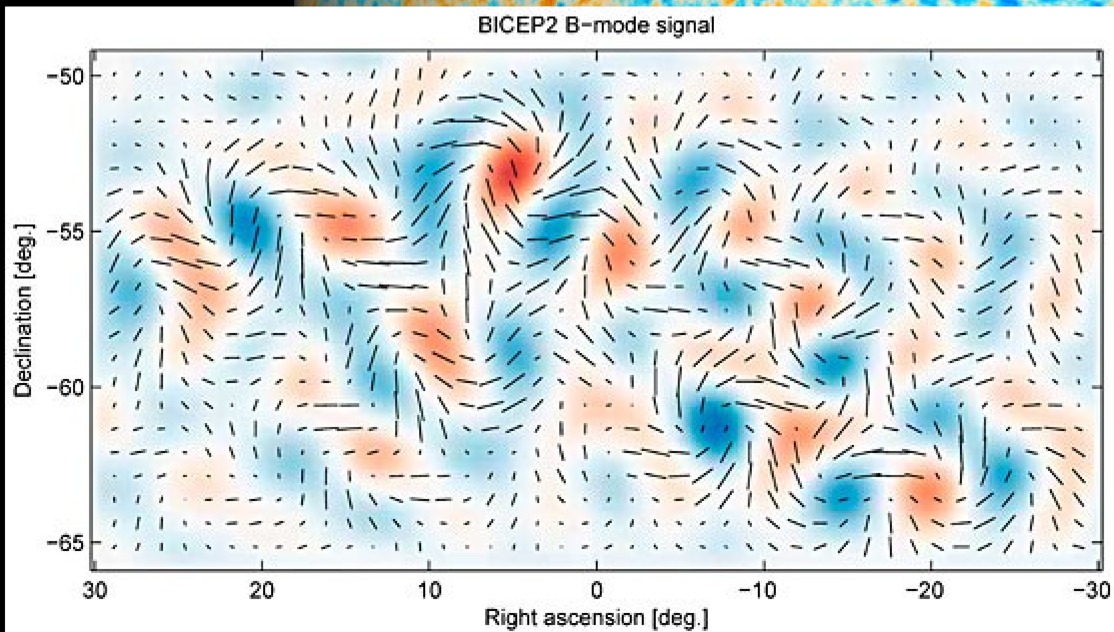
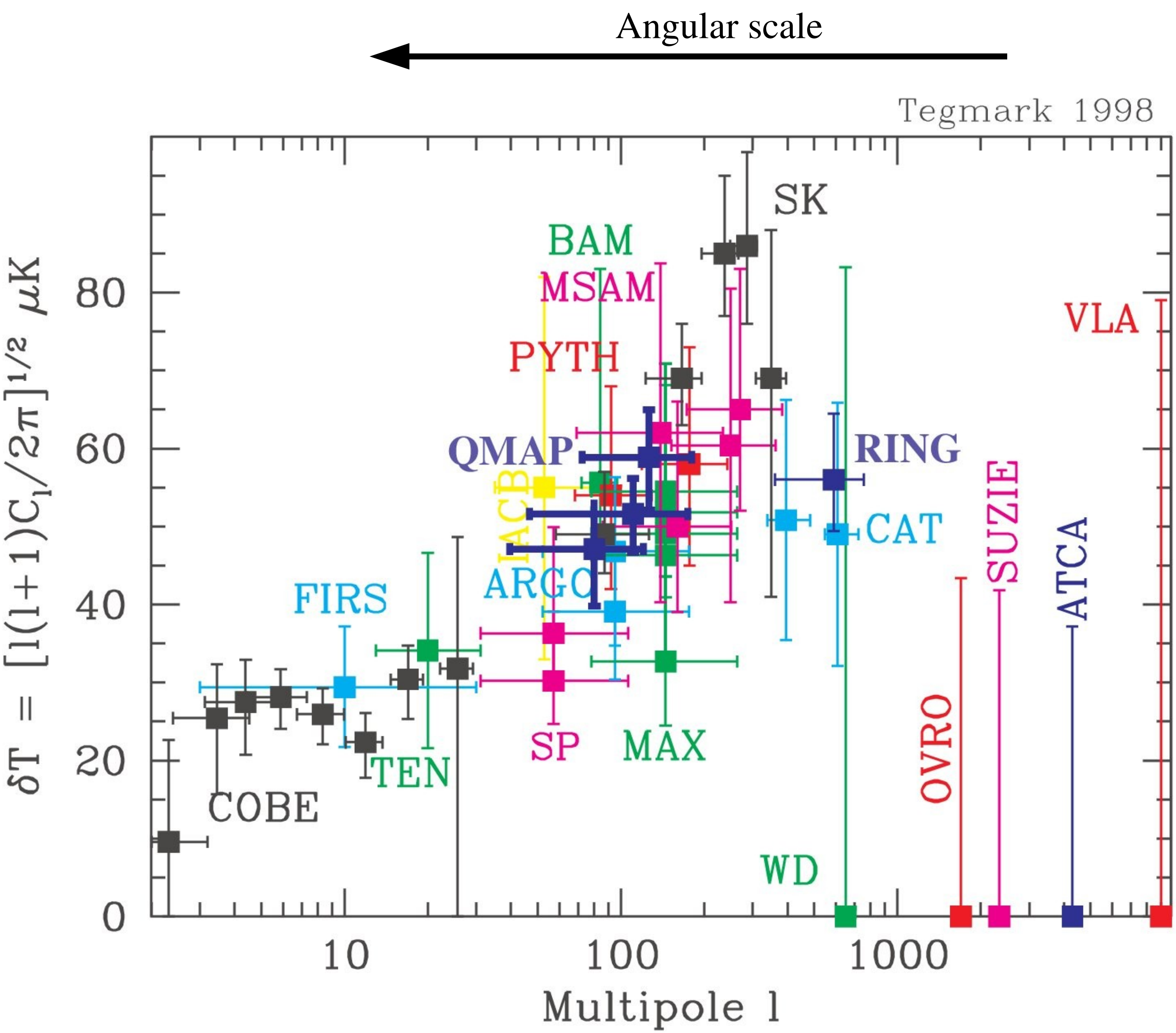
Current Status of Cosmological Inflation

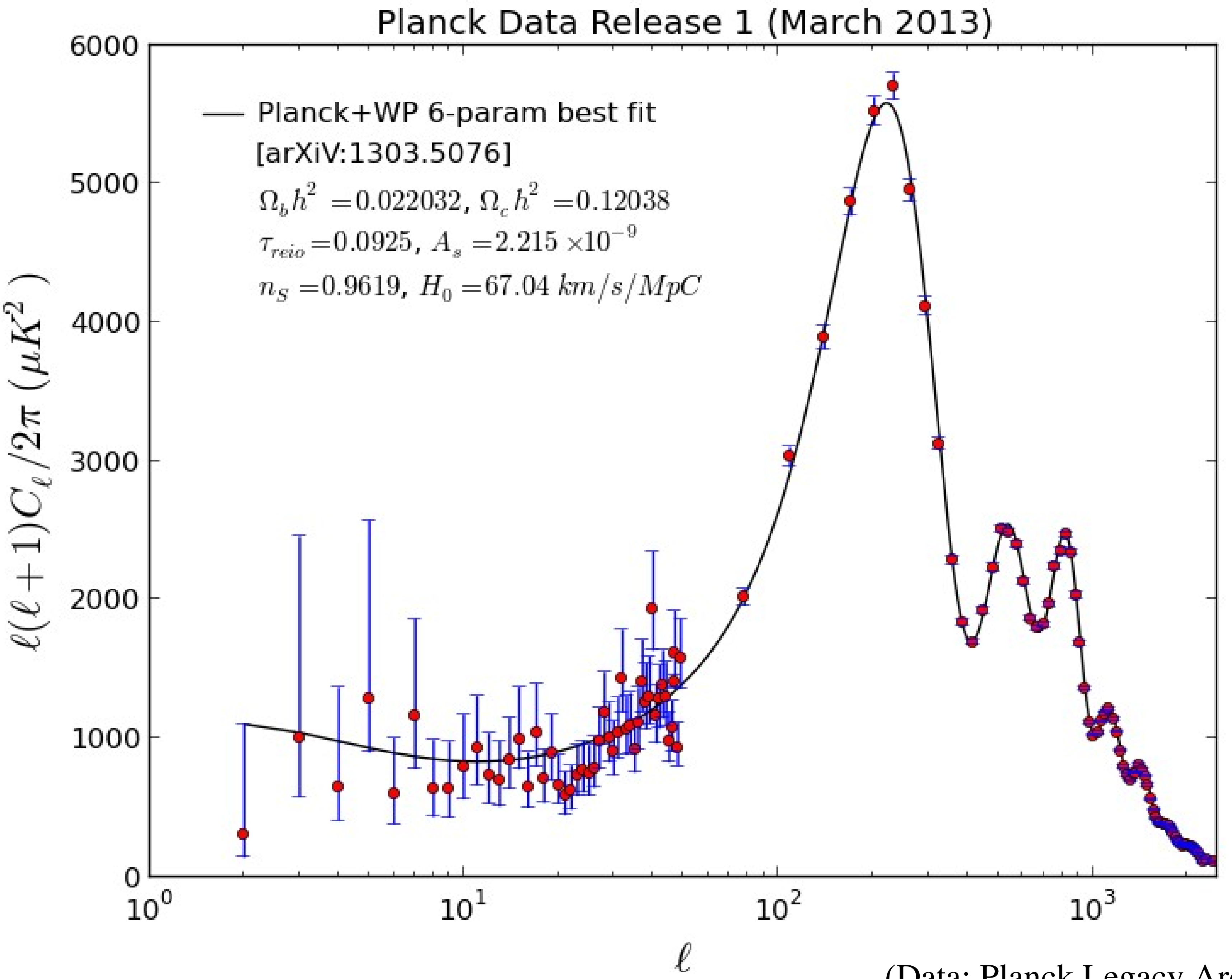


Will Kinney
Virtual Institute of Astroparticle Physics
23 January 2015

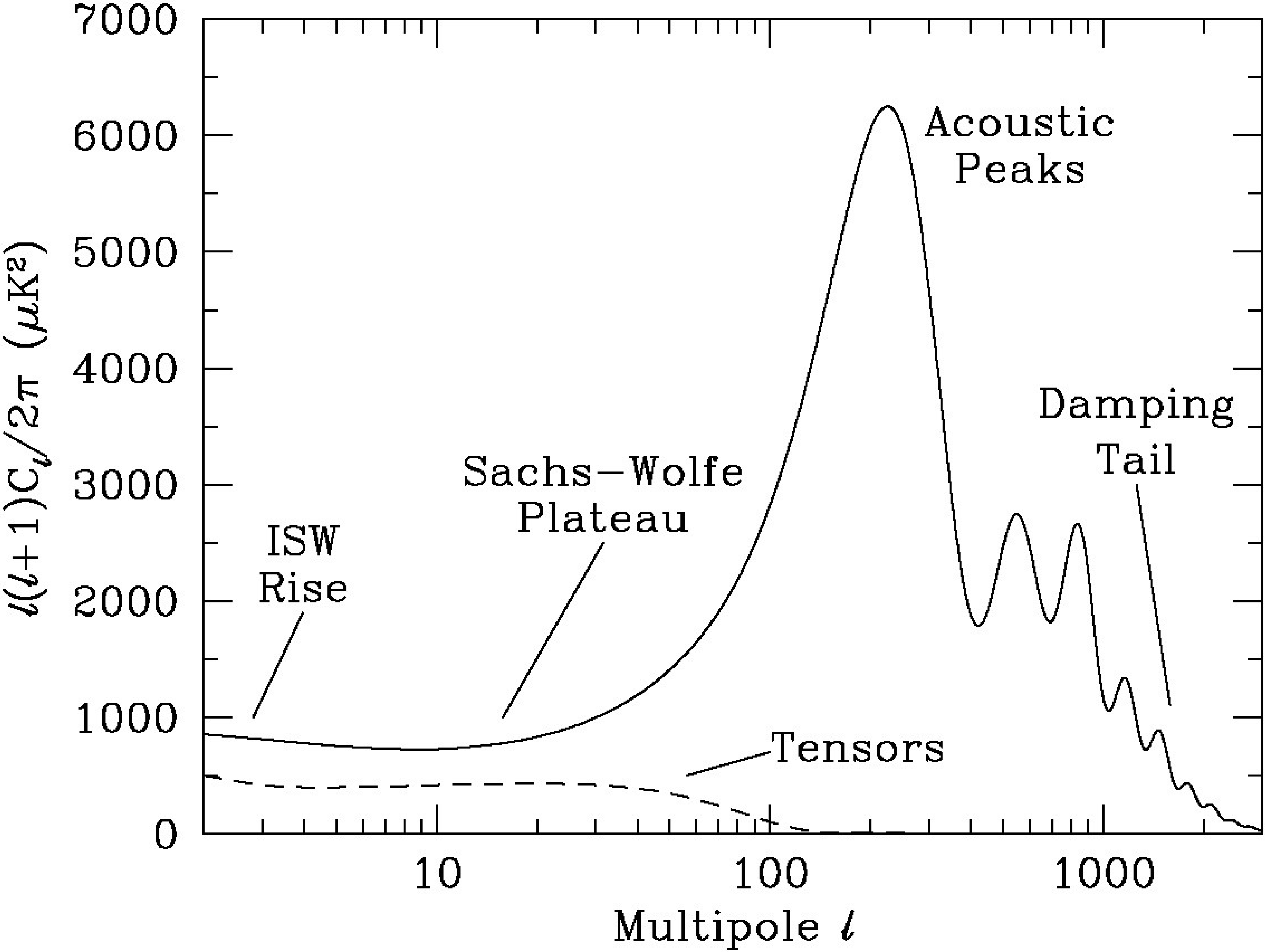
NSF
University at Buffalo *The State University of New York*

The CMB Angular Power Spectrum (1998)



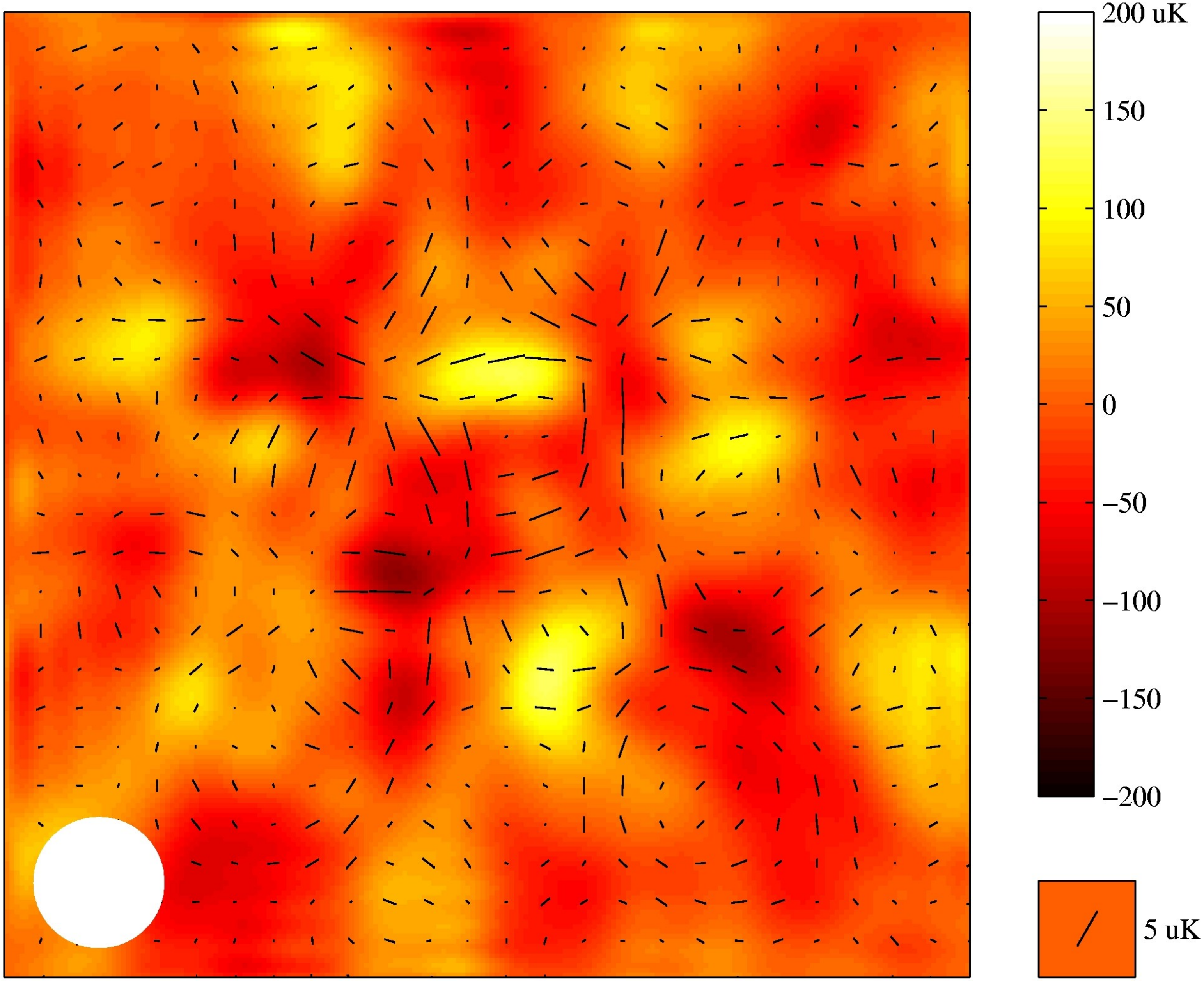


(Data: Planck Legacy Archive)



7000
6000
5000
4000
3000
2000
1000
0
10
100
1000
Multipole ℓ
ℓ(ℓ+1)C_ℓ/2π (μK²)
Acoustic Peaks
Damping Tail
Sachs–Wolfe Plateau
ISW Rise
Tensors

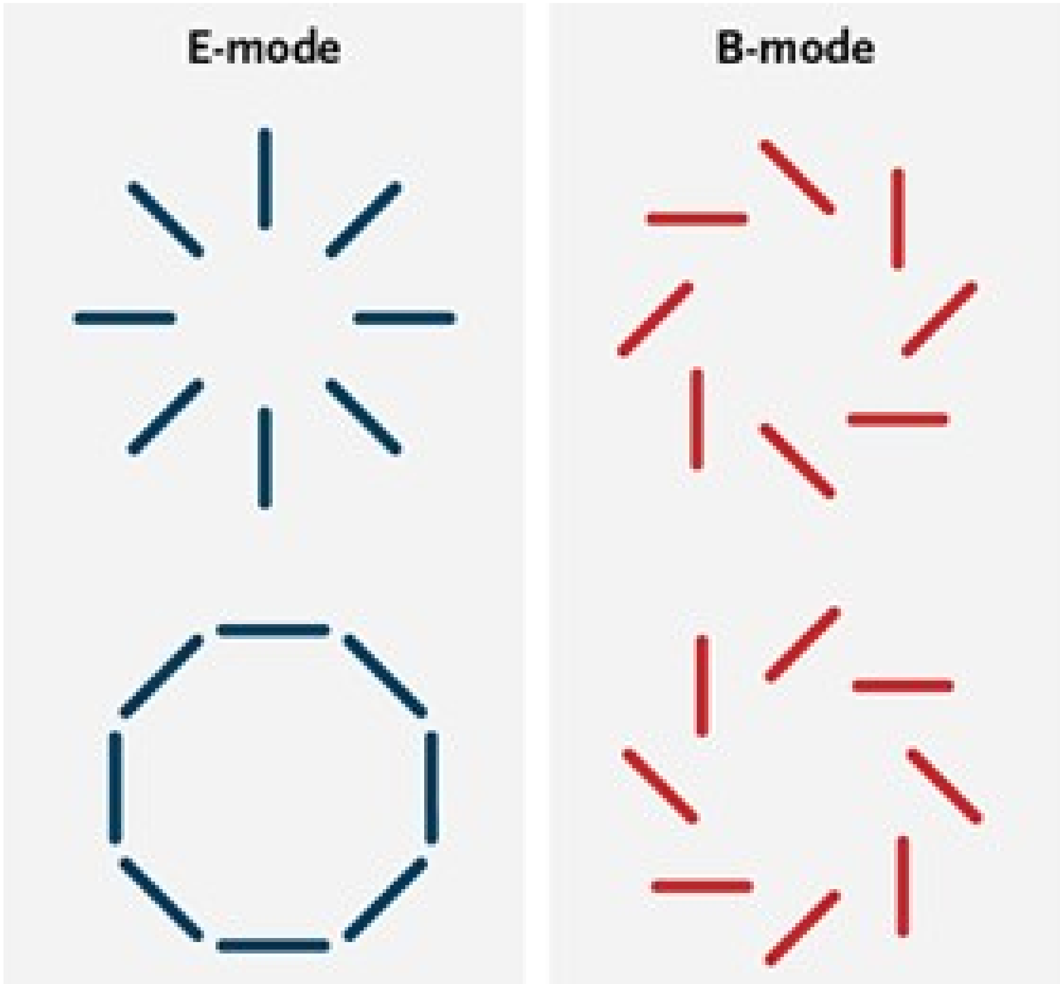
The CMB is Polarized!



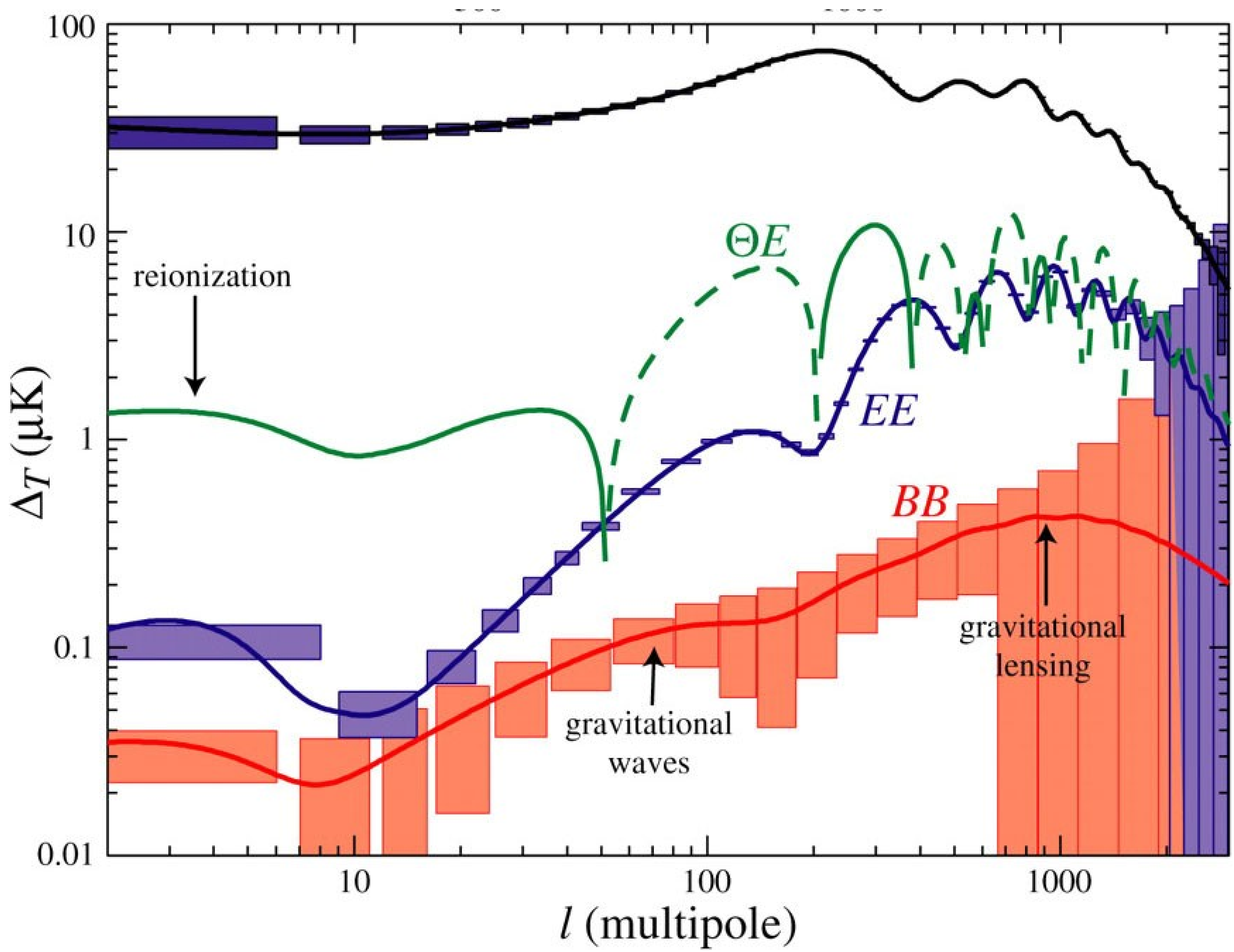
Map is 5 degrees square

(Image: DASI Collaboration)

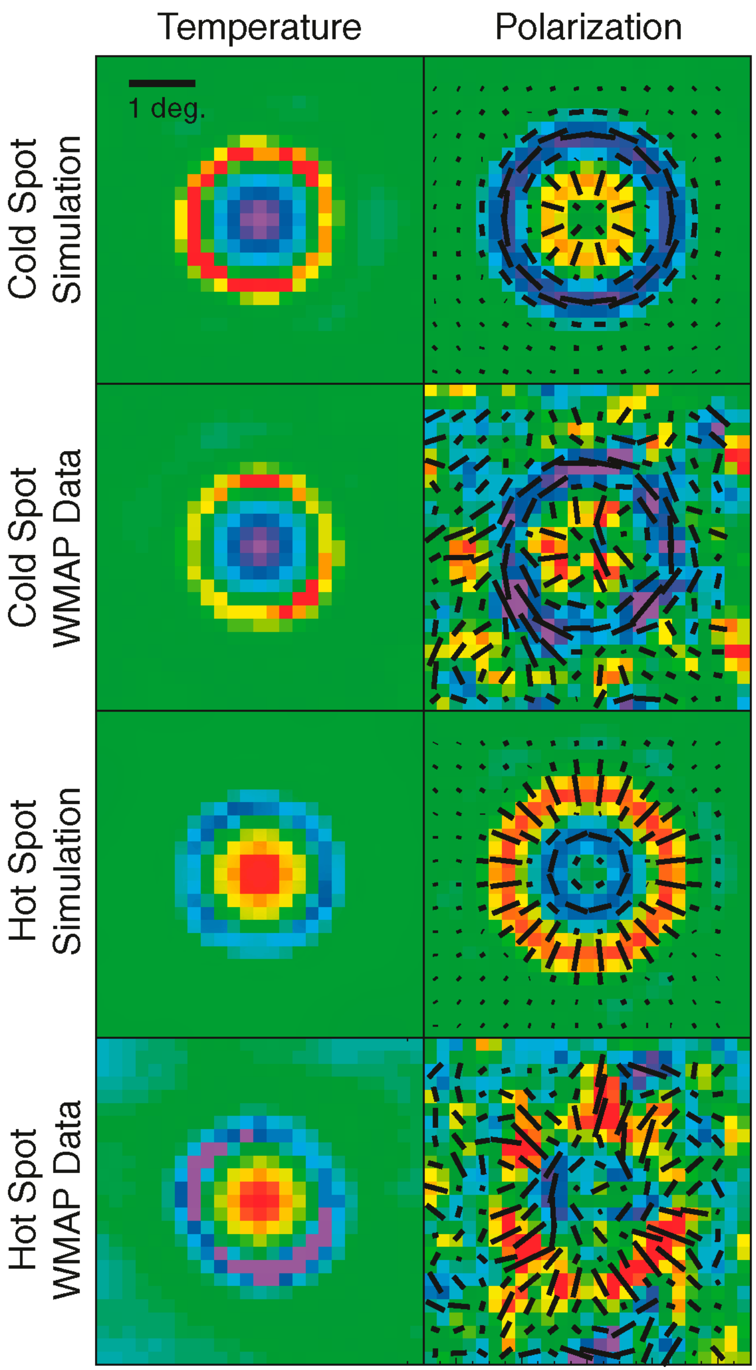
Even- and Odd-parity Polarization



CMB Polarization Angular Power Spectra



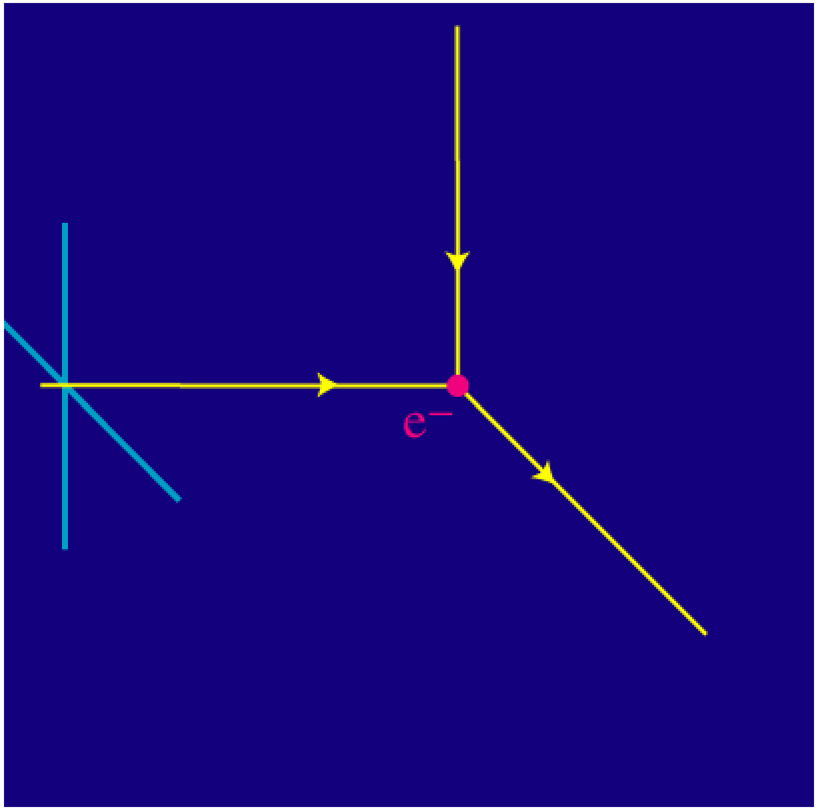
E-mode Polarization



Polarization strongest along *gradients* in temperature

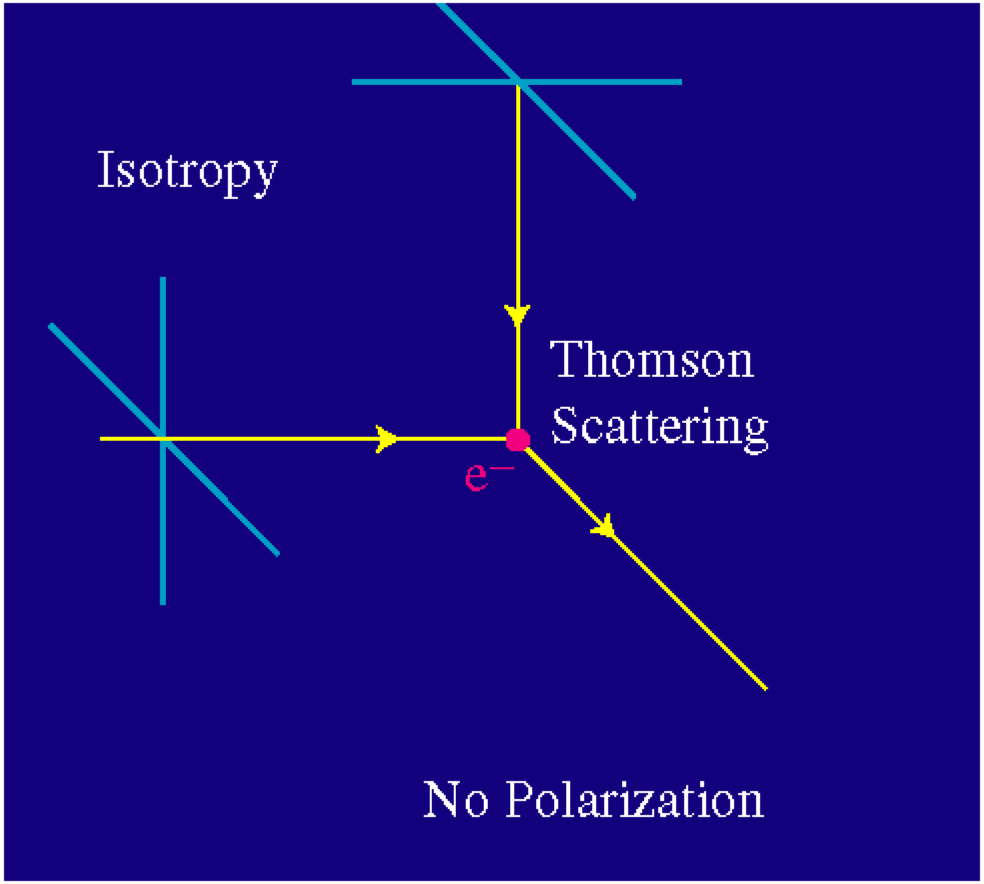
(Komatsu, *et al.*, arXiv:0912.0522)

Anisotropy and the E-mode



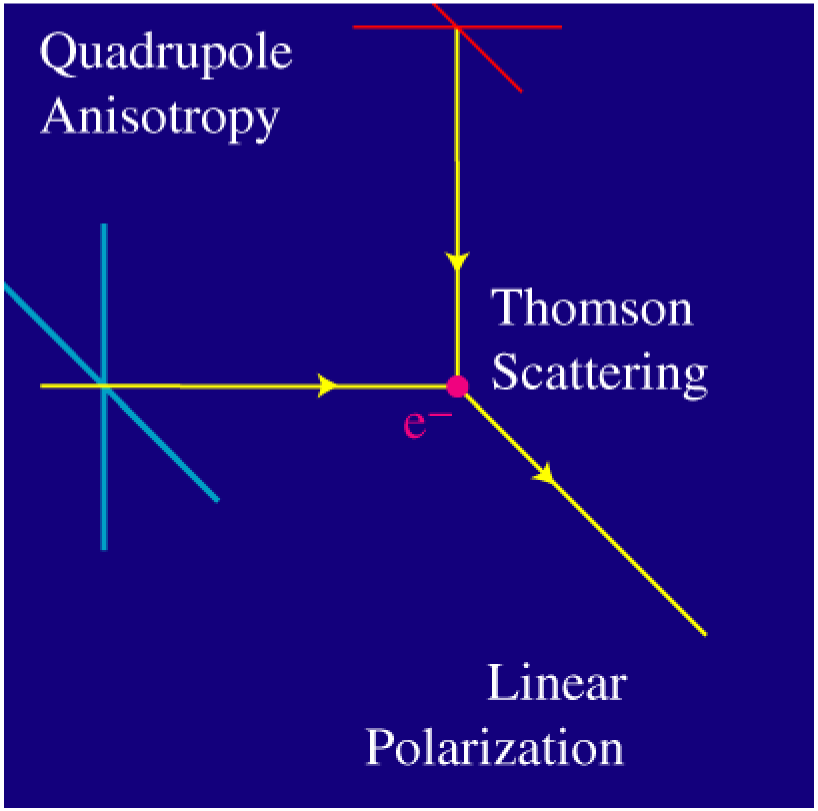
(Image: Wayne Hu)

Anisotropy and the E-mode



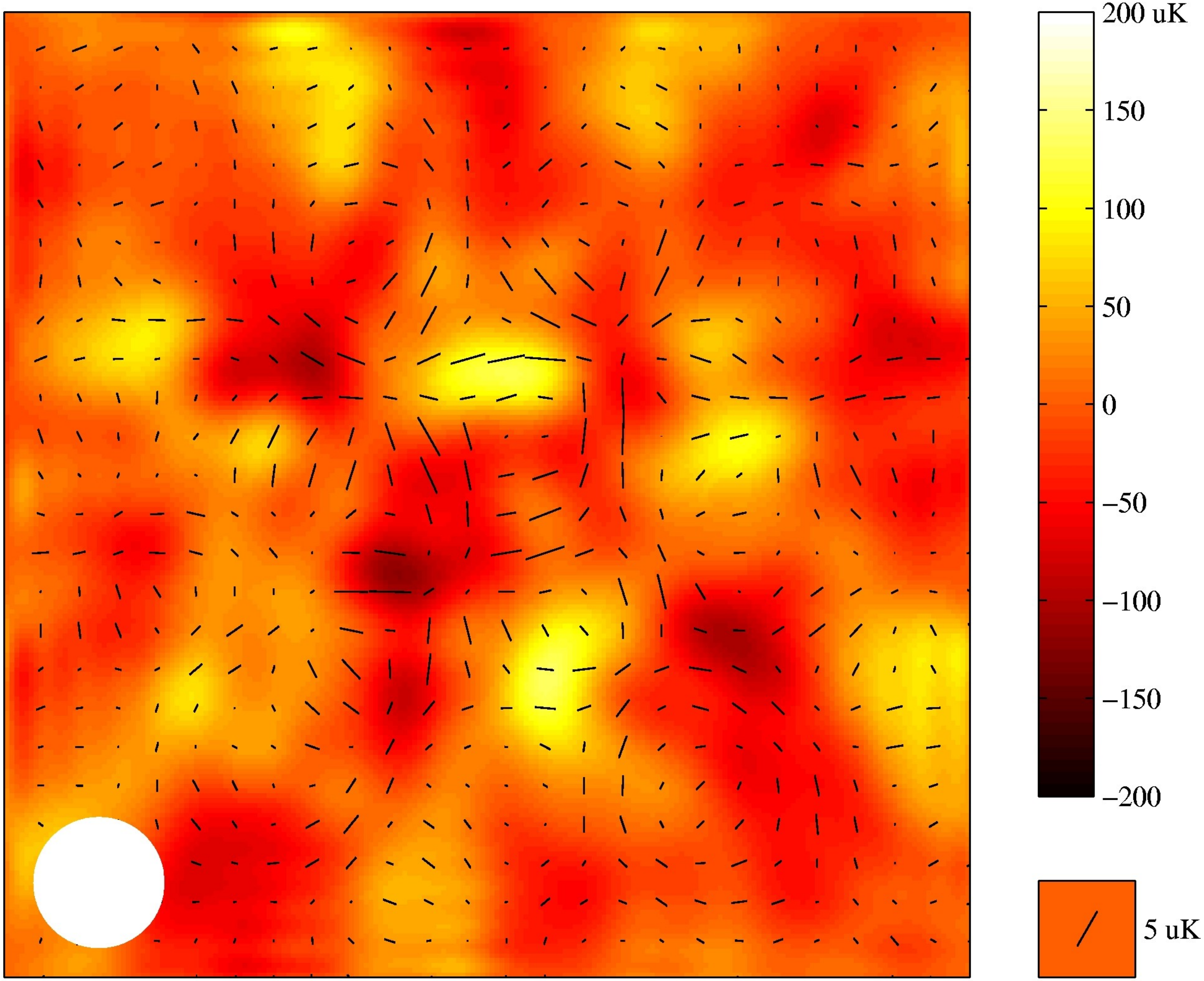
(Image: Wayne Hu)

Anisotropy and the E-mode



(Image: Wayne Hu)

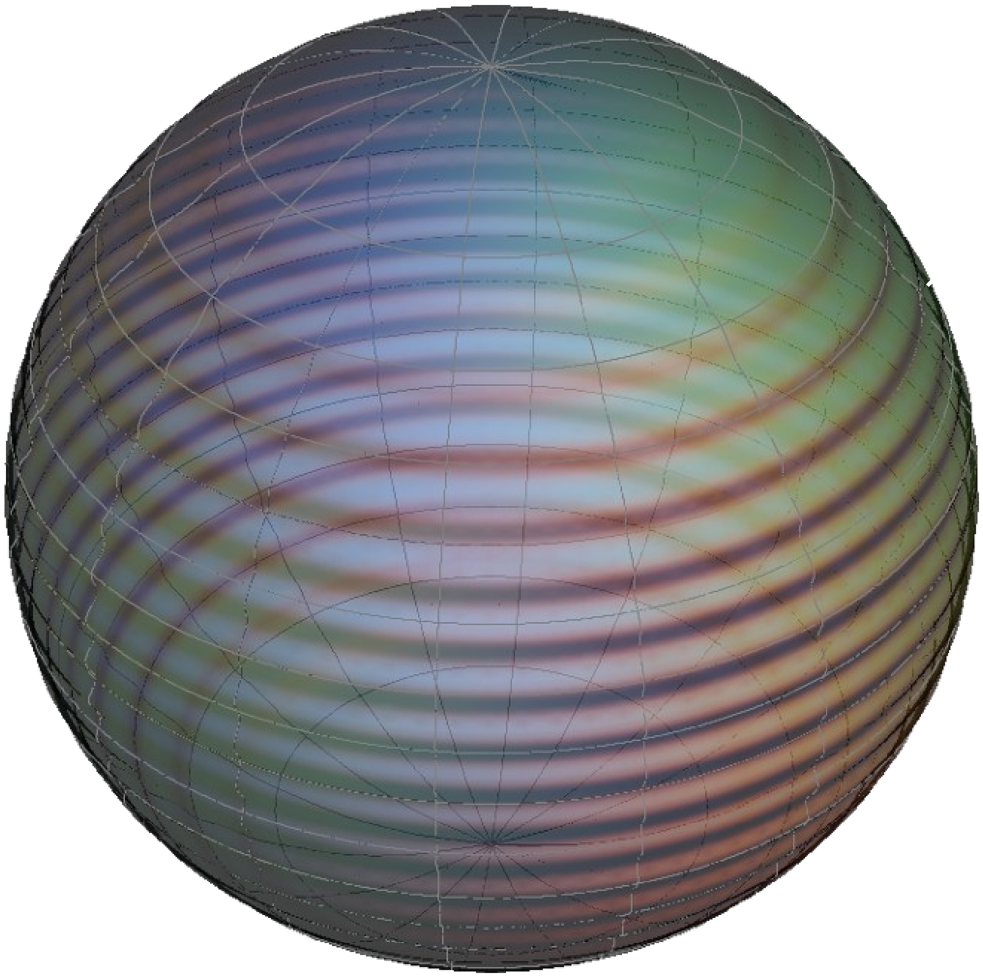
2002: DASI Detects E-mode Polarization



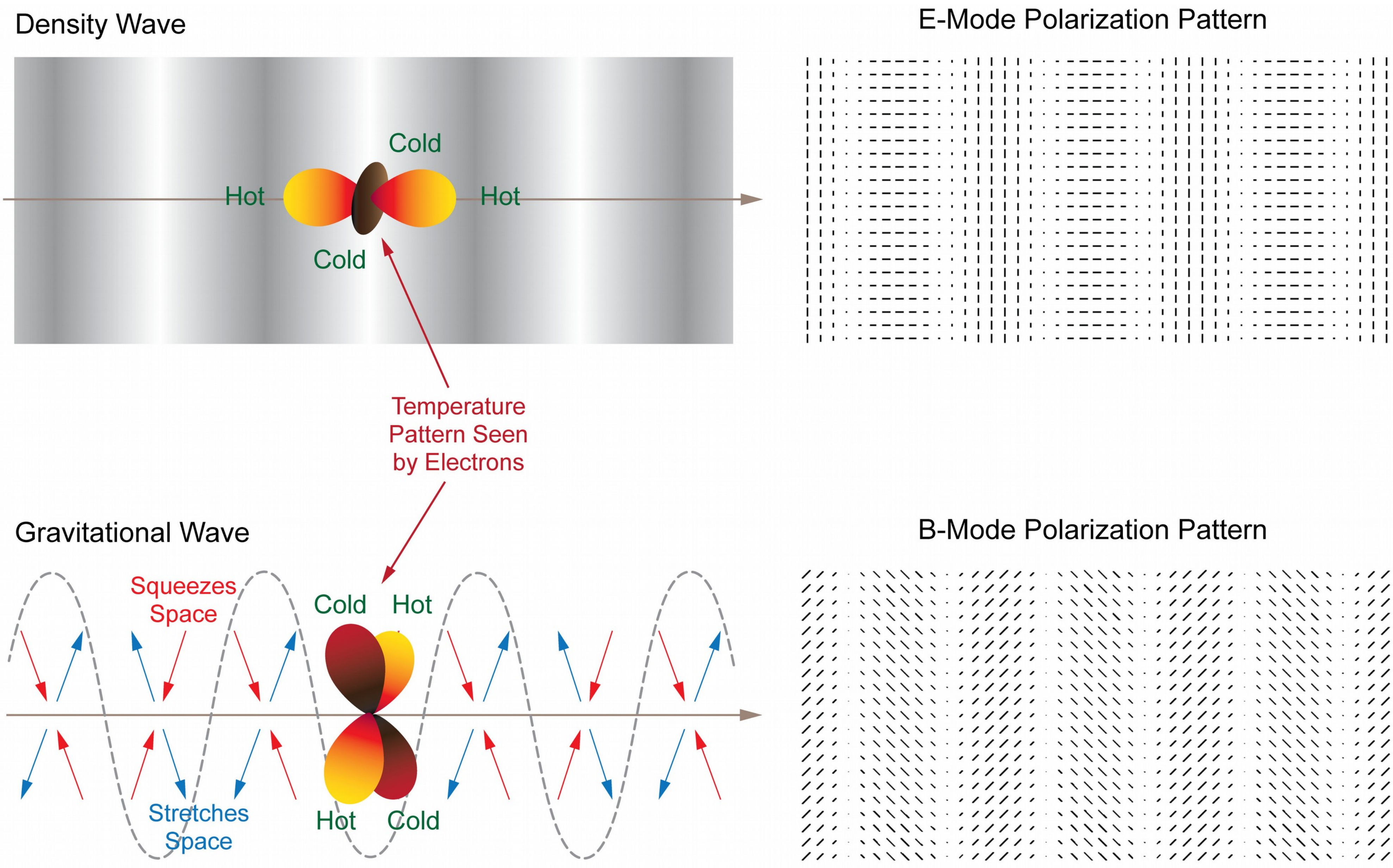
Map is 5 degrees square

(Image: DASI Collaboration)

Primordial Gravity Waves

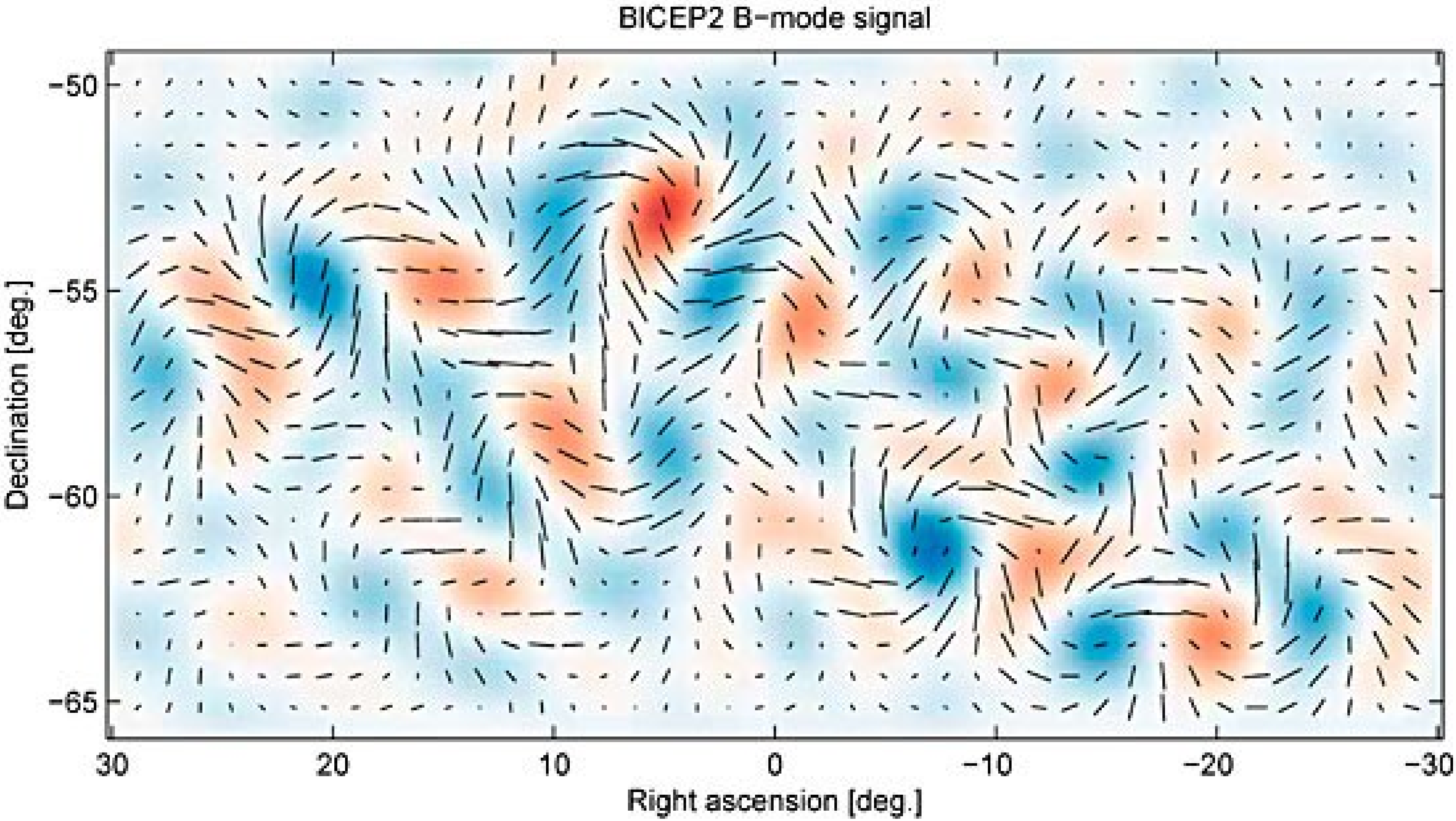


Gravity Waves Generate B-mode Polarization

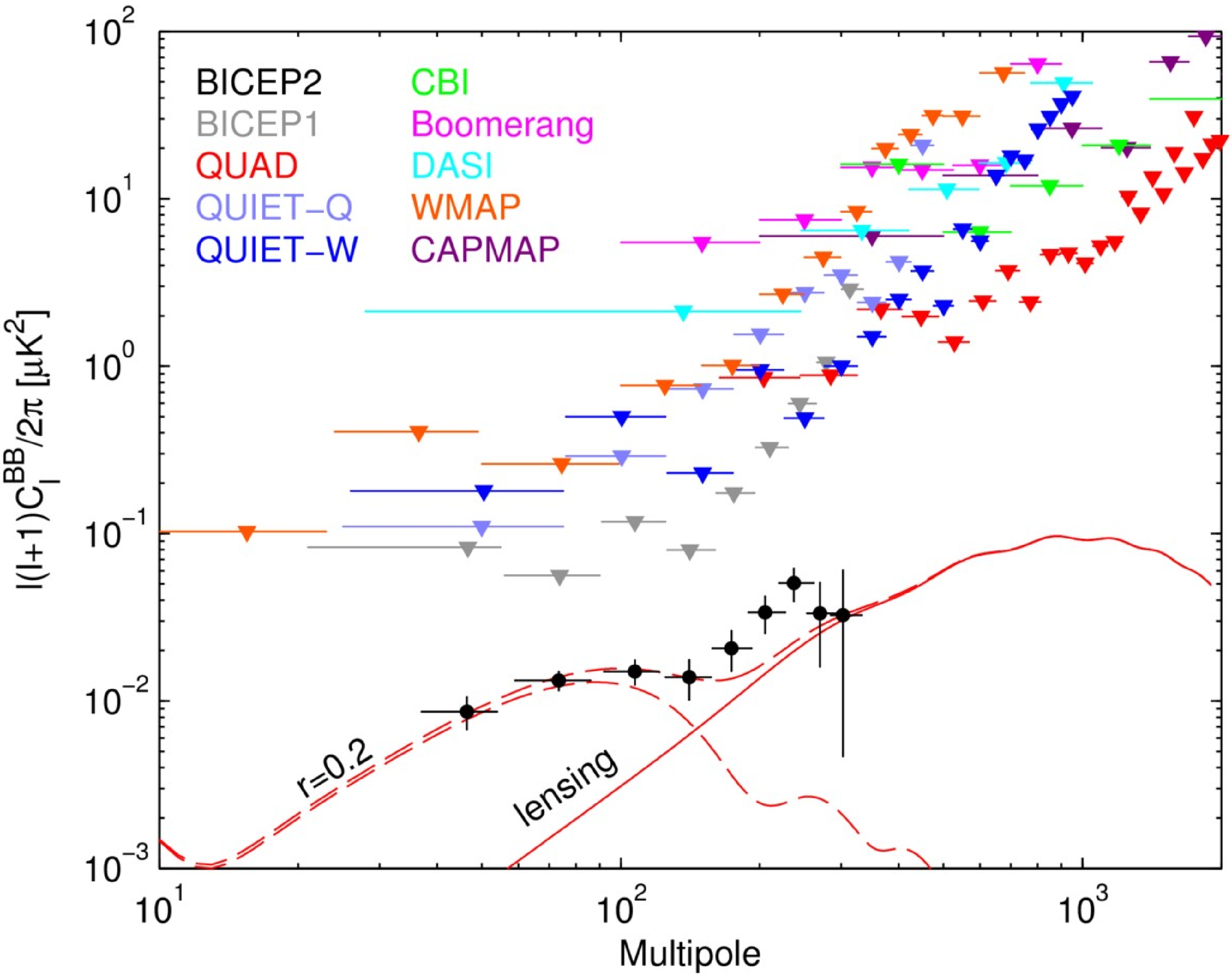


(Image: bicepkeck.org)

BICEP: Pretty Swirly Things

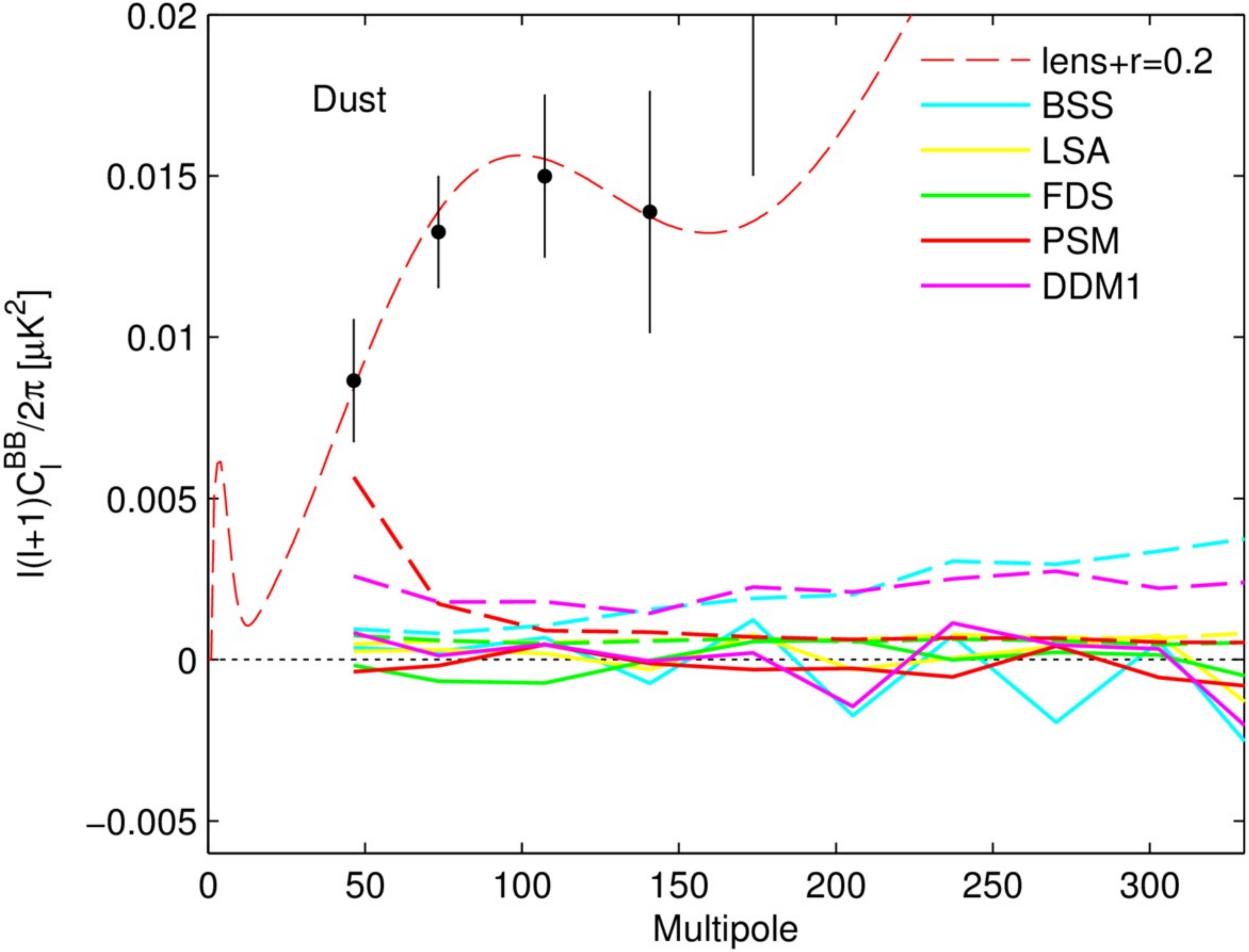


(Ade, *et al.*, arXiv:1403.3985)



(Ade, *et al.*, arXiv:1403.3985)

Is It Dust?



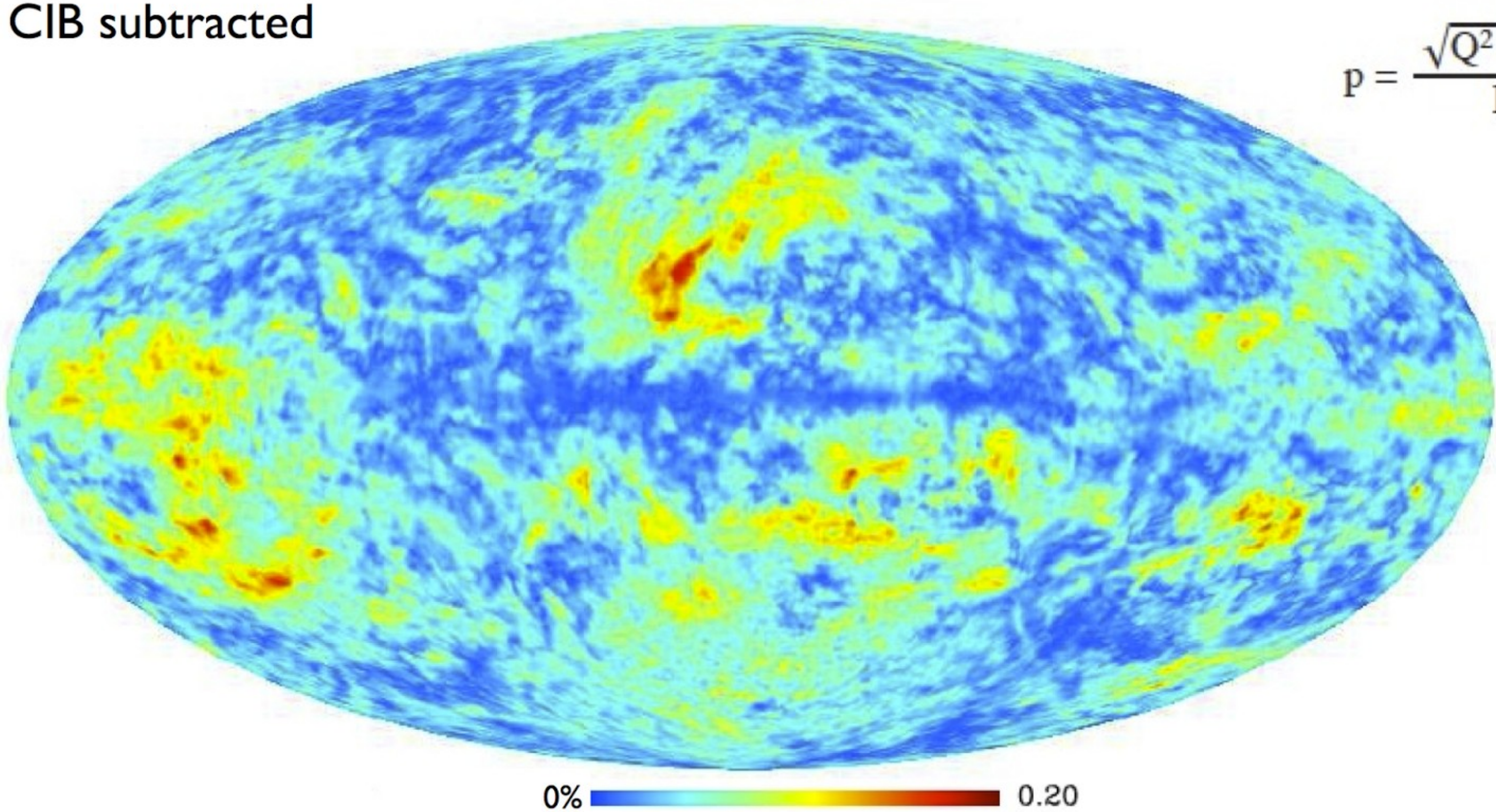
(Ade, *et al.*, arXiv:1403.3985)

BICEP: Dust Model "DDM1" (One of Five)

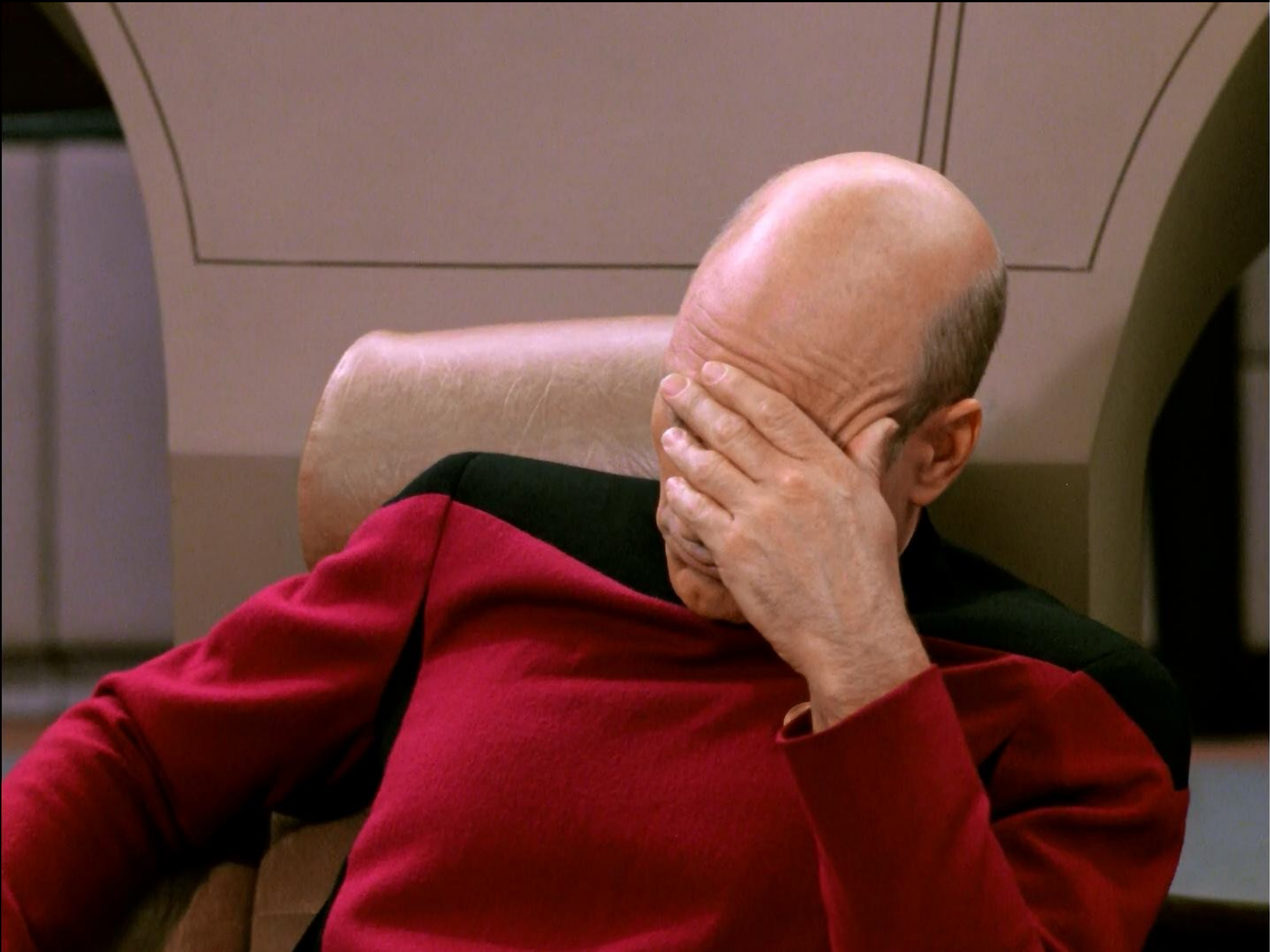
Polarization Fraction

Apparent polarization fraction (p) at 353 GHz, 1° resolutior
Not CIB subtracted

$$p = \frac{\sqrt{Q^2 + U^2}}{I}$$



p ranges from 0 to ~20%
Low p values in inner MW plane. Consistent with unpolarized CIB
Large p values in outer plane and intermediate latitudes



7

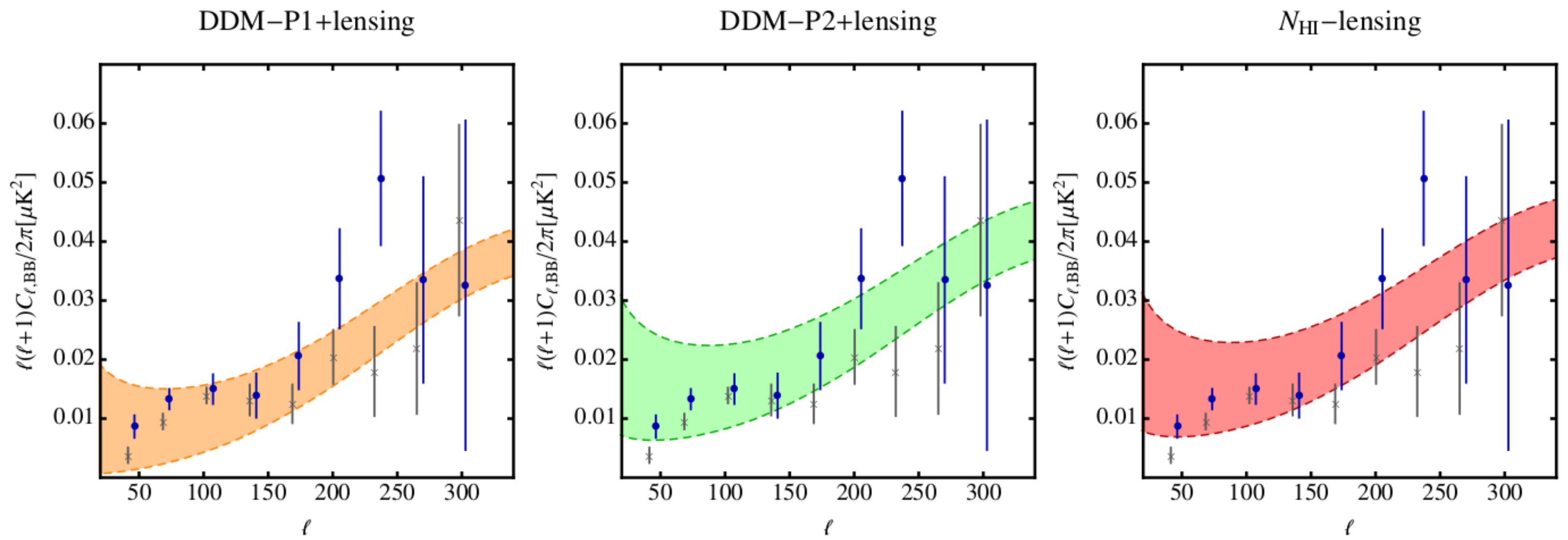
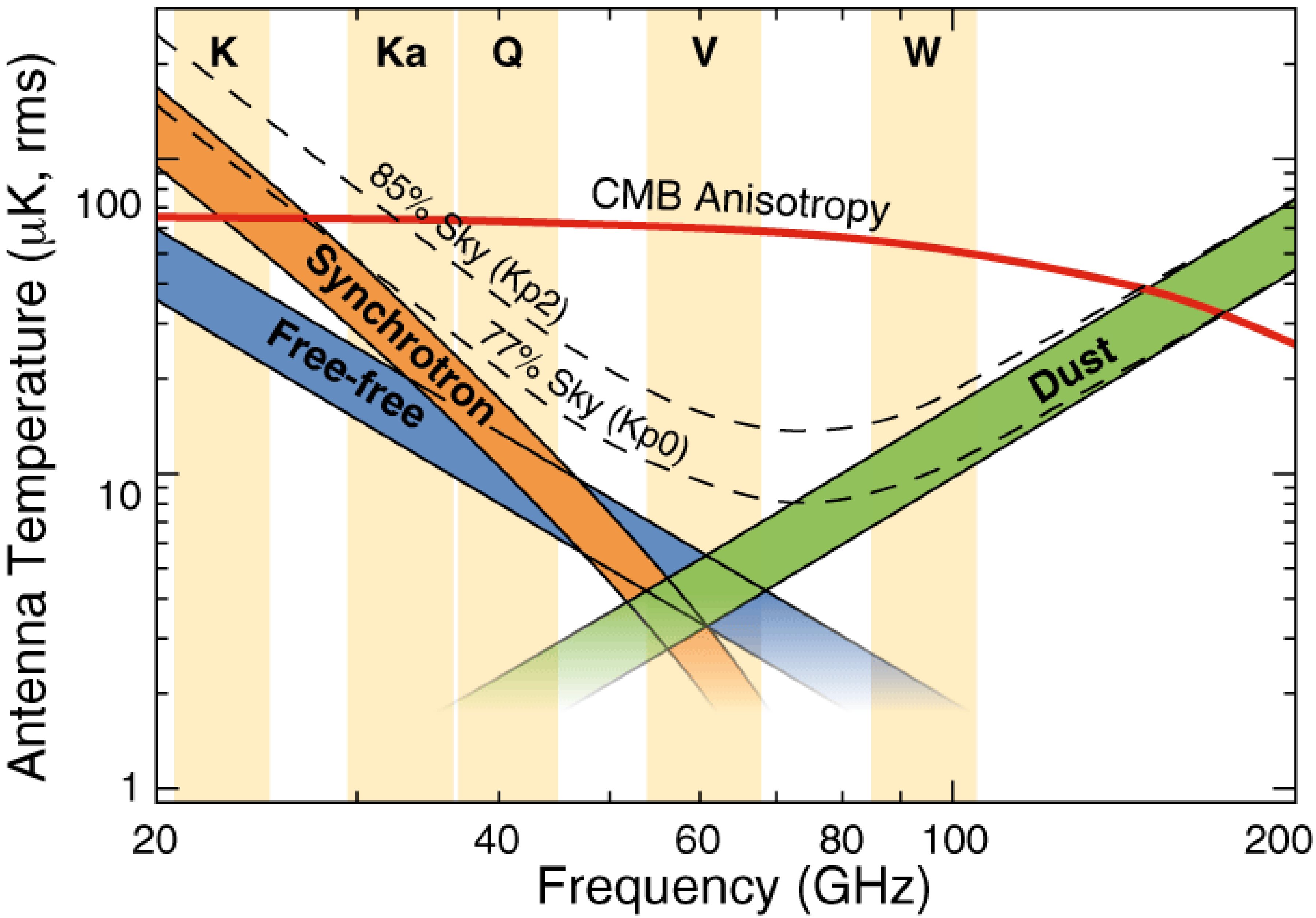


FIG. 4: Comparison of several predictions for the 150 GHz signal versus the reported BICEP2 × BICEP2 and the preliminary BICEP2 × Keck measurements. The predictions are a combination of the dust polarization signal and the predicted lensing

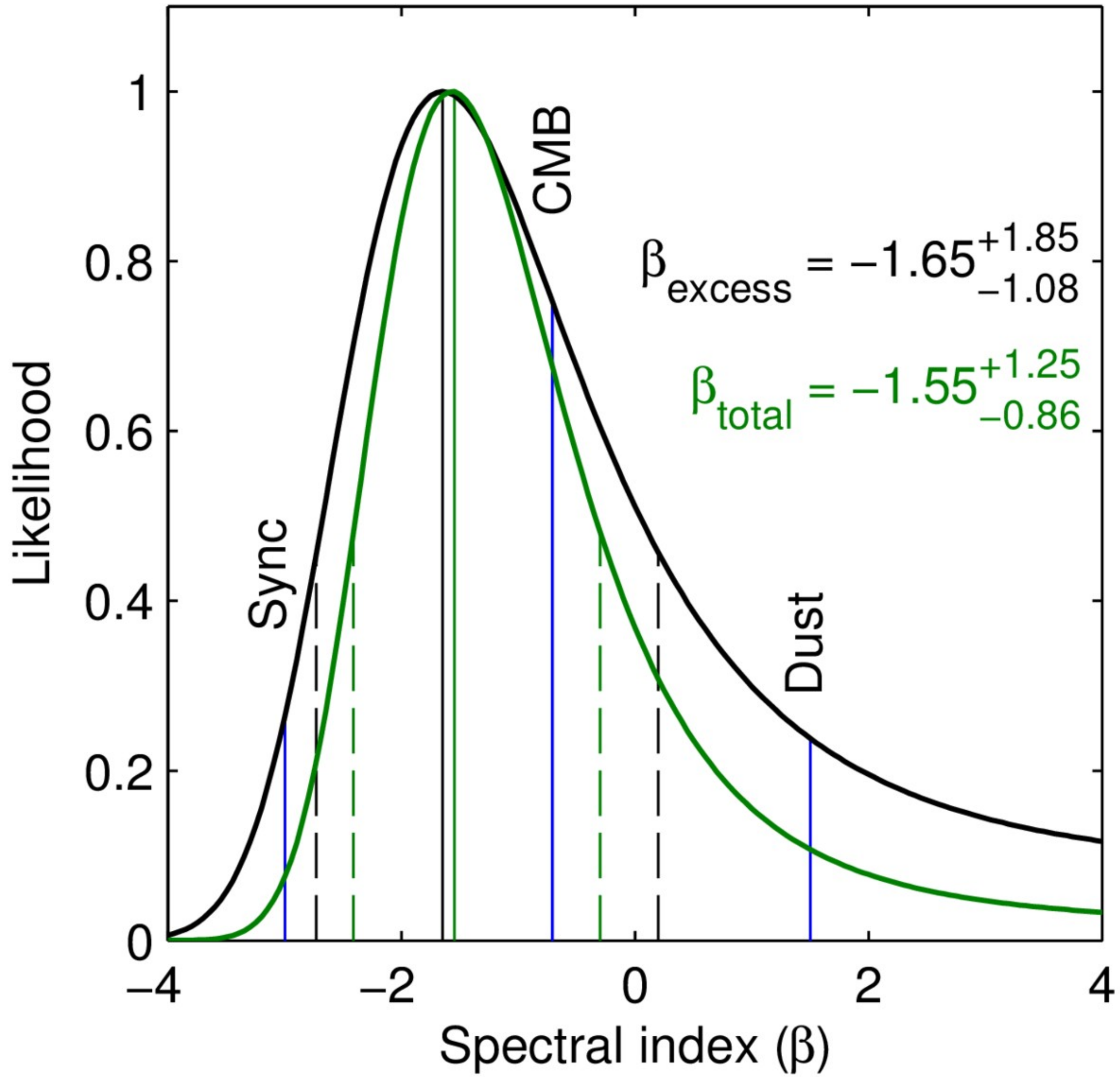
Flauger, *et al.* arXiv:1405.7351:

"To understand the noise introduced by digitization, we have developed a pipeline that takes HEALPix maps, converts them to GIF files, and inserts them into a presentation which is then saved as a PDF file. We then apply our digitization procedure to convert the PDF files back to GIFs and then to HEALPix data files. At 353 GHz, the polarized emission is dominated by dust. We thus apply this pipeline to ten simulations of dust maps. This has allowed us to characterize the effects introduced by the digitization procedure in the form of a transfer function."

Frequency Dependence of CMB Foregrounds



BICEP 100 GHz / BICEP2 150 GHz Spectrum



(Image: bicepkeck.org)

The Planck Satellite

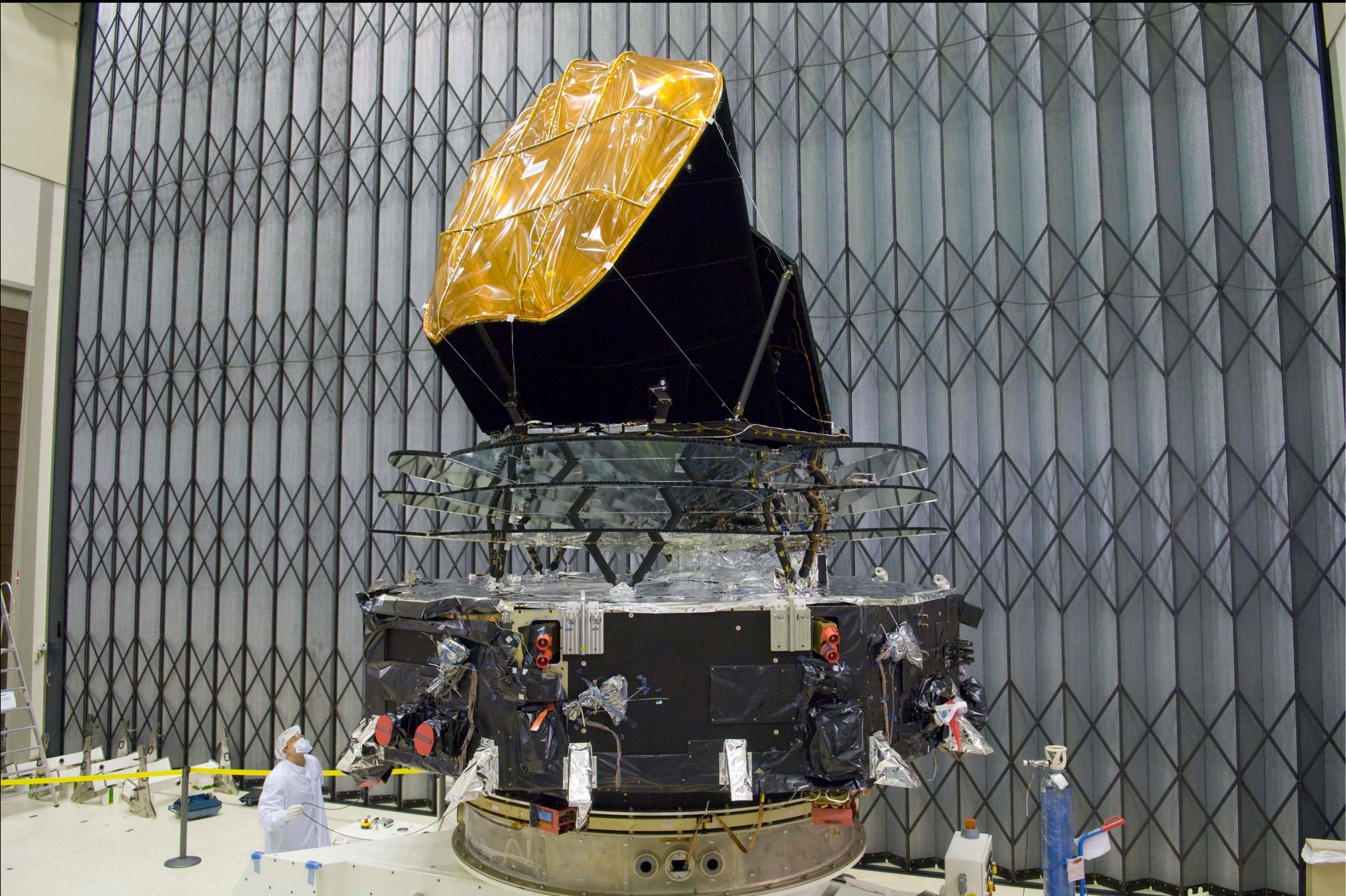
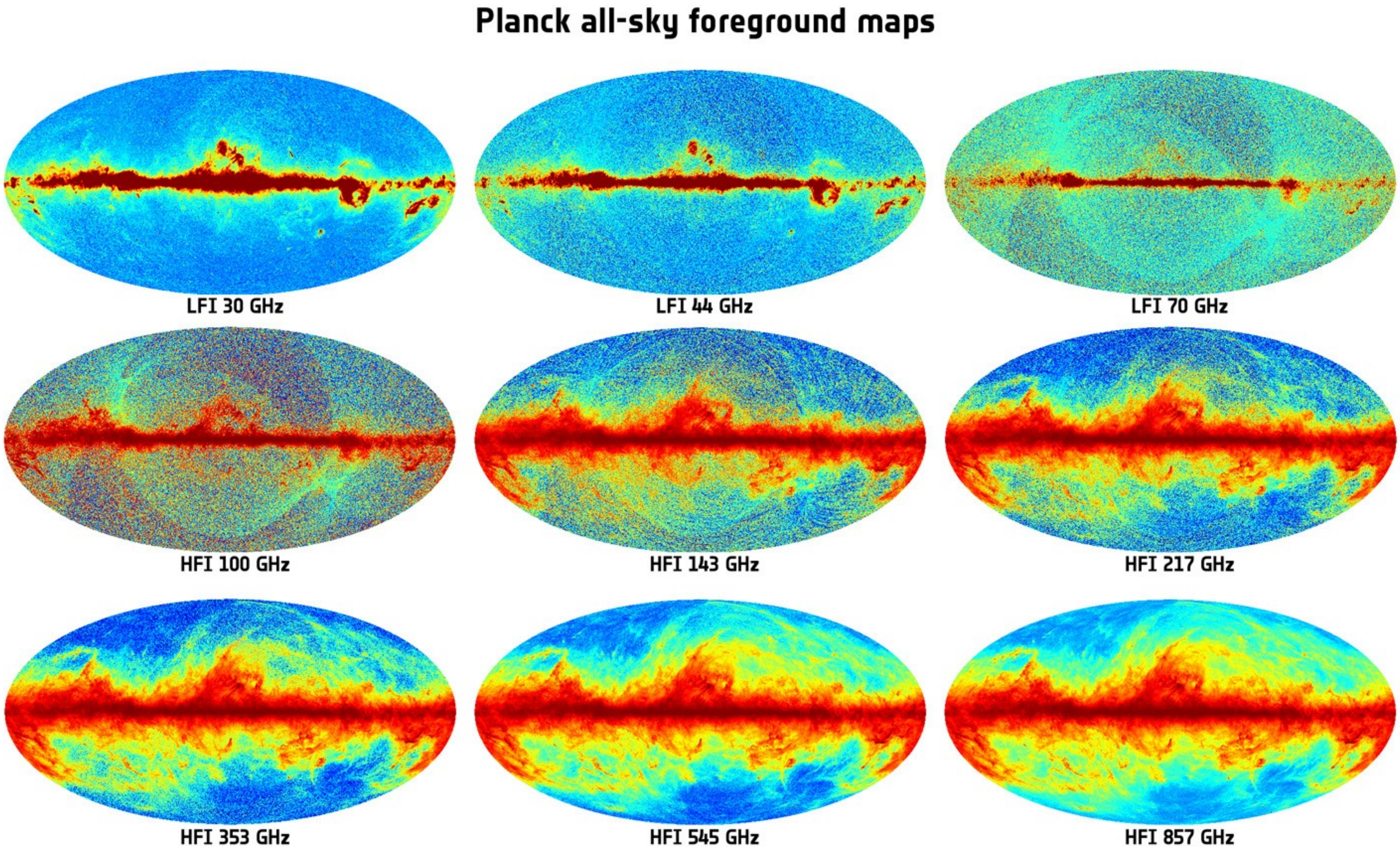
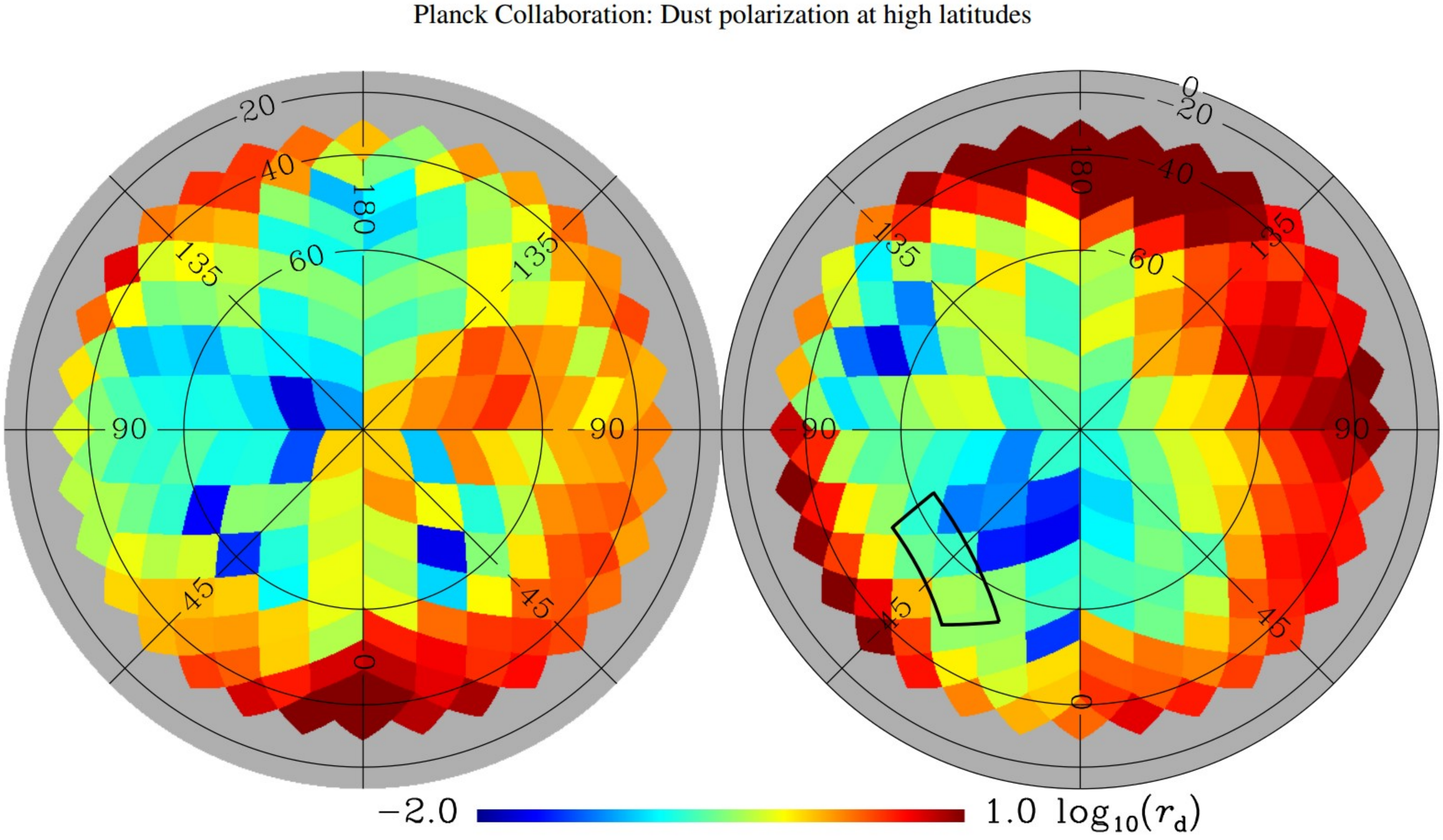


Image: ESA



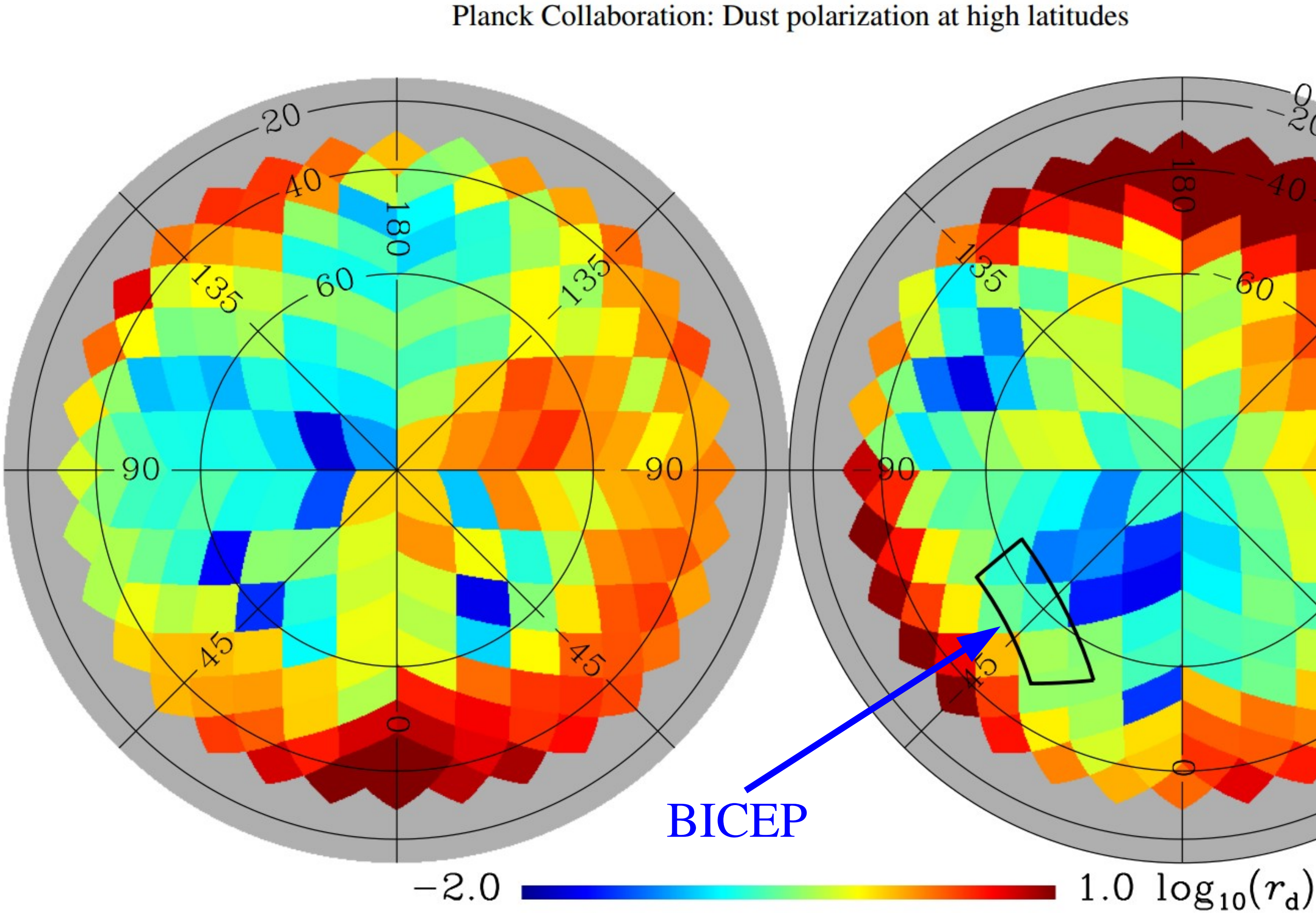
(Image: Planck Collaboration)

September 2014: Planck Dust Maps



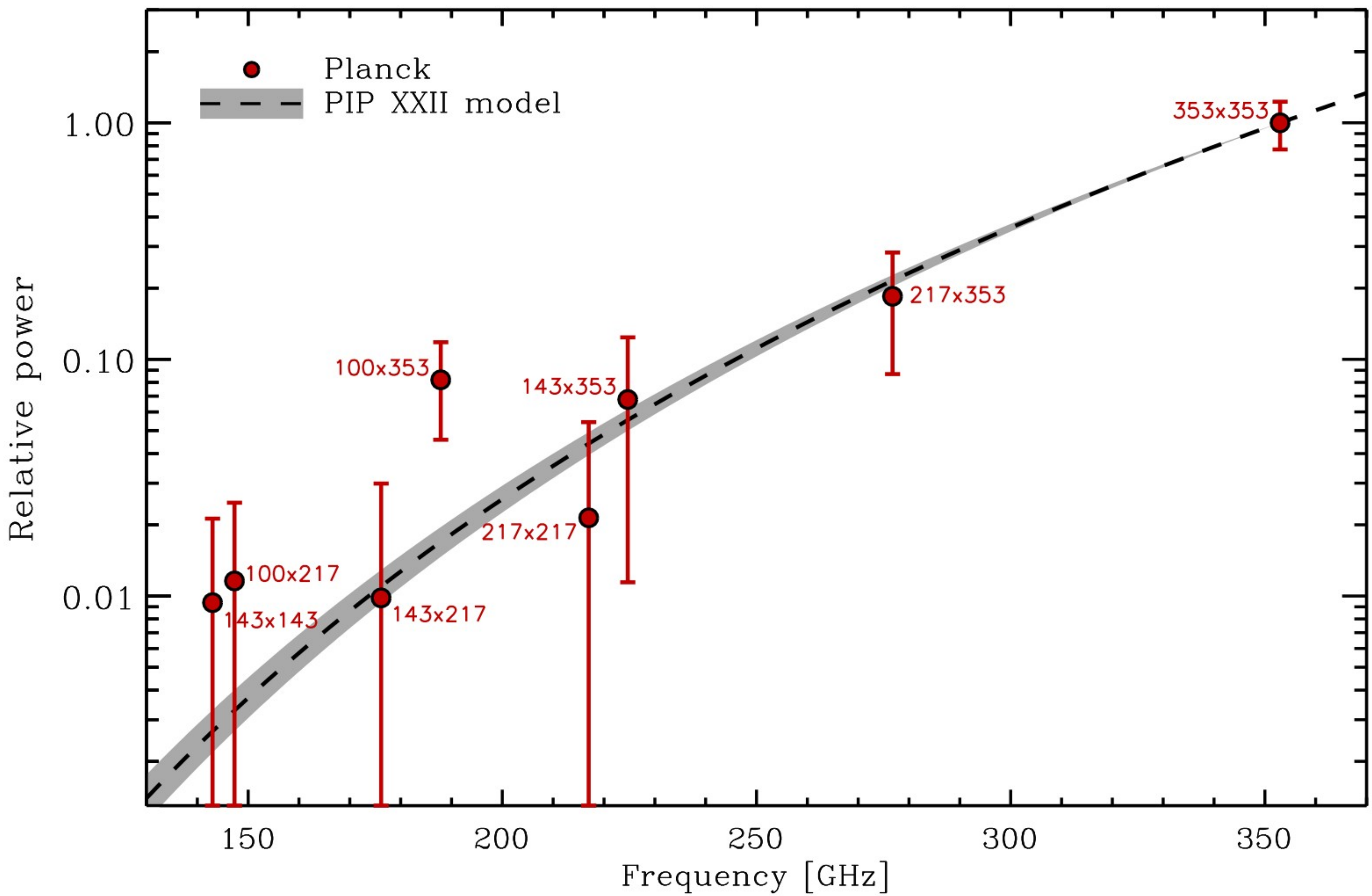
Planck Collaboration, arXiv:1409.5738

September 2014: Planck Dust Maps



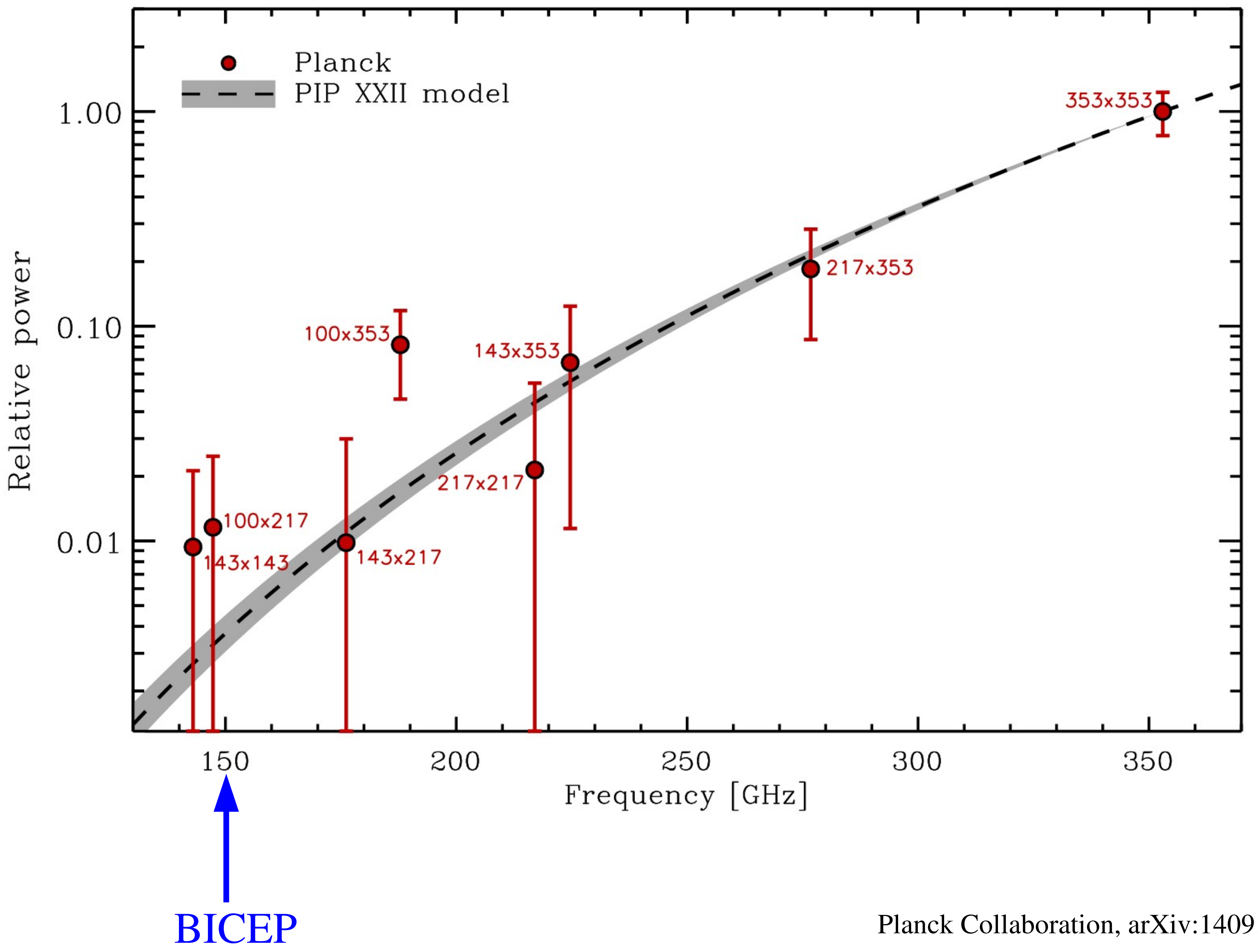
Planck Collaboration, arXiv:1409.5738

Planck: Frequency Extrapolation



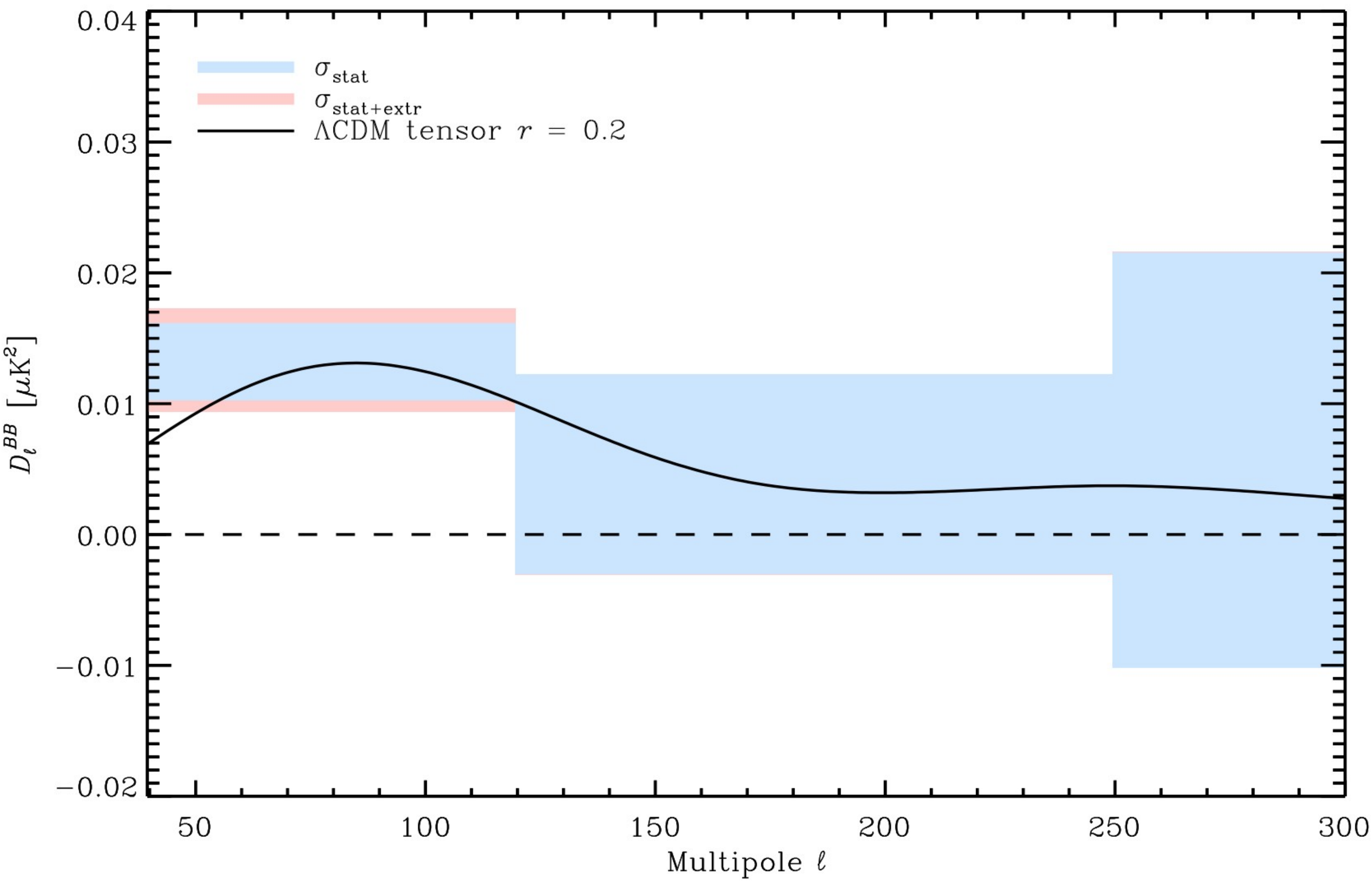
Planck Collaboration, arXiv:1409.5738

Planck: Frequency Extrapolation



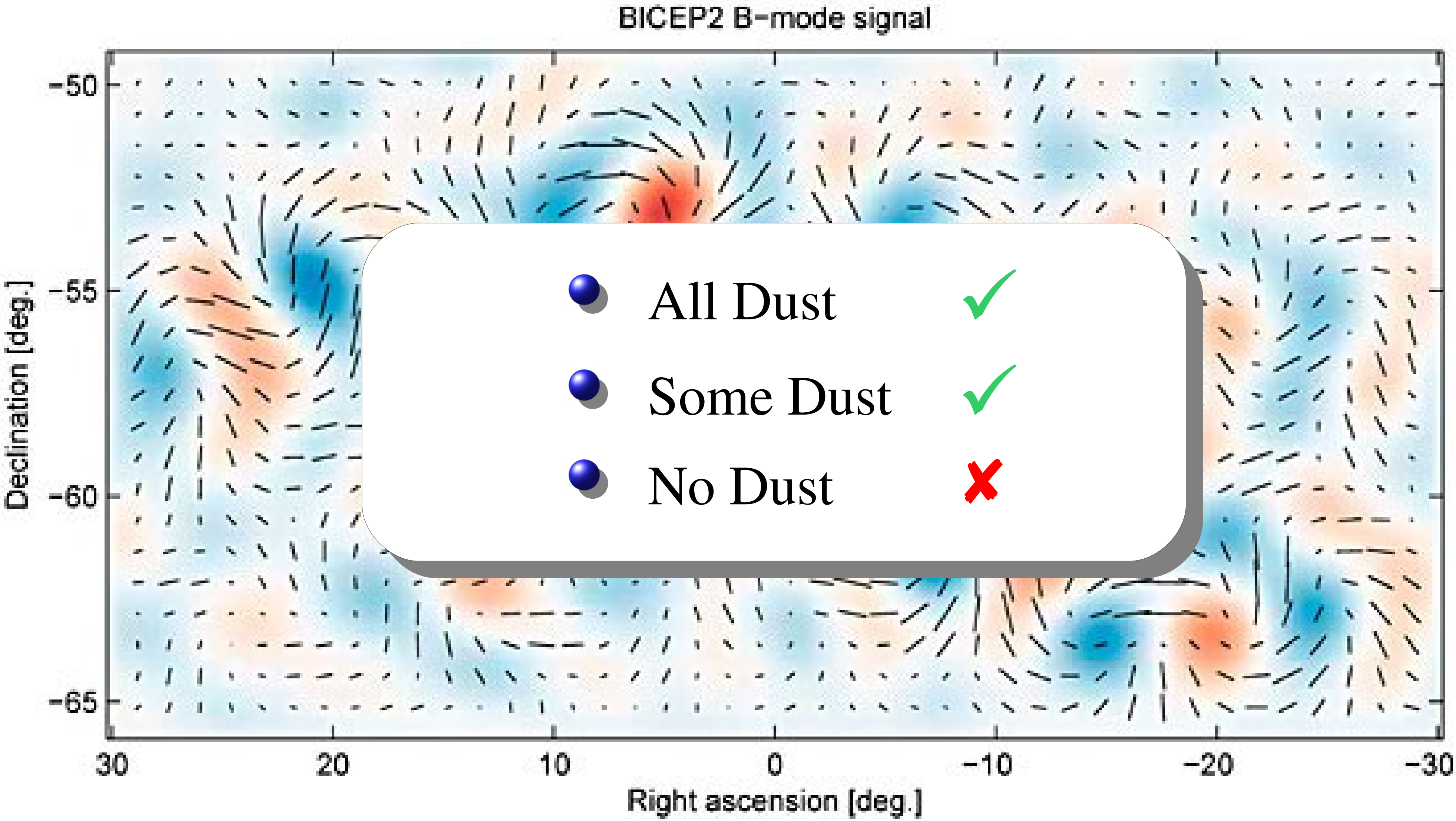
Planck Collaboration, arXiv:1409.5738

Planck: Dust Angular Power Spectrum



Planck Collaboration, arXiv:1409.5738

BICEP2 In Light of Planck Dust Maps

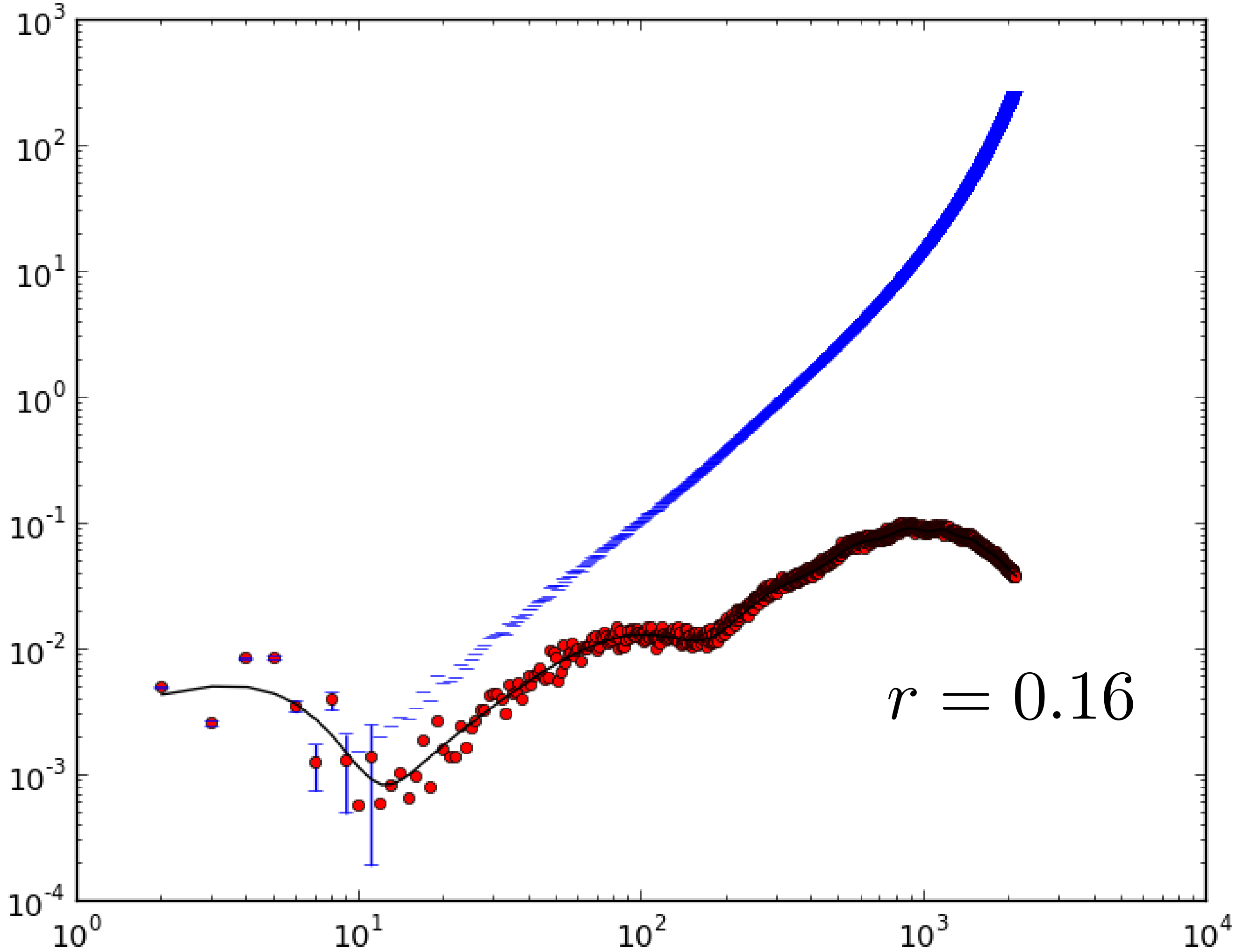


- All Dust ✓
- Some Dust ✓
- No Dust ✗

(Ade, *et al.*, arXiv:1403.3985)

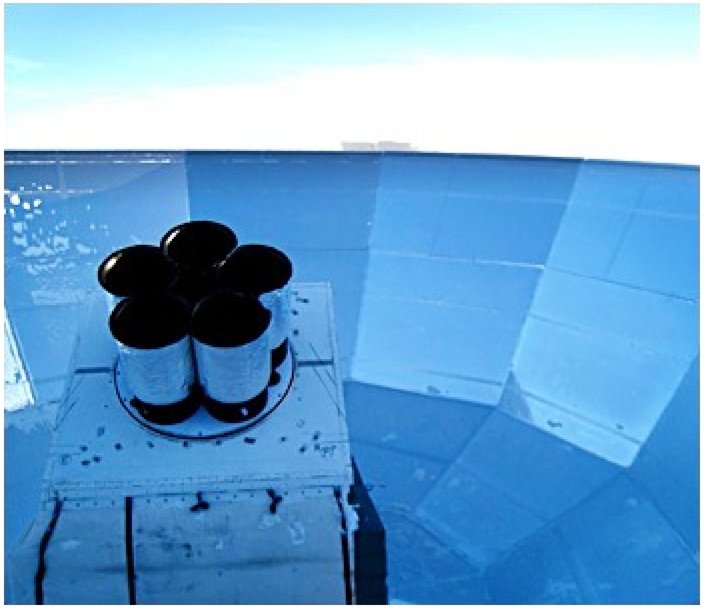
What next?

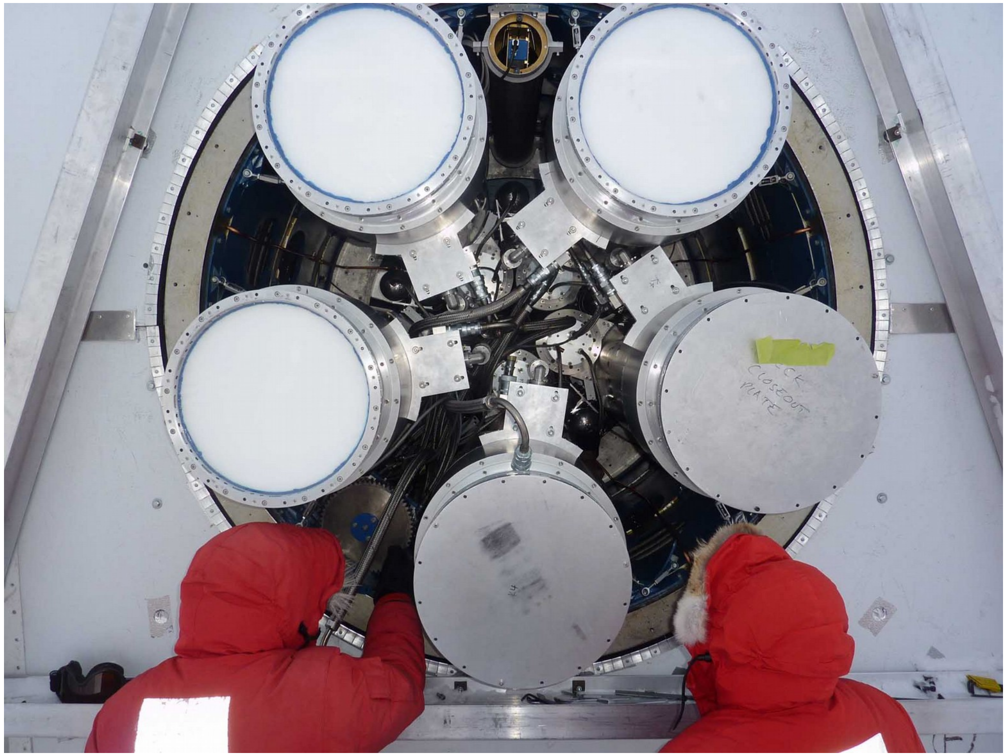
- Planck / BICEP2 joint analysis
- Planck polarization data



(WHK, Kolb, Moradinezhad, Riotto)

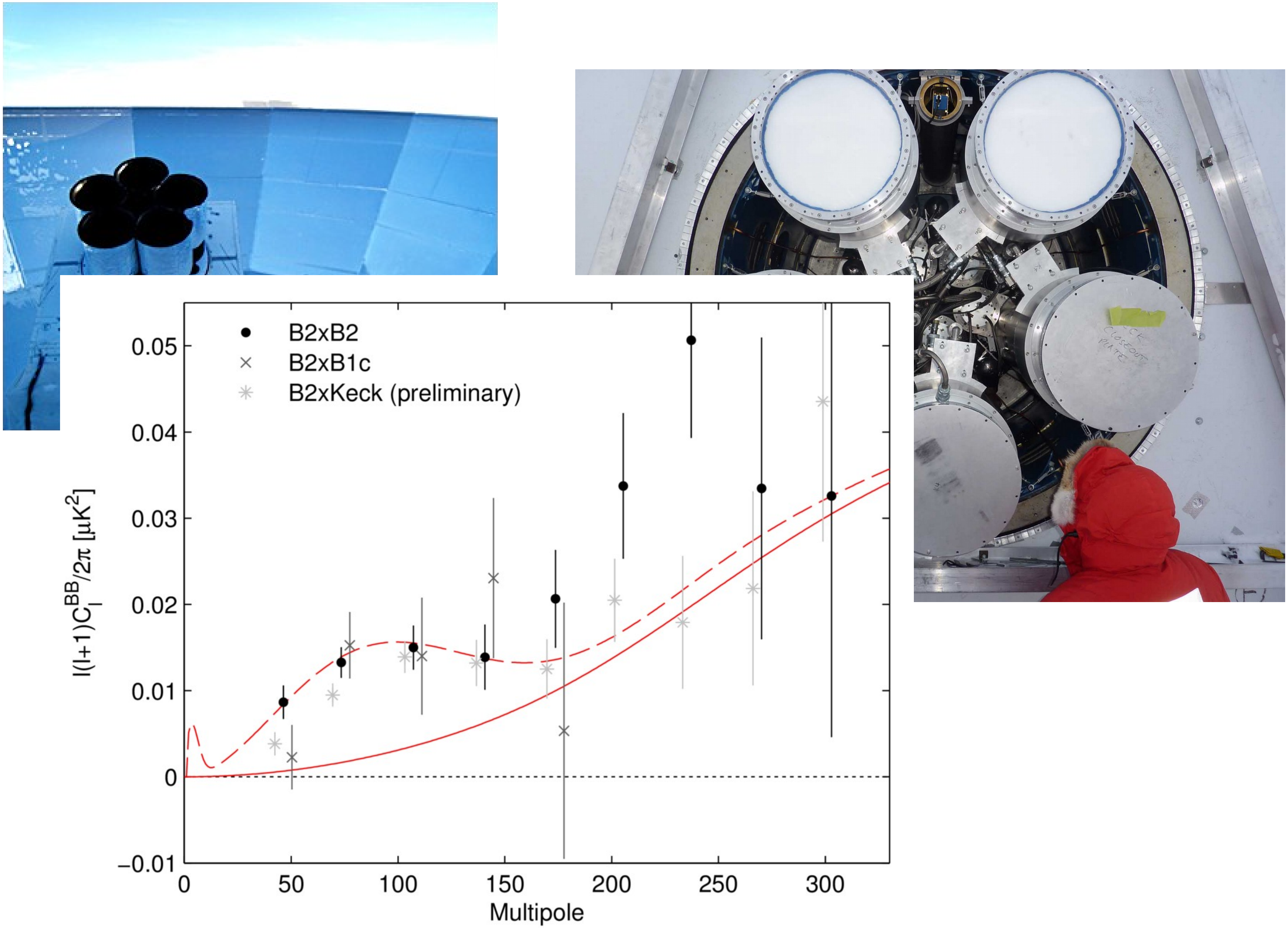
Keck Array



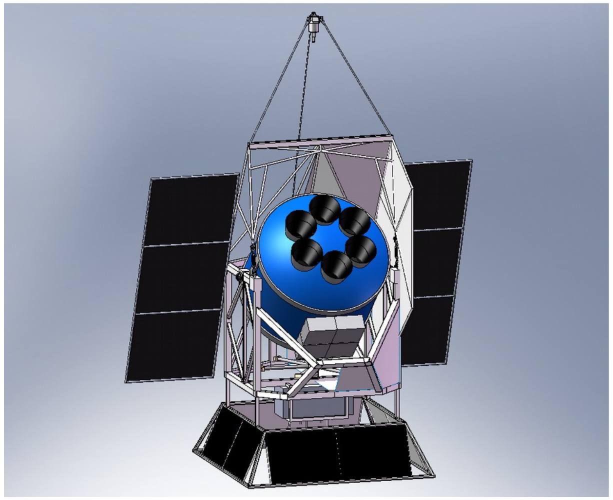


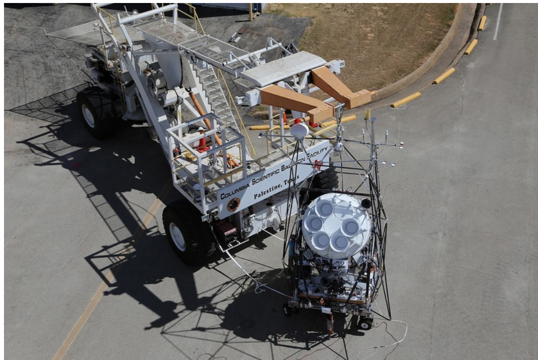
- 5× BICEP2
- 150 GHz / 100 GHz

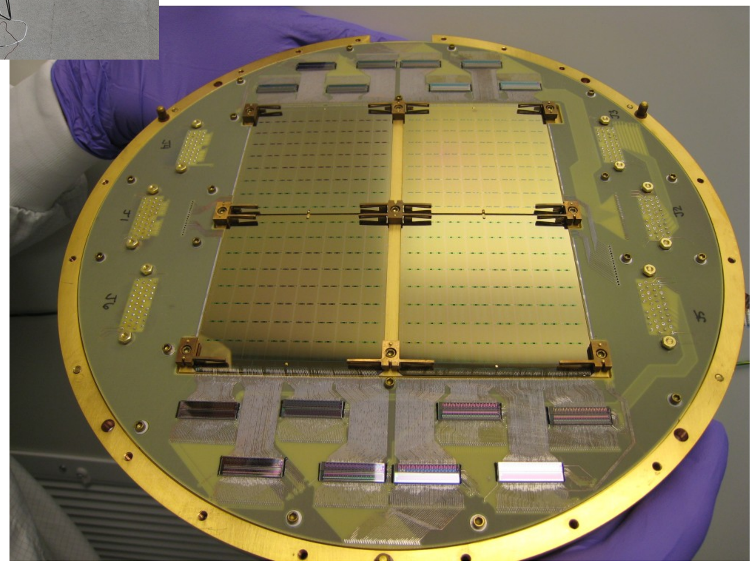
Keck Array


B2xB2
B2xB1c
B2xKeck (preliminary)
l(l+1)C_l^BB/2π [μK²]
Multipole
0.05
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200
250
300

SPIDER Balloon Experiment

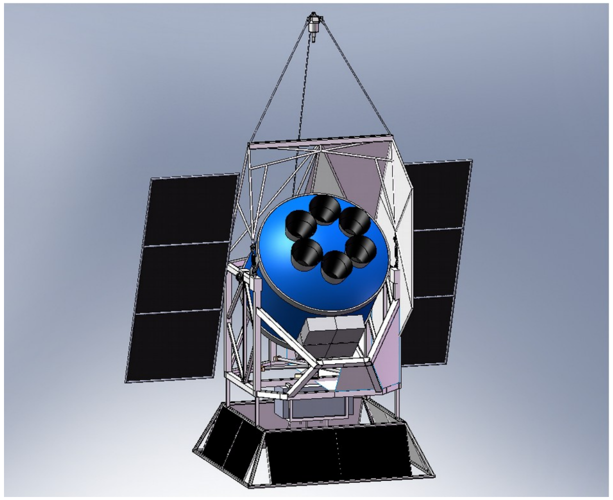


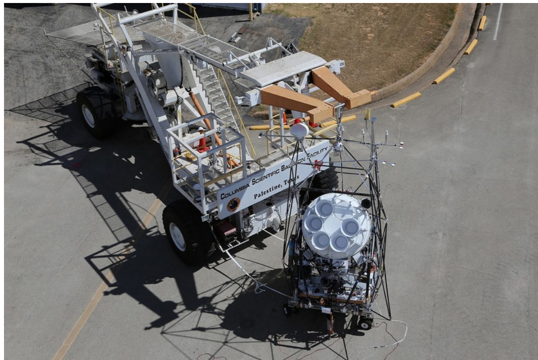


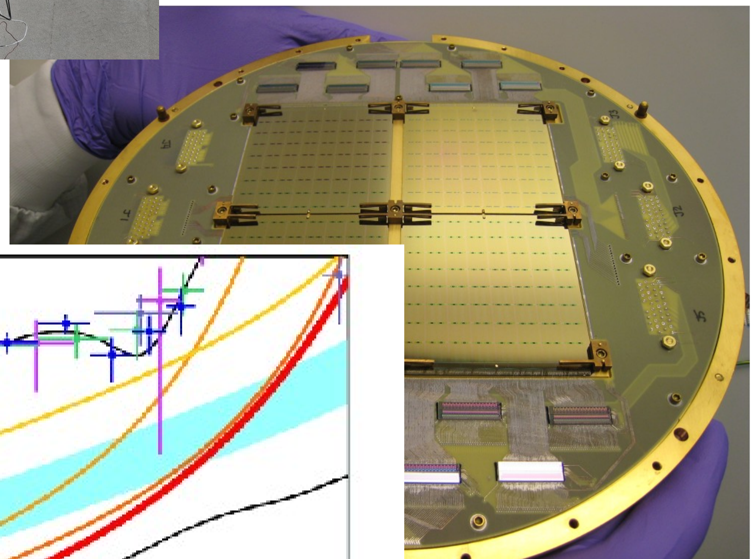


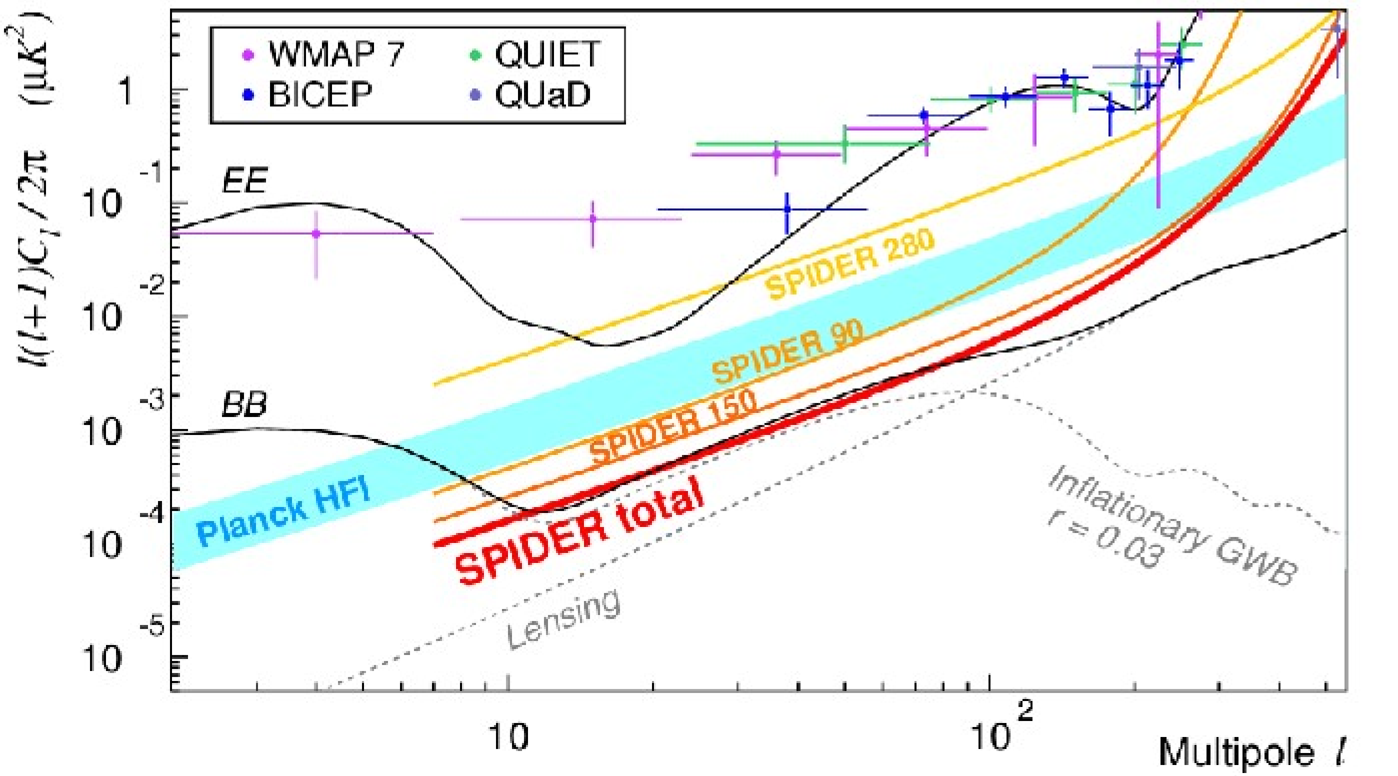
- 20-day circumpolar flight
- 90 / 150 / 280 GHz
- Delayed by govt shutdown!

SPIDER Balloon Experiment

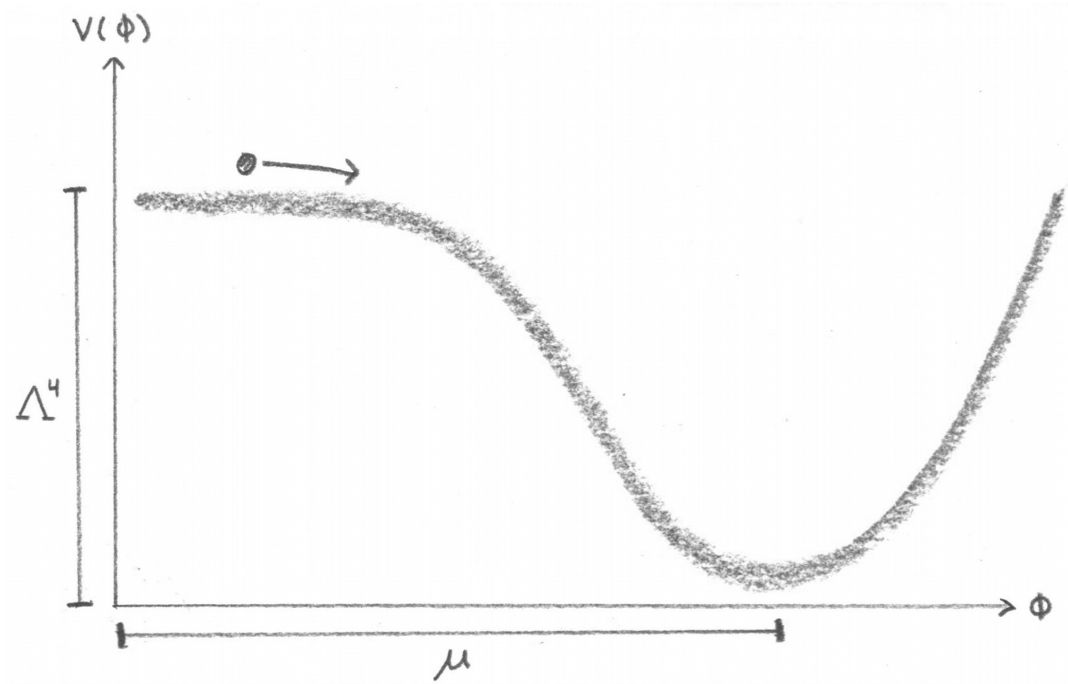








Simple Inflation Models

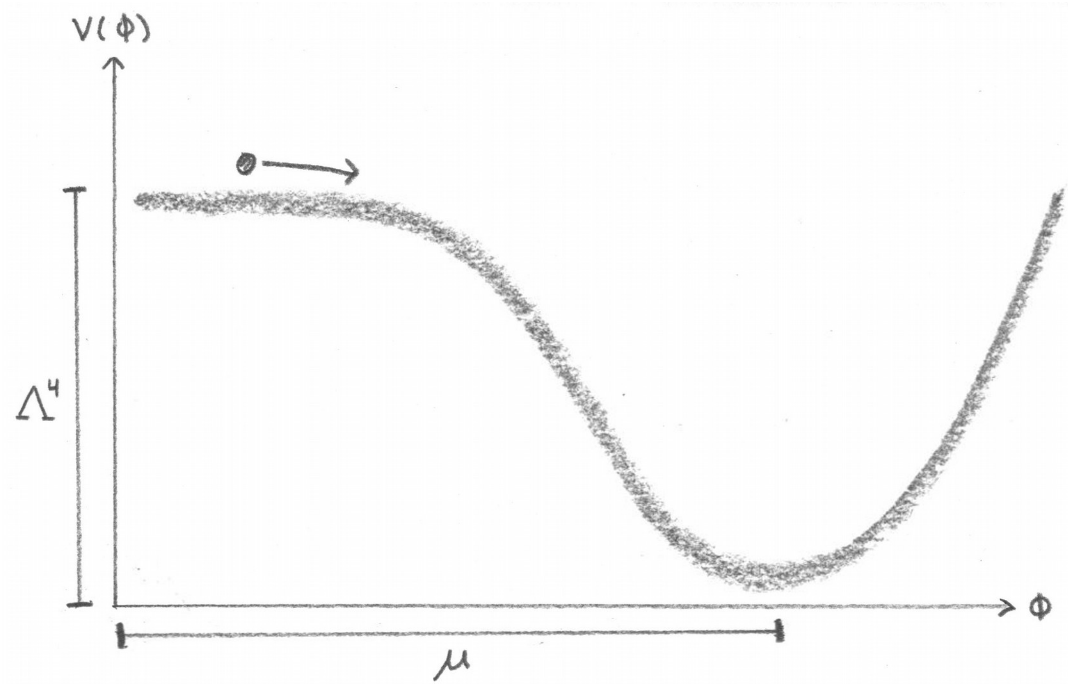


Order parameter: homogeneous scalar field ϕ

Energy density: $$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

Pressure: $$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

Simple Inflation Models



Order parameter: homogeneous scalar field ϕ

Energy density: $$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

Pressure: $$p = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

slow roll

$$p \simeq -\rho$$

Spectra of Primordial Perturbations

Tensor (gravity wave) perturbations: $P_{\mathrm{T}} \sim H \propto k^{n_{\mathrm{T}}}$

Scalar (density) fluctuations: $P_{\mathrm{S}} \sim \dfrac{H^2}{\dot{\phi}} \propto k^{n-1}$

Tensor/scalar ratio

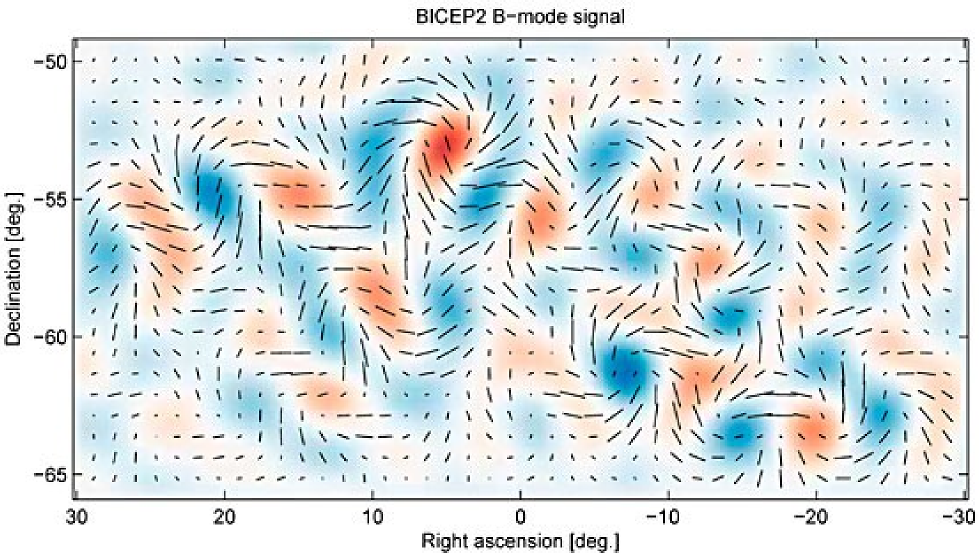
$$r \equiv \frac{P_{\mathrm{T}}}{P_{\mathrm{S}}} \sim \frac{\dot{\phi}^2}{H^2} \ll 1$$

Spectral index

$$n - 1 \sim \frac{\ddot{\phi}}{H\dot{\phi}} - \frac{\dot{\phi}^2}{H^2} \ll 1$$

Model Dependent!

BICEP: Pretty Swirly Things



$$r = 0.2^{+0.07}_{-0.05}$$

Energy scale of inflation: $\Lambda \simeq r^{1/4} \times (3.3 \times 10^{16}\ \mathrm{GeV})$

$$\Lambda = [2.1, 2.4] \times 10^{16}\ \mathrm{GeV}$$

Single-Field Inflation: The Consistency Condition

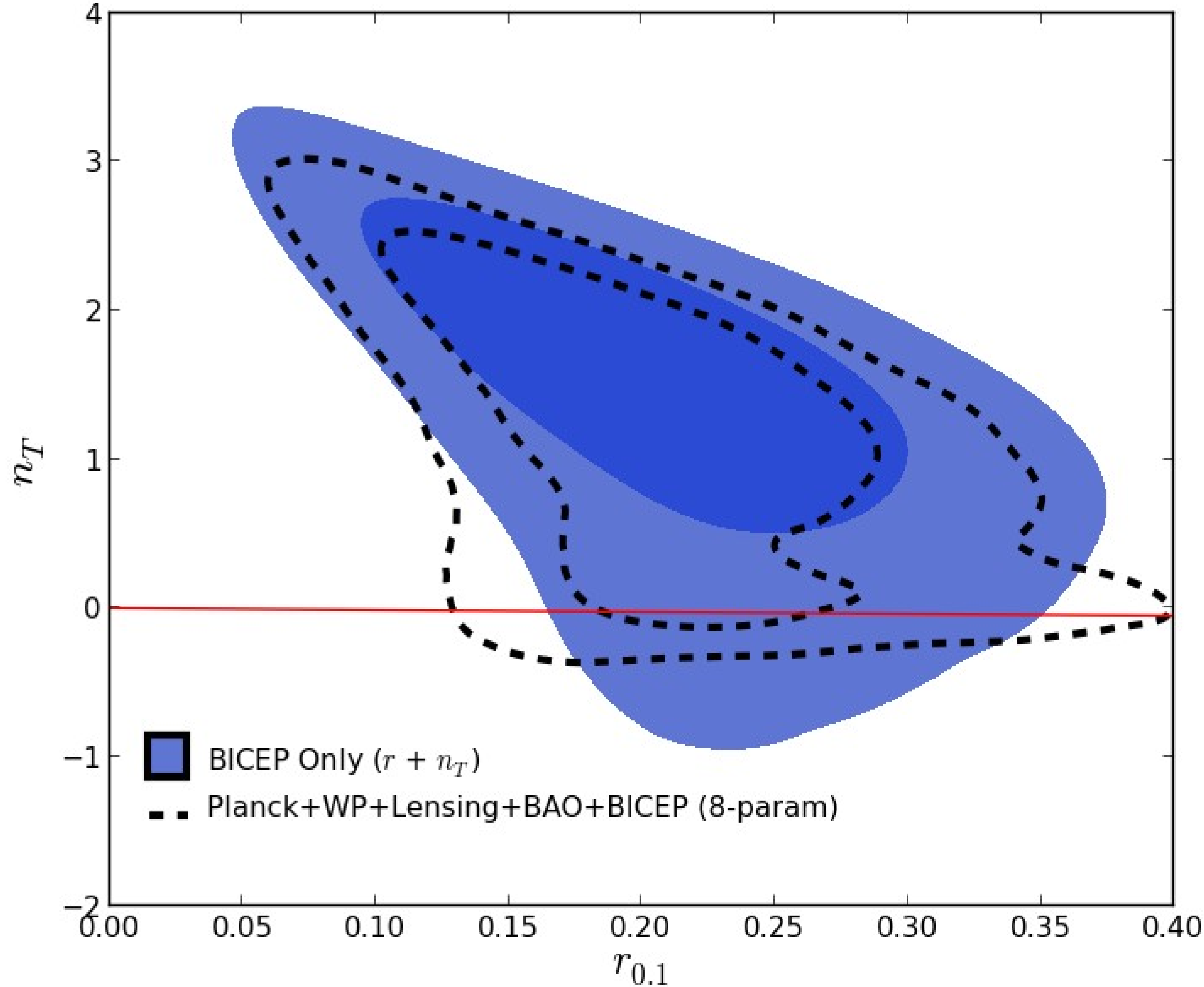
Slow Roll Parameter $\epsilon = \frac{m_{\rm Pl}^2}{16\pi}\left(\frac{V'(\phi)}{V(\phi)}\right)^2$

Tensor/Scalar Ratio $r = 16\epsilon$

Tensor Power Spectrum $P_T \propto k^{n_T} = k^{-2\epsilon}$

$$n_T = -r/8$$

Planck + BICEP Tensor Spectral Index

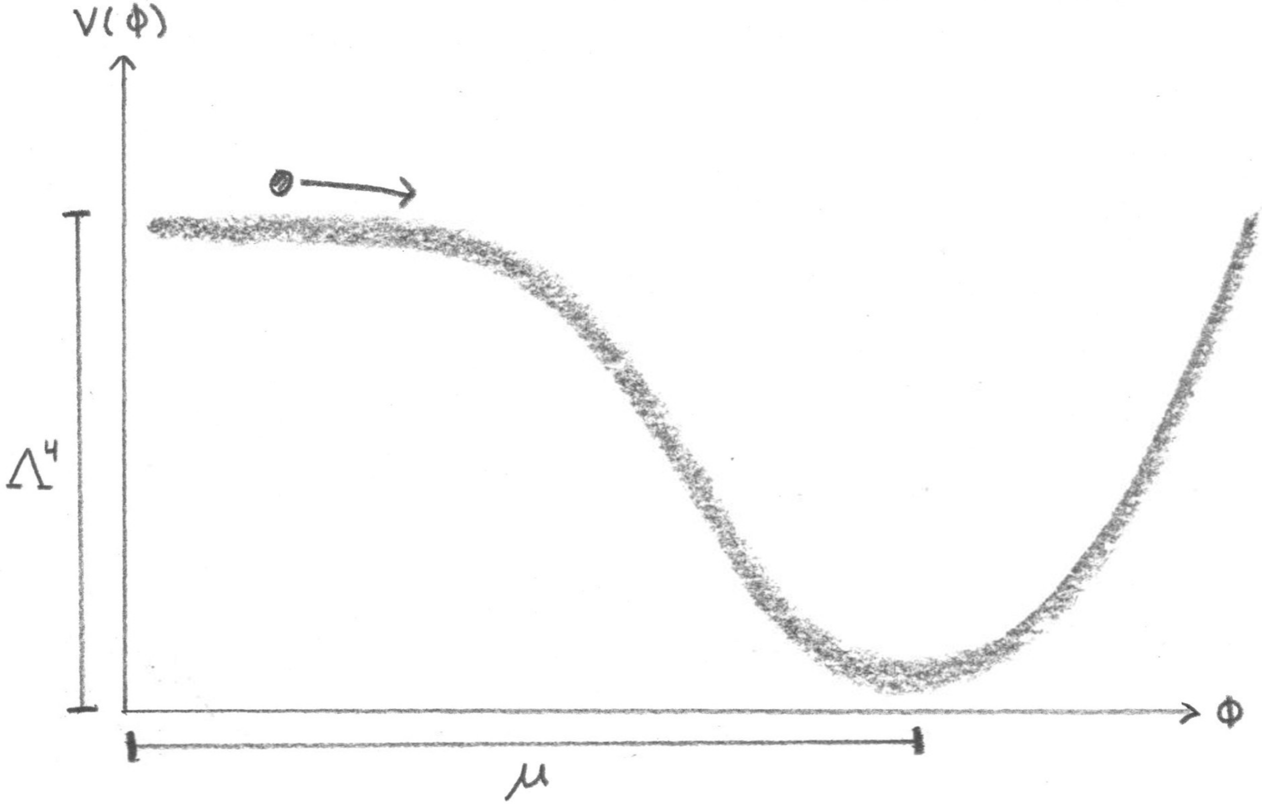


Primordial B-modes and Single-Field Inflation

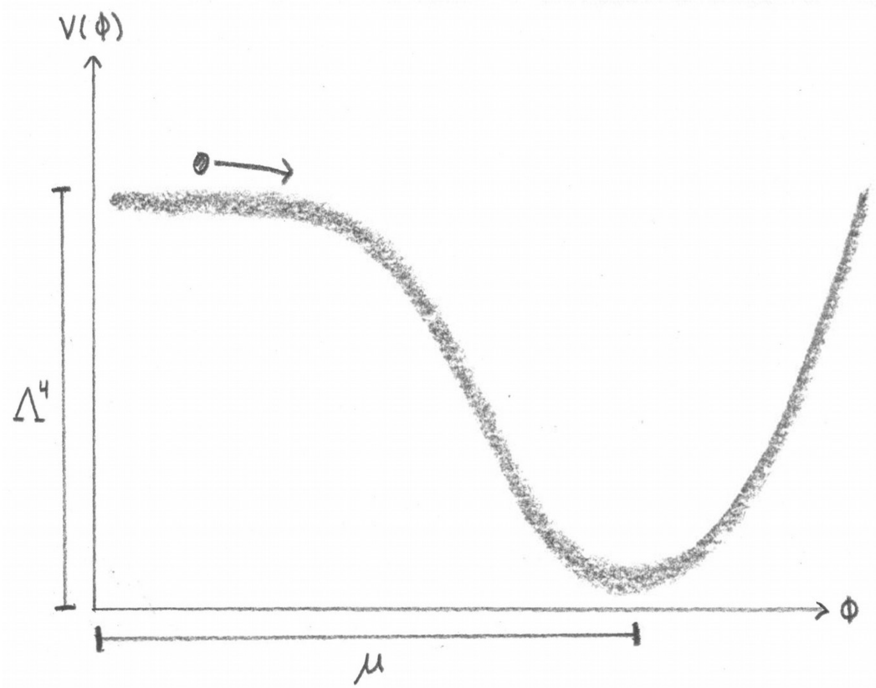
$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi)$$

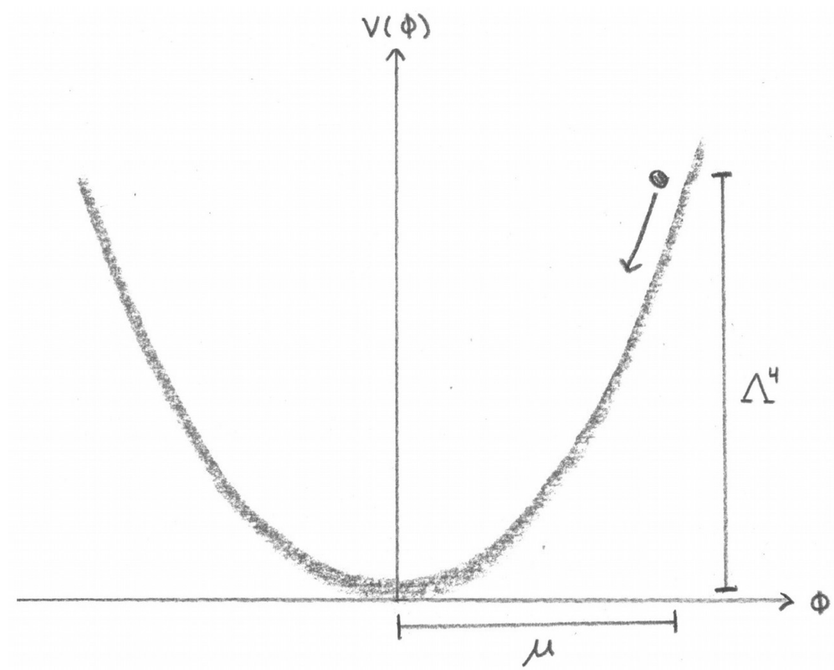
Fully consistent with data.

The Big Question: What is $V(\phi)$?



Small Field or Large Field?

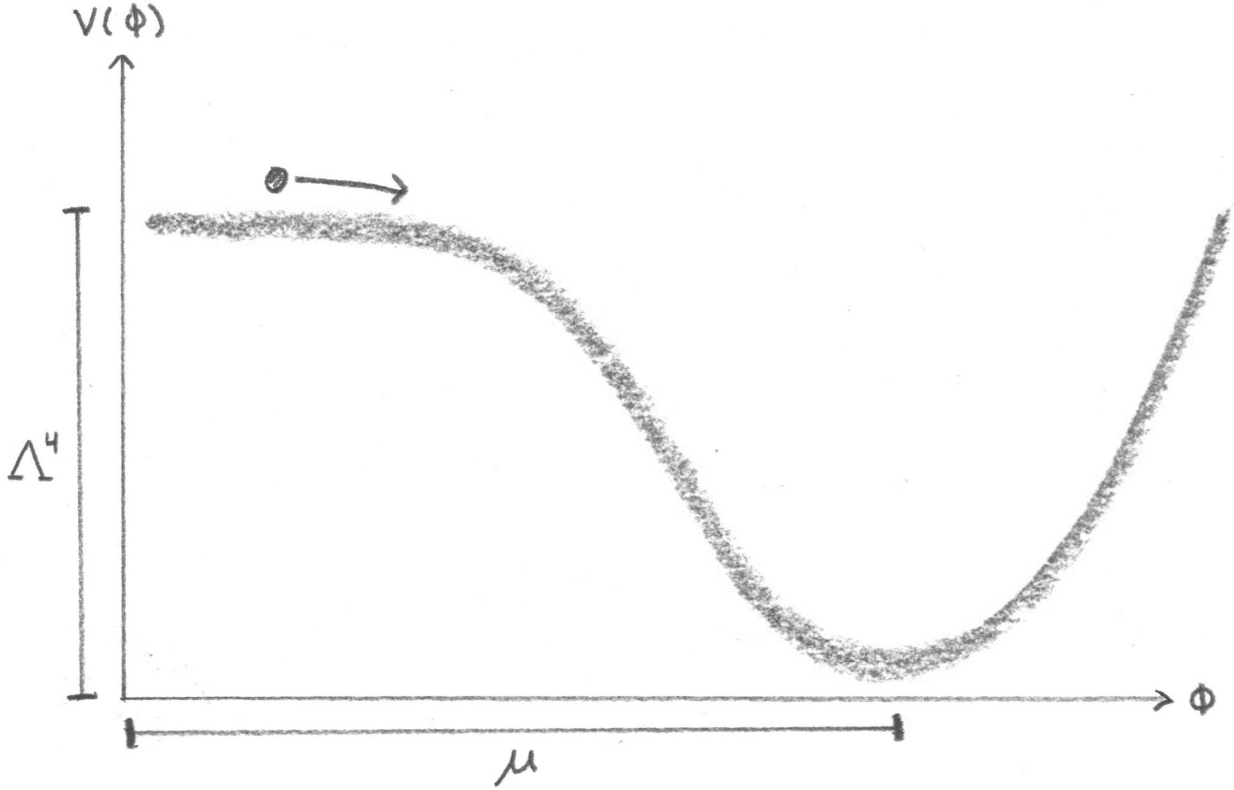




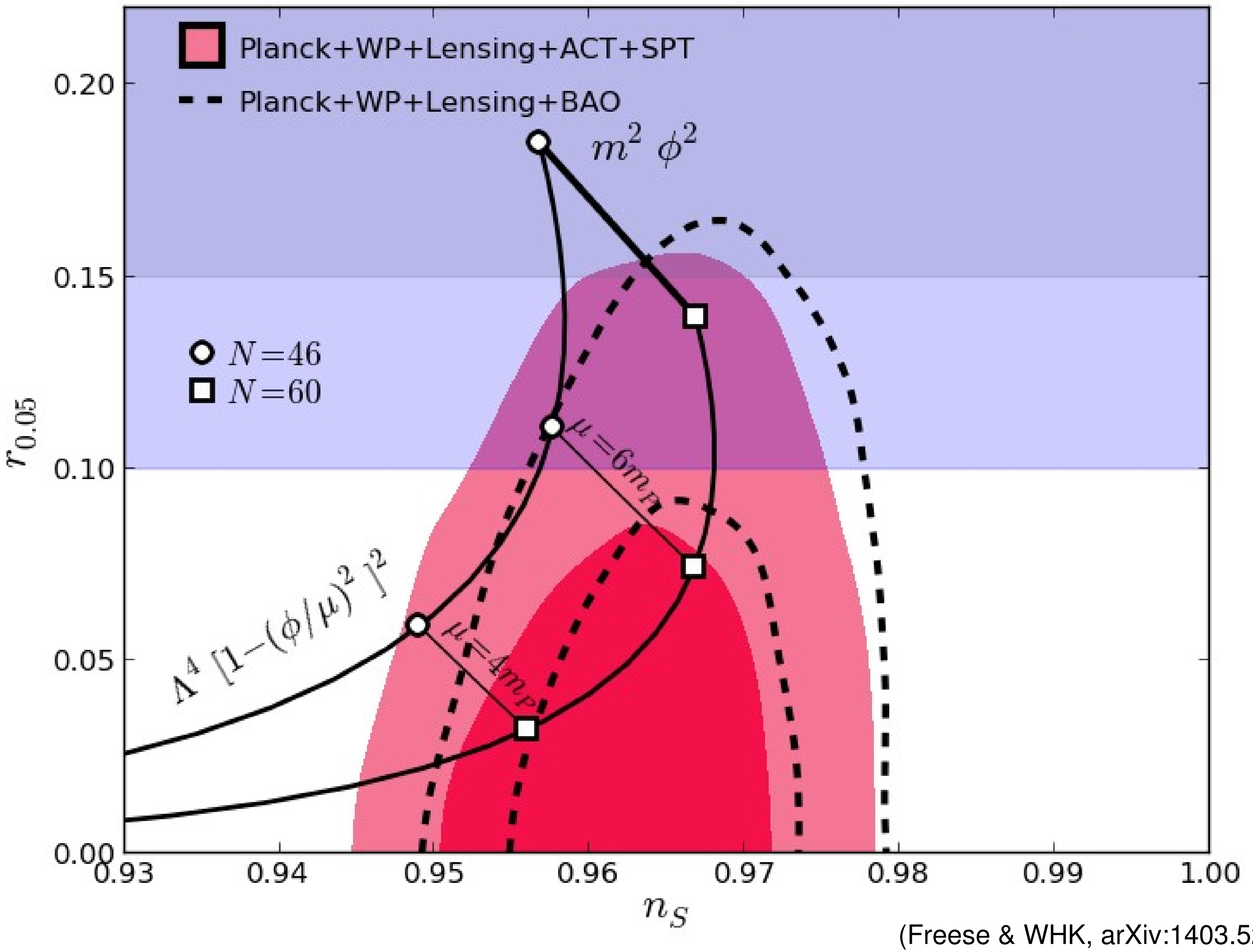
Lyth Bound

$$\frac{\Delta\phi}{M_{\rm P}} = \sqrt{2r}$$

$$\Delta\phi < 0.1 M_p \Rightarrow r < 0.01 \Rightarrow \frac{H}{M_p} < 10^{-5}$$

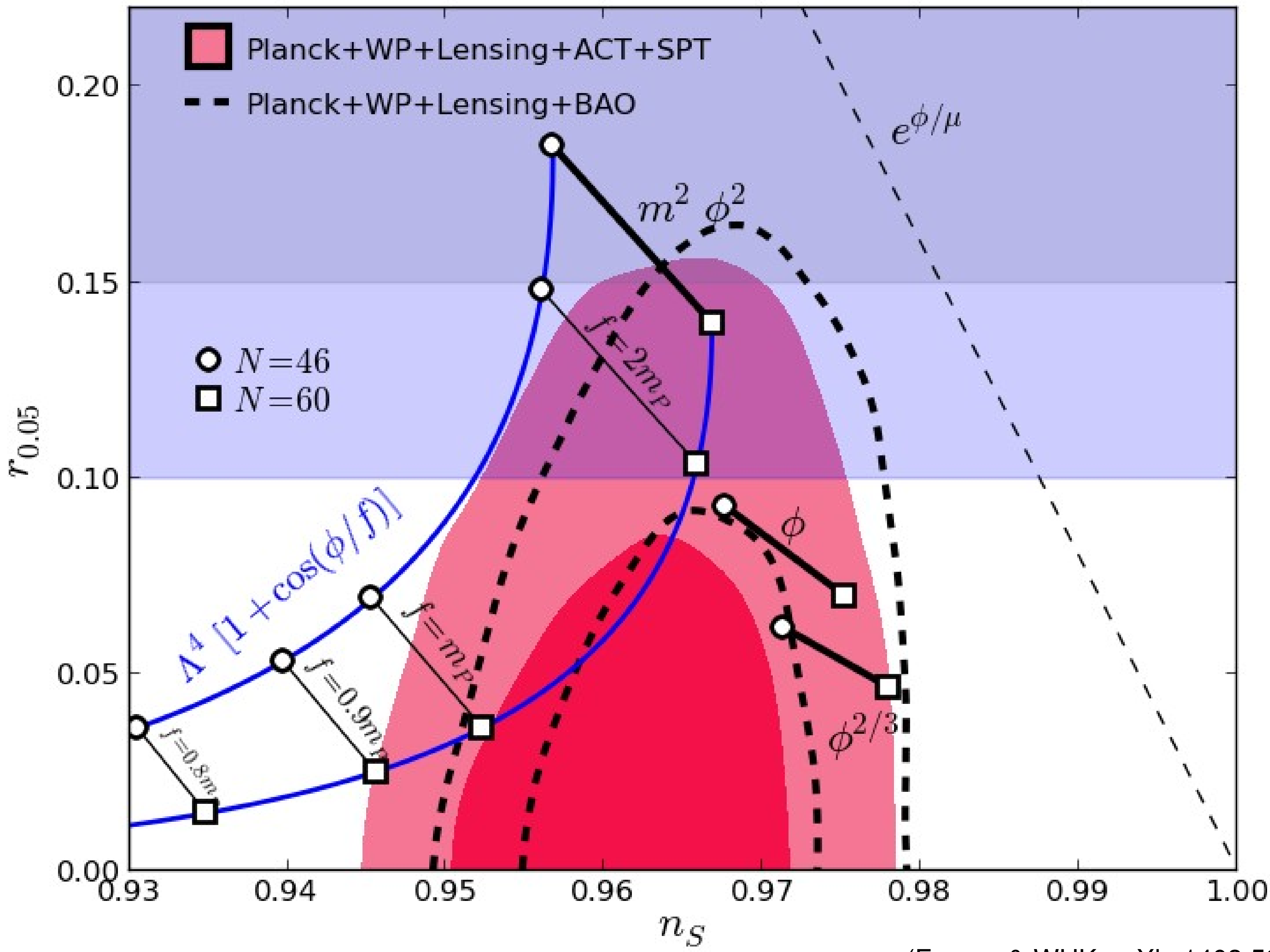


Constraints on Higgs-like Inflation



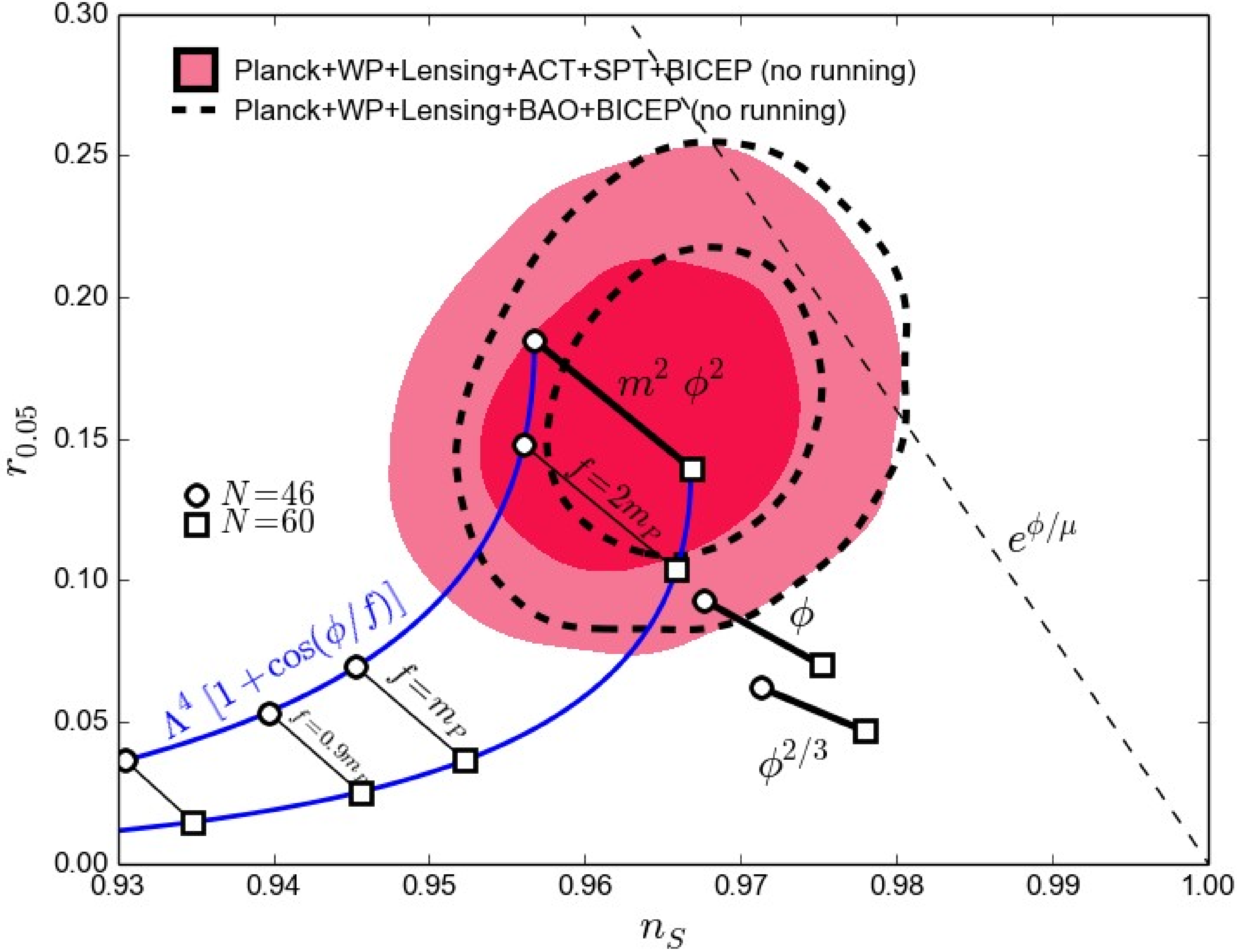
(Freese & WHK, arXiv:1403.5277)

Constraints on Natural Inflation



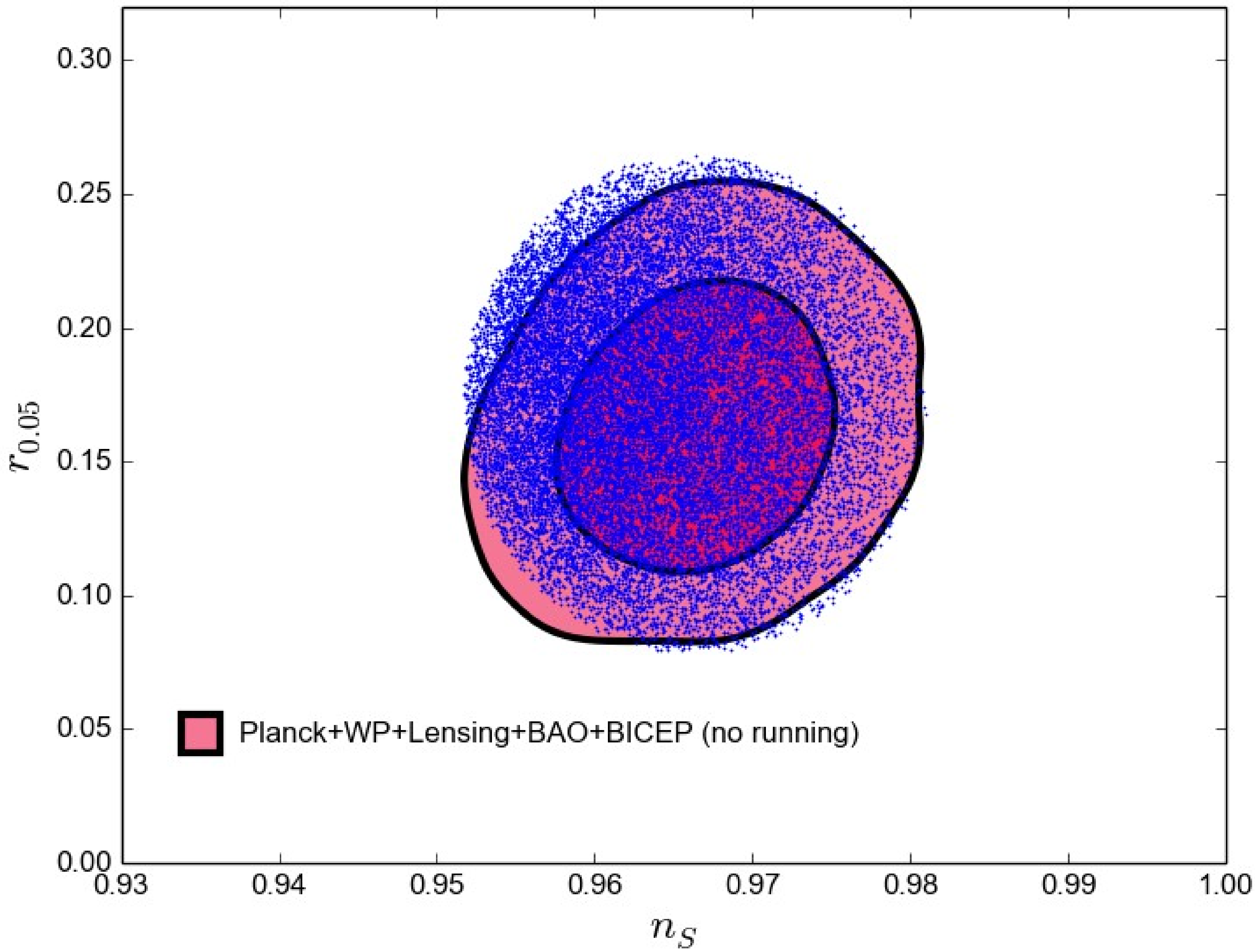
(Freese & WHK, arXiv:1403.5277)

Constraints on Natural Inflation



(Freese & WHK, arXiv:1403.5277)

Flow Monte Carlo: 20,000 Inflation Models



The Inflationary Flow Equations

$$\frac{d\epsilon}{dN} = 2\epsilon\left(\eta - \epsilon\right)$$

$$\frac{d}{dN} \propto \sqrt{\epsilon}\frac{d}{d\phi}$$

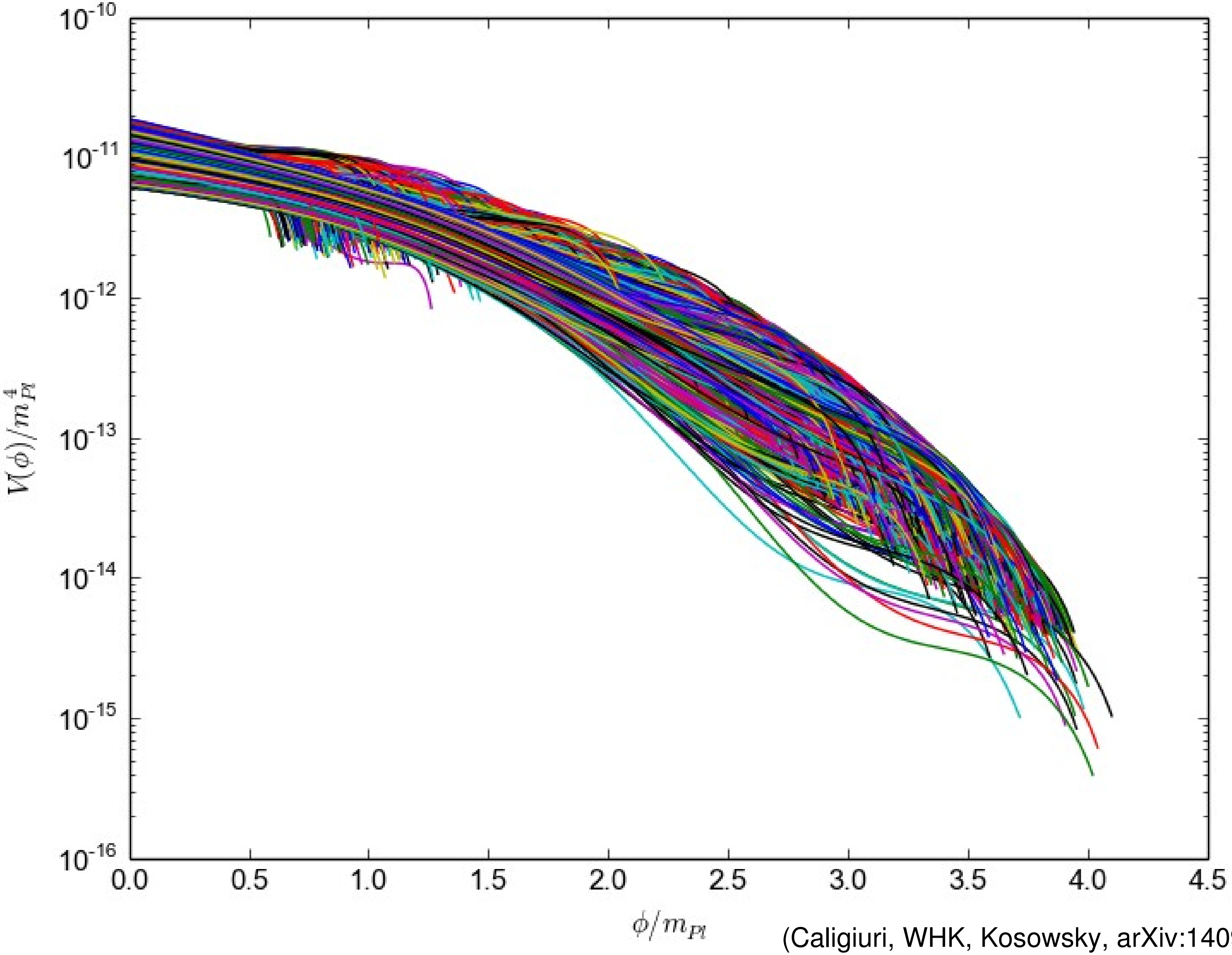
$$\frac{d\eta}{dN} = {}^{2}\lambda - \epsilon\eta$$

$$\cdots$$

$$\frac{d^{\ell}\lambda}{dN} = \left[(\ell - 1)\eta - \ell\epsilon\right]{}^{\ell}\lambda + {}^{(\ell+1)}\lambda$$

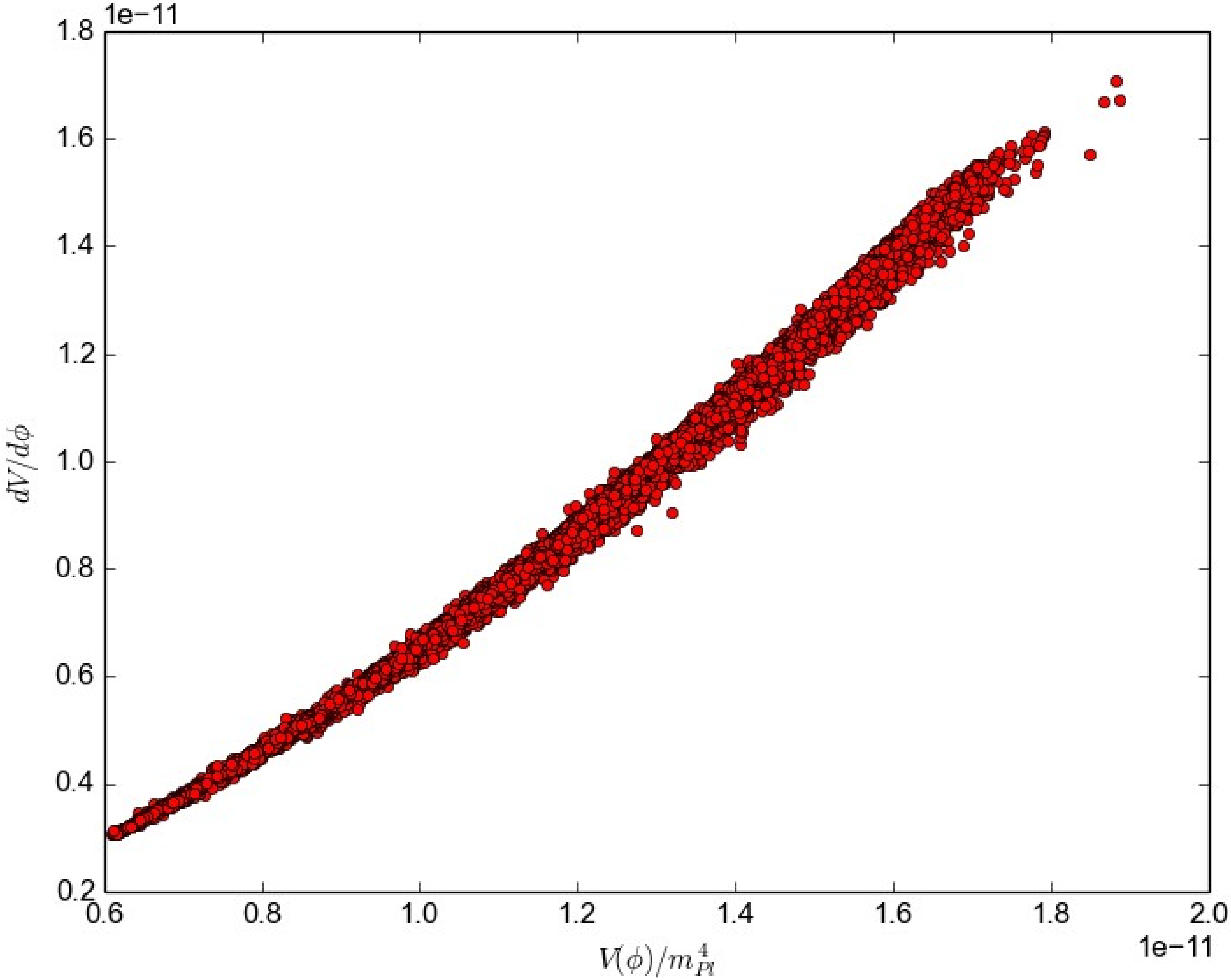
$$\ell < 8$$

Monte Carlo Potential Reconstruction



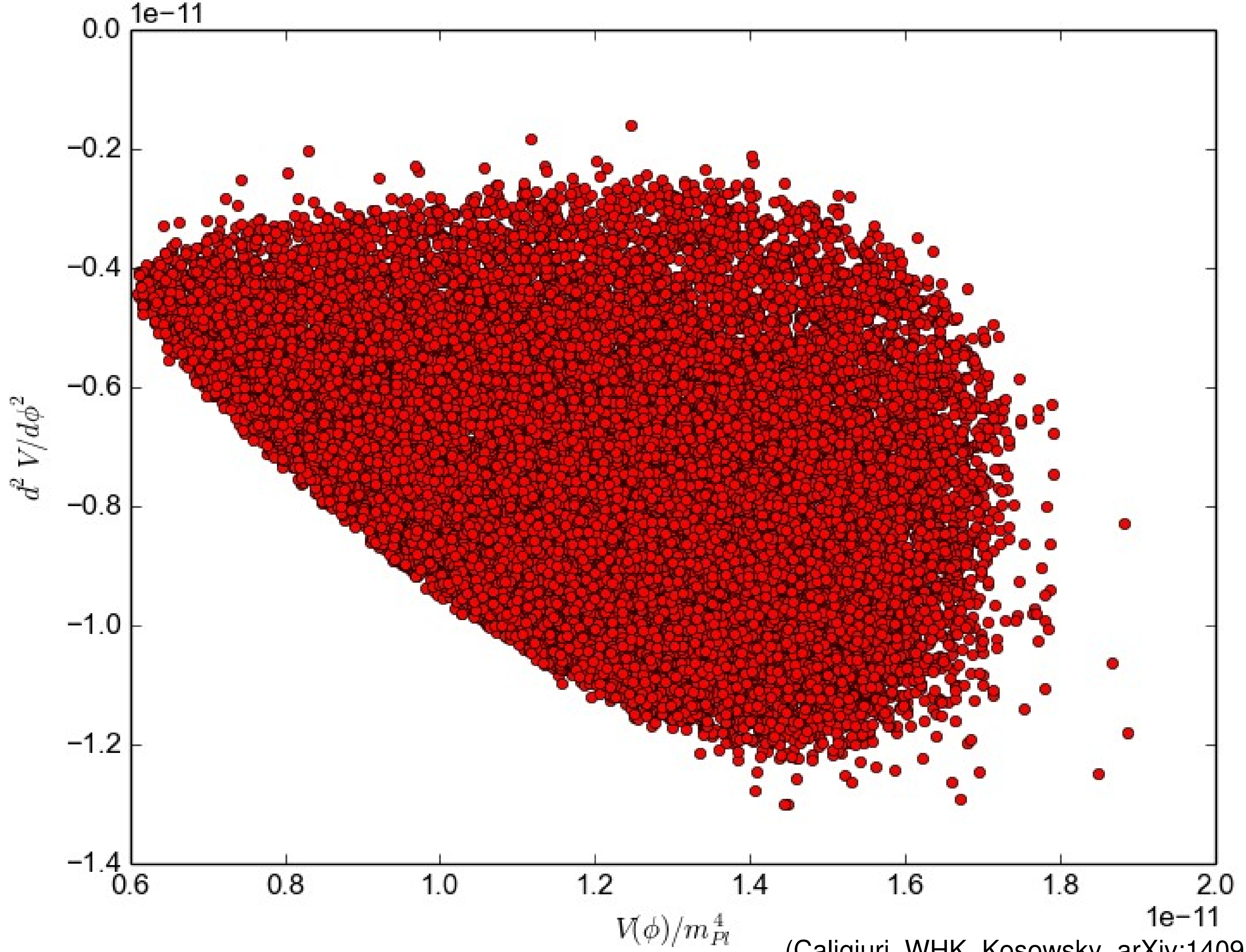
(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

Monte Carlo Potential Reconstruction



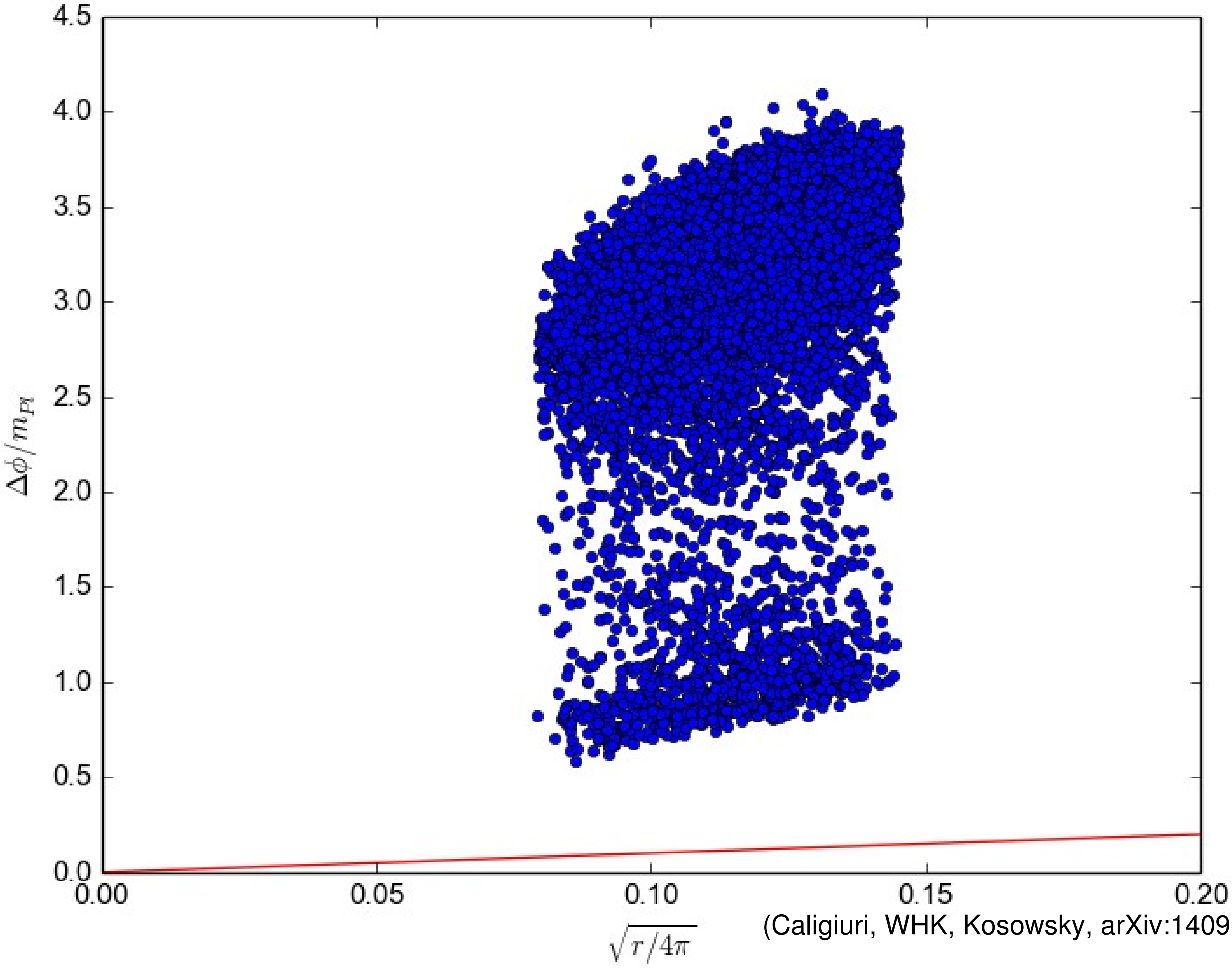
(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

Monte Carlo Potential Reconstruction



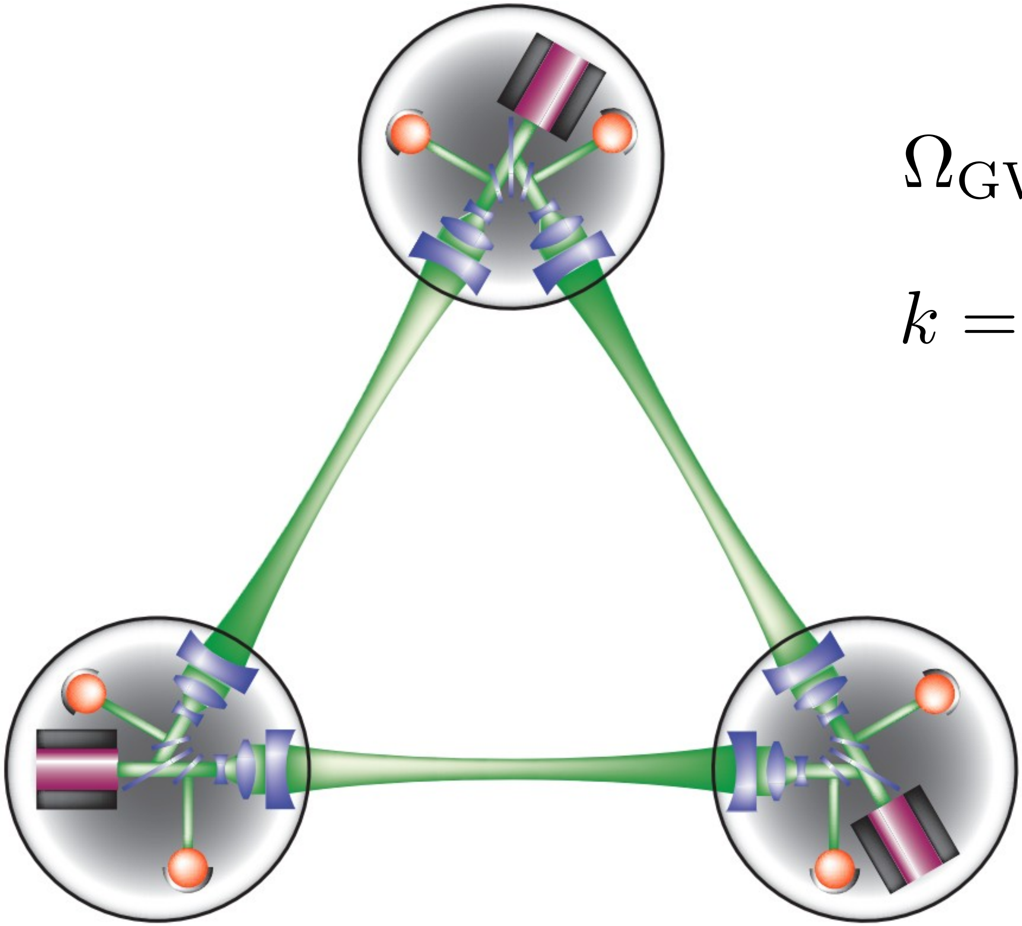
(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

Monte Carlo Potentials and the Lyth Bound



(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

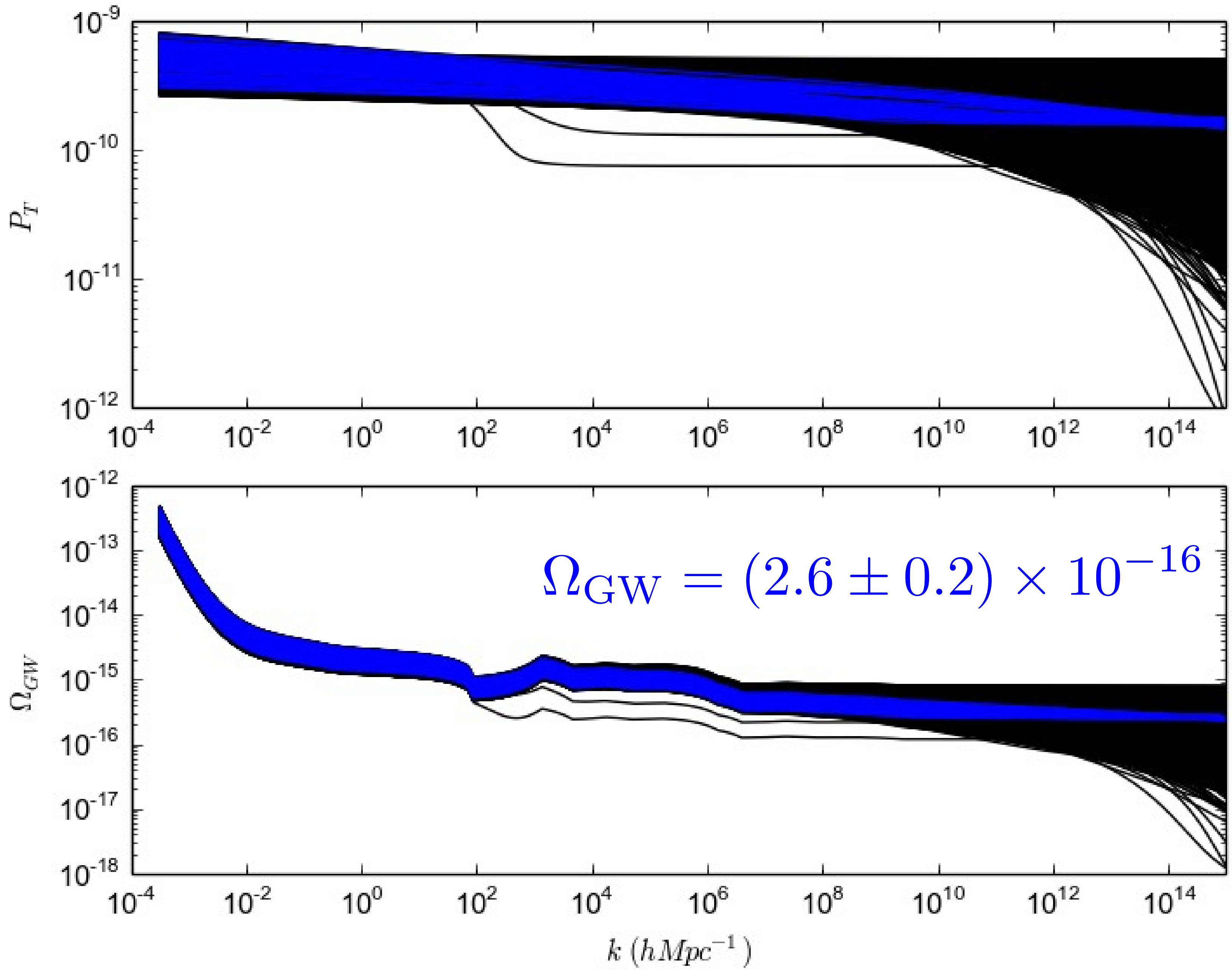
Direct Dectection: DECIGO



$$\Omega_{\rm GW} = (2.6 \pm 0.2) \times 10^{-16}$$

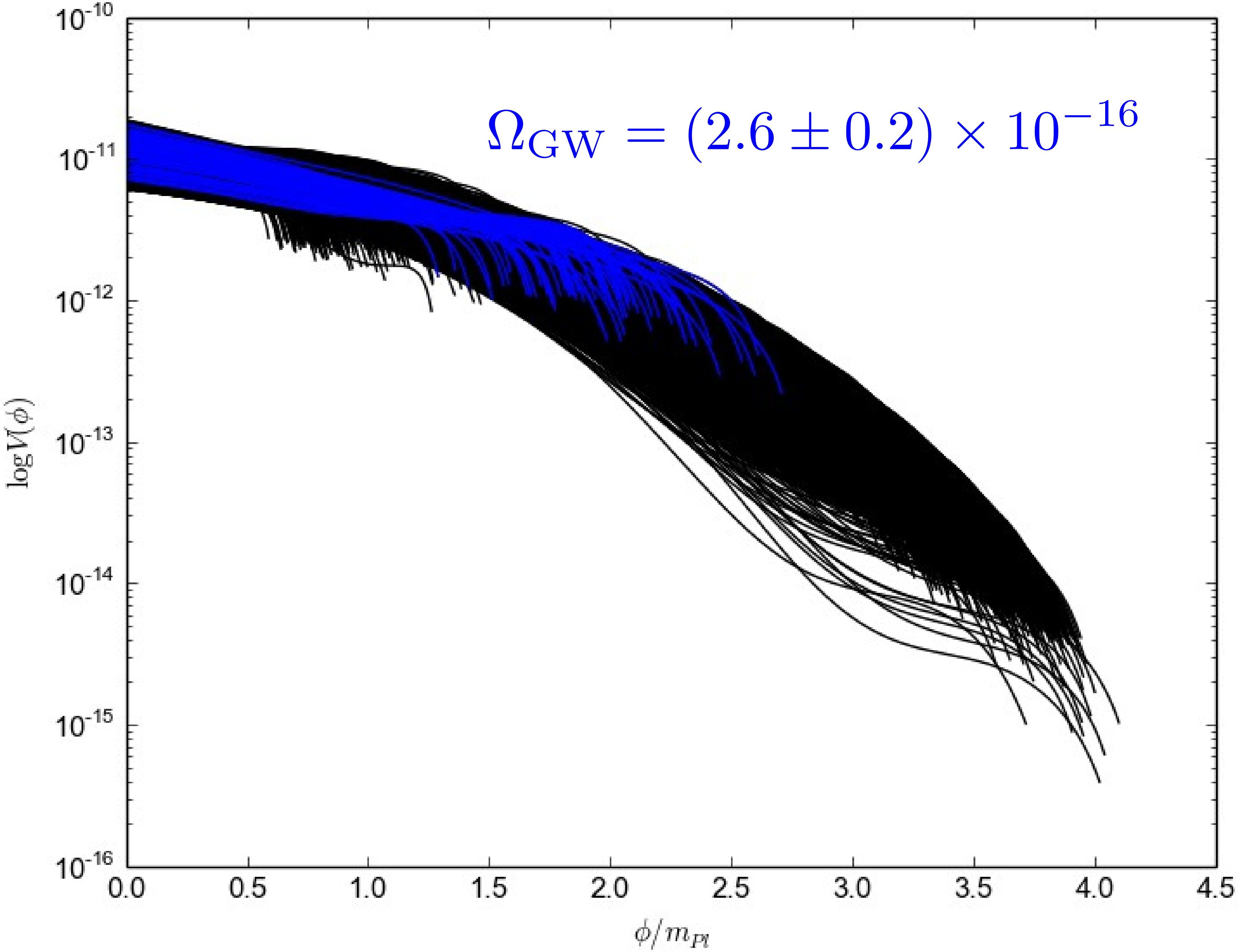
$$k = 1.6 \times 10^{14}\ {\rm Mpc}^{-1}$$

Direct Dectection: DECIGO Forecast



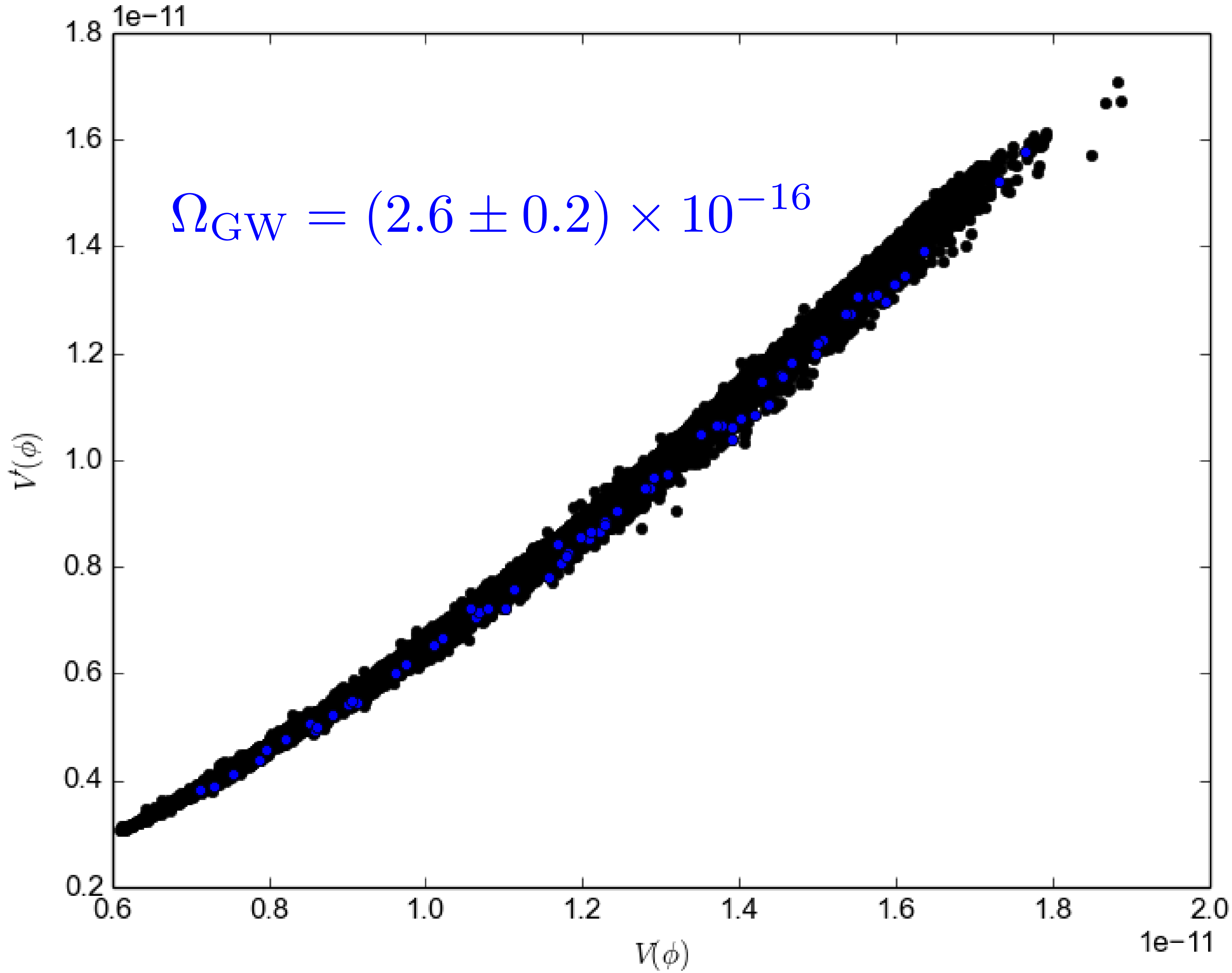
(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

Direct Dectection: DECIGO Forecast



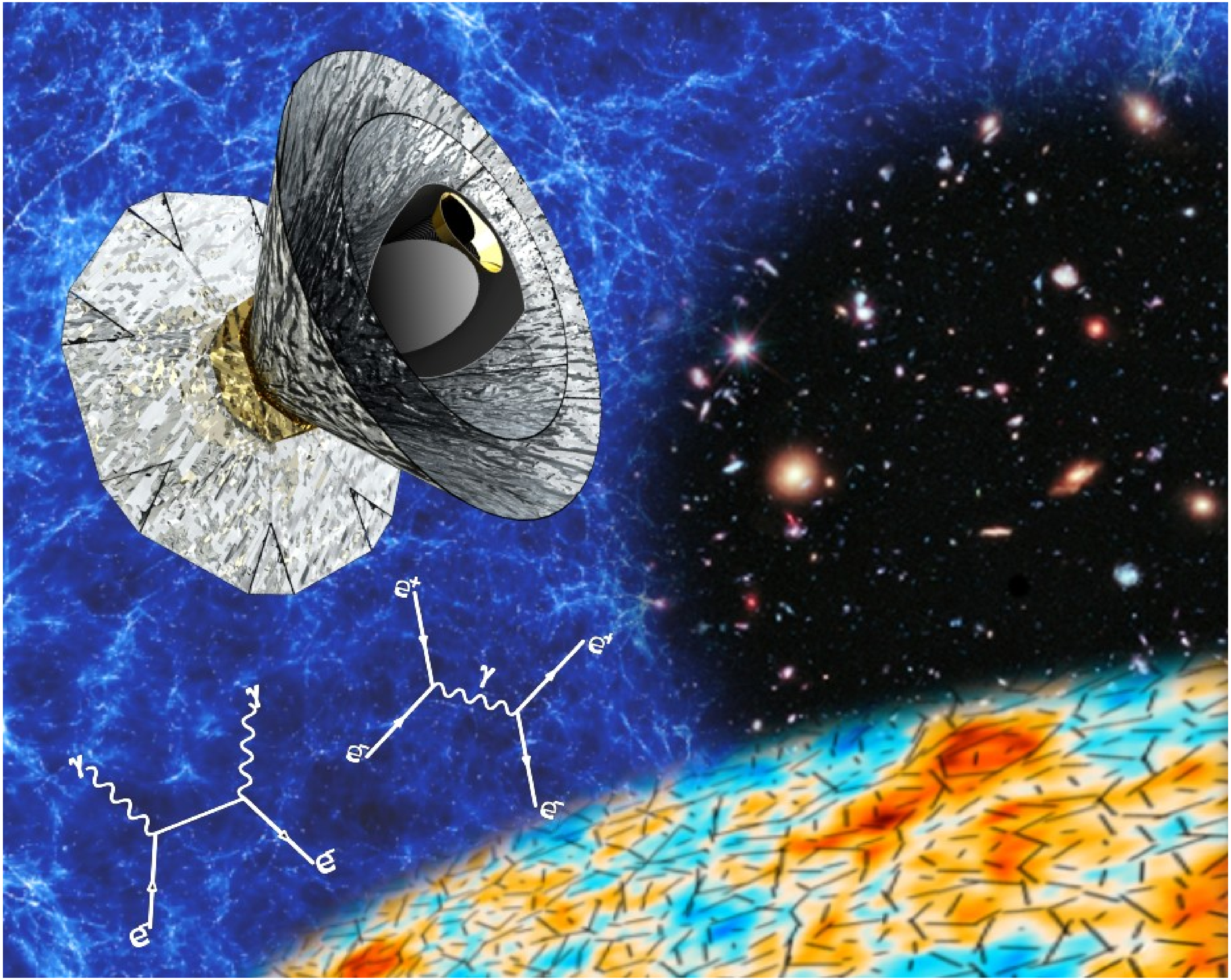
(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

Direct Dectection: DECIGO Forecast

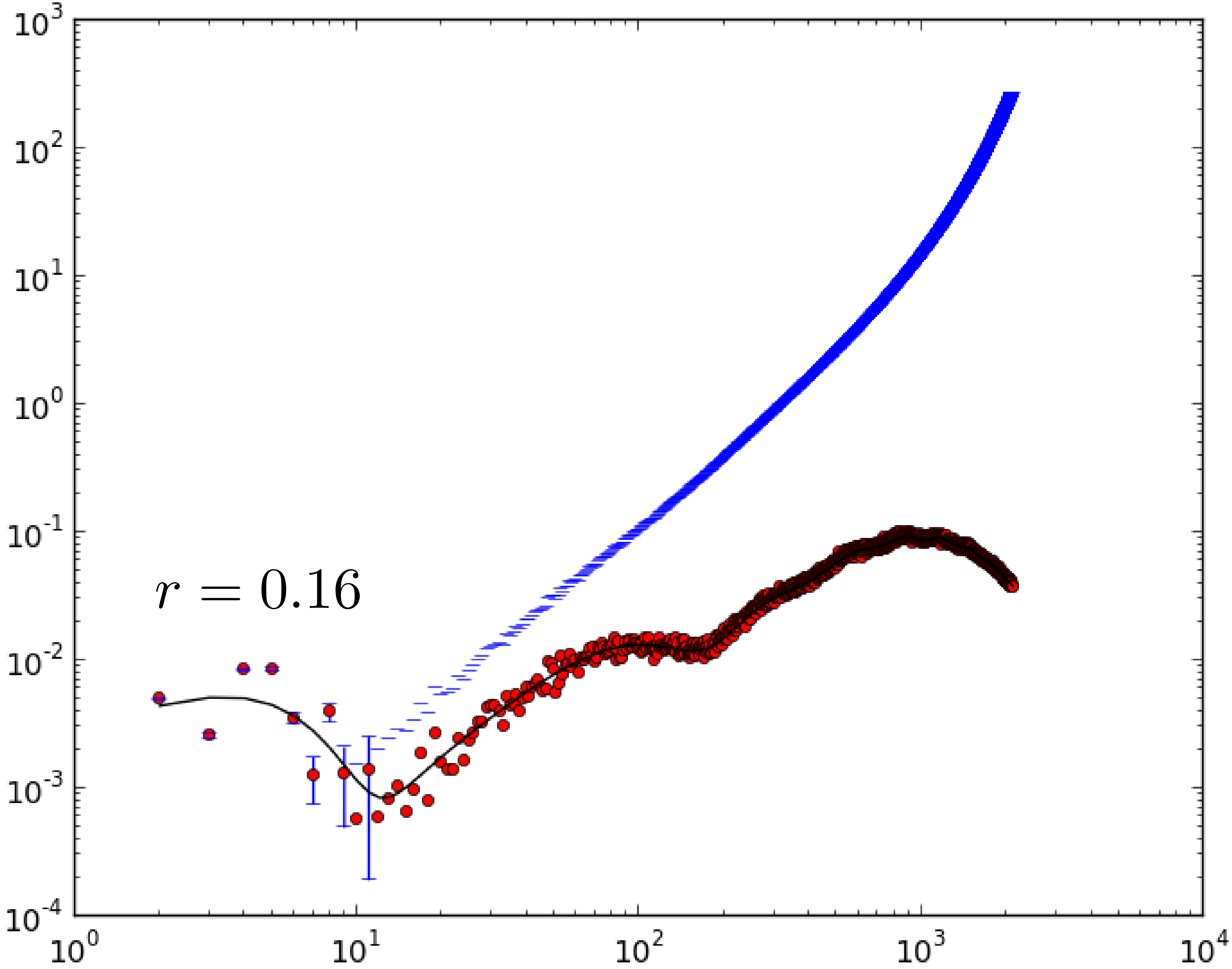


(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

Future Missions



Planck Forecast BB Sensitivity



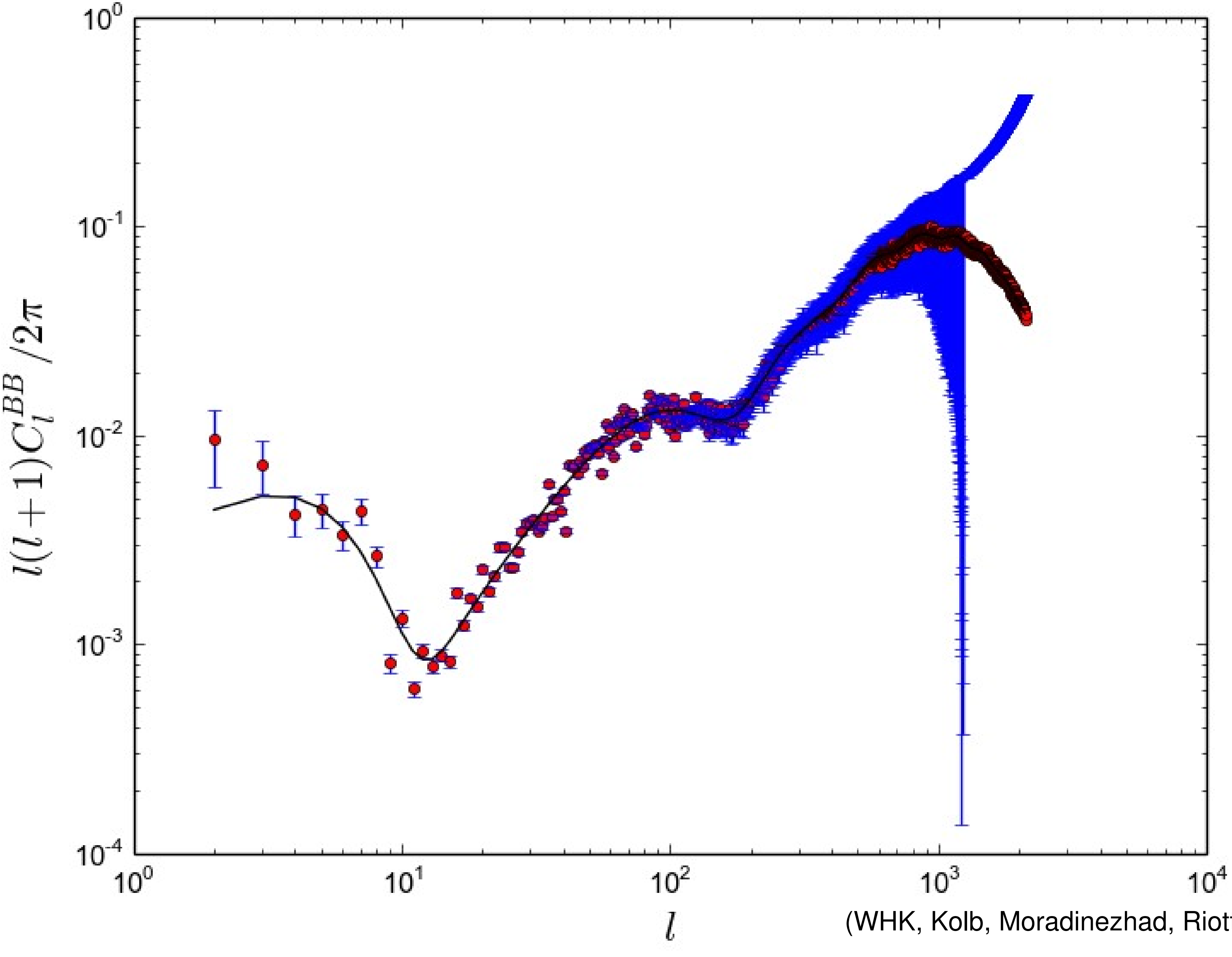
(WHK, Kolb, Moradinezhad, Riotto)

PRISM Assumed Sensitivities

ν	n_{det}	θ_{fwhm}	σ_I per det $\mu K \cdot$arcmin		$\sigma_{(Q,U)}$ per det $\mu K \cdot$arcmin	
GHz		arcmin	RJ	CMB	RJ	CMB
105	250	4.8'	34.5	45.6	48.8	64.4
135	300	3.8'	28.6	44.9	40.4	63.4
160	350	3.2'	24.4	45.5	34.5	64.3
185	350	2.8'	20.8	47.1	29.4	66.6
200	350	2.5'	18.9	48.5	26.7	68.6

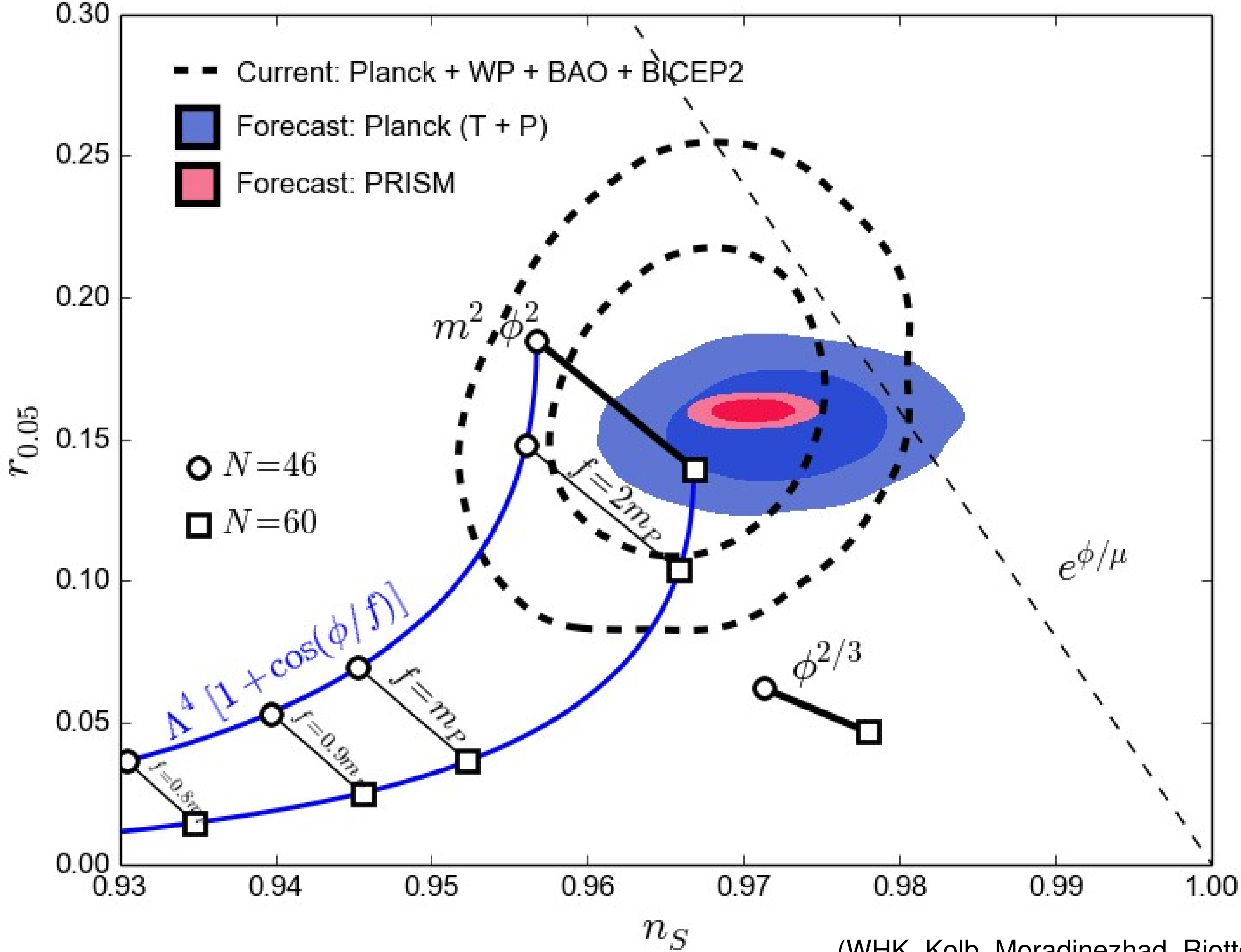
P. Andre et al. [PRISM Collaboration], arXiv:1306.2259 [astro-ph.CO].

PRISM Forecast BB Sensitivity



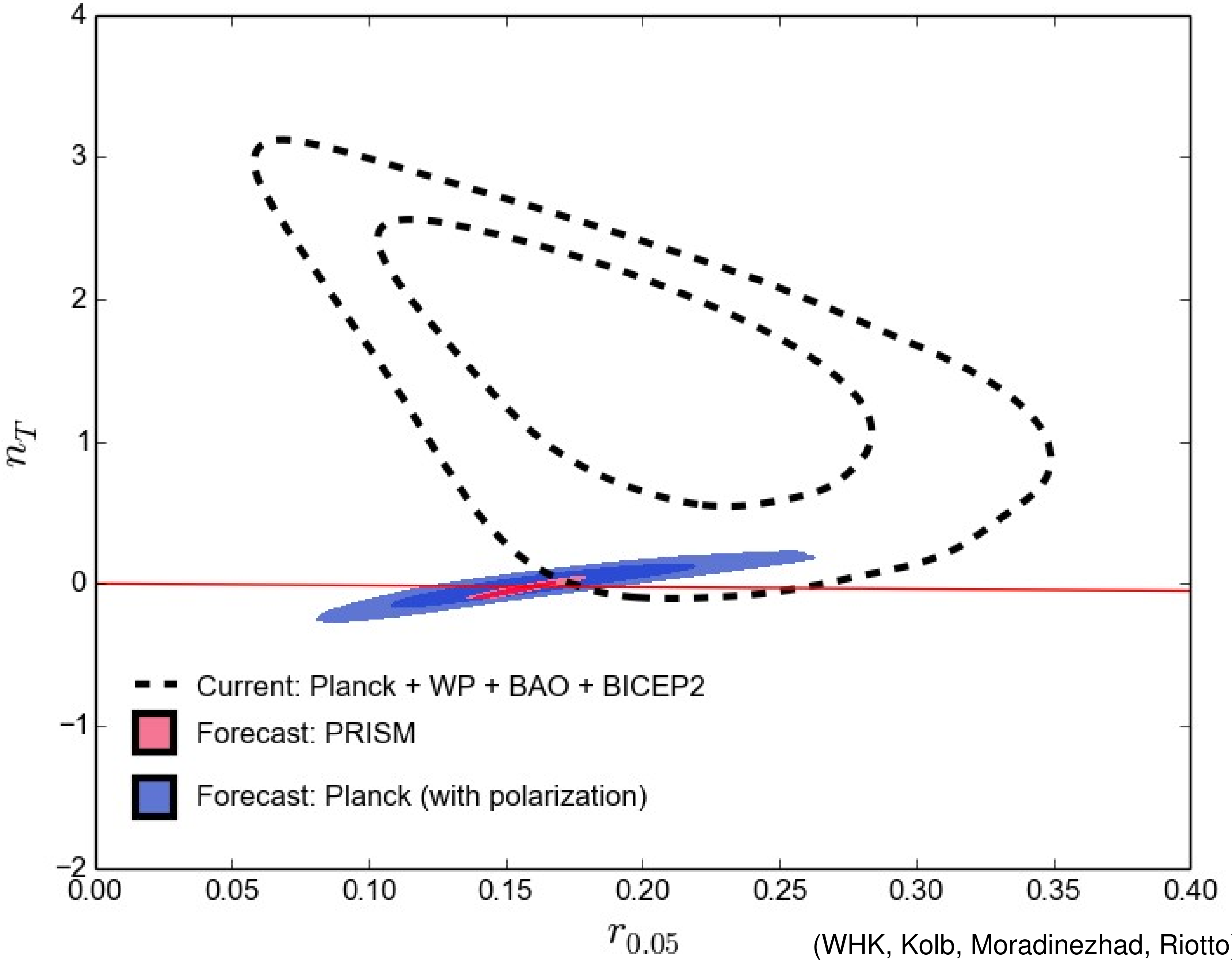
(WHK, Kolb, Moradinezhad, Riotto)

PRISM Forecast Model Constraints



(WHK, Kolb, Moradinezhad, Riotto)

PRISM Forecast: Consistency Condition



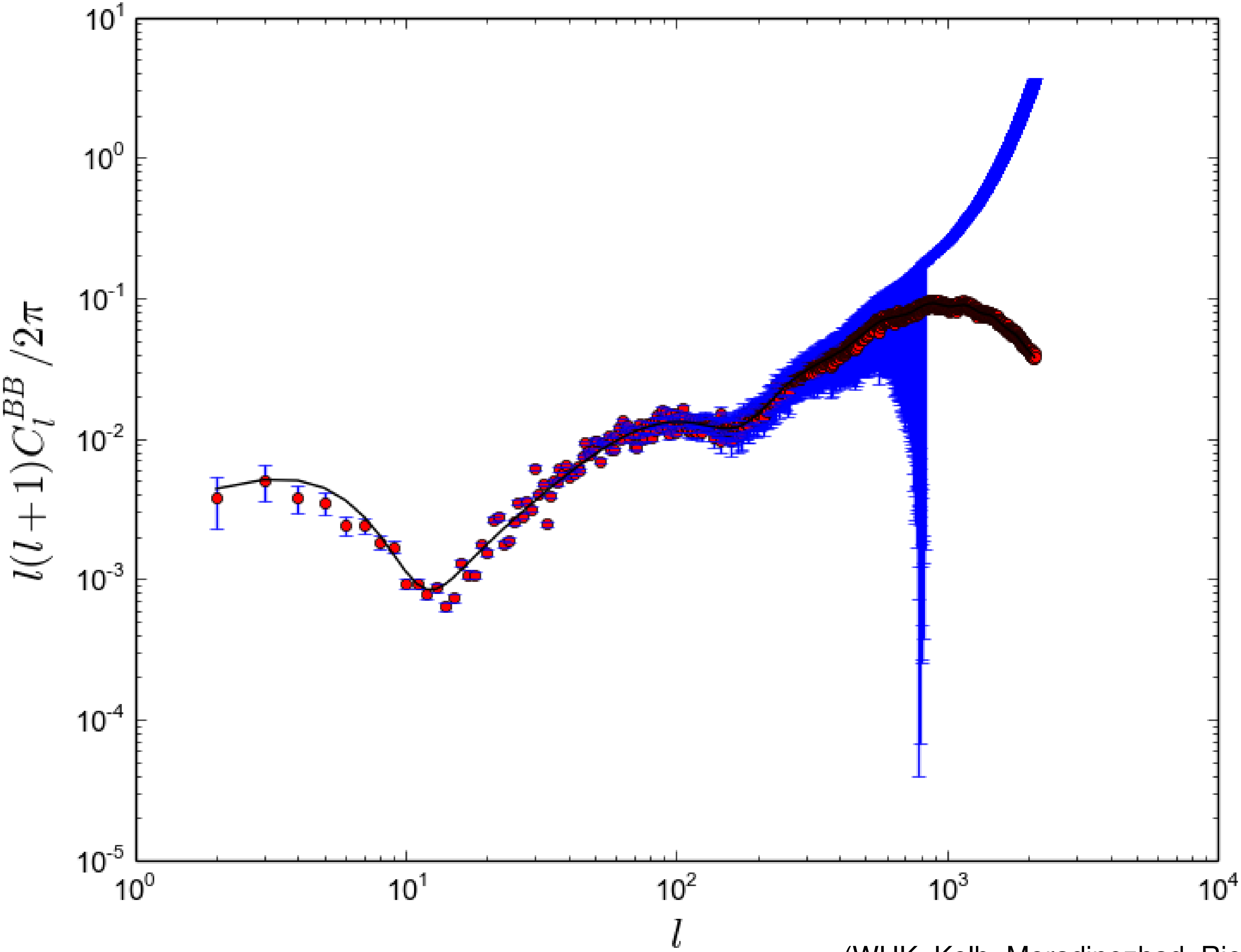
(WHK, Kolb, Moradinezhad, Riotto)

COrE Assumed Sensitivities

ν	n_{det}	θ_{fwhm}	σ_I $\mu K \cdot$arcmin		$\sigma_{(Q,U)}$ $\mu K \cdot$arcmin	
GHz		arcmin	RJ	CMB	RJ	CMB
75	300	14.0	2.36	2.73	4.09	4.72
105	400	10.0	2.03	2.68	3.50	4.63
135	550	7.8	1.68	2.63	2.90	4.55
165	750	6.4	1.38	2.67	2.38	4.61
195	1150	5.4	1.07	2.63	1.84	4.54
225	1800	4.7	0.82	2.64	1.42	4.57

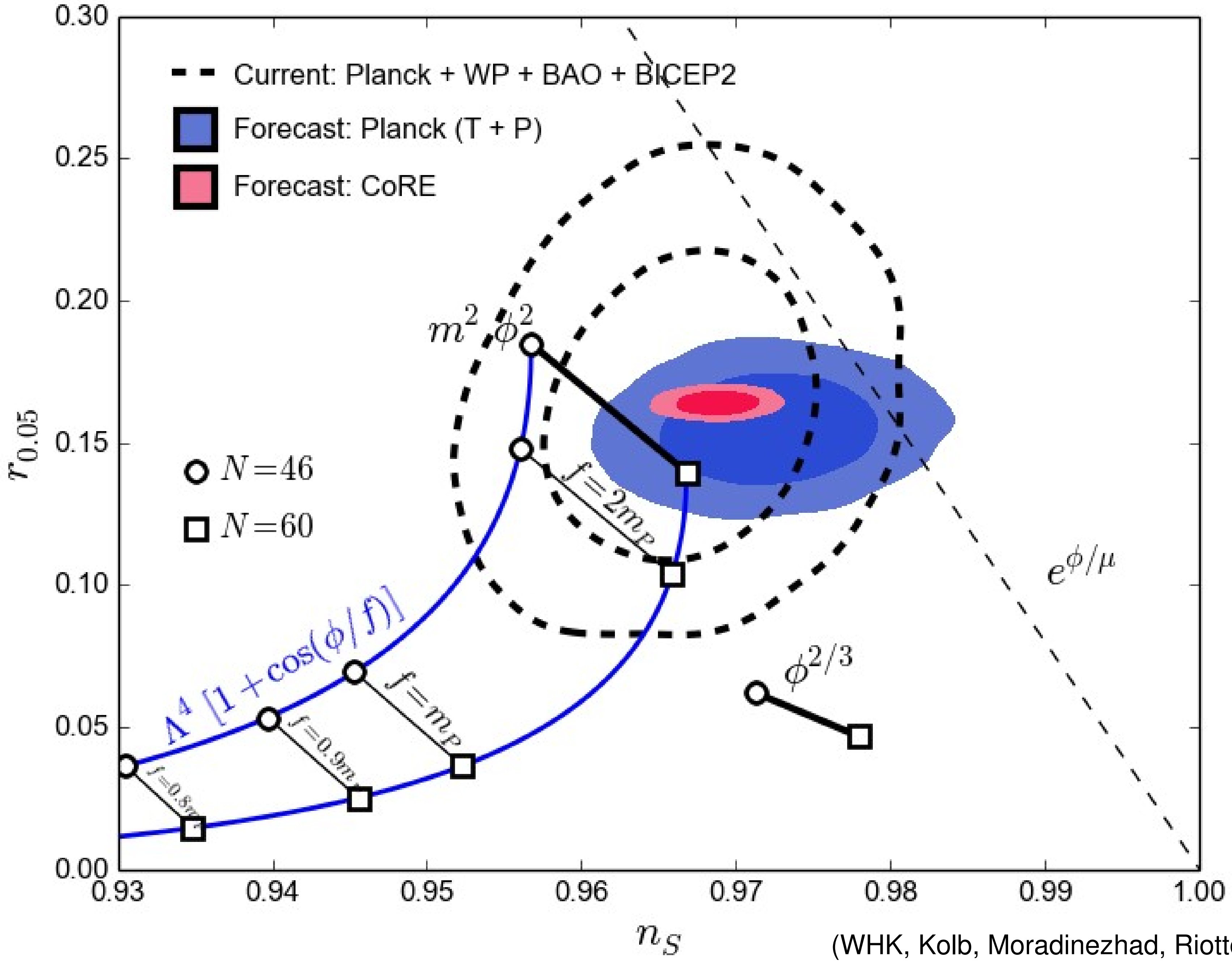
F. R. Bouchet et al. [COrE Collaboration], arXiv:1102.2181

COrE Forecast BB Sensitivity



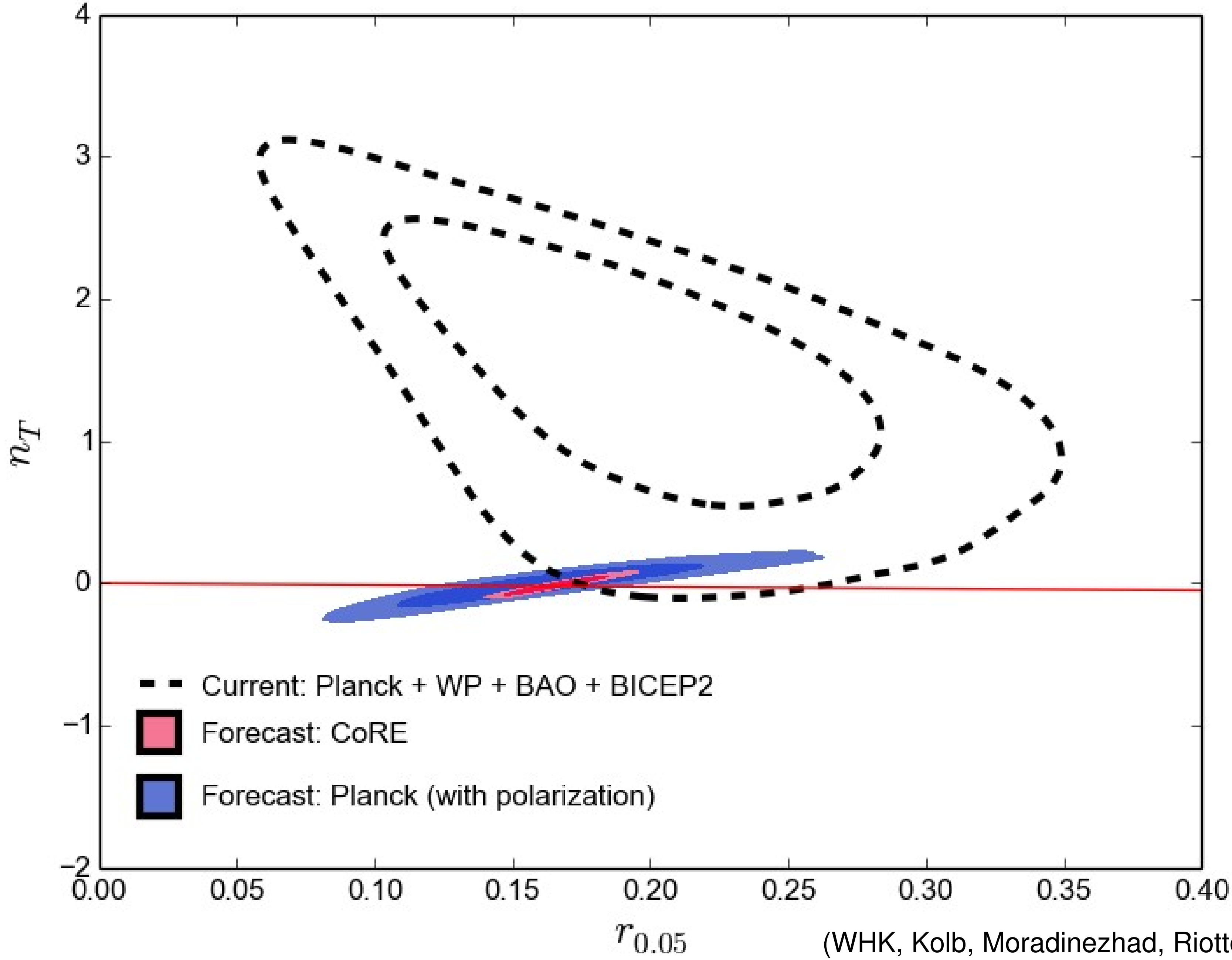
(WHK, Kolb, Moradinezhad, Riotto)

CoRE Forecast Model Constraints



(WHK, Kolb, Moradinezhad, Riotto)

COrE Forecast: Consistency Condition



(WHK, Kolb, Moradinezhad, Riotto)

Five Questions We Can (Maybe) Answer

(1) What is the shape of the tensor power spectrum? Is the consistency condition satisfied?
(Planck/DECIGO)

(2) Do we need a non-power-law scalar spectrum to resolve the tension between BICEP and Planck? (Extra neutrino?)

(3) What is the form of the leading-order operator in the inflationary potential? (Reconstruction?)

(4) Is there evidence for quantum gravity effects, for example a Planck-scale cutoff on quantum modes of order H/M?

(5) Can we explain CMB anomalies, such as the hemispherical asymmetry observed by Planck? ("Just enough" inflation?)