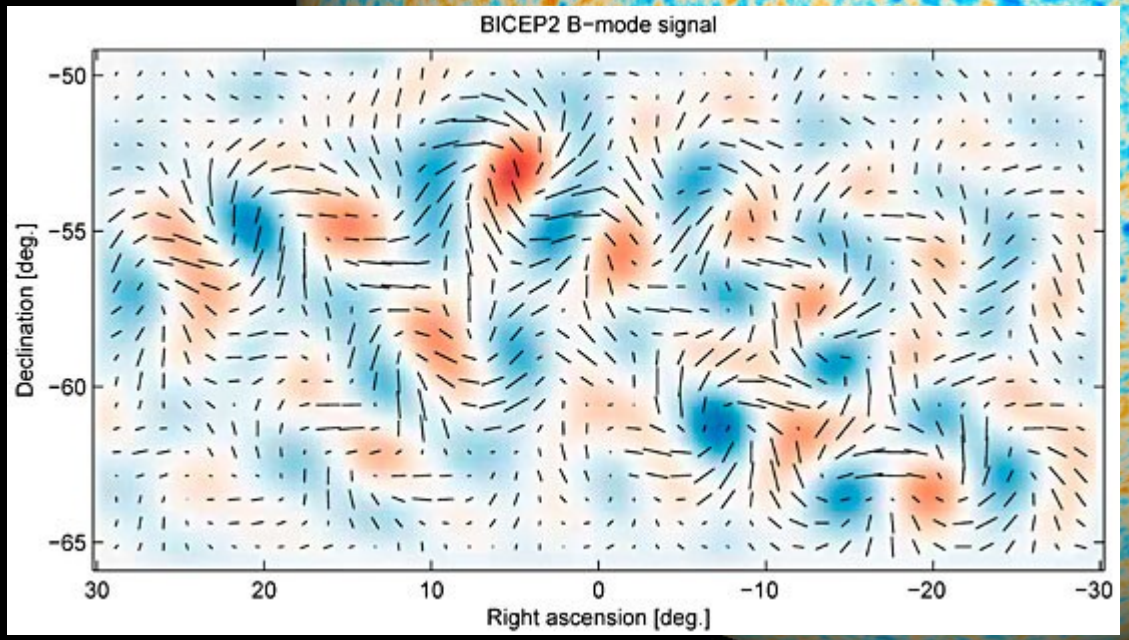
Planck, BICEP2, and Inflation



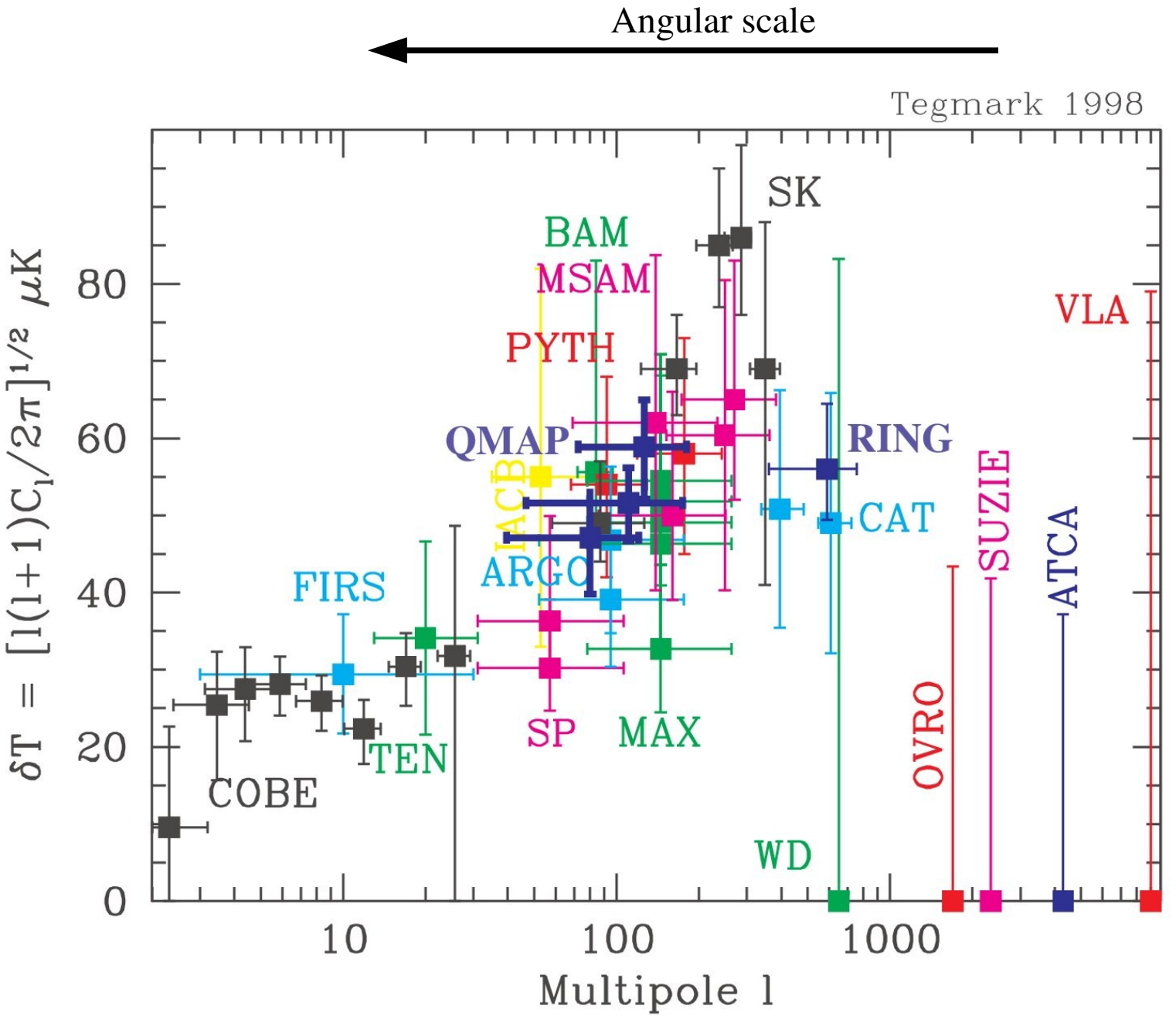
Will Kinney

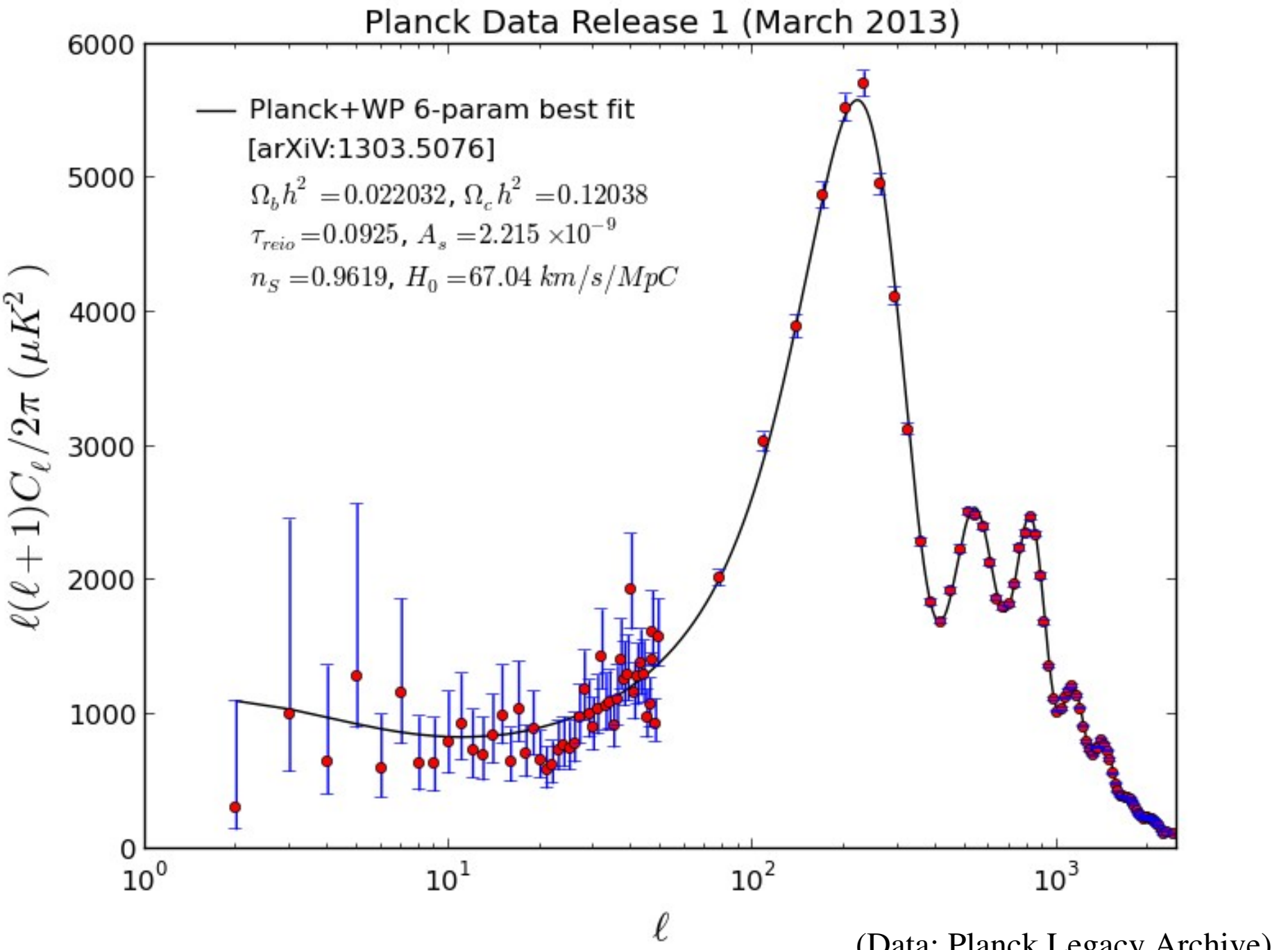
30th Institut d'Astrophysique de Paris Colloquium

17 December 2014

University at Buffalo *The State University of New York*

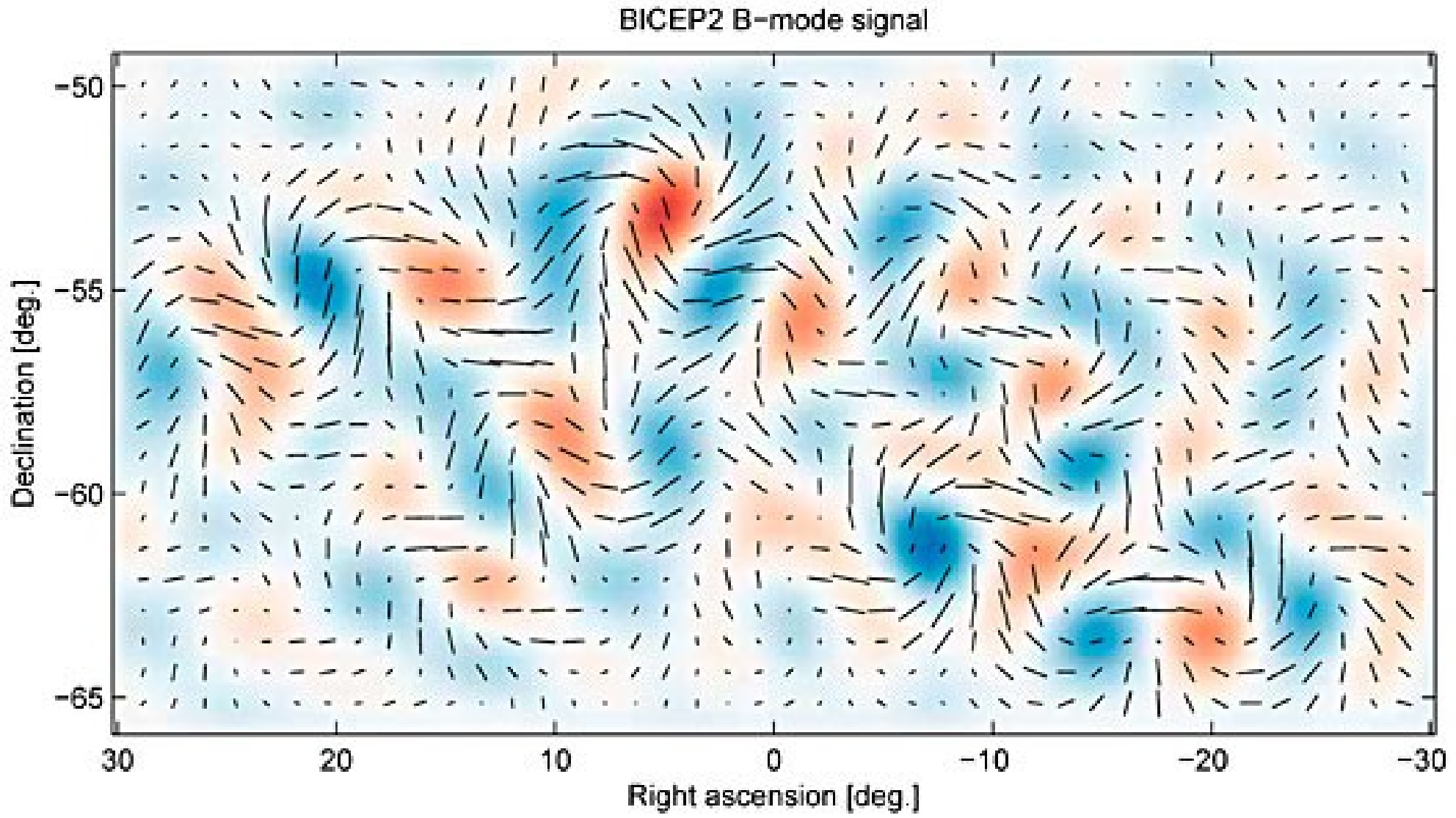
The CMB Angular Power Spectrum (1998)



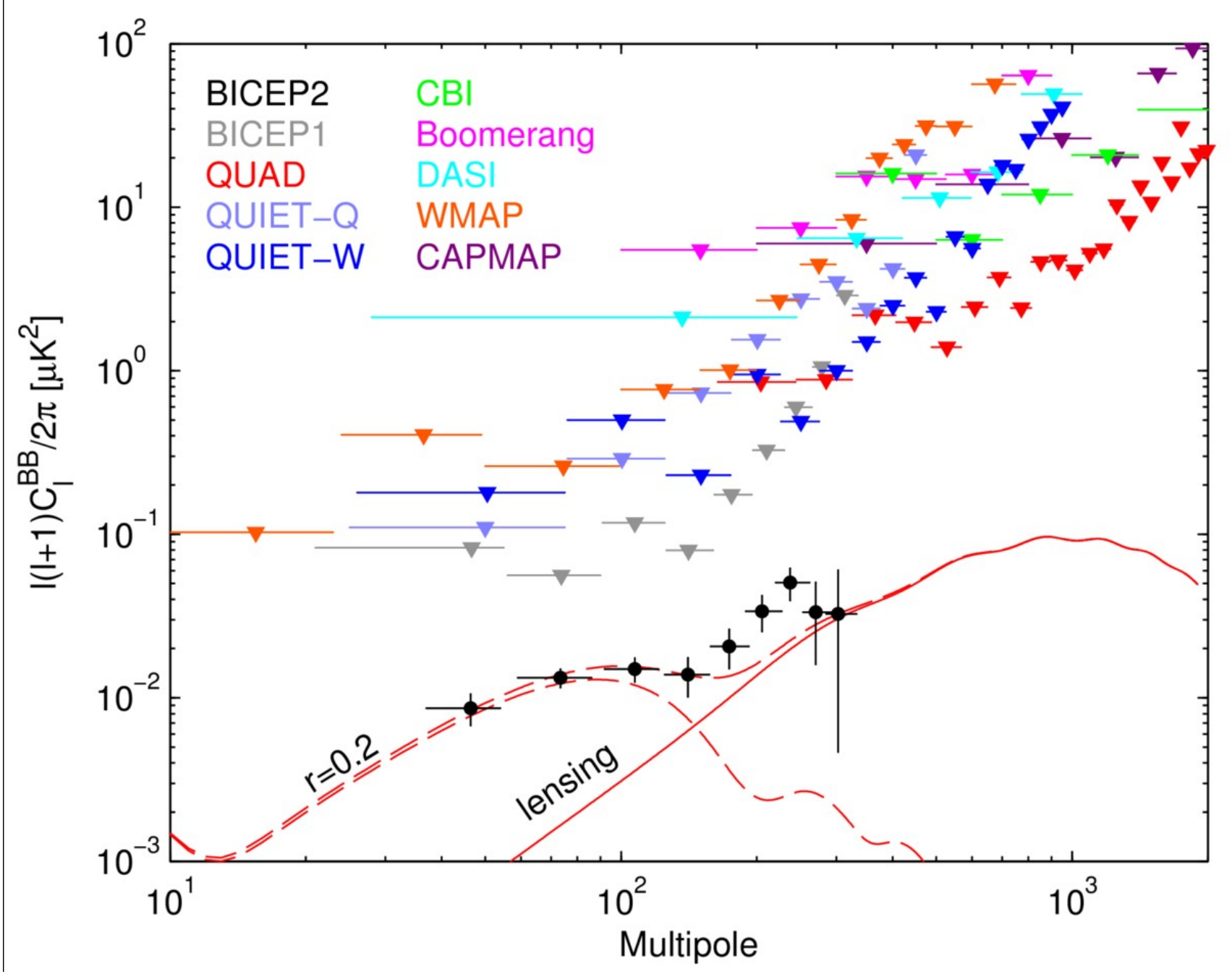


(Data: Planck Legacy Archive)

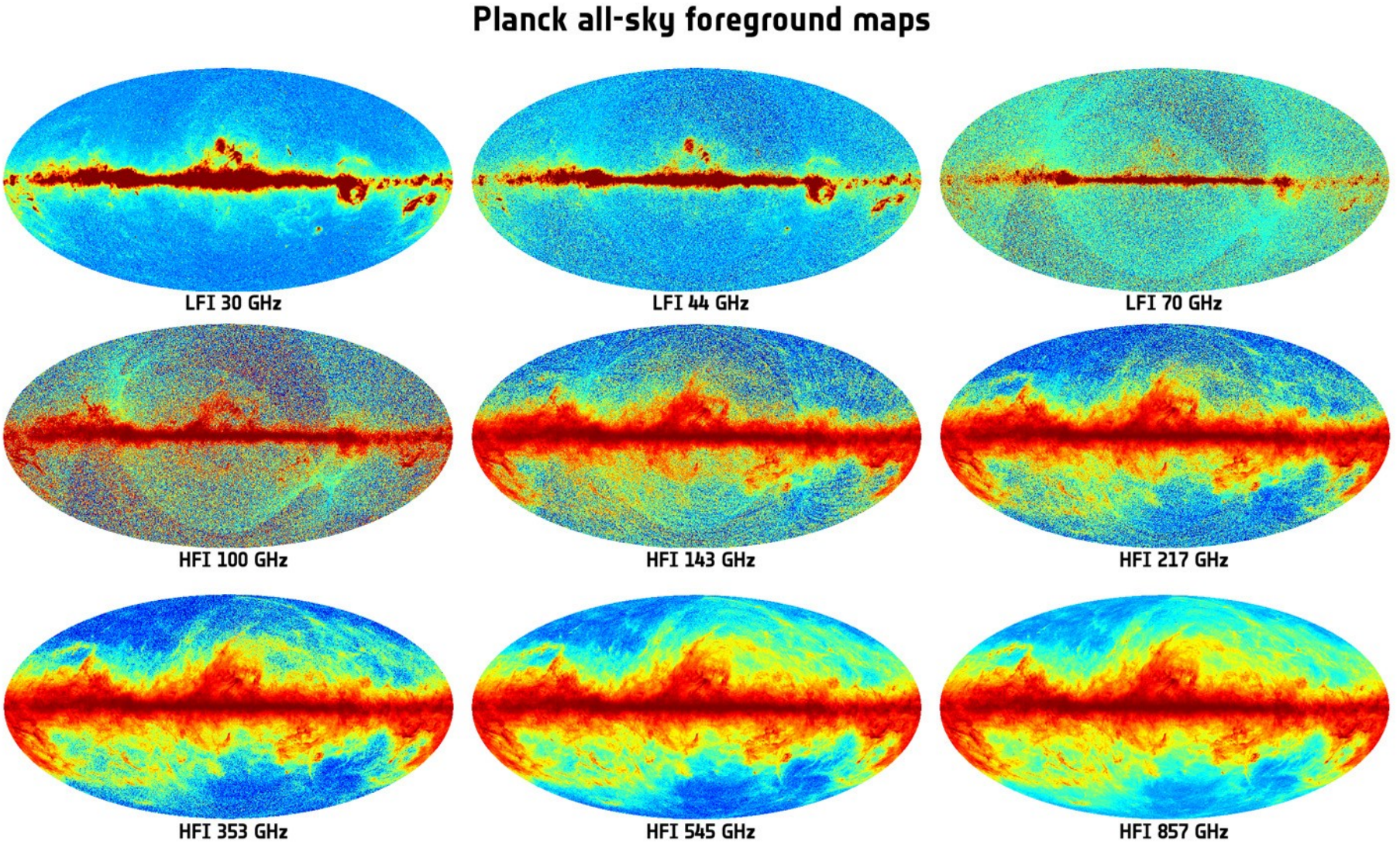
BICEP: Pretty Swirly Things



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

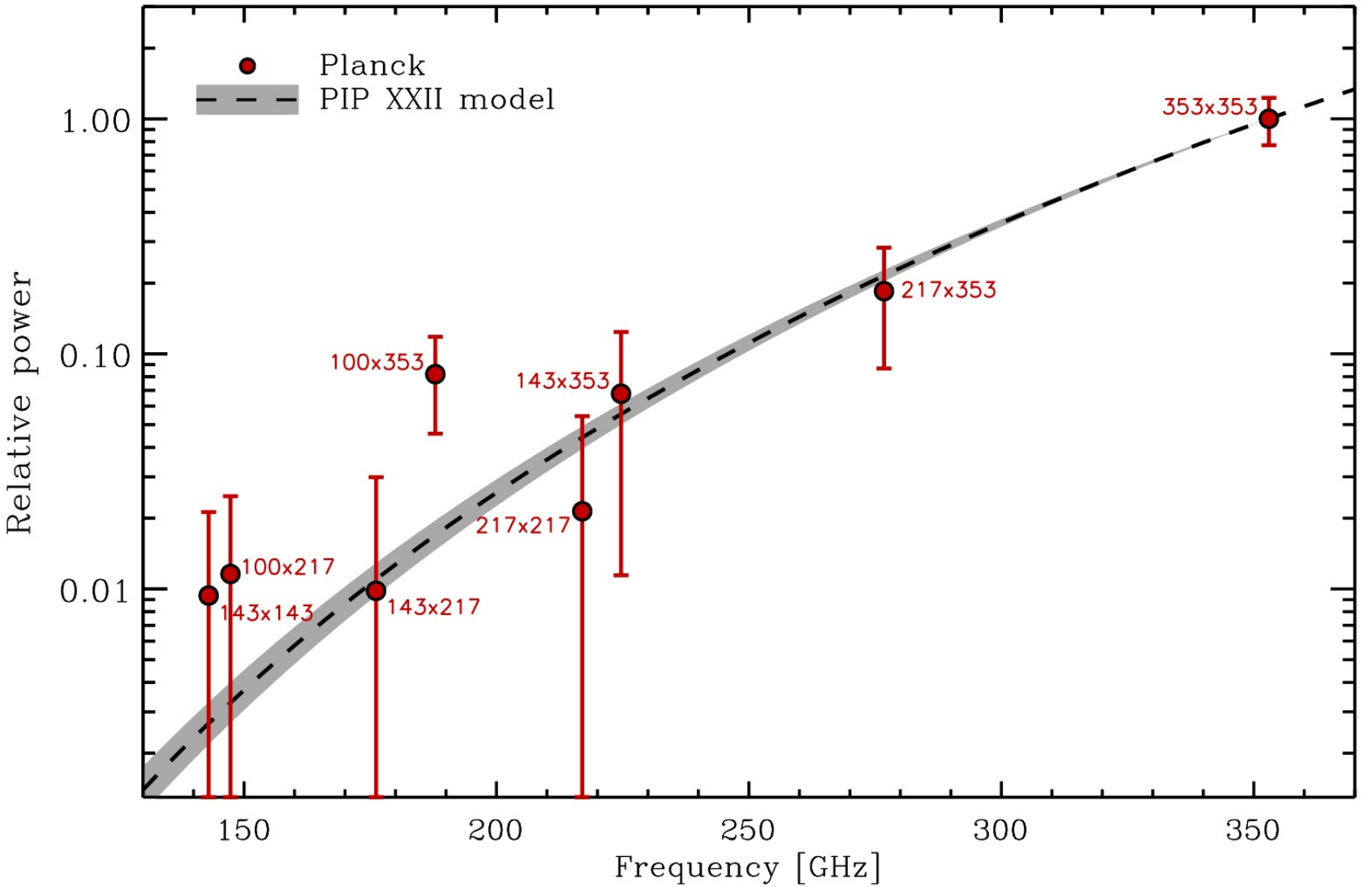


(Ade, *et al.*, arXiv:1403.3985)



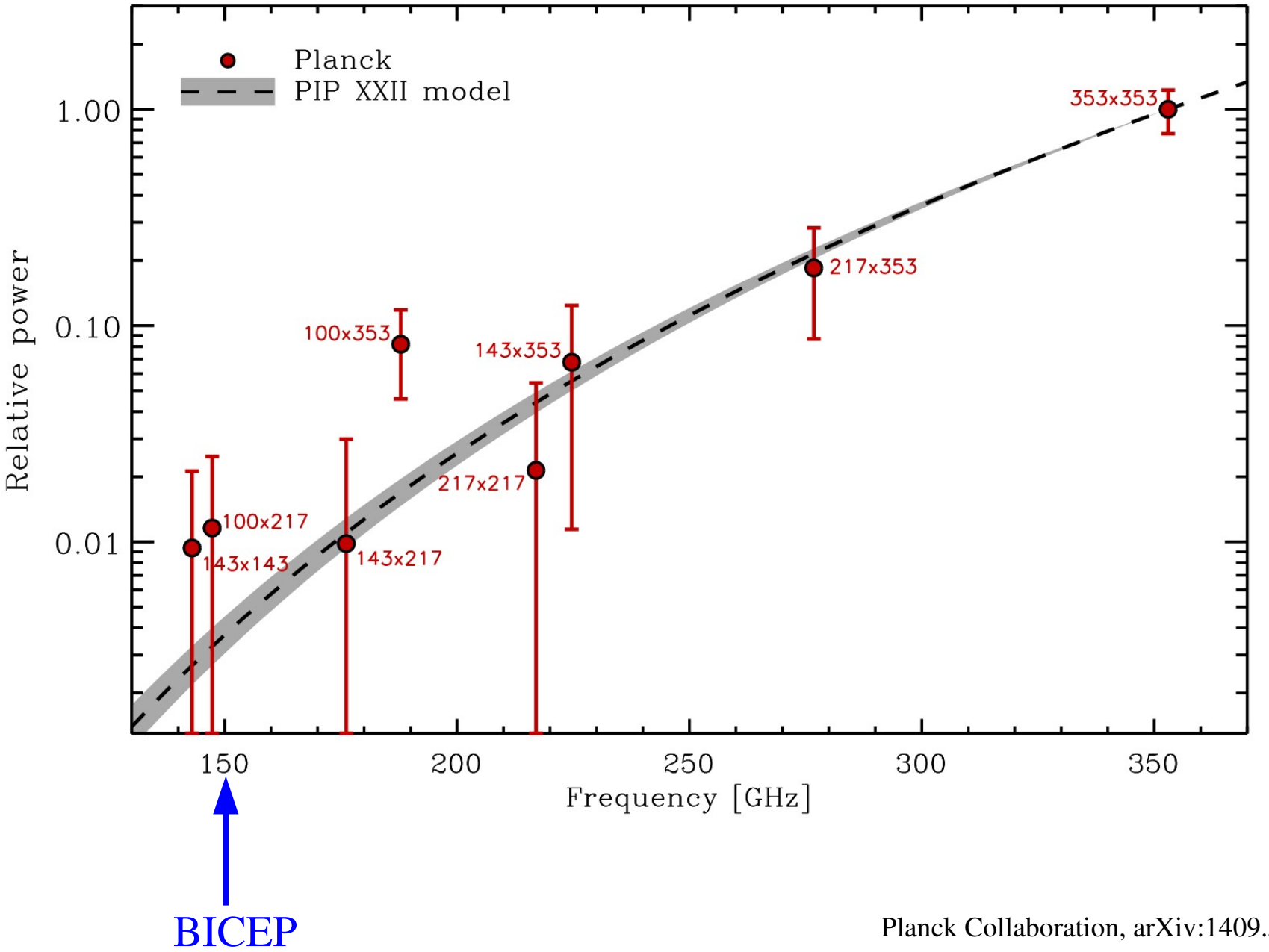
(Image: Planck Collaboration)

Planck: Dust Spectrum



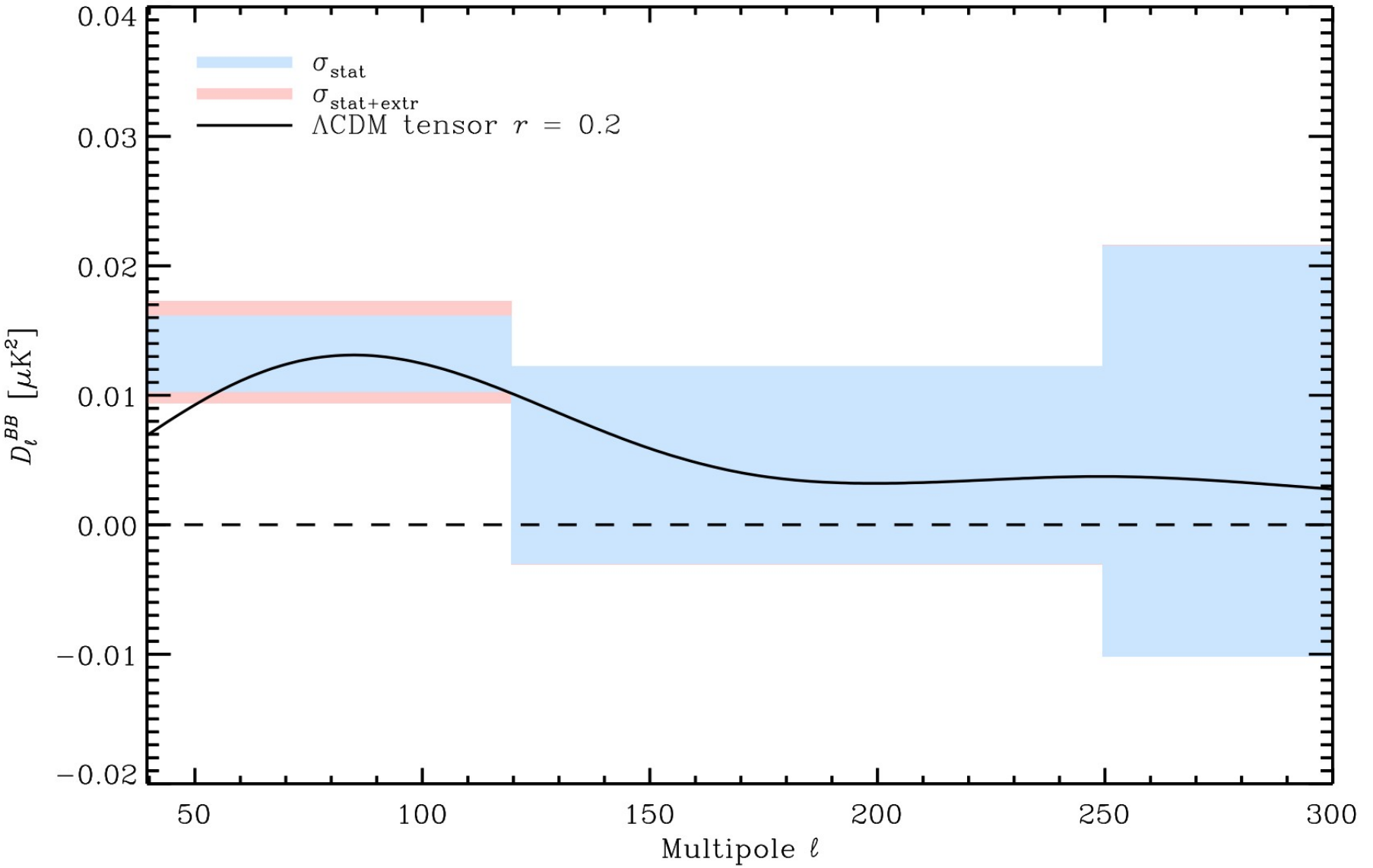
Planck Collaboration, arXiv:1409.5738

Planck: Dust Spectrum



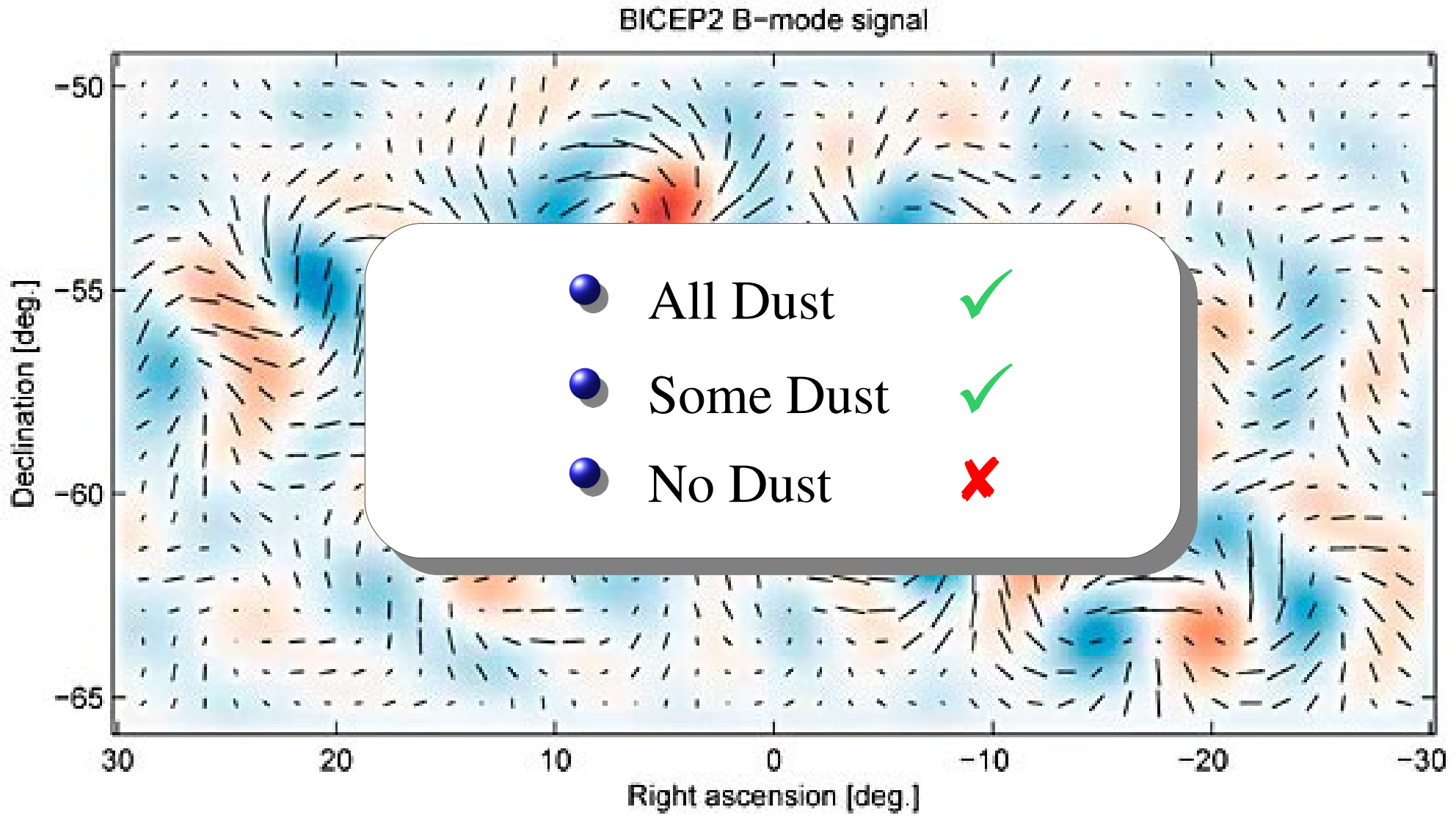
Planck Collaboration, arXiv:1409.5738

Planck: Dust Angular Power Spectrum



Planck Collaboration, arXiv:1409.5738

BICEP2 In Light of Planck Dust Maps



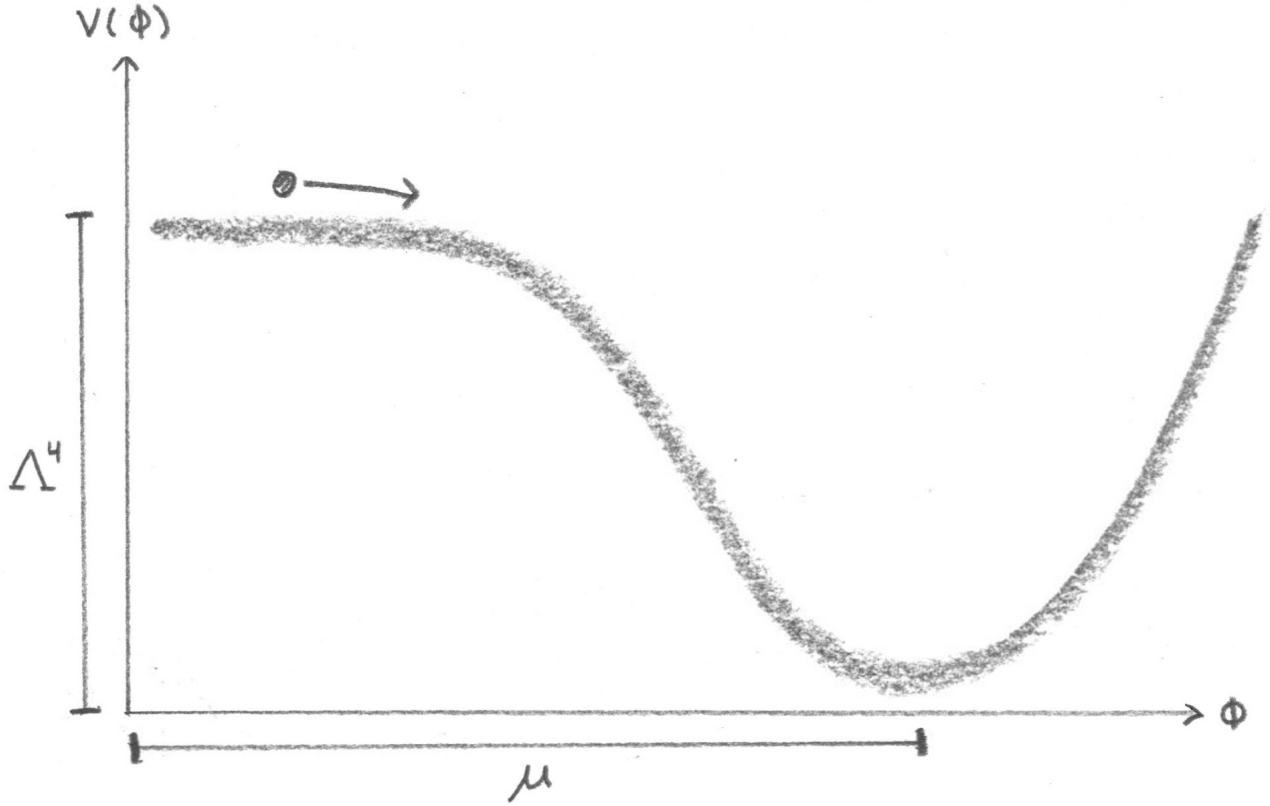
(Ade, *et al.*, arXiv:1403.3985)

Primordial B-modes and Single-Field Inflation

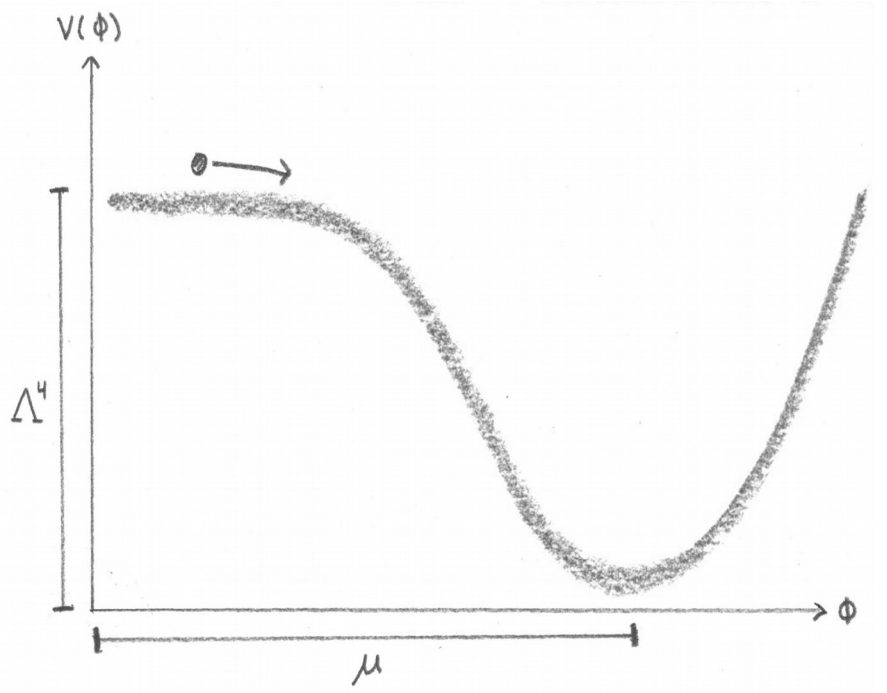
$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi - V(\phi)$$

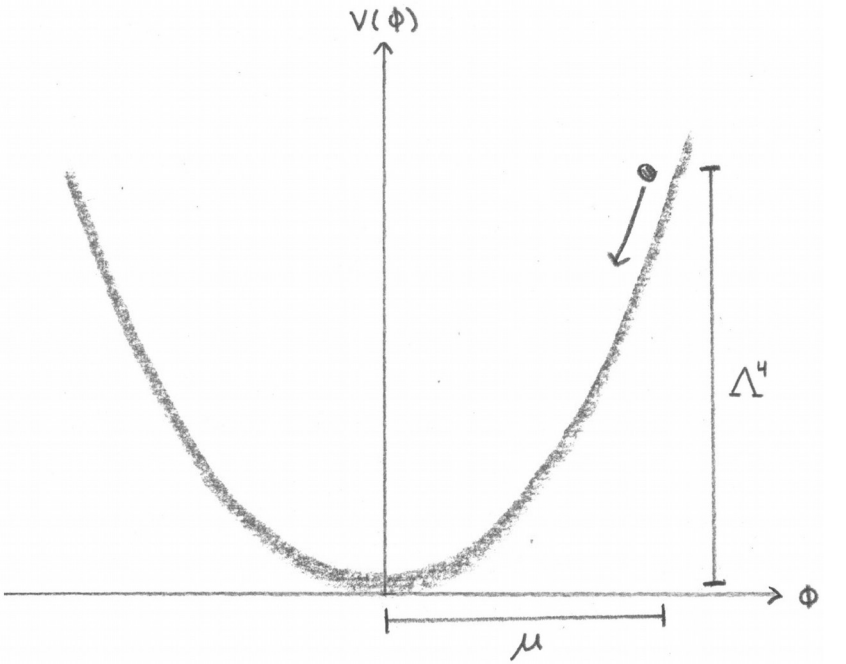
Fully consistent with data.

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

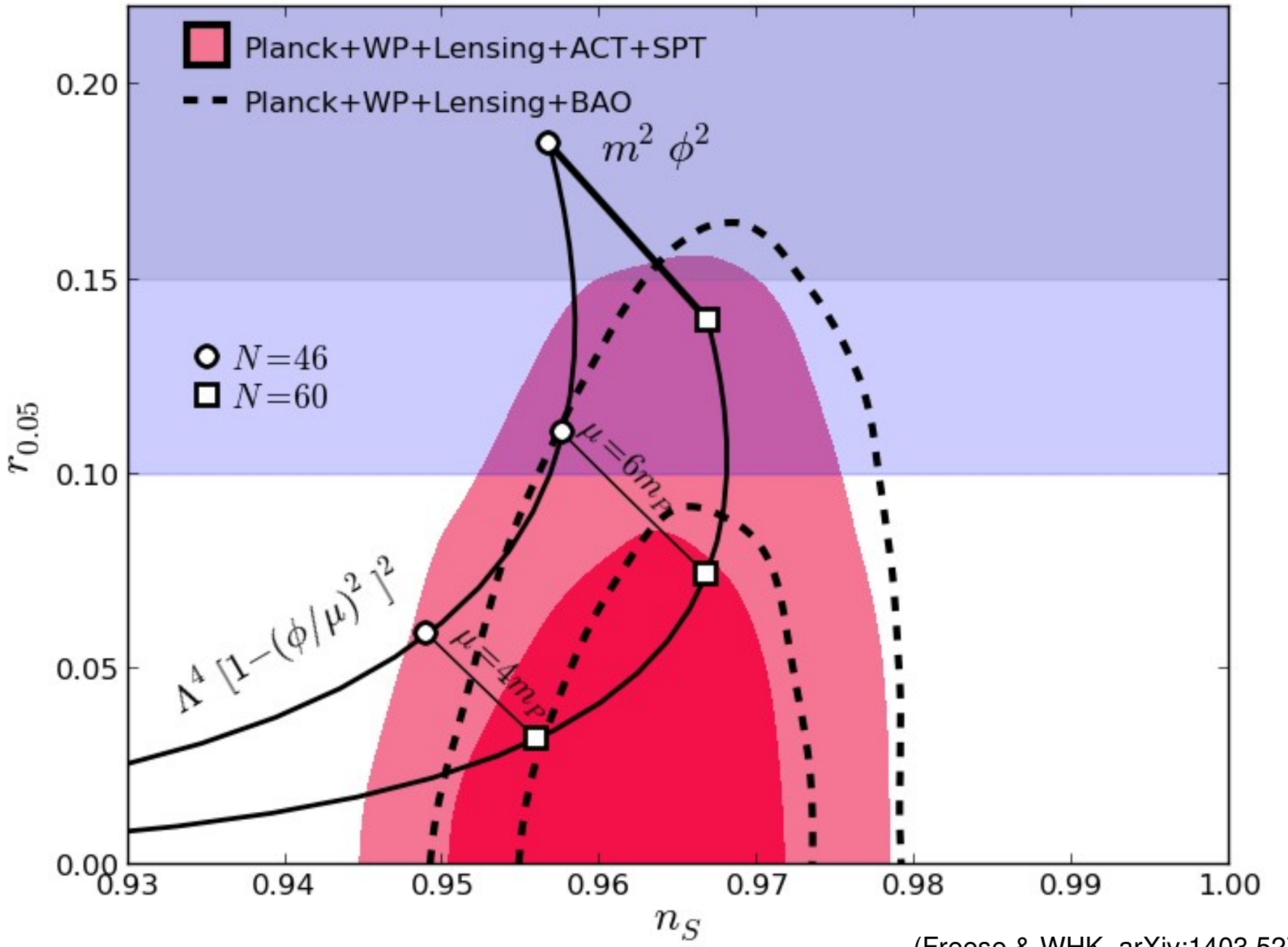


Small Field or Large Field?





Constraints on Higgs-like Inflation



(Freese & WHK, arXiv:1403.5277)

Inflation and Effective Field Theory

Effective potential suppressed by mass scale μ

$$V(\phi) = V_0 - \sum_p \lambda_p \left(\frac{\phi}{\mu}\right)^p$$

Lowest-order term *always* dominates near origin:

$$p = 2: \;\; V(\phi) \simeq V_0 - m^2\phi^2 + \cdots$$

$$p = 4: \;\; V(\phi) \simeq V_0 - \lambda\phi^4 + \cdots$$

Inflation and Effective Field Theory

Effective potential suppressed by mass scale μ

$$V(\phi) = V_0 - \sum_p \lambda_p \left(\frac{\phi}{\mu}\right)^p$$

$p = 2$: Spectral index quadratic in scale

$$n = 1 - \frac{1}{4\pi}\left(\frac{m_{\rm P}}{\mu}\right)^2$$

Inflation and Effective Field Theory

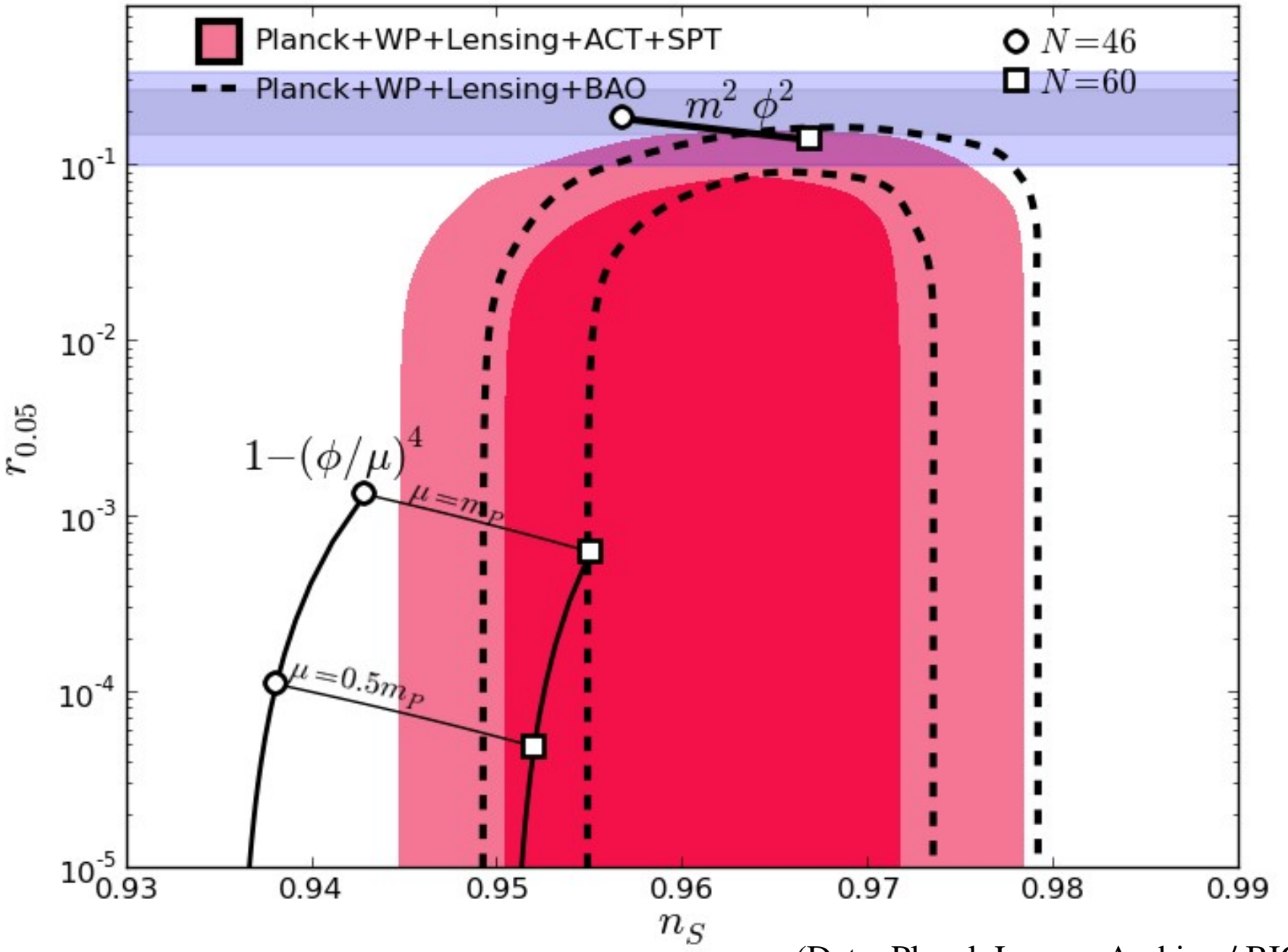
Effective potential suppressed by mass scale μ

$$V(\phi) = V_0 - \sum_p \lambda_p \left(\frac{\phi}{\mu}\right)^p$$

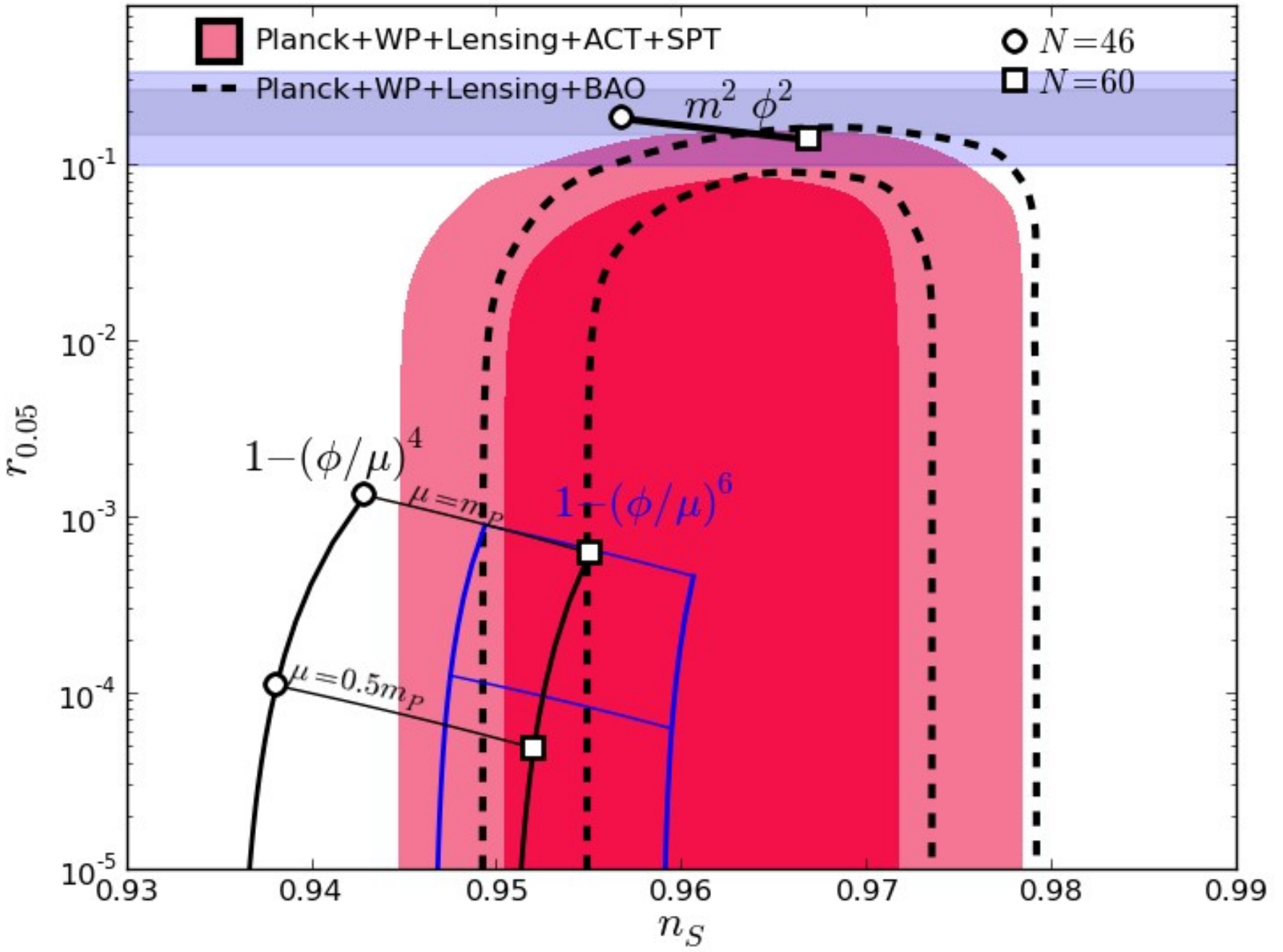
$p > 2$: Spectral index *independent* of scale $p \geq 4$

$$n = 1 - \left(\frac{2}{N}\right)\frac{p-1}{p-2} = [0.935, 0.967]$$

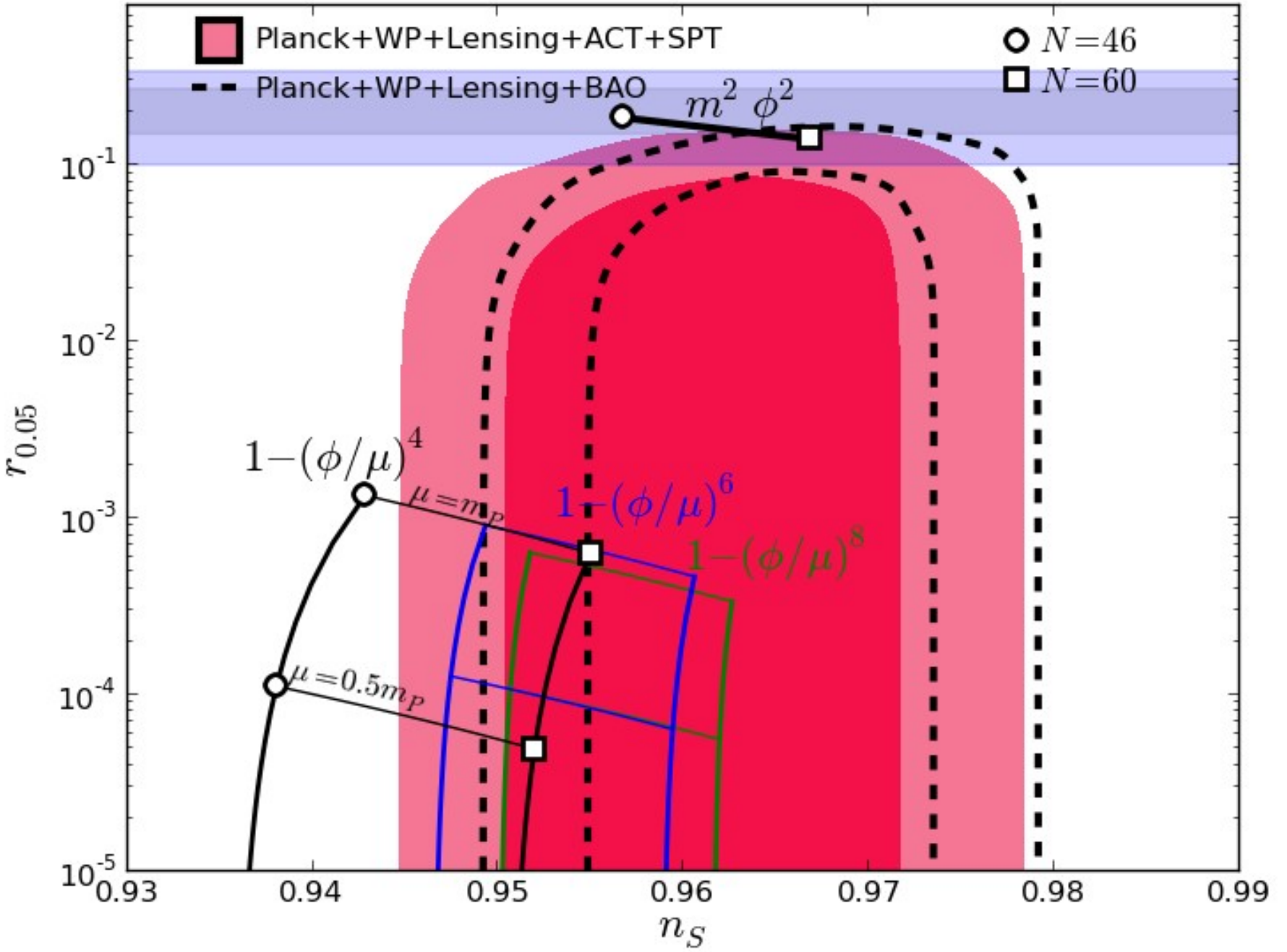
(WHK, Mahanthappa, hep-ph/9512241)



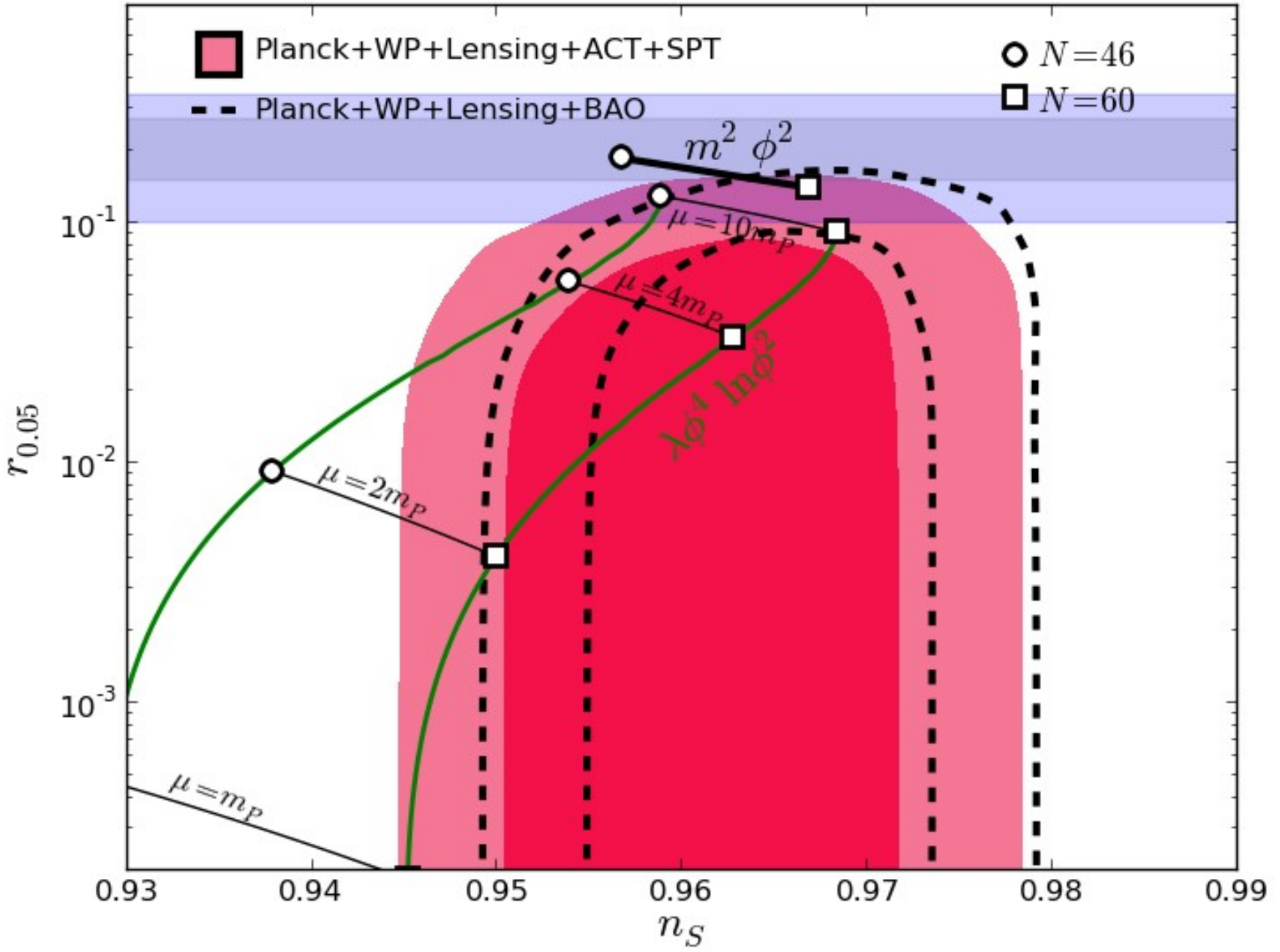
(Data: Planck Legacy Archive / BICEP)



(Freese & WHK, arXiv:1403.5277)

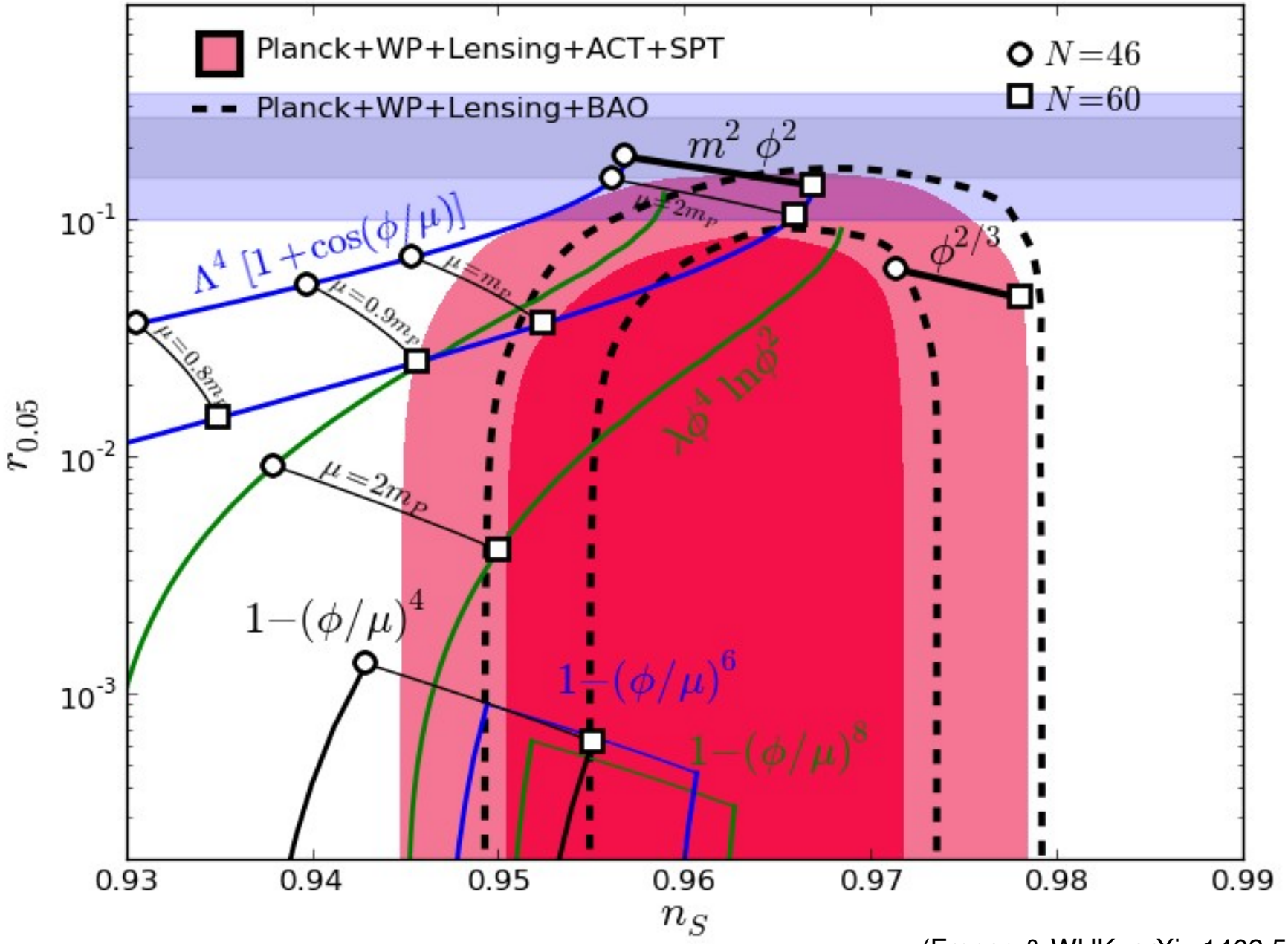


(Freese & WHK, arXiv:1403.5277)

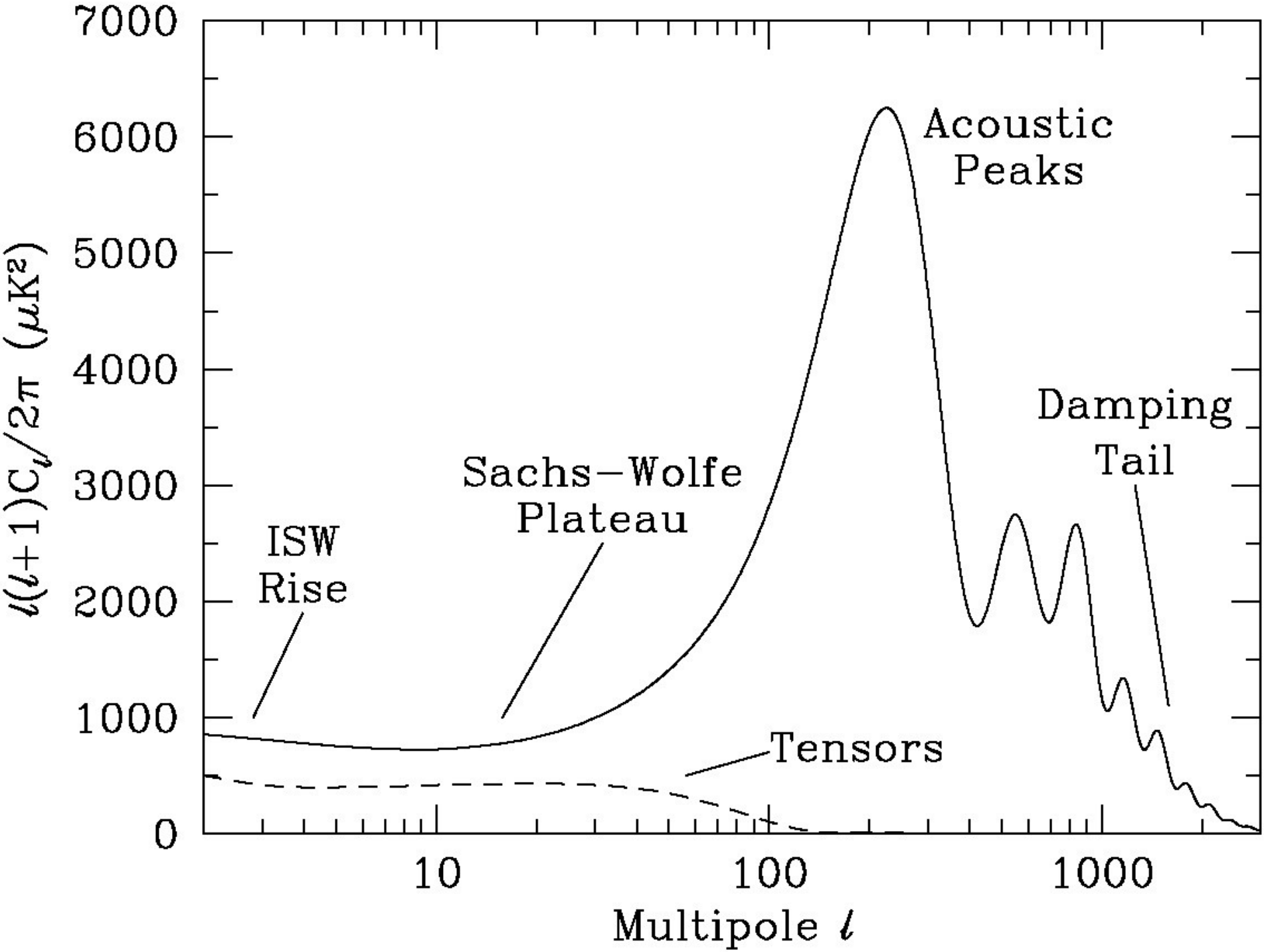


(Freese & WHK, arXiv:1403.5277)

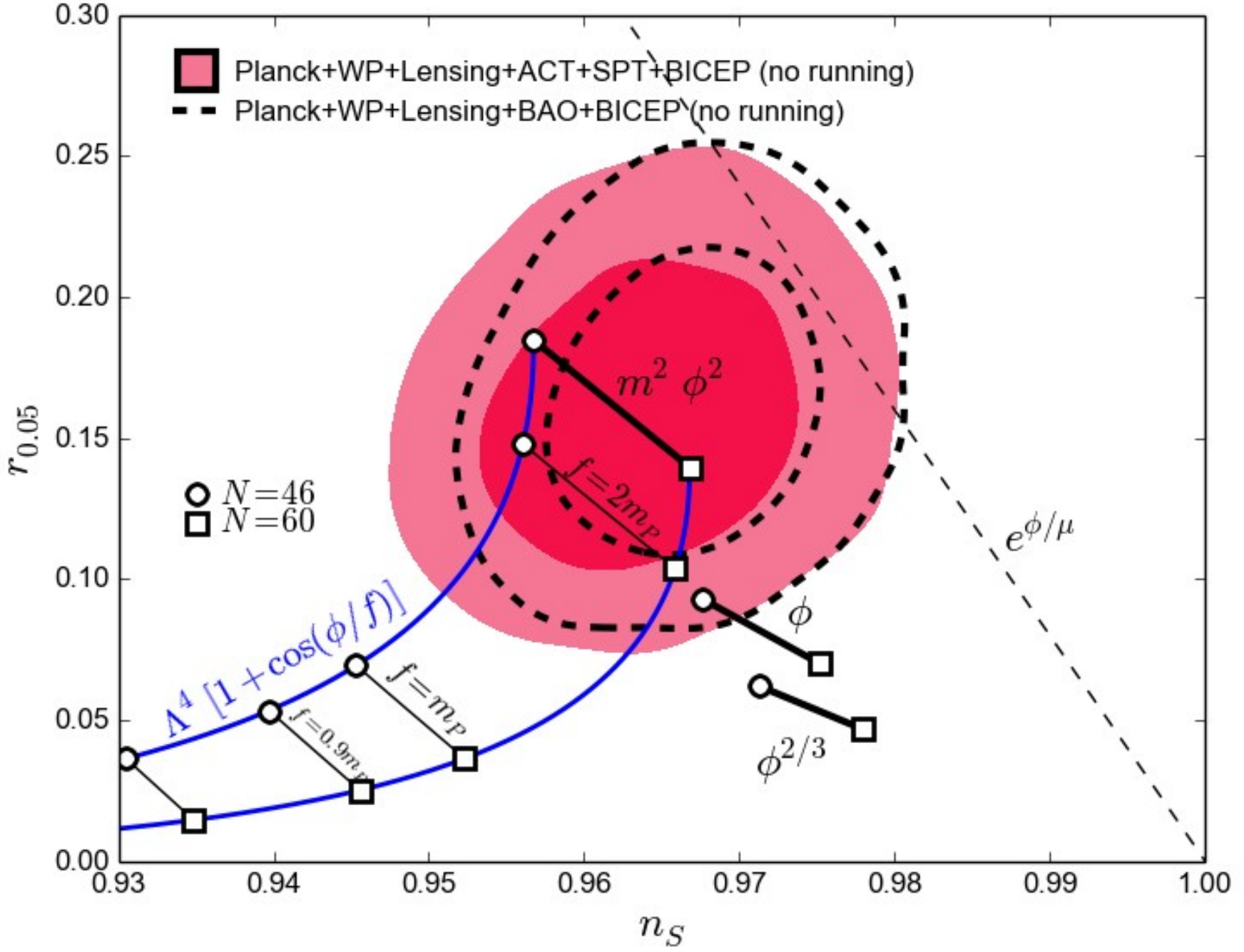
Summary: Planck / BICEP2 and Simple Inflation Models



(Freese & WHK, arXiv:1403.5277)


7000
6000
5000
4000
3000
2000
1000
0
$l(l+1)C_l/2\pi$ (μK^2)
Acoustic
Peaks
Damping
Tail
Sachs−Wolfe
Plateau
ISW
Rise
Tensors
10
100
1000
Multipole l

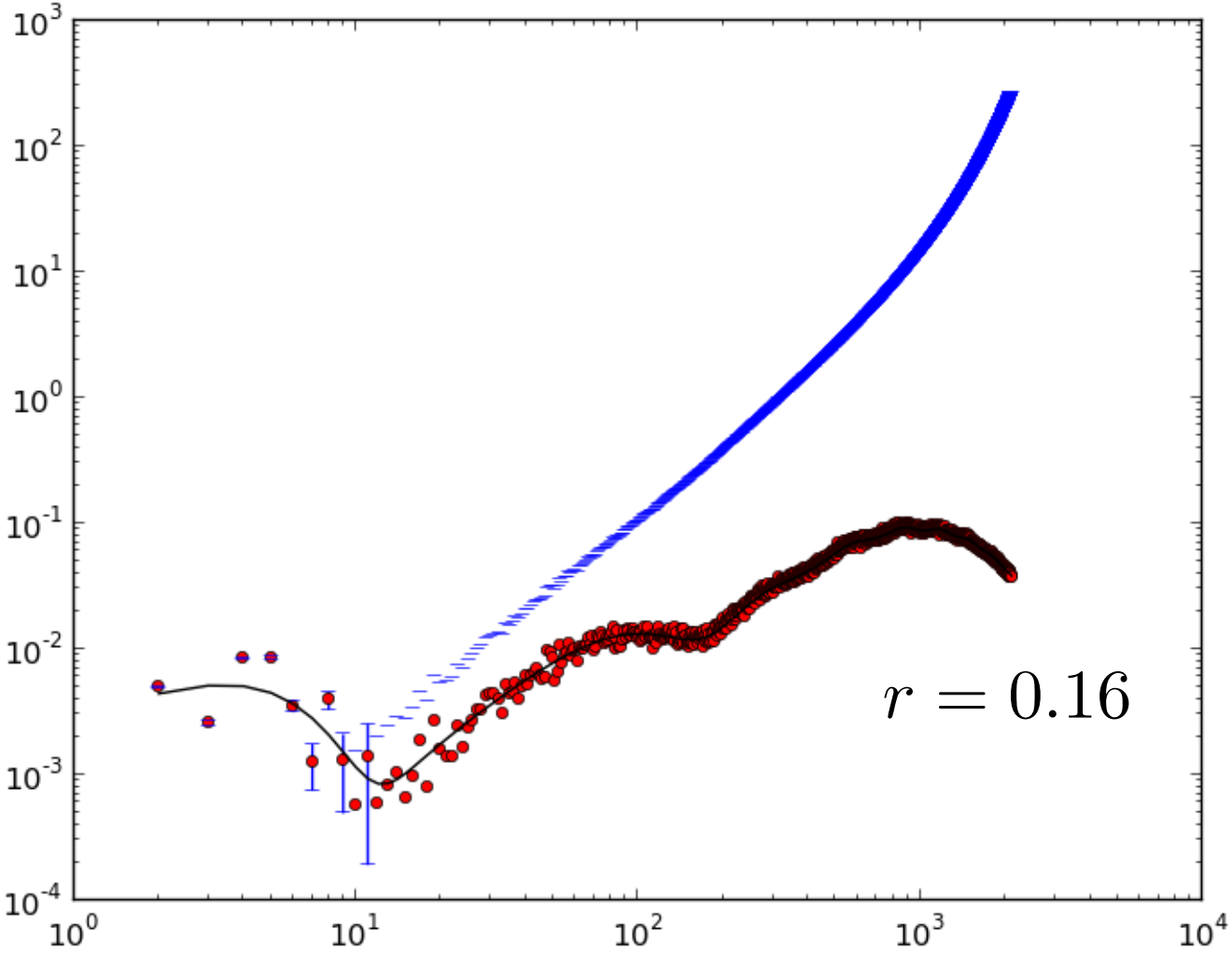
Planck + BICEP2 Joint Constraint



(Freese & WHK, arXiv:1403.5277)

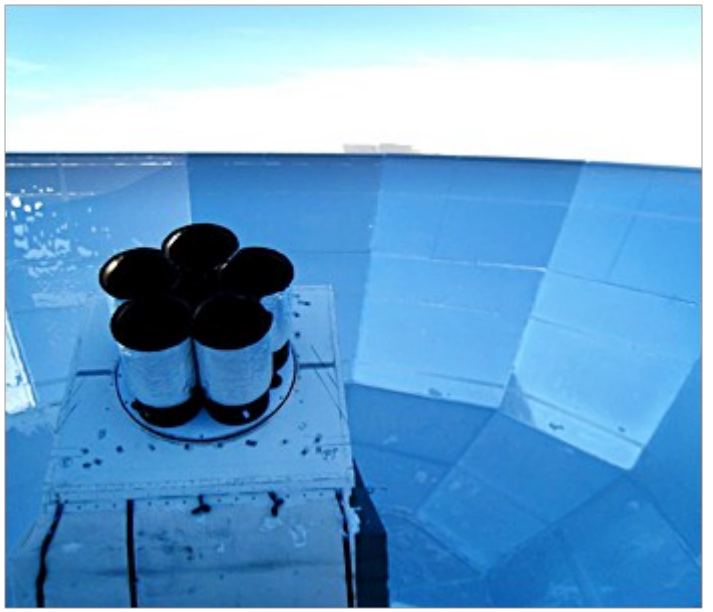
What next?

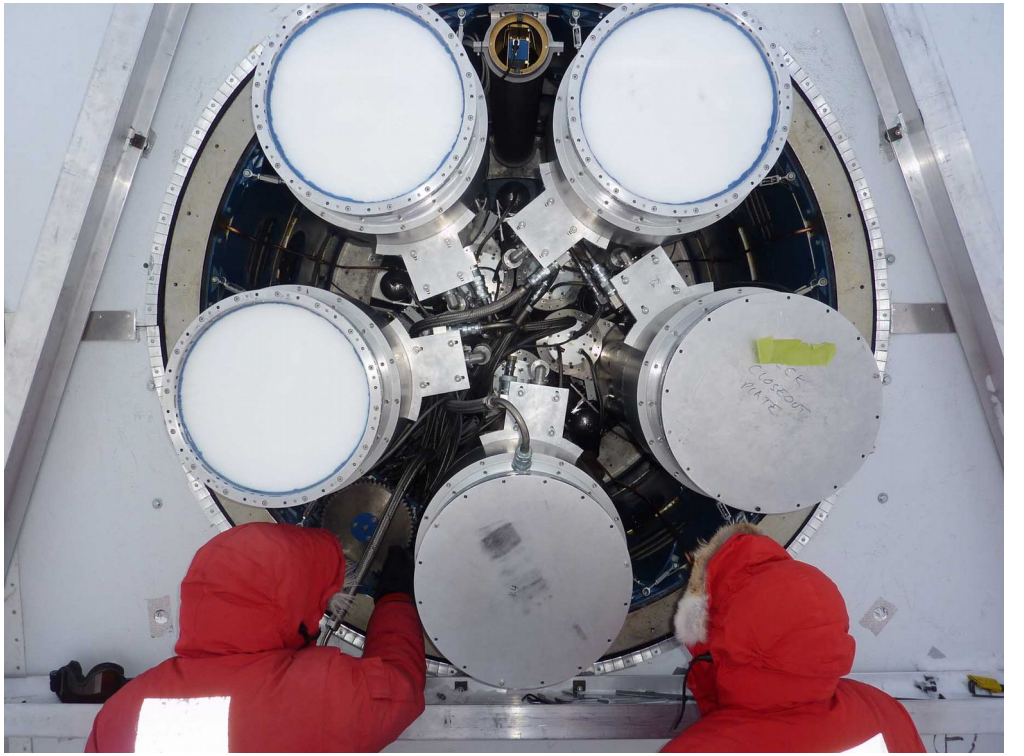
- Planck / BICEP2 joint analysis
- Planck B-mode



(WHK, Kolb, Moradinezhad, Riotto)

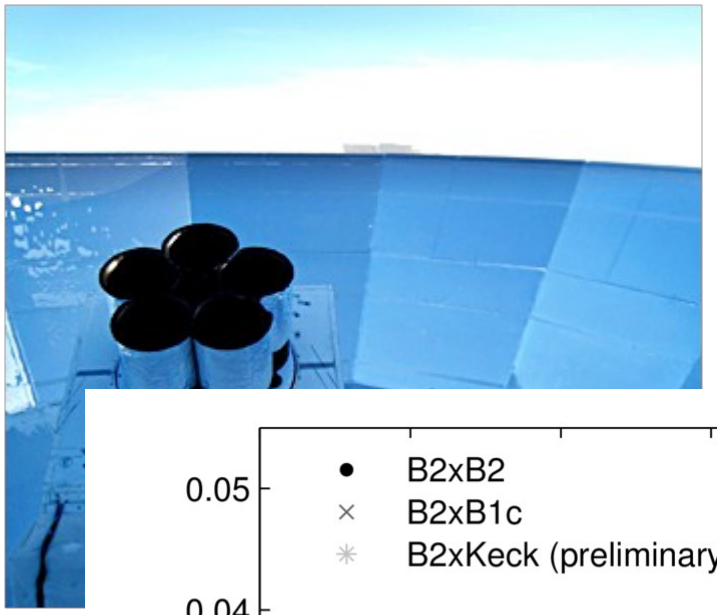
Keck Array

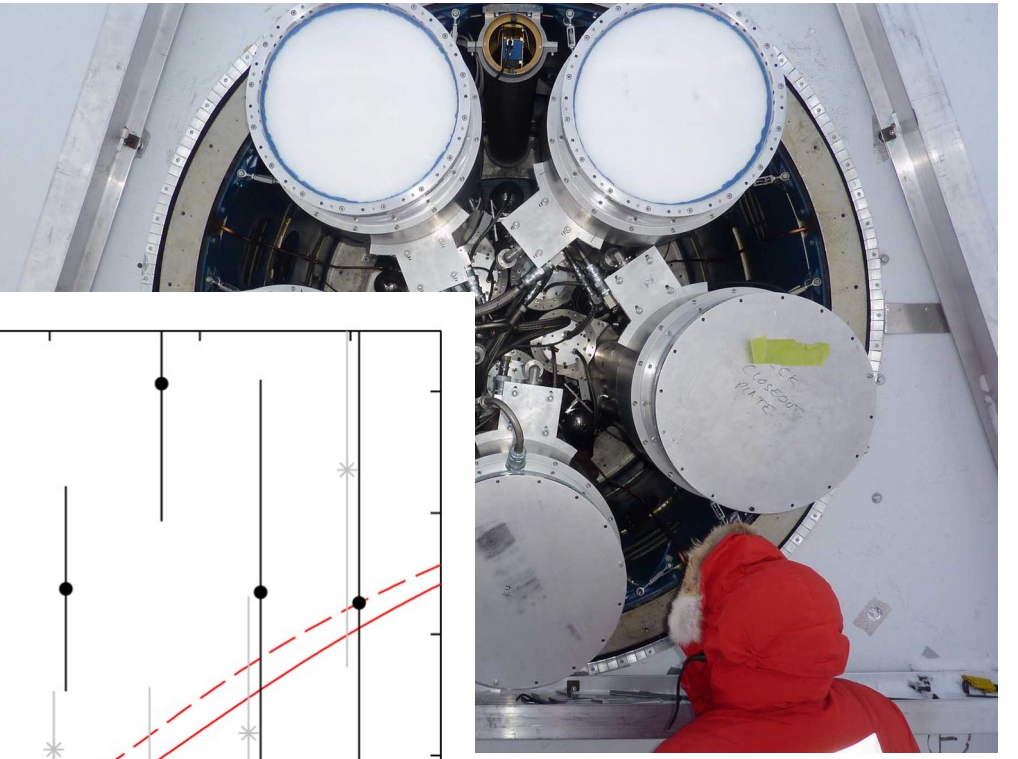


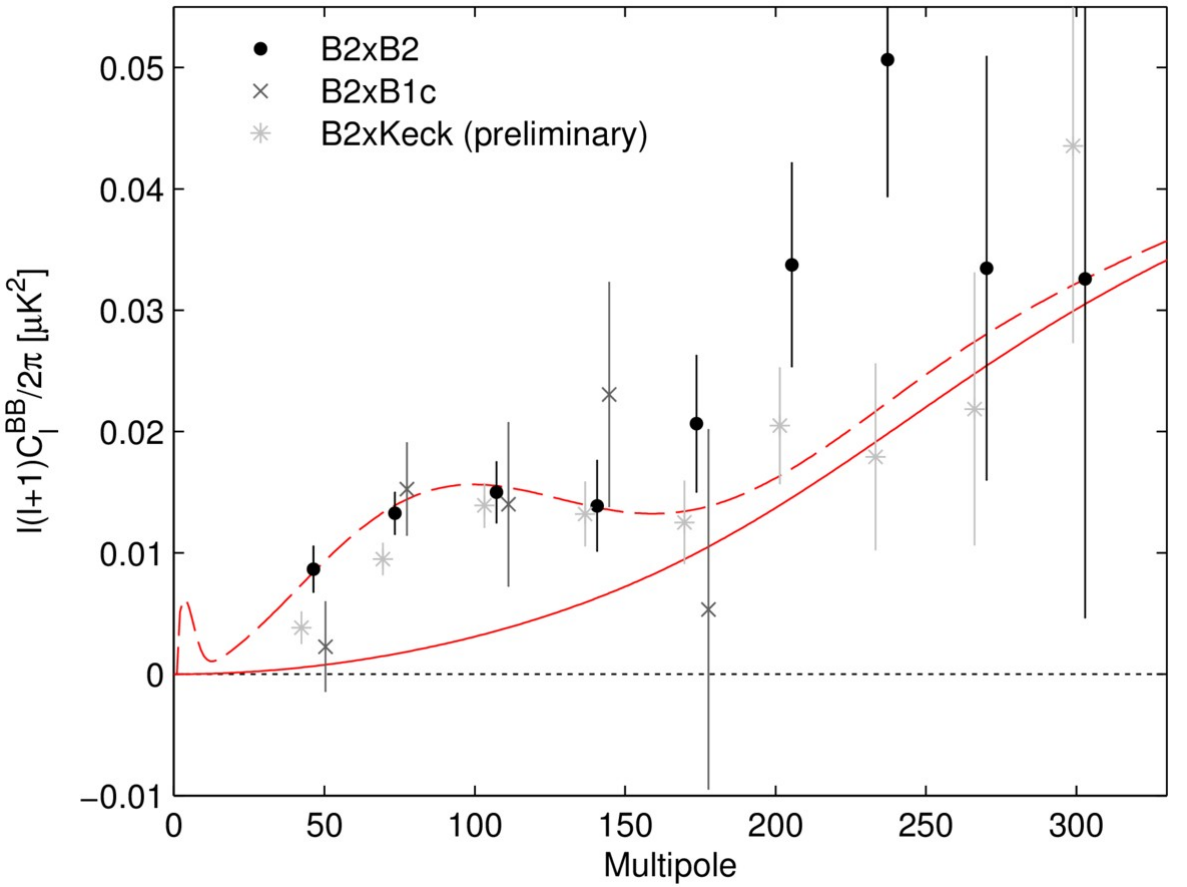


- 5× BICEP2
- 150 GHz / 100 GHz

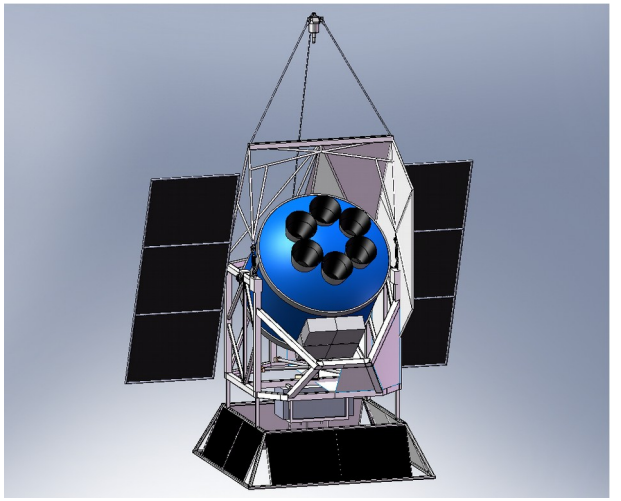
Keck Array

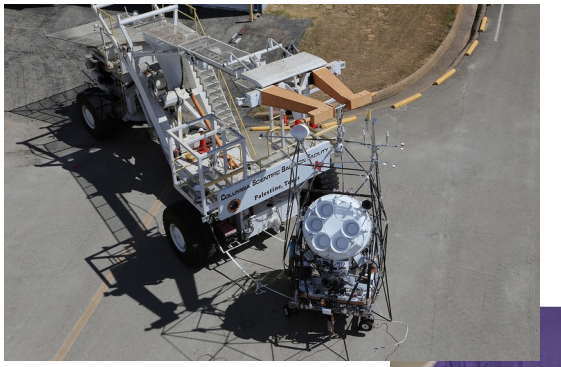


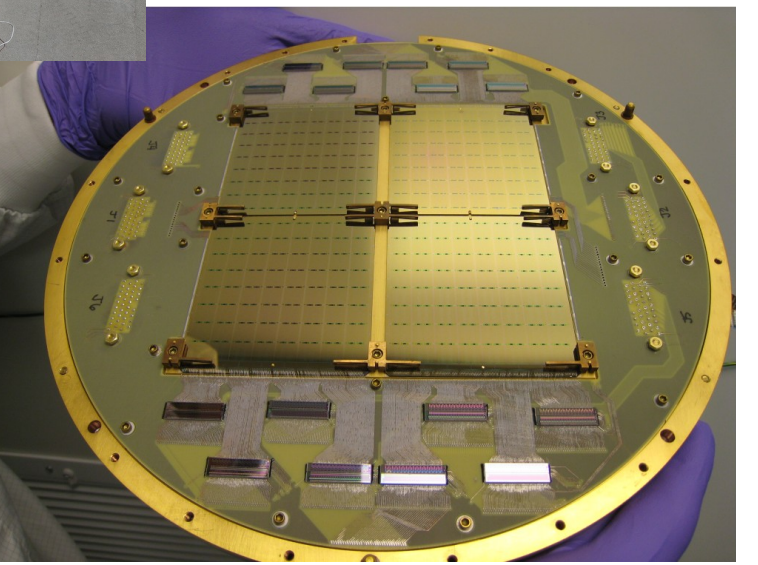



B2xB2
B2xB1c
B2xKeck (preliminary)
0.05
0.04
0.03
0.02
0.01
0
−0.01
0
50
100
150
200
250
300
Multipole
l(l+1)C_l^BB/2π [μK^2]

SPIDER Balloon Experiment

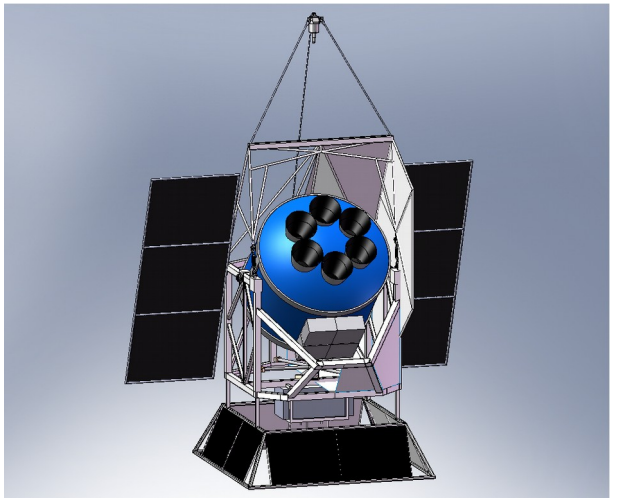


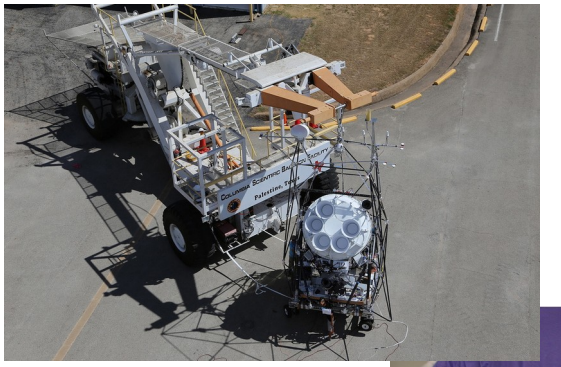


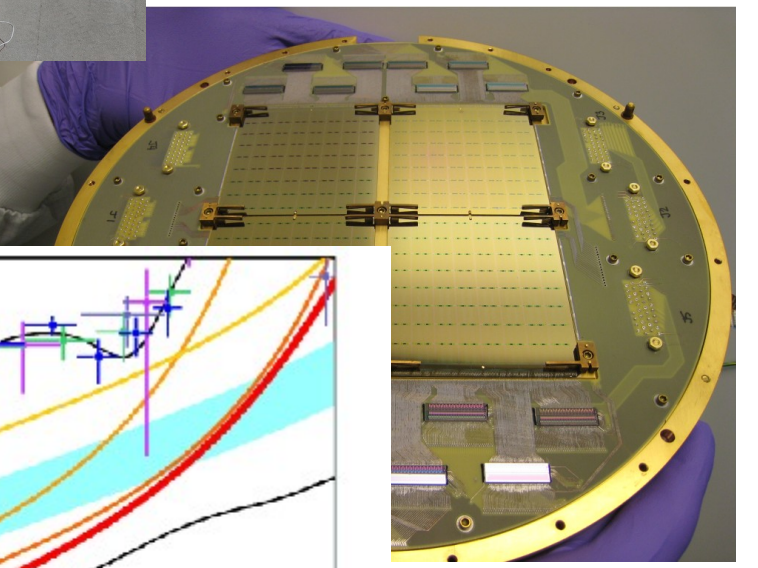


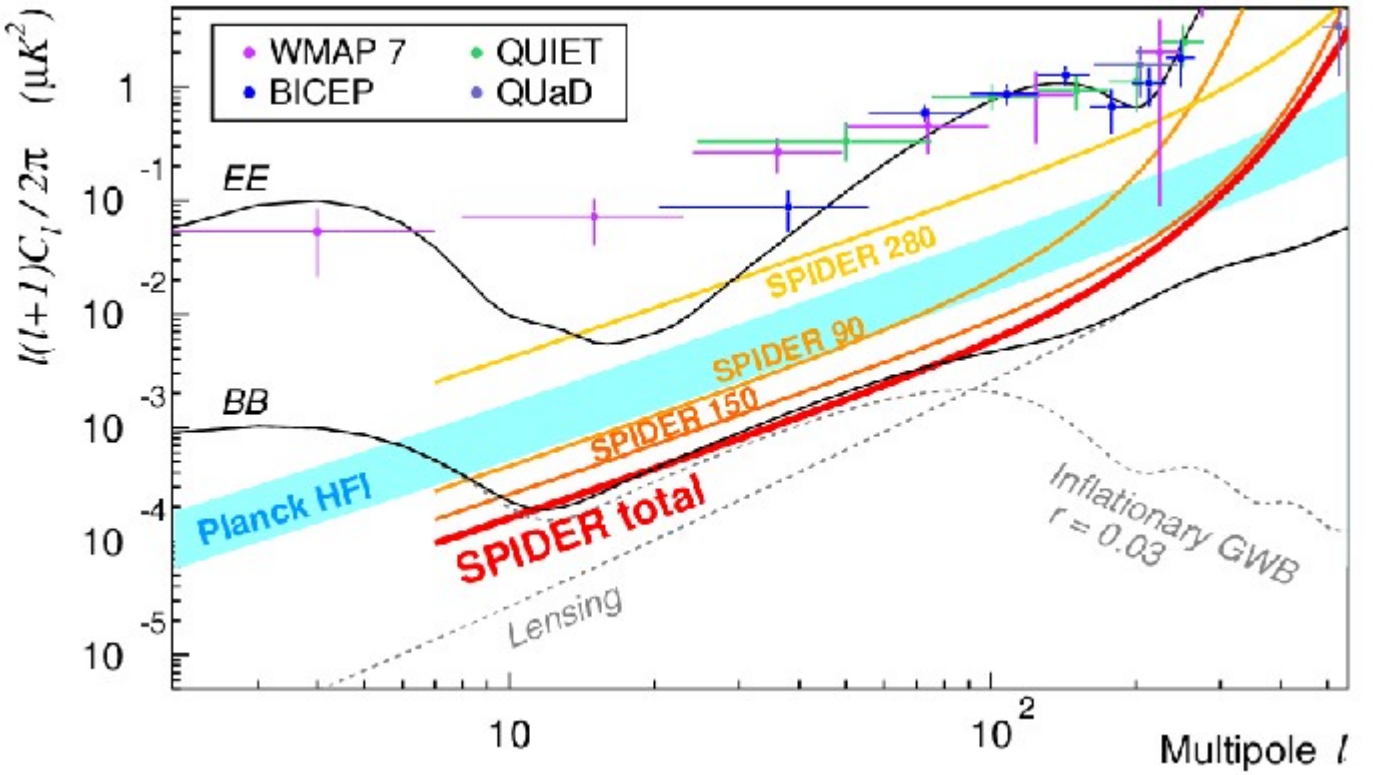
- 20-day circumpolar flight
- 90 / 150 / 280 GHz
- Delayed by govt shutdown!

SPIDER Balloon Experiment









Single-Field Inflation: The Consistency Condition

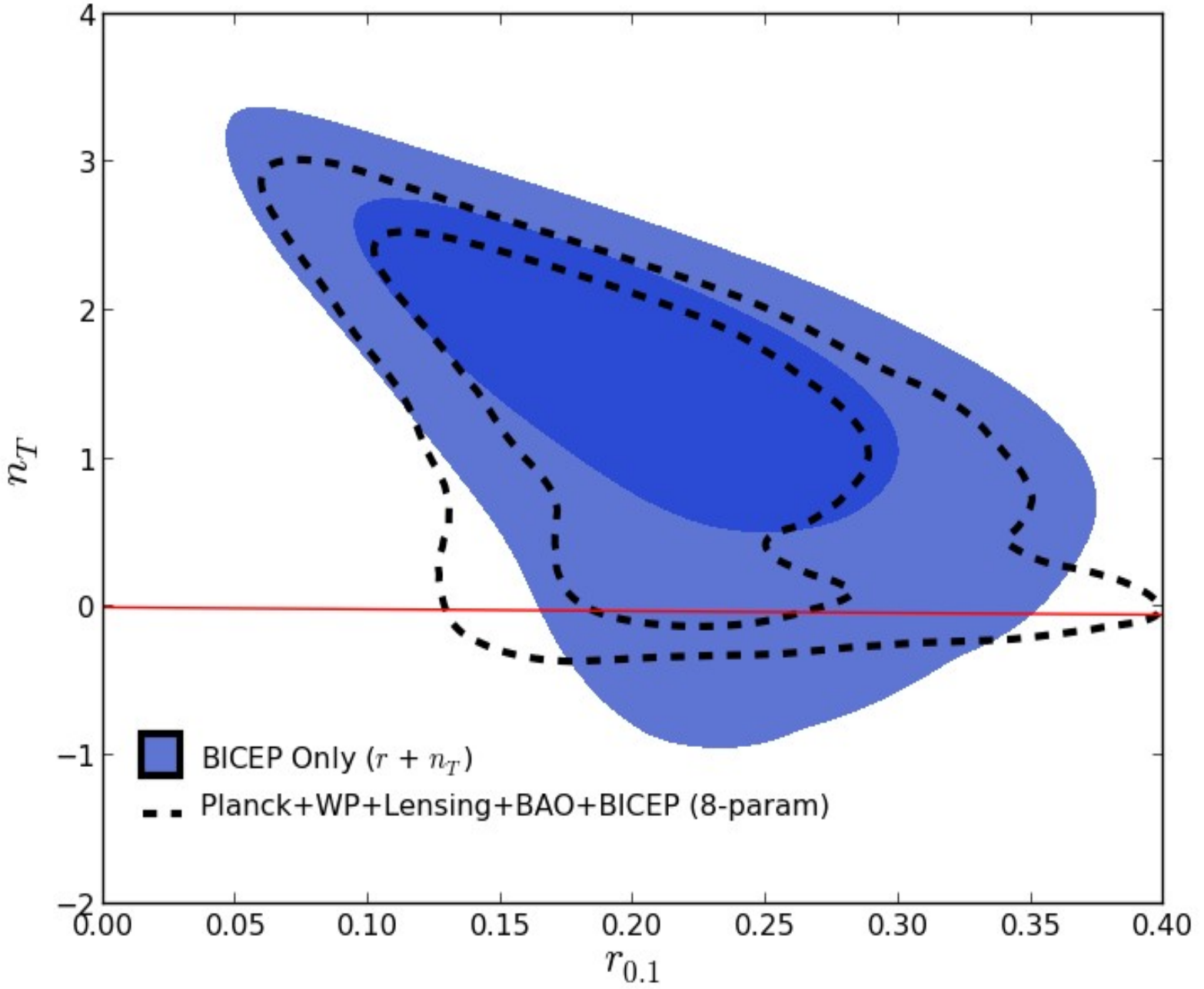
Slow Roll Parameter $\epsilon = \frac{m_{\rm Pl}^2}{16\pi}\left(\frac{V'(\phi)}{V(\phi)}\right)^2$

Tensor/Scalar Ratio $r = 16\epsilon$

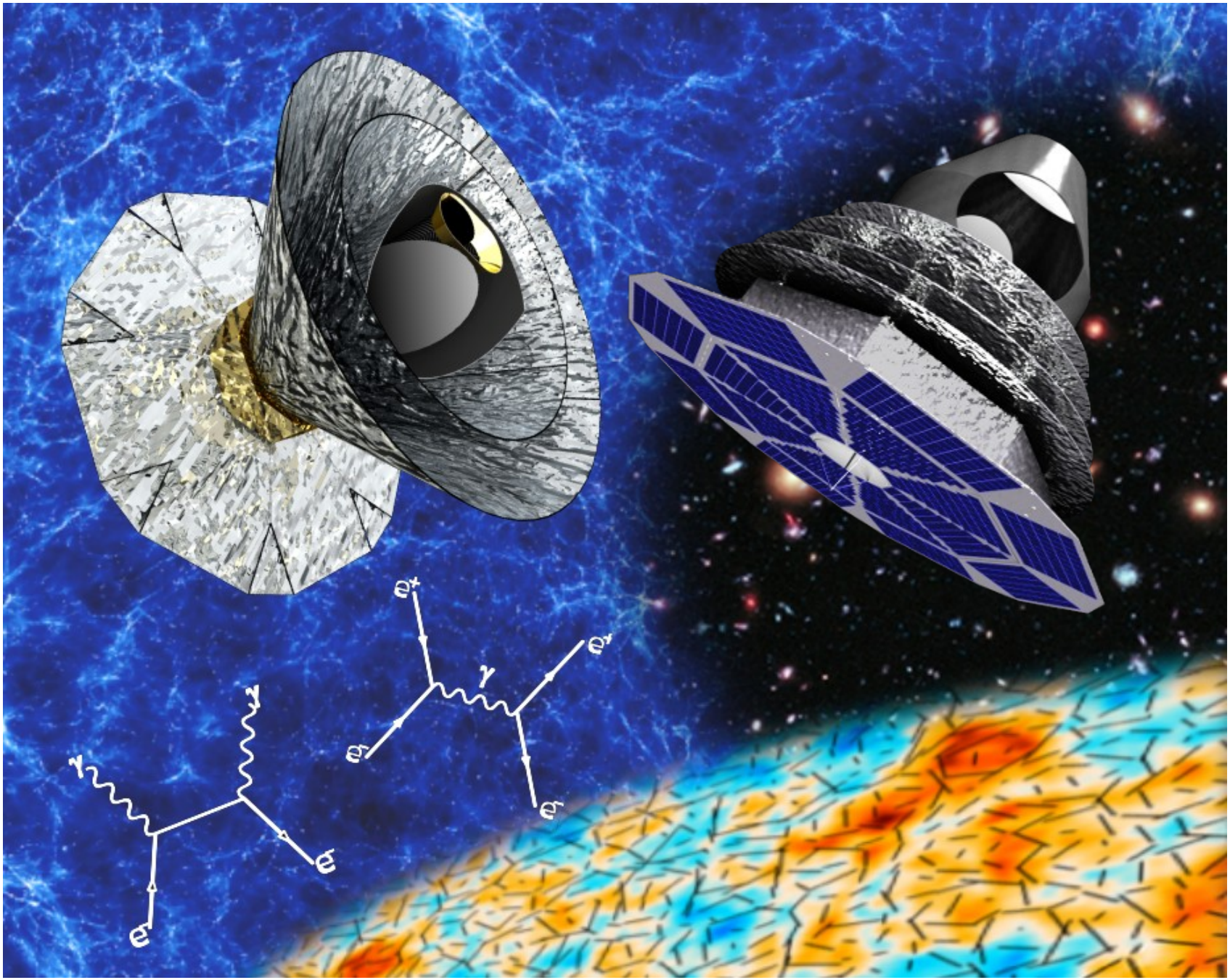
Tensor Power Spectrum $P_T \propto k^{n_T} = k^{-2\epsilon}$

$$n_T = -r/8$$

Planck + BICEP Tensor Spectral Index



Future Missions

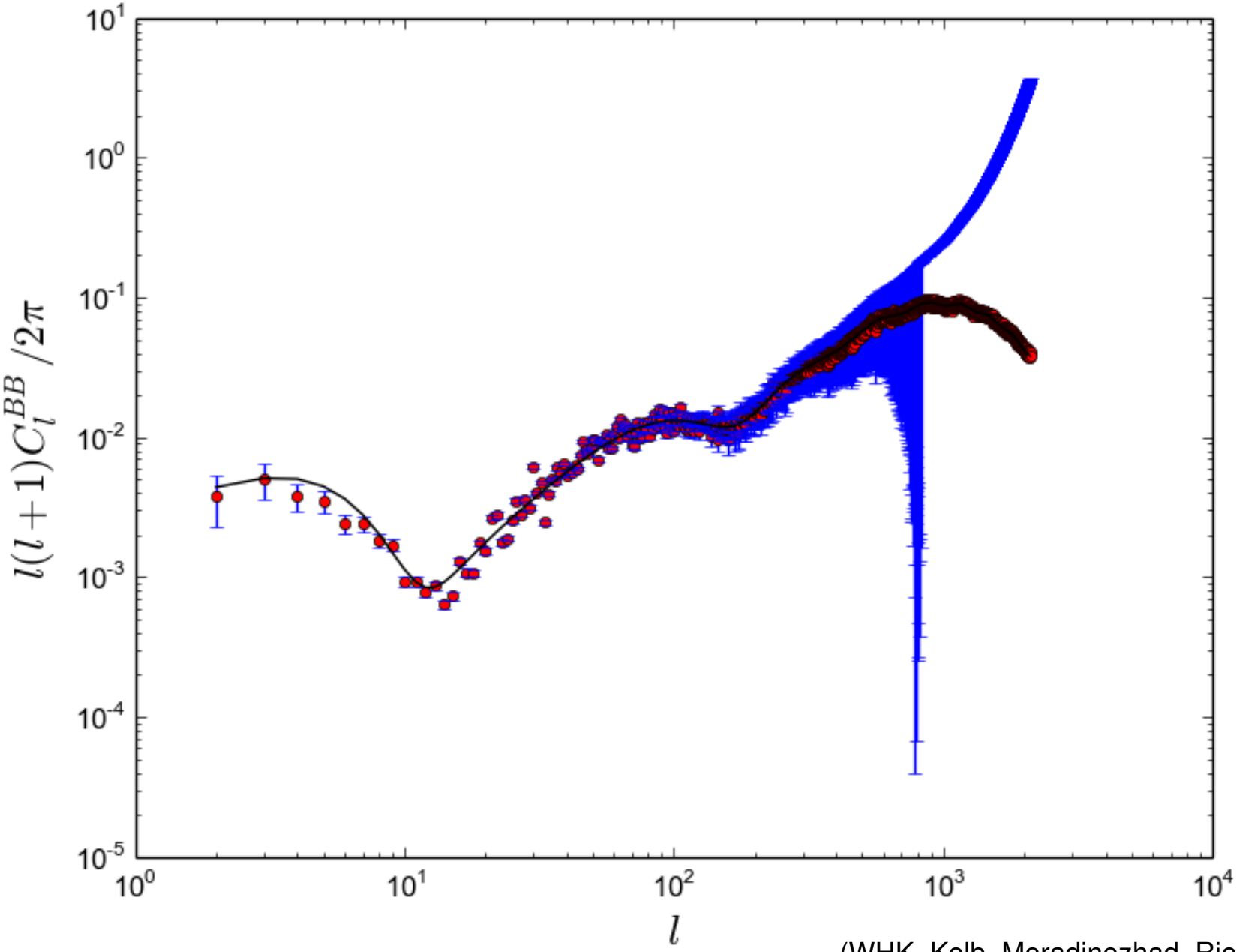


COrE+ Assumed Sensitivities

ν	$n_{\rm det}$	$\theta_{\rm fwhm}$	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

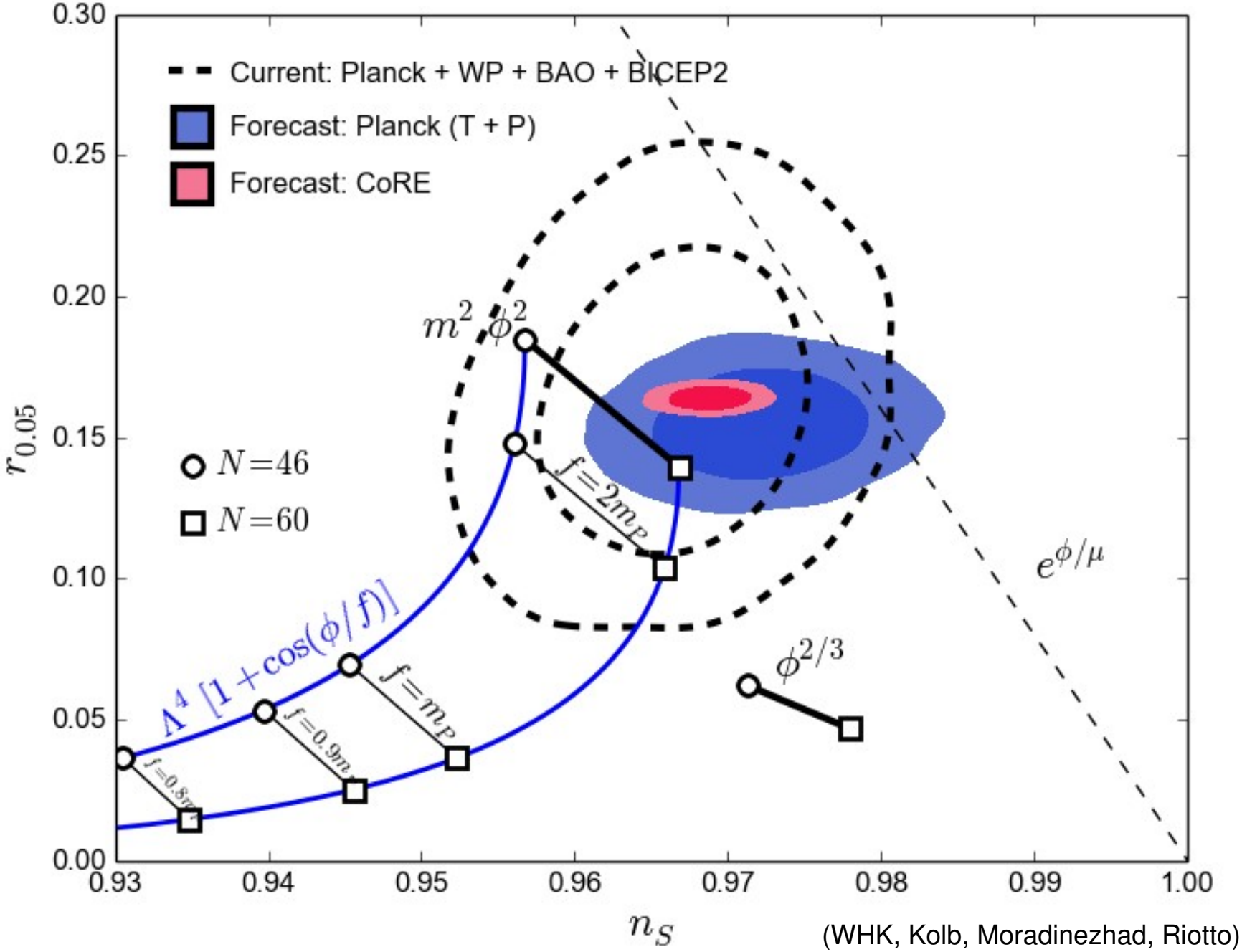
F. R. Bouchet et al. [COrE Collaboration], arXiv:1102.2181

COrE+ Forecast BB Sensitivity



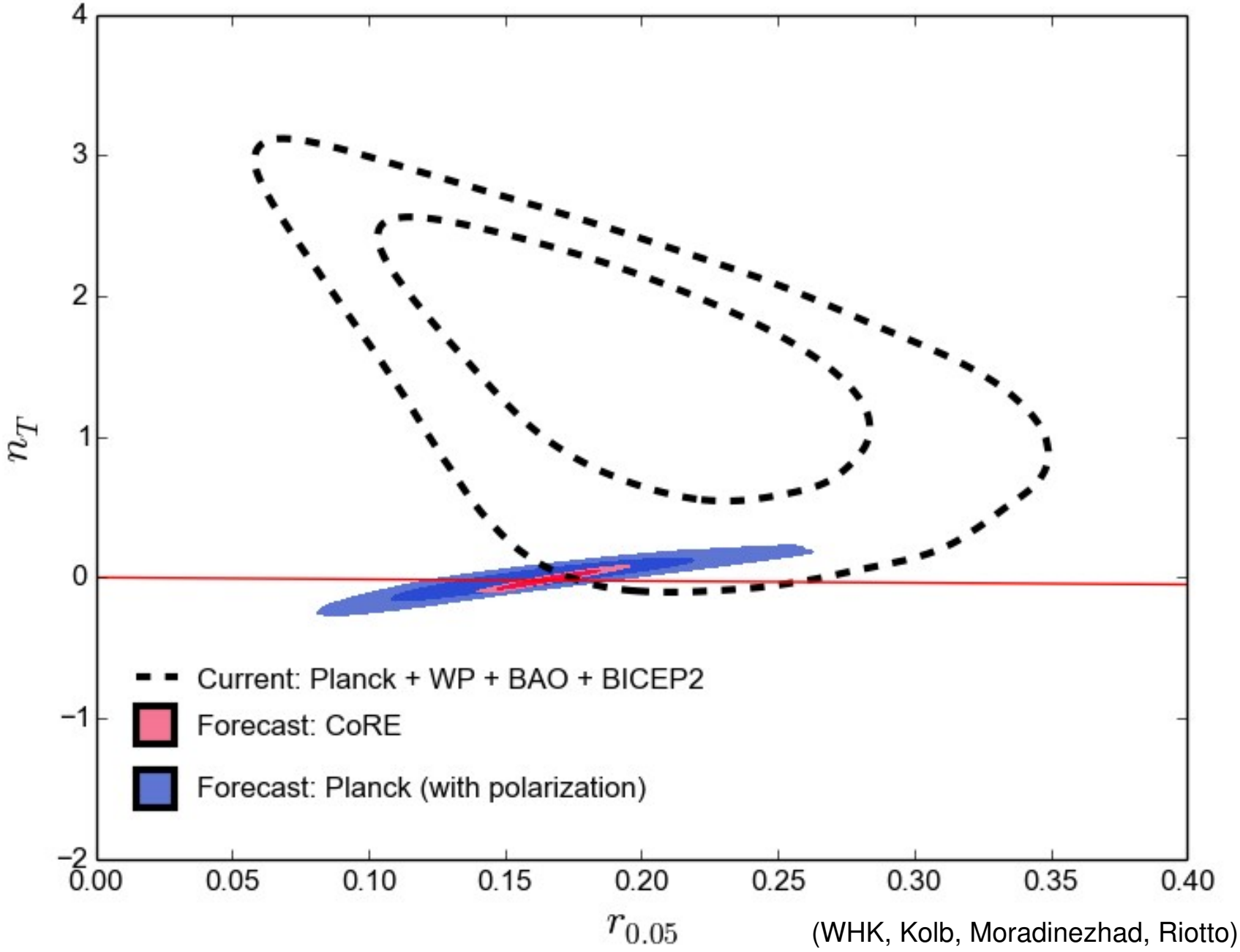
(WHK, Kolb, Moradinezhad, Riotto)

CoRE+ Forecast Model Constraints



(WHK, Kolb, Moradinezhad, Riotto)

COrE+ Forecast: Consistency Condition



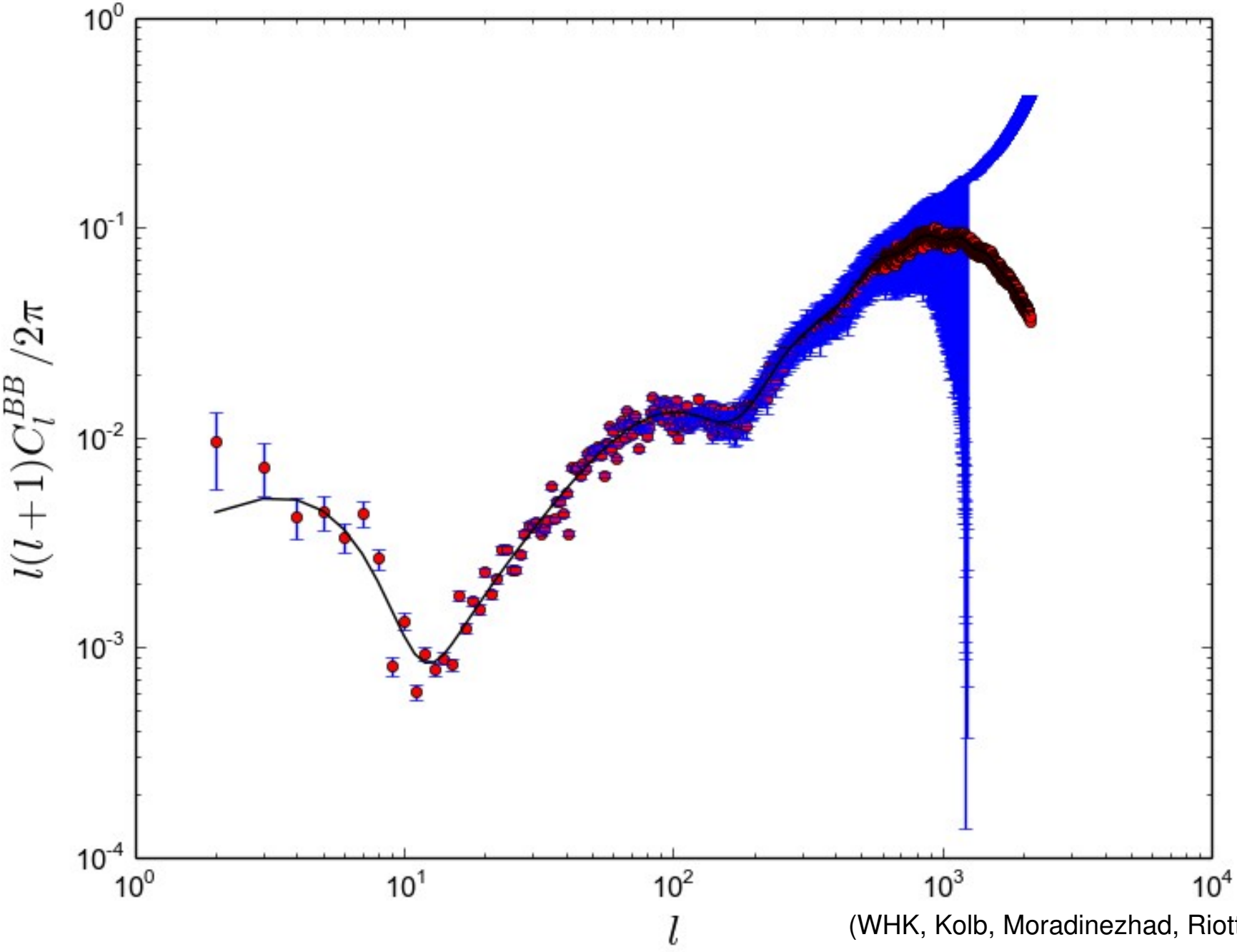
(WHK, Kolb, Moradinezhad, Riotto)

PRISM Assumed Sensitivities

ν	$n_{\rm det}$	$\theta_{\rm fwhm}$	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

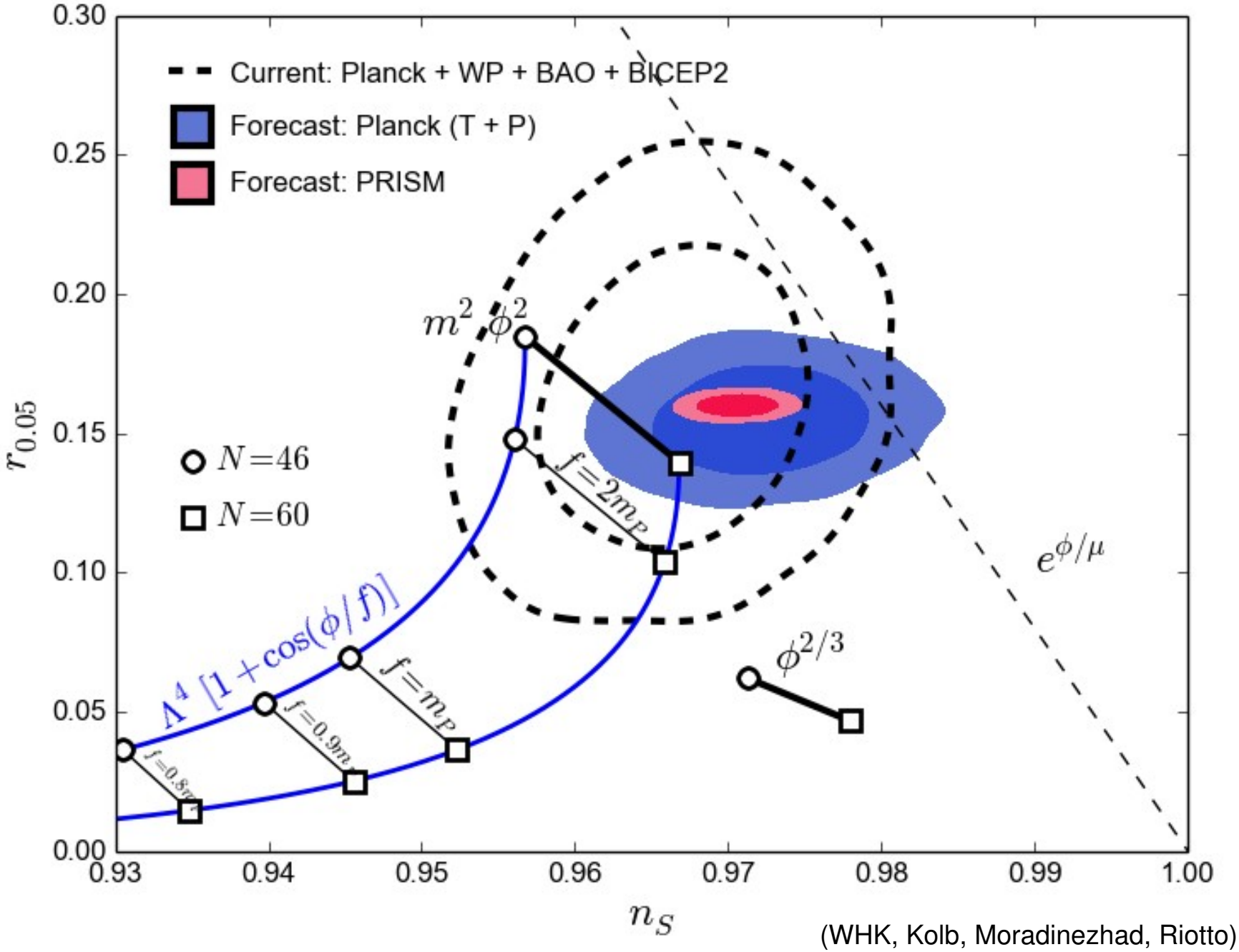
P. Andre et al. [PRISM Collaboration], arXiv:1306.2259 [astro-ph.CO].

PRISM Forecast BB Sensitivity



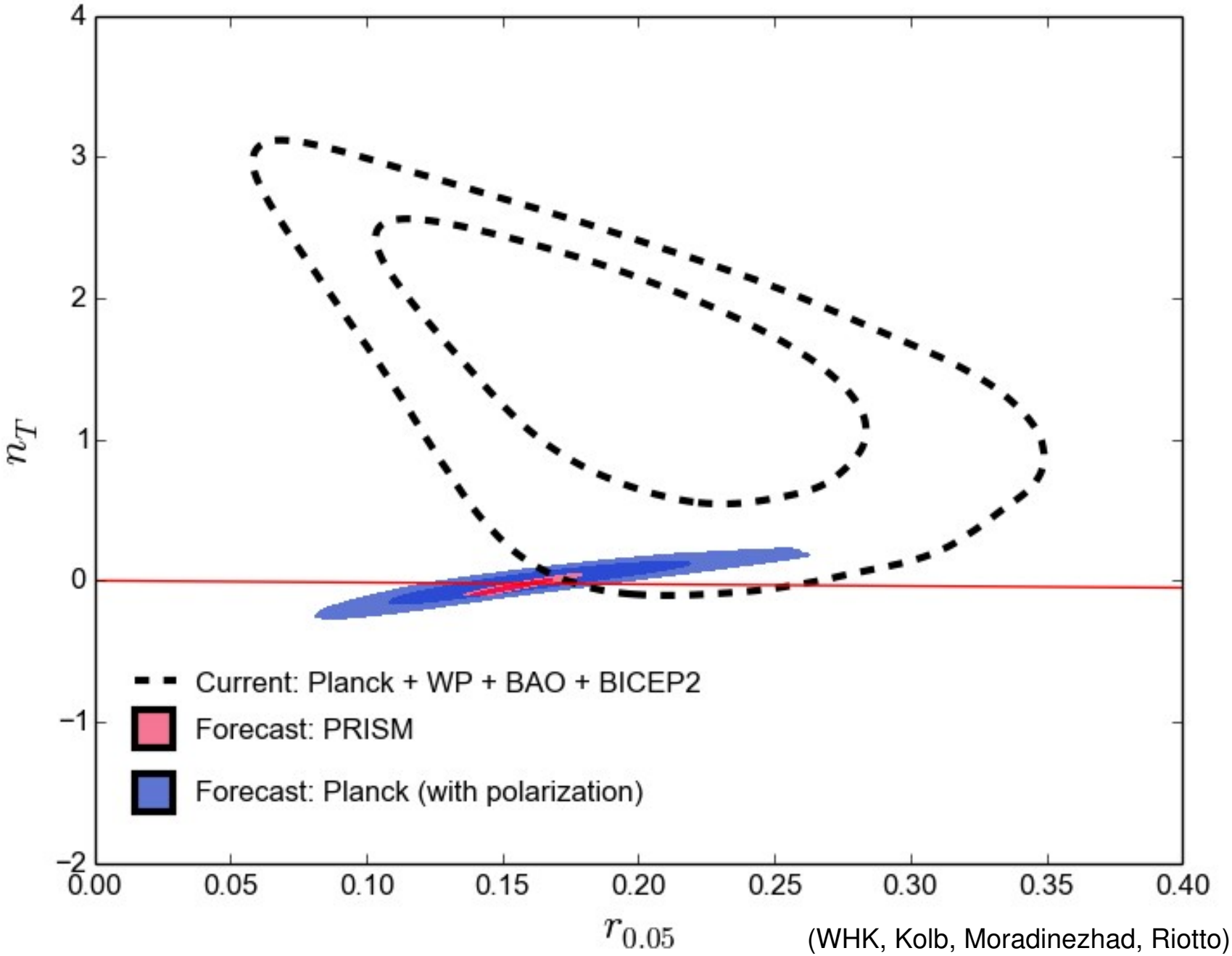
(WHK, Kolb, Moradinezhad, Riotto)

PRISM Forecast Model Constraints



(WHK, Kolb, Moradinezhad, Riotto)

PRISM Forecast: Consistency Condition



(WHK, Kolb, Moradinezhad, Riotto)

Four Questions We Can (Maybe) Answer

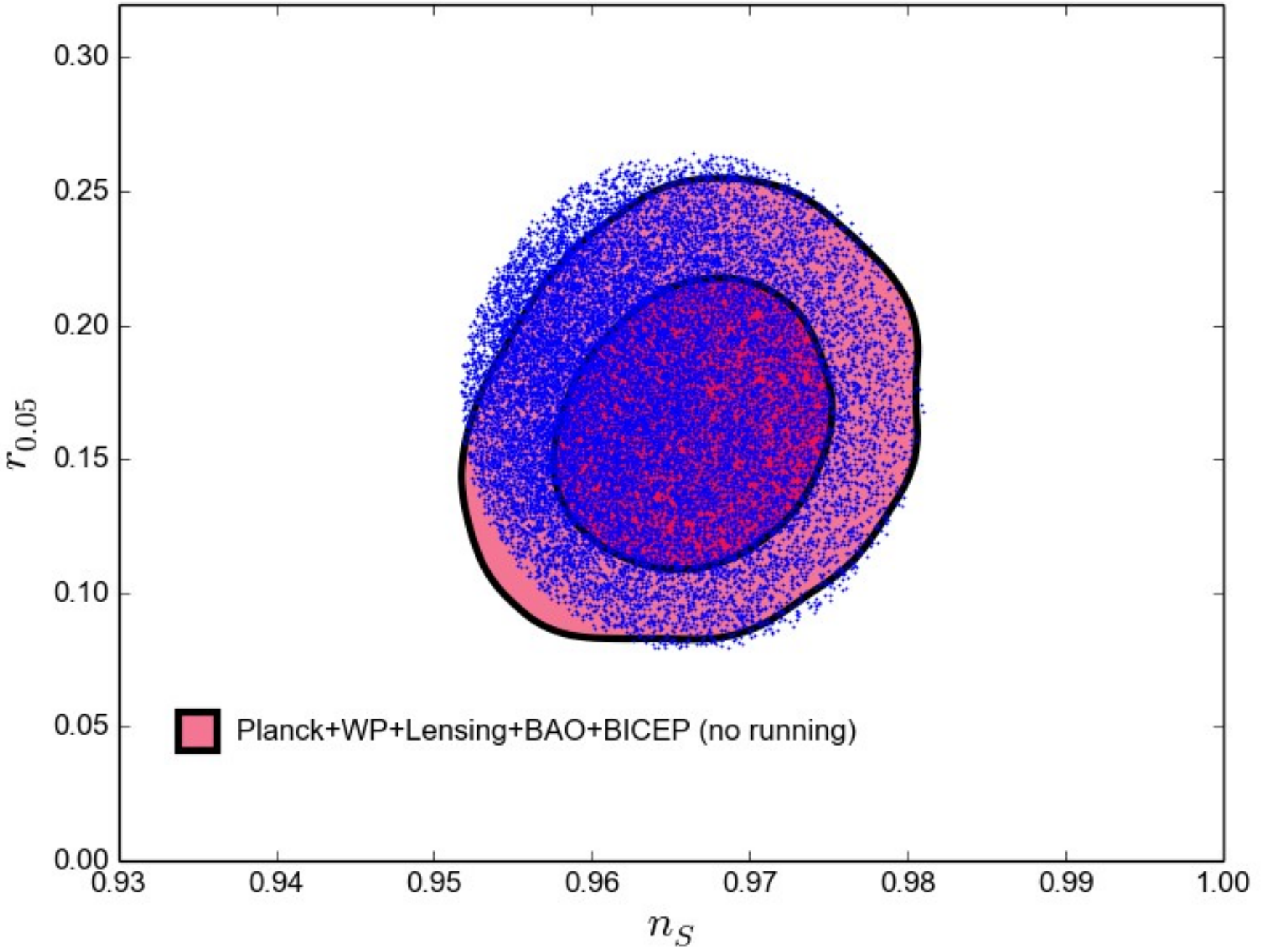
(1) What is the shape of the tensor power spectrum? Is the consistency condition satisfied?
(Planck/DECIGO)

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

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

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

Flow Monte Carlo: 20,000 Inflation Models



(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

Inflationary Flow Equations

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

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

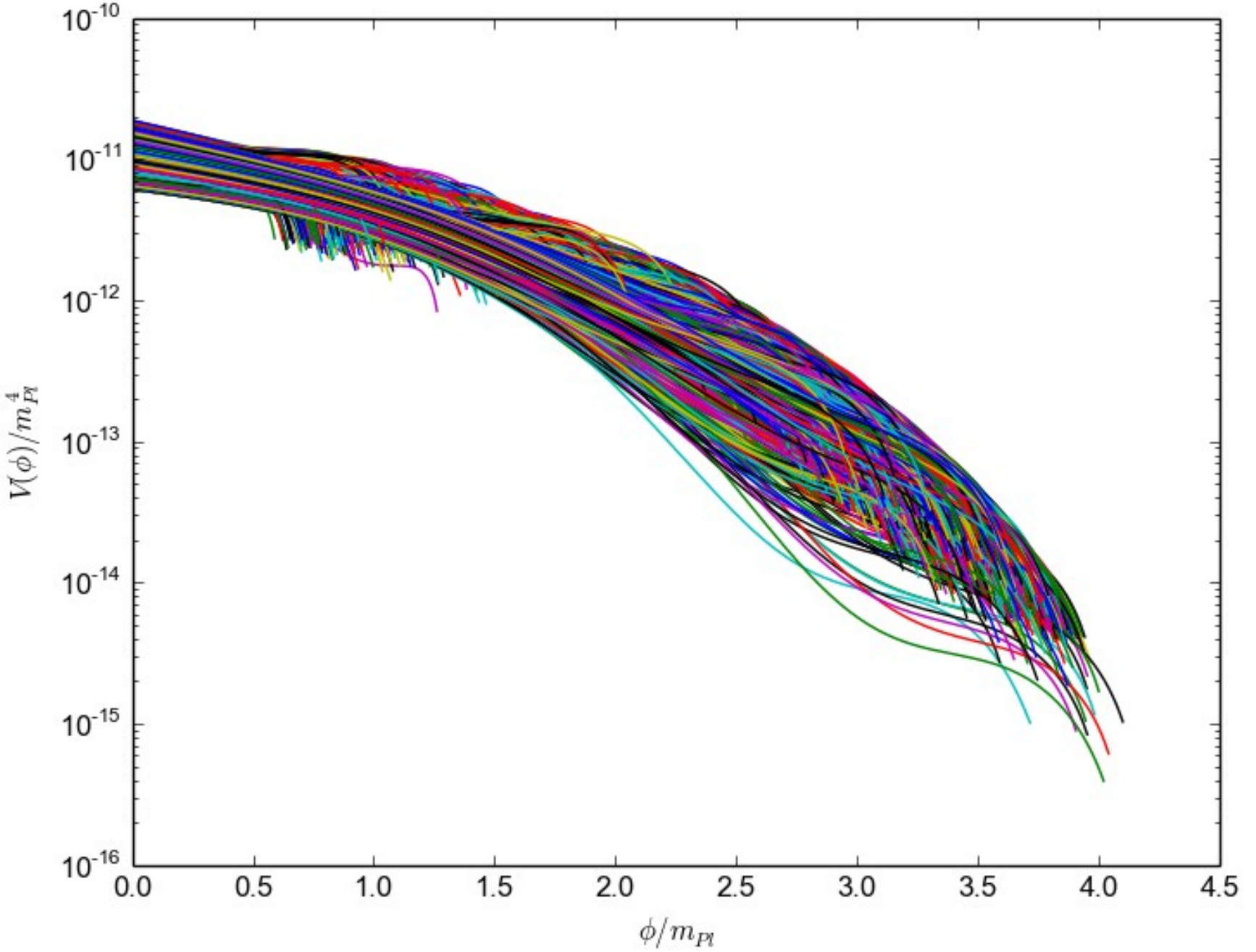
$$\cdots$$

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

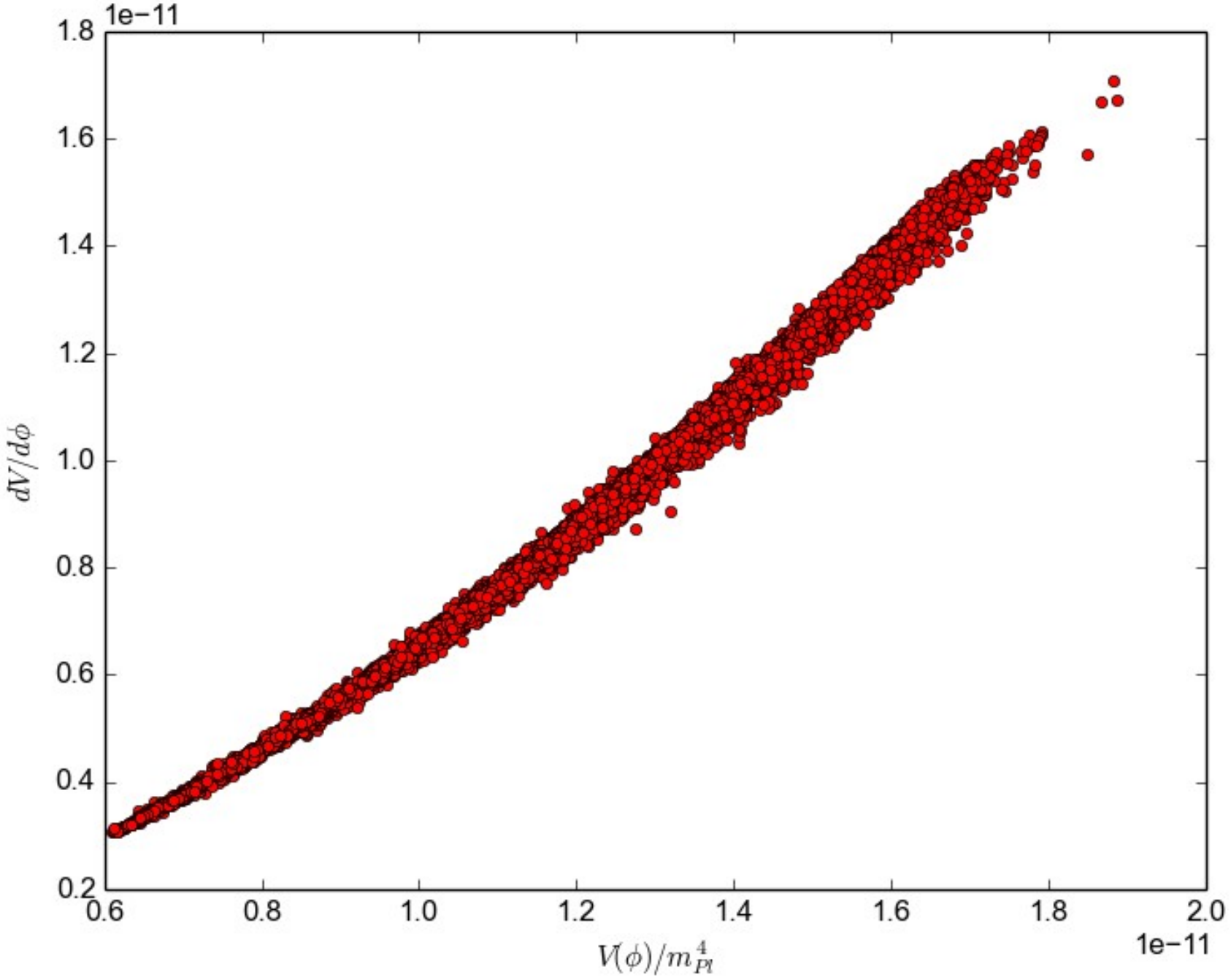
$$\frac{d}{dN} \propto \sqrt{\epsilon}\frac{d}{d\phi}$$

$$\ell < 8$$

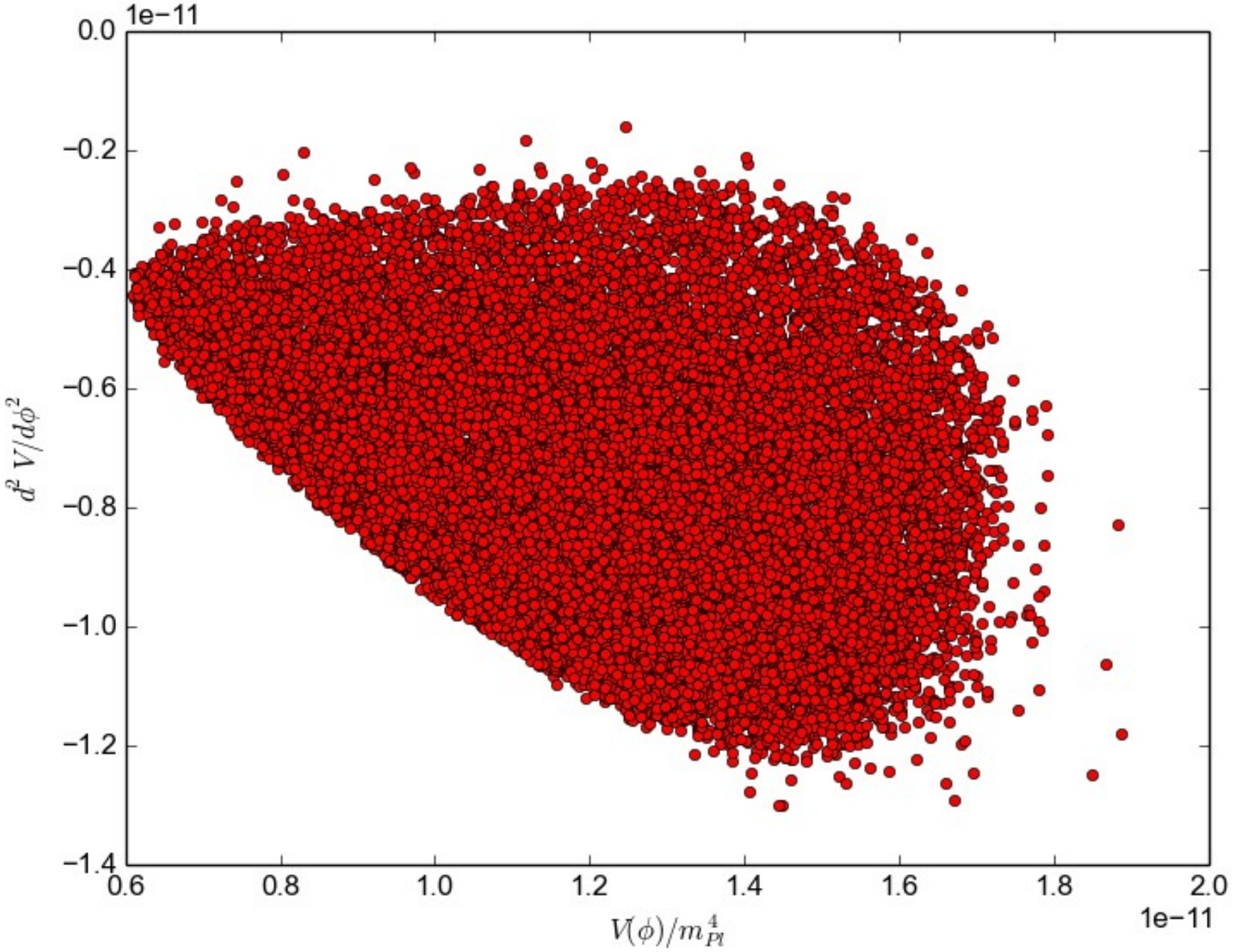
Monte Carlo Potential Reconstruction



Monte Carlo Potential Reconstruction



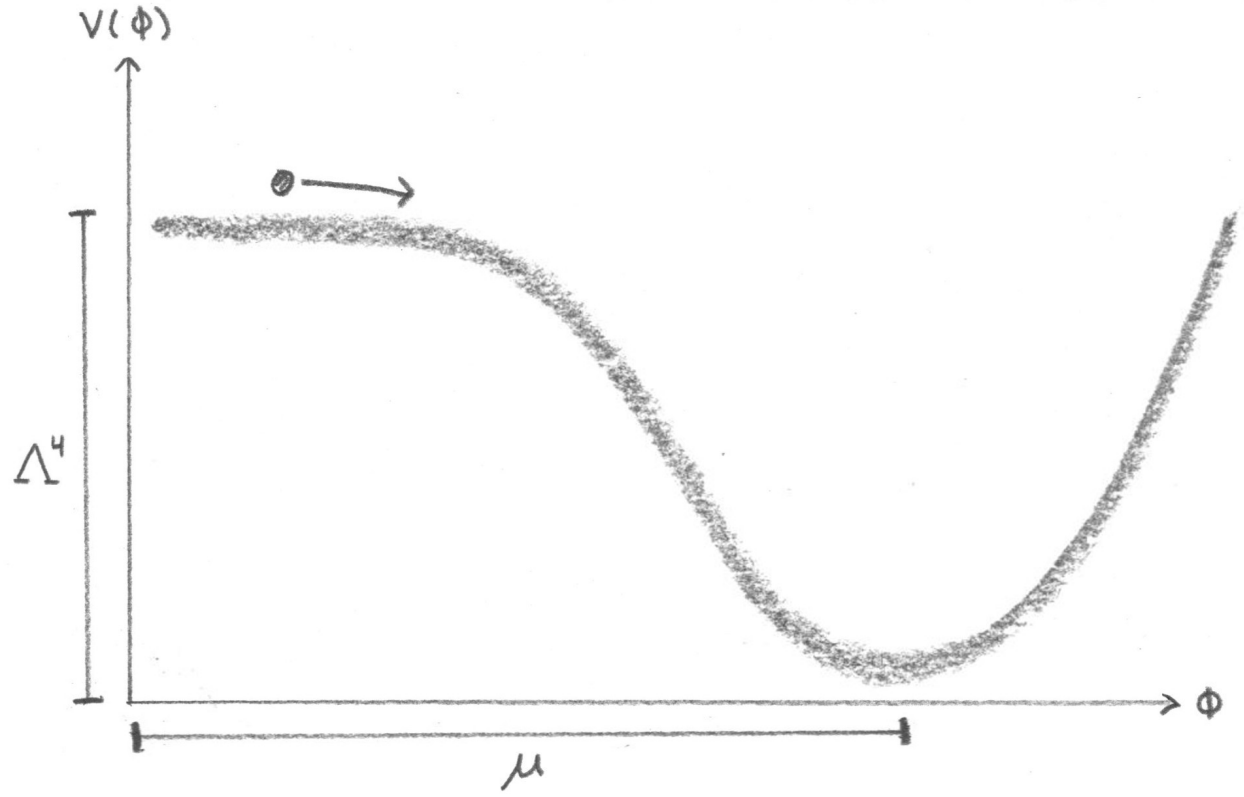
Monte Carlo Potential Reconstruction



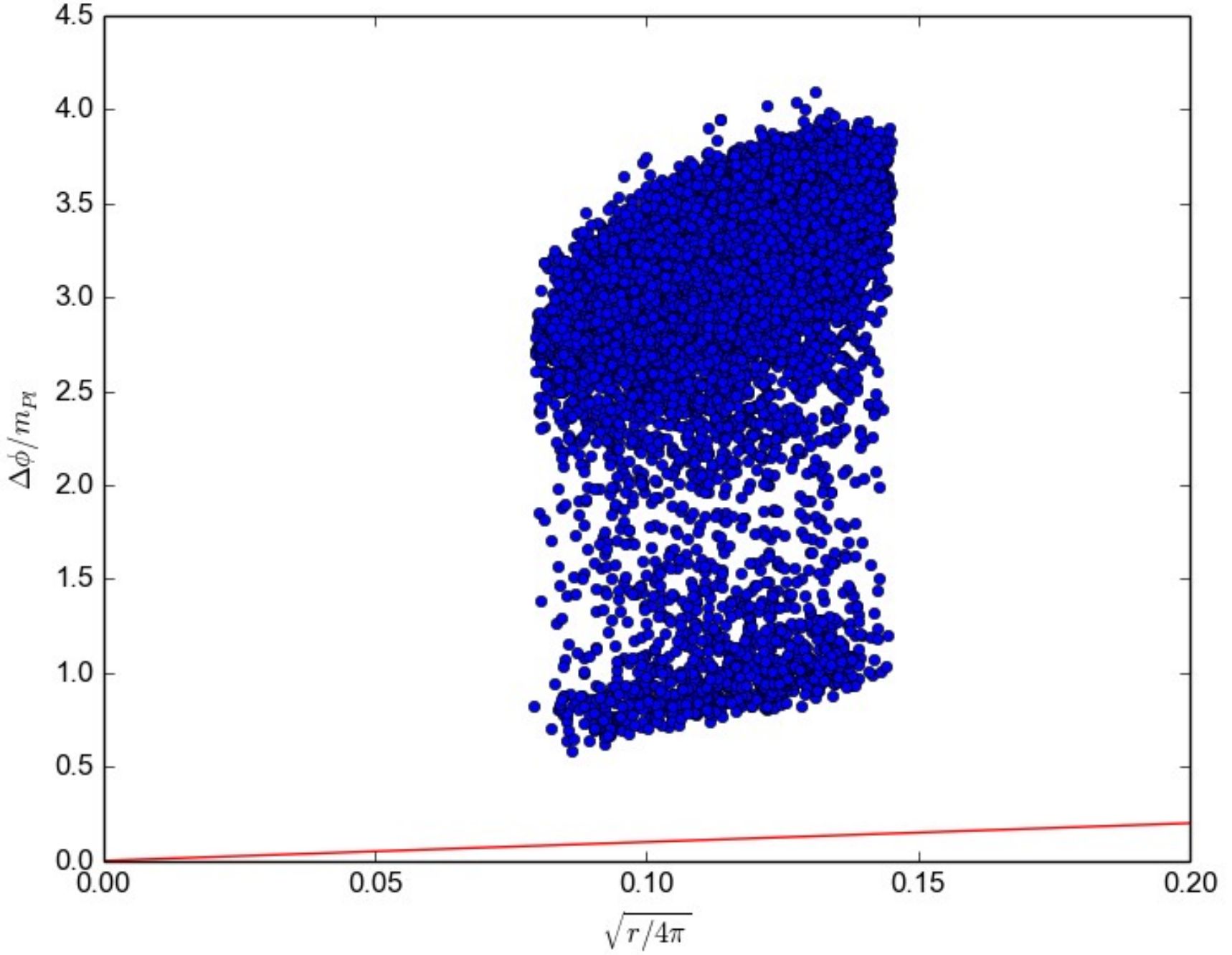
Lyth Bound

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

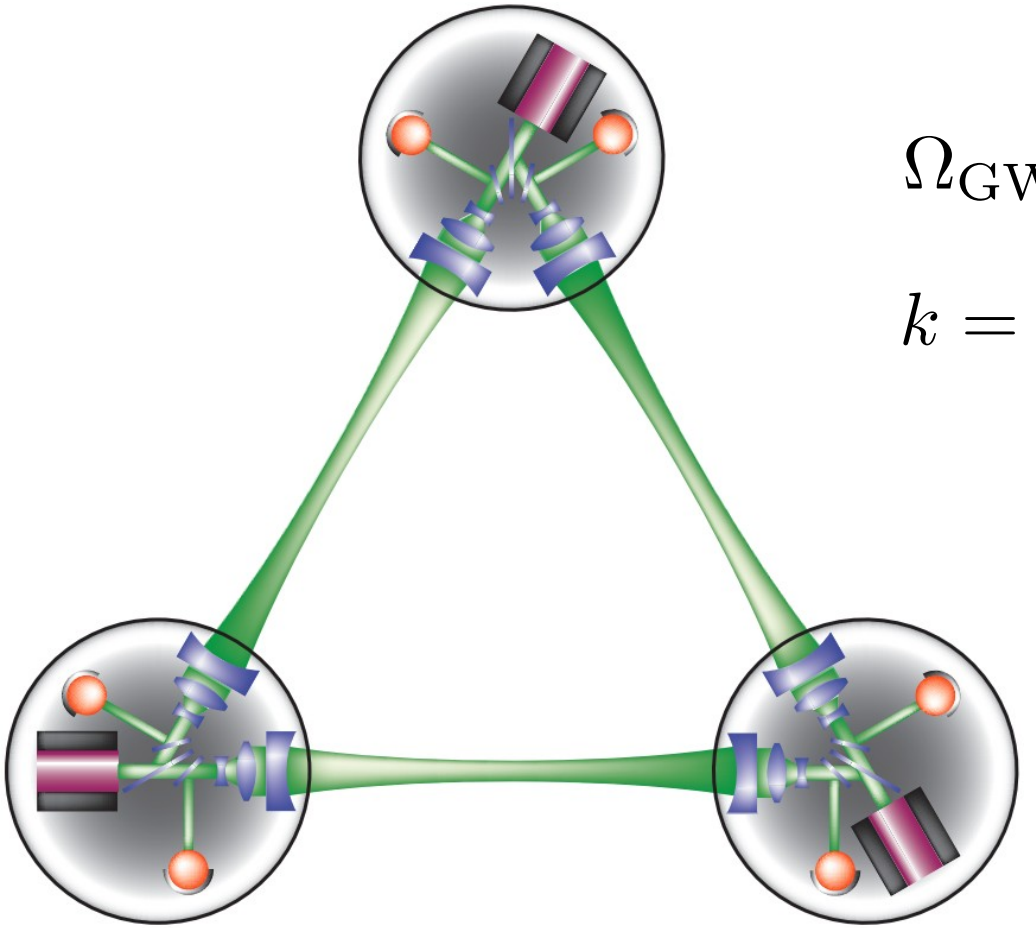
$$\Delta\phi < 0.1 M_p \Rightarrow r < 0.01 \Rightarrow \frac{H}{M_p} < 10^{-5}$$



Monte Carlo Potentials and the Lyth Bound



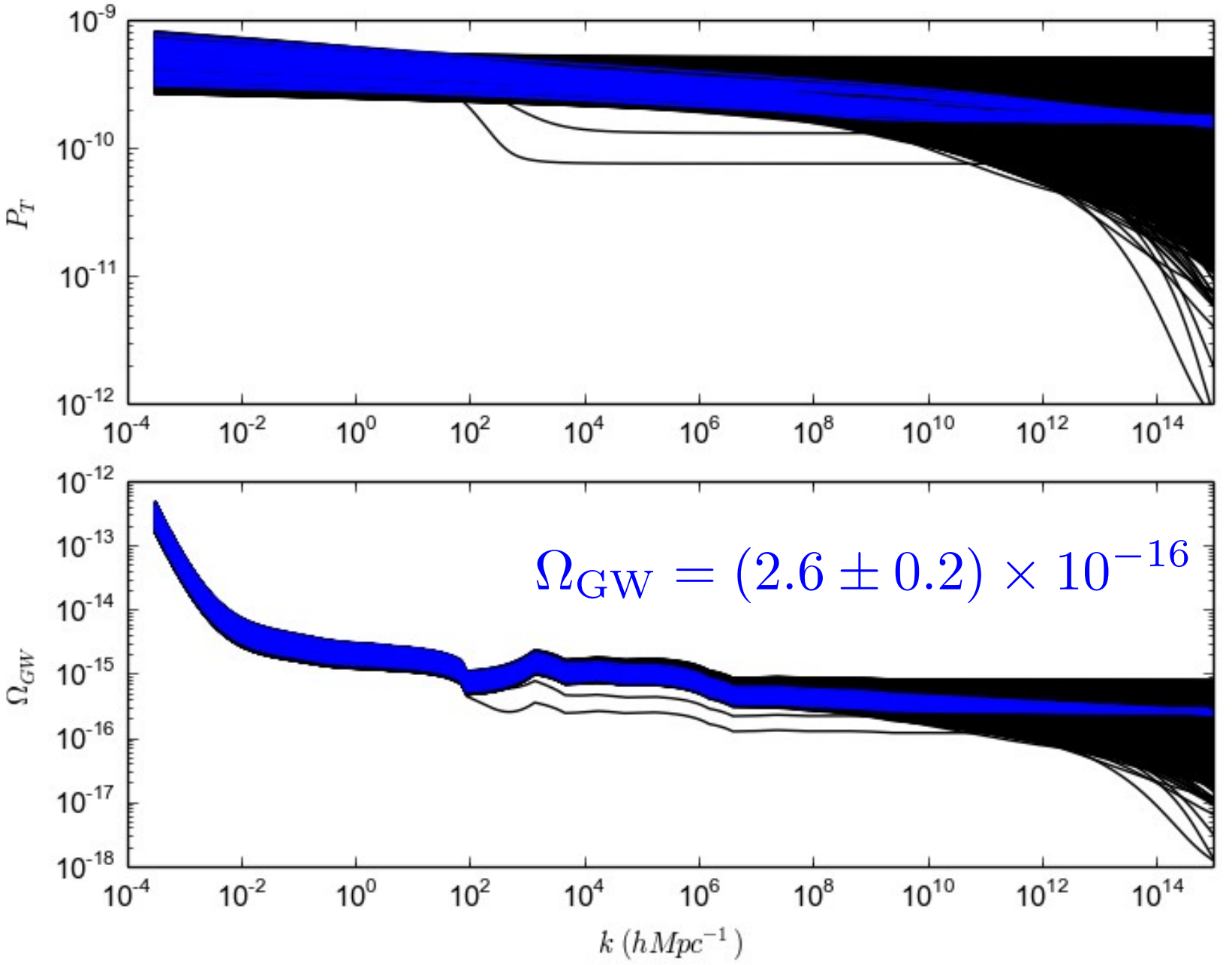
Direct Dectection: DECIGO



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

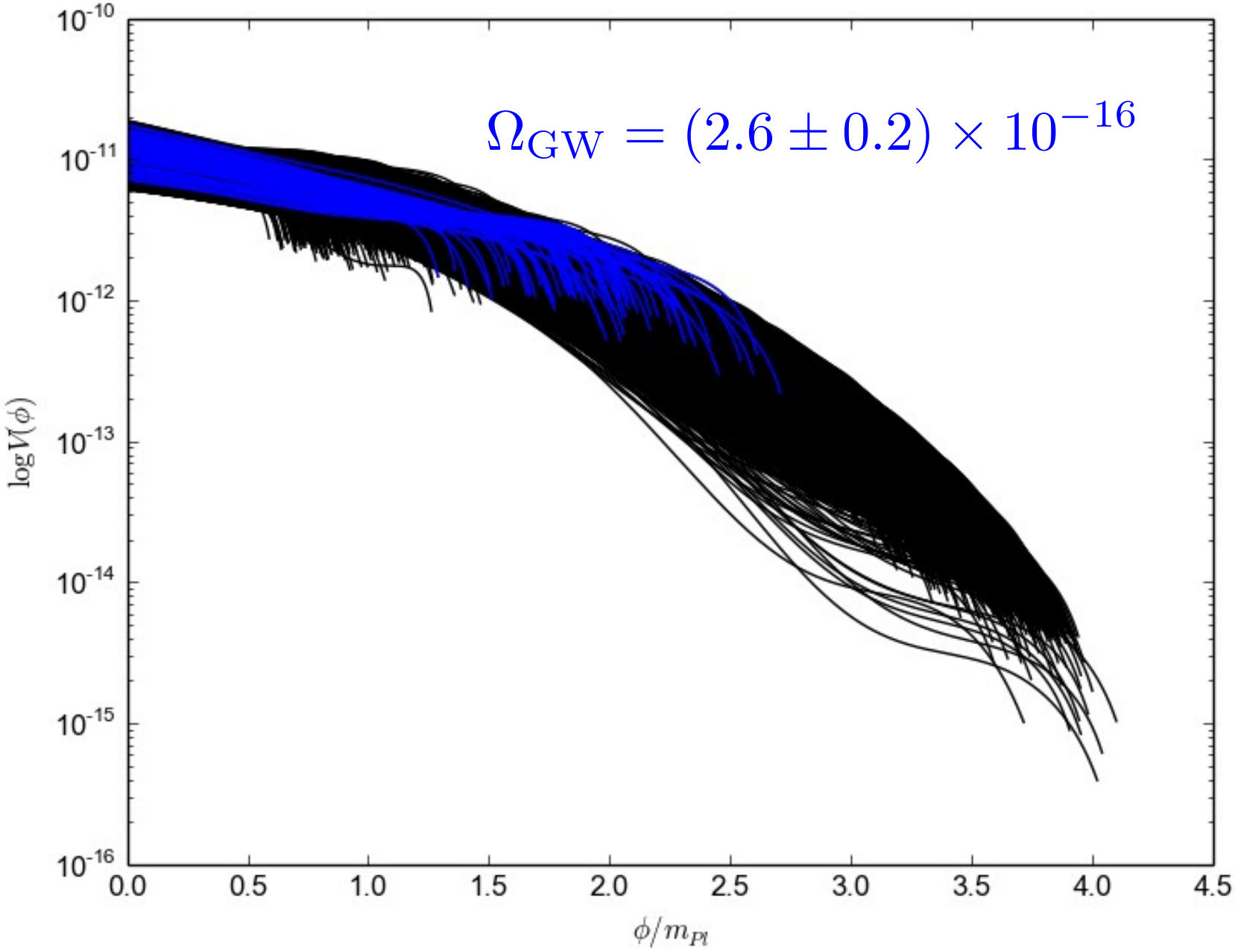
$$k = 1.6 \times 10^{14}\ {\rm Mpc}^{-1}$$

Direct Dectection: DECIGO Forecast



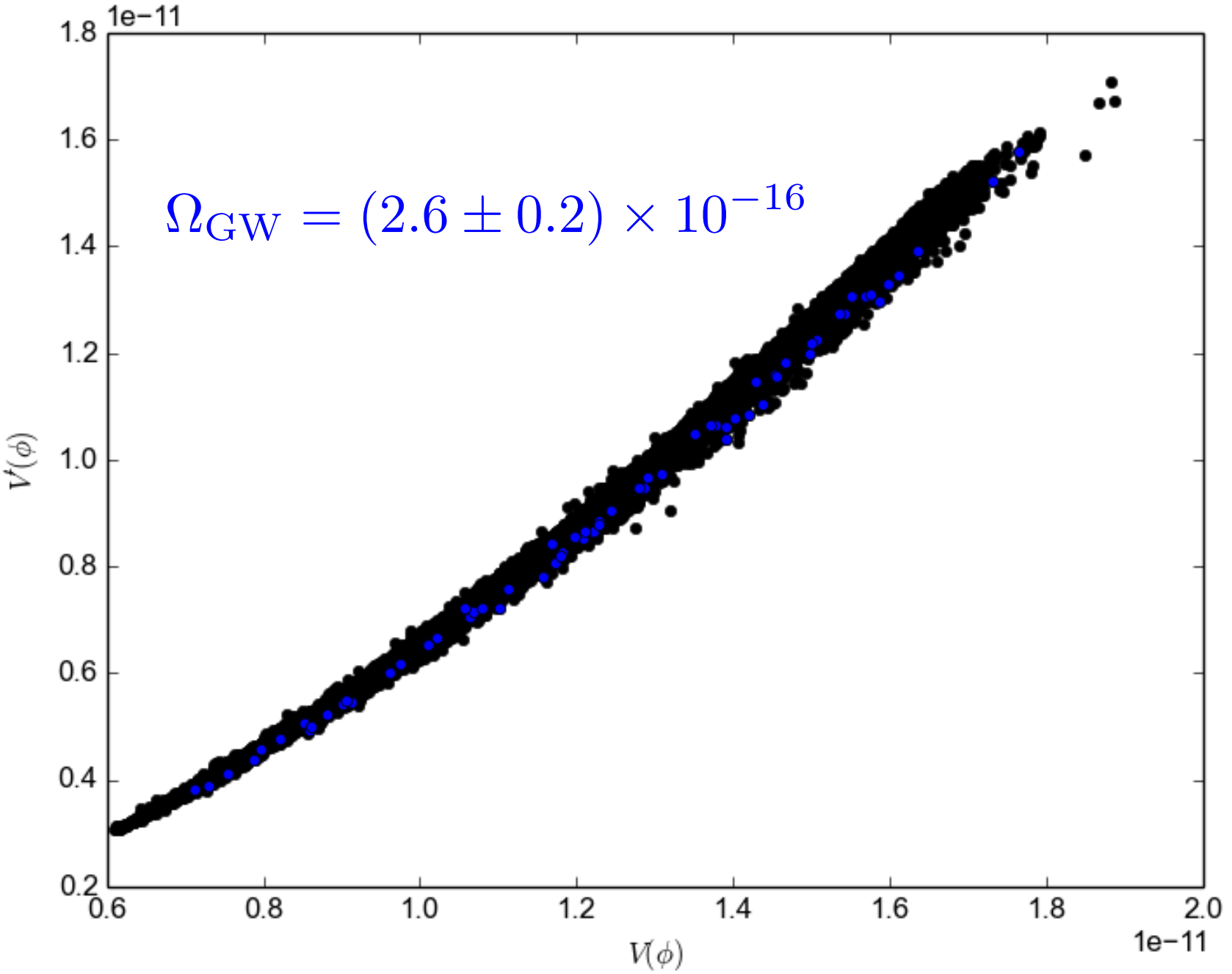
(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

Direct Dectection: DECIGO Forecast



(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

Direct Dectection: DECIGO Forecast



(Caligiuri, WHK, Kosowsky, arXiv:1409.3195)

Four Questions We Can (Maybe) Answer

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

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

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

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