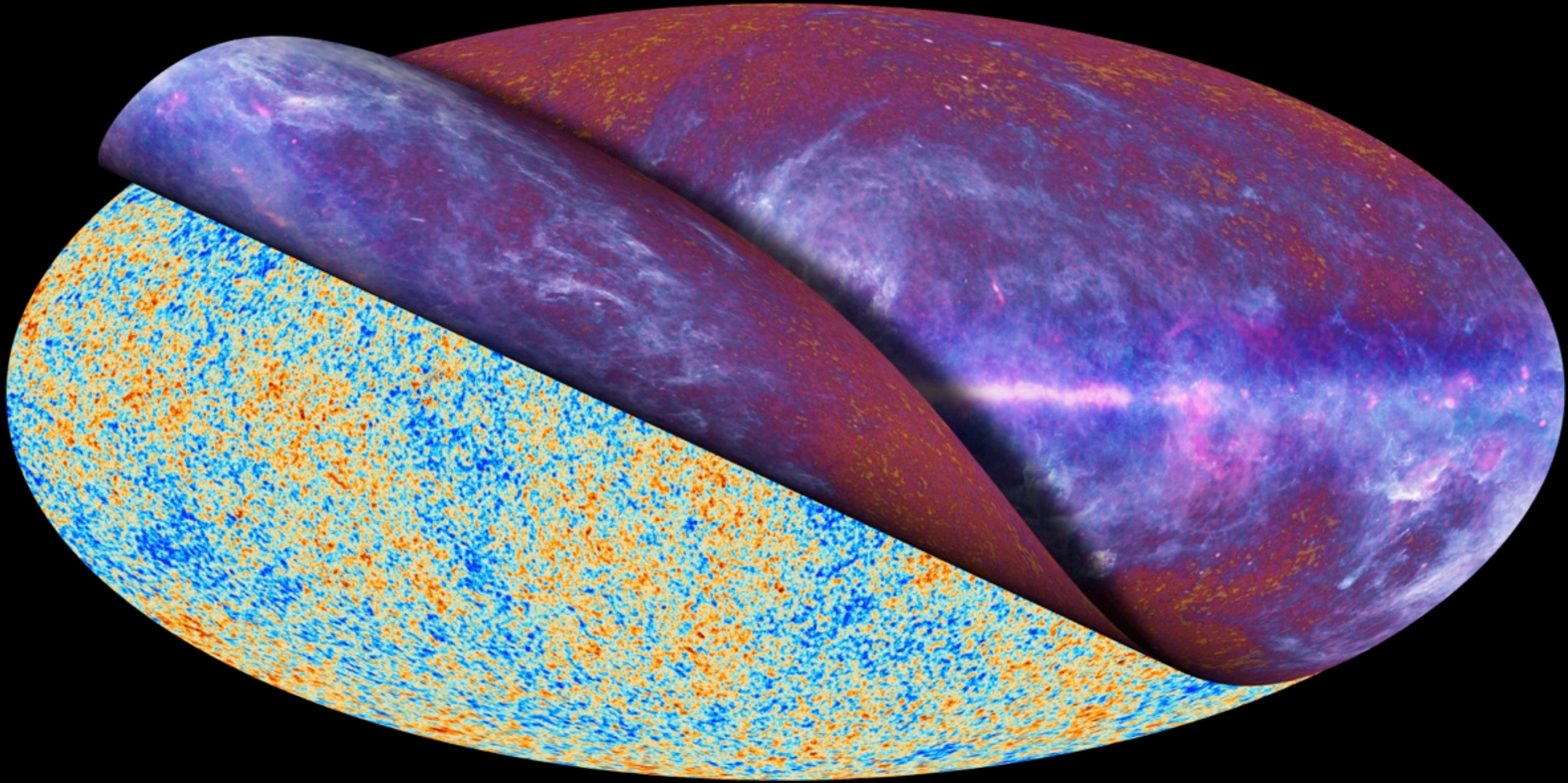


Planck unveils the Cosmic Microwave Background

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

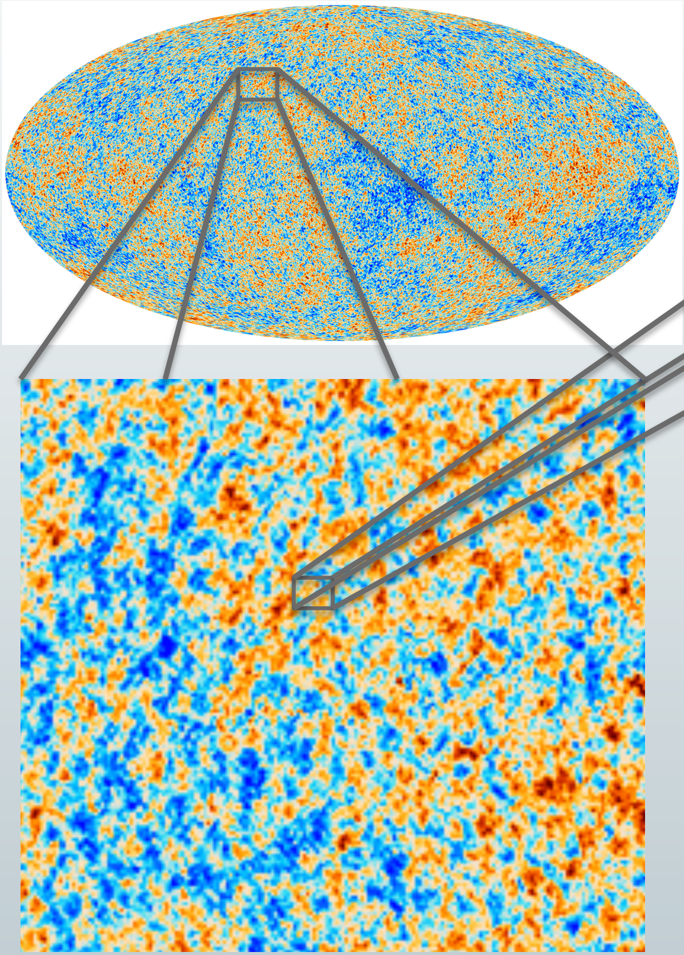
Planck is a project of the European Space Agency, with instruments provided by two scientific Consortia funded by ESA member states (in particular the lead countries: France and Italy) with contributions from NASA (USA), and telescope reflectors provided in a collaboration between ESA and a scientific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

Astrophysical probes of the initial state of the Universe

Benjamin D. Wandelt
Institut d'Astrophysique de Paris
Lagrange Institute, Paris
CNRS/UPMC, Sorbonne University
On behalf of the Planck collaboration

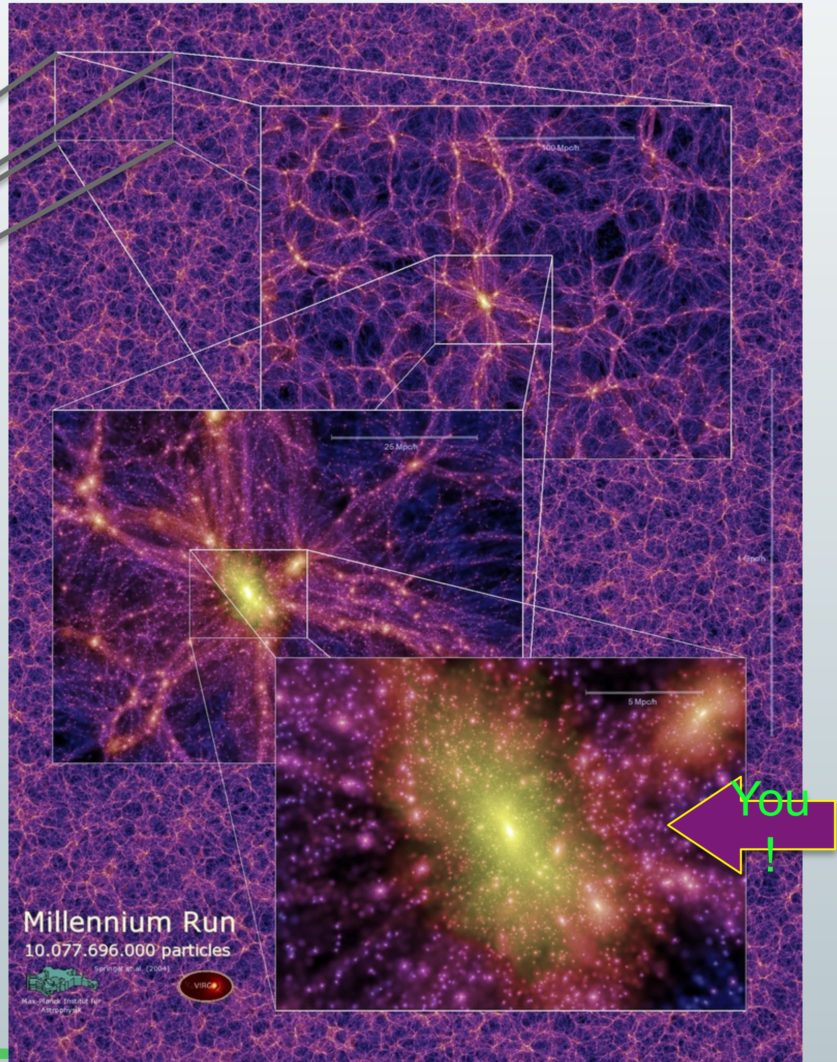
The Big Picture

Planck

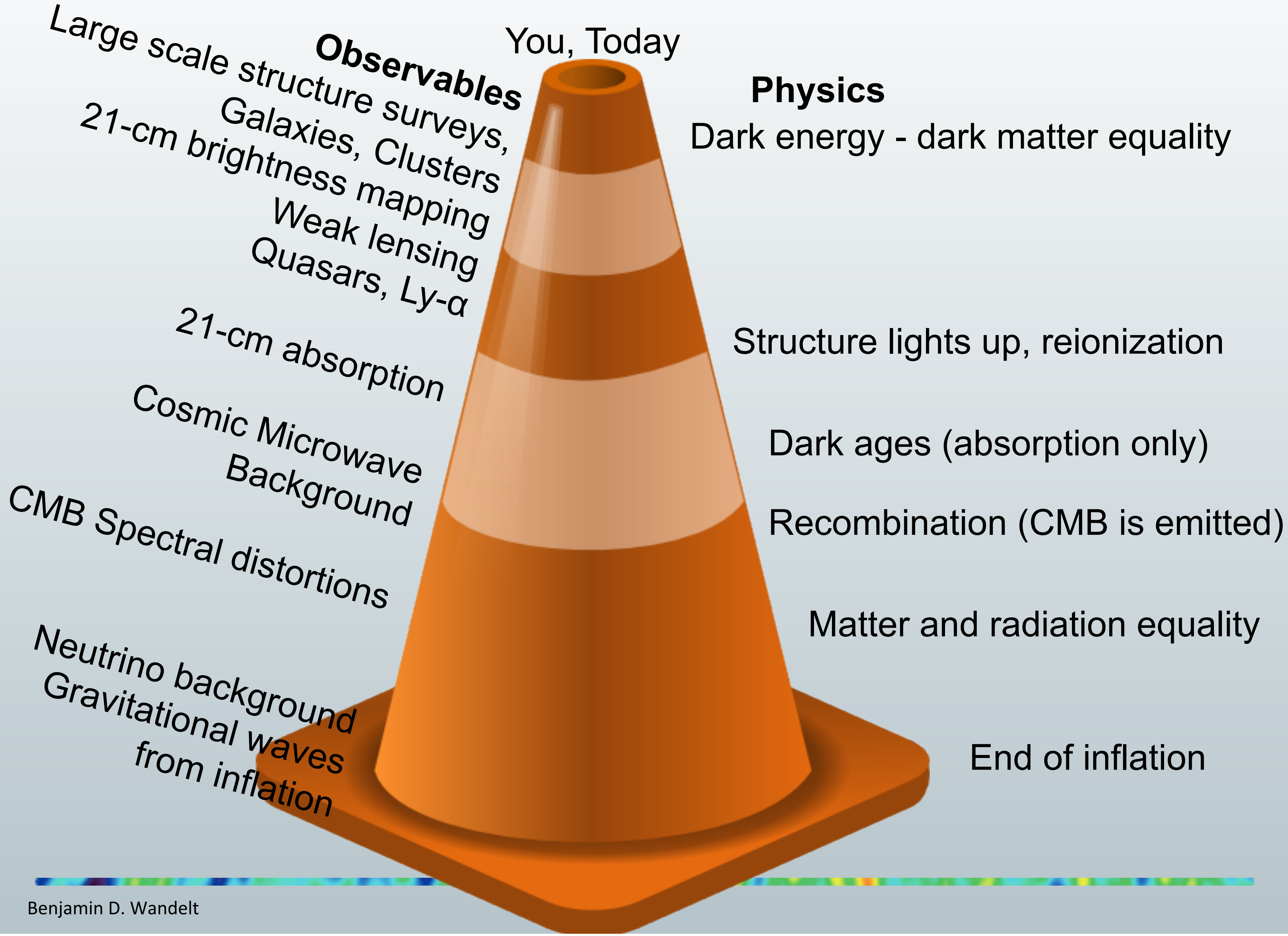


Primordial quantum perturbations as seen in the Cosmic Microwave Background

Dark matter distribution today (simulated)



What is ultimately observable?



Cosmology questions

How did the Universe begin?

How did structure appear in the Universe?

How did it evolve until today?

What is the Universe made of?

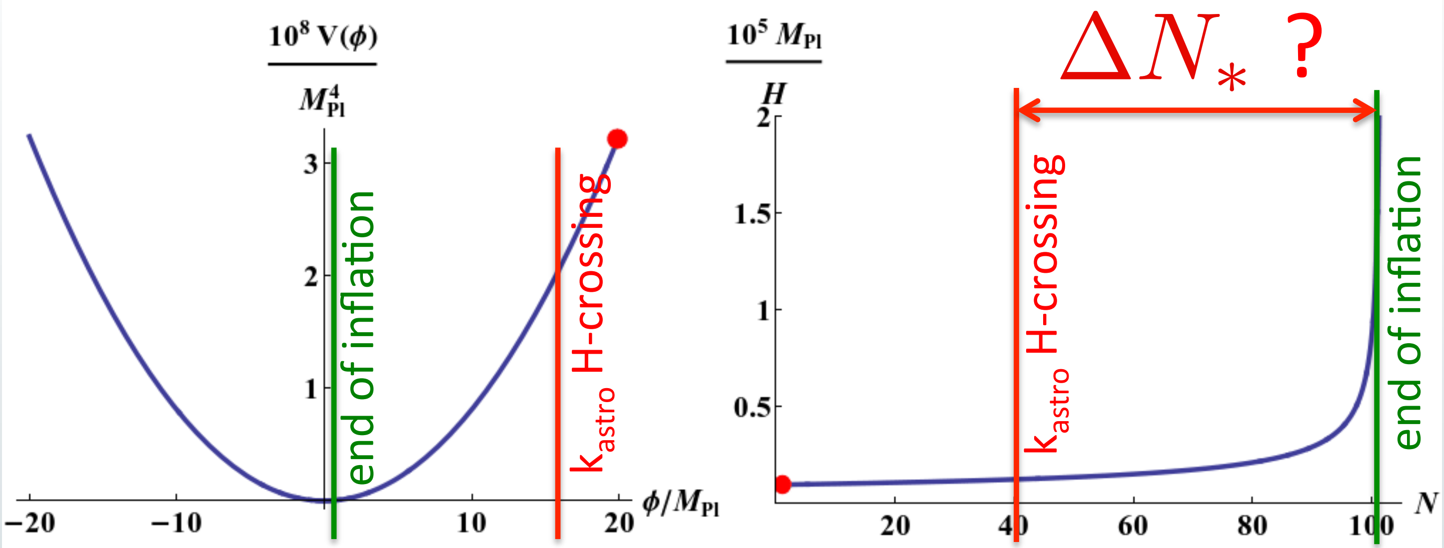
What are the properties of dark matter?

What are the properties of dark energy?

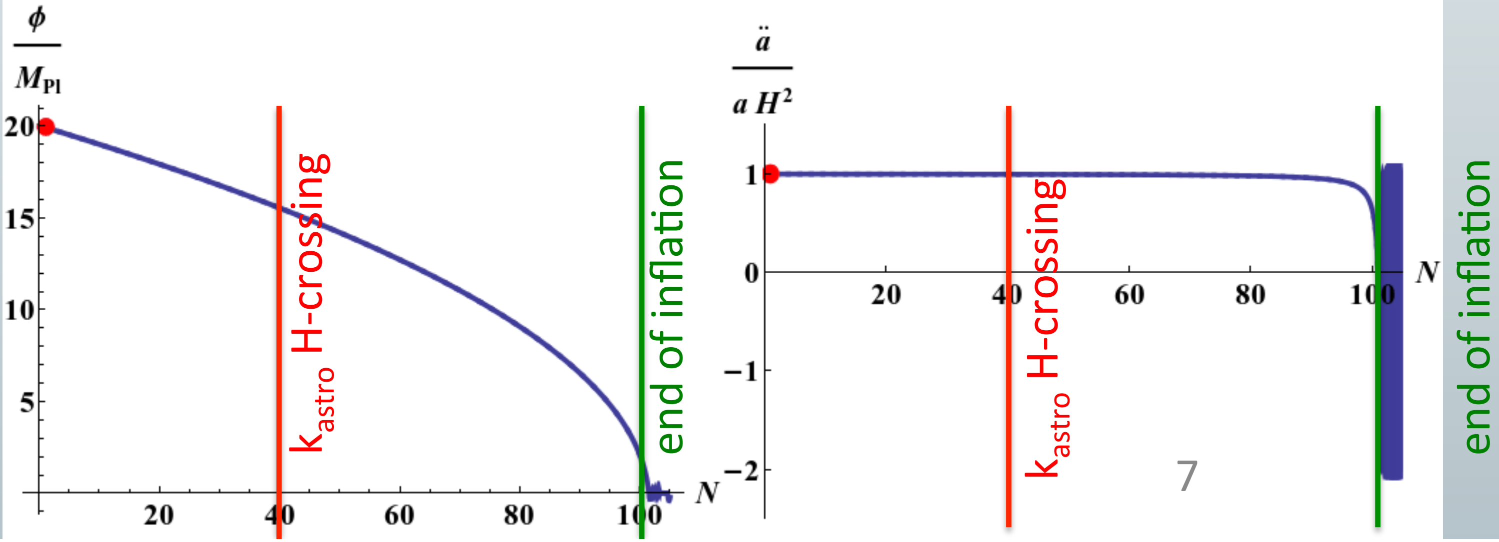
What is the geometry of the Universe?

Is the Universe “symmetric?”

Paradigm: Inflation



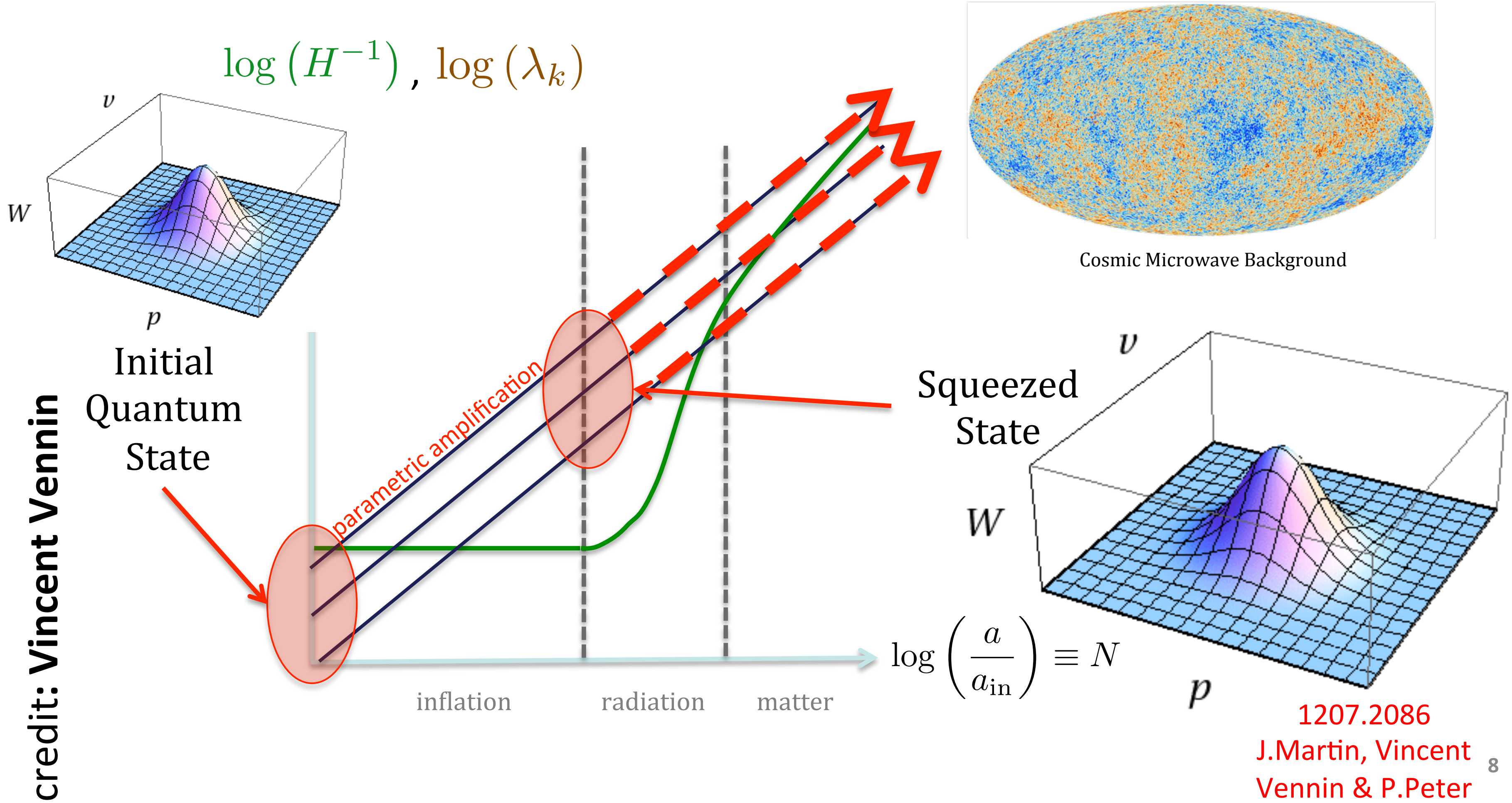
An example: « large field inflation » $$V(\phi) = \frac{m^2}{2}\phi^2$$



credit: **Vincent Vennin**

Cosmological Inflation

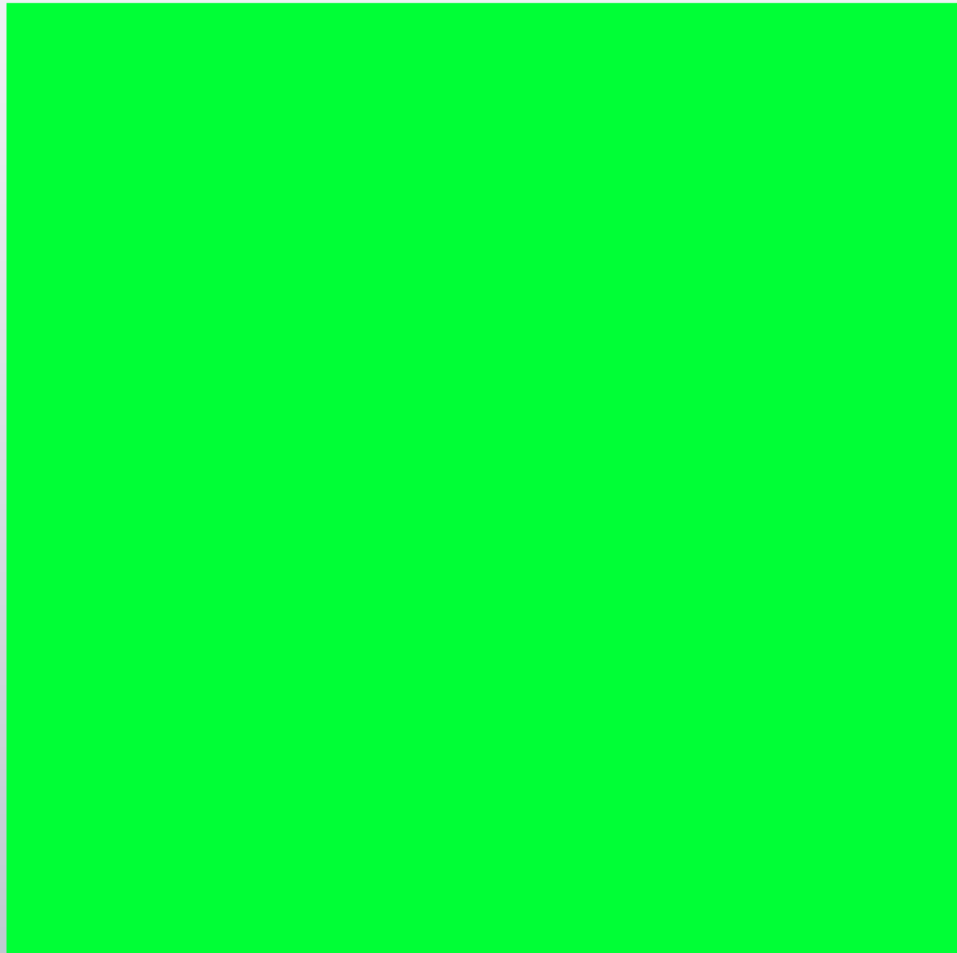
Quantized fluctuations evolved over an expanding background



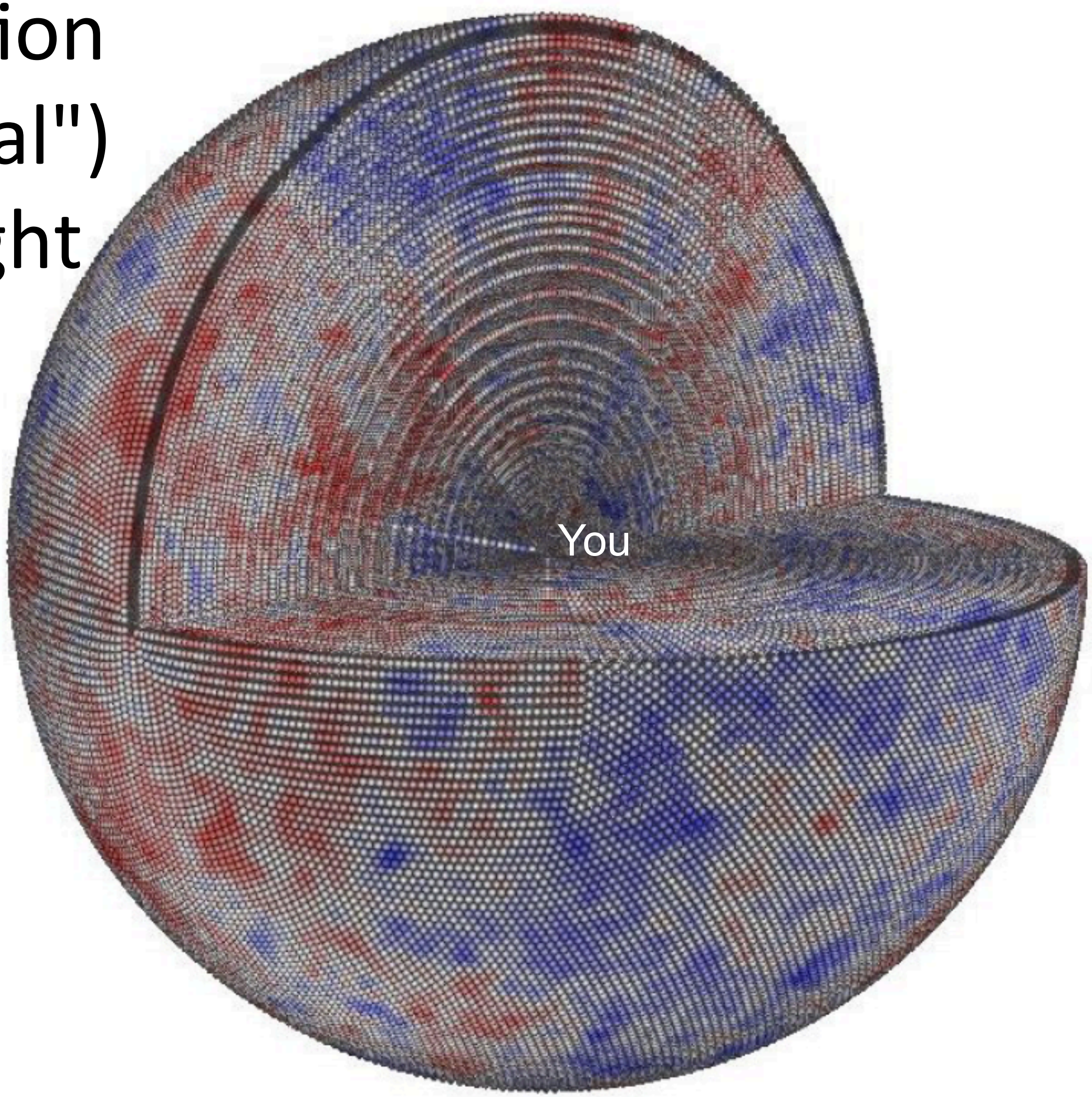
Cosmic Microwave Background

1207.2086
J.Martin, Vincent Vennin & P.Peter

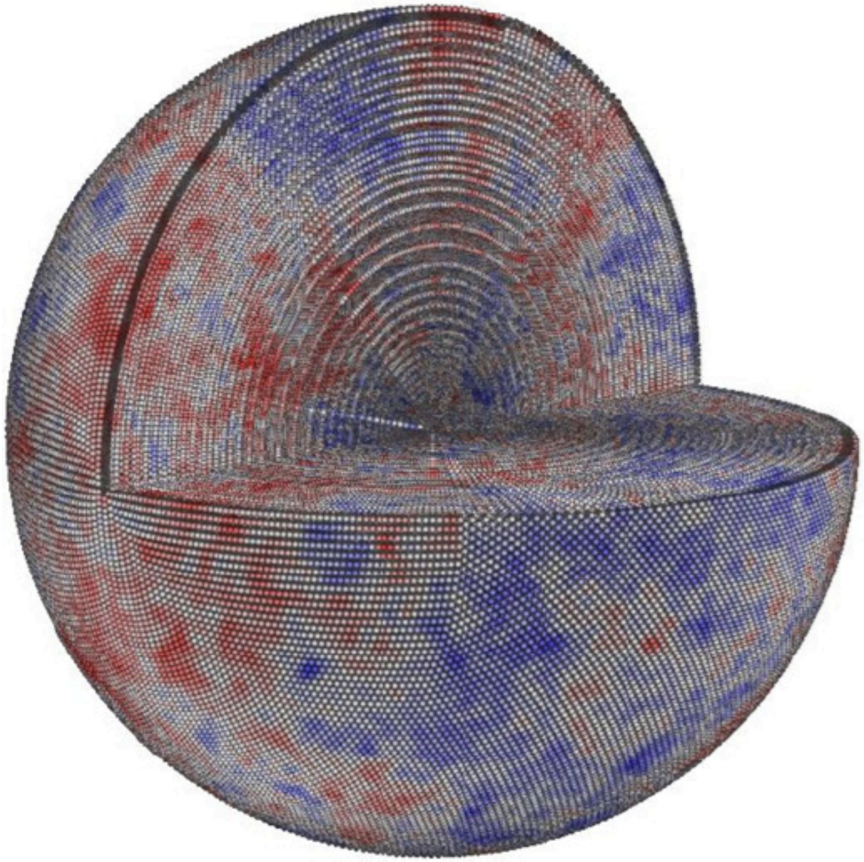
Paradigm: perturbations arise from quantum fluctuations



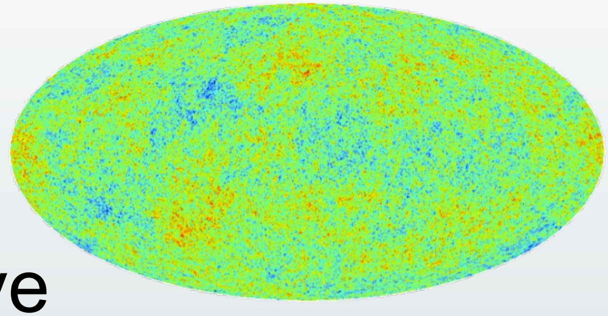
Curvature perturbation ("potential") on the light cone



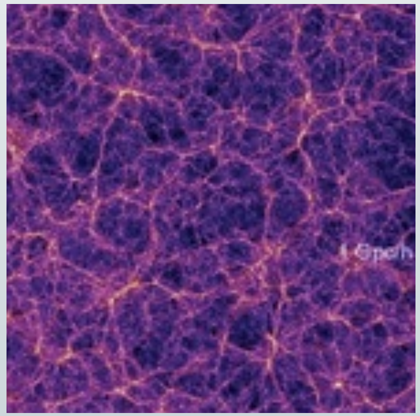
Primordial perturbations give rise to observations



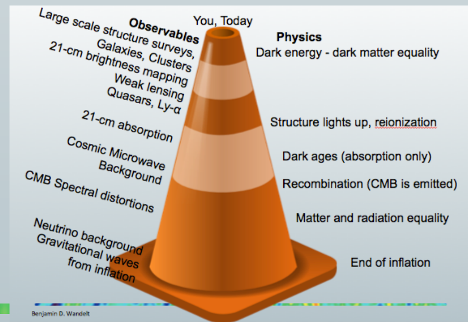
Radiative Transfer



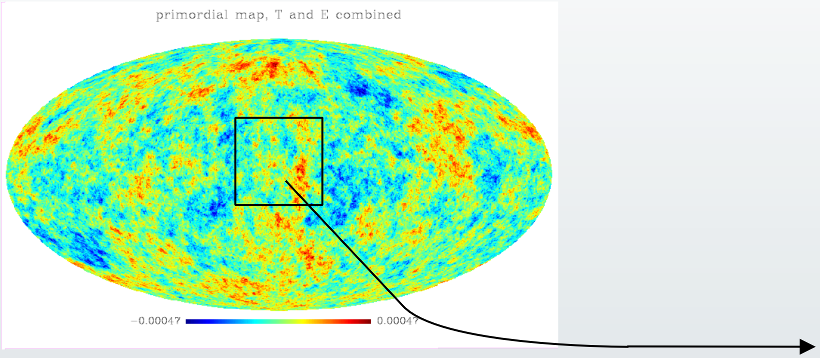
Gravity



Astro-physics

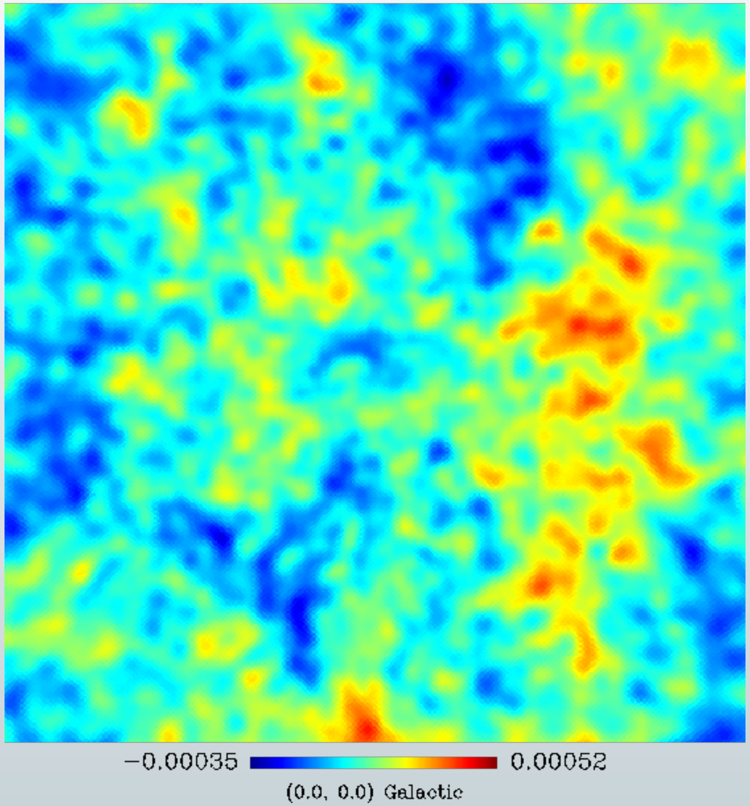


The linear physics CMB time machine



- The CMB T&E anisotropies map the Universe at t=380,000
- By "inverting" linear physics we can infer primordial curvature perturbation and test model predictions for the power spectrum and beyond.

Primordial curvature fluctuations



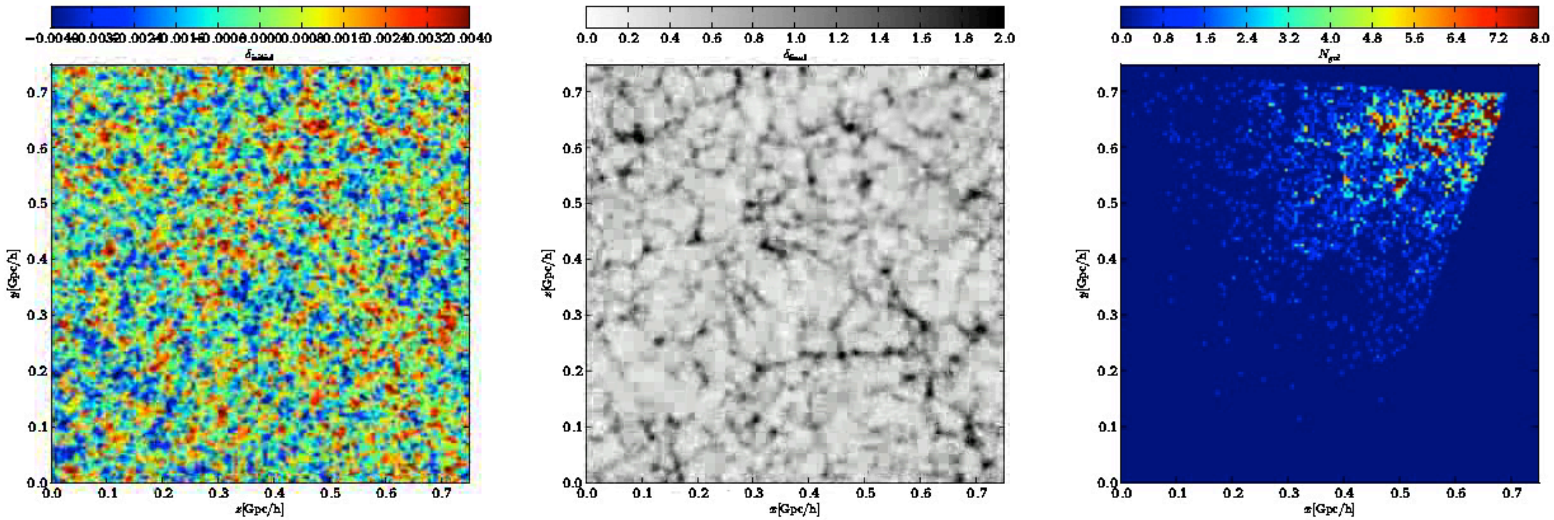
Komatsu, Spergel, Wandelt (2005)
Yadav and Wandelt, PRD (2005)

Now building non-linear time machines

Reconstructed primordial density

Reconstructed non-linear density distribution today

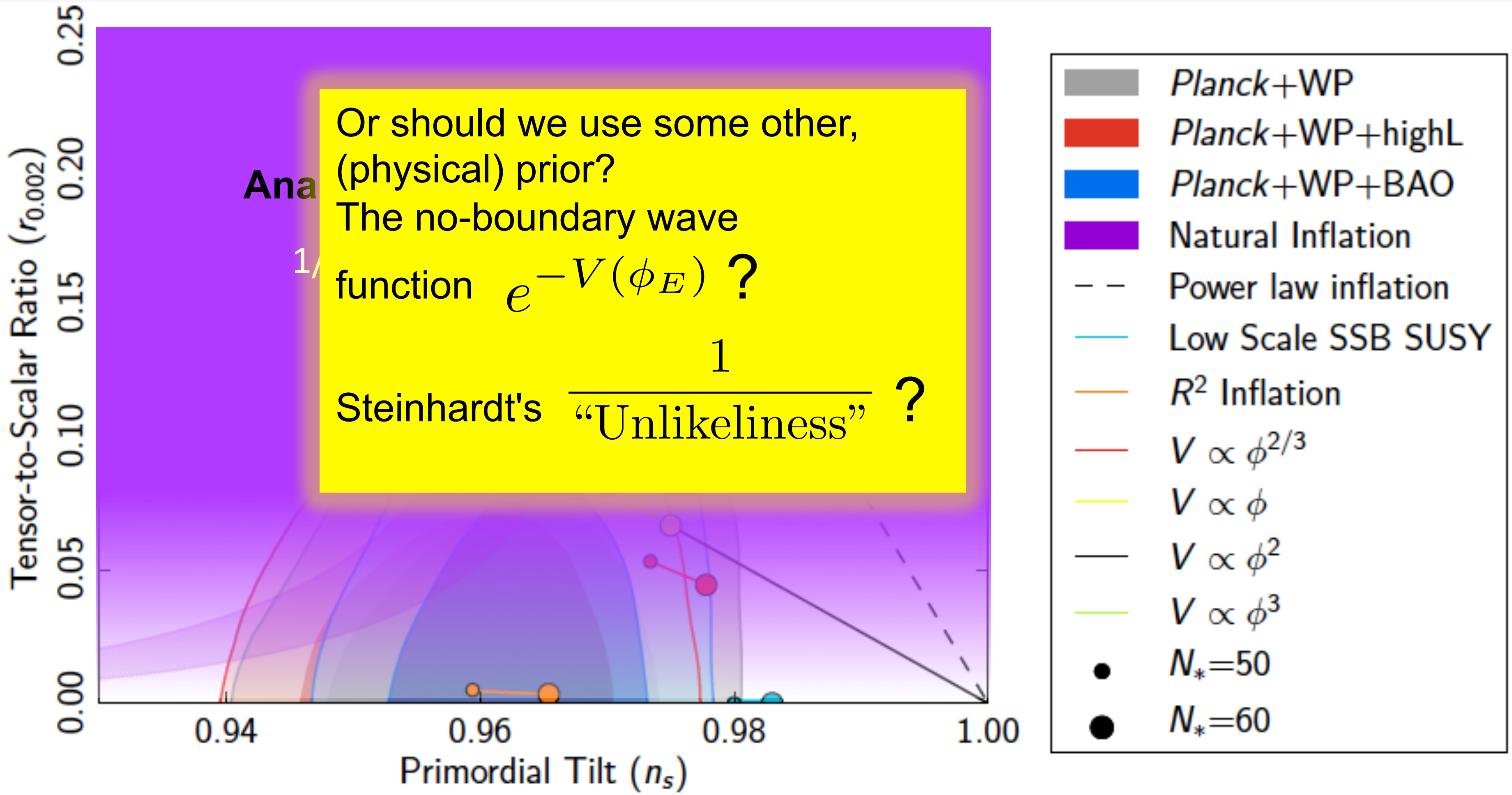
SDSS-like Galaxy mock



Animation shows uncertainties in Bayesian physical reconstruction of initial conditions from Large Scale Structure

Jasche & Wandelt, arXiv: 1203.3639

Inflation constraints from Planck



Or should we use some other, (physical) prior?

The no-boundary wave function $e^{-V(\phi_E)}$?

Steinhardt's $\dfrac{1}{\text{"Unlikeliness"}}$?

$$V_* < (1.94 \times 10^{16} GeV)^4$$

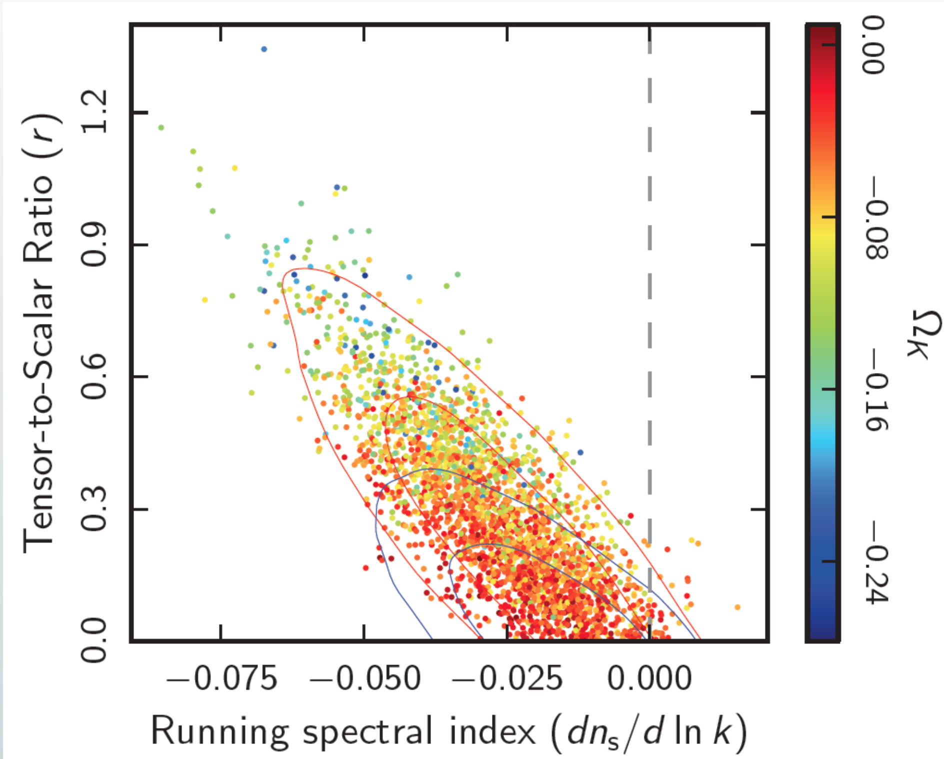
Detecting tilt!

	HZ	HZ + Y_P	HZ + N_{eff}	ΛCDM
$10^5\Omega_b h^2$	2296 ± 24	2296 ± 23	2285 ± 23	2205 ± 28
$10^4\Omega_c h^2$	1088 ± 13	1158 ± 20	1298 ± 43	1199 ± 27
$100\,\theta_{MC}$	1.04292 ± 0.00054	1.04439 ± 0.00063	1.04052 ± 0.00067	1.04131 ± 0.00063
τ	$0.125^{+0.016}_{-0.014}$	$0.109^{+0.013}_{-0.014}$	$0.105^{+0.014}_{-0.013}$	$0.089^{+0.012}_{-0.014}$
$\ln(10^{10}A_s)$	$3.133^{+0.032}_{-0.028}$	$3.137^{+0.027}_{-0.028}$	$3.143^{+0.027}_{-0.026}$	$3.089^{+0.024}_{-0.027}$
n_s	—	—	—	0.9603 ± 0.0073
N_{eff}	—	—	3.98 ± 0.19	—
Y_P	—	0.3194 ± 0.013	—	—
$-2\Delta\ln(\mathcal{L}_{max})$	27.9	2.2	2.8	0

- Harrison-Zel'dovich spectrum ruled out robustly (w, Σm_ν, reionization)
- Allowing Helium abundance to float can rescue H-Z but at the cost of Y_p inconsistent with astrophysical constraints
- Main loophole is N_{eff}

The universe is (most likely) flat

- Inflation "predicts" flatness, $|\Omega_k| \sim 10^{-5}$, though open is possible. Closed is hard.
- Planck constraints are now at the 10^{-3} level.
- With negative running *positive* curvature is possible. But large negative running is in conflict with 50 e-folds of inflation



$$\Omega_k = -0.0004 \pm 0.0036$$

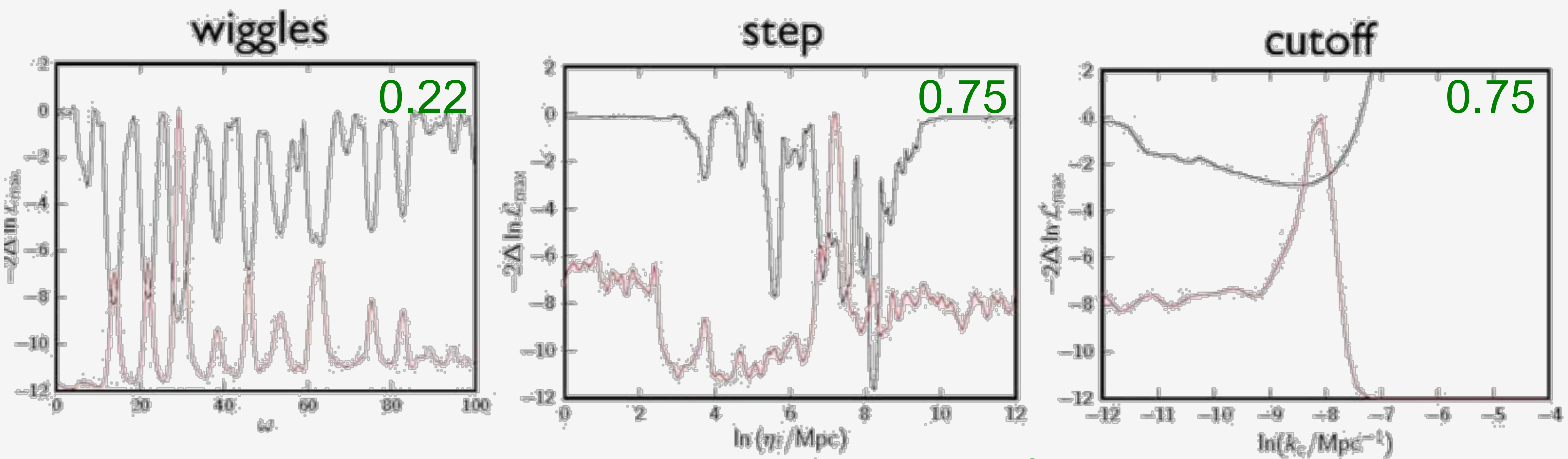
(Planck+WP+BAO)

Are there features in P(k)?

wiggles: $$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k)\left\{1 + \alpha_{\rm w}\sin\left[\omega\ln\left(\frac{k}{k_*}\right) + \varphi\right]\right\}$$

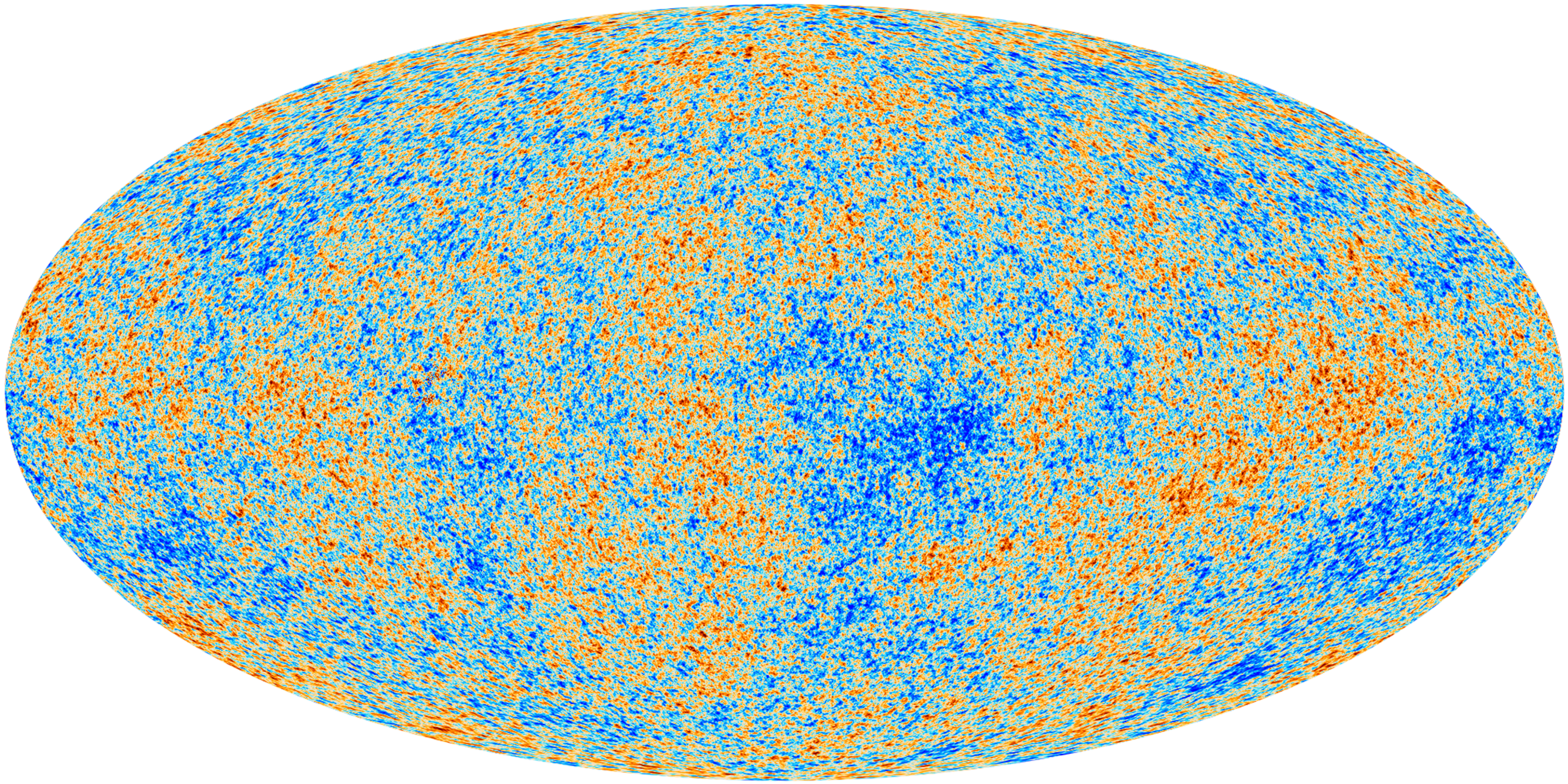
step: $$\mathcal{P}_{\mathcal{R}}(k) = \exp\left[\ln\mathcal{P}_0(k) + \frac{\mathcal{A}_{\rm f}}{3}\,\frac{k\eta_{\rm f}/x_{\rm d}}{\sinh(k\eta_{\rm f}/x_{\rm d})}W'(k\eta_{\rm f})\right]$$

cutoff: $$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k)\left\{1 - \exp\left[-\left(\frac{k}{k_{\rm c}}\right)^{\lambda_{\rm c}}\right]\right\}$$



Bayesian evidence ratio compared to featureless model

Back to the CMB **map**



Why non-Gaussianity?

- There is more information in the map than the power spectrum alone.
- Non-Gaussianity currently is the highest precision test of standard inflation

with Planck <≈0.01%

For comparison:

- Flatness in second place with now ~0.1%
- Isocurvature constraints ~1%

What would a non-Gaussian Universe look like?

An example: local f_{NL}

Salopek & Bond 1990
Gangui et al 1994
Verde et al 2000
Komatsu & Spergel 2001

$$\Phi(x) = \Phi_G(x) + f_{NL}\Phi_G^2(x)$$

Characterizes the amplitude of non-Gaussianity

- **This non-Gaussianity creates a bispectrum signature (as well as higher order moments)**

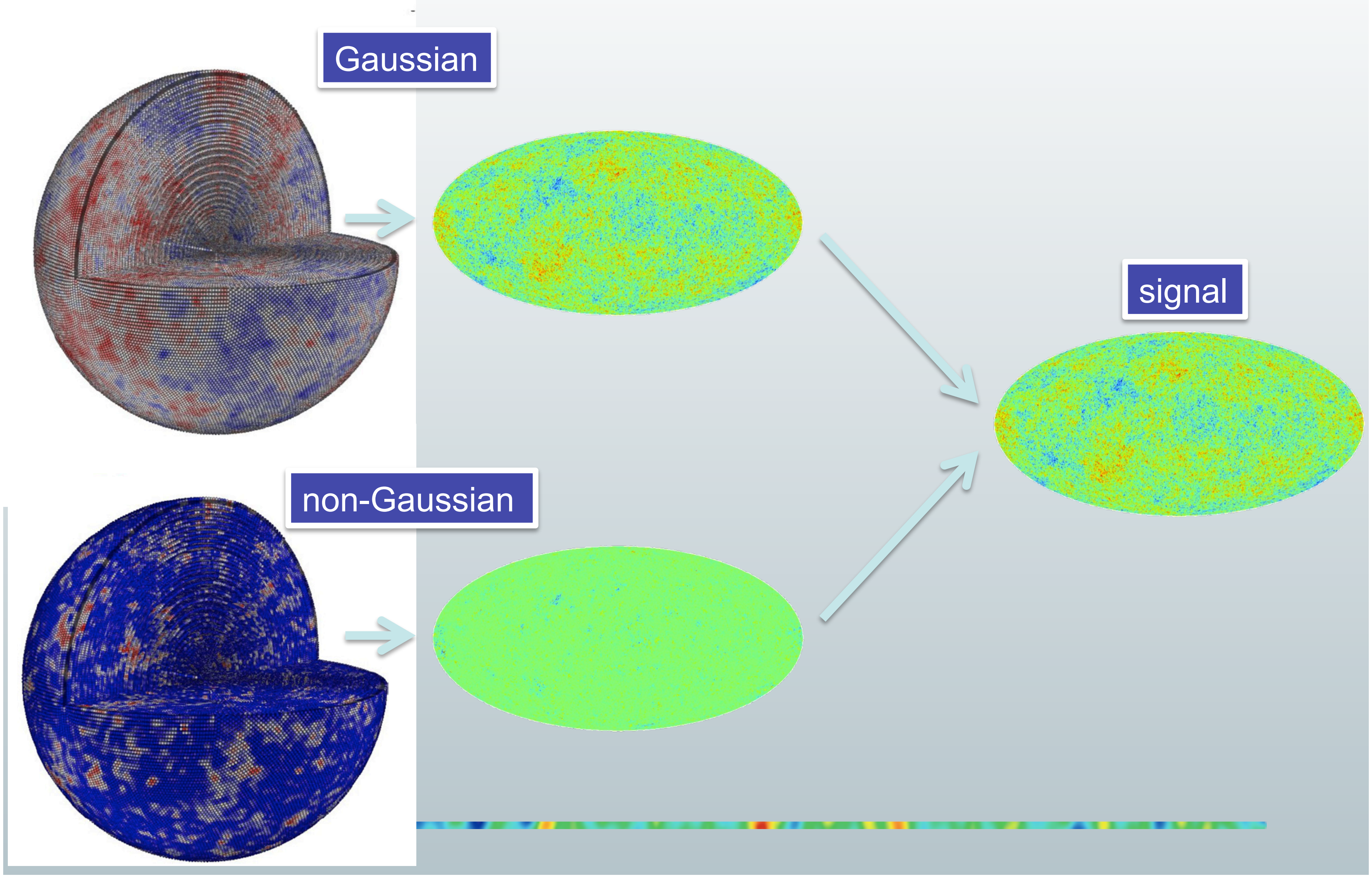
$$<\Phi(k_1)\Phi(k_2)\Phi(k_3)>=2(2\pi)^3 f_{NL}\delta(k_1+k_2+k_3)P(k_1)P(k_2),$$

where $(2\pi)^3\delta(k_1+k_2)P(k_1)=<\Phi(k_1)\Phi(k_2)>$

- **This translates into a bispectrum signature in the CMB through**

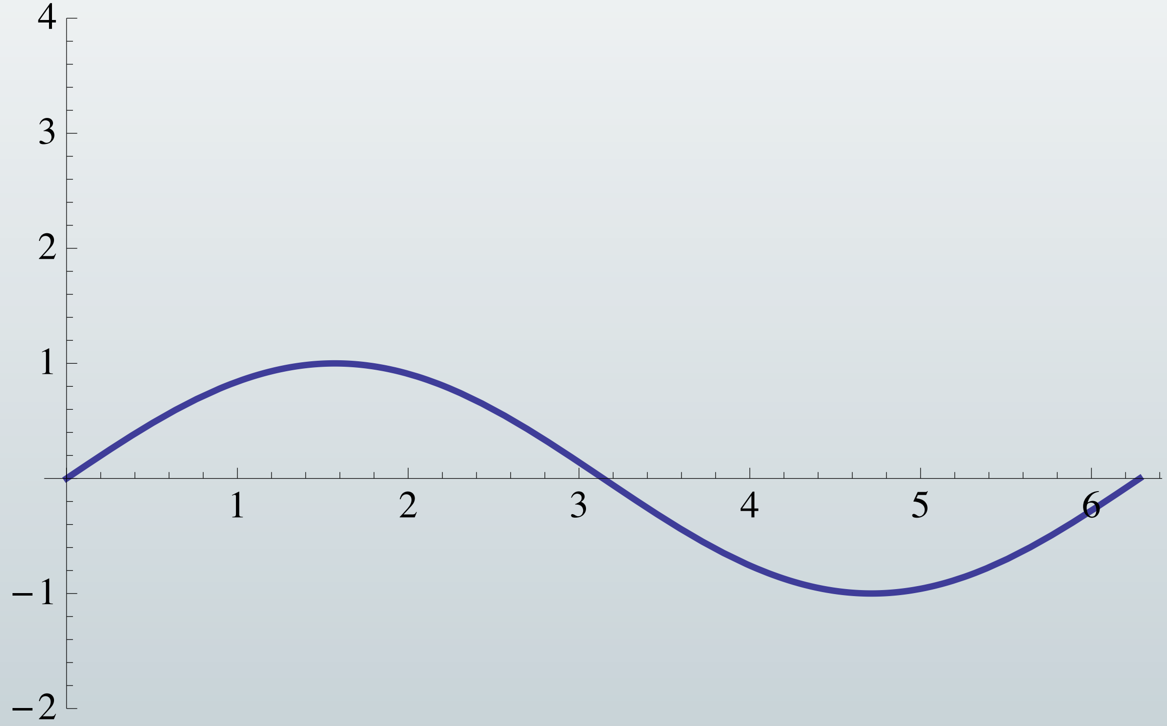
$$a_{lm} = 4\pi(-i)^l \int \frac{d^3\mathbf{k}}{(2\pi)^3}\Phi(\mathbf{k})g_{Tl}(k)Y^*_{lm}(\hat{\mathbf{k}})$$

From curvature to CMB sky



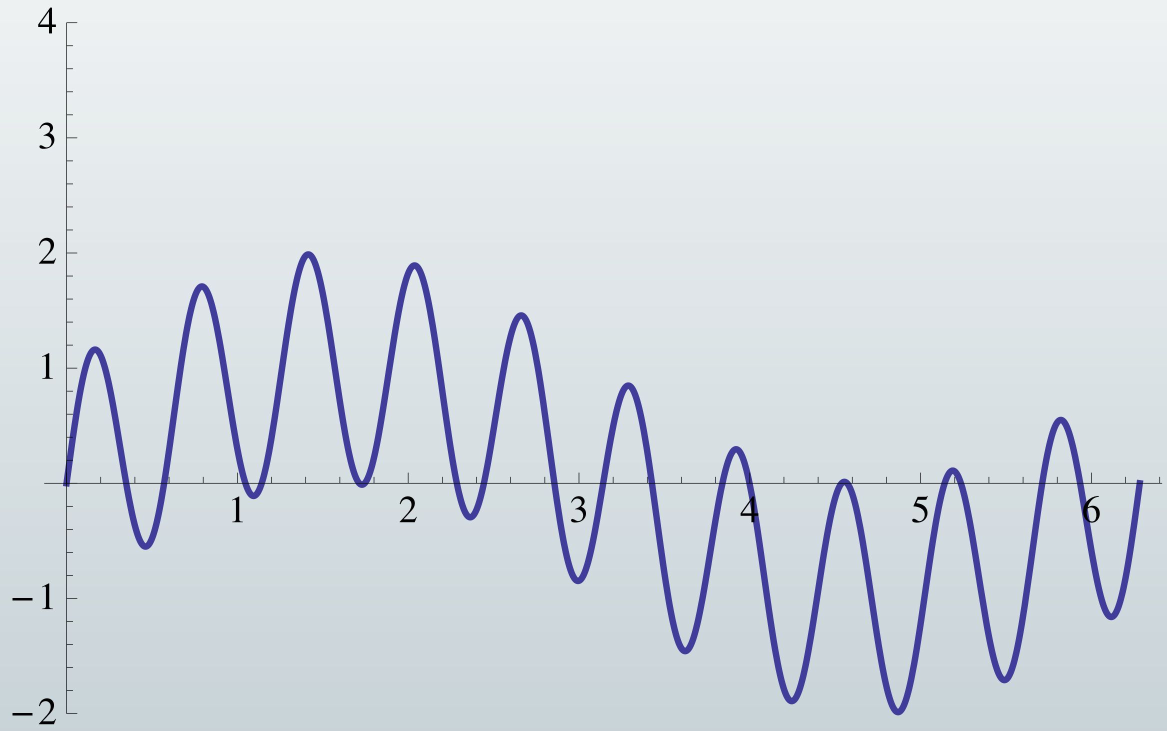
Local non-Gaussianity illustrated

Φ_{long}



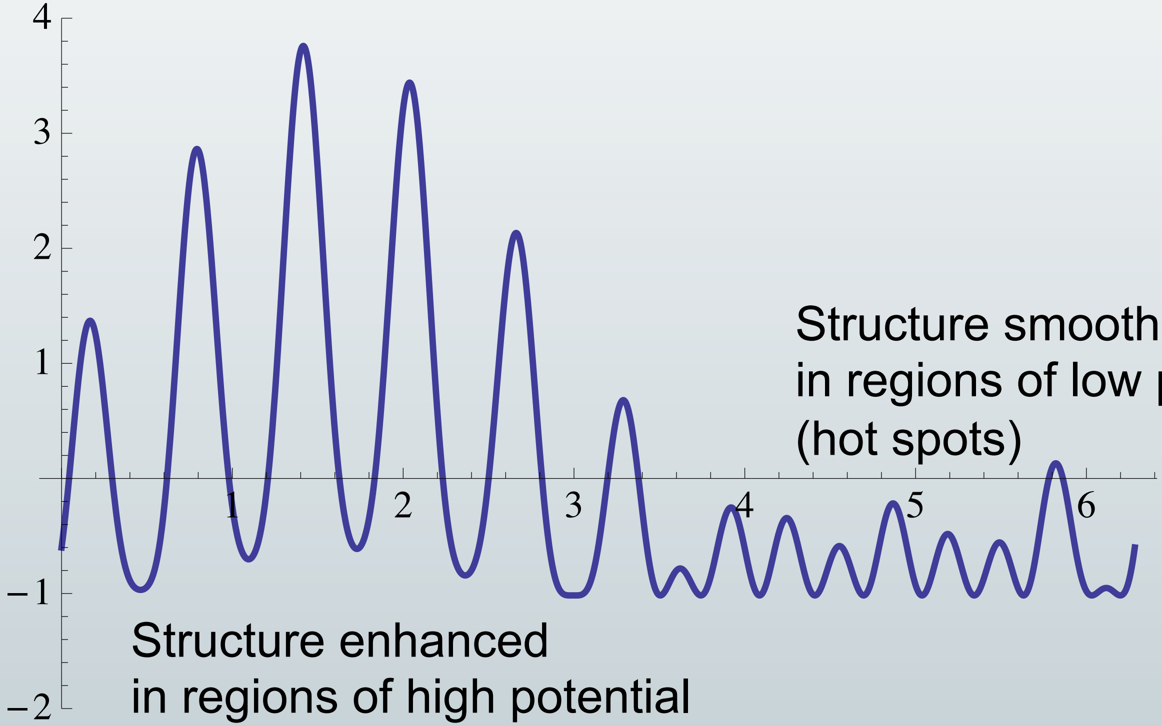
Local non-Gaussianity illustrated

$$\Phi = \Phi_{long} + \Phi_{short}$$



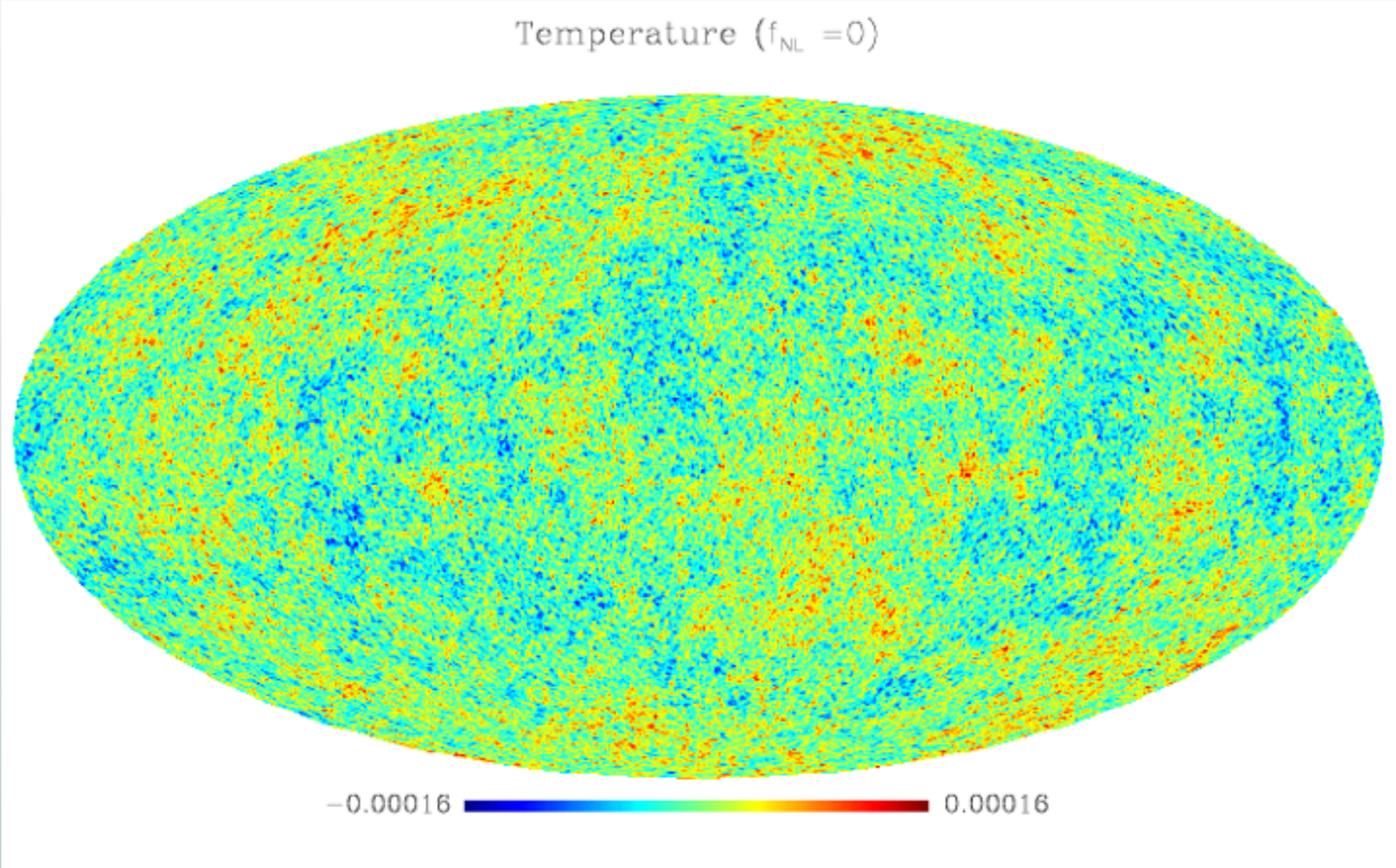
Local non-Gaussianity illustrated

$$\Phi_{NL} = \Phi + f_{NL}(\Phi^2 - \langle\Phi^2\rangle)$$

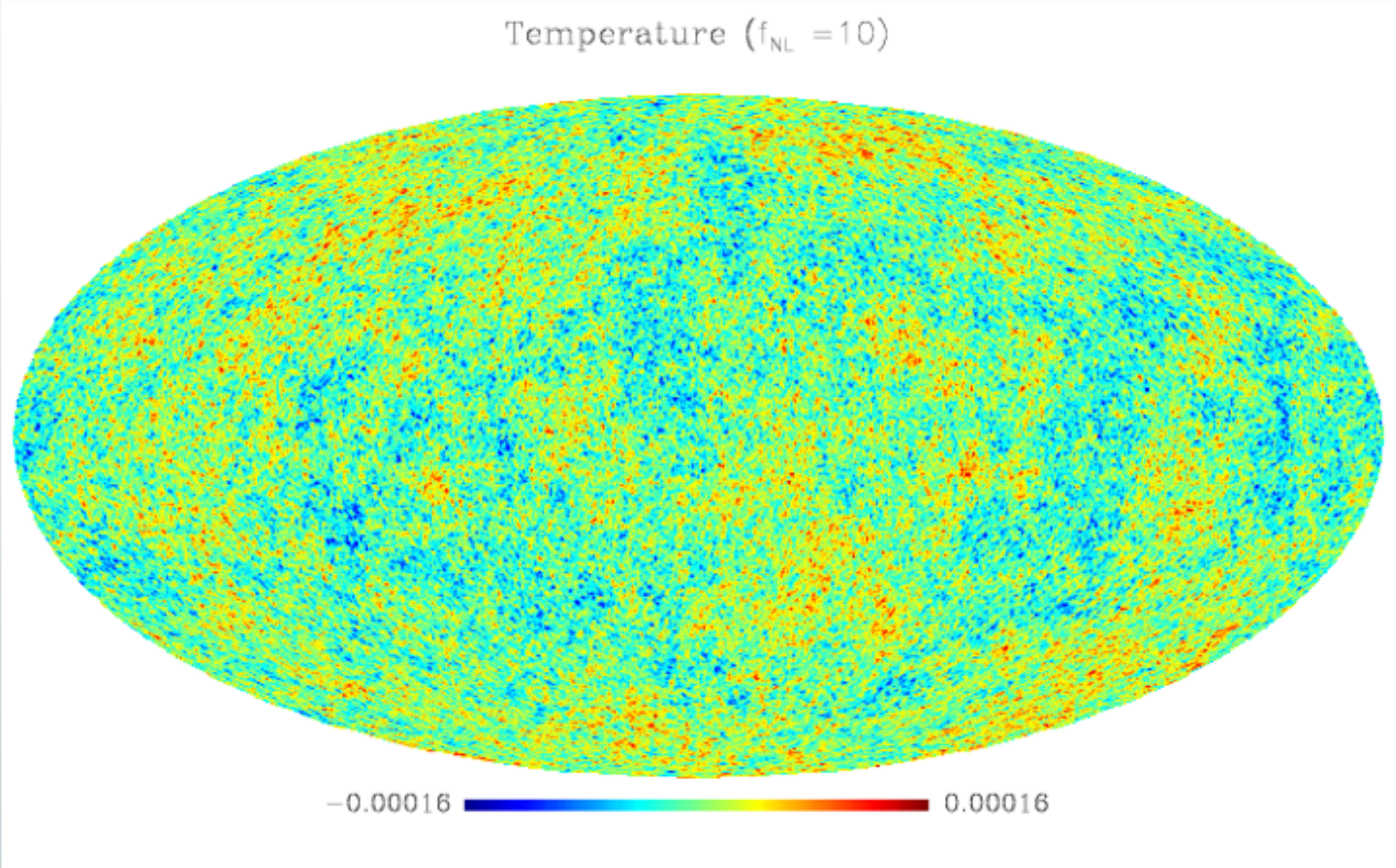


Note that this gives rise to both bispectrum and trispectrum signatures: f_{NL} and τ_{NL}

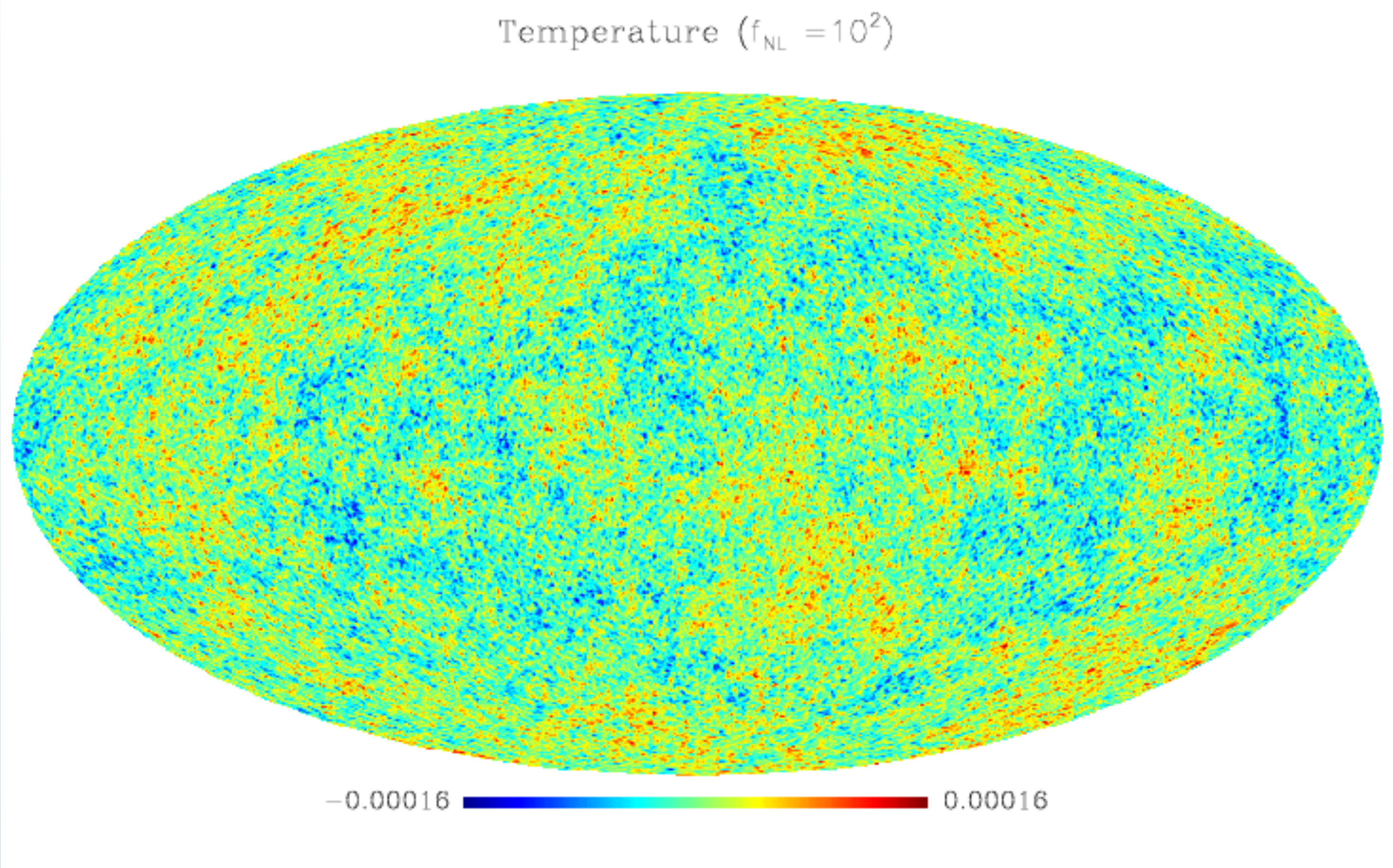
$f_{NL} = 0$



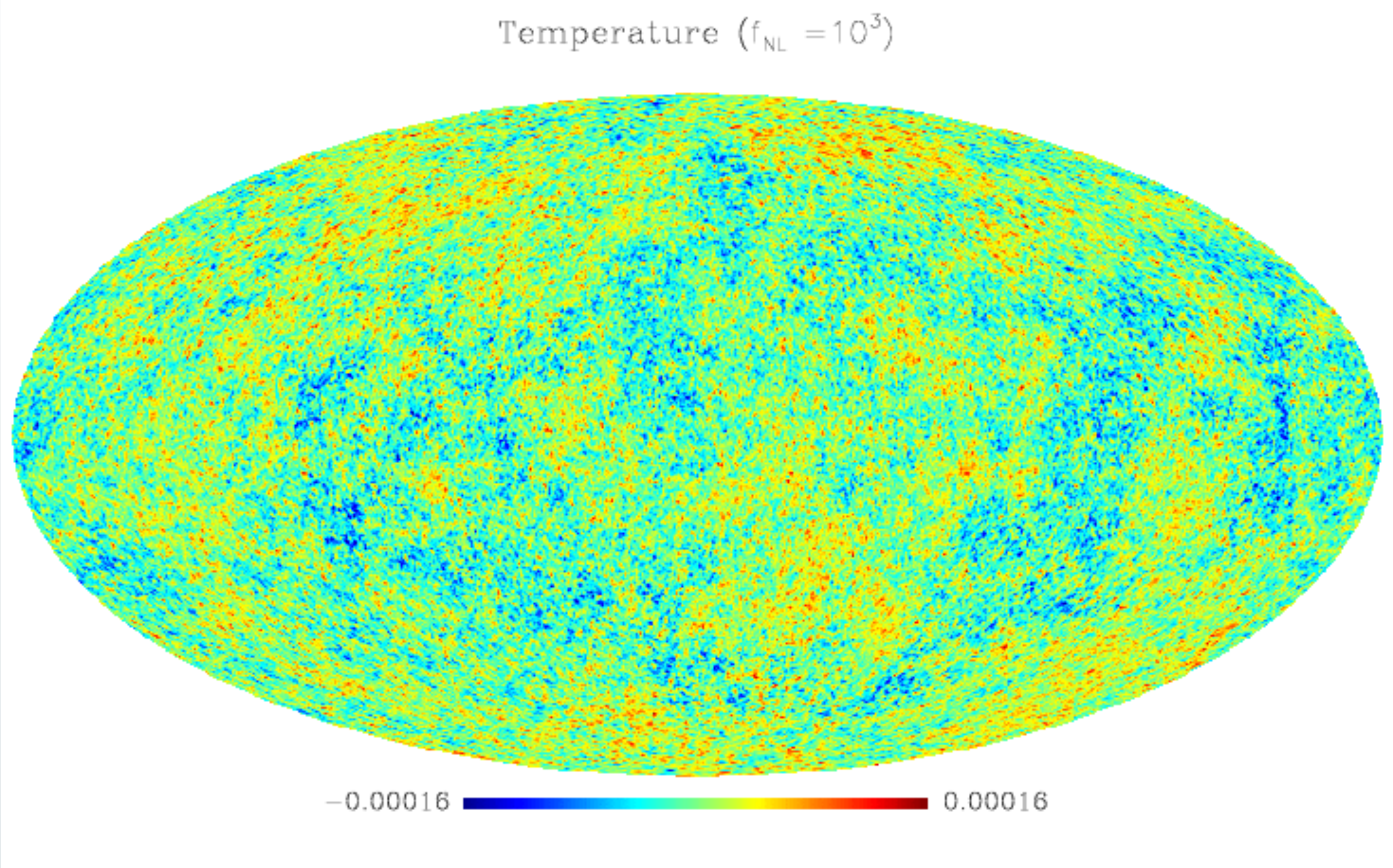
$f_{NL} = 10$



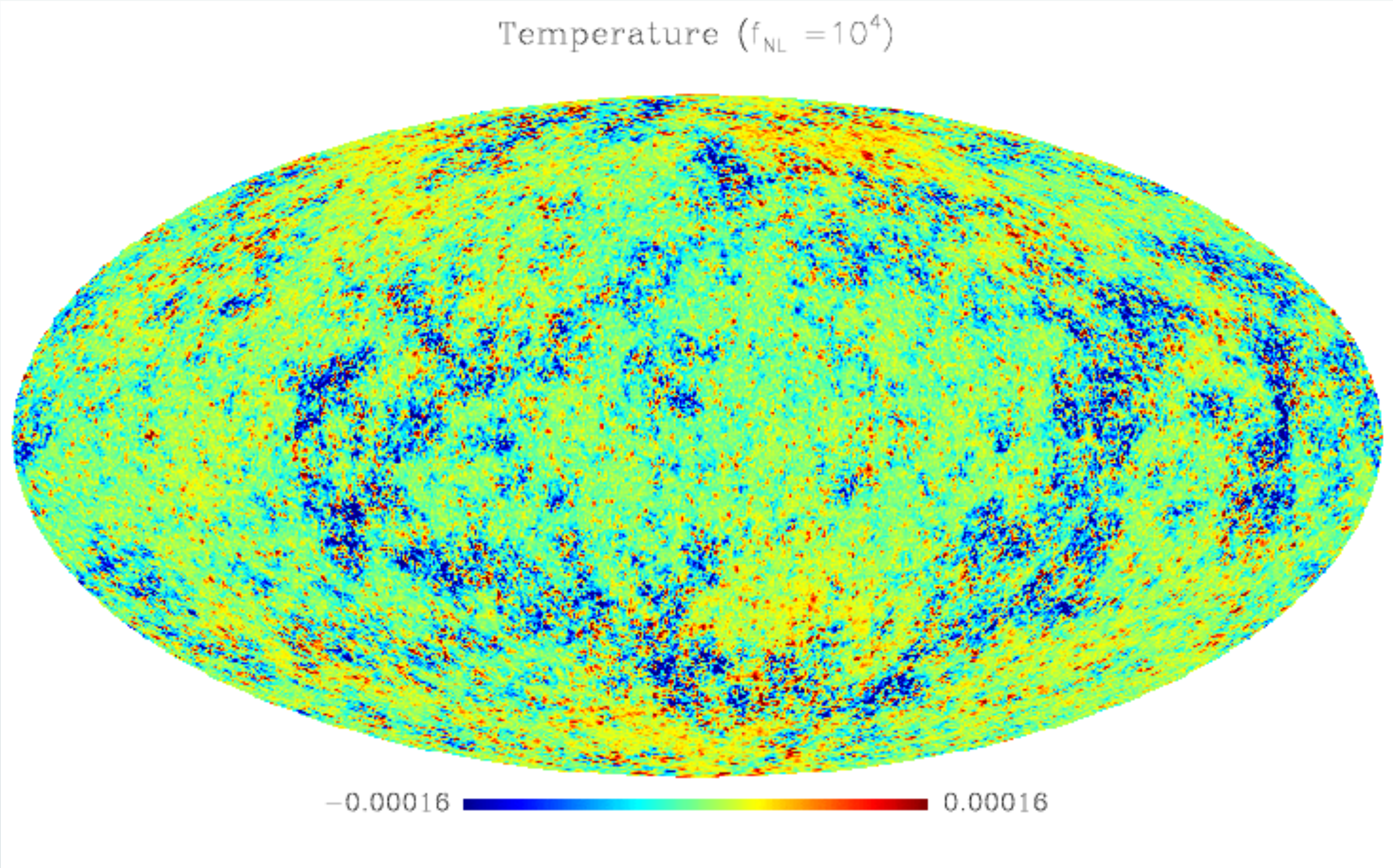
f_{NL}= 100



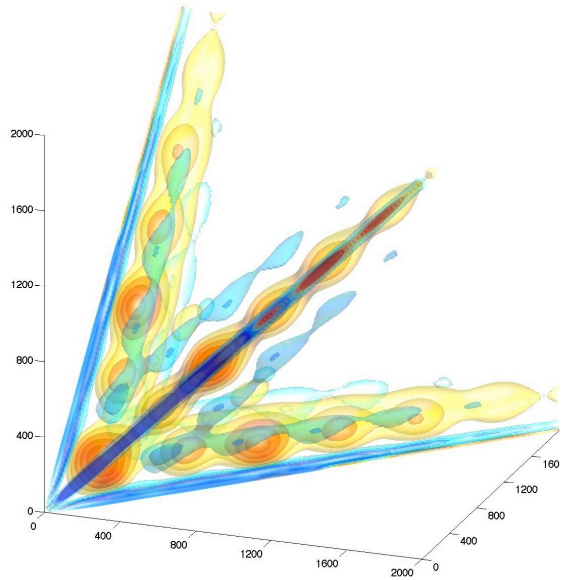
$f_{NL} = 10^3$

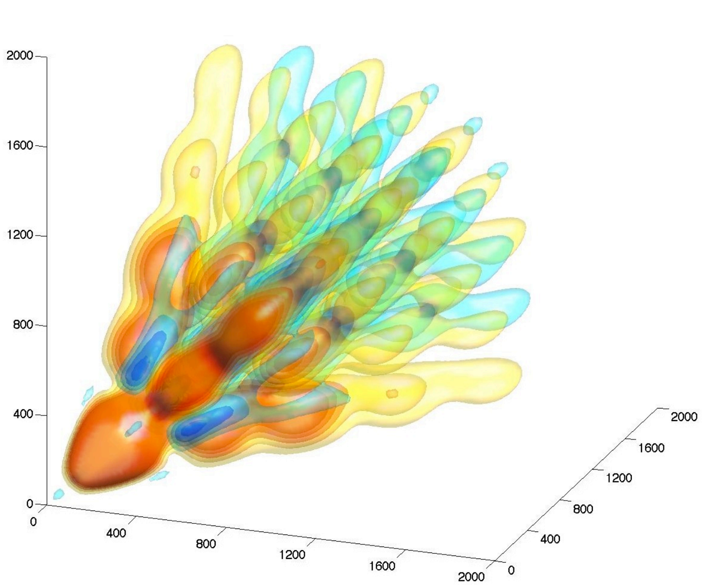


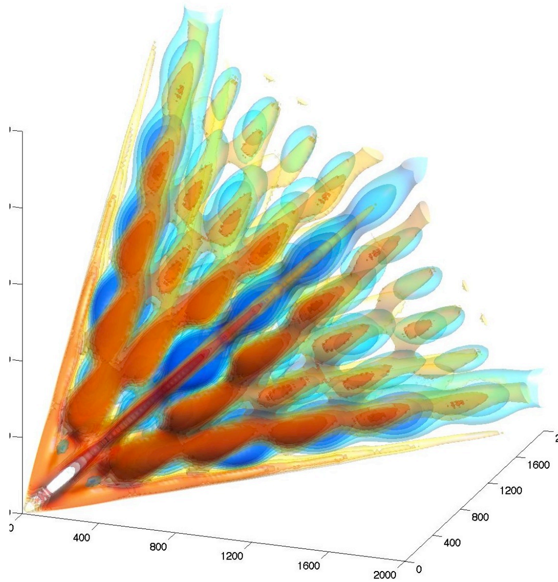
$f_{NL} = 10^4$



CMB bispectrum fingerprinting with Planck







NG of ***local*** type:

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

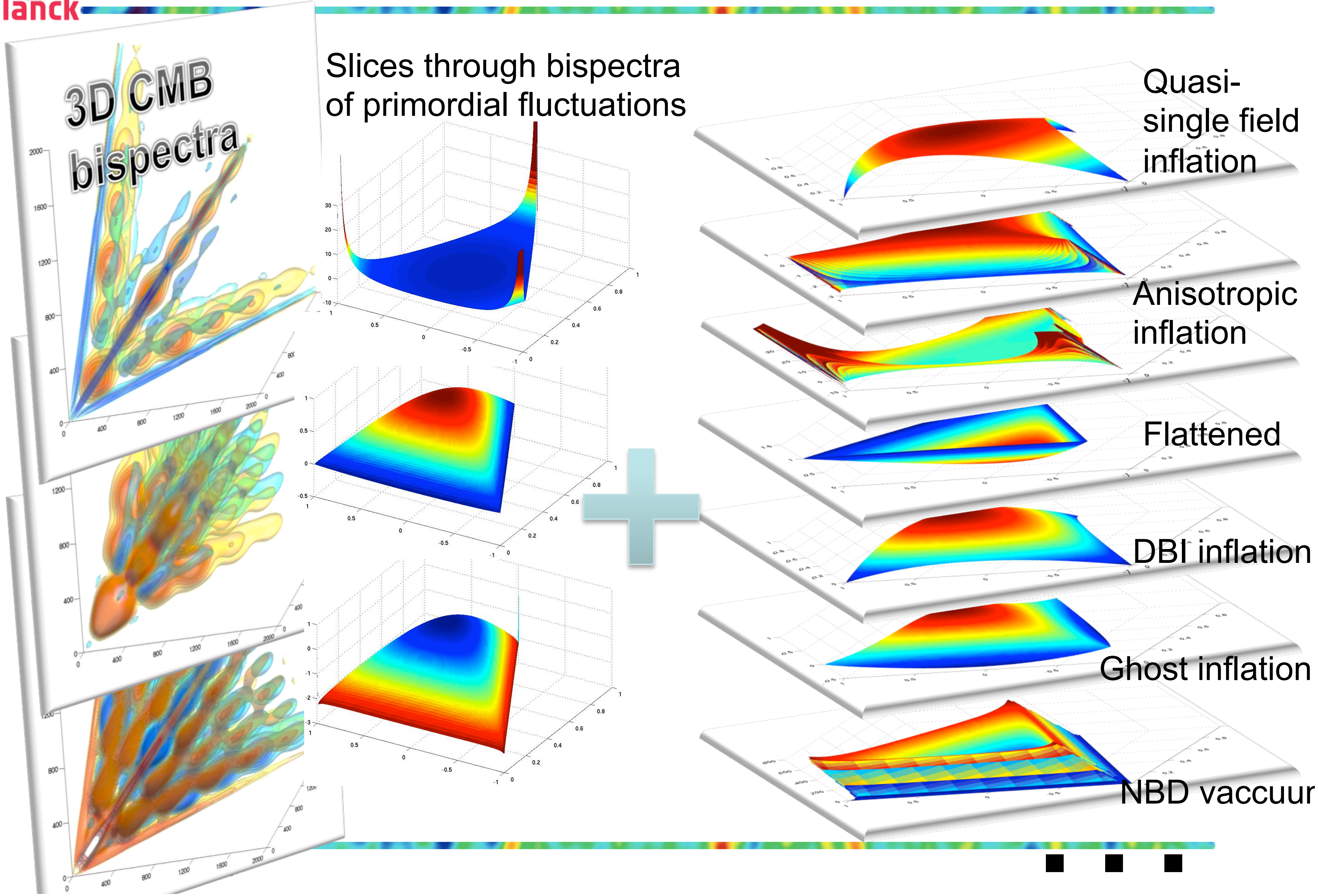
NG of ***equilateral*** type

- 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



Bispectrum measurement

Isotropic m-dependence

Theoretical template

$$\hat{f}_{\rm NL} = \frac{1}{N}\sum_{\ell_i,m_i} \mathcal{G}^{\ell_1\,\ell_2\,\ell_3}_{m_1 m_2 m_3}\, b^{\rm th}_{\ell_1\ell_2\ell_3}$$
$$\times \left[C^{-1}_{\ell_1 m_1,\ell'_1 m'_1} a_{\ell'_1 m'_1}\, C^{-1}_{\ell_2 m_2,\ell'_2 m'_2} a_{\ell'_2 m'_2}\, C^{-1}_{\ell_3 m_3,\ell'_3 m'_3} a_{\ell'_3 m'_3} \right.$$
$$\left. -\, 3\, C^{-1}_{\ell_1 m_1,\ell_2 m_2} C^{-1}_{\ell_3 m_3,\ell'_3 m'_3} a_{\ell'_3 m'_3} \right],$$

Variance-reducing
linear term

Weighted data
bispectrum

Meeting the computational challenge

$$\hat{f}_{\rm NL} = \frac{1}{N} \sum_{\ell_i, m_i} \mathcal{G}^{\ell_1\,\ell_2\,\ell_3}_{m_1 m_2 m_3} b^{\rm th}_{\ell_1 \ell_2 \ell_3} \times [C^{-1}_{\ell_1 m_1, \ell_1' m_1'} a_{\ell_1' m_1'} C^{-1}_{\ell_2 m_2, \ell_2' m_2'} a_{\ell_2' m_2'} C^{-1}_{\ell_3 m_3, \ell_3' m_3'} a_{\ell_3' m_3'} - 3\, C^{-1}_{\ell_1 m_1, \ell_2 m_2} C^{-1}_{\ell_3 m_3, \ell_3' m_3'} a_{\ell_3' m_3'}],$$

Scales as $O(L_{max}^5)$

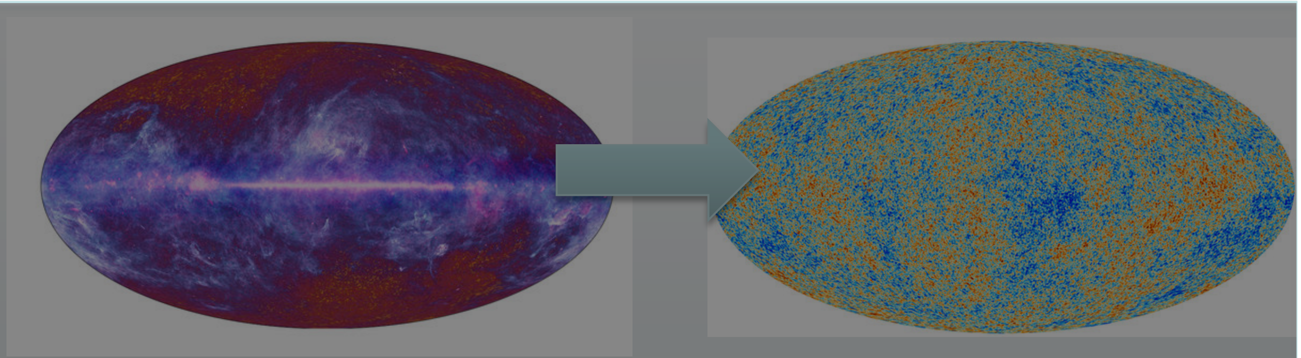
- Brute force implementation unfeasible for Planck data.
- Key idea: KSW - factorization

$$b_{\ell_1 \ell_2 \ell_3} = \sum_{ijk} X^i_{\ell_1} Y^j_{\ell_2} Z^k_{\ell_3} \Rightarrow B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_3} = b_{\ell_1 \ell_2 \ell_3} \int Y^{m_1}_{\ell_1}(\Omega) Y^{m_2}_{\ell_2}(\Omega) Y^{m_3}_{\ell_3}(\Omega)$$

- Gives L_{max}^2 speed-up: ~ 10^6 for Planck

Challenges

- Foregrounds



- Systematics

4th challenge: confirmation bias

- Computation

What is confirmation bias?

- "The wolf and the 7 little kids" is a story of confirmation bias
- The kids are waiting for their mom to come home **– they want to "detect" their mom**.
- At first the wolf's voice does not match mother sheep's a first-look analysis fails and the kids are safe.
- Then the wolf changes his voice but the kids require a systematics test: "show us your paw!" The test fails and the kids are safe.

- When the wolf paints his paw white, the test passes.
- But instead of doing further tests (*show us your face! show us your tail!*) they let the wolf in – and he eats them all up.

Confirmation bias

We have a strong prior – the canonical expectation is Gaussian Lambda CDM and red flags rise in the analysis if we depart from this model.

How we avoid being eaten:

Treat the measurement on an equal footing – whether it is a detection or a constraint.

Different Estimators

- KSW (Komatsu, Spergel, Wandelt 2003)
  - *Gives exact fit to separable bispectrum*
  - *Limited to factorizable templates*
- Modal (Fergusson, Liguori, Shellard 2009)
  - *Sum of KSW-like smooth templates to fit arbitrary templates*
  - *General up to resolution limit*
  - *Freedom to choose basis set*
  - *Fit global variations across entire L-range*
- Binned (Bucher, v. Tent, Carvalho 2009)
  - *Block-shaped templates, binning L-ranges*
  - *Compact basis in L*

Simulation tests

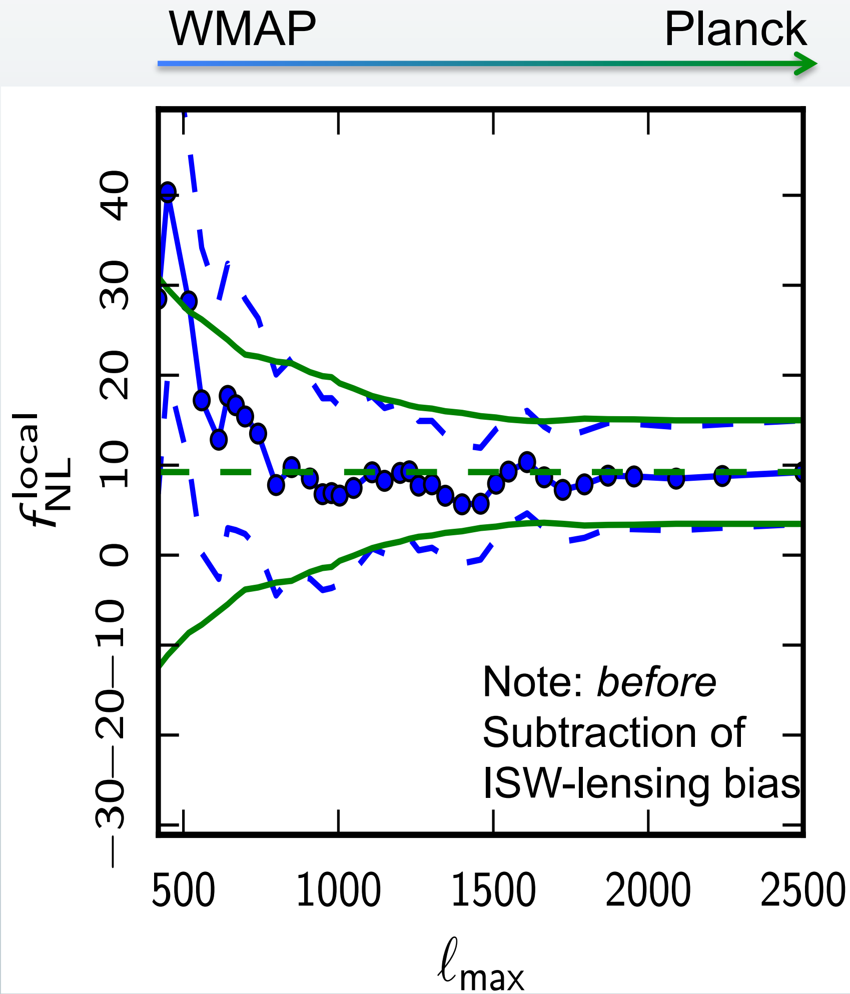
- To participate in the analysis all estimators have to pass a suite of simulation challenges for Gaussian and non-Gaussian simulations

- These simulations test
  - *Map-by-map agreement of estimators*
  - *Robustness to foreground residuals*
  - *Ability to find and accurately measure unknown non-Gaussianity from a simulated data set (FFP6, including foregrounds, correlated noise, flagging, realistic band-passes, asymmetric main beams)*

The Planck NG analysis passed an extensive validation campaign

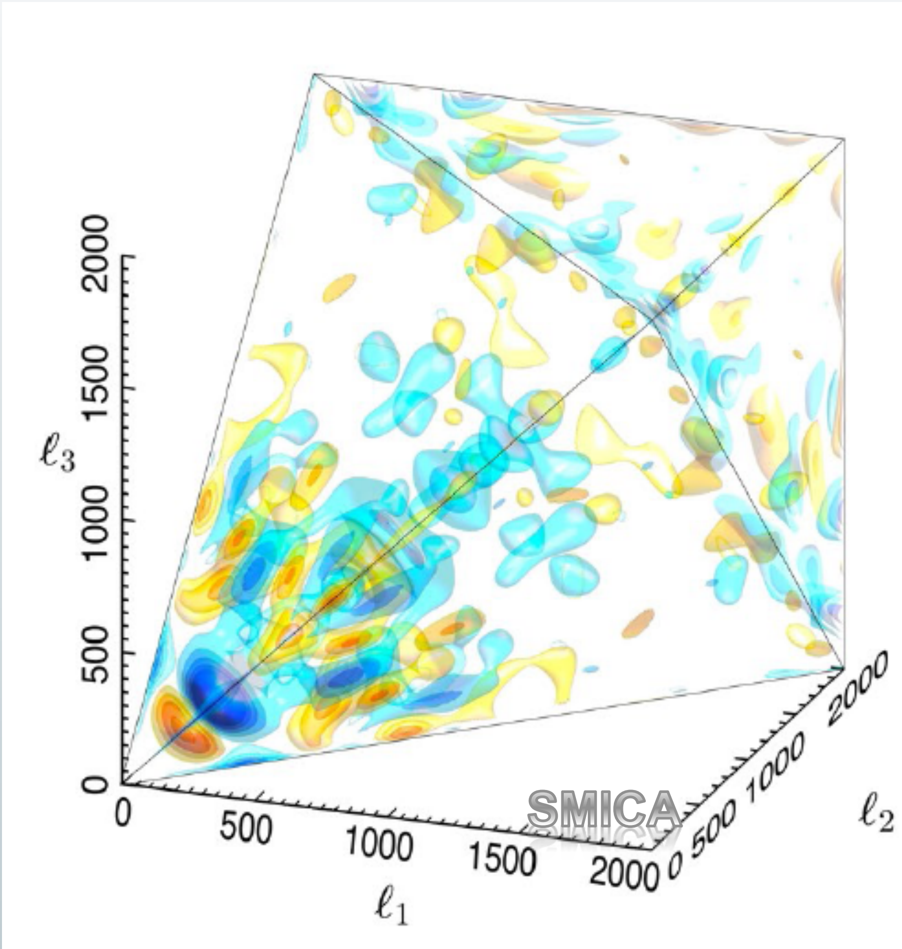
- Estimators agree
  - *KSW (Komatsu, Spergel, Wandelt 2003)*
  - *Modal (Fergusson, Liguori, Shellard, 2009)*
  - *Binned (Bucher, v. Tent, Carvalho 2009)*
  - *Skew-C_l (Munshi, Heavens 2010)*
  - *Minkowski Functionals (Ducout et al. 2012)*
- Multiple foreground cleaning methods agree
  - *SMICA*
  - *NILC*
  - *SEVEM*
  - *(C-R)*
- Negligible impact of foreground residuals
- Null tests pass
- Consistent…
  - *Resolution dependence*
  - *Frequency dependence*
  - *Mask dependence*

Consistency with WMAP hints

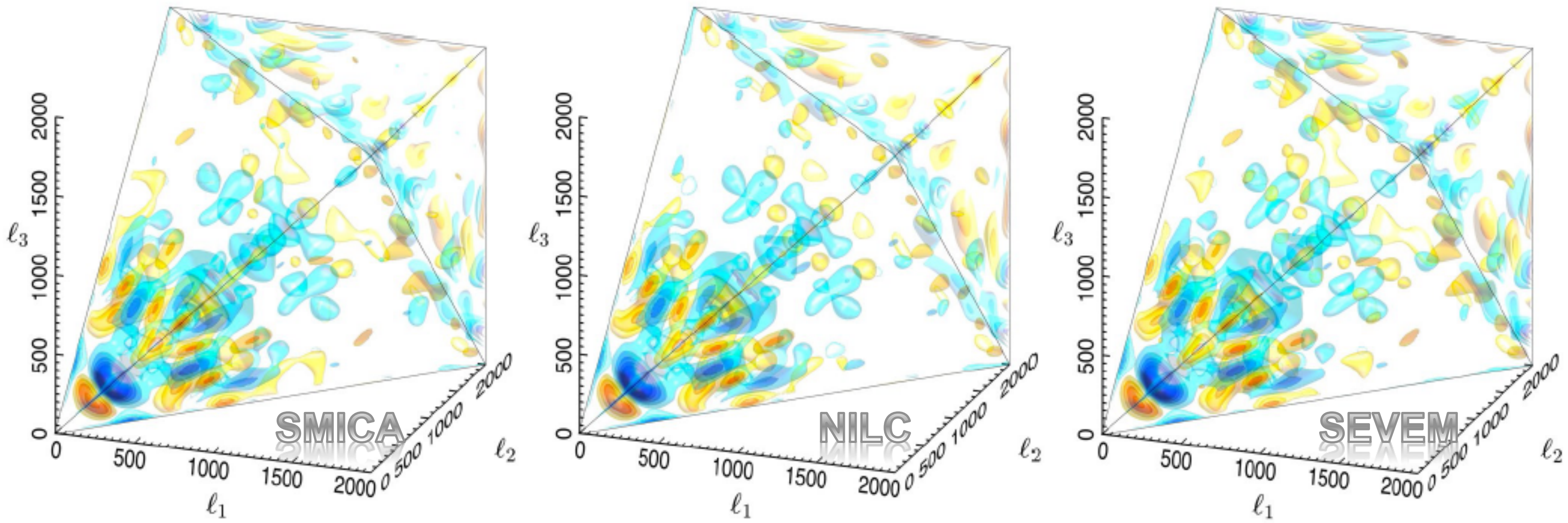


- Limiting the analysis to large scales (low l), we make contact with WMAP9 (f_{NL}^{local}=40±20)
- Planck allows using 10 times more modes and now rules out the WMAP central value by ~6 sigma.

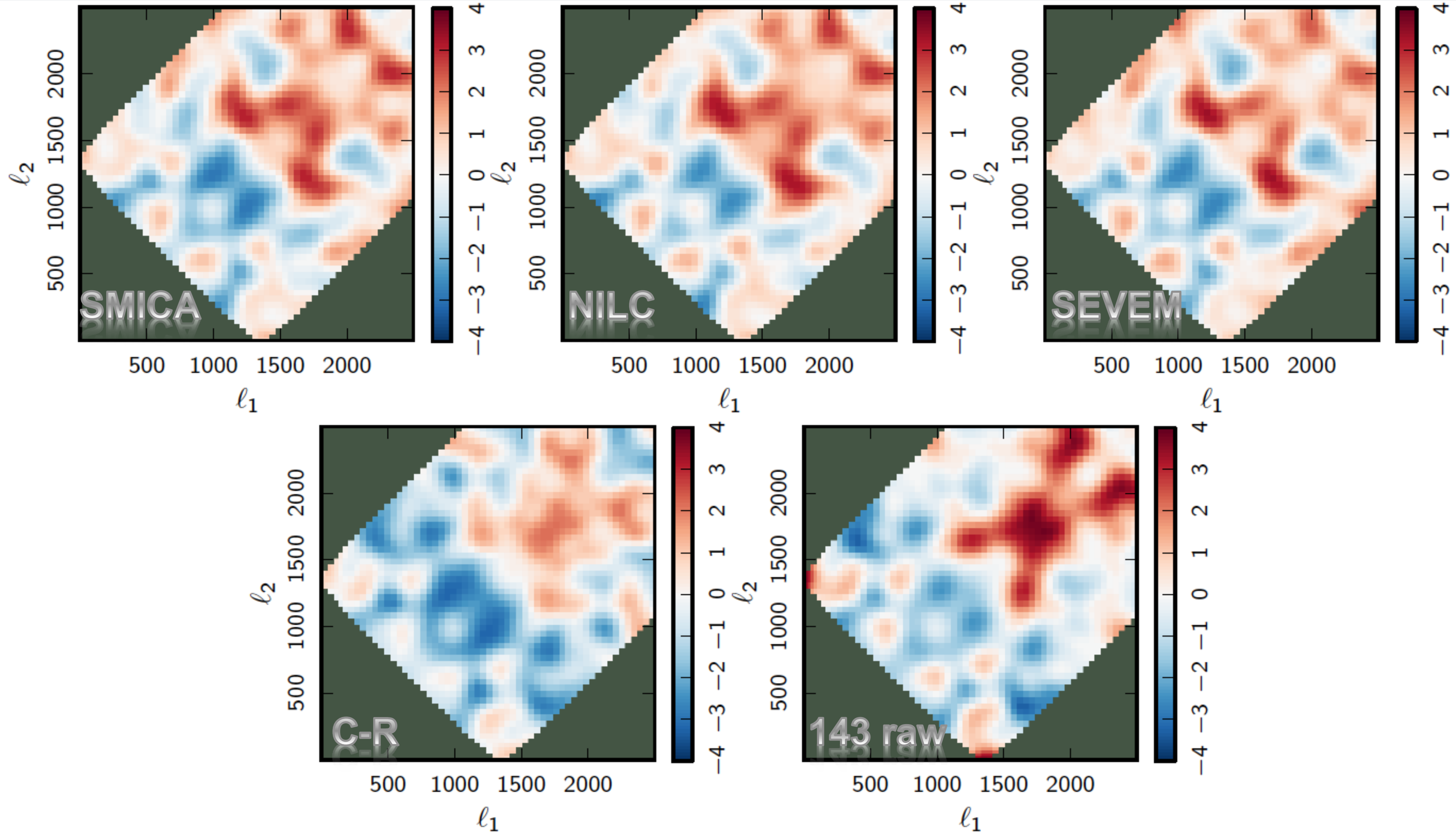
The Planck bispectrum (modal decomposition)



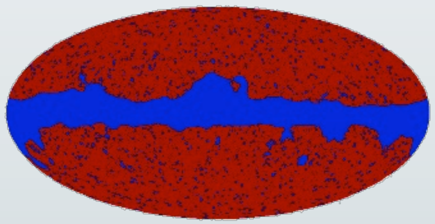
Robust to foreground cleaning: the Planck modal bispectrum

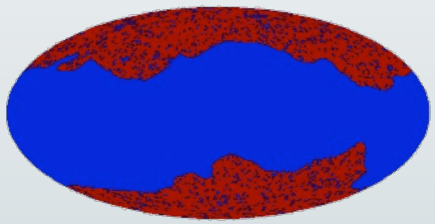


Robust to foreground cleaning: (binned bispectrum)



Masked raw frequency maps are consistent with zero f_{NL}





	SMICA	70 GHz	100 GHz	143 GHz	217 GHz
	$f_{\rm sky} = 0.73$	$f_{\rm sky} = 0.32$			
Local	9.2 ± 5.9	19.7 ± 26.0	-2.5 ± 13.2	10.4 ± 9.8	-4.7 ± 9.6
Equilateral	-20 ± 73	159 ± 188	70 ± 132	48 ± 114	-9 ± 114
Orthogonal	-39 ± 39	-78 ± 139	-106 ± 81	-101 ± 64	-84 ± 63

Planck results: the highest precision test of origin of cosmic structure

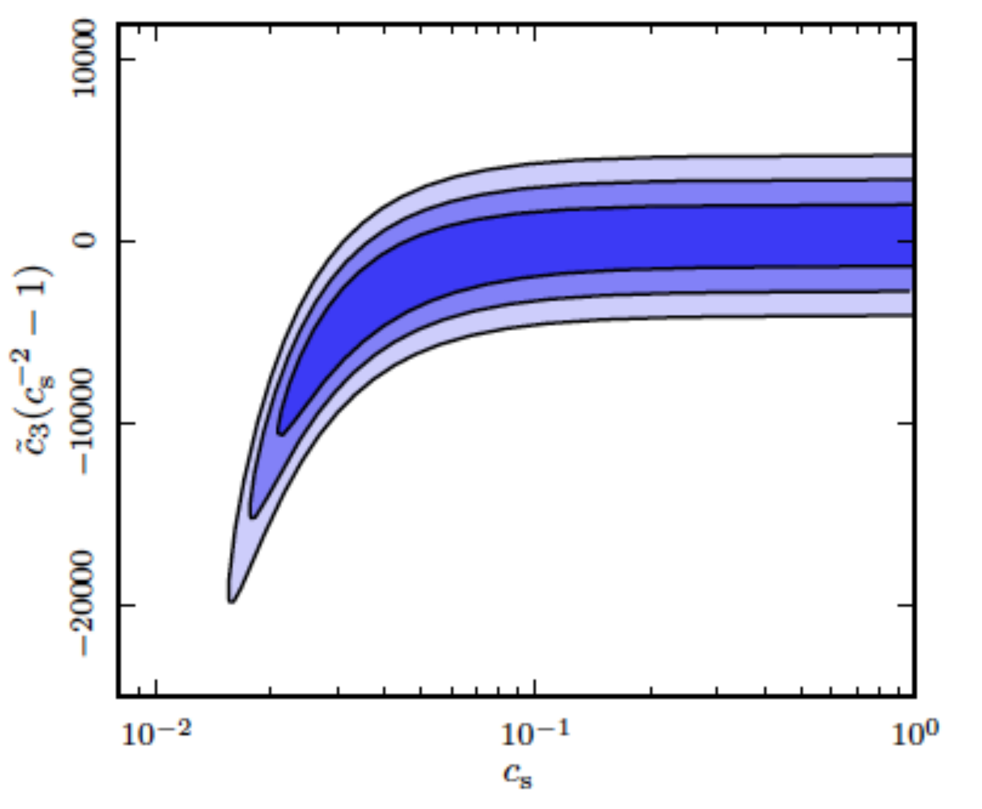
	Independent				ISW-lensing subtracted		
	KSW	Binned	Modal		KSW	Binned	Modal
SMICA							
Local	9.8 ± 5.8	9.2 ± 5.9	8.3 ± 5.9	. . . . .	**2.7 ± 5.8**	2.2 ± 5.9	1.6 ± 6.0
Equilateral	−37 ± 75	−20 ± 73	−20 ± 77	. . . . .	**−42 ± 75**	−25 ± 73	−20 ± 77
Orthogonal	−46 ± 39	−39 ± 41	−36 ± 41	. . . . .	**−25 ± 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

68% confidence intervals

Effective Field Theory constraints for single field models

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

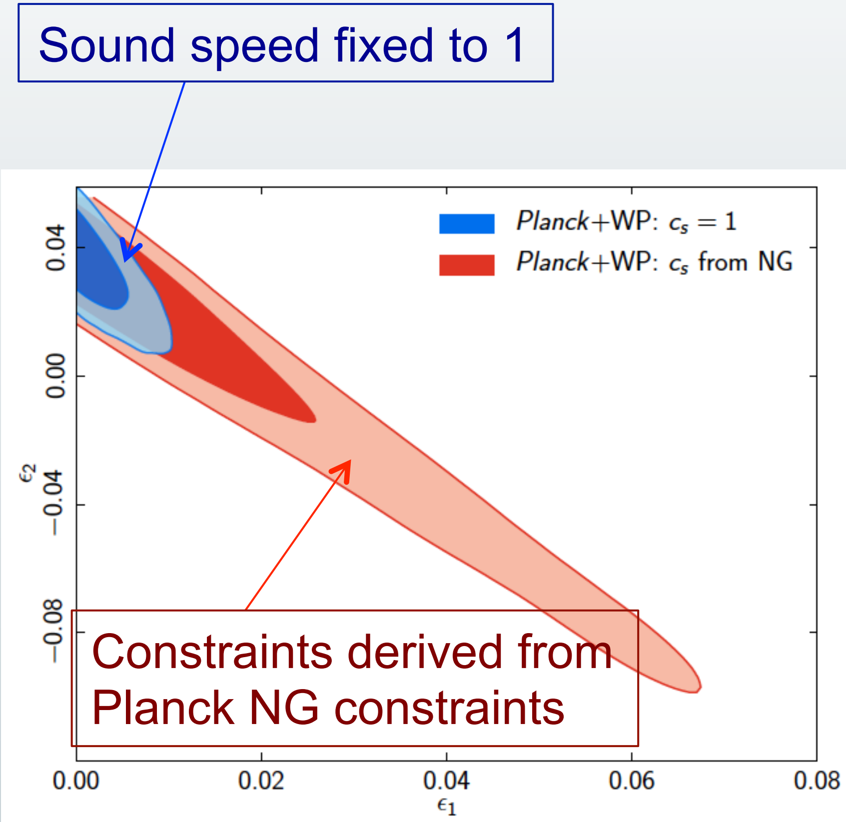
Senatore et al 2010
Chen et al. 2007, 2010



Specific bispectrum shapes correspond to cubic interaction terms in the Lagrangian

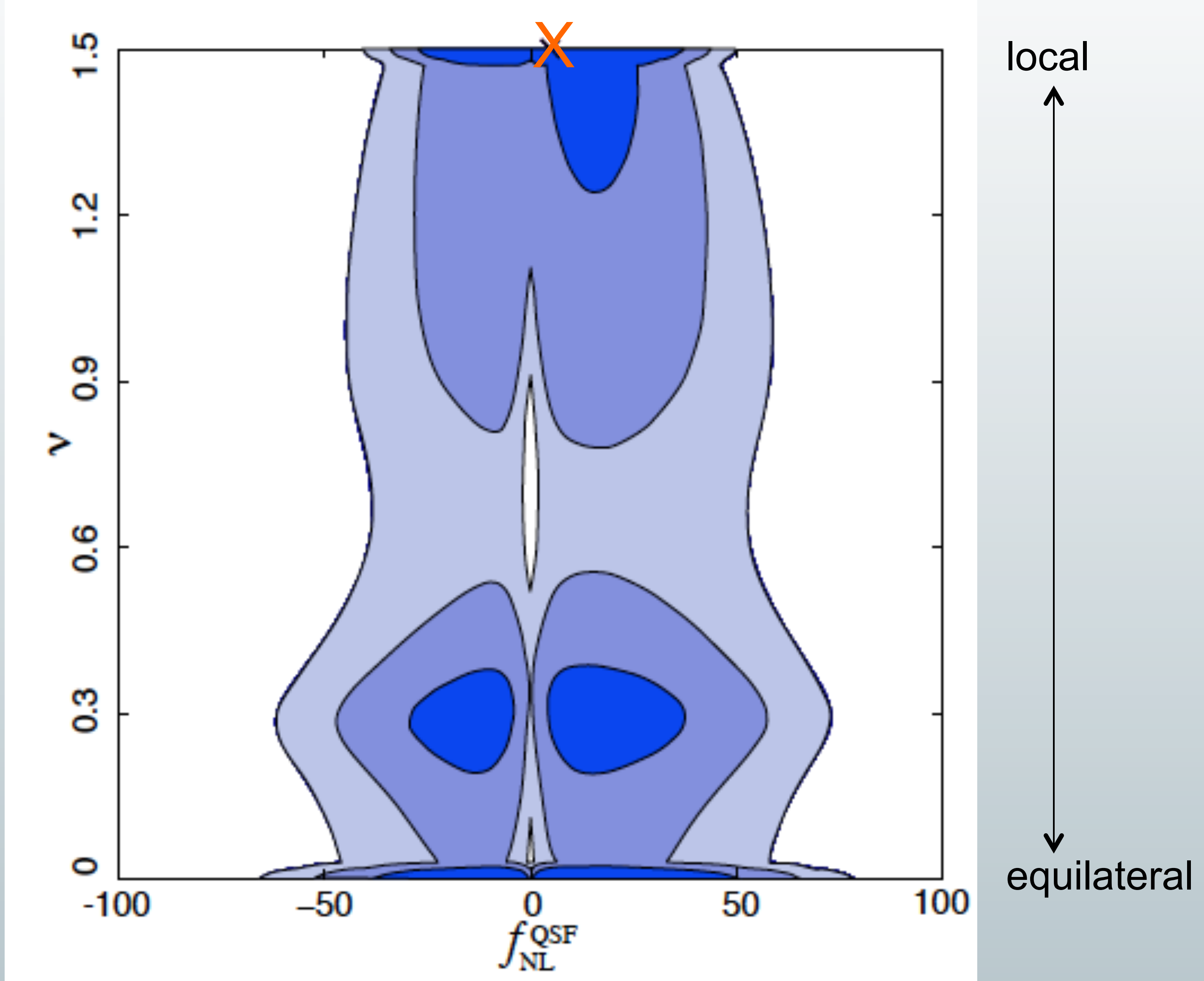
Use these to directly constrain parameters in the Lagrangian

NG impact on general single field models



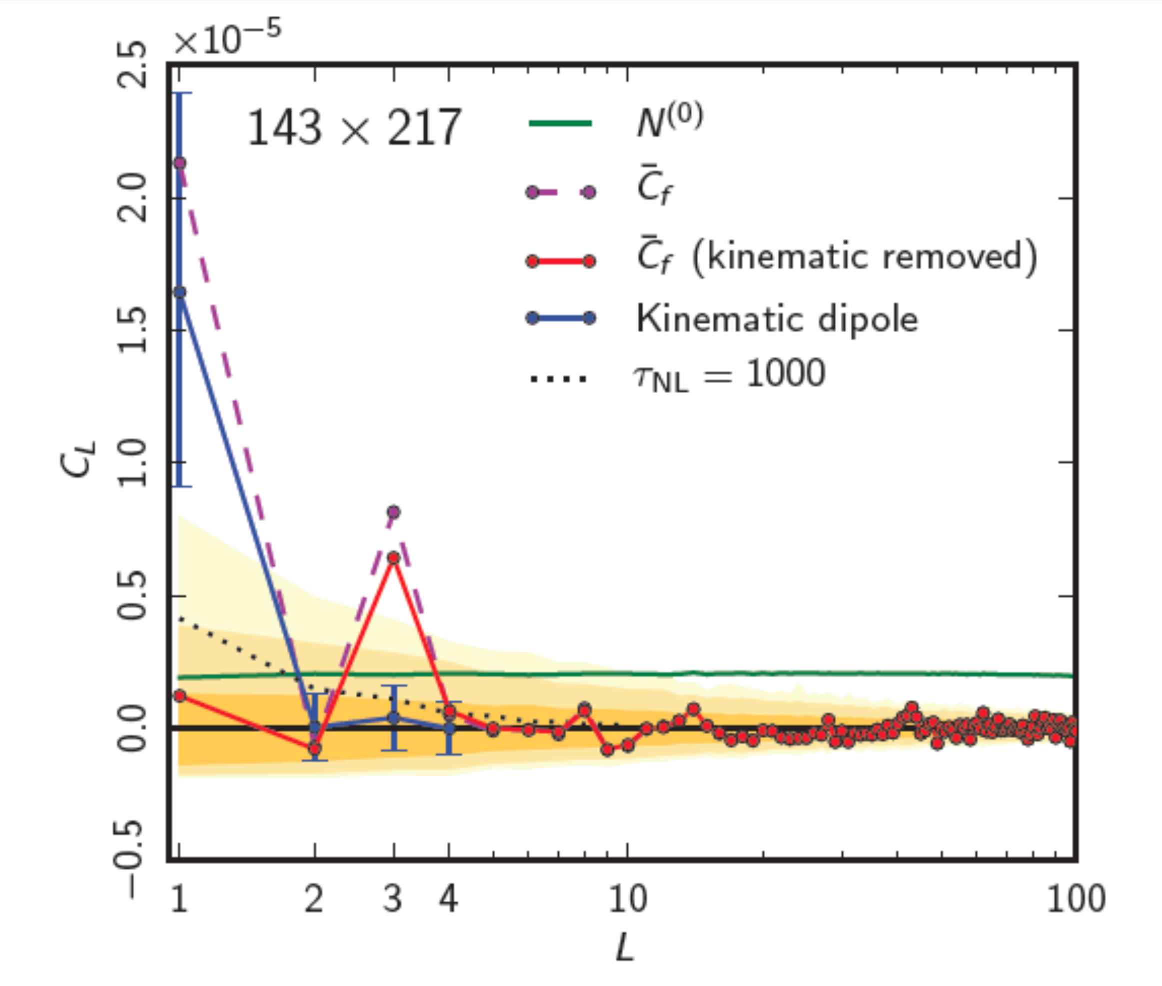
- Allowing varying sound speed through a non-standard kinetic term during inflation opens a parameter degeneracy
- But the kinetic term also produces an equilateral bispectrum. The NG constraints break the degeneracy.

Quasi-single field model



Constraint on 4-point function from local non-Gaussianity:

τ_{NL}<2800



Planck primordial non-Gaussianity results

- Slowly rolling, single scalar-field inflation models are favoured by the Planck data

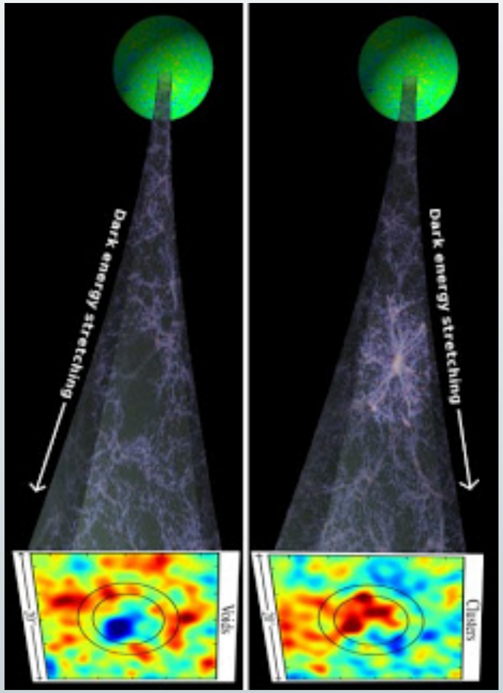
- Multi-field models are not ruled out but also not detected. The curvaton decay fraction r_D>15% (95% C.L.)
- Planck map rules out small speed of sound during inflation c_s>0.02 (95% C.L.)
- Planck map is consistent with standard BD vacuum.

- Planck strongly constrains a class of ekpyrotic/cyclic models (those with exponential potential, entropic generation of perturbations and conversion during ekpyrotic smoothing phase).

The late-time bispectrum

“Late-”time fundamental physics

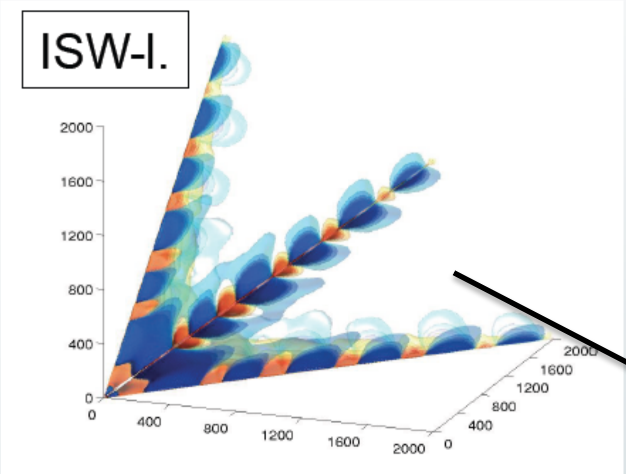
- The *erasure of structure caused by dark energy* (late-time inflation) creates a non-Gaussian signal in the CMB

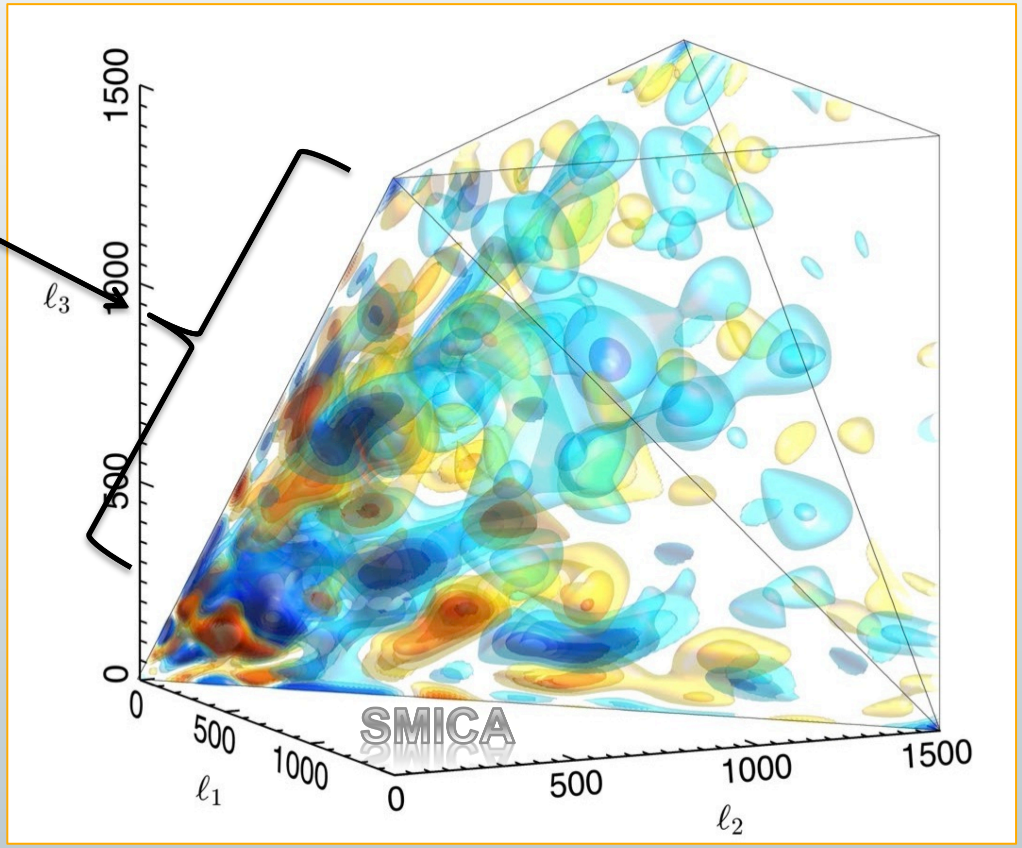


- This effect manifests as the “ISW-Lensing” bispectrum

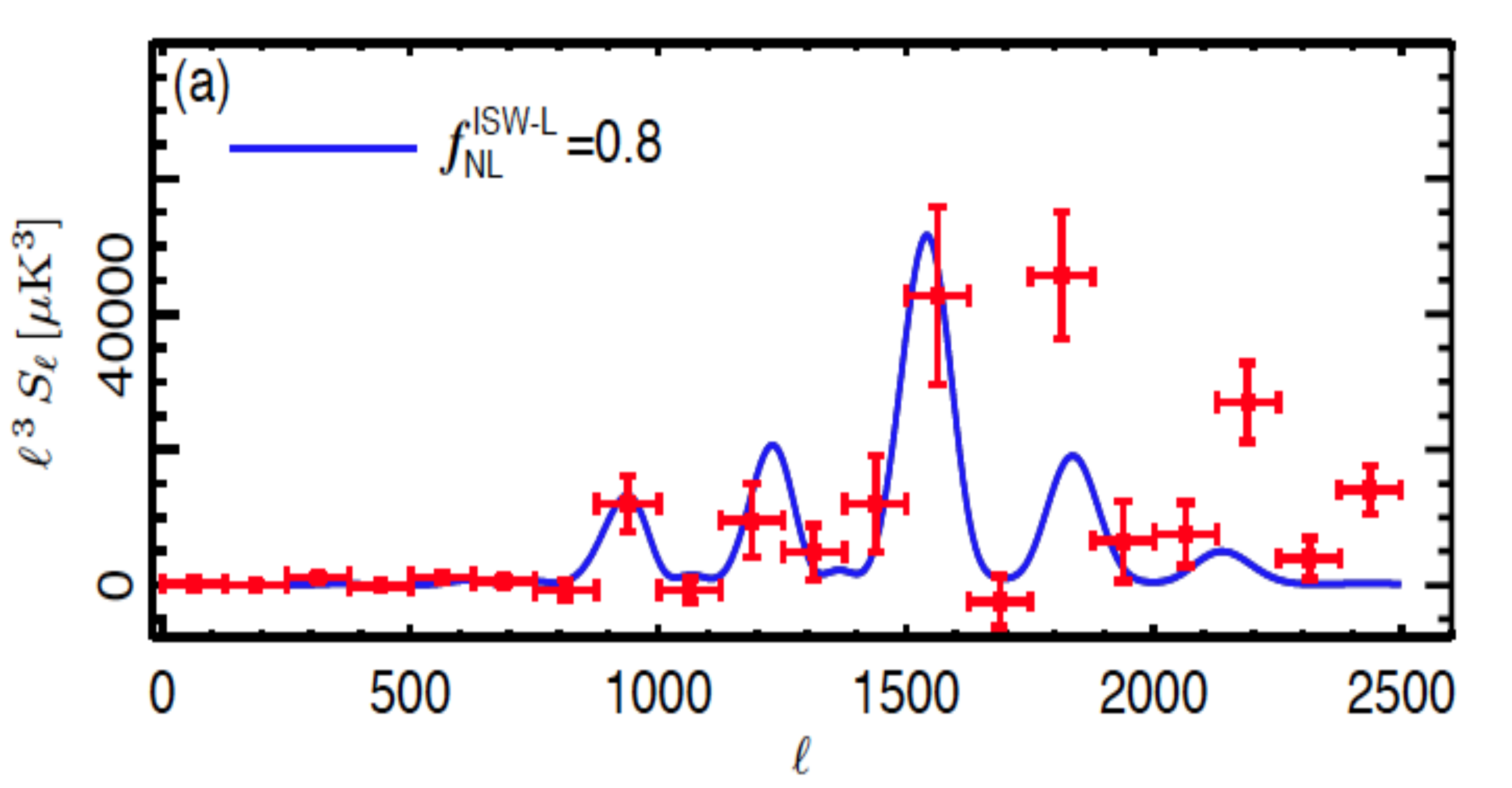
- Planck see this effect at the expected level with **2.6 sigma** significance.

The 2.6-σ ISW lensing effect – visible by eye in the Planck bispectrum





ISW-lensing bispectrum as seen by skew C_l



Can TOD processing remove Non-Gaussianity?

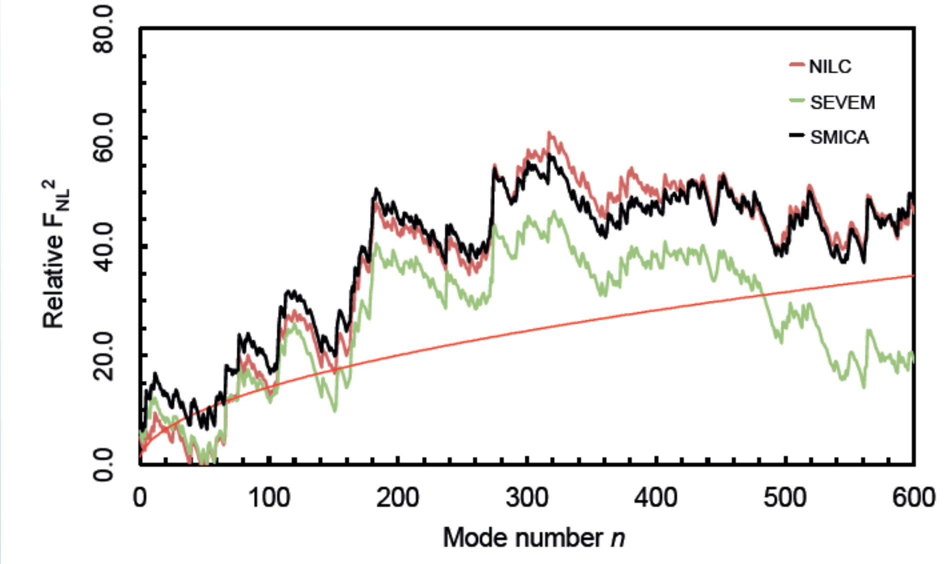
- l ~ 500 consistent with WMAP -> Any removal would have had to occur exclusively at high l
- Yet, TOD processing clearly preserved
  - *Lensing signal*
  - *Infrared-background lensing correlation*

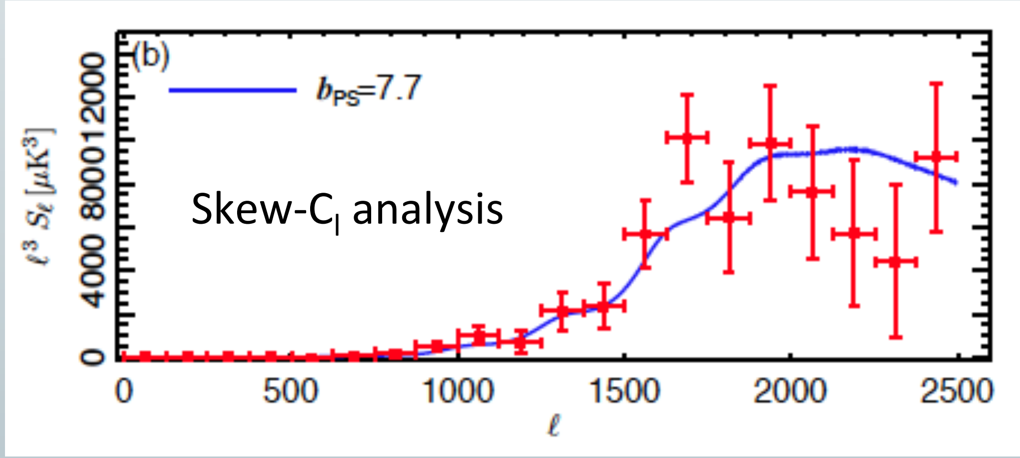
both seen with high significance in Planck data – and at the expected level.

- ISW-lensing bispectrum estimate consistent with expected level at 0.6 sigma and non-zero by 2.6 sigma. This is also a squeezed bispectrum shape.

Lots of information – large discovery potential

Blind search for excess variance looks consistent with random Gaussian bispectrum.



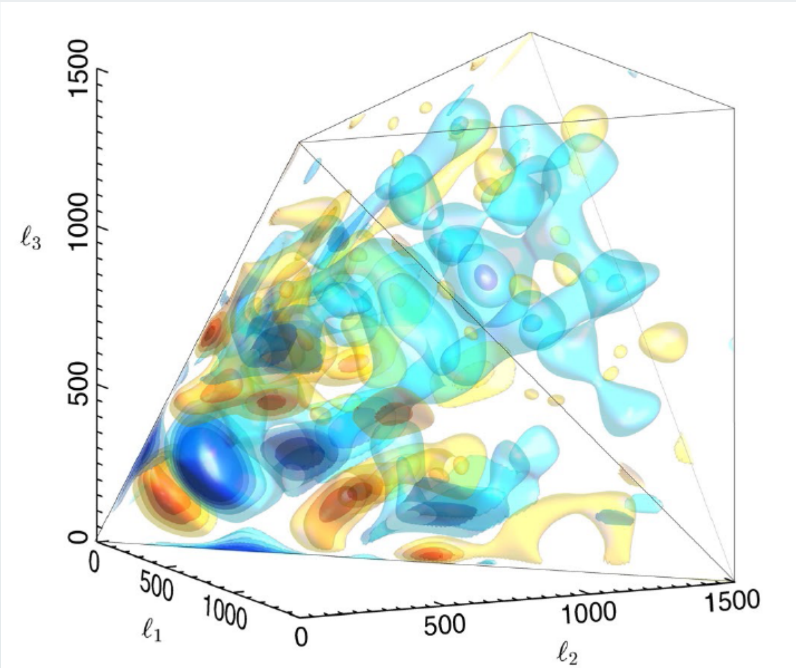


But a given template shape can have high significance.

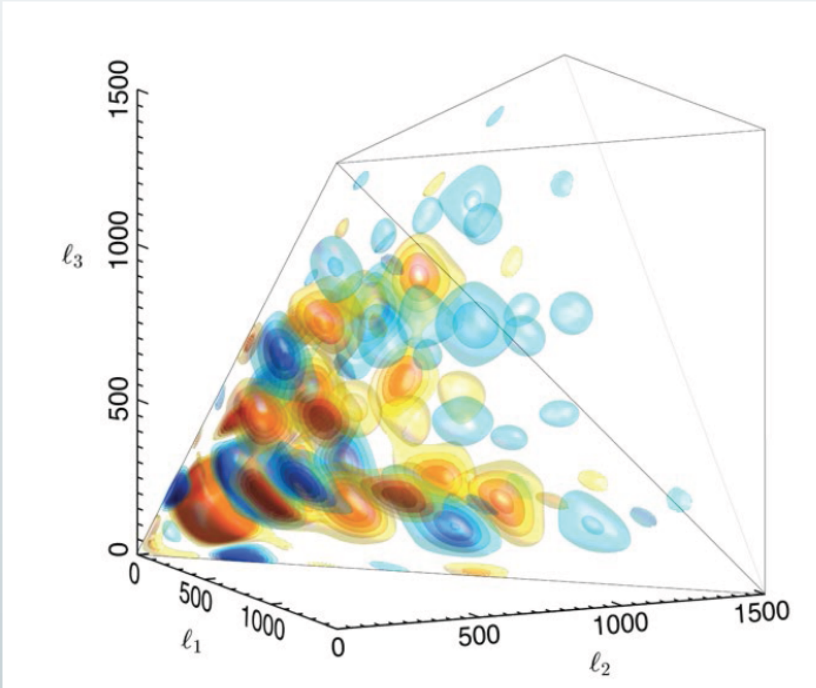
Residual point source bispectrum detected at 5 sigma in SMICA map.

3-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.

Beyond the power spectrum

- Features in the P(k) should also be visible in the bispectrum (and vice versa). Power spectrum and non-Gaussianity analyses not yet done in fully overlapping parameter range.

Example:

- k-inflation (Armendariz-Picon et al. 1999) fits the Planck power spectrum and NG separately but not both:

NG (equil): $\gamma \geq 0.05$ at 95% CL.

n_s: $0.01 \leq \gamma \leq 0.02$ at 95% CL.

The view of the initial state of the Universe after Planck

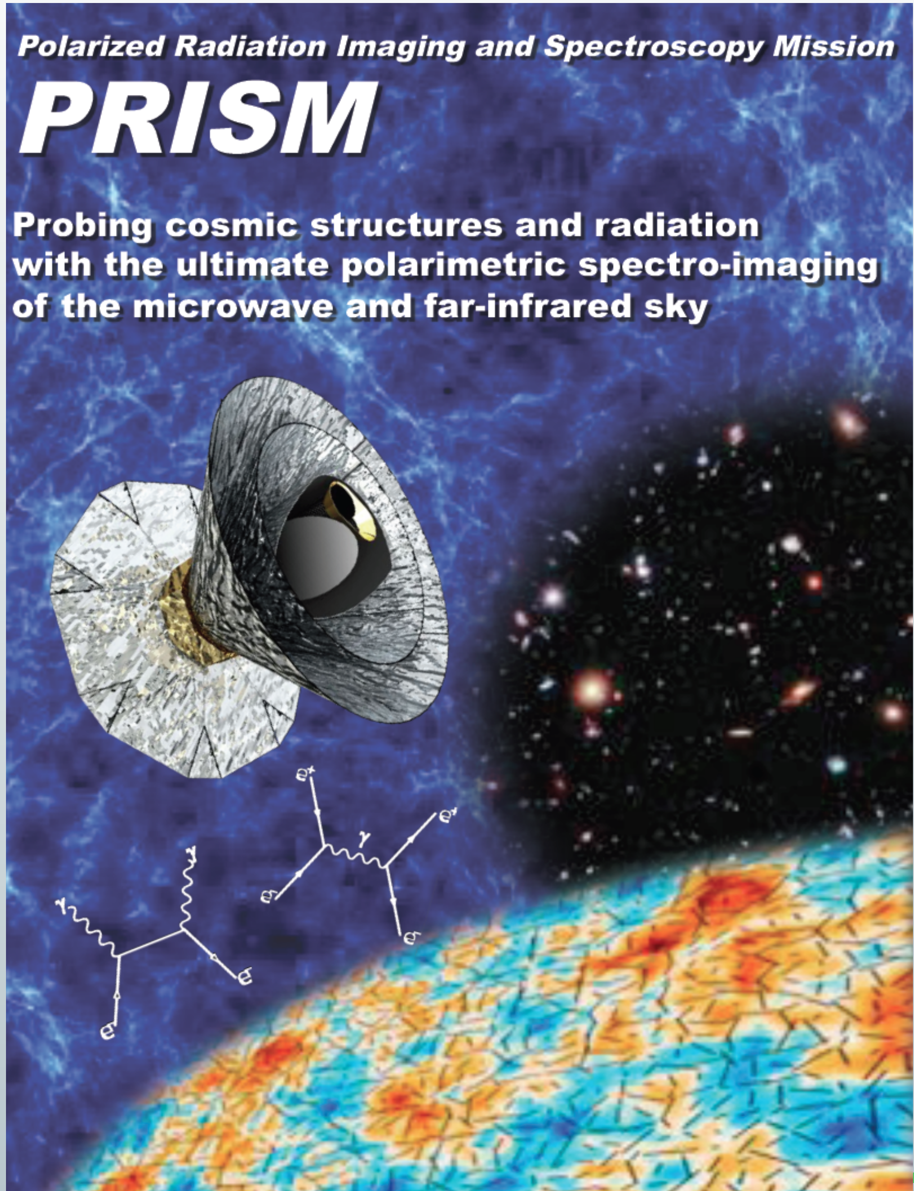
- Slowly rolling, single scalar-field inflation models are favoured by the Planck data. Questions of prior choice remain

- New constraint volume for three main NG shapes **20 times** smaller than pre-Planck.

- We do see non-primordial non-Gaussianity at levels consistent with expectations

- Planck non-Gaussianity is the highest precision test to date of the physical mechanism at the origin of cosmic structure

Beyond Planck

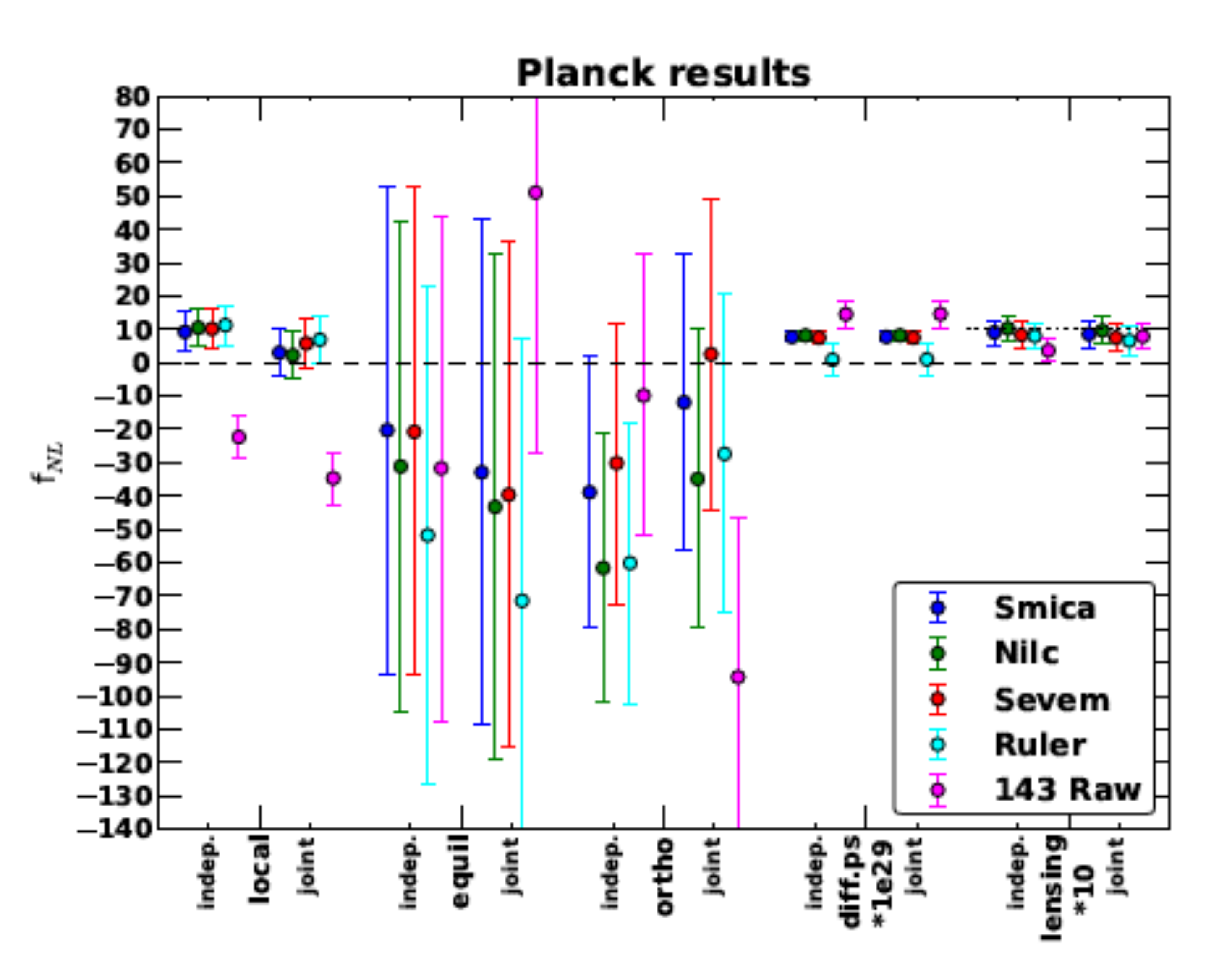


- Inflationary B-modes
- Probing new physics through CMB spectral distortions
- Full view of primordial perturbations in polarization
- The ultimate survey of clusters of galaxies
- Neutrino masses 0.04 eV from CMB alone

Please register your support at
www.prism-mission.org

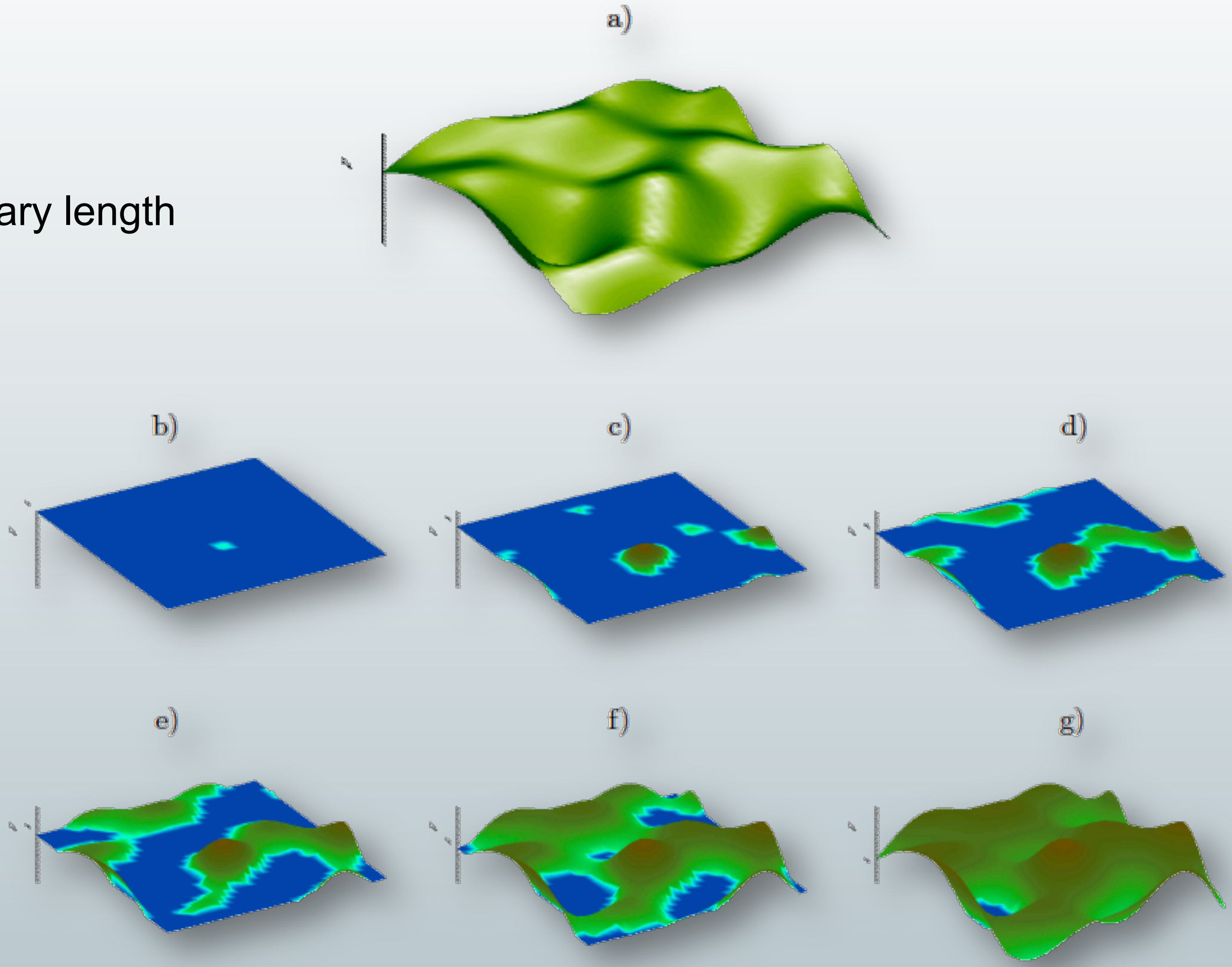
Appendices

Independent and joint analyses



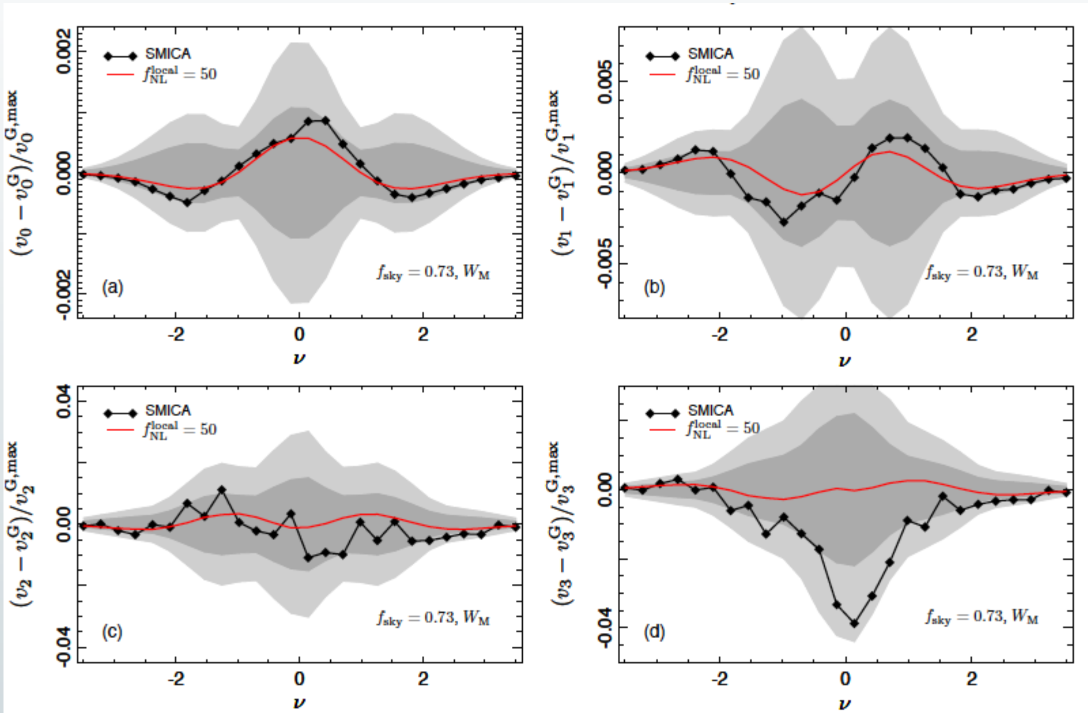
Estimator robustness: Minkowski functionals

Area
Boundary length
Genus



Ducout 2012

Minkowski functionals



	$f_{\rm NL}^{\rm local}$	Source	Corresponding $\Delta f_{\rm NL}^{\rm local}$
Raw map	19.1 ± 19.3		–
Lensing subtracted	8.5 ± 20.5	Lensing	+10.6
Lensing+PS subtracted	7.7 ± 20.3	Point sources	+0.8
Lensing+CIB subtracted	7.5 ± 20.5	CIB	+1.0
Lensing+SZ subtracted	6.0 ± 20.4	SZ	+2.5
All subtracted	$\boxed{4.2 \pm 20.5}$	All	+14.9

Planck TOI processing did not destroy non-Gaussian signals

1. ISW-lensing (3-pt, squeezed): weak 2.6-σ signal at a level consistent with expectations from LCDM
2. CIB-lensing (3-pt, squeezed): very strong detection (~40-σ), consistent with observed CIB and lensing auto-spectra
3. Lensing (4-pt): strong detection consistent with LCDM
4. Modulation due to peculiar motion (4-pt) seen at a sensible level and in a plausible direction
5. Residual point sources (3-pt) 5-σ
6. Detailed agreement with the WMAP-9 findings in the scale range where WMAP is signal dominated (l<600)

Scalar Power Spectrum

Cosmological Fluctuations:

- are combined gauge invariant perturbations of the metric and of the inflaton field v
- are the seeds of temperature anisotropies in the CMB $v \propto \frac{\delta T}{T}$
- Follow a parametric amplifying equation of motion

$$v_{\boldsymbol{k}}'' + \left[k^2 - \frac{\left(a\sqrt{\epsilon_1}\right)''}{a\sqrt{\epsilon_1}}\right] v_{\boldsymbol{k}} = 0$$

Power Spectrum:

$$P_v(k) = \frac{k^3}{2\pi^2}\left\langle \hat{v}_k^2 \right\rangle$$

$$= \frac{a^2 H^2}{8\pi^2 M_{\mathrm{Pl}}^2 \epsilon_{1\diamond}}\left[1 - (2\epsilon_{1\diamond} + \epsilon_{2\diamond} + \cdots)\ln\frac{k}{k_\diamond} + \left(2\epsilon_{1\diamond}^2 + \epsilon_{1\diamond}\epsilon_{2\diamond} + \frac{\epsilon_{2\diamond}^2}{2} - \frac{\epsilon_{2\diamond}\epsilon_{3\diamond}}{2} + \cdots\right)\ln^2\frac{k}{k_\diamond} + \cdots\right]$$

Spectral index $n_{\mathrm{S}} = \left.\frac{\mathrm{d}\ln P}{\mathrm{d}\ln k}\right|_{k_*}$

$n_{\mathrm{S}}^{\mathrm{Planck}} \sim 0.96$

Gravity waves:

$$r = \frac{P_h(k_*)}{P_v(k_*)} = 16\epsilon_{1*} + \cdots$$

credit: **Vincent Vennin**

The ekpyrotic prediction

Print Sidebar

Steinhardt.f4v

the big bang is a big bounce

no flatness or causal connectedness problem

new mechanism for smoothing the universe prior to the bang

new mechanism for generating scale-invariant density perturbations

no transplanckian problem

predictions:

no observable tensor modes in CMB

non-gaussianity $|f_{NL}(\text{local})| = 20\text{-}50$ correlated with tilt

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cyclic universe

may compete successfully with inflation (see J-L Lehners 2012)

may explain what we have learned about the state of the vacuum

-26:20

Applications

Creminelli3.hi.mp4

March, 6 2013 Perimeter