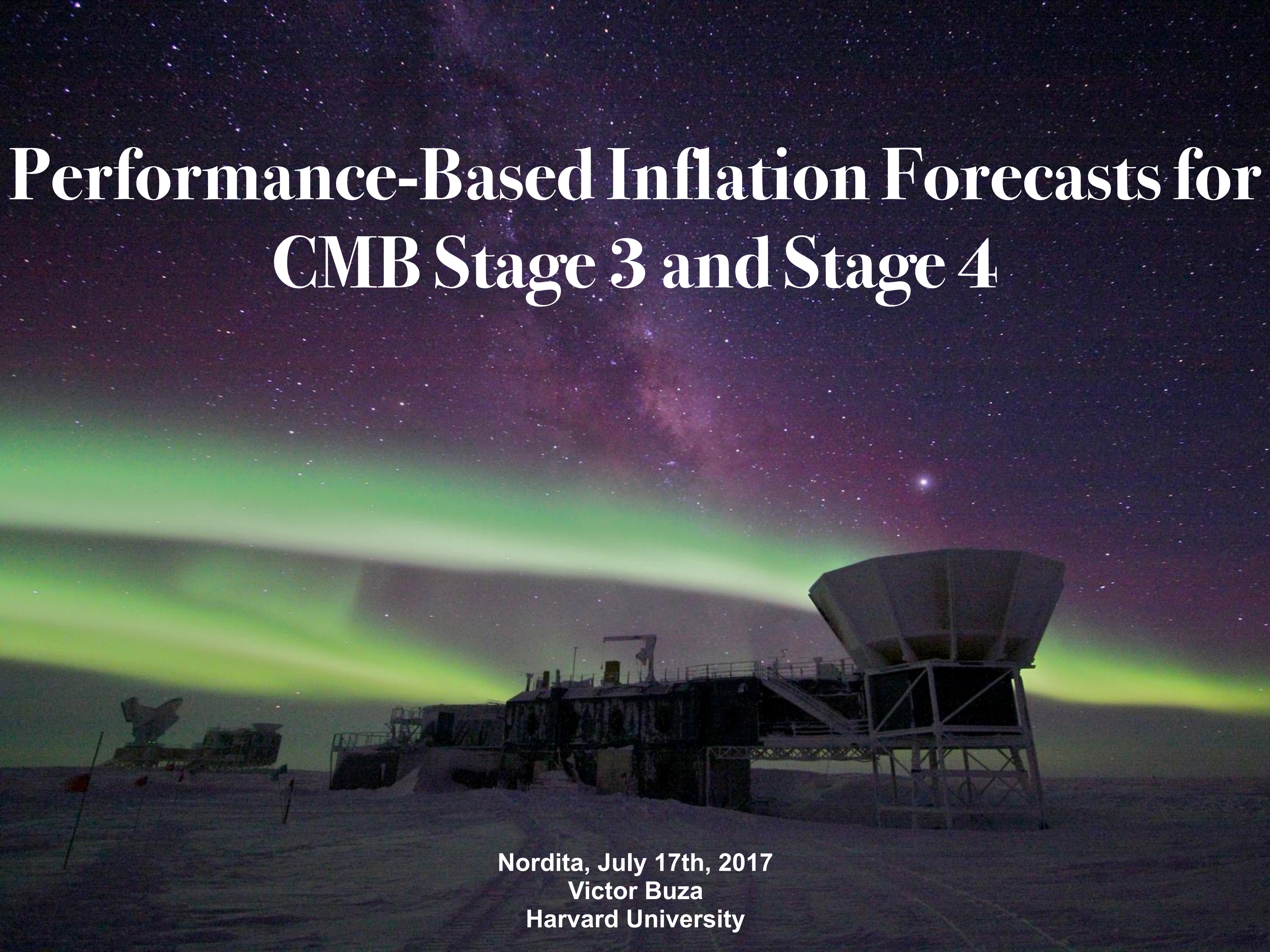
Performance-Based Inflation Forecasts for CMB Stage 3 and Stage 4



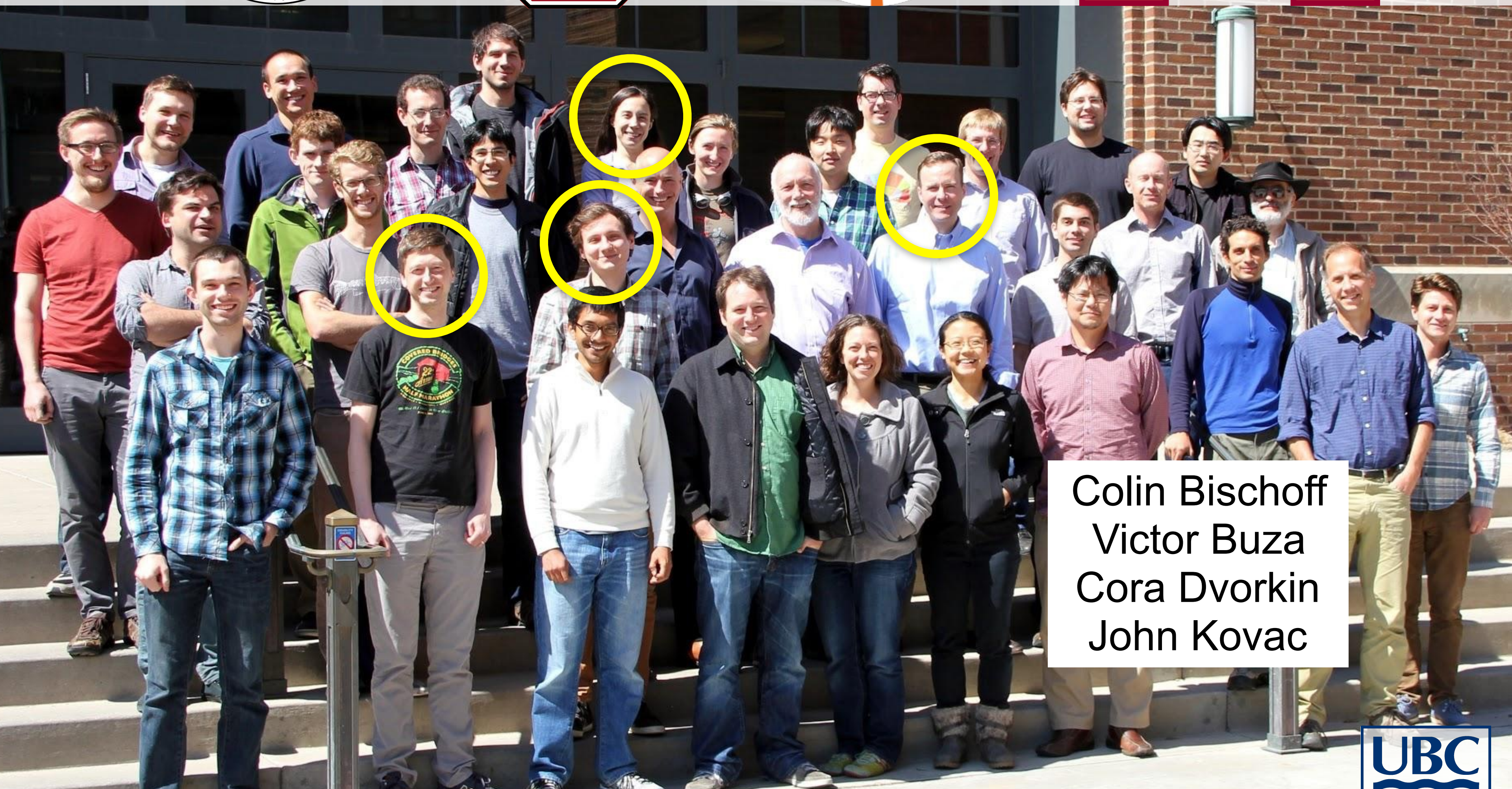
Nordita, July 17th, 2017
Victor Buza
Harvard University

Outline

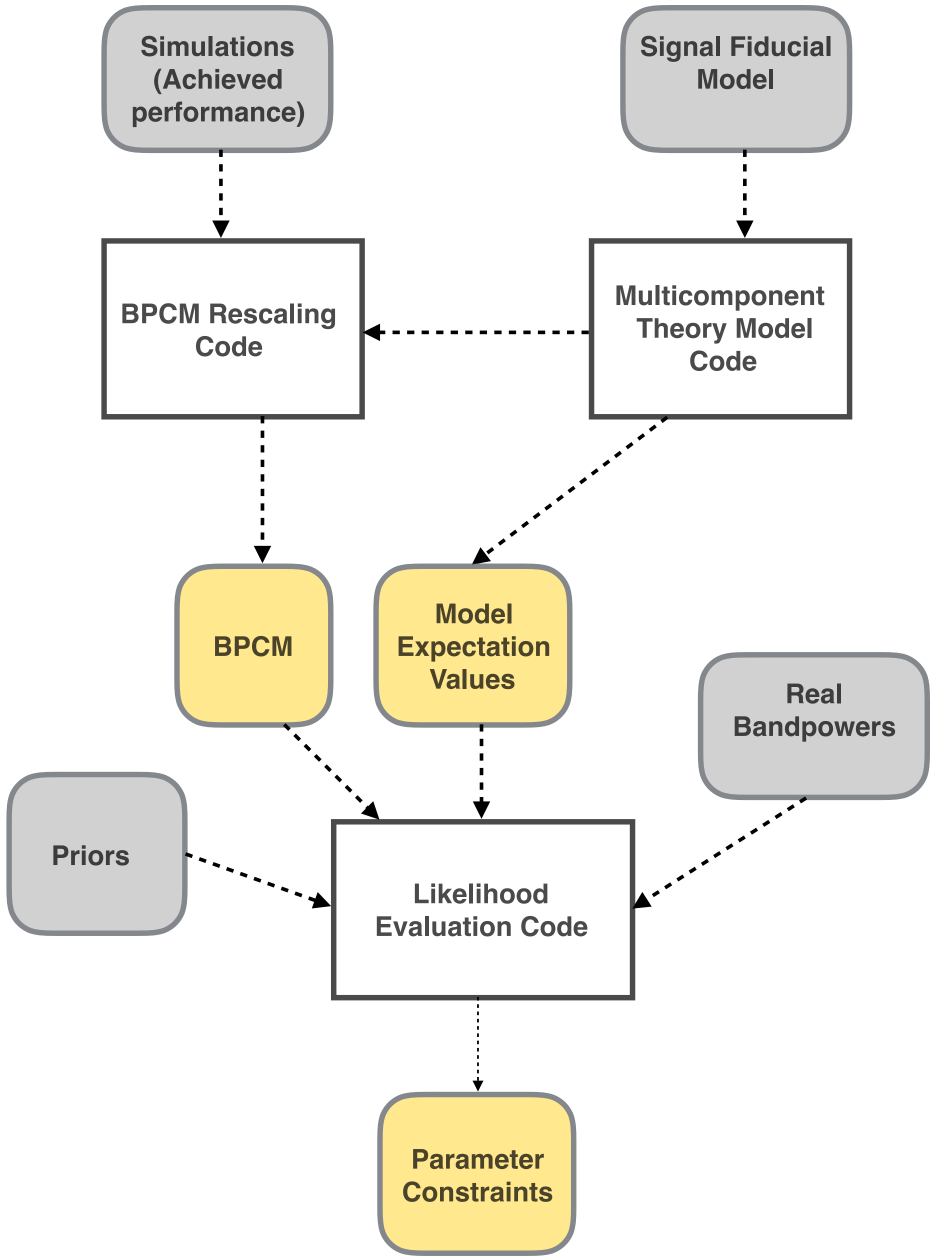
- Multicomponent analysis of CMB polarization maps using BICEP/Keck, Planck and WMAP data.
  - Framework Setup
  - Application to real data sets: BKP and BK14

- Morphing the Multicomponent Framework to a Fisher Framework
  - Comparing Fisher with BKP and BK14

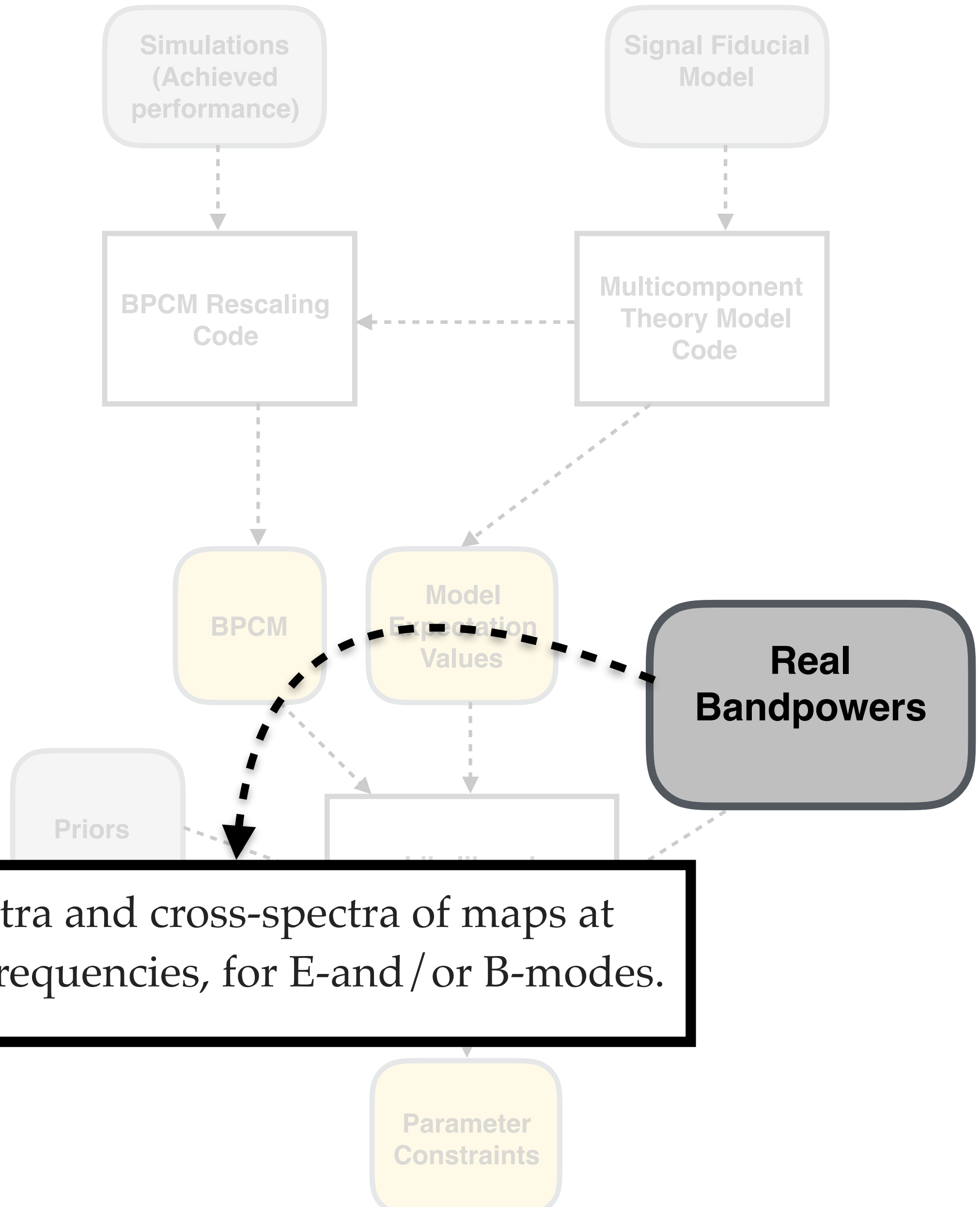
- Performance-based Inflation Forecasts for BICEP Array & CMB-S4
  - What does the near future hold?
  - What does the CMB-polarization landscape look like in 2020+?


Colin Bischoff
Victor Buza
Cora Dvorkin
John Kovac

Likelihood Framework Schematic

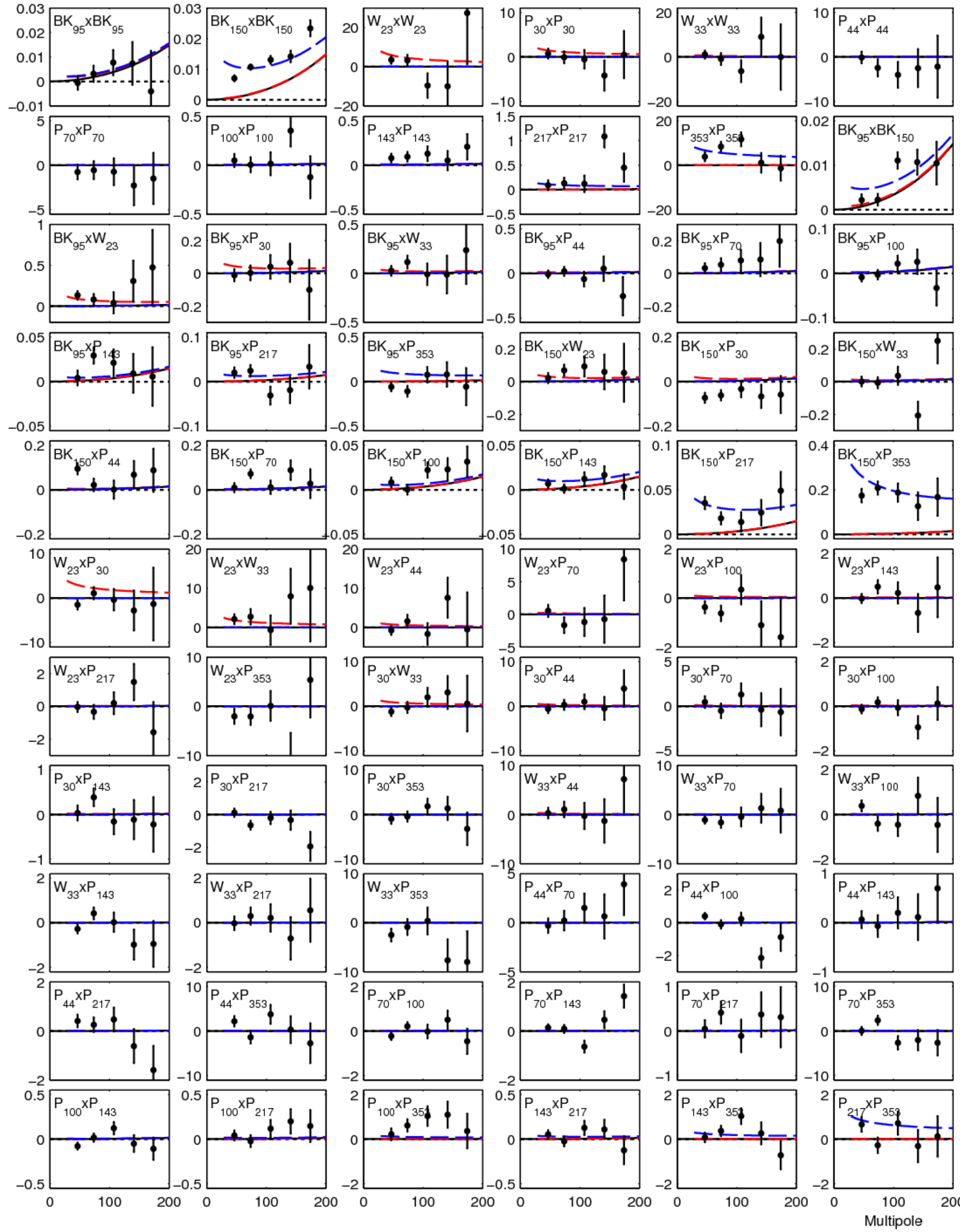


Likelihood Framework Schematic



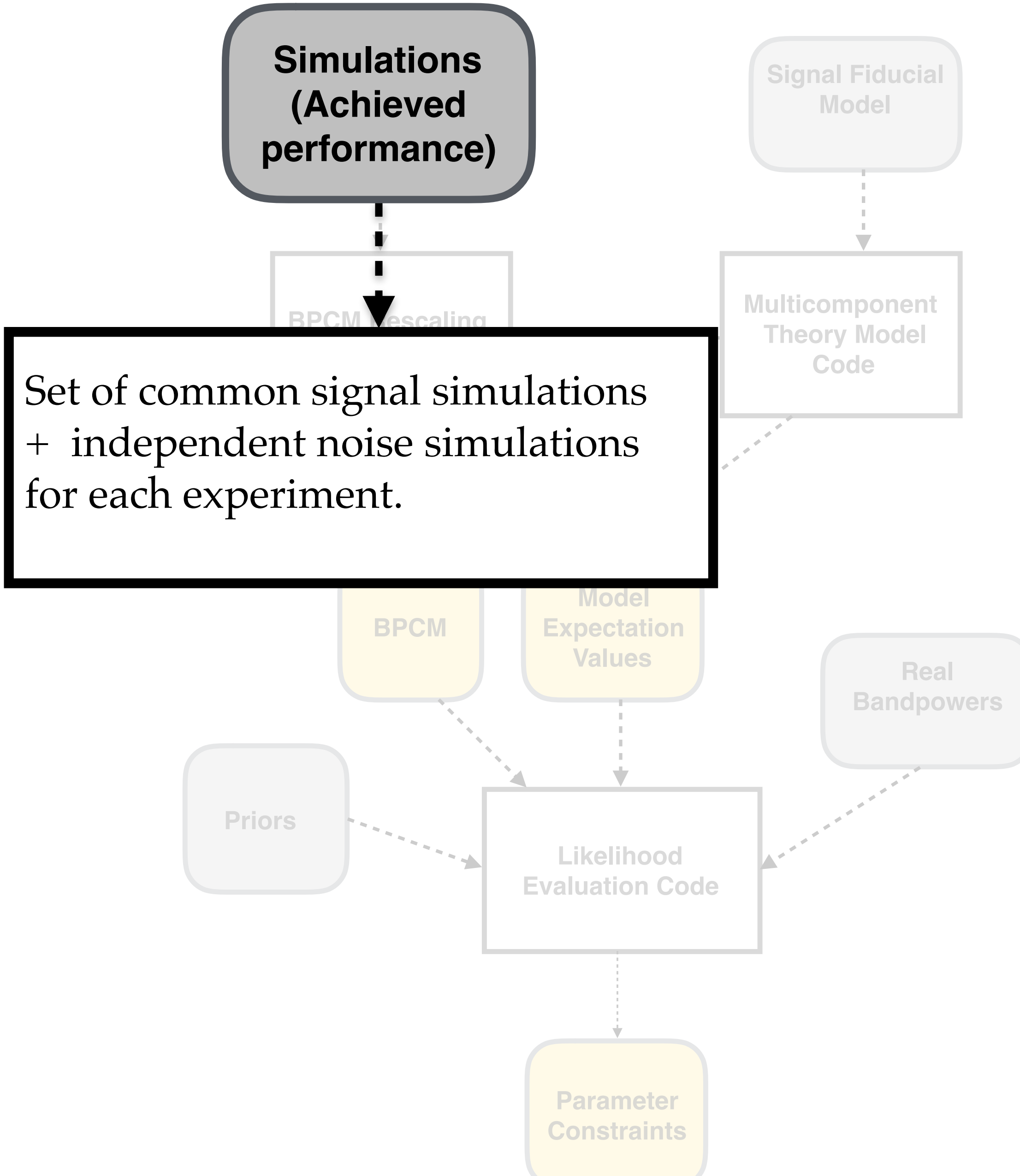
Auto-spectra and cross-spectra of maps at different frequencies, for E-and/or B-modes.

Take all possible auto- and cross spectra between BICEP/Keck, WMAP, and Planck bands



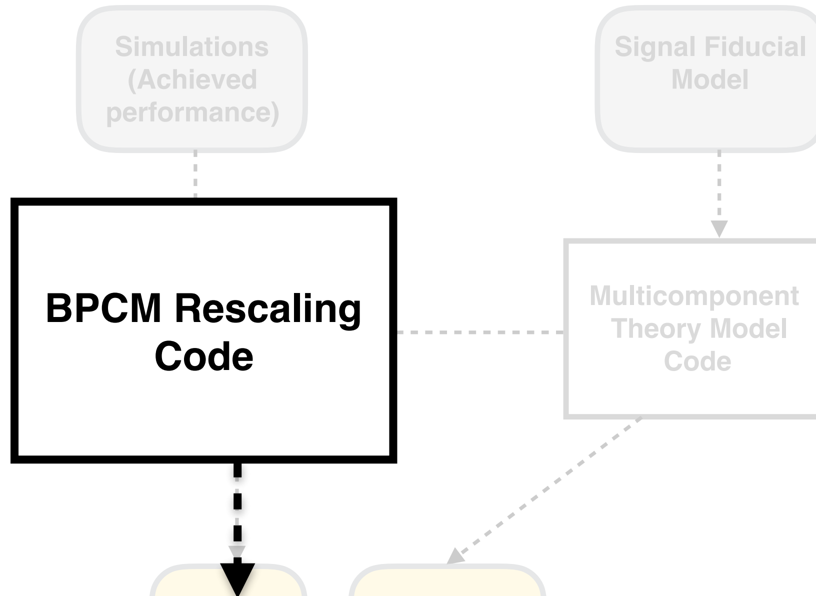
(ex. BK14)

Likelihood Framework Schematic



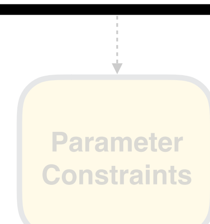
Set of common signal simulations + independent noise simulations for each experiment.

Likelihood Framework Schematic

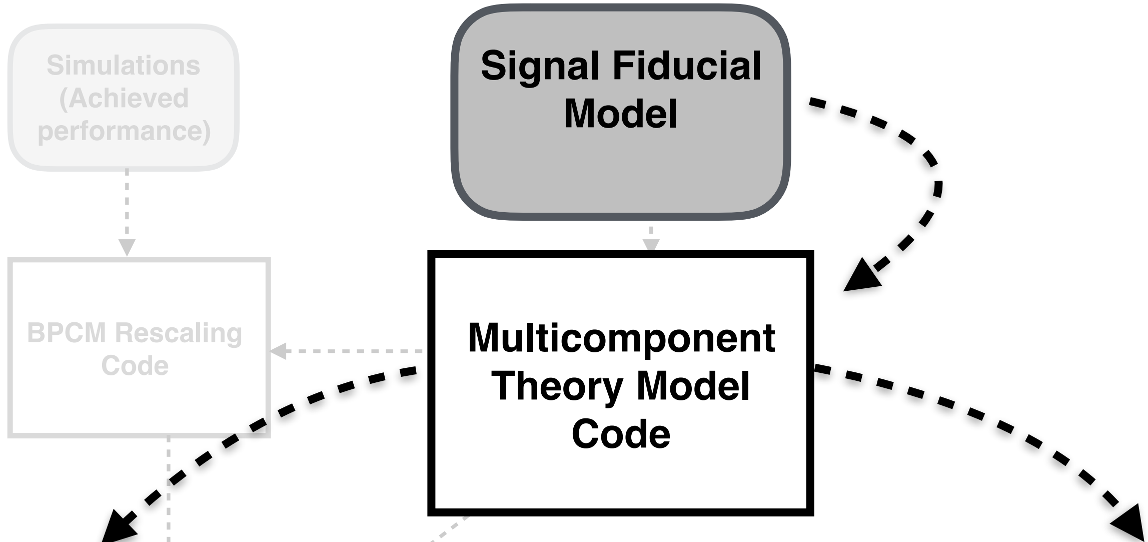


- Uses full simulations of **signal x signal**, **noise x noise**, and **signal x noise**.
- Can scale the covariance matrix to any general theory model.

- Deliberately excludes terms with zero expectation values
  - Assumes signal and noise are uncorrelated
    + that noise is uncorrelated between different experiments



Likelihood Framework Schematic



- Calculate likelihood for an arbitrary theory.
- We use a model containing the following four independent components:

1. CMB component: lensed-ΛCDM + tensors
2. Dust component
3. Synchrotron component
4. Spatially correlated dust / synchrotron

Model inputs:

- 13 parameters
- Information about the combination of experiments used

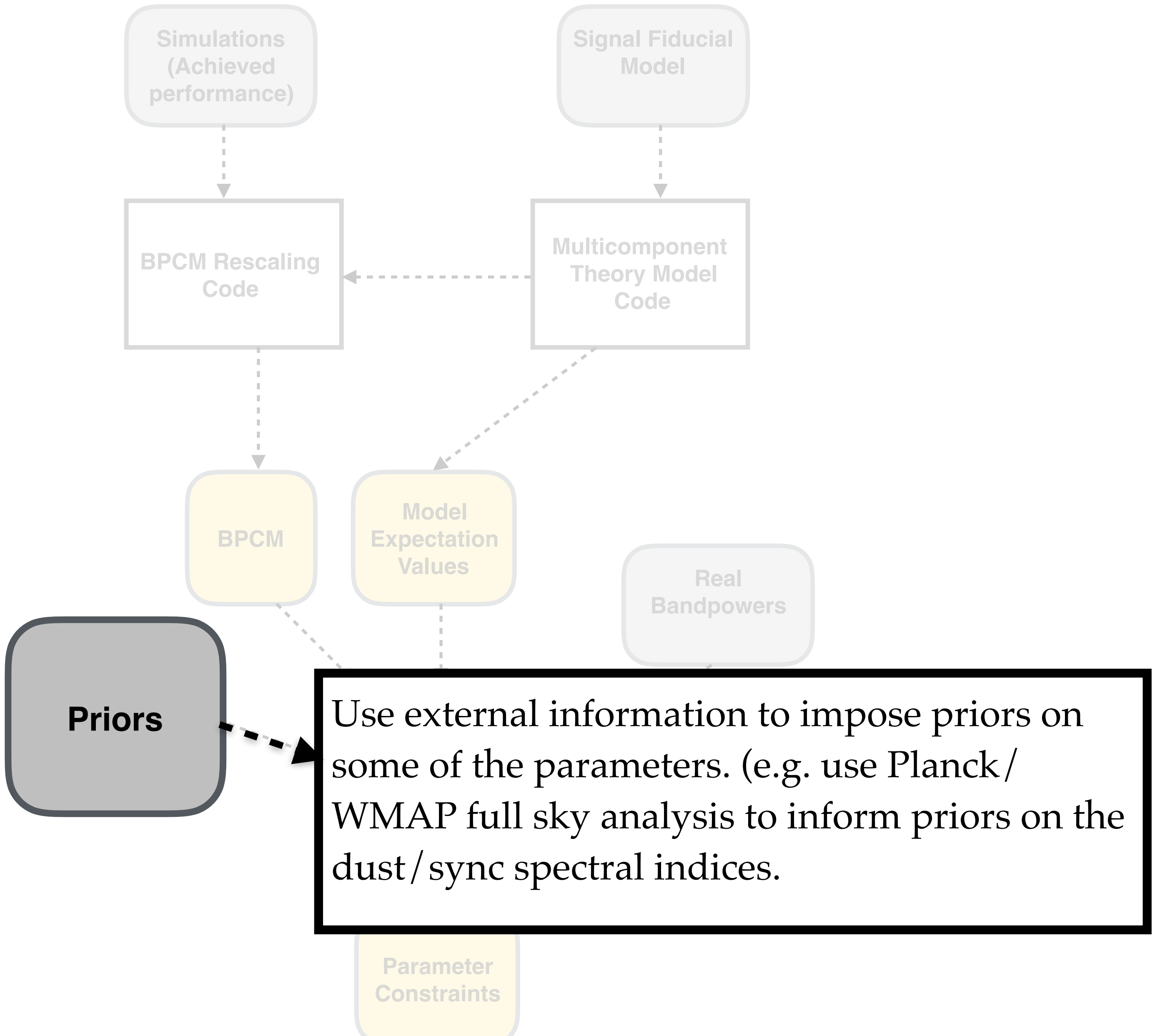
Outputs:

- Bandpower expectation values for all relevant spectra.

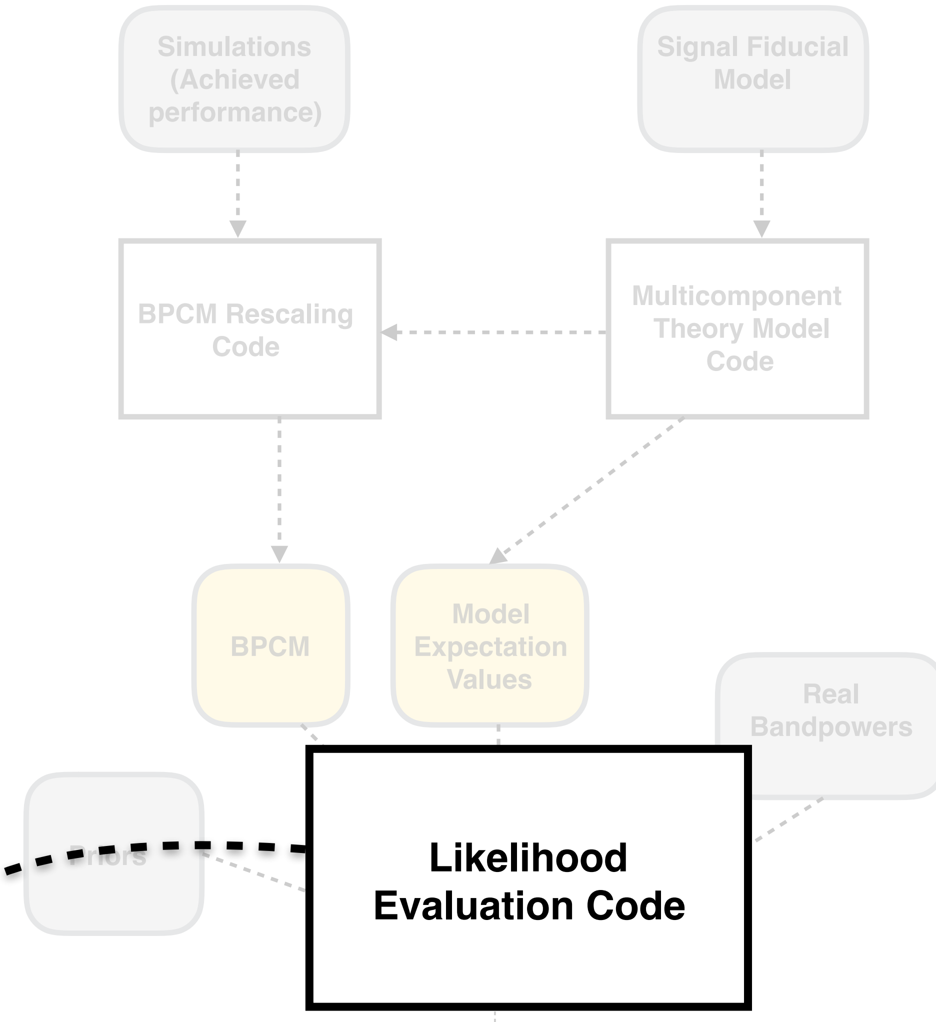
The 13 model parameters are:

1. **r — tensor-to-scalar ratio**
2. **A_L — lensing amplitude**
3. **A_d — dust amplitude, in μK_{CMB}^2, at 353 GHz and $\ell = 80$.**
4. **β_{dust} — dust spectral index**
5. **T_{dust} — dust greybody temperature**
6. **α_{dust} — dust spatial spectral index**
7. **δ_{dust} — dust frequency decorrelation**
8. **EE / BB ratio for dust**
9. **A_s — sync amplitude, in μK_{CMB}^2, at 23 GHz and $\ell = 80$.**
10. **β_{sync} — sync spectral index**
11. **α_{sync}— sync spatial spectral index**
12. **EE / BB ratio for synchroton**
13. **ε — synchrotron–dust spatial correlation**

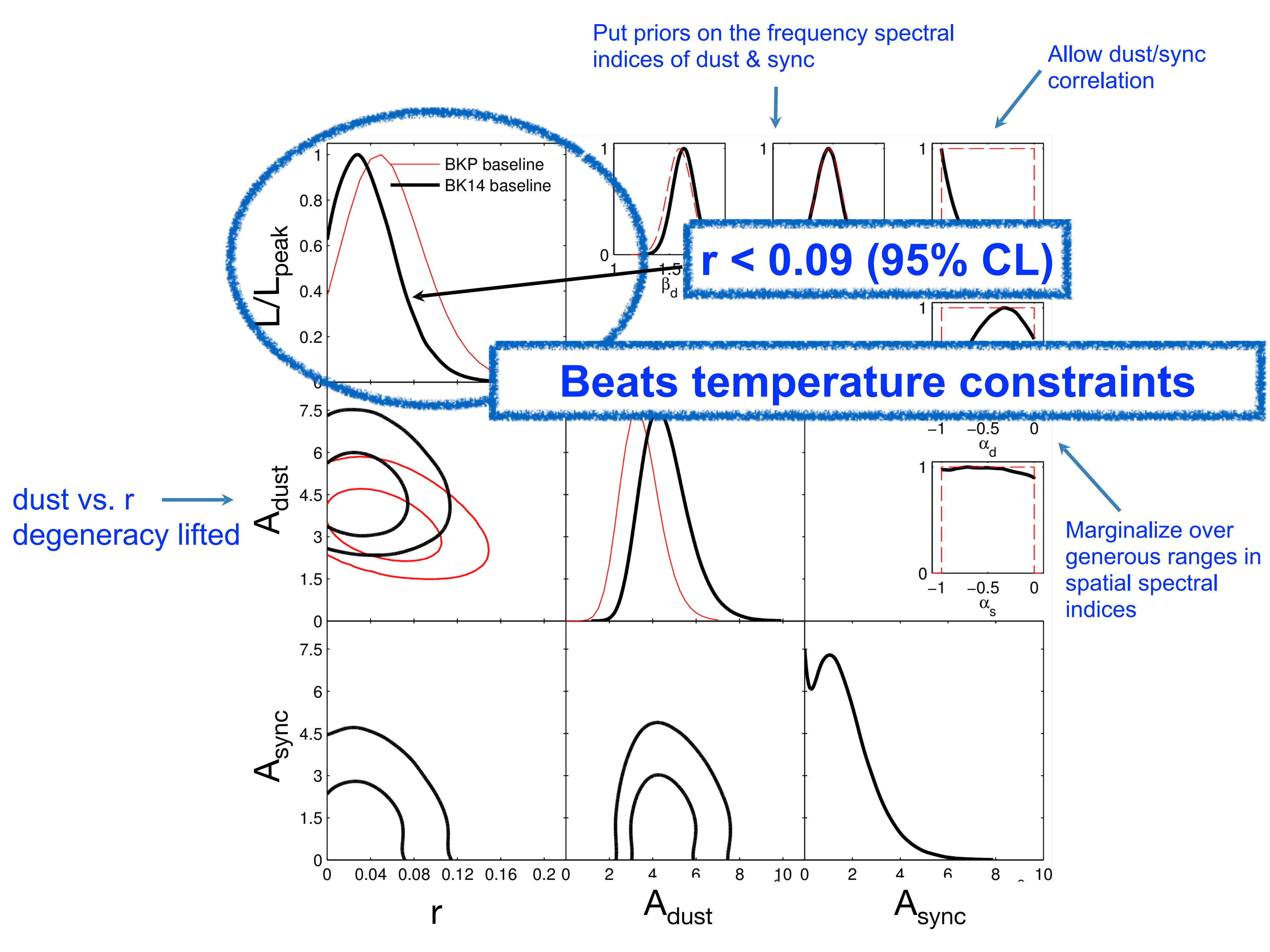
Likelihood Framework Schematic



Likelihood Framework Schematic



Use the Hamimeche-Lewis likelihood approximation (PRD 77, 103013; arXiv:0801.0554) to describe non-gaussian bandpower statistics.



Put priors on the frequency spectral indices of dust & sync
Allow dust/sync correlation
r < 0.09 (95% CL)
Beats temperature constraints
dust vs. r degeneracy lifted
Marginalize over generous ranges in spatial spectral indices
BKP baseline
BK14 baseline
L/L_peak
A_dust
A_sync
r
β_d
α_d
α_s

Fisher Formalism

Given a Likelihood function of the form

$$\mathcal{L}(\theta; d) \sim \frac{1}{\sqrt{det(\Sigma(\theta))}} exp\{-\frac{1}{2}(d-\mu(\theta))^T \Sigma(\theta)^{-1}(d-\mu(\theta))\}$$

d is the data,
θ are the theory parameters,
μ(θ) are the expectation values given the parameters
Σ(θ) is the band-power covariance matrix.

We can calculate the average of the log-likelihood curvature (the Fisher Matrix):

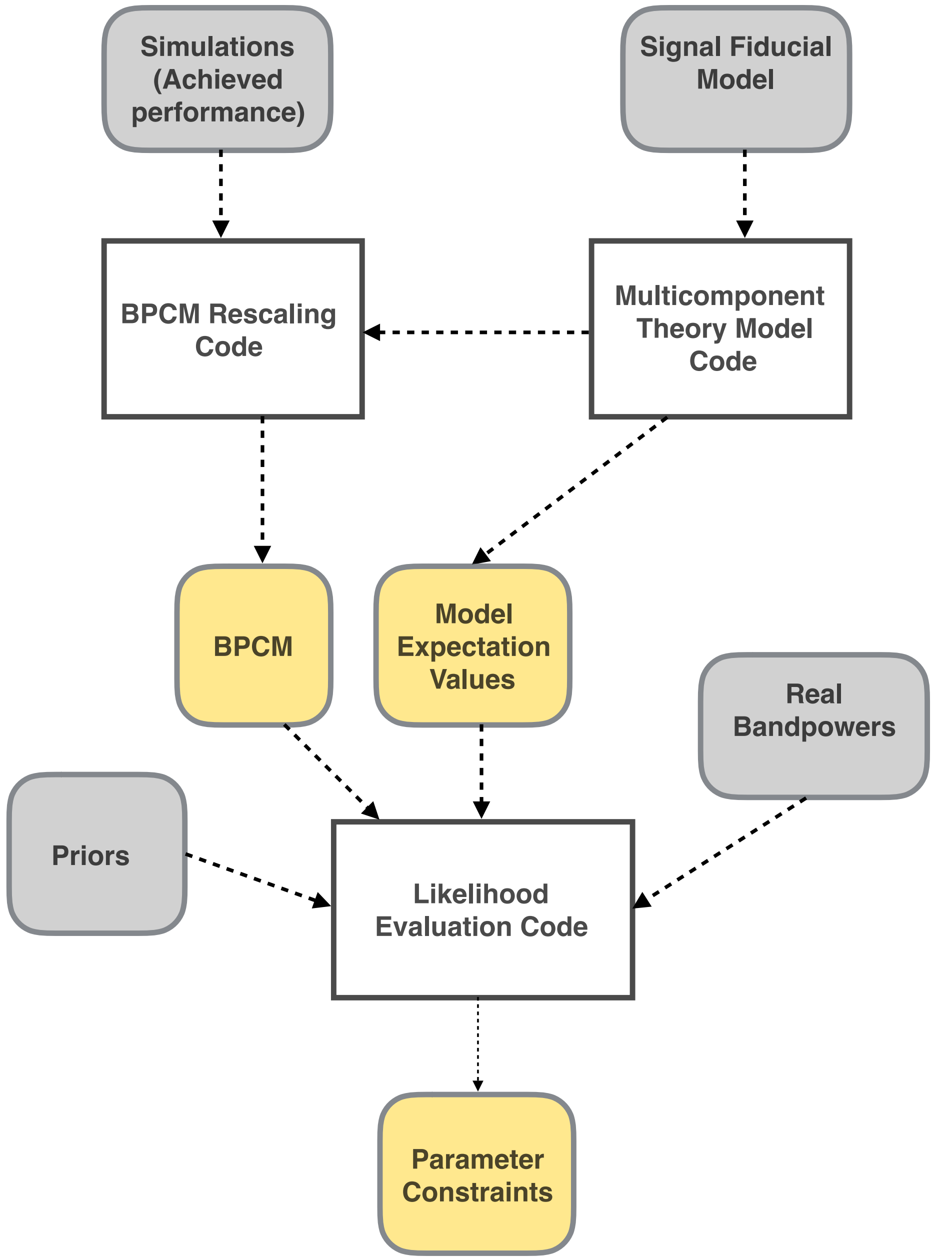
$$F_{ij} = -< \frac{\partial^2 log(\mathcal{L}(\theta; d))}{\partial\theta_i \partial\theta_j} >$$

Which can be rewritten as:

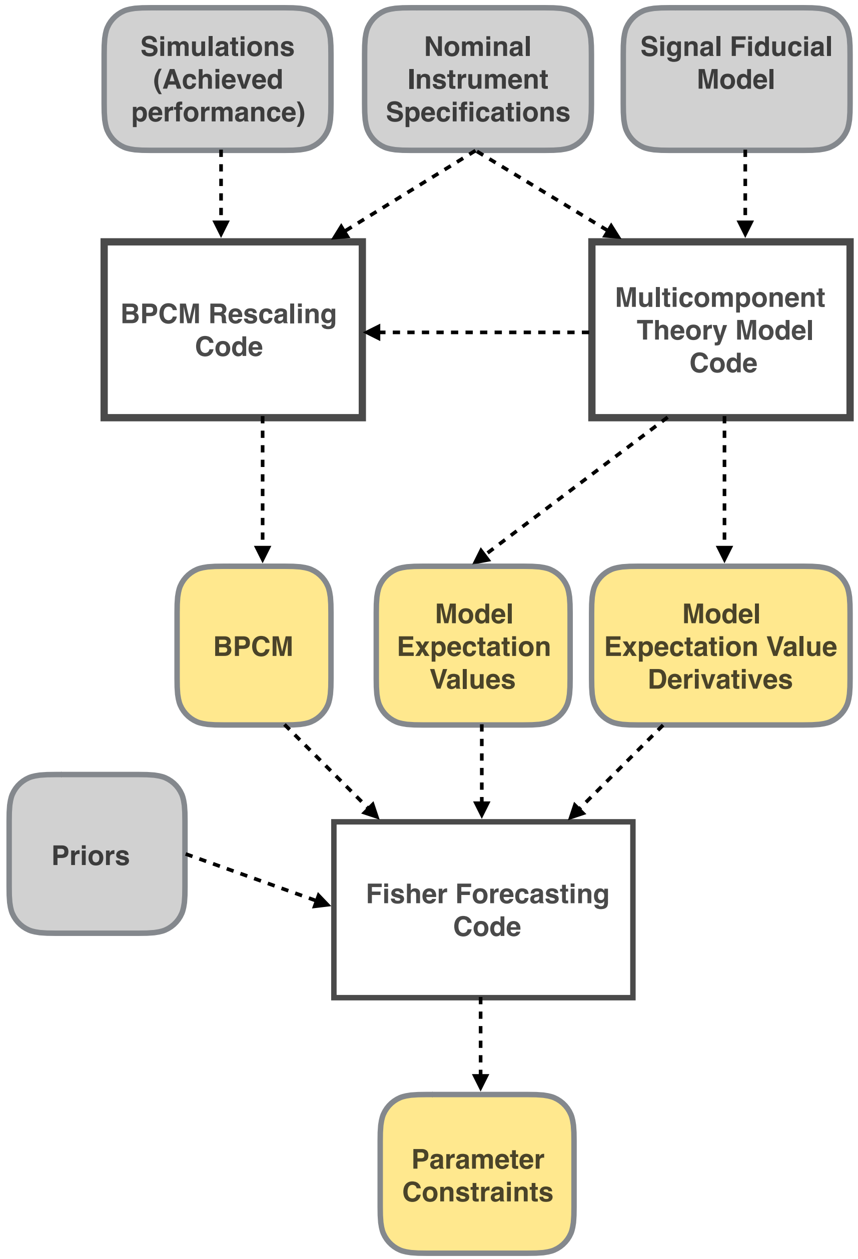
$$F_{ij} = \frac{\partial\mu^T}{\partial\theta_i}\Sigma^{-1}\frac{\partial\mu}{\partial\theta_j} + \frac{1}{2}Tr(\Sigma^{-1}\frac{\partial\Sigma}{\partial\theta_i}\Sigma^{-1}\frac{\partial\Sigma}{\partial\theta_i})$$

Very useful for projecting into the future!
Offers parameter constraints simply with the knowledge of ***μ and Σ.***

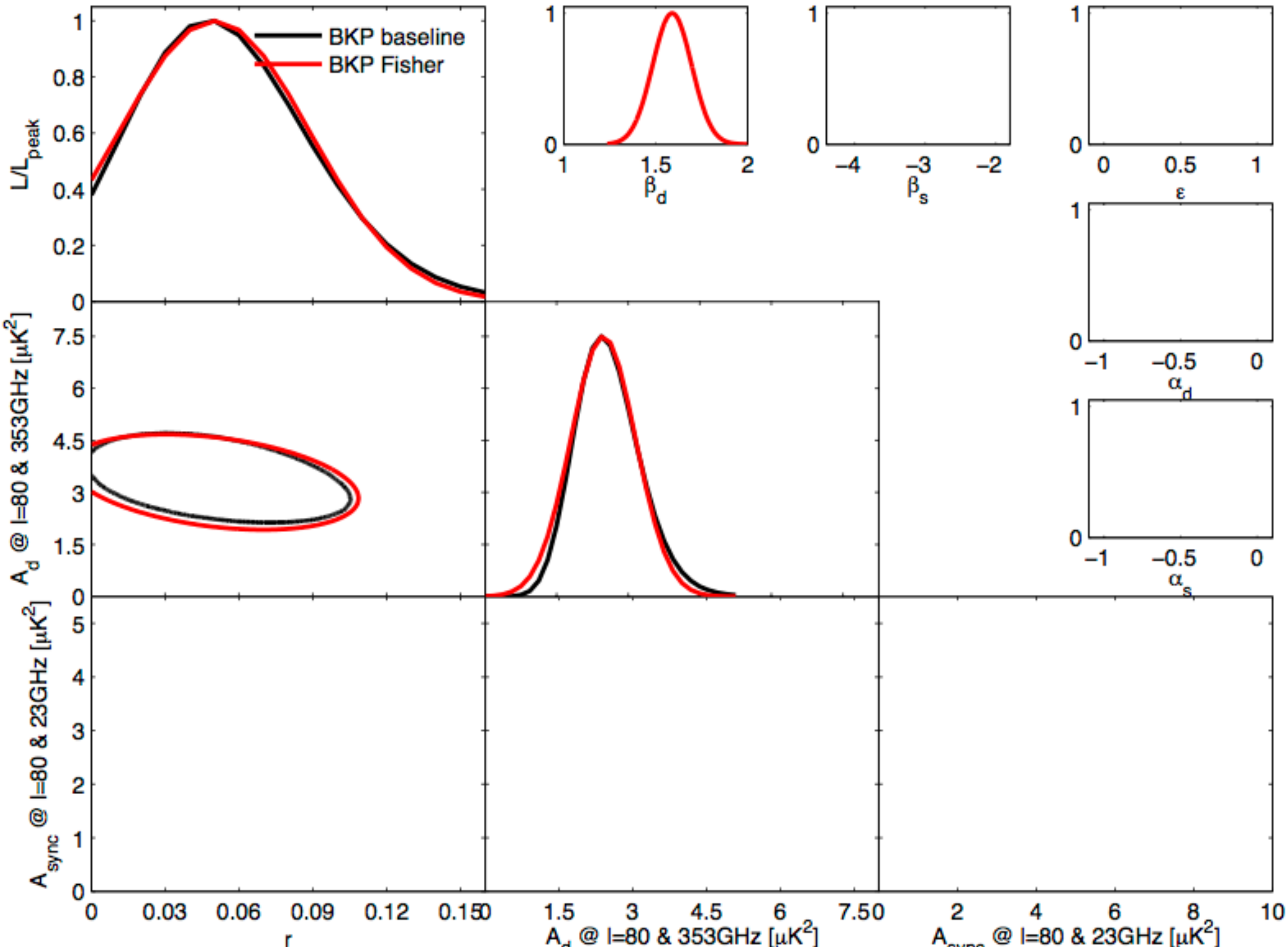
Likelihood Framework Schematic



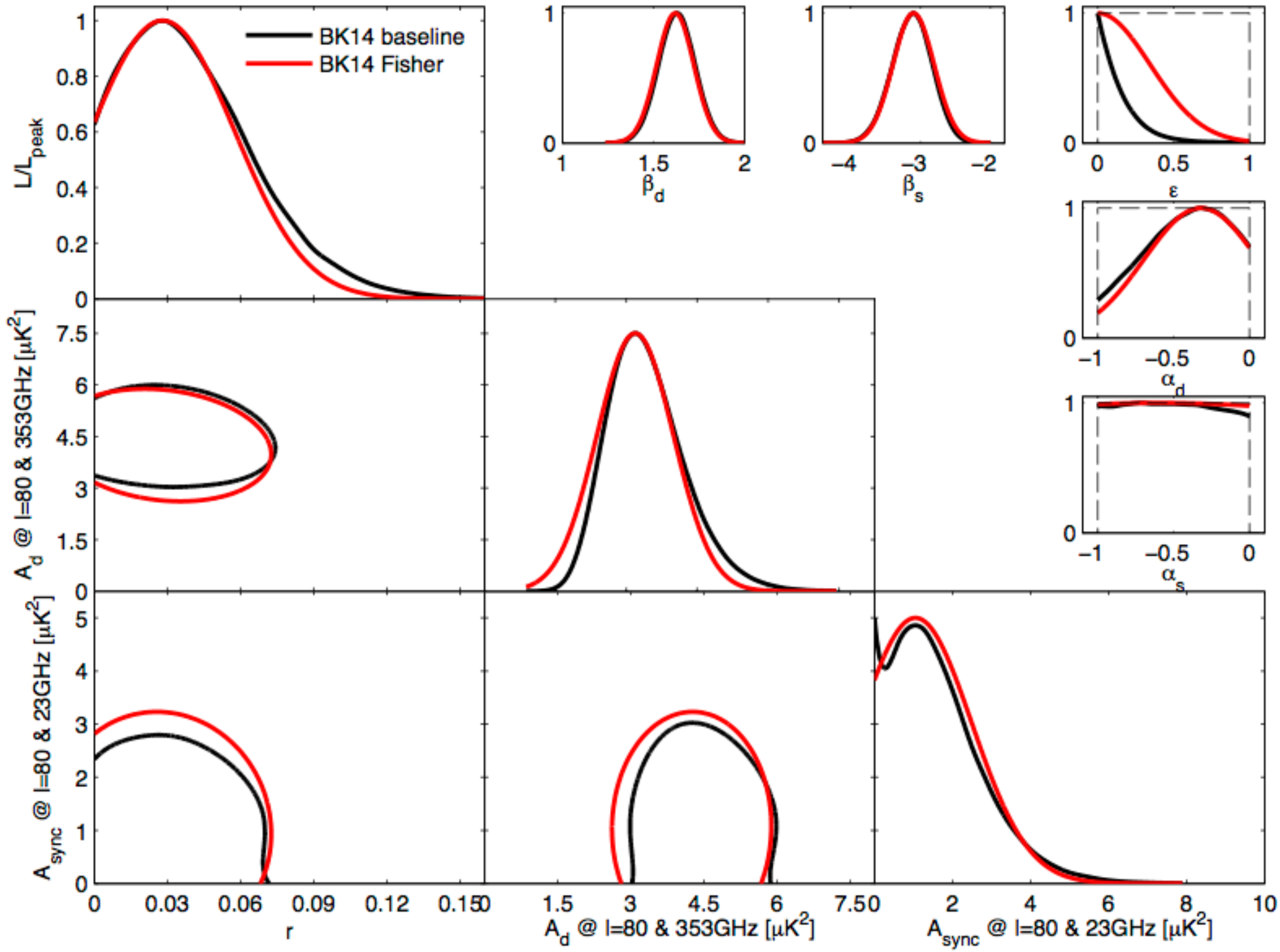
Fisher Framework Schematic

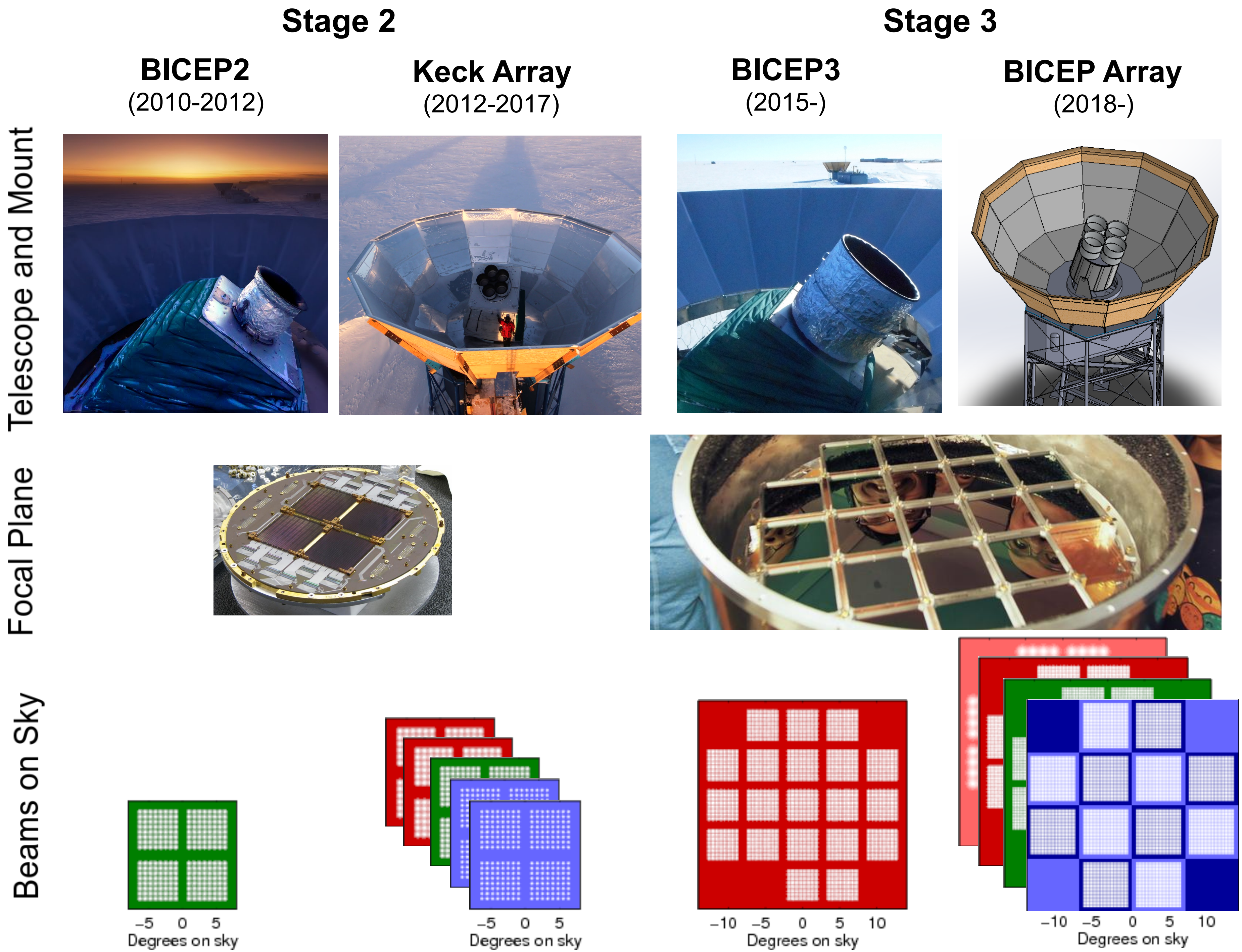


Comparing Fisher vs real BKP constraints



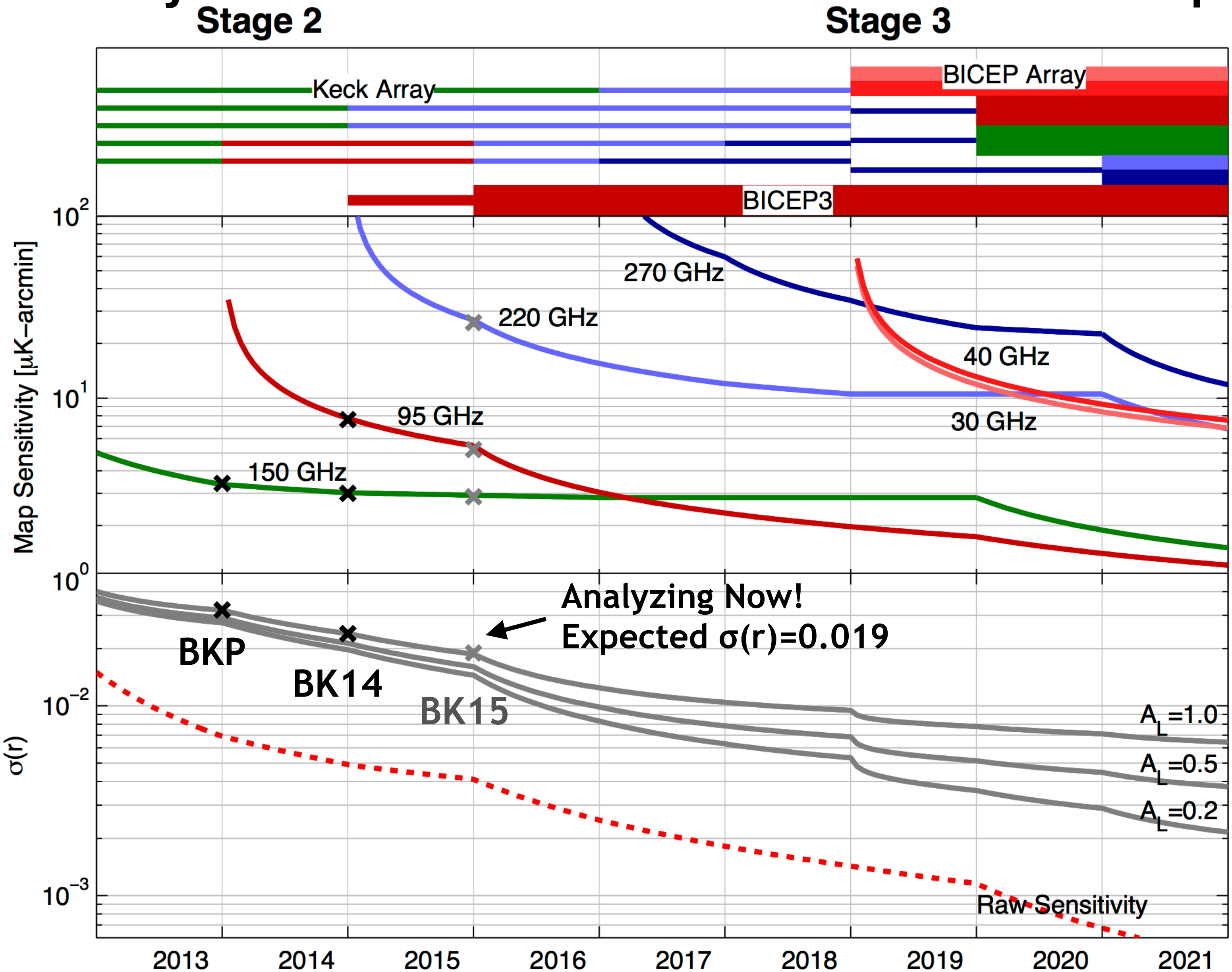
Comparing Fisher vs real BK14 constraints



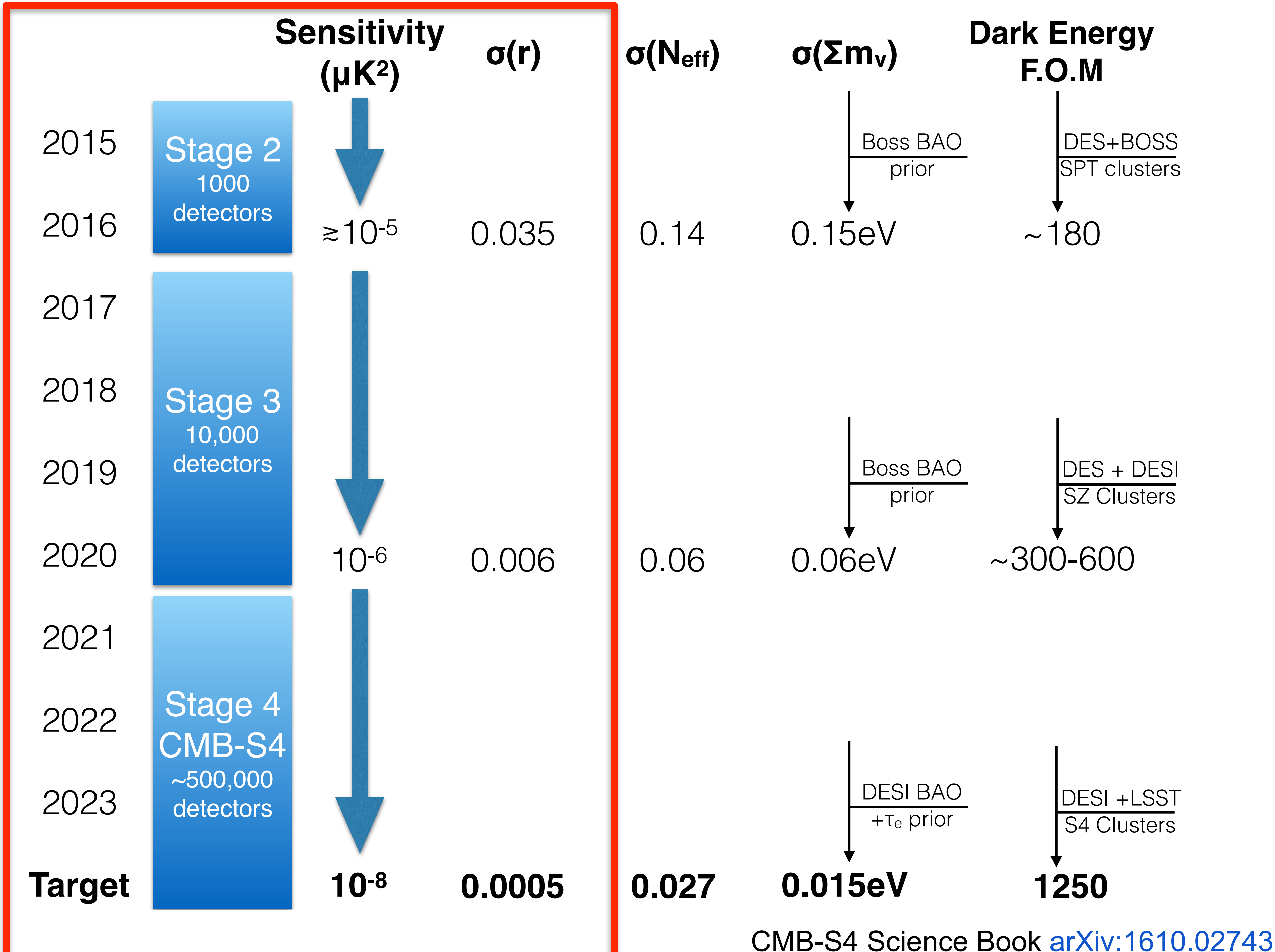


Stage 2
Stage 3
BICEP2
(2010-2012)
Keck Array
(2012-2017)
BICEP3
(2015-)
BICEP Array
(2018-)
Telescope and Mount
Focal Plane
Beams on Sky
−5 0 5
Degrees on sky
−5 0 5
Degrees on sky
−10 −5 0 5 10
Degrees on sky
−10 −5 0 5 10
Degrees on sky

BICEP Array + SPT3G as a Pathfinder for the CMB-S4 Deep Survey



- 6 band foreground control and σ(r)<0.003 by 2021
- Scaling from achieved published analyses (i.e. all real-world performance hits included)



Sensitivity (μK²)
σ(r)
σ(N_eff)
σ(Σm_ν)
Dark Energy F.O.M
2015
2016
2017
2018
2019
2020
2021
2022
2023
Target
Stage 2
1000 detectors
Stage 3
10,000 detectors
Stage 4
CMB-S4
~500,000 detectors
≳10-5
0.035
0.14
0.15eV
~180
10-6
0.006
0.06
0.06eV
~300-600
10-8
0.0005
0.027
0.015eV
1250
Boss BAO
prior
DES+BOSS
SPT clusters
Boss BAO
prior
DES + DESI
SZ Clusters
DESI BAO
+τe prior
DESI +LSST
S4 Clusters
CMB-S4 Science Book arXiv:1610.02743

CMB-S4 Science Book Baseline

- Experiment Selection:

  CMB-S4: {30, 40, 85, 95, 145, 155, 215, 270} GHz

  + Planck: {30 - 353} GHz

  + WMAP: {23, 33} GHz

CMB-S4 Science Book Baseline

- Experiment Selection:
  CMB-S4: {30, 40, 85, 95, 145, 155, 215, 270} GHz
  + Planck: {30 - 353} GHz
  + WMAP: {23, 33} GHz

- Heterogeneous survey with (500k detectors x 4 yrs = 2M det-yrs):
  - 1/2 effort (1M det-yrs) for primordial B-modes
    - small-aperture (~1m)
    - on 3% of the sky
    - fraction of effort targeting arcminute-scale information (used to remove lensing B-modes)

  - 1/2 effort (1M det-yrs) for CMB-lensing, Neutrino Science, Dark Energy, etc.
    - medium-to-large-aperture telescopes
    - on 40% of the sky

CMB-S4 Science Book Baseline

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  CMB-S4: {30, 40, 85, 95, 145, 155, 215, 270} GHz
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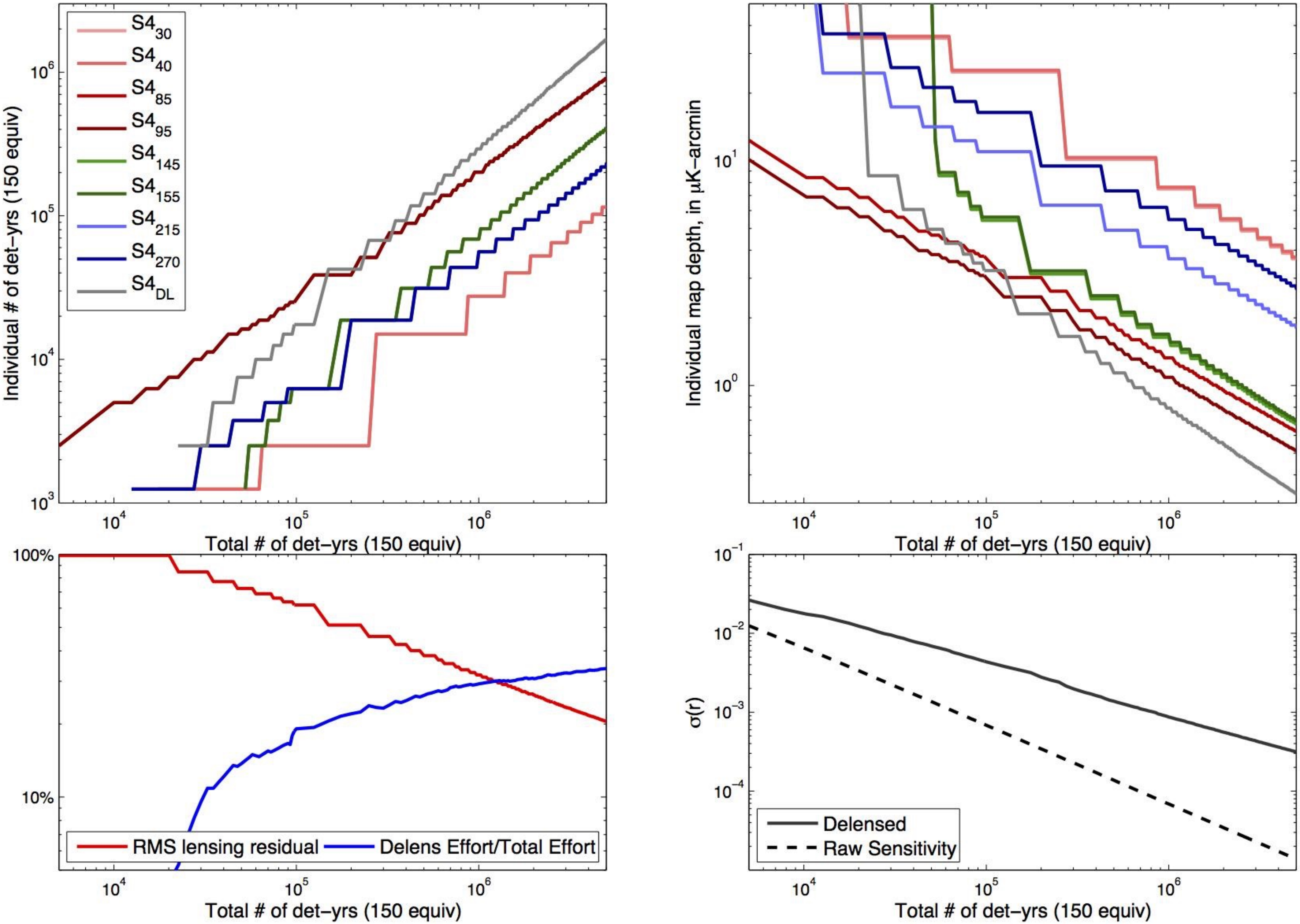
  - 1/2 effort (1M det-yrs) for CMB-lensing, Neutrino Science, Dark Energy, etc.
    - medium-to-large-aperture telescopes
    - on 40% of the sky

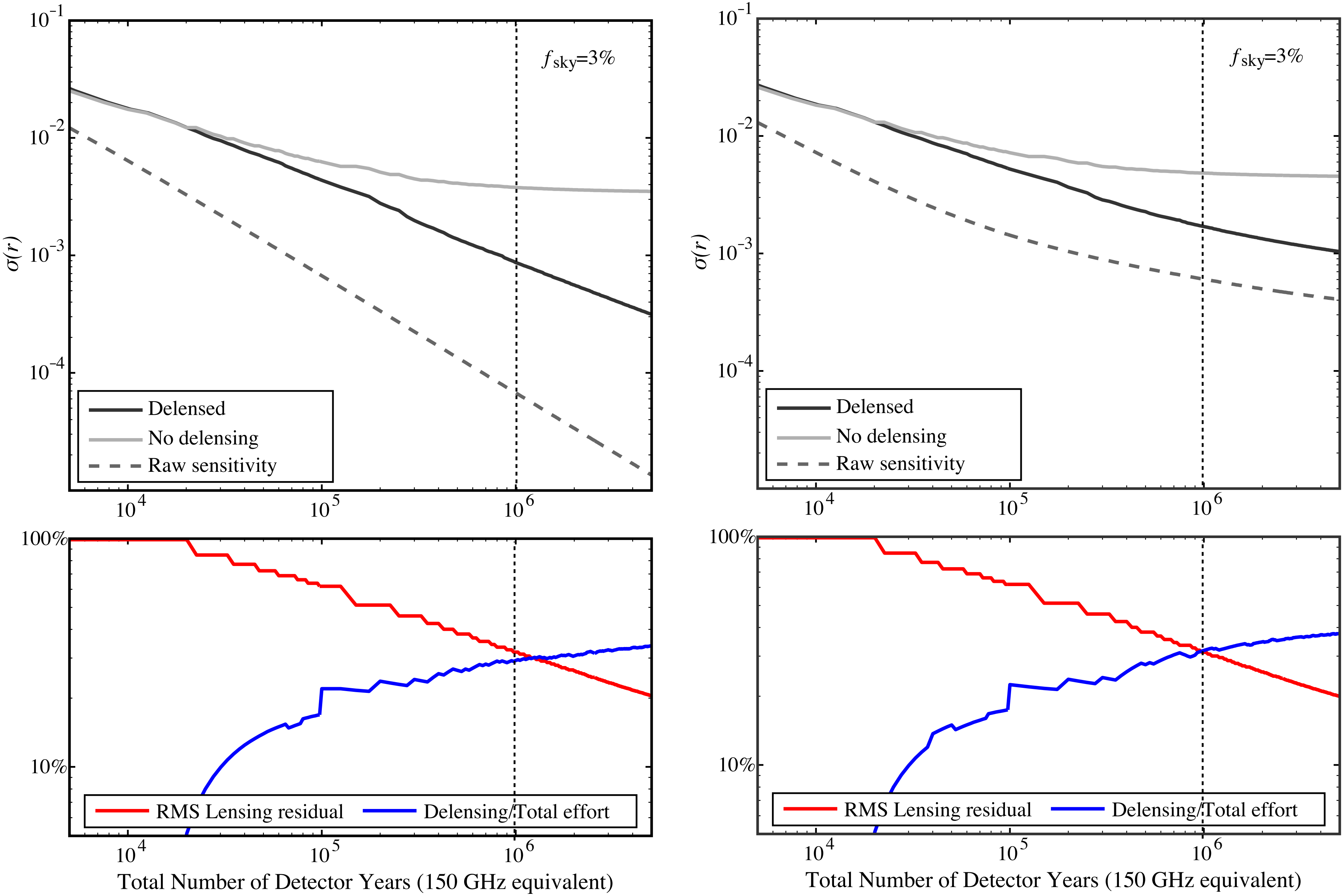
- Optimize effort, for various sky fractions, with degree-scale component separation and arcminute-scale delensing

Optimization example, assuming r = 0 and fsky=3%.



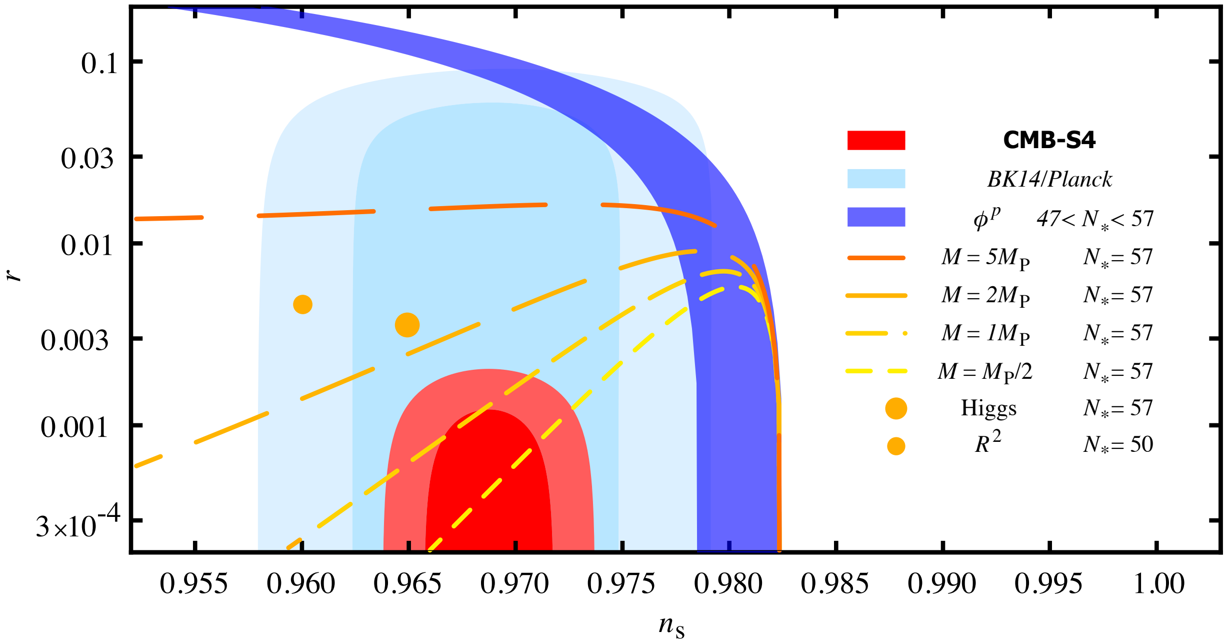
CMB-S4 Science Book [arXiv:1610.02743](https://arxiv.org/abs/1610.02743)

Uncertainty forecasts on r, assuming r = 0 (left panel) and r = 0.01 (right panel).

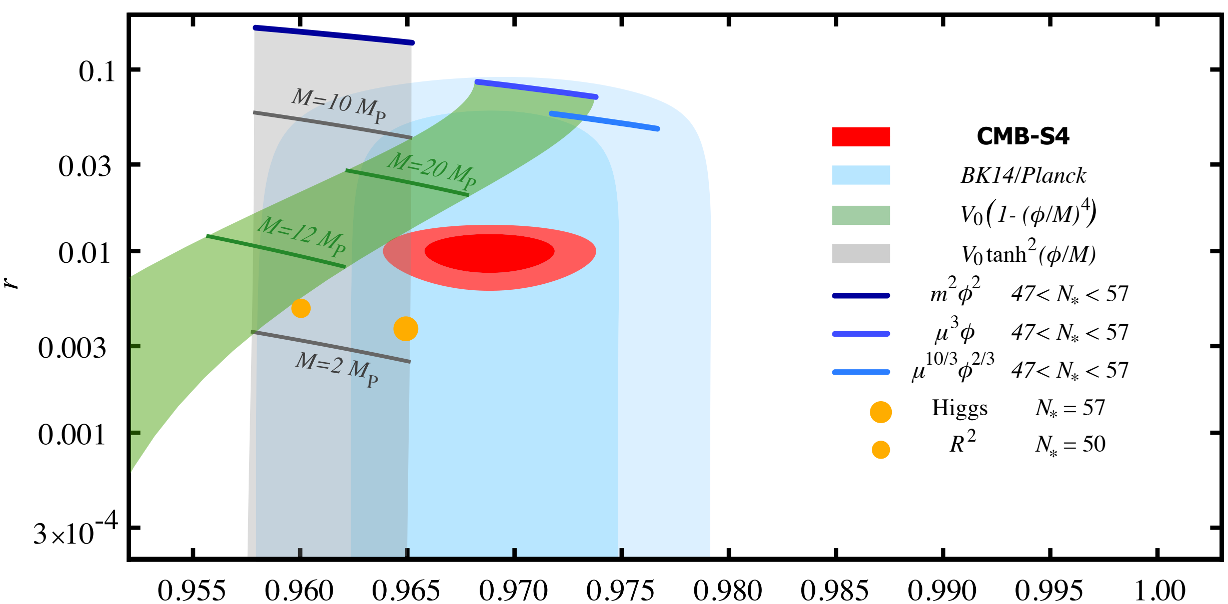


CMB-S4 Science Book arXiv:1610.02743

Forecasted CMB-S4 r-ns constraints, assuming r = 0 (top panel) and r = 0.01 (bottom panel).



- **In the absence of a detection,** CMB-S4 would rule out or disfavor all models that naturally explain the observed value of the scalar spectral index (in the sense that *ns*(*N*)-1~*1/N*) and in which the characteristic scale in field space exceeds the Planck scale.



- **A detection of primordial B modes** with CMB-S4 would provide evidence that the theory of quantum gravity must accommodate a Planckian field range for the inflaton.

CMB-S4 Science Book [arXiv:1610.02743]

Conclusions

- We use on-sky current achieved performances from various CMB experiments to make robust forecasts for future CMB-polarization endeavors.

- Used and validated in the context of optimizing various survey configurations.

- Used to calculate inflation projections for the next generation experiment in the BICEP/Keck series, and for CMB-S4.

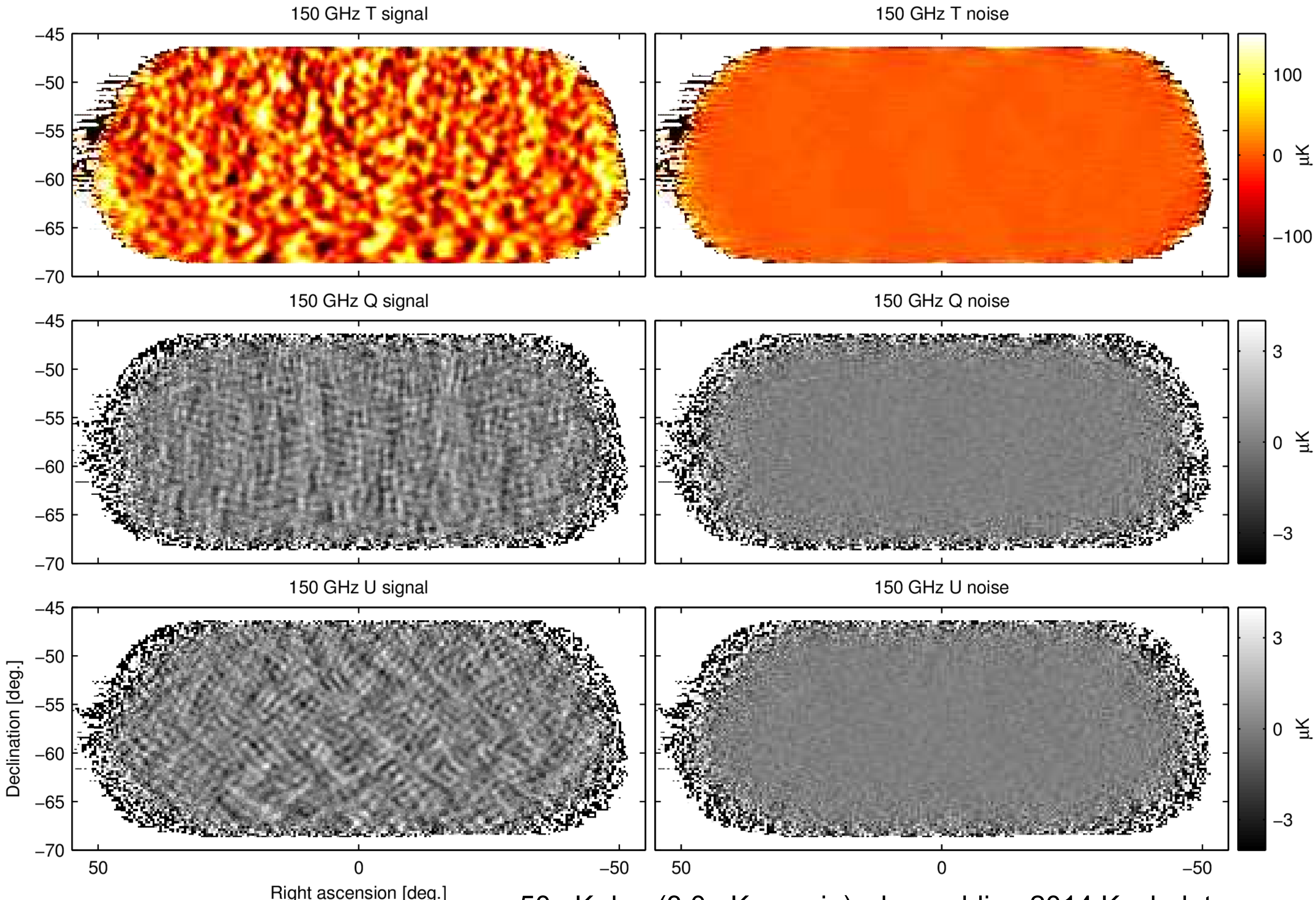
- Projecting six band foreground control and $\sigma(r)<0.003$ by 2021 with BICEP-Array

- CMB-S4 brings us to $\sigma(r)<0.0007$ allowing us to significantly narrow down the space of possible inflationary models.

Thank You!

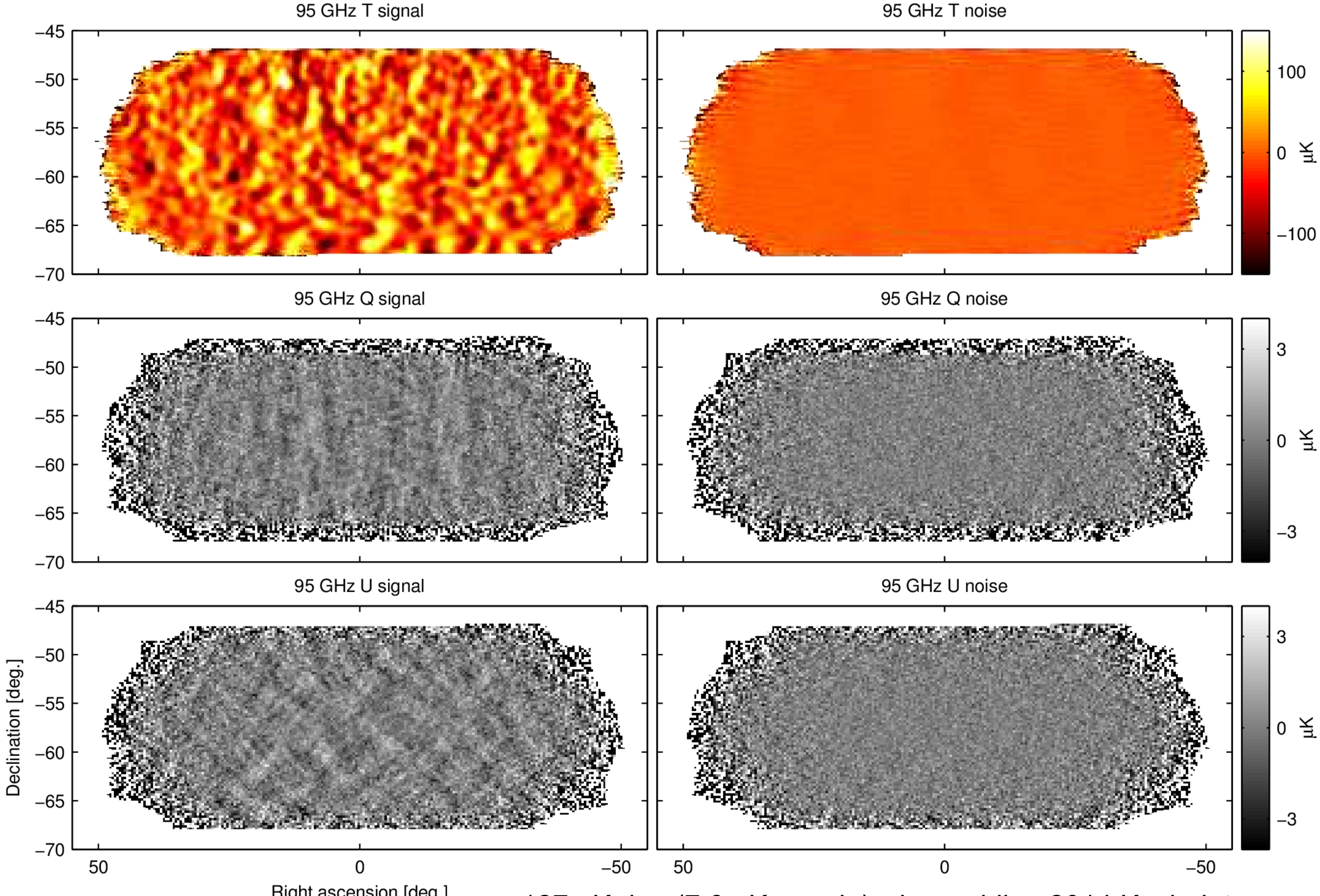
Extra Slides

T/Q/U 150 GHz maps including Keck 2014 data



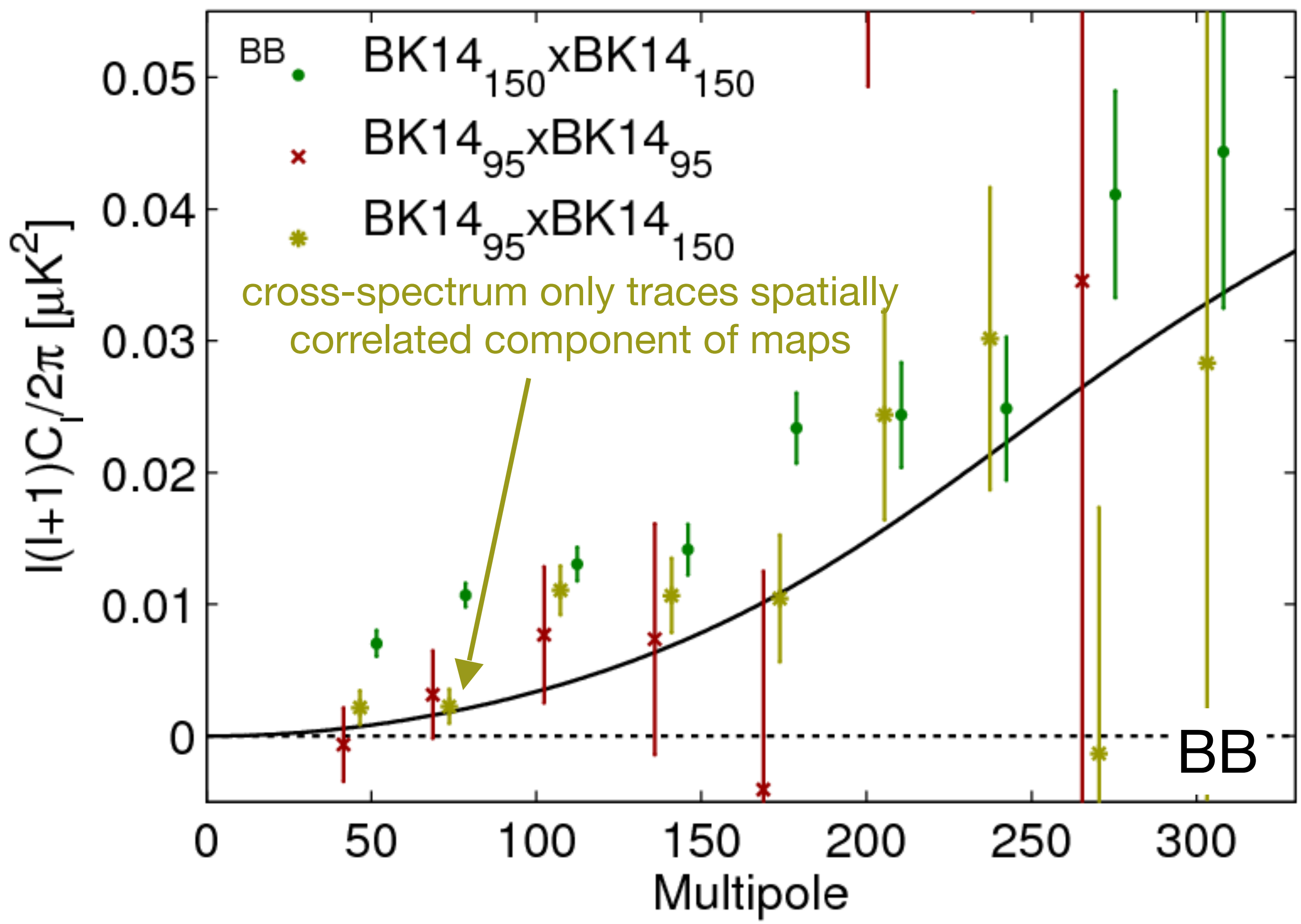
50 nK deg (3.0 μK arcmin) when adding 2014 Keck data

Keck 2014 T/Q/U 95 GHz maps



127 nK deg (7.6 μK arcmin) when adding 2014 Keck data

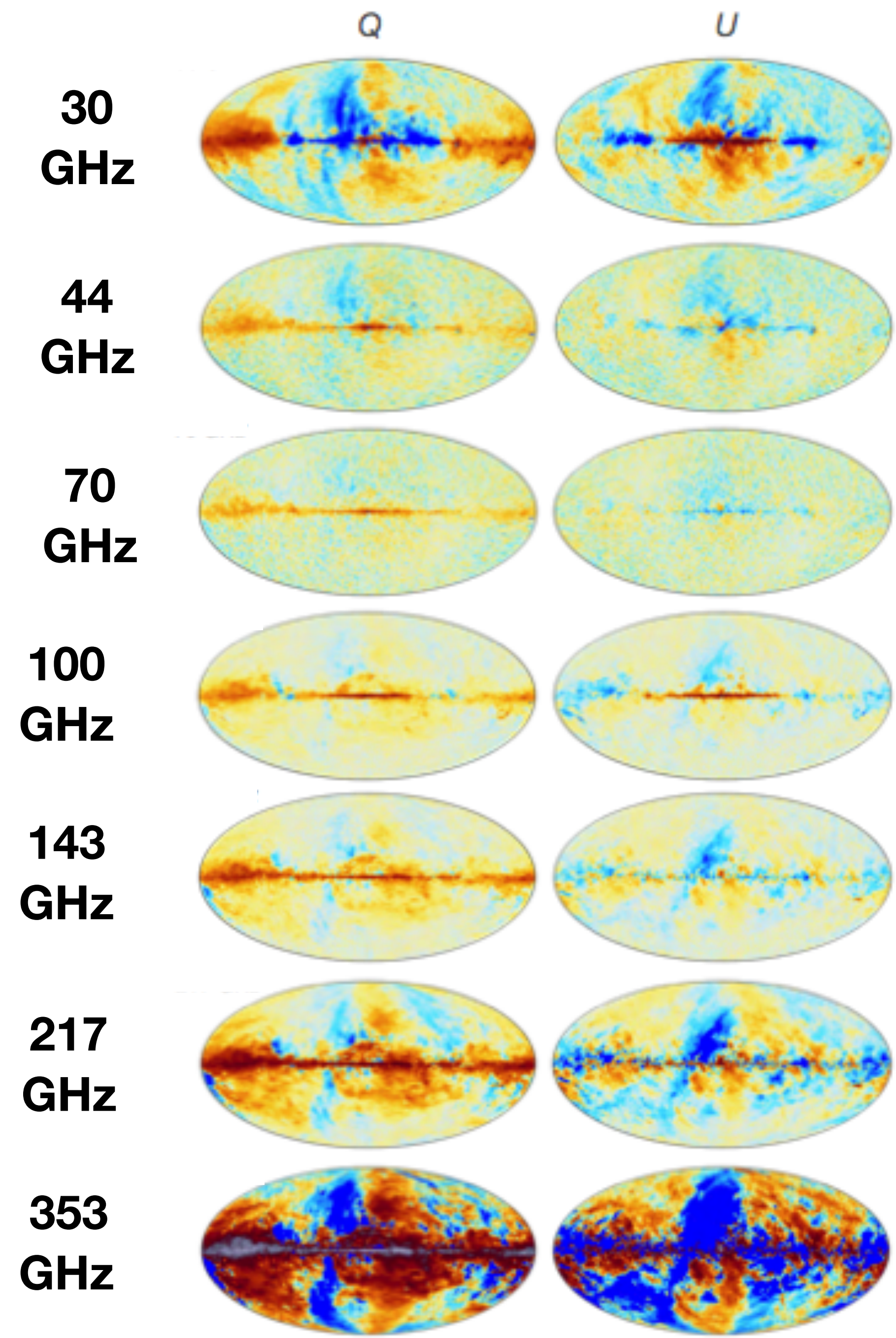
BICEP2 + Keck BB auto and cross-spectra



Polarized galactic **synchrotron** dominates at low frequencies

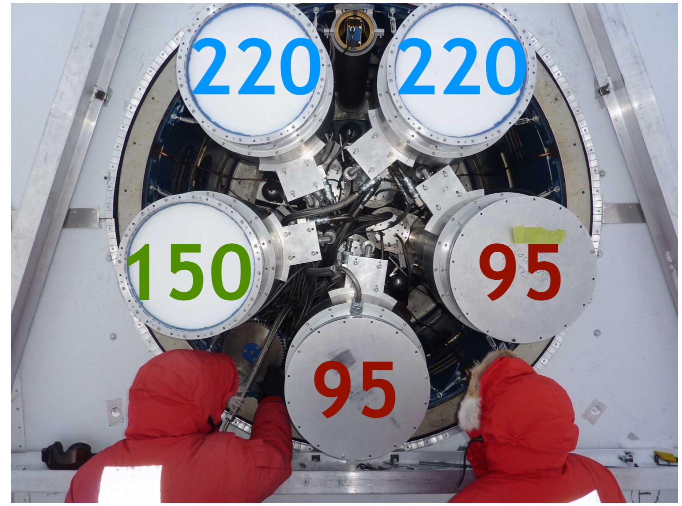
Planck then provided polarized maps at 7 frequencies (two more from WMAP at low frequencies already existed)

Polarized thermal emission (~20K) from galactic **dust** aligned in magnetic fields dominates at high frequencies

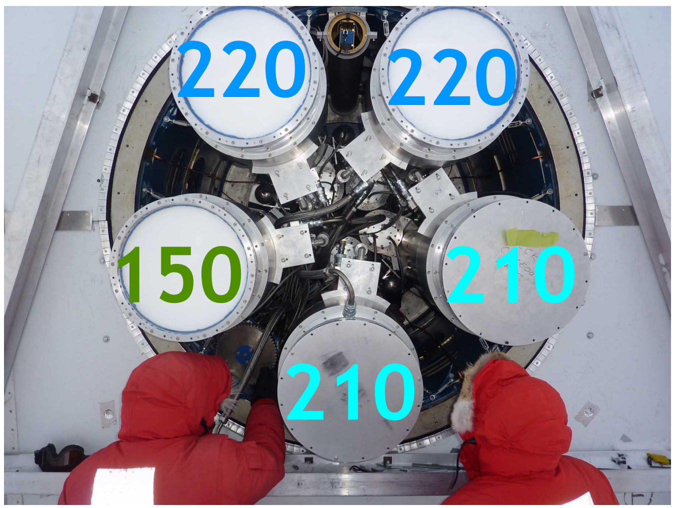


Keck Array Frequency Coverage

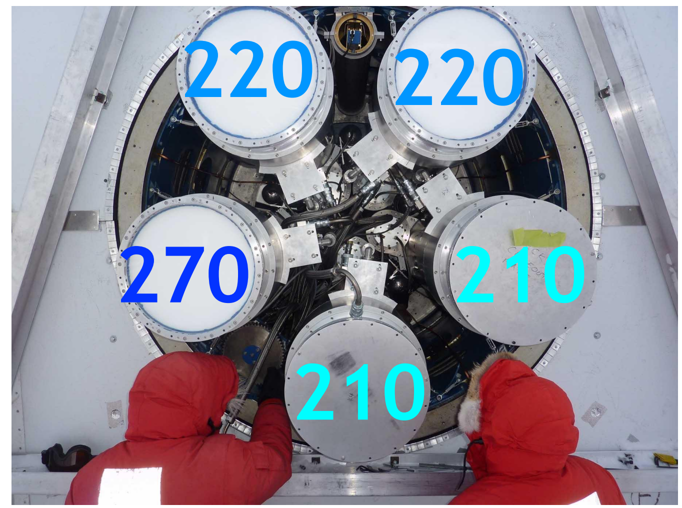
2014



2015

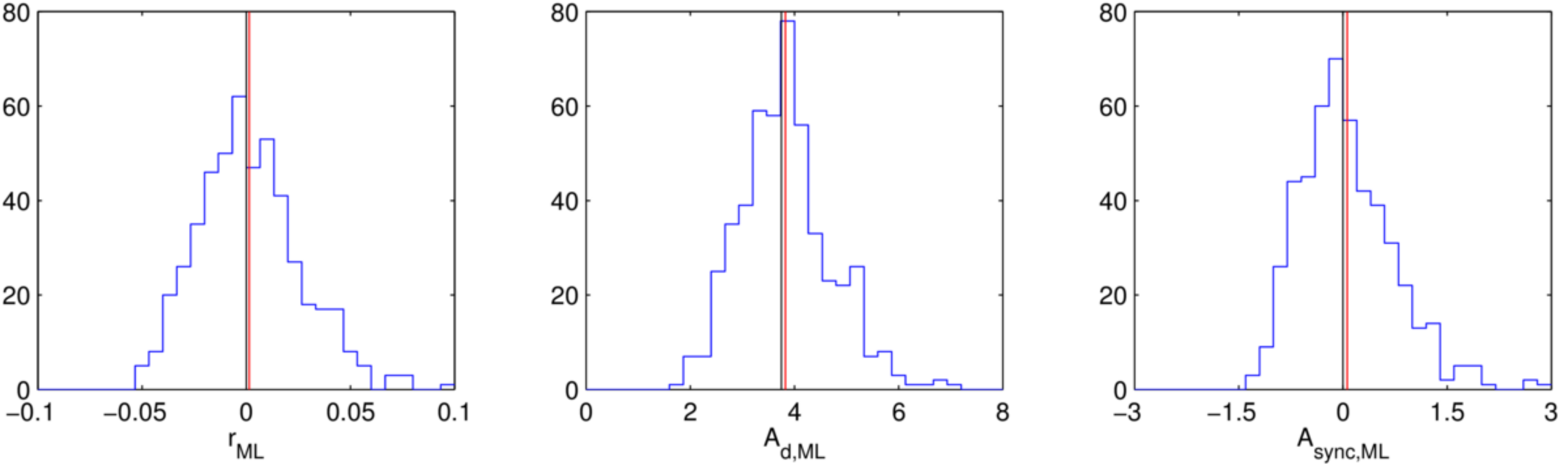


2016



2017

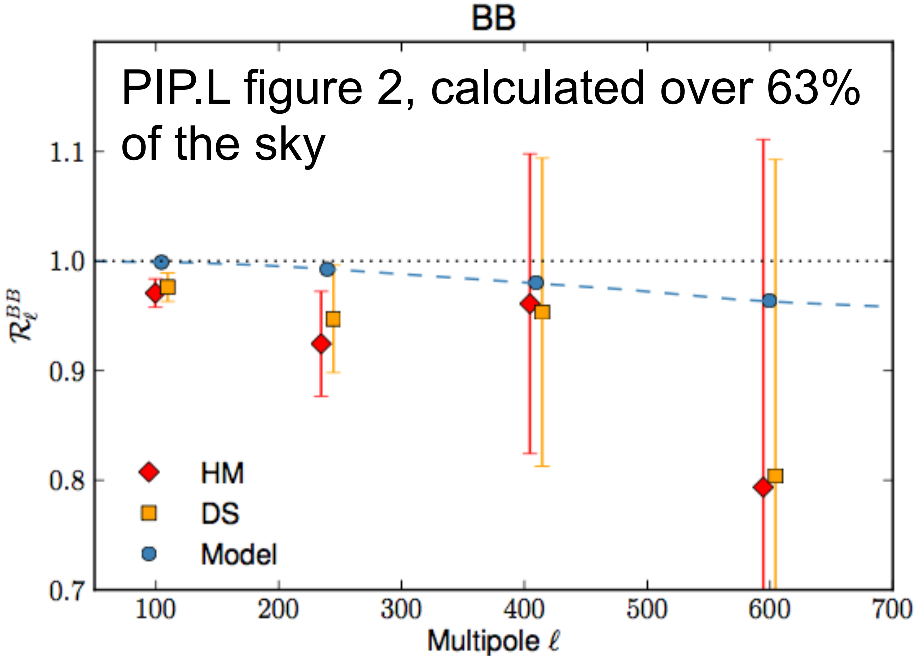
Validation Tests

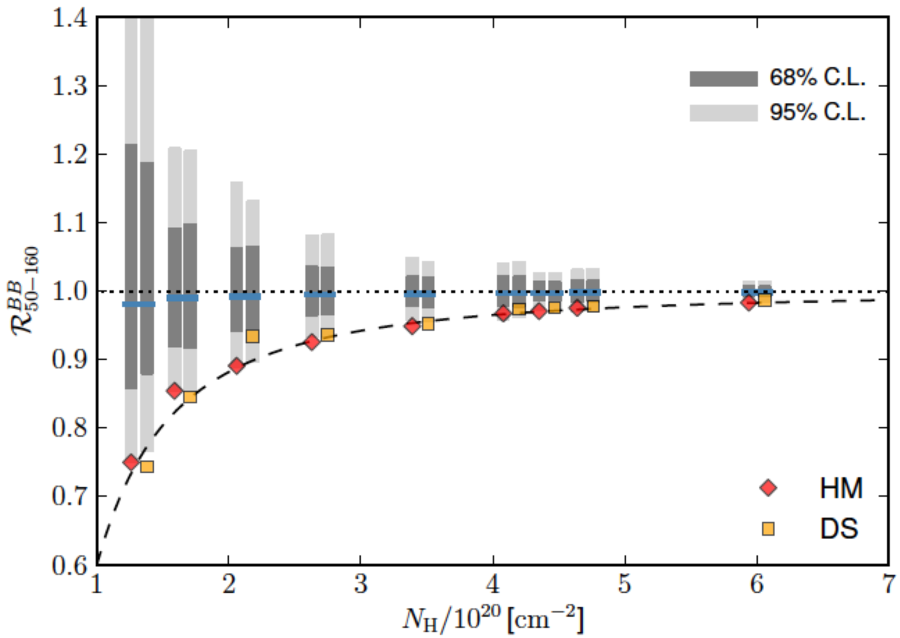


Maximum likelihoods from 500 simulations of a lensed-LCDM + dust model.

- The **means** match **the input values**.
- In the left panel the standard deviation of the histogram yields **σ(r)=0.024**

Evidence for dust decorrelation





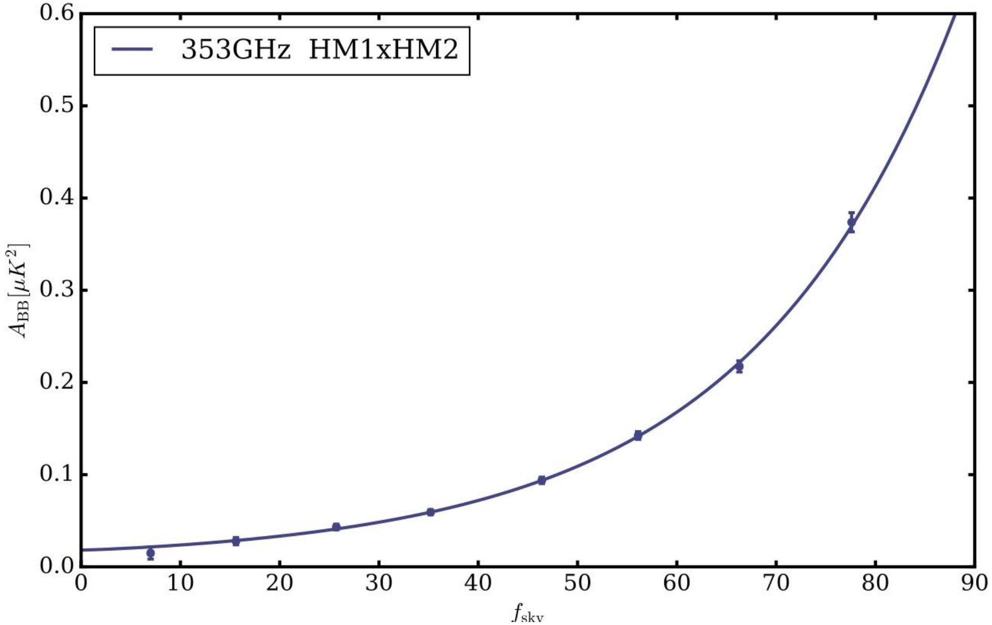
Planck Intermediate Results L, A&A 599, A51 (2017), arXiv:1606.07335

Correlation ratio calculated between 217 and 353 GHz, mostly dust-dominated for BB.

$$\mathcal{R}_\ell^{XX} \equiv \frac{C_\ell^{XX}(353\times217)}{\sqrt{C_\ell^{XX}(353\times353)\,C_\ell^{XX}(217\times217)}}, \qquad (1)$$

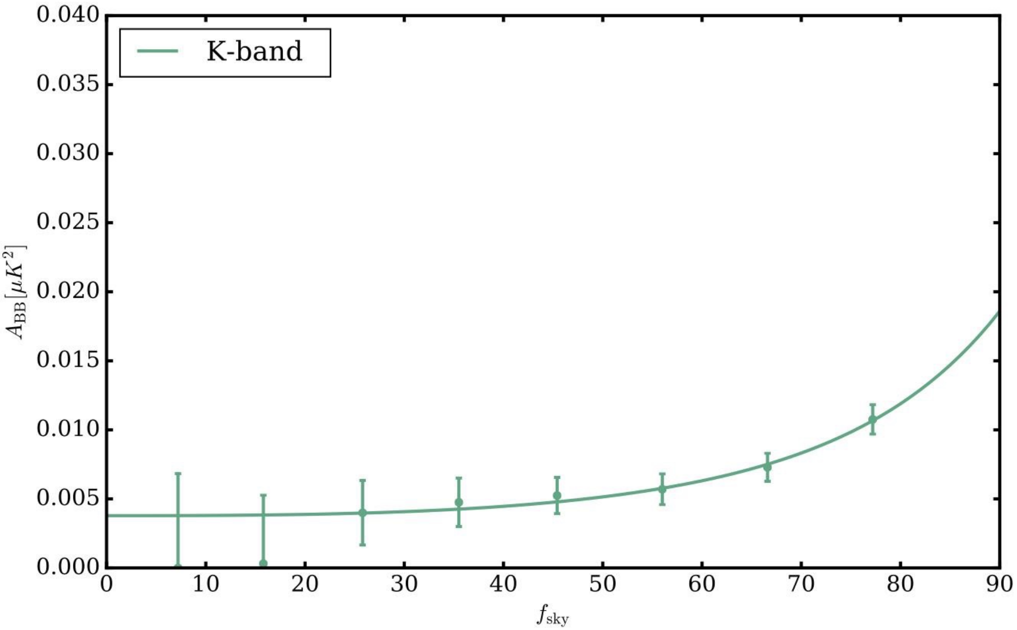
- Extrapolation to regions of low dust column density seem to suggest improbably large decorrelation for BICEP field.
- However, in Section 4, PIP.L models dust decorrelation effect on BKP analysis assuming R=0.95 between 217 and 353 GHz.
- Best constrained by our own data in our field!

Large f_{sky} features (in development)



Inclusion of foreground variation with f_{sky}.

Currently we assume equal foreground amplitudes even as we increase the sky area, whereas we know that above f_{sky} of 0.1 or so the foregrounds will get brighter.

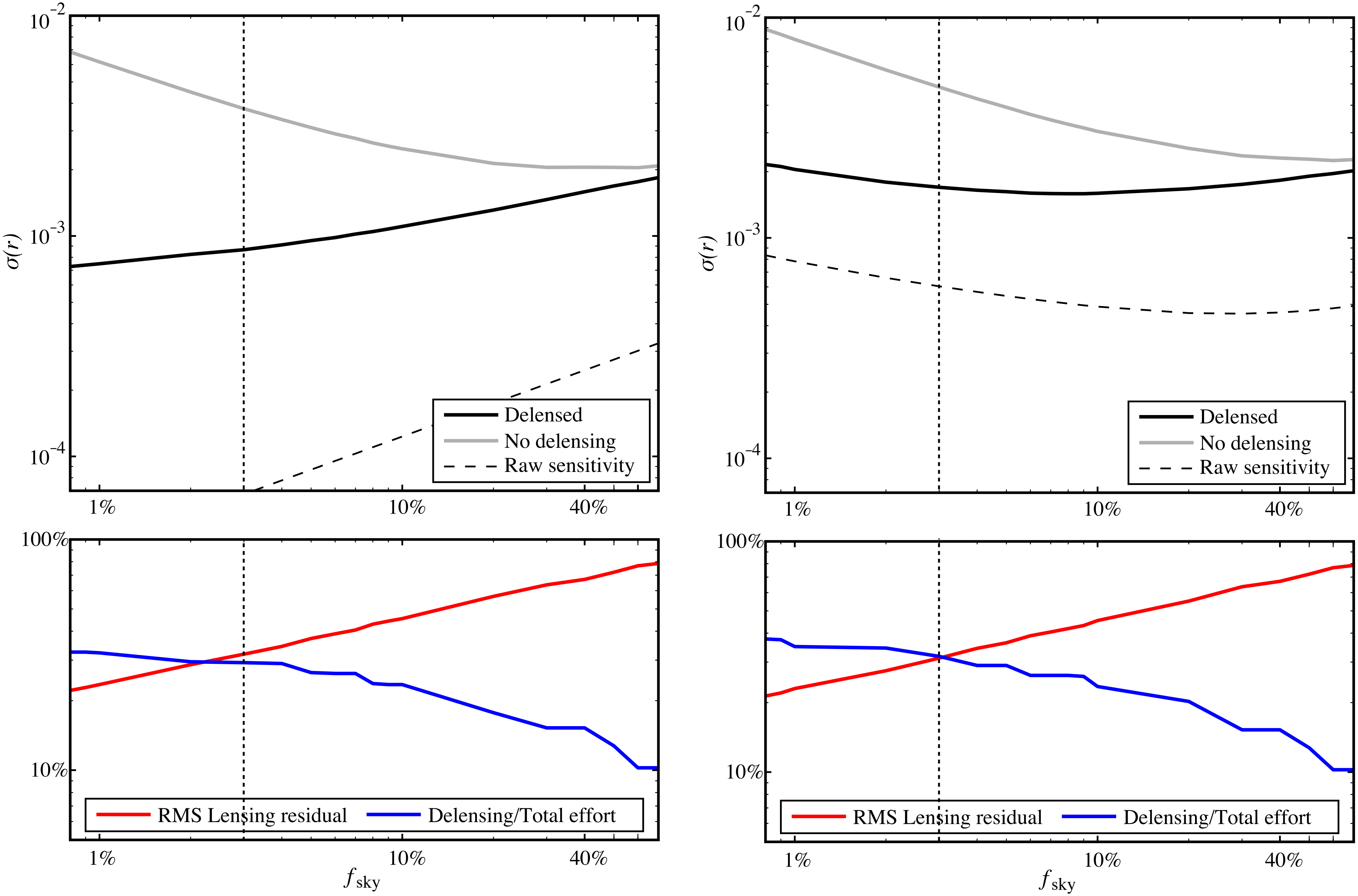


Imposing a systematic penalty and a FG floor

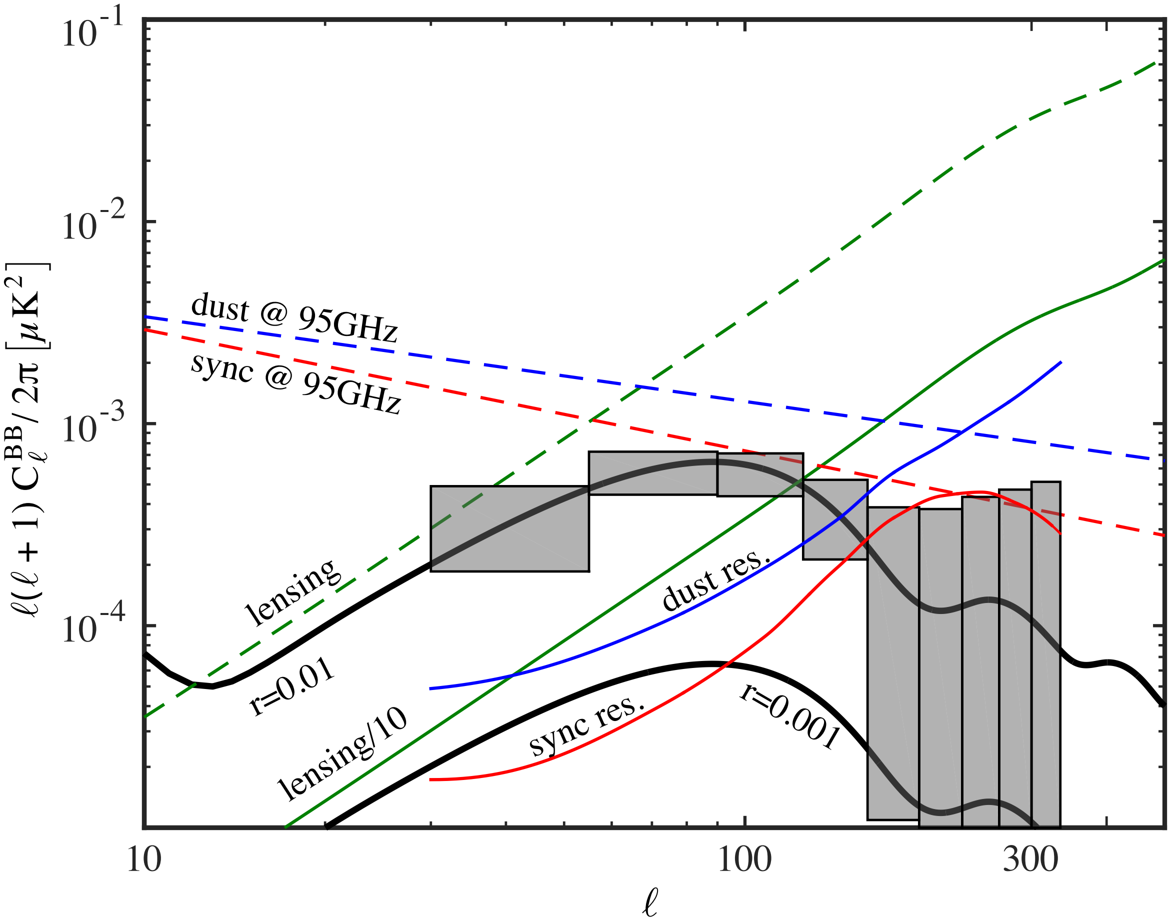
Mitigating systematics and cleaning FG's to high precision will benefit more from high S/N per mode vs raw number of modes measured. This will penalize larger f_{sky}.

Fig. by R.Flauger

Uncertainty forecasts on r, assuming r = 0 (left panel) and r = 0.01 (right panel).



CMB-S4 Science Book arXiv:1610.02743



Bin-by-bin forecasted tensor constraints for r=0.01, fsky=3%.
The contribution of dust and synchrotron to the vertical error bars are shown in solid blue and red lines. The "effective frequency" at which these foreground residuals are defined varies with each bin, allowing the residual lines to go above the input foreground model lines which are defined at a fixed frequency of 95GHz.

Current and Future Directions

- Testing the robustness of the Likelihood/Fisher frameworks on maps from sky models with extra foreground complexity (S4 Data Challenges).
- Framework extension to take in arcmin-scale information about the lensing B-modes for “delensing” — point of contact with other collaborations.
- Including extra nuisance parameters to describe more complex foregrounds and systematics.

Setting up the Validation

Notes on the method:

- Form Data Challenge 1.0 simulations:
  - Get S4 noise curves scaled from achieved performance
  - Form full sky Noise + LCDM + Dust + Sync maps
  - Apply f_sky and appodization mask

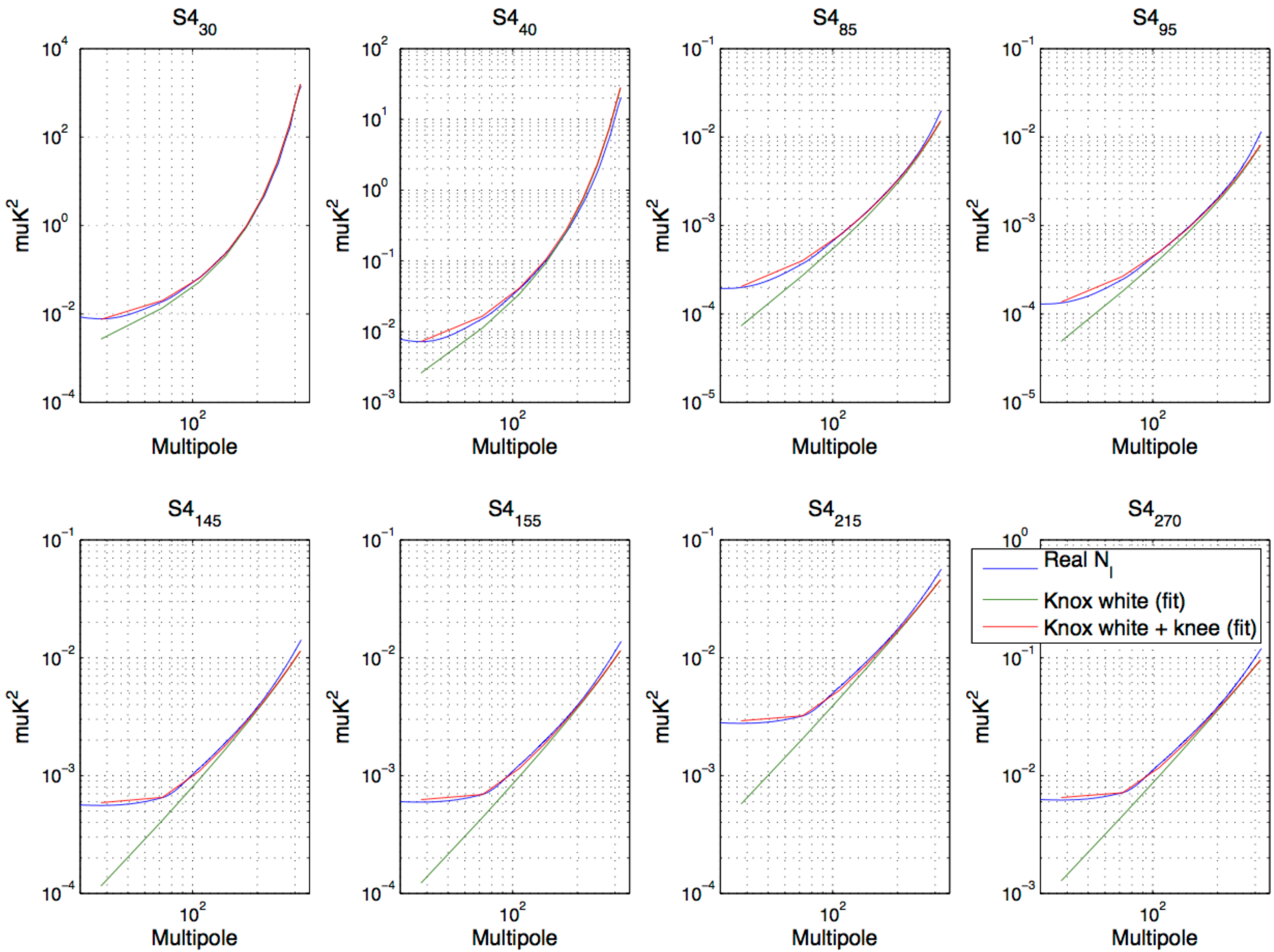
- Use a pure-B estimator (J. Grain et al, Phys. Rev. D. 79,12315) to calculate all the auto and cross spectra.

- Use the BICEP/Keck multi-component spectral-based likelihood framework.

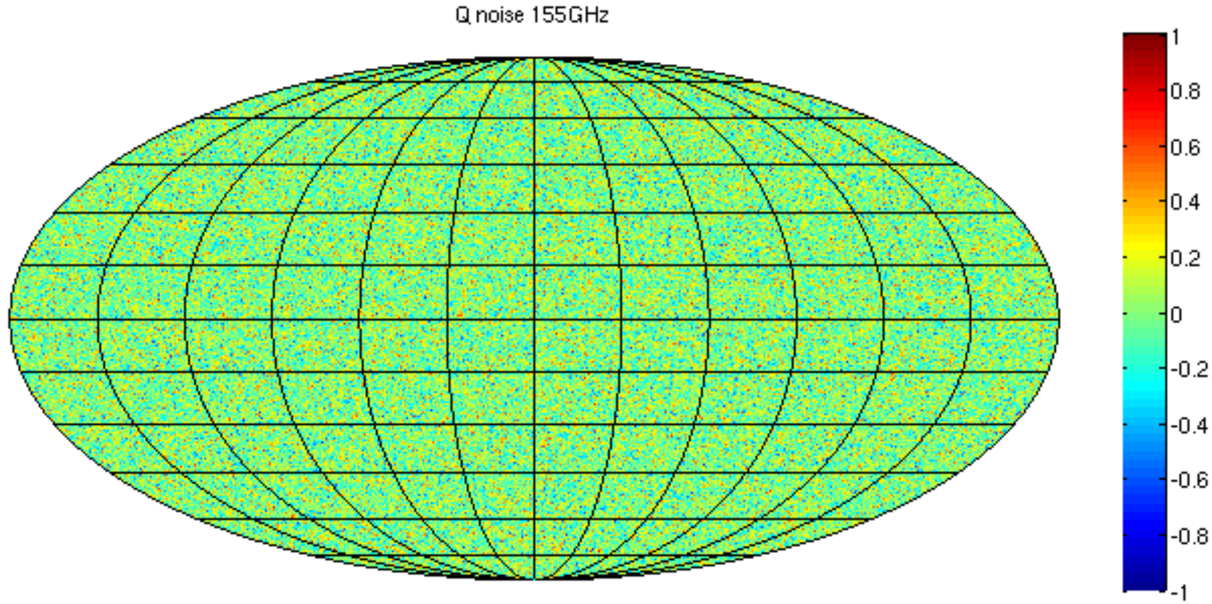
- Use a global Maximum-Likelihood peak search (of similar dimensionality as in the Science Book Fisher forecasts, bar a dust decorrelation parameter) to obtain recovered ML histograms. The standard deviations of histograms offer a measure of the constraining power in our dataset. The means of histograms offer a measure of bias.

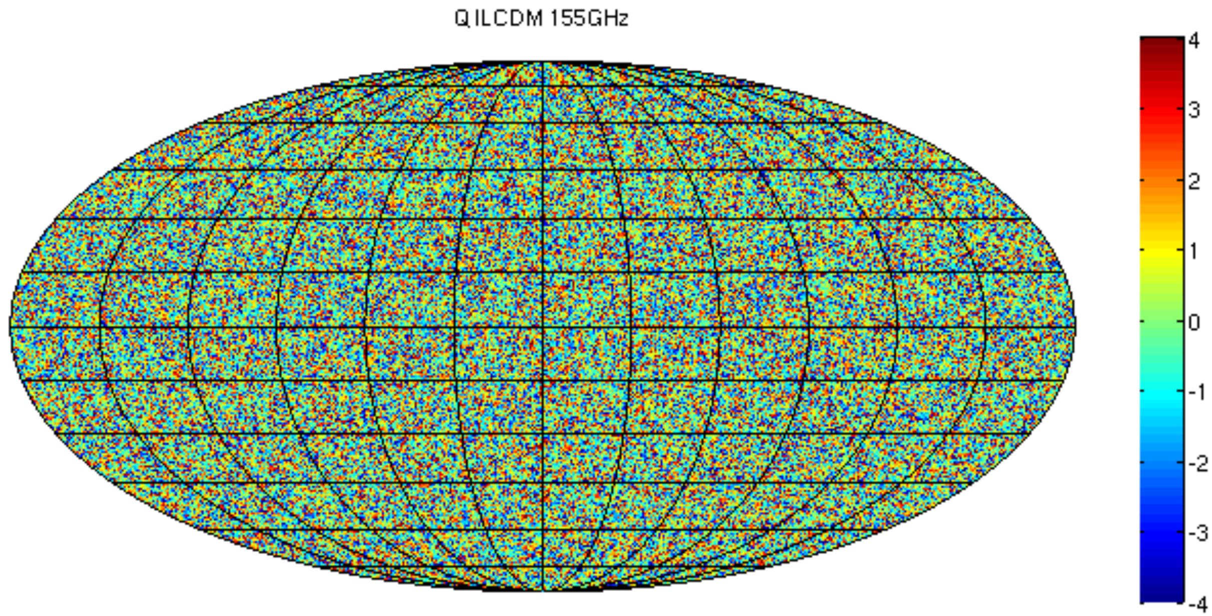
- Compare to Fisher results used in the CMB-S4 Science Book

— Fit noise curves scaled from achieved performance

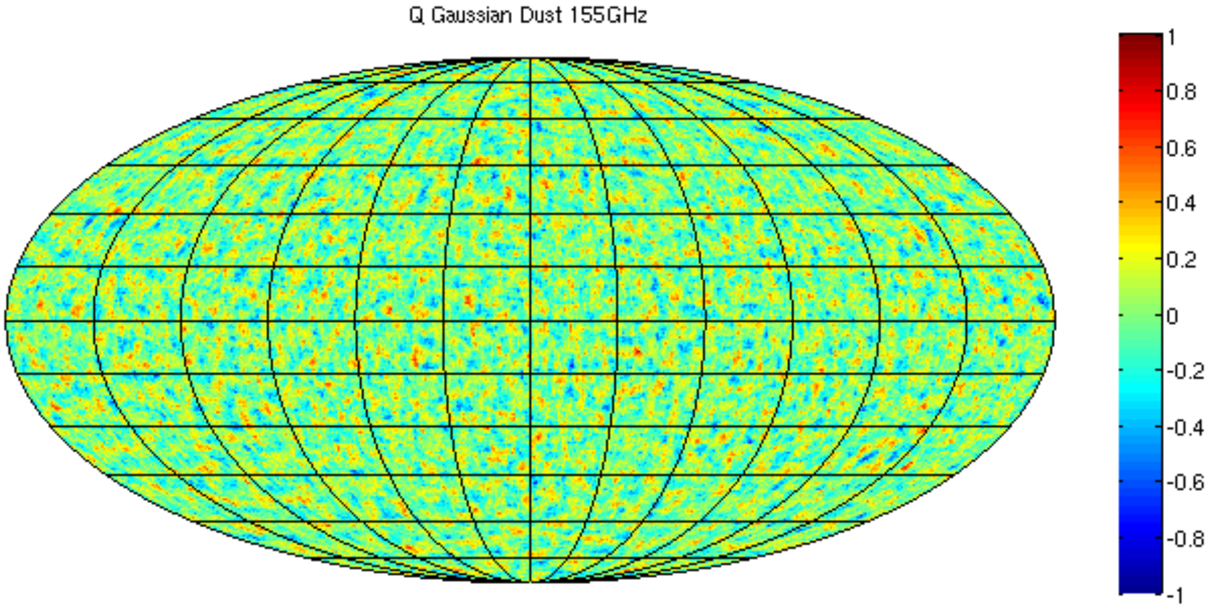


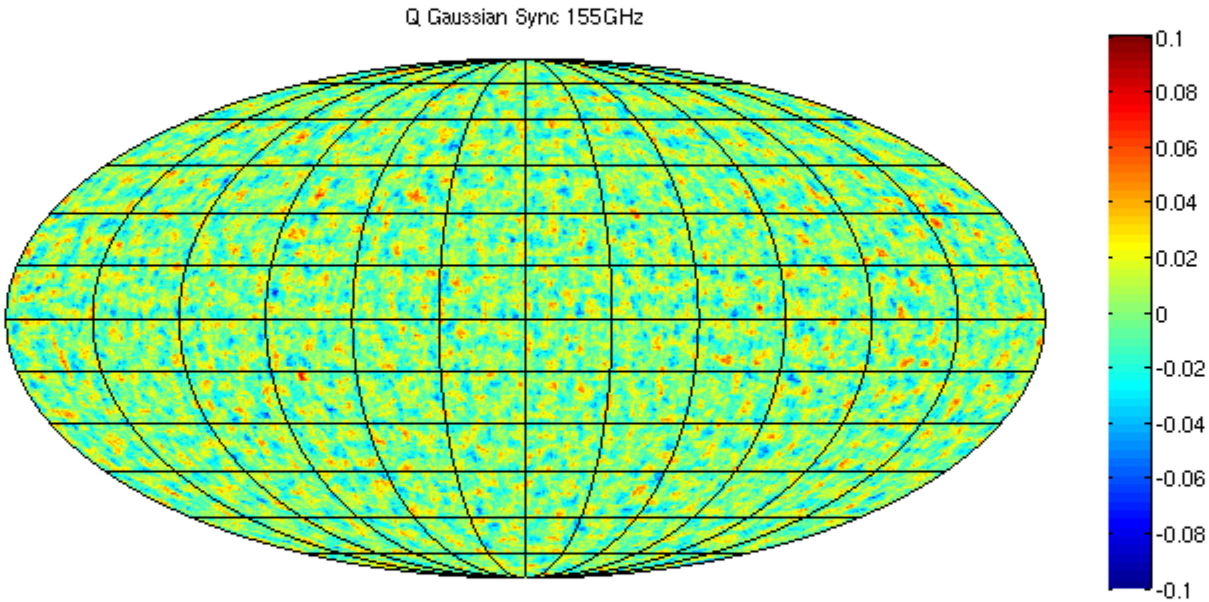
Form noise and LCDM maps



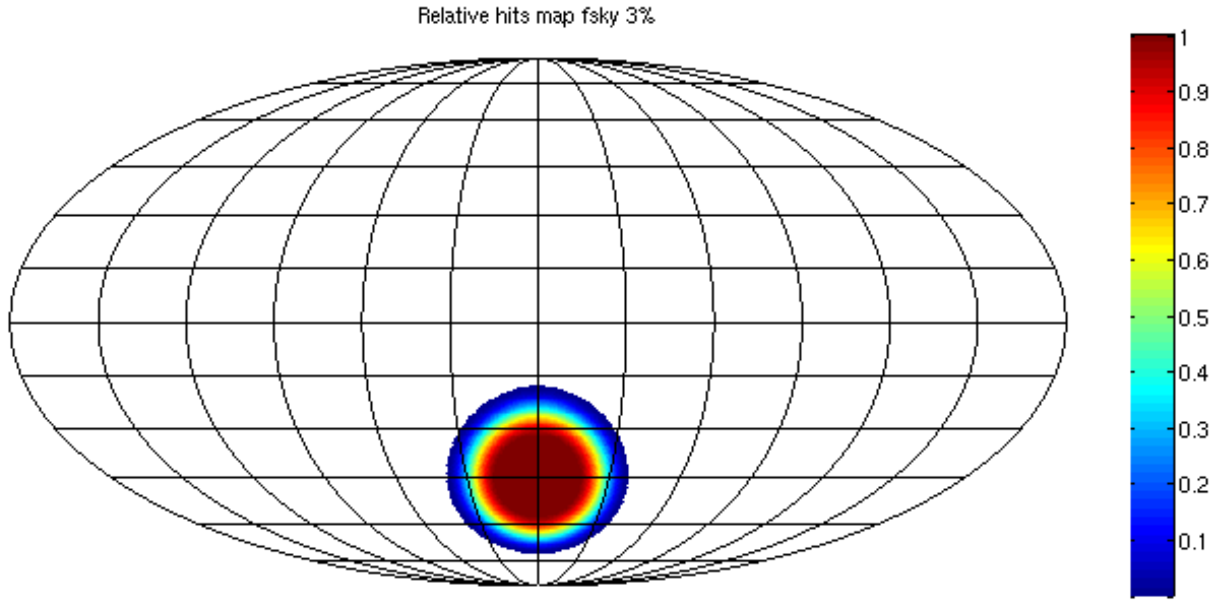


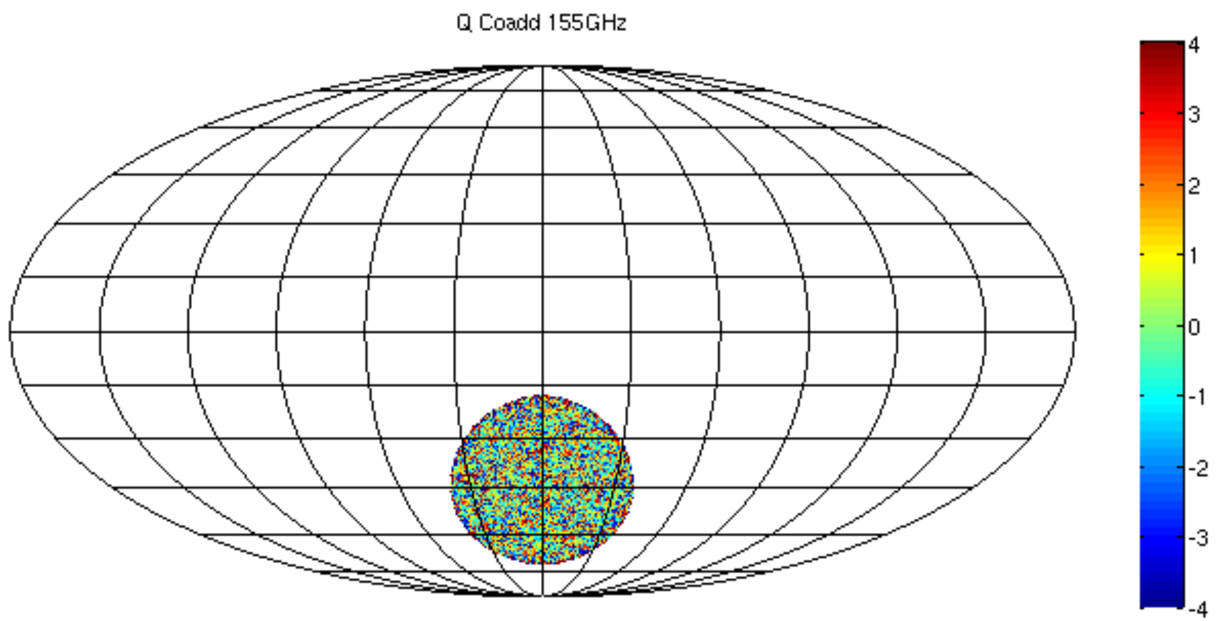
Add Gaussian Dust and Synchrotron



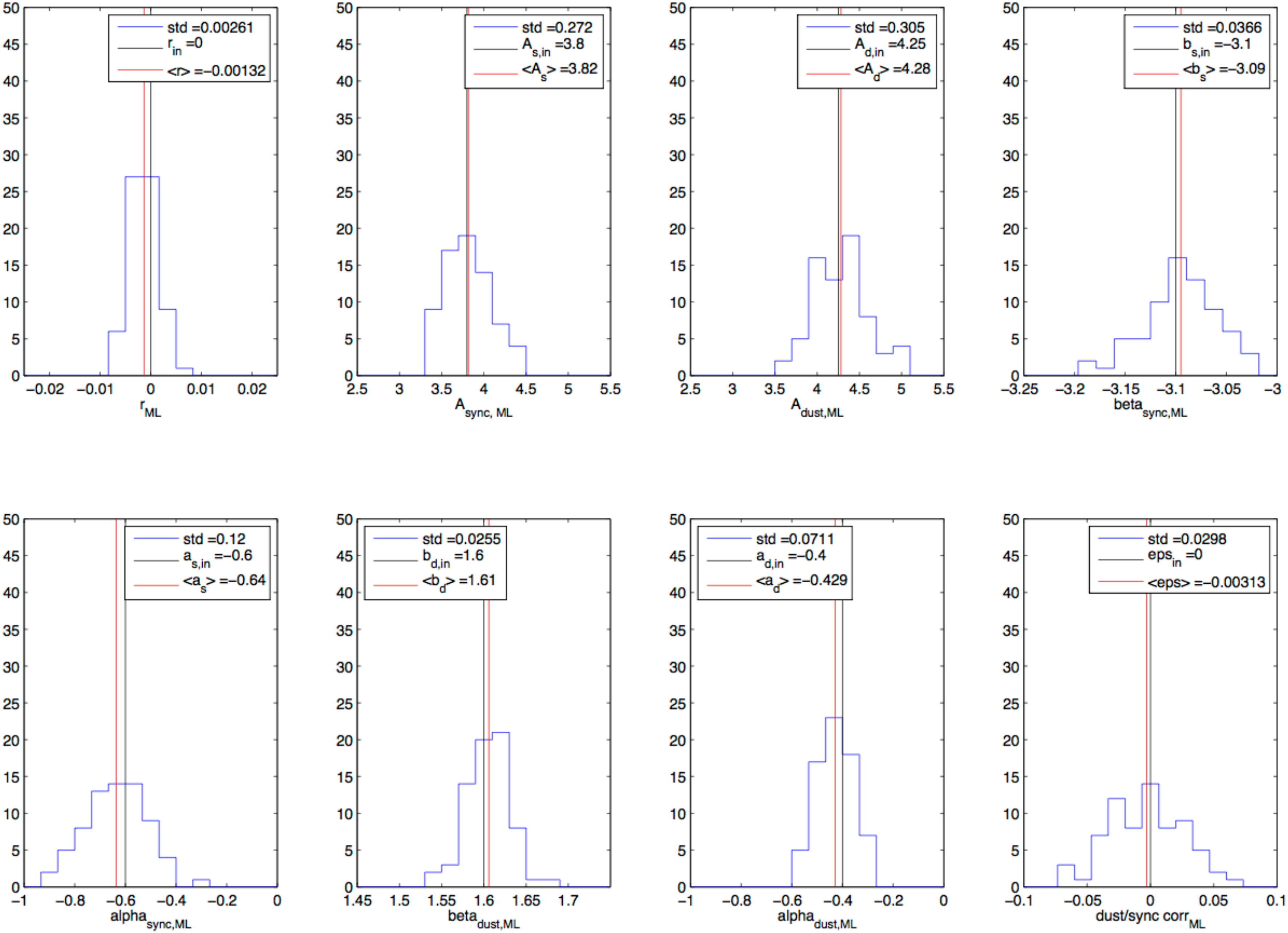


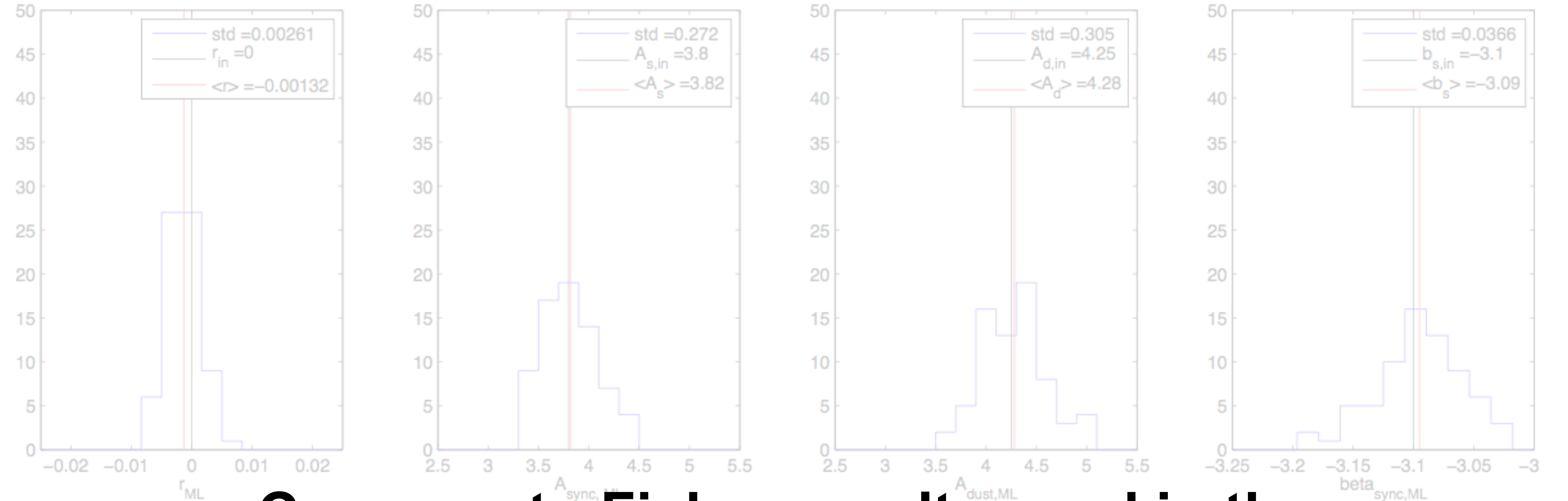
Apply Mask and Form Full Map



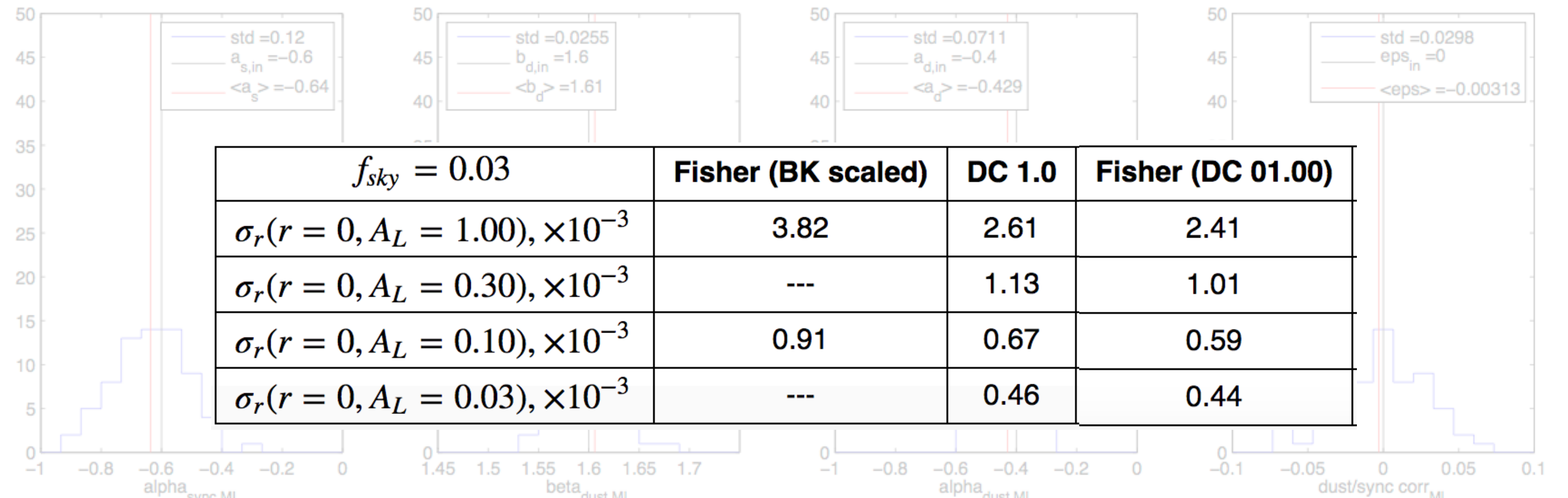


Run Global Maximum-Likelihood Search (100 rlz)





Compare to Fisher results used in the CMB-S4 Science Book



$f_{sky} = 0.03$	Fisher (BK scaled)	DC 1.0	Fisher (DC 01.00)
$\sigma_r(r = 0, A_L = 1.00), \times 10^{-3}$	3.82	2.61	2.41
$\sigma_r(r = 0, A_L = 0.30), \times 10^{-3}$	---	1.13	1.01
$\sigma_r(r = 0, A_L = 0.10), \times 10^{-3}$	0.91	0.67	0.59
$\sigma_r(r = 0, A_L = 0.03), \times 10^{-3}$	---	0.46	0.44