Constraints on Heating During the Era of First Galaxies: Recent Results from PAPER

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ICTP Workshop

Take-home points

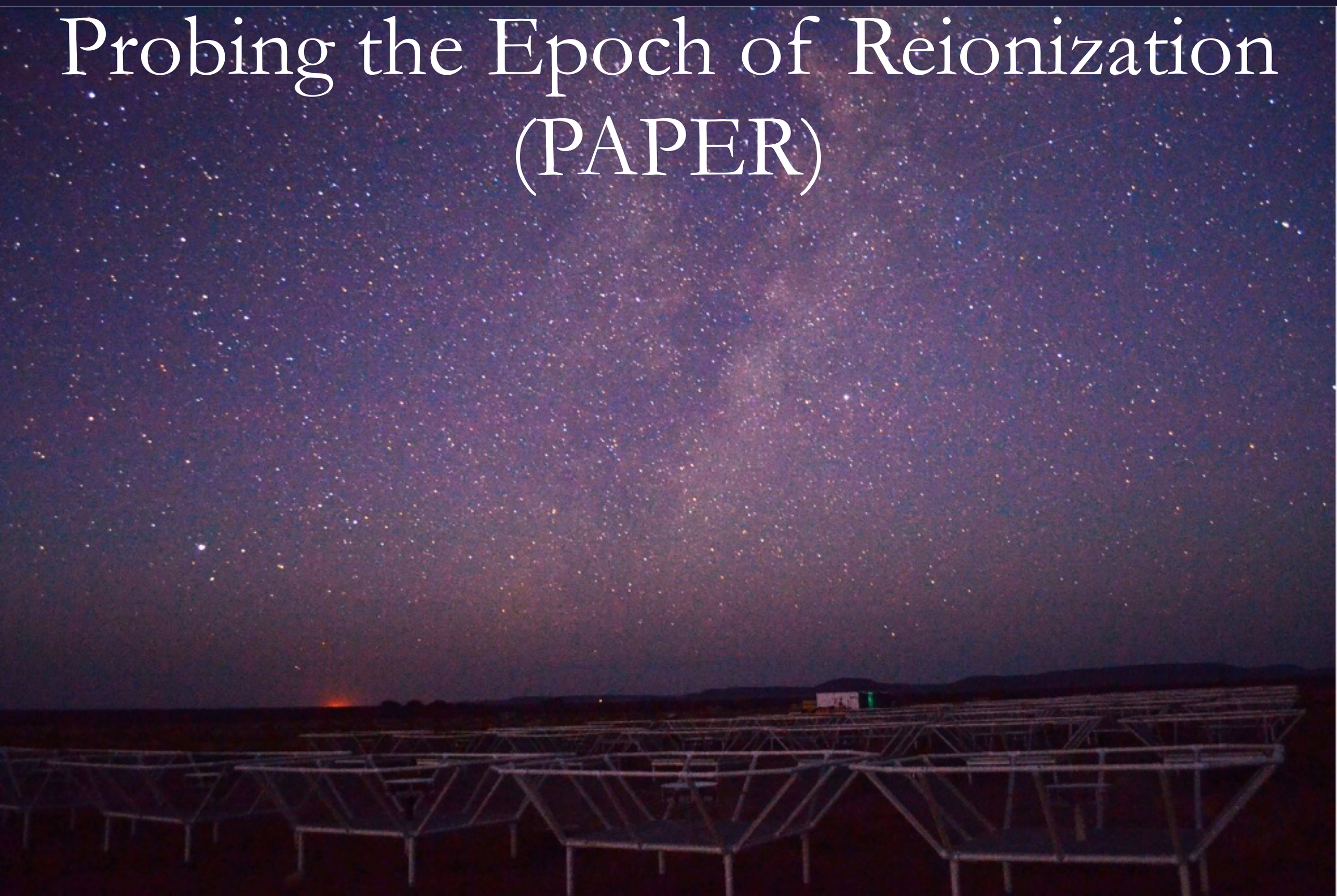
- The PAPER instrument does not look like a conventional imaging radio interferometer. Short, redundant baselines provide good sensitivity.

- PAPER's unusual design has led to some unusual analysis techniques, such as redundant baseline calibration and fringe-rate filtering.

- Recent PAPER measurements have set scientifically interesting upper limits on the 21cm power spectrum, placing constraints on heating at $z = 8.4$

The PAPER instrument

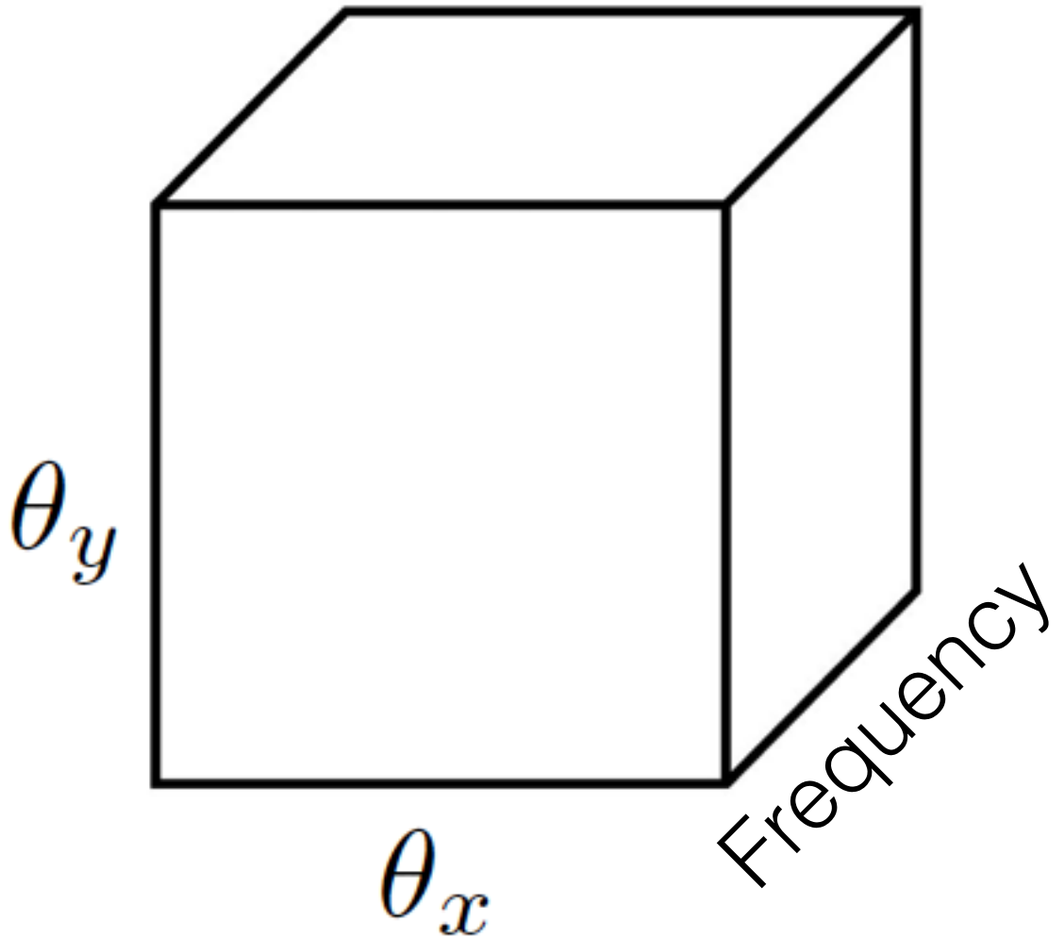
Donald C. Backer Precision Array for Probing the Epoch of Reionization (PAPER)

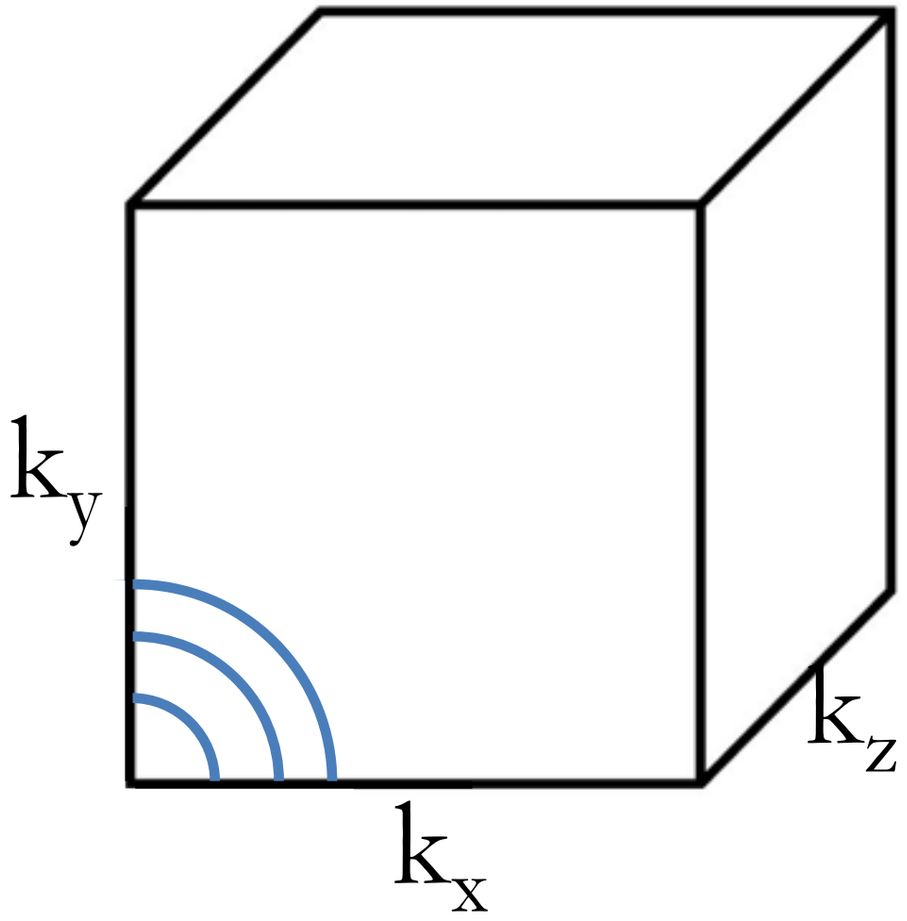


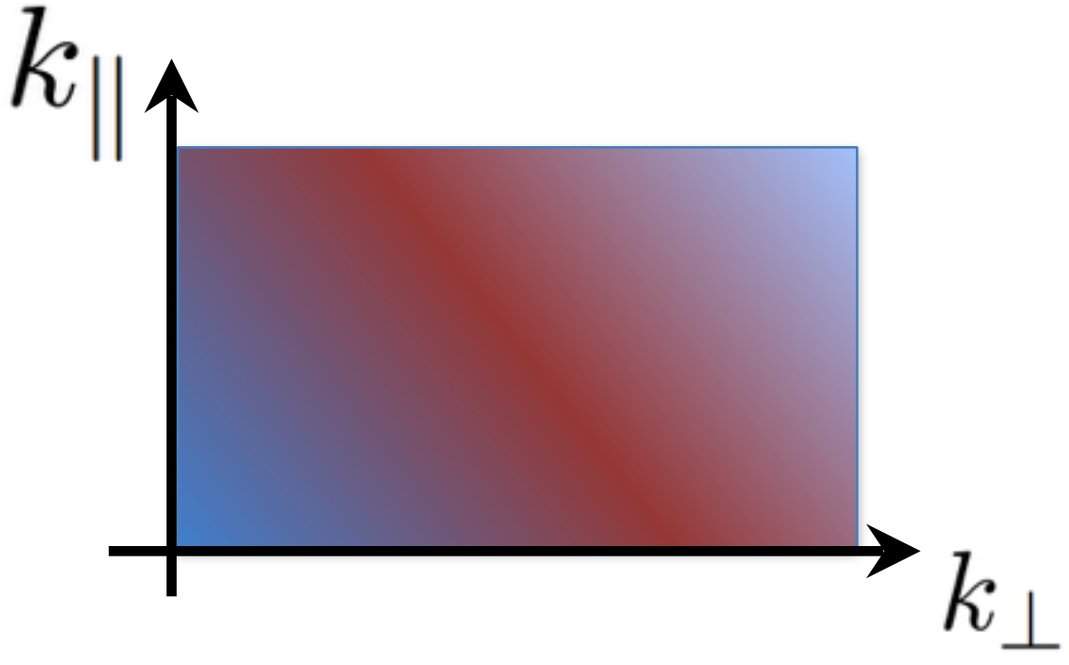
PIs: Parsons, Bradley
Co-PIs: Aguirre, Carilli

Ali, Boyd, Chang, Cheng, DeBoer, Dexter, Dillon, Greenberg, Gugliucci, Horrell, Hsyu, Jacobs, Klima, Lacasse, **AL**, MacMahon, Moore, Parshare, Pober, Stefan, Walbrugh, Zheng

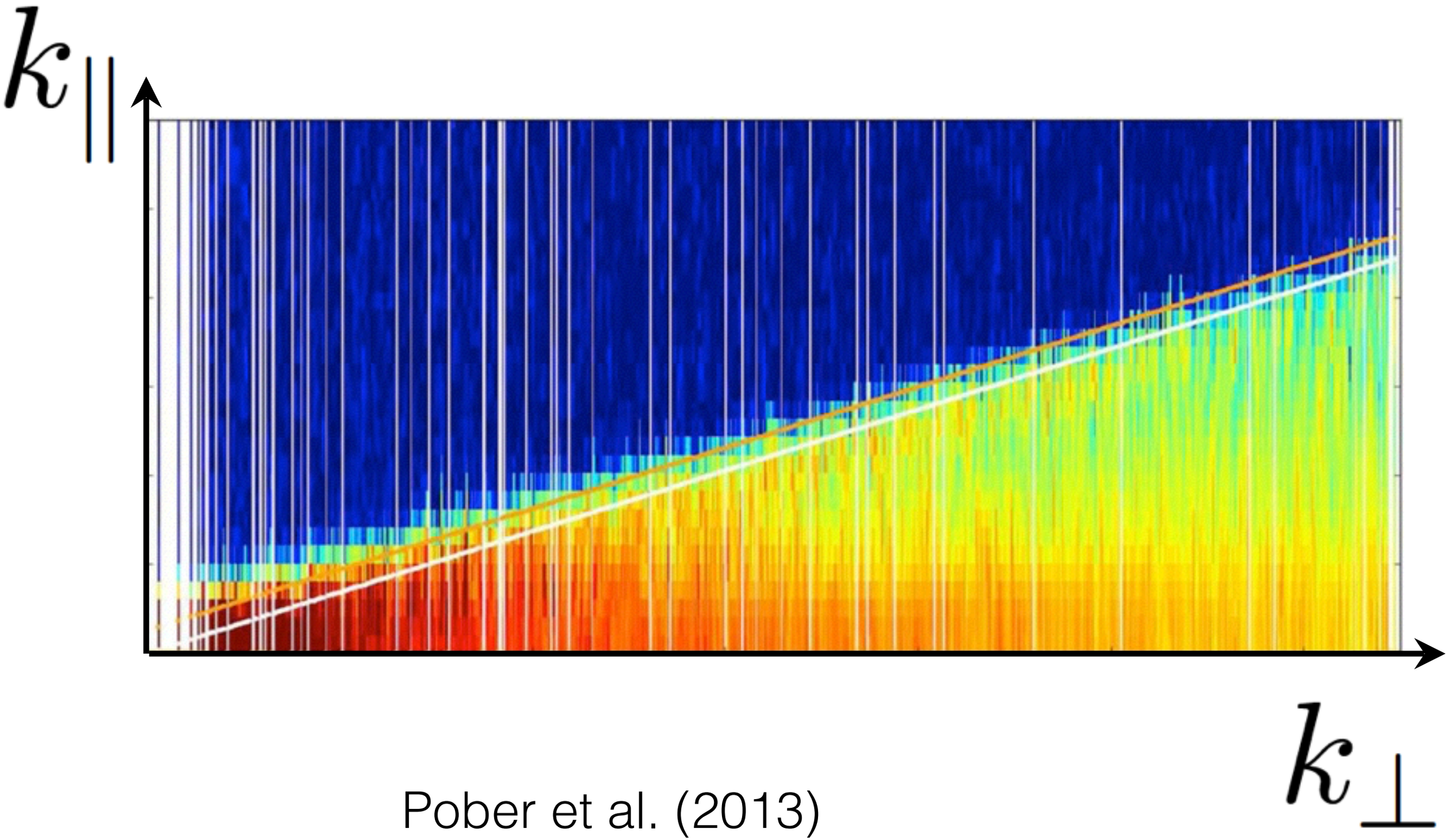
Why does PAPER look the way it does?


θ_y
θ_x
Frequency


k_y
k_z
k_x

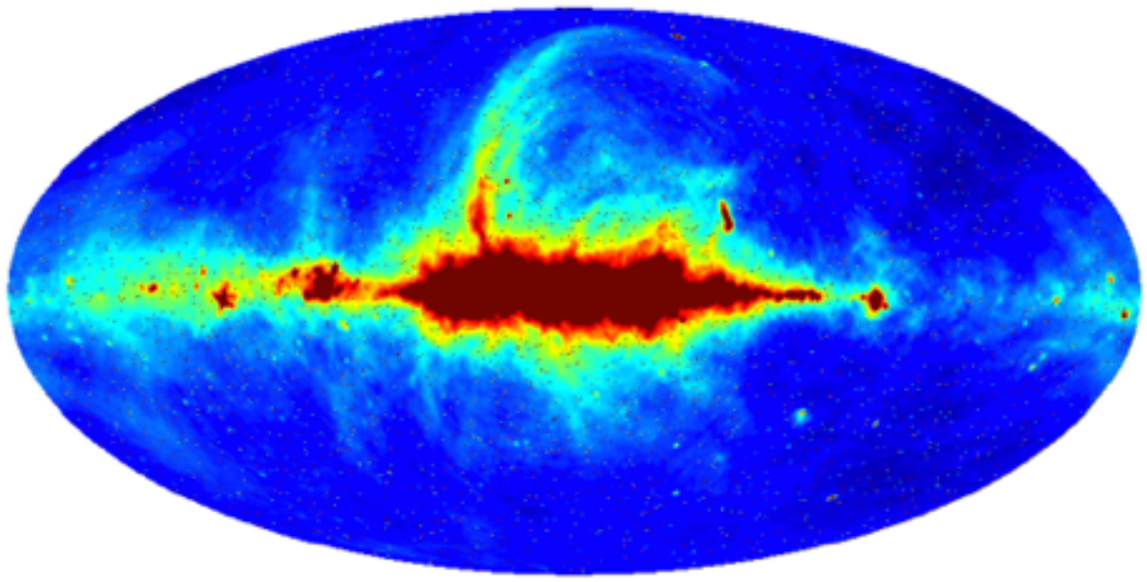

$k_{\|}$
$k_{\perp}$

A bright “wedge” appears. These are foreground contaminants

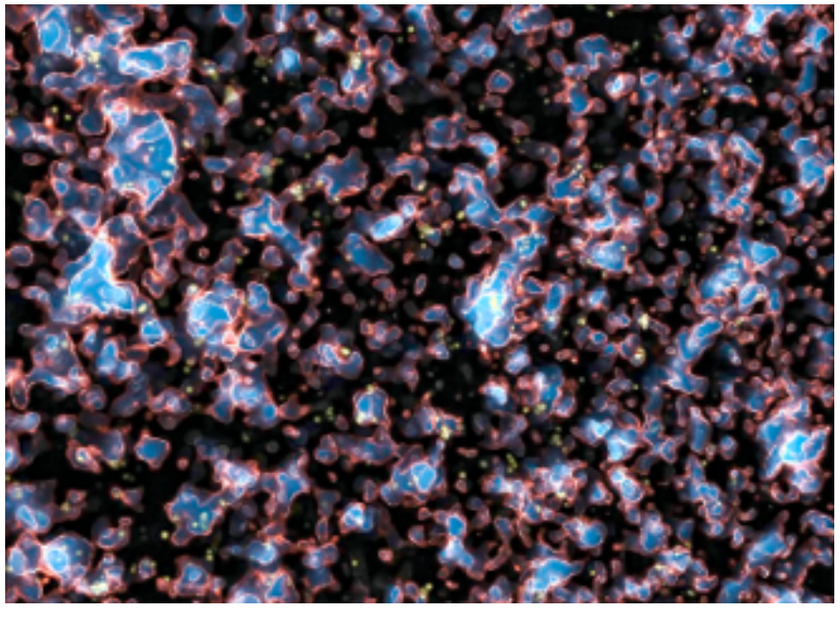


Pober et al. (2013)

Foregrounds are bright and dominate the cosmological signal



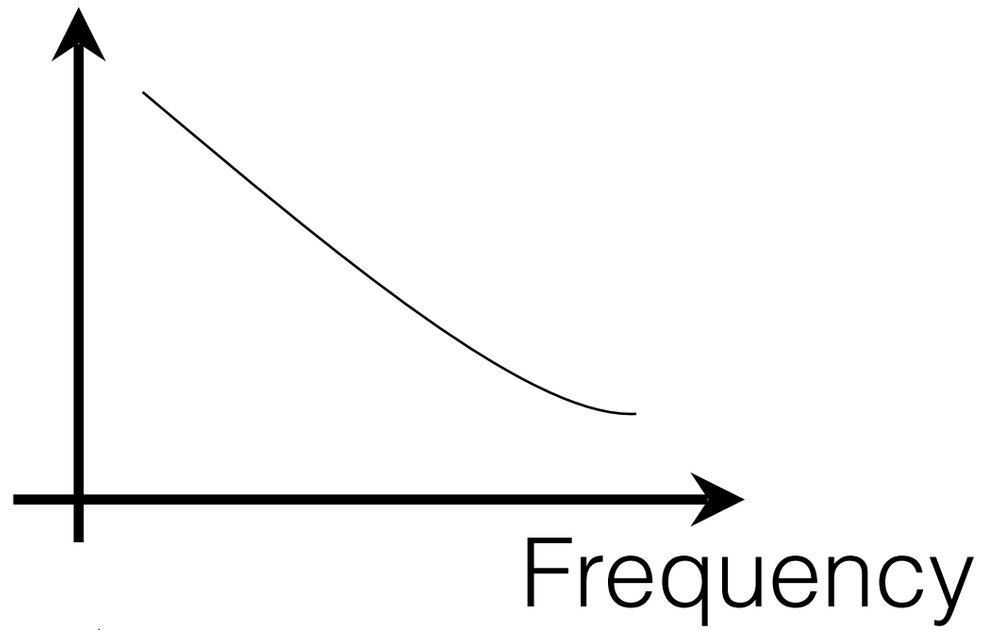
~100s to 1000s K



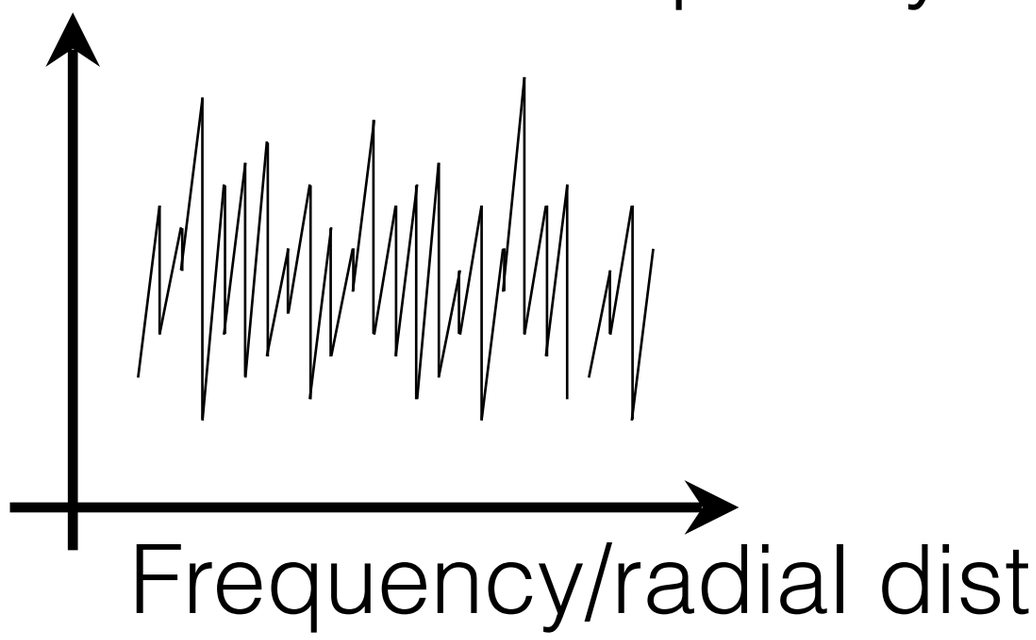
~ few mK ?

Foregrounds are expected to be smooth functions of frequency

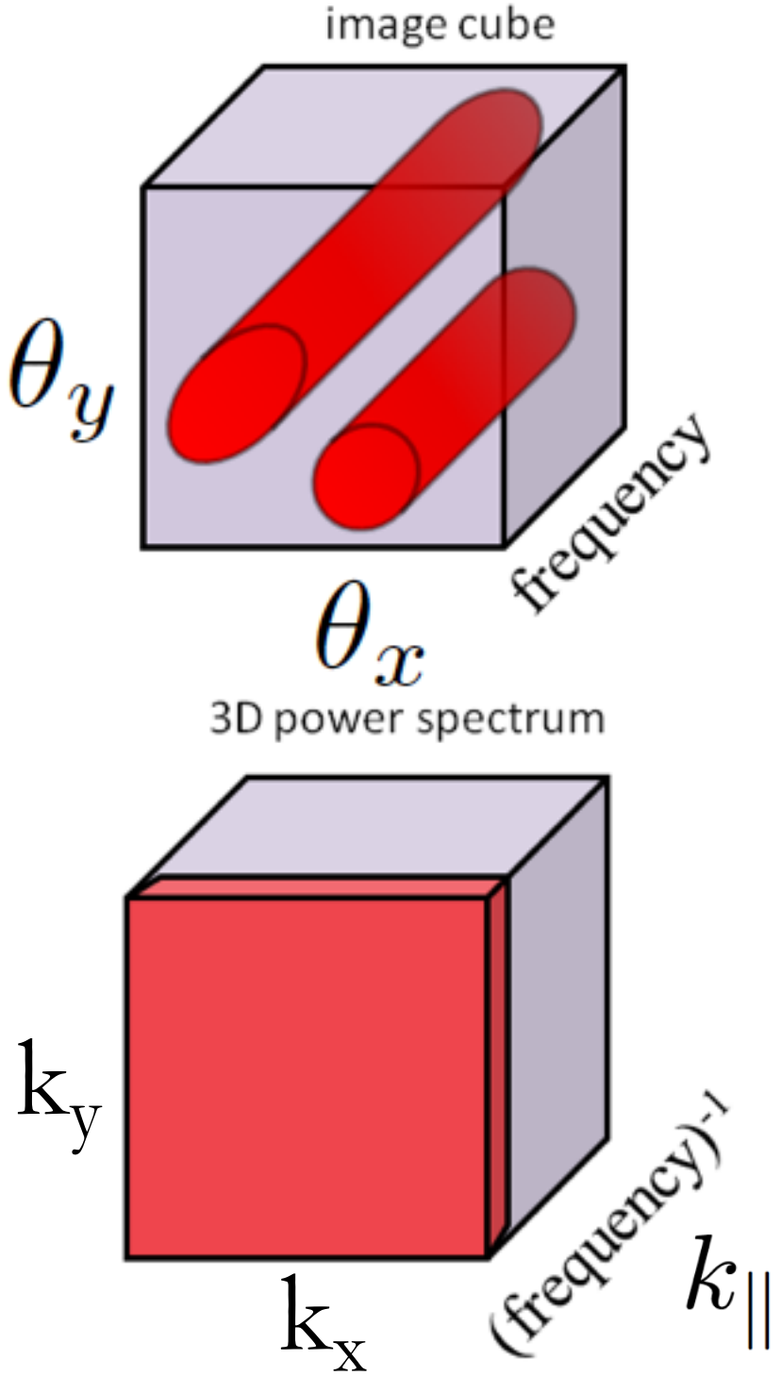
Foregrounds



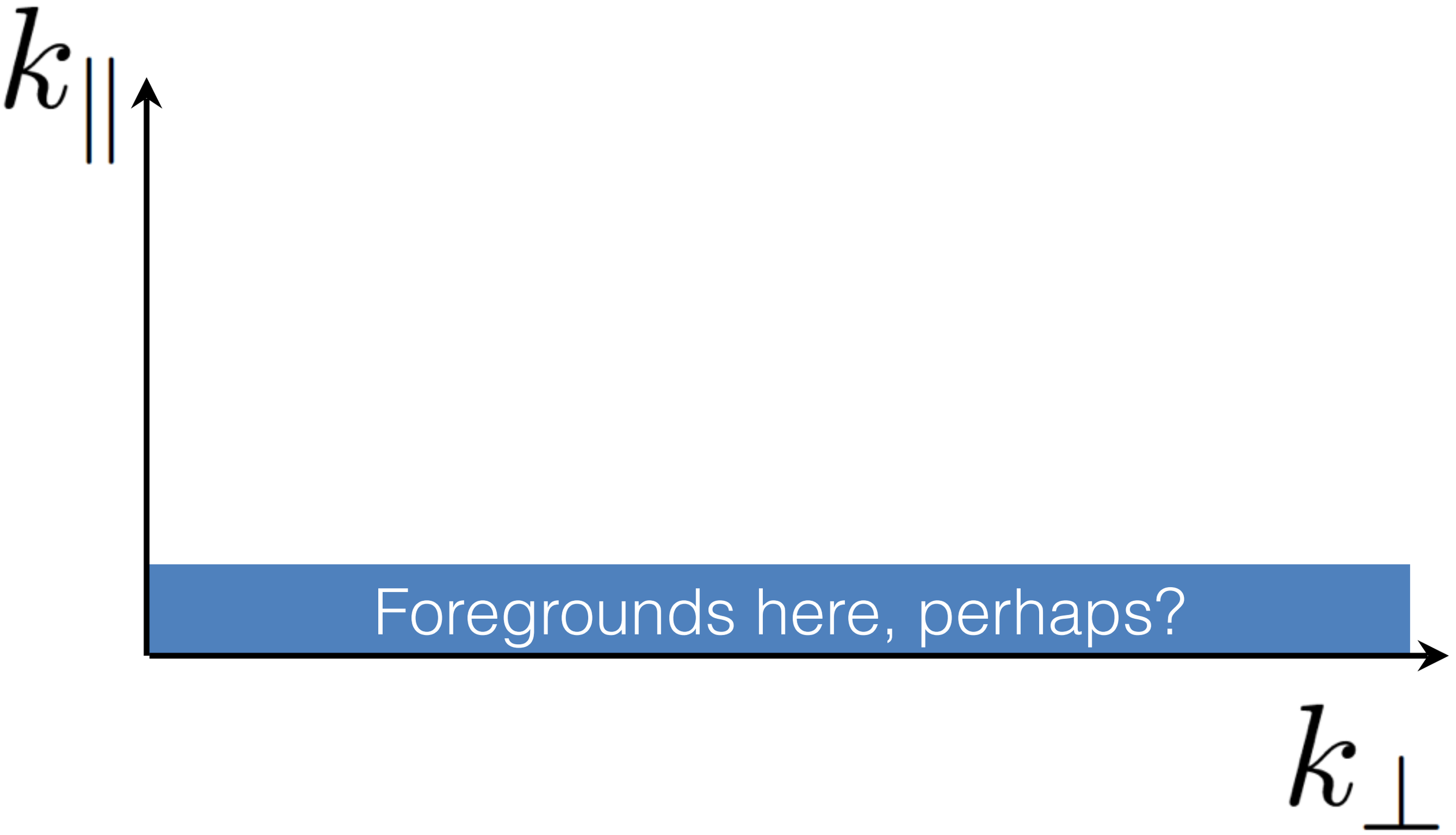
Cosmological signal



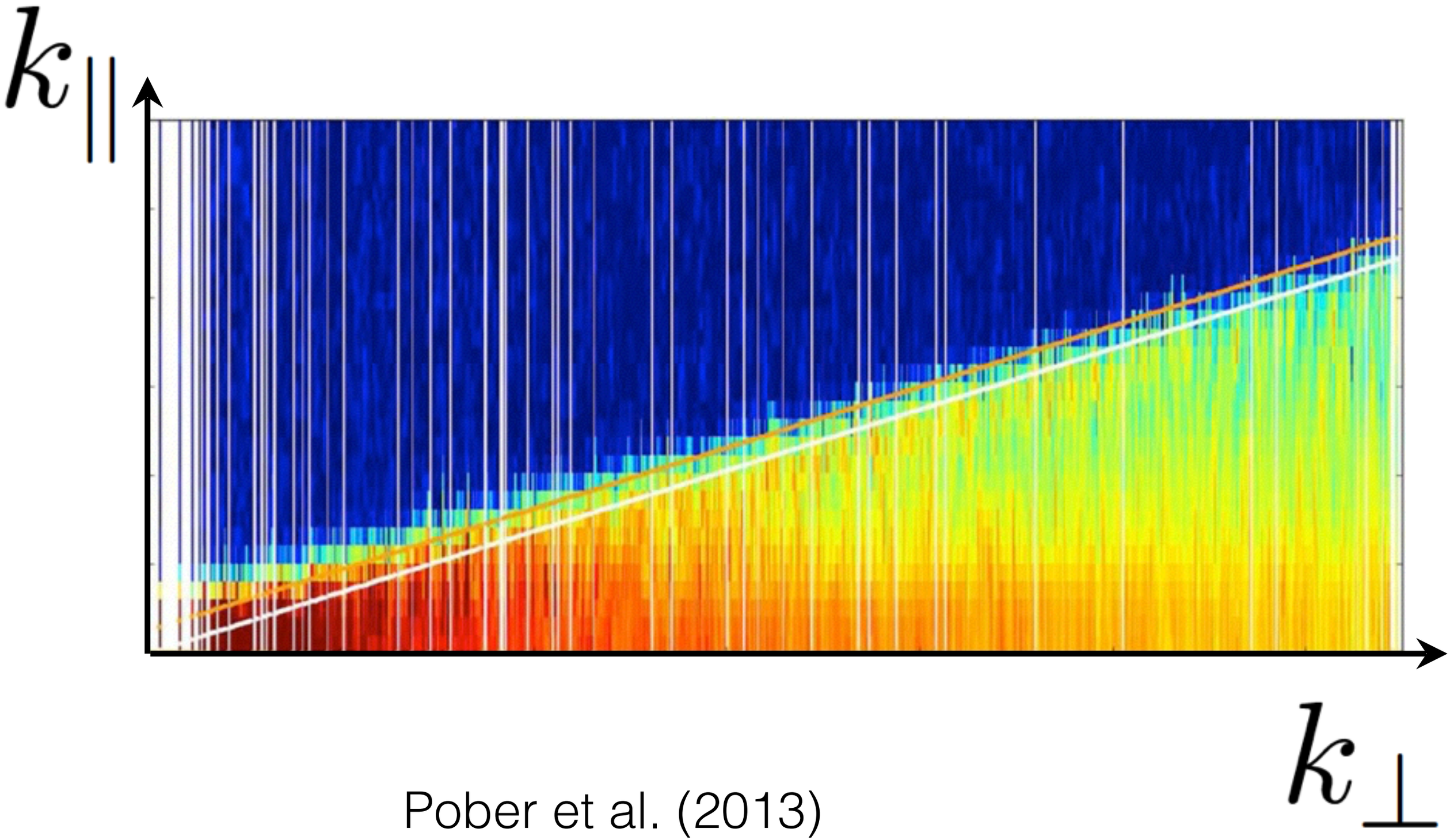
Foregrounds and power spectra



Foregrounds are probably localized in Fourier space…

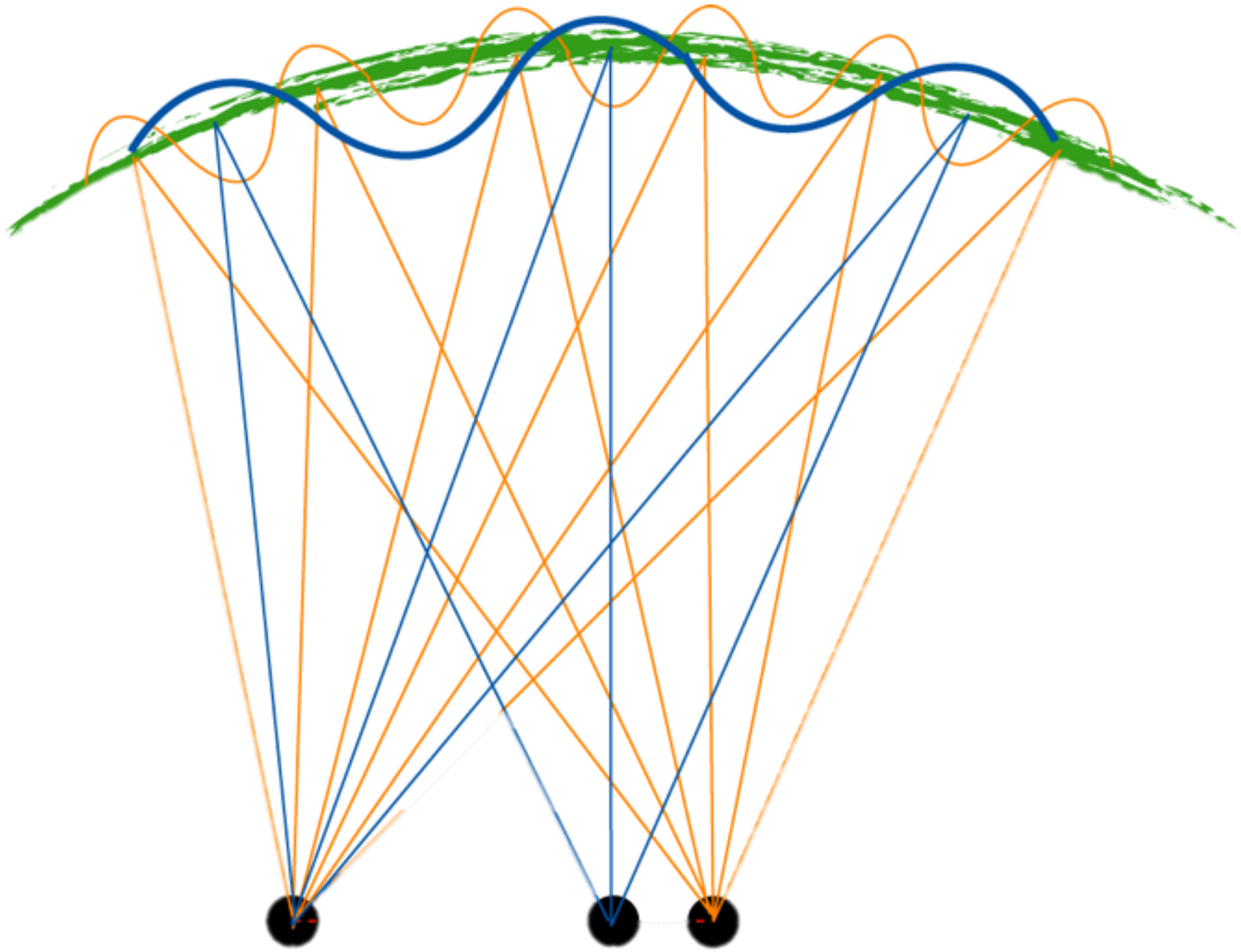


…but not THAT localized because of subtleties associated with interferometry



Pober et al. (2013)

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



Interferometry and power spectra

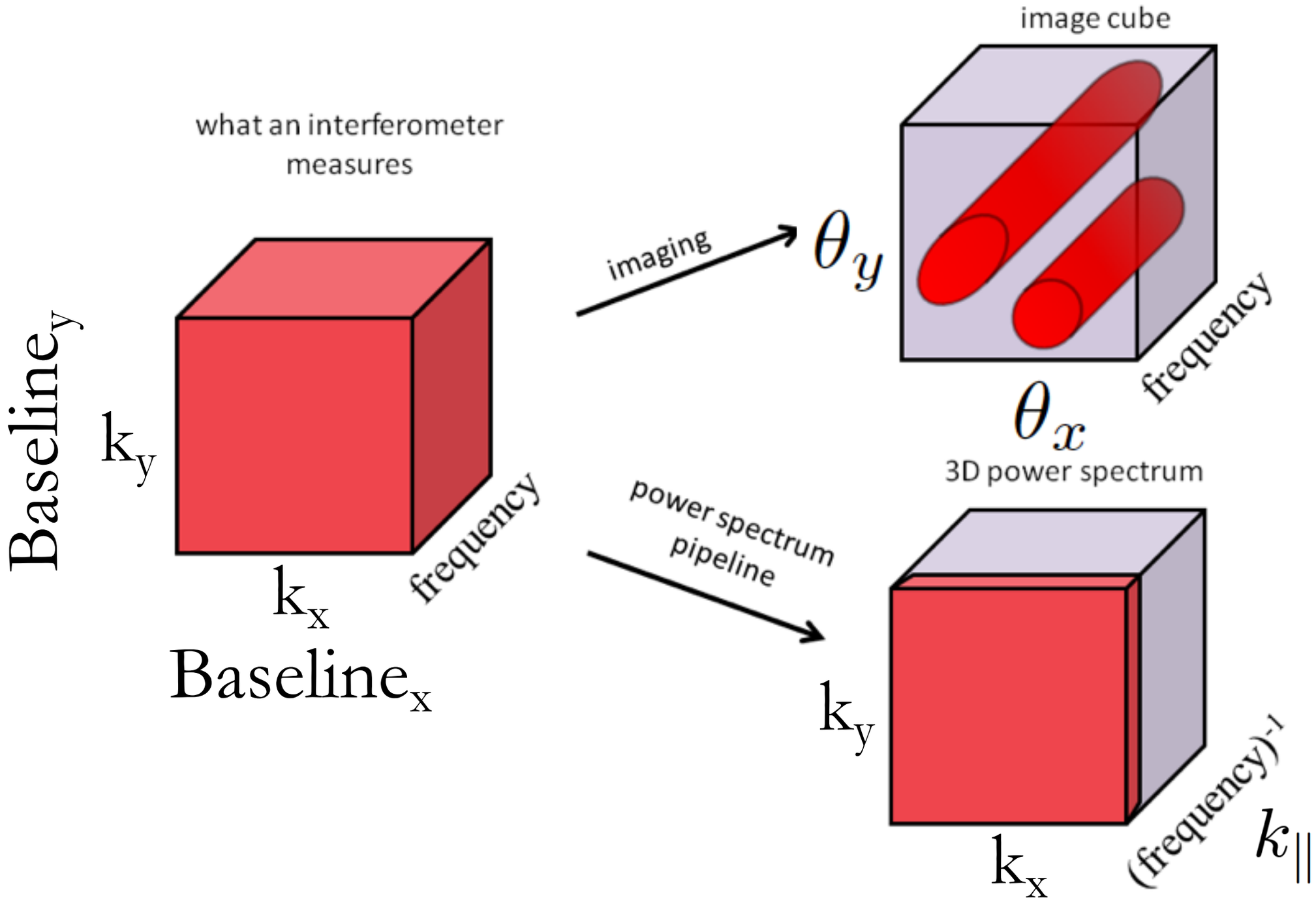
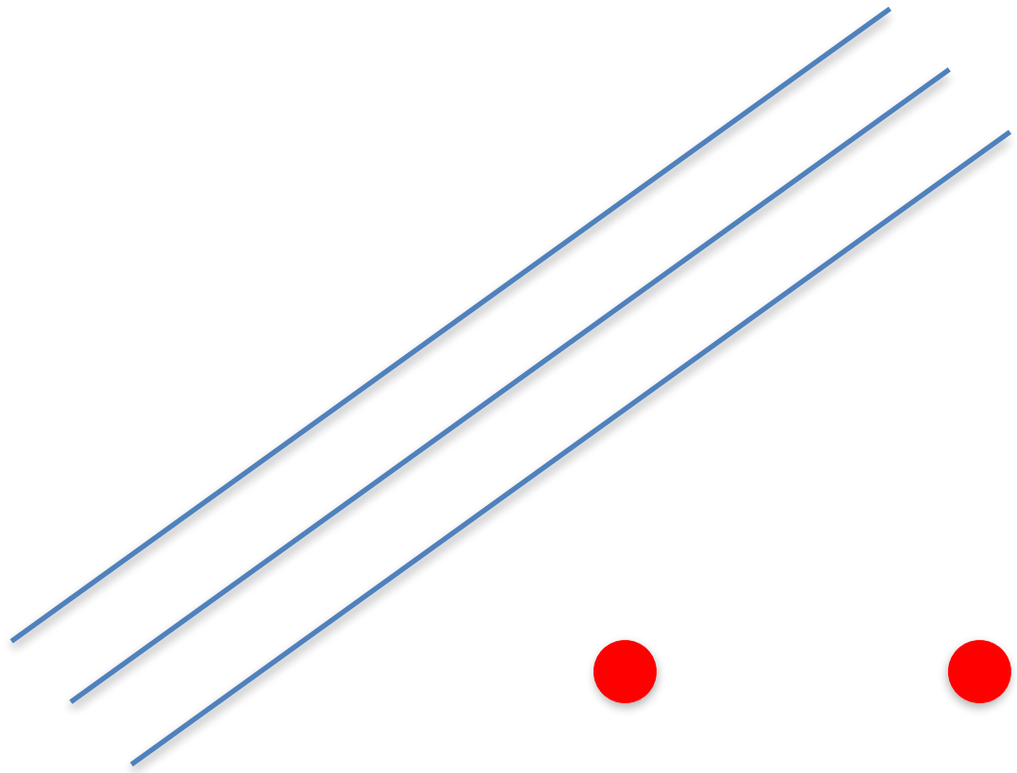
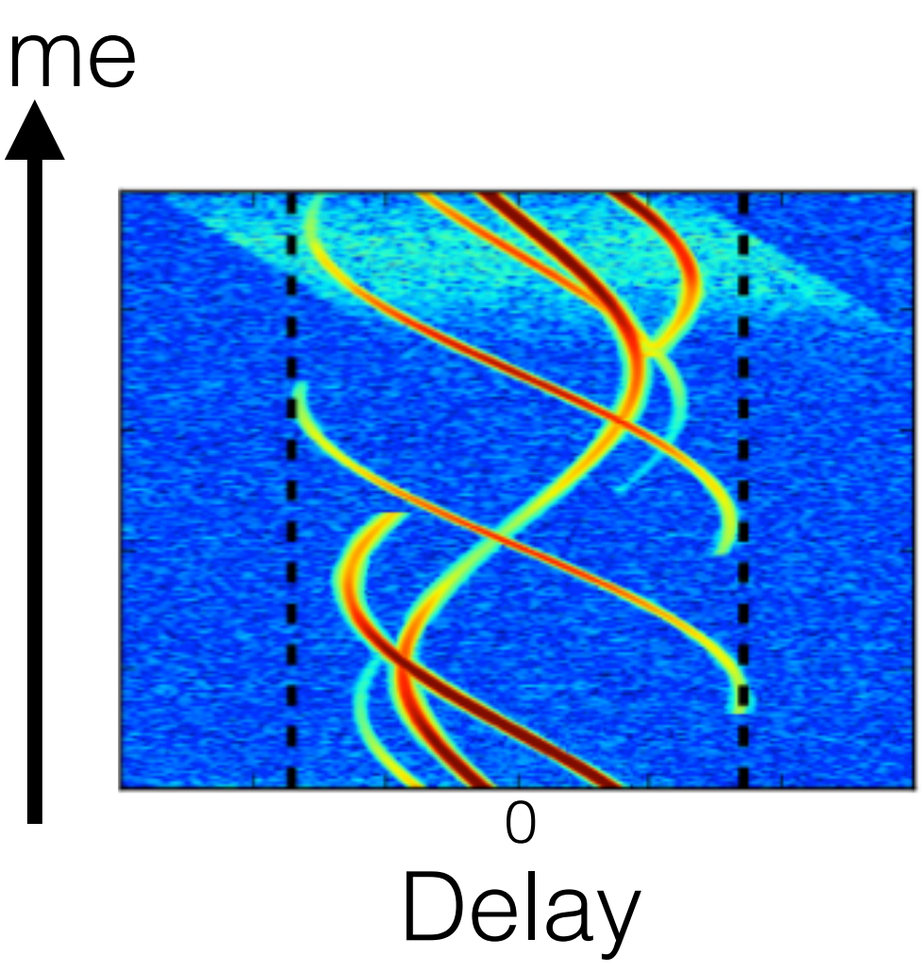


Image credit: Pober

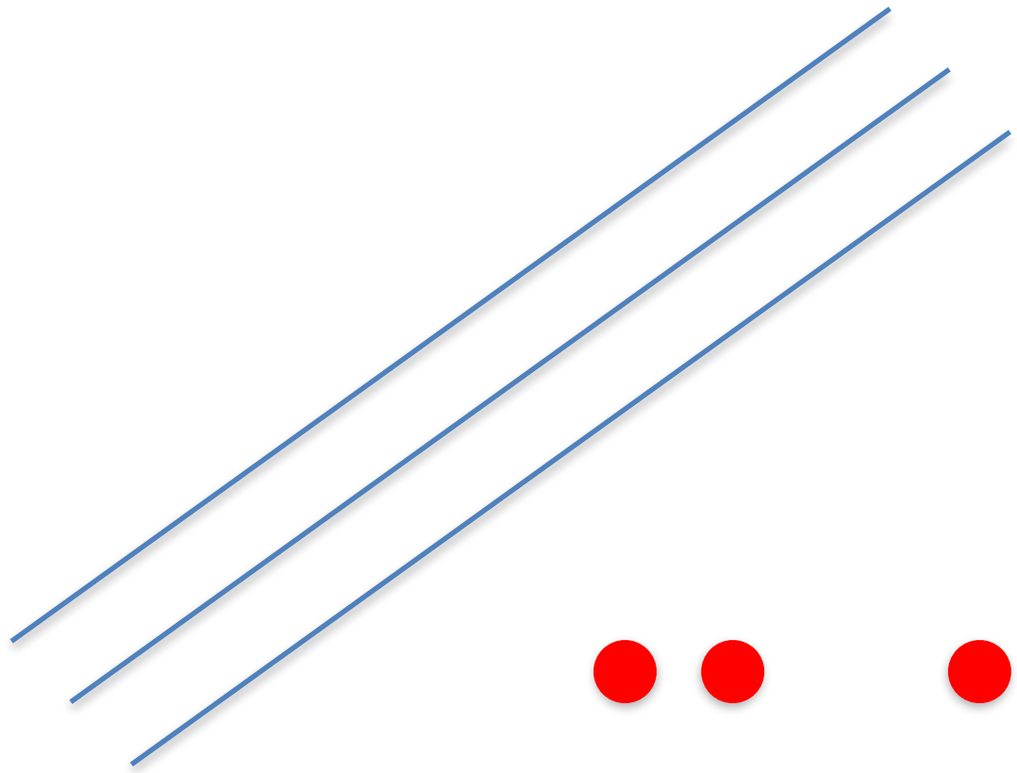
$k_{||} \sim$ Baseline time delay



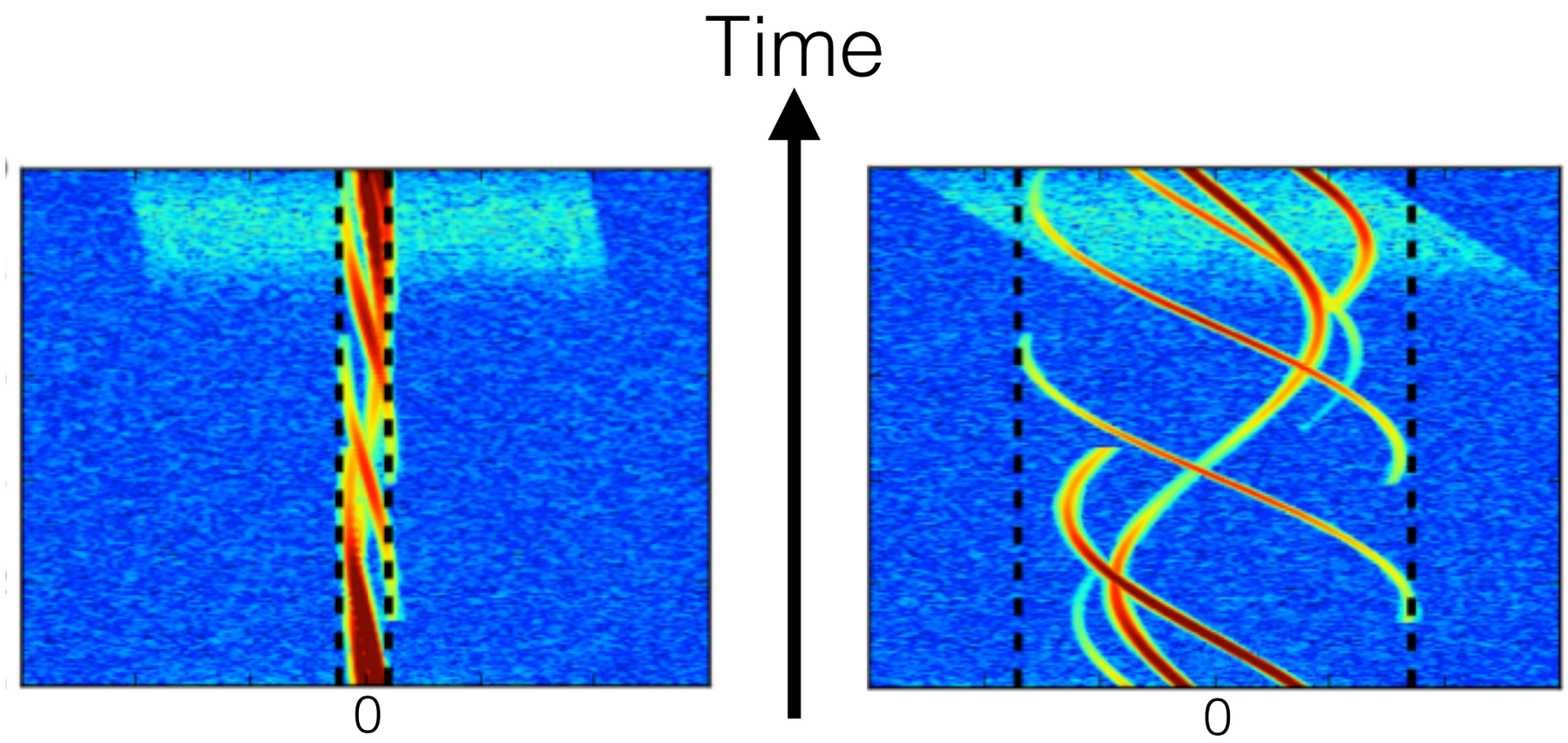
$k_{||} \sim$ Baseline time delay



$k_{||} \sim$ Baseline time delay



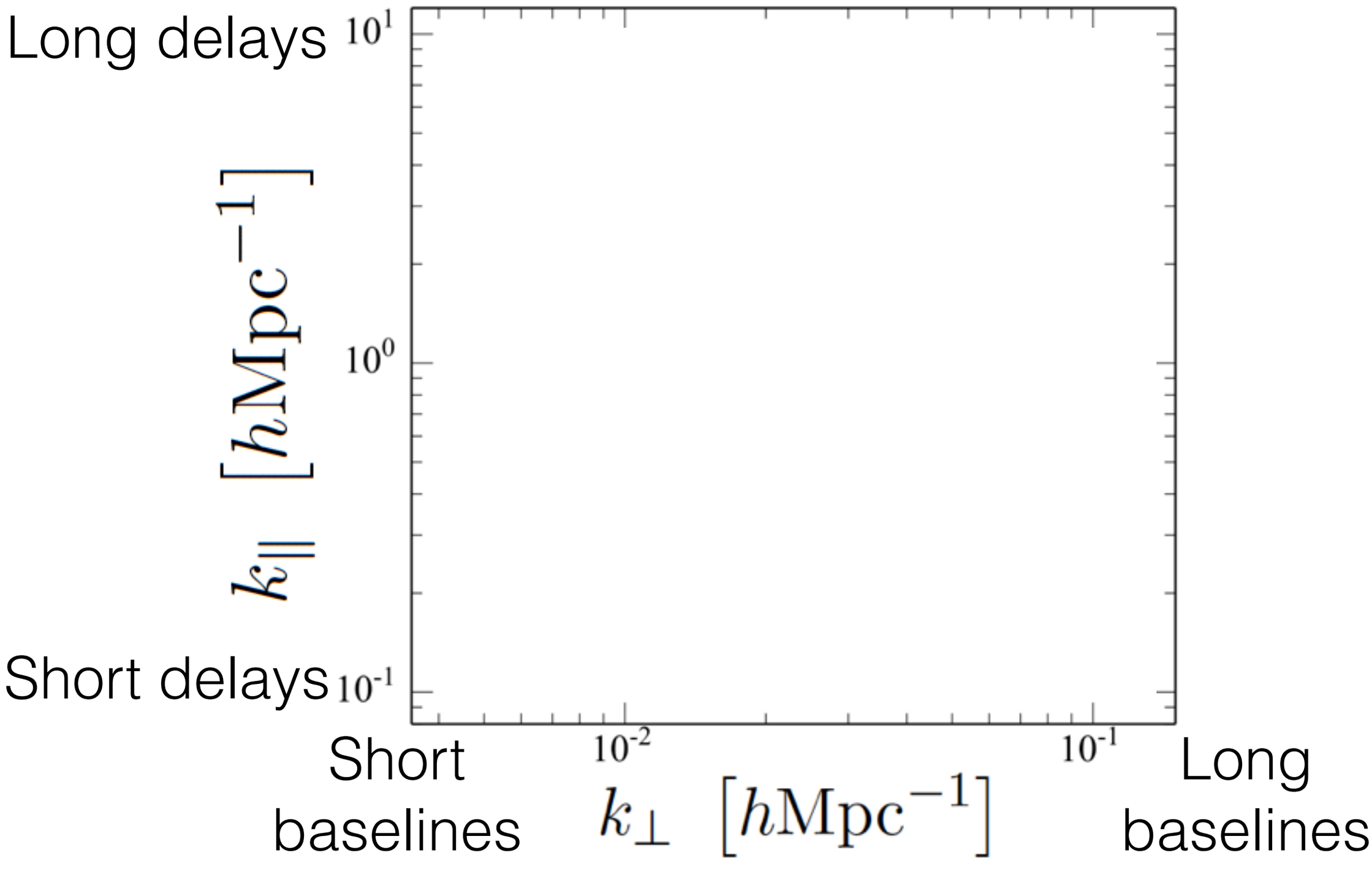
$k_{||}$ ~ Baseline time delay



Short baseline
Low $k_{\perp}$

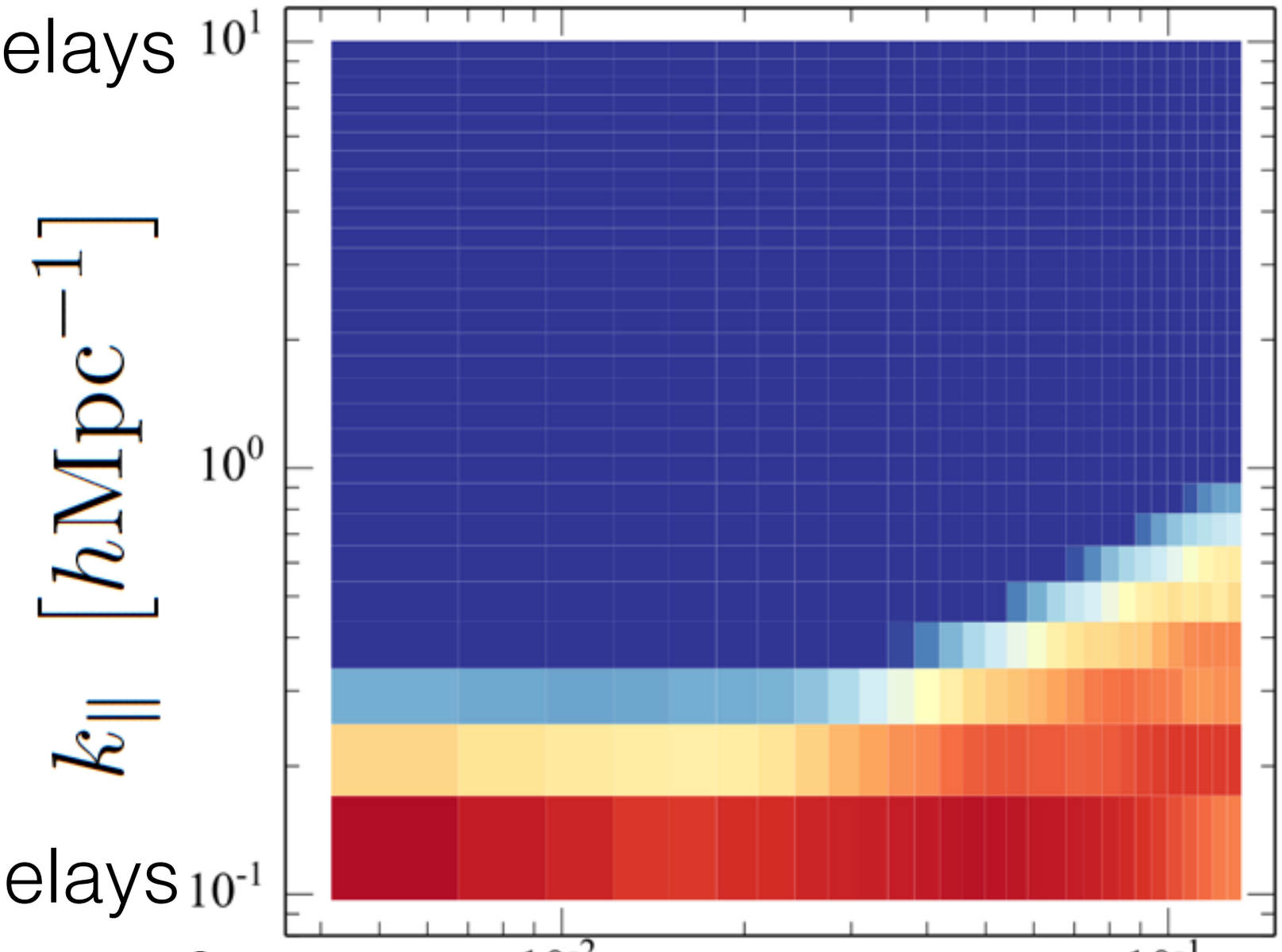
Long baseline
Large $k_{\perp}$

Foregrounds should appear in a “wedge”



Foregrounds should appear in a “wedge”

Long delays



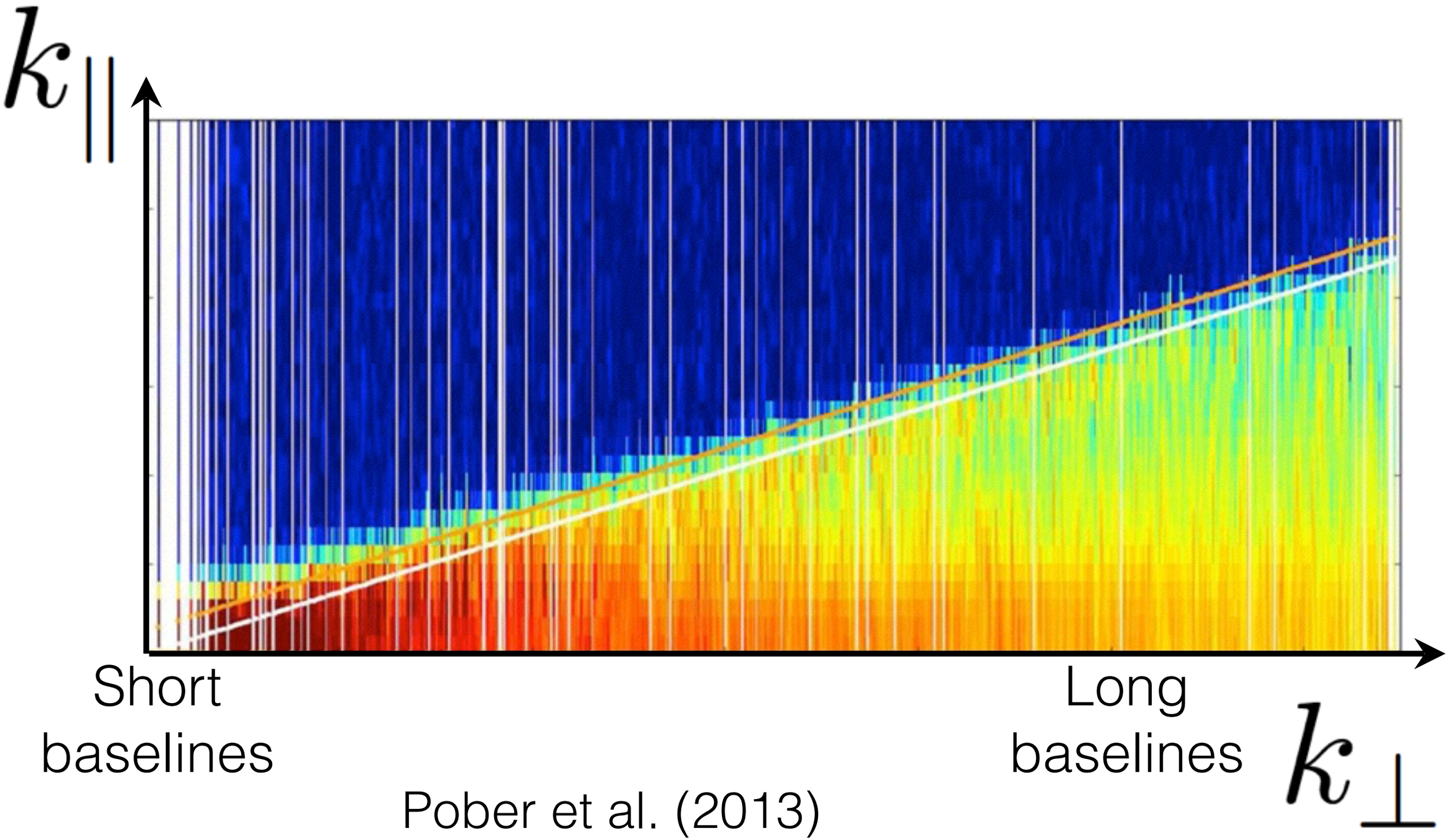
Short delays

Short baselines

Long baselines

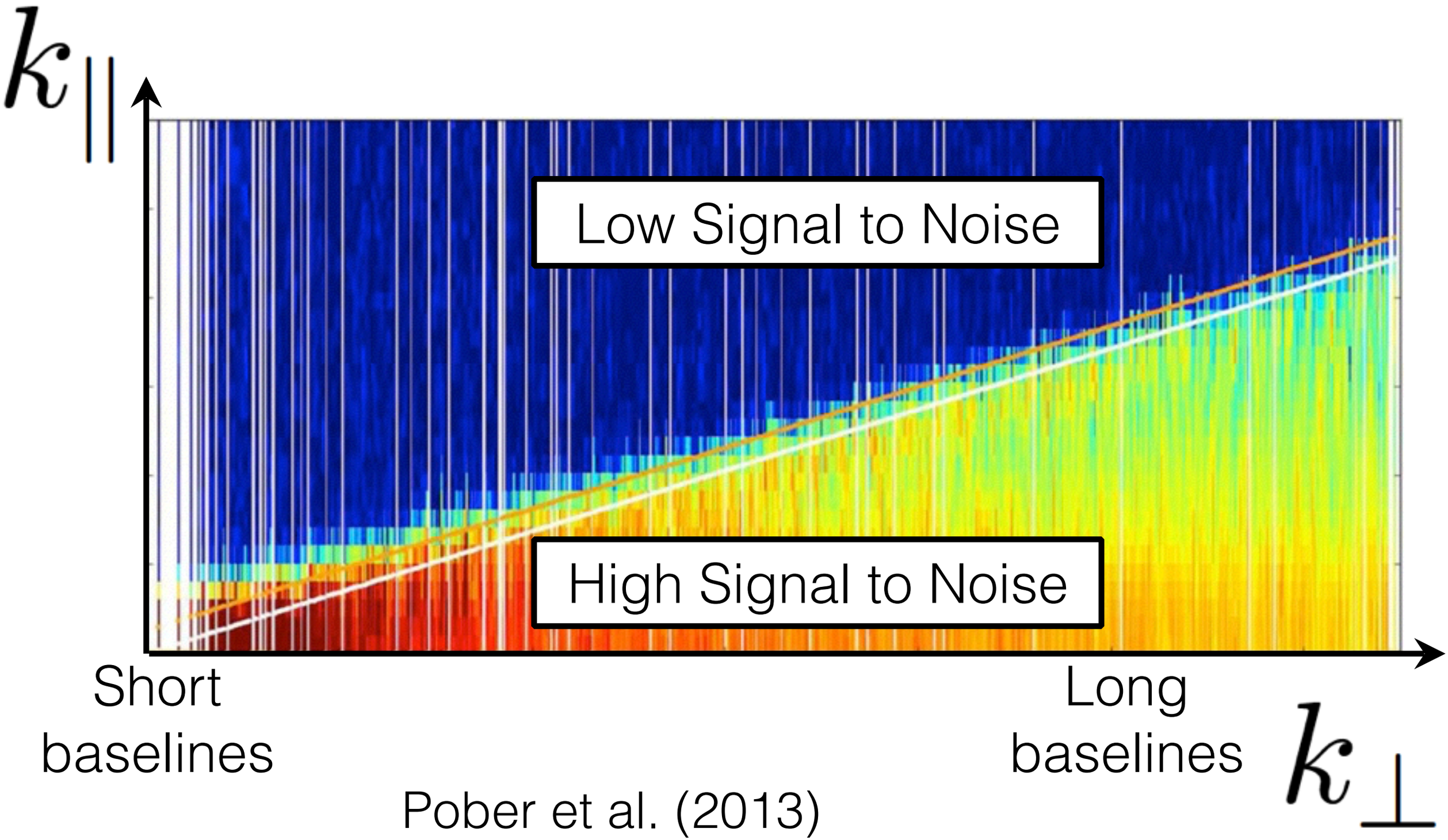
AL et al. 2014a,b

The foregrounds are dimmer at high k



Pober et al. (2013)

Signal-to-noise is best at low k, but that's where foregrounds are the worst



Pober et al. (2013)

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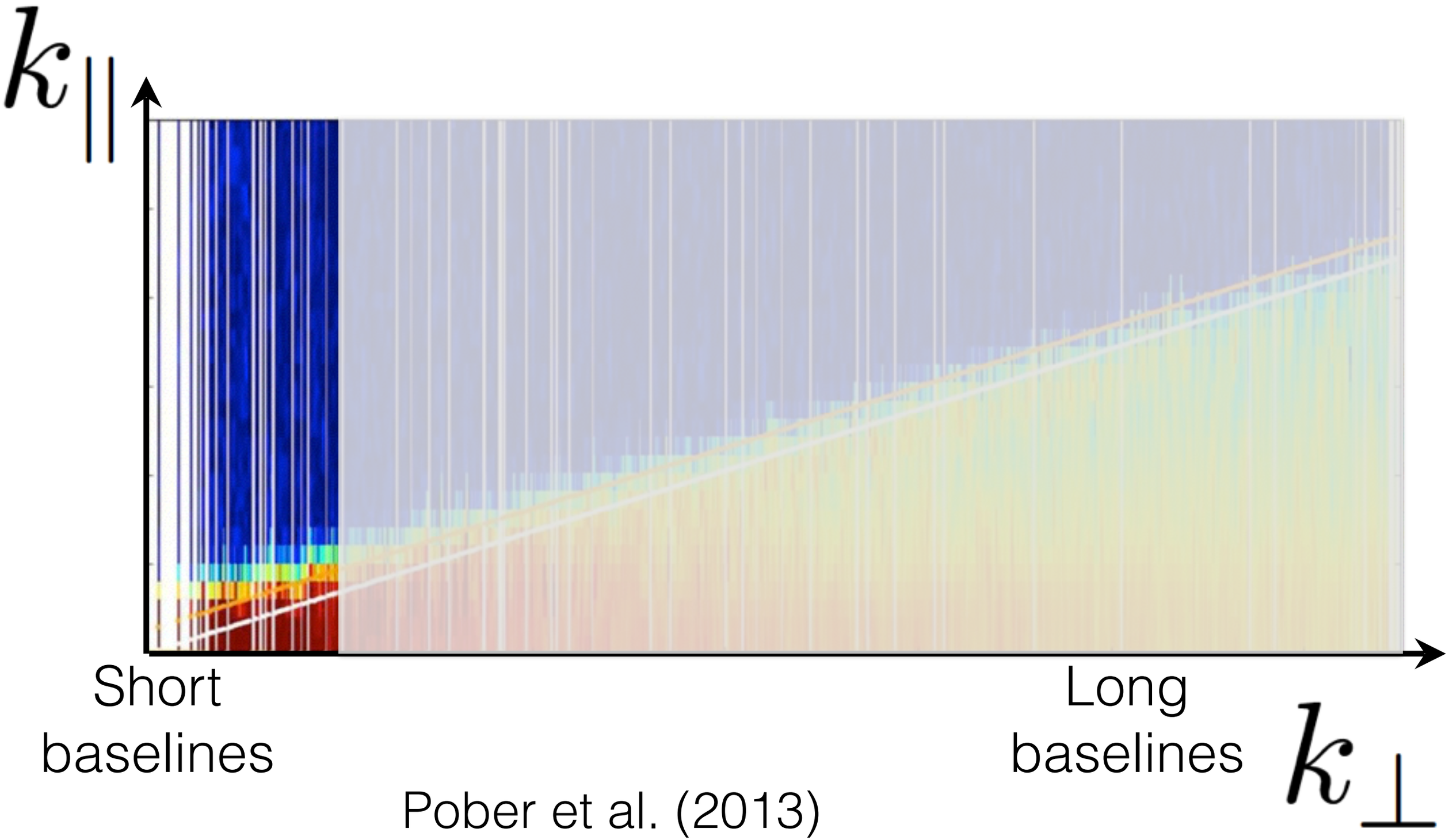

Pober et al. (2013)

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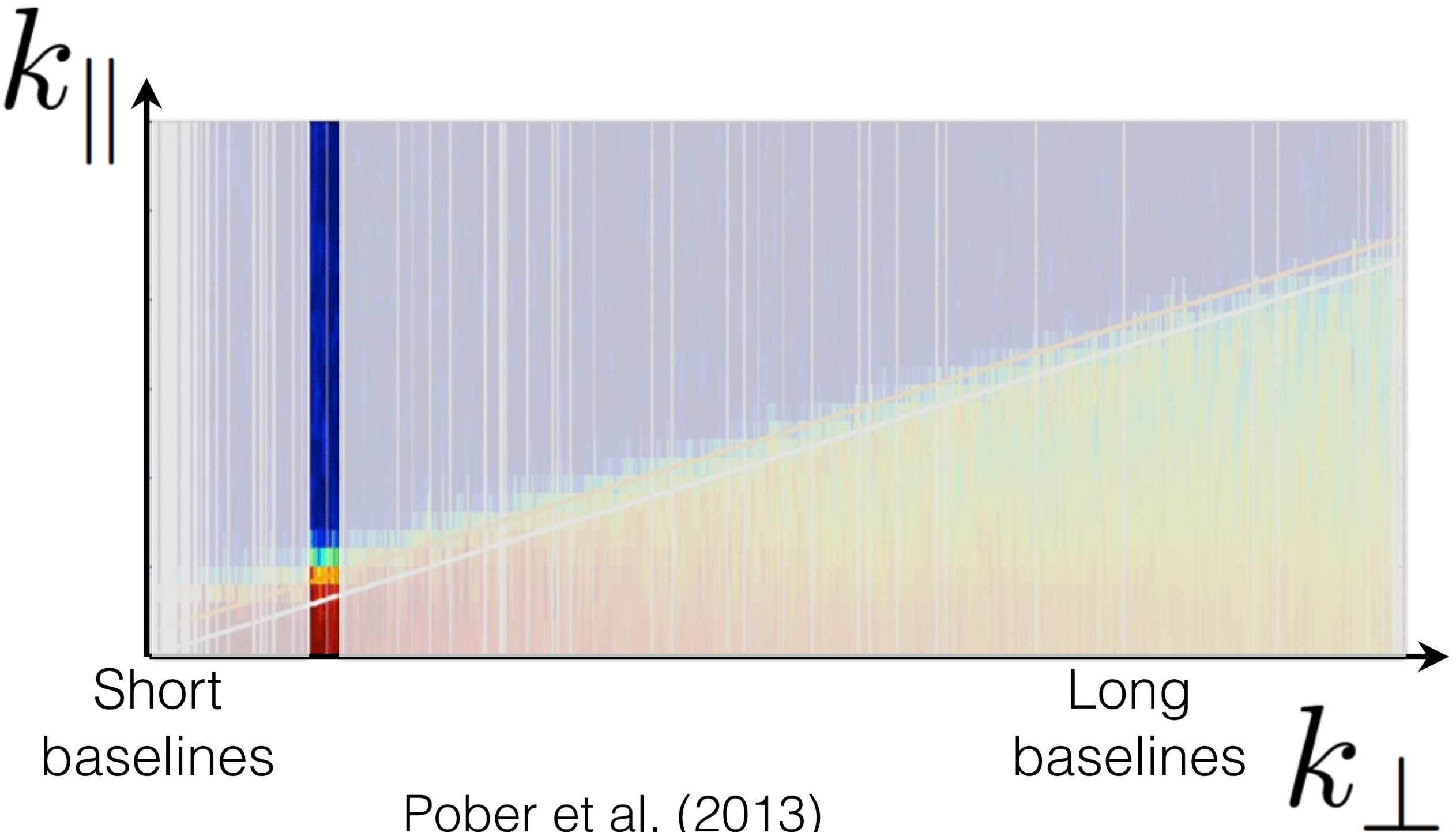
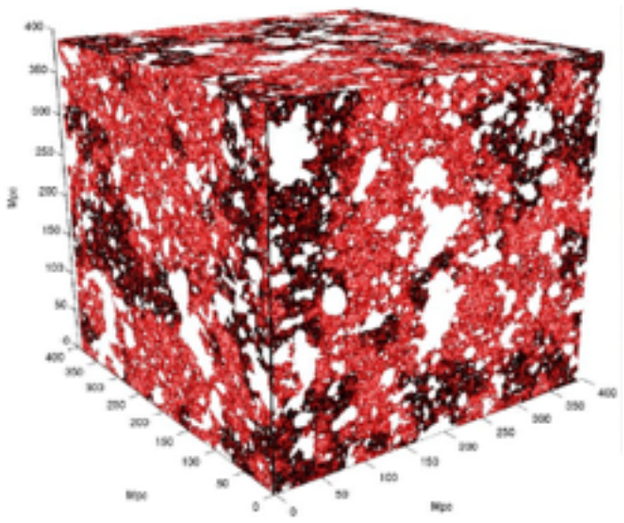


Pober et al. (2013)

Short baselines provide sensitivity while evading foregrounds and allowing novel calibration and analysis techniques

Raw data

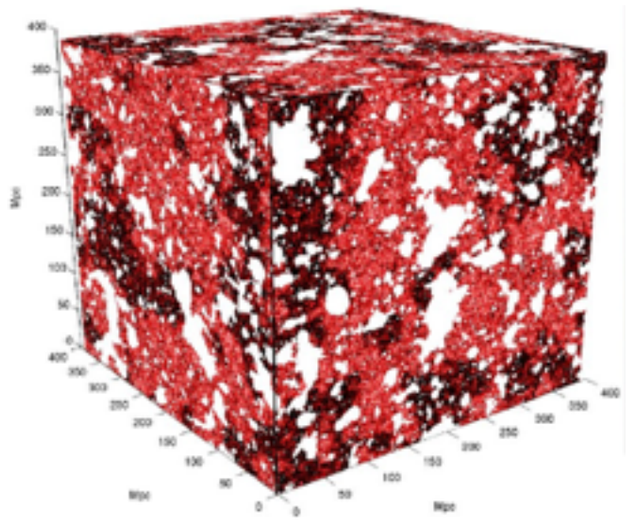


Identical baselines sample <u>exactly</u> the same modes on the sky and (Noise temp) ~ 1/sqrt(N)

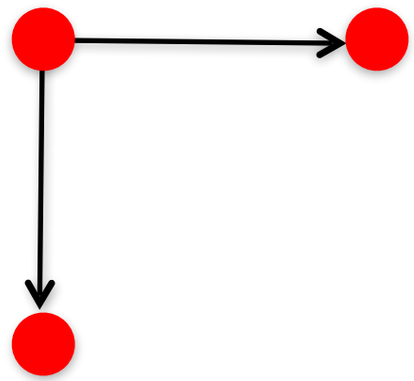
P(k)

P(k) ~(temp)^2 ~ 1/N

Raw data



P(k)



Baselines see different Fourier components and cannot be combined…

P(k) ~1/sqrt(N)

Some analysis tricks

Short, redundant baselines provide sensitivity, evade foregrounds, and…

…allow for sky-independent calibration

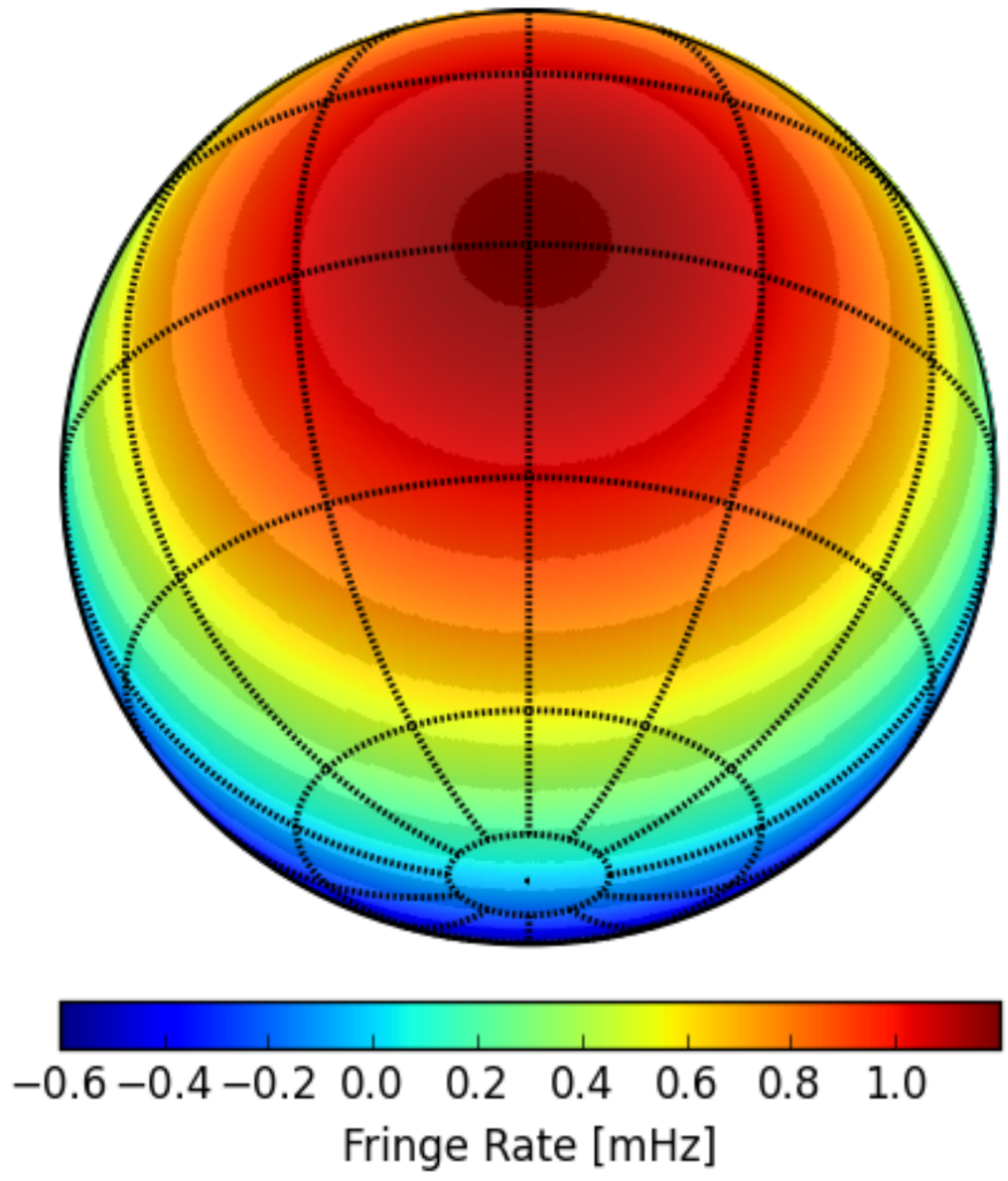
AL et al. (2010)

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

Zheng et al. (2014)

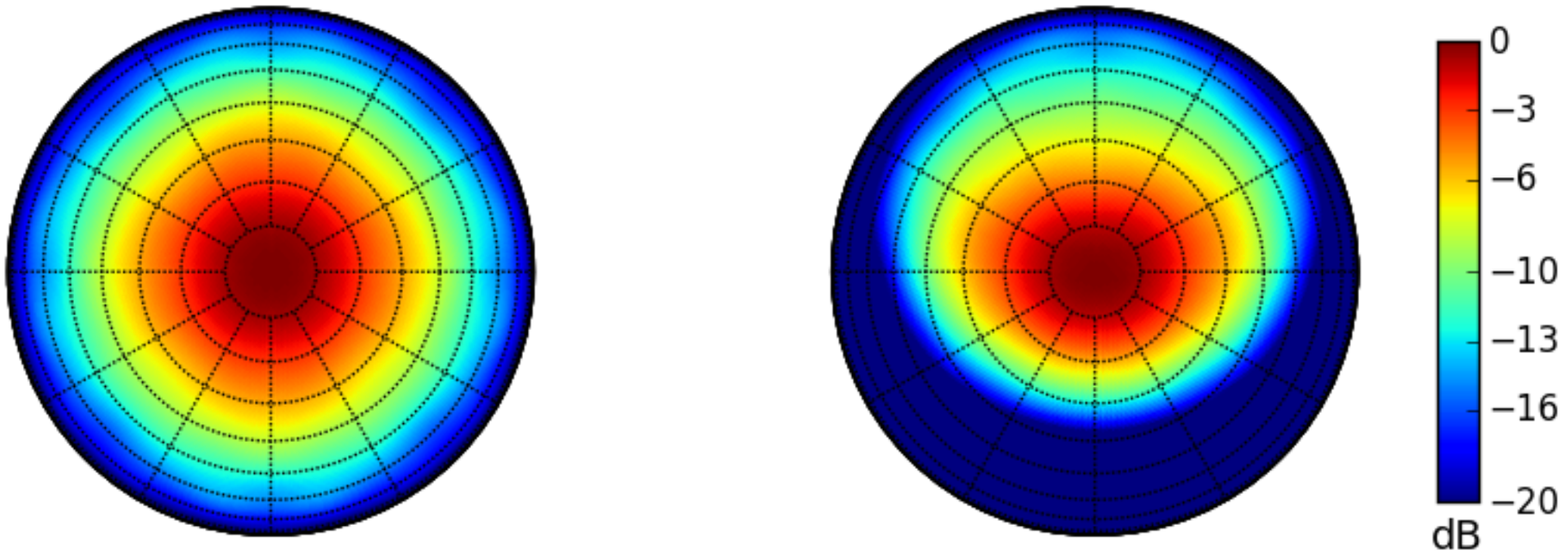
Parsons, **AL** et al. (2015)

Different fringe-rates in the data correspond to different parts of the sky



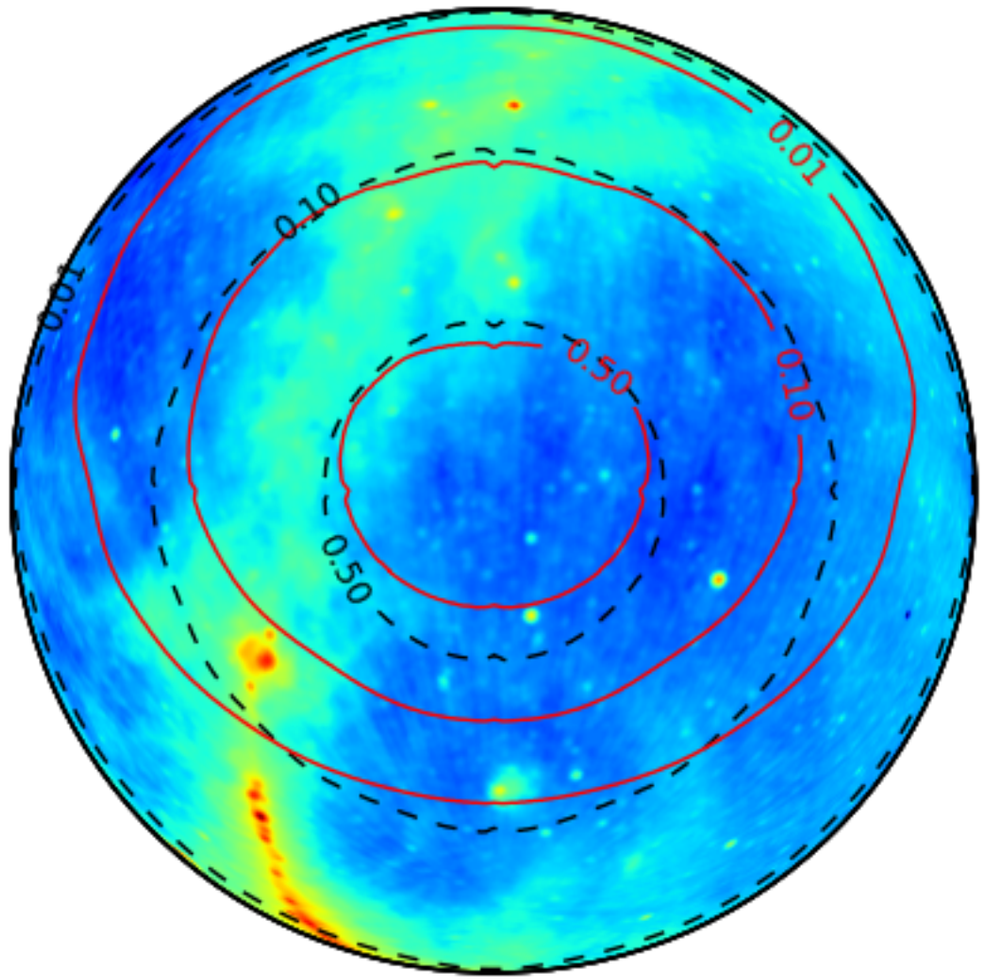
Parsons, **AL** et al. (2015)

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

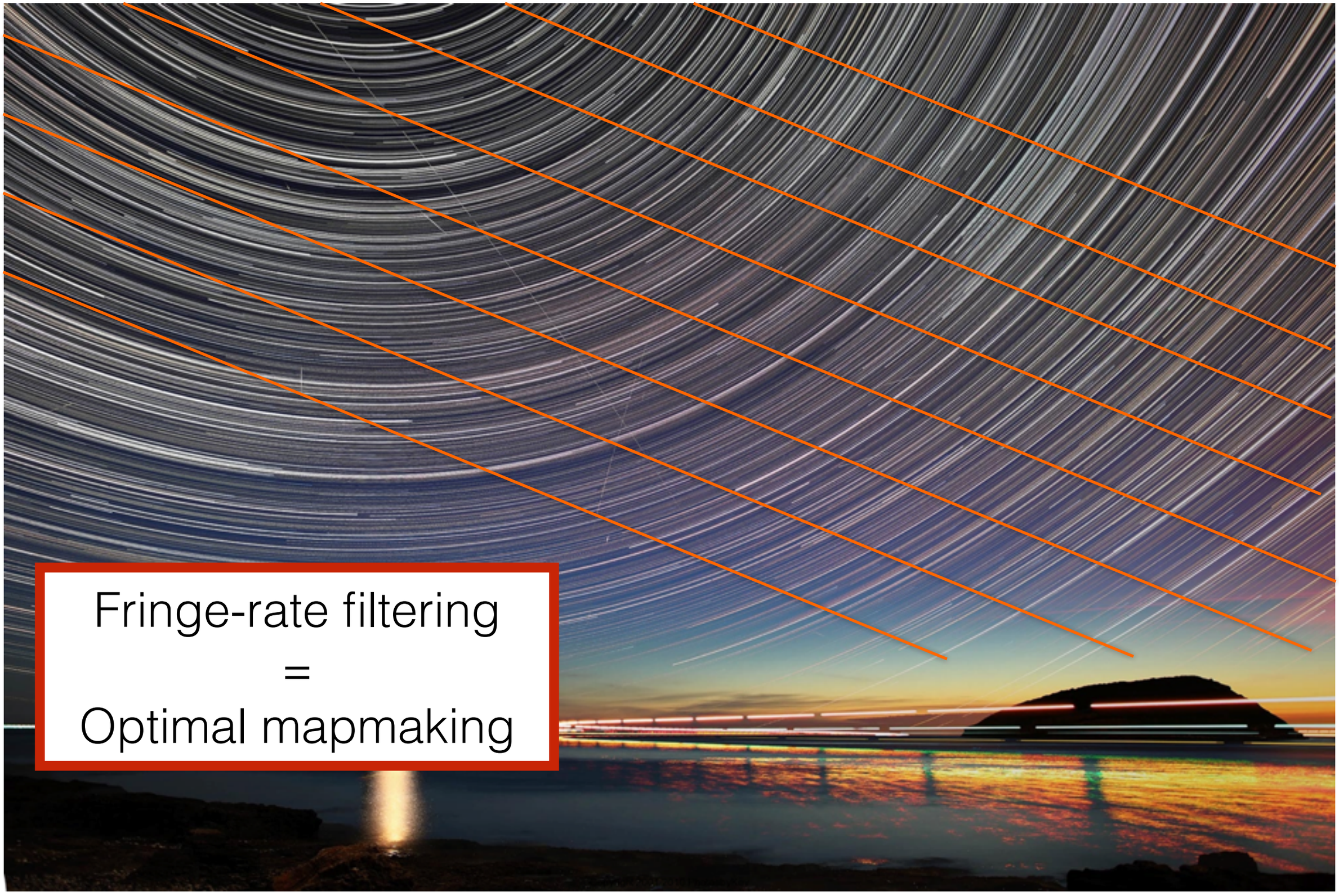


Parsons, **AL** et al. (2015)

Foreground systematics can be further mitigated by beam-sculpting



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

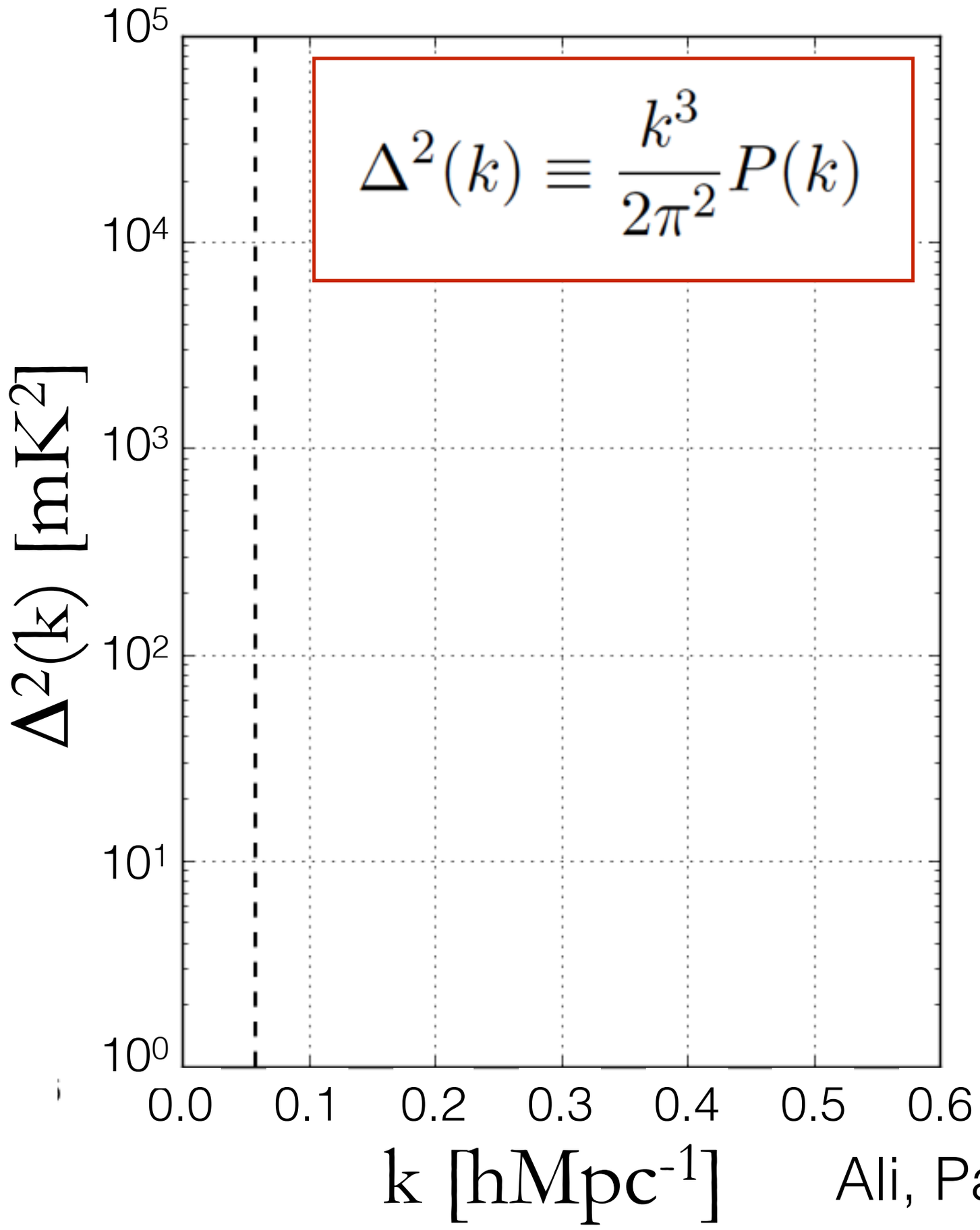


Parsons, **AL** et al. (2015)

Latest upper limits from PAPER

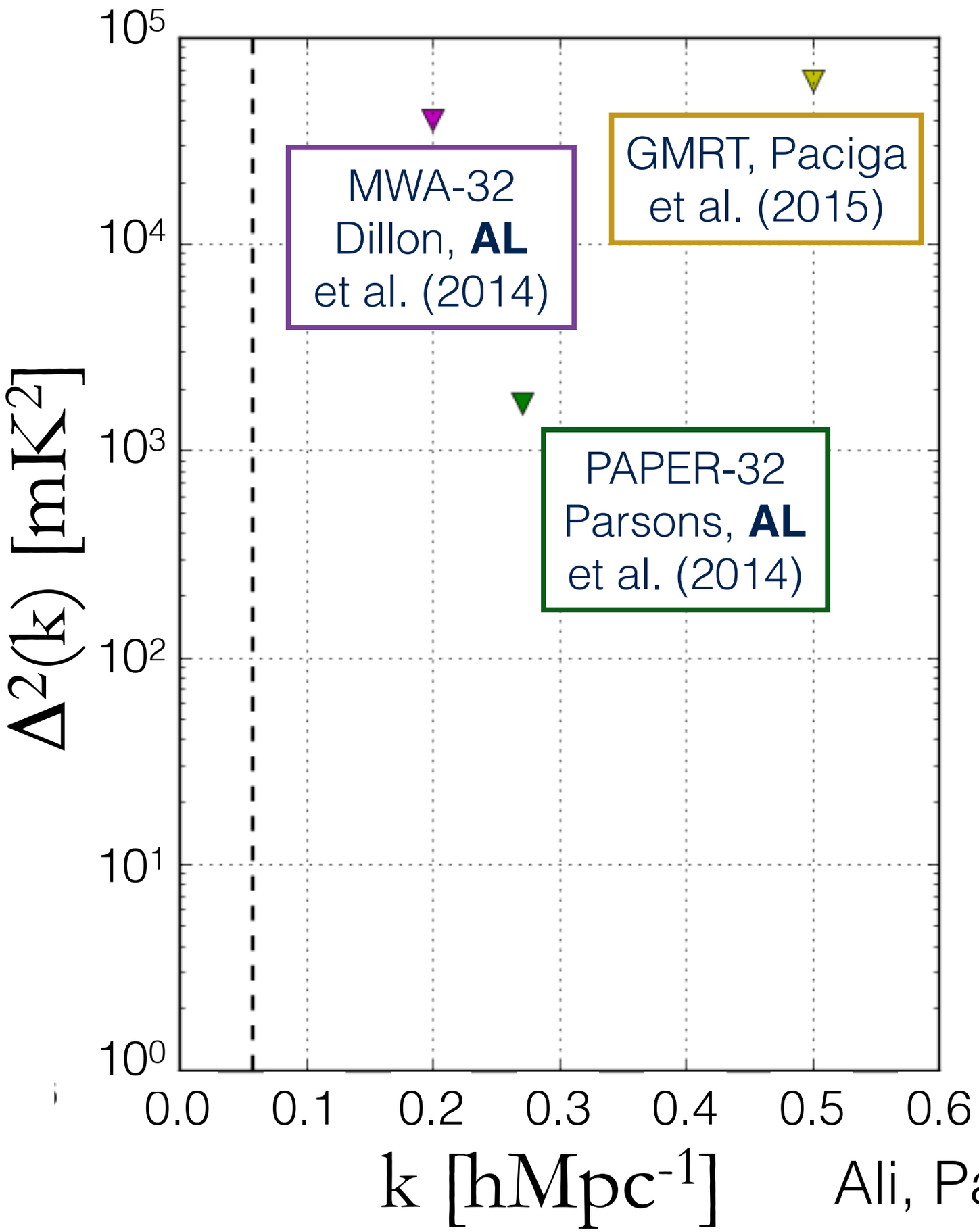
Recent upper limits from the PAPER-64 array

- 135 days of observation.
- Results centered on z ~ 8.4 (151 MHz).
- 64 element array.
- Drift-scan configuration.
- Analysis tricks:
  - Improved redundant calibration (“omnical”)
  - Near-optimal quadratic estimators
  - Fringe-rate filtering



PAPER 64-element array: Upper limit of $(22.4\ \mathrm{mK})^2$ at 2-sigma in range $0.15 < k < 0.5h\mathrm{Mpc}^{-1}$

Ali, Parsons, …, **AL** et al. (2015)



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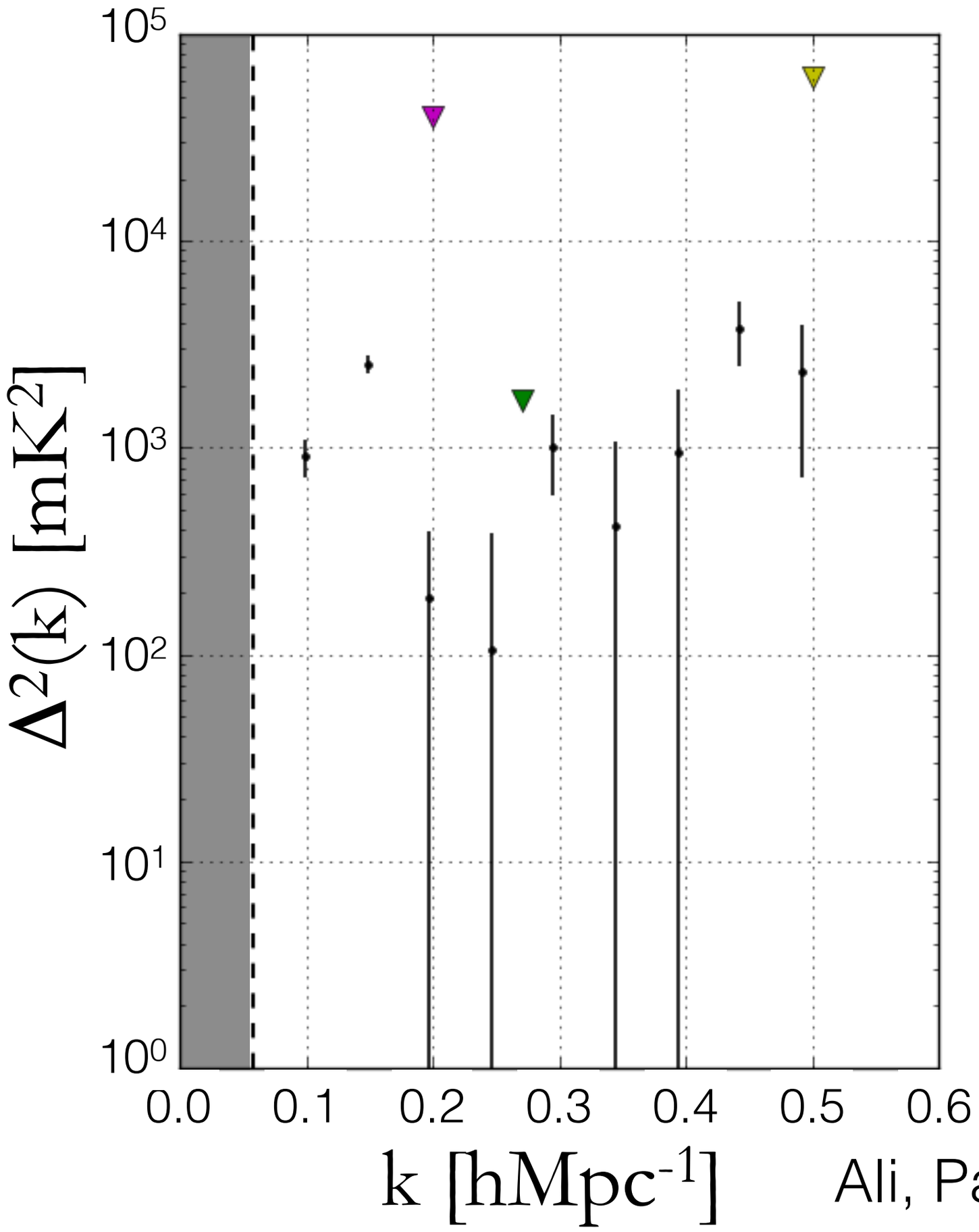

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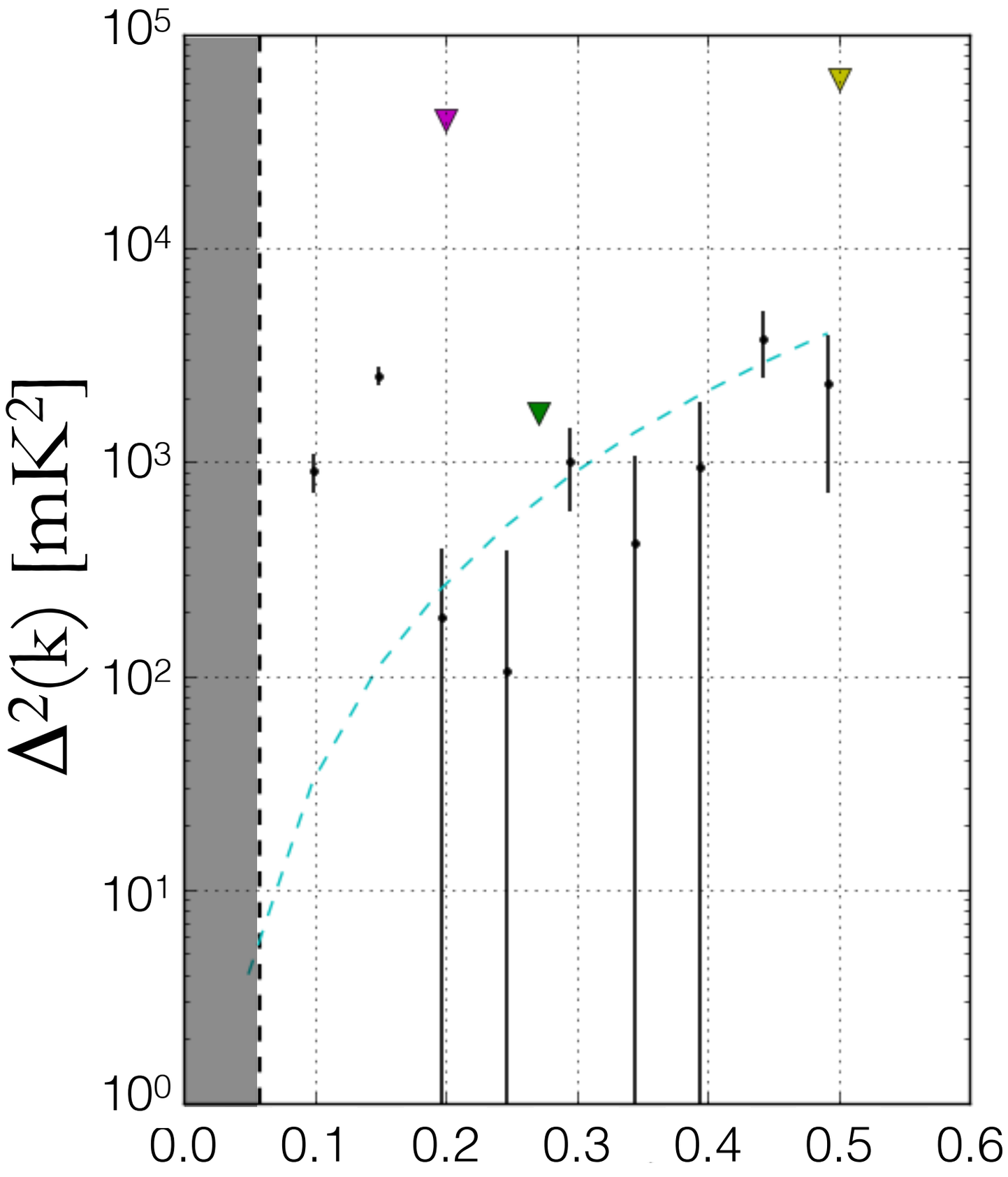

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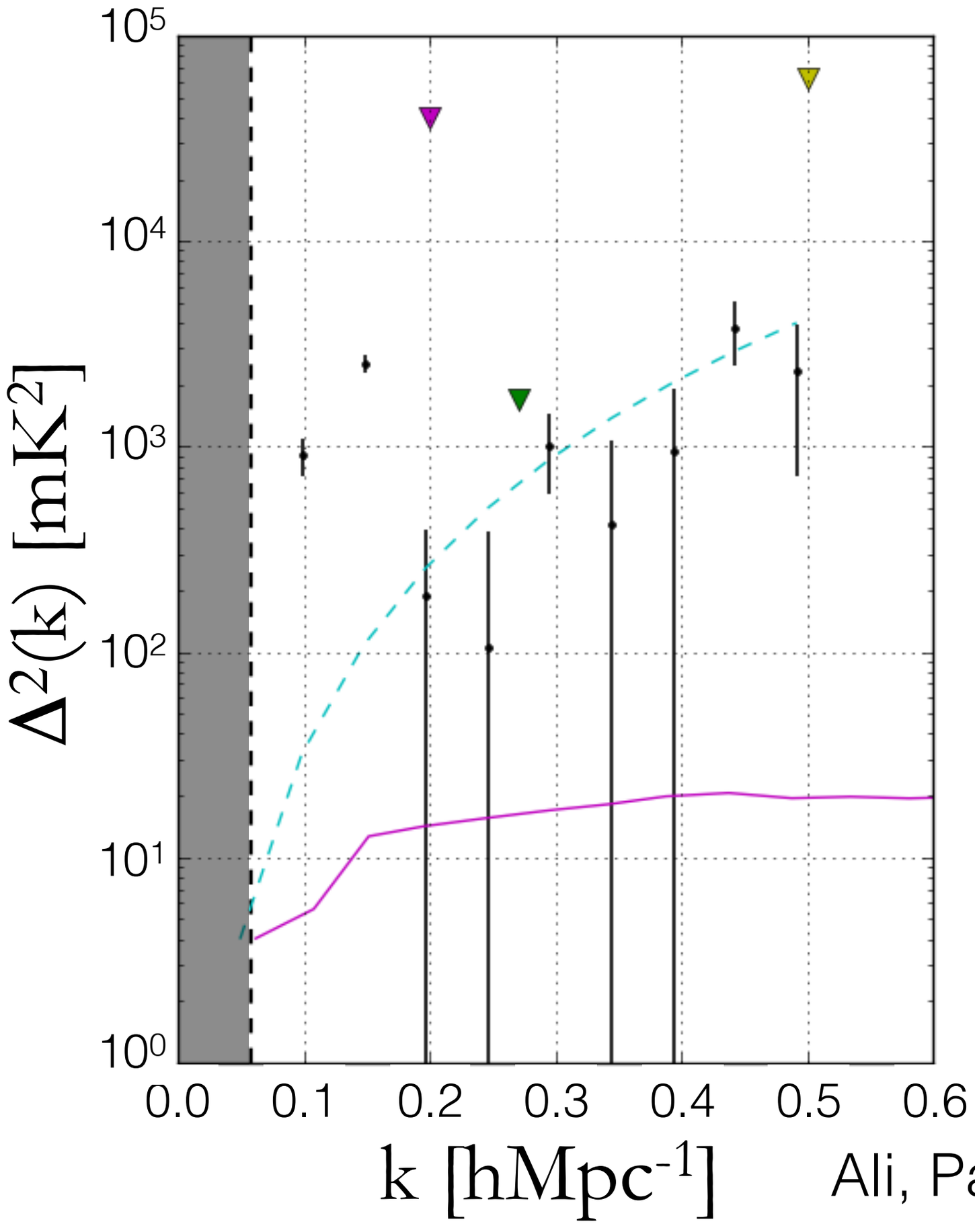

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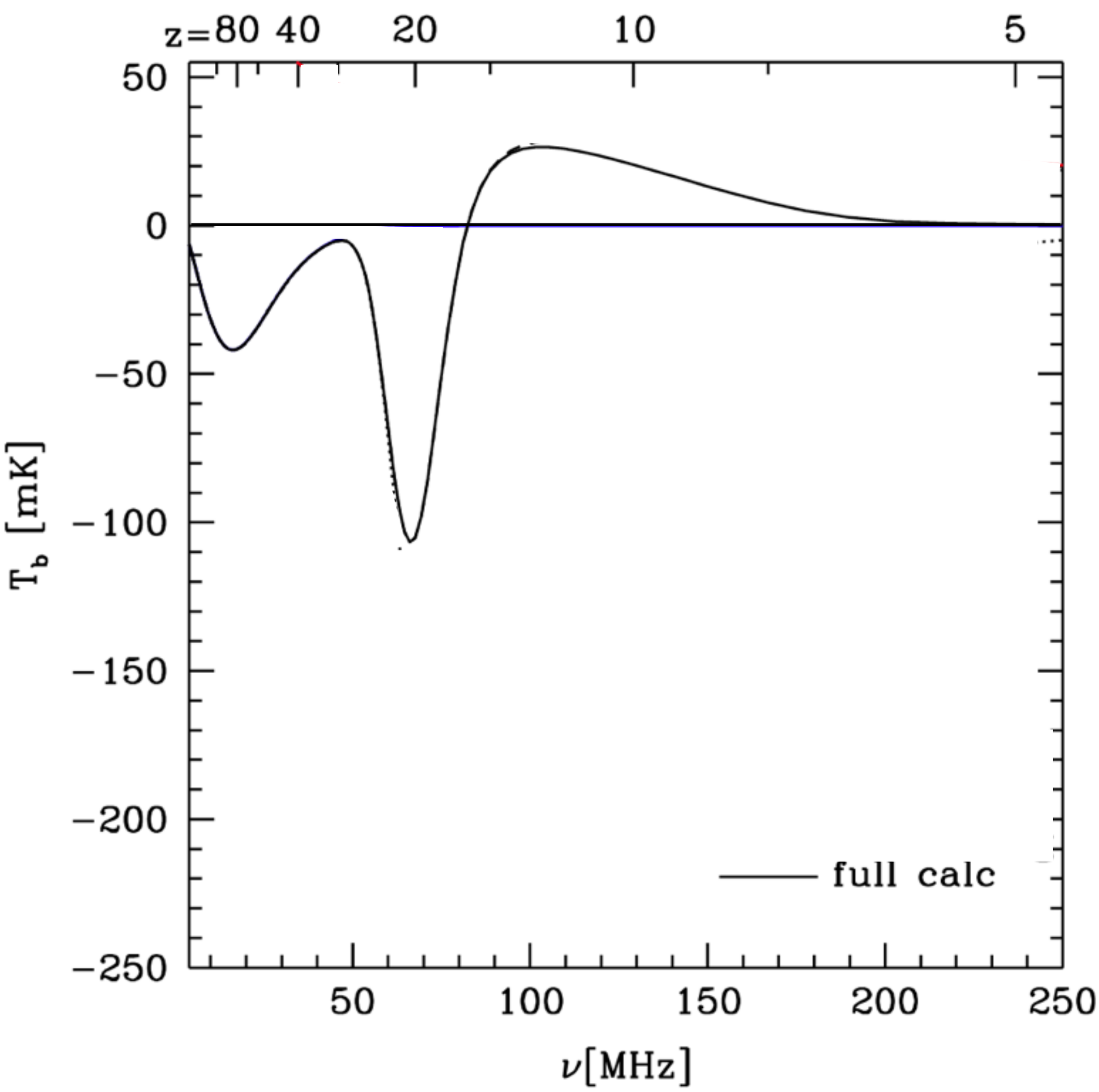
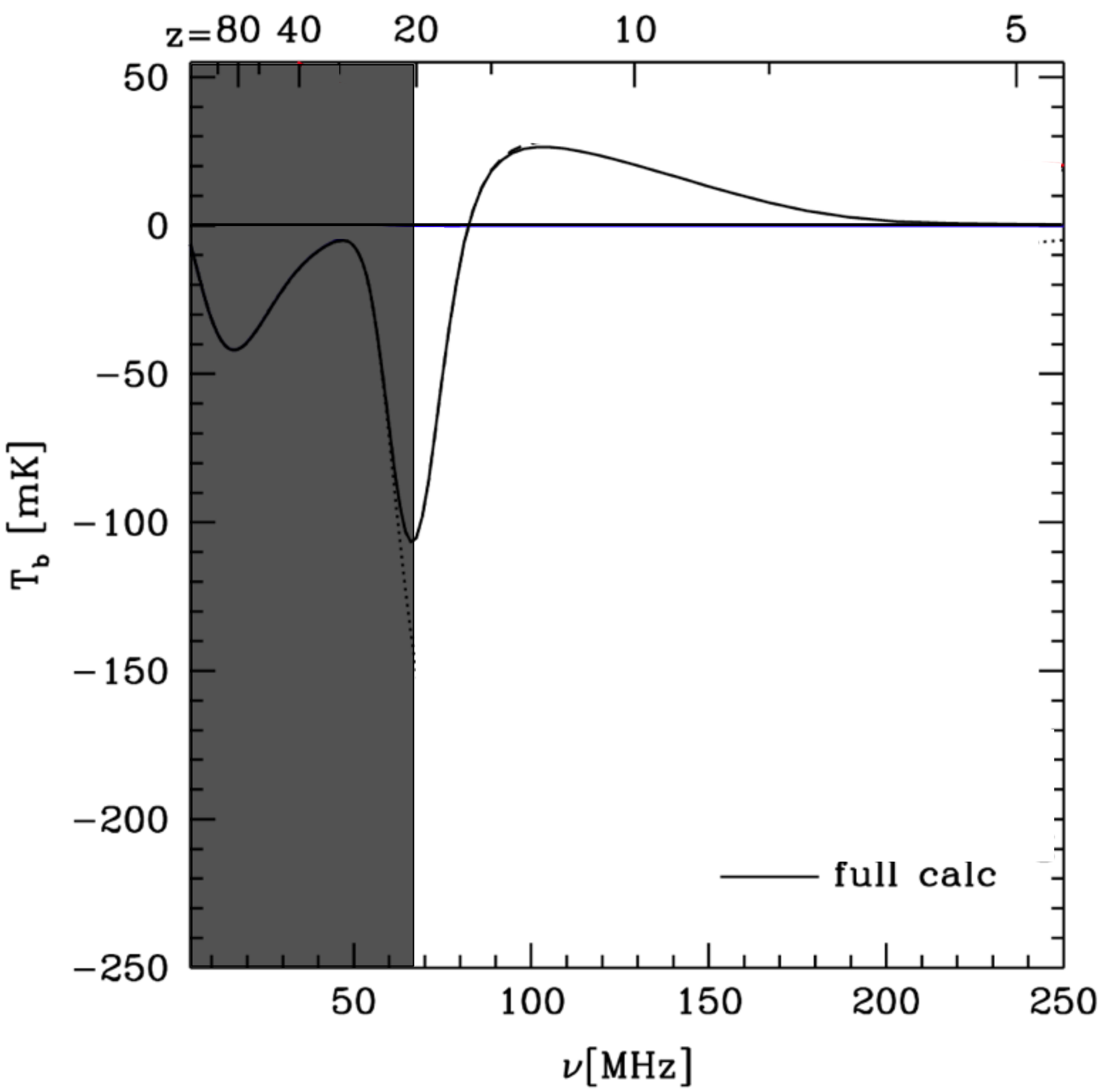


Pritchard & Loeb (2010)



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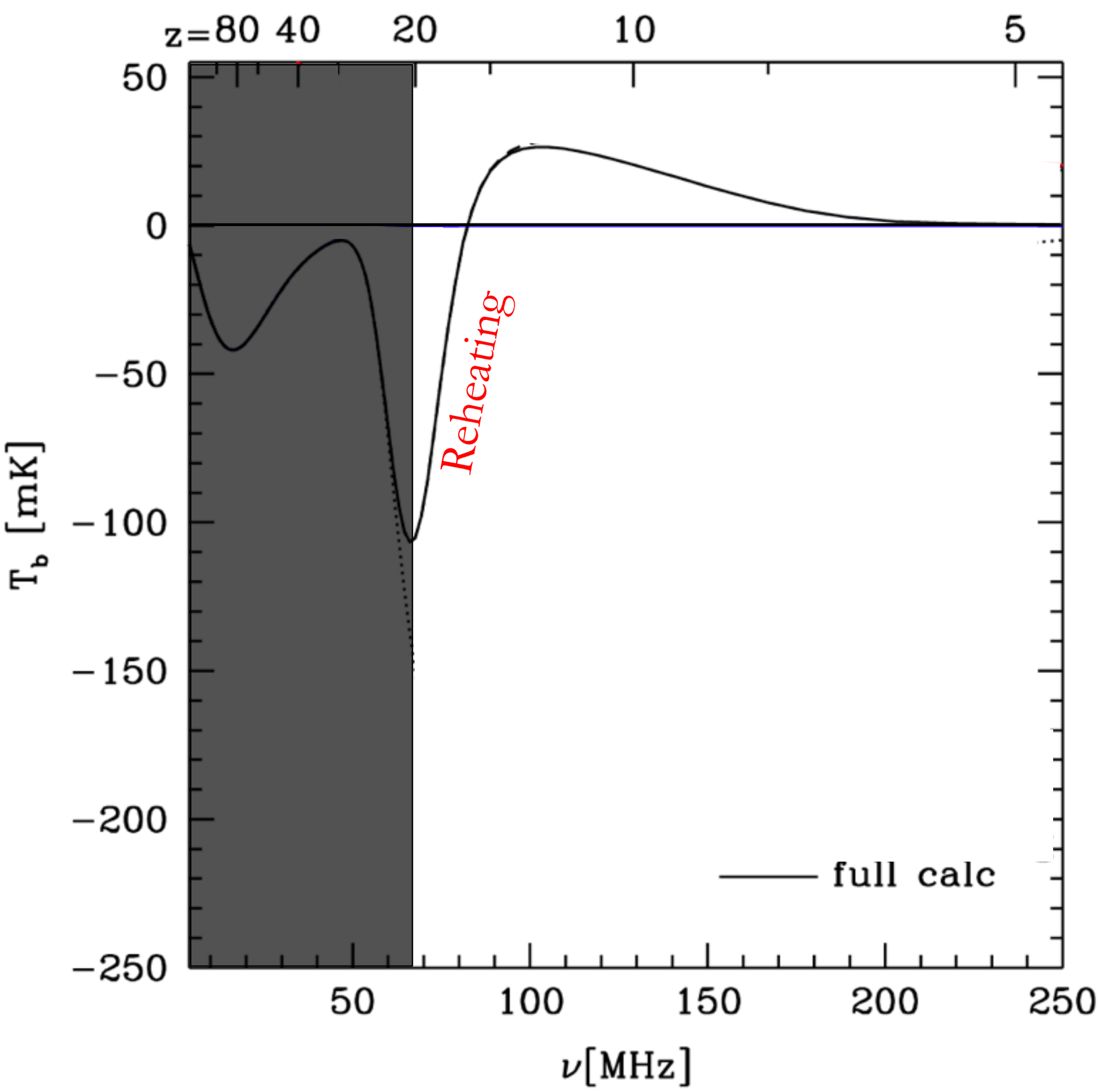
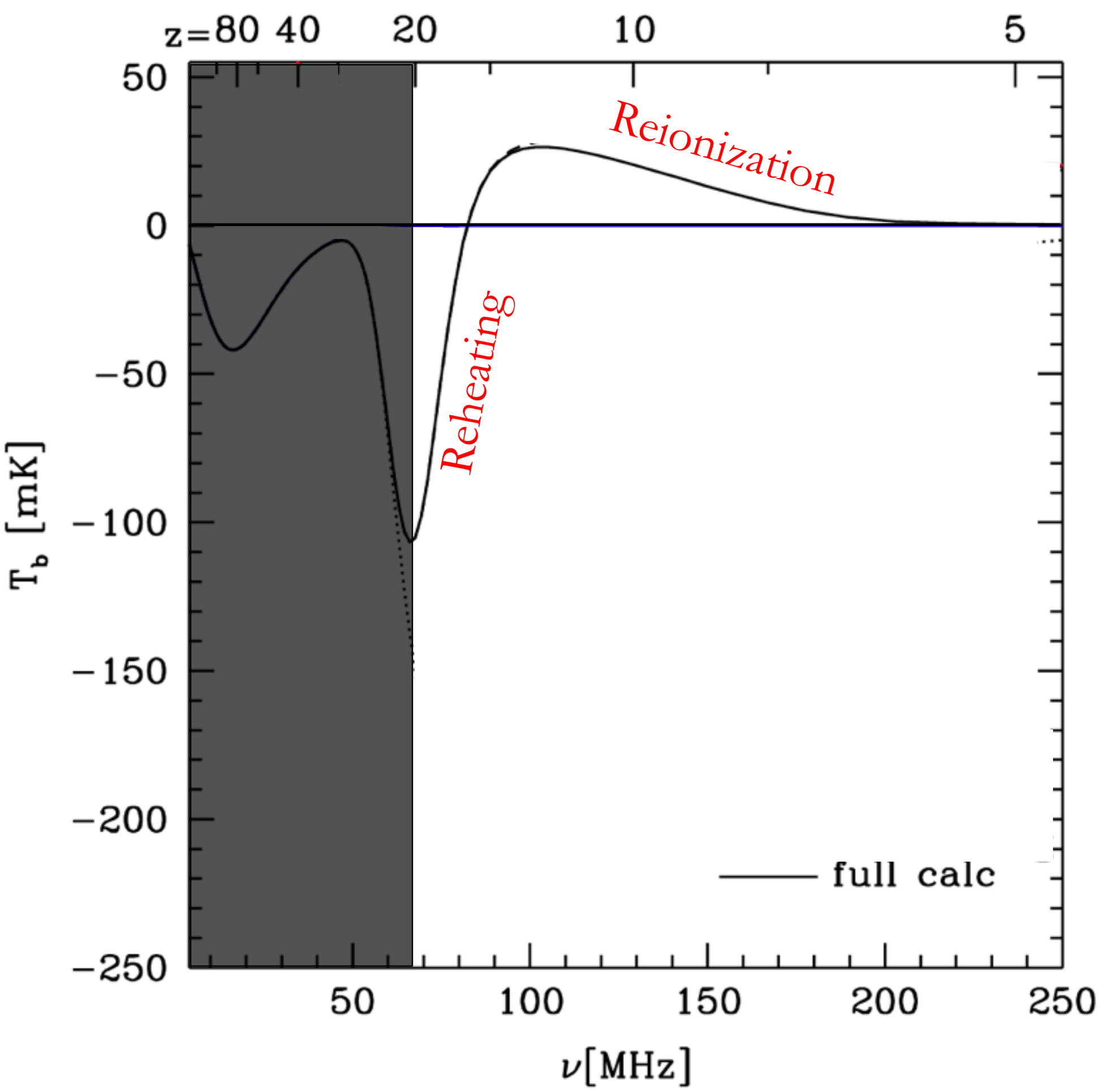
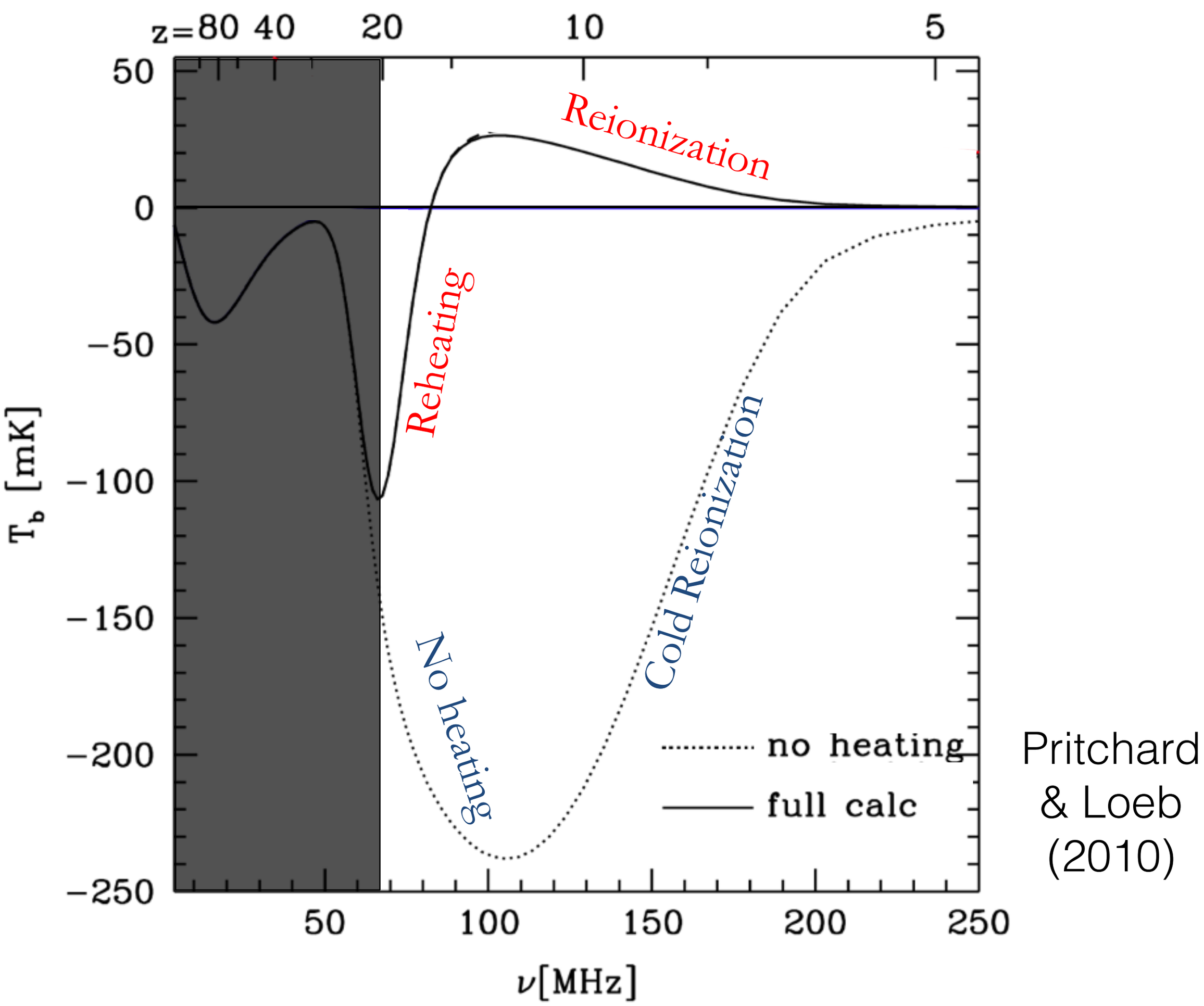


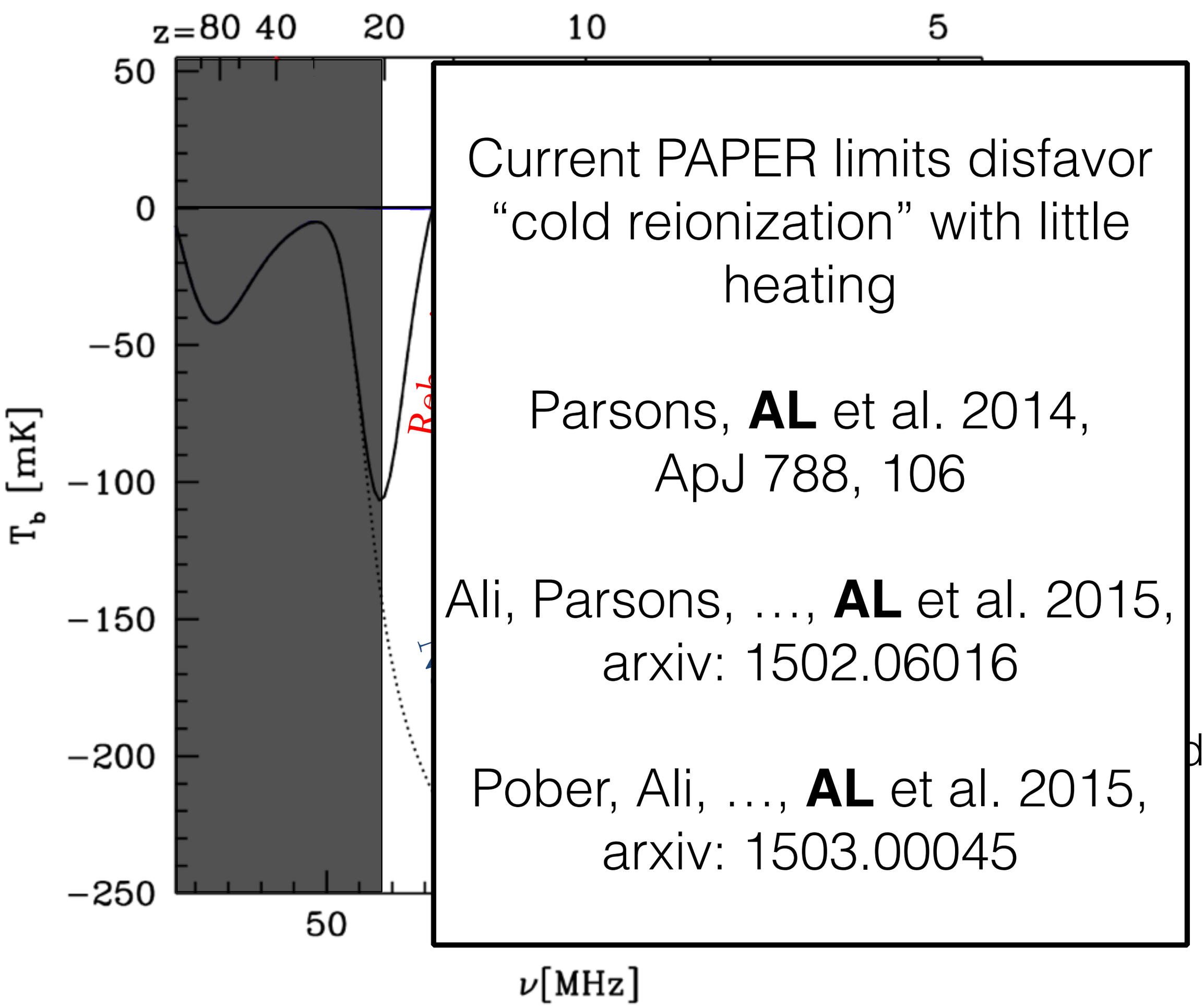
Pritchard & Loeb (2010)



Pritchard & Loeb (2010)



Pritchard & Loeb (2010)

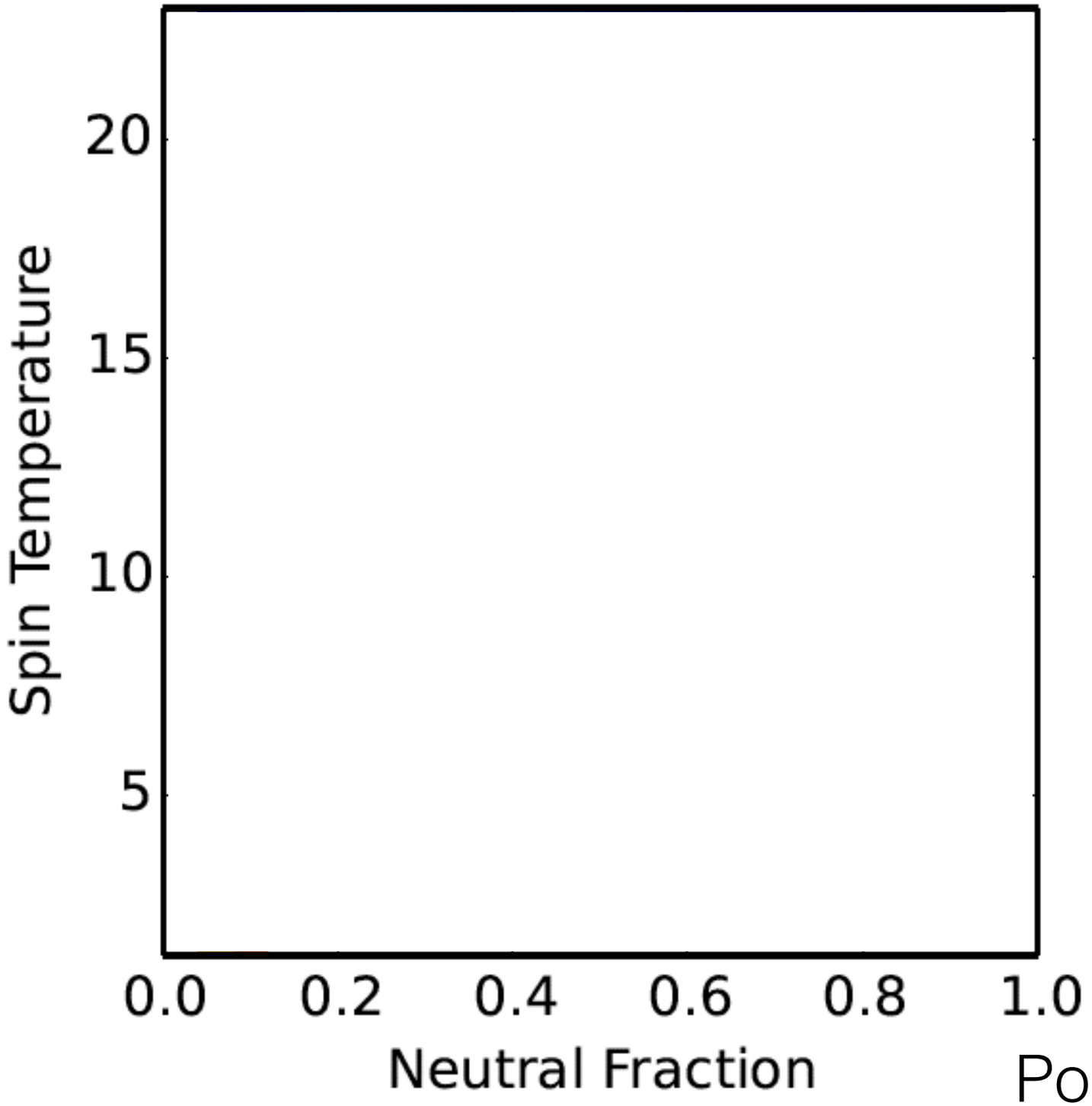


Current PAPER limits disfavor "cold reionization" with little heating

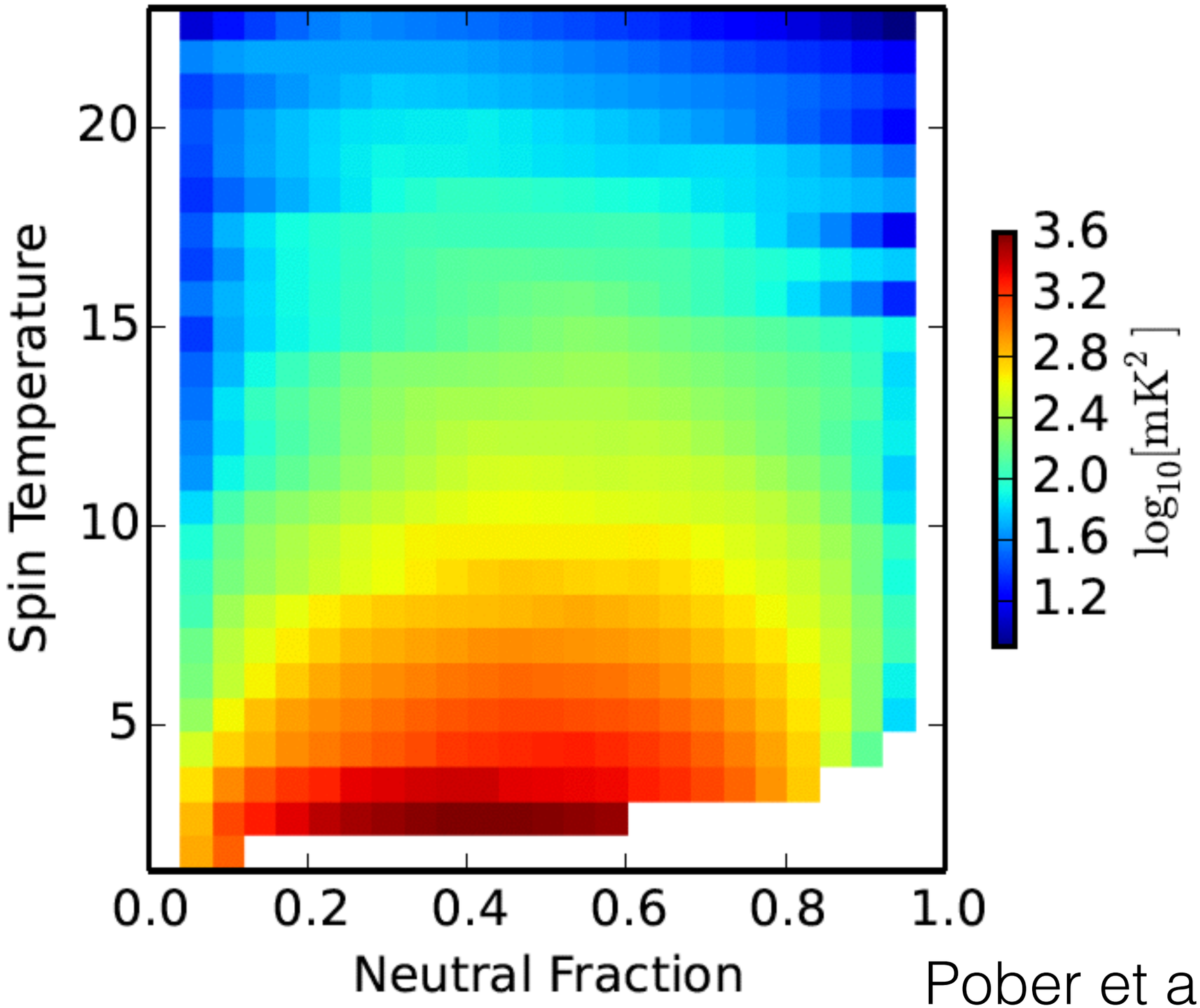
Parsons, **AL** et al. 2014, ApJ 788, 106

Ali, Parsons, …, **AL** et al. 2015, arxiv: 1502.06016

Pober, Ali, …, **AL** et al. 2015, arxiv: 1503.00045

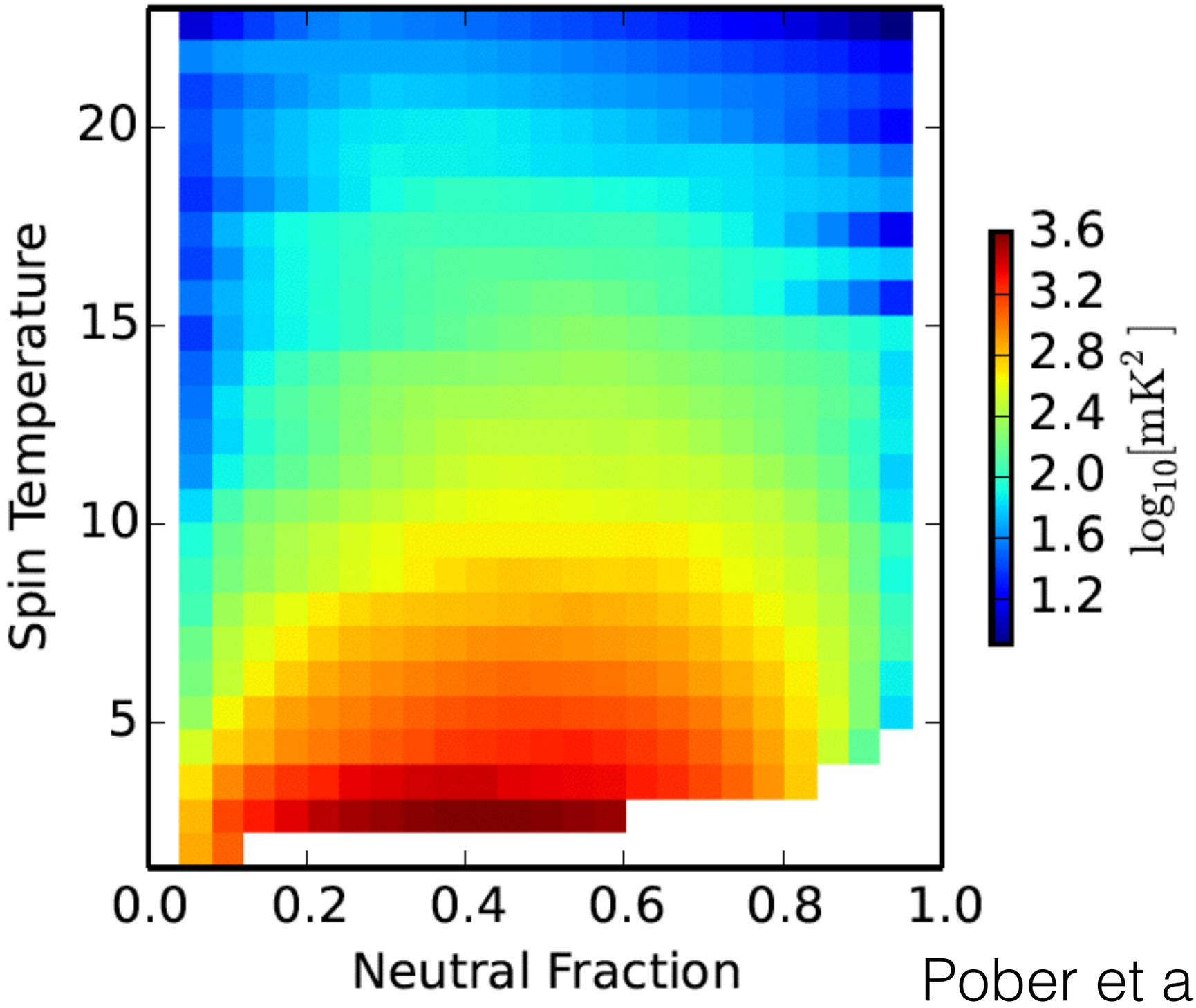


Pober et al. (2015)



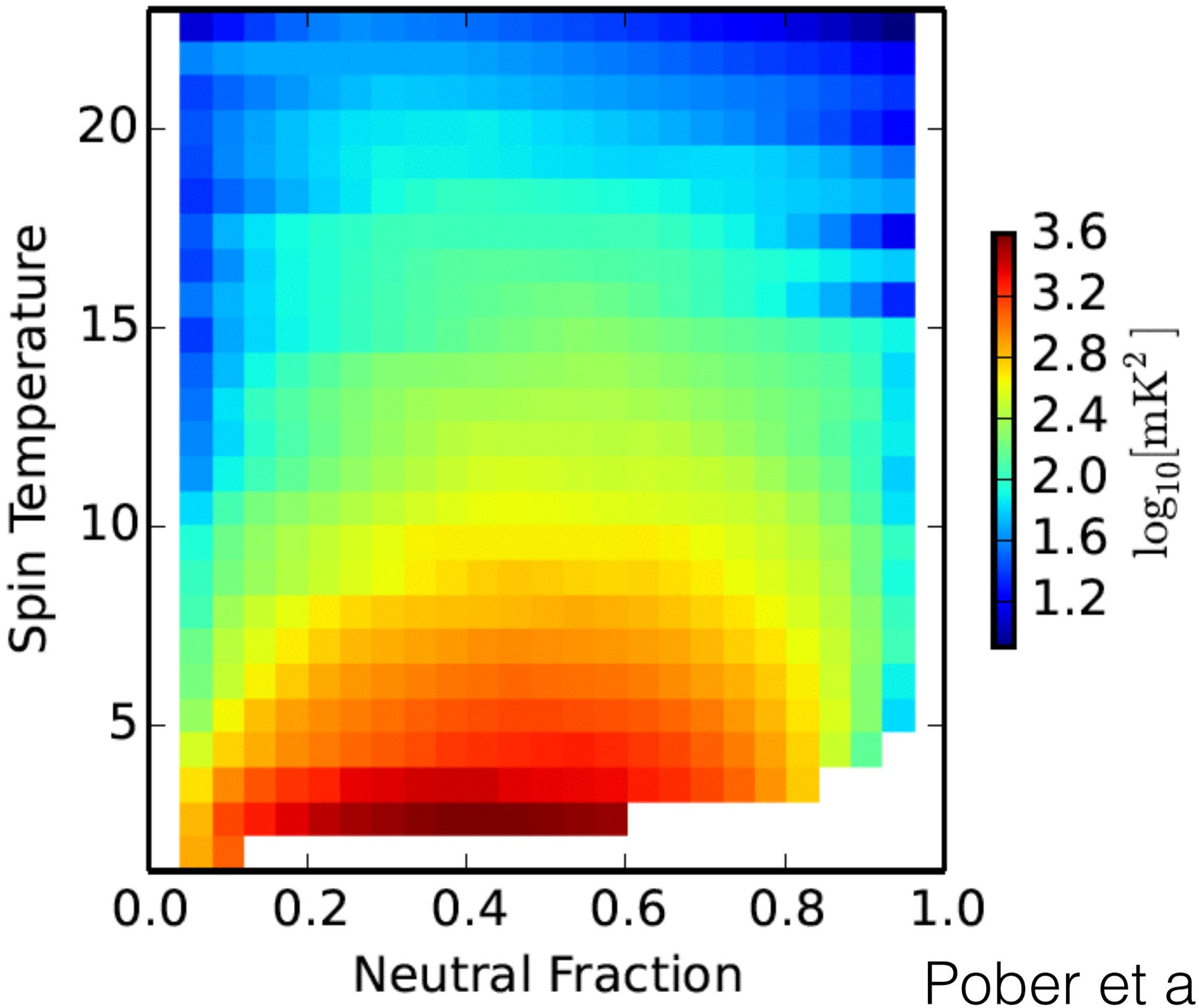
Pober et al. (2015)

Brighter spin temperatures give dimmer 21cm power spectra

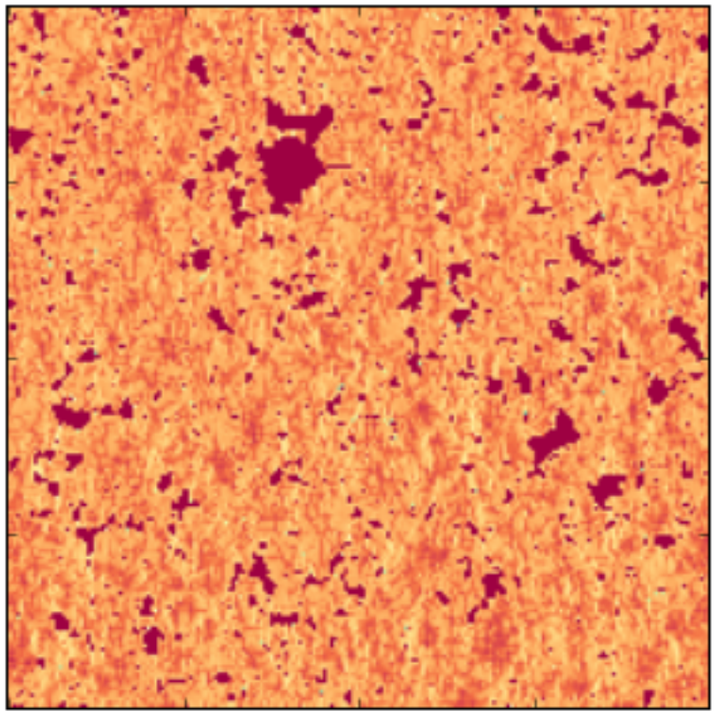


Pober et al. (2015)

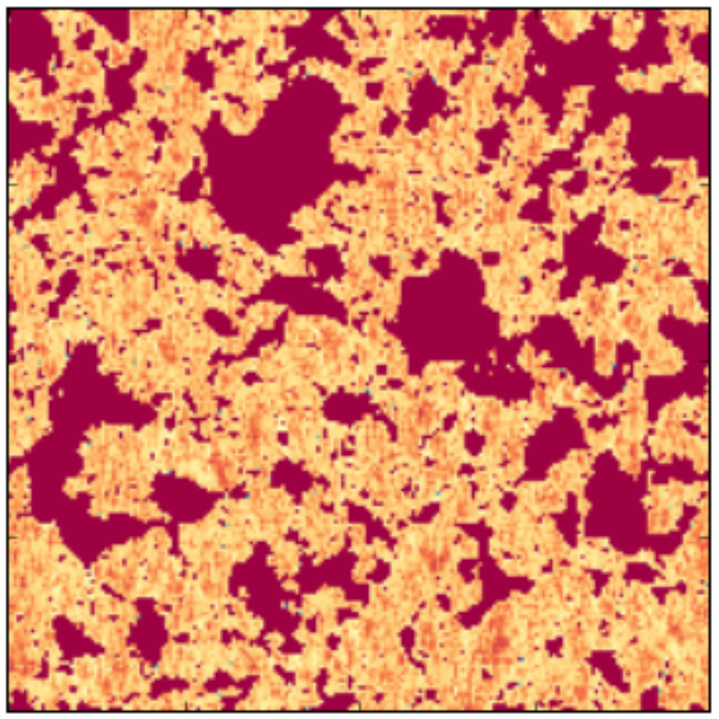
Extreme neutral fractions give dimmer 21cm power spectra



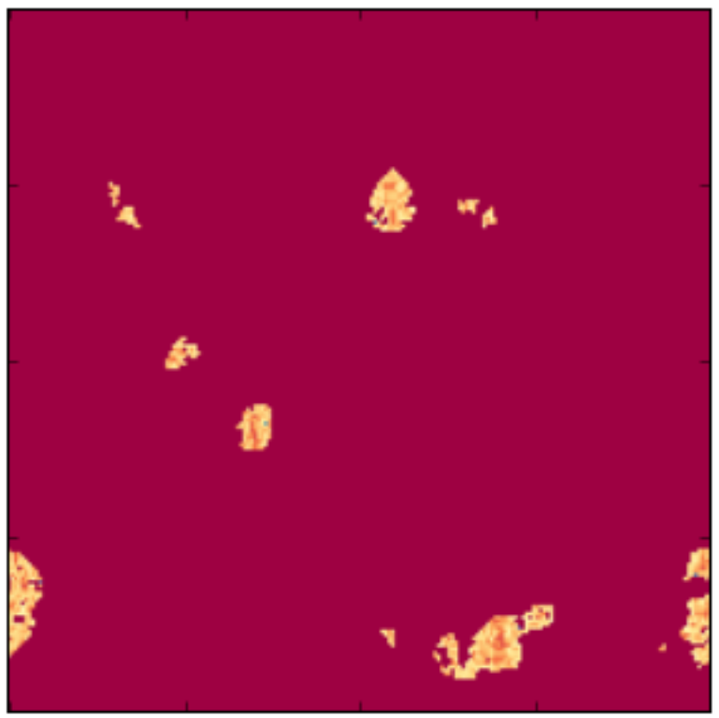
Pober et al. (2015)



Beginning of reionization



Middle of reionization



End of reionization

$k = 0.25 h\mathrm{Mpc}^{-1}$

Spin Temperature

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

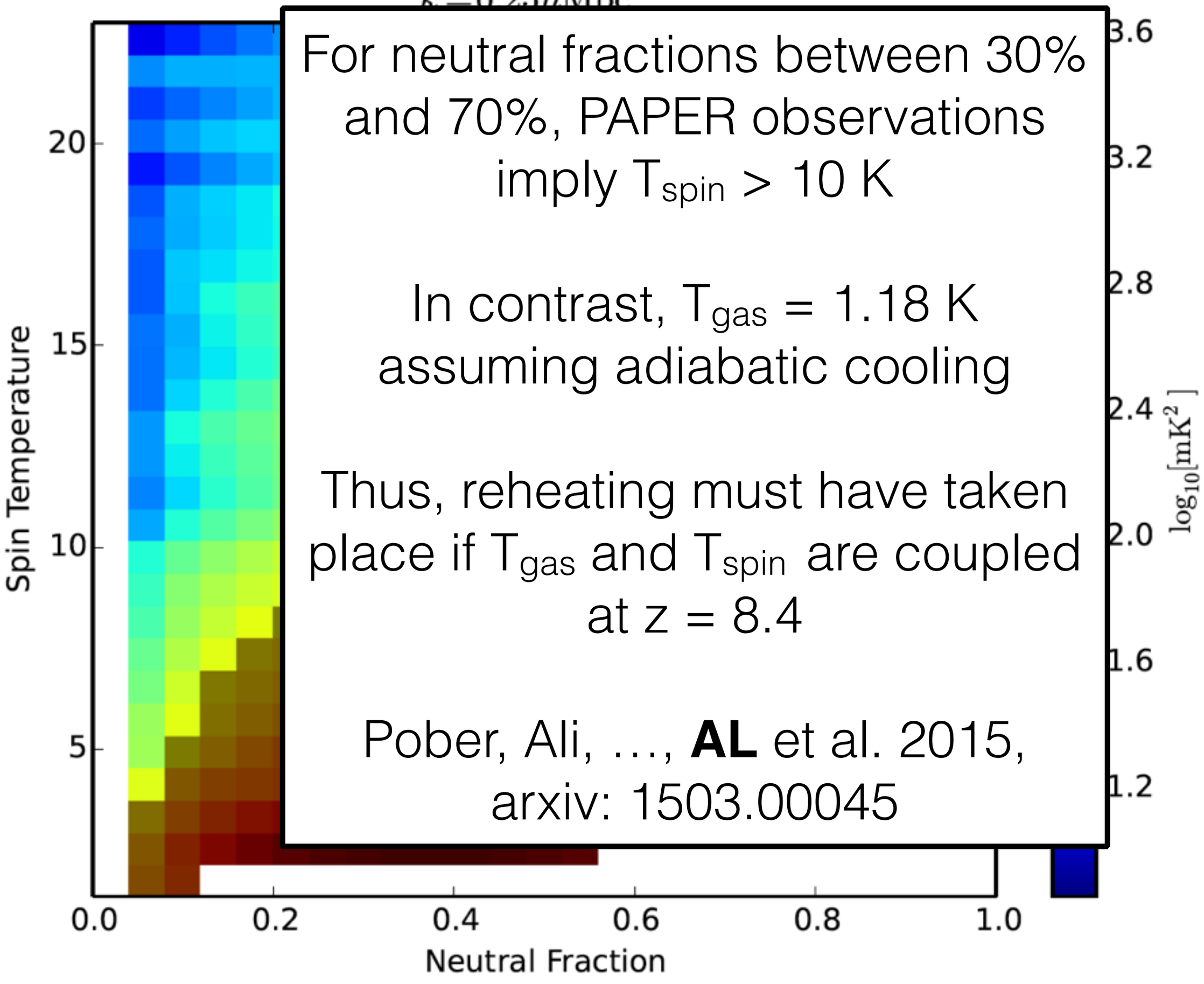
$\log_{10}[\mathrm{mK}^2]$

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

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

Thus, reheating must have taken place if T_{gas} and T_{spin} are coupled at $z = 8.4$

Pober, Ali, …, **AL** et al. 2015, arxiv: 1503.00045



Take-home points

- The PAPER instrument does not look like a conventional imaging radio interferometer. Short, redundant baselines provide good sensitivity.

- PAPER's unusual design has led to some unusual analysis techniques, such as redundant baseline calibration and fringe-rate filtering.

- Recent PAPER measurements have set scientifically interesting upper limits on the 21cm power spectrum, placing constraints on heating at $z = 8.4$