The Cosmic Microwave Background : *Extracting Cosmological Information and other signals*

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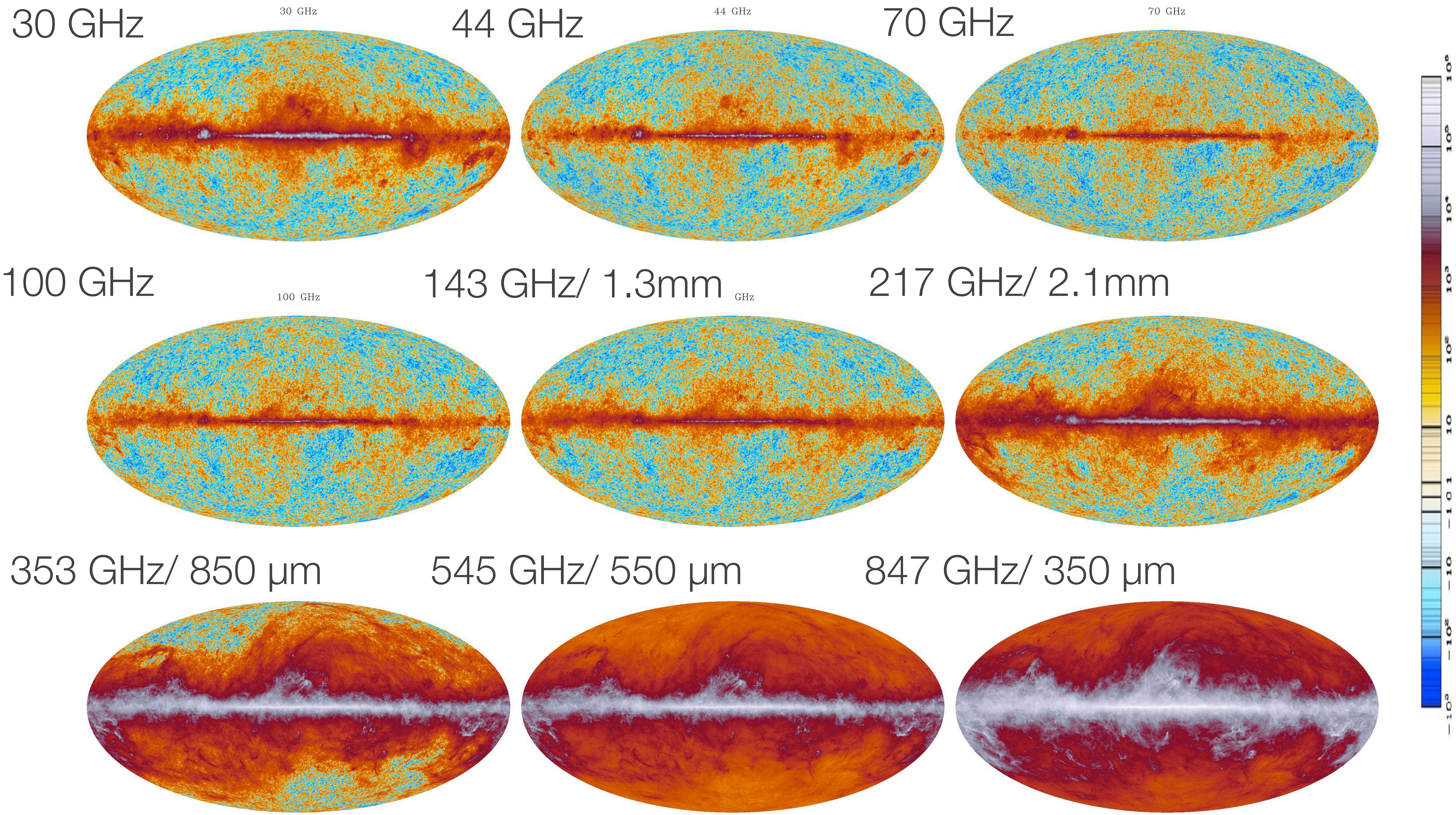
Outline

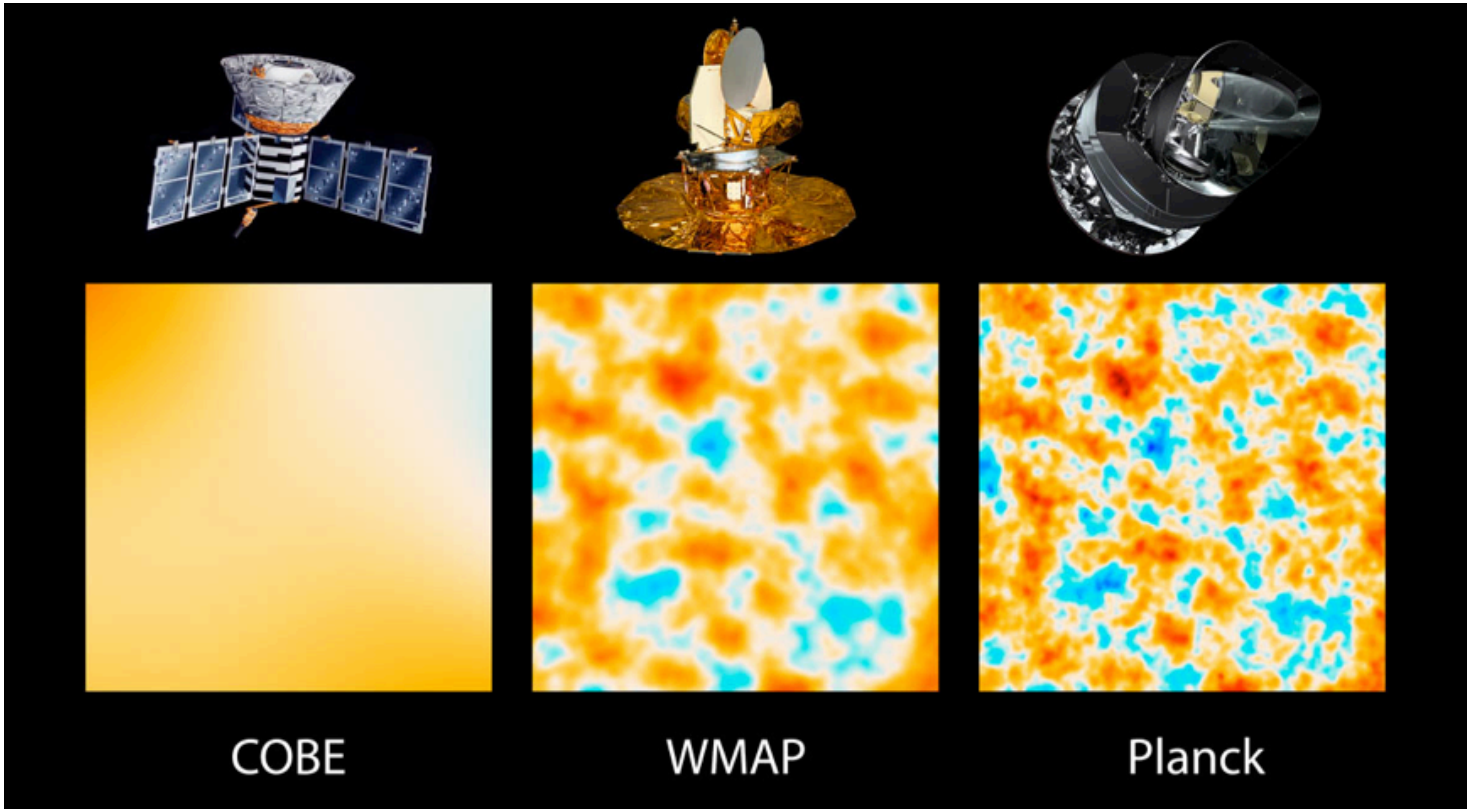
- Probing fundamental physics with current cosmological survey: the Planck example
  - ➡ Example of fundamental physical measurements performed by Planck.
- Planck and Inflation:
  - ➡ Constraining the *Initial Conditions*, and the physics of Inflation with Planck.
- Other interesting signals contained in the CMB:
  - ➡ The lensing of the CMB.
  - ➡ The cosmic infrared background.

What Planck Has Done for Astrophysics in 2013



- Noise properties on maps meet or exceed goals:
  - ➡ Precision on cosmological parameters is as per pre-flight “Blue Book” values.
- These temperature maps and many more (~200 maps) are available for download on ESA and NASA/IPAC websites.
- Lead to more than 30 published papers in 2013 (1000 pages of science!). Main cosmology paper has >1,500 citations.

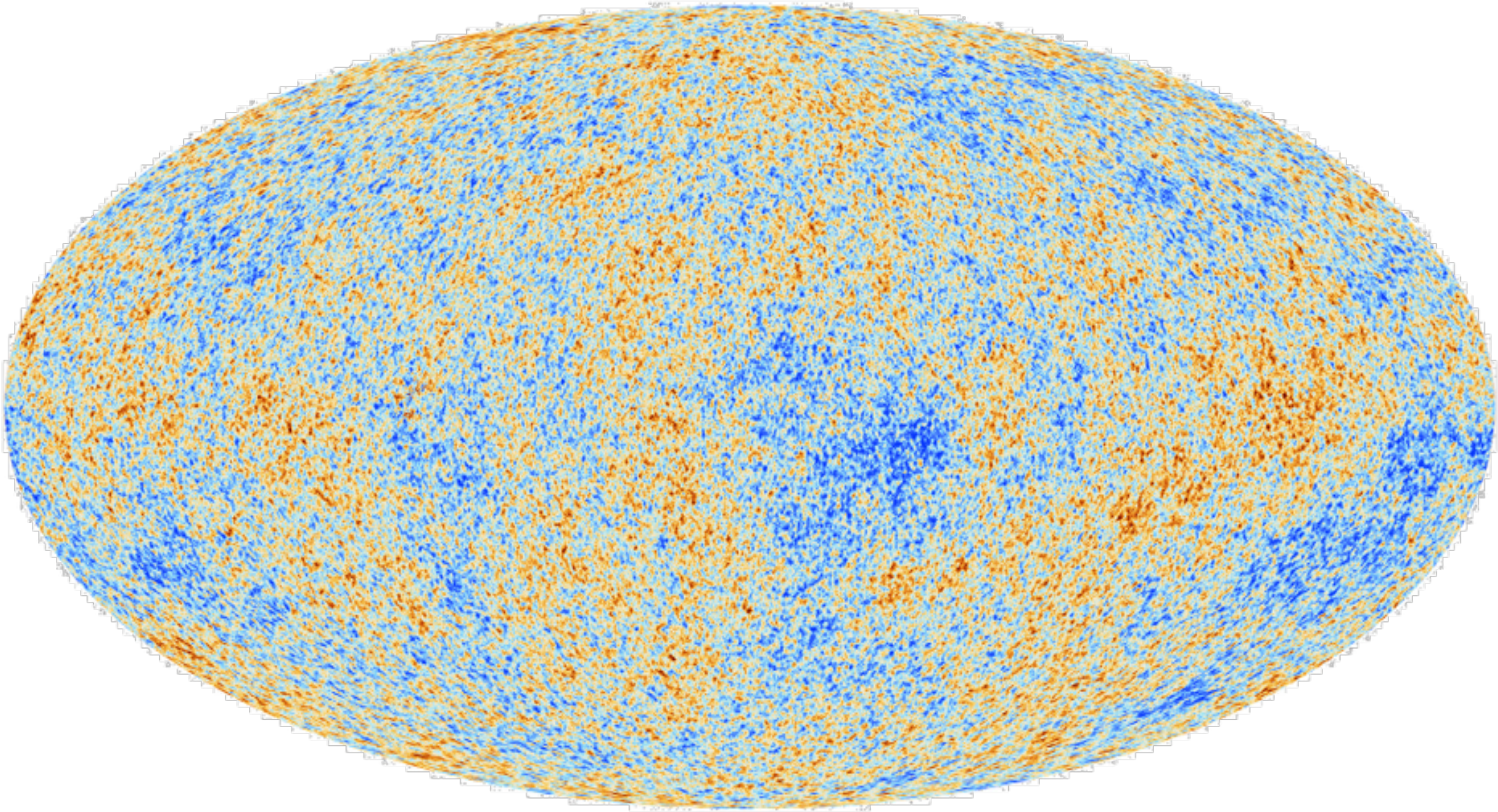
Planck, the 3d Generation CMB Satellite



- Planck aimed at being CMB photon noise limited after 1 year of observations:
  - ➡ Planck improves over WMAP by a factor 3 in angular resolution and 5 in instantaneous map sensitivity.
  - ➡ Control of foregrounds requires 9 frequencies between 30 GHz and 1 THz (7 polarized).

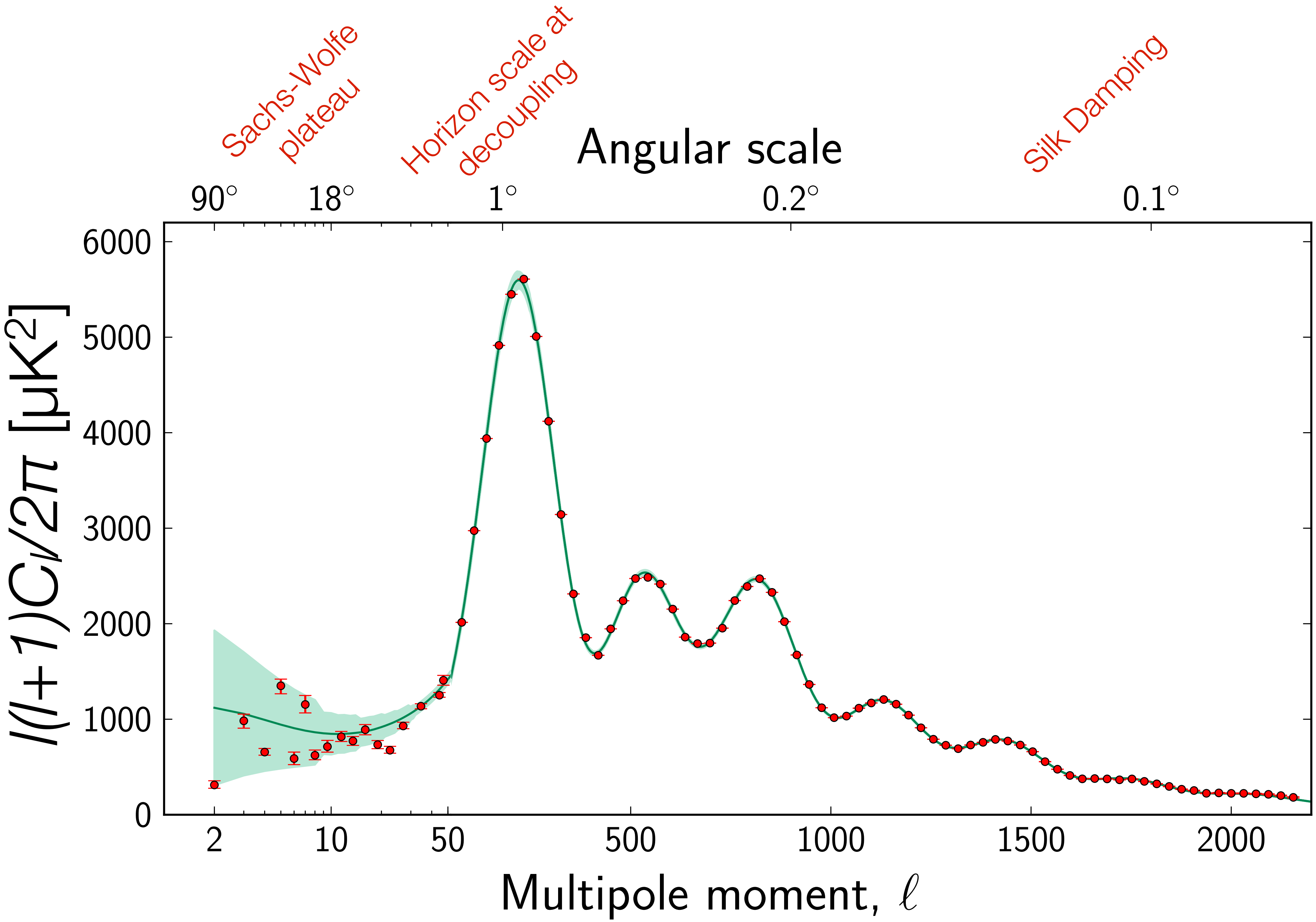
- To reach these goals required several technological breakthroughs in space:
  - ➡ Sensitive and fast bolometers, low noise read out, low and stable focal plane temperature (100 mK for HFI focal plane with < 20 nK.√Hz stability), low side lobes...

What Planck Has Done for Cosmology



- The analysis of this map allows us to address many questions (~30 papers so far):
  - ➡ Is flat ΛCDM still a good model?
  - ➡ What is the nature of Inflation? Did it happen?
  - ➡ Is Dark Energy constant?
  - ➡ What are the neutrino masses?
  - ➡ Are there extra relativistic species?
  - ➡ Are there other unexpected signatures?

Planck CMB Angular Temperature Power Spectra



- A triumph of modern physics:
  - ➡ A 6 parameter "standard" model (Ω_{cdm}, Ω_b, n_s, τ, A_s, Ω_{DE}) based on cosmological perturbation theory fits multiple data-sets across cosmic times.

Planck 2013 Results. XVI

Cosmological Constraints from Cosmological Survey

Initial conditions set by early universe model, e.g., Inflation (n_s, r, α_s, f_{NL},etc.)

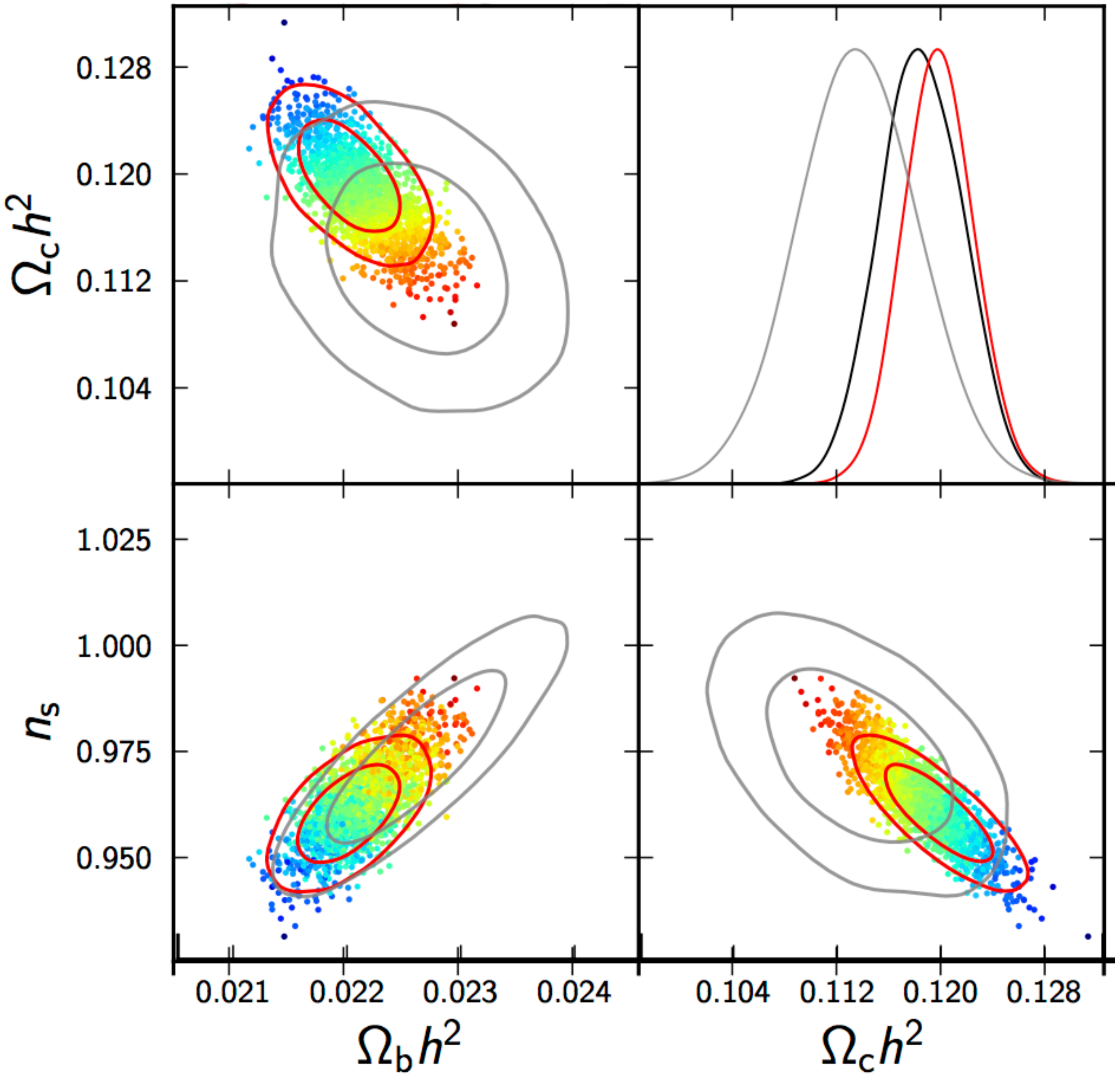
Transfer functions determined by linear perturbations theory in GR. Depends on Ω_{cdm}, Ω_b, DE, neutrino masses, Y,...

Analytical evaluation

Observables:

- CMB C_l, B_{lll}
- Galaxy P(k)
- ...

Refining the Base ΛCDM Model

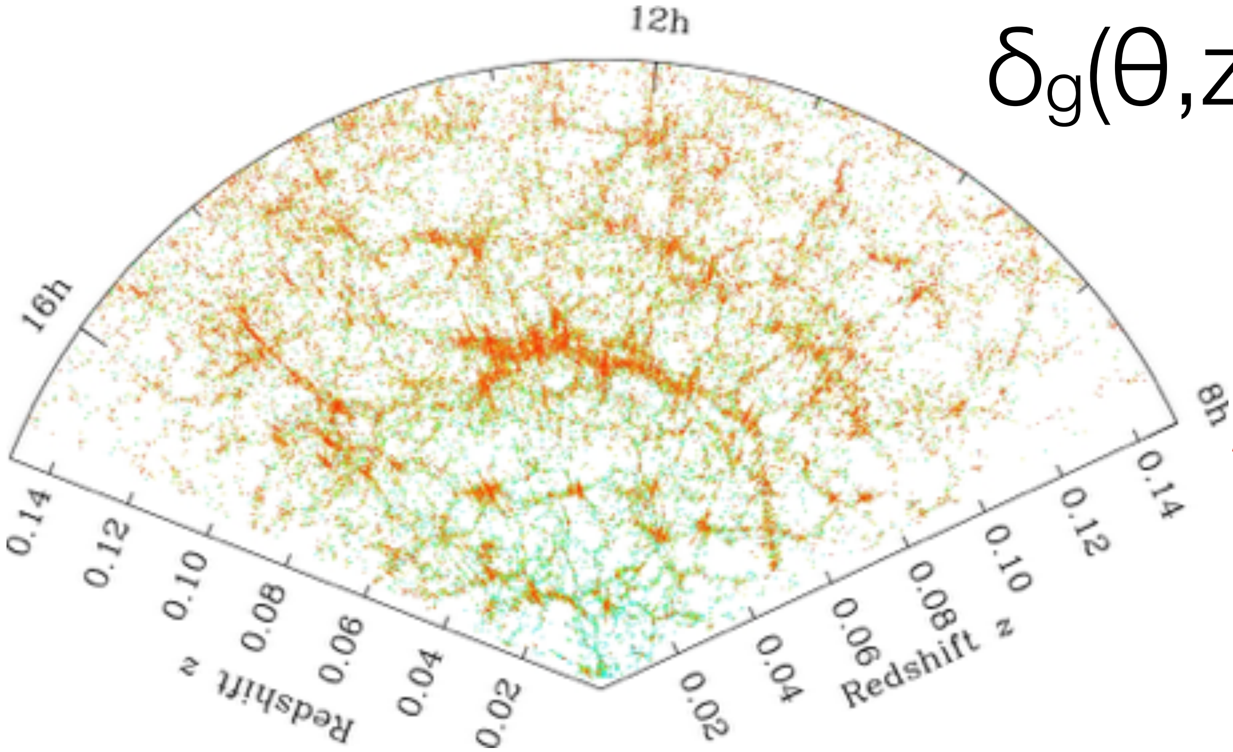


WMAP
Planck + WP
Planck + lensing

Parameter	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 68 % limits
$\Omega_b h^2$	0.022161	0.02214 ± 0.00024
$\Omega_c h^2$	0.11889	0.1187 ± 0.0017
$100\theta_{MC}$	1.04148	1.04147 ± 0.00056
τ	0.0952	0.092 ± 0.013
n_s	0.9611	0.9608 ± 0.0054
$\ln(10^{10} A_s)$	3.0973	3.091 ± 0.025

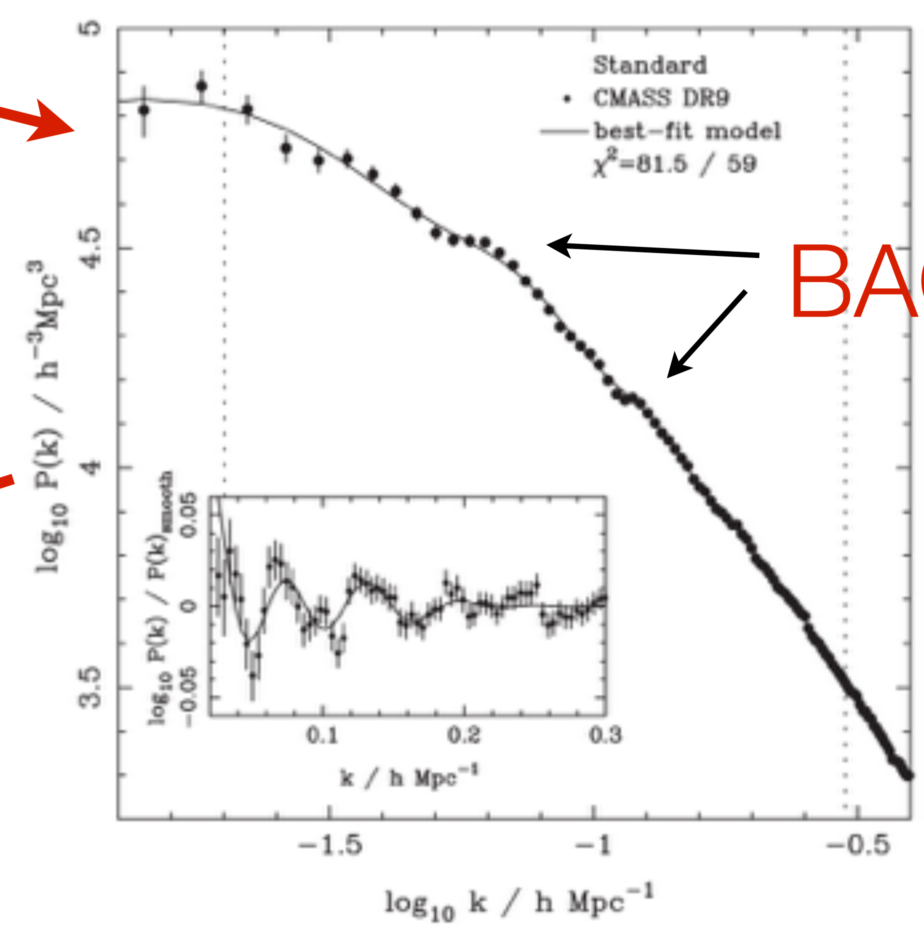
- 0.05% measurement of sound horizon →
- Rule out exact scale invariance at 6σ →

Galaxy Clustering Cosmology

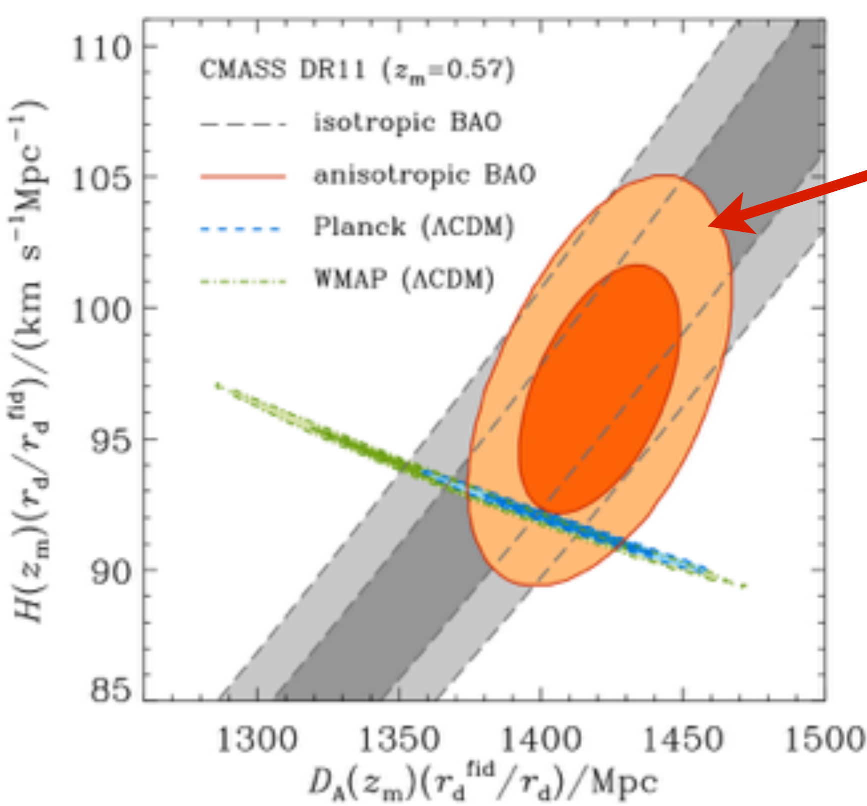


$\delta_g(\theta,z)$

$P(k) = <\delta_g(k)\, \delta_g^{*}(k)>$



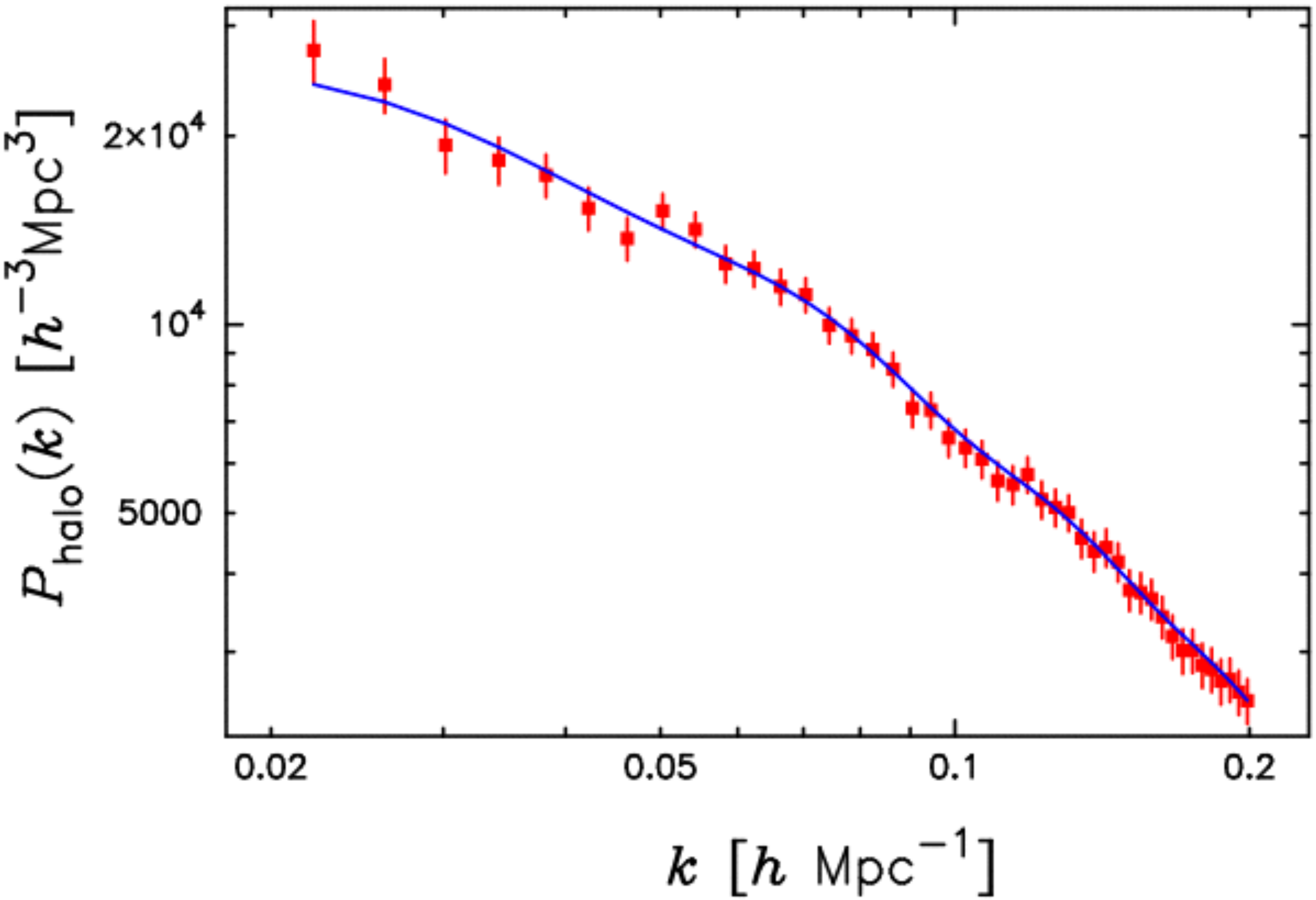
BAO



Ω_{DE}, f_{nl},…

BOSS survey, Anderson++12,13

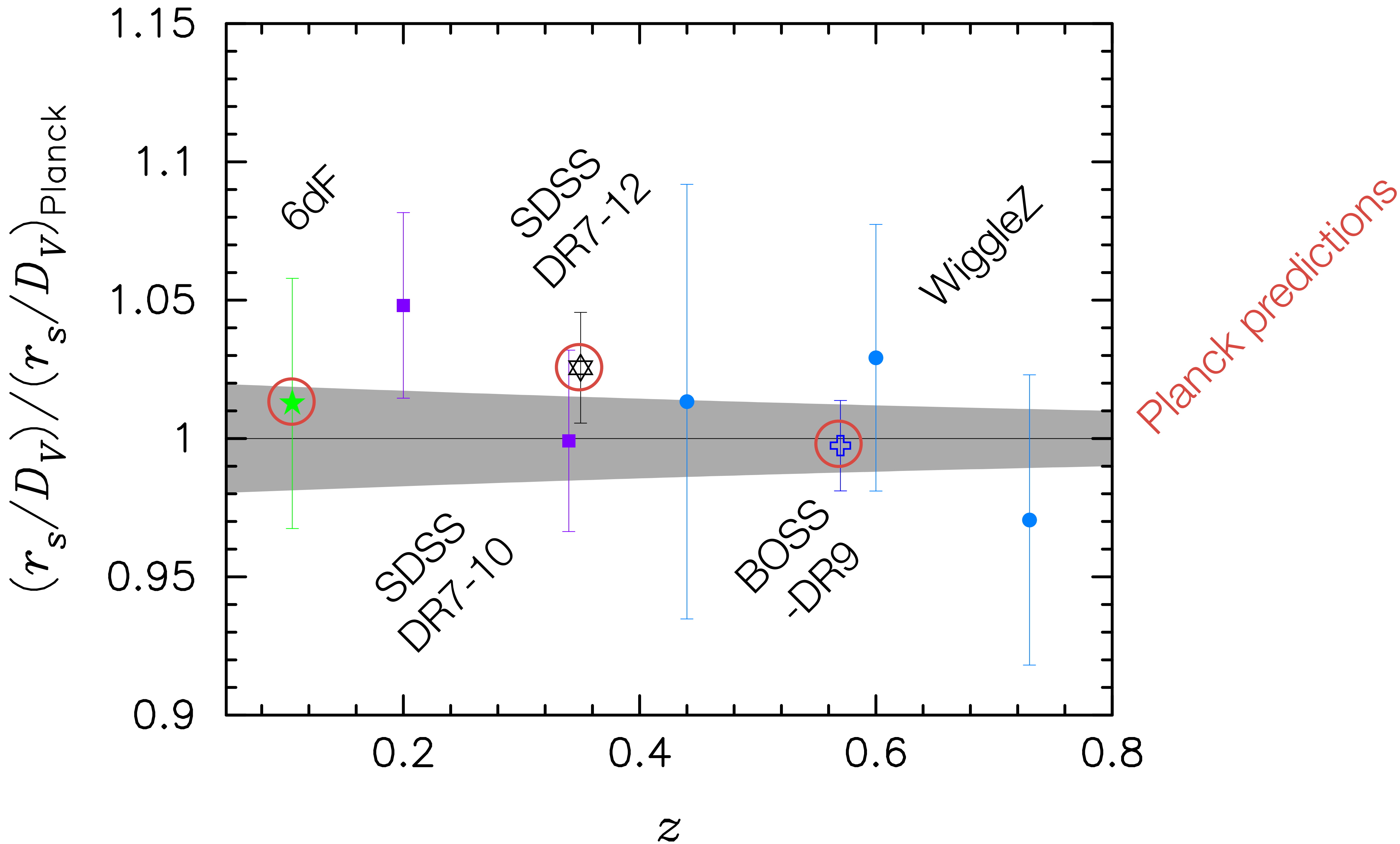
Galaxy Power Spectrum Shape Comparison



- The *predicted* shape of the power spectrum is in excellent agreement with that seen in the SDSS.

Planck 2013 Results. XVI

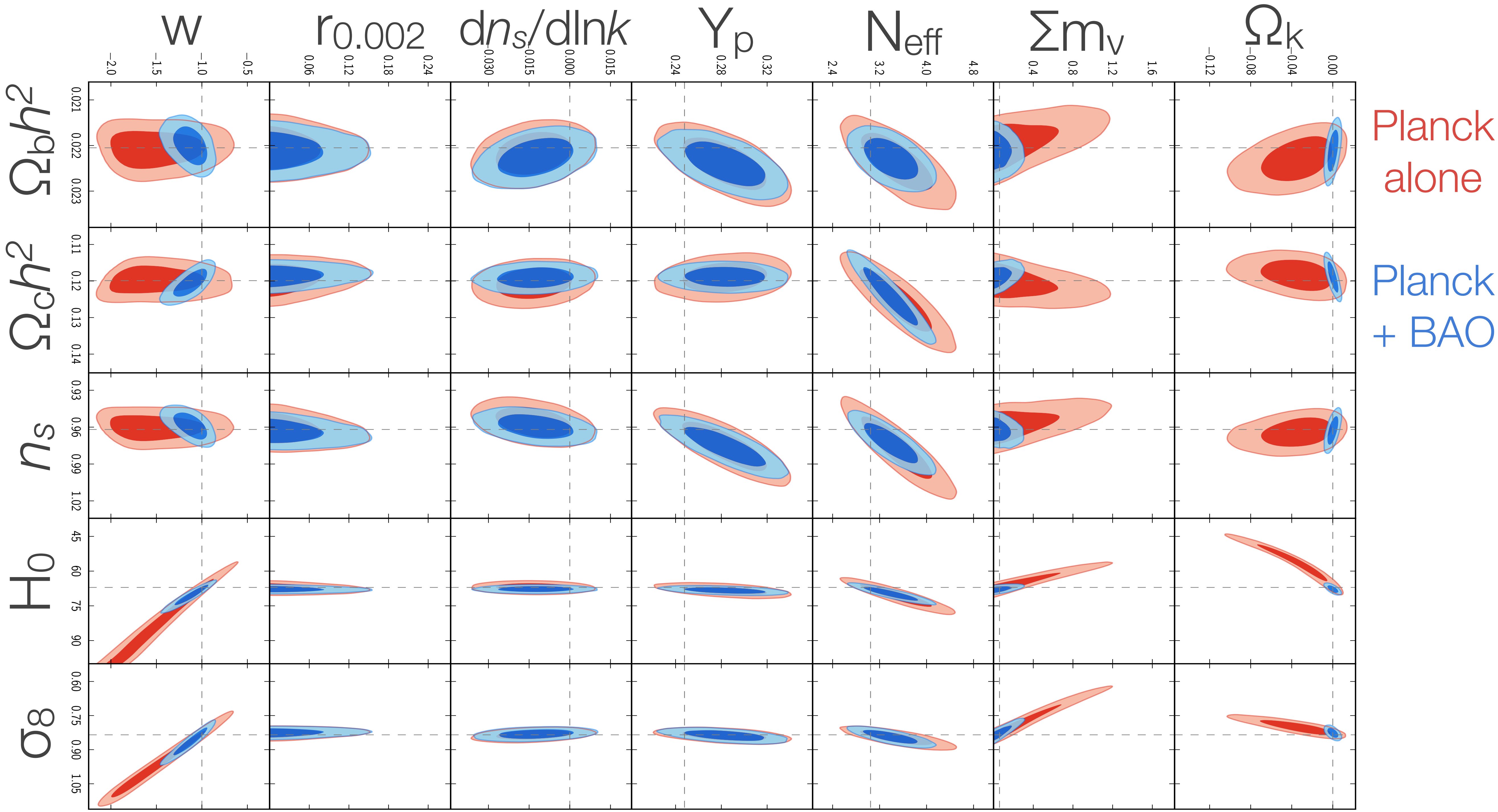
Strong Consistency with BAO Surveys



- D_V combines the angular diameter distance and the Hubble parameter:
- r_S is the comoving horizon at the baryon drag epoch.

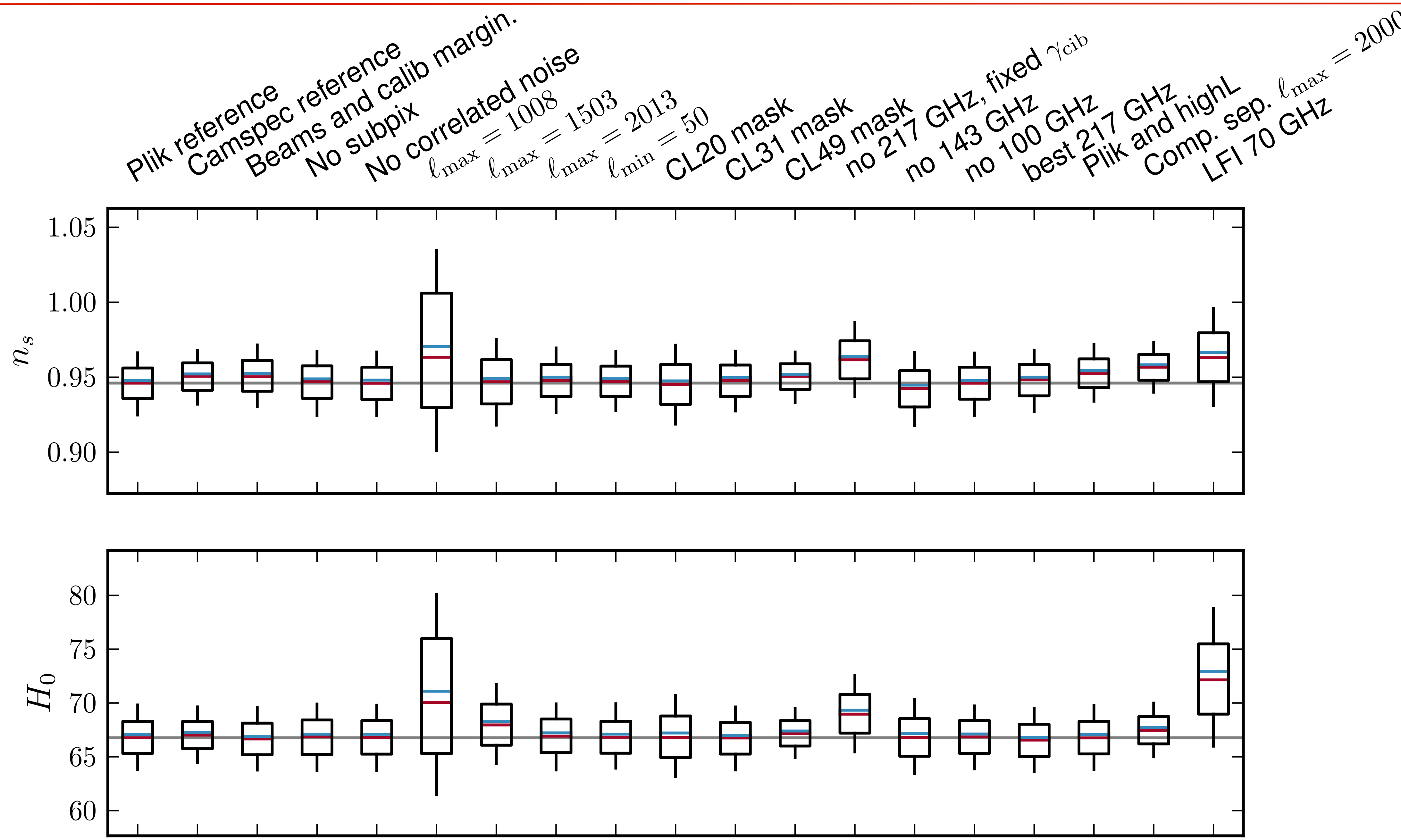
$$D_V(z) = \left[(1+z)^2 D_A^2(z) \frac{cz}{H(z)}\right]^{1/3}$$

Constraining extension to basic ΛCDM model



- Constraints on a single parameter extension of standard ΛCDM model, one parameter at a time.
- The combination of Planck and current current BAO data is powerful.
- It mostly breaks the angular diameter degeneracy.

Likelihood Analysis Robustness Tests

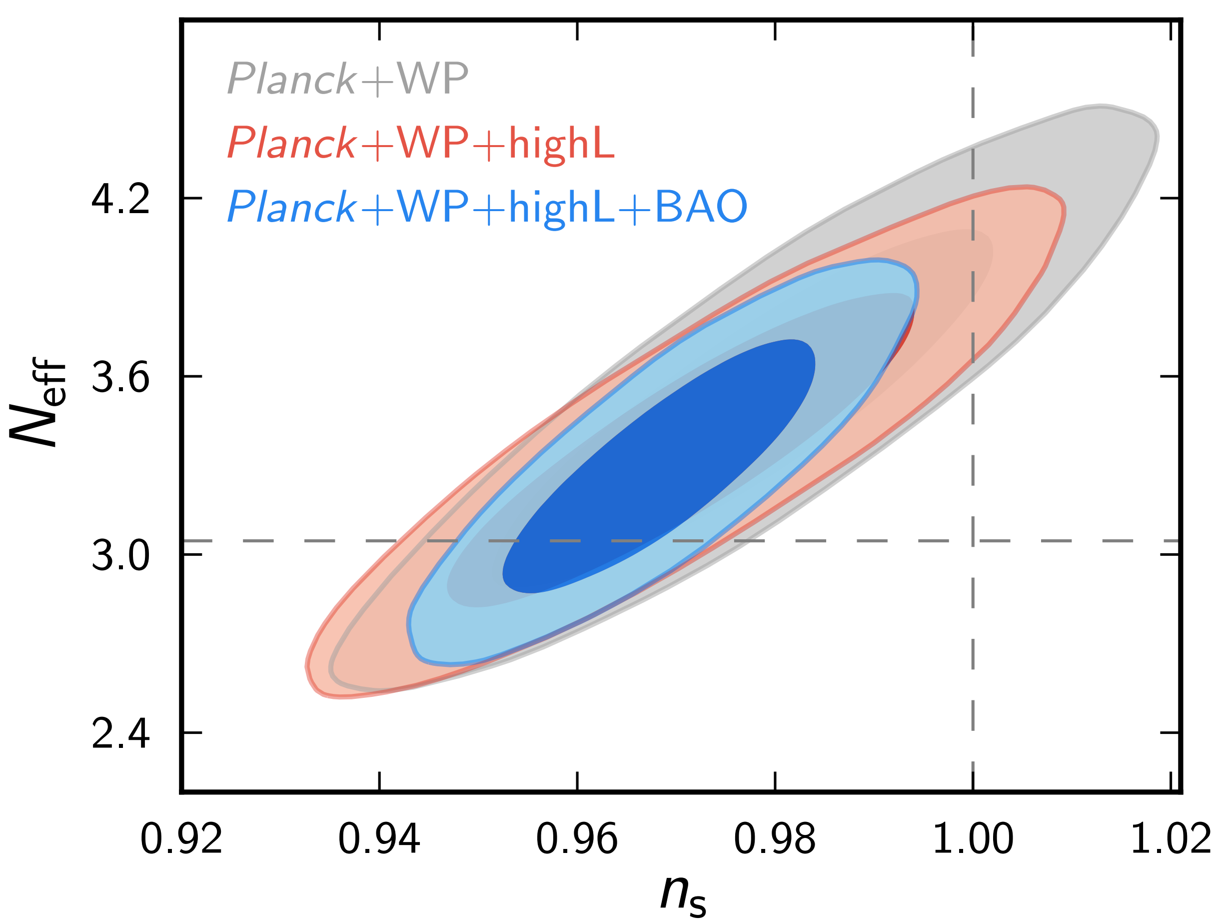


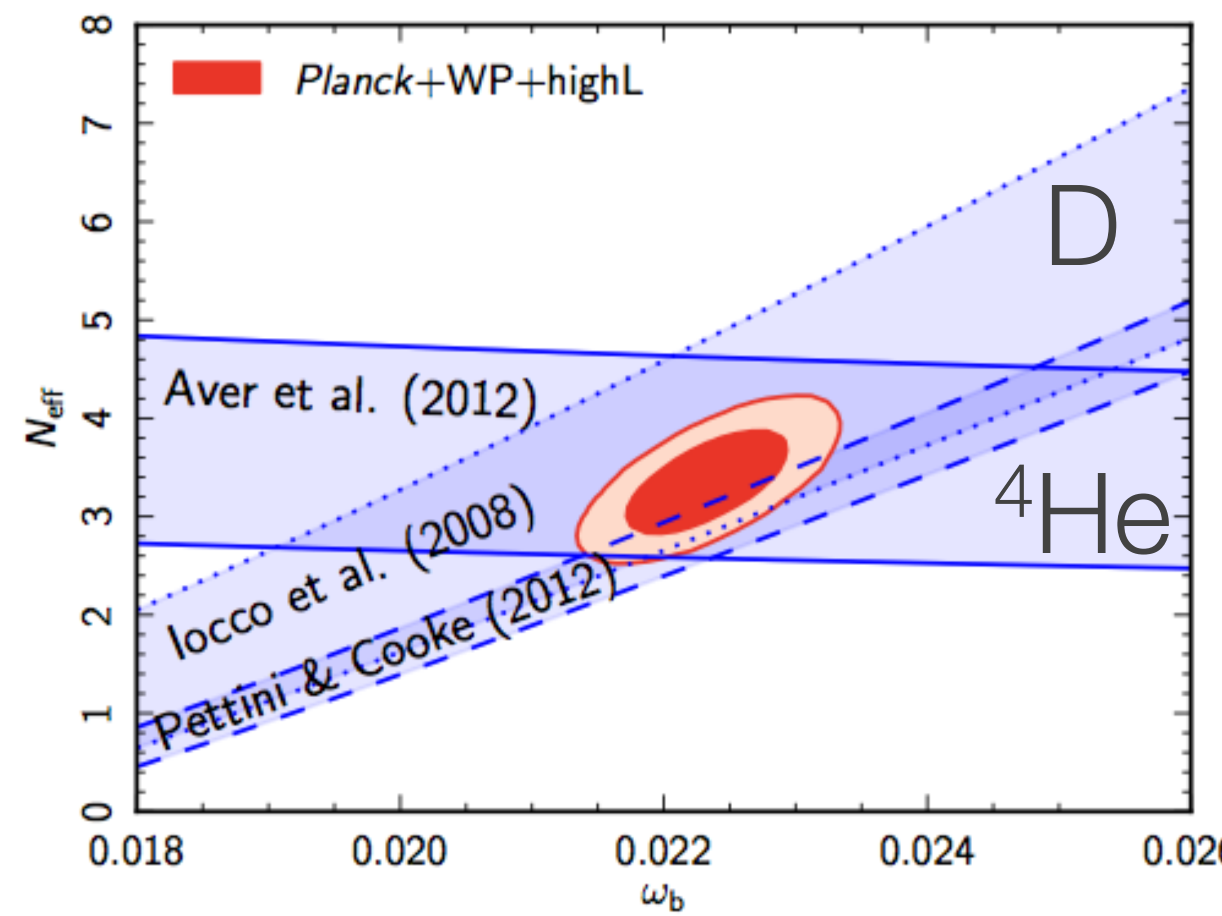
- The Planck data set enables multiple consistency tests.
- We used these extensively at all level of the analysis.
- Note that the default likelihood has 14 non-cosmological nuisance parameters.

Number of Relativistic Species

- N_{eff} is a probe of the standard model of particle physics.
- More relativistic species lead to longer radiation domination. Older oscillations in the primary CMB are suppressed.
  - ➡ N_{eff} = 3.36±0.34 (68%, Planck+WP+high L)
  - ➡ N_{eff} = 3.30±0.27 (68%, Planck+WP+high L+BAO)

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





What is Inflation?

- Inflation was introduced in the 80s to solve the problems of the “standard Big Bang” model like the *relic*, *flatness* and *horizon problem*.

- Key feature:
  - ➡ During an extended period of time, the universe is expanding exponentially. Curvature fluctuations are generated during this phase.

- This is achieved by introducing in the matter sector:
  - ➡ (a) new scalar field(s) Φ with a well chosen potential V(Φ)

- Current data supports simple Inflation paradigm *predictions*:
  - ➡ Flatness, nearly scale invariant perturbations (n_S~1), Gaussianity, adiabaticity and gravity wave background (!!!)

Starobinksy 79, Guth 81, Sato 81, Linde 82, Albrecht & Steinhardt 82
Mukhanov & Chibisov 81, Guth & Pi 82, Starobinsky 82, Hawking 82, Bardeen et al. 83
Linde 05, Lyth & Riotto 99 for reviews

Constraining the Initial Conditions

- Derived from the power spectrum:
  - ➡ Constraints on the primordial curvature perturbation power spectrum: n_s, α_s

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

  - ➡ Constraints on the amplitude of tensor perturbations, the gravity wave background that give rises to B-mode polarization: r

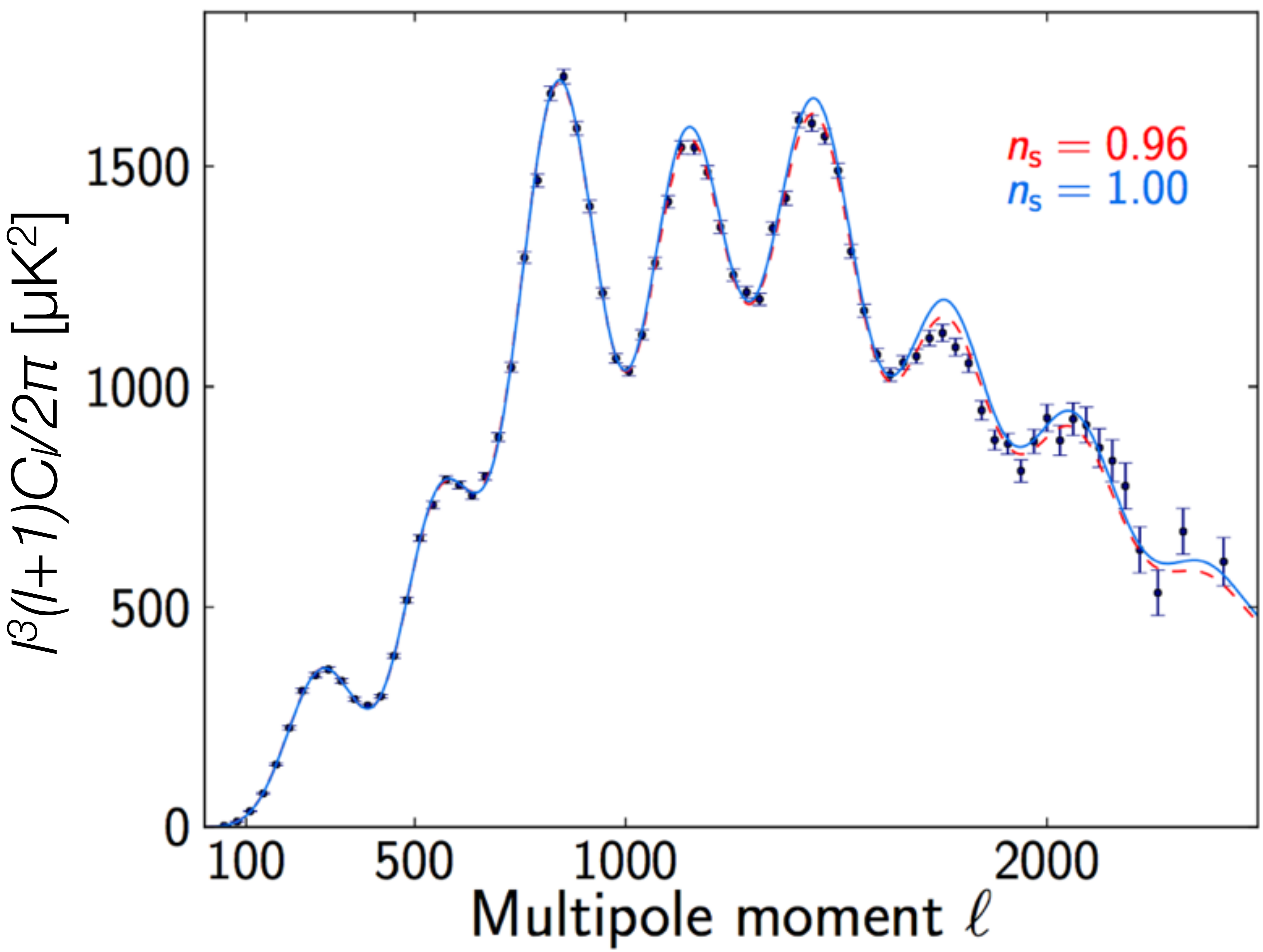
$$r = \frac{\mathcal{P}_t(k_*)}{\mathcal{P}_{\mathcal{R}}(k_*)}$$

$$V^{1/4} = 1.06 \times 10^{16}\,\mathrm{GeV} \left(\frac{r}{0.01}\right)^{1/4}$$

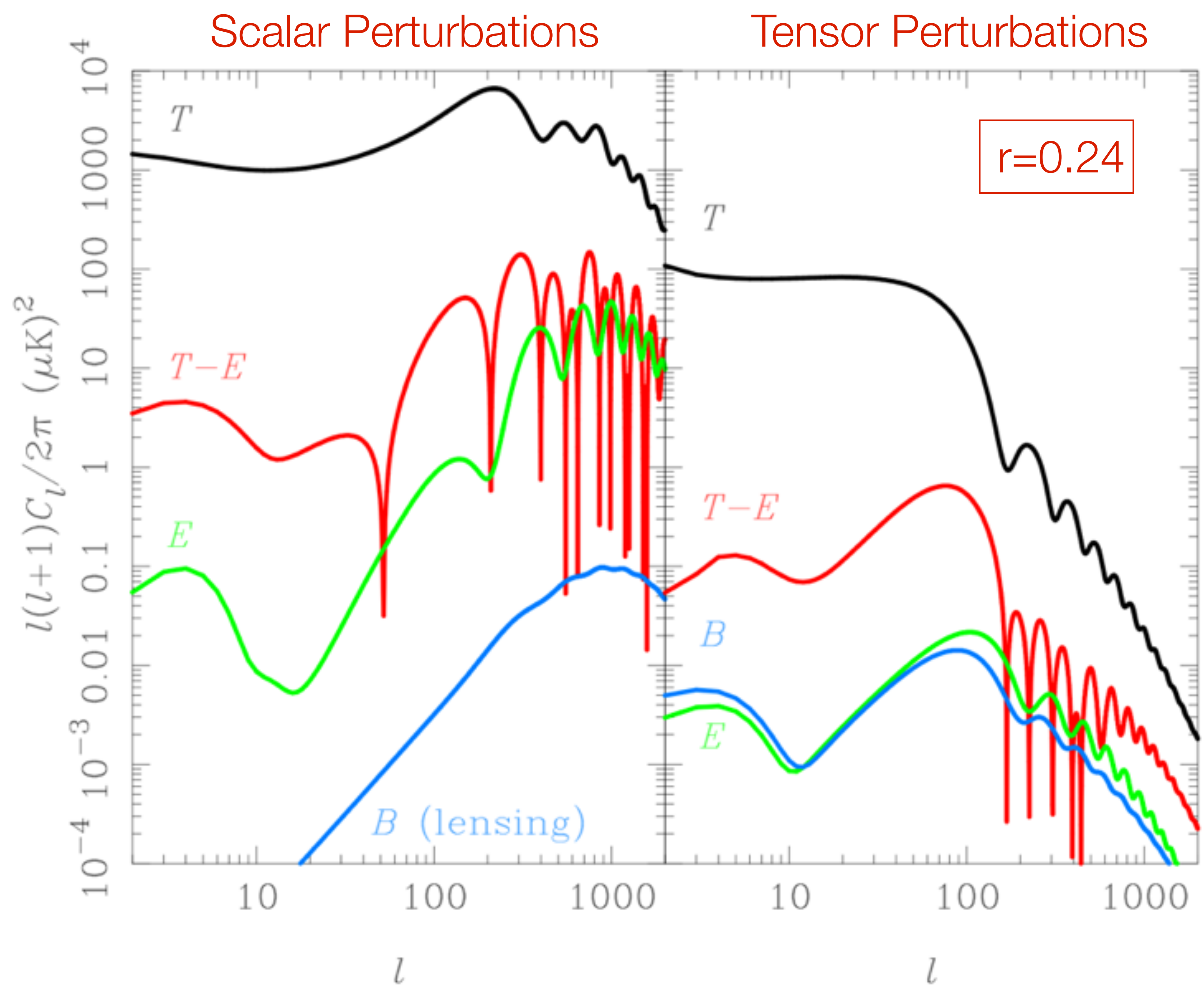
- Derived from higher order moments, and the bispectrum in particular:
  - ➡ Non-Gaussianity, i.e., a non-zero bispectrum.
  - ➡ It is often characterized by f_{nl}, ~ skewness

- For a given inflation model, n_s, α_s, r, f_{nl} and their inter-relations are specified.

Constraining Spectral Index with Temperature C_l

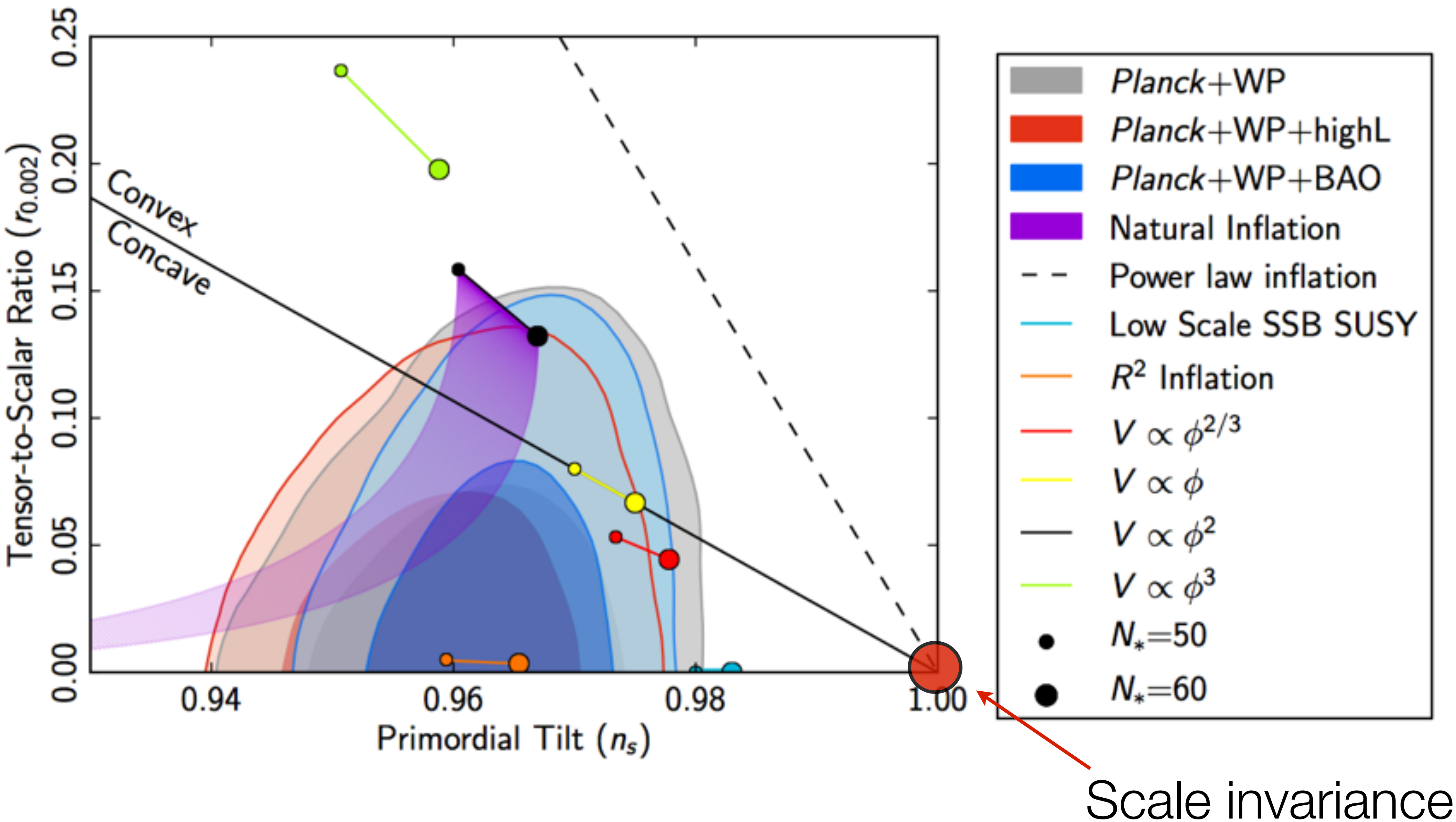


Constraining r (tensor modes) with Temperature C_l



Challinor 2012

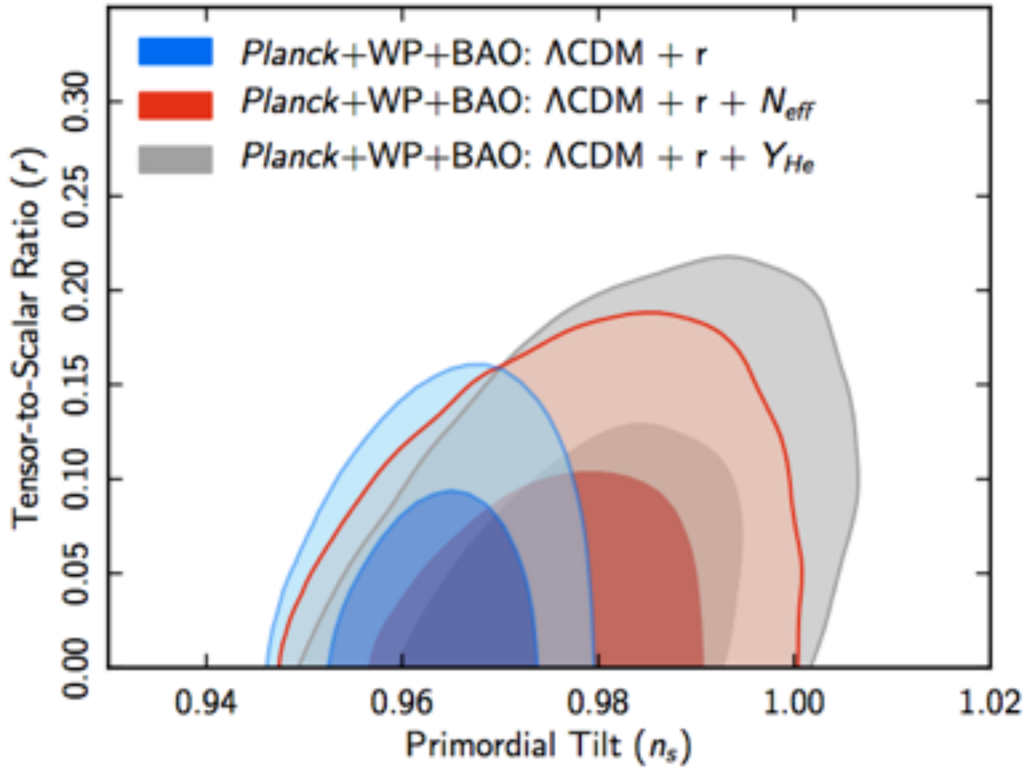
Testing Scale Invariance with Planck Alone



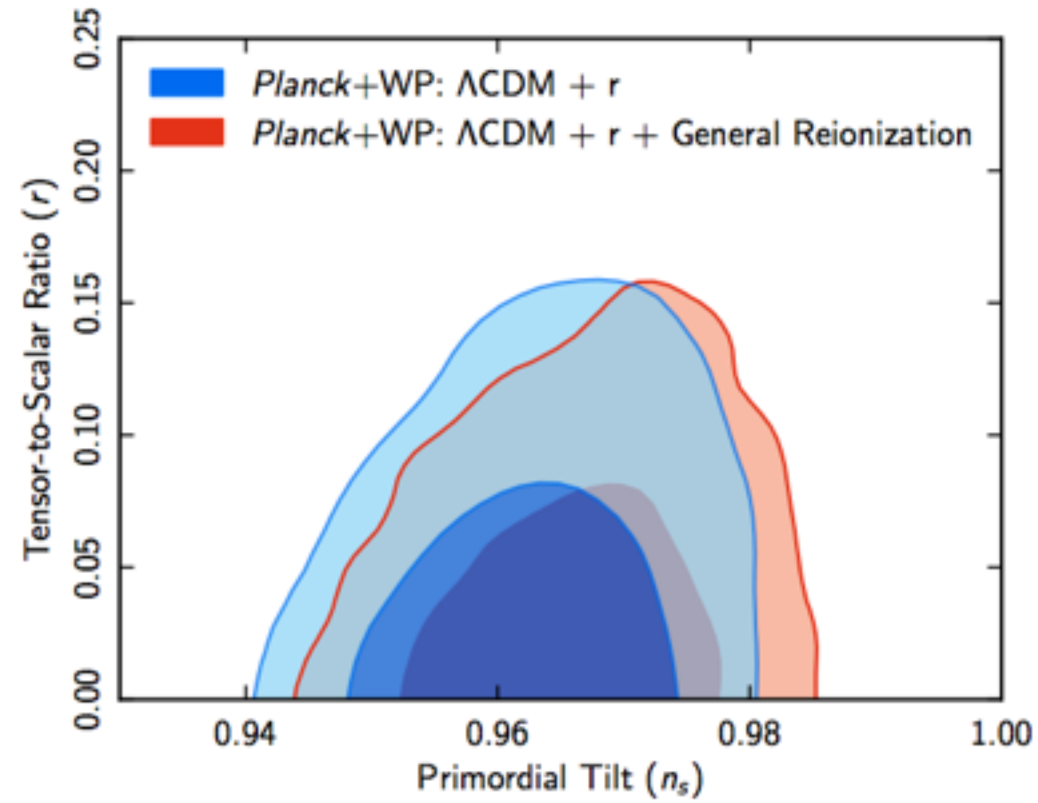
- Planck + WP:
  - ➡ $n_s = 0.9603 \pm 0.0073$, $r_{0.002} < 0.12$ (95% C.L.).
- Energy Scale of Inflation:
  - ➡ $V_* < (1.94 \times 10^{16}\ \mathrm{GeV})^4$.

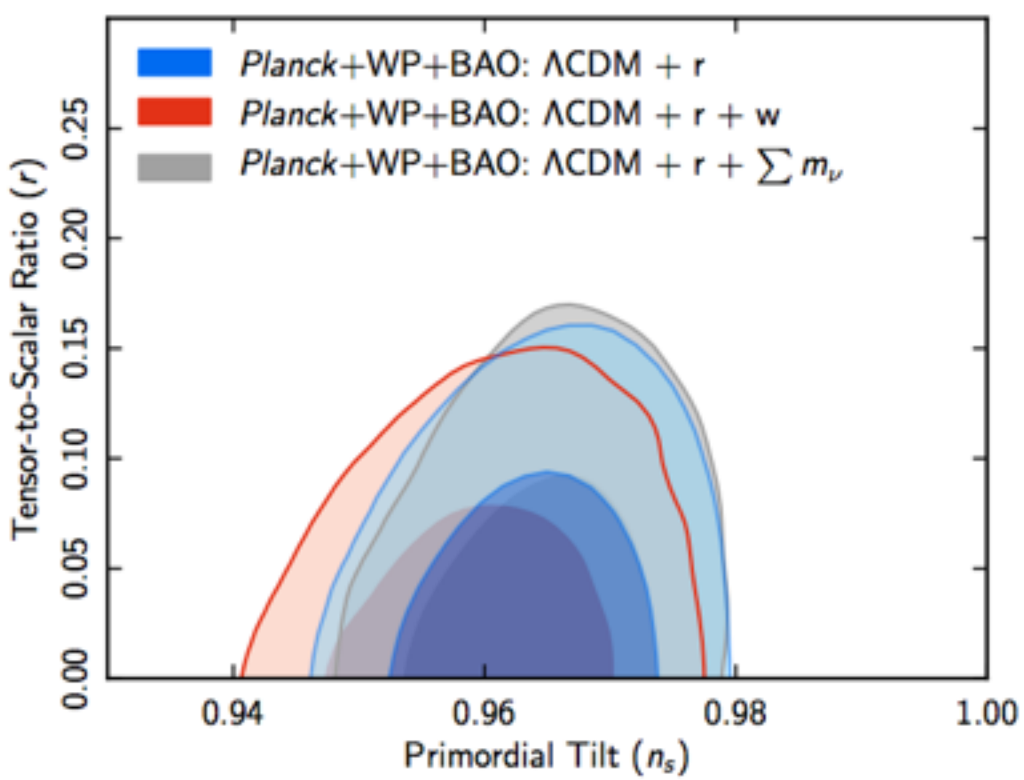
Robustness with regards to other parameters

N_{eff} or Y_{He}



Reionization

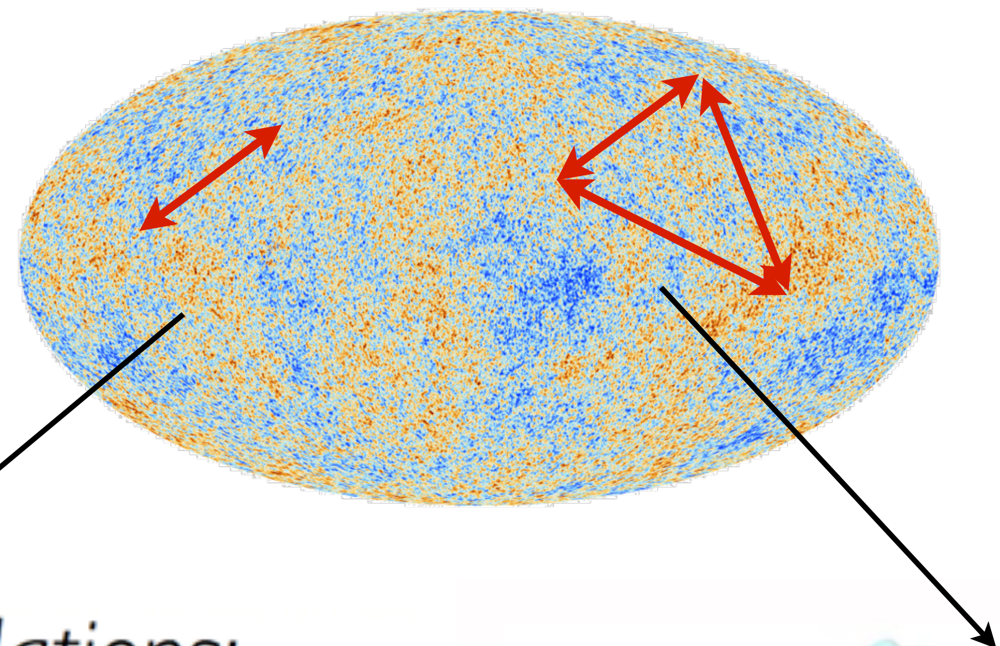




Dark Energy w
Neutrino mass

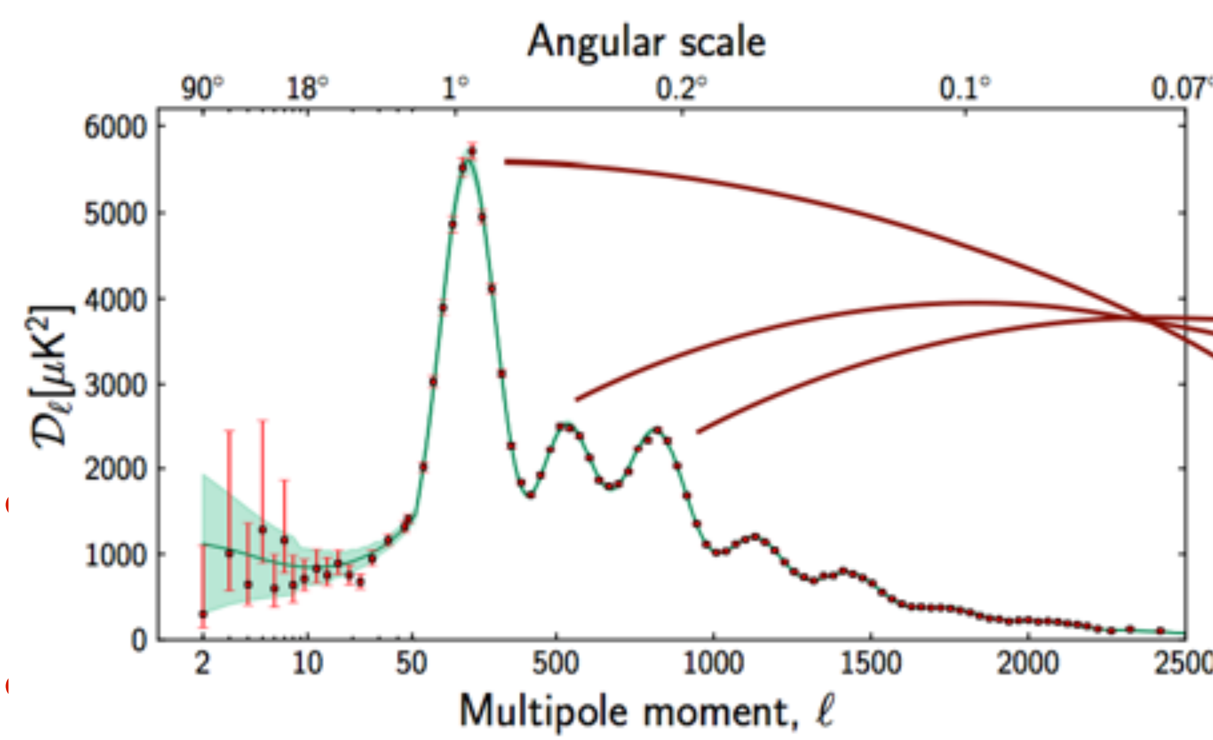
See also de Putter++14 for a complimentary analysis

Counting Triangles in the Sky

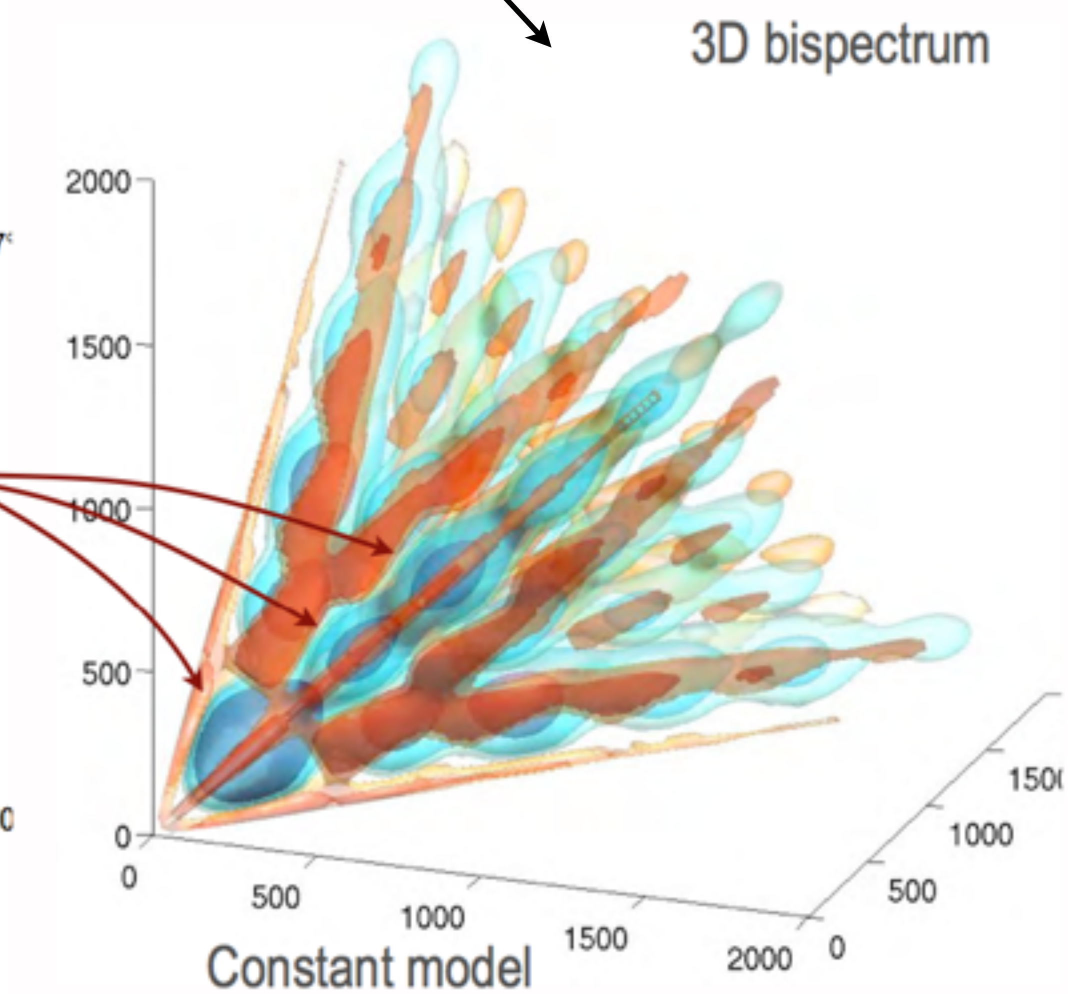


Power spectrum

Hot plasma oscillations:



Power spectrum (2pt correlator)



Planck 2013 Results. XXIV

Non-Gaussianity and Inflation models

- Non-Gaussianity ~~is~~ was arguably the most stringent test of the standard picture (1 ppM)

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

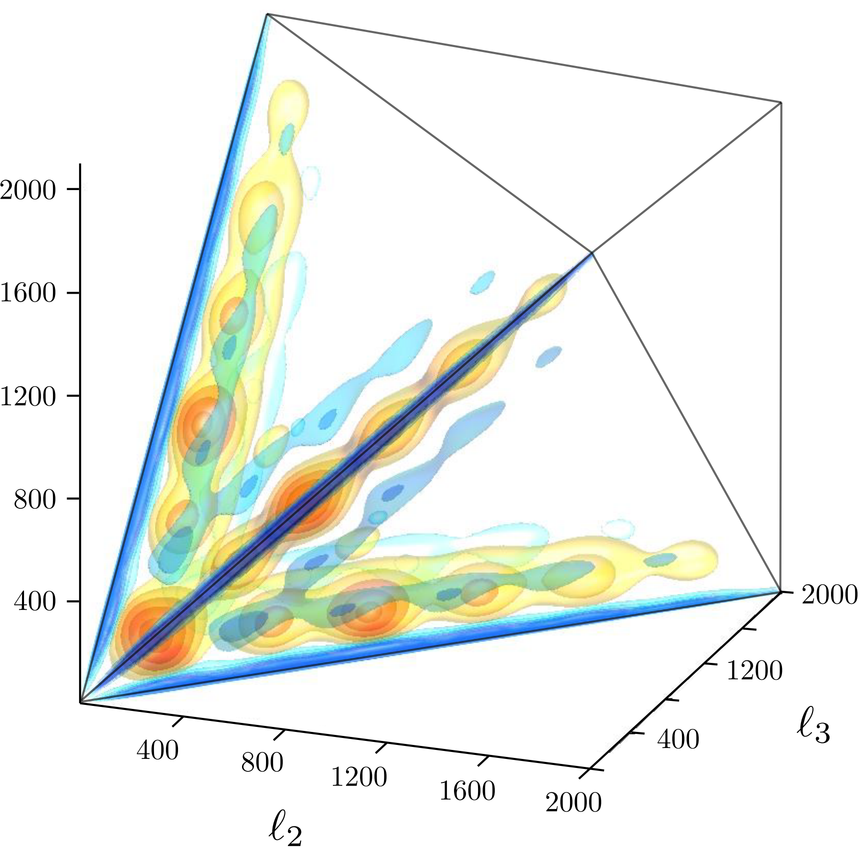
- Simple inflation models cannot generate observable non-Gaussianity:
    - ➡ Single scalar field, Canonical kinetic terms
    - ➡ Always slow roll, Ground state initial vacuum
    - ➡ Standard Einstein gravity

- But simple inflation model-building faces rigorous challenges in fundamental theory. Many new ideas/ solutions violate these conditions!

- Many models predicts a detectable level of non-Gaussianity:
    - ➡ Most multi-field inflation.
    - ➡ Non-canonical kinetic terms.
    - ➡ Excited terms.
    - ➡ Alternative to Inflation.

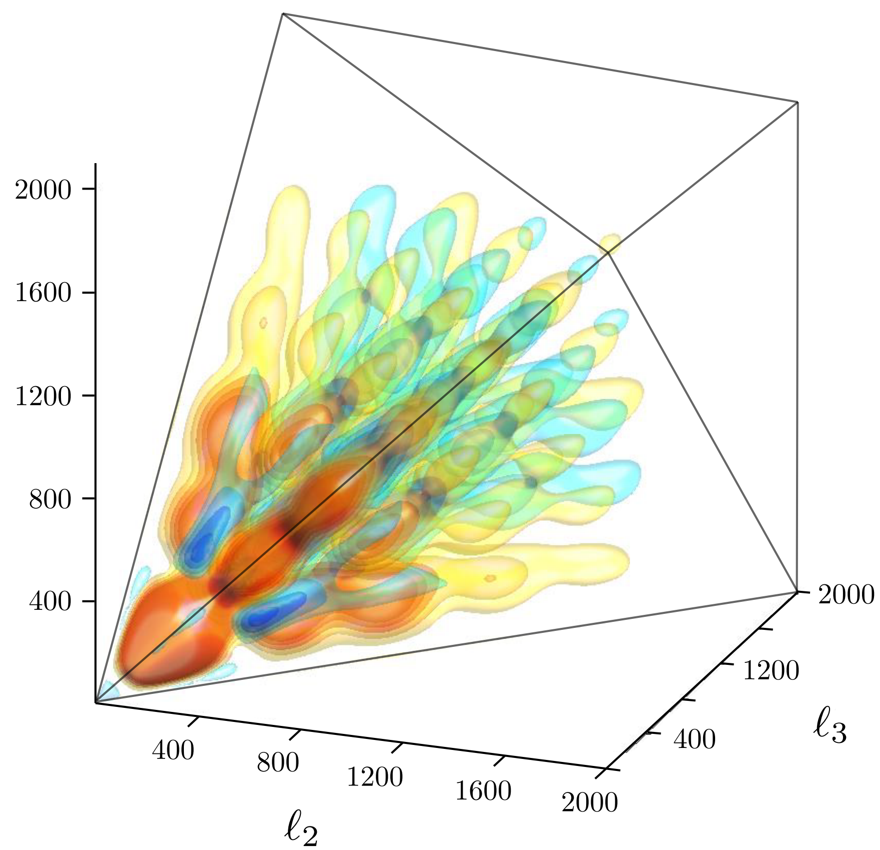
No Non-Gaussianity Detection in Data.

local



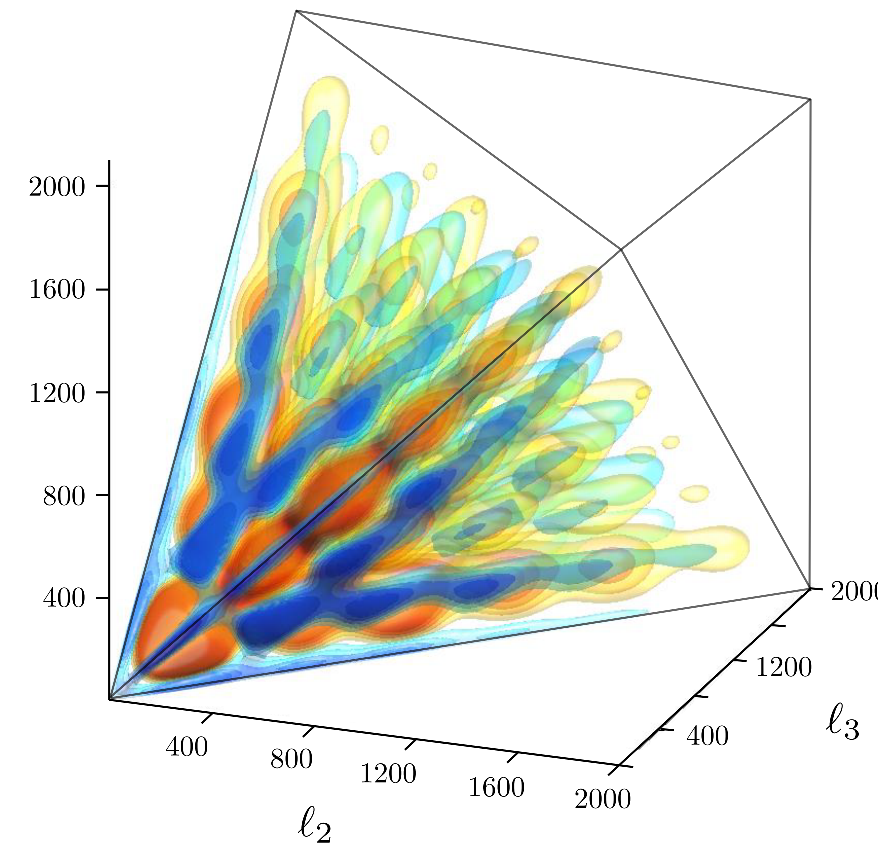
$$f_{\rm NL}^{\rm local} = 2.7 \pm 5.8$$

equilateral



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

orthogonal

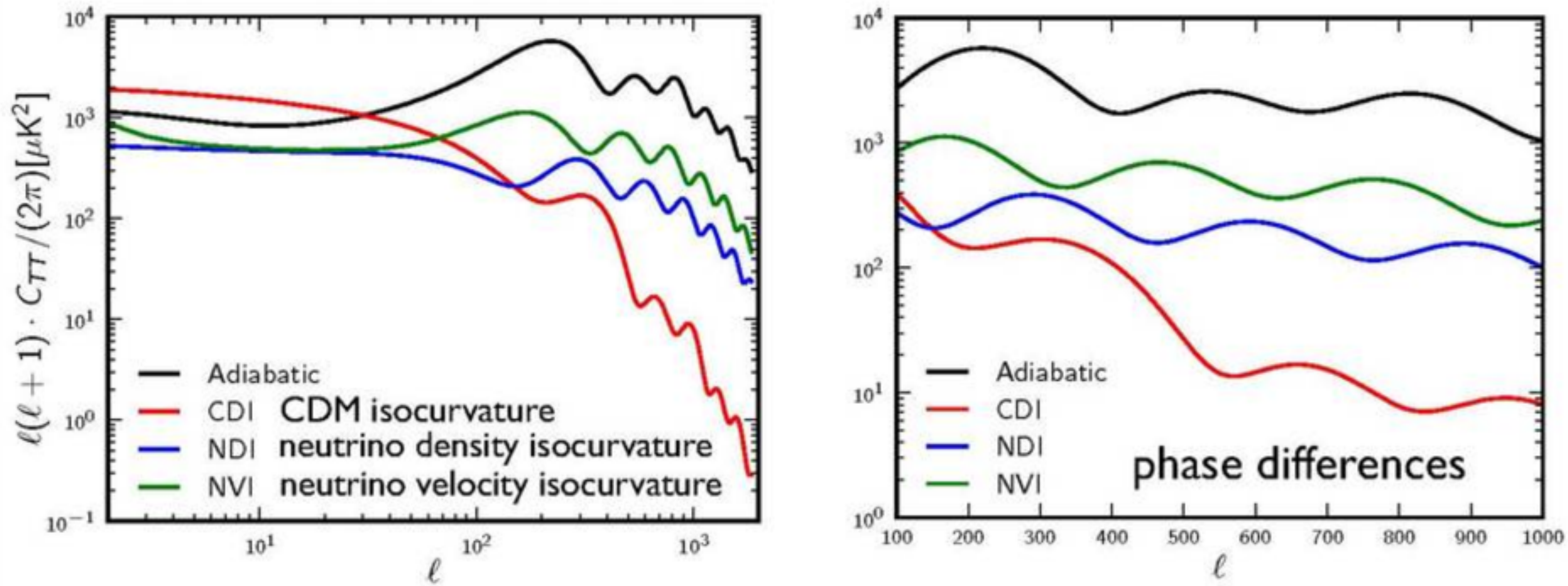


$$f_{\rm NL}^{\rm ortho} = -25 \pm 39$$

- So far, consistent with Gaussian initial conditions.

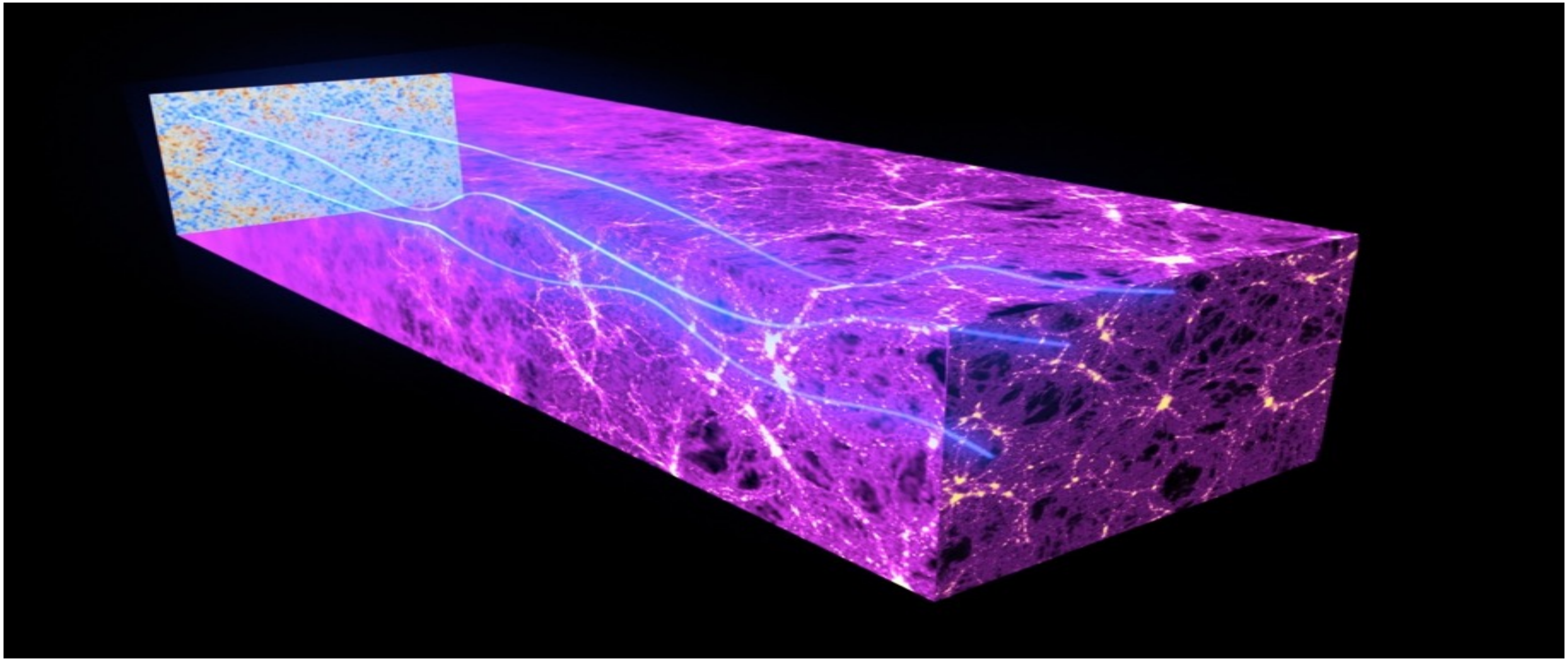
Planck 2013 Results. XXIV

Isocurvature Spectra



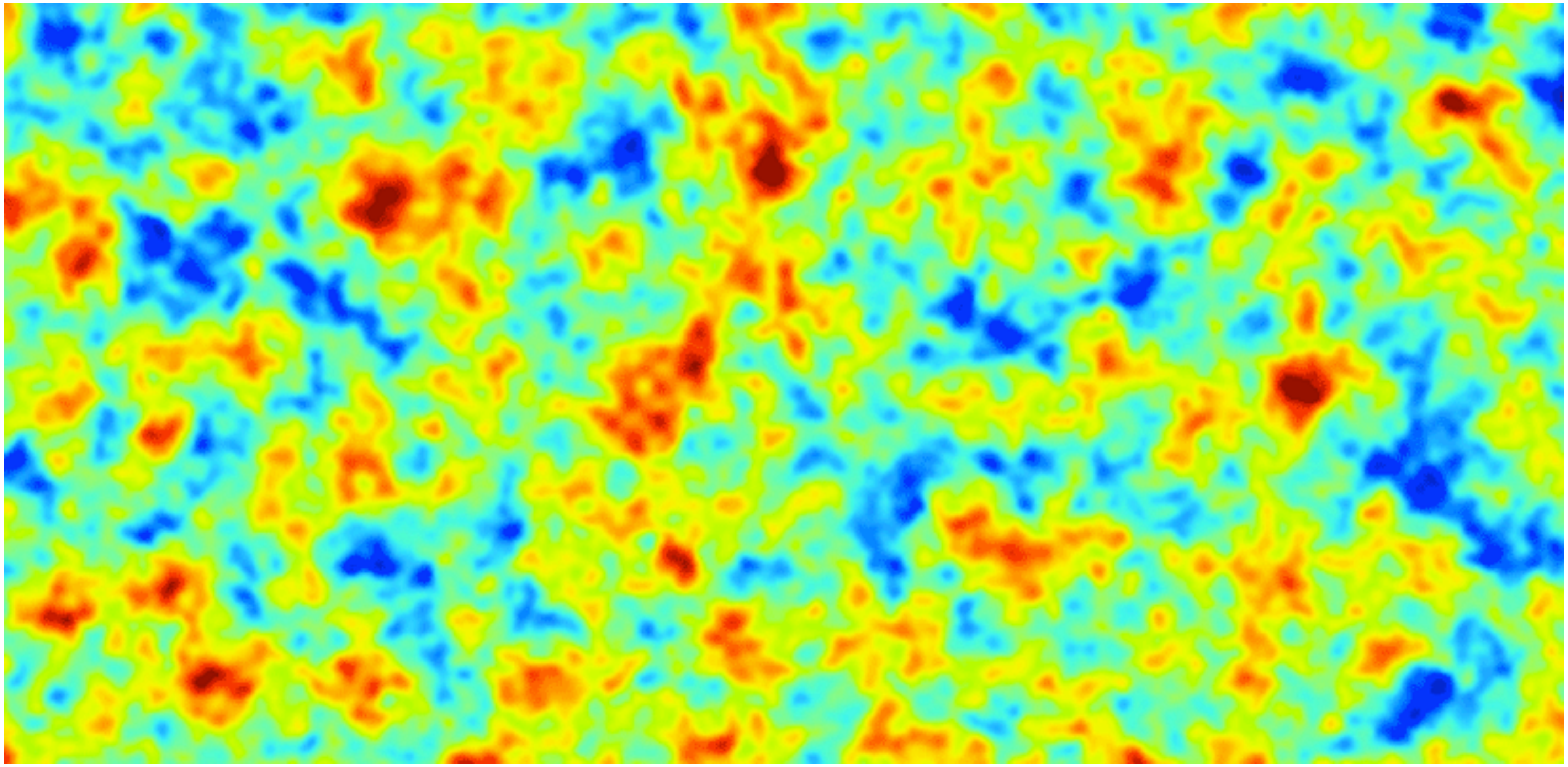
- Arise from spatial variations in the equation of state between relative velocity components.
- Might be excited in multi-fields inflations.
- Expect correlations between adiabatic and multi-field degrees of freedoms

CMB is Gravitationally Lensed by Matter



- The deflection of light (photons) by matter is one of the key prediction of Einstein's theory of general relativity.
- It is a well observed effect in astronomy, e.g.,"cosmic shear", "weak/strong gravitational lensing". It affects CMB photons too.
- The CMB is the most distant source plane we can imagine, but also one with a very precisely known redshift ($z=1090.37\pm0.65$ after Planck).
- Because the CMB photons were emitted about ~13 Gpc away, the CMB photons are deflected by all the clumps of matter in the visible Universe.

Gravitational Lensing of the CMB



Sims by D. Hanson

- Simulated patch (10 deg. wide) of CMB fluctuations before or after lensing.
- The effect of lensing can be understood as a remapping of the unlensed CMB:
  - ➡ $T^{lens}(\boldsymbol{\theta}) = T^{unlensed}(\boldsymbol{\theta}+\boldsymbol{\alpha})$.
- It is a small effect:
  - ➡ The rms of the deflection angle is about 2.5' (as compared to the 5' beam FWHM).
  - ➡ The deflection angle is coherent on degree scales, which enables its measurement.
- This measurement is performed using a tailored "4-point statistic".

CMB Lensing Reconstruction

$$T^{lensed}(\vec{\theta}) = T^{unl}(\vec{\theta} + \vec{\nabla}\phi) \simeq T^{unl}(\vec{\theta}) + \vec{\nabla}\phi \cdot \vec{\nabla}T^{unl}(\vec{\theta}) + \ldots$$

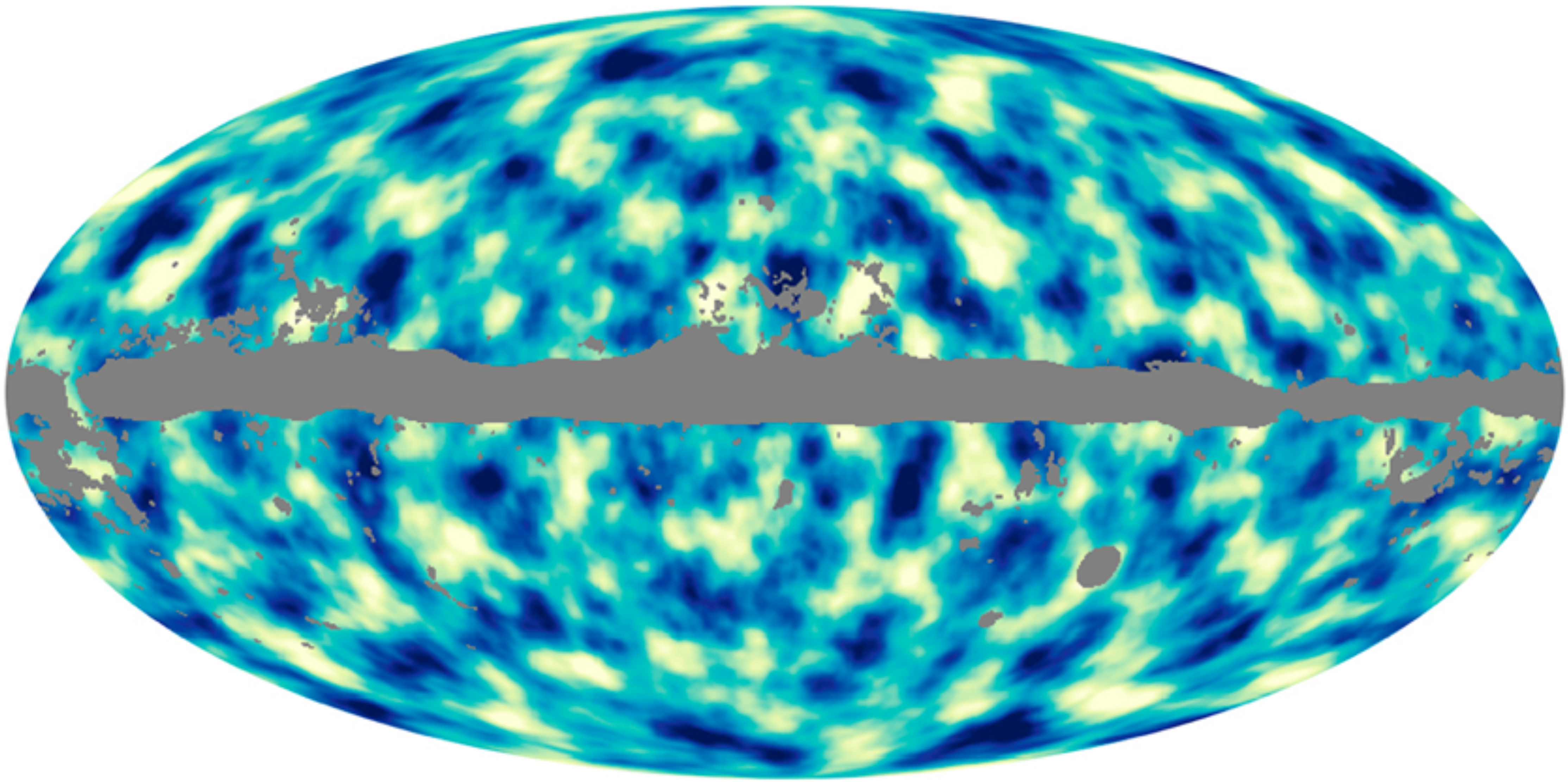
$$\phi(\hat{\boldsymbol{n}}) = -2 \int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi \hat{\boldsymbol{n}}; \eta_0 - \chi)$$

$$\bar{\nabla}\Phi \propto T \nabla T$$

$$\bar{\phi} = \Delta^{-1} \vec{\nabla} \cdot \left[C^{-1} T \vec{\nabla} (C^{-1} T) \right]$$

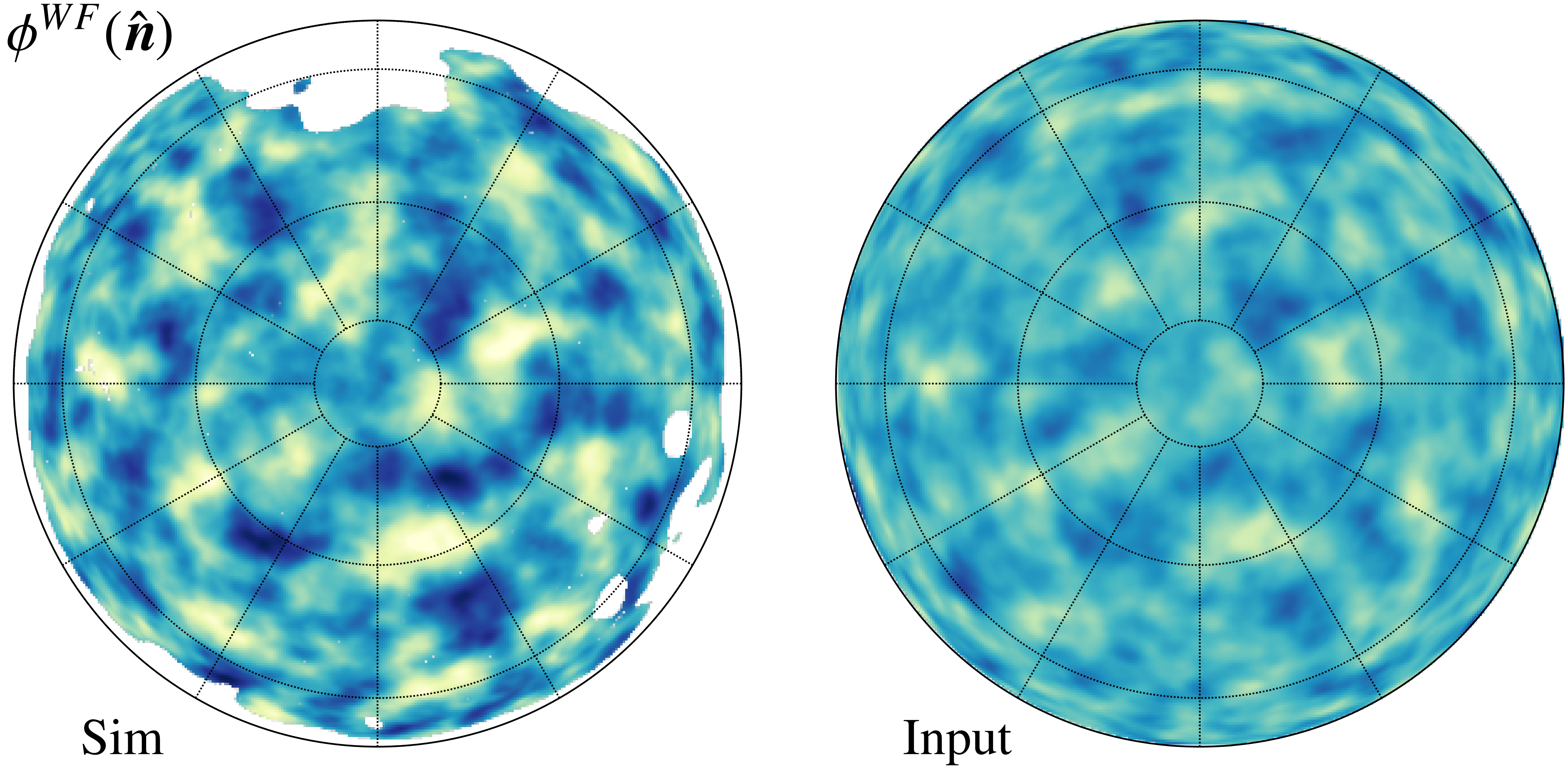
- "Quadratic estimator":
  - ➡ The estimator consists in taking two inverse variance weighted T maps.
  - ➡ Differentiate one.
  - ➡ Multiply the product with the other.
  - ➡ Normalize to get unbiased estimator.

The Projected Mass Map of the Visible Universe

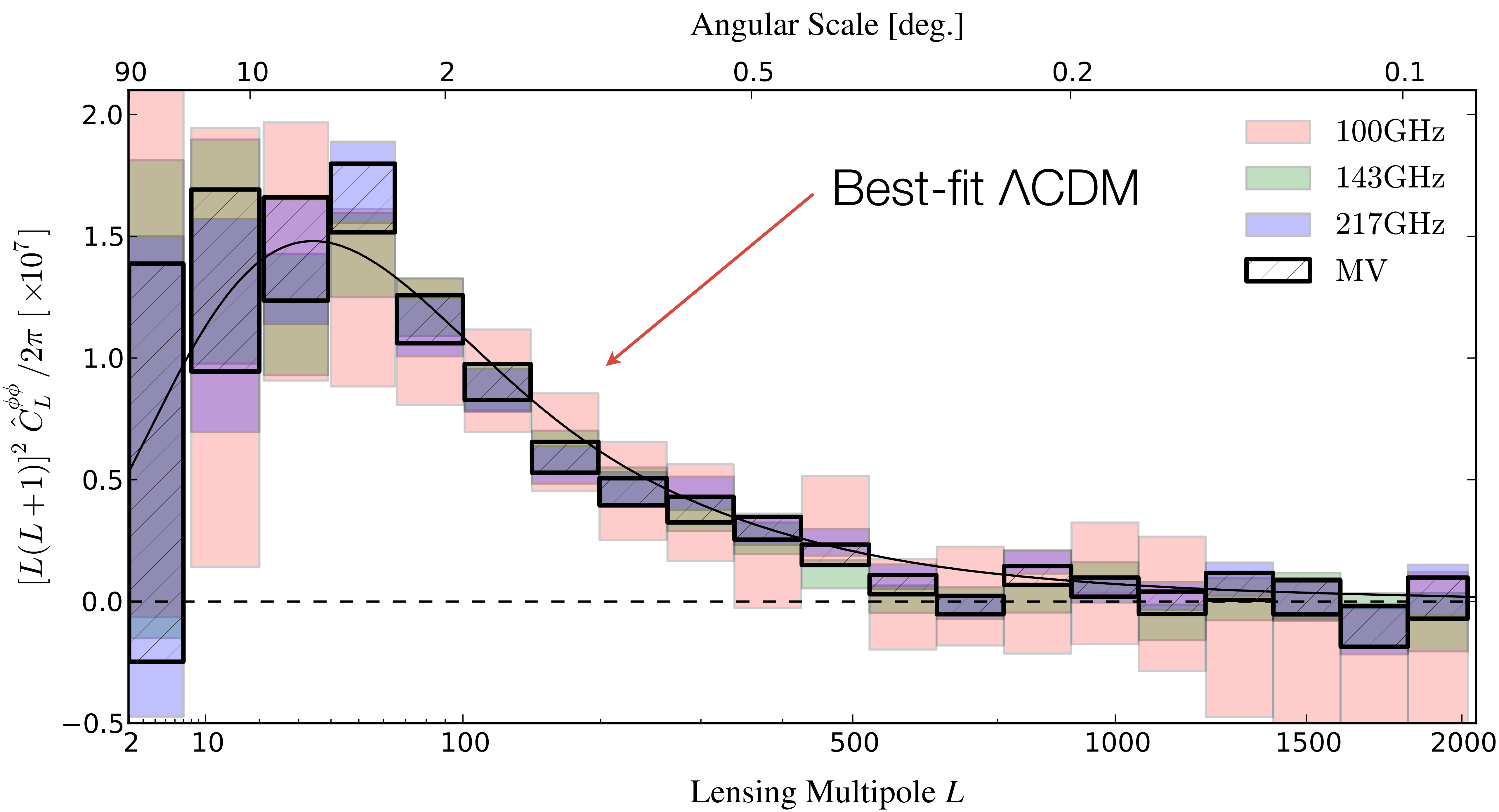


- Using Planck CMB channels (mostly 143 and 217 GHz), we can reconstruct a full sky lensing potential map (total SNR of about 25) using a quadratic estimator.
- This map is a weighted projection of the gravitational potential over the entire visible Universe, with a peak sensitivity between z~1 and 3.
- The gradient of this map gives the deflection angle.

Simulated Reconstructions



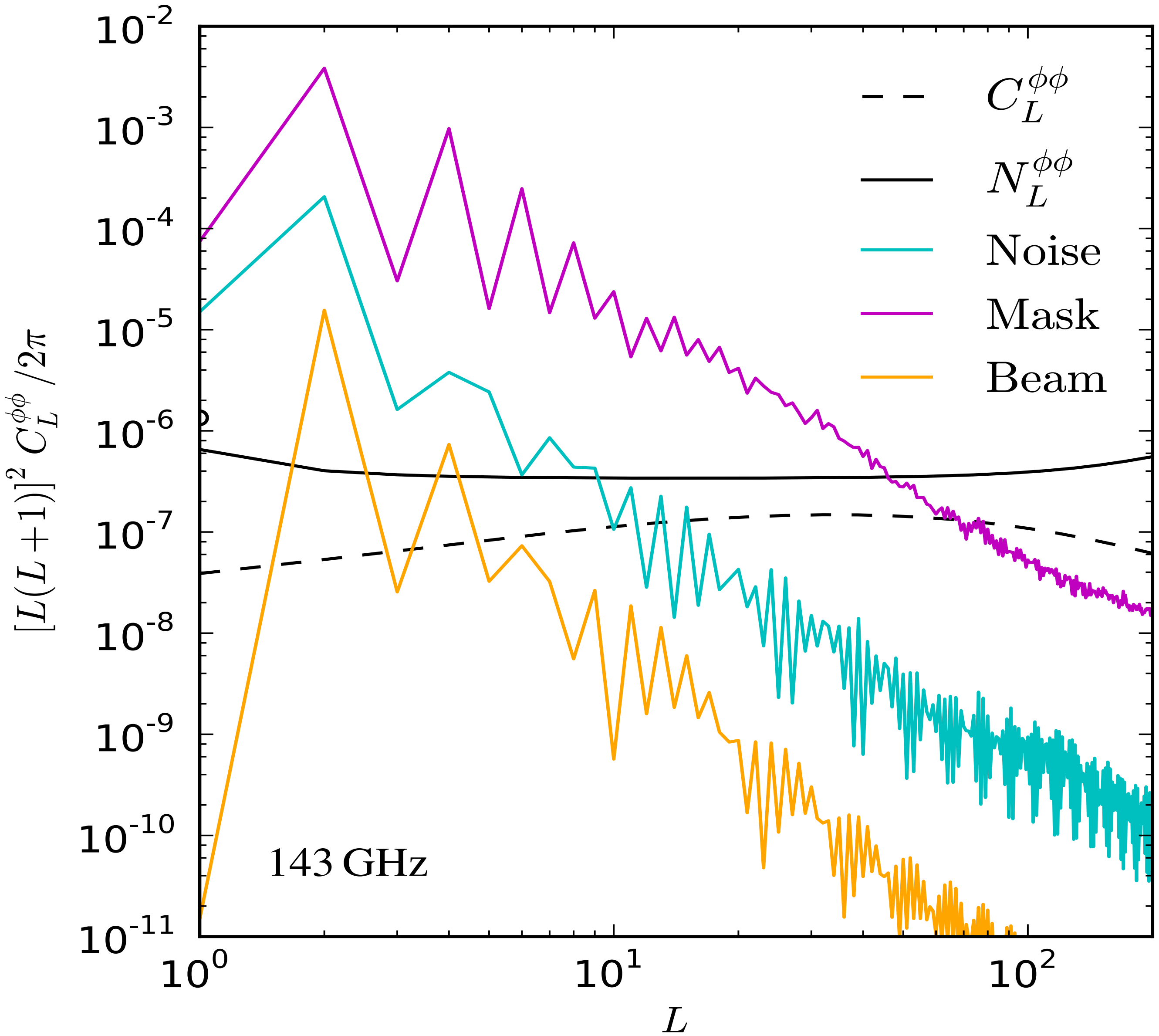
The CMB Lensing Power Spectrum is Robust

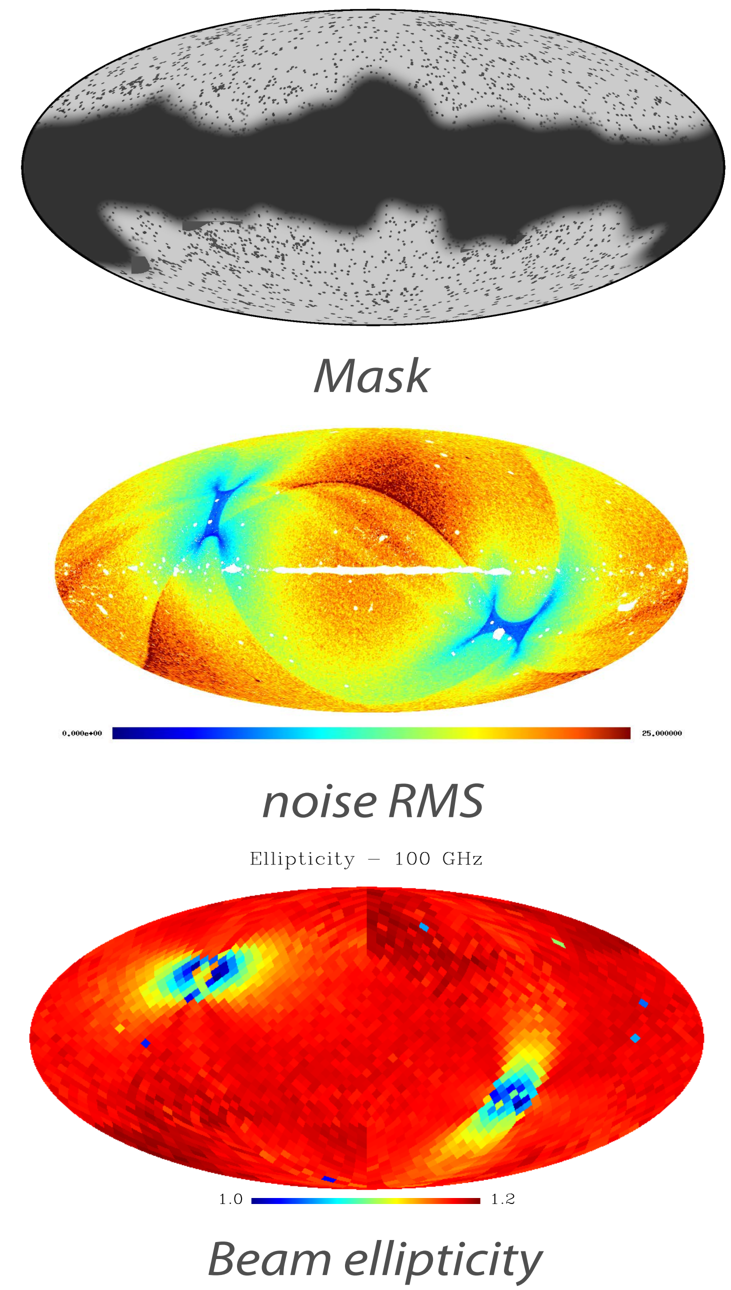


- This information lead to a ~20% gain in cosmological parameters

Planck 2013 Results. XVII

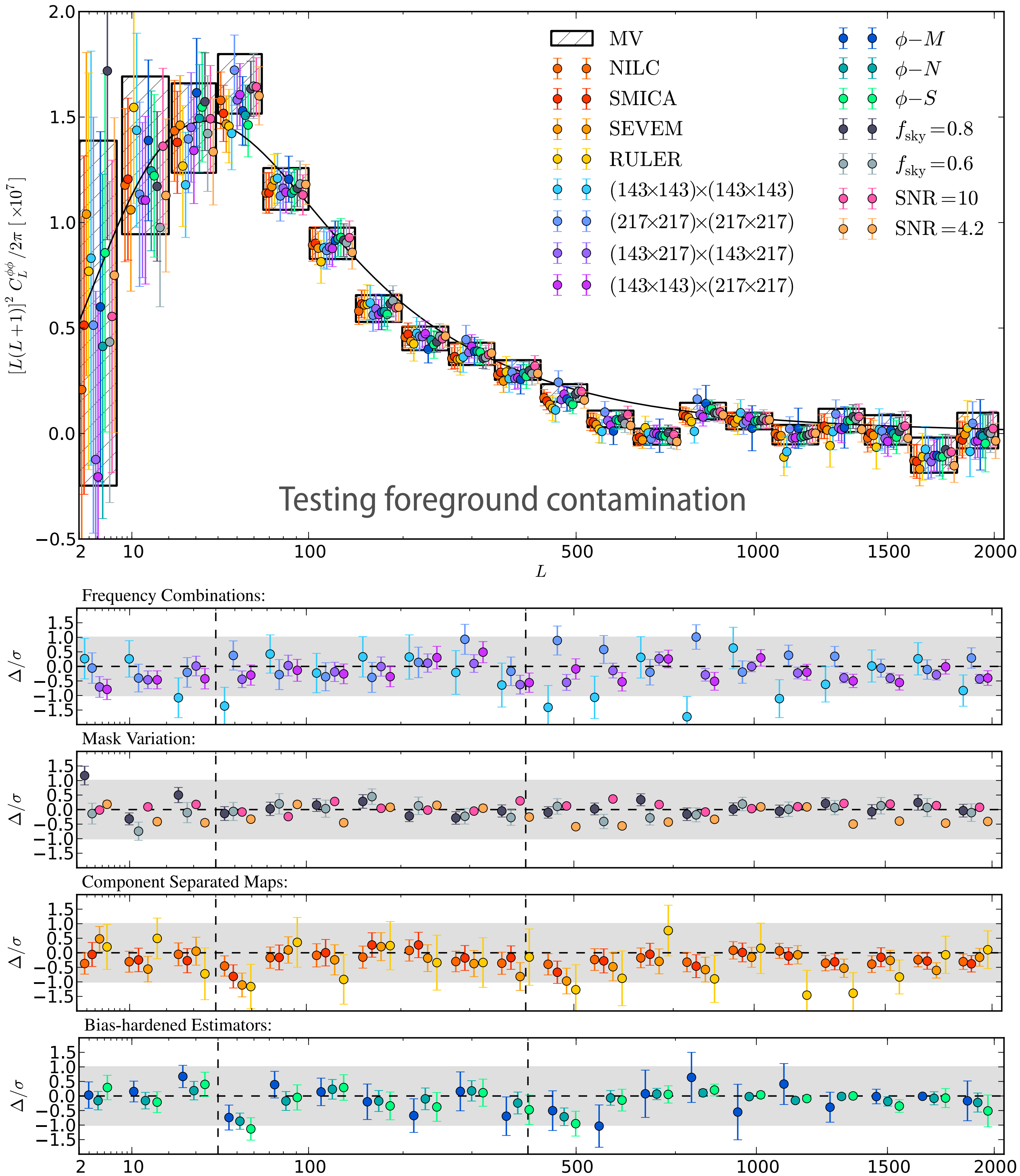
Multiple Bias at the Map Level



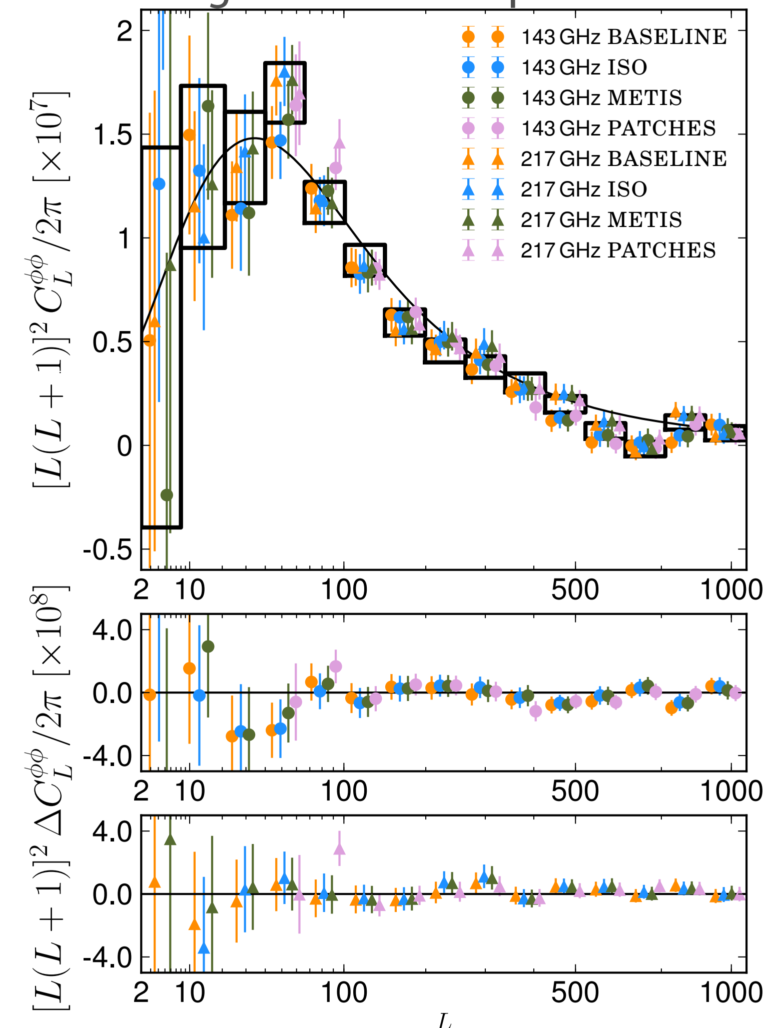


- The quadratic estimator responds to other sources of statistical anisotropies.
- They creates biases that dominate on the largest scales.
- These biases can be corrected by calibrating corrective terms using Monte-Carlos (and analytical guidance).

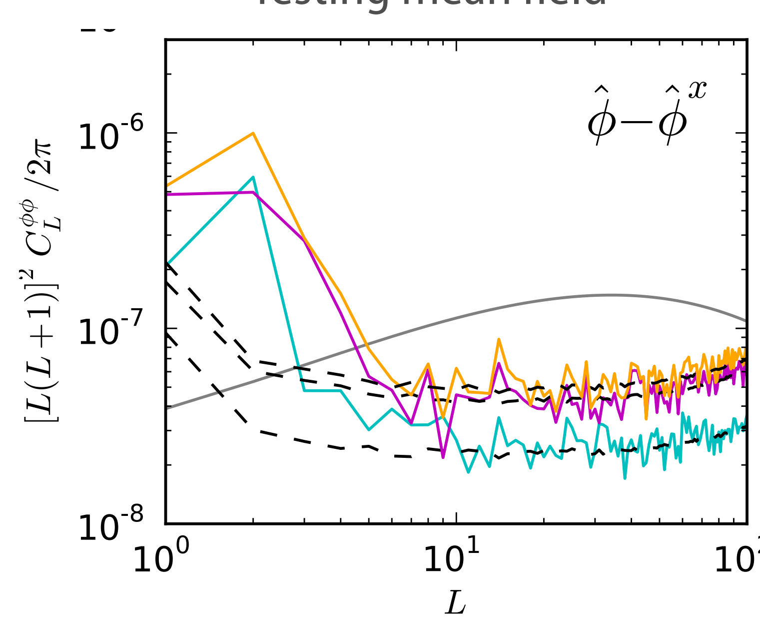
Lensing Reconstruction Robustness



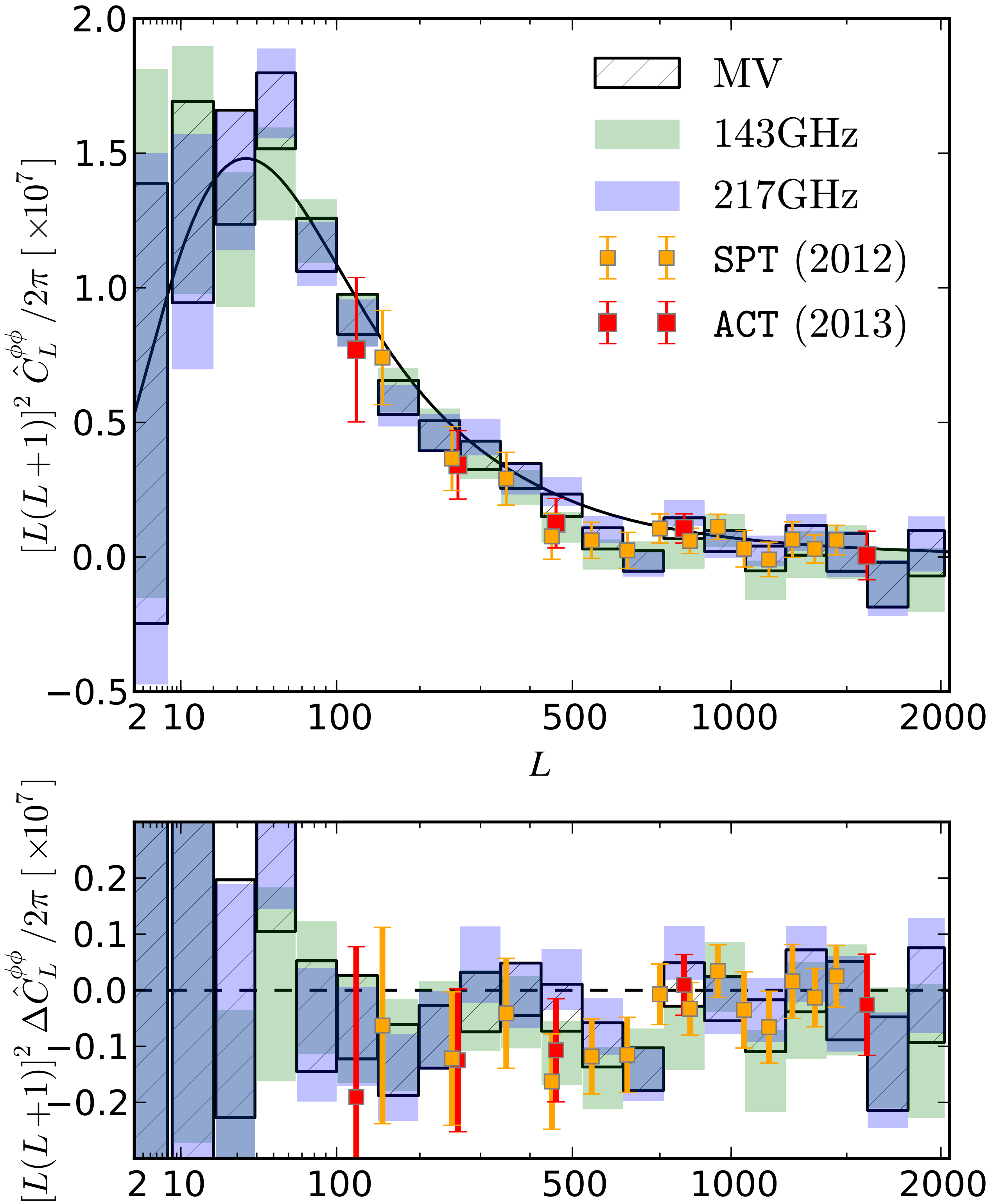
Testing the filter & implementation



Testing mean field

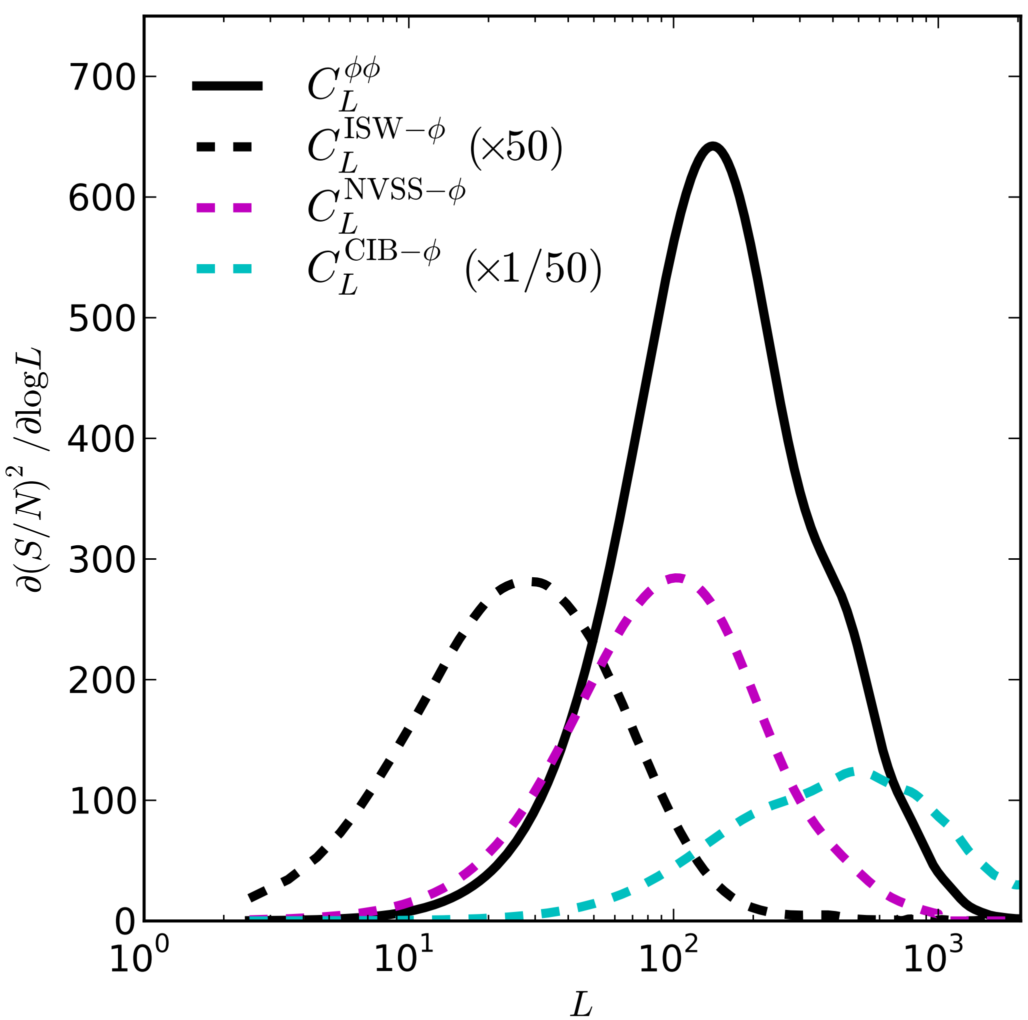


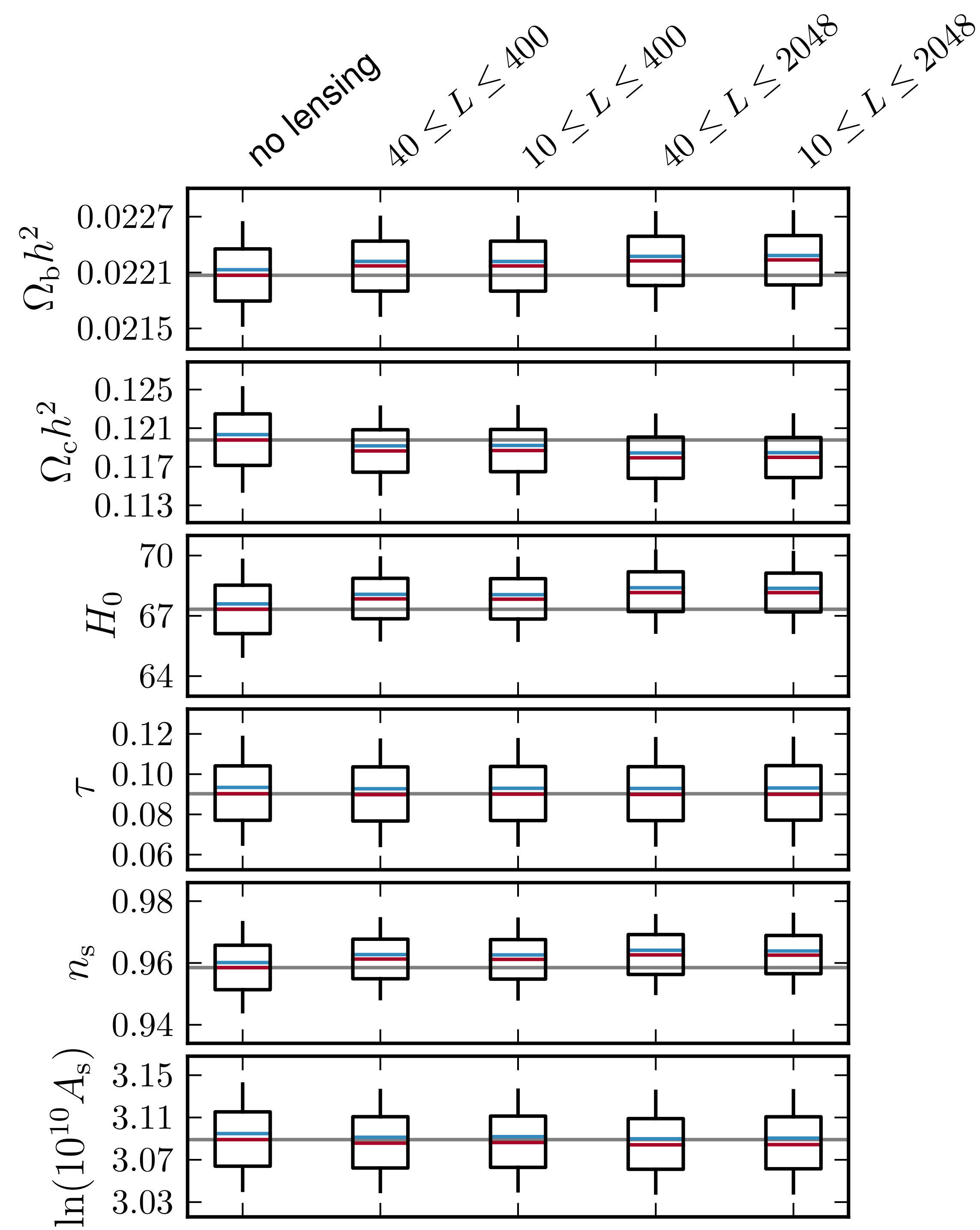
Comparison with ACT and SPT



CMB Lensing Cosmology

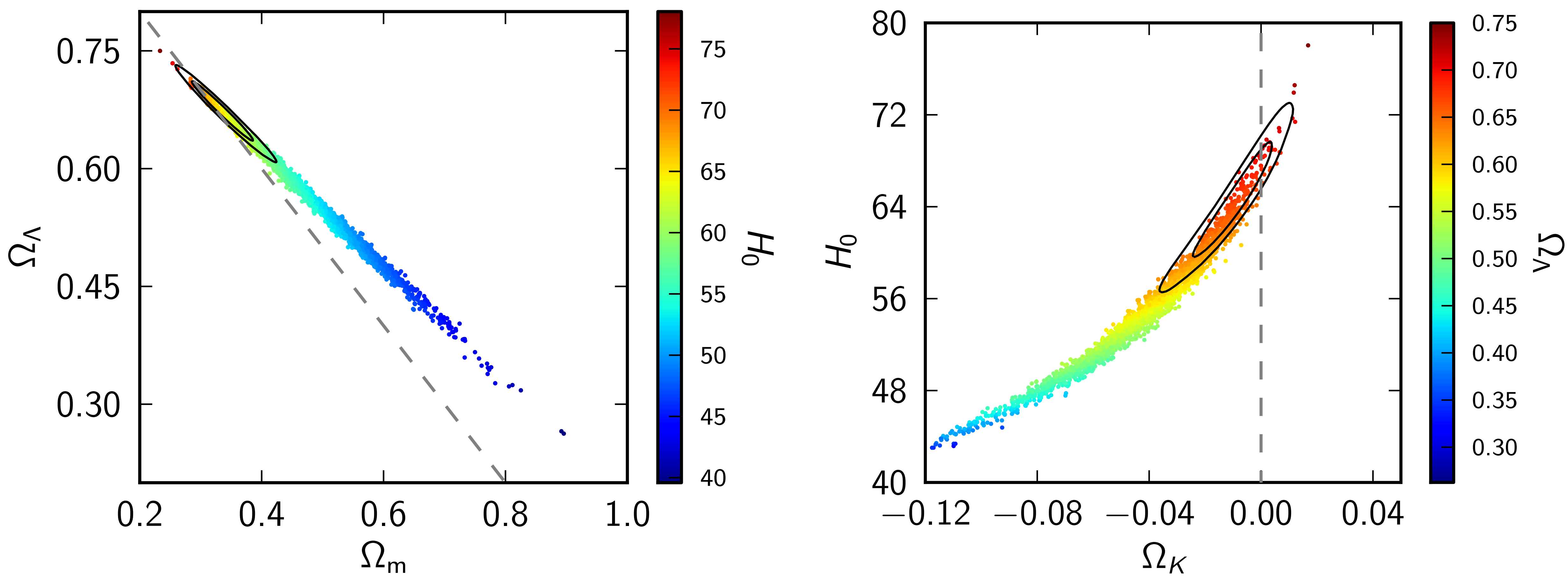
- Using only the most robust part of the CMB lensing spectra, we get a ~20% improvement on cosmological parameters





Breaking the Angular Diameter Degeneracy

- CMB lensing breaks the angular diameter degeneracy, leading to:
  - ➡ Factor of 2 improvement on curvature constraints.
  - ➡ Factor of 2 improvement on DE constraint.

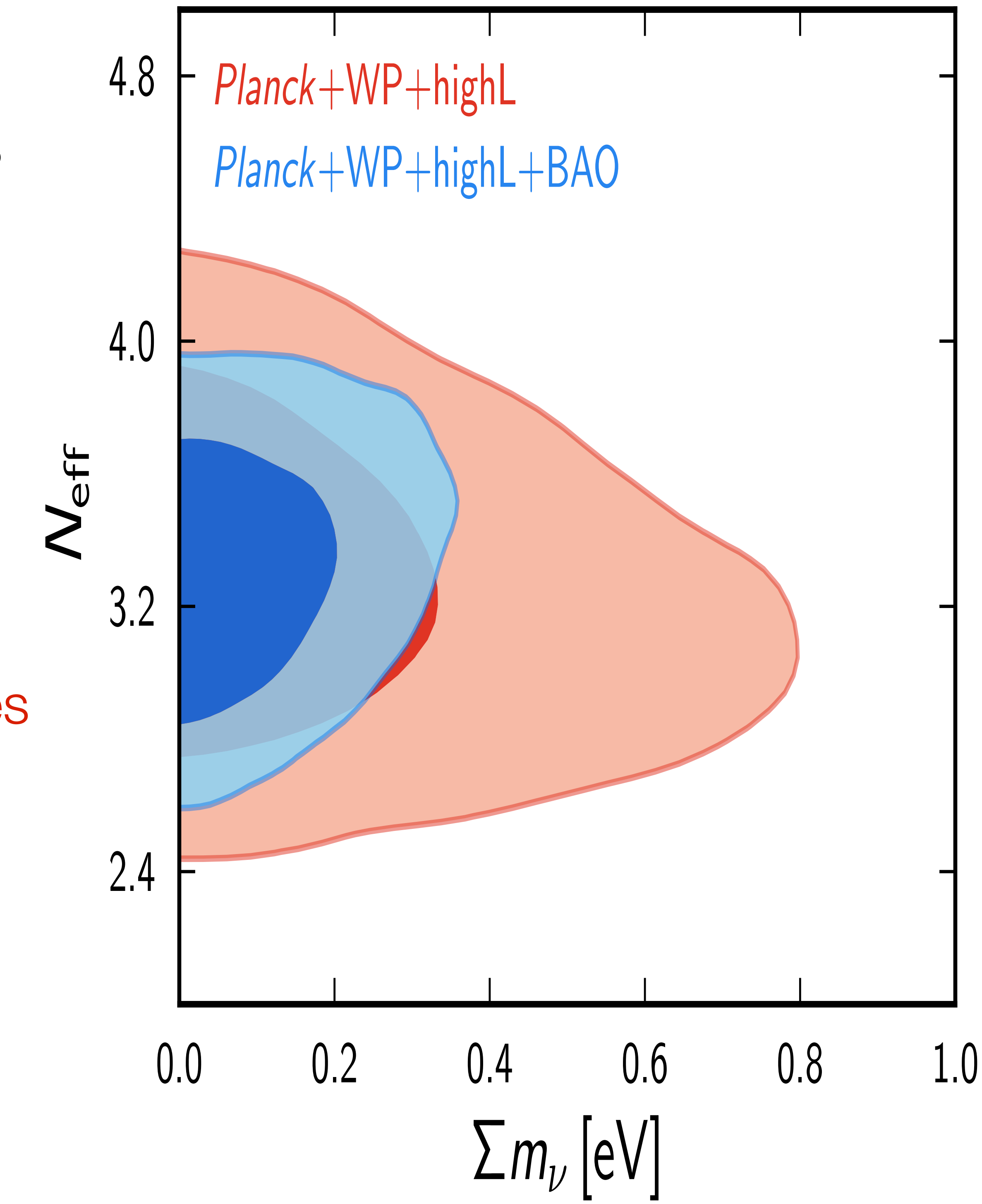


$$\Omega_\Lambda = 0.57^{+0.073}_{-0.055} \quad (68\%; \textit{Planck}+\text{WP}+\text{highL})$$

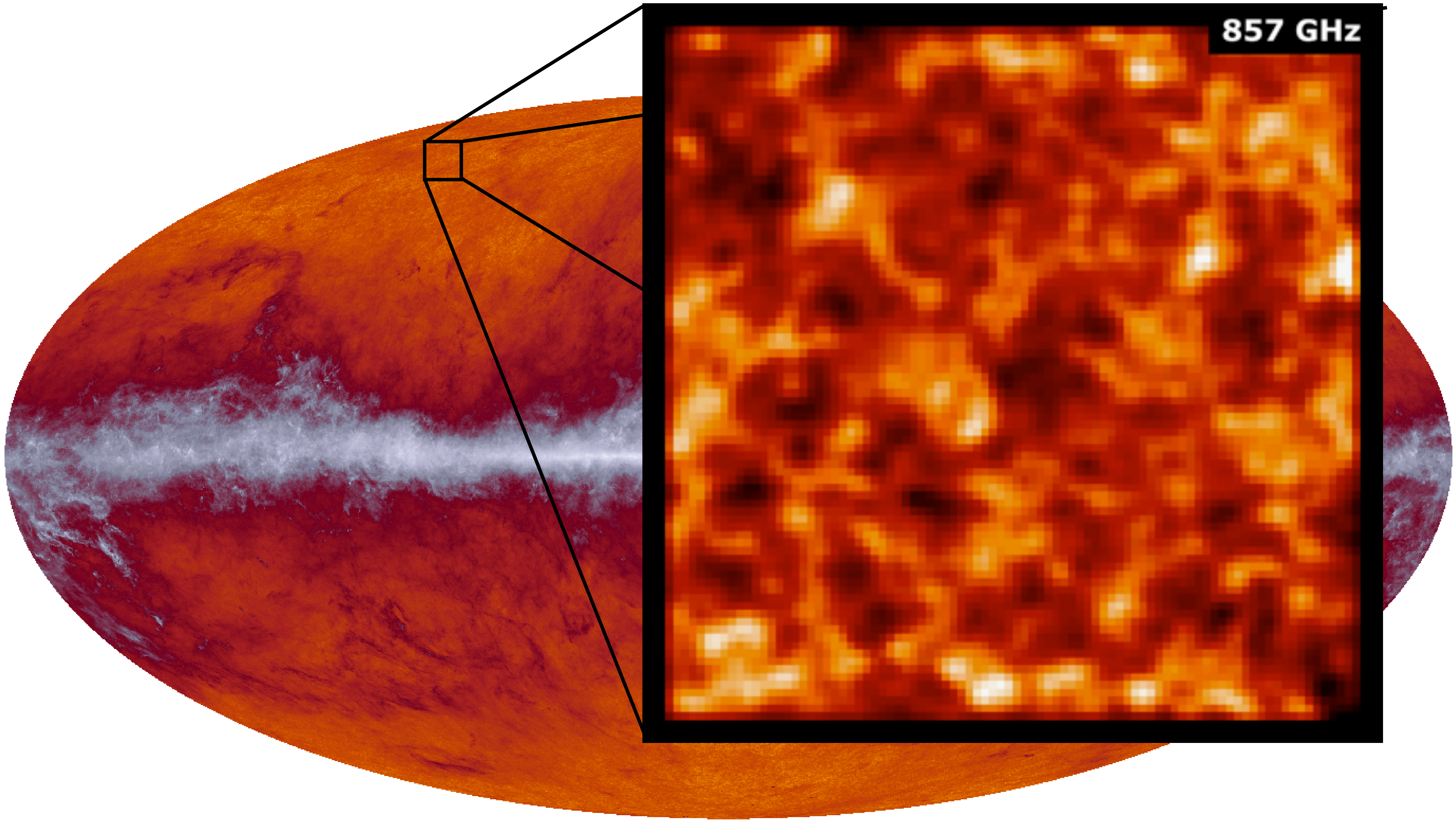
$$\Omega_\Lambda = 0.67^{+0.027}_{-0.023} \quad (68\%; \textit{Planck}+\text{lensing}+\text{WP}+\text{highL})$$

Constraining Neutrino Masses

- Neutrinos are still relativistic at recombination
- Lensing of the CMB allows to break this degeneracy and now drives $\Sigma\, m_\nu$ constraints:
  - ➡ Using C_l^{TT} only:
    - $\Sigma\, m_\nu < 0.66$ eV (95%; Planck+WP +high L)
    - $\Sigma\, m_\nu < 0.23$ eV (95%; +BAO)
  - ➡ Adding the Planck lensing “reconstruction” (trispectrum) increases the limit however.
    - $\Sigma\, m_\nu < 0.85$ eV (95%; Planck+WP +high L+ lensing)
- SZ clusters, assuming nominal mass calibration, prefer non-zero neutrino mass:
  - ➡ $\Sigma\, m_\nu = 0.22 \pm 0.09$ eV (68%)

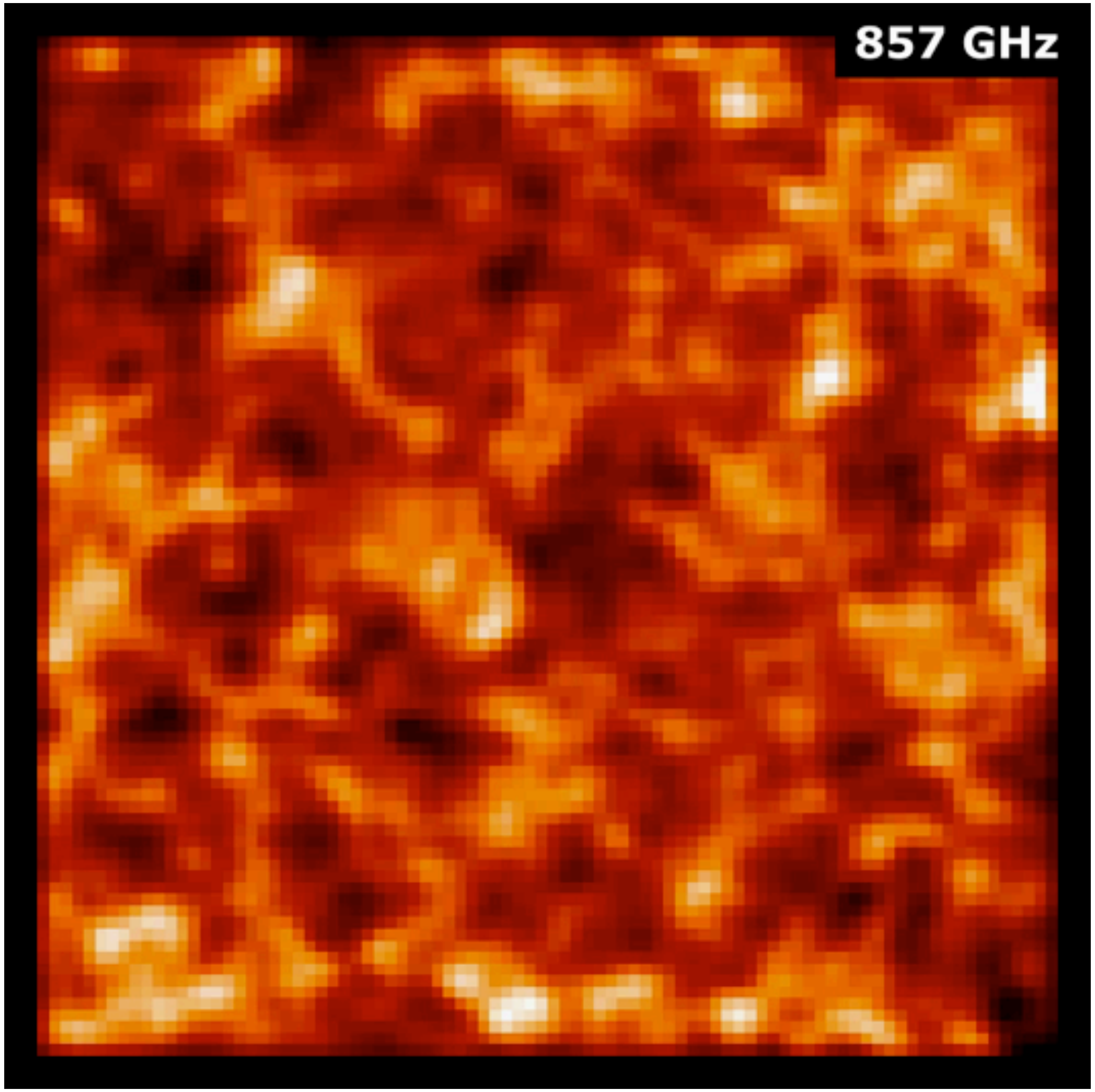


Planck Maps Exquisitely (Extra-)Galactic Dust



- At 545 GHz (~550 μm) (and all frequencies above 143 GHz), a large fraction of the signal we are mapping is composed of galactic dust *and* of the Cosmic Infrared Background (CIB).
- The CIB represents the cumulative emission of high-*z*, dusty, star forming galaxies.

Planck CIB maps at 217, 353, 545 and 857 GHz

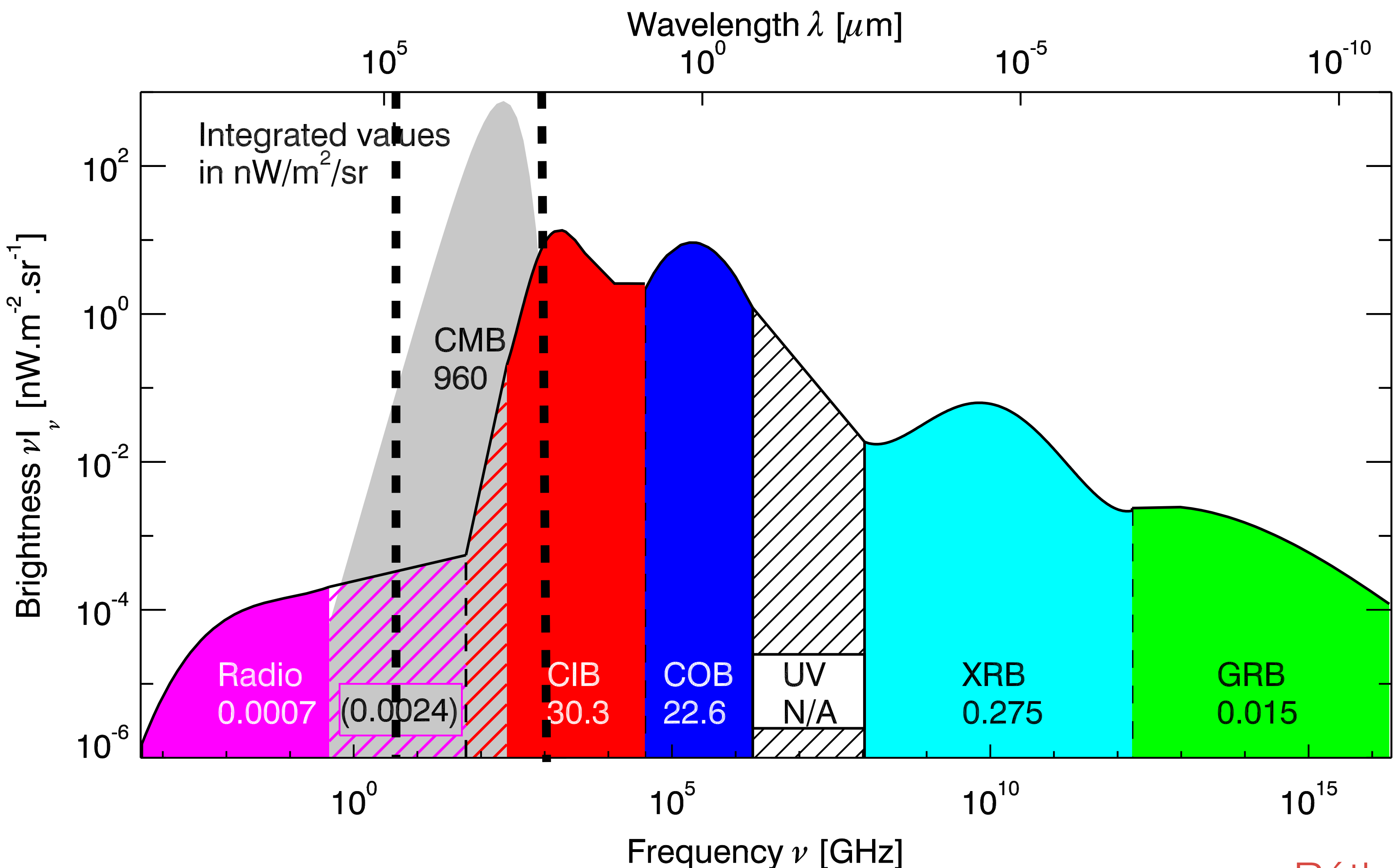


5 deg.

- High SNR sub-degree structures at all frequencies.
- Assuming sources at z~1.5, we are seeing clustering at 10 Mpc/*h* (k~0.1 *h*/Mpc).
- Structures partially correlated across frequencies.
- Clearly of cosmological interest!

Planck Early Results XVIII

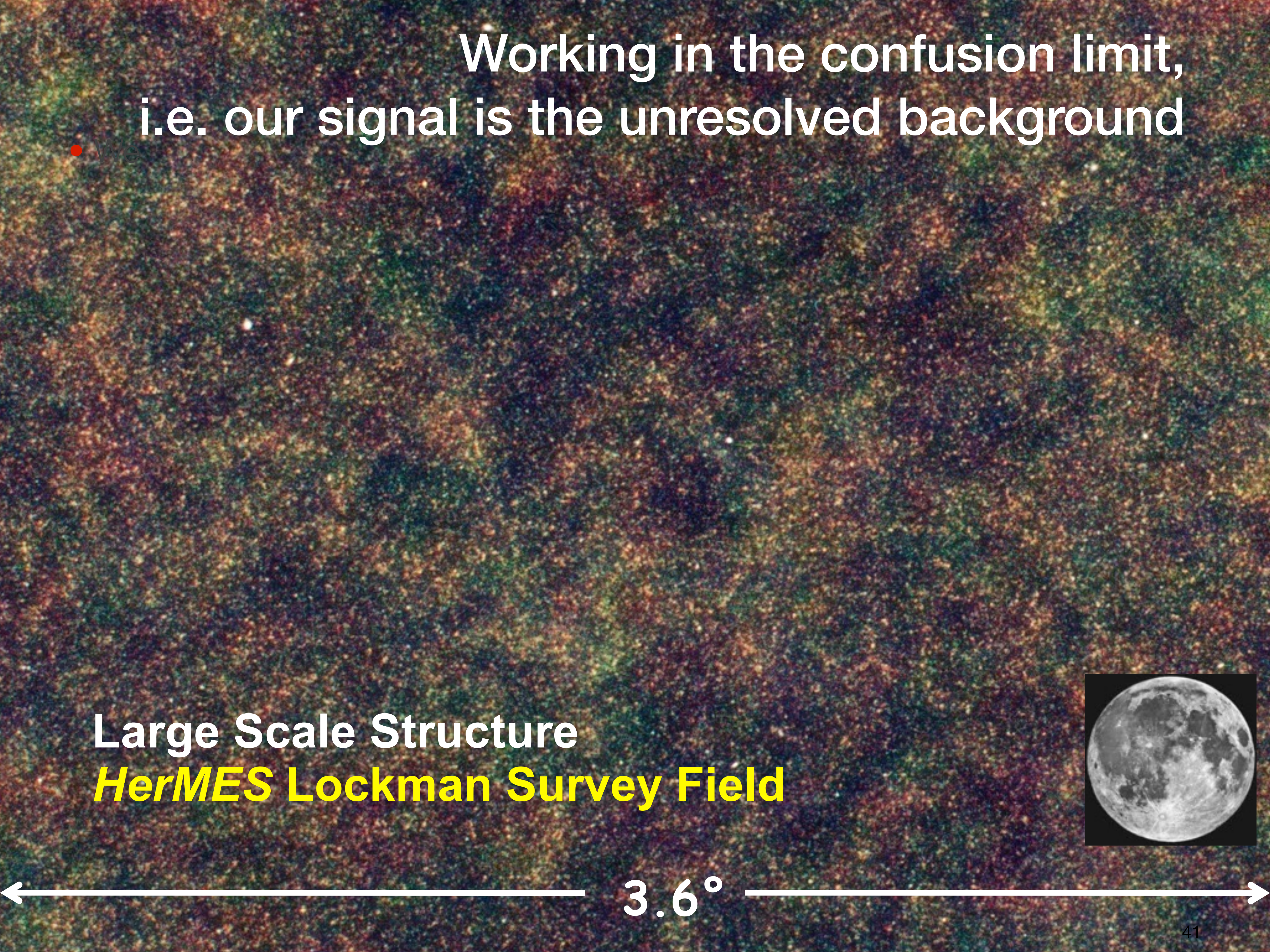
A Bright (Far-)Infrared Sky



Béthermin & Dole in prep.

- The CIB and the COB have equal contributions, instead of ~1/3 for local galaxies.
  - ➡ IR luminosity increases with *z* faster than optical luminosity because of the increased star formation rate at higher z.
- Over half of the energy produced since the surface of last scattering has been absorbed and re-emitted by dust.

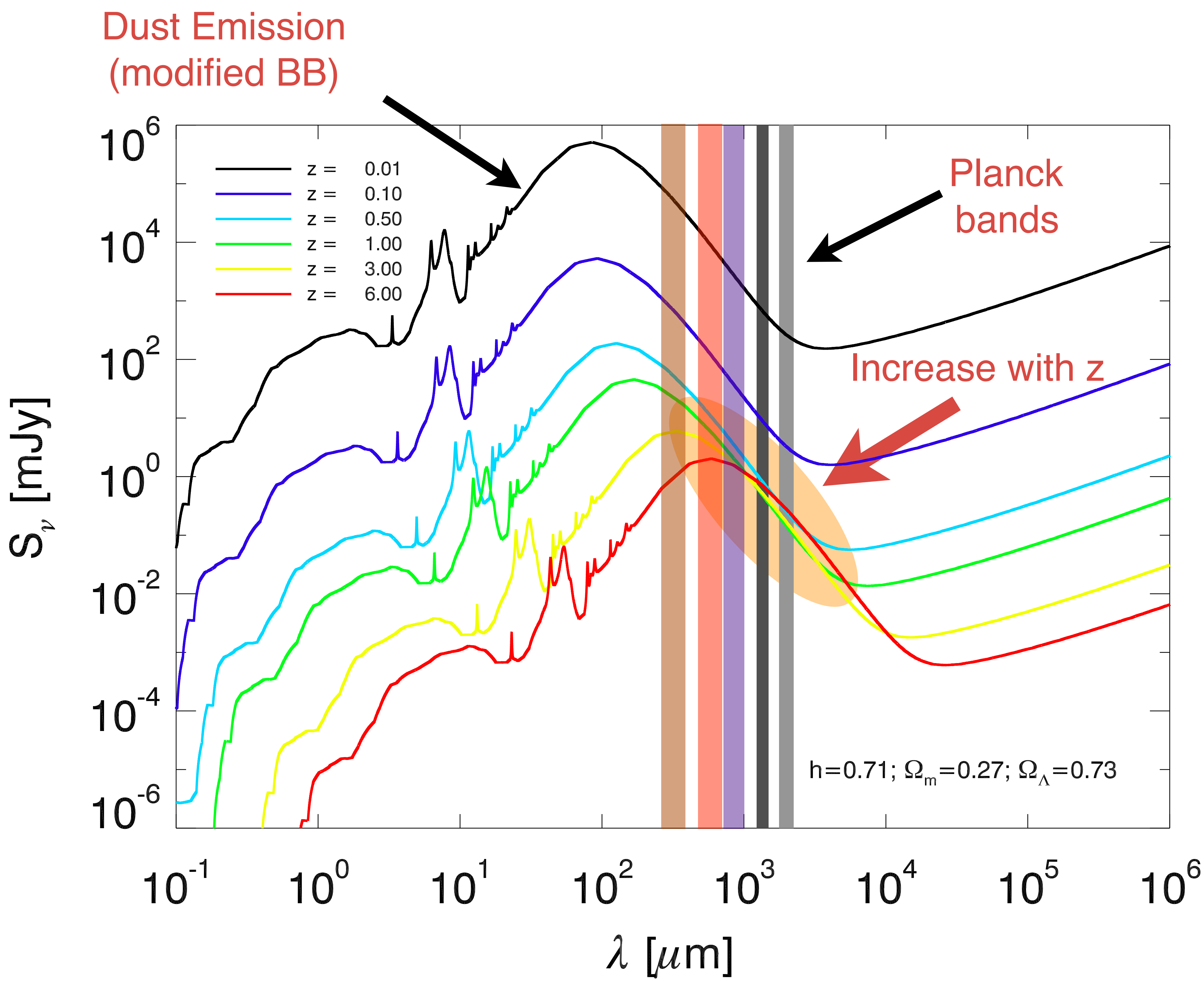
Working in the confusion limit, i.e. our signal is the unresolved background



Large Scale Structure

HerMES Lockman Survey Field

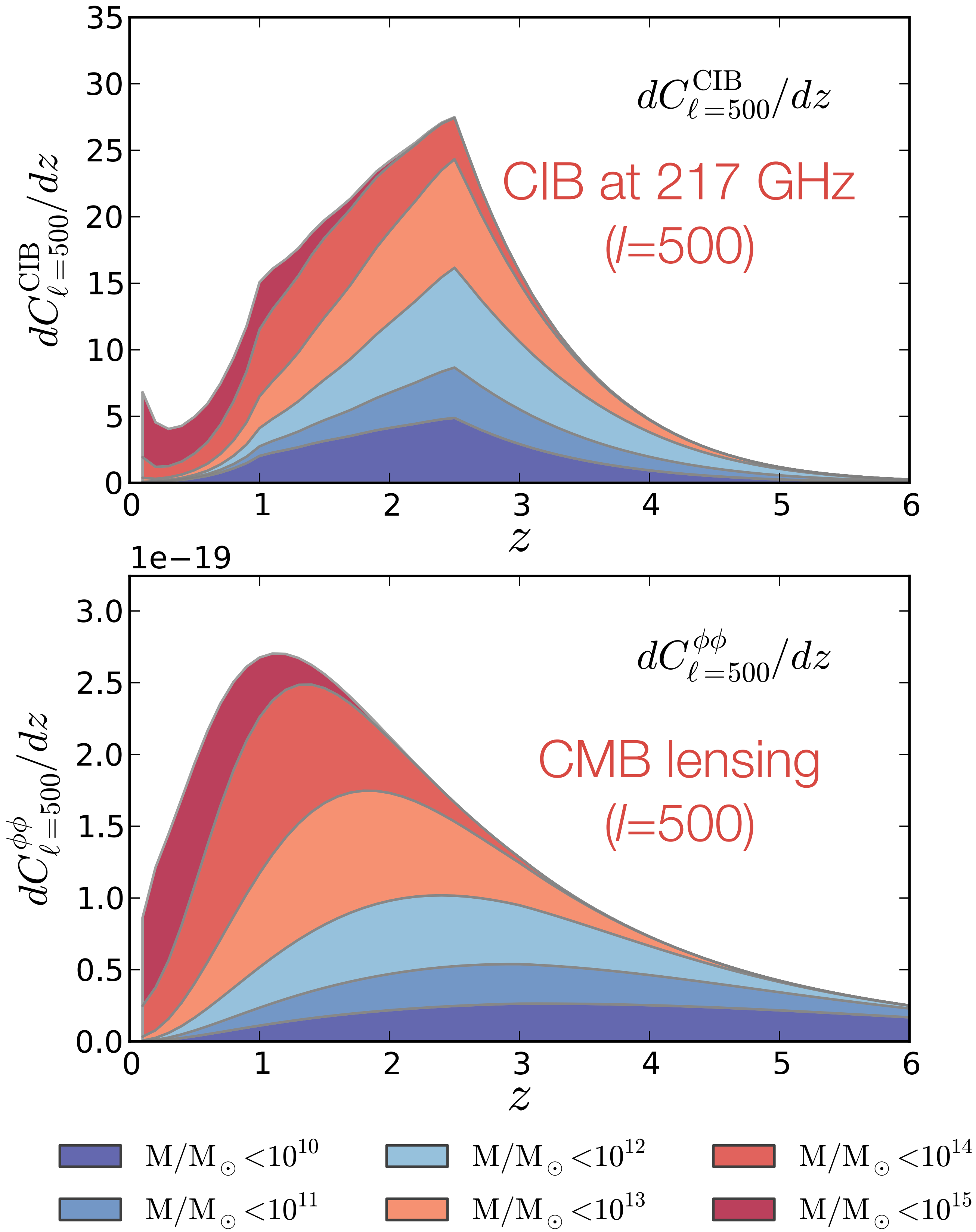
Arp 220 scaled with Redshift



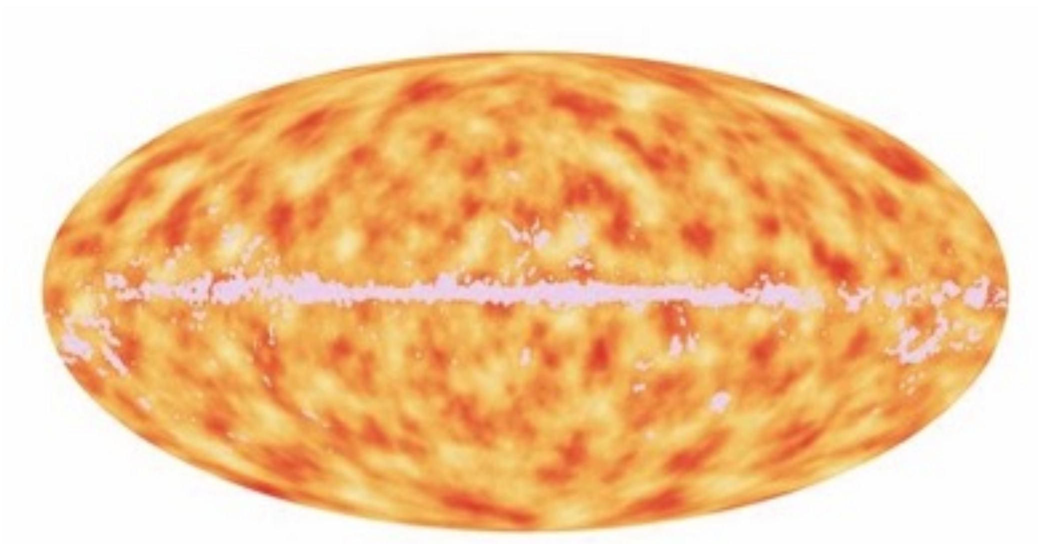
Courtesy J. Viera

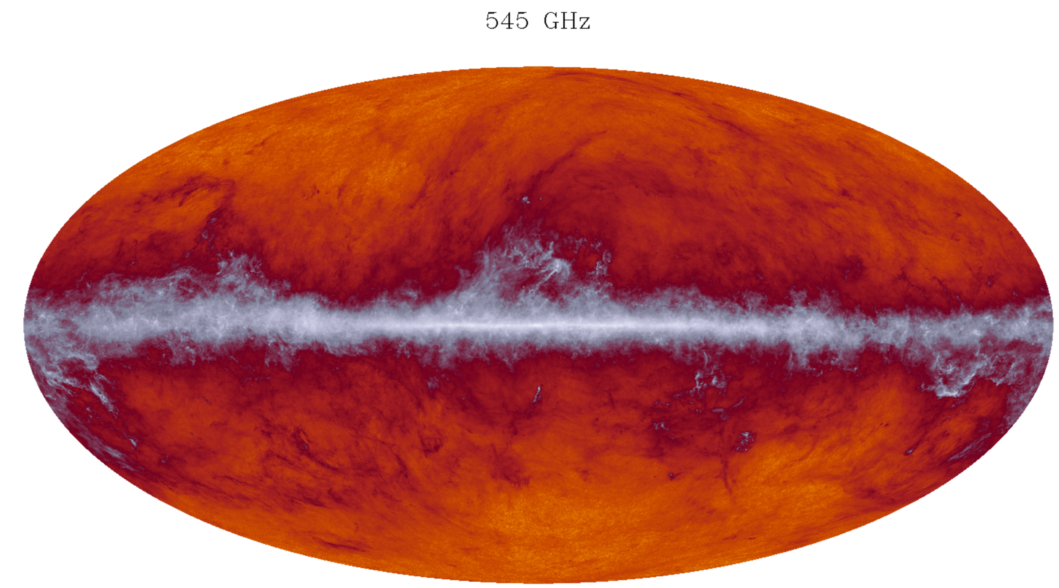
CIB Redshift and Mass Dependence

- CIB is the dominant extragalactic foreground at high frequency and is produced by the redshifted thermal radiation from UV-heated dust.
- The CIB is a thus a good probe of the SFR at high redshift.
- This signal was highlighted early on by Partridge & Peebles 67:
  - ➡ The *monopole* was discovered by Puget++96 (FIRAS) and Hauser++98 (DIRBE).
  - ➡ Tremendous progress in the last few years mapping *correlated fluctuations* in Spitzer (Lagache++07), Blast (Viero++09), Herschel (Viero++12), Planck, SPT (Hall++11) and ACT (Das++12).
  - ➡ Planck adds low frequencies, i.e., high-z, and large scales (see e.g., Planck Early Results XVIII)
- The fluctuations in this background trace the large-scale distribution of matter, and so, to some extend the clustering of matter at high-z
- This led Song++02 to posit a correlation between CIB and CMB lensing.



Investigating The CMB Lensing - CIB Correlation

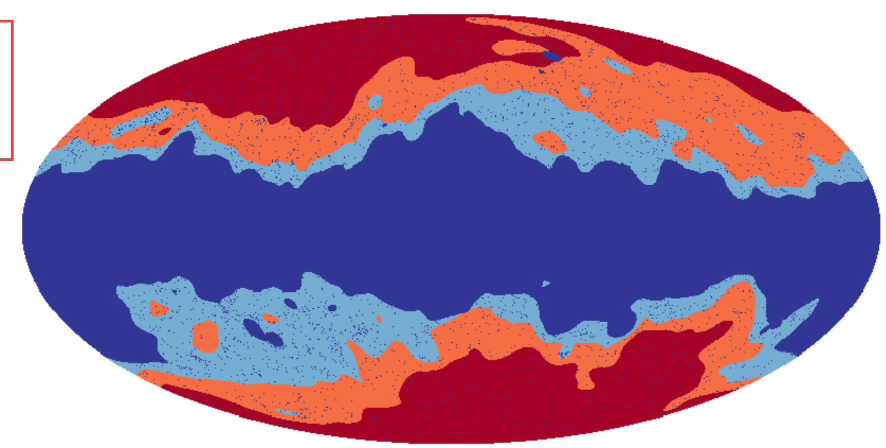




$$\sum_{\ell m} \tilde{\phi}_{\ell m} Y_{\ell m}(x) = \nabla^a \left[\alpha(x) \nabla_a \beta(x)\right]$$

$$\alpha(x) = \sum_{\ell m} \tilde{a}_{\ell m} Y_{\ell m}(x)$$

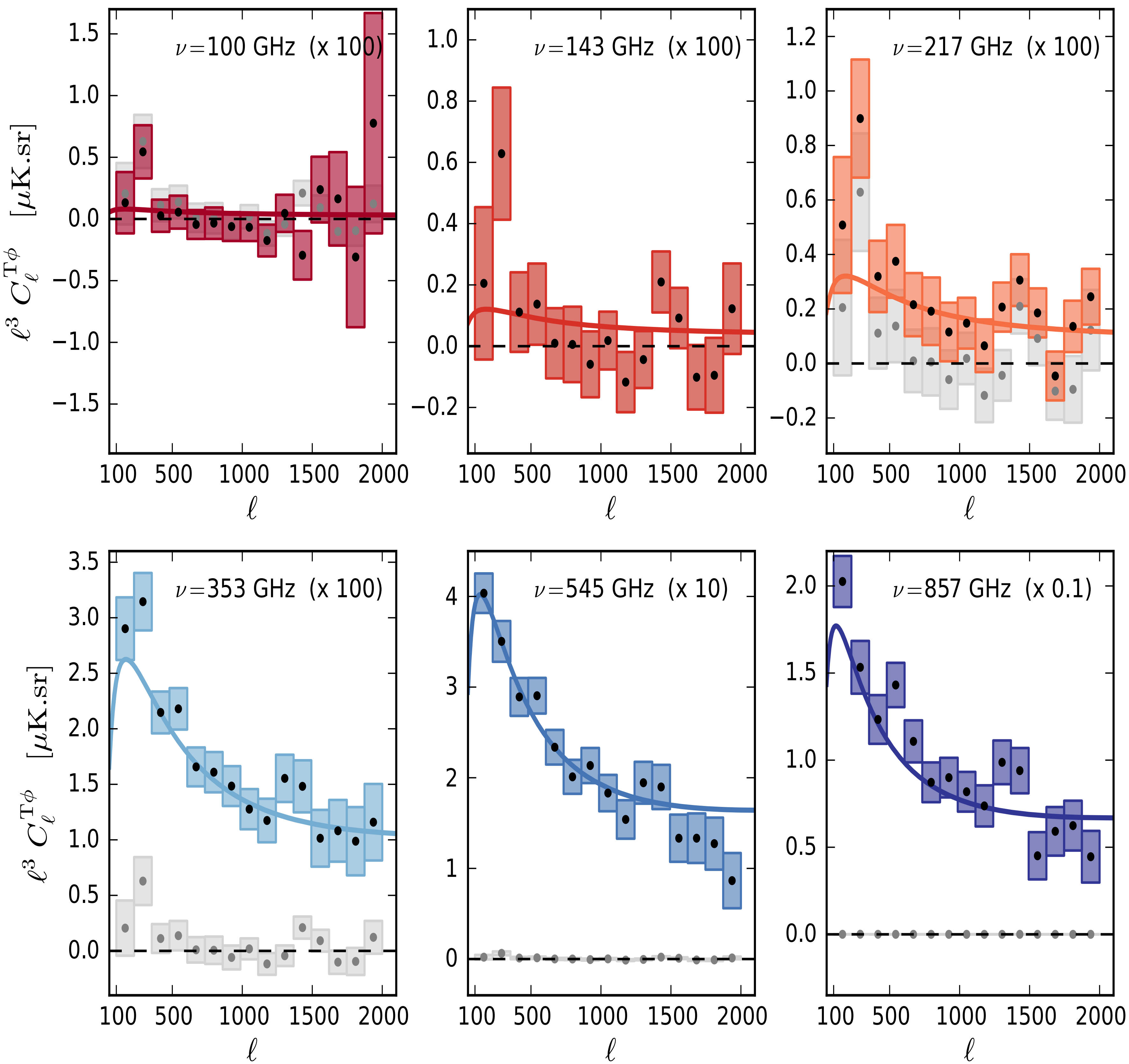
$$\beta(x) = \sum_{\ell m} C_\ell^{TT} \tilde{a}_{\ell m} Y_{\ell m}(x)$$



$$C_b^{\Phi T} = \frac{1}{N_b} \sum_{l \in b} \sum_{|m| \leq \ell} \frac{1}{\ell^2} \left(\hat{\Phi}_{\ell m} T_{\ell m}\right)$$

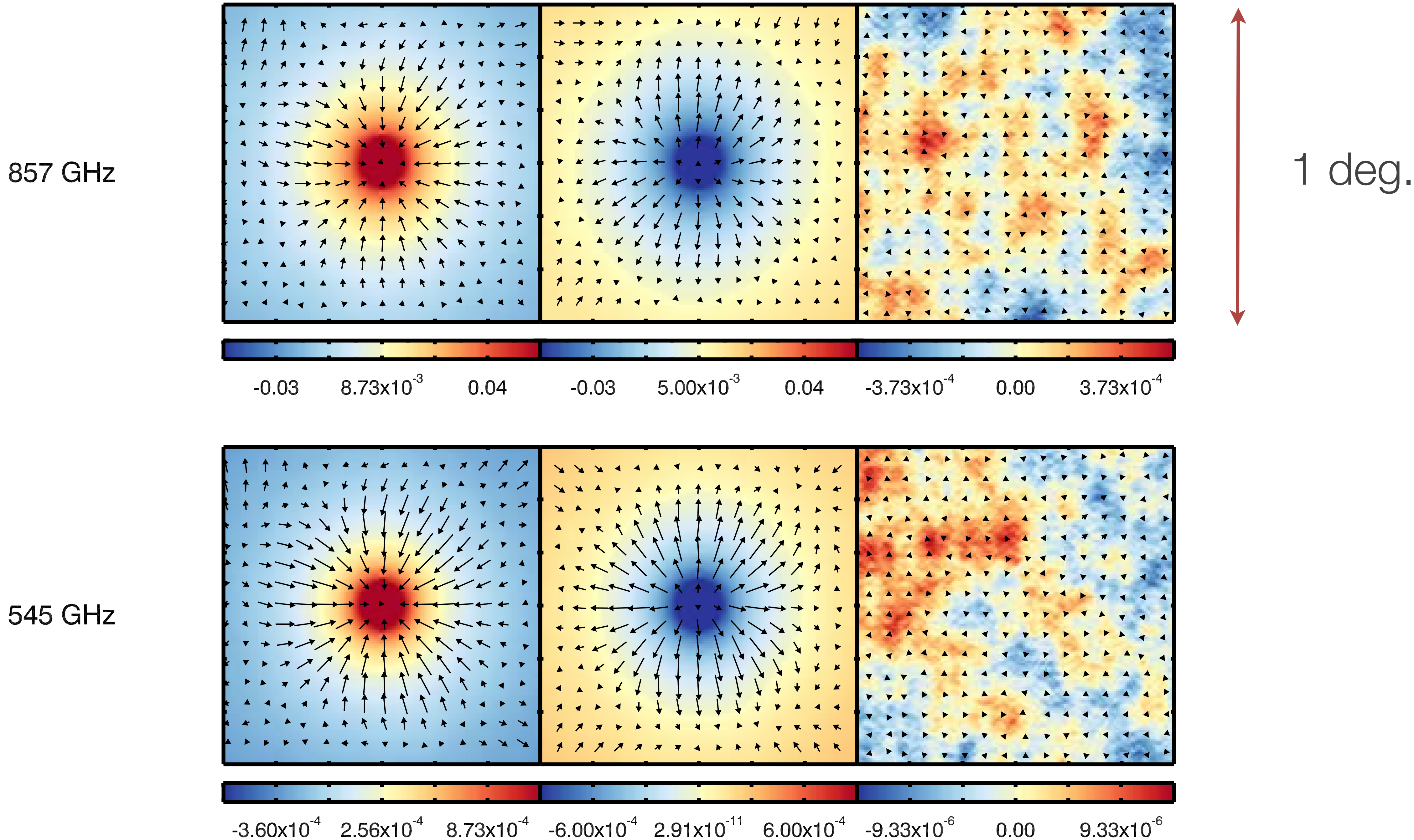
- The correlation of the inverse variance weighted reconstructed lensing potential with the temperature map is equivalent to the optimal bispectra (Smith++08).

Lensing Potential and Temperature are Correlated



- Statistical error bars only.
- Grey boxes correspond to the 143 GHz based lensing potential reconstruction x 143 GHz temperature map as a systematic proxy.
- The colored solid curves correspond to the signal prediction based on the Planck Early paper model.
- Cross-correlation enables the use of a large area of the sky (40%).

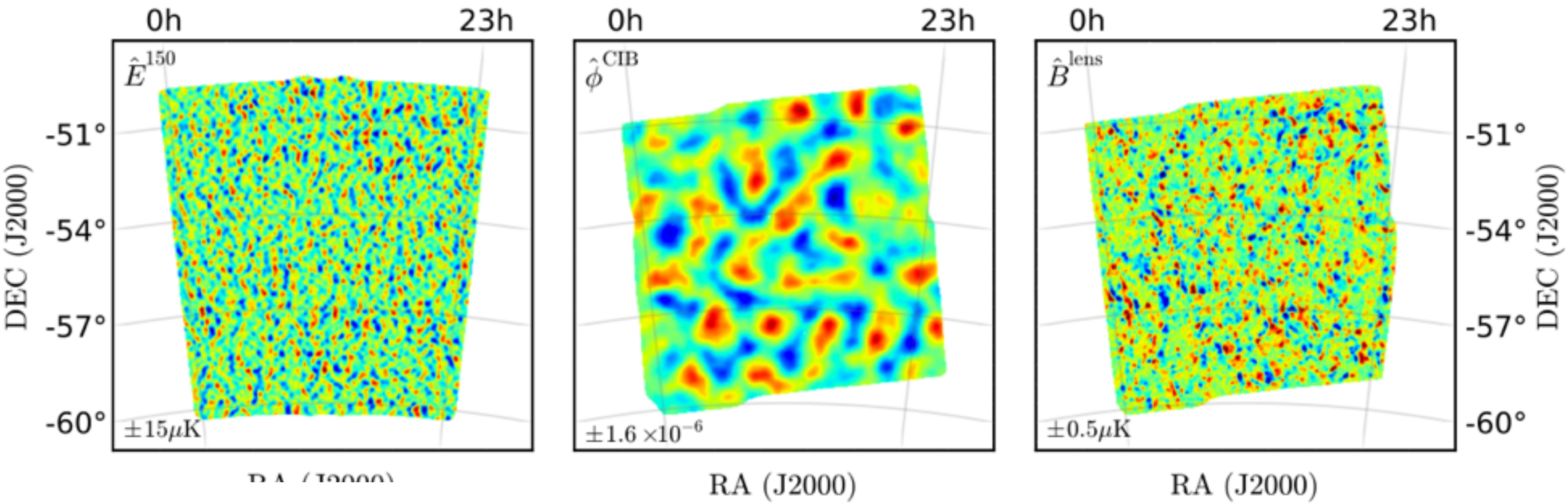
Using the CIB to “See” the Lensing of the CMB

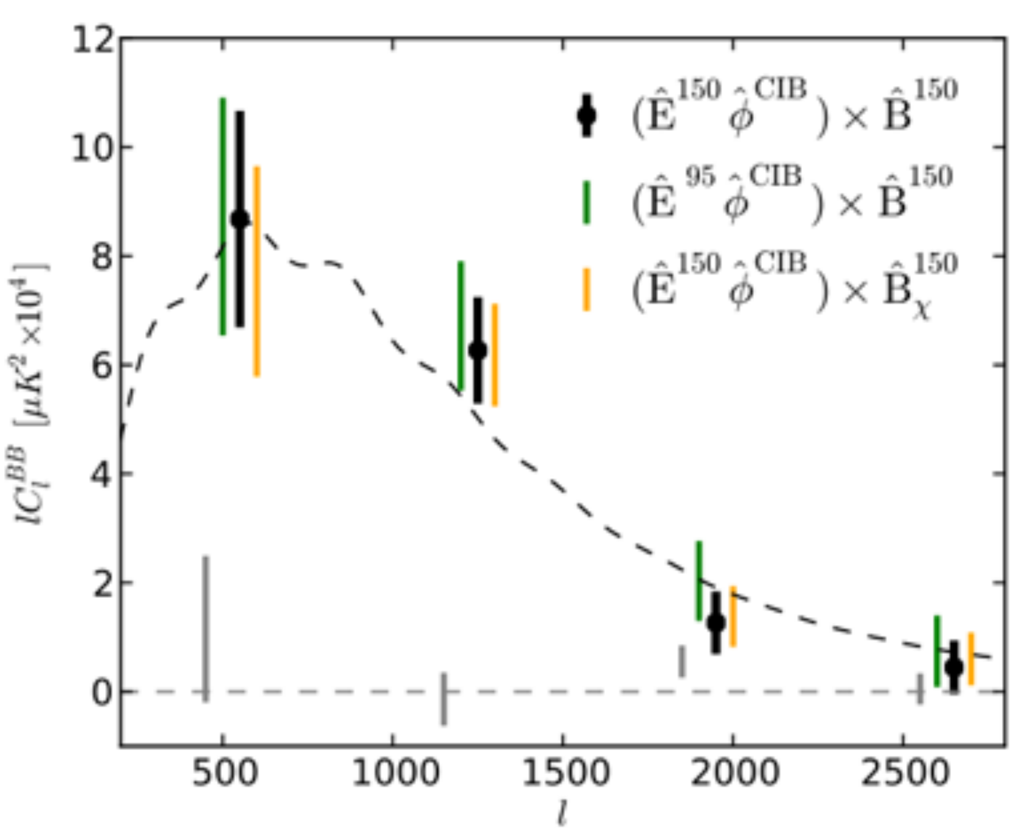


Stacking on: 20,000 T extrema | 20,000 T minima | Random location

- Stacking on 20,000, band-pass filtered, 1 deg. wide patches.
- We see the expected relation between light, matter and deflection angles.
- Incidentally, probably the first detection of lensing by voids (e.g., Krause++12).

SPT x Herschel: Detecting Lensing B-modes





- Thanks to 90 sq. deg. of overlapping SPT and Herschel observations (PI: Joaquin Vieira).
- Leads to a ~7σ first detection of lensing B modes, the first cosmological B modes!
- Foretaste of what we will be doing with DES and SPT-Pol, SPT-3G and S4.

SPT Pol, Hanson++13

Why are Large Scale Structure Survey Important?

- Cosmological inference is a statistical method:
  - ➡ The information content is ∝ # of independent modes.
- For CMB temperature, information comes from 2D sampling:
  - ➡ # modes ∝ $(2l_{max}+1)l_{max}$.
  - ➡ CMB is fundamentally band limited so that # modes is ≲ 6.e6 .
- For galaxy survey, the information comes from 3D sampling:
  - ➡ # modes ∝ $V_{effective}$

$$V_{eff} = V_{physical} \left(\frac{nP}{1+nP} \right)^2$$

$$N_{modes} = V_{eff} \frac{\frac{4}{3}\pi k_{max}^3}{(2\pi)^3}$$

LSS Surveys are Catching up with Planck

Survey	V_{eff} [Gpc/h]^3	# modes
Planck	N/A	$6.6x10^6$
SDSS-1	0.13	$1.8x10^4$
SDSS-2	0.26	$3.5x10^4$
BOSS (complete)	2.3	$3.1x10^5$
SuMIRe (PFS+HSC)	2.5	$3.4x10^5$
DESI	28	$3.8x10^6$
Euclid (Spectro)	35	$4.7x10^6$

FIN