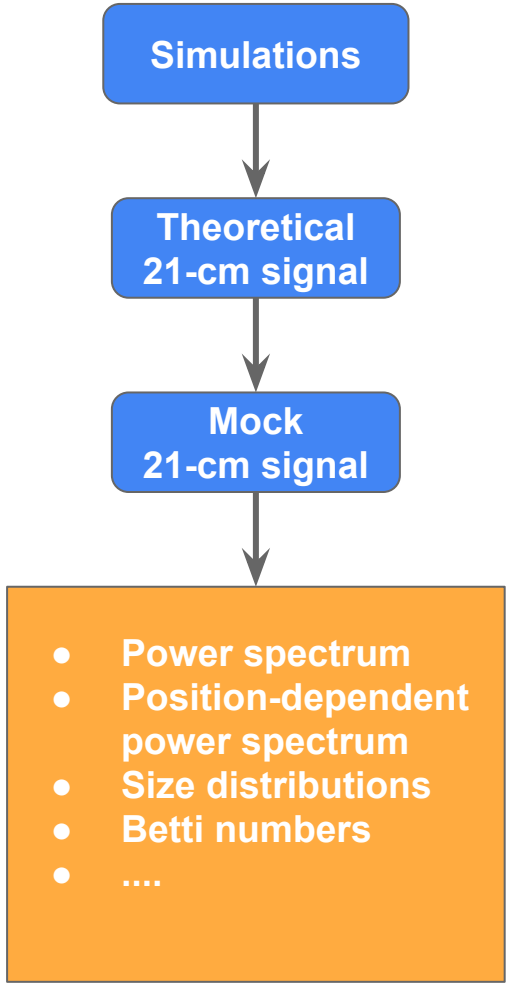
A python package for analysing 21-cm signals from the Epoch of Reionization (EoR) and Cosmic Dawn (CD). The source files can be found here.

Note: There are some modules in the package that are still under active development. Therefore please contact the authors if you get erronous results.

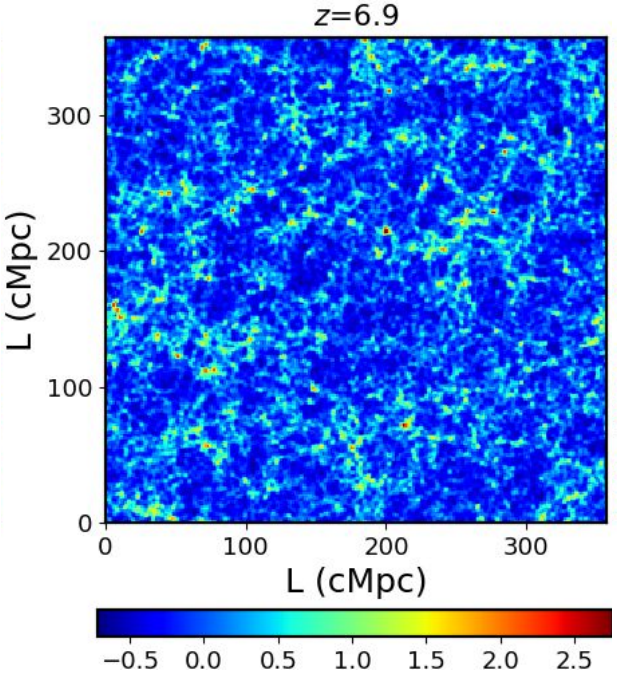
Package details

The package provides tools to analyse cosmological simulations of EoR and CD. It contains modules to create mock 21-cm observations for current and upcoming radio telescopes, such as LOFAR, MWA and SKA, and to construct statistical measures.

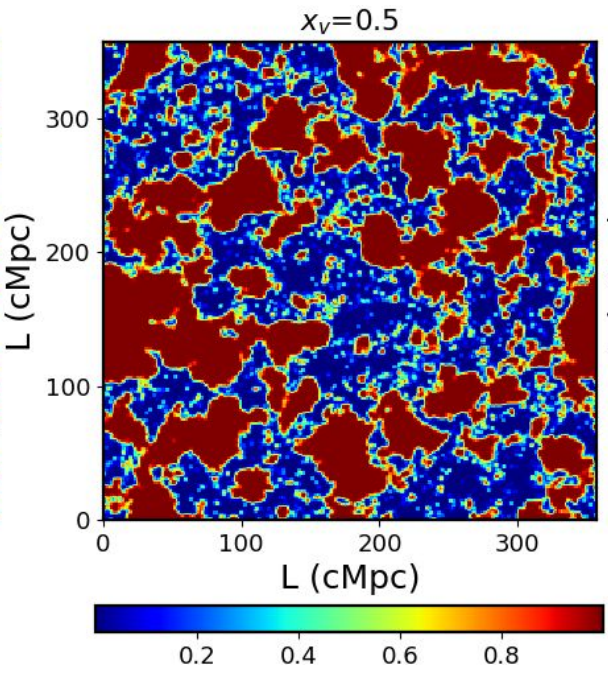
https://tools21cm.readthedocs.io/



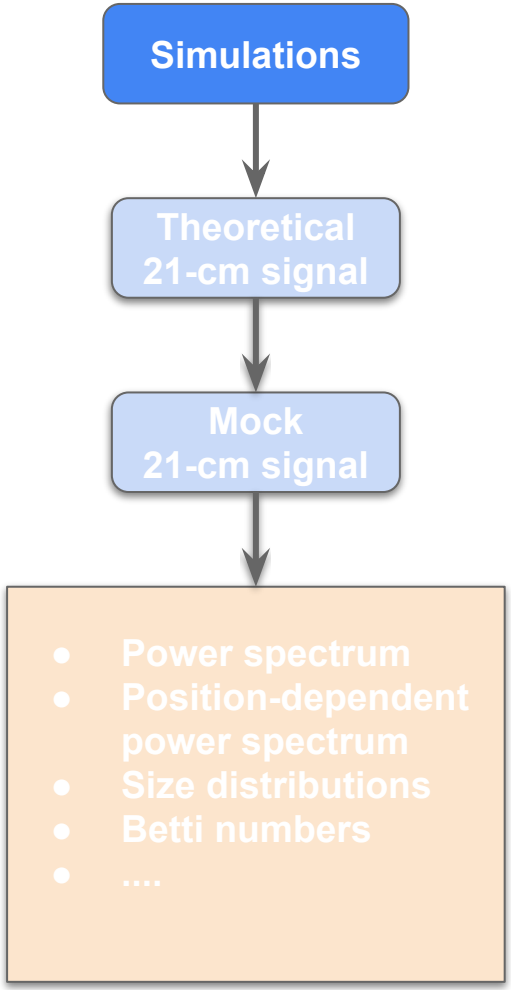
Cosmological simulations



CUBEP^{3}M simulation

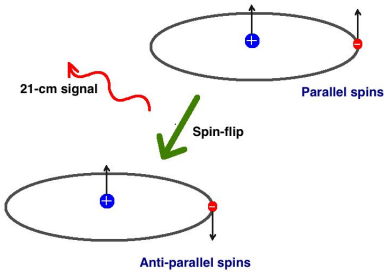


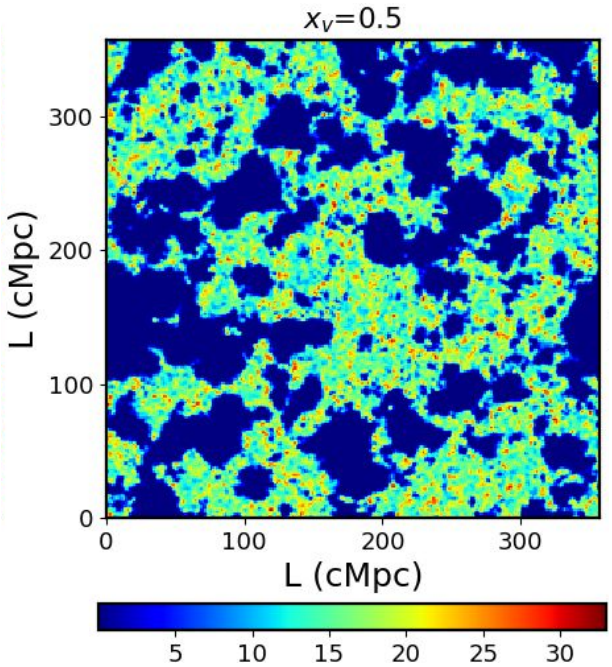
C^{2}Ray simulation



Differential brightness temperature

$$\delta T_b(\boldsymbol{r}) \propto (1 + \delta_b(\boldsymbol{r}))\ x_{\rm HI}(\boldsymbol{r})$$





Simulations

↓

Theoretical 21-cm signal

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Mock 21-cm signal

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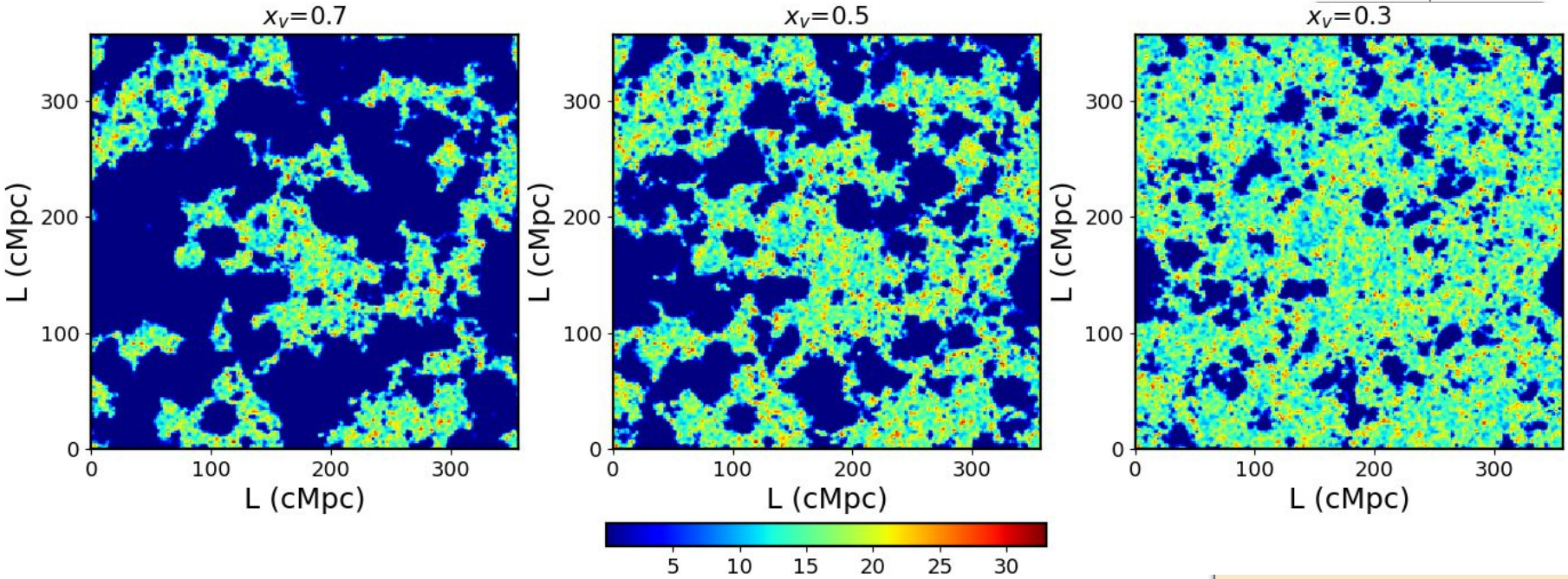
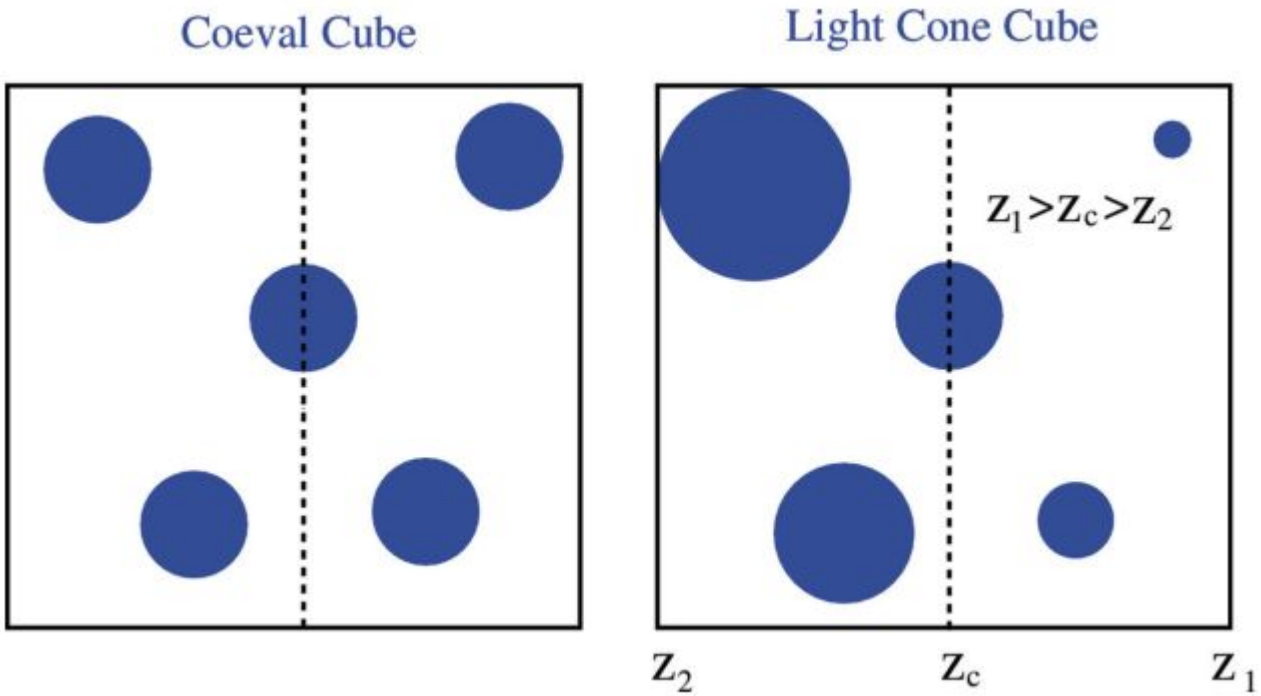
Differential brightness temperature

Simulations



21-cm signal evolves with frequency
Light-cone effect



Datta+2012

Simulations

↓

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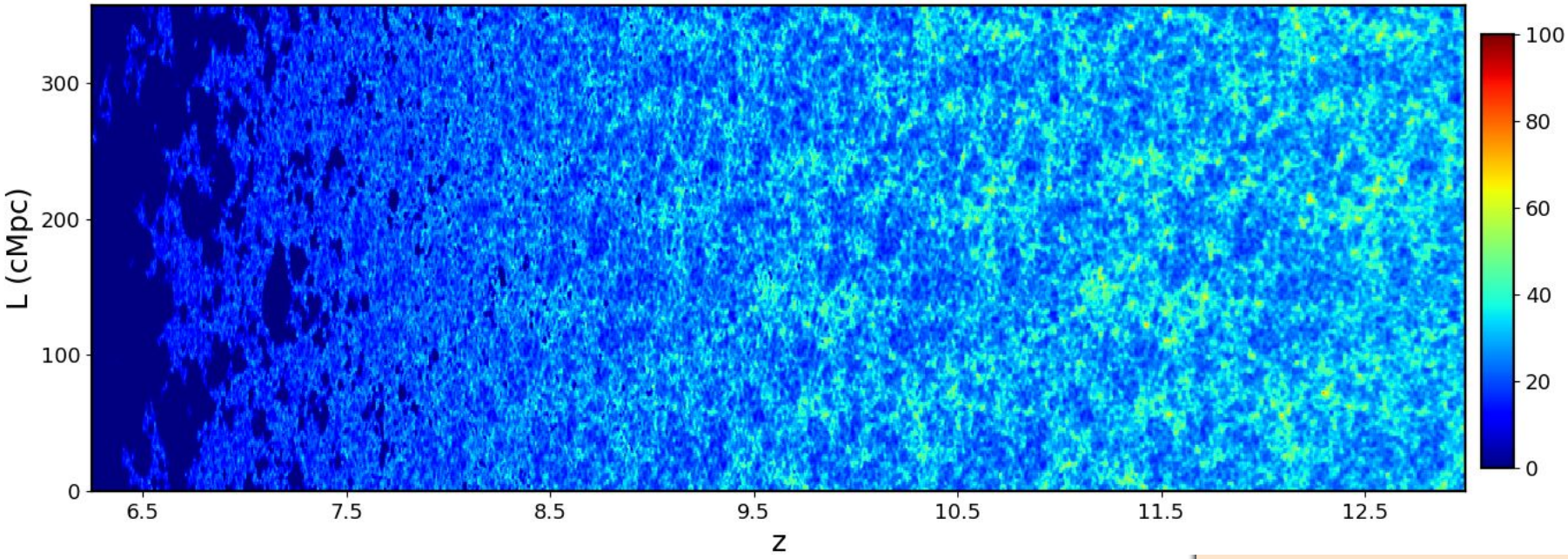
21-cm signal evolves with frequency
Light-cone effect

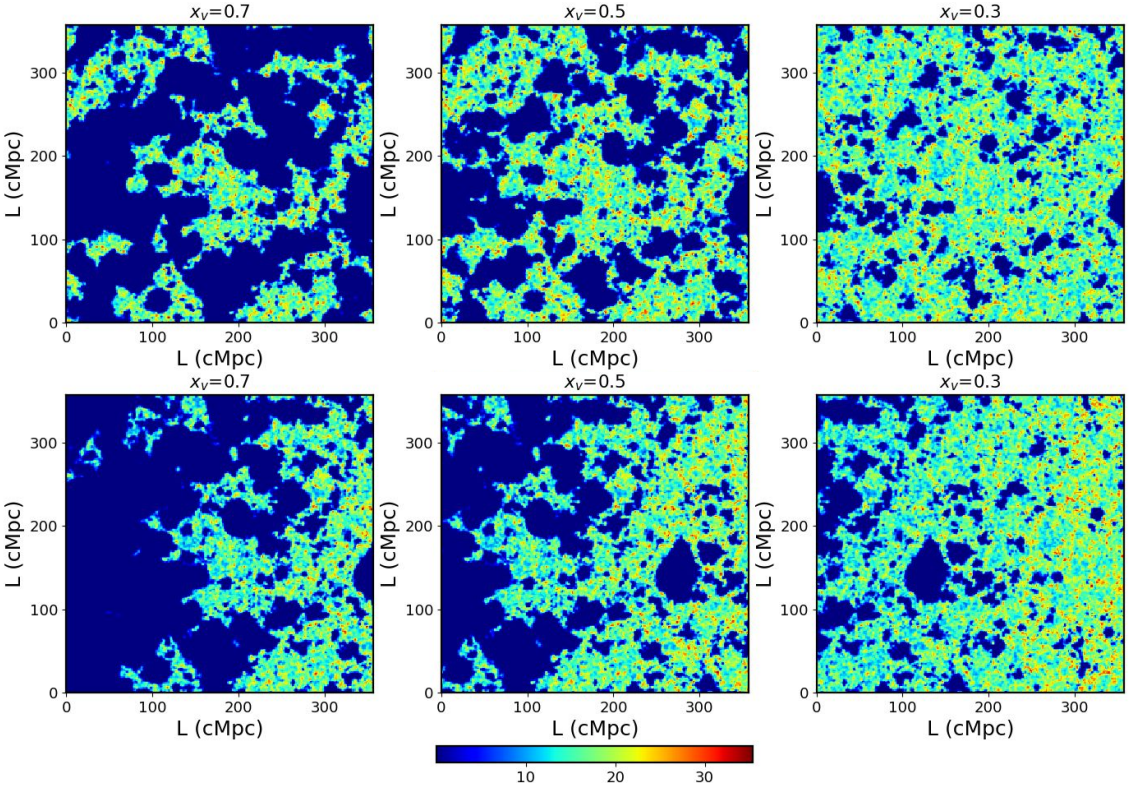
Simulations



tools21cm.make_lightcone

21-cm signal evolves with frequency

Light-cone effect



Simulations

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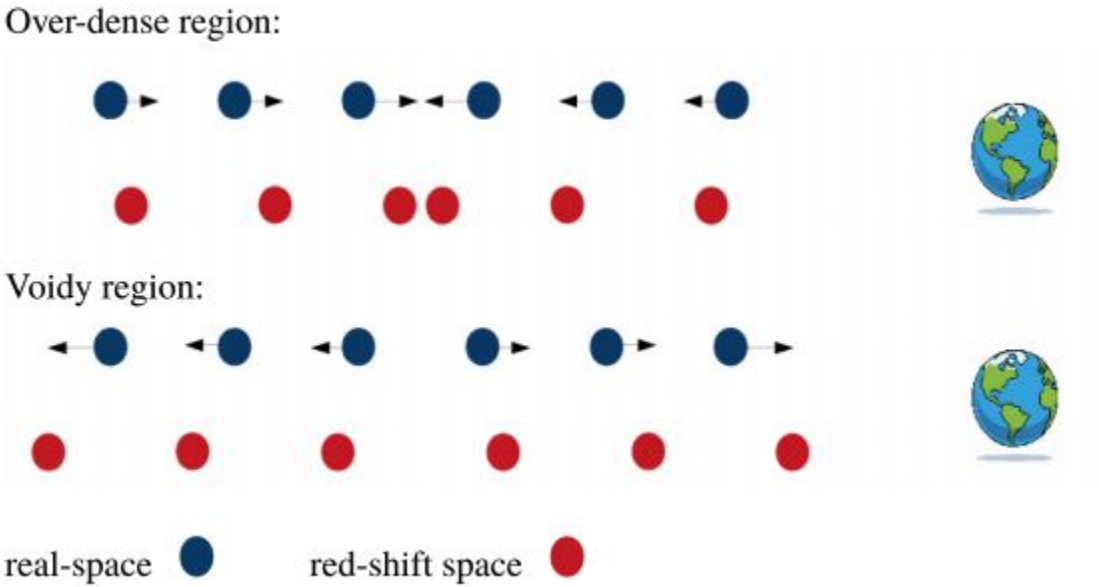
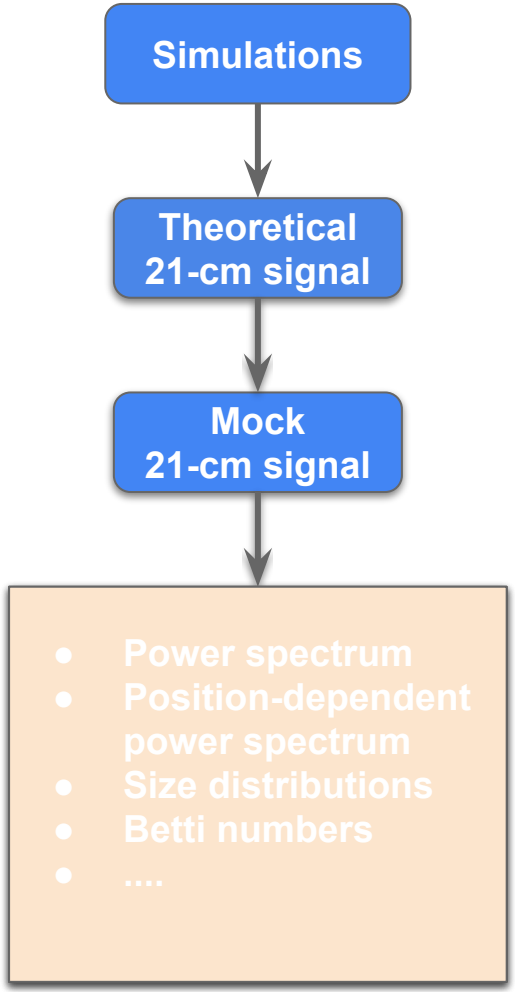
Impact of peculiar velocities
Redshift-space distortion

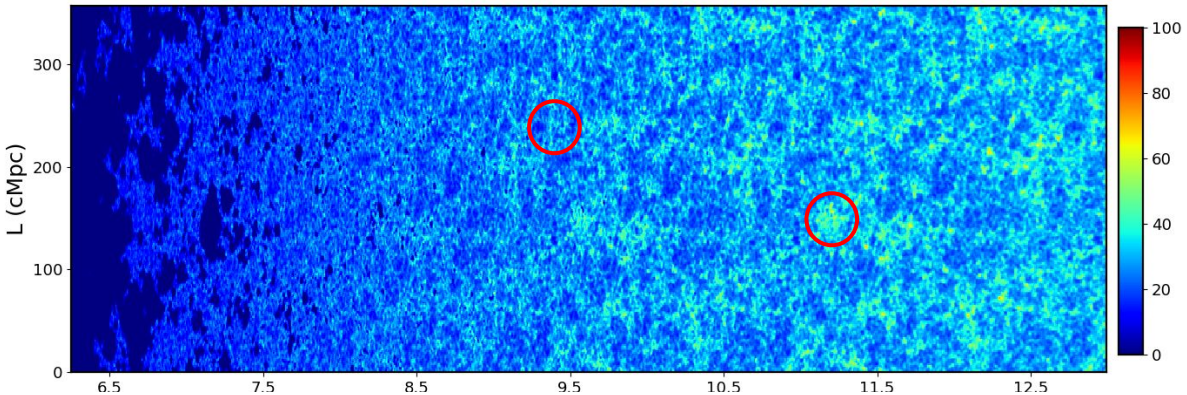


Ross,SG+2012

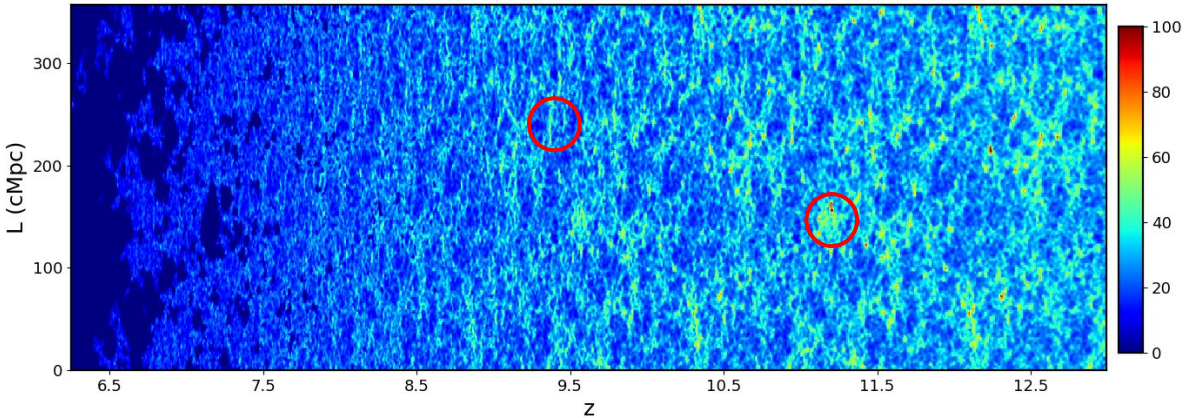


Impact of peculiar velocities
Redshift-space distortion

tools21cm.get_distorted_dt



non-distorted



distorted

Simulations

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↓

Mock 21-cm signal

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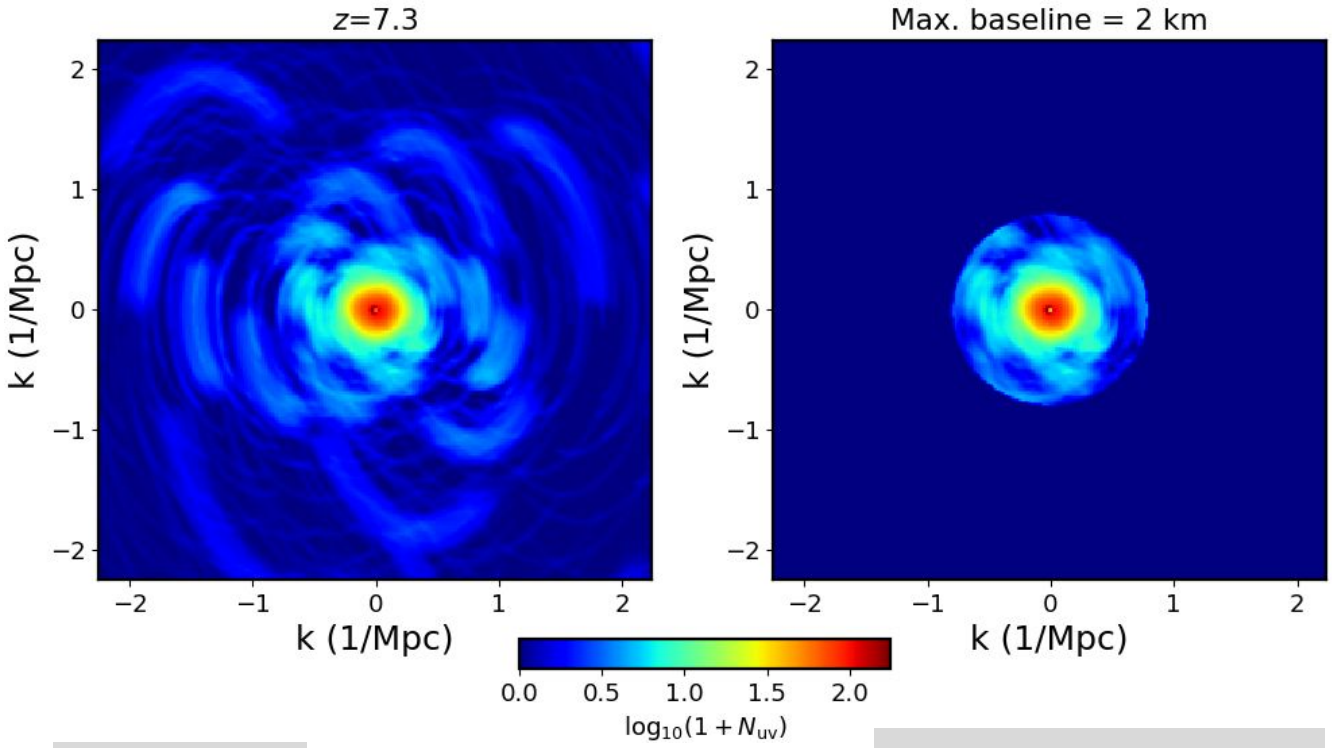
Simulating interferometric measurements



Michele's talk

tools21cm.get_uv_map

Simulations

Theoretical 21-cm signal

Mock 21-cm signal

- Power spectrum
- Position-dependent power spectrum
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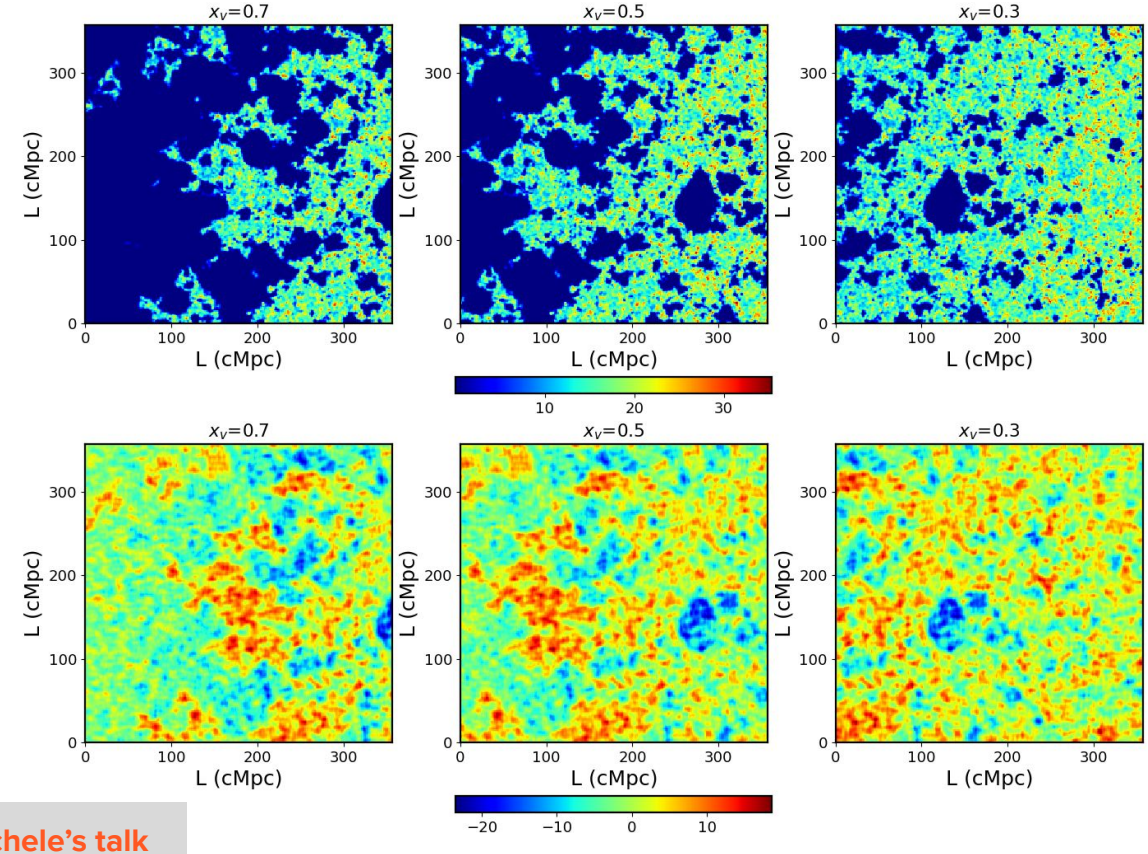
- ....

Simulating interferometric measurements



Michele's talk

- Simulations
- Theoretical 21-cm signal
- Mock 21-cm signal

- Power spectrum
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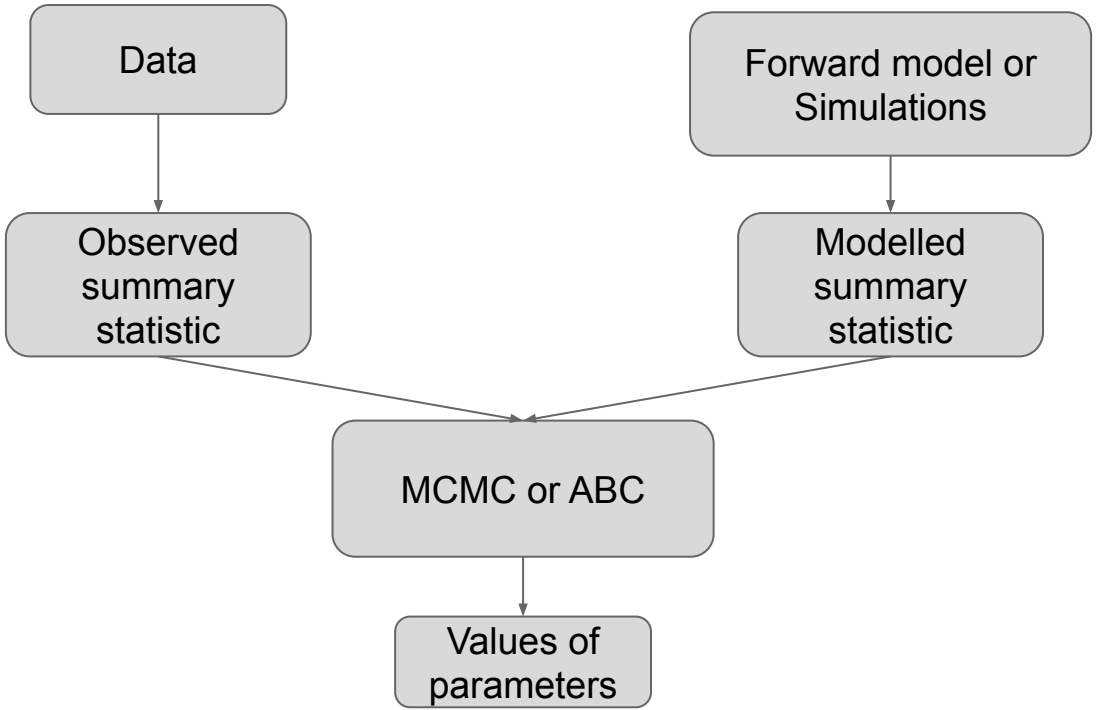
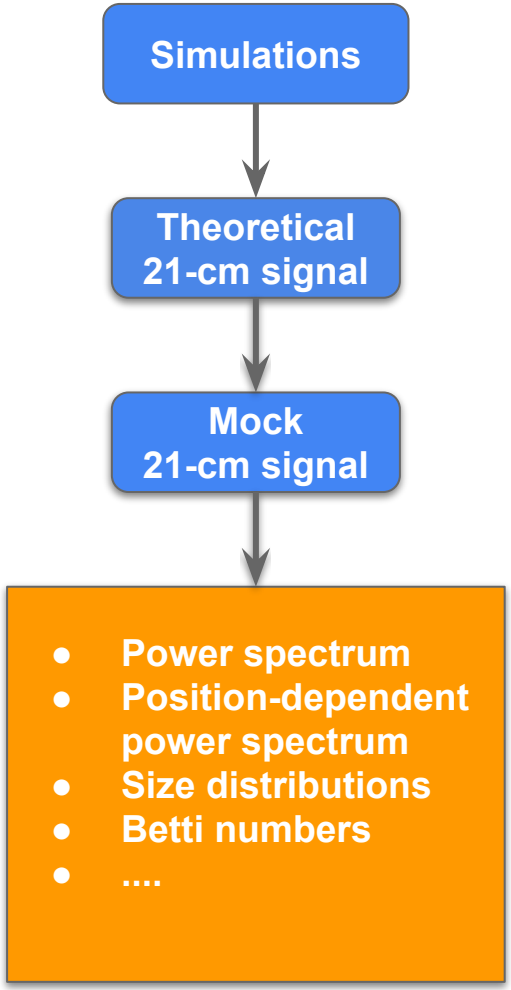
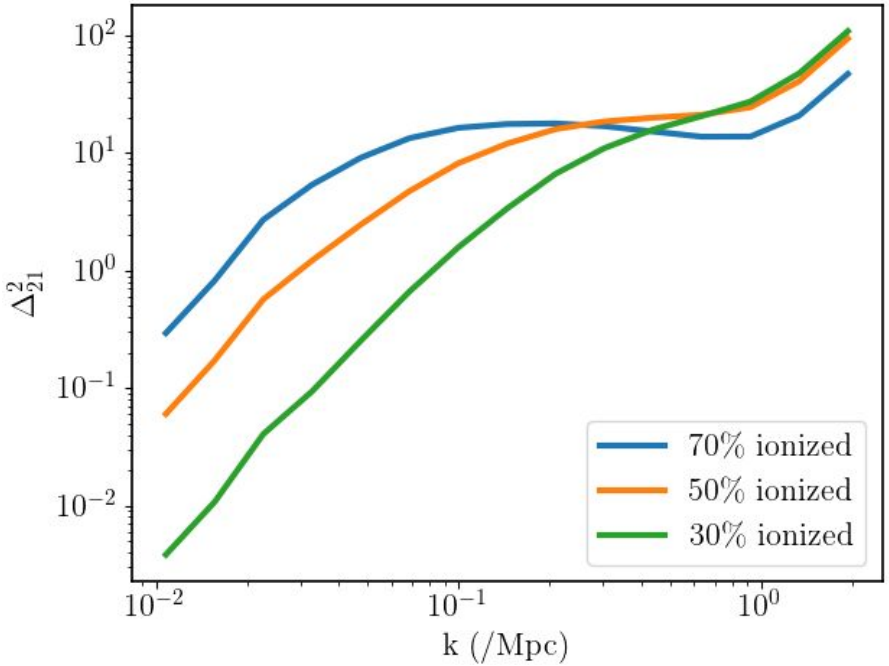
Summary statistics





Summary statistics
Power spectrum



Simulations

↓

Theoretical 21-cm signal

↓

Mock 21-cm signal

↓

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Tools21cm can...

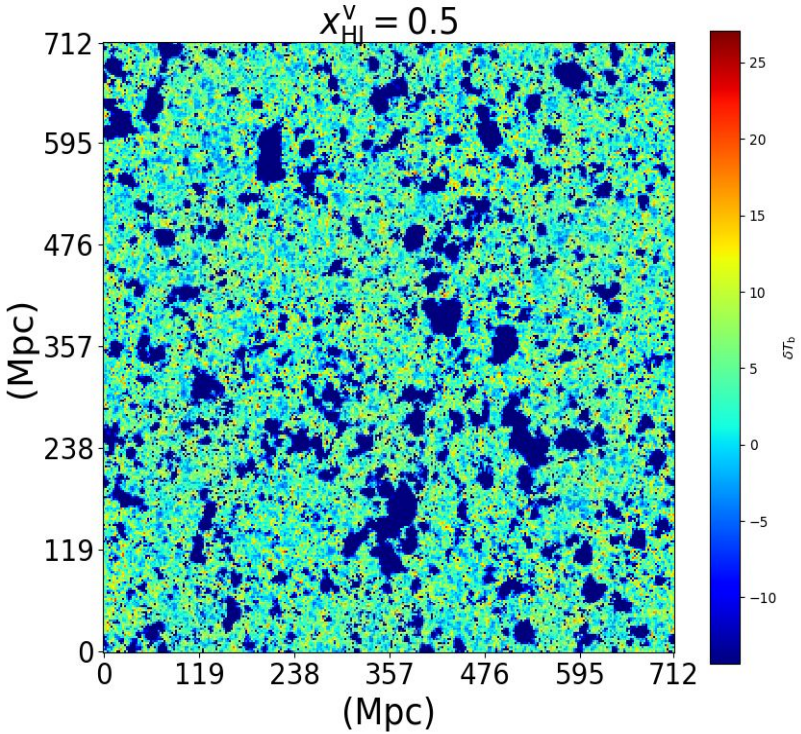
- produce 21-cm light-cones
- simulate interferometric measurements
- extract information from mock observations
- ...

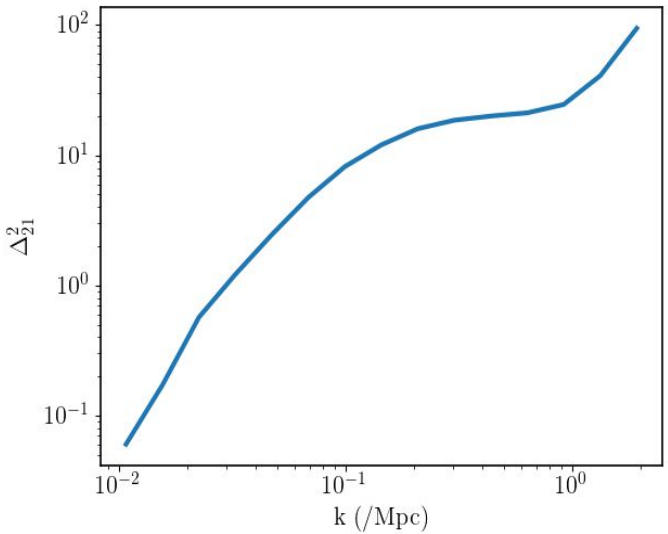
Under-development

- Simulations foreground signals
- Mitigating these foreground signal
- Persistence homology
- ...

Some backup slides

Summary statistics
Non-Gaussian information





Simulations

Theoretical 21-cm signal

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n signal

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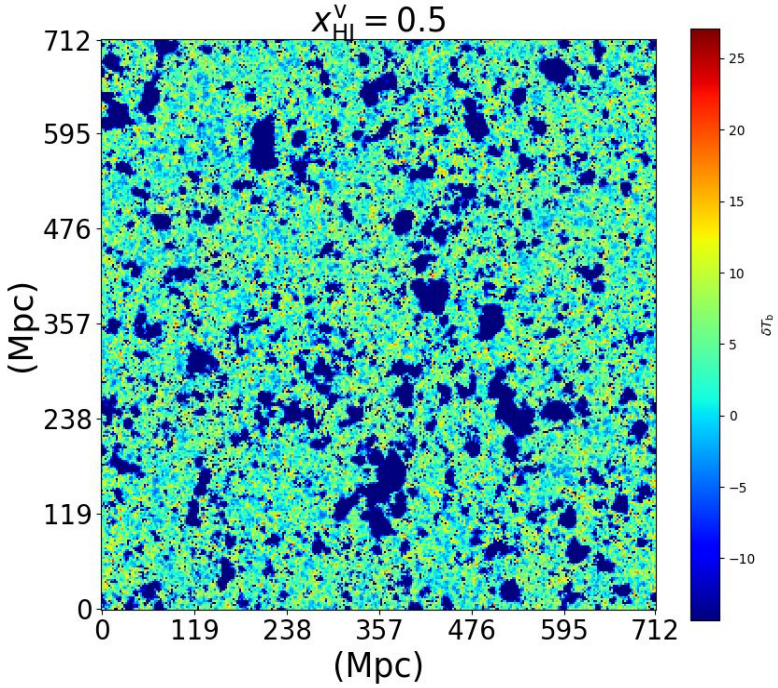
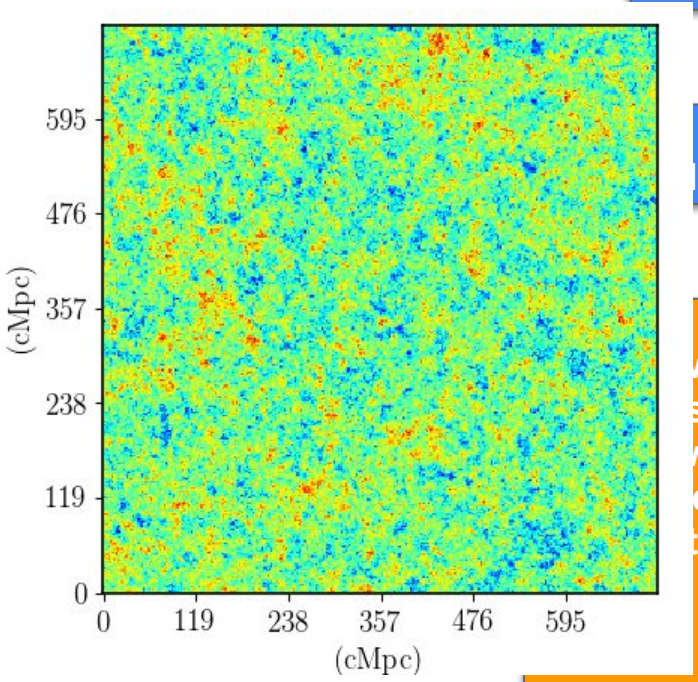
stributions
umbers

Summary statistics
Non-Gaussian information





Simulations

Theoretical 21-cm signal

Mock -cm signal

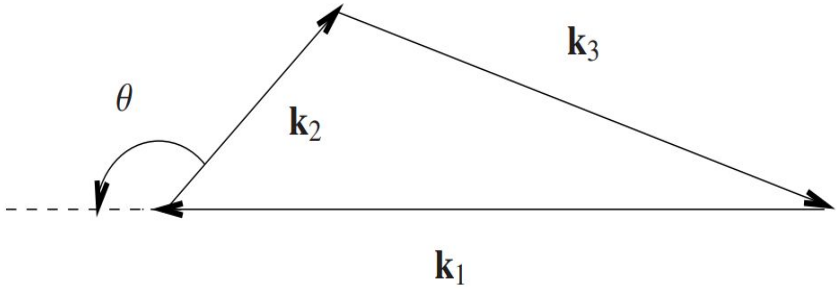
wer spectrum
sition-dependent
wer spectrum
e distributions
ti numbers

Summary statistics
Bispectrum

$$\langle \Delta_b(\mathbf{k}_1)\Delta_b(\mathbf{k}_2)\Delta_b(\mathbf{k}_3)\rangle = V\delta^K_{\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3,0}\, B_b(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3),$$

$$\hat{B}_m(\mathbf{k}_1,\mathbf{k}_2,\mathbf{k}_3) = \frac{1}{N_{\rm tri}V} \sum_{[\mathbf{k}_1+\mathbf{k}_2+\mathbf{k}_3=0]\in m} \Delta(\mathbf{k}_1)\Delta(\mathbf{k}_2)\Delta(\mathbf{k}_3),$$

Majumdar+2018



Simulations

↓

Theoretical 21-cm signal

↓

Mock 21-cm signal

↓

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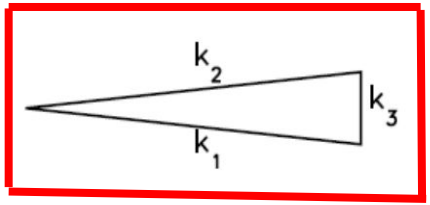
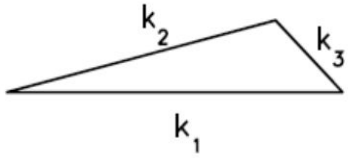
Summary statistics
Bispectrum

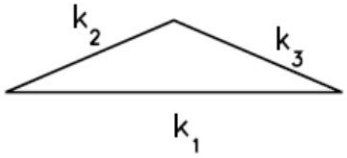
(a) squeezed triangle
$(k_1 \simeq k_2 >> k_3)$



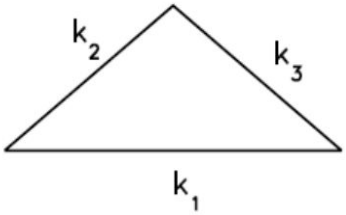
(b) elongated triangle
$(k_1 = k_2 + k_3)$



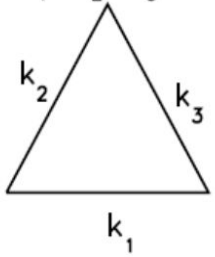
(c) folded triangle
$(k_1 = 2k_2 = 2k_3)$

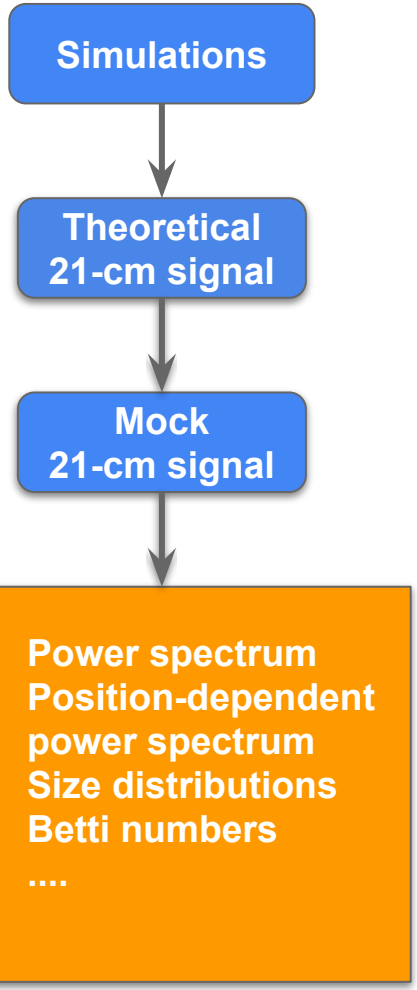


(d) isosceles triangle
$(k_1 > k_2 = k_3)$

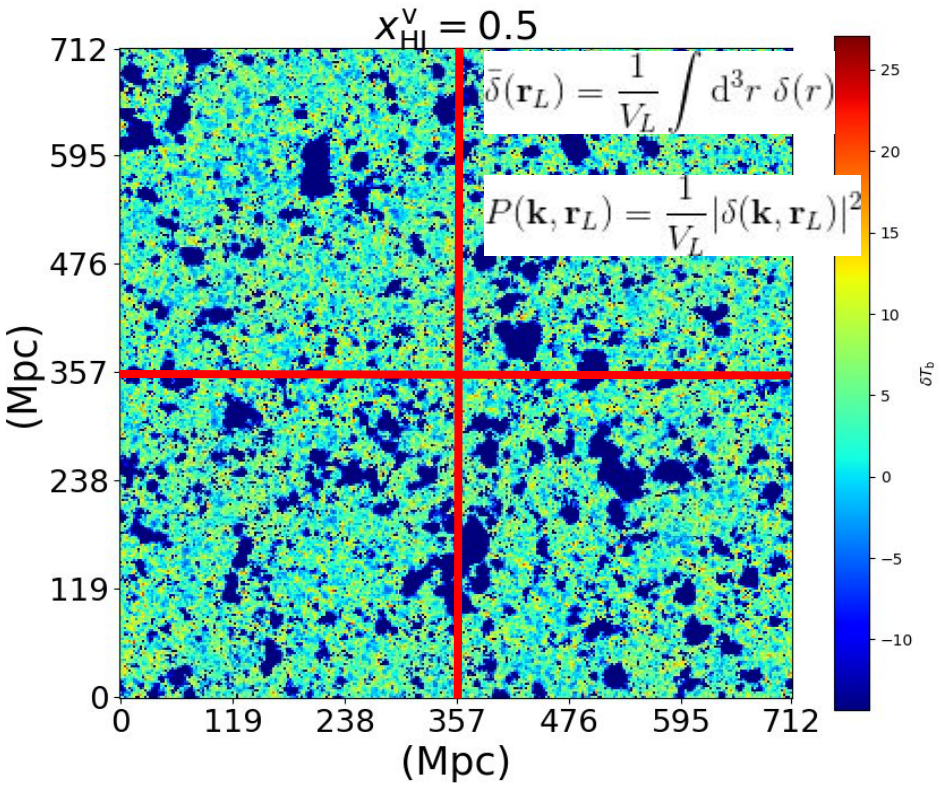


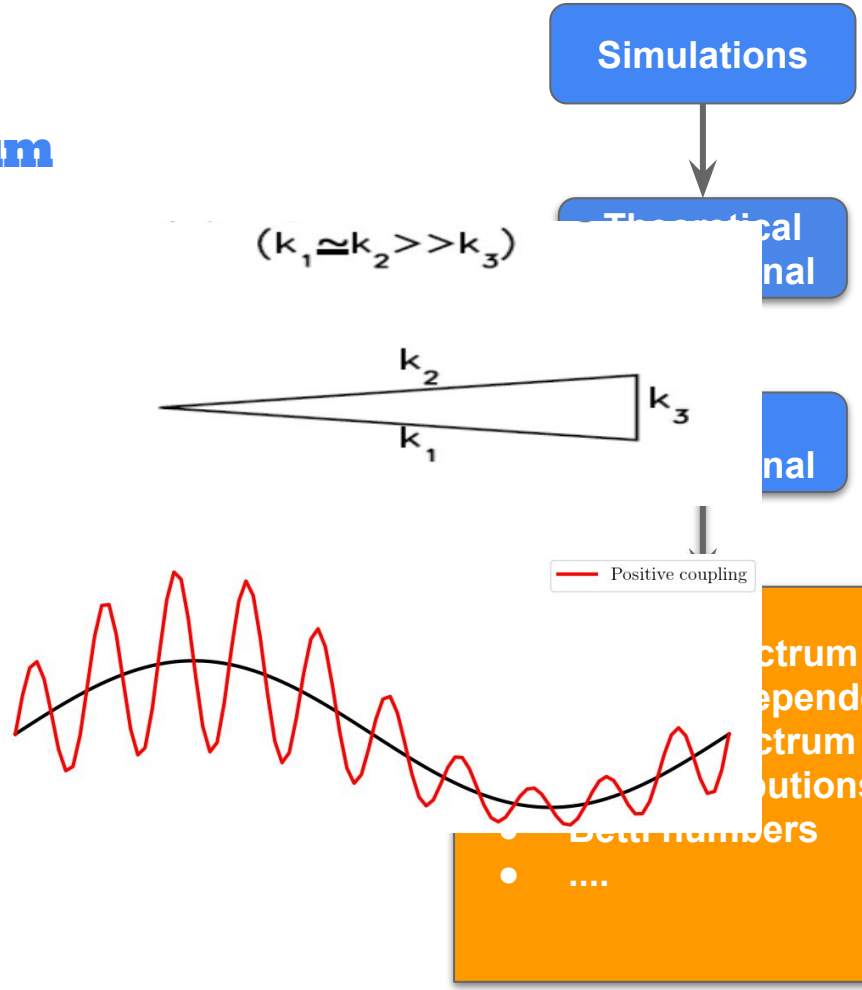
(e) equilateral triangle
$(k_1 = k_2 = k_3)$





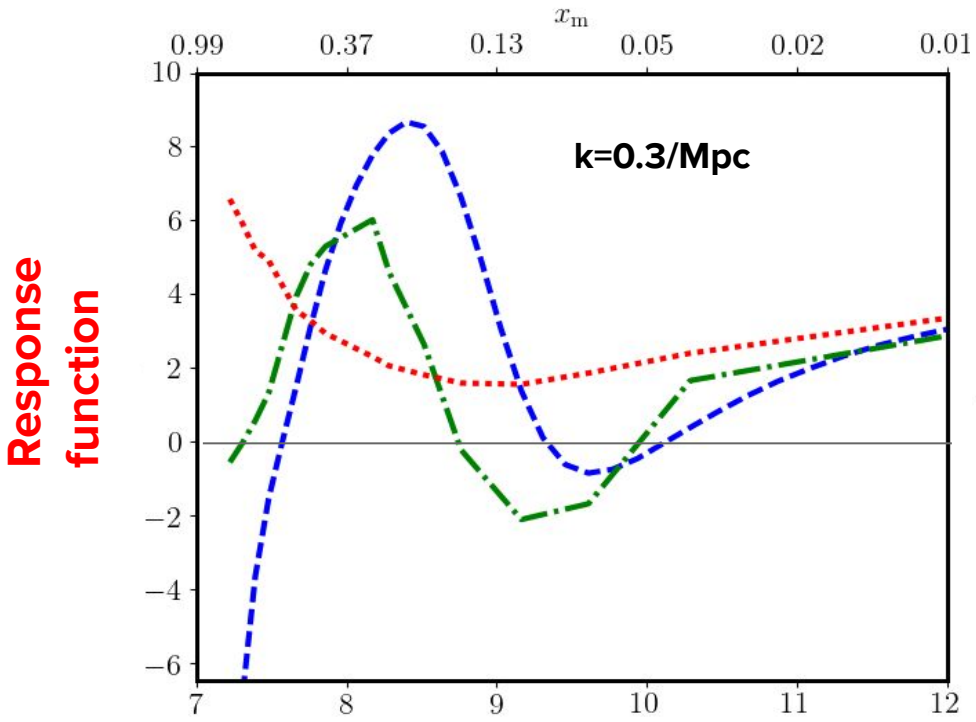
Summary statistics
Position-dependent power spectrum

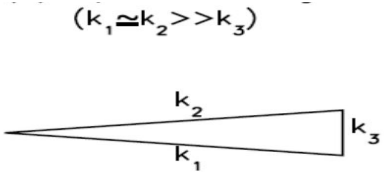


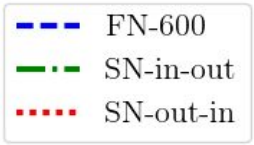


Summary statistics

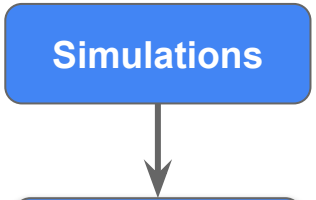
Position-dependent power spectrum

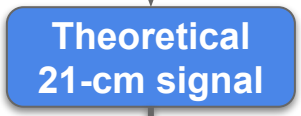






Giri+2019





- Power spectrum
- Position-dependent power spectrum
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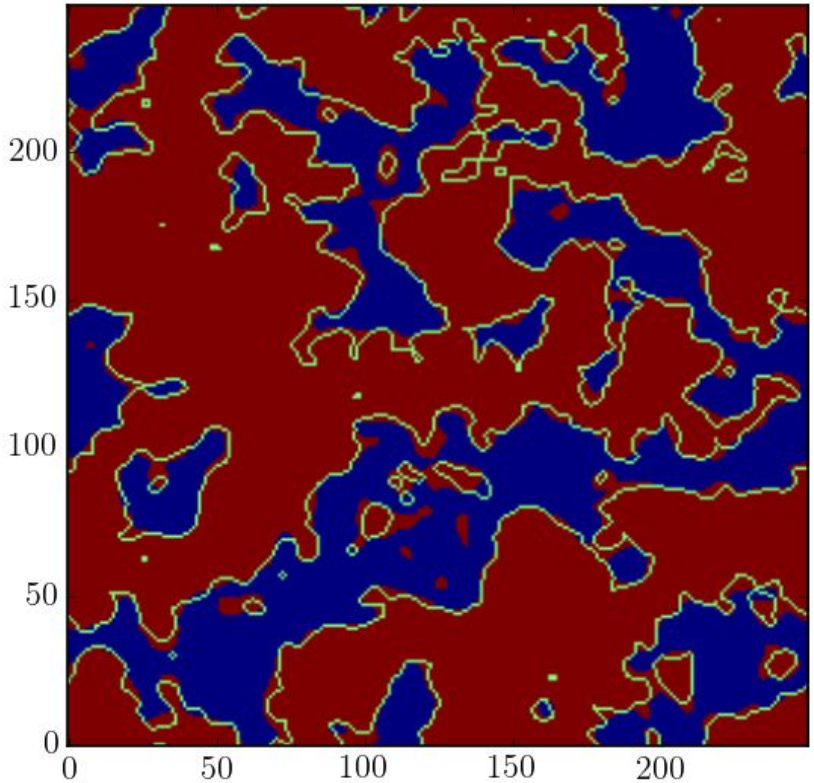
Summary statistics
21-cm images



Also in Michele's talk

Giri, Mellema & Ghara 2018

Simulations

↓

Theoretical 21-cm signal

↓

Mock 21-cm signal

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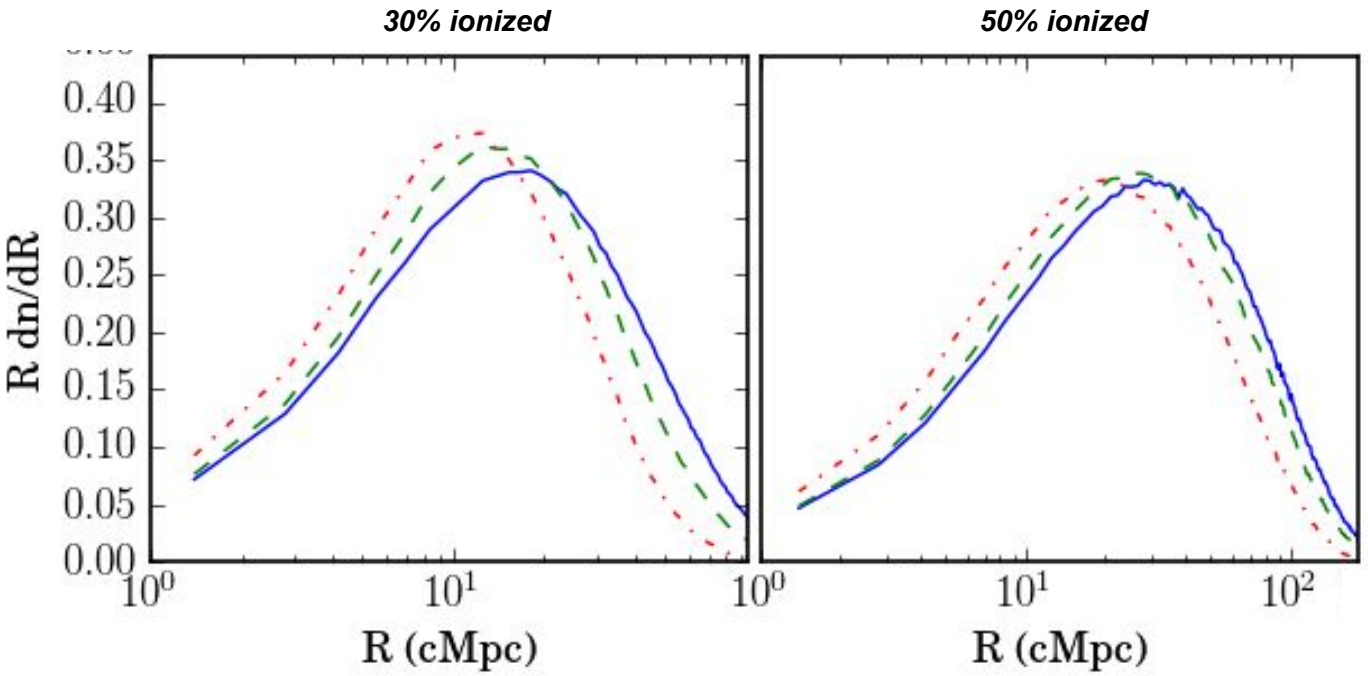
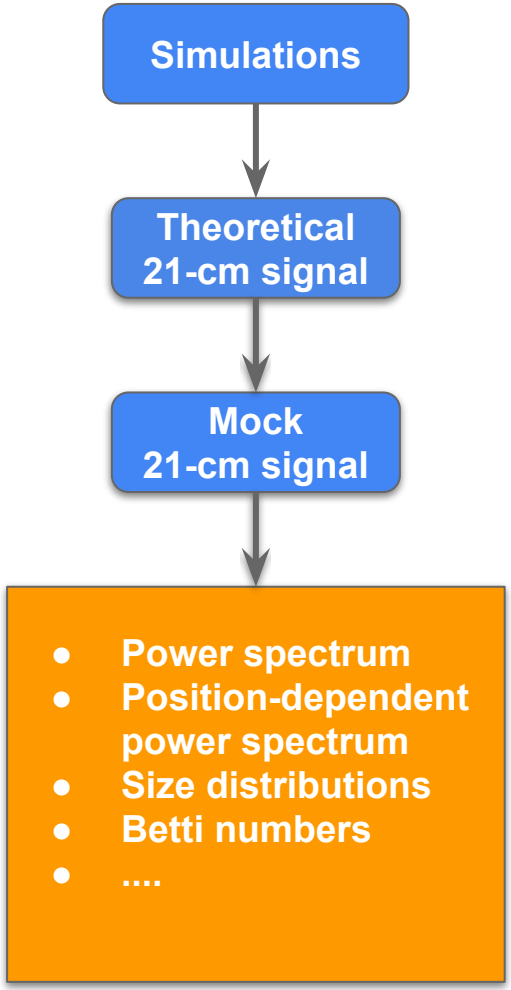
Summary statistics
Size distribution of ionized bubbles

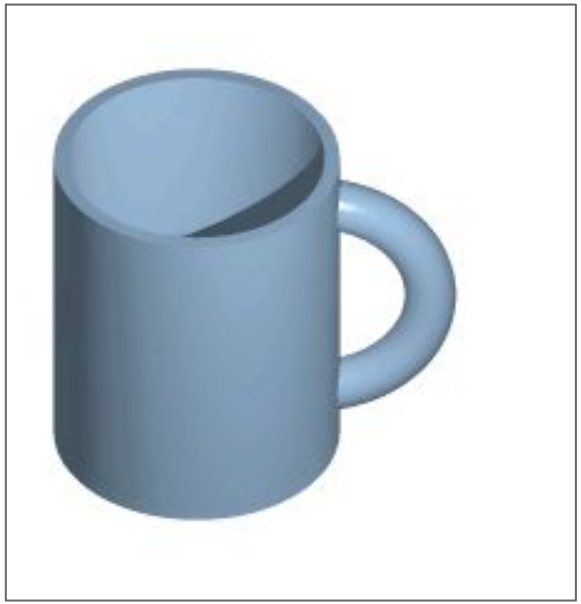


Also in Michele's talk

Giri+2018



Summary statistics
Topological information



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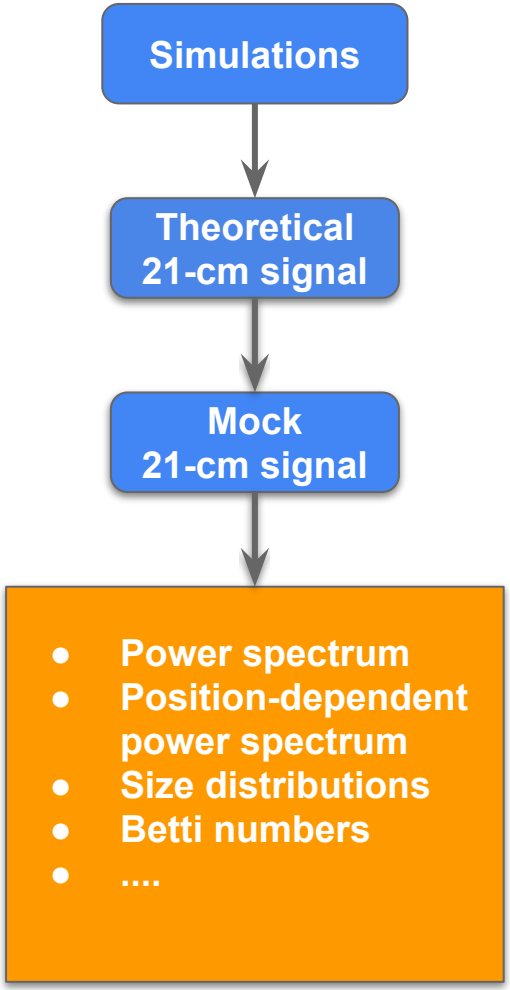
Giri & Mellema 2021

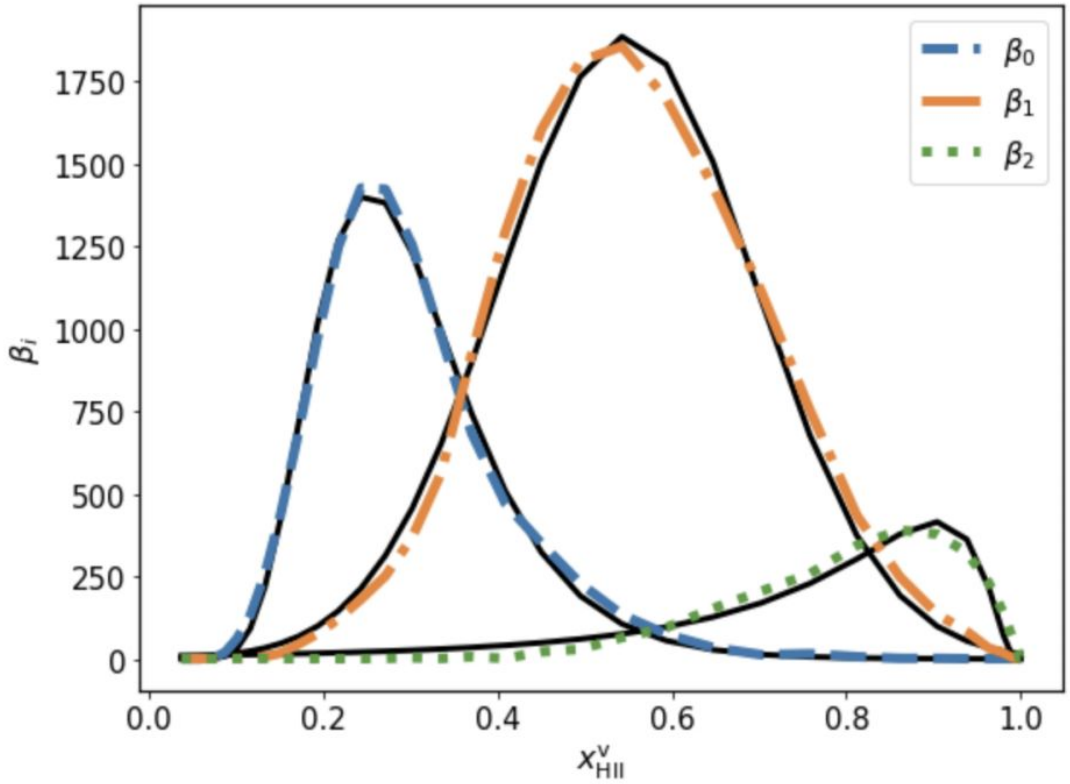
Summary statistics
Betti numbers

$$\beta_0 = \#\text{parts}$$
$$\beta_1 = \#\text{tunnels}$$
$$\beta_2 = \#\text{cavities}$$



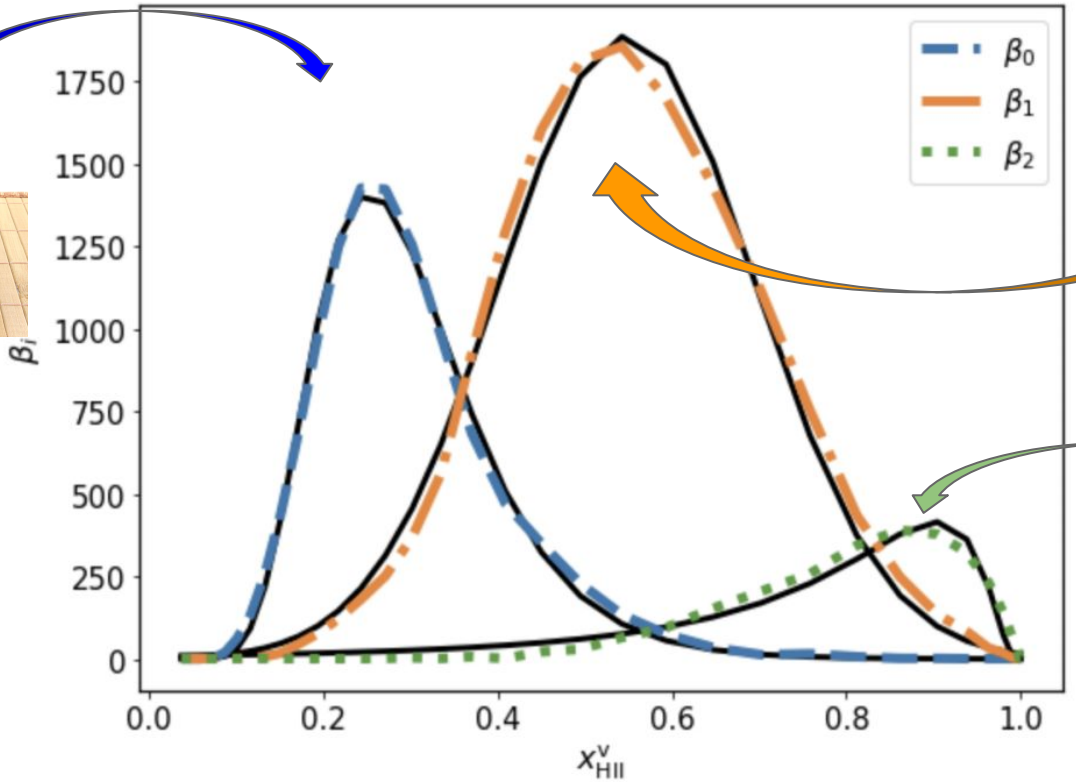
Giri & Mellema 2021

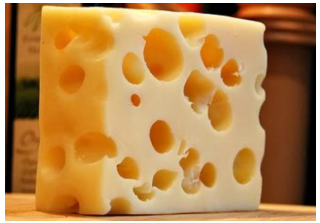
Summary statistics
Betti numbers



Summary statistics
Betti numbers

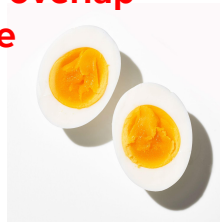
Pre-overlap stage



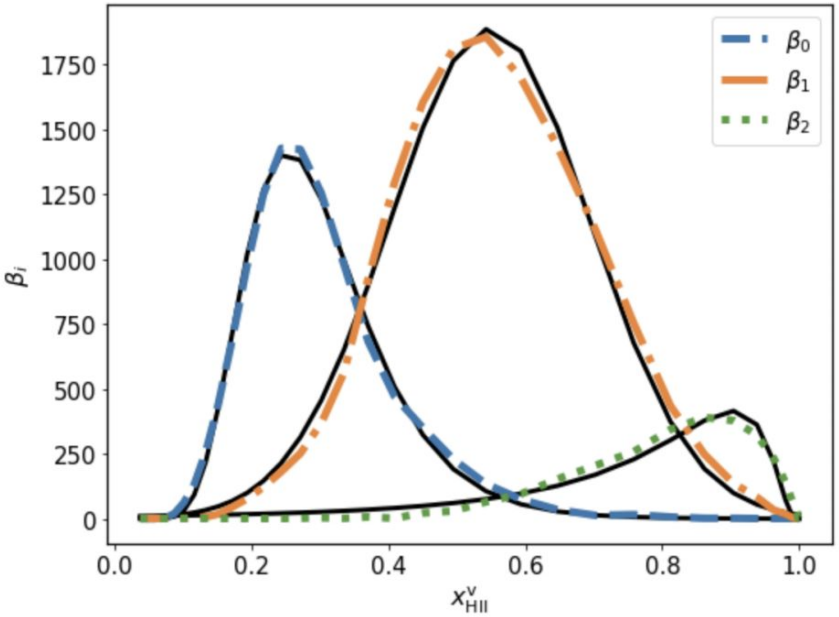


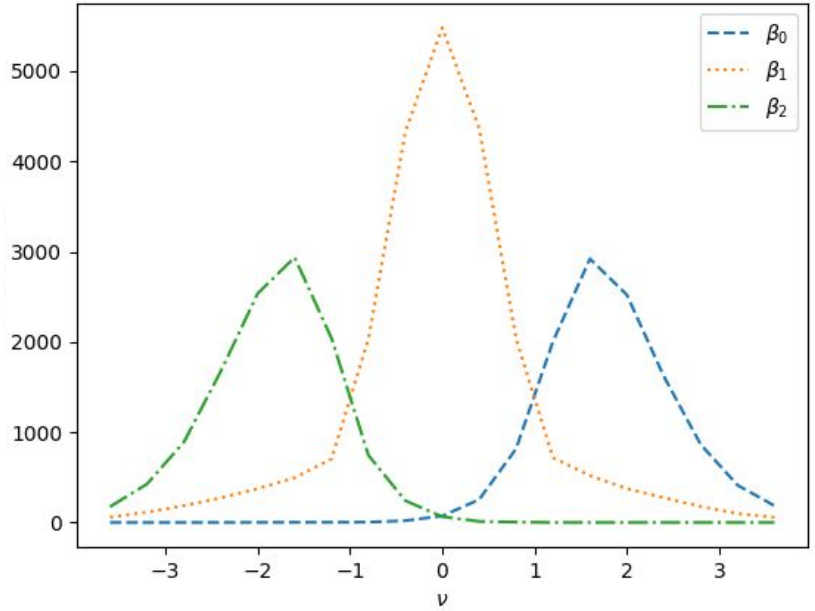
Overlap stage

Post-overlap stage

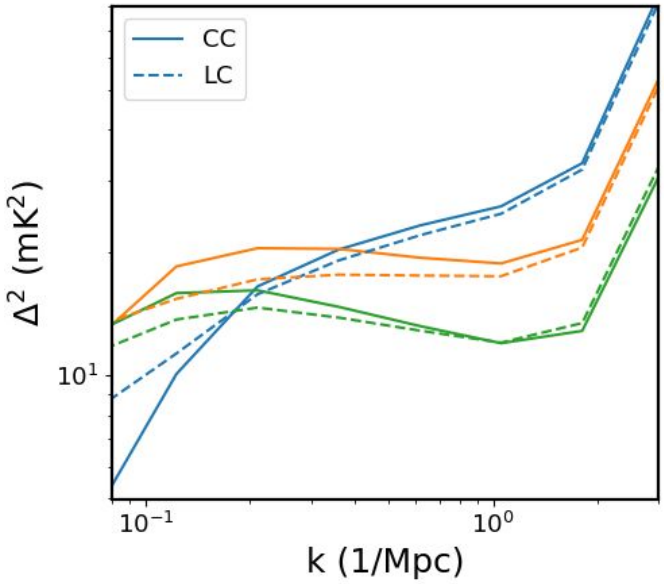


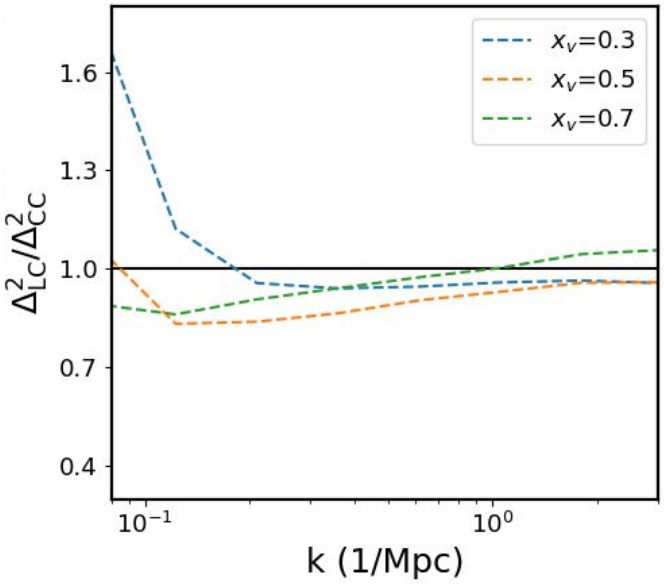
Summary statistics
Betti numbers





21-cm signal evolves with frequency
Light-cone effect





Simulations

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Theoretical 21-cm signal

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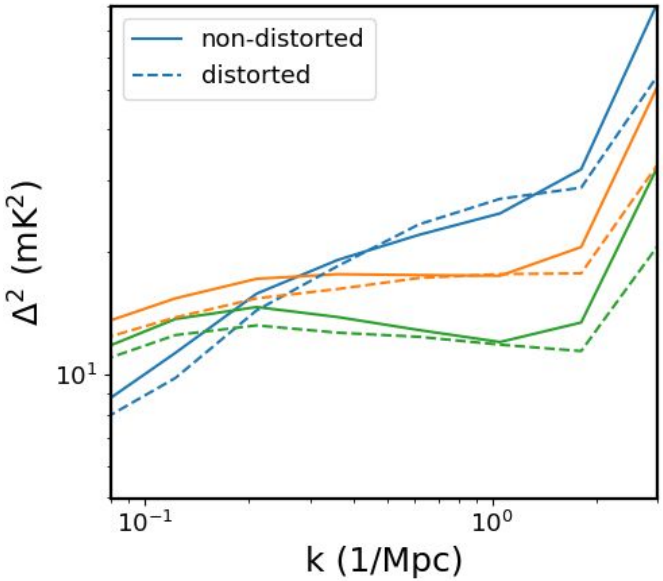
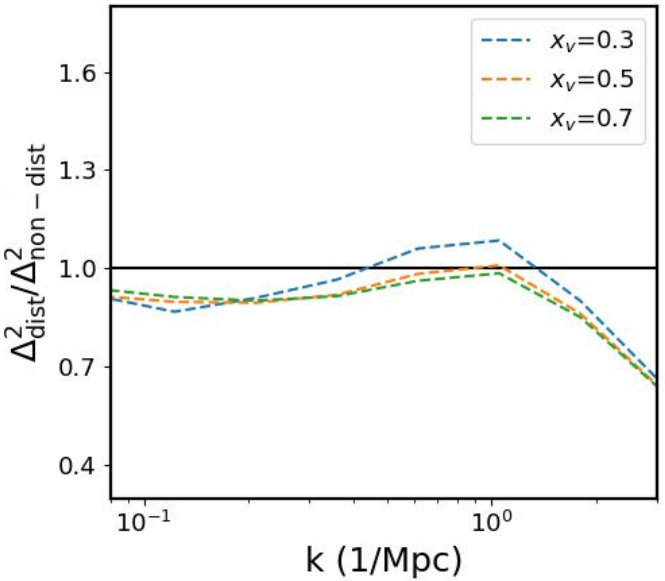
Mock 21-cm signal

↓

- Power spectrum
- Position-dependent power spectrum
- Size distributions
- Betti numbers
- ....

Impact of peculiar velocities
Redshift-space distortion





Simulations

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Theoretical 21-cm signal

↓

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