Inflation after Planck...
(... and BICEP2!)

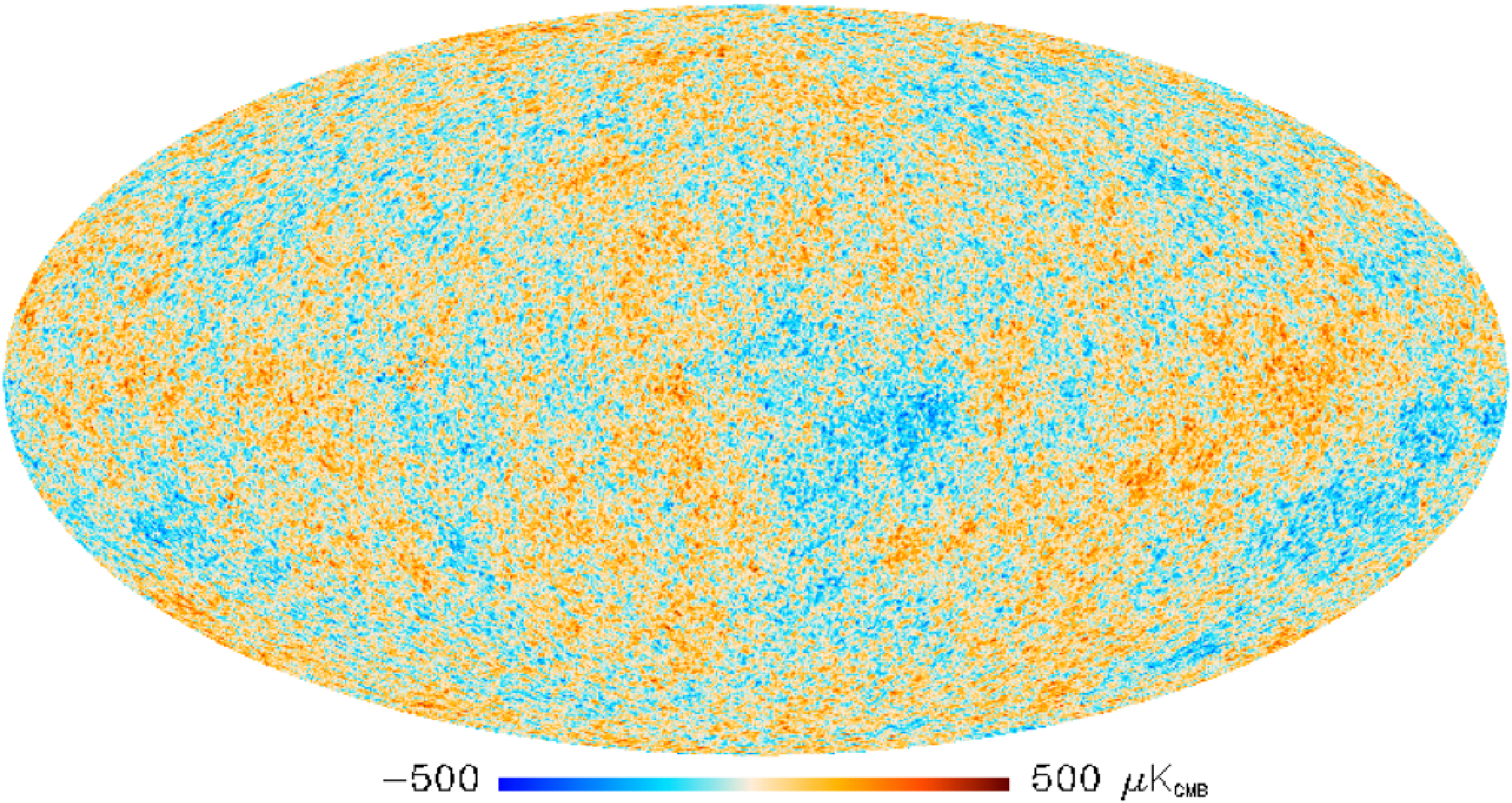
Jan Hamann

CERN

Rencontres de Moriond 2014
EW interactions and
Unified Theories

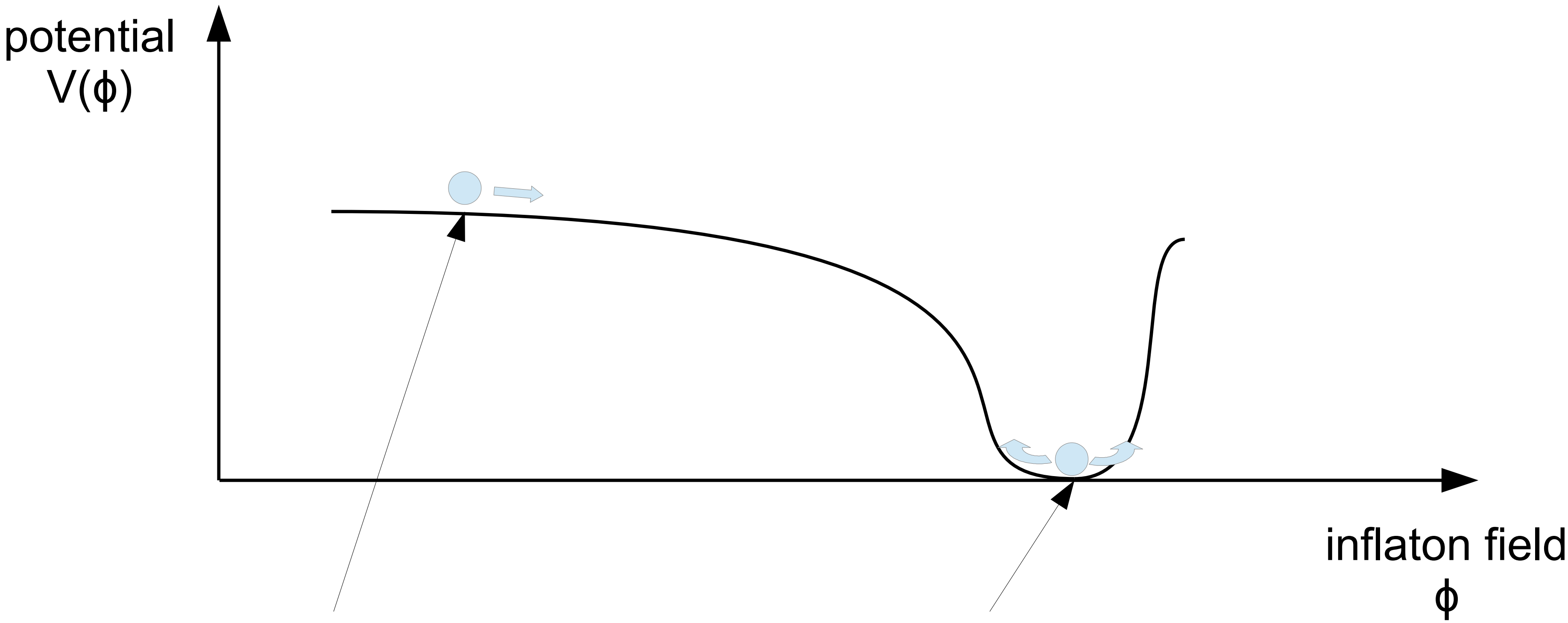
La Thuile, 16th-22th Mar 2014

Planck's CMB temperature map



Where do the anisotropies come from?

Inflation



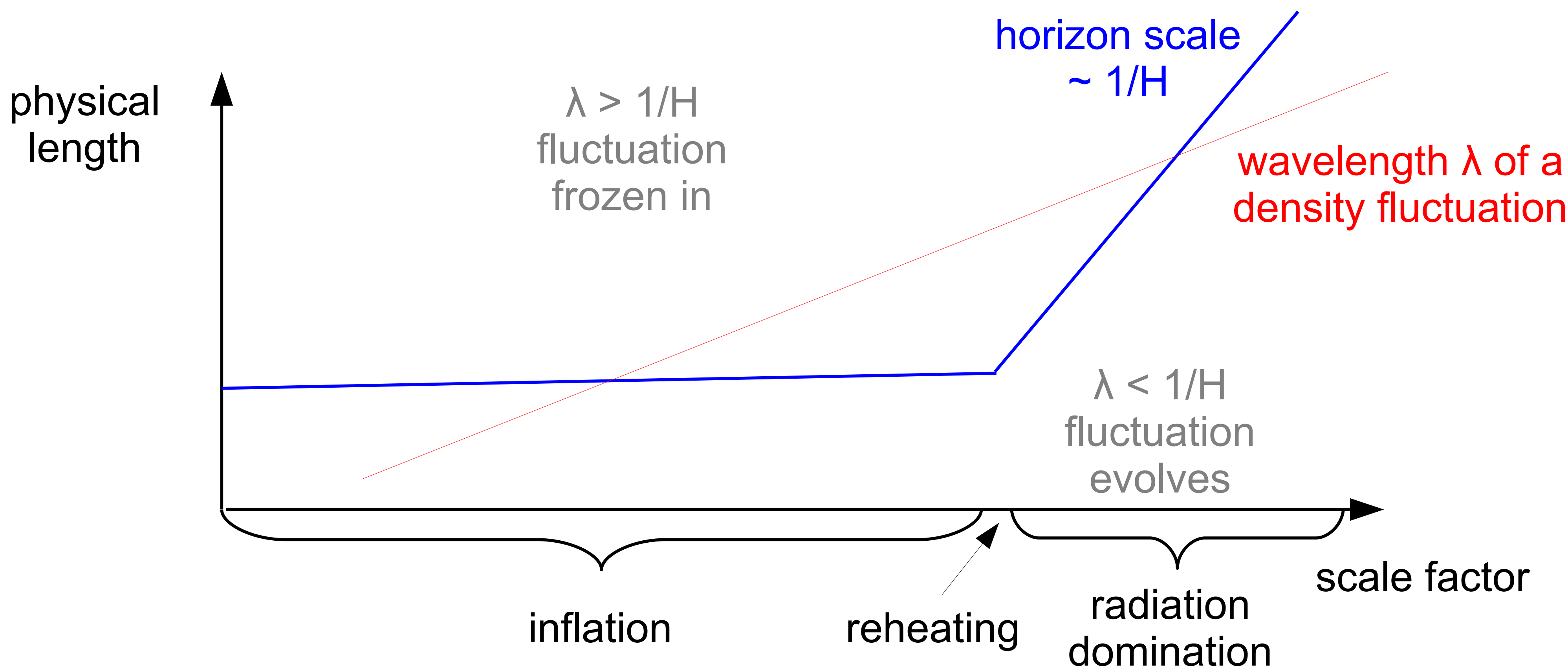
Potential energy domination
("slow-roll" inflation)

- Attractor solution
- Scale factor grows exponentially with time
- Hubble parameter close to constant
- Space is flattened

Reheating

- Potential energy is converted to standard model particles

The origin of the primordial perturbations: inflation



Quantum fluctuations of ϕ are stretched beyond the horizon and freeze in

Inflationary perturbations

Scalar (curvature) perturbations

$$\mathcal{P}_{\mathcal{R}}(k) \propto \left.\frac{V}{\epsilon}\right|_{k=aH} \approx A_{\rm s}\left(\frac{k}{k_*}\right)^{n_{\rm s}-1+\ldots}$$

$$\epsilon \propto \left(\frac{V'}{V}\right)^2$$

scalar/tensor amplitude

scalar/tensor spectral index

Tensor perturbations (gravitational waves)

$$\mathcal{P}_t(k) \propto V|_{k=aH} \approx A_{\rm t}\left(\frac{k}{k_*}\right)^{n_{\rm t}+\ldots}$$

Tensor-to-Scalar ratio

$$r \equiv \left.\frac{\mathcal{P}_{\rm t}}{\mathcal{P}_{\mathcal{R}}}\right|_{k=0.002\ {\rm Mpc}^{-1}}$$

Inflationary perturbations

Scalar (curvature) perturbations

$$\mathcal{P}_{\mathcal{R}}(k) \propto \left.\frac{V}{\epsilon}\right|_{k=aH} \approx A_{\mathrm{s}} \left(\frac{k}{k_*}\right)^{n_{\mathrm{s}}-1+\ldots}$$

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Also, generically:

- no significant non-trivial higher-order correlations (*non-Gaussianities*)
- if single field: *adiabatic* perturbations (i.e., no isocurvature modes)

Predictions of the simplest models

single-field canonical slow-roll inflation

Adiabatic initial conditions

Nearly Gaussian initial fluctuations

$f_{NL} < 1$

Background of gravitational waves (tensor perturbations)

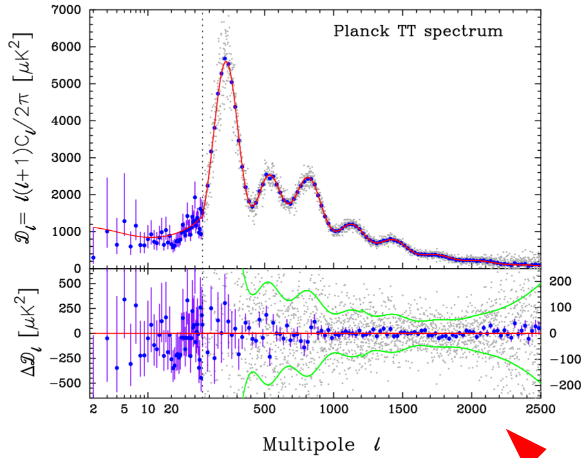
Almost (but not exactly) scale-invariant curvature perturbations

Spatial flatness

$\Omega_K \sim 10^{-5}$

Probing the predictions of inflation

CMB temperature power spectrum
(+ E-polarisation, large scale structure, ...)



Adiabatic initial conditions

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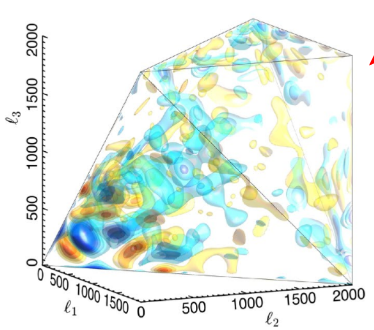
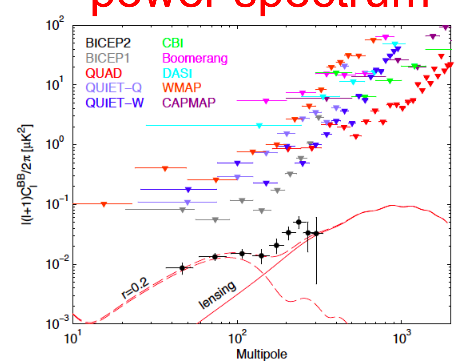
Almost (but not exactly)
scale-invariant curvature
perturbations

CMB bispectrum

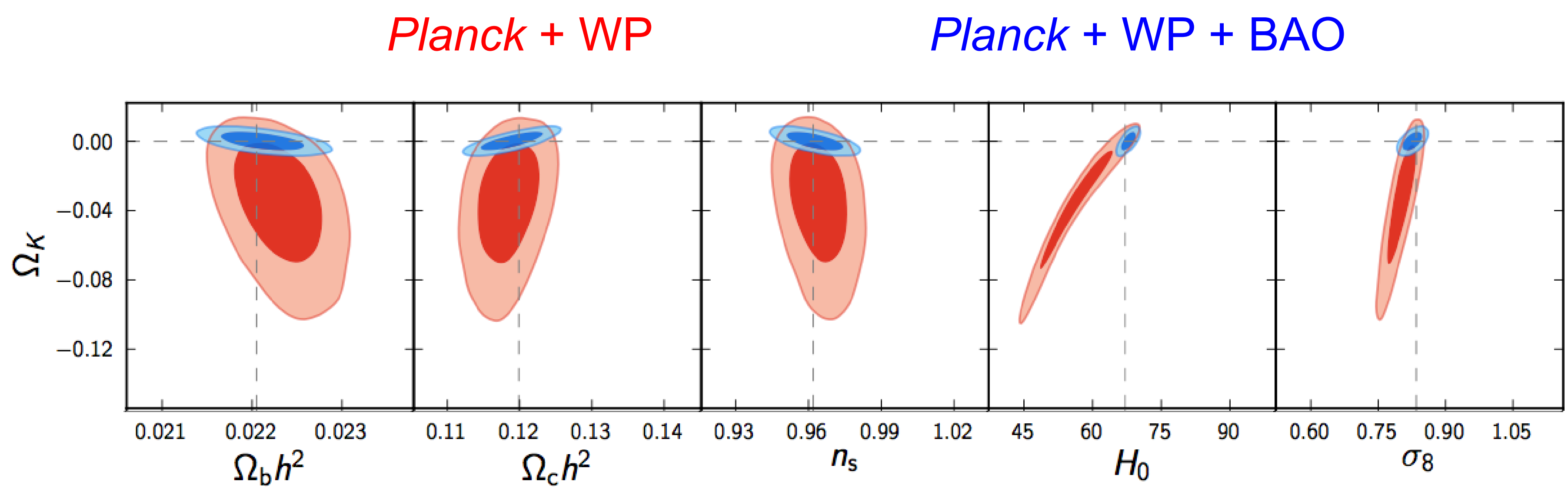


Background of
gravitational waves
(tensor perturbations)

CMB B-polarisation
power spectrum



Spatial curvature constraints



	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	−0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	−0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$

No evidence for non-zero spatial curvature

[Planck 2013]

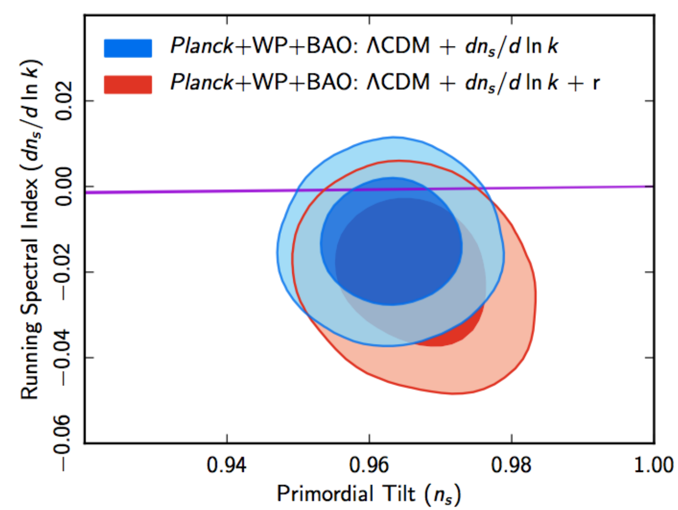
Constraints on scalar power spectrum

- Scale dependence clearly required

Planck + WP data

	HZ	ΛCDM
$10^5\Omega_b h^2$	2296 ± 24	2205 ± 28
$10^4\Omega_c h^2$	1088 ± 13	1199 ± 27
$100\,\theta_{MC}$	1.04292 ± 0.00054	1.04131 ± 0.00063
τ	$0.125^{+0.016}_{-0.014}$	$0.089^{+0.012}_{-0.014}$
$\ln(10^{10}A_s)$	$3.133^{+0.032}_{-0.028}$	$3.089^{+0.024}_{-0.027}$
n_s	—	0.9603 ± 0.0073
N_{eff}	—	—
Y_P	—	—
$-2\Delta\ln(\mathcal{L}_{max})$	27.9	0

- No hints for anything more complicated than power-law



Power-law scalar spectrum fits Planck data very well

[Planck 2013]

Adiabaticity: constraints on isocurvature perturbations

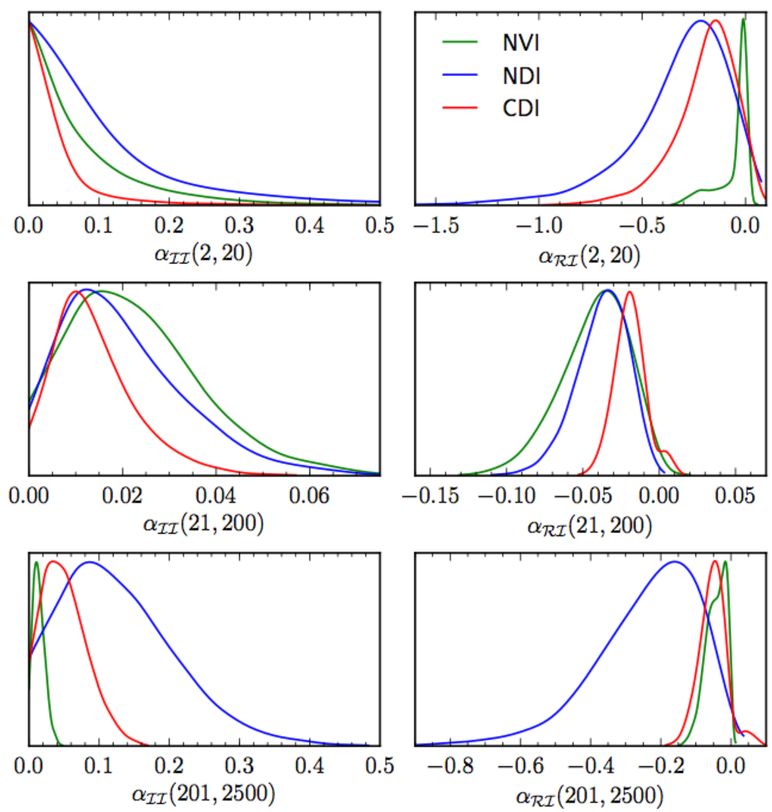
Isocurvature fraction at ...

Types of isocurvature

Large scales

Intermediate scales

Small scales



Neutrino velocity

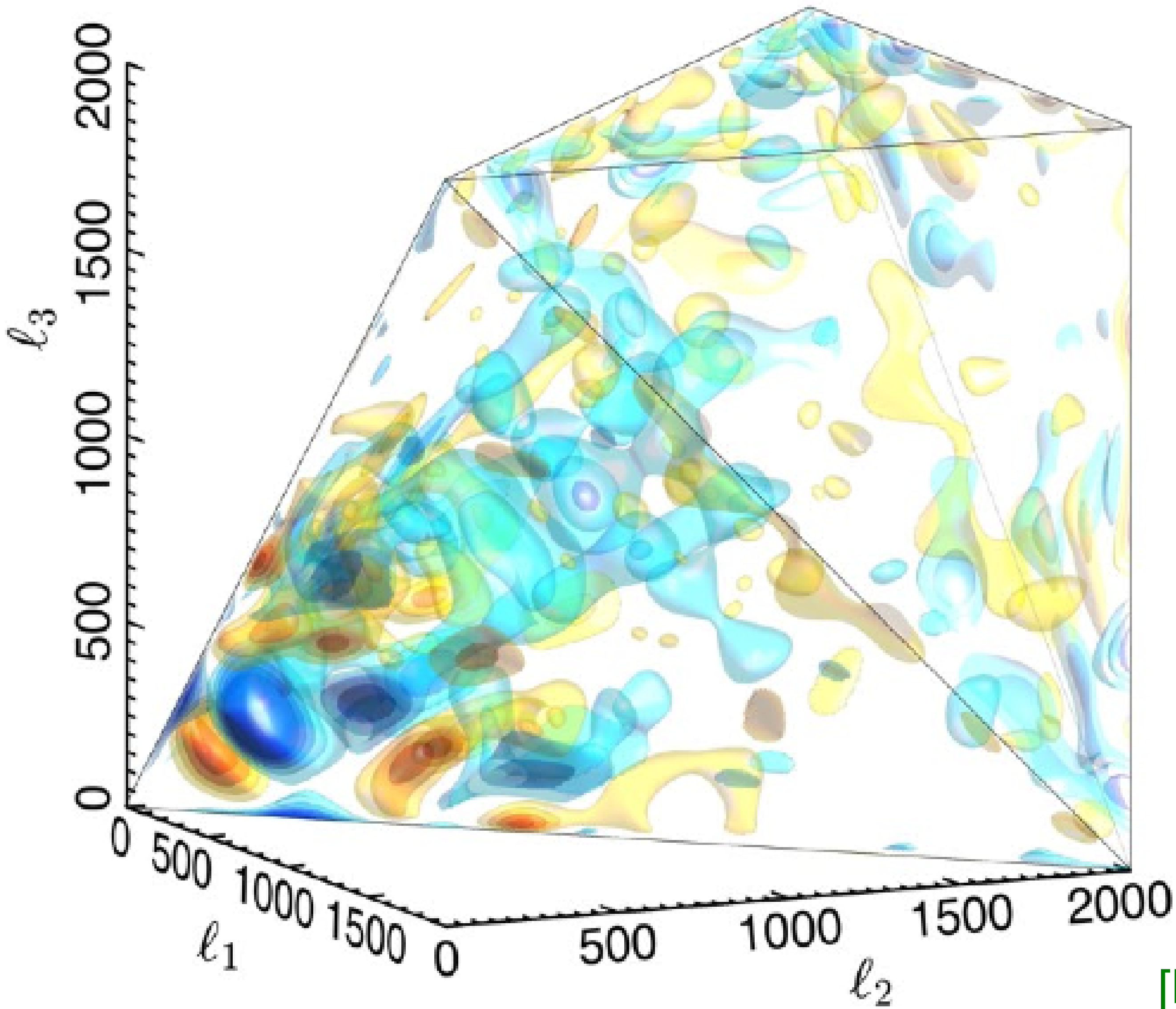
Neutrino density

CDM density

Planck data are perfectly compatible with adiabatic initial conditions

[Planck 2013]

Non-Gaussianity: CMB angular bispectrum



[Planck 2013]

Non-Gaussianity

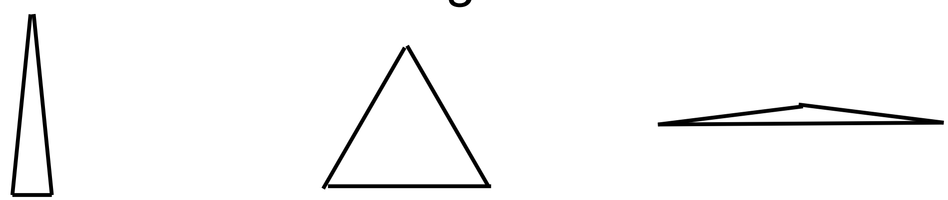
$$\underbrace{\langle \Phi(\vec{k}_1)\Phi(\vec{k}_2)\Phi(\vec{k}_3)\rangle}_{\text{Three-point correlation}} = (2\pi)^3\,\delta^{(3)}(\vec{k}_1+\vec{k}_2+\vec{k}_3)\;\underbrace{f_{\rm NL}\;F(k_1,k_2,k_3)}_{\text{Bispectrum}}$$

Three-point correlation

enforces triangular configurations

Bispectrum

Three limiting cases

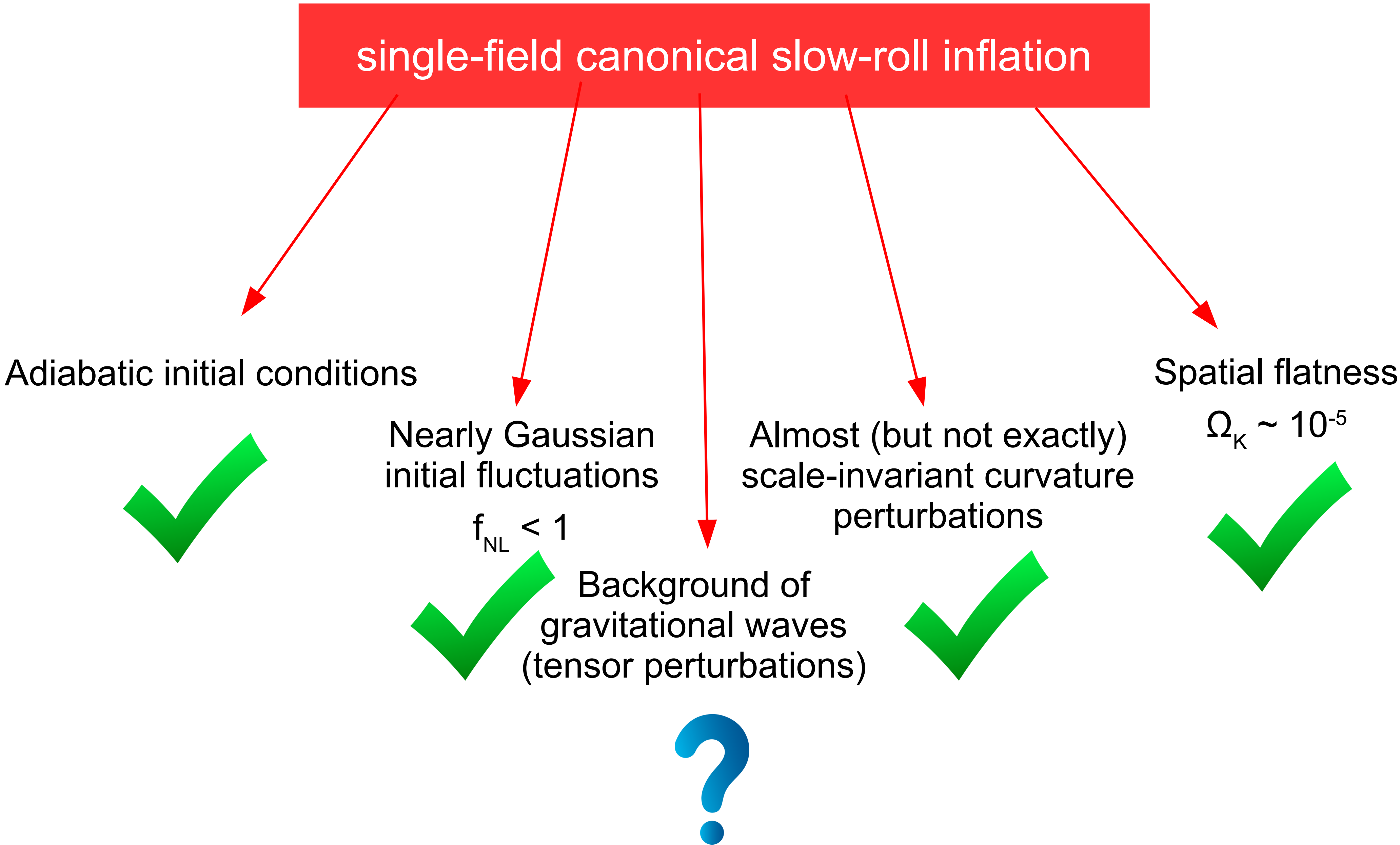


	$f_{\rm NL}$	
Local	Equilateral	Orthogonal
2.7 ± 5.8	−42 ± 75	−25 ± 39

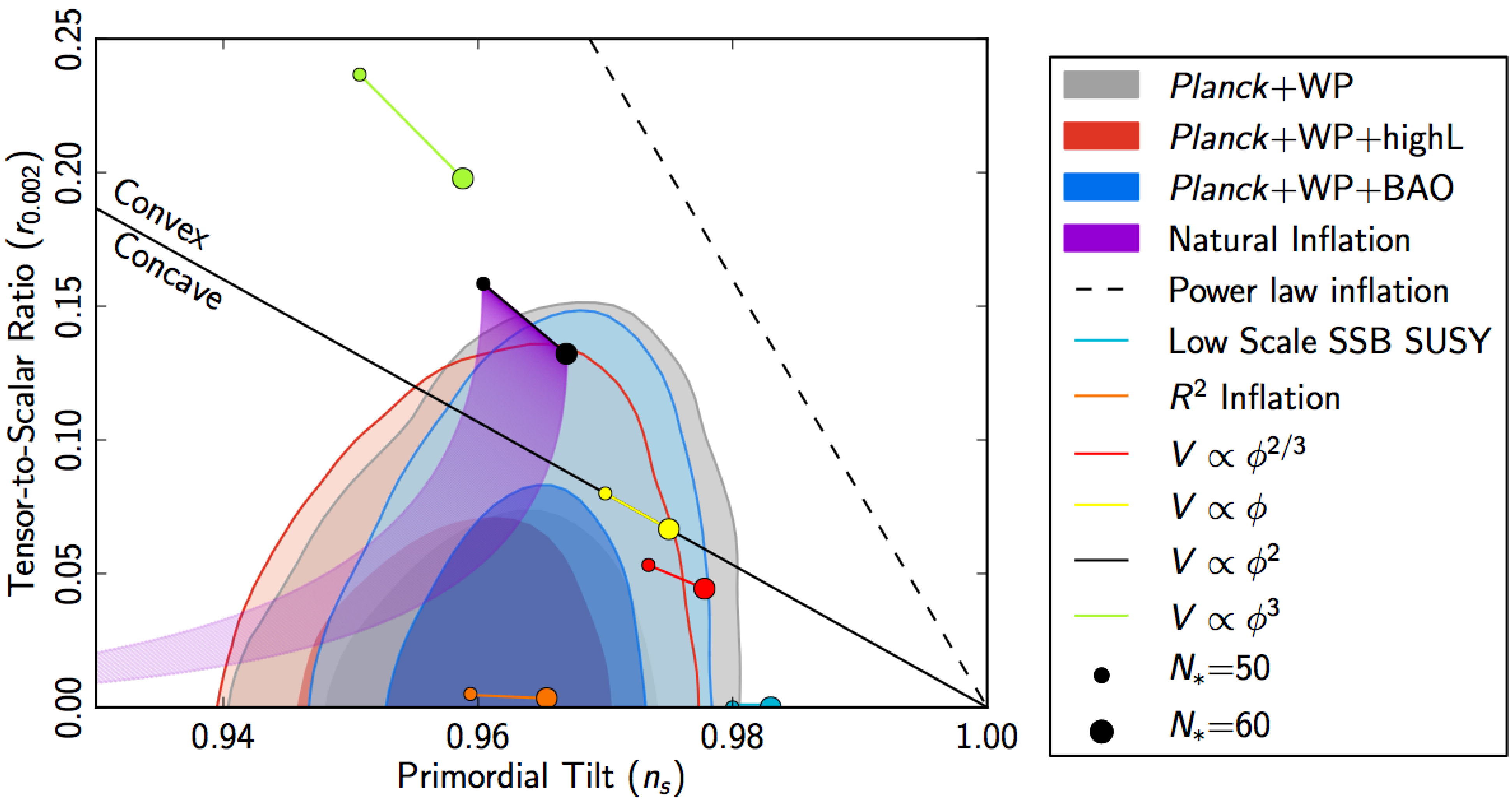
No evidence for non-Gaussianity

[Planck 2013]

Status of inflation last week

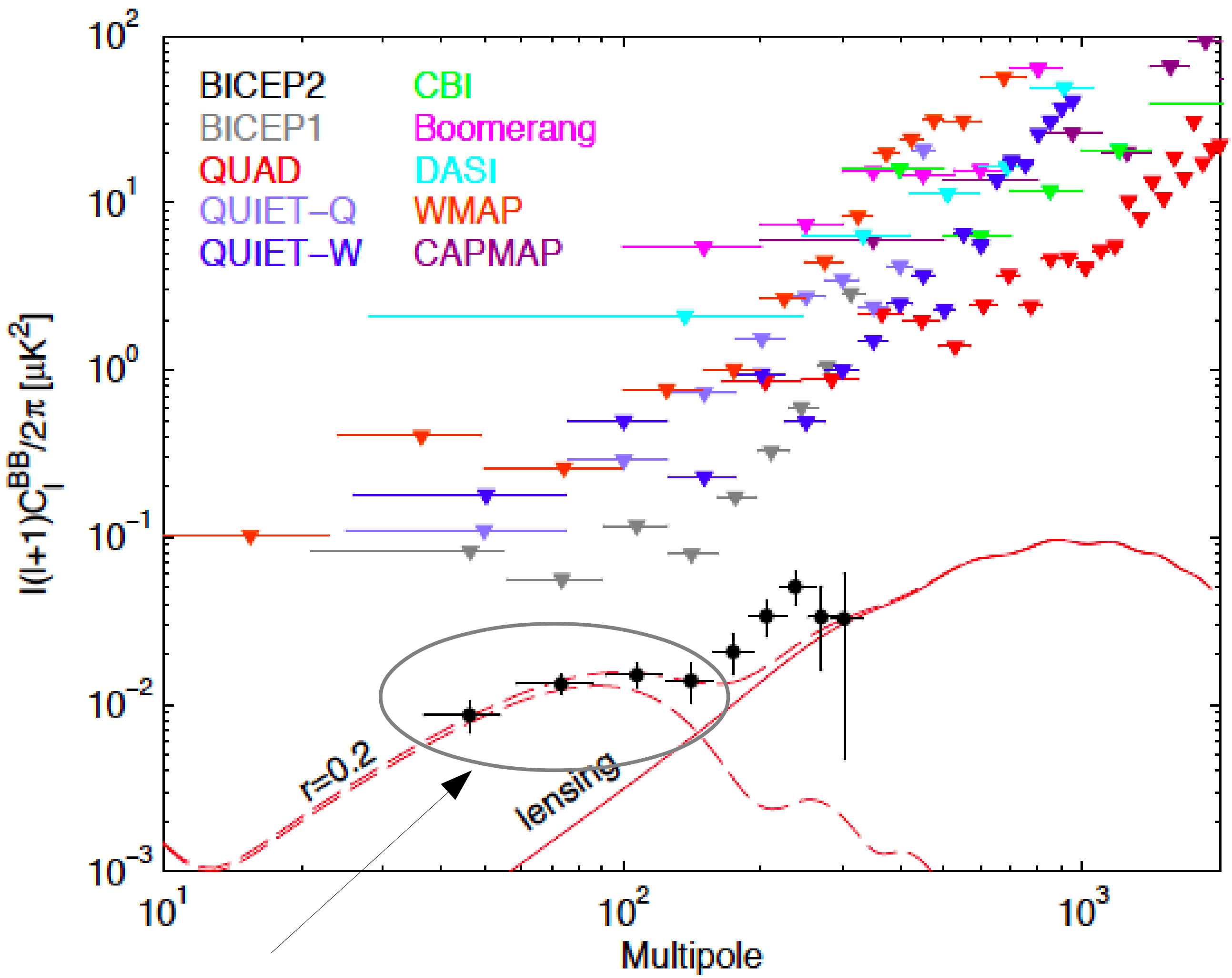


Inflation model constraints (last week)



[Planck 2013]

BB angular power spectrum measured by BICEP2



Signal due to tensor modes (?)

[BICEP2 2014]

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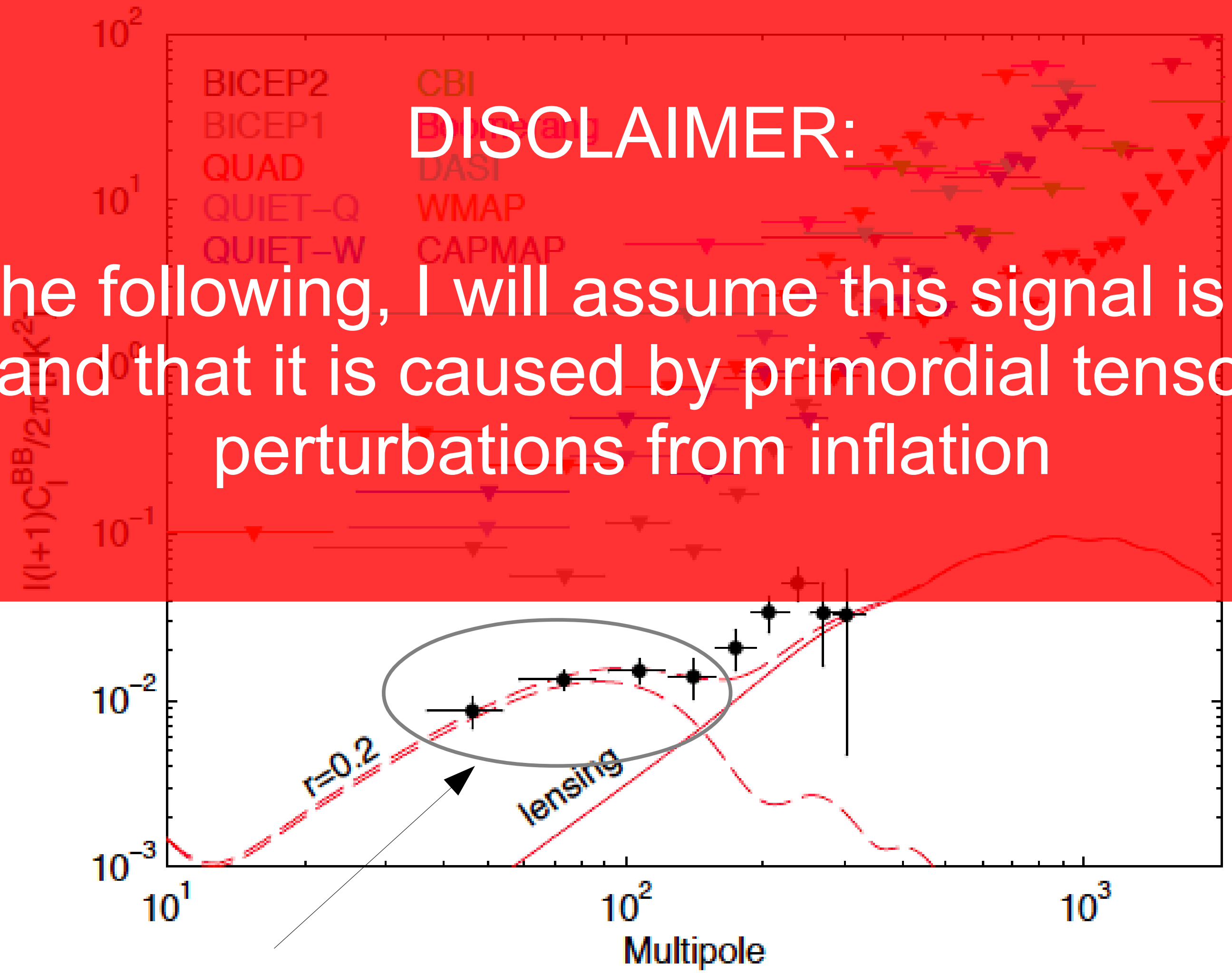


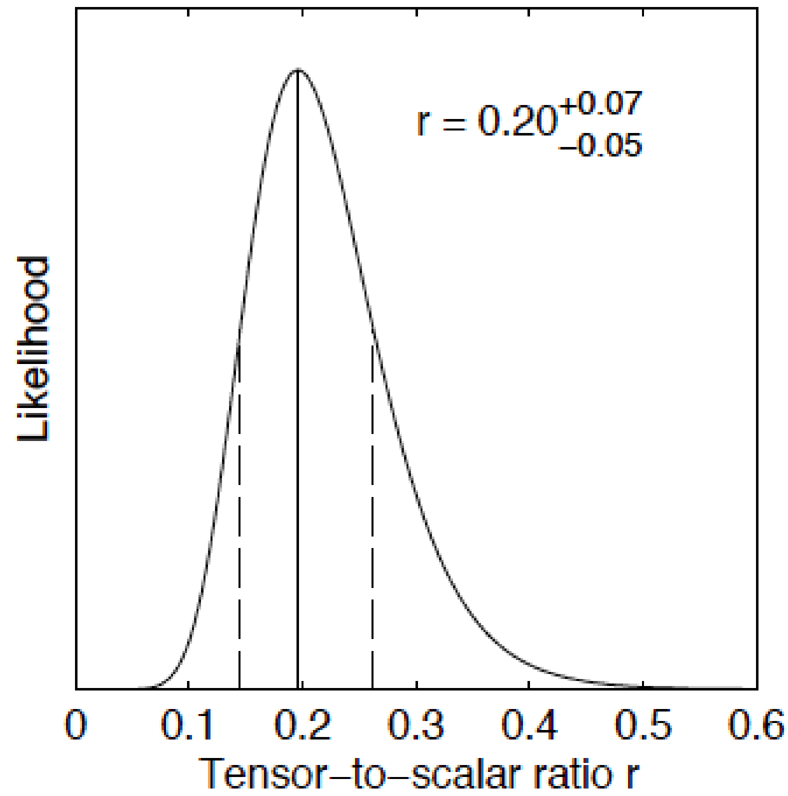
DISCLAIMER:

In the following, I will assume this signal is real and that it is caused by primordial tensor perturbations from inflation

Signal due to tensor modes (?)

[BICEP2 2014]

Implications of BICEP2 results



[BICEP2 2014]

Energy scale of inflation:

$$V_{\rm inf}^{1/4} \approx 2.2 \cdot 10^{16} \left(\frac{r}{0.2}\right)^{1/4} \ \mathrm{GeV}$$

(This could in principle have been as low as O(10) MeV, we are incredibly lucky!)

Implications of BICEP2 results

- Lyth bound:
  For inflation to last sufficiently long, ϕ has to take on super-Planckian values

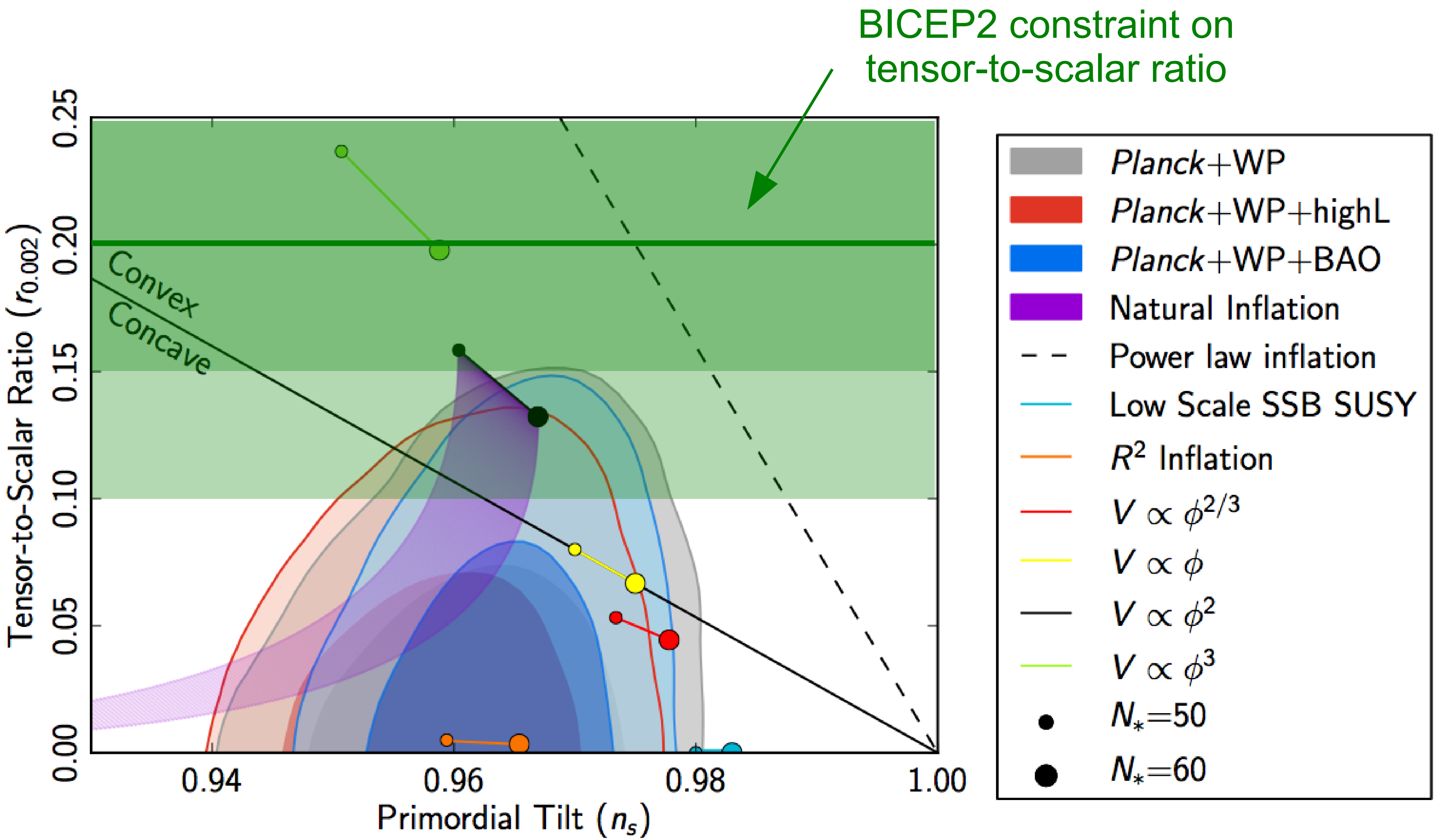
$$\Delta\phi \gtrsim m_{\mathrm{Pl}}\,(r/0.01)^{1/2}$$

[Lyth 1997]

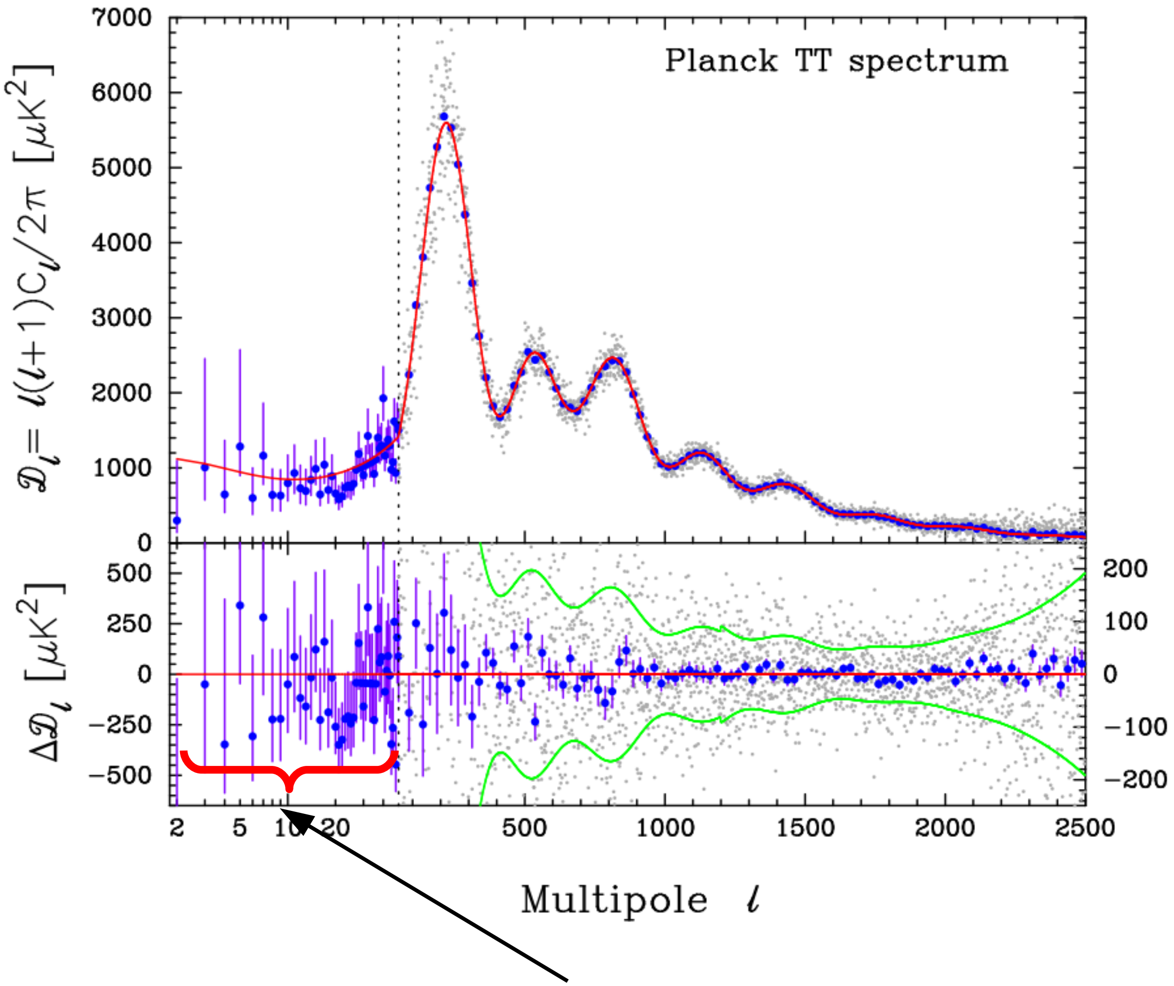
- In effective field theory, Planck-mass suppressed higher order operators would mess up things...

  → Challenge for inflation model-builders

Inflation model constraints (post BICEP2)



Tension with temperature data?



Even in ΛCDM with r=0, there is a lack of power at the largest scales
Adding a tensor contribution would exacerbate the problem

Possible solutions:

- Suppress primordial scalar power at large scales
- Suppress late integrated Sachs-Wolfe effect (DE)
- Anticorrelated isocurvature perturbations
- Anticorrelated tensor perturbations

[Contaldi, Peloso, Sorbo 2014]

Conclusions

- Predictions of simplest inflationary models pass all challenges thrown at them by Planck data
- BICEP2 measurement of the CMB's BB angular power spectrum (if confirmed) probably most spectacular result in cosmology in last 15 years
  - Can be interpreted as gravitational wave signal from inflation
  - Energy scale of inflation ~ GUT scale
  - Inflation was large-field
  - Quite possibly signs of further new physics
- These measurements do not prove inflation happened, but certainly make it look even more attractive than before!