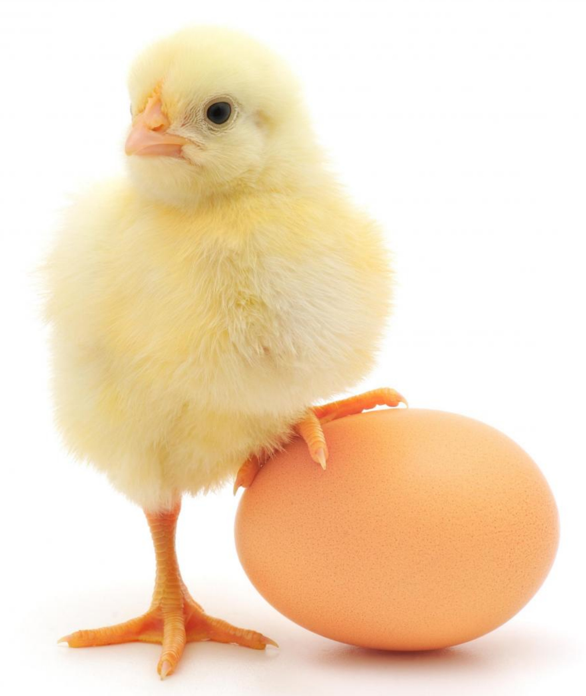
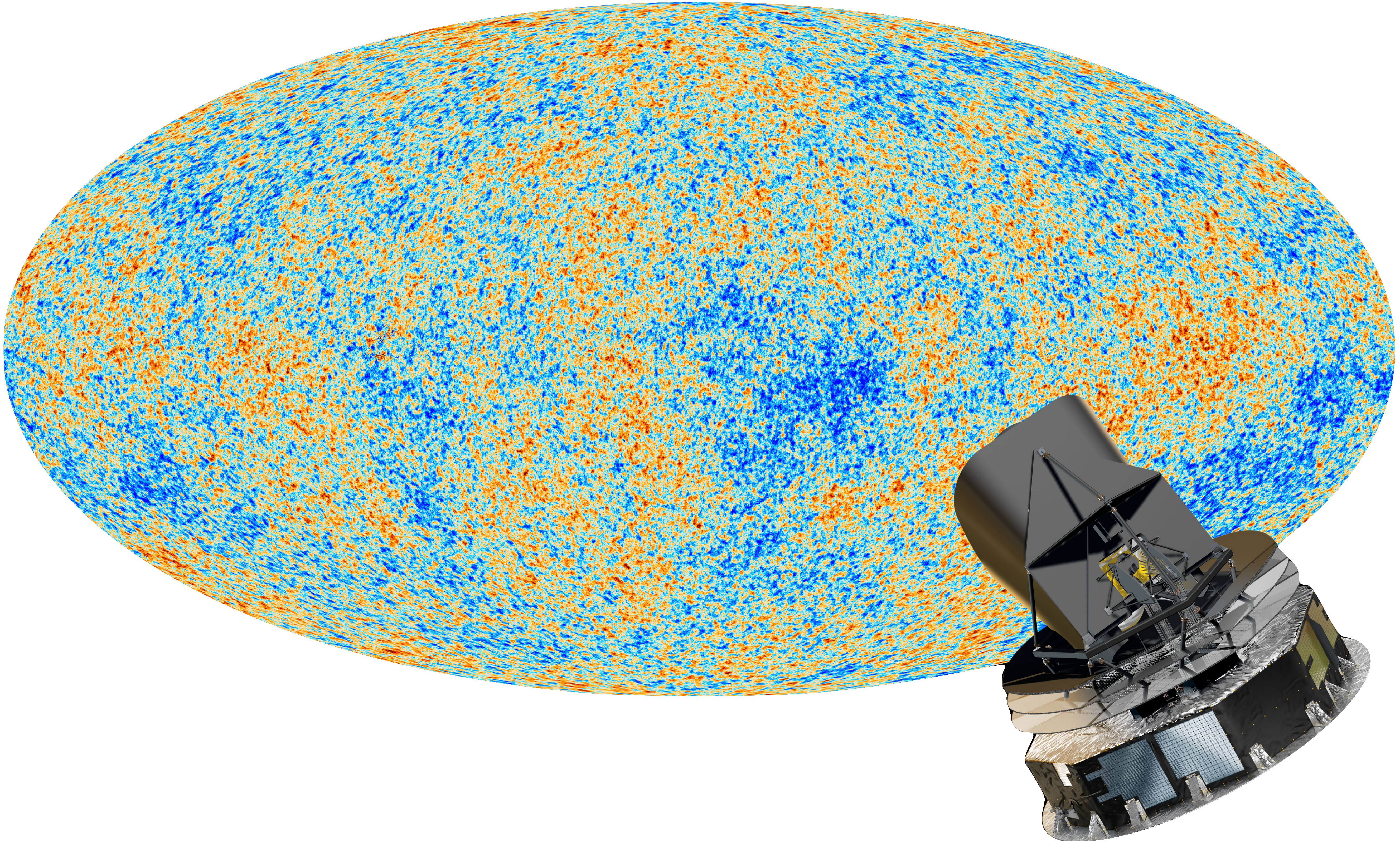
Touching the beginning



Filippo Vernizzi
IPhT, CEA/Saclay

RPP, January 16, 2015

Planck (2013)



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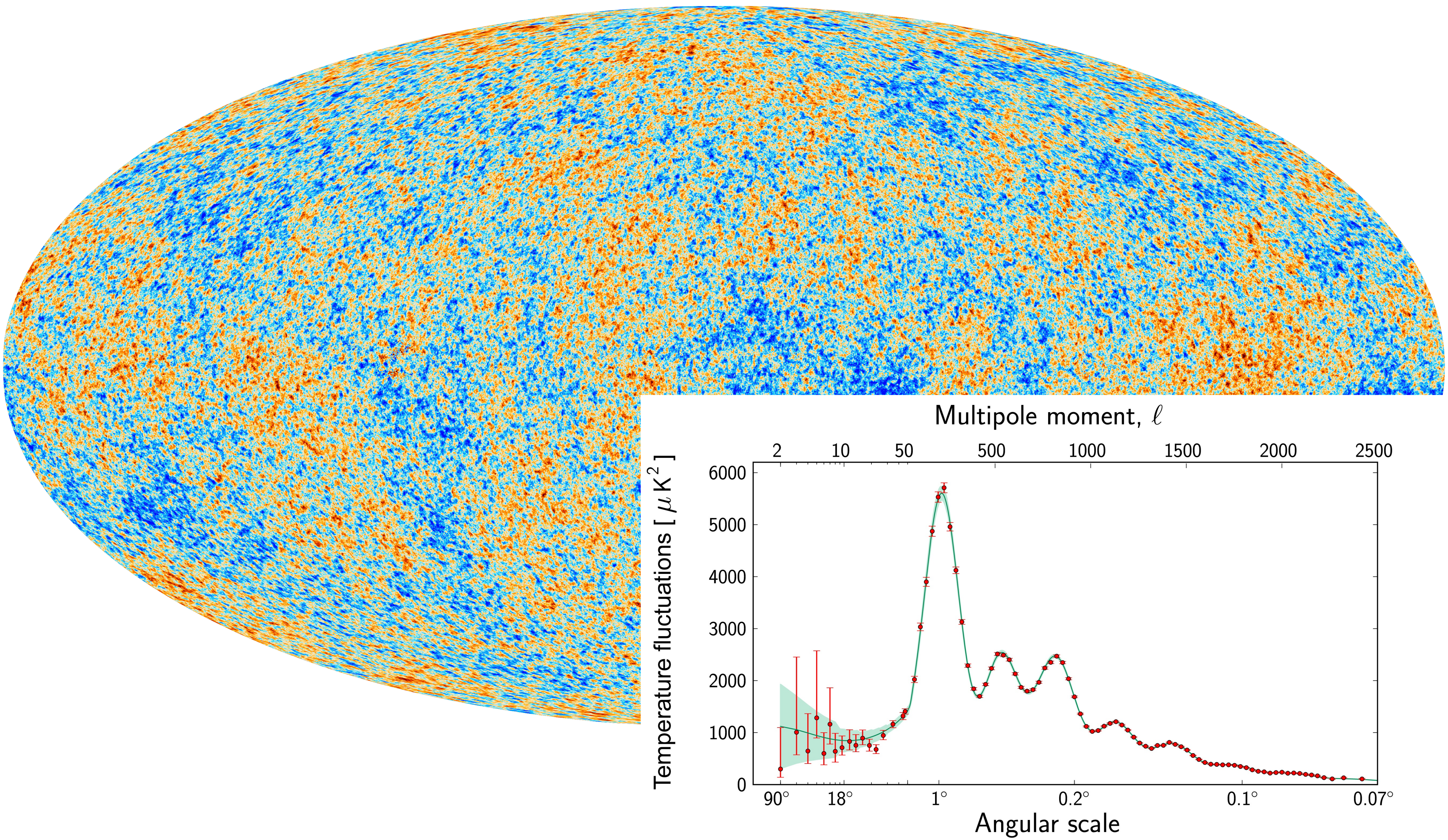
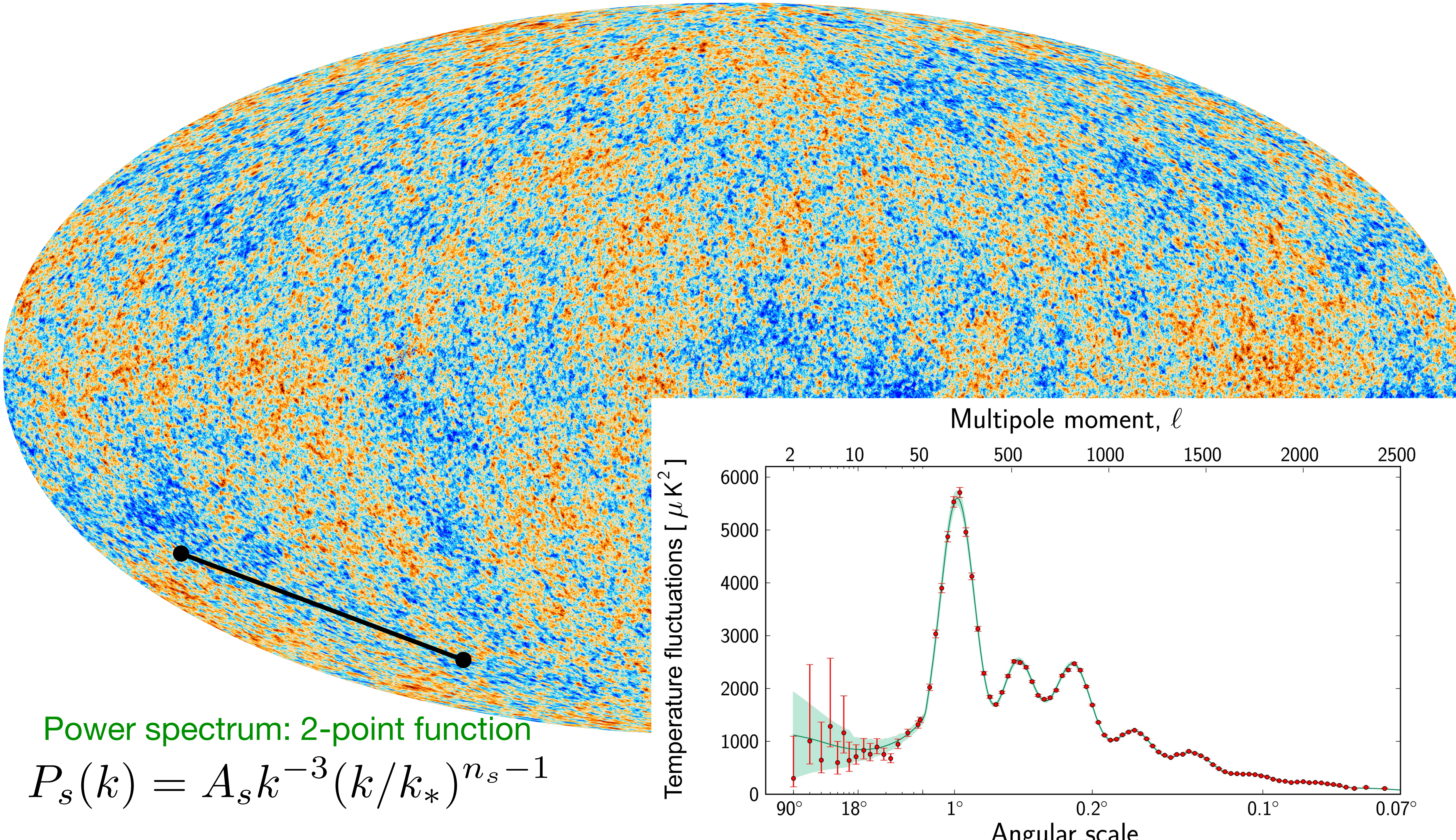


Only few parameters: $\Omega_{\rm b}\,,\quad \Omega_{\rm CDM}\,,\quad H_0\,,\quad \tau\,,\quad A_s\,,\quad n_s$

Planck (2013)



Power spectrum: 2-point function

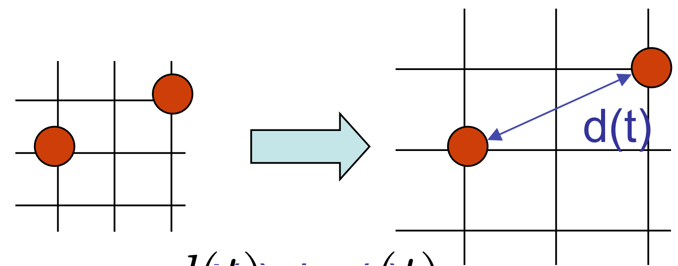
$$P_s(k) = A_s k^{-3} (k/k_*)^{n_s - 1}$$

$$n_s - 1 \simeq -0.04$$

Only few parameters: Ω_{b} , Ω_{CDM} , H_0 , τ , A_s, n_s

(Slow-roll) Inflation

- (Flat) FRW metric: $$ds^2 = -dt^2 + a^2(t)d\vec{x}^2$$ $$H \equiv \frac{\dot{a}}{a}$$ Hubble rate (rate of expansion)



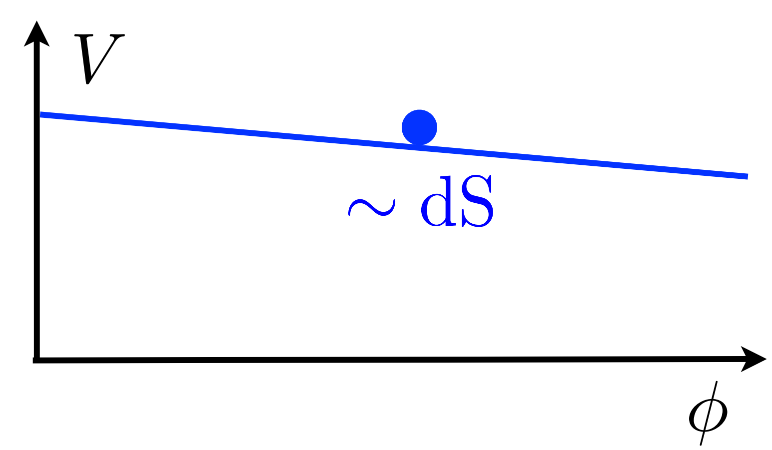
$$d(t) \propto a(t)$$

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

Slow-roll inflation, almost CC (slowly varying clock):

$$H \simeq \sqrt{\frac{V}{3m_P^2}}$$

$$\epsilon \equiv -\frac{\dot{H}}{H^2} \ll 1$$



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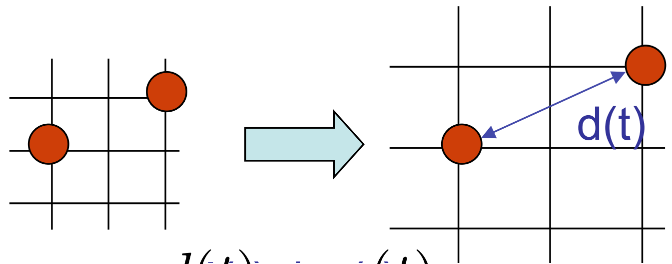

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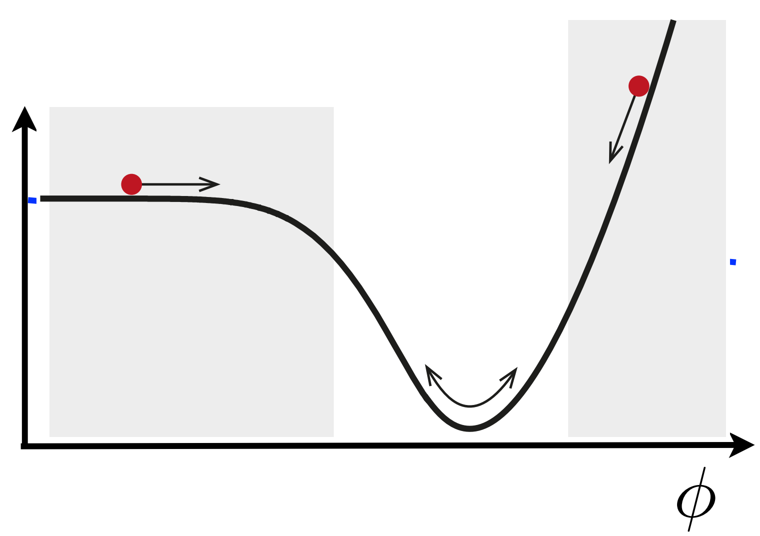

Scalar fluctuations

Each Fourier mode behaves as a quantum harmonic oscillator with time dependent spring "constant"

$$S = \int d^4x\, \epsilon\, a^3\, M_{\rm Pl}^2 \left[\dot{\zeta}^2 - \frac{1}{a^2}(\partial_i\zeta)^2\right]$$

$$\phi = \phi(t)$$

$$g_{ij} = a^2(t) e^{2\zeta}\delta_{ij}$$

$$\omega = \frac{k}{a} \simeq k e^{-Ht}$$

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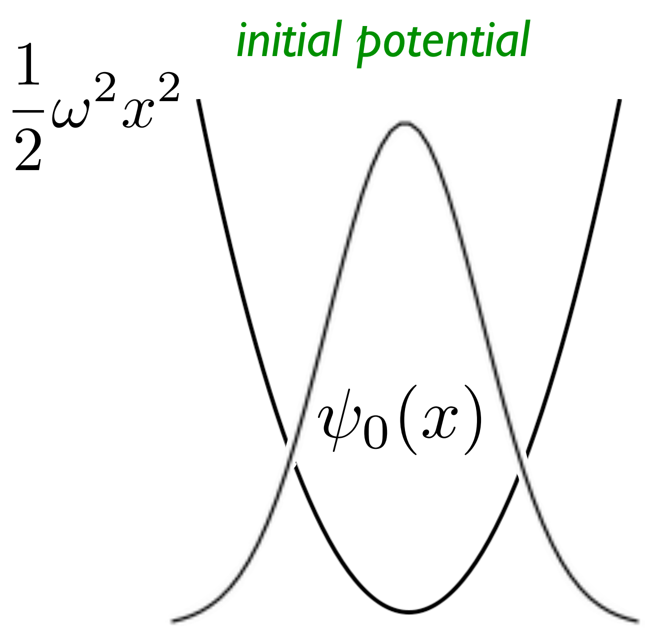

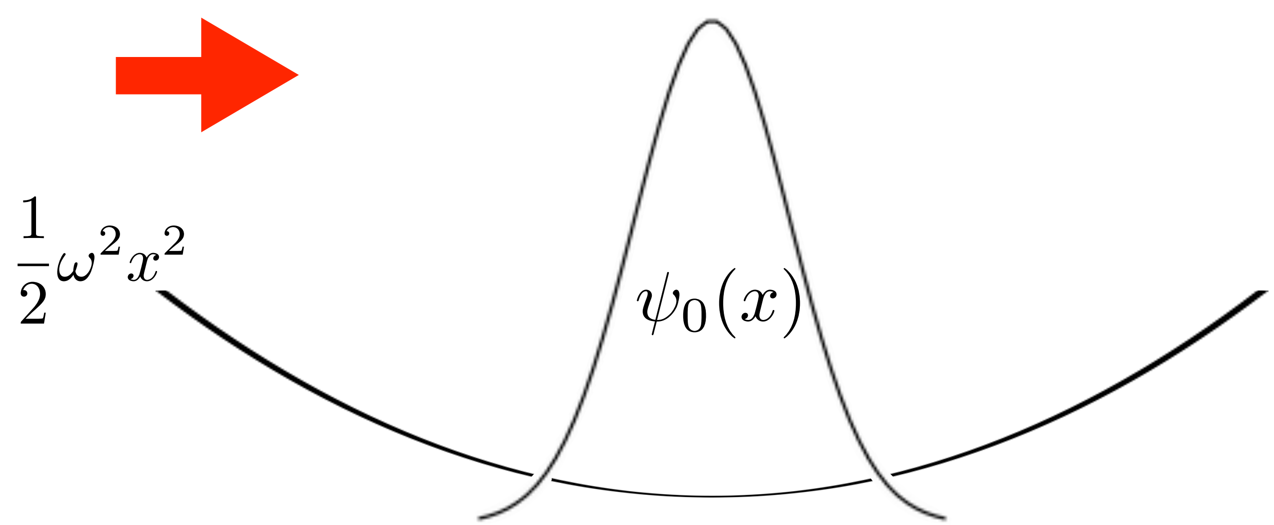

- Inside Hubble radius: vacuum I.C.
- Outside Hubble radius: fluctuations freeze-in

$$\langle (\zeta_k)^2 \rangle = \frac{\hbar}{2k^3} \, \frac{1}{\epsilon} \frac{H^2}{M_{\rm Pl}^2} \bigg|_{k=aH}$$

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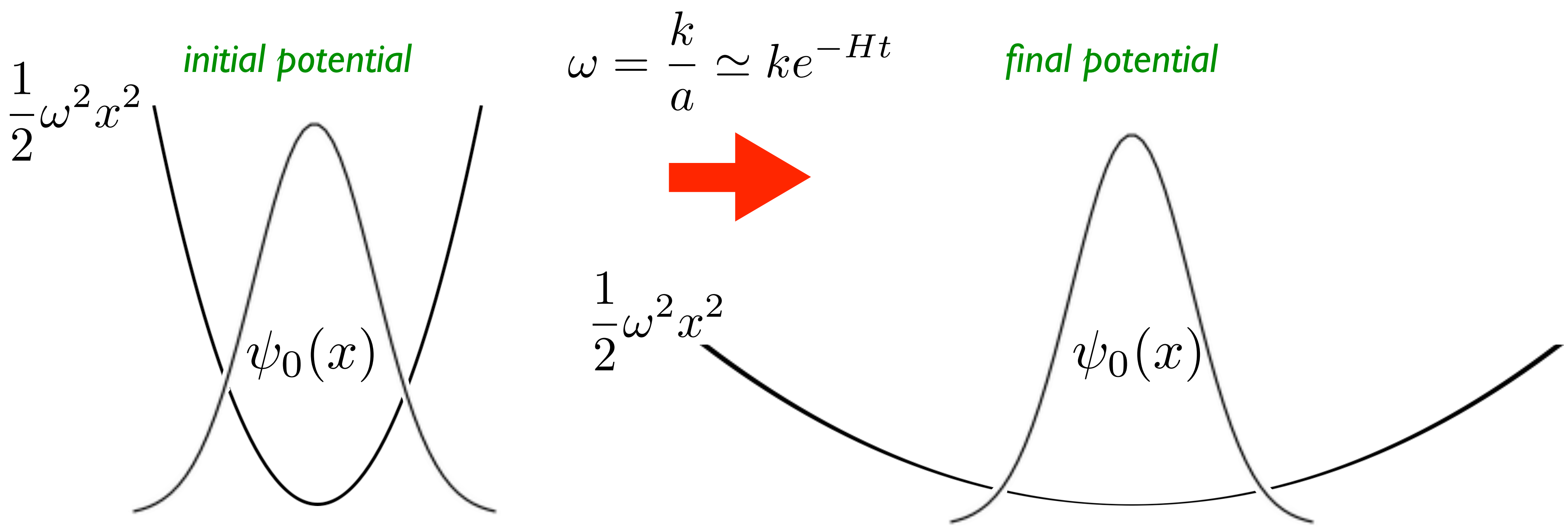
$$g_{ij} = a^2(t)(\delta_{ij} + h_{ij}) \; , \qquad h_{ii} = 0 = \partial_j h_i^j$$



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$$\langle (h_k)^2 \rangle = \frac{8\hbar}{k^3} \, \frac{H^2}{M_{\rm Pl}^2}\bigg|_{k=aH}$$

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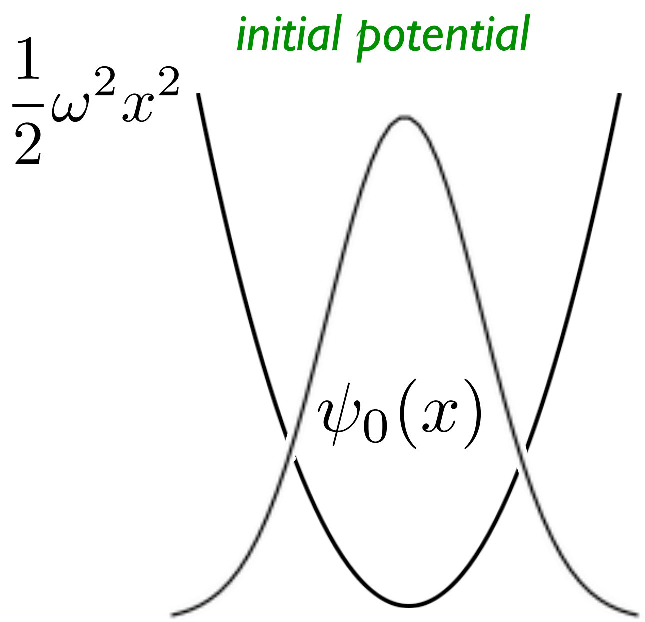

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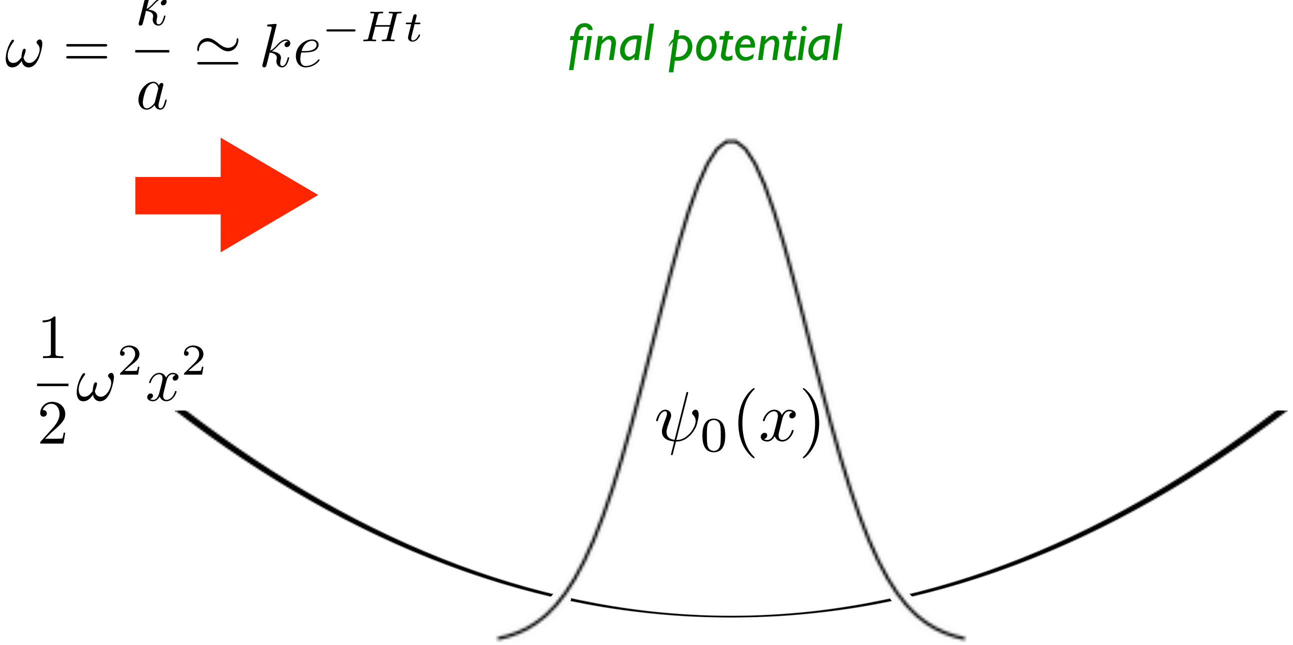

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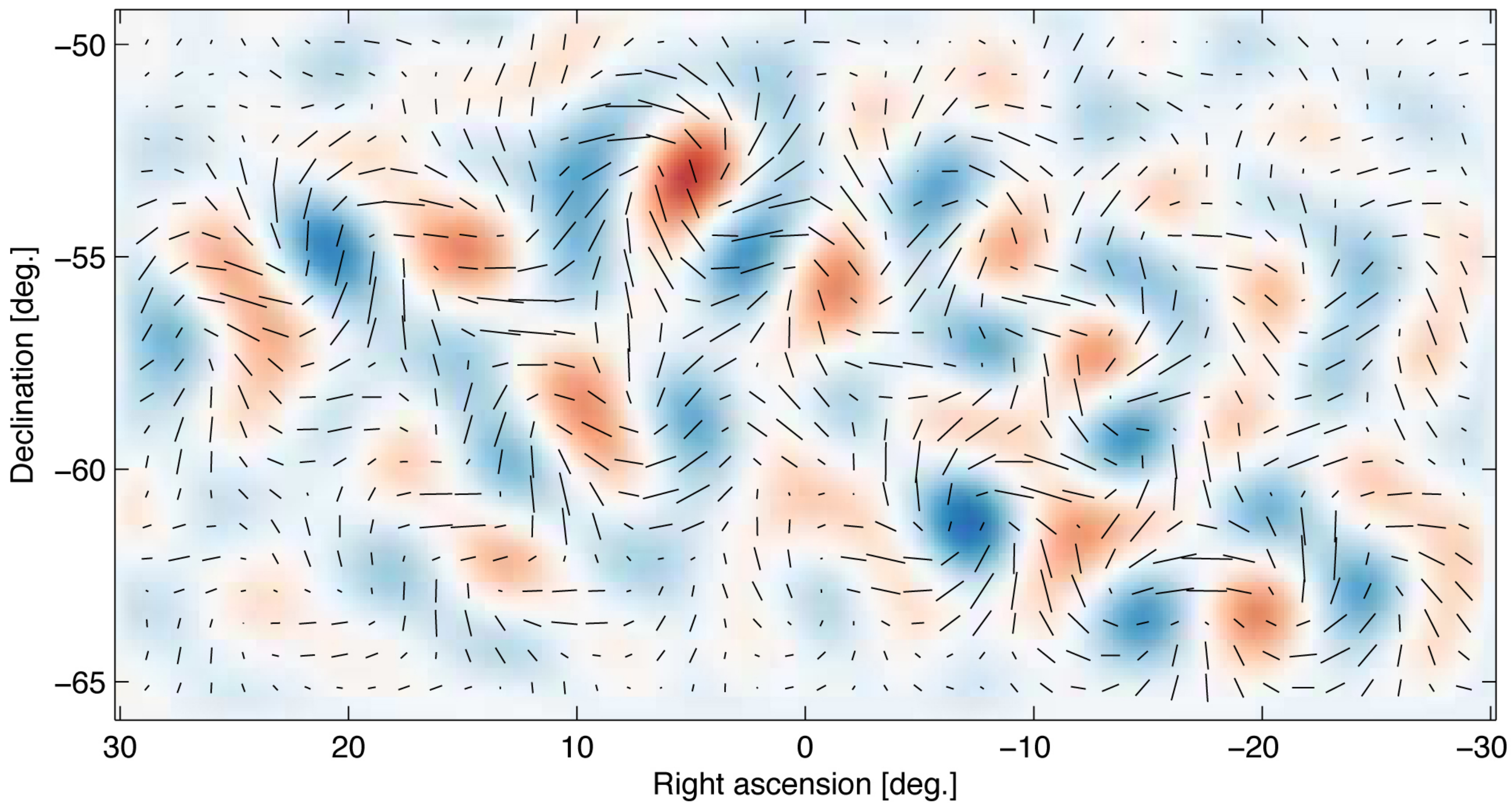
$$\langle (\zeta_k)^2 \rangle = \frac{\hbar}{2k^3} \, \frac{1}{\epsilon} \, \frac{H^2}{M_{\rm Pl}^2}\bigg|_{k=aH}$$

Tensor-to-scalar ratio: $r = 16\epsilon$

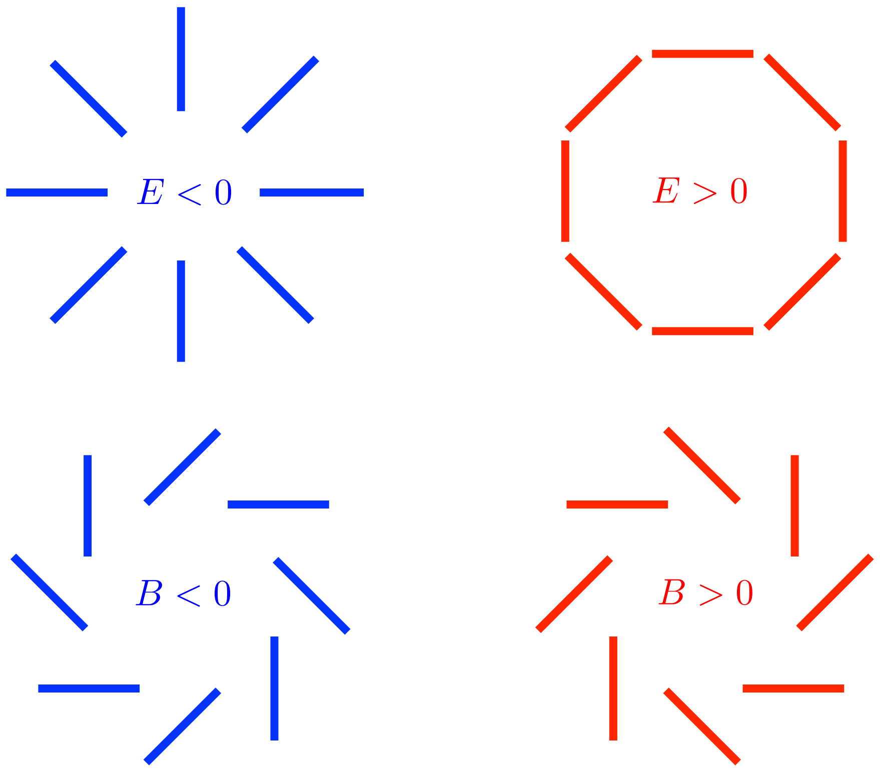
E & B modes



Linear polarization: spin-2 field
$Q \pm iU$ (Q,U are Stokes parameters, $V=0$)

Density perts.
&
gravity waves

Gravity waves

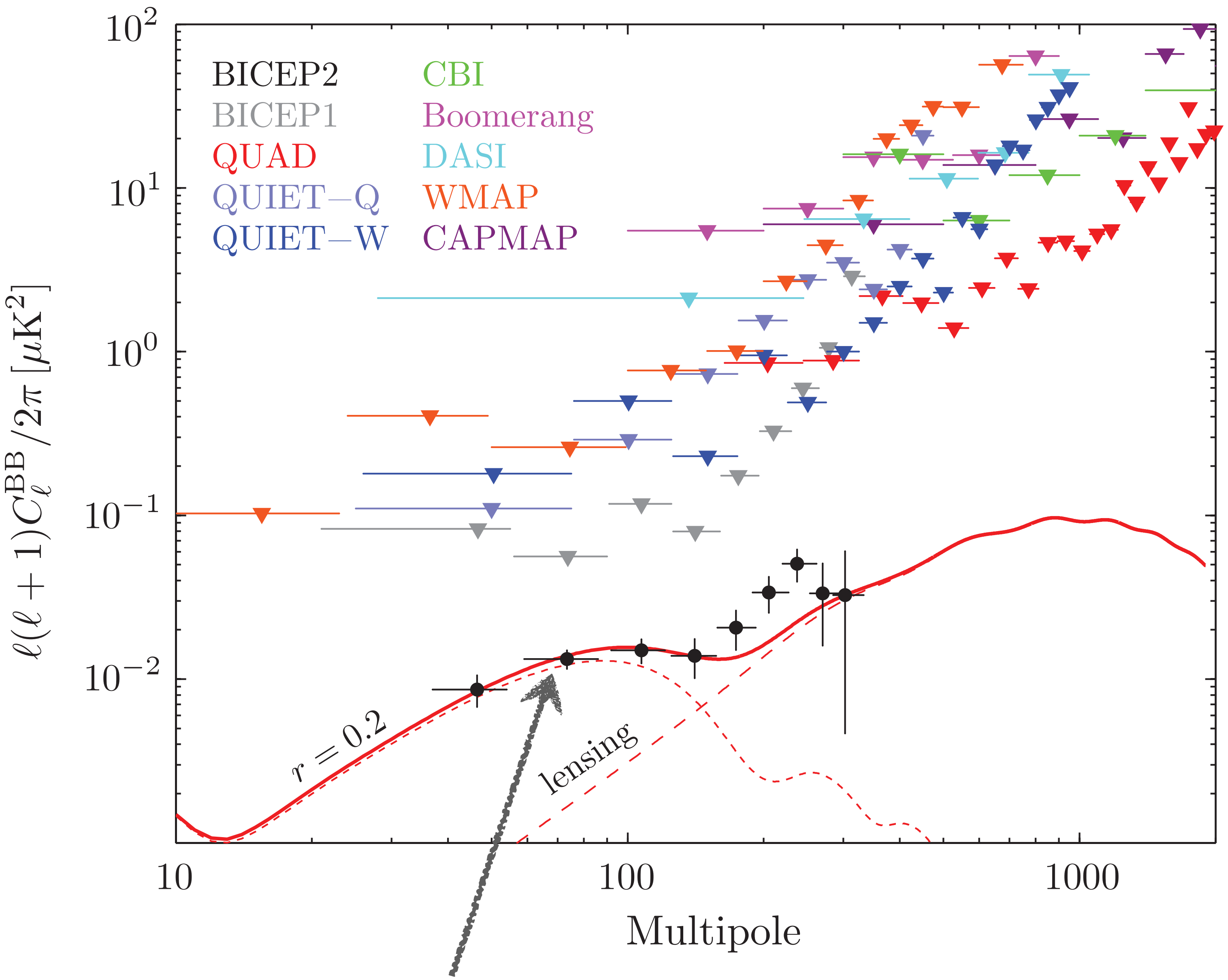


Equivalently: *E* (scalar) & *B* (pseudoscalar)

(Seljak '97; Kamionkowski et al. '97; Seljak, Zaldarriaga '97)

The era of B-modes

Ade et al 1403.3985



$$r = 0.20^{+0.07}_{-0.05}$$

Presumed signal

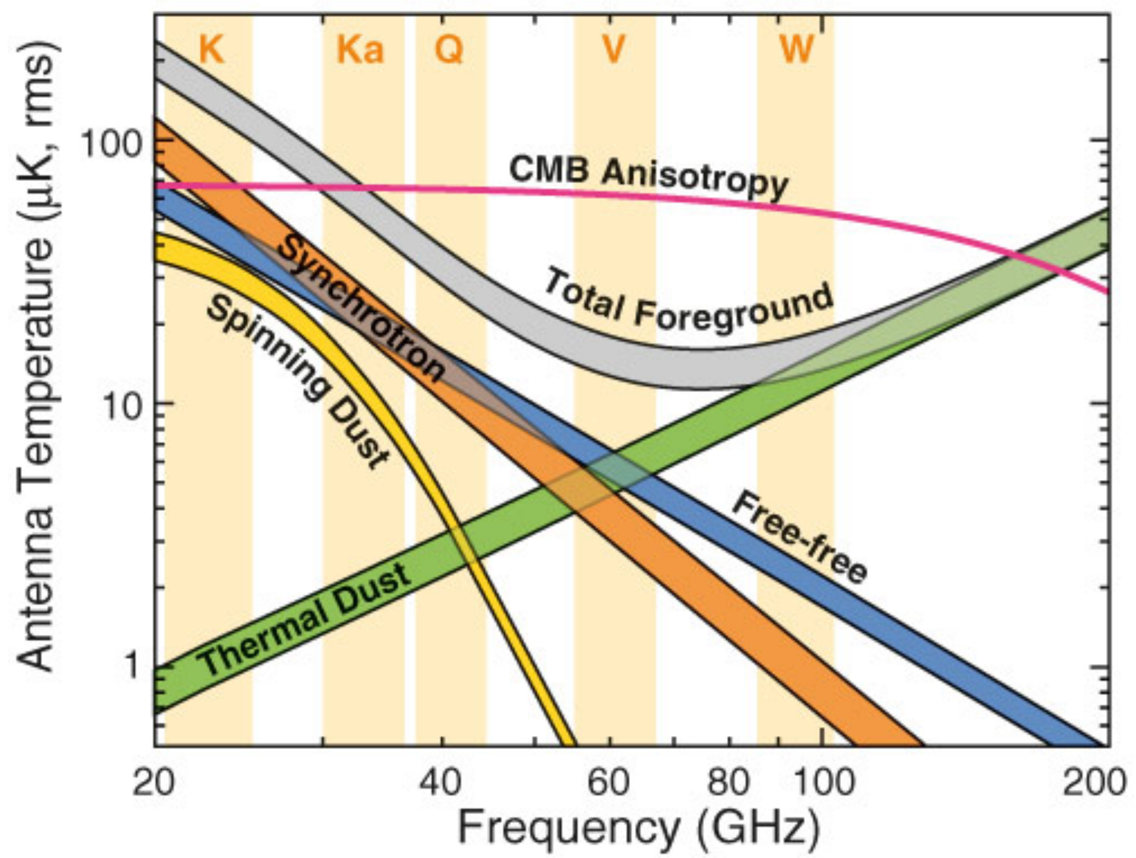
- Amazing recent improvement in experimental sensitivity

$$\Delta P \sim 5\ \mu\mathrm{K\ arcmin}$$

(vs $\Delta P \sim 45\ \mu\mathrm{K\ arcmin}$ for Planck)

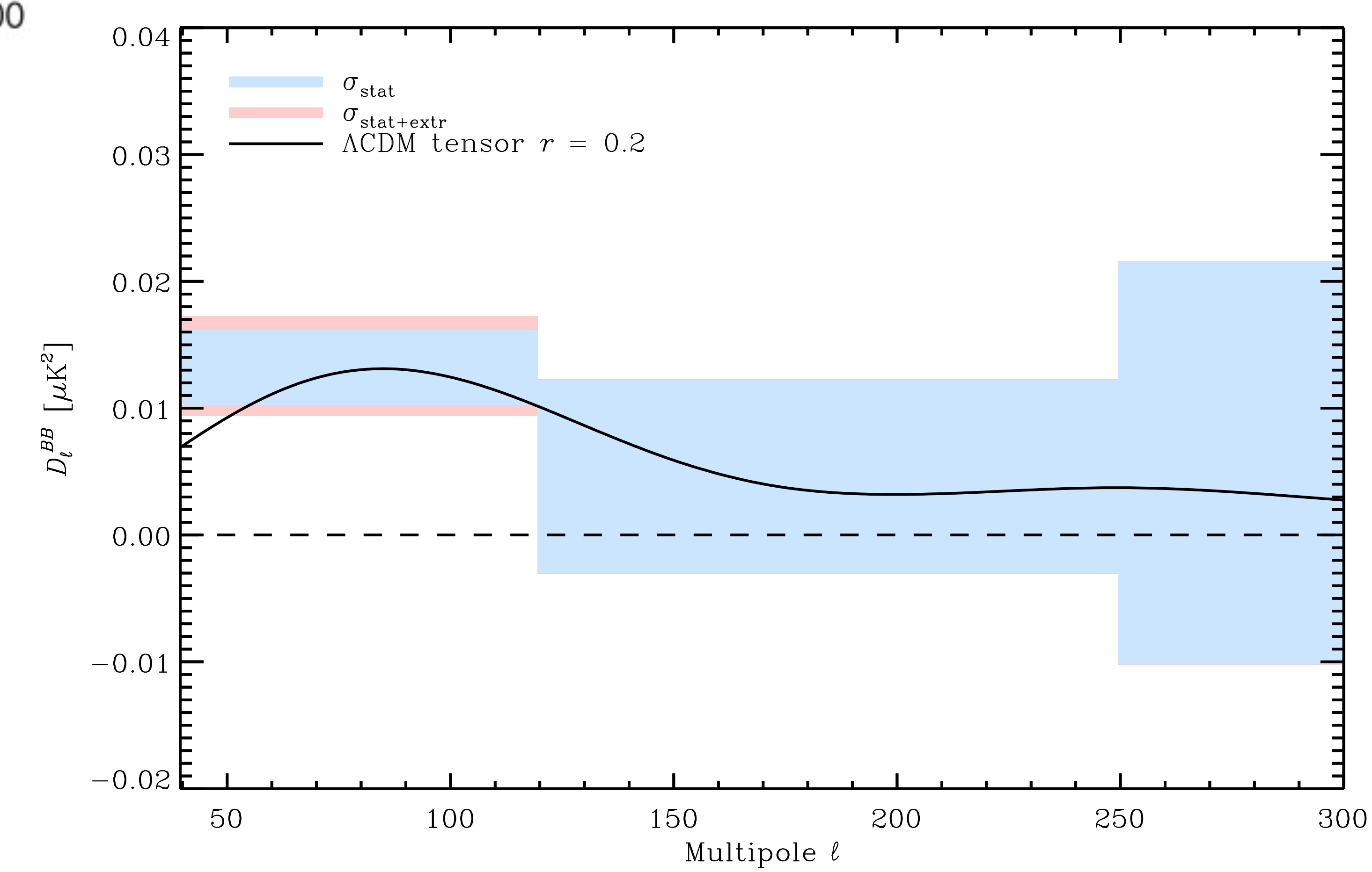
- Start probing theoretically motivated region

Dust under the carpet



- Signal is there but we have to deal with foregrounds
- BICEP2 has only 1 frequency (vs 5 in WMAP or 9 in Planck)!

Planck extrapolated from 353 GHz
[1409.5738 - XXX Planck intermediate results]



- BICEP2 is compatible with being only dust!


Gravitational
waves

Robust signature

▶ It's easy to play with scalar fluctuations

- Choice of potential $V(\phi) \quad \Rightarrow \quad A_s \,, \quad n_s - 1$
- Speed of propagation c_s

$$S = \int d^4x \, \epsilon \, a^3 \, M_{\rm Pl}^2 \left[\dot{\zeta}^2 - \frac{c_s^2}{a^2} (\partial_i \zeta)^2 \right] \qquad \Rightarrow \qquad \langle (\zeta_k)^2 \rangle = \frac{\hbar}{2k^3} \, \frac{1}{c_s \, \epsilon} \, \frac{H^2}{M_{\rm Pl}^2} \bigg|_{k=aH}$$

- Multiple scalars

Robust signature

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• Multiple scalars

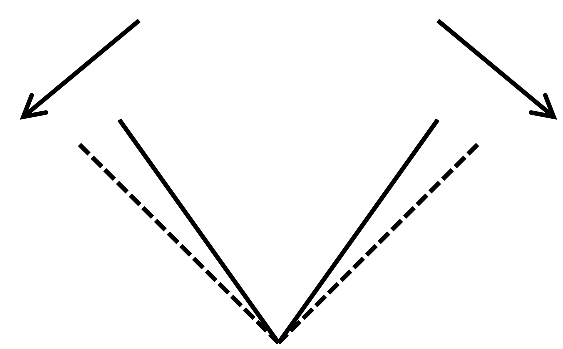
- It's not easy to play with gravity. Gravity waves directly probe H!

• No potential, only two polarizations

• A graviton speed of propagation ≠ 1 can be set = 1 by a disformal transformation

Creminelli, Gleyzes, Noreña, FV '14

$$g_{\mu\nu} \mapsto g_{\mu\nu} - (1 - c_T^2) \partial_\mu \phi \partial_\nu \phi / (\partial \phi)^2$$



GWs predictions very robust!

What can we learn?

- Energy scale of inflation $$\langle (h_k)^2 \rangle = \frac{8\hbar}{k^3} \frac{H^2}{M_{\rm Pl}^2}\bigg|_{k=aH}$$

$$E_{\rm inflation} = V^{1/4} = 1.8 \times 10^{16}\,{\rm GeV} \times \left(\frac{r}{0.1}\right)^{1/4}$$

Observable primordial GWs ($r > 0.001$) require GUT-scale energies

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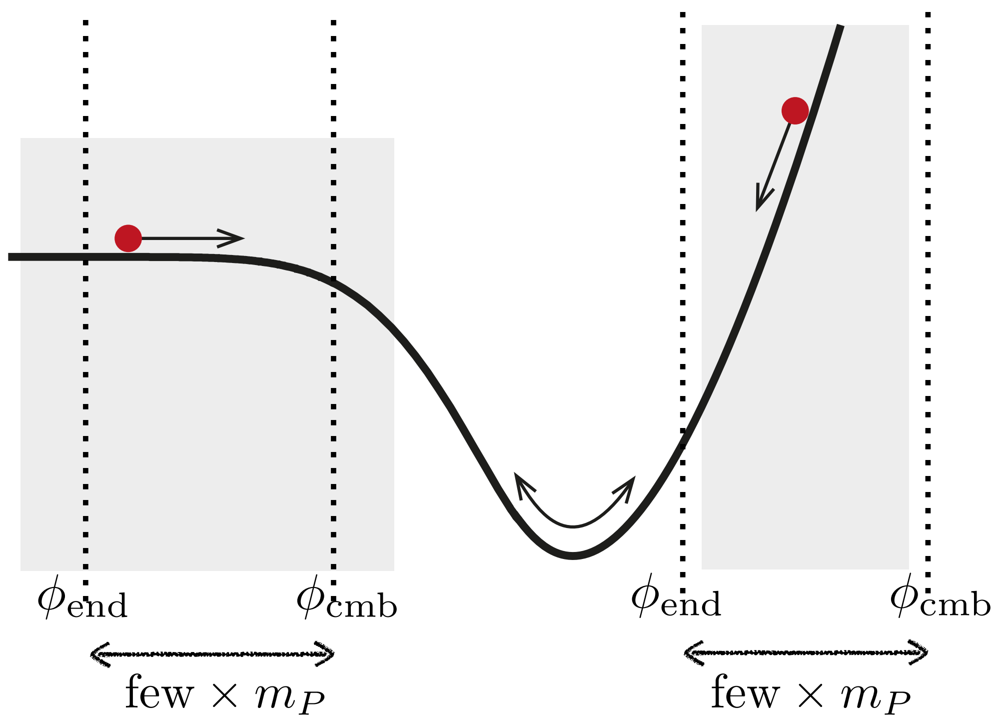
- Trans-Planckian field excursion (Lyth bound):

$$\frac{\Delta\phi}{m_P} \simeq 6.7 \times \left(\frac{r_*}{0.1}\right)^{1/2}$$

Lyth '96

Observable primordial GWs ($r > 0.001$) require super-Planckian field variations



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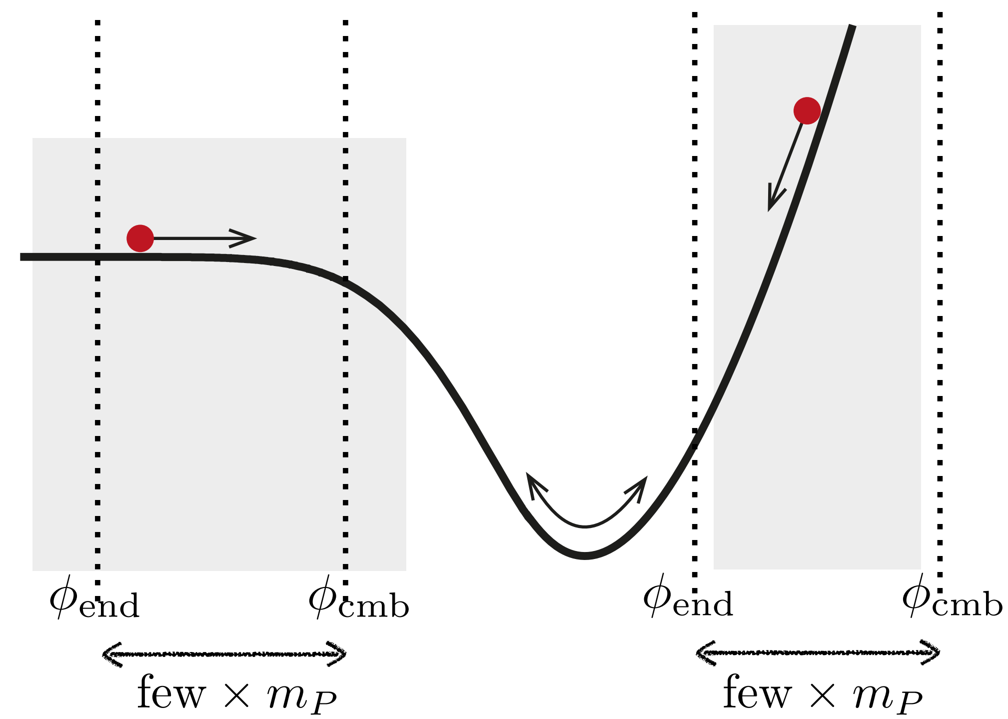
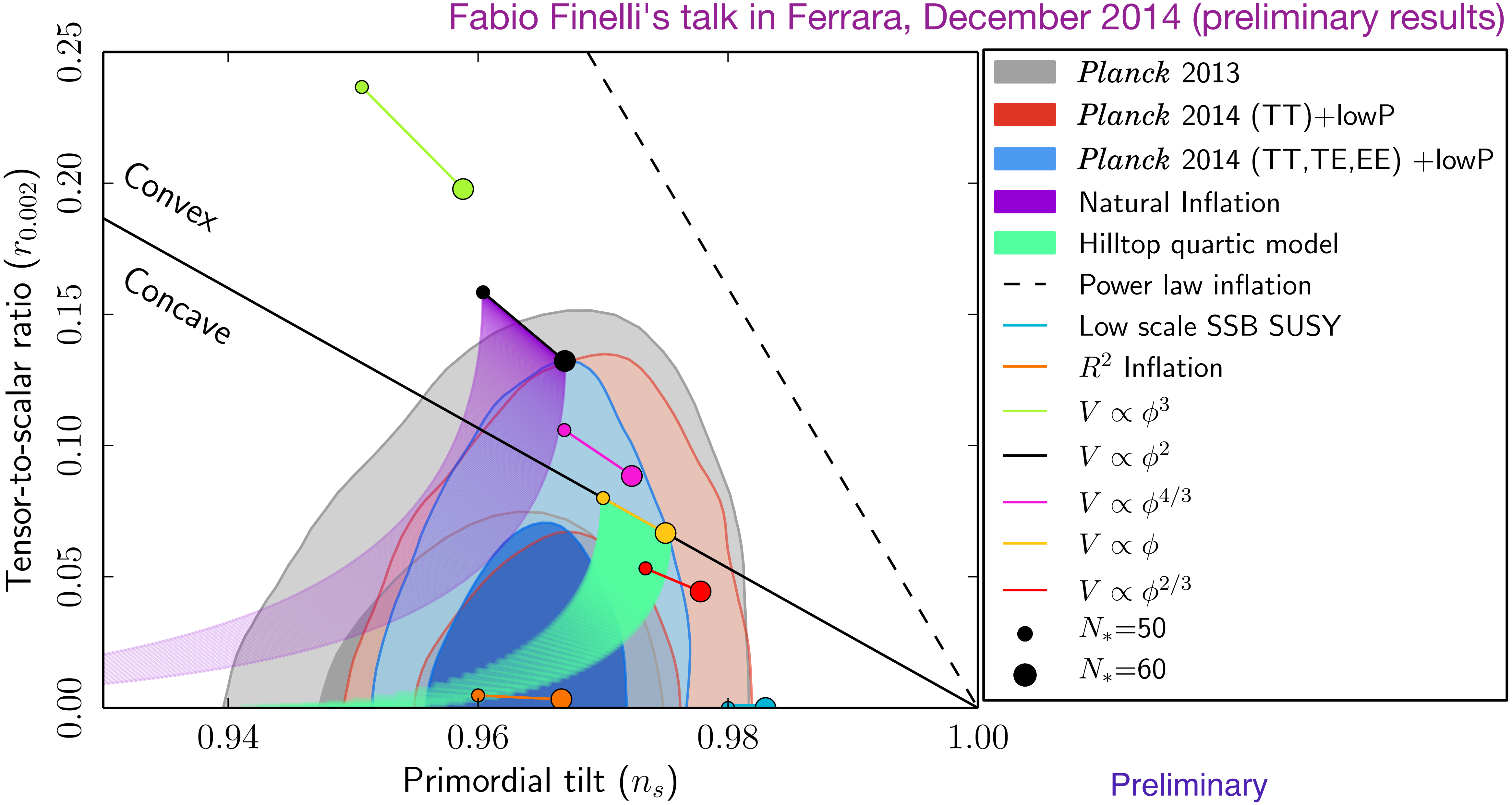


- Test of acceleration $$n_T = \frac{\dot{H}}{H^2}$$ $$P_T(k) = A_T k^{-3} (k/k_*)^{n_T}$$

Planck 2014

Fabio Finelli's talk in Ferrara, December 2014 (preliminary results)



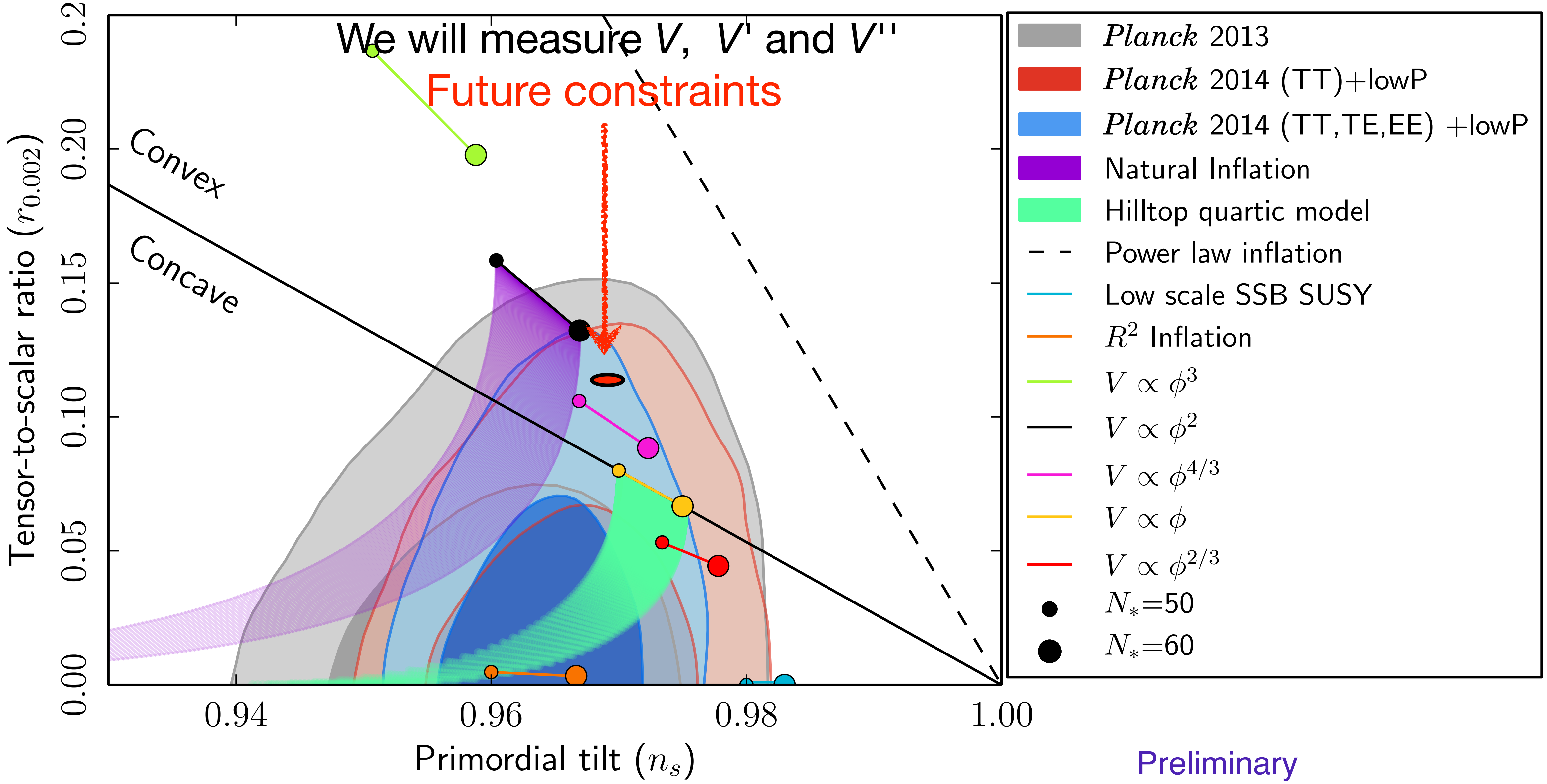
Preliminary

$$n_s = 1 - 2\epsilon + \frac{d\ln\epsilon}{d\ln a}$$

Scale-invariance excluded at 5σ!
First real evidence of inflation.

Planck 2014

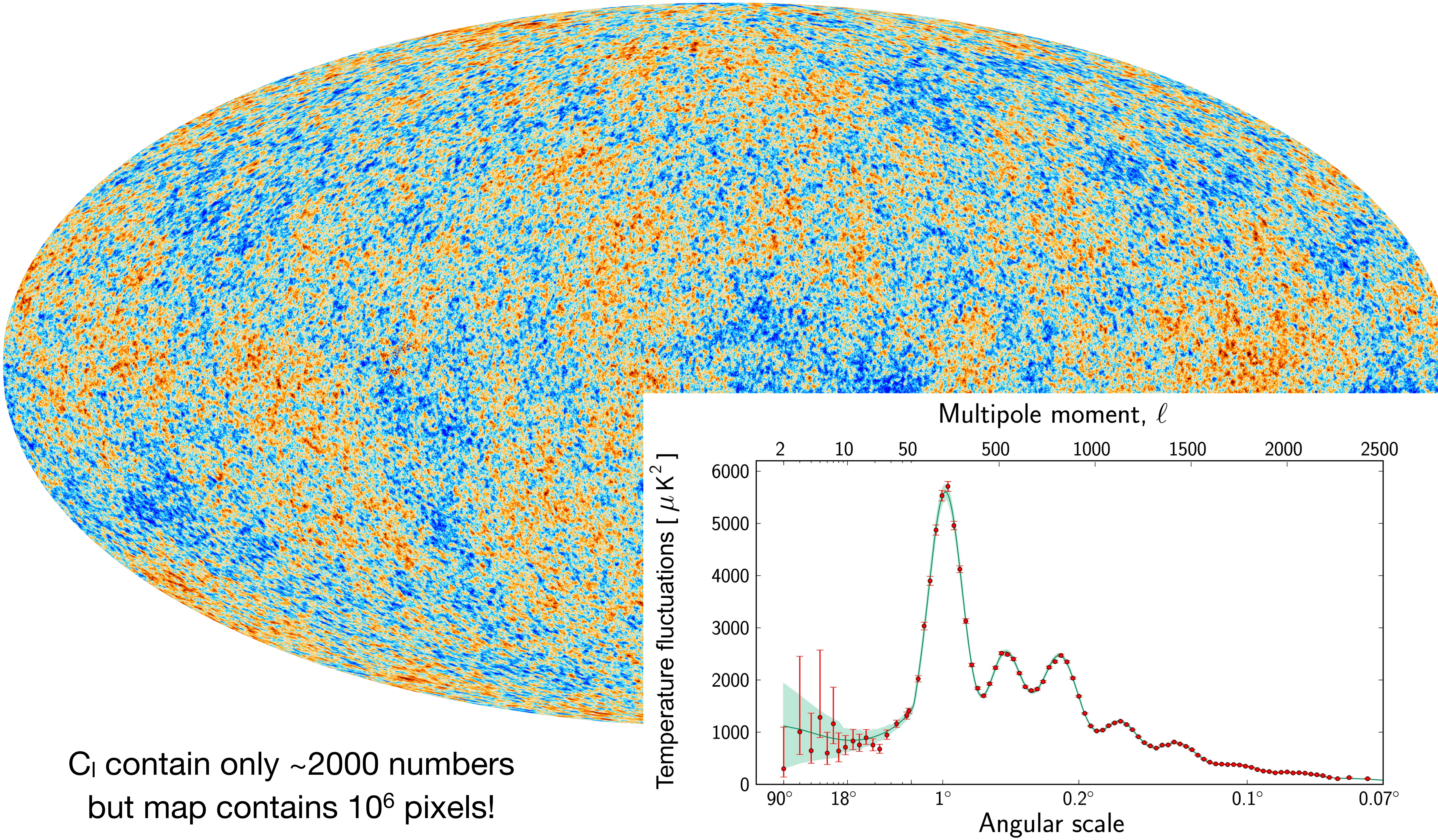
Fabio Finelli's talk in Ferrara, December 2014 (preliminary results)



B-modes search is ongoing by many experiments:

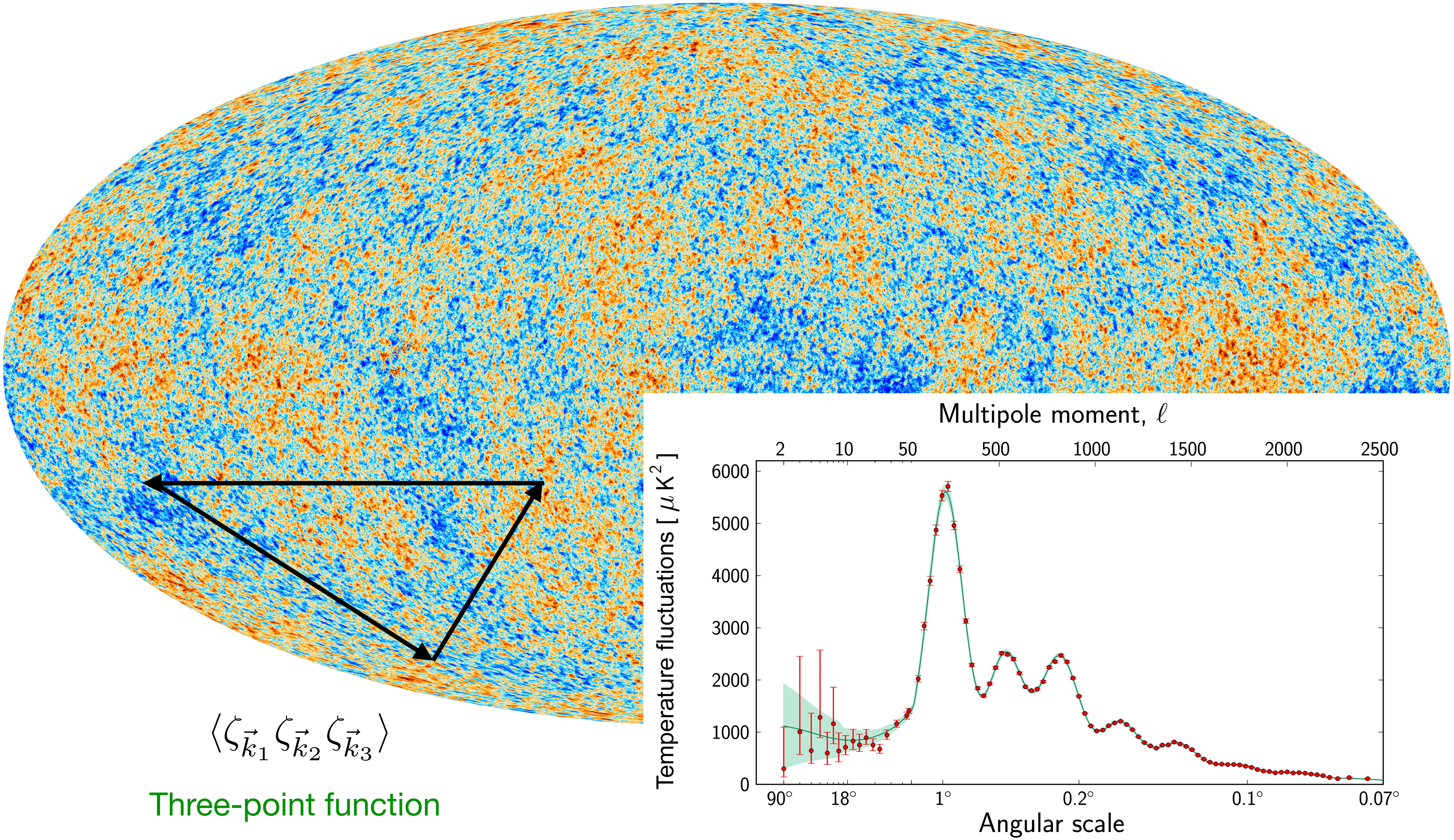
- Ground based telescopes: ABS, ACTpol, CLASS, Keck Array, Qubic, Quijote, Polarbear, Spud, SPTpol, BICEP3 (>2014);
- Balloon experiments: EBEX (2012), Lspe (2015), SPIDER, PIPER (2015);
- Planck satellite mission;
- Future satellite missions: Pixie (NASA), EPIC (NASA), LiteBIRD (KEK), CoRE+ (ESA).

If we do not see GWs?



C_l contain only ~2000 numbers
but map contains 10^6 pixels!

Non-Gaussianity



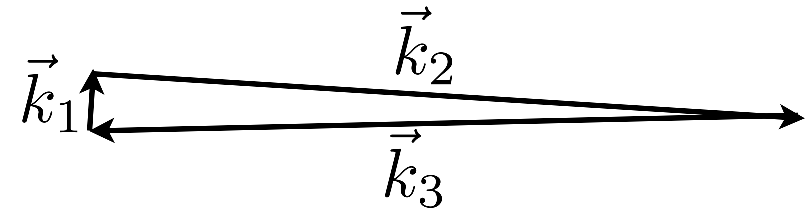
$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle$$

Three-point function

Deviation from Gaussianity

Single-field predictions

- Squeezed limit:



Maldacena '02

$$\langle \zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\rangle = \left[-(n_s-1)+\mathcal{O}\left(\frac{k_1^2}{k_2^2}\right)\right]P(k_1)P(k_2)\ , \qquad k_1 \ll k_2 \approx k_3$$

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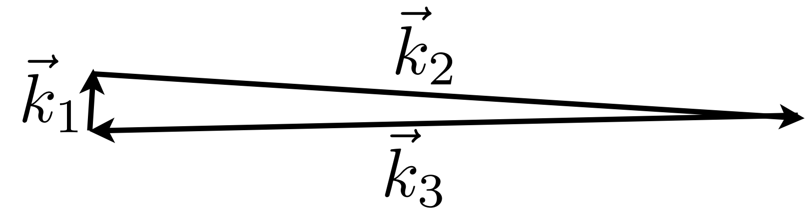

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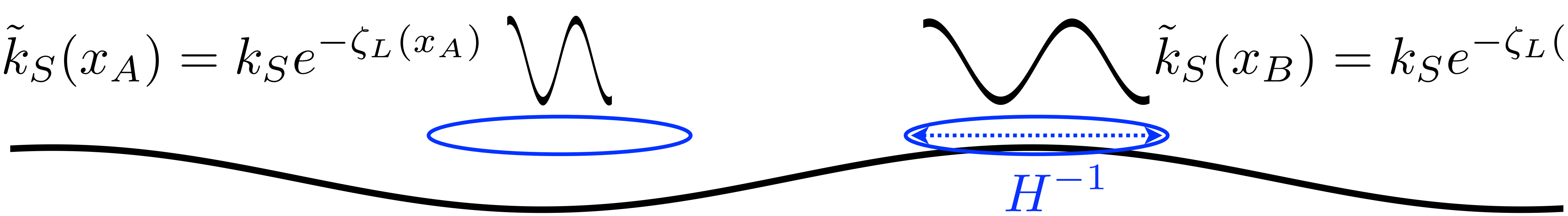
The long mode redefines the background (rescaling of the momenta):

$$g_{ij} dx^i dx^j = a^2(t) e^{2\zeta_L(\vec{x})} d\vec{x}^2 = a^2(t) d\tilde{\vec{x}}^2 \quad \Rightarrow \quad \tilde{k} = k e^{-\zeta_L}$$

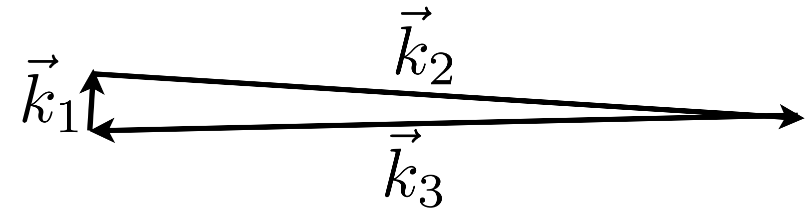
$$\tilde{k}_S(x_A) = k_S e^{-\zeta_L(x_A)} \qquad \tilde{k}_S(x_B) = k_S e^{-\zeta_L(x_B)}$$



Flat spectrum n_s-1=0

Single-field predictions

- Squeezed limit:



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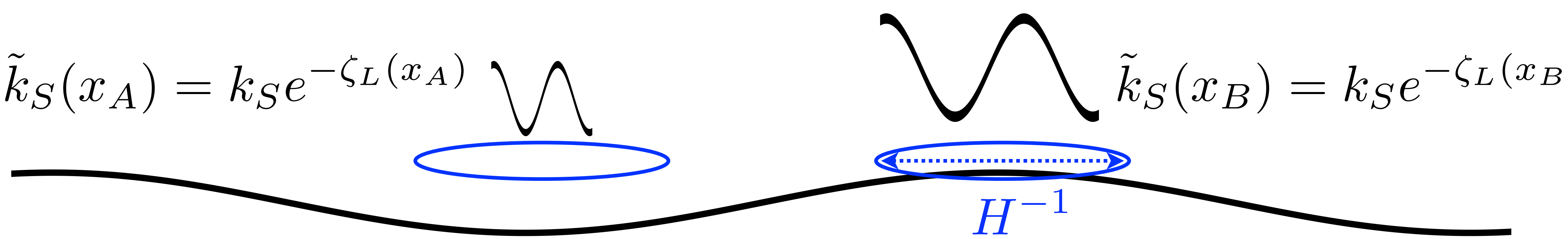

Red spectrum n_s-1<0

Single-field predictions

- Slow-roll:

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Single-field predictions

- Slow-roll:

$$\langle \zeta_{\vec{k}_1} \zeta_{\vec{k}_2} \zeta_{\vec{k}_3} \rangle = \left[\underbrace{-(n_s - 1)}_{f_{\mathrm{NL}}^{\mathrm{local}}} + \underbrace{\epsilon\, \mathcal{O}\left(\frac{k_1^2}{k_2^2} \right)}_{f_{\mathrm{NL}}^{\mathrm{equilateral}}} \right] P(k_1) P(k_2) \ , \qquad k_1 \ll k_2 \approx k_3$$

- $f_{\mathrm{NL}}^{\mathrm{loc}} \ll 1$ due to attractor nature of single-field inflation
- $f_{\mathrm{NL}}^{\mathrm{eq}} \ll 1$ due to smallness of inflaton self-interactions in slow-roll

Single-field predictions

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$f_{\rm NL}^{\rm local}$ $\qquad$ $f_{\rm NL}^{\rm equilateral}$

  - $f_{\rm NL}^{\rm loc} \ll 1$ due to attractor nature of single-field inflation
  - $f_{\rm NL}^{\rm eq} \ll 1$ due to smallness of inflaton self-interactions in slow-roll

- $f_{\rm NL}^{\rm loc} \gtrsim 1$: extra fields, local correlation between long and short modes

- $f_{\rm NL}^{\rm eq} \gtrsim 1$: large self-interactions:

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \frac{1}{\Lambda^4}(\partial_\mu\phi\partial^\mu\phi)^2 \qquad f_{\rm NL}^{\rm eq} \sim \frac{\dot{\phi}^2}{\Lambda^4} \sim \frac{1}{c_s^2}$$

Creminelli '03

Constraints

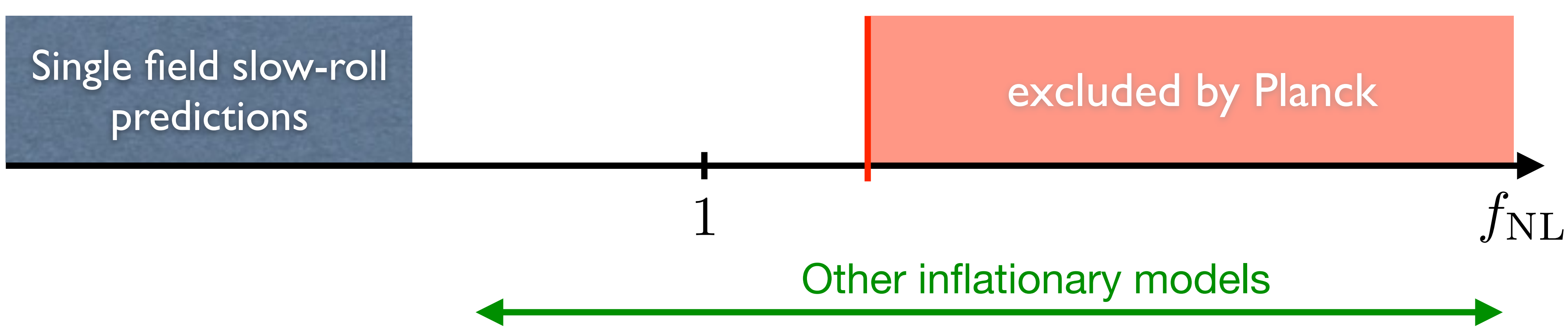
- Current constraints:

SMICA (T+E)	$f_{\rm NL}$
Local	**0.71 ± 5.1**
Equilateral	**−9.5 ± 44**

$$\frac{\text{non-Gaussian}}{\text{Gaussian}} \sim 10^{-3} \div 10^{-4}$$

Ben Wandelt's talk in Ferrara, December 2014 (preliminary results!)

- Future experimental target, reachable by CMB + LSS:
  - $f_{\rm NL}^{\rm loc} \lesssim 1$ single-field
  - $f_{\rm NL}^{\rm eq} \lesssim 1$ slow-roll



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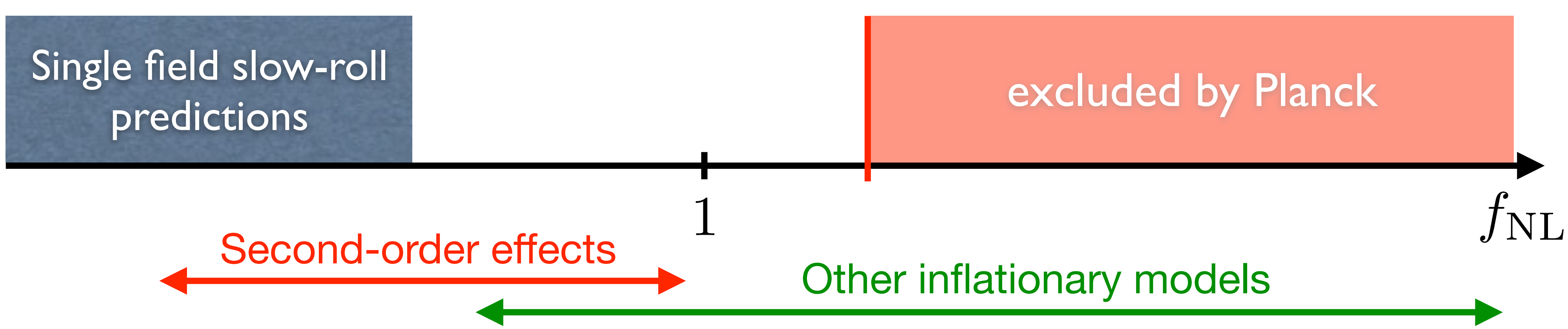


- Intrinsic nonlinearities in GR and baryon-photon fluid $f_{\rm NL} \sim \mathcal{O}(1)$

Template computed with second-order Boltzmann codes Huang and FV '12, '13

Conclusions

- We entered the B-mode era.

- Primordial gravity waves predictions extremely robust. Window on the highest energies and probe of early acceleration.

- Large non-Gaussianity would rule out all single-field slow-roll models. Probe of new early universe physics: multi-field models and self-interactions.

- Future experiments are very close to targets $f_{\rm NL} \sim \mathcal{O}(1)$.

Backup slides

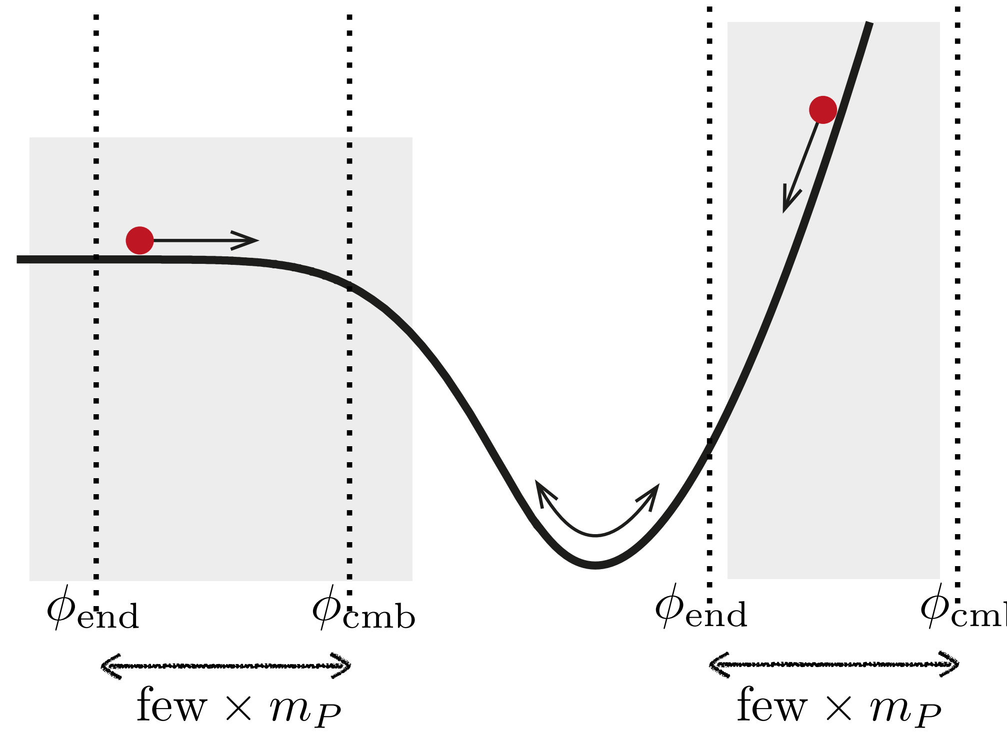
Lyth bound

• Observable gravity waves = super-Planckian field excursion

$$\frac{r}{0.1} = 10 \times 16\epsilon = 160 \times \frac{m_P^2}{2}\left(\frac{V'}{V}\right)^2$$

$$\approx 0.02 \times \left(\frac{\Delta\phi}{m_P}\right)^2$$

Lyth '96

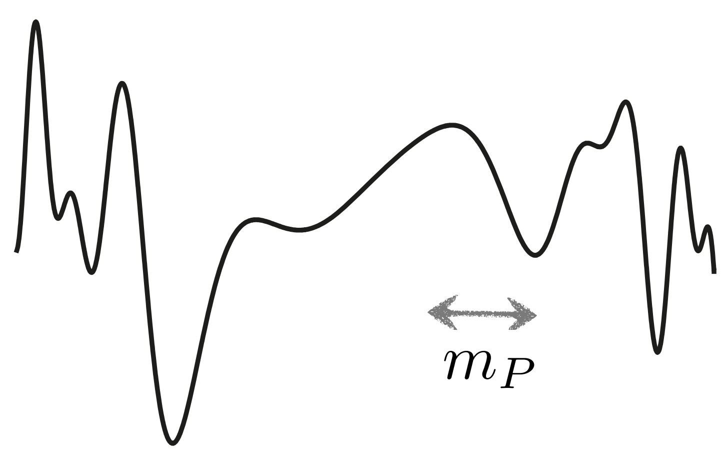


1) Trans-Planckian energy? No! $$V = \frac{1}{2}m^2\phi^2 \ll m_P^4$$

2) Do I loose control of the EFT? $$\Delta V = \sum_n c_n \frac{\phi^{4+n}}{m_P^n}$$

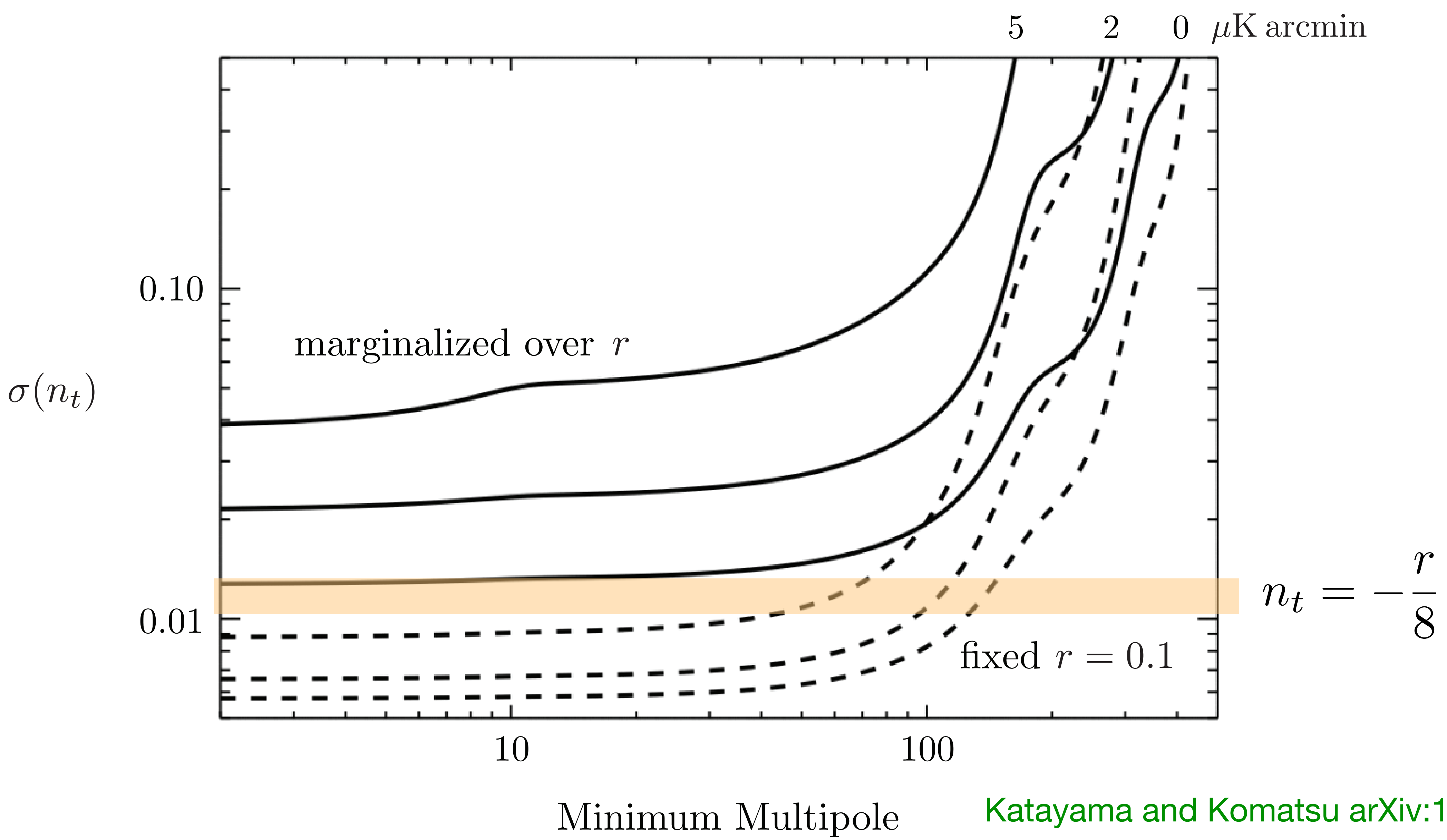
Need a symmetry to protect the potential. Ex: $\phi \to \phi + c$

• Generically, expected smooth potentials over small field excursions



$$\frac{\Delta V}{V} = \sum_n c_n \left(\frac{\phi}{m_P}\right)^n$$

Measuring the consistency relation (with CMB)



Katayama and Komatsu arXiv:1101.5210

Non-minimal kinetic term

- The inflaton can have non-minimal kinetic term (ex. DBI):

$$S = \int d^4x\sqrt{-g}P(\phi, X) \qquad\qquad X \equiv g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi$$

- Speed of sound of fluctuations: $$c_s^2 = \frac{P_{,X}}{P_{,X} + 2XP_{,XX}} \ll 1$$

- Enhanced scalar fluctuations: $$k^3\langle(\zeta_k)^2\rangle = \frac{1}{c_s} \times \frac{1}{2\epsilon}\frac{H^2}{m_P^2}$$

Smaller tensor-to-scalar ratio $\quad r = 16\,\epsilon\,c_s \ll 16\epsilon$

$$r = 0.2 \qquad \Rightarrow \qquad c_s \sim \frac{10^{-2}}{\epsilon} \sim 10^{-2}N$$

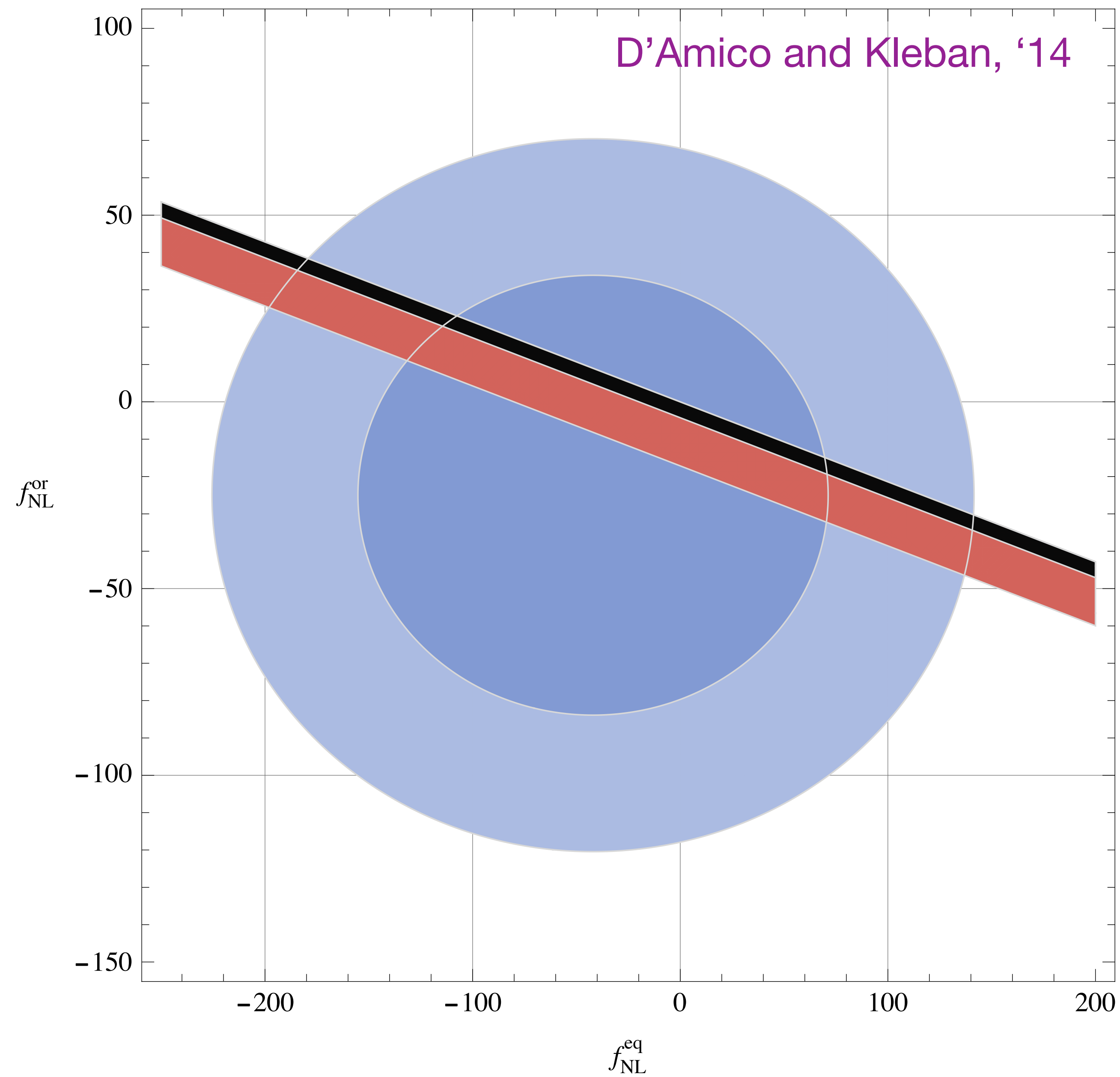
- ⇒ Models where non-Gaussianity comes from cubic operators enhanced by $1/c_s^2$ for small sound-speed are strongly constrained. (Current constraint from Planck: $c_s^2 \geq 0.02$)

Non-Gaussianity

- Scalar fluctuations around an expanding FRW universe are described by:

$$S_\pi = \int a^3 \frac{M_{\rm Pl}^2 |\dot{H}|}{c_s^2} \left[\left(\dot{\pi}^2 - c_s^2 \frac{(\partial_i \pi)^2}{a^2} \right) - (1 - c_s^2) \dot{\pi} \frac{(\partial_i \pi)^2}{a^2} + \left(1 - c_s^2 + \frac{2}{3} c_p \right) \dot{\pi}^3 \right]$$

- One can have $c_p \gg 1$ and $c_s^2 \simeq 1$

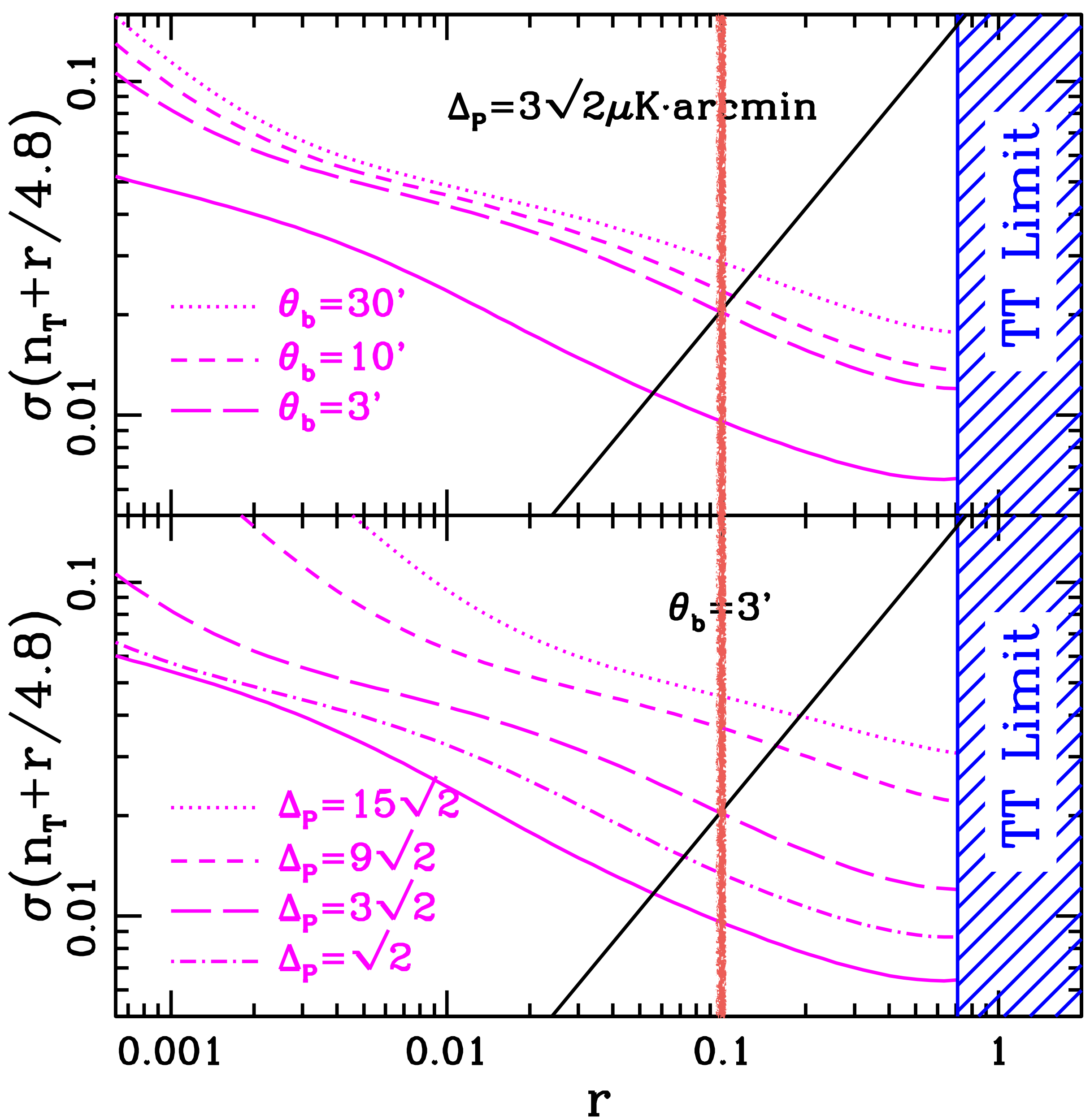


Non-Gaussian constraints assuming $c_s > 0.1$ (narrow black) or $c_s > 0.05$ (red+black) compared to Planck constraints on non-Gaussianity (1 and 2σ)

Consistency relation from space

- Testing the consistency relation requires $\sigma(n_T) \sim 0.01$

$$n_T = -\frac{1}{8}r$$



Song and Knox '03

FIG. 3: The error on $n_T + r/4.8$ as a function of r. The cosmic variance limit is the solid line in both panels. In the upper panel, we fix $\Delta_P = 3\sqrt{2}\mu K\cdot$arcmin and vary the angular resolution: $\theta_b = 1'$ (long dash), $\theta_b = 3'$ (dash) and $\theta_b = 5'$ (dots). In the lower panel, we fix the angular resolution at $\theta_b = 3'$ and vary the weight per solid angle: $\Delta_P = \sqrt{2}\mu K \cdot$ arcmin (dot-dashed), $\Delta_P = 3\sqrt{2}\mu K \cdot$ arcmin (long dash), $\Delta_P = 9\sqrt{2}\mu K \cdot$ arcmin (dash) and $\Delta_P = 15\sqrt{2}\mu K \cdot$ arcmin (dots). The shaded area is excluded by observations of the temperature power spectrum [30].

Consistency relation from the ground

	$\sigma(r)$			$\sigma(n_t)$		
f_{sky}	0.25	0.50	0.75	0.25	0.50	0.75
$\mathbf{r_{fid} = 0.2}$						
$10^4 N_{\rm det}$	0.030	0.026	0.025	0.09	0.08	0.07
$10^5 N_{\rm det}$	0.021	0.016	0.014	0.07	0.05	0.04
$10^6 N_{\rm det}$	0.020	0.015	0.012	0.06	0.05	0.04
$\mathbf{r_{fid} = 0.1}$						
$10^4 N_{\rm det}$	0.022	0.020	0.019	0.13	0.11	0.11
$10^5 N_{\rm det}$	0.016	0.012	0.010	0.10	0.07	0.06
$10^6 N_{\rm det}$	0.015	0.011	0.009	0.09	0.07	0.05
$\mathbf{r_{fid} = 0.05}$						
$10^4 N_{\rm det}$	0.016	0.015	0.014	0.18	0.16	0.16
$10^5 N_{\rm det}$	0.012	0.009	0.007	0.14	0.10	0.08
$10^6 N_{\rm det}$	0.011	0.008	0.007	0.13	0.09	0.08
$\mathbf{r_{fid} = 0.02}$						
$10^4 N_{\rm det}$	0.012	0.011	0.011	0.31	0.29	0.28
$10^5 N_{\rm det}$	0.008	0.006	0.005	0.22	0.16	0.14
$10^6 N_{\rm det}$	0.008	0.005	0.004	0.21	0.15	0.12

Table IX: 1-σ constraints for r and n_t for various detector count and sky fraction at $4'$ beam size.

Wu et al. arXiv:1402.4108

Resolving BICEP2 vs Planck tension

- If tension with Planck is real, how to interpret it?
  - Foreground
  - Running
  - Magnetic fields
  - Tensor-scalar correlation
  - Suppression of scalar power at large scales (features in the potential, etc.)
  - Anticorrelated isocurvature perturbations
  - Inflaton + curvaton with running
  - Extra sterile neutrinos
  - Strong blue tensor tilt
  - Your model

Models

- *Planck*+WP
- *Planck*+WP+highL
- *Planck*+WP+BAO
- Natural Inflation
- Power law inflation
- Low Scale SSB SUSY
- R^2 Inflation
- $V \propto \phi^{2/3}$
- $V \propto \phi$
- $V \propto \phi^2$
- $V \propto \phi^3$
- $N_* = 50$
- $N_* = 60$

$$V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$$

$$V(\phi) = \Lambda^4 \exp\left(-\lambda \frac{\phi}{M_{\rm pl}}\right)$$

$$U(\phi) = \alpha_{\rm h} \Lambda^4 \ln\left(\frac{\phi}{\mu}\right)$$

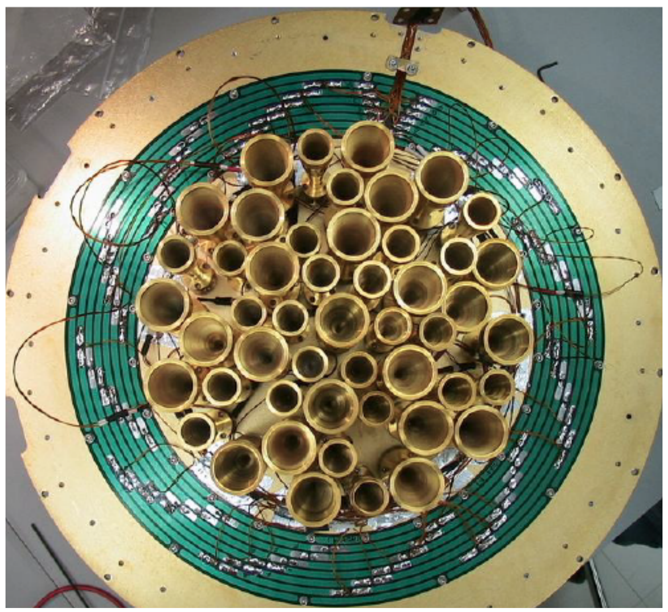
$$S = \int d^4x \sqrt{-g} \frac{M_{\rm pl}^2}{2} \left(R + \frac{R^2}{6M^2}\right)$$

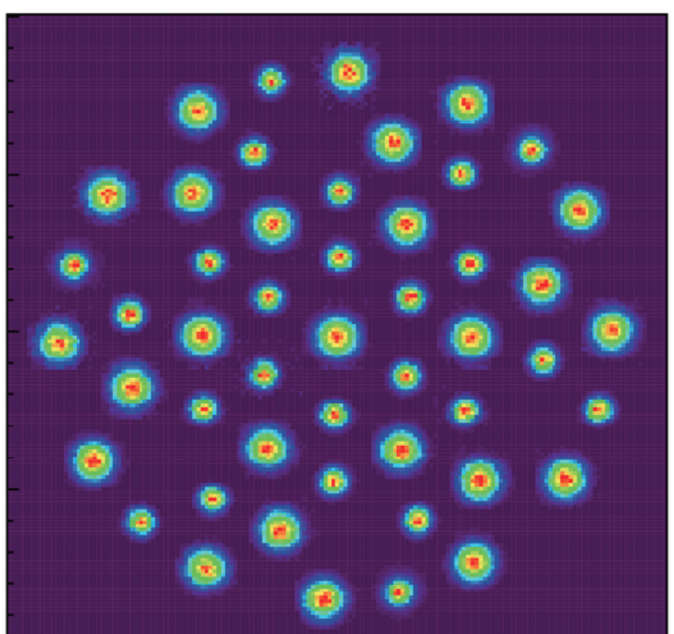
$$V(\phi) = \lambda M_{\rm pl}^4 \left(\frac{\phi}{M_{\rm pl}}\right)^n$$

Focal planes

BICEP1

2006-2008



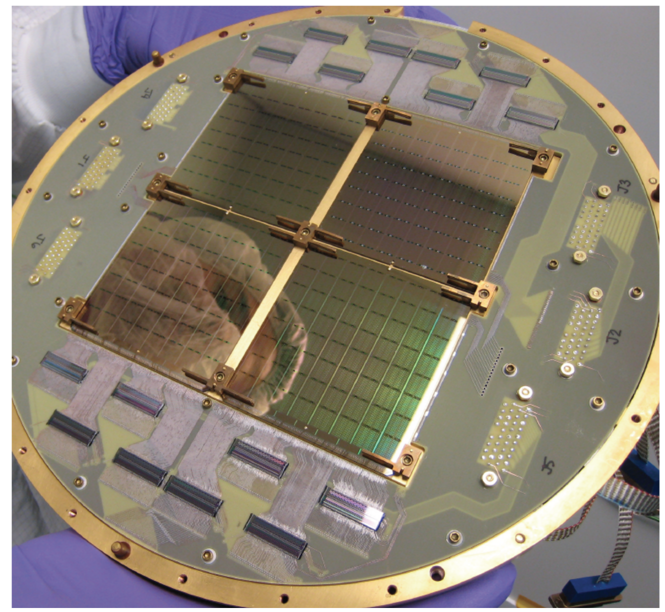


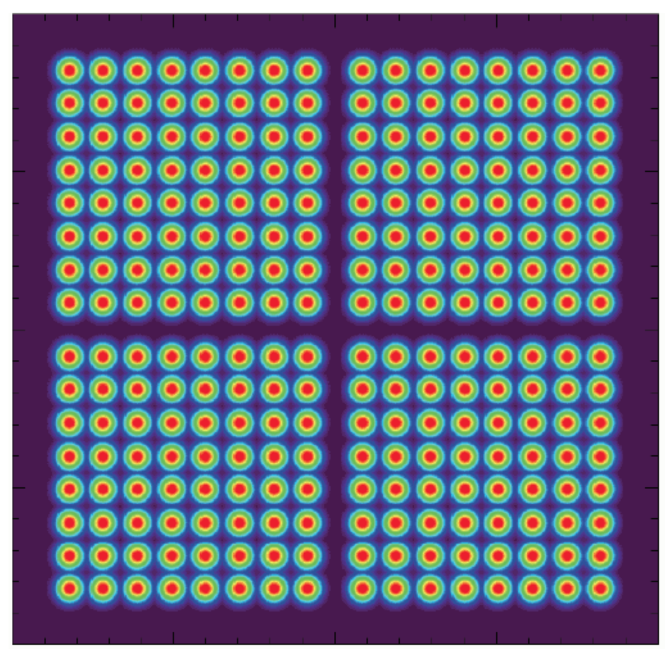
50 @ 100 GHz

48 @ 150 GHz

BICEP2

2010-2012

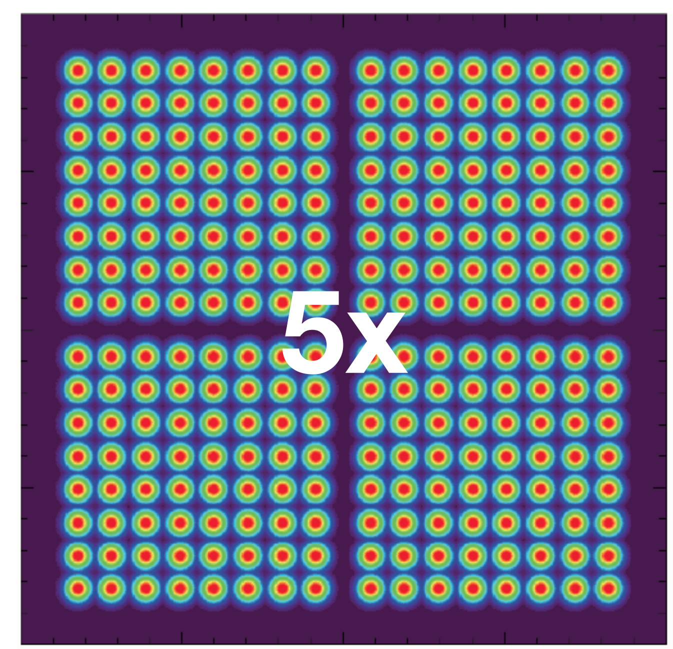




512 @ 150 GHz

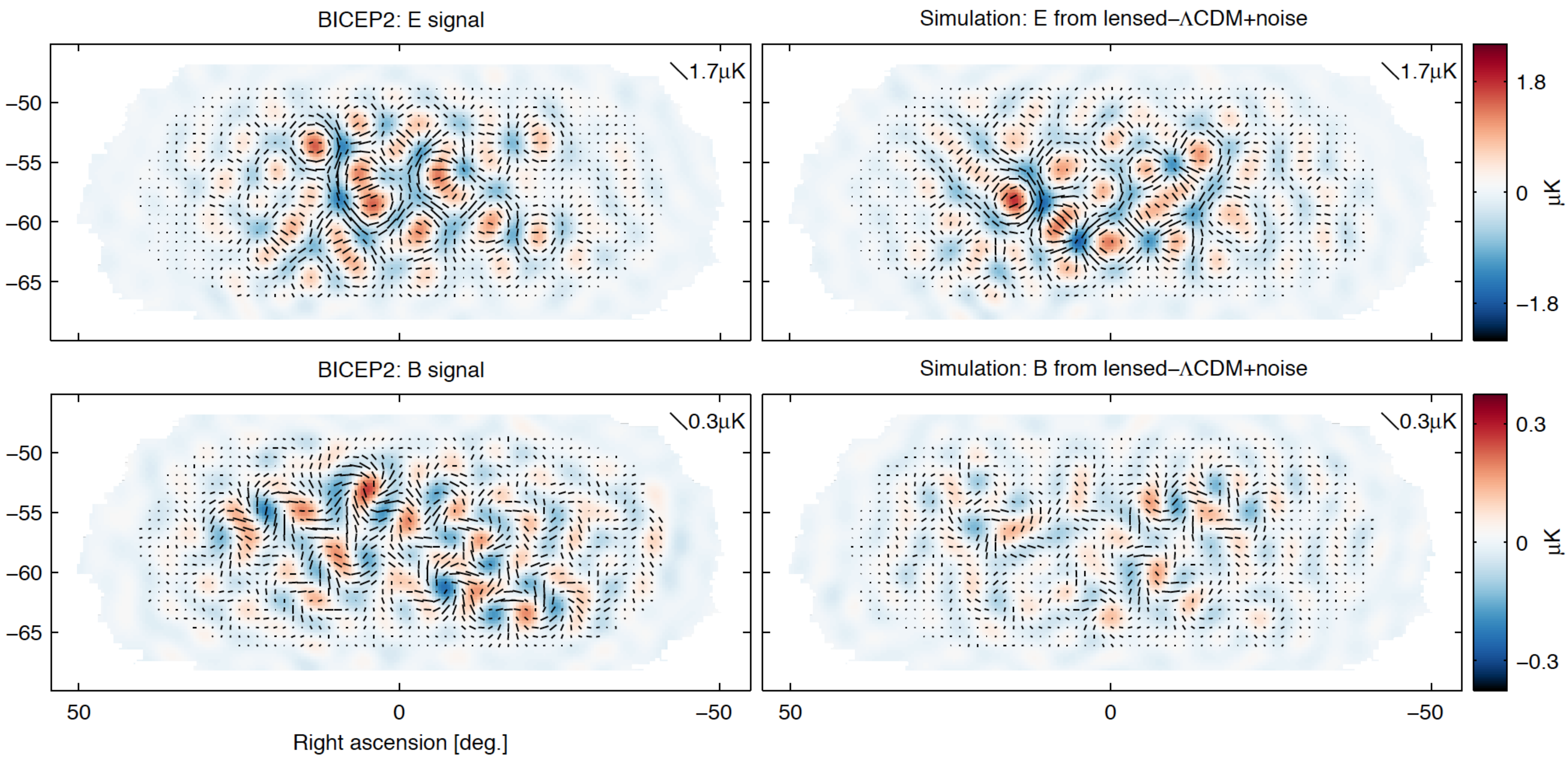
KECK Array

2011-2016

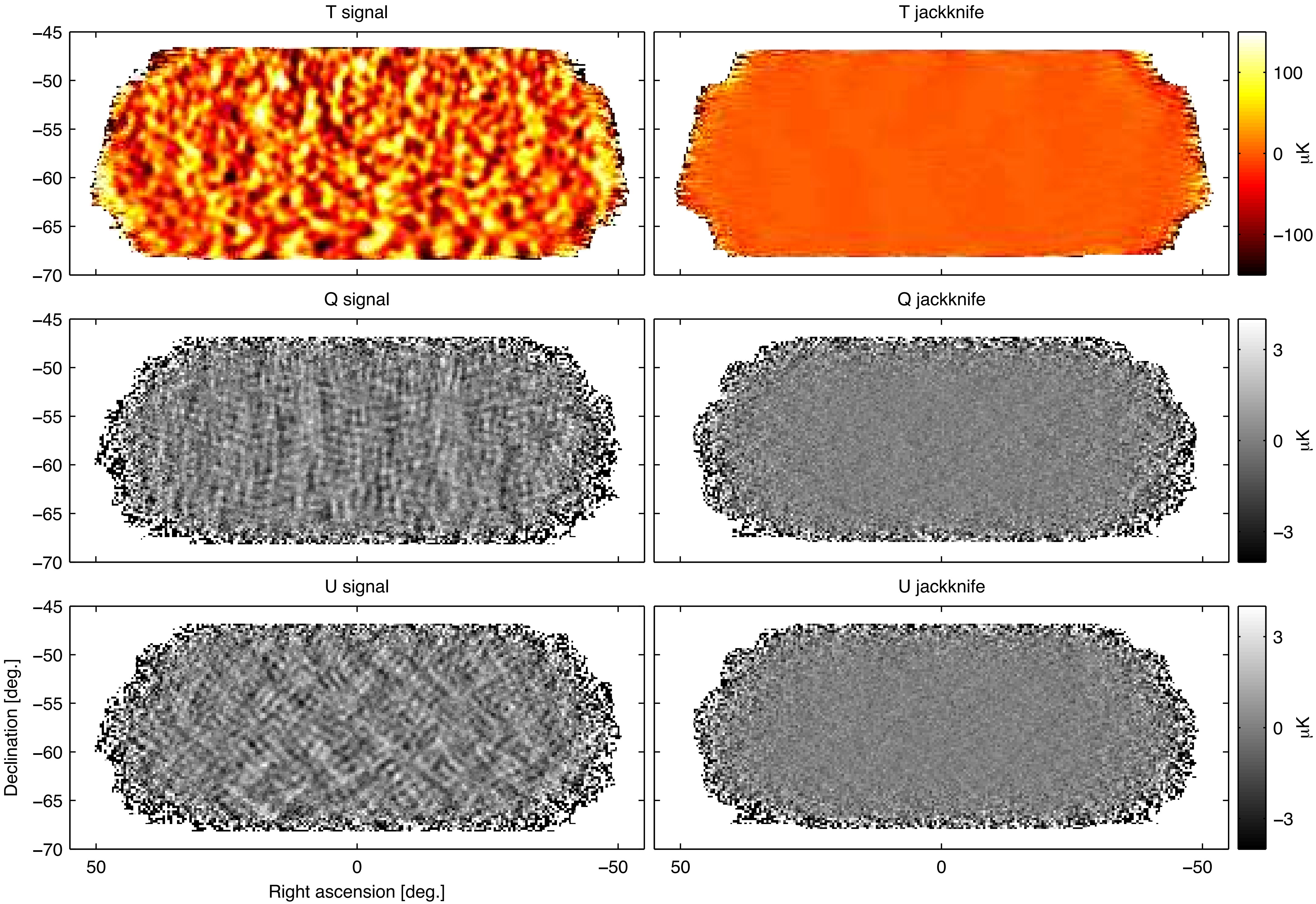


5 x 512 @ 150 GHz

Results

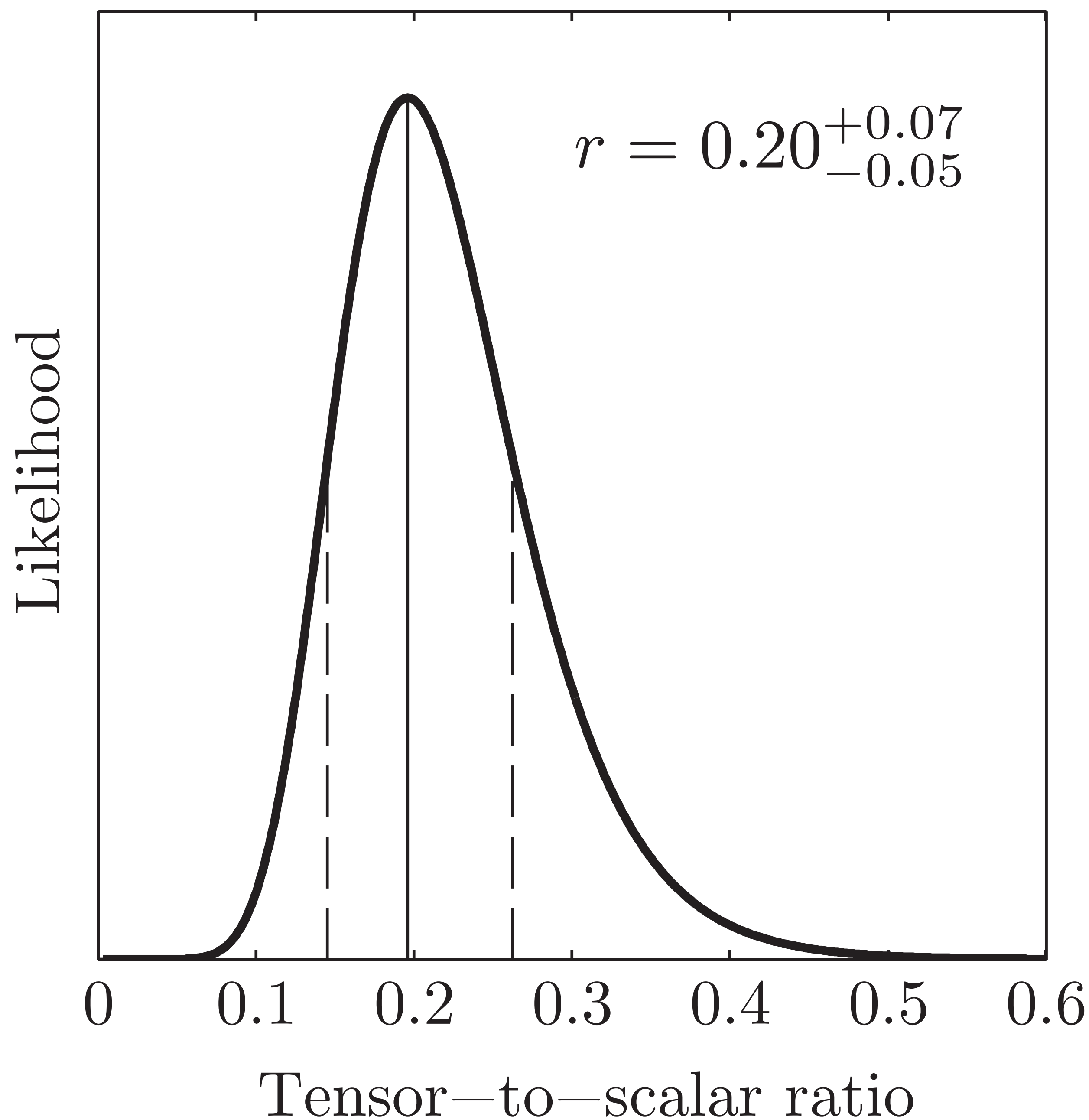

BICEP2: E signal
Simulation: E from lensed–ΛCDM+noise
BICEP2: B signal
Simulation: B from lensed–ΛCDM+noise
1.7μK
0.3μK
−50
−55
−60
−65
50
0
−50
Right ascension [deg.]
1.8
0
−1.8
0.3
−0.3
μK

Systematics

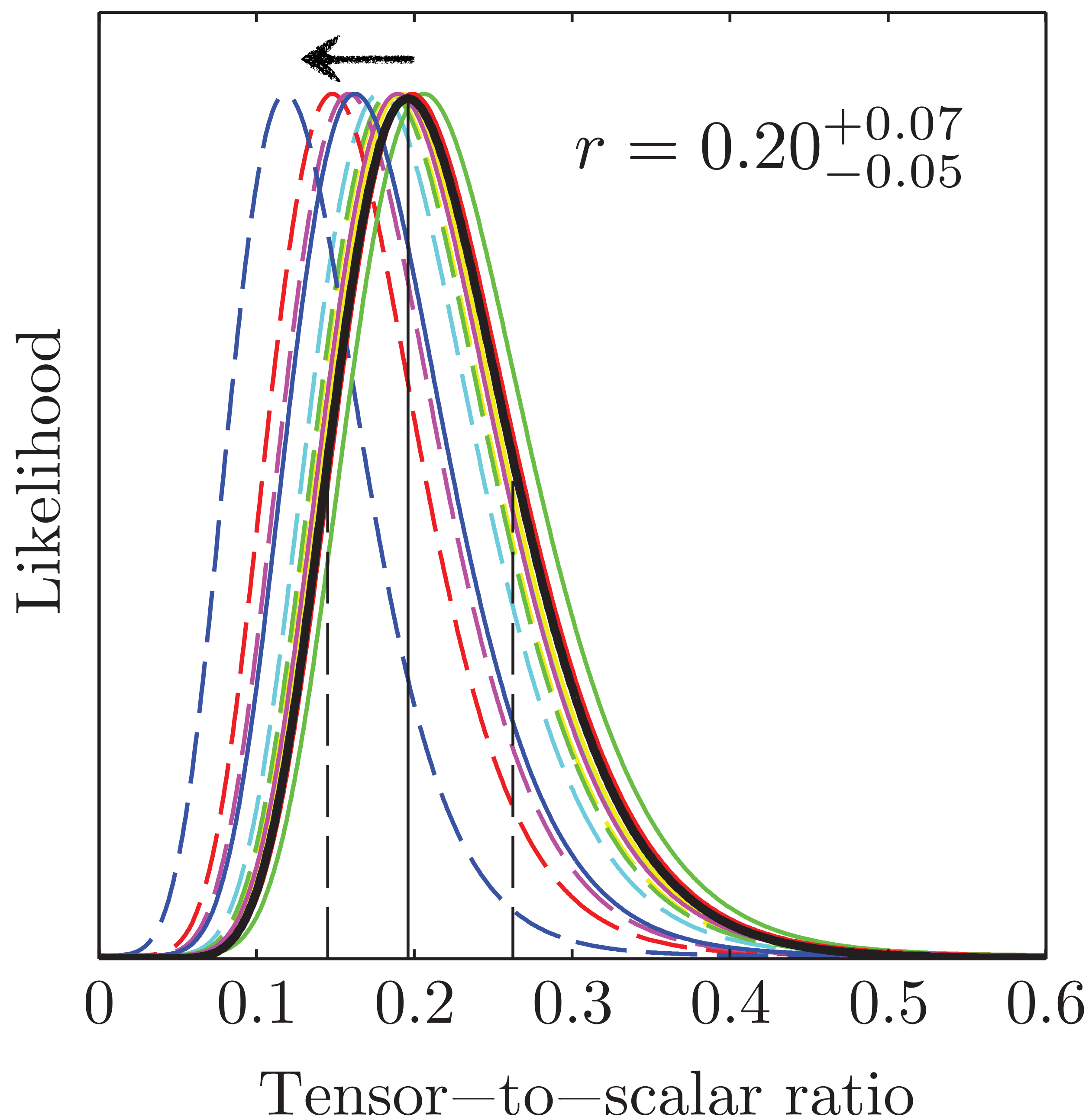


Systematics contamination much smaller than observed excess

Tensor/scalar ratio *r*



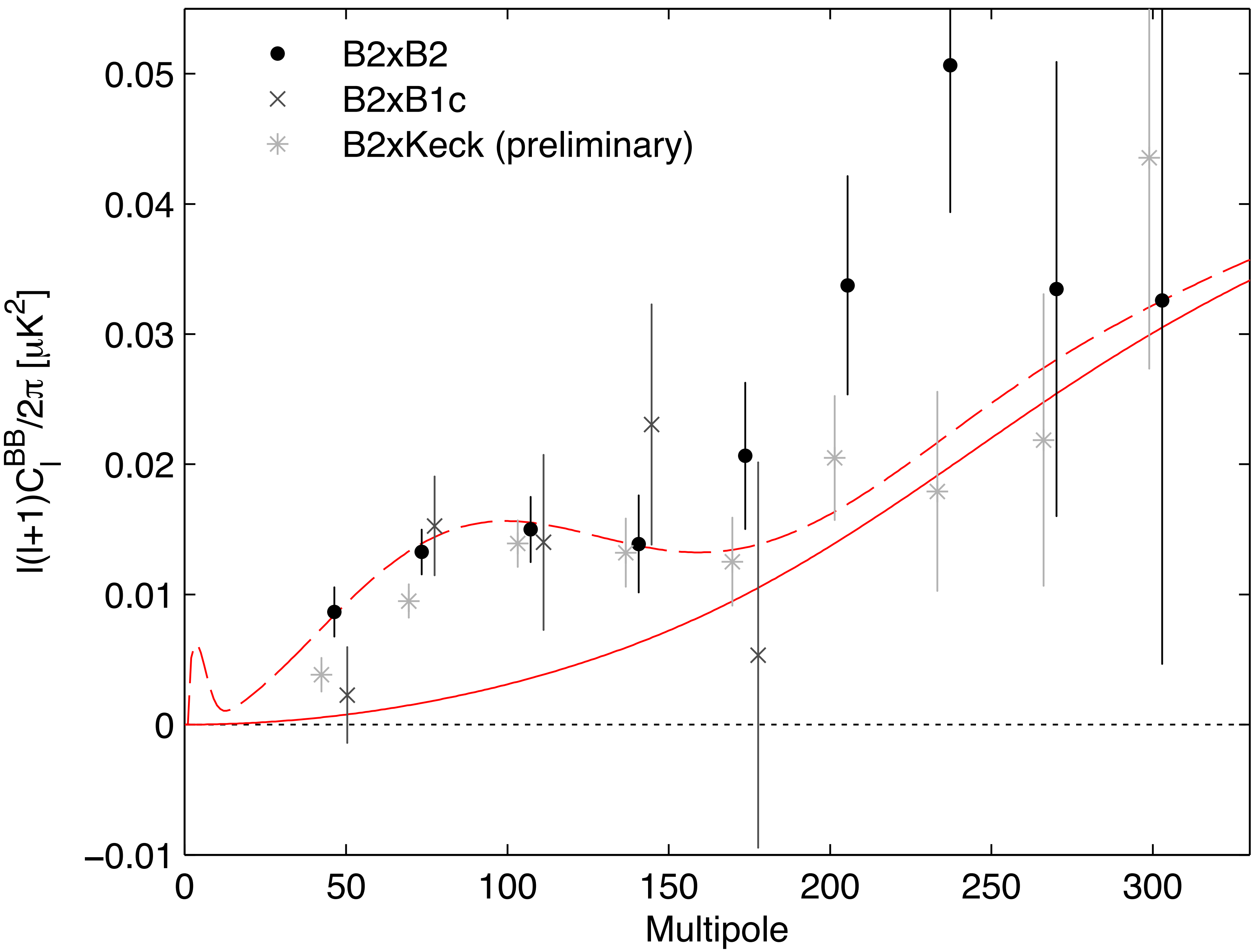
Effect of foregrounds on *r*



Foreground subtraction tends to reduce the value of r = tensor/scalar ratio

After known foreground subtraction: $r = 0.16^{+0.06}_{-0.05}$

Main concern: a single frequency



BICEP2 auto-spectrum compatible with correlating with 100 GHz BICEP1 and Keck-Array. Spectral index consistent with that of CMB, disfavoring synchrotron and dust at ~2.2σ.