Planck constraints on fundamental physics

XXII. Constraints on inflation
XXIV Constraints on primordial non-Gaussianity
XXV. Searches for cosmic strings and other topological defects

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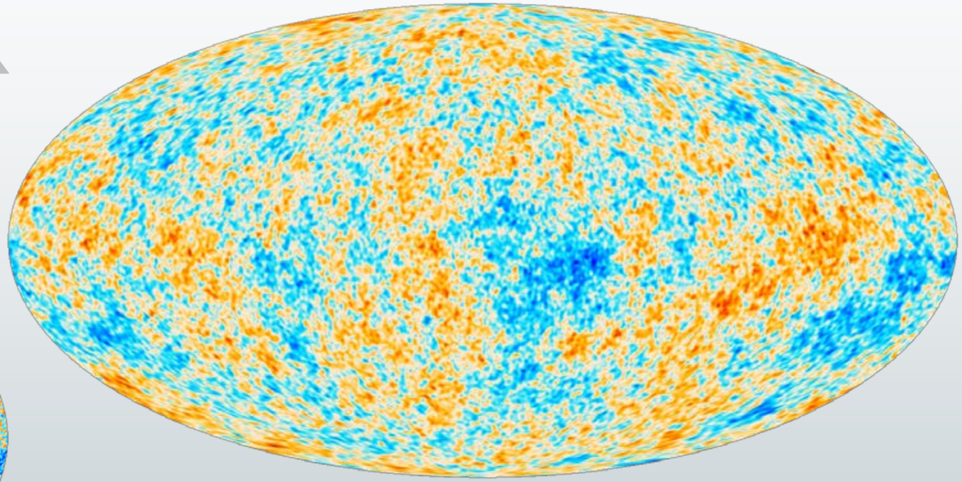
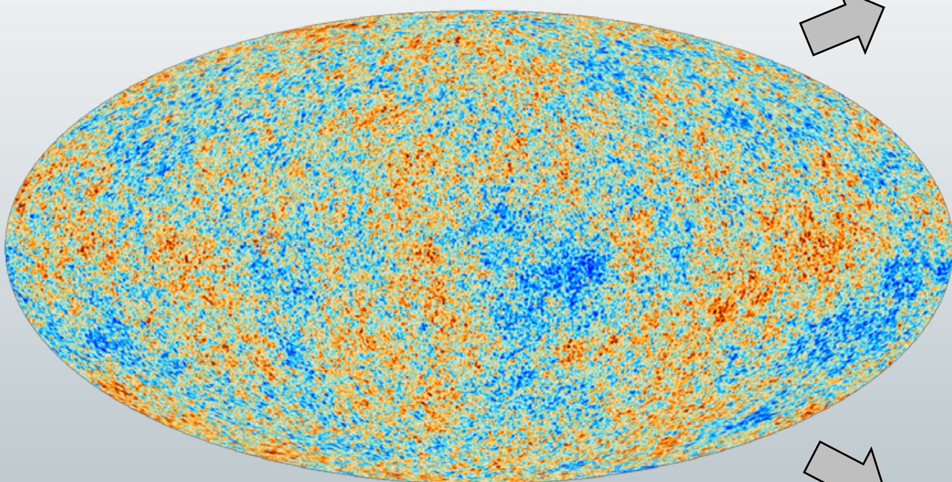
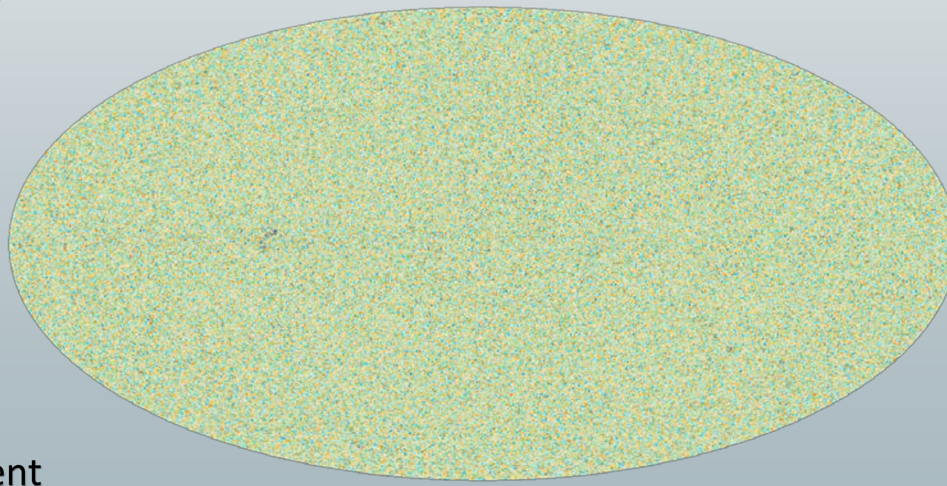
Our window

Smoothed map (suppressing scales θ < 1 deg) :
Quantum Fluctuations imprinted
When the age of the Universe was in the
interval [10-30, 10-12] seconds

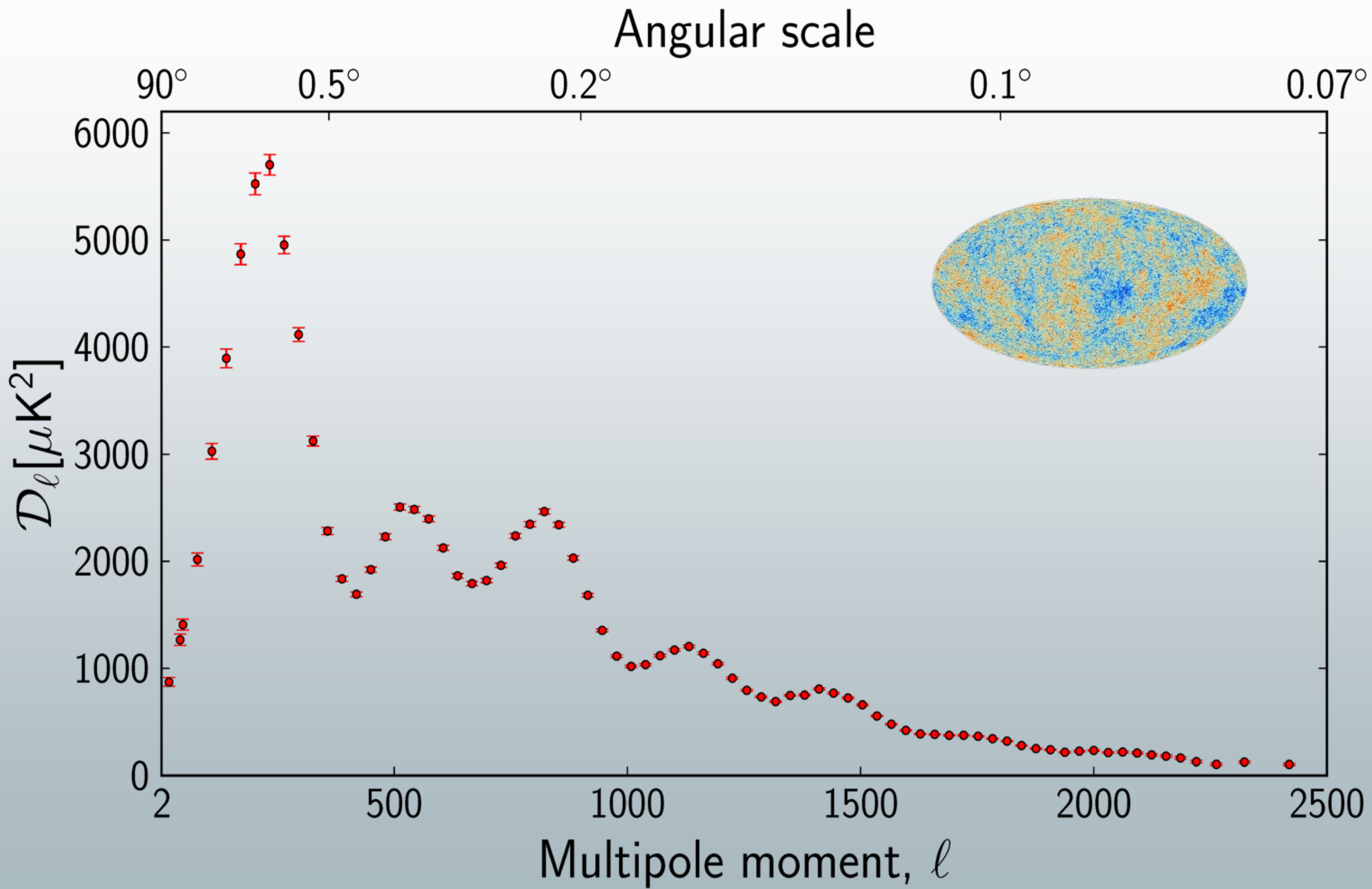




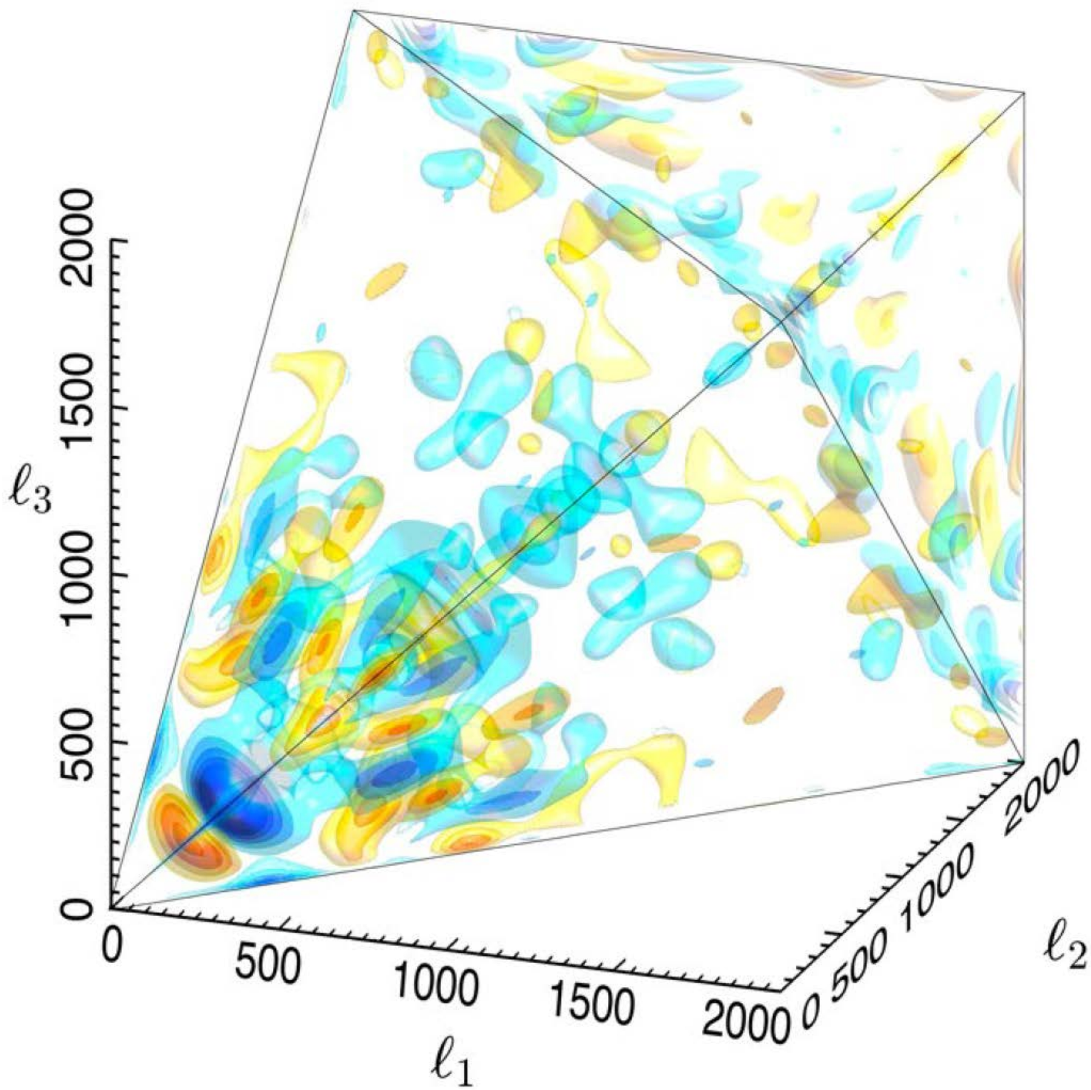


Difference map (scales θ < 1 deg) :
Acoustic oscillations at small scales
< ct when t=380 000 years (~150Mpc today).
Which allows to take a census of the Universe content

The Planck spectrum of Temperature anisotropies



The Planck bi-spectrum of Temperature anisotropies



Base ΛCDM model 6 parameters

	Planck (CMB+lensing)		*Planck*+WP+highL+BAO	
Parameter	Best fit	68 % limits	Best fit	68 % limits
$\Omega_b h^2$	0.022242	0.02217 ± 0.00033	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11805	0.1186 ± 0.0031	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04150	1.04141 ± 0.00067	1.04148	1.04147 ± 0.00056
τ	0.0949	0.089 ± 0.032	0.0952	0.092 ± 0.013
n_s	0.9675	0.9635 ± 0.0094	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.098	3.085 ± 0.057	3.0973	3.091 ± 0.025

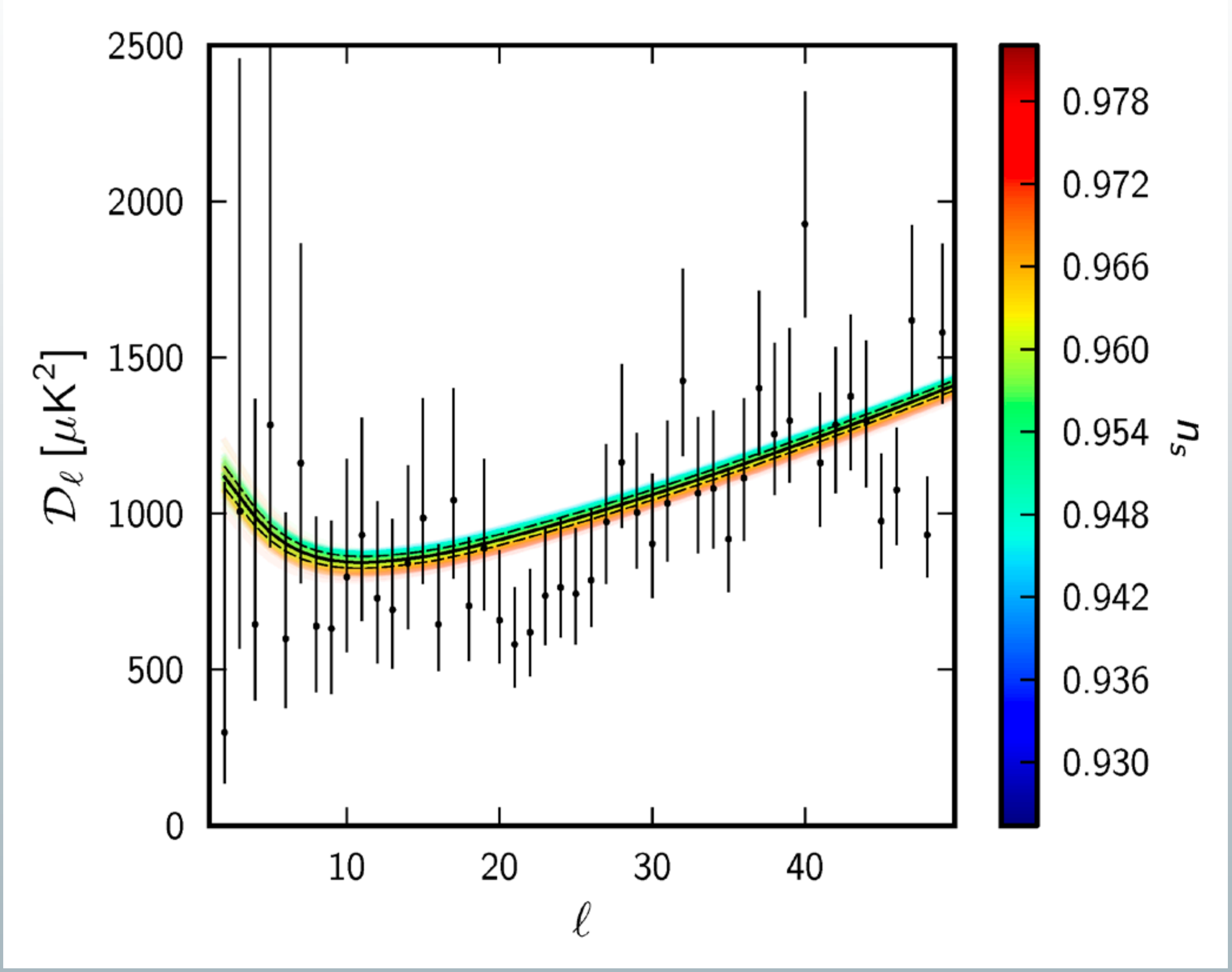
The sound horizon, θ, determined by the positions of the peaks, is now determined with 0.05% precision
(links together $\Omega_b h^2$, $\Omega_c h^2$, H_0)

$$\theta_* = (1.04148 \pm 0.00066) \times 10^{-2} = 0.596724^\circ \pm 0.00038^\circ$$

Exact scale invariance of the primordial fluctuations is ruled out, at more than 7σ

(as predicted by base inflation models)

The low-multipole surprise/tension



Inflation has a few variants…

- assisted brane inflation
- anomaly-induced inflation
- assisted inflation
- assisted chaotic inflation
- B-inflation
- boundary inflation
- brane inflation
- brane-assisted inflation
- brane gas inflation
- brane-antibrane inflation
- braneworld inflation
- Brans-Dicke chaotic inflation
- Brans-Dicke inflation
- bulky brane inflation
- chaotic inflation
- chaotic hybrid inflation
- chaotic new inflation
- Chromo-Natural Inflation
- D-brane inflation
- D-term inflation
- dilaton-driven inflation
- dilaton-driven brane inflation
- double inflation
- double D-term inflation
- dual inflation
- dynamical inflation
- dynamical SUSY inflation
- S-dimensional assisted inflation
- eternal inflation
- extended inflation
- extended open inflation
- extended warm inflation
- extra dimensional inflation
- …

- F-term inflation
- F-term hybrid inflation
- false-vacuum inflation
- false-vacuum chaotic inflation
- fast-roll inflation
- first-order inflation
- gauged inflation
- Ghost inflation
- Hagedorn inflation

- higher-curvature inflation
- hybrid inflation
- Hyper-extended inflation
- induced gravity inflation
- intermediate inflation
- inverted hybrid inflation
- Power-law inflation
- K-inflation
- Super symmetric inflation

- Quintessential inflation
- Roulette inflation
- curvature inflation
- Natural inflation
- Warm natural inflation
- Super inflation
- Super natural inflation
- Thermal inflation
- Discrete inflation
- Polarcap inflation
- Open inflation
- Topological inflation
- Multiple inflation
- Warm inflation
- Stochastic inflation
- Generalised assisted inflation
- Self-sustained inflation
- Graduated inflation
- Local inflation
- Singular inflation
- Slinky inflation
- Locked inflation
- Elastic inflation
- Mixed inflation
- Phantom inflation
- Non-commutative inflation
- Tachyonic inflation
- Tsunami inflation
- Lambda inflation
- Steep inflation
- Oscillating inflation
- Mutated hybrid inflation
- Inhomogeneous inflation
- …

But there is a simple reference model

- Ω_k =0, single inflaton field, obeying slow-roll conditions (small derivatives of the potential, ε,η,ξ), deriving from a standard Lagrangian, with fluctuations behaving as in flat space at asymptotically early times and short distances (Bunch-Davies Initial conditions)

➔ Adiabatic fluctuations, $P_R(k)=A_s\,(k/k_*)^{ns-1}$, $n_s < 1$, no running, $N_* \in [50,60]$, with negligible non-Gaussianity.

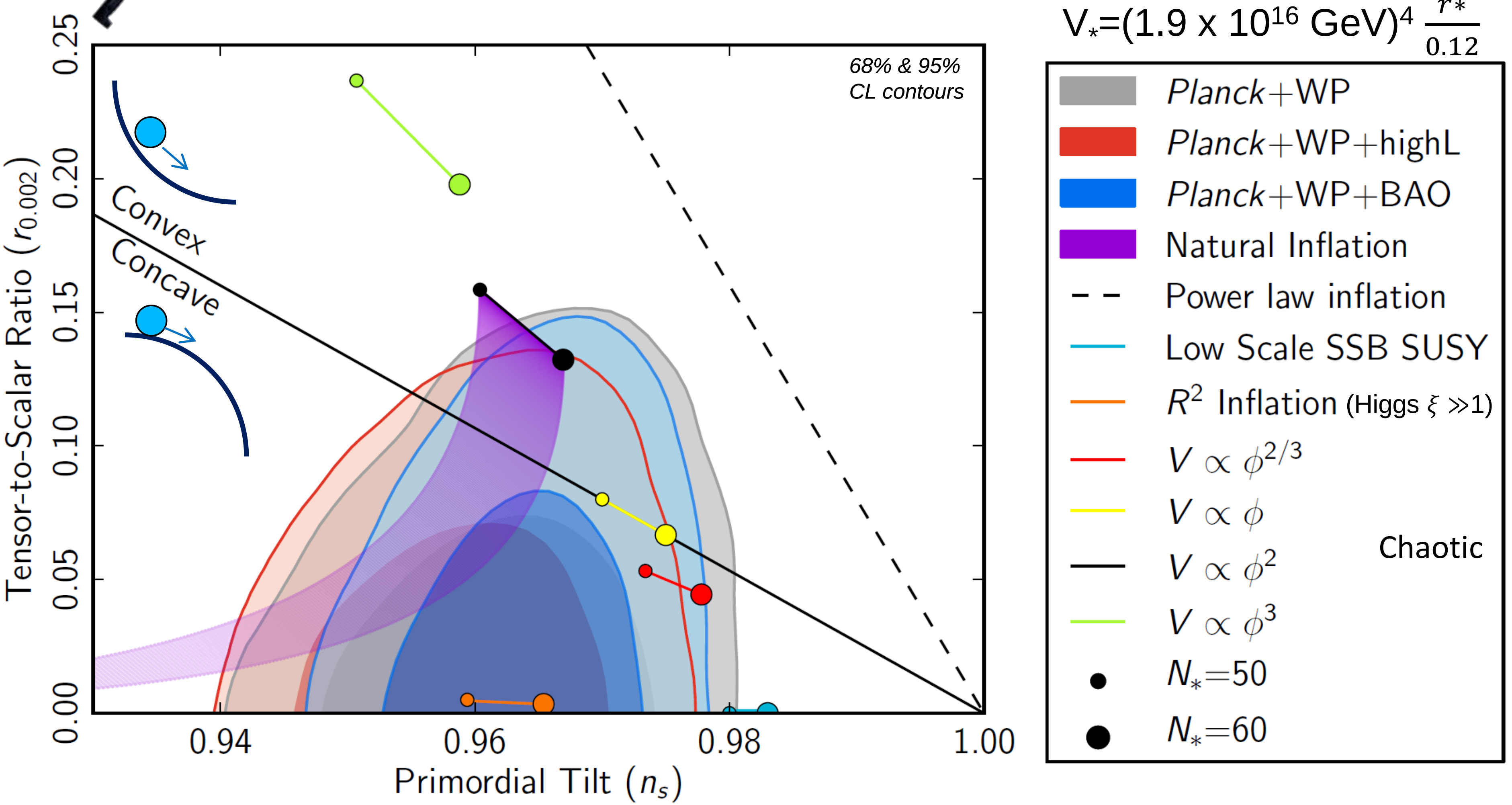
- We shall probe Ω_k, n_s, running ($dn_s/d\ln k$), non-slow-roll, features in P(k) (parametric and non-parametric), isocurvature fluctuations, existence of defects, LEO non-gaussianity and a few more…

Few "specimen" in the slow roll approximation

- Power law potential and chaotic inflation $V(\phi) = \lambda M_{\rm pl}^4 \left(\frac{\phi}{M_{\rm pl}}\right)^n$
  - *Simplest is n=2* *(Linde 1983)*
  - *Axion monodromy → n=1, n=2/3* *(2010, 2008)*
- Exponential potential & power law inf. $V(\phi) = \Lambda^4 \exp\left(-\lambda \frac{\phi}{M_{\rm pl}}\right)$ *(1985)* $a(t) \propto t^{2/\lambda^2}$
- Inverse power law $V(\phi) = \Lambda^4 \left(\frac{\phi}{M_{\rm pl}}\right)^{-\beta}$ *(1990)*
- Hill-top model $V(\phi) \approx \Lambda^4 \left(1 - \frac{\phi^p}{\mu^p} + \ldots\right)$ *(Linde 1982, Albrecht & Steinhardt)*
- SB potential $V(\phi) = \Lambda^4 \left(1 - \frac{\phi^2}{\mu^2}\right)^2$ *(1990)*
- Natural inflation $V(\phi) = \Lambda^4 \left[1 + \cos\left(\frac{\phi}{f}\right)\right]$ *(1990)*
- Hybrid inflation $V(\phi,\chi) = \Lambda^4 \left(1 - \frac{\chi^2}{\mu^2}\right)^2 + U(\phi) + \frac{g^2}{2}\phi^2\chi^2$ W $U(\phi) = \alpha_{\rm h}\Lambda^4 \ln\left(\frac{\phi}{\mu}\right)$ SBSUSY *(1994)*
- R2 inflation $S = \int d^4x \sqrt{-g}\frac{M_{\rm pl}^2}{2}\left(R + \frac{R^2}{6M^2}\right)$ *(Starobinsly 1980, Mukhanov & Chibisov 1981)*
- … *(Naming arbitrarily stopped at 1983)*

Constraint on representative Inflation models

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



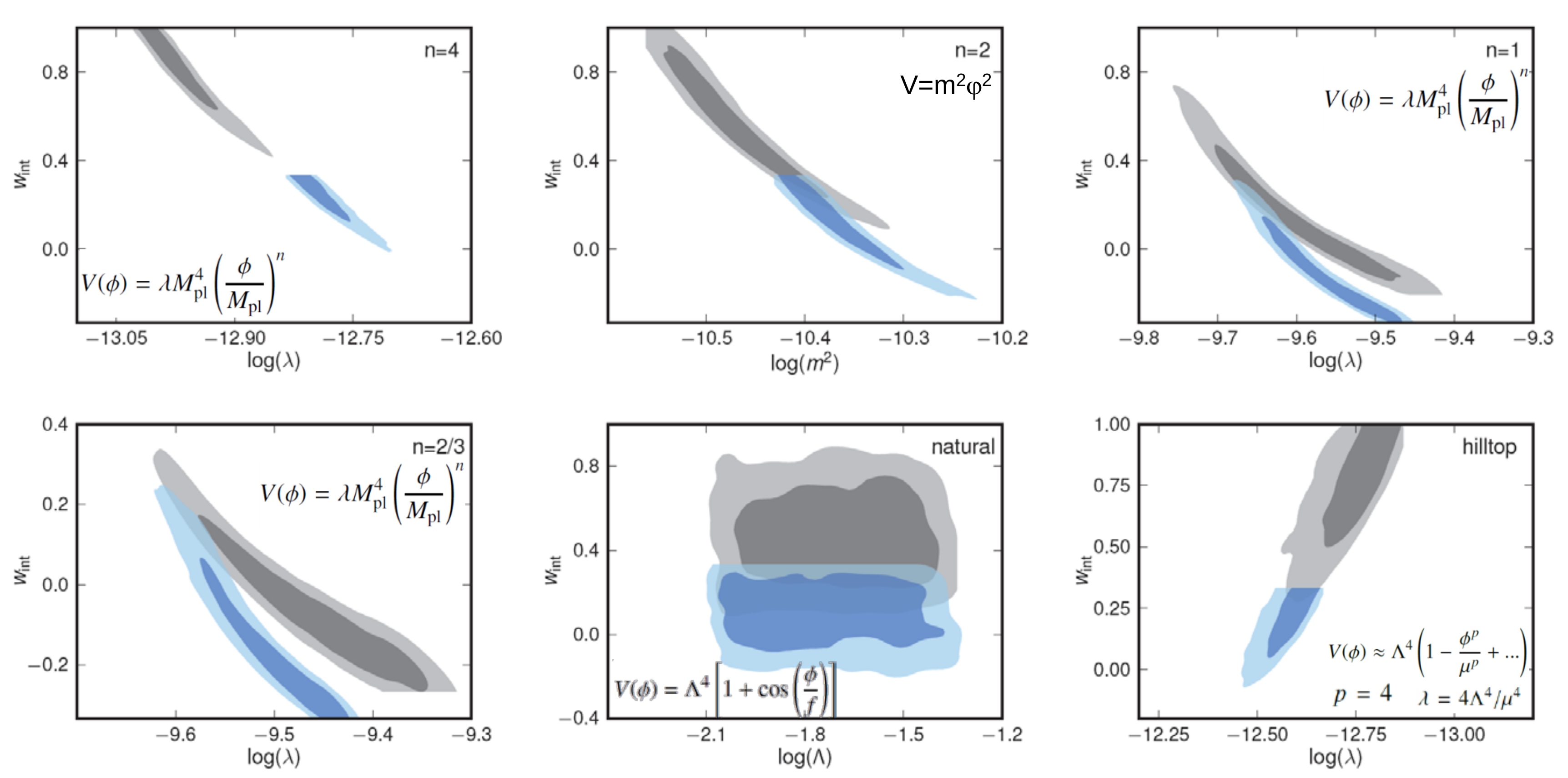
➔Exponential potential models(power-law inf.), simplest hybrid inflationary models (SB SUSY), monomial potential models of degree n >2 do not provide a good fit to the data.

Running through the herbarium…

$$N_* \approx 71.21 - \ln\left(\frac{k_*}{a_0 H_0}\right) + \frac{1}{4}\ln\left(\frac{V_{\rm hor}}{M_{\rm pl}^4}\right) + \frac{1}{4}\ln\left(\frac{V_{\rm hor}}{\rho_{\rm end}}\right) + \frac{1-3w_{\rm int}}{12(1+w_{\rm int})}\ln\left(\frac{\rho_{\rm th}}{\rho_{\rm end}}\right)$$

2t~3, 3t~-10, 4t~O(1)
→ $N_* \in [50, 60]$)

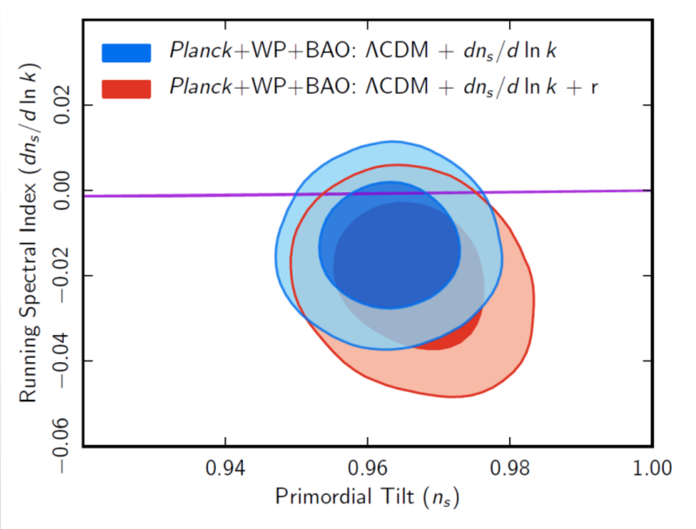
w_{int}= parameter of *effective* equation of state between end of inflation and thermalisation (instantaneous ↔ w_{int}=1/3)



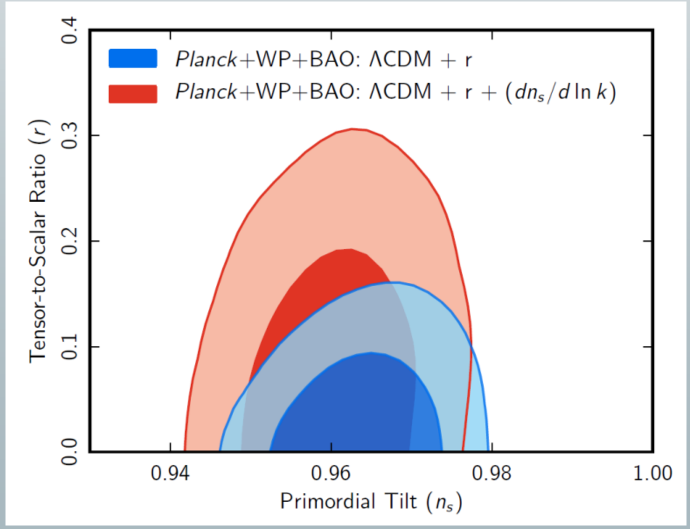
Blue and grey area respectively correspond to the restrictive ($\rho_{th}^{1/4} = 10^9 GeV, w_{int} \in [-\frac{1}{3}, \frac{1}{3}]$) and permissive ($\rho_{th}^{1/4} = 10^3 GeV, w_{int} \in [-\frac{1}{3}, 1]$) entropy generation scenario; red is instantaneous reheating for natural and hilltop.

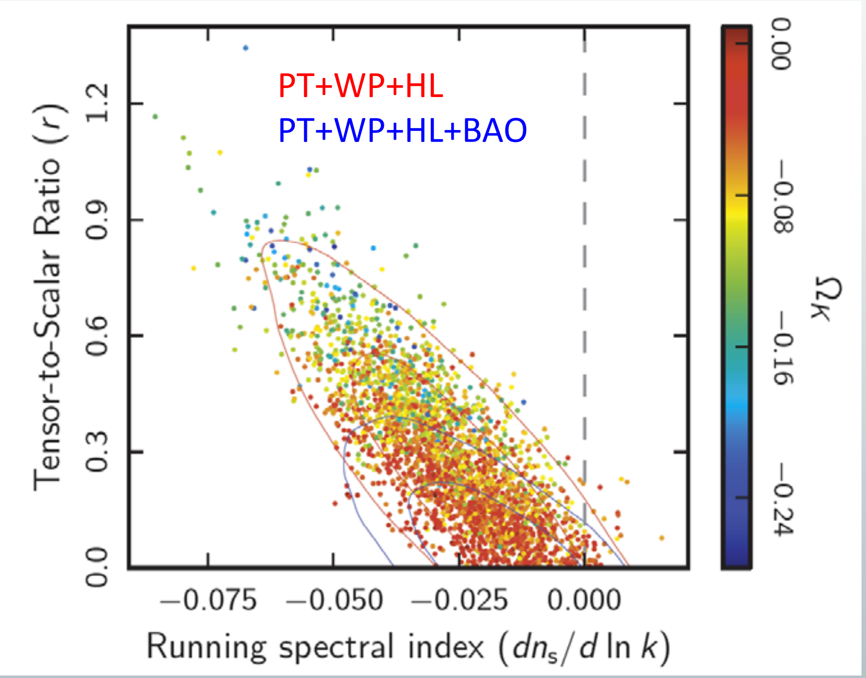
Running tests

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_*}\right)^{n_s - 1 + \frac{1}{2}\, dn_s/d\ln k\, \ln(k/k_*)}$$



purple strip is the prediction for single monomial chaotic inflationary models with $50 < N_* < 60$.



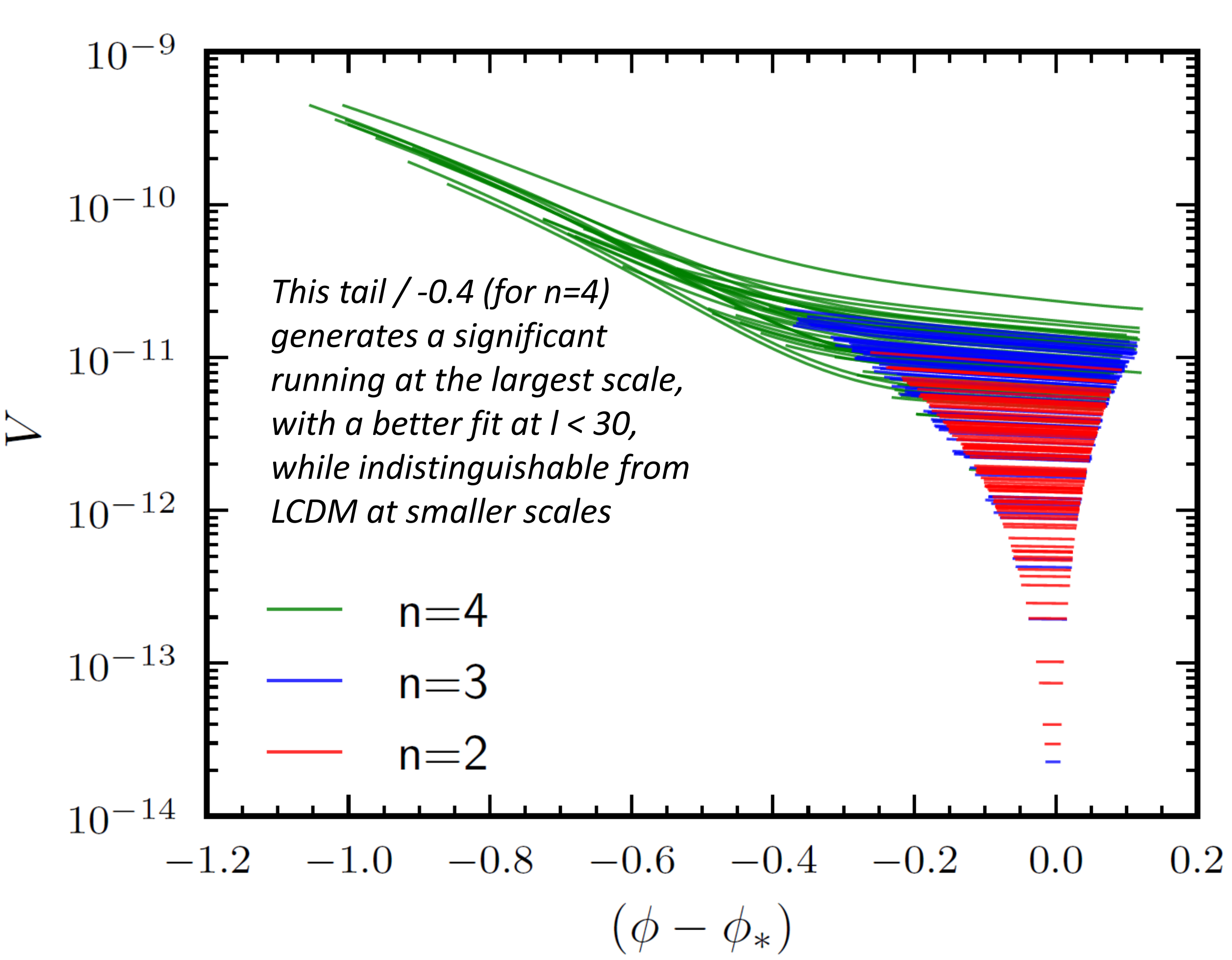


→ Open inflation is not needed (to explain $|\Omega_k| \gtrsim 10^{-5}$)

LCDM+dn_s/dlnk =-0.013±0.009 PT+WP

LCDM+r → 0.021±0.012 PT+WP

Inflaton potential reconstruction



Best fitting potentials, when V(ϕ) is Taylor expanded at the n-th order around the pivot scale;

Planck-T+WP;

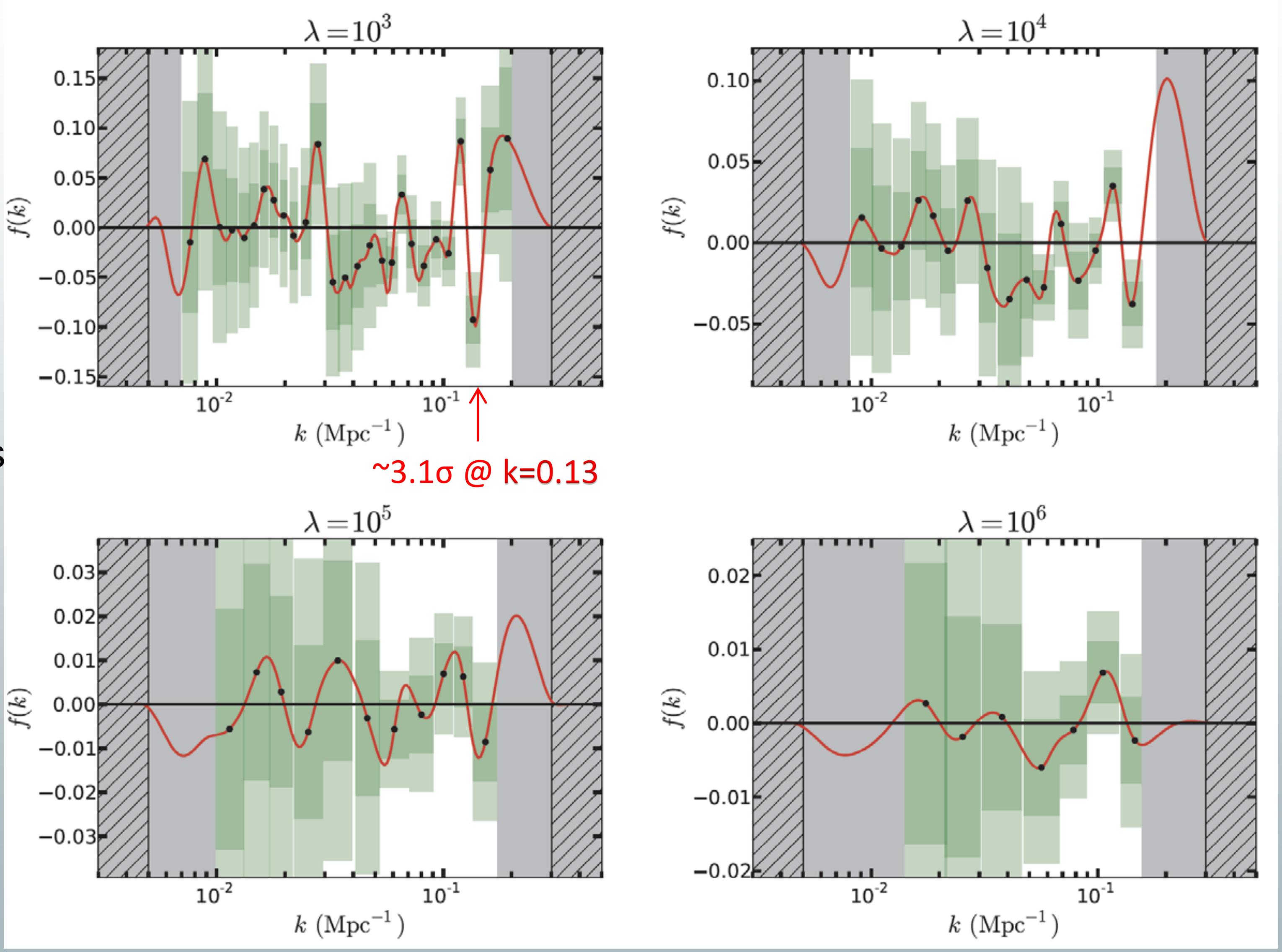
Flat priors on ε, η, ξ^2;

Φ_* in natural units / $(8\pi)^{1/2}$Mp=1.

	from $V(\phi)$		
n	2	3	4
$\ln[10^{10} A_s]$	$3.087^{+0.050}_{-0.050}$	$3.115^{+0.066}_{-0.063}$	$3.130^{+0.071}_{-0.066}$
n_s	$0.961^{+0.015}_{-0.015}$	$0.958^{+0.017}_{-0.016}$	$0.954^{+0.018}_{-0.018}$
$100\, dn_s/d\ln k$	$-0.05^{+0.13}_{-0.14}$	$-2.2^{+2.2}_{-2.3}$	$-0.61^{+3.1}_{-3.1}$
$100\, d^2n_s/d\ln k^2$	$-0.01^{+0.73}_{-0.75}$	$-0.3^{+1.0}_{-1.2}$	$6.3^{+8.6}_{-7.8}$
r	< 0.12	< 0.22	< 0.35

Features search in P(k) - non-parametric

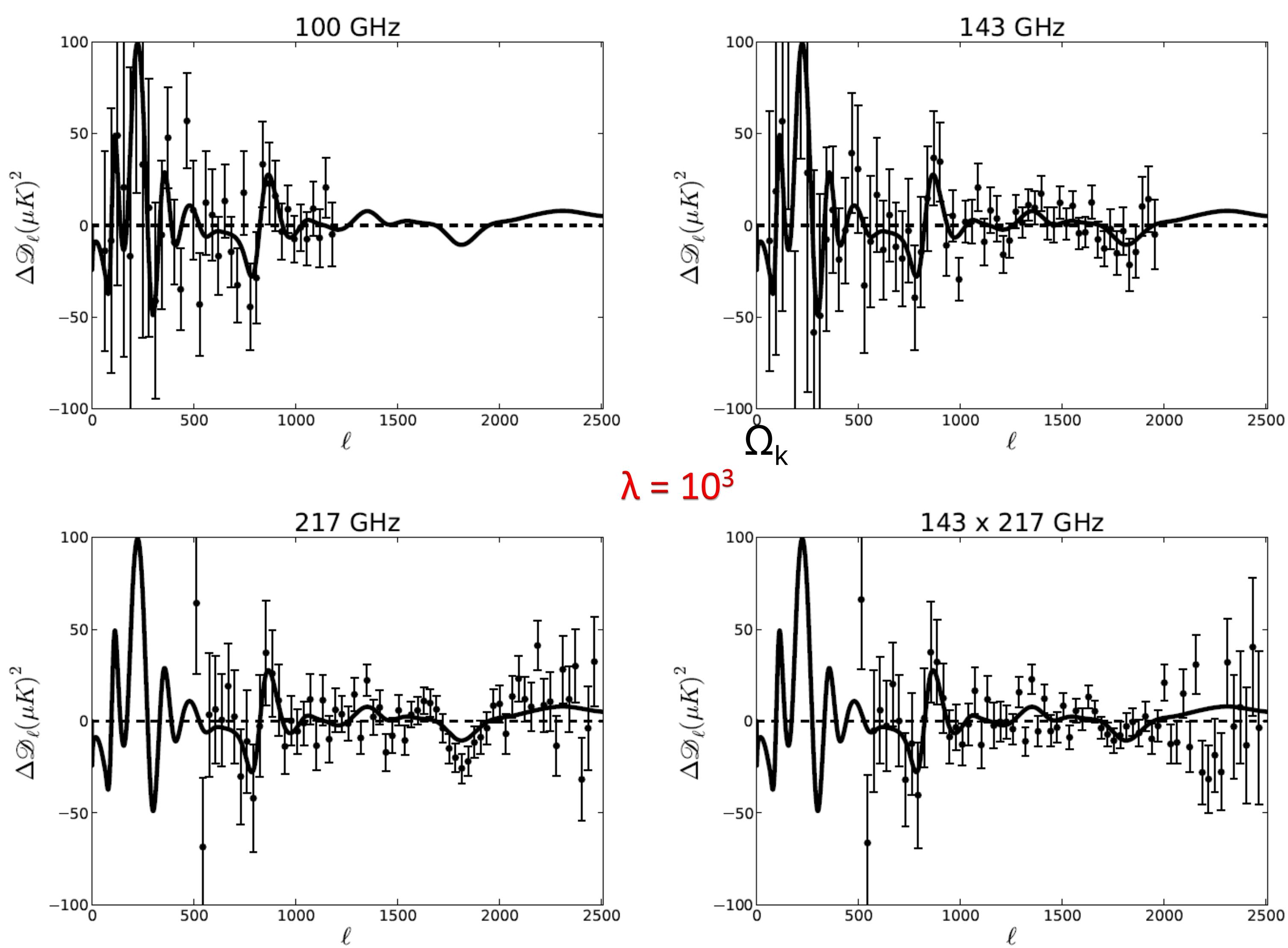
1&2σ boxes



Red=ML solution for given smoothing parameter λ

Nuisance parameters (beams) fixed to their fiducial best fit values

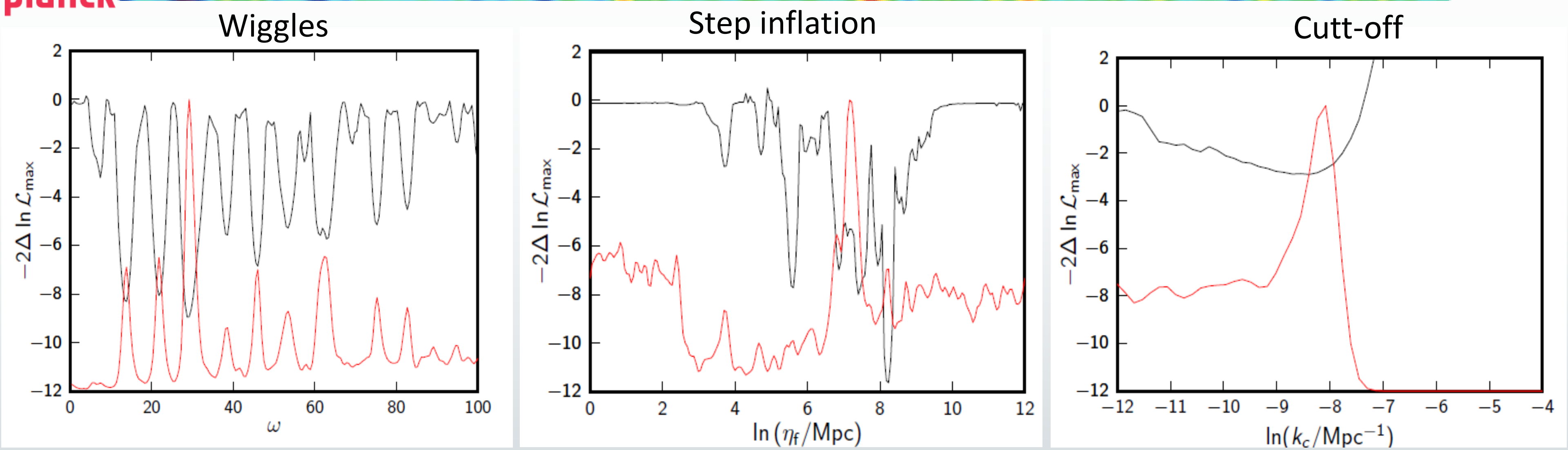
What is fitted in the Cl's?



The features in the T power spectrum, (broad dip at 1800) , cannot be explained by any of the known systematics which we propagated through the data analysis pipeline.

Analysis of the full mission data will help assessing whether these small departures from the best fit LCDM spectrum may possibly be due to unknown systematic effects, (or inaccurate propagation of known syst. effects), into the final power spectra.

Features search (parametric)



Profile likelihood & Posterior probability (marginalised)

$$\mathcal{P}_0(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} \quad \mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k)\left\{1 + \alpha_w \sin\left[\omega \ln\left(\frac{k}{k_*}\right) + \varphi\right]\right\}$$

wiggles

$$\mathcal{P}_{\mathcal{R}}(k) = \exp\left[\ln \mathcal{P}_0(k) + \frac{\mathcal{A}_f}{3}\frac{k\eta_f/x_d}{\sinh(k\eta_f/x_d)} W'(k\eta_f)\right]$$

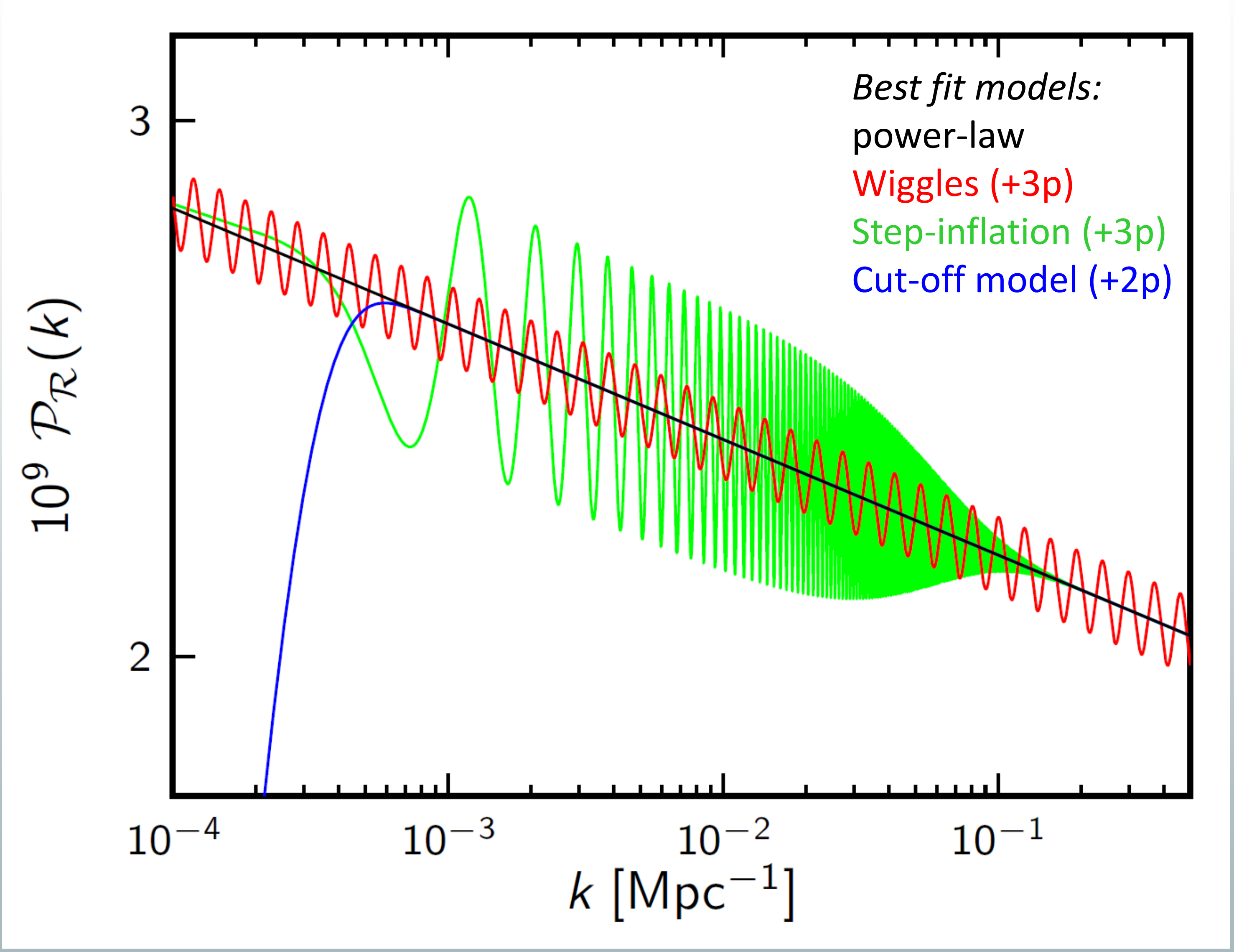
Step-inflation model

$$W'(x) = \left(-3 + \frac{9}{x^2}\right)\cos 2x + \left(15 - \frac{9}{x^2}\right)\frac{\sin 2x}{2x}$$

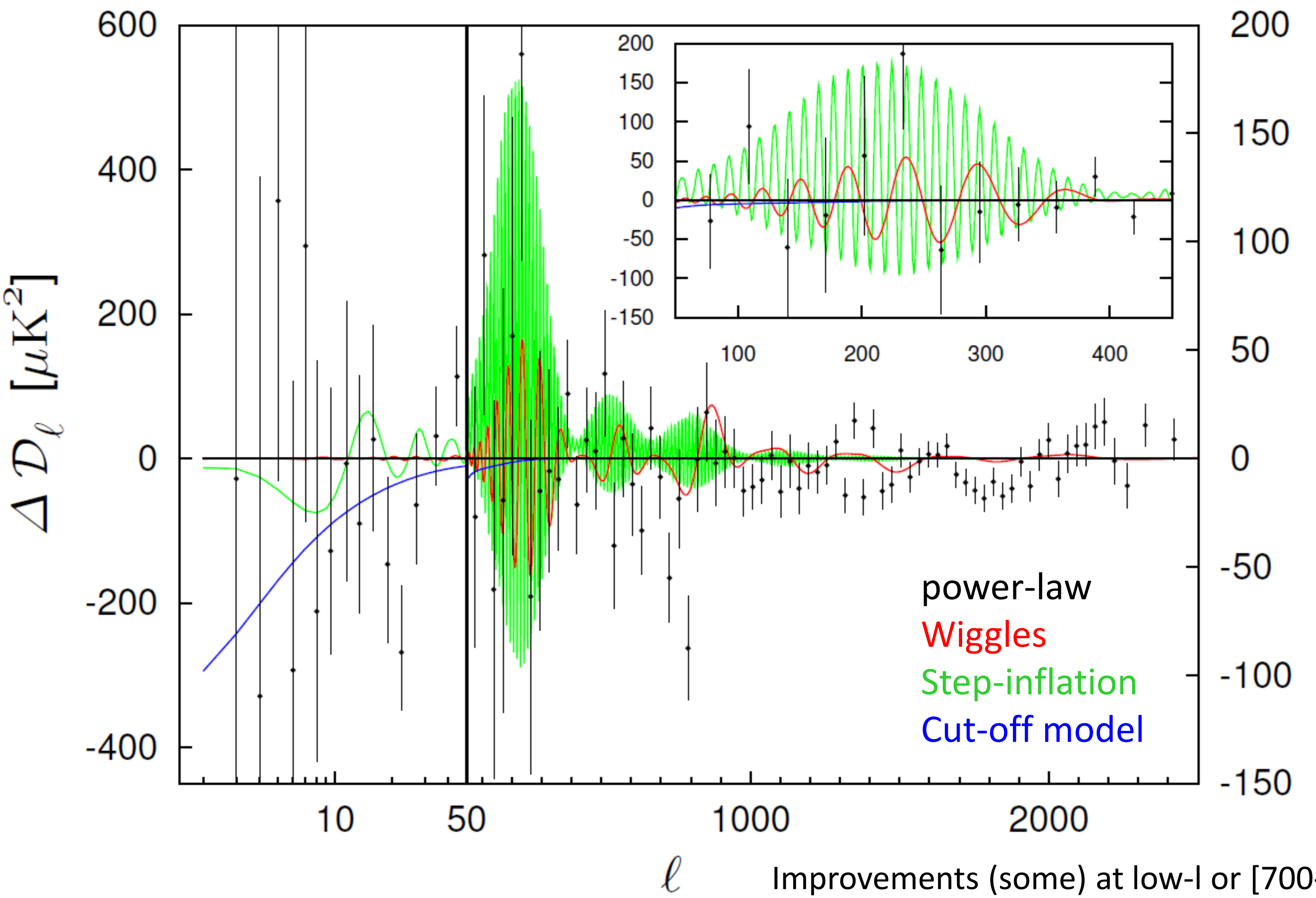
$$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k)\left\{1 - \exp\left[-\left(\frac{k}{k_c}\right)^{\lambda_c}\right]\right\}$$

Cut-off model

Best fit for these specific feature models



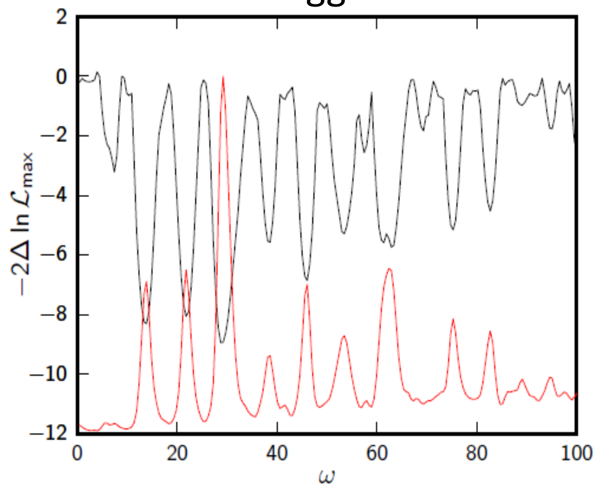
Temperature residuals



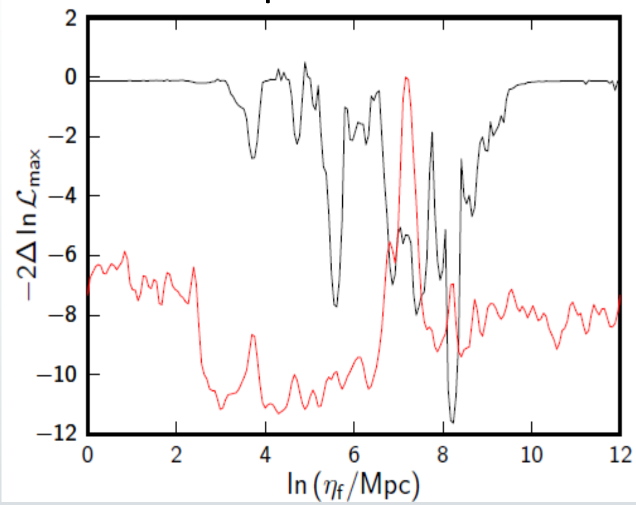
Improvements (some) at low-l or [700-1000]

Features search (parametric)

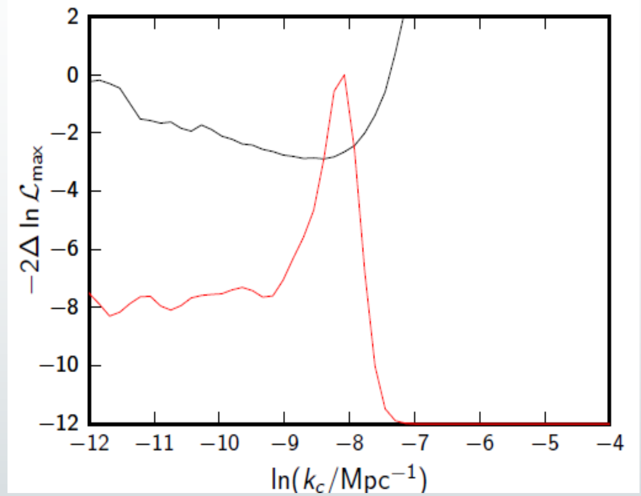
Wiggles



Step inflation



Cutt-off



Profile likelihood & Posterior probability (marginalised)

Are these improvements significant ?

• We have not run a full frequentist analysis to account for the “look elsewhere” effect

• Bayes: these models are not predictive enough (for our choice of prior) **-> LCDM preferred**

• If real, likely to show up in polarisation and NG searches

Model	$-2\Delta \ln \mathcal{L}_{max}$	$\ln B_{0X}$	Parameter	Best fit value
Wiggles	-9.0	1.5	α_w	0.0294
			ω	28.90
			φ	0.075 π
Step-inflation	-11.7	0.3	$\mathcal{A}_f$	0.102
			$\ln(\eta_f/\mathrm{Mpc})$	8.214
			$\ln x_d$	4.47
Cutoff	-2.9	0.3	$\ln(k_c/\mathrm{Mpc}^{-1})$	−8.493
			λ_c	0.474

NB: Some improvement had already been noted earlier

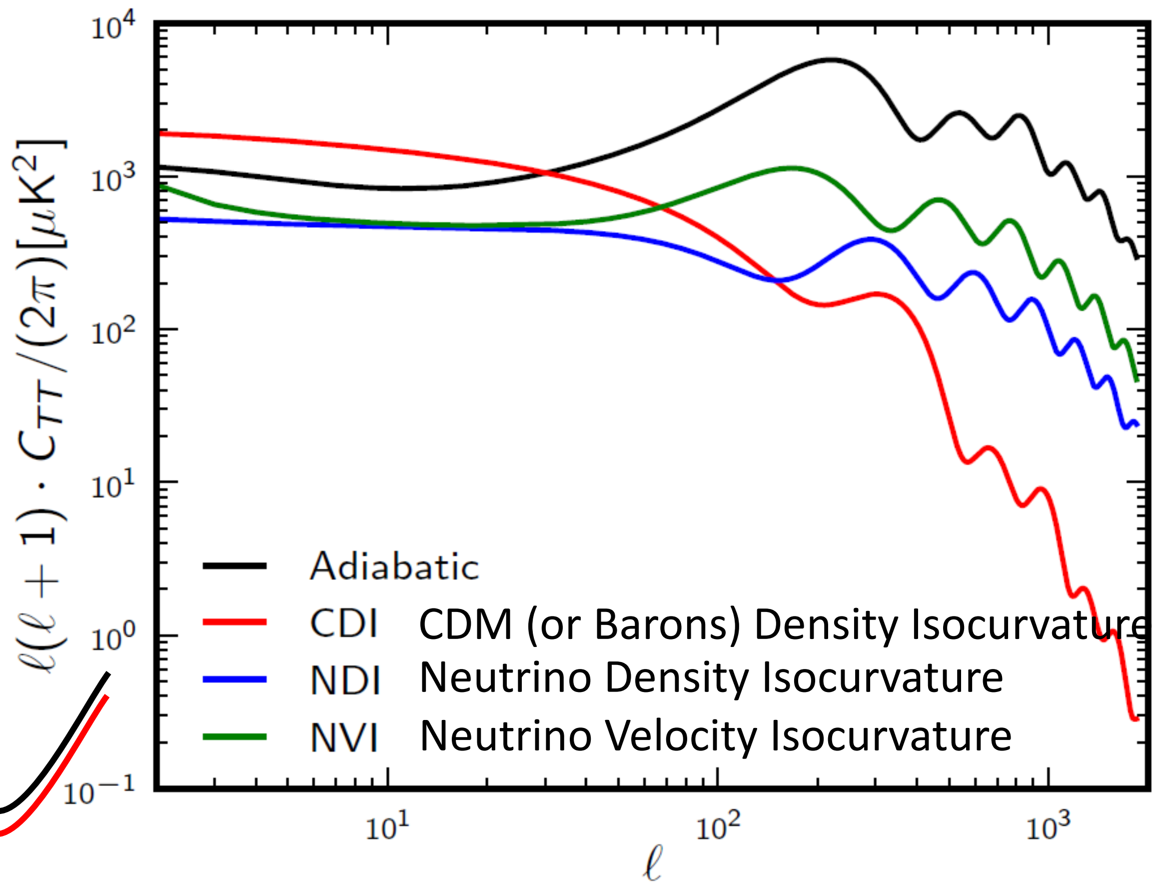
Isocurvature modes

Isocurvature modes arise from spatial variations in the equation of state or from relative velocities between the components.

I.e. the density perturbations in the various components (e.g., baryons&leptons, CDM, photons, neutrinos) are not locked together.

These might be excited, e.g., with multi-component inflaton field.

Expect correlations between isocurvature and curvature degrees of freedom



$$\boldsymbol{\mathcal{P}}(k) = \begin{pmatrix} \mathcal{P}_{\mathcal{R}\mathcal{R}}(k) & \mathcal{P}_{\mathcal{R}\mathcal{I}_{\rm CDI}}(k) & \mathcal{P}_{\mathcal{R}\mathcal{I}_{\rm NDI}}(k) & \mathcal{P}_{\mathcal{R}\mathcal{I}_{\rm NVI}}(k) \\ \mathcal{P}_{\mathcal{I}_{\rm CDI}\mathcal{R}}(k) & \mathcal{P}_{\mathcal{I}_{\rm CDI}\mathcal{I}_{\rm CDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm CDI}\mathcal{I}_{\rm NDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm CDI}\mathcal{I}_{\rm NVI}}(k) \\ \mathcal{P}_{\mathcal{I}_{\rm NDI}\mathcal{R}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NDI}\mathcal{I}_{\rm CDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NDI}\mathcal{I}_{\rm NDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NDI}\mathcal{I}_{\rm NVI}}(k) \\ \mathcal{P}_{\mathcal{I}_{\rm NVI}\mathcal{R}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NVI}\mathcal{I}_{\rm CDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NVI}\mathcal{I}_{\rm NDI}}(k) & \mathcal{P}_{\mathcal{I}_{\rm NVI}\mathcal{I}_{\rm NVI}}(k) \end{pmatrix}$$

Assuming a single isocurvature mode

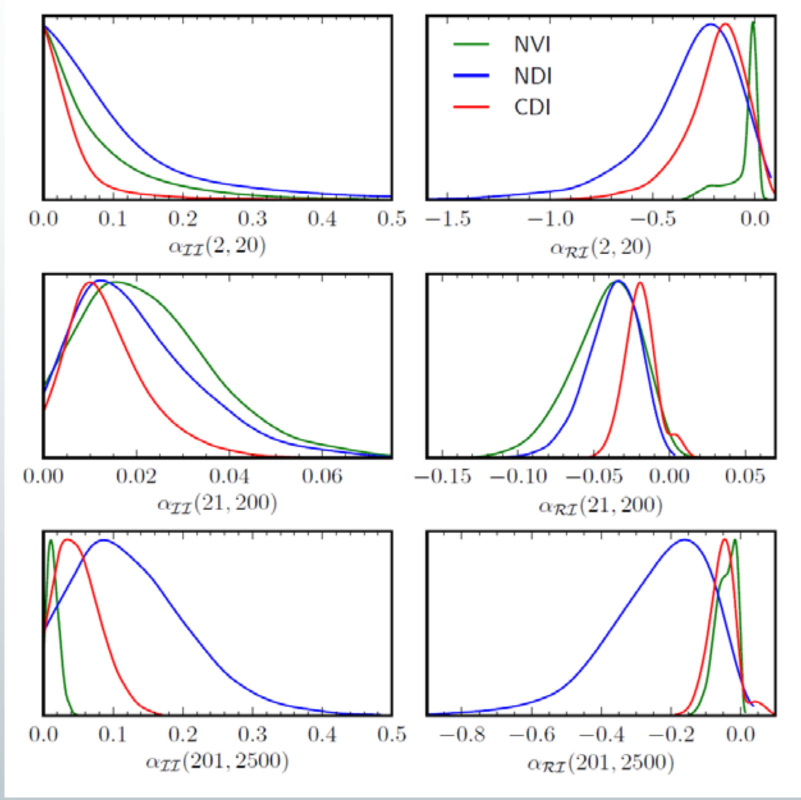
Only weak fractional contribution in various l-ranges allowed:

$$\alpha_{II}(\ell_{\min}, \ell_{\max}) = \frac{(\Delta T)^2_{II}(\ell_{\min}, \ell_{\max})}{(\Delta T)^2_{\rm tot}(\ell_{\min}, \ell_{\max})}$$

$$\alpha_{RI}(\ell_{\min}, \ell_{\max}) = \frac{(\Delta T)^2_{RI}(\ell_{\min}, \ell_{\max})}{(\Delta T)^2_{\rm tot}(\ell_{\min}, \ell_{\max})}$$

with

$$(\Delta T)^2_X(\ell_{\min}, \ell_{\max}) = \sum_{\ell=\ell_{\min}}^{\ell_{\max}} (2\ell + 1) C^{TT}_{X,\ell}$$



Low-l [2,20]

Mid-l [21,200]

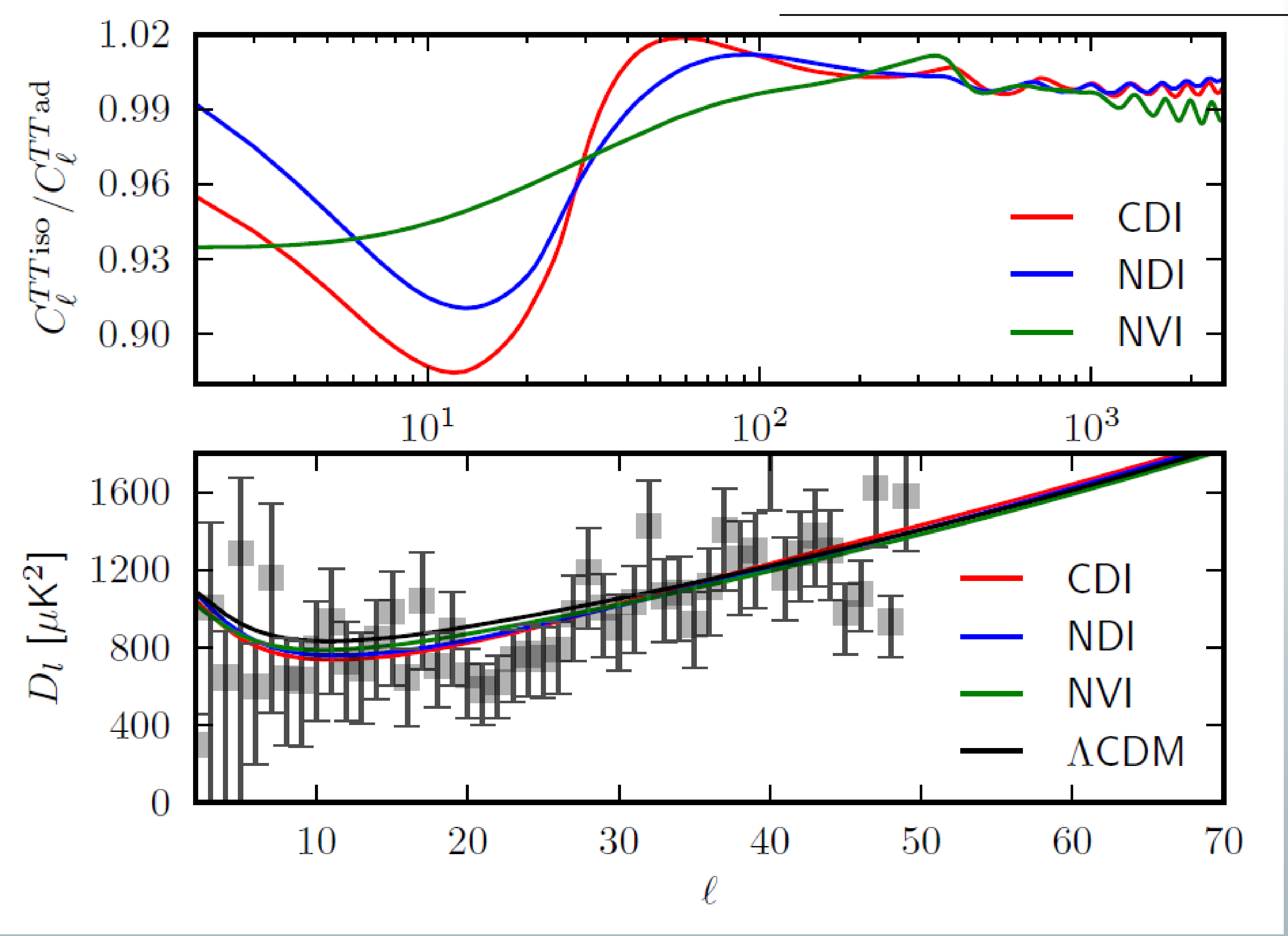
High-l [201,2500]

Model *95%CL bounds*	$\alpha_{RR}^{(2,2500)}$	$\alpha_{II}^{(2,2500)}$	$\alpha_{RI}^{(2,2500)}$	Δn	$-2\Delta \ln \mathcal{L}_{\max}$
General model:					
CDM isocurvature	[0.98:1.07]	0.039	[-0.093:0.014]	4	-4.6
ND isocurvature	[0.99:1.09]	0.093	[-0.18:0]	4	-4.2
NV isocurvature	[0.96:1.05]	0.068	[-0.090:0.026]	4	-2.5
Special CDM isocurvature cases:					
Uncorrelated, $n_{II} = 1$, ("axion")	[0.98:1]	0.016	–	1	0
Fully correlated, $n_{II} = n_{RR}$, ("curvaton")	[0.97:1]	0.0011	[0:0.028]	1	0
Fully anti-correlated, $n_{II} = n_{RR}$	[1:1.06]	0.0046	[-0.067:0]	1	-1.3

$r_D > 0.98$

Only weak evidence

Assuming a single isocurvature mode

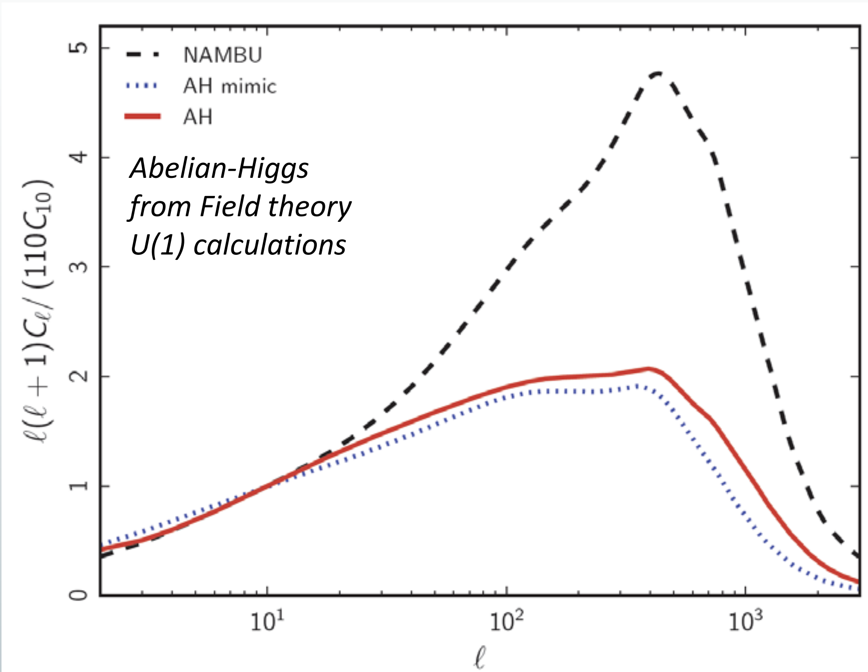


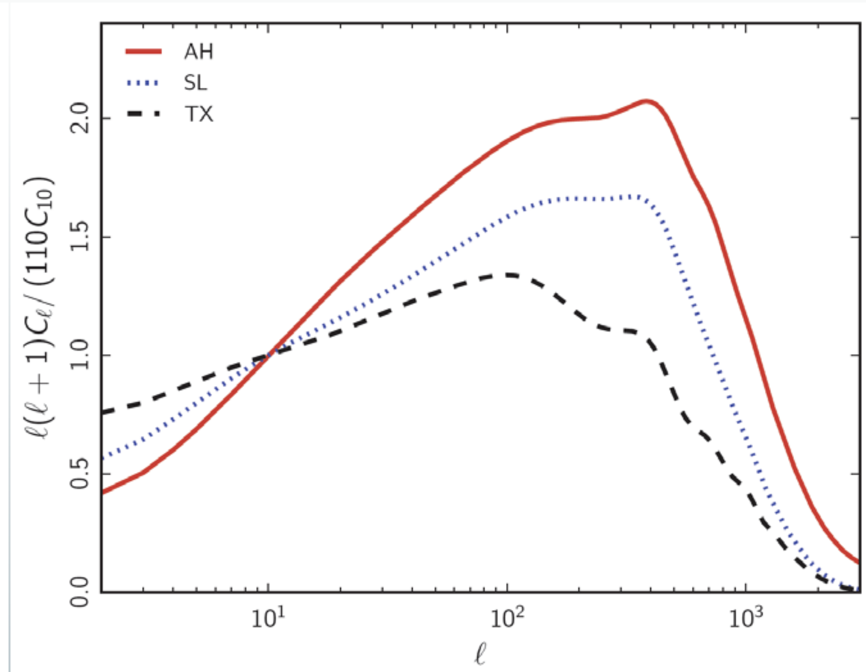
… helps (somewhat) at low-l (again!)

Cosmic defects

- Cosmic defects are a generic outcome of symmetry-breaking phase transitions in the early Universe.
  - *Strings appear in a variety of supersymmetric and other grand unified theories, forming at the end of inflation.*
  - *Cosmic (super-)strings also emerge in higher-dimensional theories for LSS, as in brane inflation.*
  - *Comparable effects can also be caused by other types of cosmic defects, notably semi-local strings and global textures.*
- The discovery of any of these objects would identify GUT-scale symmetry breaking patterns, perhaps even providing direct evidence for extra dimensions. Conversely, their absence tightly constrains symmetry breaking schemes.
- The most stringent constraints on the string tension arise from predicted backgrounds of gravitational waves from decaying loops, thus rely on most uncertain part of string physics (loop production scale and nature of string radiation from cusps)
- Defects affect both CMB power spectrum and NG properties.

Spectra used in this analysis





Cosmic strings, normalised to equal power at l=10 (around 2 10^{-6} with W7 ➔ less than 3% of overall spectrum

Comparison between global texture (black dashed) and semilocal (blue dotted) string power spectra and the AH field theory strings (red solid)

Cosmic strings: none in sight yet

From power spectrum analysis: (other parameters, inc. n_s, unaffected)

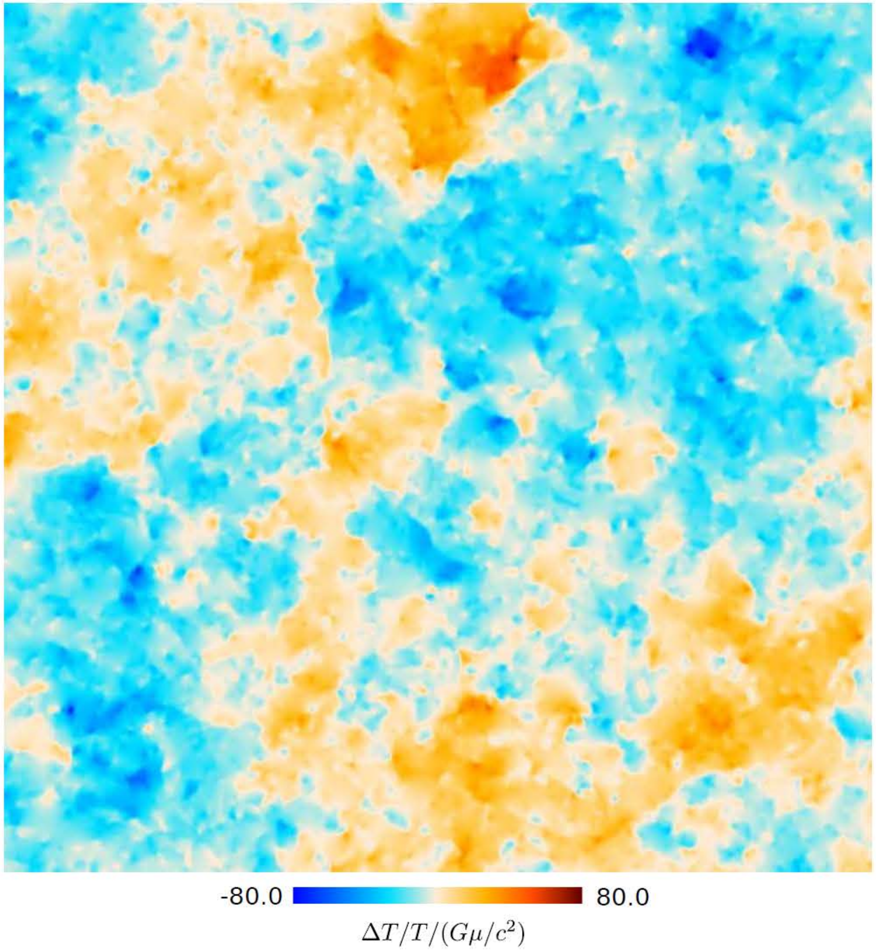
Defect type	*Planck*+WP f_{10}	*Planck*+WP $G\mu/c^2$	*Planck*+WP+highL f_{10}	*Planck*+WP+highL $G\mu/c^2$
NAMBU	0.015	1.5×10^{-7}	0.010	1.3×10^{-7}
AH-mimic	0.033	3.6×10^{-7}	0.034	3.7×10^{-7}
AH	0.028	3.2×10^{-7}	0.024	3.0×10^{-7}
SL Semilocal	0.043	11.0×10^{-7}	0.041	10.7×10^{-7}
TX Global texture	0.055	10.6×10^{-7}	0.054	10.5×10^{-7}

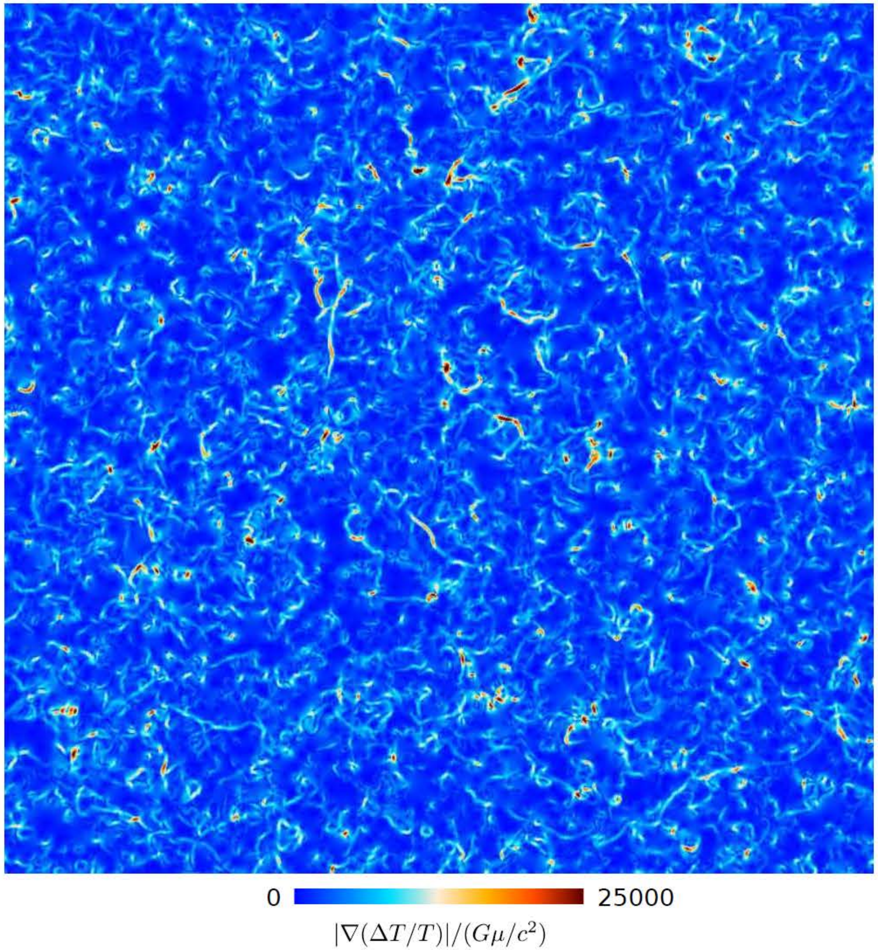
Cosmological parameters are unaffected

f_{10} = fractional contribution at l=10
Mass per unit length, $G\mu/c^2 = (\eta/m_p)^2$, η = energy scale of symmetry breaking
(ie $\eta < 4.7 \times 10^{15}$ GeV for Nambu-Goto strings)

Zooming in reveals the NG aspect

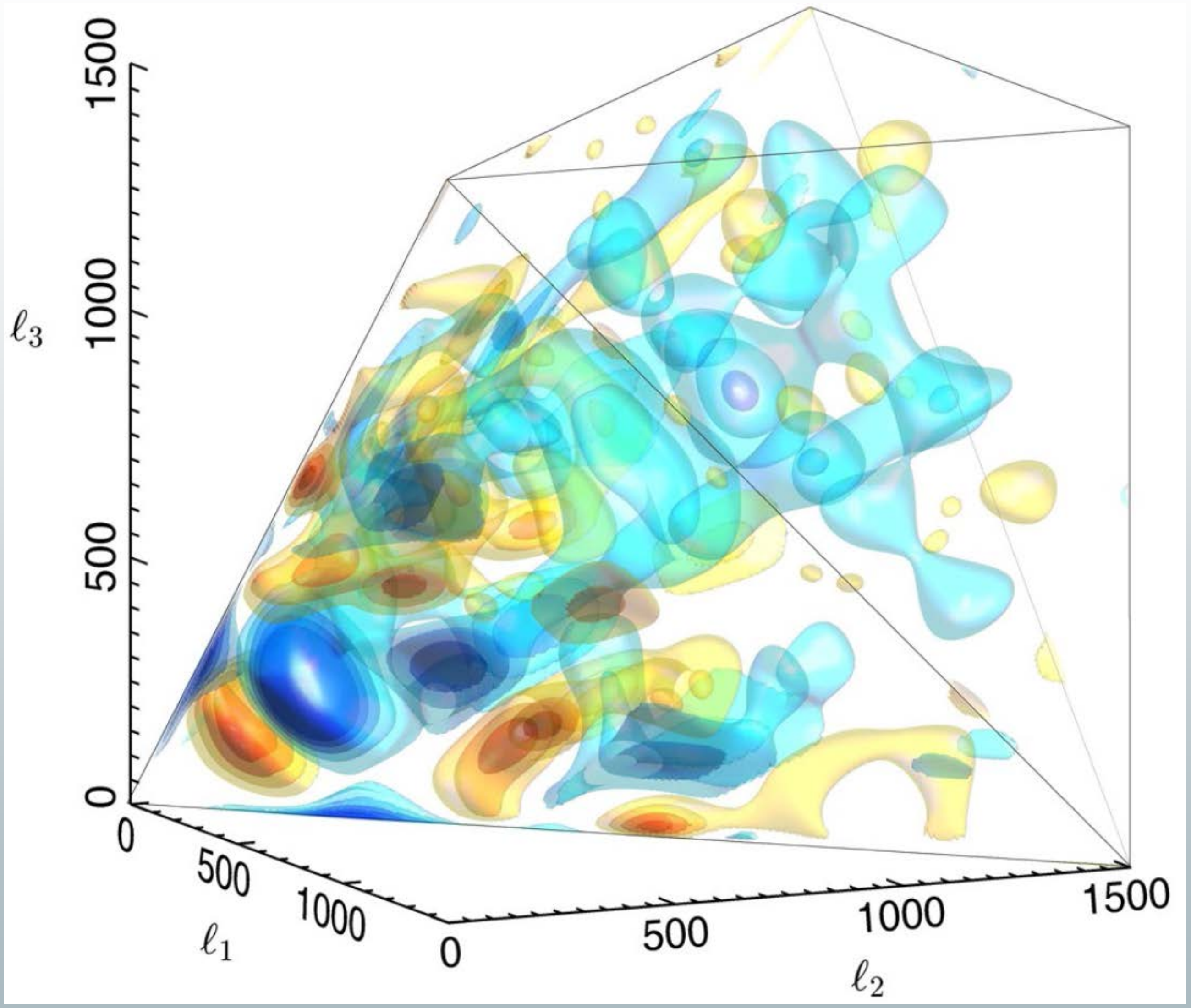
A zoom on a 20 degree patch extracted from a full sky simulated makes temperature steps visible. Applying the spherical gradient magnitude operator enhances the steps, and thus the string locations.





→ Modal bispectrum: $G\mu/c^2 < 8.8 \times 10^{-7}$ (95%CL); Minkowski functionals : $G\mu/c^2 < 7.8 \times 10^{-7}$ (95%CL); (post rec)

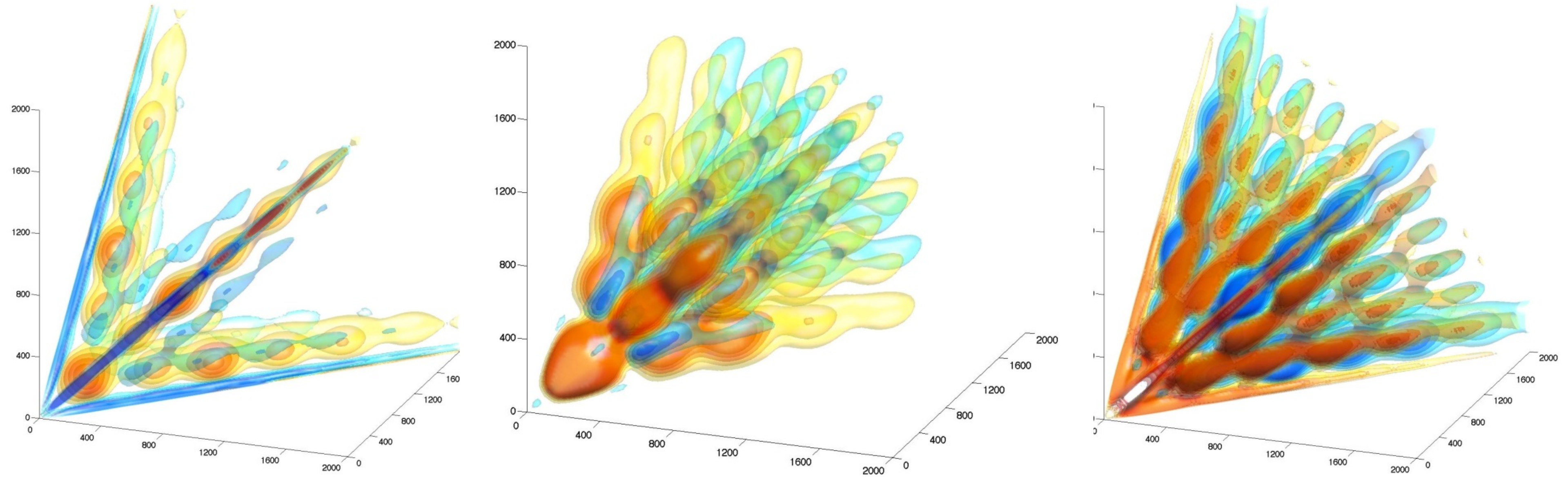
The Planck CMB bispectrum



(modal decomposition on SMICA)

CMB bispectrum fingerprinting with Planck

LEO (local, Equilateral, Orthogonal) are common outputs



NG of ***local*** type:

- ➢ Multi-field models
- ➢ Curvaton
- ➢ Ekpyrotic/cyclic models

(Also NG of Folded type

- ➢ Non Bunch-Davis
- ➢ Higher derivative)

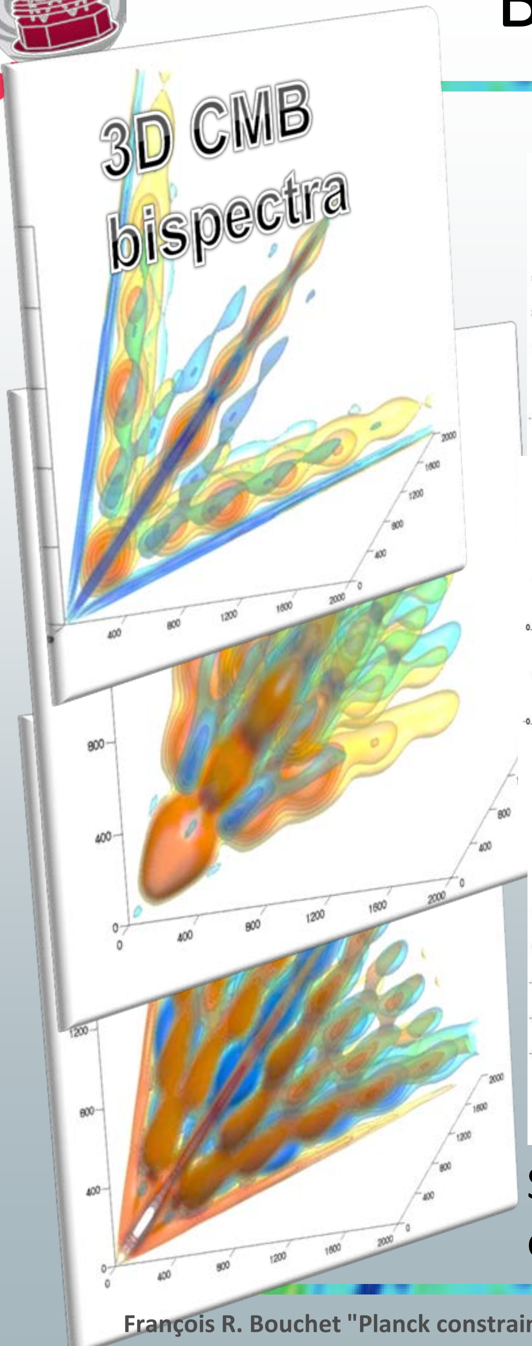
NG of ***equilateral*** type:

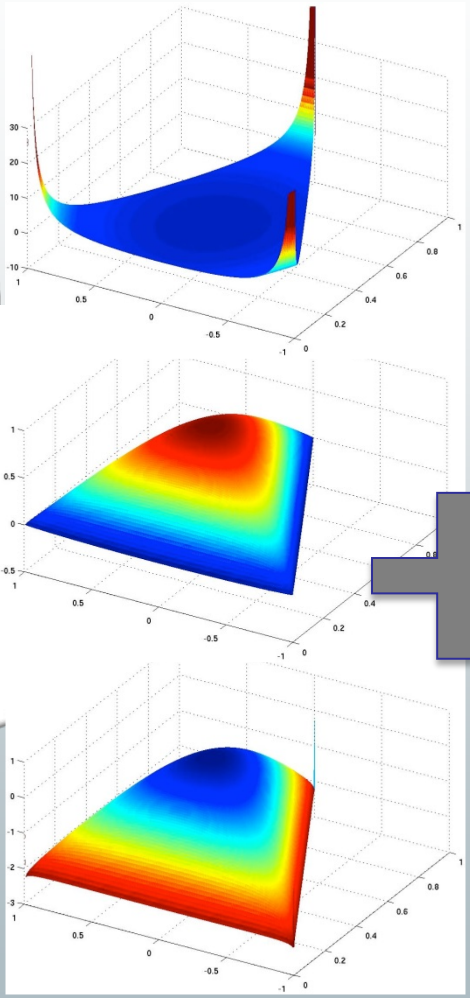
- ➢ Non-canonical kinetic term
  - – K-inflation
  - – DBI inflation
- ➢ Higher-derivate terms in Lagrangian
  - – Ghost inflation
- ➢ Effective field theory

NG of ***orthogonal*** type:

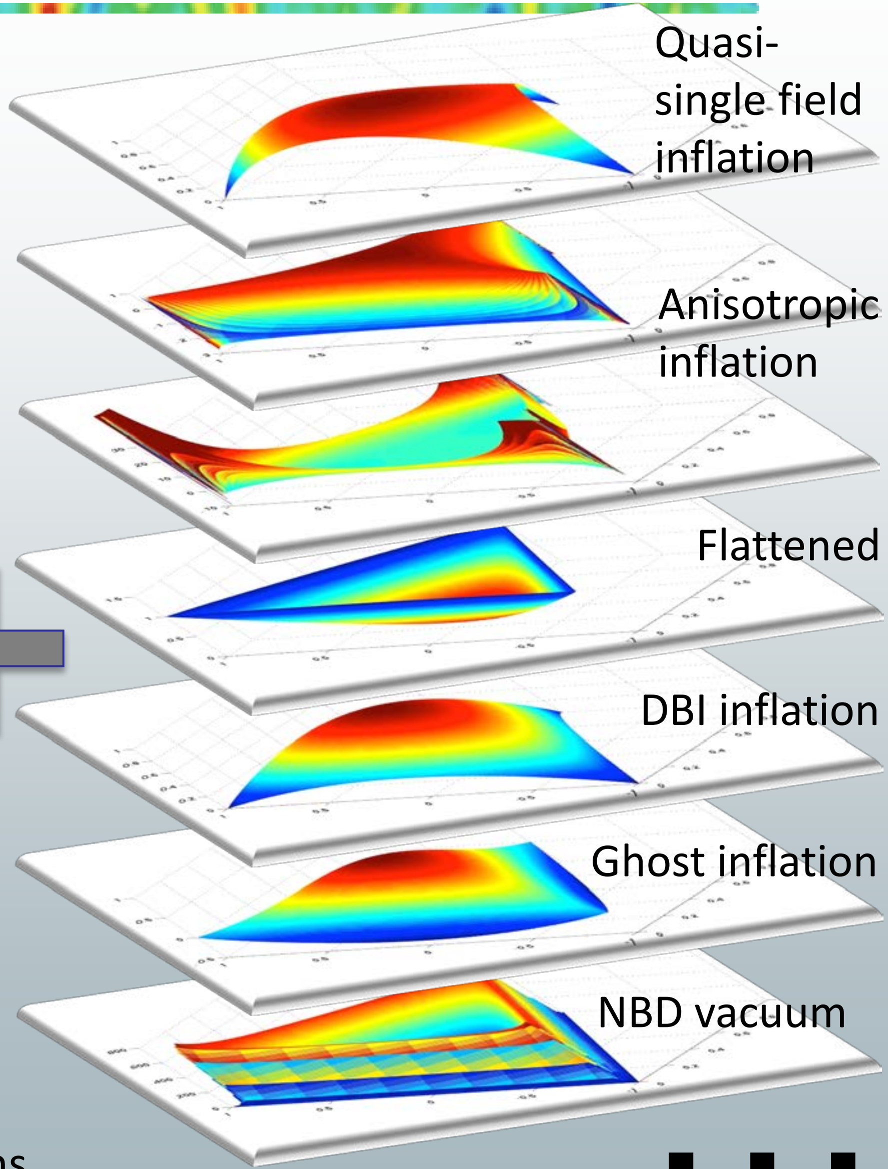
- ➢ Distinguishes between different variants of
  - – Non-canonical kinetic term
  - – Higher derivative interactions
- ➢ Galileon inflation

Bispectrum fingerprinting

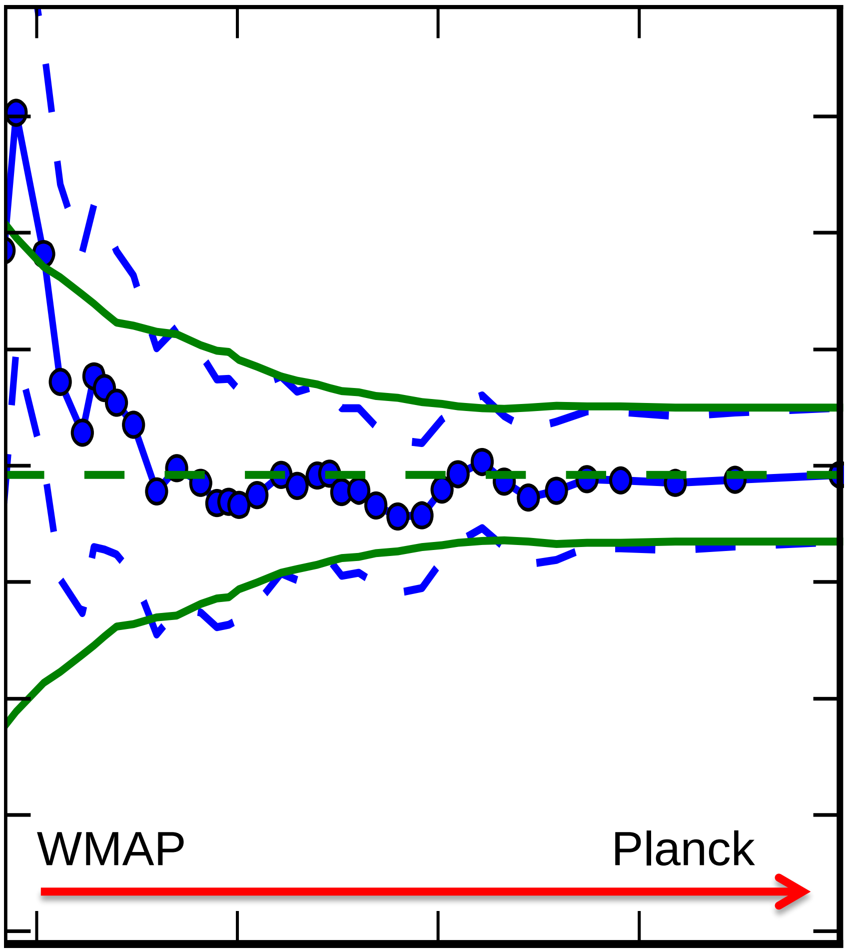




Slices through bispectra
of primordial fluctuations



More modes helps ☺



Limiting the analysis to large scales (low l), we make contact with WMAP9 (which gave f_{NL}^{local}=37.2 ± 20)

Planck now rules out the WMAP central value by ~6 sigma.

this figure is before subtraction of ISW X lensing bias, *which is clearly visible*

Planck results on standard LEO shapes

	Independent KSW	Independent Binned	Independent Modal		ISW-lensing subtracted KSW	ISW-lensing subtracted Binned	ISW-lensing subtracted Modal
SMICA							
Local	9.8 ± 5.8	9.2 ± 5.9	8.3 ± 5.9	. . . . .	**2.7 ± 5.8**	2.2 ± 5.9	1.6 ± 6.0
Equilateral	−37 ± 75	−20 ± 73	−20 ± 77	. . . . .	**−42 ± 75**	−25 ± 73	−20 ± 77
Orthogonal	−46 ± 39	−39 ± 41	−36 ± 41	. . . . .	**−25 ± 39**	−17 ± 41	−14 ± 42
NILC							
Local	11.6 ± 5.8	10.5 ± 5.8	9.4 ± 5.9	. . . . .	4.5 ± 5.8	3.6 ± 5.8	2.7 ± 6.0
Equilateral	−41 ± 76	−31 ± 73	−20 ± 76	. . . . .	−48 ± 76	−38 ± 73	−20 ± 78
Orthogonal	−74 ± 40	−62 ± 41	−60 ± 40	. . . . .	−53 ± 40	−41 ± 41	−37 ± 43
SEVEM							
Local	10.5 ± 5.9	10.1 ± 6.2	9.4 ± 6.0	. . . . .	3.4 ± 5.9	3.2 ± 6.2	2.6 ± 6.0
Equilateral	−32 ± 76	−21 ± 73	−13 ± 77	. . . . .	−36 ± 76	−25 ± 73	−13 ± 78
Orthogonal	−34 ± 40	−30 ± 42	−24 ± 42	. . . . .	−14 ± 40	−9 ± 42	−2 ± 42
C-R							
Local	12.4 ± 6.0	11.3 ± 5.9	10.9 ± 5.9	. . . . .	6.4 ± 6.0	5.5 ± 5.9	5.1 ± 5.9
Equilateral	−60 ± 79	−52 ± 74	−33 ± 78	. . . . .	−62 ± 79	−55 ± 74	−32 ± 78
Orthogonal	−76 ± 42	−60 ± 42	−63 ± 42	. . . . .	−57 ± 42	−41 ± 42	−42 ± 42

Estimators agree

- KSW *(Komatsu, Spergel, Wandelt 2003)*
- Modal *(Fergusson, Liguori, Shellard, 2009)*
- Binned *(Bucher, v. Tent, Carvalho 2009)*
- Skew-Cl *(Munshi, Heavens 2010)*
- Minkowski functionals *(Ducout et al. 2012)*

Foreground cleaning methods agree

- *SMICA*
- *NILC*
- *SEVEM*
- *(C-R)*

Negligible impact of FG residuals

Null tests pass

Consistency test pass

- *Resolution dependence*
- *Frequency dependence*
- *Mask dependence*

Searching specific shapes...

→ To no avail for flattened shapes...

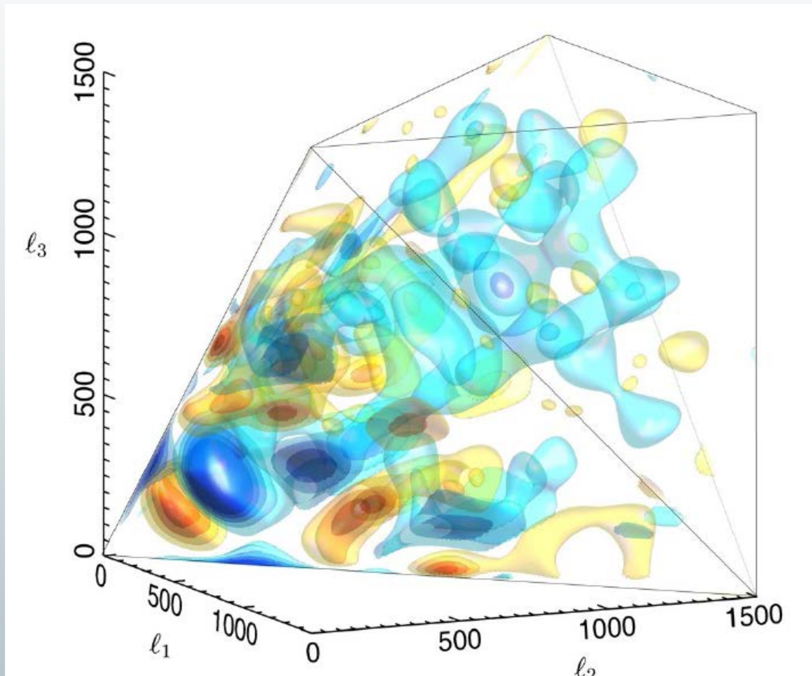
Flattened model (Eq. number)	Raw f_{NL}	Clean f_{NL}	Δf_{NL}	σ	Clean σ
Flat model (13)	70	37	77	0.9	0.5
Non-Bunch-Davies (NBD)	178	155	78	2.2	2.0
Single-field NBD1 flattened (14)	31	19	13	2.4	1.4
Single-field NBD2 squeezed (14)	0.8	0.2	0.4	1.8	0.5
Non-canonical NBD3 (15)	13	9.6	9.7	1.3	1.0
Vector model $L = 1$ (19)	−18	−4.6	47	−0.4	−0.1
Vector model $L = 2$ (19)	2.8	−0.4	2.9	1.0	−0.1

→ And with tantalising hints for some feature models...

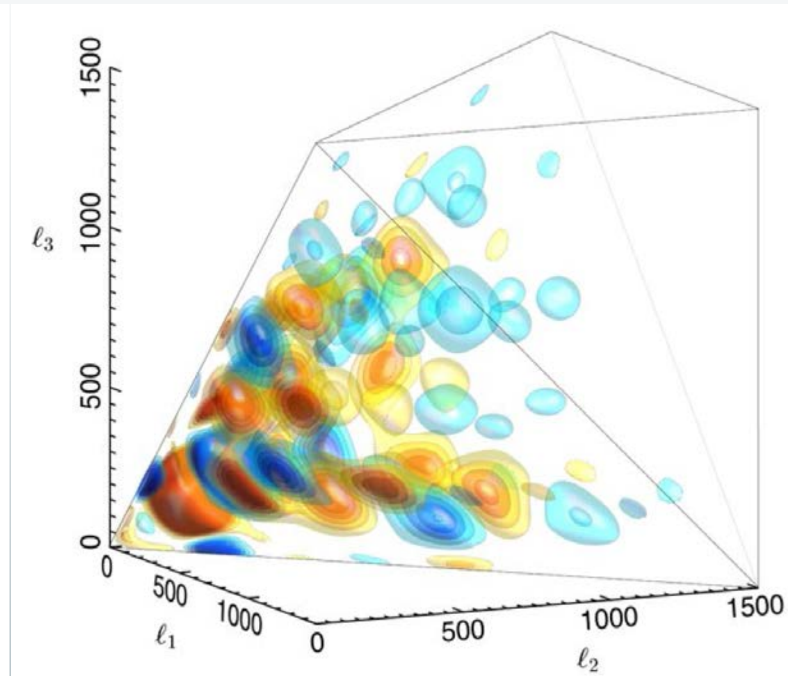
Width	$\Delta k = 0.015$	$\Delta k = 0.03$	$\Delta k = 0.045$	Full
Model	$f_{NL} \pm \Delta f_{NL}$ (σ)	$f_{NL} \pm \Delta f_{NL}$ (σ)	$f_{NL} \pm \Delta f_{NL}$ (σ)	$f_{NL} \pm \Delta f_{NL}$ (σ)
$k_c = 0.01125;\ \phi = 0$.	765 ± 275 (2.8)	703 ± 241 (2.9)	648 ± 218 (3.0)	434 ± 170 (2.6)
$k_c = 0.01750;\ \phi = 0$.	−661 ± 234 (−2.8)	−494 ± 192 (−2.6)	−425 ± 171 (−2.5)	−335 ± 137 (−2.4)
$k_c = 0.01750;\ \phi = 3\pi/4$	399 ± 207 (1.9)	438 ± 183 (2.4)	442 ± 165 (2.7)	366 ± 126 (2.9)
$k_c = 0.01875;\ \phi = 0$.	−562 ± 211 (−2.7)	−559 ± 180 (−3.1)	−515 ± 159 (−3.2)	−348 ± 118 (−3.0)
$k_c = 0.01875;\ \phi = \pi/4$	−646 ± 240 (−2.7)	−525 ± 189 (−2.8)	−468 ± 164 (−2.9)	−323 ± 120 (−2.7)
$k_c = 0.02000;\ \phi = \pi/4$	−665 ± 229 (−2.9)	−593 ± 185 (−3.2)	−500 ± 160 (−3.1)	−298 ± 119 (−2.5)

3.2-sigma hint of oscillatory feature?

Data



Best fit feature model bispectrum



Not (yet?) highly significant if "look-elsewhere" effect is taken into account.
➔ Warrants further analysis.

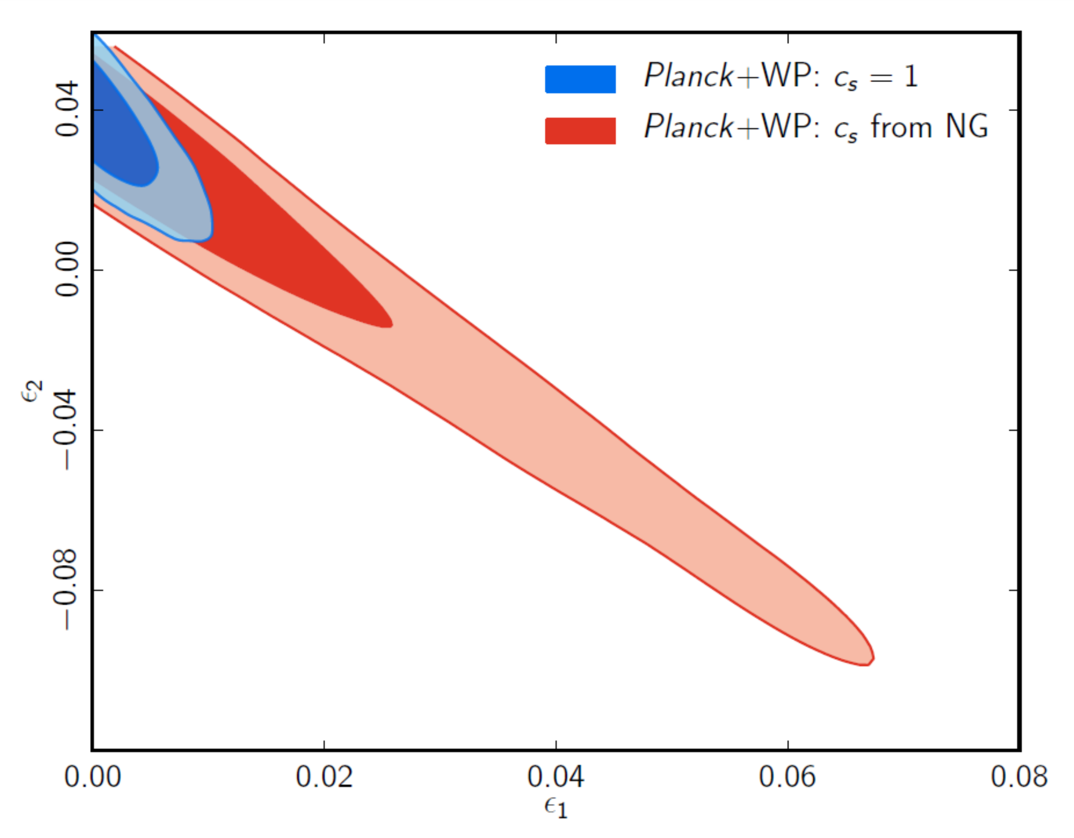
Cases of joint C(l)-f_{NL} constraints

- **Case 1**: c_s=constant
NG → $c_s > 0.02$(95%CL)
This reduce degeneracies
→ one get the constraint (adjacent) between the 1st two Hubble Flow Functions

- **Case 2**: IR-DBI
$V=V0-½\beta H^2\phi^2$, $.1< \beta <10^9$
Planck constraint on $n_s + f_{NL}^{DBI}$
→ $\beta < 0.7$ (95%CL)

- **Case 3**: k-inflation
One class depends on single param. γ (Amendariz-Picon et al 99). Planck:
f_{NL}^{equi} → $\gamma > 0.05$ (95%CL)
n_s → $0.01< \gamma<0.02$ 95%CL !

- **Case 4**: ekpyrotic alternative to inf. « conversion mechanism » decisely ruled out. Viable parameter space for « kinetic conversion » dramatically restricted



NB: the absence of isocurvature modes (the curvaton fully correlated case $n_{II}=n_R$) yields the stronger constraints $R_D > 0.98$ than $r_D > 0.15$ from the f_{NL}^{local} limit

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 $H_* < 3.7 \times 10^{-5} M_p$) 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...*


The journey
Just began!

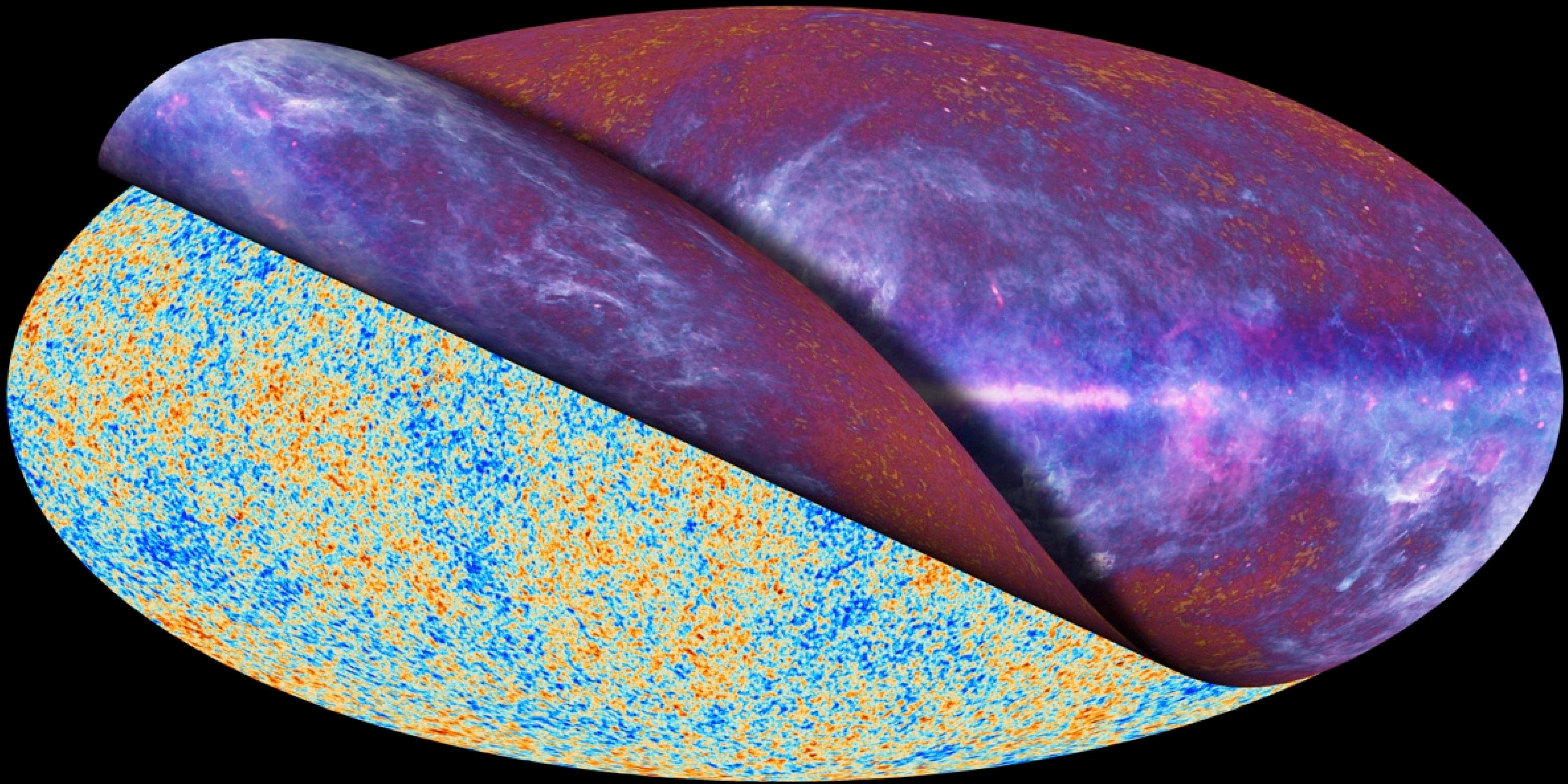
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific Consortium led and funded by Denmark.

A full cryogenic life

HFI starts cooling,
Hotel des roches,
Kourou
14 mai 2009

HFI starts warming up
HFI Core team meeting
Institut d'Astrophysique de Paris,
14 janvier 2012



Planck unveils the Cosmic Microwave Background