Strings and the CMB

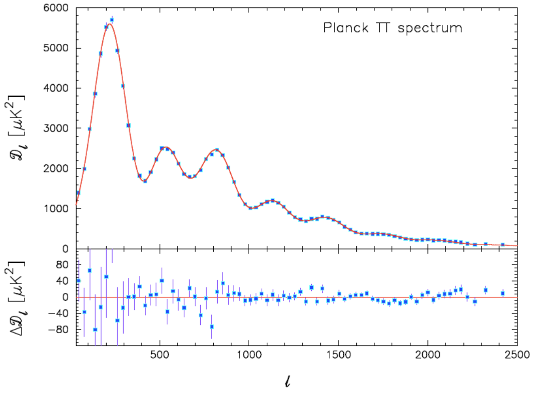
(not a review)

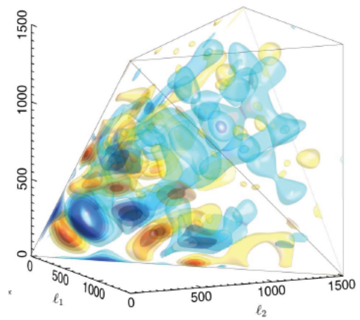
work with V. Atal, S. Cespedes, J-O. Gong, S. Hardeman, S. Mooij, P. Ortiz, G. Palma, S. Patil, M. Postma, J. Torrado

A. Achucarro (Leiden/UPV-EHU Bilbao)

The String Theory Universe, Mainz, 22/9/14

The 2013-2014 roller-coaster





March 2013: Planck's primordial bispectrum

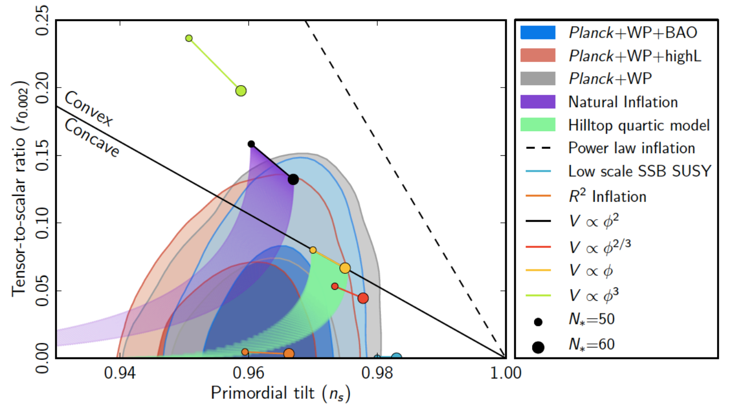
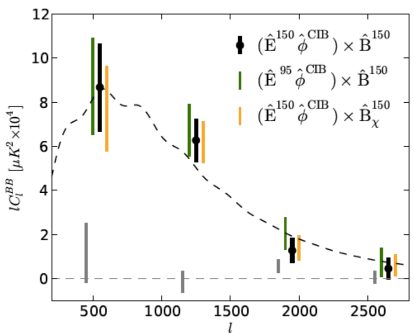


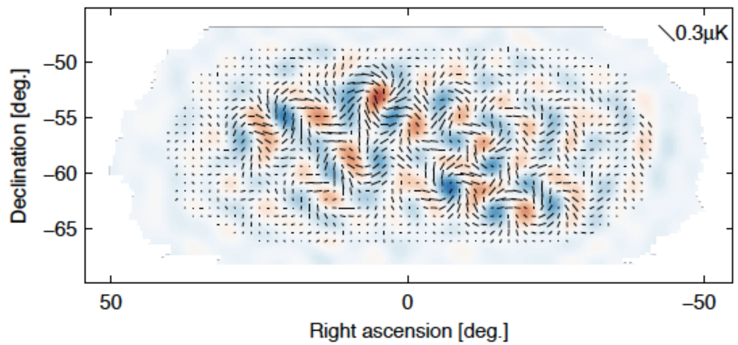
Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

July 2013: South Pole Telescope's First detection of lensing B-modes

March 2014: Polarbear



March 2014: BICEP2's first detection of B-modes on degree angular scales



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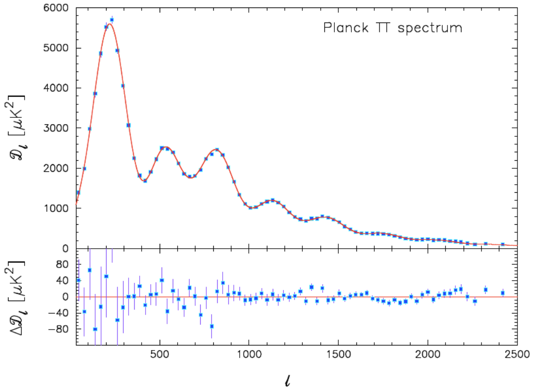
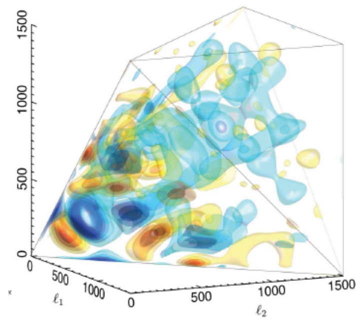
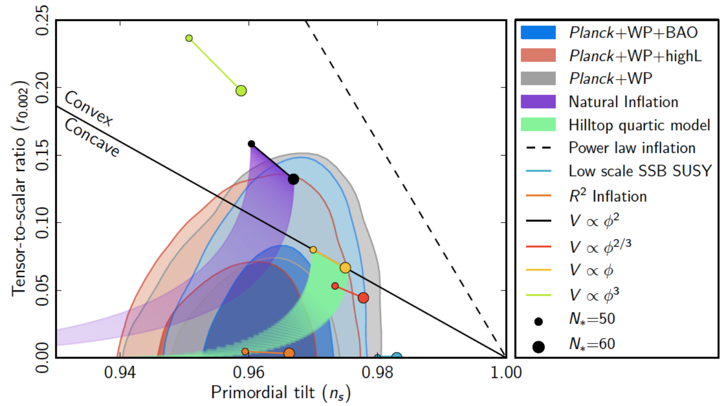




March 2013: Planck's primordial bispectrum



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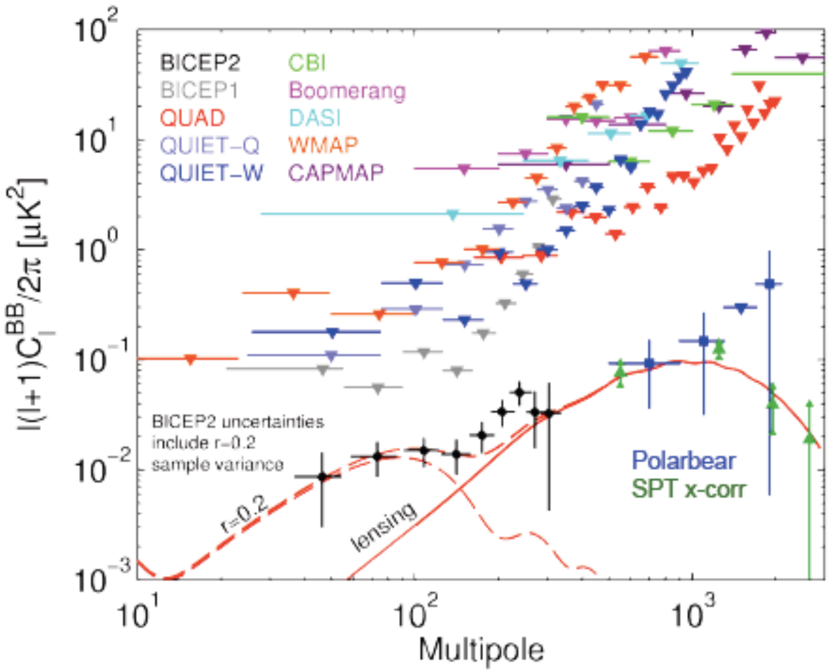
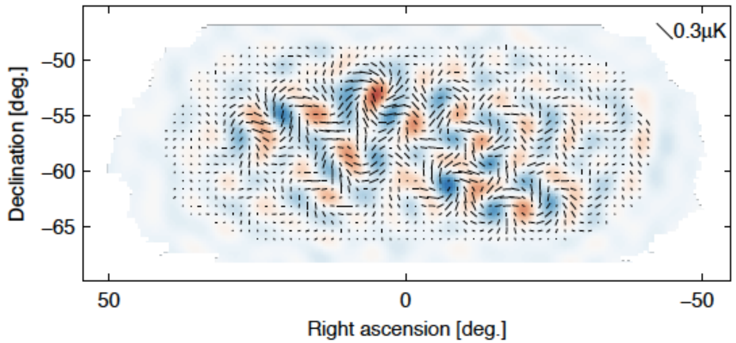


March 2014: BICEP2's first detection of B-modes on degree angular scales



A temperature quadrupole generates net polarization

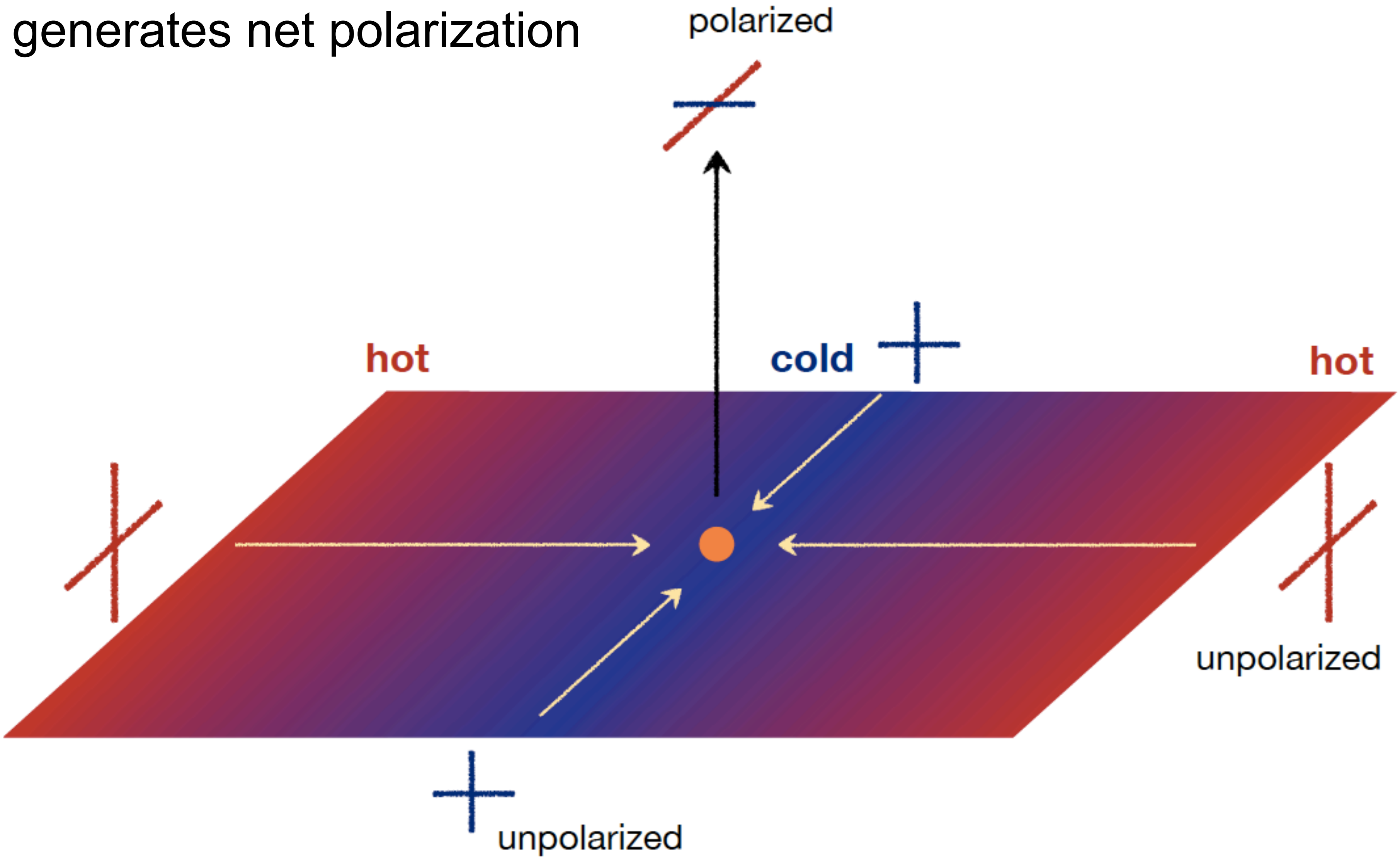
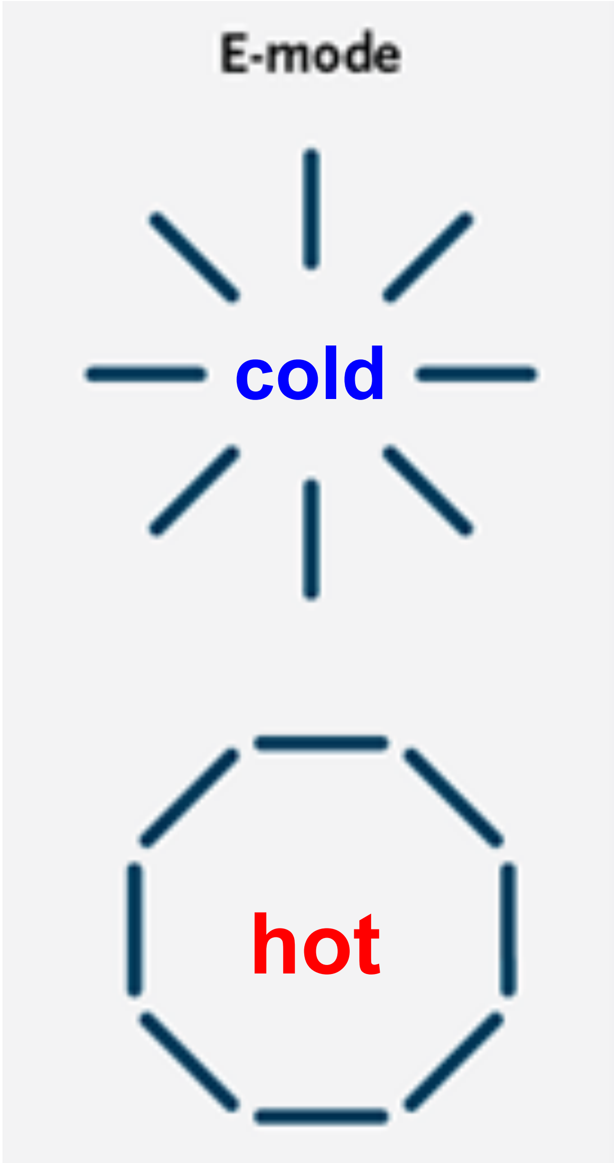
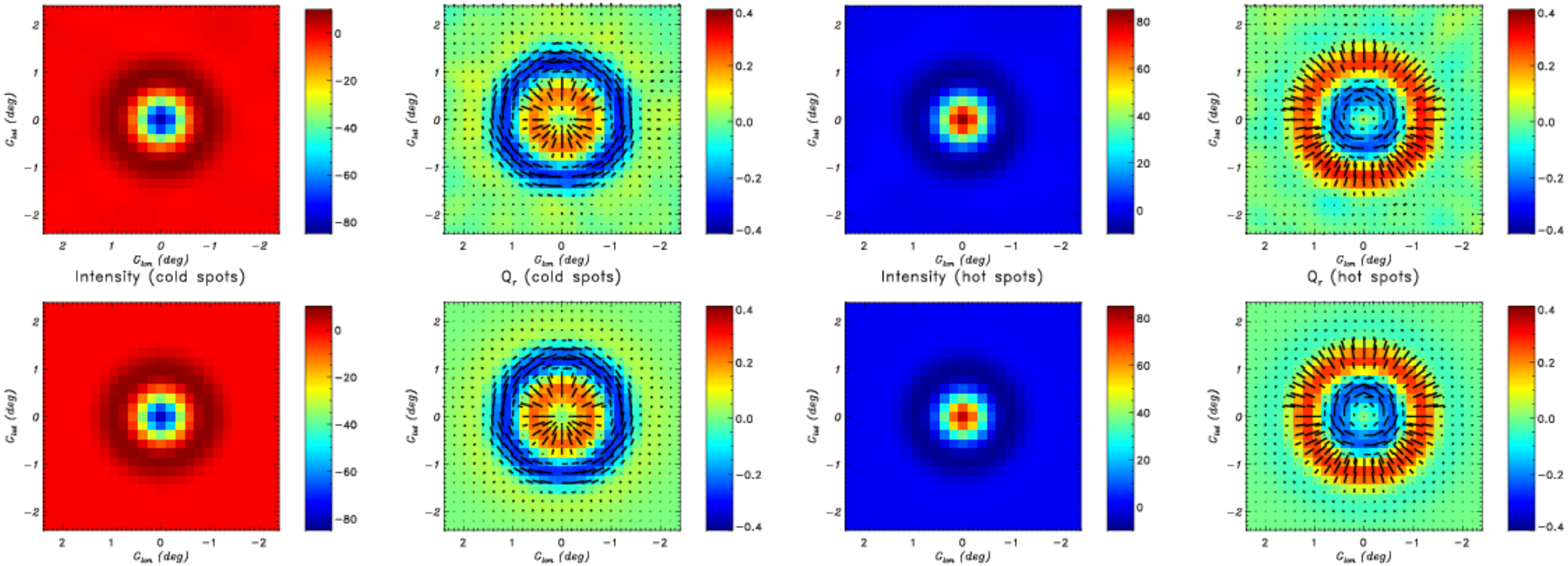


image: Daniel Baumann

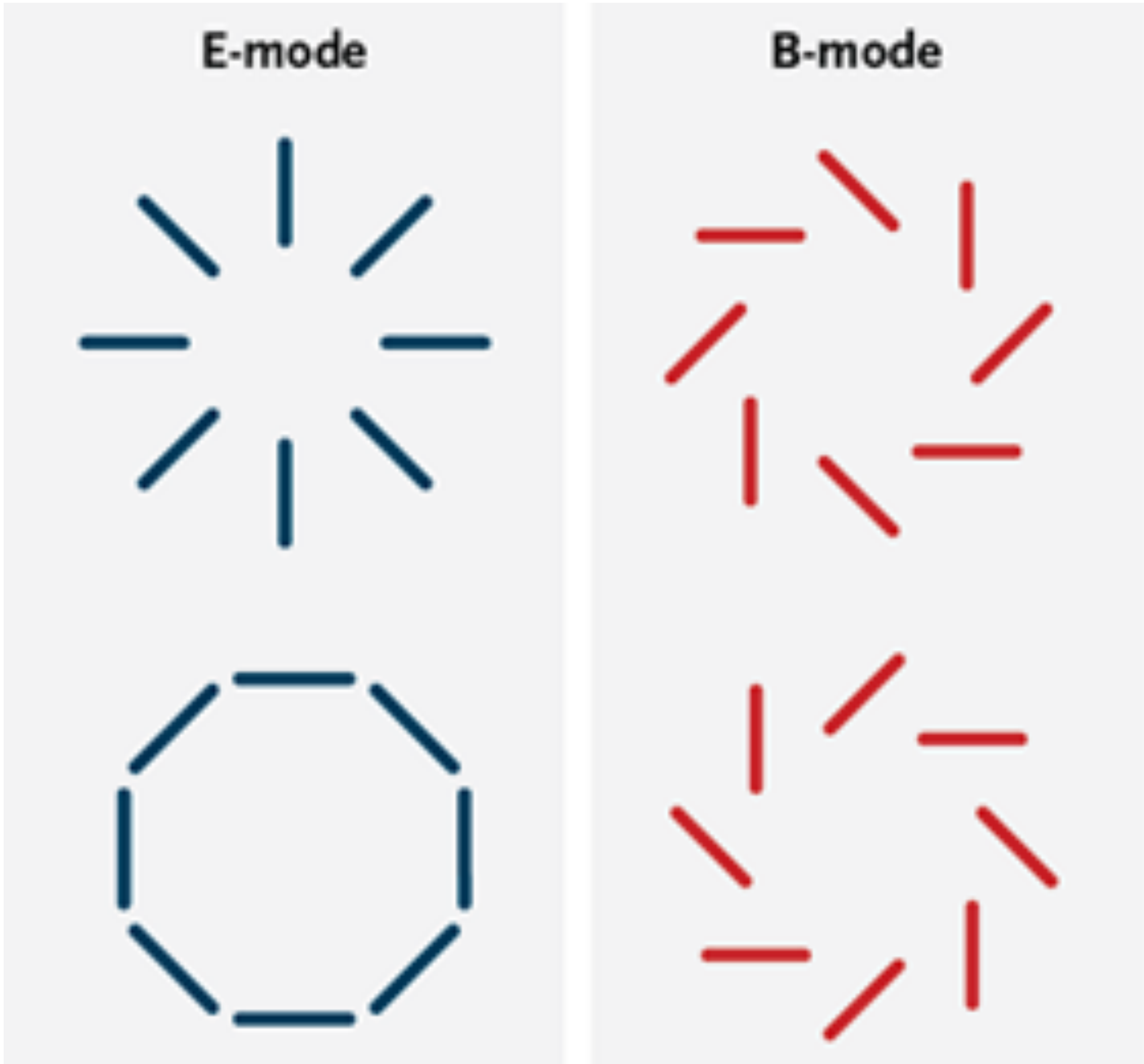


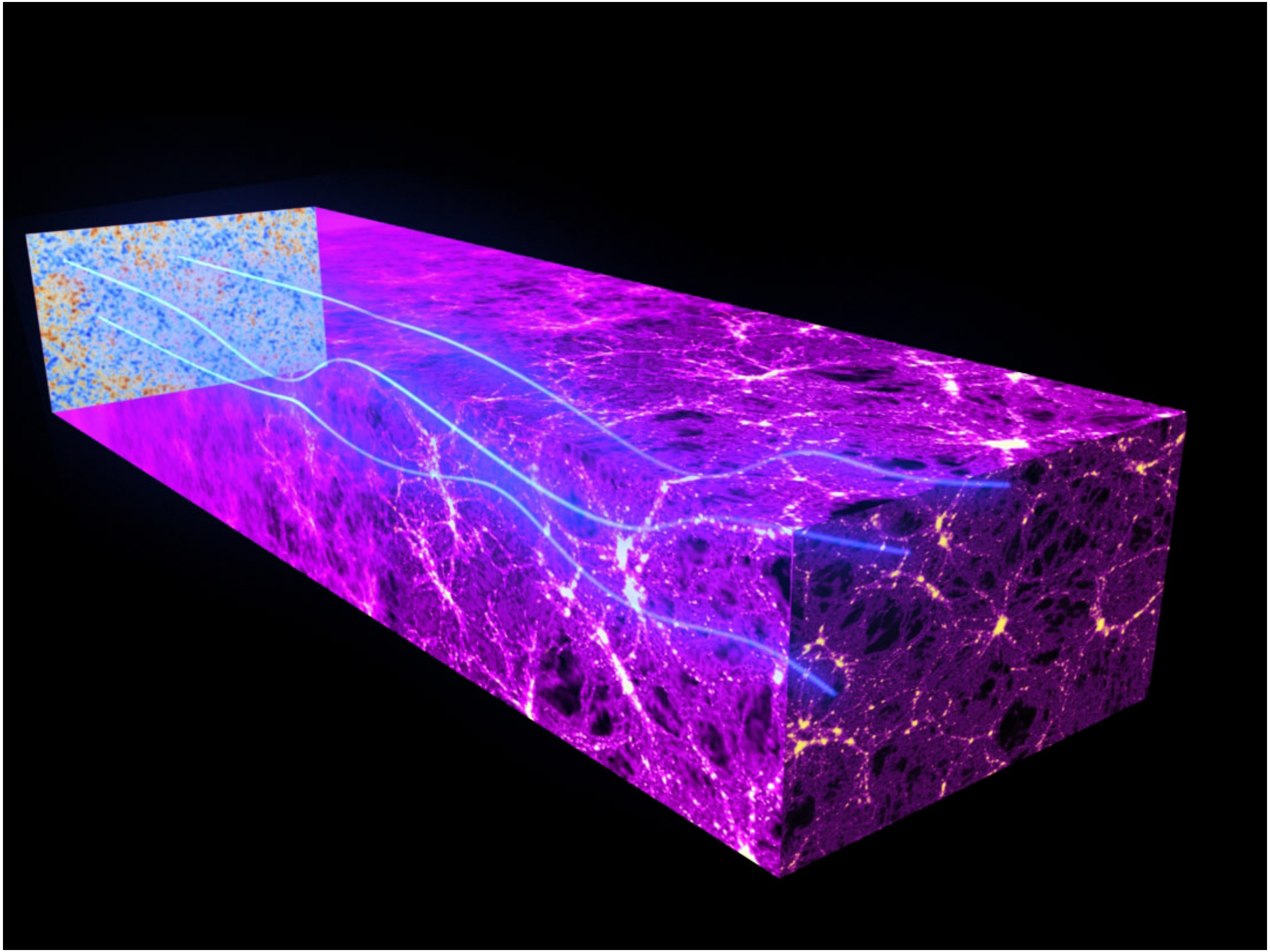
Primordial density fluctuation: correlated patterns

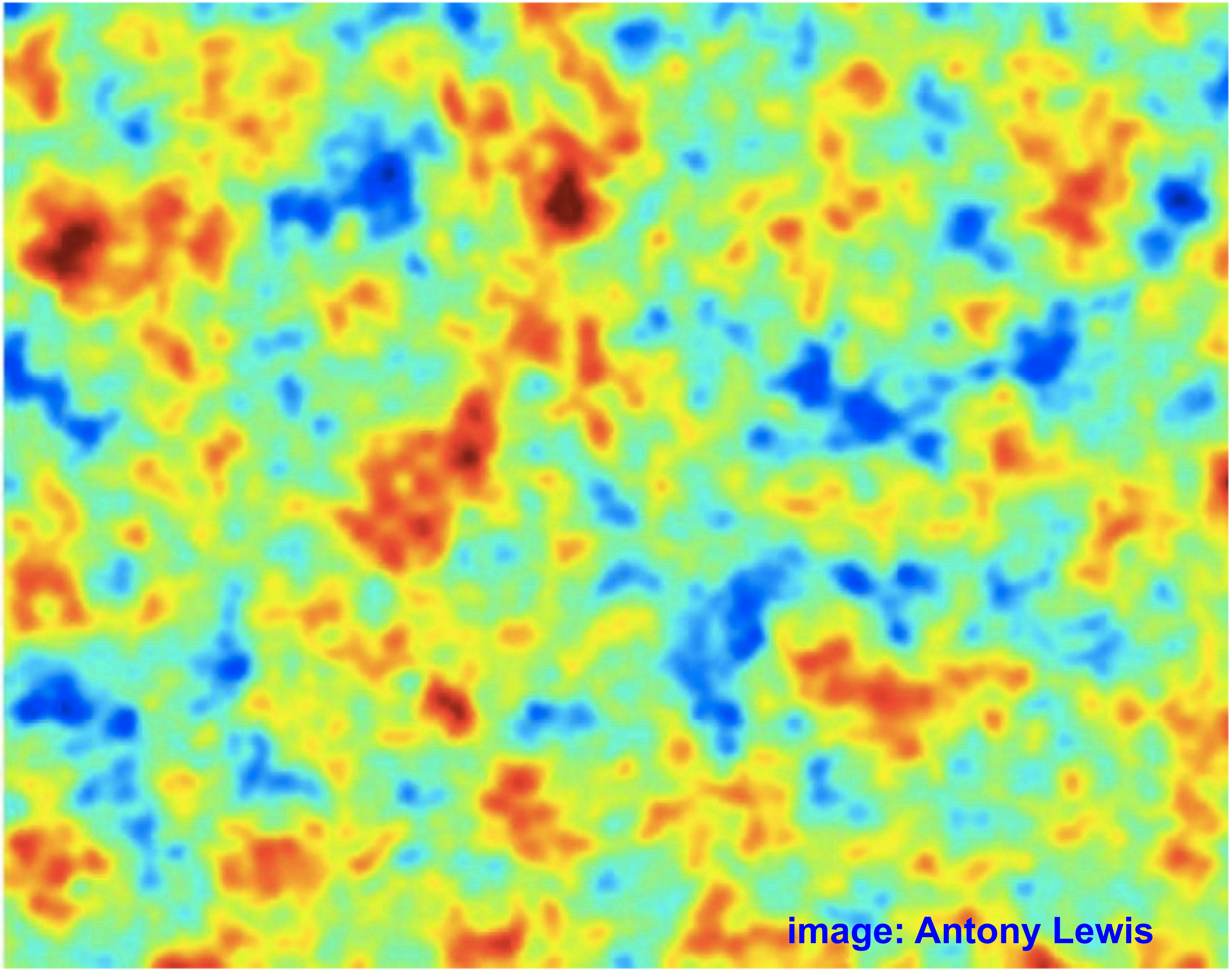
PLANCK 2013



Intensity (cold spots)
Q_r (cold spots)
Intensity (hot spots)
Q_r (hot spots)
G_lon (deg)
G_lat (deg)
0
−20
−40
−60
−80
0.4
0.2
0.0
−0.2
−0.4
80
60
40
20
0

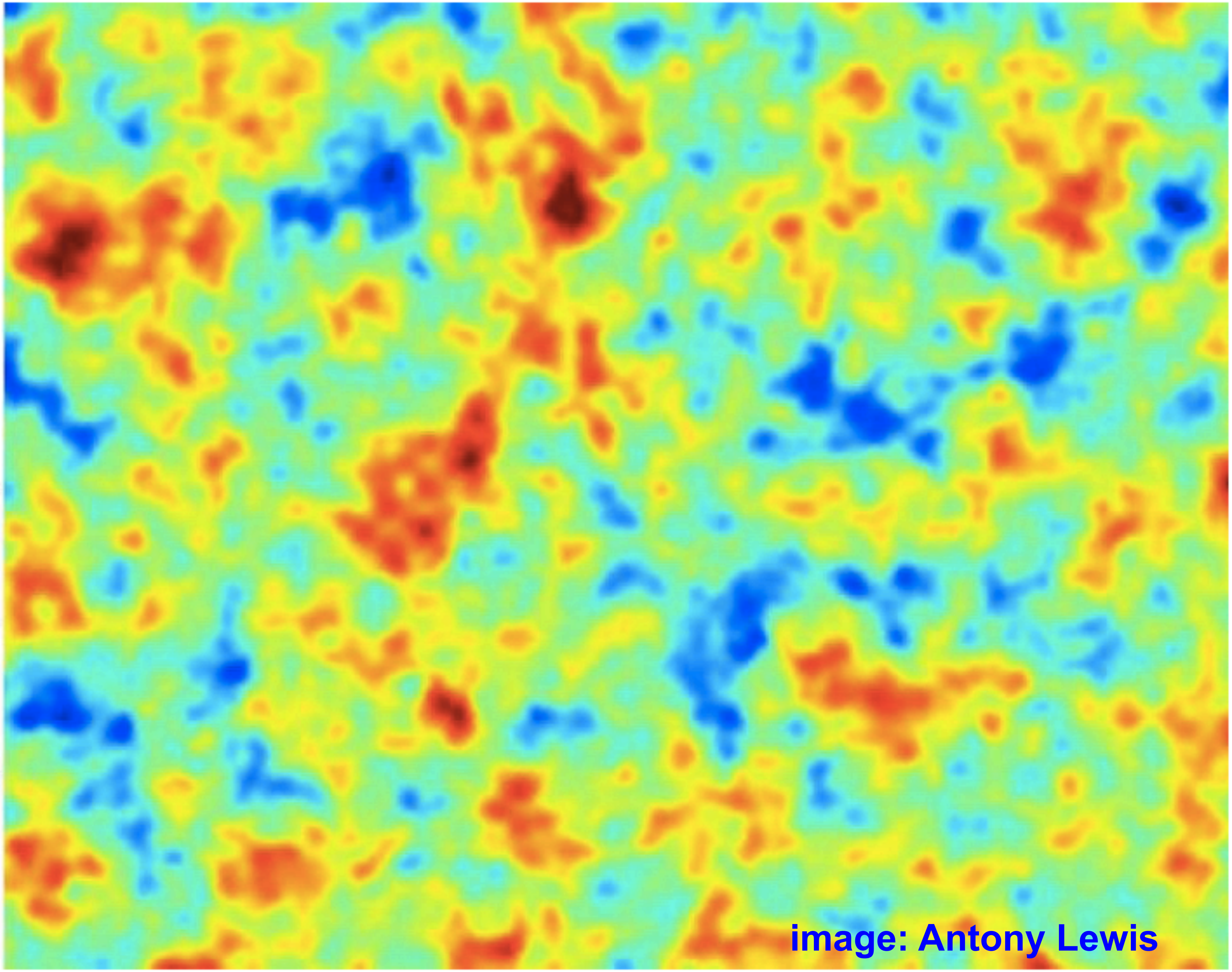

E-mode
B-mode



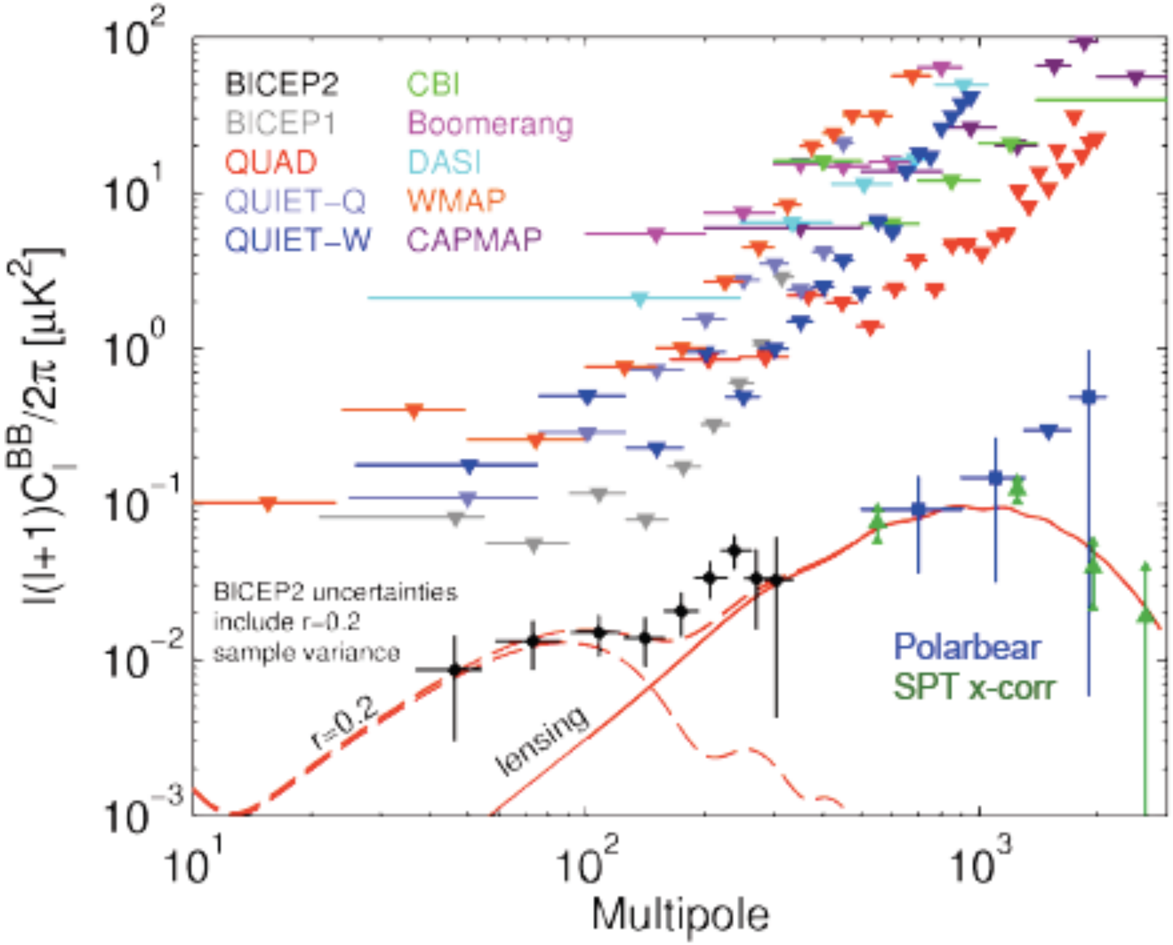


CMB Temperature (Unlensed)

CMB Temperature (Lensed)



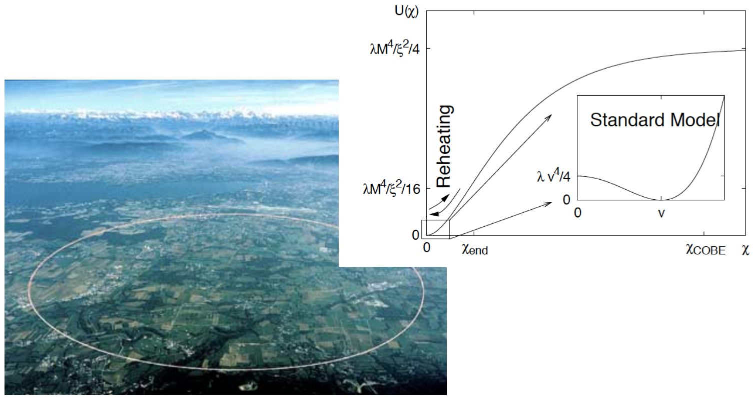
Kovac's talk at Strings 2014



but we have to wait to see if Bicep2 signal is indeed primordial

Occam's razor

Bezrukov Shaposhnikov 2008



"Just" the Higgs,

+ non-minimal coupling to gravity

Higgs inflation

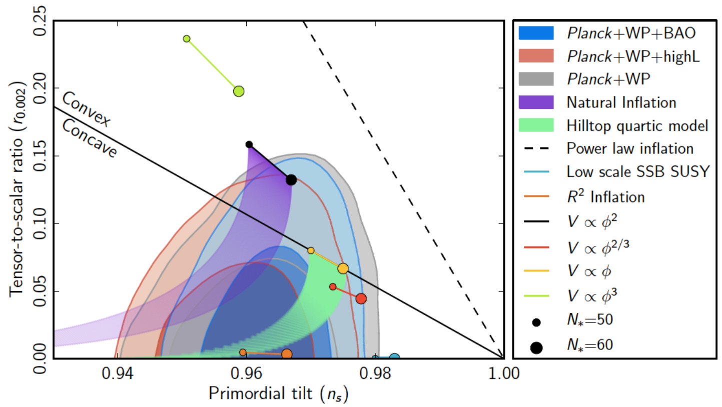


Fig. 1. Marginalized joint 68% and 95% CL regions for n_s and $r_{0.002}$ from *Planck* in combination with other data sets compared to the theoretical predictions of selected inflationary models.

Sterile neutrino dark matter ?

DETECTION OF AN UNIDENTIFIED EMISSION LINE IN THE STACKED X-RAY SPECTRUM OF GALAXY CLUSTERS

Esra Bulbul[1,2], Maxim Markevitch[2], Adam Foster[1], Randall K. Smith[1] Michael Loewenstein[2], and Scott W. Randall[1]

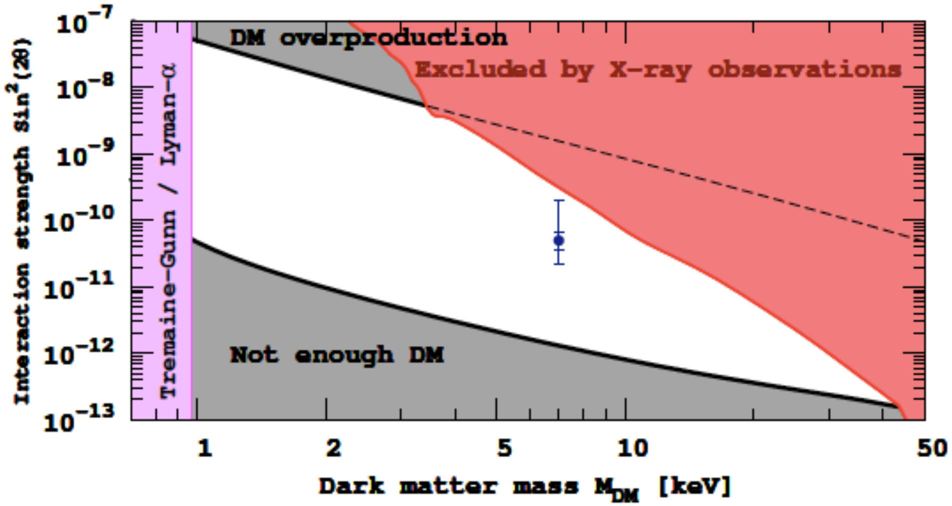
[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138.
[2] NASA Goddard Space Flight Center, Greenbelt, MD, USA.

Submitted to ApJ, 2014 February 10

An unidentified line in X-ray spectra of the Andromeda galaxy and Perseus galaxy cluster

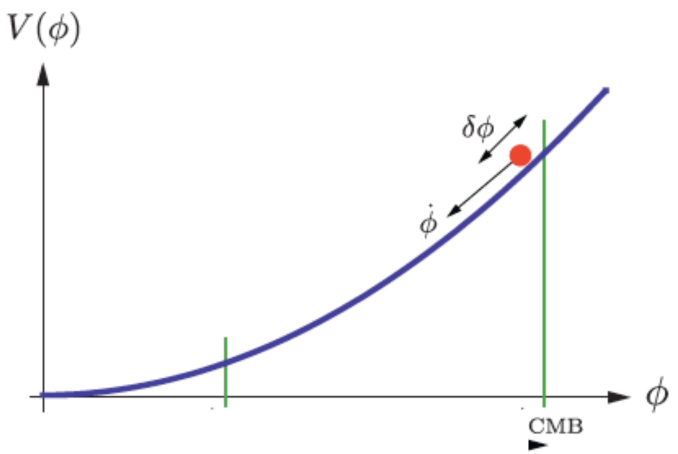
A. Boyarsky[1], O. Ruchayskiy[2], D. Iakubovskyi[3,4] and J. Franse[1,5]

[1] Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands
[2] Ecole Polytechnique Fédérale de Lausanne, FSB/ITP/LPPC, BSP, CH-1015, Lausanne, Switzerland
[3] Bogolyubov Institute of Theoretical Physics, Metrologichna Str. 14-b, 03680, Kyiv, Ukraine
[4] National University "Kyiv-Mohyla Academy", Skovorody Str. 2, 04070, Kyiv, Ukraine
[5] Leiden Observatory, Leiden University, Niels Bohrweg 2, Leiden, The Netherlands



… or Occam's razor?

Linde 1983



$$V(\phi) = \frac{1}{2} m^2 \phi^2$$

canonical, single-field
chaotic inflation

field excursion superplanckian
large field

GUT scale

Kallosh, Linde, Roest 2013

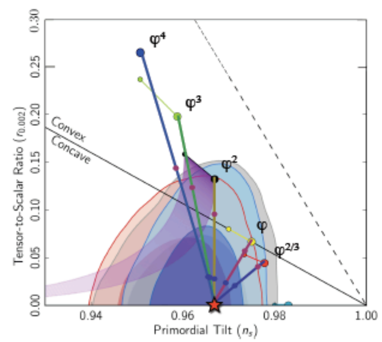


Figure 2: *The cosmological observables (n_s, r) for different scalar potentials $\tanh^{2n}(\frac{\varphi}{\sqrt{6\alpha}})$ with $2n = (2/3, 1, 2, 3, 4)$ for $N = 60$. These continuously interpolate between the predictions of the simplest inflationary models with the monomial potentials φ^{2n} for $\alpha \to \infty$, and the attractor point $n_s = 1 - 2/N$, $r = 0$ for $\alpha \to 0$, shown by the red star. The different trajectories form a fan-like structure for $\alpha \gg n^2$. The set of dark red dots at the upper parts of the interpolating straight lines corresponds to $\alpha = 100$. The set of dark blue dots corresponds to $\alpha = 10$. The lines gradually merge for $\alpha = O(1)$.*

See talks by Kallosh, Shiu,
Zavala, Blumenhagen, Ibáñez

Single-field inflation assumes all other fields are decoupled from the inflaton during inflation.

Not so easy to achieve in string theory (or SUGRA)

inflation is UV sensitive

It opens the possibility to **detect** heavy fields that interact with the inflaton

e.g. through **changes in the speed of sound** of the perturbations

The effective field theory of (the fluctuations of) single-field inflation:

Cheung, Creminelli, Fitzpatrick, Kaplan, Senatore JHEP 2008 0709.0293

$$S = \int \sqrt{-g}\, d^4x \left[\frac{M_{\rm Pl}^2}{2} R - \frac{1}{2} \gamma_{ab} g^{\mu\nu} \partial_\mu \phi^a \partial_\nu \phi^b - V(\phi) \right] \ldots]$$

or

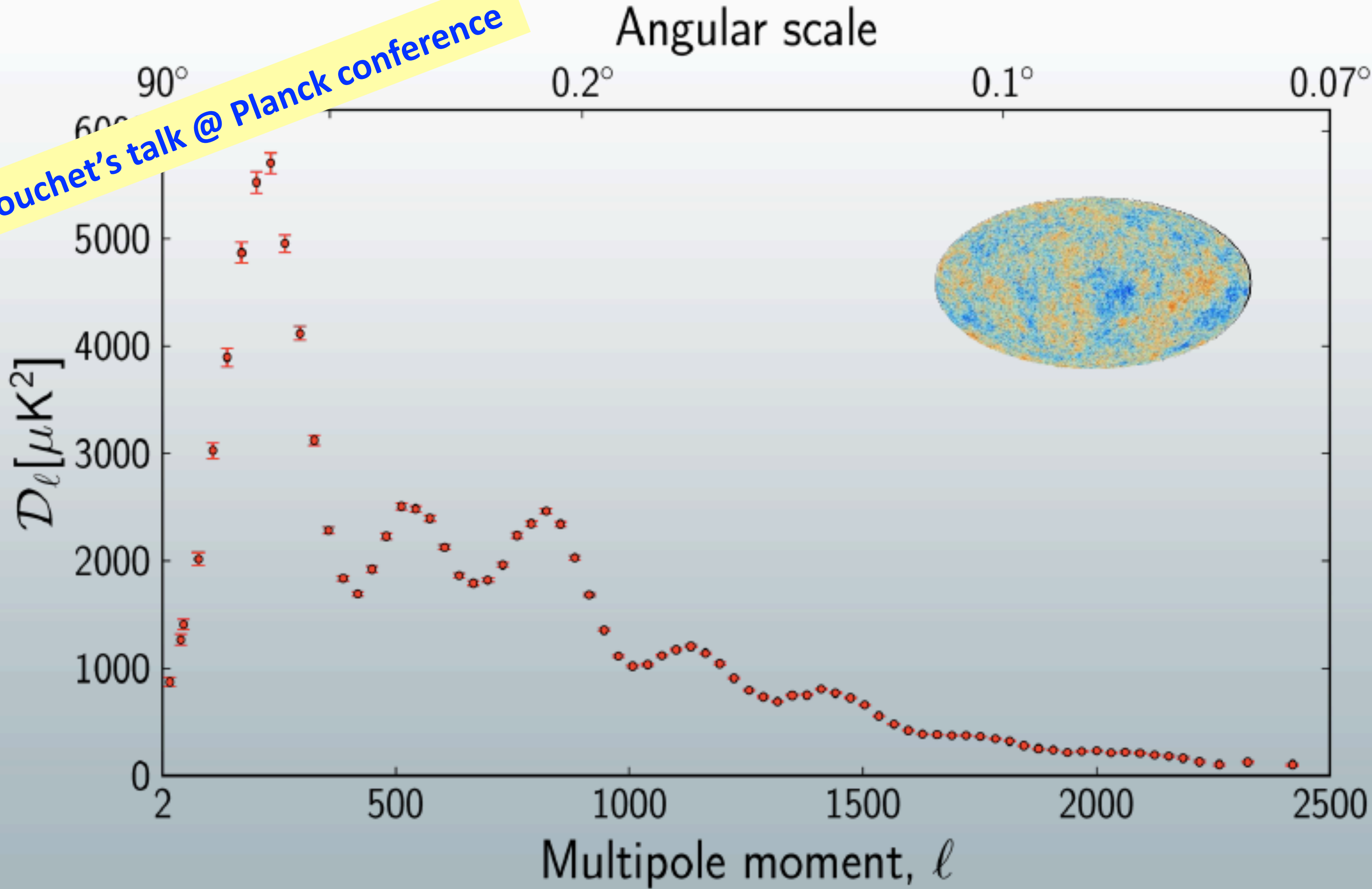
$$c_s^{-2} = 1 - \frac{2M_2^4}{M_{\rm Pl}^2 \dot{H}}$$

$$S_\pi = \int d^4x \, \sqrt{-g} \left[-\frac{M_{\rm Pl}^2 \dot{H}}{c_s^2} \left(\dot{\pi}^2 - c_s^2 \frac{(\partial_i \pi)^2}{a^2} \right) + M_{\rm Pl}^2 \dot{H} \left(1 - \frac{1}{c_s^2} \right) \left(\dot{\pi}^3 - \dot{\pi} \frac{(\partial_i \pi)^2}{a^2} \right) - \frac{4}{3} M_3^4 \dot{\pi}^3 \ldots \right]$$

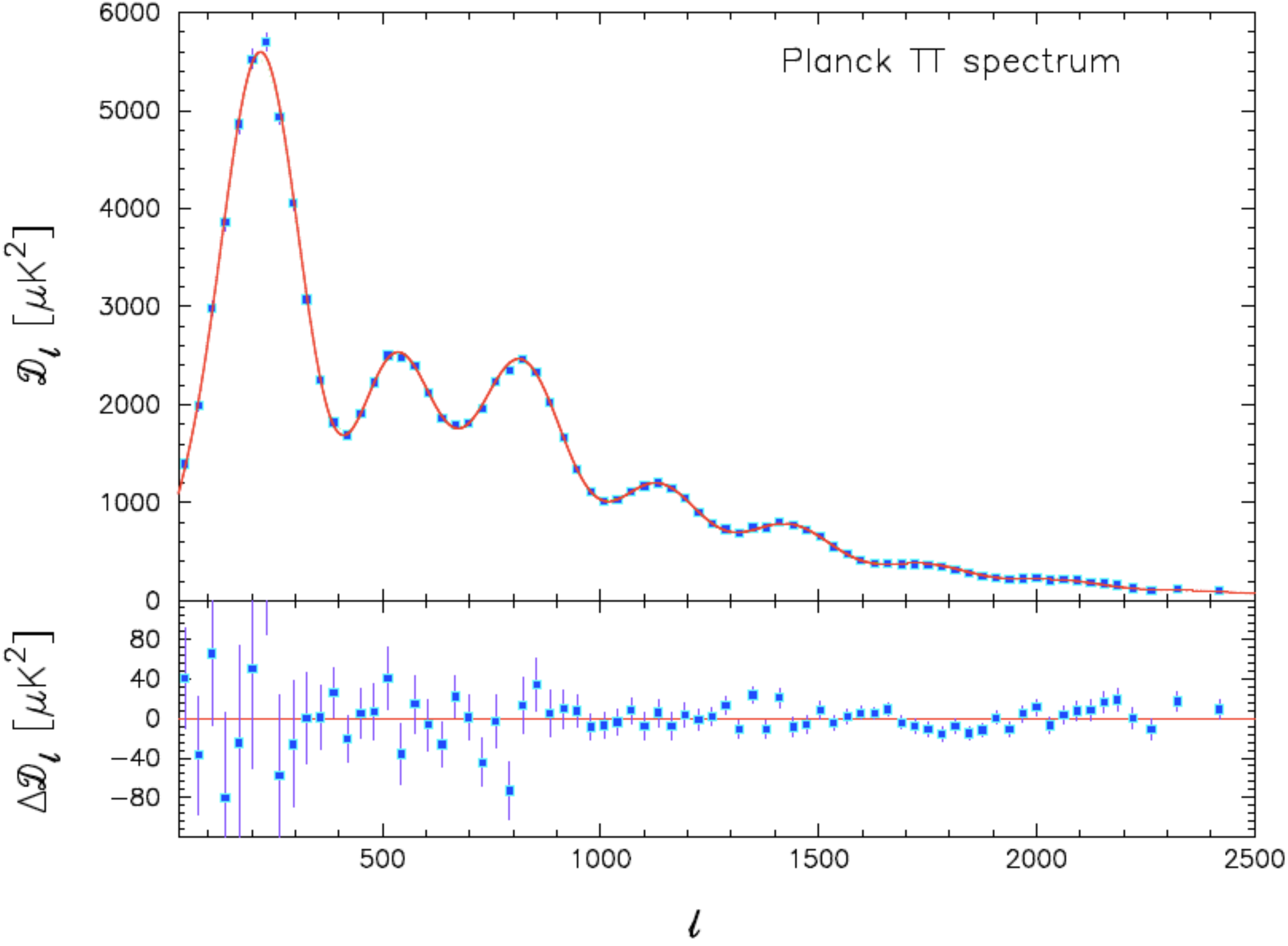
Π is the Goldstone boson of broken time-translations

$$g_{ij} = a^2(t) \left[(1 + 2\zeta(t, \vec{x}))\delta_{ij} + \gamma_{ij} \right] \qquad \zeta(t, \vec{x}) = -H\pi(t, \vec{x})$$

The Planck spectrum of Temperature anisotropies



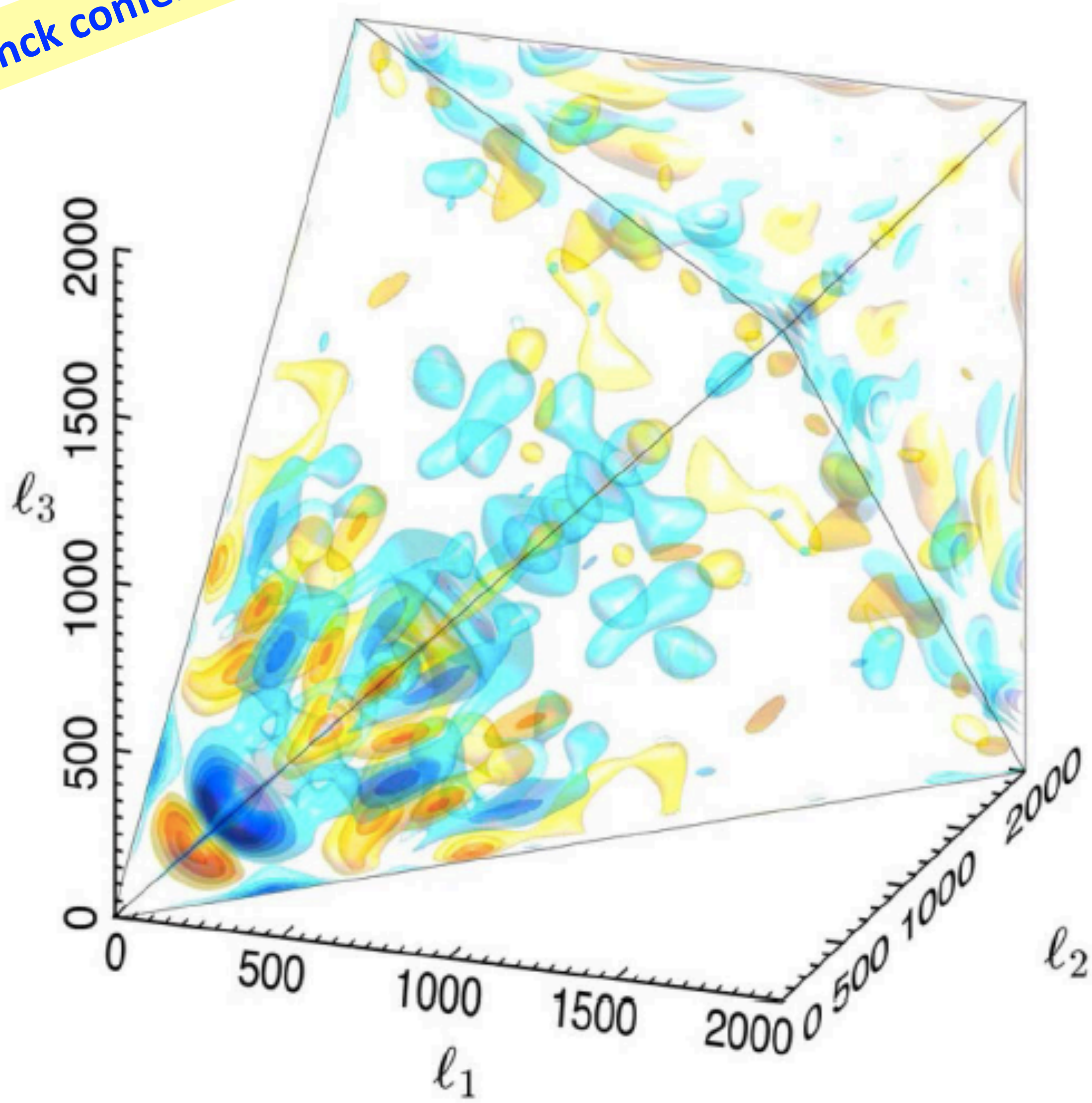
Bouchet's talk @ Planck conference



Planck TT spectrum
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell$ [μK^2]
80
40
0
−40
−80
$\Delta\mathcal{D}_\ell$ [μK^2]
500
1000
1500
2000
2500
ℓ

The Planck bi-spectrum of Temperature anisotropies

Bouchet's talk @ Planck conference



Bouchet's talk @ Planck conference

Conclusions

- Ω_K=-0.006±0.018 at 95%CL from Planck-T+Planck-L (PT+PL)
- f_{NL}^{LEO} is consistent with zero; f_{NL}^{local} = 2.7±5.8, f_{NL}^{equi} =-42±75, f_{NL}^{orth}=-25±39; (and other shapes)
- No evidence for defects. Nambu-Goto strings have $G\mu/c^2 < 1.3 \times 10^{-7}$ ($\eta < 4.7 \times 10^{15}$ GeV)

- n_s=0.963 ±0.006 from PT+WP+BAO; HZ robustly excluded (even N_{eff} or Y_p worse by $\Delta\chi^2_{eff}$ = 4.6, 8)
- No evidence for running (nor running of running)
- $r_{0.002}$ < 0.12 (PTWP) → inflation energy scale < 1.9×10^{16} GeV (or $H_* < 3.7 \times 10^{-5}$Mp) at 95%CL
- Concave potential preferred. Exponential potential, monomial with p>2, hybrid driven by quadratic term are all disfavored at more than 95% confidence. Simple Quadratic large field at the edge...
- Strong constraints on parameters values of specific inflationary scenario (e.g. limit on scale parameter of natural inflation),
- Planck limits possibilities for unknown physics between end of inflation and the beginning of the radiation era (w_{int}).
- Potential reconstructed in observable window shows that allowing a fourth order leads to deviation to slow-roll, and allows to better fit the low-l (improvement of $\Delta\chi^2_{eff}$ ~4)
- Penalized Likelihood reconstruction of primordial spectrum hints at features; parameterized models (as motivated by NBD, axion monodromy or step in the potential) improve $\Delta\chi^2_{eff}$ by ~10, but no strong Bayesian evidence. Polarization will help .
- No strong evidence for non-decaying isocurvature modes (one at a time, but arbitrarily correlated to adiabatic mode). Axion and curvaton scenario (either uncorrelated or fully correlated) are not favored. But arbitrary correlation help lowering the low-l part of the spectrum ($\Delta\chi^2_{eff}$ >4)

- *Excellent agreement between the Planck CMB data at high l and the predictions of the ΛCDM model using the simplest slow-roll inflationary models, but with tantalizing hints both at low-l (<30) and high-l...*

Bouchet's talk @ Planck conference

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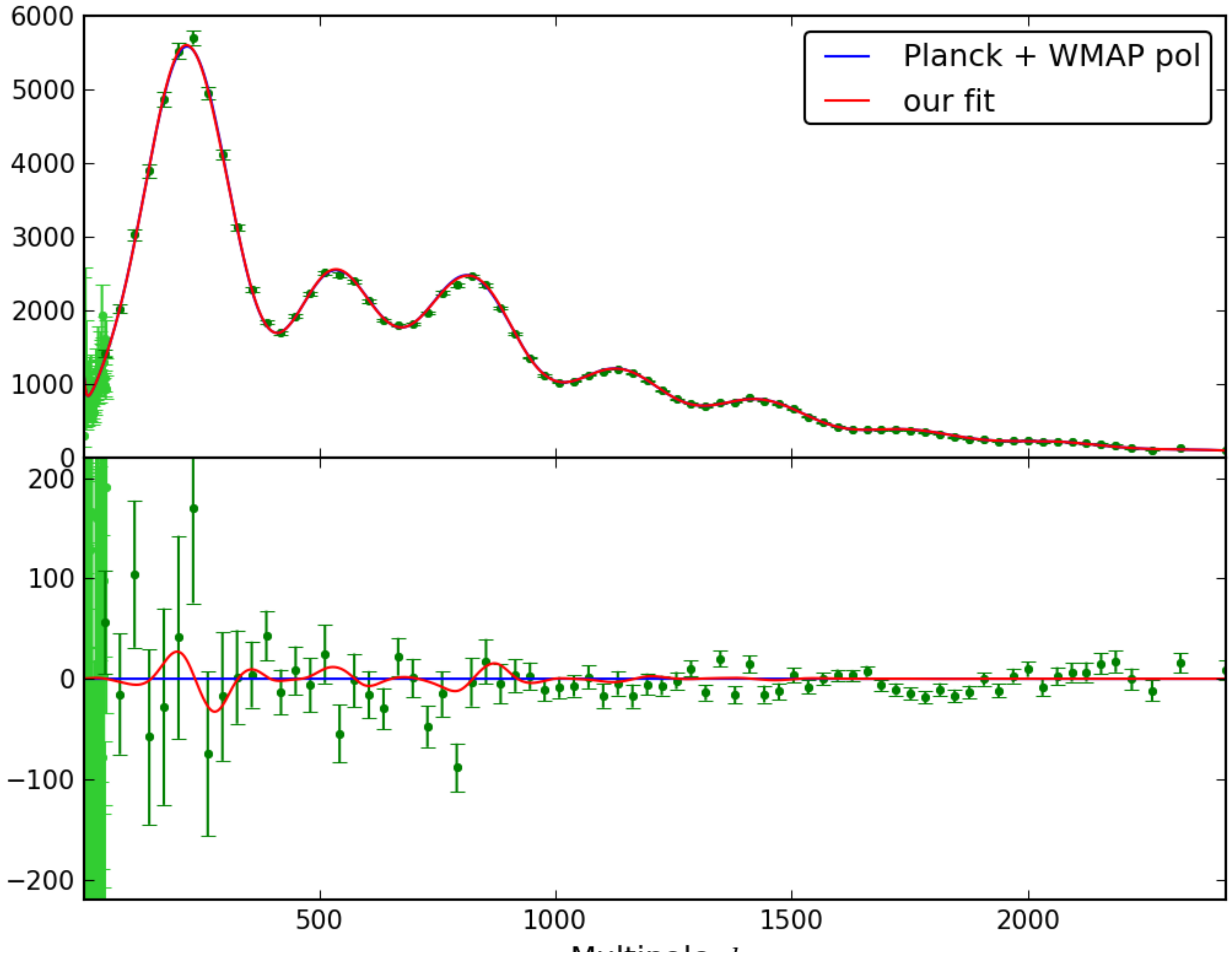


Planck + WMAP pol
our fit
6000
5000
4000
3000
2000
1000
0
200
100
0
−100
−200
500
1000
1500
2000

Inflation in multi-scalar theories

single-field or multi-field ?

Inflation

(accelerated expansion)

-dilutes massive relics (e.g. monopoles)

-solves horizon problem

-solves flatness problem if it lasts long enough (~ 55 e-folds)

-gives mechanism for approximately scale invariant primordial inhomogeneities (from quantum fluctuations)

-produces a background of gravitational waves

Single-field slow-roll inflation with **canonical** kinetic terms
predicts perturbations that are

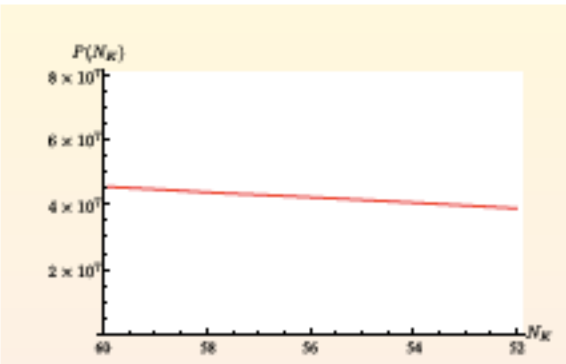
and Bunch Davies vacuum,
minimal coupling to gravity

adiabatic
near scale-invariant
almost gaussian

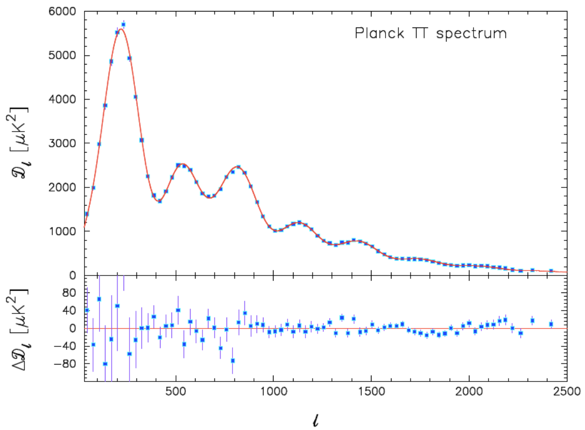
self-interactions (in the potential) are limited by the slow roll condition

Bispectrum is negligible, O(slow roll)

Primordial power spectrum

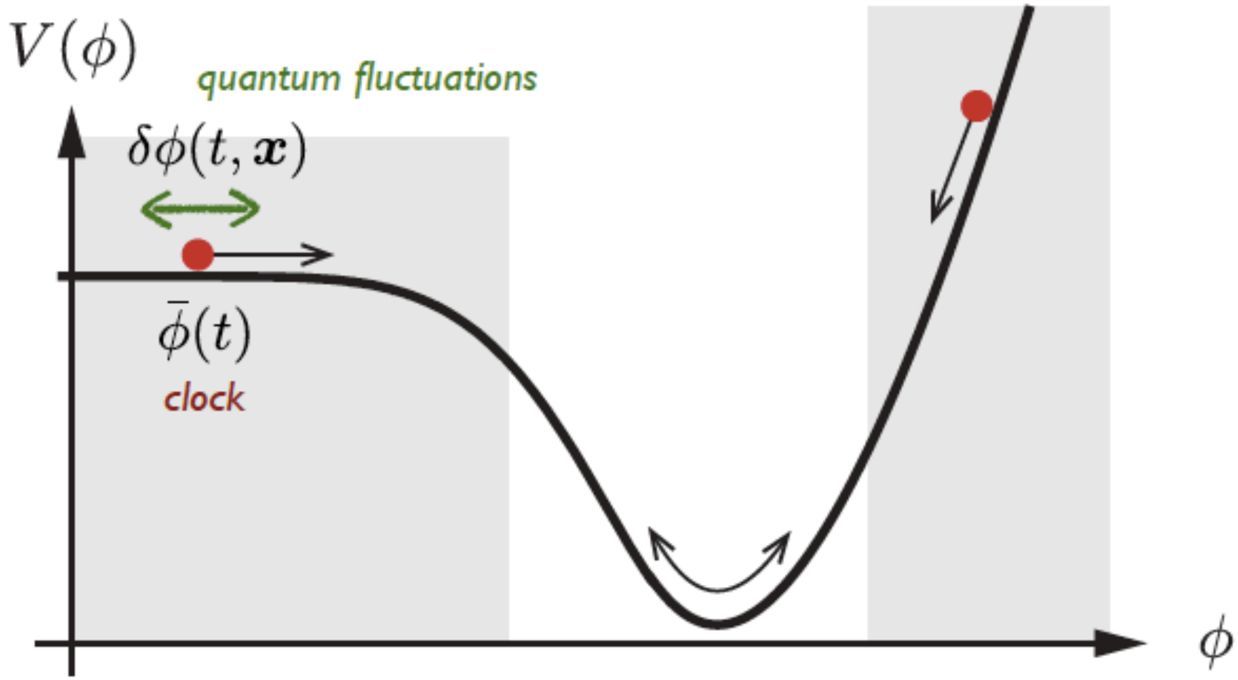


CMB power spectrum



Baumann's 2013 lectures @ Varenna

The quantum origin of density perturbations is quite intuitive:



vacuum fluctuations spread the inflaton vev ...

... which translates into density fluctuations after inflation

$$\delta\phi(\boldsymbol{x}) \longrightarrow \delta t(\boldsymbol{x}) \longrightarrow \delta\rho(\boldsymbol{x}) \longrightarrow \delta T(\boldsymbol{x})$$

... which induces a local time delay for the end of inflation

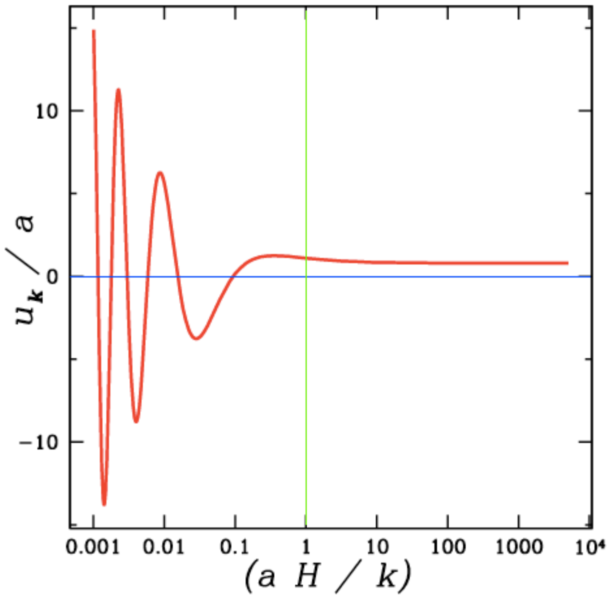
... which become the CMB anisotropies.

Fluctuation equations are like a simple harmonic oscillator
with friction from the expansion

$$\delta\ddot{\phi}_k + 3H\,\delta\dot{\phi}_k + \frac{k^2}{a^2}\delta\phi_k + \ldots = 0$$

Large k "inside the horizon" : friction negligible

Small k "outside the horizon" : friction dominates,



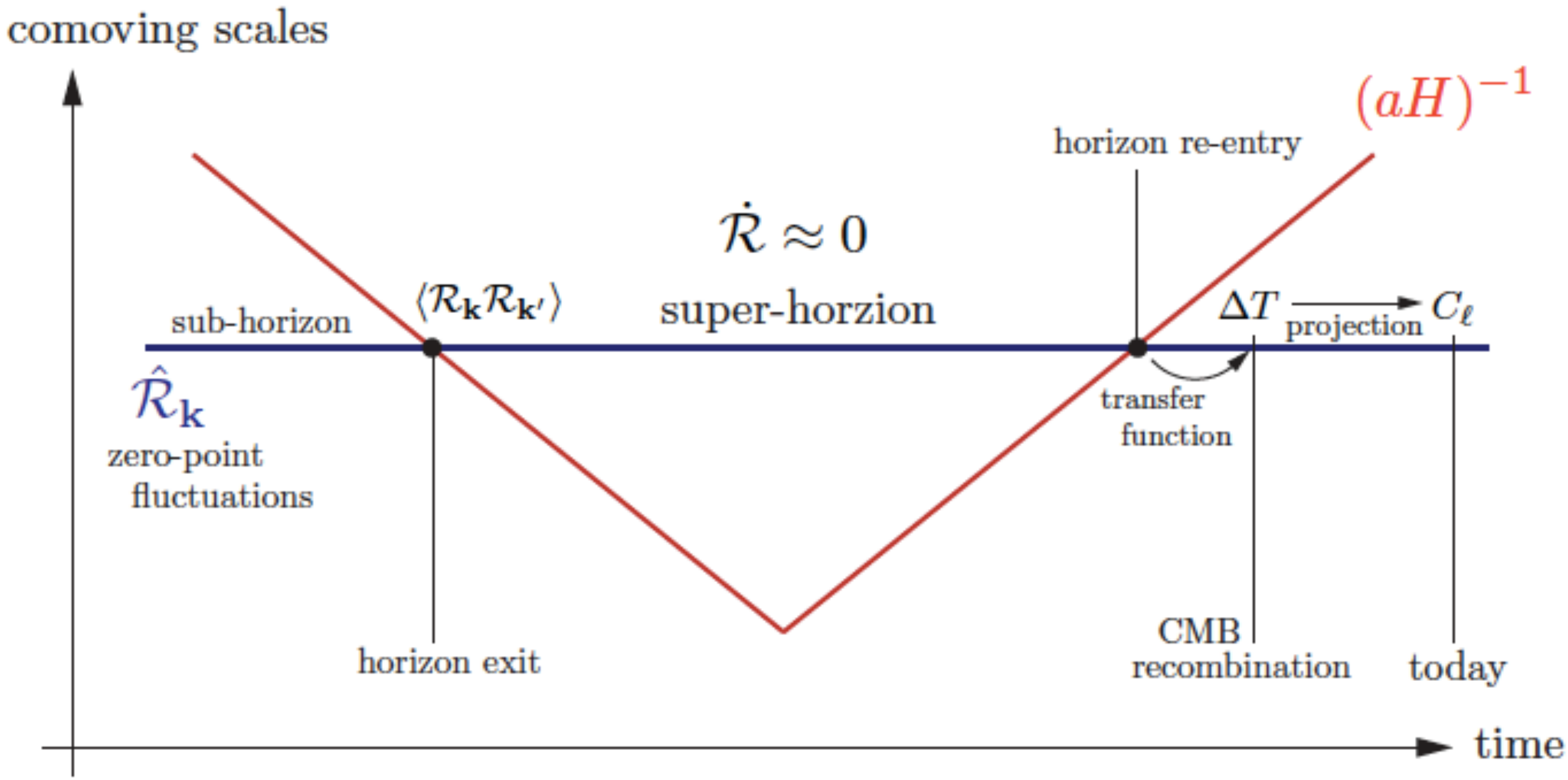
fluctuations freeze out at

$$k/a_\star = H_\star$$

Can trade fluctuations in scalar field for fluctuations in spatial curvature

$$\delta\phi = 0\,, \qquad g_{ij} = a^2[(1-2\mathcal{R})\delta_{ij} + h_{ij}]\,, \qquad \partial_i h_{ij} = h^i_i = 0$$

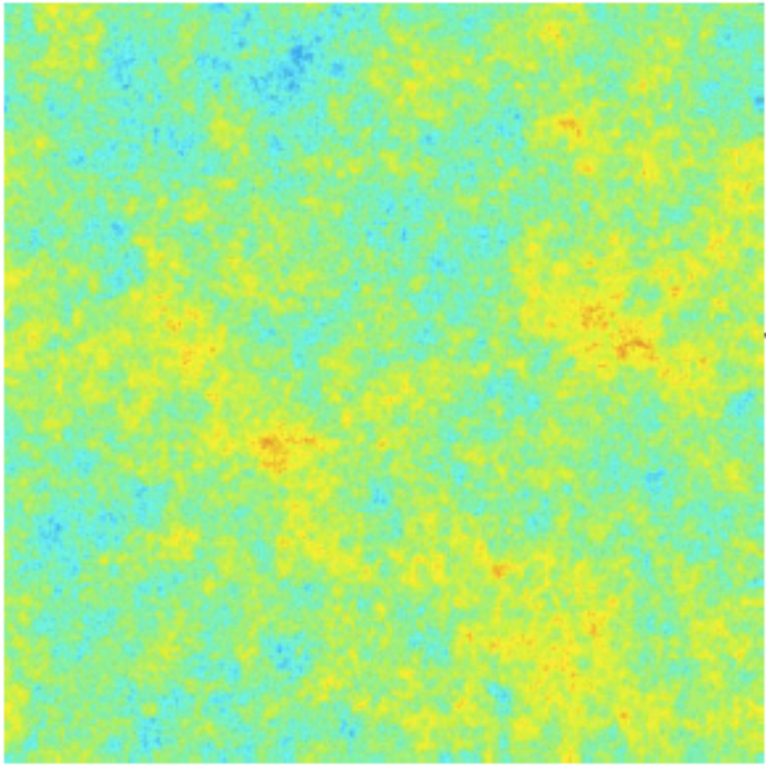
In single-clock inflation these are conserved on superhorizon scales
(regardless of the details of reheating)



Baumann TASI lectures arxiv 0907.5424

CMB temperature

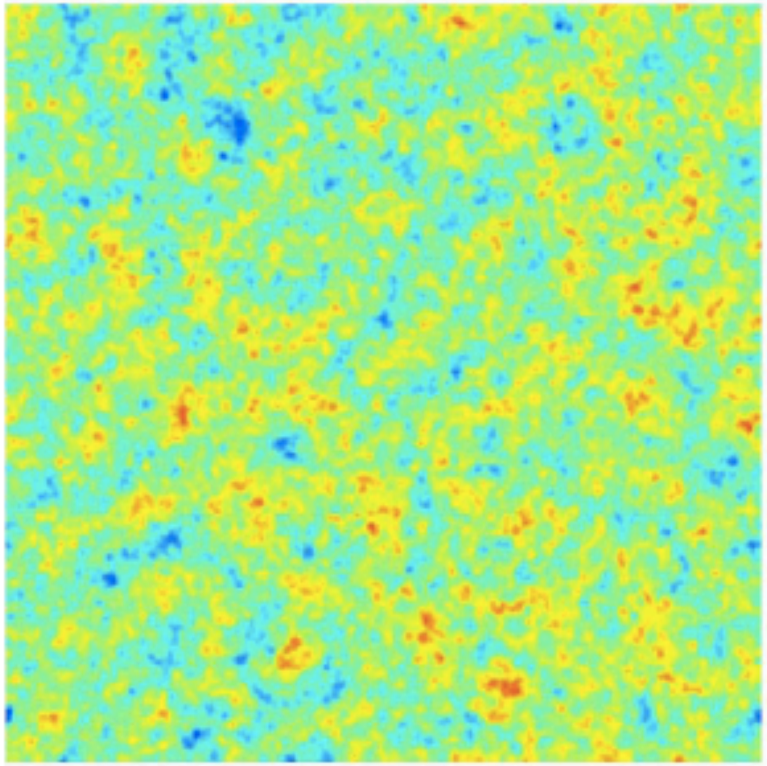
End of inflation



Perturbations super-horizon

gravity+
pressure+
diffusion
→

Last scattering surface



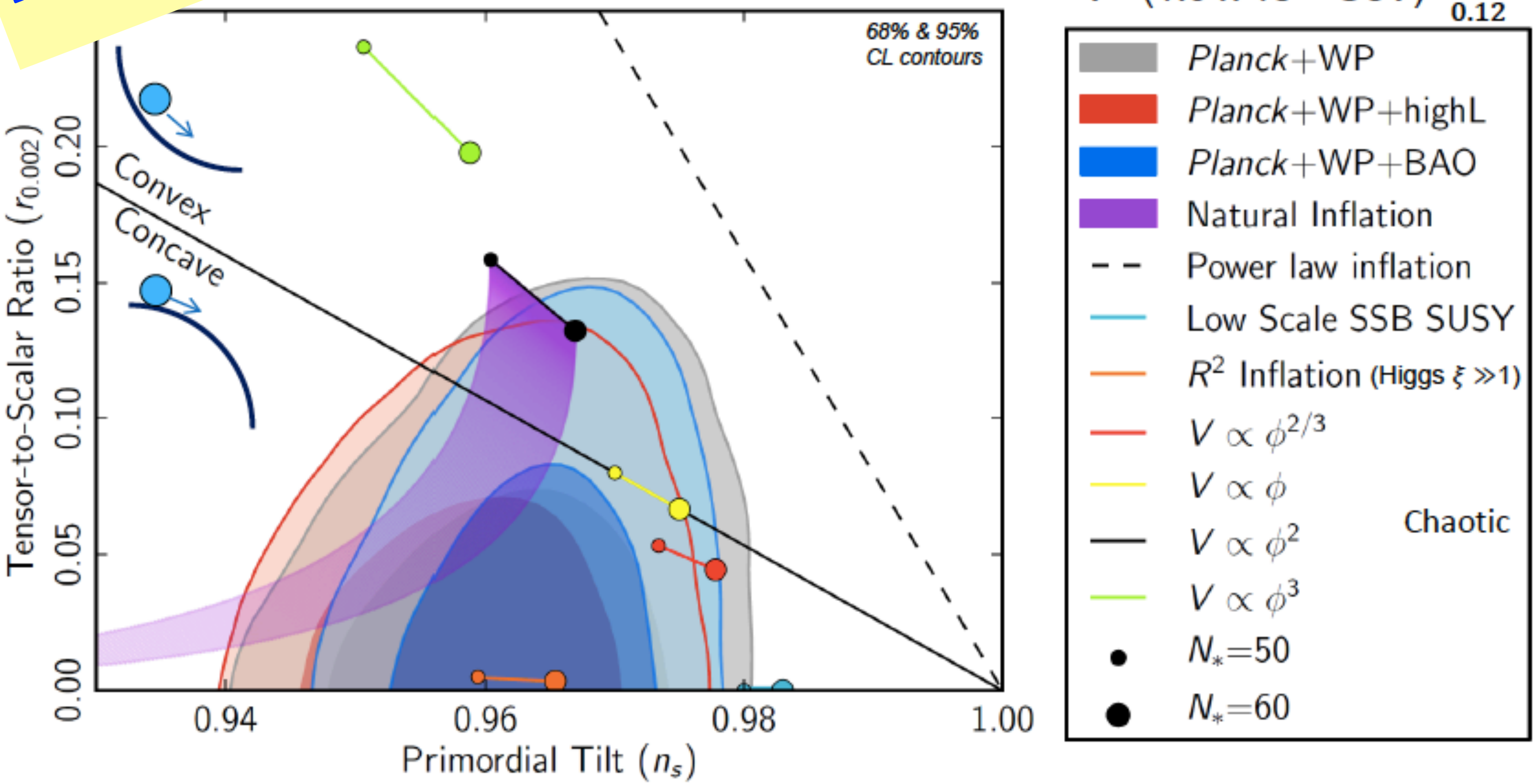
Sub-horizon acoustic oscillations
+ modes that are still super-horizon

Antony Lewis' talk at Benasque 2012

Bouchet's talk @ Planck conference April 2013

... representative Inflation models

$V_* = (1.9 \times 10^{16}\ \text{GeV})^4 \frac{r_*}{0.12}$



→ Exponential potential models(power-law inf.), simplest hybrid inflationary models (SB SUSY), monomial potential models of degree n >2 do not provide a good fit to the data.

Multi-field inflation = inflation with several **light** fields

(a turn in the trajectory couples the adiabatic and isocurvature modes)

but: isocurvature modes tightly constrained by the CMB

Turning trajectories have been studied extensively in the context of inflation with **many light fields**

"multifield inflation"

in the **slow roll** regime under the assumption of **slow/mild turns**.

Gordon Wands Bassett Maartens 2001

Groot Nibbelink van Tent 2001, 2002

Lalak Langlois Pokorski Turzynski 2007

Peterson Tegmark 2011

The effect of the turn is to couple the adiabatic and isocurvature modes.

The curvature perturbation does not remain constant on superhorizon scales, it is sourced by the isocurvature mode.

Chen Wang 2010 (M ~ H, **quasi single field inflation**, **constant turn**, equilateral NG) ***

Here we are interested in the effect of very heavy fields (M >> H) on the (single) inflaton. In this case, **strong turns are consistent with slow roll**.

The heavy fields leave an imprint on the primordial spectrum:

The isocurvature mode is very massive, it decays.

Action

$$S = \int \sqrt{-g}\, d^4x \left[\frac{M_{\rm Pl}^2}{2} R - \frac{1}{2}\gamma_{ab} g^{\mu\nu} \partial_\mu \phi^a \partial_\nu \phi^b - V(\phi) \right]$$

Equations of motion

$$\Box \phi^a + \Gamma^a_{bc} g^{\mu\nu} \partial_\mu \phi^b \partial_\nu \phi^c = V^a$$

Background

$$\phi^a = \phi_0^a(t)$$

$$ds^2 = -dt^2 + a^2(t) d\mathbf{x}^2$$

$$\dot{\phi}_0^2 \equiv \gamma_{ab} \dot{\phi}_0^a \dot{\phi}_0^b$$

$$\frac{D}{dt}\dot{\phi}_0^a + 3H\dot{\phi}_0^a + V^a = 0$$

$$H^2 = \frac{1}{3M_{\rm Pl}^2}\left[\frac{1}{2}\dot{\phi}_0^2 + V\right]$$

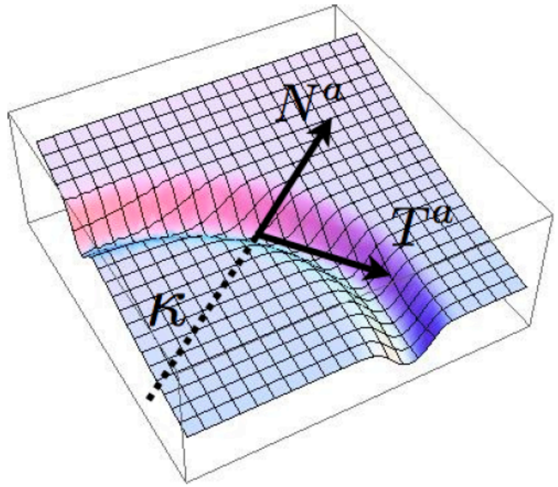
$$\dot{H} = -\frac{1}{2M_{\rm Pl}^2}\dot{\phi}_0^2$$

Eqs. of motion -- tangential projection

$$\ddot{\phi}_0 + 3H\dot{\phi}_0 + V_\phi = 0,$$

(single-field inflation)

$T^a V_a$ tangential projection



Eqs. of motion -- normal projection

2 x kinetic energy $2\epsilon H^2$

$$\frac{\dot{\phi}_0^2}{\kappa} = N^a V_a$$

radius of turn

normal projection

$$T^a \equiv \frac{\dot{\phi}_0^a}{\dot{\phi}_0}$$

$$\frac{DT^a}{d\phi_0} = -\frac{1}{\kappa} N^a$$

$$\frac{D}{dt} \equiv \dot{\phi}_0 T^a \nabla_a = \dot{\phi}_0 \nabla_\phi.$$

Slow roll parameters

$$\dot{\phi}_0 = \sqrt{2\epsilon} H M_{\rm Pl}$$

$$\epsilon \equiv -\frac{\dot{H}}{H^2} = \frac{\dot{\phi}_0^2}{2M_{\rm Pl}^2 H^2} \quad \ll 1$$

$$\eta^a \equiv -\frac{1}{H\dot{\phi}_0}\frac{D\dot{\phi}_0^a}{dt}$$

$$\eta_{||} = -\frac{\ddot{\phi}_0}{H\dot{\phi}_0} \quad \ll 1$$

Project: $\eta^a = \eta_{||} T^a + \eta_\perp N^a$

$$\eta_\perp = \sqrt{2\epsilon}\frac{M_{\rm Pl}}{\kappa}$$

Not necessarily small

(strong turns are consistent with slow roll inflation)

Beyond single field Inflation

m = mass of lightest field
M = mass of other fields

$m^2 \sim M^2 \ll H^2$

several light fields
"multifield inflation"

both adiabatic and isocurvature pertns.

curv. pert. **not** conserved on superhorizon scales, sourced by isoc. pertn

(Reheating!)
NG Squeezed (local) + …

$m^2 \ll M^2 \sim H^2$

Messy – but very relevant !

If "steady state":
"quasi-single field inflation"

Chen Wang 2010

$M^2 \gg H^2 \gg m^2$

one light field
"effectively single field"

adiabatic perts. with variable speed of sound

curv. pert. conserved on superhorizon scales

NG equilateral + …

If $M^2 \gg H^2$,
a sufficiently heavy field can **still** be integrated out --

Get an effective single-field theory with a **reduced speed of sound** for the adiabatic mode

$$c_s^{-2} = 1 + \frac{4\dot{\theta}^2}{M_{\rm eff}^2}$$

effective mass of heavy field at turn

$$M_{\rm eff}^2 = M^2 - \dot{\theta}^2$$

mass of heavy field on straight trajectory
(including effect of curvature of field manifold)

Reduced speed of sound requires large turning rate

effective mass of heavy field is reduced

is this consistent??
(can the heavy field still be integrated out?)

Adiabaticity conditions

HEAVY vs LIGHT – what is the “right” definition ? (tree level)

1) Calculate the mass matrix from V

2) Calculate the mass matrix of fluctuations about the classical solution

3) Calculate natural frequencies of fluctuations - fast vs slow

All three agree on a static background -- otherwise, not, in general

On a turning trajectory:

1) If the heavy field has mass^2 = M^2 on a straight trajectory

2) The heavy fluctuation has mass^2 = $$M_{\text{eff}}^2 = M^2 - \dot{\theta}^2$$

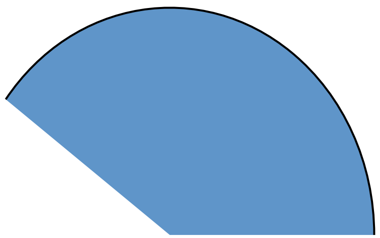
3) The fast mode has frequency $$\omega_{heavy}^2 = M_{eff}^2 c_s^{-2} = M^2 + 3\dot{\theta}^2$$

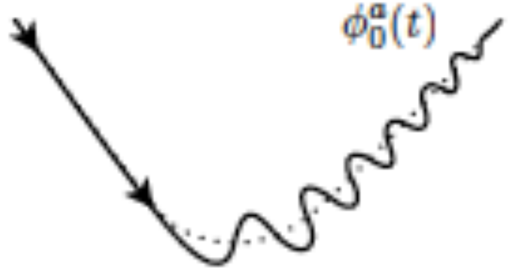
(long wavelengths)

Need to distinguish between

STRONG and **SUDDEN** turns.

small, constant c | **large changes in c**





adiabatic evolution x

no heavy particle production x

consistent with slow roll x

EFT works x

Shiu Xu 2011

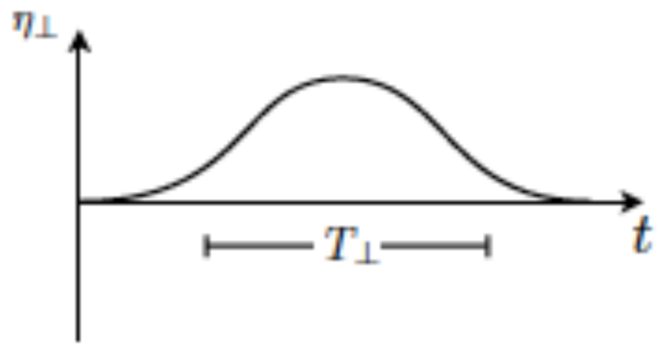
Adiabaticity condition is

$$\left|\frac{\ddot{\theta}}{\dot{\theta}}\right| \ll M_{\rm eff}$$

Cespedes Atal Palma 2011

The sweet spot in between…

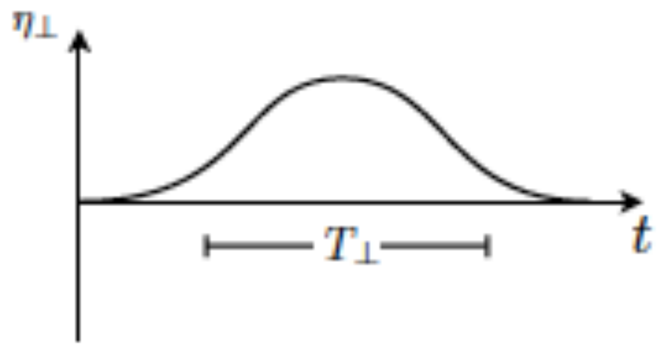
$$\Delta c_s / c_s \sim 0.1$$



O(1) efold

The sweet spot in between…

$$\Delta c_s / c_s \sim 0.1$$



O(1) efold

This is the interesting regime where we can calculate the **full bispectrum** analytically (to leading order)

as a function of the power spectrum feature and up to two derivatives

without knowledge of the parent theory.

To leading order in slow roll parameters:

$$S_{\rm eff} = -\int d^4x\, a^3 m_{\rm Pl}^2 \dot{H} \left\{ \dot{\pi}^2 - \frac{(\nabla\pi)^2}{a^2} + \left(c_s^{-2} - 1\right)\dot{\pi}^2 + \right.$$

$$\left. \left(c_s^{-2} - 1\right)\dot{\pi}\left[\dot{\pi}^2 - \frac{(\nabla\pi)^2}{a^2}\right] + \left(c_s^{-2} - 1\right)^2 \frac{\dot{\pi}^3}{2} - 2\frac{\dot{c}_s}{c_s^3}\pi\dot{\pi}^2 - 2H\eta_{\parallel}\pi\left[c_s^{-2}\dot{\pi}^2 - \frac{(\nabla\pi)^2}{a^2}\right] \right\}$$

Changes in the speed of sound seed correlated features in the power spectrum and in the bispectrum

$$\Delta\mathcal{P}_{\mathcal{R}} \sim \mathcal{O}(u)$$

$$\Delta B_{\mathcal{R}} \sim \mathcal{O}(s, u)$$

$$u = 1 - c_s^{-2}$$

$$s = \frac{\dot{c}_s}{H c_s}$$

$$O(\epsilon,\eta) \ll \left(\frac{1}{c_s^2(\tau)}-1\right) \ll 1$$

$$\Rightarrow \frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}}}(k) = -k\int_{-\infty}^{0} d\tau \left(\frac{1}{c_s^2(\tau)}-1\right)\sin(2k\tau)$$

+ subleading terms (#)

Inverting (#) gives the change in the **bispectrum analytically as a function of the power spectrum feature and its first and second derivatives** only, to leading order (subject to some adiabaticity conditions)
:

$$\Delta B_{\mathcal{R}}(k_1,k_2,k_3) =$$

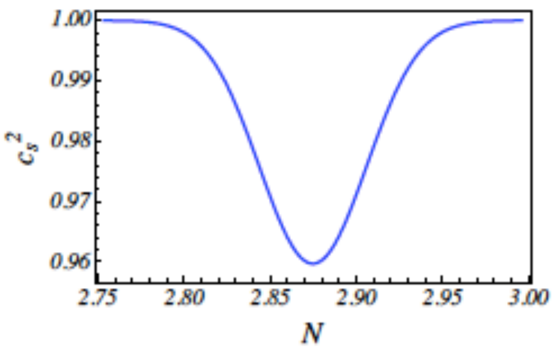
$$\frac{(2\pi)^4\mathcal{P}_{\mathcal{R}}^2}{(k_1k_2k_3)^2}\left\{-\frac{3}{2}\frac{k_1k_2}{k_3}\left[\frac{1}{2k}\left(1+\frac{k_3}{2k}\right)\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}}}(k)-\frac{k_3}{4k^2}\frac{d}{d\log k}\left(\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}}}\right)\right]+2\text{ perm}\right.$$
$$+\frac{1}{4}\frac{k_1^2+k_2^2+k_3^2}{k_1k_2k_3}\left[\frac{1}{2k}\left(4k^2-k_1k_2-k_2k_3-k_3k_2-\frac{k_1k_2k_3}{2k}\right)\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}}}(k)\right.$$
$$\left.\left.-\frac{k_1k_2+k_2k_3+k_3k_1}{2k}\frac{d}{d\log k}\left(\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}}}\right)+\frac{k_1k_2k_3}{4k^2}\frac{d^2}{d\log k^2}\left(\frac{\Delta\mathcal{P}_{\mathcal{R}}}{\mathcal{P}_{\mathcal{R}}}\right)\right]\right\}\Bigg|_{k=(k_1+k_2+k_3)/2}$$

+ subleading terms

This is the full bispectrum (all scales, all shapes) to leading order.

Detecting non-Gaussianity and features in the primordial spectrum is challenging – establishing correlations like these should help.

A search in the Planck data



a(ny) reduction in the speed of sound

$$u = 1 - c_s^{-2}$$

$$s = \frac{\dot{c}_s}{H c_s}$$

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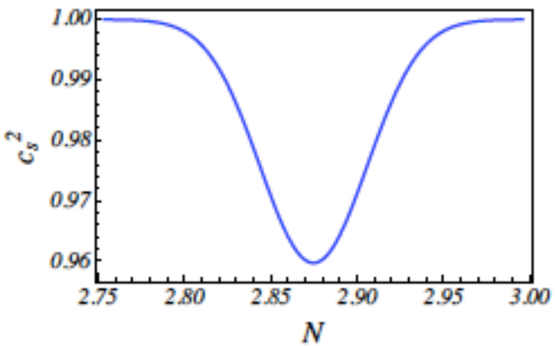
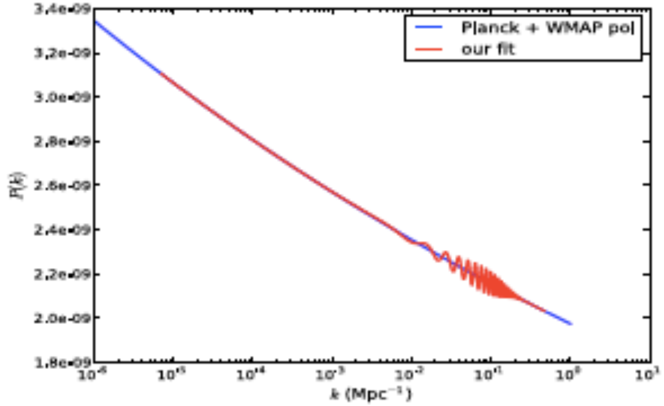
A search in the Planck data





Primordial Power spectrum

Perturbative regime, uninterrupted slow roll – calculation simple

$$\mathcal{O}(\epsilon, \eta) \ll |u| < 1$$
$$\mathcal{O}(\epsilon, \eta) \ll |s| < 1$$

$$\frac{\Delta P}{P}(k) = k \int_{-\infty}^{0} \mathrm{d}\tau \, u(\tau) \sin(2k\tau)$$

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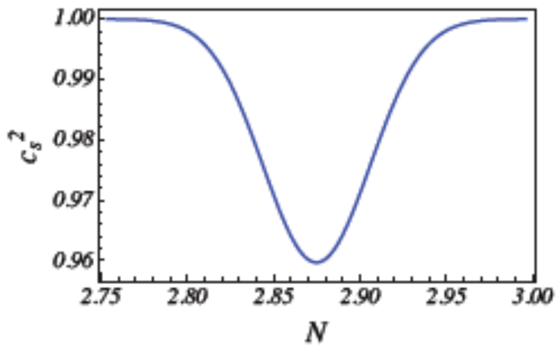
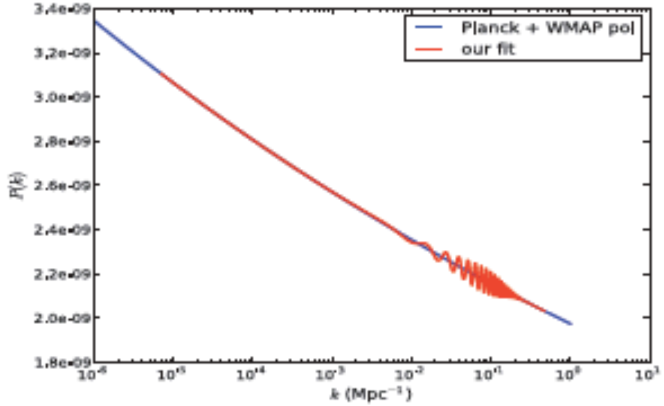
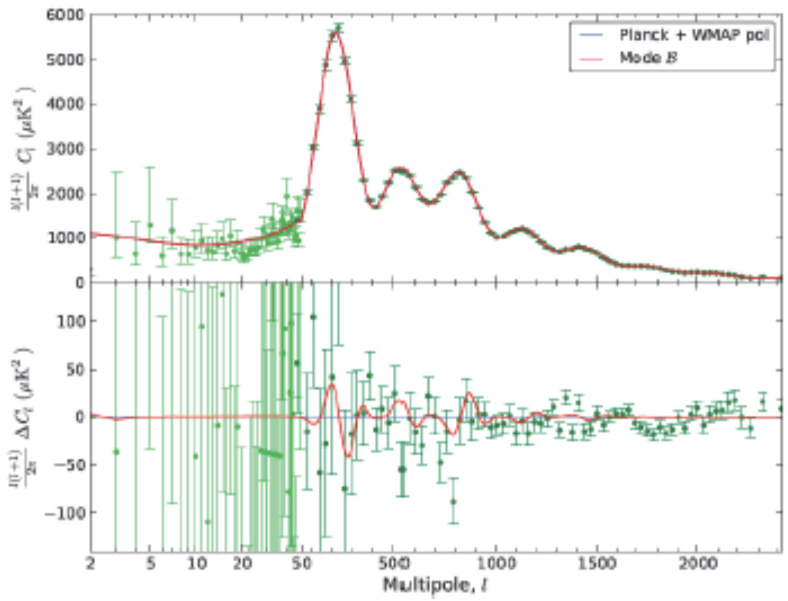
A search in the Planck data







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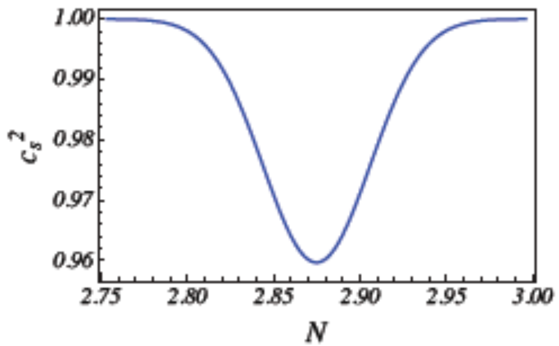
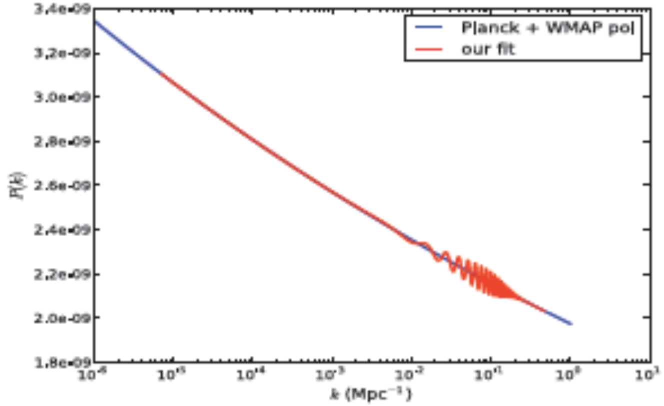
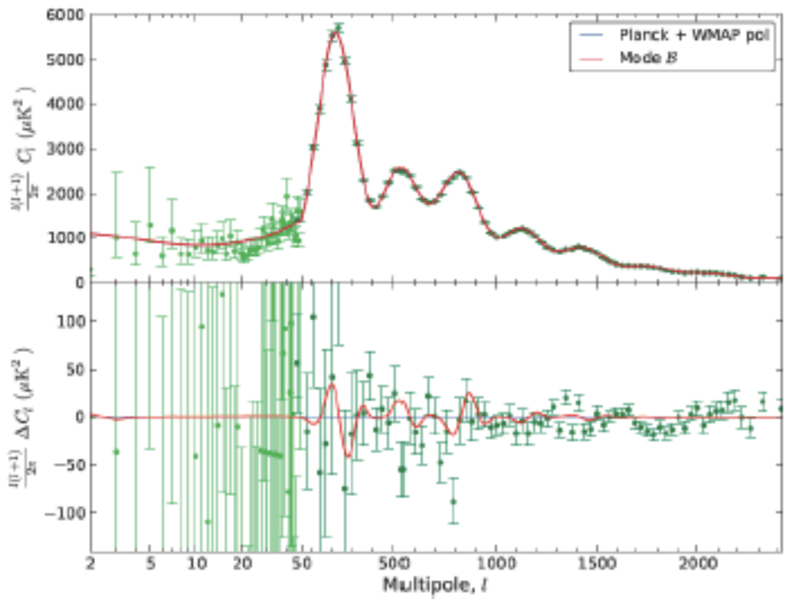
CMB Power spectrum

A search in the Planck data







Fit to Planck power spectrum

Calculate primordial bispectrum

Compare to data…

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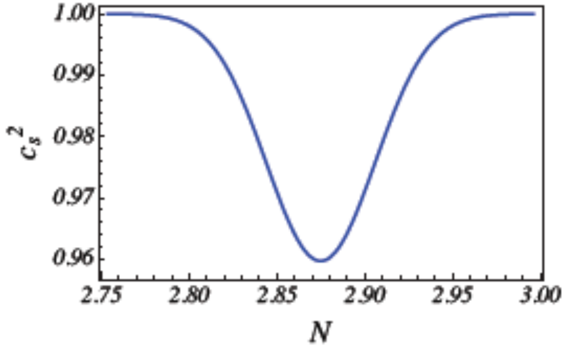
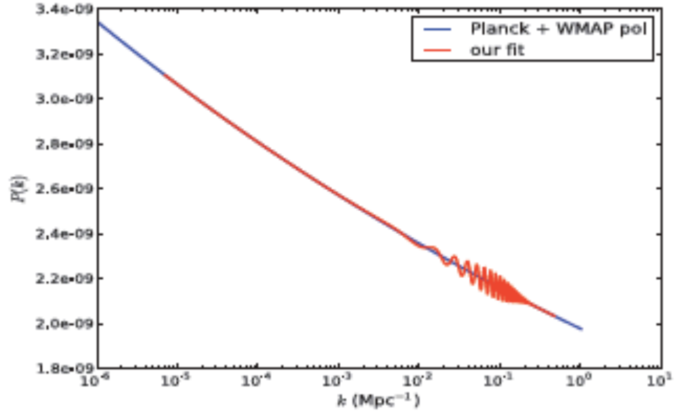
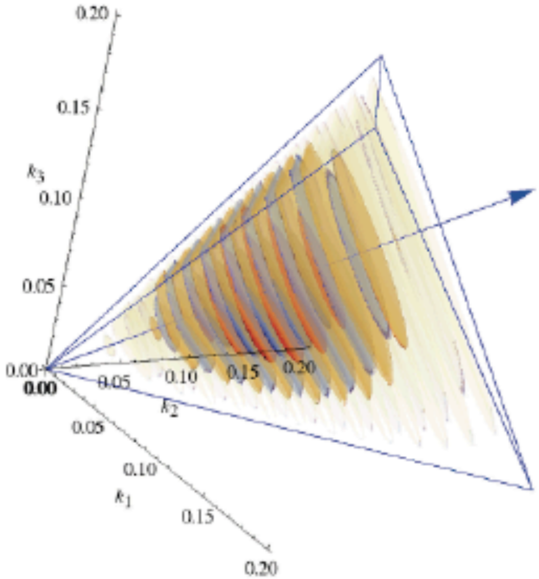
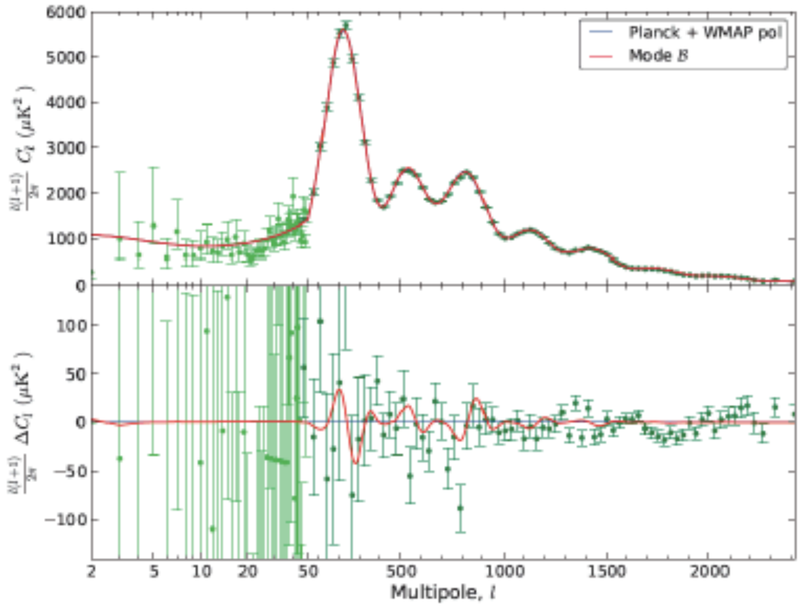
A search in the Planck data









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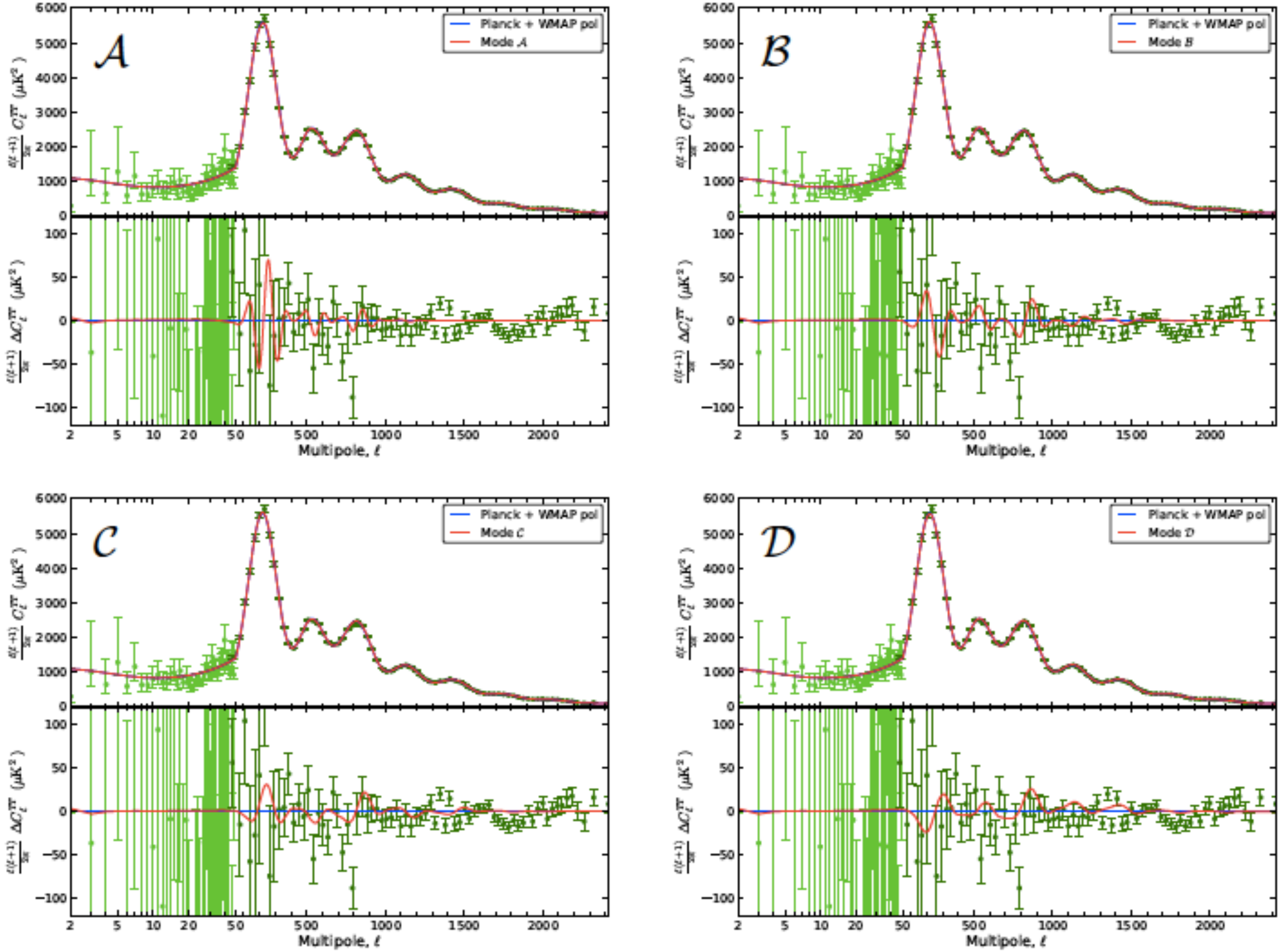
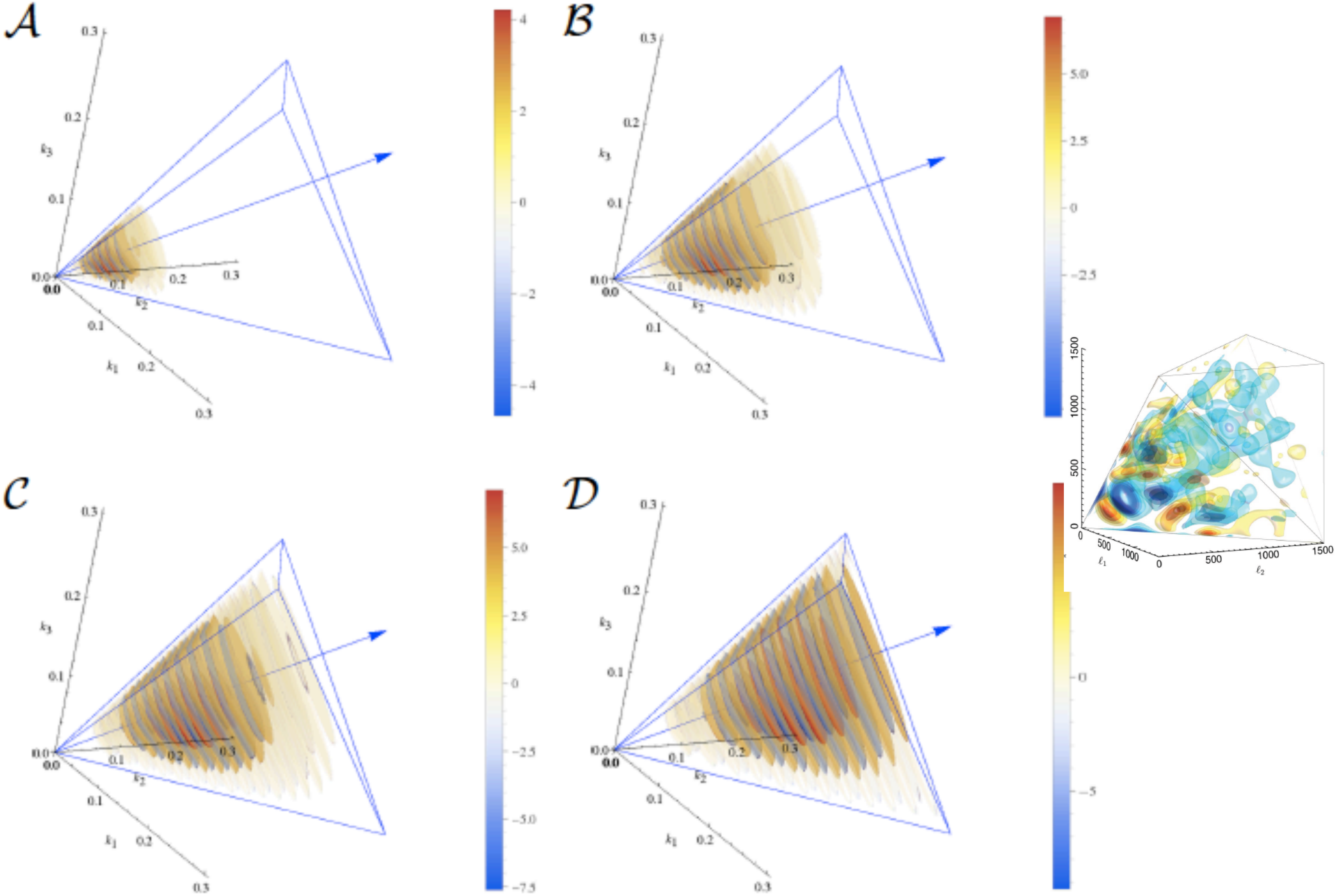
Predictions for the full **3D** primordial bispectrum

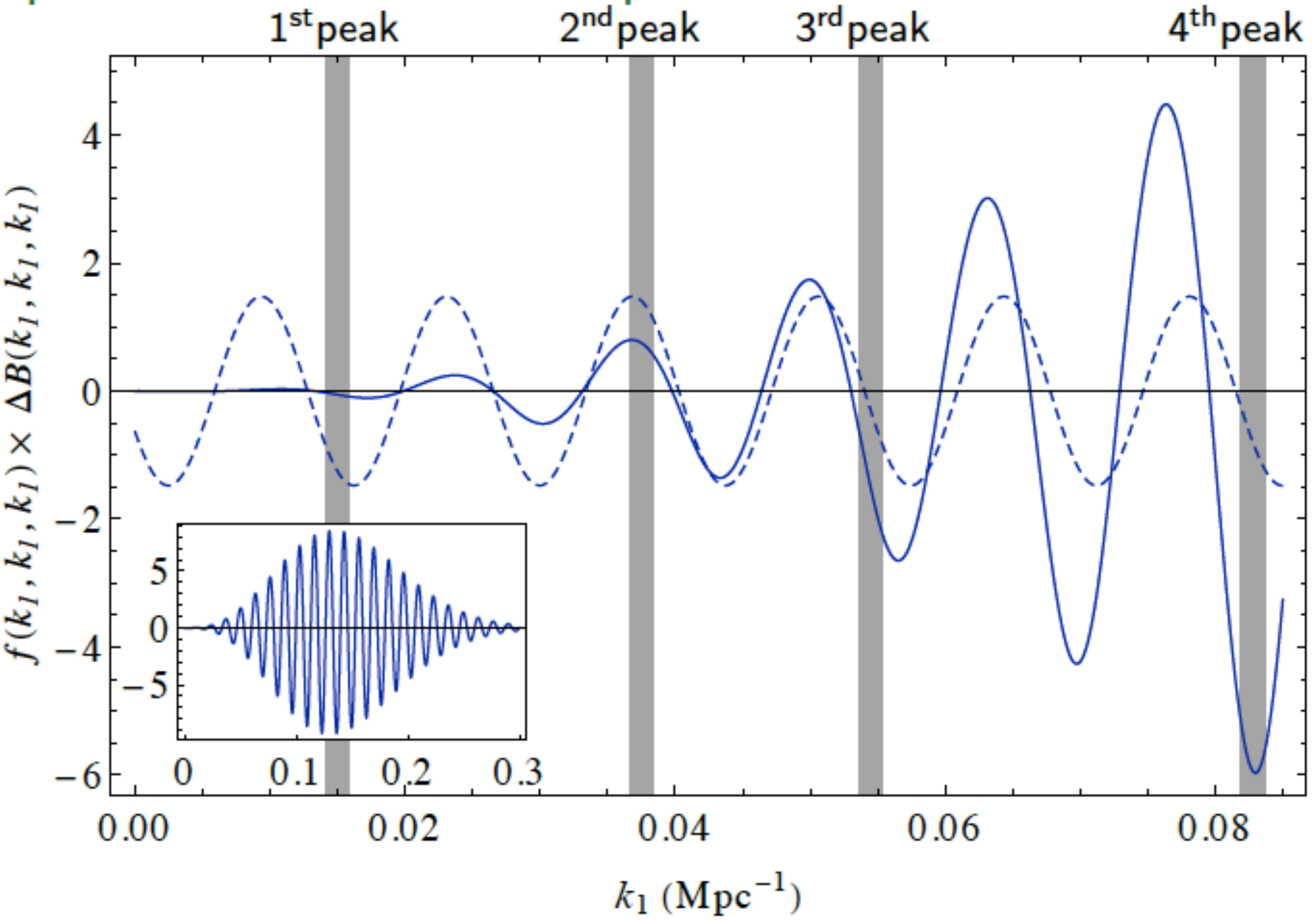


Predictions for the full **3D** primordial bispectrum



* The predicition for mode $\mathcal{E}$ is not trustable, since for it $s \sim u \sim \mathcal{O}(\epsilon, \eta)$

Comparison of mode $\mathcal{D}$ – Equilateral direction



- - - Fit of Planck with $k = 0.01375\,\mathrm{Mpc}^{-1},\ f_{\mathrm{NL}} = 345,\ \phi = \pi/2\ (2.3\sigma)$

—— Best fit of our mode $\mathcal{D}$

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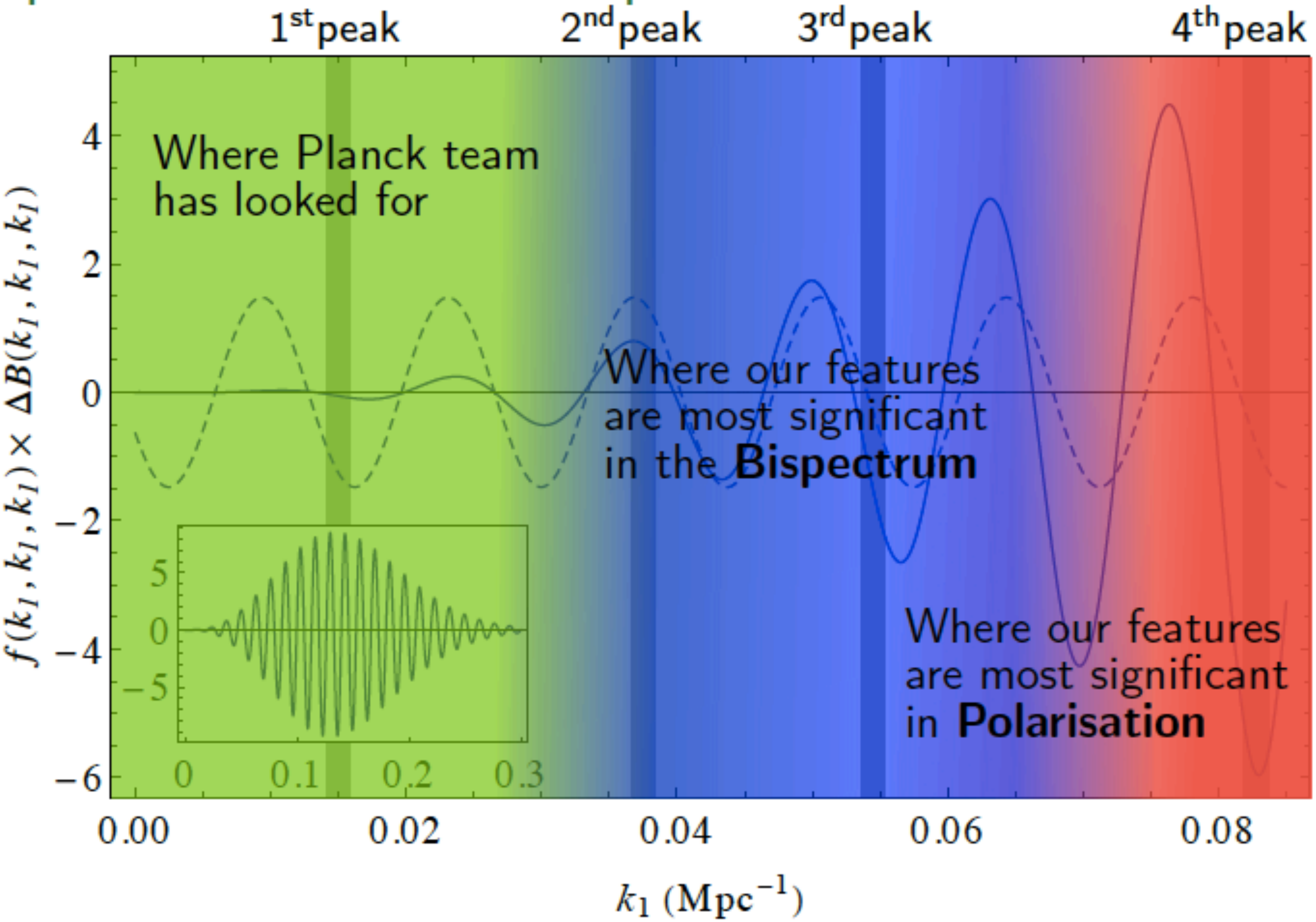
Comparison of mode $\mathcal{D}$ – Equilateral direction



- - - Fit of Planck with $k = 0.01375\,\mathrm{Mpc}^{-1}$, $f_{\mathrm{NL}} = 345$, $\phi = \pi/2$ (2.3σ)

—— Best fit of our mode $\mathcal{D}$

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Summary of search:

Evidence of new physics during inflation (if it is there) will come from **correlations** between different observables

Transient reductions in the speed of sound, if found, would be evidence of **other degrees of freedom** interacting with the single-field inflaton

We find **hints** of these correlations – but we do not have the data yet, we are exploiting a lucky coincidence.

These correlations can be disproved/confirmed once the bispectrum is public, and also by polarization (eventually). Other checks are possible.

Summary (cont.) :

These are very exciting times !

And a few more mundane remarks to do with model building.

The Bicep2 announcement was followed by many papers with large field inflationary scenarios in SUGRA; these almost invariably involve many scalars.

Truncating (as opposed to integrating out) heavy fields at their minima misses the coupling effect of turns (curvature and isocurvature perturbations coupled, masses are not given by $\nabla_a \nabla_b V$, reductions in speed of sound) $M_{\rm eff}^2 = M^2 - \dot{\theta}^2$

In scenarios with stabilized scalars, it is important to check that the inflationary trajectories are geodesics of the (full) sigma model metric.

Otherwise, check if turns may be observable !