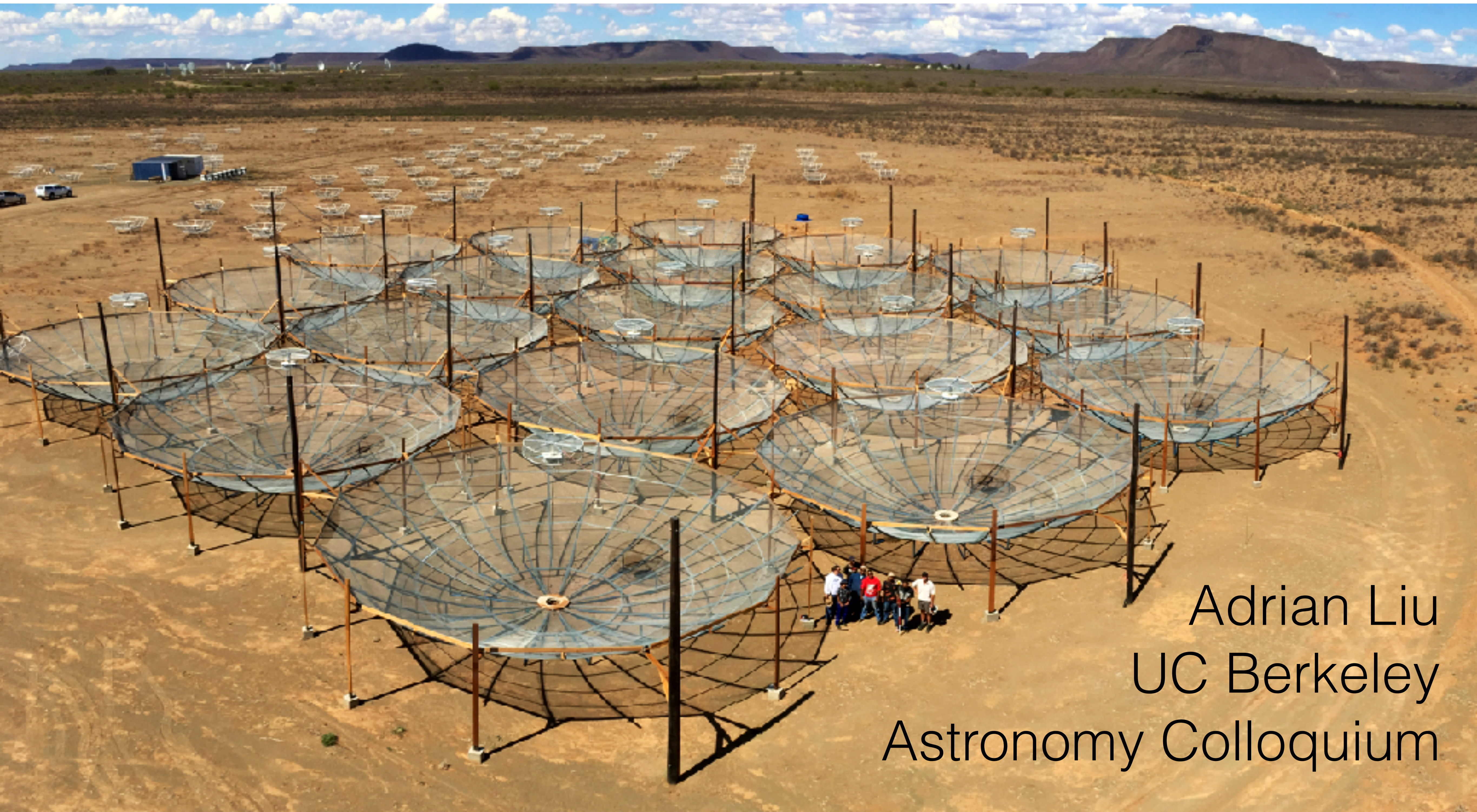
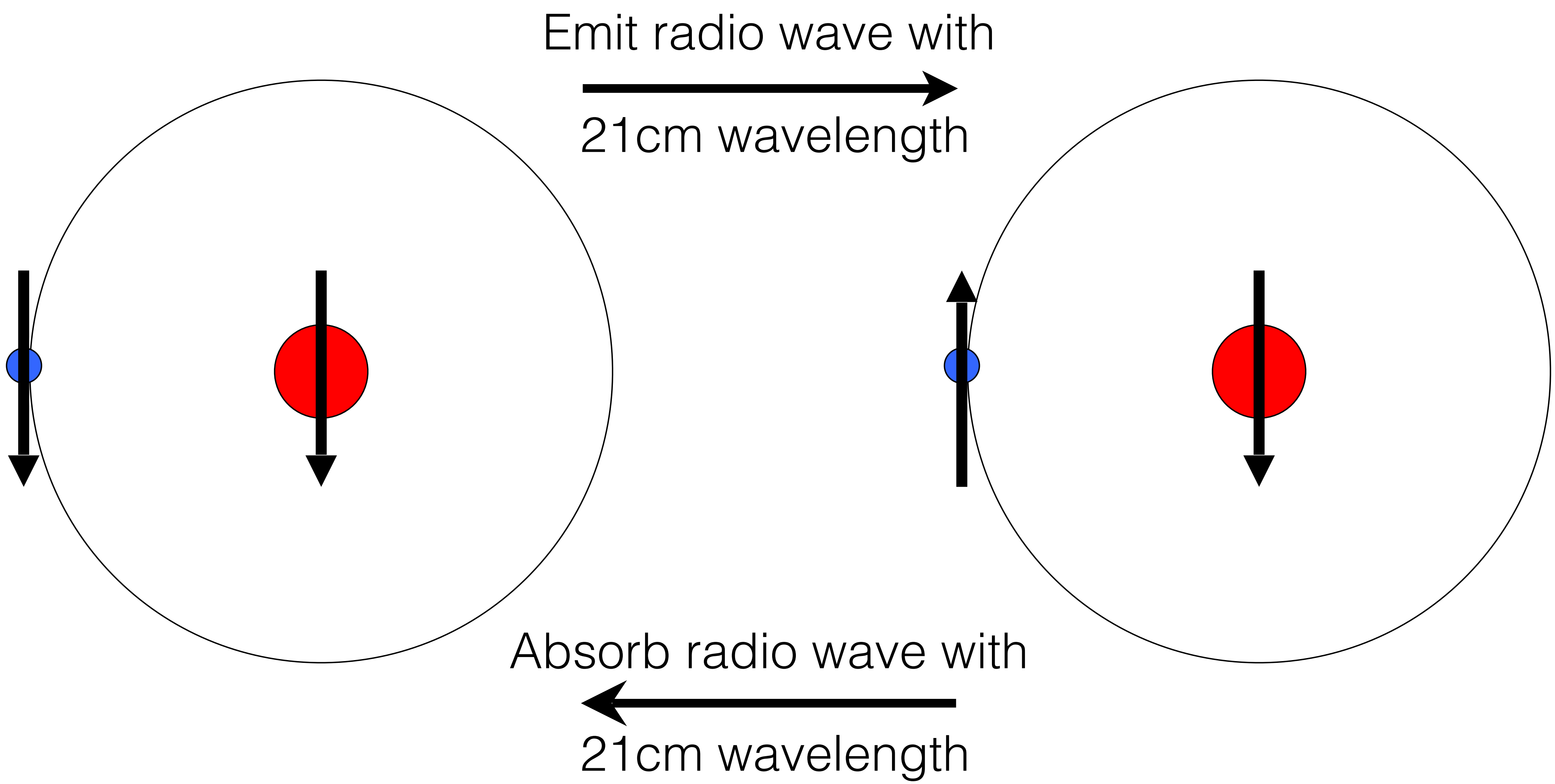
Accessing Cosmic Dawn via the Hydrogen Epoch of Reionization Array



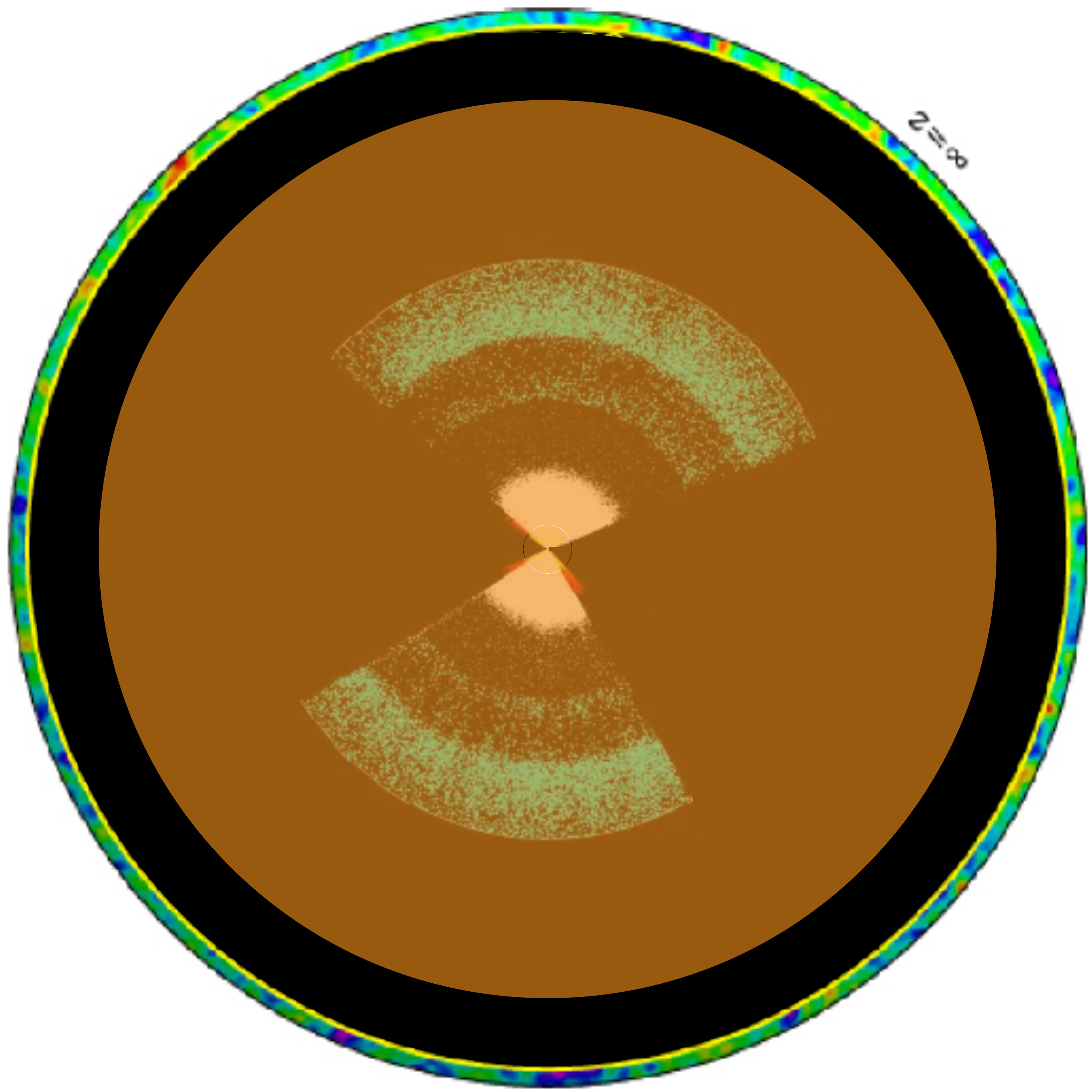
Adrian Liu
UC Berkeley
Astronomy Colloquium

We have yet to observe most of the observable Universe

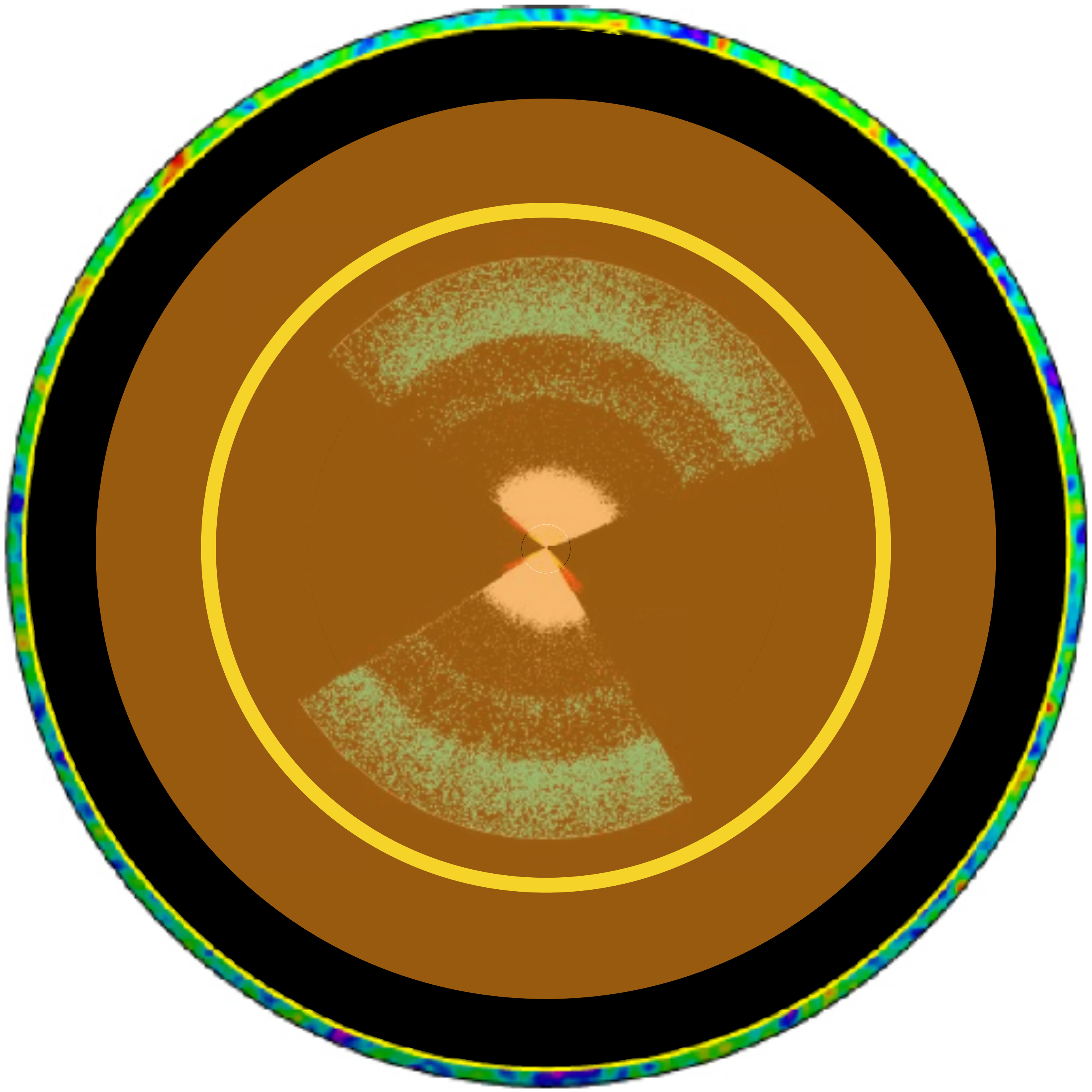
Hydrogen is everywhere, and the 21cm line allows us to trace hydrogen

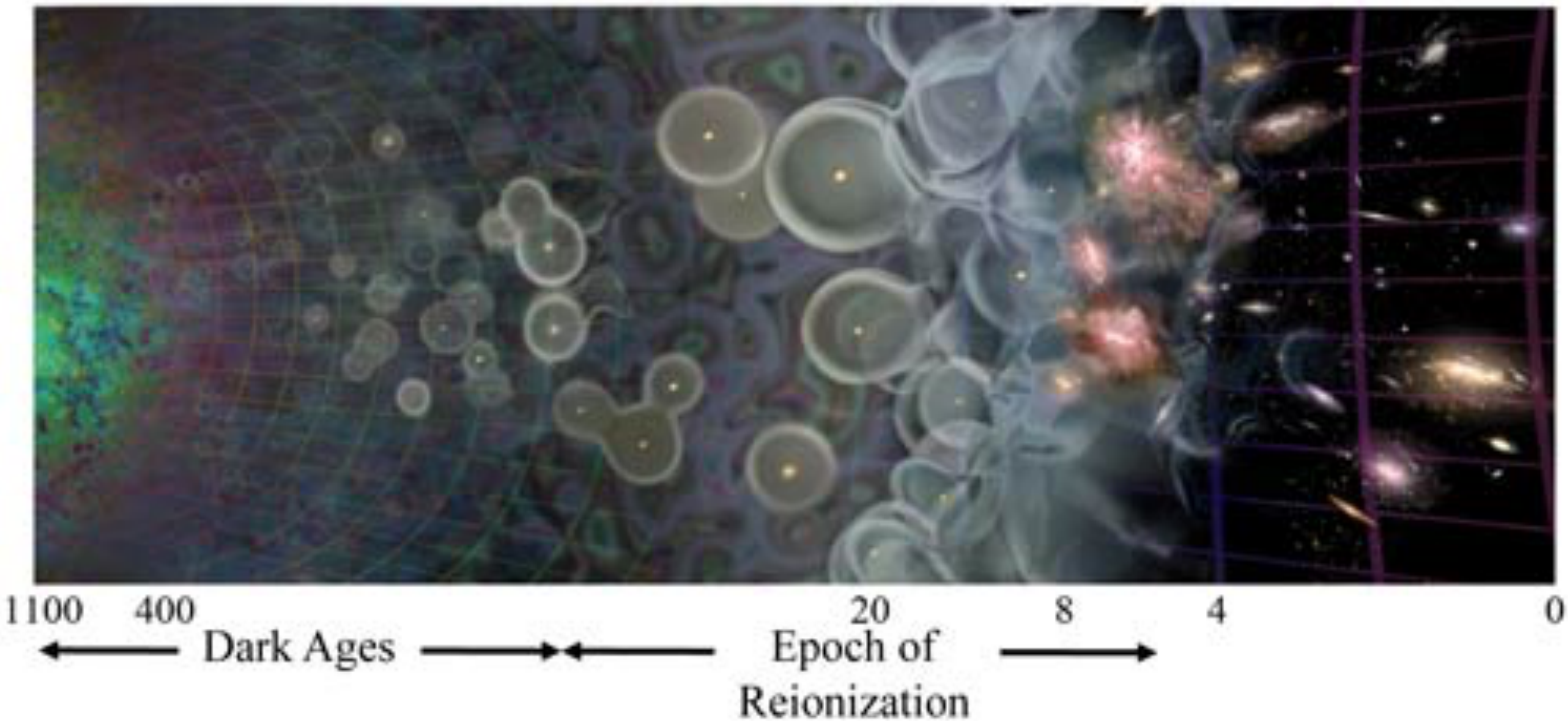


The spectral nature of the 21cm line allows us to fill in this volume

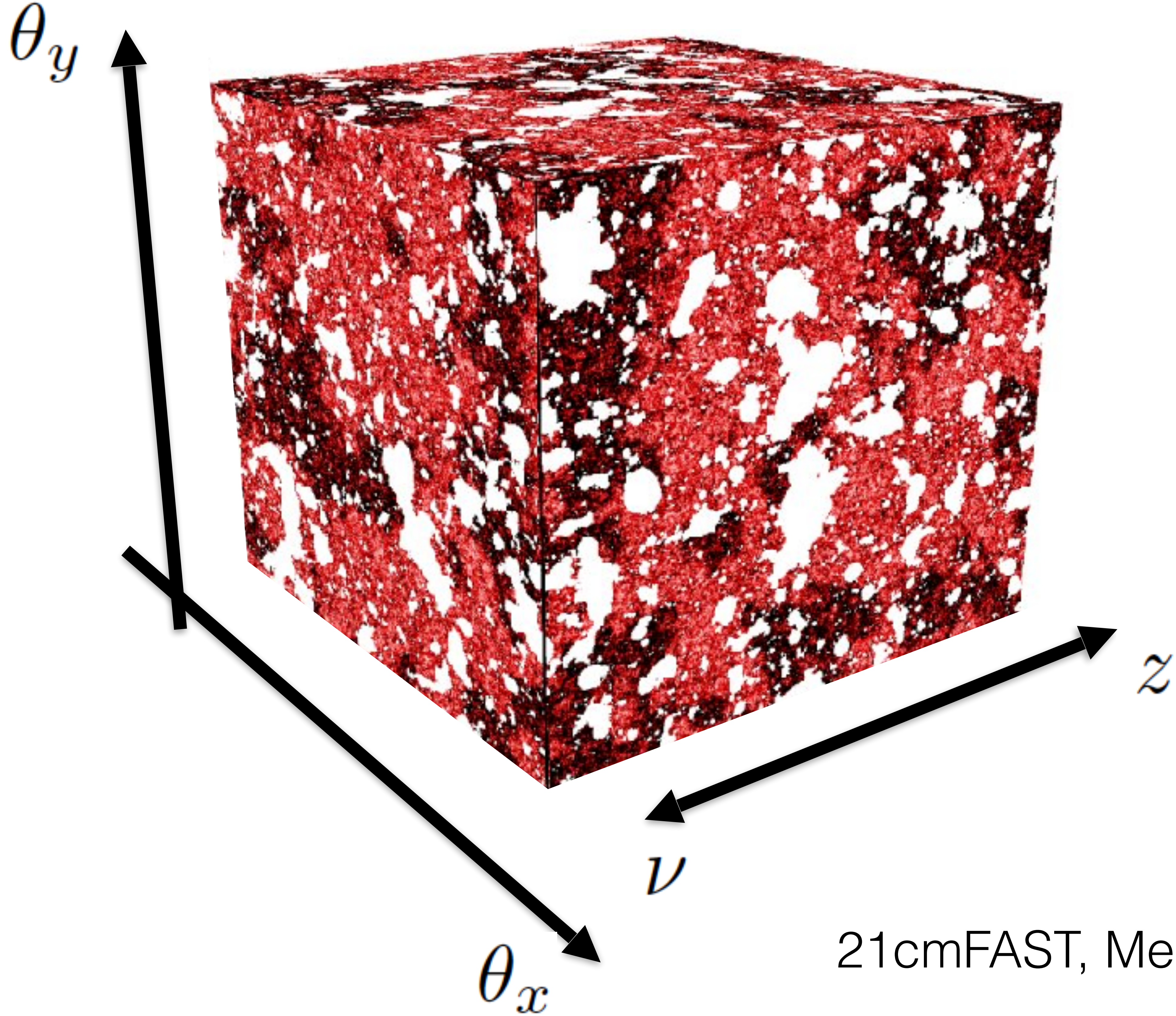


Current generation experiments are targeting the Epoch of Reionization (EoR)



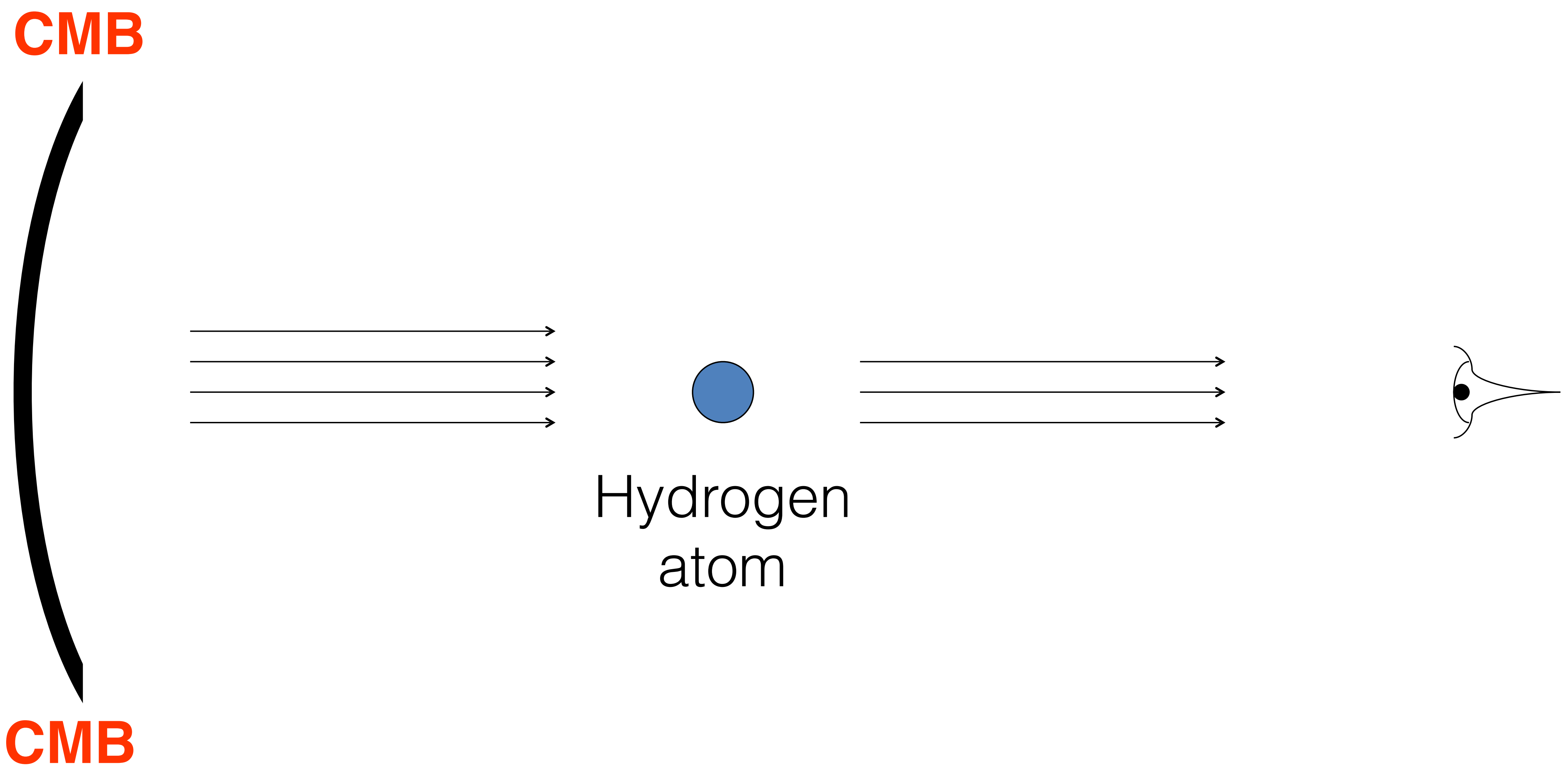

1100
400
20
8
4
0
Dark Ages
Epoch of Reionization

Alvarez et al. (2009)

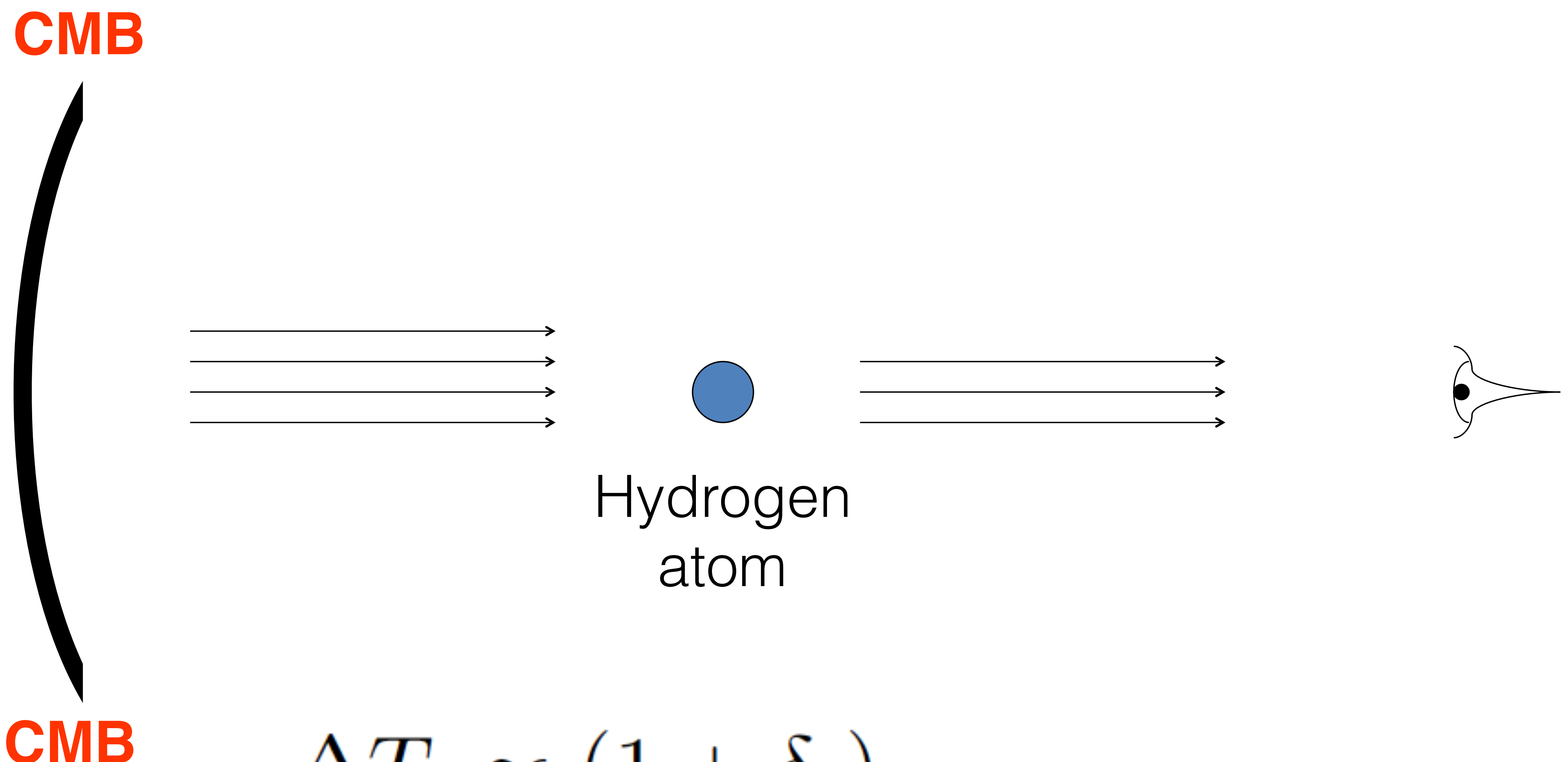


21cmFAST, Mesinger et al.

The redshifted 21cm line is very sensitive to astrophysics

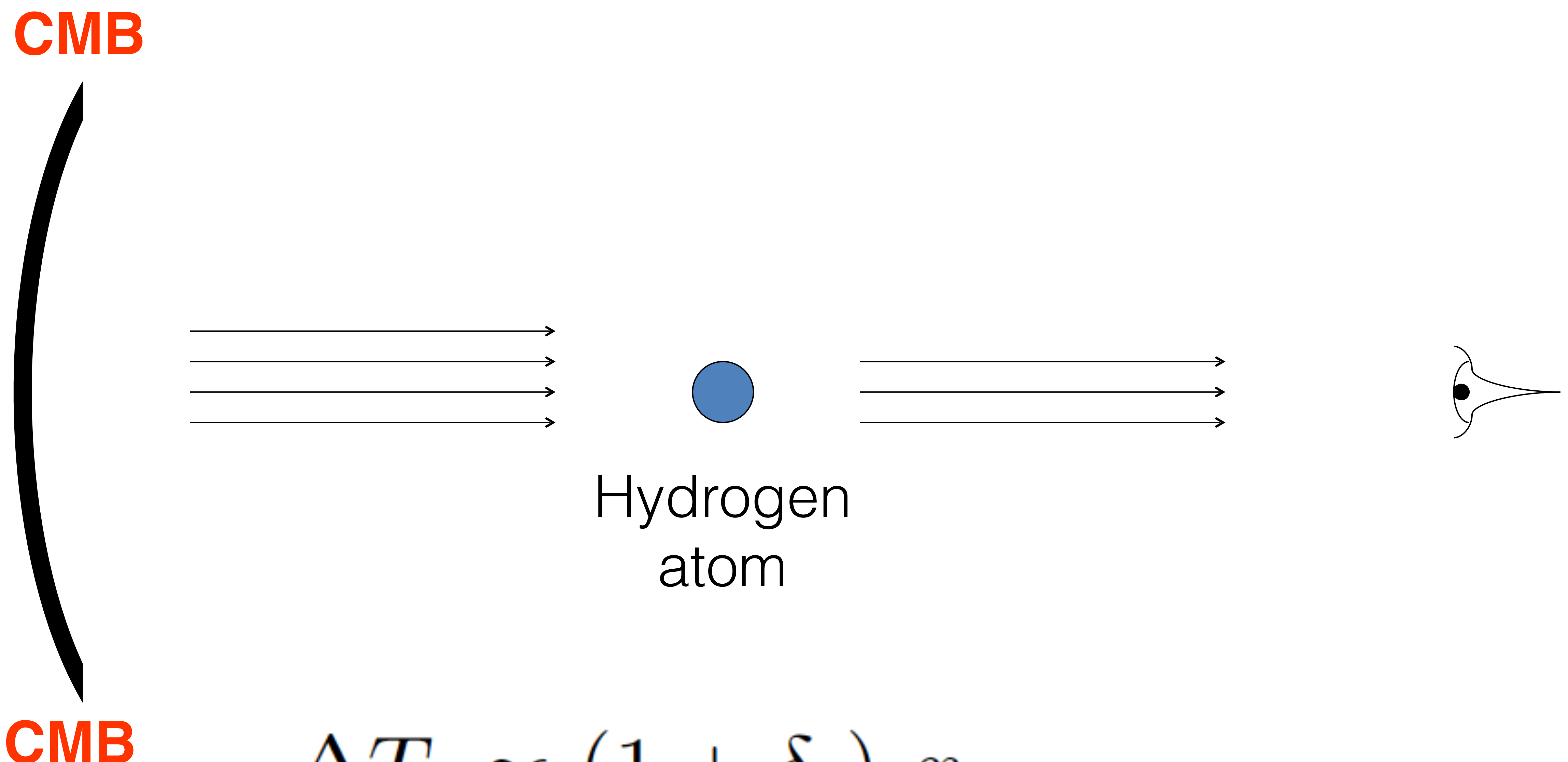


The redshifted 21cm line is very sensitive to astrophysics



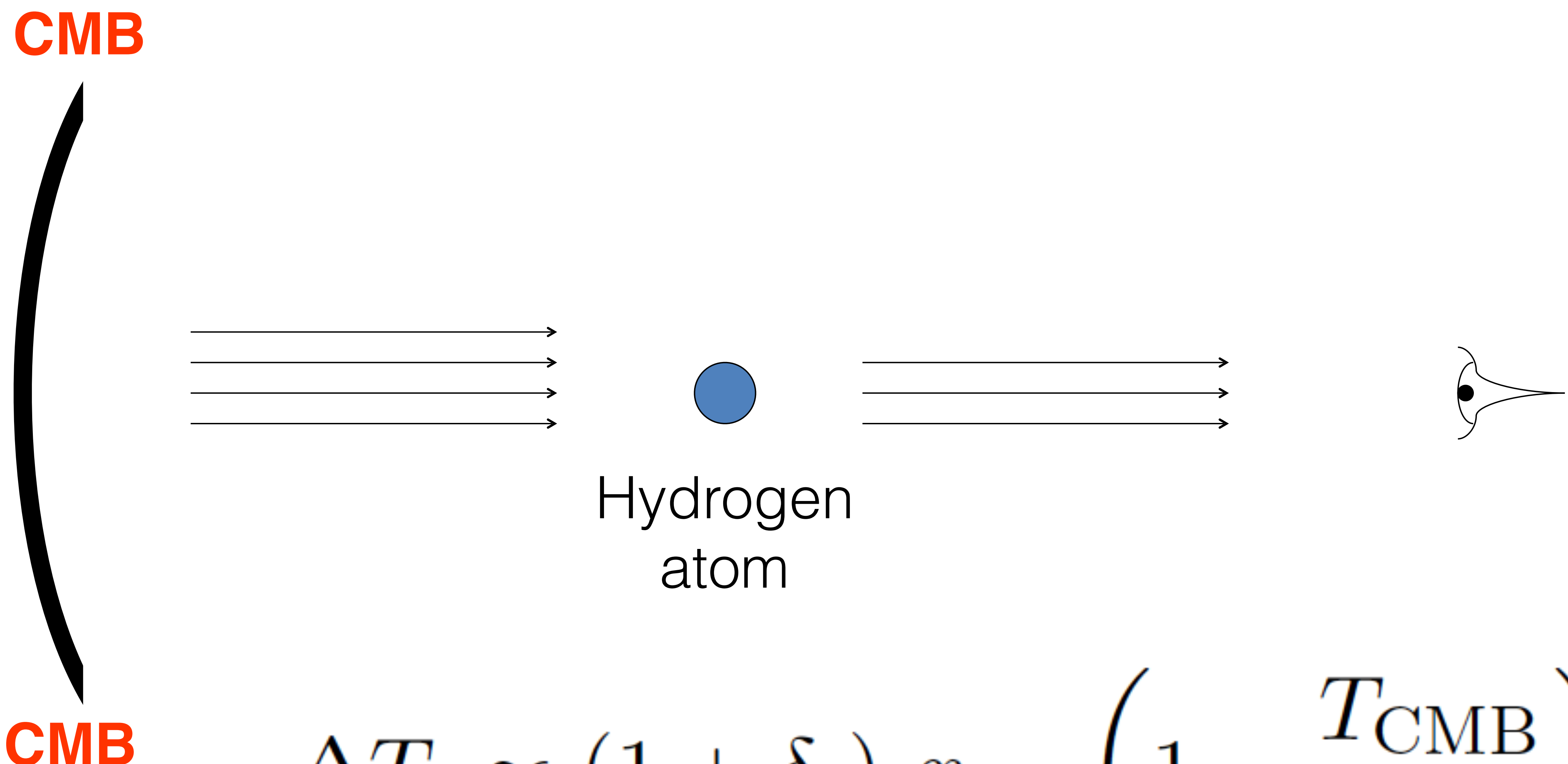
$$\Delta T_b \propto (1 + \delta_b)$$

The redshifted 21cm line is very sensitive to astrophysics



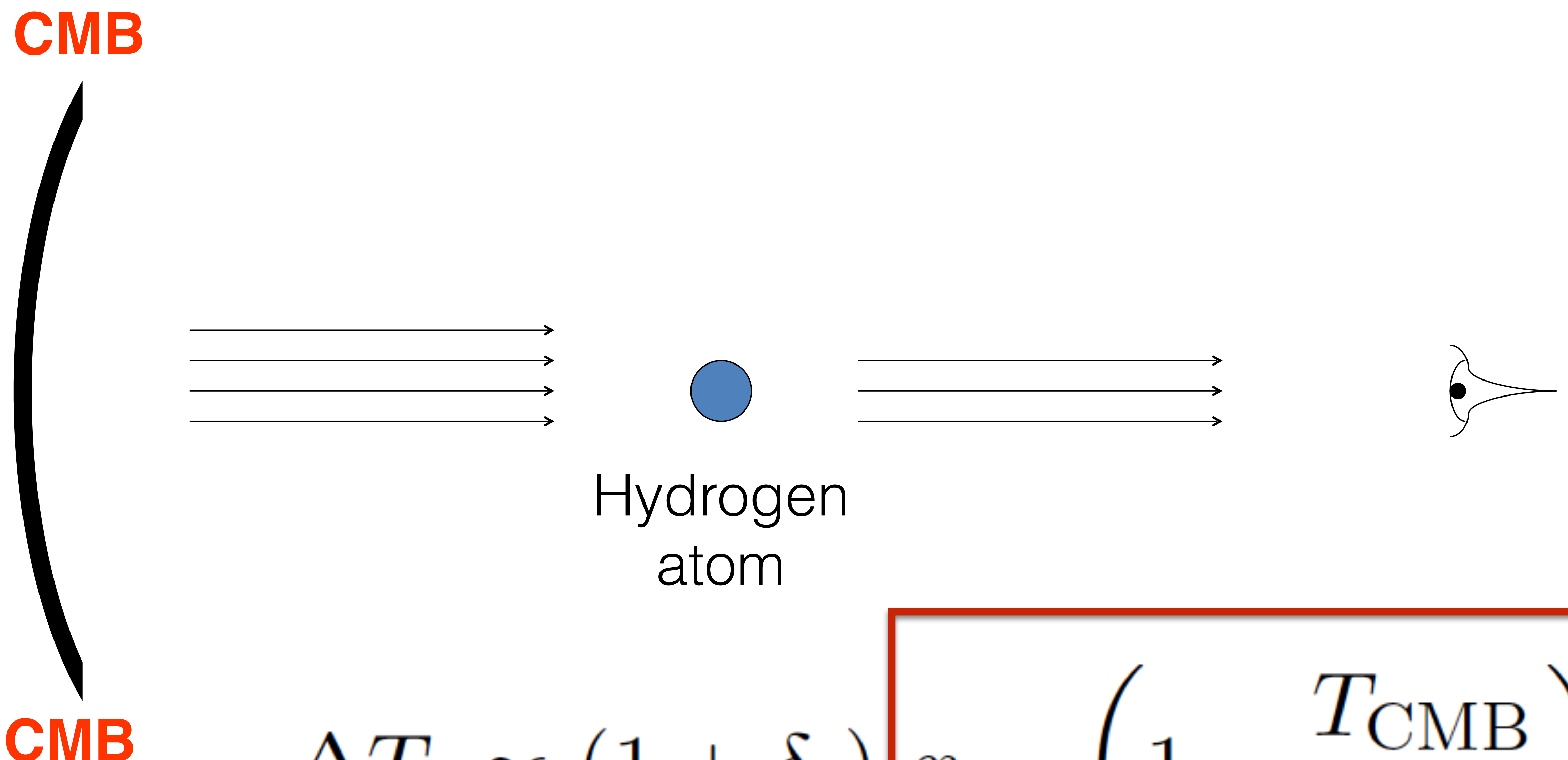
$$\Delta T_b \propto (1 + \delta_b)\, x_{HI}$$

The redshifted 21cm line is very sensitive to astrophysics

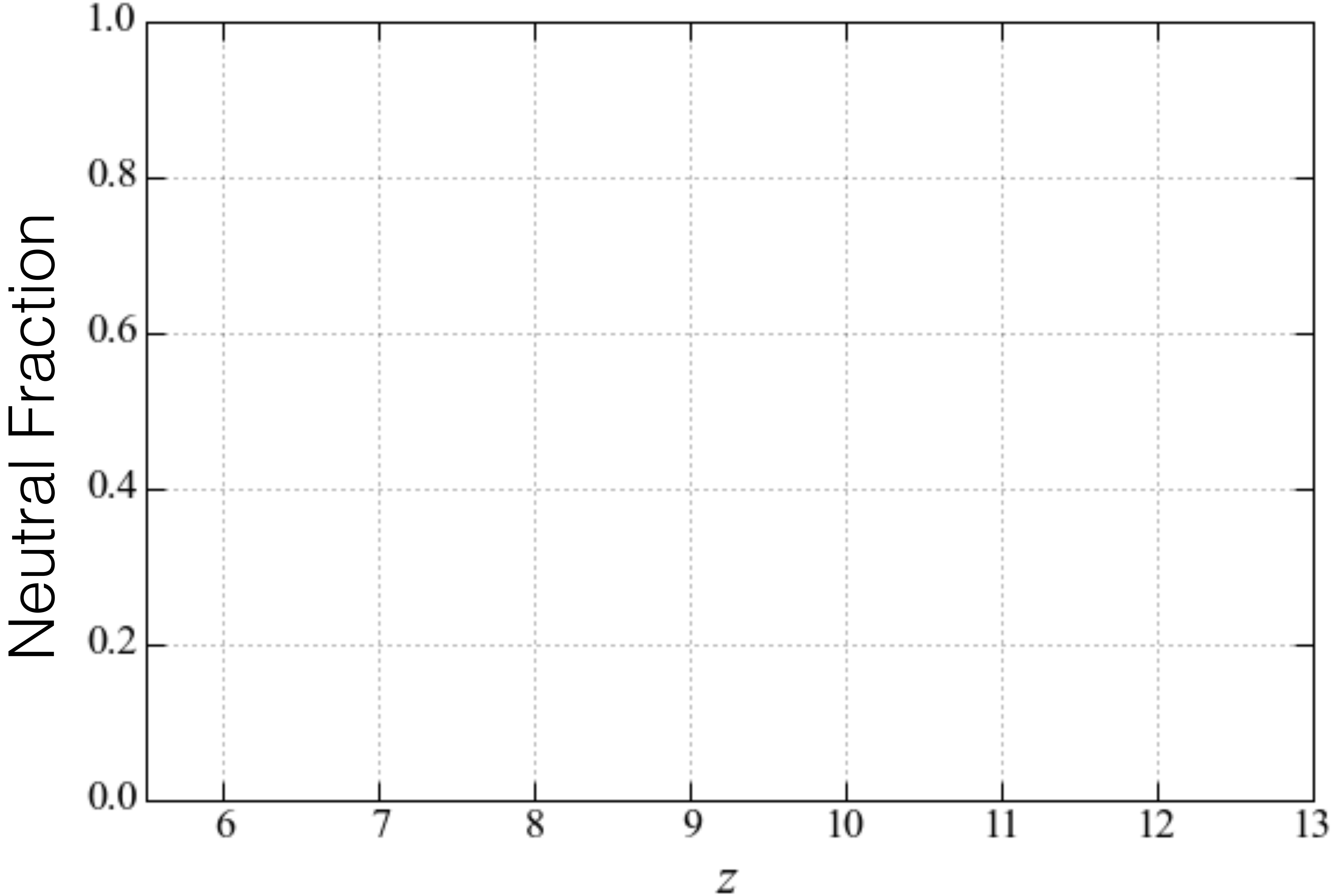


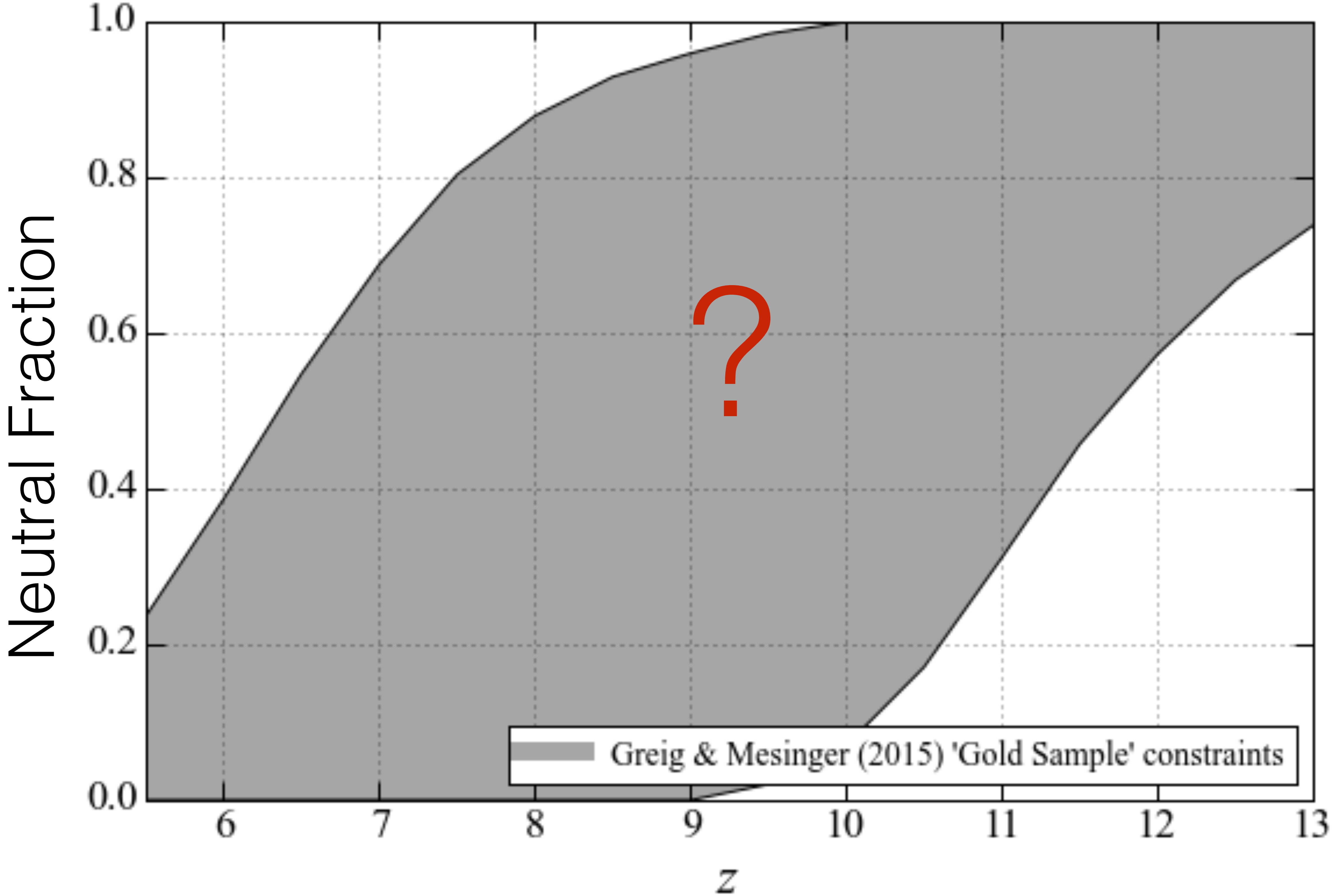
$$\Delta T_b \propto (1+\delta_b)\, x_{HI} \left(1 - \frac{T_{\mathrm{CMB}}}{T_{\mathrm{spin}}}\right)$$

The redshifted 21cm line is very sensitive to astrophysics



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


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



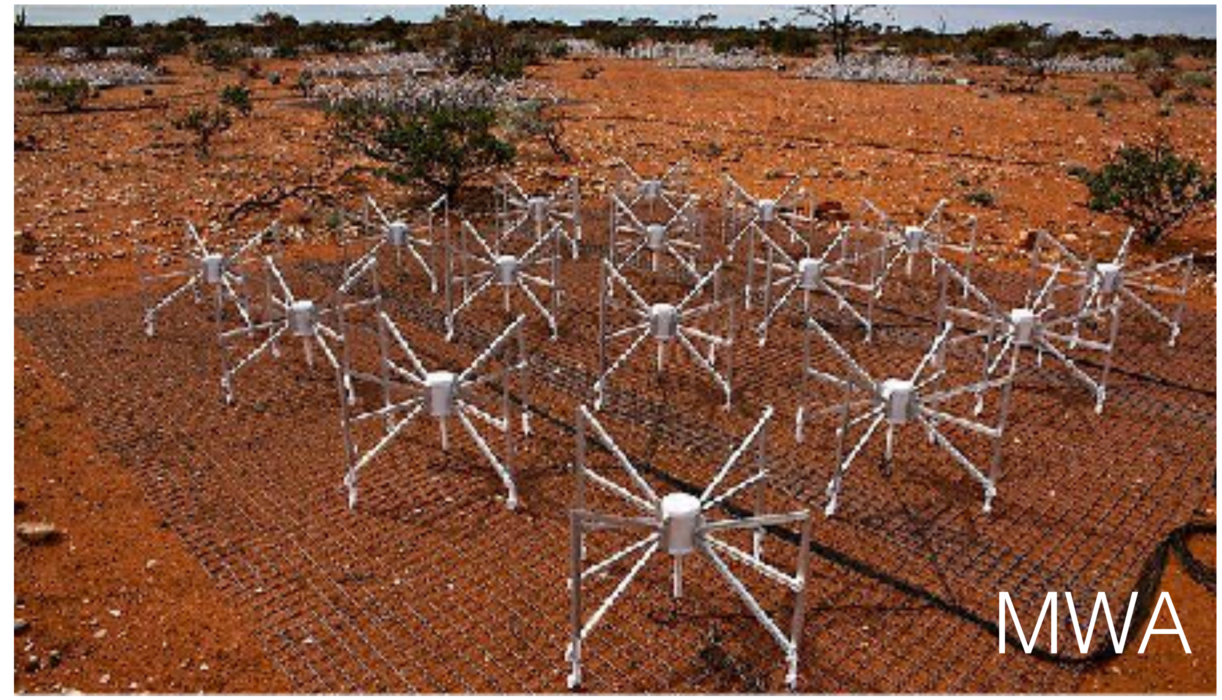
Neutral Fraction
1.0
0.8
0.6
0.4
0.2
0.0
6
7
8
9
10
11
12
13
z
?
Greig & Mesinger (2015) 'Gold Sample' constraints

Take-home messages

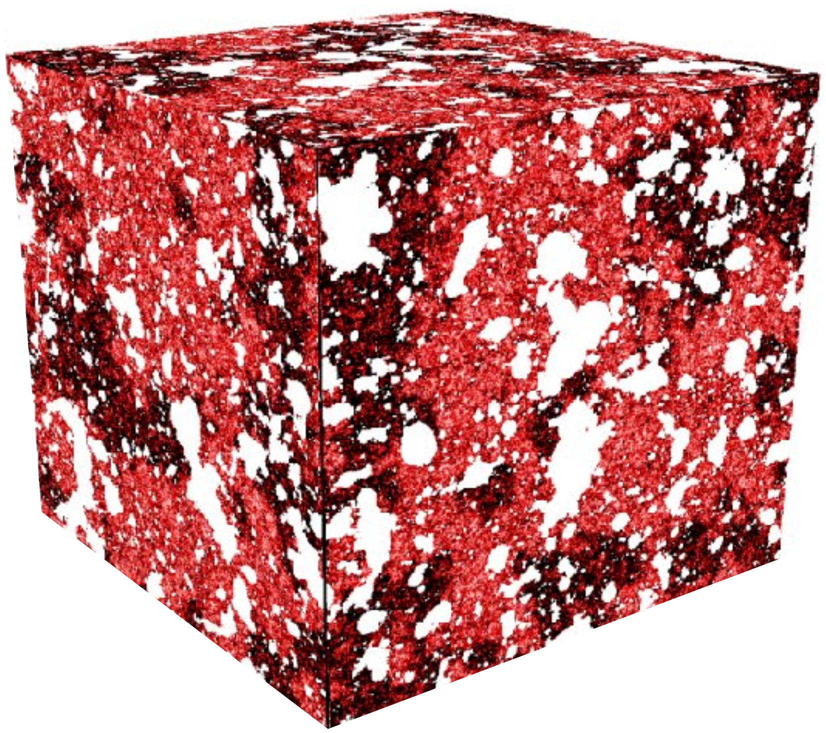
- We're getting close to detecting the 21cm signal—close enough to start improving our understanding of reionization.
- Foregrounds and sensitivity are the main challenges of 21cm cosmology.
- Two frontiers in field:
    - **Analysis** efforts are advancing, with progress on foreground models and machine learning.
    - **Observational** efforts are advancing, with HERA poised to deliver qualitatively new constraints on astrophysics and cosmology.

The status of high-z 21cm measurements

A number of current instruments are placing increasingly tight limits on the amplitude of spatial fluctuations



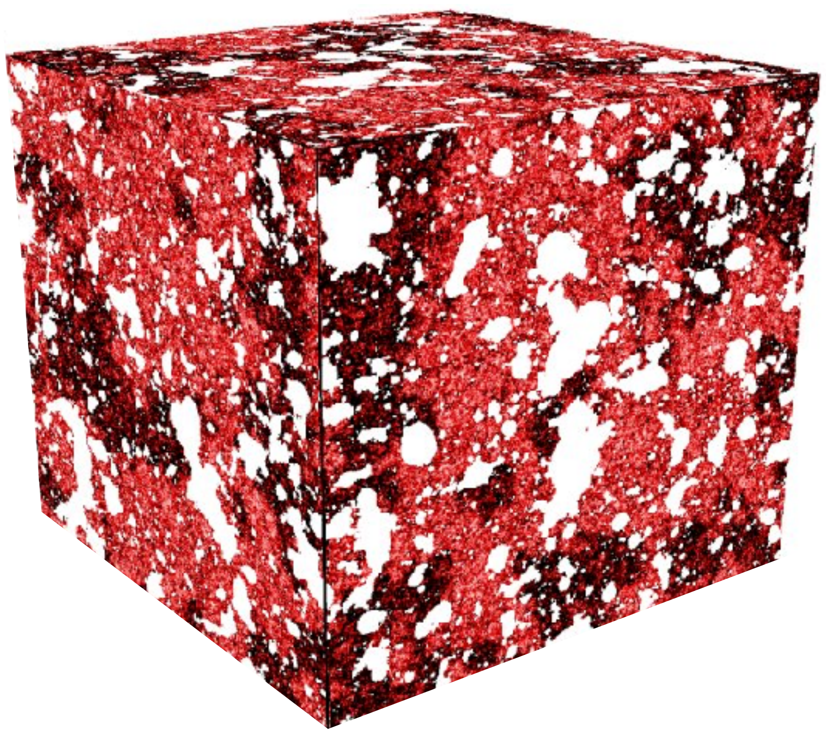
Theory

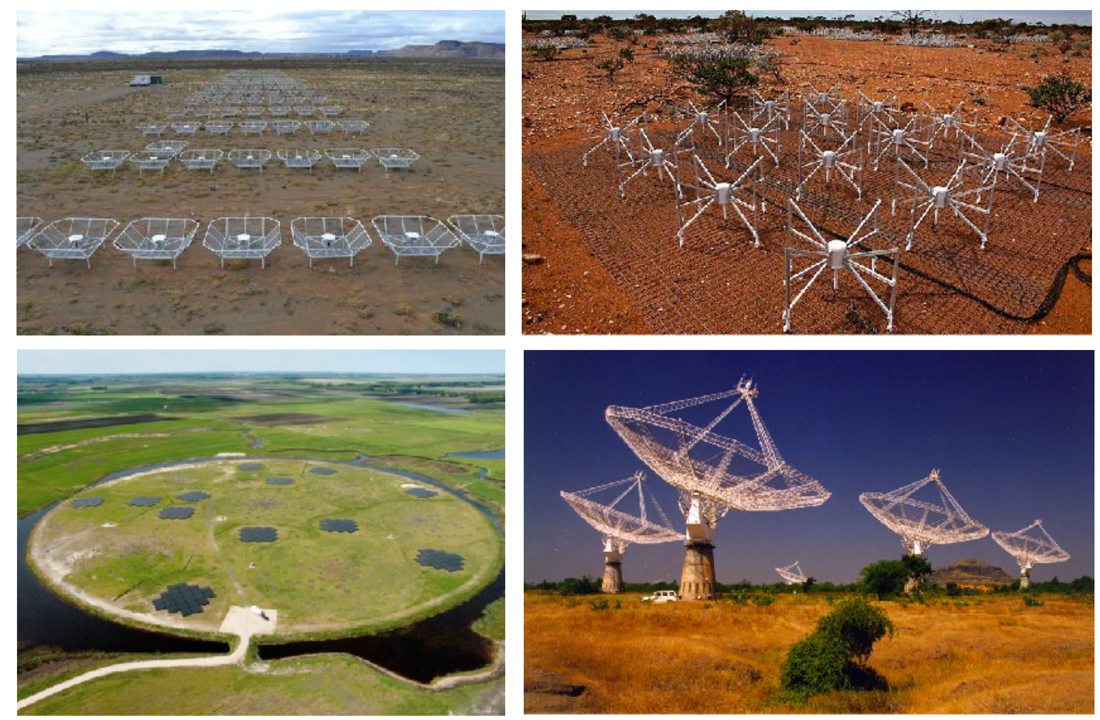


T_{21} ~ a few mK

Theory

Observations





T_{21} ~ a few mK

T_{21} less than ~100 mK

Current upper limits rule out the possibility of an extremely **cold** intergalactic medium at $z \sim 8$ to 10

Cold hydrogen
gas

(Relatively)
hot CMB

Cold hydrogen
gas

(Relatively)
hot CMB

Cold hydrogen
gas

BIG
contrast,
large signal

(Relatively) hot CMB

Cold hydrogen gas

BIG contrast, large signal

(Relatively) hot CMB

Warm 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 current sensitivities

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 current sensitivities

Some mechanism must have heated up the gas

At the relevant redshifts, T_{gas} ~ 1 to 2 K assuming adiabatic cooling.

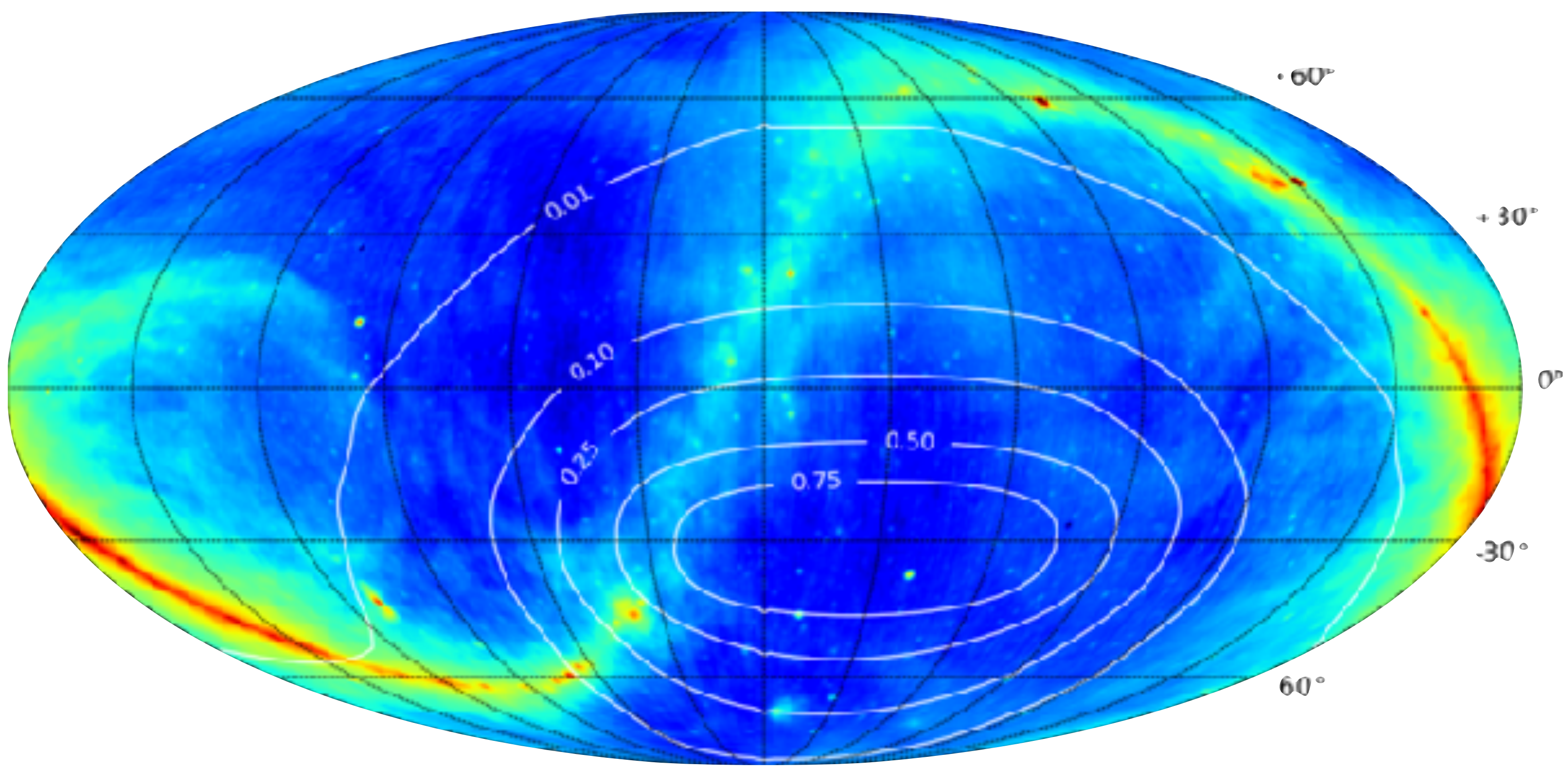
Assuming a neutral fraction between 0.3 and 0.7 at those redshifts, T_{gas} is likely at least a few K above this.

Paciga et al. 2011, MNRAS 413, 1174
Parsons, **AL** et al. 2014, ApJ 788, 106
Ali, …, **AL** et al. 2015, ApJ 809, 61
Pober, Ali, …, **AL** et al. 2015, ApJ 809, 62
Cheng et al., in prep.
Kolopanis et al., in prep.

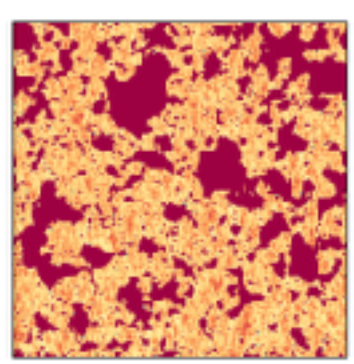
The challenges of 21cm measurements

Astrophysical foreground contaminants

Contaminants are bright and dominate the cosmological signal

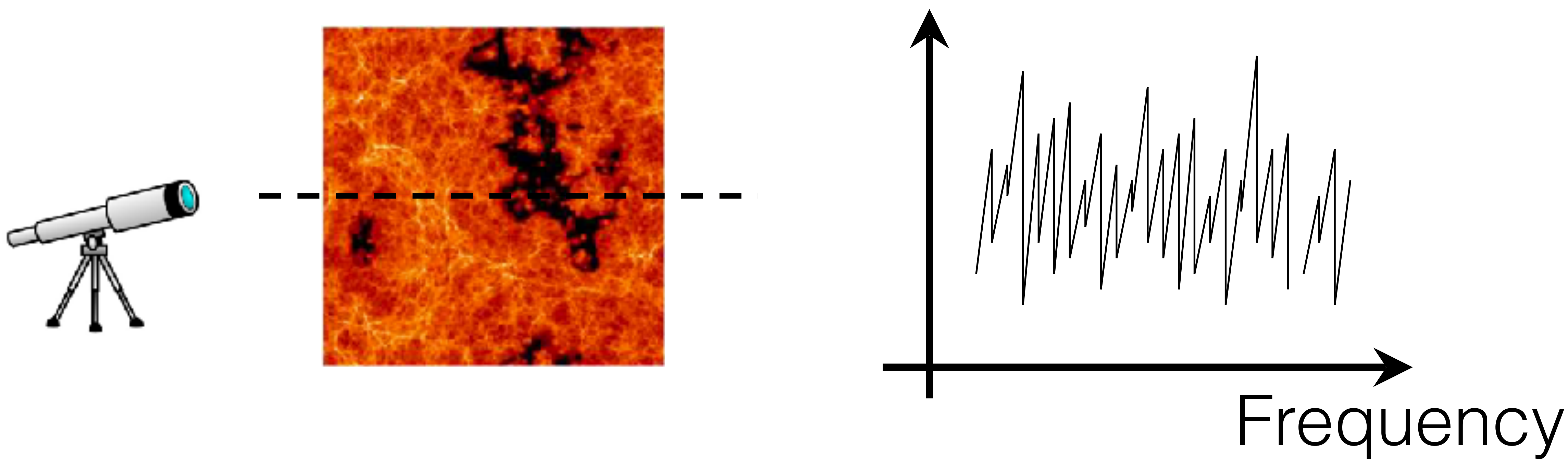


$\sim 10^5$ mK



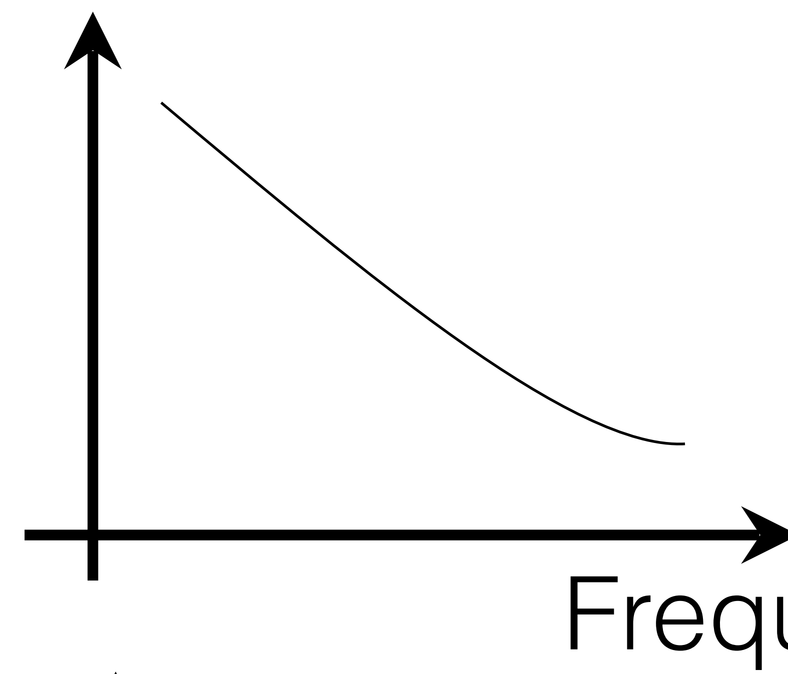
~ a few mK

The cosmological signal is expected to vary rapidly with changing frequency

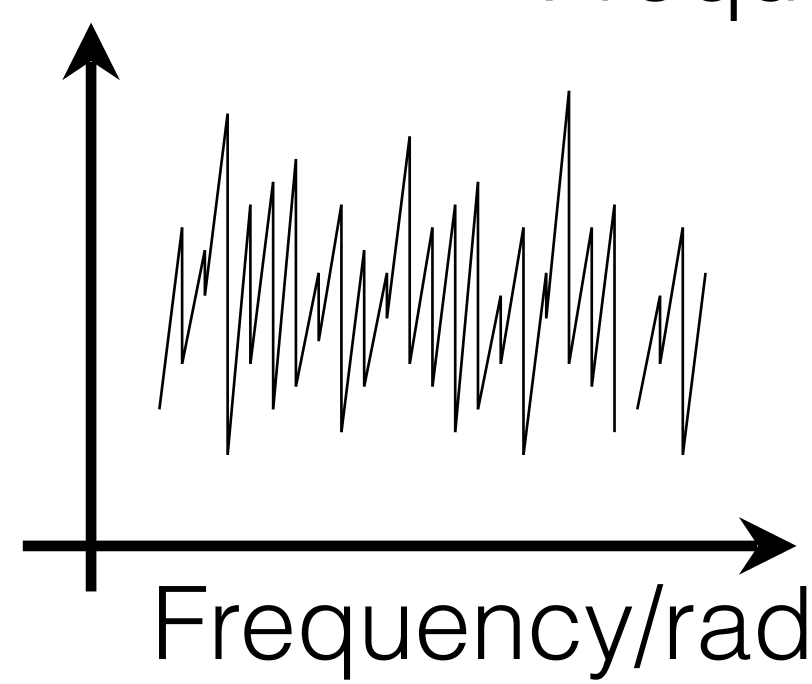


Foregrounds are expected to be smooth functions of frequency

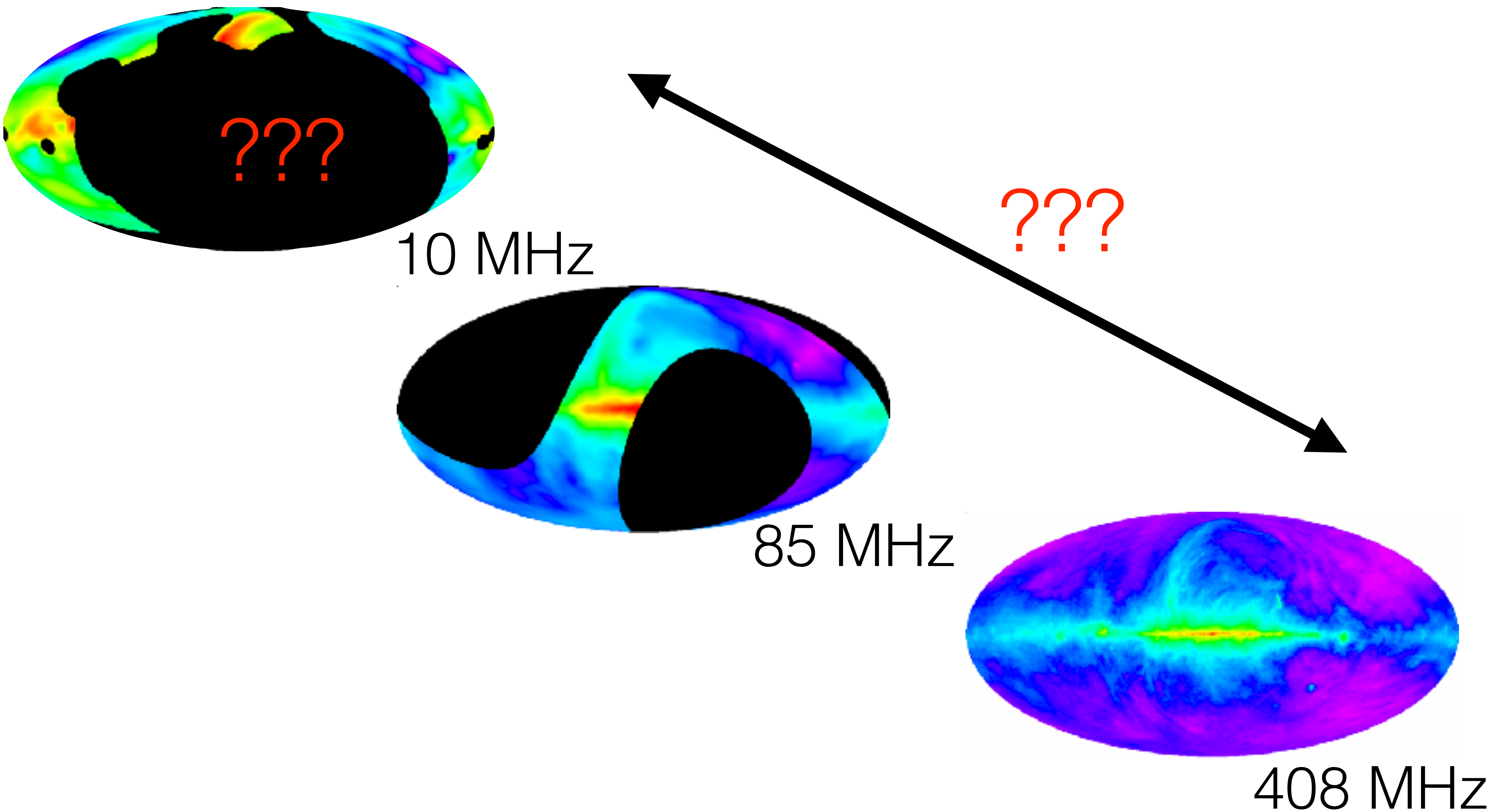
Foregrounds



Cosmological signal



"Know your enemy"…but our knowledge of the low-frequency radio sky is particularly poor



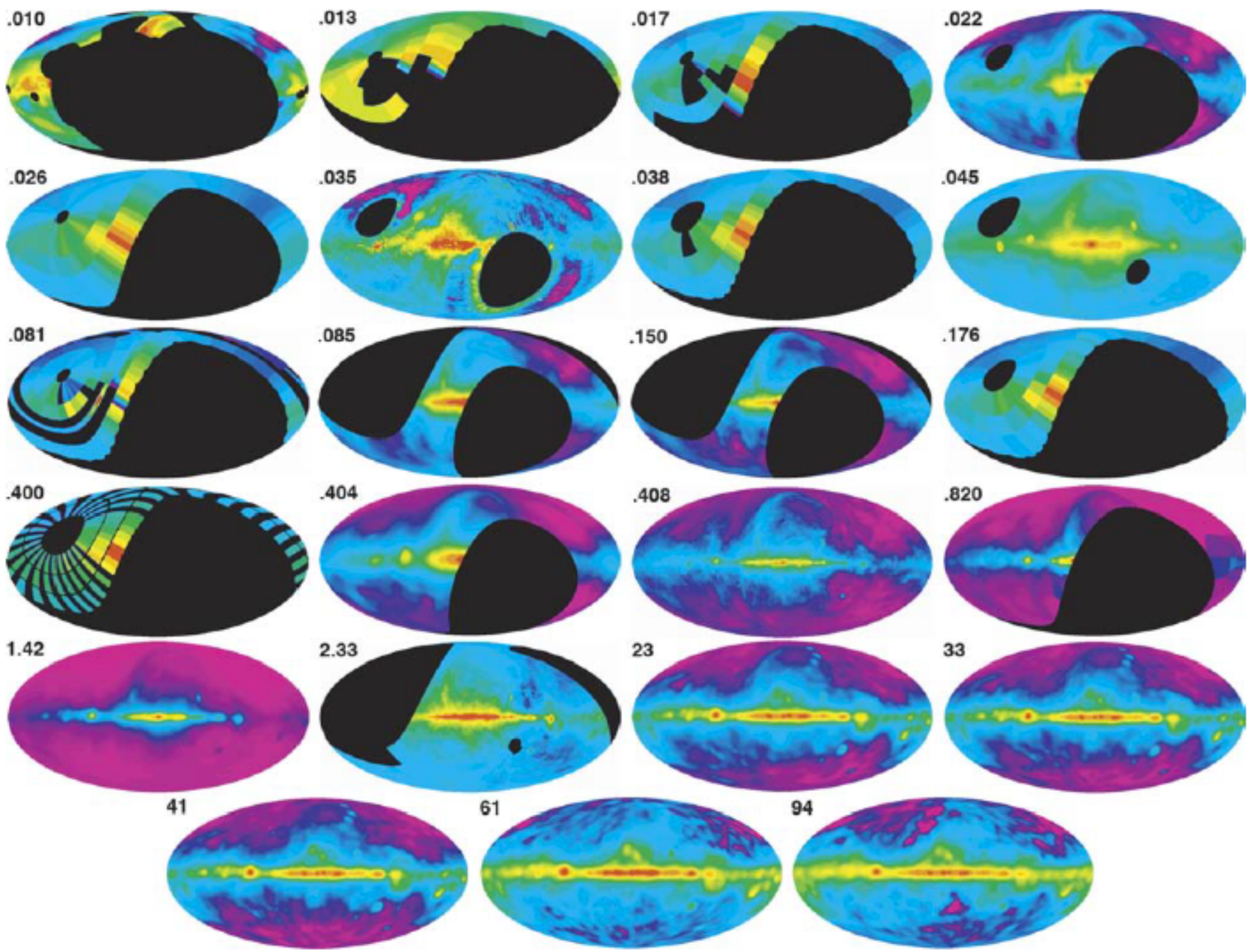
The extended Global Sky Model (eGSM): “What does the sky look like in all directions and all frequencies?”

PI: **AL**
Aaron Parsons, UC Berkeley
Doyeon “Avery” Kim, UC Berkeley
Josh Dillon, UC Berkeley
Eric Switzer, NASA Goddard
Max Tegmark, MIT
Haoxuan “Jeff” Zheng, MIT/Intel

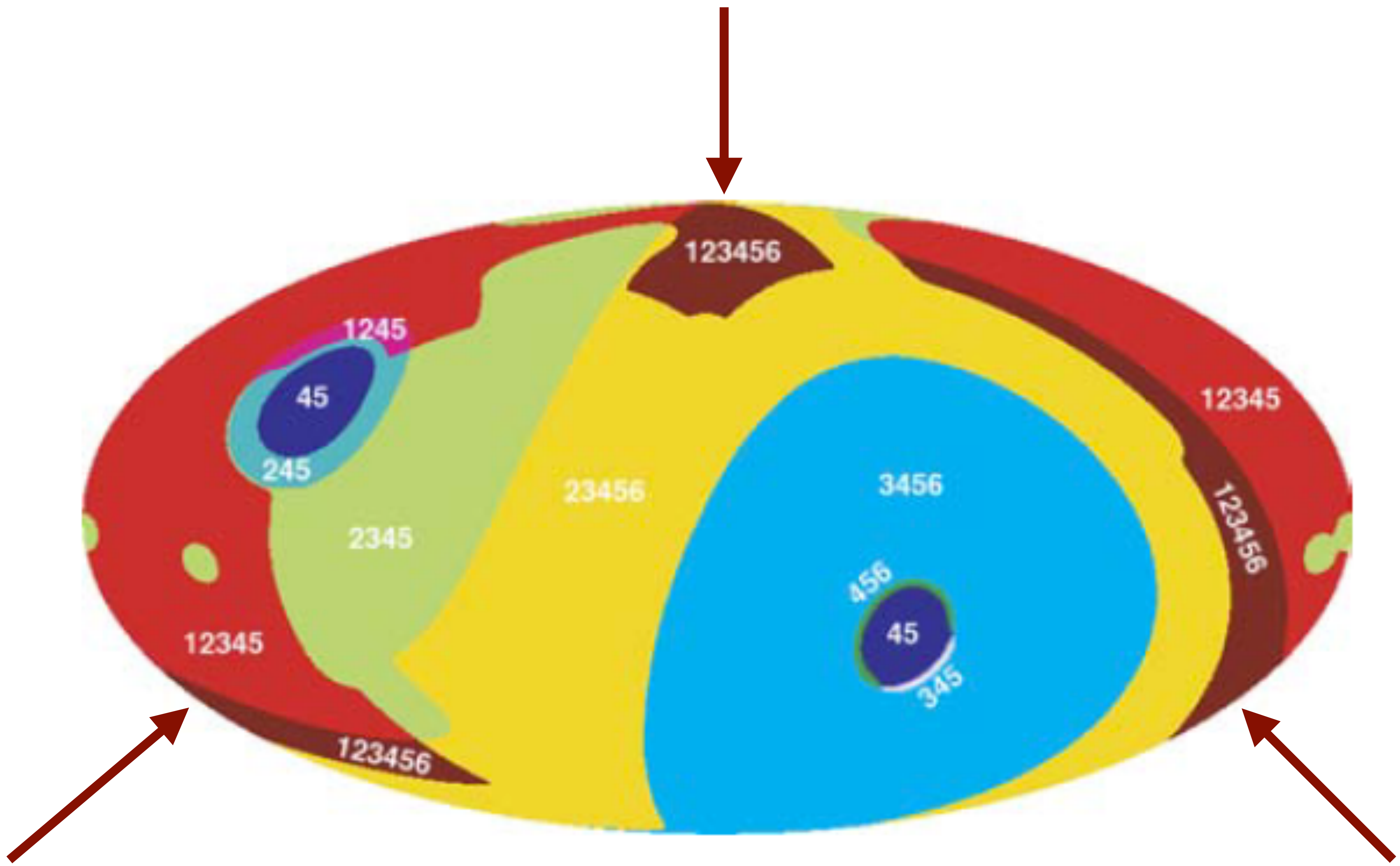
Global Sky Model

de Oliveira-Costa et al. 2008, MNRAS 388, 247
Zheng… Kim, **AL**… et al. 2017, MNRAS 464, 3486
Kim, **AL**… et al. 2017, in prep.

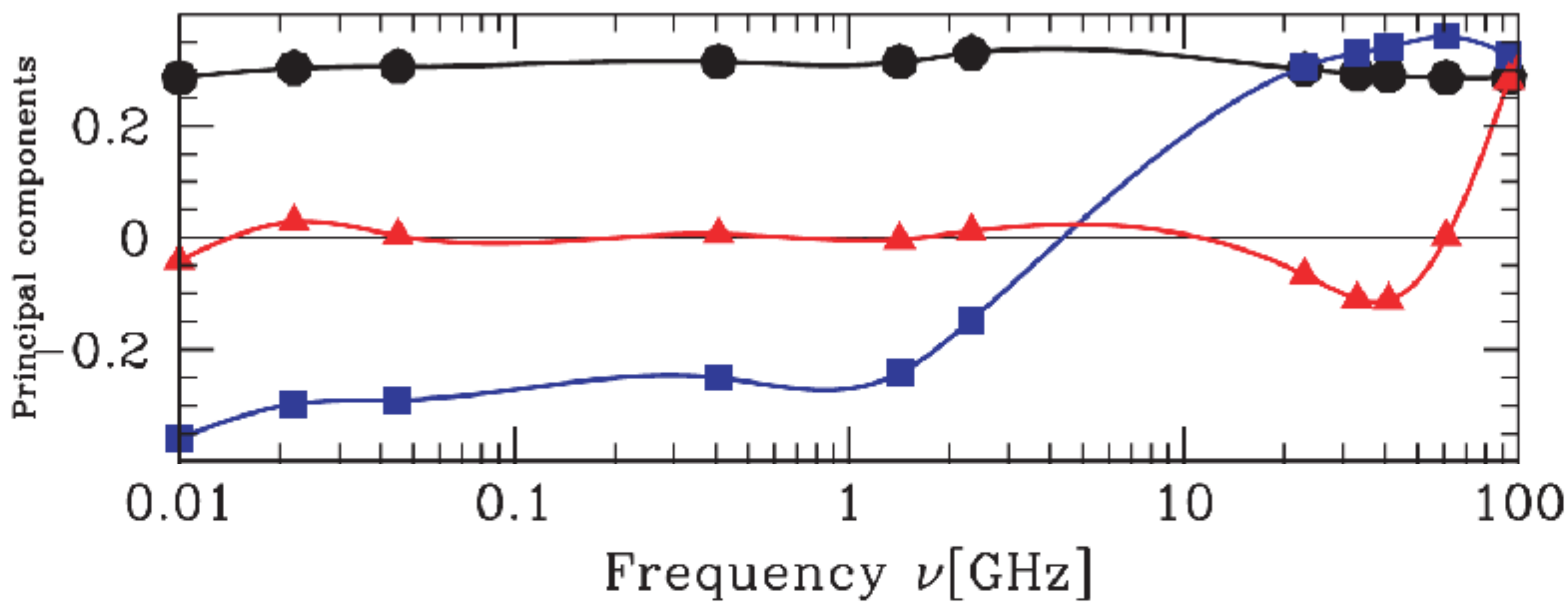
Take a wide selection of survey data…



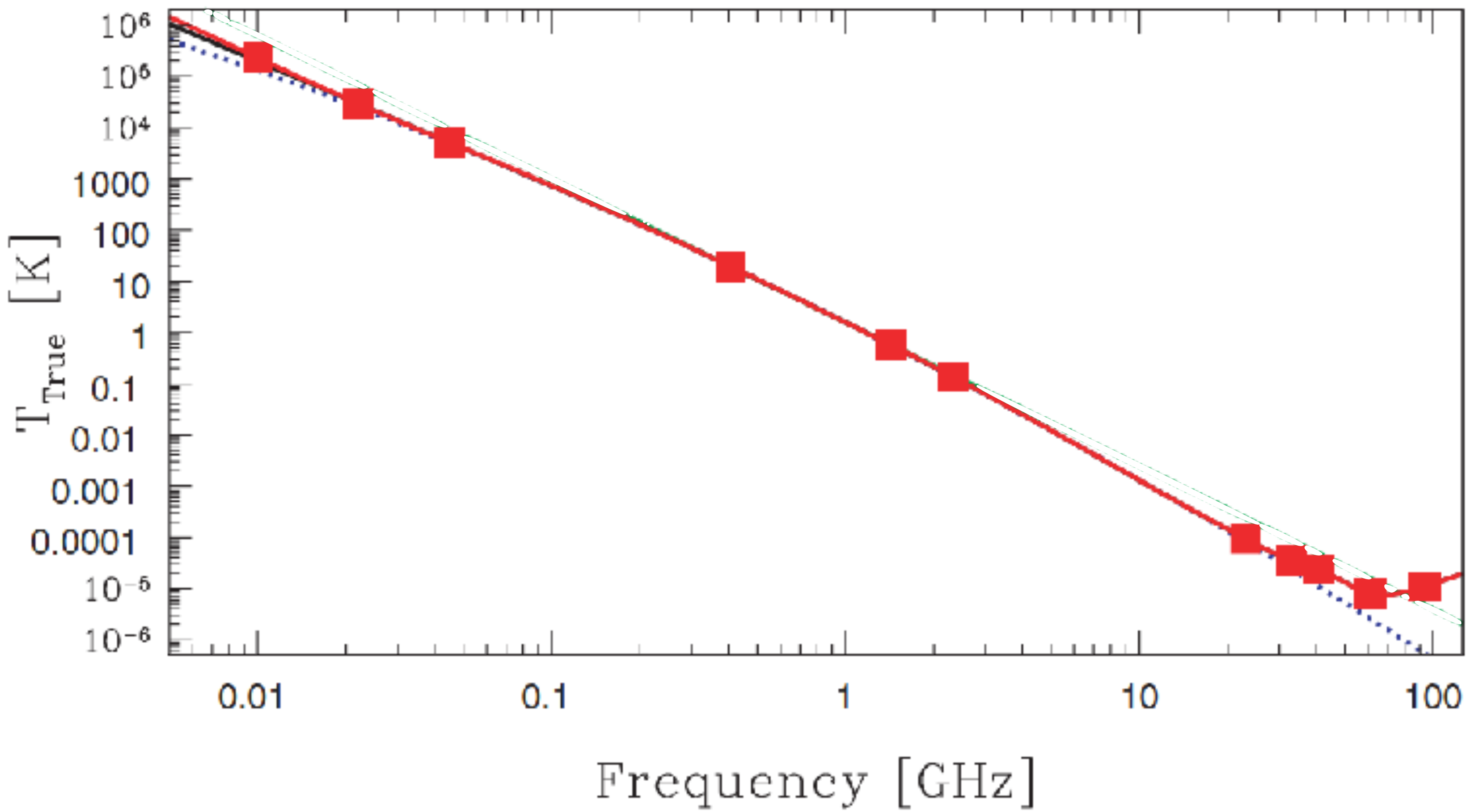
…identify common regions…



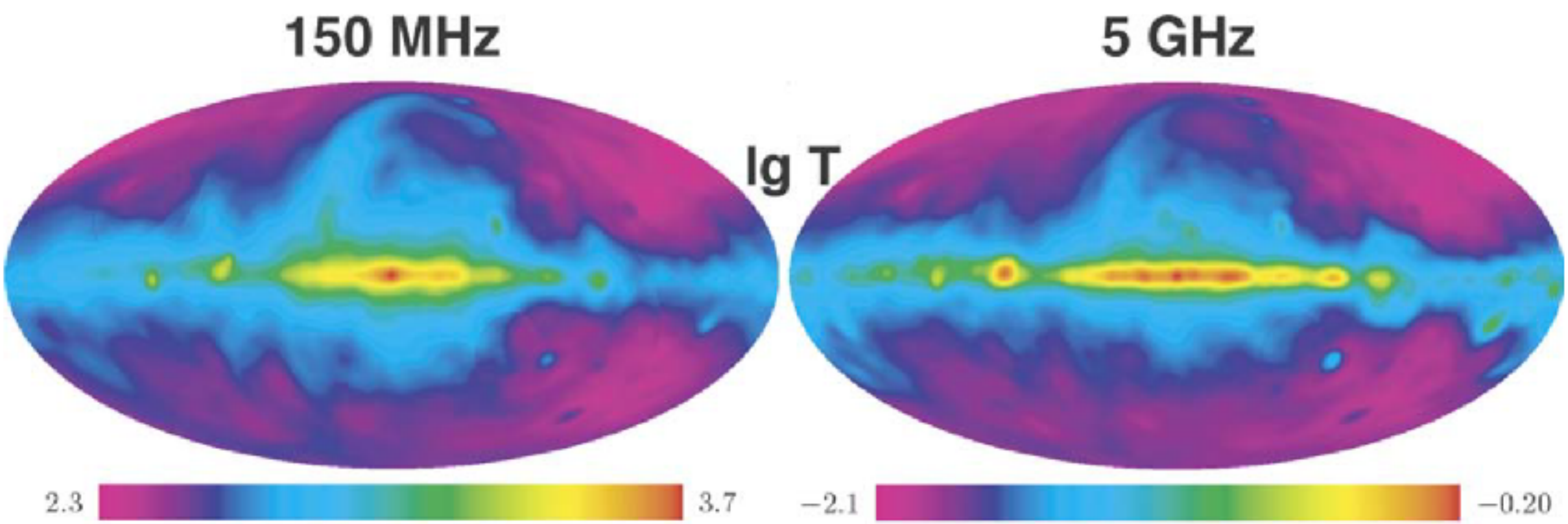
…and use the most dominant eigenvectors as templates…



…that are used to fit the spectra in every pixel of the sky…



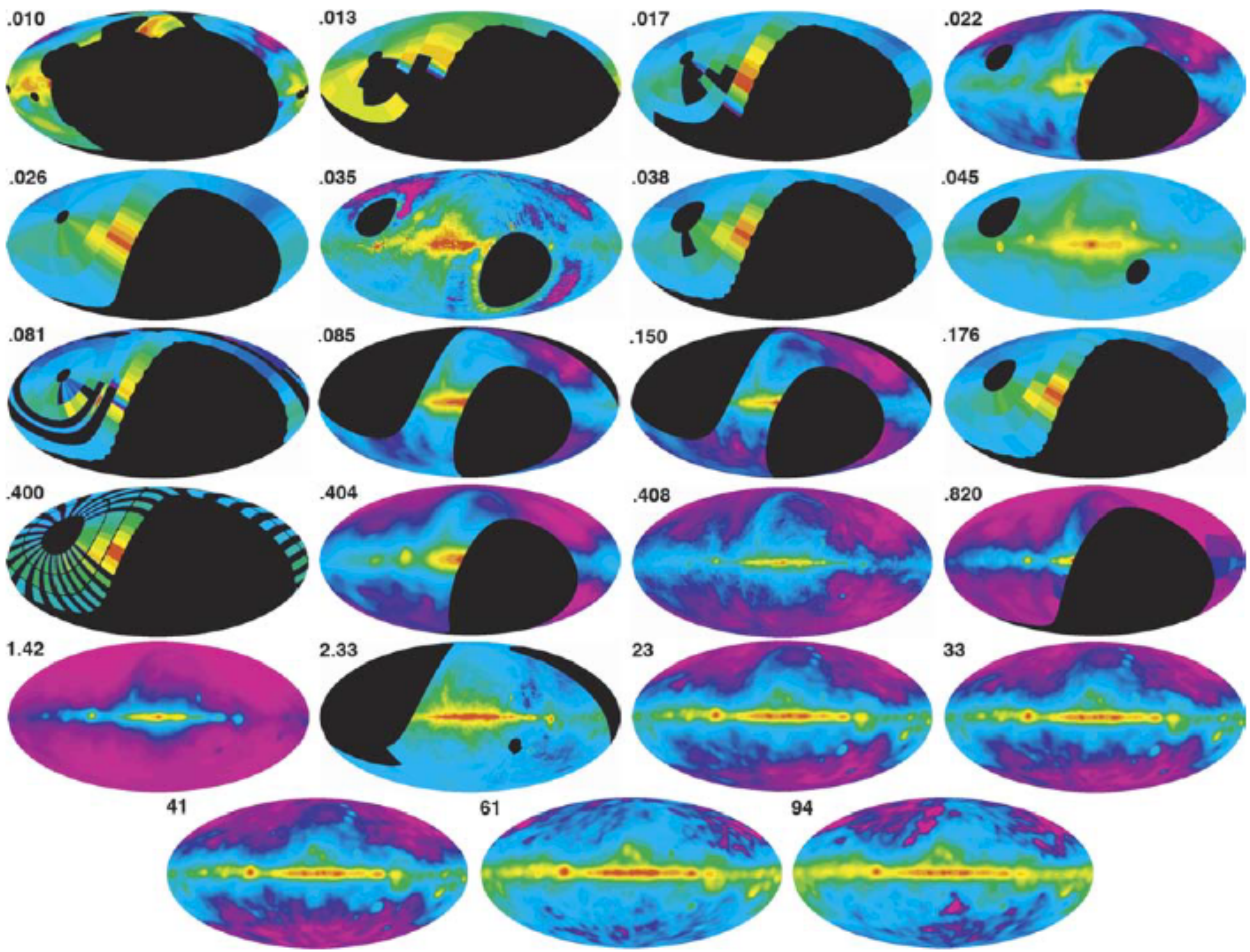
…and are interpolated to produces maps of the sky at “any” frequency



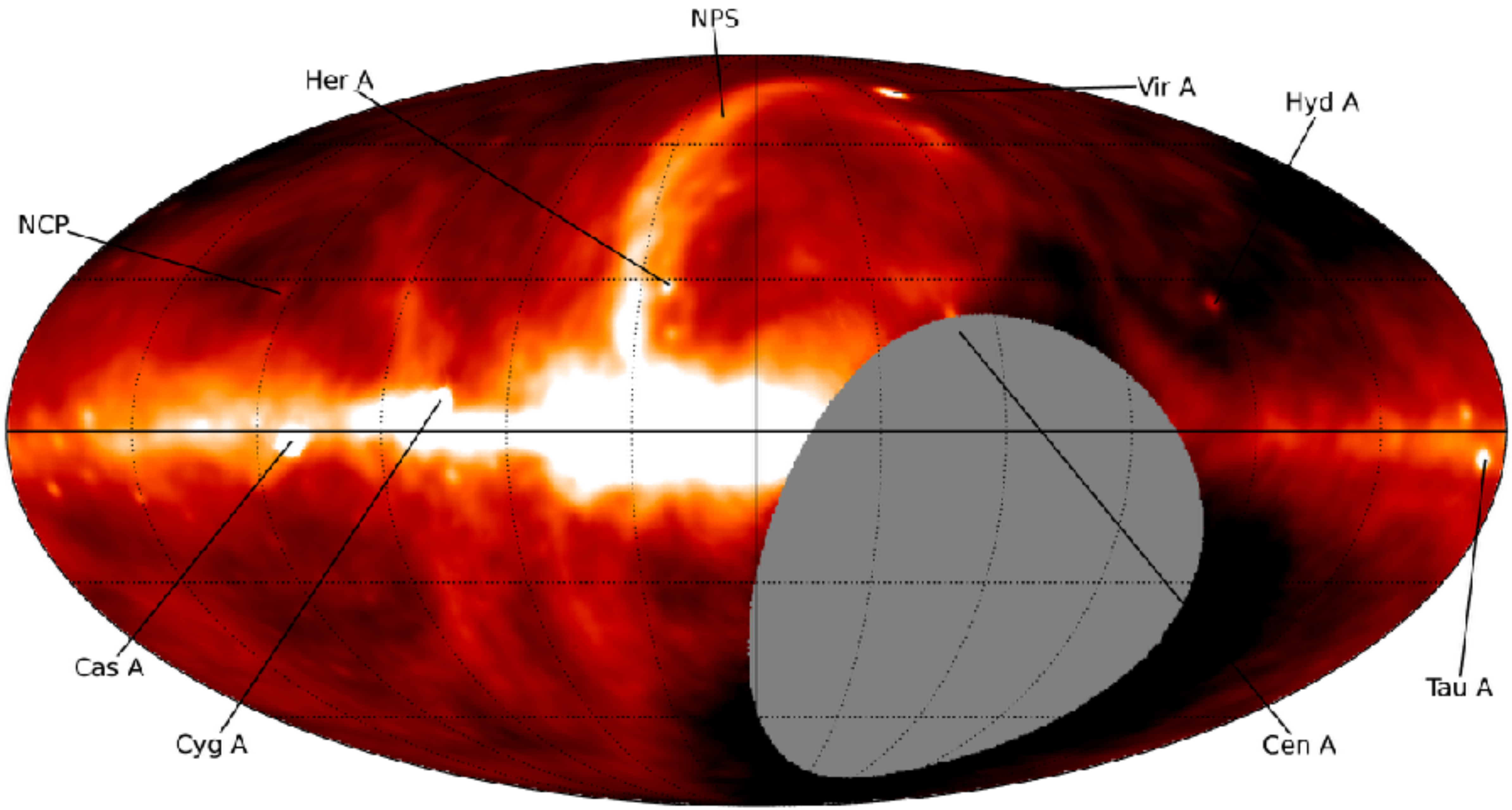
extended Global Sky Model

Kim, **AL**… et al. 2017, in prep.

Problem 1: a good low-frequency anchor is lacking

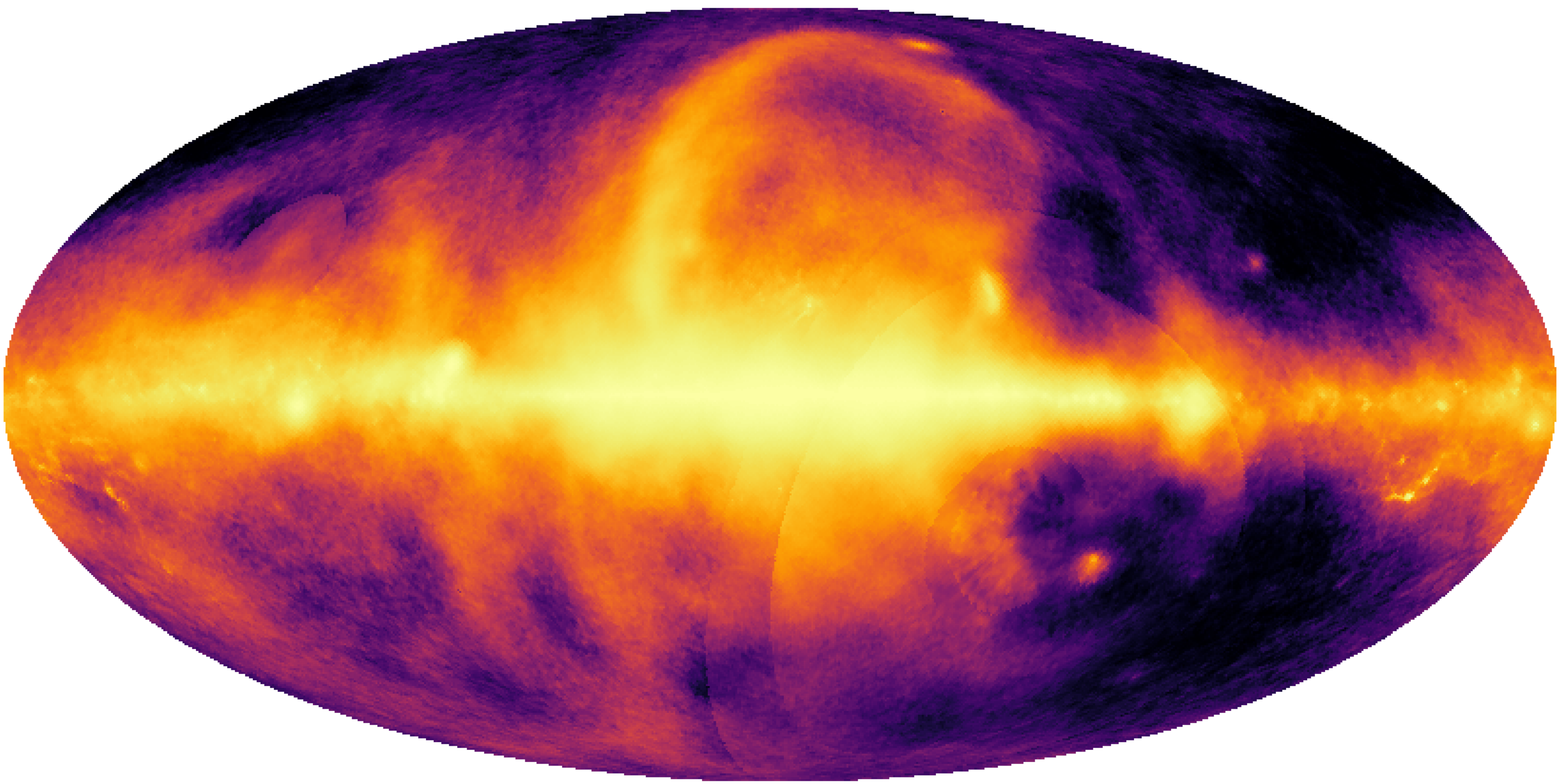


Solution: incorporate new low-frequency datasets



LWA 74 MHz, Dowell et al. (2017)

An example 408 MHz prediction



Problem 2: the GSM does not output error bars!

Solution: construct models for the errors in the input data, and Monte Carlo to get final errors in our predictions

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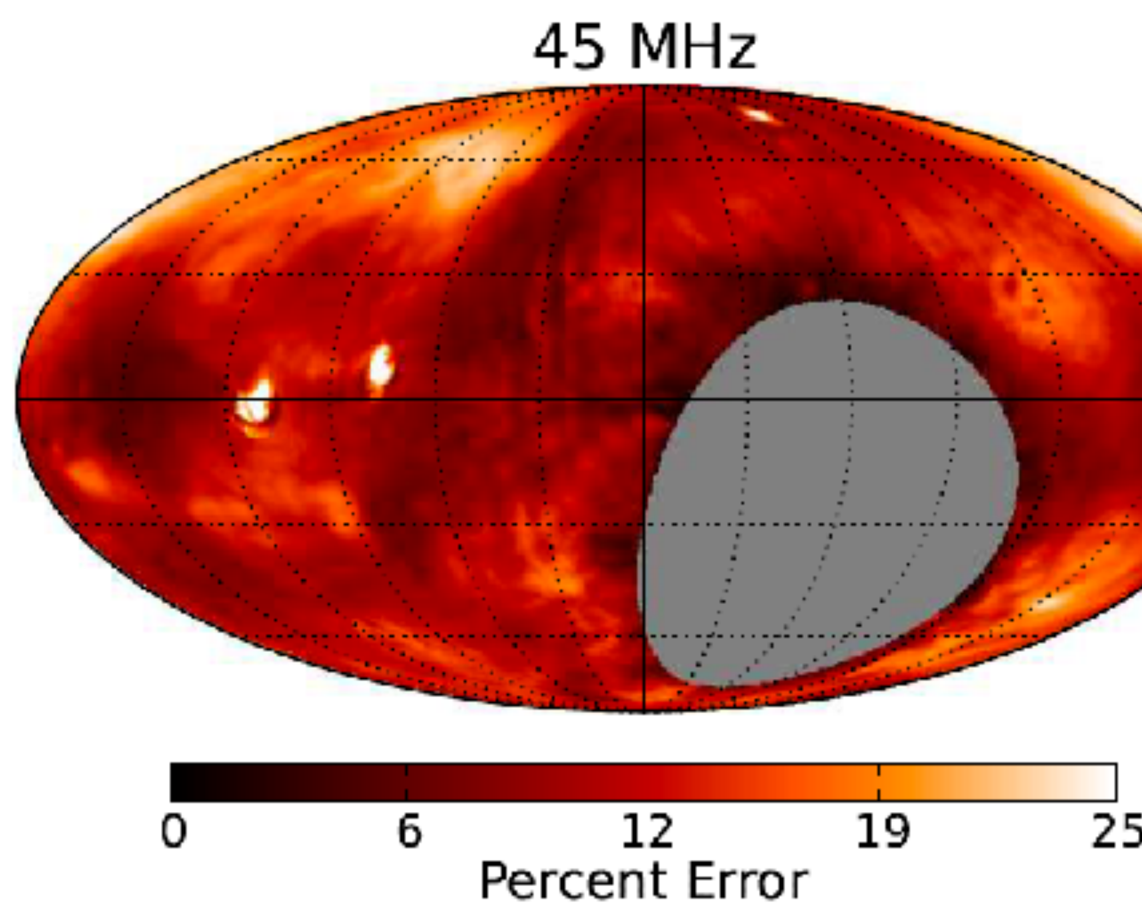
- Where available, use provided estimates of errors and covariances

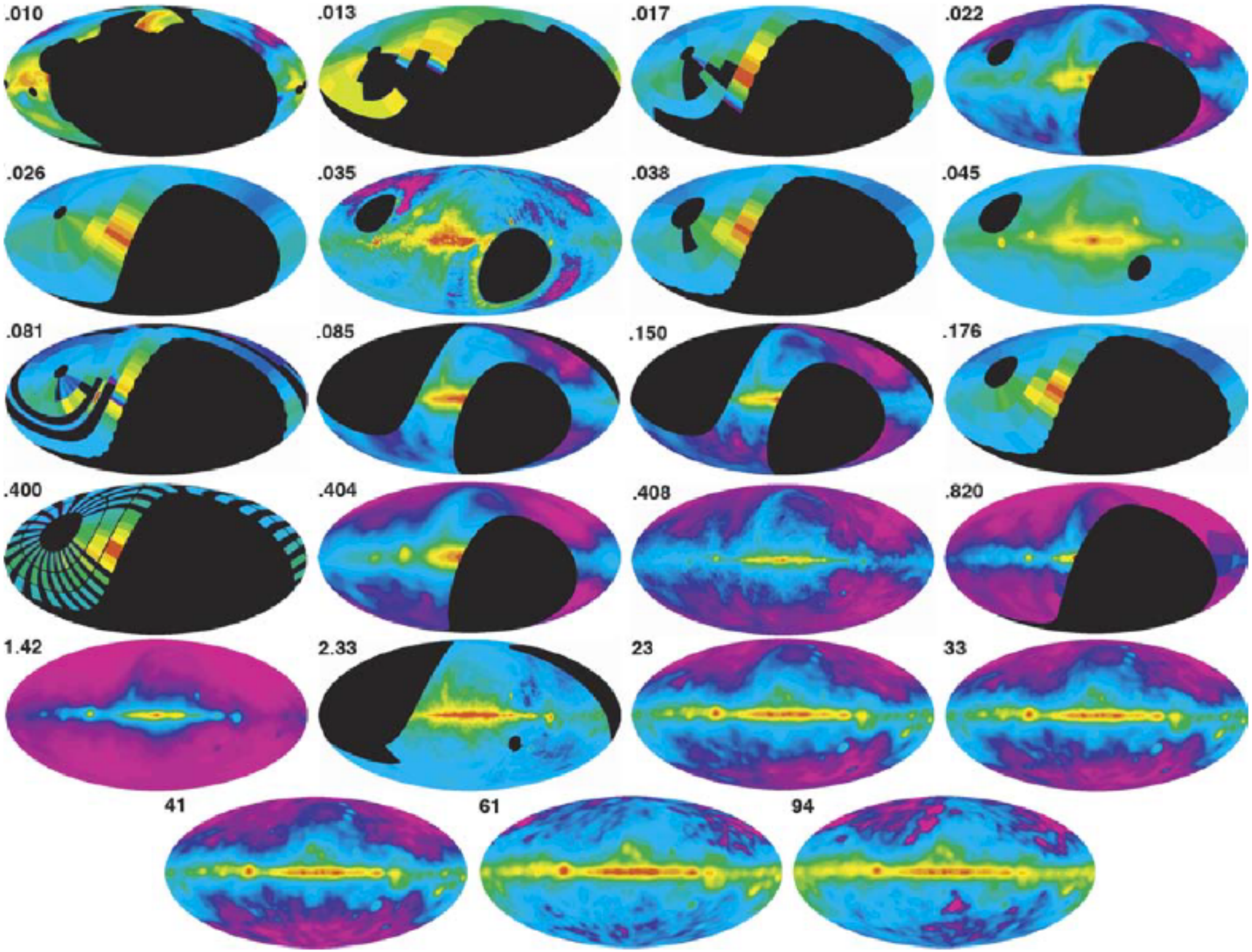


LWA 74 MHz, Dowell et al. (2017)

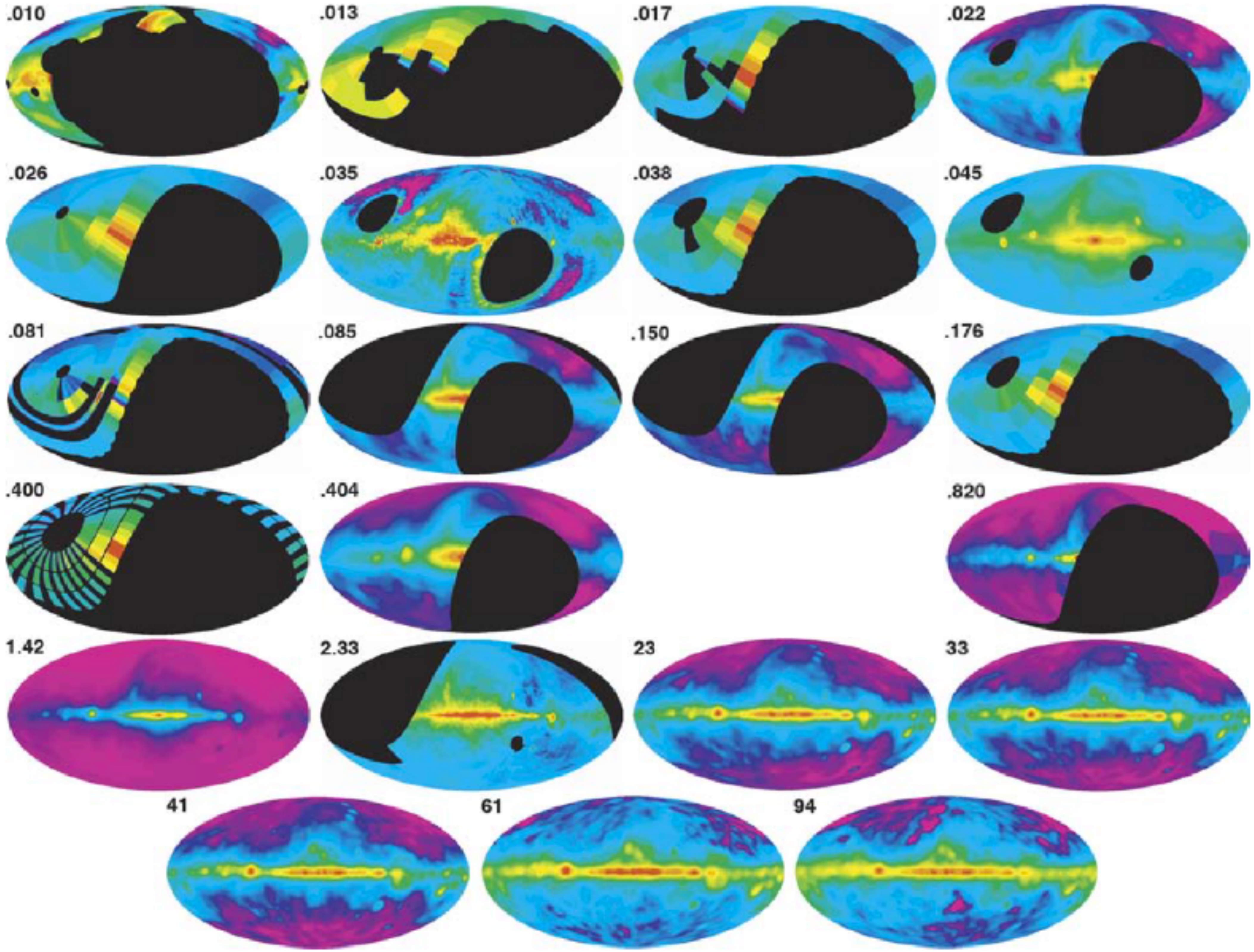
Solution: construct models for the errors in the input data, and Monte Carlo to get final errors in our predictions

- Where available, use provided estimates of errors and covariances

- Where errors are not available, model the errors empirically

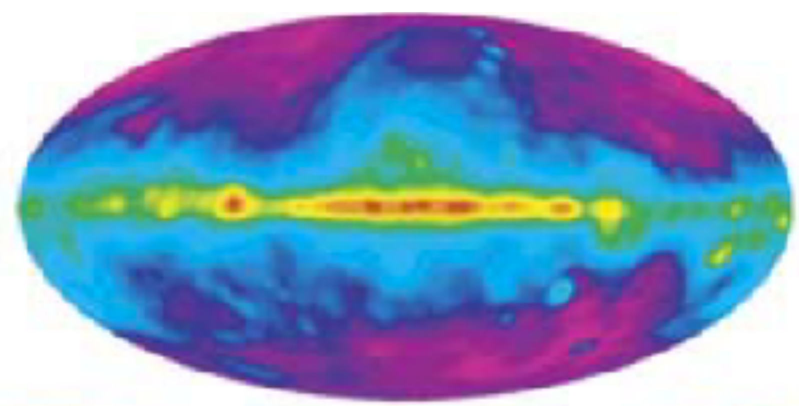


.010
.013
.017
.022
.026
.035
.038
.045
.081
.085
.150
.176
.400
.404
.408
.820
1.42
2.33
23
33
41
61
94



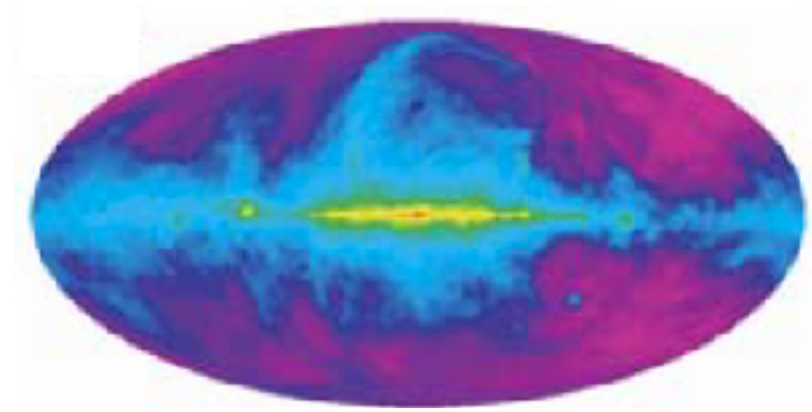
Run model again with an input map removed, making a prediction for the missing map

Prediction



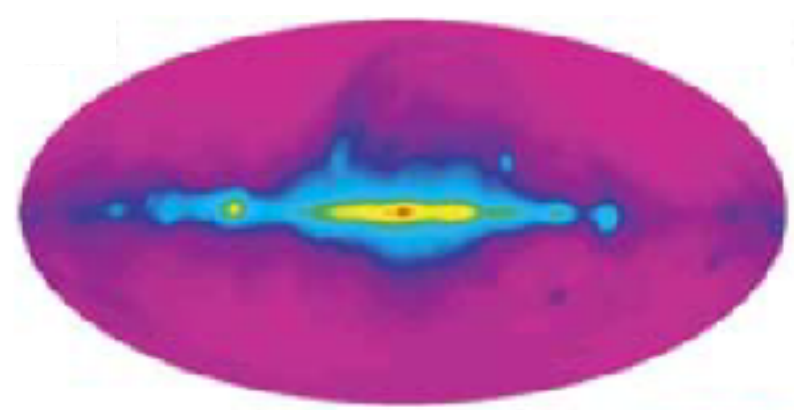
—

Data



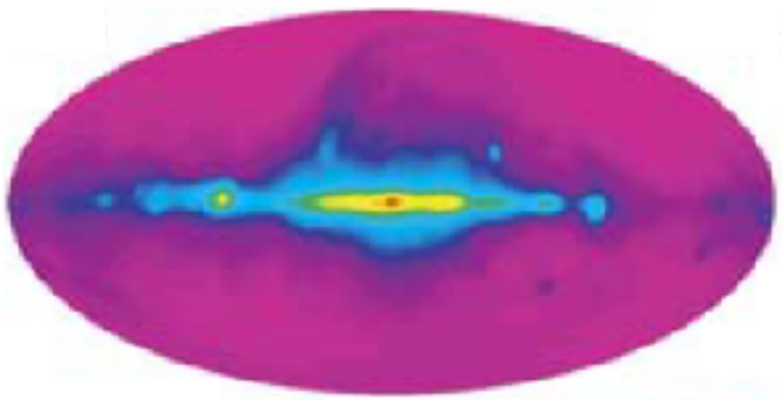
“Error”

=



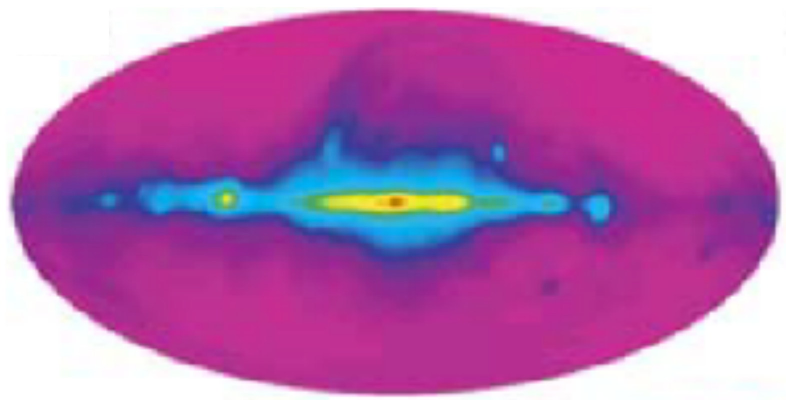
Subtract the new predicted map from the observed data

“Error”



Error model

“Error”

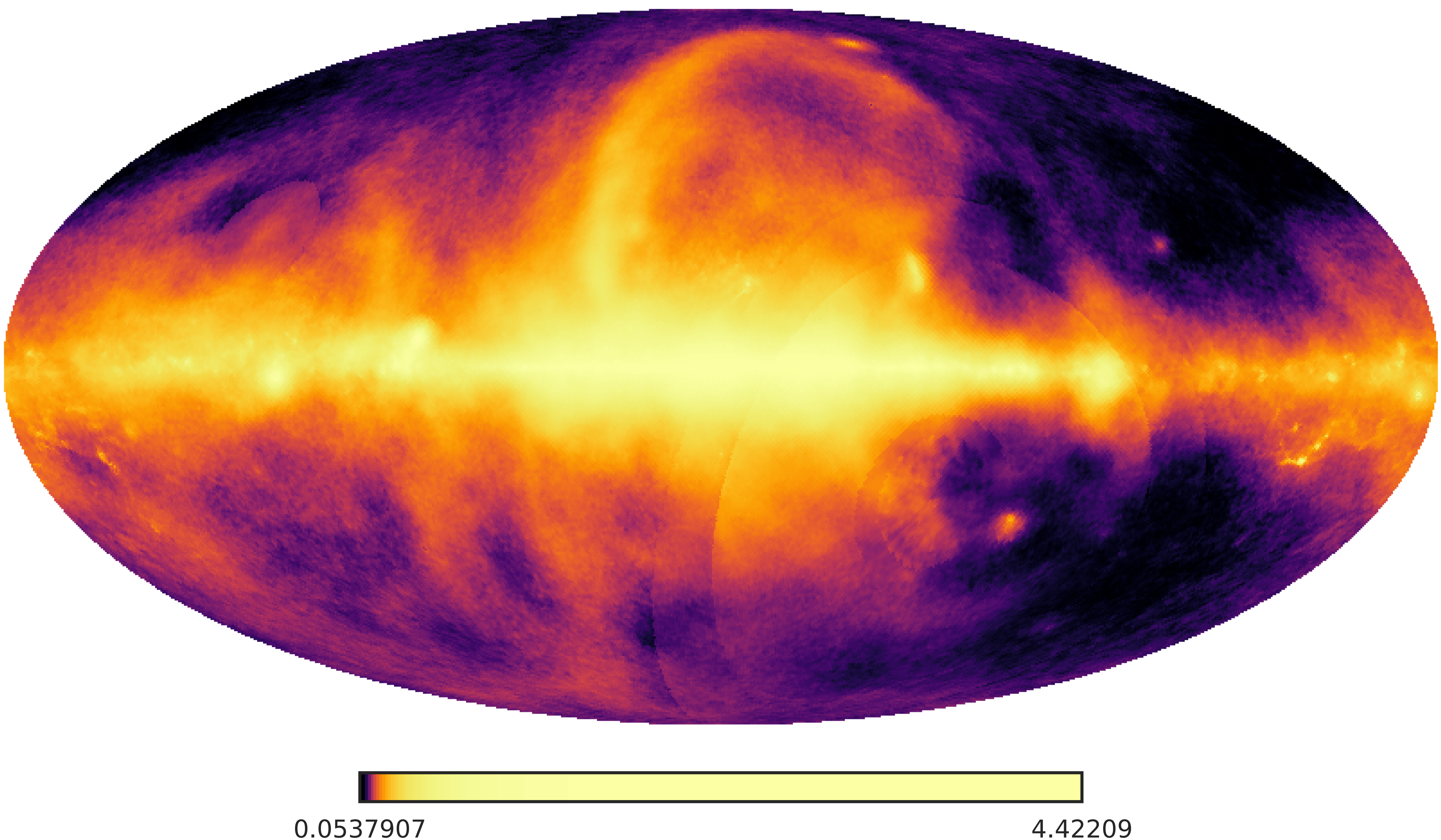


Ansatz for errors in image space: proportional to error map

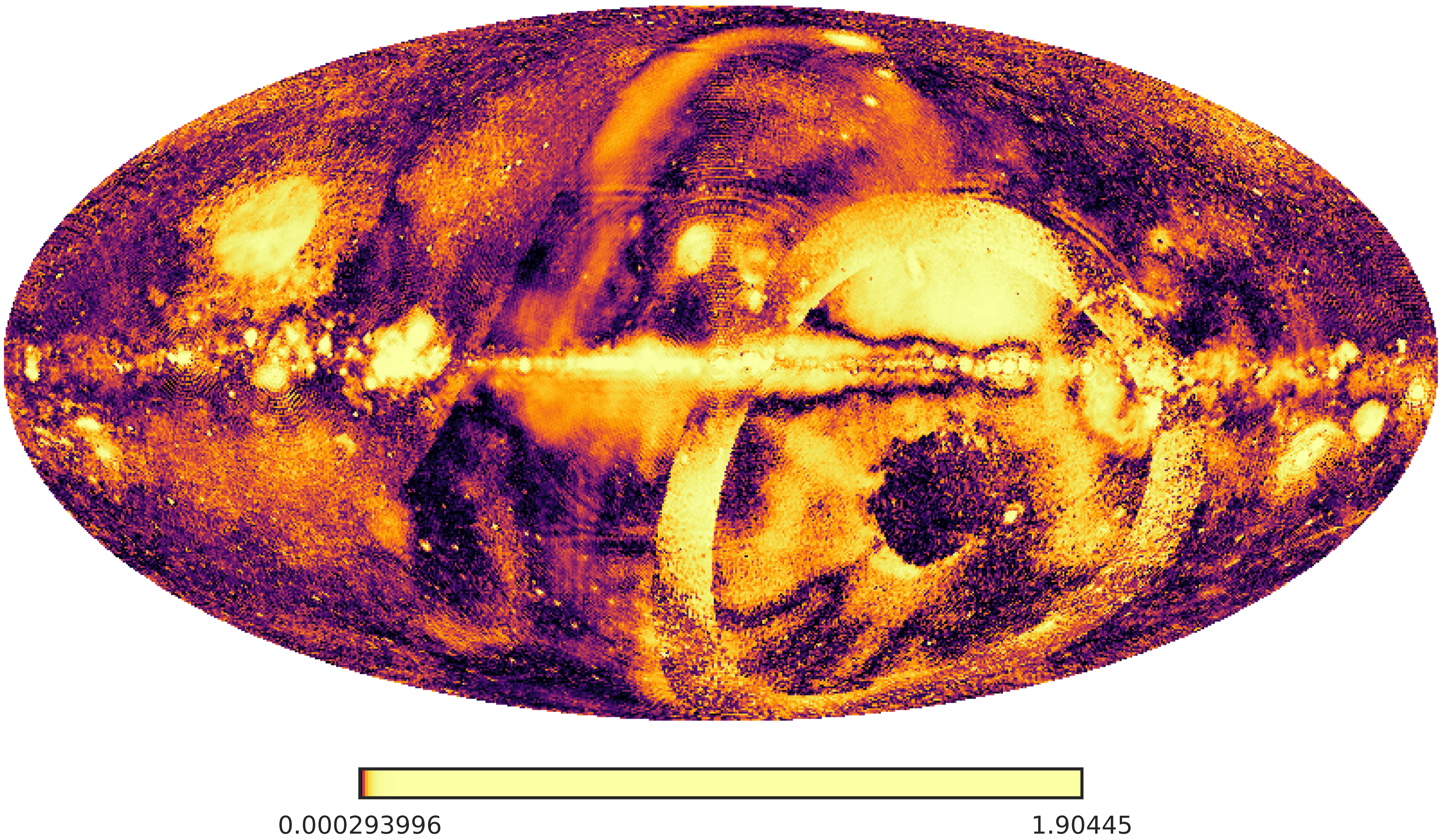
Ansatz for harmonic space: determined by C_l of whitened error map

Error model

An example 408 MHz prediction



Errors on the 408 MHz prediction



Problem 3:

Why three principal components? (v1.0)
Why six principal components? (v2.0)

Problem 3:

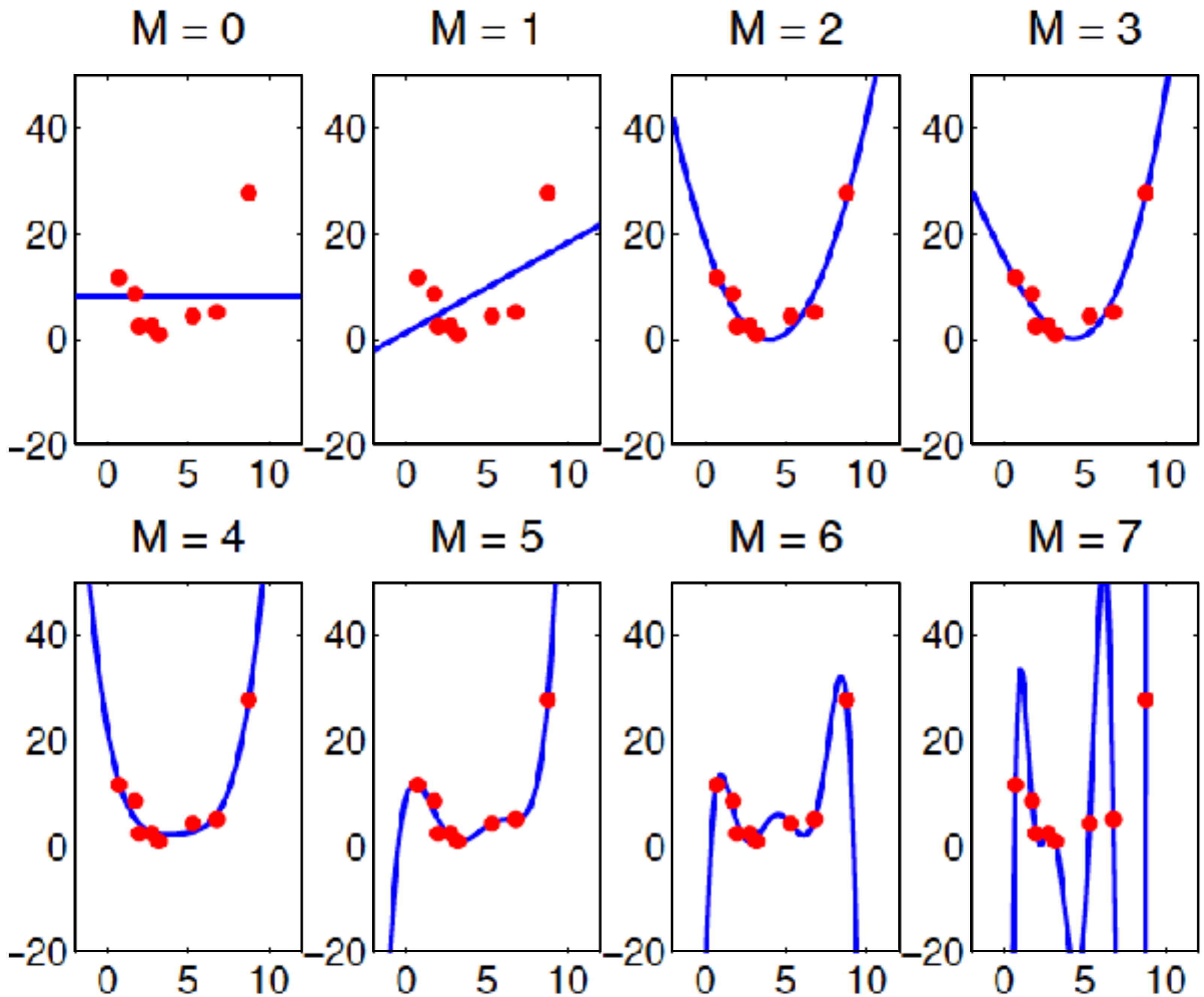
Why three principal components? (v1.0)
Why six principal components? (v2.0)

Too few components: inadequate fits to data
Too many components: overfitting of data

Computing the Bayesian Evidence provides a way to determine the optimal number of principal components to fit

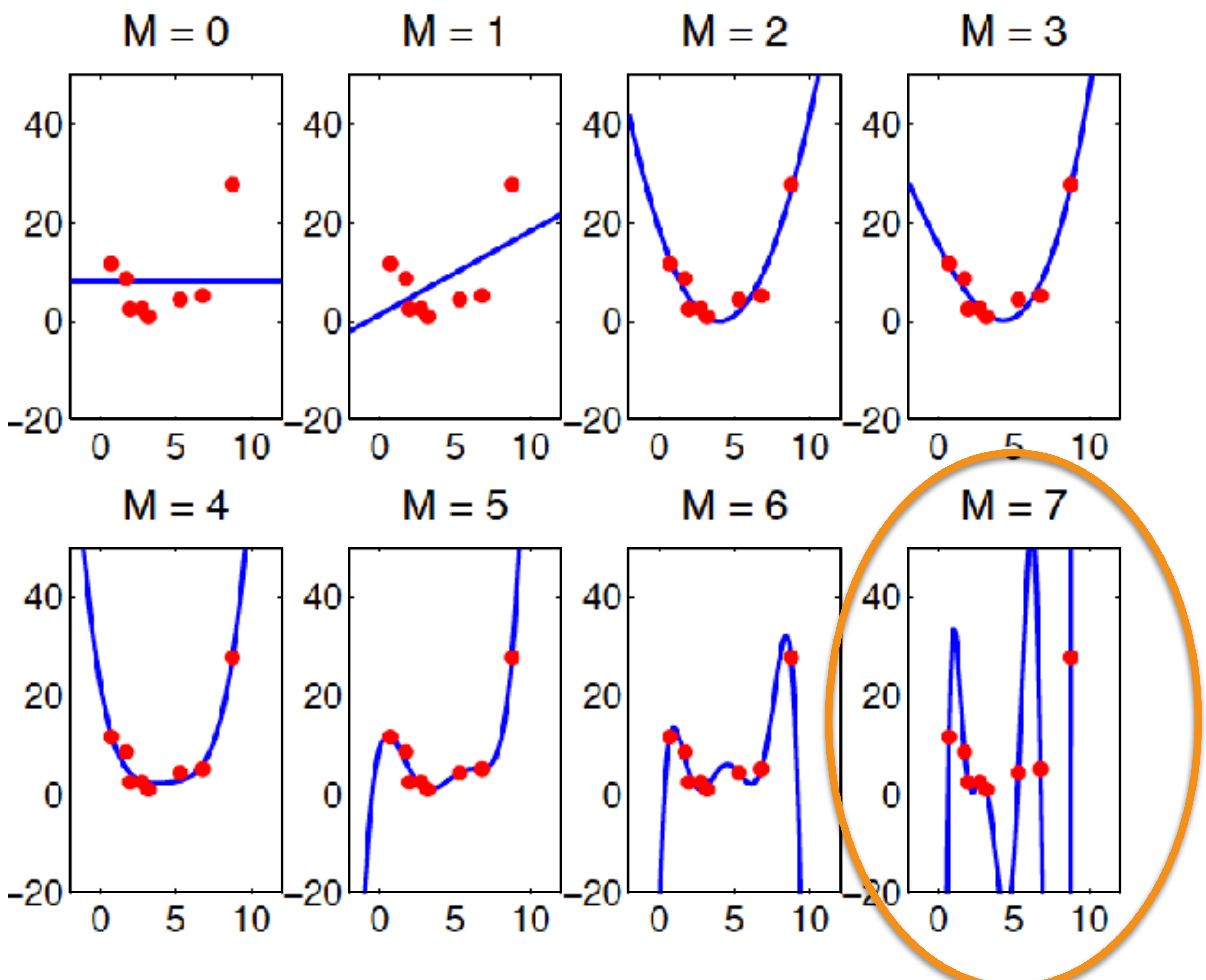
Computing the Bayesian Evidence provides a way to determine the optimal number of principal components to fit

Image credit: Zoubin Ghahramani



Computing the Bayesian Evidence provides a way to determine the optimal number of principal components to fit

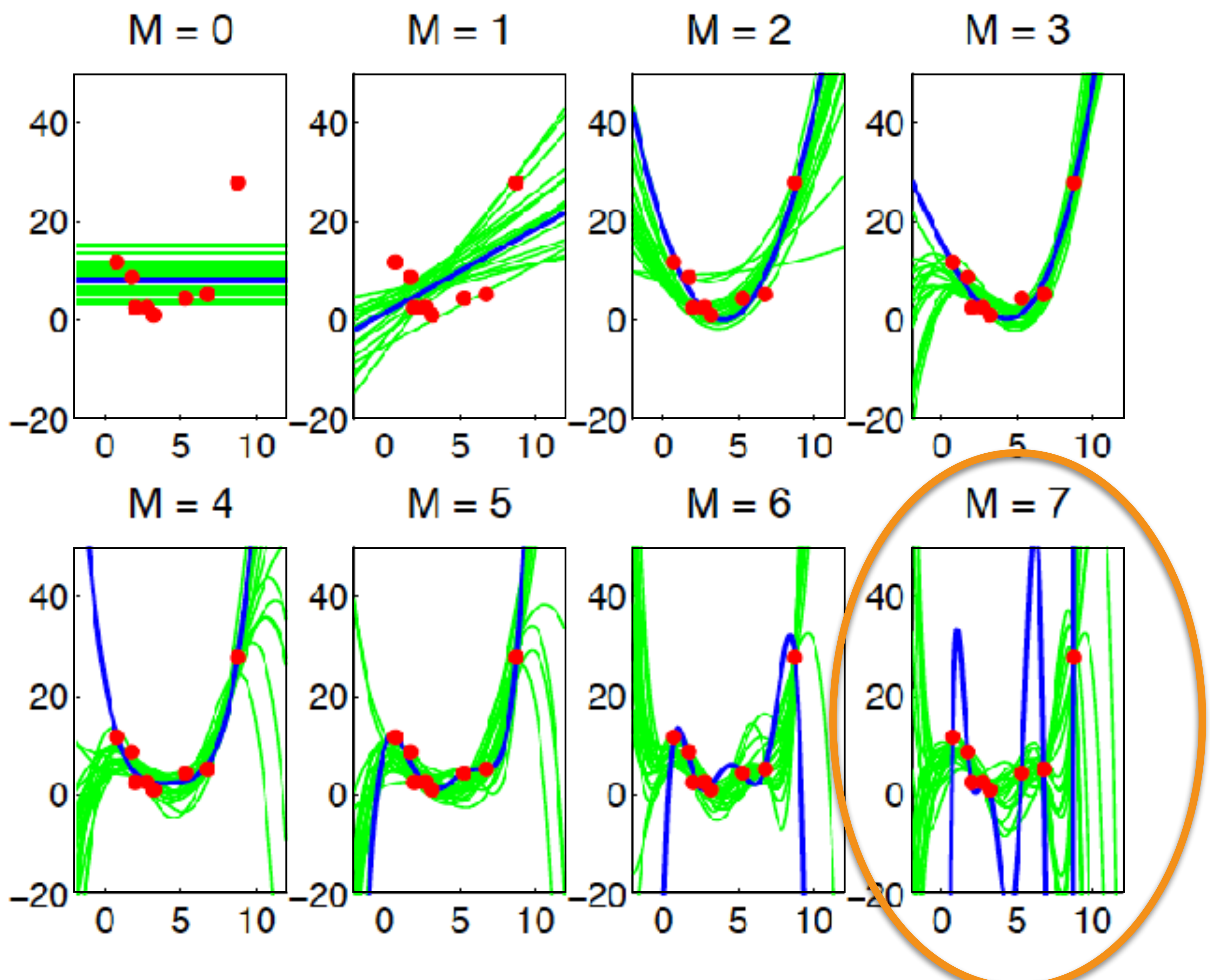
Image credit:
Zoubin Ghahramani



Maximum likelihood

Computing the Bayesian Evidence provides a way to determine the optimal number of principal components to fit

Image credit:
Zoubin Ghahramani



Maximum likelihood

Computing the Bayesian Evidence provides a way to determine the optimal number of principal components to fit

Image credit:
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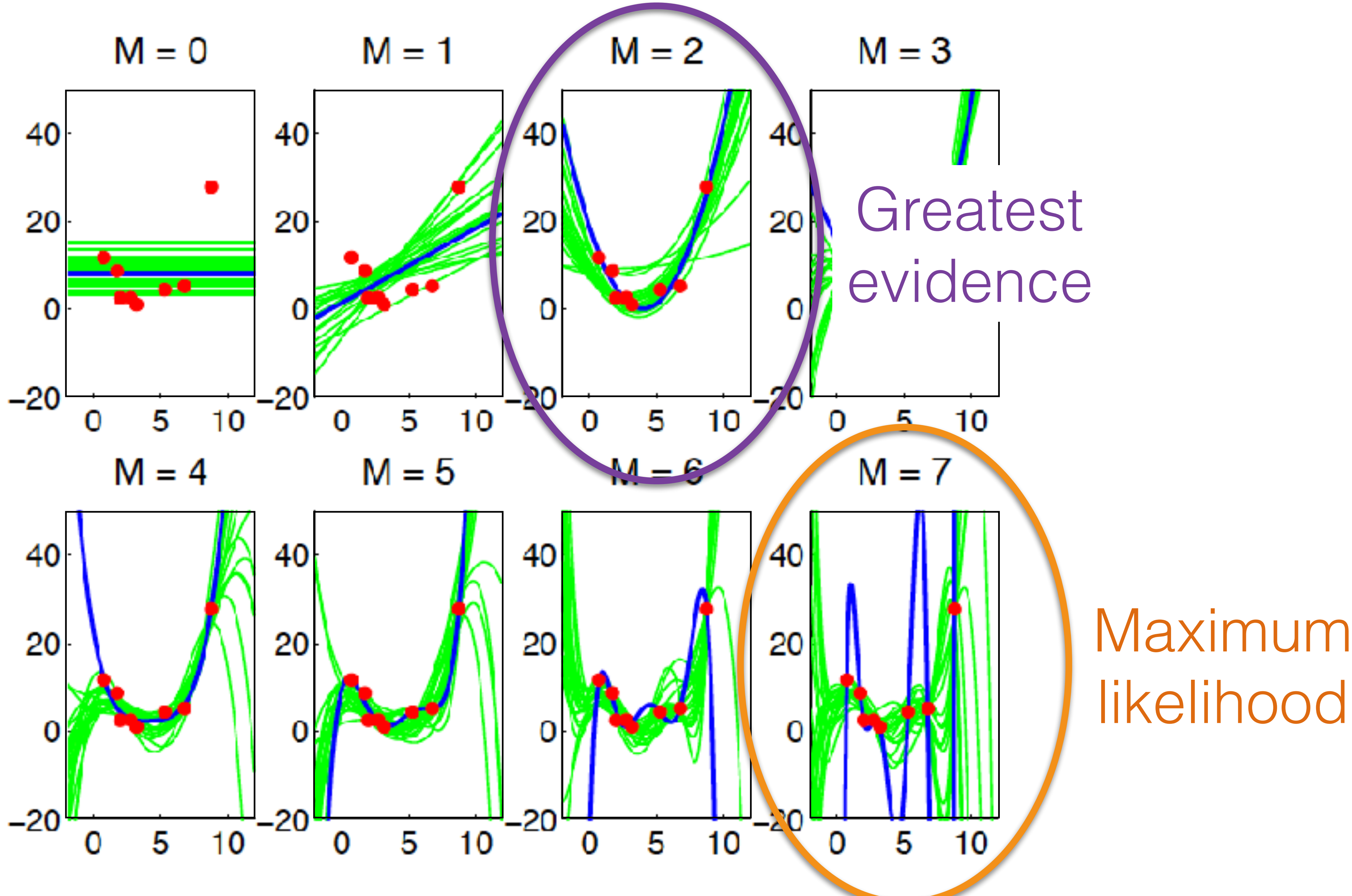
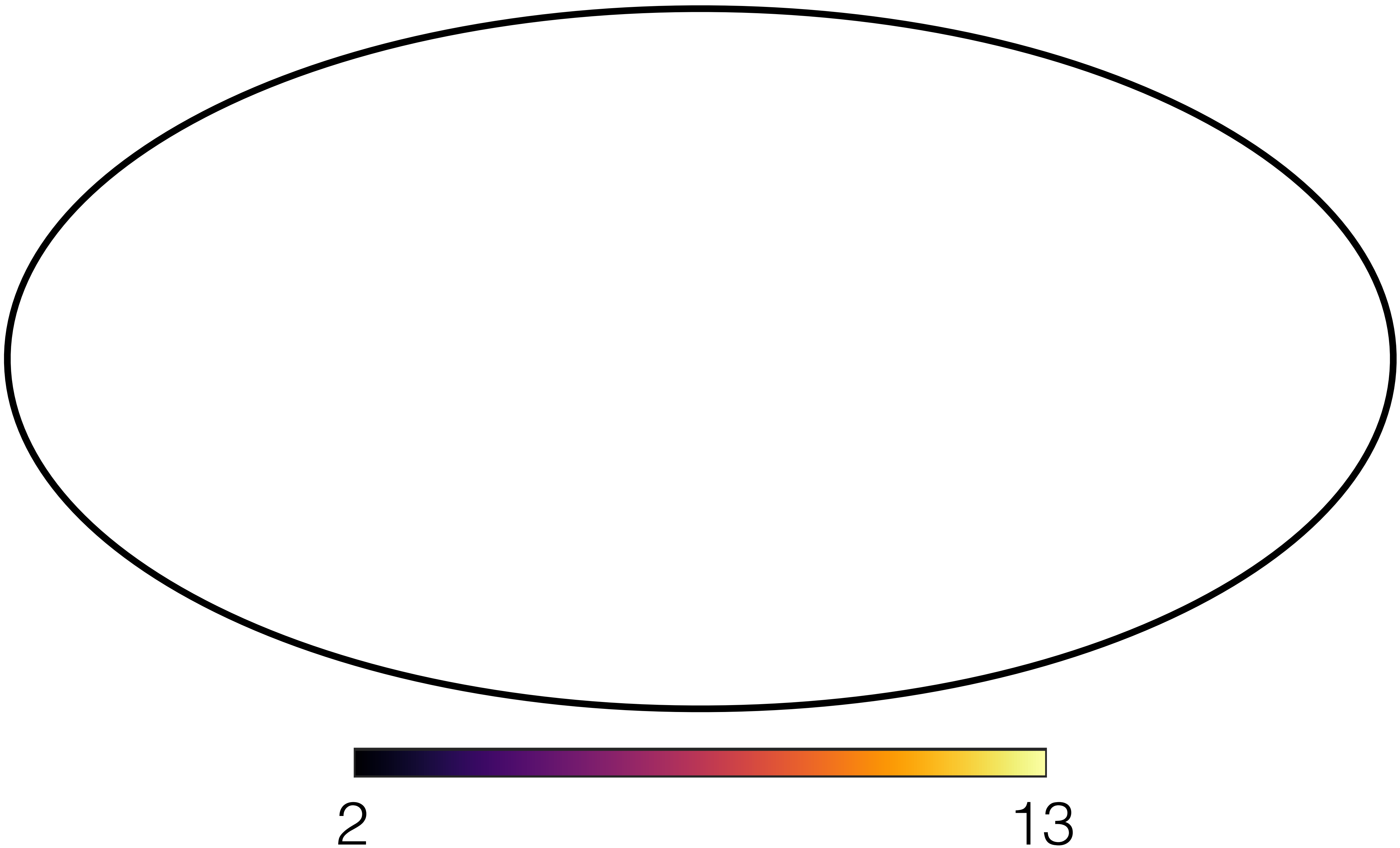
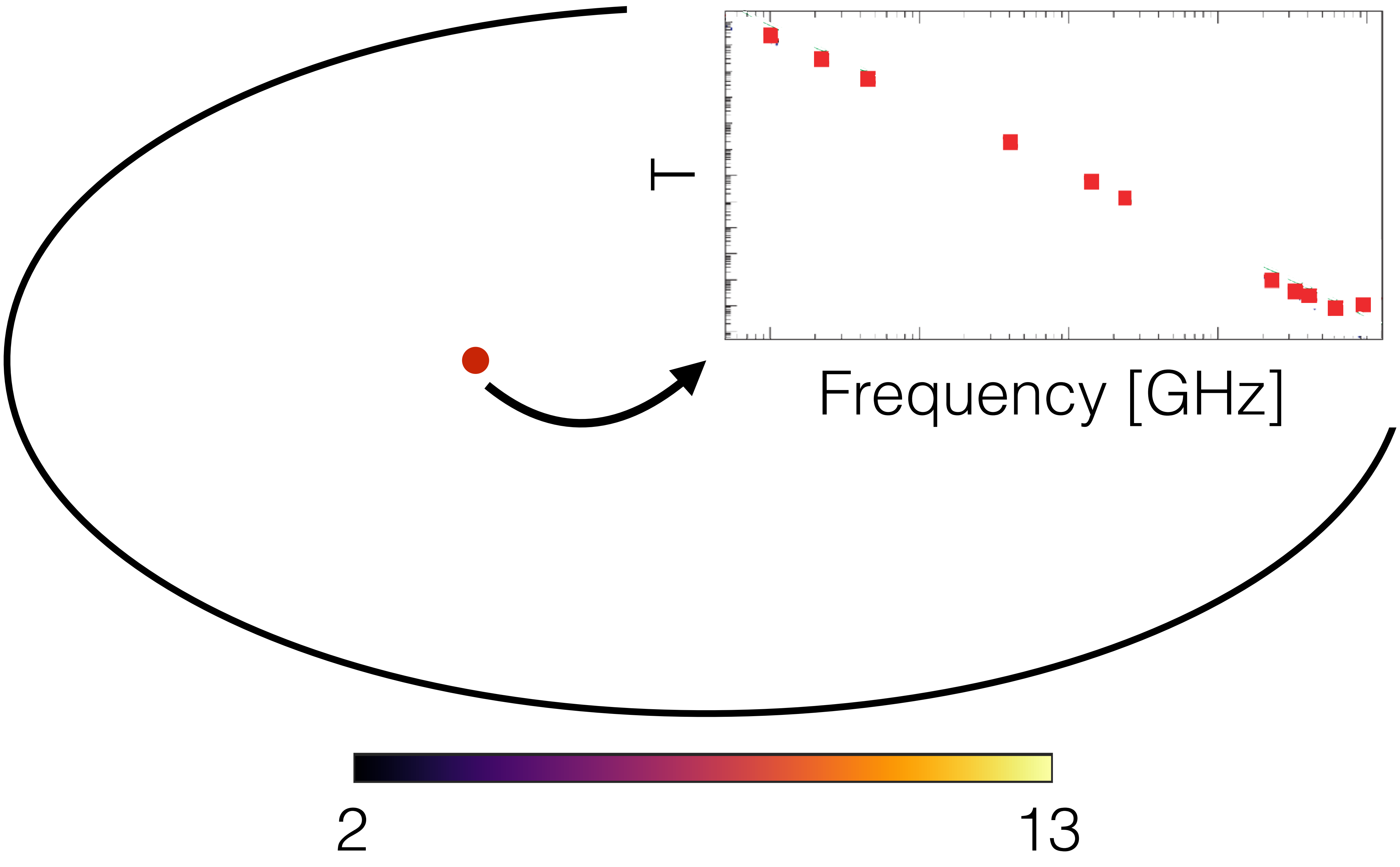


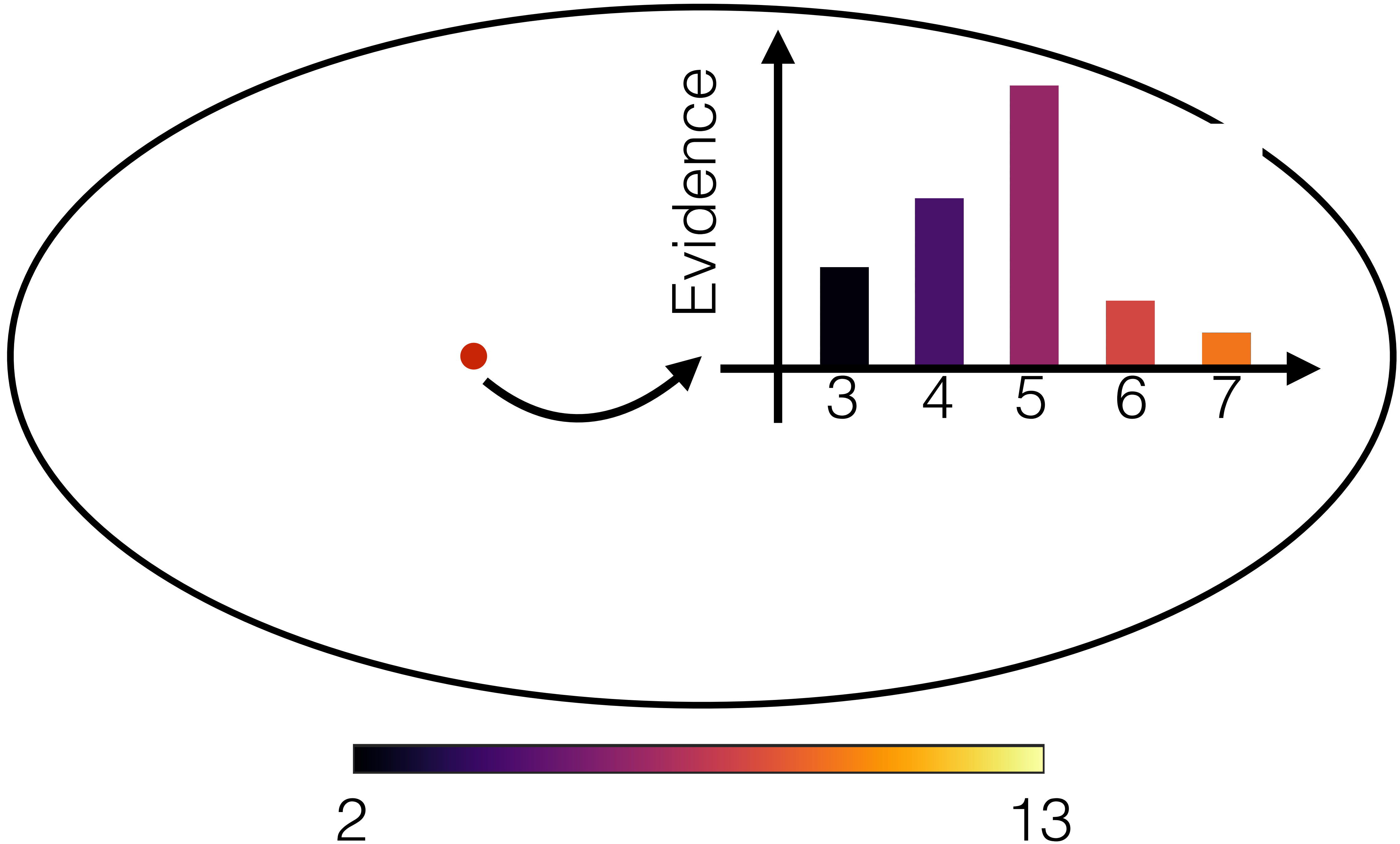
Optimal number of principal components



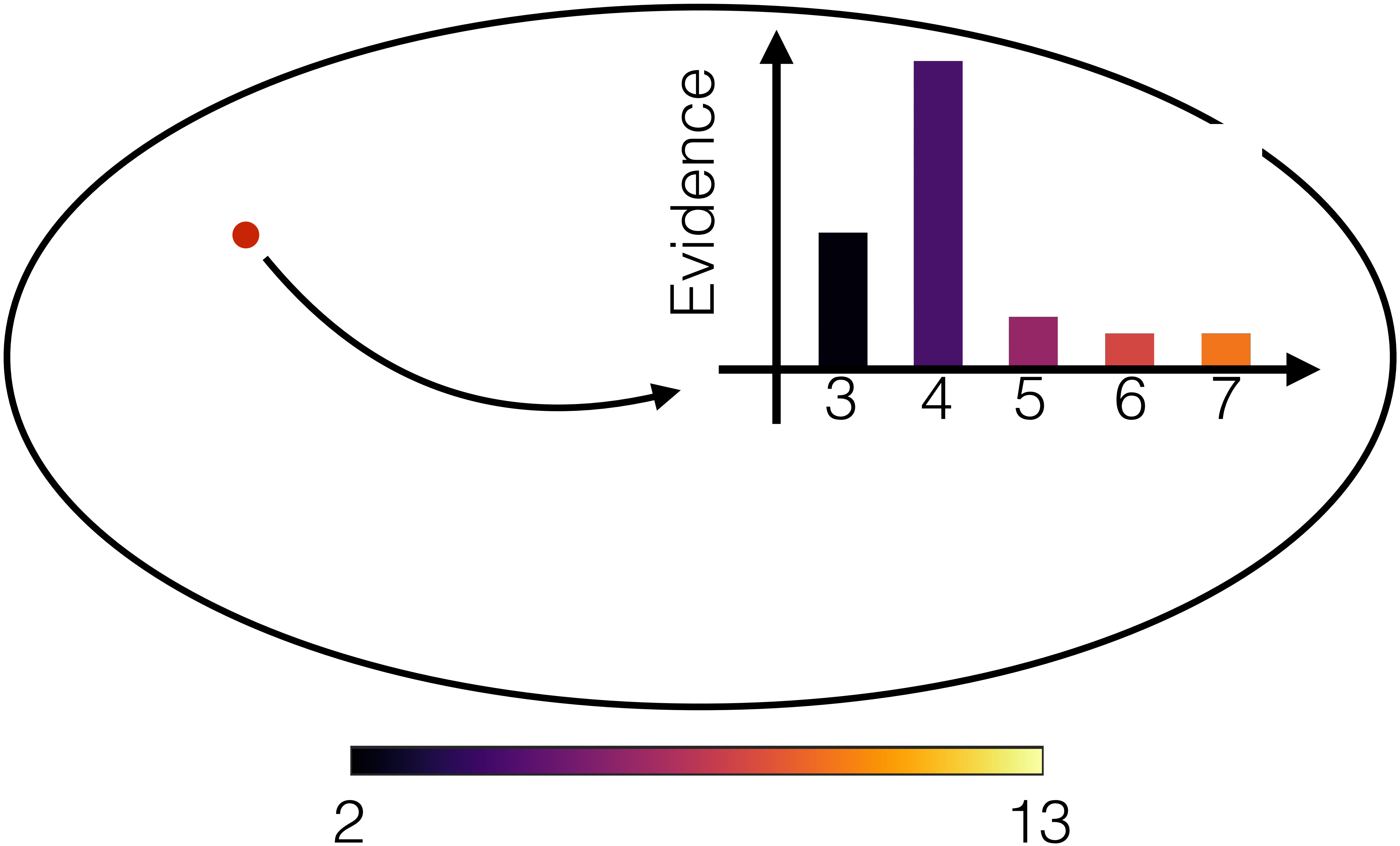
Optimal number of principal components



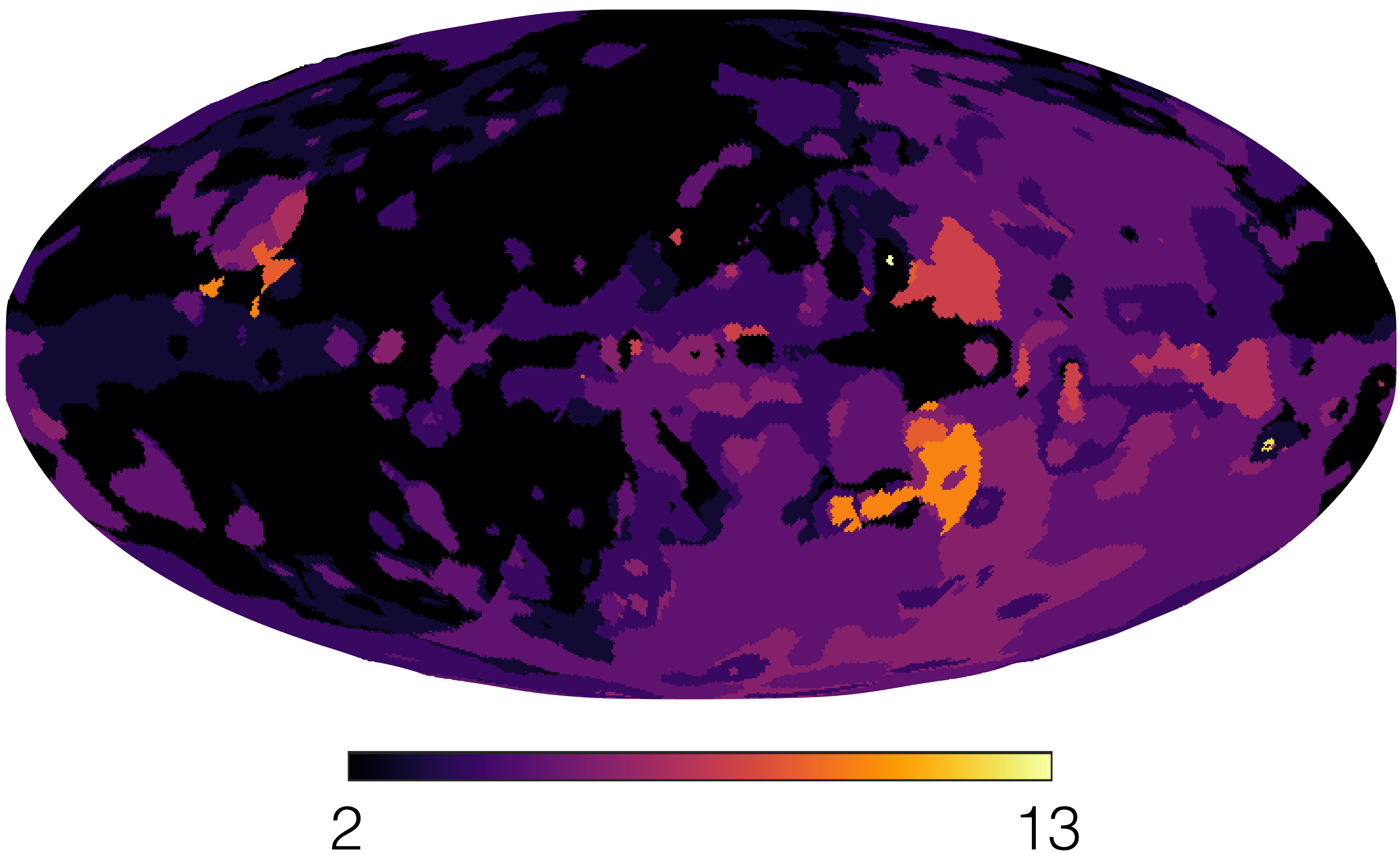
Optimal number of principal components



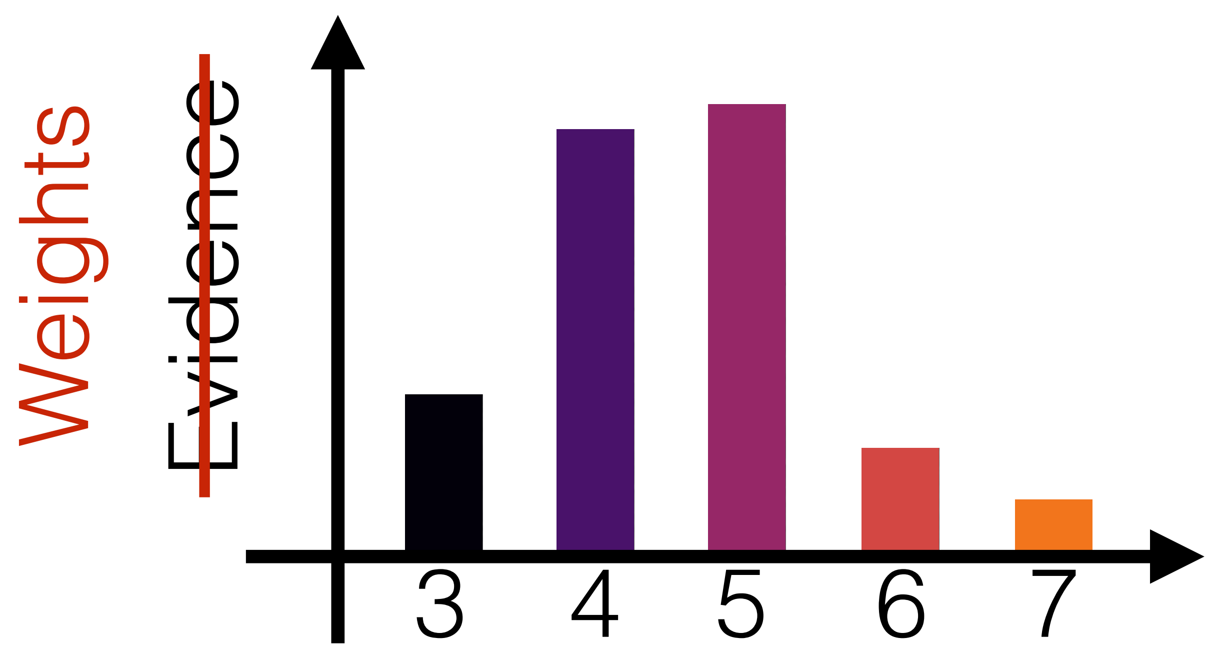
Optimal number of principal components



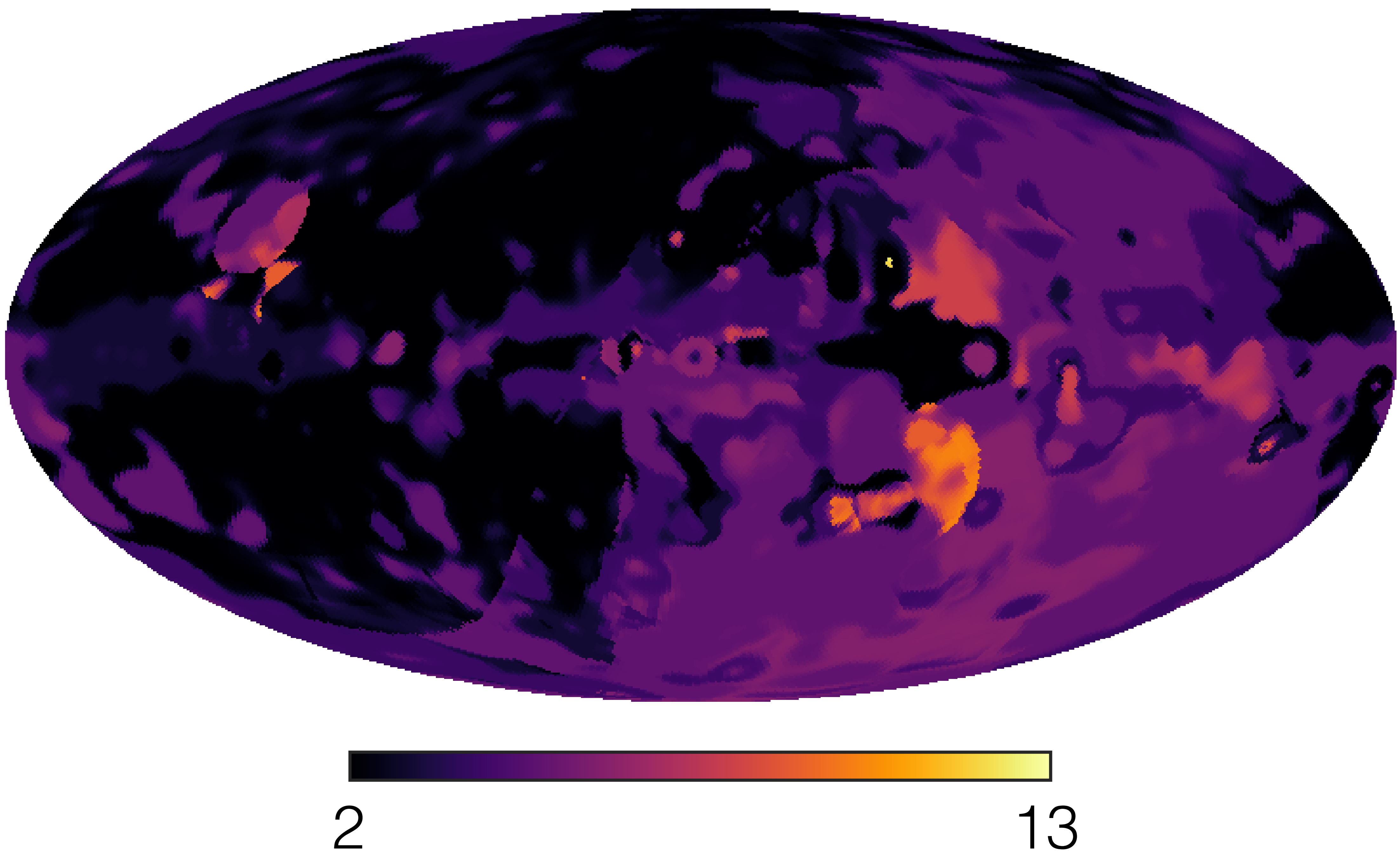
Optimal number of principal components



But why even commit to a model? Use evidence as a weight for constructing hybrid models that are noncommittal to the number of components



Effective number of principal components



Lots more coming soon to a Github repo near you!

- Position-dependent number of components.
- Error bars in output maps.
- Framework for incorporating monopole measurements.
- Inclusion of new map data.

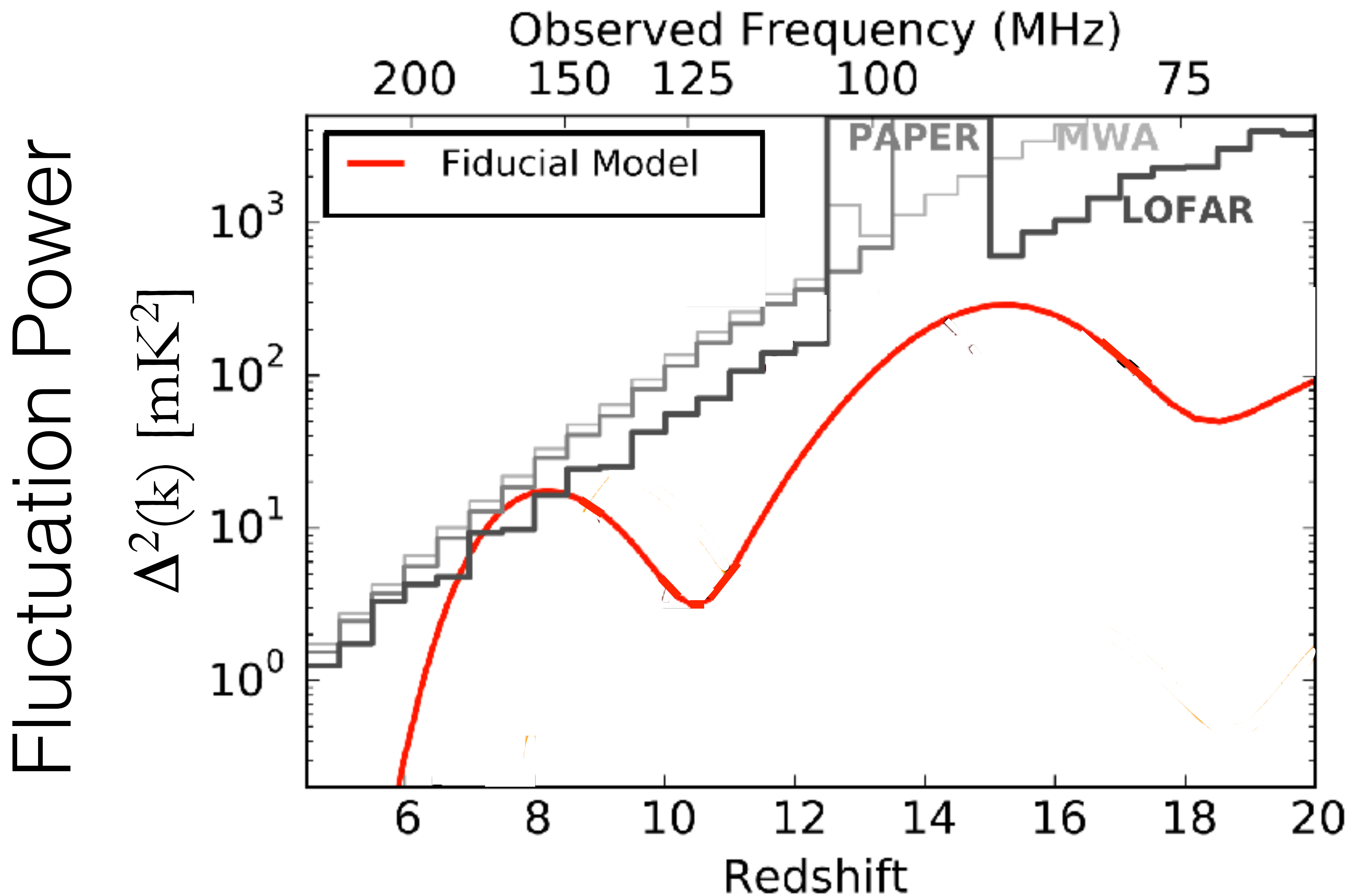
Lots more coming soon to a Github repo near you!

- Position-dependent number of components.

End goal: a publicly hosted, self-updating, best-guess model of the sky

The sensitivity challenge

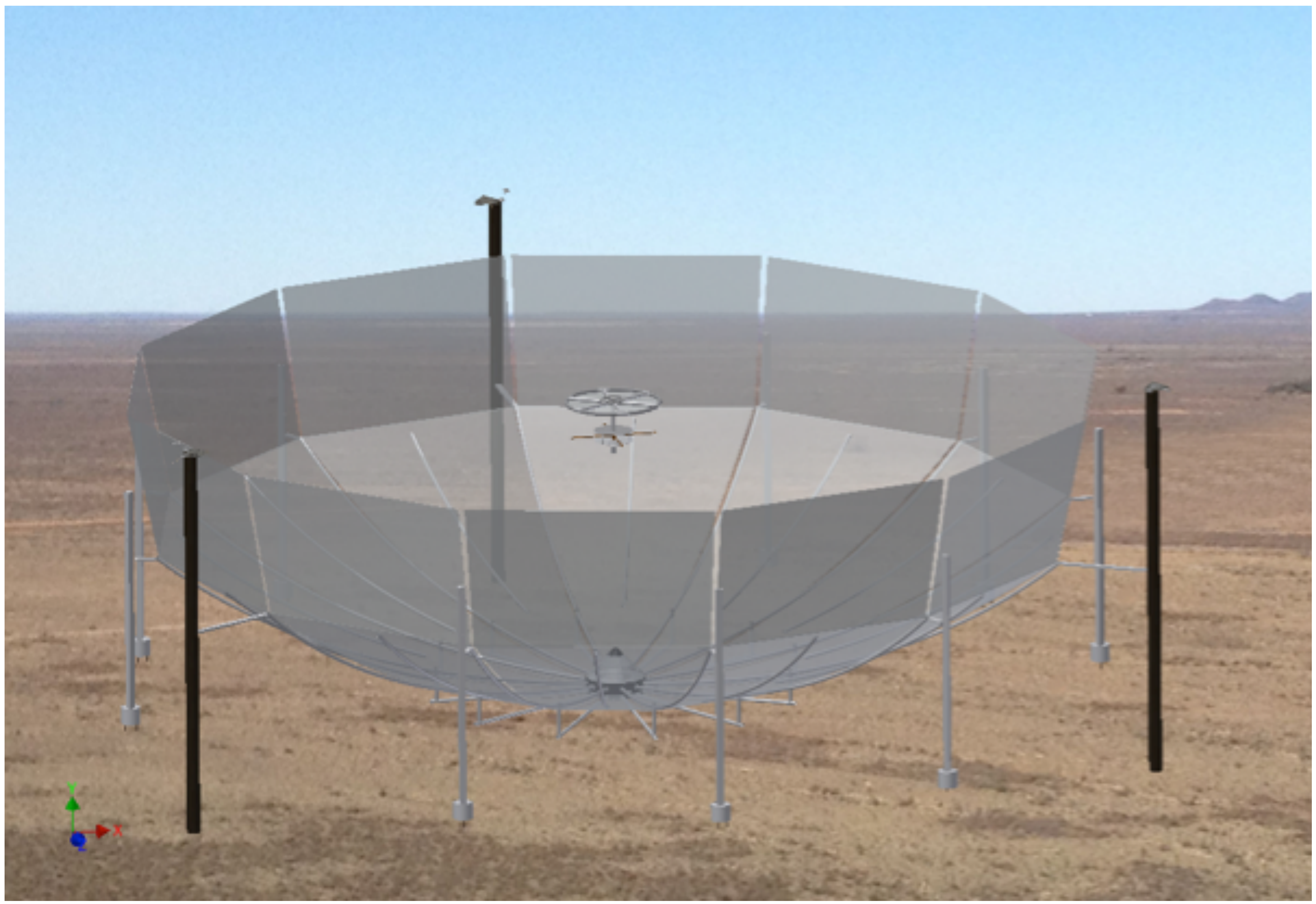
Current instruments lack sensitivity



The Hydrogen Epoch of Reionization Array (HERA) is designed to measure the power spectrum of spatial fluctuations to high significance

Take a relatively simple antenna…

…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

UNIVERSITY OF WASHINGTON · 1861 · LVX SIT

THE UNIVERSITY OF CALIFORNIA · BERKELEY · 1868

MASSACHUSETTS INSTITUTE OF TECHNOLOGY · 1861 · MENS ET MANUS

ARIZONA STATE UNIVERSITY · 1885 · GREAT SEAL OF THE STATE OF ARIZONA · DITAT DEUS · 1912

Penn
UNIVERSITY of PENNSYLVANIA

UNIVERSITY OF CAMBRIDGE

McGill

SCUOLA NORMALE SUPERIORE

HERA

UNIVERSITY of the WESTERN CAPE
RESPICE PROSPICE

UNIVERSITY OF KWAZULU-NATAL

SKA AFRICA
SQUARE KILOMETRE ARRAY

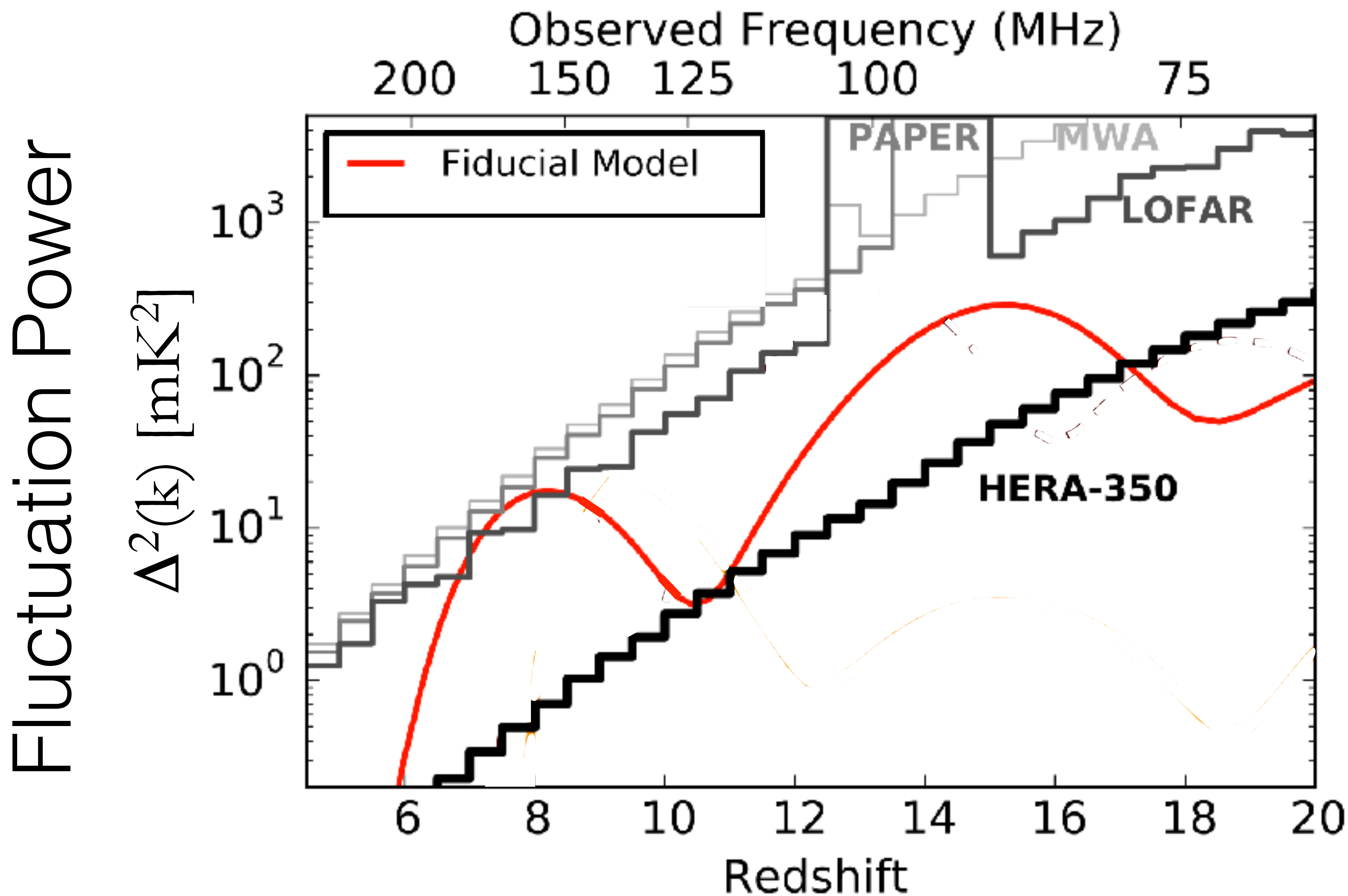
CAL POLY POMONA

VE RI TAS
HARVARD

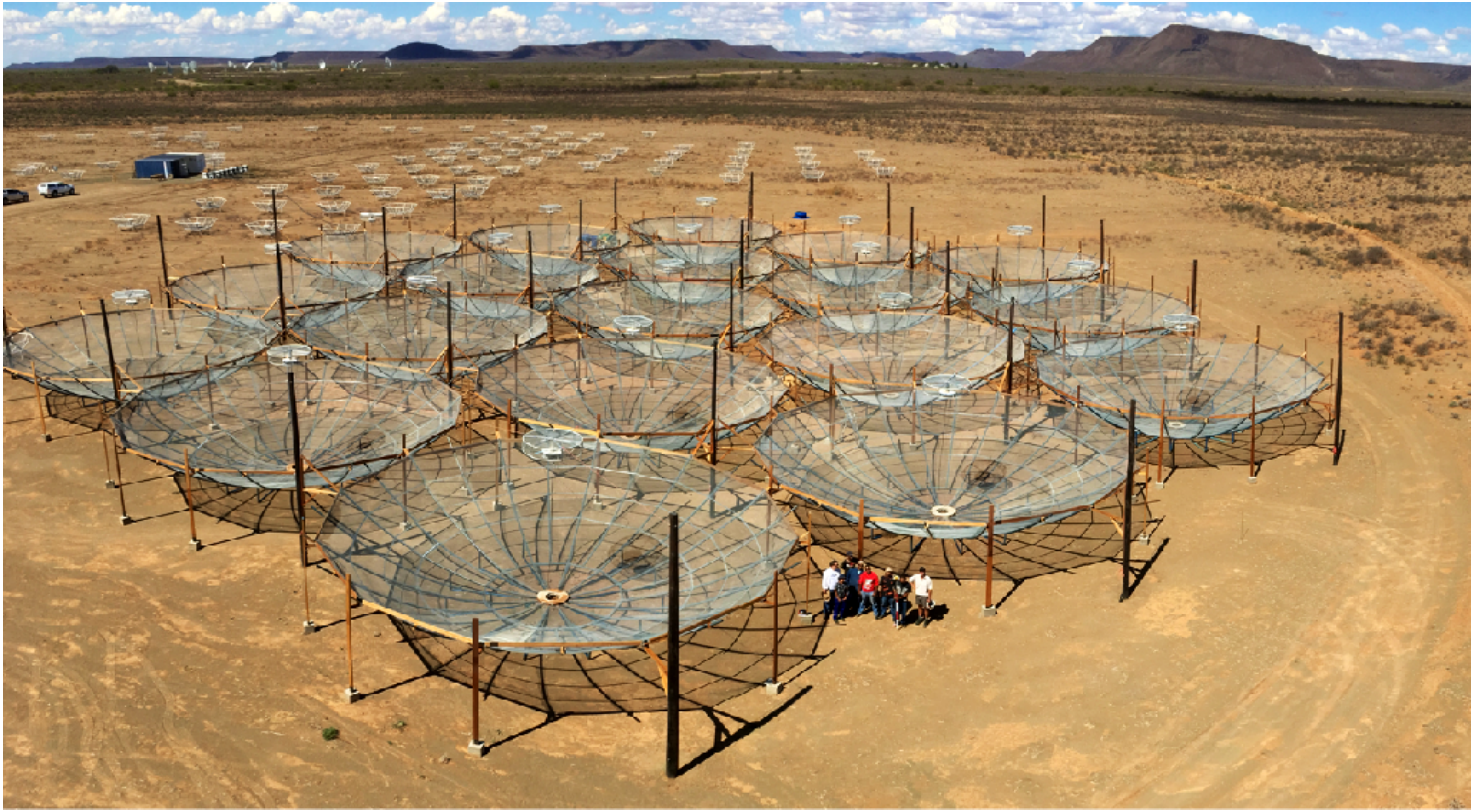
BROWN

NRAO

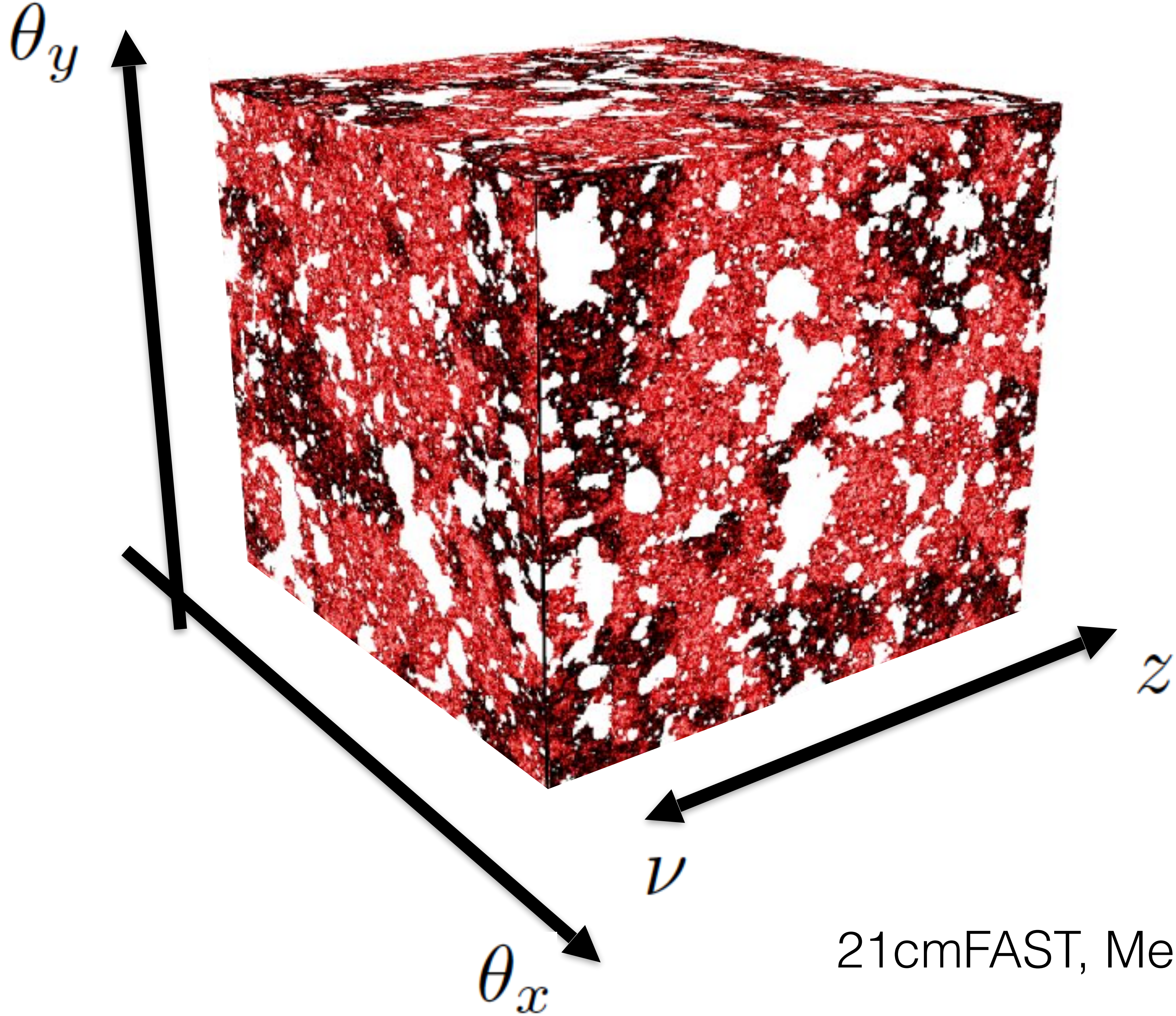
HERA will make a high significance measurement within ~5 years



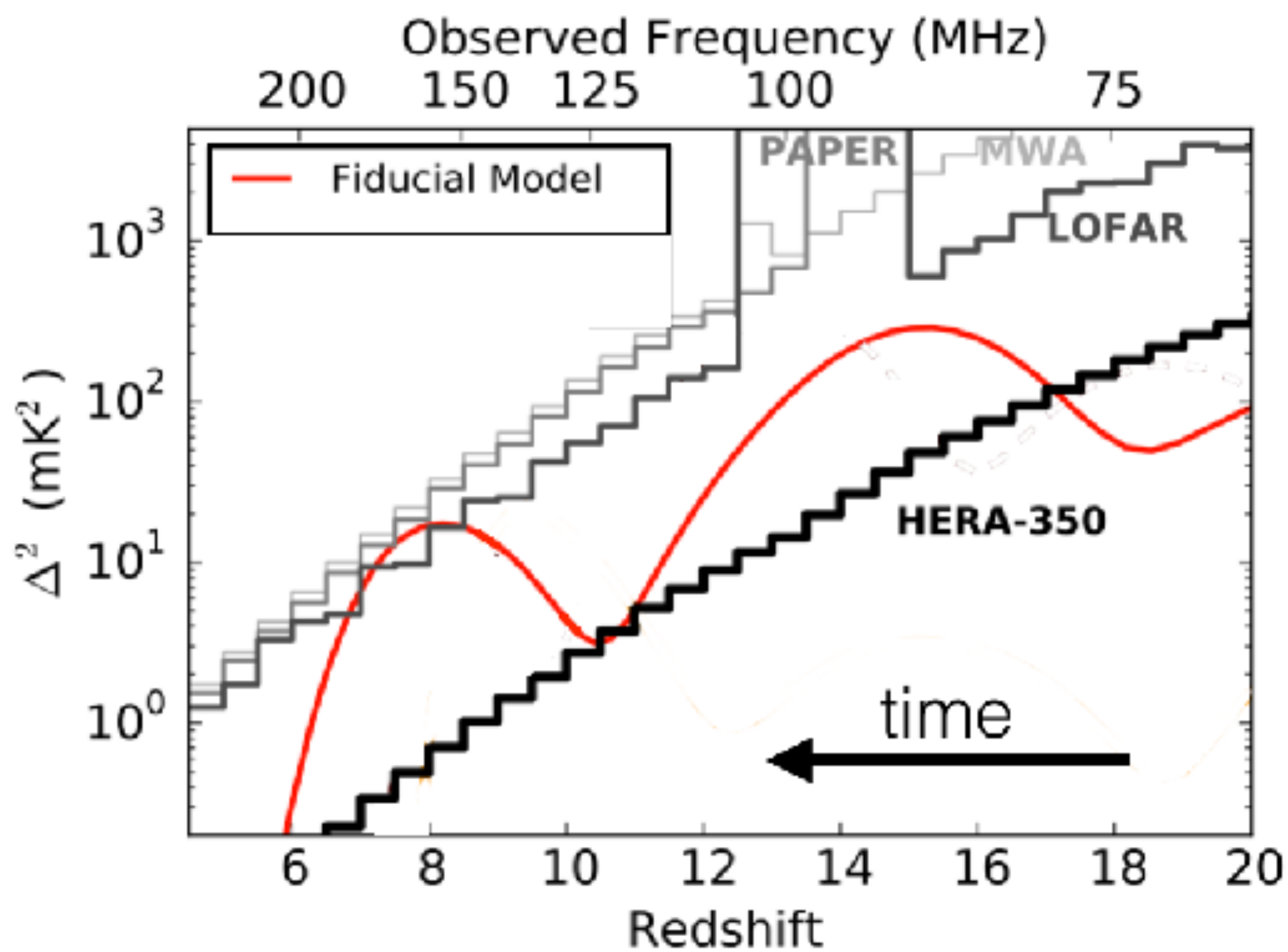

OPEN MIC NIGHT



The promise of 21cm cosmology

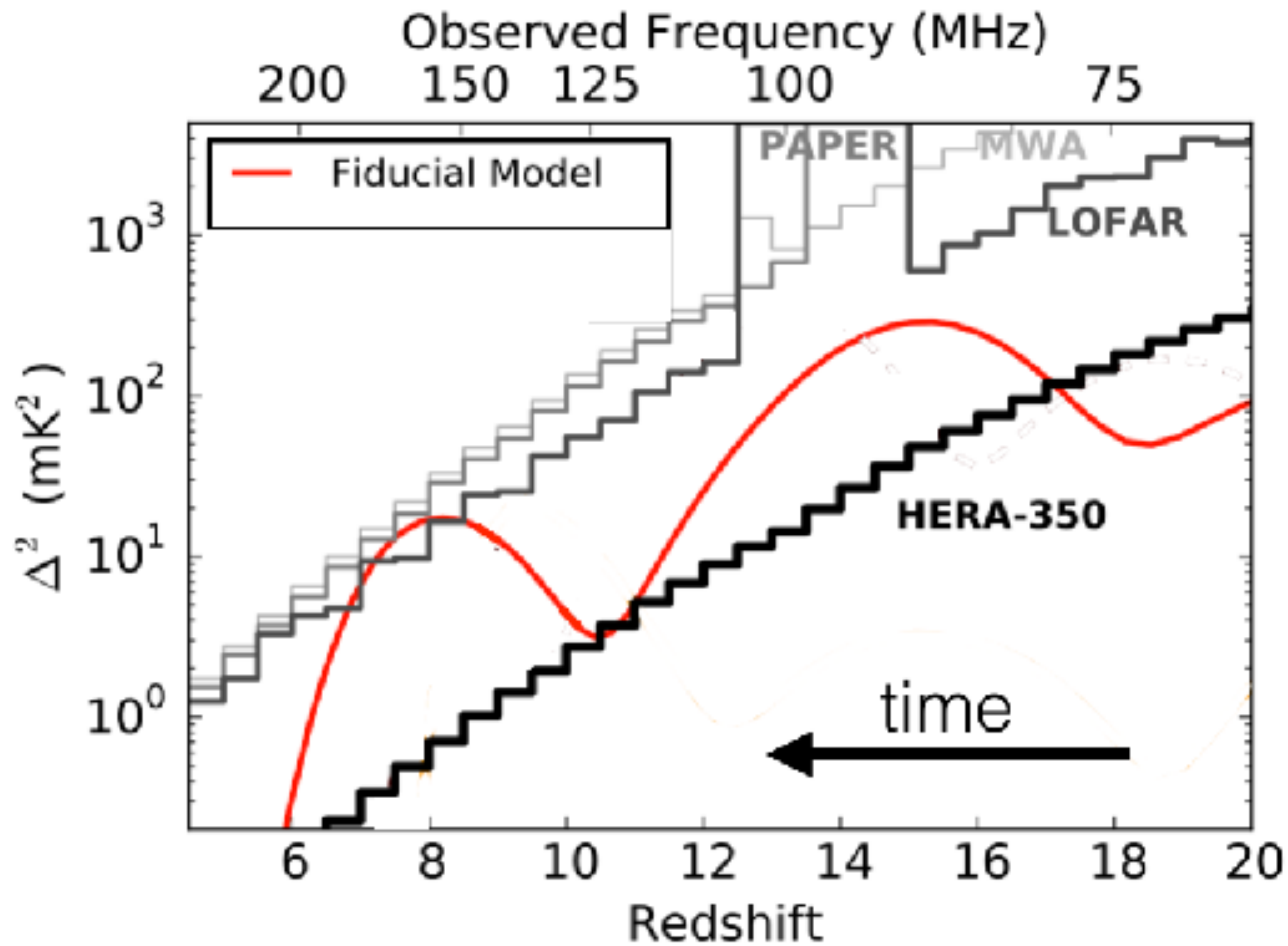


21cmFAST, Mesinger et al.



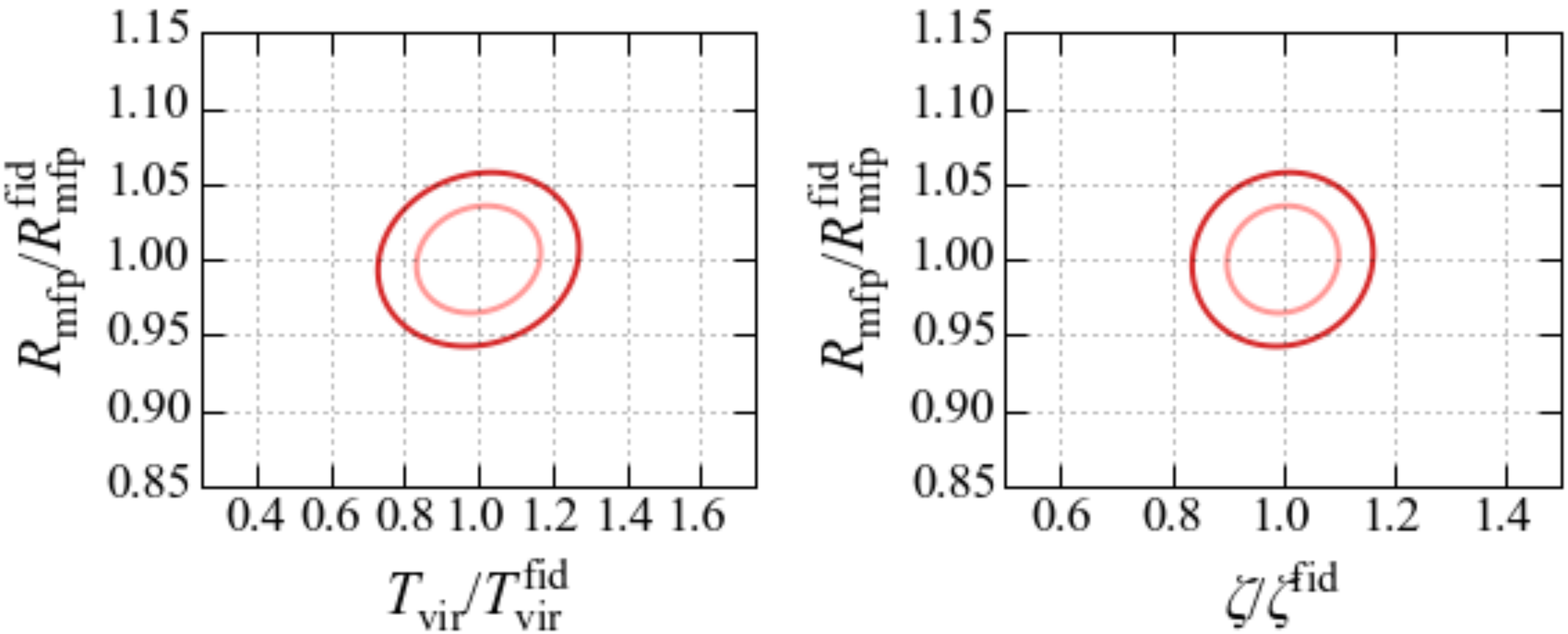
Observed Frequency (MHz)
200
150
125
100
75
Fiducial Model
PAPER
MWA
LOFAR
HERA-350
10^3
10^2
10^1
10^0
Δ^2 (mK^2)
time
6
8
10
12
14
16
18
20
Redshift

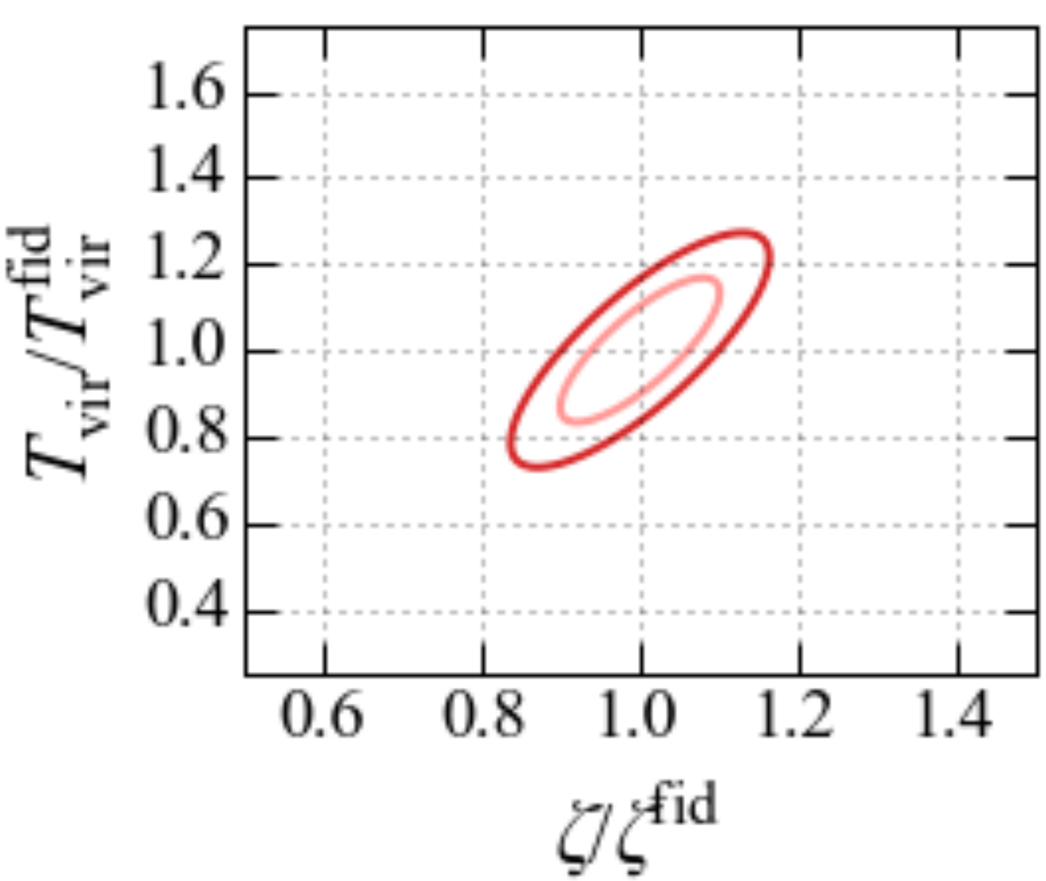
R_{mfp}: mean free path of ionizing photons



ζ: ionizing efficiency of first galaxies

T_{vir}: minimum virial temperature of first ionizing galaxies

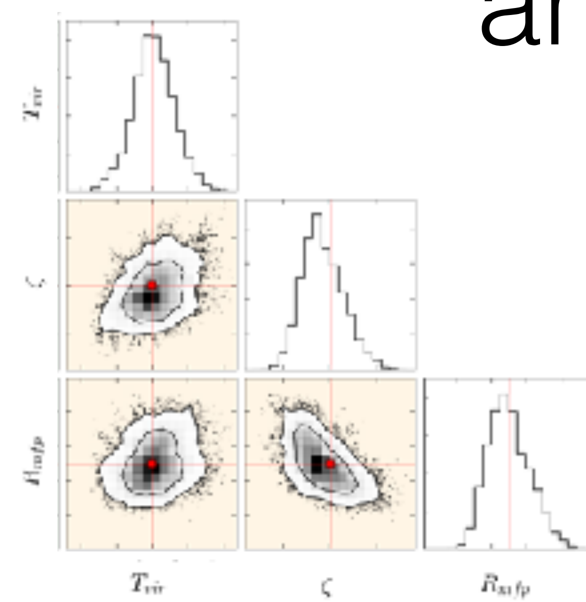


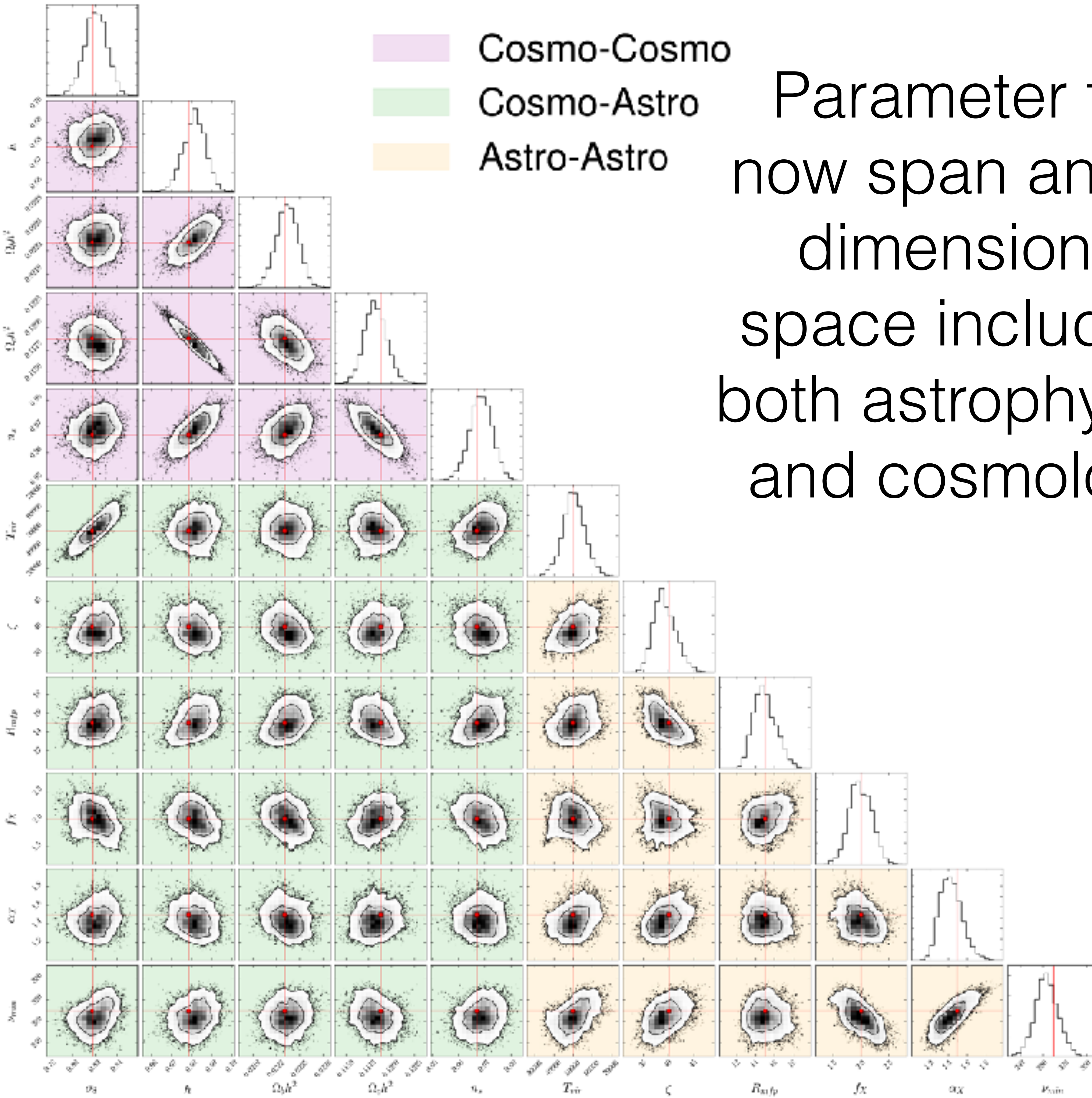


The recently commenced HERA experiment is forecasted to deliver ~5% errors on astrophysical parameters

AL & Parsons (2015b)

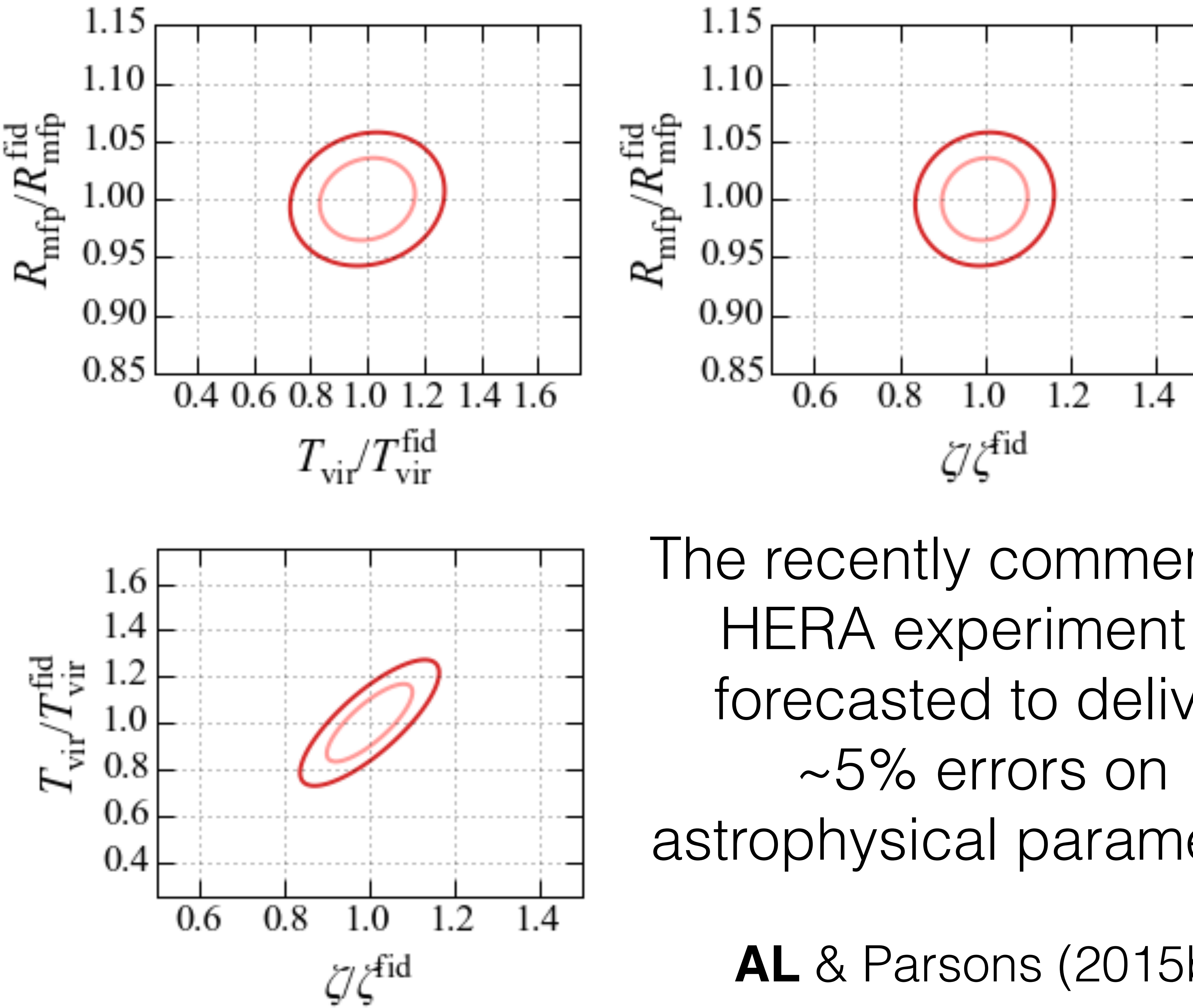
Parameter fits now span an 11-dimensional space including both astrophysics and cosmology





Parameter fits now span an 11-dimensional space including both astrophysics and cosmology

Kern, **AL** et al. (2017)



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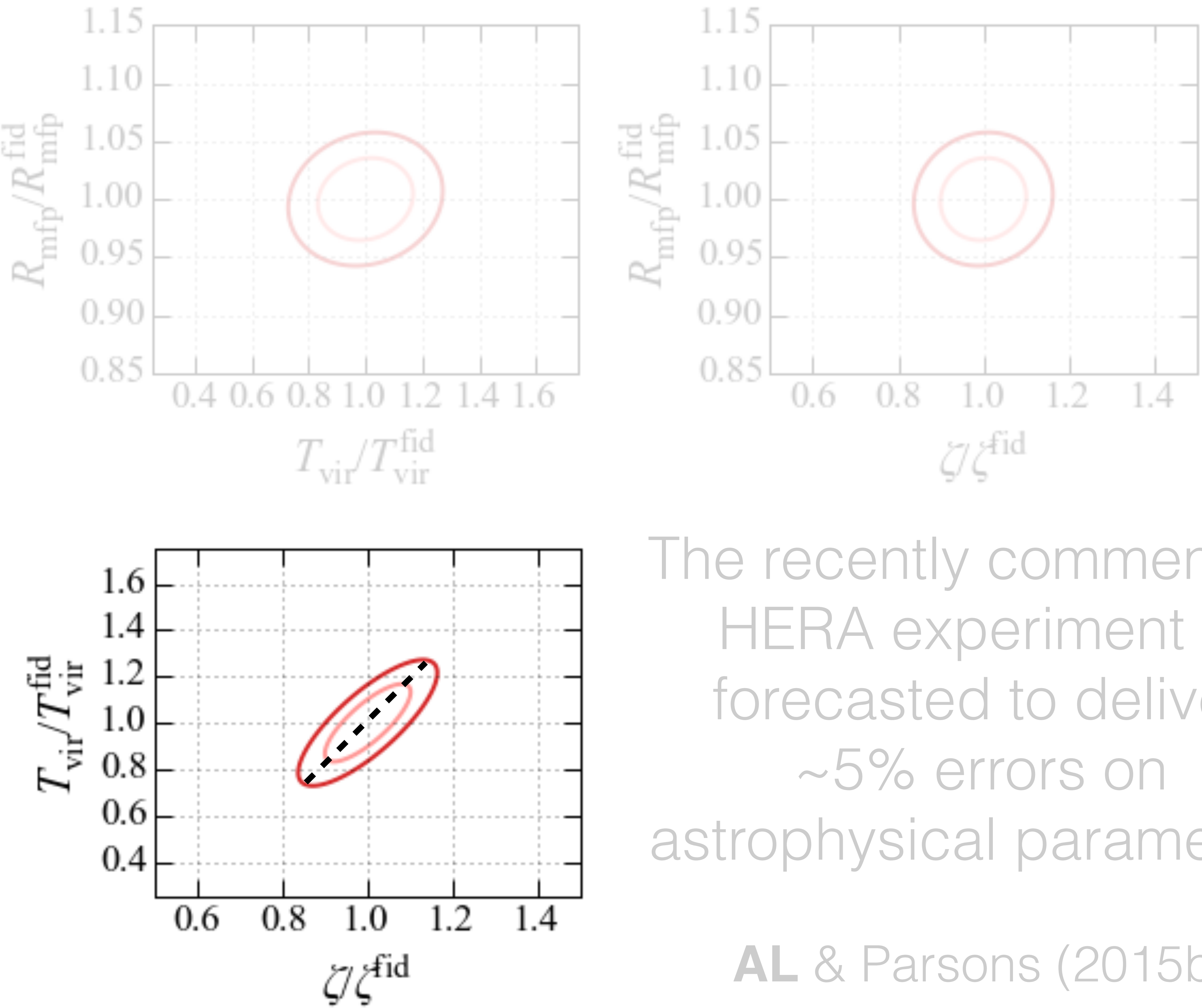
AL & Parsons (2015b)



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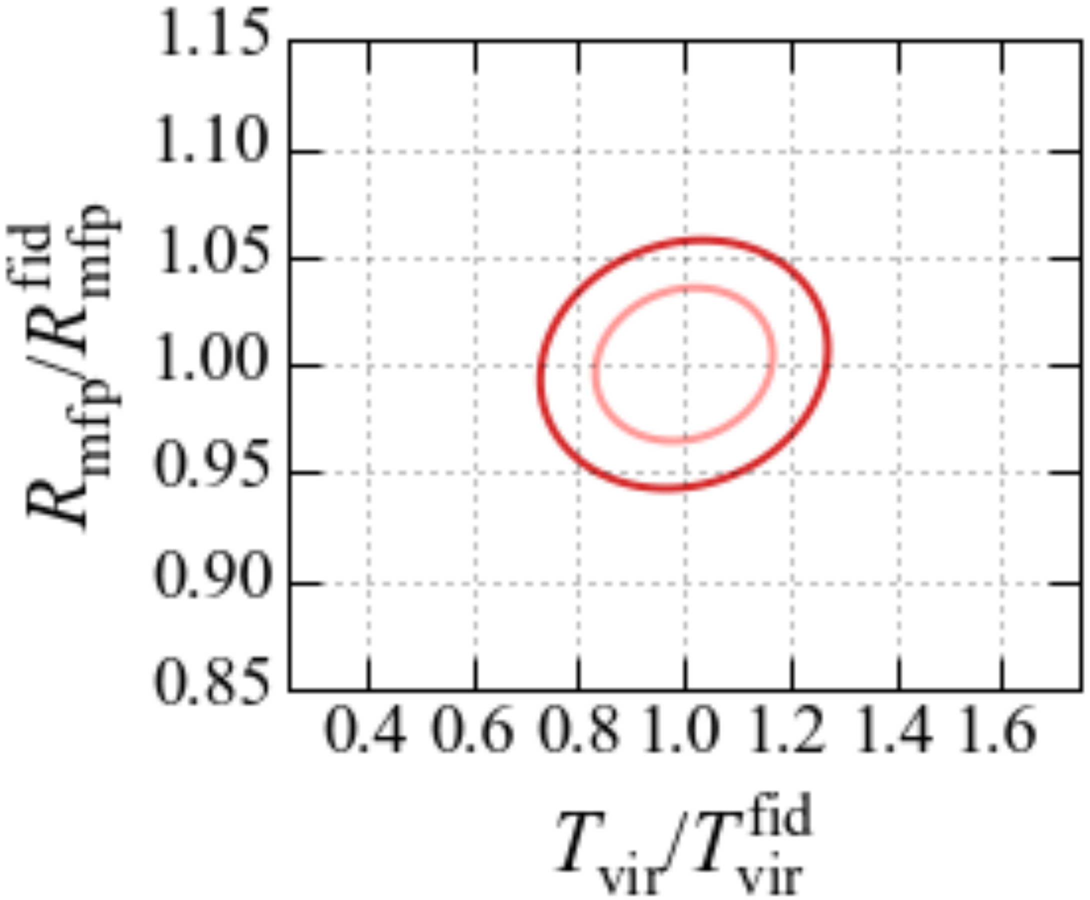

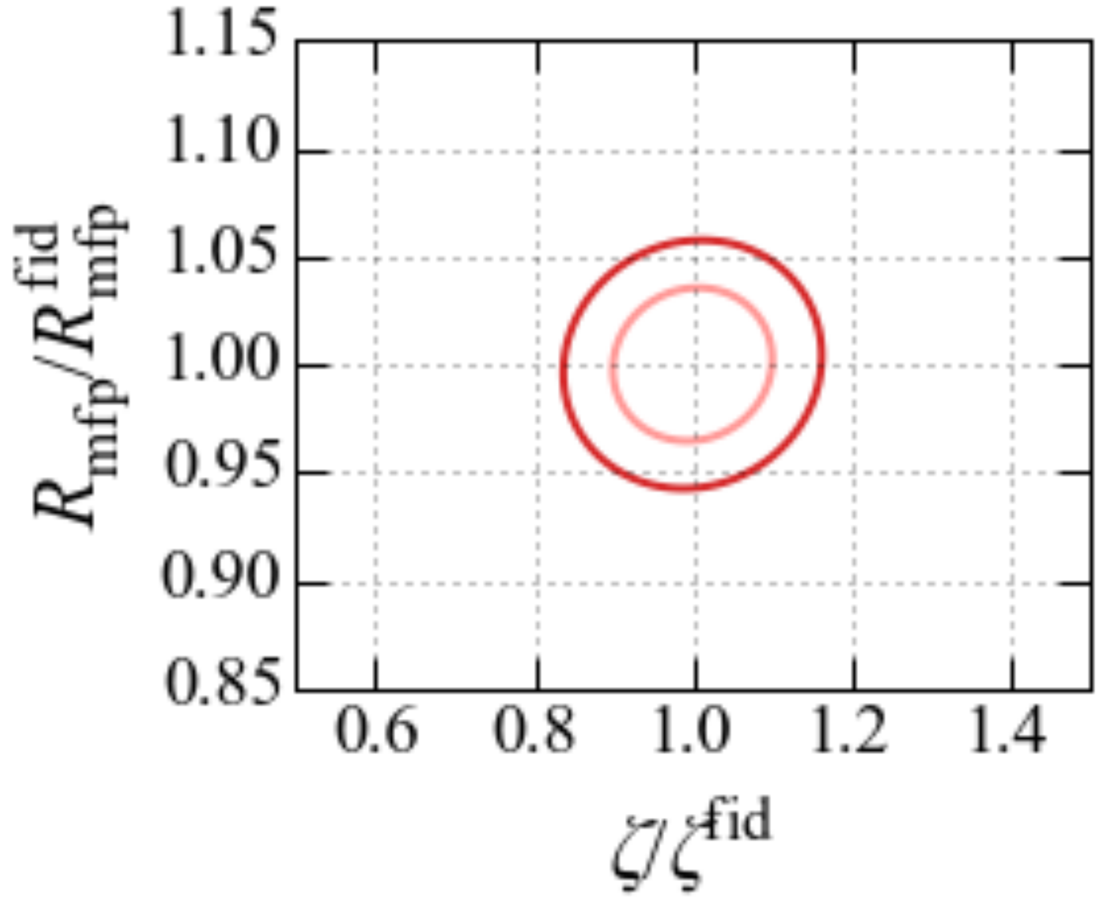

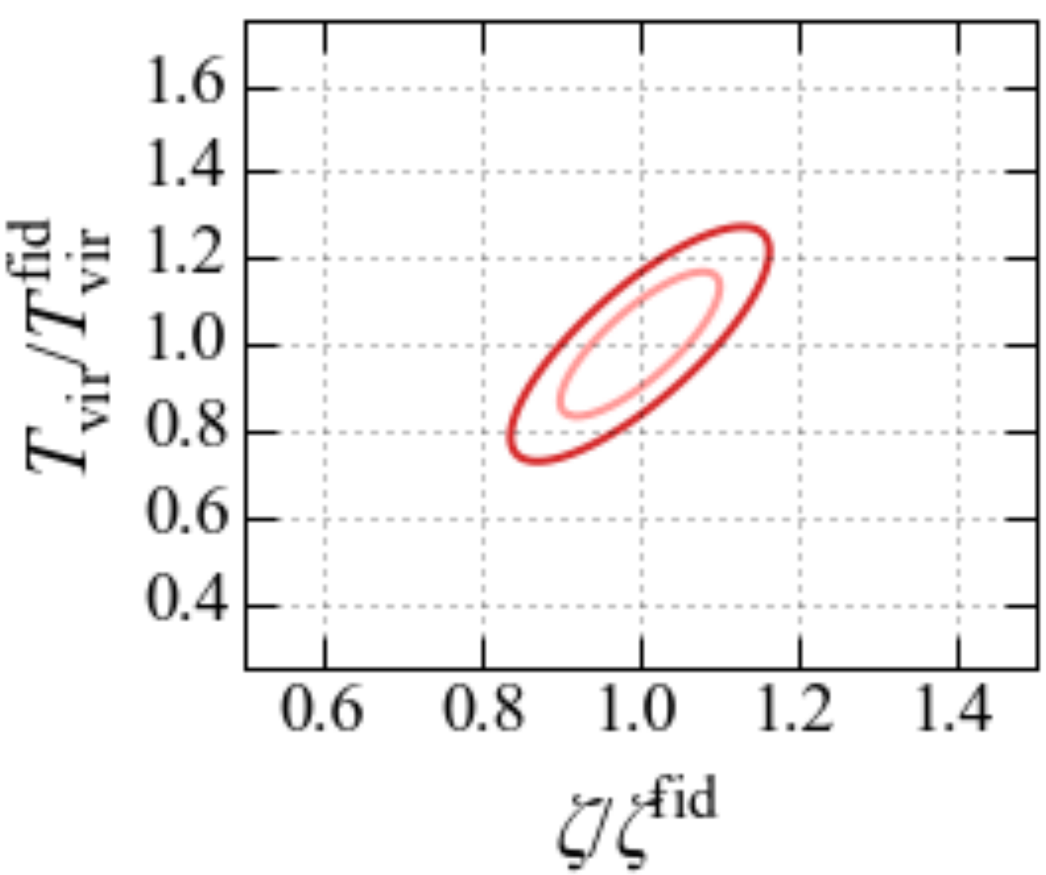

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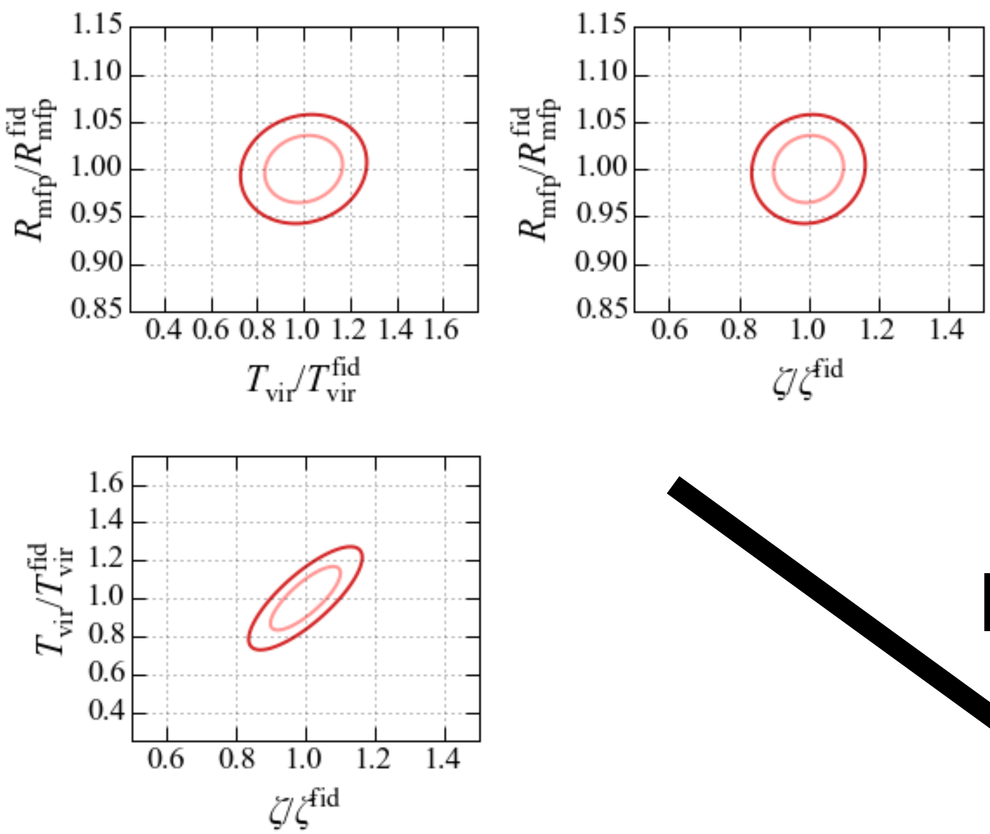
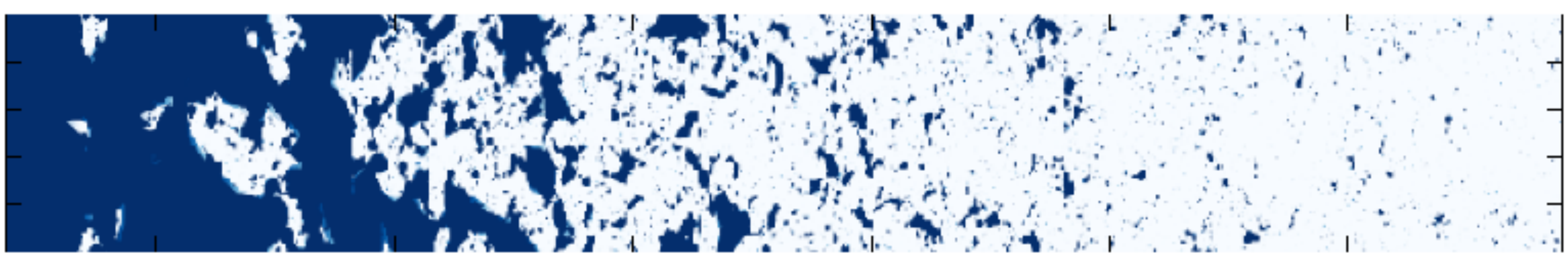
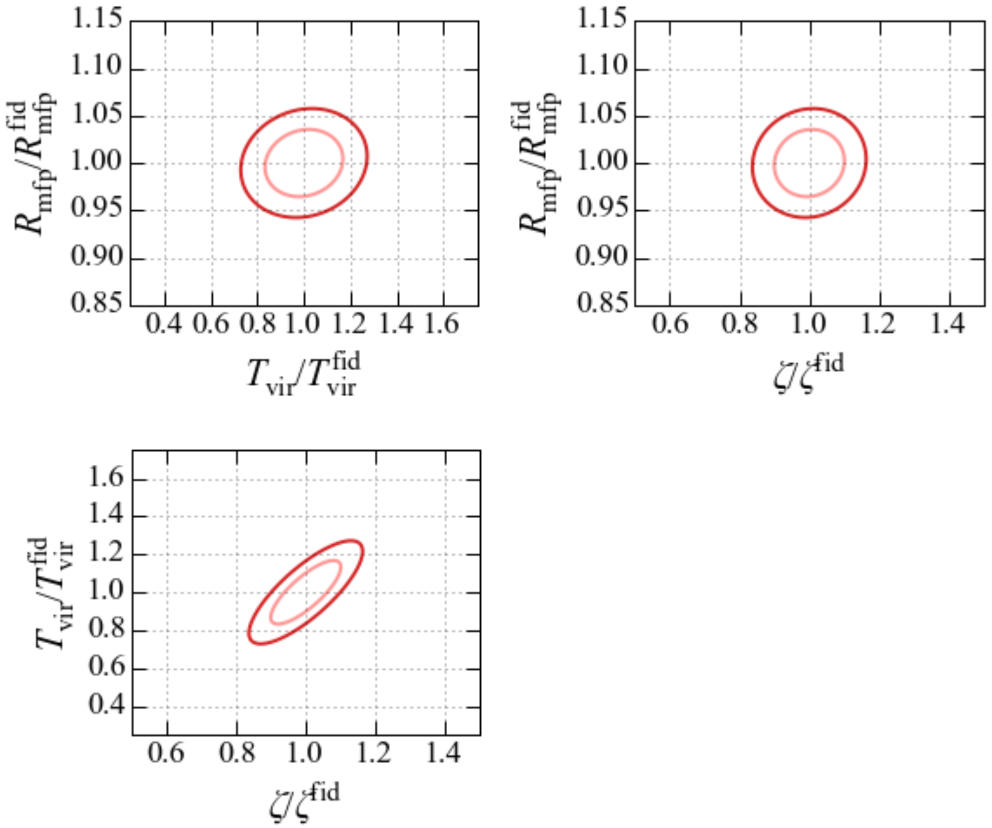

$R_{\rm mfp}/R_{\rm mfp}^{\rm fid}$
$T_{\rm vir}/T_{\rm vir}^{\rm fid}$
$\zeta/\zeta^{\rm fid}$
$R_{\rm mfp}/R_{\rm mfp}^{\rm fid}$
$T_{\rm vir}/T_{\rm vir}^{\rm fid}$
$\zeta/\zeta^{\rm fid}$

model



time



$R_{\mathrm{mfp}}/R_{\mathrm{mfp}}^{\mathrm{fid}}$
$T_{\mathrm{vir}}/T_{\mathrm{vir}}^{\mathrm{fid}}$
$\zeta/\zeta^{\mathrm{fid}}$
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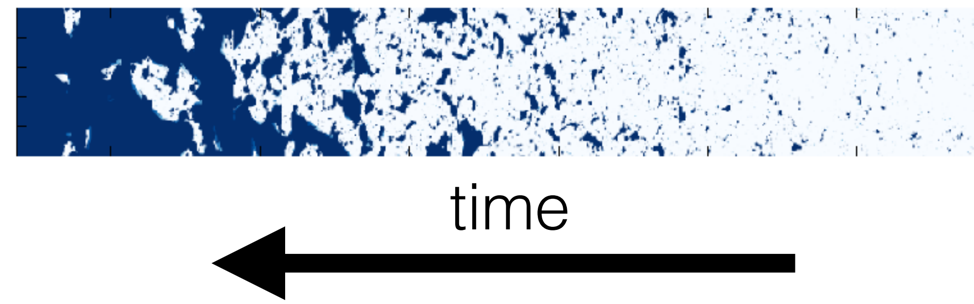
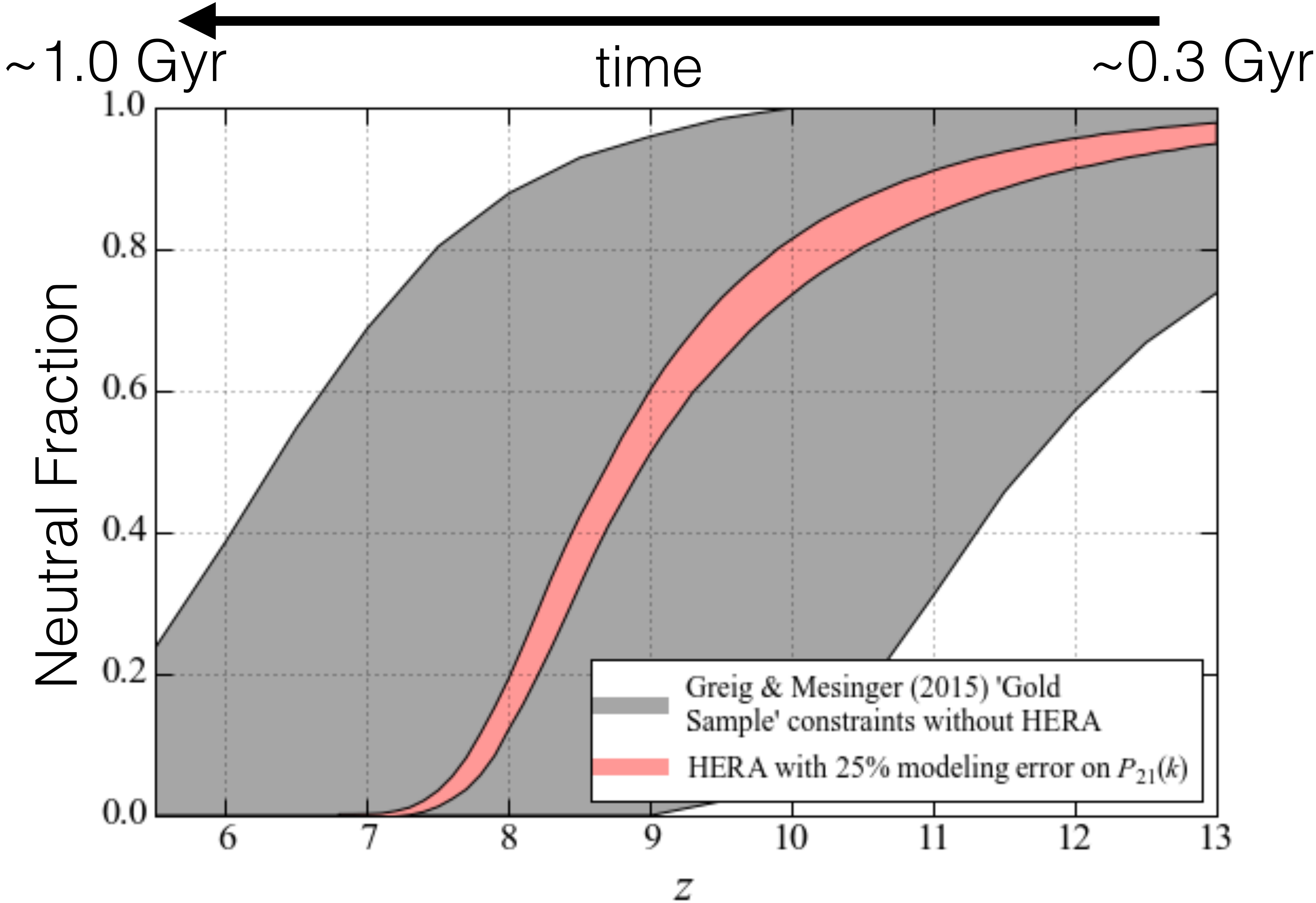


time



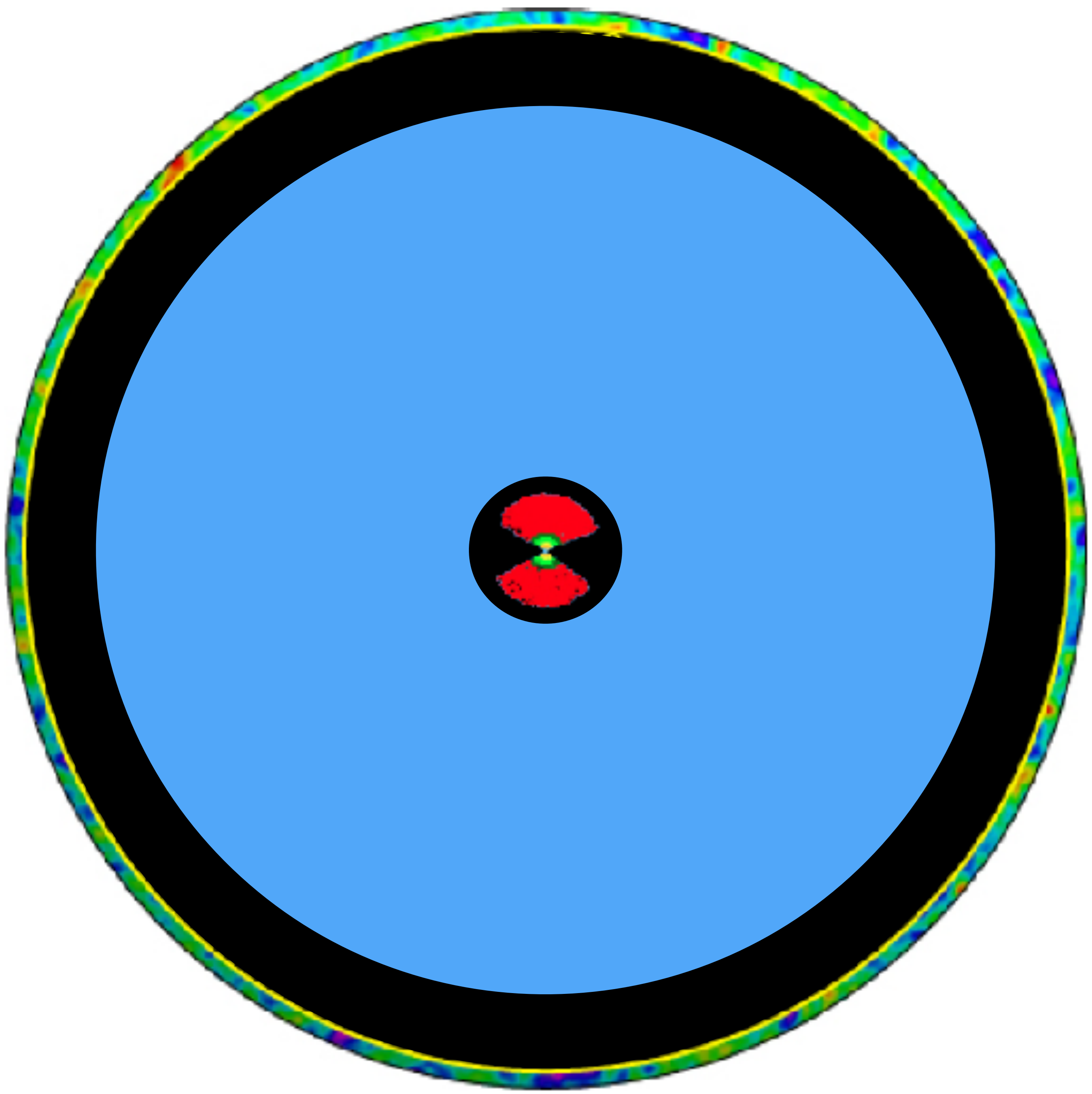
AL & Parsons (2015)

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?

A first step towards cosmological parameters?

Futuristic 21cm experiments may function as large scale surveys



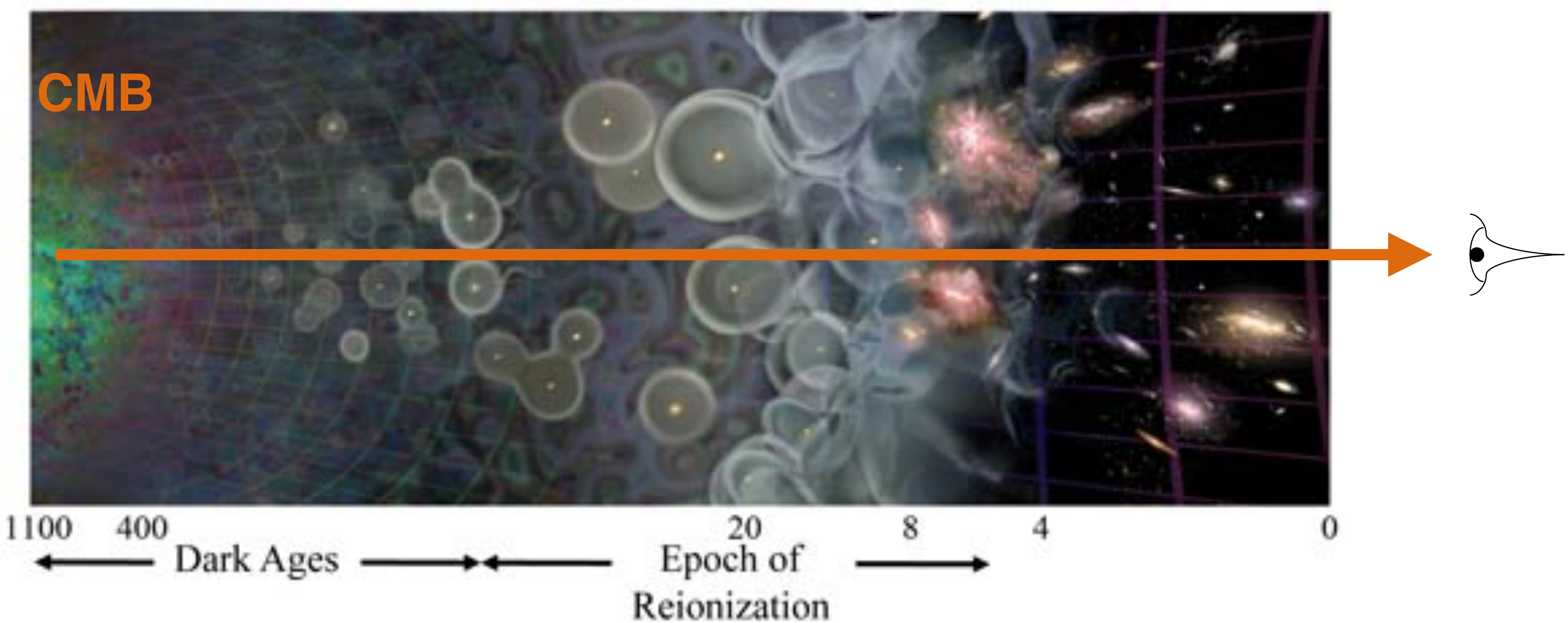
$$\Delta\Omega_k = 0.0002$$

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

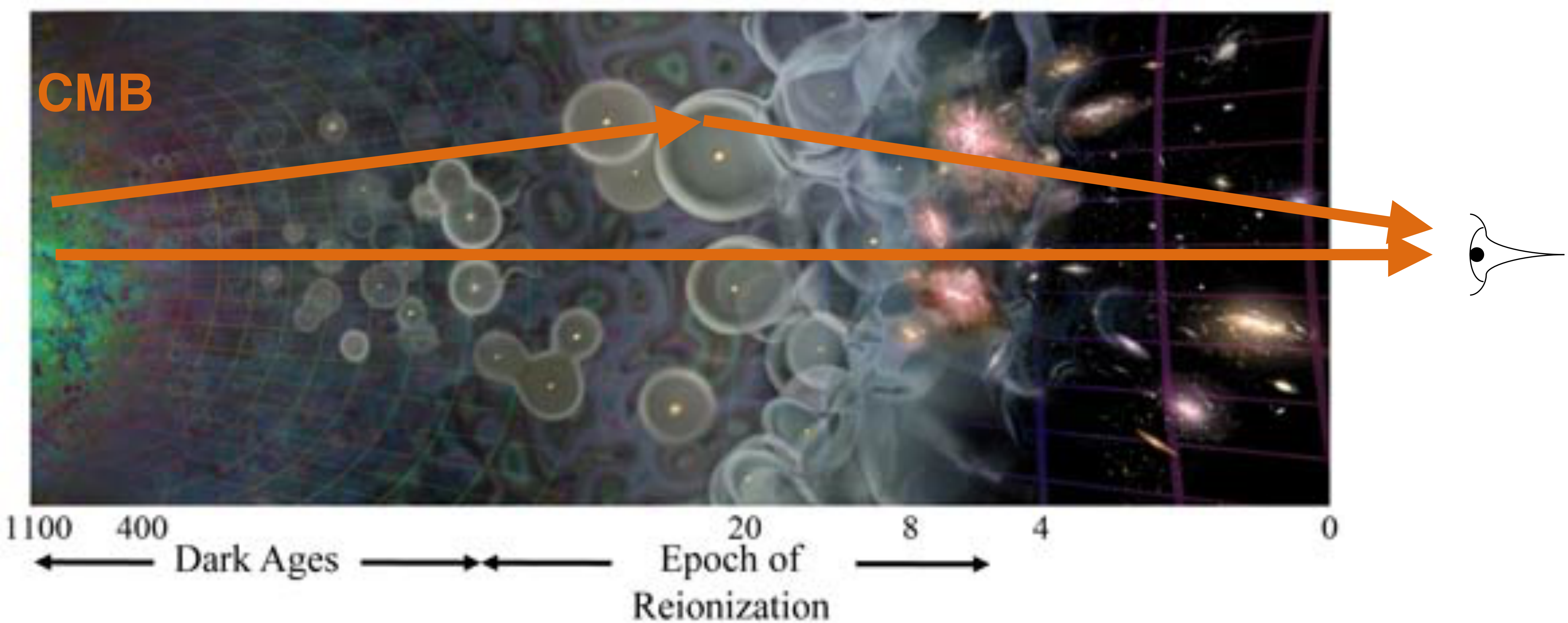
Mao et al. 2008

For now…better cosmology through better astrophysics!

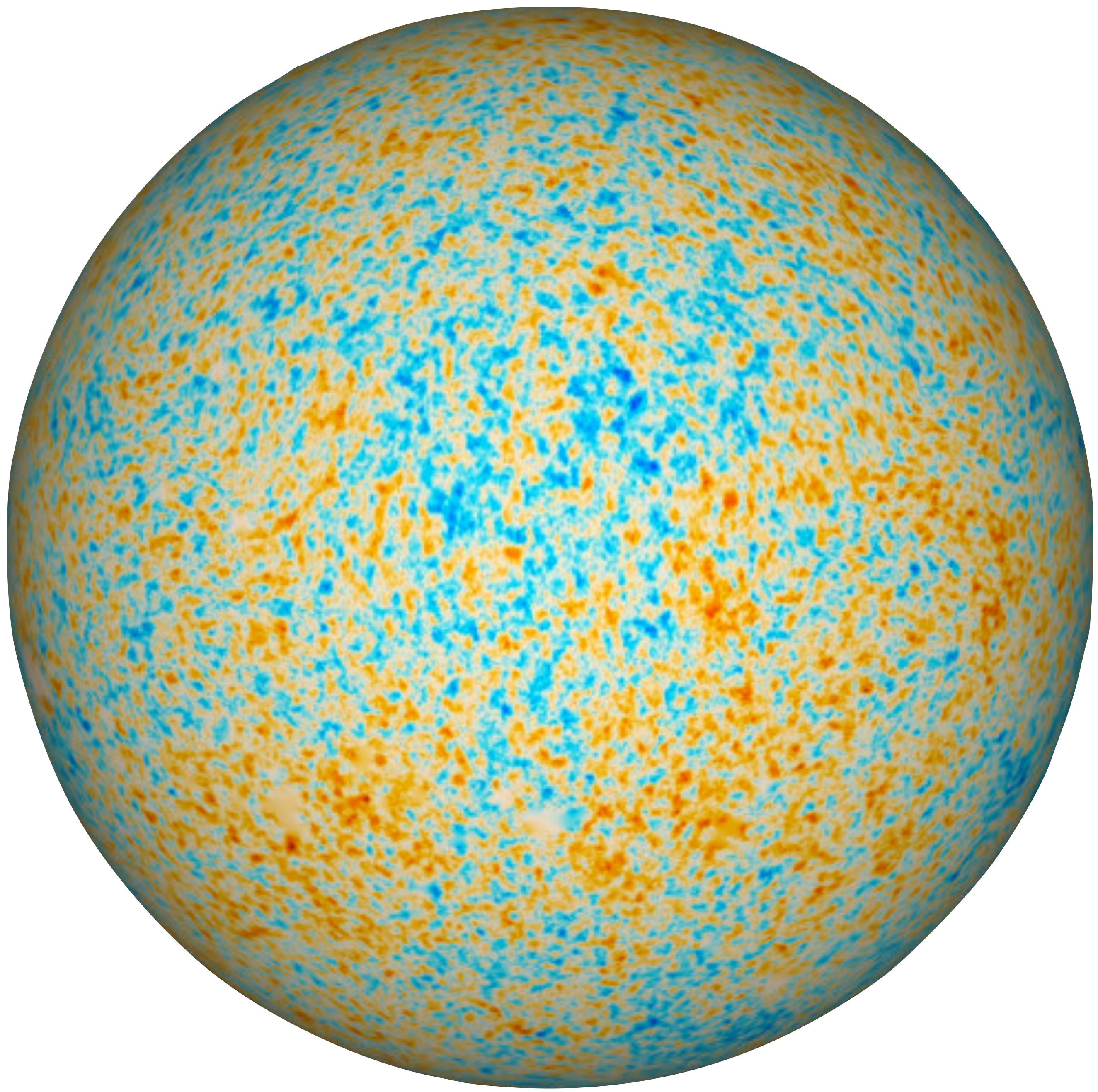
Reionization is a nuisance for CMB measurements

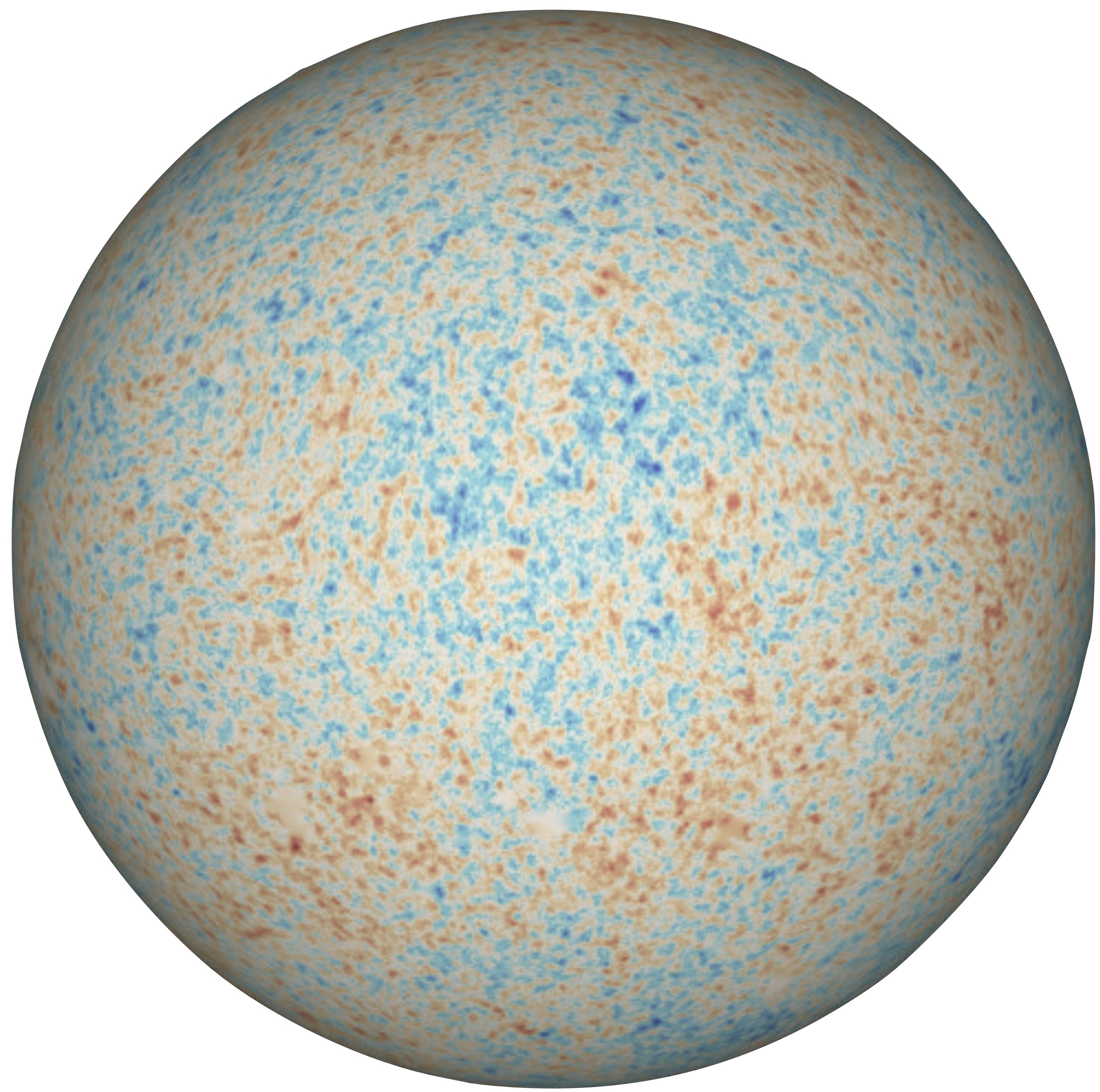


Reionization is a nuisance for CMB measurements



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



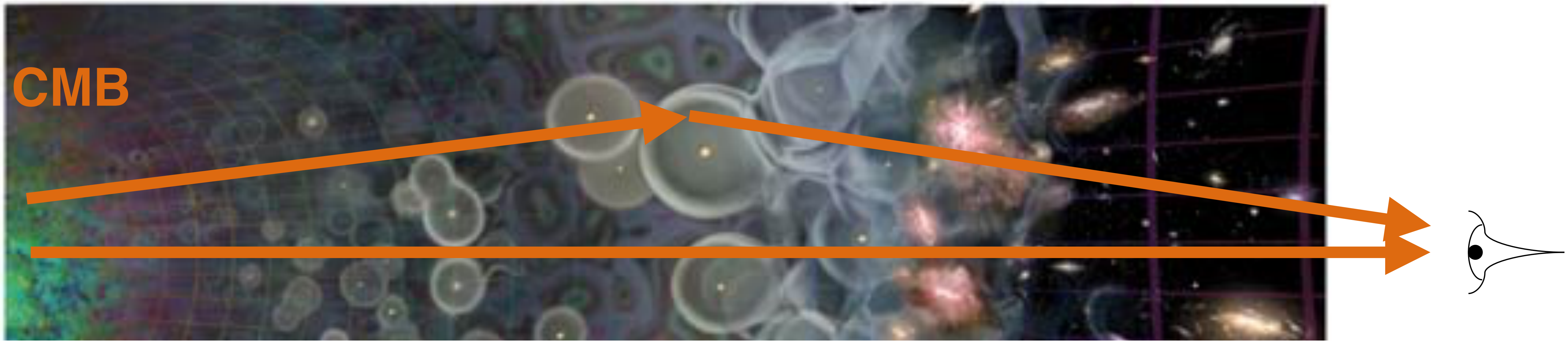


Scattering → Reduces amplitude of density fluctuations

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

VS

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



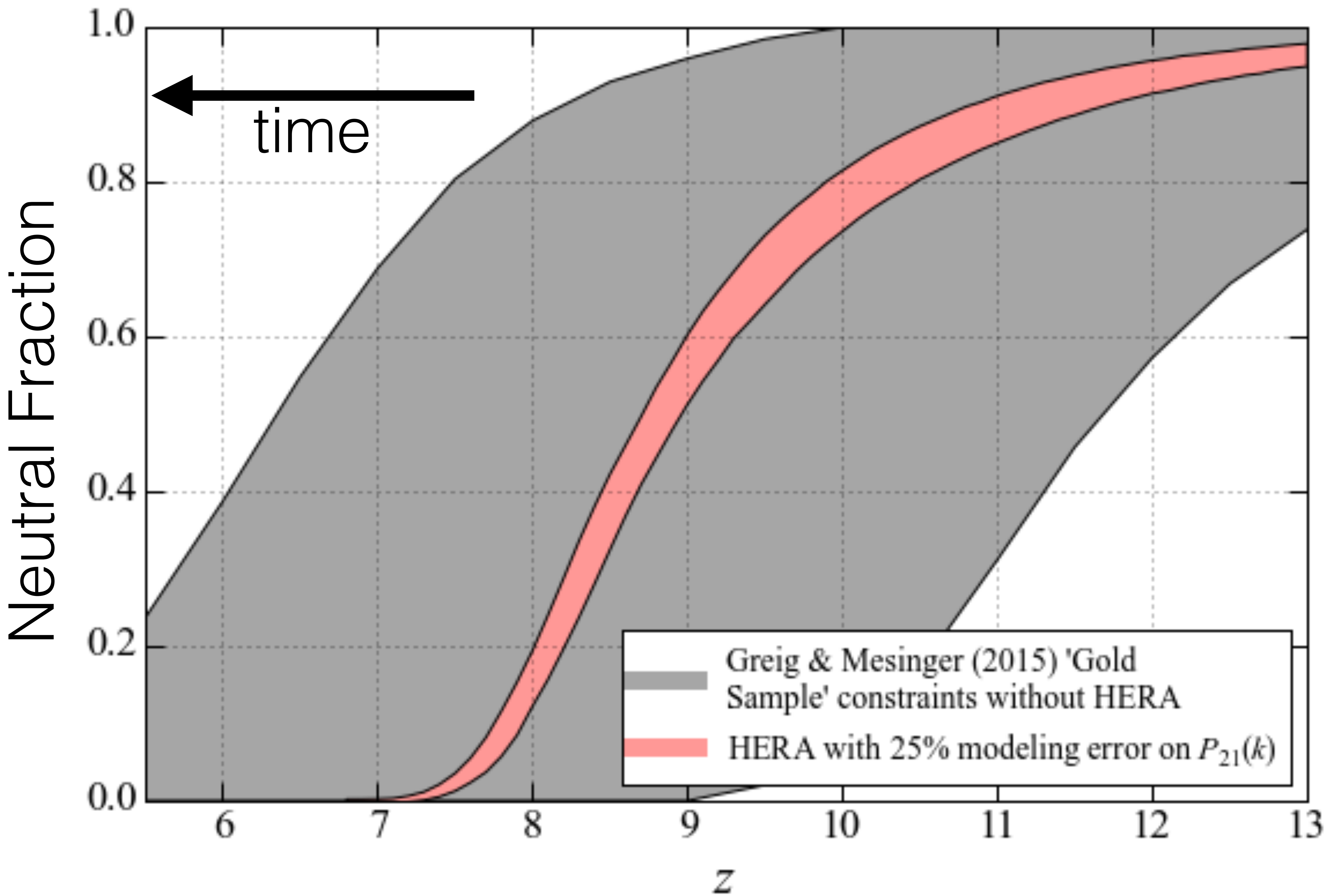
- Early reionization (higher optical depth)
  + Large primordial fluctuations A_s

vs

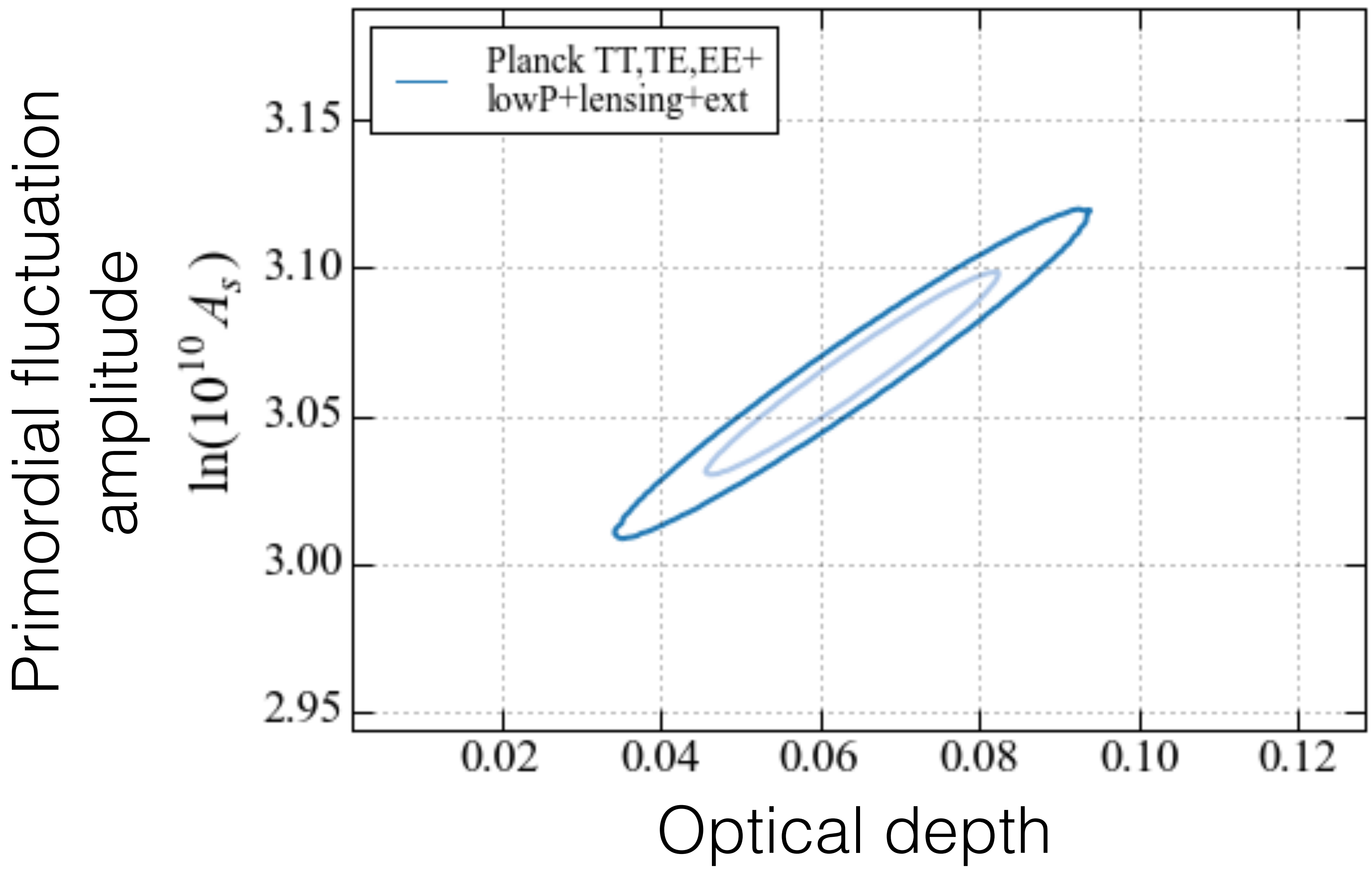
- Late reionization (lower optical depth)
  + Small primordial fluctuations A_s

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



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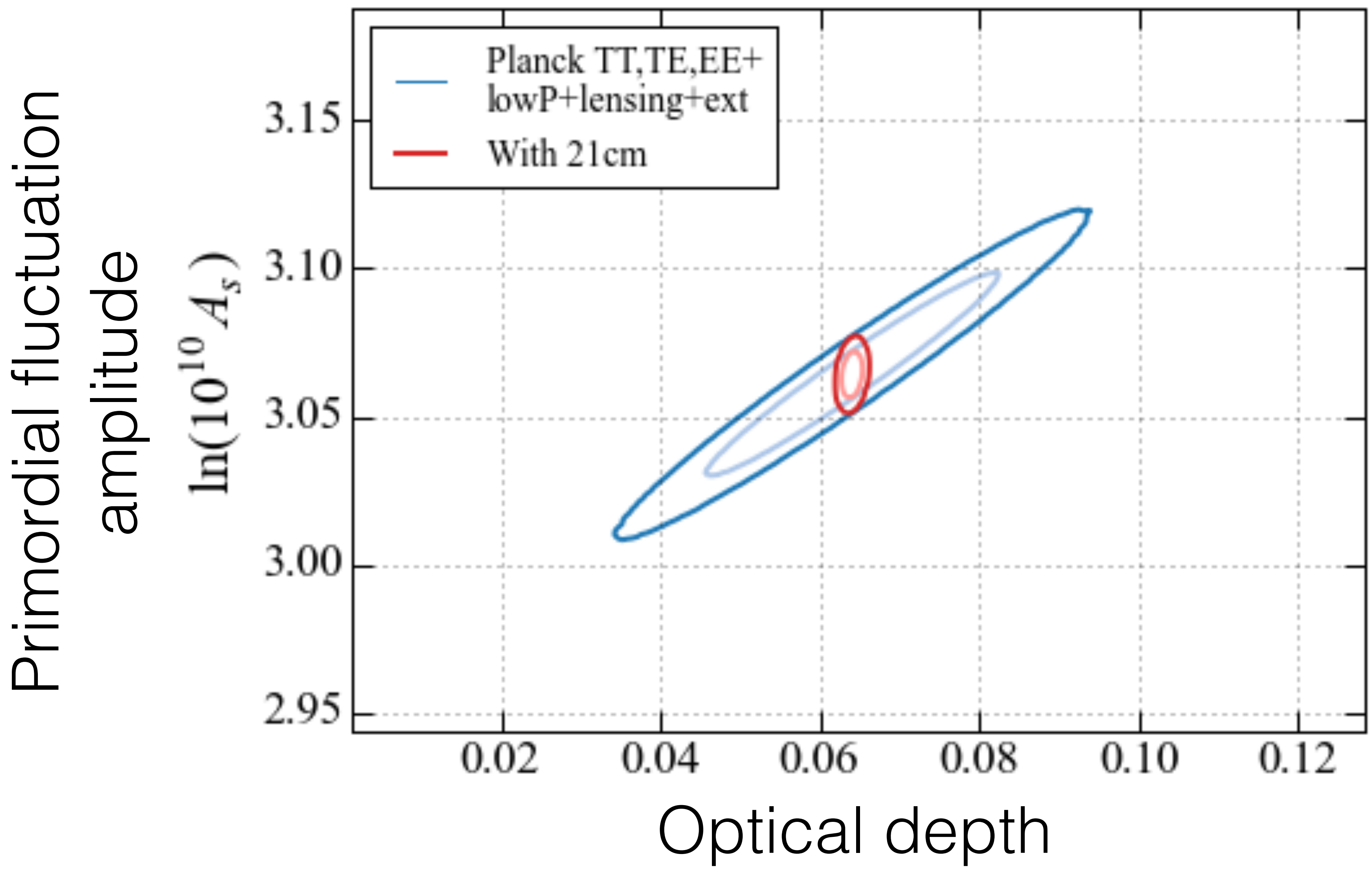

AL et al. (2015a)

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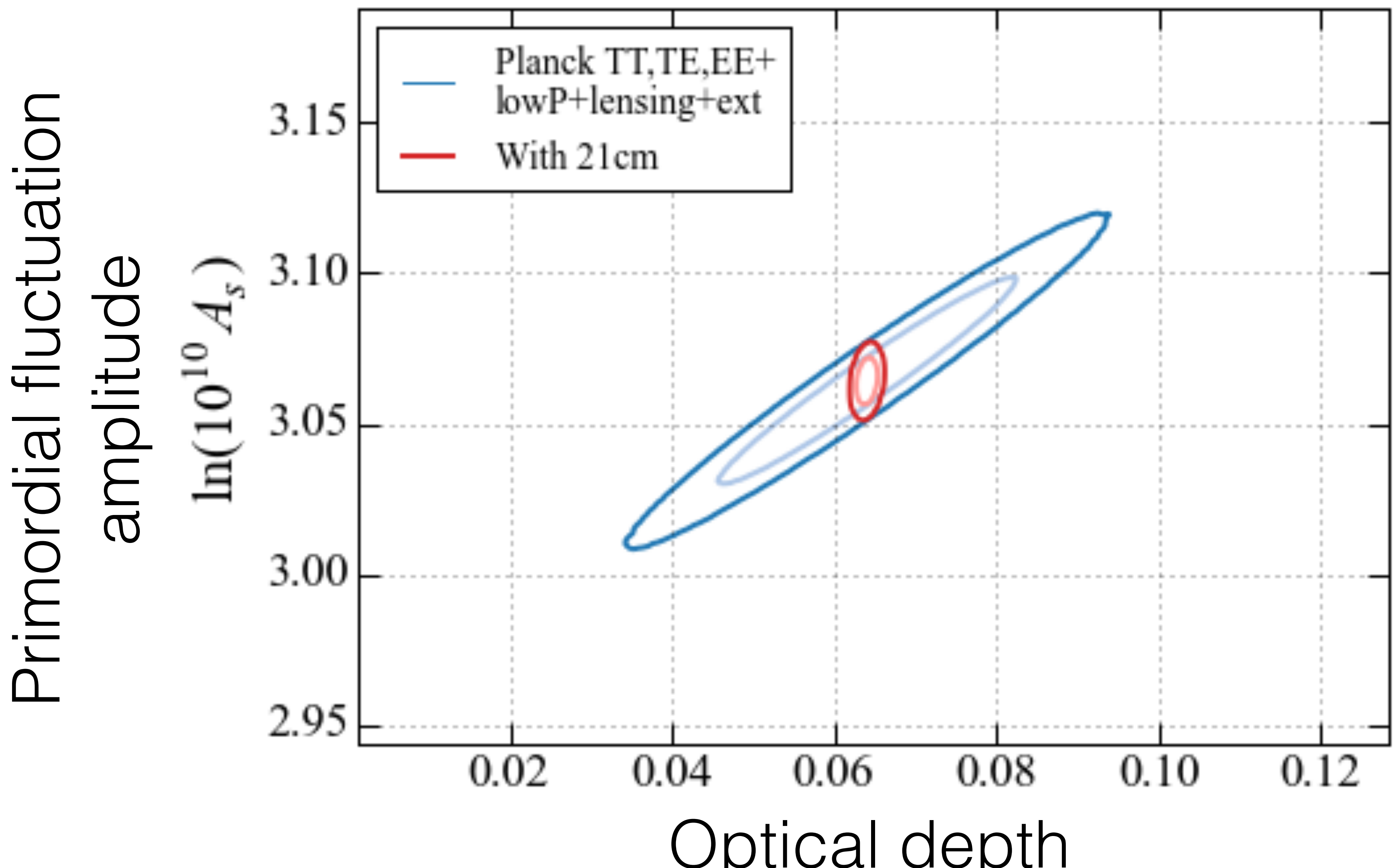
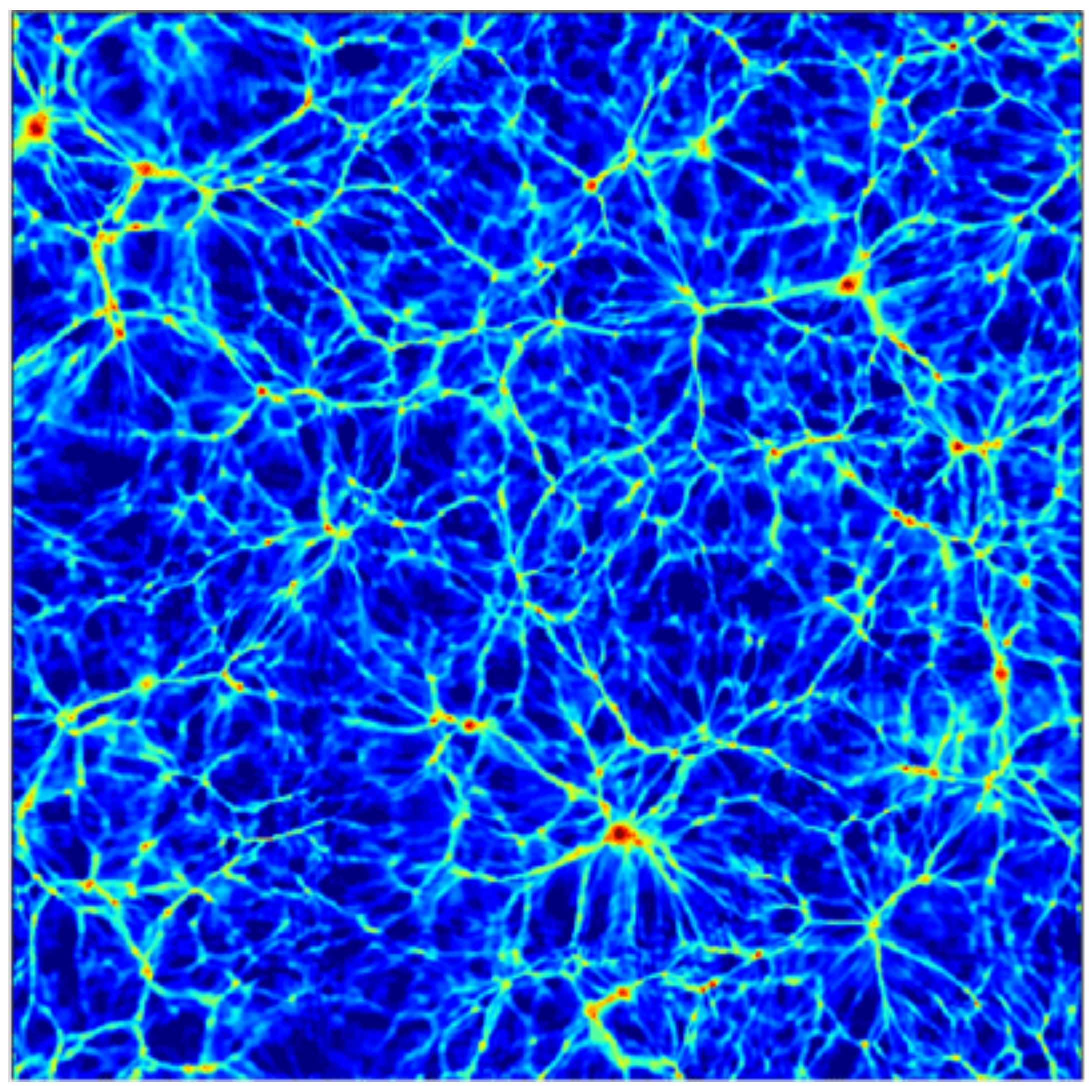


AL et al. (2015a)

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

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

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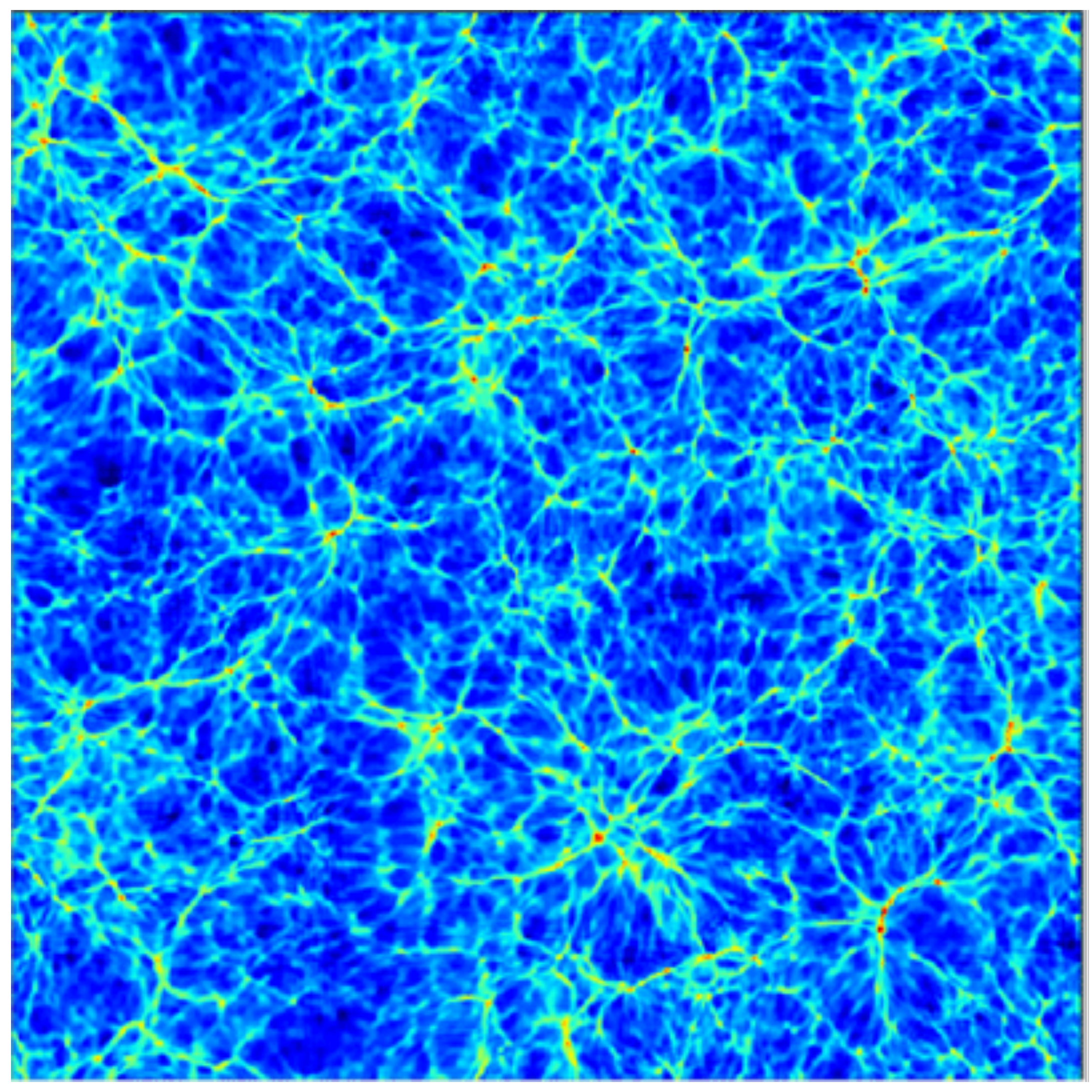

With neutrinos

Agarwal & Feldman 2011

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

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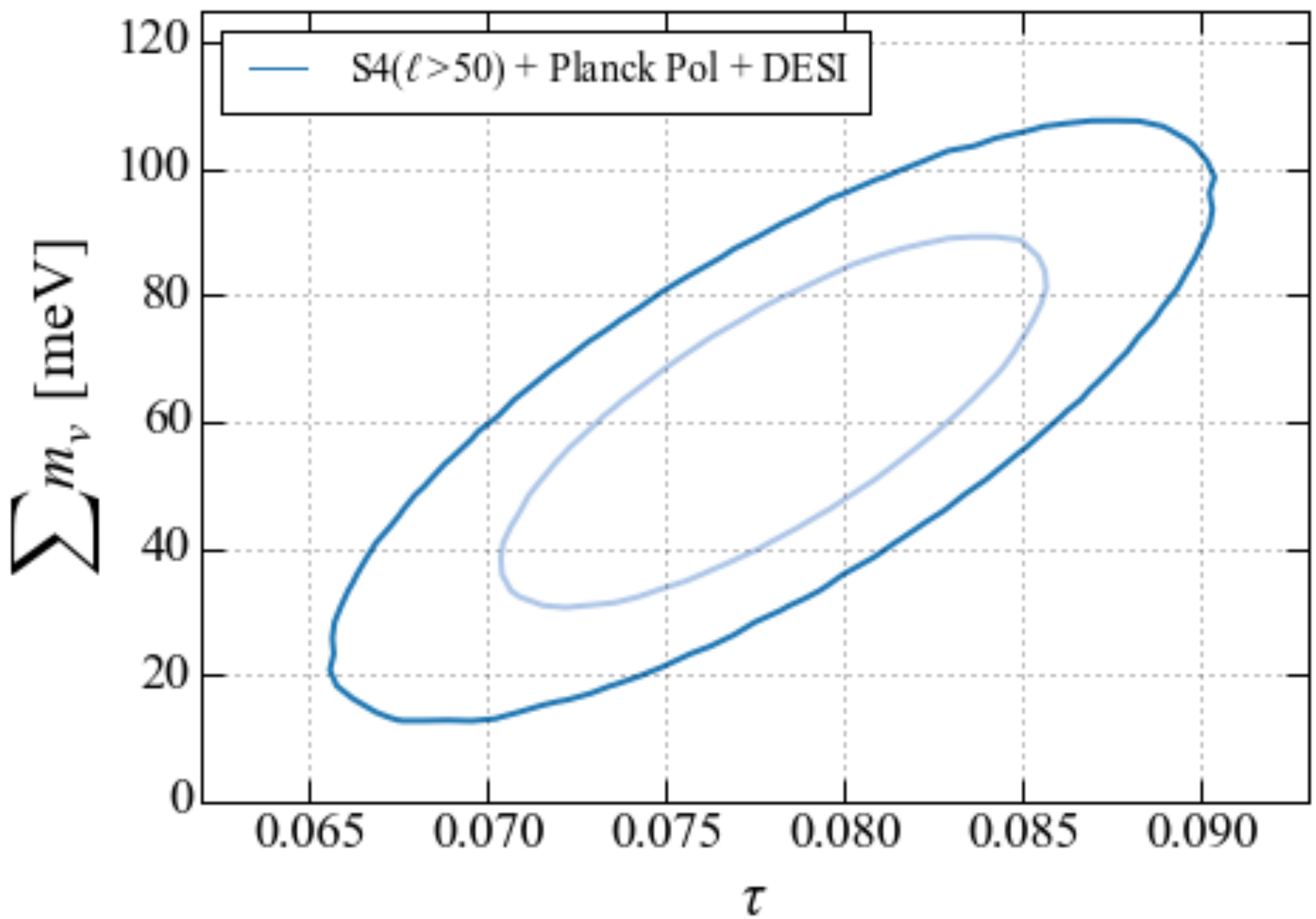

Allison et al. (2015)

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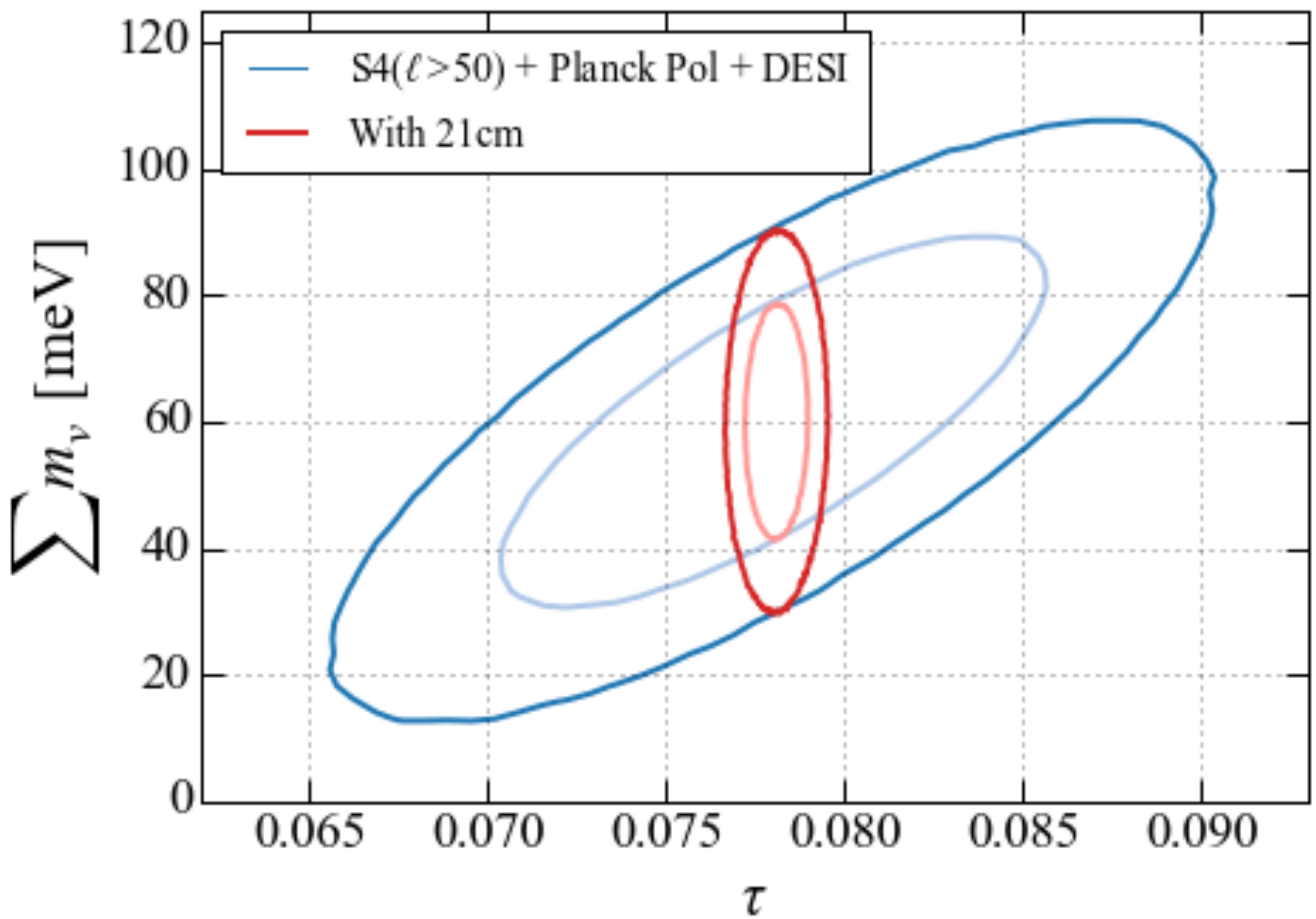


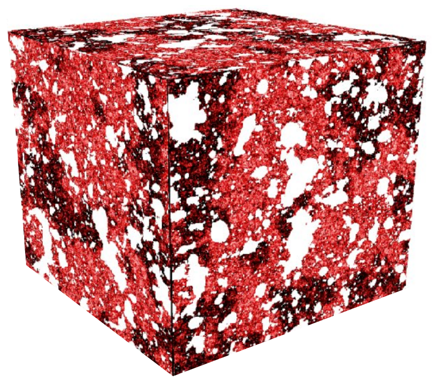
Allison et al. (2015)

AL et al. (2015a)

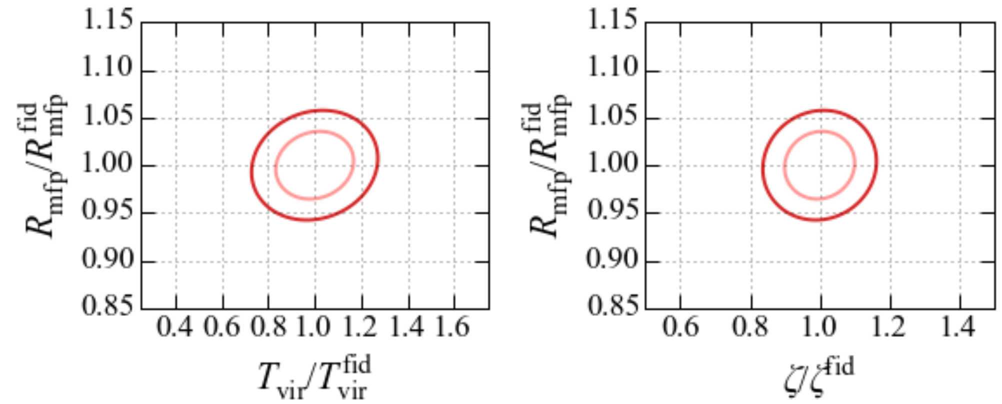
$$\sum m_\nu = 60 \pm 19\,\mathrm{meV} \longrightarrow \pm 12\,\mathrm{meV}$$

Isn’t this awfully model-dependent?

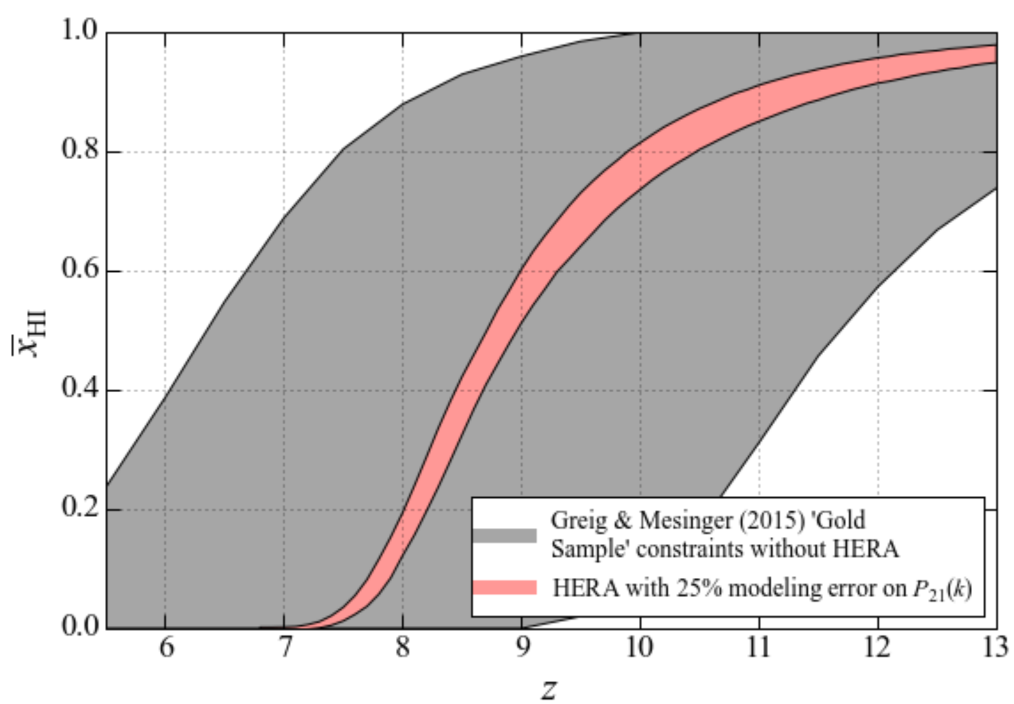
Alternate signal extraction algorithms may also alleviate model-dependence



Observations



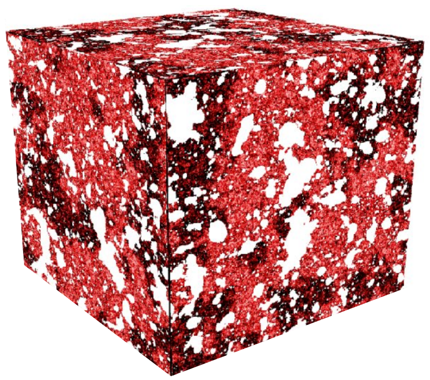
Model parameters



Theory prediction

τ

Alternate signal extraction algorithms may also alleviate model-dependence

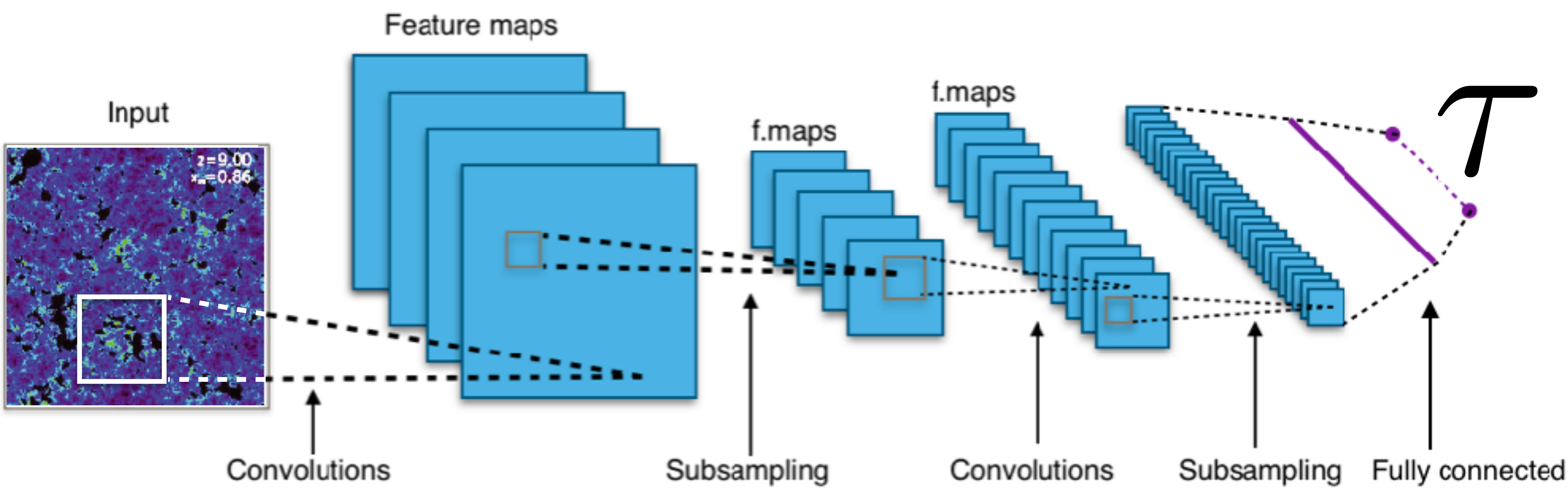


Observations

Convolutional
Neural Network

τ

Convolutional neural nets process data through a series of convolutions, thresholdings, and averages



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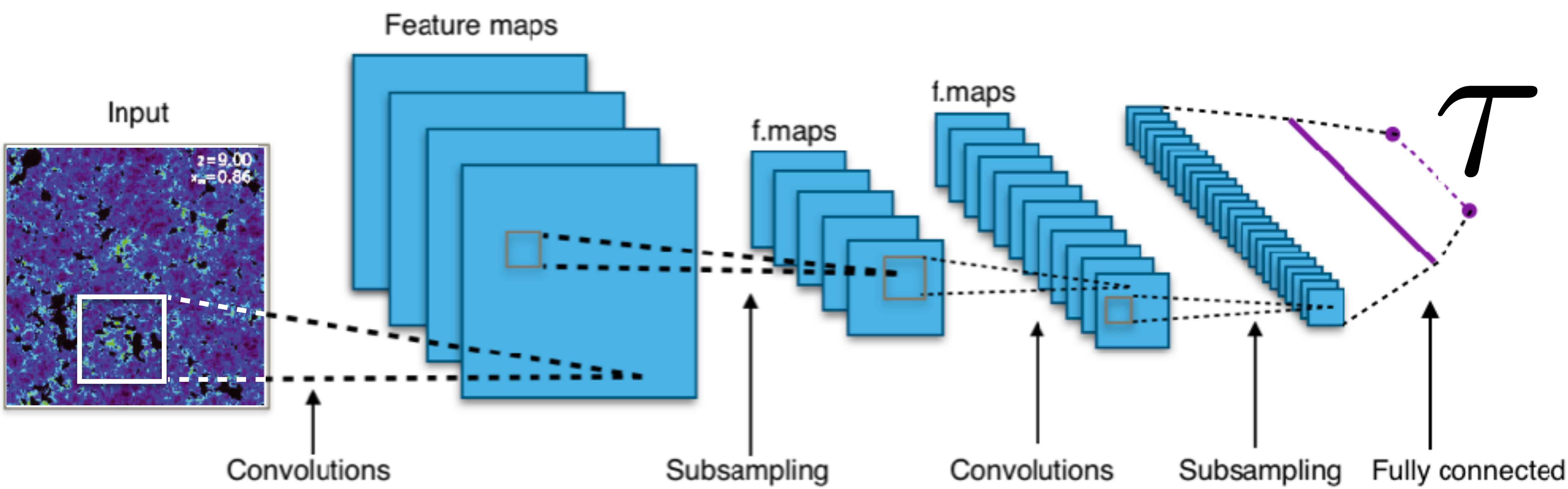
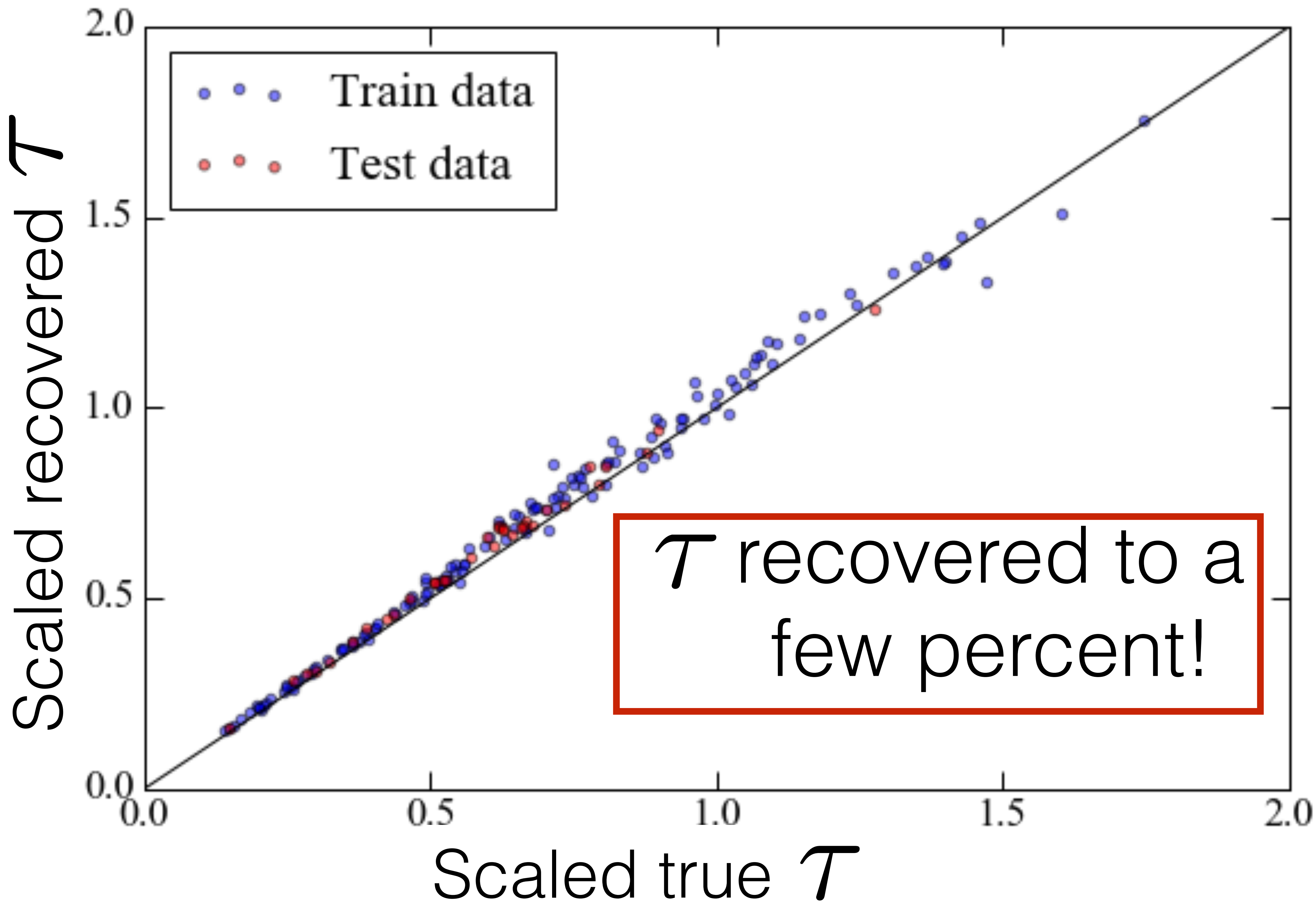


Repeated exposure to training data allows the optimization of the convolution kernels for extracting parameters of interest

Initial results suggest that CNNs can extract the optical depth



AL et al., in prep.

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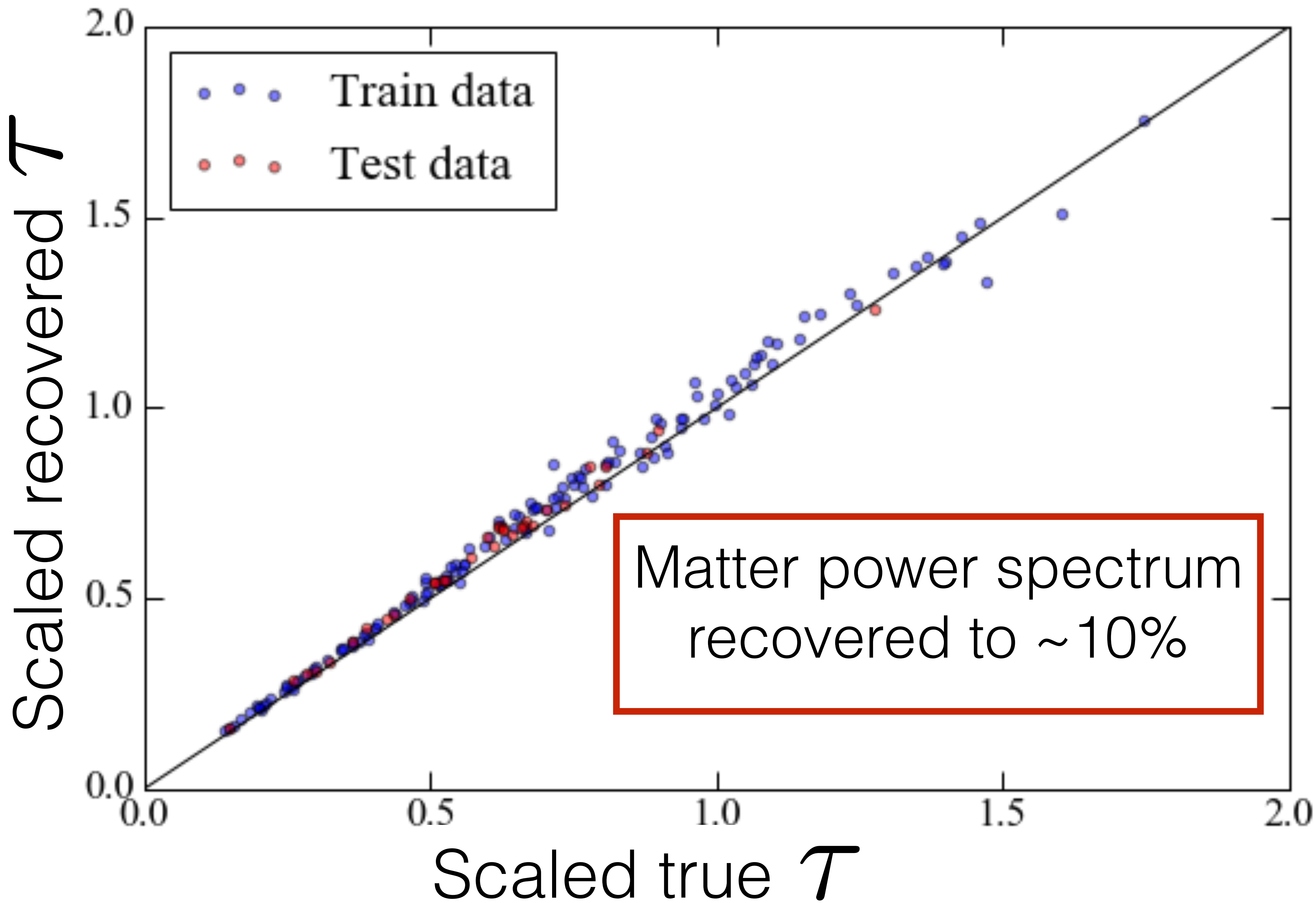

AL et al., in prep.

Exciting times are ahead!

- We're getting close to detecting the 21cm signal—close enough to start improving our understanding of reionization.
- Foregrounds and sensitivity are the main challenges of 21cm cosmology.
- Two frontiers in field:
    - **Analysis** efforts are advancing, with progress on foreground models and machine learning.
    - **Observational** efforts are advancing, with HERA poised to deliver qualitatively new constraints on astrophysics and cosmology.