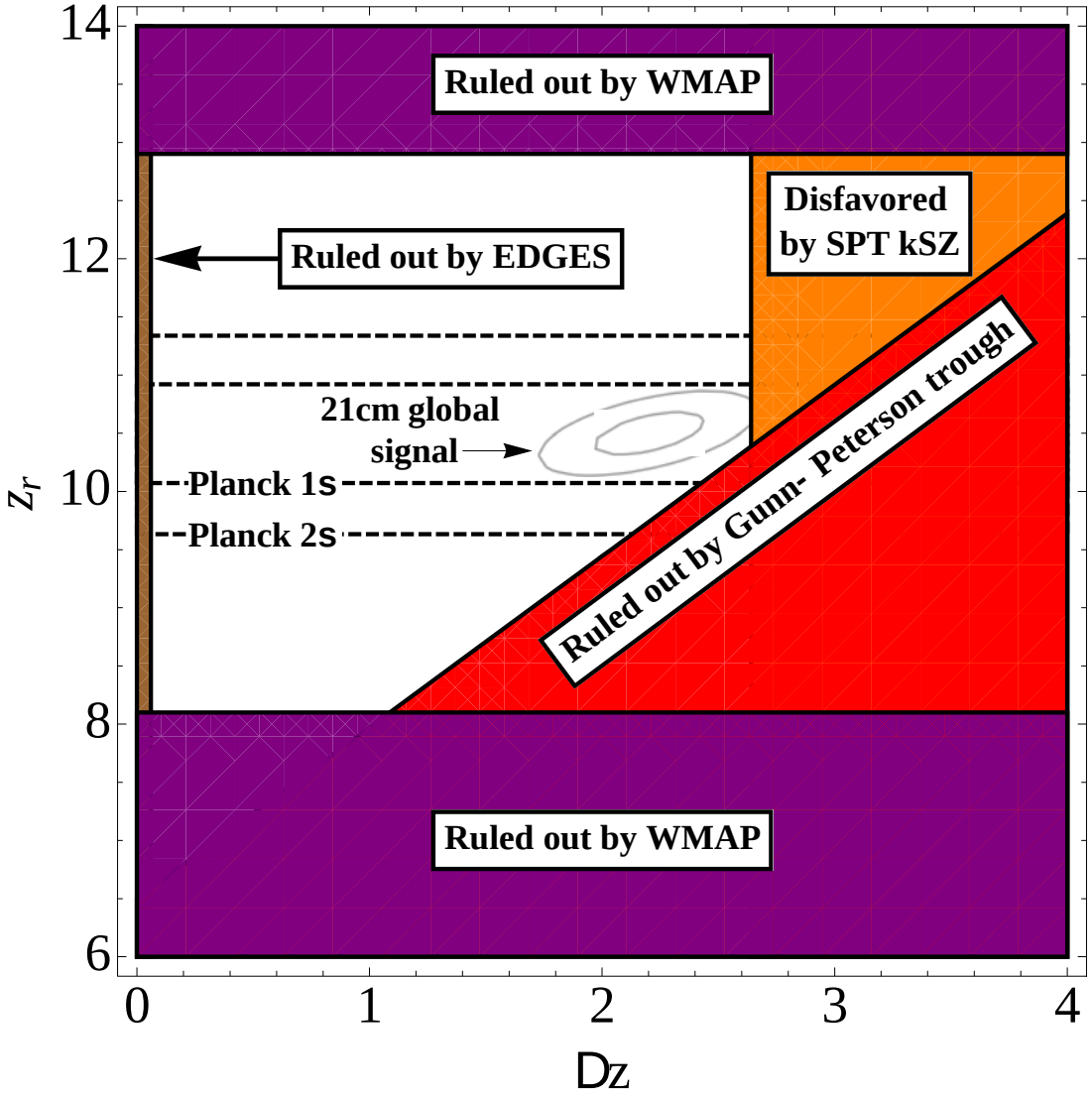
Global 21cm Experiments: A Designer's Guide



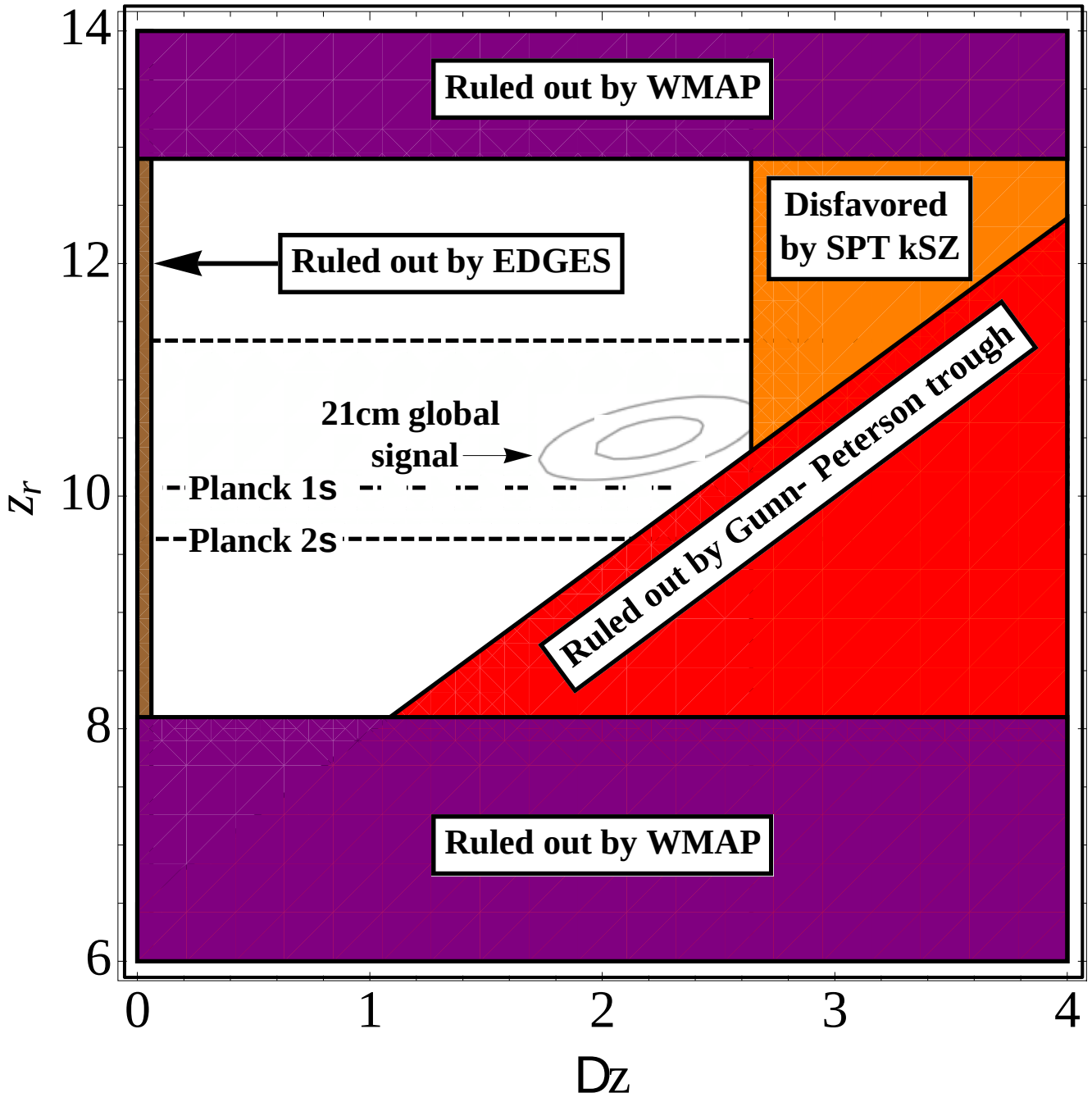
Based on AL, Pritchard, Tegmark, Loeb (arXiv: 1211.3743)

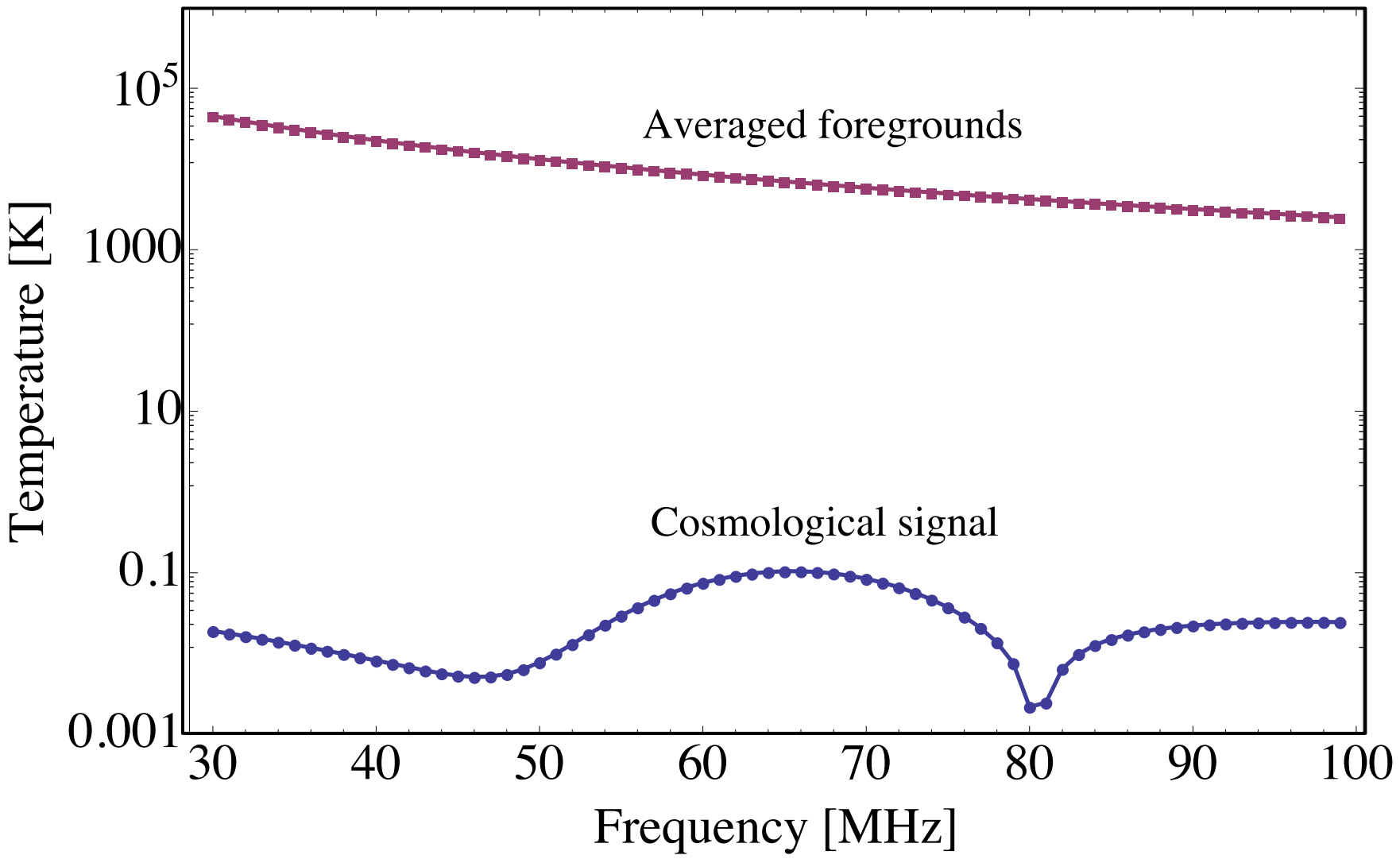
CAASTRO,

21st November 2012

Adrian Liu

The Vision for Global Signal Measurements


Ruled out by WMAP
Disfavored by SPT kSZ
Ruled out by EDGES
21cm global signal
Planck 1s
Planck 2s
Ruled out by Gunn- Peterson trough
Ruled out by WMAP
14
12
10
8
6
0
1
2
3
4
z_r
Dz


Averaged foregrounds
Cosmological signal
Temperature [K]
10^5
1000
10
0.1
0.001
30
40
50
60
70
80
90
100
Frequency [MHz]

Take-home messages

- Spectral-only foreground subtraction methods are insufficient.
- Better spectra from finer angular resolution: using spatial information reduces foreground residual errors.
- Using angular information allows high significance detections of both the Dark Ages and Reionization.

Spectral-only methods

A model of the foregrounds

A data analysis algorithm

The Global Sky Model is a good start…

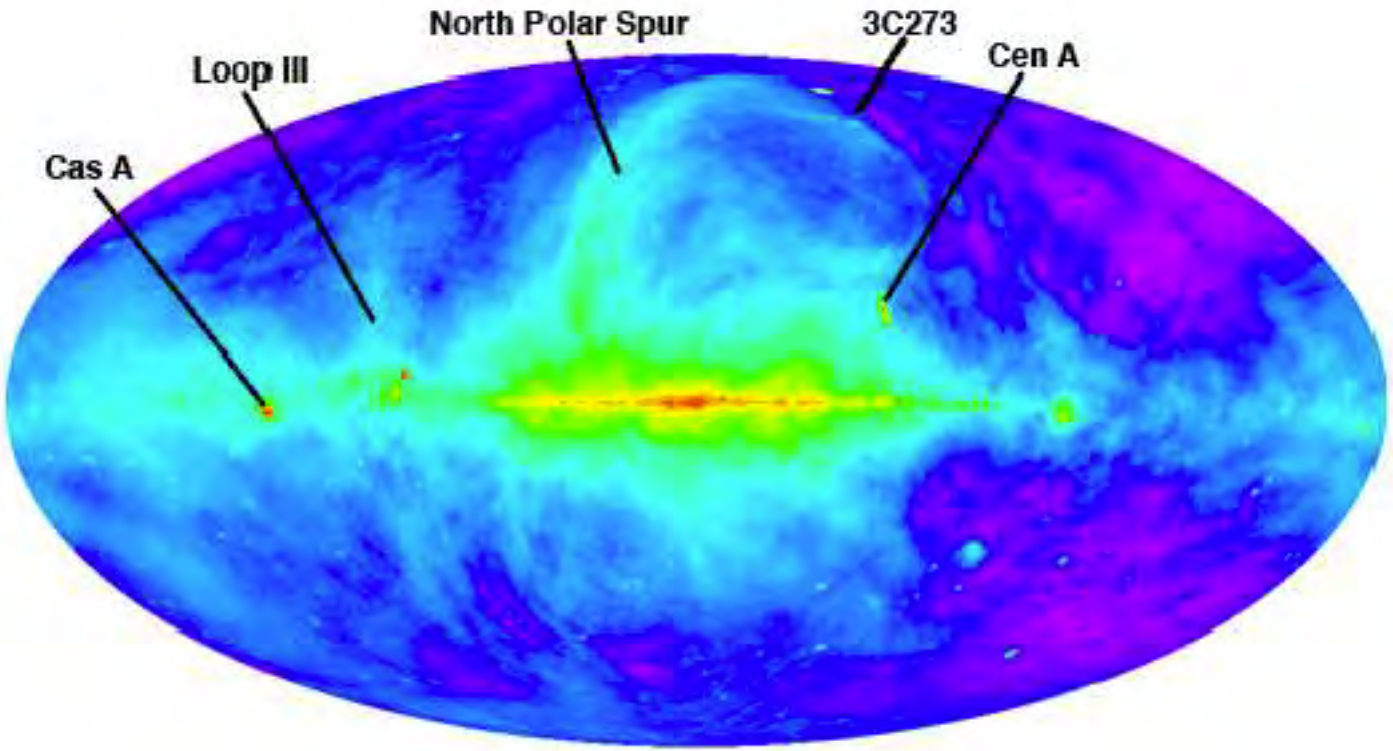
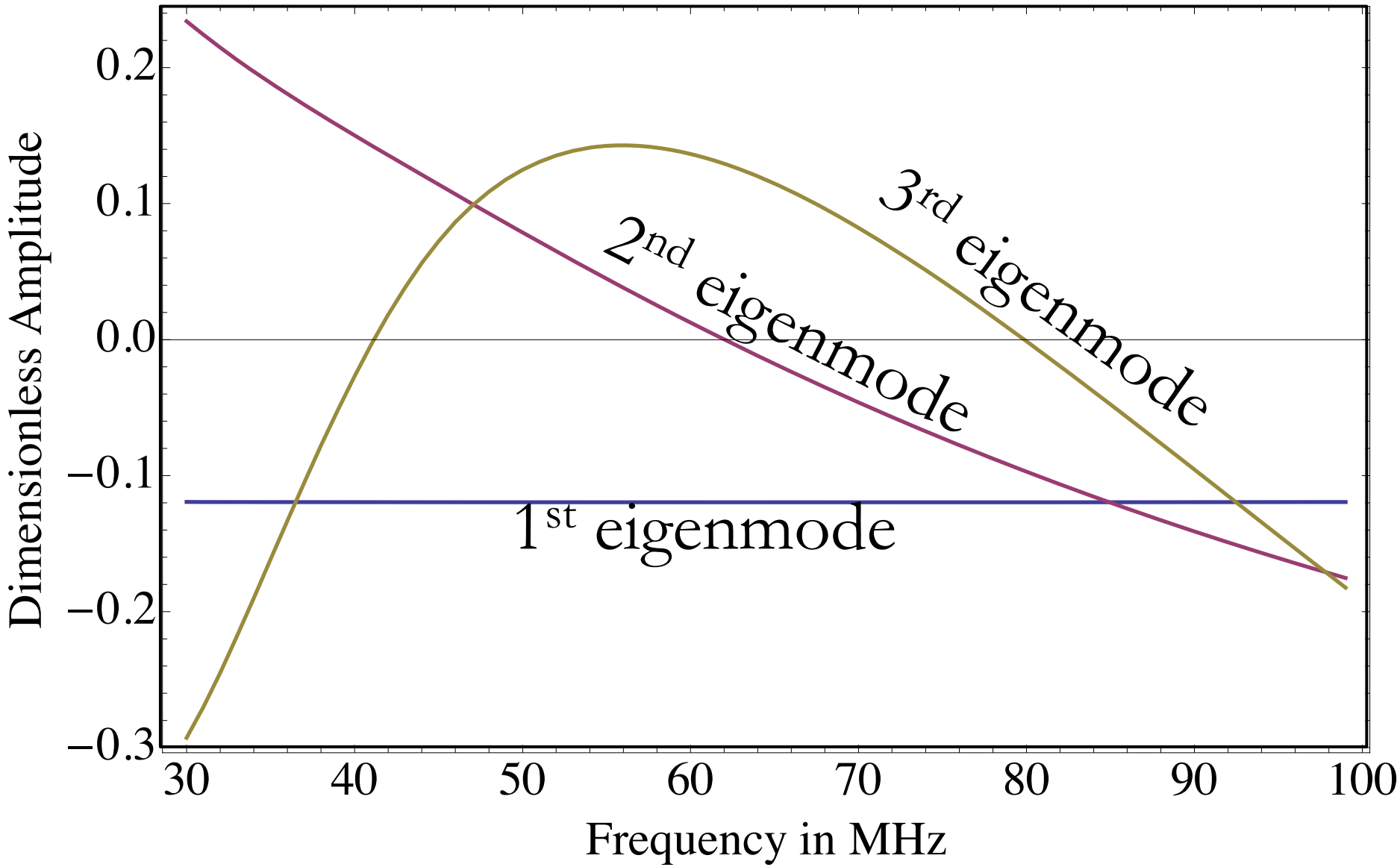
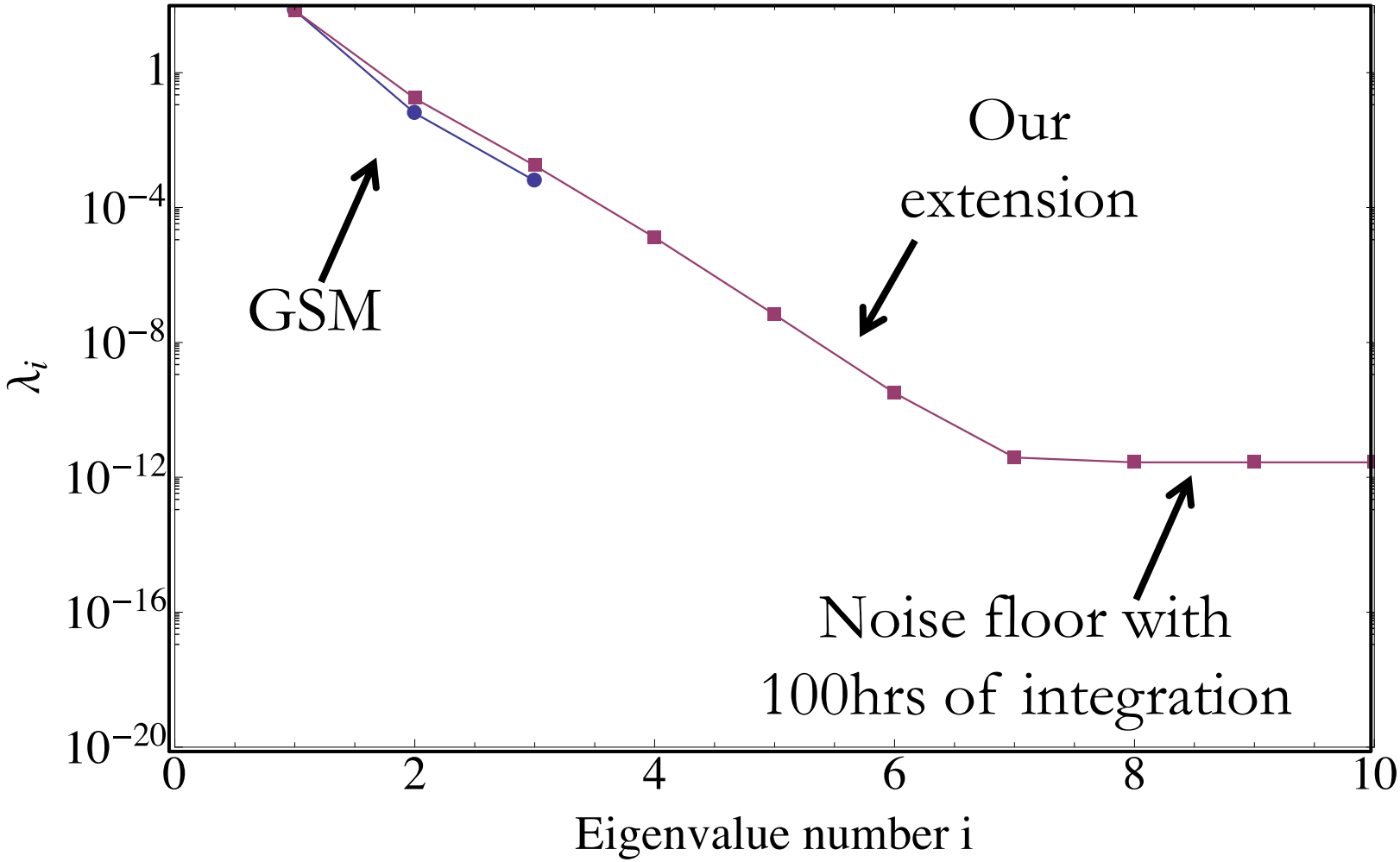


Image credit: de Oliveira-Costa et. al. 2008


Dimensionless Amplitude
0.2
0.1
0.0
−0.1
−0.2
−0.3
30
40
50
60
70
80
90
100
Frequency in MHz
3rd eigenmode
2nd eigenmode
1st eigenmode

…but it needs to be supplemented



A model of the foregrounds

A data analysis algorithm

Minimizing the variance tells us to subtract off a best-guess model but to do nothing more

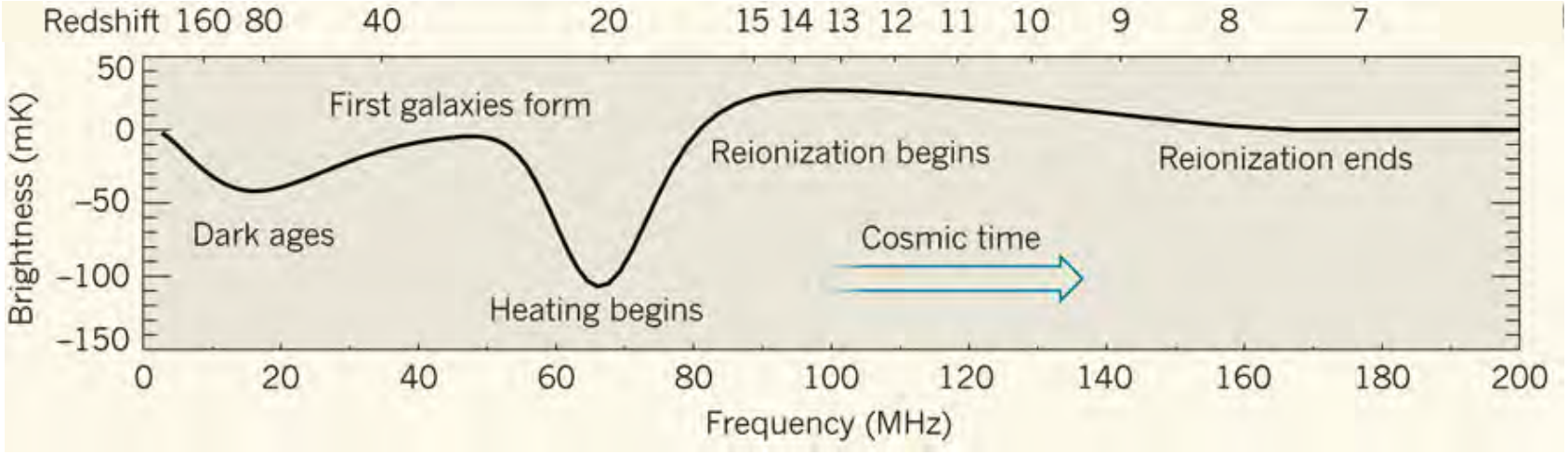
$$\widehat{\mathbf{x}}_s = \mathbf{z} - \langle \mathbf{c} \rangle$$

Global signal spectrum estimator

Measured spectrum

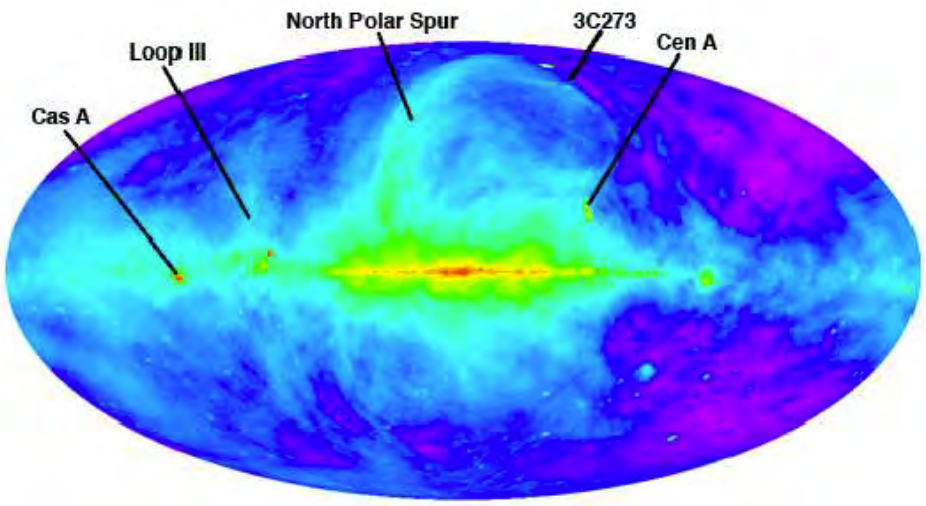
"Best guess" foreground model

Spectral-only methods cannot provide safeguards against errors in the foreground model because they do not possess redundancy



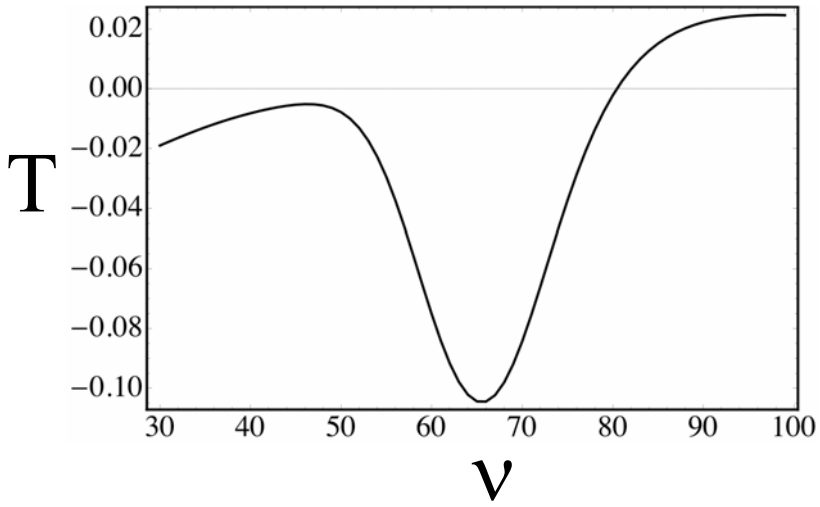
Pritchard & Loeb, Nature, 468, 722 (2010)

The performance of spectral-only methods



Σ

Measurement covariance

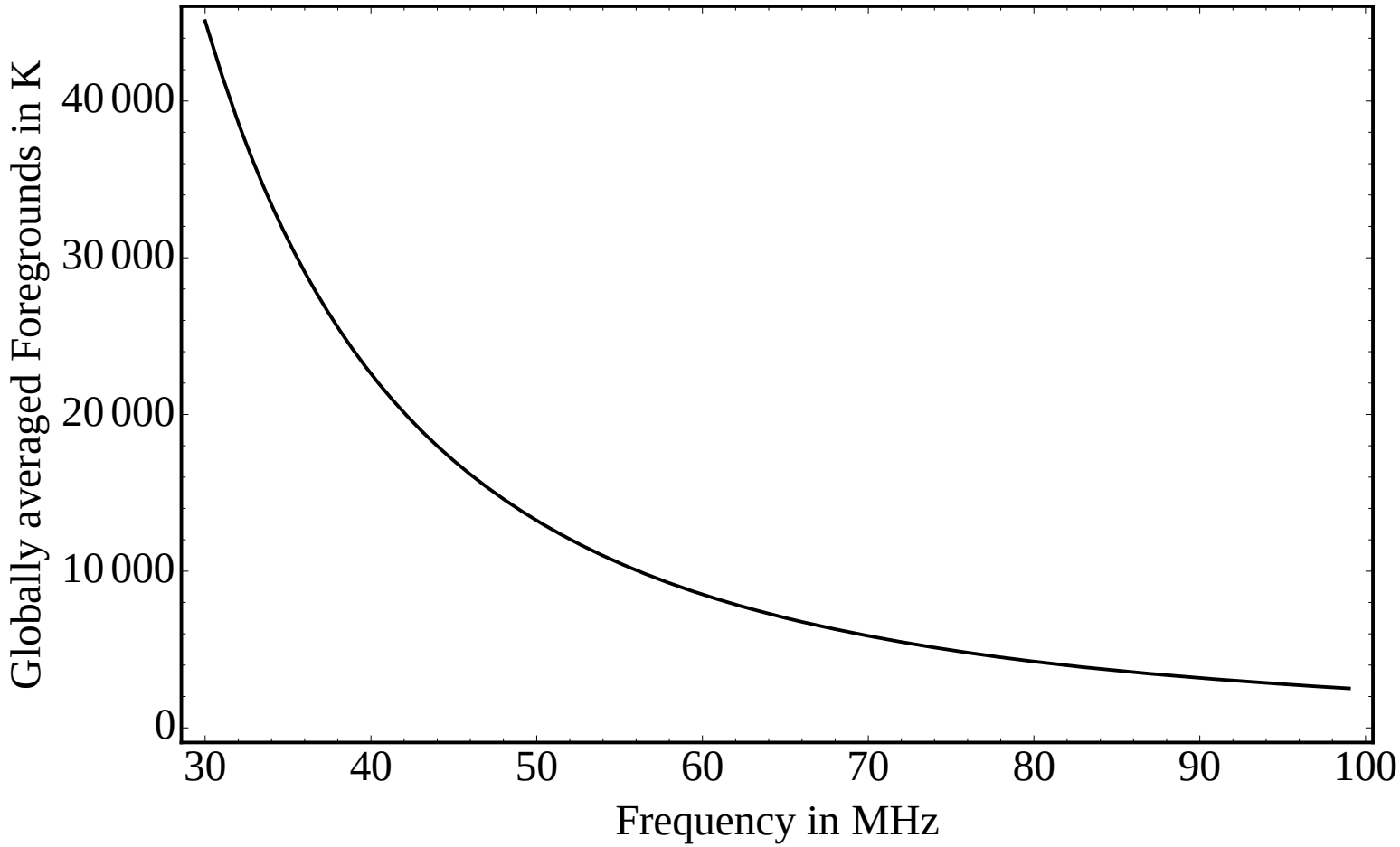


S

Expected signal

$$(s^t \Sigma^{-1} s)^{1/2} \sim 14$$

Surprising that it works so well!



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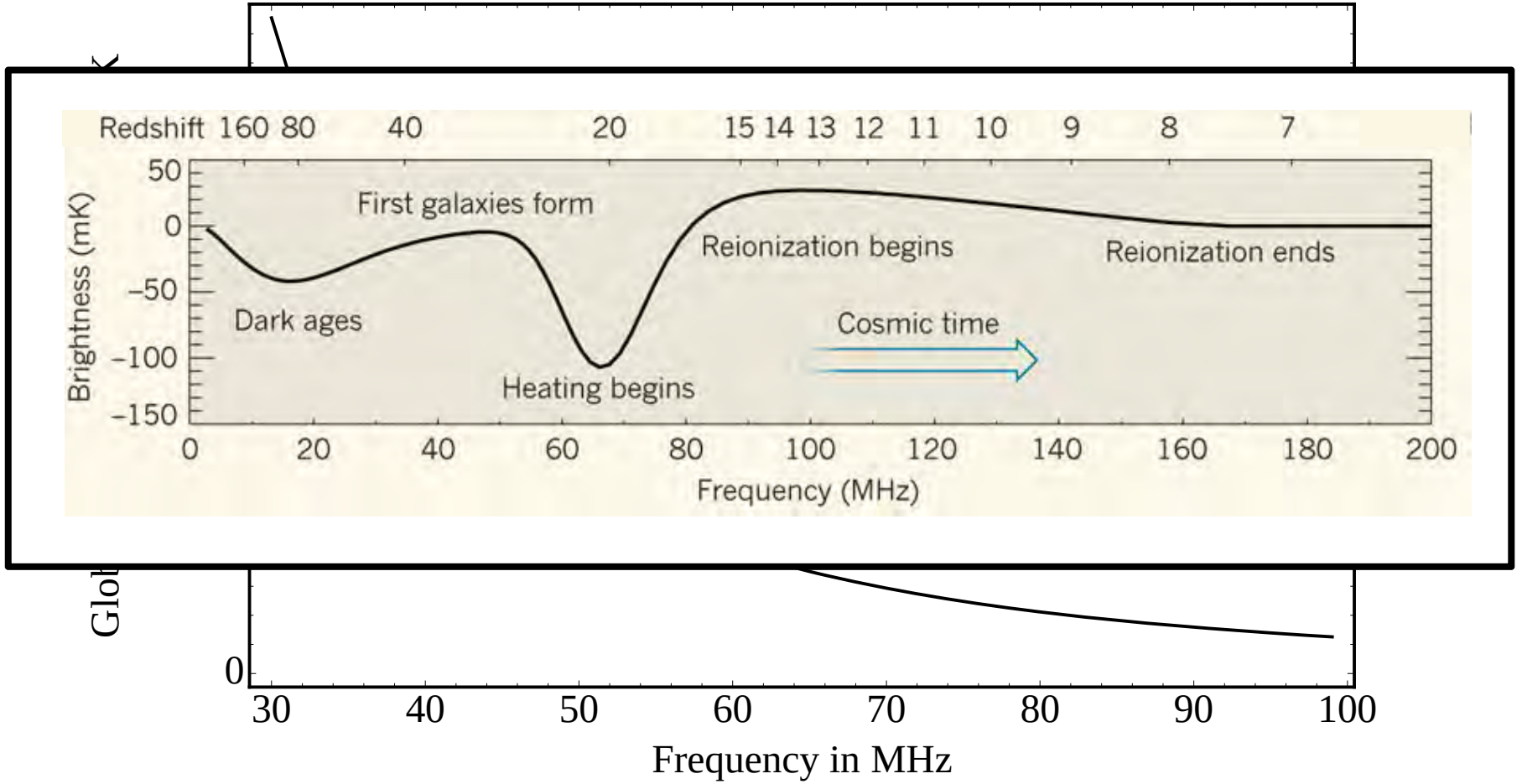
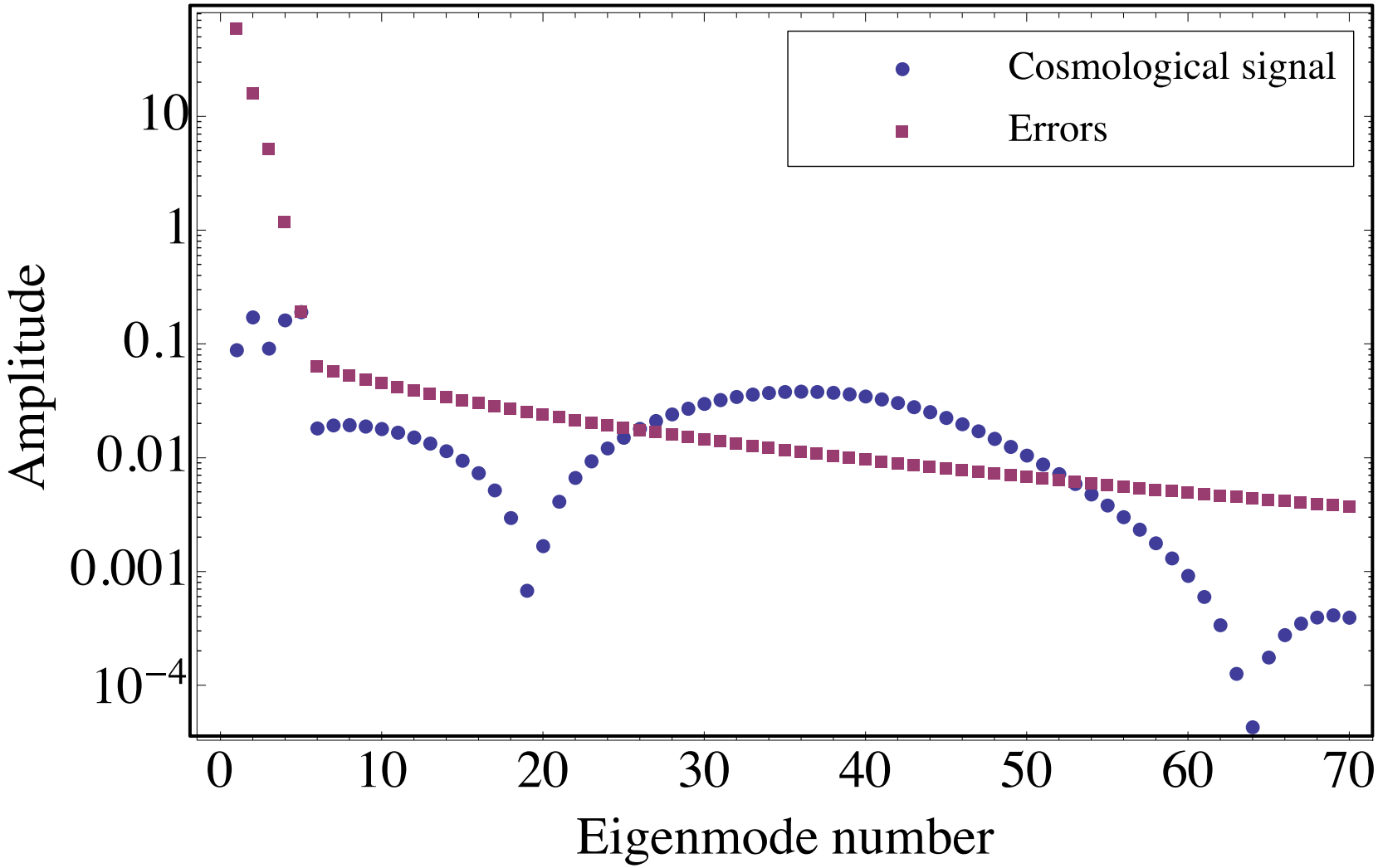
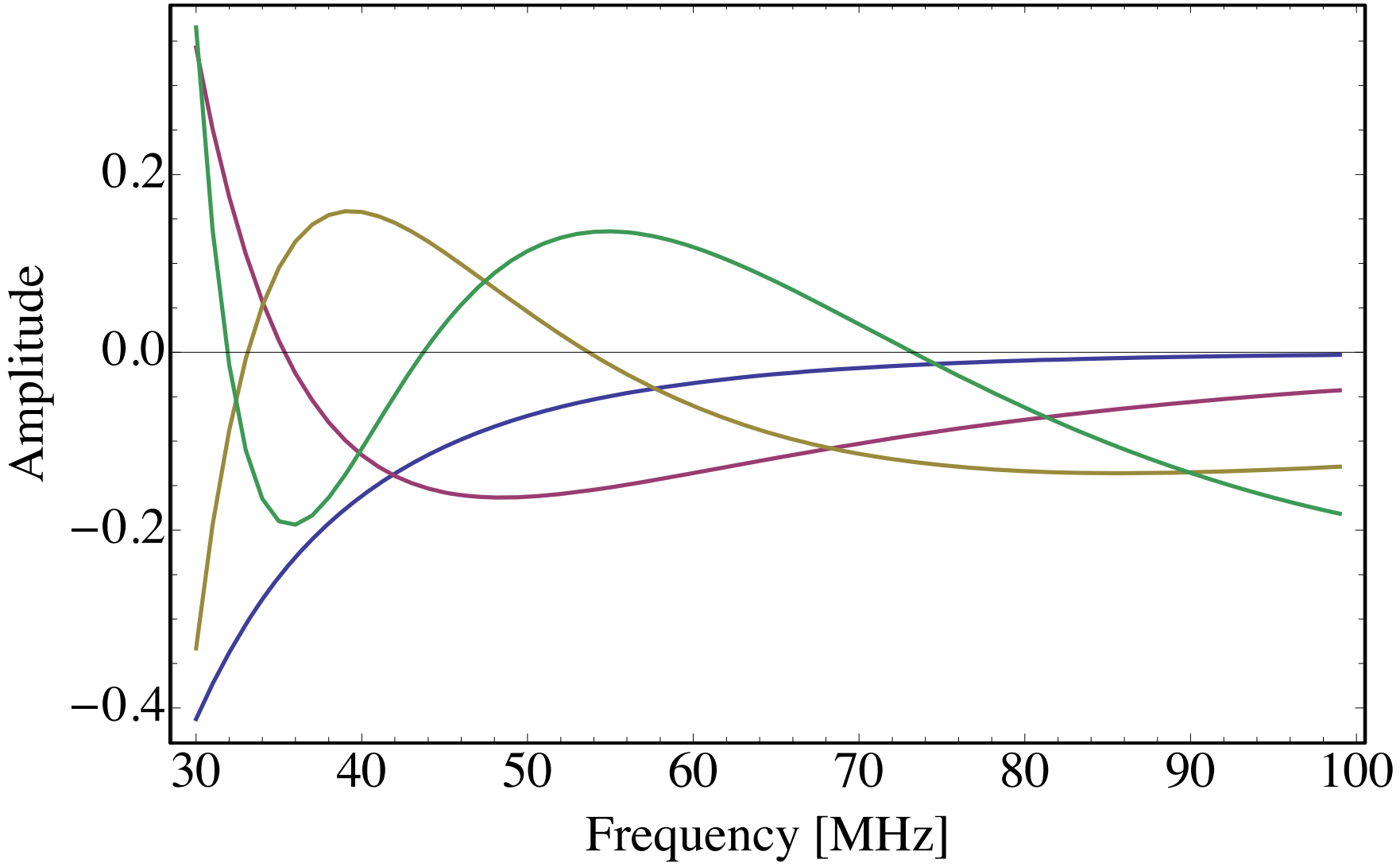


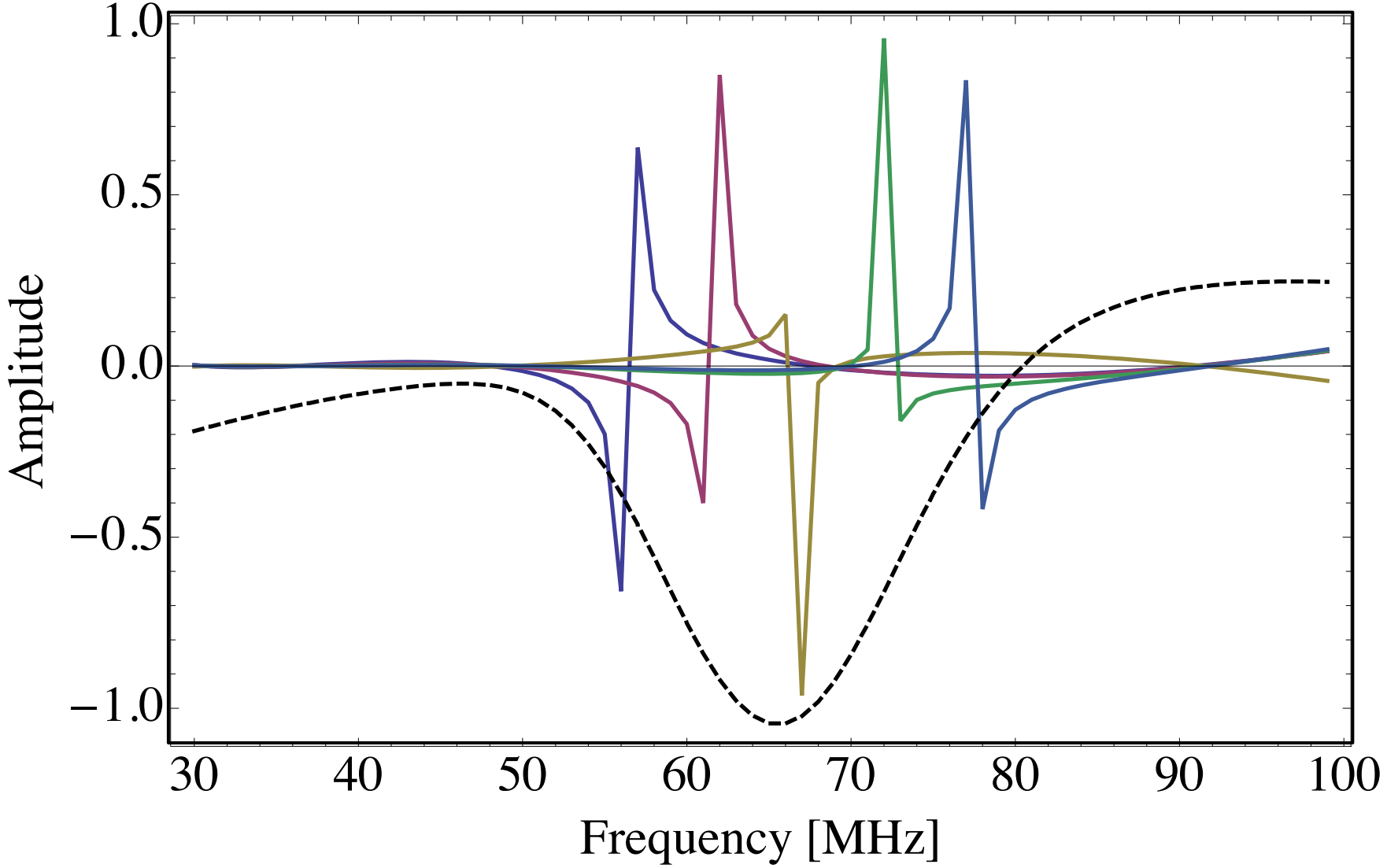
The high statistical significance comes from a small handful of modes



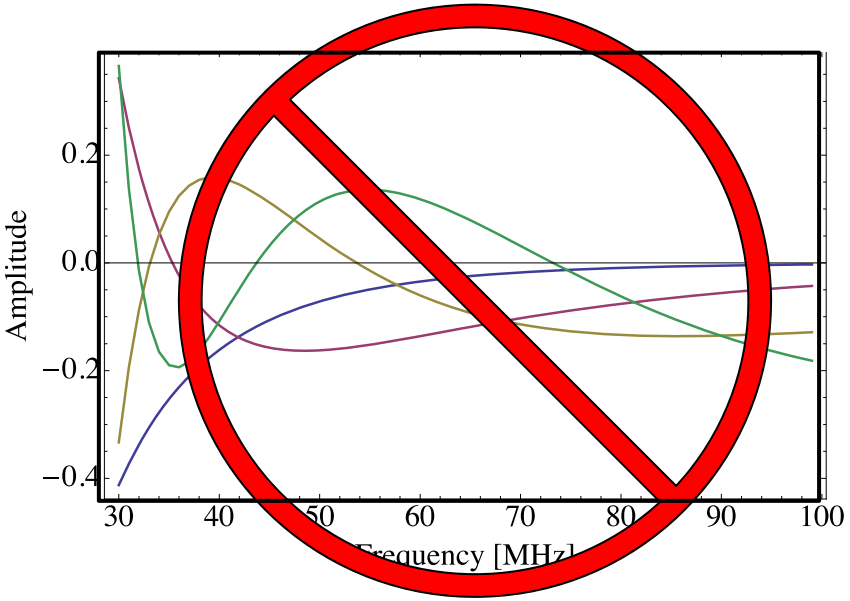
The modes that cannot be measured are the smooth foreground contaminated ones

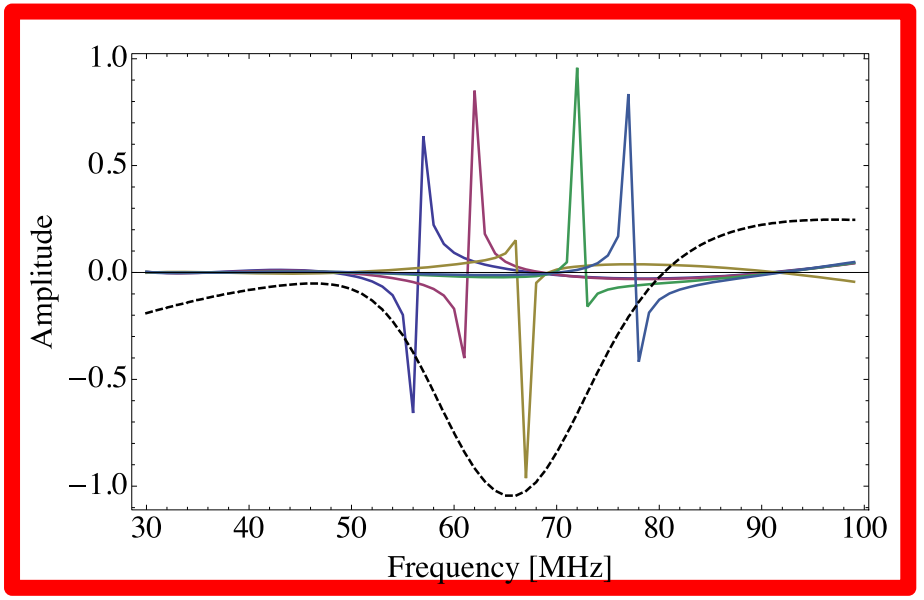


Detection is based on derivatives of the trough



Mission Accomplished?





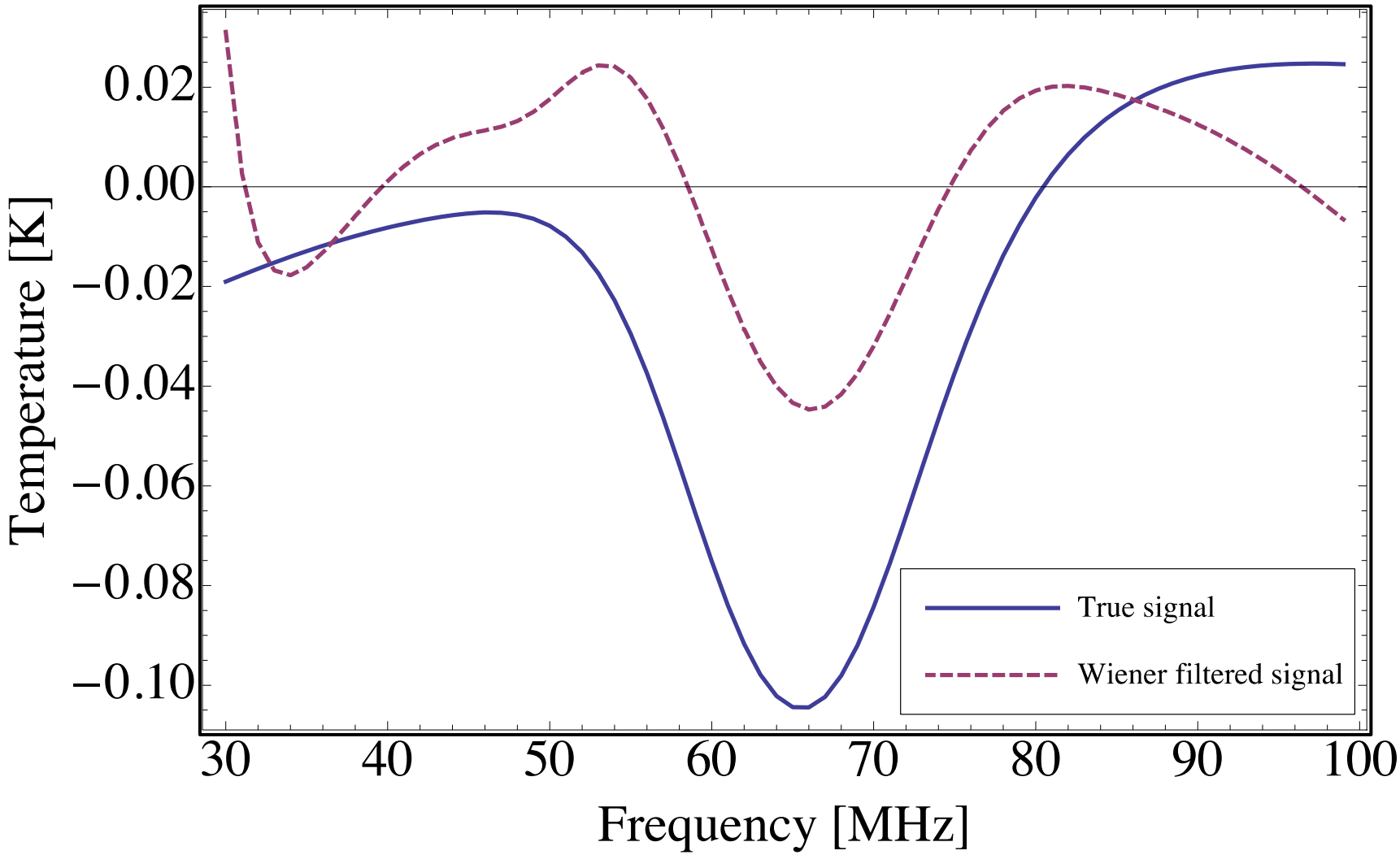
Use Wiener filtering/weighting to reconstruct signal

$$w = \frac{\text{Signal}}{\text{Signal} + \text{Noise}}$$

~1 for clean modes

~S/N for dirty modes

Much of the signal is gone



$$(s^t \Sigma^{-1} s)^{1/2} \sim 14$$

but

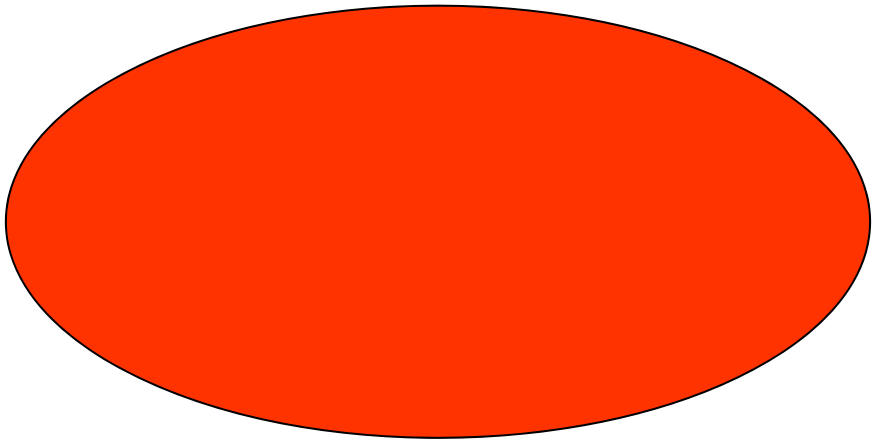
$$(\Sigma_{\alpha\alpha})^{1/2} \sim 11K$$

(at 79MHz)

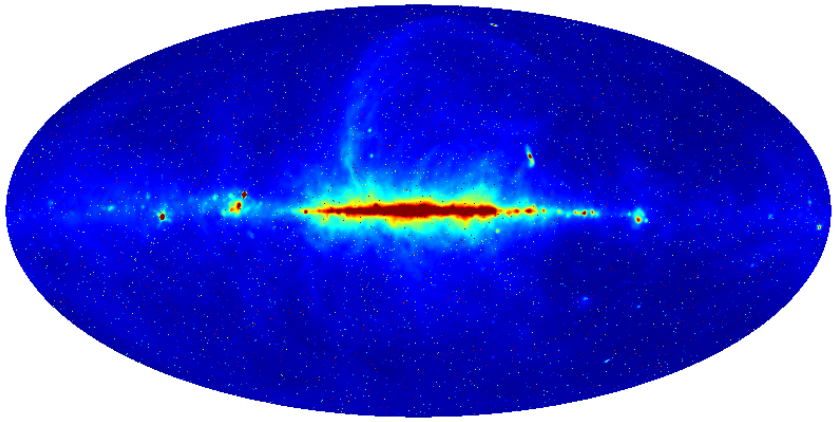
Take-home messages

- Spectral-only foreground subtraction methods are insufficient.
- Better spectra from finer angular resolution: using spatial information reduces foreground residual errors.

Angular resolution can break degeneracies between cosmological signal and foregrounds



Cosmological Signal



Foreground contaminants

An analogy: To get the angular dependence of the CMB, we exploit redundancy in frequency

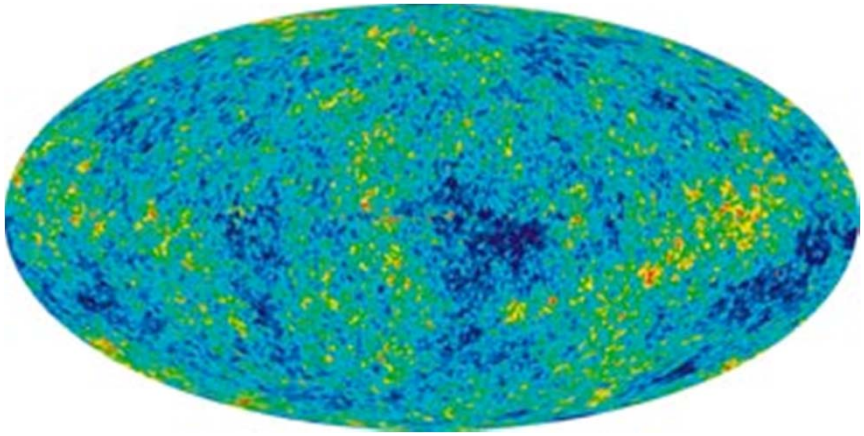


Image credit: WMAP Team

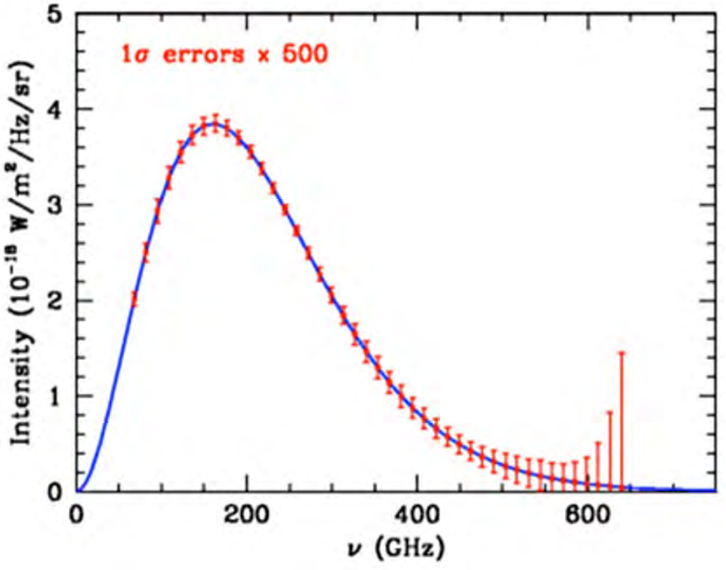


Image credit: COBE Team

An analogy: To get the angular dependence of the CMB, we exploit redundancy in frequency

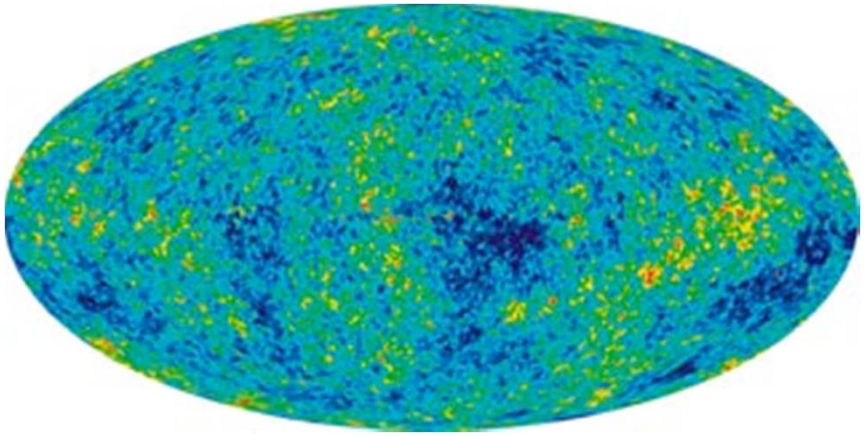


Image credit: WMAP Team

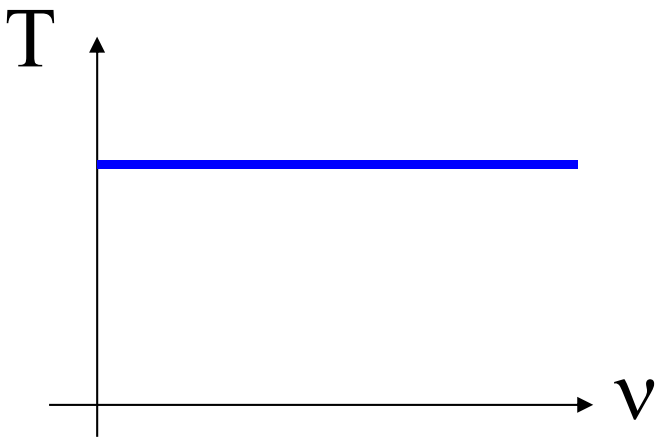
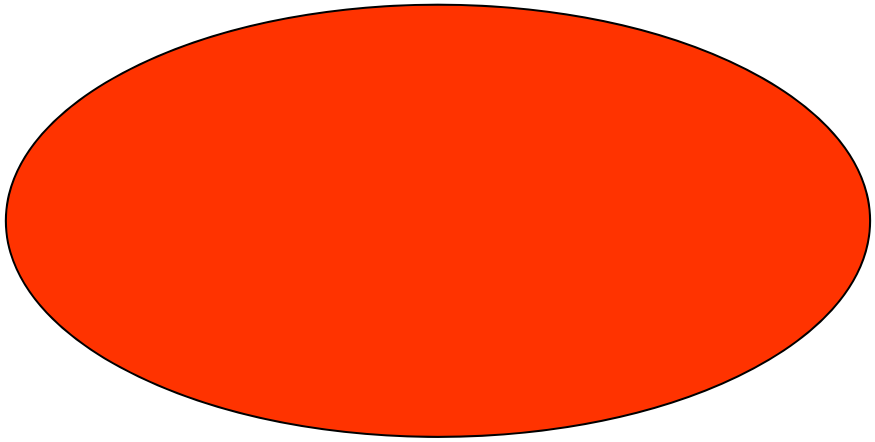
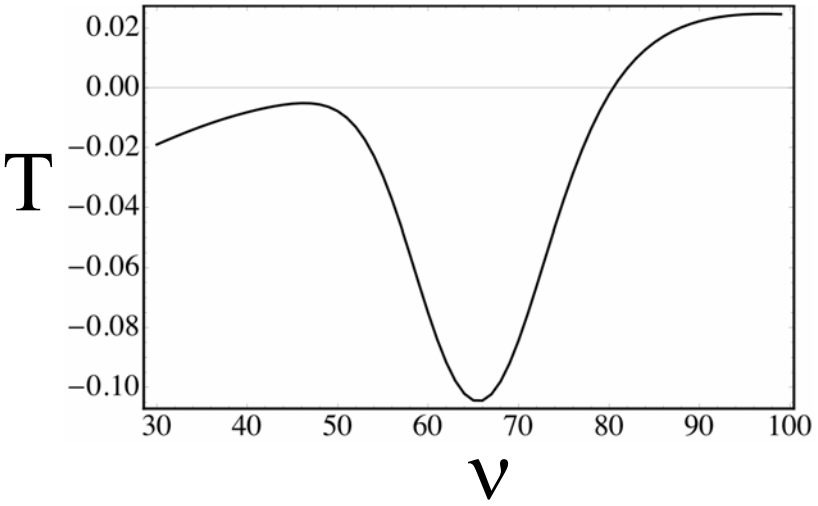


Image credit: Powerpoint

An analogy: To get the frequency dependence of the global signal, we exploit angular redundancy

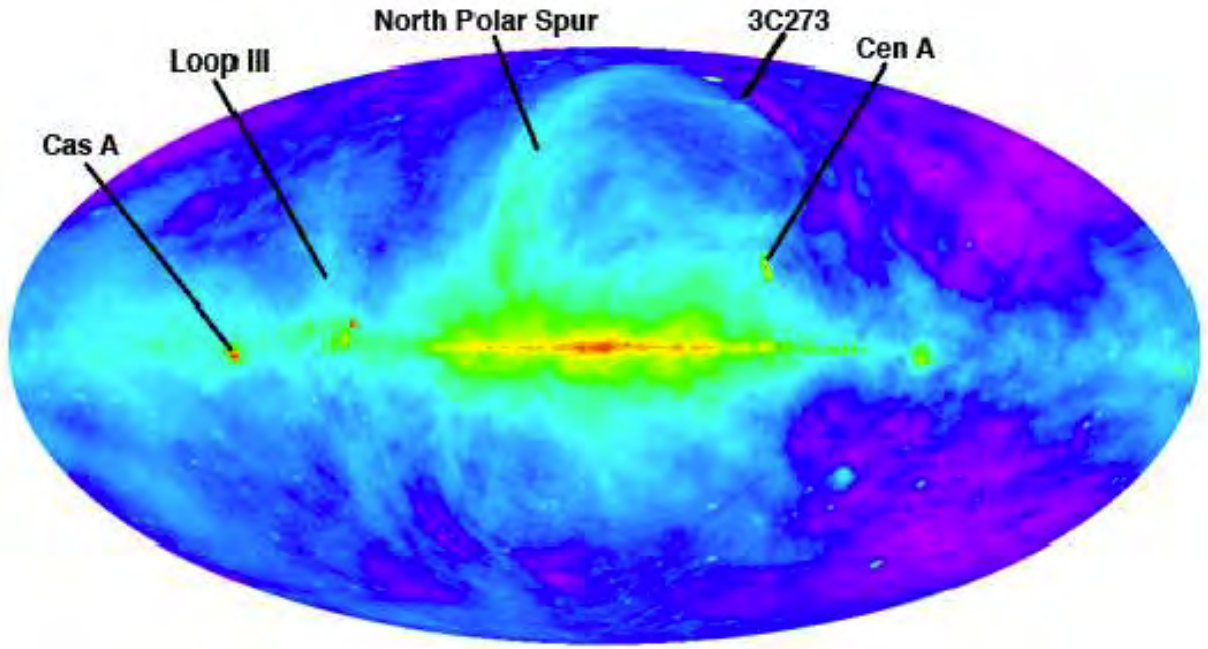




Despite our ultimate goal of measuring the monopole, angular resolution is necessary.

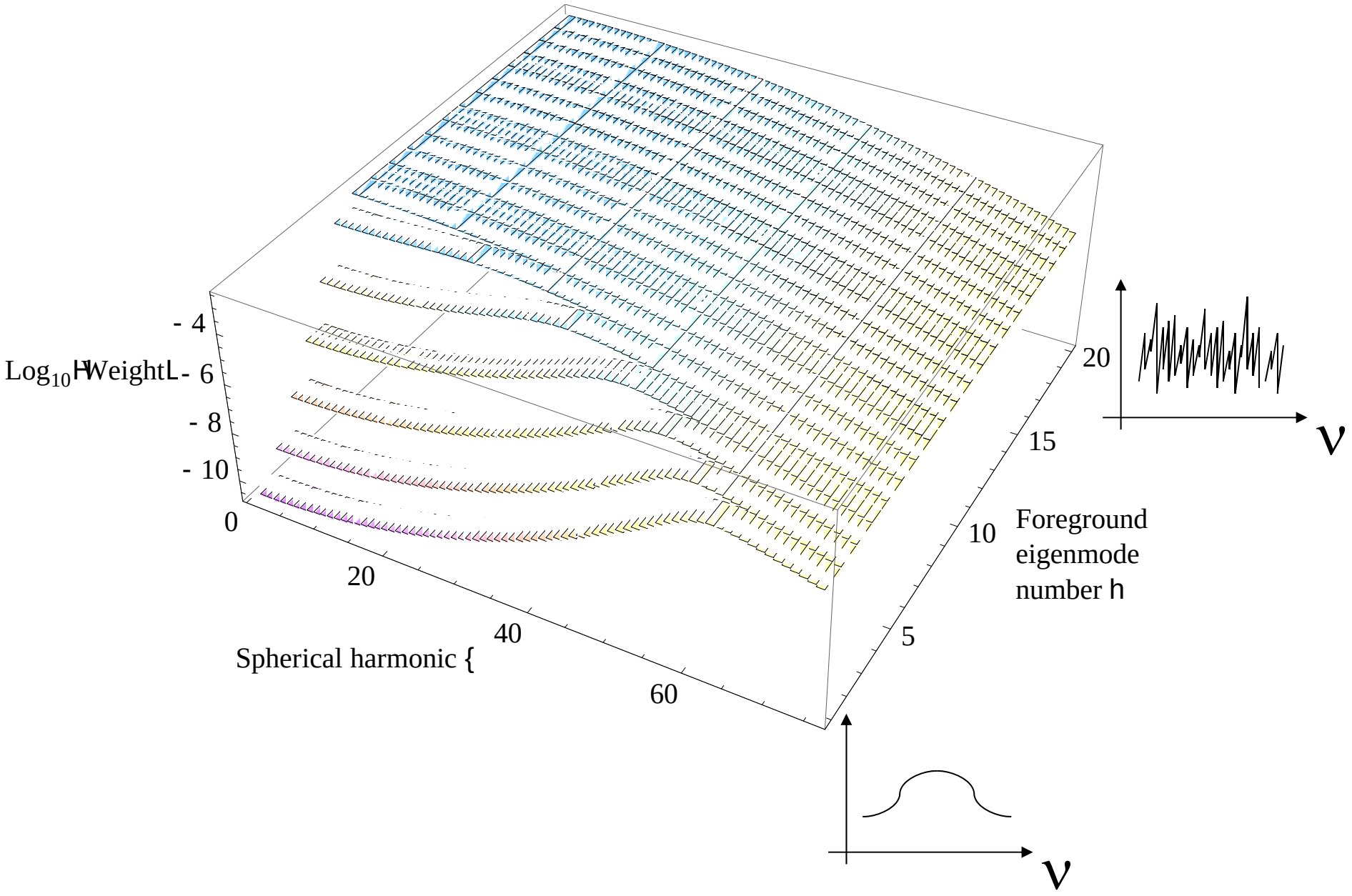
The details of angular foreground mitigation

- Downweight or discard heavily contaminated regions.
- Use spatial correlations to remove foregrounds

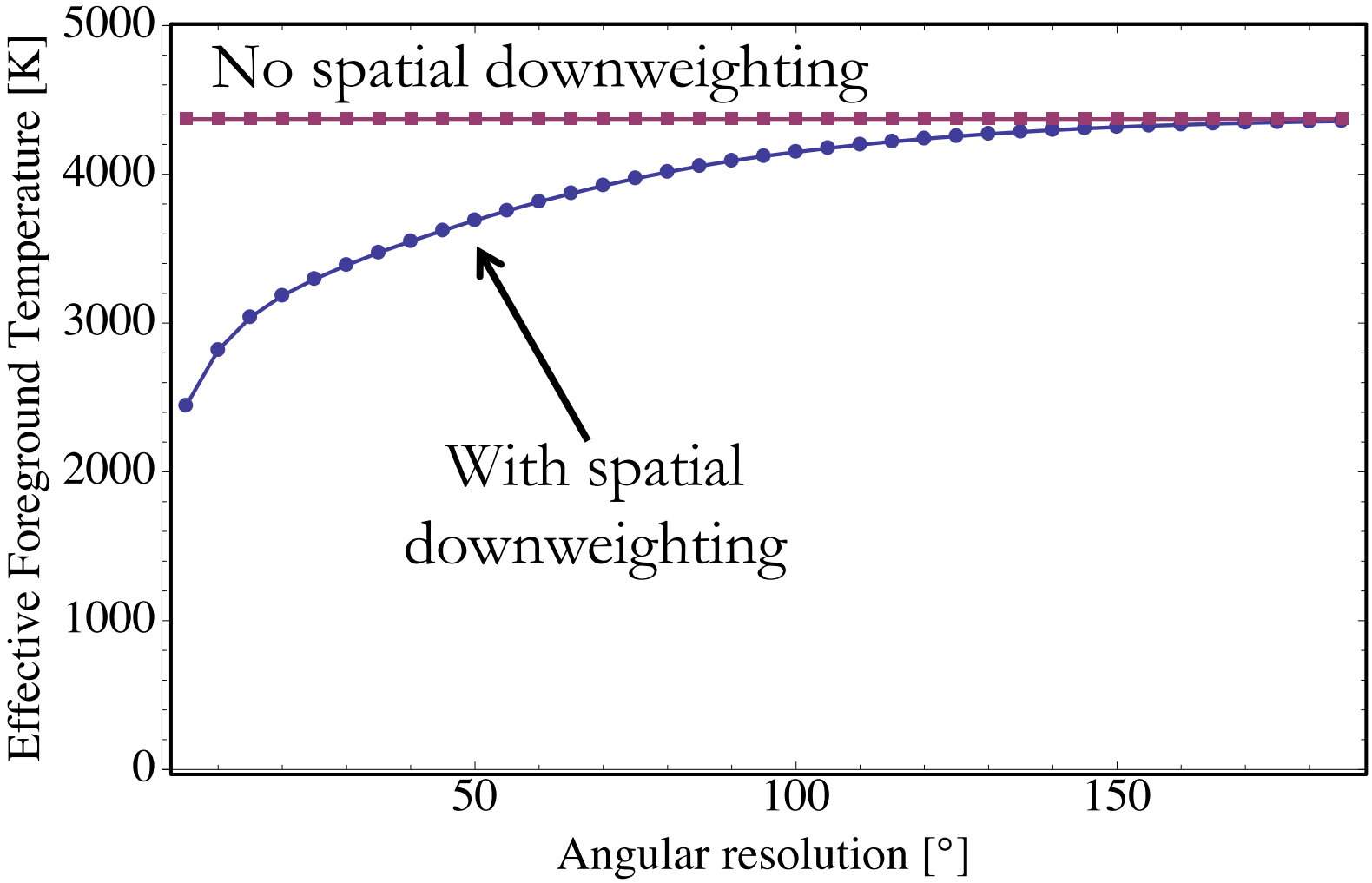


The minimum variance recipe with angular information

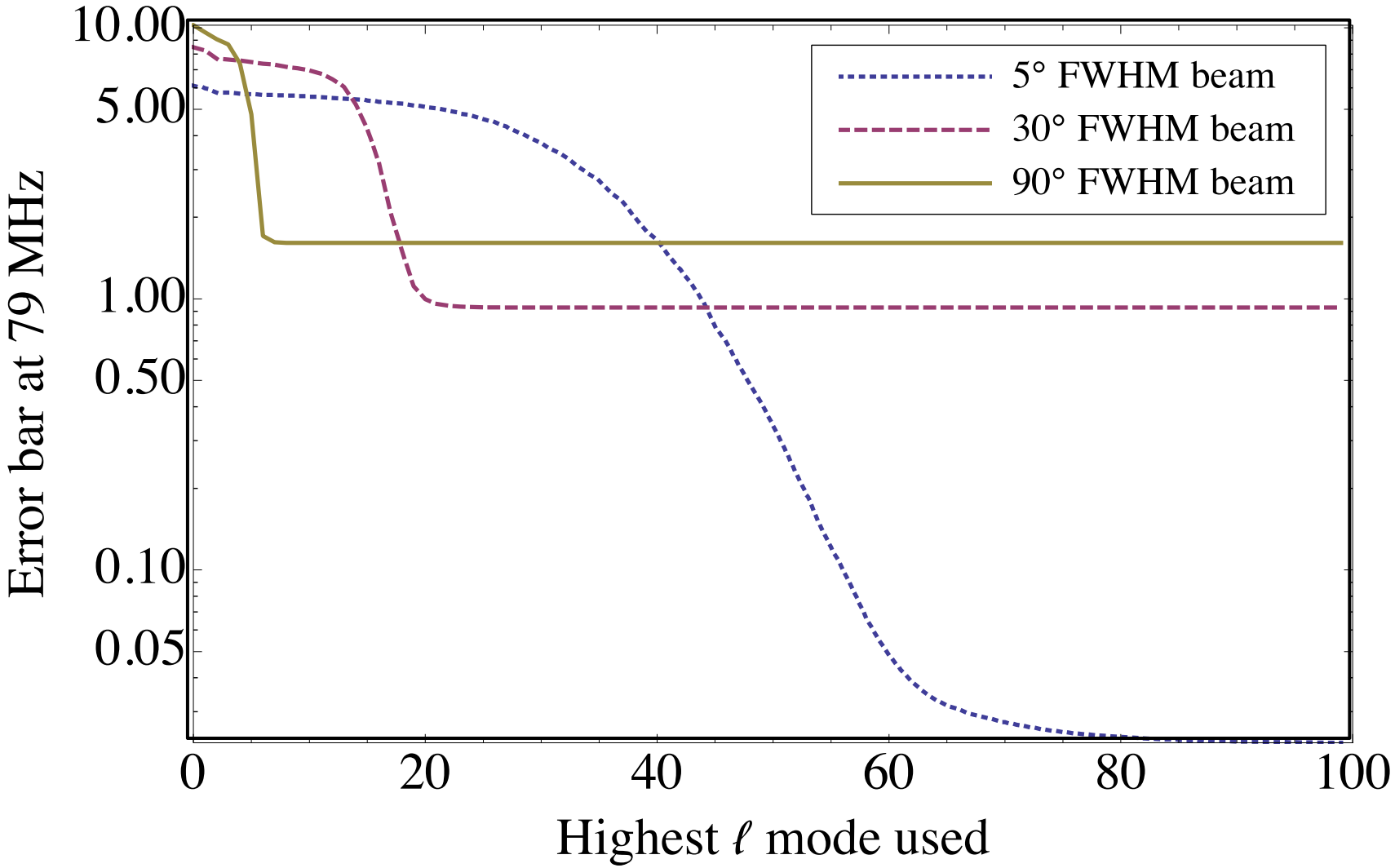
1. Divide the measured map by one factor of the foreground model.
2. Switch to spherical harmonic and spectral eigenmode basis.
3. Weight each spatial and spectral scale.
4. Switch back to original basis.
5. Divide by one more factor of model.
6. Sum over all pixels to form a spectrum.
7. Renormalize spectrum.


- 4
Log10[Weight] - 6
- 8
- 10
0
20
40
60
Spherical harmonic {
5
10
15
20
Foreground
eigenmode
number h
ν
ν

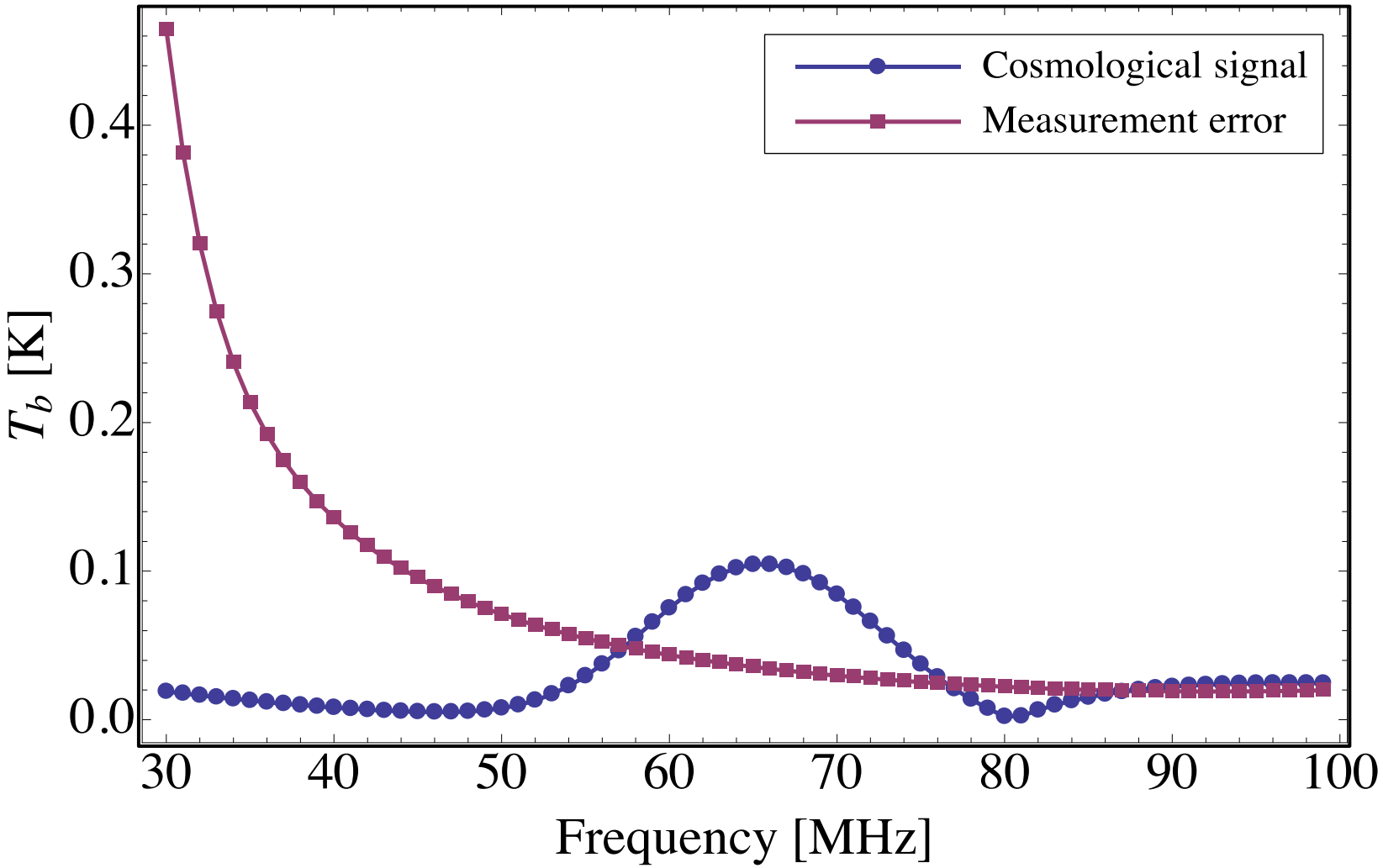
Downweighting reduces error bars by about a factor of two



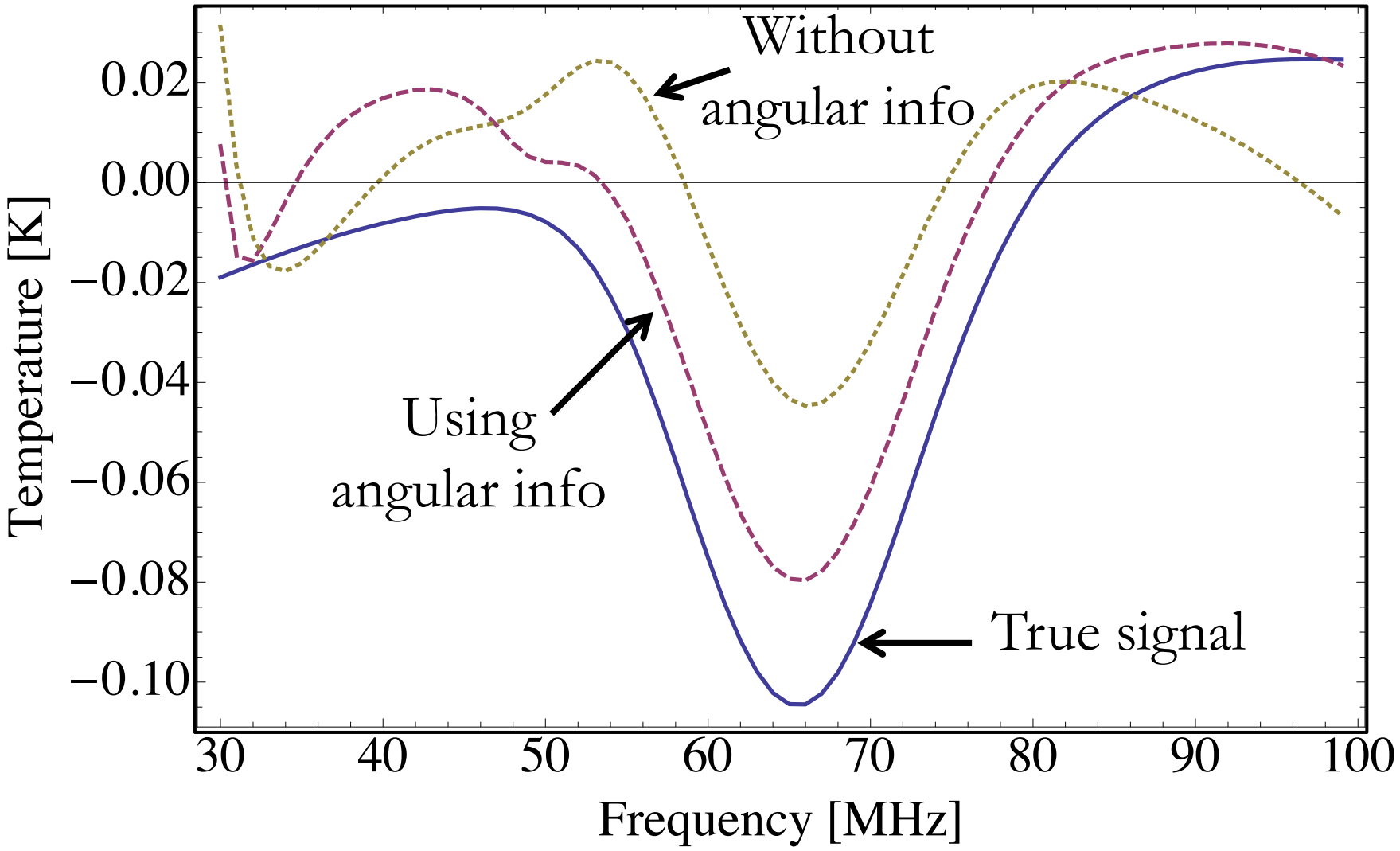
Taking advantage of spatial correlations further reduces errors



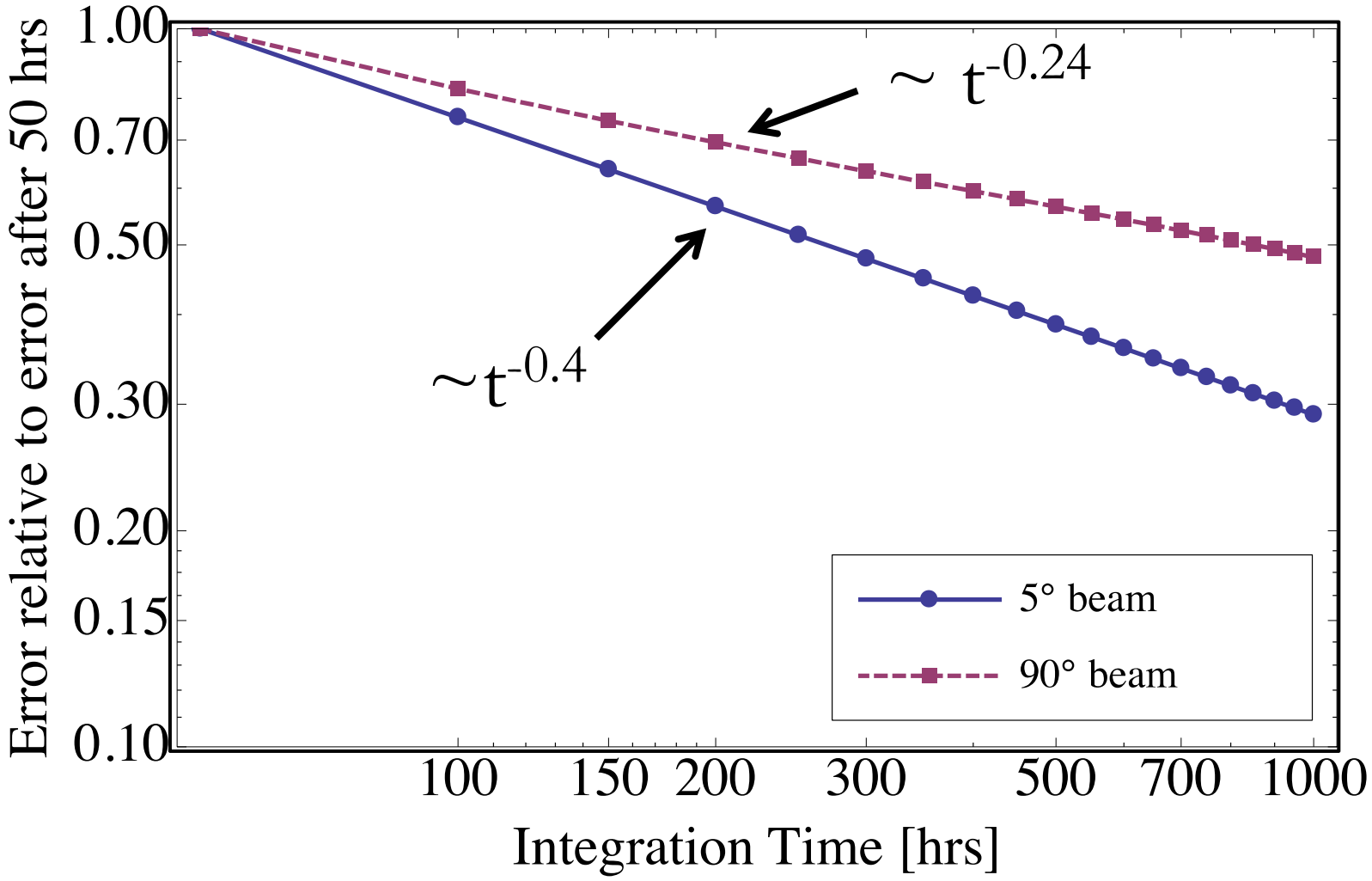
A 100hr integration gives a 25σ detection



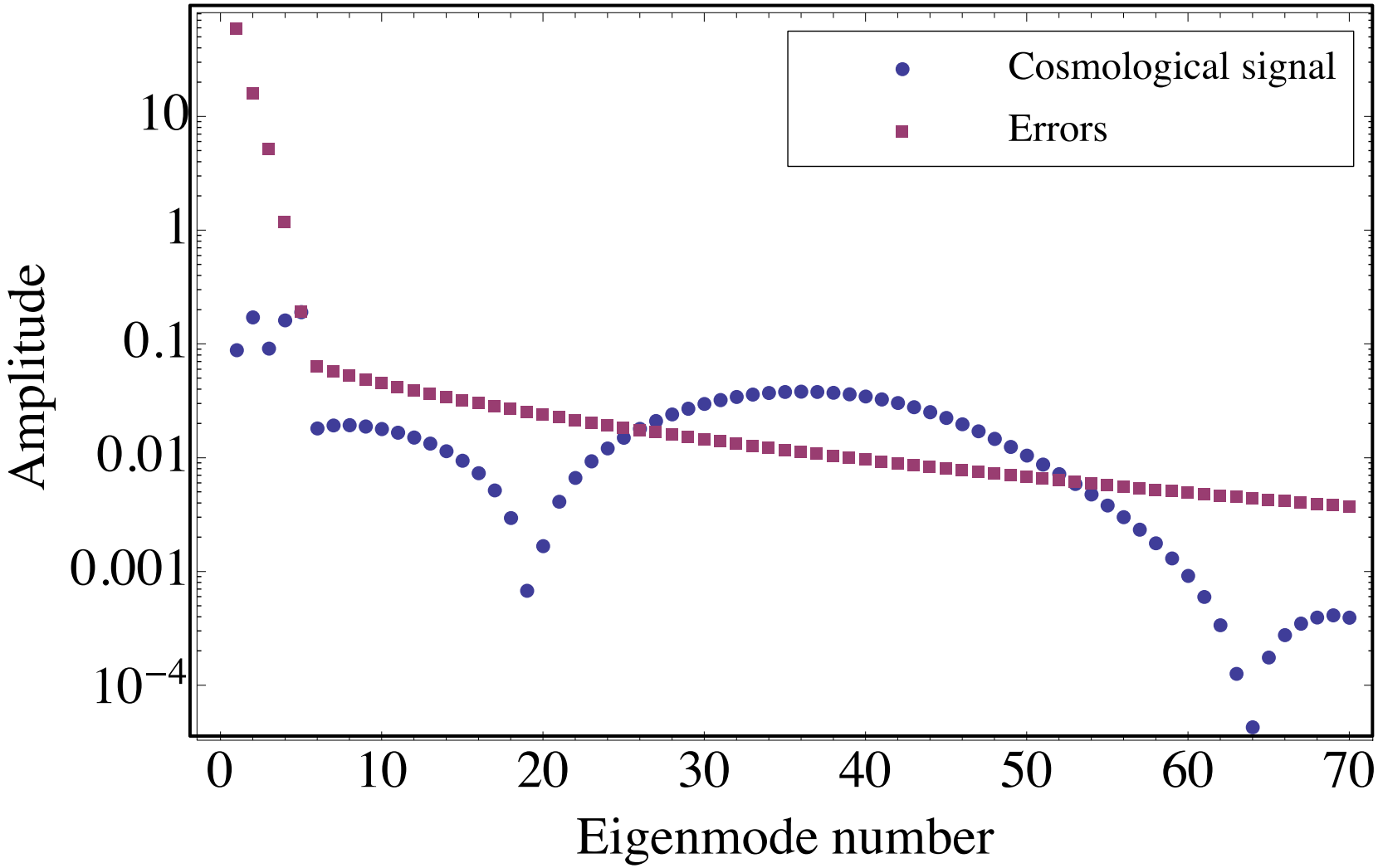
A better reconstruction



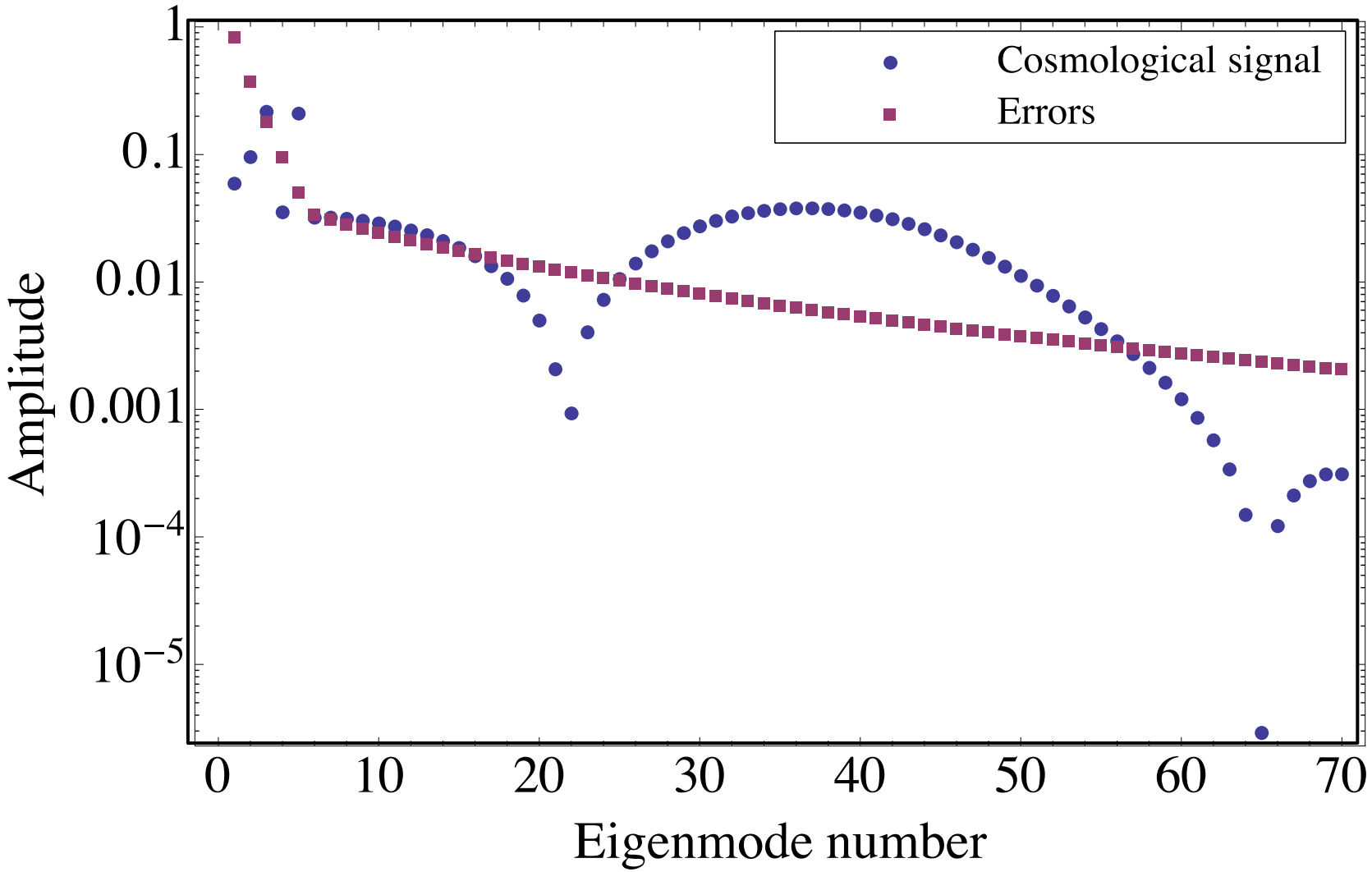
Errors also average down faster



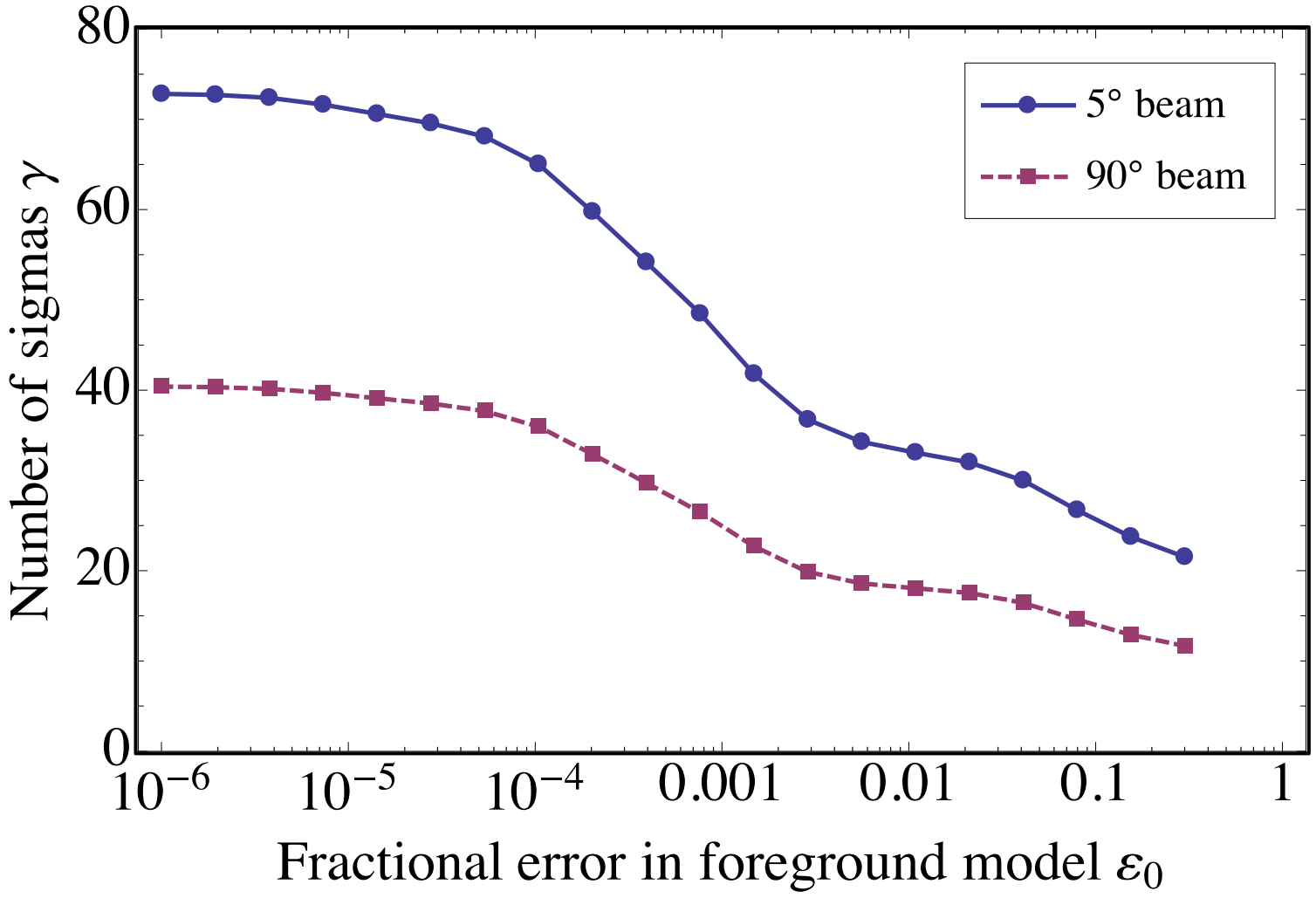
With no angular info, integration time goes into measuring a few modes better



Using angular information allows more modes to be integrated down



Improving foreground models will help, but improvements may saturate



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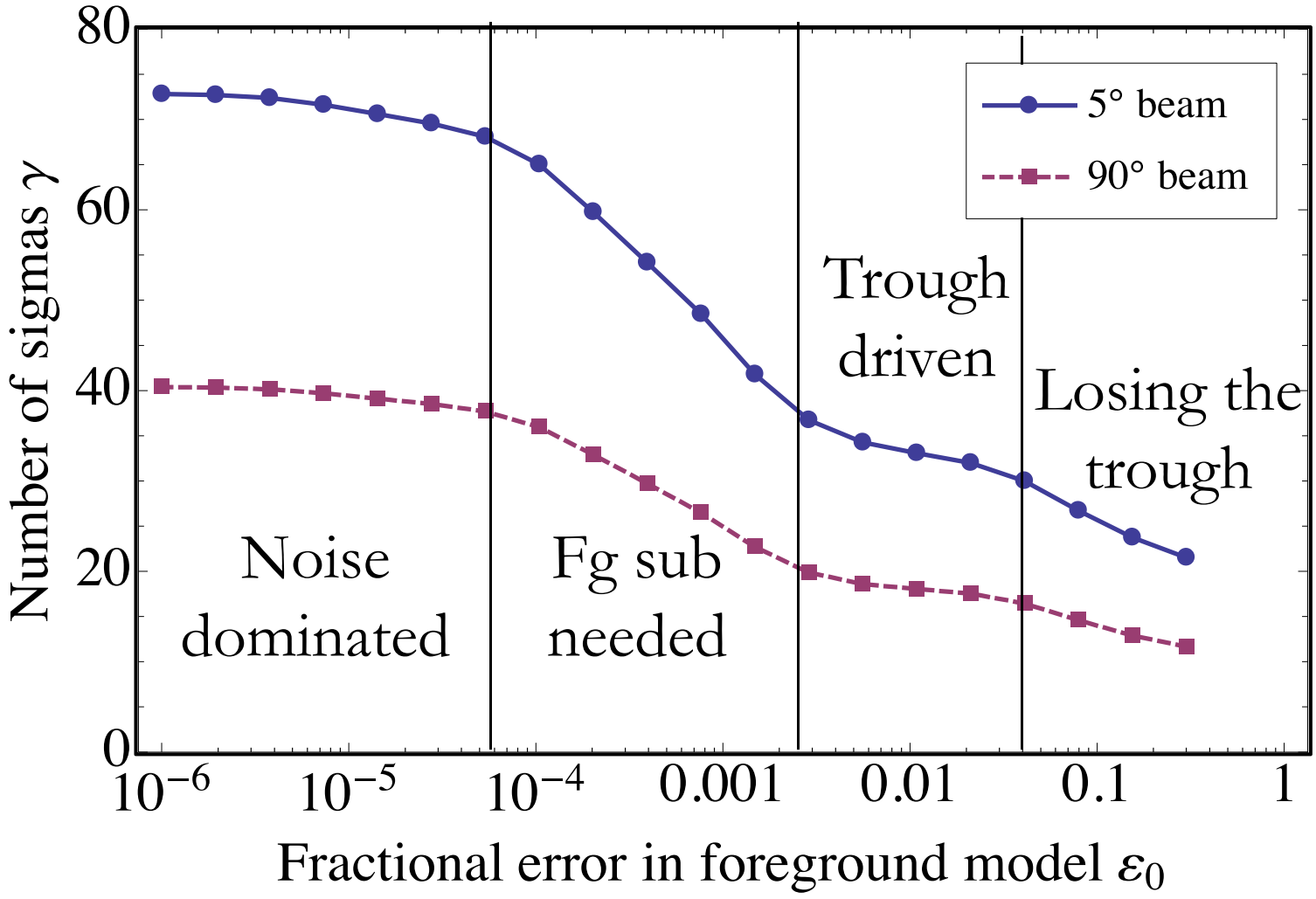
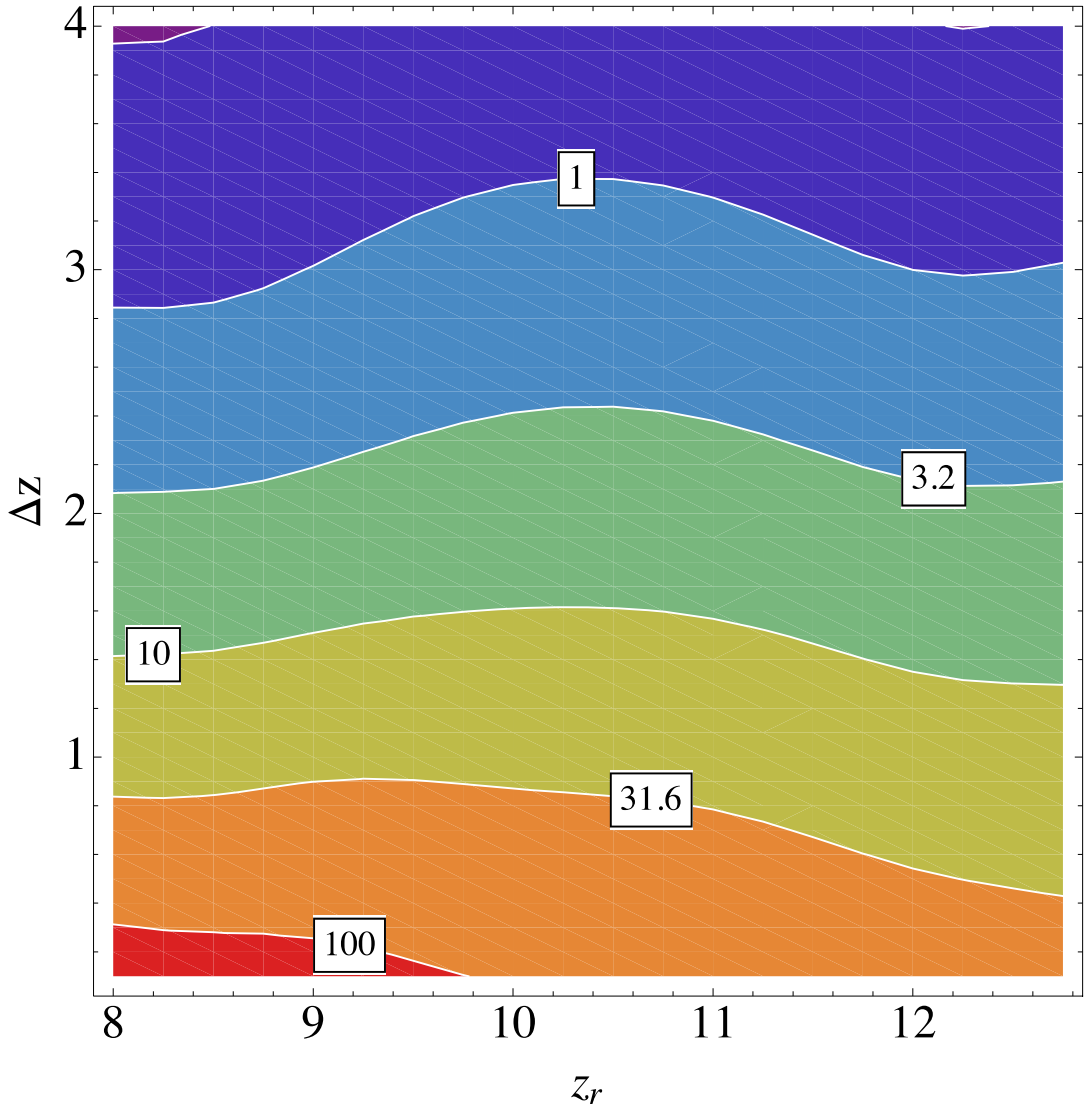


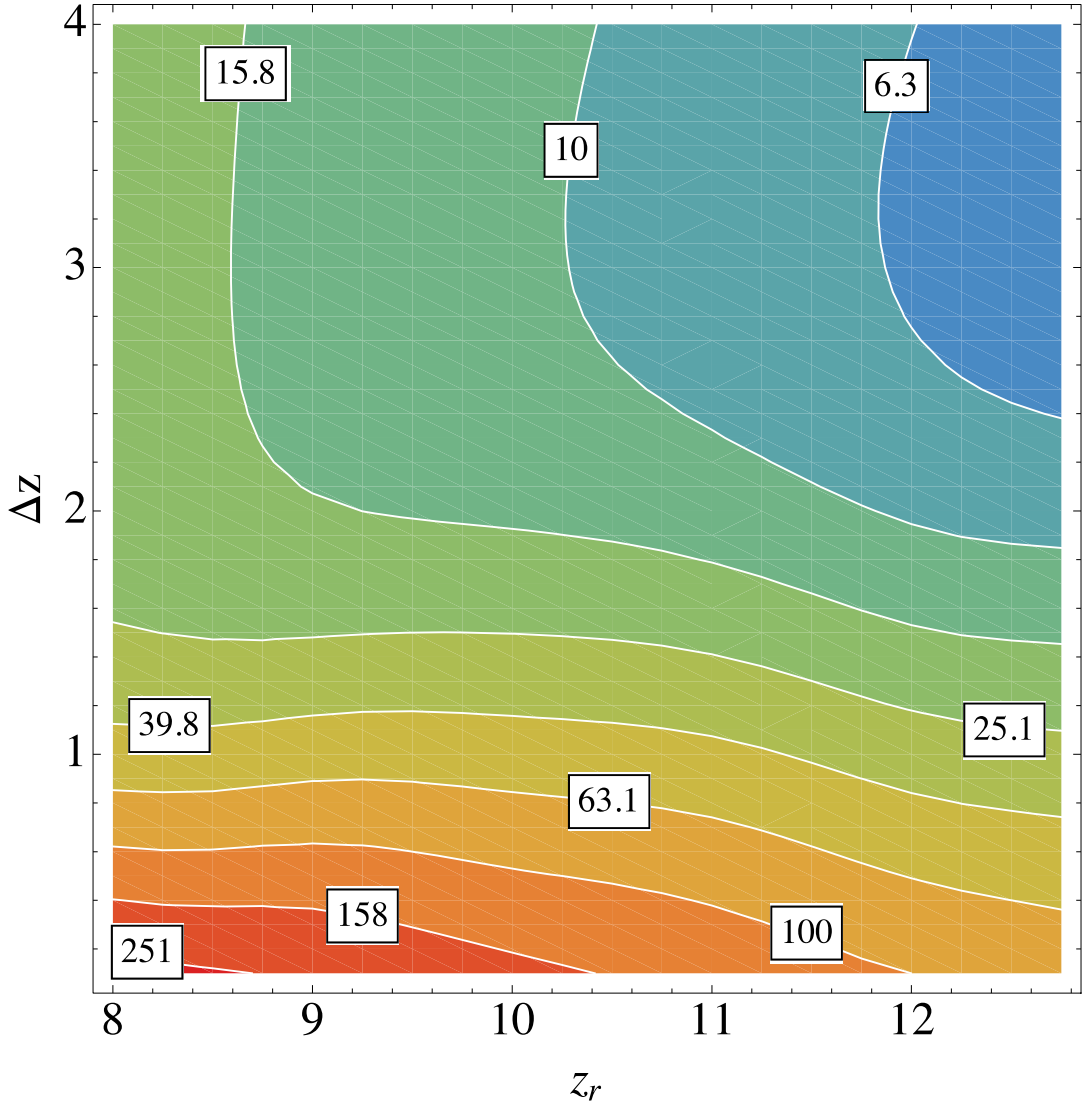
Take-home messages

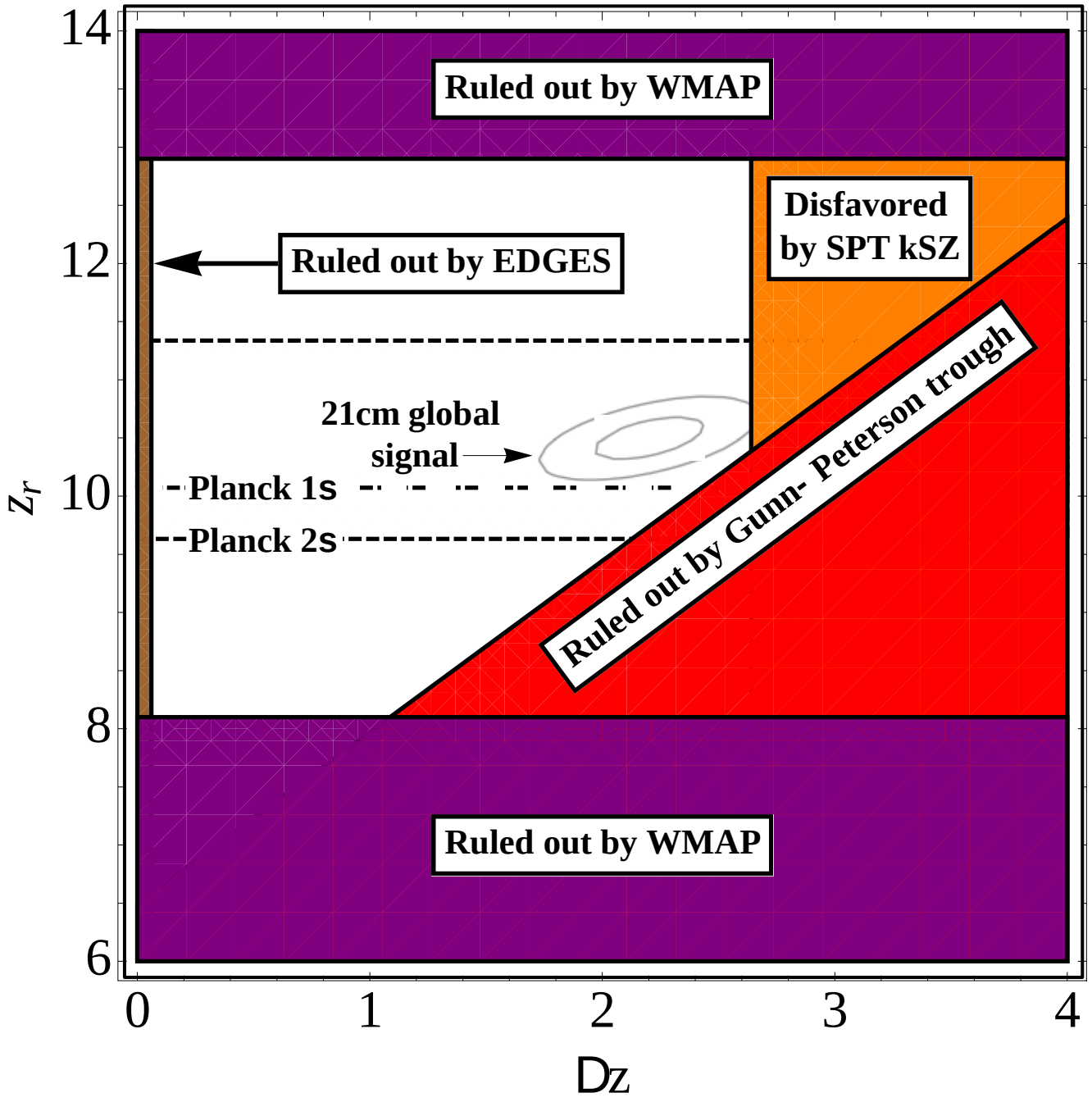
- Spectral-only foreground subtraction methods are insufficient.
- Better spectra from finer angular resolution: using spatial information reduces foreground residual errors.
- Using angular information allows high significance detections of both the Dark Ages and Reionization.

Gradual reionization is difficult to detect without angular resolution



Using angular information allows extended reionization to be detected

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14
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z_r
Dz

Better spectra from finer angular resolution

"Global 21cm Experiments: A Designer's Guide"
arXiv: 1211.3743
AL, Pritchard, Tegmark, Loeb