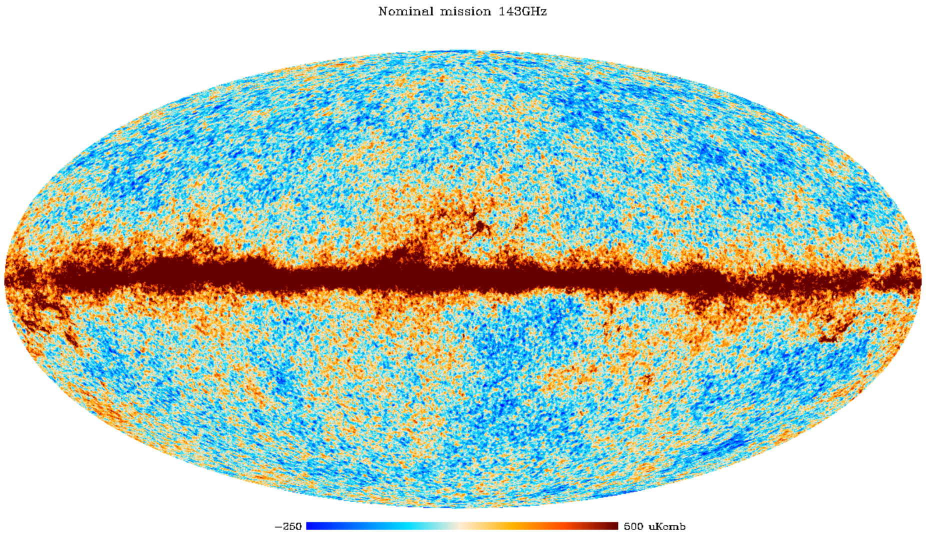
Planck and neutrino physics



University of Sussex

Antony Lewis

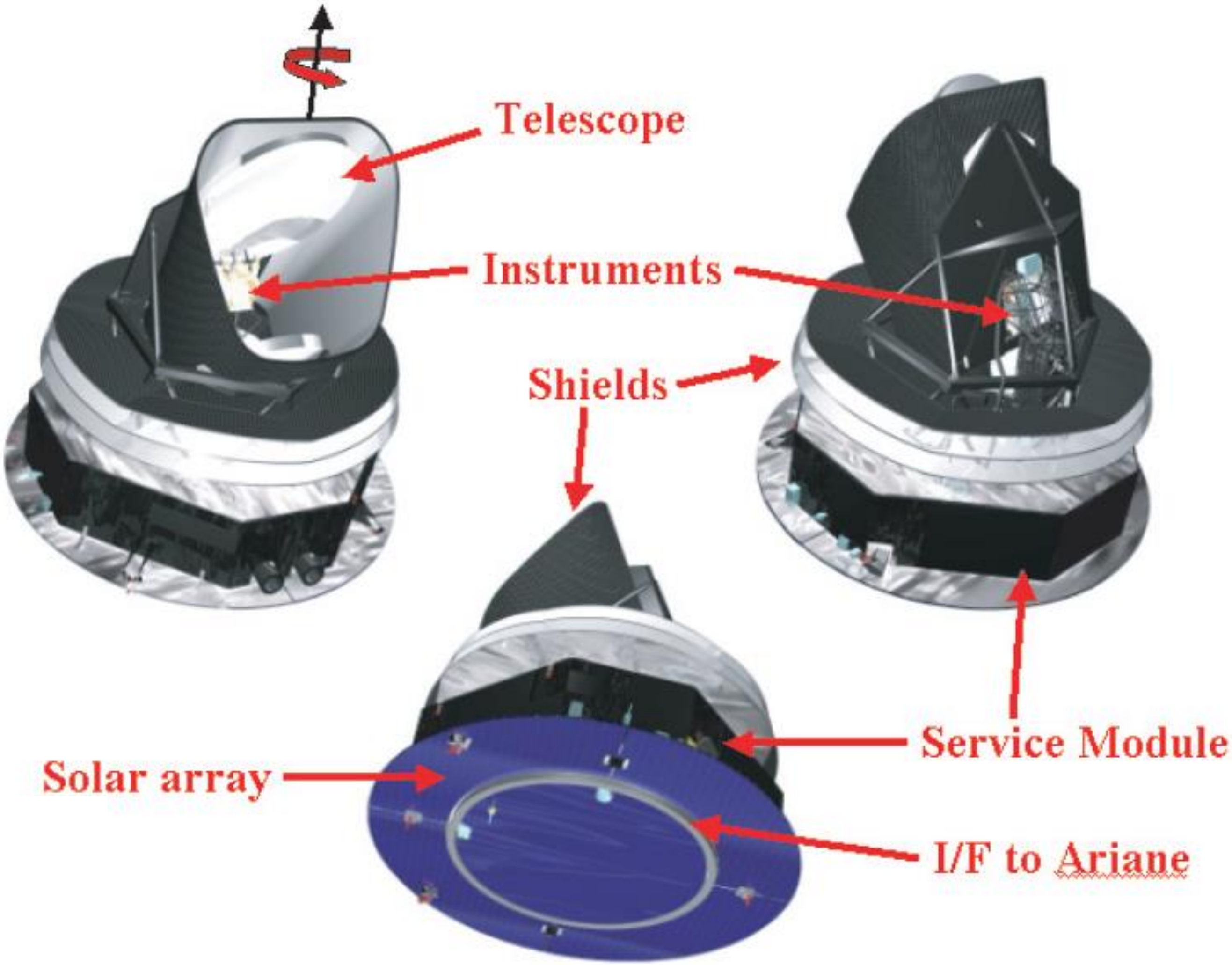
http://cosmologist.info/

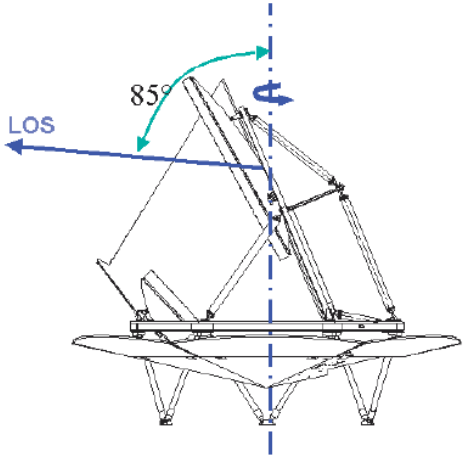
on behalf of the Planck collaboration

Outline

- Planck recap
- What we measure
- What we can learn from it
- Constraining on neutrino physics

PLANCK



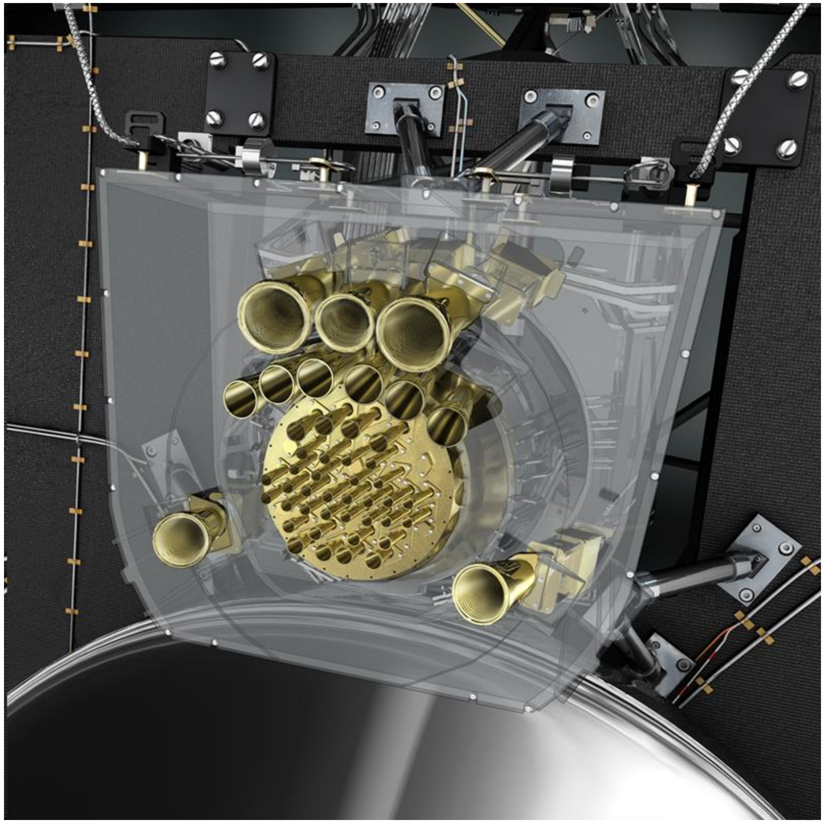


Blue book

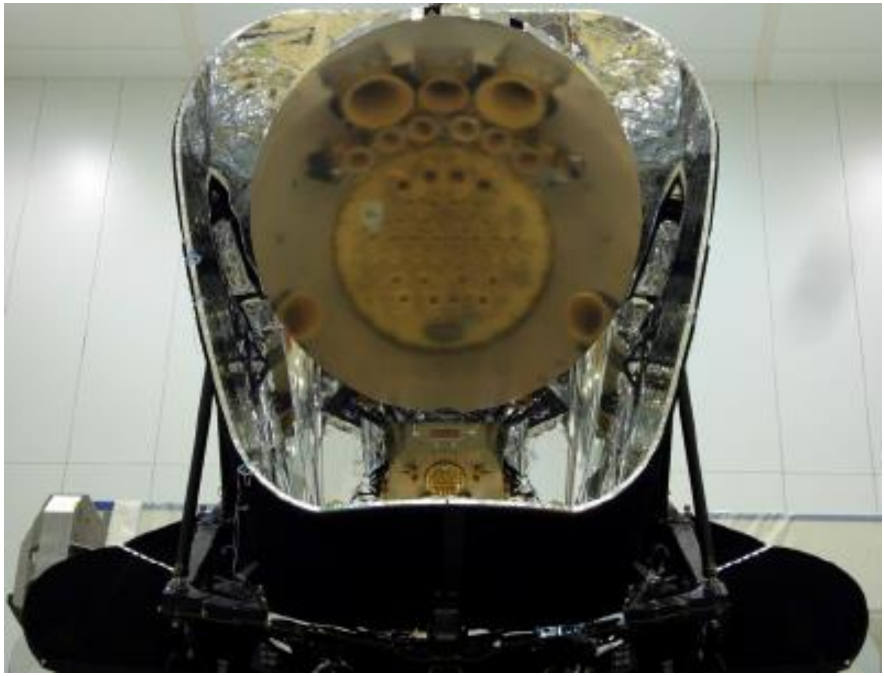
Instrument Characteristic	LFI			HFI					
Detector Technology	HEMT arrays			Bolometer arrays					
Center Frequency [GHz]	30	44	70	100	143	217	353	545	857
Bandwidth ($\Delta\nu/\nu$)	0.2	0.2	0.2	0.33	0.33	0.33	0.33	0.33	0.33
Angular Resolution (arcmin)	33	24	14	10	7.1	5.0	5.0	5.0	5.0
$\Delta T/T$ per pixel (Stokes I)[a]	2.0	2.7	4.7	2.5	2.2	4.8	14.7	147	6700
$\Delta T/T$ per pixel (Stokes Q &U)[a]	2.8	3.9	6.7	4.0	4.2	9.8	29.8	...	...

[a] Goal (μK/K, 1σ), 14 months integration, square pixels whose sides are given in the row "Angular Resolution".

~ SZ null



Planck focal plane

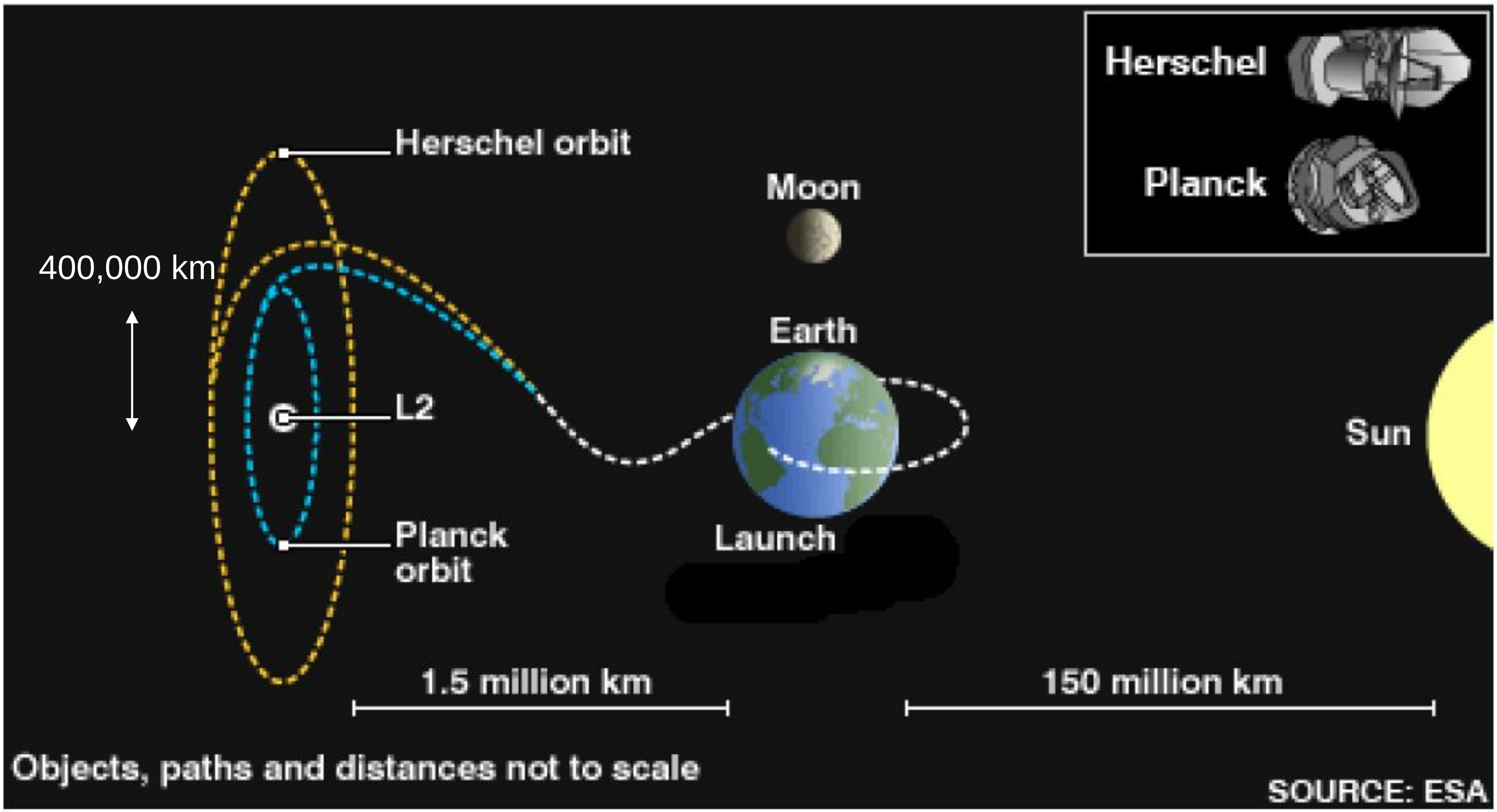


ESA/AOES Medialab

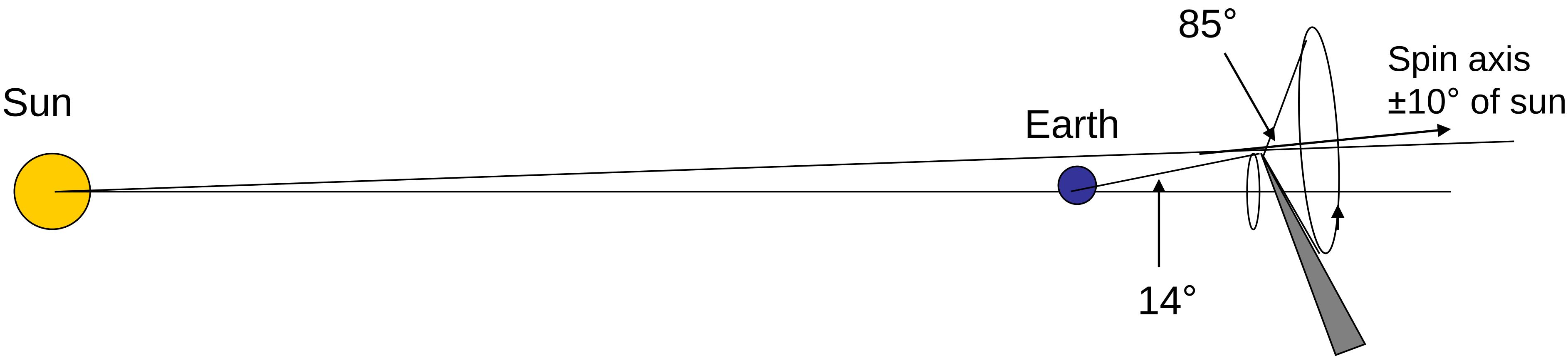
Images: ESA

14 May 2009

DISTANT OUTPOST: HERSCHEL AND PLANCK IN ORBIT



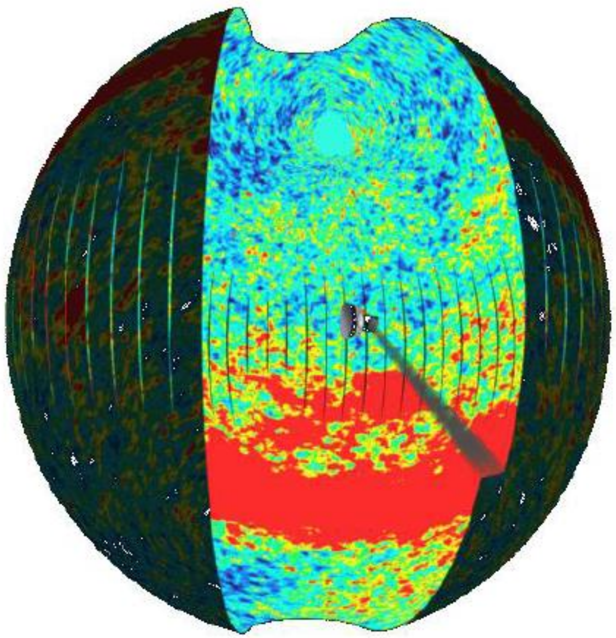
Corrections to stay in Lissajous L2 orbit every 30 days



- Spacecraft rotates at 1 rpm

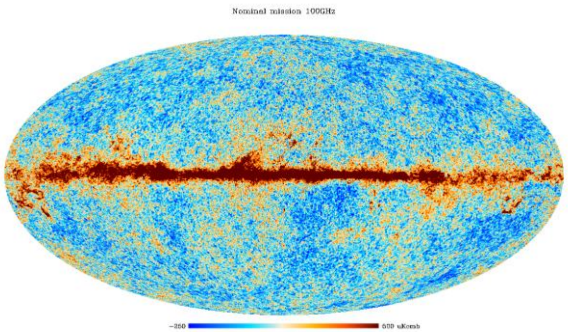
- Optic axis at 85° traces large circles on the CMB
(small precession to cover whole sky)

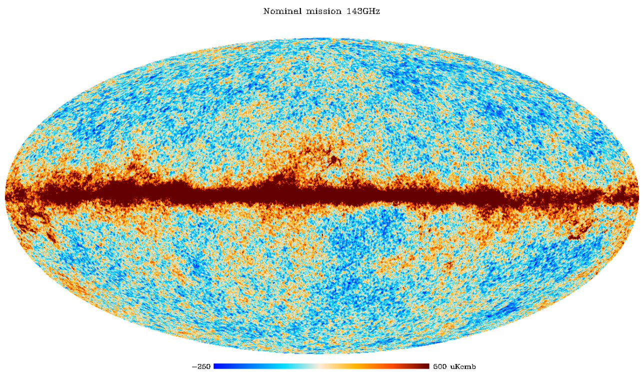
- Re-points every hour

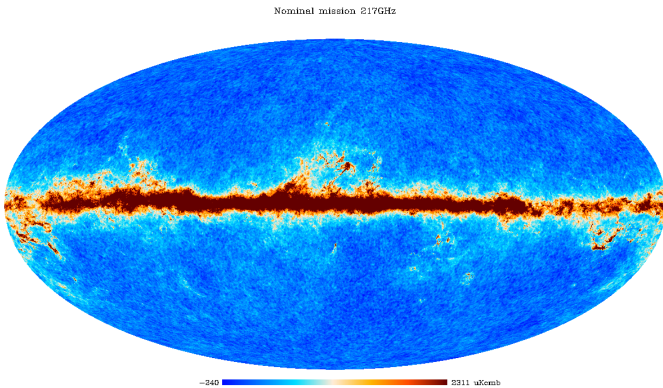


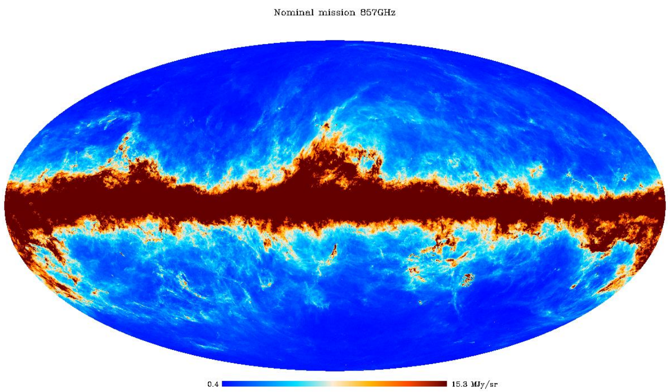
Full sky every 6-7 months: this year 2 sky surveys, then next year 4 full scans

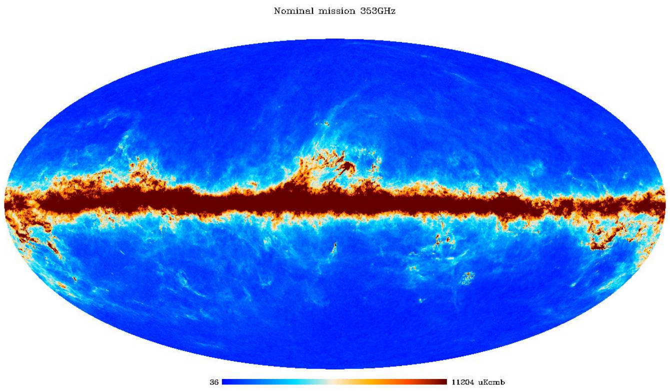
Make full-sky maps at many frequencies



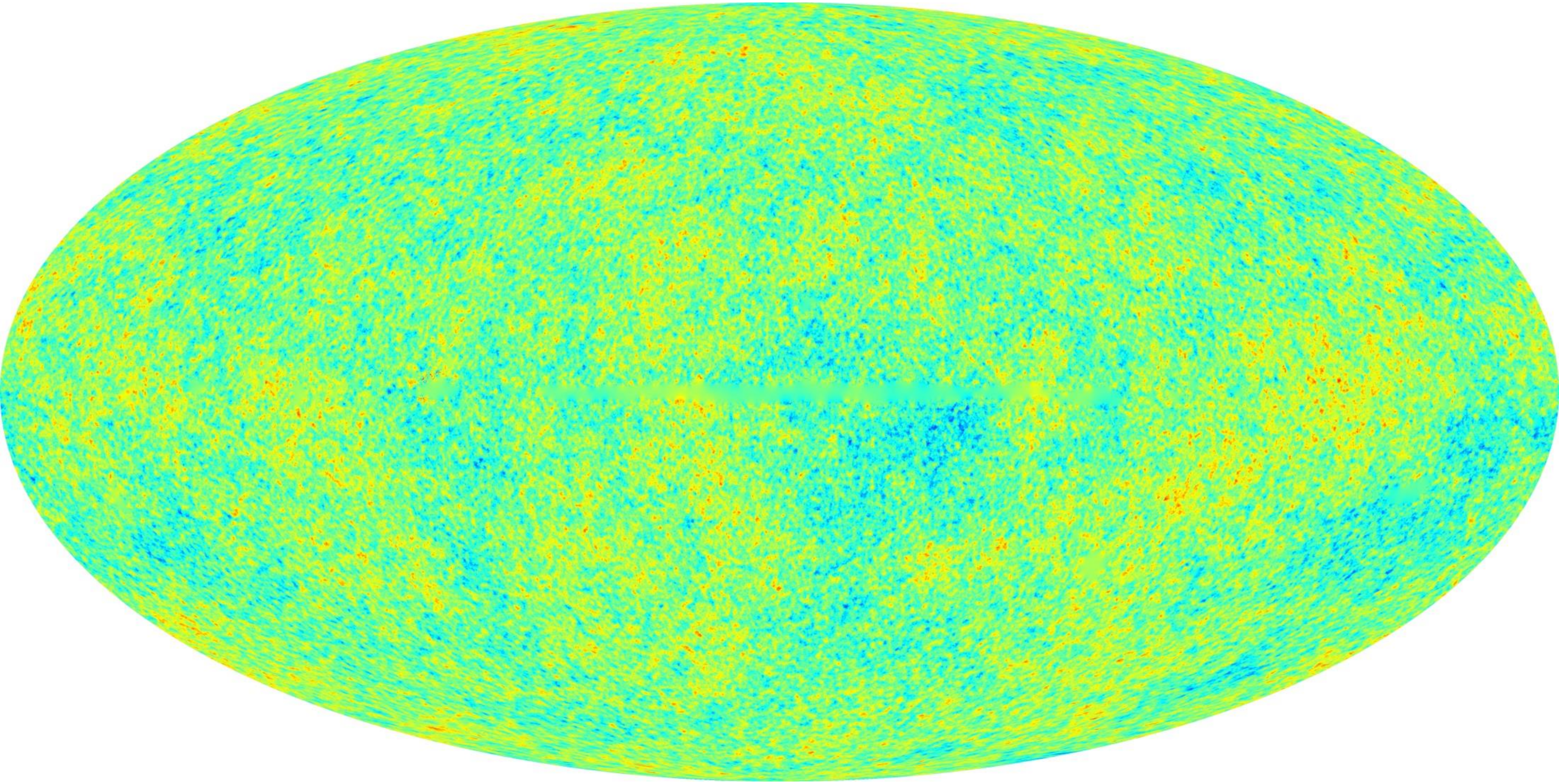






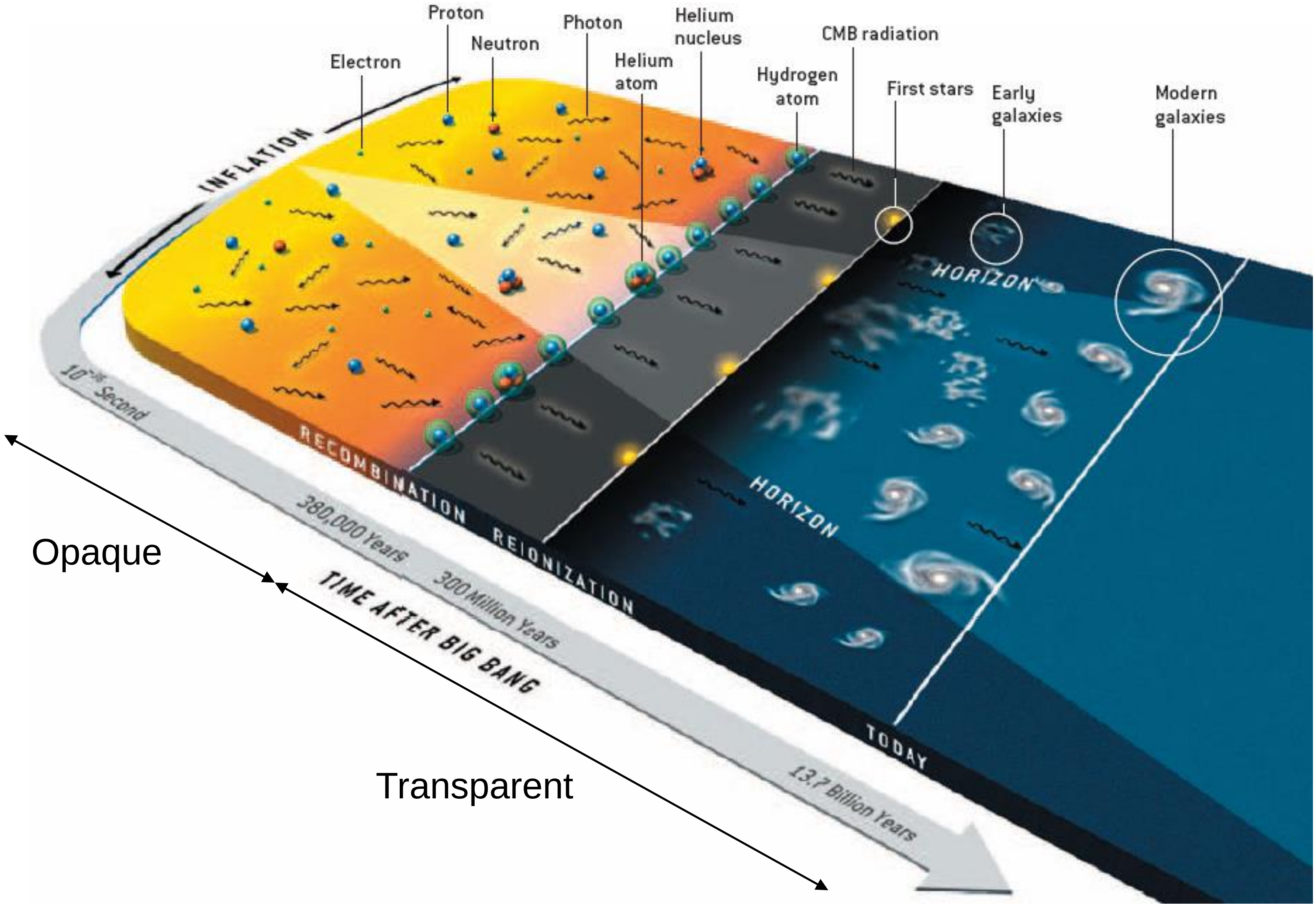


CMB Blackbody – can separate or model foregrounds



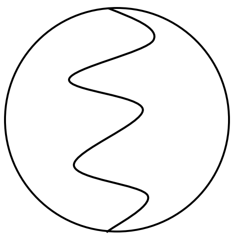
For parameter analysis actually cut and model rather than clean

Evolution of the universe



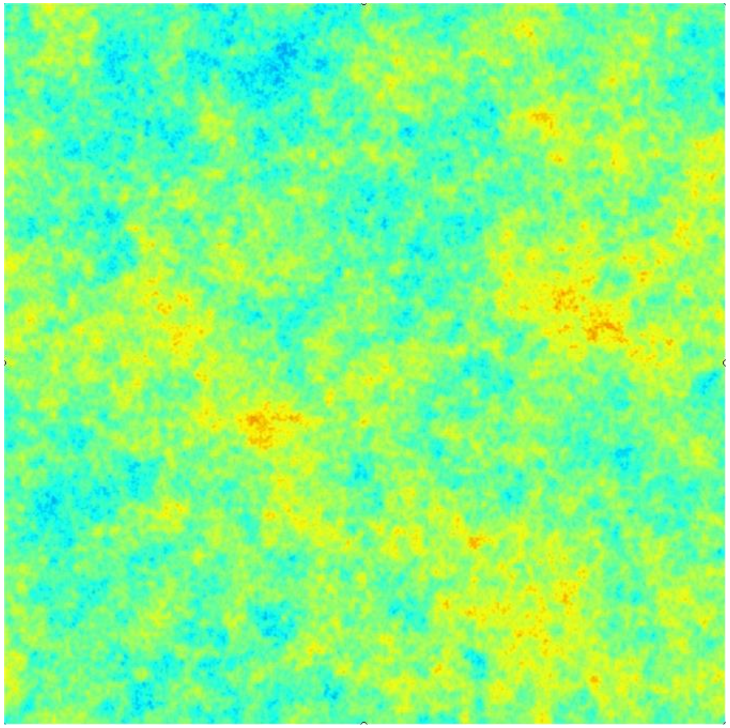
Hu & White, Sci. Am., 290 44 (2004)

Where do the perturbations come from?



Quantum Mechanics
"waves in a box"

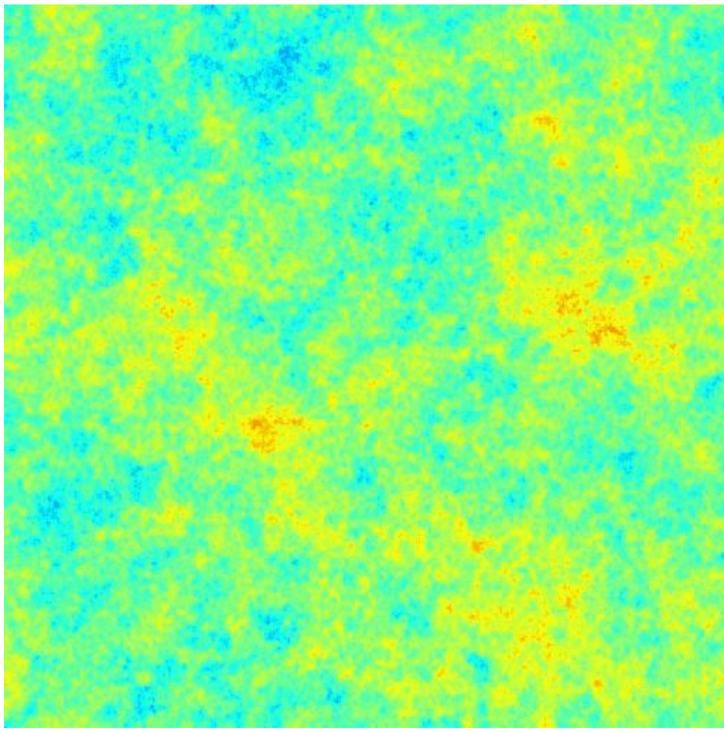
Inflation
make $>10^{30}$ times bigger



After inflation
Huge size, amplitude ~ 10^{-5}

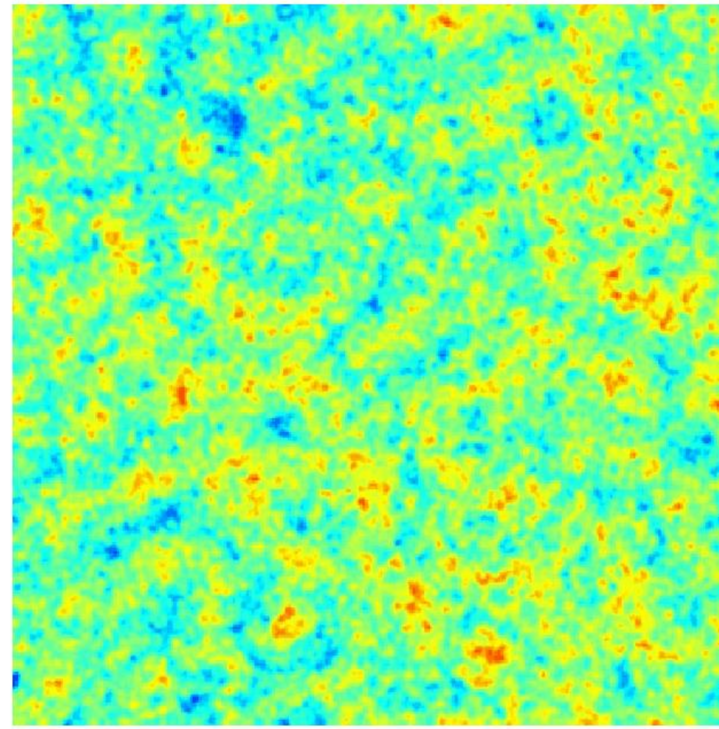
CMB temperature

End of inflation



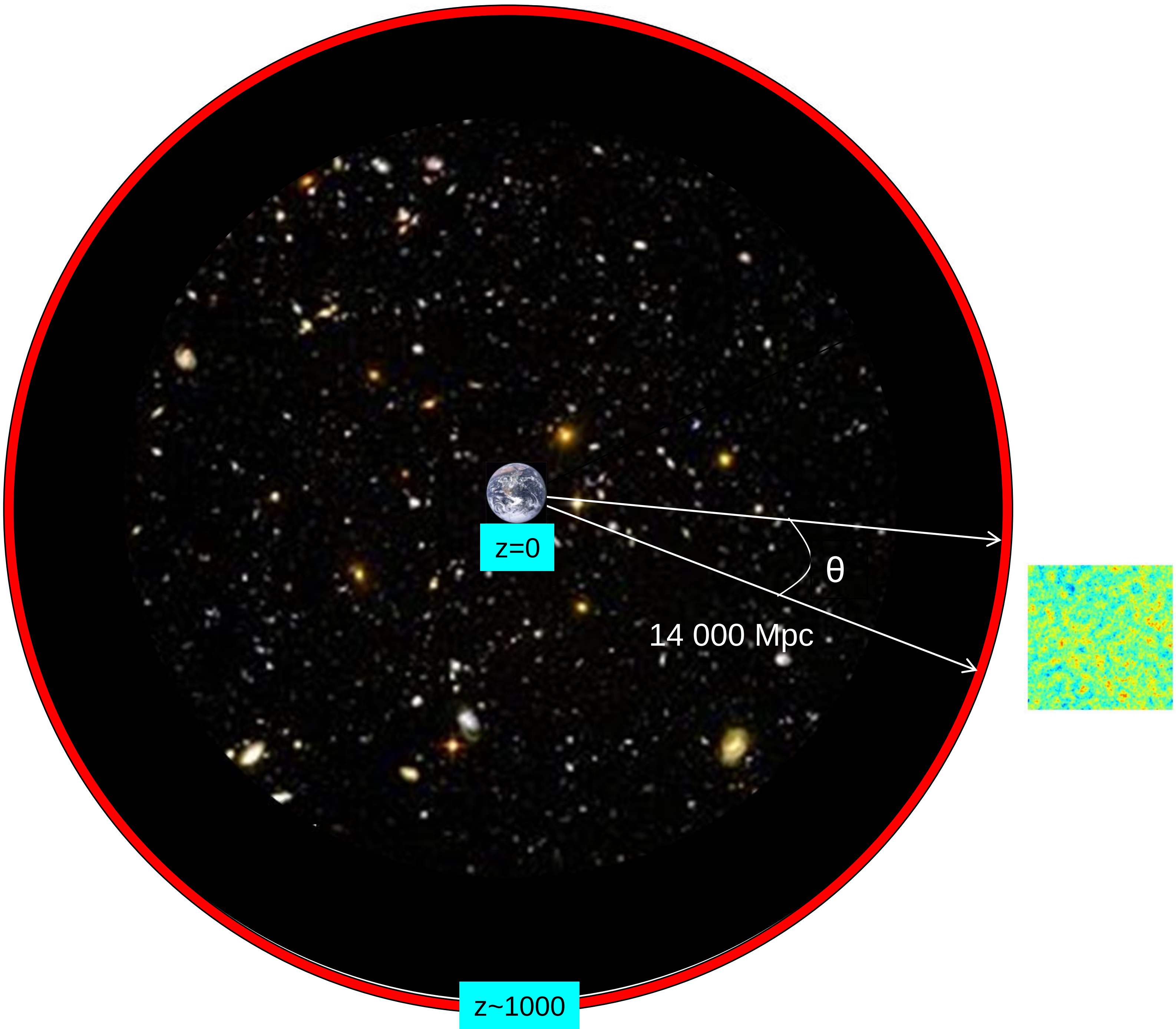
gravity+
pressure+
diffusion

Last scattering surface



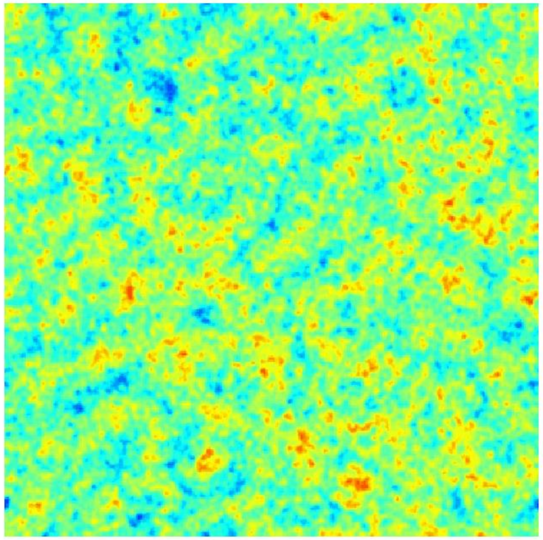
10^{-5} perturbations ⇒ Linear theory predictions very accurate

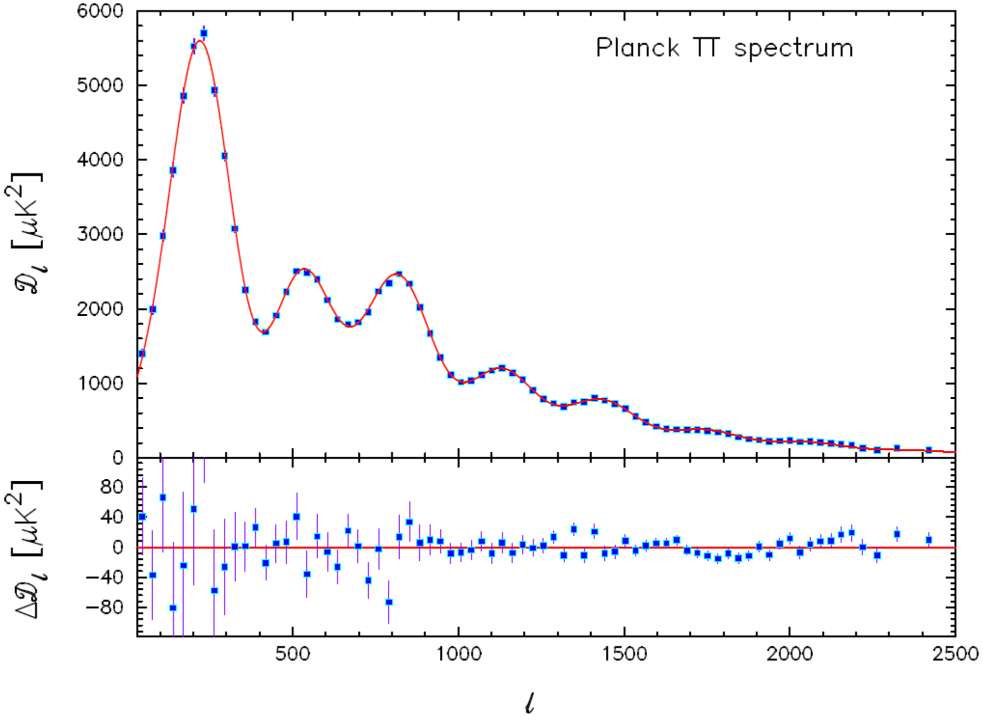
⇒ Gaussian fluctuations from inflation remain Gaussian


z=0
θ
14 000 Mpc
z~1000

Observed CMB temperature power spectrum

Primordial perturbations + known physics with unknown parameters





Observations

Constrain theory of early universe
+ evolution parameters and geometry

Detailed measurement of 6 power spectrum acoustic peaks

⇒ Accurate measurement of cosmological parameters?

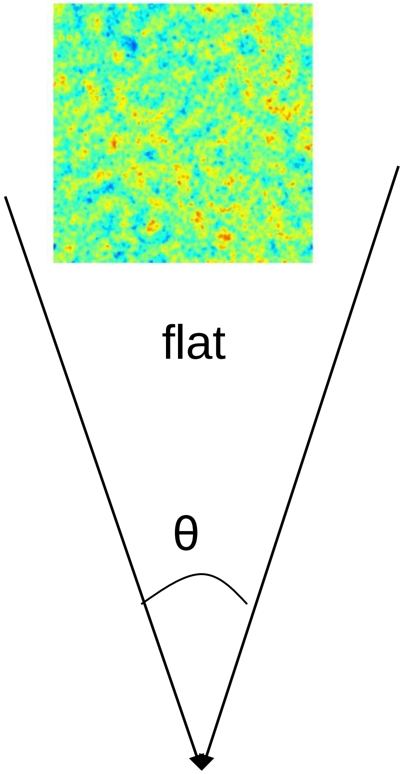
YES: some particular parameters measured very accurately

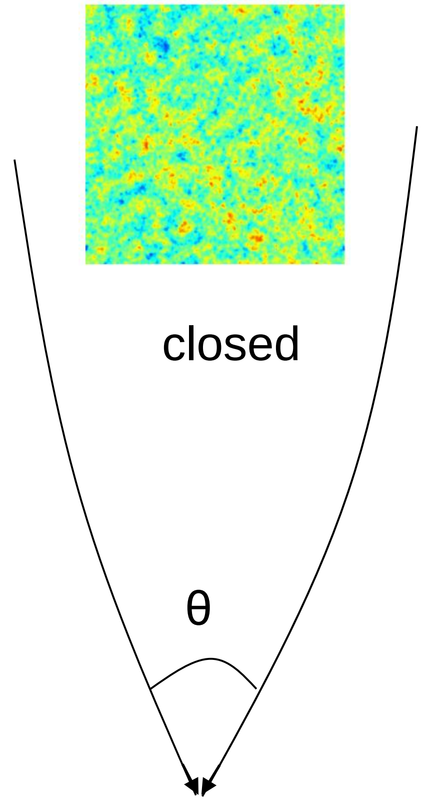
0.1% accurate measurement of the acoustic scale:

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

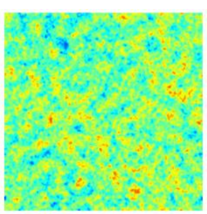
But need full cosmological model to relate to underlying physical parameters..

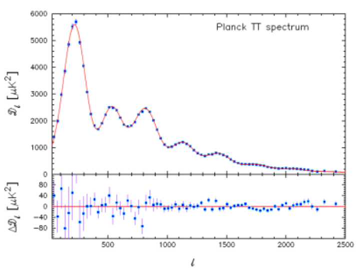
e.g. Geometry: curvature

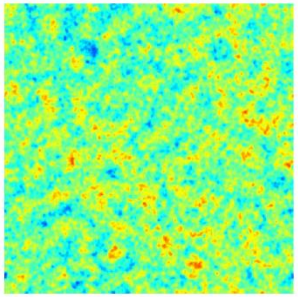


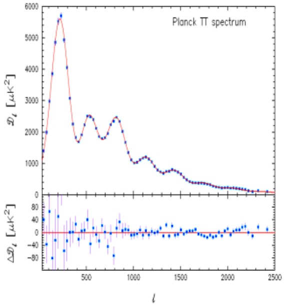


We see:

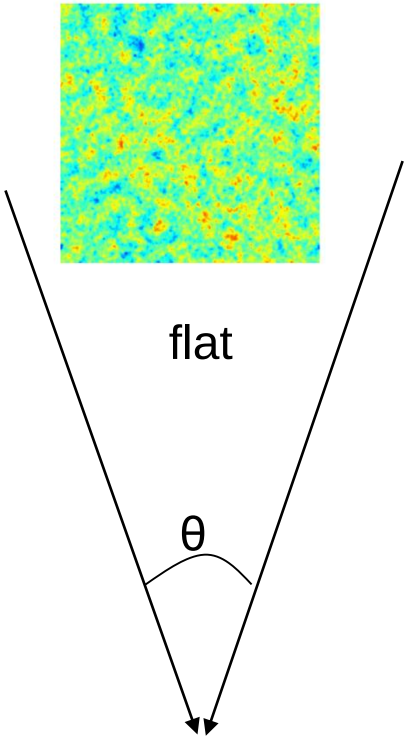


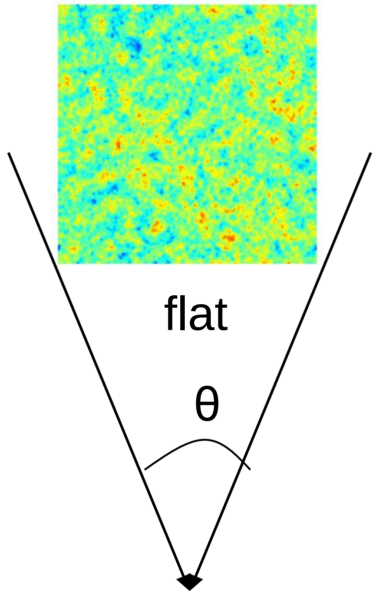




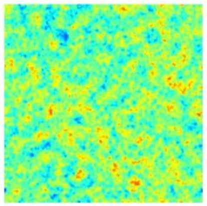


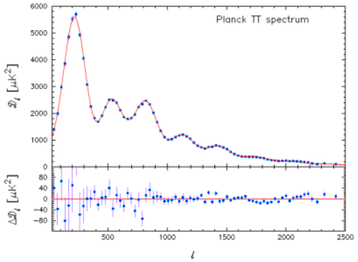
or is it just closer??

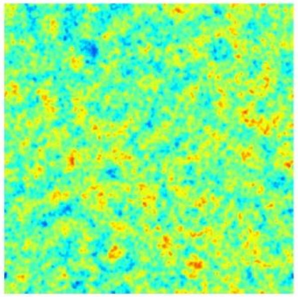


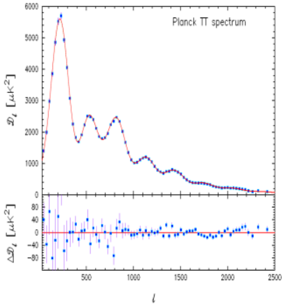


We see:

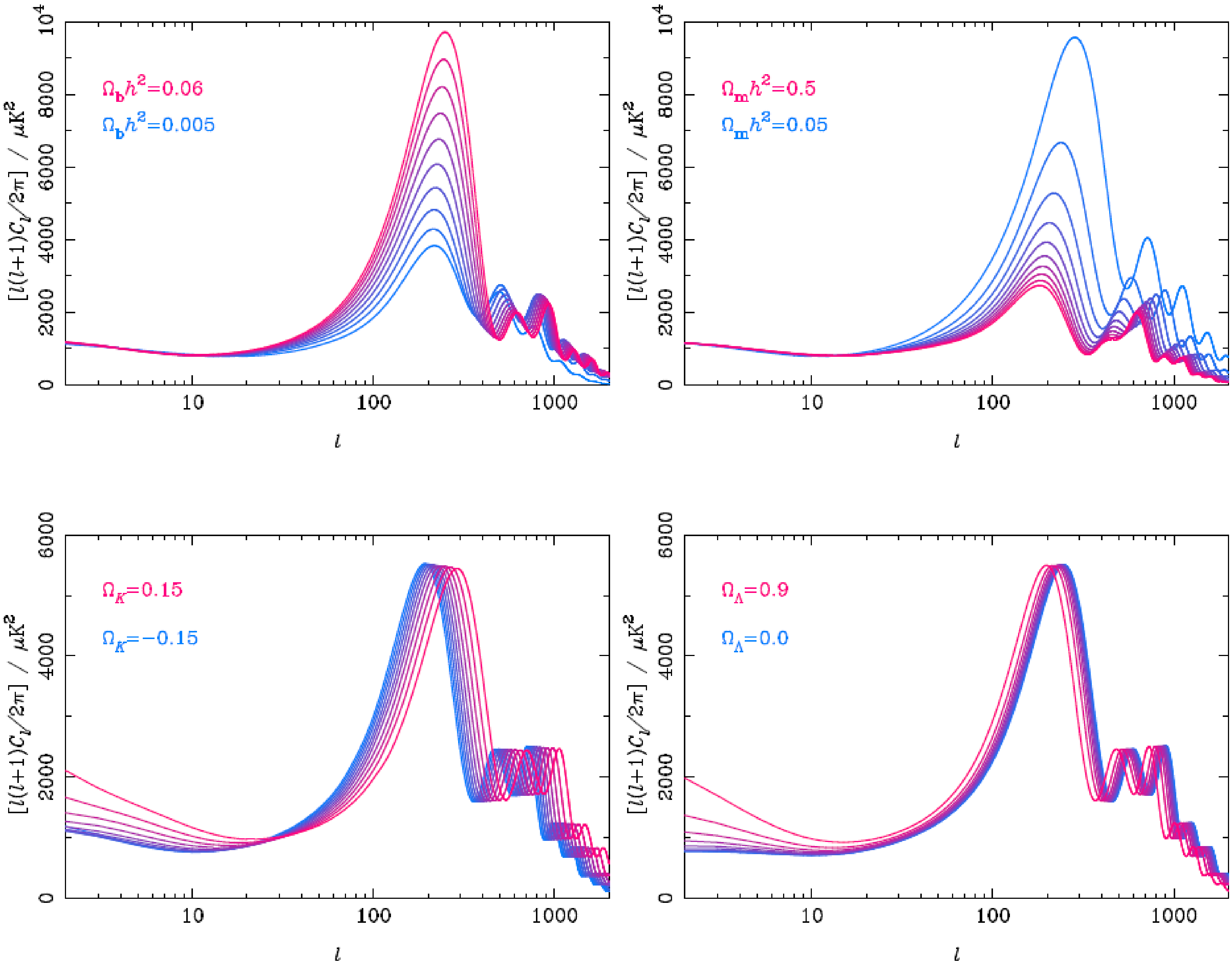








Degeneracies between parameters



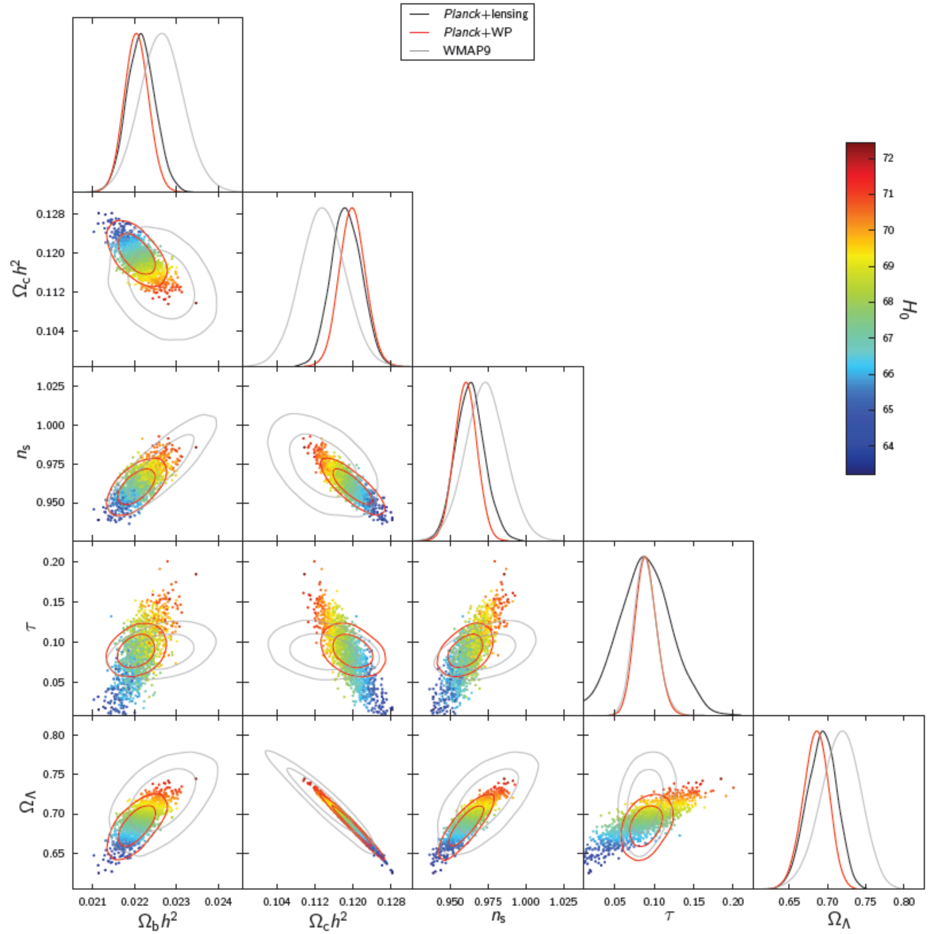
Credit: Anthony Challinor

1. Assume a model

LCDM baseline model:

Flat, dark matter, cosmological constant, neutrinos, photons: six free parameters.
Assume 3 neutrinos, minimal-mass hierarchy with $\sum m_\nu = 0.06\mathrm{eV}$.

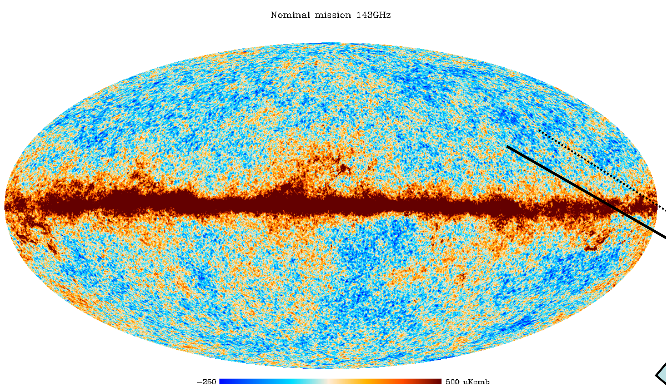
	Planck	
Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068
τ	0.0925	0.097 ± 0.038
n_s	0.9624	0.9616 ± 0.0094
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072
Ω_Λ	0.6825	0.686 ± 0.020
Ω_m	0.3175	0.314 ± 0.020
σ_8	0.8344	0.834 ± 0.027
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$
H_0	67.11	67.4 ± 1.4



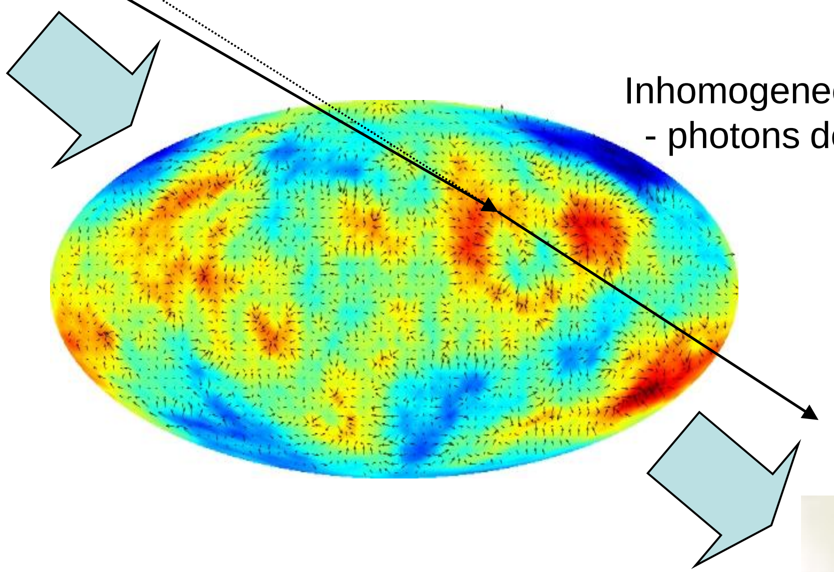
2. Use additional data to break degeneracies

CMB Lensing

Weak lensing to break CMB degeneracies



Last scattering surface



Inhomogeneous universe
- photons deflected

Observer

Review: Lewis & Challinor *Phys. Rept . 429, 1-65 (2006)*: astro-ph/0601594

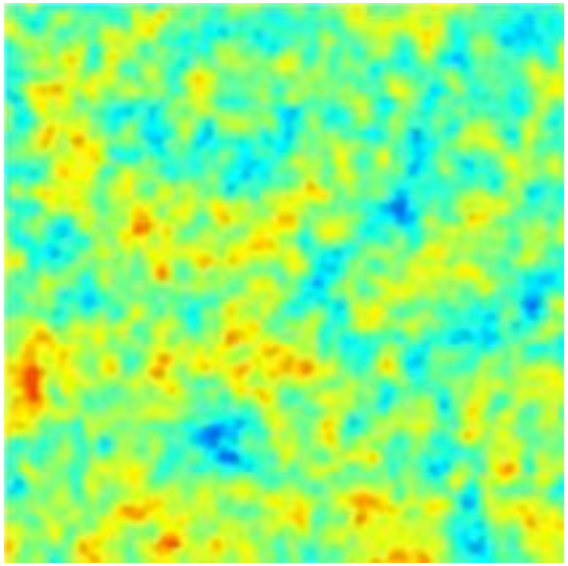
- smooths the power spectra
- Introduces non-Gaussianity: use trispectrum to reconstruct lensing potential ϕ

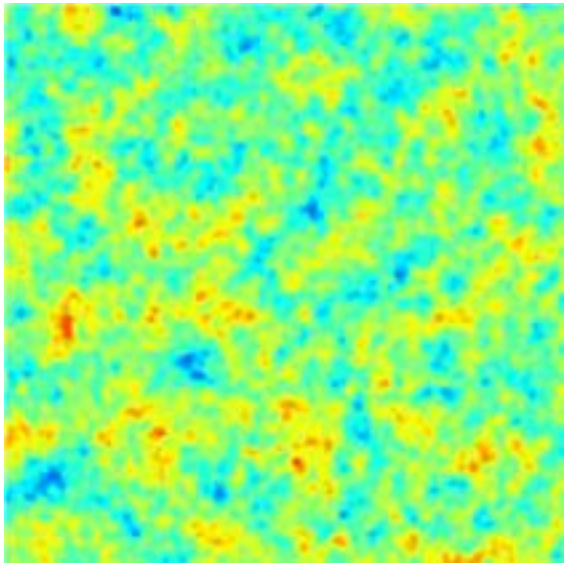
Beyond the power spectrum

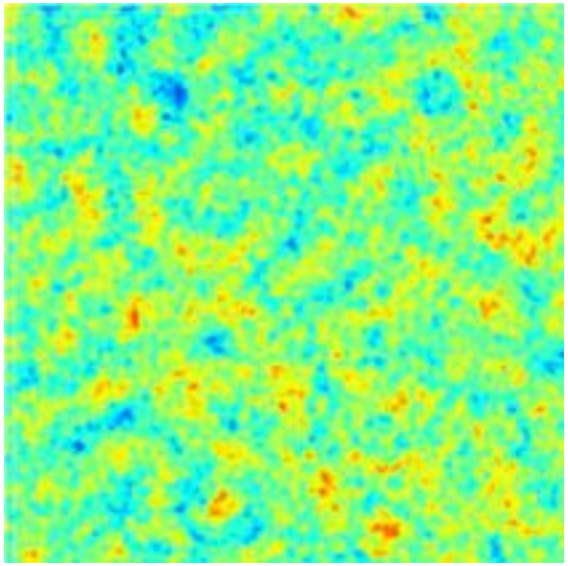
Magnified

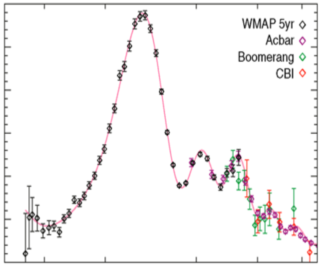
Unlensed

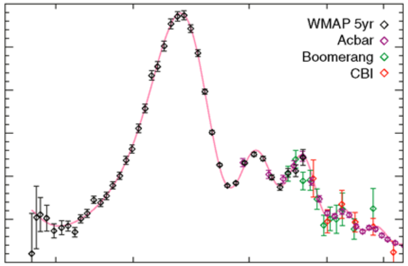
Demagnified

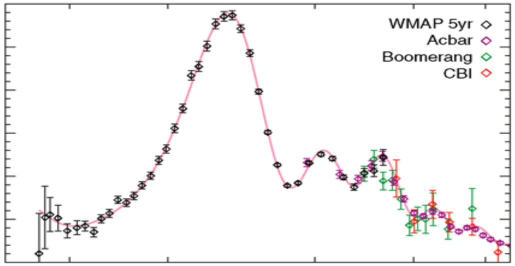








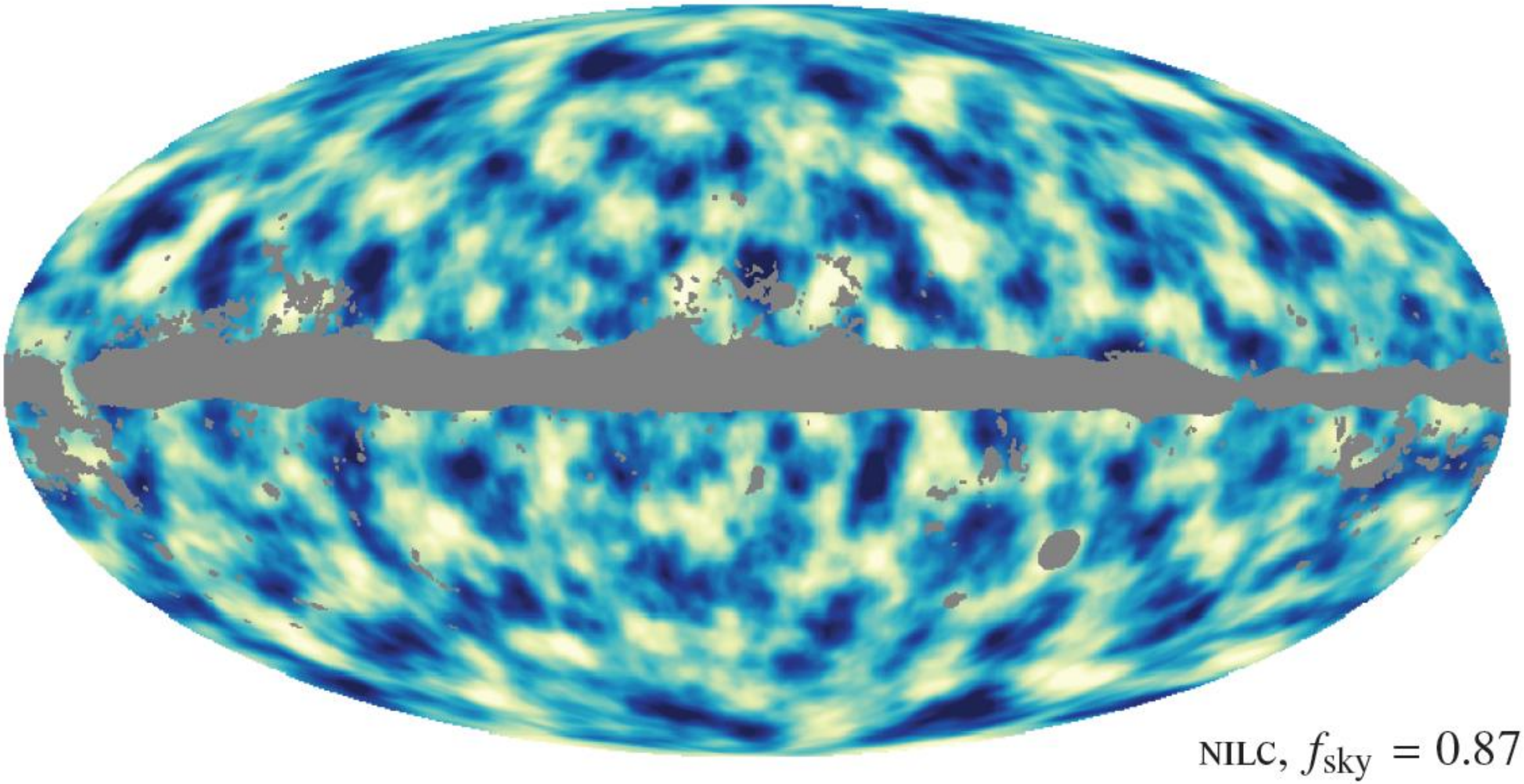




Concept: measure magnification and shear as function of position on sky

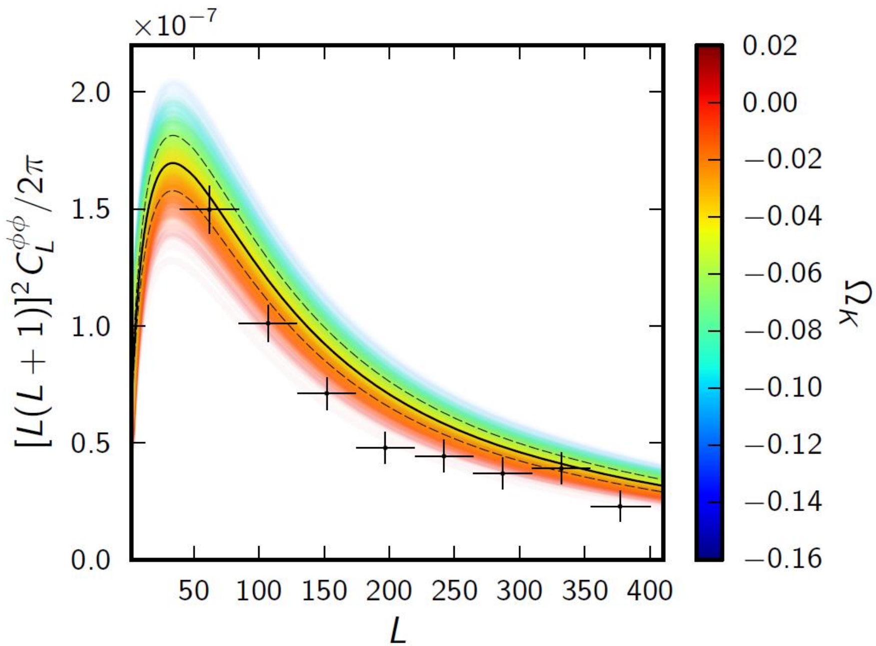
→ measure $\kappa(\hat{\boldsymbol{n}})$

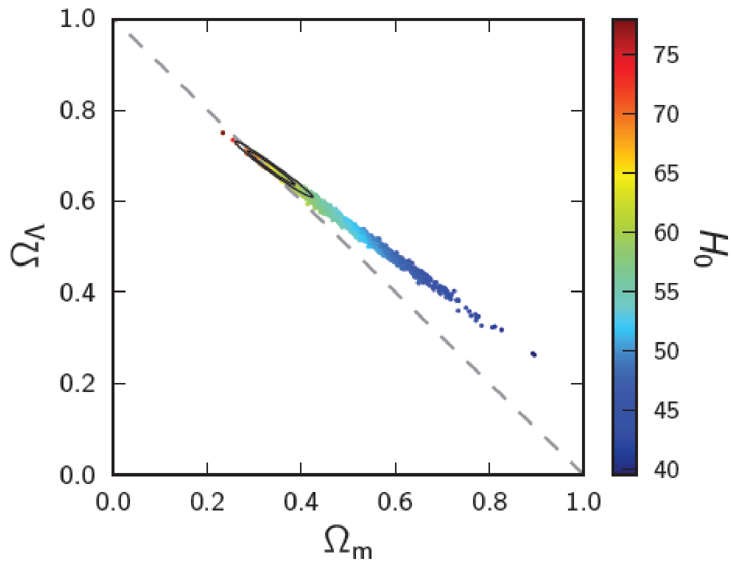
Planck lensing potential reconstruction (north and south galactic)

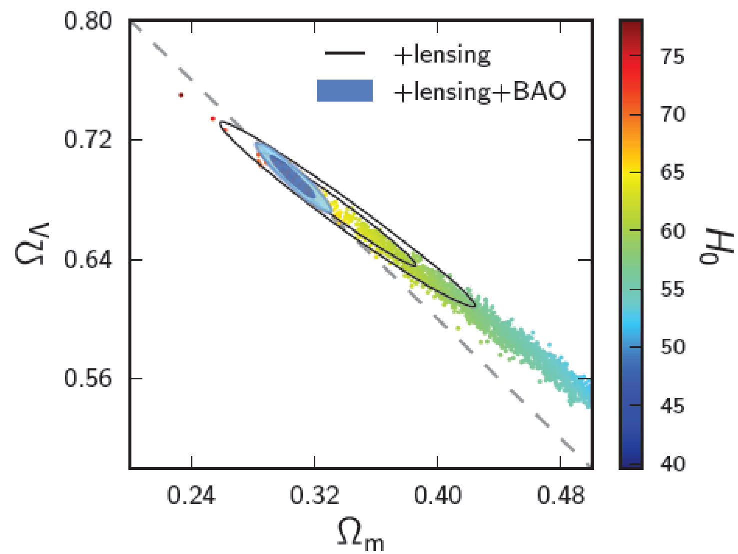


Note – about half signal, half noise, not all structures are real
map is effectively Wiener filtered

Planck lensing power spectrum







External data used for joint constraints

- WMAP polarization ("WP") on large scales – constrains optical depth τ
- High-L data from other CMB (ACT/SPT; "highL")
  - useful for constraining foreground model
- BAO: baryon oscillations – measures the comoving acoustic oscillation scale in distribution of galaxies (z~0.6; scale is bump in correlation function)
  - very consistent with Planck for LCDM model
- H_0: local measurements of Hubble parameter (Riess et al)
  - significantly higher H_0 than favoured by Planck
- Supernovae: marginally consistent with Planck

Neutrino physics with Planck

(using GR to measure neutrino densities)

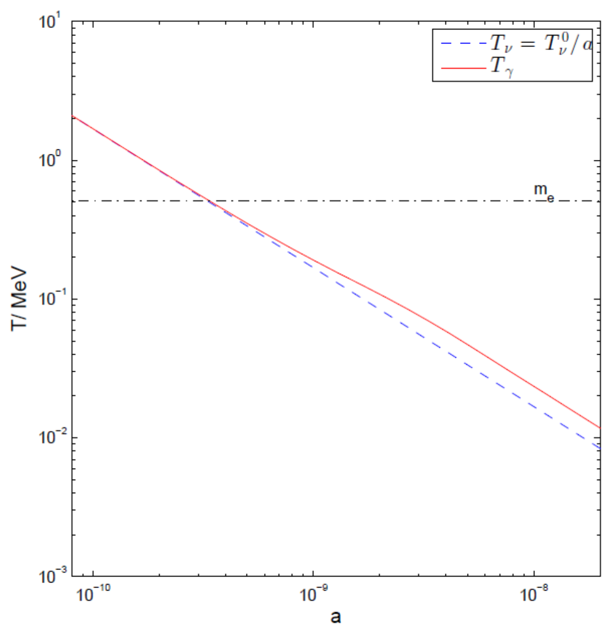
Friedmann Equation:

$$H^2 = \frac{8\pi G}{3}\rho = \frac{8\pi G}{3}(\rho_\gamma + \rho_\nu + \rho_m + \rho_{DE})$$

- Expansion history sensitive to total neutrino energy density

Standard scenario:

- 3 neutrinos, coupled to photons, e^+/e^- until $T \sim 1$MeV
- at $T \sim 0.5$ MeV electrons and positrons annihilate, heating photons



Thermal equilibrium before + entropy conservation ⇒

$$T_\gamma = \left(\frac{11}{4}\right)^{\frac{1}{3}} T_\nu$$

at late times. Both remain thermal distributions.

We measure $T_{CMB}^0 = T_\gamma^0 = 2.726K$. So know $T_\nu^0 \sim 1.92K$

In general define N_{eff} to determine neutrino density

$$\rho_\nu = N_{\text{eff}} \frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \rho_\gamma$$

- 3 neutrinos with annihilation well after decoupling $\Rightarrow N_{\text{eff}} = 3$
- 3 neutrinos with slight neutrino heating $\Rightarrow N_{\text{eff}} = 3.046$ (Mangano et al)
- Extra or sterile thermal neutrinos at same temperature $N_{\text{eff}} = 3.046 + \Delta N$
- Extra neutrinos that are non-thermal or at different temperature gives non-integer change to N_{eff}

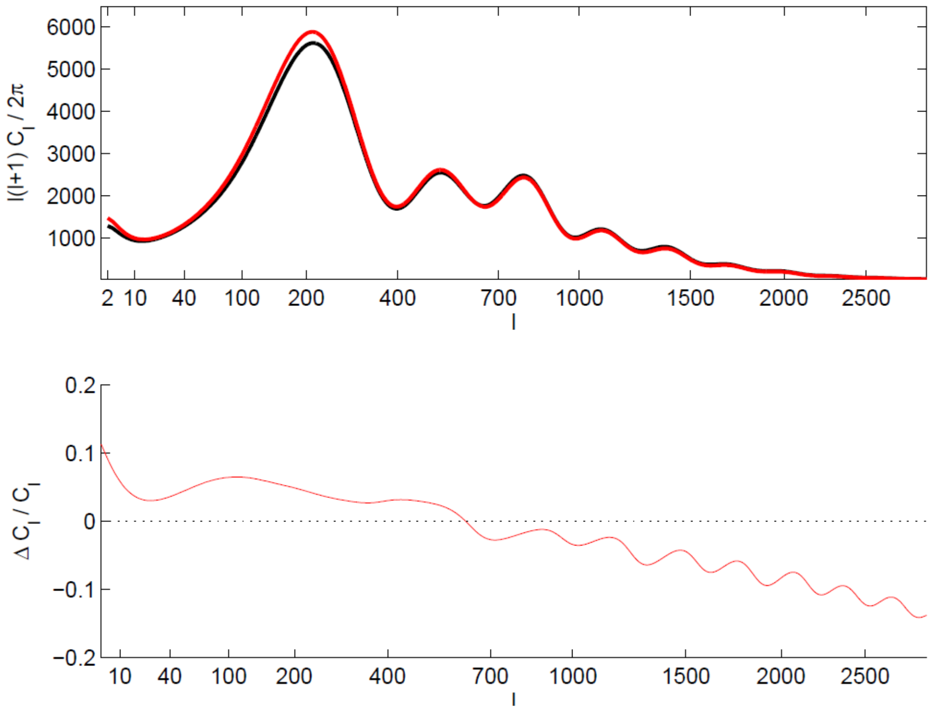
Cosmology of massless neutrinos only sensitive to total N_{eff}
- does not depend on distribution (could be any relativistic decoupled particles)

Neutrino impact on the CMB

- H(z) via ρ_ν : change to distances and perturbation growth rates

- Neutrino free streaming – damping of small-scale perturbations

Note both effects also depend on what other components of the model are doing
- constraints are generally model dependent



$N_{eff} = 3$ *vs.* $N_{eff} = 4$ (fixing θ_*)

- Measured by amount of small-scale Damping

(first peak right after adjusting $\Omega_c h^2$ but also degenerate with n_s)

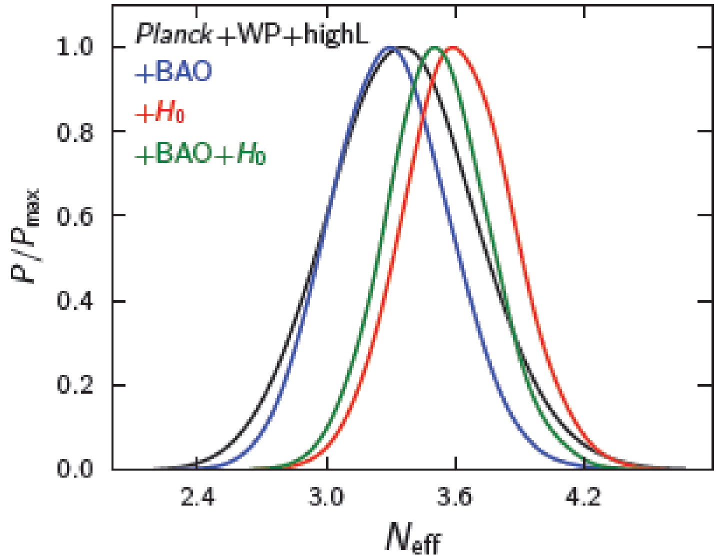
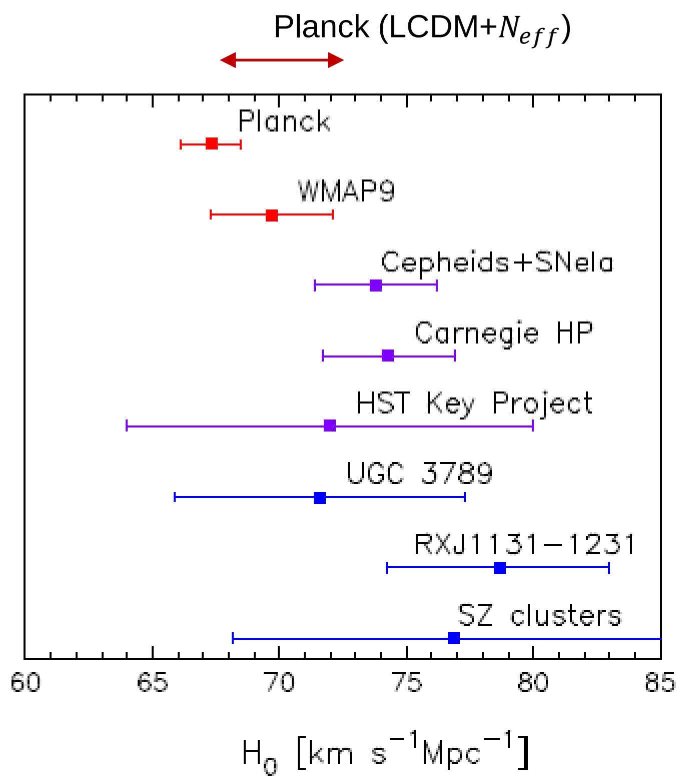


Fig. 27. Marginalized posterior distribution of N_{eff} for *Planck*+WP+highL (black) and additionally BAO (blue), the H_0 measurement (red), and both BAO and H_0 (green).

Planck+WP+highL+BAO

$N_{eff} < 4$ at 99% confidence



$Note$: H_0 'discrepancy' with Planck in LCDM more consistent if $N_{eff} > 3$

(note: other data points are moving)

Neutrino mass

Massless neutrinos contribute $\Omega_\nu \sim 10^{-5}$ today: negligible today

But large number density. If massive $\rho_\nu = n_\nu m_\nu$. With $N_{\rm eff} = 3.046$

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93.04\ \mathrm{eV}}$$

High-redshift ⇒ $T \gg m_\nu$: behave like massless neutrinos
Low-redshift ⇒ $T \ll m_\nu$: behave like cold dark matter

⇒ Linear CMB anisotropies cannot constrain $m_\nu \ll T_* \sim 1\mathrm{eV}$ (recombination temperature)

- behave just like massless neutrinos until recombination
- do change H(z) at late times, but completely degenerate with e.g. $\mathrm{H}_0, \Omega_\Lambda$

BUT: lensing *is* sensitive to lighter neutrinos, and other data (BAO) can break degeneracy

Approximate as three degenerate masses, parameterized by $\sum m_\nu$

One-parameter extensions to LCDM model, constraints from *Planck* TT

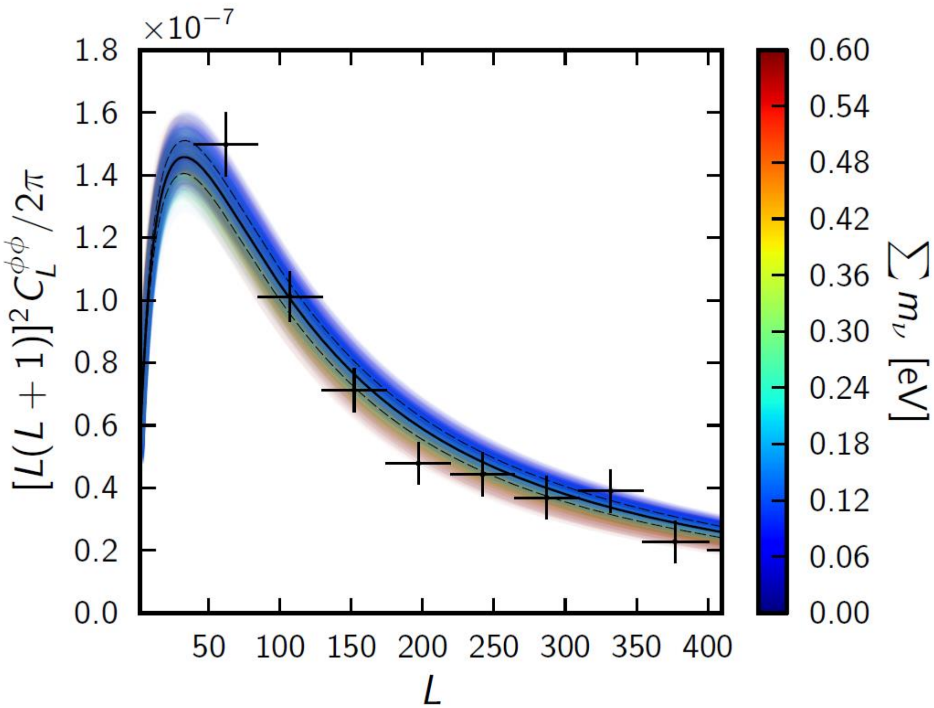
	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
$N_{\rm eff}$	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
$Y_{\rm P}$	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_s/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

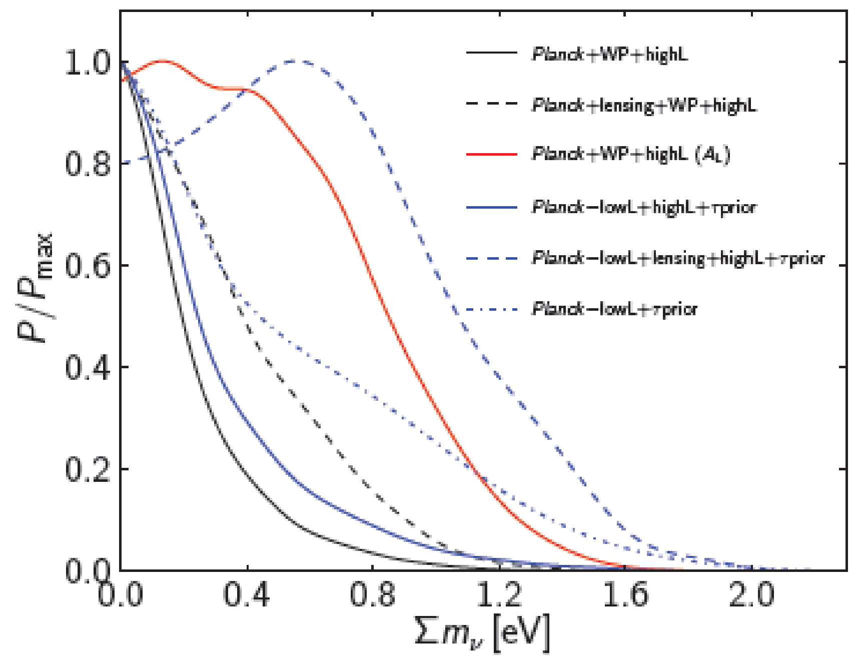
Table 10. Constraints on one-parameter extensions to the base ΛCDM model. Data combinations all include *Planck* combined with *WMAP* polarization, and results are shown for combinations with high-ℓ CMB data and BAO. Note that we quote 95% limits here.

No evidence for $m_\nu > 0$, or $N_{\rm eff}$ > 3.046 from *Planck*+BAO

But things to note:

Lensing spectrum fairly consistent with higher neutrino masses





Planck+lensing constraint is actually *worse* than Planck alone

TT spectrum favours strong lensing ⇒ disfavours $m_\nu > 0$ more than you'd expect

SZ and galaxy clusters (Paper XX)

- Number of clusters depends on matter perturbation amplitude σ_8
- Clusters contain hot gas: up-scatter CMB photon temperature
- See clusters in SZ, amount of signal depends on amount of gas and temperature
- Astrophysical modelling ⇒ relation between temperature and mass
- Measure N(m)
- Compare with prediction from cosmological model.

SZ prefers lower σ_8 than Planck TT

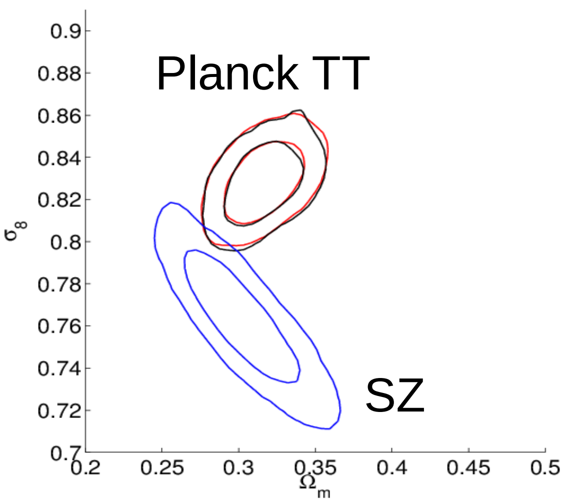
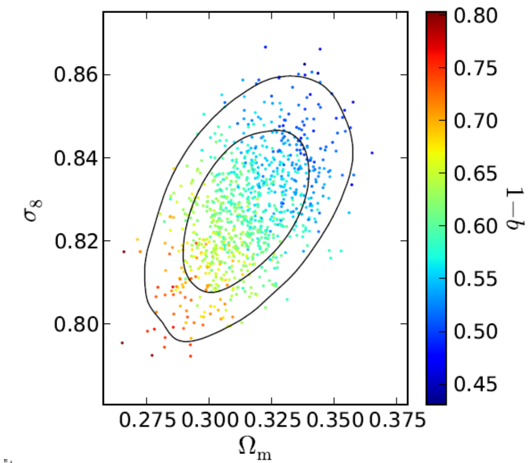


Fig. 11. 2D Ω_m–σ_8 likelihood contours for the analysis witn *Planck* CMB only (red); *Planck* SZ + BAO + BBN (blue); and the combined *Planck* CMB + SZ analysis where the bias $(1 - b)$ is a free parameter (black).

Planck TT+SZ



Evidence for neutrino mass??

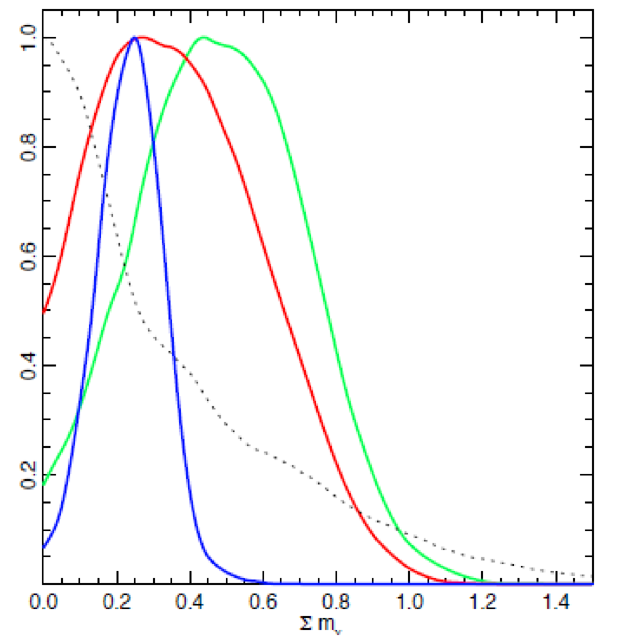


Fig. 12. Cosmological constraints when including neutrino masses $\sum m_\nu$ from: *Planck* CMB data alone (black dotted line); *Planck* CMB + SZ with $1 - b$ in [0.7, 1] (red); *Planck* CMB + SZ + BAO with $1 - b$ in [0.7, 1] (blue); and *Planck* CMB + SZ with $1 - b = 0.8$ (green).

(note: this is assuming one massive neutrino)

Or something wrong with astrophysical model and/or selection function, e.g. low 1-b

Beyond Gaussianity – general possibilities

Flat sky approximation: $\Theta(x) = \frac{1}{2\pi}\int d^2l\,\Theta(l)e^{ix\cdot l}$ $(\Theta = T)$

Gaussian + statistical isotropy

$$\langle\Theta(l_1)\Theta(l_2)\rangle = \delta(l_1 + l_2)C_l$$

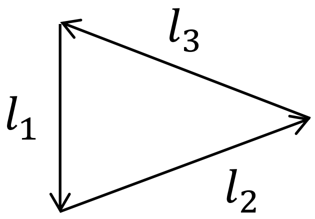
- power spectrum encodes all the information
- modes with different wavenumber are independent

Higher-point correlations

Gaussian: can be written in terms of C_l

Non-Gaussian: non-zero connected n-point functions

Bispectrum



$$\boldsymbol{l_1} + \boldsymbol{l_2} + \boldsymbol{l_3} = \boldsymbol{0}$$

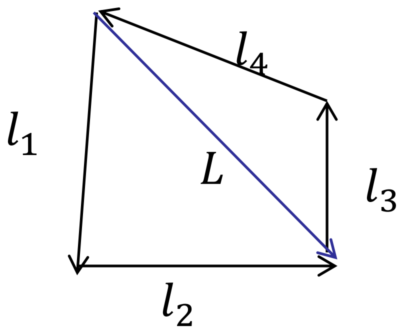
Flat sky approximation: $\langle \Theta(l_1)\Theta(l_2)\Theta(l_3)\rangle = \dfrac{1}{2\pi}\delta(l_1 + l_2 + l_3) b_{l_1 l_2 l_3}$

If you know $\Theta(l_1), \Theta(l_2)$, sign of $b_{l_1 l_2 l_3}$tells you which sign of $\Theta(l_3)$ is more likely

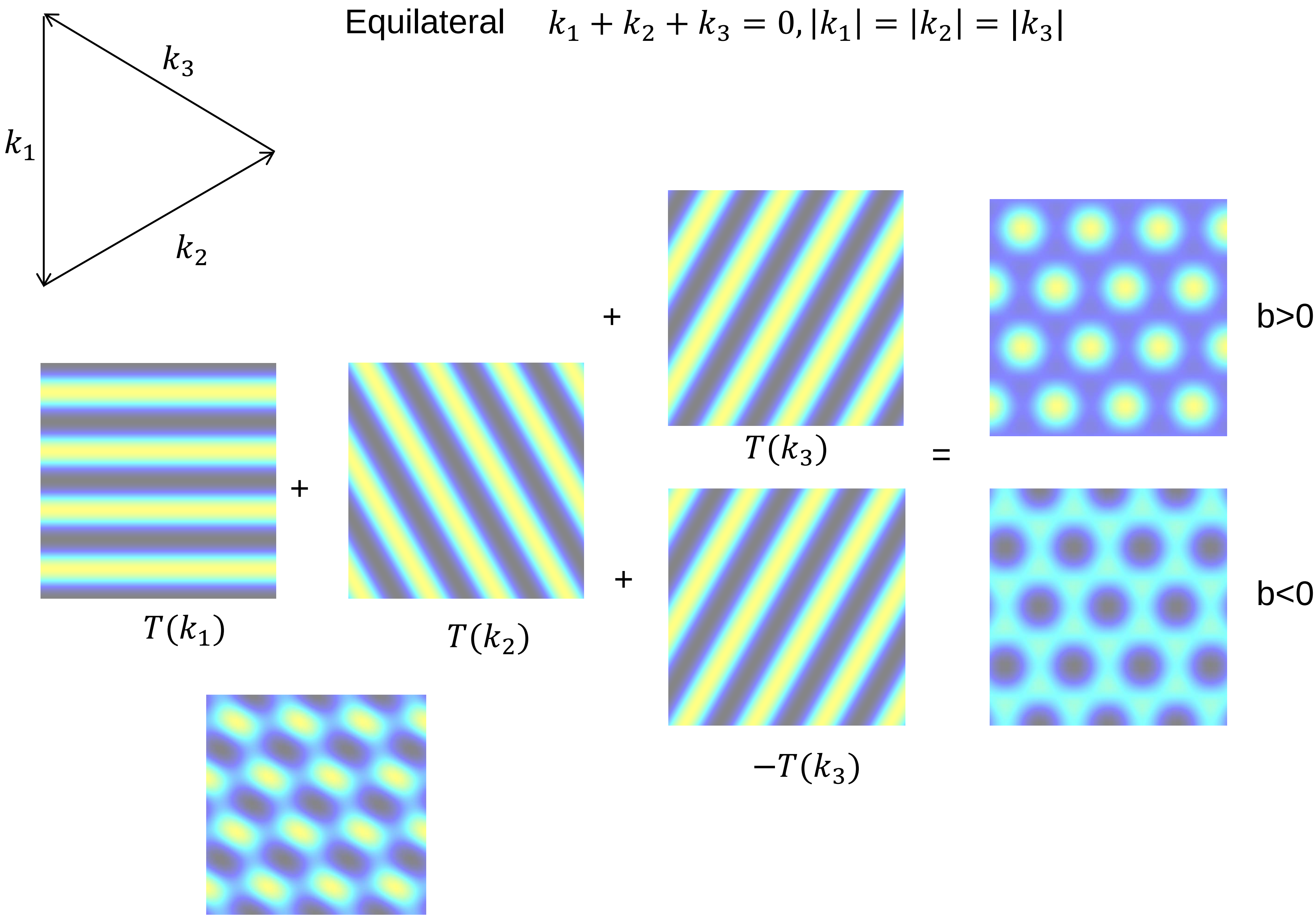
Trispectrum

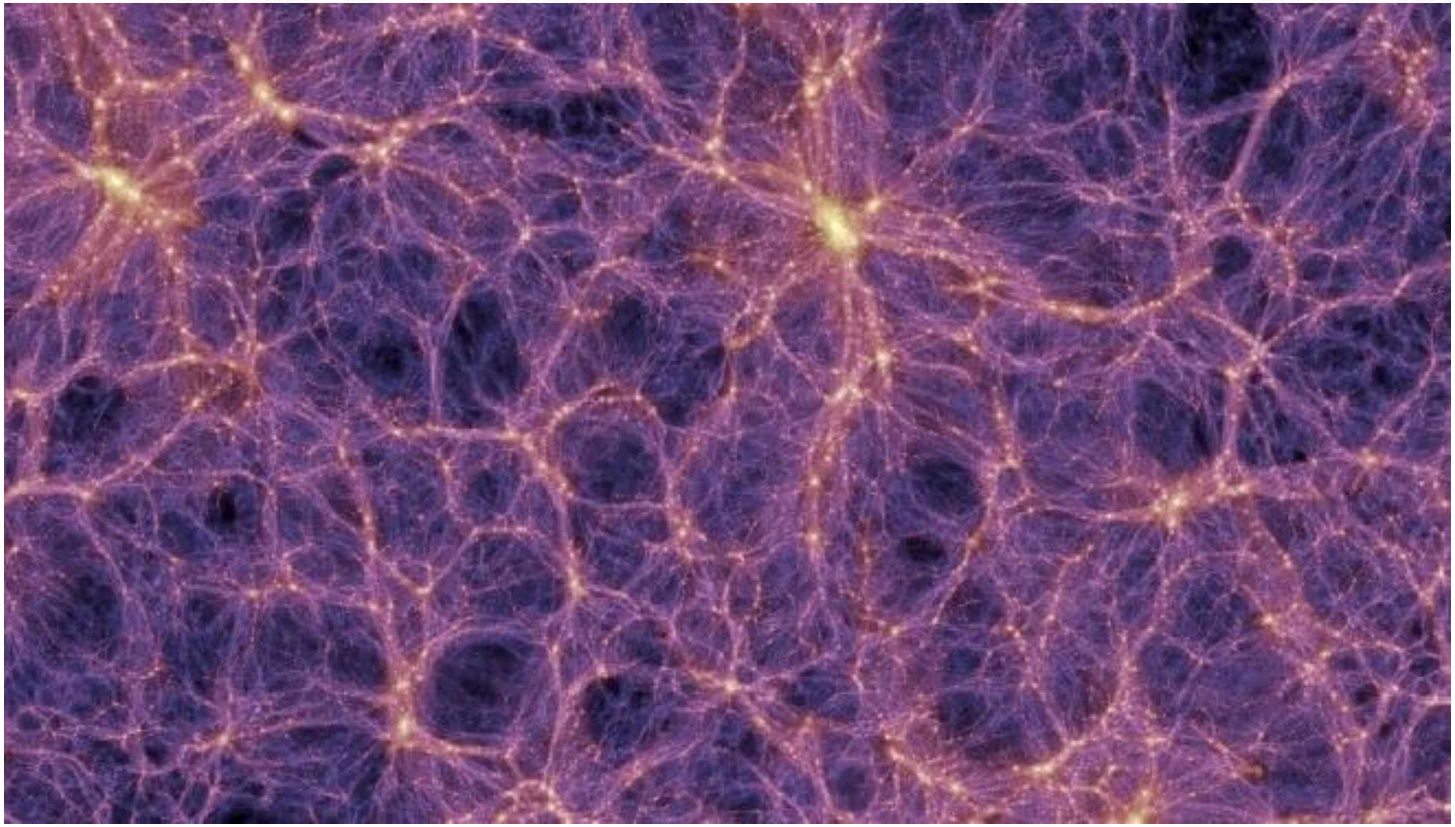
$$\langle \Theta(\mathbf{l}_1)\Theta(\mathbf{l}_2)\Theta(\mathbf{l}_3)\Theta(\mathbf{l}_4)\rangle_C = (2\pi)^{-2}\delta(\mathbf{l}_1 + \mathbf{l}_2 + \mathbf{l}_3 + \mathbf{l}_4) T(\mathbf{l}_1, \mathbf{l}_2, \mathbf{l}_3, \mathbf{l}_4)$$

$$\langle \Theta(\mathbf{l}_1)\Theta(\mathbf{l}_2)\Theta(\mathbf{l}_3)\Theta(\mathbf{l}_4)\rangle_C = \frac{1}{2}\int \frac{d^2\mathbf{L}}{(2\pi)^2}\delta(\mathbf{l}_1 + \mathbf{l}_2 + \mathbf{L})\delta(\mathbf{l}_3 + \mathbf{l}_4 - \mathbf{L})\mathbb{T}^{(\ell_1\ell_2)}_{(\ell_3\ell_4)}(L) + \text{perms.}$$



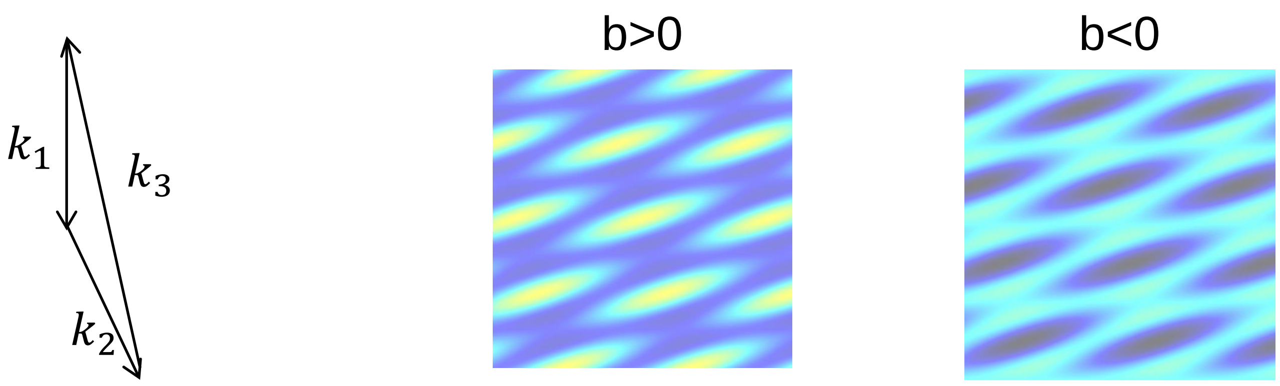
N-spectra…


Equilateral $k_1 + k_2 + k_3 = 0, |k_1| = |k_2| = |k_3|$
k_3
k_1
k_2
+
b>0
+
$T(k_3)$
=
$T(k_1)$
$T(k_2)$
+
b<0
$-T(k_3)$

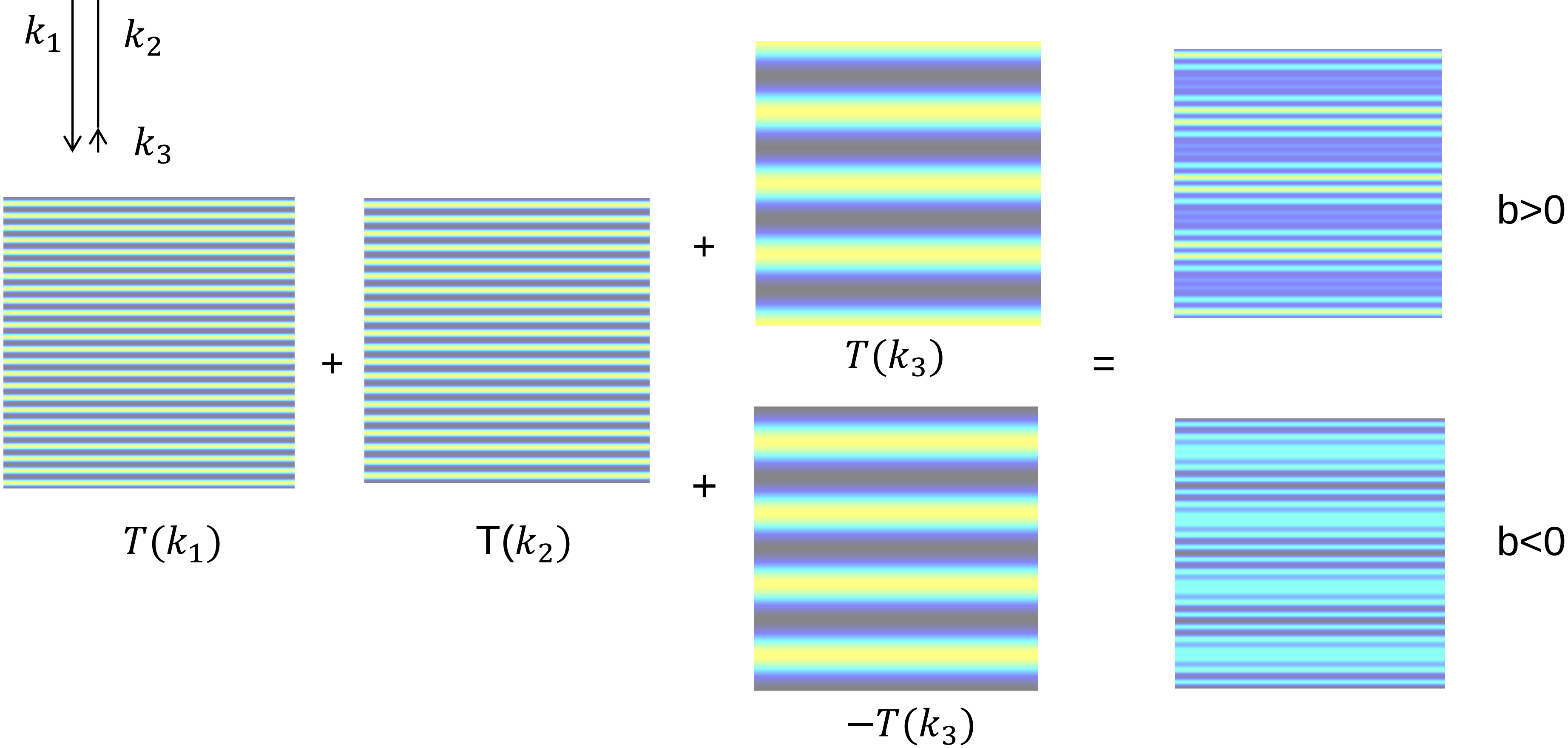


Millennium simulation

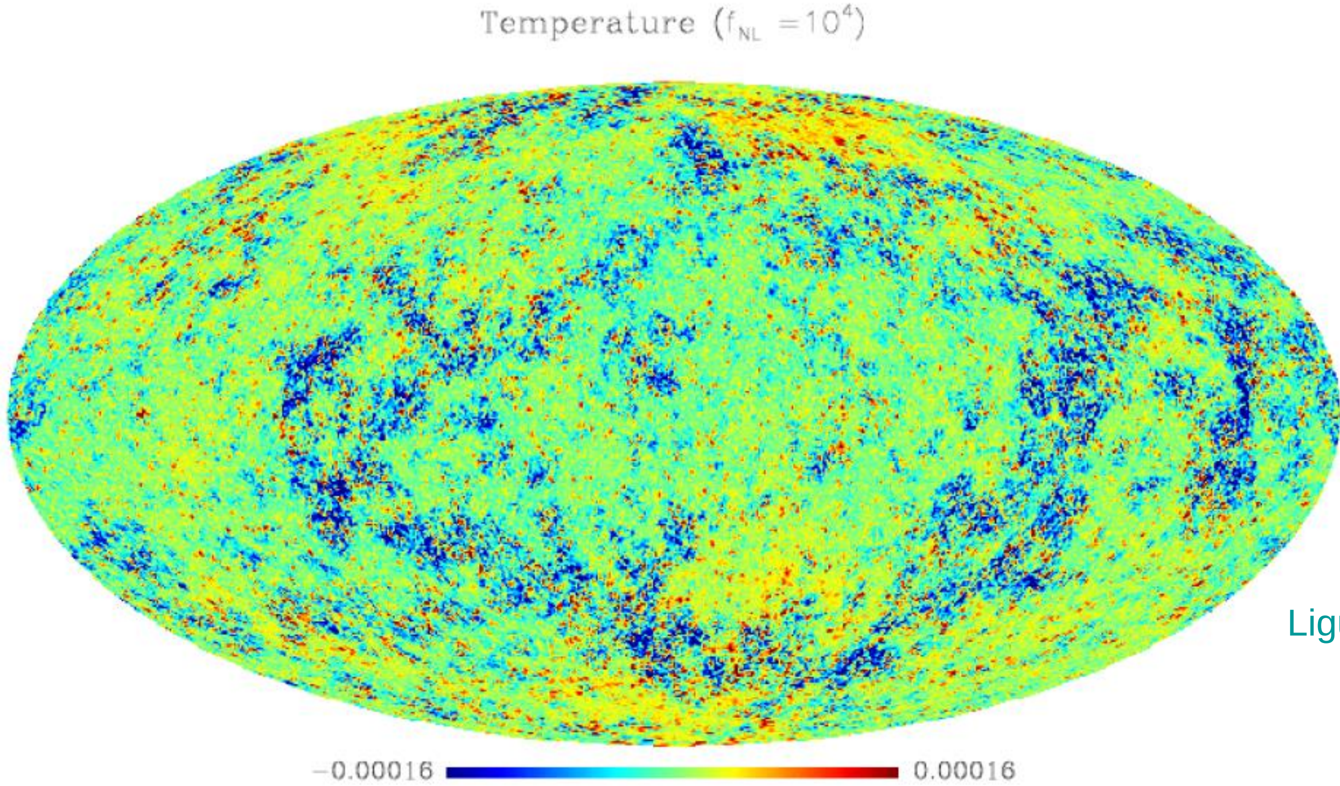
Near-equilateral to flattened:



Local (squeezed) $k_1 + k_2 + k_3 = 0, \quad k_1 \ll k_2, k_3 \quad k_2 \sim -k_3$



Squeezed bispectrum is a *correlation* of small-scale power with large-scale modes e.g. $\chi = \chi_0(1 + f_{NL}\chi_0)$



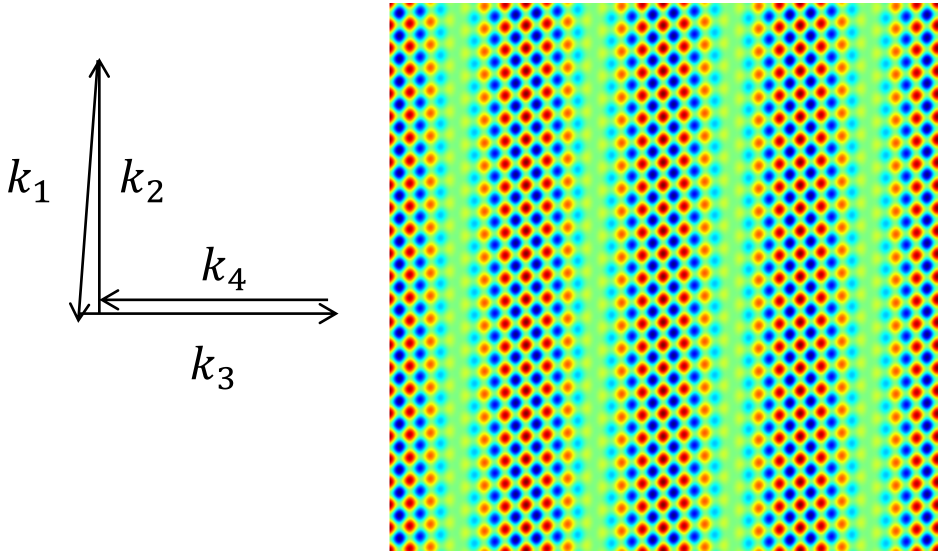
Liguori et al 2007

Planck only sees expected lensing-induced modulations
- no evidence for primordial non-Gaussianities

Table 8. Results for the $f_{\rm NL}$ parameters of the primordial local, equilateral, and orthogonal shapes, determined by the KSW estimator from the SMICA foreground-cleaned map. Both independent single-shape results and results marginalized over the point source bispectrum and with the ISW-lensing bias subtracted are reported; error bars are 68% CL.

	Independent KSW	ISW-lensing subtracted KSW
SMICA		
Local	9.8 ± 5.8	$\mathbf{2.7 \pm 5.8}$
Equilateral	-37 ± 75	$\mathbf{-42 \pm 75}$
Orthogonal	-46 ± 39	$\mathbf{-25 \pm 39}$

Diagonal squeezed trispectra $|k_1| \sim |k_2|, |k_3| \sim |k_4|, |k_1 + k_2| = |k_3 + k_4| \ll |k_2|, |k_3|$



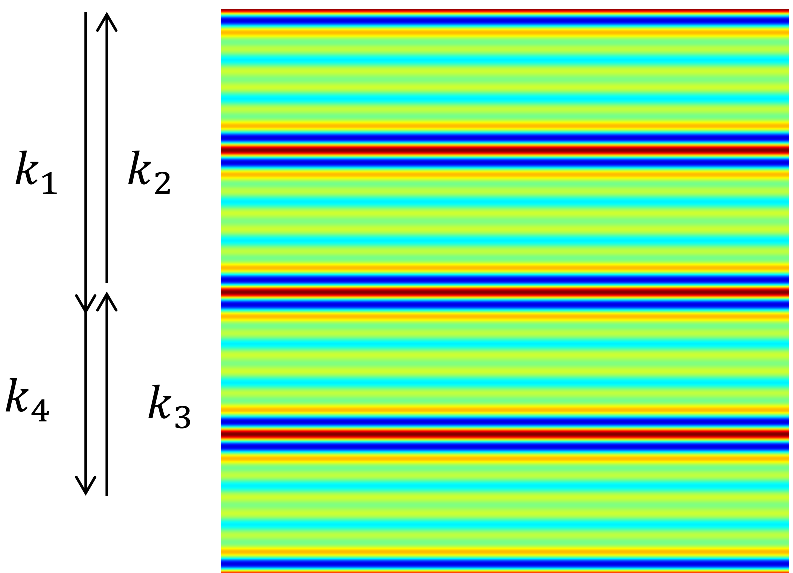
Trispectrum = power spectrum of modulation

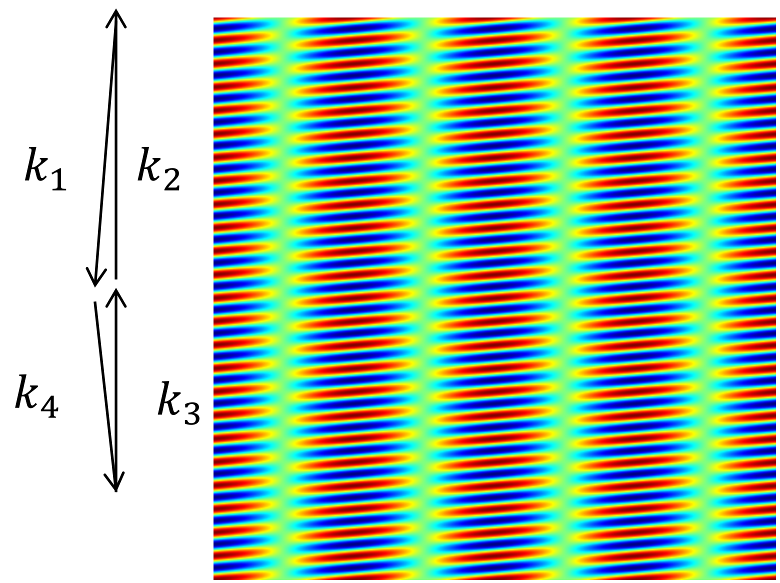
e.g. $\chi = \chi_0(1 + f_{NL}\chi_0\ )$

$\tau_{NL} \sim f_{NL}^2$

or $\chi = \chi_0(1 + \phi)$

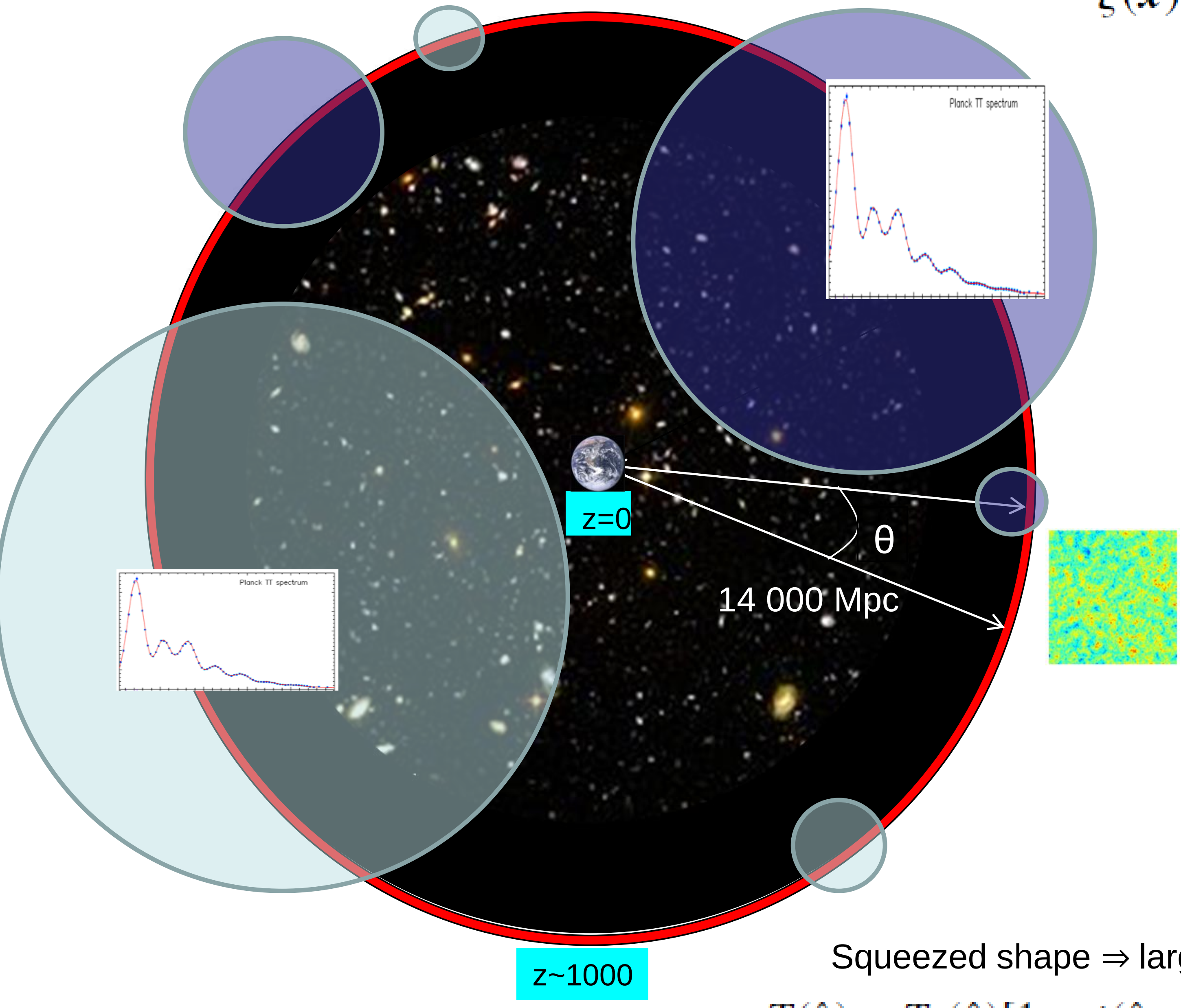
(any correlation, $\tau_{NL} > f_{NL}^2$)





Primordial curvature modulation:

$$\zeta(\boldsymbol{x}) = \zeta_0(\boldsymbol{x})[1 + \phi(\boldsymbol{x})]$$



Squeezed shape ⇒ large-scale modulation

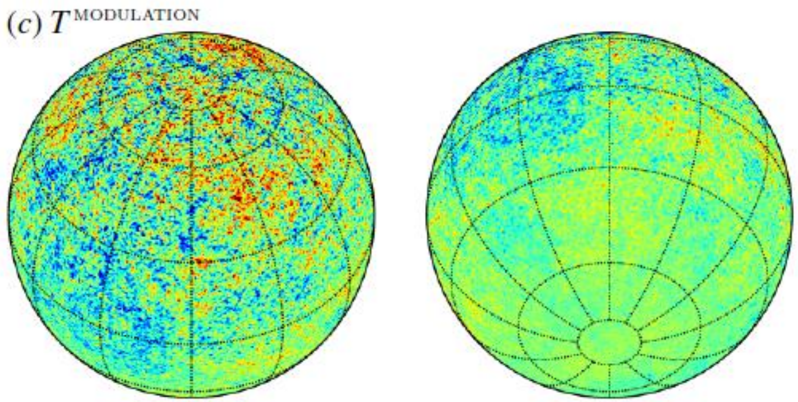
$$T(\hat{\boldsymbol{n}}) \approx T_{\rm g}(\hat{\boldsymbol{n}})[1 + \phi(\hat{\boldsymbol{n}}, r_*)] \equiv T_{\rm g}(\hat{\boldsymbol{n}})[1 + f(\hat{\boldsymbol{n}})]$$

Complication: Kinematic dipole signal

Modulation

$$\Delta\Theta(\hat{\boldsymbol{n}}) \to \left[1 + \hat{\boldsymbol{n}}\cdot\boldsymbol{v} + T\frac{\mathrm{d}^2 I_\nu/\mathrm{d}T^2}{\mathrm{d}I_\nu/\mathrm{d}T}\hat{\boldsymbol{n}}\cdot\boldsymbol{v}\right]\Delta\Theta(\hat{\boldsymbol{n}})$$
$$= (1 + [x\coth(x/2) - 1]\,\hat{\boldsymbol{n}}\cdot\boldsymbol{v})\,\Delta\Theta(\hat{\boldsymbol{n}}),$$

$$x \equiv h\nu/k_b T$$

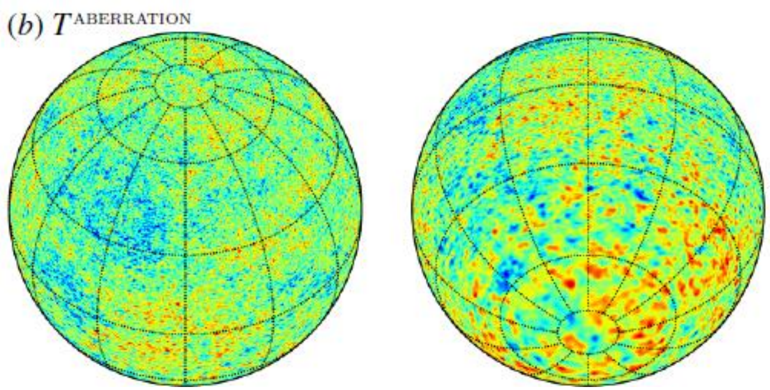


Illustrated for $\frac{v}{c} = 0.85$

Aberration

$$\hat{\boldsymbol{n}} \to \hat{\boldsymbol{n}} \quad + \nabla(\hat{\boldsymbol{n}}\cdot\boldsymbol{v})$$

- just like a dipole lensing convergence



Challinor & van Leeuwen 2002

Subtract aberration effect ⇒

Local trispectrum often measured by

$$\hat{\tau}_{\rm NL} \approx N^{-1} \sum_{L=L_{\rm min}}^{L_{\rm max}} \frac{2L+1}{L^2(L+1)^2} \frac{\hat{C}_L^f}{C_L^{\zeta_\star}}$$

modulation power

(optimal to percent level)

Conventional normalization to primordial power

Planck τ_{NL} trispectrum constraint

Estimator result $\hat{\tau}_{\rm NL} = 442$,

Gaussian simulations:

$$-452 < \hat{\tau}_{\rm NL} < 835 \text{ at } 95\% \text{ CL } (\sigma_{\tau_{\rm NL}} \approx 335)$$

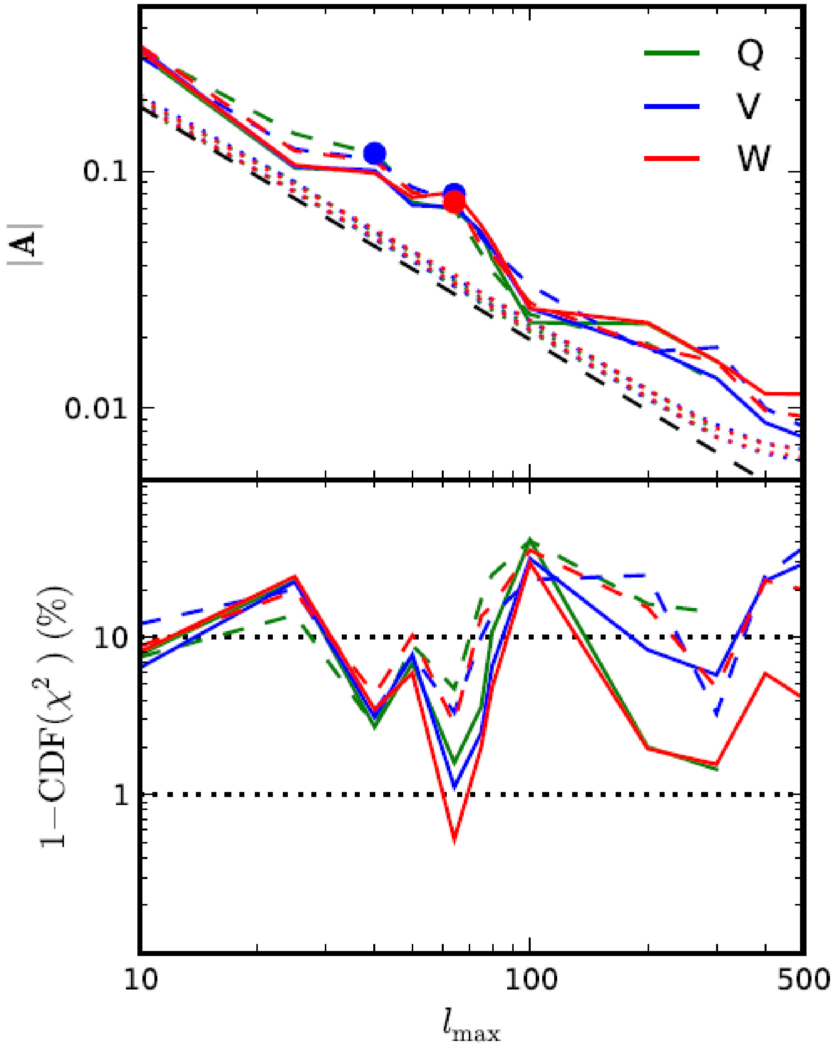
Consistent with Gaussian null hypothesis (octopole has small weight)

Conservative upper limit, allowing octopole to be physical using Bayesian posterior

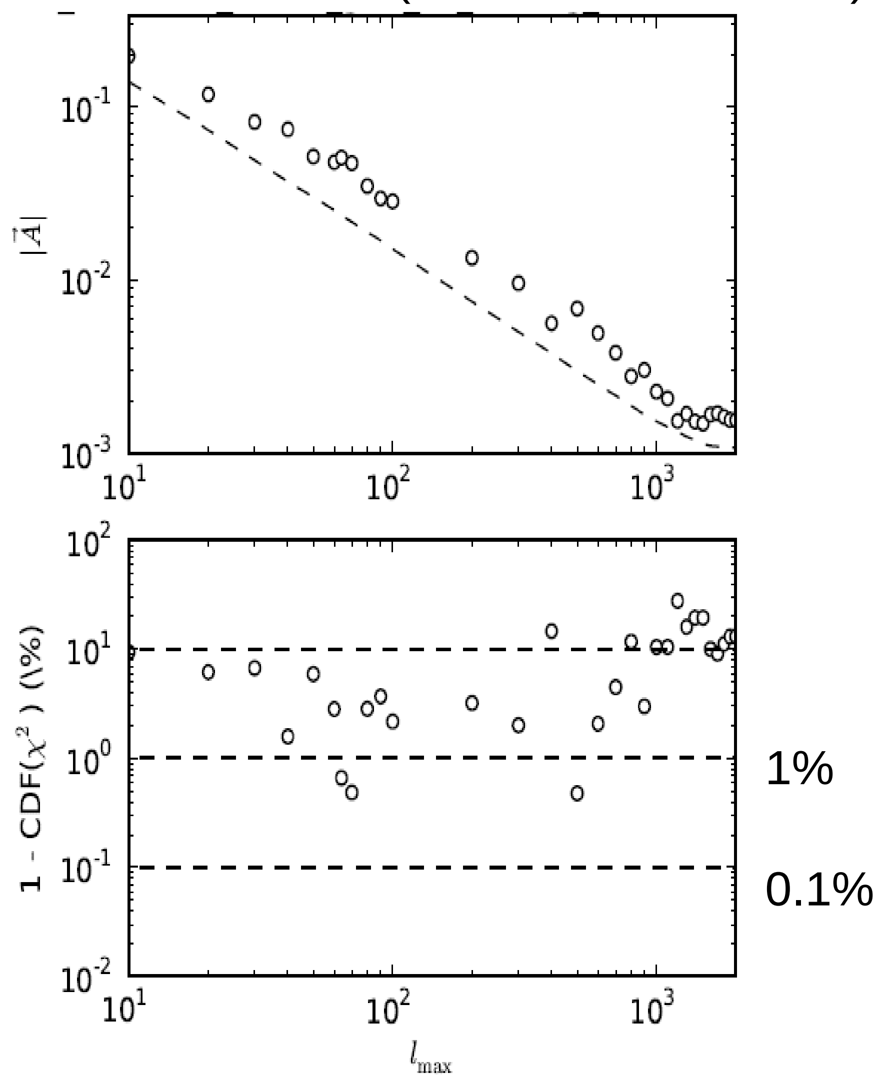
$$\tau_{\rm NL} < 2800 \text{ at } 95\% \text{ CL}$$

Power modulation dipole? Result for amplitude at $l \leq l_{\max}$

WMAP 5 (Hanson & Lewis 2009)



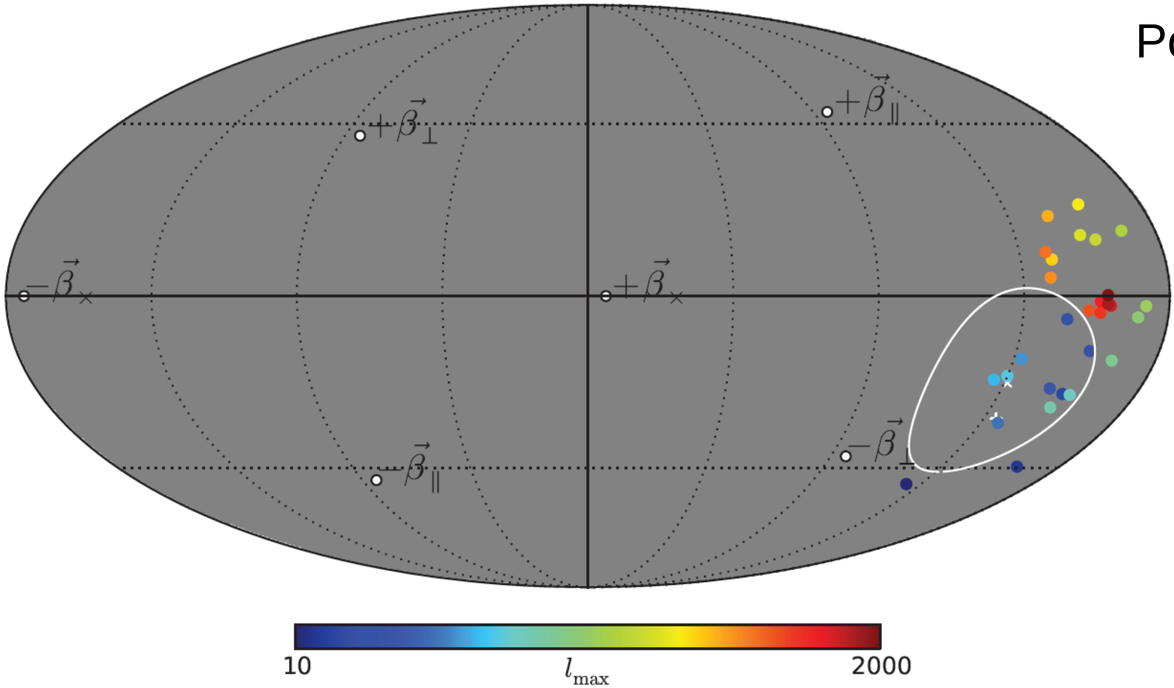
Planck 217x143 (kinematic subtracted)



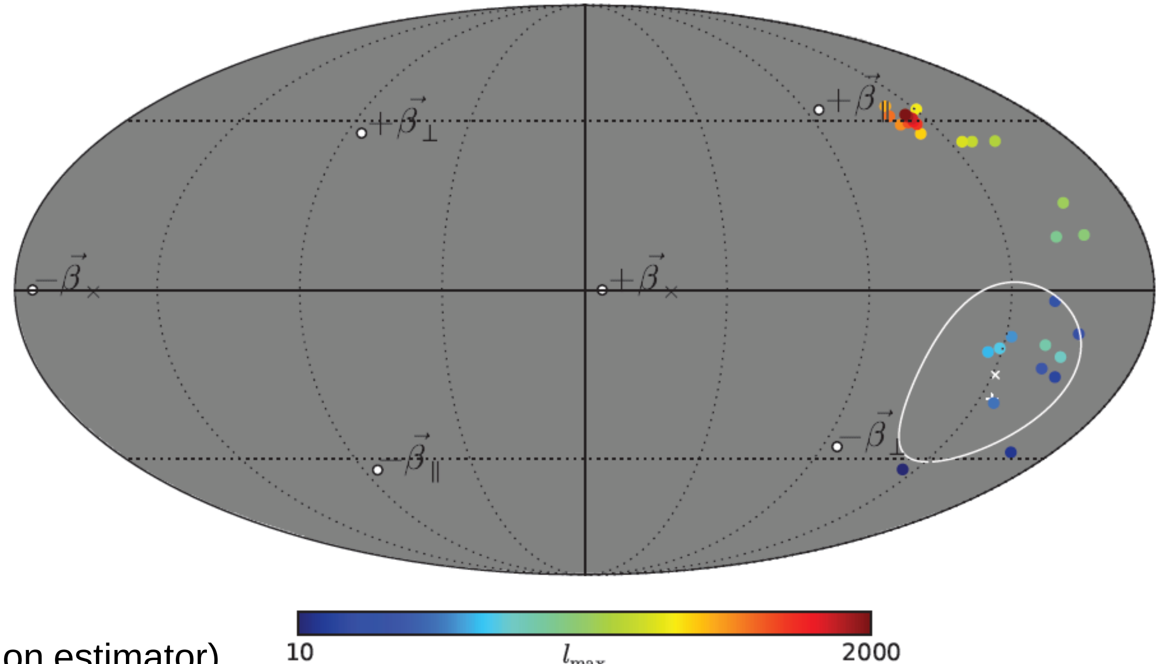
Modulation < 1% for $l \leq l_{\max} = 500$

Modulation < 0.2% for $l_{\max} = 1500 - 2000$

Power dipole directions ($l \leq l_{\max}$)



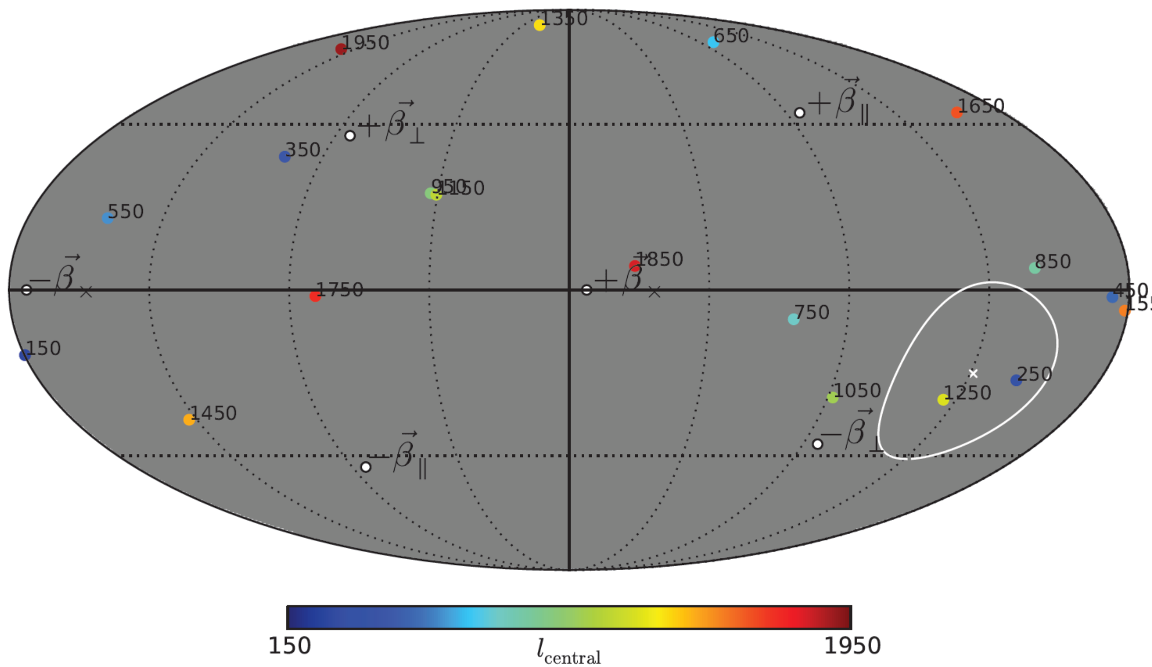
Kinematic subtracted



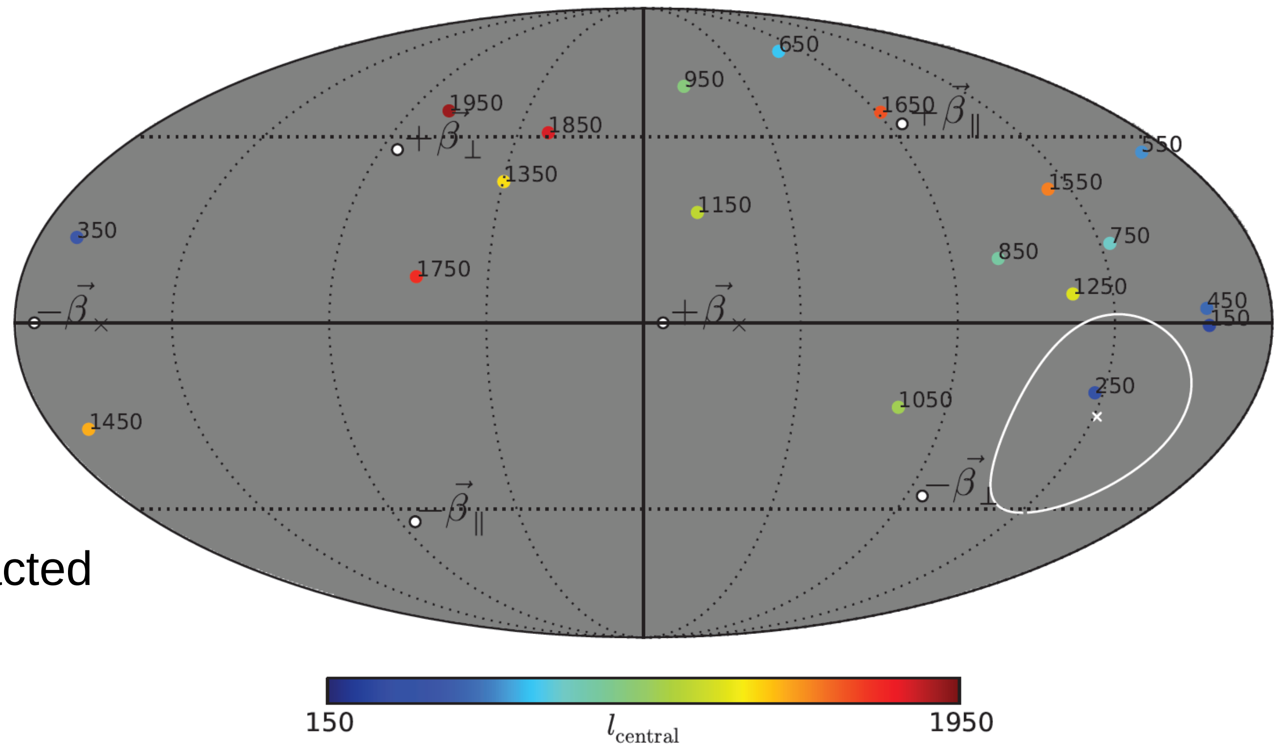
Kinematics not subtracted

(as in Doppler paper but here pure modulation estimator)

Power dipoles in $\Delta l = 100$ bands



Kinematic subtracted



Kinematics not subtracted

NG conclusions

- No evidence for primordial non-Gaussianity yet
- Dipole modulation signal clearly seen
- Large-scale modulation power “nearly” consistent with zero after kinematic subtraction going to high l
- Marginally anomalous but a posteriori power asymmetry at $l \leq 500$ (consistent with WMAP and previous analyses)
- Dipole power modulations at low L do not persist to high L after kinematic subtraction: $|f| < 0.2\%$ at $l_{\max} = 2000$.
  (but possible foreground issues, ongoing work..)

Planck parameters - conclusions

- Planck measures *combinations* of parameters to high precision

- Some individual parameter constraints model dependent, or require additional data

- CMB lensing just starting to be useful – much more to come
  (SPT, ACTpol, SPTpol, POLARBEAR…)

- First Planck TT power spectrum results gives no strong evidence for deviations from LCDM with standard 3.046 light neutrinos

- BUT, some interesting discrepancies.
  Astrophysics? Possible $m_\nu \sim 0.2\mathrm{eV}$? Modified gravity??
  - upcoming CMB lensing data will be very useful

-

- Next year: Planck polarization, +4 sky surveys of data
  (+ many analysis improvements)