# 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.

Benjamin D. Wandelt

# Fundamental Physics from Cosmology in the (post-)Planck era

Ben Wandelt

Institute for Astrophysics, Paris
Lagrange Institute, Paris
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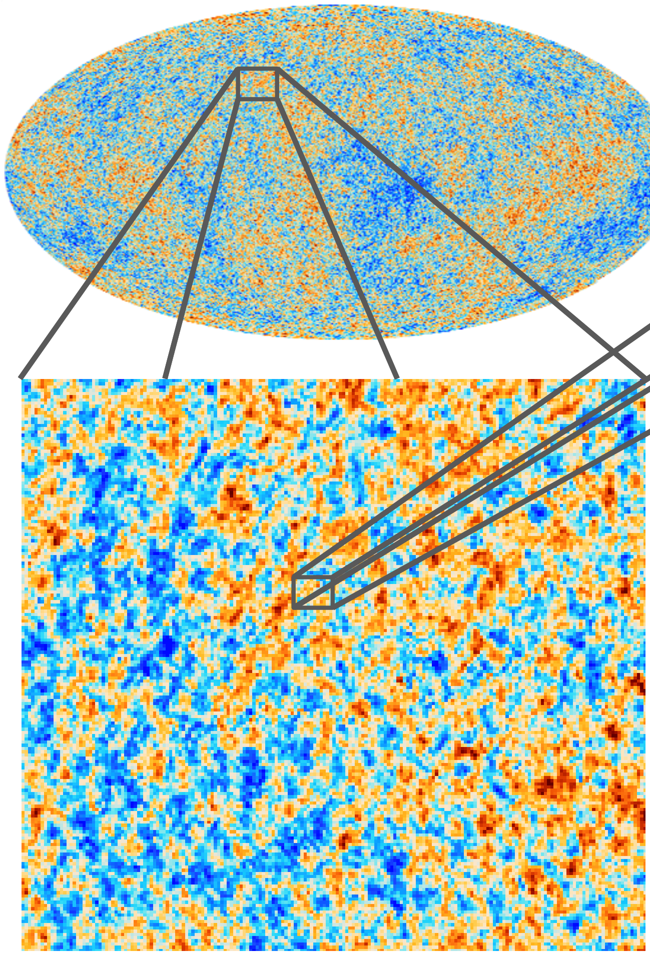
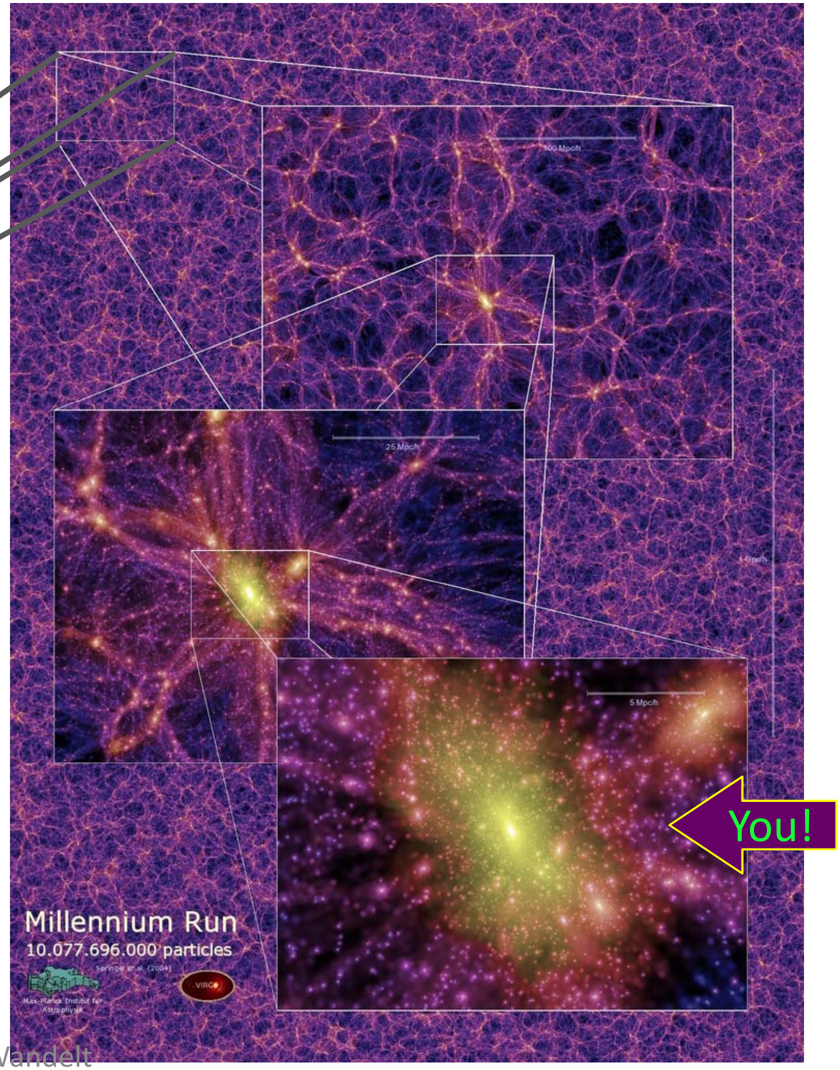
# The Big Picture

Planck

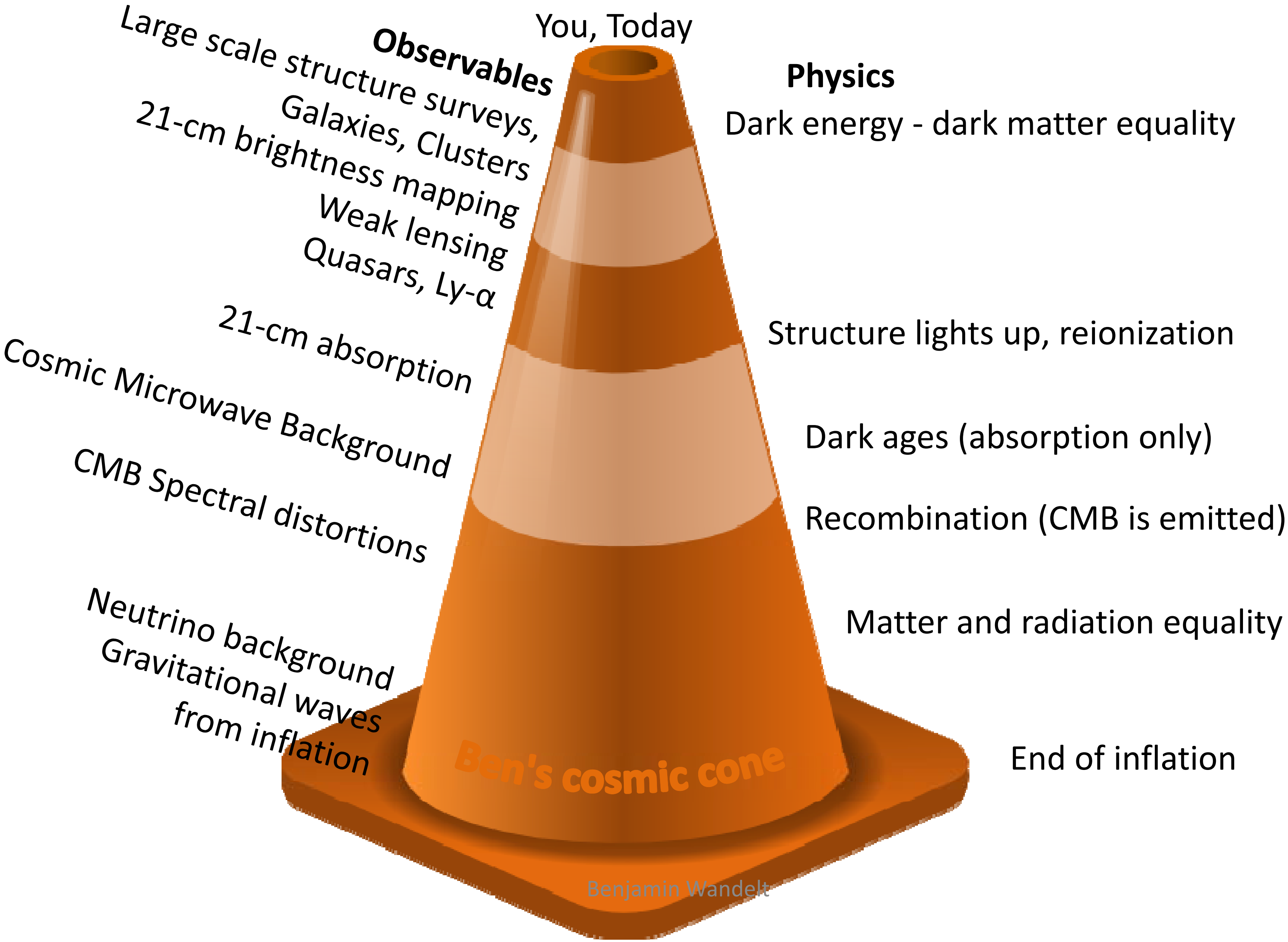


Primordial quantum perturbations as seen in the Cosmic Microwave Background

Dark matter distribution today (simulated)



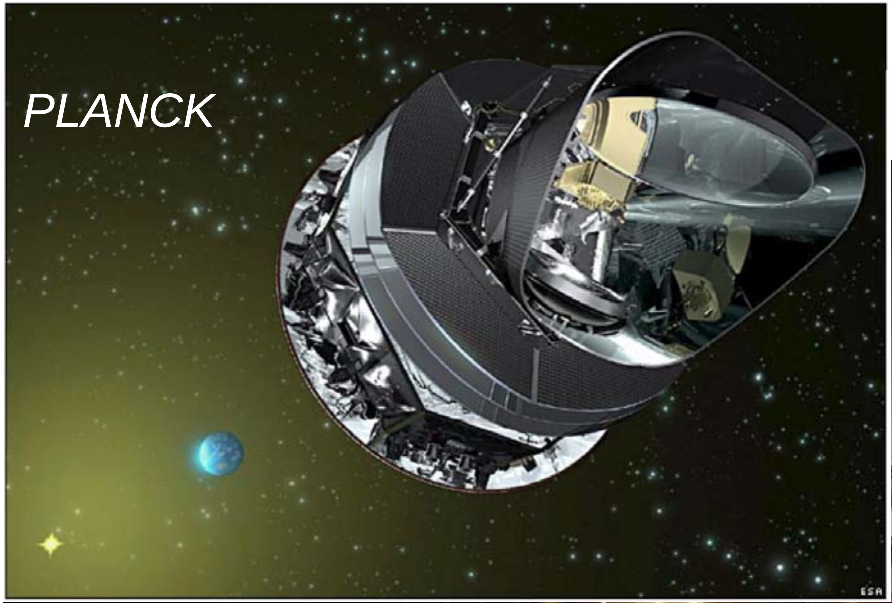
# What is ultimately observable?



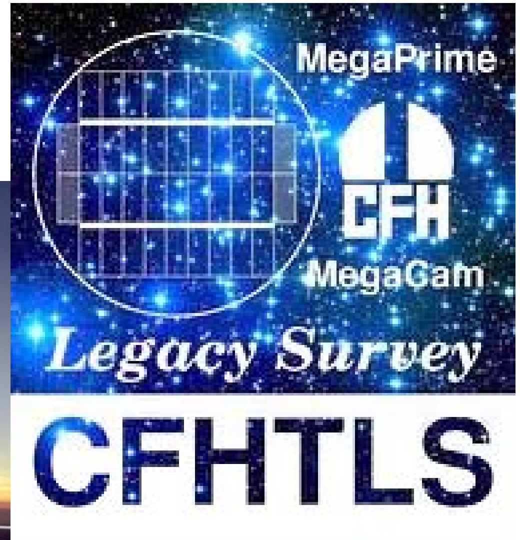
# Cosmology's list of modest questions

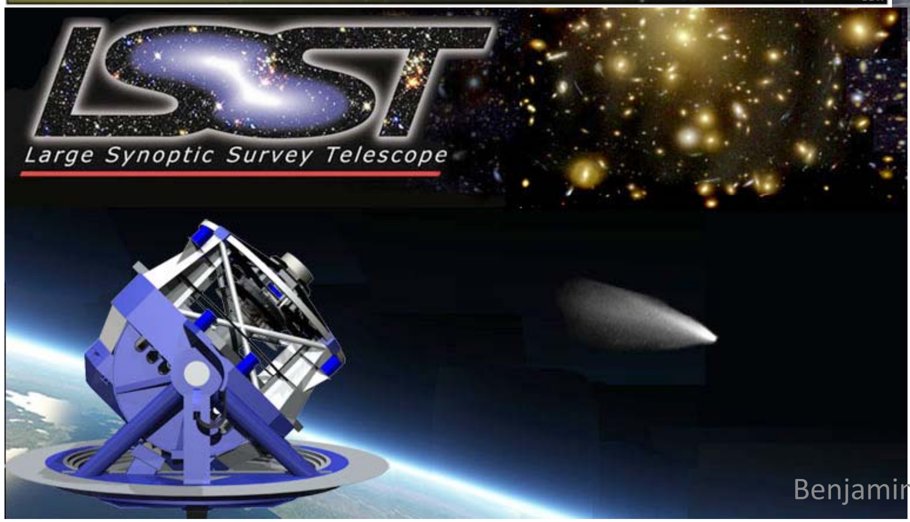
- What banged at the Big Bang?
- How did structure appear in the Universe?
- How did it evolve until today?
- What is the Universe made of?
- What are the properties of dark matter?
- What are the properties of dark energy?
- What is the geometry and the symmetry of the Universe?

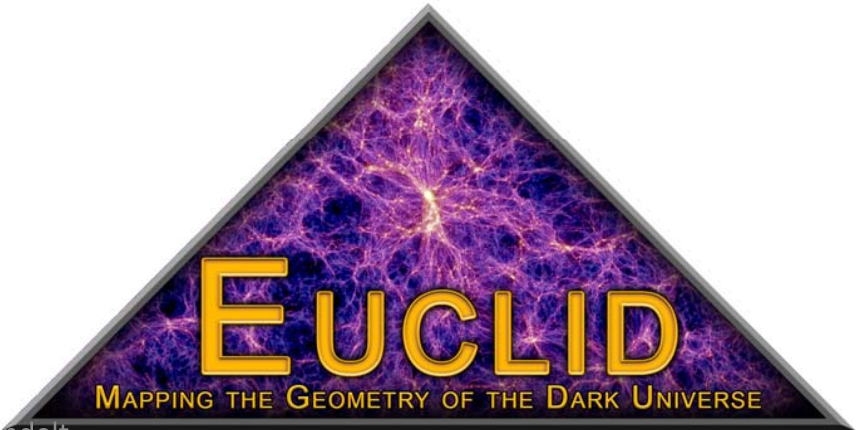
# We are trying to address these questions with large surveys



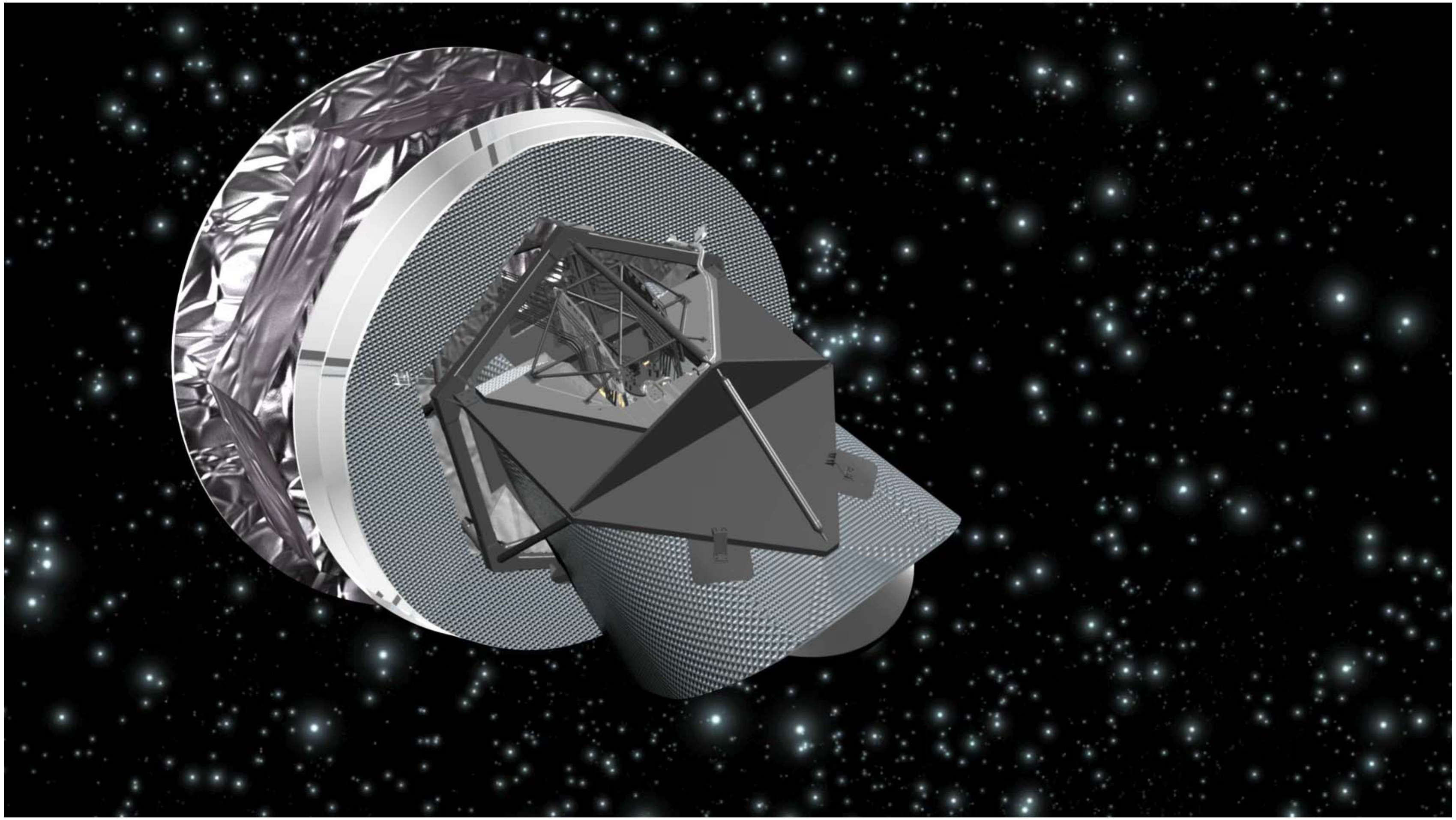


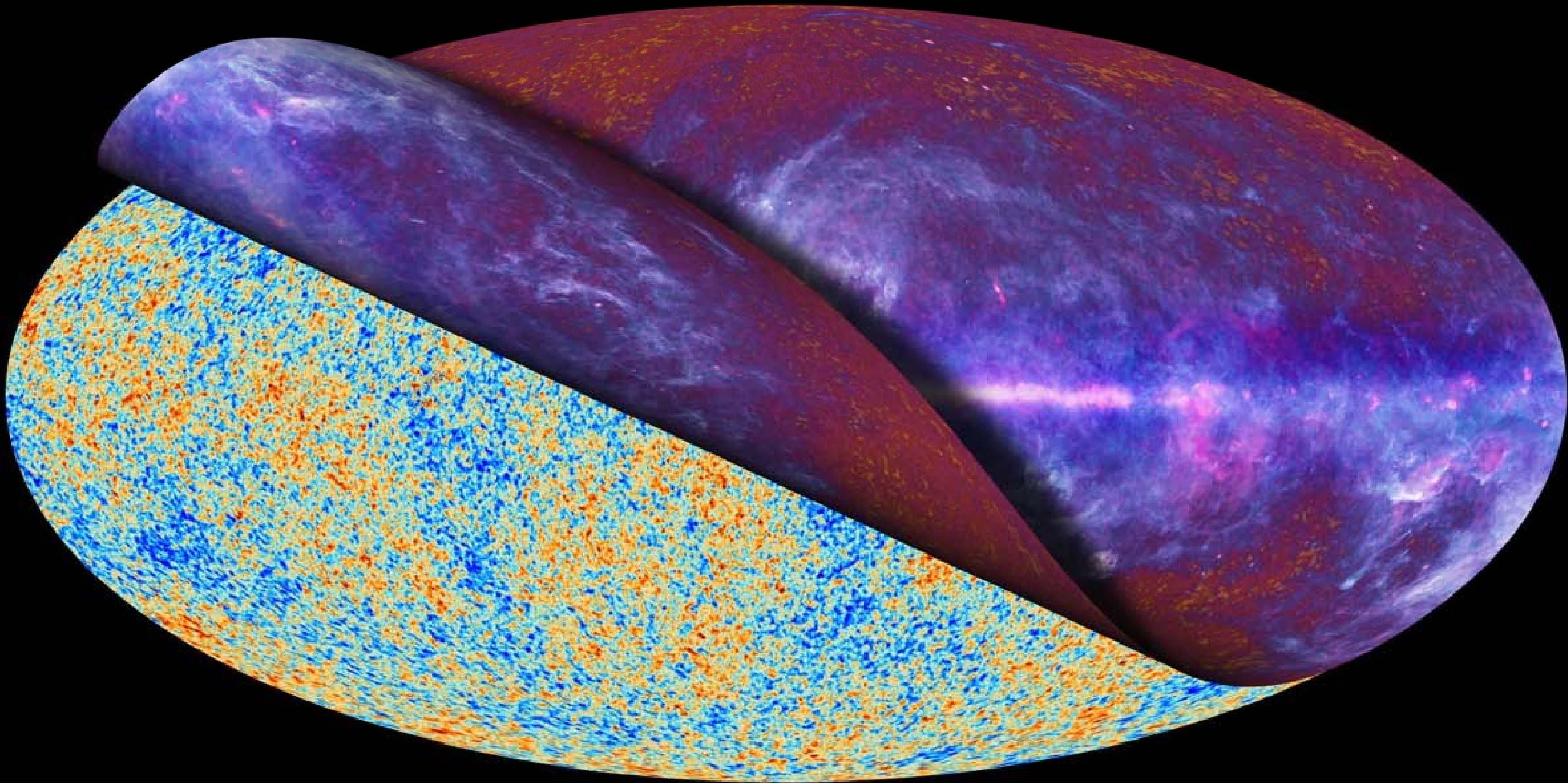


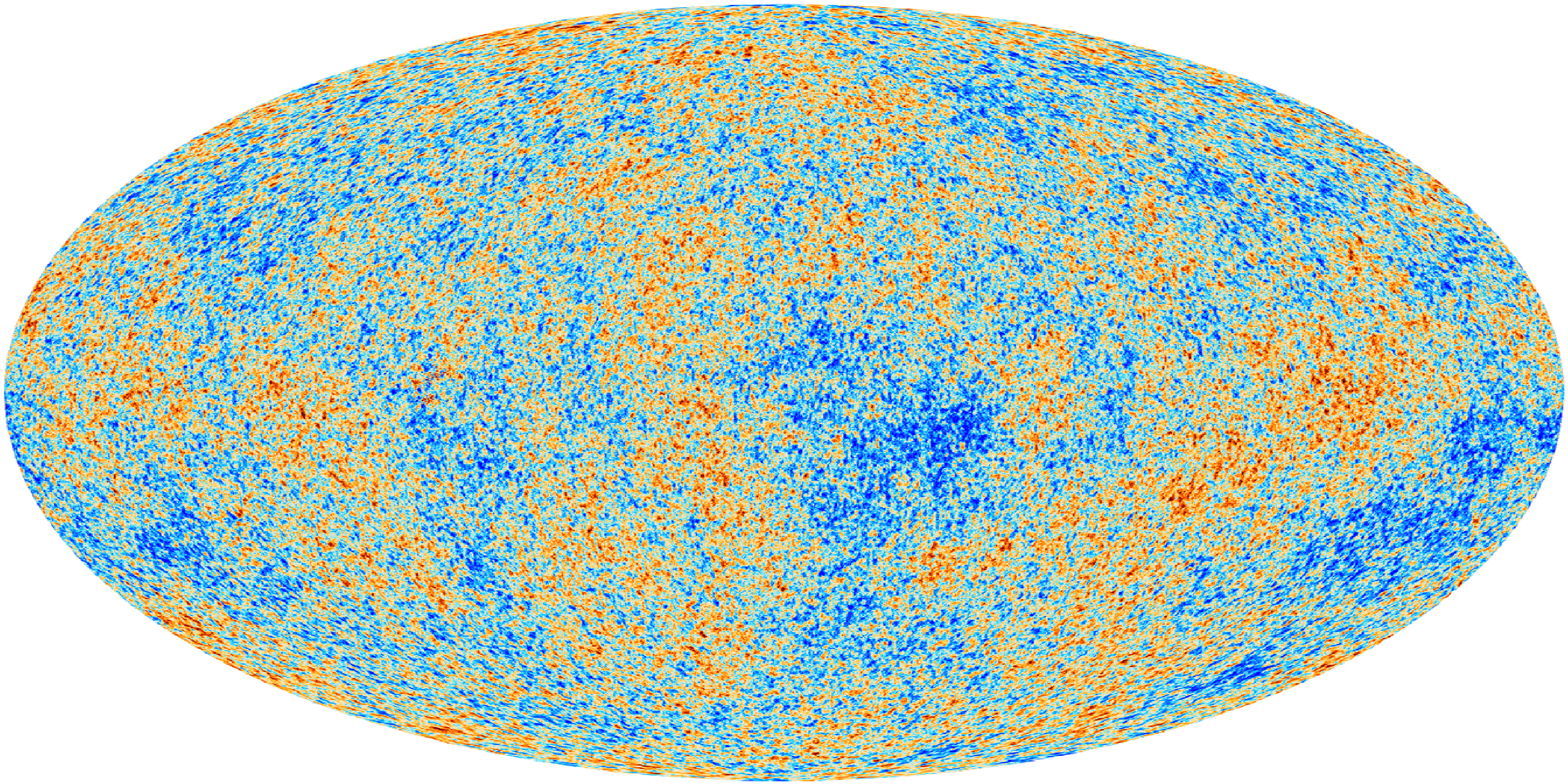



# Planck





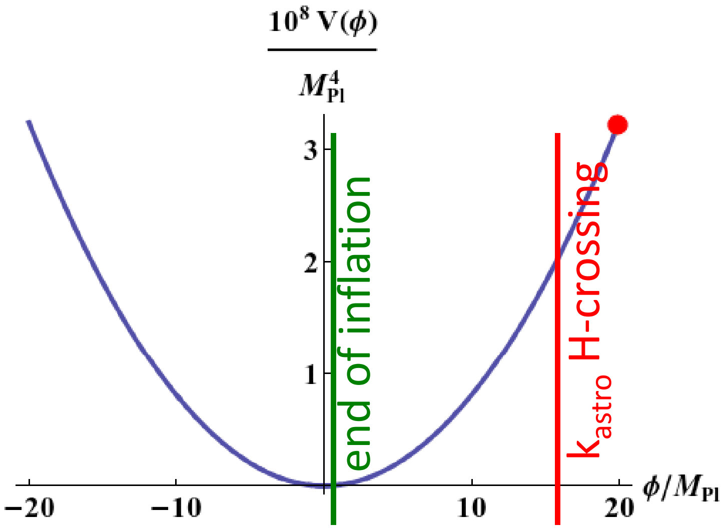
# The Planck CMB map: a view of primordial vacuum fluctuations

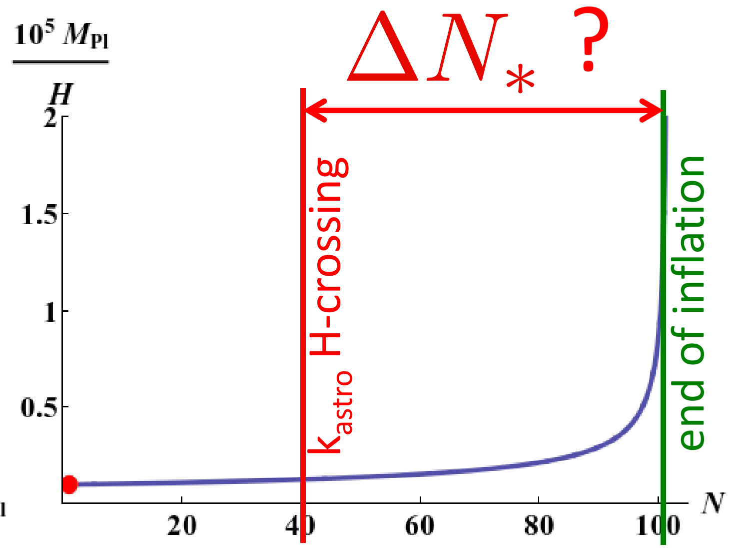


# *How do these observations relate to what we want to know?*

*"Do not believe any observational result until it is confirmed by theory." (Sir Arthur Eddington)*

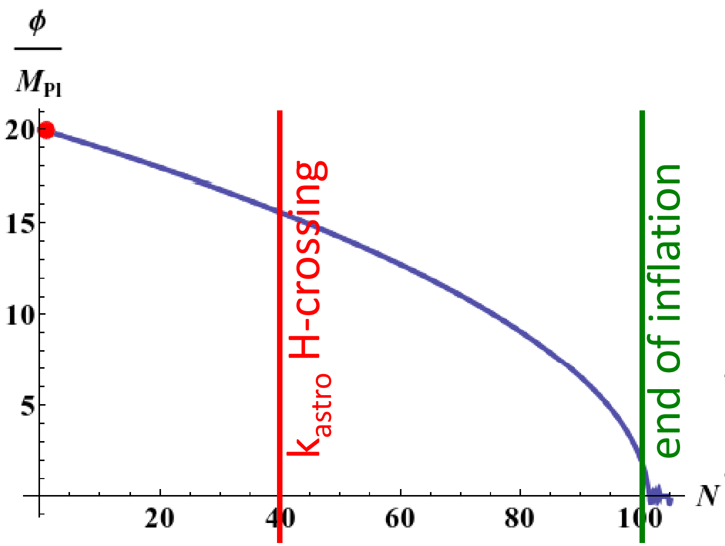
# Choose paradigm for interpreting observations: Inflation

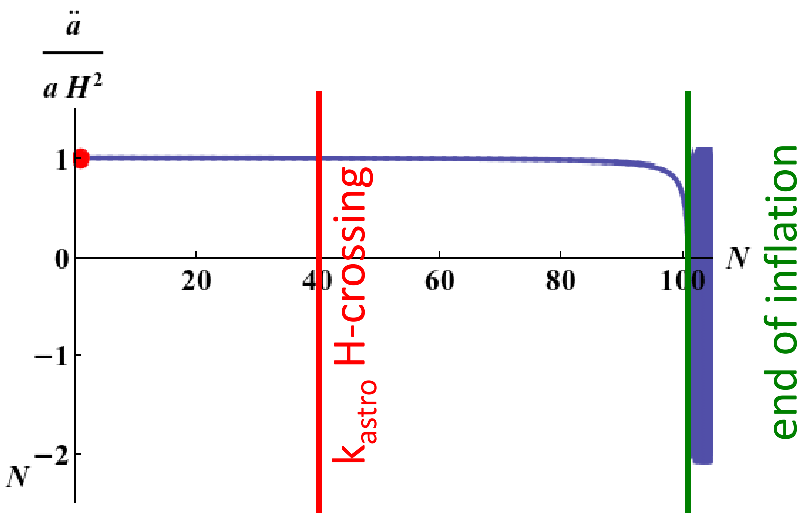



An example: « large field inflation » $V\left(\phi\right) = \frac{m^2}{2}\phi^2$

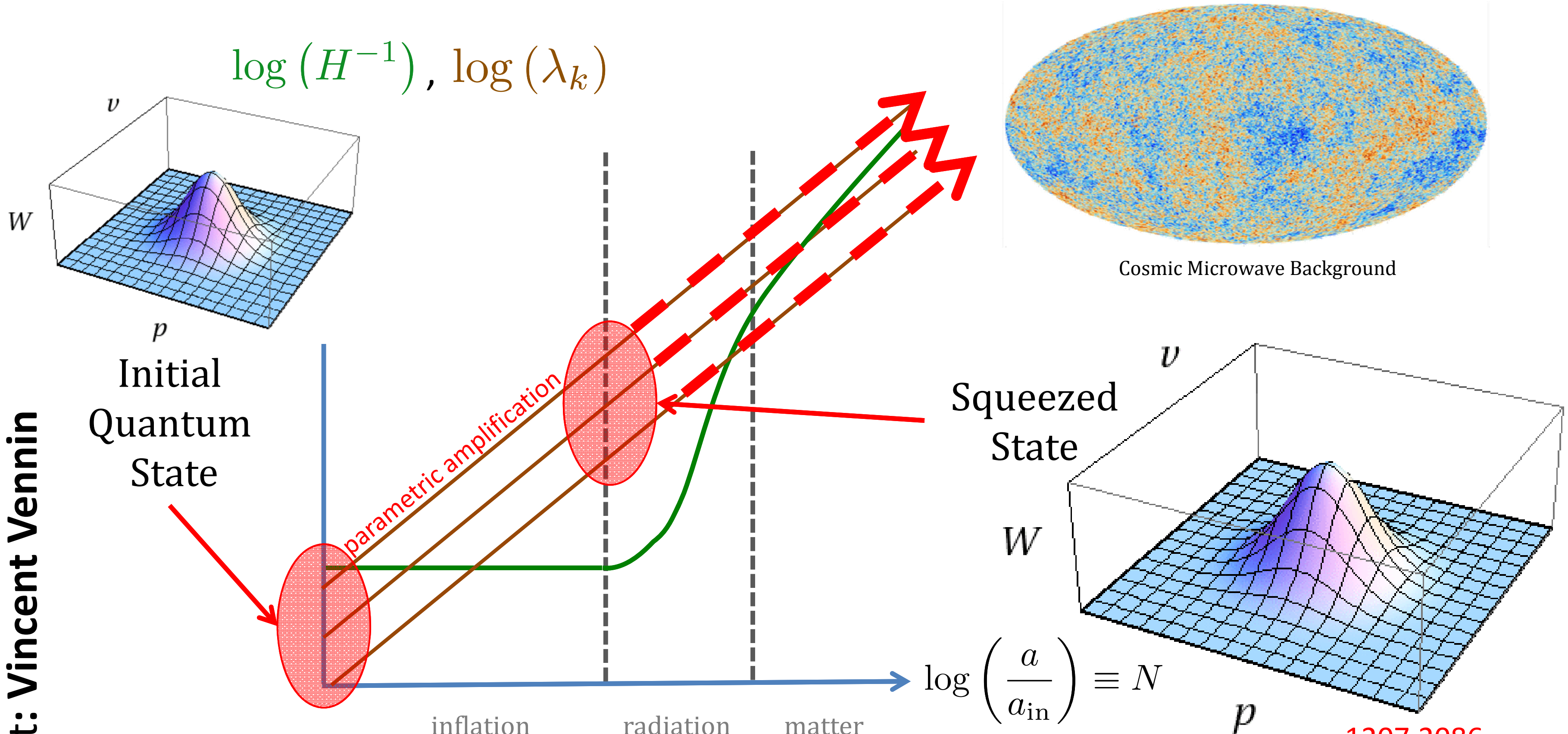
credit: **Vincent Vennin**



# Cosmological Inflation

Quantized fluctuations evolved over an
expanding background




Cosmic Microwave Background

1207.2086
J.Martin, Vincent
Vennin & P.Peter

credit: Vincent Vennin

# 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:

credit: Vincent Vennin

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

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

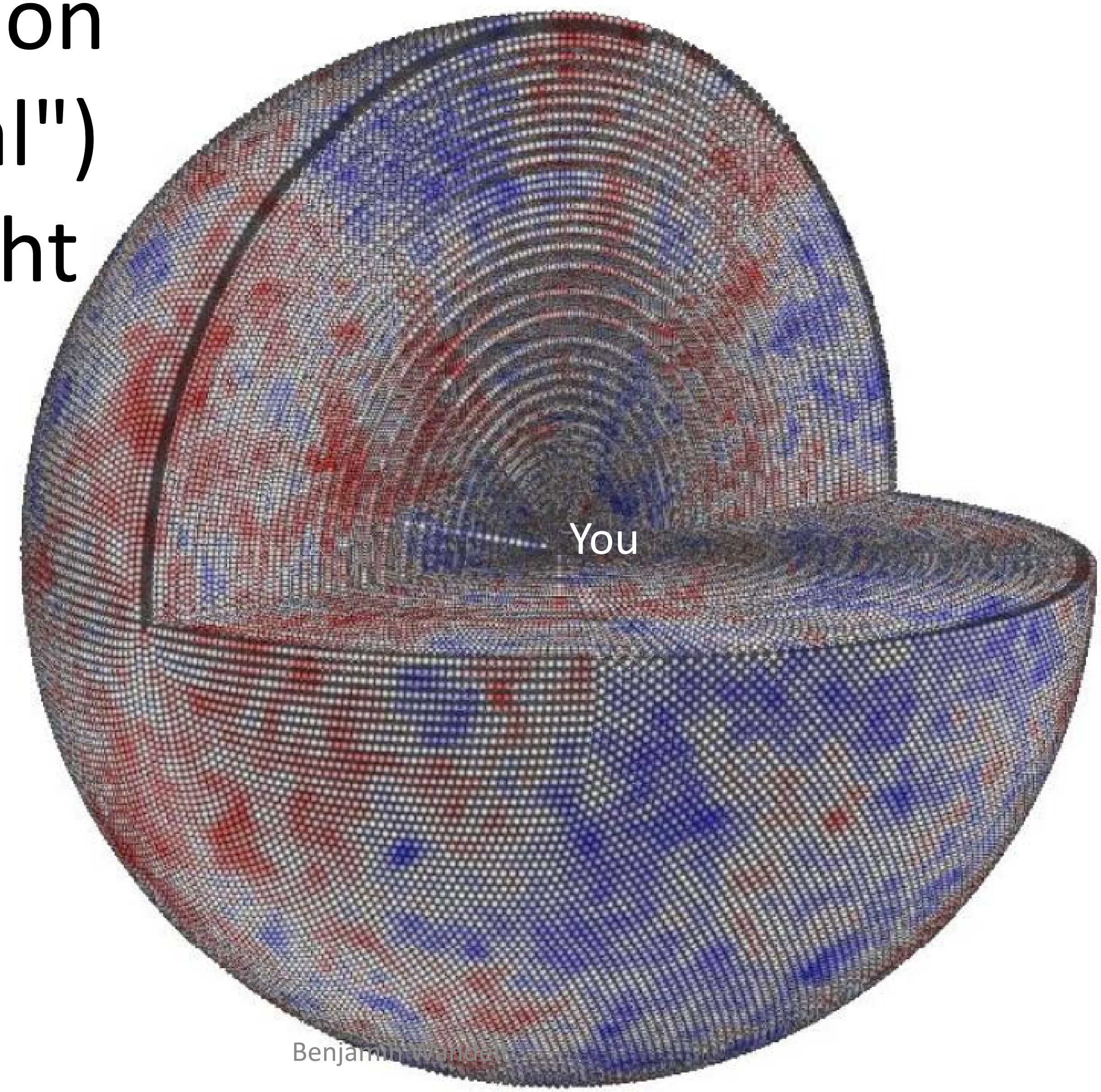
Spectral index $n_{\rm S} = \left.\frac{{\rm d}\ln P}{{\rm d}\ln k}\right|_{k_*}$

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

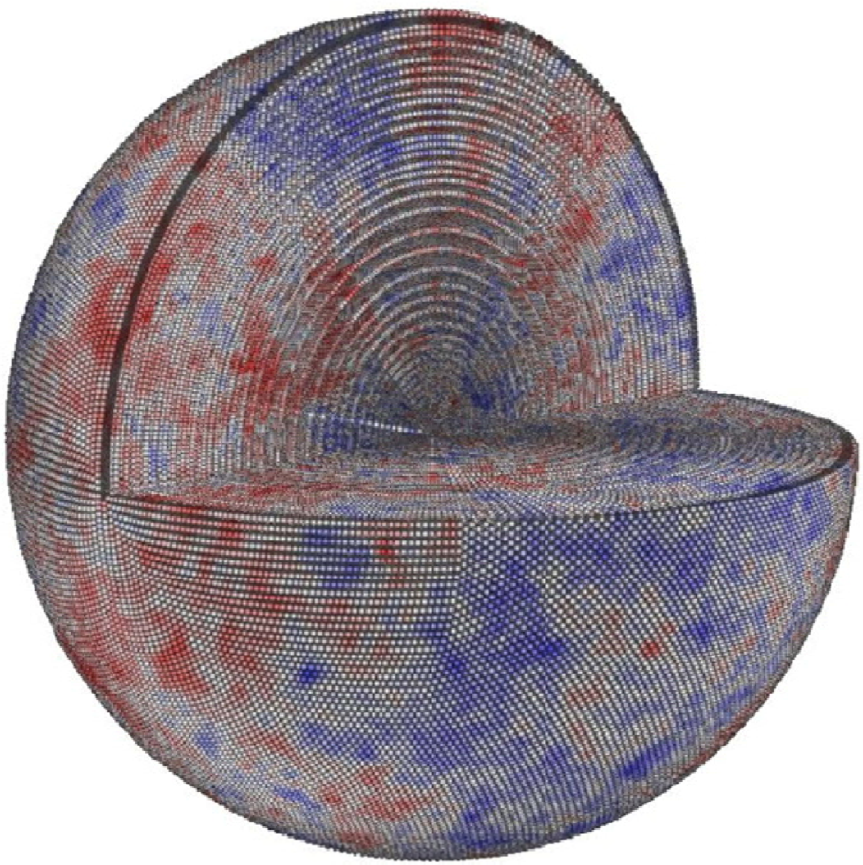
Gravity waves:

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

# Curvature perturbation ("potential") on the light cone



# Primordial perturbations give rise to observations



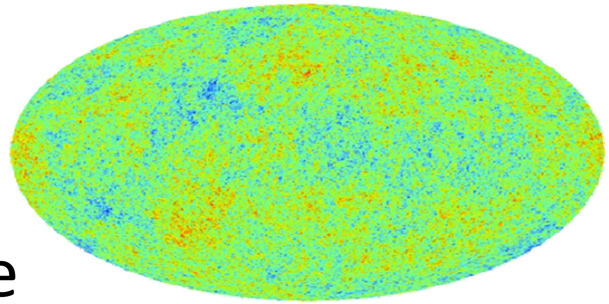
Radiative Transfer

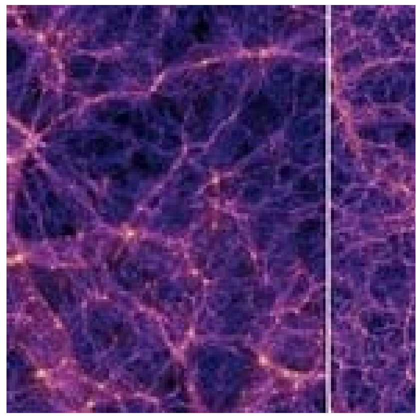
\+

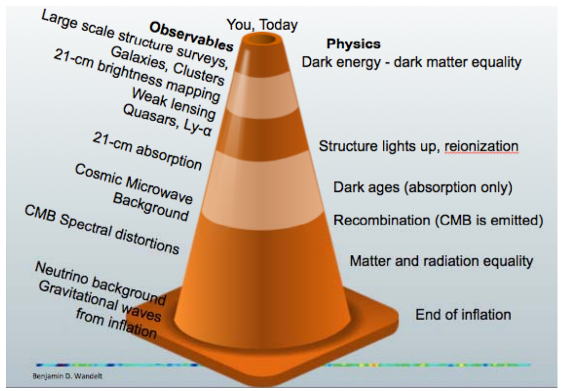
Gravity

\+

Astro-physics







# Linear radiative transport

- Most general way the observable temperature anisotropy can be related linearly related to initial perturbations:

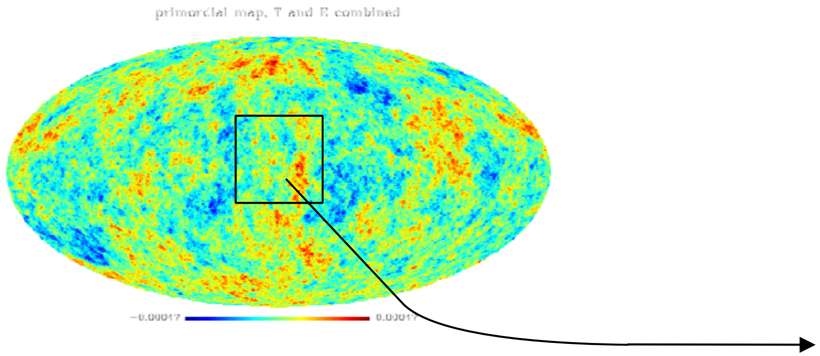
$$a_{lm} = \int d^3k \phi_k g_{lm\,k}$$

- In a homogeneous and isotropic universe the transfer function must be

$$g_{lm\,k} = g_l(|k|) i^l Y^*_{lm}(\hat{k})$$

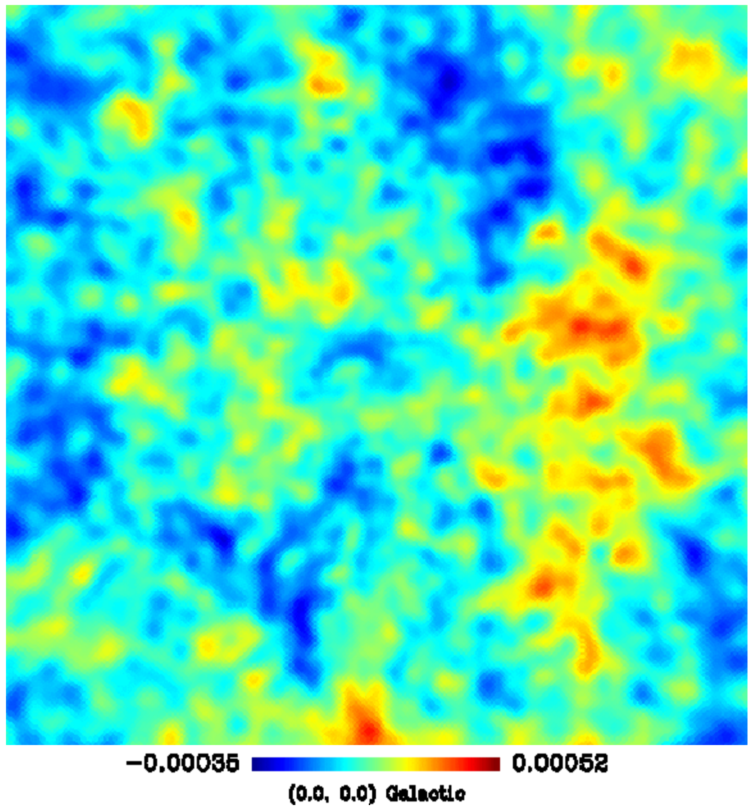
- **This** is the power of the CMB

# The linear physics CMB time machine



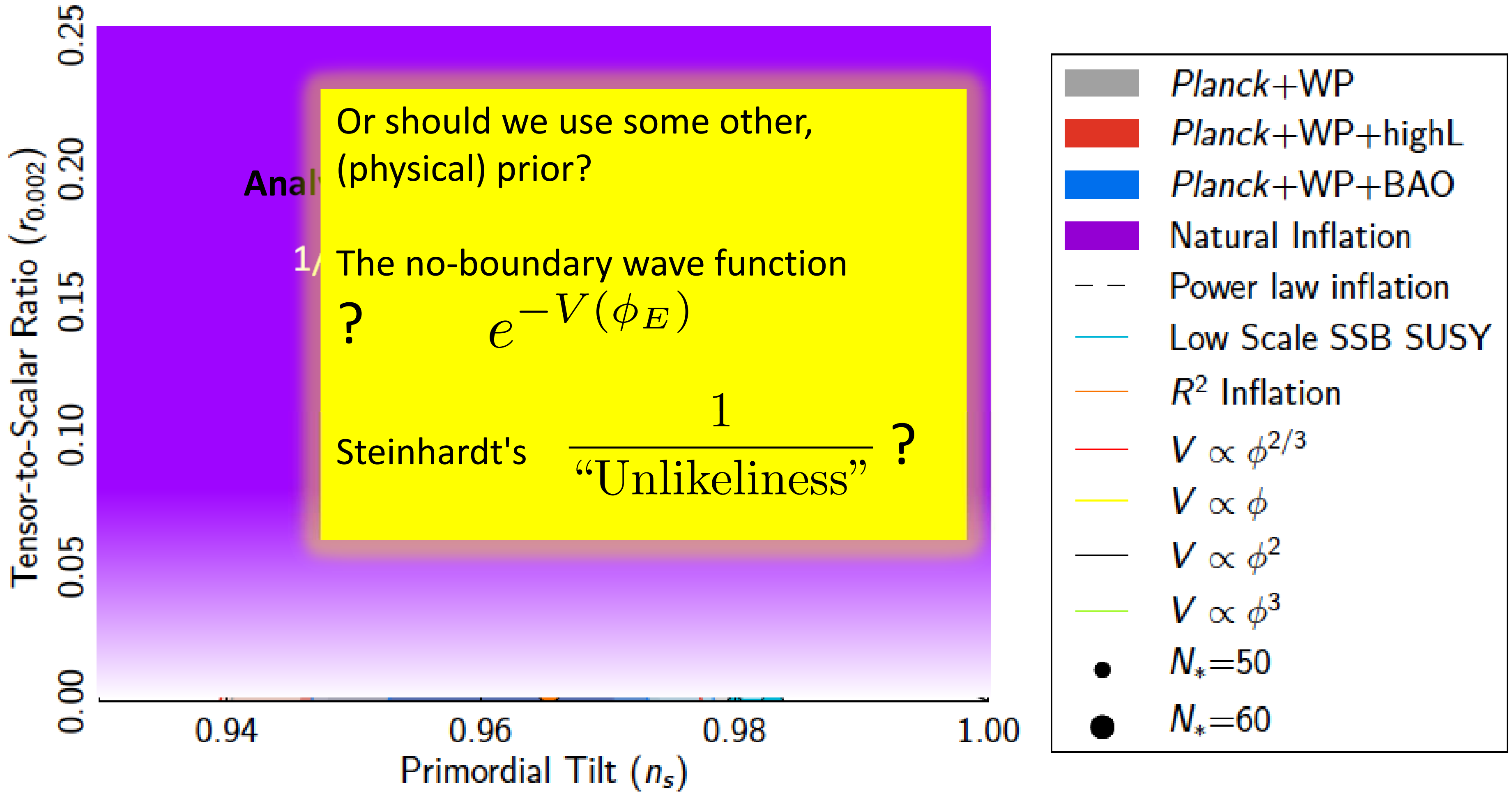

- The CMB T&E anisotropies map the Universe at t=380,000
- By "inverting" linear physics we can infer primordial curvature perturbation and test model predictions for the power spectrum and beyond.

Primordial curvature fluctuations




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

# Inflation constraints from Planck




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

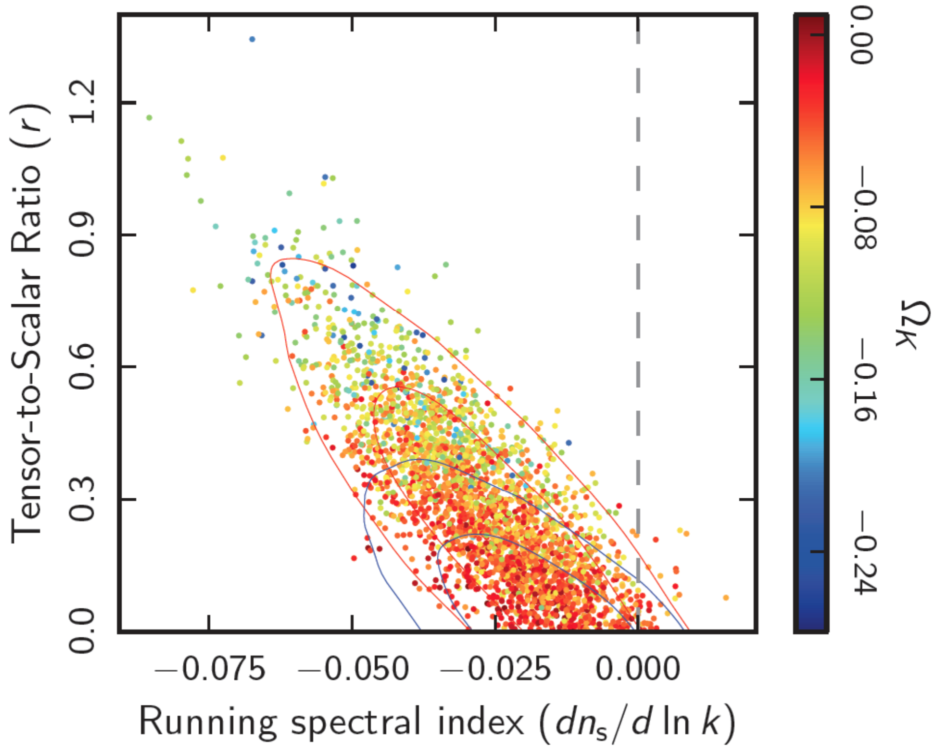
# Detecting the slowdown of inflation

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

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

# The universe is (most likely) flat

- Inflation "predicts" flatness, $|\Omega_k|\sim10^{-5}$, 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




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

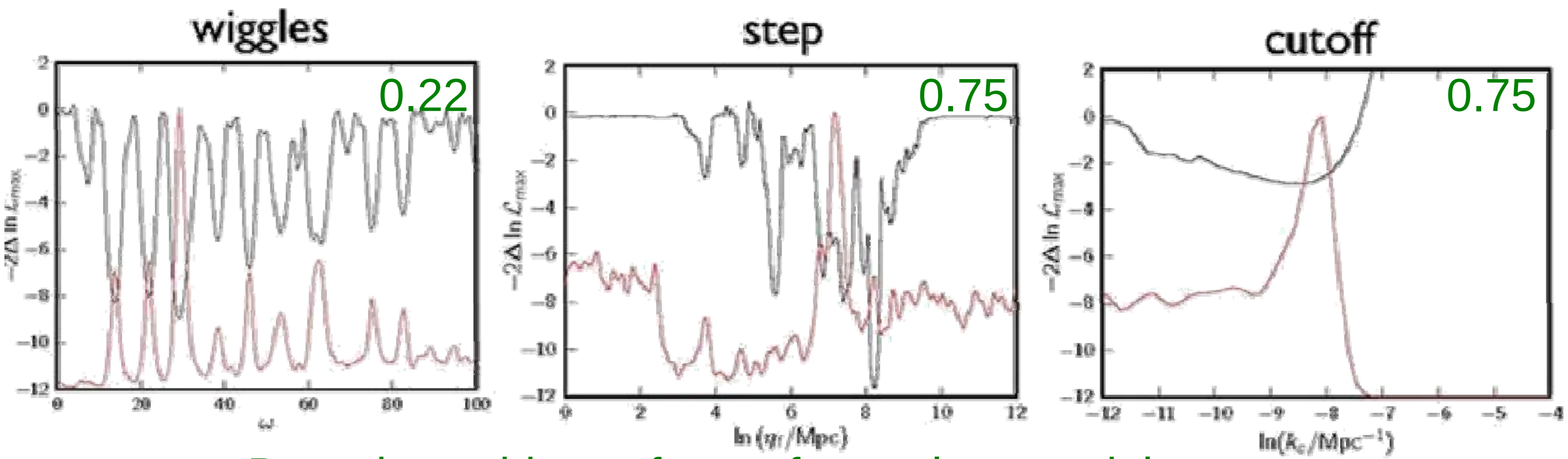
(Planck+WP+BAO)

# Are there features in the primordial power spectrum (e.g. axion monodromy)?

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

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

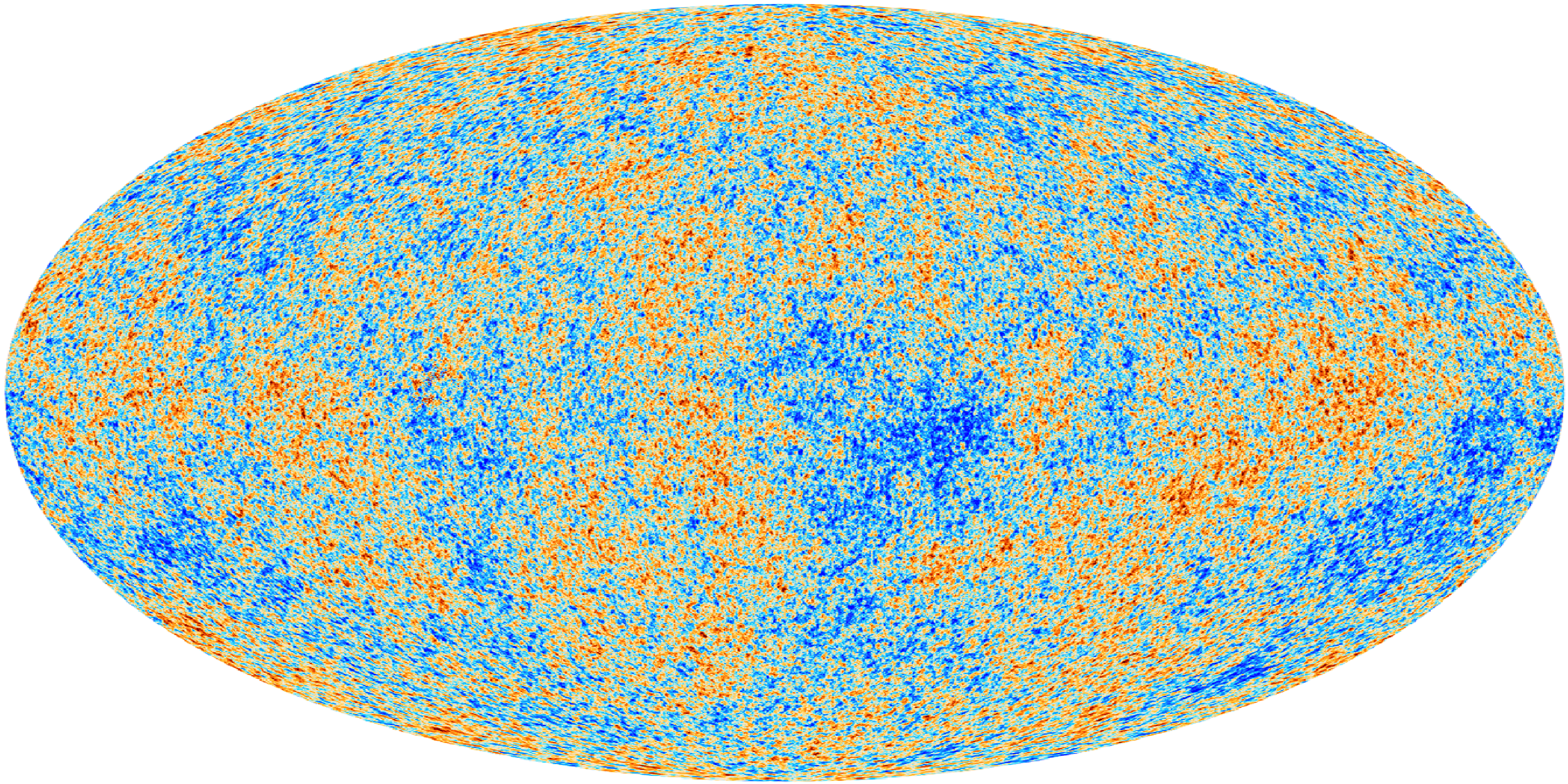
**cutoff:** $$\mathcal{P}_{\mathcal{R}}(k) = \mathcal{P}_0(k)\left\{1 - \exp\left[-\left(\frac{k}{k_{\mathrm{c}}}\right)^{\lambda_{\mathrm{c}}}\right]\right\}$$




Bayesian evidence favors featureless model

Extended searches agree (Meerburg, Spergel 2013; Easther, Flauger 2013).

# Back to the CMB **map**



# Going beyond 2nd order correlations pays off

- 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% (hence tight constraints on topological defects, such as cosmic strings)

# An example: local non-Gaussianity

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

Characterizes the amplitude of non-Gaussianity

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

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

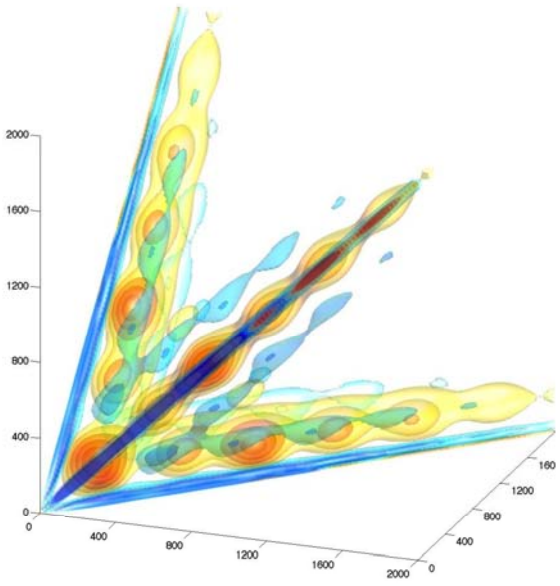
$$<\Phi(k_1)\Phi(k_2)\Phi(k_3)> = 2(2\pi)^3 f_{NL}\delta(k_1+k_2+k_3)P(k_1)P(k_2),$$

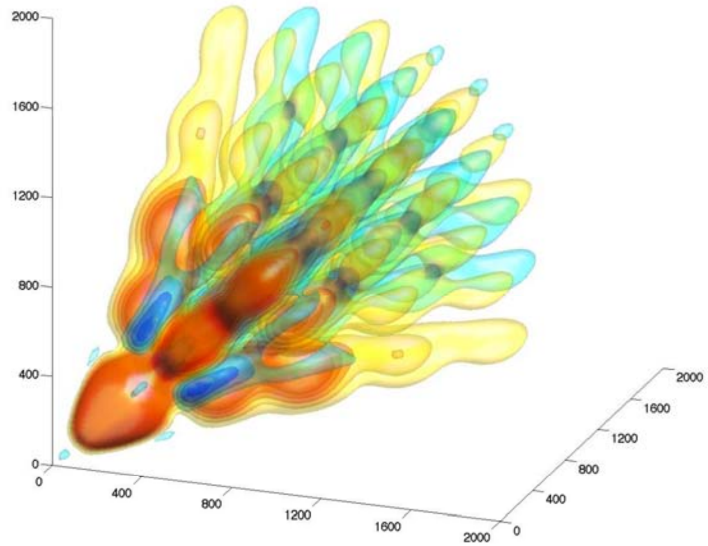
where $(2\pi)^3\delta(k_1+k_2)P(k_1) = <\Phi(k_1)\Phi(k_2)>$

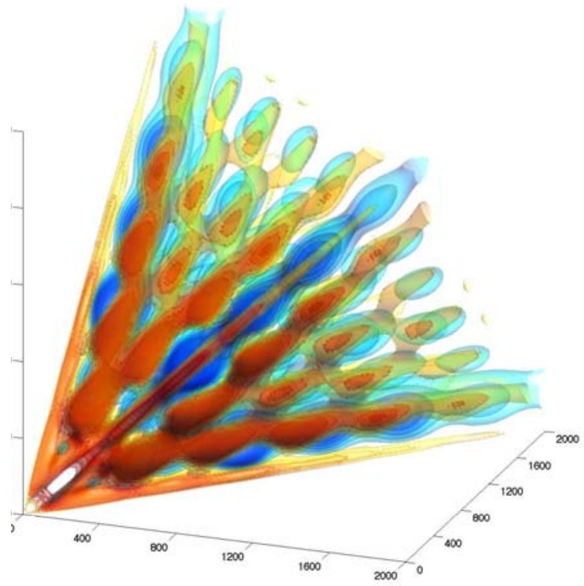
- This translates into a bispectrum signature in the CMB through

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

# CMB bispectrum fingerprinting







NG of ***local*** type:

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

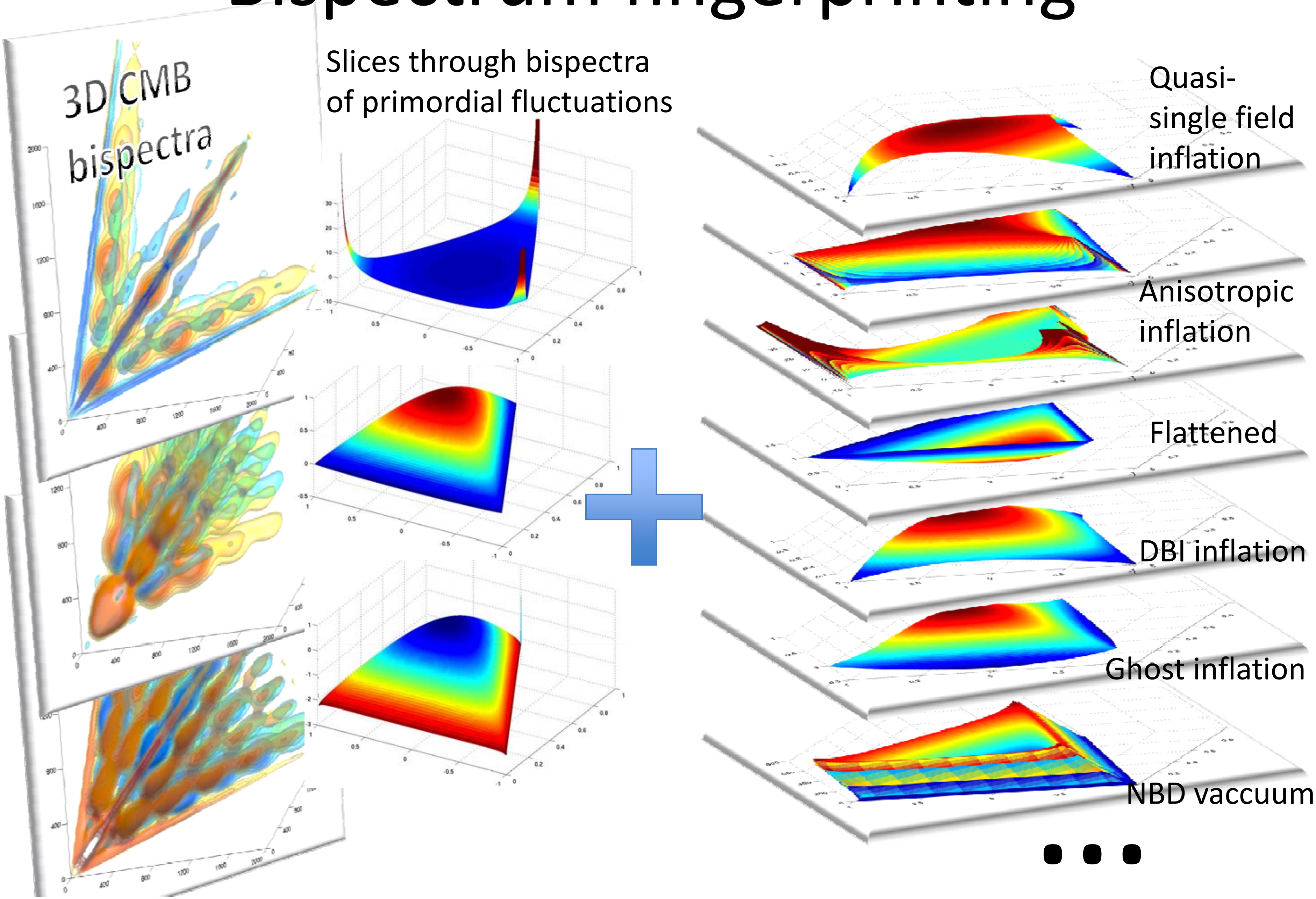
NG of ***equilateral*** type

- 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



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

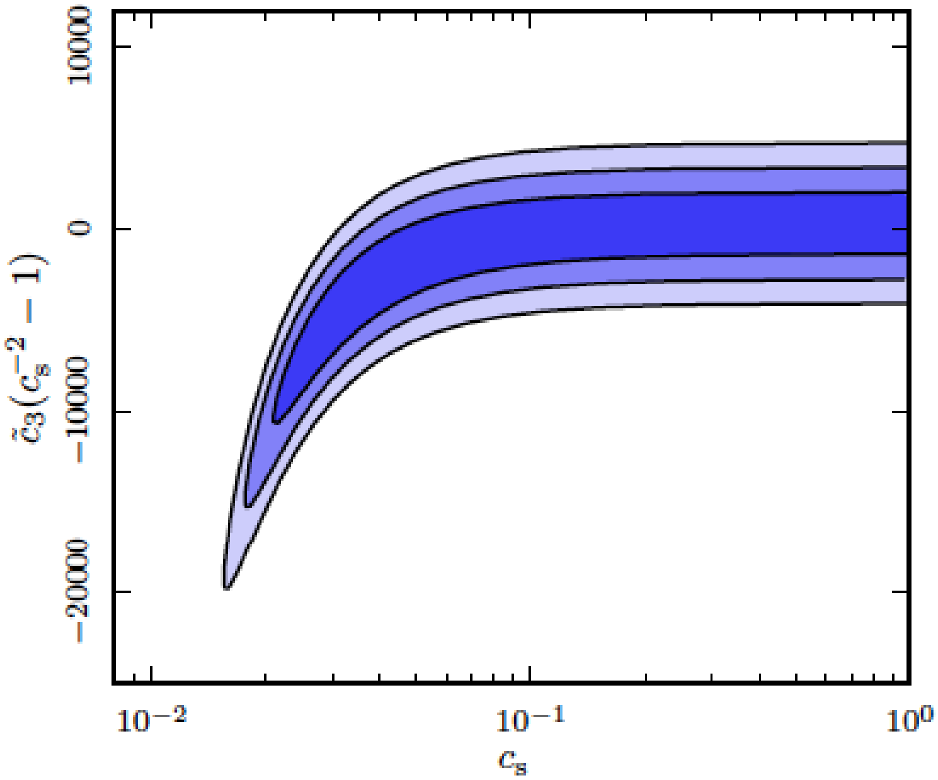
| | Independent | | | | ISW-lensing subtracted | | |
|---|---|---|---|---|---|---|---|
| | KSW | Binned | Modal | | KSW | Binned | Modal |
| SMICA | | | | | | | |
| Local . . . . . . . . . . . . . . . . . | 9.8 ± 5.8 | 9.2 ± 5.9 | 8.3 ± 5.9 | . . . . . | **2.7 ± 5.8** | 2.2 ± 5.9 | 1.6 ± 6.0 |
| Equilateral . . . . . . . . . . . . | −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

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

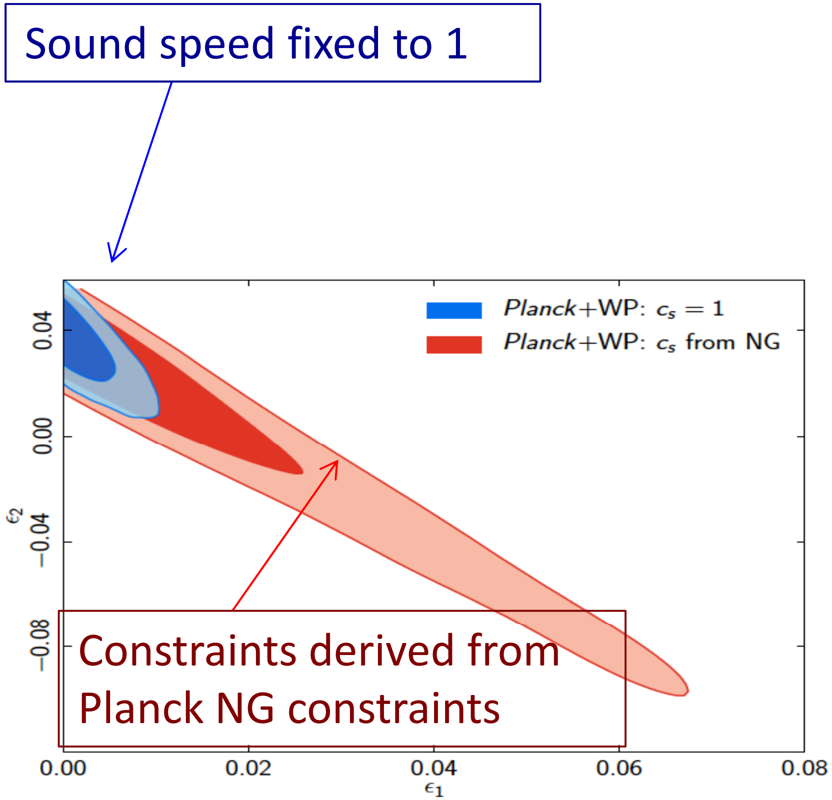
Senatore et al 2010
Chen et al. 2007, 2010




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.

# 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.

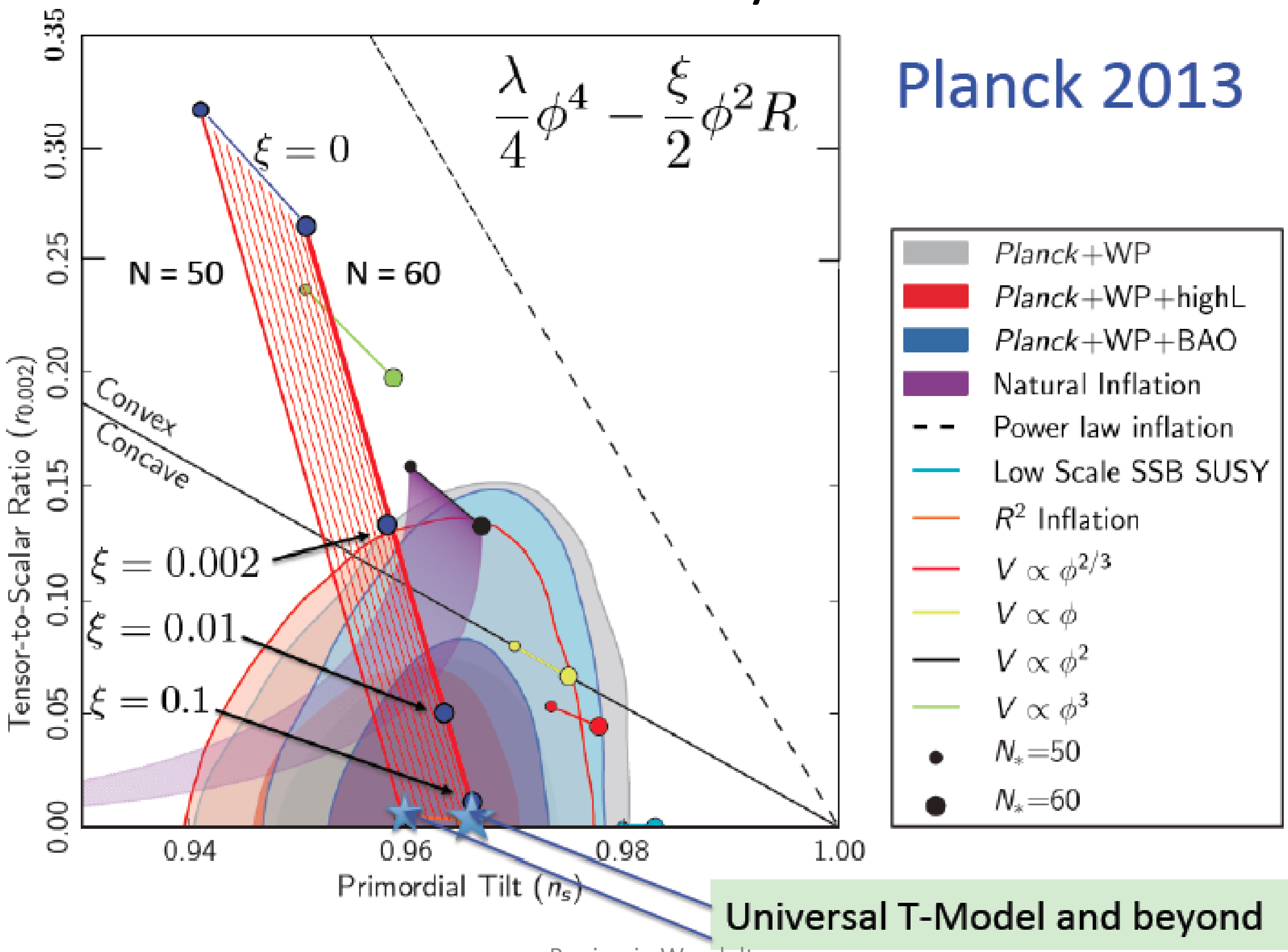
- Planck strongly constrains a class of ekpyrotic/cyclic models (those with exponential potential, entropic generation of perturbations and conversion during ekpyrotic smoothing phase).

# Challenge: Paradigms of Cosmic Beginning

- Planck2013 results are a success for inflationary *models*
  - Nearly scale invariant spectrum
  - Consistent with Gaussian primordial fluctuations
  - Consistent with flatness
- What can we learn about UV completions?
  - T/S measurements test large-field models
  - Stringy motivation for oscillatory potentials
  - Linde/Kallosh: universality class of inflationary models motivated by conformal symmetry in SUGRA with attractor

$$1 - n_s = 2/N\,, \qquad r = 12/N^2$$

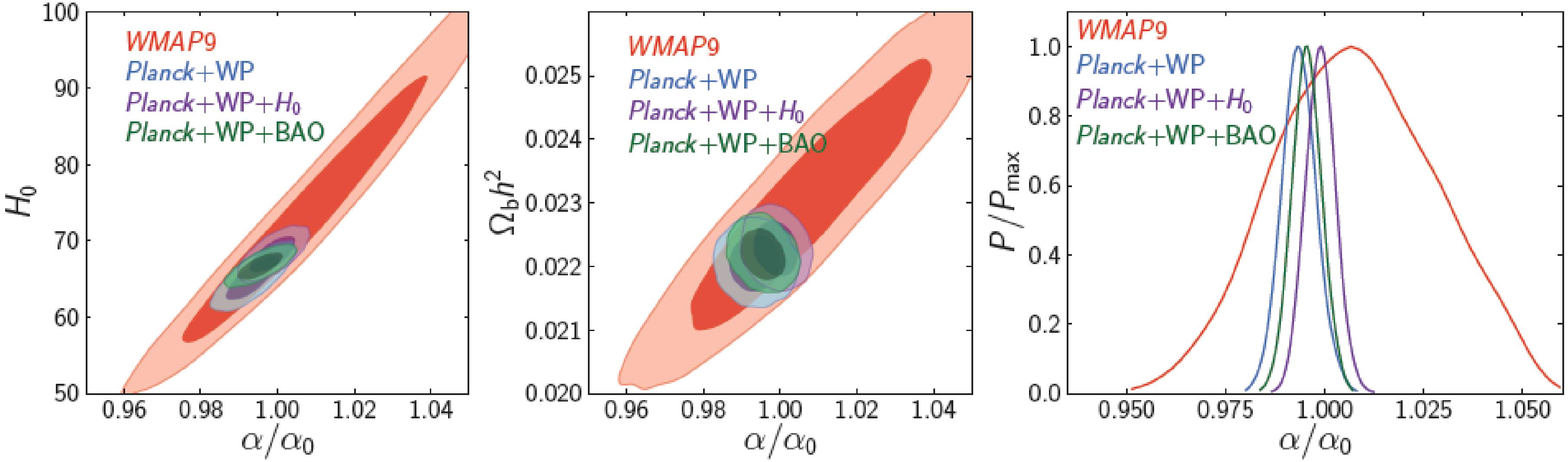
# Superconformal generalization of chaotic inflation: a class of inflationary scenarios




Benjamin Wandelt

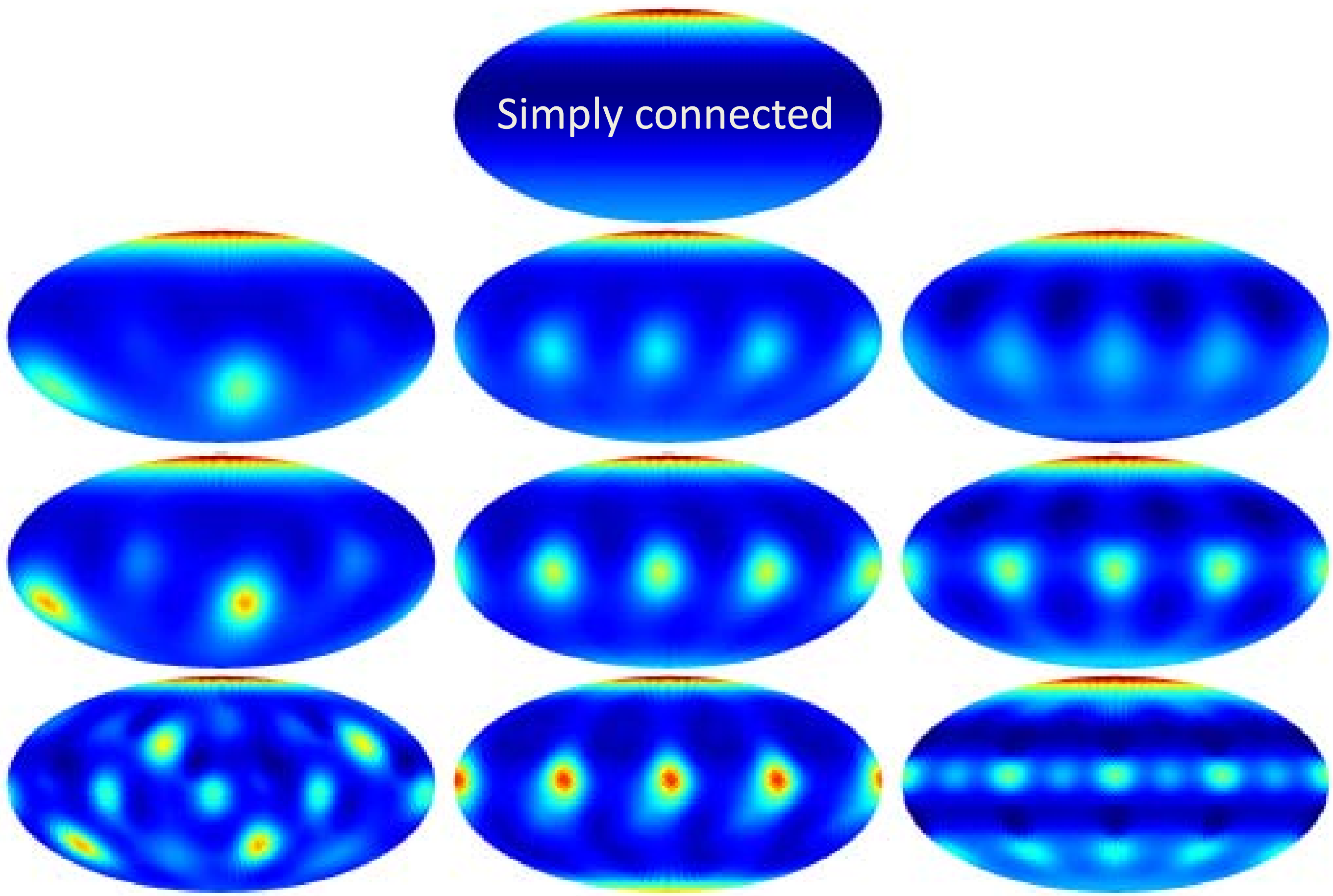
Ferrara, Kallosh, Linde, Porrati, 2013

# Variation of the fine structure constant since last scattering




- 1 % constraint on $\delta\alpha/\alpha$

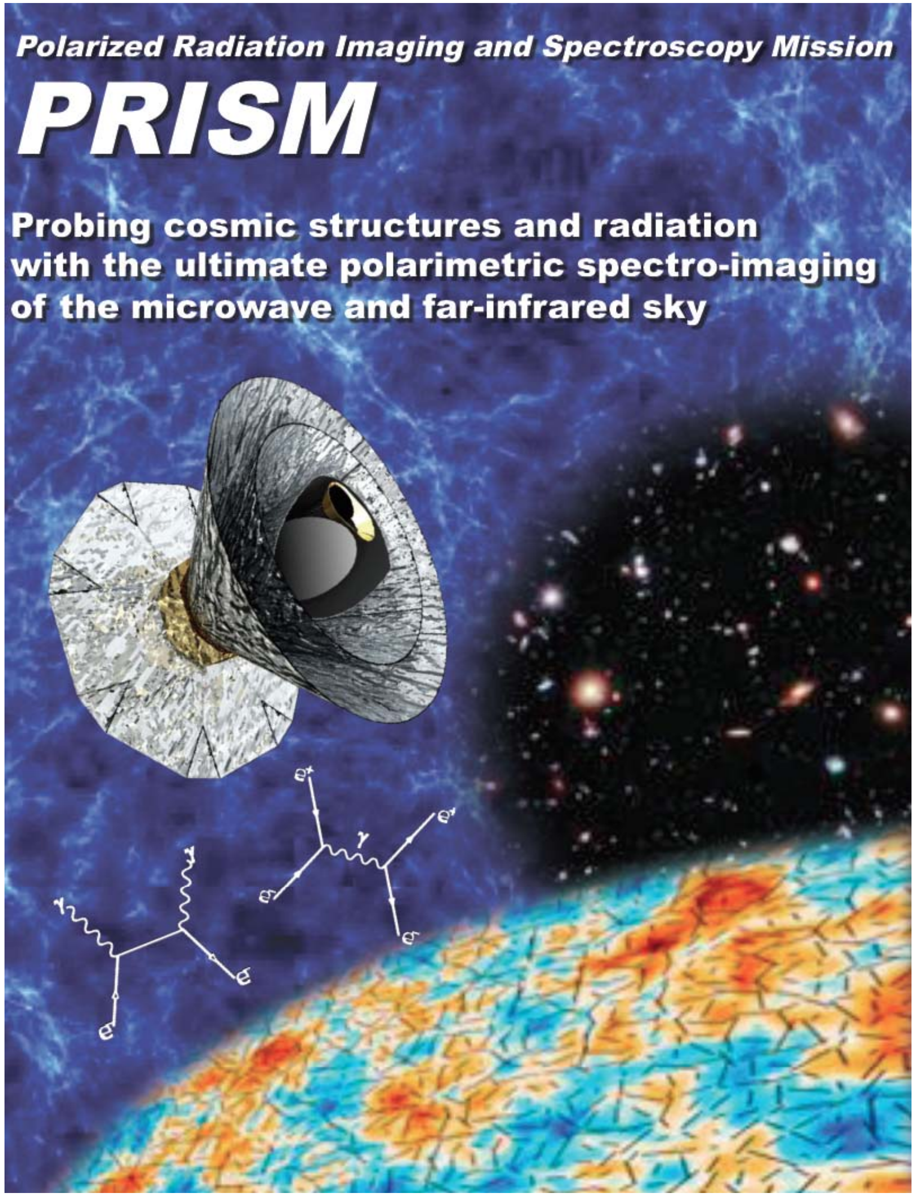
# Global topology of the universe




Dodecahedral Octahedral Toroidal

Planck2013 finds no evidence for non-standard topology: fundamental domain sizes are constrained to be larger than the distance to the LSS surface.

# 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 (all above $10^{14}$ $M_{\odot}$
- Neutrino masses 0.04 eV from CMB alone.

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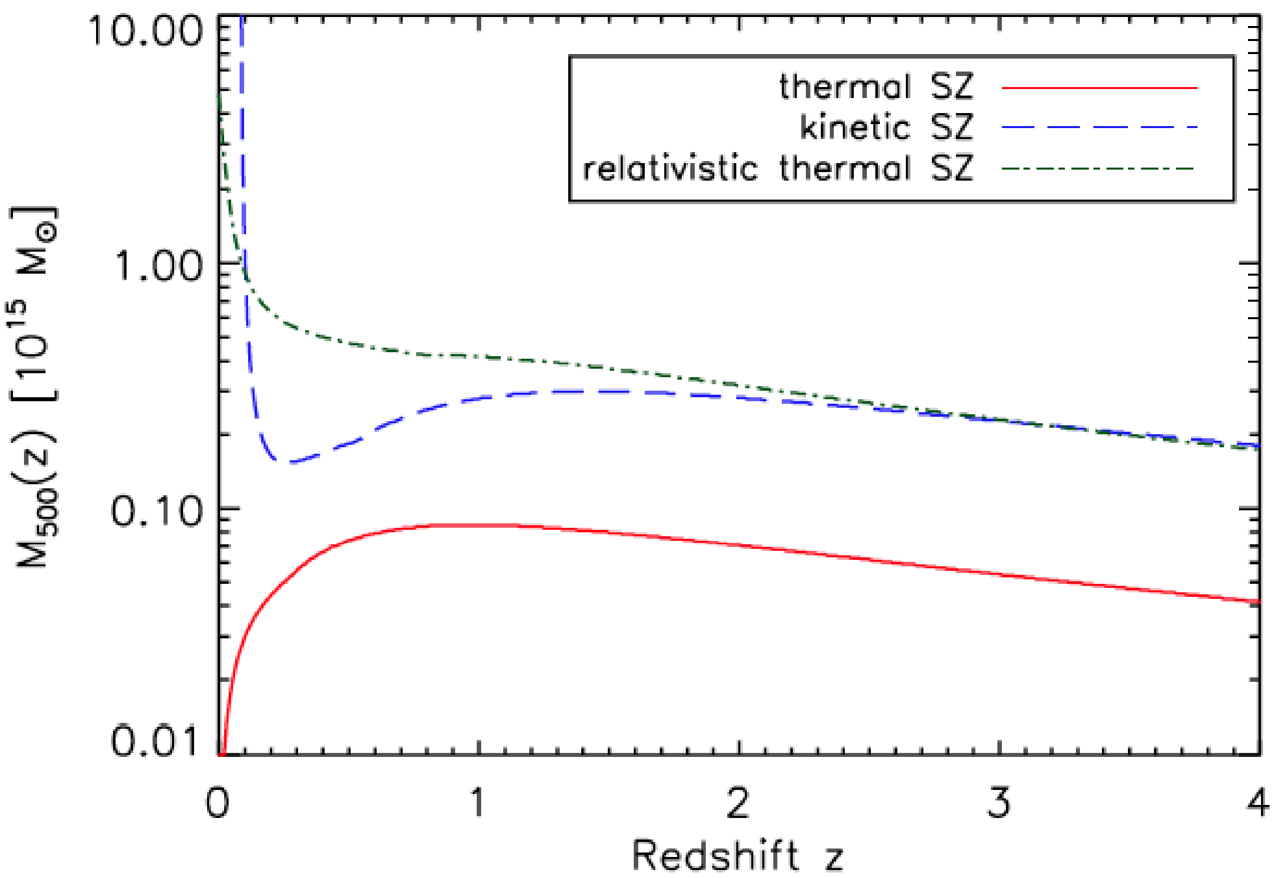
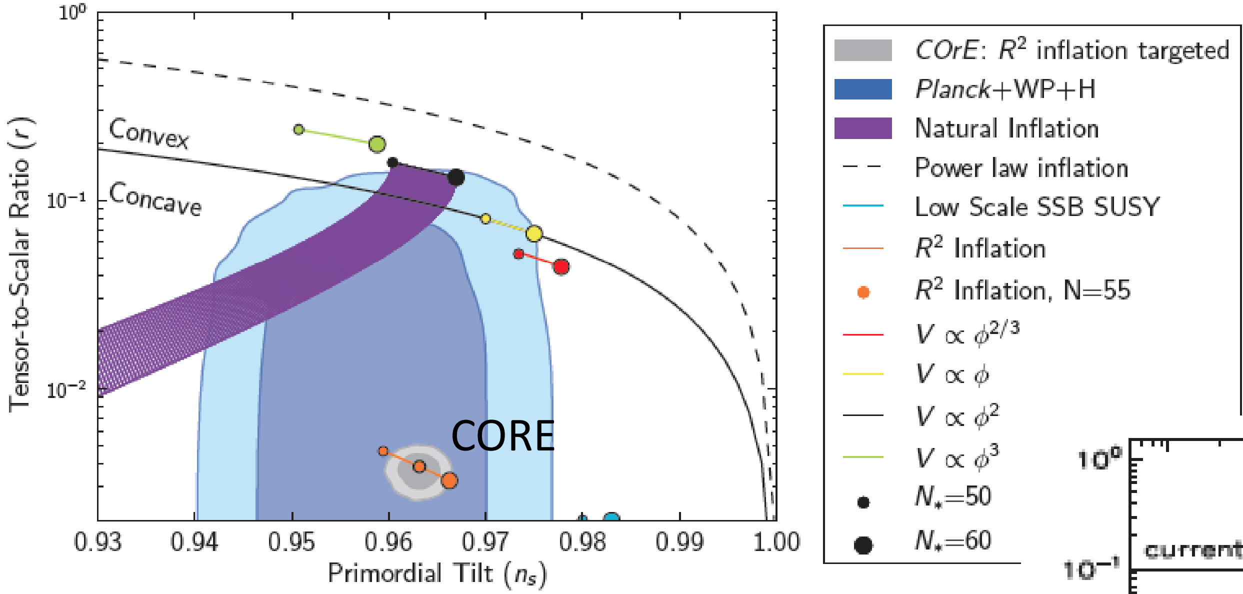
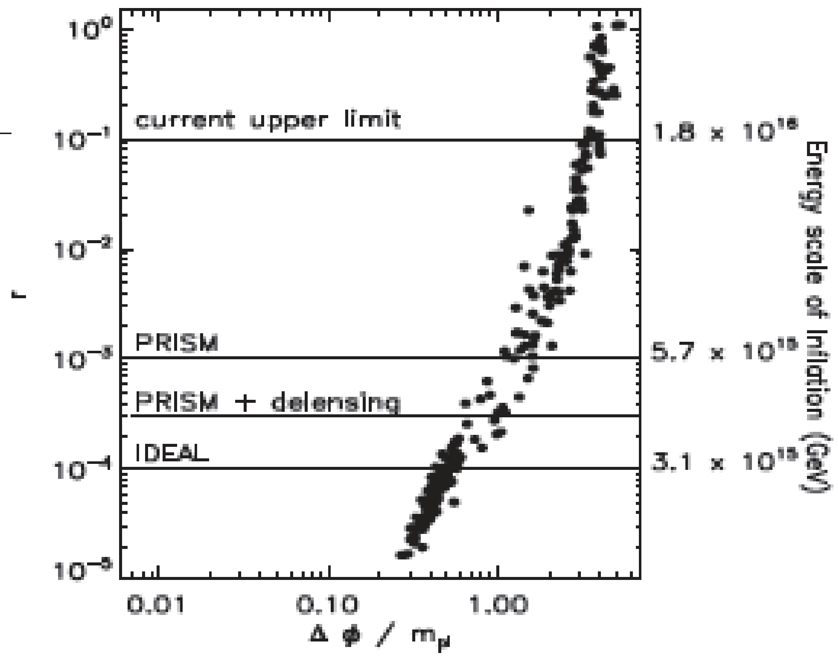
# PRSIM SZ survey will detect all clusters in the universe



# Inflation with COrE/PRISM




Forecast **r** sensitivity **~ 5x10$^{-4}$**

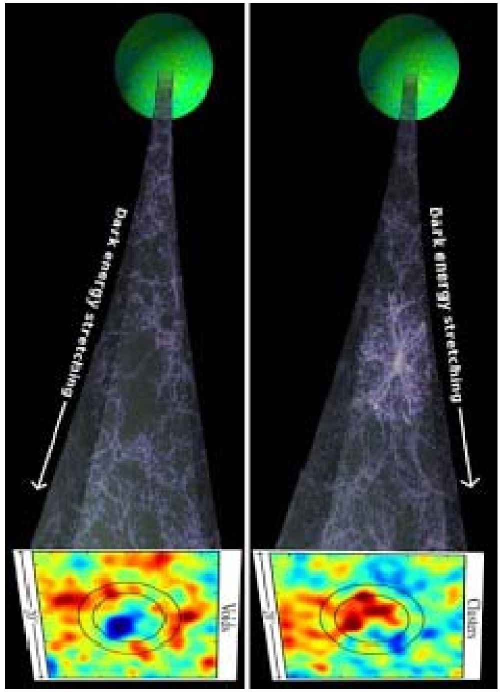
# “Late-”time fundamental physics

- 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

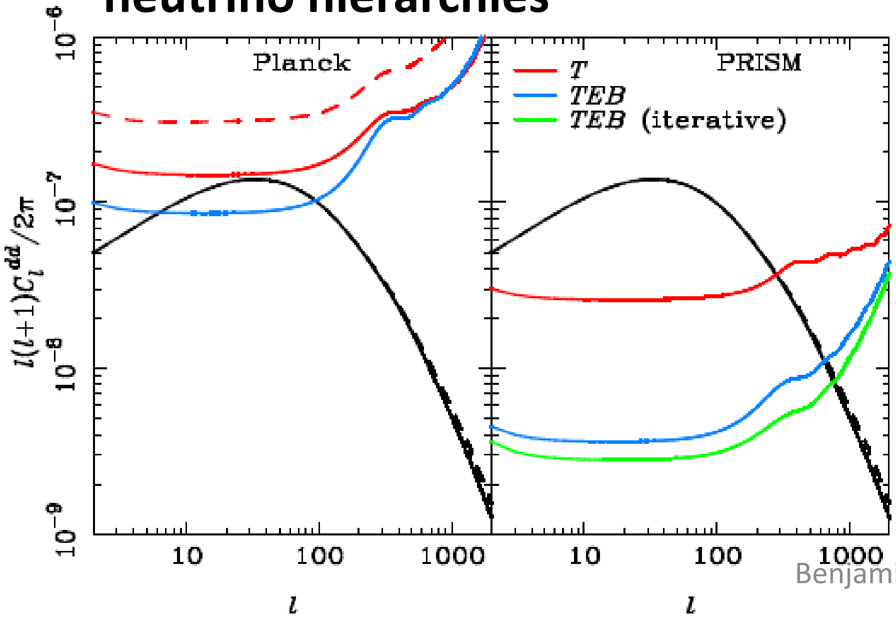
- Planck sees this effect at the expected level with **2.6 sigma** significance.

- PRISM expected to see this at 9 sigma.

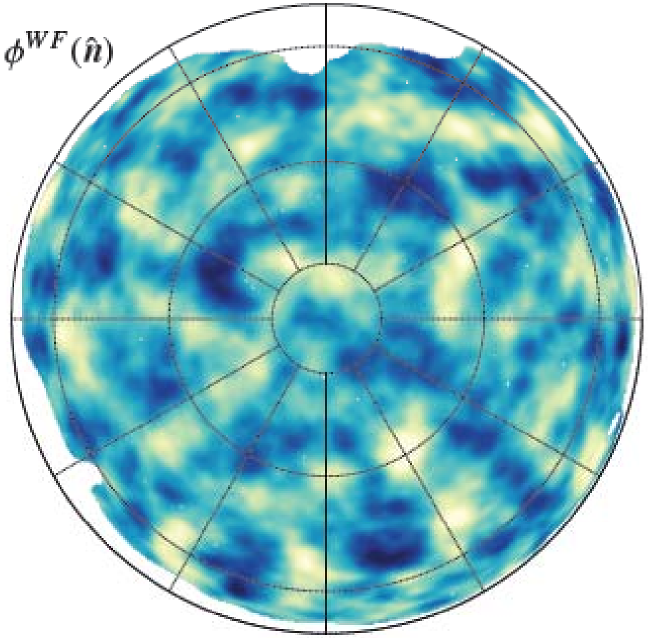


# CMB Lensing

- Planck2013 detects weak gravitational lensing of the CMB, at more than 25 sigma
- PRISM would make **a high S/N map of the mass** of the universe, similar to how WMAP improved on COBE.
- PRISM+BAO would allow **distinguishing between the normal and inverted neutrino hierarchies**

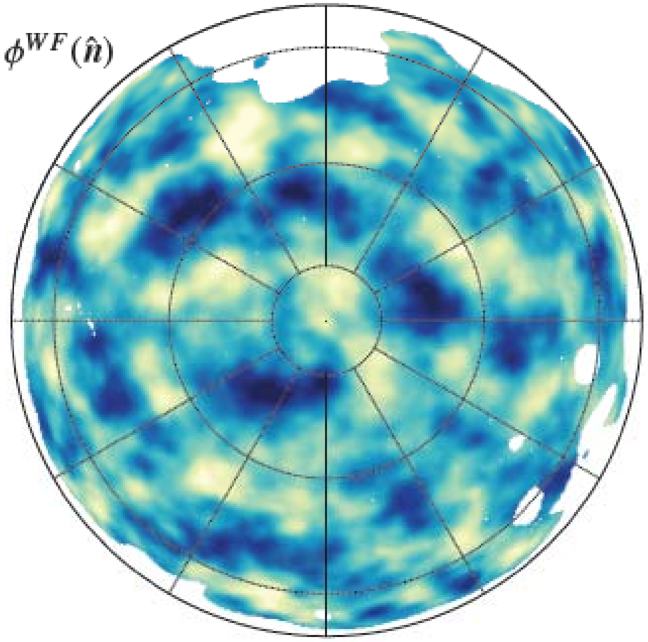



Planck $\phi^{WF}(\hat{n})$



Galactic North

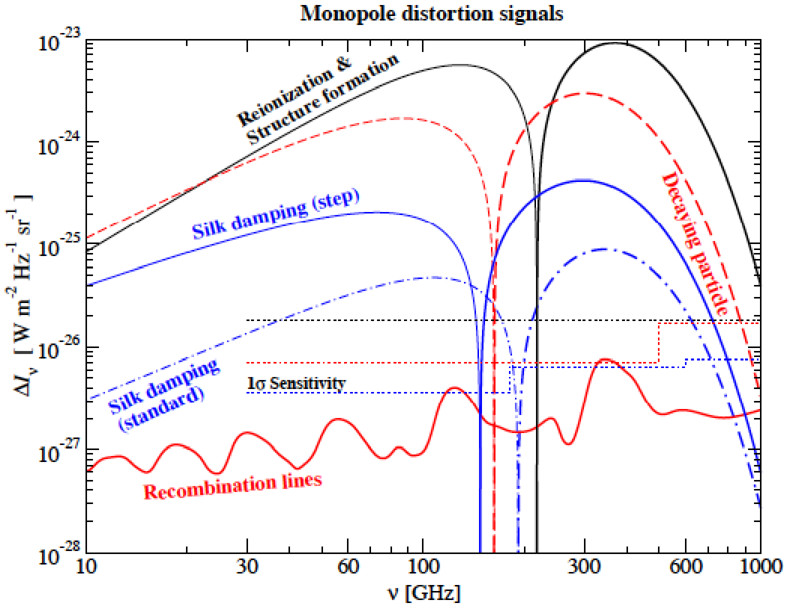
Planck $\phi^{WF}(\hat{n})$



Galactic South

Benjamin Wandelt

# CMB spectral distortions can "see" beyond the surface of last scattering



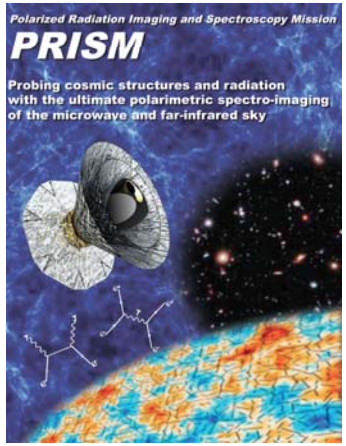

- Unprecedented constraints on small scale fluctuations
- Sensitive to any form of heating
  - particle decays
  - Topological defects
  - ...

# PRISM Non-Gaussianity

- Will reach cosmic variance limit for CMB from T+E modes for all shapes $\delta f_{NL,\ local} \sim 1$
- Will test non-Gaussianity on currently unobservable scales (up to $10^4$ times smaller than visible in the CMB map) using CMB spectral distortions (Pajer&Zaldarriaga 2012).

# Conclusions

- There are plenty of new challenges for early Universe cosmology
- The Post-Planck research agenda
  - Paradigms of Cosmic Beginning
- The (post-)Planck era is an exciting time




**www.prism-mission.org**