Title: The Past, Present, and Future of 21cm Cosmology

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Abstract: Despite tremendous recent progress, gaps remain in our knowledge of our cosmic history. For example, we have yet to make observations of Cosmic Dawn or the subsequent Epoch of Reionization. Together, these represent the important period when the first stars and galaxies were formed, dramatically altering their surroundings in the process. Radio telescopes targeting the 21cm line will open up these crucial epochs to direct observations in the next few years, filling in a missing chapter in our cosmic story. I will review our recent results from the Precision Array to Probe the Epoch of Reionization (PAPER) experiment. These results have begun to shed light on heating processes during reionization. I will also motivate unconventional ideas in experiment design that have been proposed and implemented to deal with the unique technical challenges of 21cm cosmology. Cognizant of "lessons learned" from the current generation of instruments, I will describe our recently commenced Hydrogen Epoch of Reionization Array (HERA), including its forecasted promise to provide exquisite constraints on reionization astrophysics as well as on fundamental parameters such as the neutrino mass.

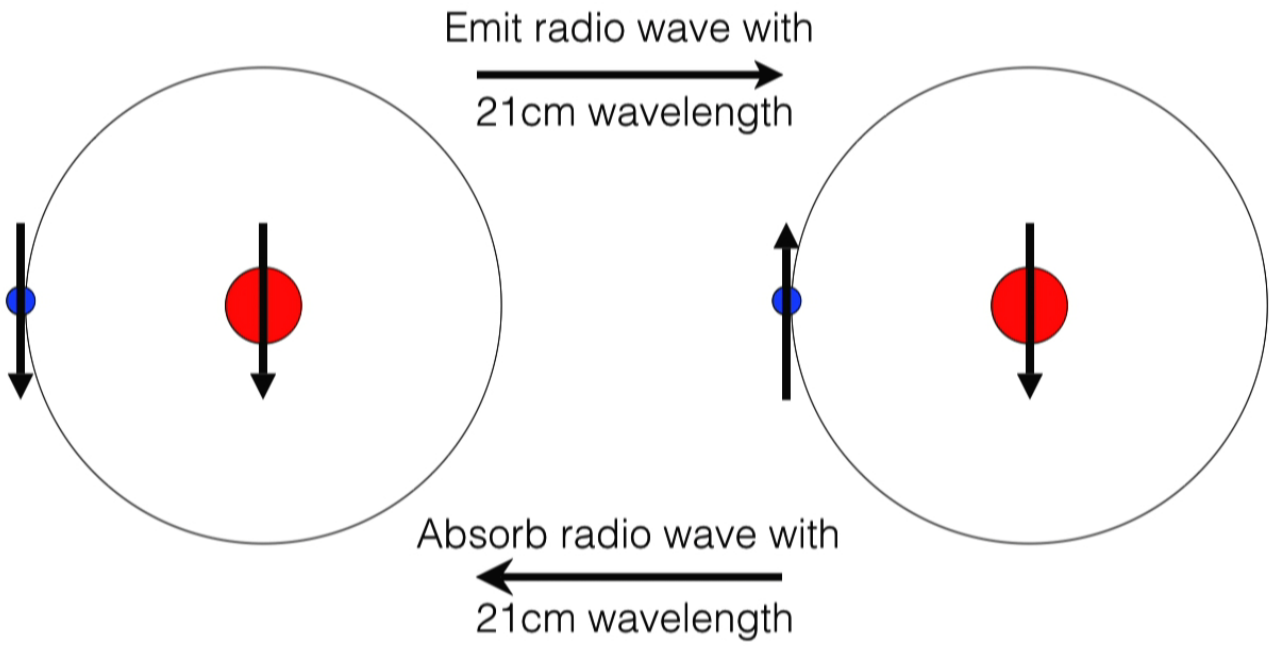
The Past, Present, and Future of 21cm Cosmology

Adrian Liu, Hubble Fellow, UC Berkeley

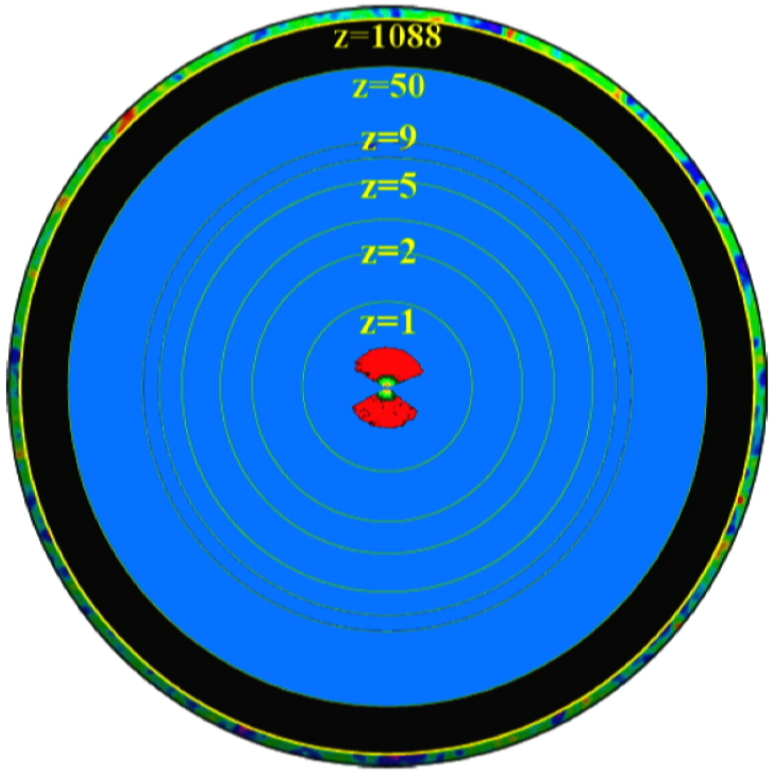
Vision

We have yet to observe most of the observable Universe

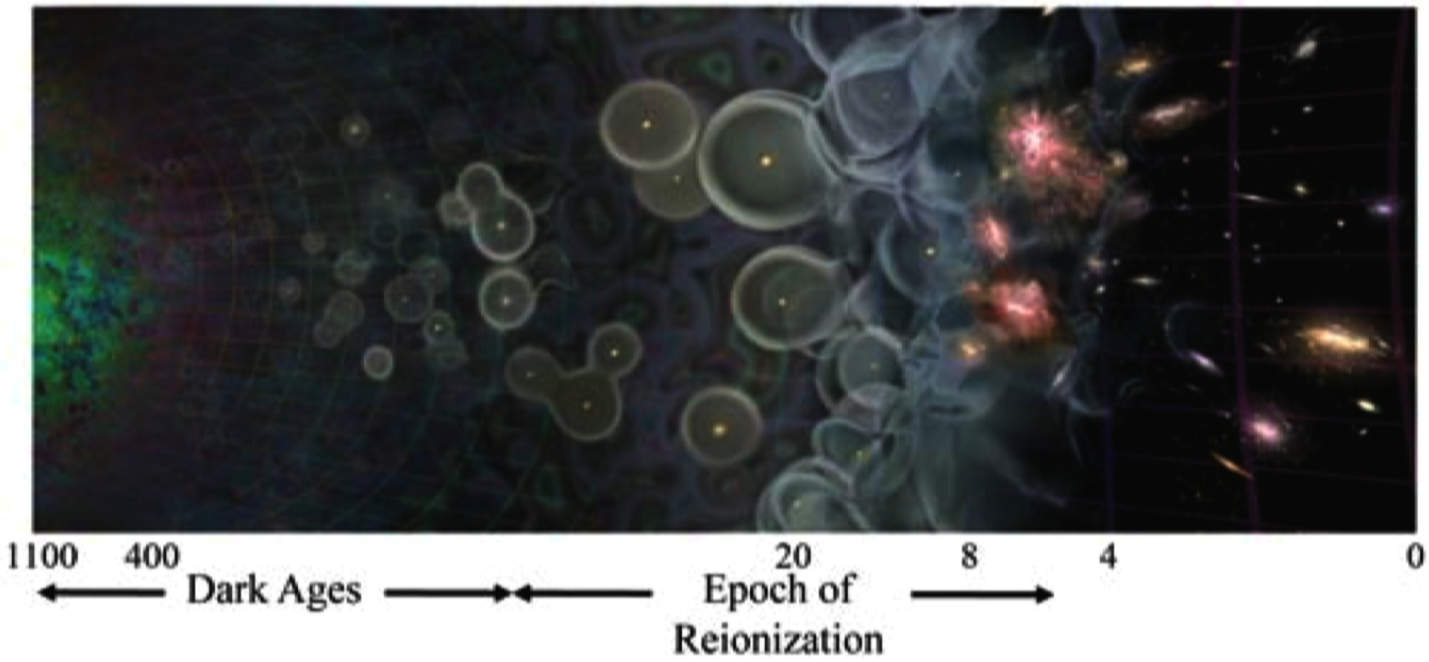
Hydrogen is everywhere, and the 21cm line allows us to trace hydrogen



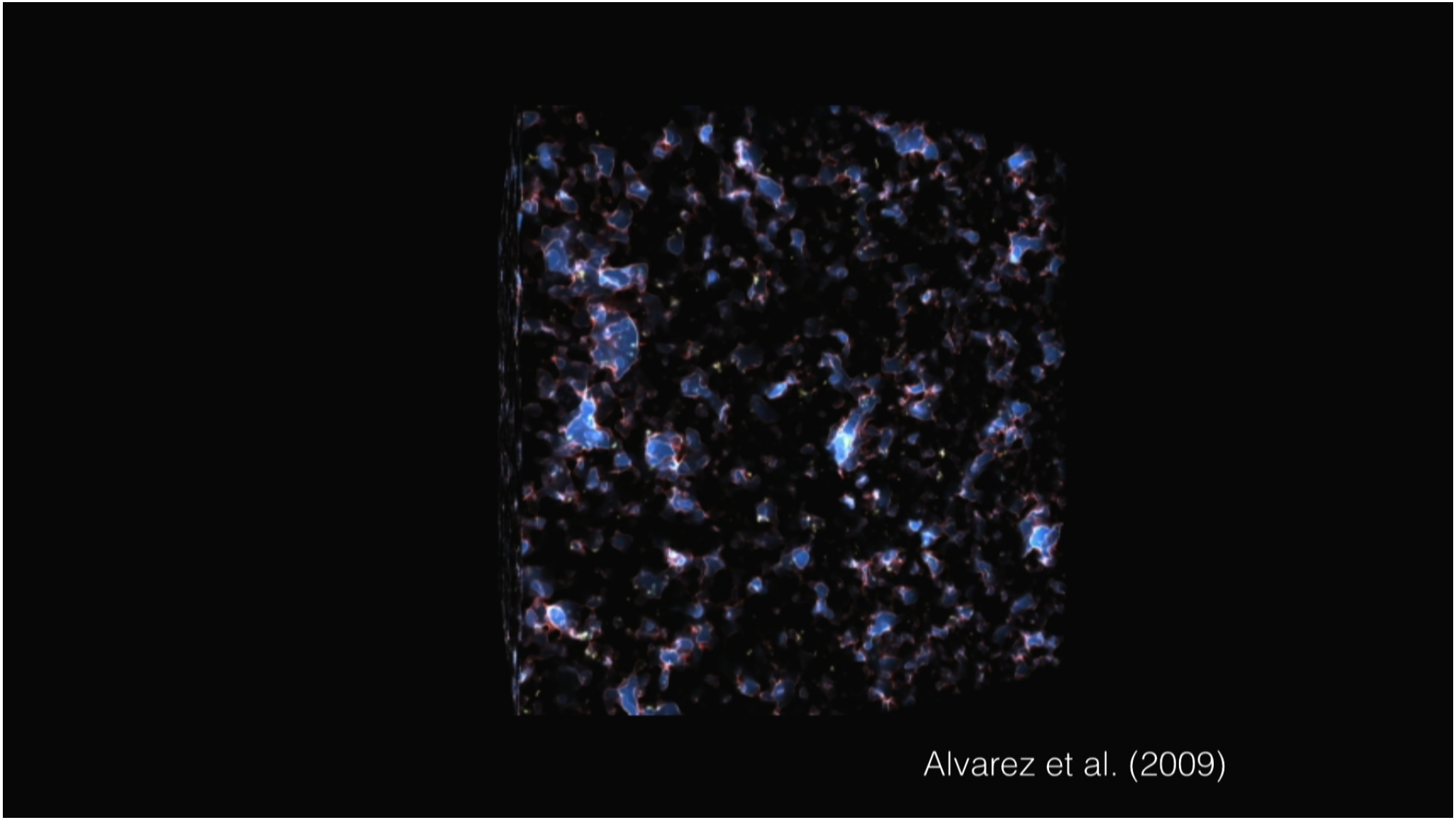
The spectral nature of the 21cm line allows us to fill in this volume

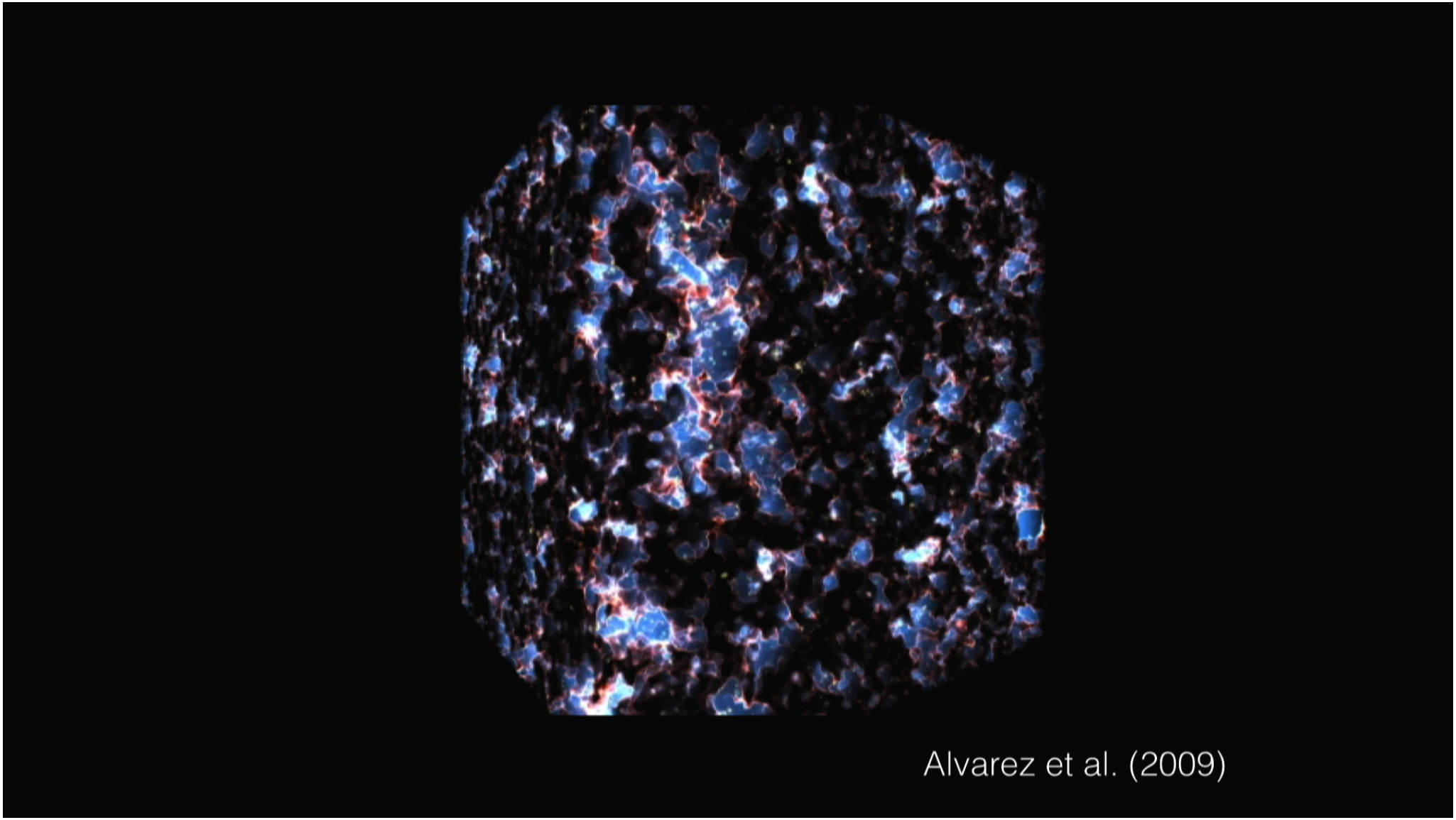


Current generation experiments are targeting the Epoch of Reionization (EoR)

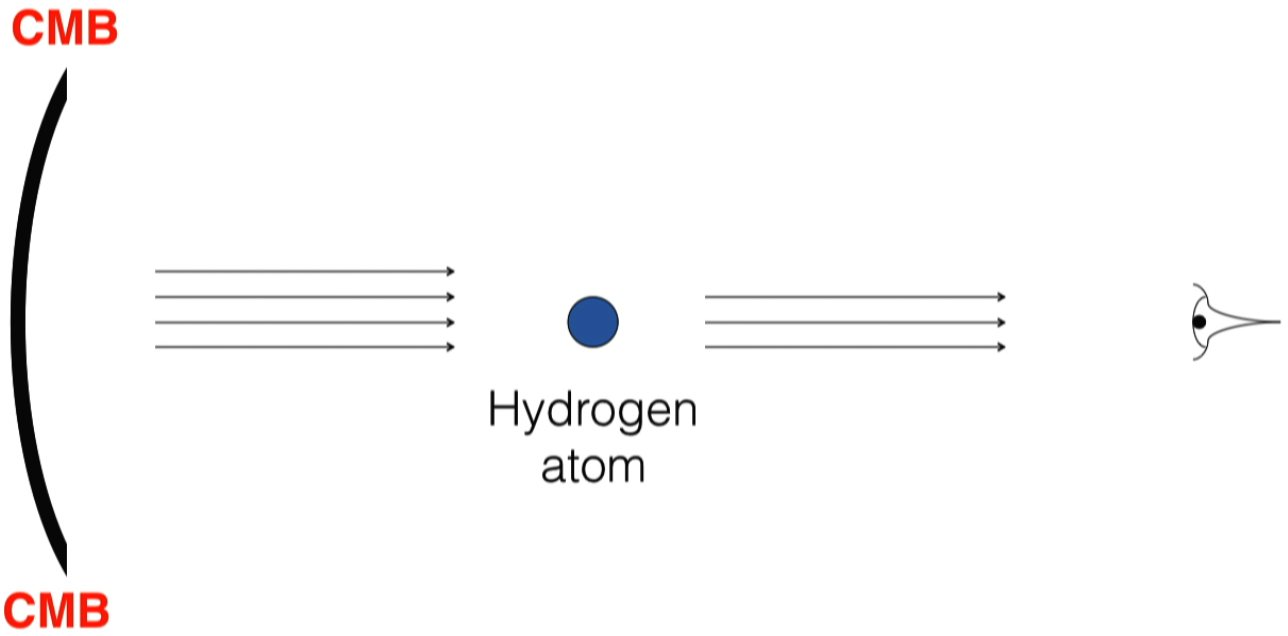

1100
400
20
8
4
0
Dark Ages
Epoch of
Reionization


Alvarez et al. (2009)

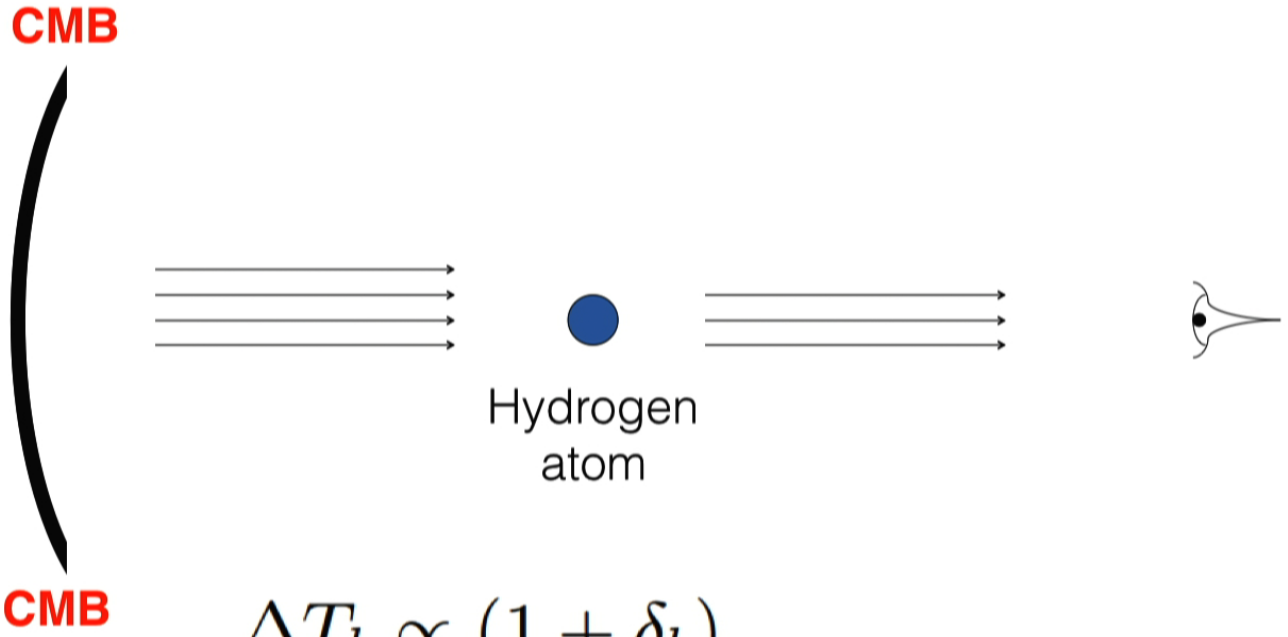

Alvarez et al. (2009)


Alvarez et al. (2009)

The redshifted 21cm line is very sensitive to astrophysics

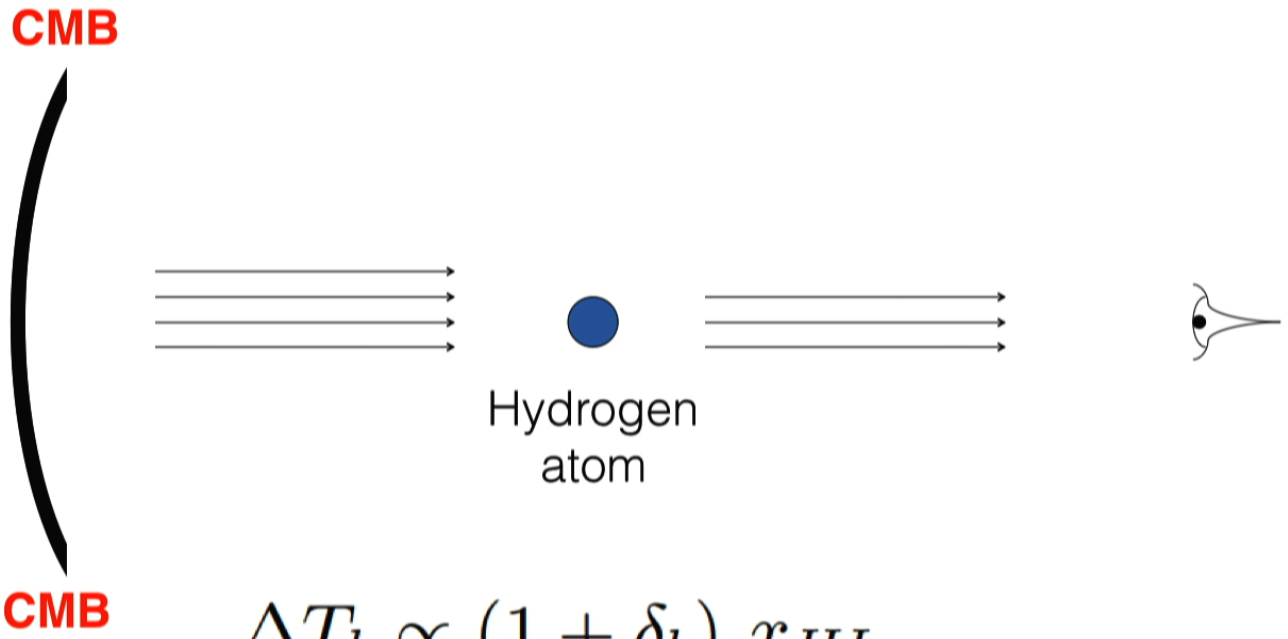


The redshifted 21cm line is very sensitive to astrophysics



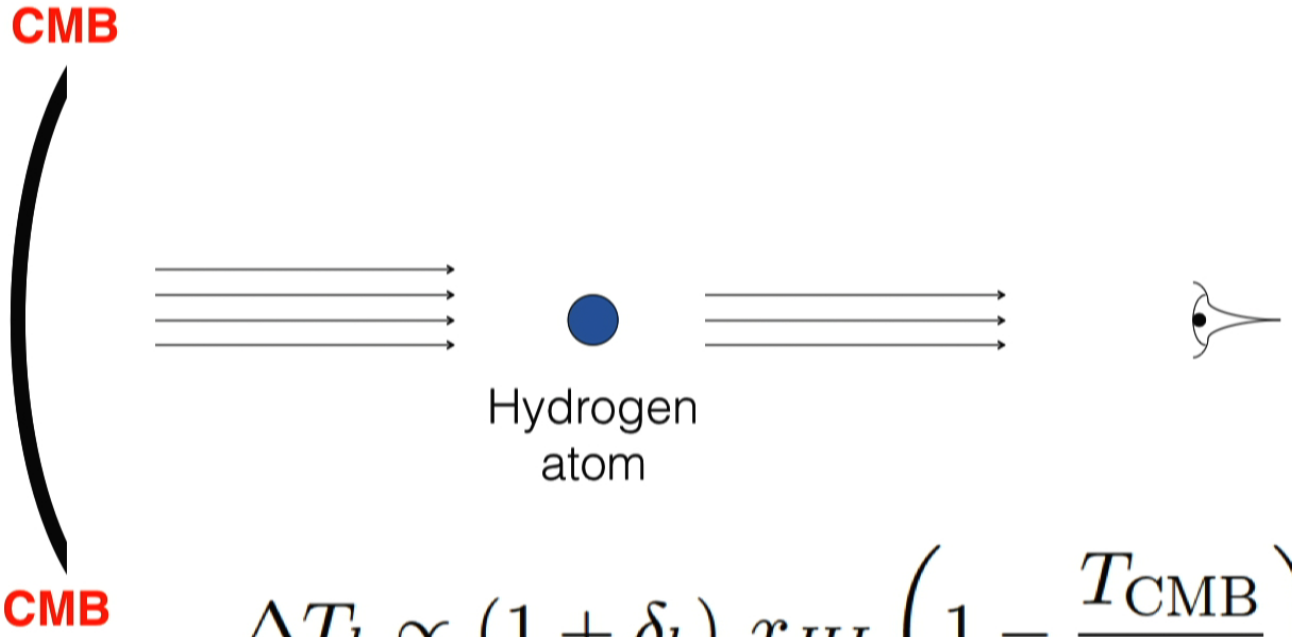
$$\Delta T_b \propto (1 + \delta_b)$$

The redshifted 21cm line is very sensitive to astrophysics



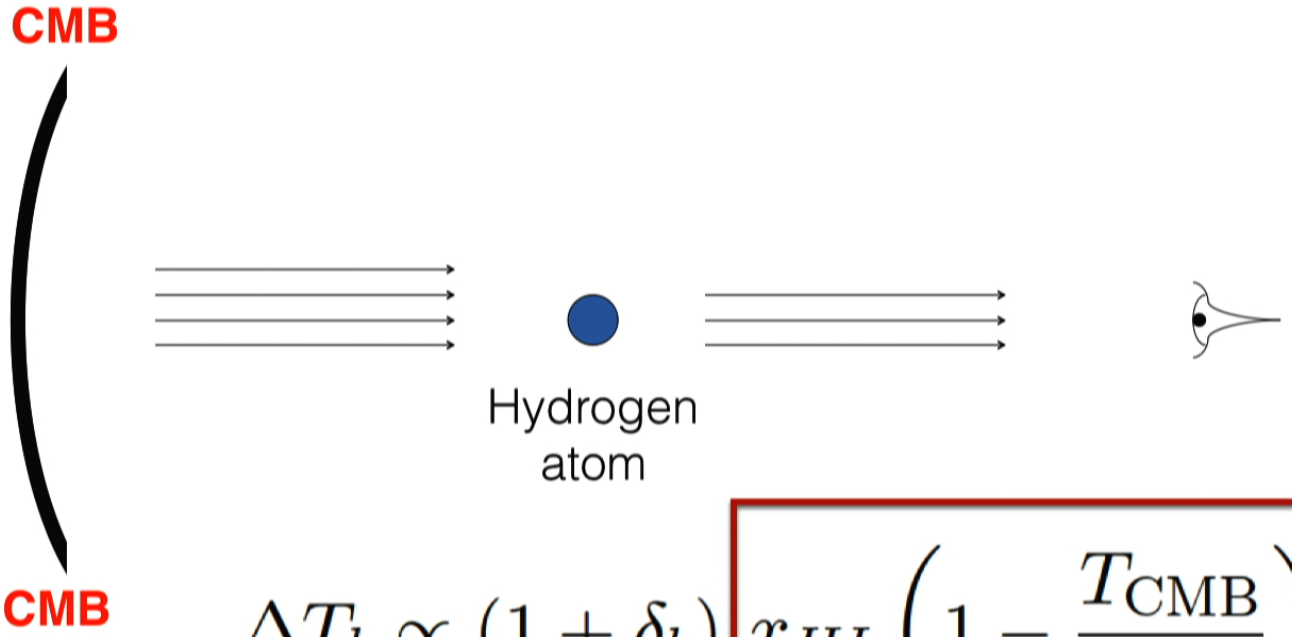
$$\Delta T_b \propto (1+\delta_b)\, x_{HI}$$

The redshifted 21cm line is very sensitive to astrophysics

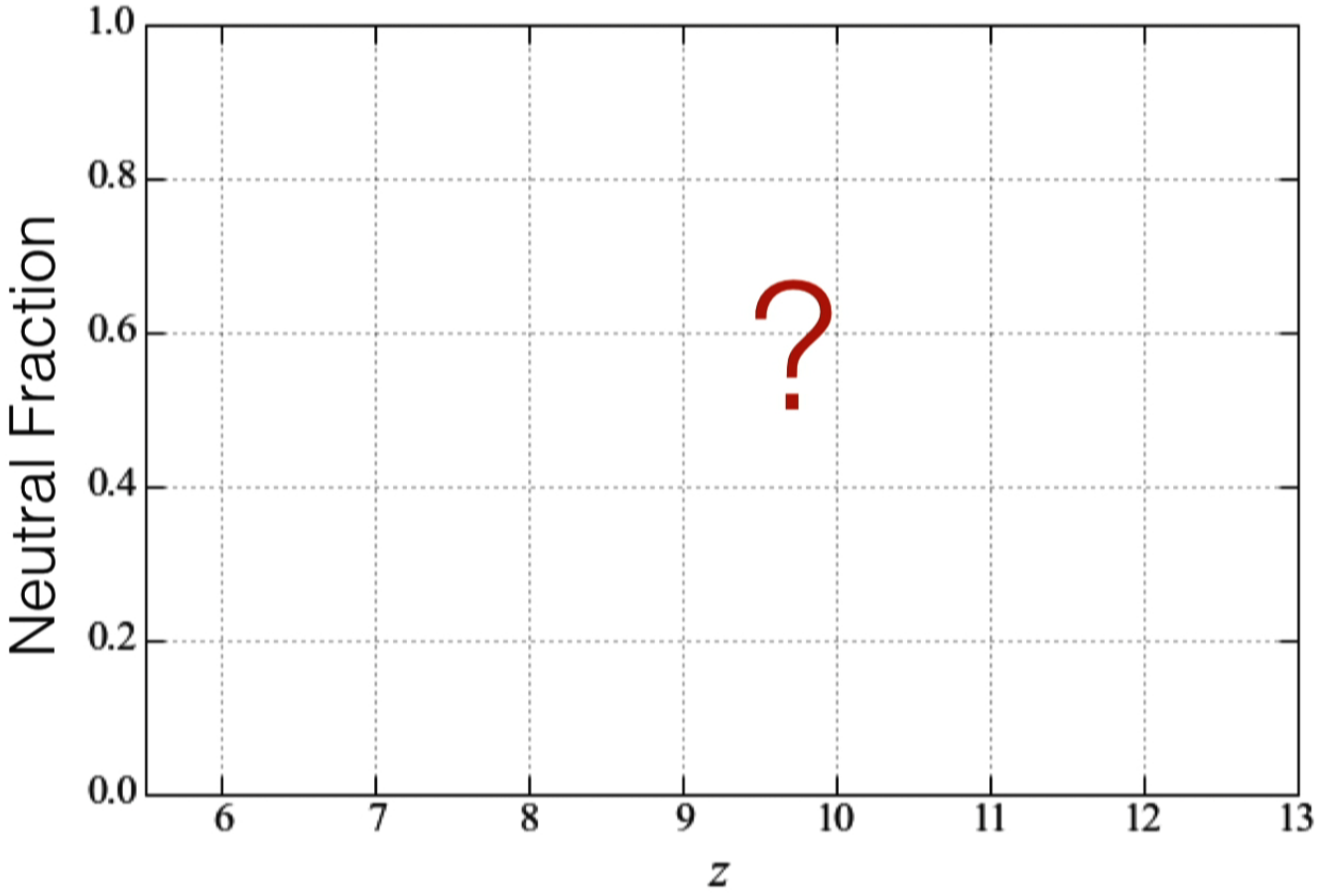


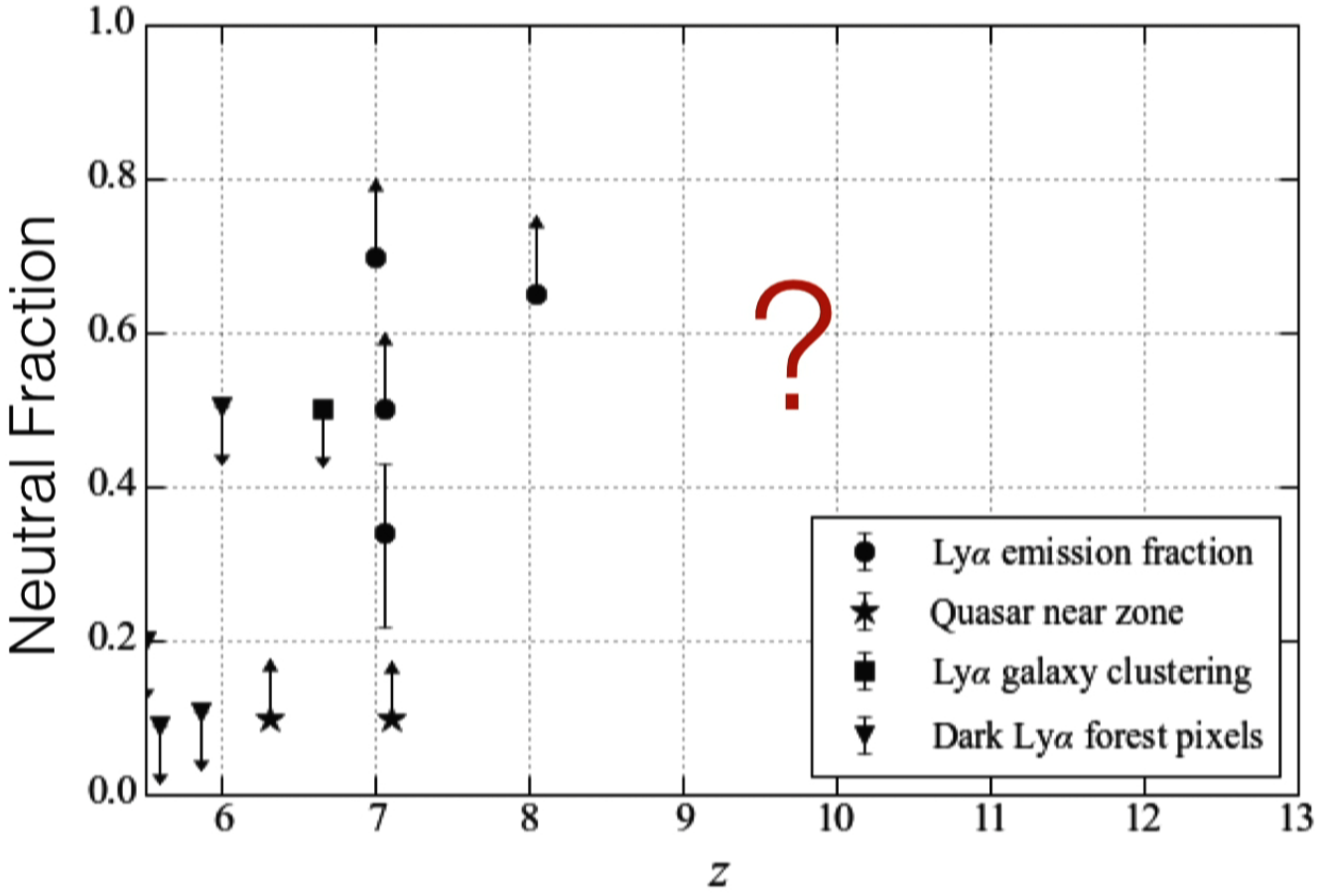
$$\Delta T_b \propto (1+\delta_b)\, x_{HI} \left(1 - \frac{T_{\rm CMB}}{T_{\rm spin}}\right)$$

The redshifted 21cm line is very sensitive to astrophysics

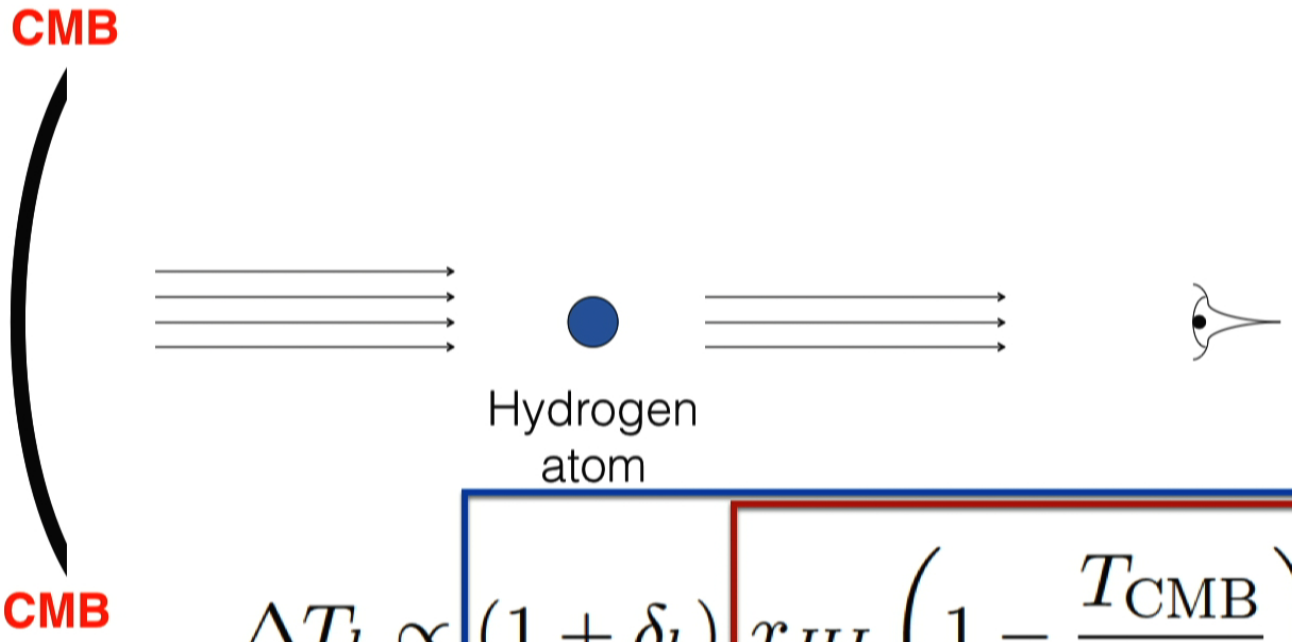


$$\Delta T_b \propto (1+\delta_b)\, x_{HI} \left(1 - \frac{T_{\rm CMB}}{T_{\rm spin}}\right)$$


Neutral Fraction
1.0
0.8
0.6
0.4
0.2
0.0
6
7
8
9
10
11
12
13
z
?


Neutral Fraction
1.0
0.8
0.6
0.4
0.2
0.0
6
7
8
9
10
11
12
13
z
?
Lyα emission fraction
Quasar near zone
Lyα galaxy clustering
Dark Lyα forest pixels

The redshifted 21cm line is very sensitive to astrophysics and cosmology

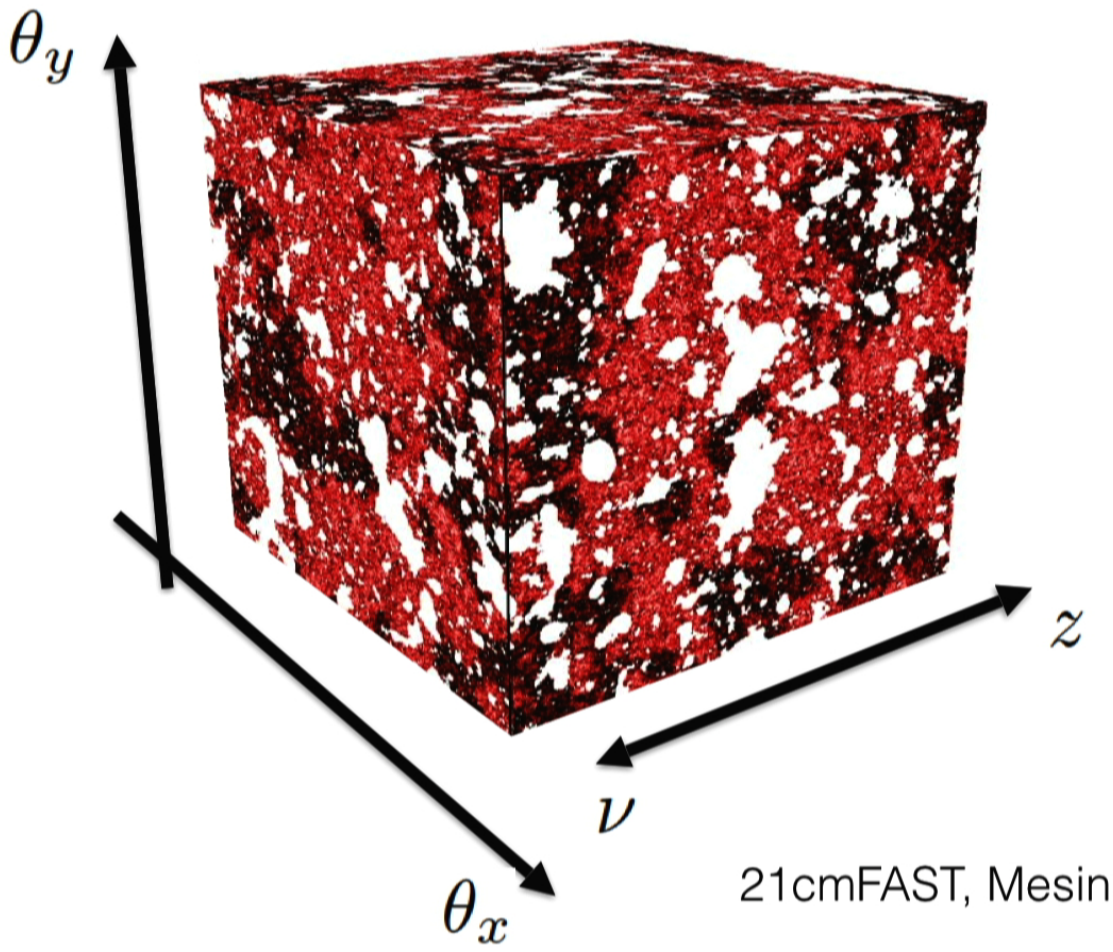


$$\Delta T_b \propto (1+\delta_b)\, x_{HI} \left(1 - \frac{T_{\rm CMB}}{T_{\rm spin}}\right)$$

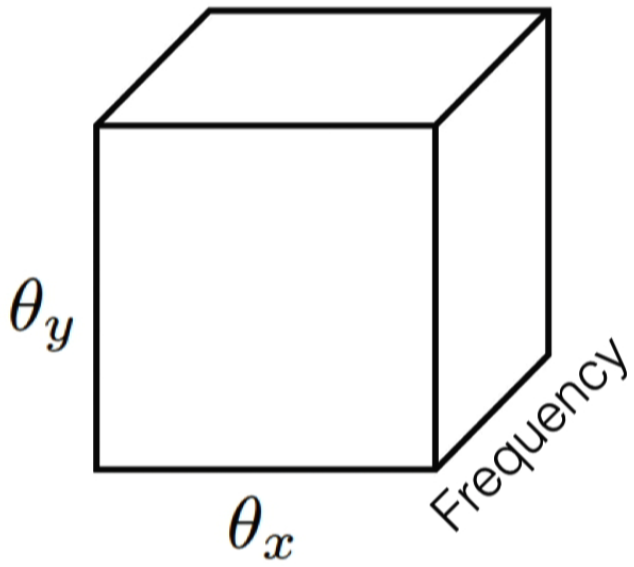
Take-home messages

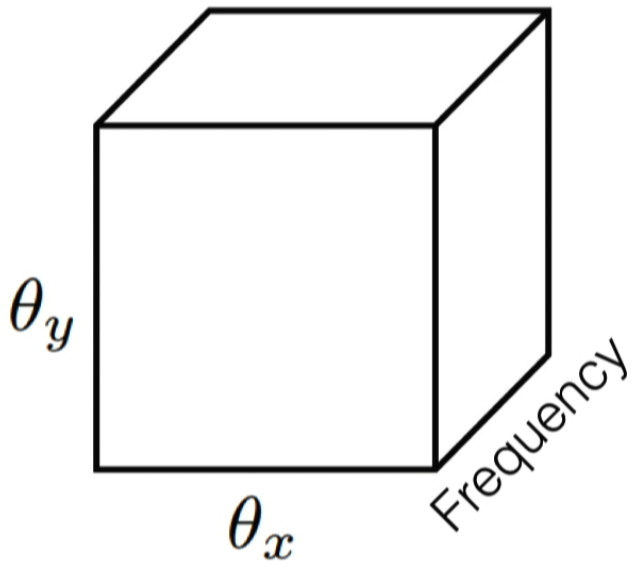
- We're getting close to detecting the 21cm signal—close enough to start improving our understanding of reionization.
- 21cm cosmology is an unconventional application of radio astronomy, requiring unconventional experimental setups.
- The HERA experiment is being built now, and promises to deliver qualitatively new constraints on astrophysics and cosmology.

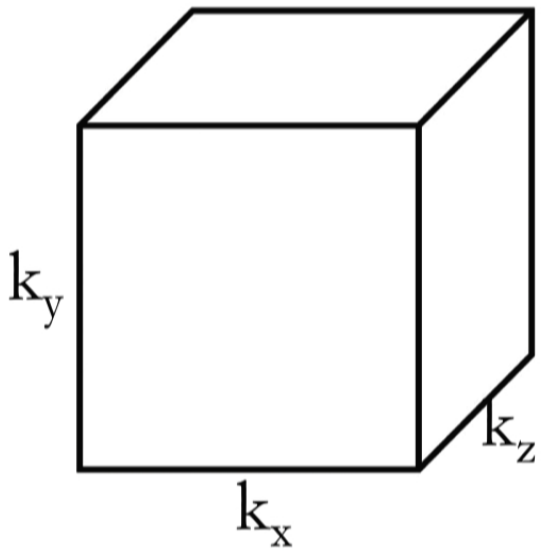
The promise of 21cm measurements

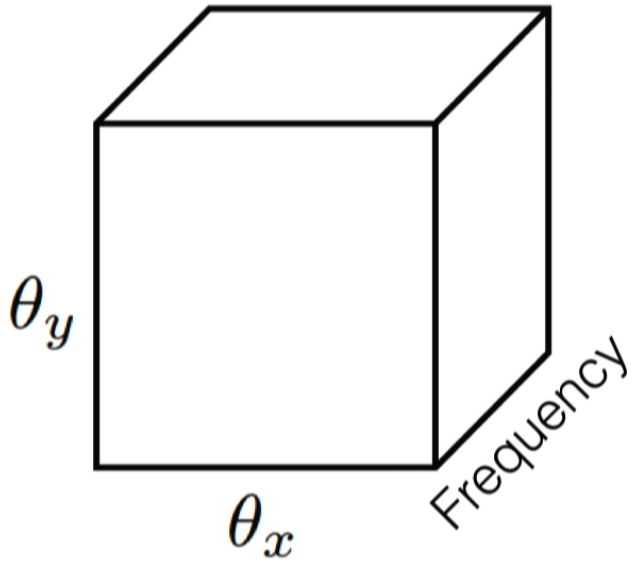


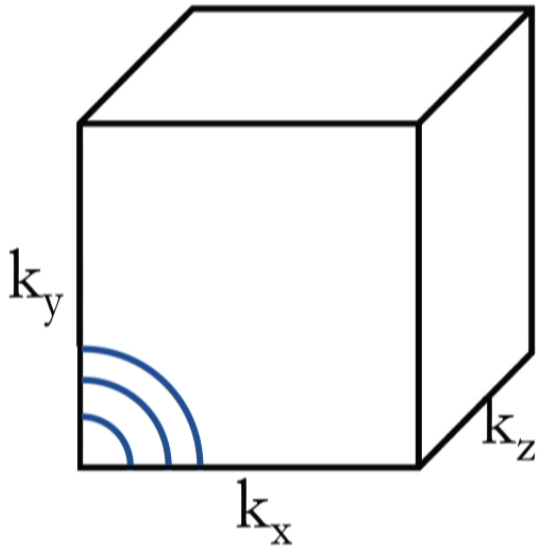
21cmFAST, Mesinger et al.

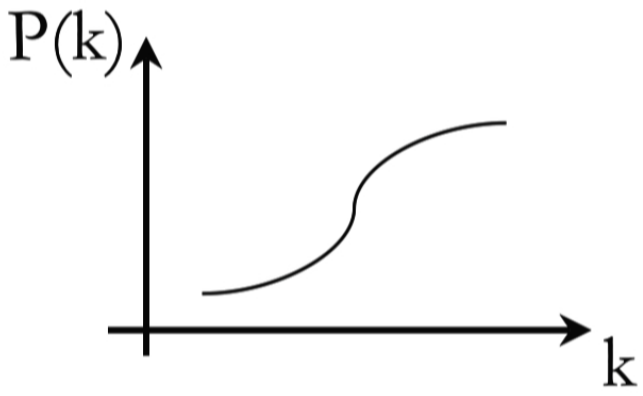

θ_y
θ_x
Frequency

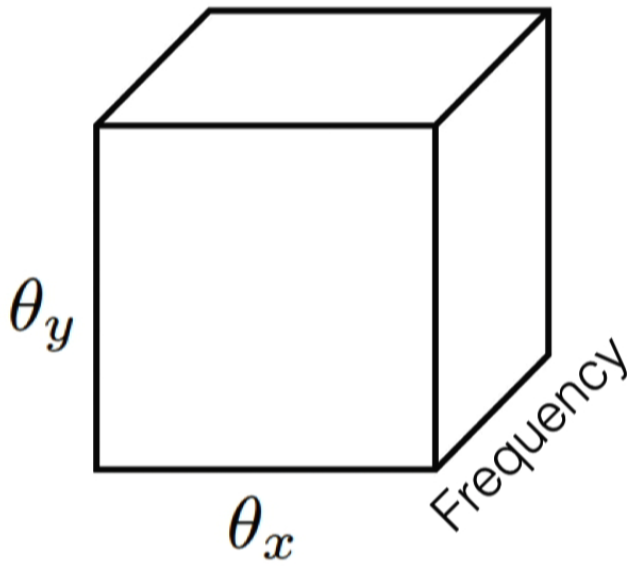

θ_y
θ_x
Frequency

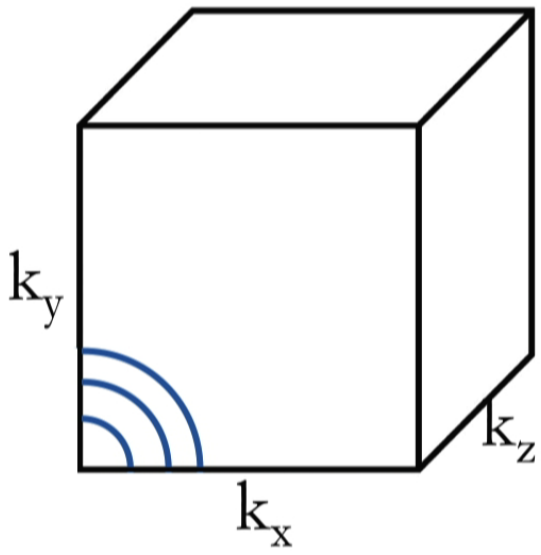

k_y
k_z
k_x

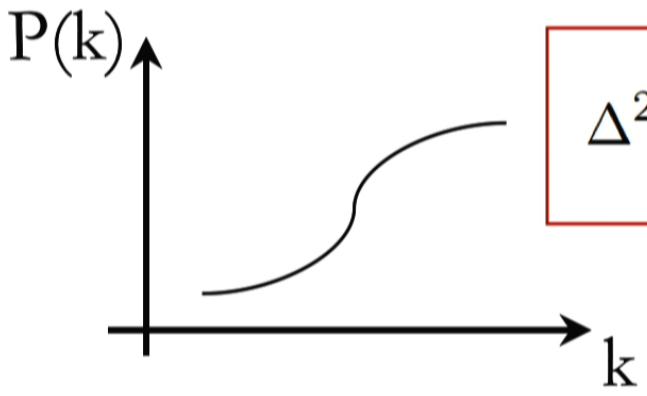

θ_y
θ_x
Frequency


k_y
k_z
k_x

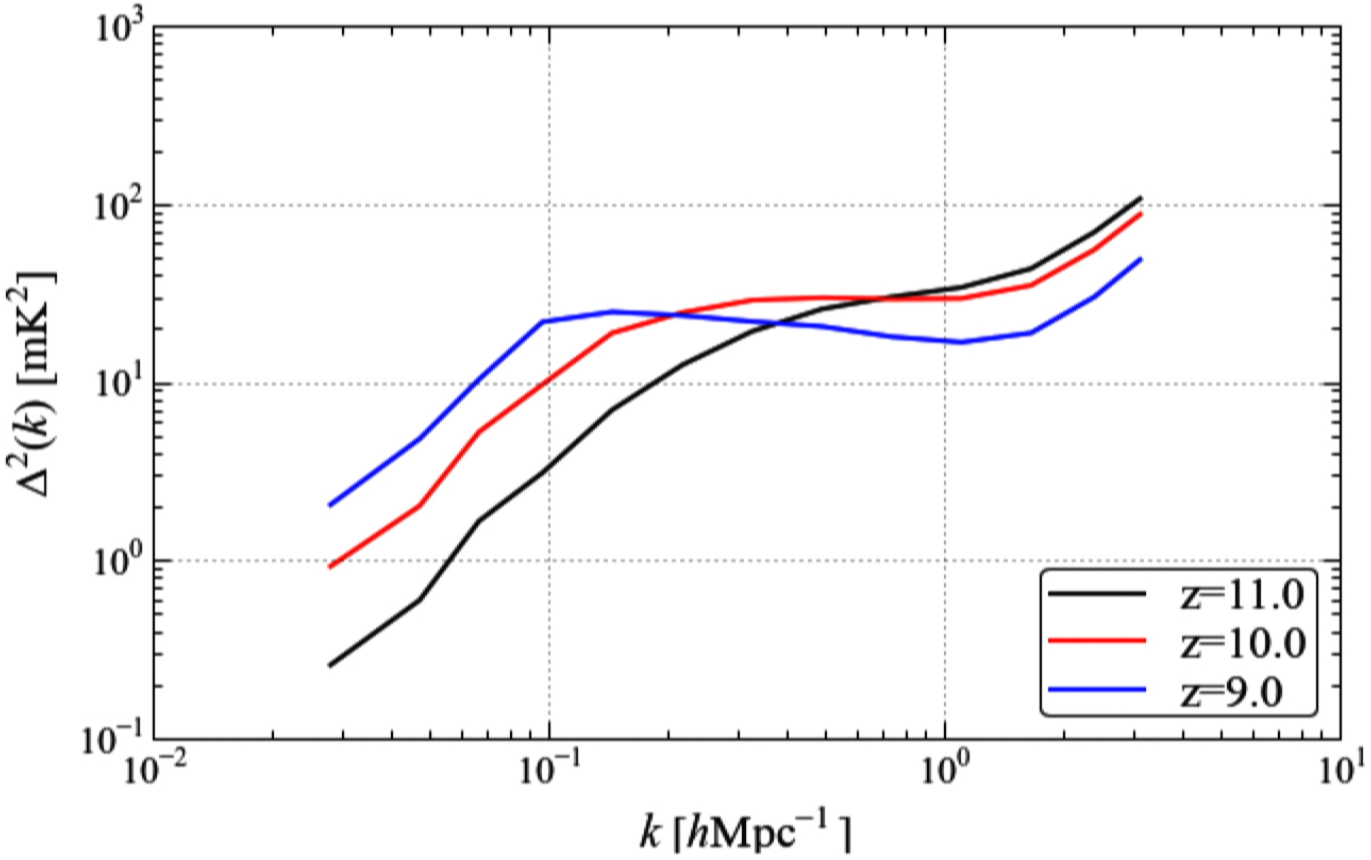

P(k)
k

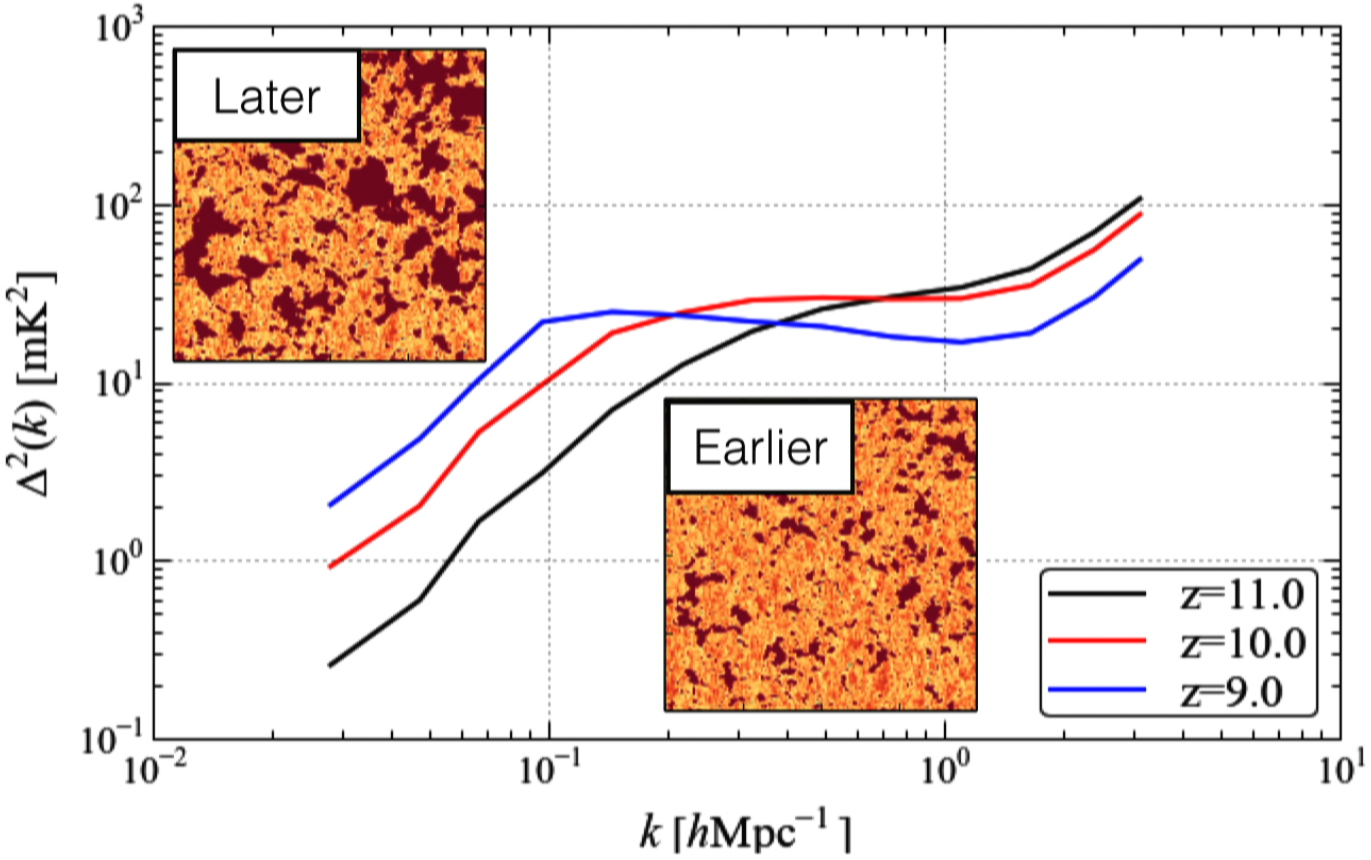






$$\Delta^2(k) \equiv \frac{k^3}{2\pi^2} P(k)$$


10^3
10^2
10^1
10^0
10^{-1}
$\Delta^2(k)$ [mK^2]
10^{-2}
10^{-1}
10^0
10^1
k [hMpc^{-1}]
z=11.0
z=10.0
z=9.0


Later
Earlier
z=11.0
z=10.0
z=9.0
$\Delta^2(k)$ [mK^2]
k [hMpc^{-1}]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-1}
10^0
10^1

A three-parameter reionization model

A three-parameter reionization model

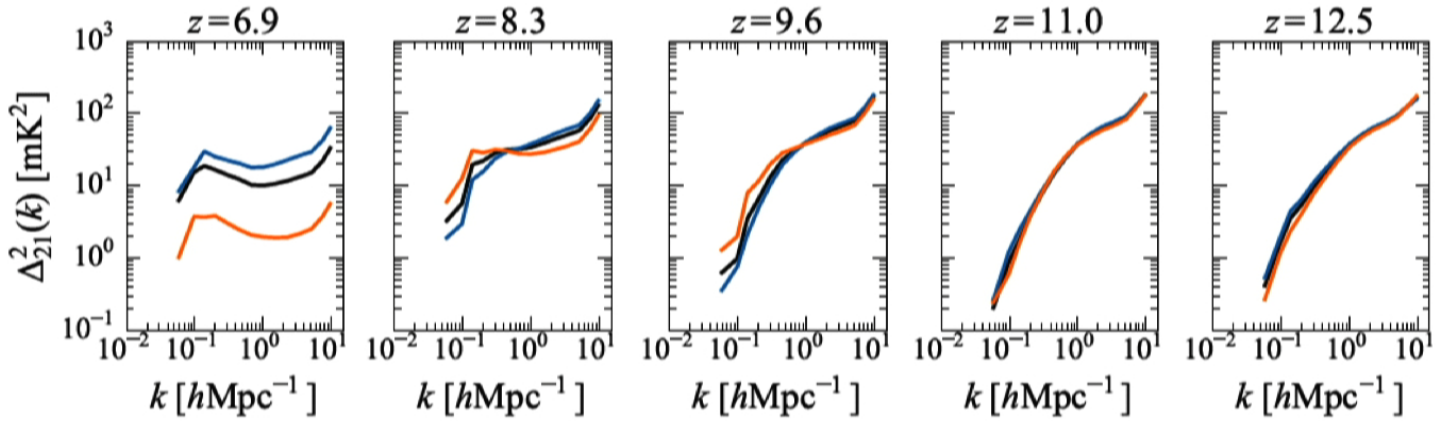
- ζ: ionizing efficiency of first galaxies

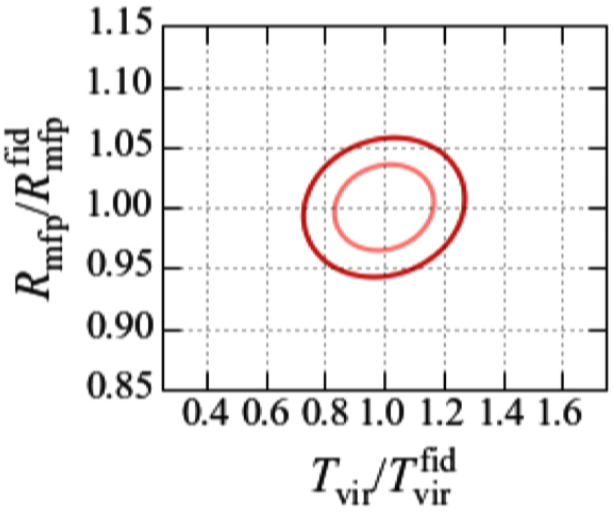
A three-parameter reionization model

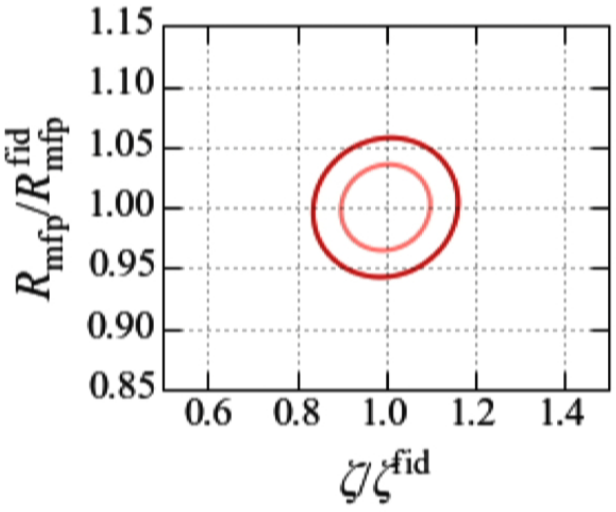
- ζ: ionizing efficiency of first galaxies
- T_{vir}: minimum virial temperature (proxy for mass) of first ionizing galaxies

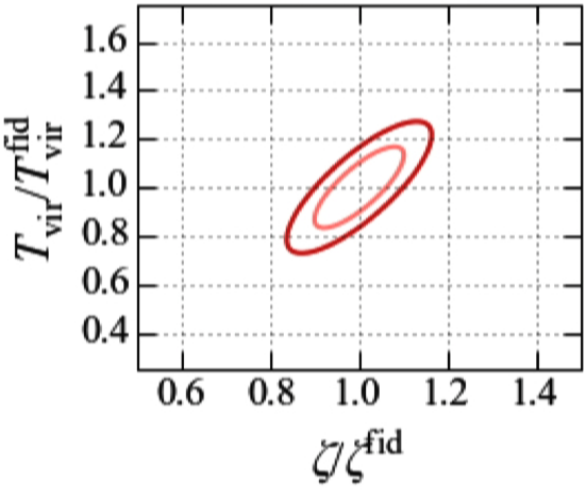
A three-parameter reionization model

- ζ: ionizing efficiency of first galaxies
- T_{vir}: minimum virial temperature (proxy for mass) of first ionizing galaxies
- R_{mfp}: mean free path of ionizing photons


z=6.9
z=8.3
z=9.6
z=11.0
z=12.5
$\Delta^2_{21}(k)$ [mK^2]
k [hMpc^{-1}]



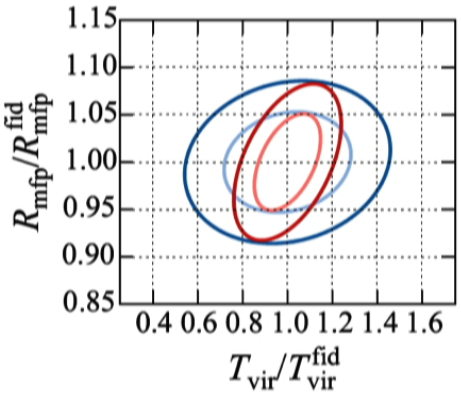


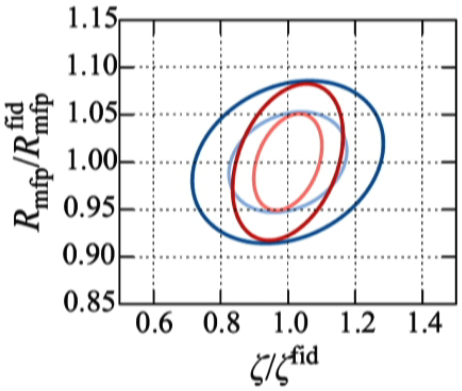


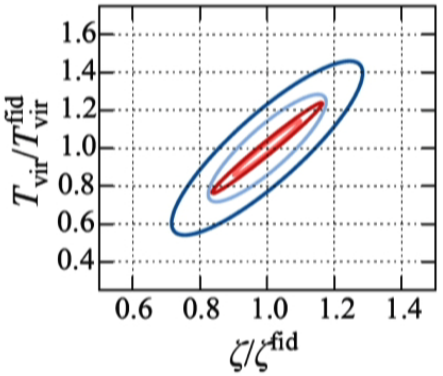
The recently commenced HERA experiment is forecasted to deliver ~5% errors on astrophysical parameters

AL & Parsons (2015b)

Note that cosmological parameter uncertainties are non-negligible



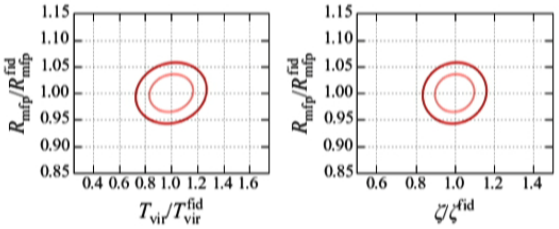




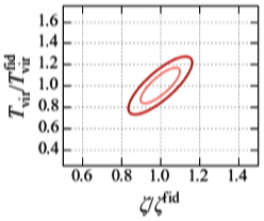
Cosmo params fixed

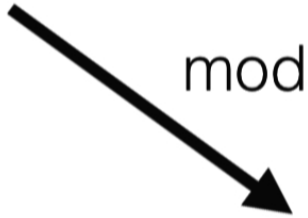
Cosmo params varied

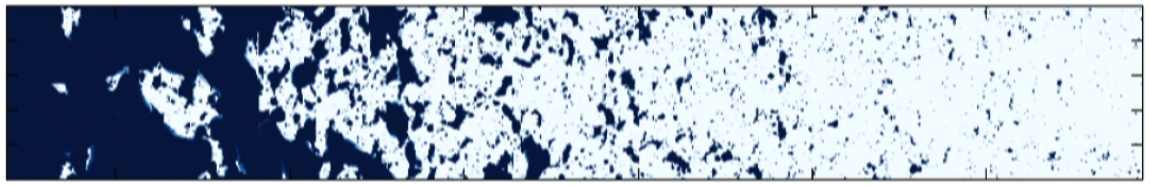
AL & Parsons (2015b)


1.15
1.10
1.05
1.00
0.95
0.90
0.85
$R_{\rm mfp}/R_{\rm mfp}^{\rm fid}$
0.4 0.6 0.8 1.0 1.2 1.4 1.6
$T_{\rm vir}/T_{\rm vir}^{\rm fid}$

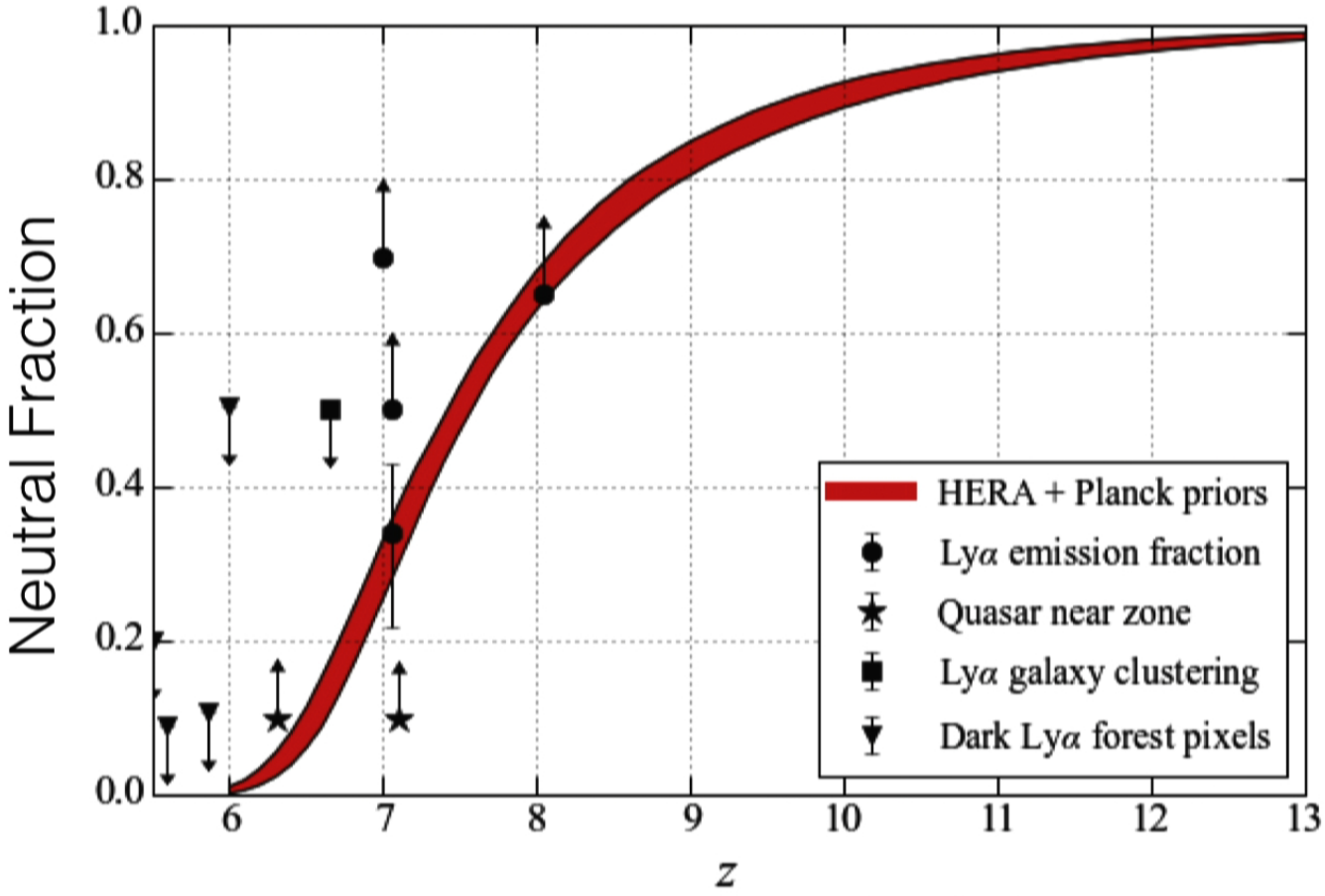
1.15
1.10
1.05
1.00
0.95
0.90
0.85
$R_{\rm mfp}/R_{\rm mfp}^{\rm fid}$
0.6 0.8 1.0 1.2 1.4
$\zeta/\zeta^{\rm fid}$


1.6
1.4
1.2
1.0
0.8
0.6
0.4
$T_{\rm vir}/T_{\rm vir}^{\rm fid}$
0.6 0.8 1.0 1.2 1.4
$\zeta/\zeta^{\rm fid}$


model




time

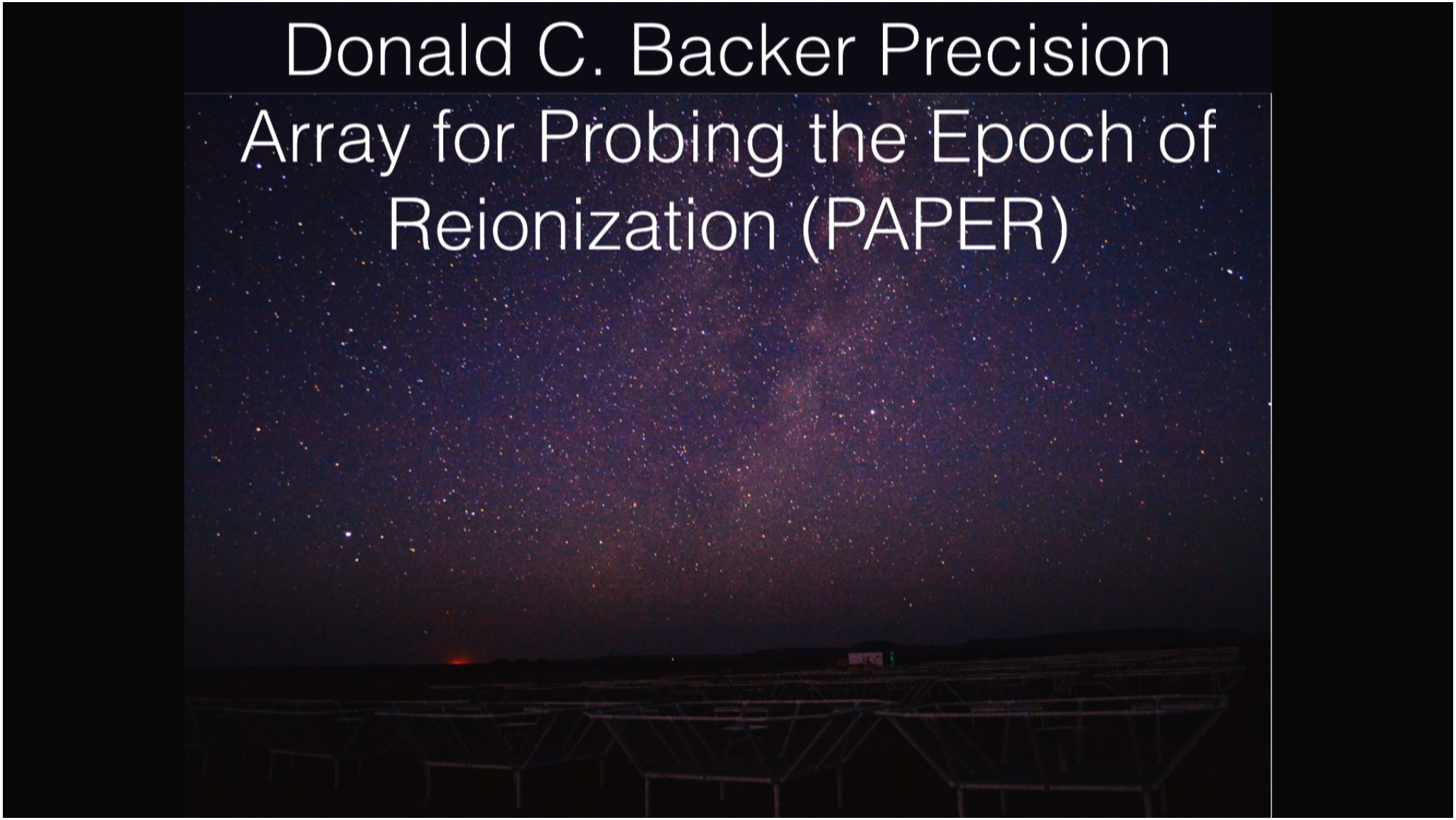


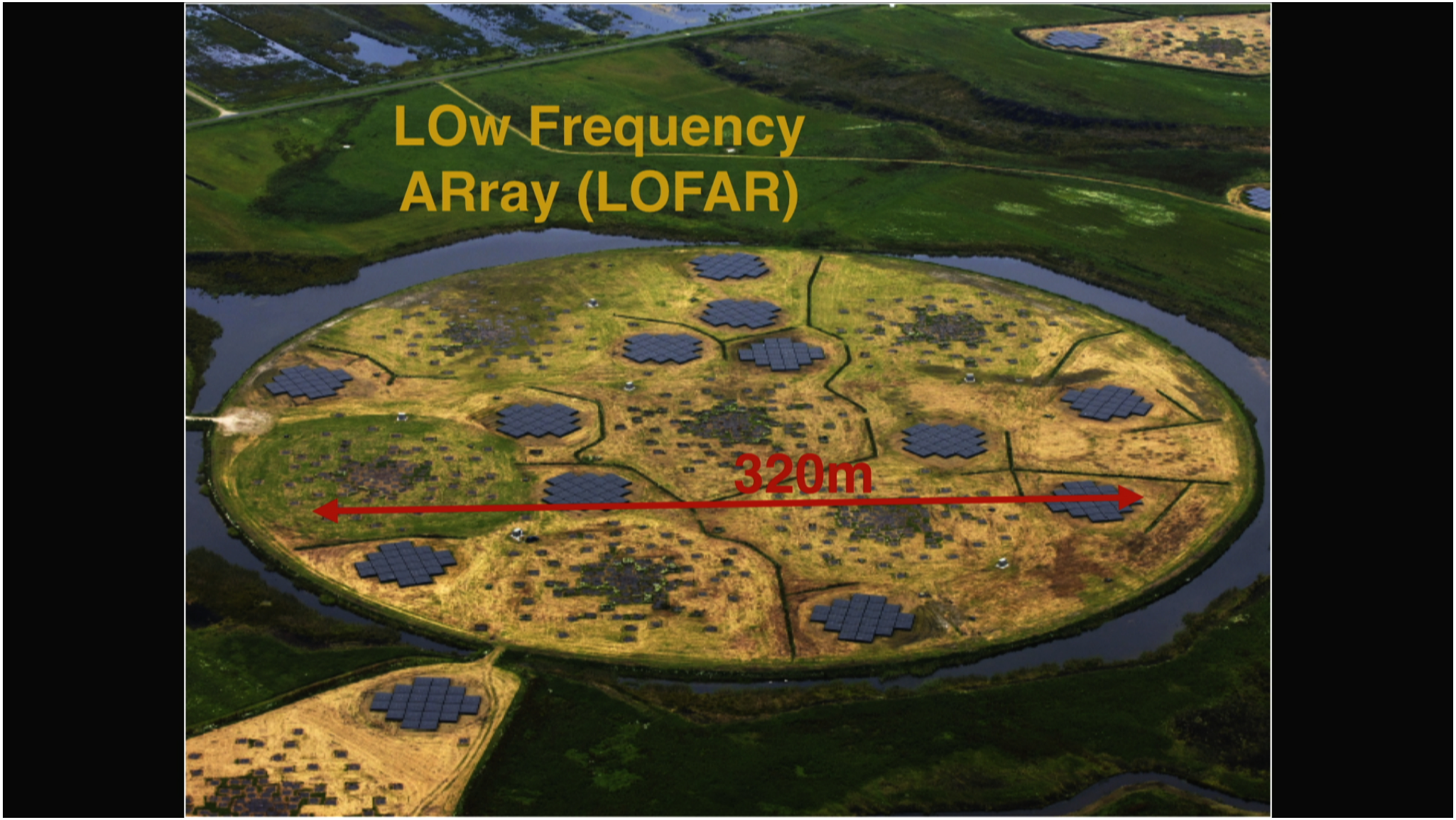
AL & Parsons (2015)
Presley, **AL** et al. (ongoing)

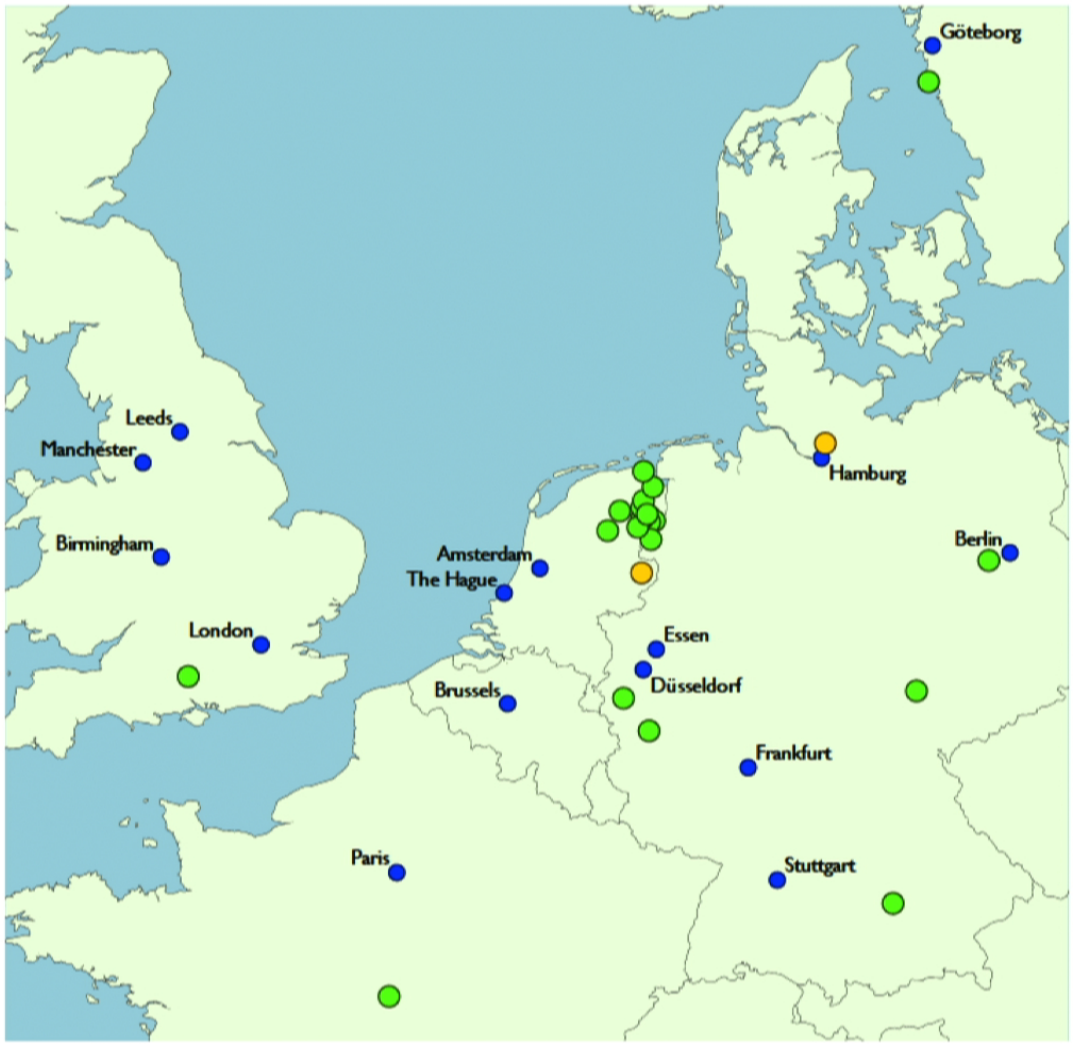
Questions we can now begin to ask

- How and when was the IGM heated?
- Were there any exotic mechanisms at play?
- What was the nature of the first stars and galaxies?
- Were galaxies solely responsible for reionization?
- How does fundamental physics play into this? Dark energy? Neutrino mass?

21cm cosmology: an unconventional application of radio astronomy

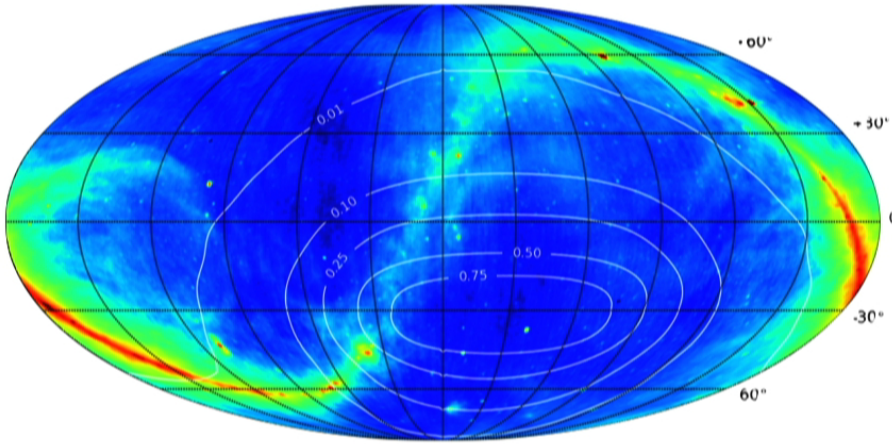

Donald C. Backer Precision
Array for Probing the Epoch of
Reionization (PAPER)


LOw Frequency
ARray (LOFAR)
320m

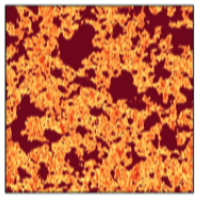

Göteborg
Leeds
Manchester
Hamburg
Birmingham
Amsterdam
The Hague
Berlin
London
Essen
Düsseldorf
Brussels
Frankfurt
Paris
Stuttgart

The foreground challenge

Foreground contaminants are bright and dominate the cosmological signal

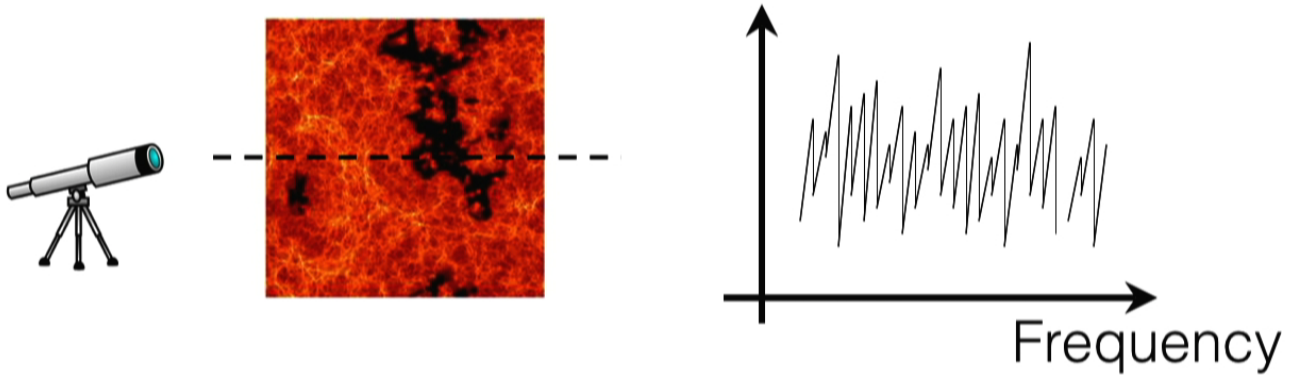


$\sim 10^{10}$ mK^2



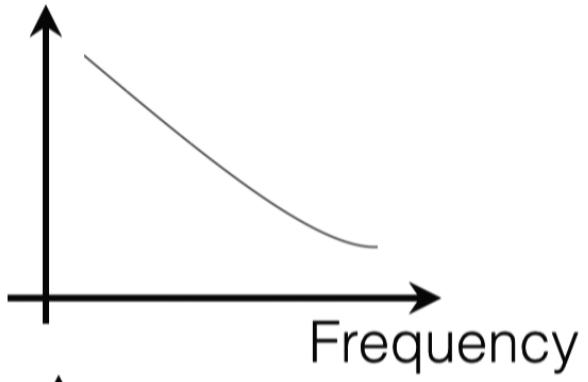
~ 10 mK^2

The cosmological signal is expected to vary rapidly with changing frequency

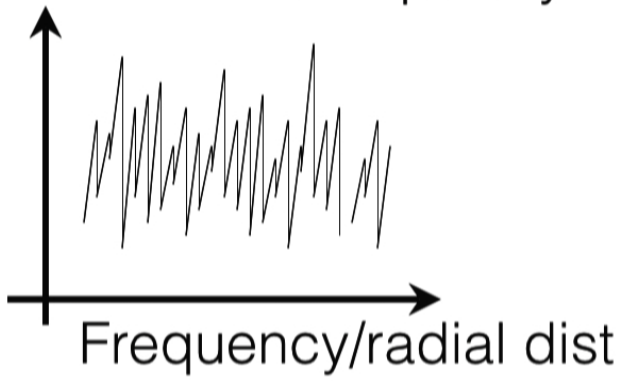


Foregrounds are expected to be smooth functions of frequency

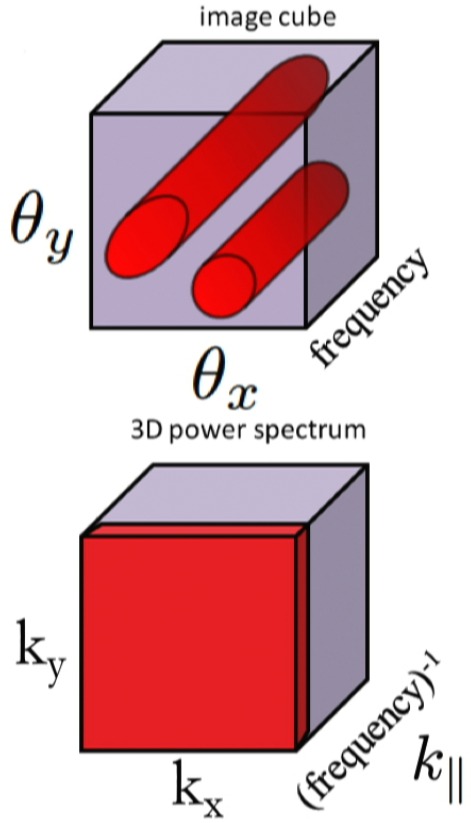
Foregrounds



Cosmological signal



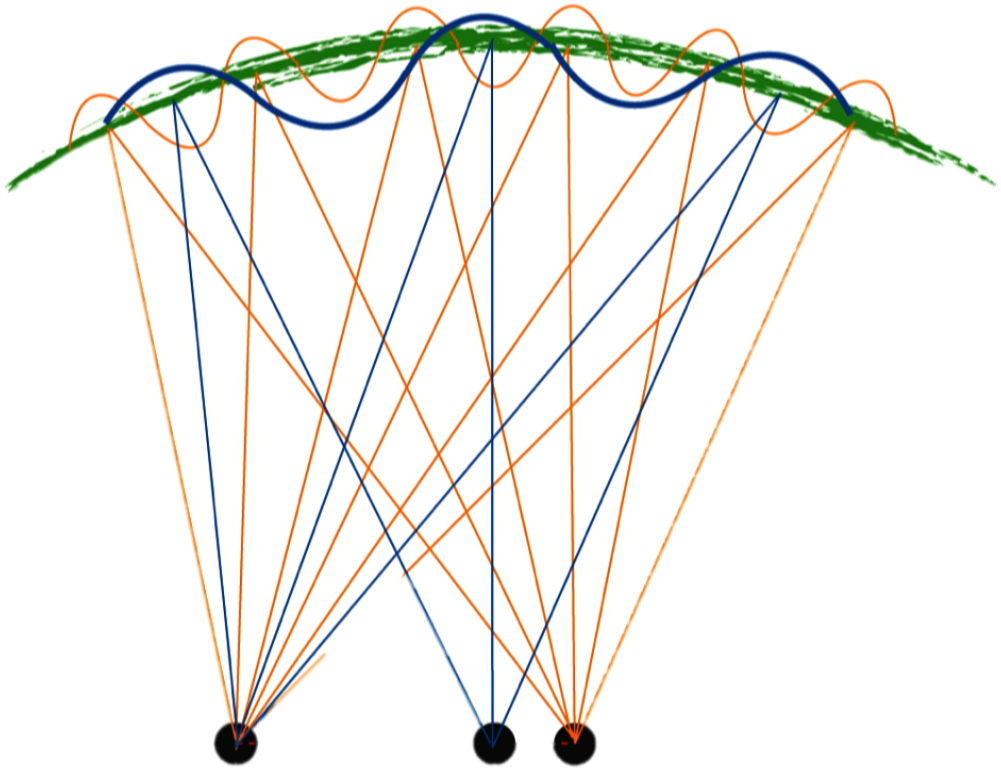
Fourier space is a natural space for foreground separation



Foregrounds are probably localized in Fourier space…

Foregrounds are probably localized in Fourier space…

An interferometer builds up a picture of the sky Fourier mode by Fourier mode



Interferometers are naturally chromatic instruments

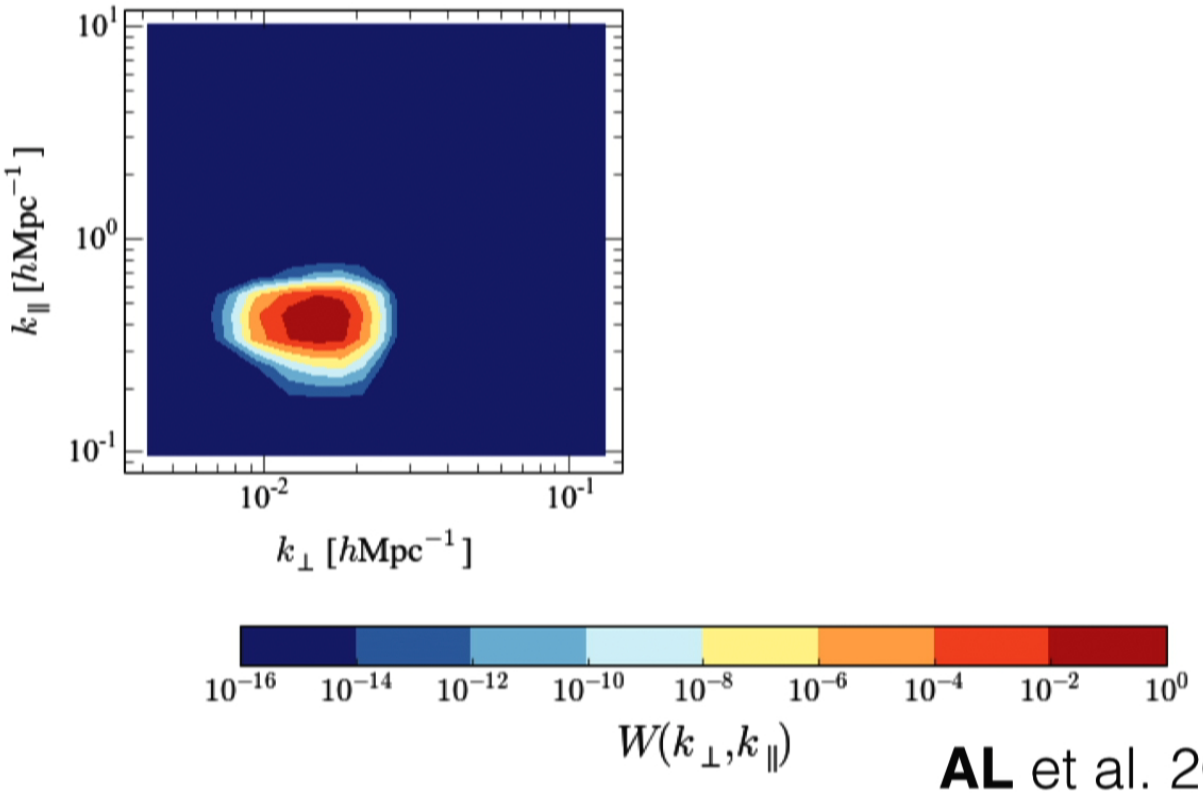
$$\int T(\theta) \exp\left(-i\frac{2\pi\, b\, \nu\, \theta}{c}\right) d\theta$$

Pushing the mathematics through…

Window functions

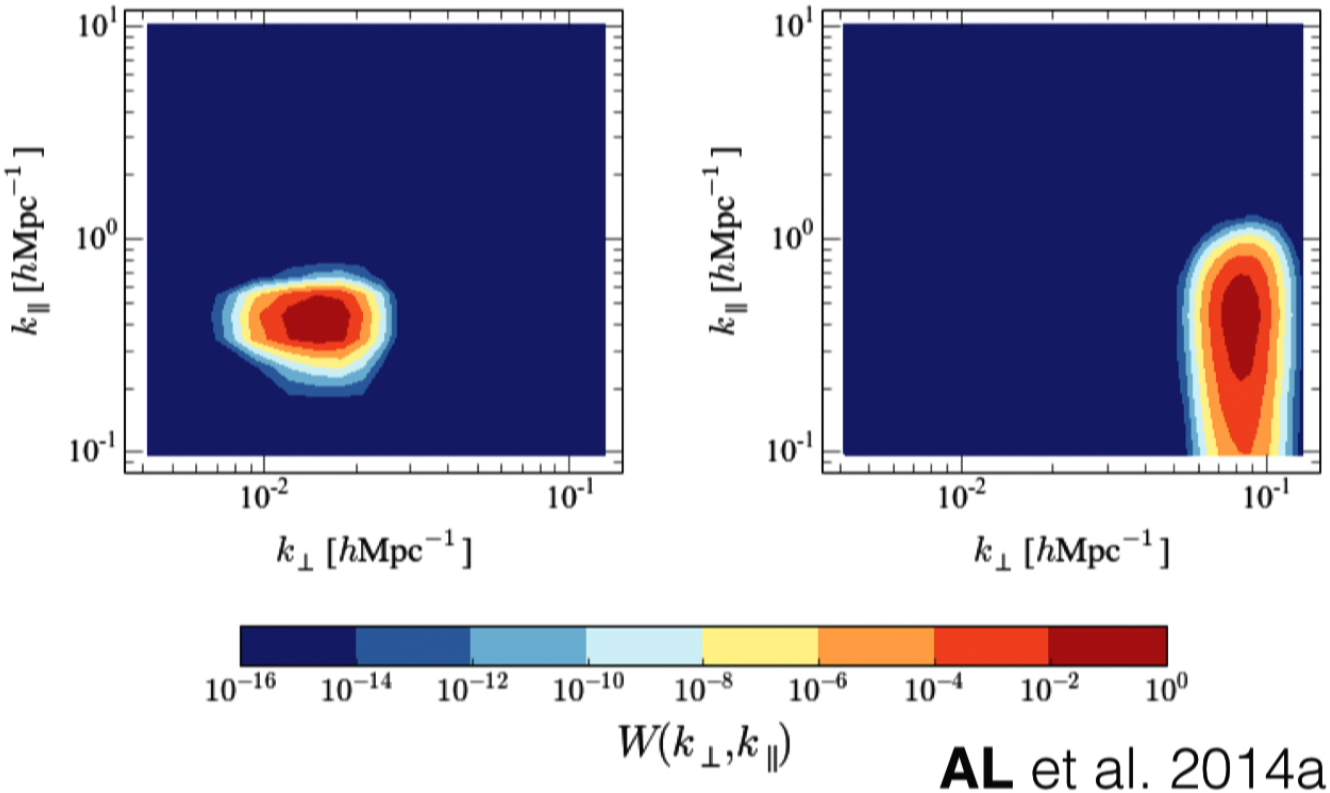
$$P_{\rm meas}(\mathbf{k}) = \int d^3\mathbf{k}' W(\mathbf{k},\mathbf{k}') P_{\rm true}(\mathbf{k}')$$

Window functions at low $k_\perp$ are relatively compact



AL et al. 2014a,b

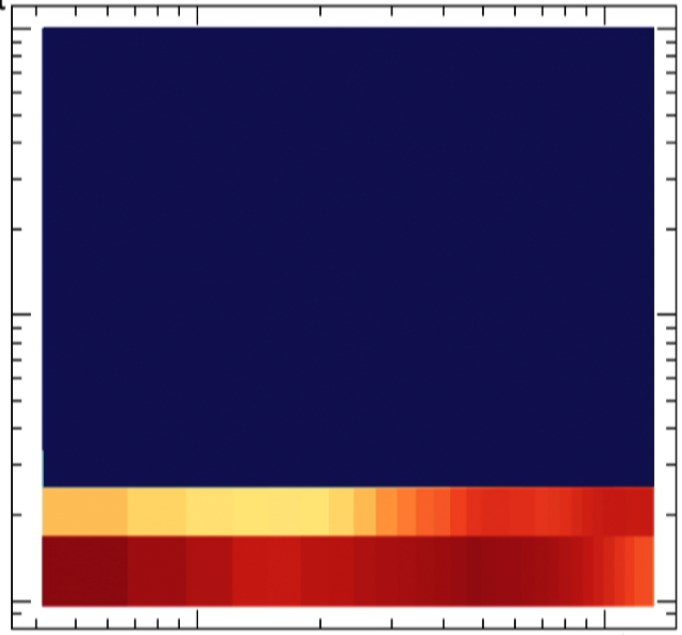
Window functions at high $k_\perp$ have long tails towards low $k_\parallel$



AL et al. 2014a,b

The instrument takes intrinsically smooth spectra…

Unsmooth spectra

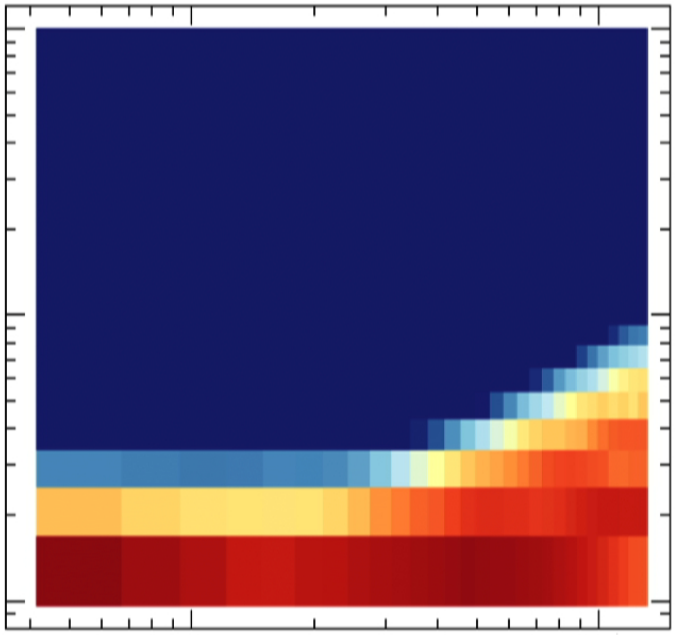


Smooth spectra

AL et al. 2014a,b

…and invades more of Fourier space

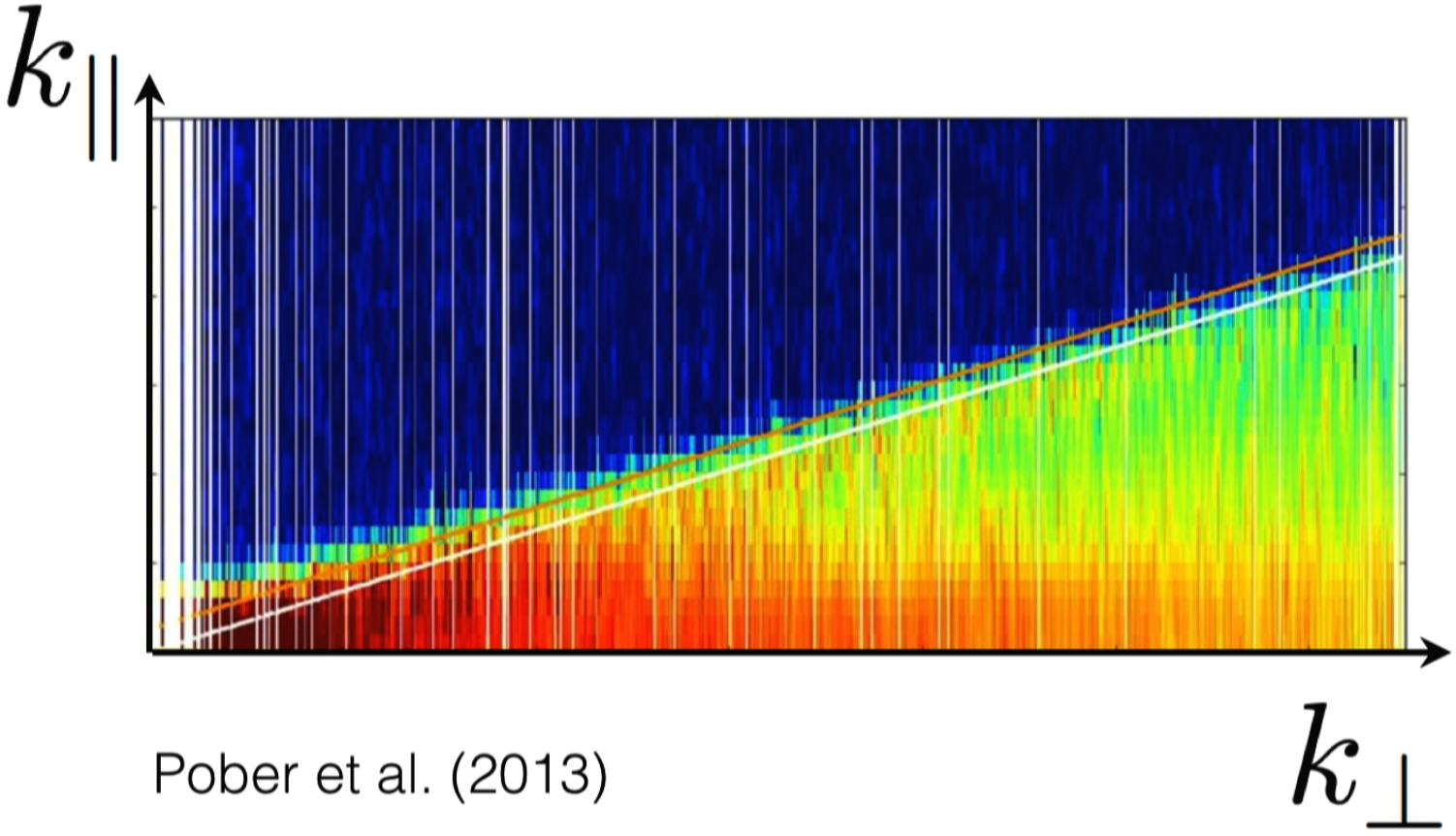
Unsmooth spectra



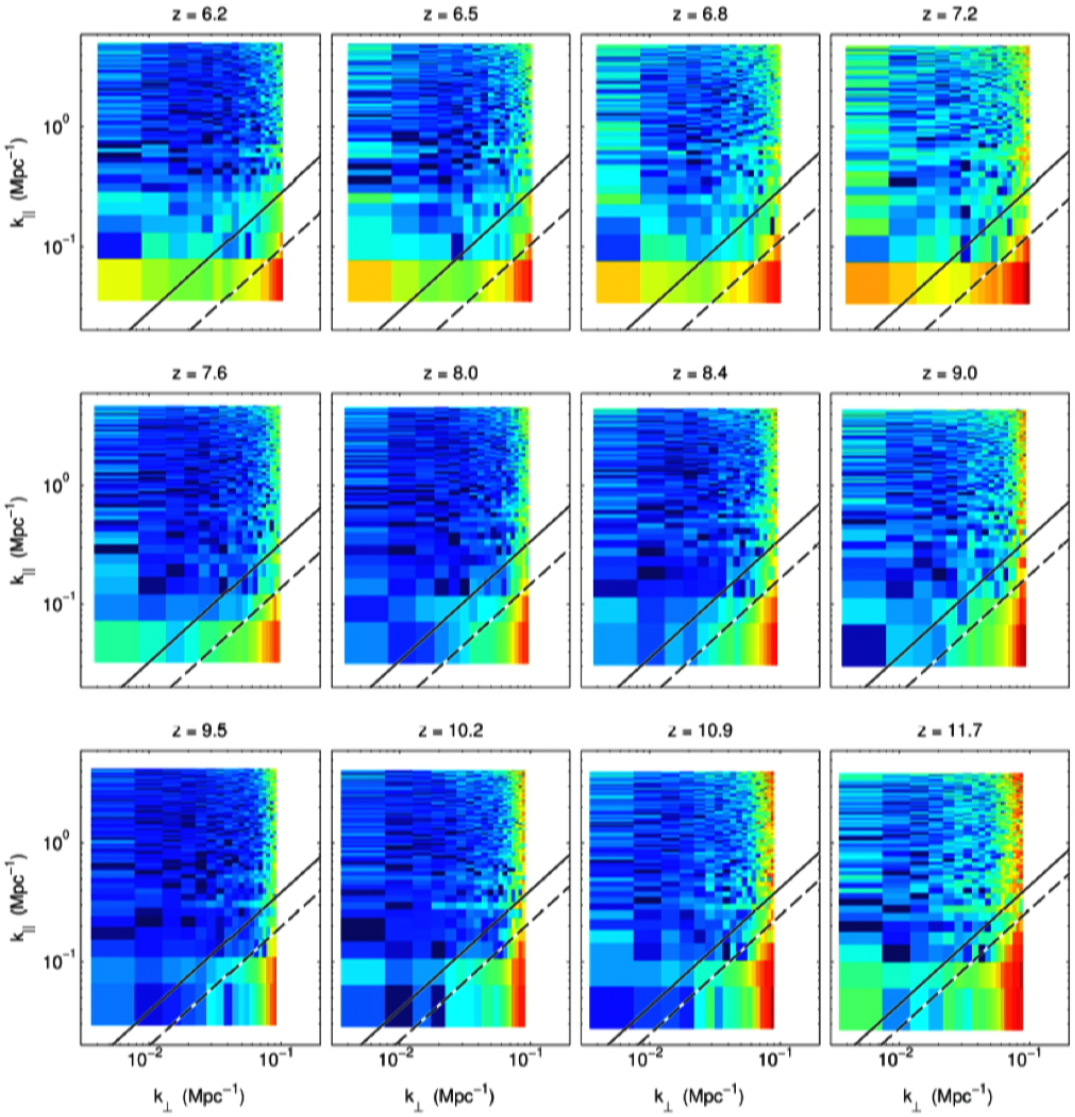
Smooth spectra

AL et al. 2014a,b

PAPER observations confirm the predicted "wedge" structure



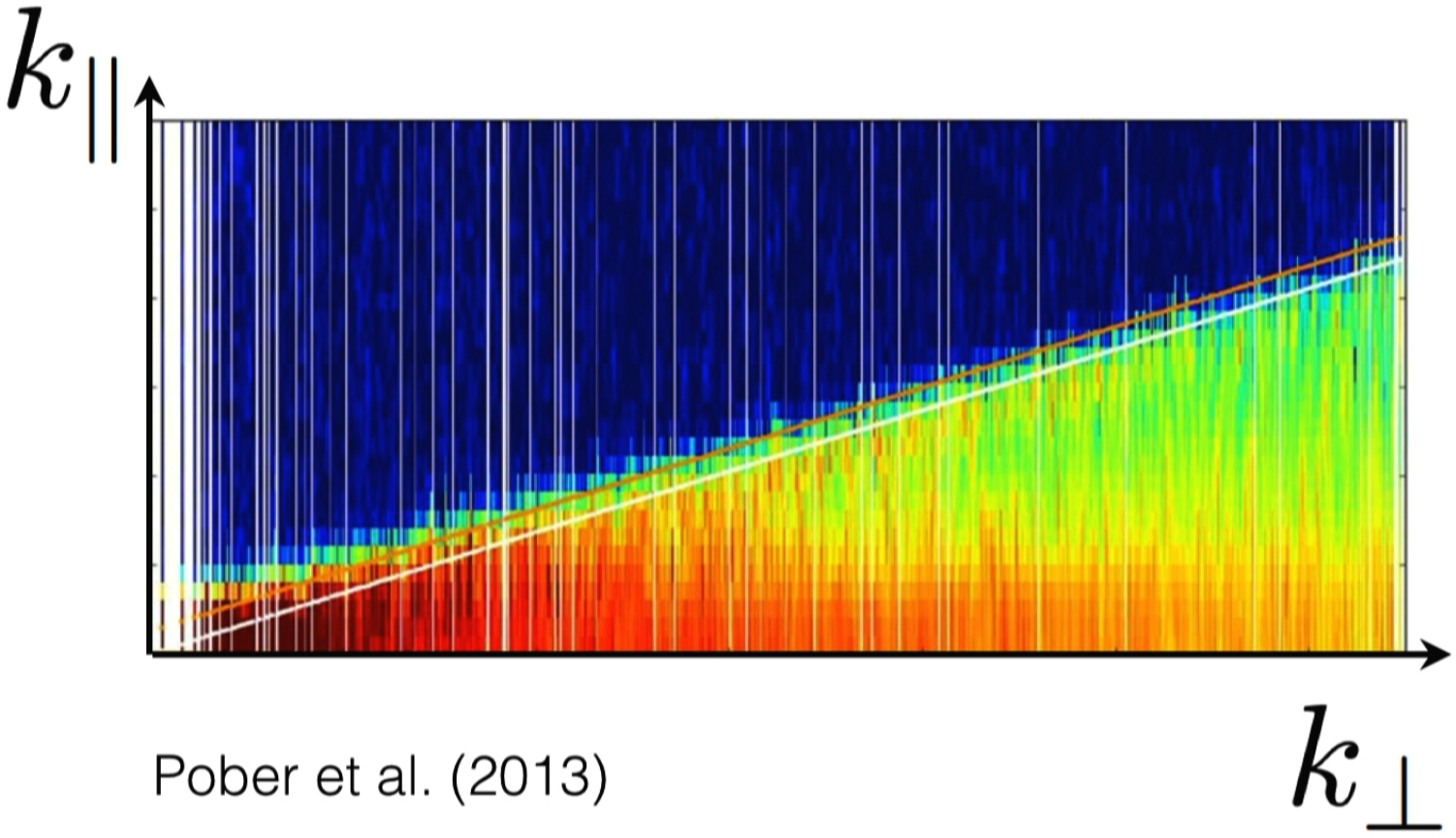
Pober et al. (2013)



Multi-frequency MWA data shows similar wedge behavior

Dillon, **AL** et al. (2014)

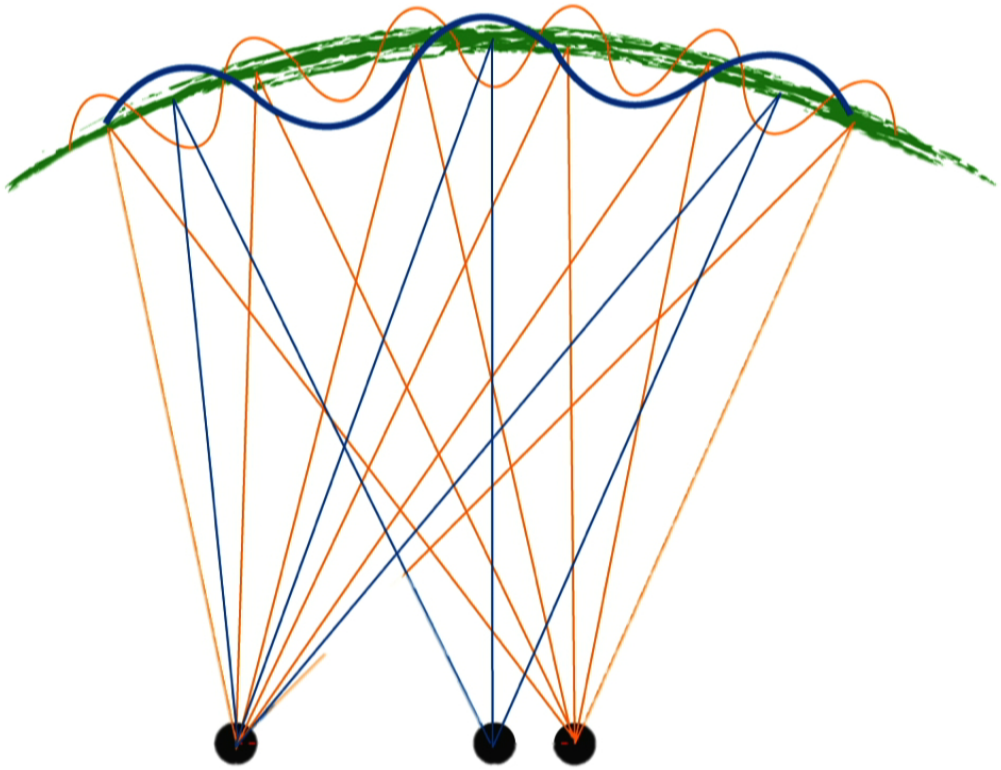
Moral of the story: avoid high $k_\perp$ if possible



Pober et al. (2013)

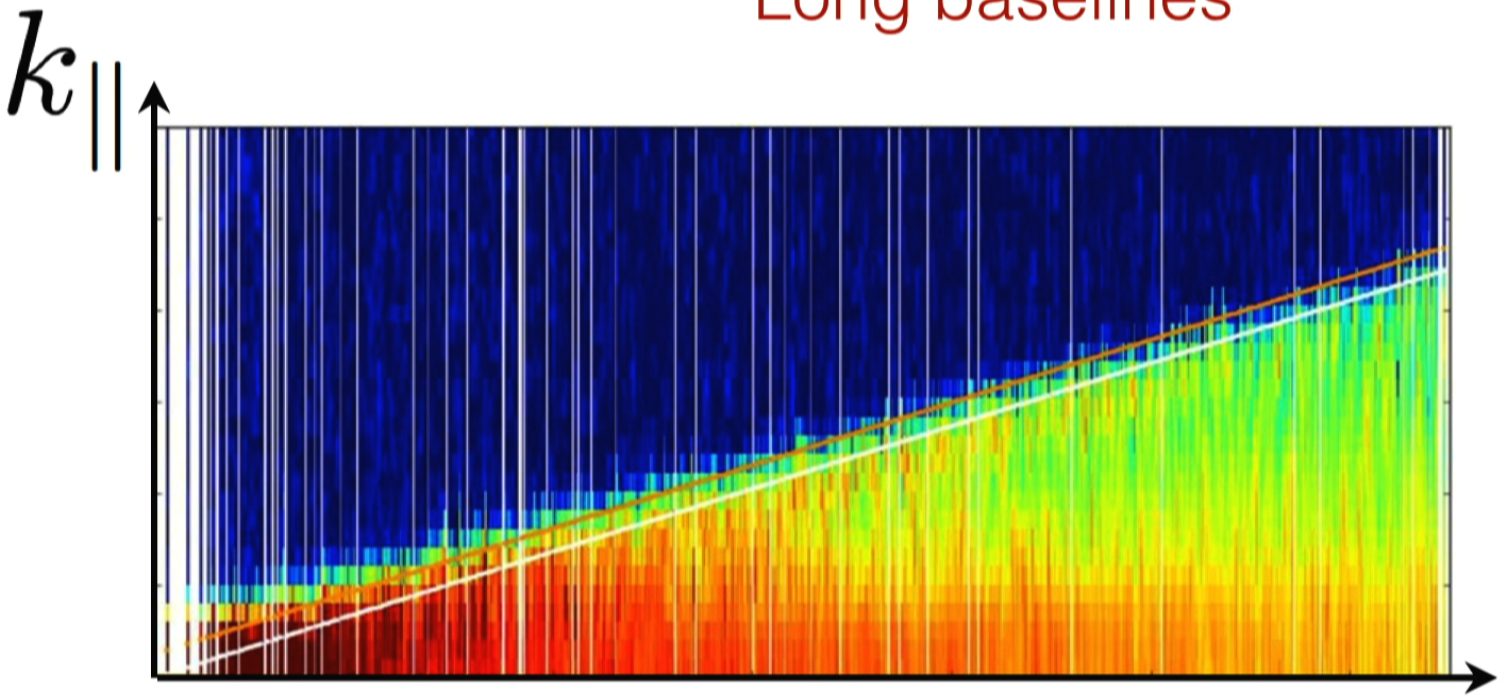
Short baselines: low $k_\perp$ modes

Long baselines: high $k_\perp$ modes

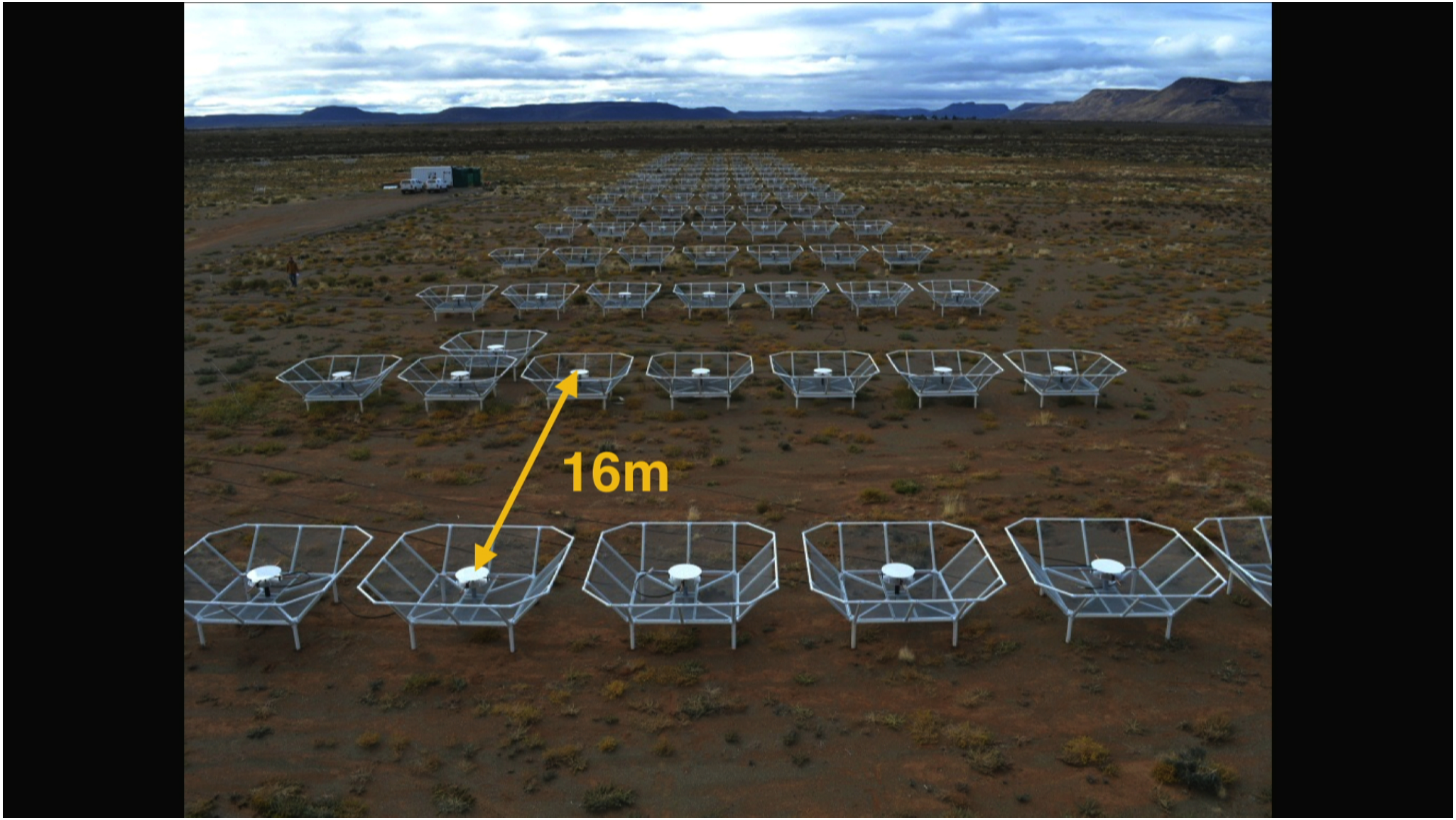


Moral of the story: avoid ~~high $k_\perp$~~ if possible

Long baselines

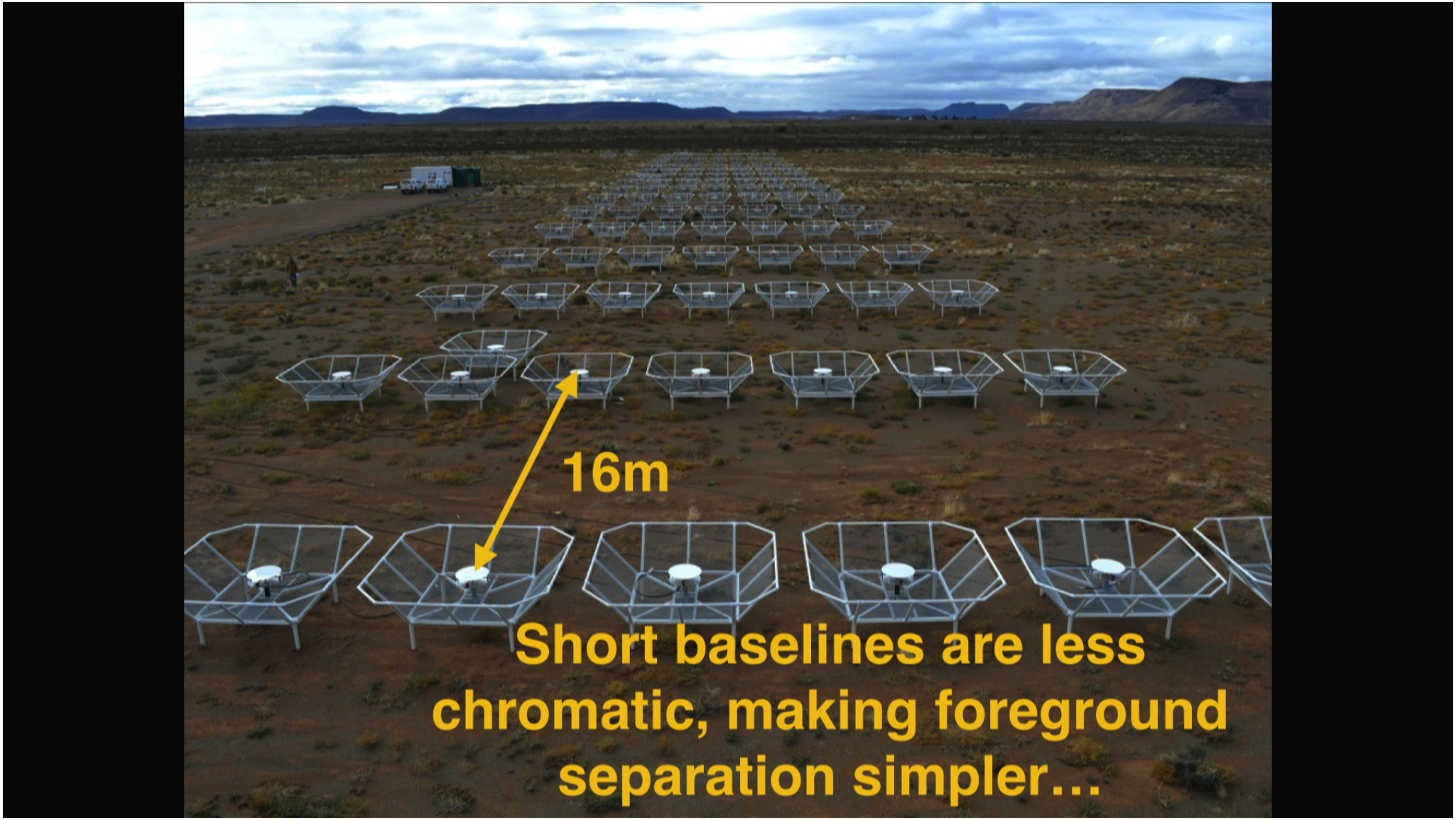


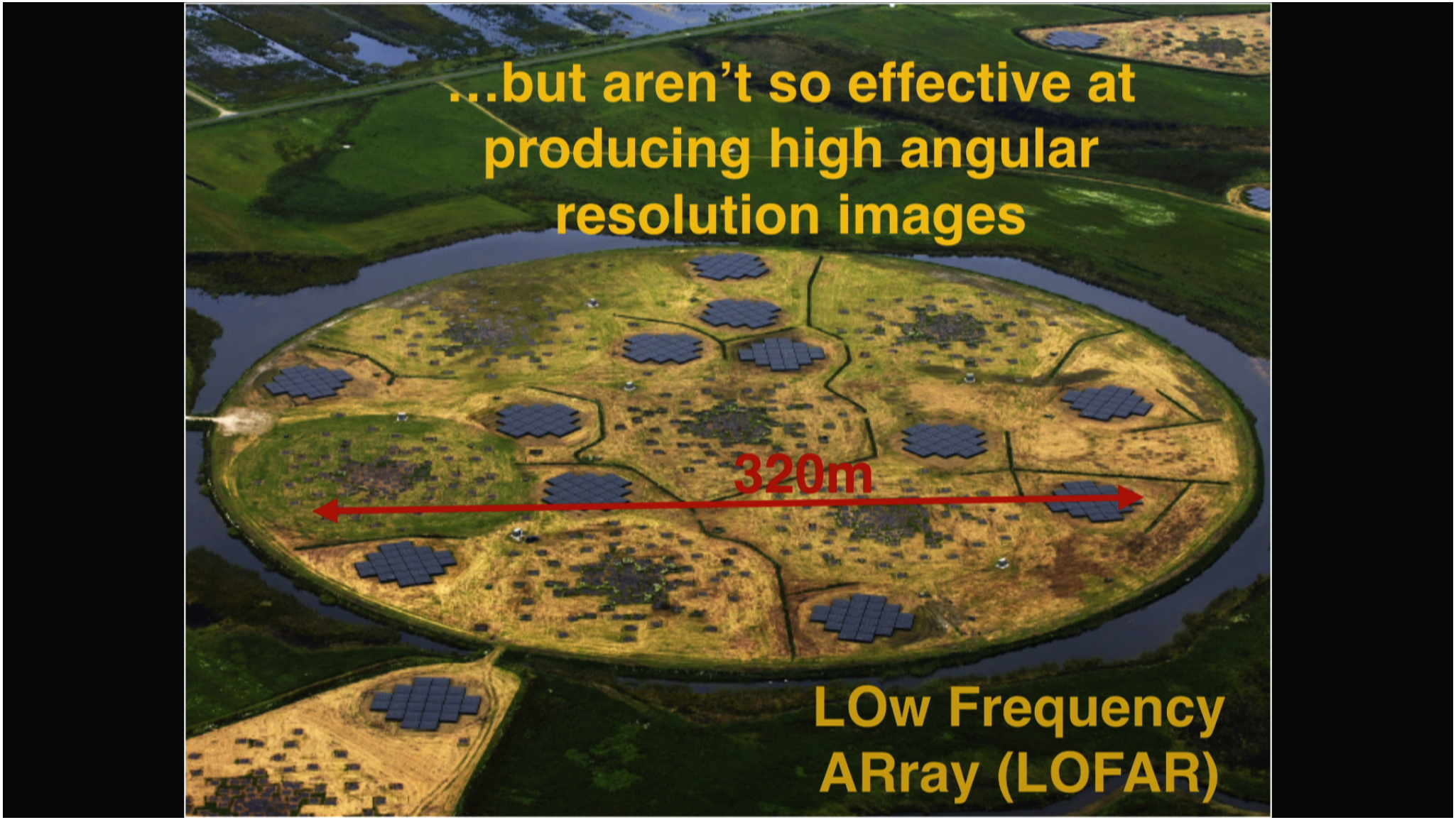
Pober et al. (2013)


16m

Long baselines are inherently more chromatic than short ones

$$\int T(\theta) \exp\left(-i \frac{2\pi\, b\, \nu\, \theta}{c}\right) d\theta$$


16m
Short baselines are less chromatic, making foreground separation simpler…

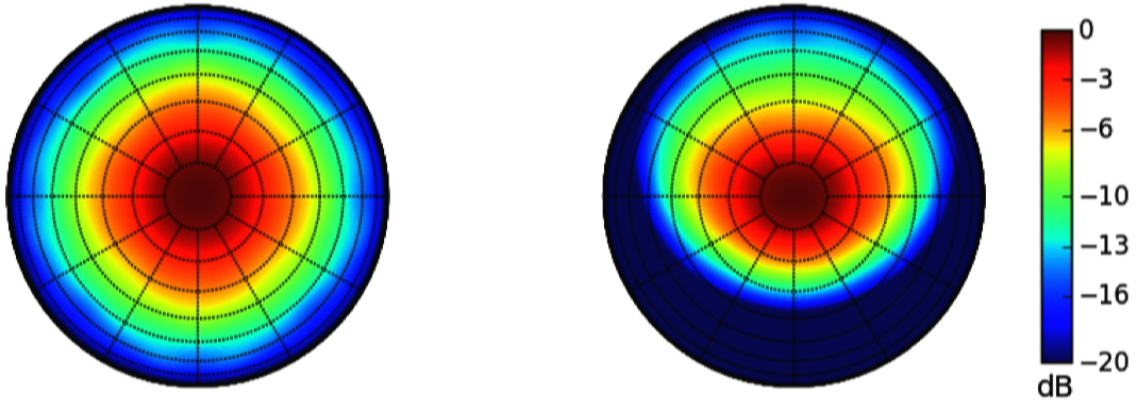

…but aren't so effective at producing high angular resolution images
320m
LOw Frequency ARray (LOFAR)

Short baselines sacrifice angular information, but some of this can be recovered in data analysis

Parsons, **AL** et al. (2015)

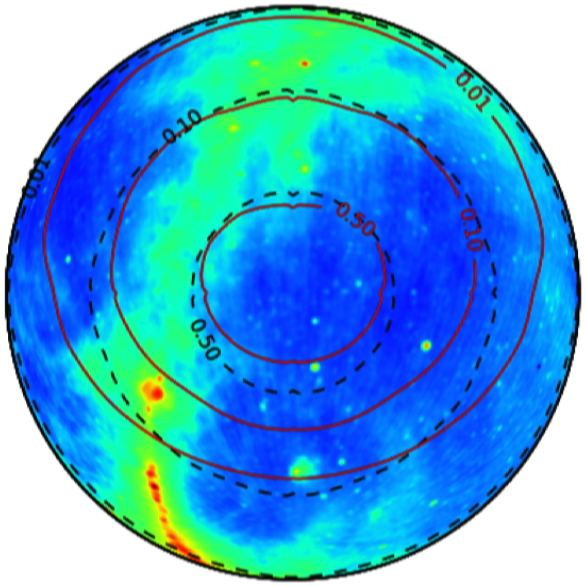
Parsons, **AL** et al. (2015)

A careful weighting of fringe-rates allows different parts of the sky to be isolated



Parsons, **AL** et al. (2015)

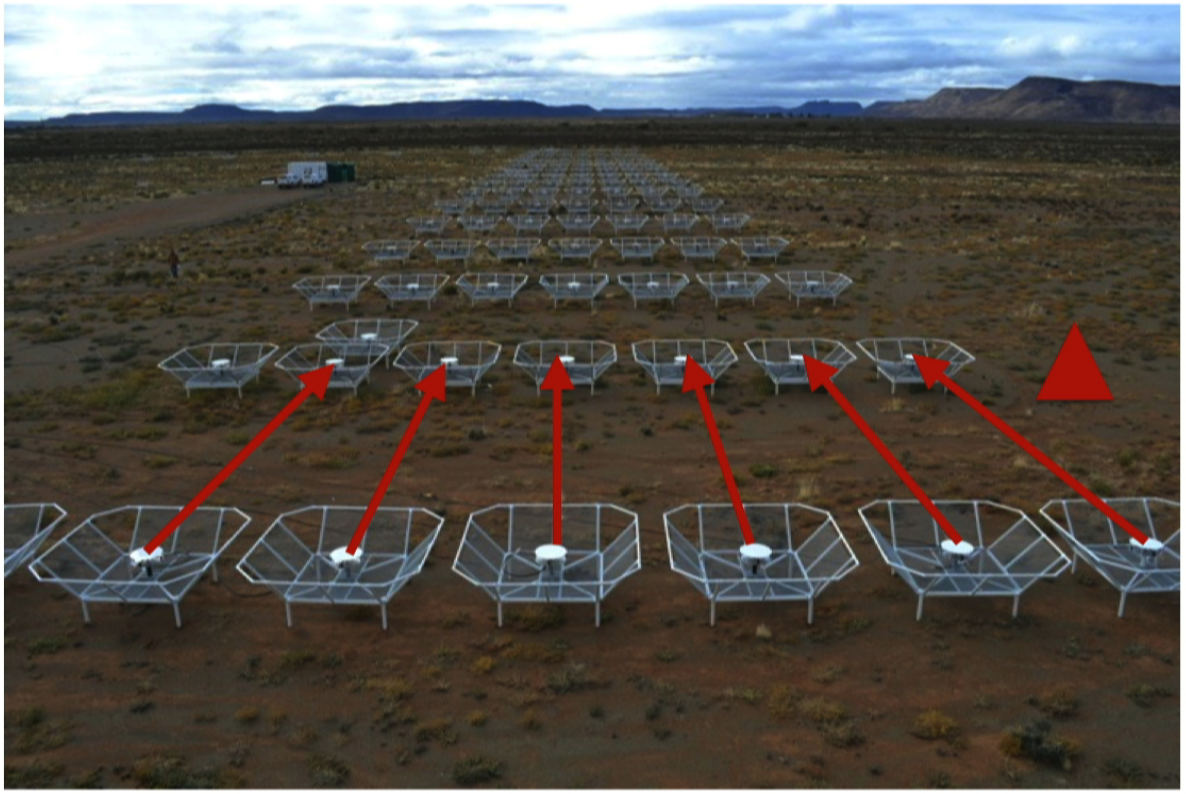
Foreground systematics can be further mitigated by beam-sculpting



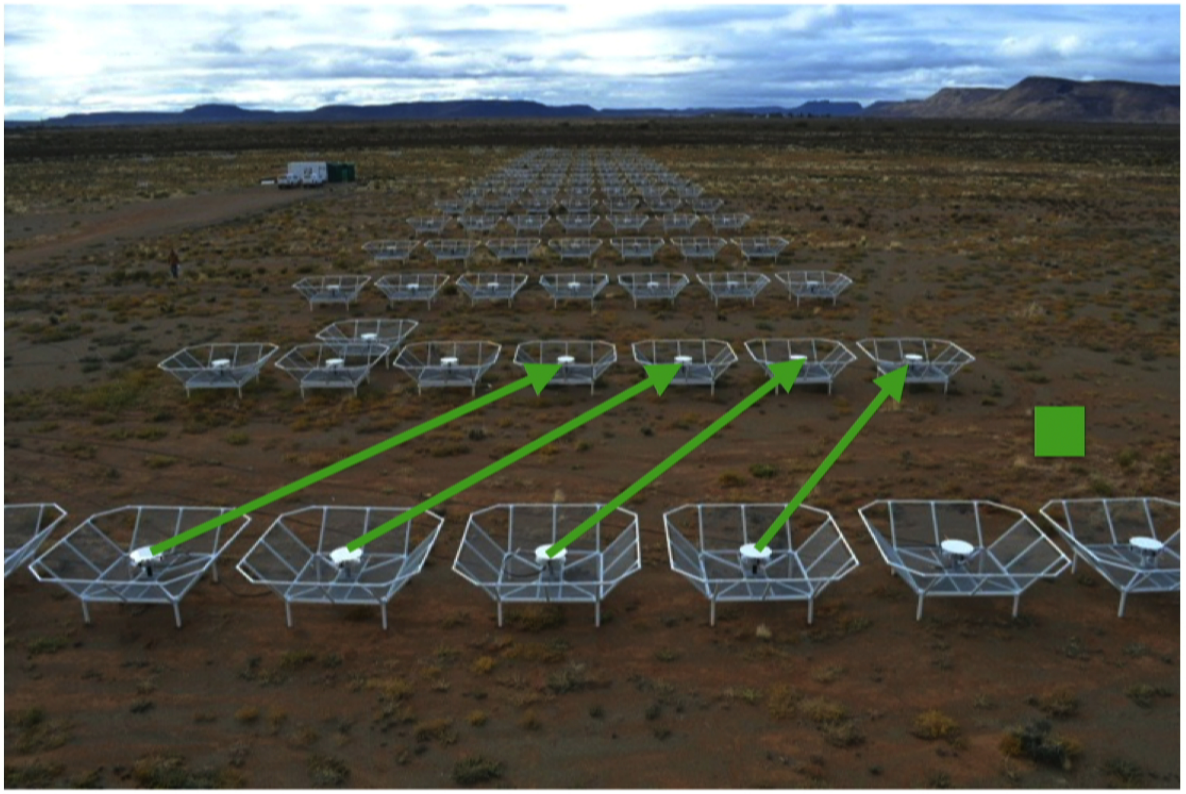
Parsons, **AL** et al. (2015)

Short, repeated baselines enable sky-independent calibration

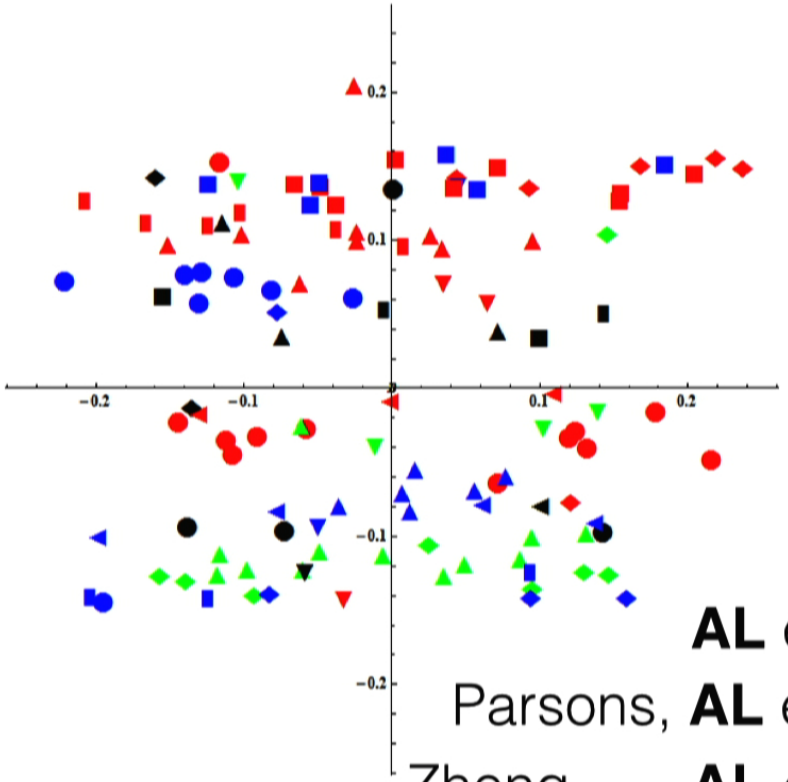
Short, repeated baselines enable sky-independent calibration



Short, repeated baselines enable sky-independent calibration



$$\int T(\theta) \exp\left(-i \frac{2\pi\, b\, \nu\, \theta}{c}\right) d\theta$$

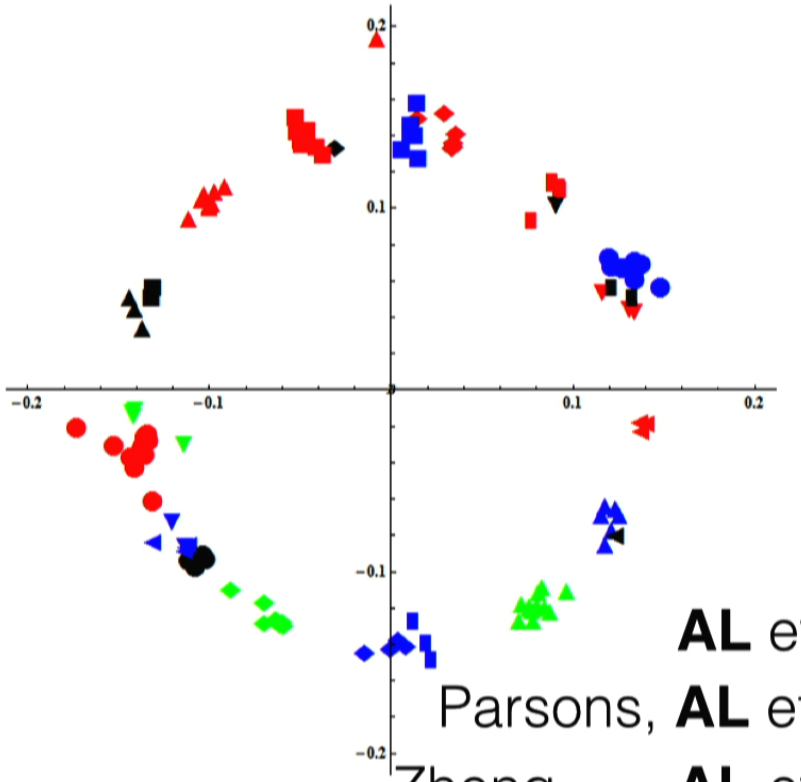


AL et al. (2010)

Parsons, **AL** et al. (2014)

Zheng, …, **AL** et al. (2014)

Demanding consistently redundant solutions allows sky-independent calibration



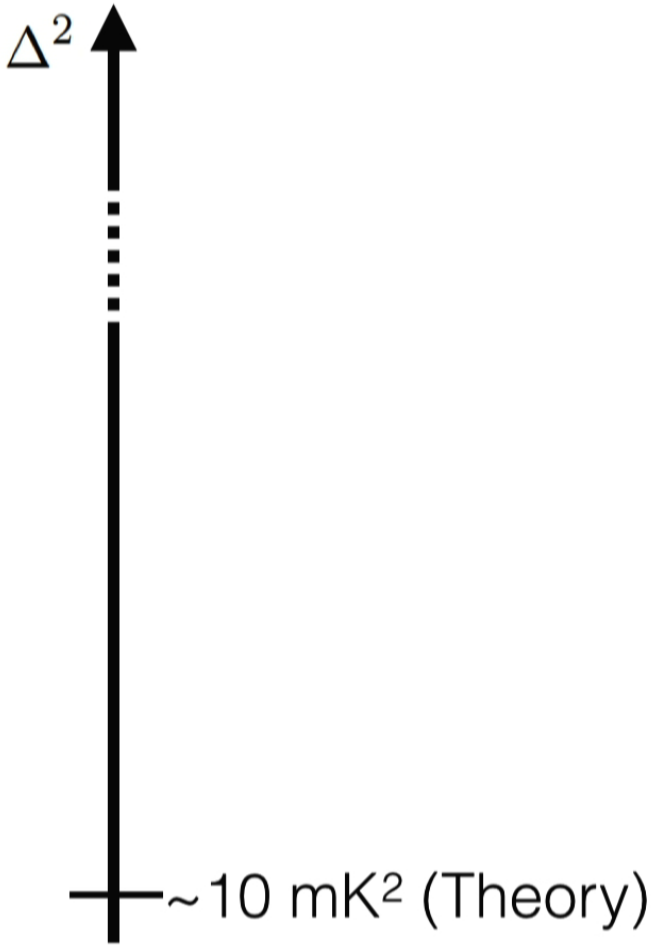
AL et al. (2010)

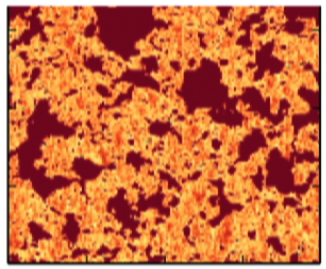
Parsons, **AL** et al. (2014)

Zheng, …, **AL** et al. (2014)

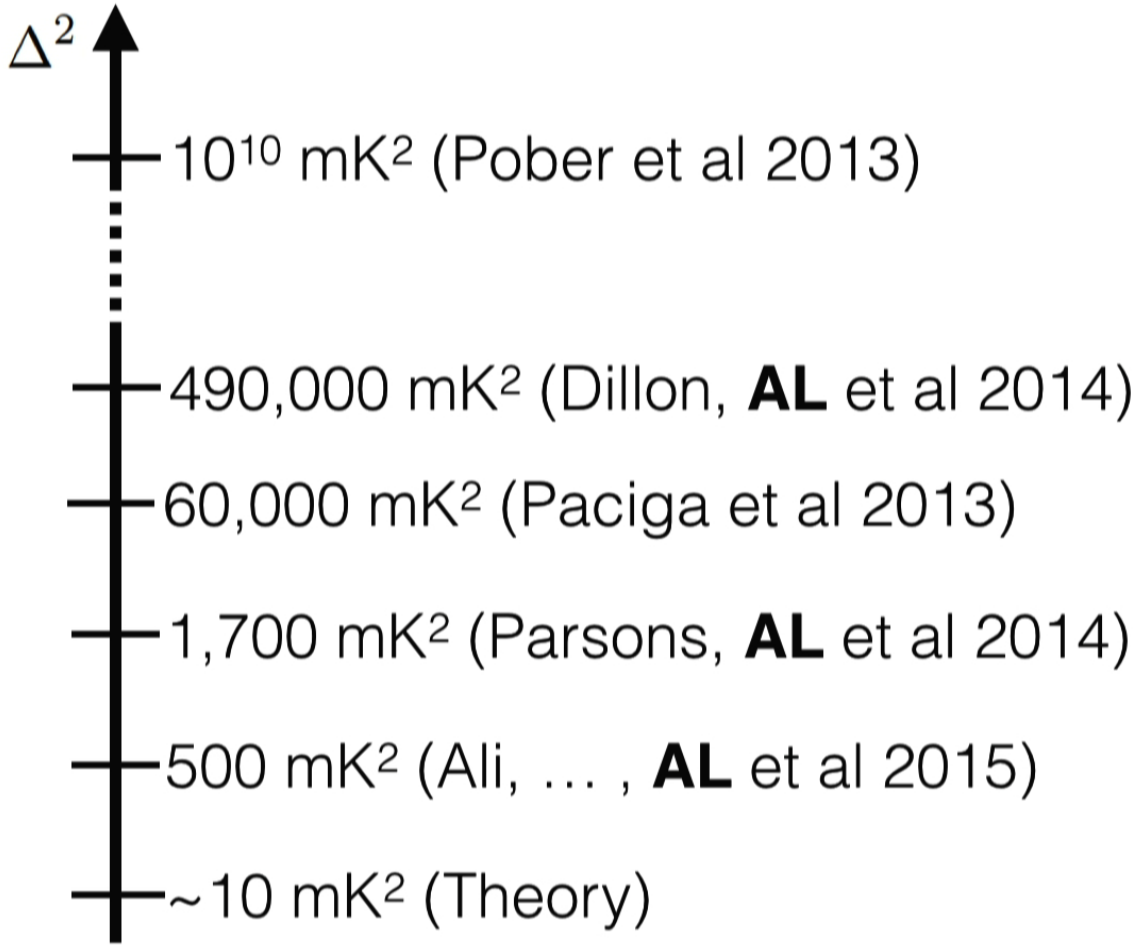
PAPER: state-of-the-art upper limits on the power spectrum

Upper limits for 7.5 < z < 8.5

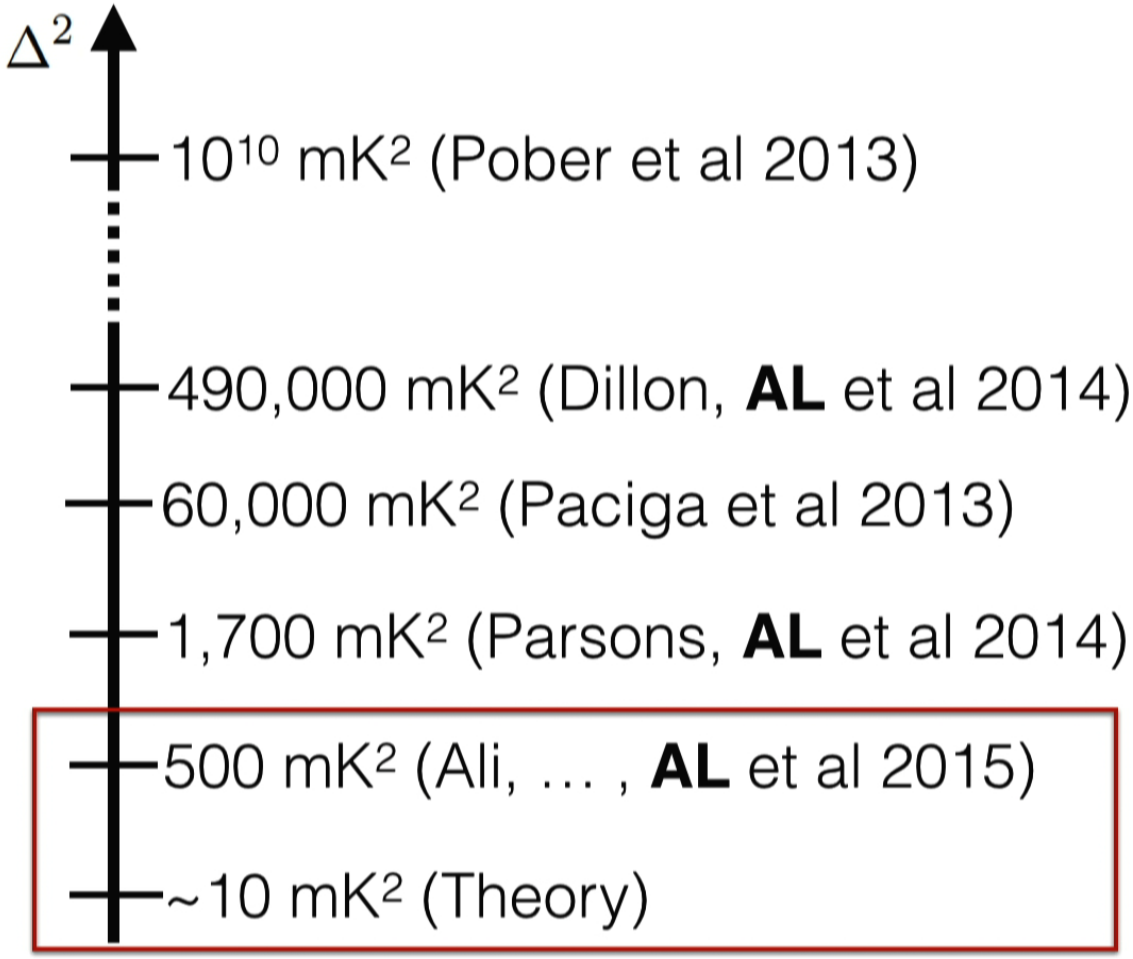




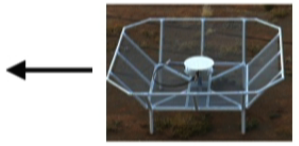
Upper limits for $7.5 < z < 8.5$



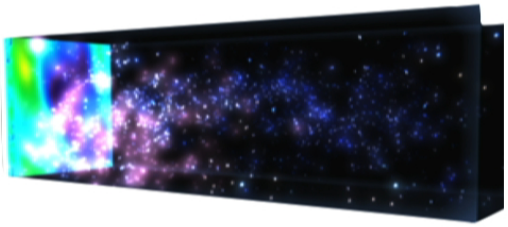
Upper limits for $7.5 < z < 8.5$



Current PAPER upper limits rule out the possibility of an extremely **cold** intergalactic medium at $z \sim 8.4$

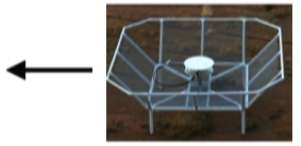


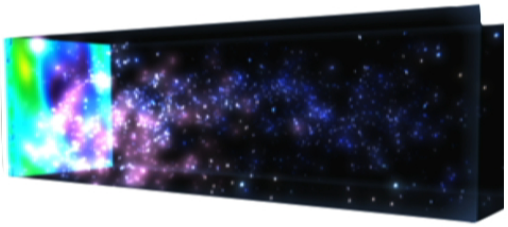
Cold hydrogen
gas



(Relatively) hot CMB

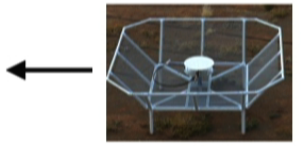
Cold hydrogen gas



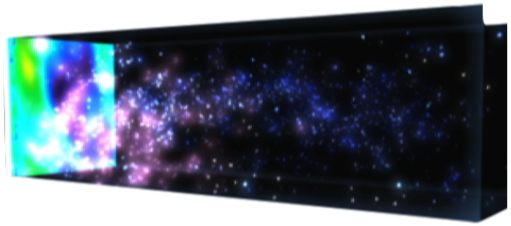


(Relatively) hot CMB

Cold hydrogen gas

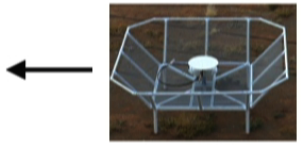


BIG contrast, large signal



(Relatively) hot CMB

Warm hydrogen gas

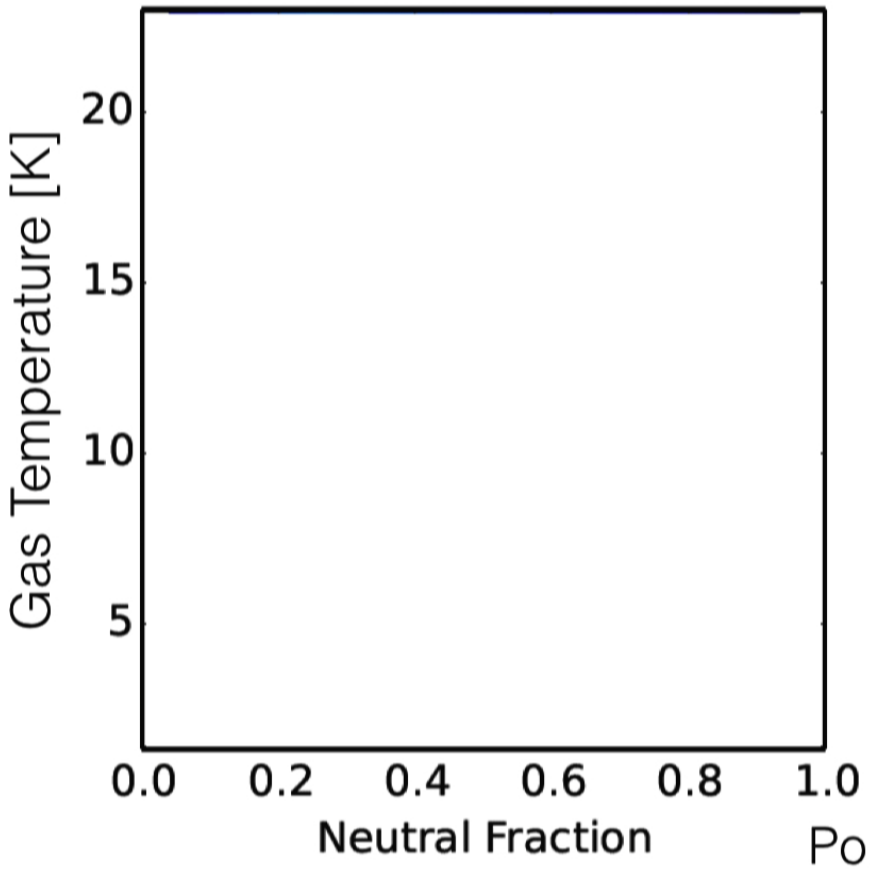


Small contrast, small signal

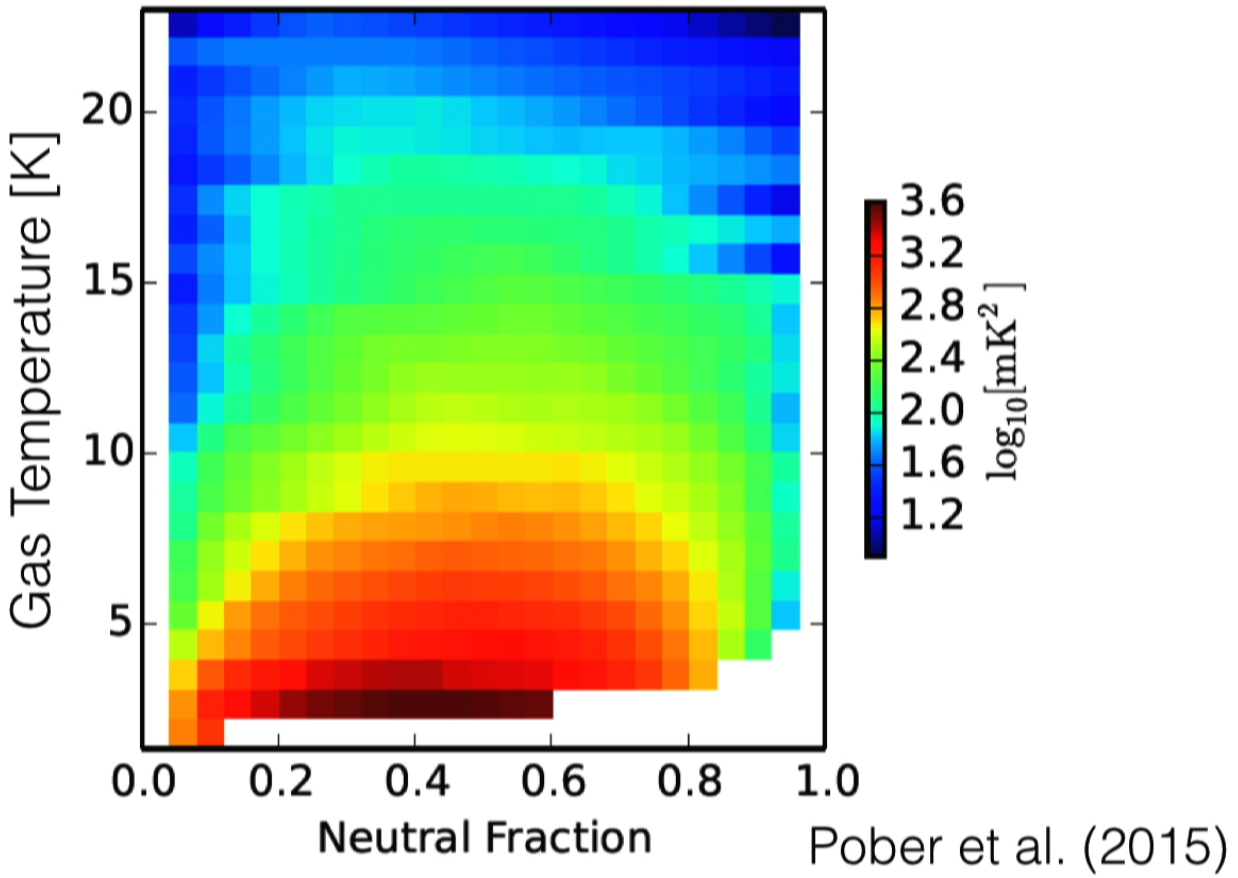
If the intergalactic medium had cooled adiabatically, the hydrogen gas would be cold enough to produce a large signal—large enough to be seen by now, with PAPER's sensitivity

If the intergalactic medium had cooled adiabatically, the hydrogen gas would be cold enough to produce a large signal—large enough to be seen by now, with PAPER's sensitivity

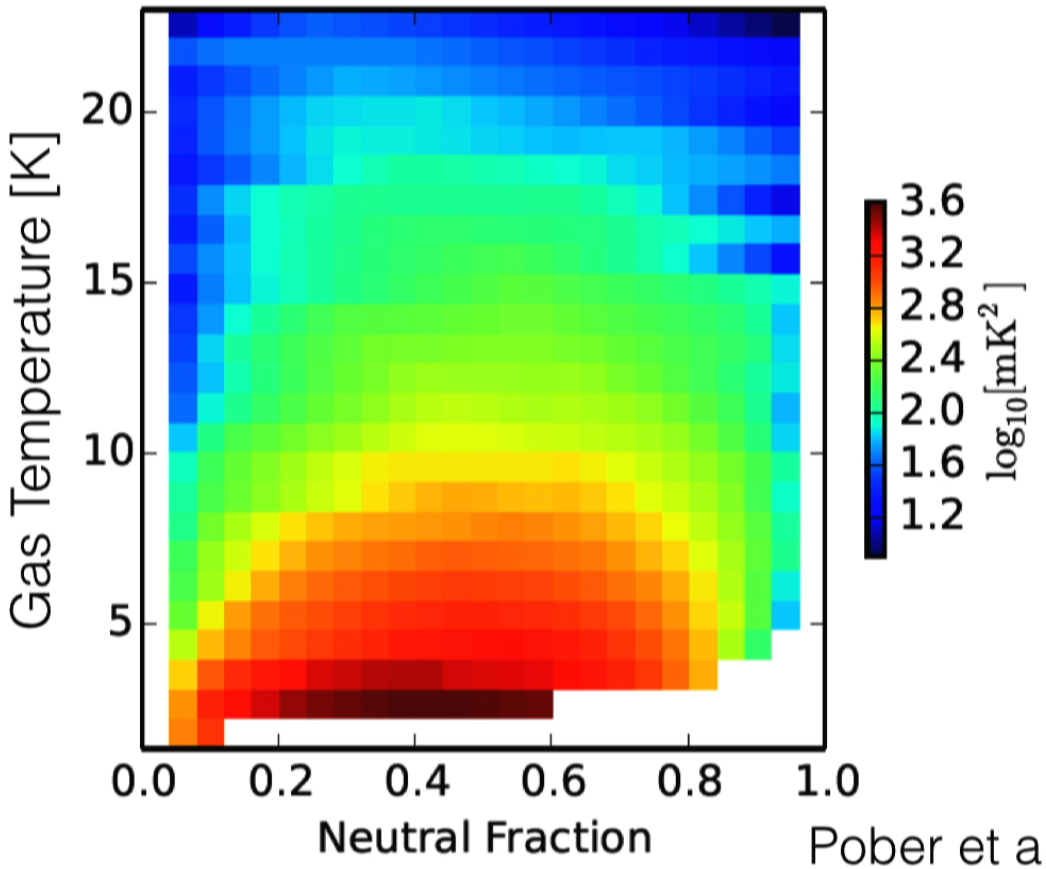
Some mechanism must have heated up the gas



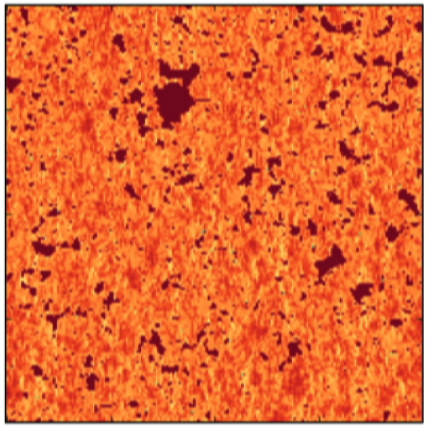
Pober et al. (2015)


Gas Temperature [K]
20
15
10
5
0.0
0.2
0.4
0.6
0.8
1.0
Neutral Fraction
3.6
3.2
2.8
2.4
2.0
1.6
1.2
$\log_{10}[\mathrm{mK}^2]$
Pober et al. (2015)

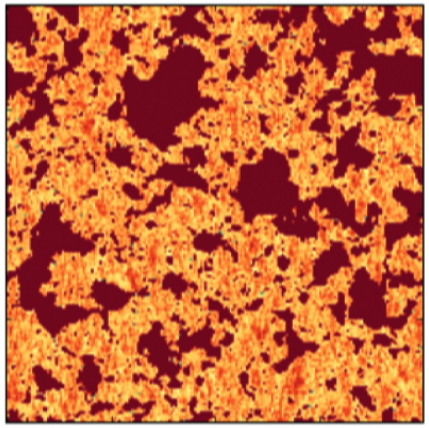
Extreme neutral fractions give dimmer 21cm power spectra



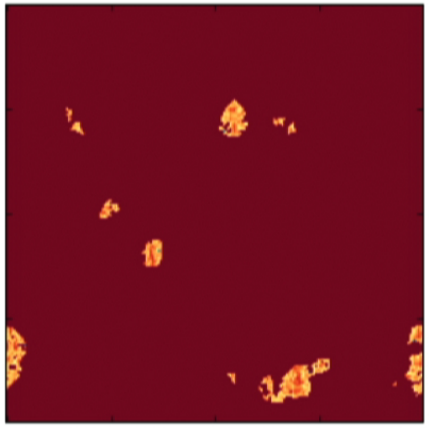
Pober et al. (2015)



Beginning of reionization



Middle of reionization



End of reionization

For neutral fractions between 30% and 70%, PAPER observations imply $T_{gas} > 10$ K

In contrast, $T_{gas} = 1.18$ K assuming adiabatic cooling

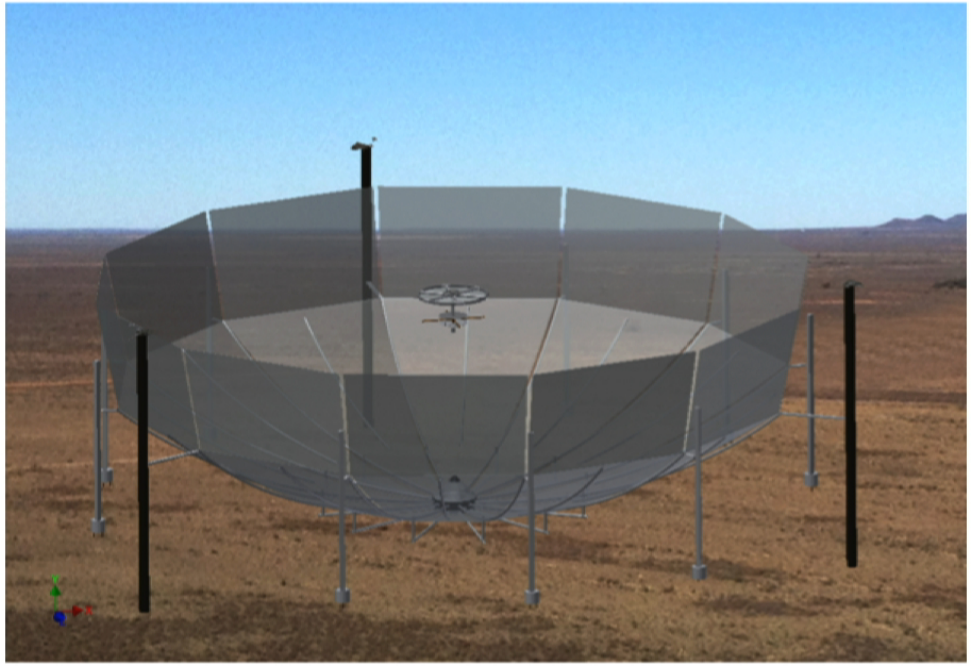
Thus, some sort of reheating must've taken place

Pober, Ali, …, **AL** et al. 2015, ApJ 809, 62

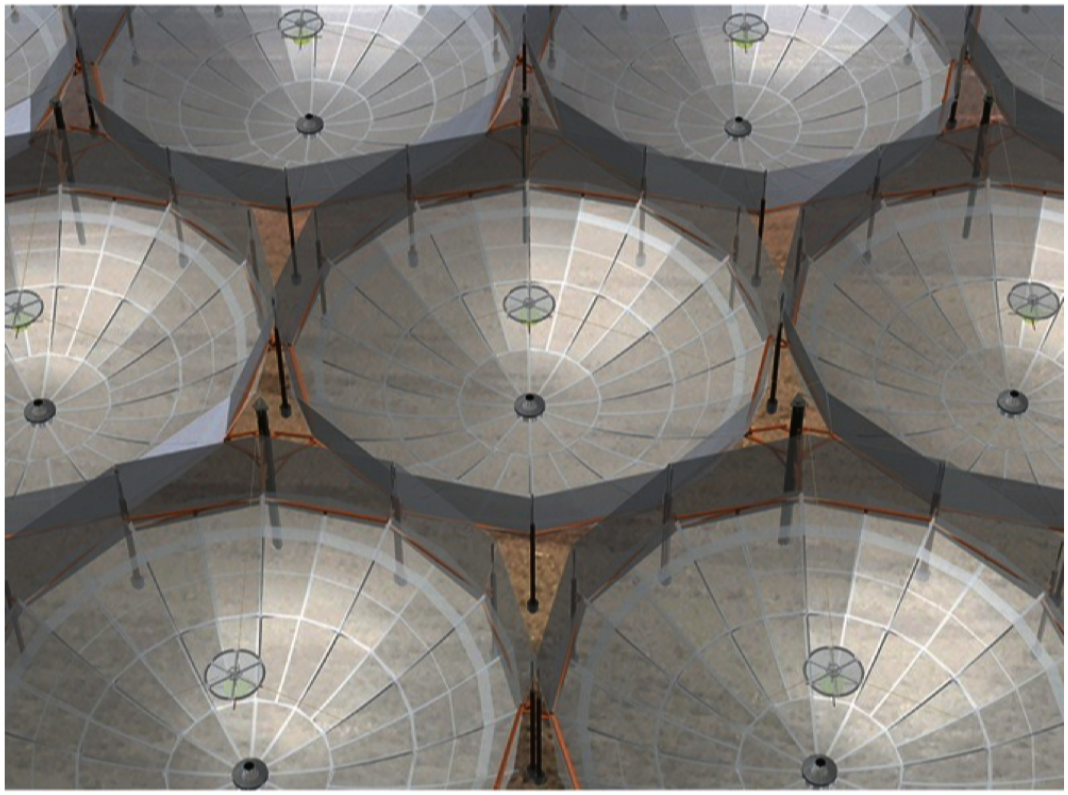
What’s next?

Take a PAPER dipole…

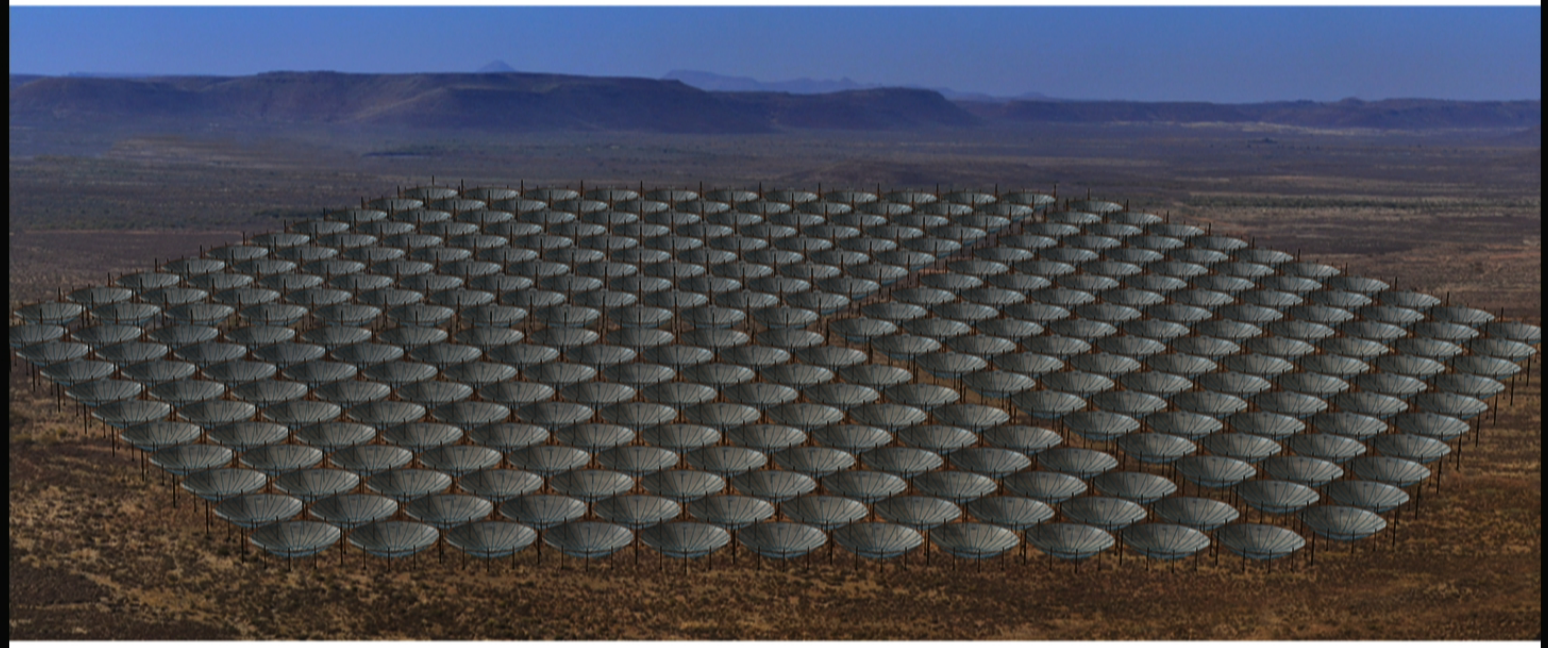
…flip it upside down and give it a large (14 m diameter) reflector…



…hex-pack them as closely as possible…



…get the Hydrogen Epoch of Reionization Array (HERA)

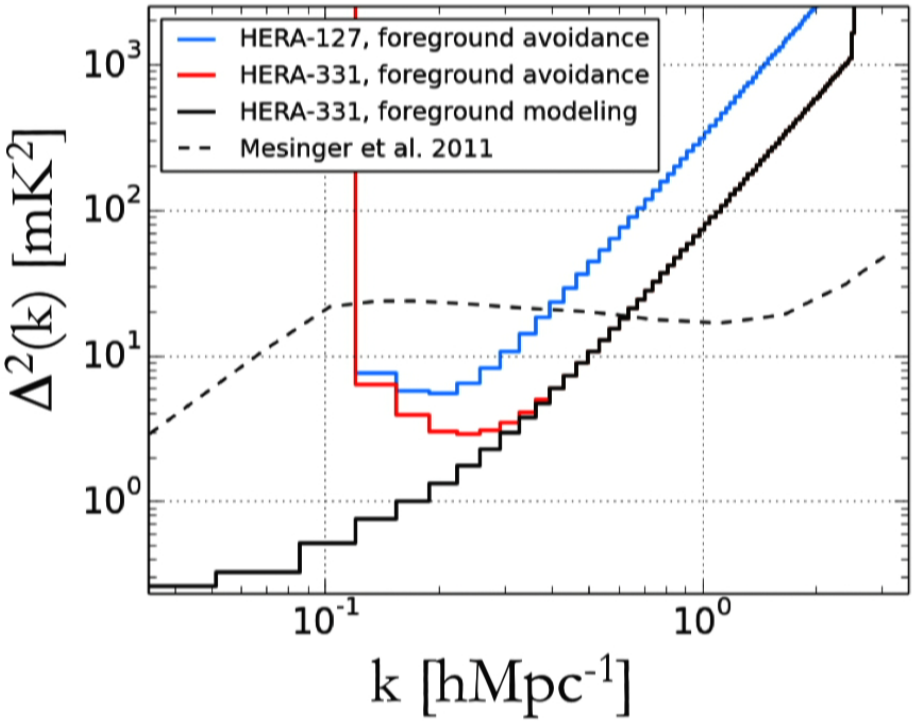


154 m


THE UNIVERSITY OF CALIFORNIA
UCLA
LET THERE BE LIGHT
UNIVERSITY OF WASHINGTON
1861
LVX SIT
THE UNIVERSITY OF CALIFORNIA BERKELEY
1868
LET THERE BE LIGHT
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ARIZONA STATE UNIVERSITY
1885
DITAT DEUS
Penn
UNIVERSITY of PENNSYLVANIA
UNIVERSITY OF CAMBRIDGE
SCUOLA NORMALE SUPERIORE
H1ERA
UNIVERSITY of the WESTERN CAPE
RESPICE PROSPICE
UNIVERSITY OF KWAZULU-NATAL
CAL POLY POMONA
VE RI TAS
HARVARD
BROWN
NRAO
SKA
SKA AFRICA
SQUARE KILOMETRE ARRAY

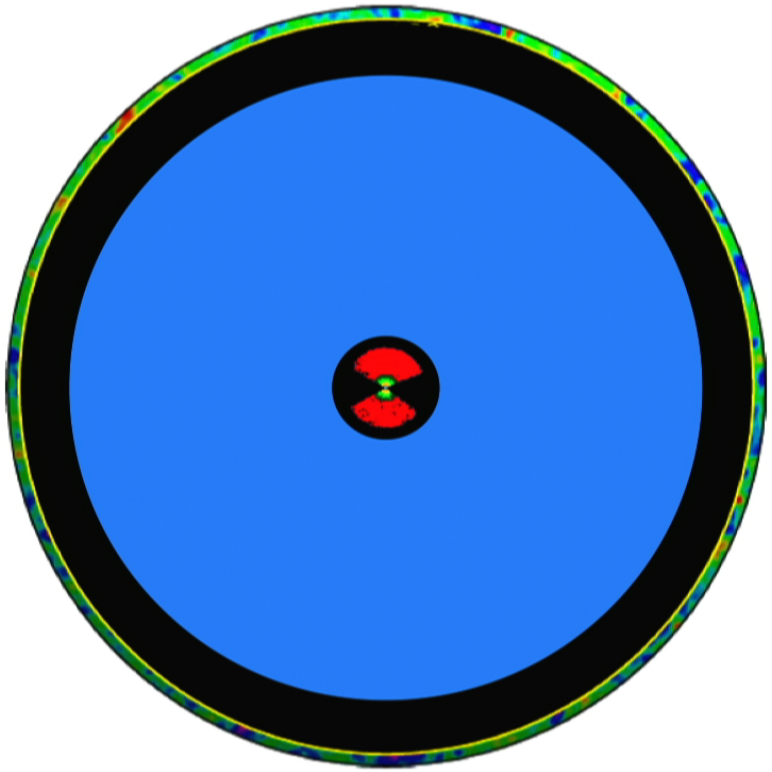
HERA will make a high significance measurement

- Current generation instruments: marginal detection.
- HERA: high significance measurement.



Cosmology with HERA

Futuristic 21cm experiments may function as large scale surveys



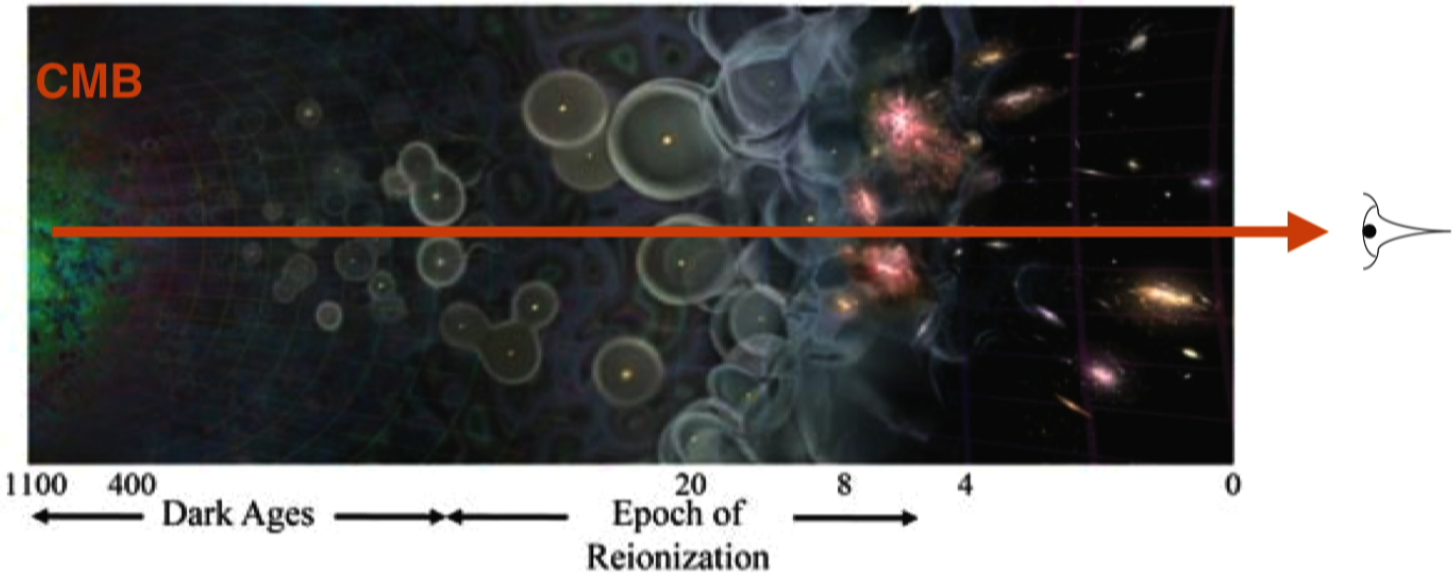
$$\Delta\Omega_k = 0.0002$$

$$\Delta\left(\sum m_\nu\right) = 0.007\mathrm{eV}$$

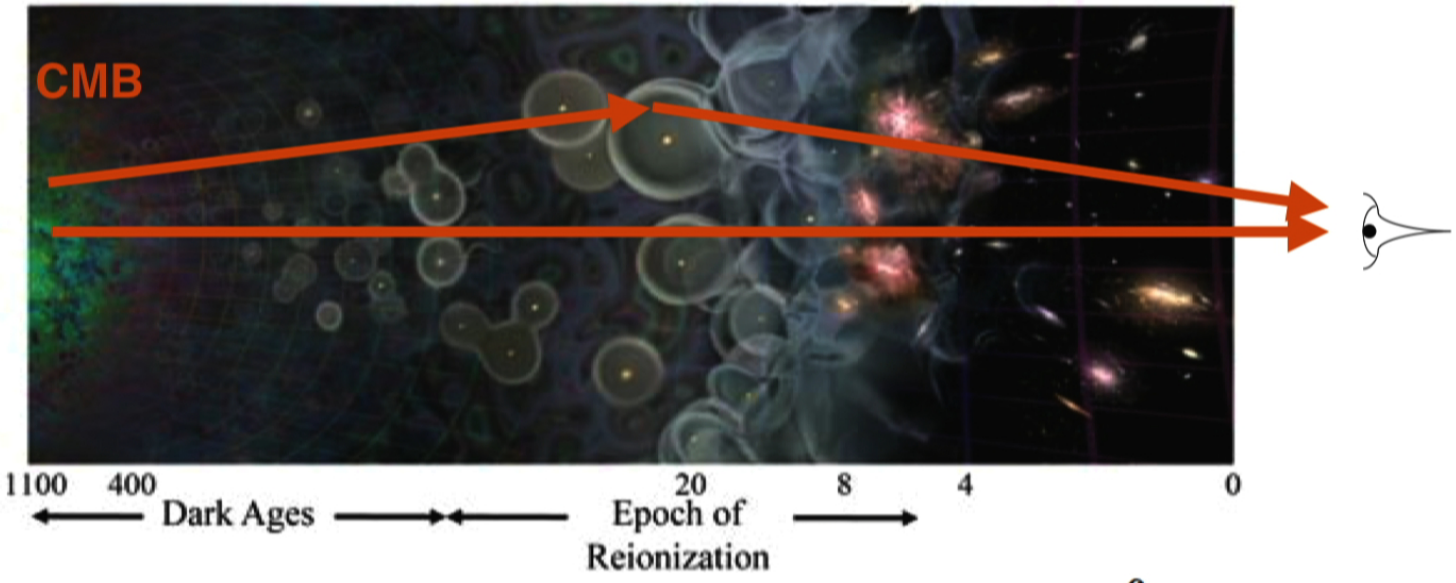
Mao et al. 2008

For now…better cosmology through better astrophysics!

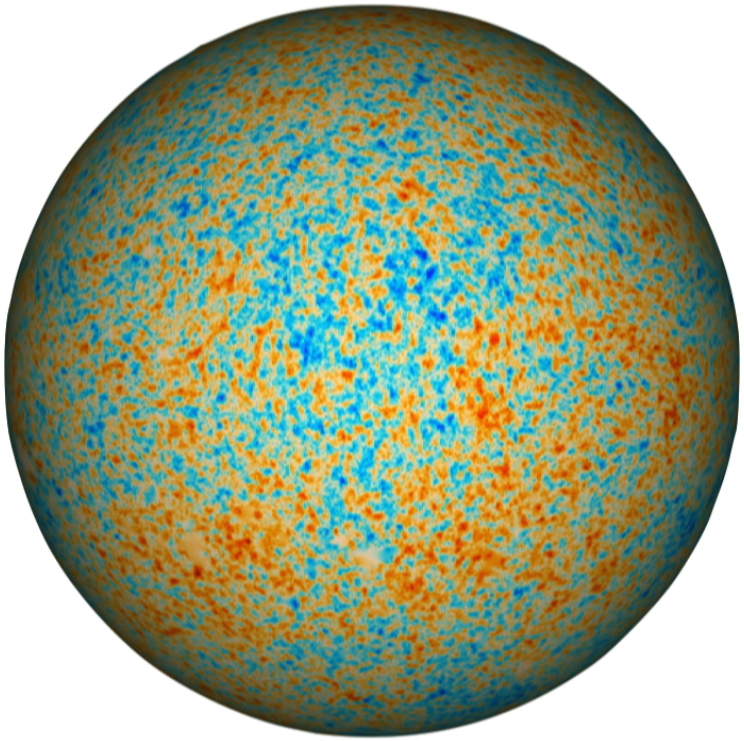
Reionization is a nuisance for CMB measurements



Reionization is a nuisance for CMB measurements



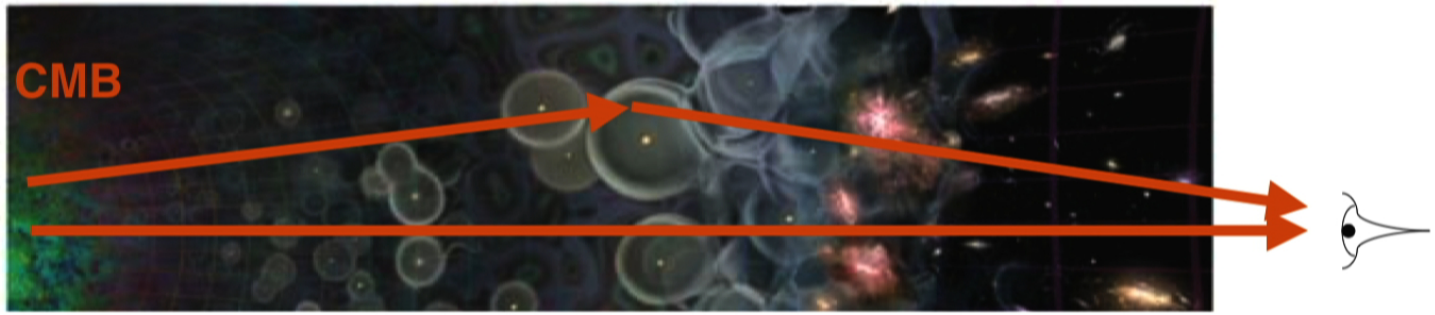
Extra optical depth parameter: $\tau \propto \int \langle x_i \rho_b \rangle dz$



- Early reionization (higher optical depth)
  + Large primordial fluctuations A_s

VS

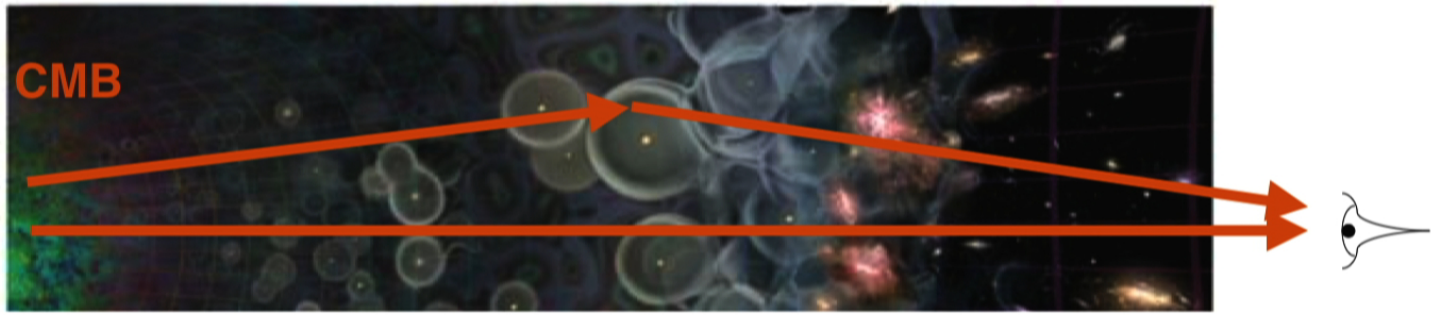
- Late reionization (lower optical depth)
  + Small primordial fluctuations A_s



- Early reionization (higher optical depth)
  + Large primordial fluctuations A_s

VS

- Late reionization (lower optical depth)
  + Small primordial fluctuations A_s



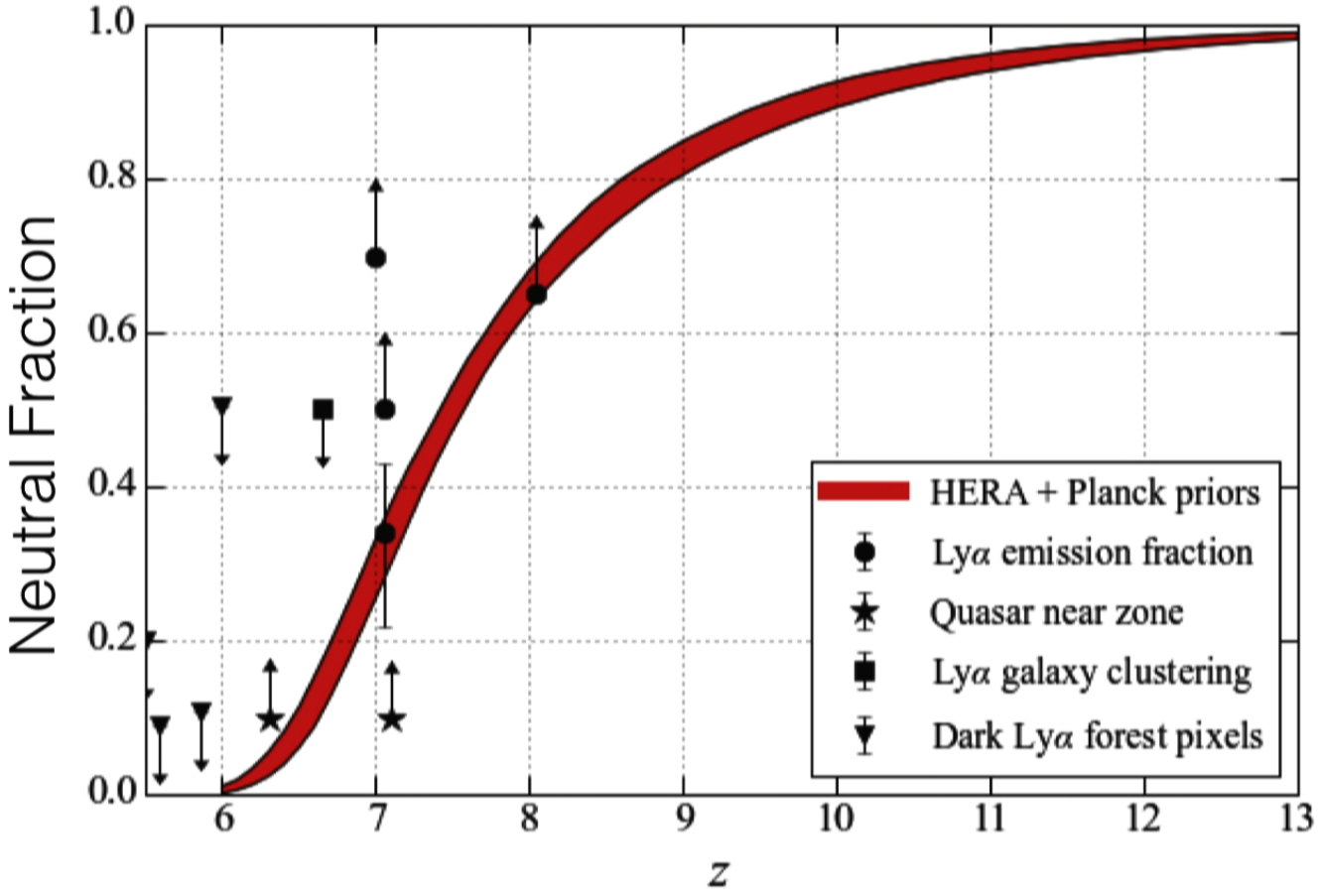
- Early reionization (higher optical depth)
  + Large primordial fluctuations A_s

VS

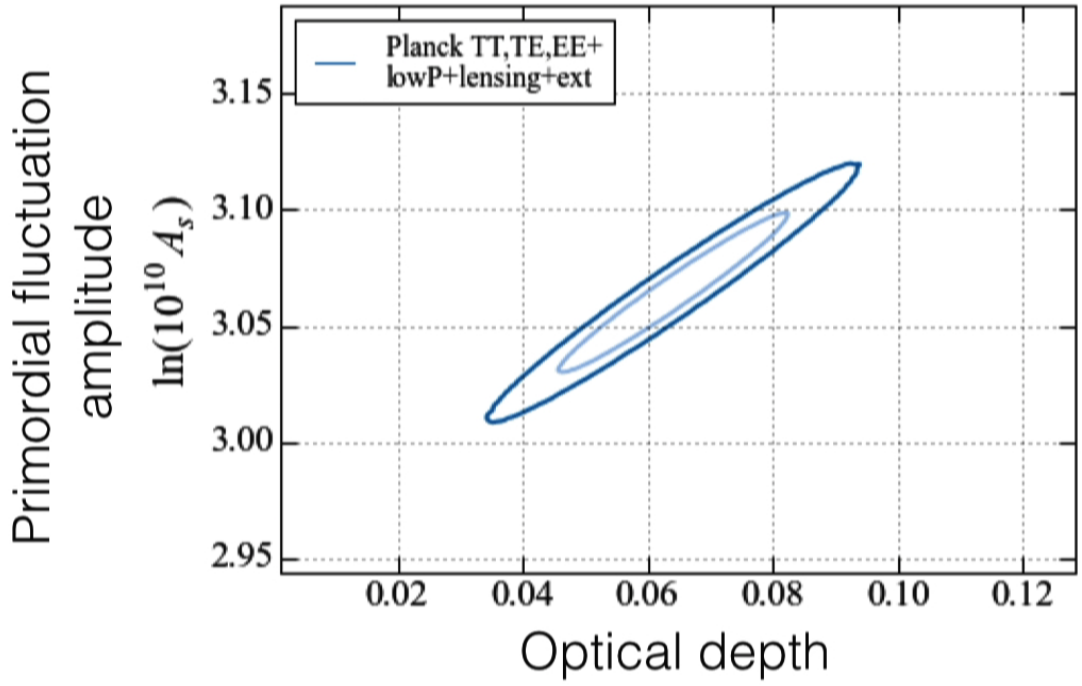
- Late reionization (lower optical depth)
  + Small primordial fluctuations A_s

Understanding reionization (especially the CMB optical depth) can improve constraints on other cosmological parameters

HERA provides us with exactly what we need

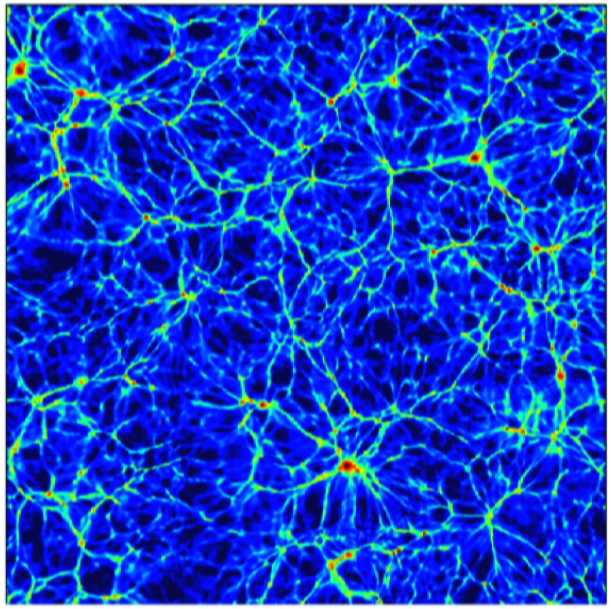


21cm information breaks the degeneracy between the amplitude of fluctuations and the optical depth



Futuristic cosmology experiments targeting the neutrino mass also benefit

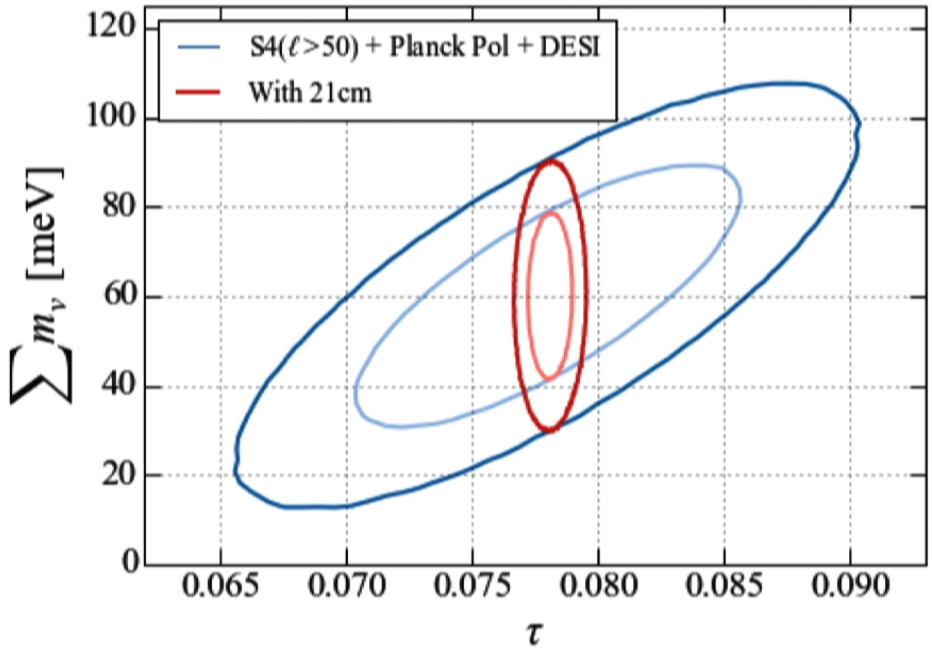
- Neutrinos free-stream out of over-densities and dampen structure formation



Without neutrinos

Agarwal & Feldman 2011

Both the neutrino mass and the optical depth can affect the observed amount of small scale structure, leading to degeneracies



Allison et al. (2015)

AL et al. (2015a)

$$\sum m_\nu = 60 \pm 19\,\mathrm{meV} \longrightarrow \pm 12\,\mathrm{meV}$$

Exciting times are ahead!

- We're getting close to detecting the 21cm signal—close enough to start improving our understanding of reionization.
- 21cm cosmology is an unconventional application of radio astronomy, requiring unconventional experimental setups.
- The HERA experiment is being built now, and promises to deliver qualitatively new constraints on astrophysics and cosmology.