Probing High Redshift Star Formation with Planck

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on behalf of the Planck Collaboration

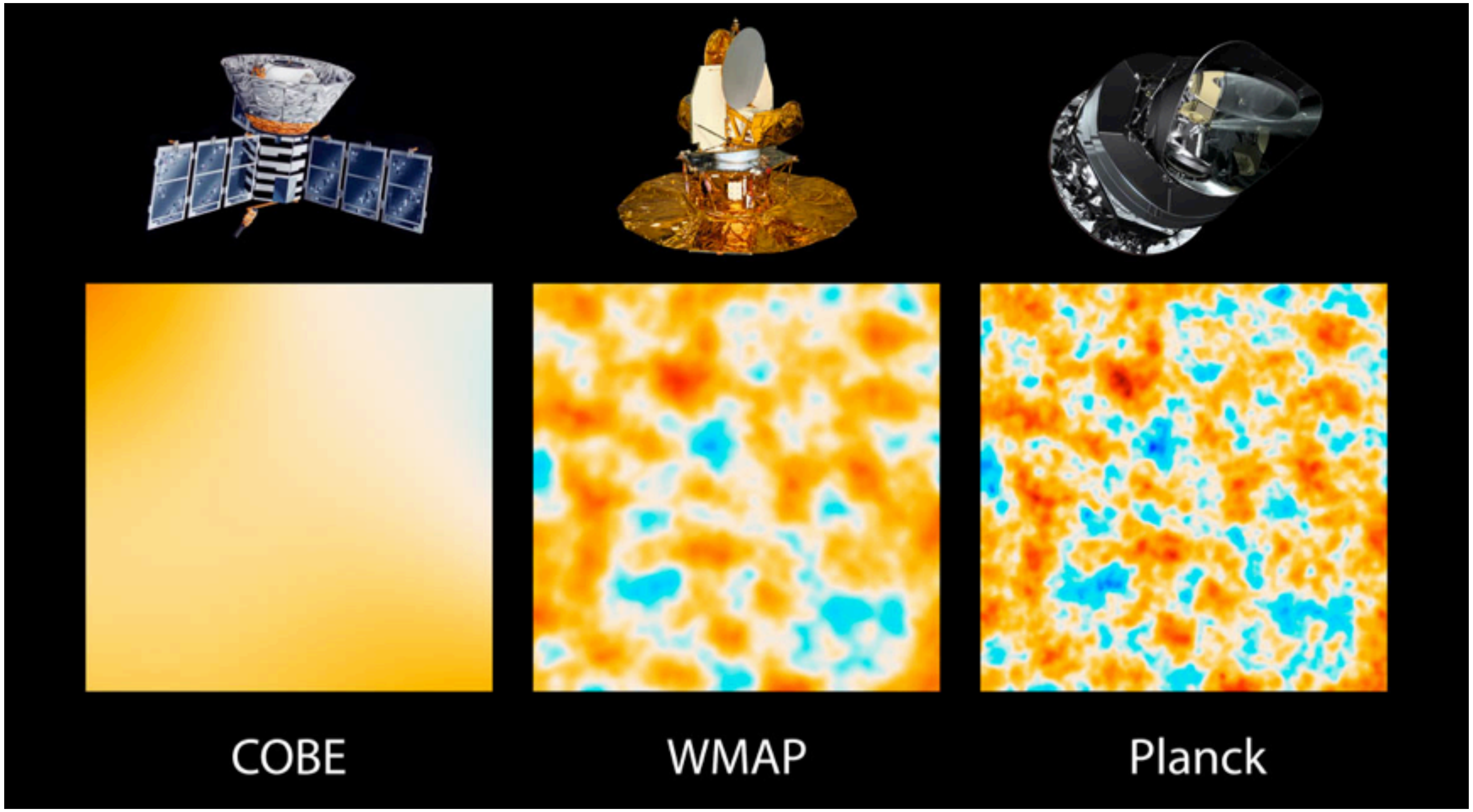
The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 100 scientific institutes in Europe, the USA and Canada

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

Outline

- A quick Planck overview.
- Probing large scale scale structure with Planck
  - ➡ The Cosmic Infrared Background (CIB) example.
- CIB induced cross-correlations:
  - ➡ The lensing of the CMB.
  - ➡ Galaxy surveys at multiple redshifts.
- SPHEREx:
  - ➡ A small satellite to map LSS in 3D and probe map Lya from first stars.

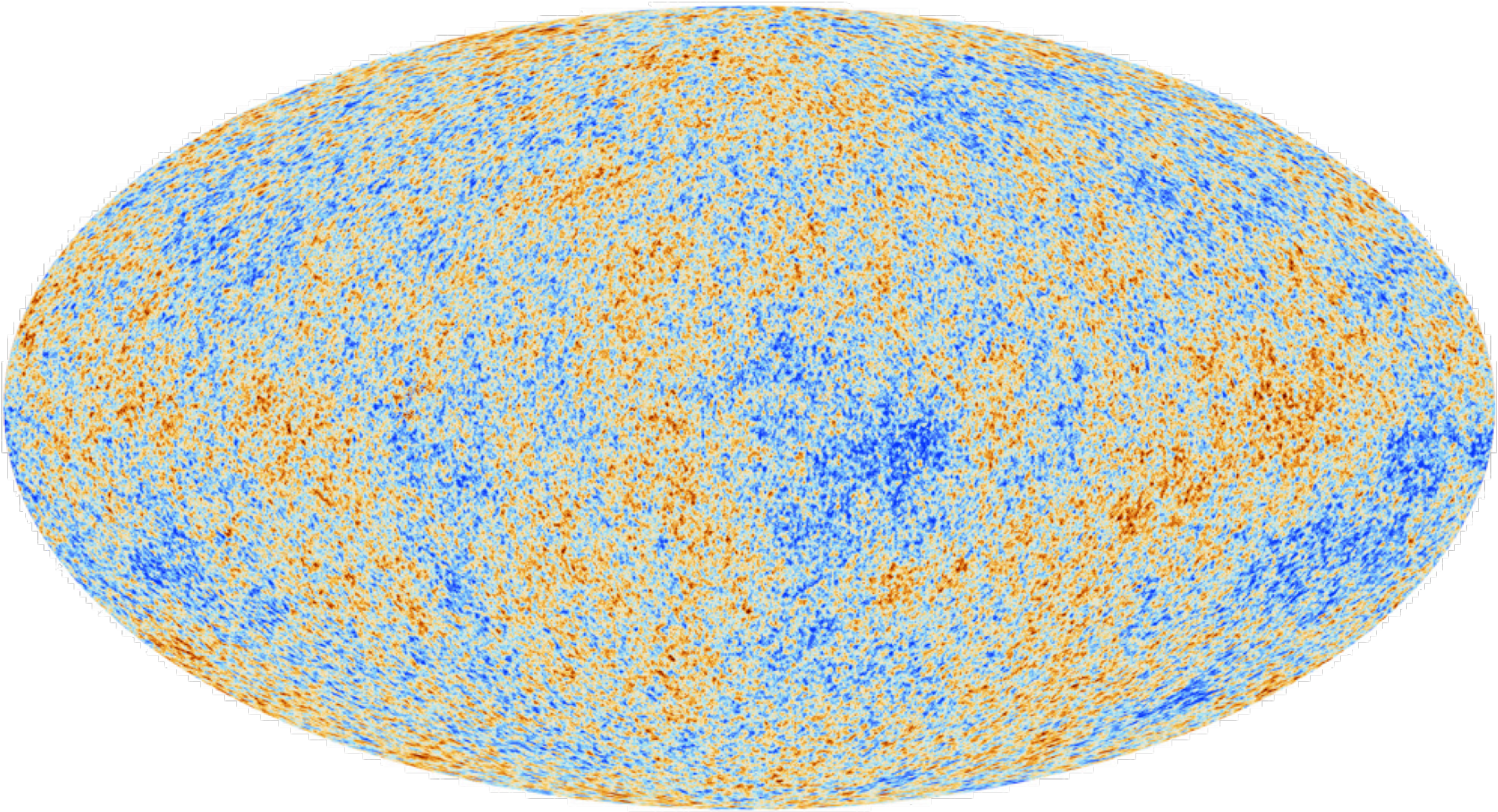
Planck, the 3d Generation CMB Satellite



- 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).

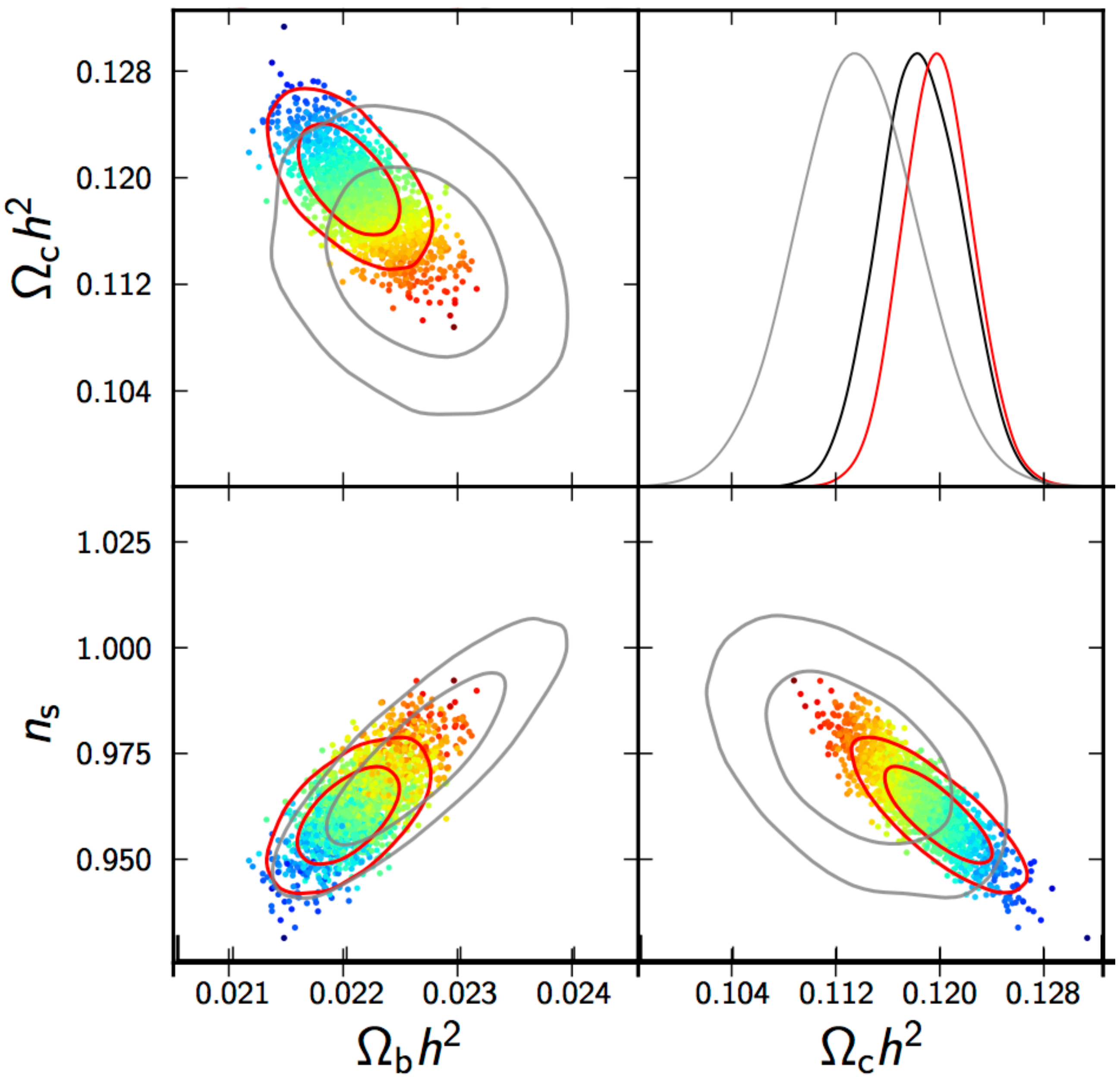
- To reach these goals required several technological breakthroughs in space:
  - ➡ Sensitive and fast bolometers, low noise read out, low and stable focal plane temperature (100 mK for HFI focal plane with < 20 nK.√Hz stability), low side lobes...

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?

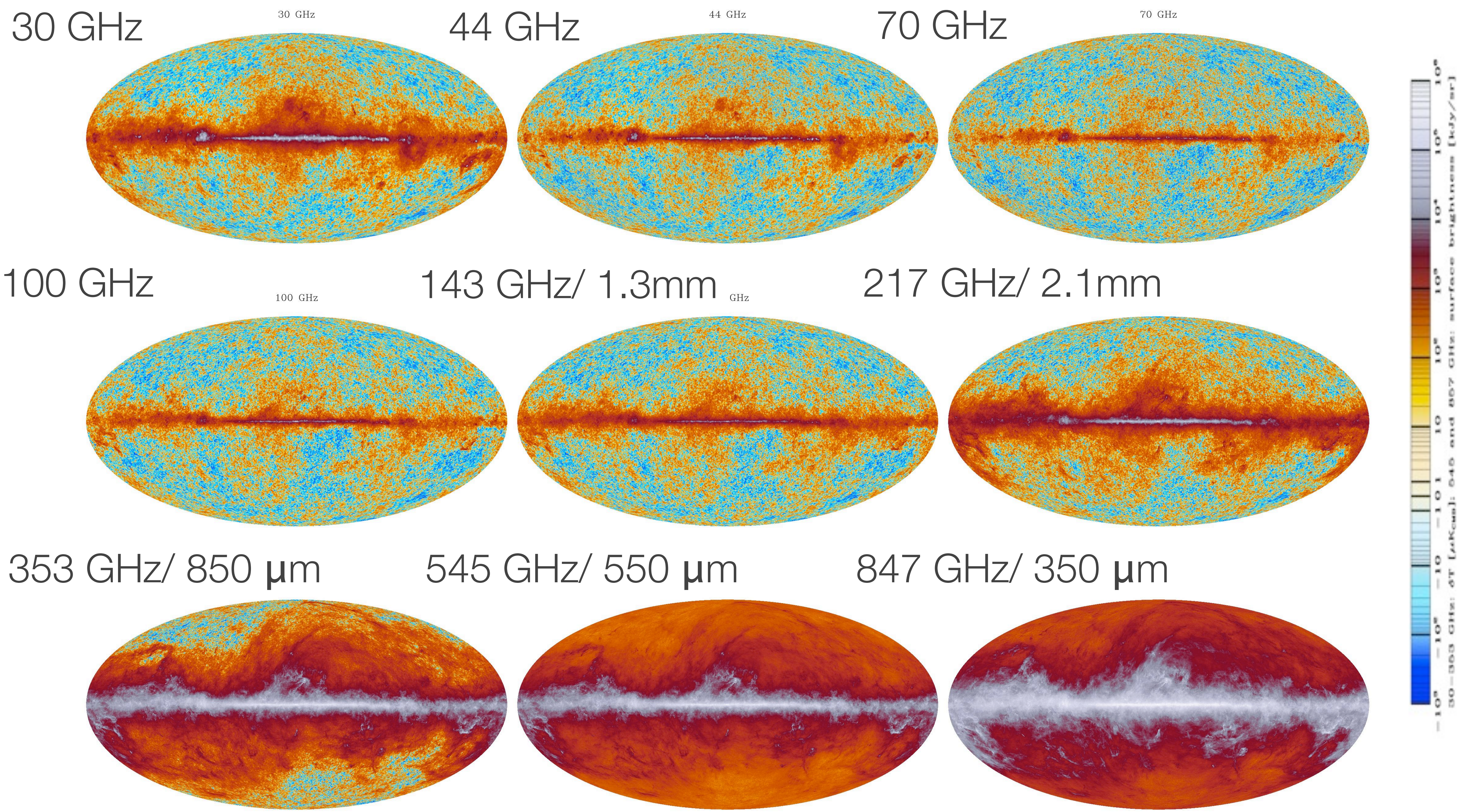
Refining the Base ΛCDM Model



	Planck+WP+highL+BAO	
Parameter	Best fit	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

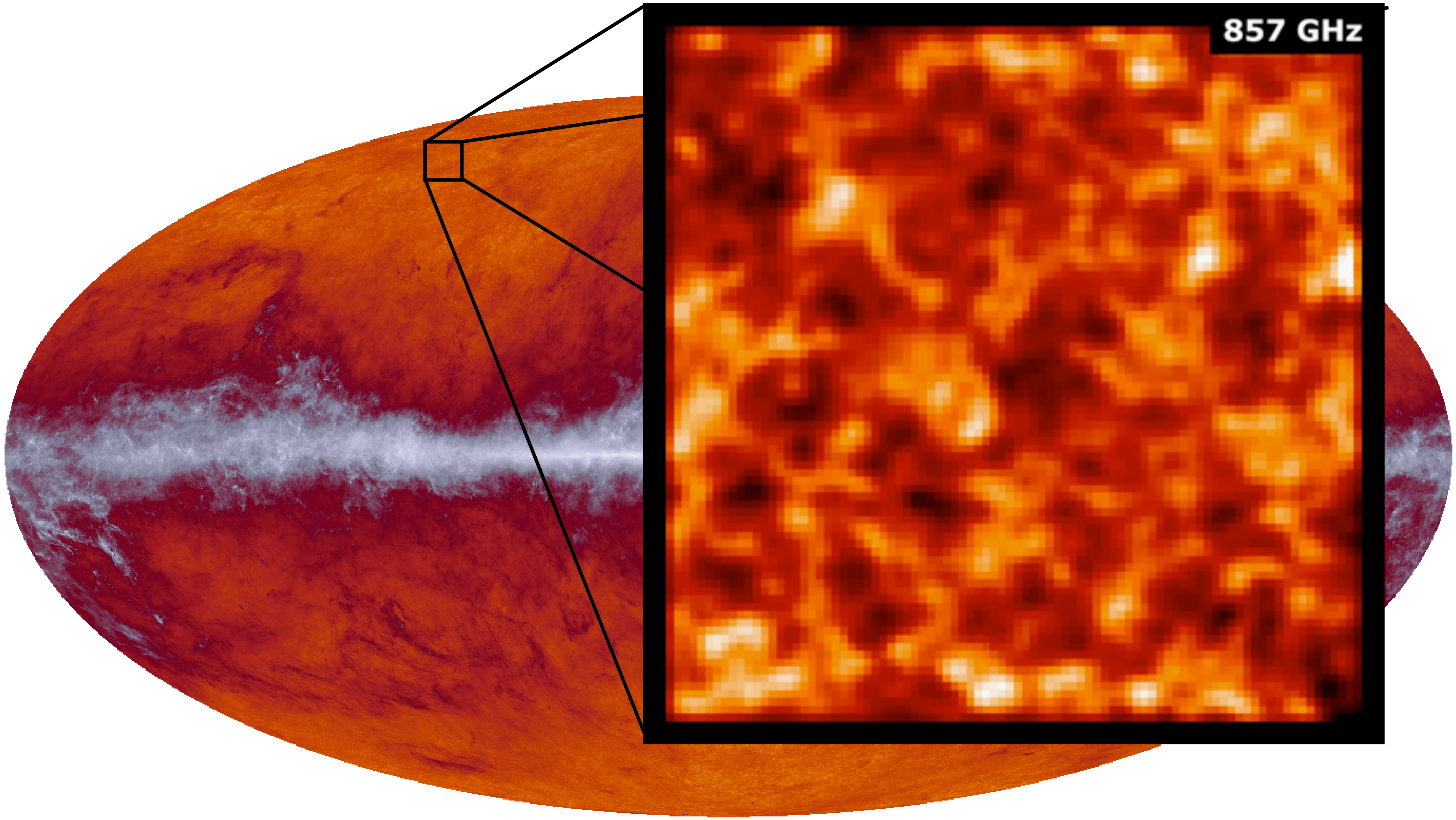
- 0.05% measurement of sound horizon →
- Rule out exact scale invariance at 6σ →

What Planck Has Done for Astrophysics in 2013



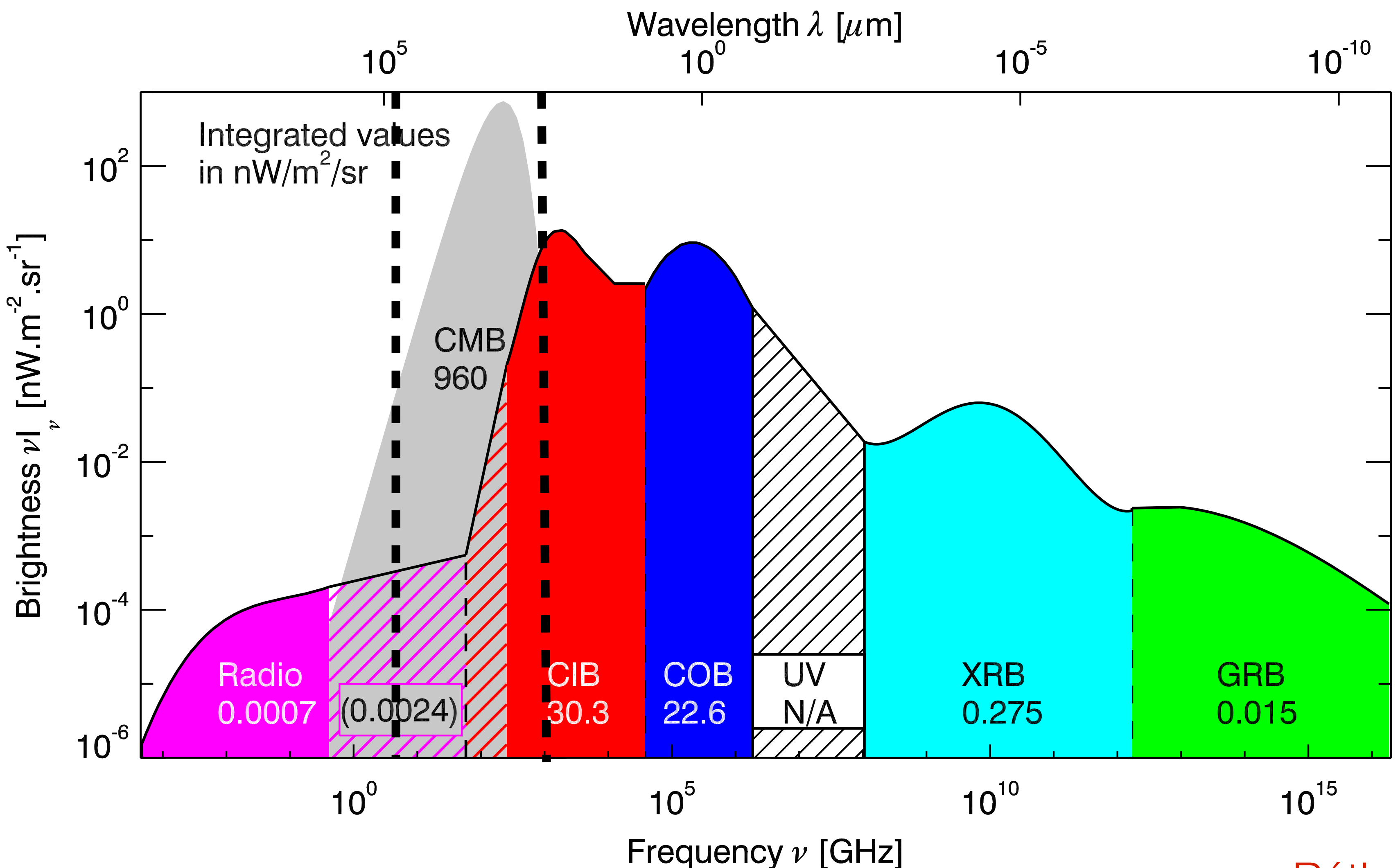
- Noise properties on maps meet or exceed goals:
  - ➡ Precision on cosmological parameters is as per pre-flight “Blue Book” values.
- These temperature maps and many more (~200 maps) are available for download on ESA and NASA/IPAC websites.
- Lead to more than 30 published papers in 2013 (1000 pages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

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.

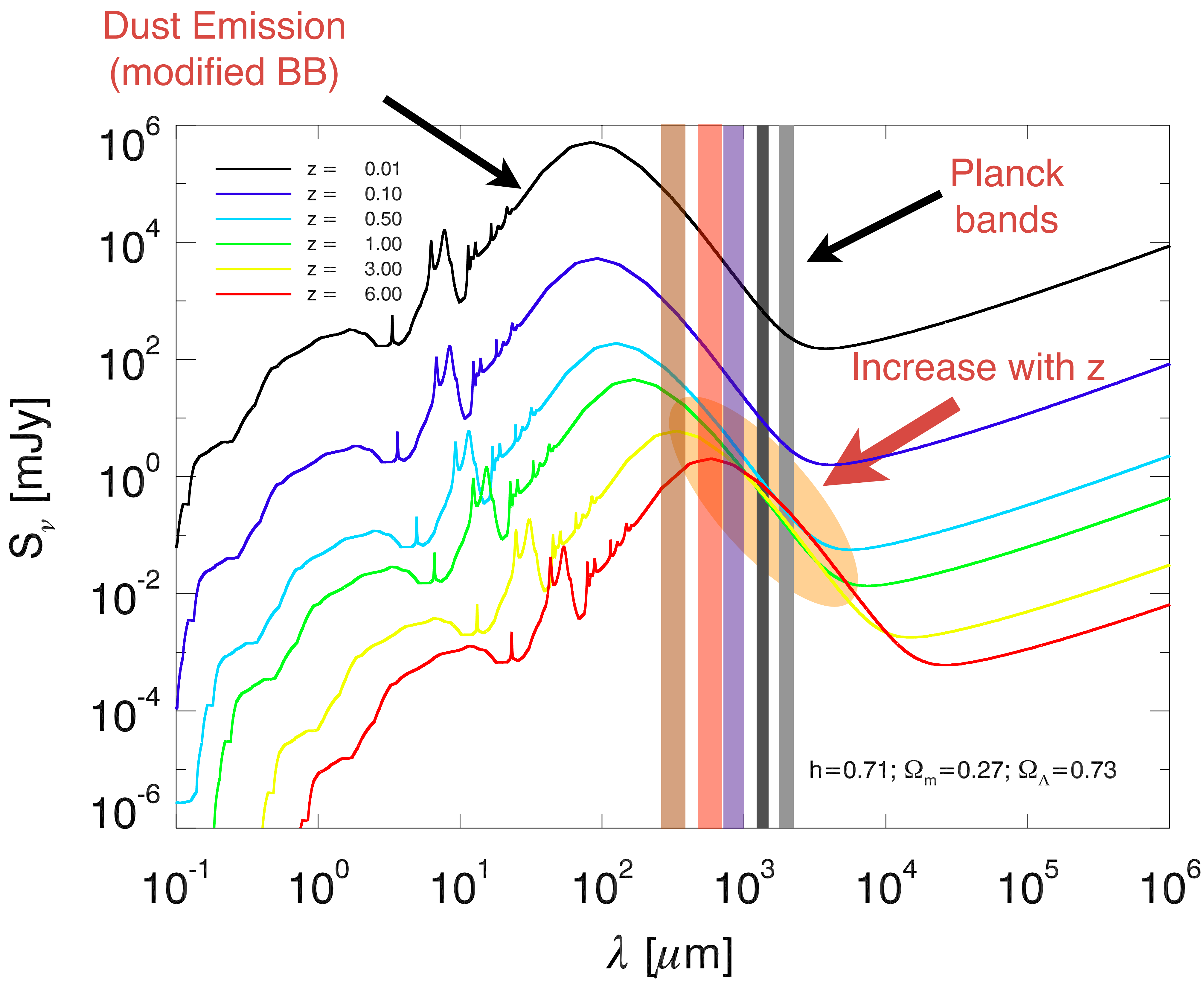
A Bright (Far-)Infrared Sky



Béthermin & Dole in prep.

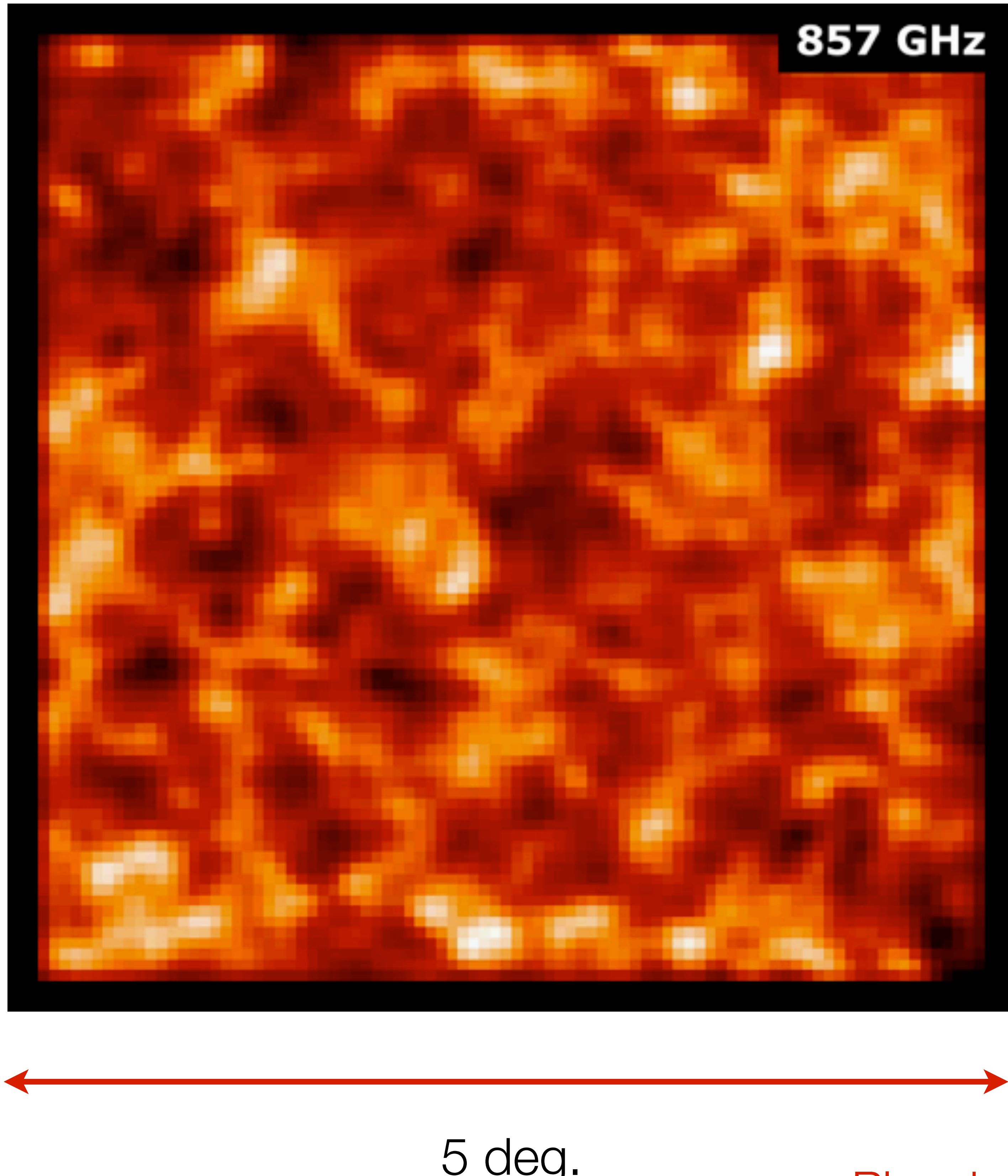
- The CIB and the COB have equal contributions, instead of ~1/3 for local galaxies.
  - ➡ IR luminosity increases with *z* faster than optical luminosity because of the increased star formation rate at higher z.
- Over half of the energy produced since the surface of last scattering has been absorbed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

Arp 220 scaled with Redshift



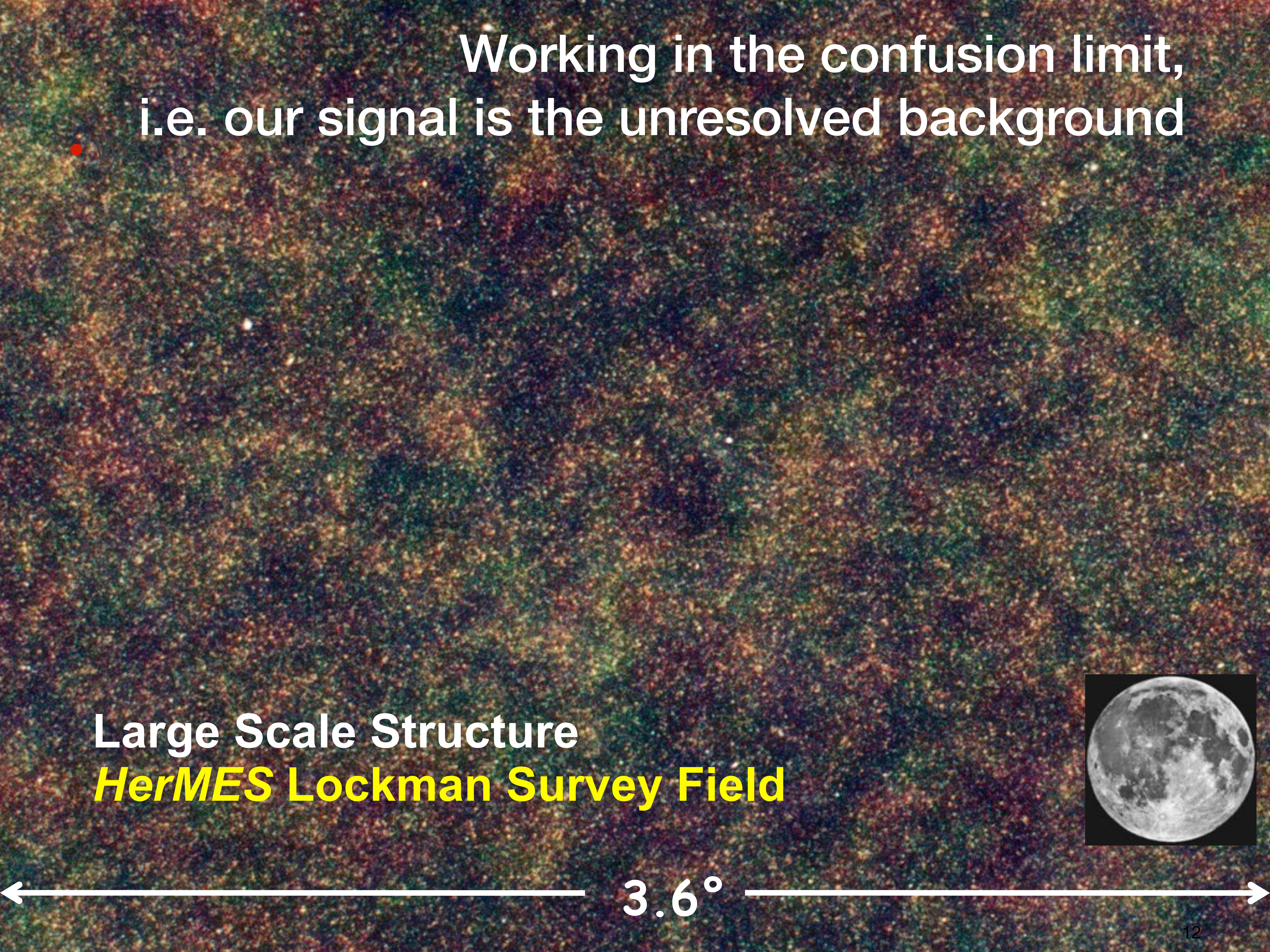
Courtesy J. Viera

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

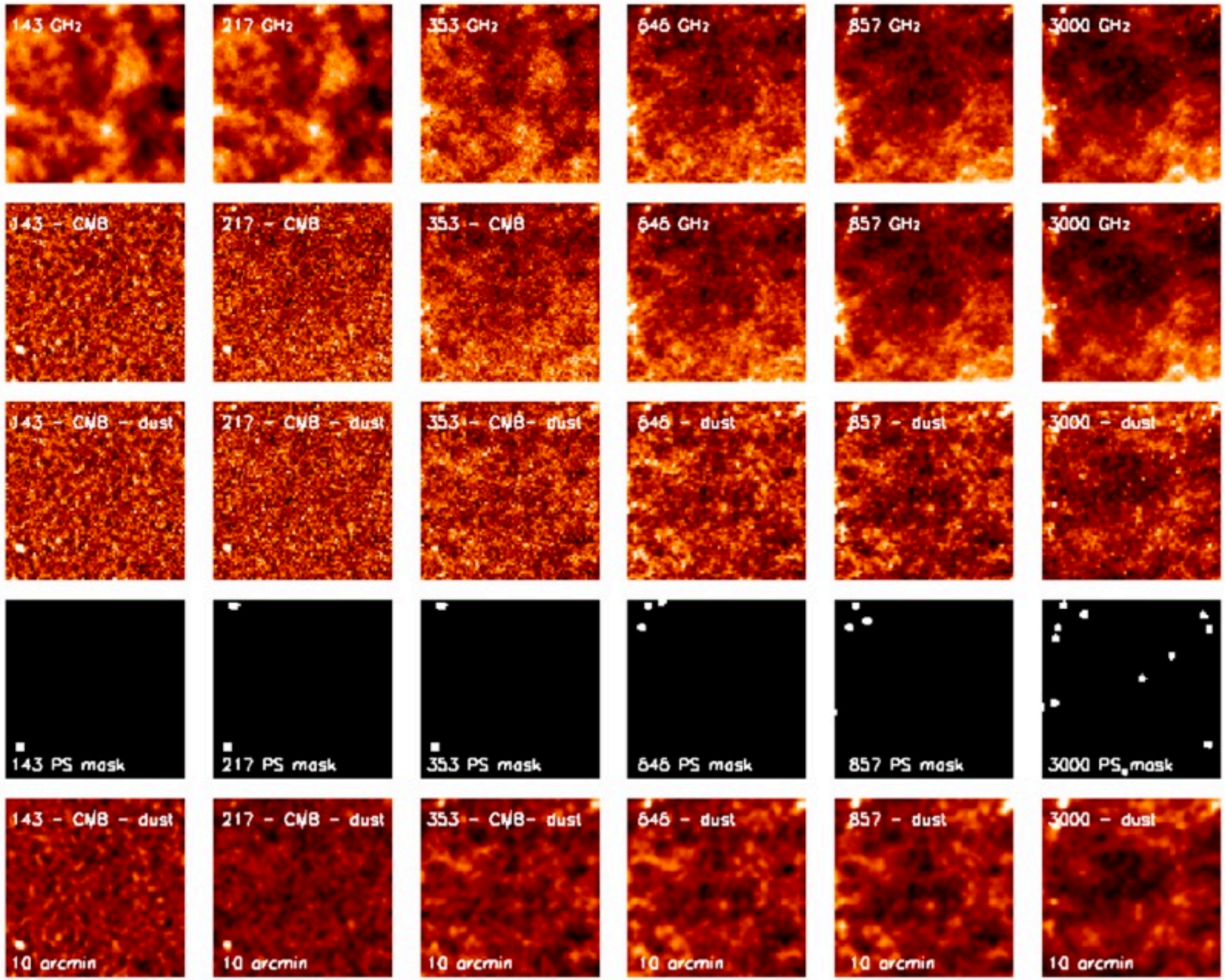


- High SNR sub-degree structures at all frequencies.
- Assuming sources at z~1.5, we are seeing clustering at 10 Mpc/*h* (k~0.1 *h*/Mpc).
- Structures partially correlated across frequencies.
- Clearly of cosmological interest!

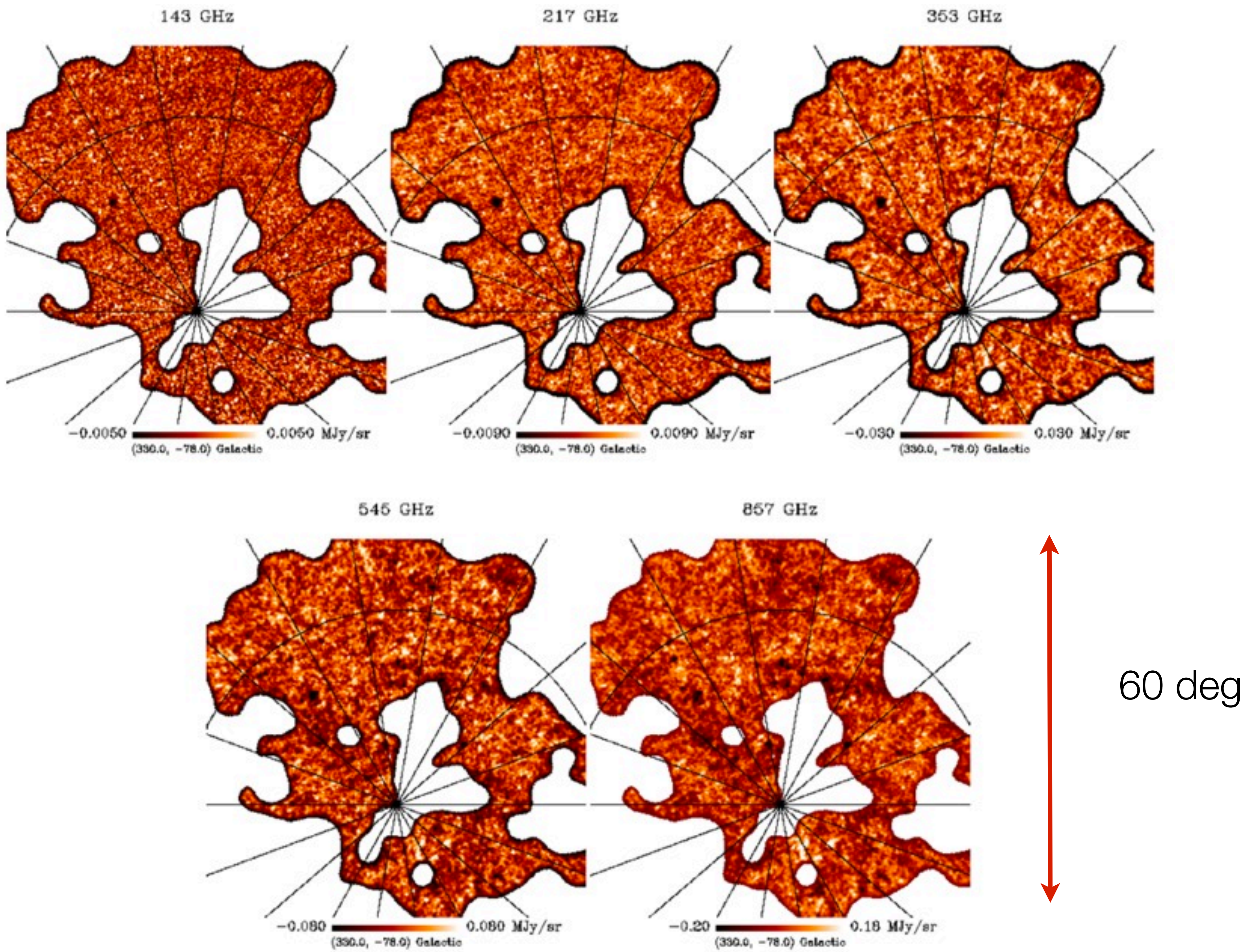
Planck Early Results XVIII, Planck 2013 XXX


Working in the confusion limit,
i.e. our signal is the unresolved background
Large Scale Structure
HerMES Lockman Survey Field
3.6°

CMB and Dust Cleaning

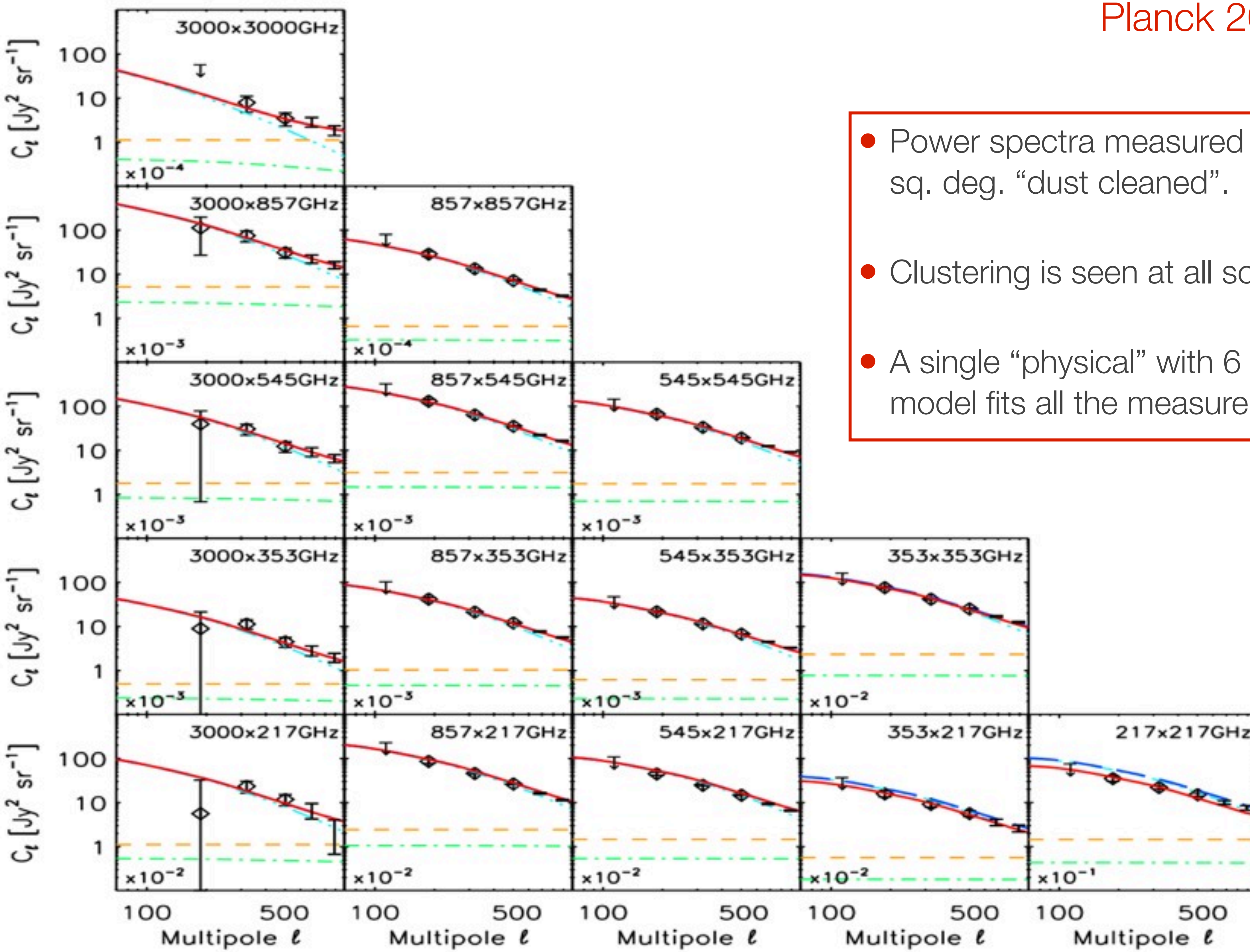


Extended “Clean” Cosmic Infrared Background Maps



CIB Angular (Cross-) Power Spectrum

Planck 2013 XXX



- Power spectra measured over 2,400 sq. deg. “dust cleaned”.
- Clustering is seen at all scales.
- A single “physical” with 6 parameters model fits all the measurement.

Required elements for a "physical" model

(1) Light traces galaxies which trace dark matter on large scales

(2)Prescription for the spatial distribution of galaxies and its redshift evolution: $P_{gg}(k,z)$

➡Linear model with bias constant in redshift: $P_{gg}(k,z) = b_{lin}^2 P_{lin}(k,z)$

➡HOD approach: clustering of DM through a halo models, whose halos we populate using Halo Occupation Density model

(3)Luminosity function and its redshift evolution for the relevant galaxies: $j(z)$

➡Use of a parametric model of the LF and the SED.

$$\bar{j}_\nu(z) = \int dM \frac{dN}{dM}(z) \frac{1}{4\pi} \Big\{ N_{\rm cen} L_{{\rm cen},(1+z)\nu}(M_{\rm H}, z) + \int dm_{\rm SH} \frac{dn}{dm}(m_{\rm SH}, z) L_{{\rm sat},(1+z)\nu}(m_{\rm SH}, z) \Big\}$$

$$C_\ell^{\nu\nu'} = \int dz \left(\frac{d\chi}{dz}\right)\left(\frac{a}{\chi}\right)^2 \bar{j}_\nu(z)\bar{j}_{\nu'}(z) P_{gg}(k = \ell/\chi, z)$$

Shang++12, Planck 2013 XXX

Model Parameters

- Luminosity mass relation: $L_{(1+z)\nu}(M,z) = L_0\Phi(z)\Sigma(M,z)\Theta[(1+z)\nu]$,

- Global normalization of the L-M relation:
  - ➡ $L_0\Phi(z) = L_0(1+z)^\delta$

- SFR-M relation:

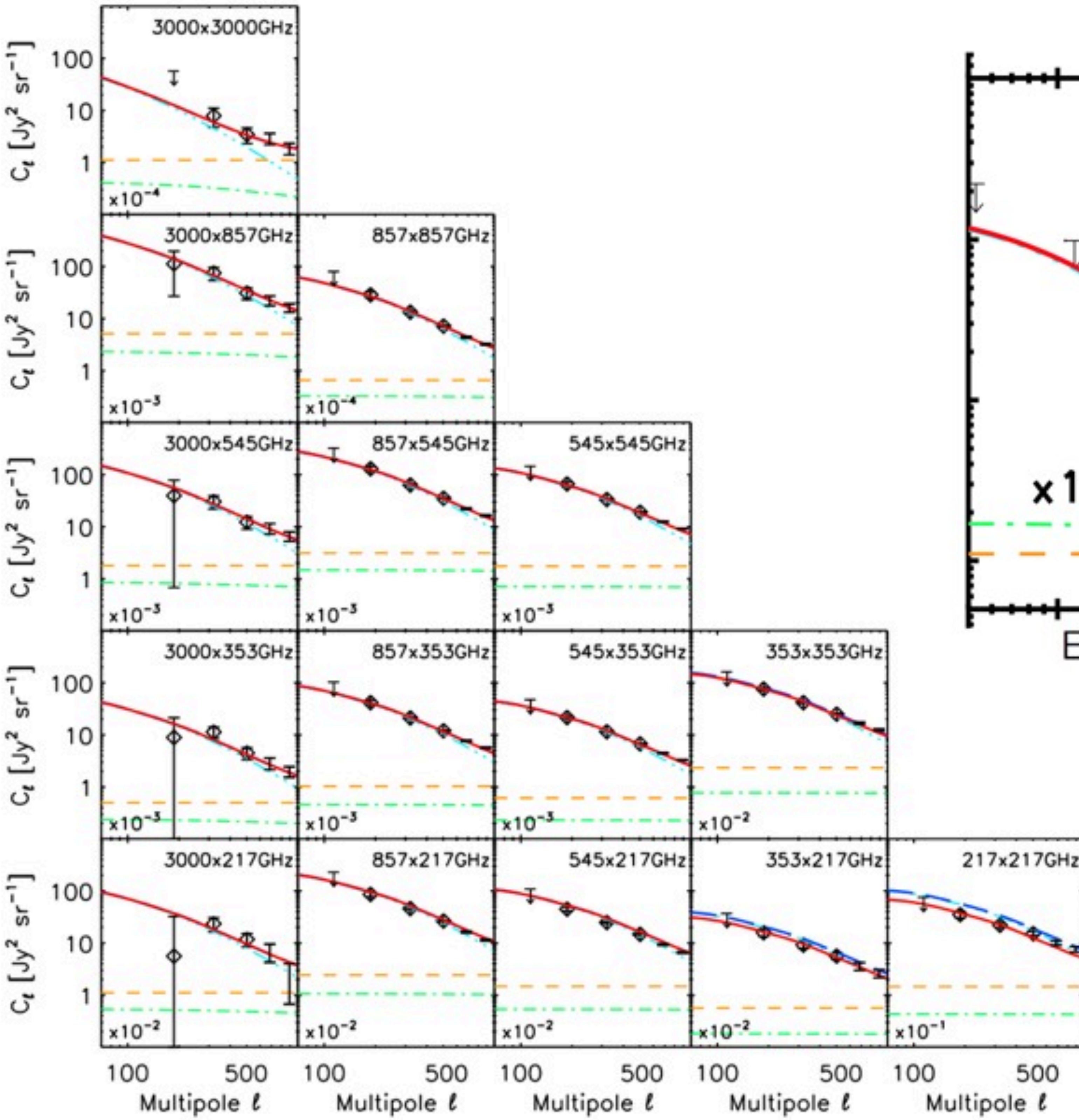
$$\Sigma(M,z) = M\frac{1}{(2\pi\sigma^2_{L/M})^{1/2}}e^{-(\log_{10}(M)-\log_{10}(M_{\rm eff}))^2/2\sigma^2_{L/M}}$$

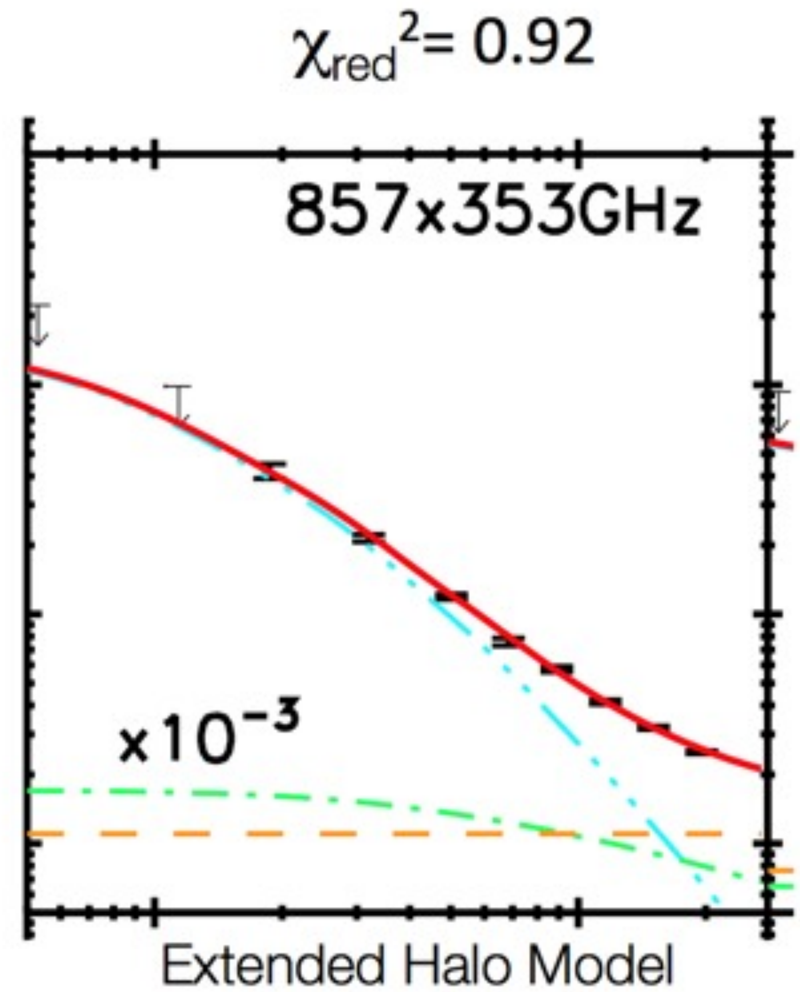
- SED, modified black-body:
  - ➡ $\theta(\nu) = \nu^\beta B(T_0(1+z)^\alpha)$ for $\nu<\nu_0$
  - ➡ $\theta(\nu) \propto \nu^\gamma$ for $\nu\geq\nu_0$

- All shot-noise levels are fixed by the LF model with a 20% errors.

- Eventually 8 free parameters: M_{min}, M_{eff}, L_0, δ, α, β, T_0, γ

Angular Power Spectrum





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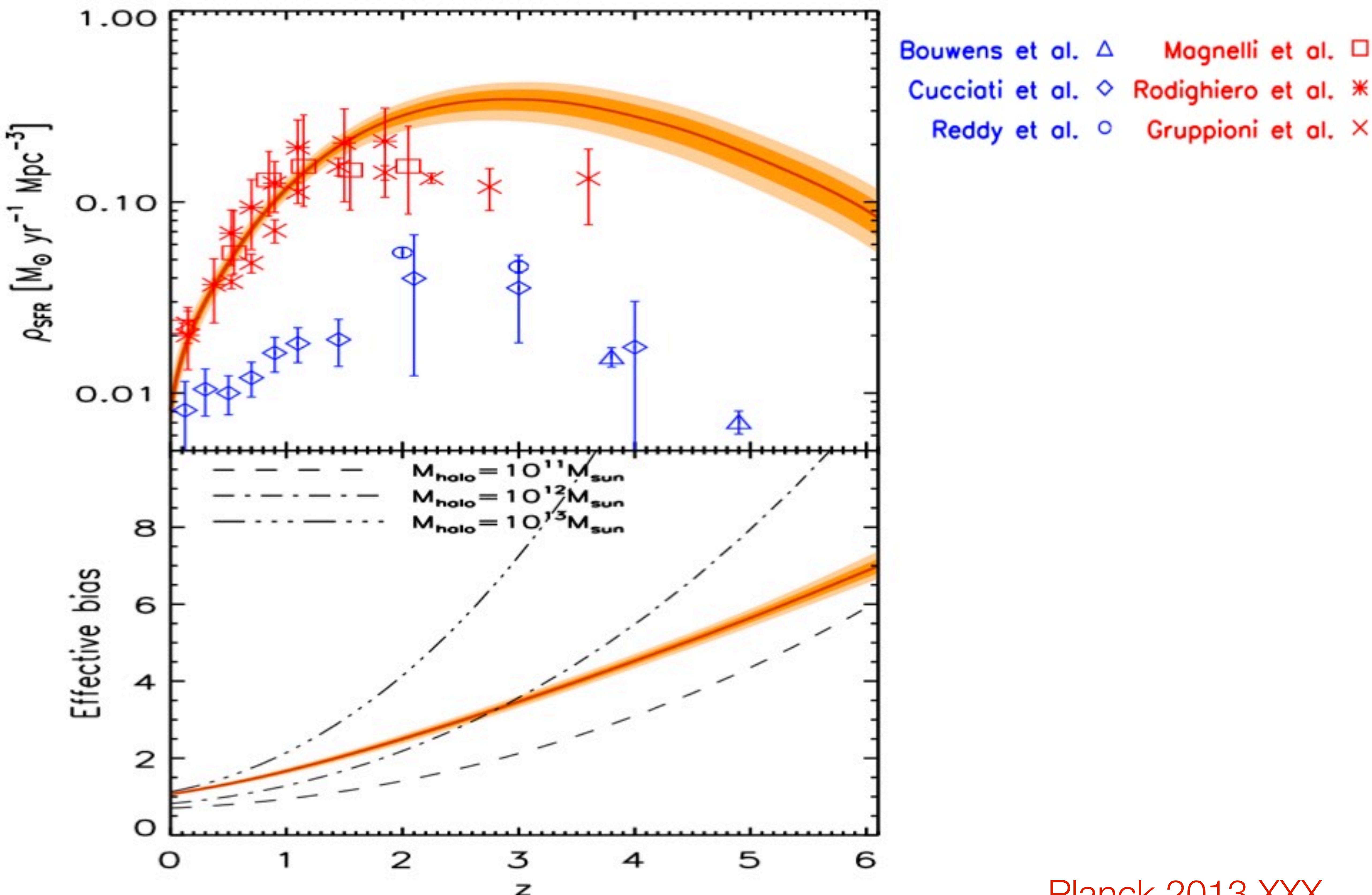
Best-fit Parameters

- Fit simultaneously all frequencies with only one set of parameters.

- Most efficient mass M_{eff}:
  - ➡ $\log(M_{eff}/M_{\odot}) = 12.2 \pm 0.13$
  - ➡ No significant redshift evolution.

- Variation of temperature with redshift:
  - ➡ Dust spectral index: $\beta = 1.85 \pm 0.06$
  - ➡ $T_0 = (24.4 \pm 1.9)$ K and $\alpha = 0.36 \pm 0.05$
  - ➡ Significant redshift evolution:
    - A harder interstellar radiation field for z>2.5 (Magdis et al. 2012)?

Constraining the SFR at High Redshift



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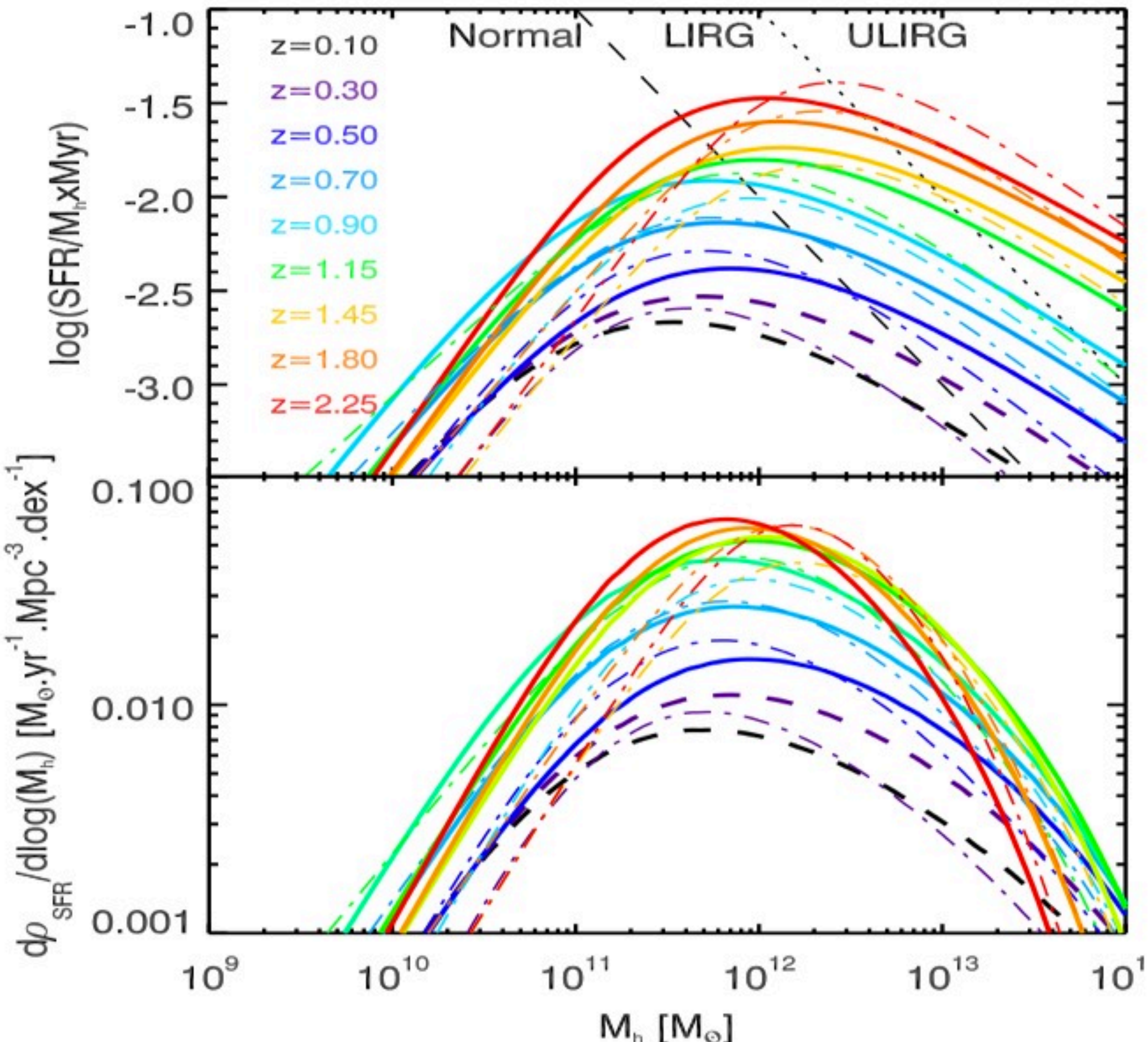
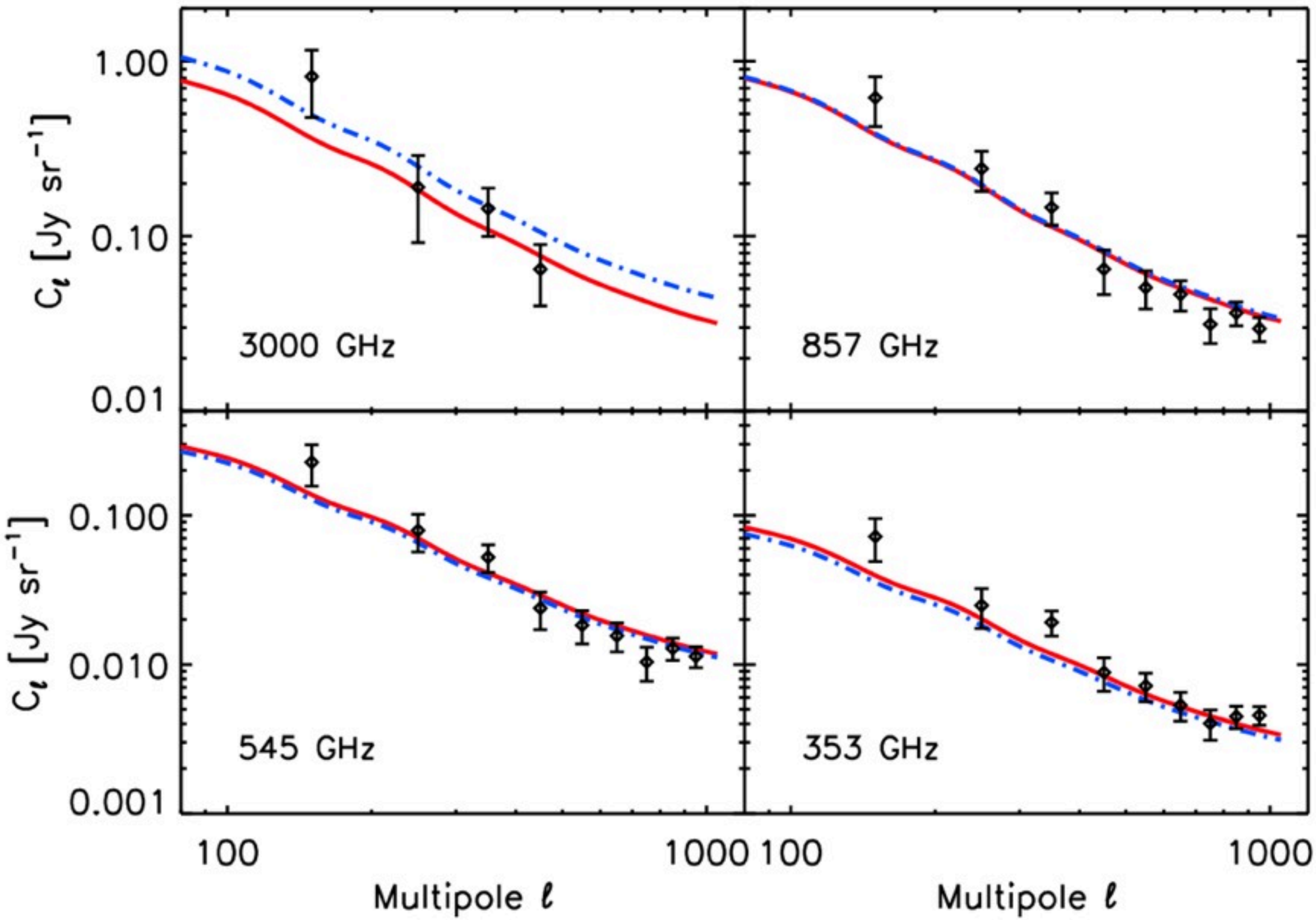
Consistent Masses with Abundance Matching



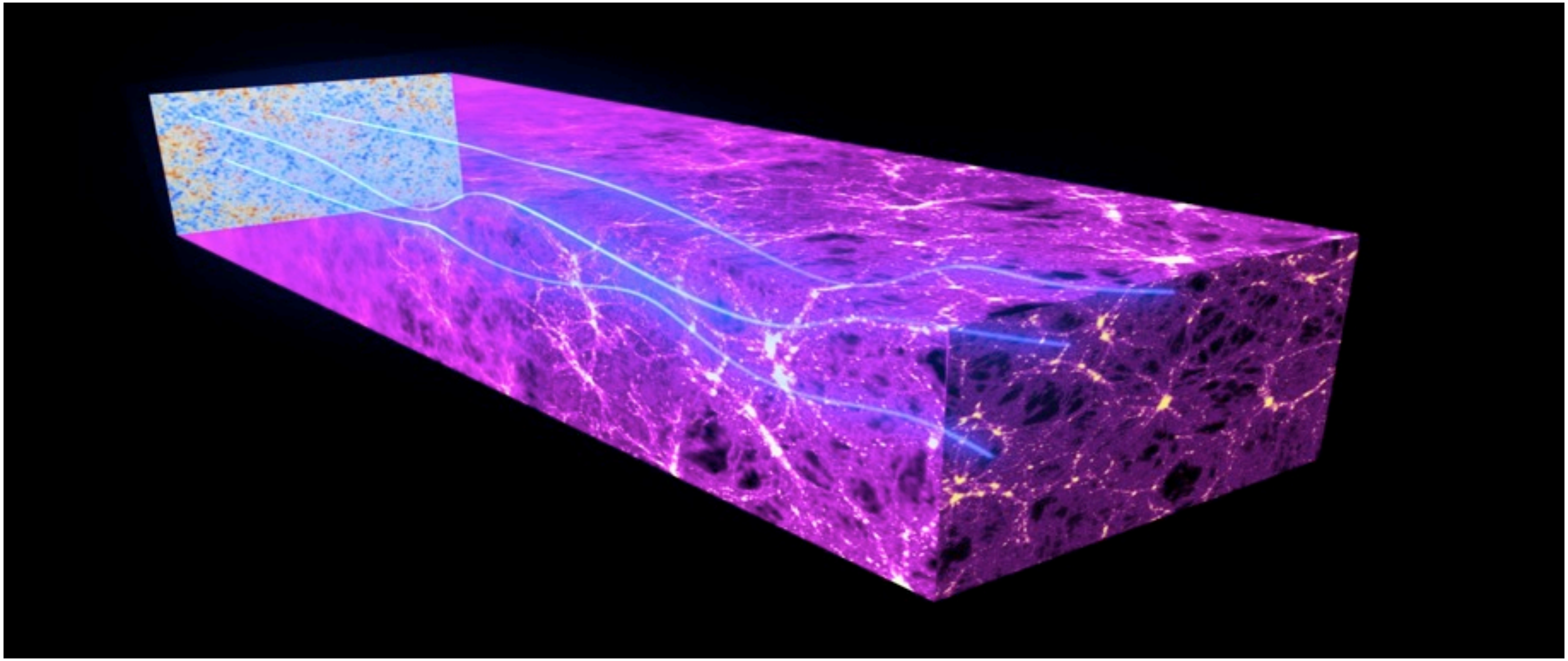
Béthermin, OD, Lagache 12

Validating with Cross-Correlations - BOSS LRGs



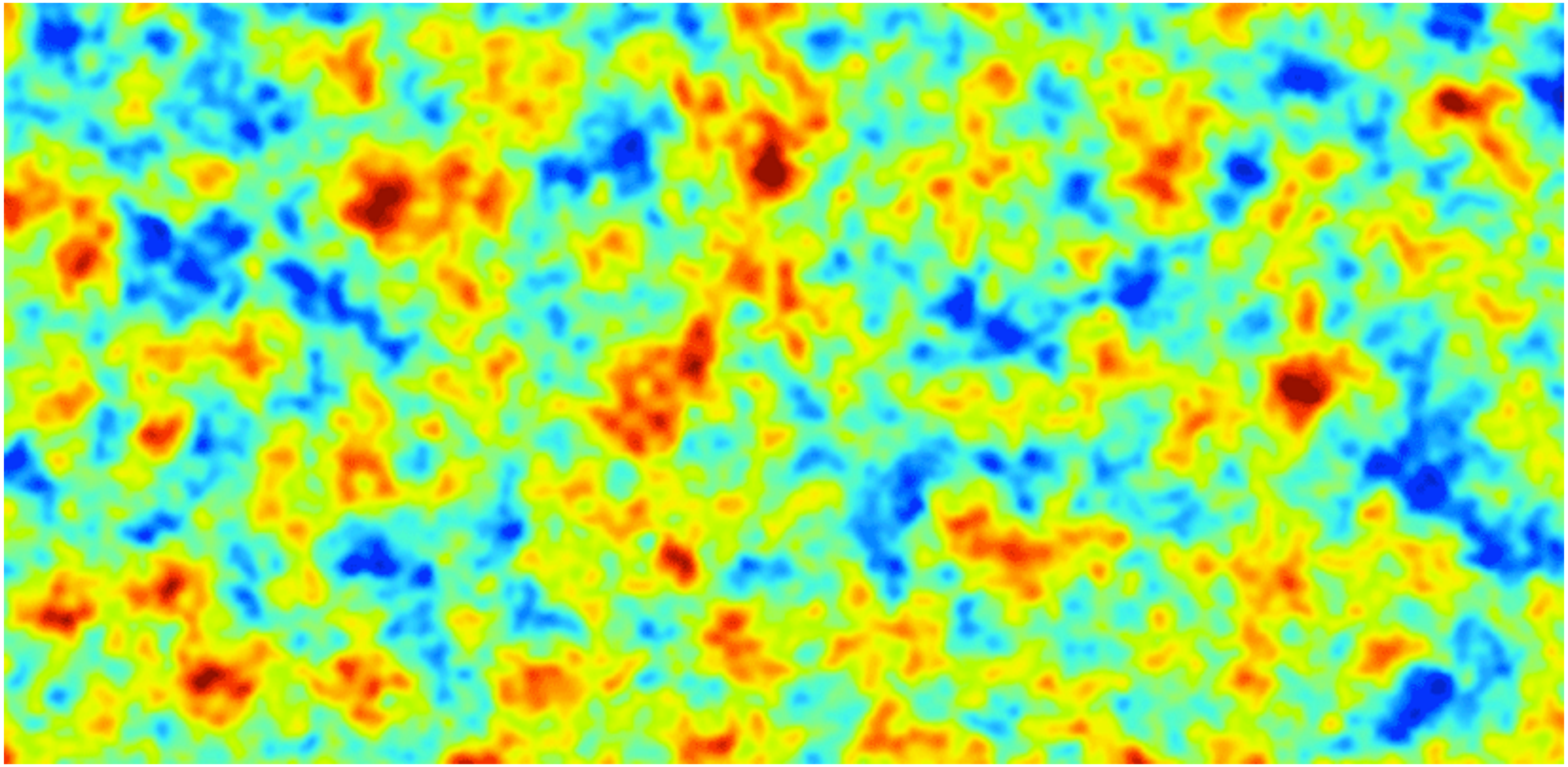
Serra++2014

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 <u>all</u> 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:
  - ➡ $T^{lens}(\boldsymbol{\theta}) = T^{unlensed}(\boldsymbol{\theta}+\boldsymbol{\alpha}) = T^{unlensed}(\boldsymbol{\theta}+\boldsymbol{\nabla\Phi})$
- 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

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

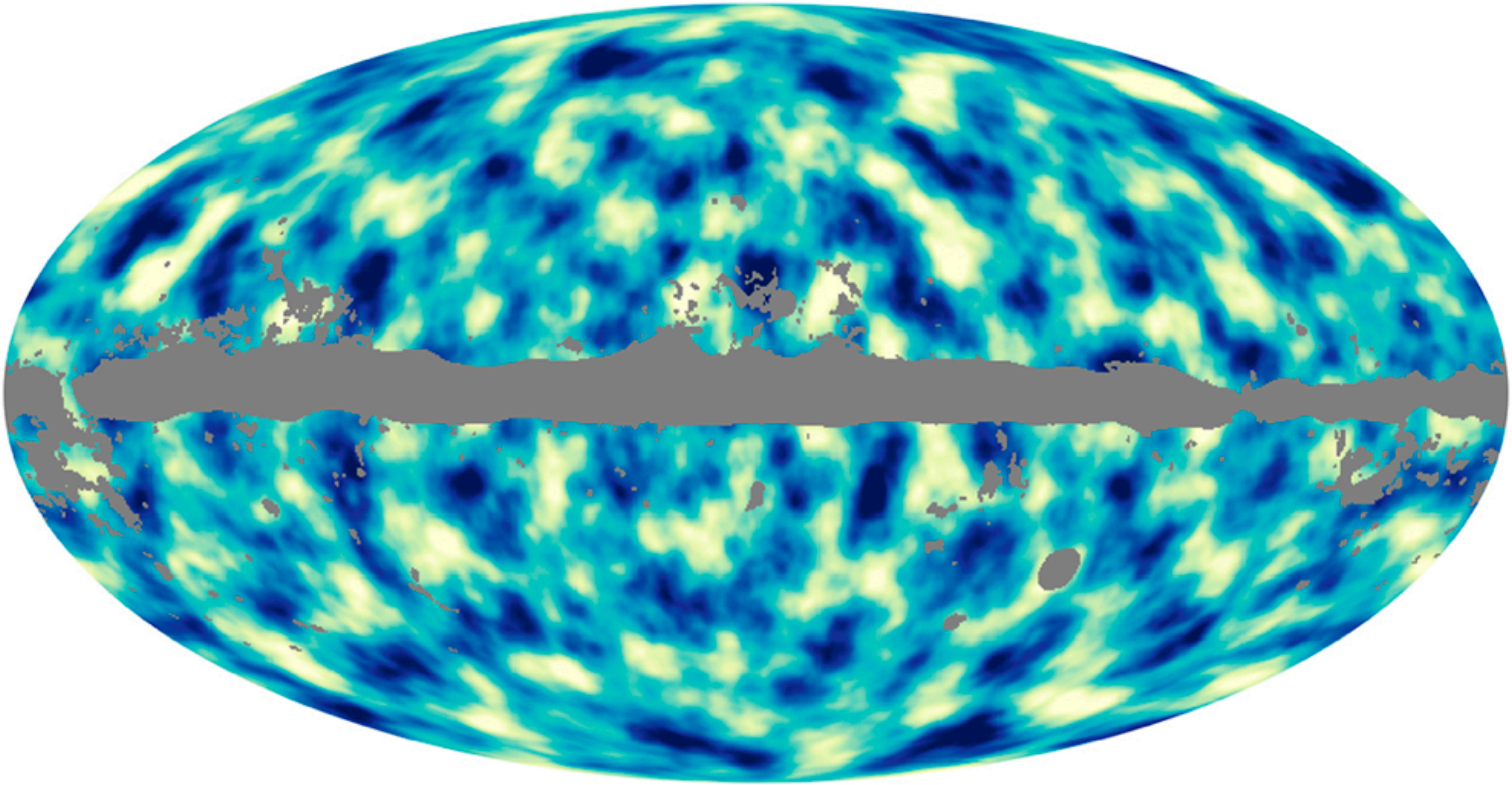
$$\phi(\hat{\boldsymbol{n}}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*)f_K(\chi)} \Psi(\chi\hat{\boldsymbol{n}}; \eta_0 - \chi)$$

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

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

- “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.

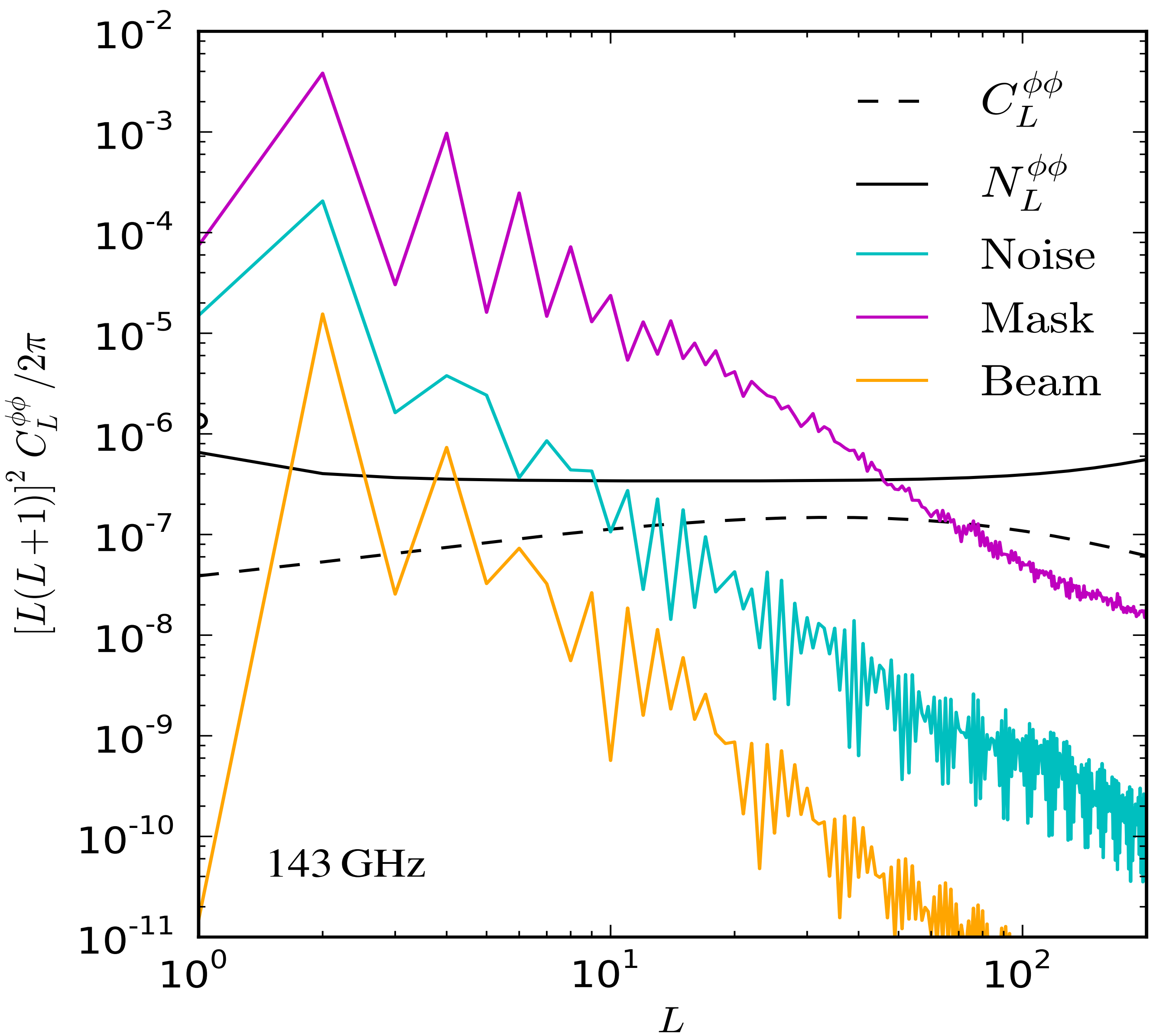
The Projected Mass Map of the Visible Universe

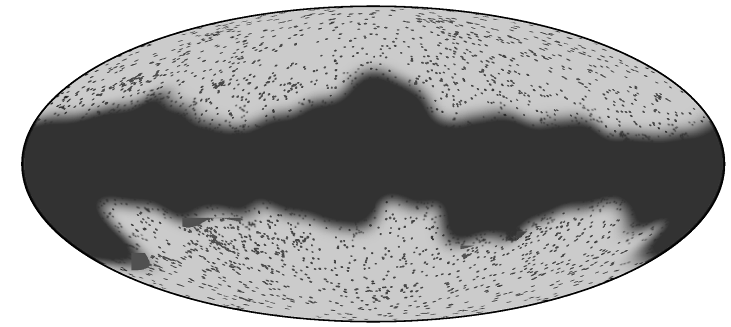


- This map is a weighted projection of the gravitational potential over the entire visible Universe, with a peak sensitivity between z~1 and 3.
- The gradient of this map gives the deflection angle.

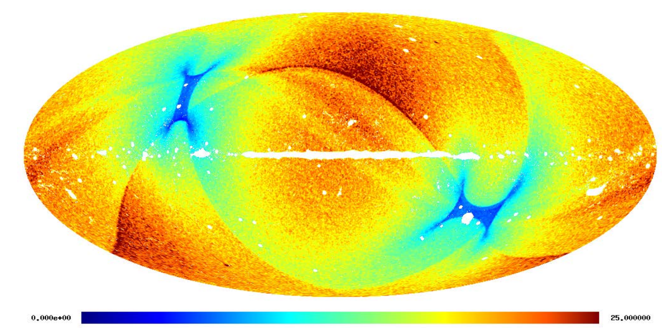
Planck 2013 Results. XVII

Multiple Bias at the Map Level



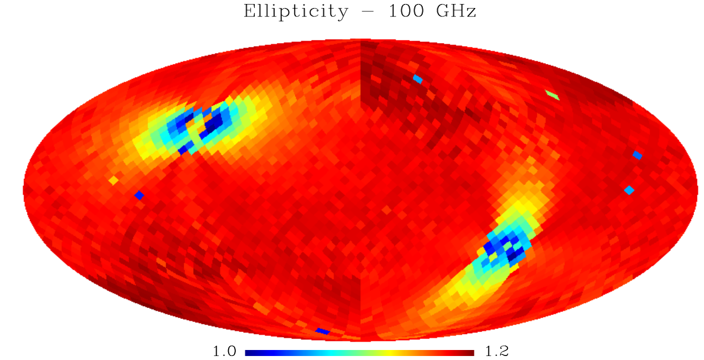


Mask



noise RMS

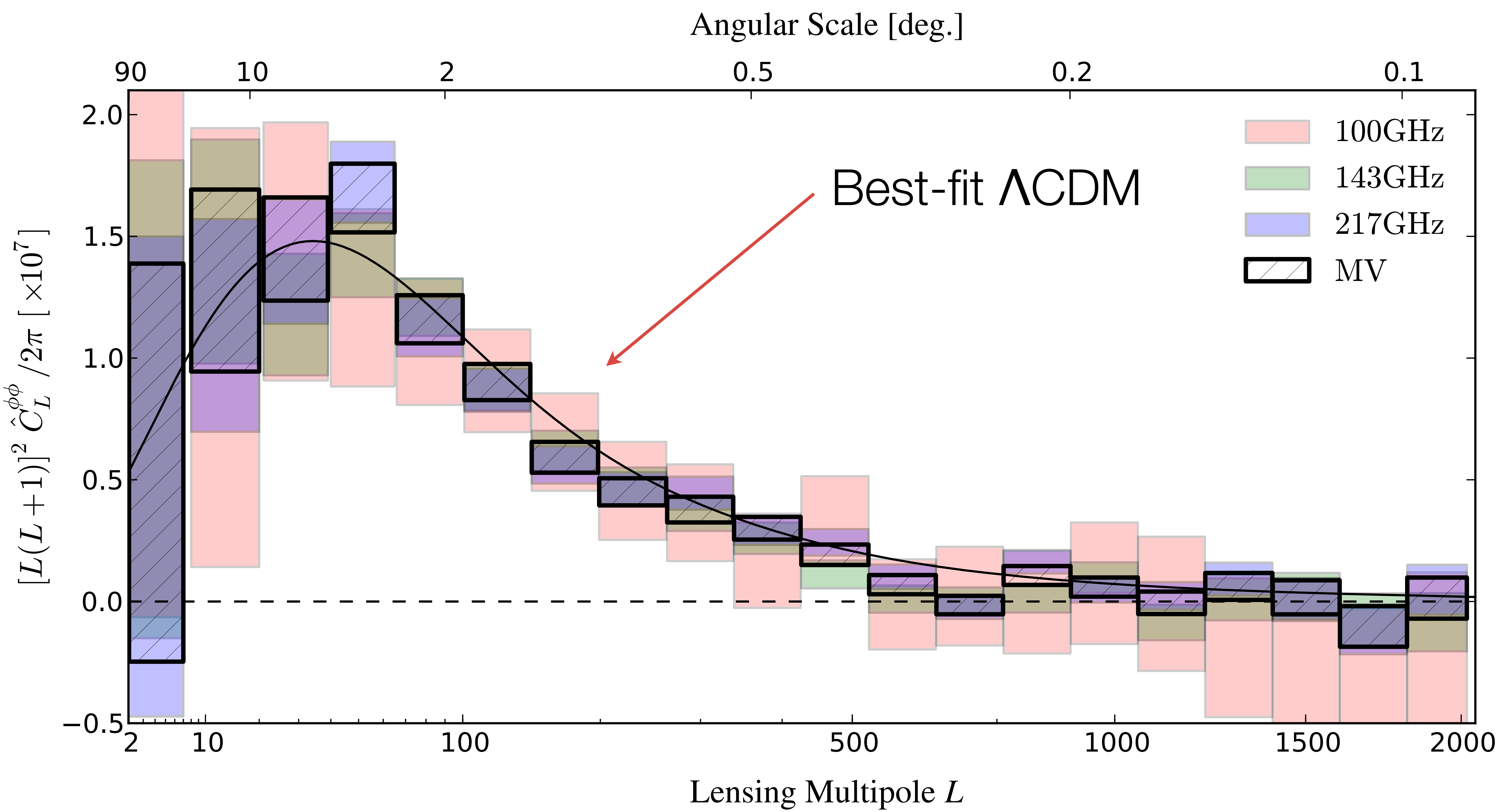
Ellipticity – 100 GHz



Beam ellipticity

- 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).

The CMB Lensing Power Spectrum is Robust

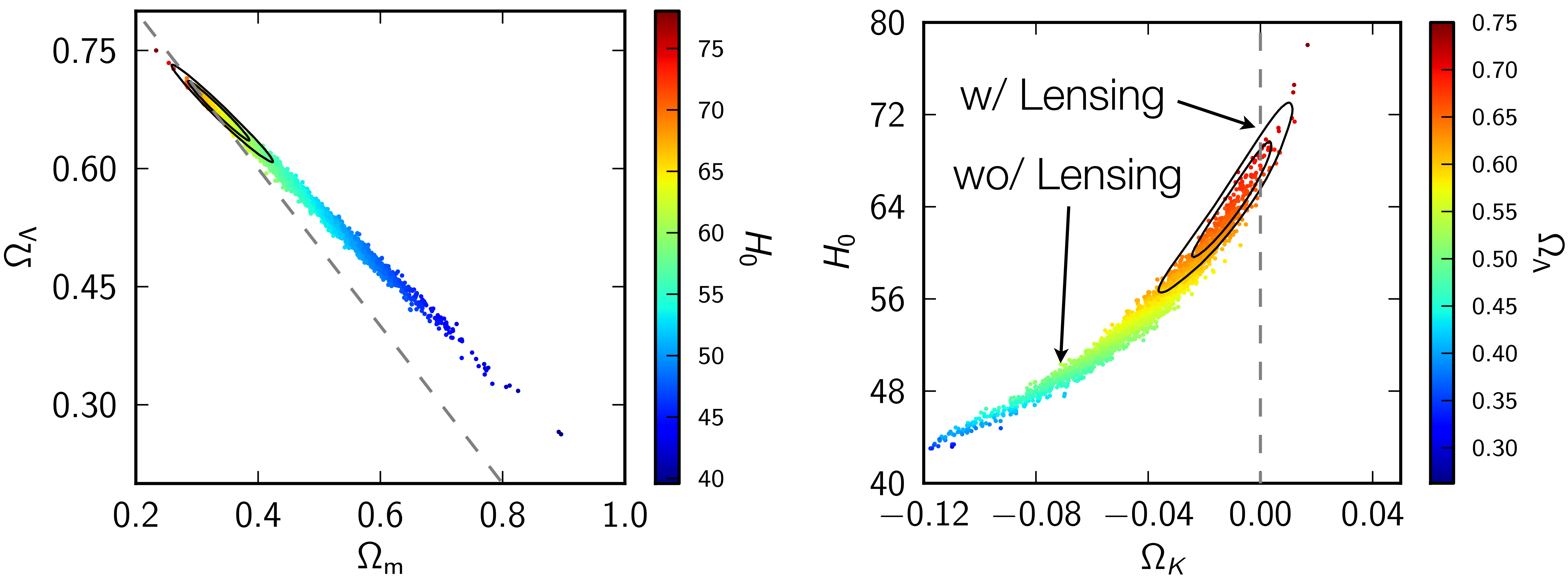


- This information lead to a ~20% gain in cosmological parameters

Planck 2013 Results. XVII

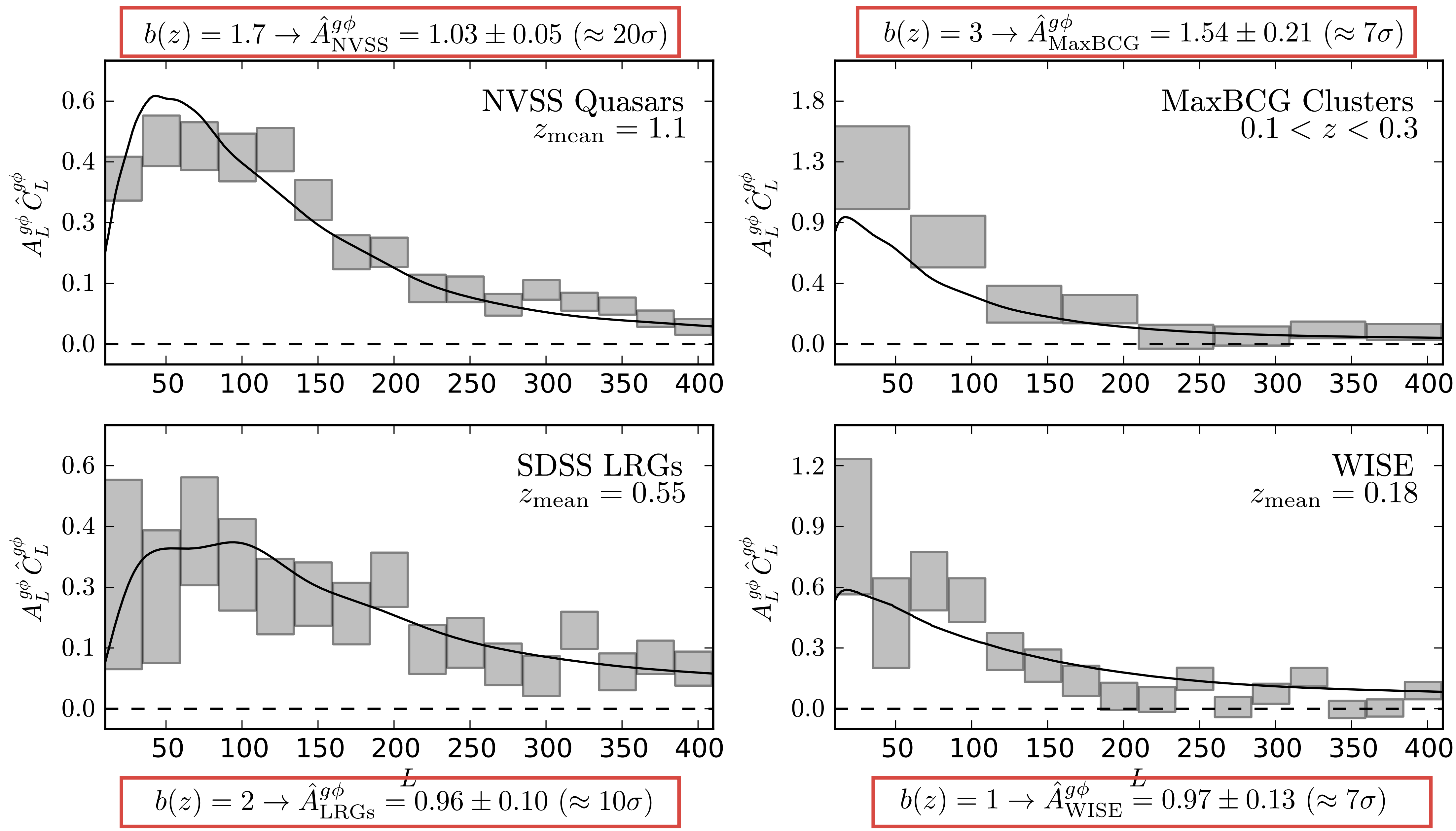
Breaking the Angular Diameter Degeneracy

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



$$\Omega_\Lambda = 0.57^{+0.073}_{-0.055} \quad (68\%;\ Planck\text{+WP+highL})$$
$$\Omega_\Lambda = 0.67^{+0.027}_{-0.023} \quad (68\%;\ Planck\text{+lensing+WP+highL})$$

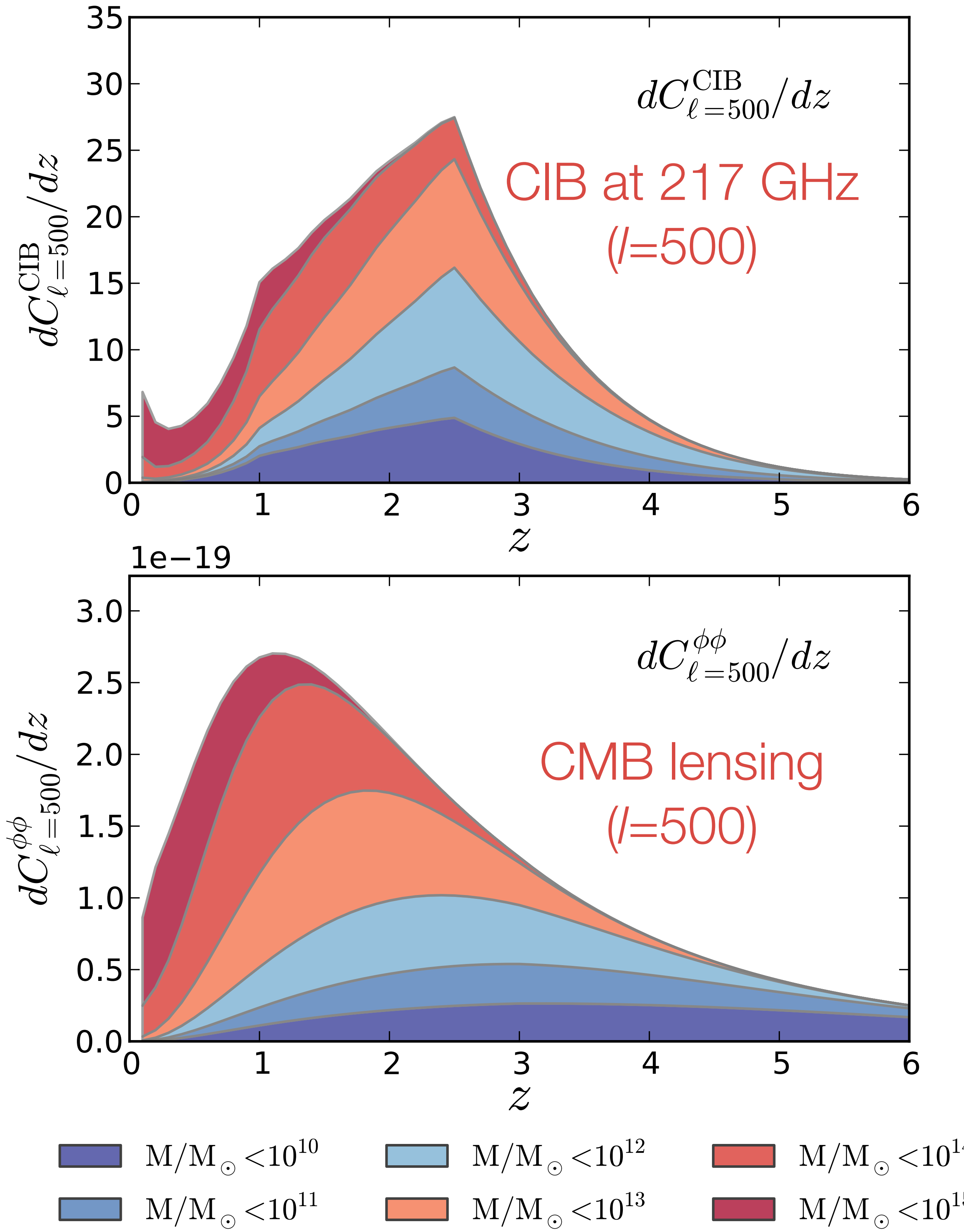
CMB Lensing Correlates with Galaxy Surveys



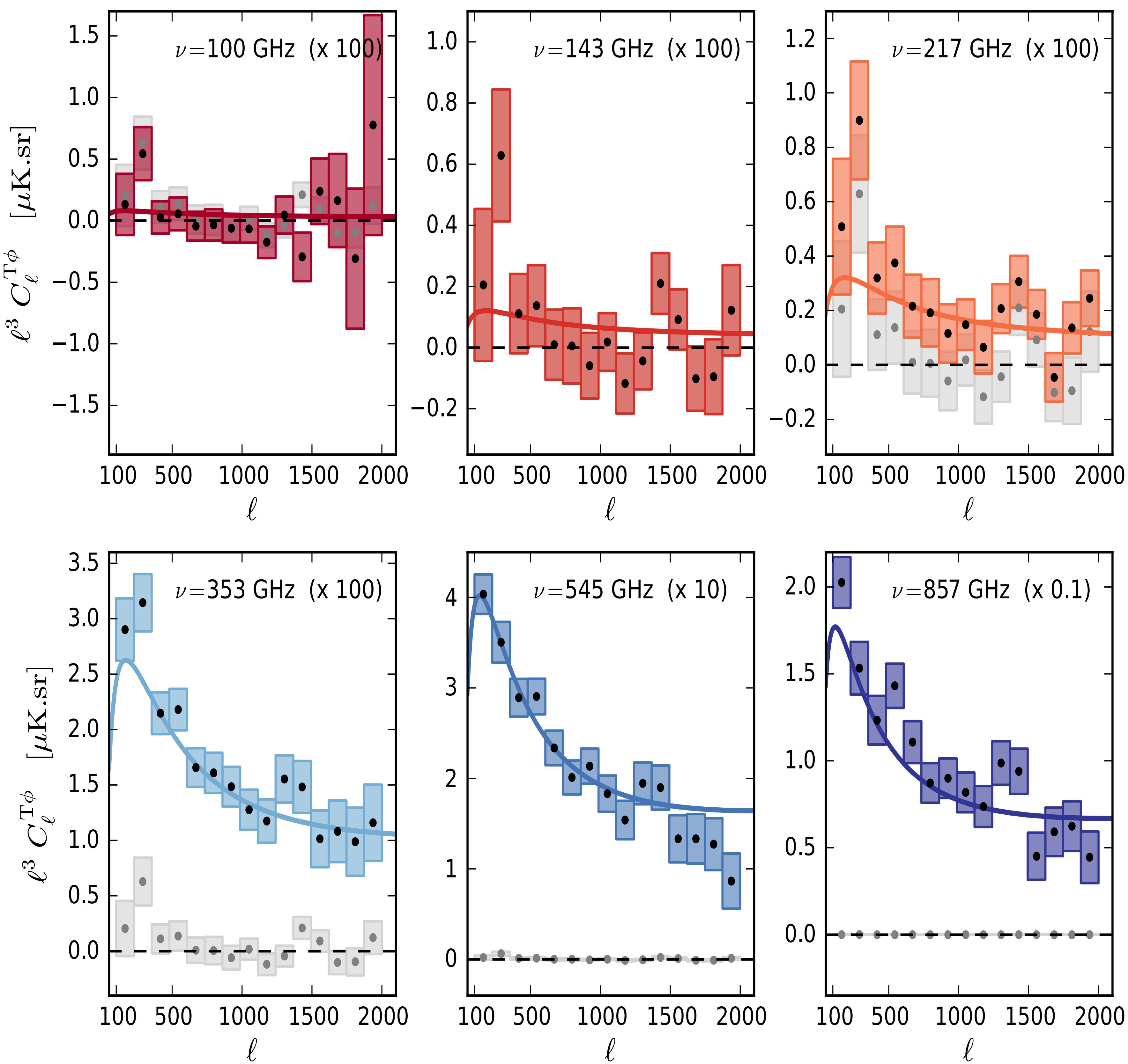
- This correlation is an important consistency test.
- It offers an opportunity to measure the galaxy survey (bias x dN/dz).
- Our lensing map overlaps with YOUR survey

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.



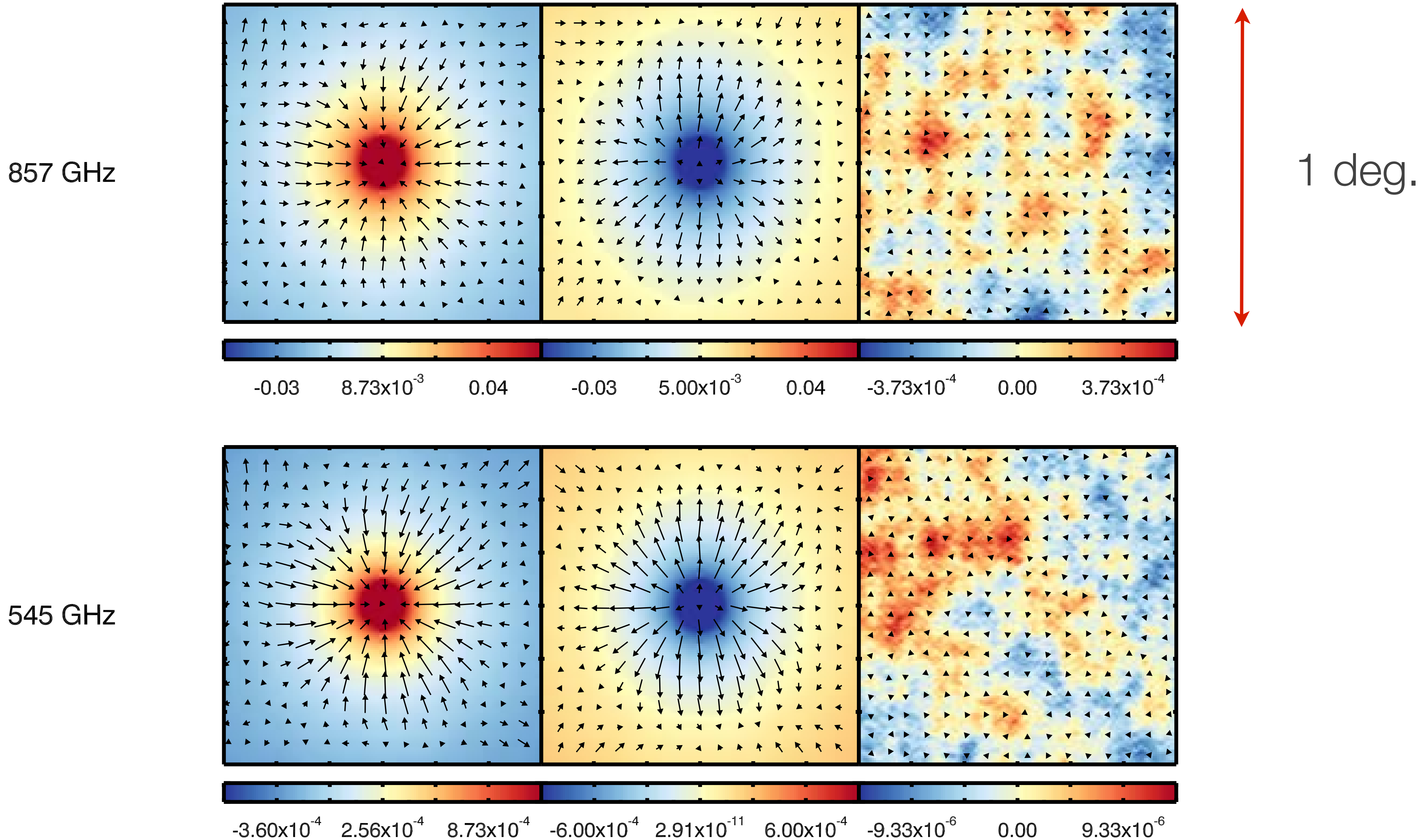
Validating with Cross-Correlations - Planck CMB Lensing



- 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%).

Planck 2013 XVIII

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, OD++12, Melchior++13).

Summary

- Planck can be used as a powerful large scale structure survey.
- The CIB is well measured at multiple frequencies over ~2000 sq. Deg.:
  - ➡ Its modeling leads to interesting constraints on the SFR at high redshift.
  - ➡ It leads to rich and new cross-correlations:
    - New insights and model validation.
- Planck detected the gravitational lensing of the CMB at ~30σ:
  - ➡ Leads to improved constraints on neutrino masses.
  - ➡ Breaks the angular diameter degeneracy.
- Using Planck data alone, we detected a strong correlation (~80%) between the CMB lensing gravitational potential and the CIB:
- This strong correlation holds great promise for novel CIB and CMB focused science.
  - ➡ The CIB is now established as an ideal tracer of CMB lensing (B mode detection of Hanson++13, delensing, ...)
  - ➡ CMB lensing appears promising as a probe of the origin of the CIB.
- Low resolution spectroscopic survey offers a very promising way to map LSS in 3D: SPHEREx

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