Cosmological Implications from BICEP2

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based on some works done with
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New perspectives on cosmology, HKUST-IAS
ITP-CAS, Beijing
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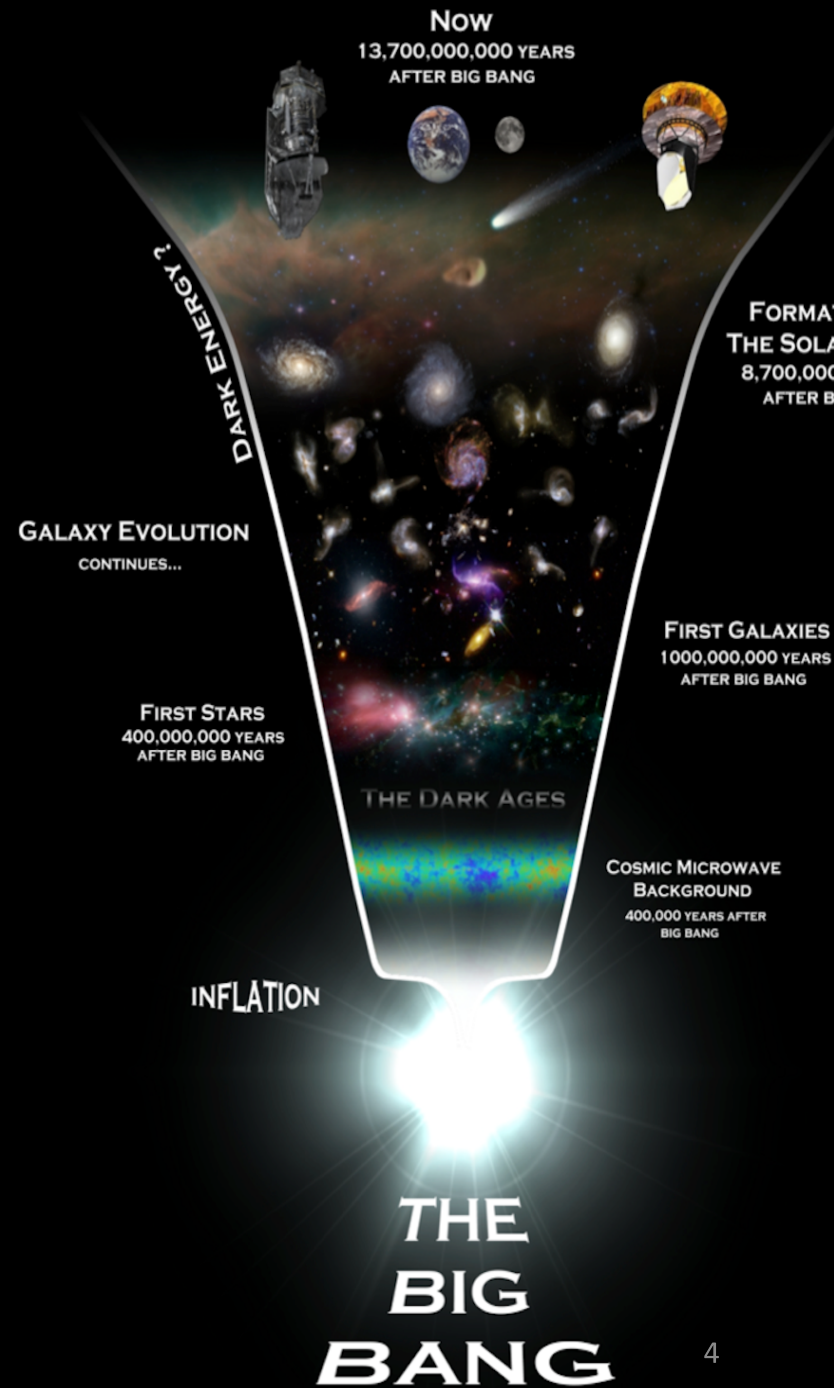
Outline

- Probing the inflationary universe from low-l CMB data
- How to reconcile Planck with BICEP2
- The tilt of relic gravitational waves power spectrum
- Summary

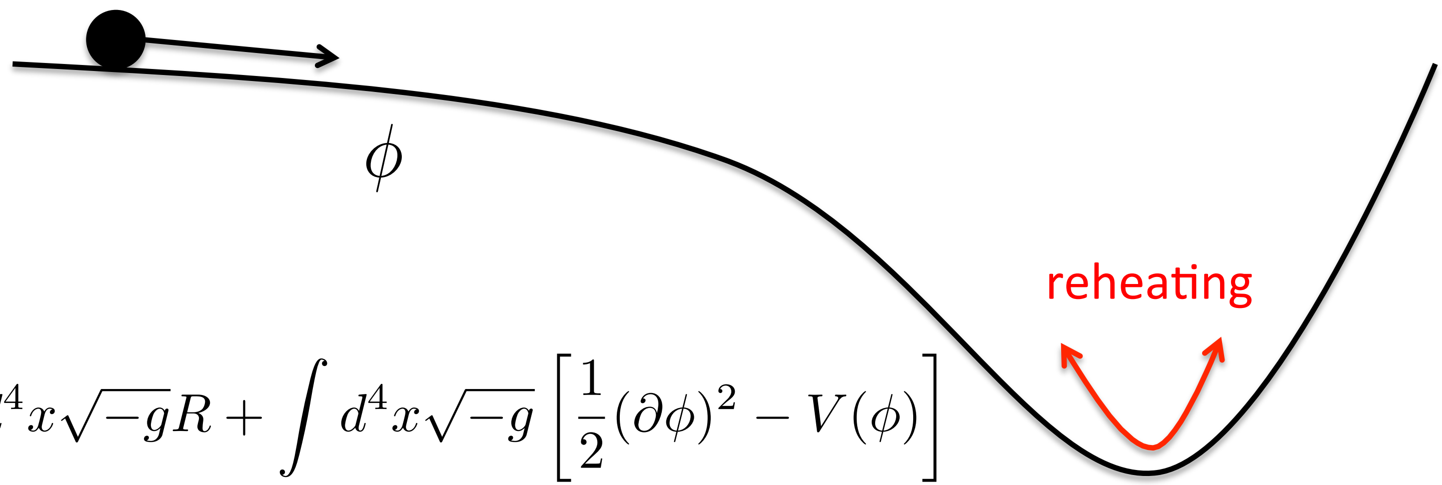
Probing the inflationary universe from low-l CMB data

Successes of Inflation:

- ❑ The Universe is big
- ❑ Homogeneity and isotropy
- ❑ Flatness problem
- ❑ Why no magnetic monopole?
- ❑ Nearly scale-invariant, adiabatic and Gaussian density perturbations.
- ❑ Nearly scale-invariant relic gravitational waves.
- ❑ ......



Slow-Roll Inflation



$$S = \frac{M_p^2}{2}\int d^4x\sqrt{-g}R + \int d^4x\sqrt{-g}\left[\frac{1}{2}(\partial\phi)^2 - V(\phi)\right]$$

$$H^2 = \frac{1}{3M_p^2}\left(\frac{1}{2}\dot{\phi}^2 + V(\phi)\right) \qquad \ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$$

$$\epsilon = \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 \ll 1$$

$$\left|\eta = M_p^2\frac{V''}{V}\right| \ll 1$$

$$H^2 \simeq \frac{V}{3M_p^2}$$

$$3H\dot{\phi} \simeq -V'$$

$$a(t) \sim e^{Ht}$$

- There are three kinds of perturbations: scalar, vector and tensor (gravitational waves) perturbations.
- At the linear order, these three kinds of perturbations evolve independently and therefore we can analyze them separately.
- Since there are no rotational velocity fields during inflation, the vector perturbations are not excited.

Scalar perturbations:

$$\zeta = \delta N = H\delta t = \frac{H}{\dot{\phi}}\delta\phi = -\frac{1}{\sqrt{2\epsilon}M_p}\delta\phi$$

$$P_s = \frac{H^2/M_p^2}{8\pi^2\epsilon}$$

$$n_s \equiv 1 + \frac{d\ln P_s}{d\ln k} = 1 - 6\epsilon + 2\eta$$

Gravitational waves:

$$P_t = \frac{H^2/M_p^2}{\pi^2/2}$$

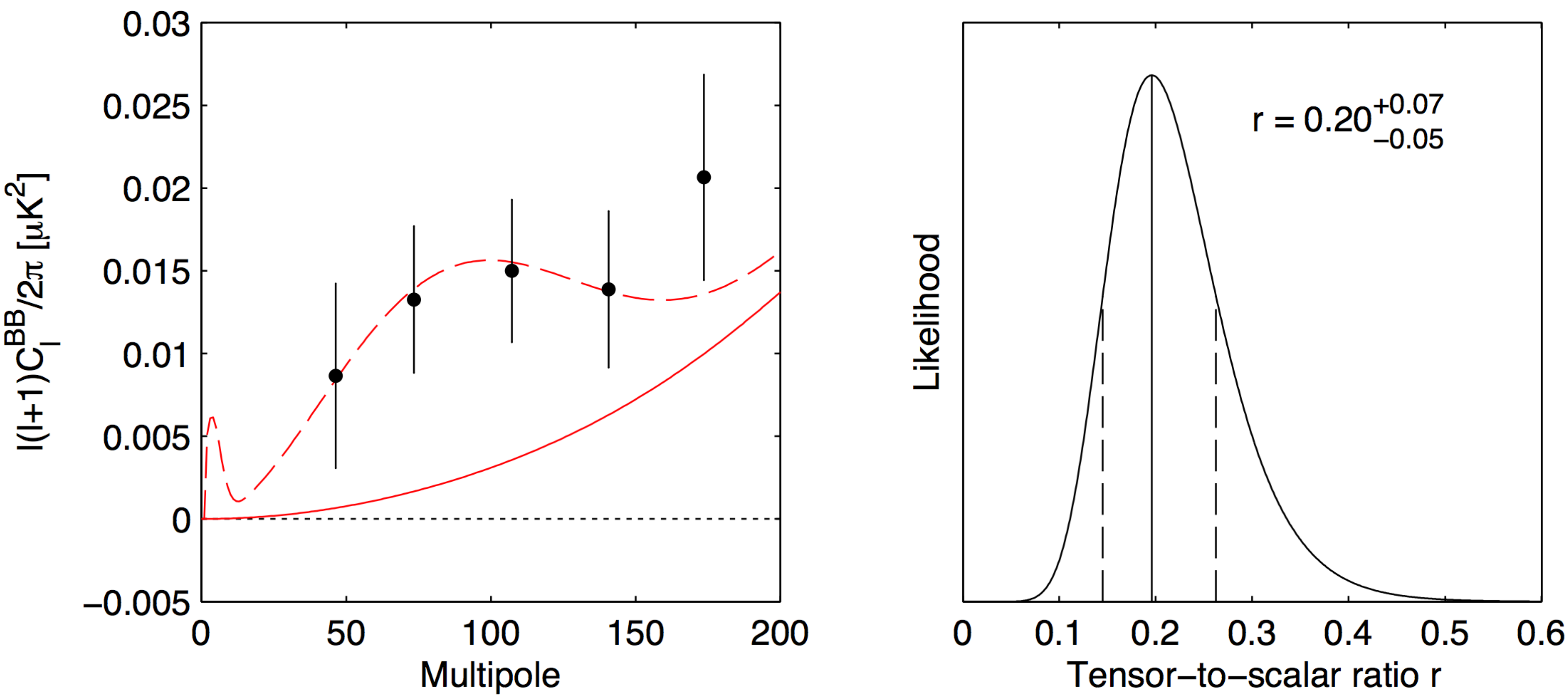
$$r = P_t/P_s = 16\epsilon$$

$$n_t = -2\epsilon$$

$$n_t = -r/8$$

Nearly scale-invariant!

Discovery of relic gravitational waves (BICEP2)



$$r = 0.2^{+0.07}_{-0.05},\ \text{with } r = 0 \text{ is disfavored at } 7.0\sigma$$

BICEP2 collaboration, arXiv:1403.3985

Naturalness of inflation?

$$\frac{\Delta T}{T} \sim 10^{-5} \quad \Longleftrightarrow \quad \text{A small dimensionless parameter}$$

Lyth Bound:

$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V'}{V}\right)^2 = \frac{1}{2}\frac{\dot{\phi}^2}{M_p^2 H^2}$$

$$r = 16\epsilon$$

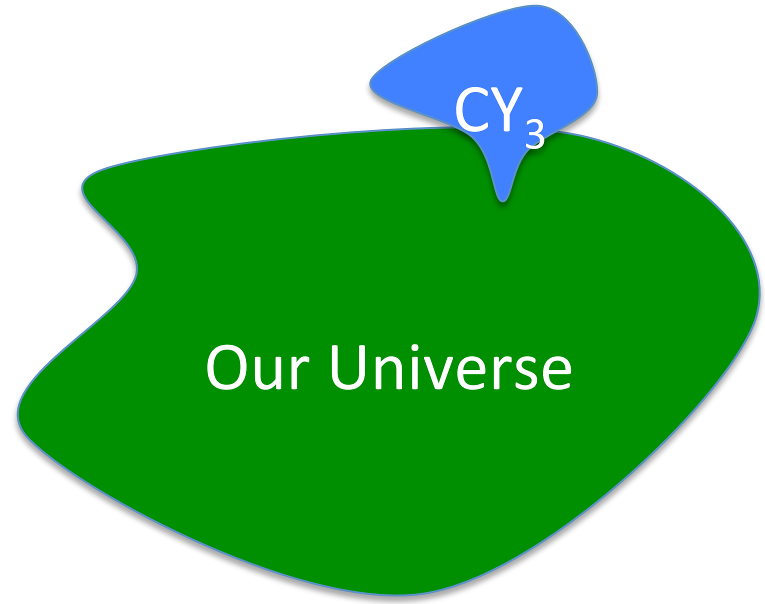
$$\frac{d\phi}{M_p} = \sqrt{\frac{r}{8}} H dt = \sqrt{\frac{r}{8}} dN$$

$$\frac{|\Delta\phi|}{M_p} \simeq \sqrt{\frac{r}{8}}\Delta N$$

$$\text{For } r = 0.2,\ \frac{|\Delta\phi|}{M_p} \simeq 0.16\Delta N$$

Lyth, 1997(PRL)

Warped D-brane inflation

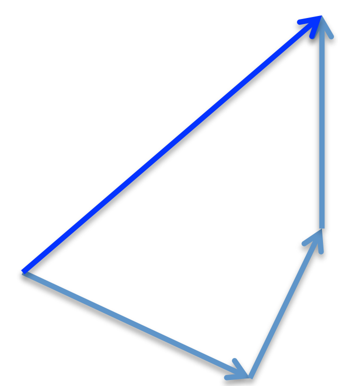


$$M_p^2 \sim \frac{M_s^8}{g_s^2} V_6$$

Single brane: $|\Delta\phi| = \sqrt{T_3}r \leq \frac{2}{\sqrt{N_B}} M_p$

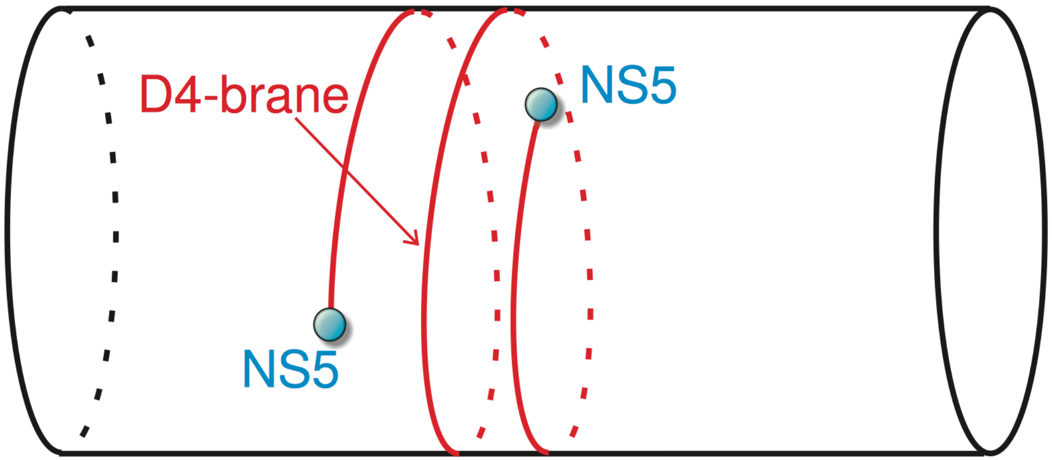
A stack of D-branes (N): $|\Delta\phi| = \sqrt{T_3}r \leq \frac{2}{\sqrt{N}} M_p$

$$\Delta\Phi \equiv \sqrt{\sum (\Delta\phi_i)^2} \leq 2M_p$$



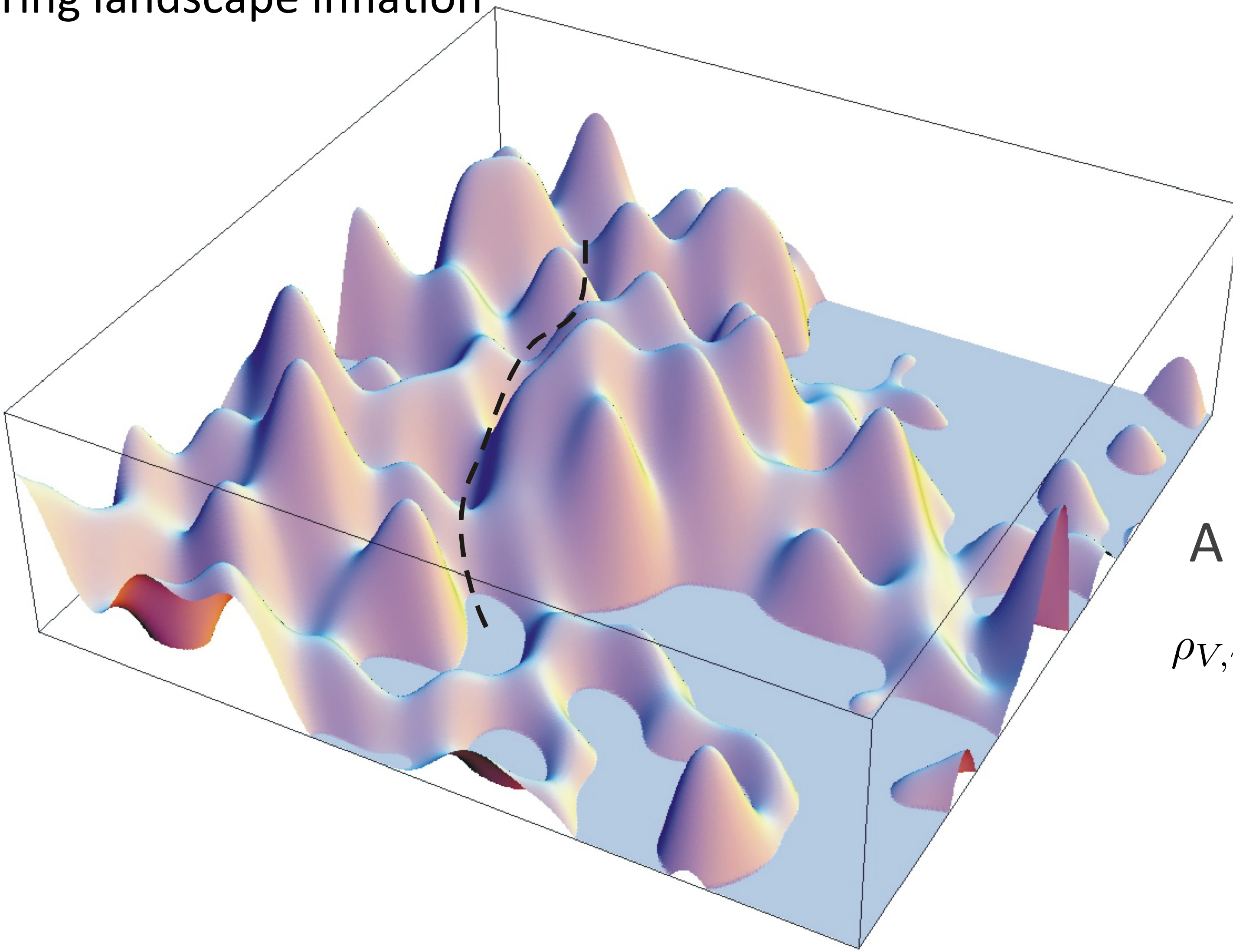
Baumann, McAllister, 2007

Monodromy axion inflation in string theory



$V \sim \phi^{2/3}$	Silverstein and Westphal, 2008
$V \sim \phi$	McAllister, Silverstein and Westphal, 2008
$V \sim \phi^2$	Marchesano, Shiu, Uranga, 2014
$V \sim \phi^3, \ldots$	McAllister, Silverstein, Westphal, Wrase, 2014
	…………

String landscape inflation



A Toy Model

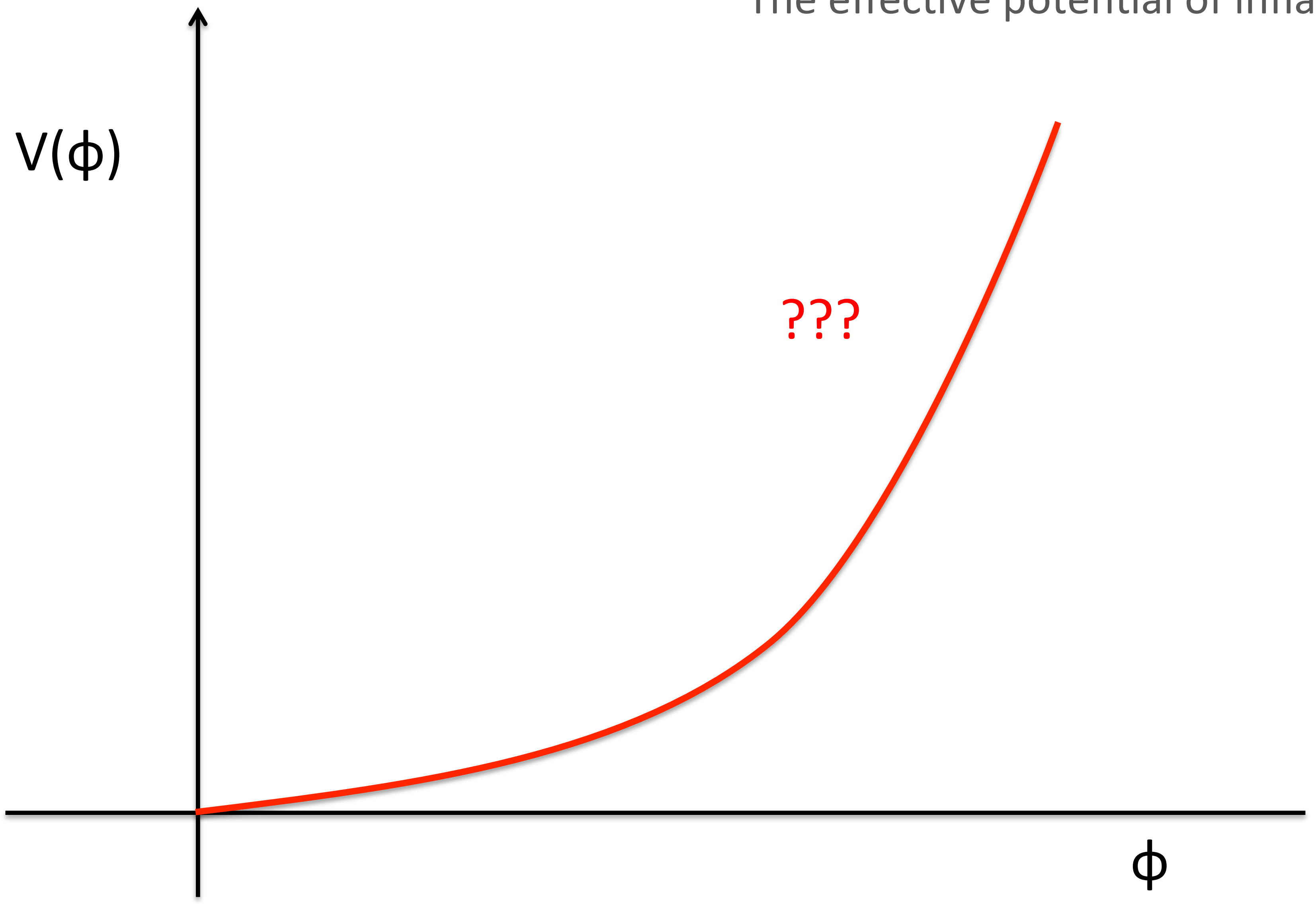
$$\rho_{V,n+1} - \rho_{V,n} = \sigma$$

$$n_s = 1 - \frac{5}{3N}$$

$$r = \frac{16}{3N}$$

QGH, JCAP 05(2007)009

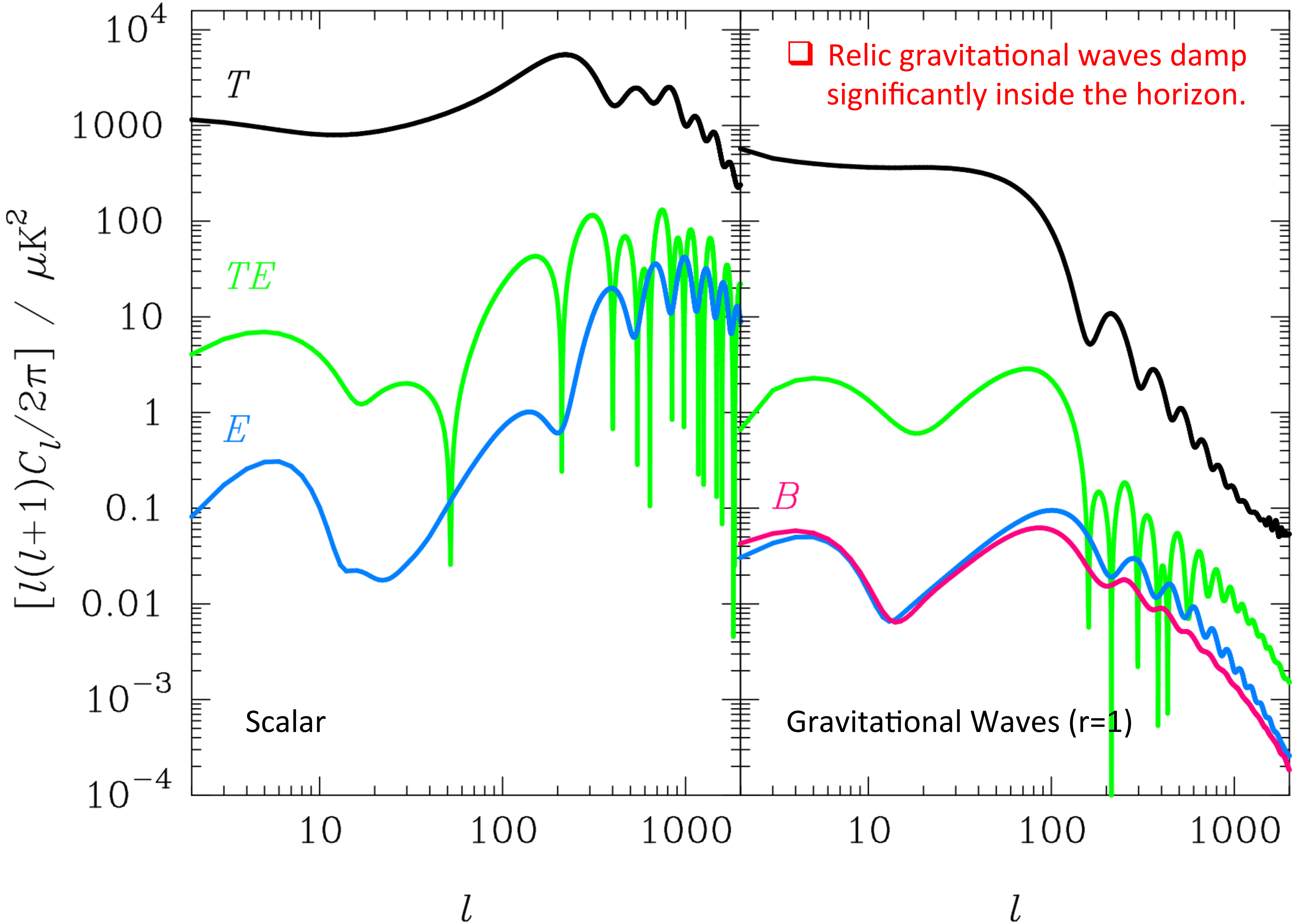
The effective potential of inflaton



Everything is encoded in the data.

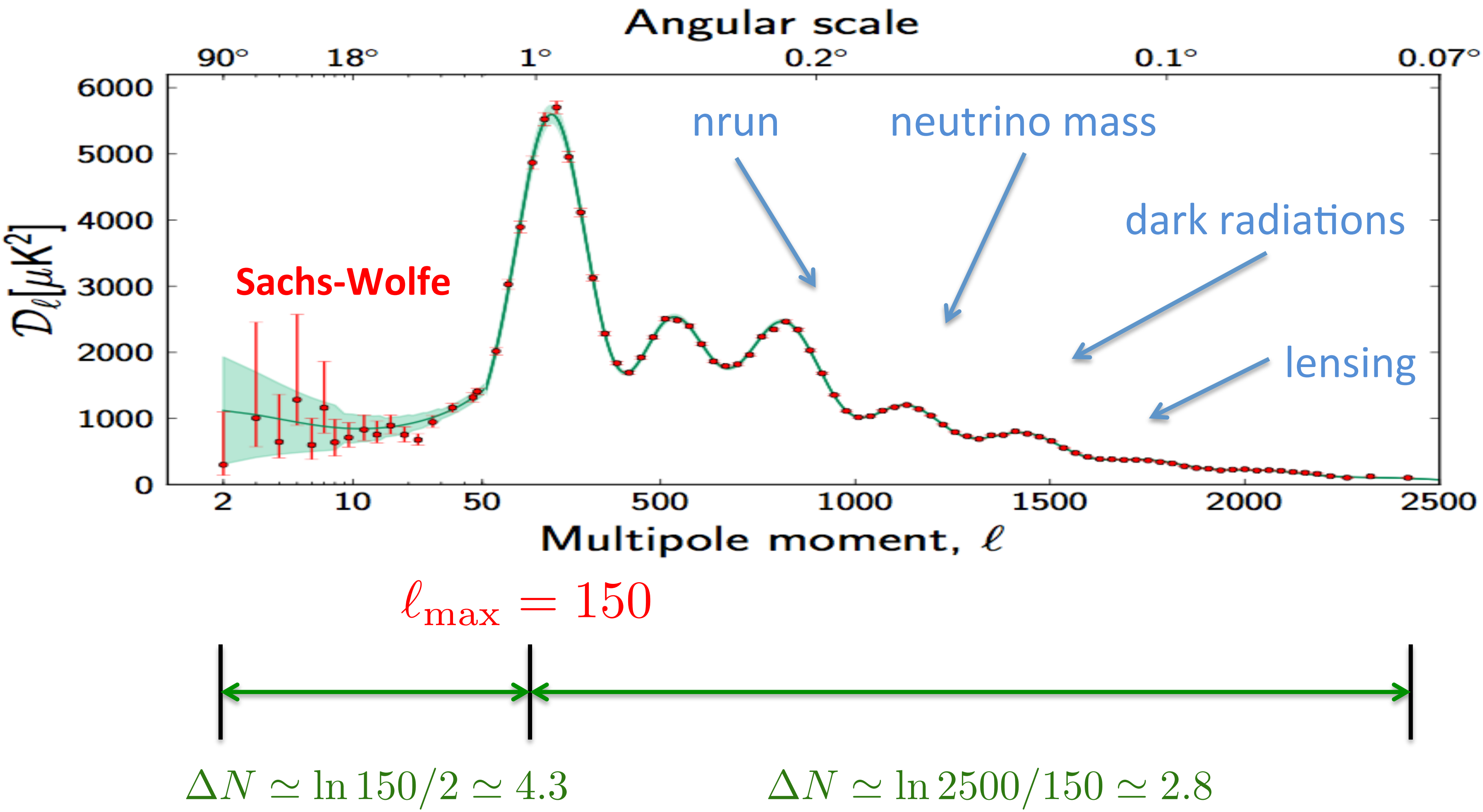
How to correctly extract the information from the data?

Global fitting may not be the best strategy.

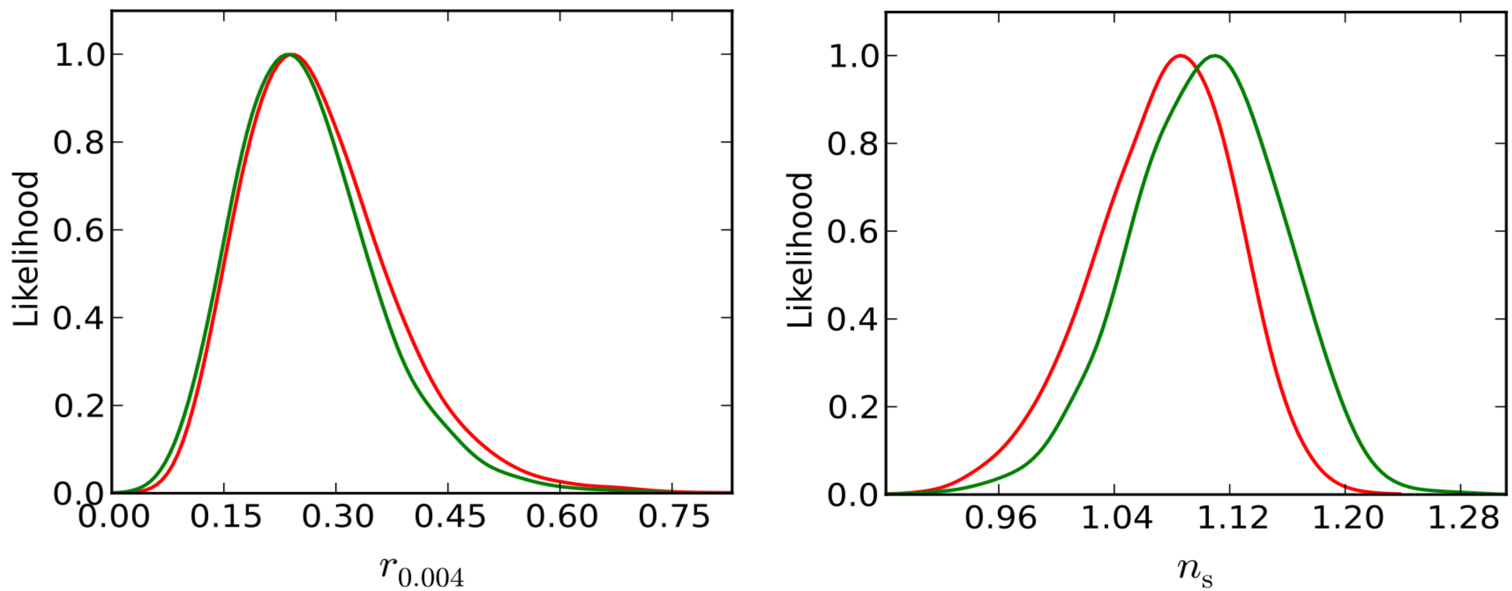


Relic gravitational waves damp significantly inside the horizon.
T
TE
E
B
Scalar
Gravitational Waves (r=1)
$[l(l+1)C_l/2\pi]$ / μK^2
10^4
1000
100
10
1
0.1
0.01
10^{-3}
10^{-4}
10
100
1000
l

- On large scales (>1°) any causal effects have not had time to operate.
- Low-l CMB power spectra are dominated by the Sachs-Wolfe effect.



B2+P13 (TT) + W9 (TE)
B2+W9 (TT, TE)



$n_t = -r/8$	B2+W9 ($\ell_{\max} = 150$)		B2+P13+WP ($\ell_{\max} = 150$)	
parameters	best fit	68% limits	best fit	68% limits
$\Omega_b h^2$	0.0192	$0.0270^{+0.0074}_{-0.0104}$	0.0209	$0.0263^{+0.0077}_{-0.0149}$
$\Omega_c h^2$	0.140	$0.166^{+0.029}_{-0.046}$	0.141	$0.141^{+0.018}_{-0.038}$
$100\theta_{\rm MC}$	1.116	$1.104^{+0.046}_{-0.048}$	1.142	$1.098^{+0.044}_{-0.027}$
τ	0.095	$0.099^{+0.015}_{-0.018}$	0.105	$0.099^{+0.015}_{-0.018}$
$\ln(10^{10} A_s)$	3.106	$3.051^{+0.061}_{-0.054}$	3.021	$3.024^{+0.065}_{-0.057}$
n_s	1.098	$1.104^{+0.052}_{-0.051}$	1.120	$1.074^{+0.056}_{-0.042}$
r	0.19	$0.26^{+0.07}_{-0.11}$	0.23	$0.28^{+0.07}_{-0.12}$

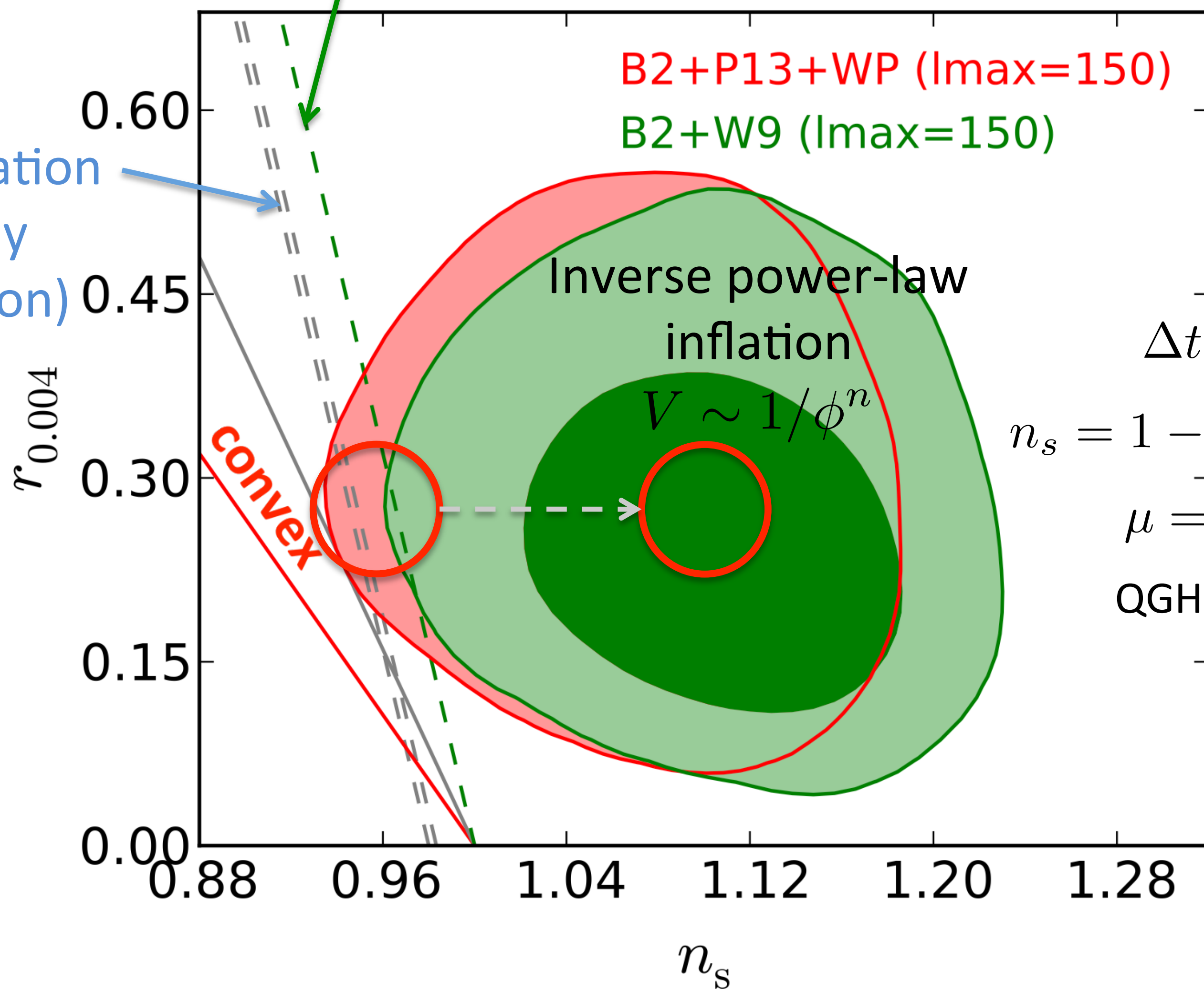
C. Cheng, QGH, arXiv:1405.0349

Power-law Inflation

$V \sim \exp(-\sqrt{2/p}\phi/M_p)$

Chaotic Inflation (monodromy axion inflation)

$V \sim \phi^n$



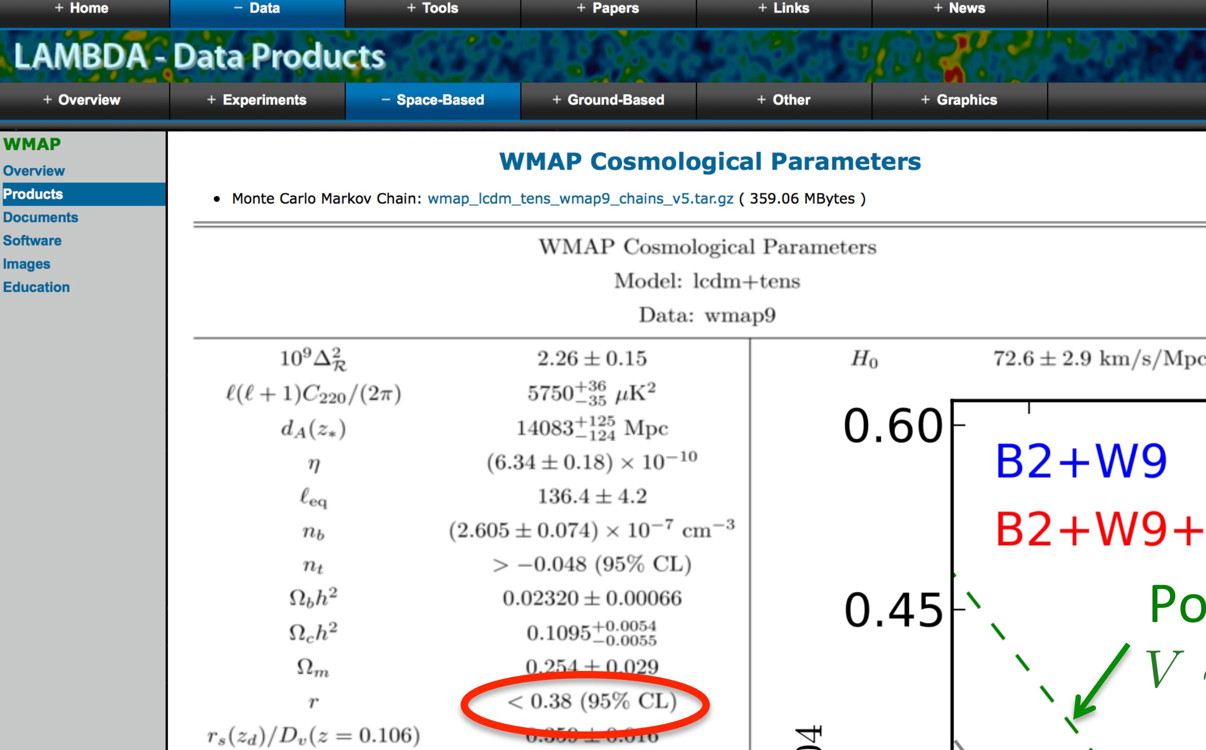
$\Delta t \Delta x \gtrsim 1/M_s^2$

$n_s = 1 - 6\epsilon + 2\eta + r\mu$

$\mu = H^2 k^2 / a^2 M_s^4$

QGH and M. Li, 2003

C. Cheng, QGH, arXiv:1405.0349



WMAP Cosmological Parameters

- Monte Carlo Markov Chain: wmap_lcdm_tens_wmap9_chains_v5.tar.gz (359.06 MBytes)

WMAP Cosmological Parameters

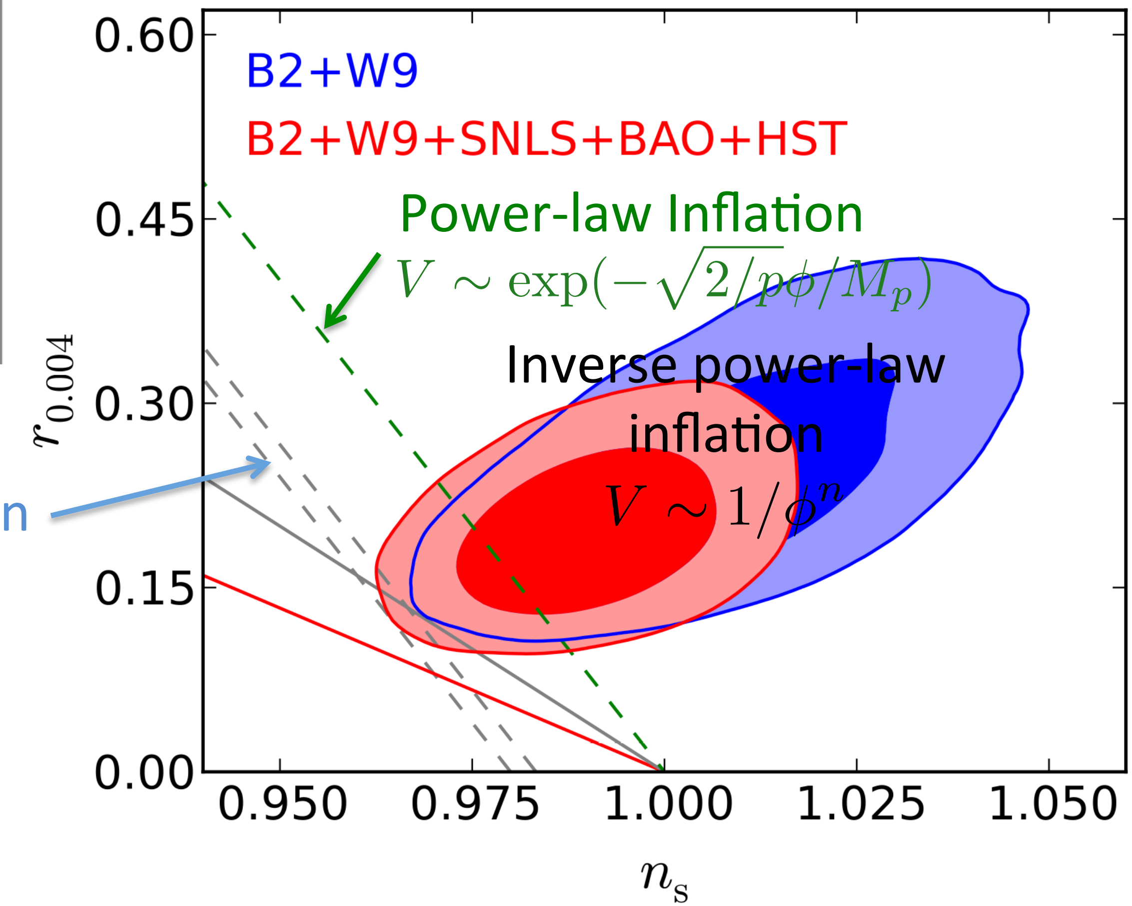
Model: lcdm+tens

Data: wmap9

$10^9\Delta^2_{\mathcal{R}}$	2.26 ± 0.15	H_0	72.6 ± 2.9 km/s/Mpc
$\ell(\ell+1)C_{220}/(2\pi)$	$5750^{+36}_{-35}\ \mu\mathrm{K}^2$		
$d_A(z_*)$	14083^{+125}_{-124} Mpc		
η	$(6.34 \pm 0.18) \times 10^{-10}$		
ℓ_{eq}	136.4 ± 4.2		
n_b	$(2.605 \pm 0.074) \times 10^{-7}$ cm^{-3}		
n_t	> -0.048 (95% CL)		
$\Omega_b h^2$	0.02320 ± 0.00066		
$\Omega_c h^2$	$0.1095^{+0.0054}_{-0.0055}$		
Ω_m	0.254 ± 0.029		
r	< 0.38 (95% CL)		
$r_s(z_d)/D_v(z=0.106)$	[illegible] ± 0.016		

Chaotic Inflation (monodromy axion inflation)

$V \sim \phi^n$



C. Cheng, QGH, arXiv:1404.1230

How to reconcile Planck with BICEP2

NO TENSION between Planck and BICEP2 on large scales.

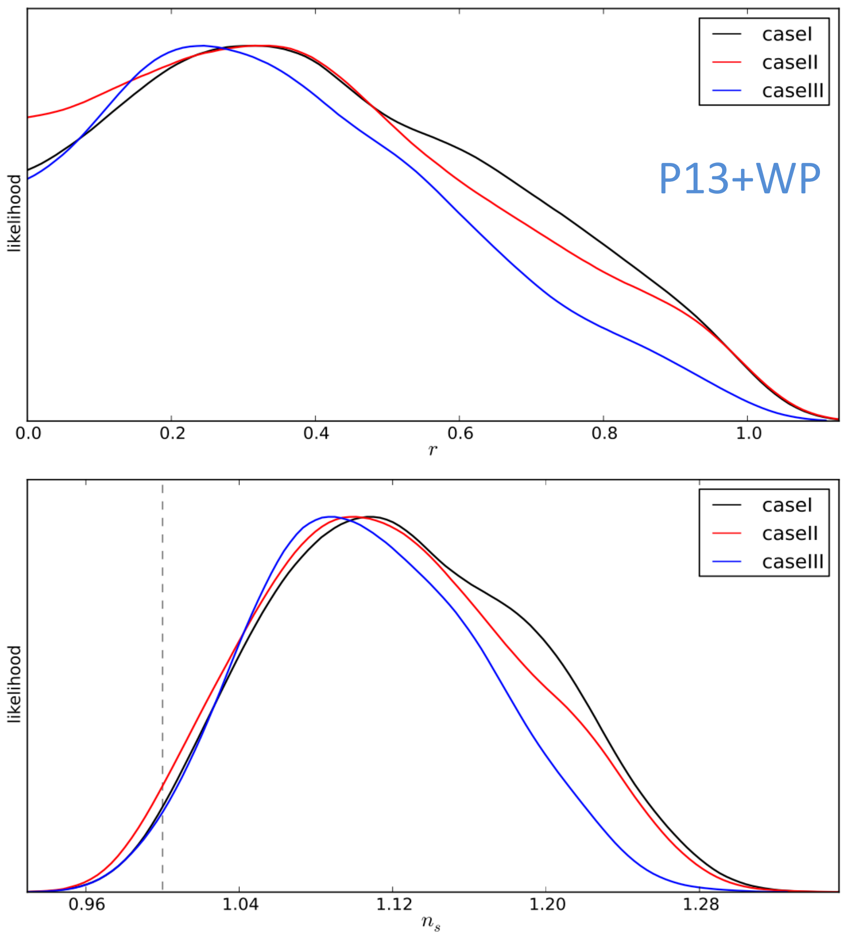
- The TT and TE power spectra generated by the relic gravitational waves are significant only the large scales. We take l_max=100.
- We fix the background parameters ($\Omega_b h^2$, $\Omega_c h^2$, 100 θ_{MC}, τ) at their best-fit values in the ΛCDM model from Planck, and the free running parameters are A_s, n_s and r.

$$C_\ell^{TT} = C_{\ell,s}^{TT} + C_{\ell,t}^{TT}$$

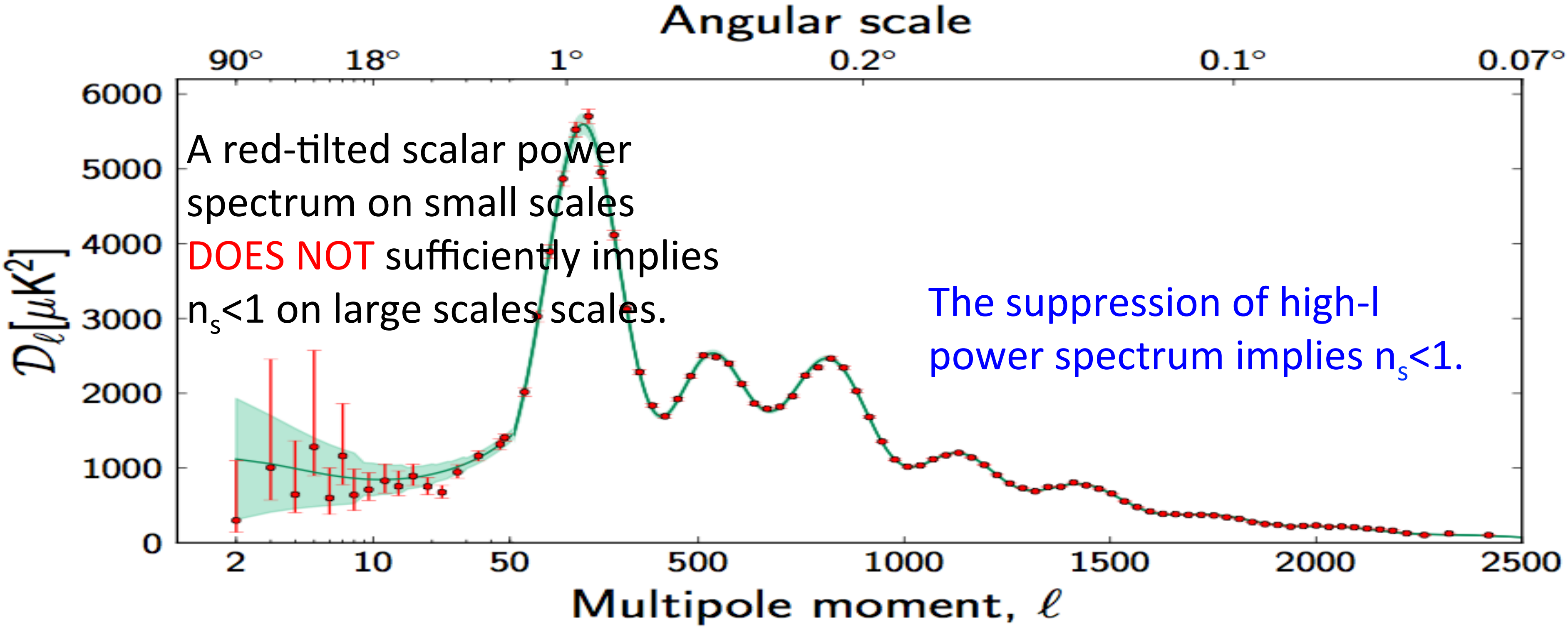
$$C_\ell^{TE} = C_{\ell,s}^{TE} + C_{\ell,t}^{TE}$$

$$C_{\ell,t}^{TT} > 0, \; C_{\ell,t}^{TE} < 0$$

- The tensor-to-scalar ratio is peaked at around 0.2.
- The spectral index n_s>1.



W. Zhao, C. Cheng and QGH, arXiv:1403.3919



A red-tilted scalar power spectrum on small scales DOES NOT sufficiently implies $n_s<1$ on large scales scales.

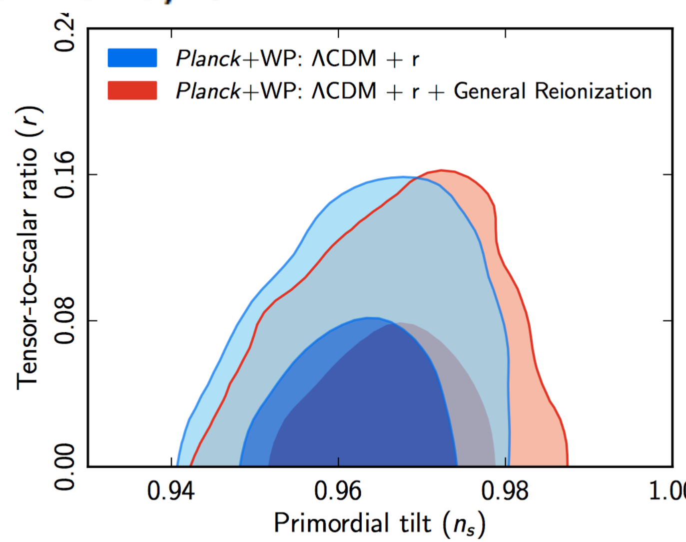
The suppression of high-l power spectrum implies $n_s<1$.

$$n_s = 0.9650 \pm 0.0080$$

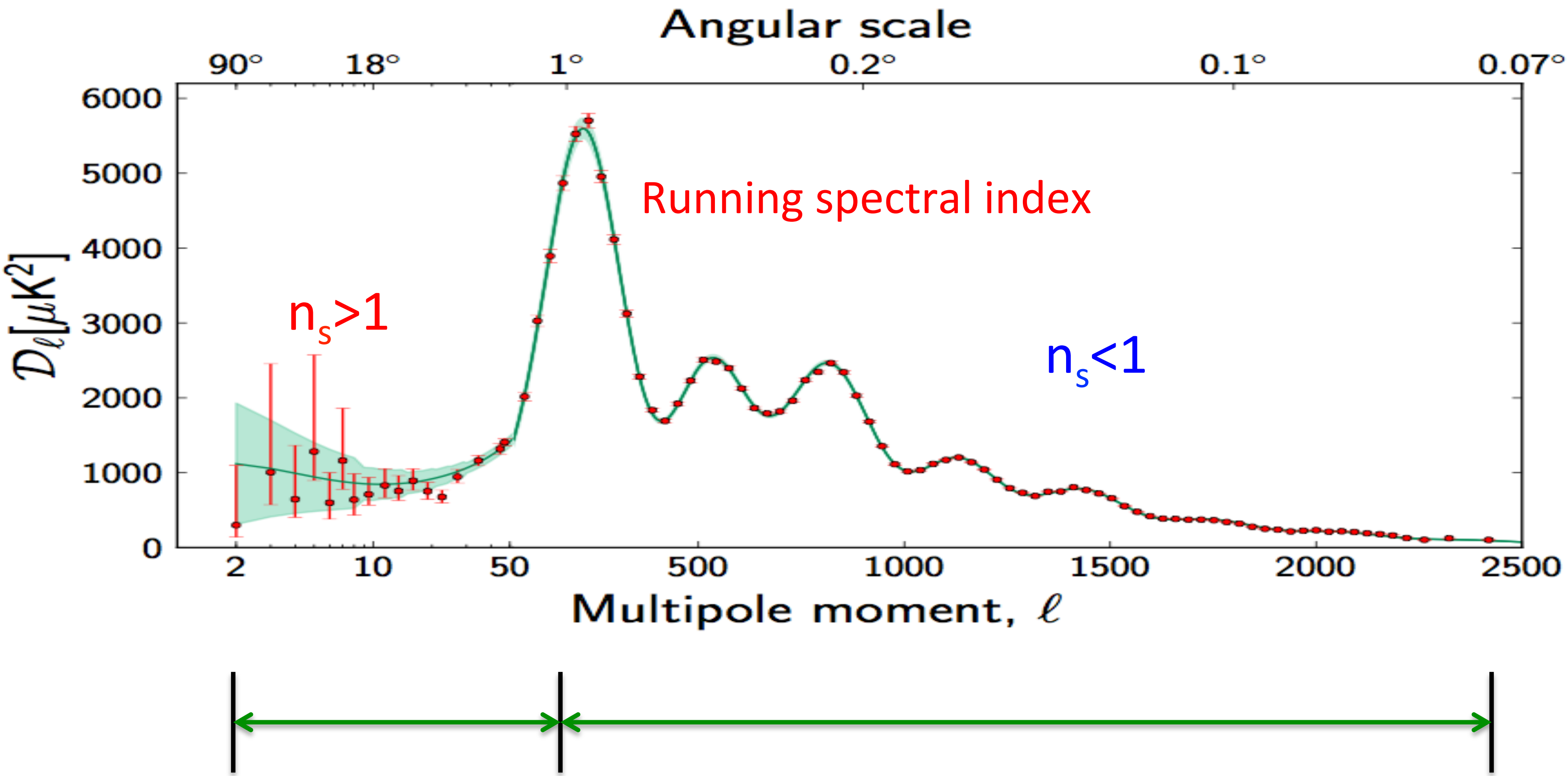
$$C_\ell^{TT} = C_{\ell,s}^{TT} + C_{\ell,t}^{TT}$$

$$r_{0.002} < 0.13, \quad @\ 95\%\ CL$$

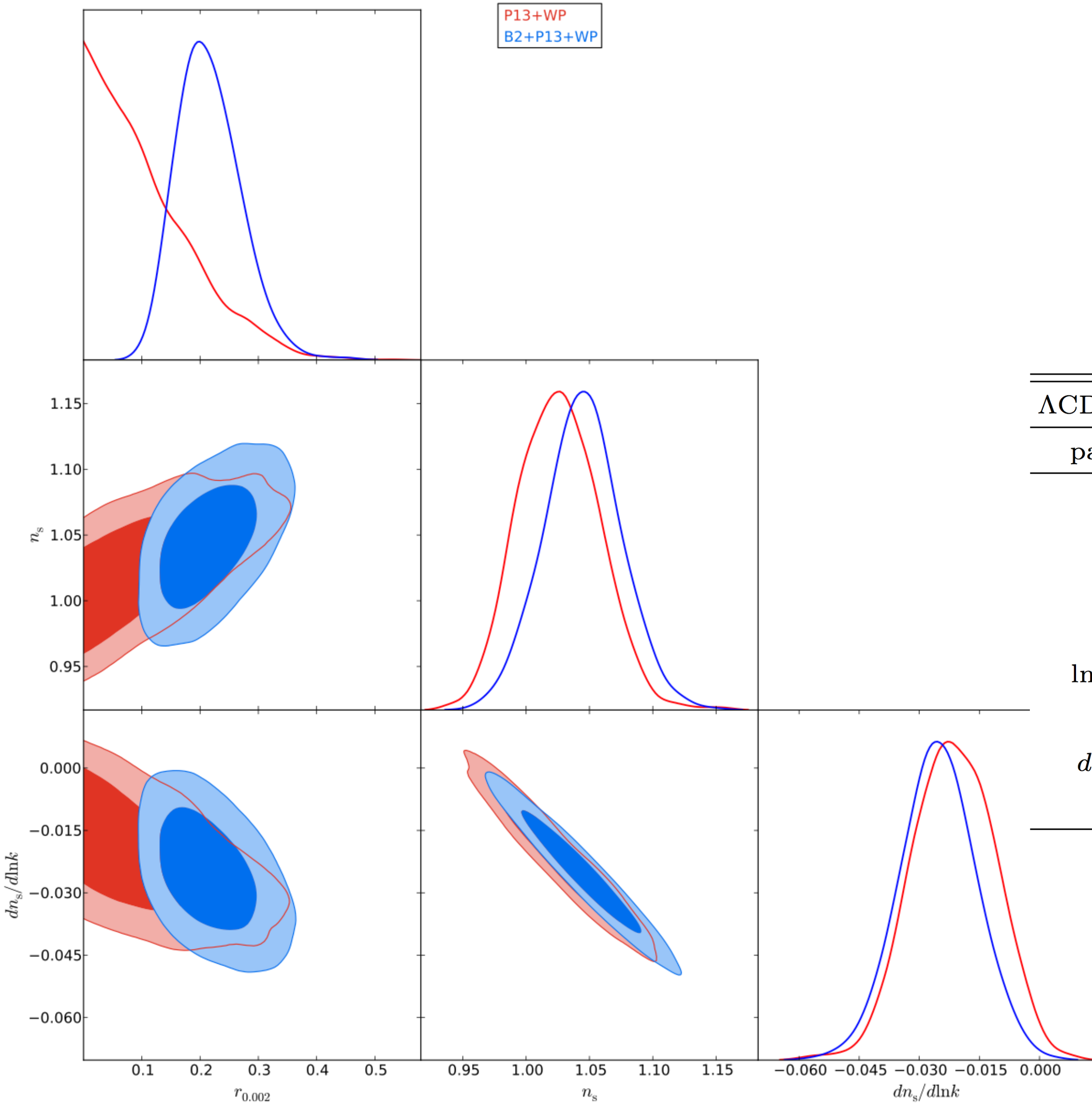
The apparent tension comes from the assumption of the base six-parameter ΛCDM model with a power-law scalar power spectrum.



Planck collaboration, arXiv:1303.5076, 1303.5082



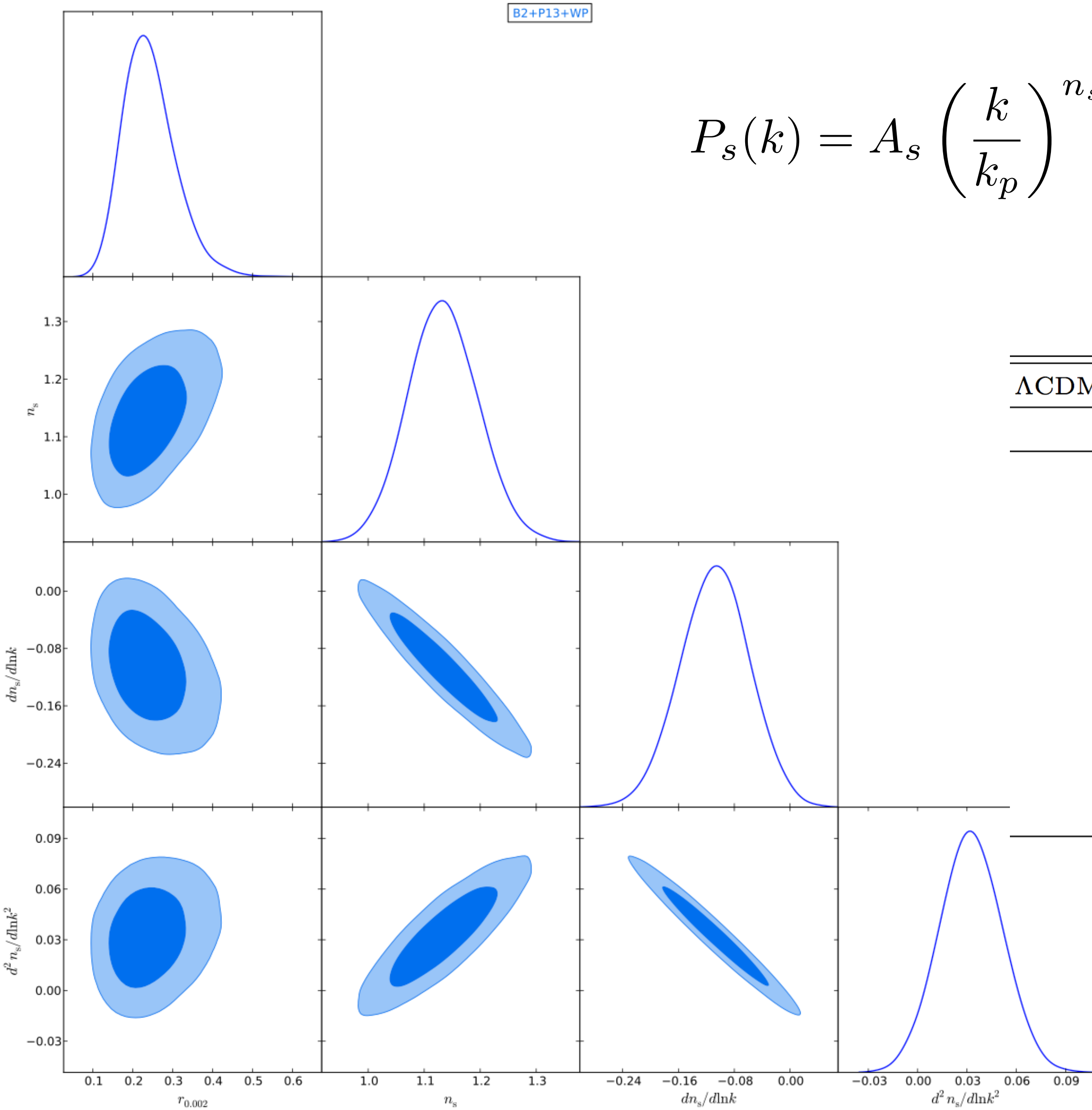
$\Delta N \simeq \ln 150/2 \simeq 4.3$ $\Delta N \simeq \ln 2500/150 \simeq 2.8$



+nrun

ΛCDM+nrun+r	B2+P13+WP	
parameters	Best fit	68% limits
$\Omega_b h^2$	0.02229	$0.02246^{+0.00030}_{-0.00032}$
$\Omega_c h^2$	0.1187	$0.1173^{+0.0022}_{-0.0021}$
$100\theta_{\rm MC}$	1.04154	$1.04162^{+0.00061}_{-0.00062}$
τ	0.0991	$0.1011^{+0.0137}_{-0.0161}$
$\ln(10^{10}A_s)$	3.117	$3.098^{+0.045}_{-0.041}$
n_s	1.0336	$1.0447^{+0.0295}_{-0.0297}$
$dn_s/d\ln k$	-0.0228	-0.0253 ± 0.0093
$r_{0.002}$	0.18	$0.22^{+0.04}_{-0.07}$

C. Cheng, QGH, W. Zhao, arXiv:1404.3467



$$P_s(k) = A_s \left(\frac{k}{k_p}\right)^{n_s - 1 + \frac{1}{2}\frac{dn_s}{d\ln k}\ln\frac{k}{k_p} + \frac{1}{6}\frac{d^2 n_s}{d\ln k^2}\ln^2\frac{k}{k_p}}$$

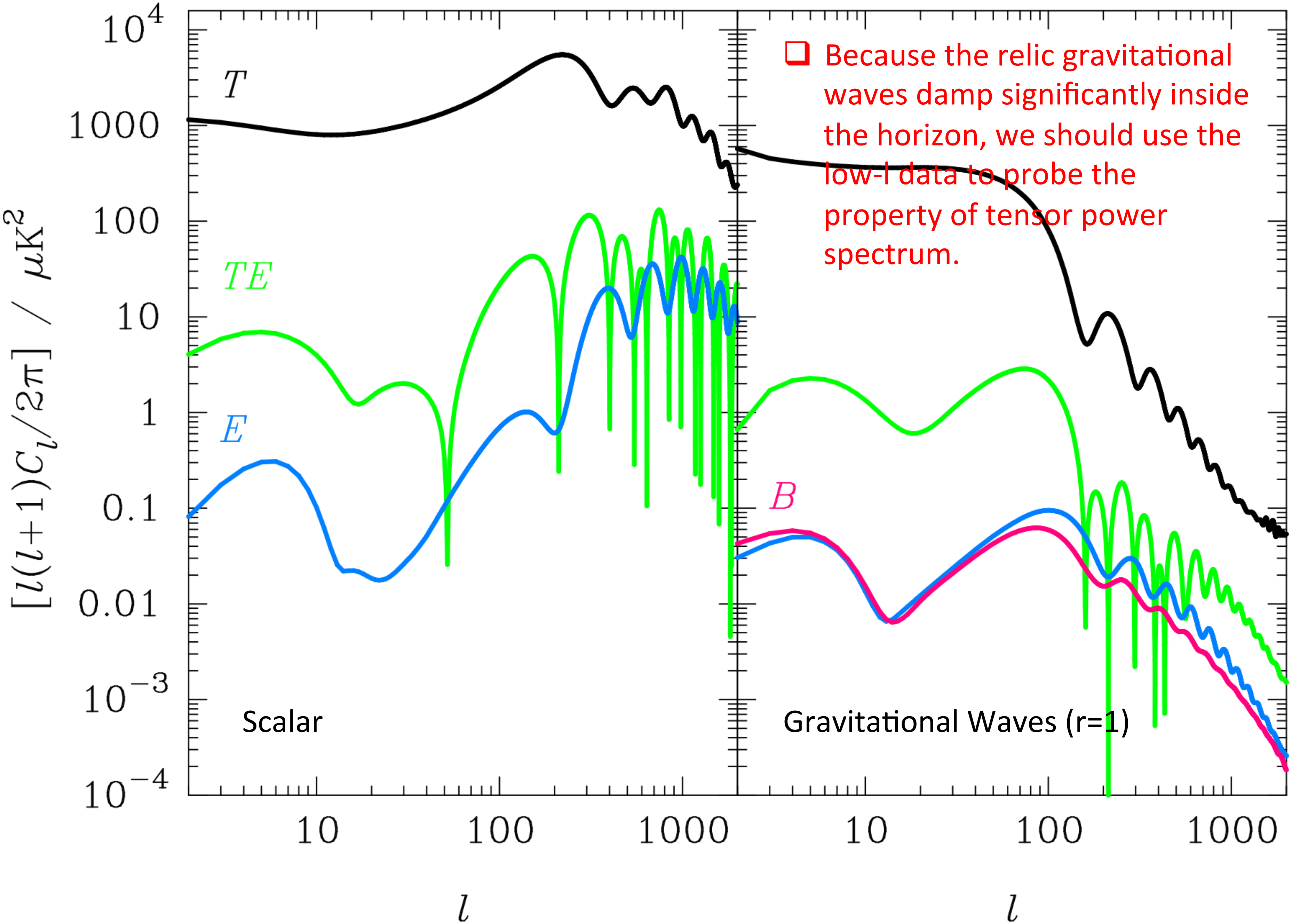
ΛCDM+nrun+nrunrun+r	B2+P13+WP	
parameters	Best fit	68% limits
$\Omega_b h^2$	0.02221	0.02217 ± 0.00035
$\Omega_c h^2$	0.1203	0.1184 ± 0.0023
$100\theta_{\rm MC}$	1.04145	$1.04142^{+0.00064}_{-0.00063}$
τ	0.0983	$0.1054^{+0.0142}_{-0.0168}$
$\ln(10^{10} A_s)$	3.047	$3.063^{+0.066}_{-0.050}$
n_s	1.1656	$1.1344^{+0.0612}_{-0.0608}$
$dn_s/d\ln k$	-0.139	$-0.108^{+0.049}_{-0.048}$
$d^2 n_s/d\ln k^2$	0.045	$0.033^{+0.018}_{-0.019}$
$r_{0.002}$	0.22	$0.24^{+0.05}_{-0.07}$

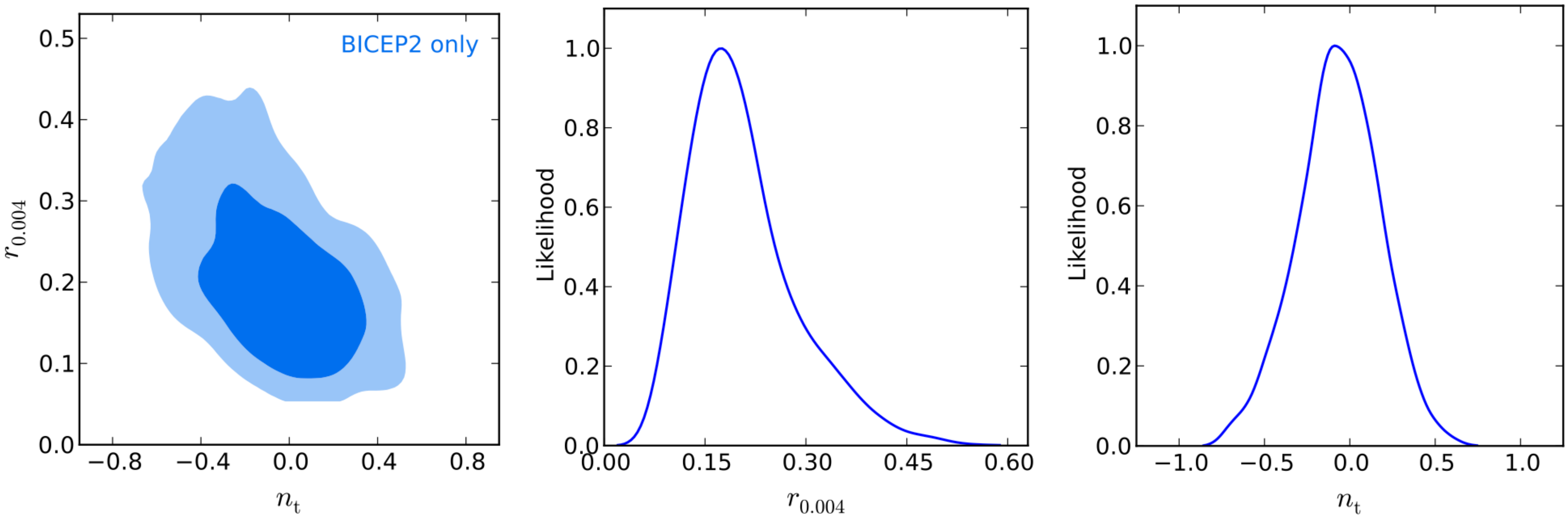
$$\Delta\chi^2 = -3.12$$

C. Cheng, QGH, W. Zhao, arXiv:1404.3467

The tilt of relic gravitational waves power spectrum

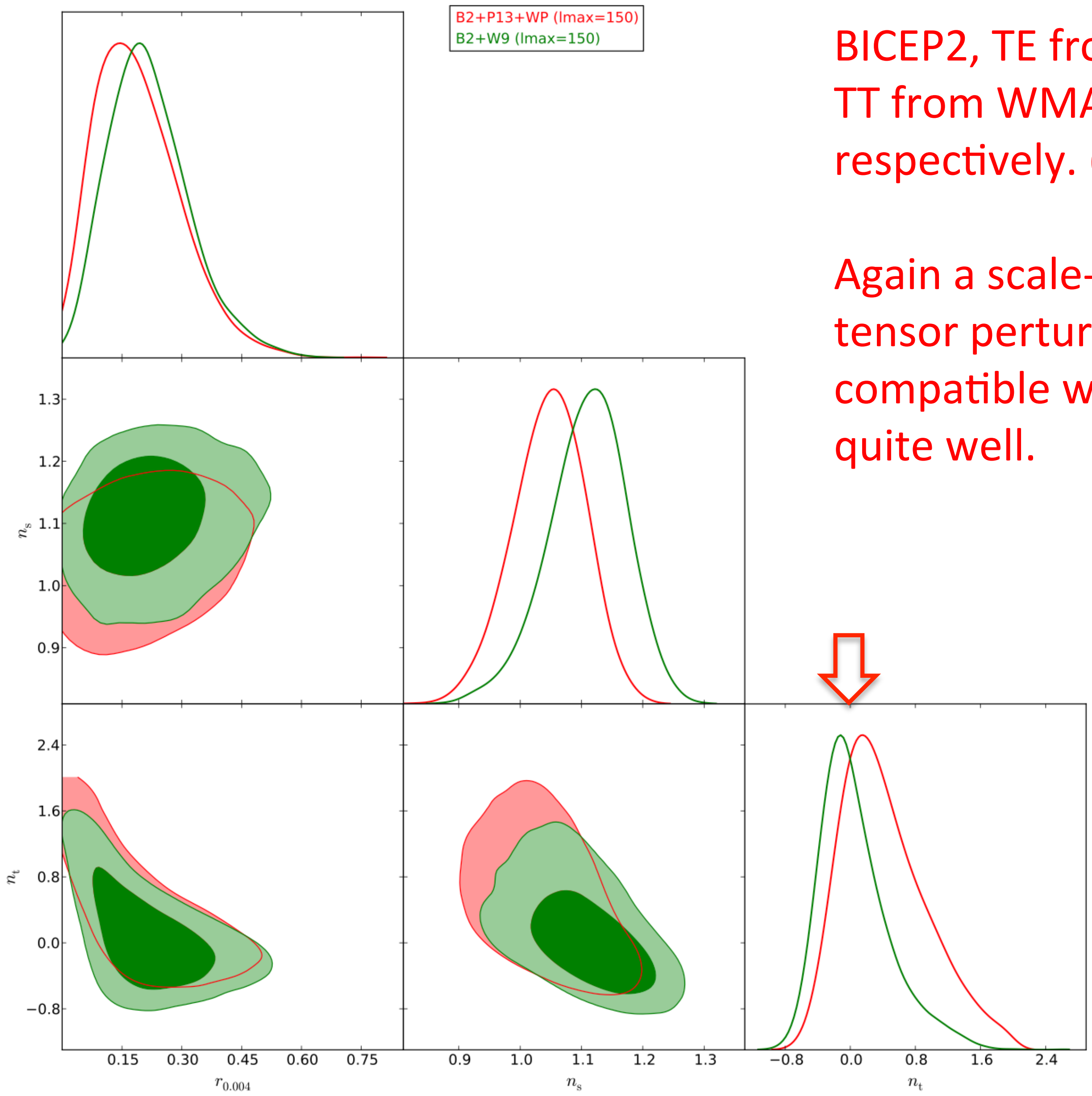
- Because the relic gravitational waves damp significantly inside the horizon, we should use the low-l data to probe the property of tensor power spectrum.





$$P_t = A_t \left(\frac{k}{k_p} \right)^{n_t} \qquad r = 0.21^{+0.04}_{-0.10} \qquad n_t = -0.06^{+0.25}_{-0.23}$$

C. Cheng and QGH, arXiv:1403.5463



BICEP2, TE from WMAP, and TT from WMAP and Planck respectively. (l_max=150)

Again a scale-invariant tensor perturbation is compatible with the data quite well.

C. Cheng, QGH, arXiv:1405.0349

Summary

- **A red-tilt tensor power spectrum** is compatible with the data, and the simplest version of inflation is consistent with the data.

- **A blue-tilted scalar power spectrum** is preferred on the large scales (e.g. l<150).

- The inflation model with inverse power-law potential can fit the data quite well.

- The space-time non-commutativity can help chaotic inflation and power-law inflation to fit the data.

- A negative running of spectral index is favored at around 3 sigma level.

- Furthermore, a positive running of running is preferred at around 1.7 sigma level.

Thank You!