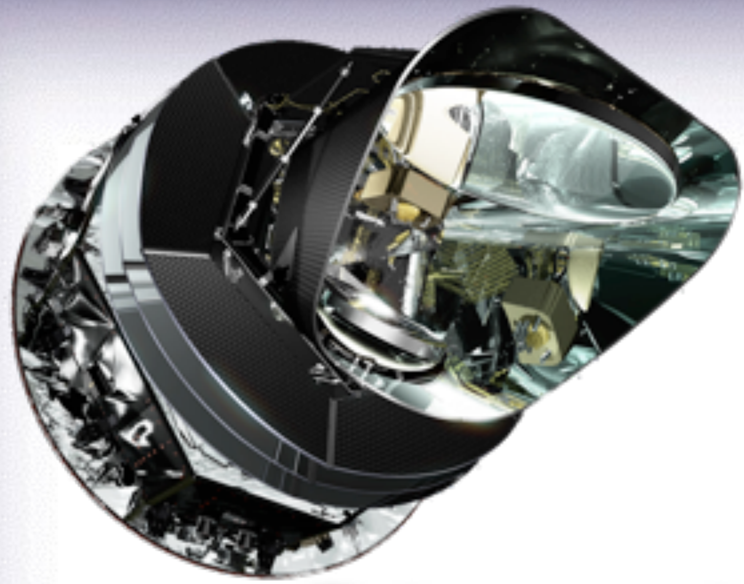


SUSY 2014

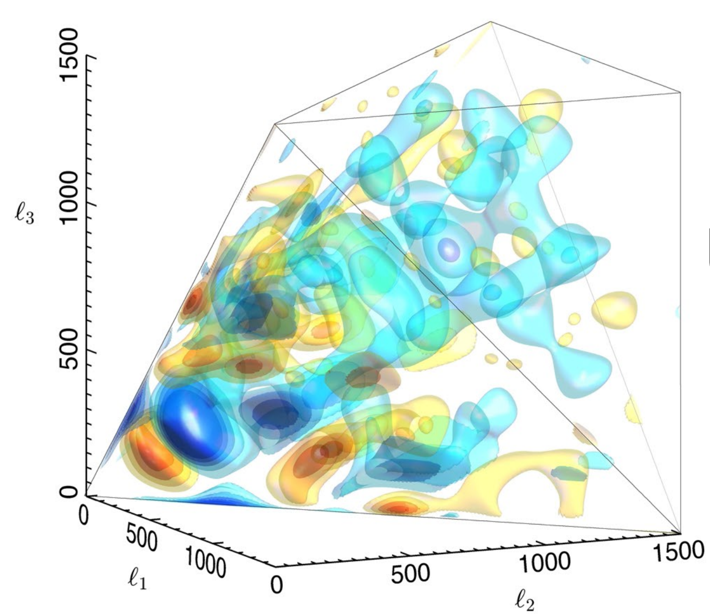
Planck Results for the CMB

Paul Shellard

Centre for Theoretical Cosmology,

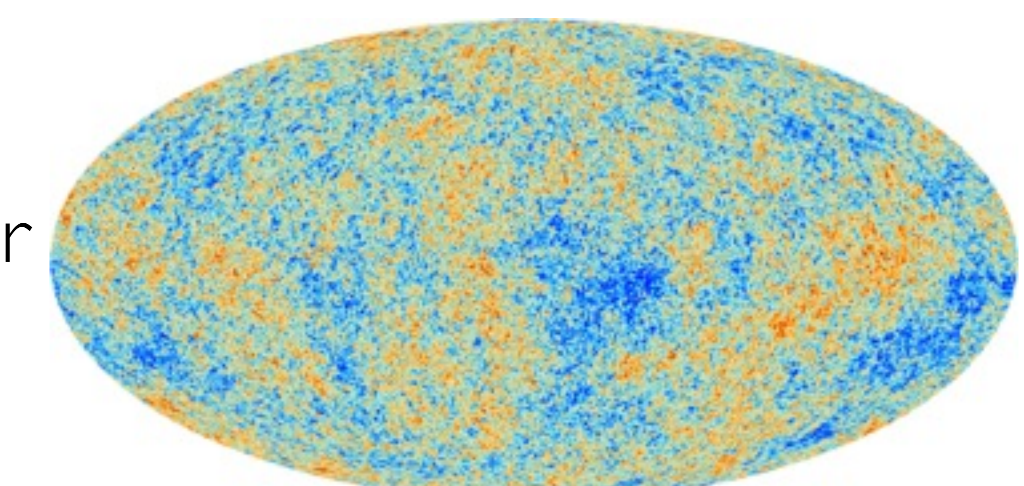
DAMTP, University of Cambridge

(on behalf of the Planck collaboration)



University of Manchester

22nd July 2014



Acknowledgements

esa
planck
cnes
asi agenzia spaziale italiana
NASA
cnrs
DTU Space National Space Institute
INAF Istituto Nazionale di Astrofisica
HFI PLANCK
PLANCK LFI
Science & Technology Facilities Council
CSIC
National Research Council of Italy
Gobierno de España Ministerio de Ciencia e Innovación
IAS orsay
IAP
INAF - IASF BO Istituto Nazionale di Astrofisica Istituto di Astrofisica Spaziale e Fisica Cosmica di Bologna
CSA ASC
DLR Deutsches Zentrum für Luft- und Raumfahrt e.V.
UK SPACE AGENCY
Max-Planck-Gesellschaft
ioa
KICC
University of Cambridge
Cardiff University Prifysgol Caerdydd
irfu cea saclay
cea
CESR
CITA–ICAT
cnrs IN2P3
ipac Infrared Processing and Analysis Center
Helsinki Institute of Physics
IFCA
Imperial College London
Università degli Studi di Milano
NÉEL Institut
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LAL
l'Observatoire de Paris LERMA
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MilliLab
NUI Maynooth
INAF Osservatorio Astronomico di Padova
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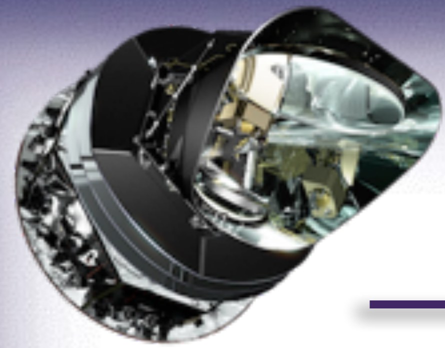
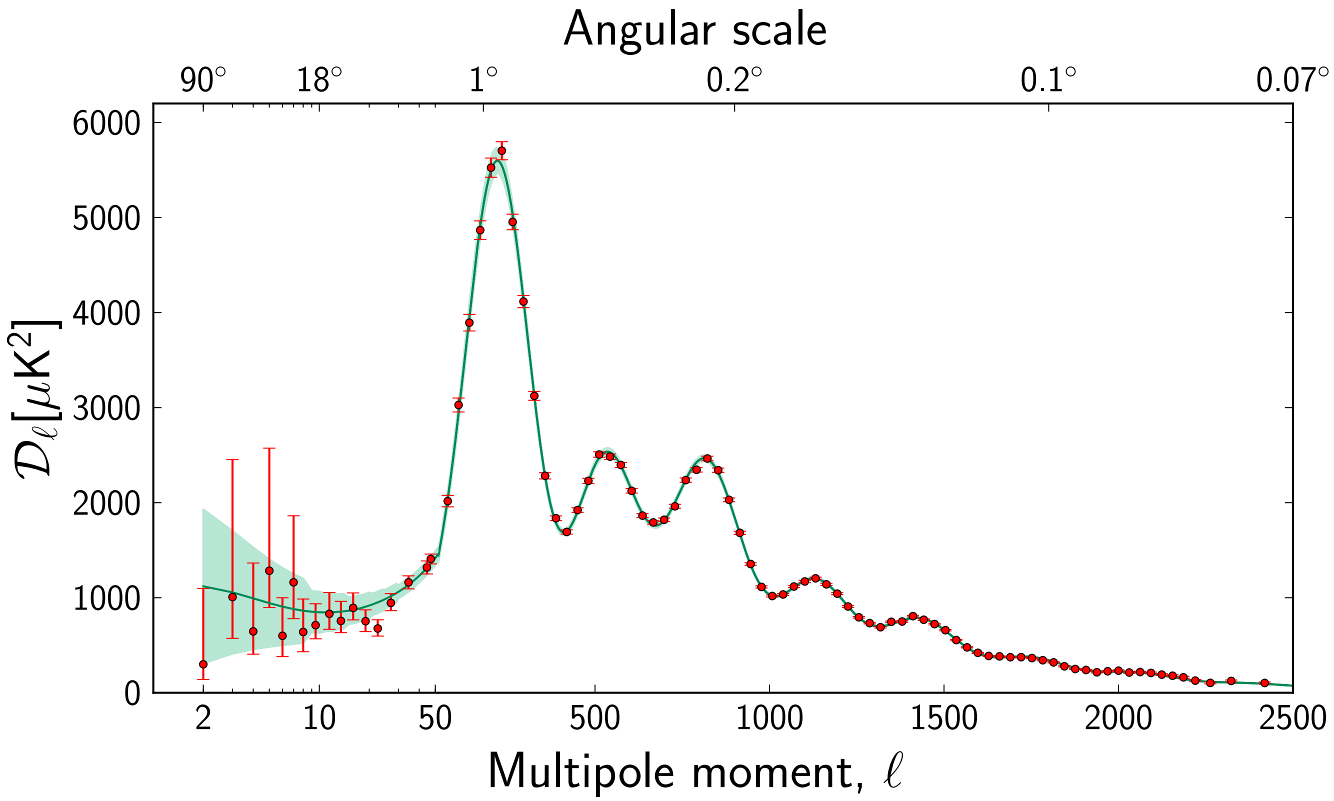
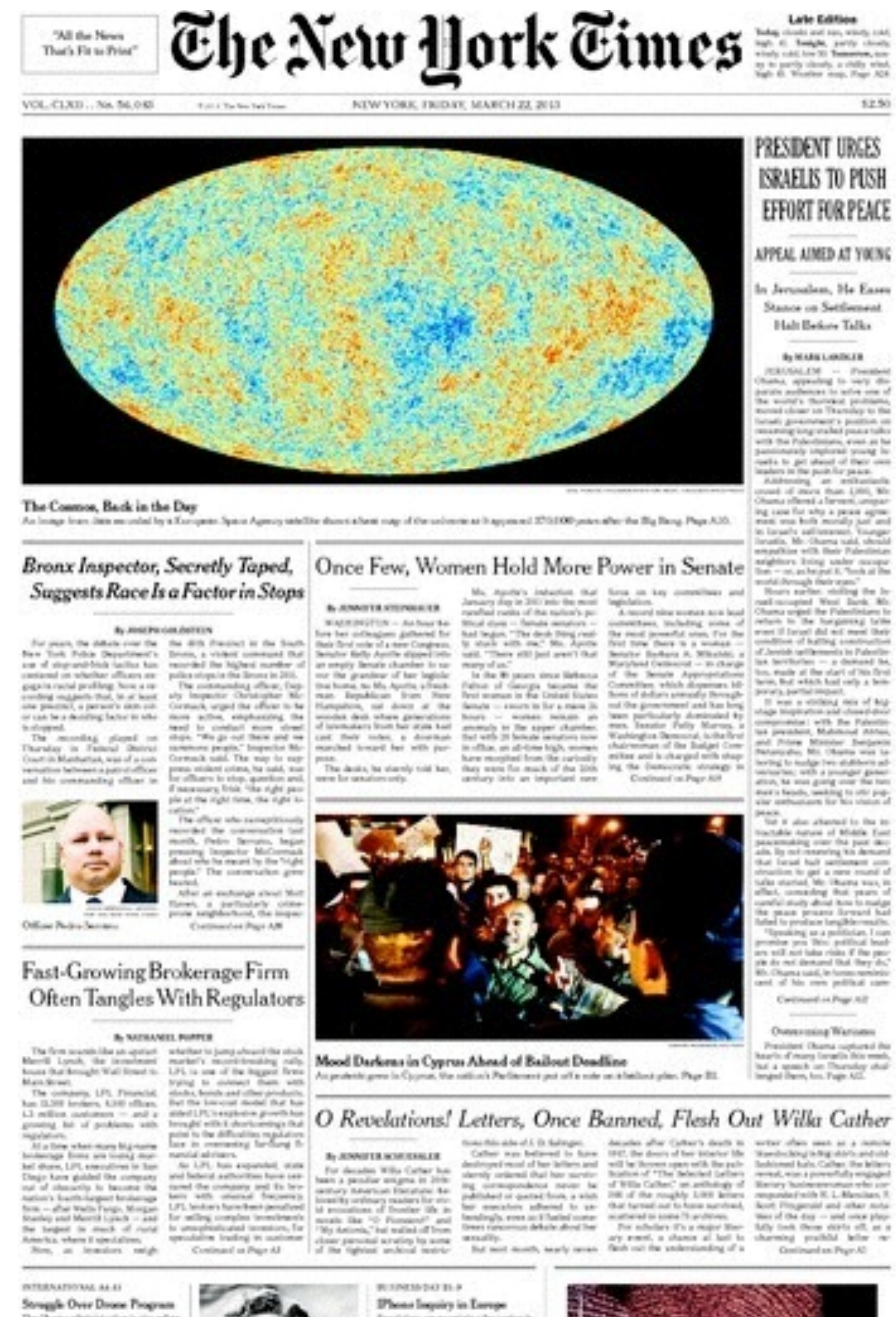


Planck Satellite

Excellent match between theory and observation



Planck CMB results: 21st March 2013



The New York Times

"All the News That's Fit to Print"

Late Edition

NEW YORK, FRIDAY, MARCH 22, 2013

PRESIDENT URGES ISRAELIS TO PUSH EFFORT FOR PEACE

APPEAL AIMED AT YOUNG

In Jerusalem, He Eases Stance on Settlement Halt Before Talks

The Cosmos, Back in the Day

Bronx Inspector, Secretly Taped, Suggests Race Is a Factor in Stops

Once Few, Women Hold More Power in Senate

Fast-Growing Brokerage Firm Often Tangles With Regulators

Mood Darkens in Cyprus Ahead of Bailout Deadline

O Revelations! Letters, Once Banned, Flesh Out Willa Cather

Precision estimates of cosmological parameters

Hubble constant	$H_0 = 67.3 \pm 1.2$ (km/s)/Mpc	
Universe age	$t_0 = 13.798 \pm 0.037$ billion years	
Dark energy	$\Omega_\Lambda = 0.683 \pm 0.009$	68.3%
Dark matter	$\Omega_M = 0.227 \pm 0.013$	26.8%
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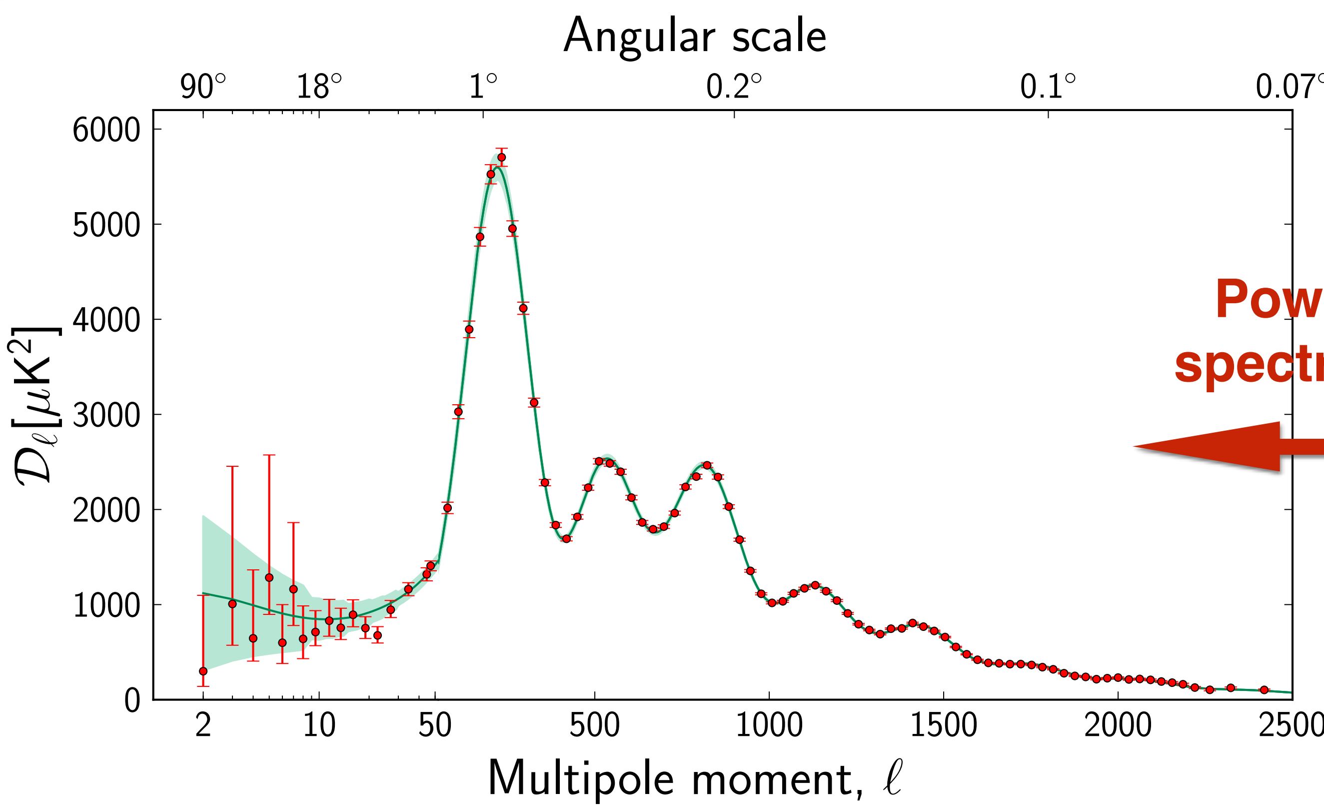
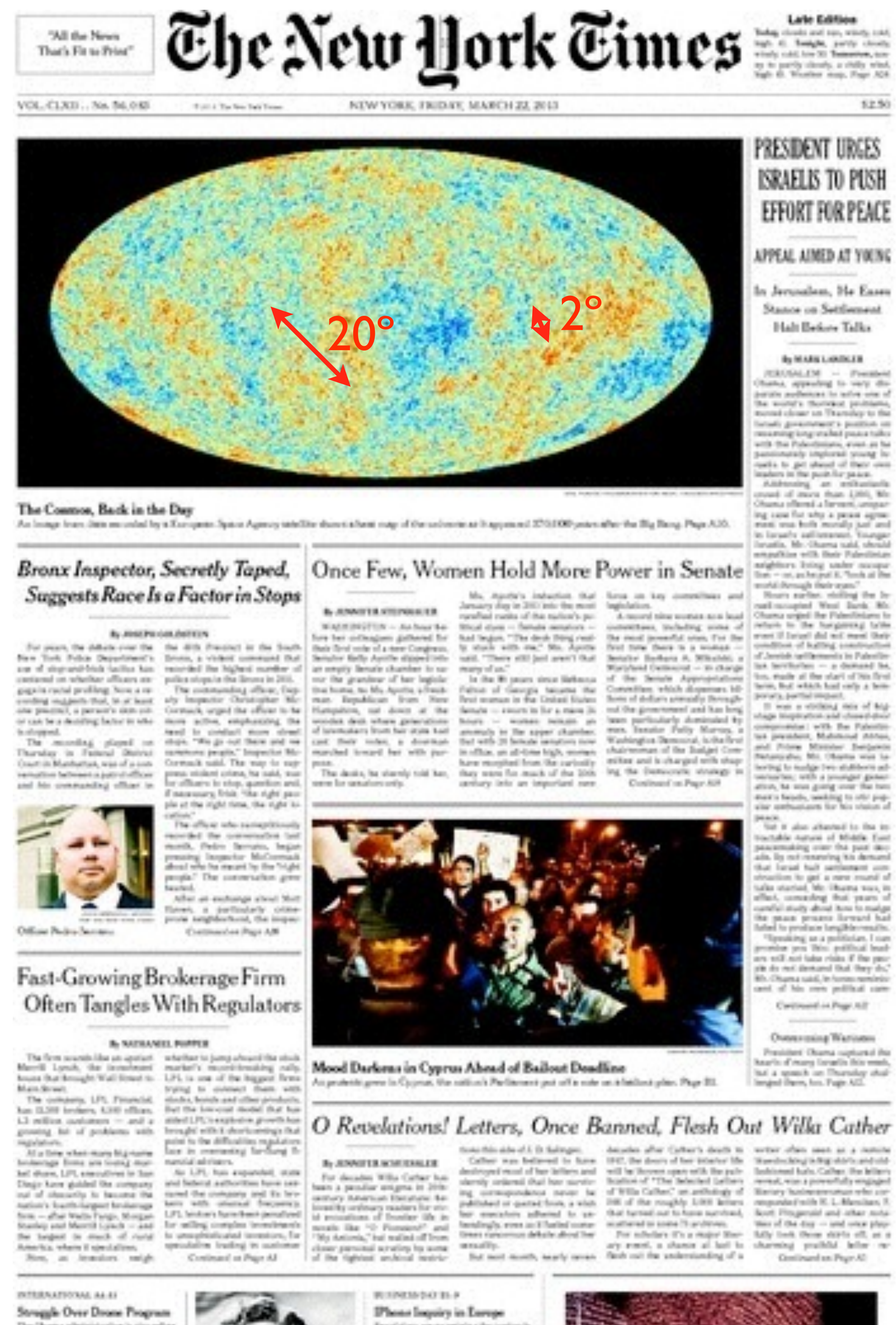


Power spectrum



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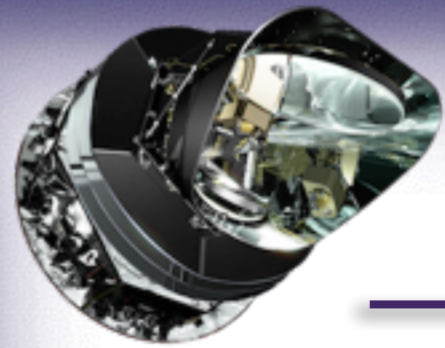

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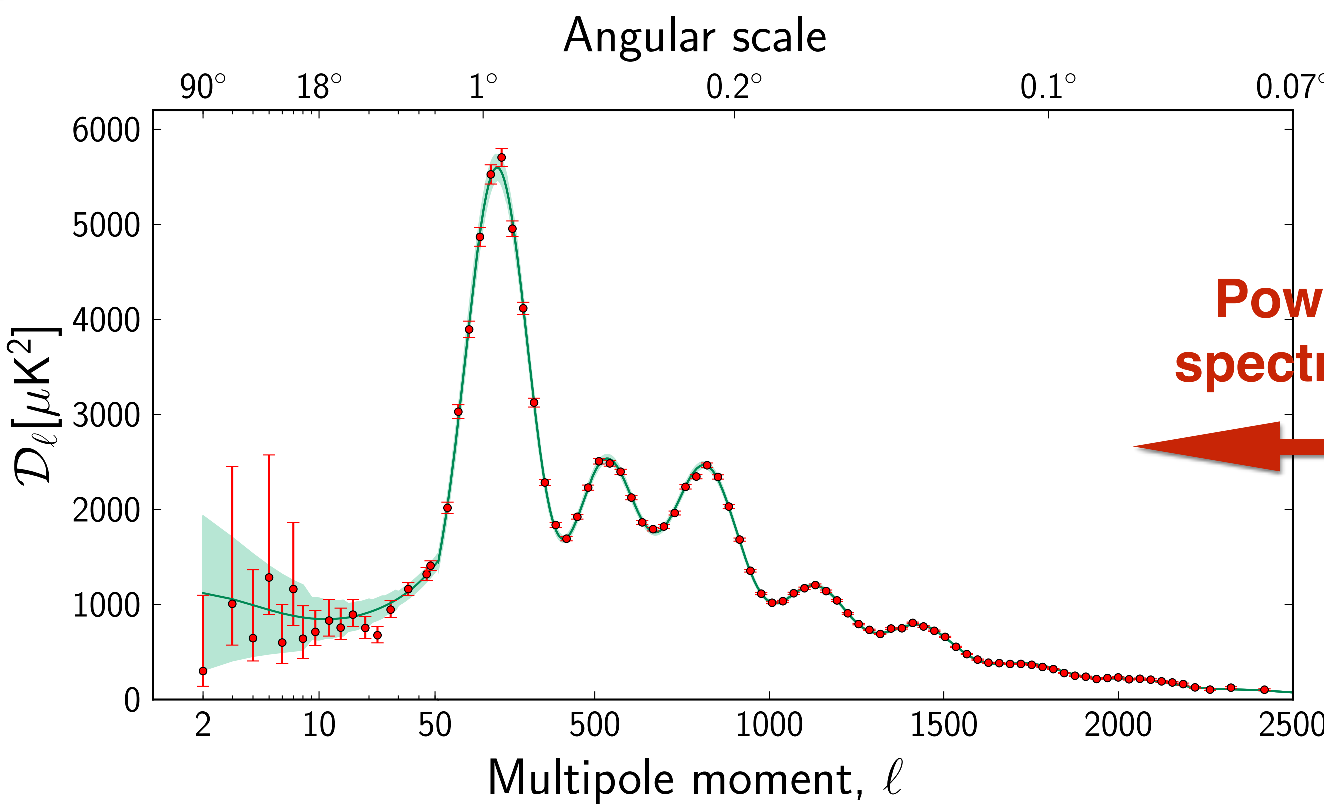

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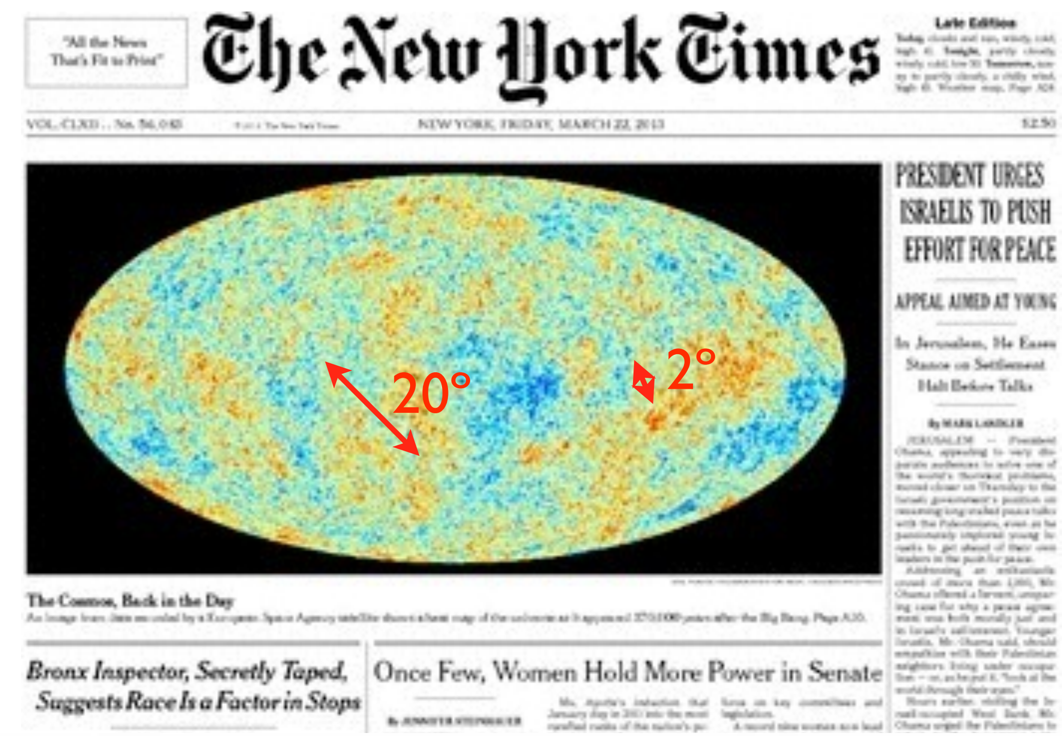

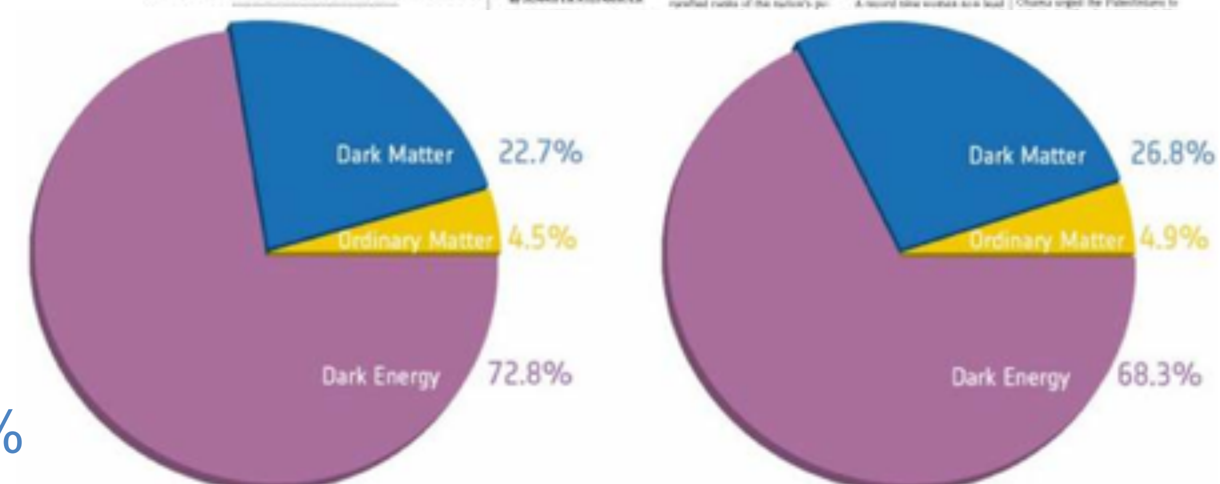

Before Planck After Planck

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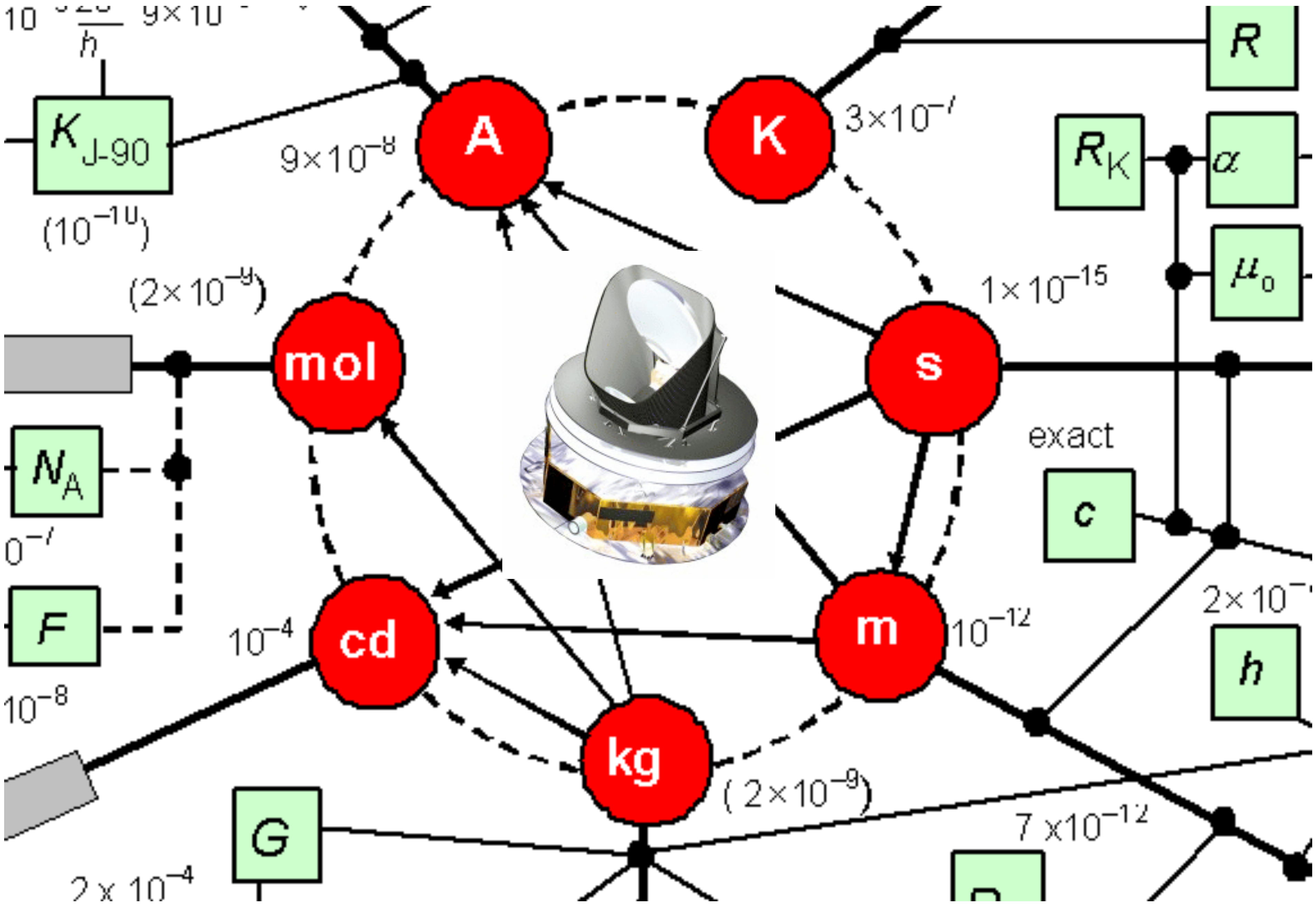
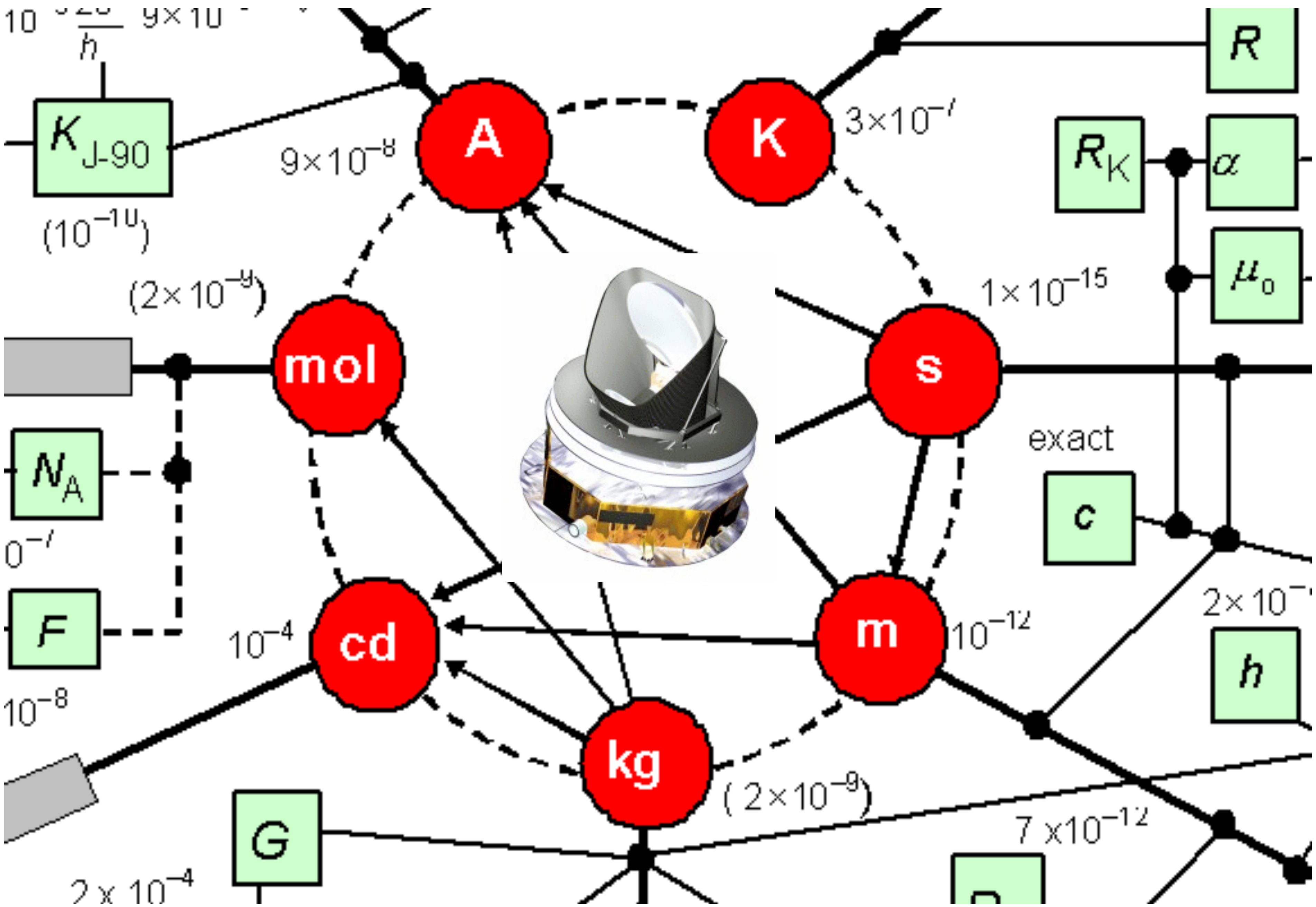


Planck Satellite results

Planck is not just a standards laboratory getting the next decimal point on cosmological parameters like H_0 etc



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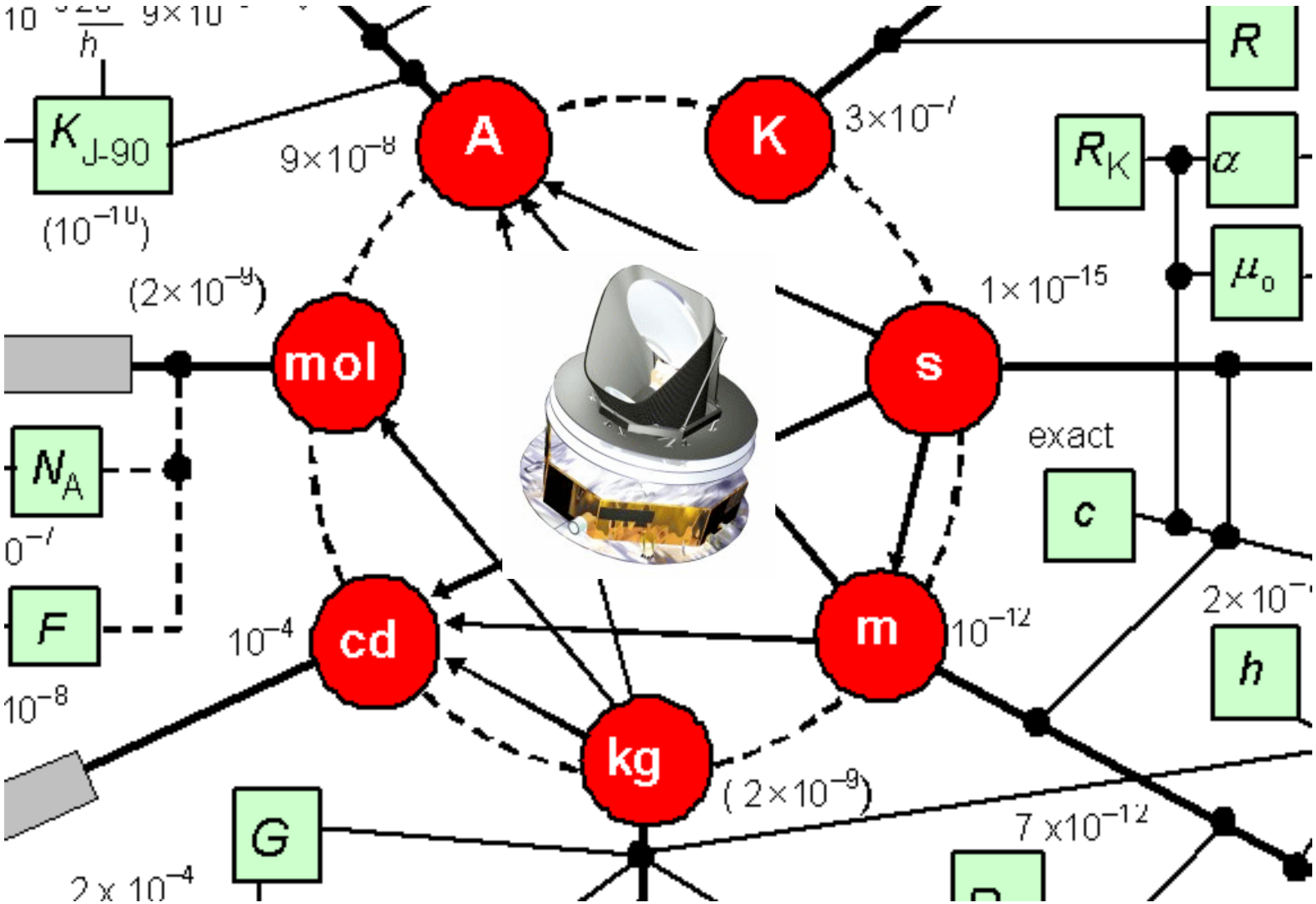

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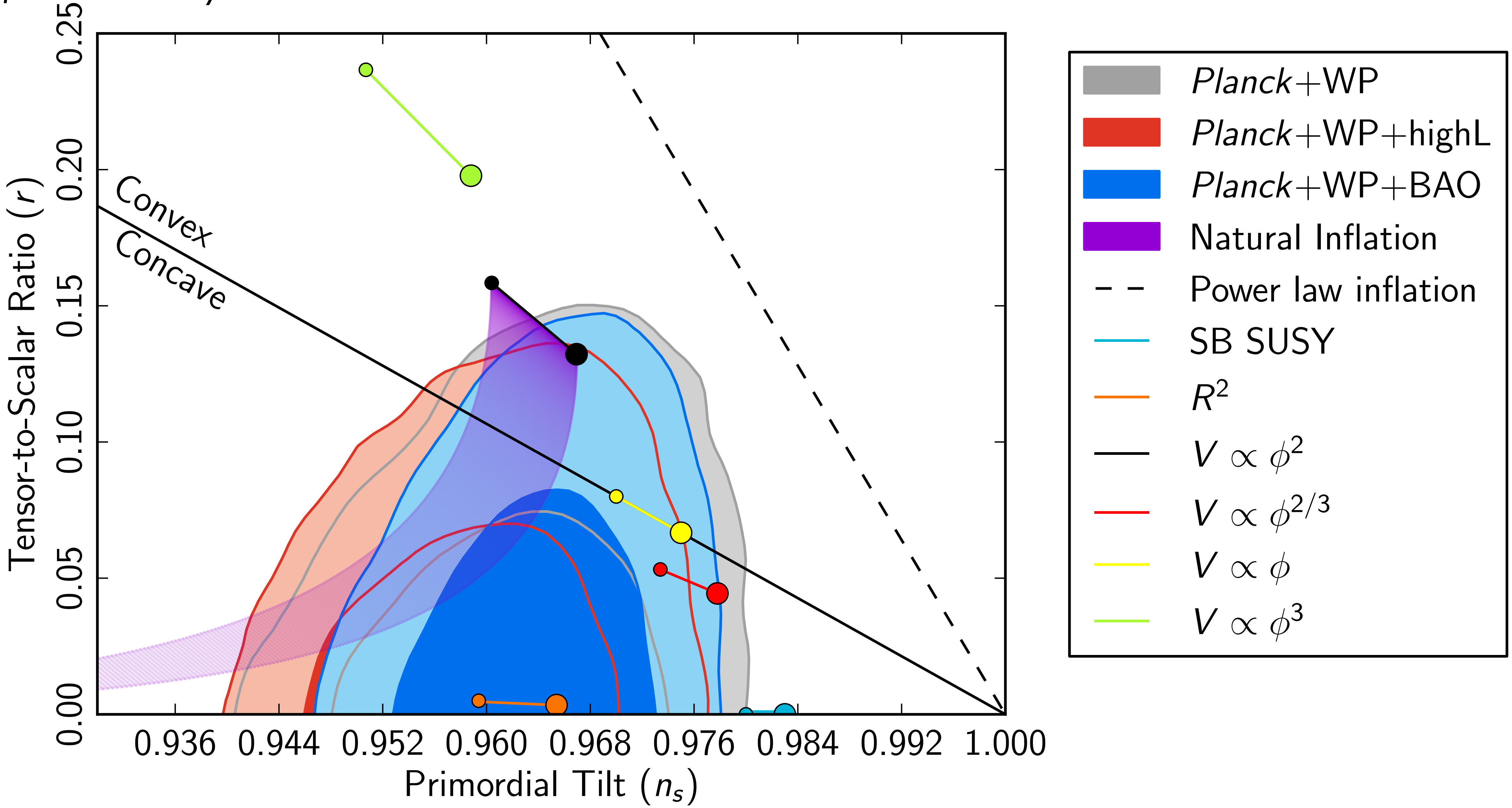
<u>*Inflationary model constraints:*</u>



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- Gravitational lensing detected at very high significance
- Non-Gaussianity 3D bispectrum
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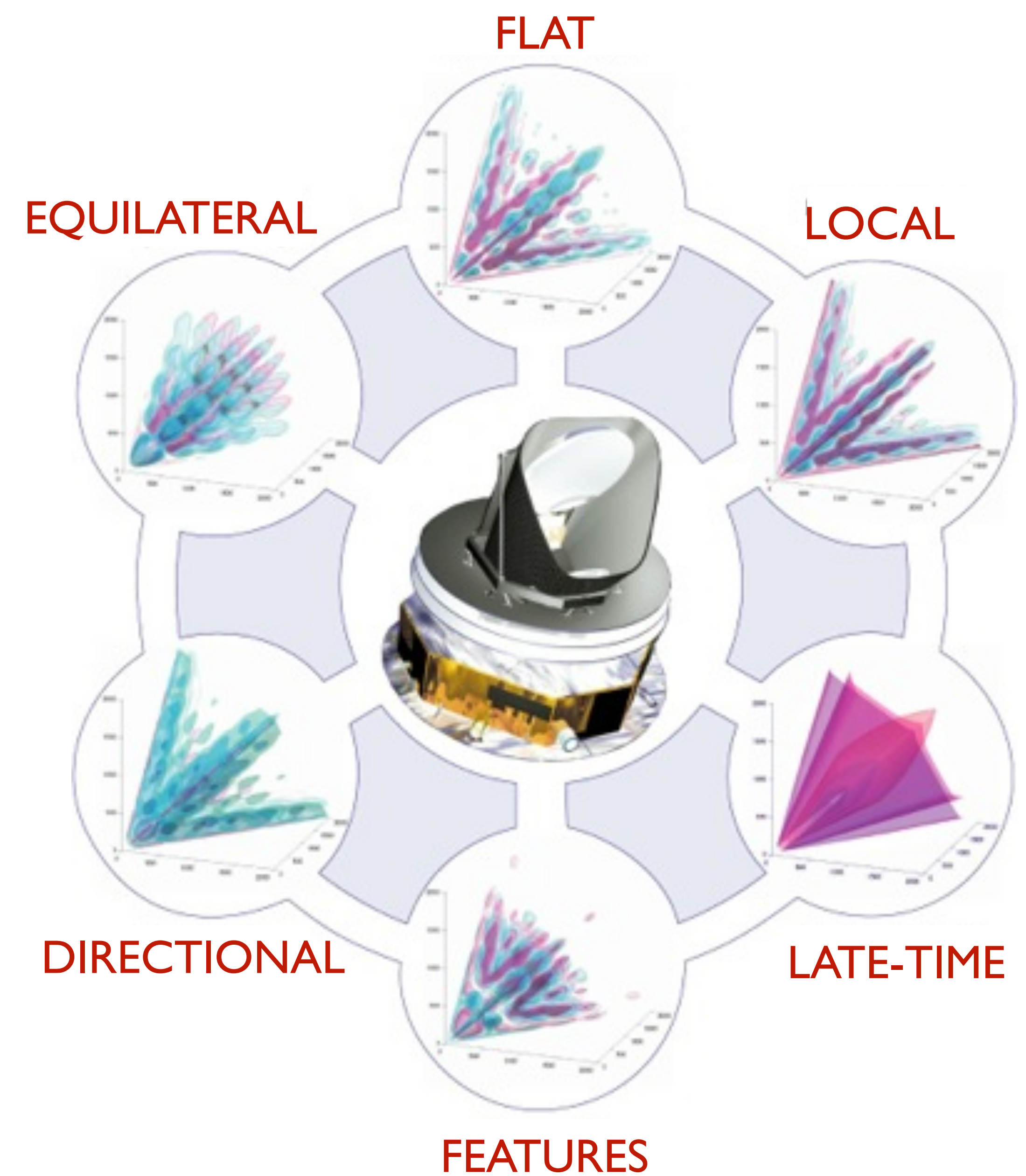
- Astrophysical insights (CIB etc)



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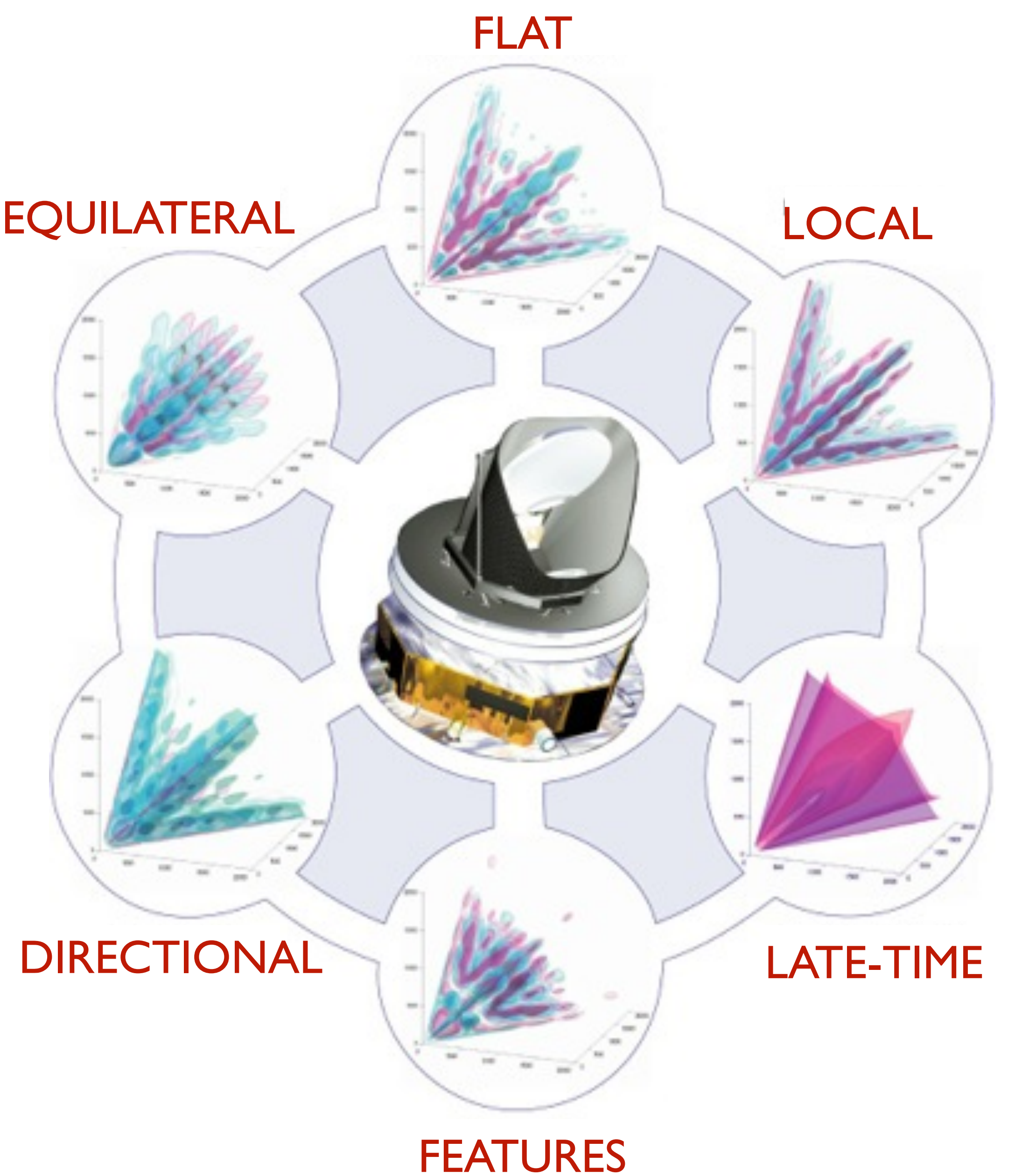

<u>New polarization data with Second Release in October/November 2014</u>

Discovery of Gravitational Waves?

U.S. INTERNATIONAL 中文网

The New York Times

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West Steps Up Sanctions on Russia After Crimea Vote

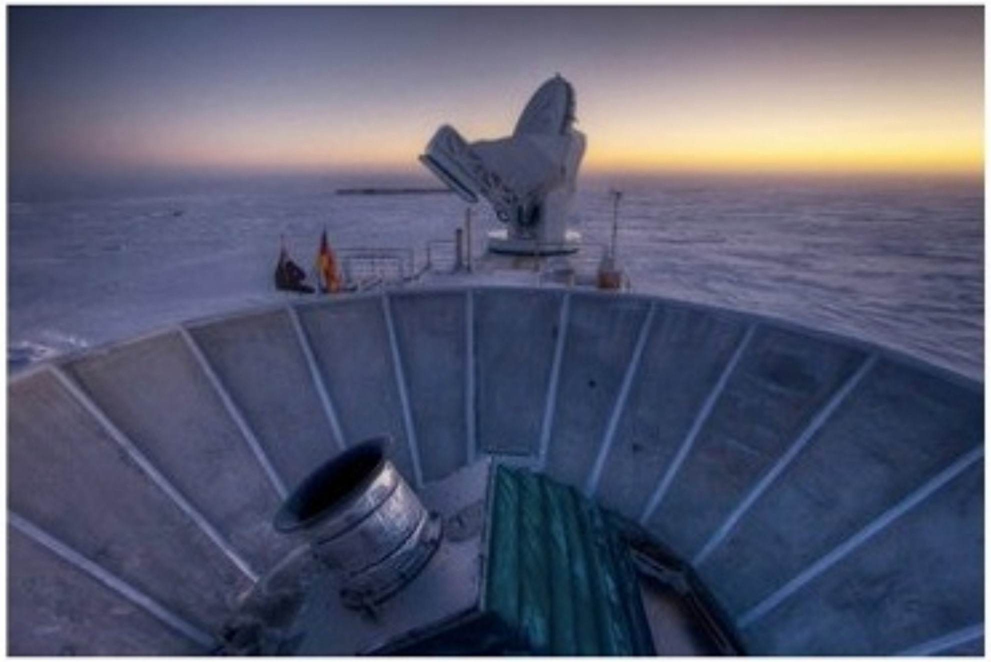
By PETER BAKER 11:14 AM ET

"We're making it clear there are consequences for these actions," President Obama said in announcing sanctions on those deemed to be responsible for the seizing of Crimea.

Crimean Lawmakers Move Swiftly to Split From Ukraine

By DAVID M. HERSZENHORN and ALAN COWELL 9:17 AM ET

The Crimean Parliament declared its independence from Ukraine and formally asked to join Russia, and while Moscow embraced the result of Sunday's vote, the Kremlin has not declared its intent to annex Crimea.



Steffen Richter/Associated Press

Ripples in Space-Time Support Big Bang

By DENNIS OVERBYE 10:46 AM ET

Astronomers found gravitational waves that buttress the theory of a universe wrenched violently apart around its inception. Above, the telescope used to detect the waves.

West's Drought and Growth Intensify Water Conflict

By MICHAEL WINES

The explosive growth of cities is raising the stakes for farmers and industry amid a series of fierce legal and political battles over water.

110 Comments

The Opinion Pages

OP-ED CONTRIBUTOR

The Story of Bridie and Mo

By ROSEMARY MAHONEY

Two red-haired girls on the Dublin docks, at the end of an Irish boom.

- Editorial: The Flute, the Flute Is Calling

MORE IN OPINION

- Op-Ed: The Ugandan Tabloid That Stole Our Pride
- Bittner: Is Crimea the Next Yugoslavia?

THE GREAT DIVIDE

On the Wrong Side of Globalization

By JOSEPH E. STIGLITZ

Trade agreements like the Trans-Pacific Partnership would make our problems worse.

- Editorial: A Hard Turn for De Blasio | Charter Schools
- Krugman: That Old-Time Whistle
- Taking Note: Metro-North Review

MARKETS » At 1:05 PM ET

S.&P. 500	Dow	Nasdaq
1,859.38	16,247.12	4,292.29
+18.25	+181.45	+46.89
+0.99%	+1.13%	+1.10%

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A New Model for Music: Big Bands, Big Brands

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BICEP2 results: World media - 18th March 2014

U.S. INTERNATIONAL 中文网

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Primordial gravitational wave discovery heralds 'whole new era' in physics

Gravitational waves could help unite general relativity and quantum mechanics to reveal a 'theory of everything'

Stuart Clark

The Guardian, Monday 17 March 2014 18.08 GMT

Jump to comments (1675)

Scientists detected telltale signs of gravitational waves using the Bicep2 telescope (far left) at the south pole. Photograph: Keith Vanderlinde/NSF

theguardian

Generation Y: the price of youth

NO CUTS

PM pitches to families with childcare cash

Waves from the big bang herald dawn of a new era

SCIENTIFIC AMERICAN

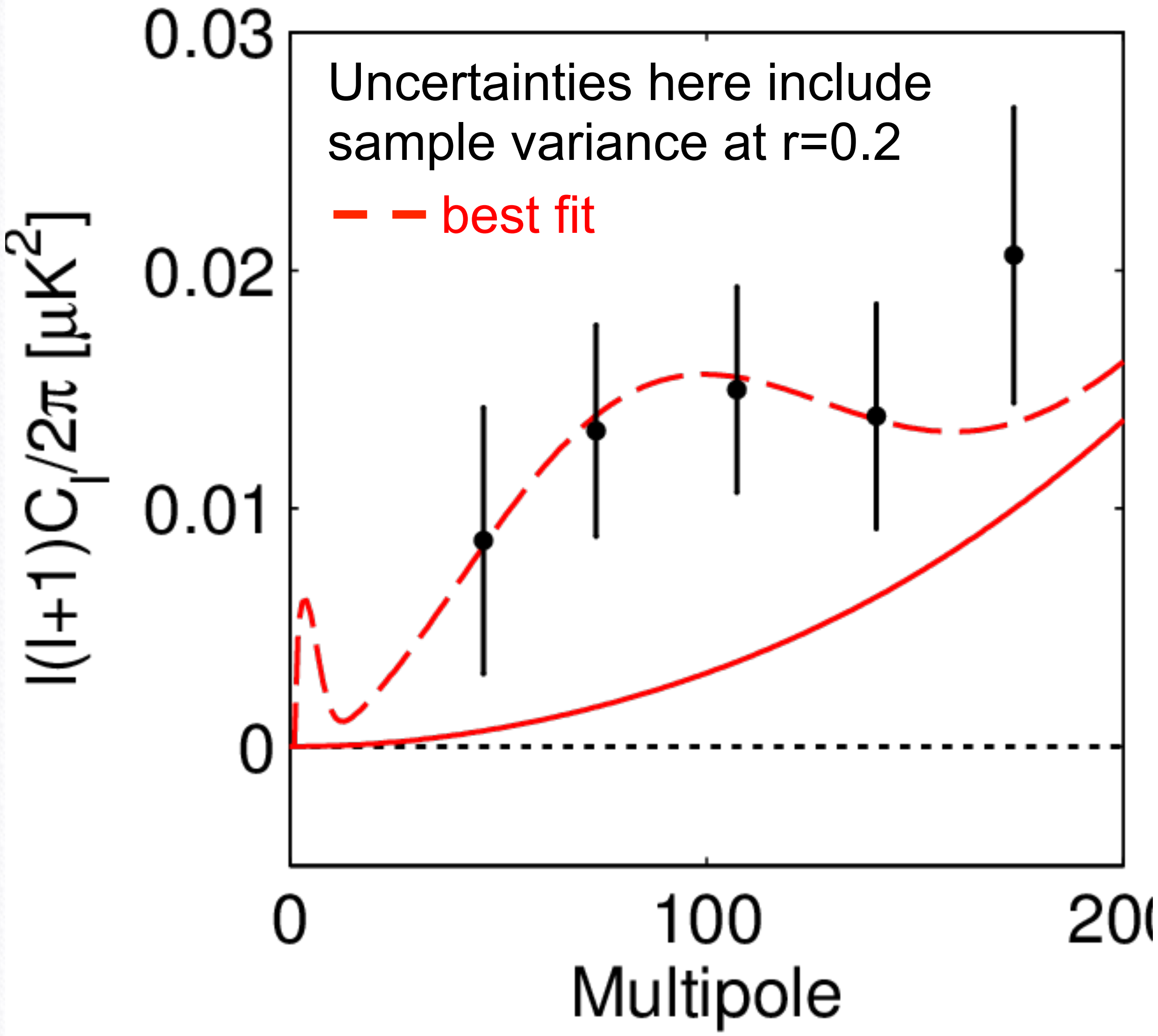
Gravitational Waves from Big Bang Detected

A curved signature in the cosmic microwave background light provides proof of inflation and spacetime ripples

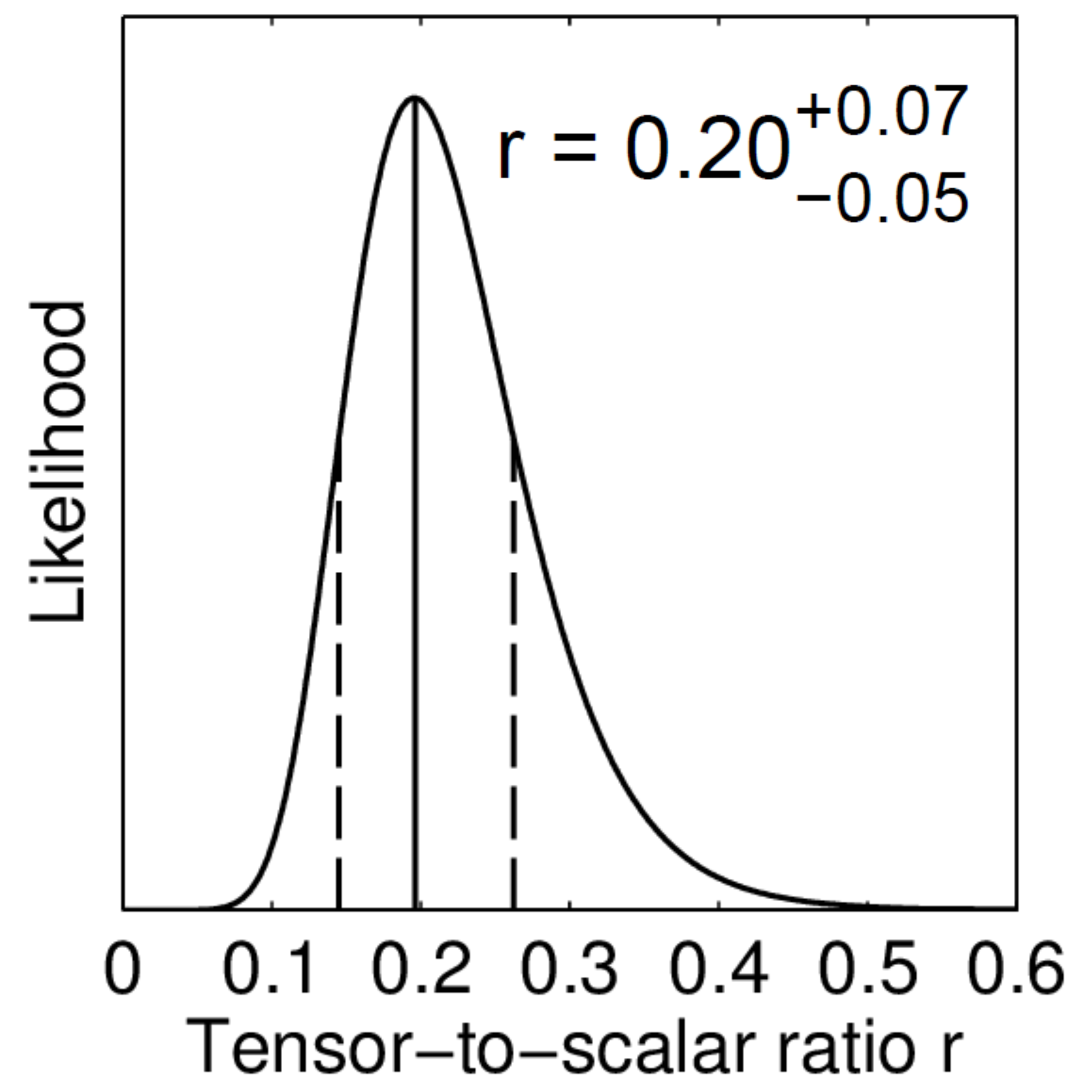
Physicists have found a long-predicted twist in light from the big bang that represents the first image of ripples in the universe called gravitational waves, researchers announced today. The finding is direct proof of the theory of inflation, the idea that the universe expanded extremely quickly in the first fraction of a nanosecond after it was born. What's more, the signal is coming through much more strongly than expected, ruling out a large class of inflation models

BICEP2 Results

B-mode power spectrum shows large "excess" with best-fit tensor model r = 0.2



Likelihood comparing with noise + concordance model simulations - 7σ deviation



Latest: BICEP2 team strongly maintains a tensor signal dominant …
- subtracting dust yields r = 0.15 - 0.19.

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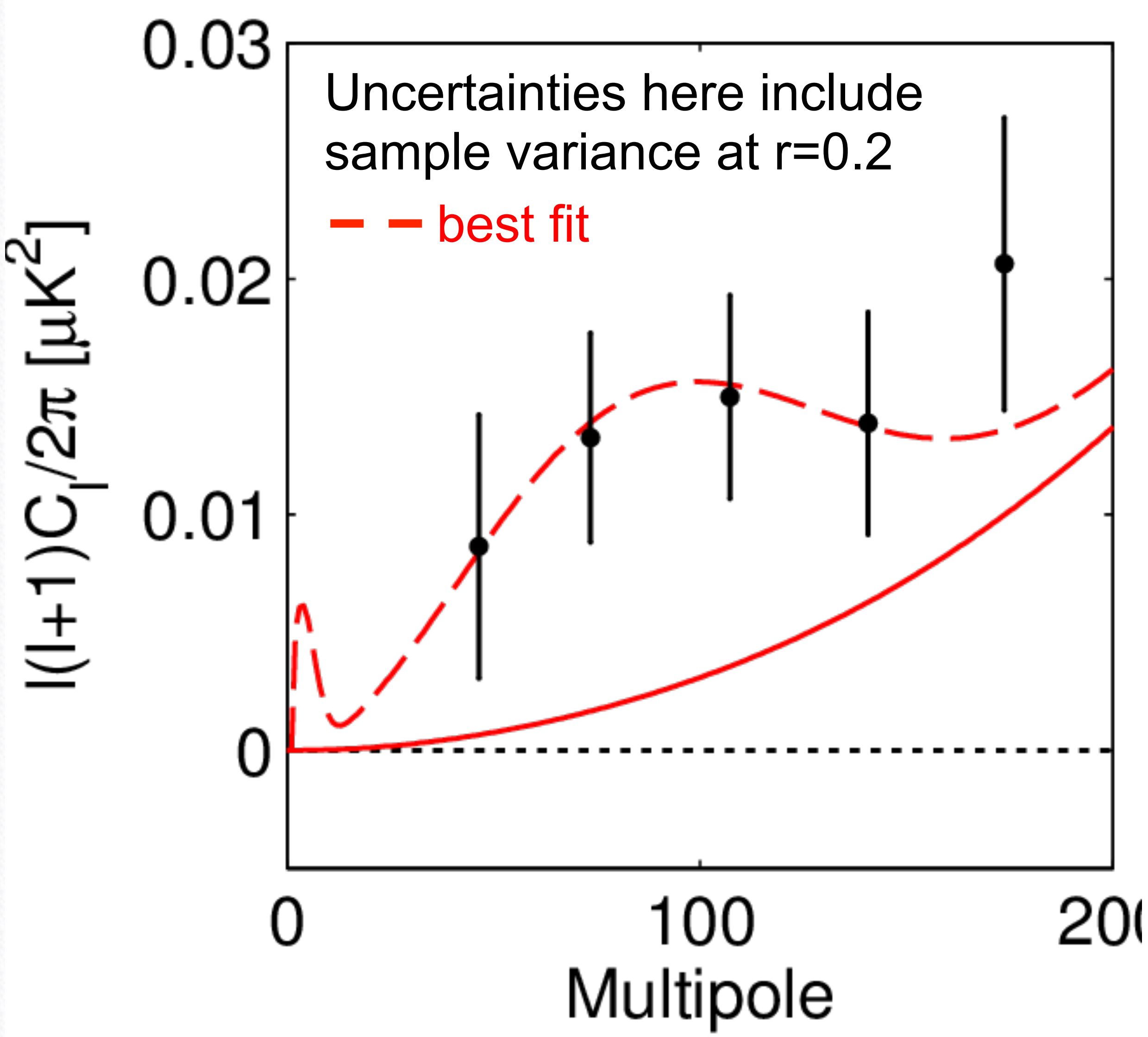

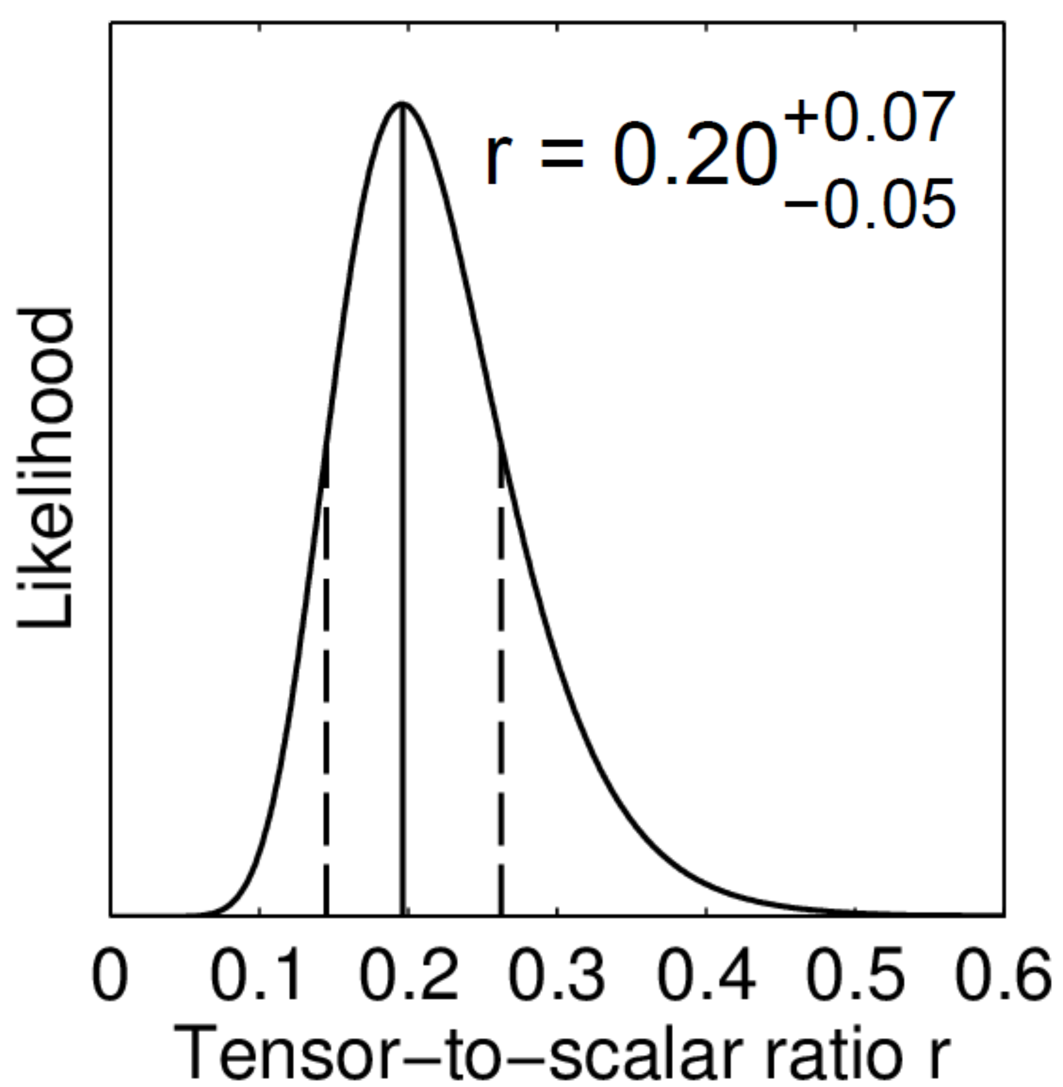

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But are they right?

BICEP2 & UV Completion

BICEP2 ***r = 0.16*** *presents special challenges for inflation model-building*

The tensor-to-scalar ratio

$$r = \frac{\mathcal{P}_h(k)}{\mathcal{P}_\zeta(k)} = \frac{H^2}{M_{\rm Pl}} \Big/ \frac{H^4}{\dot{\phi}^2},$$

evaluated for $k_{\rm ls}/100 < k < k_{\rm ls}$ where $k_{\rm ls}^{-1} \approx 14000\,{\rm Mpc}$ is the distance to last-scattering surface.

With $r = 0.16$, yields energy density & Hubble param. (during inflation)

$$\rho^{1/4} = 1.5 \times 10^{16}{\rm GeV} \quad \text{and} \quad H = 1.0 \times 10^{14}\ {\rm GeV}$$

where we have used $\mathcal{P}_\zeta(k_0)^{1/2} = 4.69 \pm 0.02$ with $k_0^{-1} = 20\,{\rm Mpc}$

Lyth relation for number of e-foldings:

$$\mathcal{N} = \int \frac{da}{a} = \int H dt = \int \frac{H M_{\rm Pl}}{\dot{\phi}} \frac{d\phi}{M_{\rm Pl}} = \sqrt{\frac{8}{r}} \frac{\Delta\phi}{M_{\rm Pl}}$$

So typically with $N \sim 60$ we have super-Planckian excursions

$$\Delta\phi > M_{\rm Pl} \quad \text{for} \quad r > 0.01$$

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Post-BICEP2 model-building?

Super-Planckian excursions $\Delta\phi > M_{\rm Pl}$ for $r > 0.01$ implies

$$V(\phi) = V_0 + \sum_n c_n \frac{(\phi - \phi_0)^n}{{M_{\rm Pl}}^n}$$

lots of sensitivity to Planck-suppressed operators …

Need UV complete theory with e.g. shift symmetry $\phi \longrightarrow \phi + \text{const.}$

String theory is a well-motivated candidate for quantum gravity …

Recent proposal examples (with large r):

- Axion monodromy with symmetric large field range and large *r*

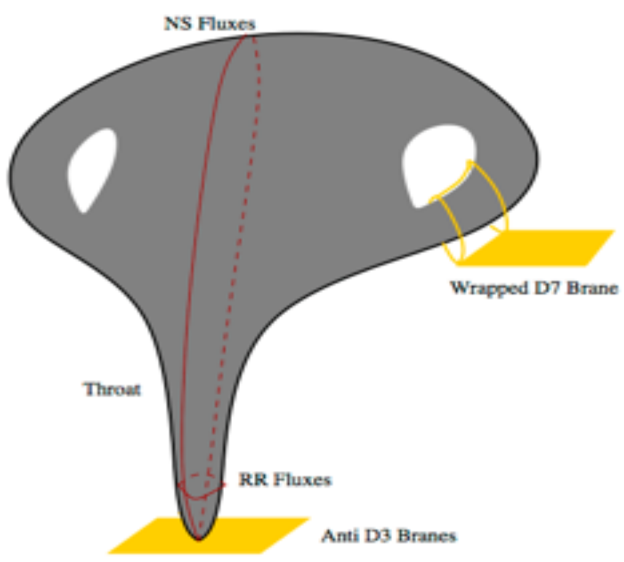
  $$V(\phi) \approx \mu^2\phi + \Lambda^4 \cos\left(\frac{\phi}{f} + \gamma\right)$$

  E.g McAllister, Silverstein, Westphal; Flauger et al.

  yielding oscillatory (non-Gaussian) signatures.
- Quasi-single Field Inflation - shift symmetry only protects one field with others having masses near m ~ H (curvature significant) again yielding NG signatures; also higher spin particles with mass

  E.g Chen & Wang; Arkani-Hamed & Maldacena (in prep.)
- Chaotic inflation in supergravity *Kallosh, Linde & Westphal* • Higgs inf. *etc*
- *See Ed Copeland's SUSY 2014 talk ….*

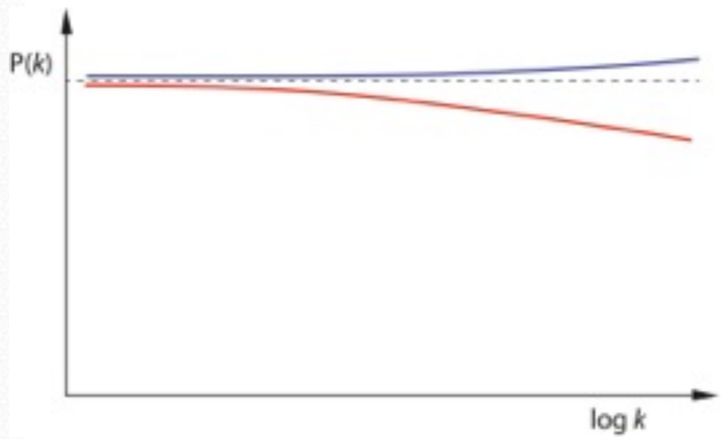
Confrontation of theory & observation



Fundamental Theory
(Inflationary Model)

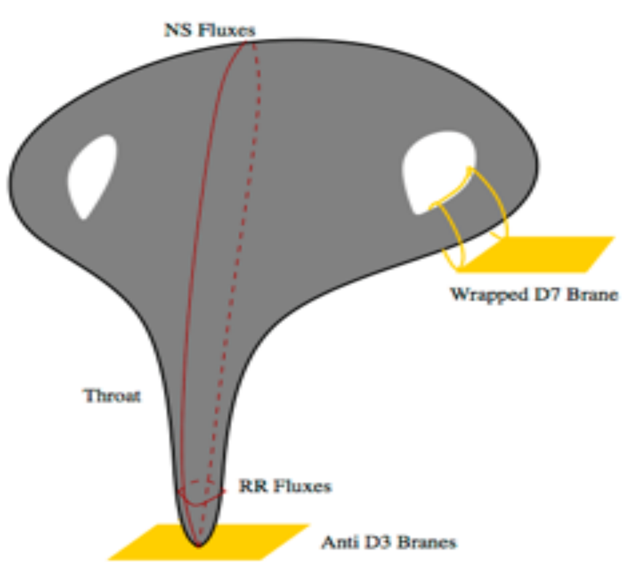
Confrontation of theory & observation

Primordial power spectrum



EUREKA

Modelling inflation and early universe transitions



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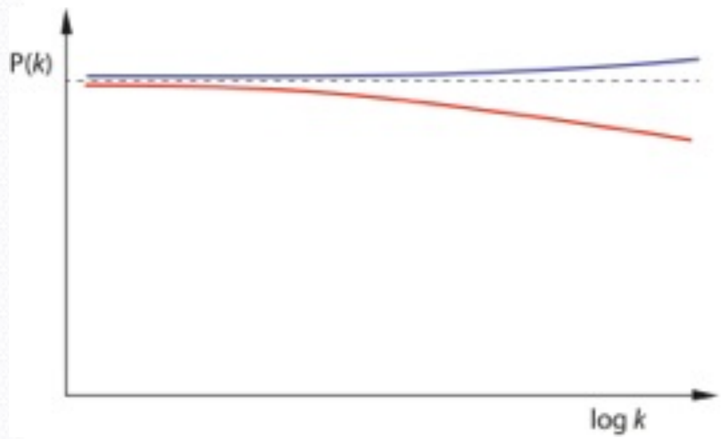
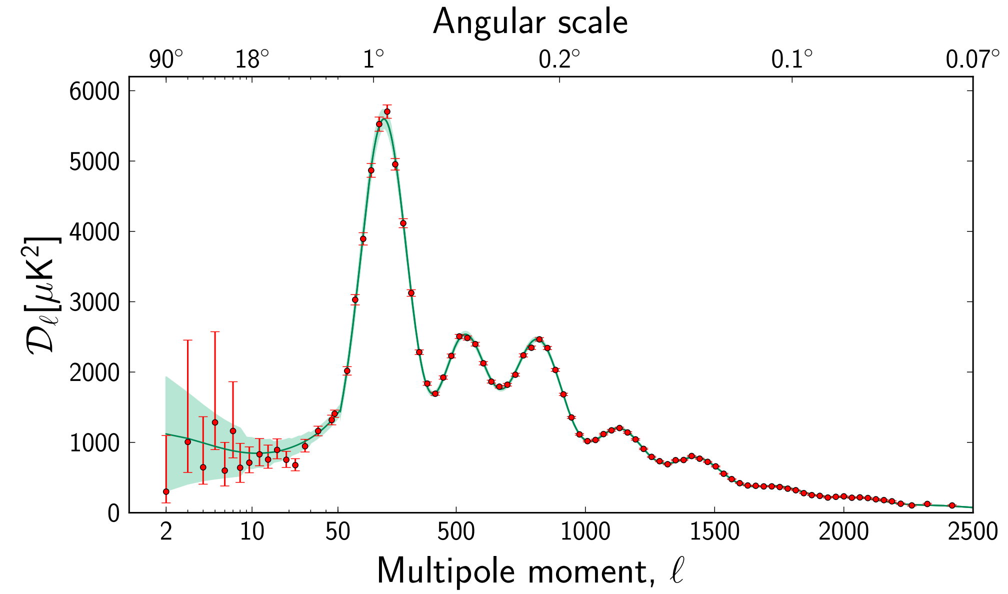


ENLIGHTEN

Plasma physics of the standard cosmology e.g. CAMB / CLASS

CMB angular power spectrum



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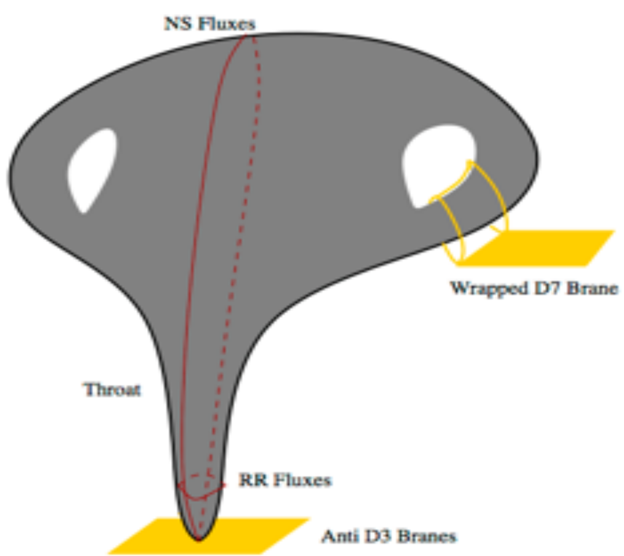

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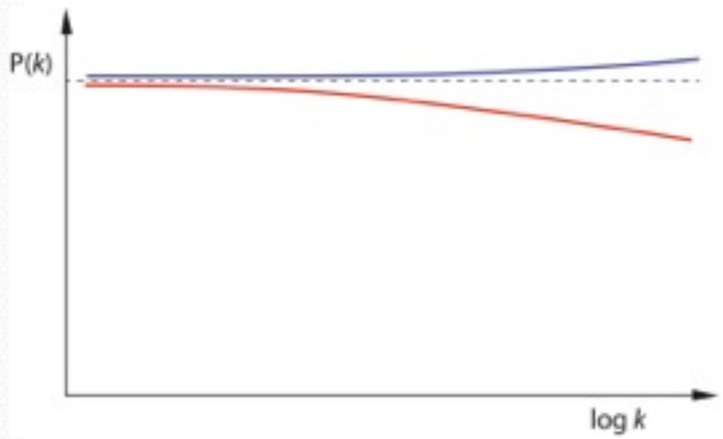

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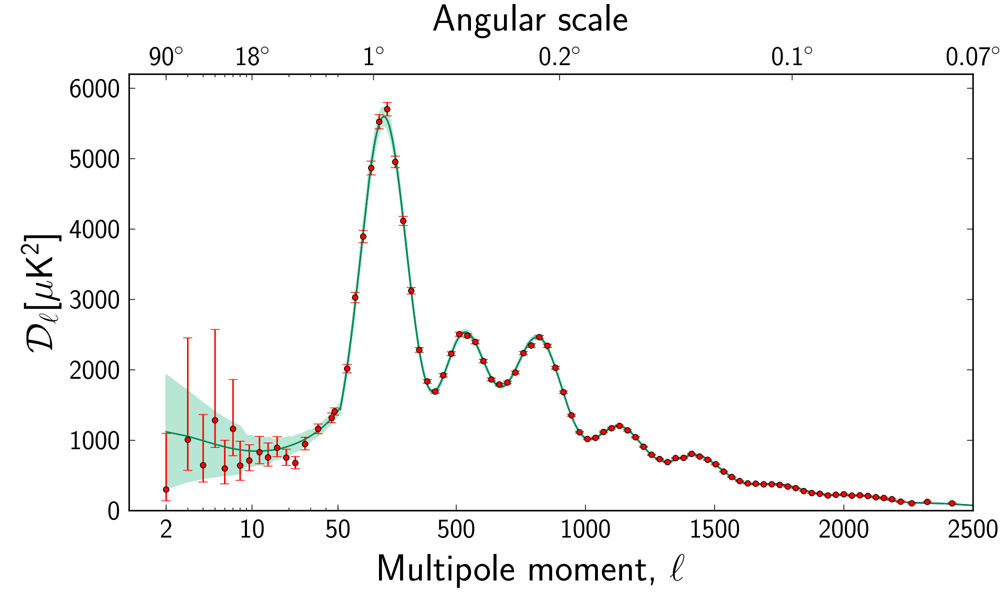

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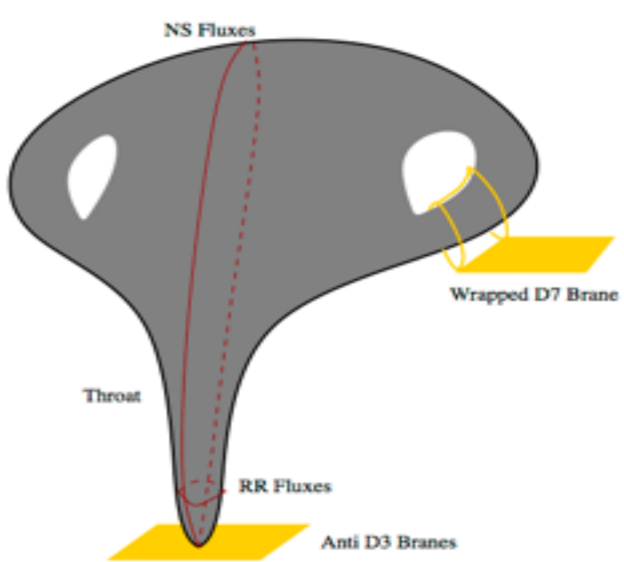
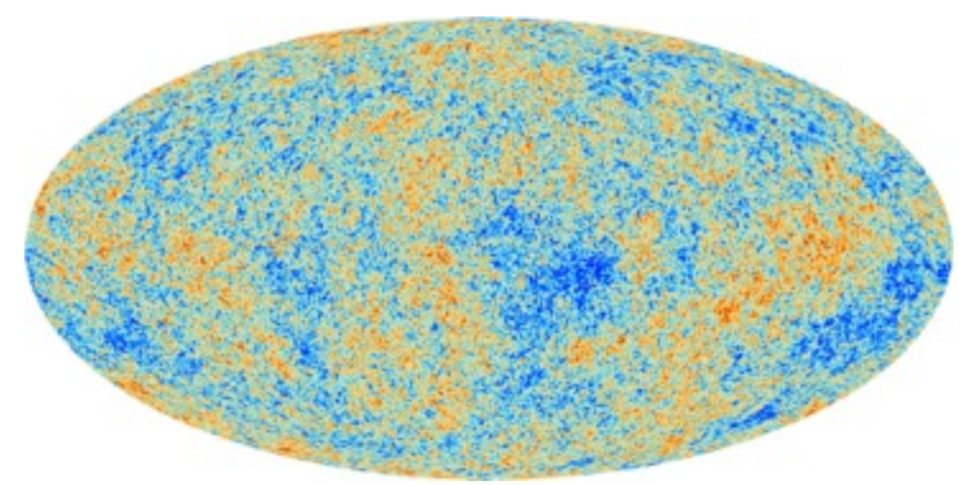
Modelling inflation and early universe transitions

EXPOSE

Estimating signal power on different angular scales



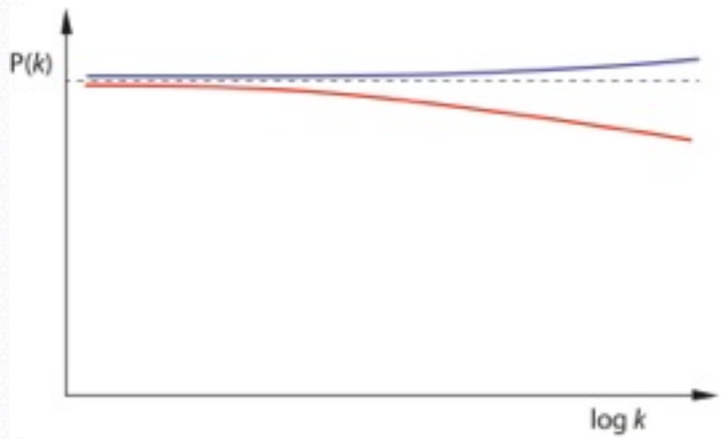
Fundamental Theory (Inflationary Model)



Observational data (Planck CMB Maps)

Confrontation of theory & observation

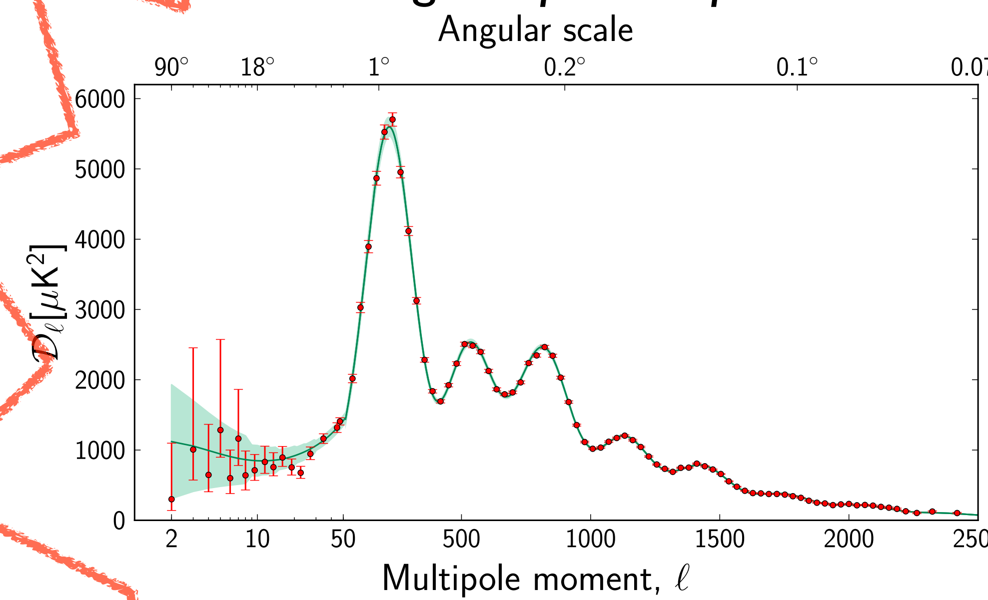
Primordial power spectrum



ENLIGHTEN

Plasma physics of the standard cosmology e.g. CAMB / CLASS

CMB angular power spectrum



EUREKA

Modelling inflation and early universe transitions

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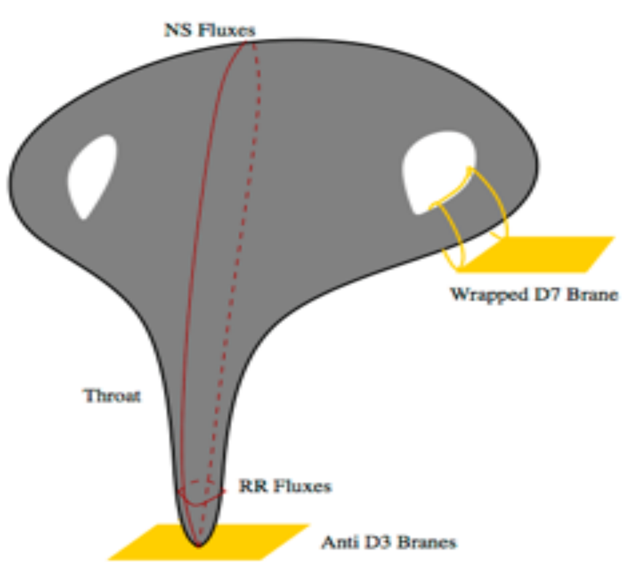
Estimating signal power on different angular scales



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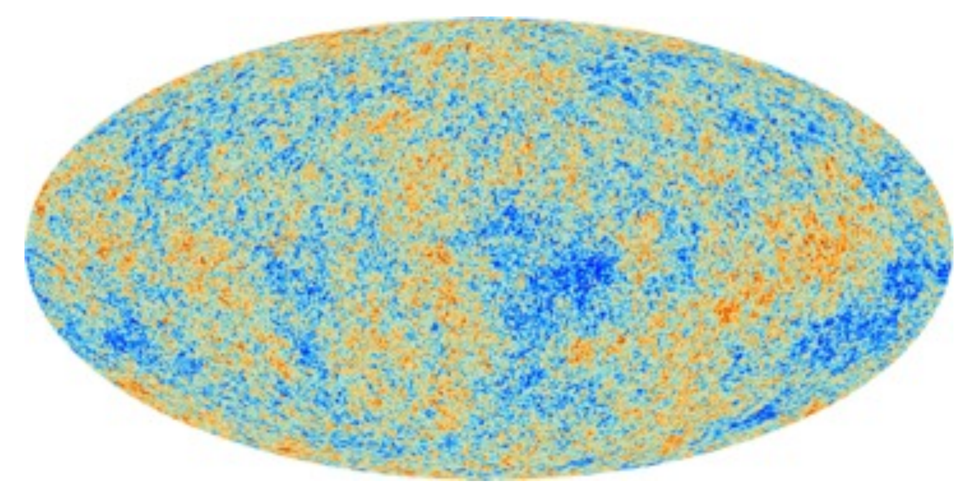

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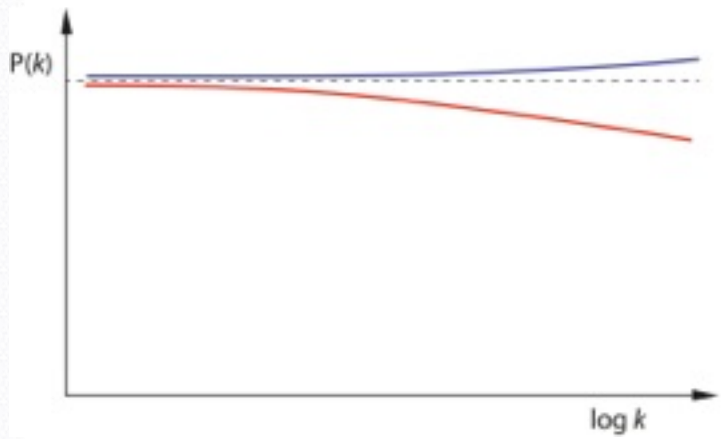

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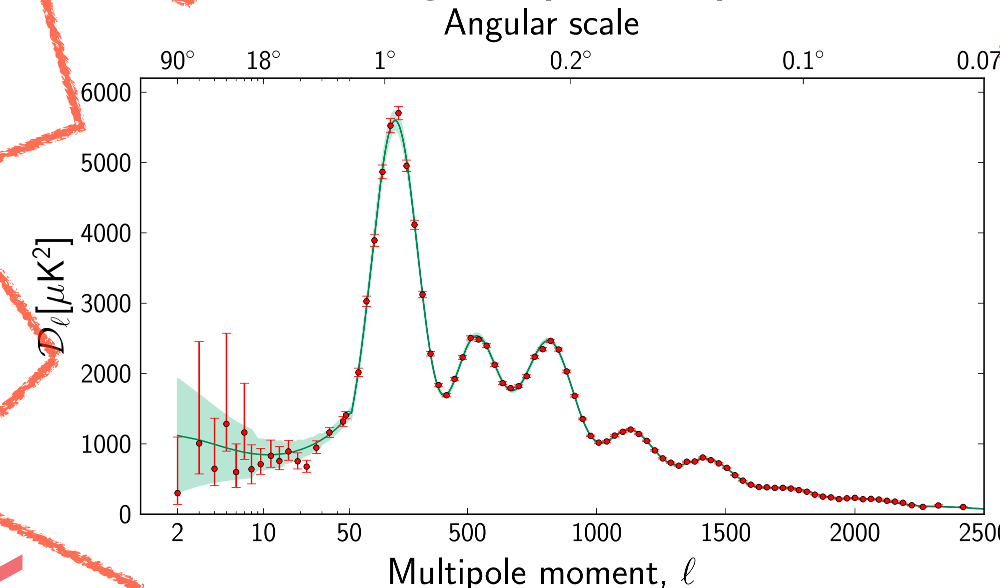


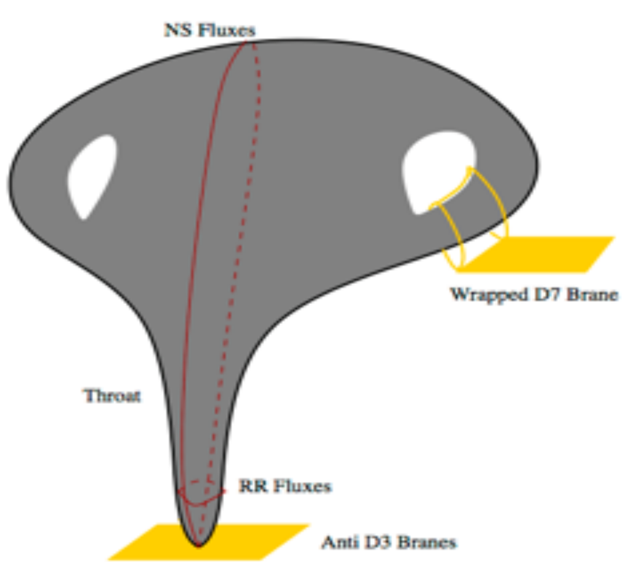
EUREKA

Modelling inflation and early universe transitions

New insights or constraints

EXPOSE

Estimating signal power on different angular scales



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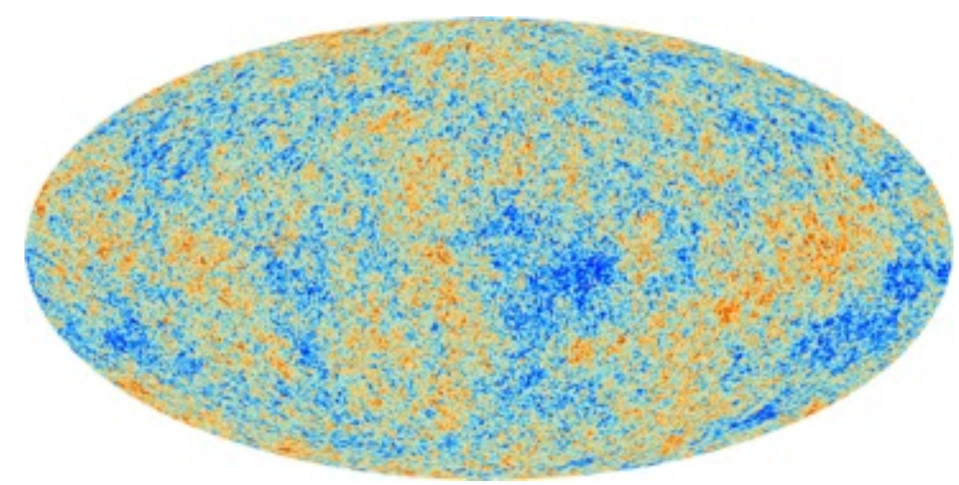

Observational data (Planck CMB Maps)

Inflationary Innovation Problem

5-dimensional assisted inflation
anisotropic brane inflation
anomaly-induced inflation
assisted inflation
assisted chaotic 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 hybrid inflation
chaotic inflation
chaotic new 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

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
generalised inflation
generalized assisted inflation
generalized slow-roll inflation
gravity driven inflation
Hagedorn inflation
higher-curvature inflation
hybrid inflation
hyperextended inflation
induced gravity inflation
induced gravity open inflation
intermediate inflation
inverted hybrid inflation
isocurvature inflation
K inflation
kinetic inflation
lambda inflation

late-time mild inflation
low-scale inflation
low-scale supergravity inflation
M-theory inflation
mass inflation
massive chaotic inflation
moduli inflation
multi-scalar inflation
multiple inflation
multiple-field slow-roll inflation
multiple-stage inflation
natural inflation
natural Chaotic inflation
natural double inflation
natural supergravity inflation
new inflation
next-to-minimal supersymmetric hybrid inflation
non-commutative inflation
non-slow-roll inflation
nonminimal chaotic inflation
old inflation
open hybrid inflation
open inflation
oscillating inflation
polynomial chaotic inflation

pre-
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scala
scala
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Inflationary Innovation Problem

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power-law inflation

primordial inflation
quasi-open inflation
quintessential inflation
R-invariant topological inflation
rapid asymmetric inflation
running inflation
scalar-tensor gravity inflation
scalar-tensor stochastic inflation
Seiberg-Witten inflation
single-bubble open inflation
spinodal inflation
stable starobinsky-type inflation
steady-state eternal inflation
steep inflation
stochastic inflation
string-forming open inflation
successful D-term inflation
supergravity inflation
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supersymmetric hybrid inflation
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supersymmetric new inflation
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TeV-scale hybrid inflation

Inflationary Innovation Problem

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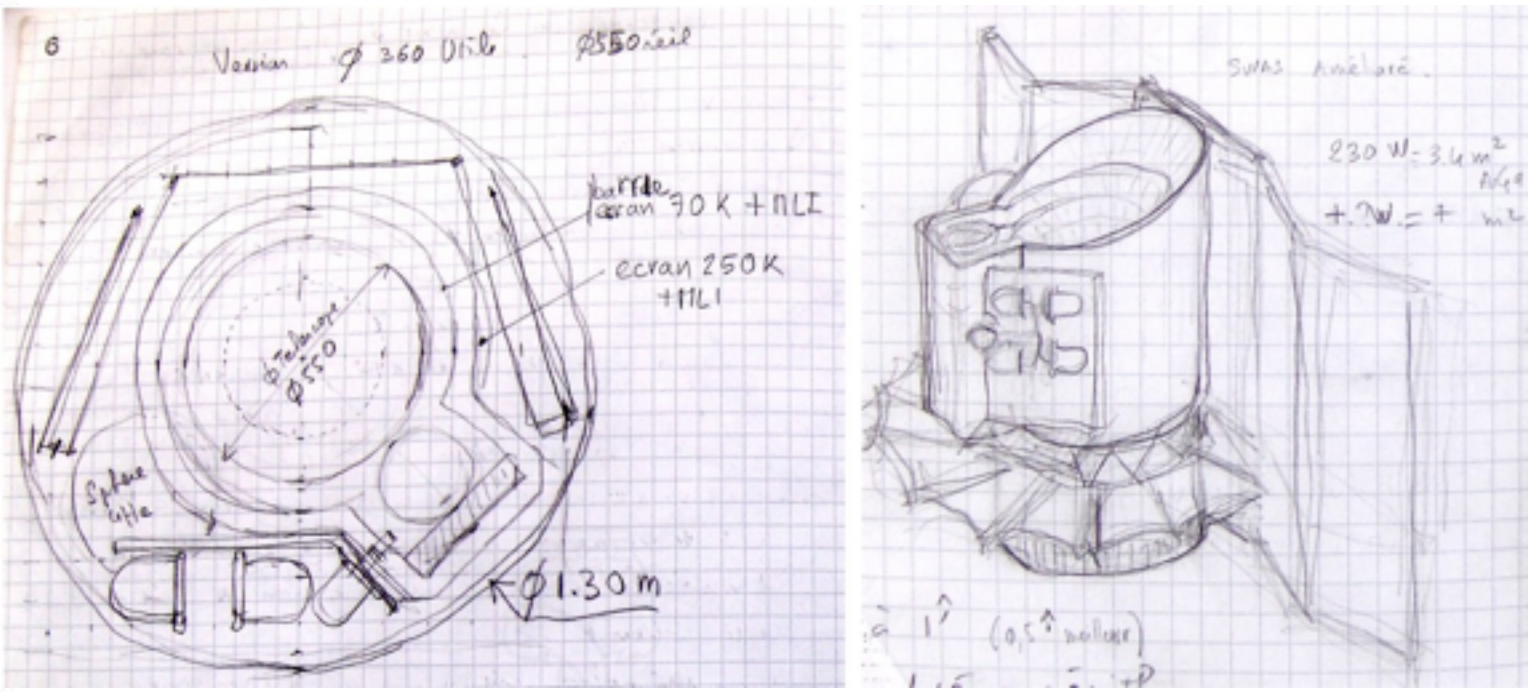
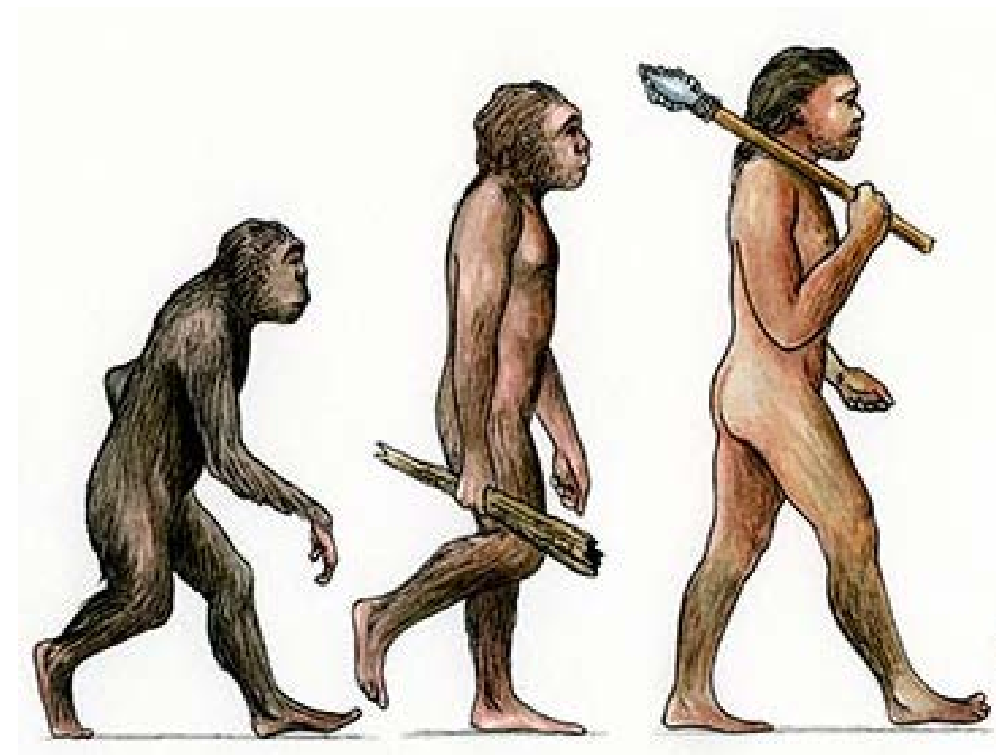
Origins of Planck

First proposed in 1993 as two satellites COBRAS & SAMBA

Conceptual drawings (©Jean-Michelle Lamarre, Observatoire de Paris)





Selected as COBRAS/SAMBA in 1996 in ESA Horizons
- became Planck (launch planned for 2003 with Herschel):

Low Frequency Instrument - HEMT radio arrays @ 100K

High Frequency Instrument - Bolometer arrays @ 0.1 K

In 2000, tender won by Alcatel (now Thales Alenia Space)

Various hiccups and delays (e.g. 100GHz LFI channel)

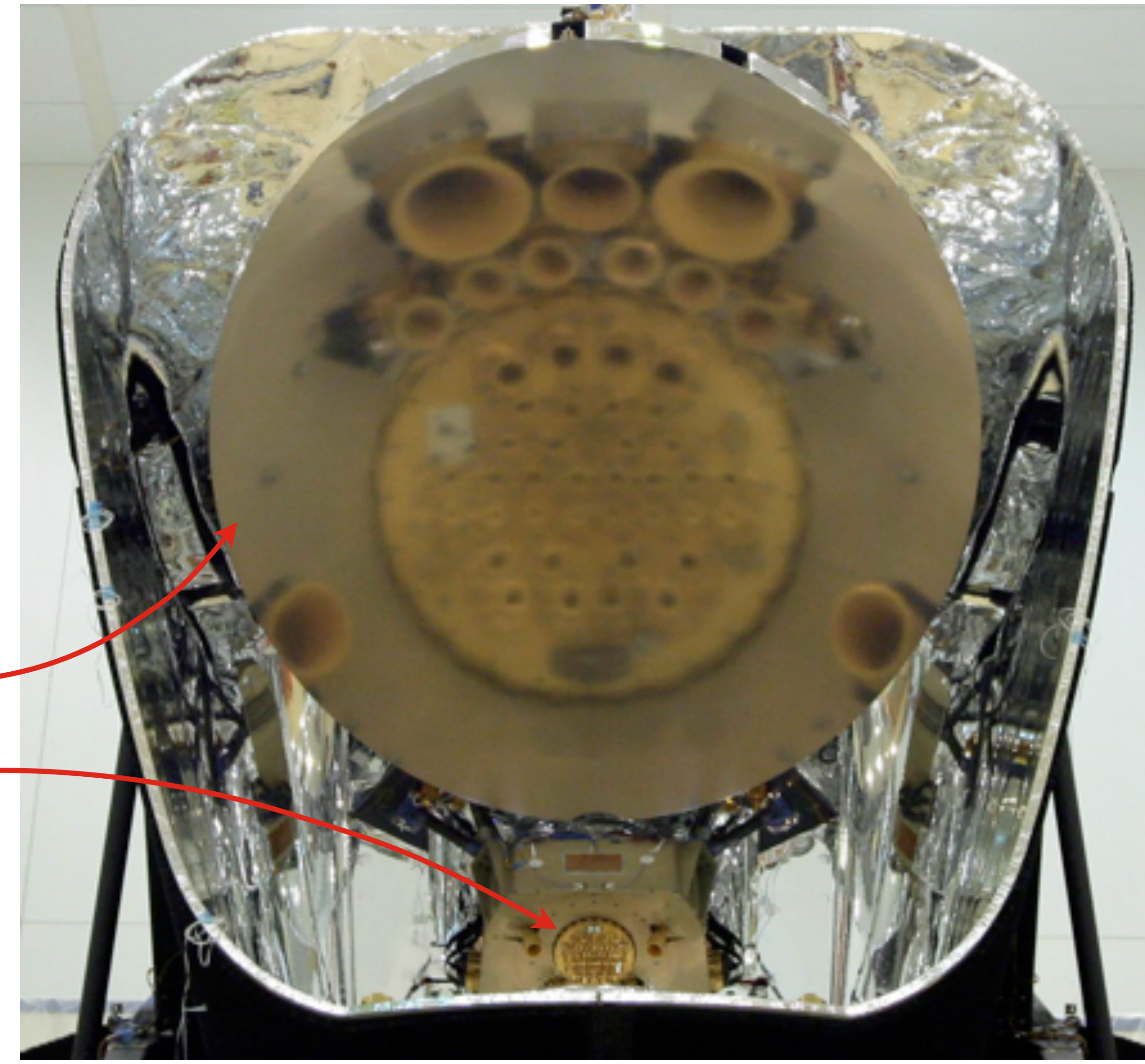
HFI experiment

The Planck High Frequency Instrument (HFI) detects photons using bolometers in 6 freq. bands

- *48 bolometers (thermal detectors) absorptive elements, radiation raises their temp measured by thermistor (32 pol. sensitive detectors, 4 freq.)*
- *A chain of coolers, culminating in dilution coolers maintains a temperature of 0.1K*

Mirror

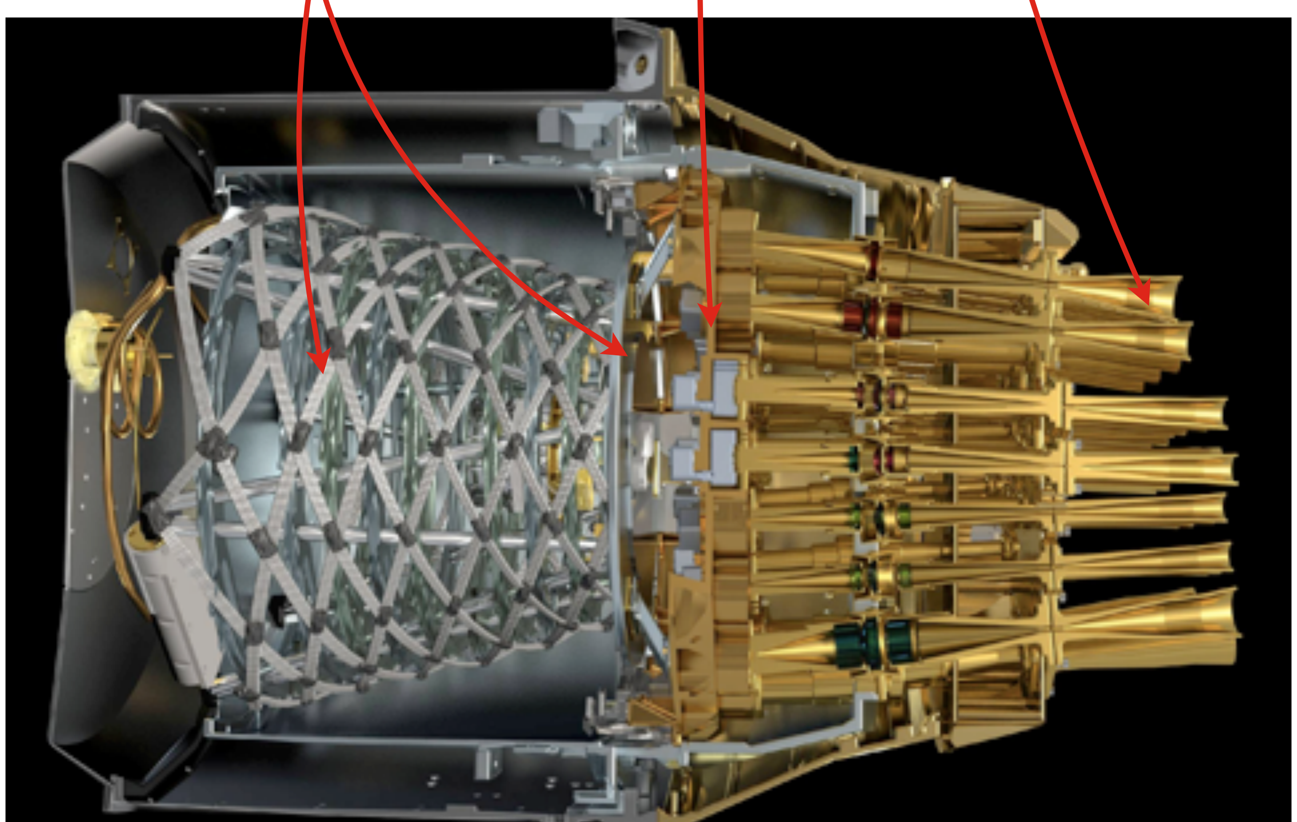
HFI



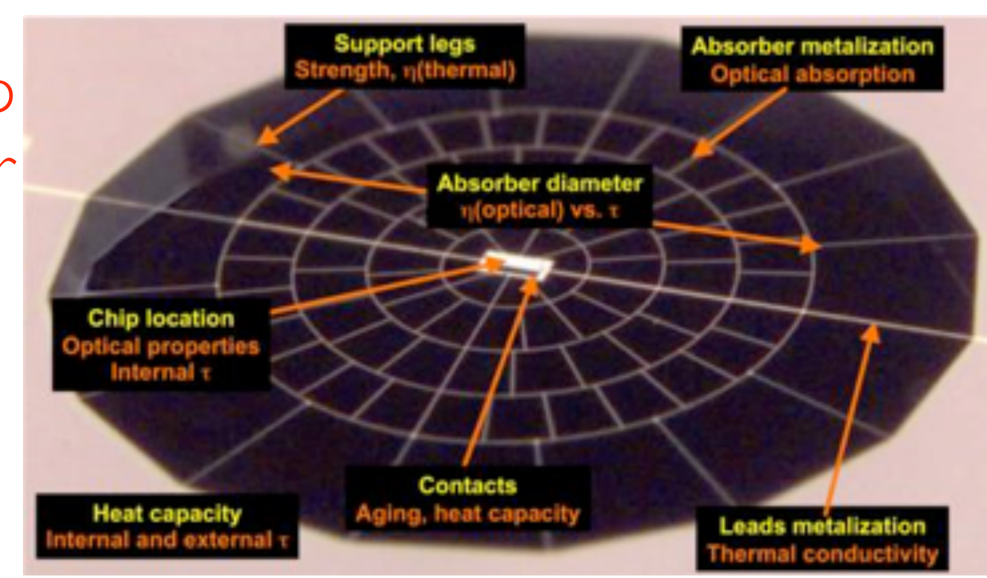
Cooling chain

Bolometers

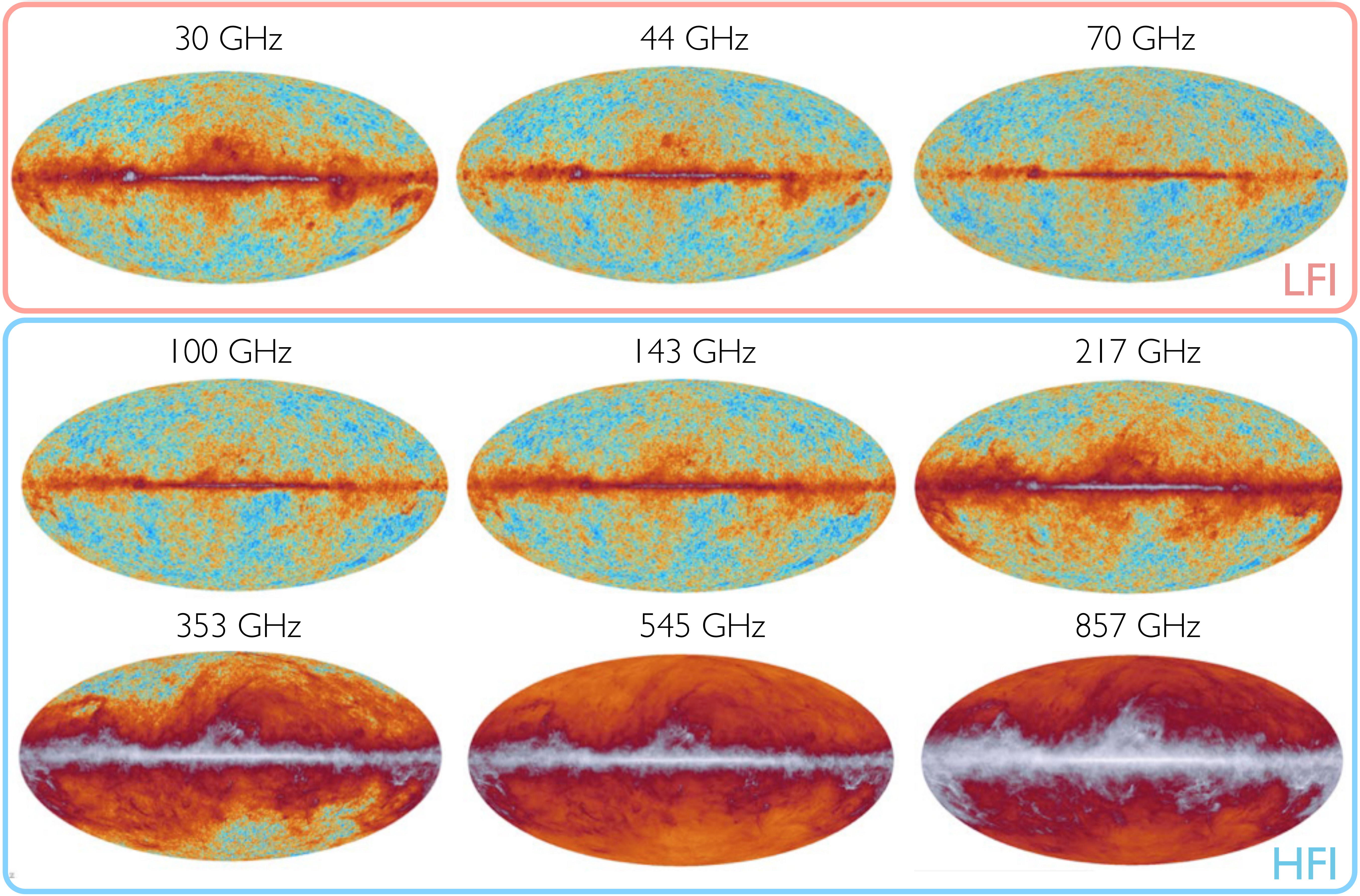
Horns



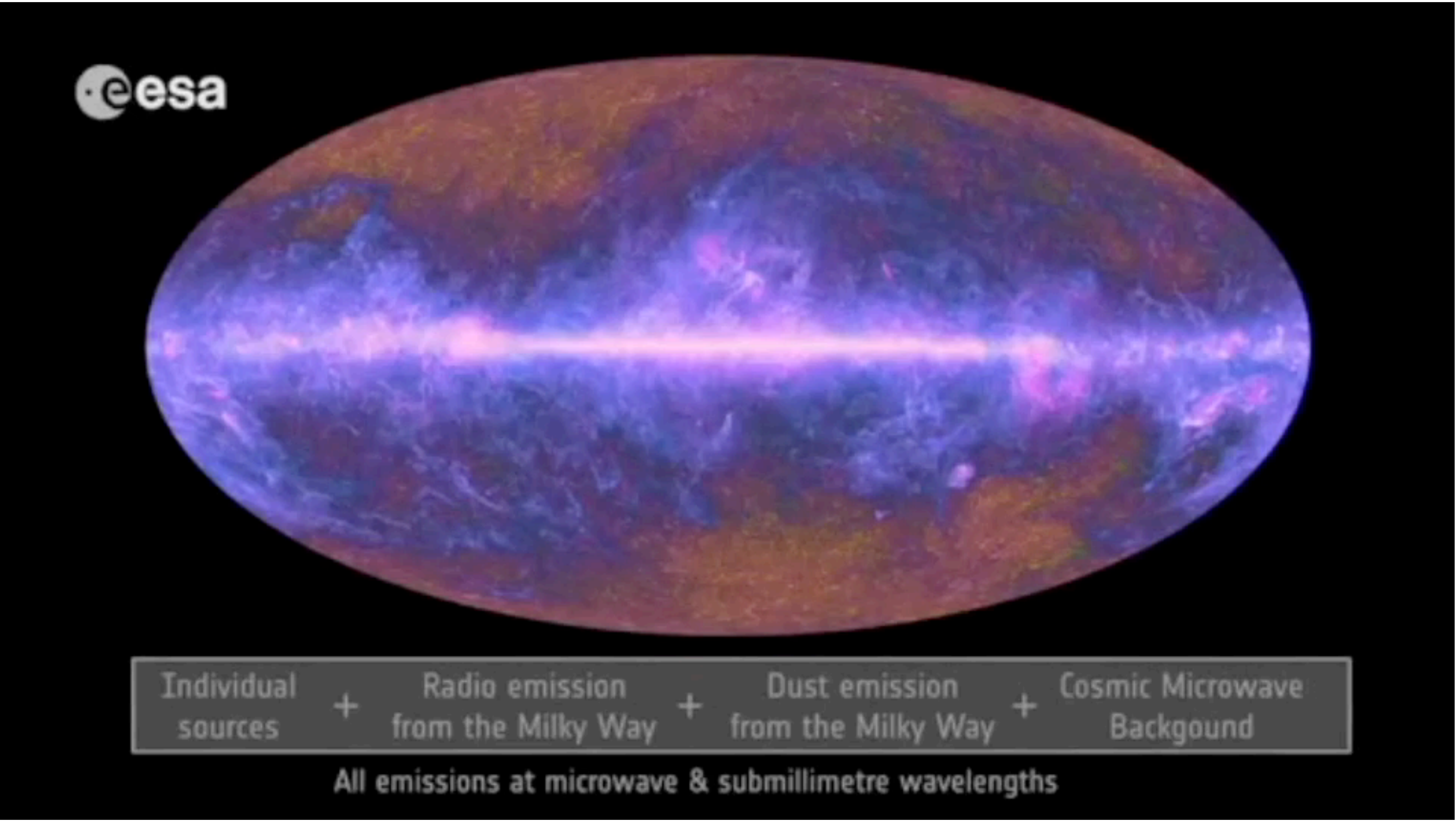
Spiderweb bolometer



Planck frequency maps



Cleaning foregrounds from the CMB



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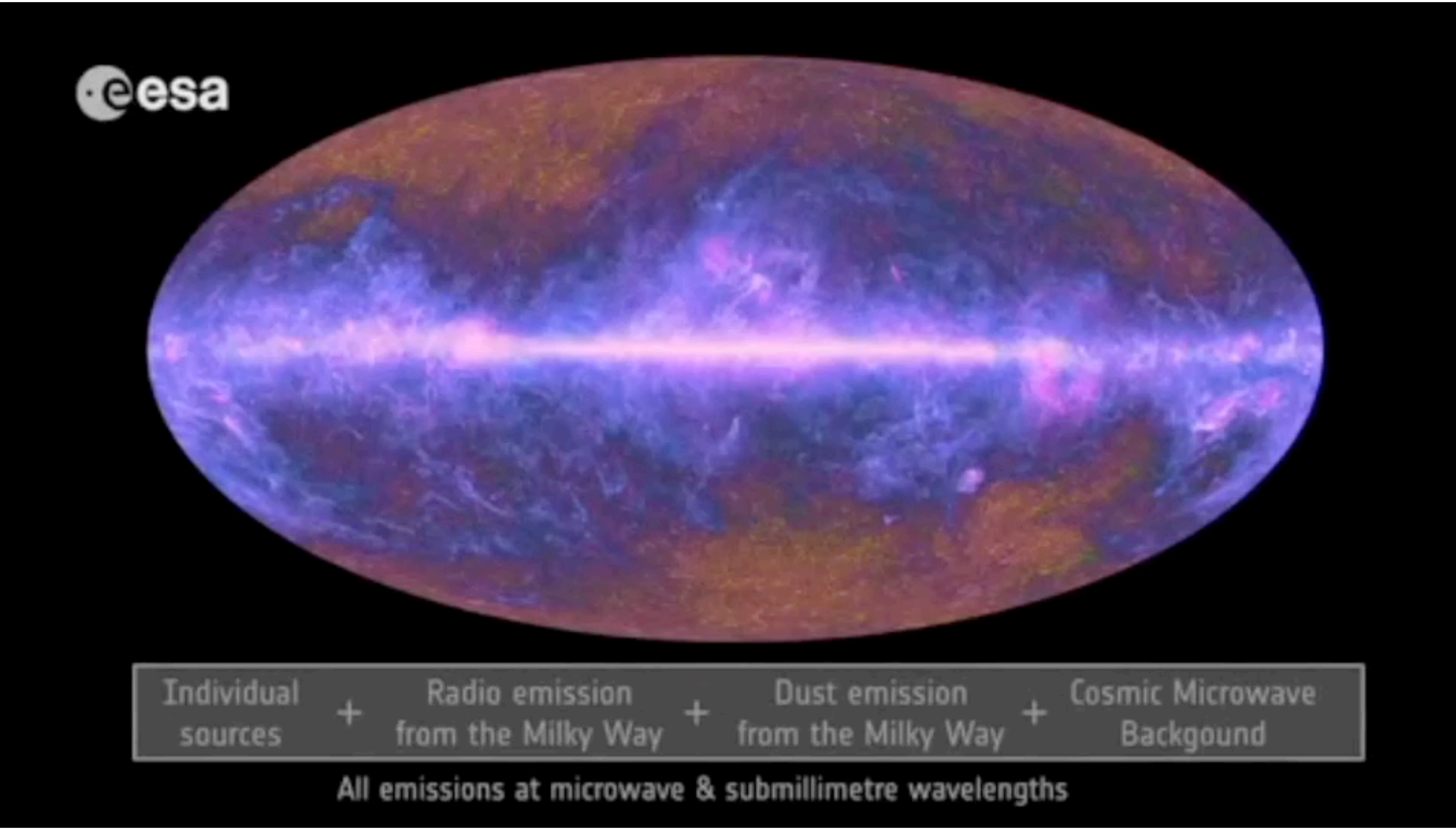
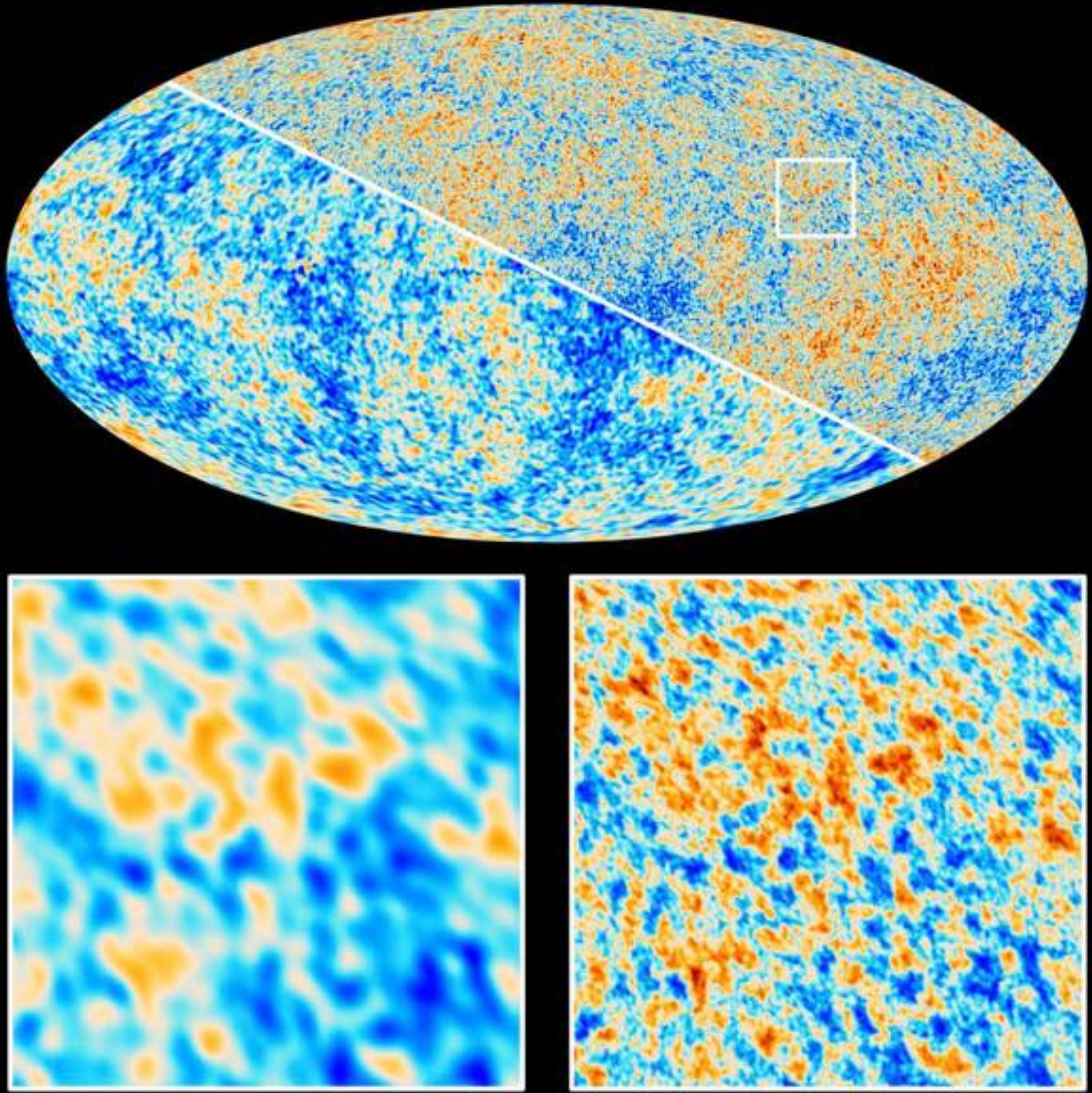


WMAP vs Planck

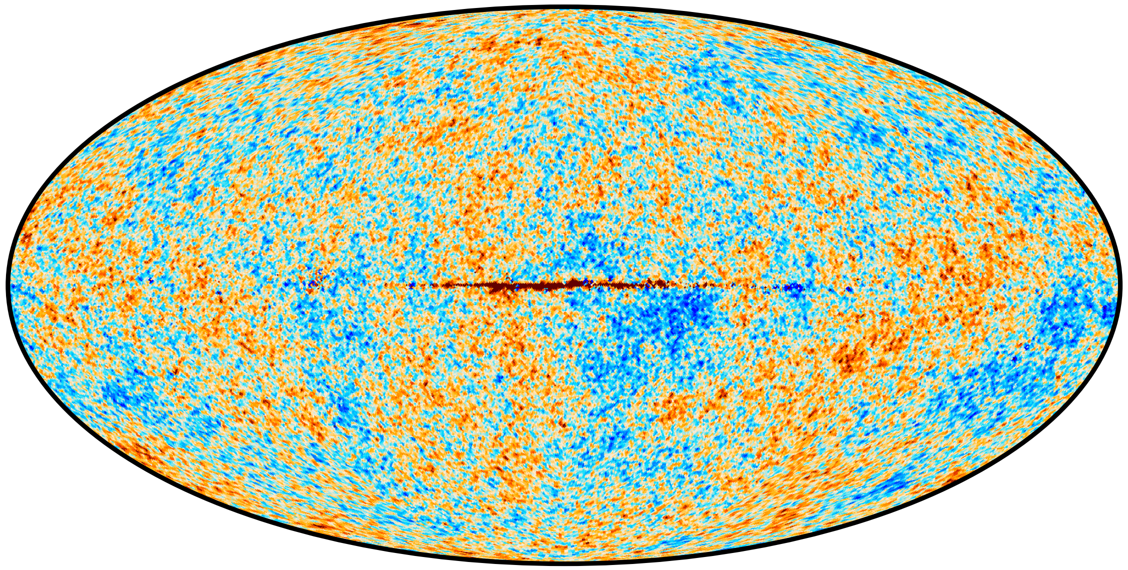


Foreground-cleaned CMB maps

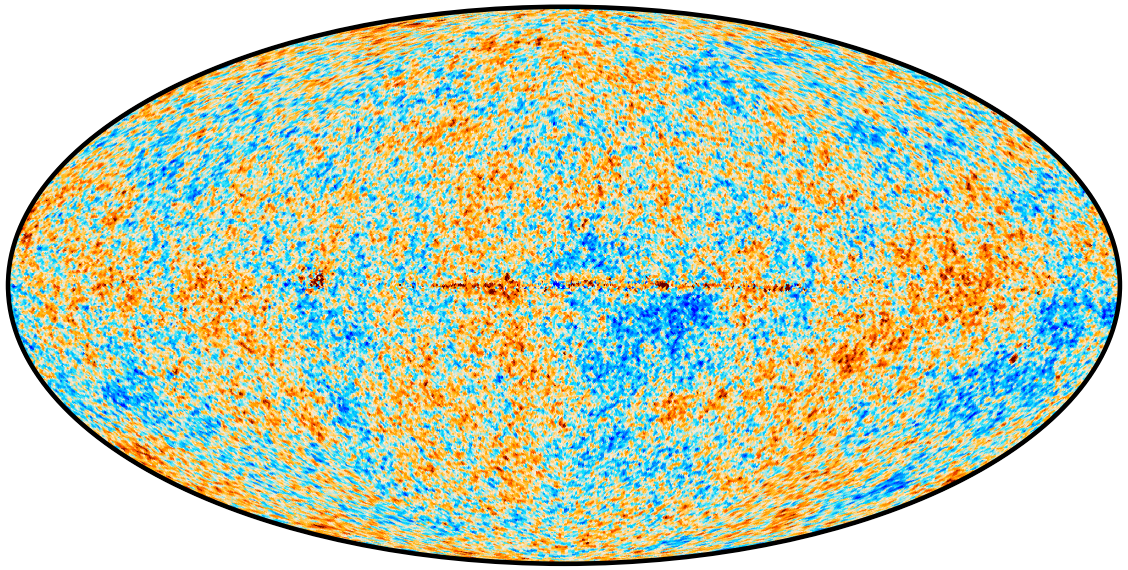
Commander-Ruler (C-R) - *Pixel domain: fits parametrized model of CMB and foregrounds*

Internal linear combination (NILC) *Needlet (wavelet) domain: minimizes variance of CMB signal*

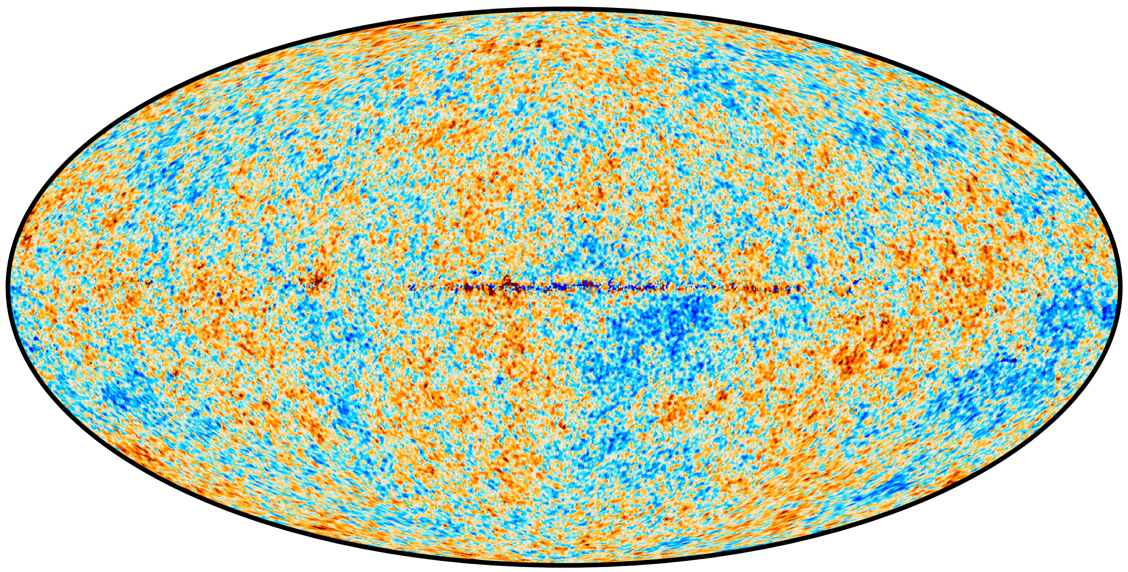
C-R



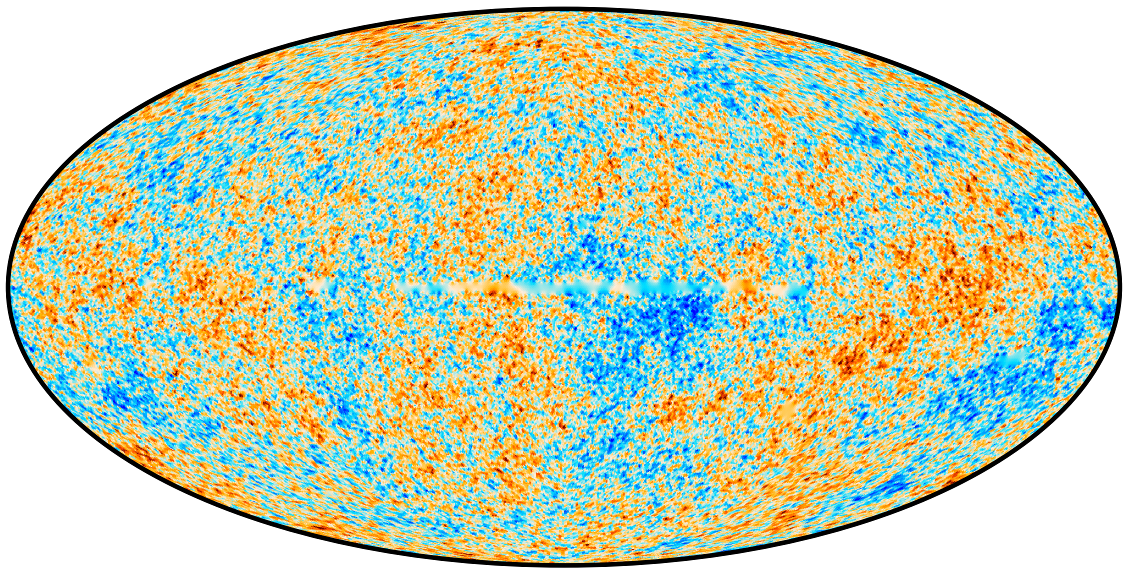
NILC



SEVEM



SMICA

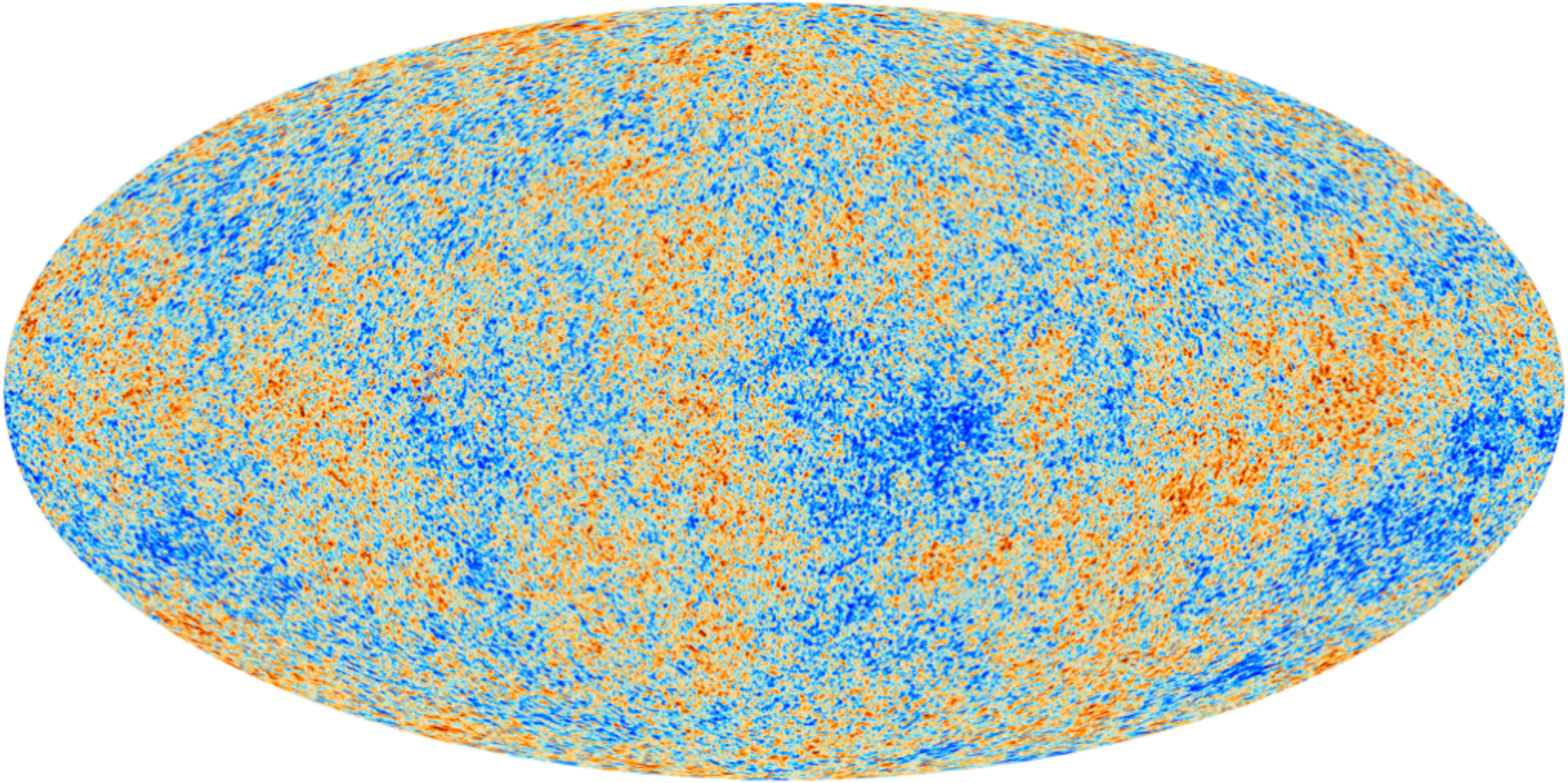


Template fitting (SEVEM) - *Pixel domain: removes templates found by subtracting frequency channels*

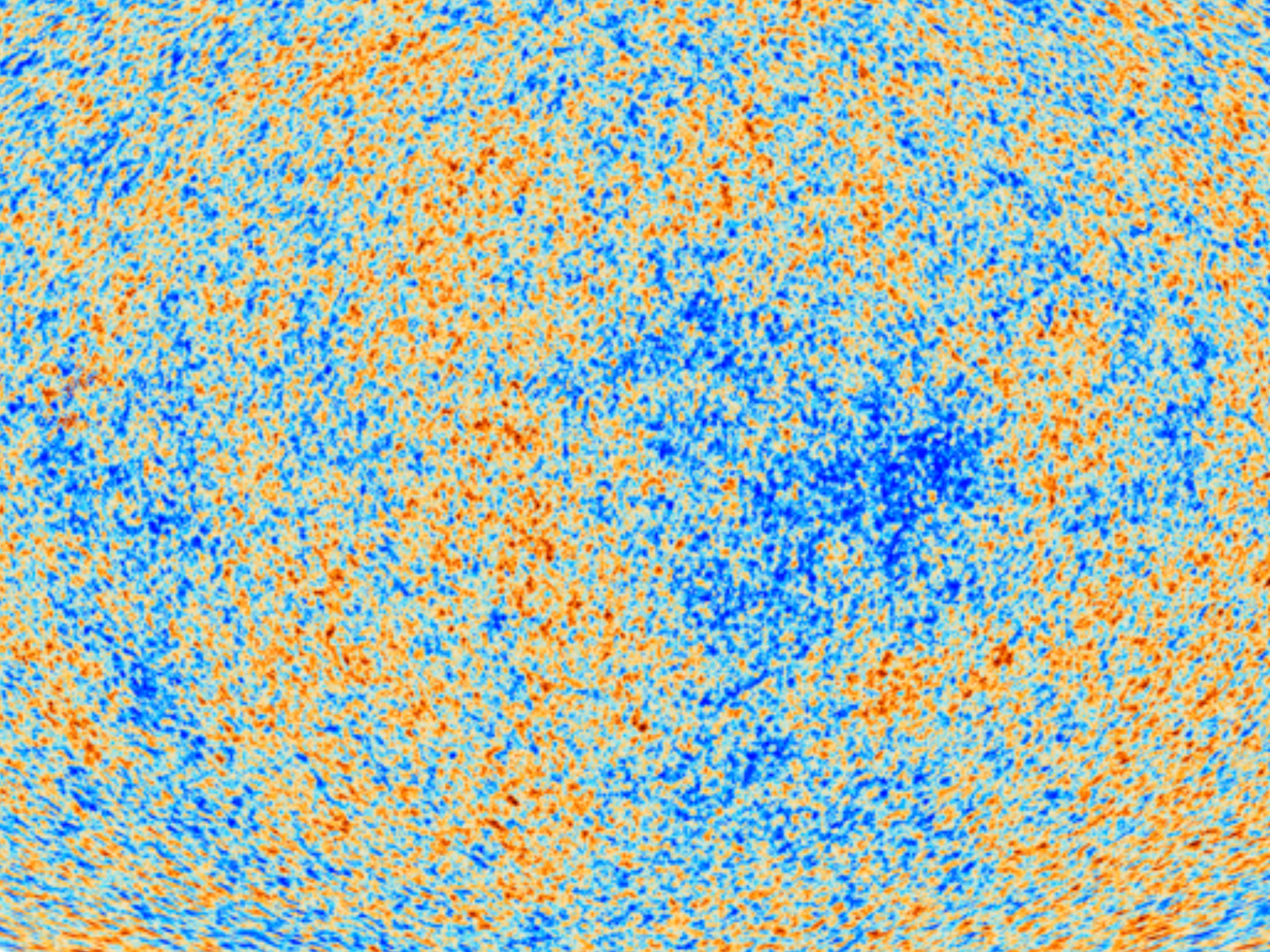
Spectral matching (SMICA) *Harmonic domain: fits model of foregrounds and solves for CMB*

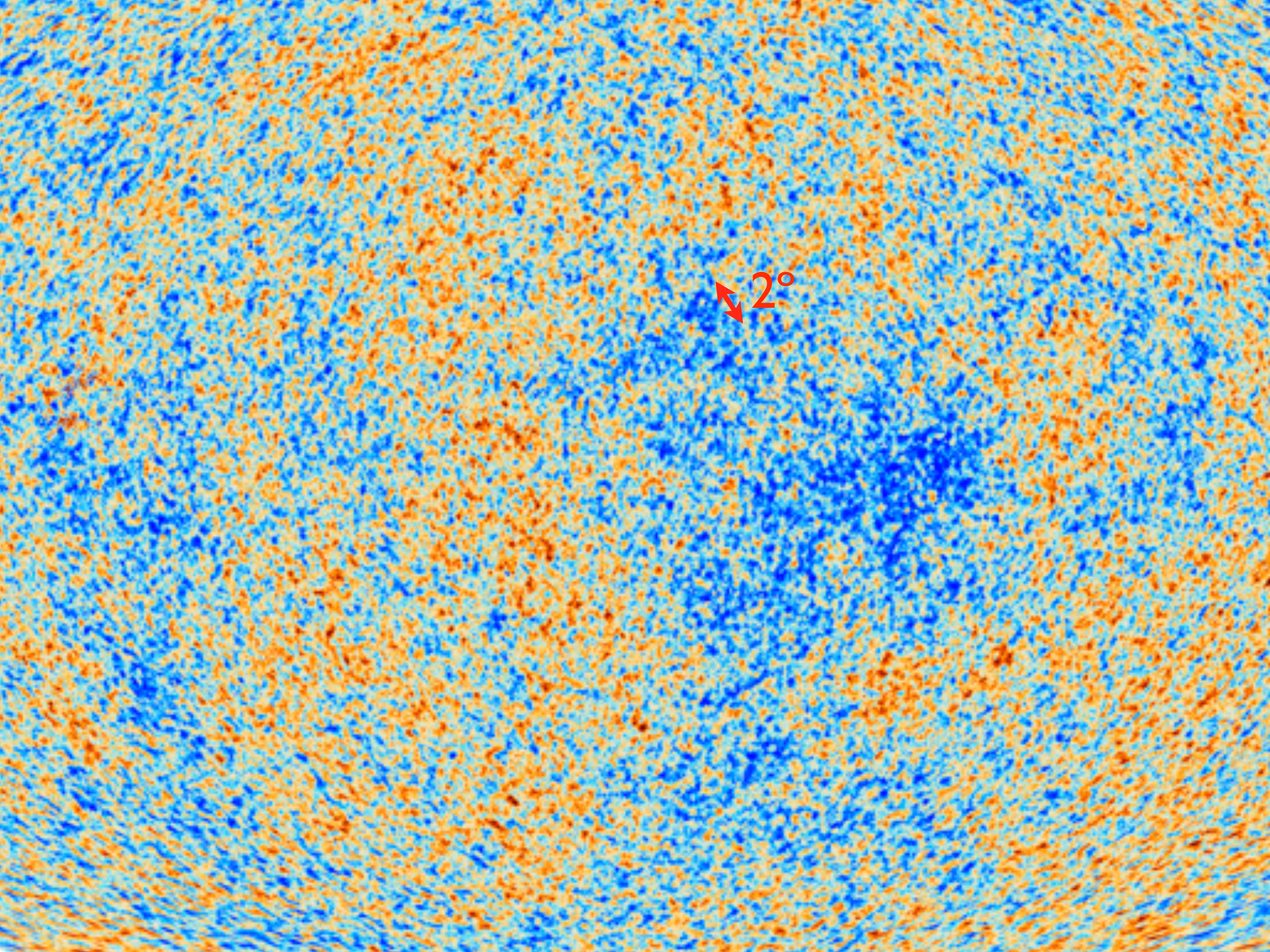
Planck SMICA CMB map

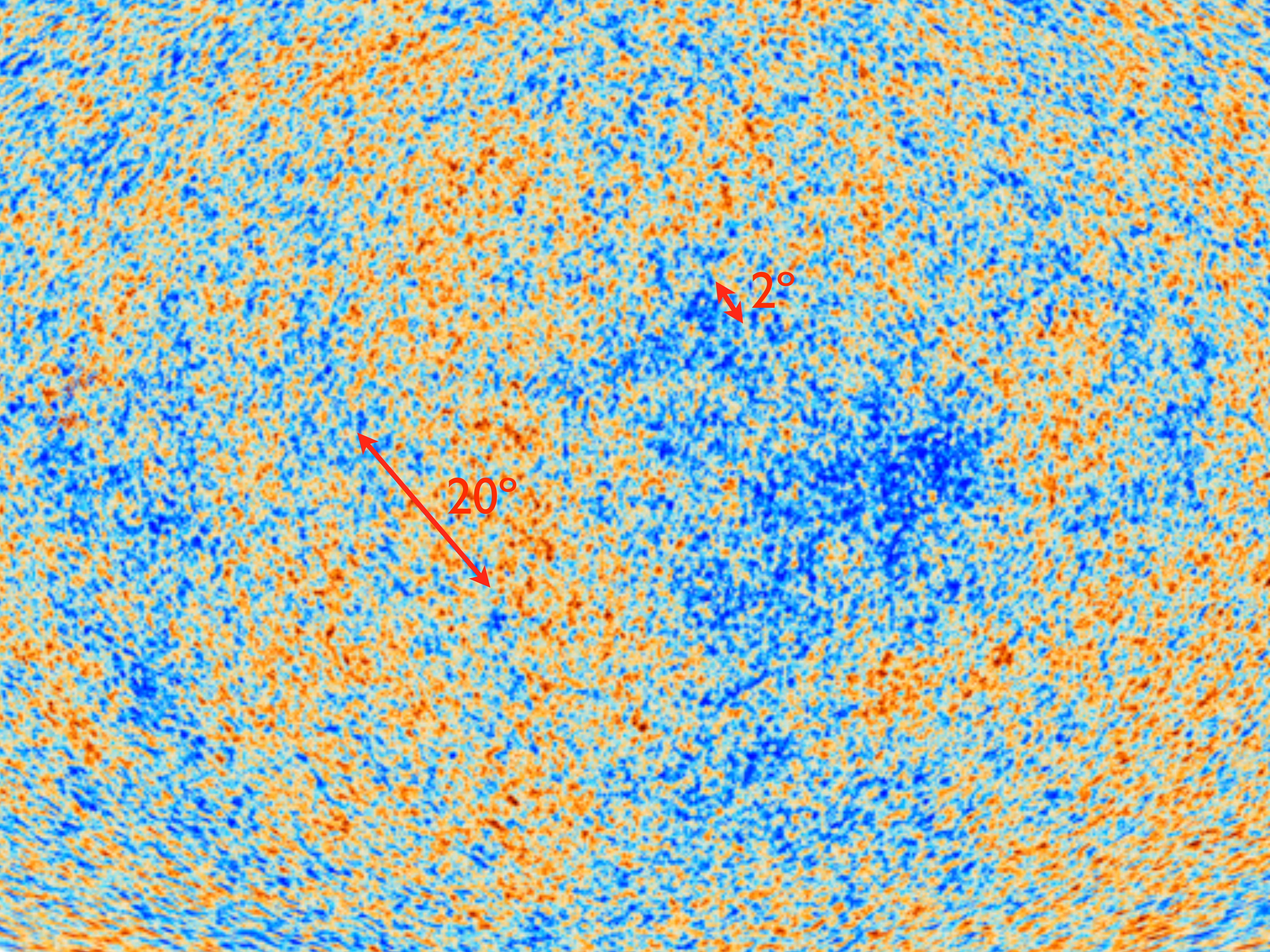
Leading method for high-l analysis - min. foreground residuals and preserves non-Gaussianity - the 3% processing mask has been filled in with a constrained realization



Key public data product from the Planck mission, refer to:
http://www.sciops.esa.int/index.php?project=planck&page=Planck_Legacy_Archive



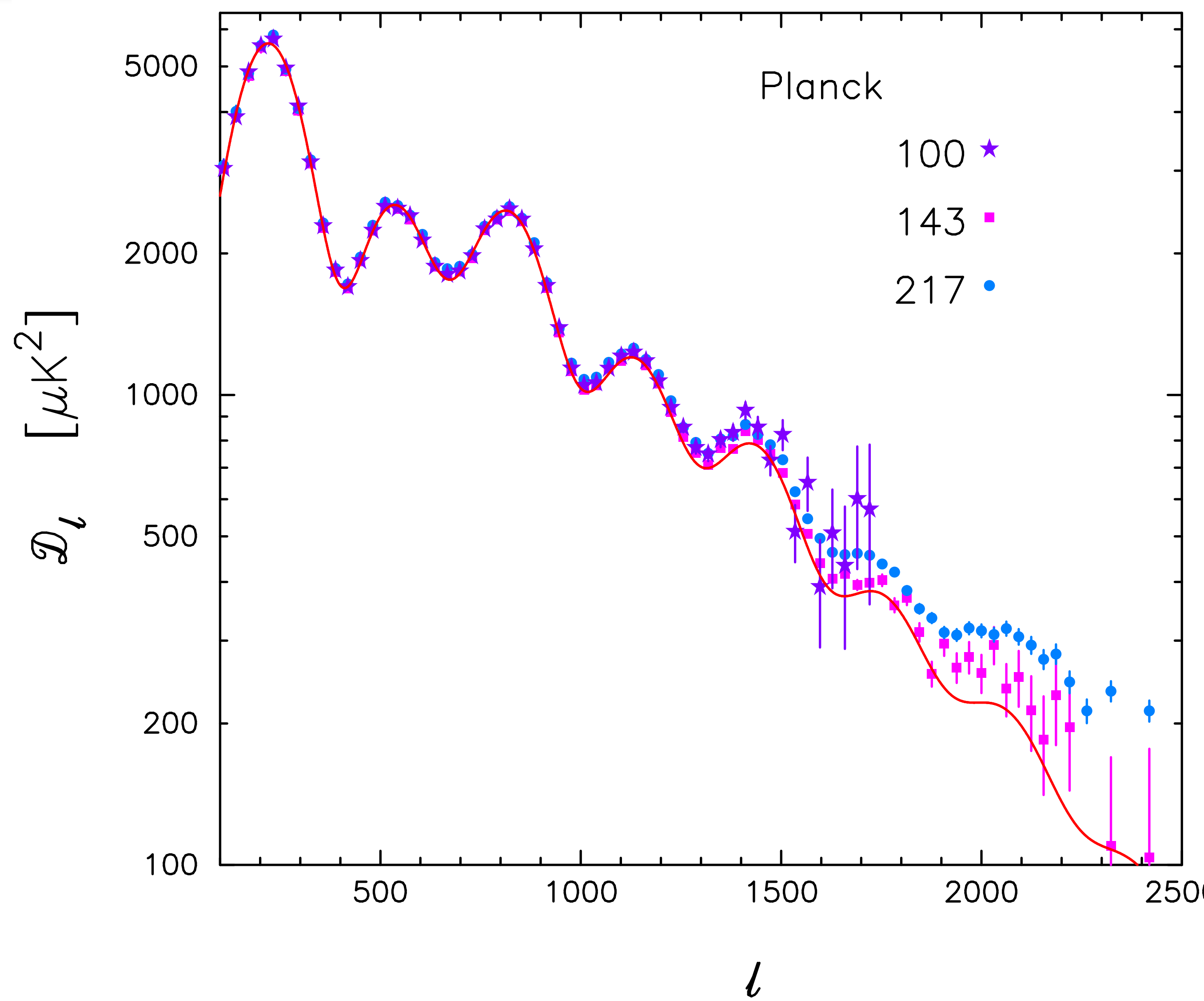

2°


2°
20°

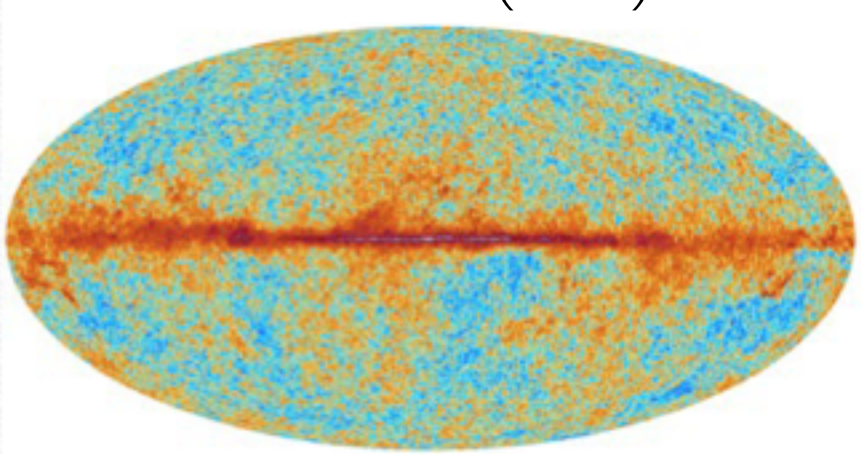
Planck power spectrum

Conservative spectral analysis

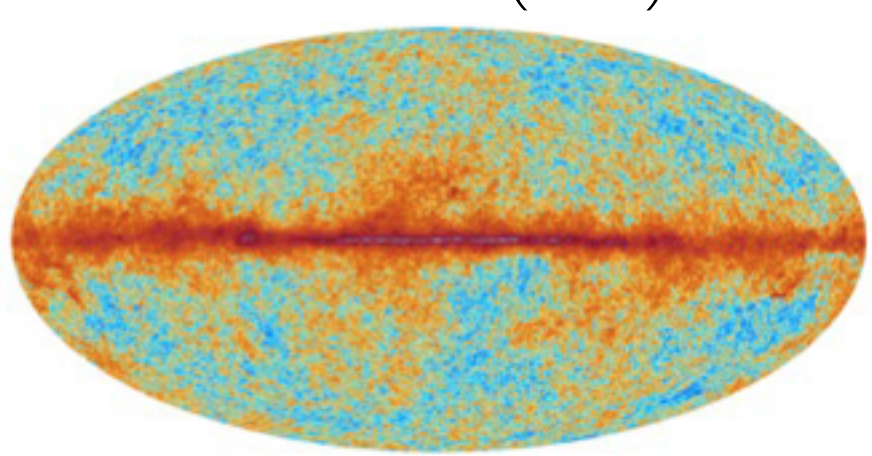
- *Uses small portions of the sky with minimal foreground contamination*
- *Uses detector cross-spectra to remove uncorrelated noise from power*
- *Non-CMB spectra at small-scales are modeled with extra parameters (dust, SZ, CIB etc)*
- *CMB likelihoods published ...*



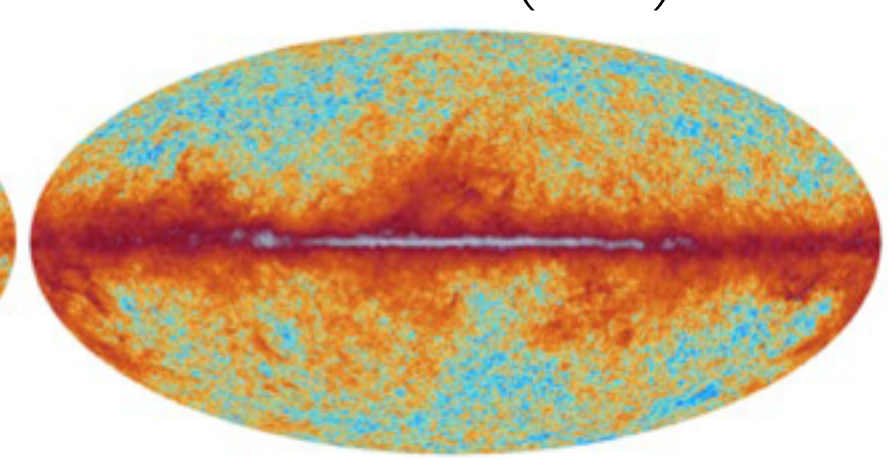
100 GHz (49%)



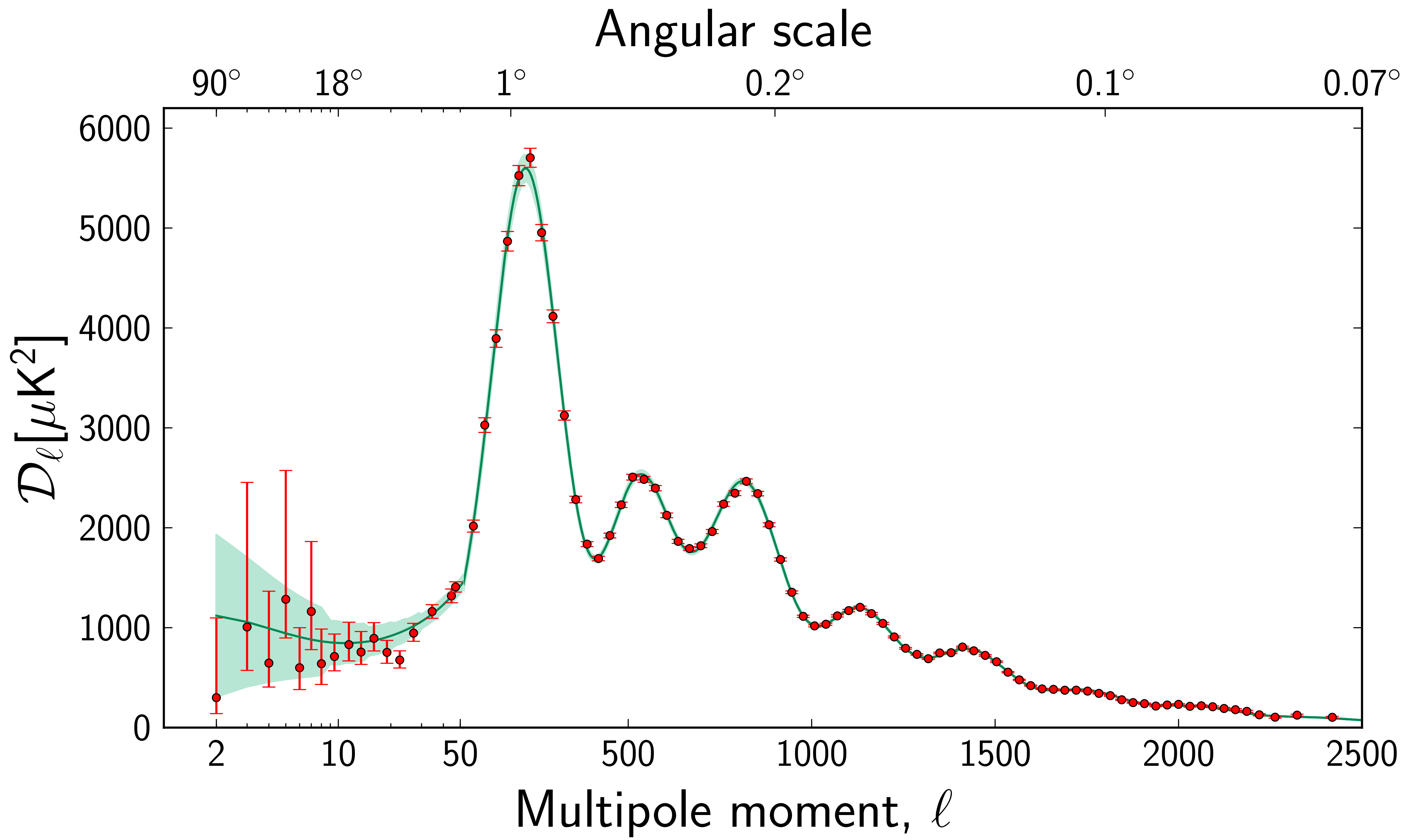
143 GHz (31%)



217 GHz (31%)



Planck CMB power spectrum



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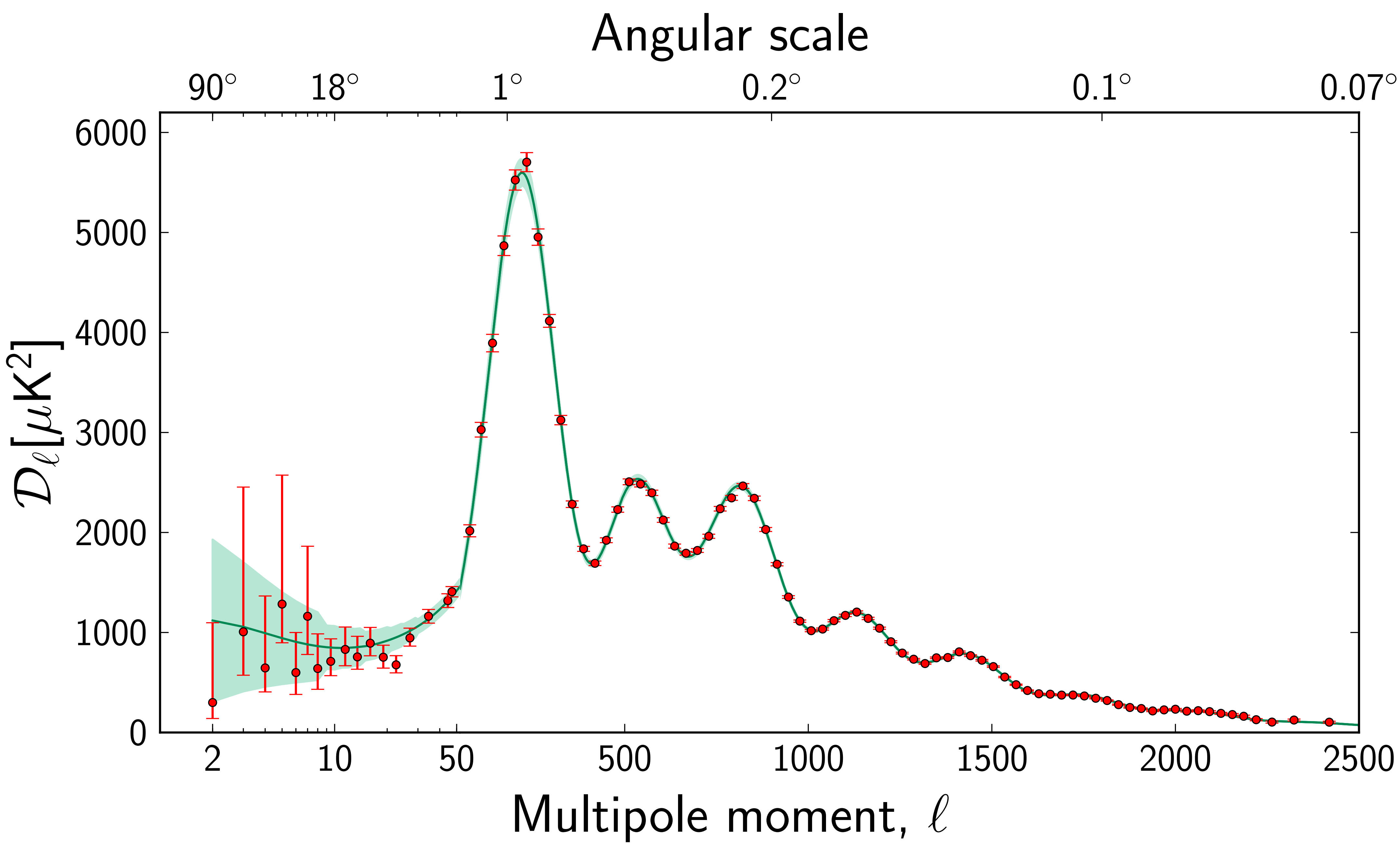
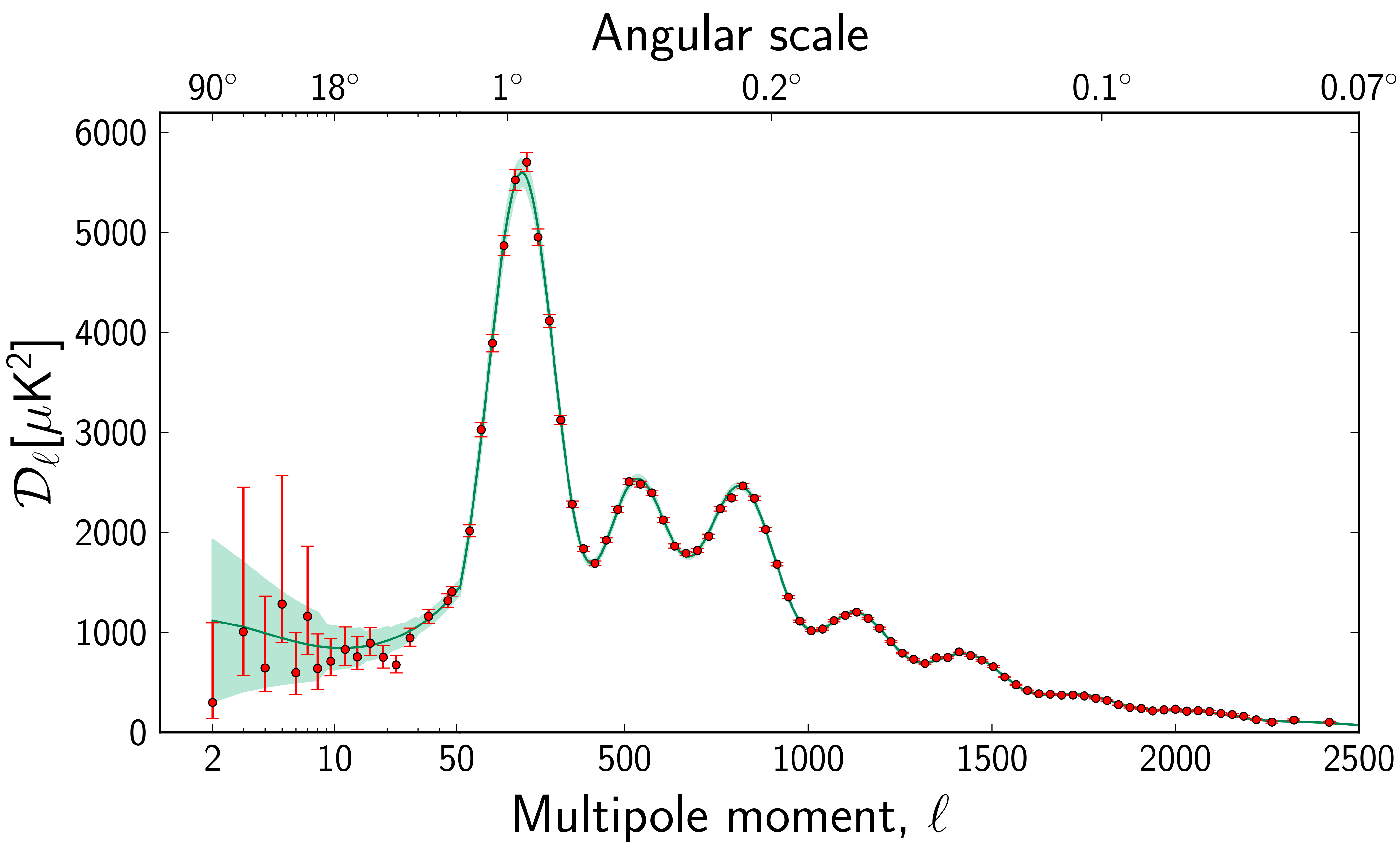


THE BIG QUESTIONS

Does standard ΛCDM still fit?

Does the inflationary paradigm work?
Which models are favoured?

Planck CMB power spectrum



THE BIG QUESTIONS

Does standard ΛCDM still fit?

Does the inflationary paradigm work?
Which models are favoured?

Is dark energy constant or is it dynamical?

What are neutrino masses?

Are there extra relativistic species?

Are there signatures of new physics?

ΛCDM cosmological parameters

Standard 6 parameter ΛCDM model fits the data well ...

Cosmological parameters from joint analysis
with Planck + WMAP-P + BAO (and priors)

• *Baryon density*	$\Omega_b h^2$	0.02207±0.00027
• *Cold dark matter*	$\Omega_c h^2$	0.1198±0.0026
• *Dark energy*	Ω_Λ	0.685±0.017
• *Hubble parameter*	H_0	67.3±1.2
• *Age of the Universe*	t_0	13.798 ± 0.037
• *Sound horizon*	$100\theta_*$	1.04148±0.00062
• *Matter fluctuation*	σ_8	0.828±0.012
• *Spectral index*	n_s	0.9585±0.0070
• *Optical depth*	τ	0.091±0.014
• *Reionization redshift*	z_{re}	11.1±1.1

ΛCDM cosmological parameters

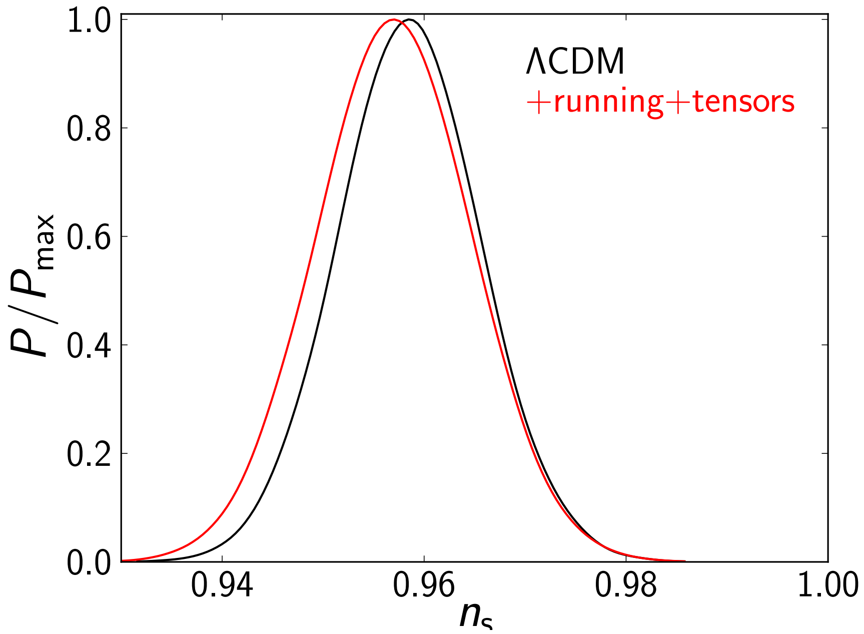
Standard 6 parameter ΛCDM model fits the data well ...

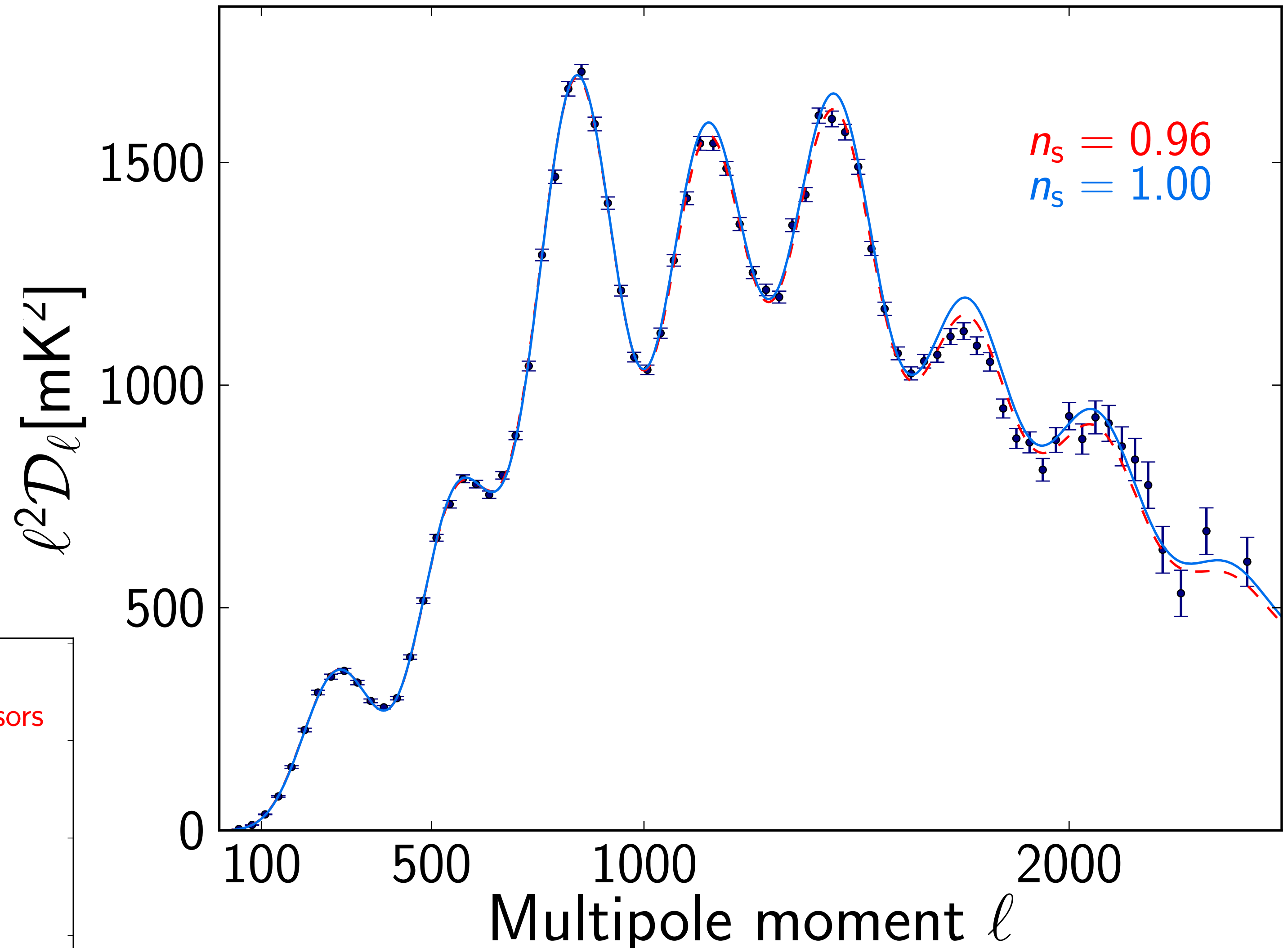
Cosmological parameters from joint analysis with Planck + WMAP-P + BAO (and priors)			Notable shifts from WMAP9 results
• *Baryon density*	$\Omega_b h^2$	0.02207±0.00027	*2.4% down*
• *Cold dark matter*	$\Omega_c h^2$	0.1198±0.0026	*5.4% up*
• *Dark energy*	Ω_Λ	0.685±0.017	*6.5% down*
• *Hubble parameter*	H_0	67.3±1.2	*3.9% smaller*
• *Age of the Universe*	t_0	13.798 ± 0.037	*0.4% older*
• *Sound horizon*	$100\theta_*$	1.04148±0.00062	.
• *Matter fluctuation*	σ_8	0.828±0.012	.
• *Spectral index*	n_s	0.9585±0.0070	.
• *Optical depth*	τ	0.091±0.014	.
• *Reionization redshift*	z_{re}	11.1±1.1	.

Implications for Inflation

Scalar spectral index n < 1

Scale-invariant HZ spectrum has insufficient power on small scales (ruled out at 5σ) $n_s = 0.960 \pm 0.007$





See earlier inflationary constraints

Parameters from extended models

Planck offered no compelling evidence for additions to standard ΛCDM

• Curvature parameter	Ω_k	-0.0005±0.0066
• Neutrino masses	Σm_ν	< 0.23 eV
• Spin degrees	N_{eff}	3.30±0.54
• Helium fraction	Y_P	0.267±0.040
• Running spectral index	$dn_s/d\ln k$	-0.014±0.017
• Tensor-scalar ratio	$r_{0.002}$	< 0.11
• Equation of state	w	-1.13±0.24

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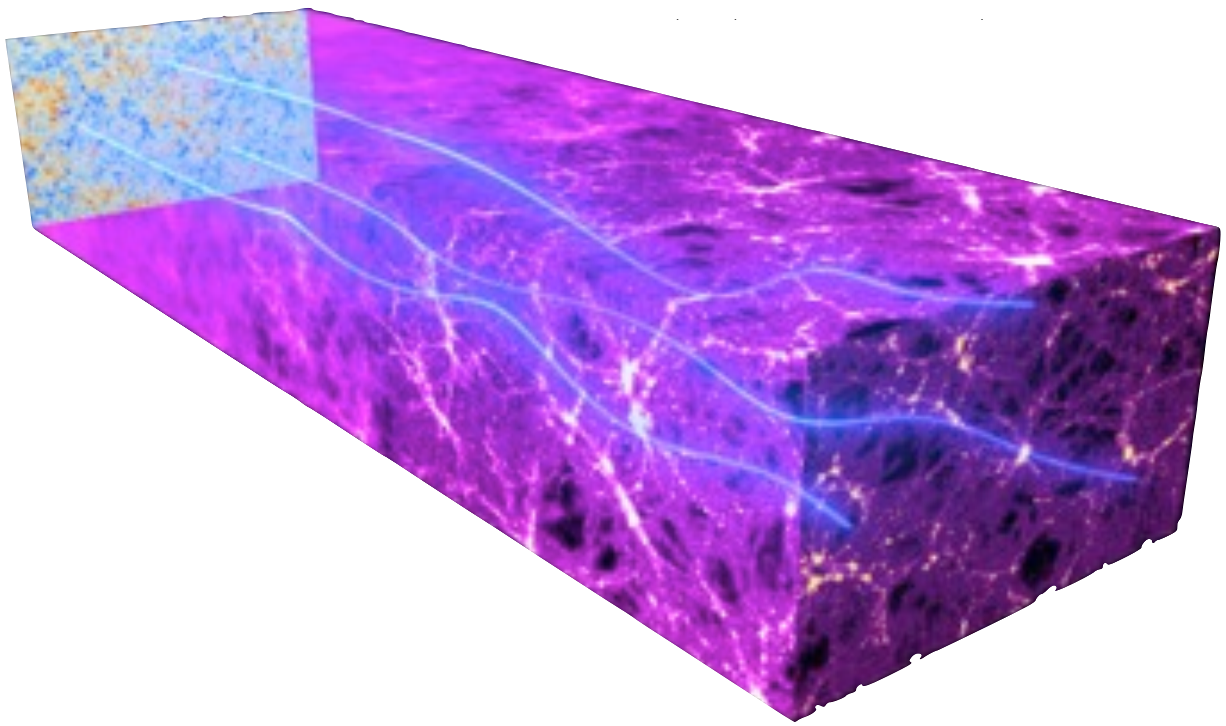
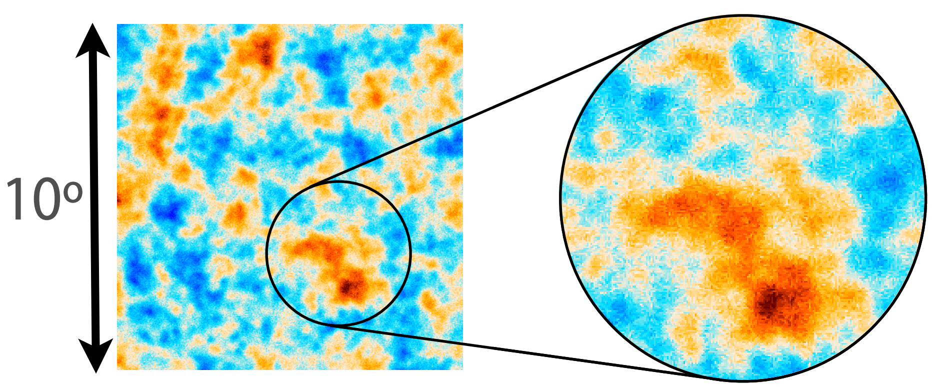
All changed with BICEP2 results, with consistency requiring e.g. (beyond r)

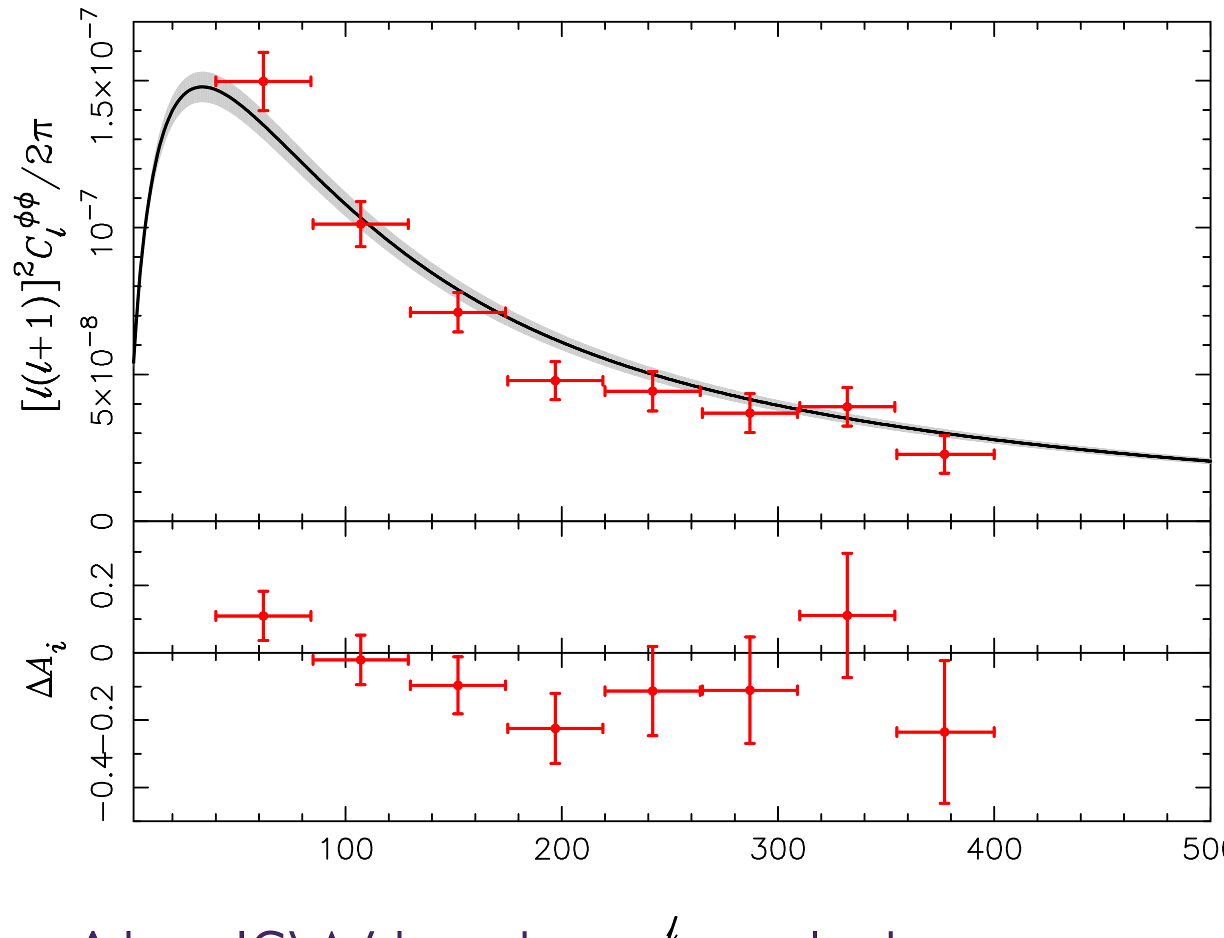
- Running spectral index
- Sterile neutrino species
- Tilt of tensor modes etc …

Gravitational lensing

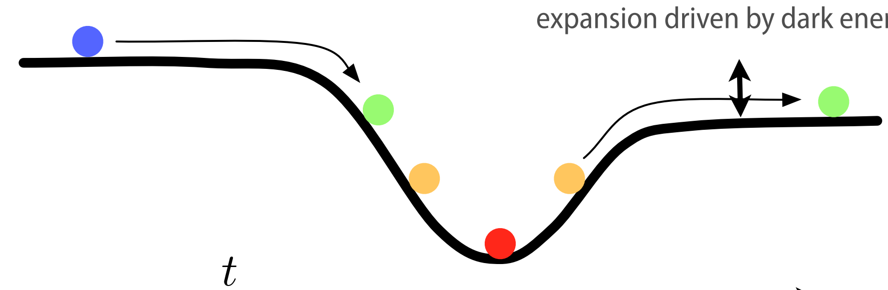




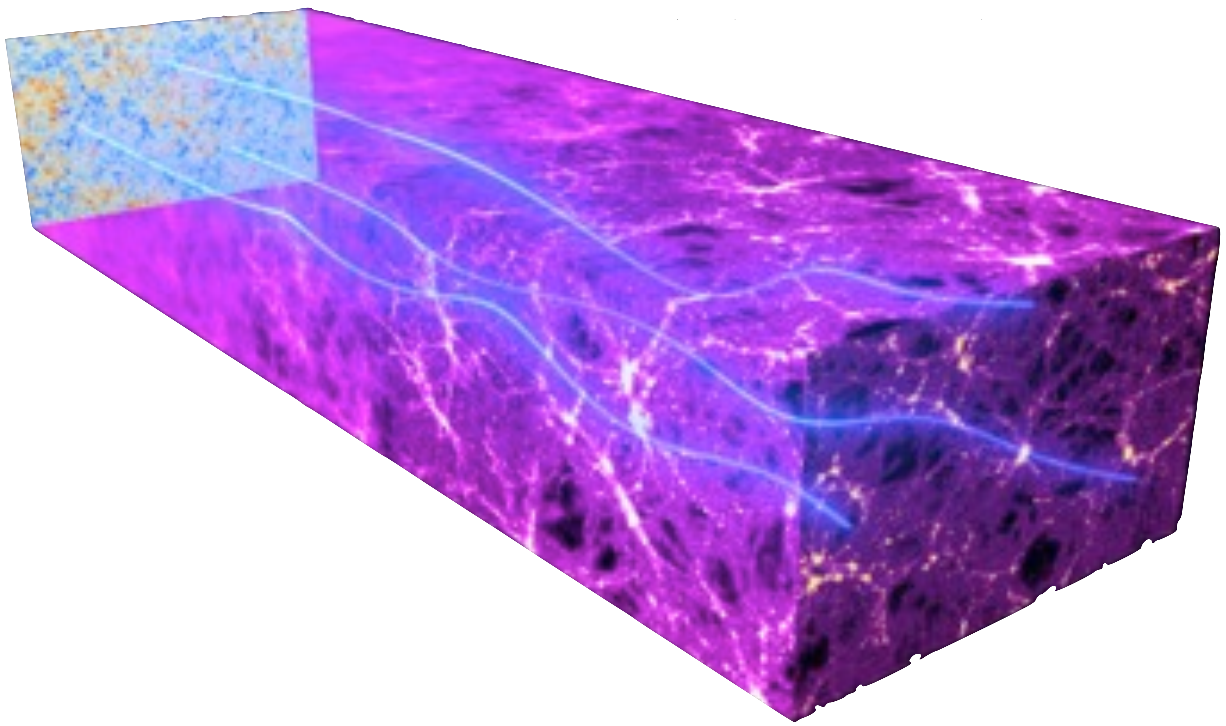
Gravitational lensing signal detected at high significance

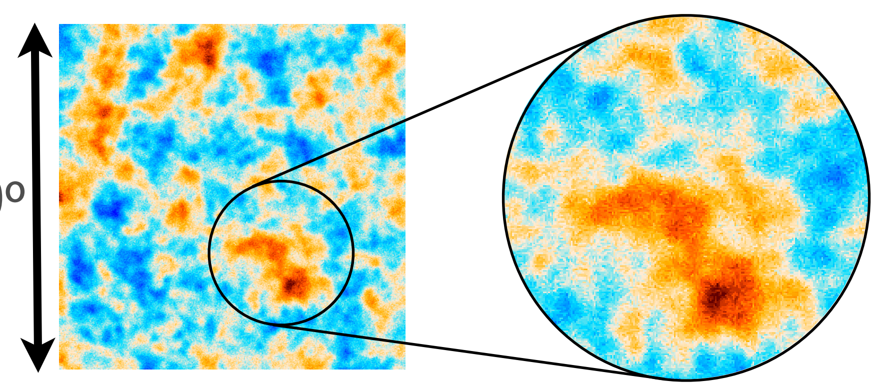


Also ISW-lensing correlations detected at 2.5**σ** (see later)



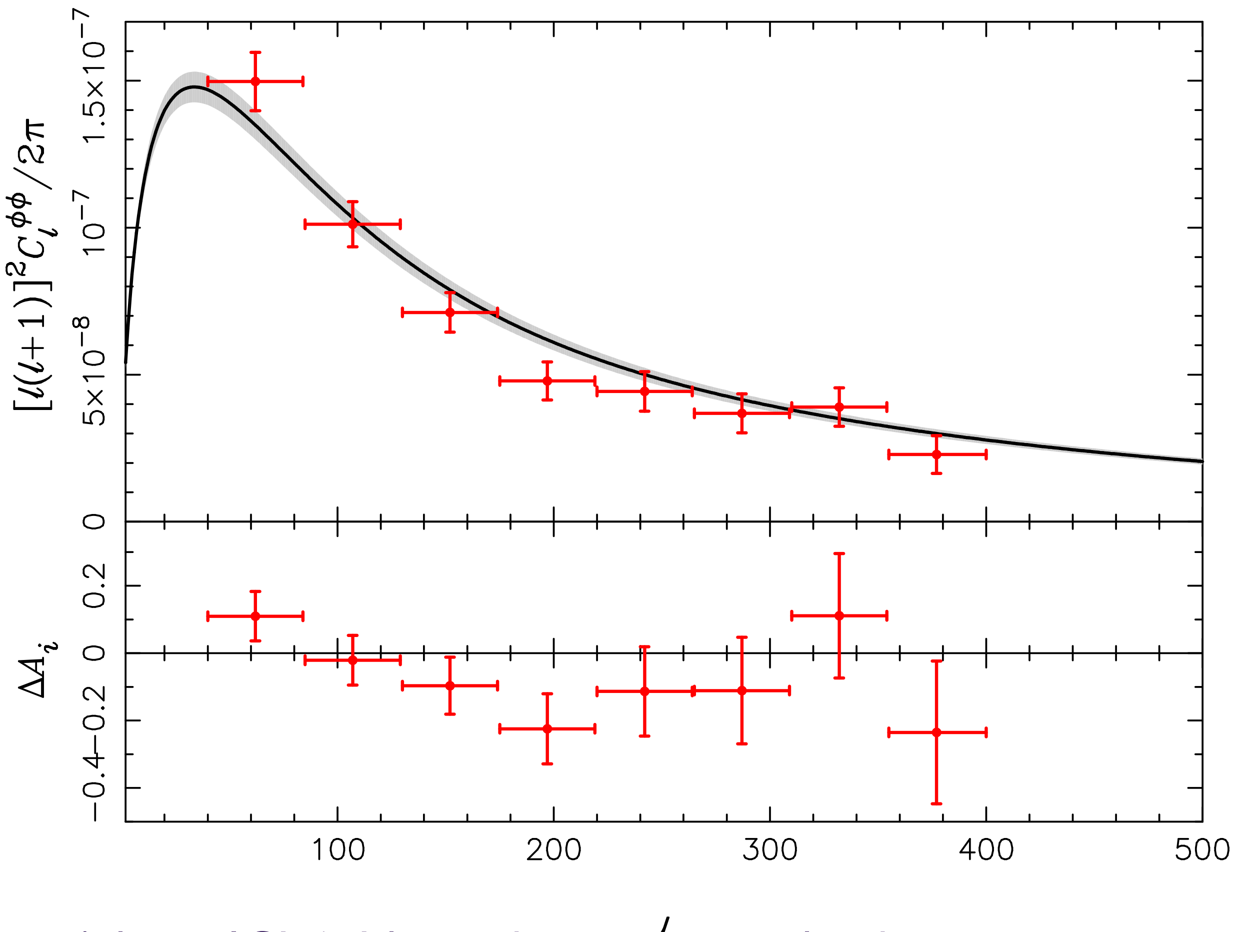
Gravitational lensing



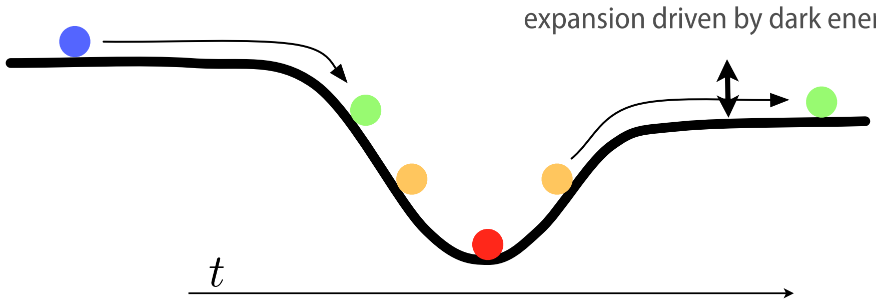


Lensed

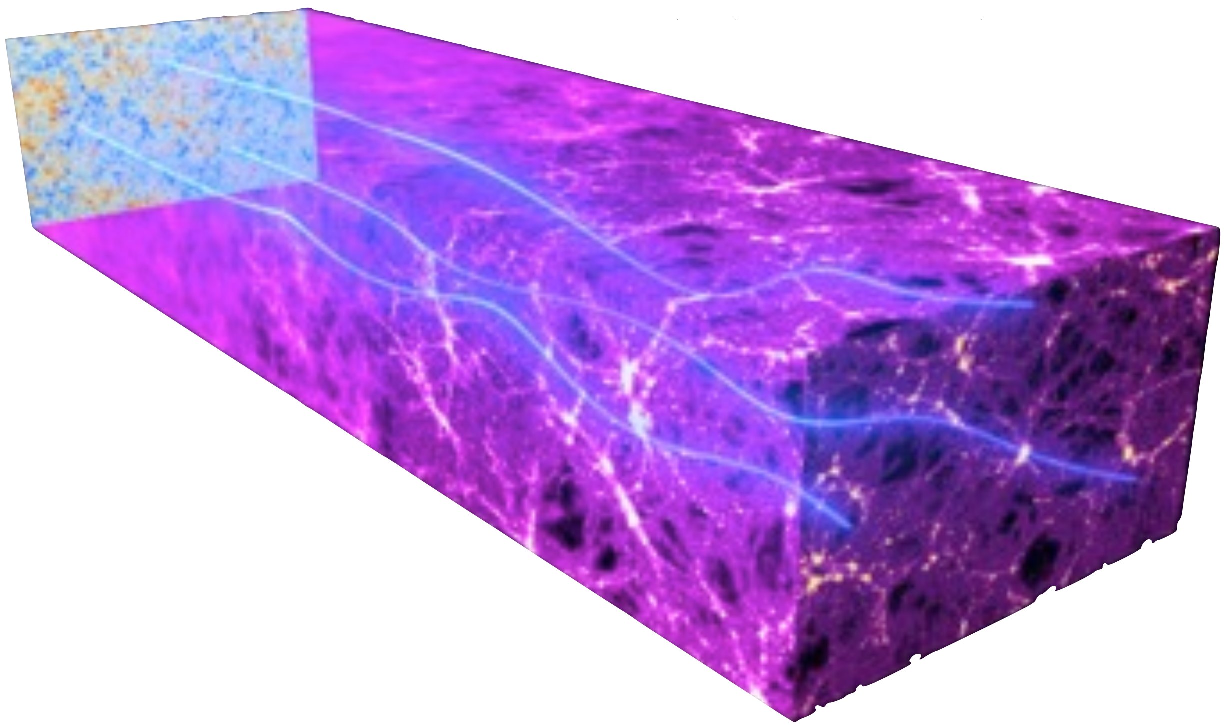
Gravitational lensing signal detected at high significance

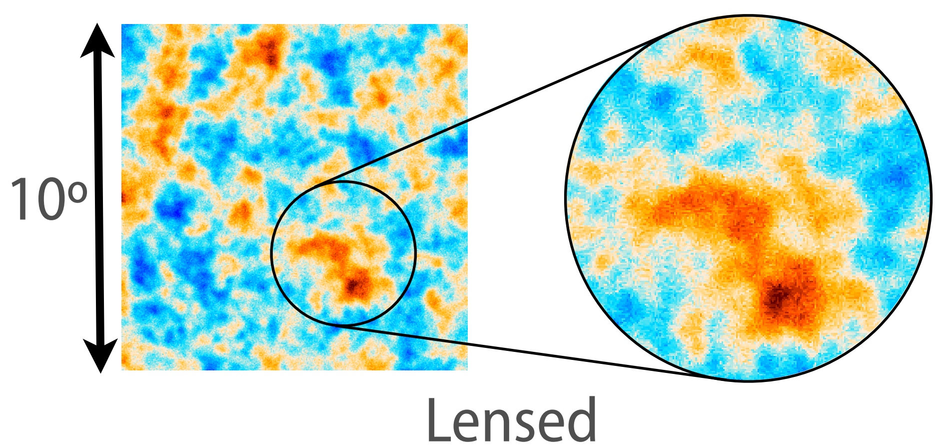


Also ISW-lensing correlations detected at 2.5σ (see later)



Gravitational lensing





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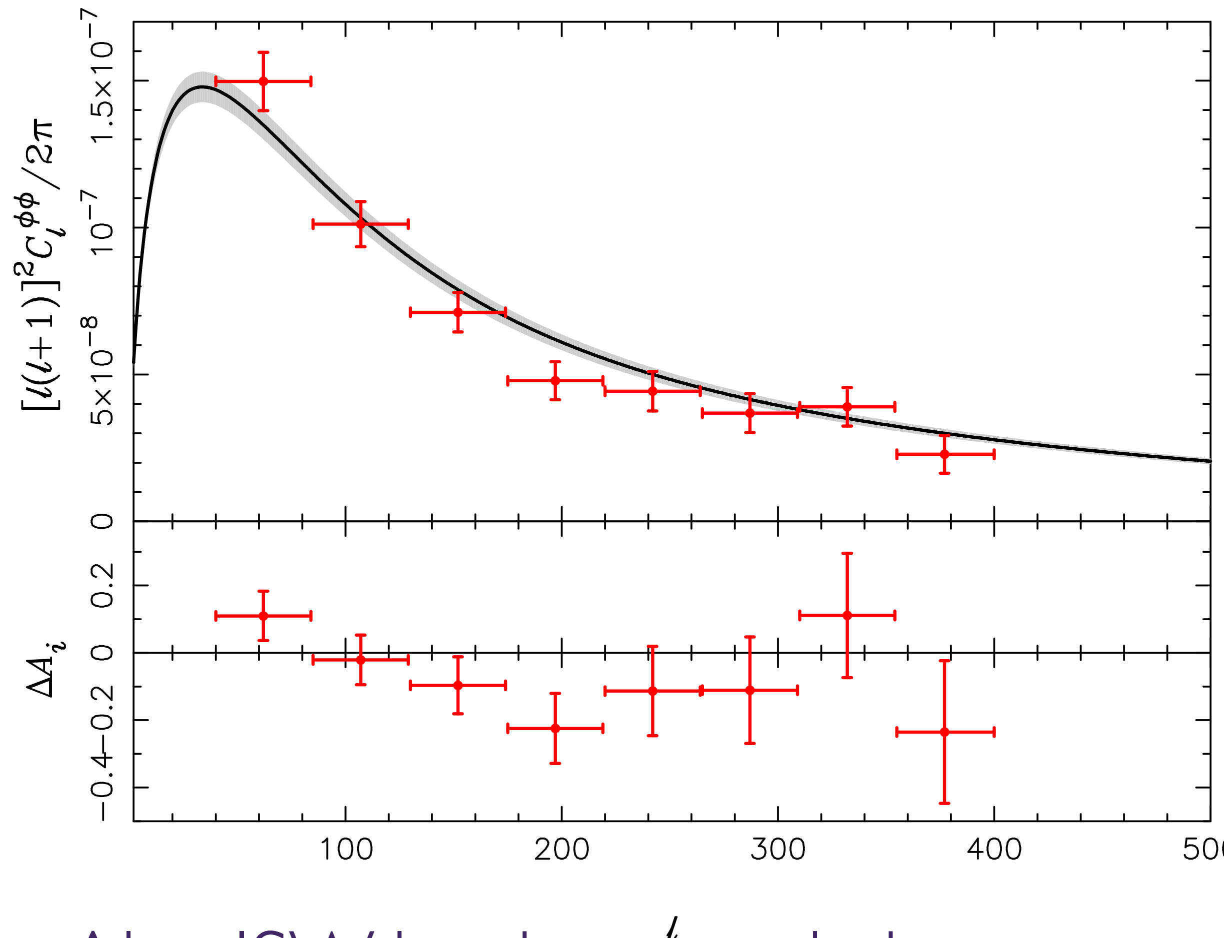

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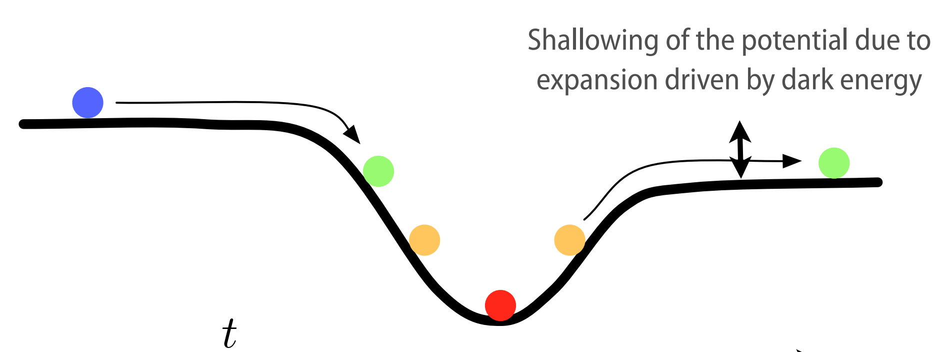
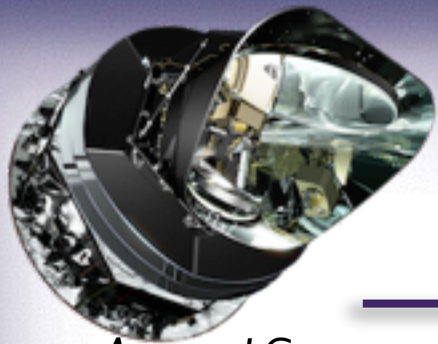


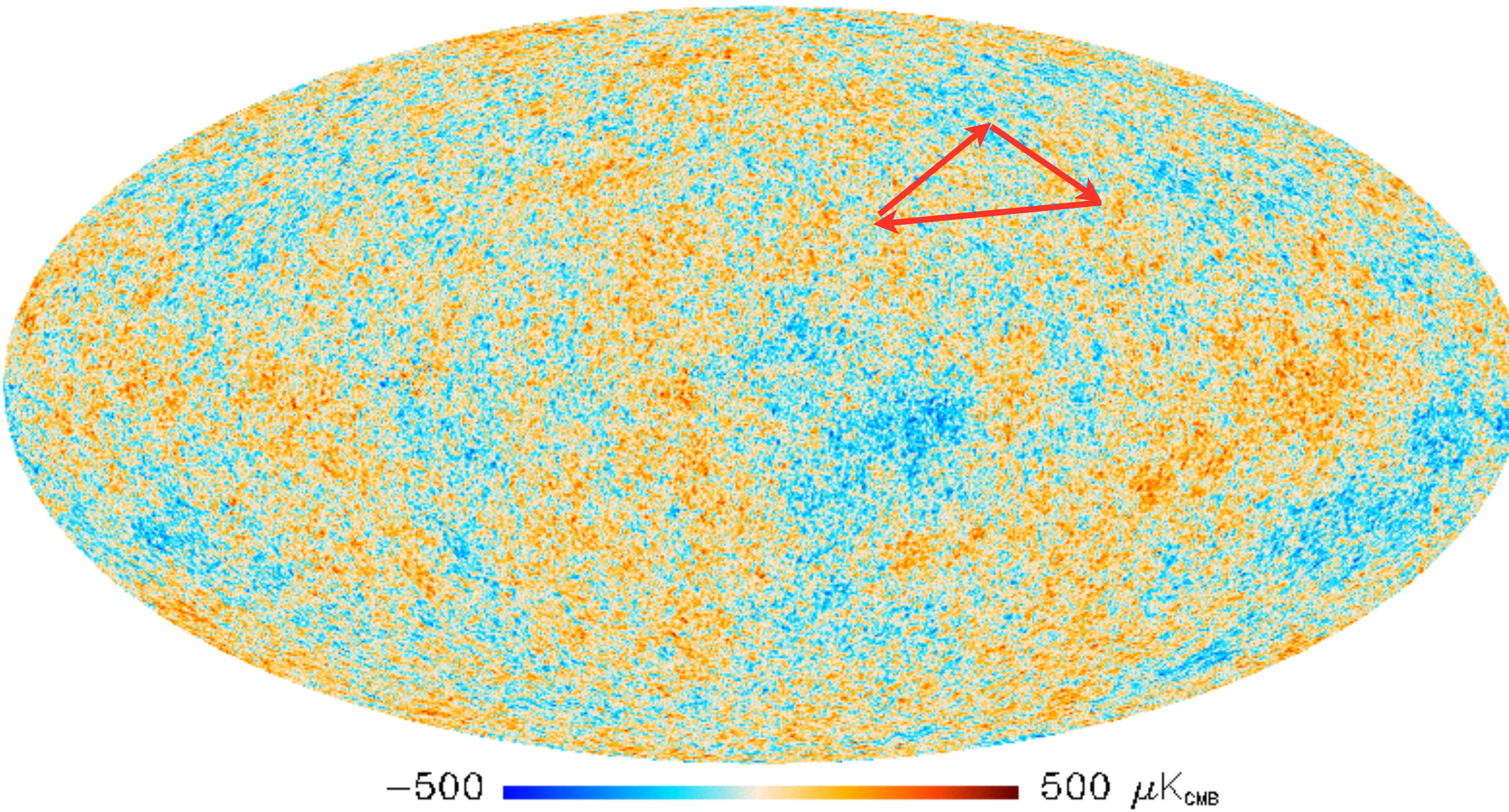
SZ cluster science: Also promising exploiting new Planck SZ clusters

Like lensing results remains in tension ...

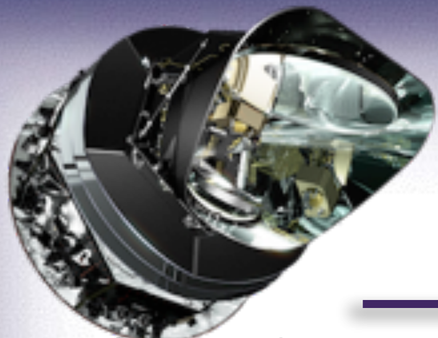


Non-Gaussianity

A self-consistent concordance model based on two-point correlator or C_l's



The CMB Bispectrum - 3pt correlator or "triangles in the sky"



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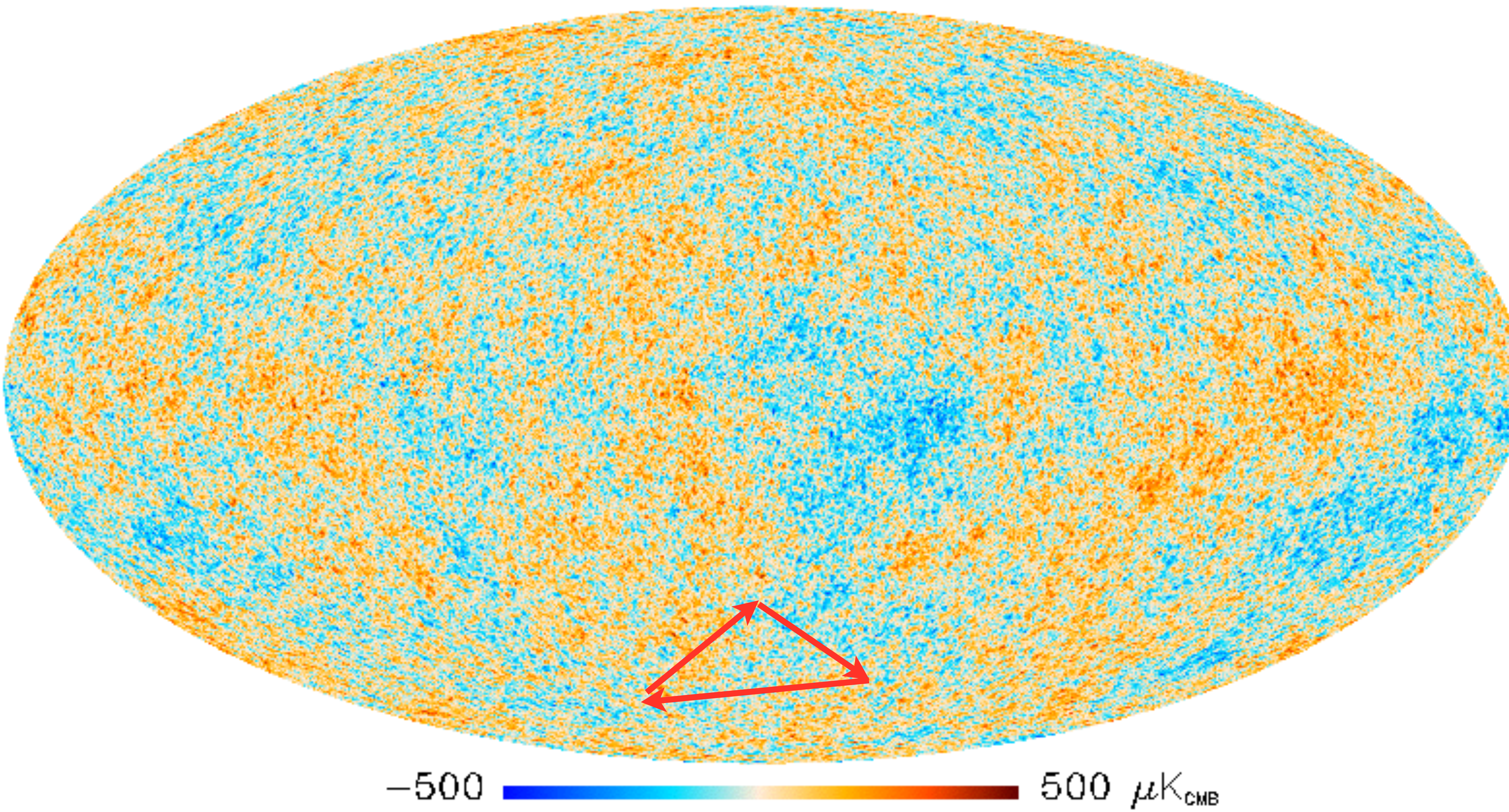


The CMB Bispectrum - 3pt correlator or "triangles in the sky"

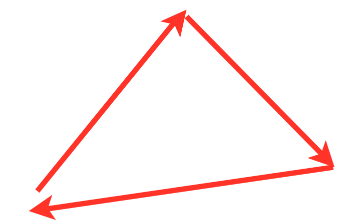
Tetrapyd - Bispectrum domain

Allowed multipoles l_1, l_2, l_3 for the CMB bispectrum live in the domain

Resolution: $l_1, l_2, l_3 \le l_{\max}\,, \quad l_1, l_2, l_3 \in \mathbb{N}\,,$

Triangle condition: $l_1 \le l_2 + l_3$ for $l_1 \ge l_2,\, l_3,$ + cyclic perms.

Parity condition: $l_1 + l_2 + l_3 = 2n\,, \quad n \in \mathbb{N}\,.$



Reduced bispectrum $b_{l_1 l_2 l_3}$ from primordial bispectrum $B(k_1,k_2,k_3)$

$$b_{l_1l_2l_3} = \left(\frac{2}{\pi}\right)^3 \int x^2 dx \int dk_1 dk_2 dk_3 (k_1k_2k_3)^2 B(k_1,k_2,k_3) \Delta_{l_1}(k_1)\Delta_{l_2}(k_2)\Delta_{l_3}(k_3) j_{l_1}(xk_1) j_{l_2}(xk_2) j_{l_3}(xk_3)$$

Primordial bispectrum

Transfer functions

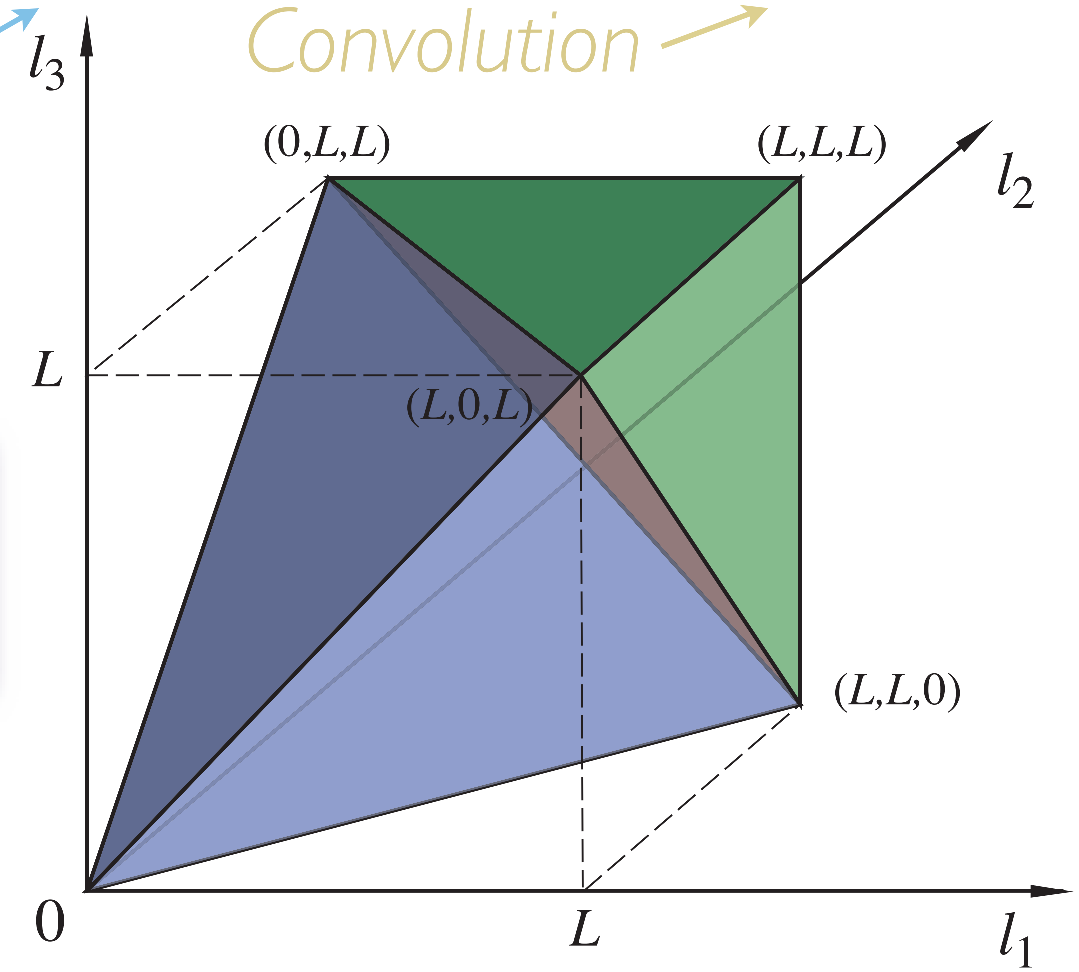
Convolution

Inner product:

Defined by estimator sum

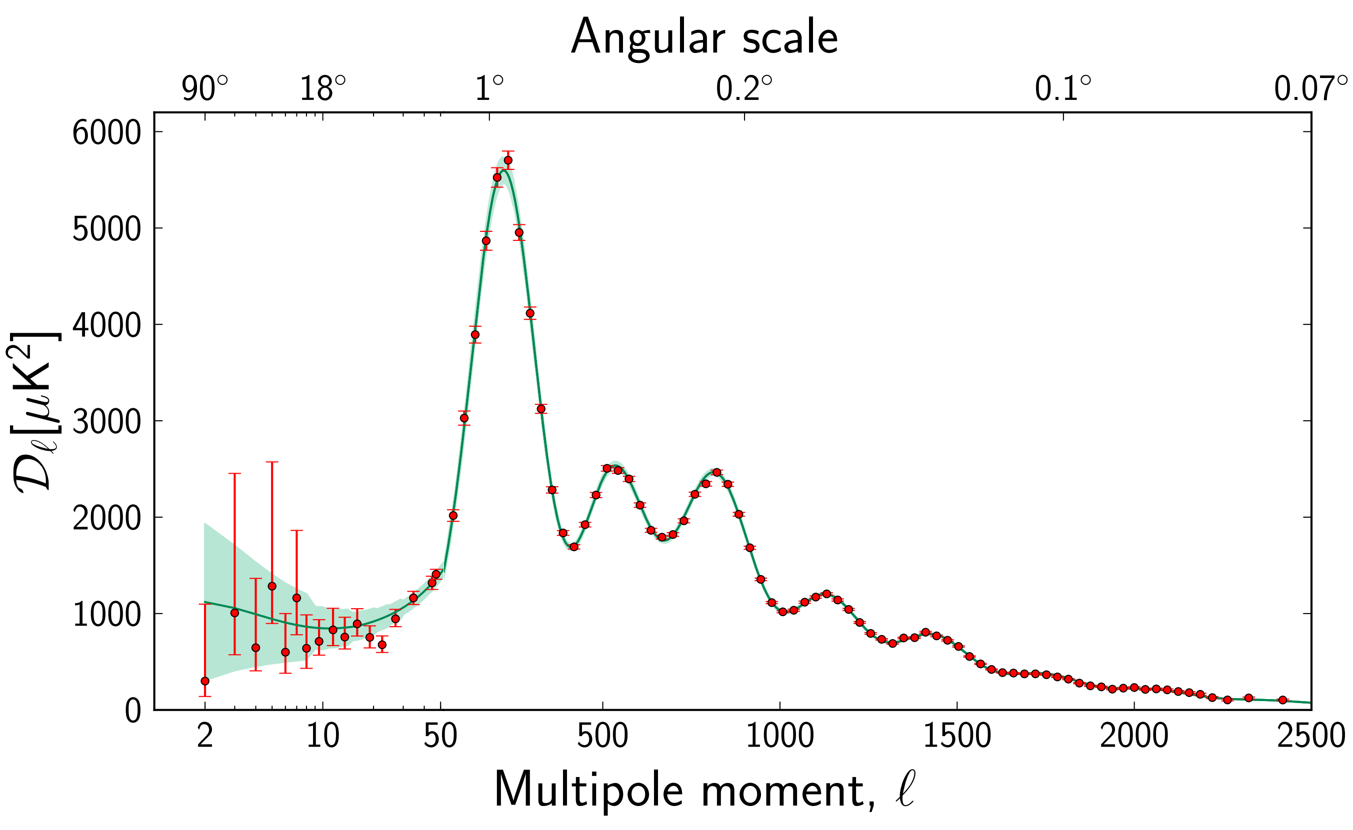
$$\langle b,\, b' \rangle \;\equiv \sum_{l_1,l_2,l_3 \in \mathcal{V}_{\mathcal{T}}} w_{l_1l_2l_3}\, b_{l_1l_2l_3}\, b'_{l_1l_2l_3}$$

with weight $\quad w_{l_1l_2l_3} = h^2_{l_1l_2l_3}$

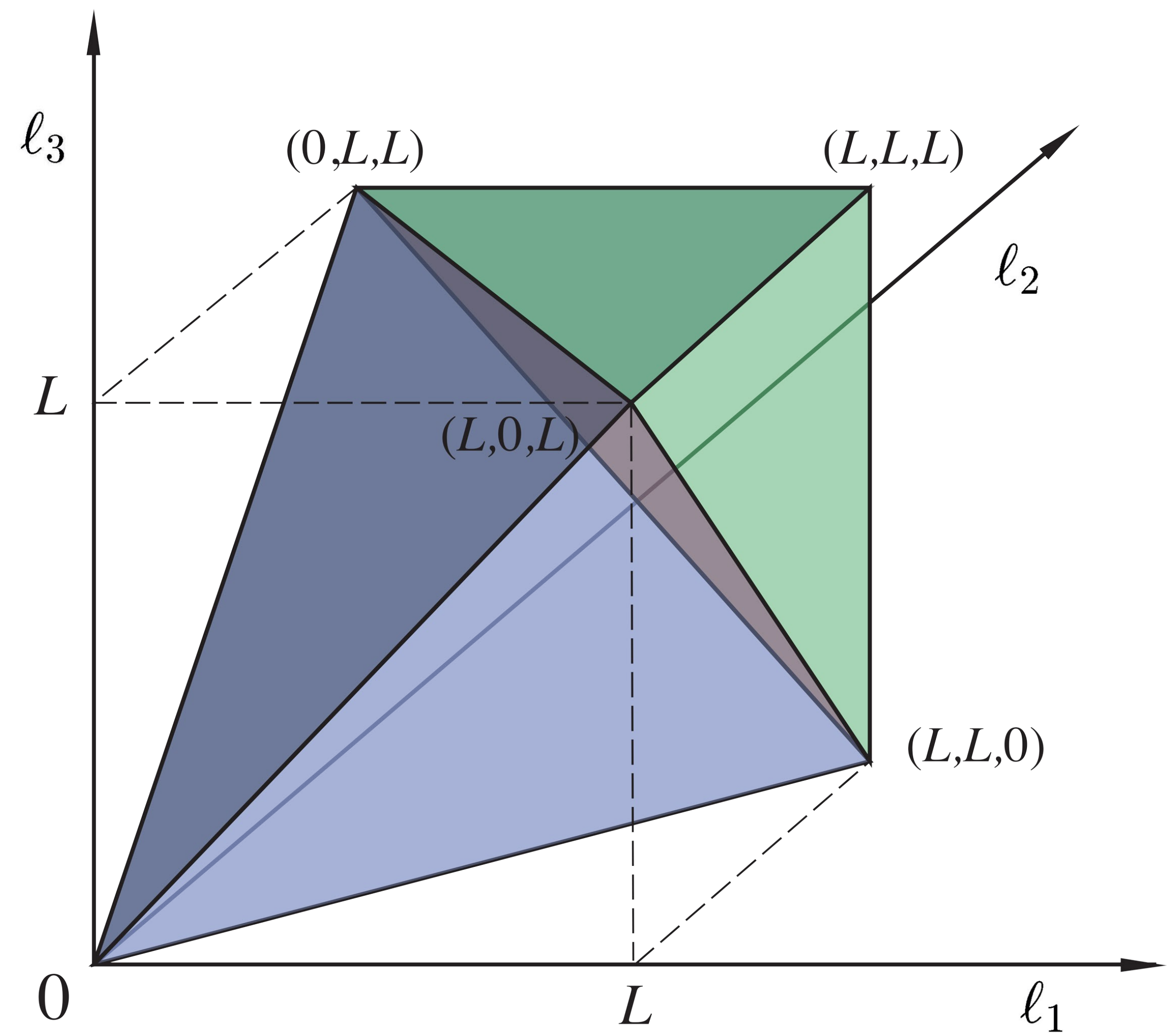


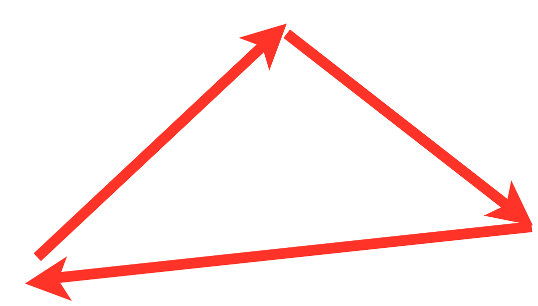
Inflation and the bispectrum

Hot plasma oscillations create patterns of acoustic peaks:



Power spectrum (2pt correlator)





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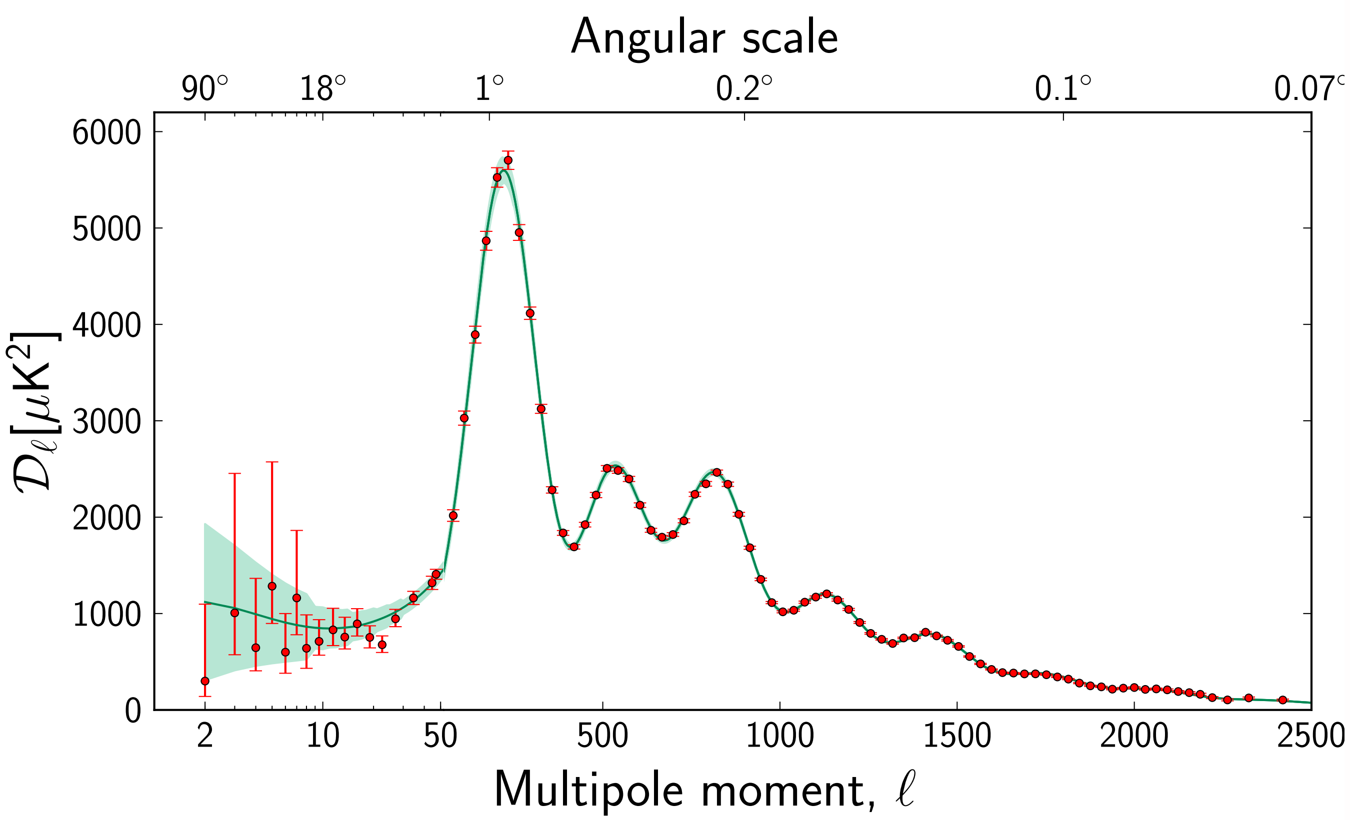

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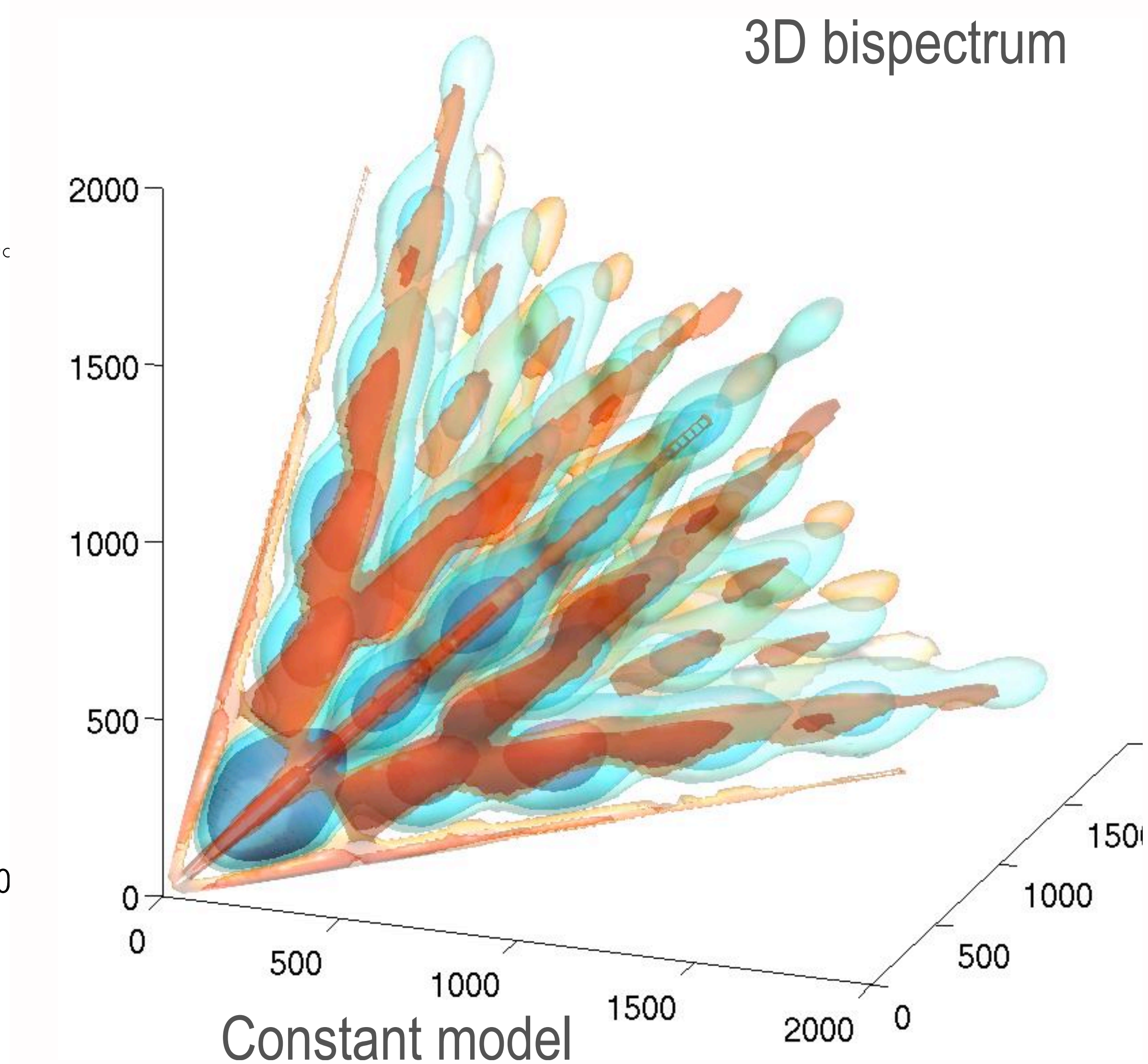

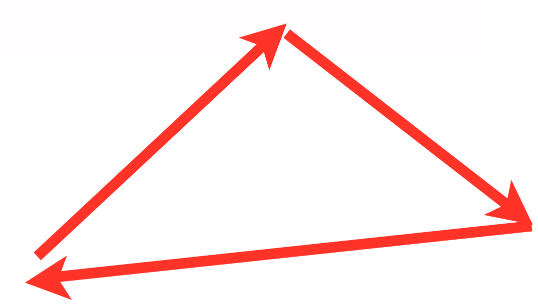

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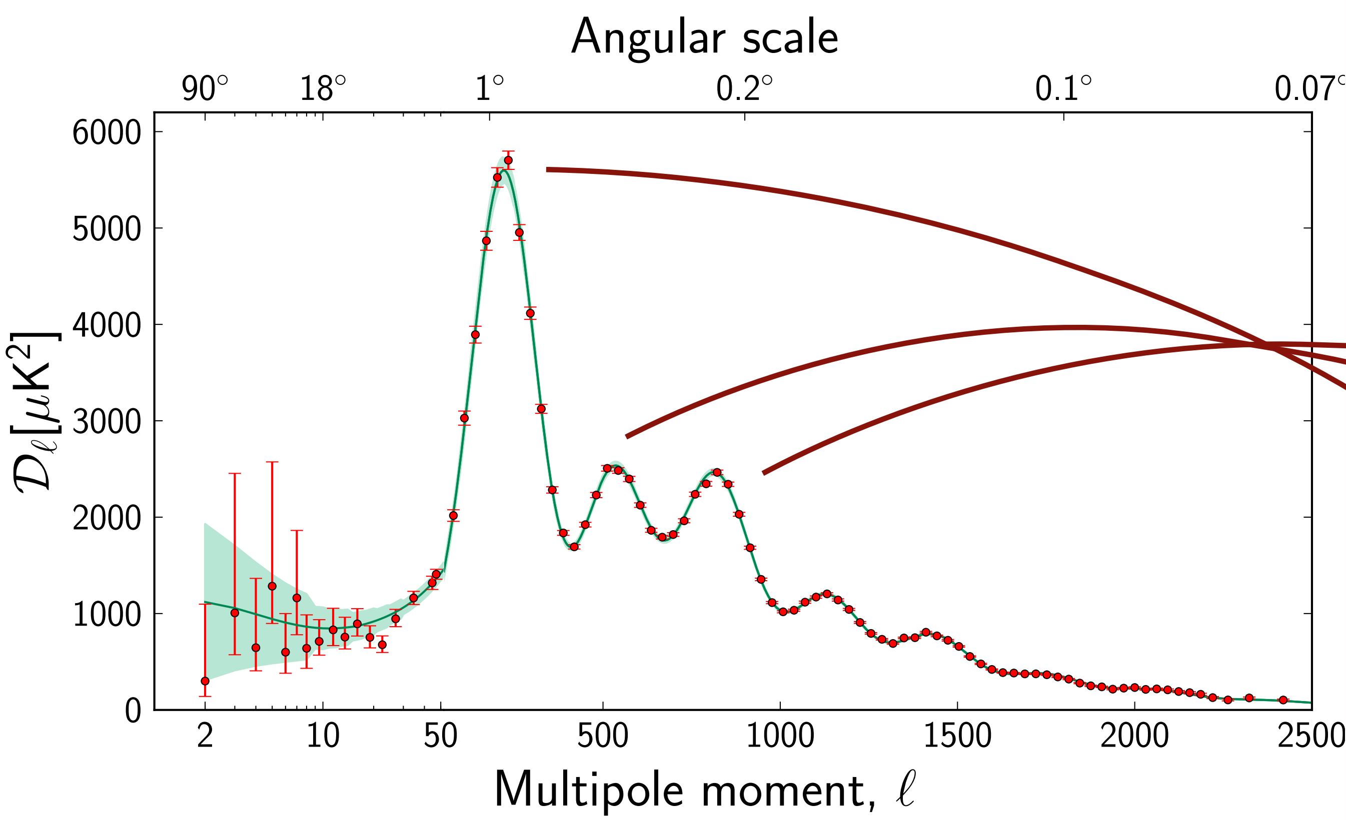

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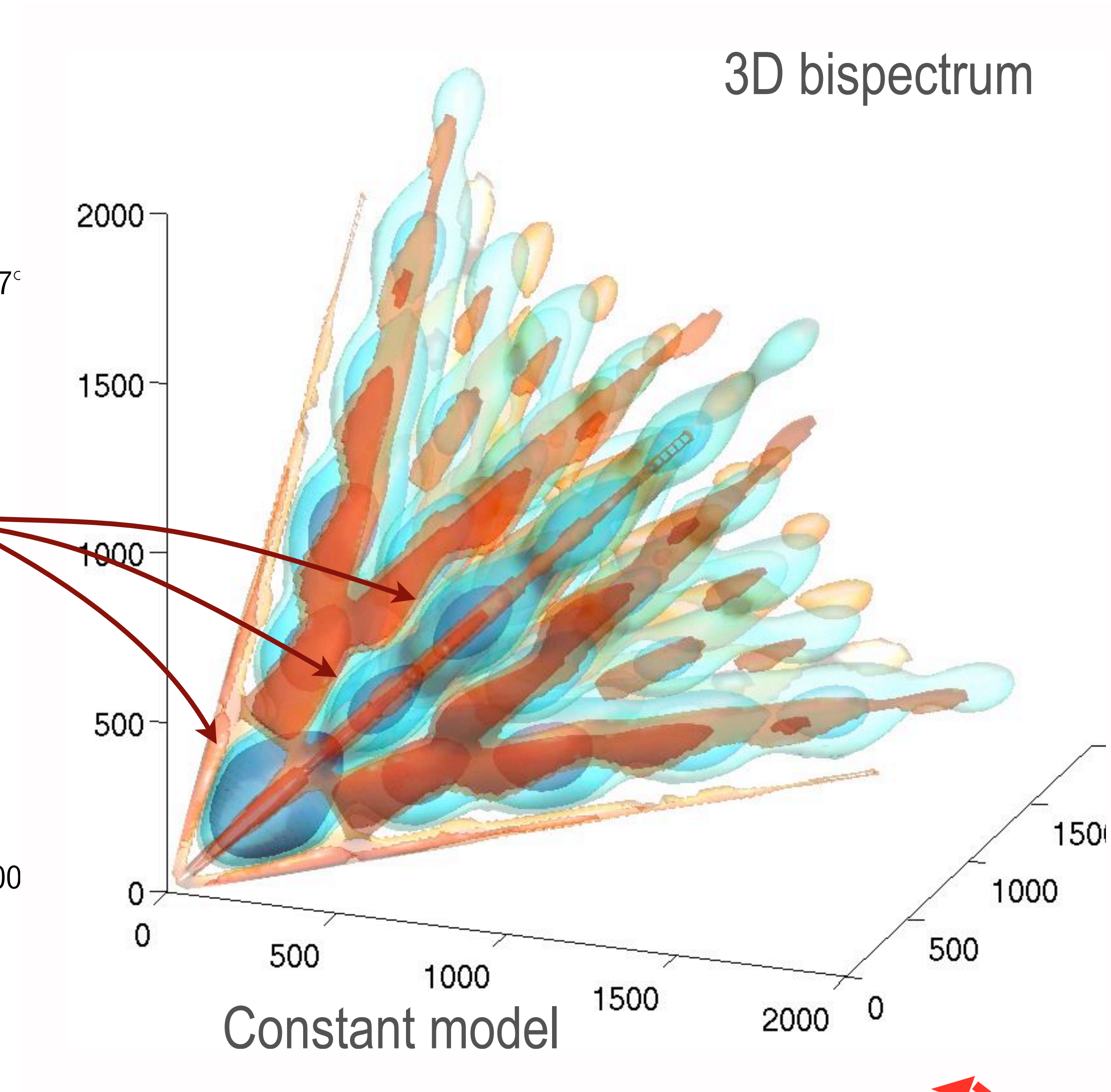
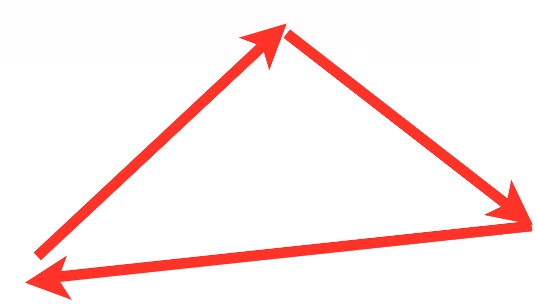
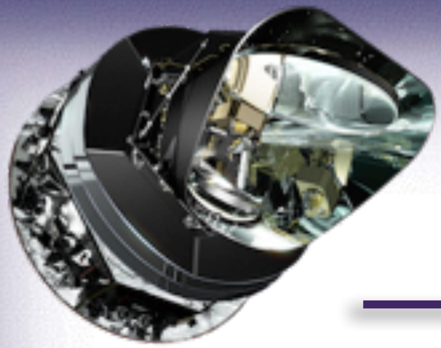


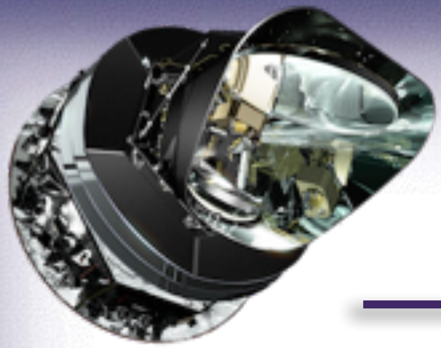




No-Go for Inflation

Simple inflation models *cannot* generate observable non-Gaussianity:

- single scalar field
- canonical kinetic terms
- always slow roll
- ground state initial vacuum
- standard Einstein gravity



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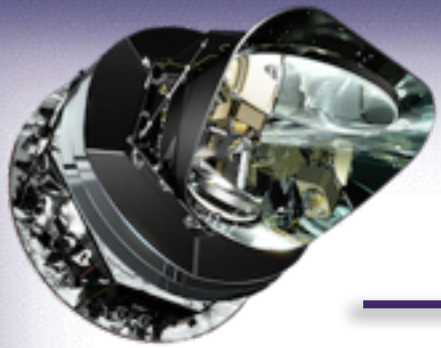
I.e. simple inflation predicts no (observable) randomness

$B \sim P^{3/2} / 1{,}000{,}000$

so deviations less than 1 part in a million!

Non-Gaussianity arguably the most stringent test of standard picture



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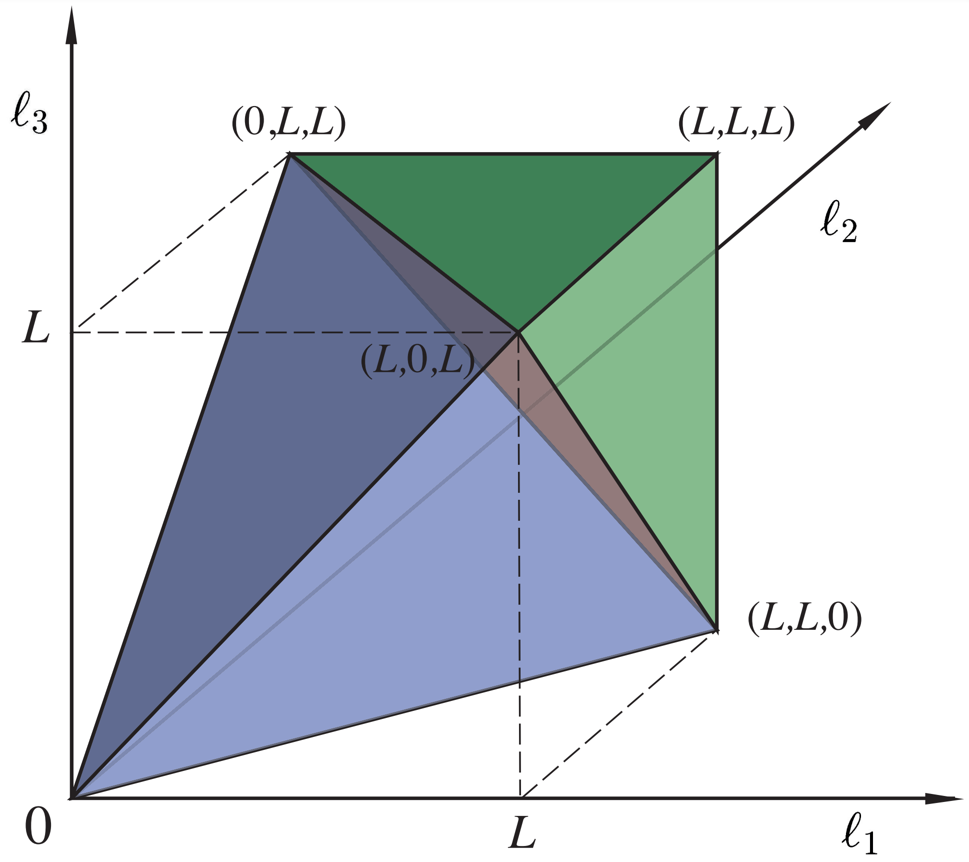
Non-Gaussianity arguably the most stringent test of standard picture

But simple inflation model-building faces rigorous challenges in fundamental theory (e.g. *eta problem and super-Planckian field values*). Many fundamental cosmology ideas/solutions violate these conditions!

Aside: tetrapyd triangles

Tetrapyd



Aside: tetrapyd triangles

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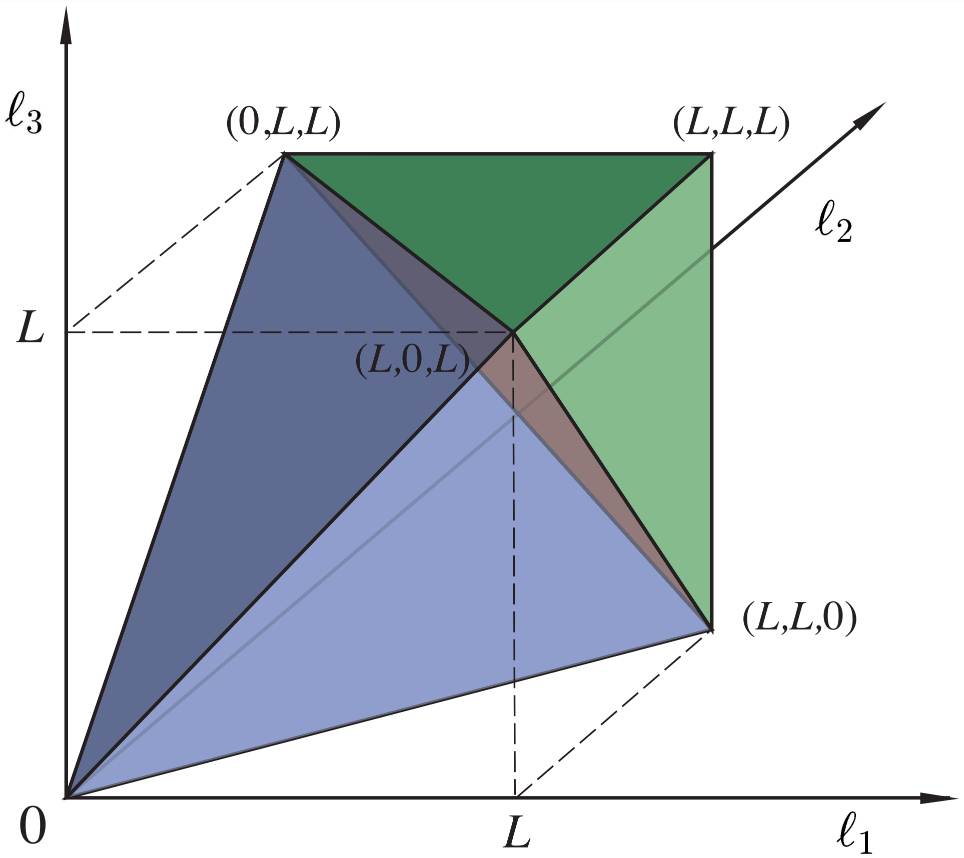
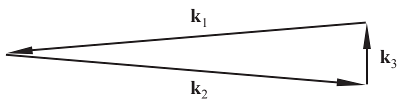
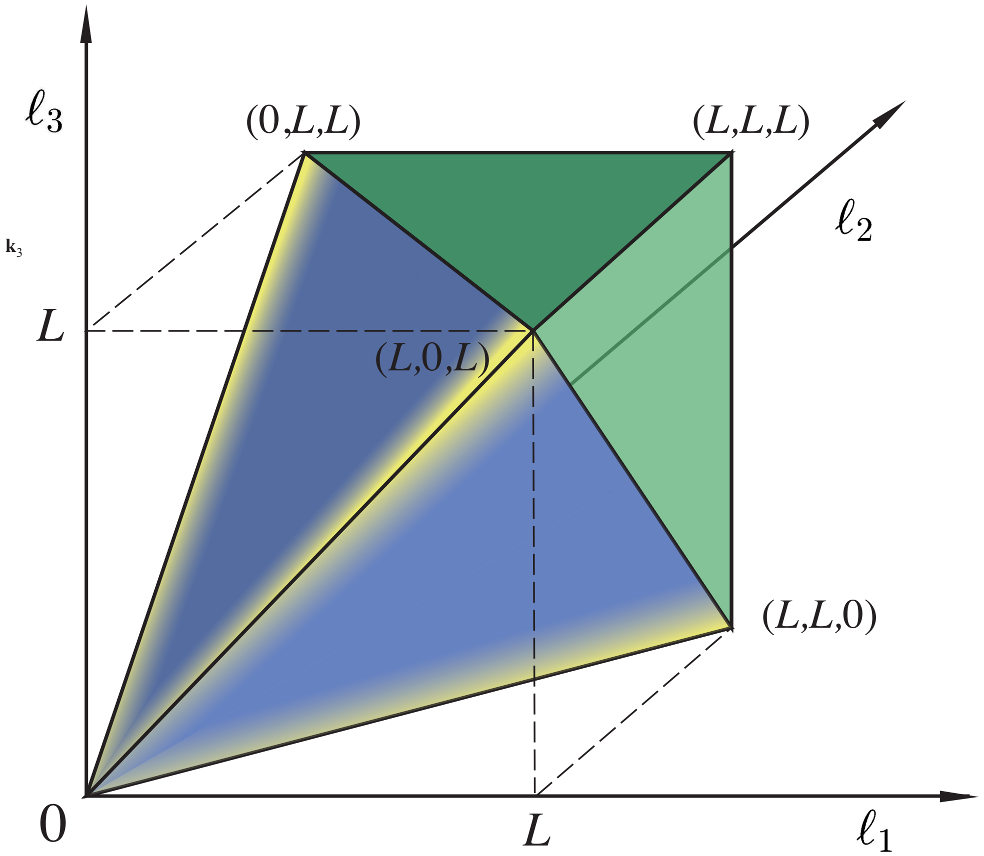


Squeezed





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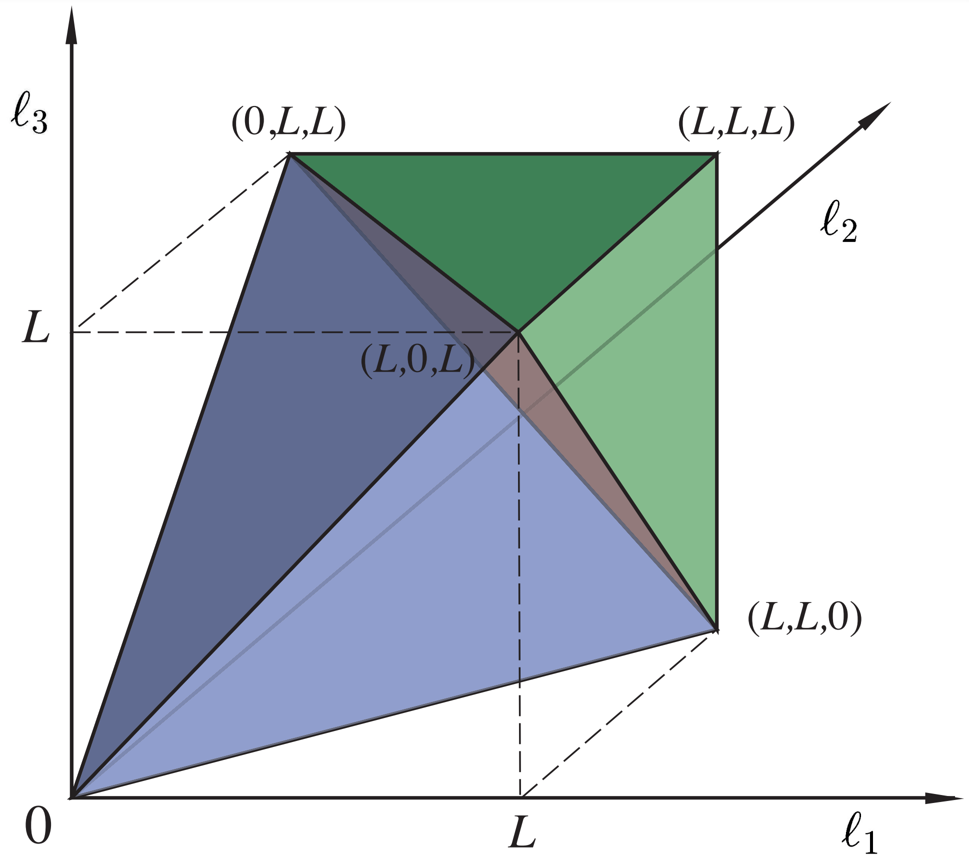

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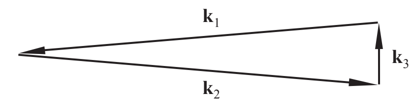
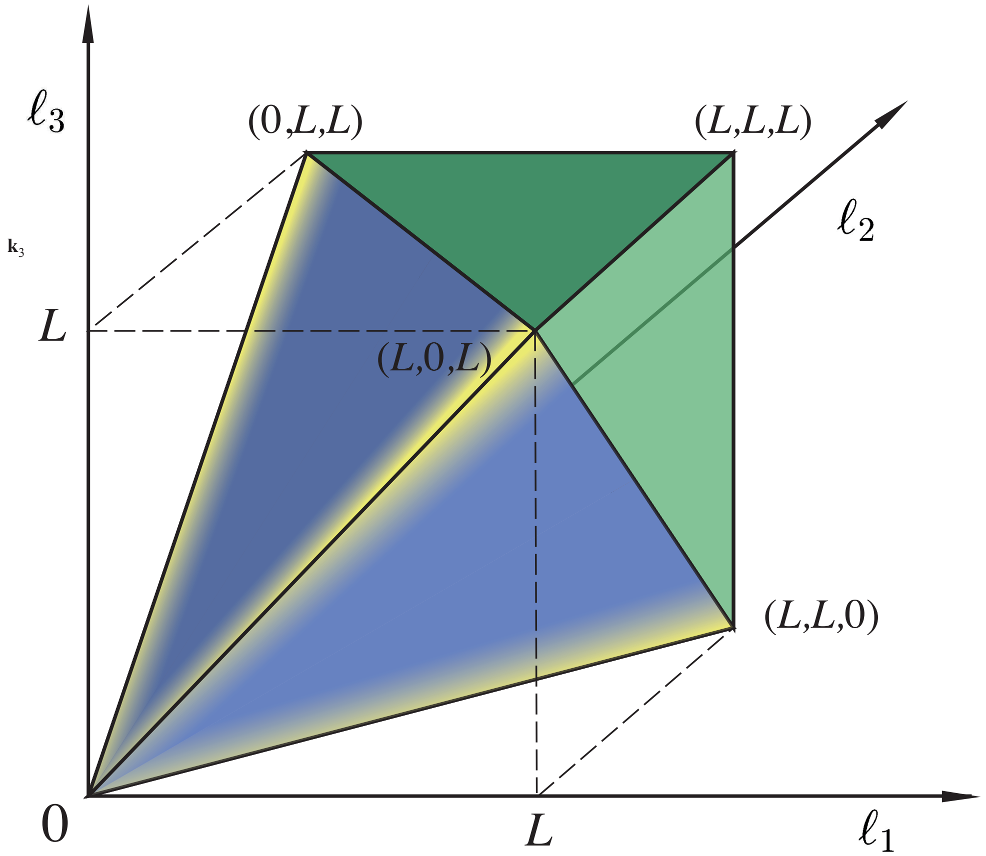
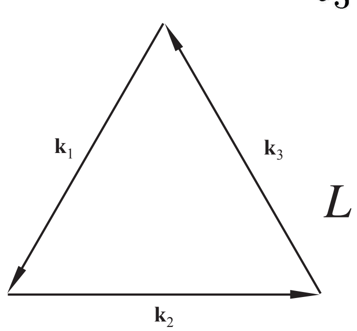
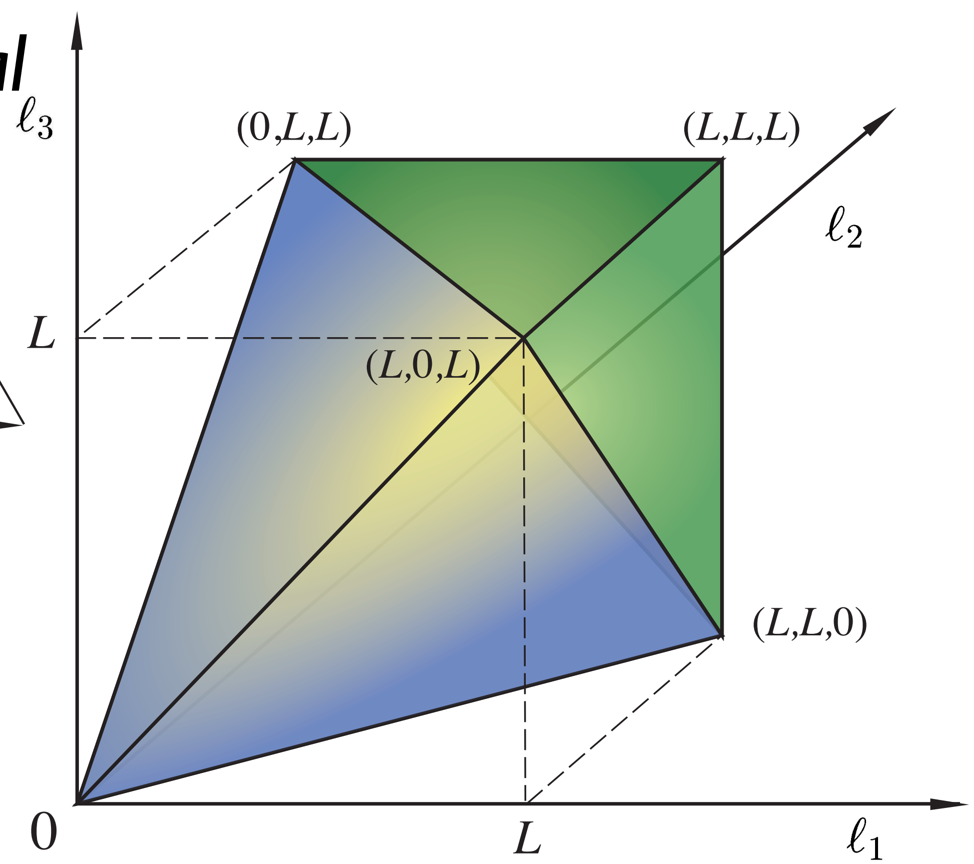




Equilateral





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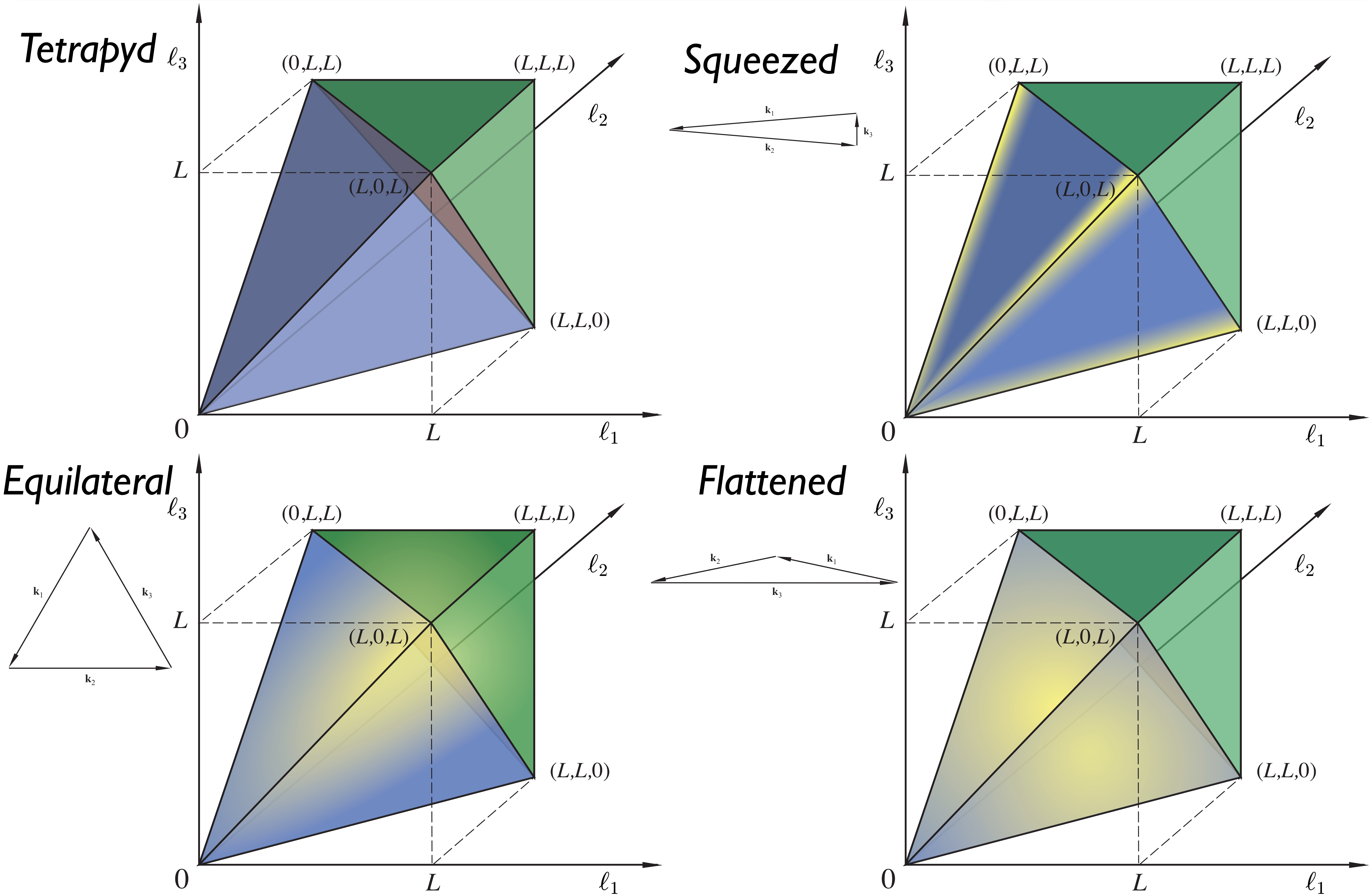
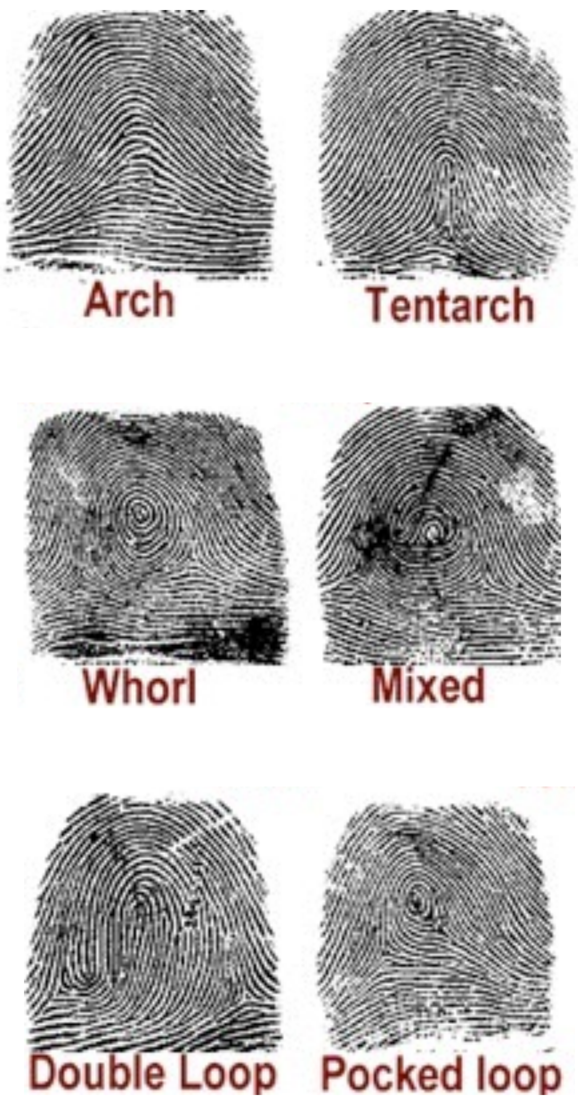
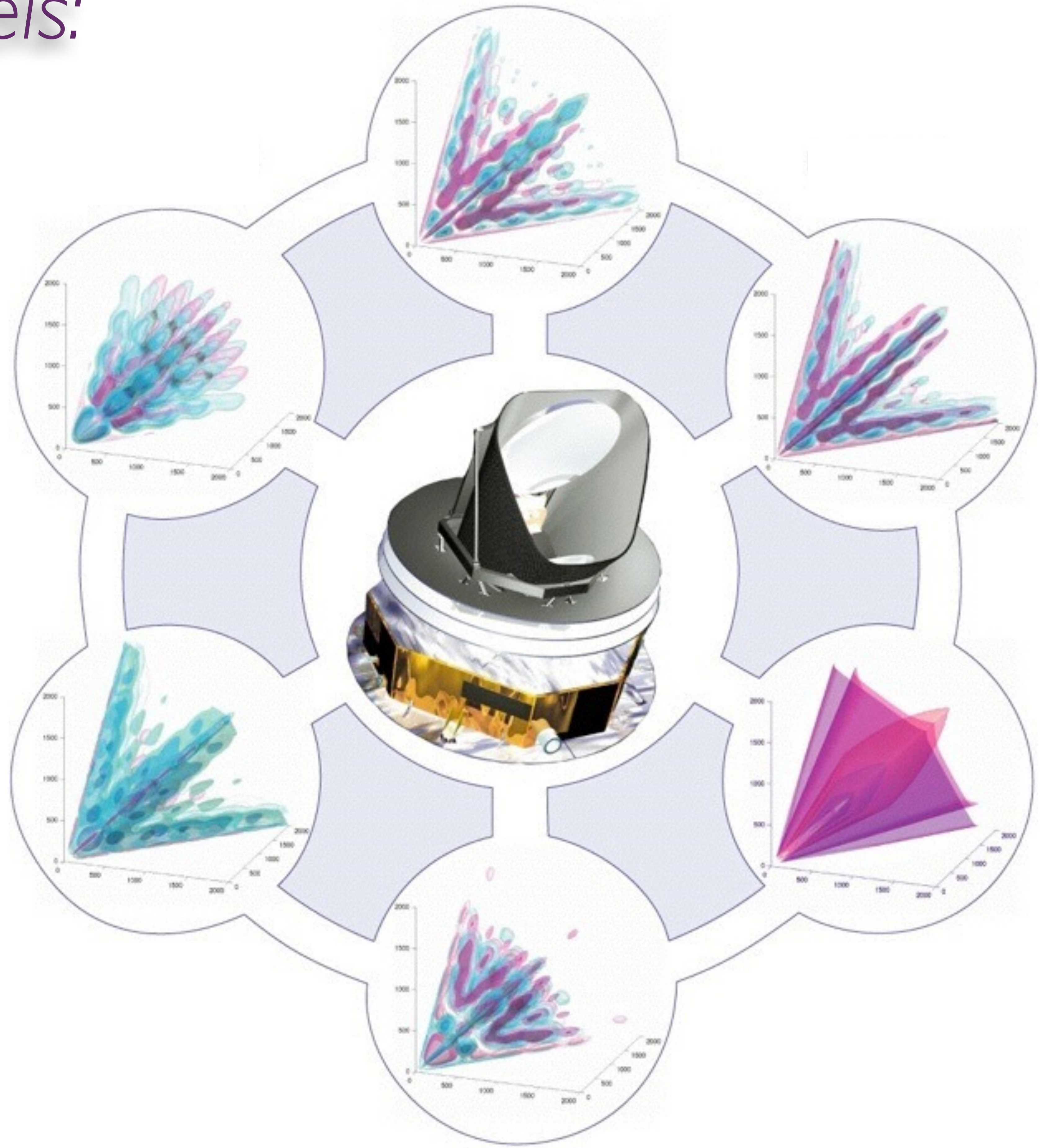


Alternative models: Fingerprints of the very early Universe?





Fergusson and EPS, 2008

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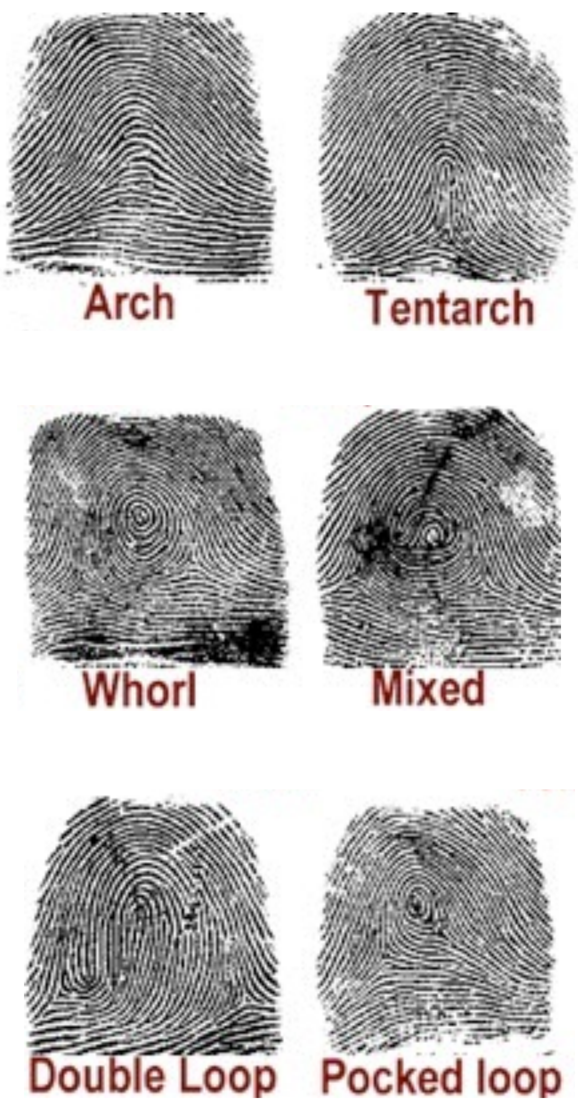


Fergusson and EPS, 2008

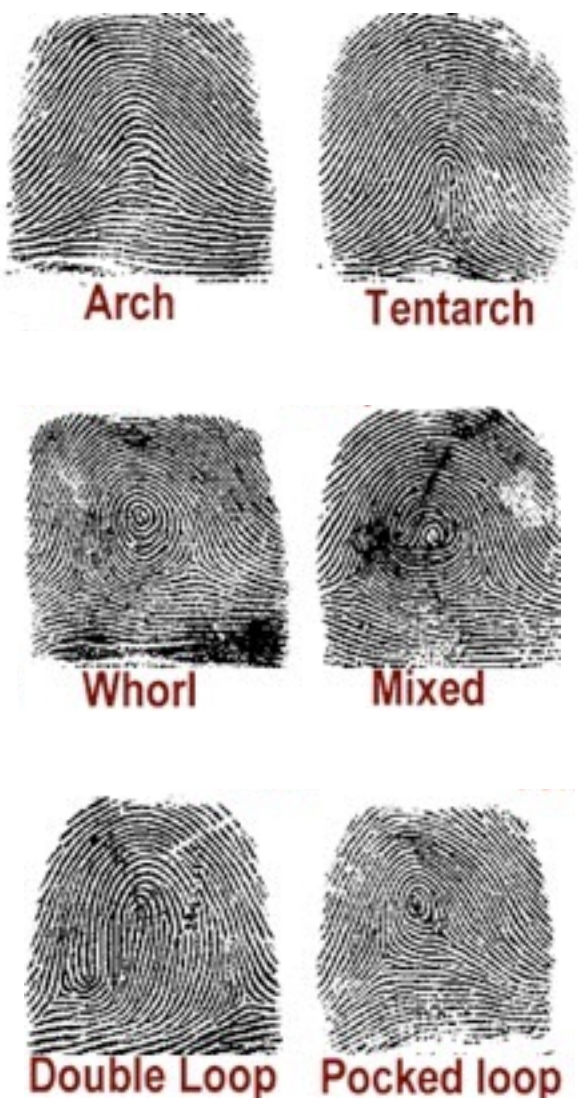
LOCAL

Multifield

Alternative models: Fingerprints of the very early Universe?

FLAT *Excited states*

LOCAL *Multifield*



Fergusson and EPS, 2008

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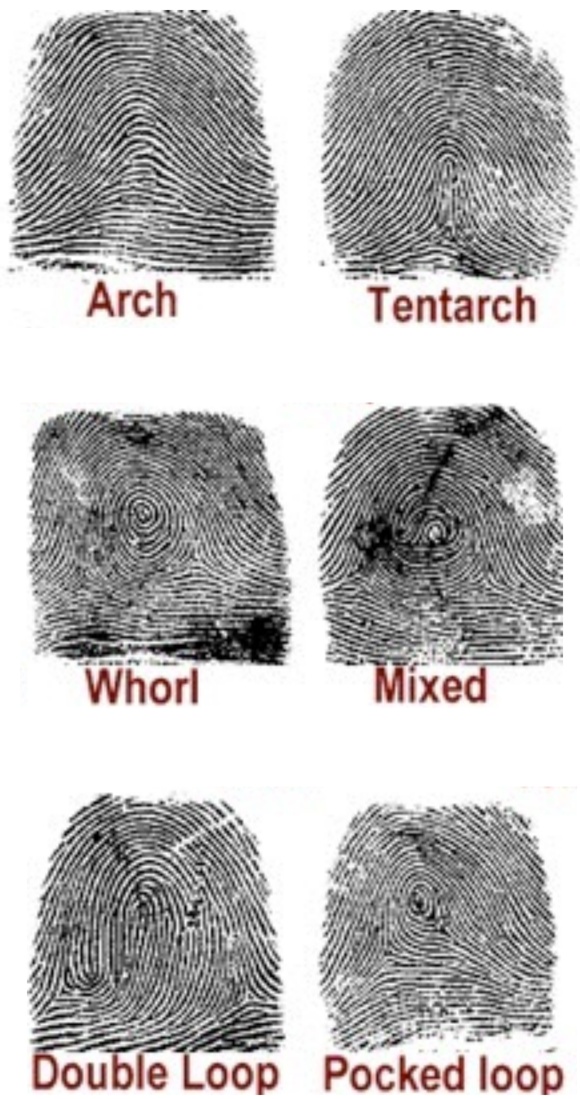

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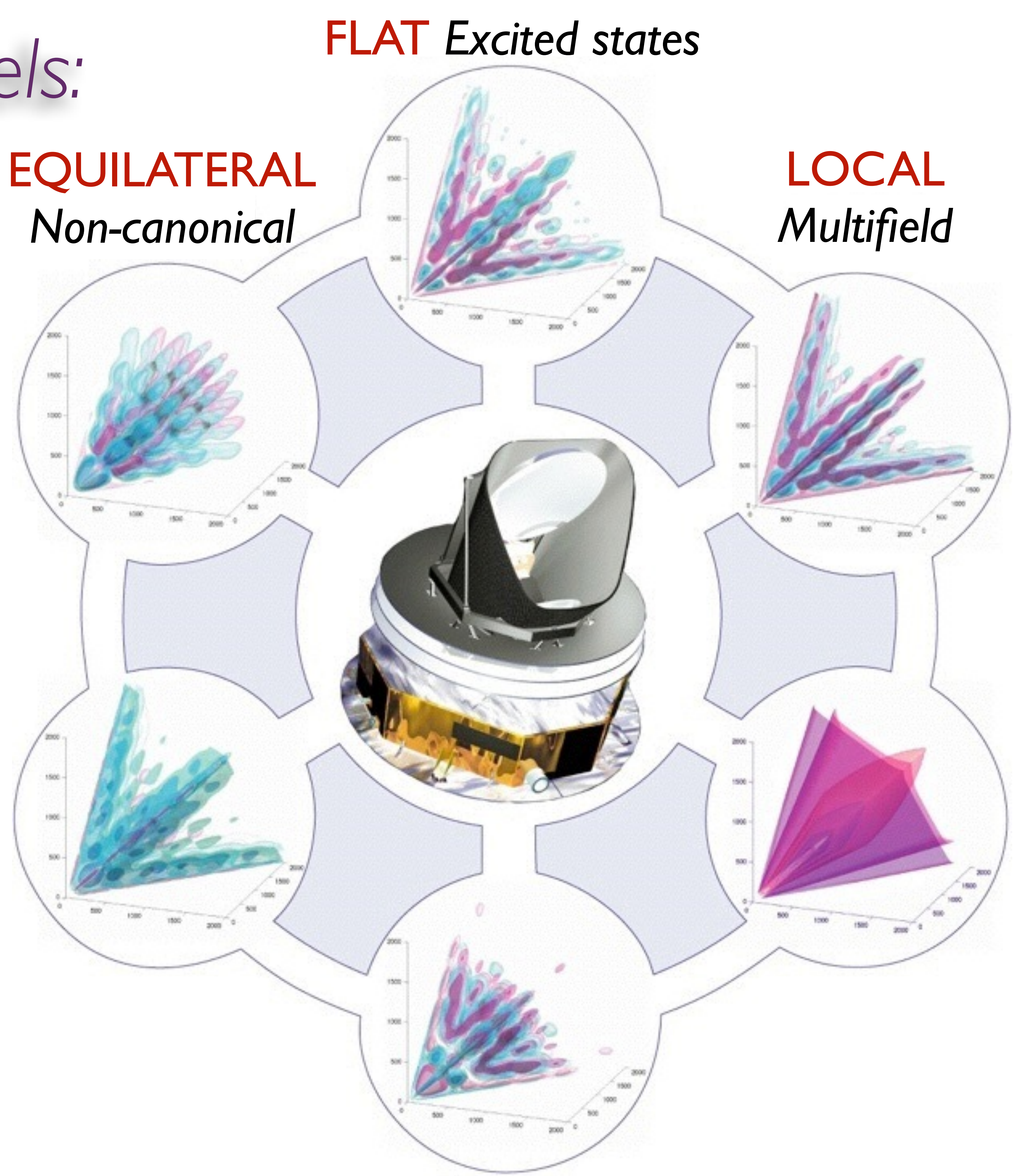

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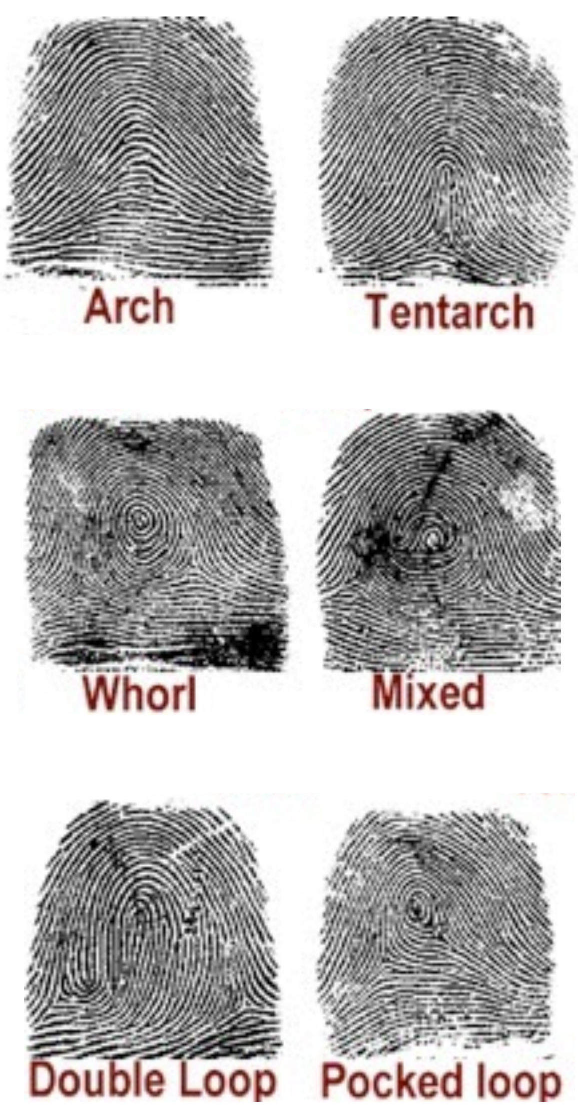

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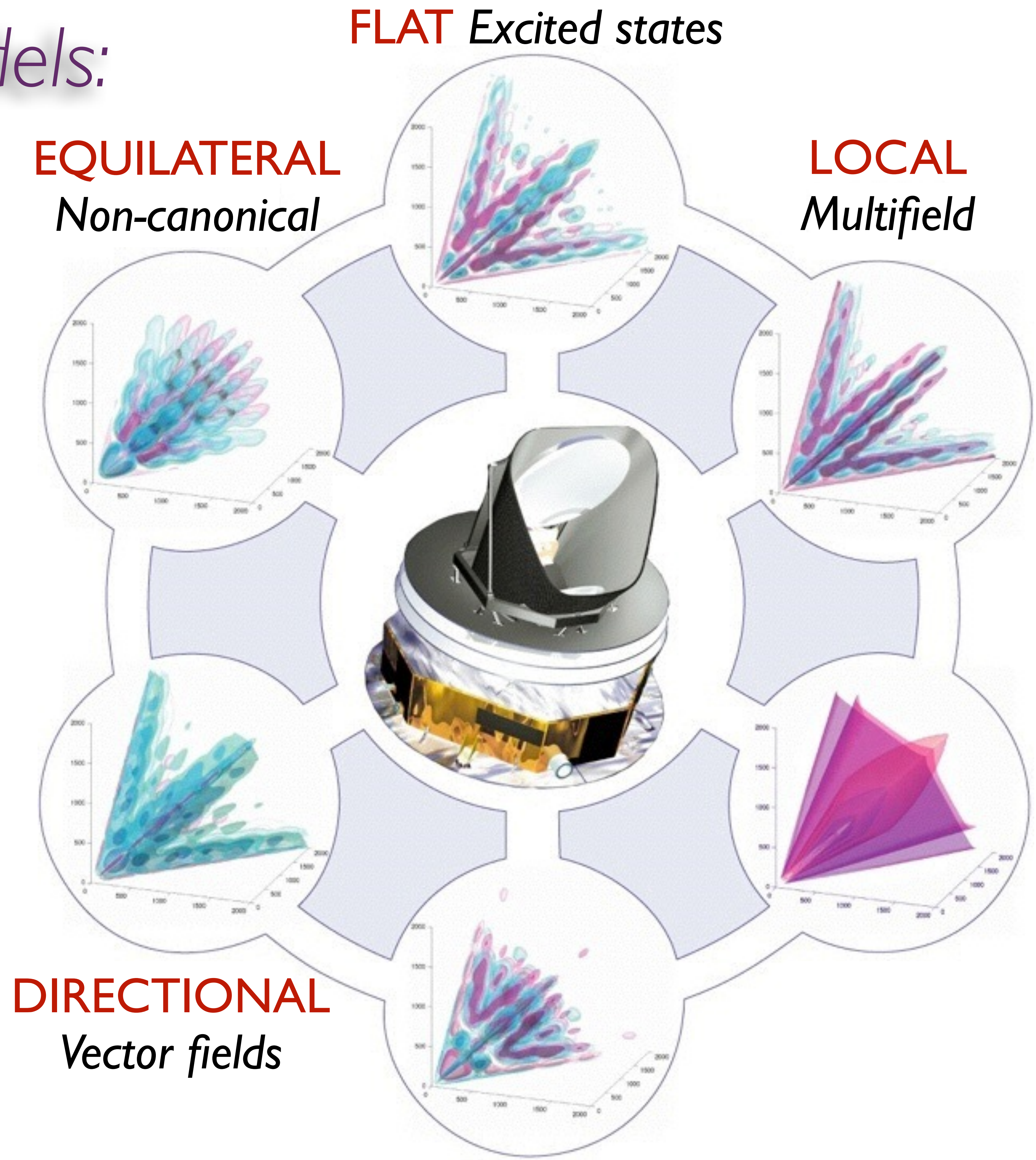

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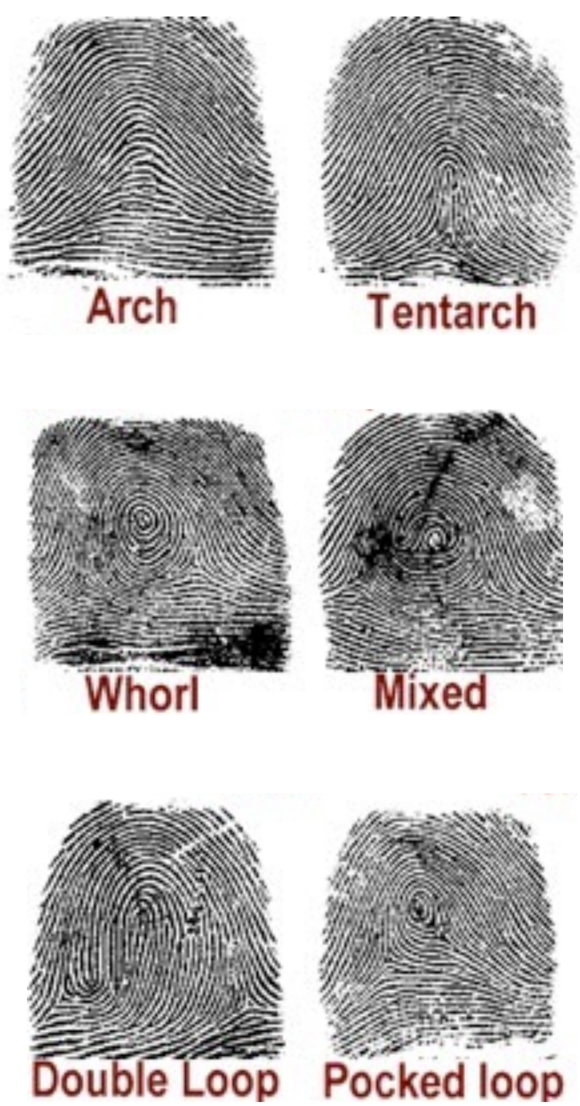

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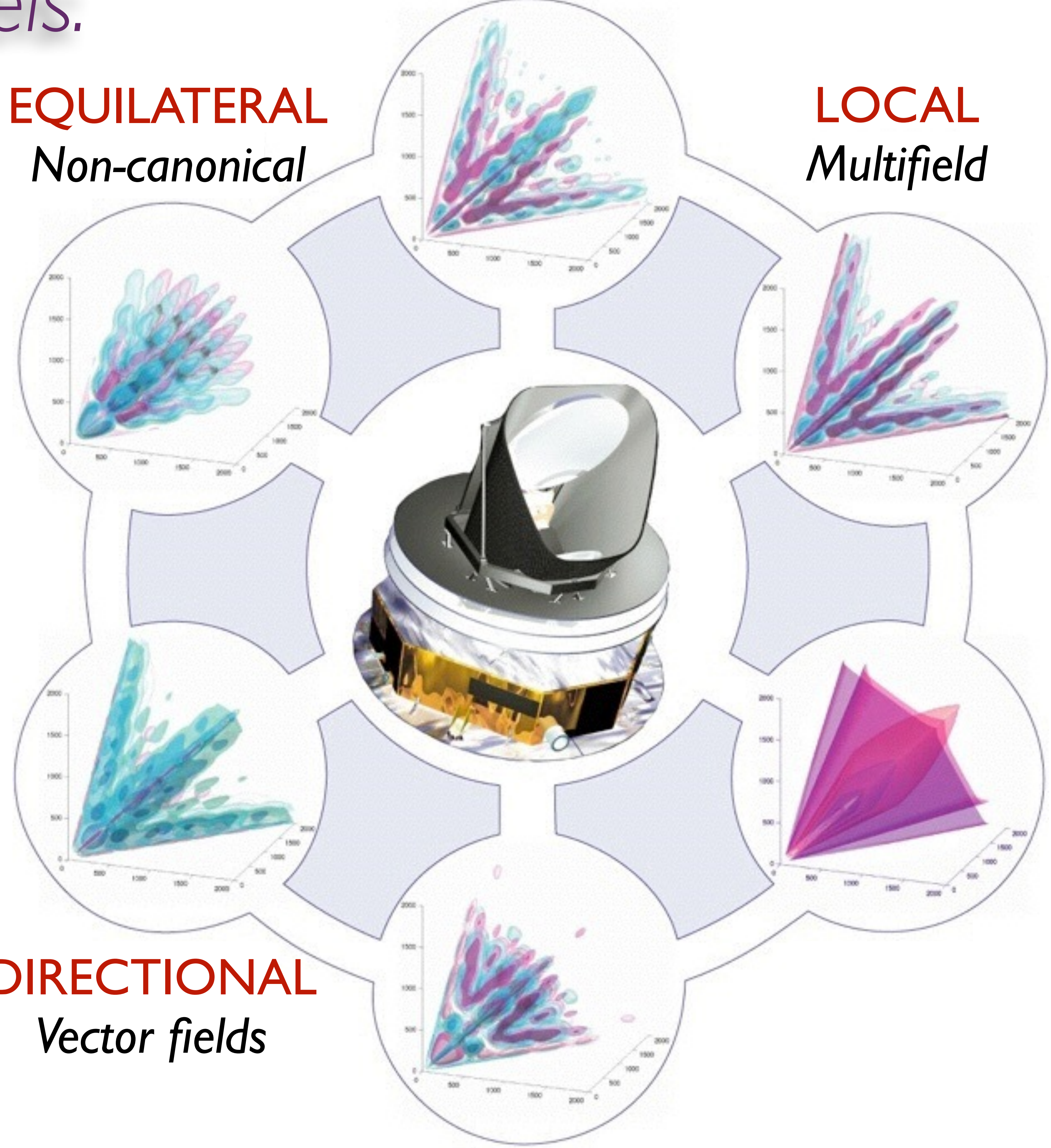

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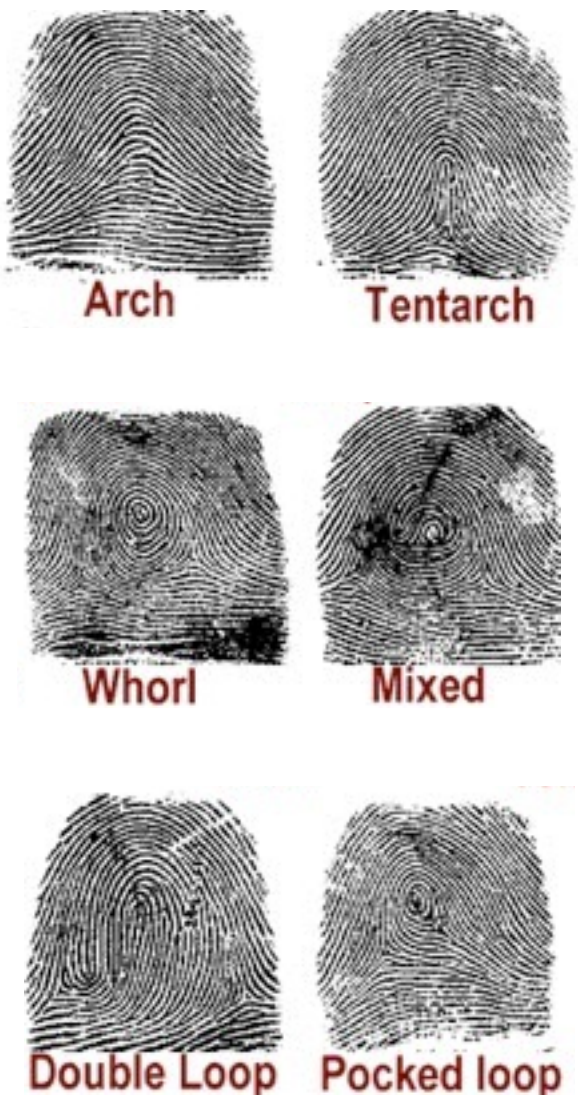
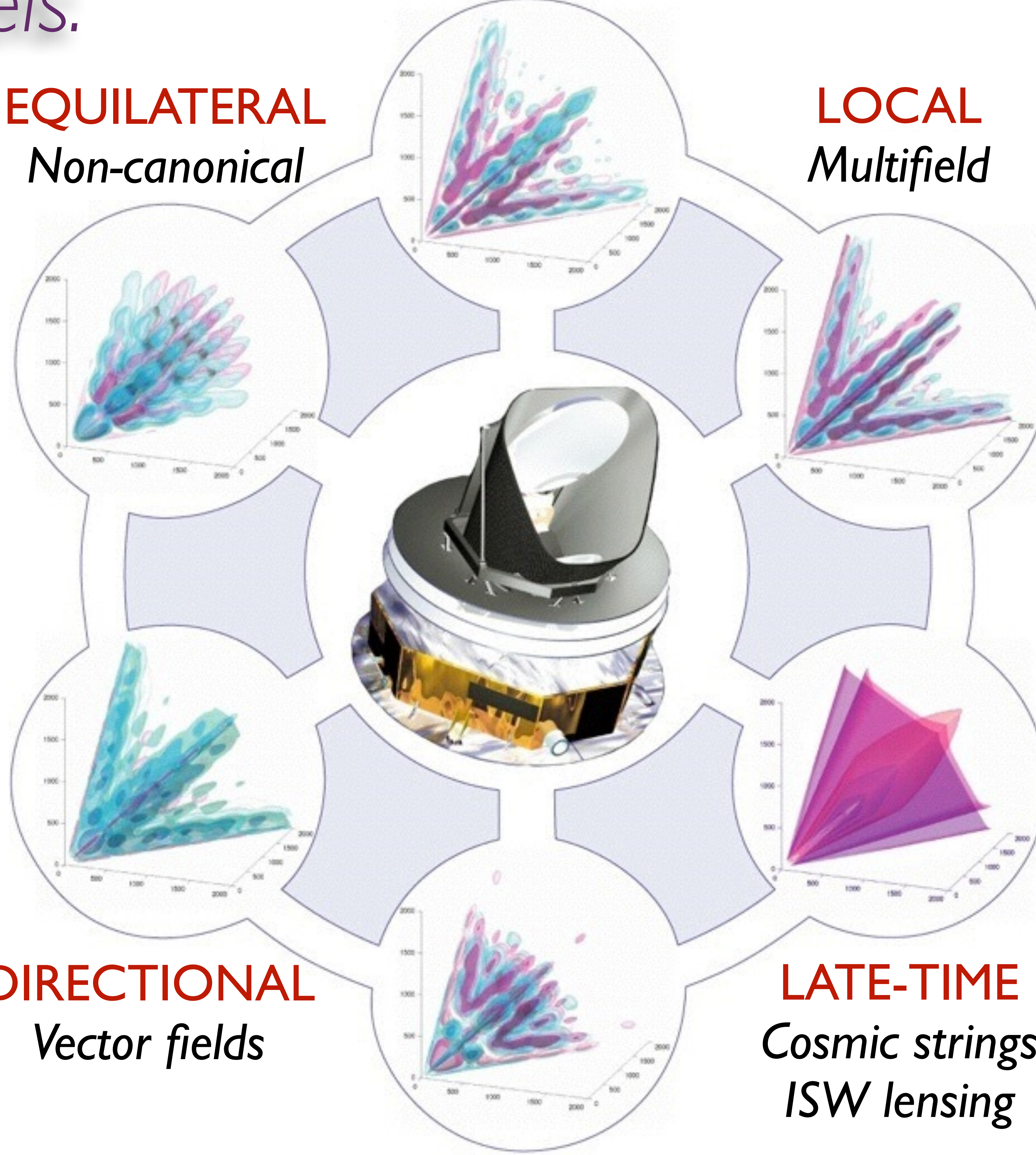


Fergusson and EPS, 2008

FLAT *Excited states*

EQUILATERAL
Non-canonical

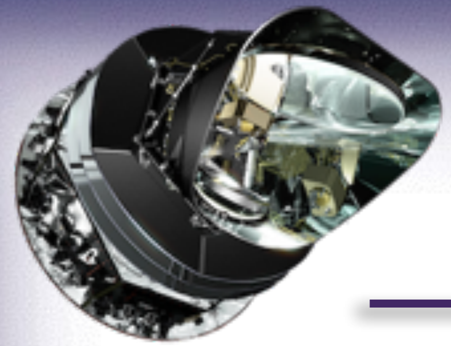
LOCAL
Multifield



DIRECTIONAL
Vector fields

LATE-TIME
Cosmic strings
ISW lensing

NON-SCALING *Oscillatory features*

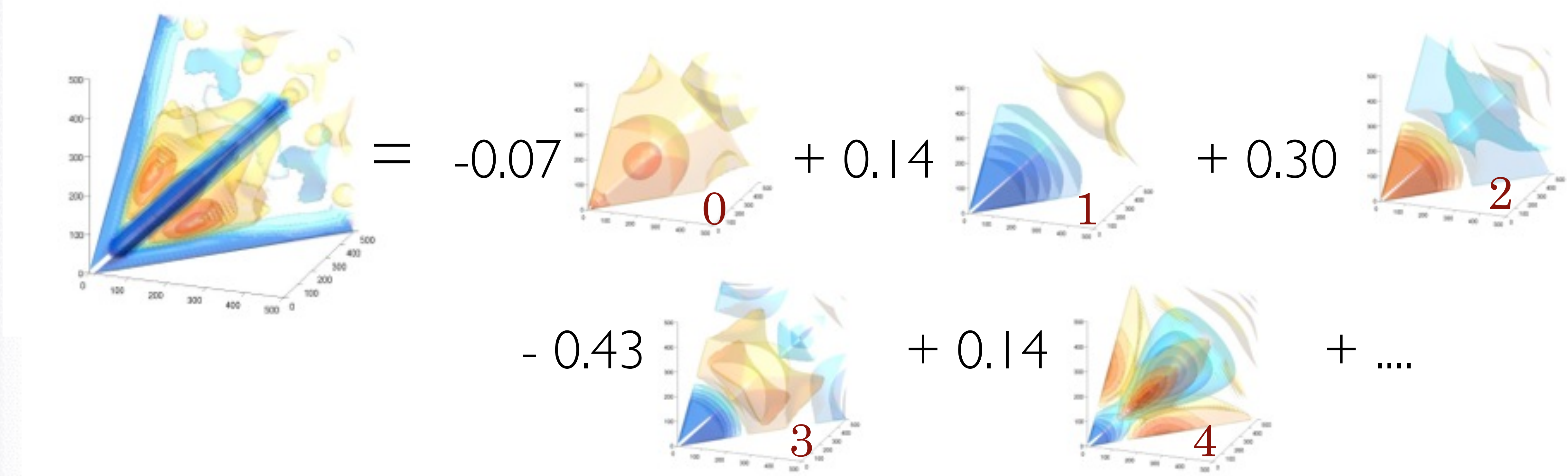


$B_{l_1 l_2 l_3}$ reconstruction

Expand any (nonseparable) bispectrum signal strength in modes as

$$\frac{v_{l_1} v_{l_2} v_{l_3}}{\sqrt{C_{l_1} C_{l_2} C_{l_3}}} b_{l_1 l_2 l_3} = \sum_n \bar{\alpha}_n^{\mathcal{R}} \overline{\mathcal{R}}_n$$

E.g. Local f_{NL} Modal expansion:

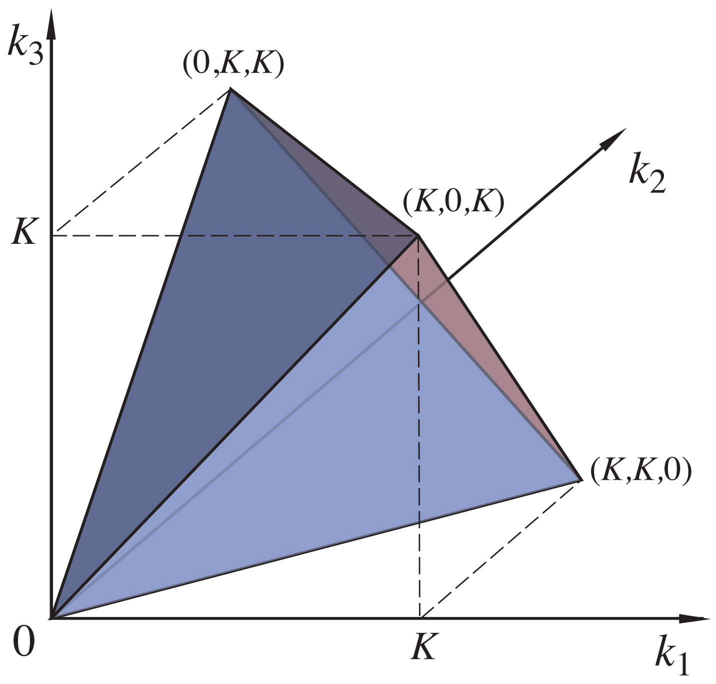


OR filter the Planck data with these modes and *reconstruct* bispectrum

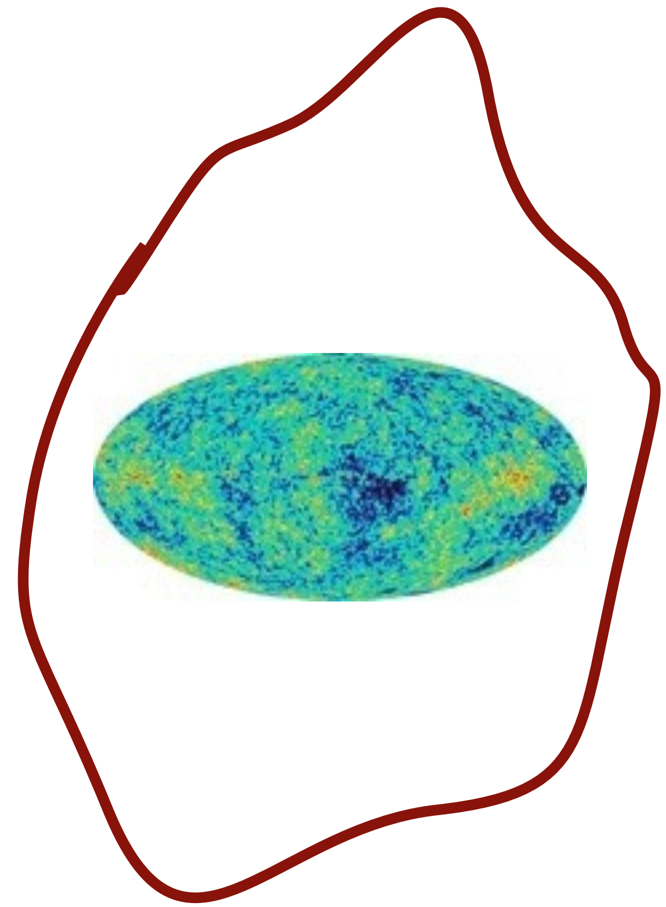
Fergusson, Liguori and EPS, 2009

Modal Polyspectra Estimation

THEORY
Primordial bispectra
(k-space)



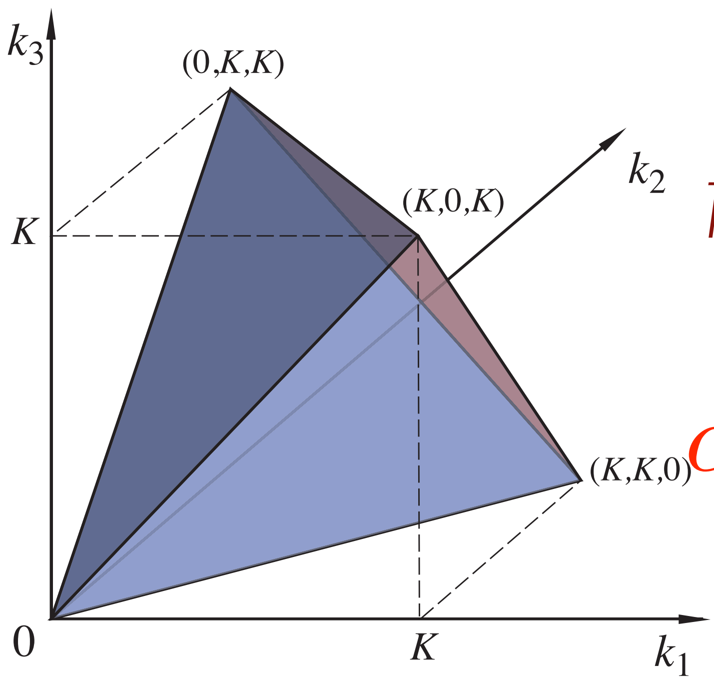
OBSERVATION
CMB map



Fergusson, Liguori and EPS, 2009

Modal Polyspectra Estimation

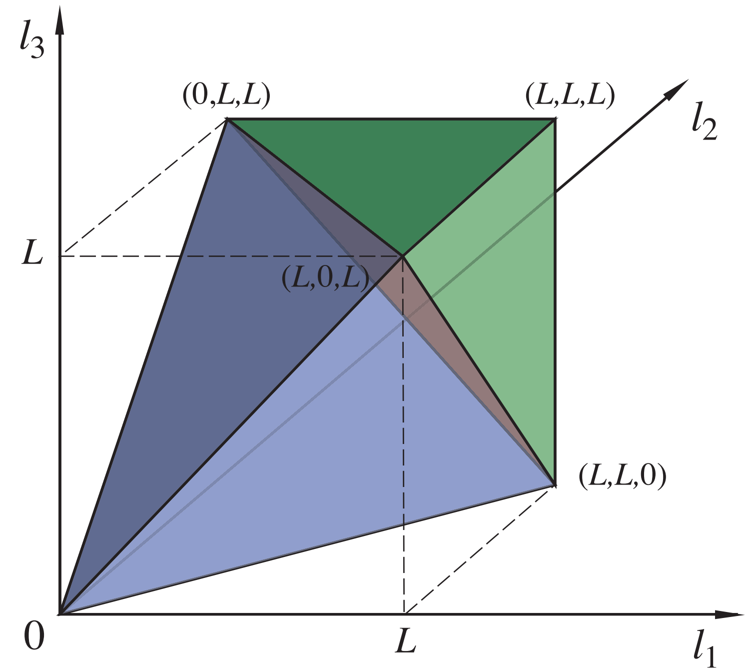
<u>THEORY</u>
Primordial bispectra
(*k*-space)



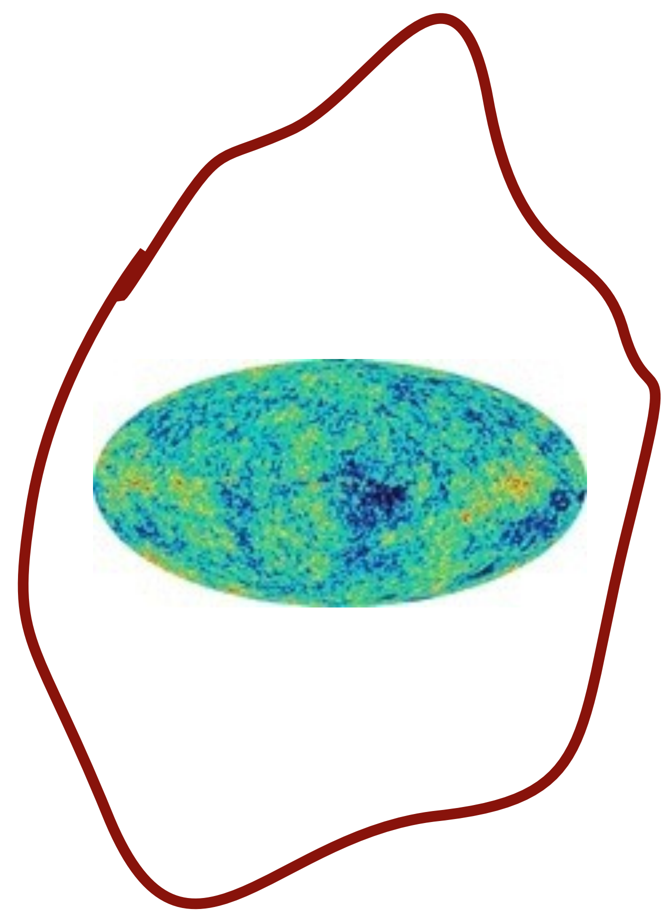
Mode transfer functions

$\alpha_n \rightarrow \bar{\alpha}_n$

<u>CMB bispectra</u>
(*l*-space)



<u>OBSERVATION</u>
CMB map



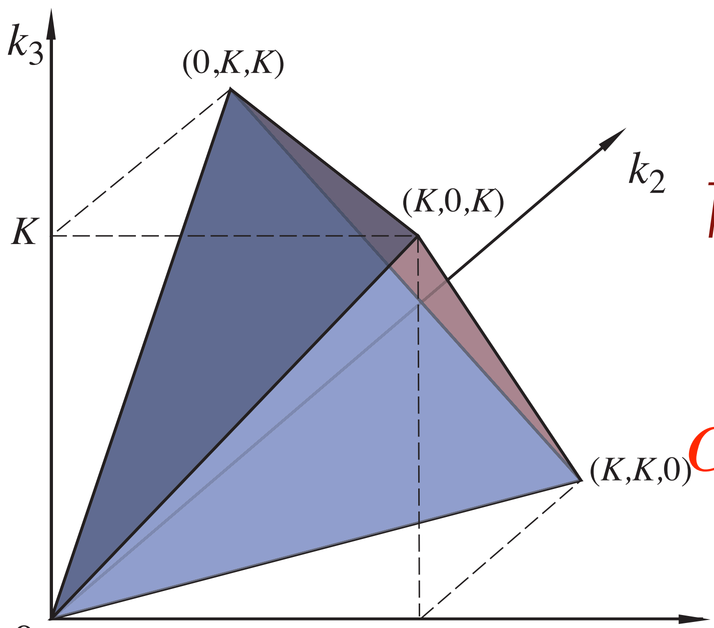
Fergusson, Liguori and EPS, 2009

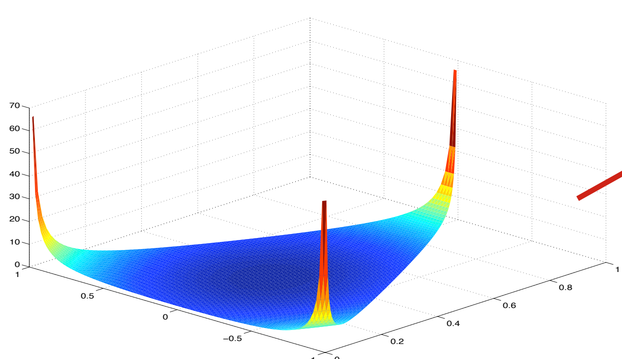
Modal Polyspectra Estimation

THEORY

Primordial bispectra

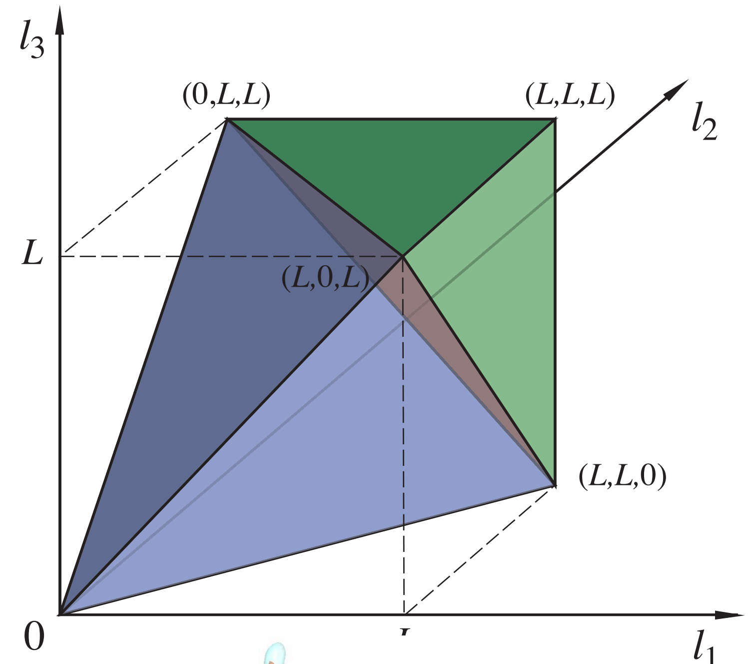
(k-space)

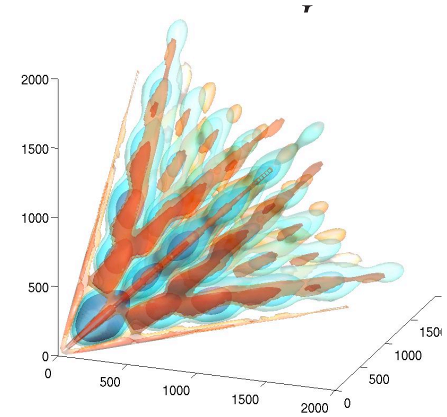




CMB bispectra

(l-space)





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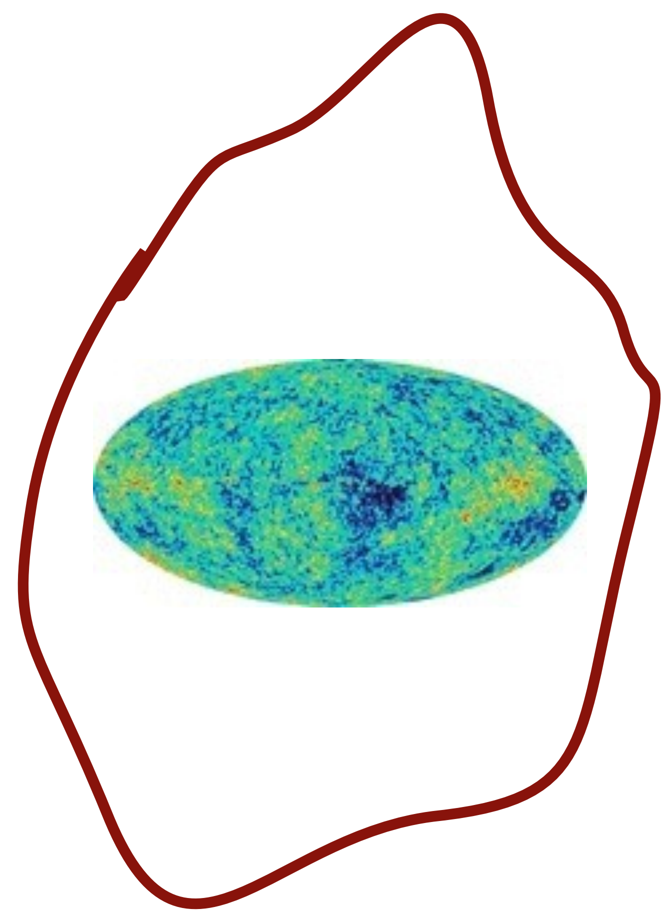

Mode transfer functions

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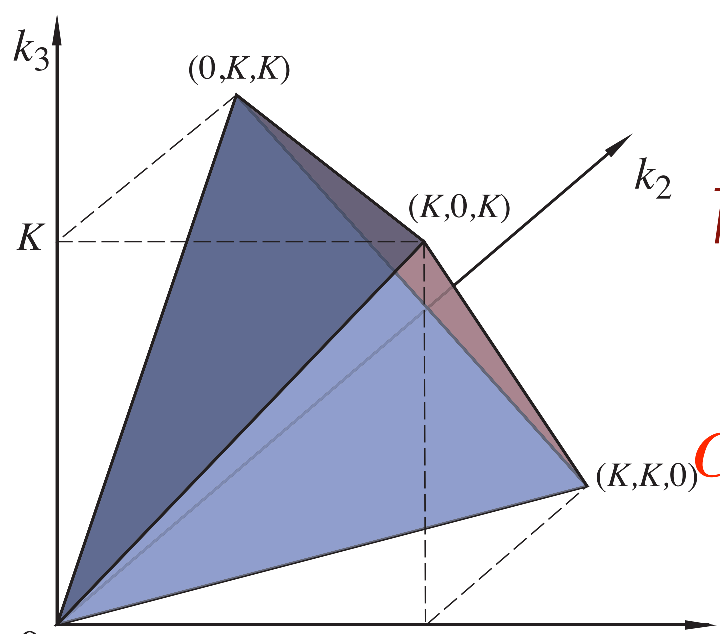
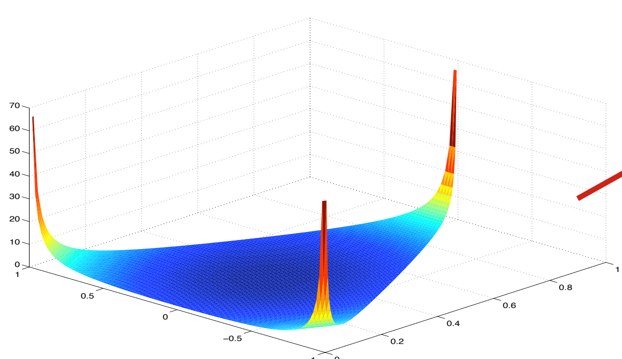
Expand any model with primordial modes α_n

Fergusson, Liguori and EPS, 2009

Modal Polyspectra Estimation

<u>THEORY</u>
Primordial bispectra
(k-space)





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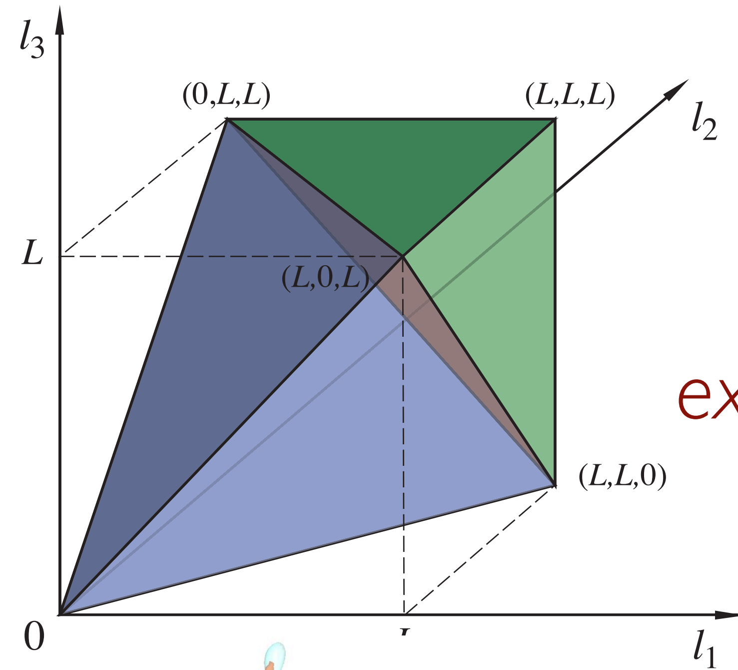
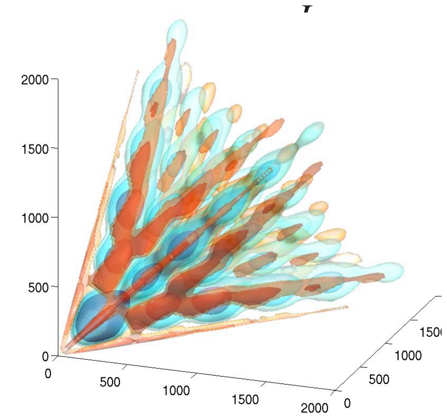
<u>CMB bispectra</u>
(l-space)

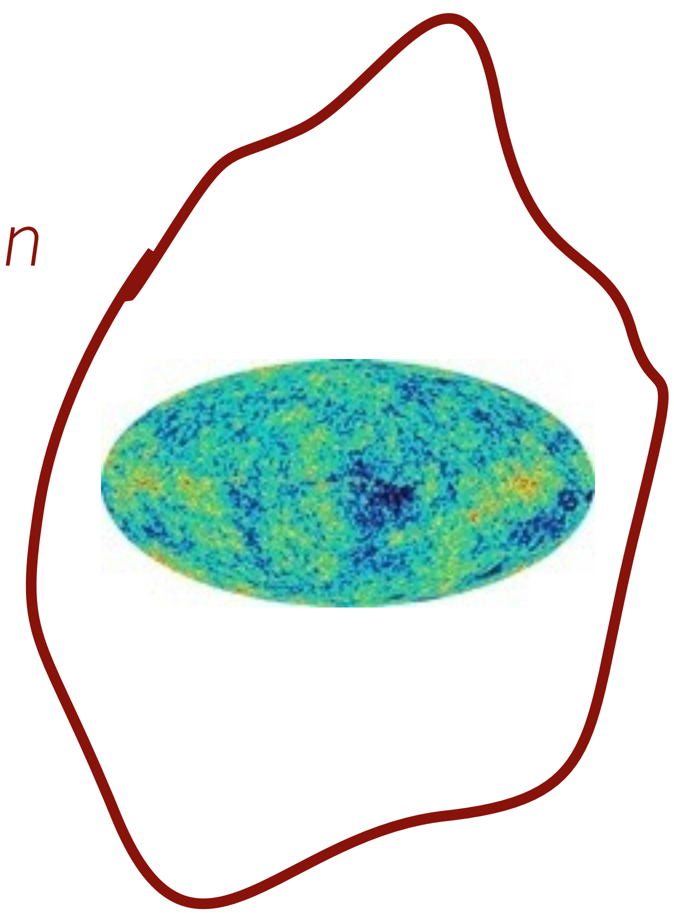




Map extraction

$\bar{\beta}$

<u>OBSERVATION</u>
CMB map

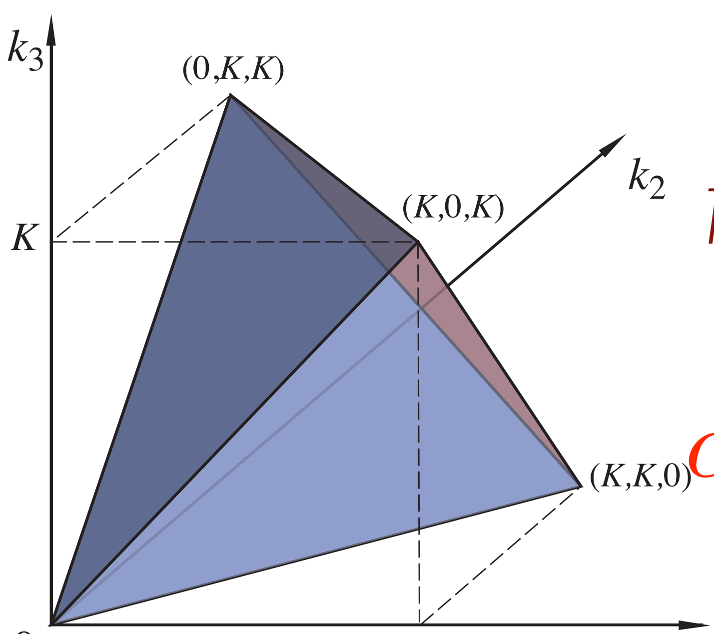


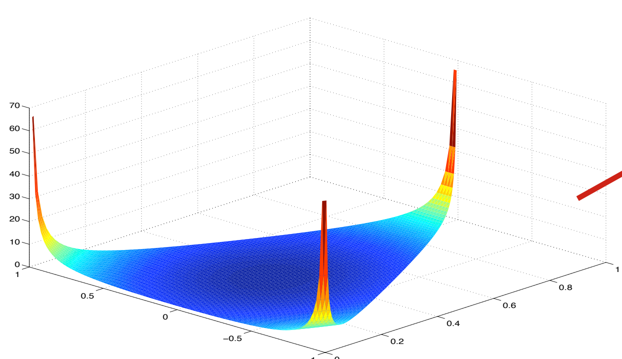
Filter with sufficient separable eigenmodes

Fergusson, Liguori and EPS, 2009

Modal Polyspectra Estimation

THEORY
Primordial bispectra
(*k*-space)





Expand any model with primordial modes α_n

Mode transfer functions

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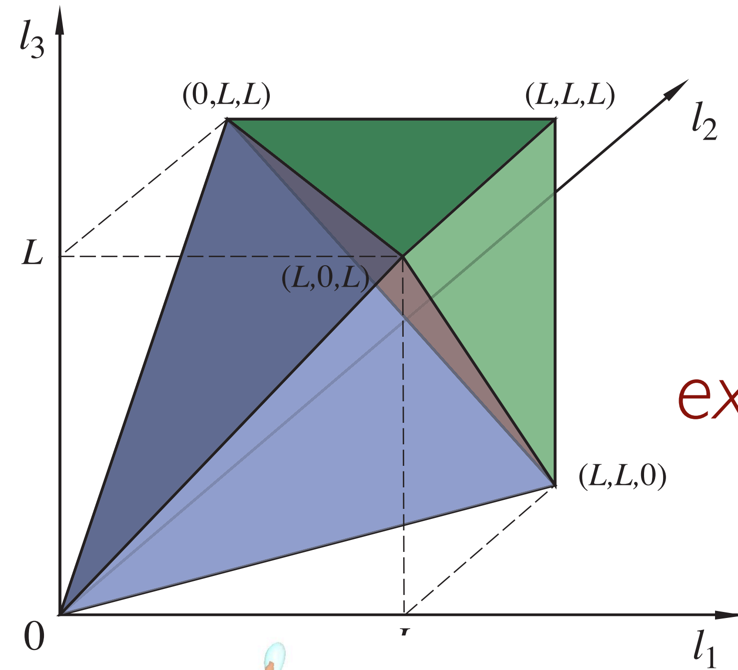
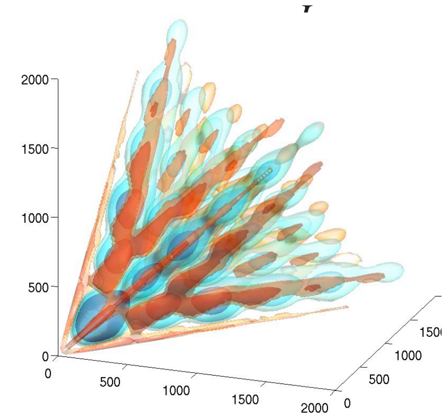
CMB bispectra
(*l*-space)





Modal estimator

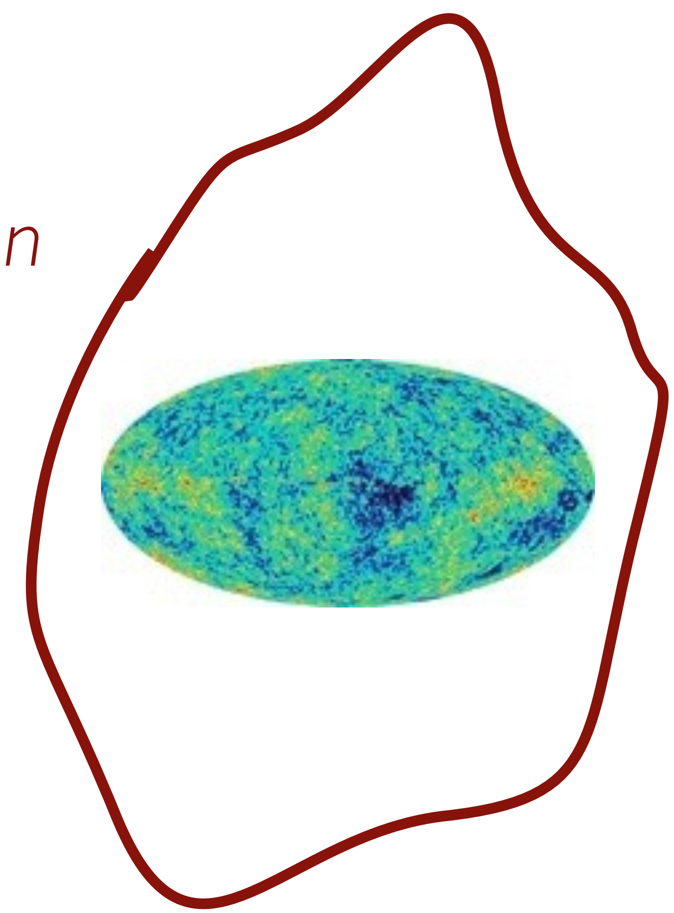
$$\mathcal{E} = \frac{\sum_n \bar{\alpha}_n^R \bar{\beta}_n^R}{\sum_n (\bar{\alpha}_n^R)^2}$$

Fergusson, Liguori and EPS, 2009

OBSERVATION
CMB map

Map extraction

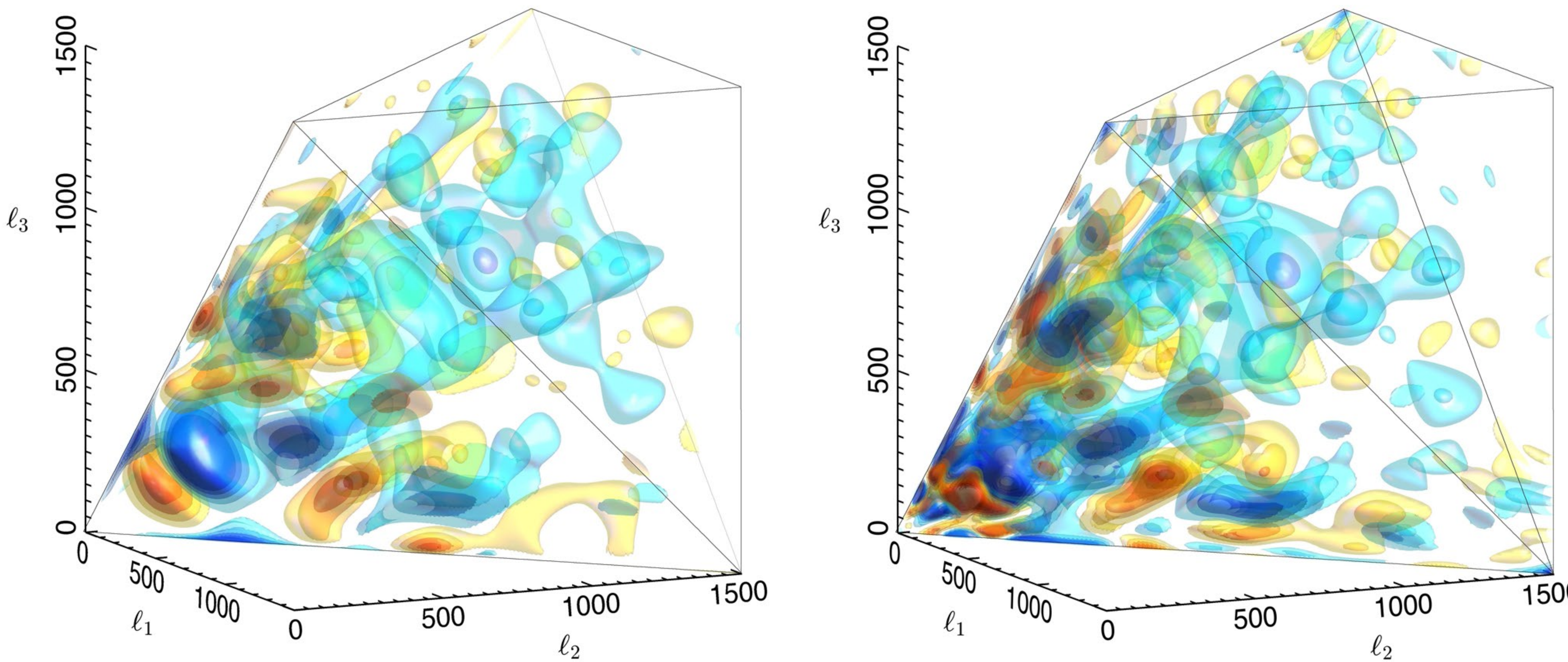
$\bar{\beta}$



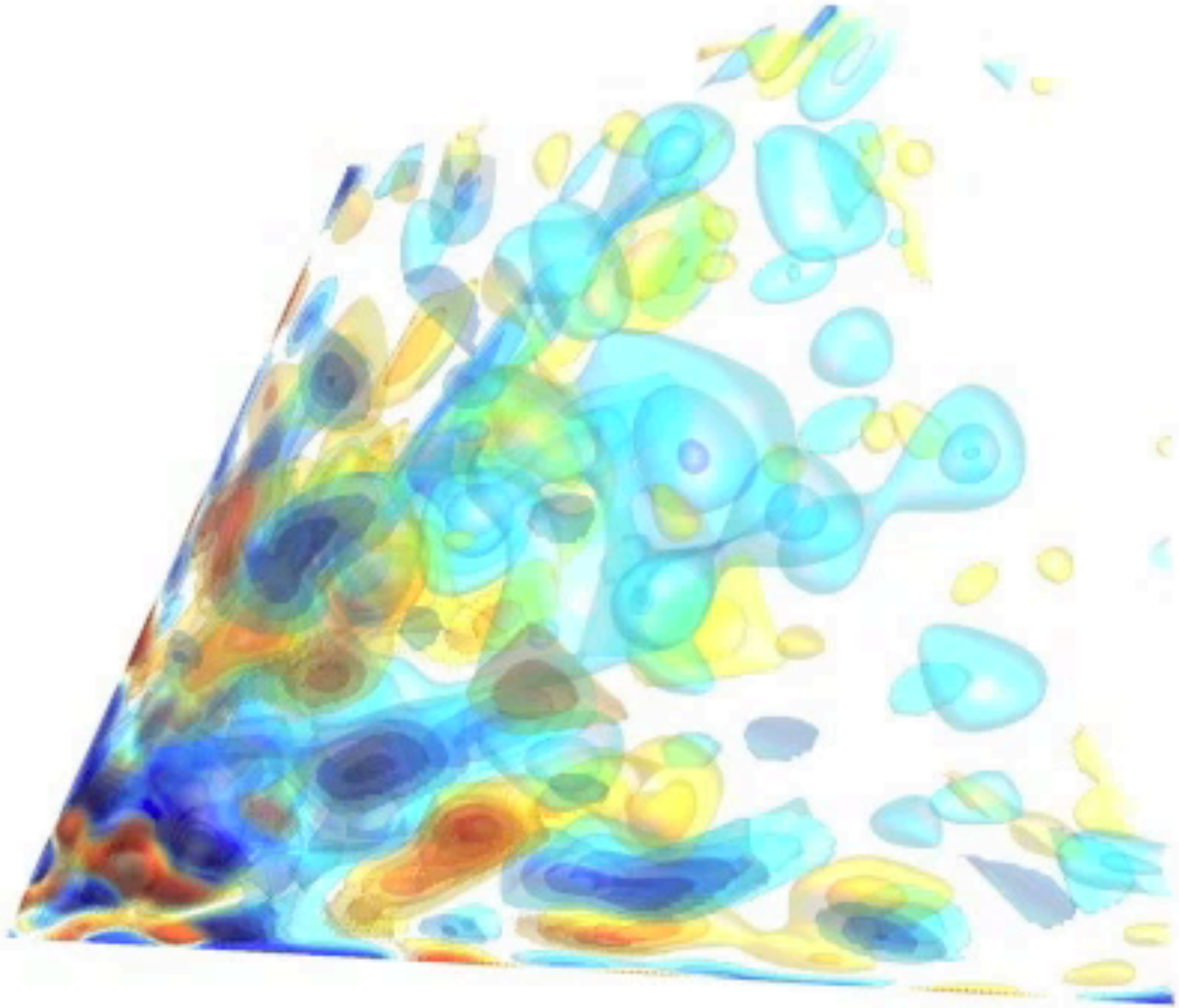
Filter with sufficient separable eigenmodes

The Planck Bispectrum

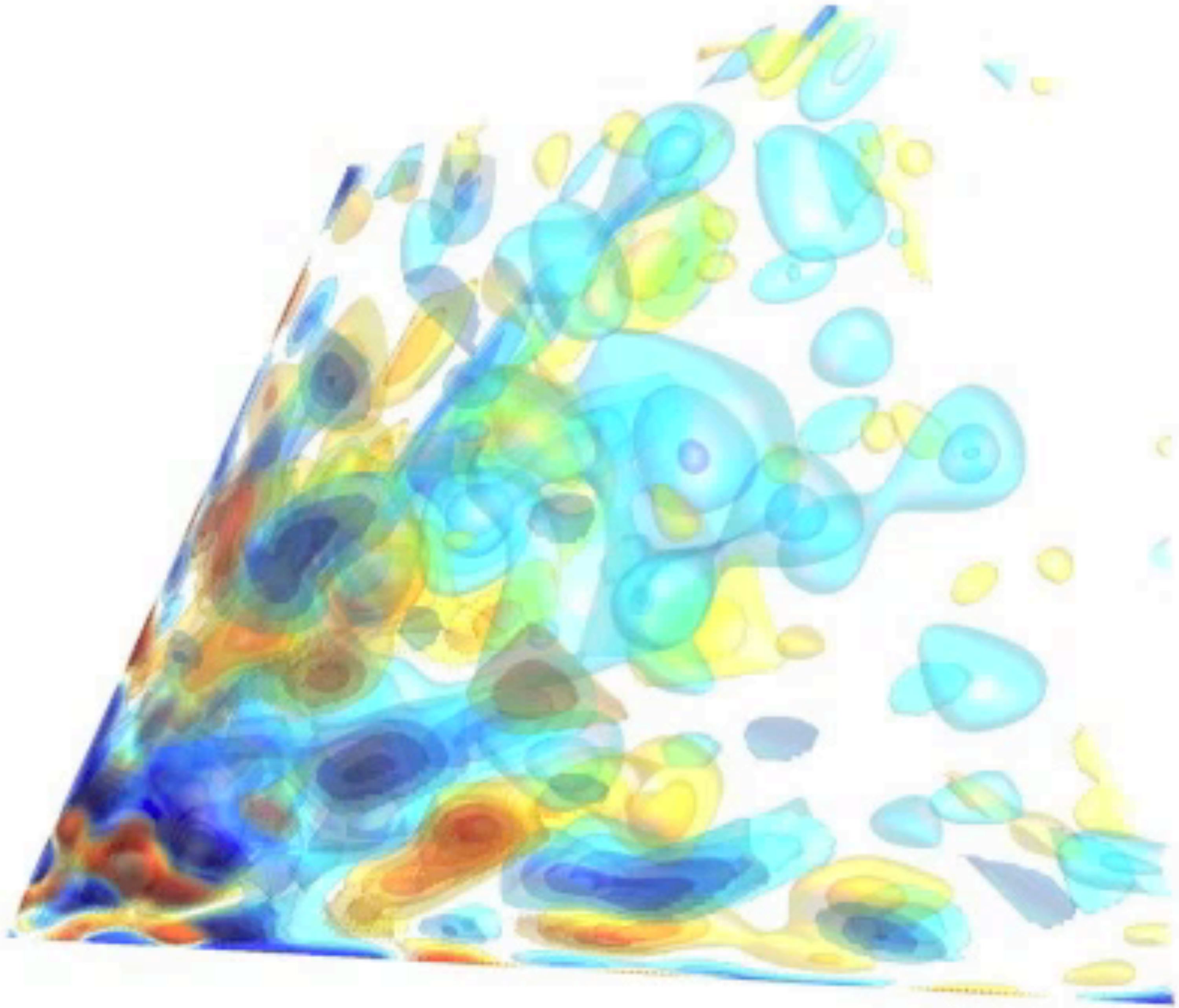
Modal reconstruction of the full 3D Planck bispectrum



Fourier modes vs Polynomials



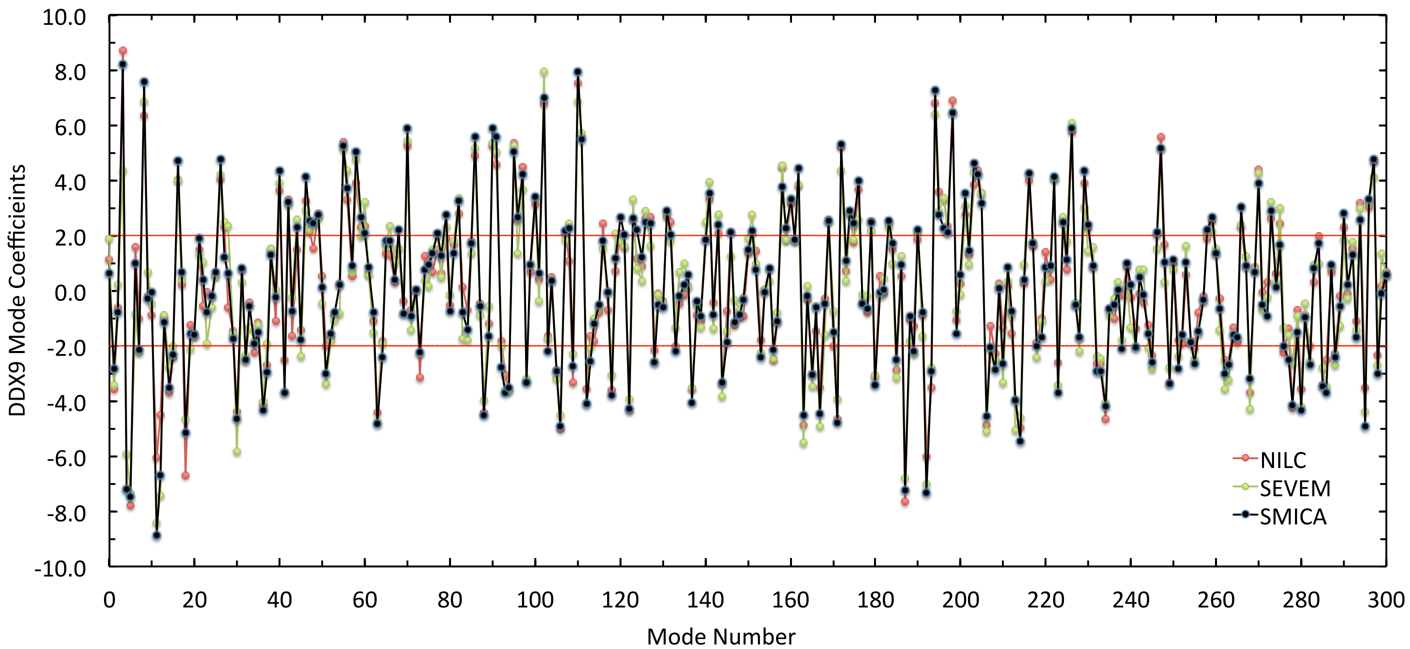
Modal FLS Bispectrum Reconstruction (Planck Collaboration 2013)



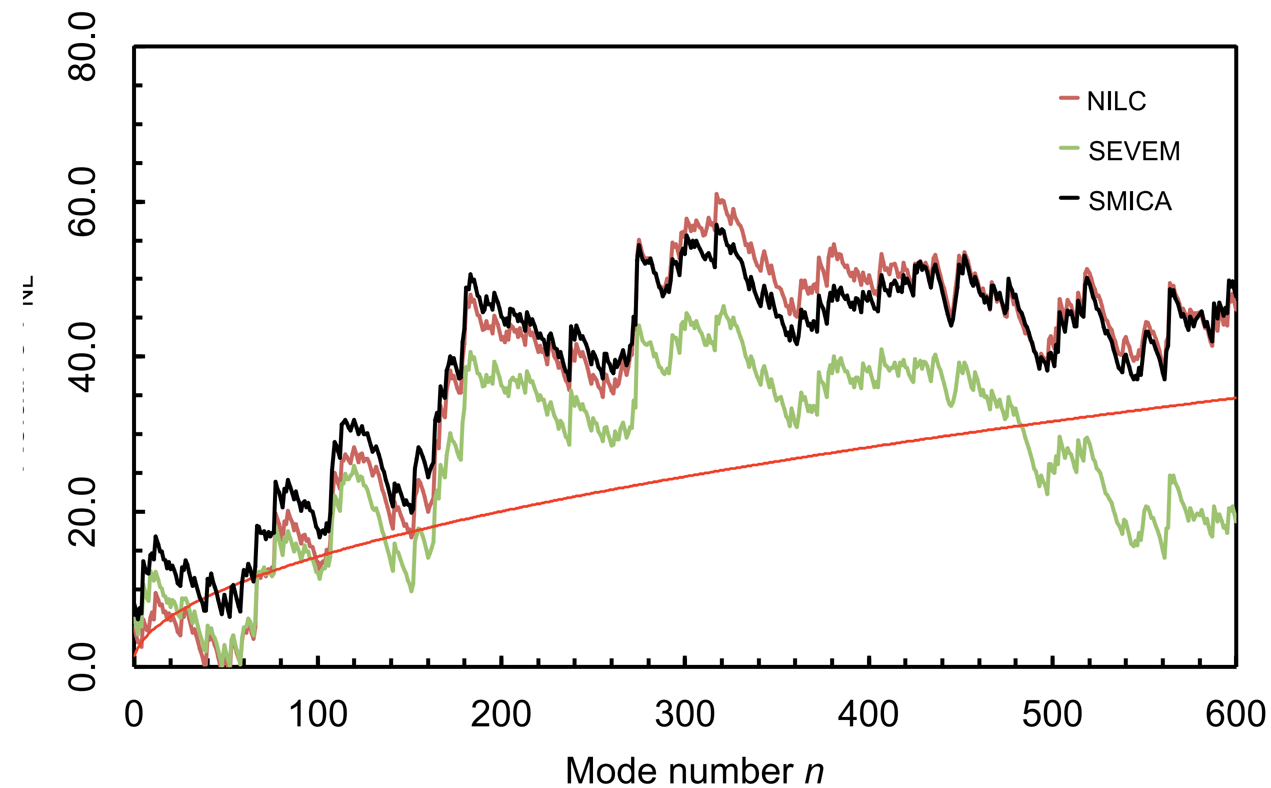
Modal FLS Bispectrum Reconstruction (Planck Collaboration 2013)

High bispectrum signal

Bispectrum expansion coefficients

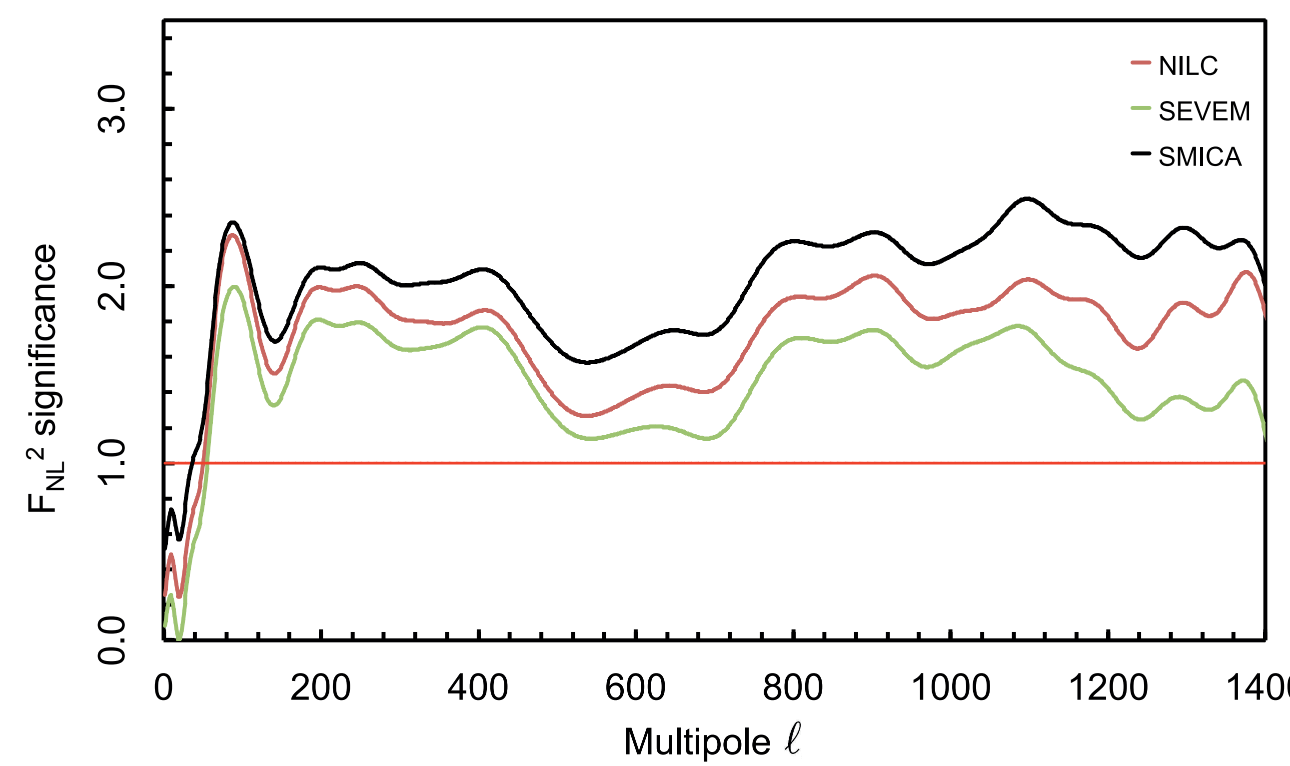


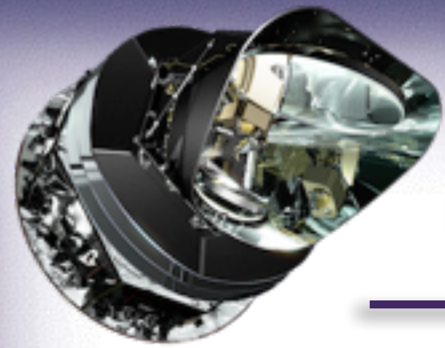
Cumulative sum vs Gaussian 2σ



χ^2-tests for integrated bispectrum consistent with Gaussianity, but signal always high.

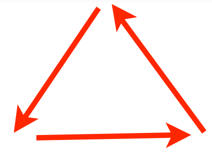
Comparison with 200 lensed CMB Gaussian maps with Planck noise.





Scale-invariant Bispectra

Equilateral bispectra

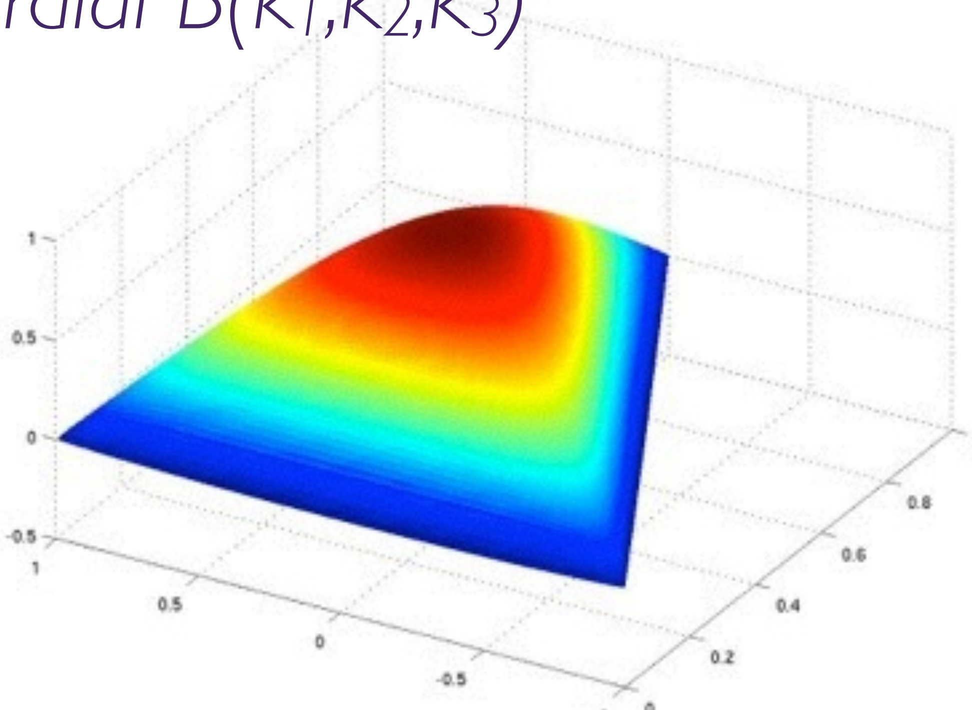


$$f_{NL}^{equil} = -42 \pm 75$$

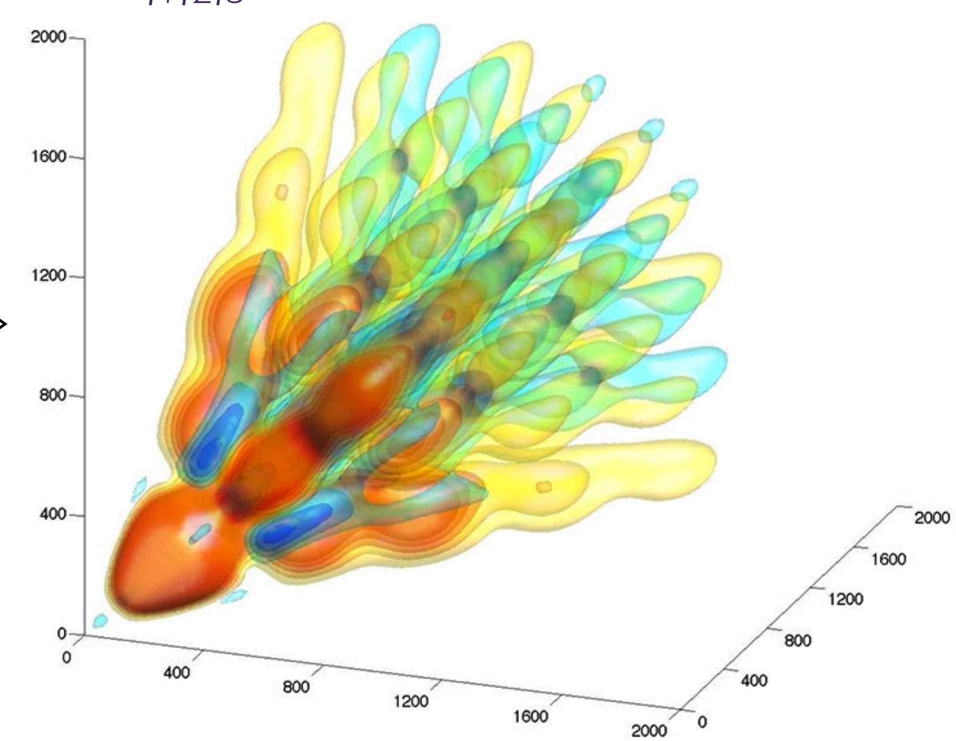
Inflation from higher dimensions

Single-field - sound speed $c_s << c$

Primordial $B(k_1,k_2,k_3)$



CMB $B_{l_1 l_2 l_3}$



Fergusson & EPS, arXiv:1008.1730

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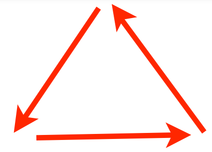
Equilateral bispectra



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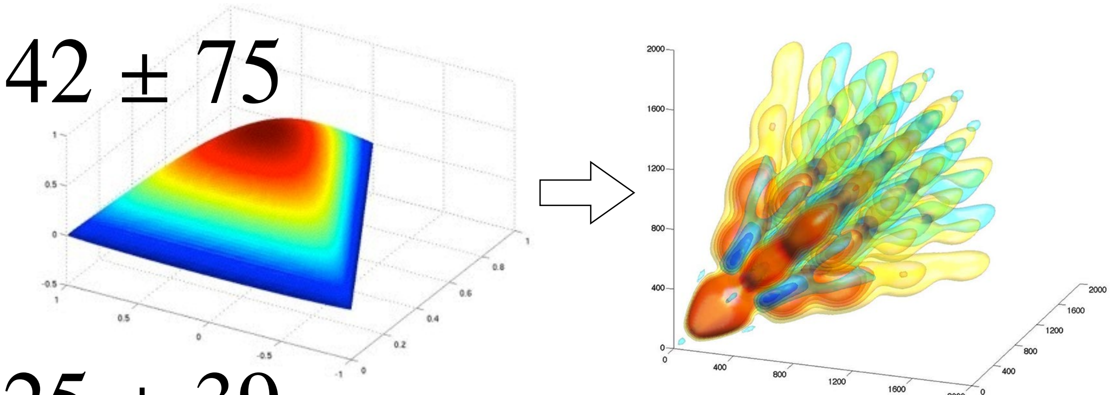
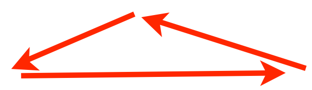


Inflation from higher dimensions

Single-field - sound speed $c_s << c$

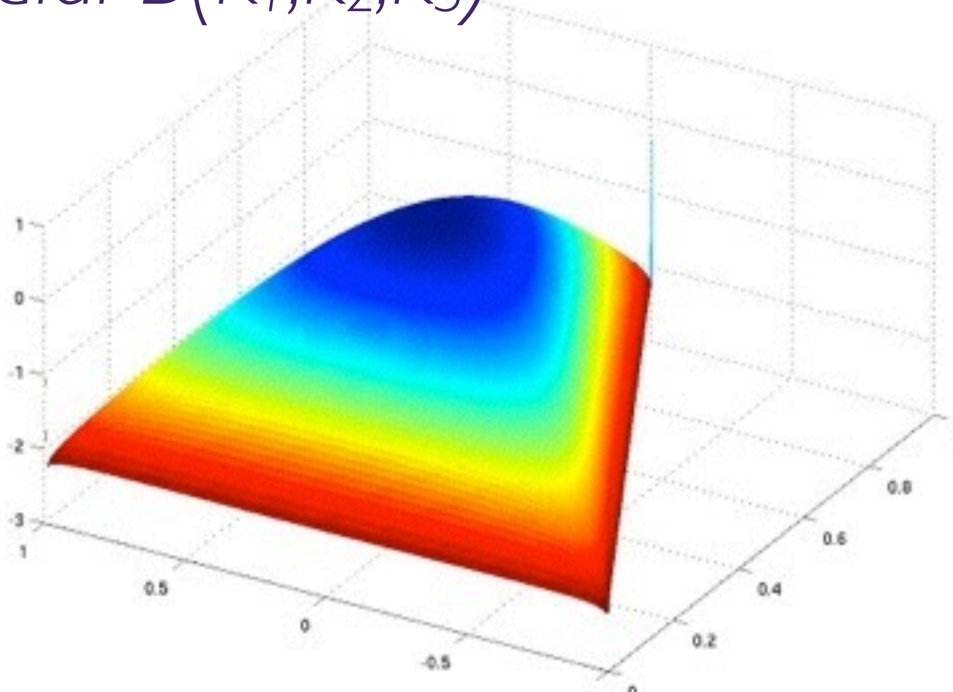
Orthogonal bispectra



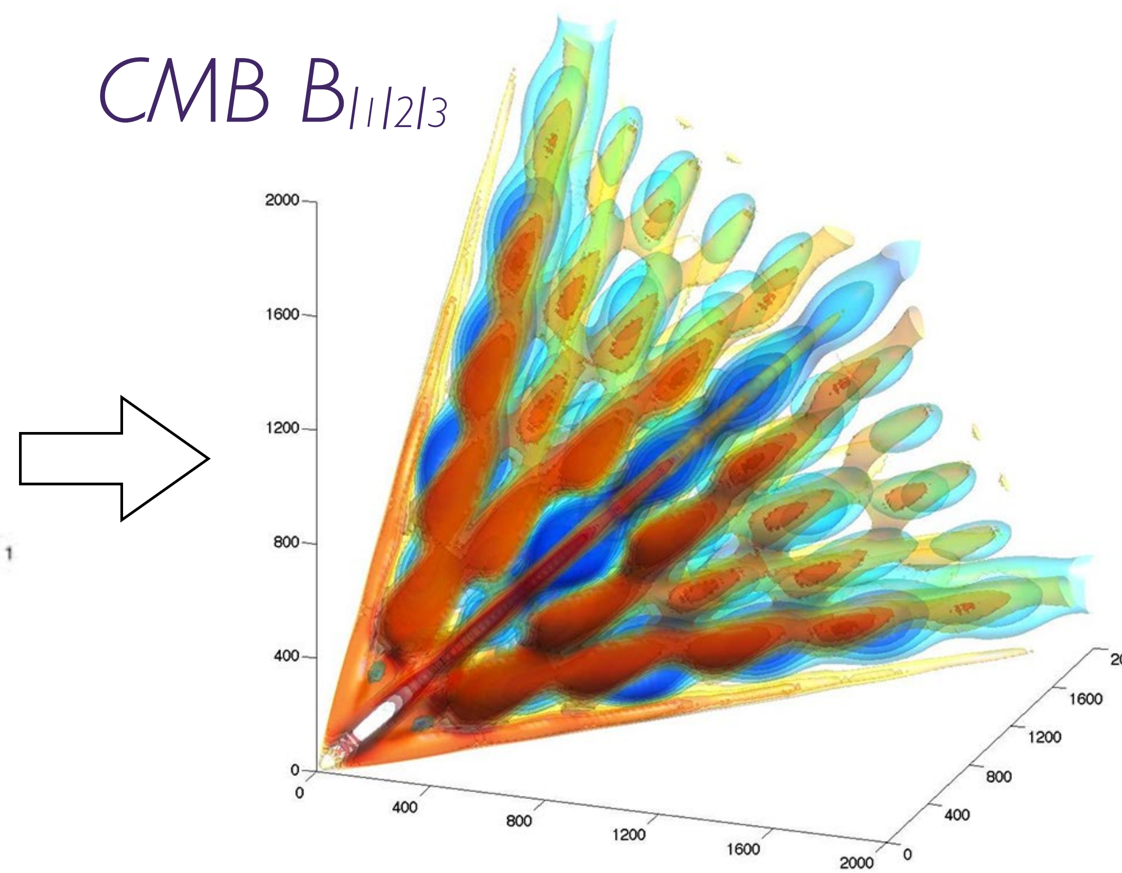
$$f_{NL}^{ortho} = -25 \pm 39$$

Single-field, complement of equilateral

Primordial $B(k_1,k_2,k_3)$



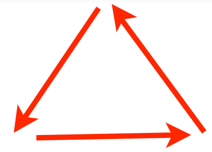
CMB $B_{l_1 l_2 l_3}$



Fergusson & EPS, arXiv:1008.1730

Scale-invariant Bispectra

Equilateral bispectra



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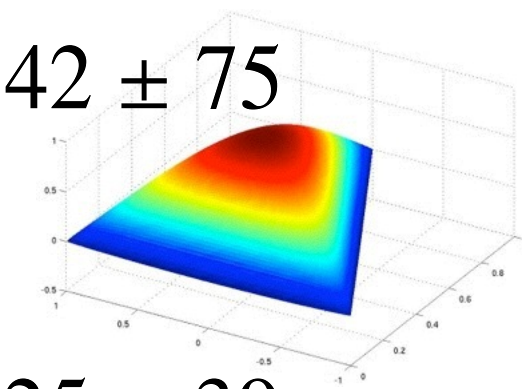
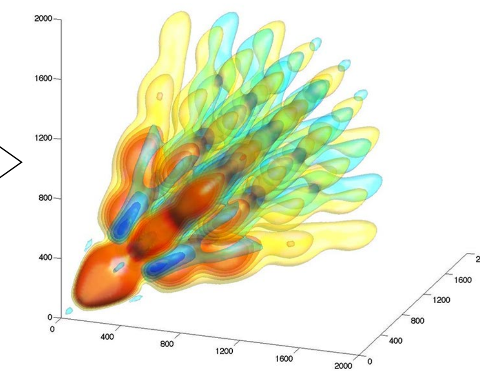
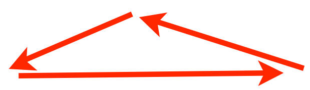




Inflation from higher dimensions

Single-field - sound speed $c_s << c$

Orthogonal bispectra



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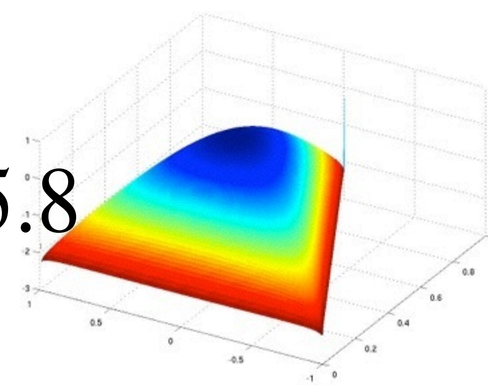
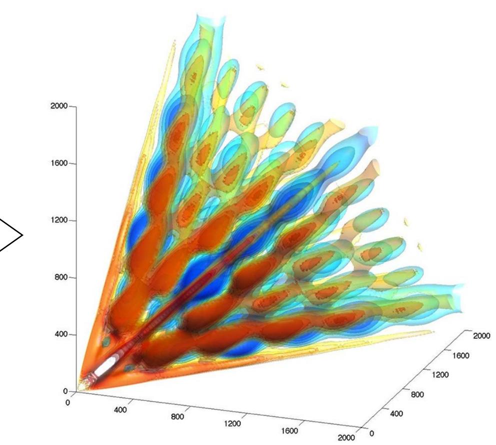
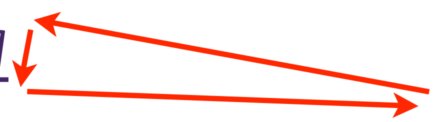




Local bispectra

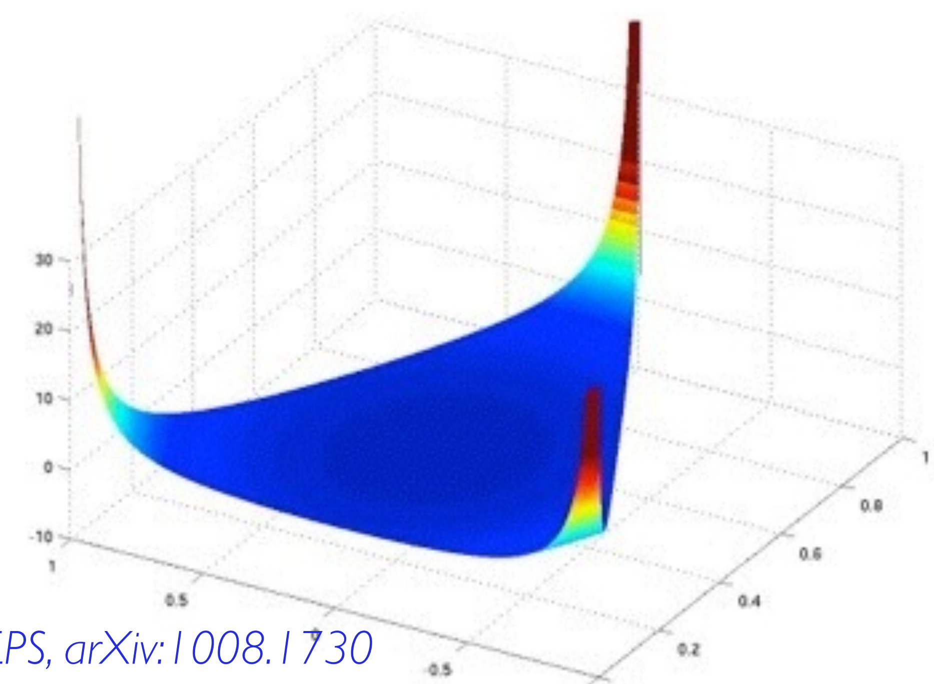


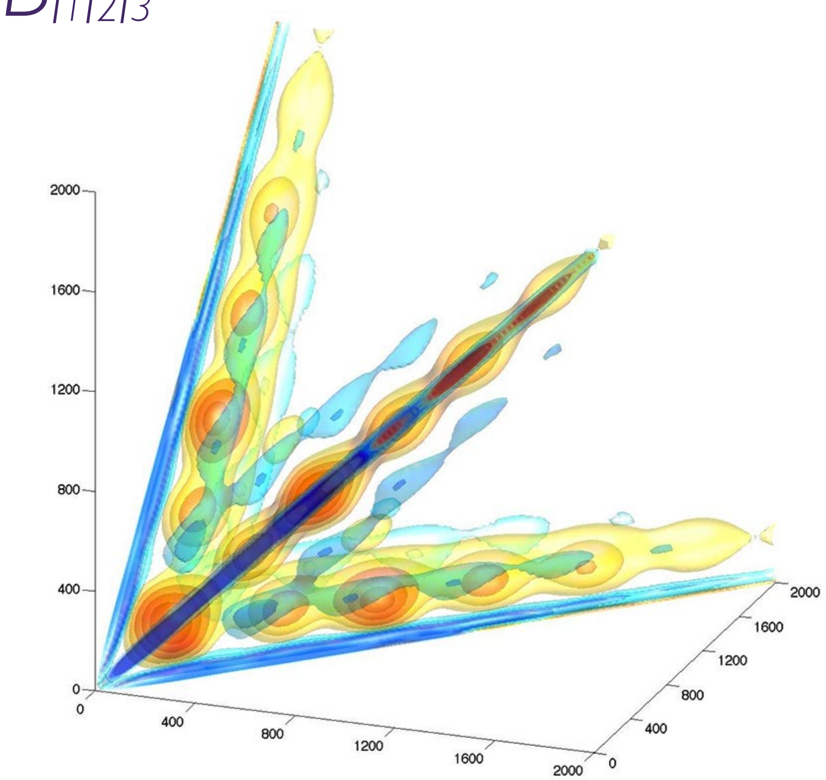
$$f_{NL}^{local} = 2.7 \pm 5.8$$

Multifield inflation, curvaton etc.

Primordial $B(k_1,k_2,k_3)$

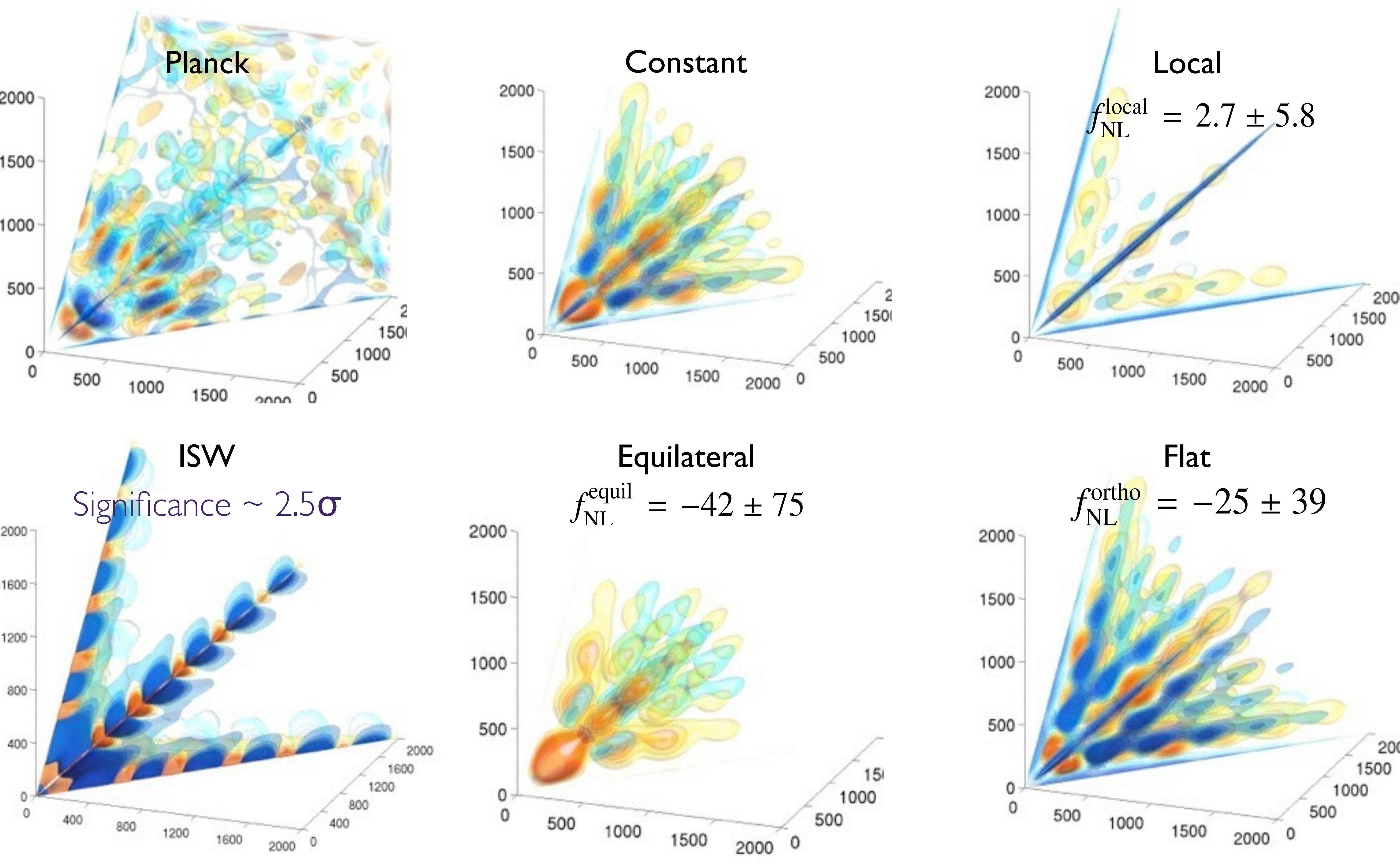
CMB $B_{l_1 l_2 l_3}$





Fergusson & EPS, arXiv:1008.1730

Bispectrum in detail



Axion Monodromy

Large-field inflation predicts gravitational waves - r ~ 0.05 - but ...

- large excursions with a flat potential not natural (corrections)

- slow-roll inflation requires an effective shift symmetry $\Phi \rightarrow \Phi + c$

Ingredients: UV completion - string theory

Shift symmetry - axions $a \rightarrow a + 2\pi$

Axion potential recycled - monodromy

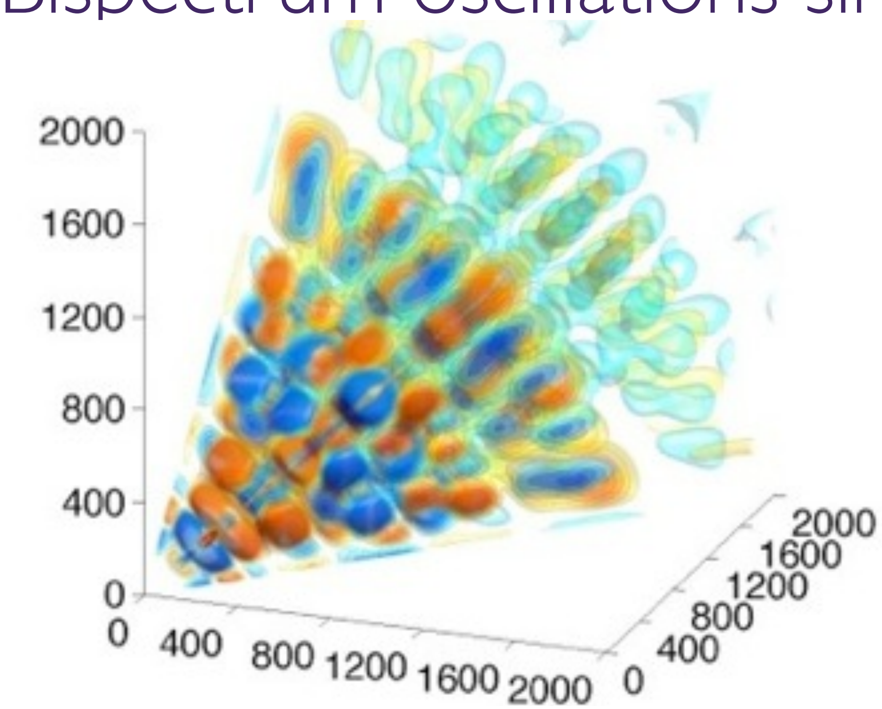
e.g. Silverstein & Westphal 2008

Flauger et al 2009

Predictions: Tensor modes r>0.07

Power spectrum periodicity

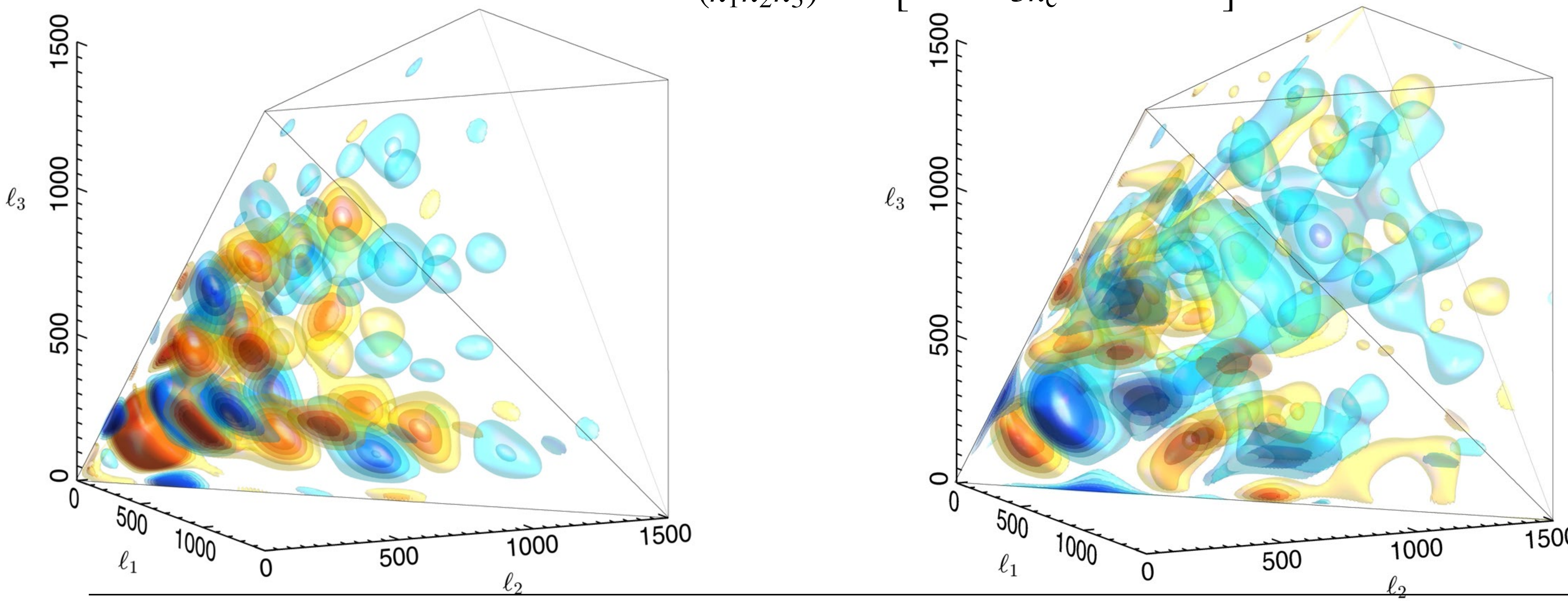
Bispectrum oscillations sin[log (k)+c]



Feature model bispectrum

Inflaton potential can have a feature which disturbs slow-roll:

$$B_\Phi^{\rm feat}(k_1,k_2,k_3) = \frac{6A^2 f_{\rm NL}^{\rm feat}}{(k_1k_2k_3)^2}\sin\left[\frac{2\pi(k_1+k_2+k_3)}{3k_{\rm c}}+\phi\right]$$



Width Model	$\Delta k = 0.015$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	$\Delta k = 0.03$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	$\Delta k = 0.045$ $f_{\rm NL} \pm \Delta f_{\rm NL}$ (σ)	Full $f_{\rm NL} \pm \Delta f_{\rm NL}$ (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)
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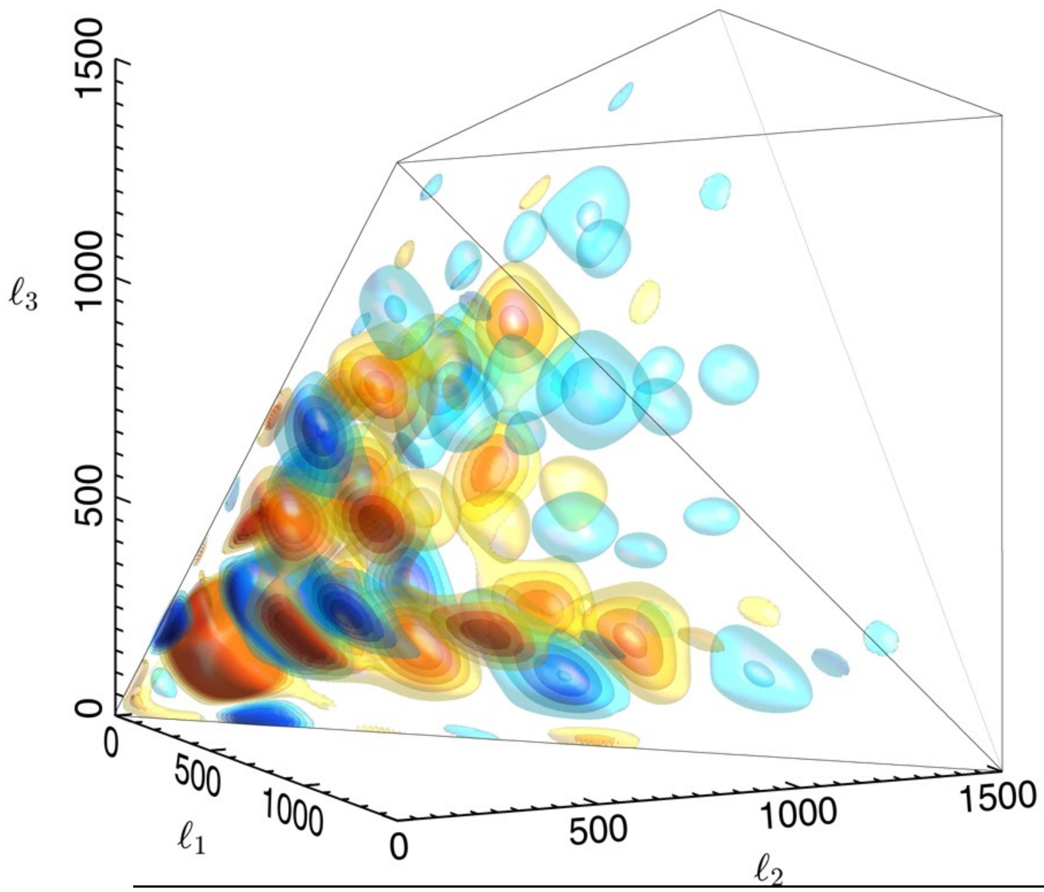

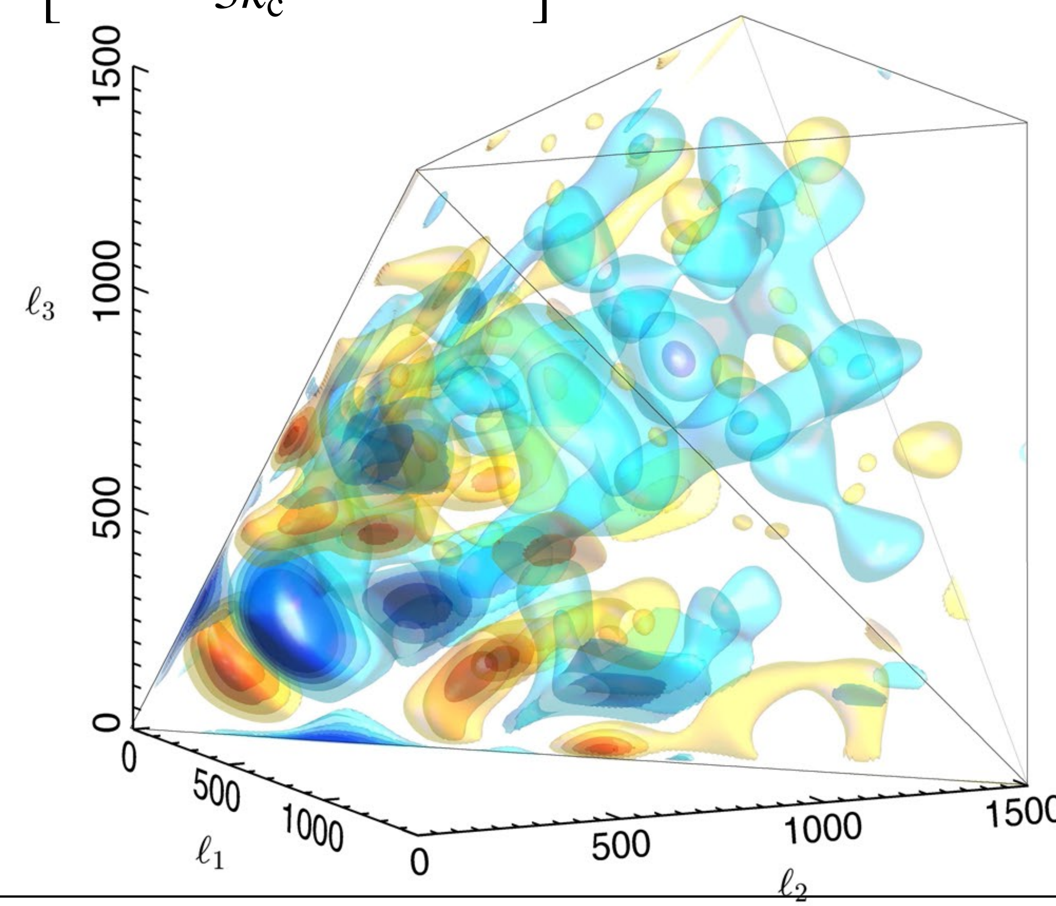

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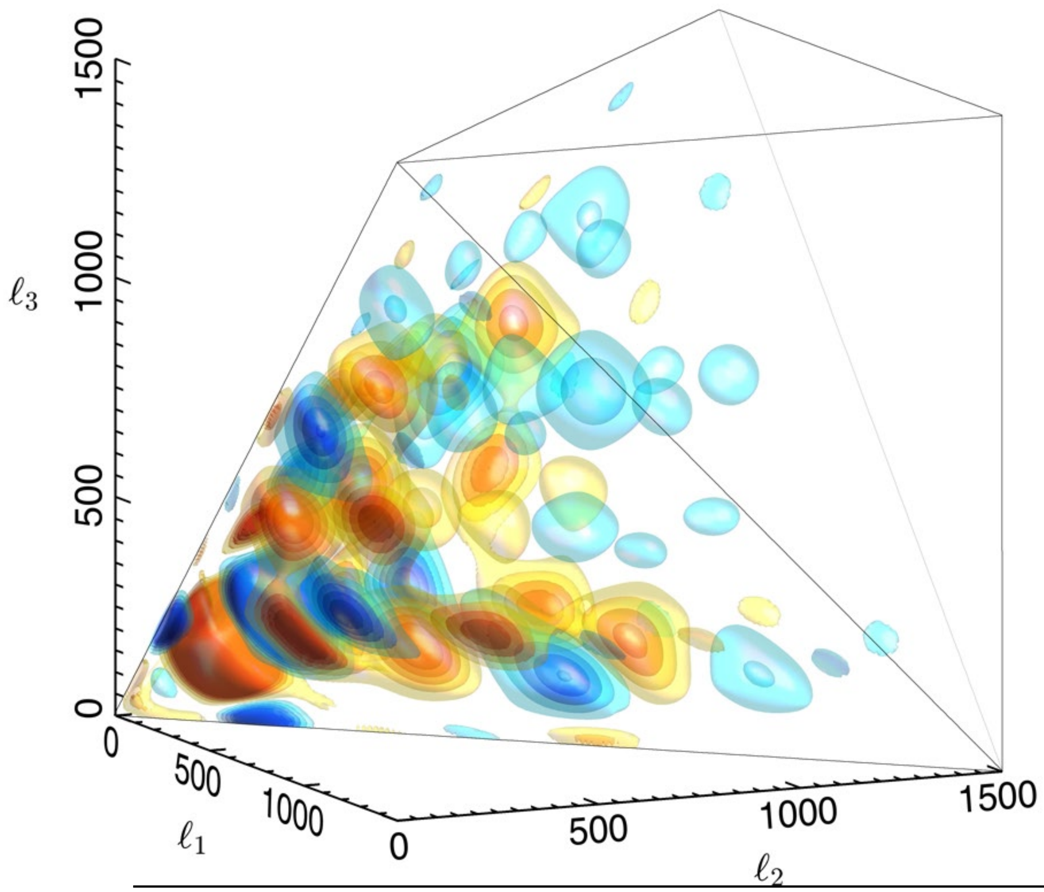

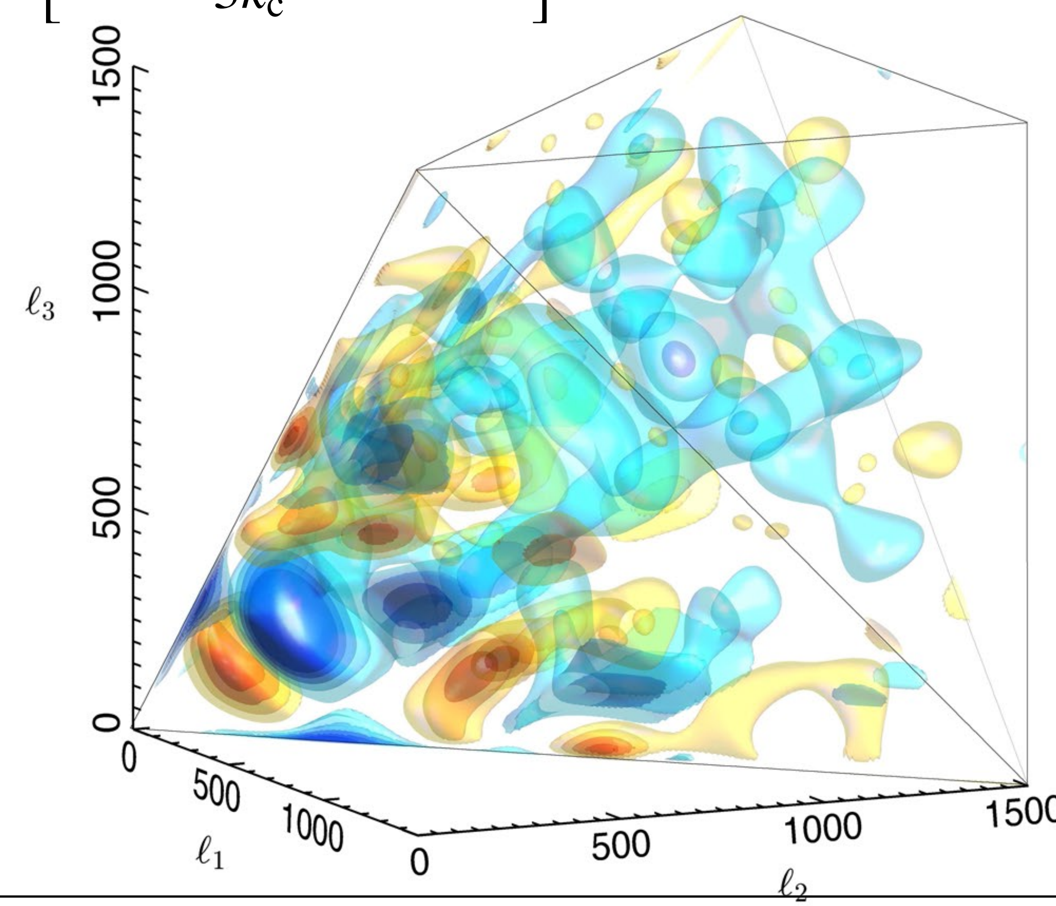

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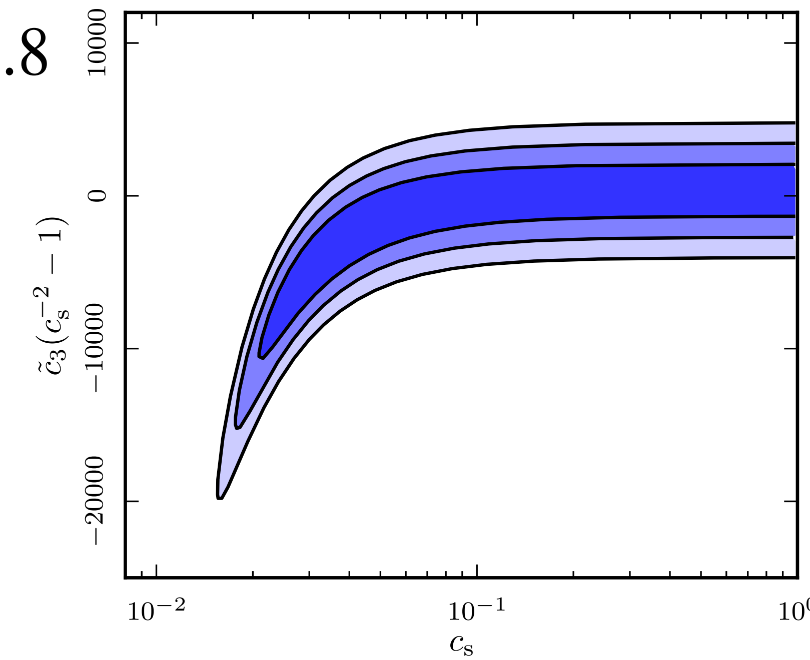
Extra parameters reduce significance through the "look elsewhere effect" …

NG Conclusions

Scale-invariant primordial non-Gaussianity is strongly constrained

- Local, equilateral and orthogonal shapes, e.g. $f_{NL}^{local} = 2.7 \pm 5.8$
- Constrains many models (in combination with Cl's):
    - Effective field theory sound speed $c_s > 0.02$
    - For DBI inflation sound speed $c_s > 0.07$
    - Power law K-inflation ruled out (cf power spectrum)
    - Curvaton model constraint on "decay fraction" r_D
    - Ekpyrotic/cyclic "conversion mechanism" ruled out

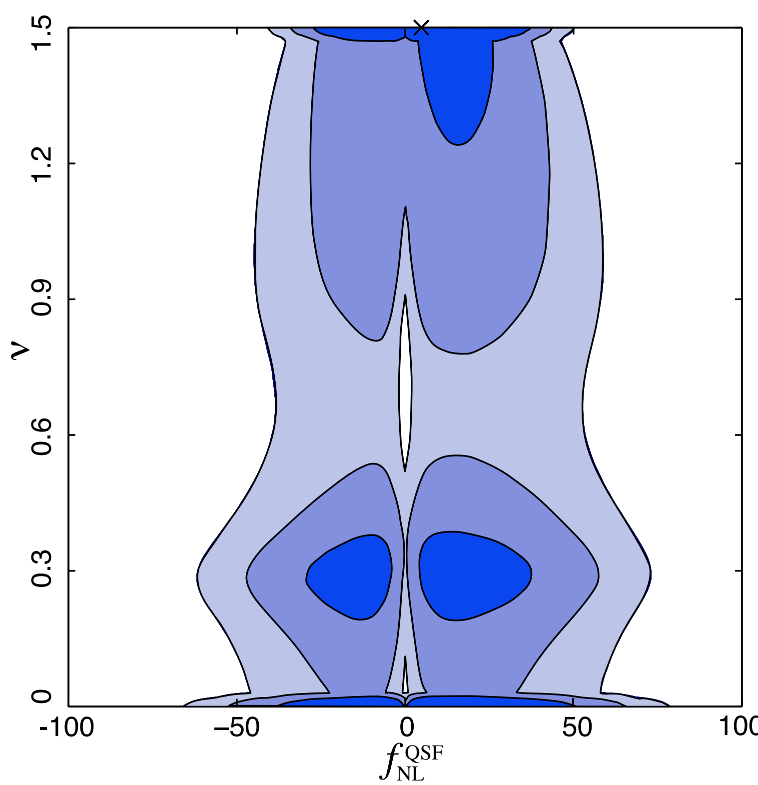


Planck bispectrum reconstruction - large NG signal

Alternative bispectrum paradigms investigated:

squeezed, equil, non-Bunch Davies, oscillatory

Oscillatory "patterns": further investigation ongoing



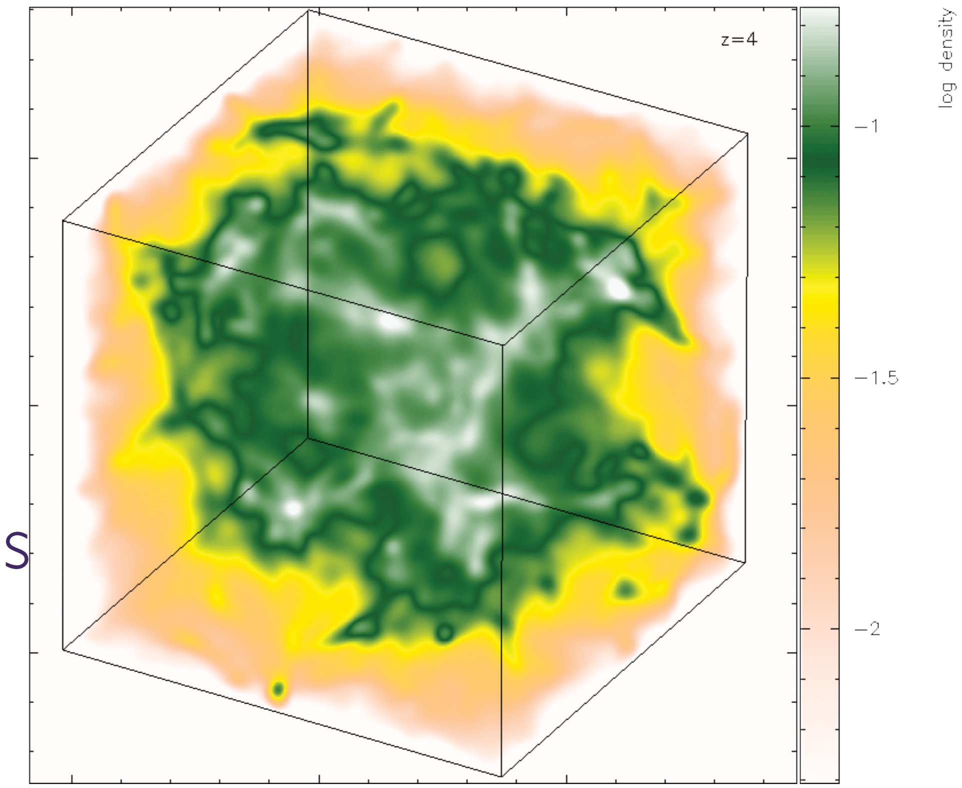
Also first results for trispectrum $\tau_{NL} < 2800$ (weak)

Aside: Galaxy/N-body bispectra

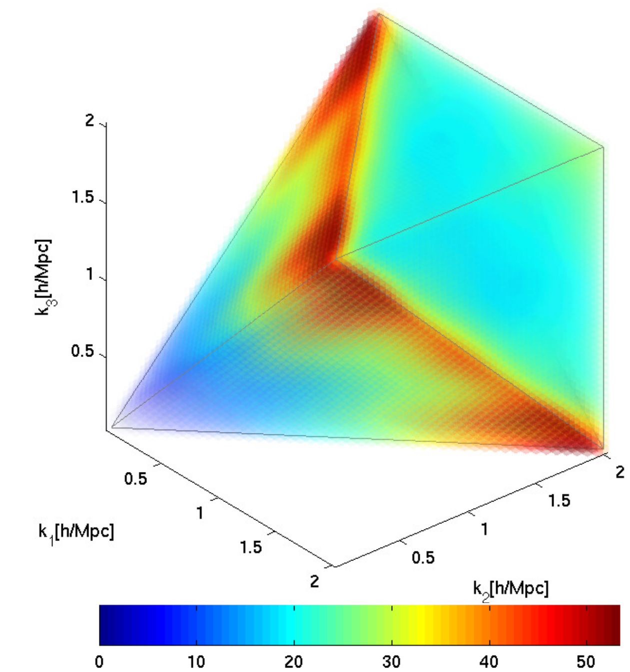
Gravitational bispectra from galaxy surveys & N-body simulations

Schmittfull, Regan & EPS, arXiv:1207.5678

Higher density of states $f_{NL} = 1$ attainable?

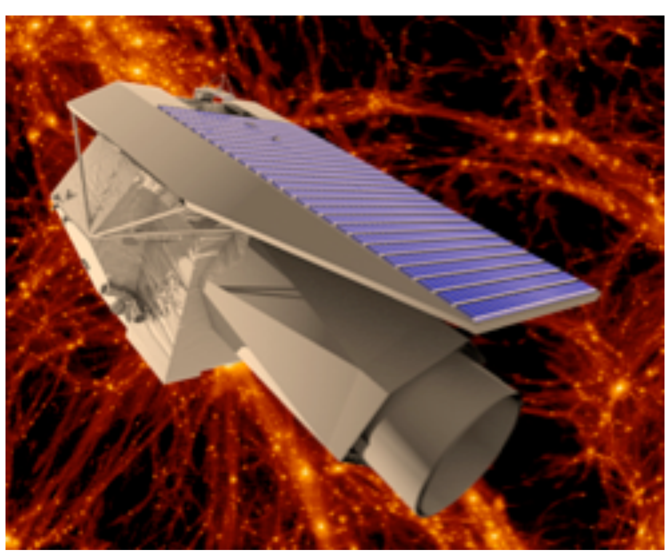


(a) Dark matter, $z = 4$

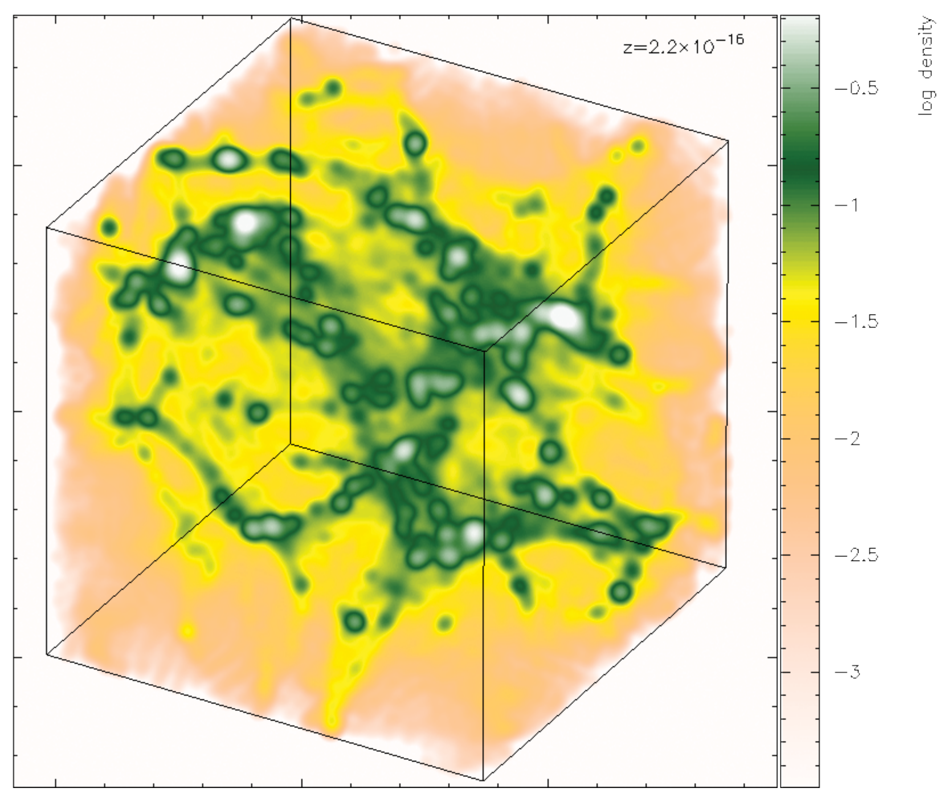


(b) Bispectrum signal, $z = 4$

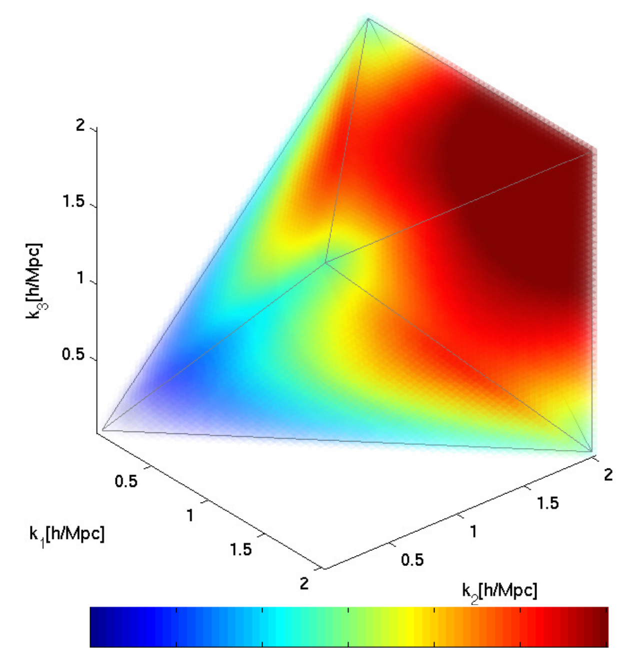
Dark Energy Survey



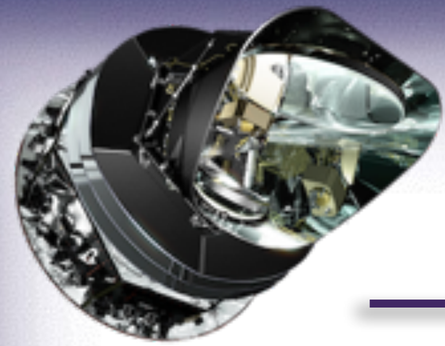
ESA Euclid satellite (construction began July 2013)



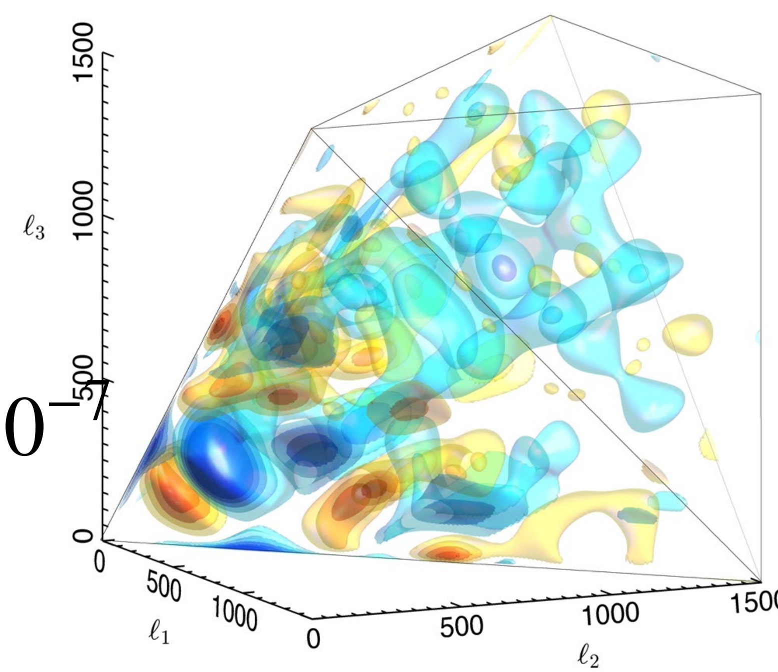
(e) Dark matter, $z = 0$



(f) Bispectrum signal, $z = 0$



String constraints



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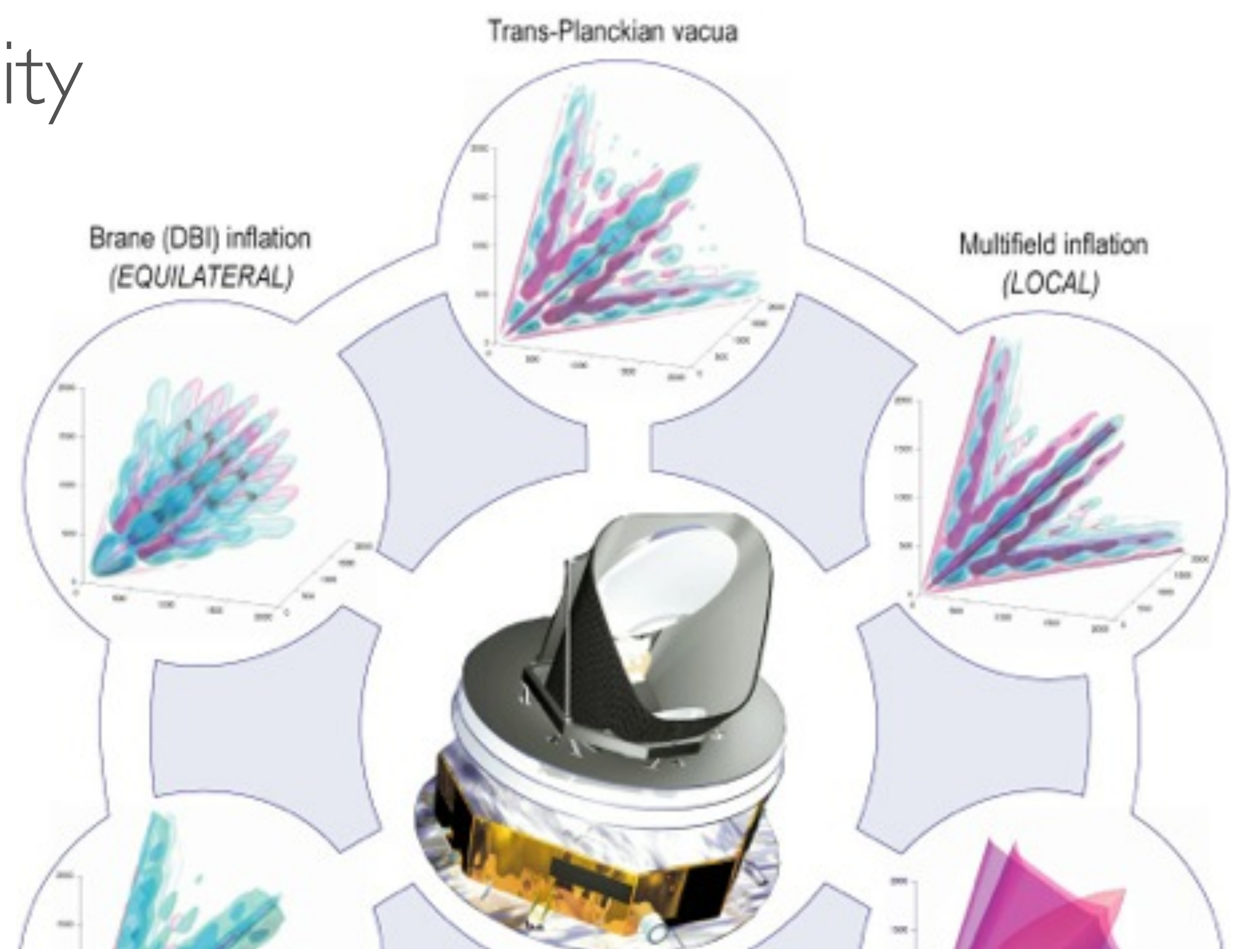
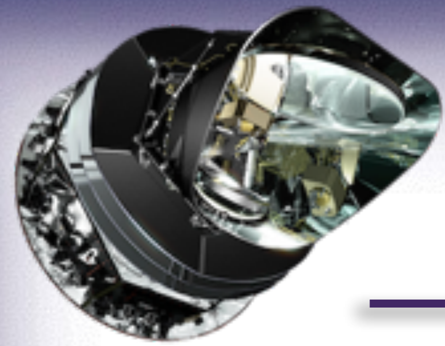
Key NG issues are to eliminate systematics

- Prospects for Planck non-Gaussianity

$$\Delta G\mu < 2\times10^{-7}$$





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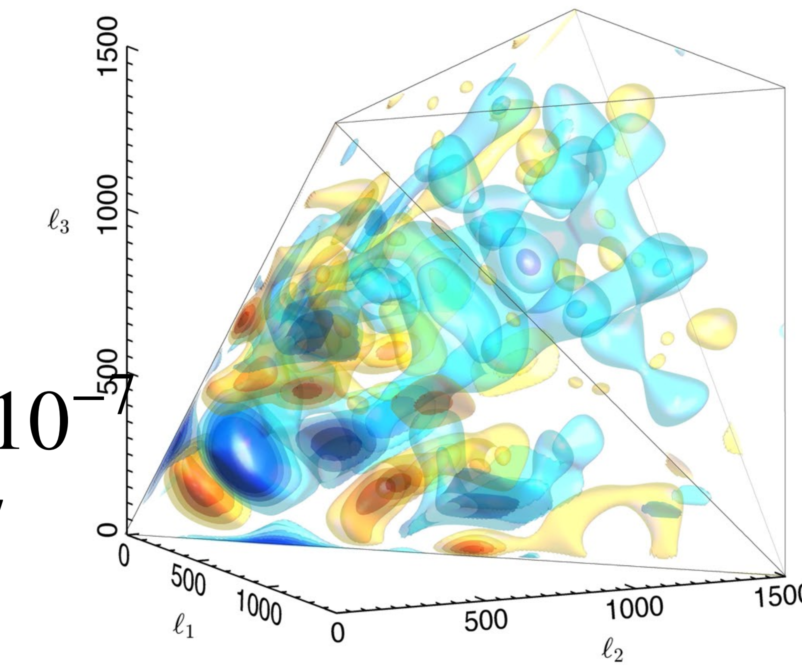

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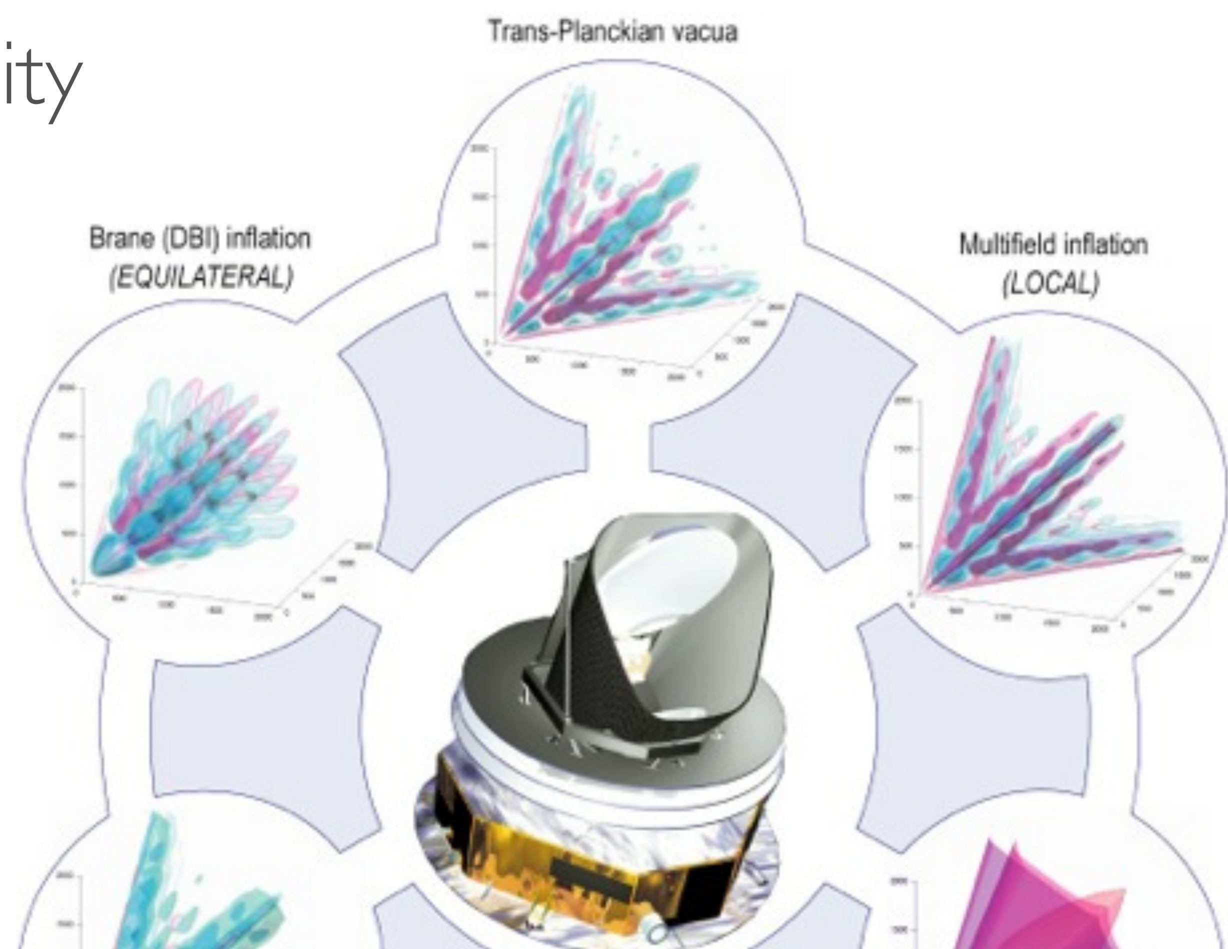

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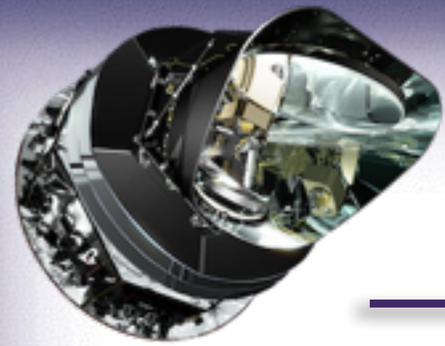

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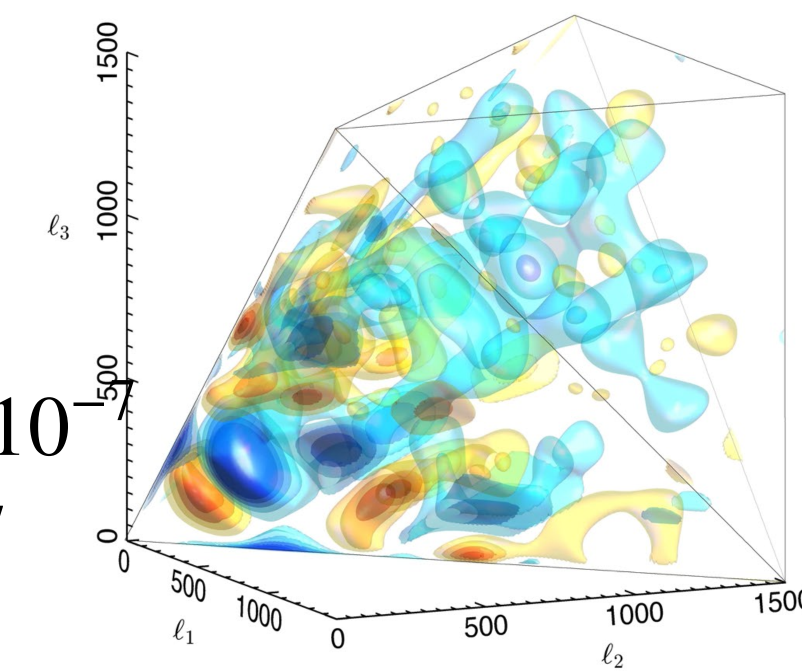

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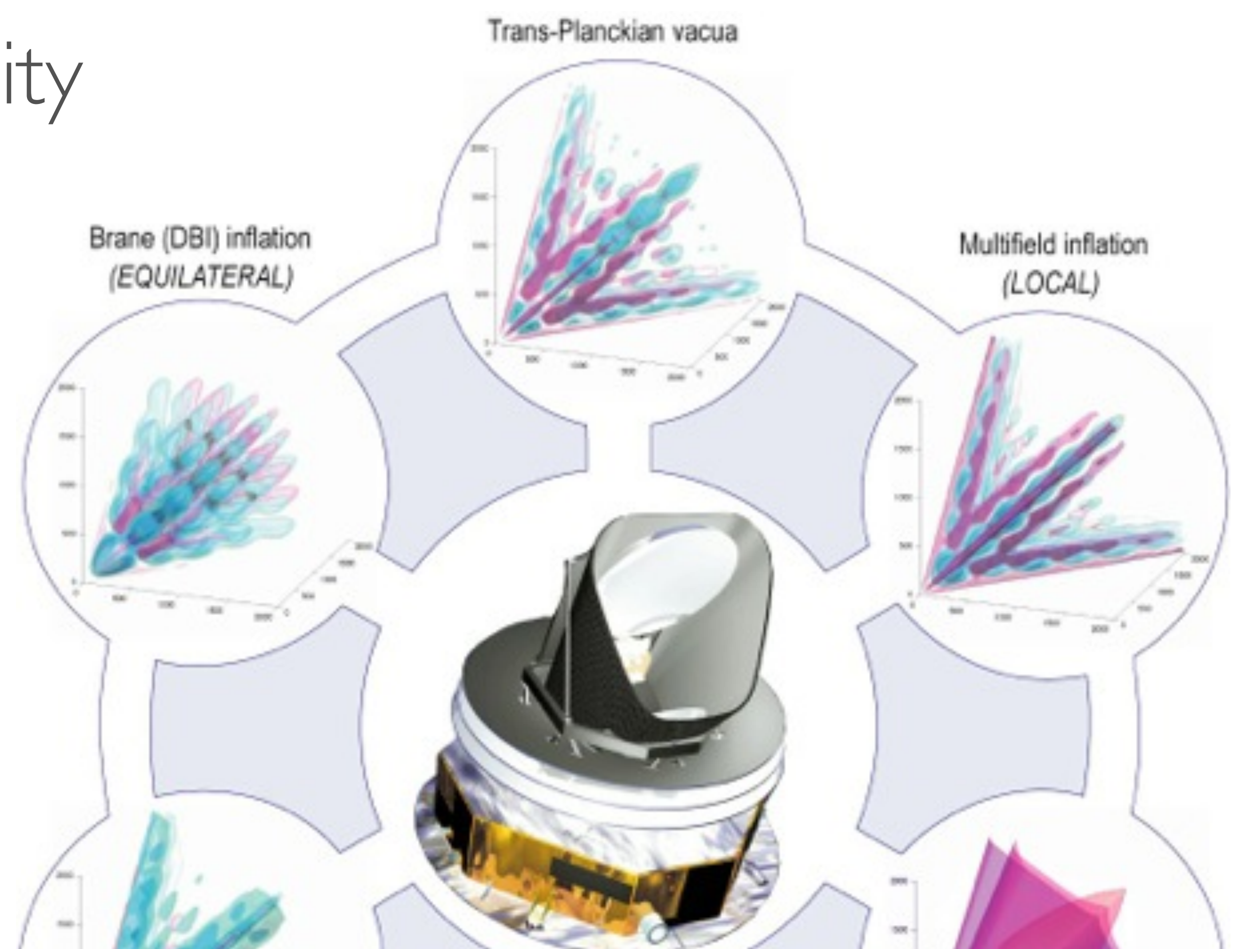

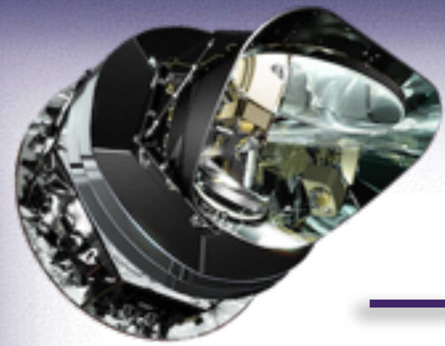

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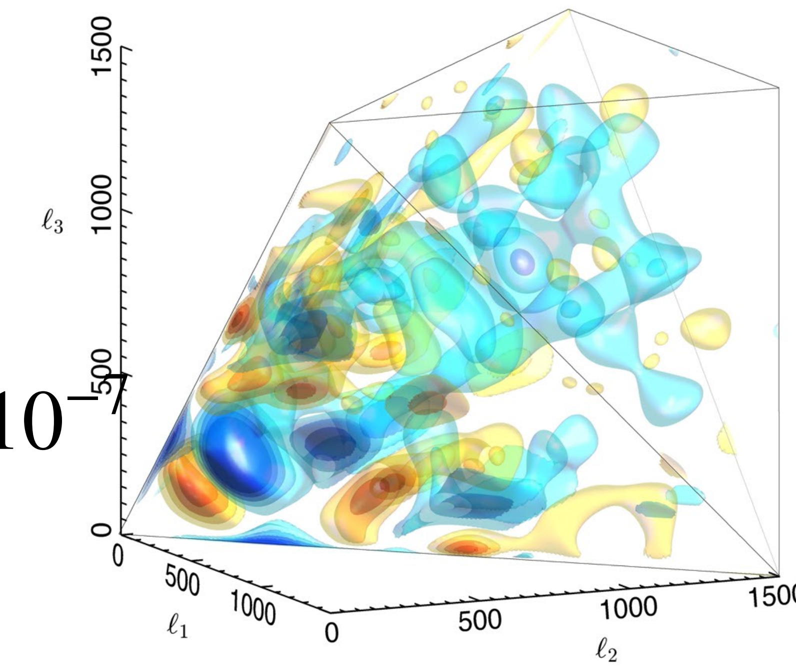

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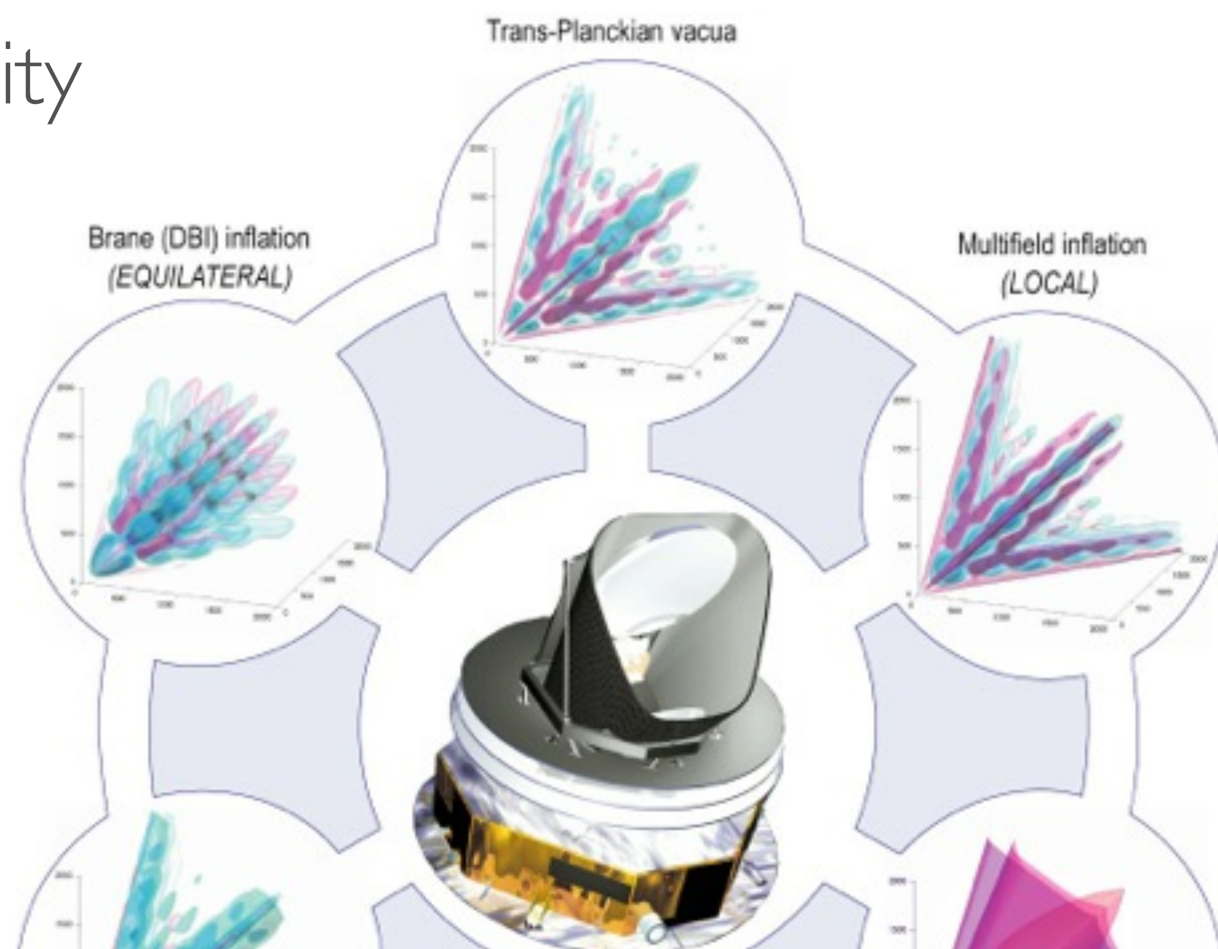
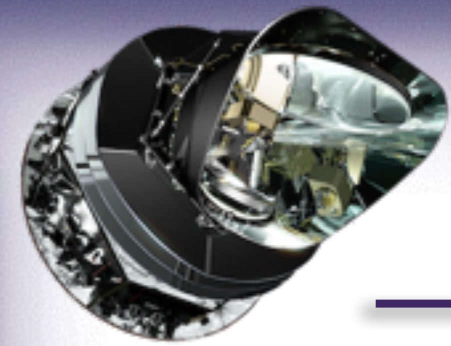
COBE few parts in 100





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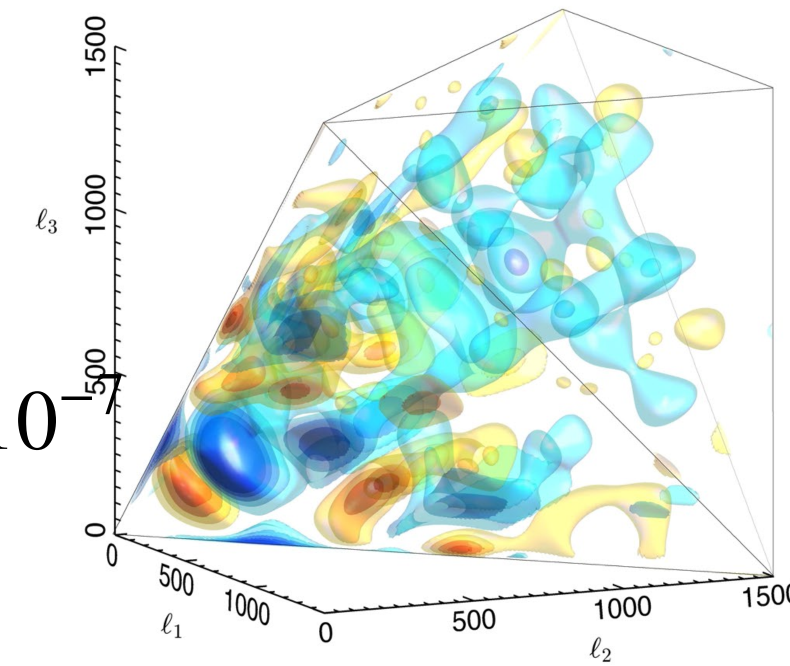

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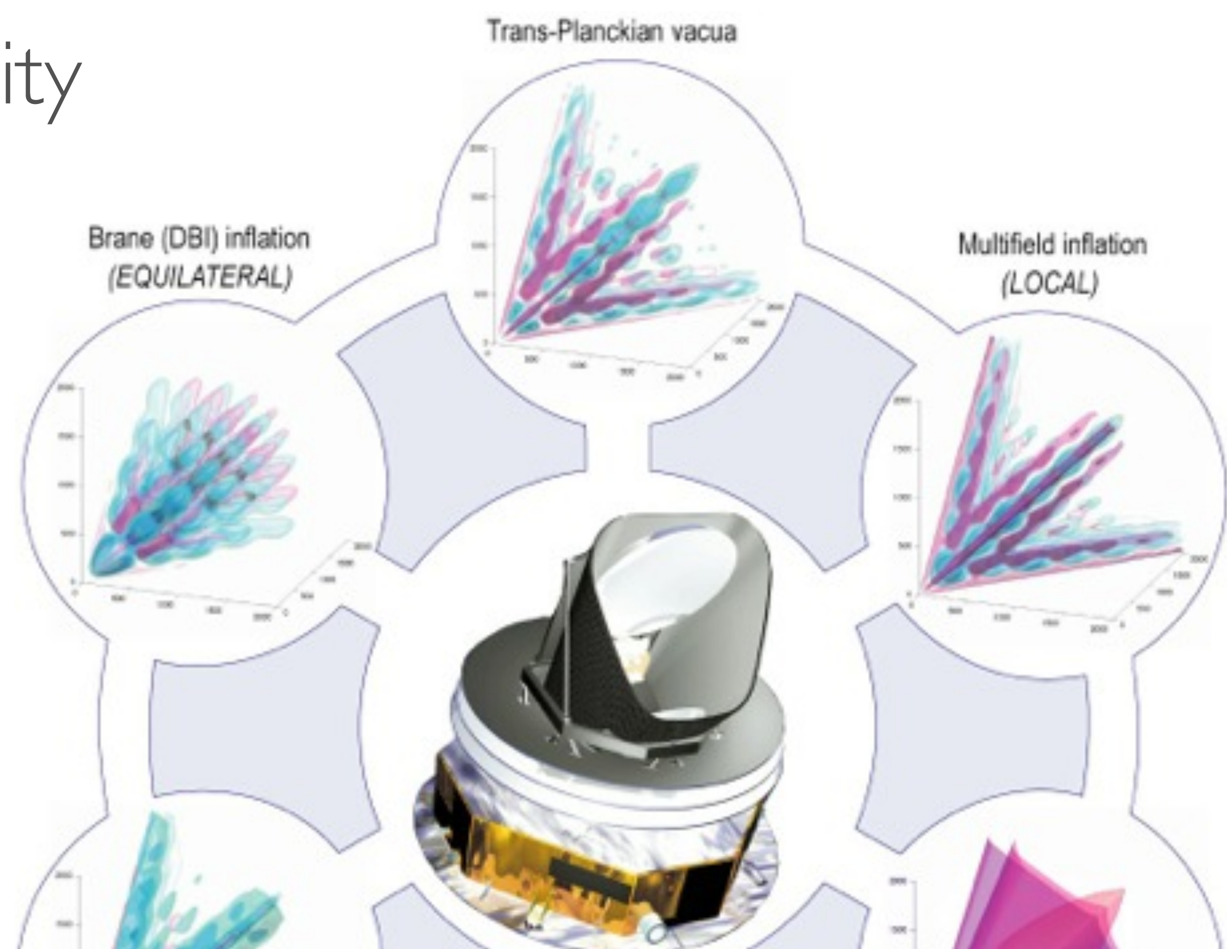
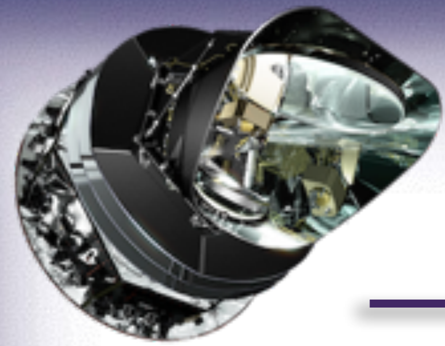
COBE few parts in 100

WMAP 2-3 parts in 10,000





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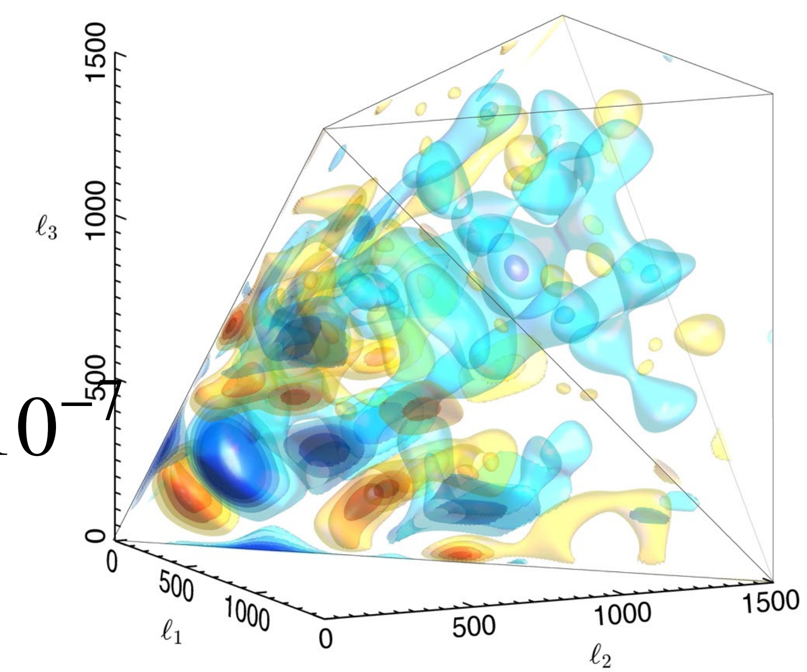

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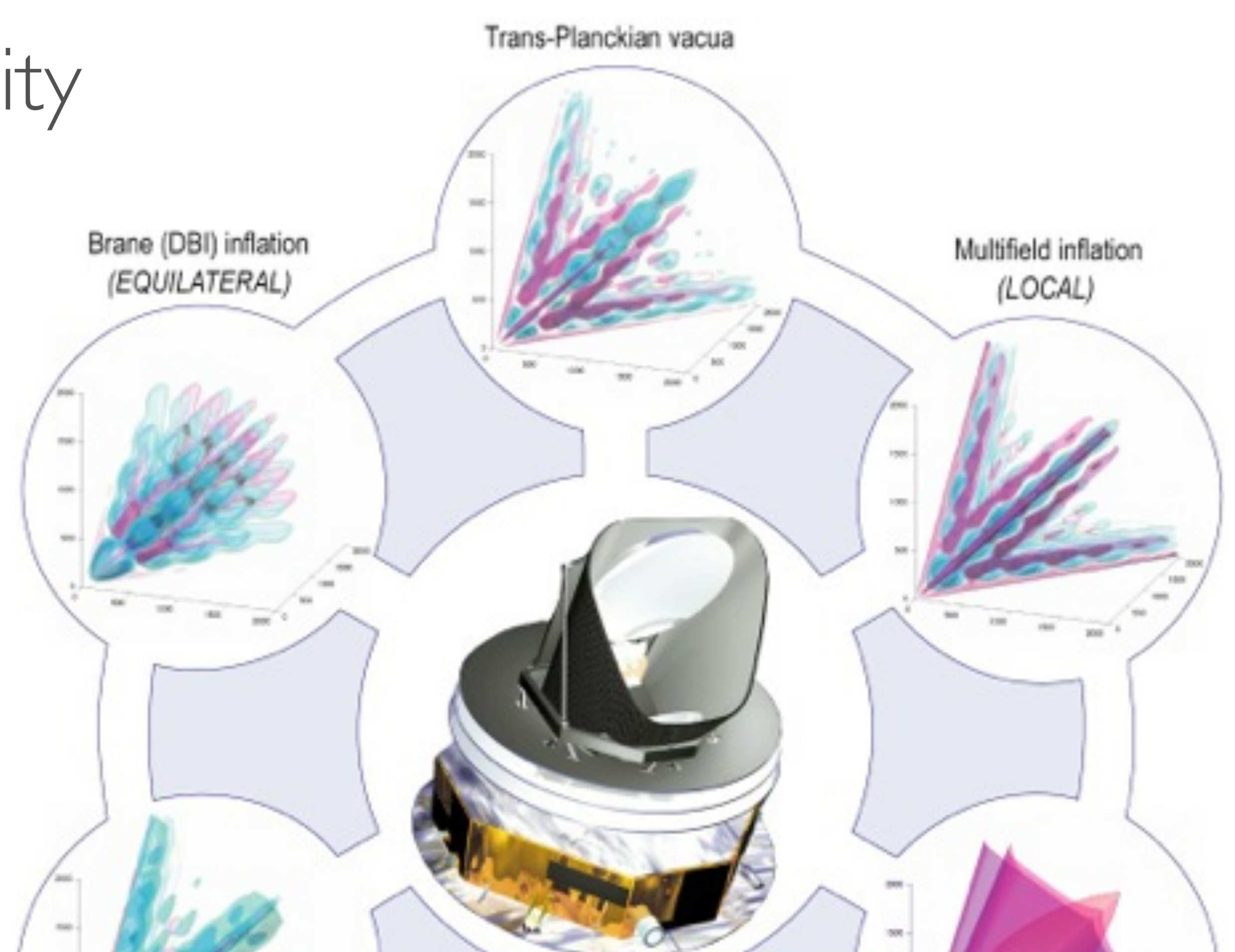
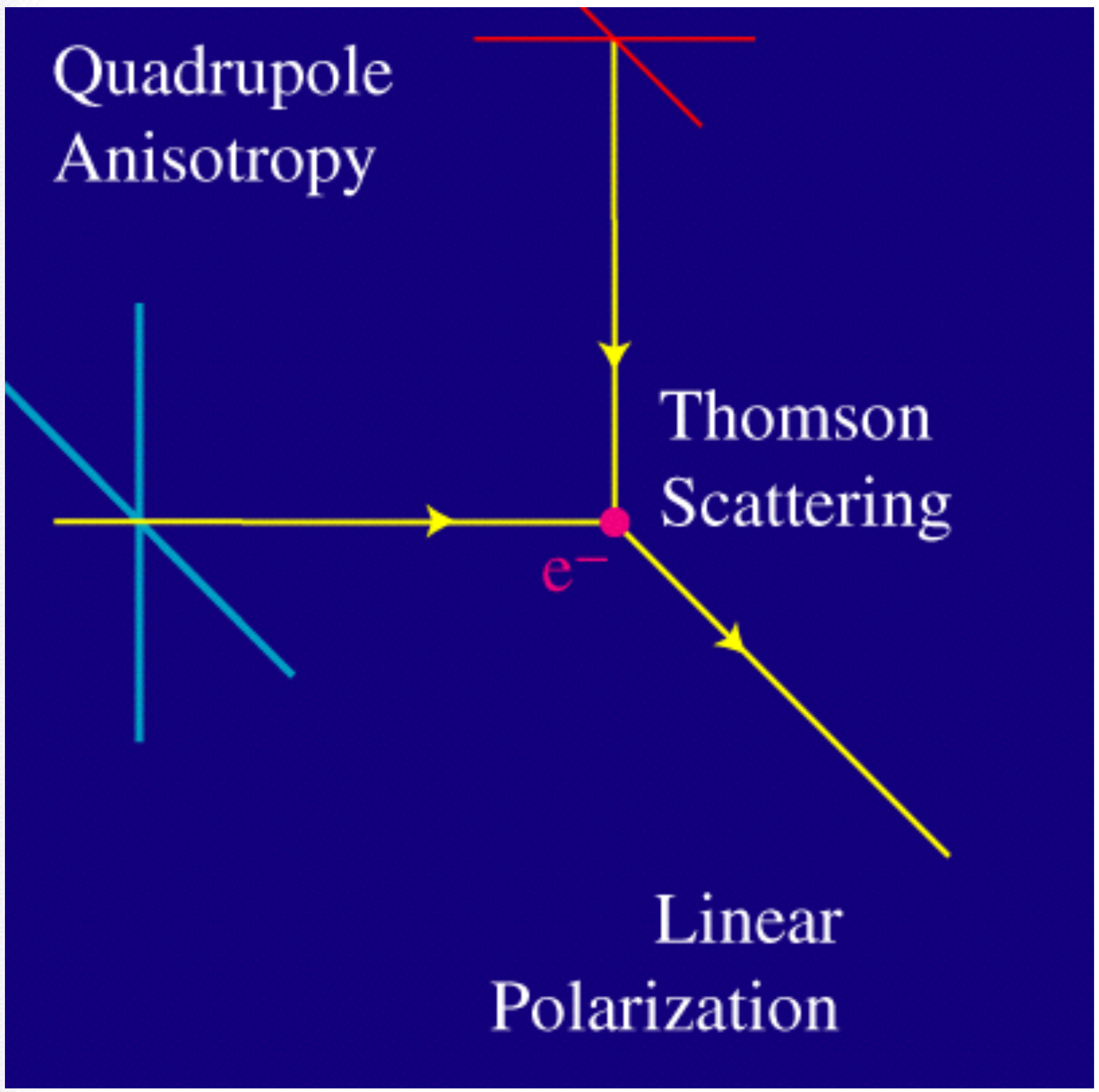
COBE	few parts in 100
WMAP	2-3 parts in 10,000
Planck	few parts in 100,000

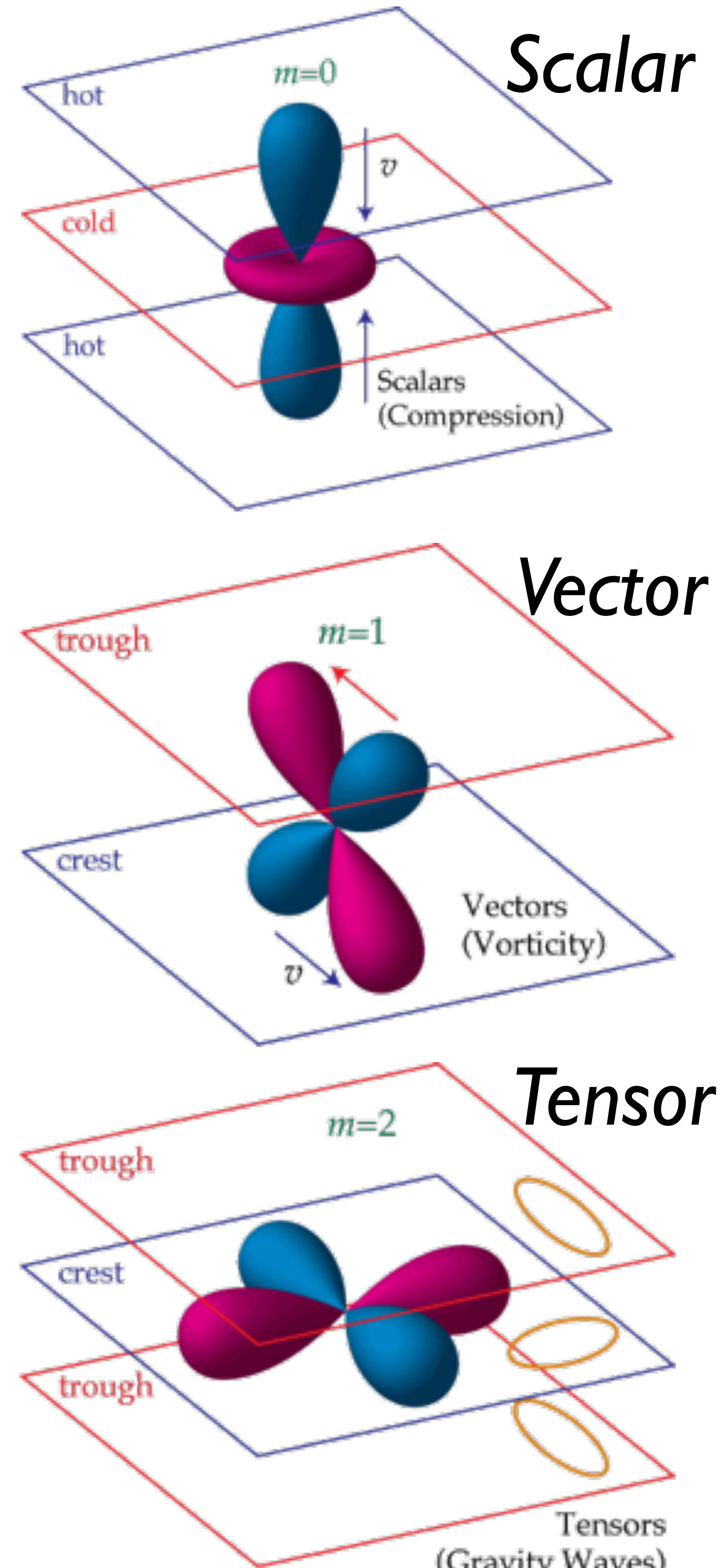


CMB Polarisation

CMB becomes polarised through Thomson scattering off electrons.

To obtain a *net* signal we must have a <u>*quadrupole anisotropy*</u>





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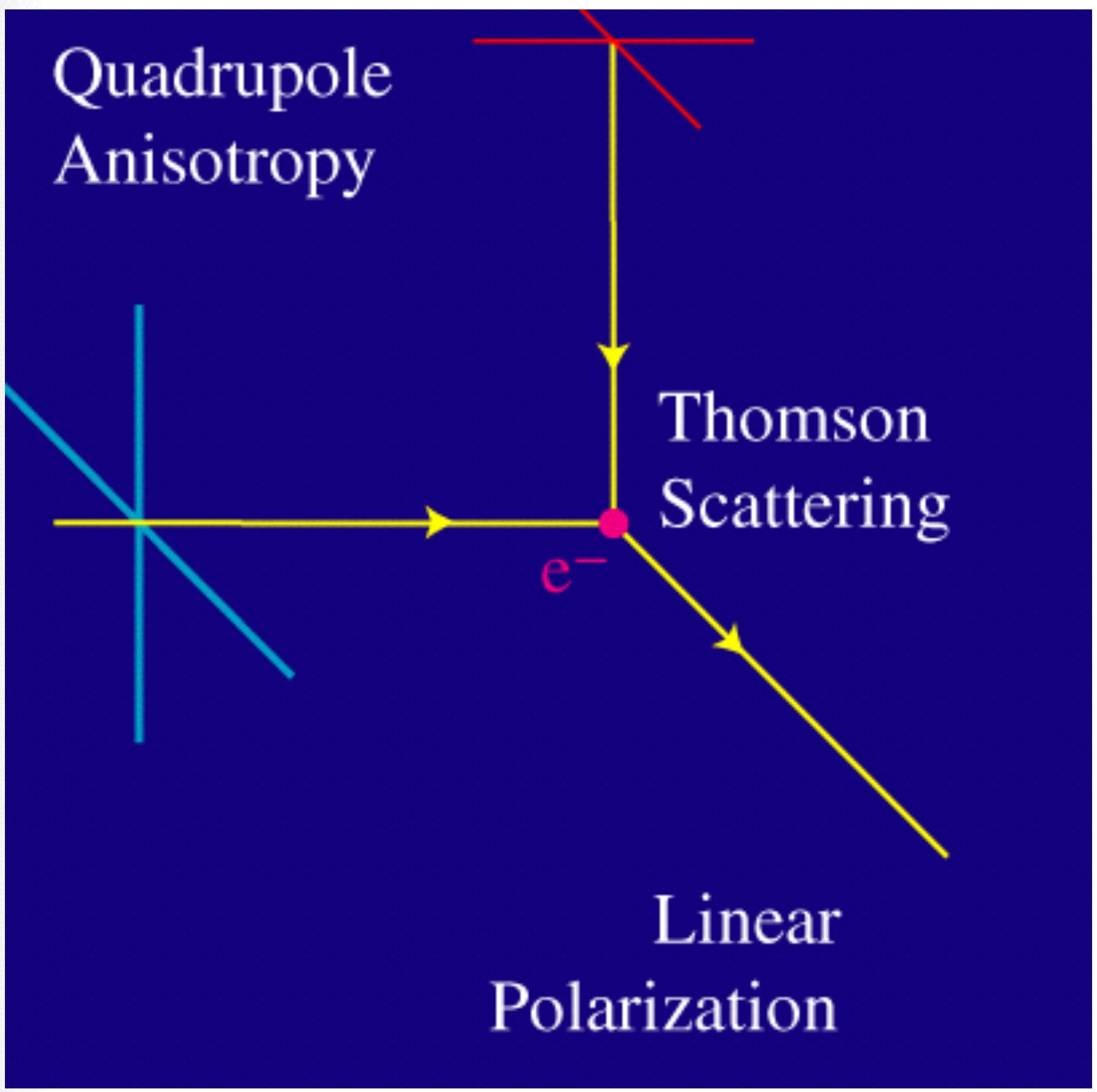

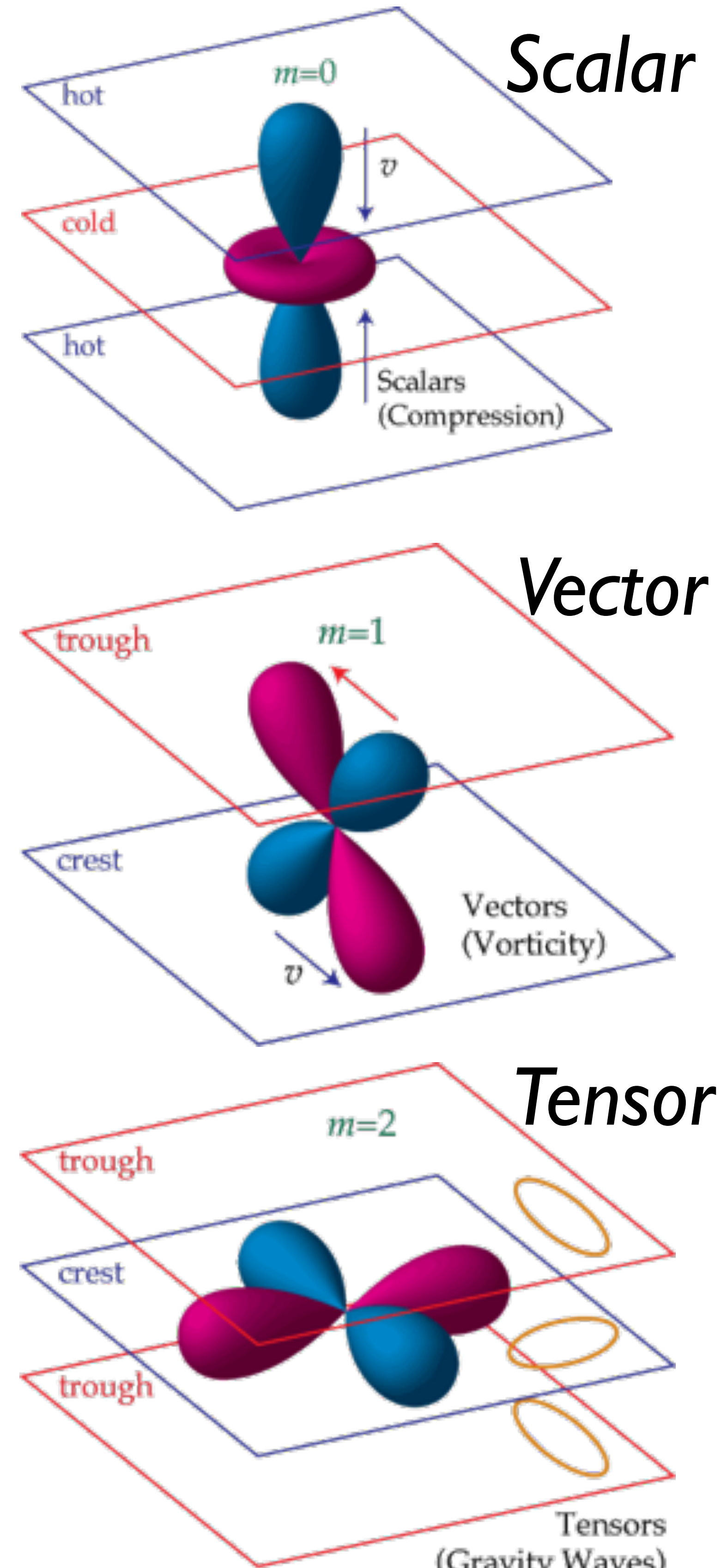

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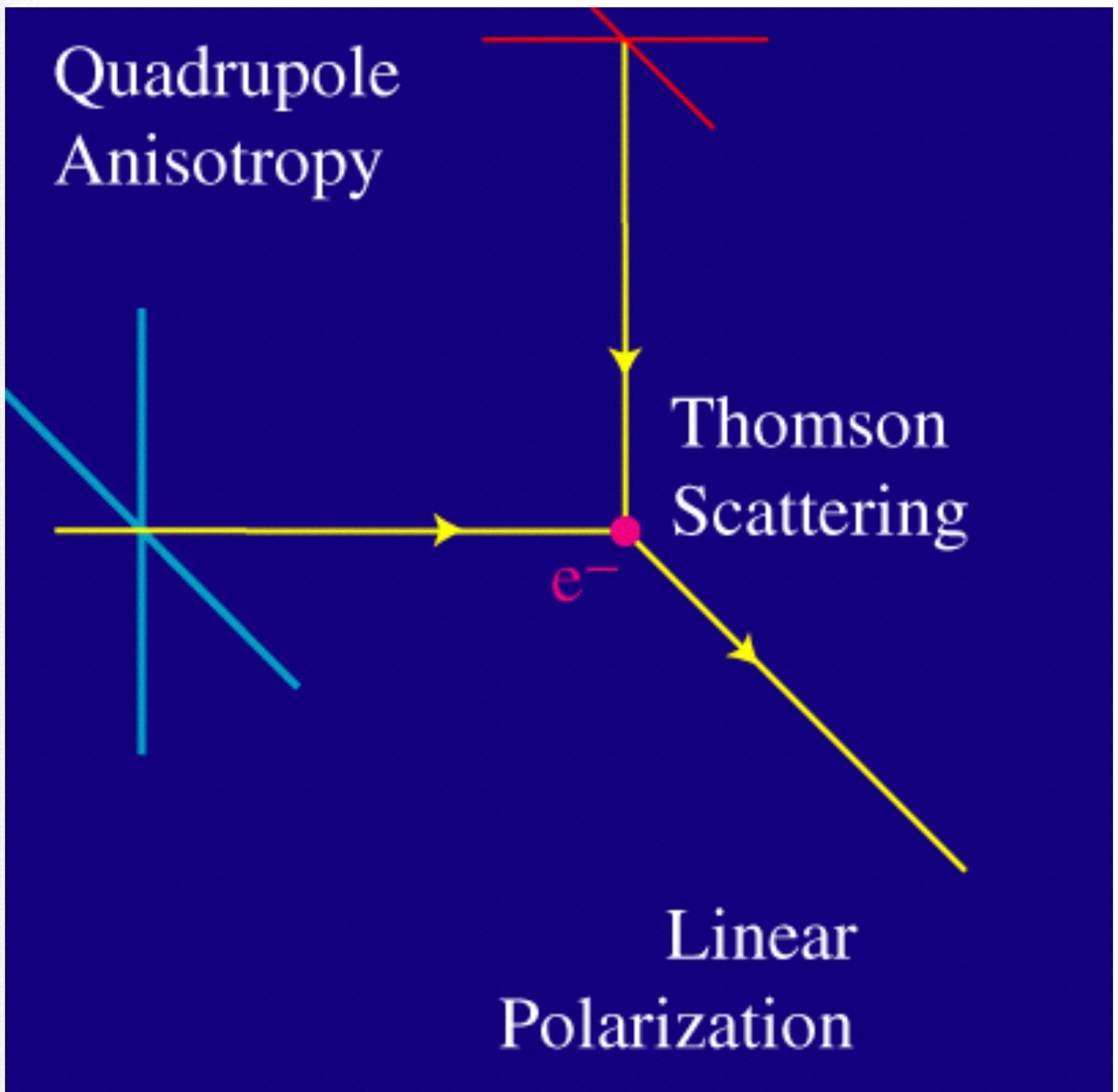

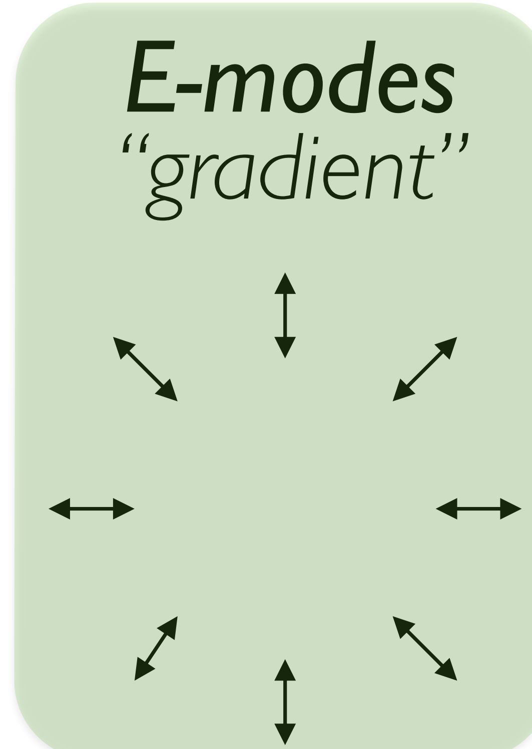

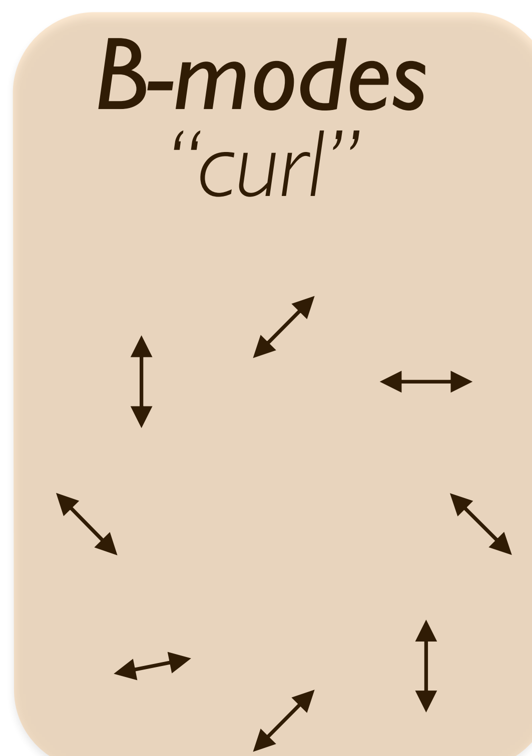

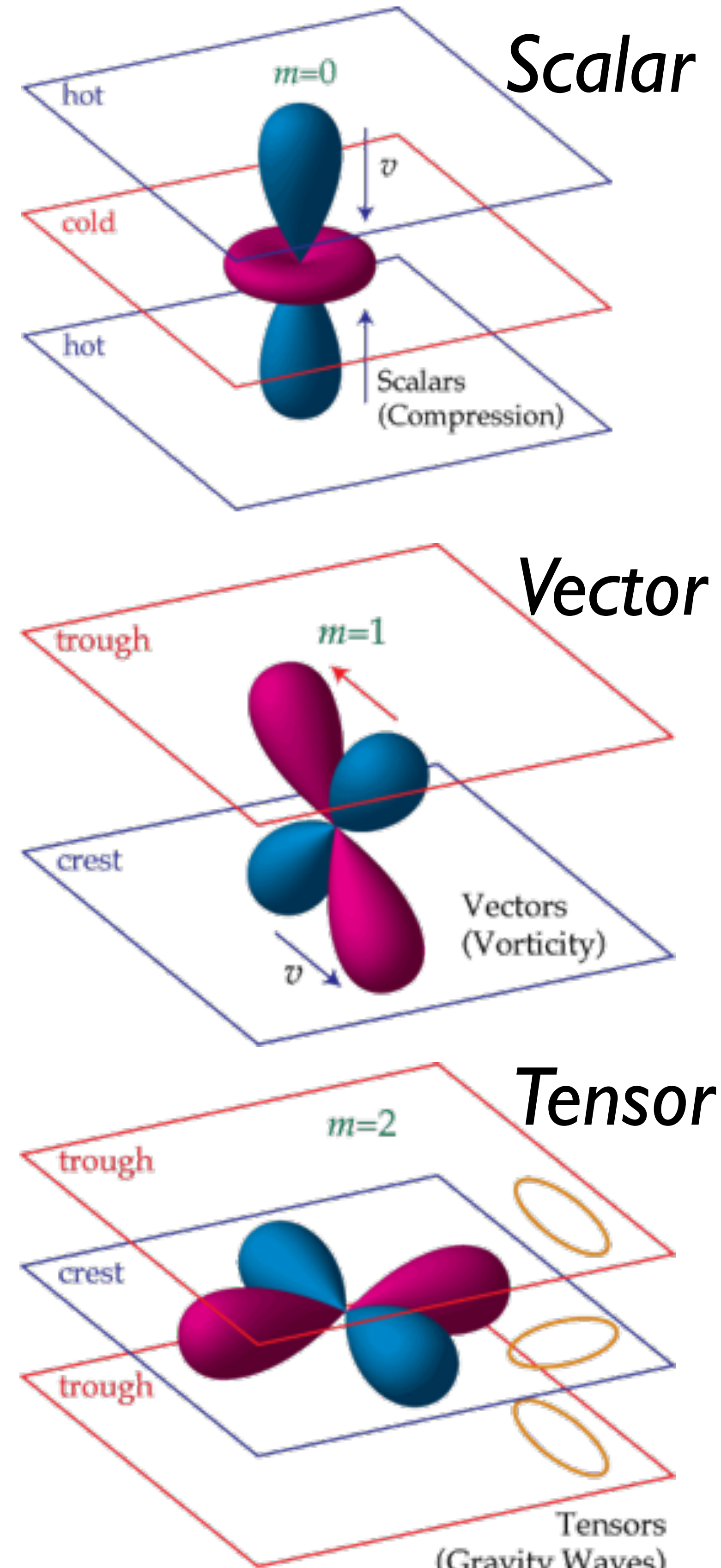

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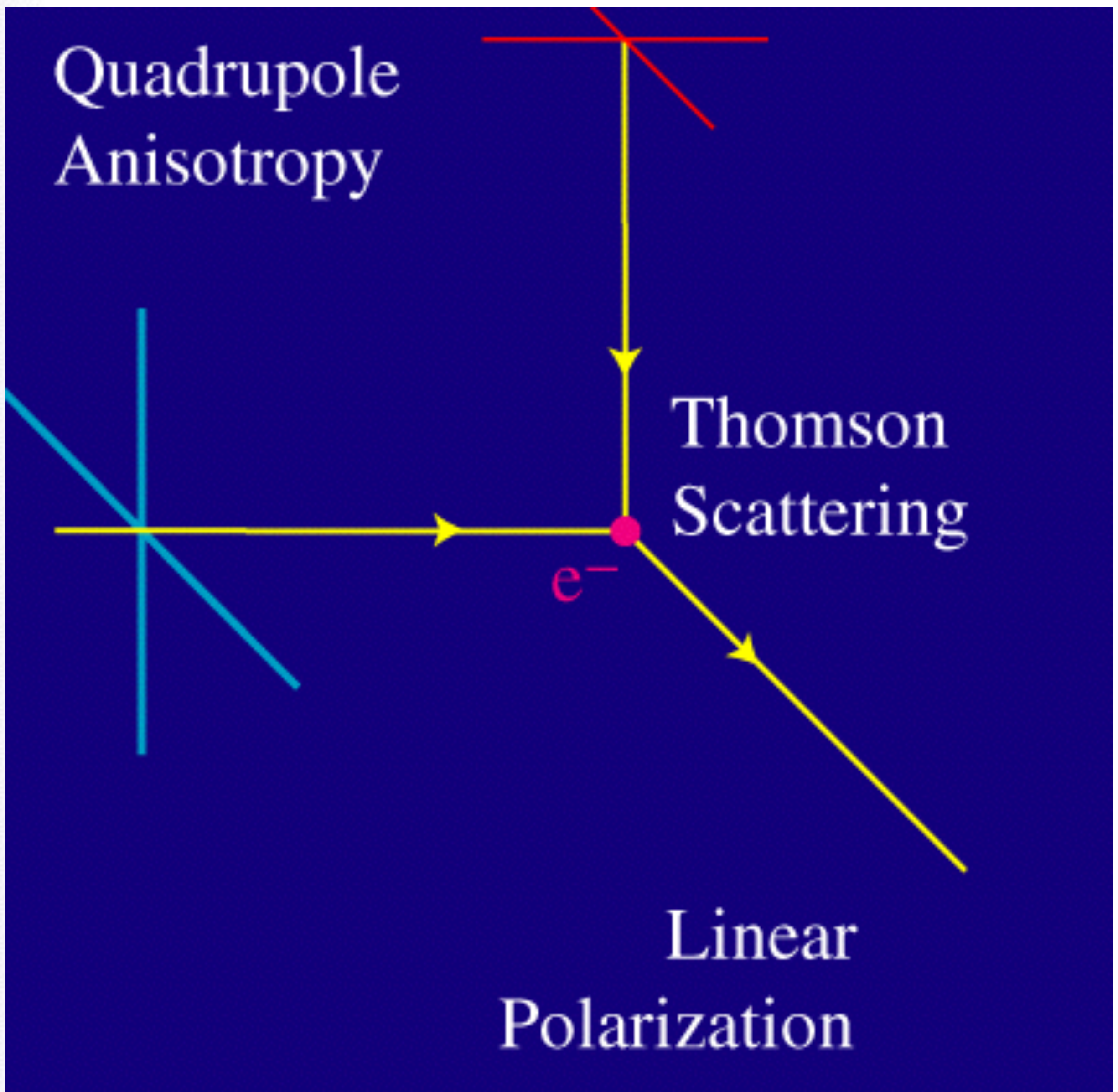

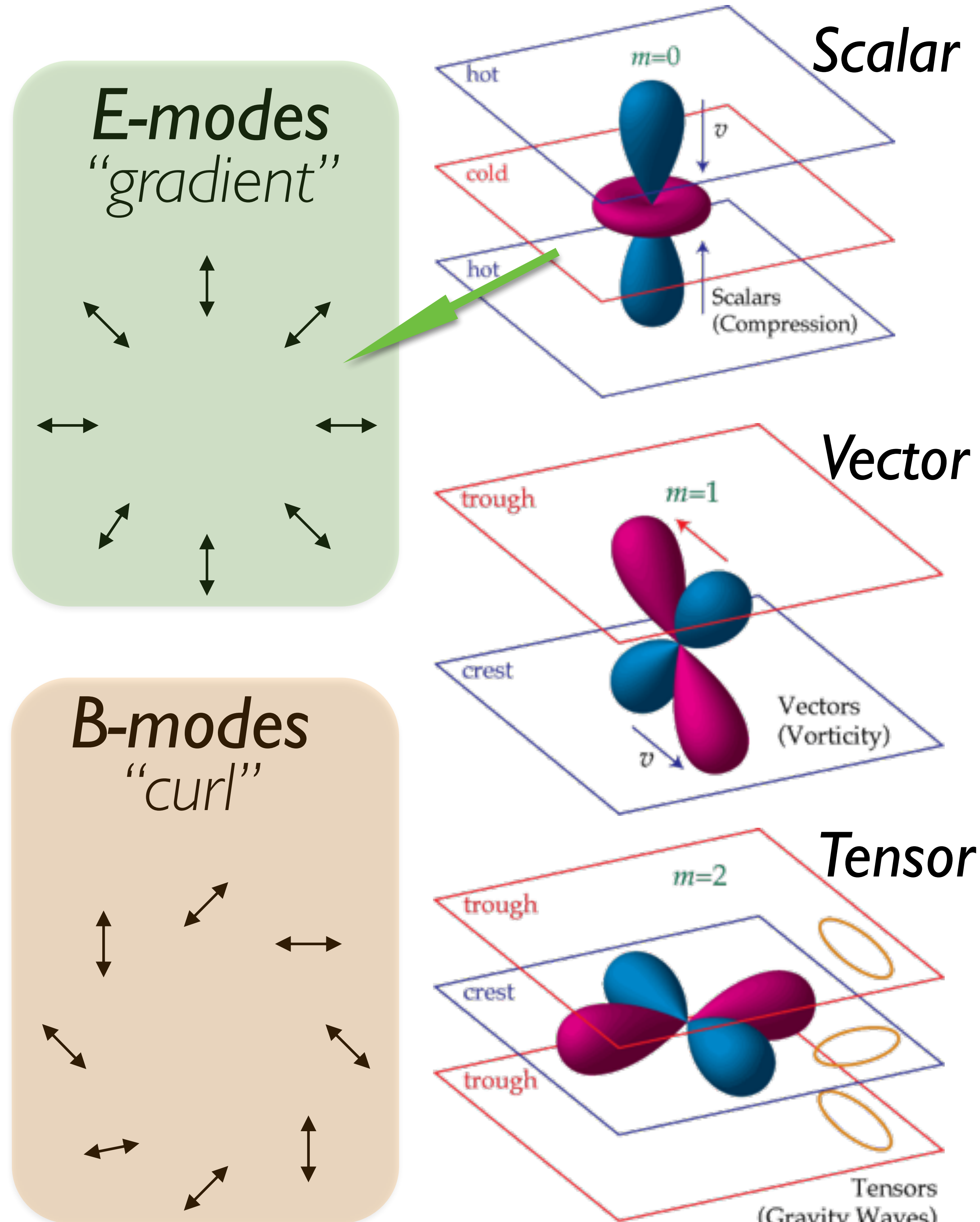

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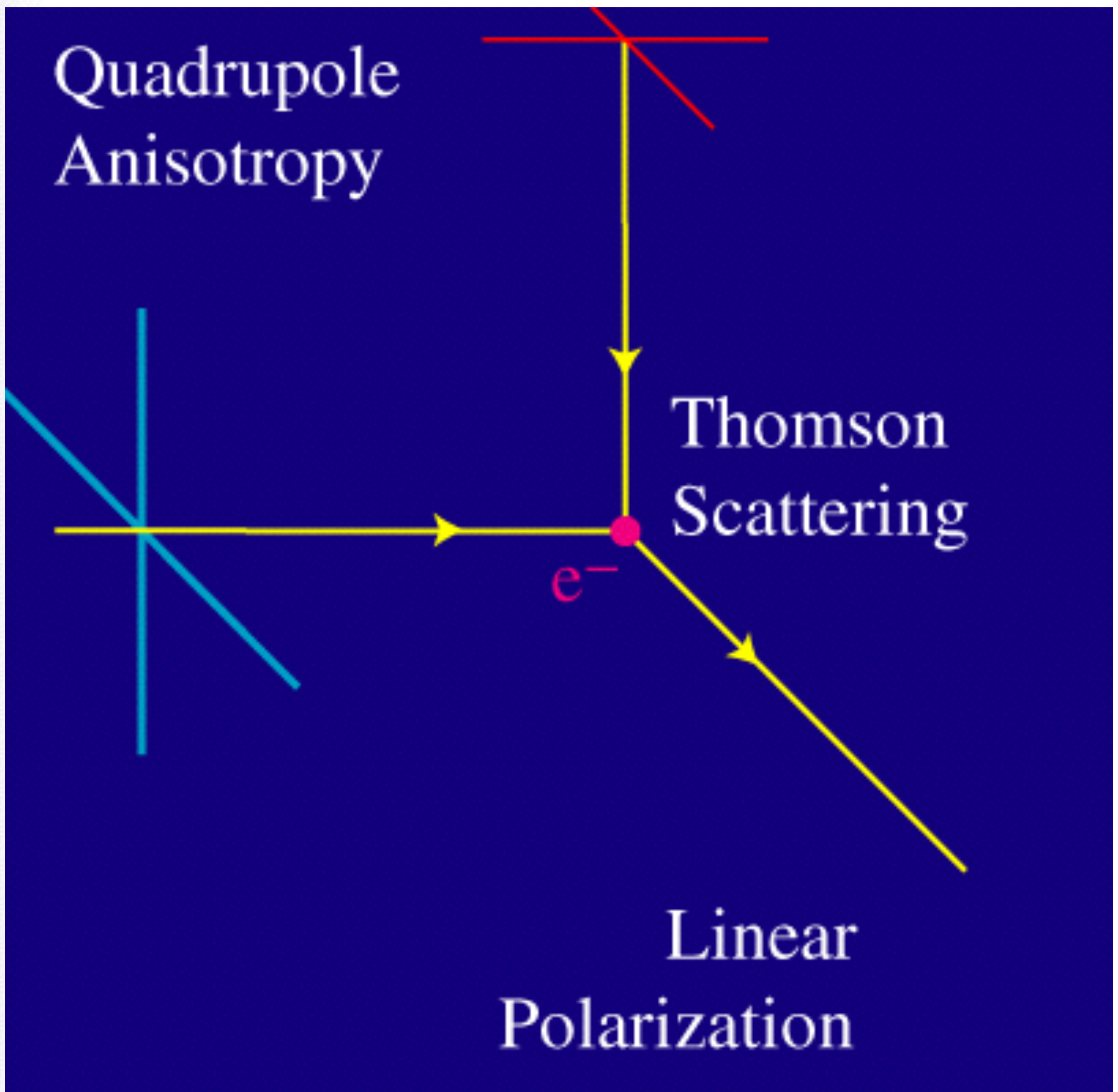

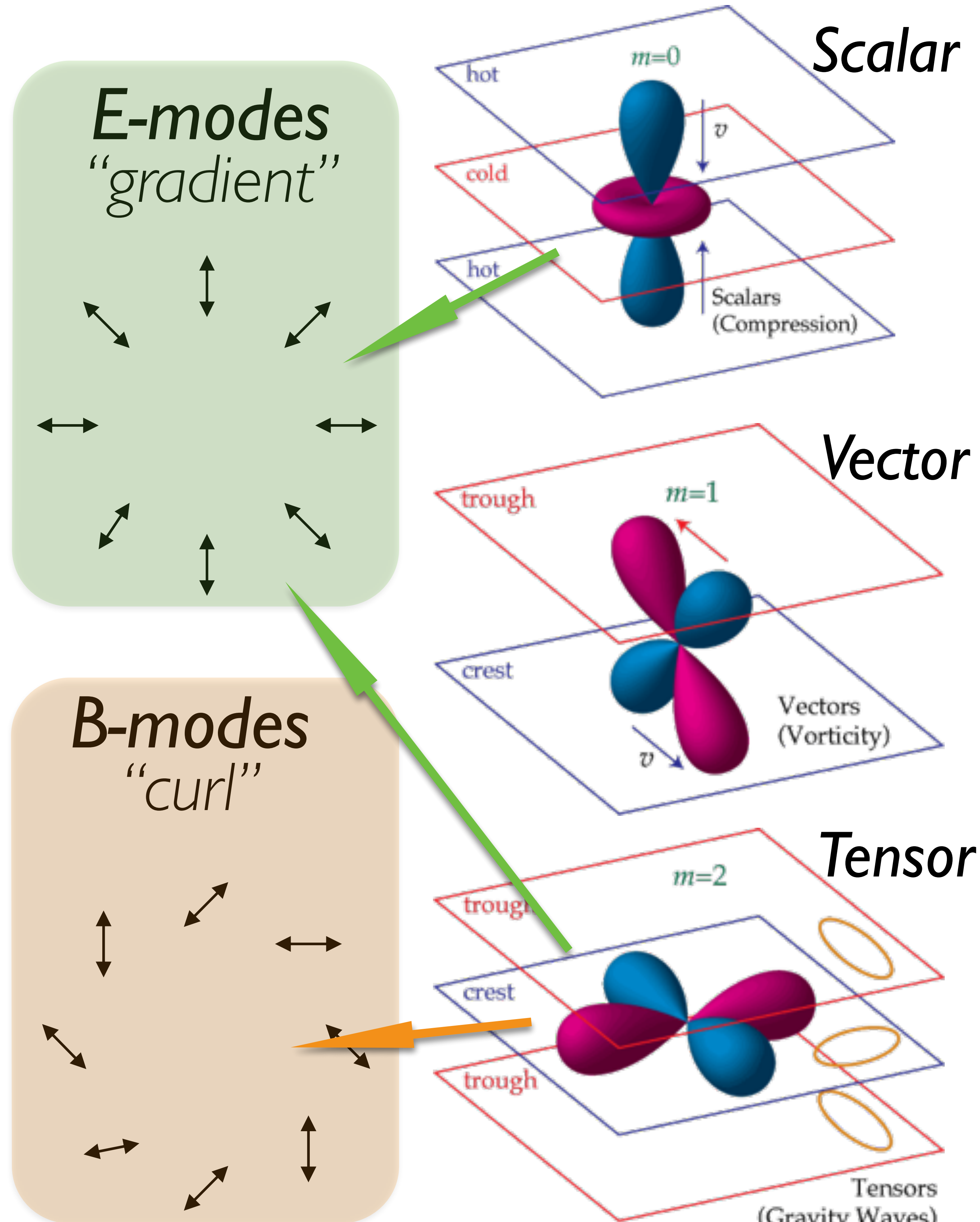

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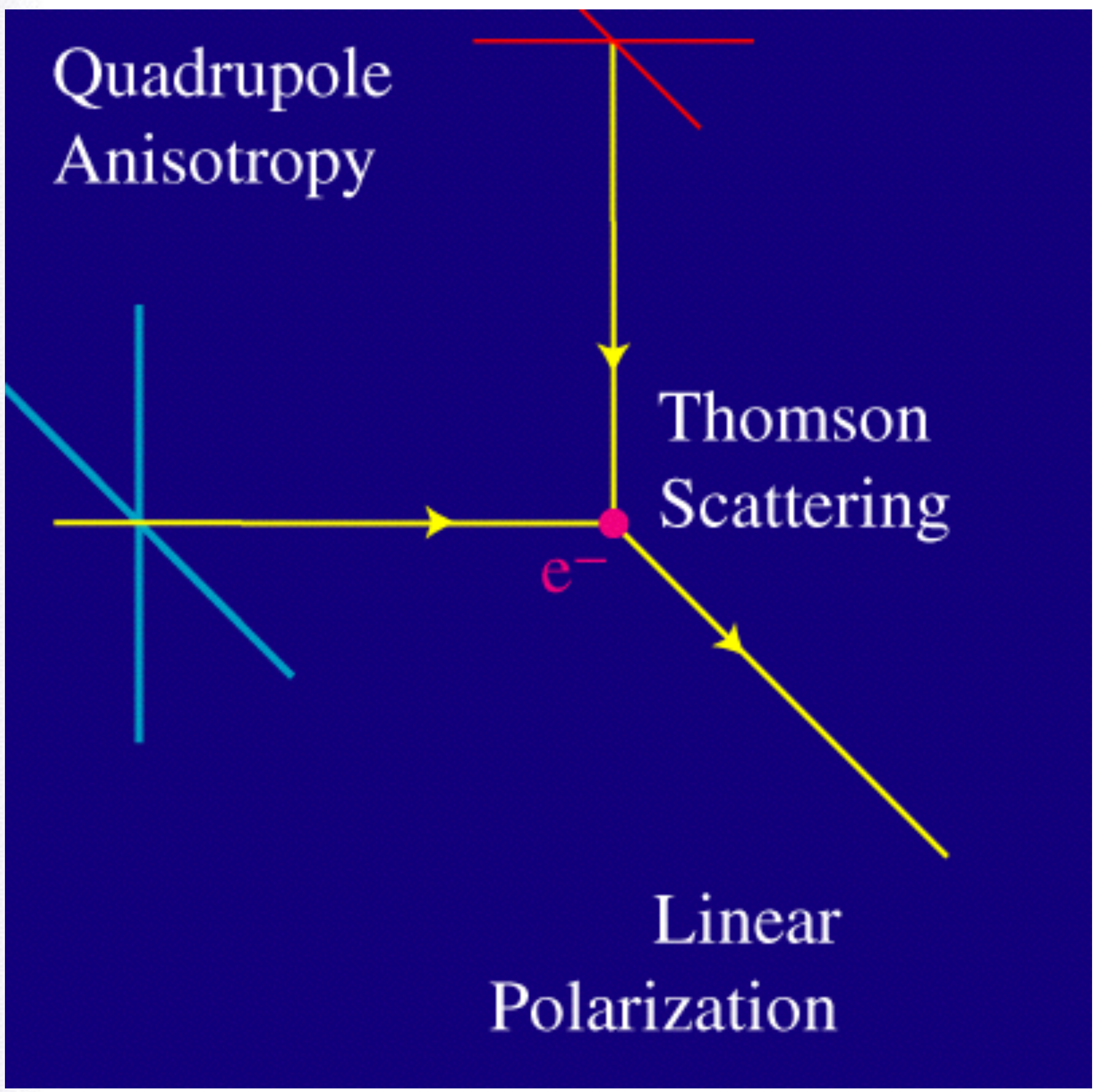
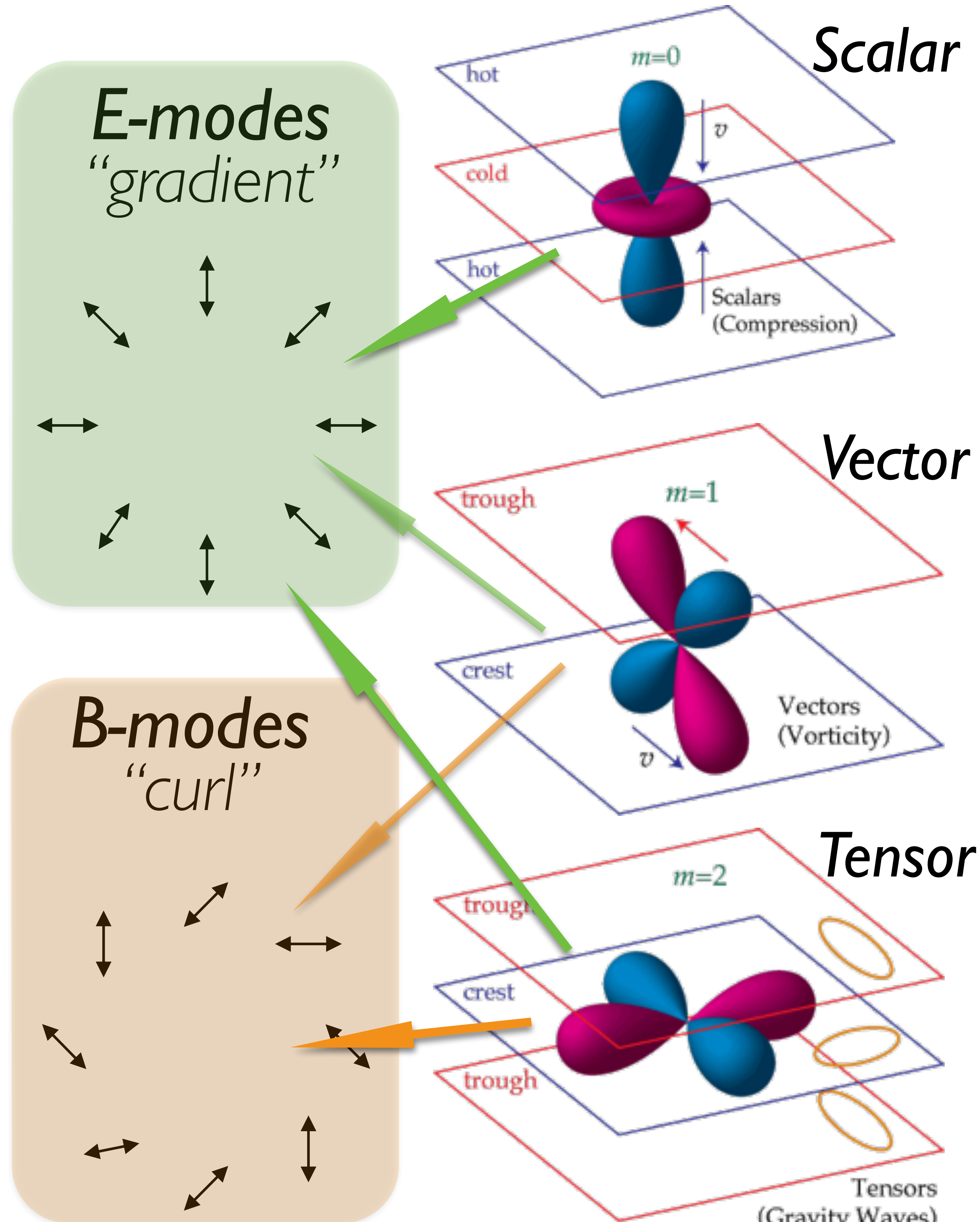




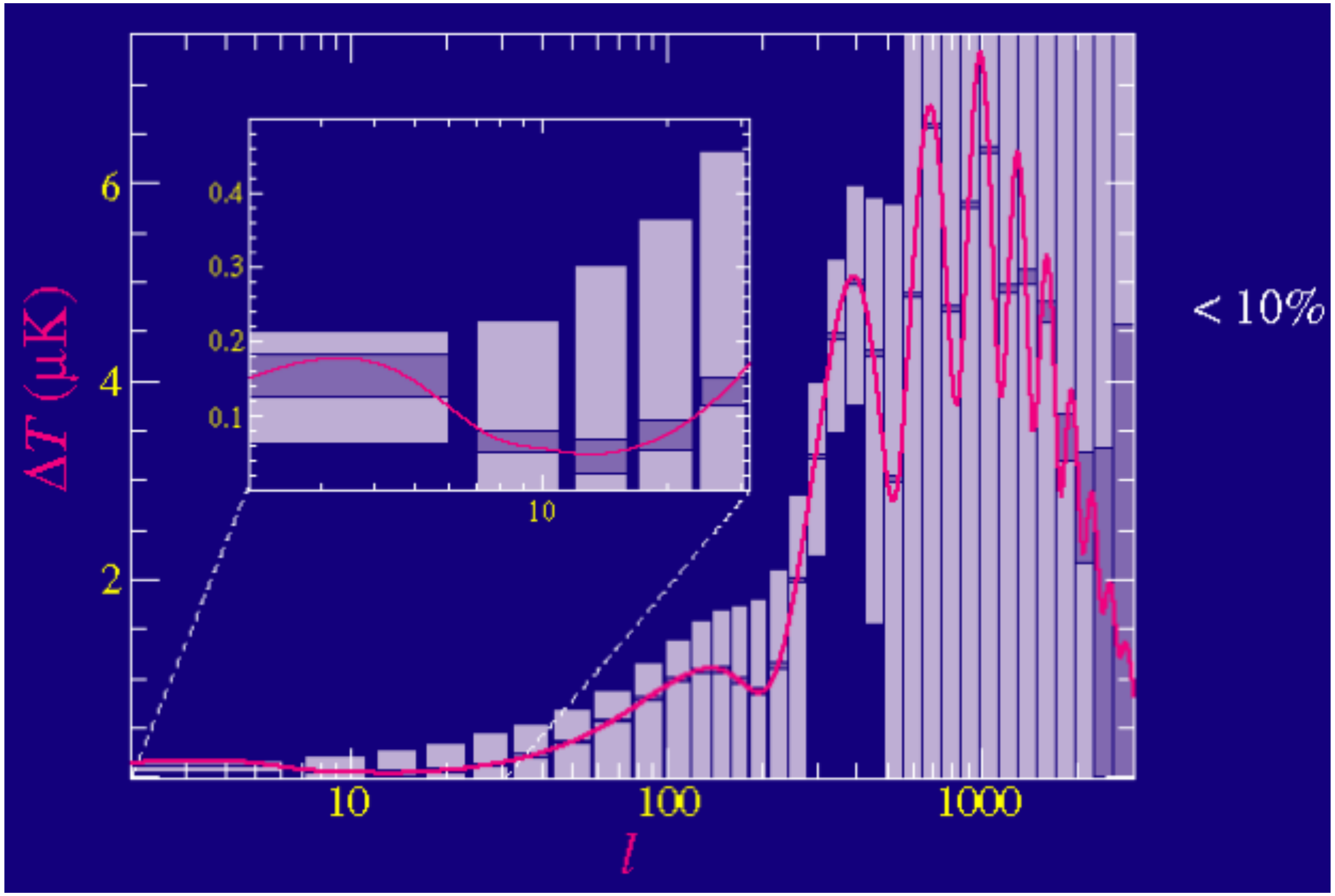
Courtesy Wayne Hu

Planck E-mode polarisation

The CMB is polarised at about the 10% level (~0.1 μK)

Series of acoustic peaks from plasma motions (out-of-phase with *T*)

Additional reionisation 'bump' at small *l* (associated with first stars)

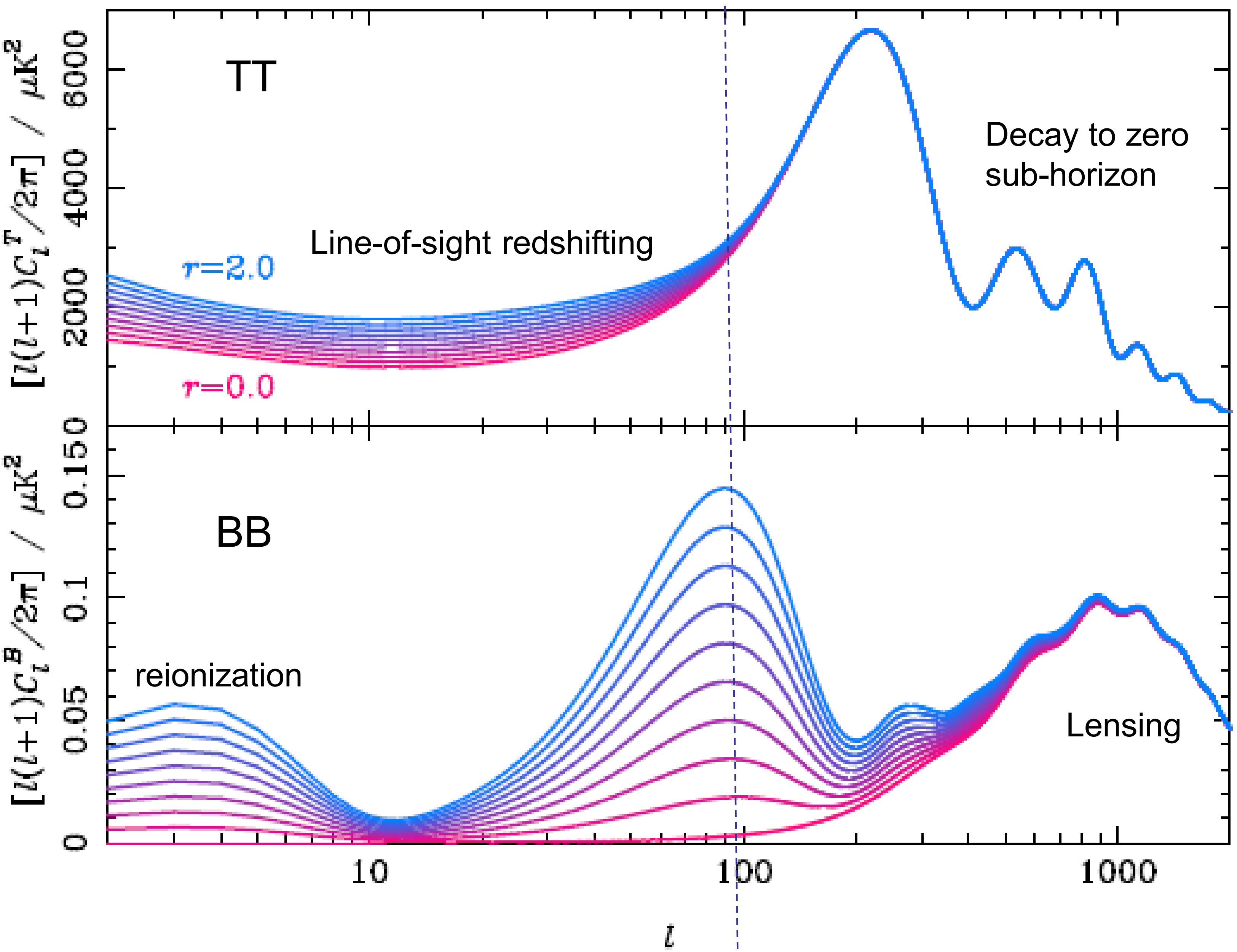


Planck will observe and report this series of E-mode peaks at high precision in 2014

- Extra information about cosmological parameters (*H_0 etc to move*)
- Insight into the ionisation history of the Universe.

Planck B-mode polarisation

Primordial gravitational waves will induce a B-mode signal



A. Lewis, 2014

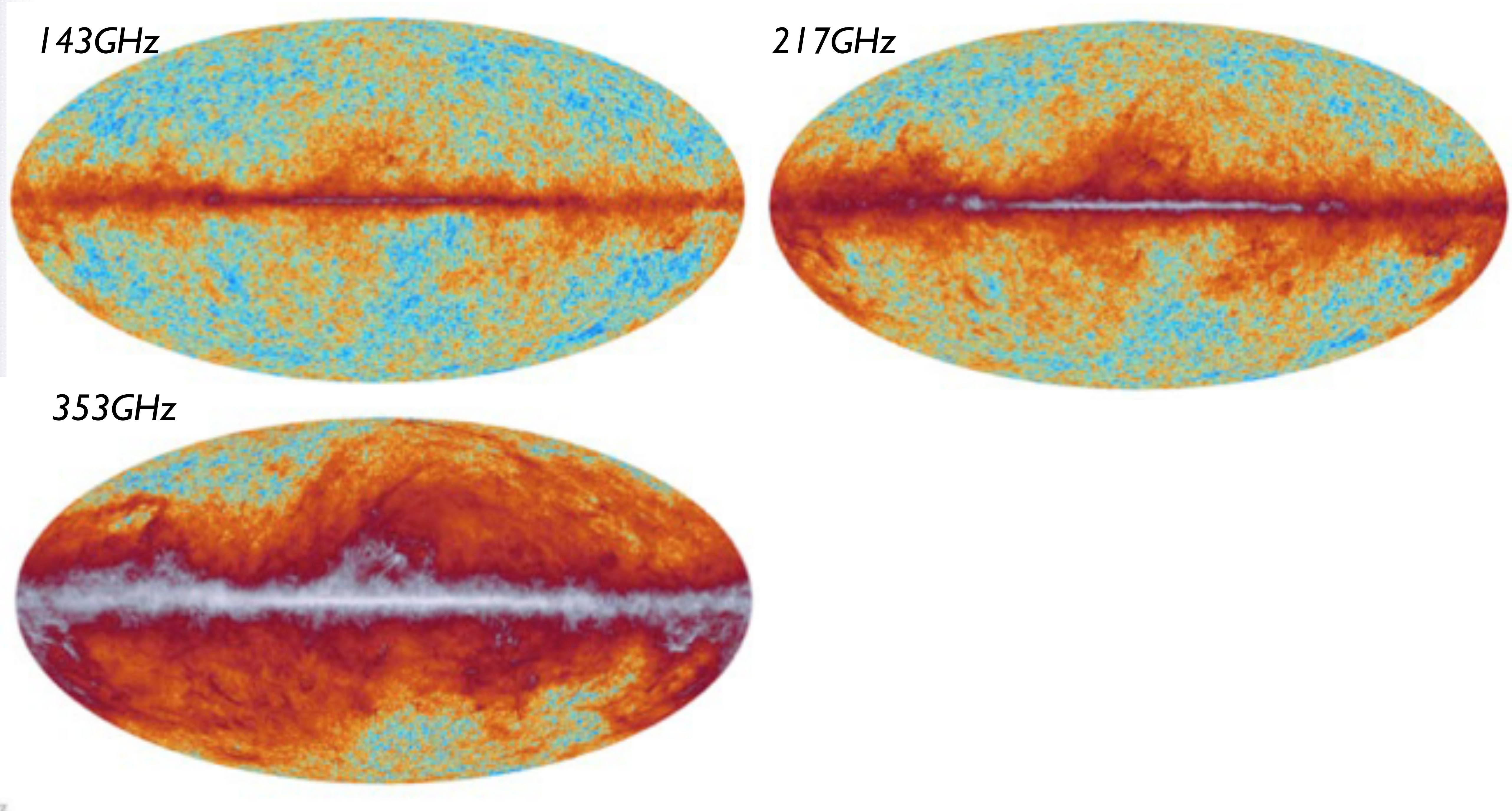
Planck alone: original BlueBook forecast r ~ 0.1 from reionization signal

- but τ^2 detection dependence drops to 2σ (because of fall in τ)
- full-sky recombination bump 2.5σ possible,, but many systematics

Planck polarised foregrounds

Primordial GWs should have a blackbody spectrum

Distinguish from foreground contributions using frequency dependence:



Planck can extrapolate B-mode dust contamination in the BICEP2 field

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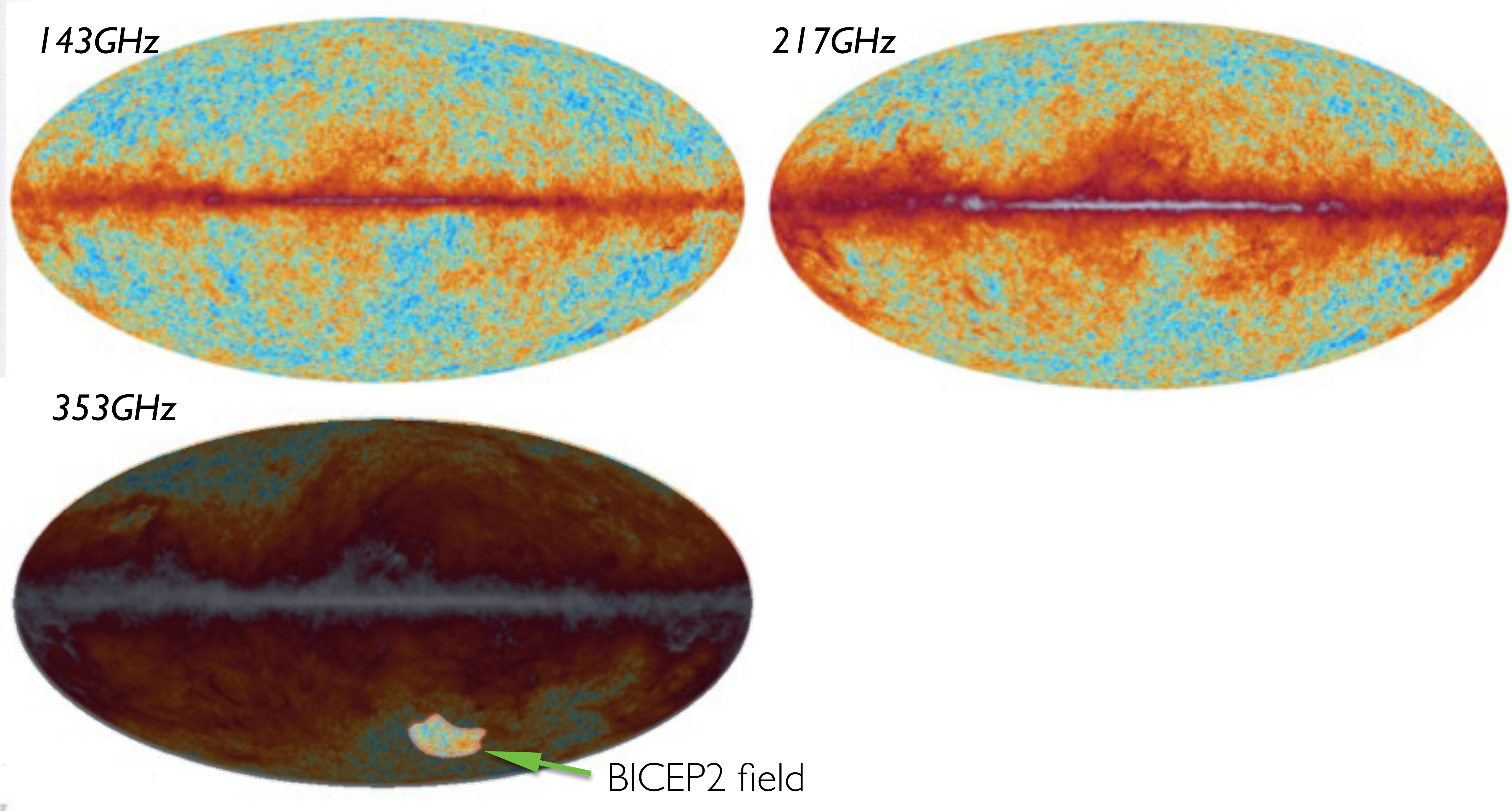

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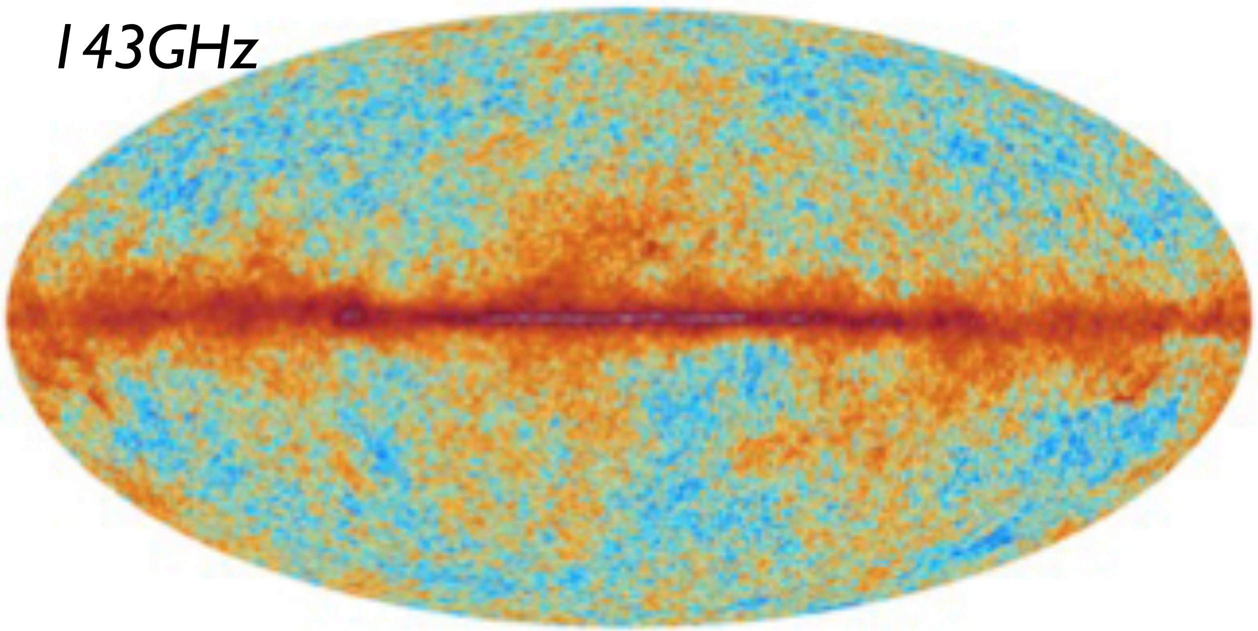
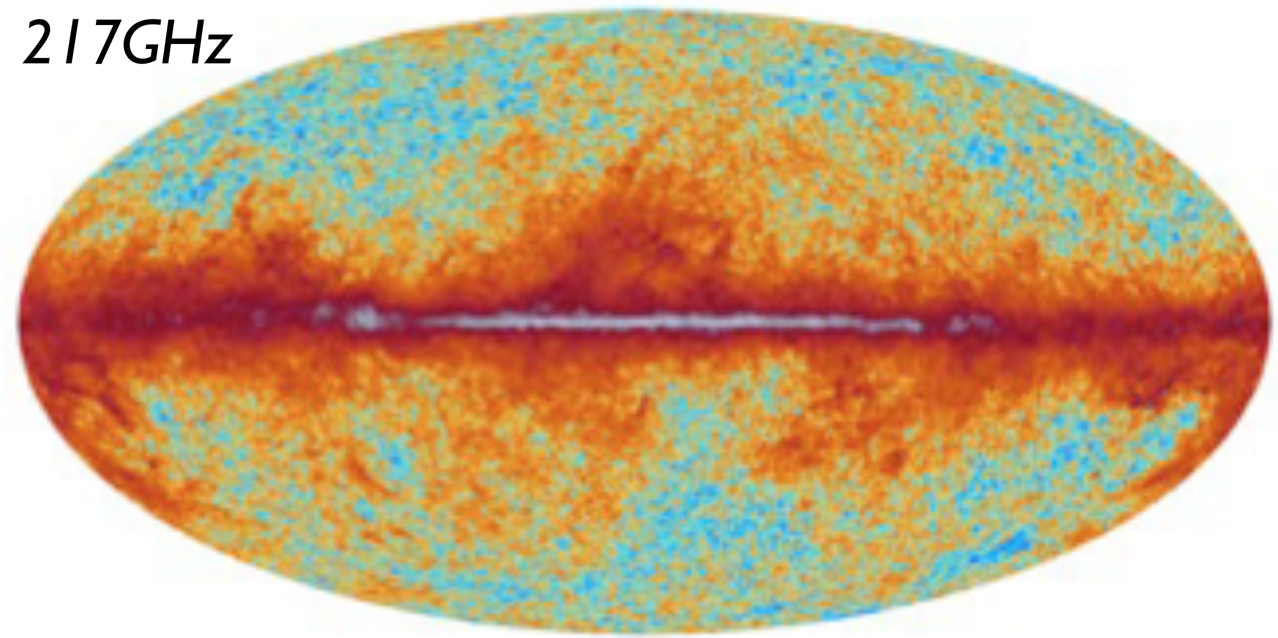
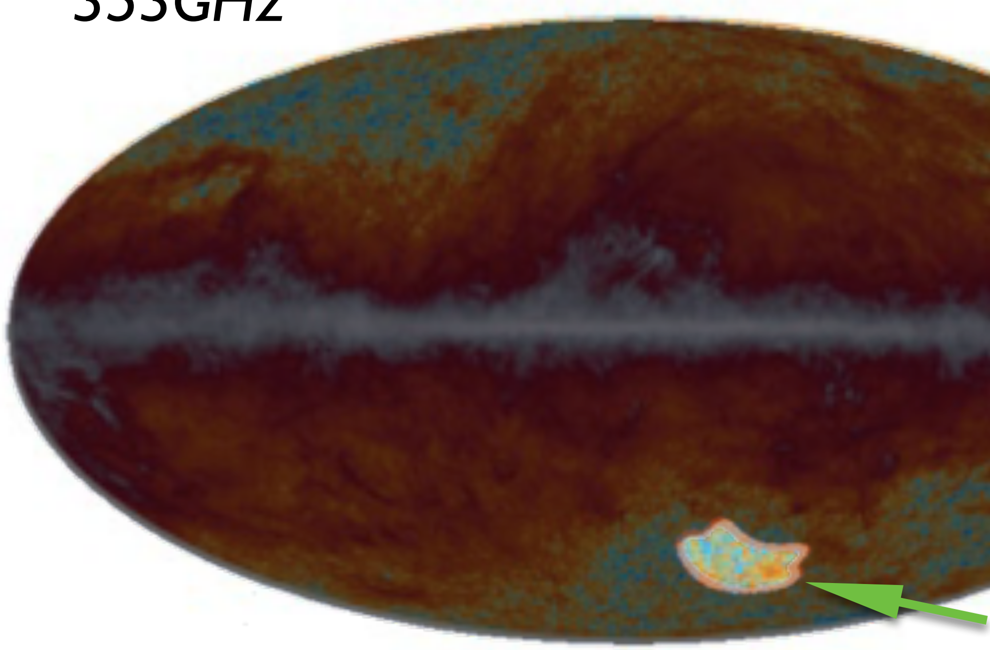


217GHz

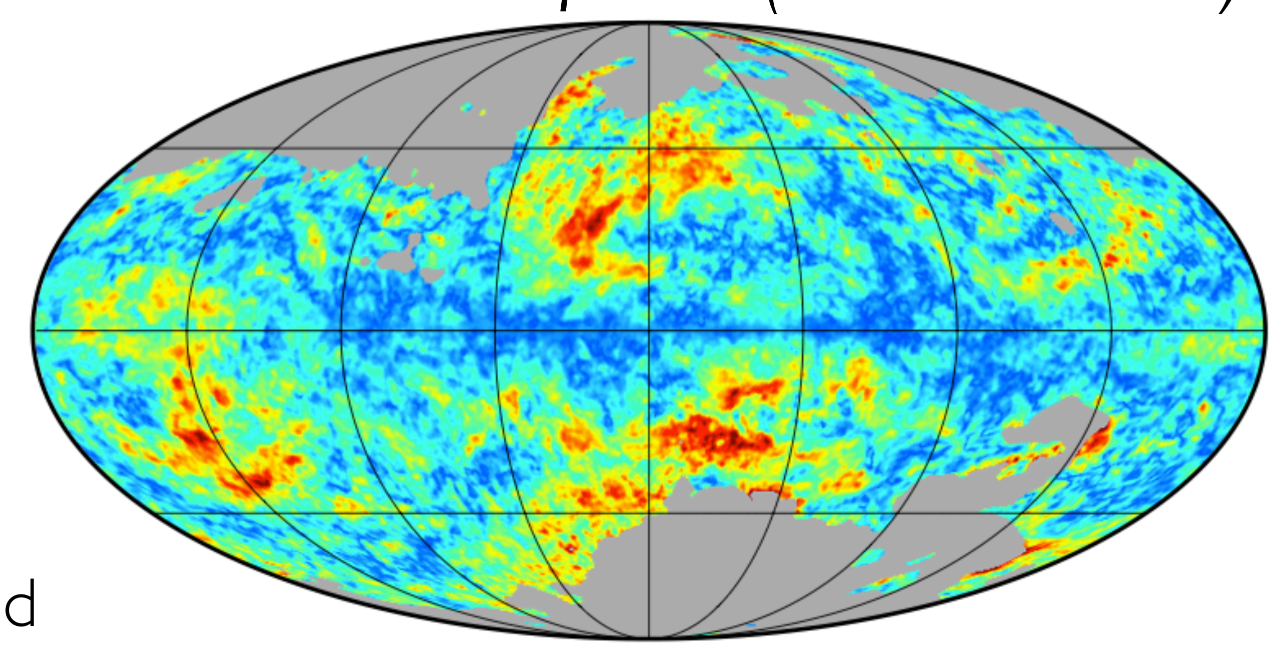


353GHz



BICEP2 field

353GHz Polarisation fraction (arXiv:1405.0871)



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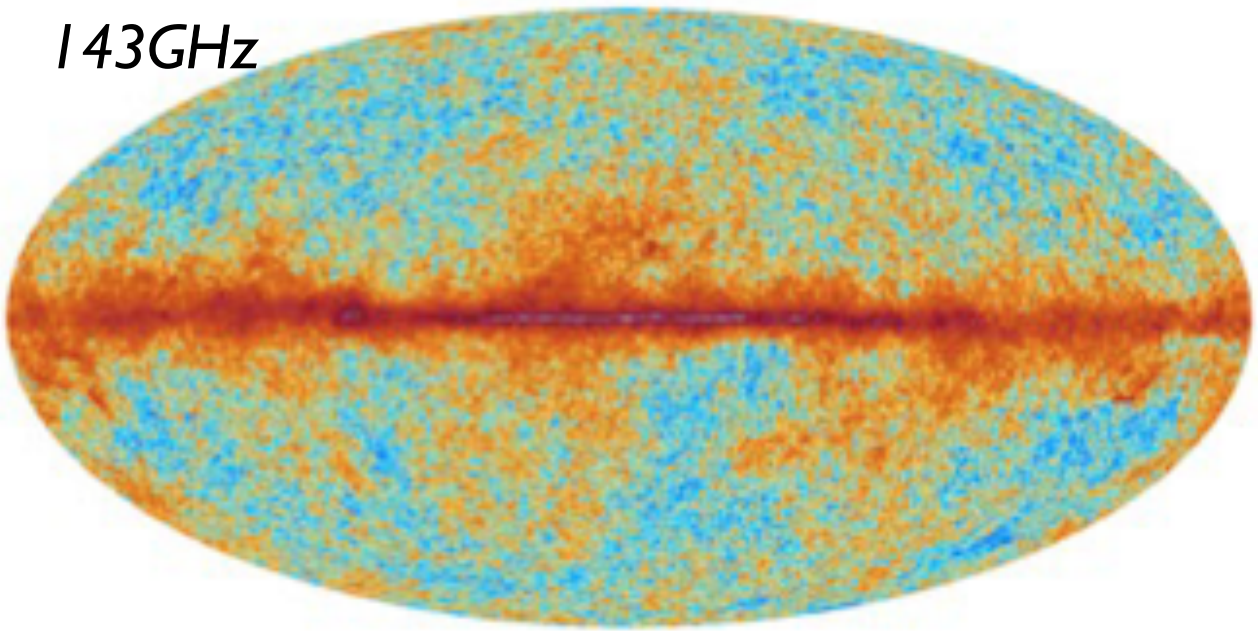

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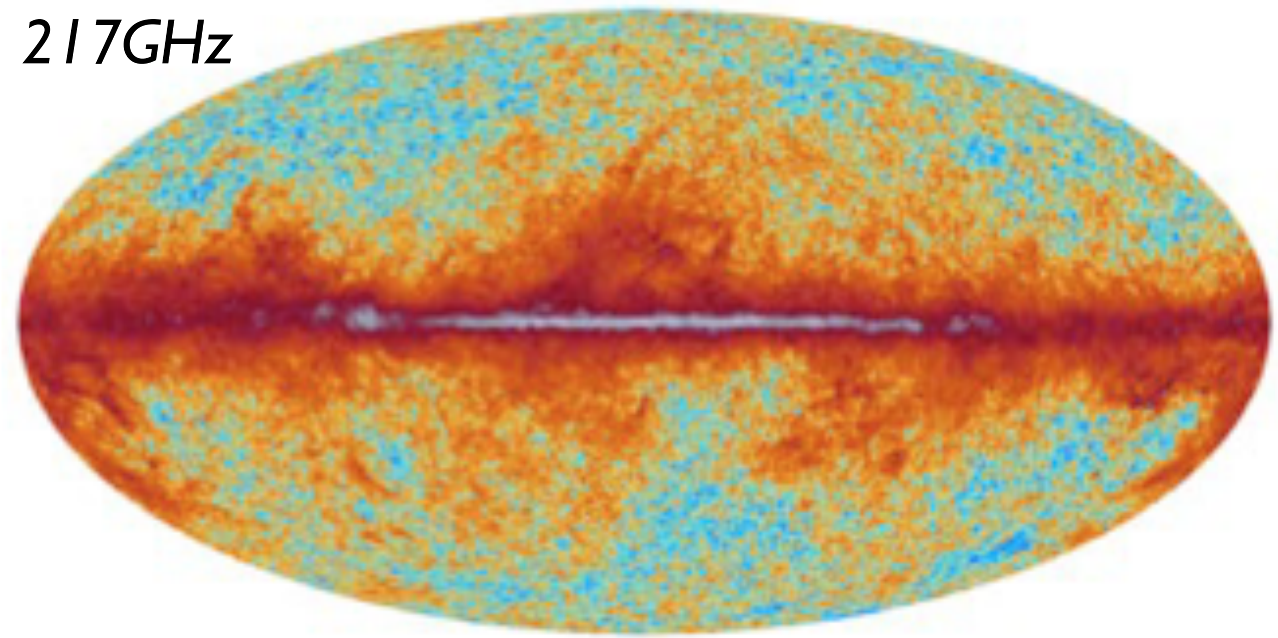

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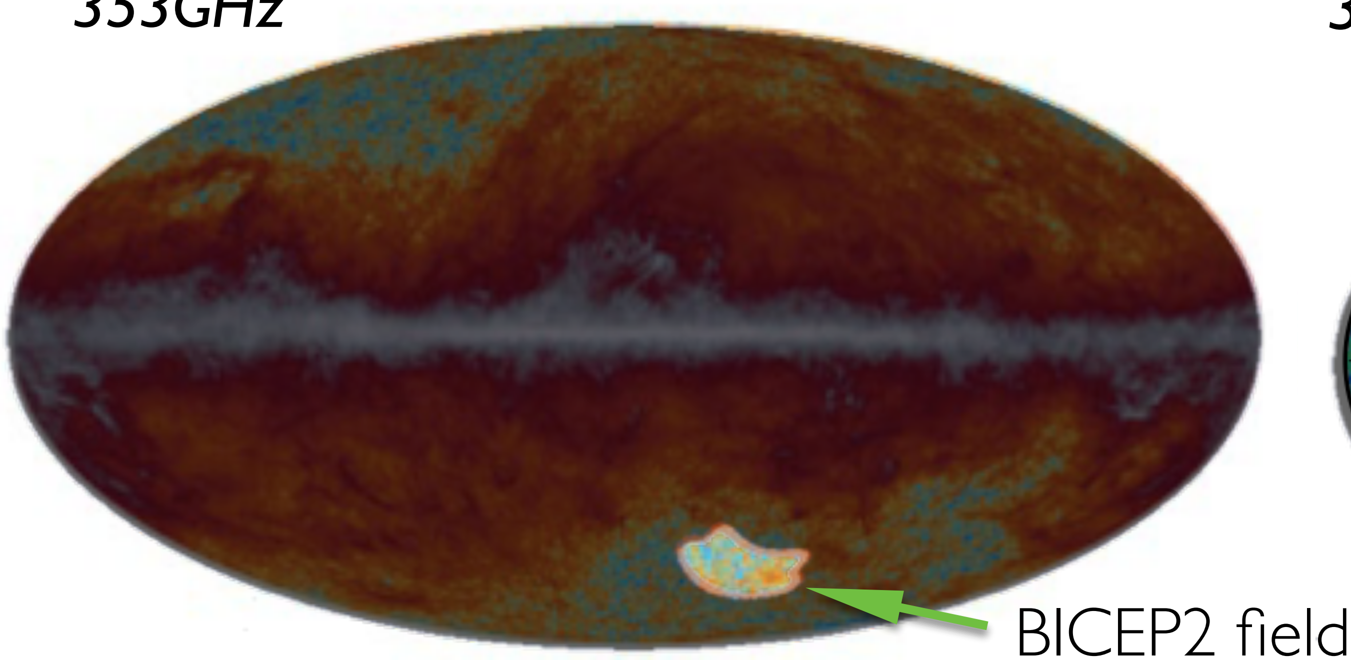

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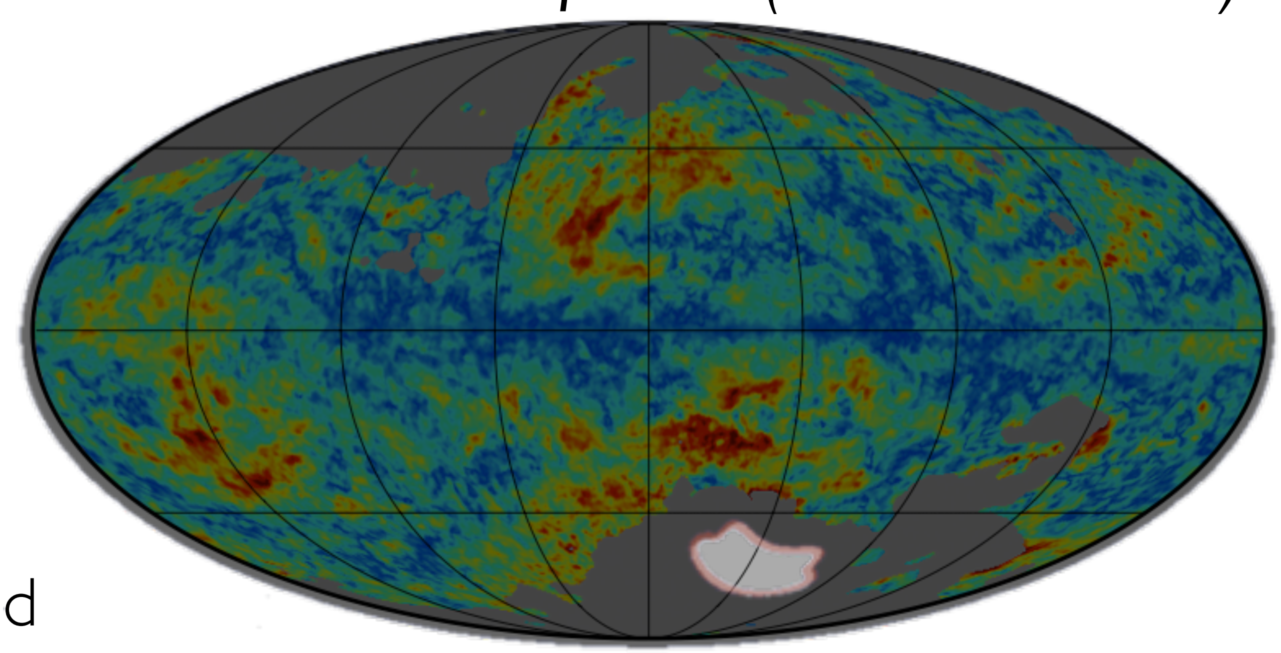

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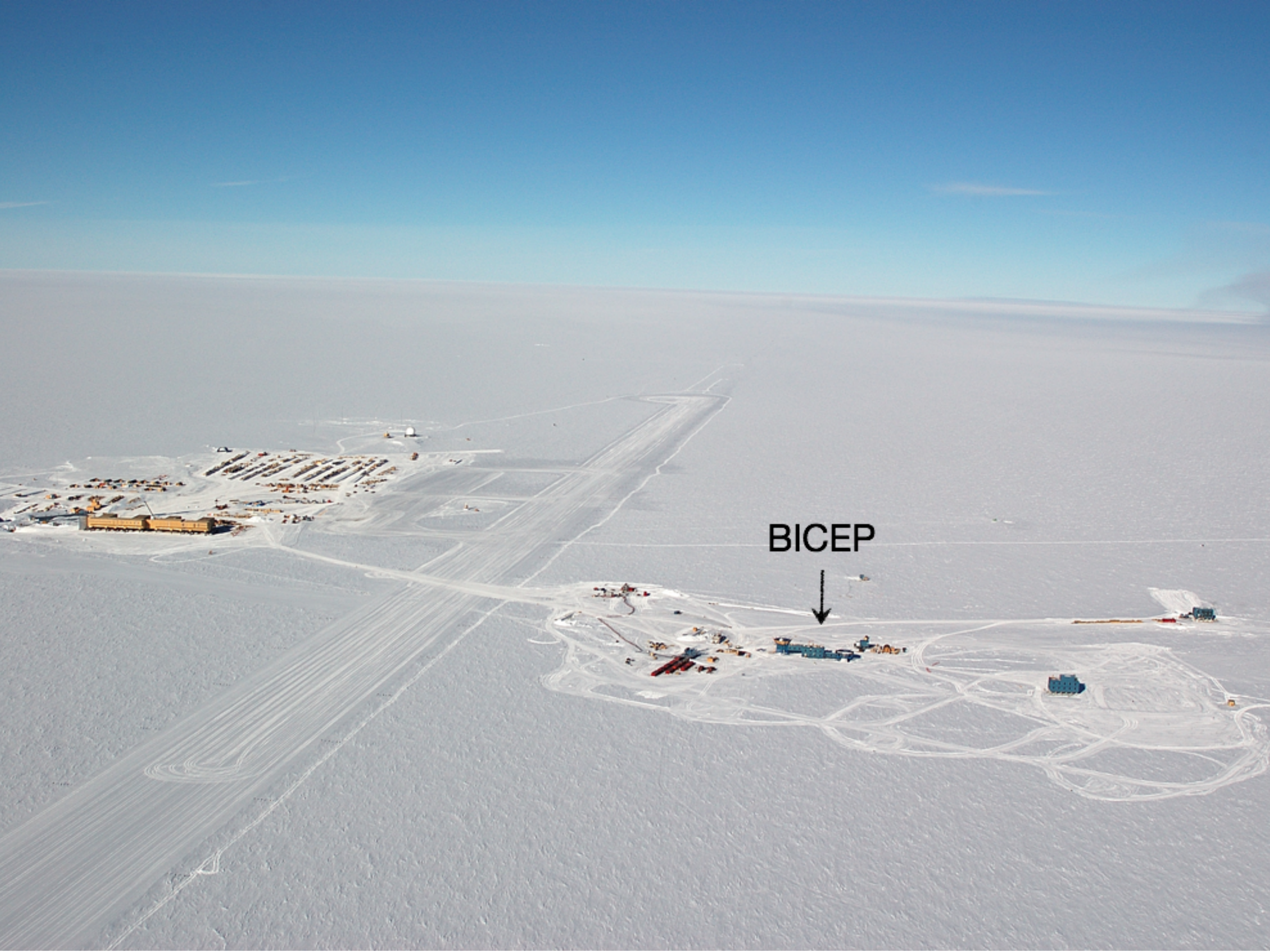
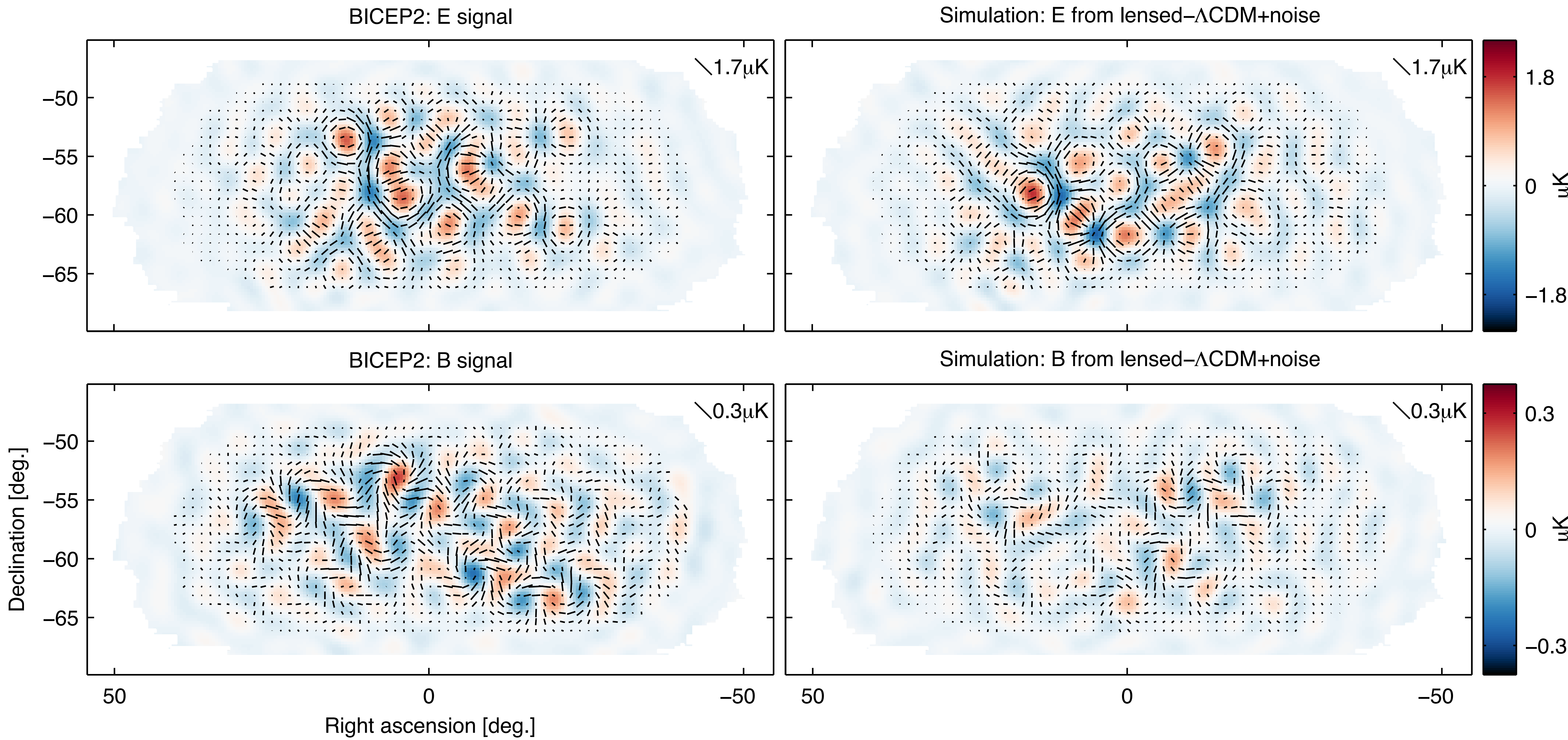

BICEP

BICEP2 Revisited

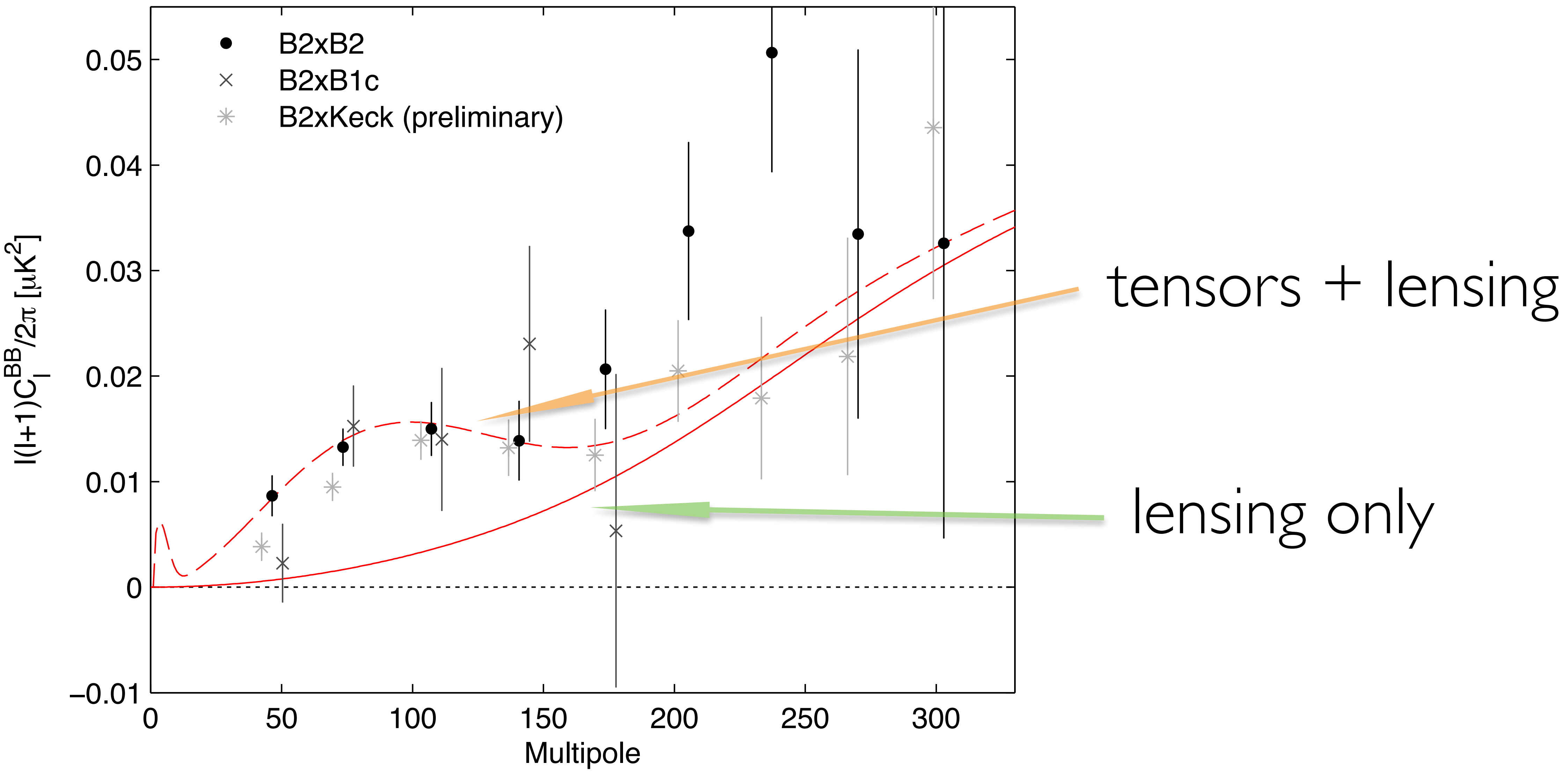
First map of B-modes at 150GHz (previously upper limits) with remarkable sensitivity of 87nK (Planck only at **μK**)



B-modes at levels well above noise simulations for **Λ**-CDM (right)

BICEP2 B-mode power spectrum

If primordial, then inflationary GWs provide a good explanation



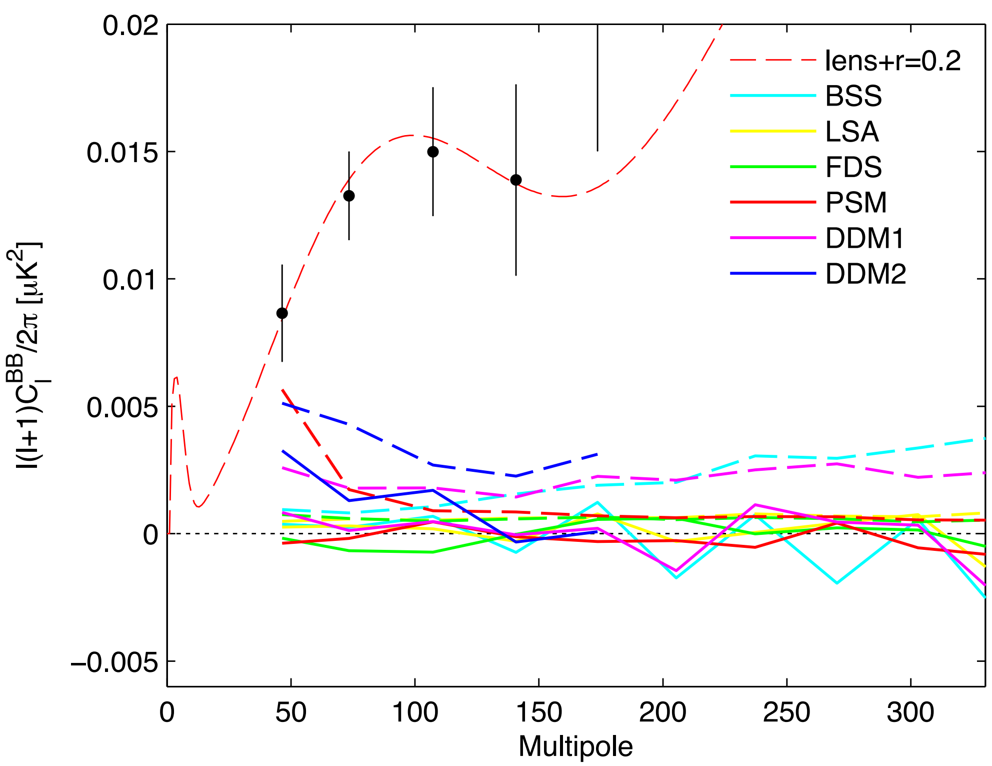
But unexpectedly high at r = 0.2 (accentuating QG problems)

Makes Planck large-scale power deficit worse (need running etc)

BICEP2 Foregrounds

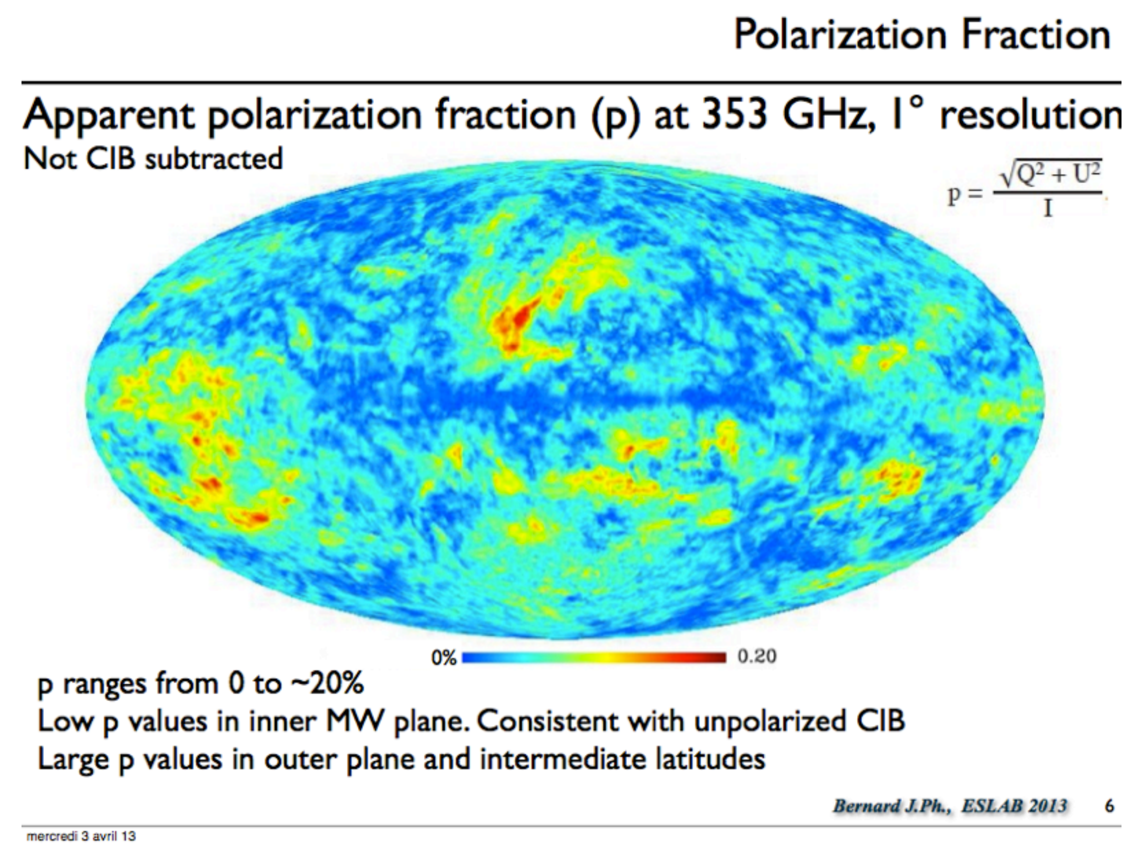
How did BICEP2 eliminate foregrounds?

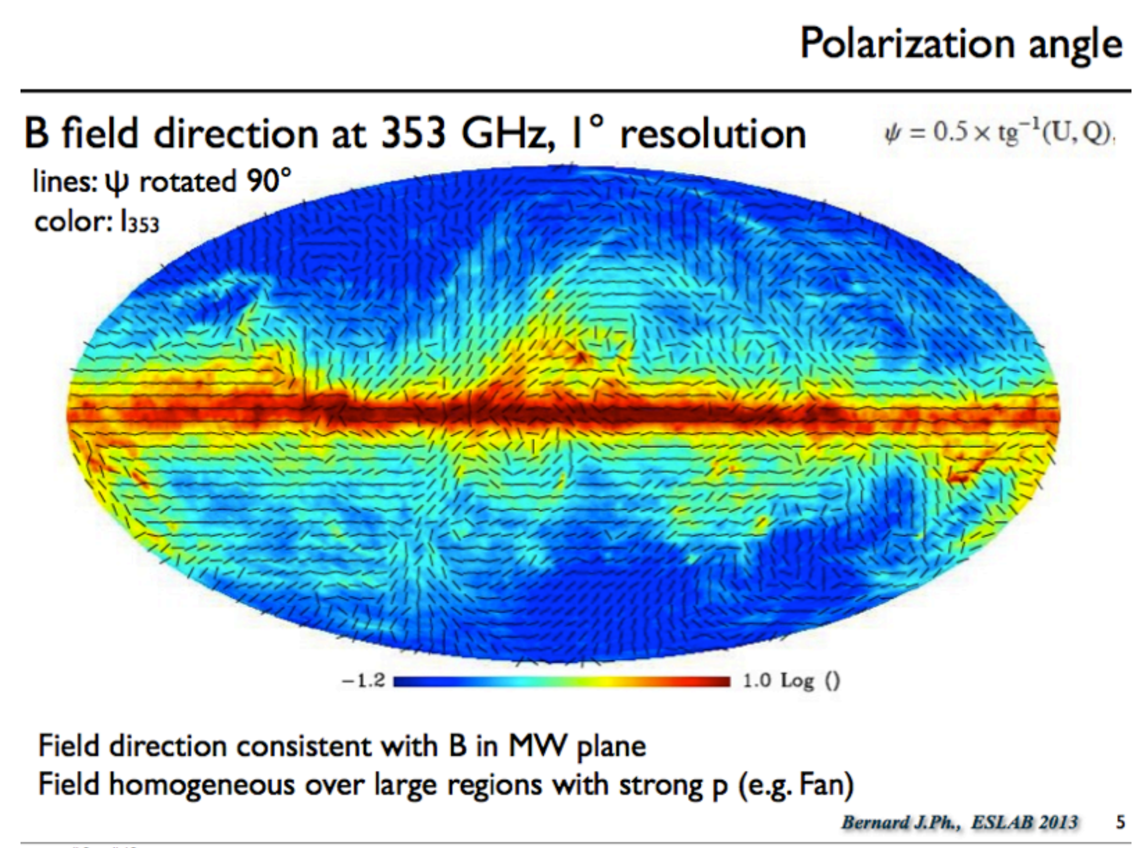
- Put simply, they (mainly) used Planck data …
- ESLAB 2013 talk by Bernard released polarisation fraction and angle maps (pre-publication)
- Talk maps digitised for key DDM1/2 models



BICEP2 results exhibited non-negligible foreground dependence for tensor-to-scalar ratio r !

r	unsubtracted	DDM2 cross	DDM2 auto
BICEP2	$0.2^{+0.07}_{-0.05}$	$0.16^{+0.06}_{-0.05}$	$0.12^{+0.05}_{-0.04}$
BICEP2×Keck	$0.13^{+0.04}_{-0.03}$	$0.10^{+0.04}_{-0.03}$	$0.06^{+0.04}_{-0.03}$





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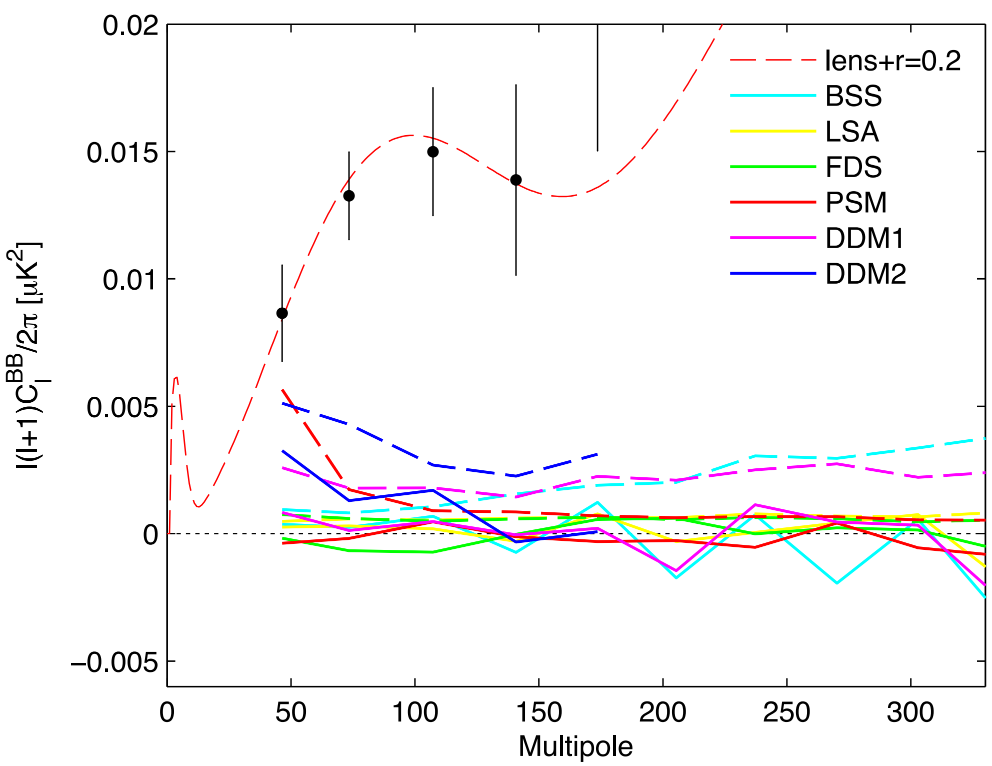

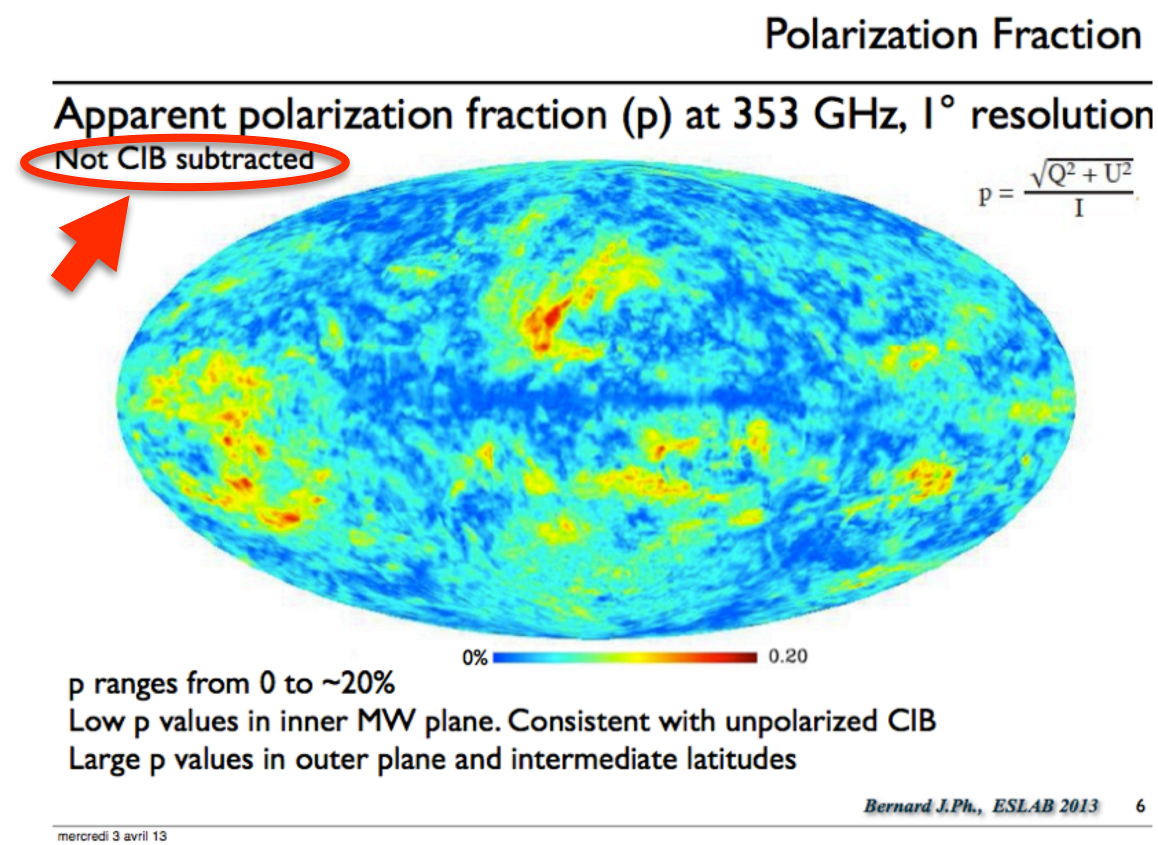

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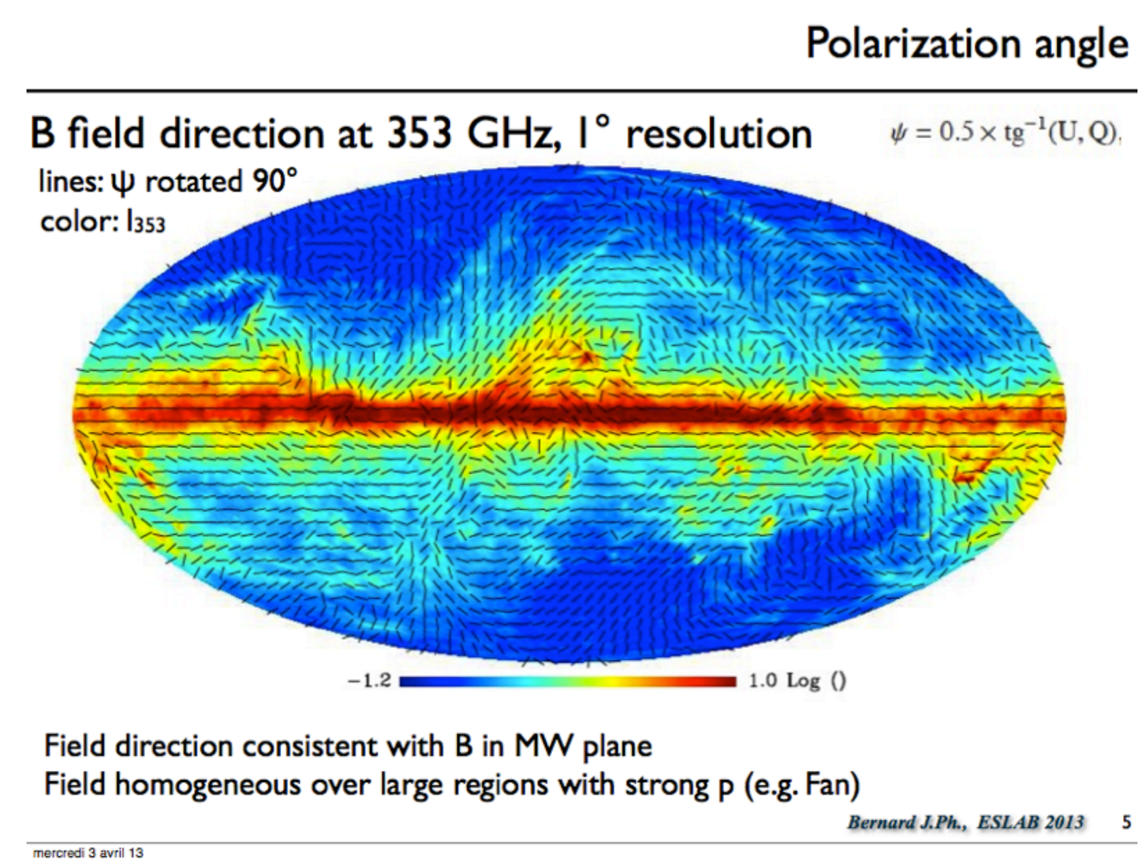

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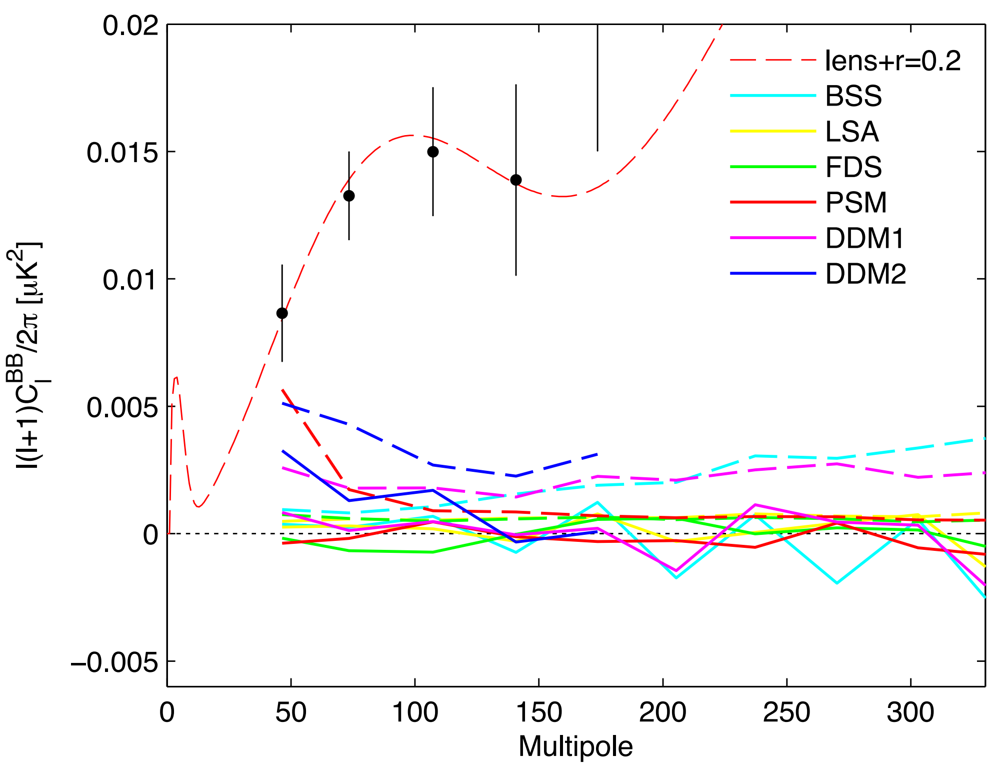

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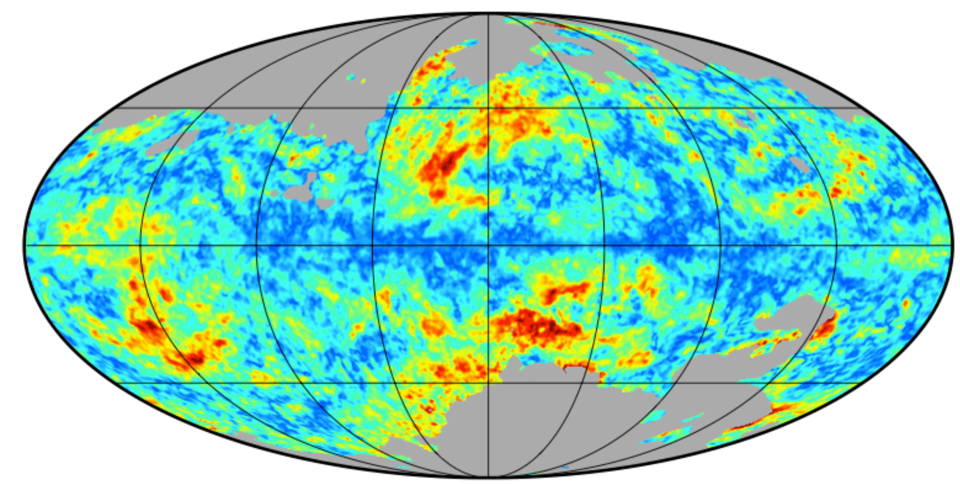
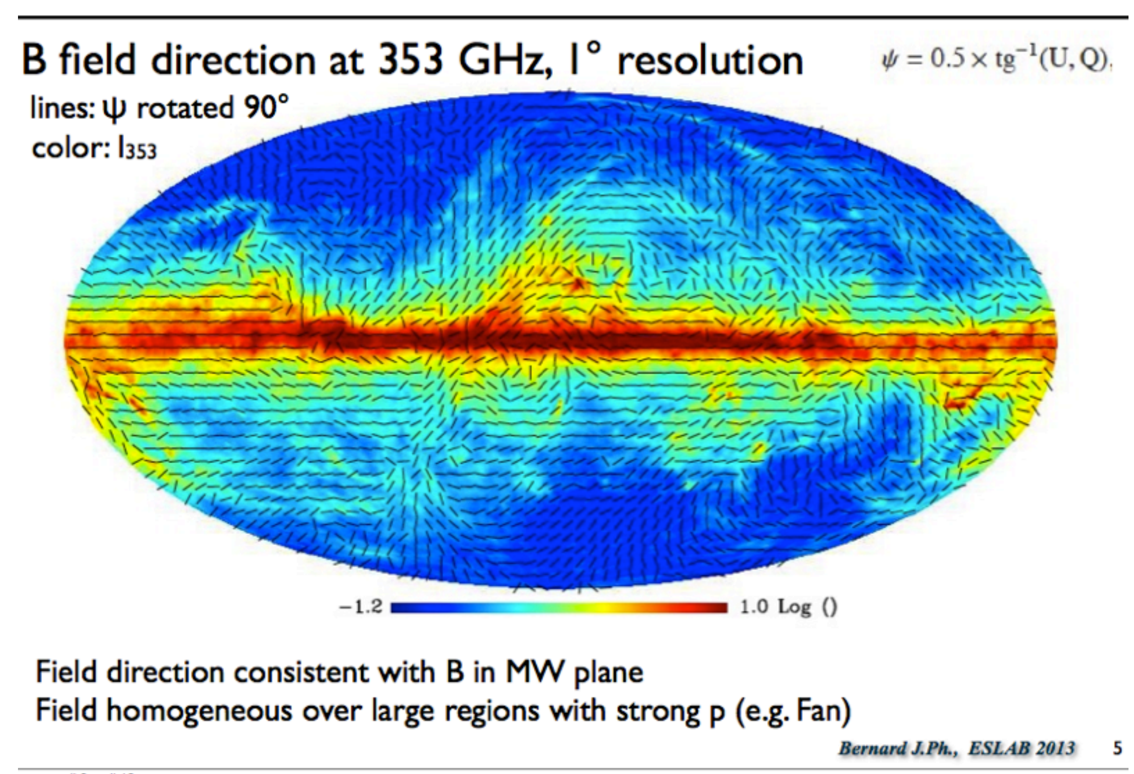
BICEP2	$0.2^{+0.07}_{-0.05}$	$0.16^{+0.06}_{-0.05}$	$0.12^{+0.05}_{-0.04}$
BICEP2×Keck	$0.13^{+0.04}_{-0.03}$	$0.10^{+0.04}_{-0.03}$	$0.06^{+0.04}_{-0.03}$

Polarization Fraction



Planck galactic dust (arXiv:1405.0871)

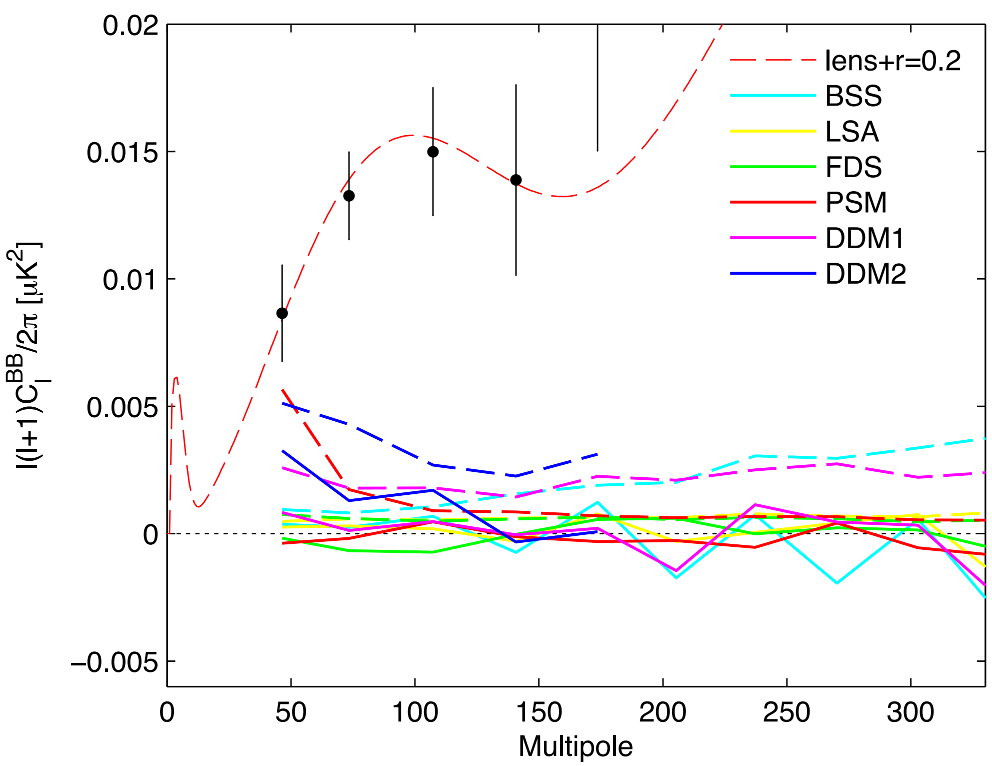
Polarization angle



BICEP2 Foregrounds

How did BICEP2 eliminate foregrounds?

- Put simply, they (mainly) used Planck data …
- ESLAB 2013 talk by Bernard released polarisation fraction and angle maps (pre-publication)
- Talk maps digitised for key DDM1/2 models



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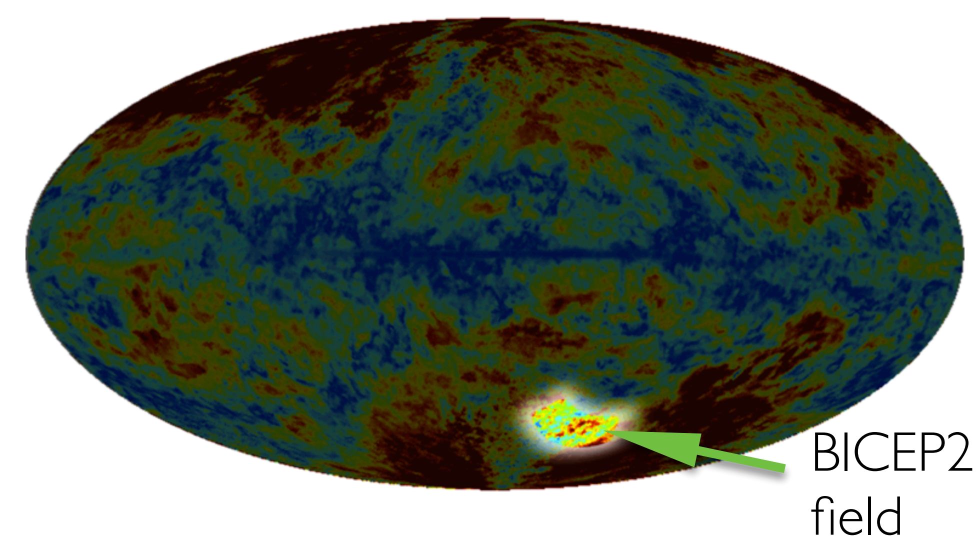
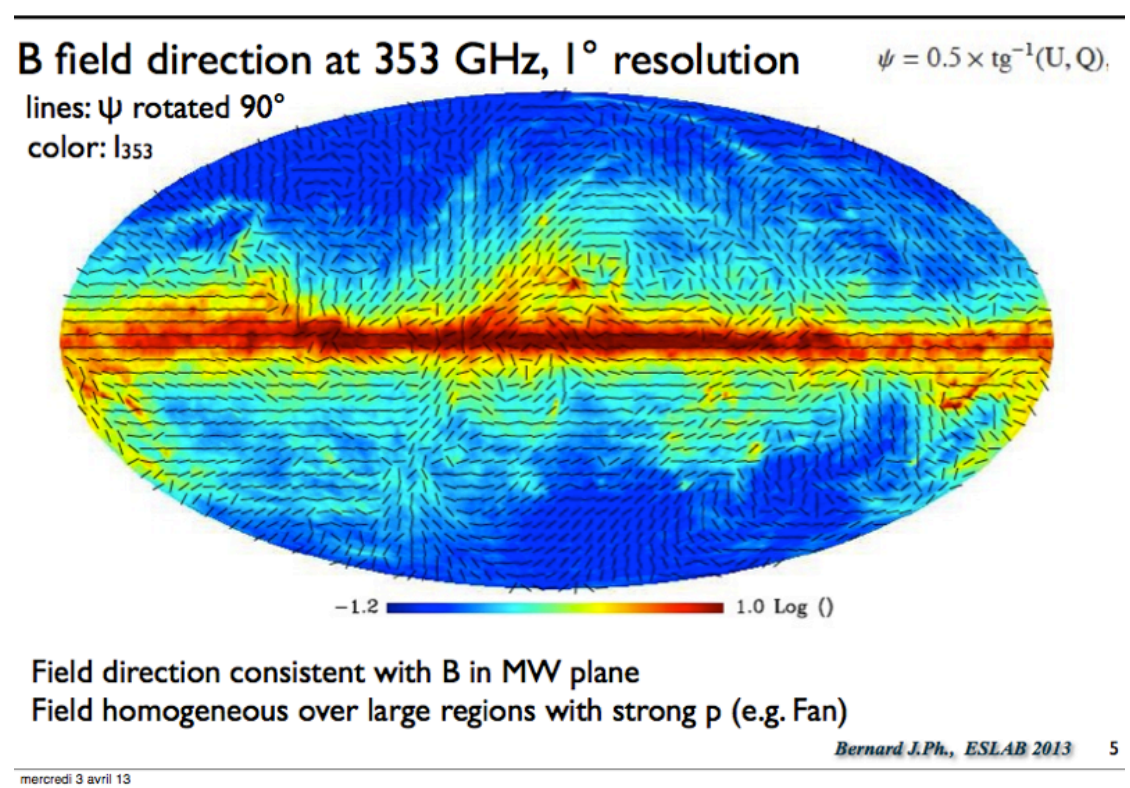


Polarization angle

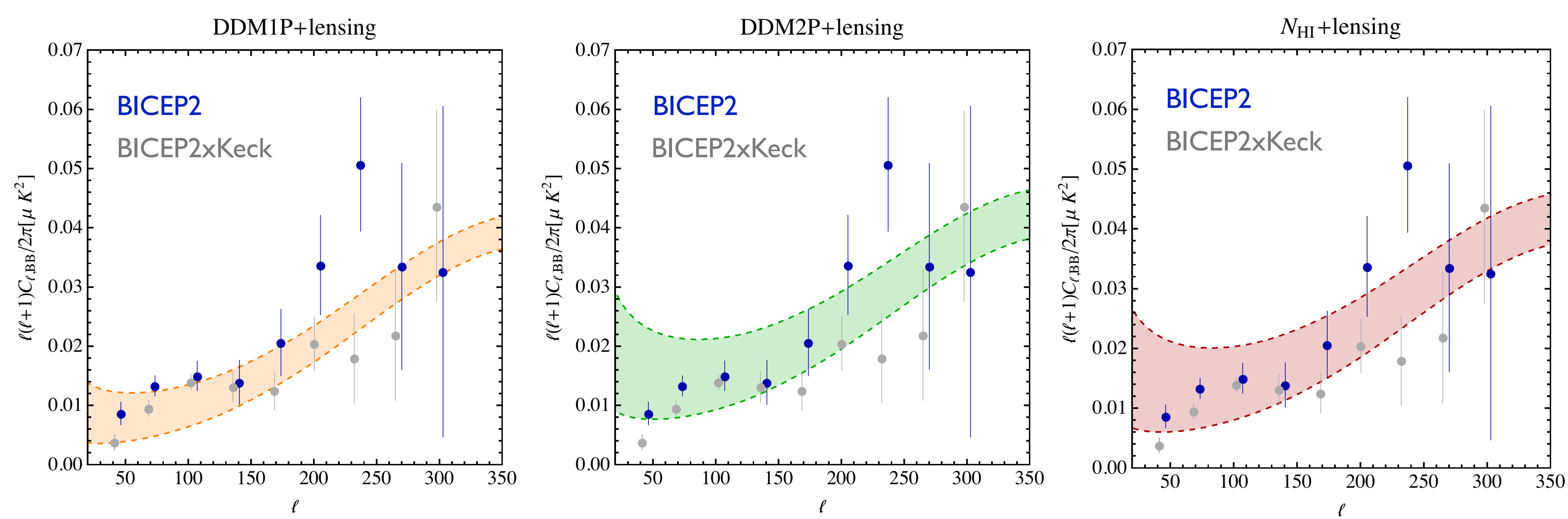


BICEP2 Dust-up

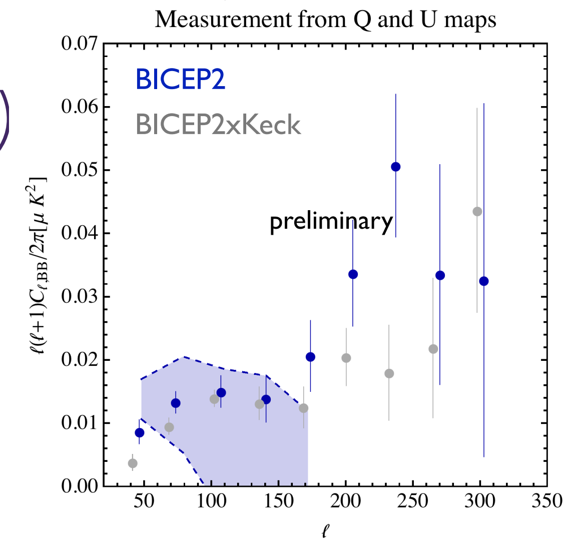
Re-analysis using (digitised) Planck ESLAB talk maps

- CIB subtracted polarisation maps *(Bernard, 2013)* indicates larger foreground contamination likely

Flauger, Hill, Spergel arXiv:1405.5857



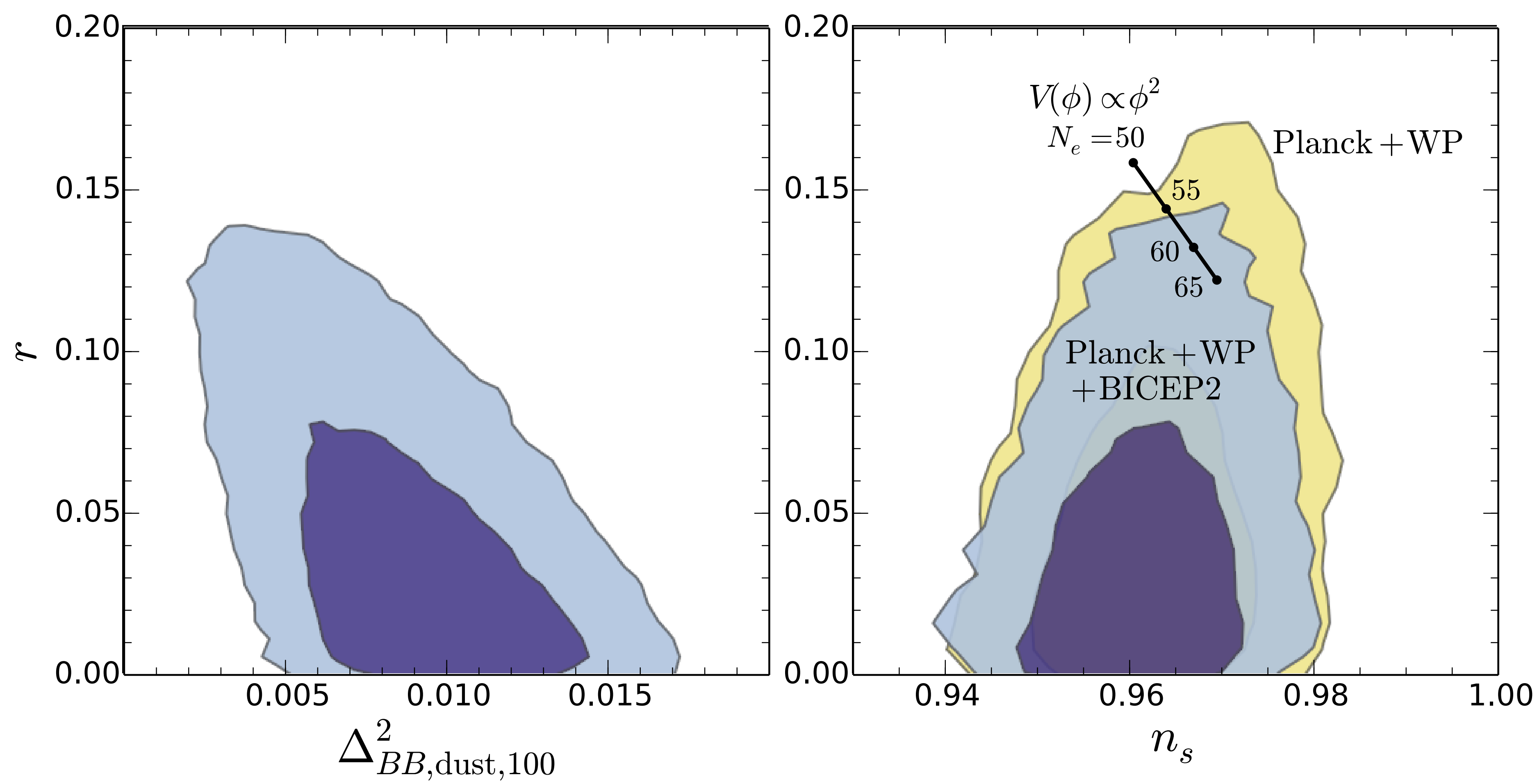
- Also H I column density estimates *(Aumont talk, 2013)*
- 353 GHz Q and U maps with dust extrapolation for 100 GHz BICEP2 field *(Boulanger talk, 2013)*



BICEP2 Dust-up (cont.)

Joint Planck/BICEP2 analysis without polarisation assumptions

(Mortonson & Seljak, arXiv:1405.5857)



Likelihood constraints favour *no* gravitational waves with r < 0.11 (95%) (i.e. null hypothesis with significant dust polarisation component). Projects a combined Planck / BICEP2 constraint up to r < 0.05.

BICEP2 outcomes

Impact on BICEP2 paper - original (18 March 2014):

"Subtracting … foreground dust, r = 0 is disfavored at 5.9σ."

To actual PRL 20th June 2014):

"Accounting for foreground dust will shift this value downward by an amount which will be better constrained with upcoming data sets."

SECTIONS HOME SEARCH The New York Times

SPACE & COSMOS

Astronomers Hedge on Big Bang Detection Claim

By DENNIS OVERBYE JUNE 19, 2014

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A group of astronomers who announced in March that they had detected space-time disturbances — gravitational waves — from the beginning of the Big Bang reaffirmed their claim on Thursday but conceded that dust from the Milky Way galaxy might have interfered with their observations.

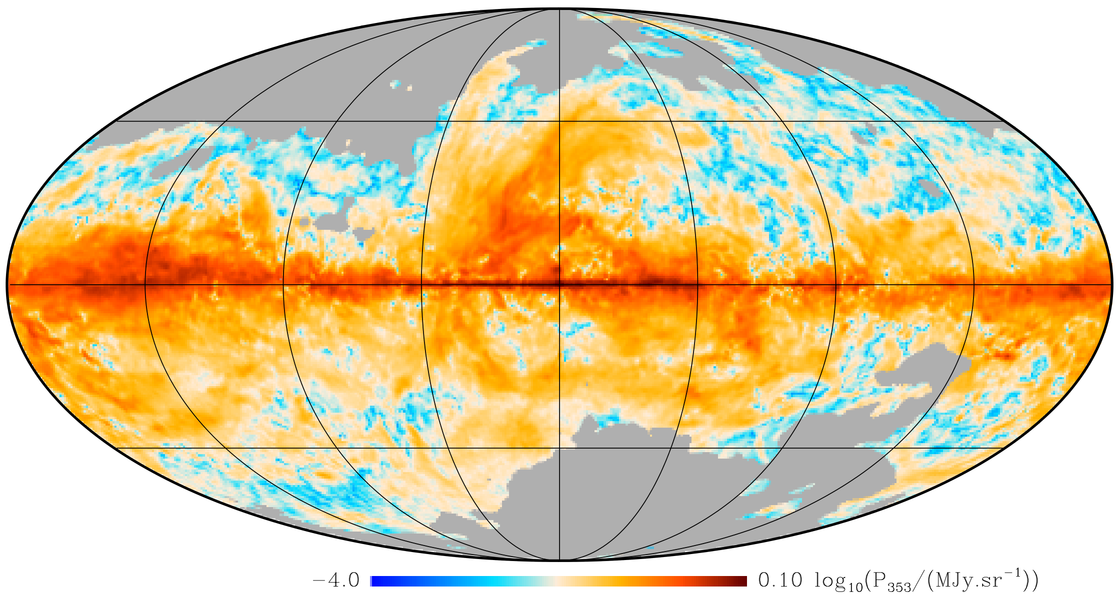
Interim summary:

A phenomenal B-mode measurement, but arguably not a GWs detection yet?

BICEP2 and Planck2

- Planck intermediate papers dust widespread with 8-10% polarisation fraction *(arXiv:1405.0871)*
- Planck B-mode polarisation paper - *coming very soon …*
  - Will describe B-modes in low contamination regions (incl. BICEP2 field but *no* detailed power spectrum analysis).
  - What will it say? Hints only …
    Nature 20 June 2014: "Puget reported that polarisation from interstellar dust grains plays a significant role and might account for much of the BICEP2 signal.

Planck 353 GHz polarized intensity map



The B-mode future -

- Planck / BICEP 2 will share data (announced late June 2014)
  - publication on the Planck second release timeframe (Nov 2014)
- Keck Array 100GHz accumulating data with analysis soon
- Many other B-mode experiments (looking at high-*l* lensing) shifting to tensors: SPTpol (same patch) Polarbear, ACTpol, ABS, Spider, EBEX and Planck

Future prospects

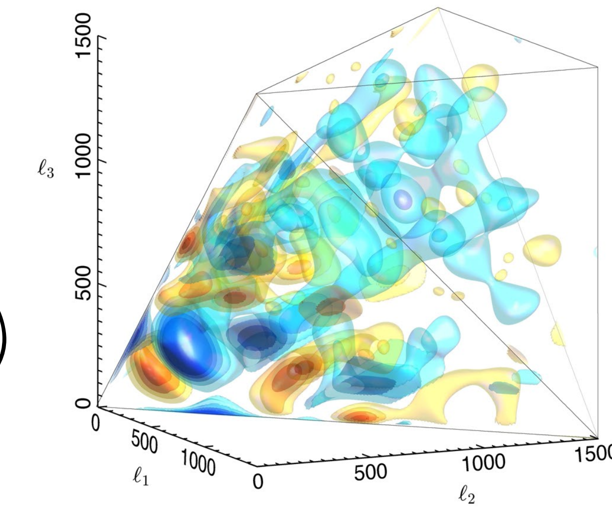
Planck full mission data release - soon *(Oct/Nov 2014)*

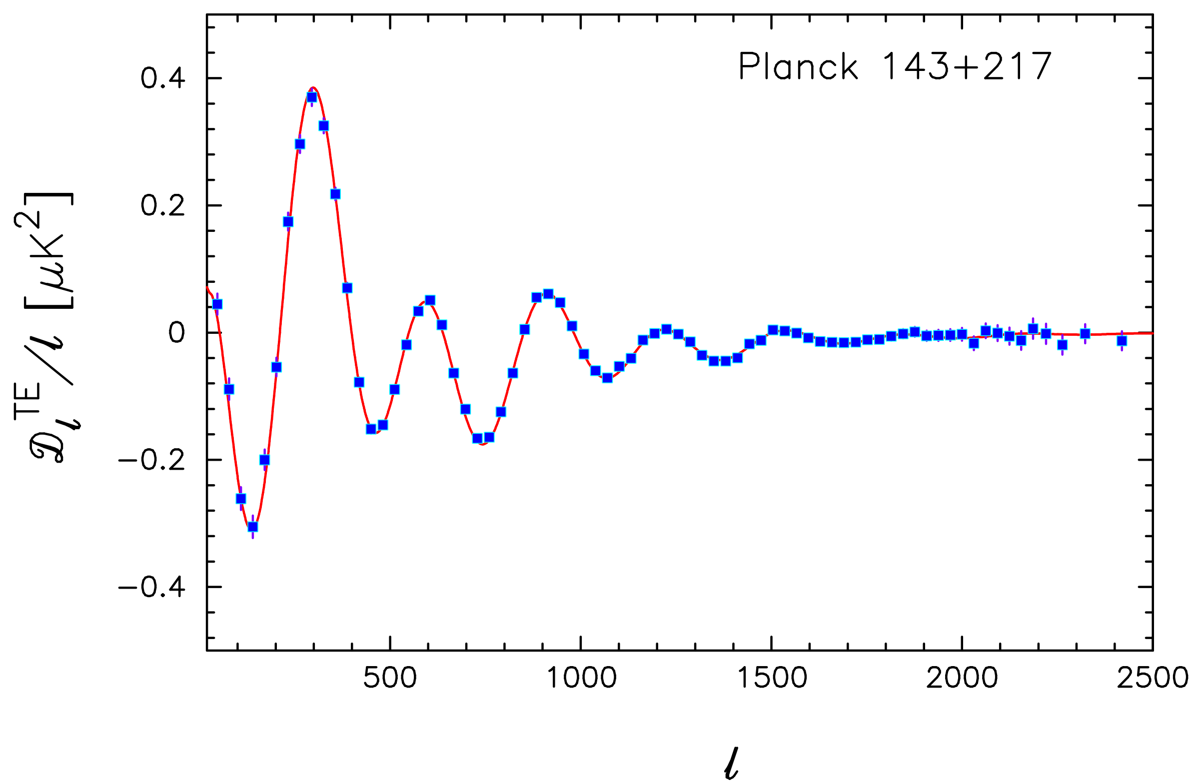
More than double the temperature data still to be analysed

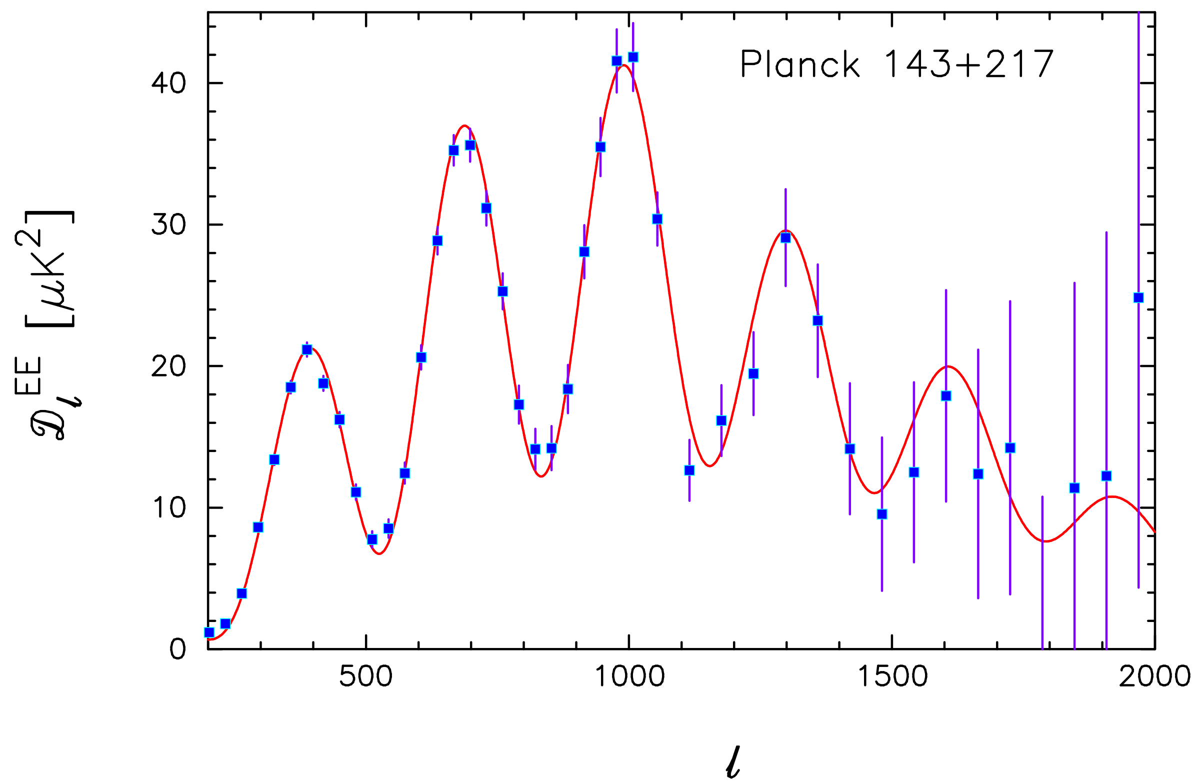
Analysis of the polarisation data to be included (joint BICEP2)

Power spectrum, bispectrum (and trispectrum) joint analysis

Improvements in methodology (final Planck analysis planned for late 2015)







B-modes offer a new window on the Universe - many experiments

- Prism satellite proposed, spectrometer and imager

Next generation of galaxy surveys (grav. lensing; 3D non-Gaussianity)