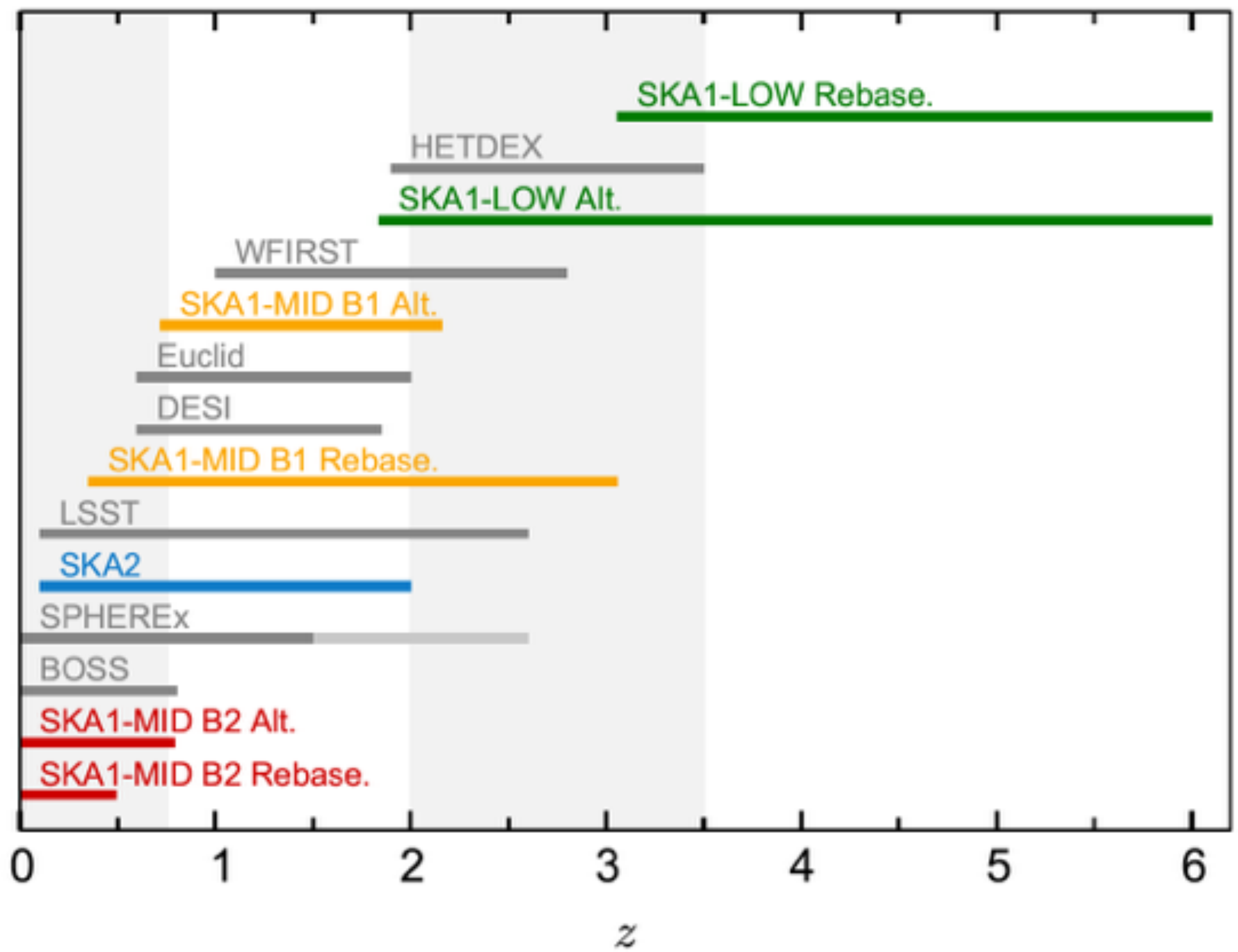
The Promise and Challenges of 21cm Cosmology

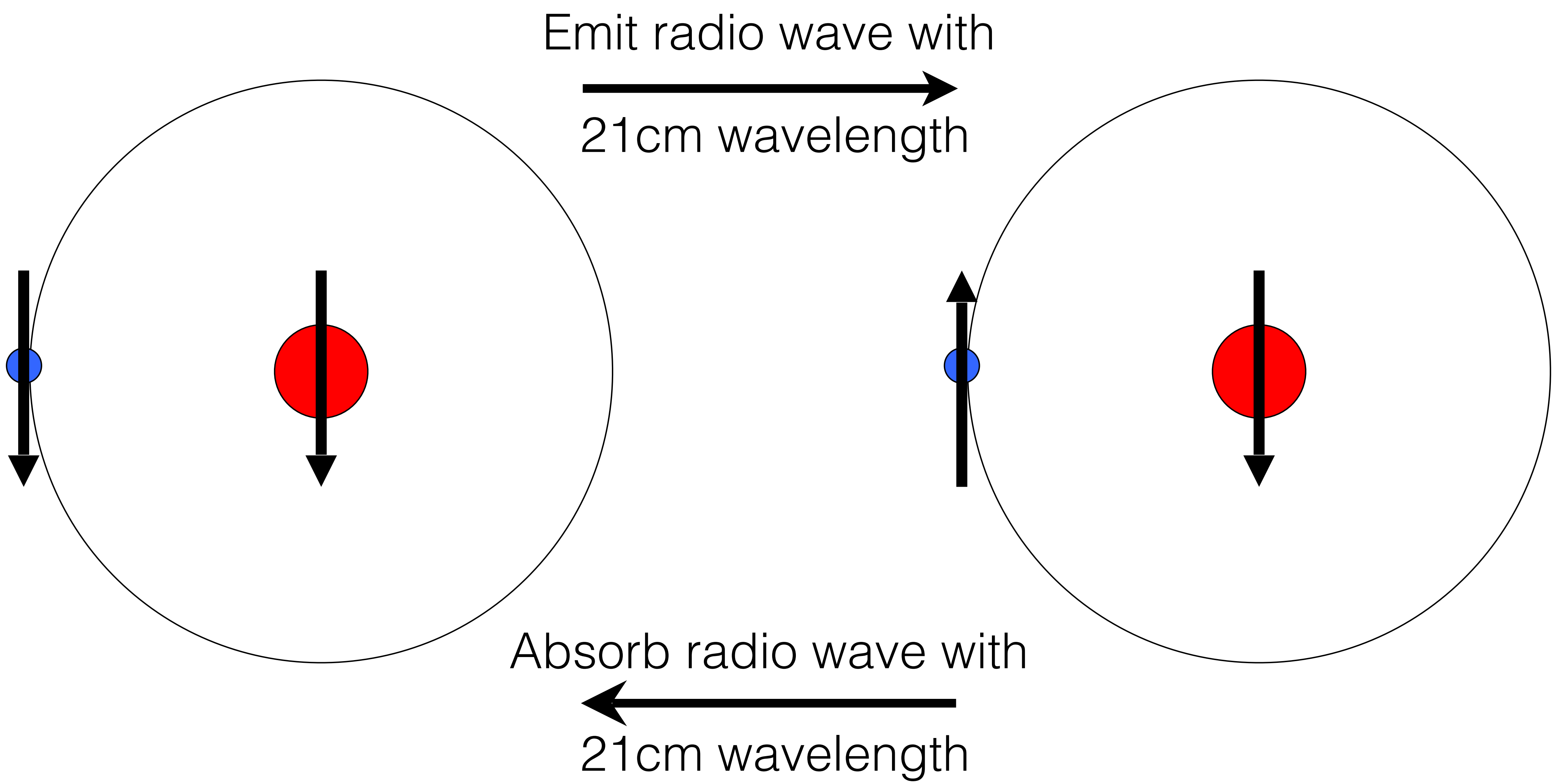


Bull et al. (2015)

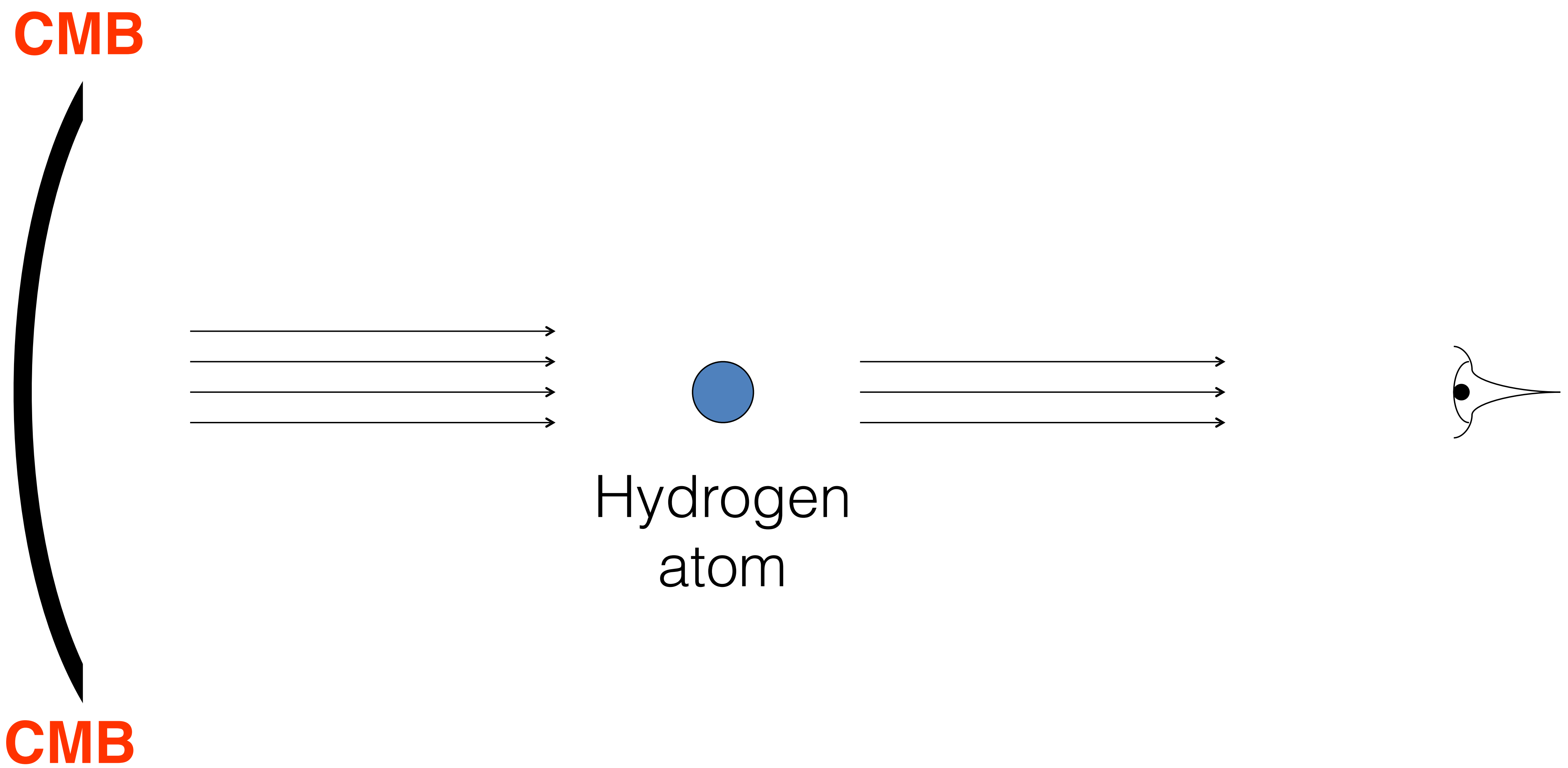
Adrian Liu, Hubble Fellow, UC Berkeley

Using the 21cm line as a probe of our Universe

Hydrogen is everywhere, and we seek to trace hydrogen at high redshifts using the 21cm line



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



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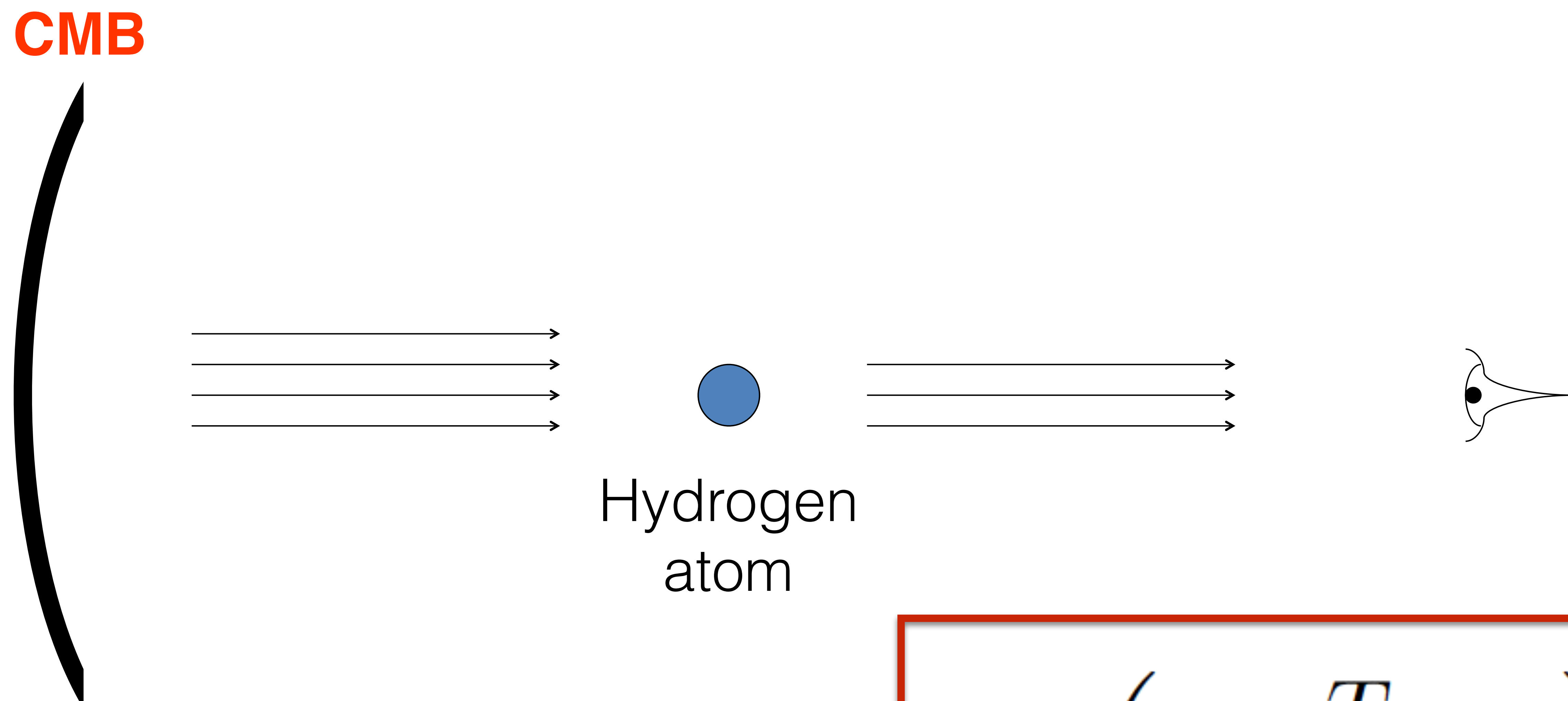
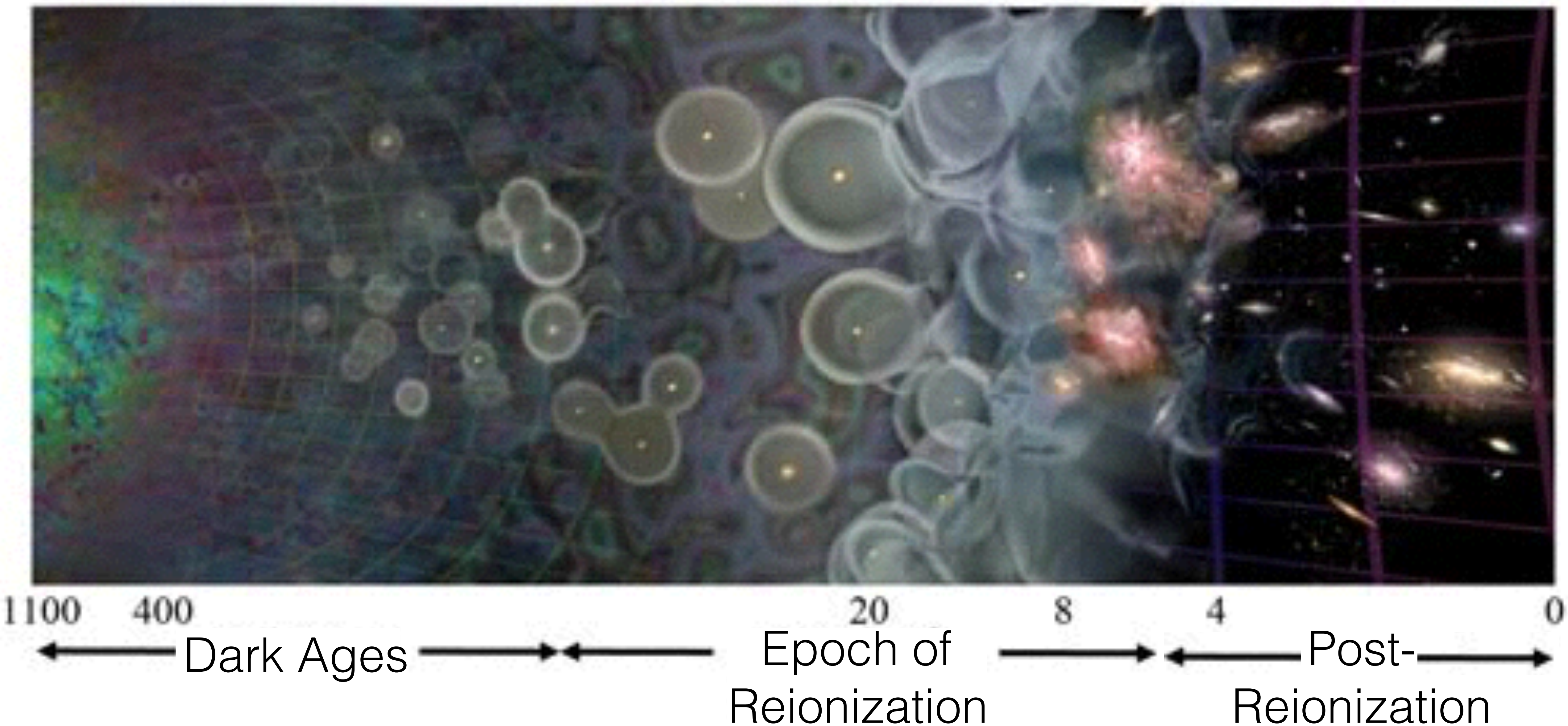


$$\Delta T_b \propto \boxed{(1+\delta_b)}\,\boxed{x_{HI}\left(1-\frac{T_{\rm CMB}}{T_{\rm spin}}\right)}$$


1100
400
20
8
4
0
Dark Ages
Epoch of Reionization
Post-Reionization

The spectral nature of the 21cm line allows our Universe to be mapped out in 3D

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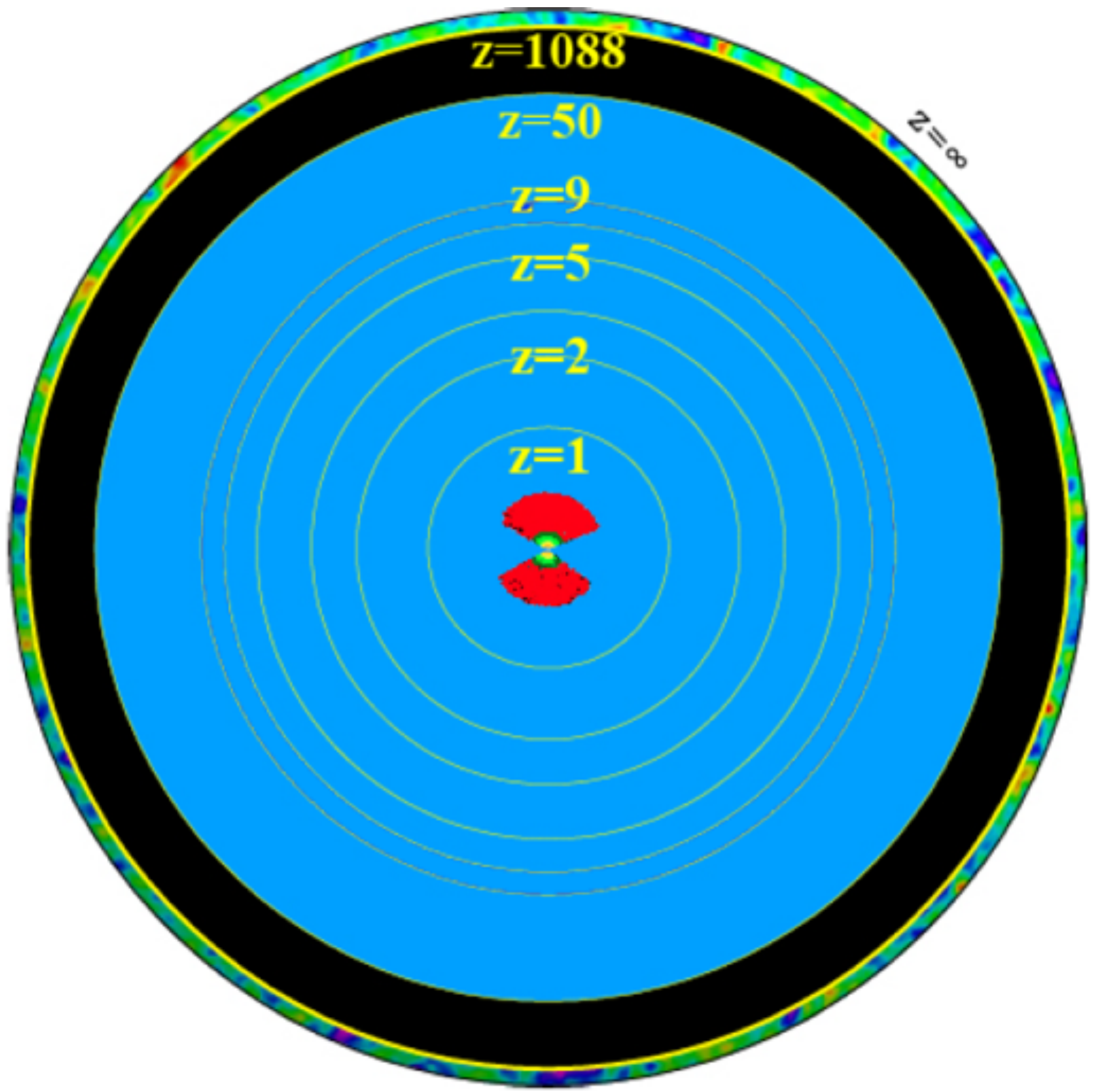

Example 21cm instruments

Current Epoch of Reionization Instruments $6 < z < 13$

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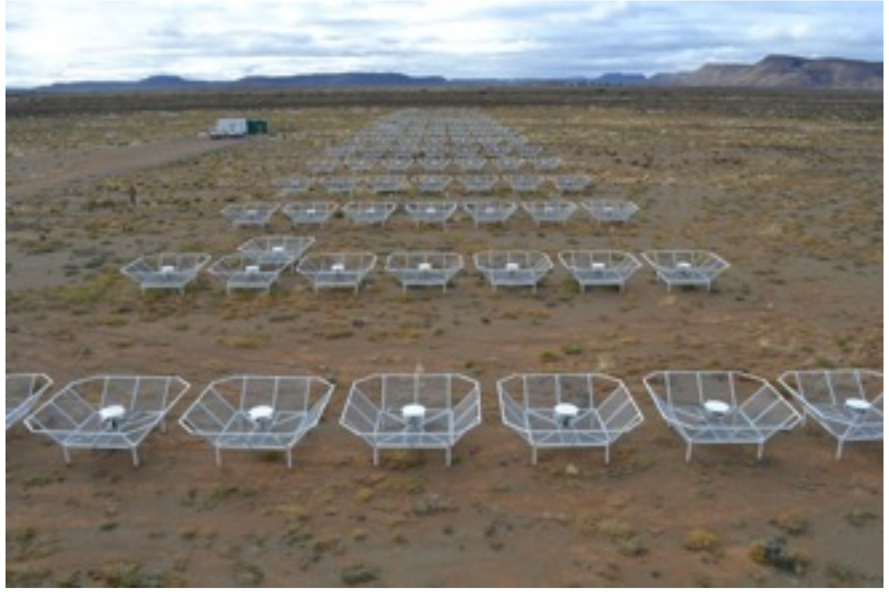


PAPER

MWA

LOFAR

Under-construction / commissioning

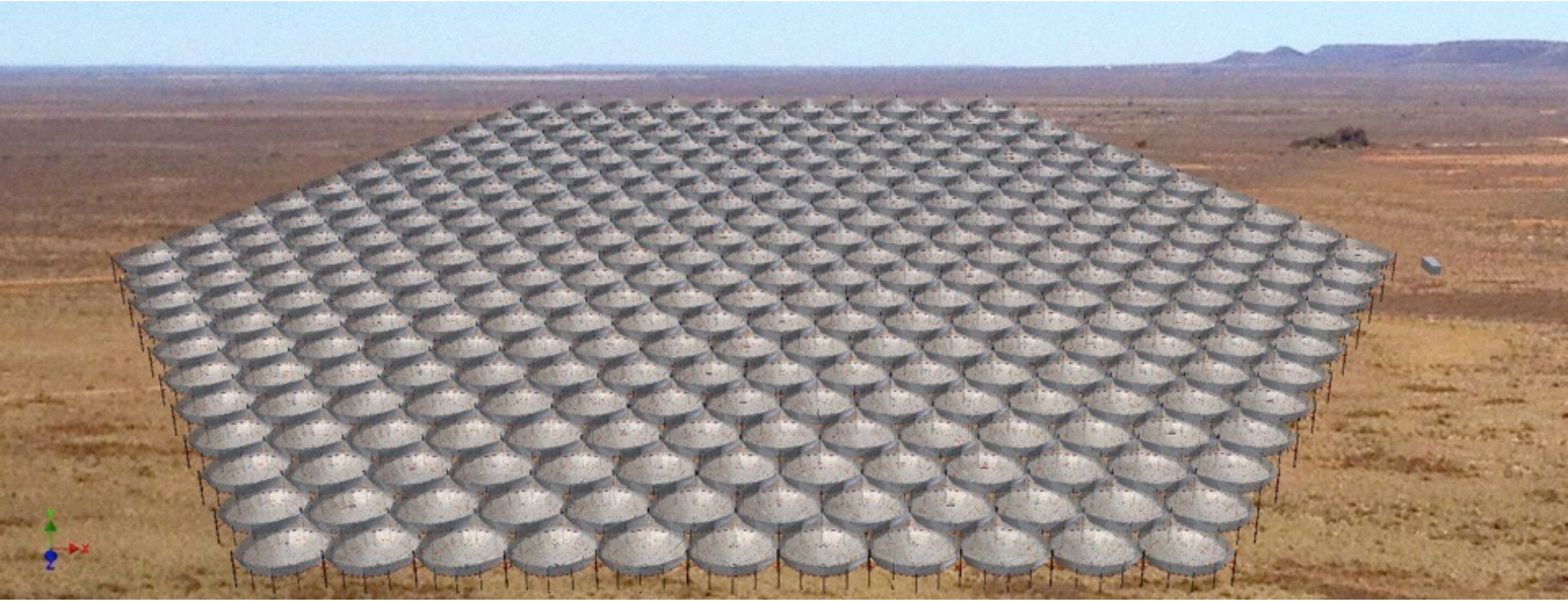
Under-construction / commissioning

Hydrogen Epoch of Reionization Array

Under-construction / commissioning

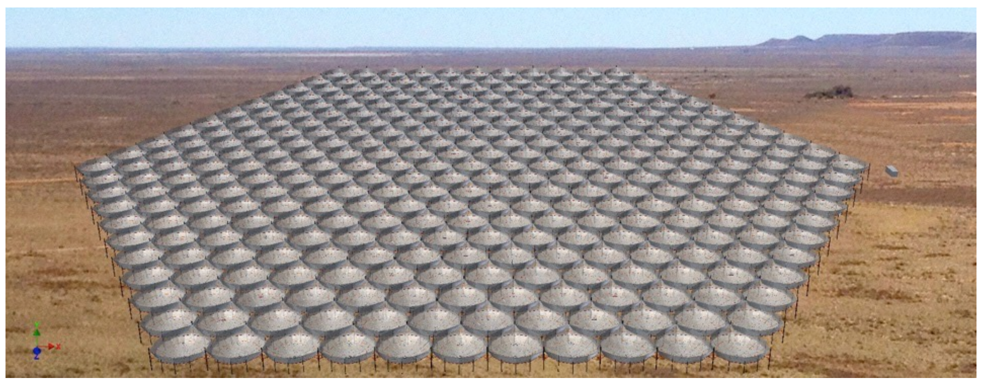
Hydrogen Epoch of Reionization Array

Under-construction / commissioning



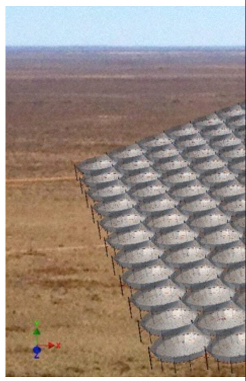
Hydrogen Epoch of Reionization Array

Under-construction / commissioning



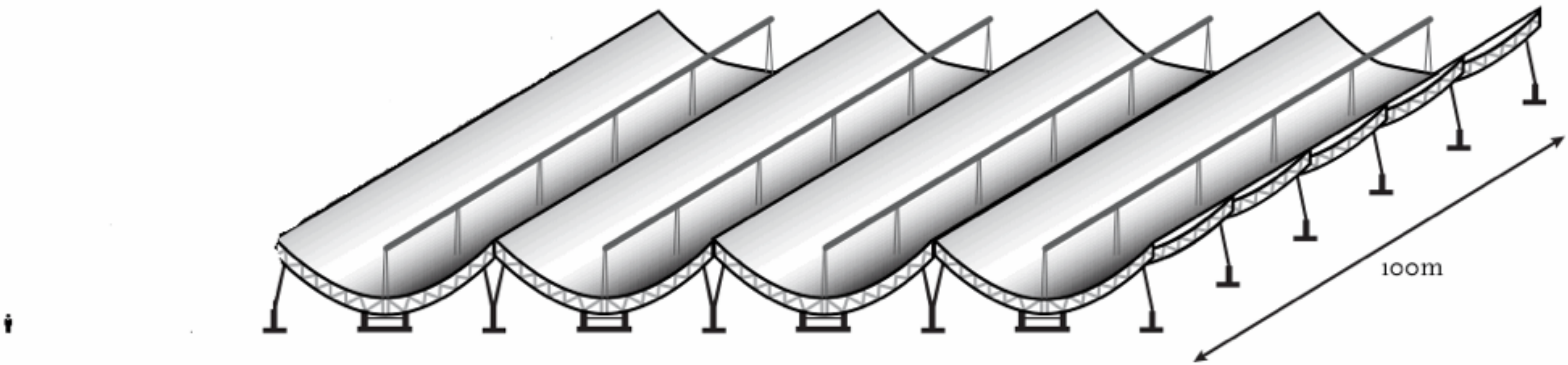
HERA

Under-construction / commissioning



Canadian Hydrogen Intensity
Mapping Experiment

Under-construction / commissioning



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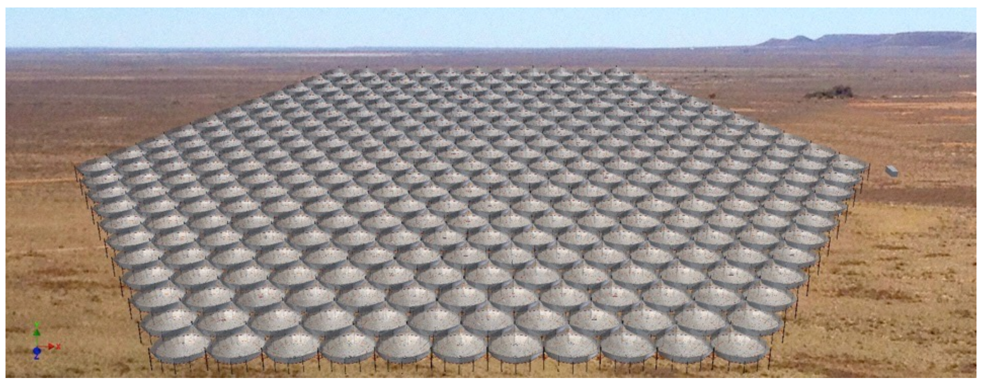

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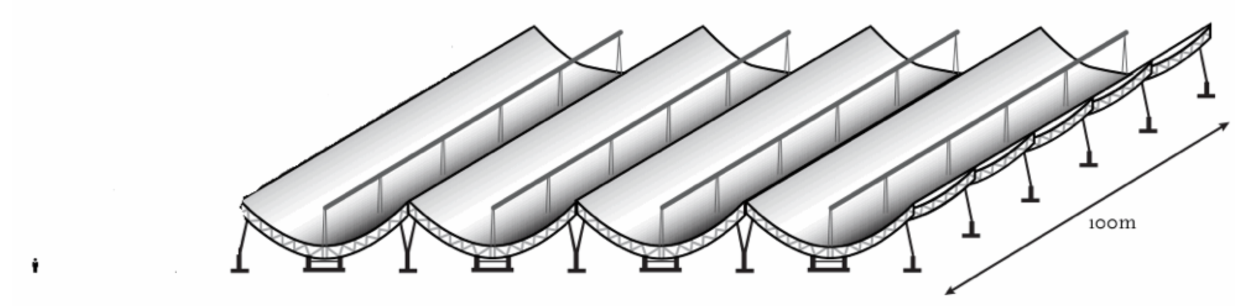
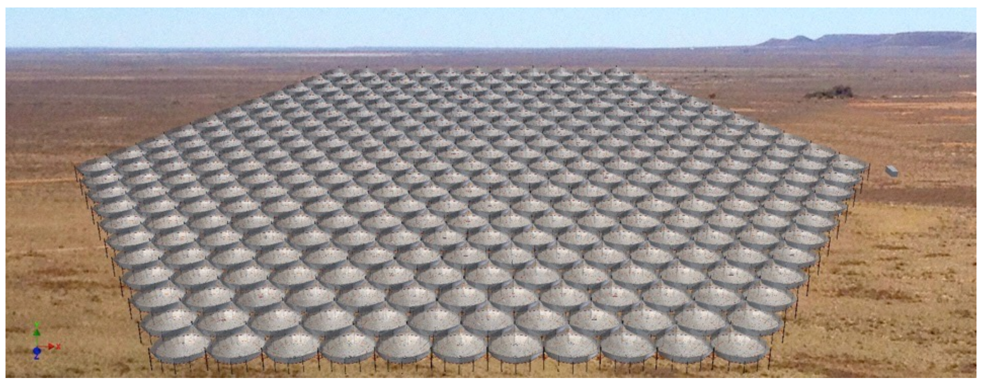


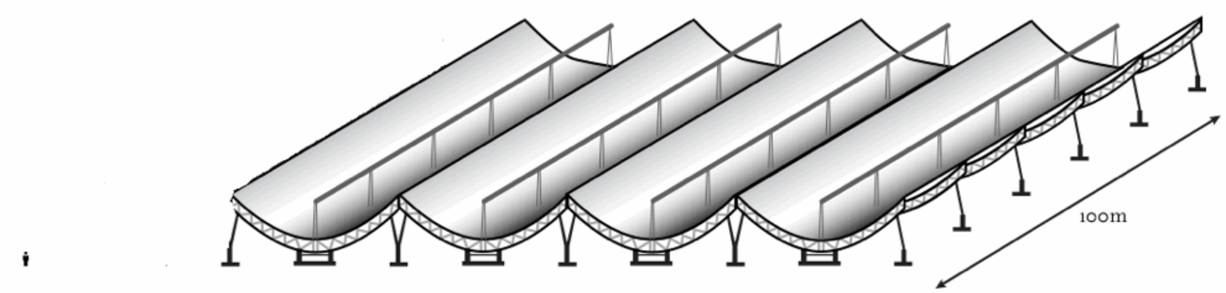
CHIME

Under-construction / commissioning



HERA

6 < z < 13
Mainly targeting reionization
Collecting Area: 51,000 m^2

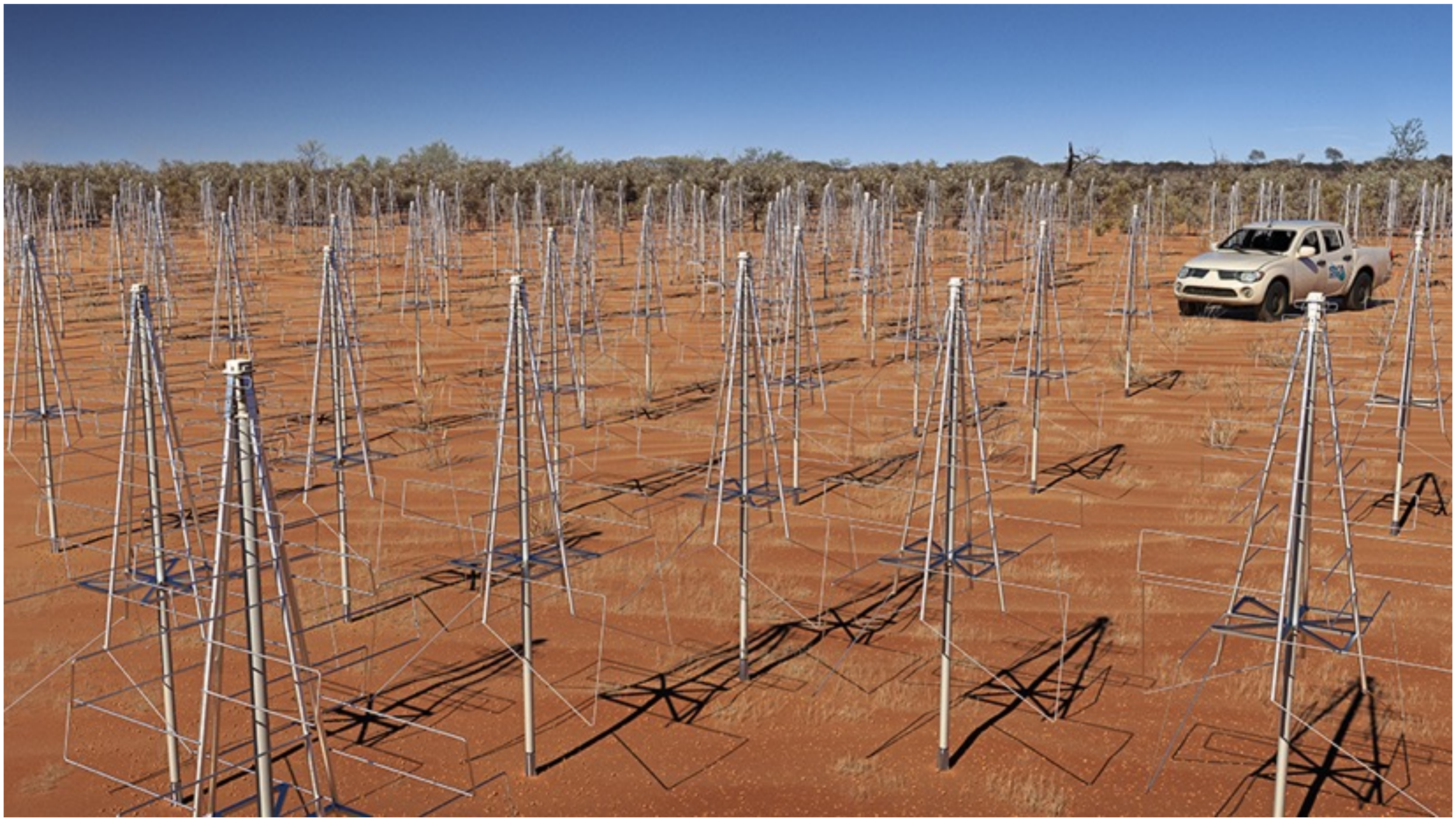


CHIME

0.8 < z < 2.5
Targeting post-reionization LSS 21cm signal
Collecting Area: 10,000 m^2

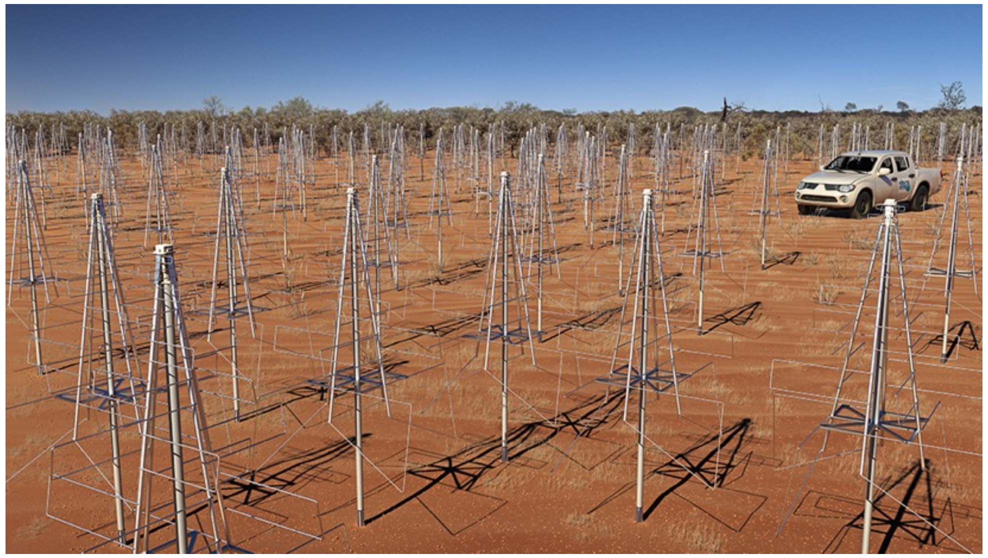
Proposed

Proposed



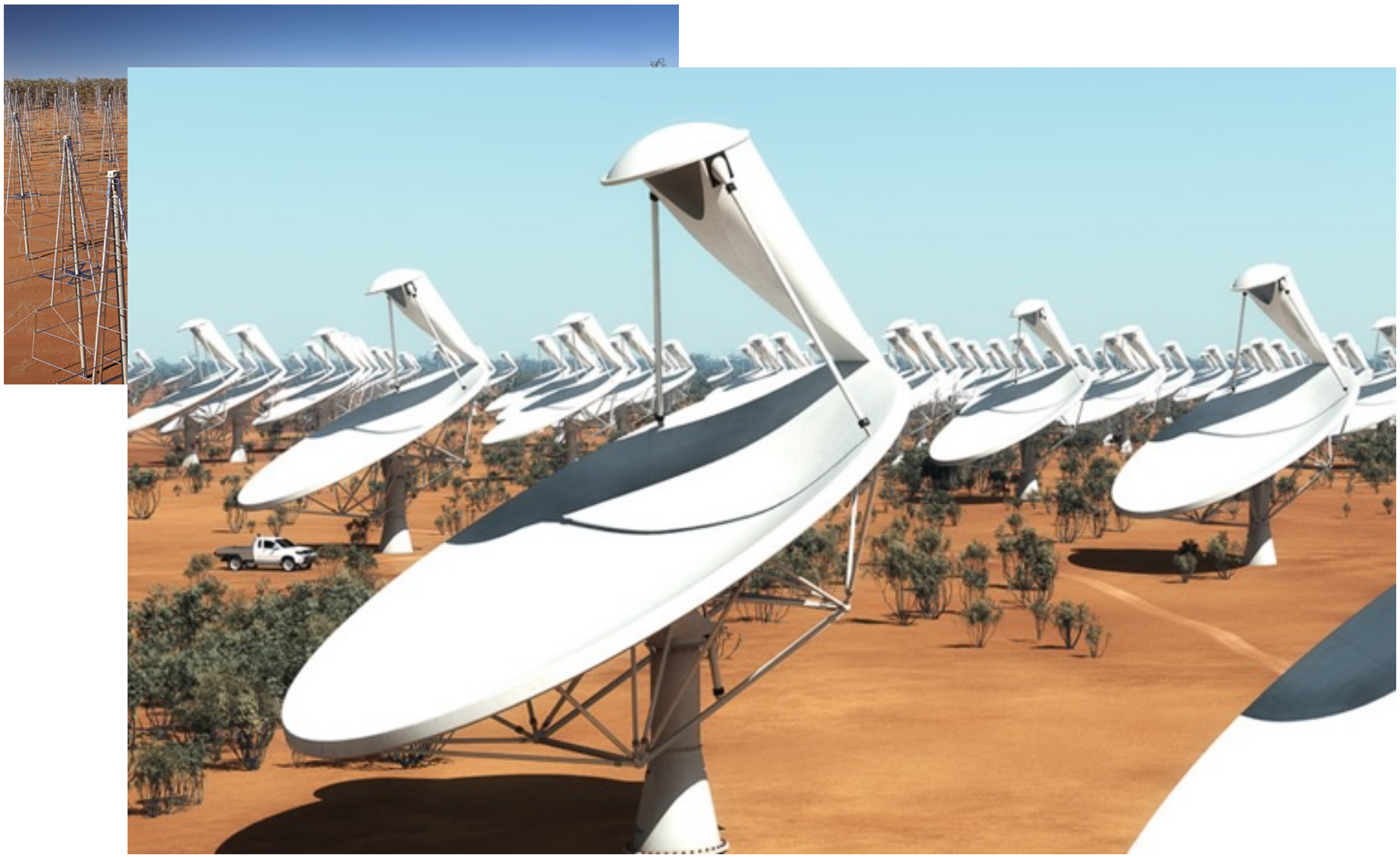
Square Kilometer Array Low

Proposed



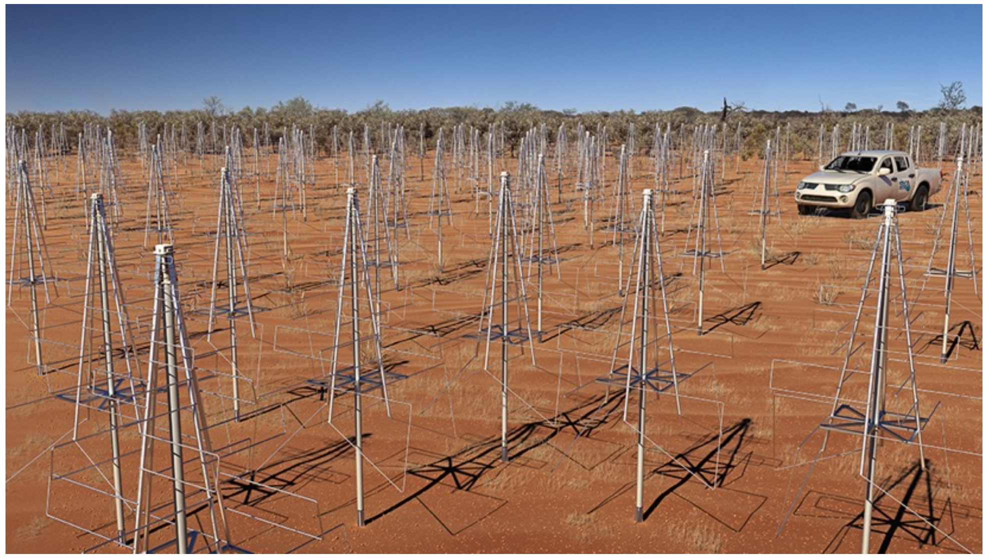
SKA-Low

Proposed

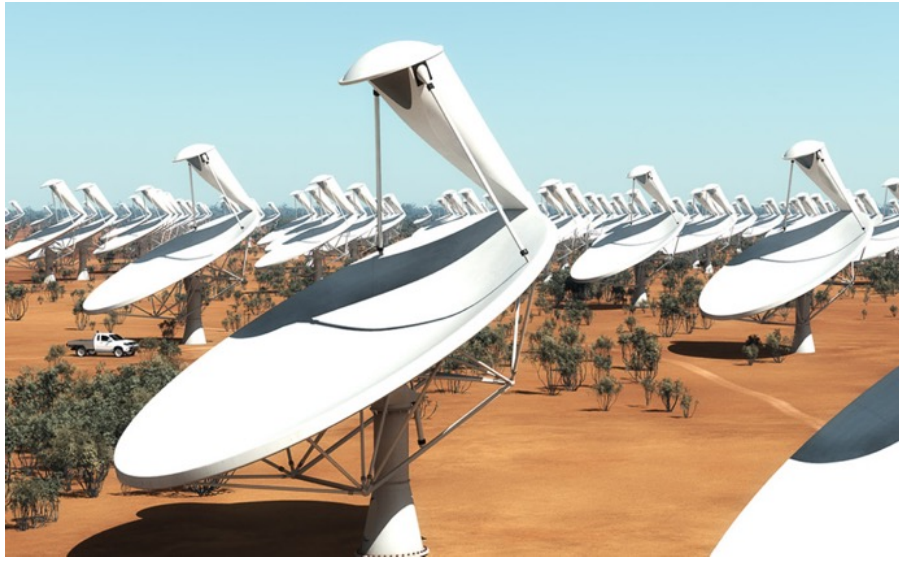


Square Kilometer Array Mid

Proposed

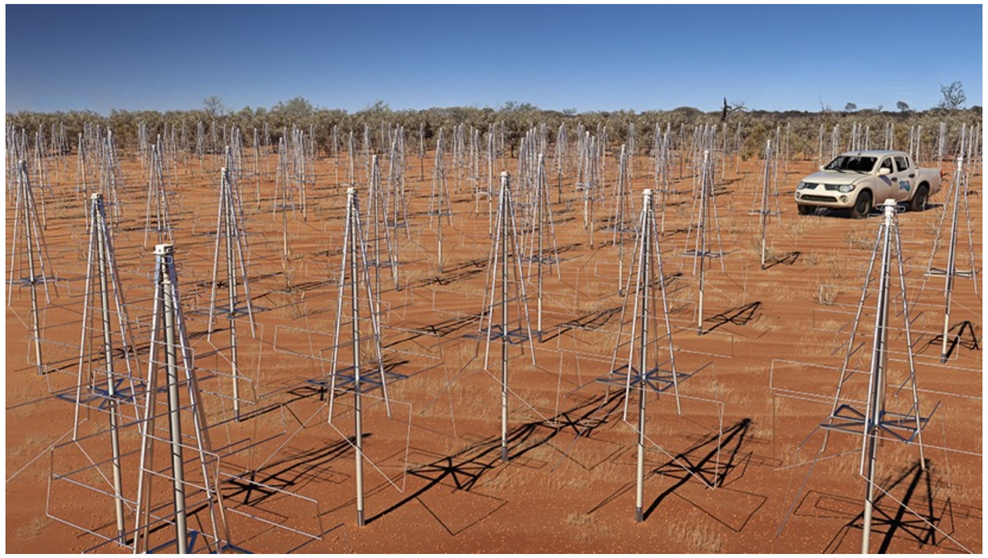


SKA-Low

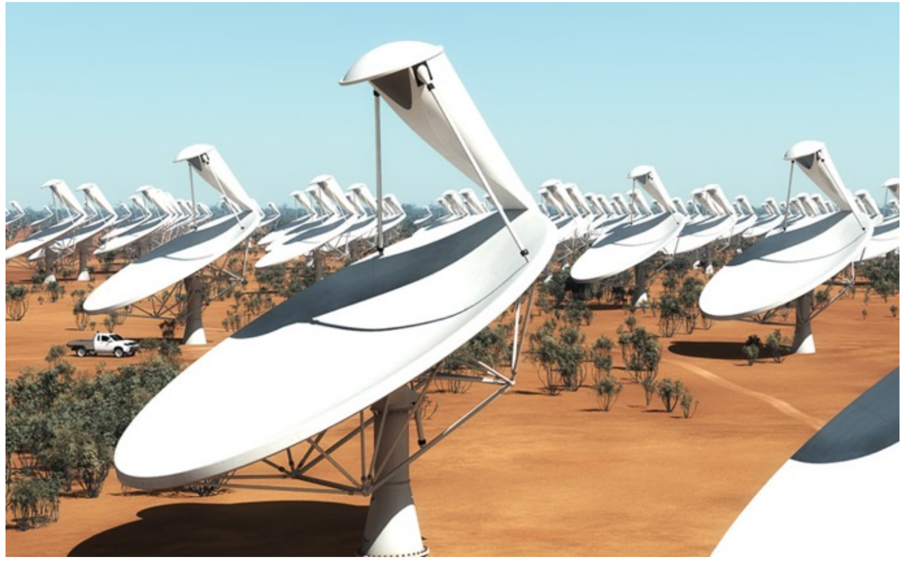


SKA-Mid

Proposed



SKA-Low



SKA-Mid

$3.1 < z < 27$
Collecting Area: 0.4 km^2

$0 < z < 3.1$
Collecting Area: 33,000 m^2

To zeroth order, radio interferometer arrays are fairly simple

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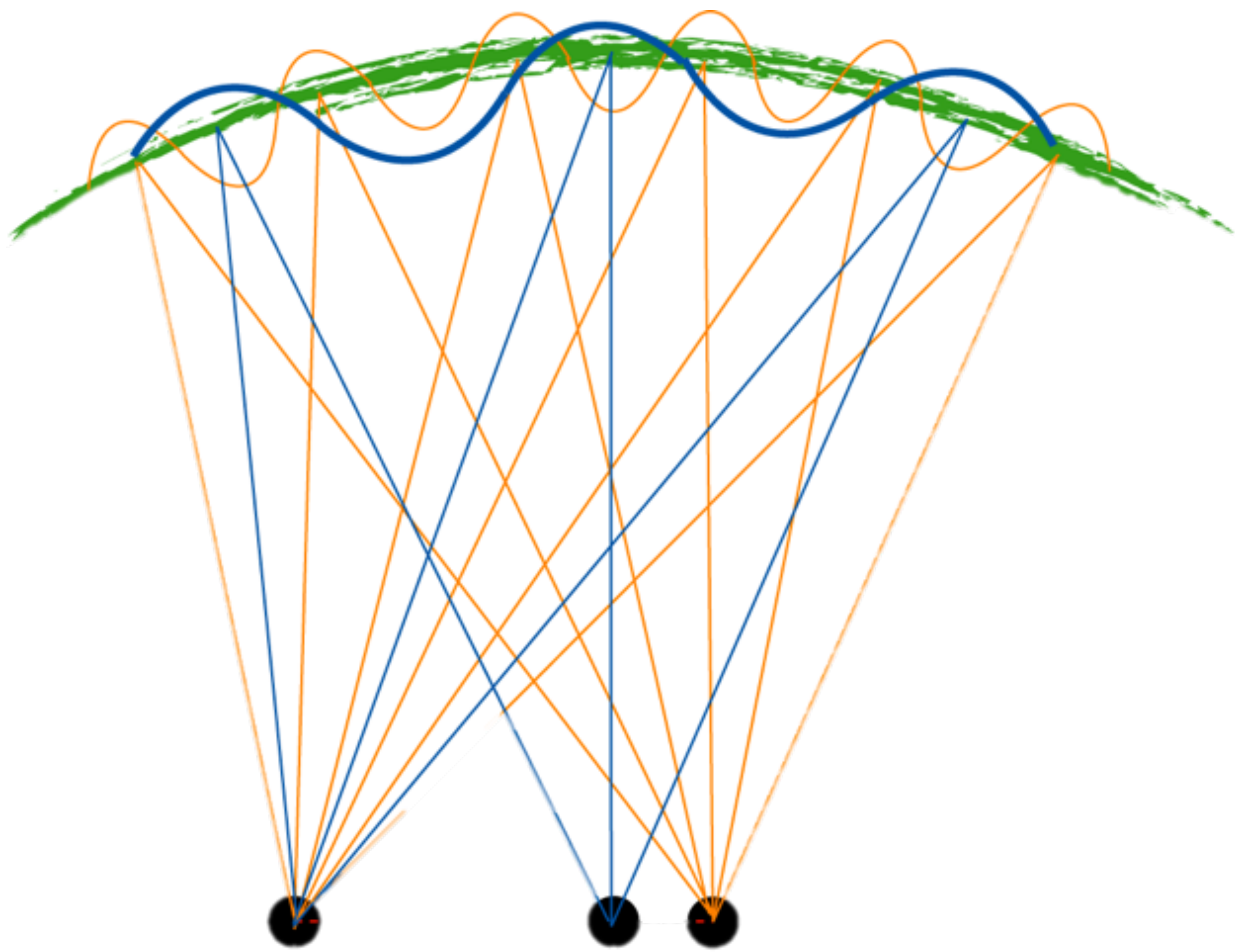
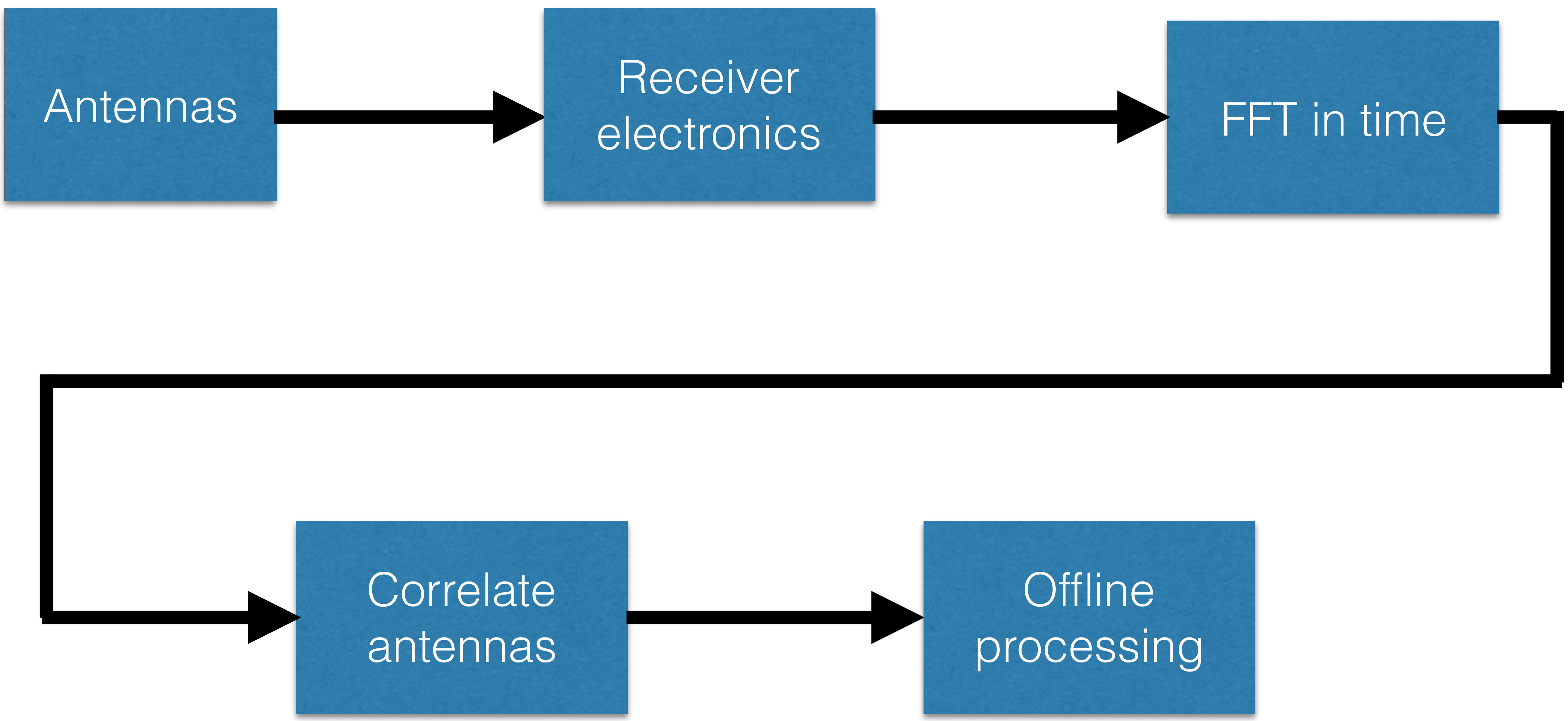


To zeroth order, low frequency radio interferometer hardware is fairly simple



How to use 21cm interferometers to do cosmology

Ways to do cosmology with the 21cm line

Ways to do cosmology with the 21cm line

- With high-redshift (reionization) experiments

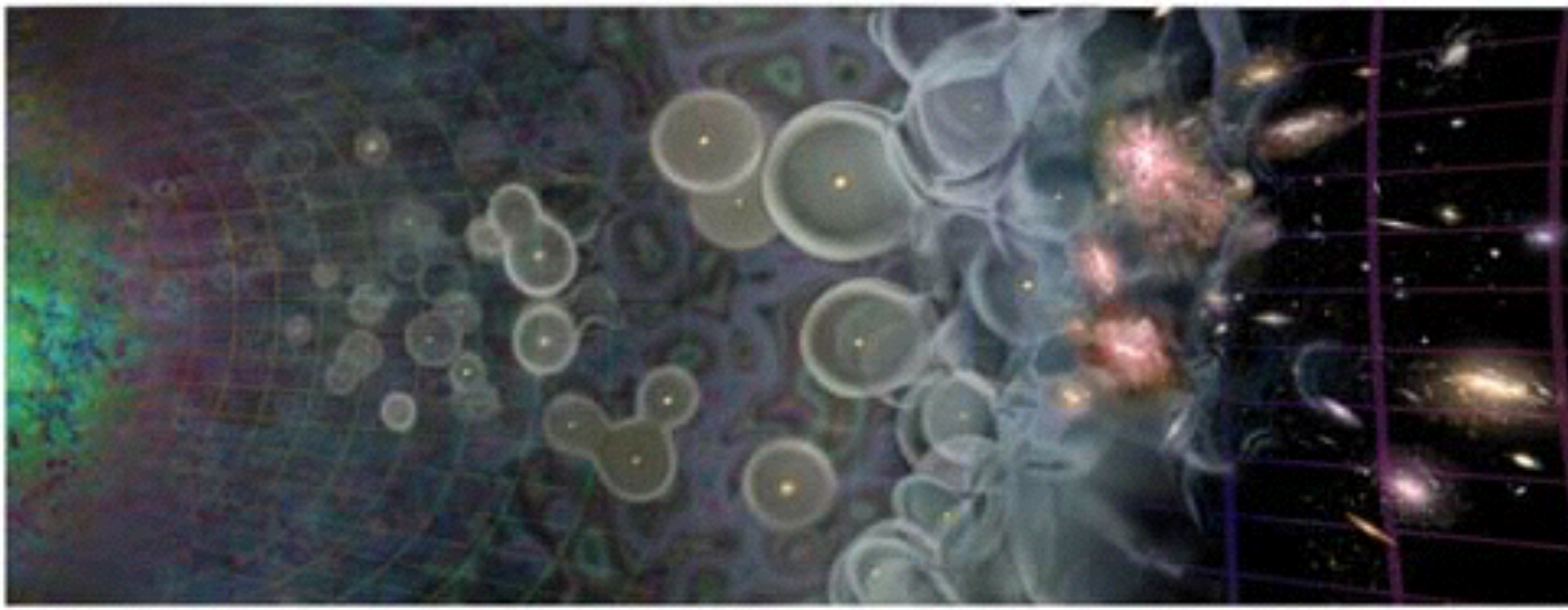
- With low-redshift (post-reionization) experiments

Ways to do cosmology with the 21cm line

- With high-redshift (reionization) experiments
    - Parameterize the astrophysics.
- With low-redshift (post-reionization) experiments

$$\mathcal{P}_{xx}(k) = b_{\mathrm{xx}}^2[1 + \alpha_{\mathrm{xx}}(kR_{\mathrm{xx}}) + (kR_{\mathrm{xx}})^2]^{-(\gamma_{\mathrm{xx}}/2)}\mathcal{P}_{\delta\delta}^{(\mathrm{fid})}$$

$$\mathcal{P}_{x\delta}(k) = b_{\mathrm{x}\delta}^2 \exp[-\alpha_{\mathrm{x}\delta}(kR_{\mathrm{x}\delta}) - (kR_{\mathrm{x}\delta})^2]\mathcal{P}_{\delta\delta}^{(\mathrm{fid})}$$



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$\sum m_\nu \sim \pm 0.06$ eV with SKA

± 0.0007 eV with a specialized array

Mao et al. 2008

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Mao et al. 2008

To make progress: Check parameterizations like these with early data

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- With high-redshift (reionization) experiments
  - Parameterize the astrophysics.
- With low-redshift (post-reionization) experiments

Ways to do cosmology with the 21cm line

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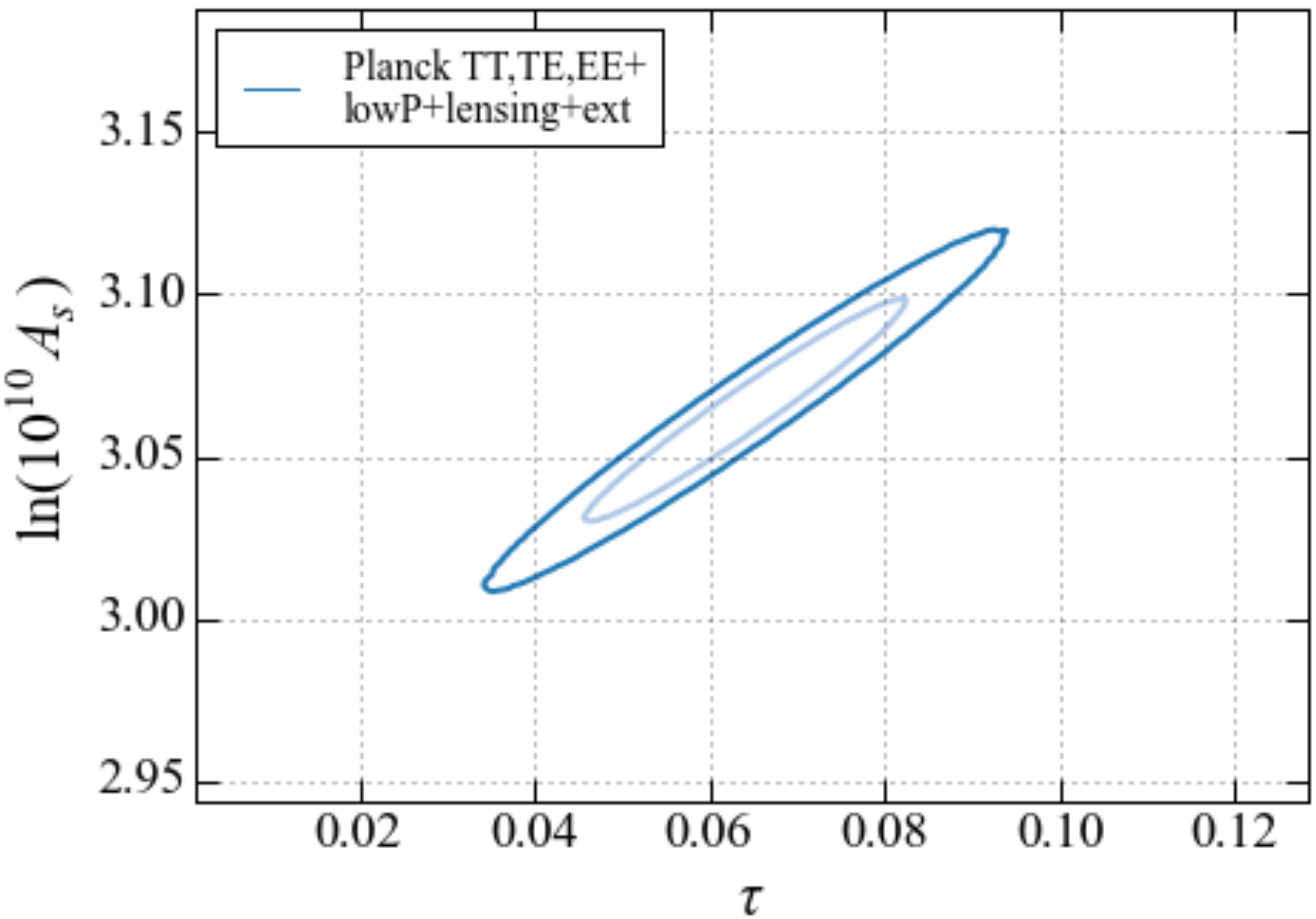
  - Understand reionization so well that it’s not a nuisance for the CMB.
- With low-redshift (post-reionization) experiments

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



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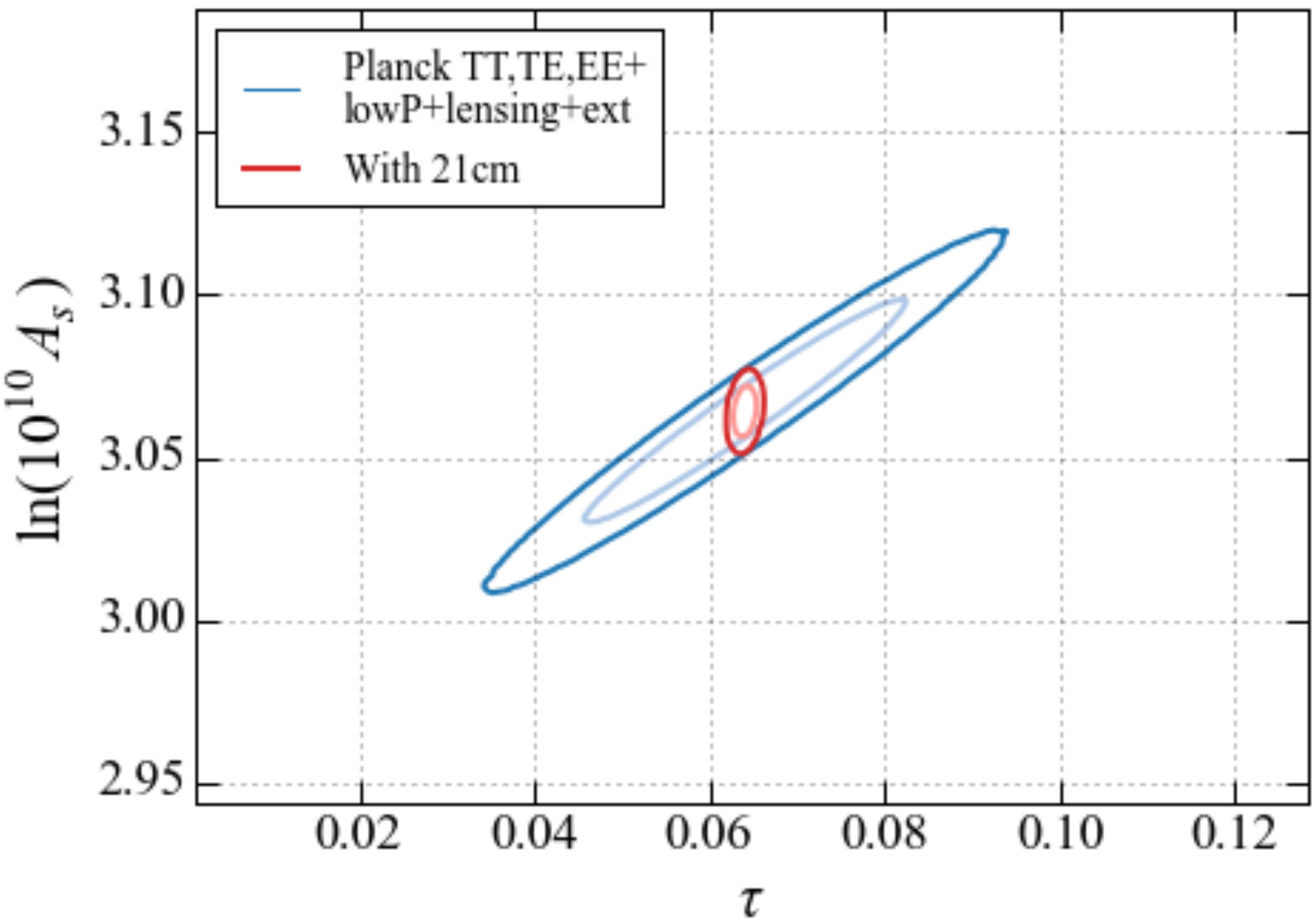

AL et al. (2015)

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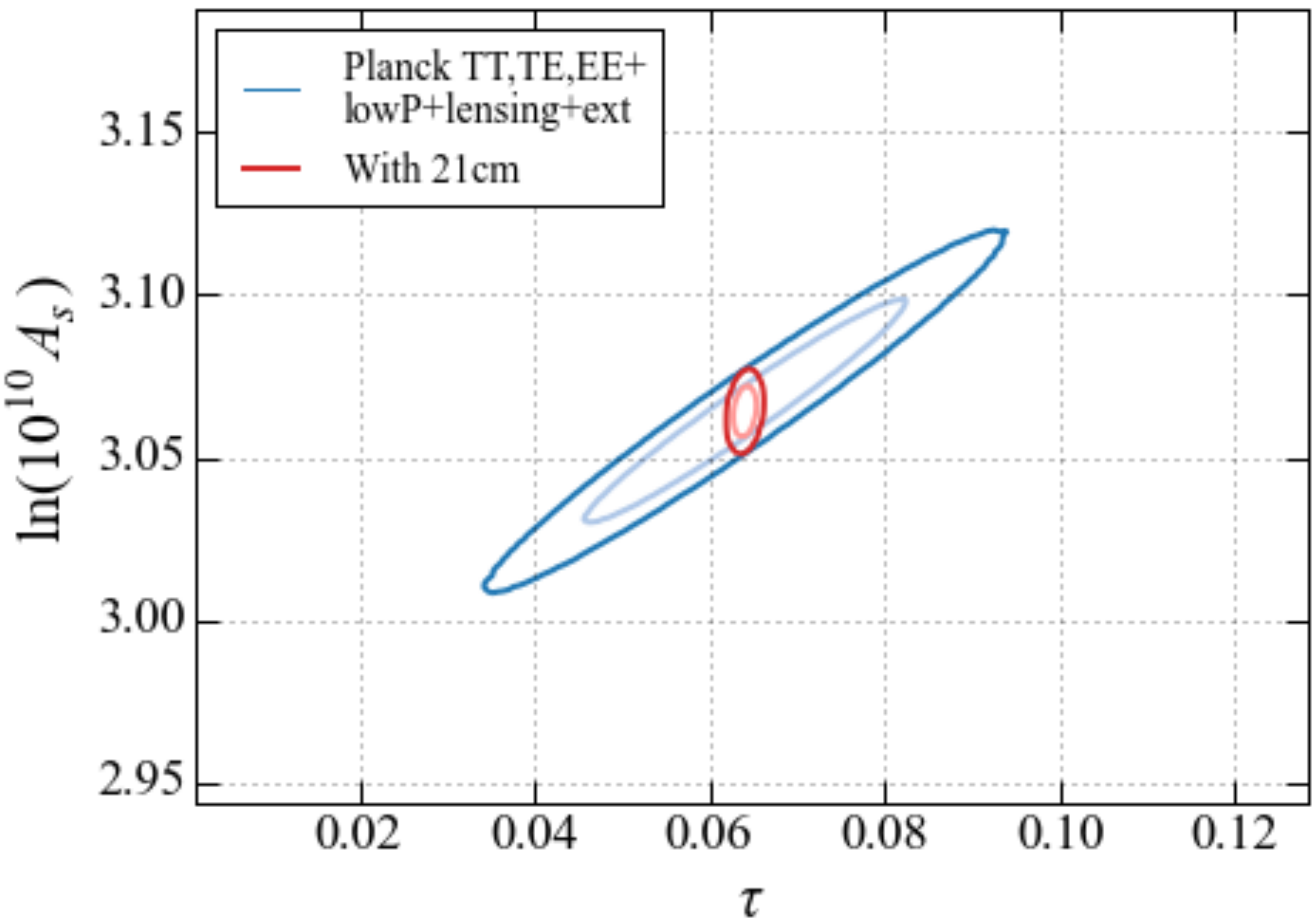
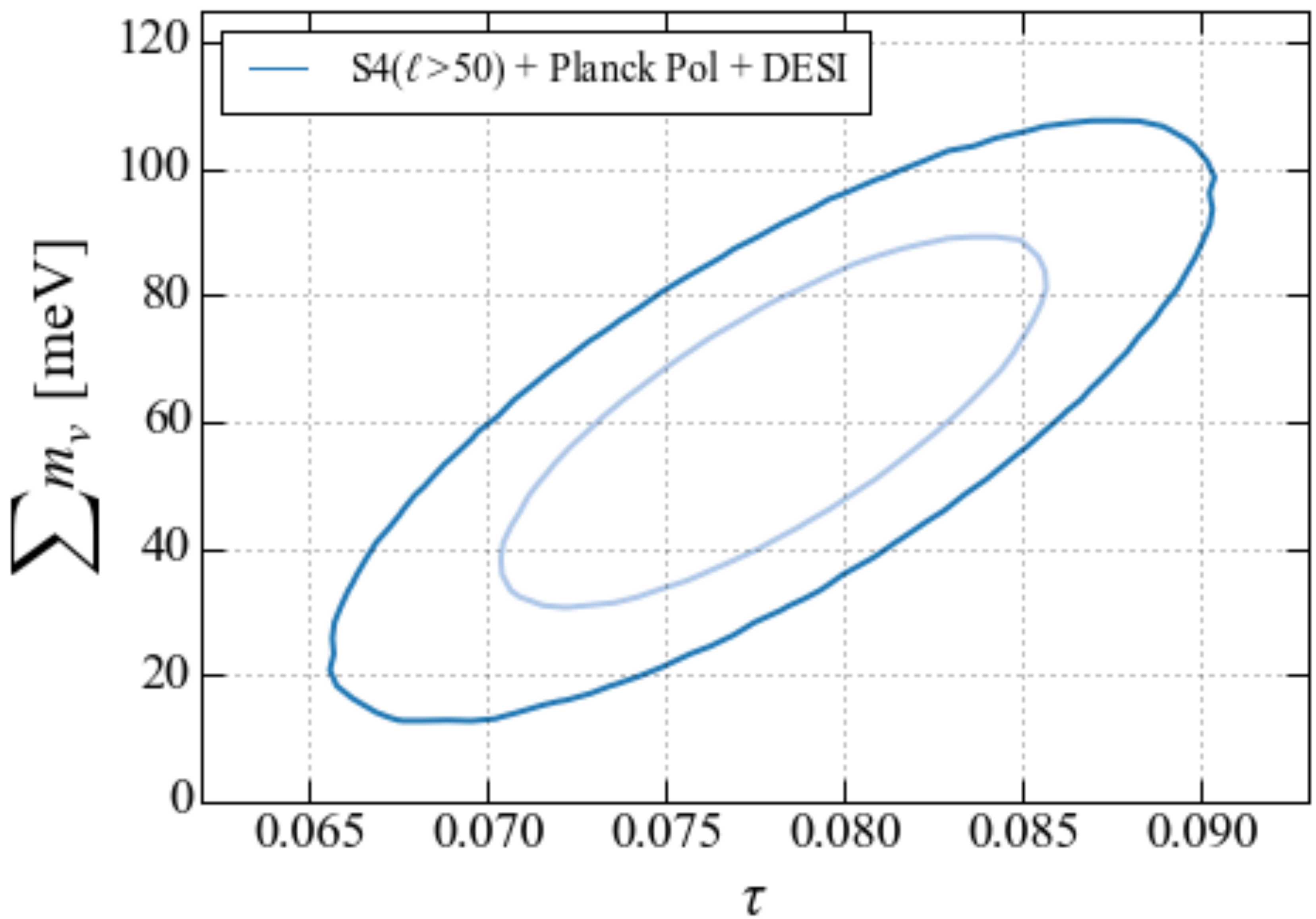


AL et al. (2015)

$$\Delta \ln(10^{10}A_s) = \pm 0.023 \longrightarrow \pm 0.0053$$

Both A_s and the neutrino mass can affect small scale power, leading to degeneracies



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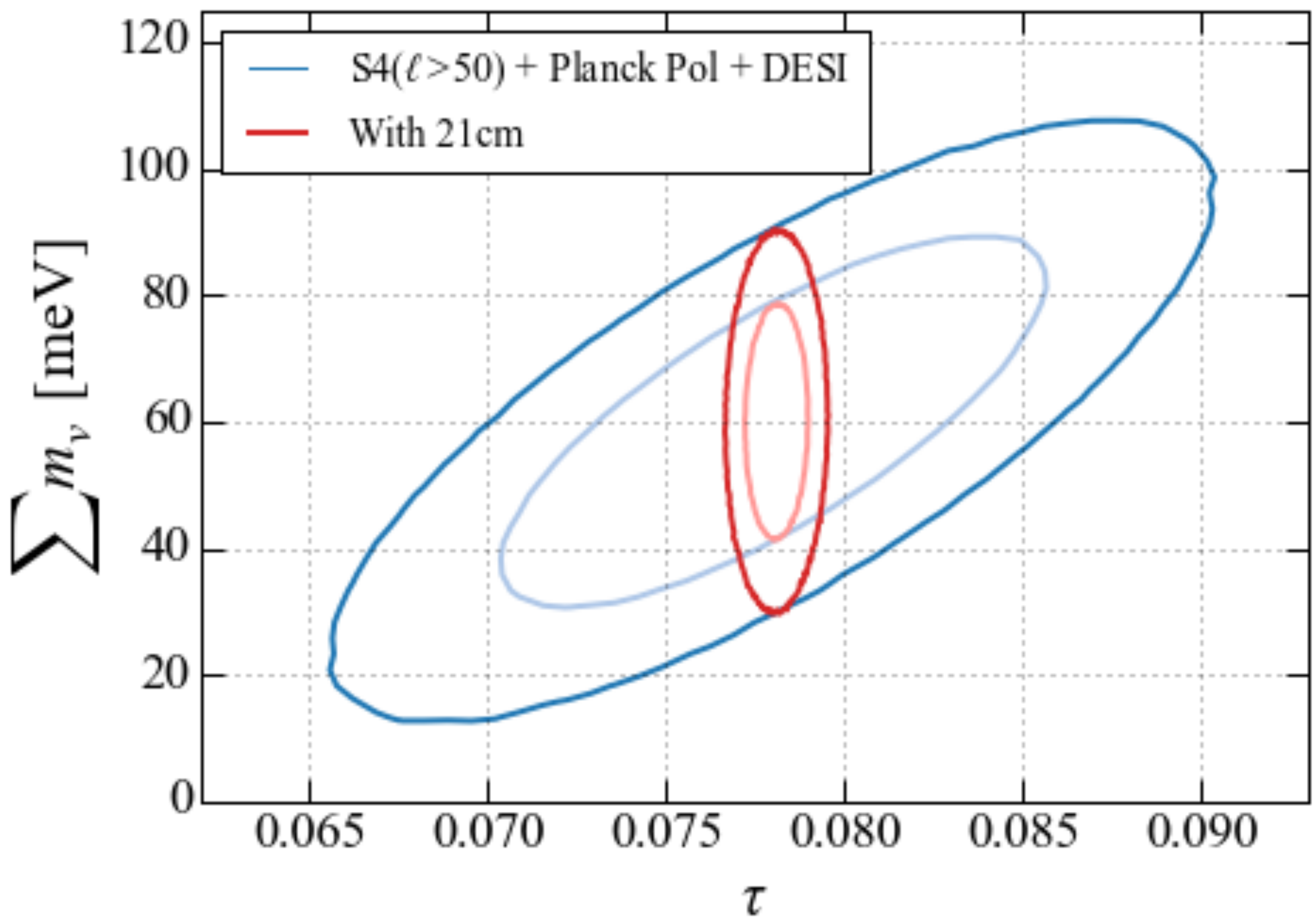

AL et al. (2015)

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

Ways to do cosmology with the 21cm line

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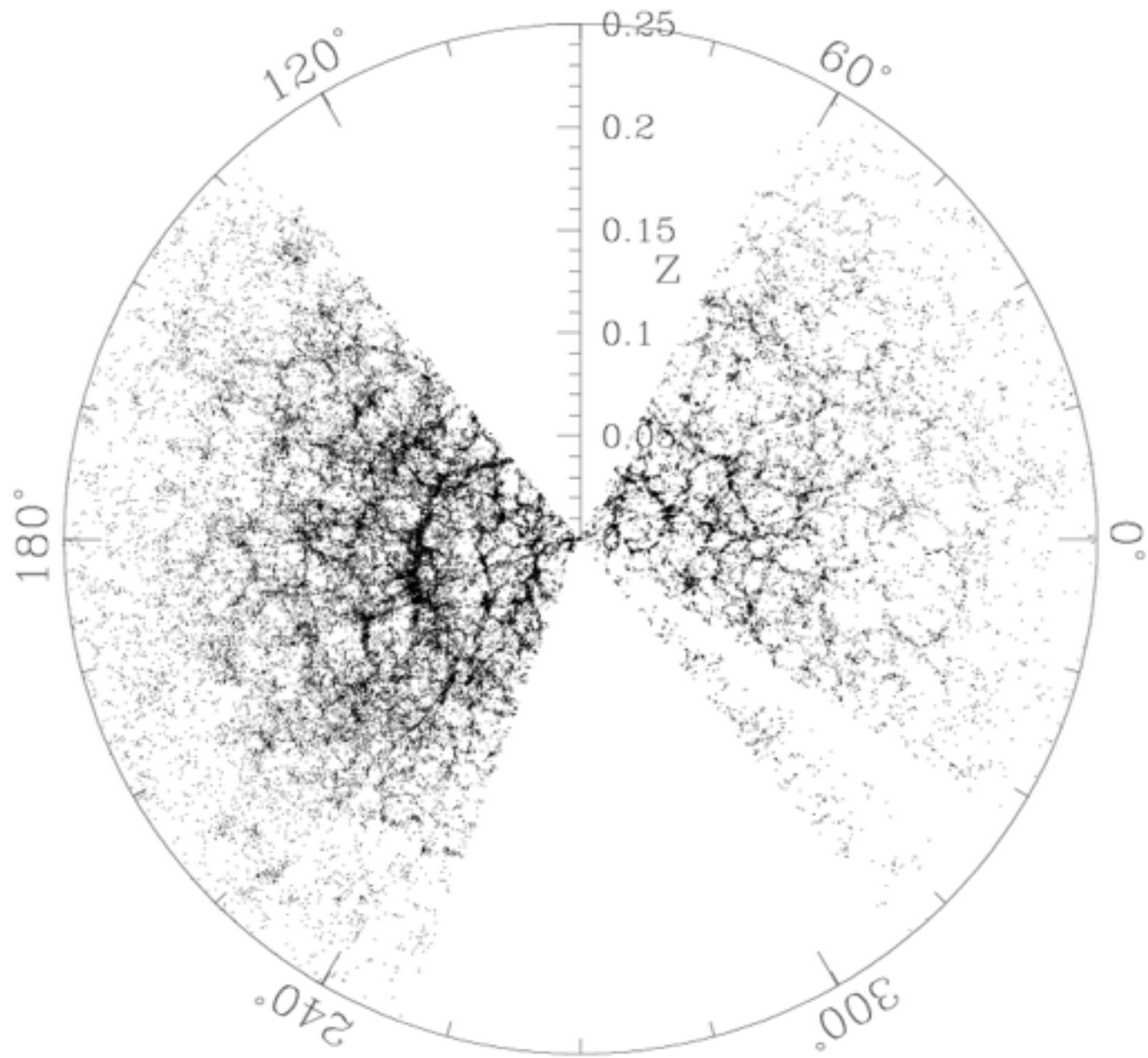
Ways to do cosmology with the 21cm line

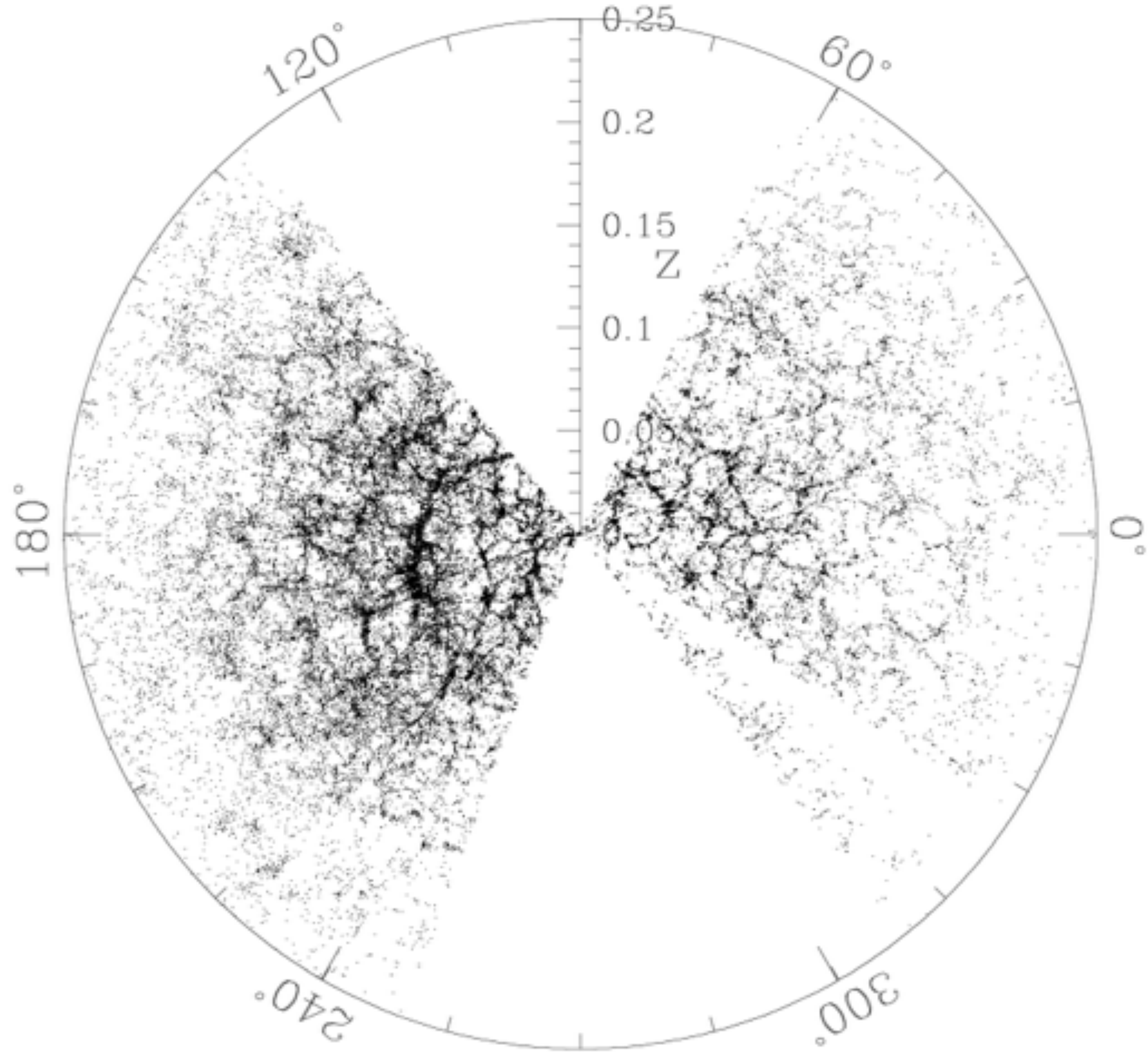
- With high-redshift (reionization) experiments
  - Parameterize the astrophysics.
  - Understand reionization so well that it’s not a nuisance for the CMB.
- With low-redshift (post-reionization) experiments
  - Unresolved intensity mapping.
  - Resolved survey of radio galaxies.

Resolved surveys of radio galaxies operate pick out individual galaxies



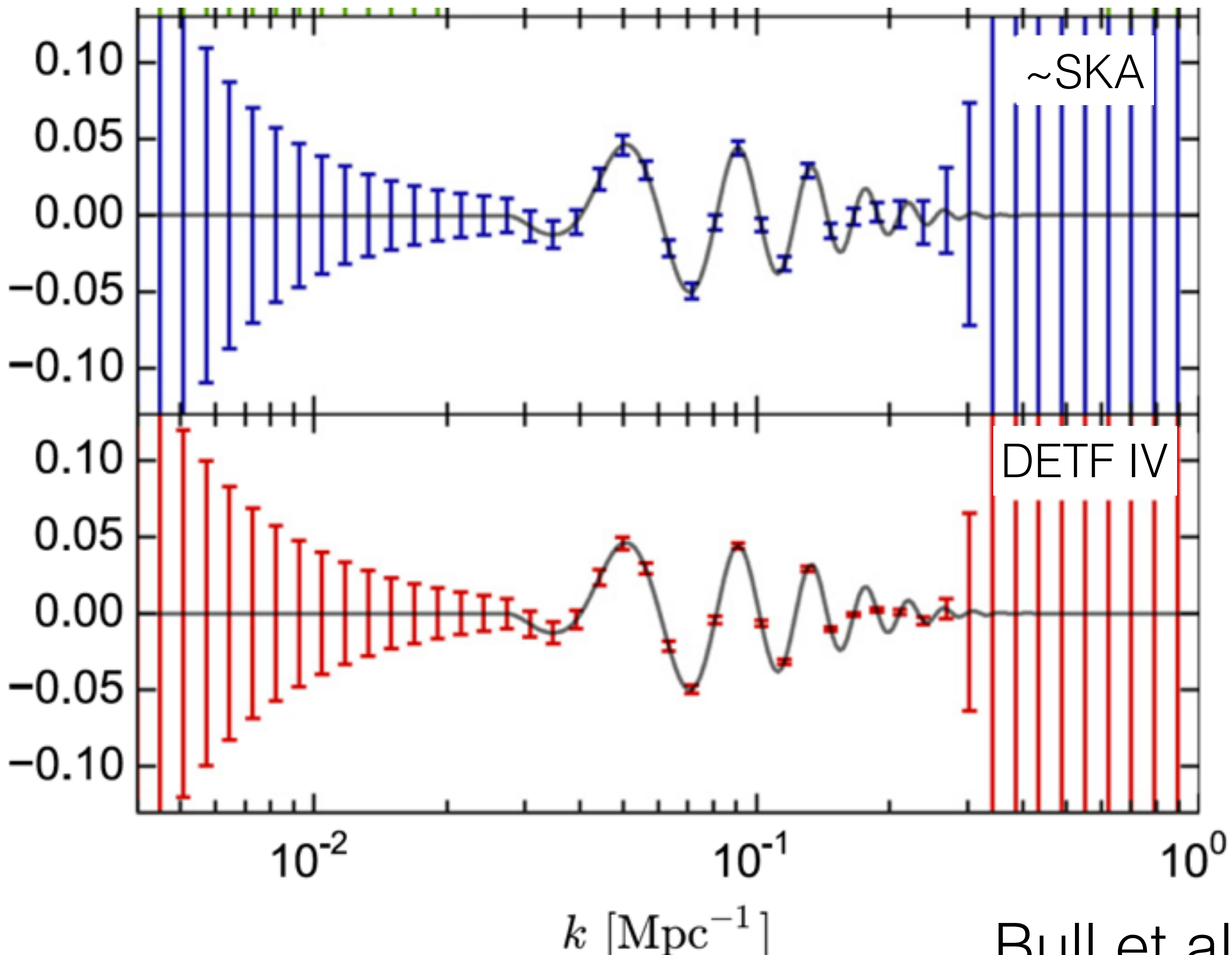
Blanton et al. (2003)

Intensity mapping averages over all 21cm emission from galaxies with resolving objects

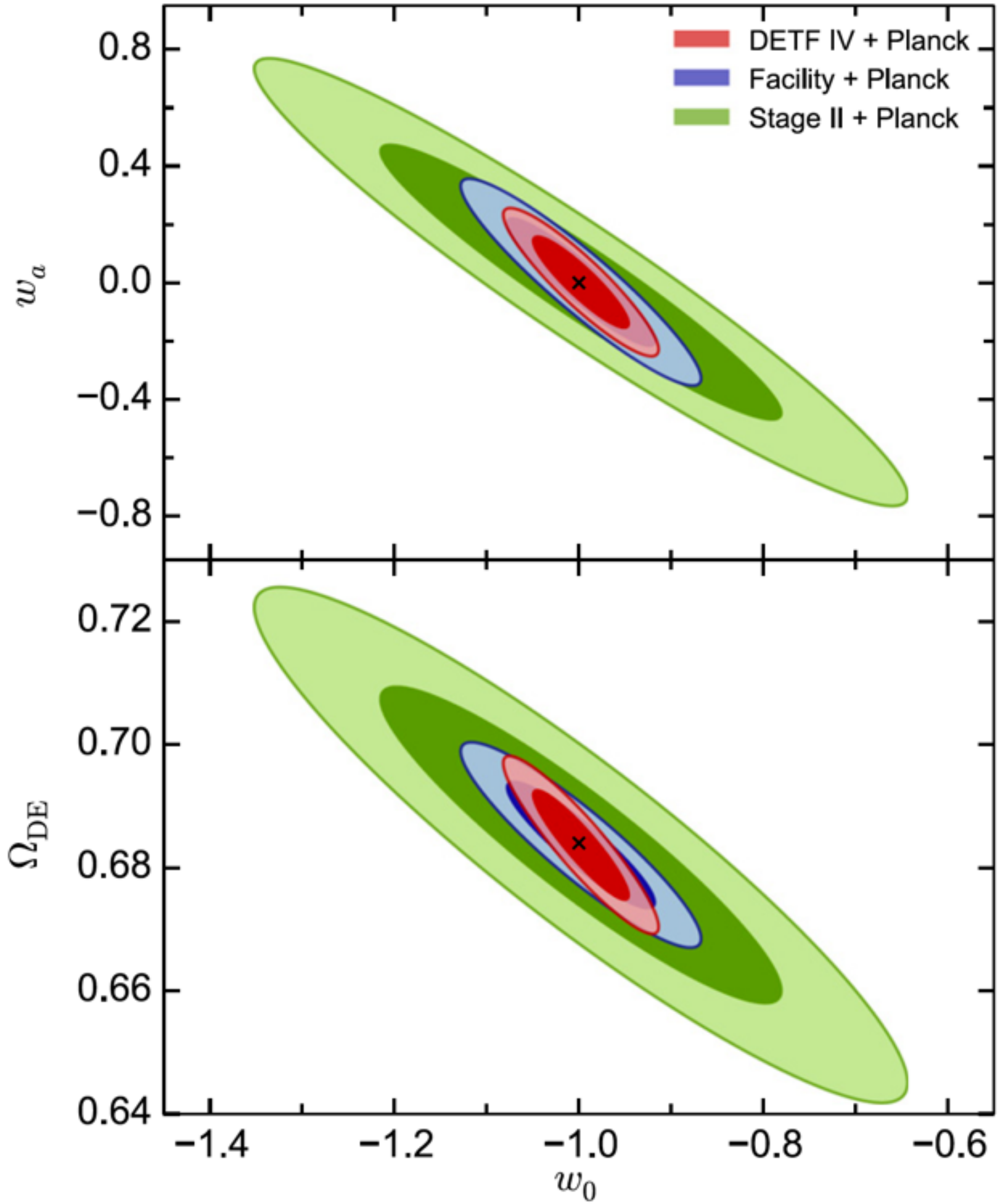


Blanton et al. (2003)

The BAO feature is measured with comparable precision to a DETF Stage IV spectroscopic galaxy redshift survey

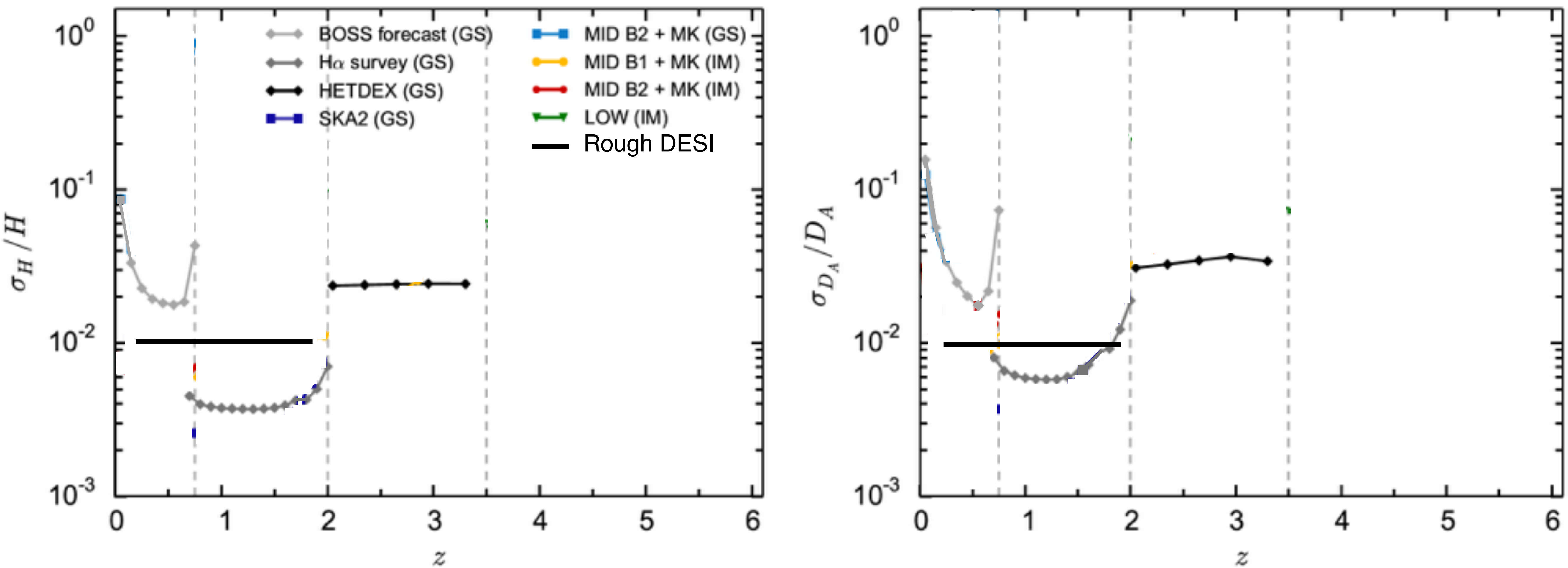


Bull et al. (2015)



Bull et al. (2015)

The 21cm line can produce comparable independent constraints and extend the redshift reach of surveys



Bull et al. (2015)

Font-Ribera et al. (2014)

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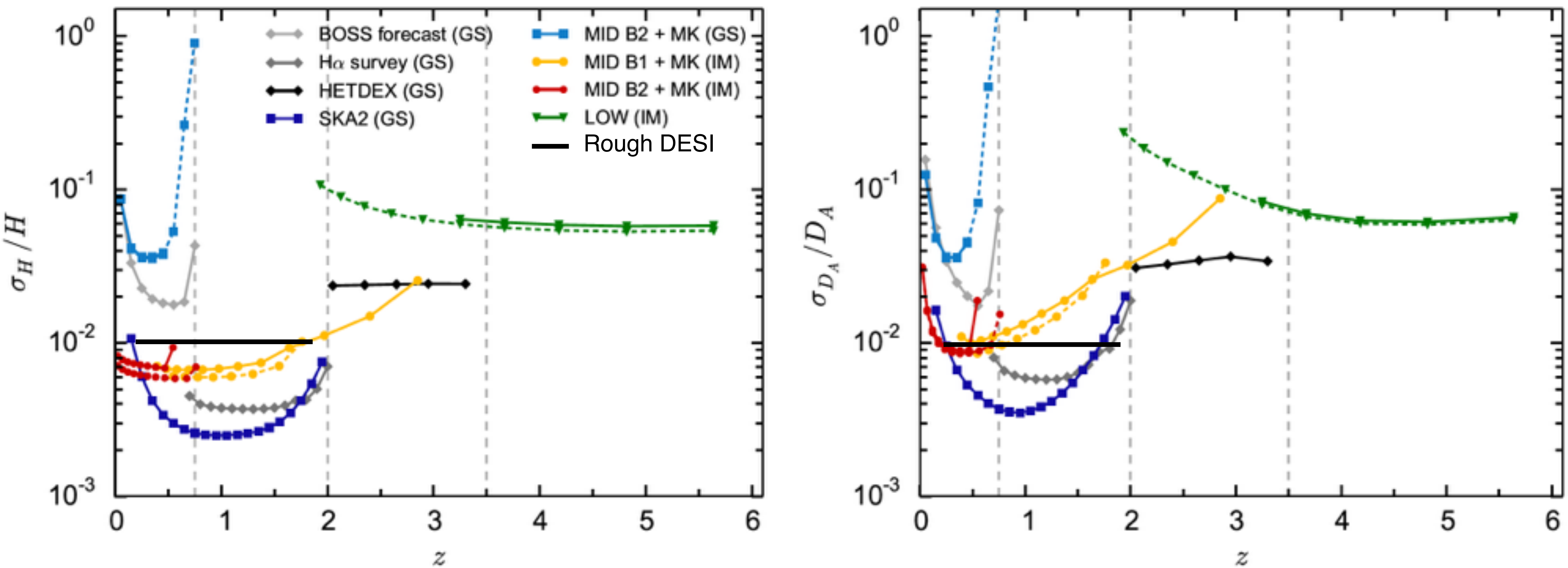

Bull et al. (2015)

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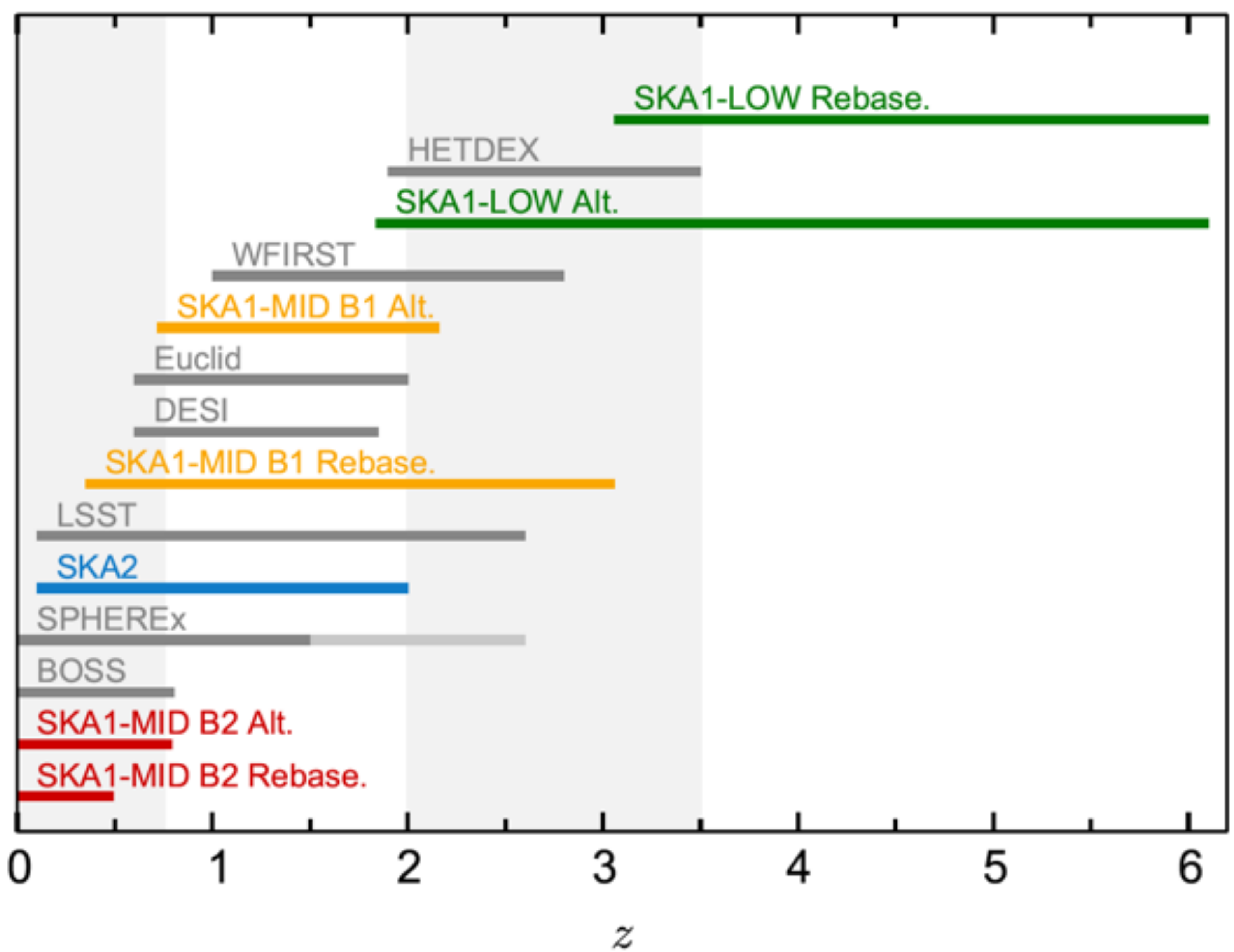


Bull et al. (2015)

Challenges of 21cm cosmology

Challenges of 21cm cosmology

Challenges of 21cm cosmology

- Sensitivity

Challenges of 21cm cosmology

- Sensitivity

    - Astrophysical forecasts assume ~1000 hrs of integration; Cosmological forecasts often assume ~10,000 hrs of integration.

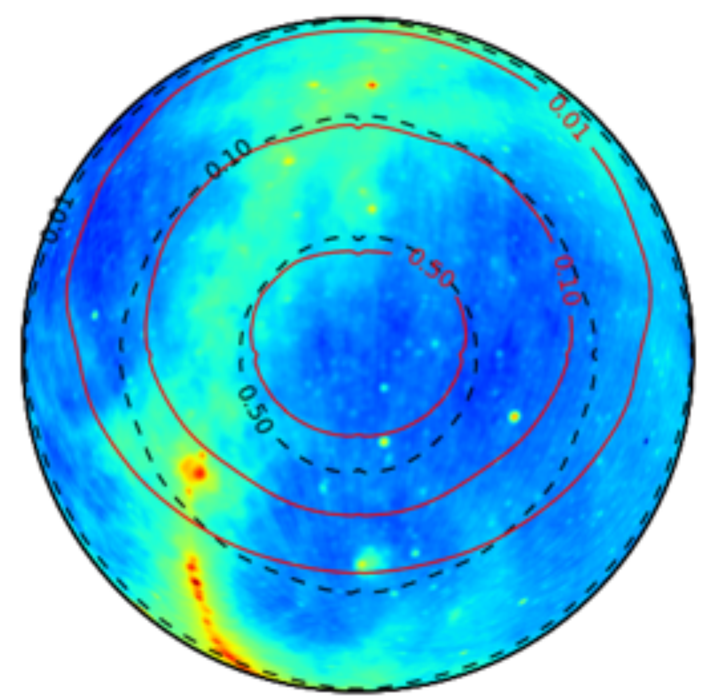
    - Dedicated instruments? More antennas?

Challenges of 21cm cosmology

- Sensitivity
- Foregrounds

Challenges of 21cm cosmology

- Sensitivity
- Foregrounds
    - Typically 10^4 to 10^5 times brighter than cosmological signal



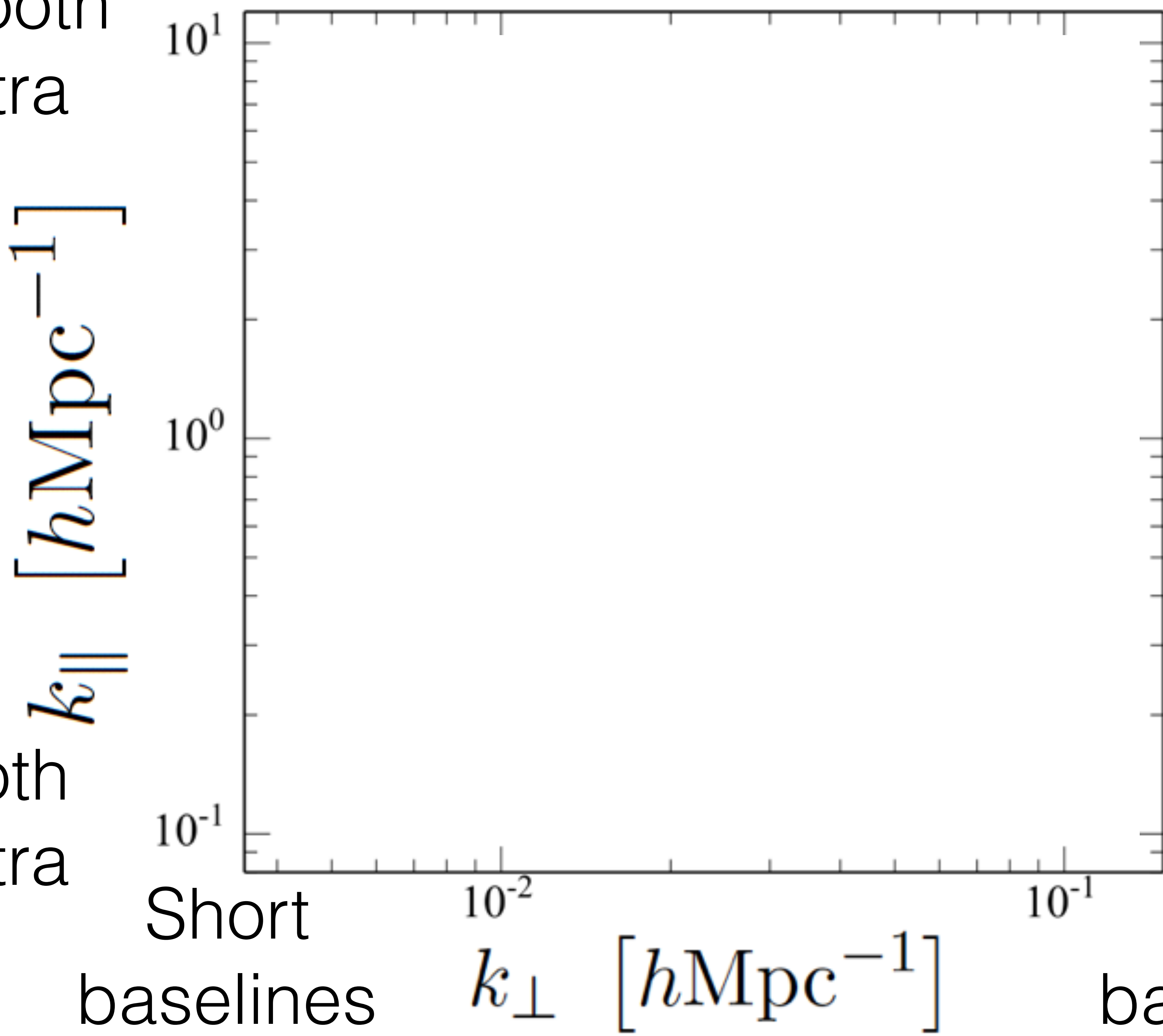
Parsons, **AL** et al. (2015)

Challenges of 21cm cosmology

- Sensitivity
- Foregrounds
    - Typically 10^4 to 10^5 times brighter than cosmological signal.
    - Usually assumed to be spectrally smooth.

Foregrounds in Fourier space

Unsmooth spectra



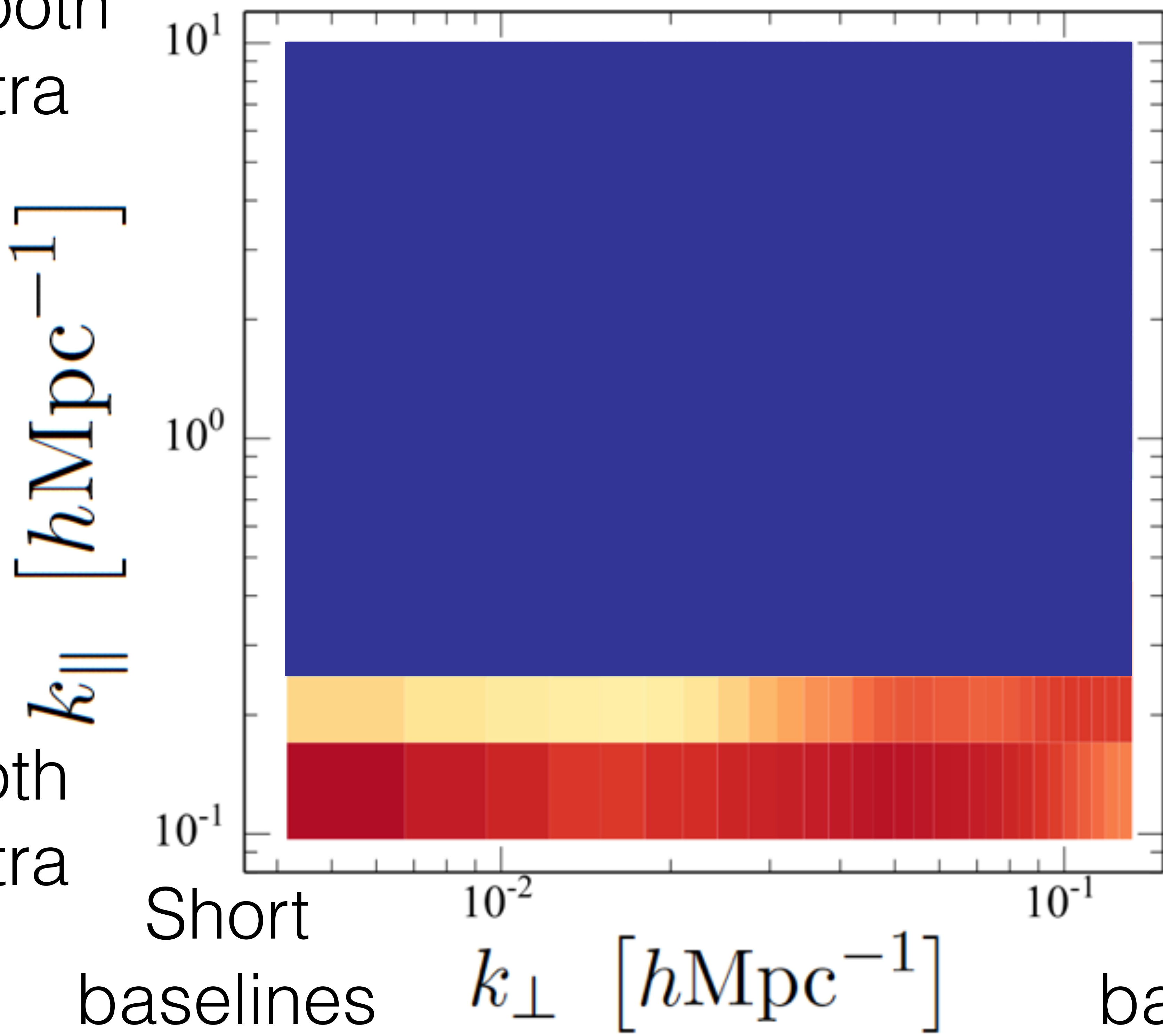
Smooth spectra

Short baselines

Long baselines

Foregrounds in Fourier space

Unsmooth spectra



Smooth spectra

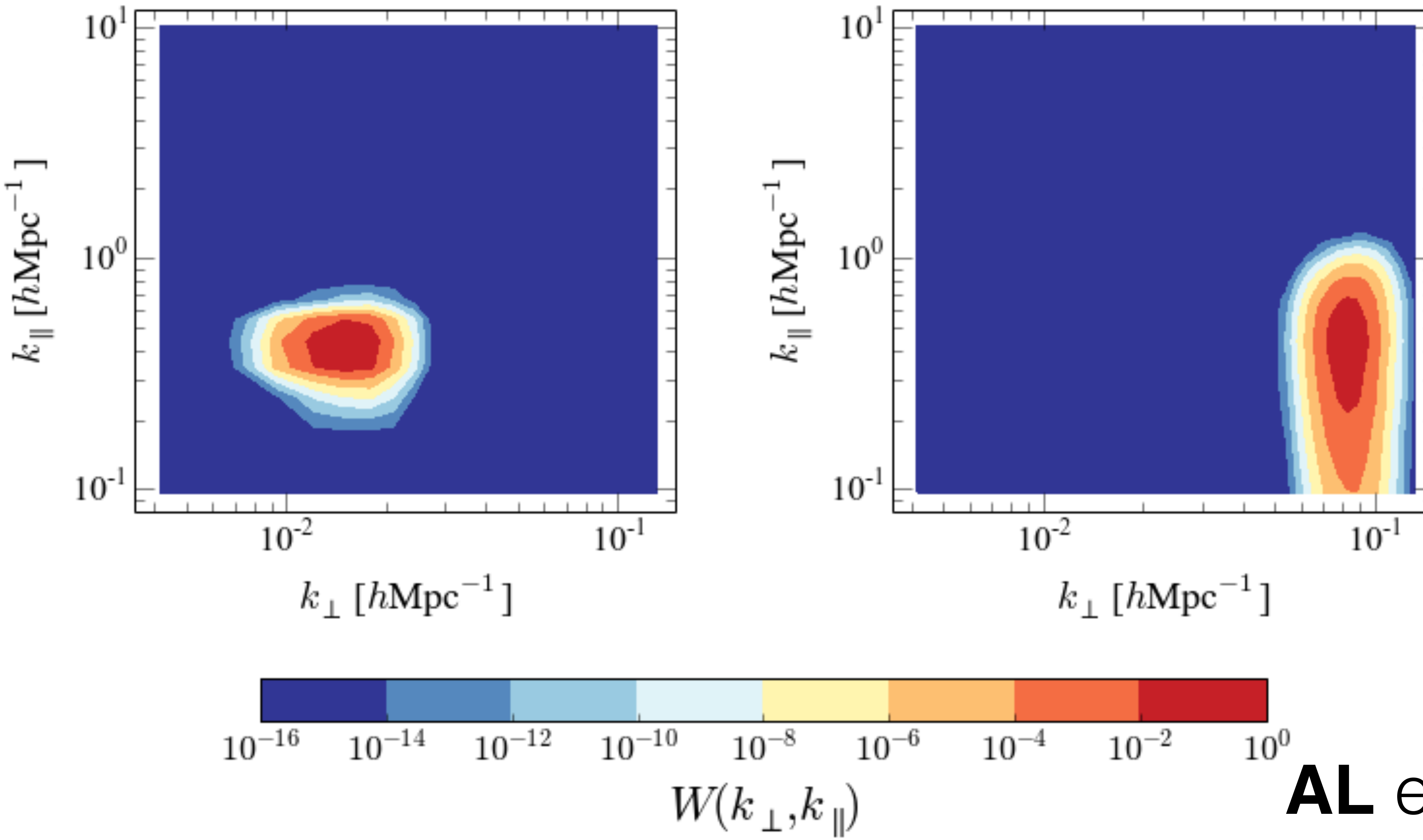
Short baselines

Long baselines

Window functions

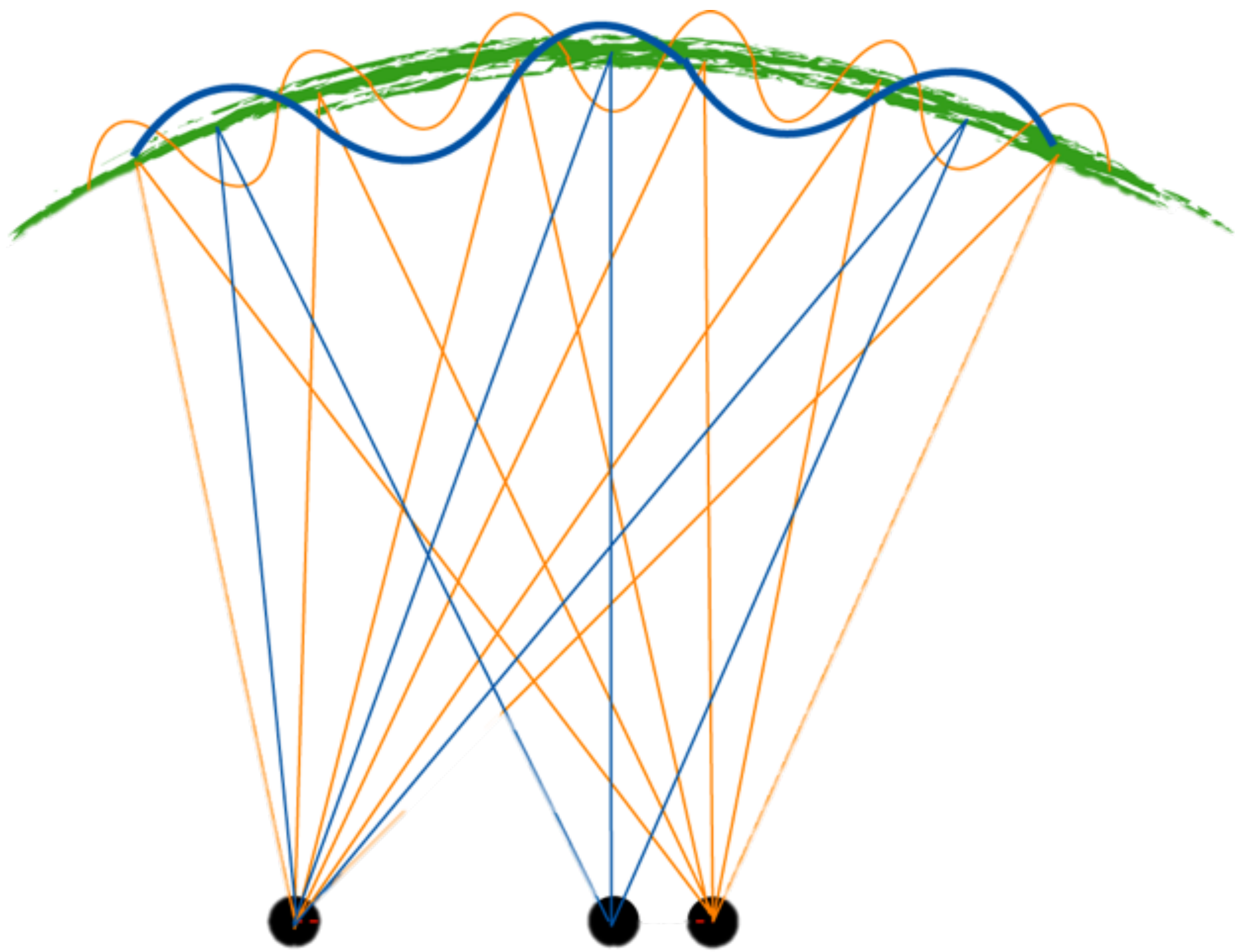
$$P_{\mathrm{meas}}(\mathbf{k}) = \int d^3\mathbf{k}' \underline{W(\mathbf{k}, \mathbf{k}')} P_{\mathrm{true}}(\mathbf{k}')$$

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



AL et al. 2014a,b

Long baselines are inherently more chromatic, making intrinsically smooth spectra appear more



Foregrounds in Fourier space

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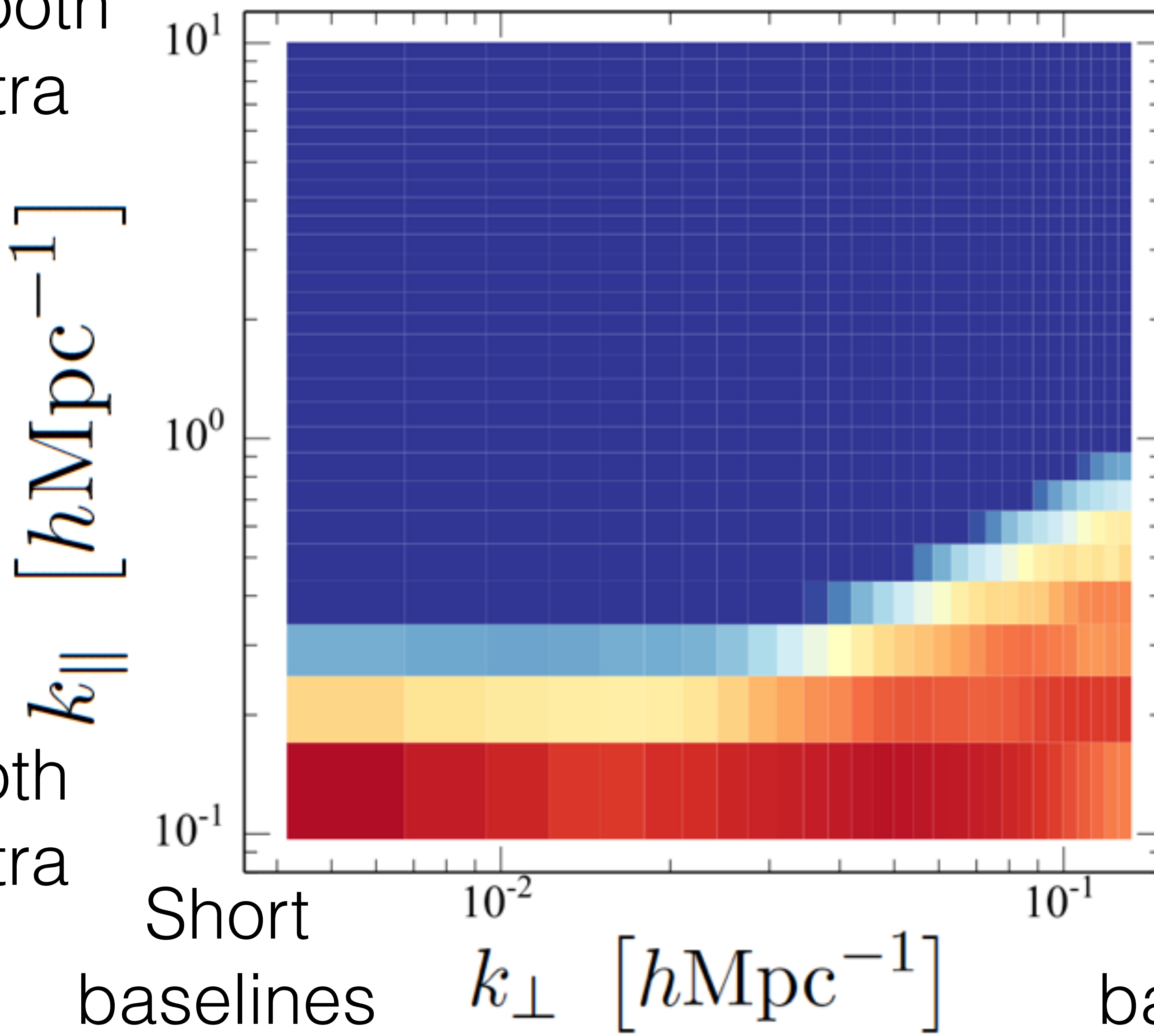

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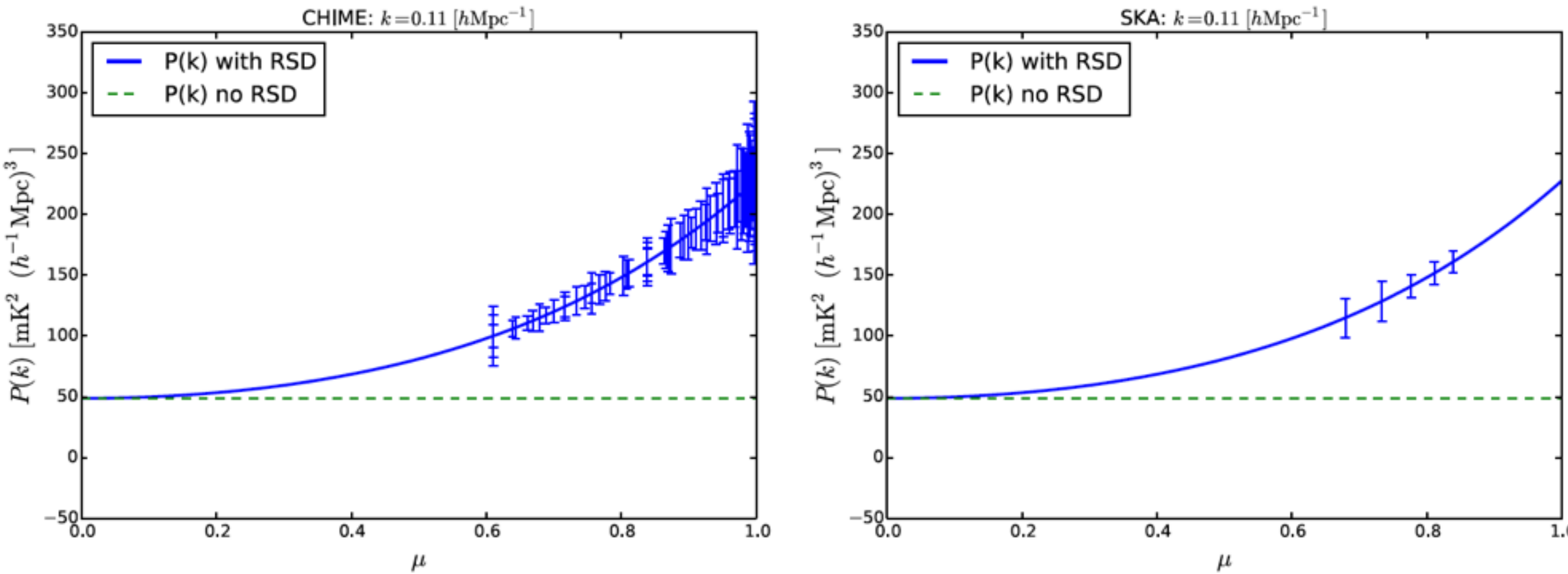
AL et al. 2014a,b


CHIME: $k = 0.11$ $[h\mathrm{Mpc}^{-1}]$
P(k) with RSD
P(k) no RSD
$P(k)$ $[\mathrm{mK}^2\ (h^{-1}\mathrm{Mpc})^3]$
μ
SKA: $k = 0.11$ $[h\mathrm{Mpc}^{-1}]$
P(k) with RSD
P(k) no RSD
$P(k)$ $[\mathrm{mK}^2\ (h^{-1}\mathrm{Mpc})^3]$
μ

Pober (2015)

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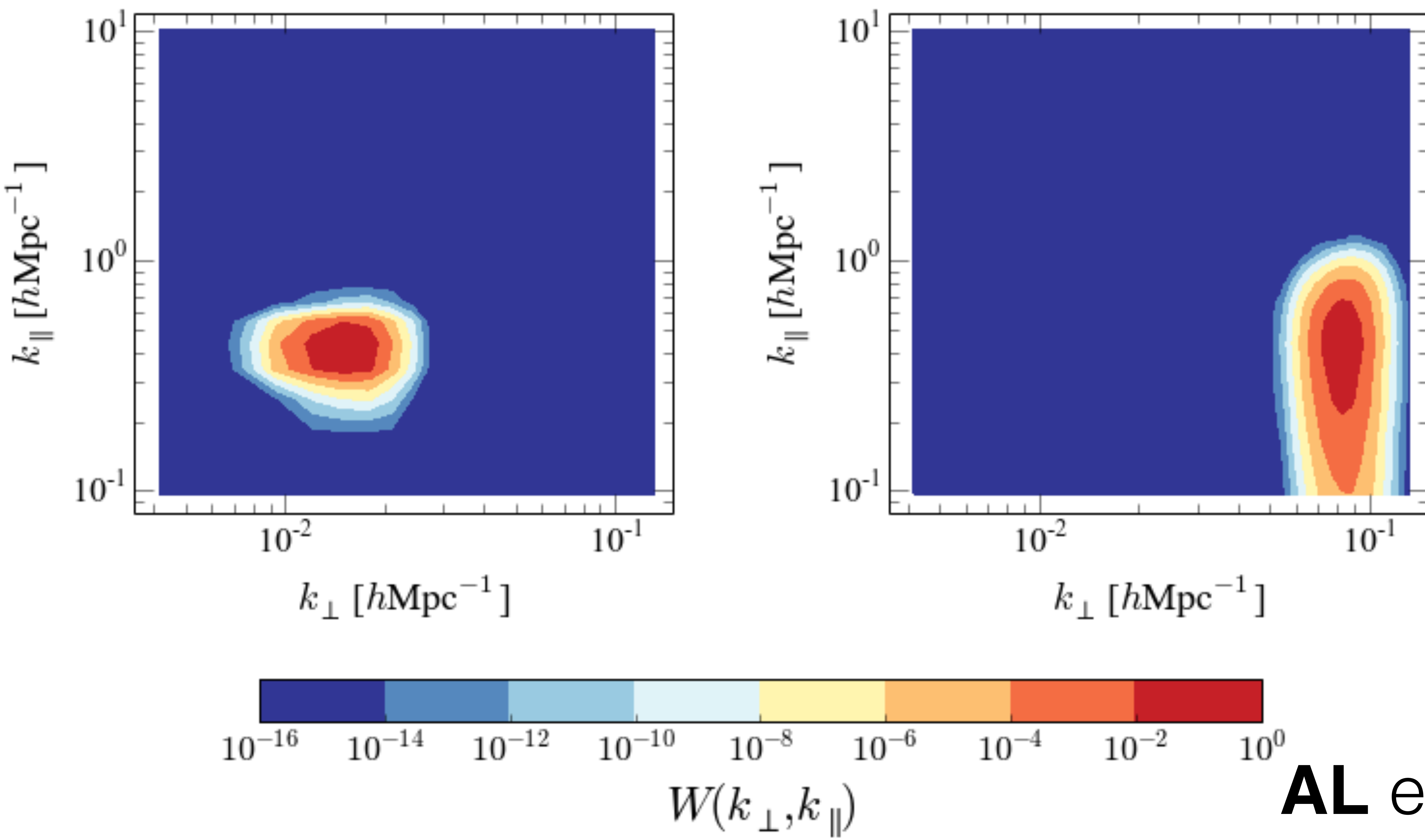

AL et al. 2014a,b

Challenges of 21cm cosmology

- Sensitivity
- Foregrounds
- Calibration and next-generation correlators

Correlators that scale as O(n log n) instead of O(n^2)

$\sum m_\nu \sim \pm 0.06$ eV with SKA

± 0.0007 eV with a

~~specialized array~~

10^6 element FFTT

Mao et al. 2008

The Promise and Challenges of 21cm Cosmology

- 21cm cosmology has multiple pathways for contributing to cosmology.
- These give independent cosmological constraints, potentially reaching higher redshifts.
- Taking full advantage of the cosmological potential of the 21cm line involves tackling challenges in foreground mitigation and calibration.