The childhood of the Universe in 21-cm emission

Hannes Jensen, SU

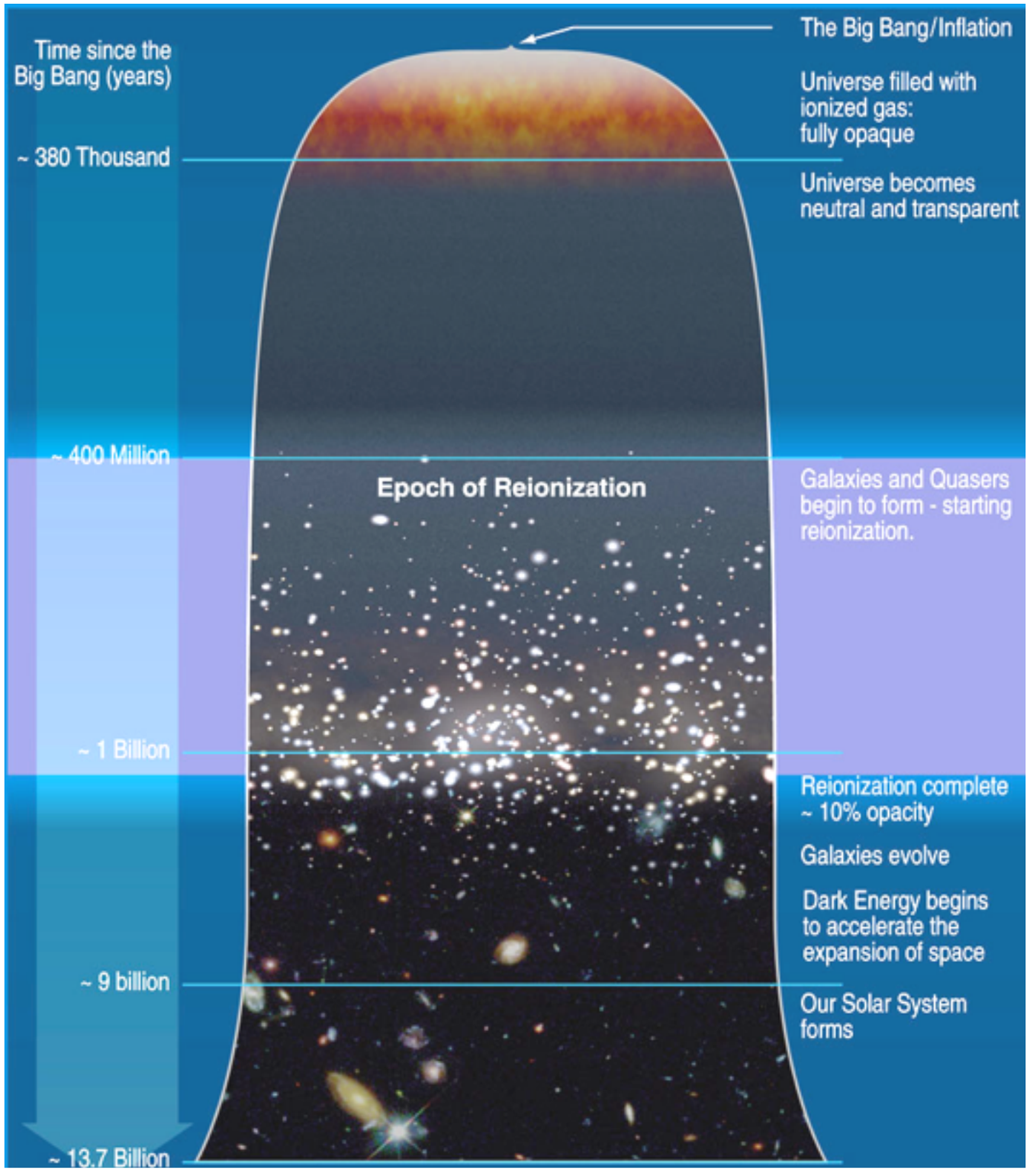
Intro:

- What is the Epoch of Reionization?
- The 21-cm signal
- The 21-cm power spectrum

My own stuff:

- Redshift space distortions

The Epoch of Reionization (EoR)



Why study EoR?

- Filling in the gap
- Learn about first stars
- Exotic physics?

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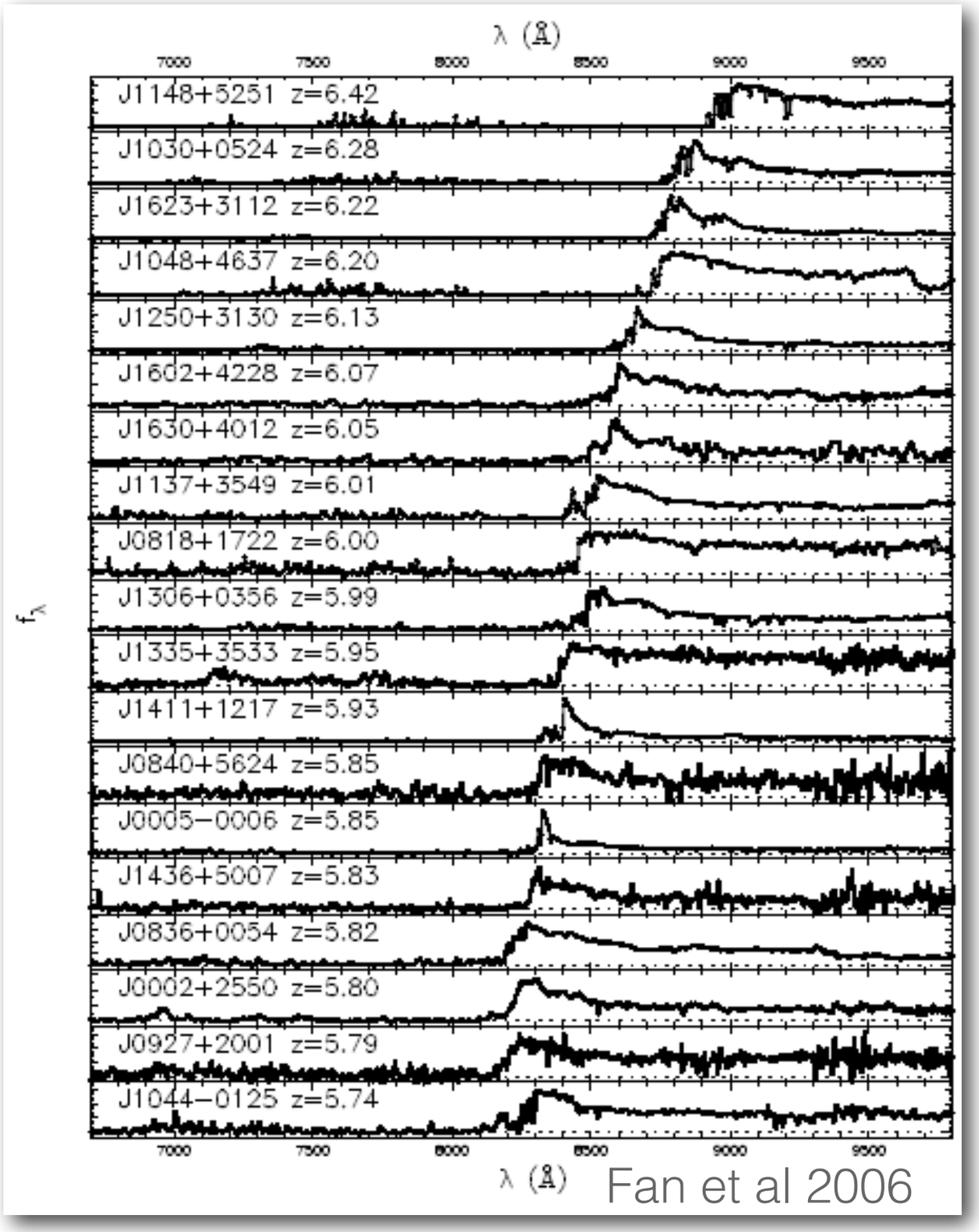
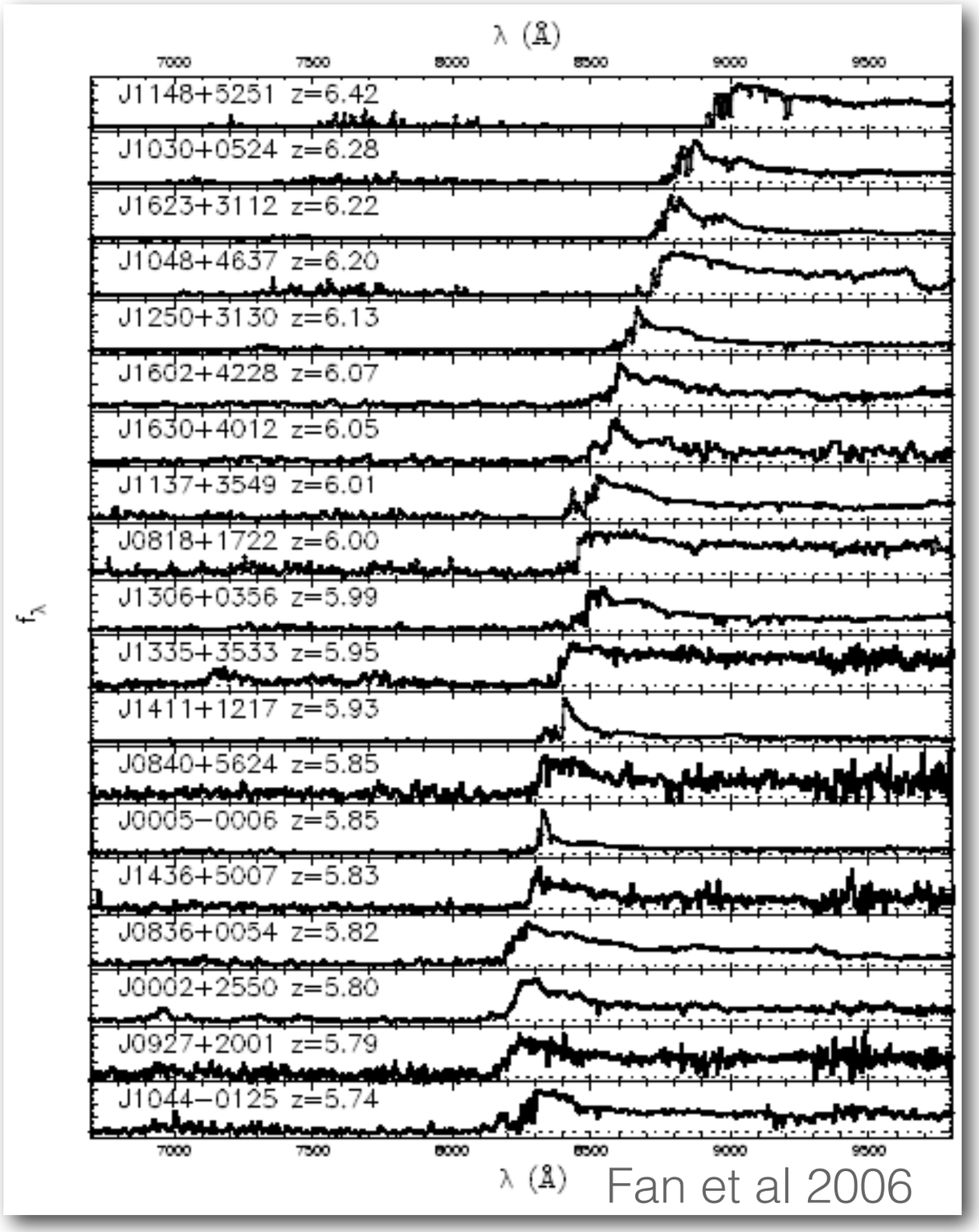
When?



Fan et al 2006

When?



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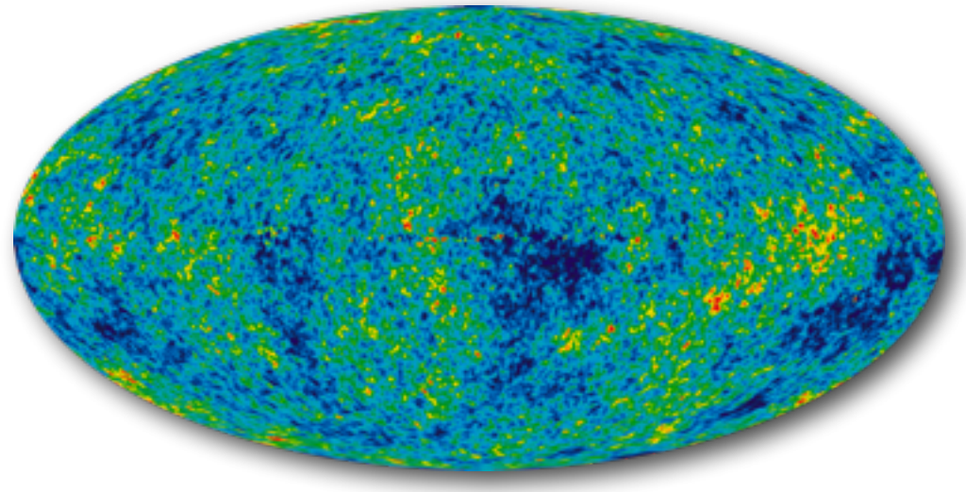
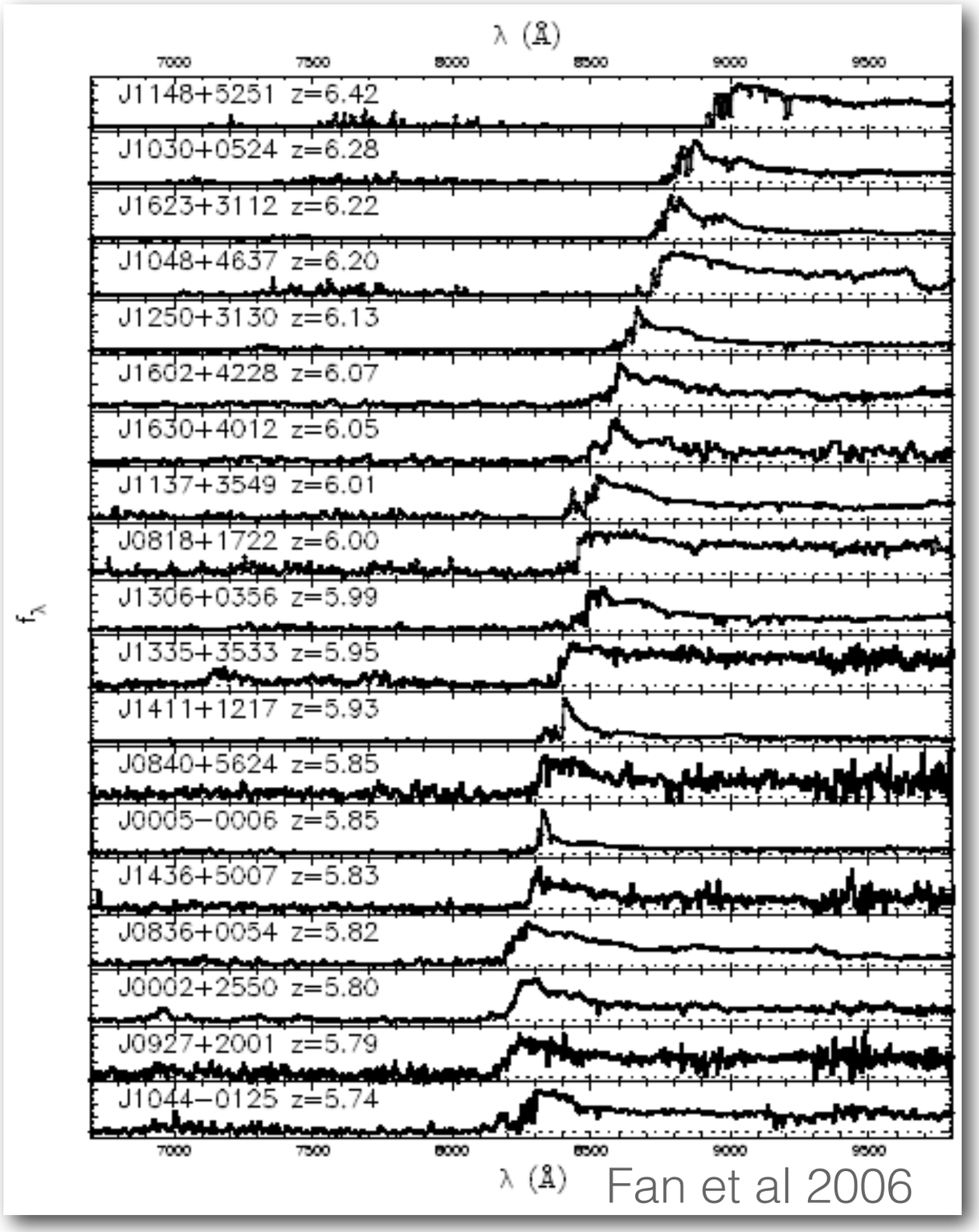


CMB measurements

When?



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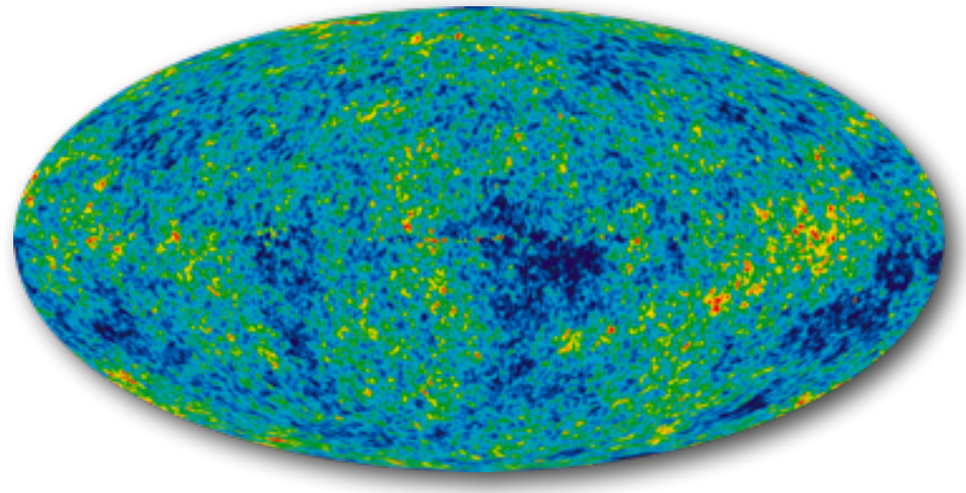
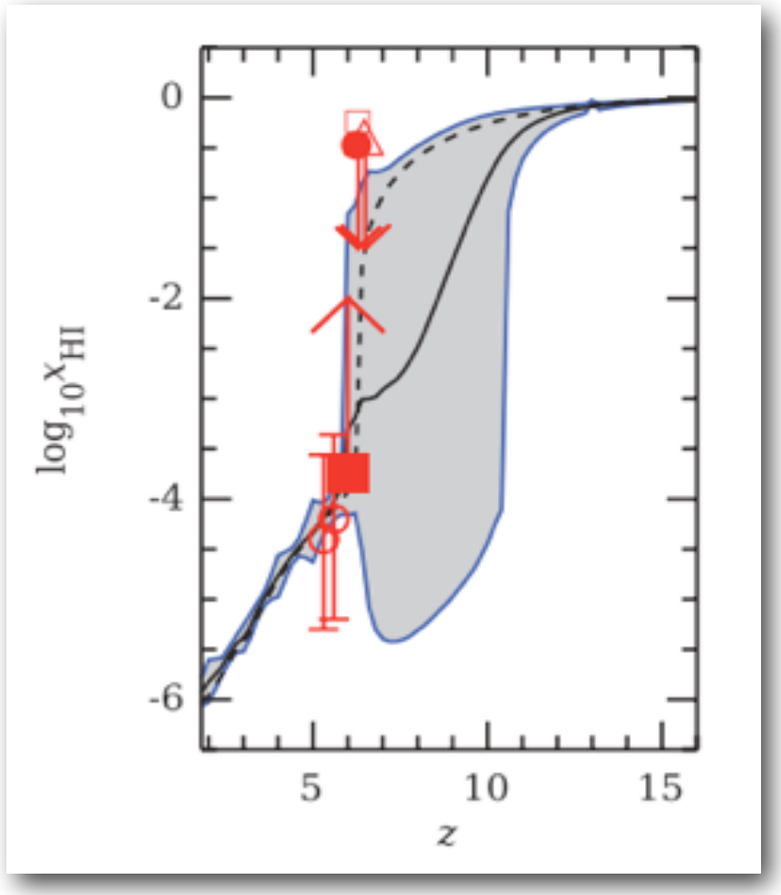


CMB measurements



Mitra et al 2012

What?

Galaxies

Quasars

What?

Galaxies

Quasars

- Pop III stars

What?

Galaxies

Quasars

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- Annihilating DM

What?

Galaxies

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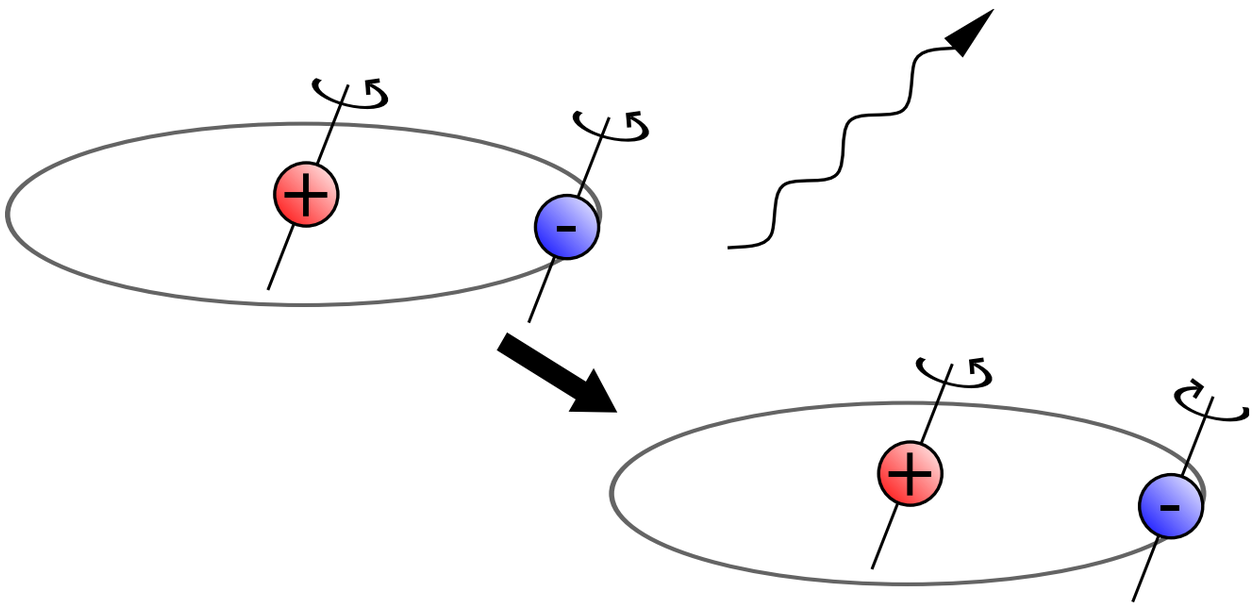
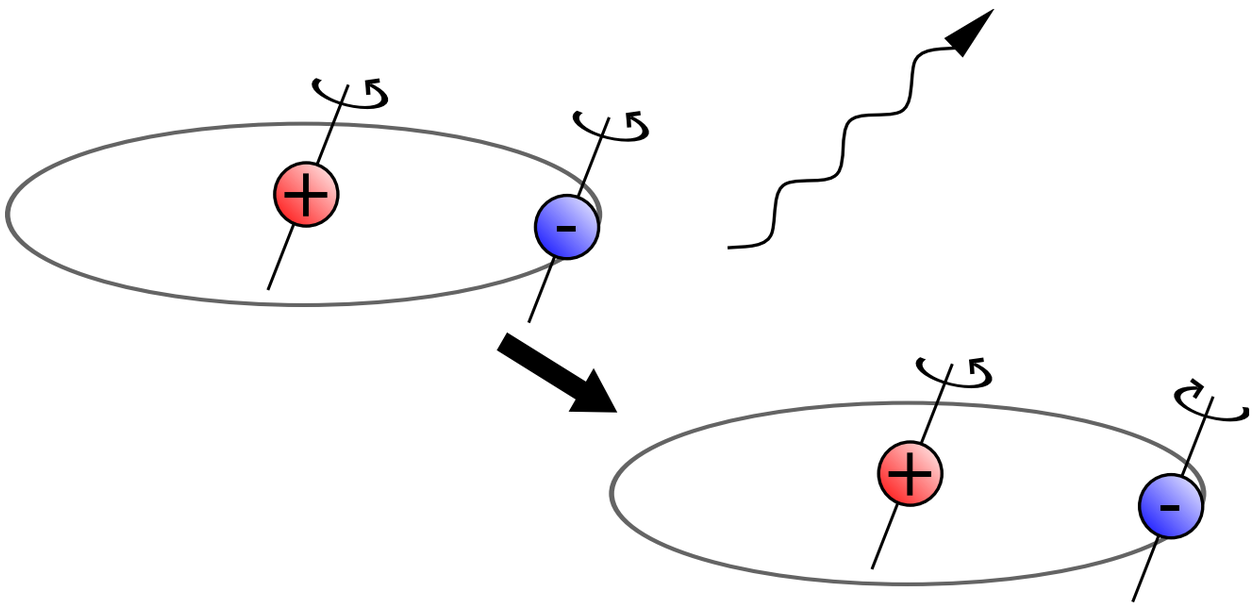
21-cm signal



- Density
- Ionized fraction
- (Spin temperature)

21-cm signal



- Density
- Ionized fraction
- (Spin temperature)

~proportional to neutral hydrogen

21-cm signal from IGM

Cosmology

Dark matter fluctuations

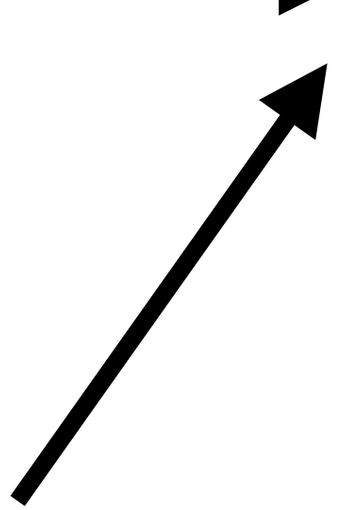
Astrophysics

Star formation

Galaxy formation

Radiative transfer effects

…

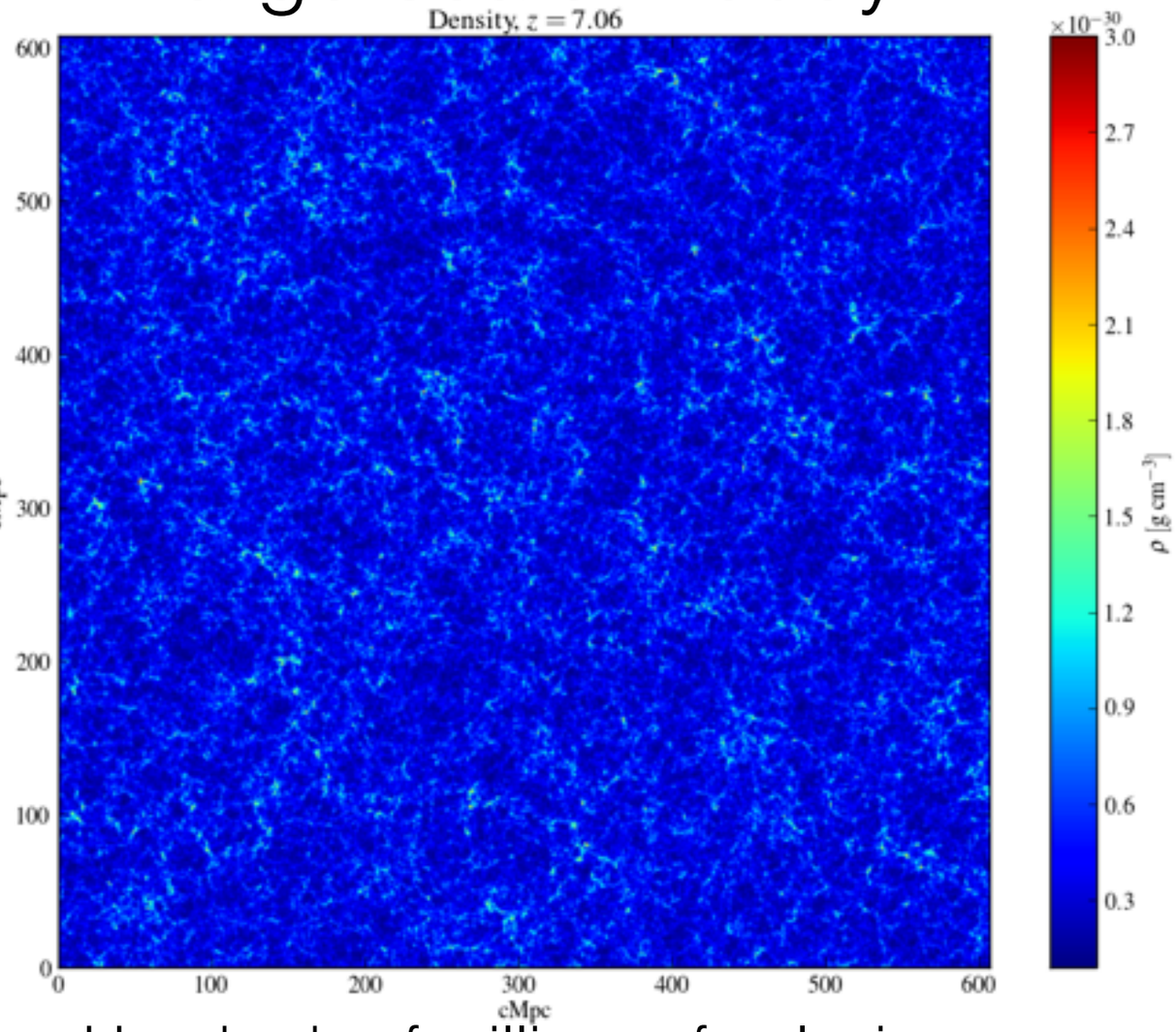


$\delta T_b(\mathrm{r})$

21-cm brightness temp

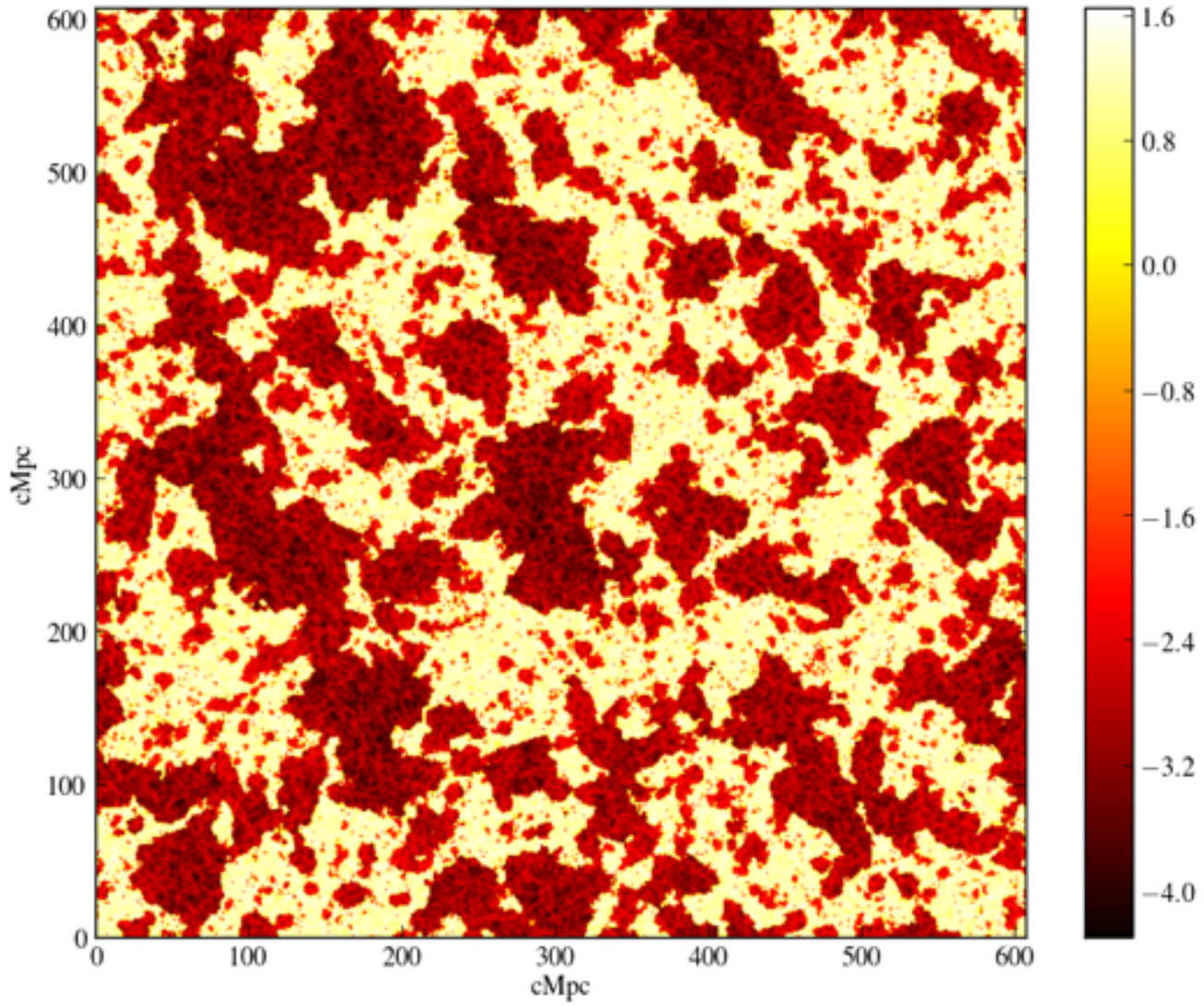
Simulations

Large-scale n-body

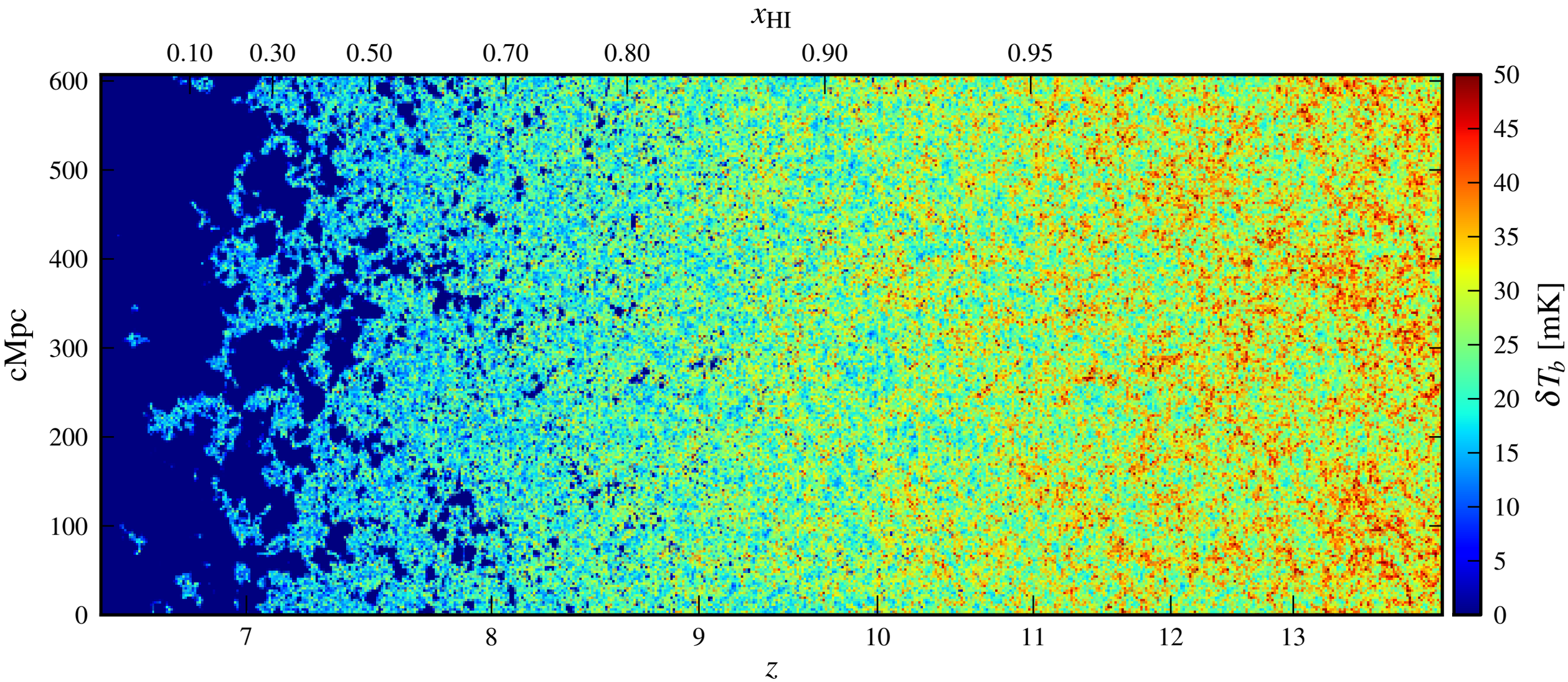


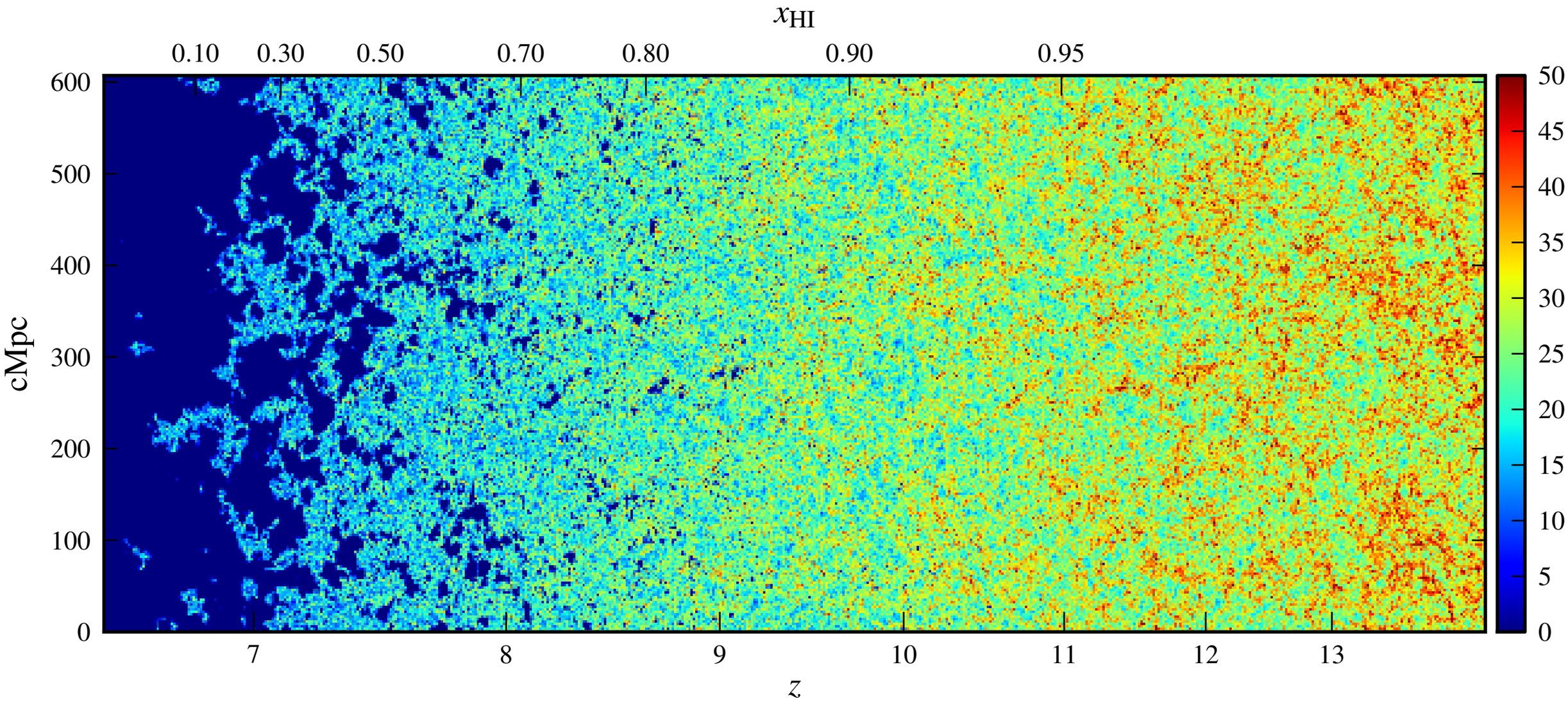
Hundreds of millions of galaxies…

Radiative transfer

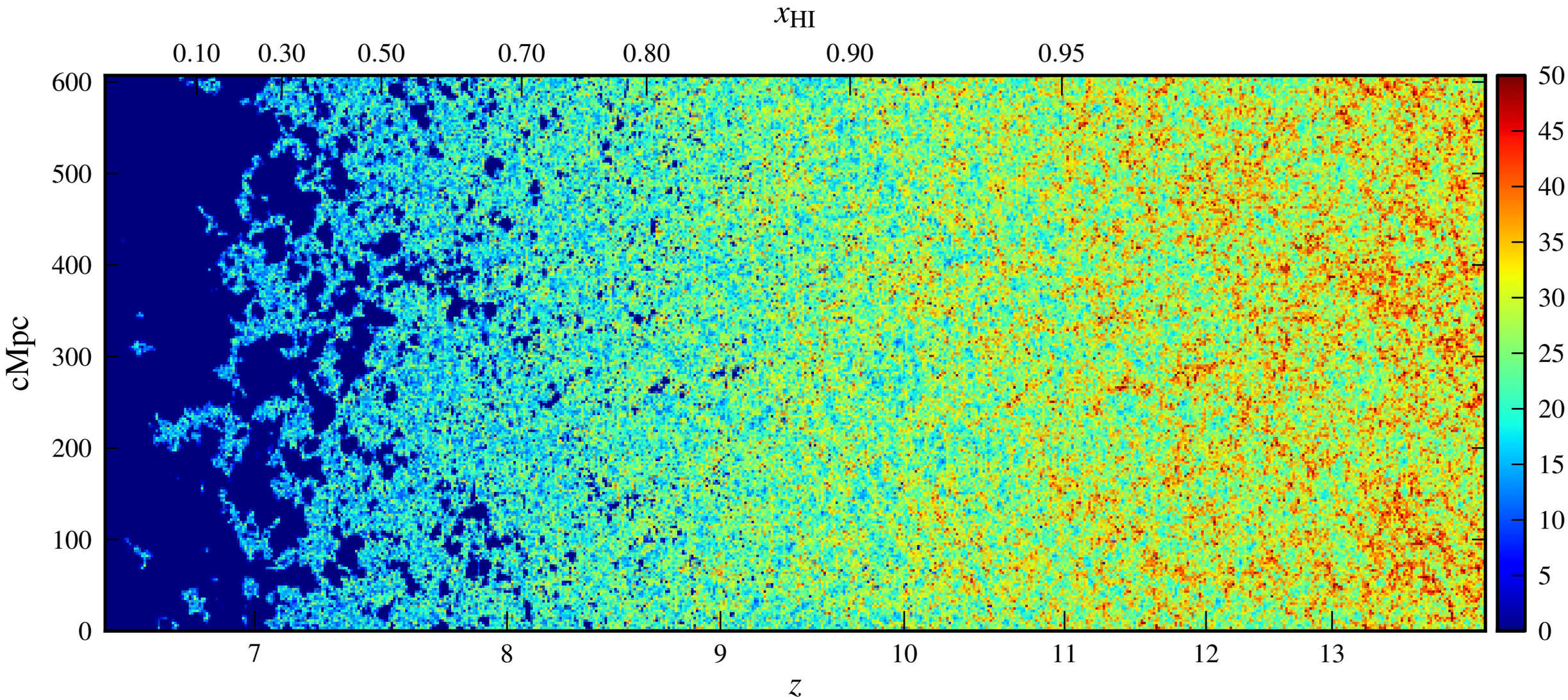


…ionize the surrounding IGM


$x_{\rm HI}$
0.10
0.30
0.50
0.70
0.80
0.90
0.95
cMpc
600
500
400
300
200
100
0
7
8
9
10
11
12
13
z
50
45
40
35
30
25
20
15
10
5
0
δT_b [mK]

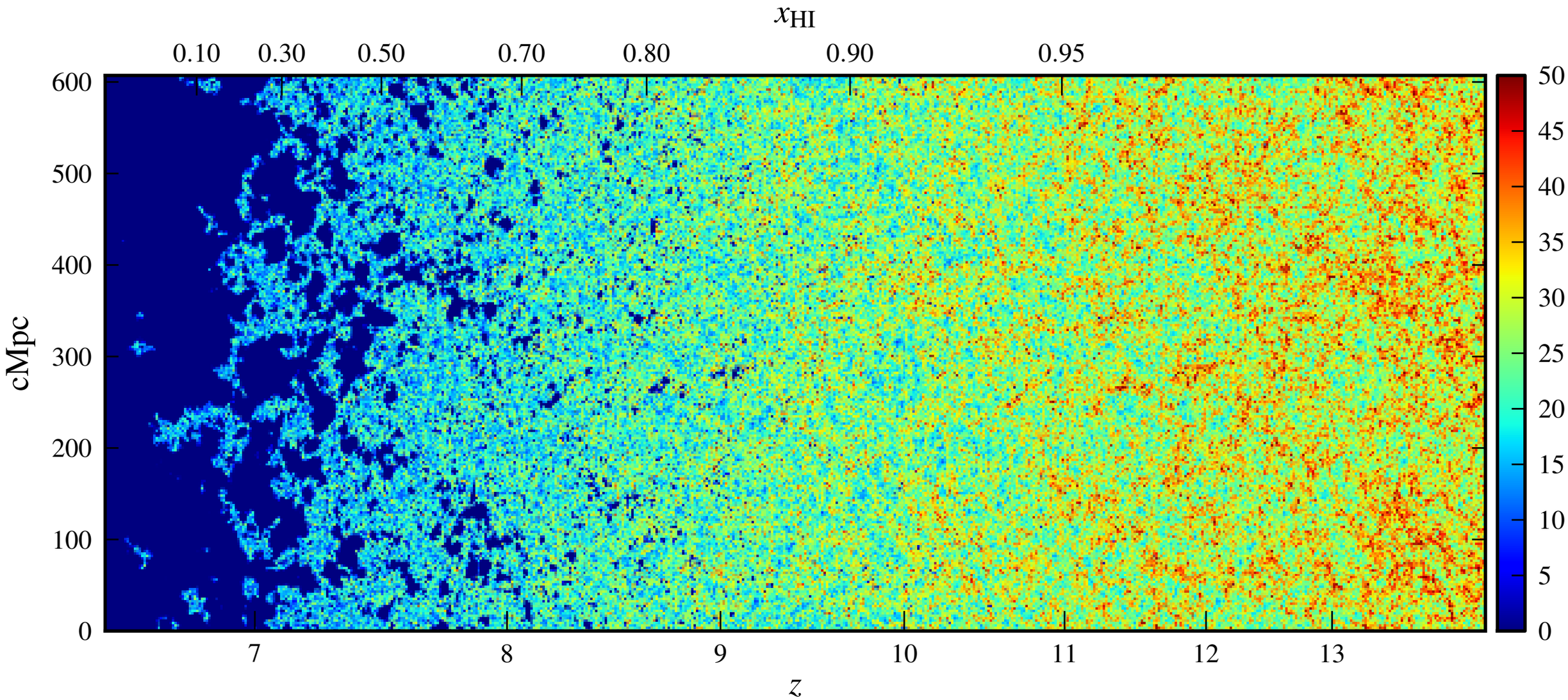


To observe this we need:



To observe this we need:

- High sensitivity



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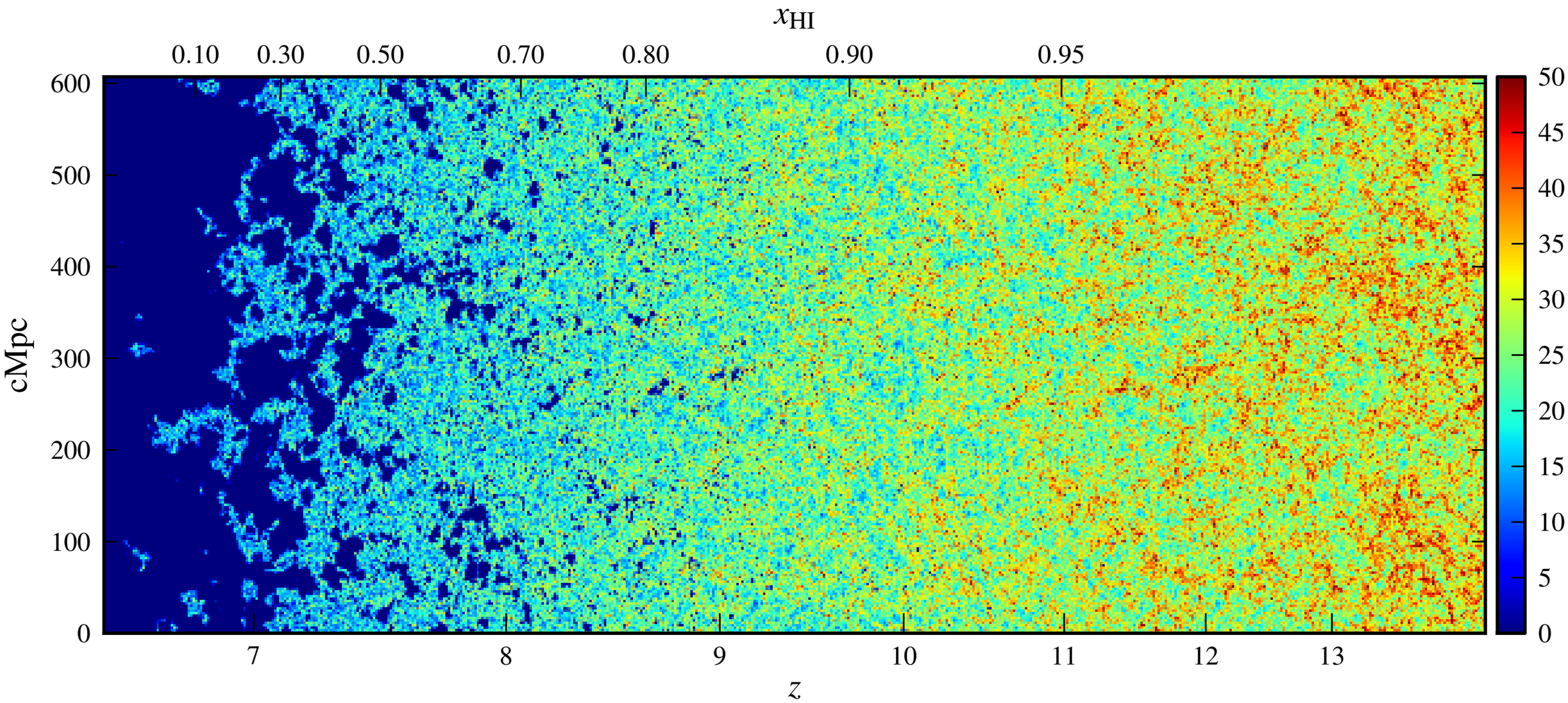
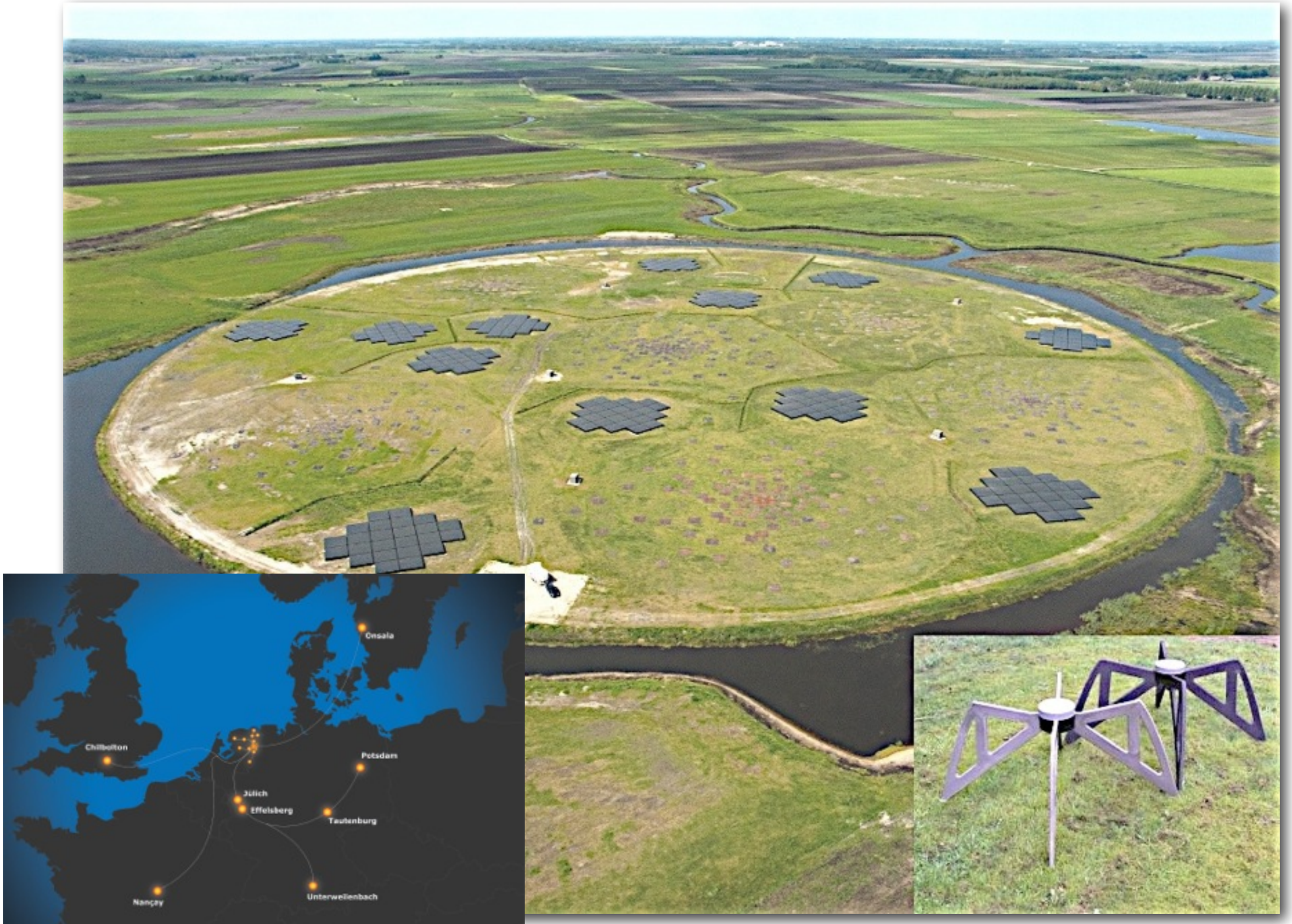
- Low frequency



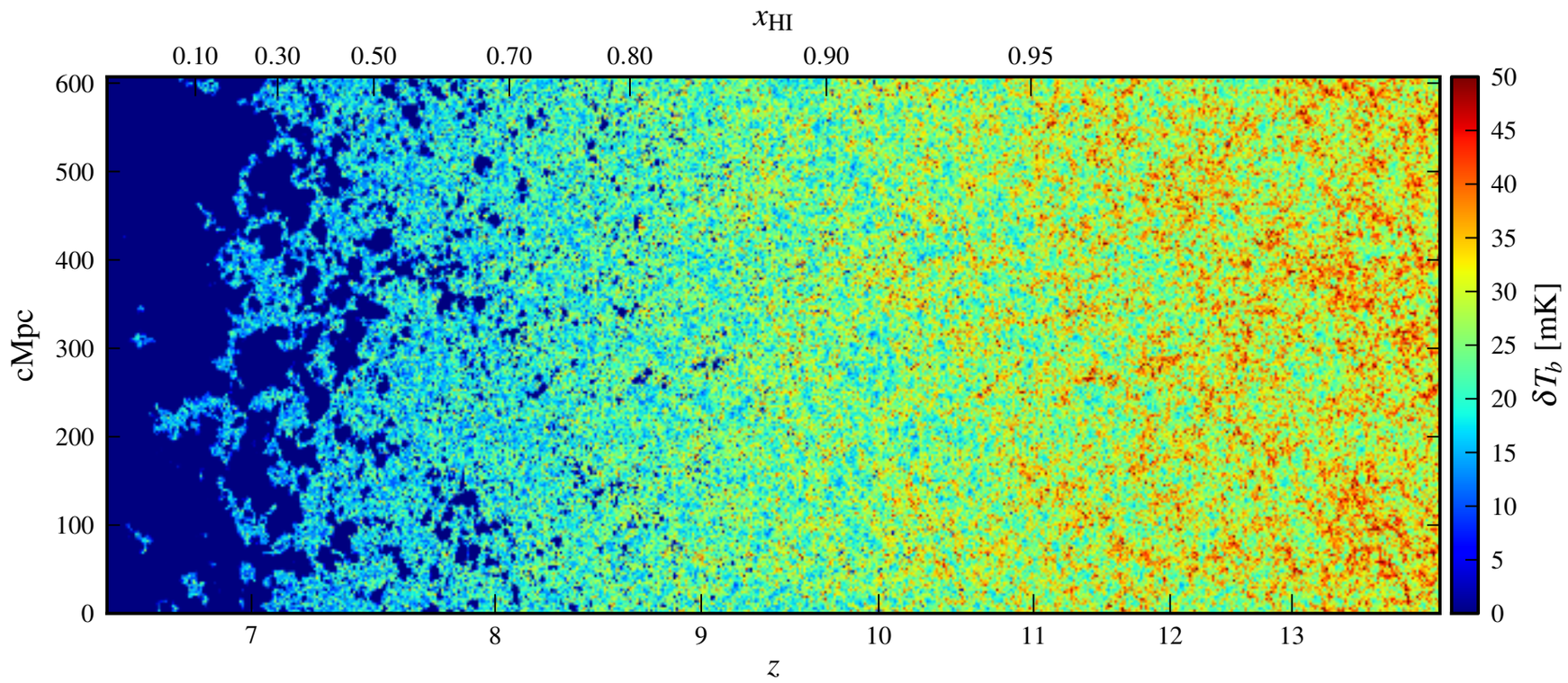
To observe this we need:

- High sensitivity
- Low frequency
- Arcmin resolution

LOFAR (the LOw Frequency ARray)



What will LOFAR see?



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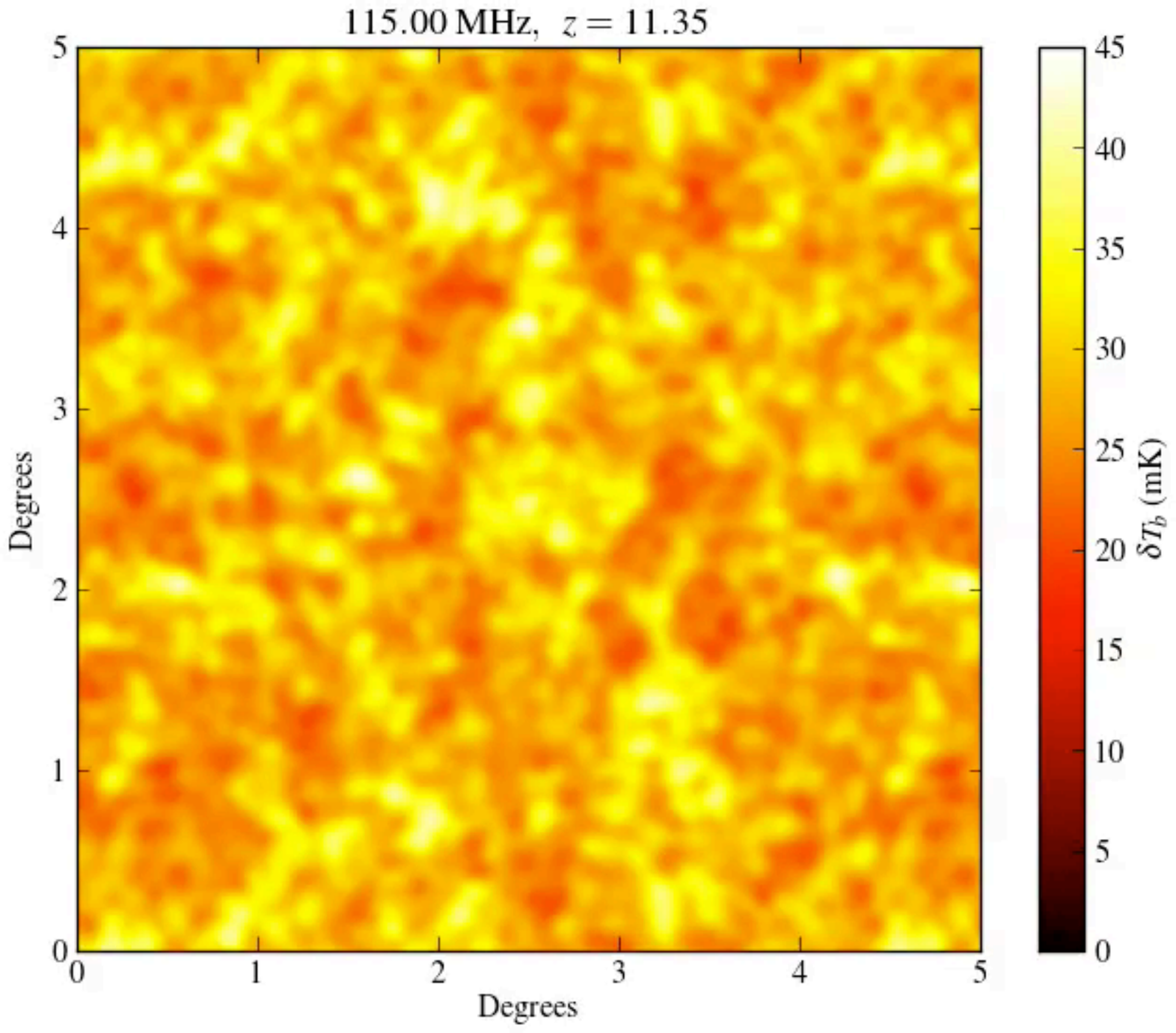

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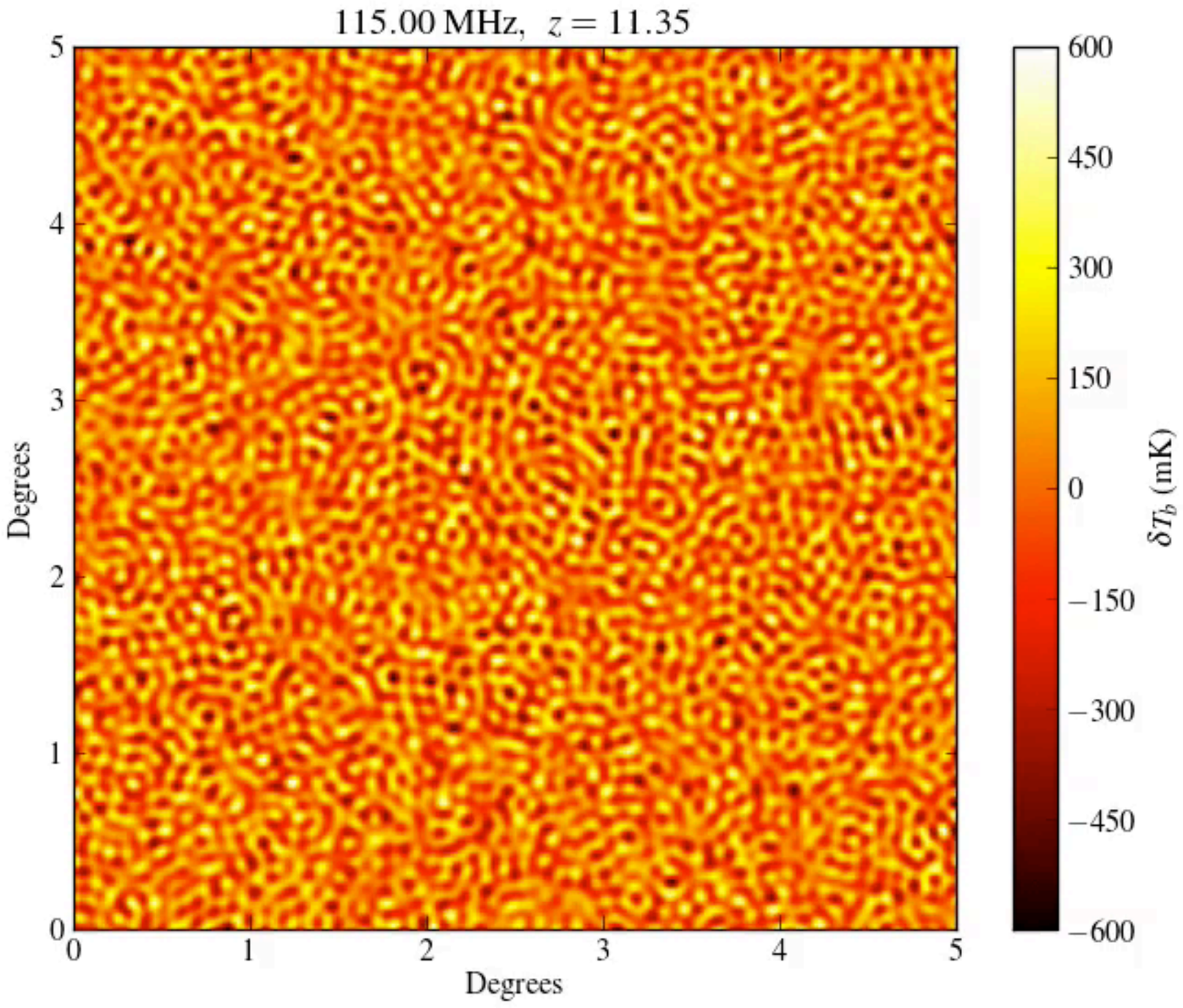
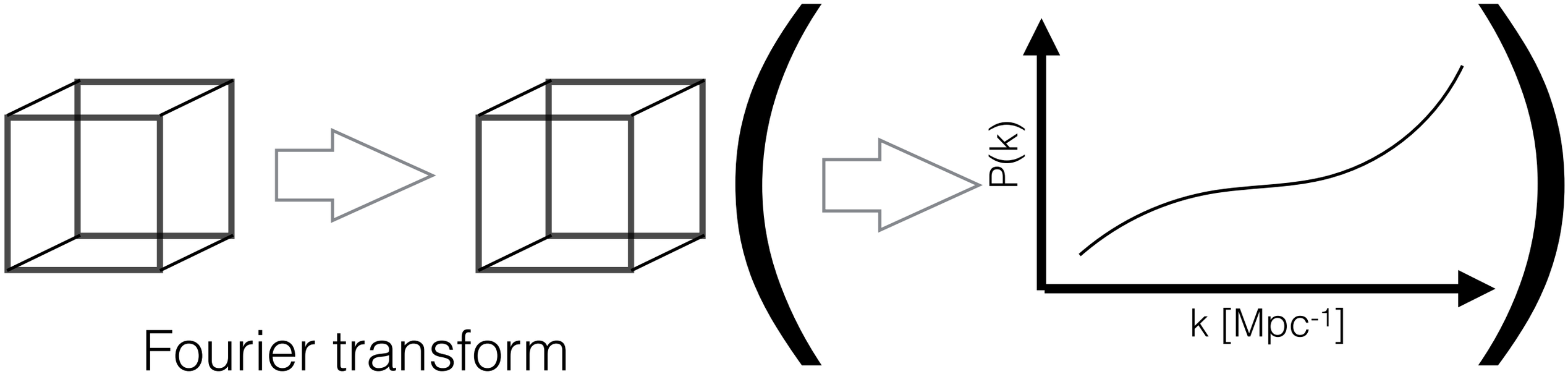


21-cm power spectrum

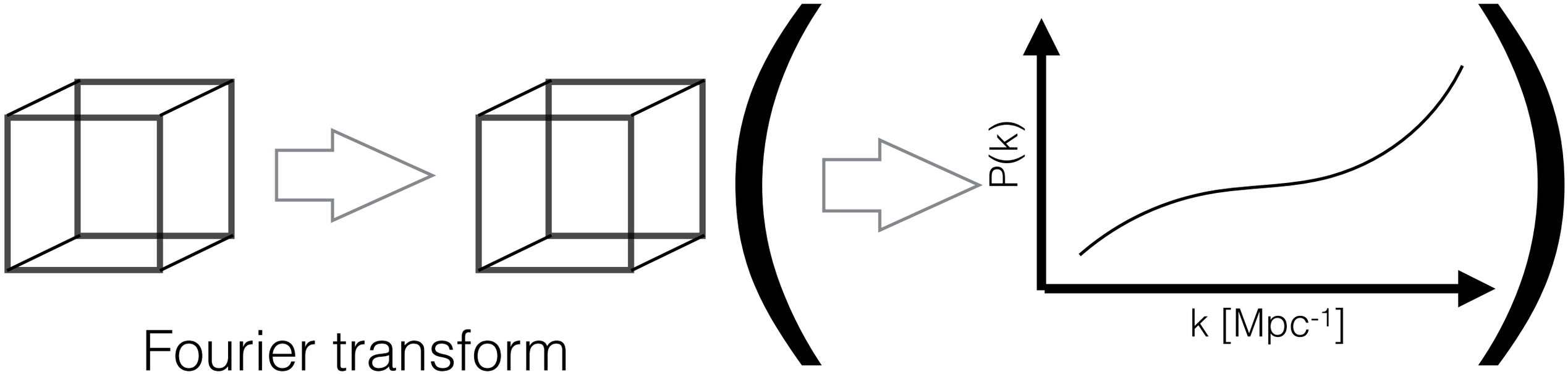


Fourier transform
and square

Bin in spherical
shells

Measures signal
fluctuations
on different scales

21-cm power spectrum



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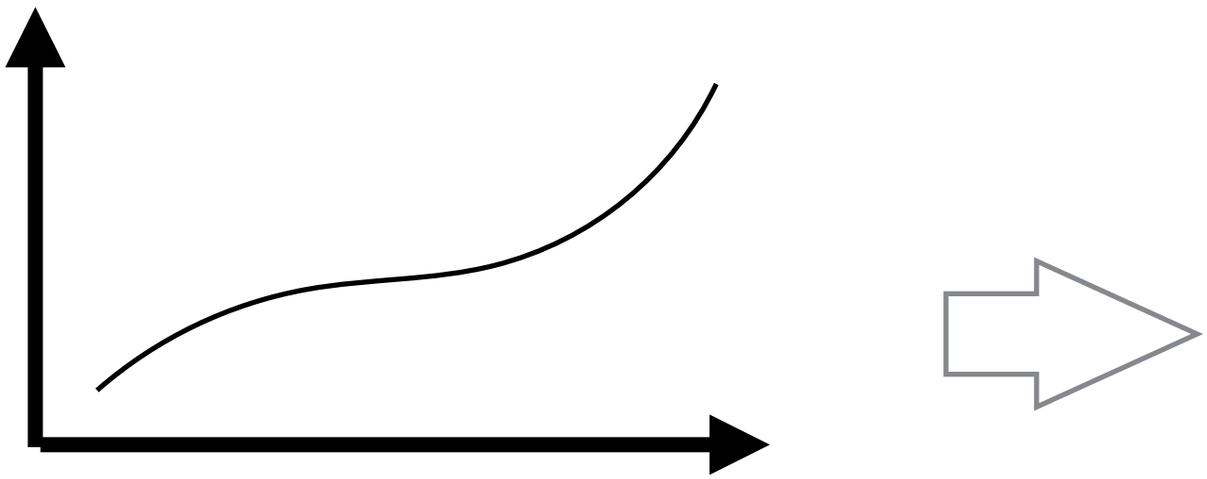
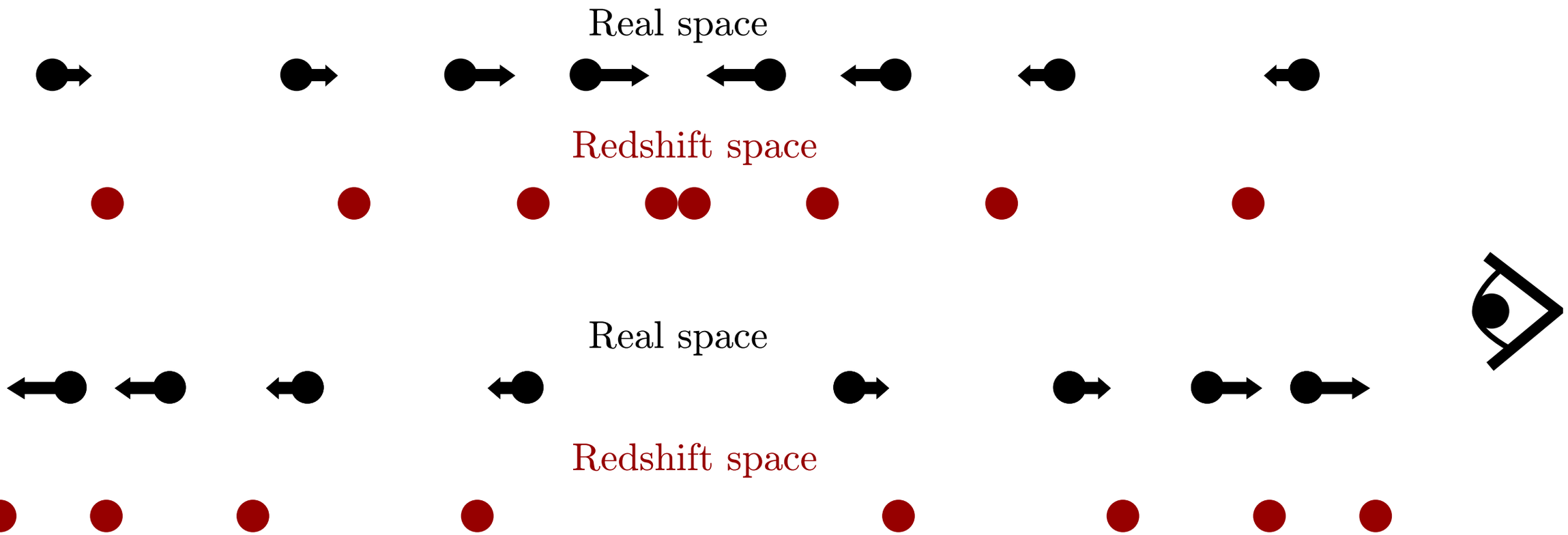
Power spectrum -> physics?



Redshift space distortions



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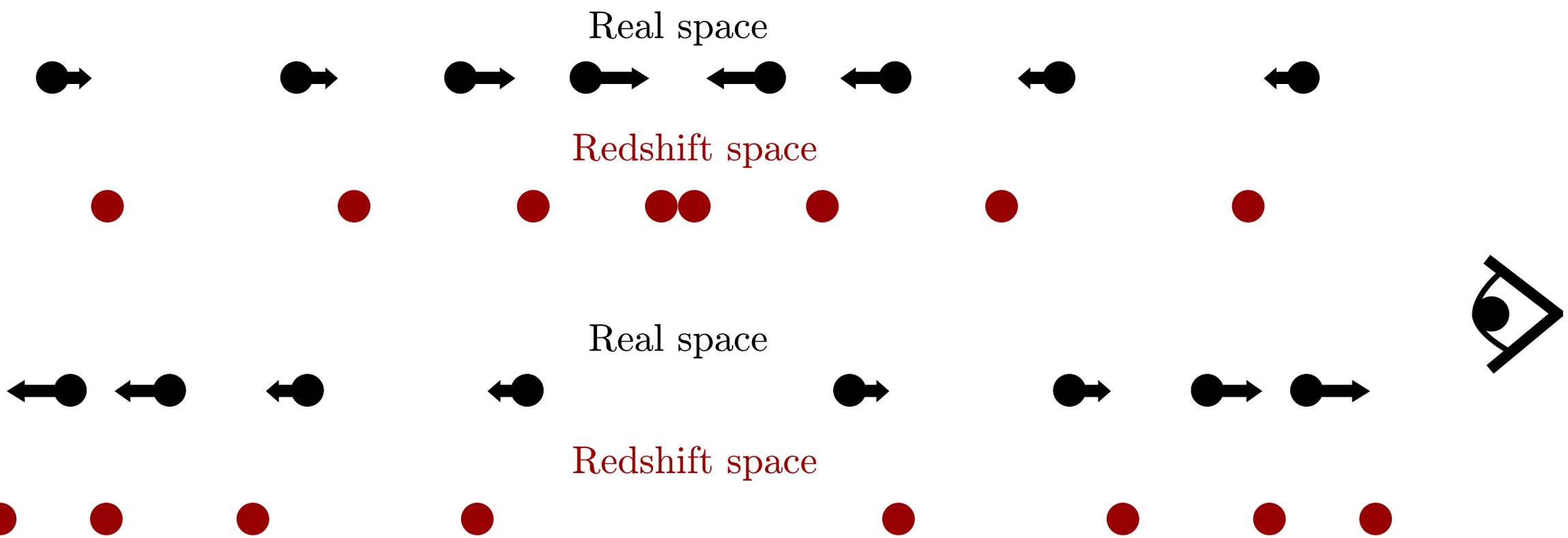
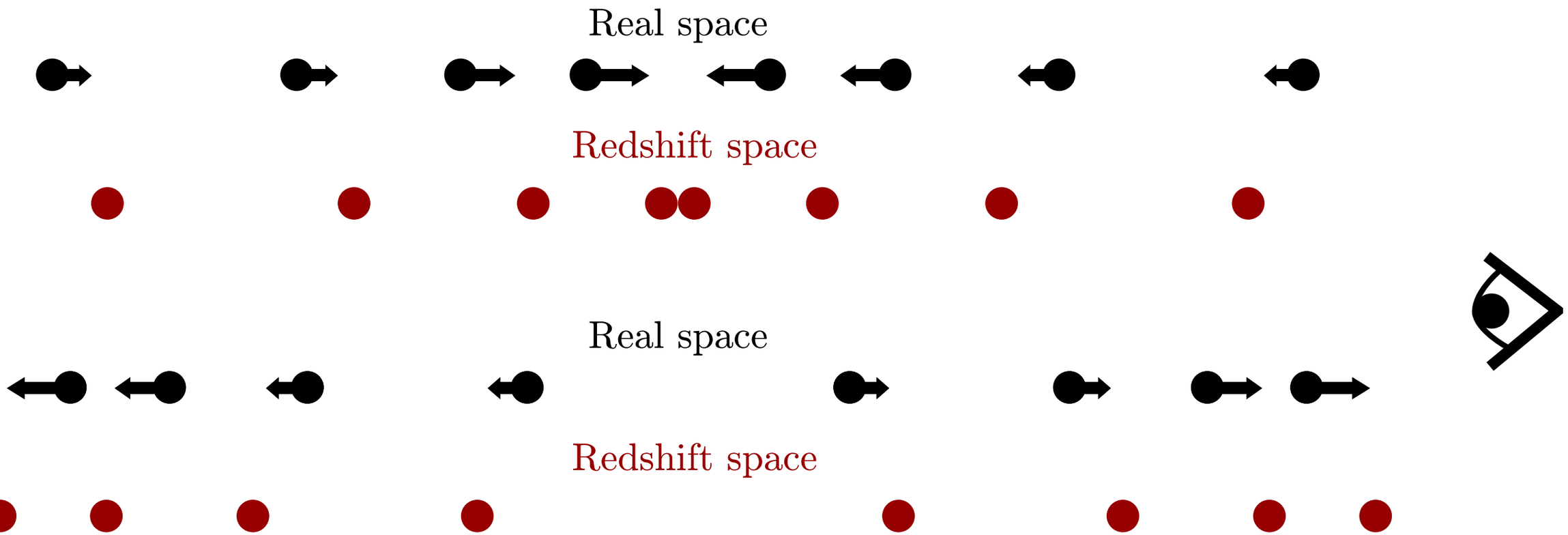


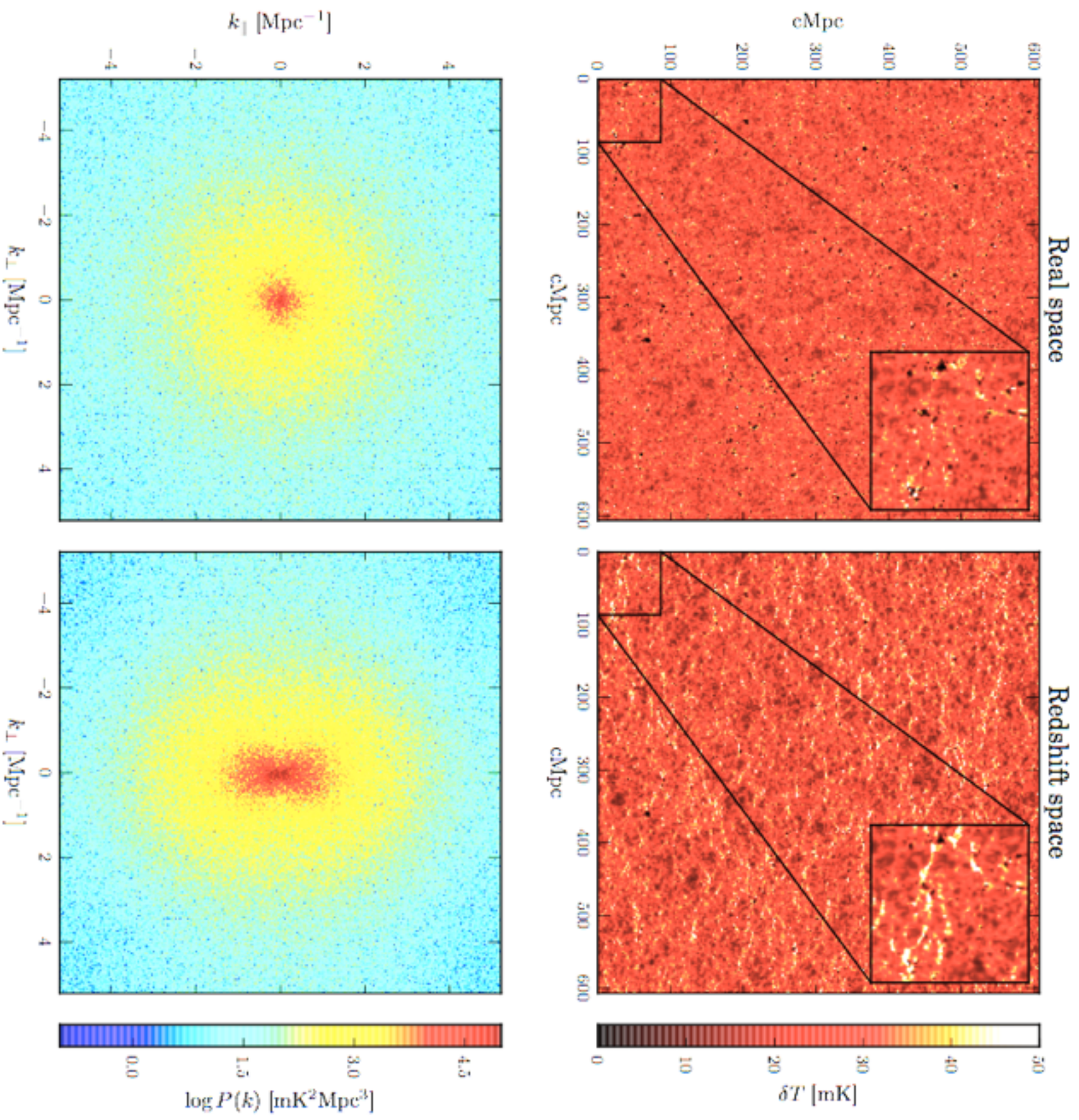
- Changes contrast of the signal

Redshift space distortions



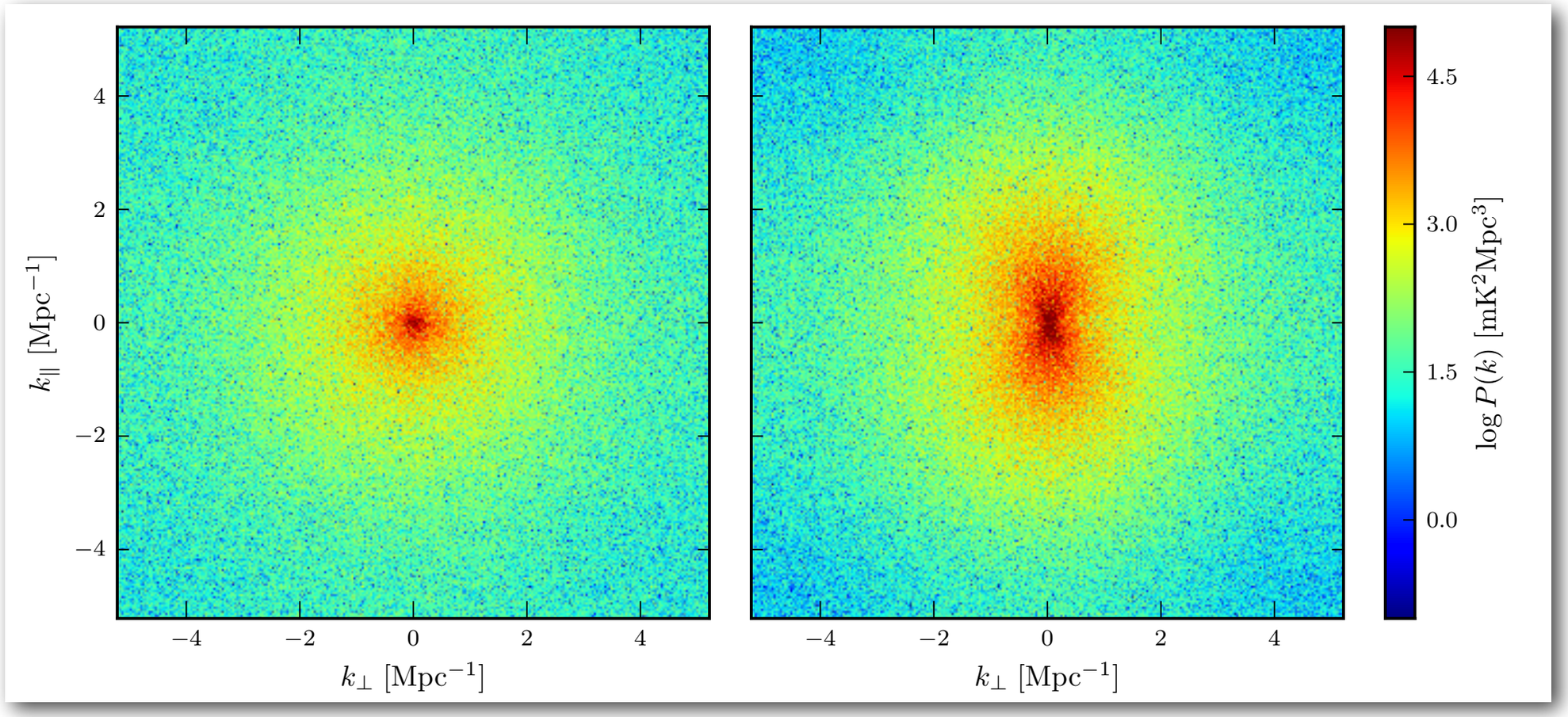
- Changes contrast of the signal
- Makes the signal anisotropic

Line-of-sight



$$P(k) = P_{\mu^0} + P_{\mu^2}\mu^2 + P_{\mu^4}\mu^4$$

$$\mu = k_\parallel / |\mathbf{k}|$$



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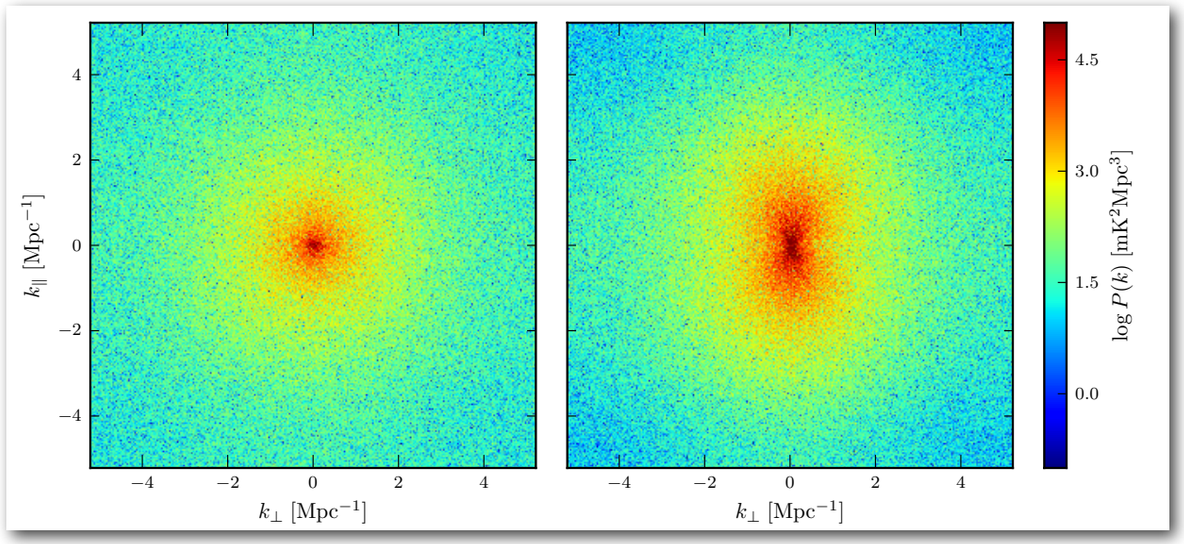

$$P_{\mu^0} = \delta\hat{T}_b{}^2 P_{\delta_{\rho_{HI}},\delta_{\rho_{HI}}}(k)$$

$$P(k) = P_{\mu^0} + P_{\mu^2}\mu^2 + P_{\mu^4}\mu^4$$

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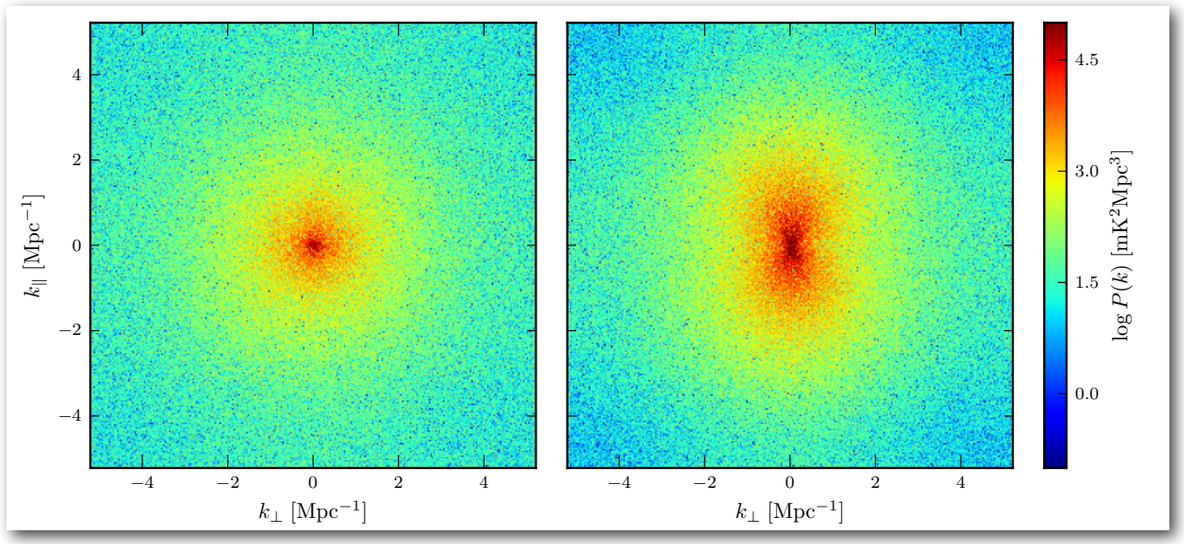

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$$P_{\mu^2} = 2\delta\hat{T}_b{}^2 P_{\delta_{\rho_{HI}},\delta_{\rho_H}}(k)$$

$$P(k) = P_{\mu^0} + P_{\mu^2}\mu^2 + P_{\mu^4}\mu^4$$

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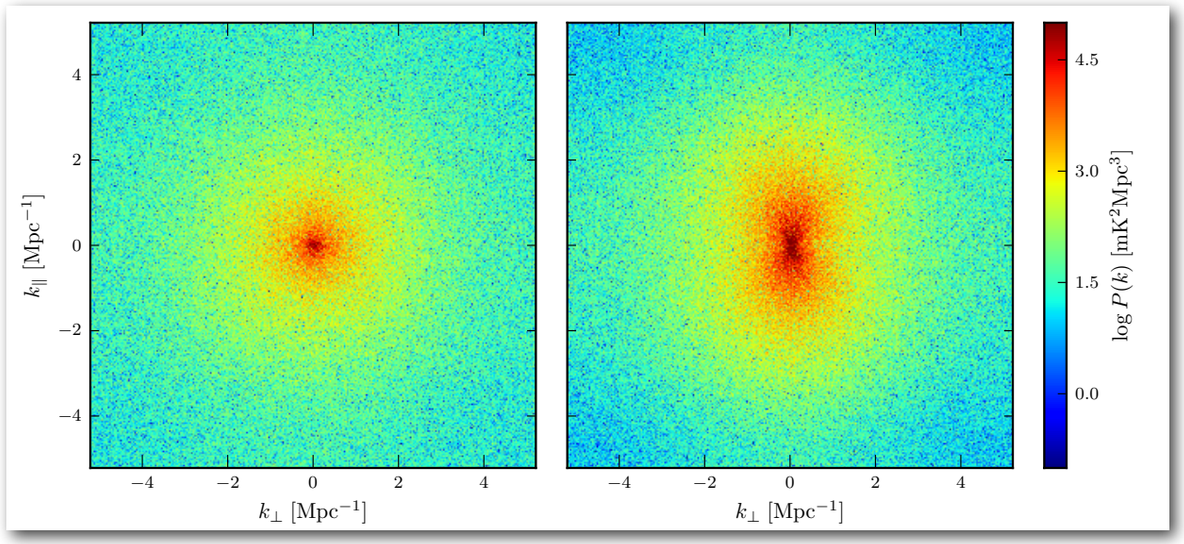

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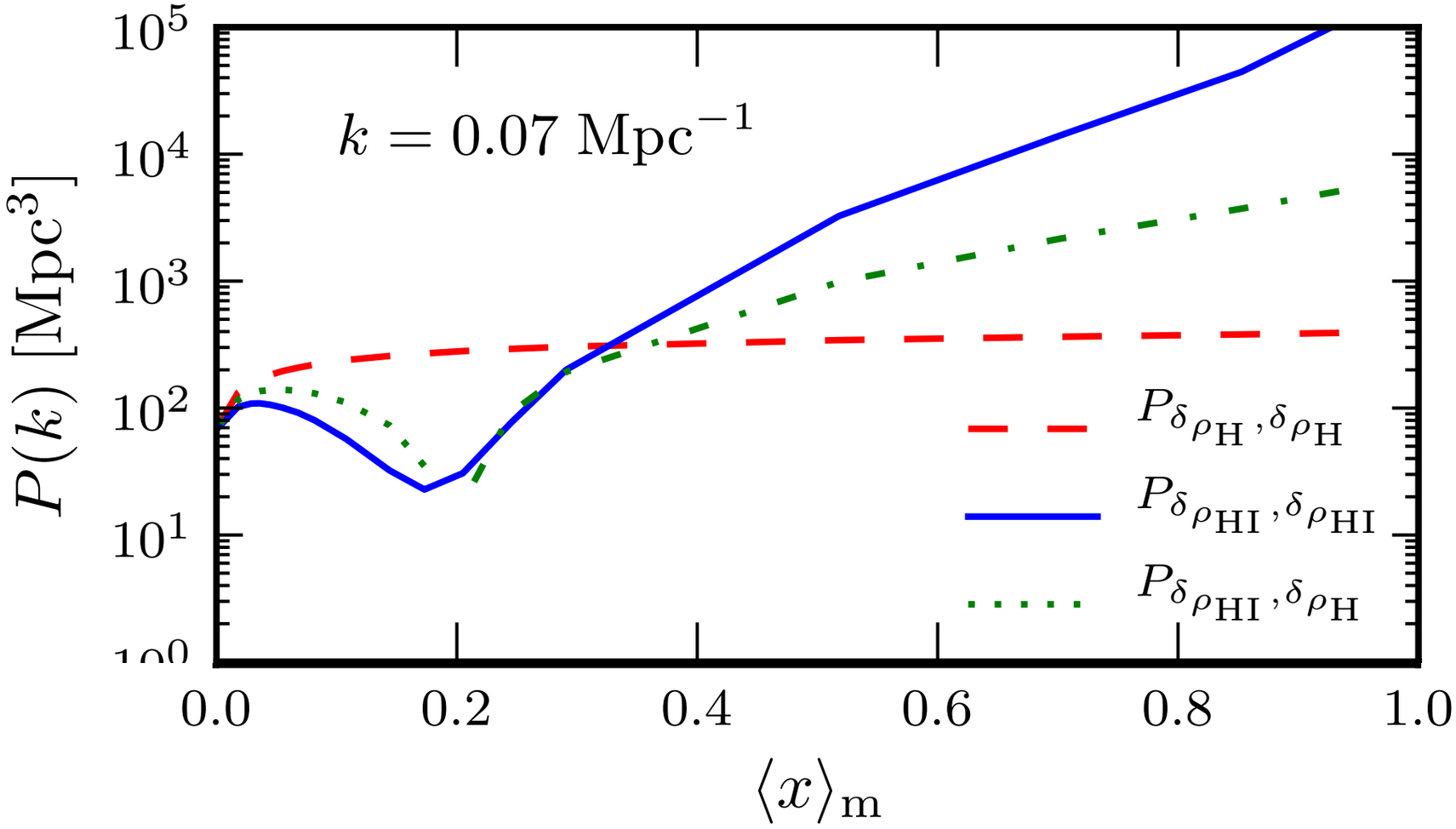
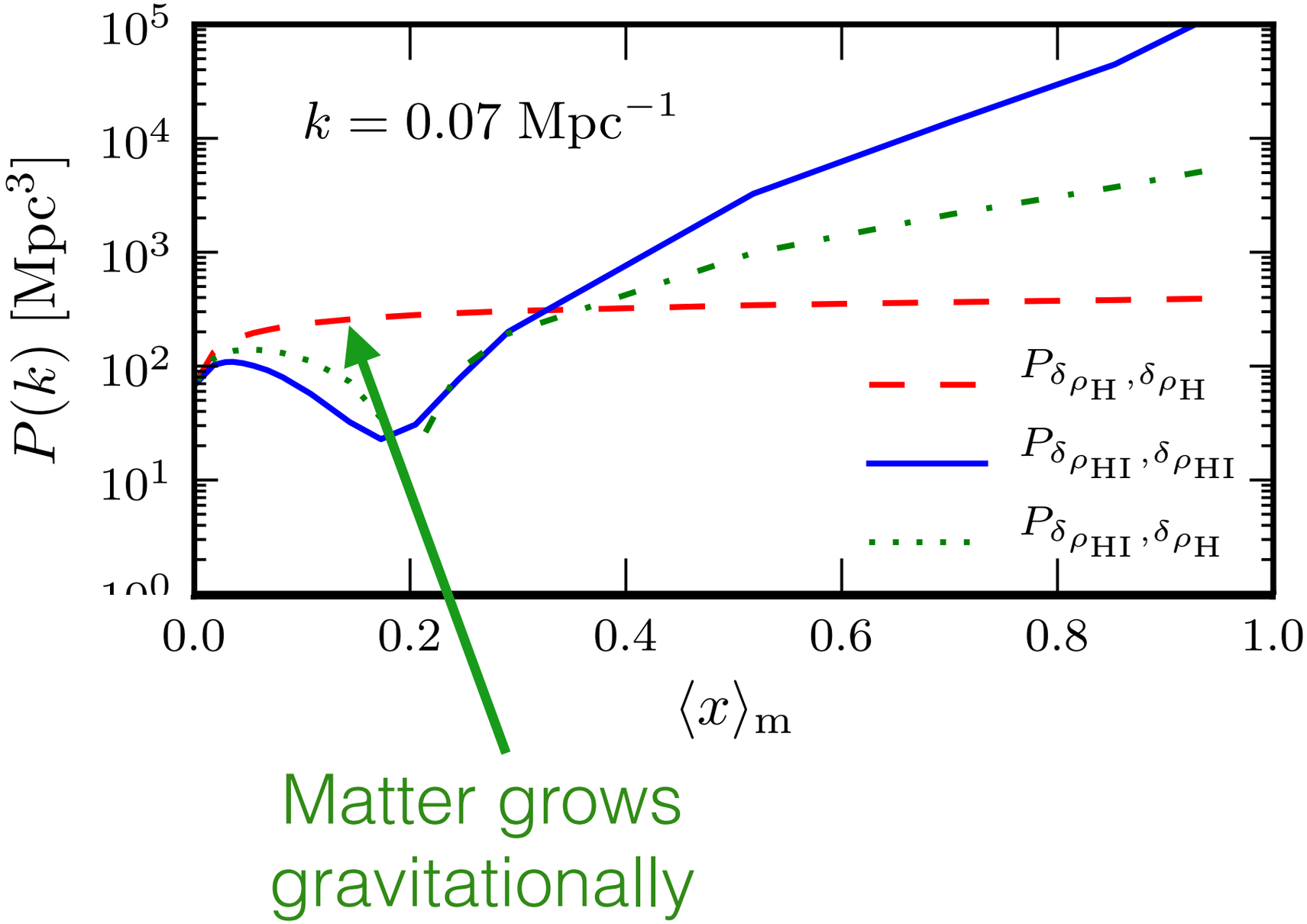

$k = 0.07\ \mathrm{Mpc}^{-1}$
$P(k)\ [\mathrm{Mpc}^3]$
10^5
10^4
10^3
10^2
10^1
10^0
0.0
0.2
0.4
0.6
0.8
1.0
$\langle x \rangle_\mathrm{m}$
$P_{\delta\rho_\mathrm{H},\delta\rho_\mathrm{H}}$
$P_{\delta\rho_\mathrm{HI},\delta\rho_\mathrm{HI}}$
$P_{\delta\rho_\mathrm{HI},\delta\rho_\mathrm{H}}$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10^5
10^4
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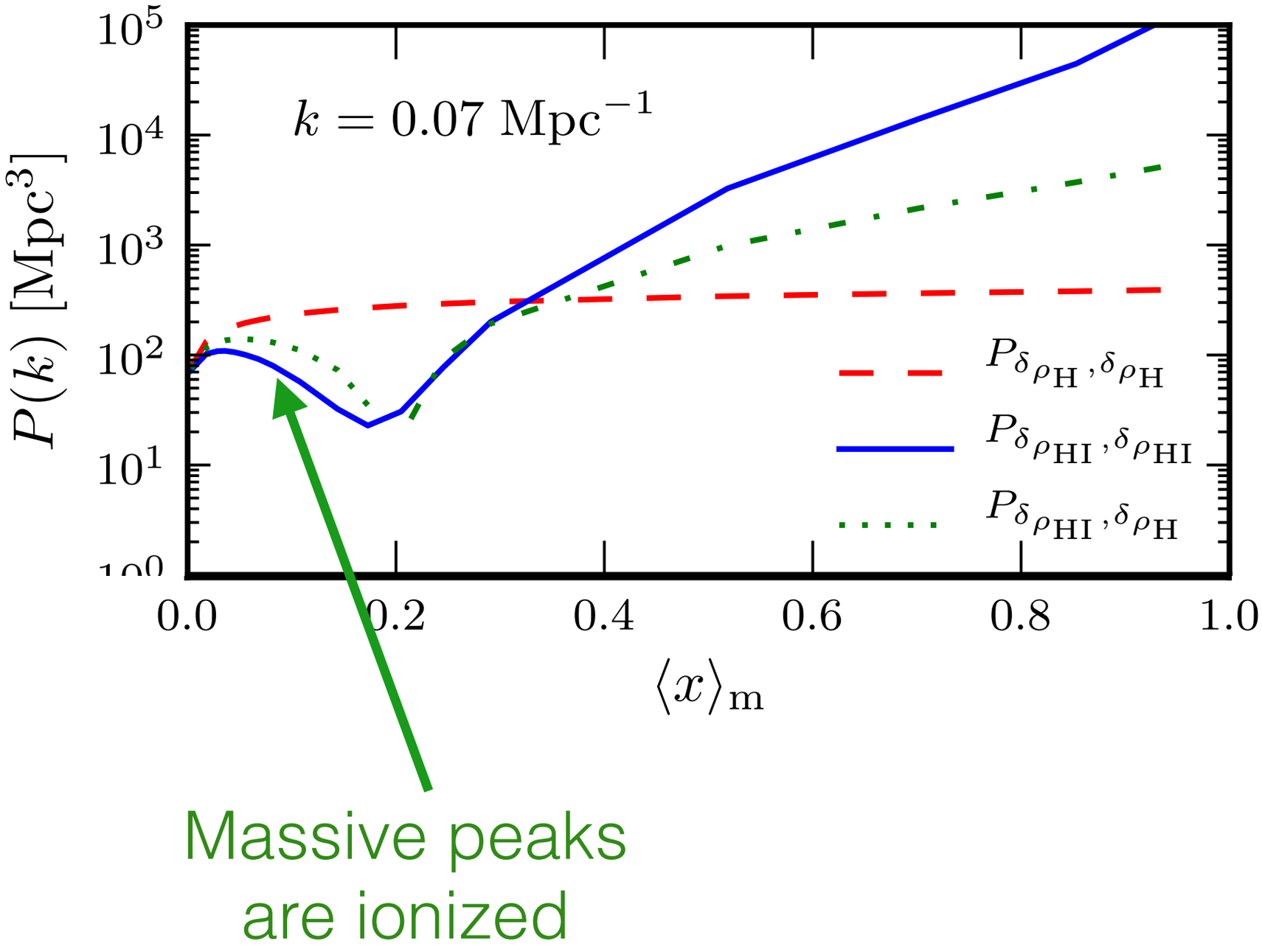
$\langle x \rangle_\mathrm{m}$
$P_{\delta\rho_\mathrm{H},\delta\rho_\mathrm{H}}$
$P_{\delta\rho_\mathrm{HI},\delta\rho_\mathrm{HI}}$
$P_{\delta\rho_\mathrm{HI},\delta\rho_\mathrm{H}}$
Matter grows gravitationally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10^5
10^4
10^3
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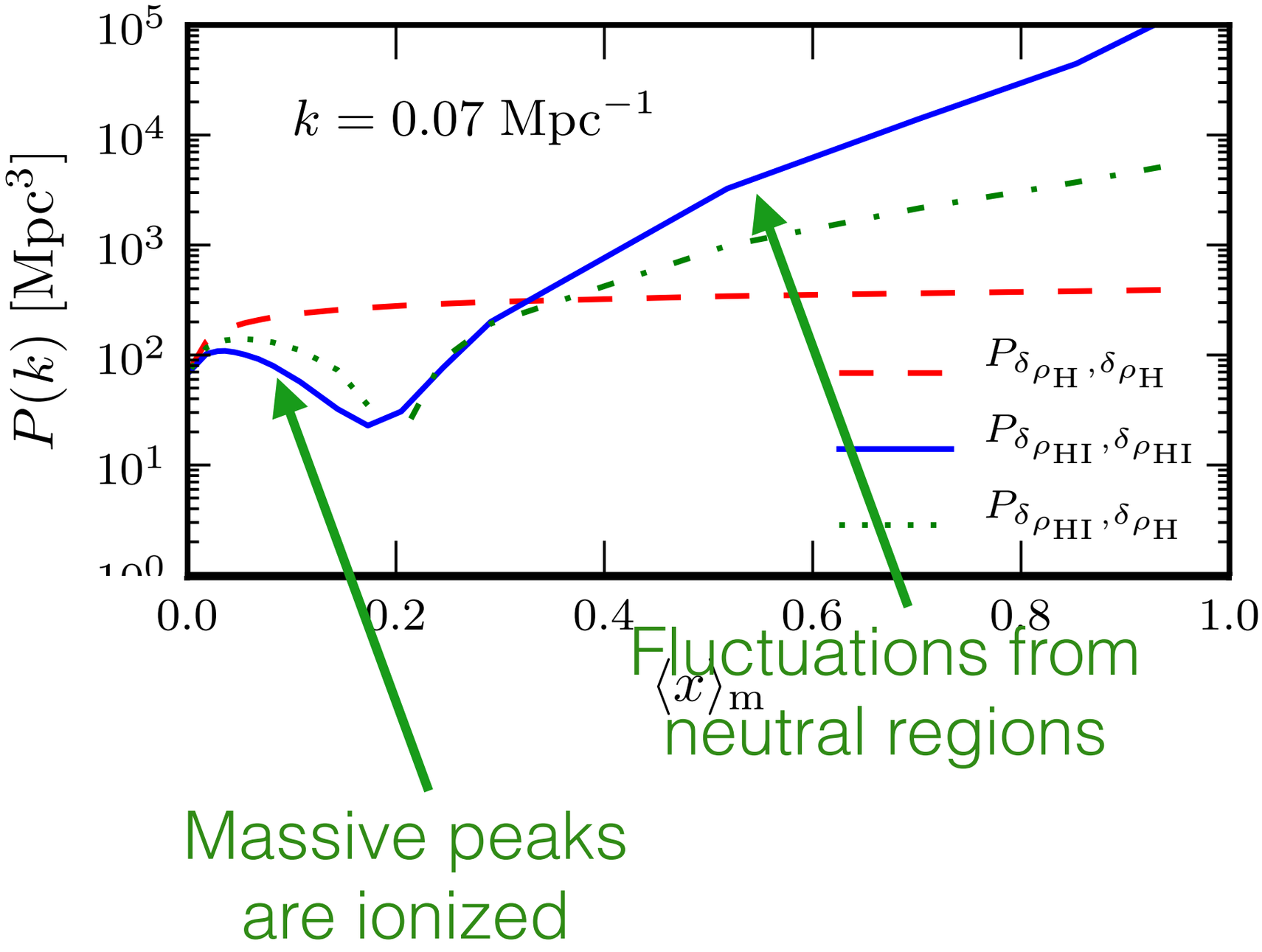
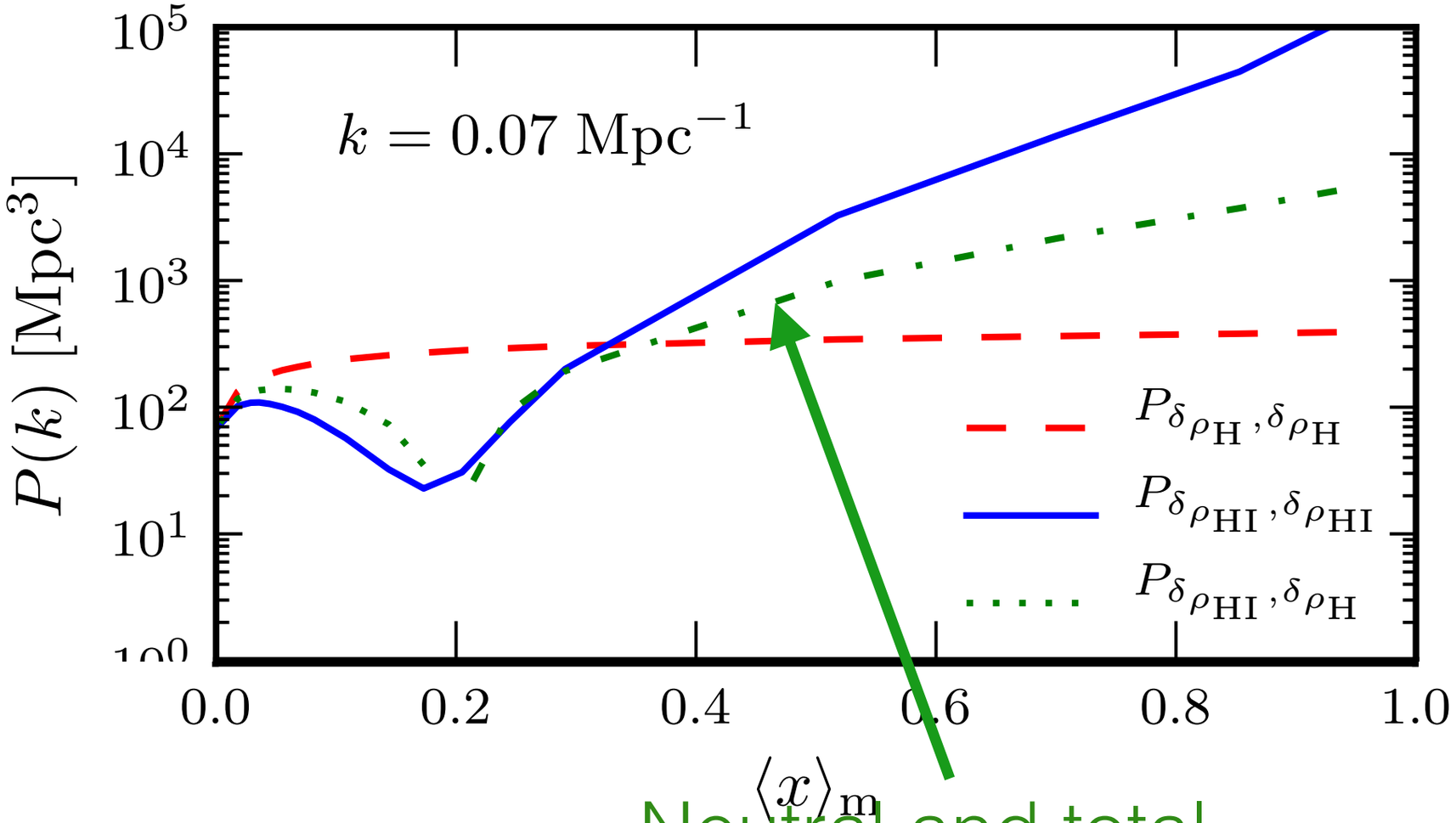
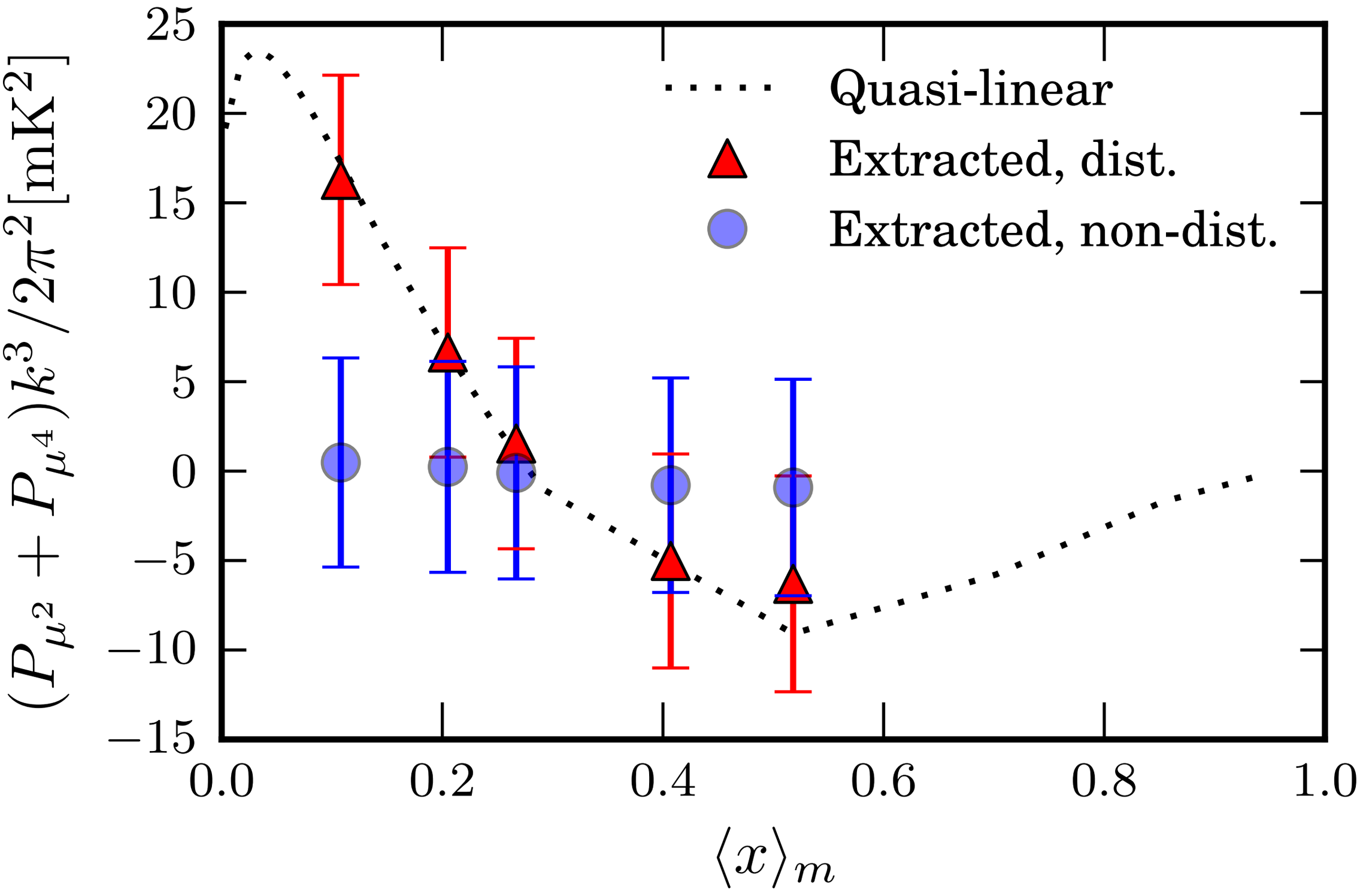
0.2
0.4
0.6
0.8
1.0
$\langle x \rangle_\mathrm{m}$
$P_{\delta\rho_\mathrm{H},\delta\rho_\mathrm{H}}$
$P_{\delta\rho_\mathrm{HI},\delta\rho_\mathrm{HI}}$
$P_{\delta\rho_\mathrm{HI},\delta\rho_\mathrm{H}}$
Massive peaks
are ionized


$k = 0.07$ Mpc^{-1}
$P(k)$ [Mpc^3]
10^5
10^4
10^3
10^2
10^1
10^0
0.0
0.2
0.4
0.6
0.8
1.0
$\langle x \rangle_{\rm m}$
$P_{\delta\rho_{\rm H},\delta\rho_{\rm H}}$
$P_{\delta\rho_{\rm HI},\delta\rho_{\rm HI}}$
$P_{\delta\rho_{\rm HI},\delta\rho_{\rm H}}$
Massive peaks
are ionized
Fluctuations from
neutral regions



Neutral and total densities are anti-correlated

Simulated 2000-hour LOFAR observation



Summary

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- Epoch of reionization is a largely unexplored time period
- Lots of information in 21-cm signal
- First-generation instruments have to focus on statistics, e.g. power spectrum
- Even power spectrum has lots of information
- Need to understand many effects, such as redshift space distortions