The CMB Lensed by Star-Forming Galaxies

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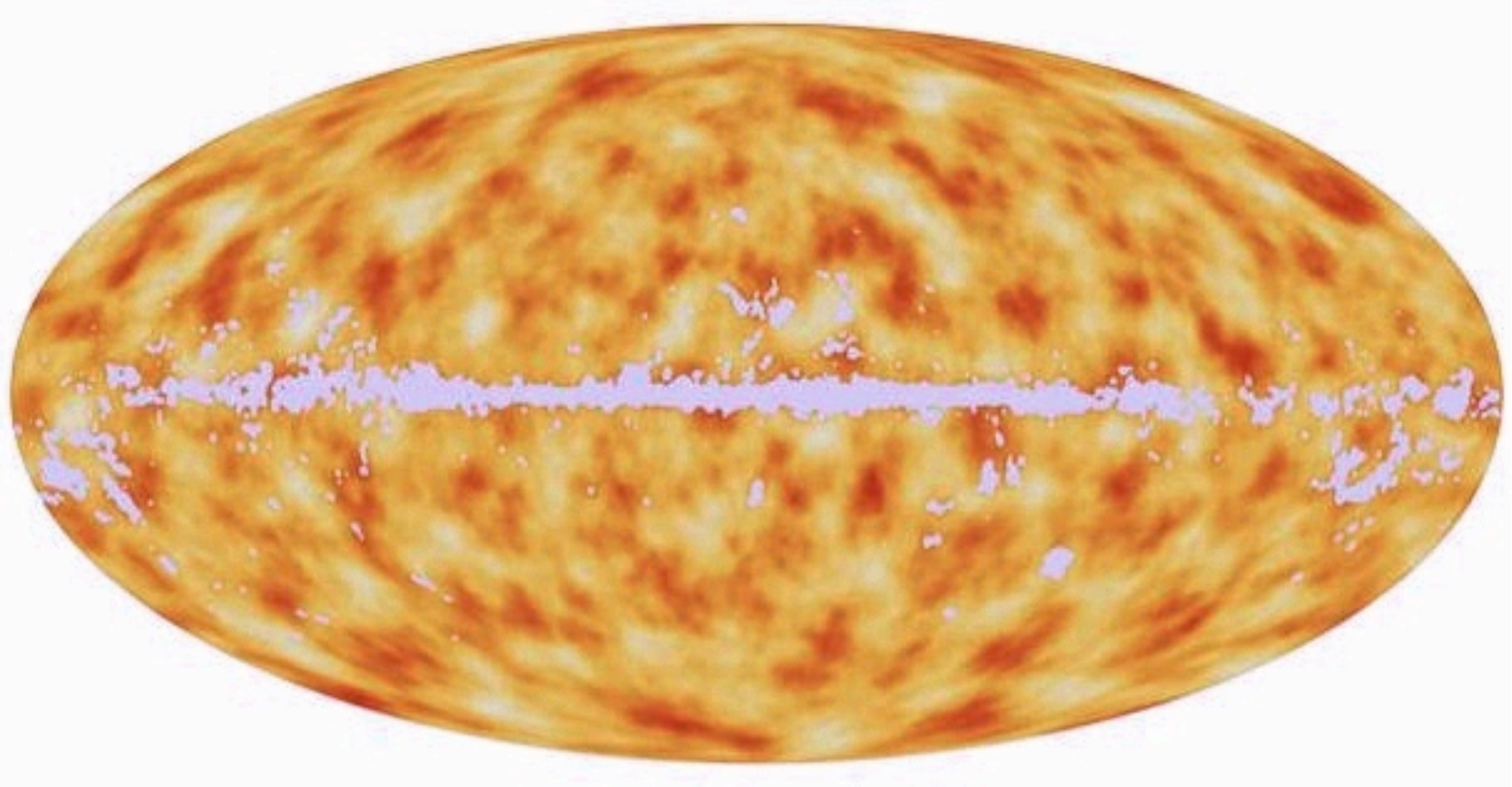
on behalf of the Planck Collaboration

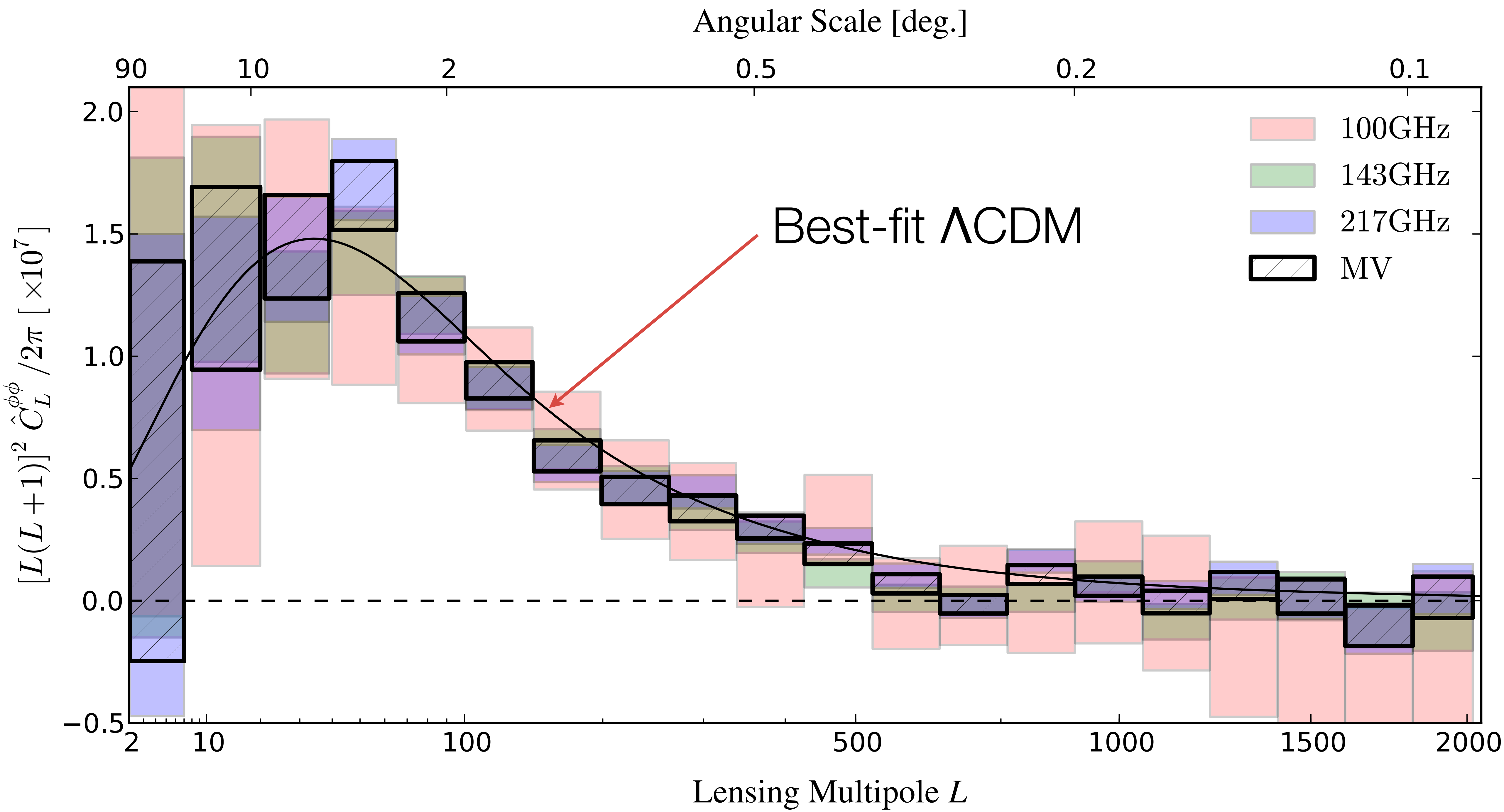
Planck 2013 results, XVII, XVIII, XXX

The Projected Mass Map of the Visible Universe



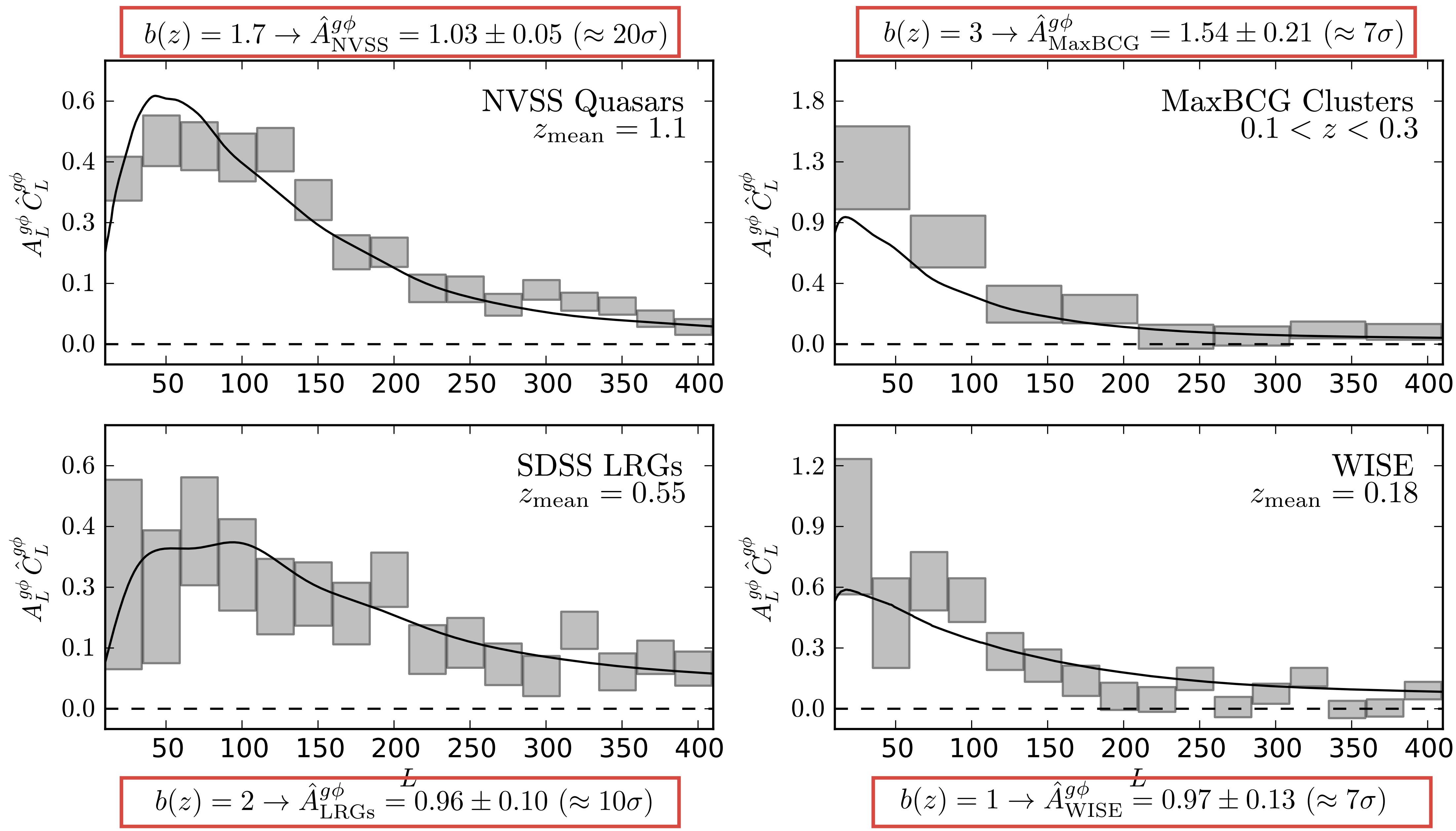
- Using Planck CMB channels (mostly 143 and 217 GHz), we can reconstruct a full sky lensing potential map (total SNR of about 25) using a quadratic estimator.
- This map is a weighted projection of the gravitational potential over the entire visible Universe, with a peak sensitivity between z~1 and 3.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

The CMB Lensing Power Spectrum is Robust



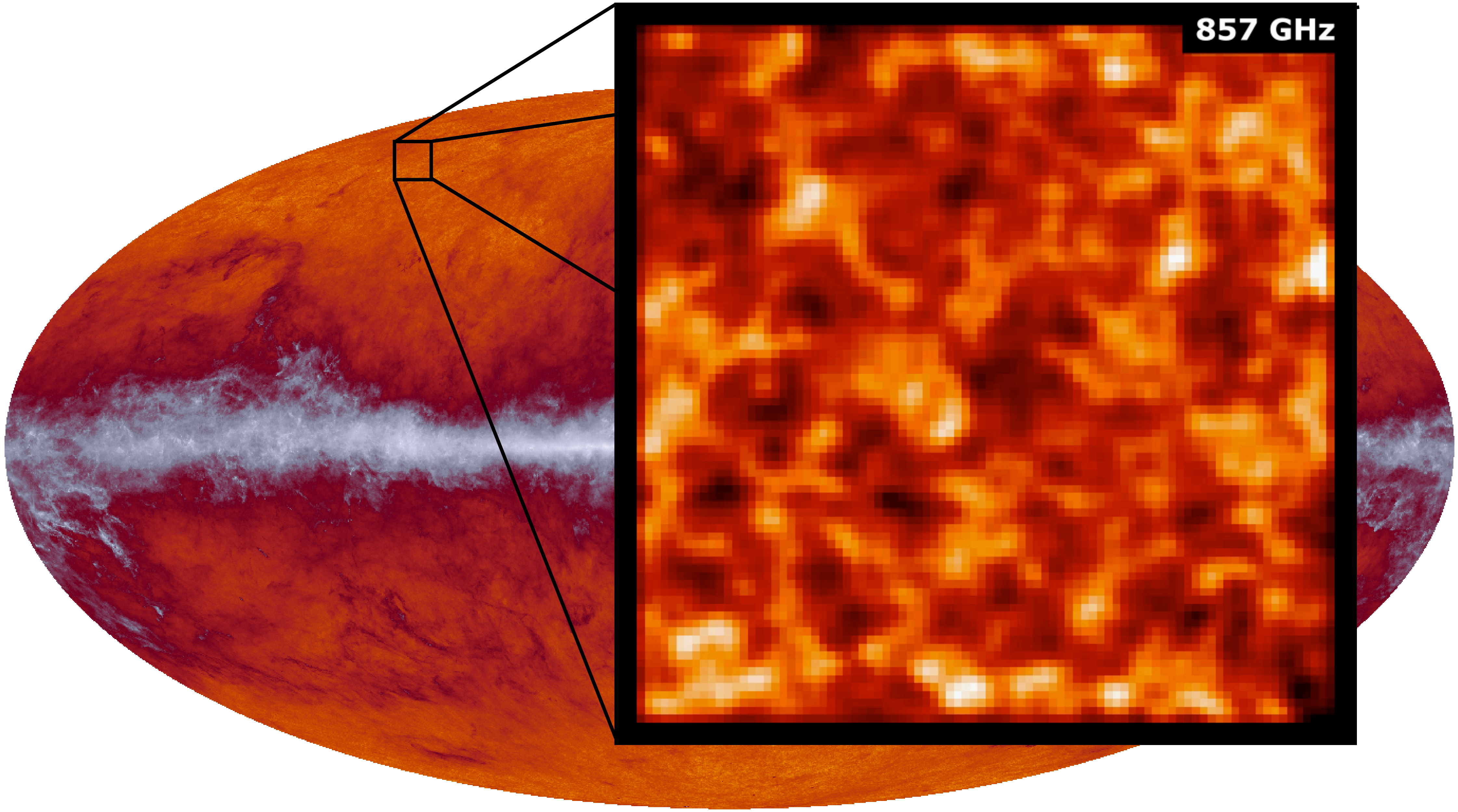
Planck 2013 Results. XVII

CMB Lensing Correlates with Galaxy Surveys



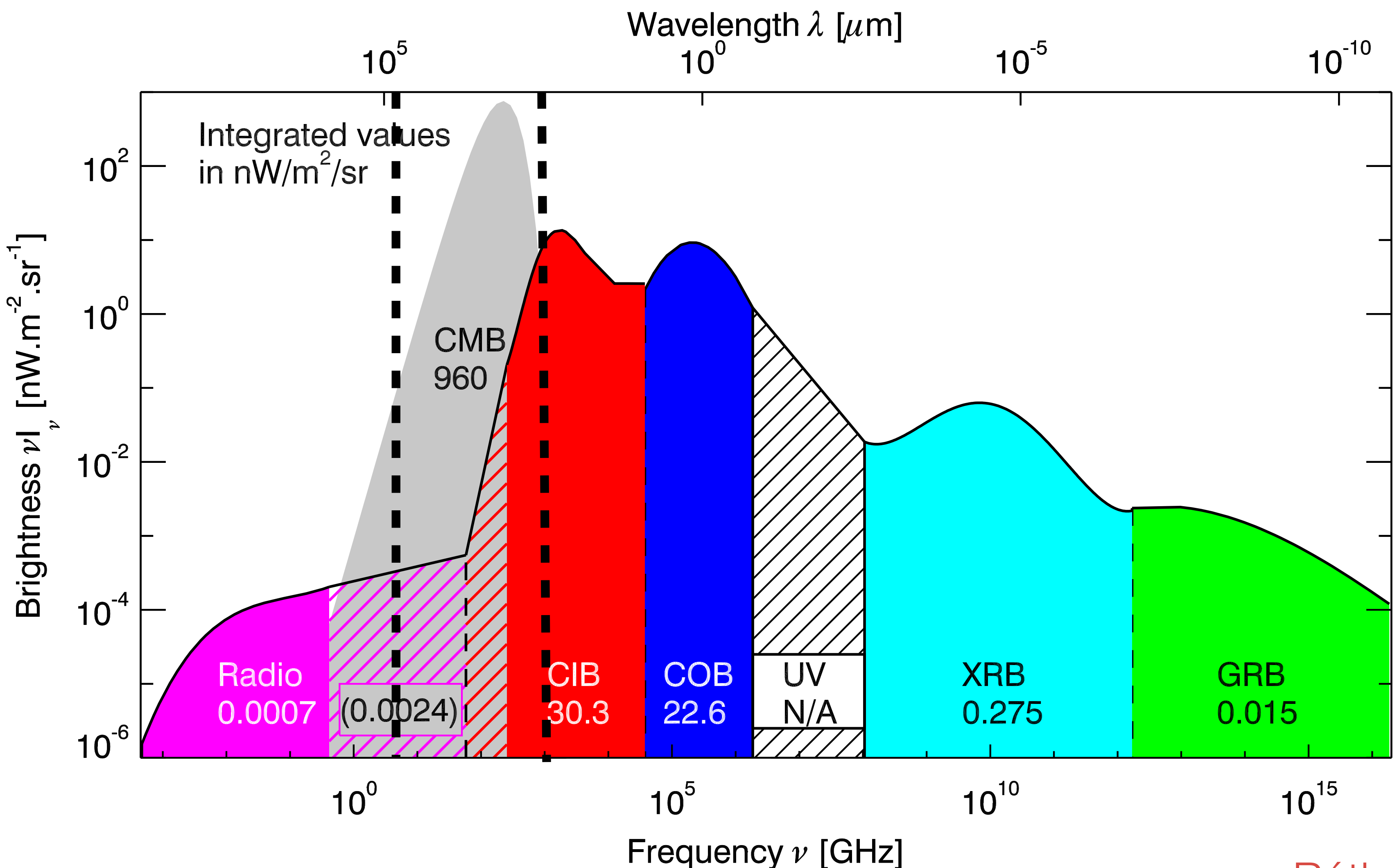
- This correlation is an important consistency test.
- It offers an opportunity to measure the galaxy survey (bias x dN/dz).
- Our lensing map overlaps with YOUR survey

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 produces exquisite maps of the CIB on large scales (provided galactic dust cleaning).

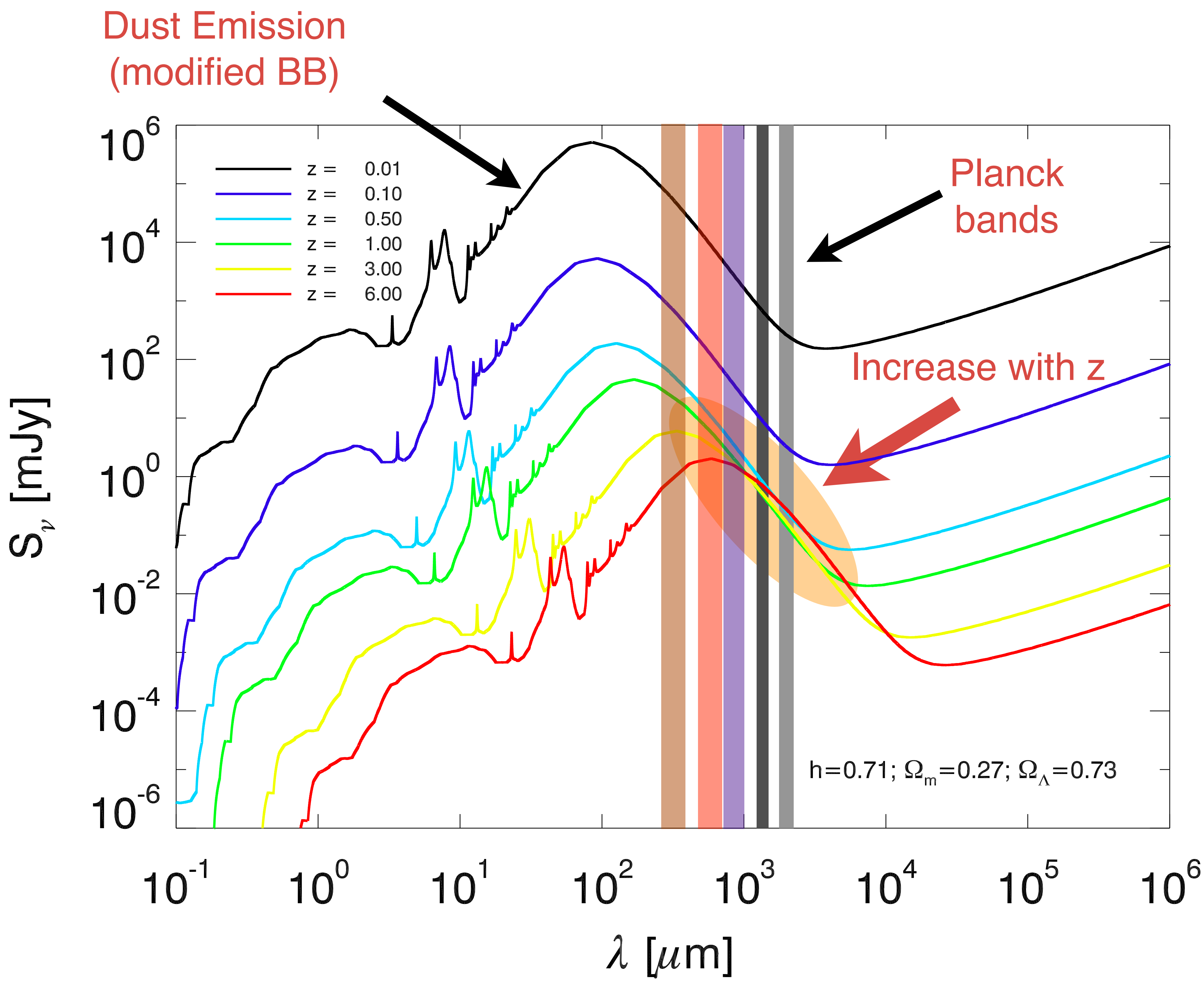
A Bright (Far-)Infrared Sky



Béthermin & Dole in prep.

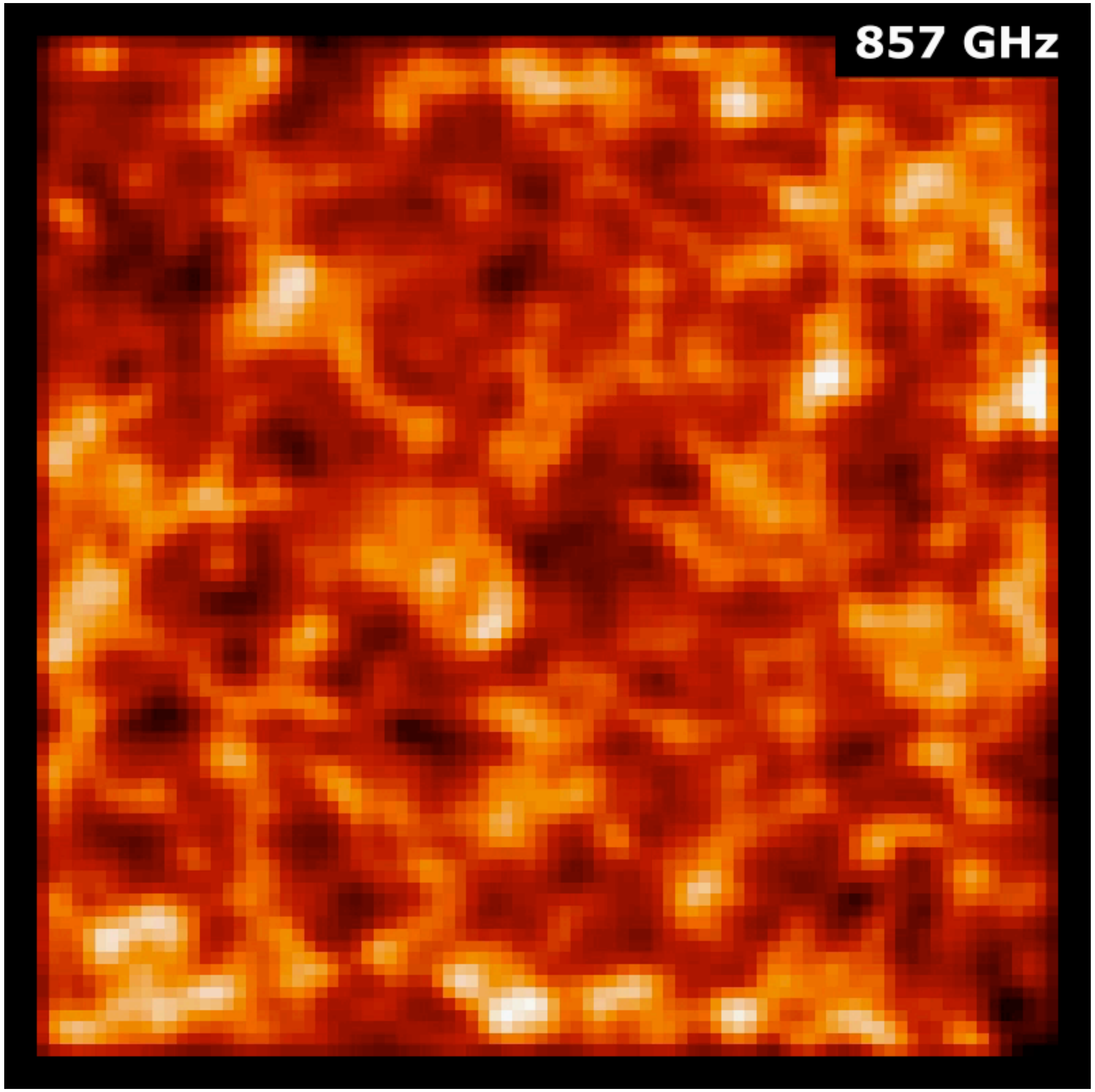
- The CIB and the COB have equal contributions, instead of ~1/3 for local galaxies.
  - IR luminosity increases with *z* faster than optical luminosity because of the increased star formation rate at higher z.
- Over half of the energy produced since the surface of last scattering has been absorbed and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

Arp 220 scaled with Redshift



Courtesy J. Viera

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



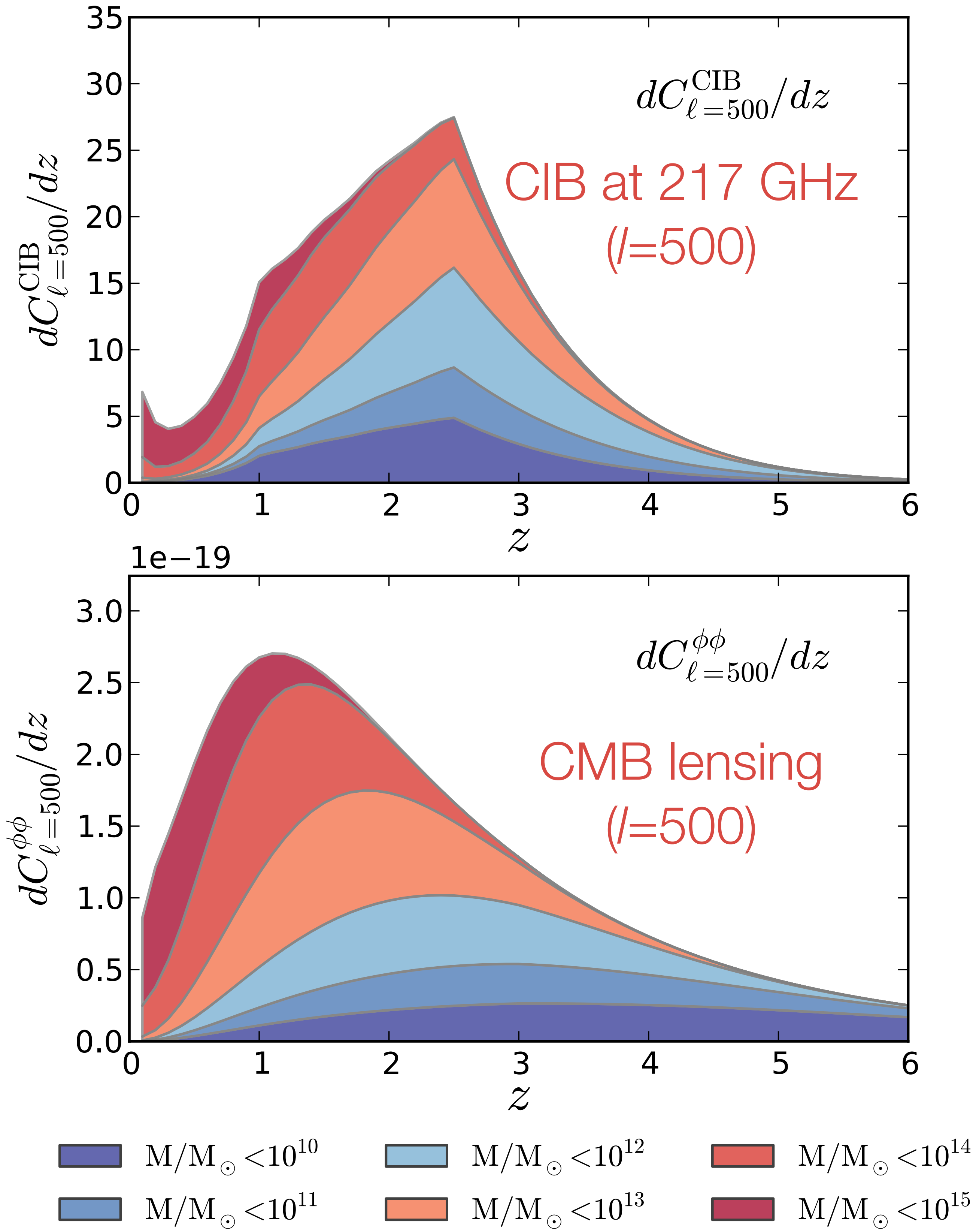
5 deg.

- 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!

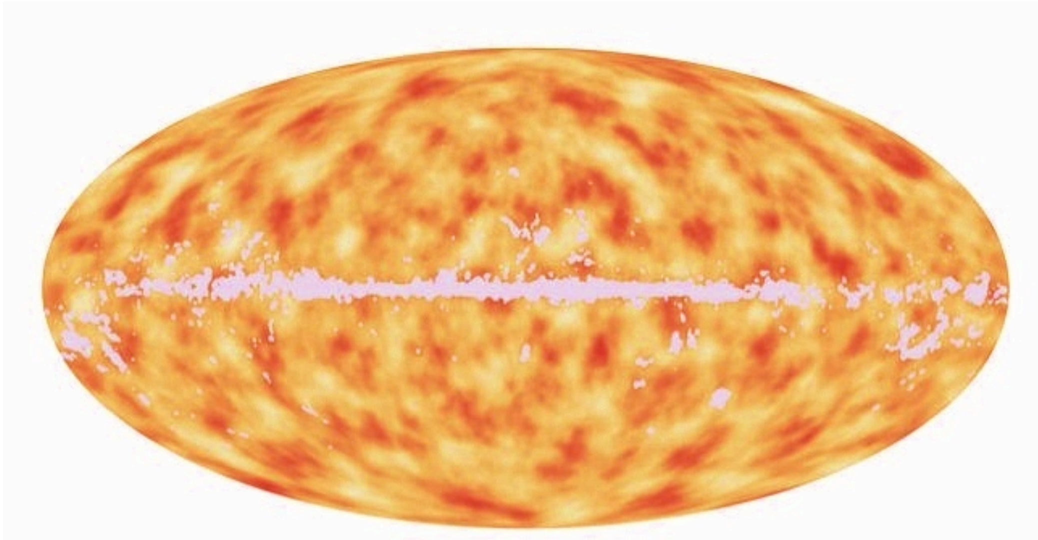
Planck Early Results XVIII

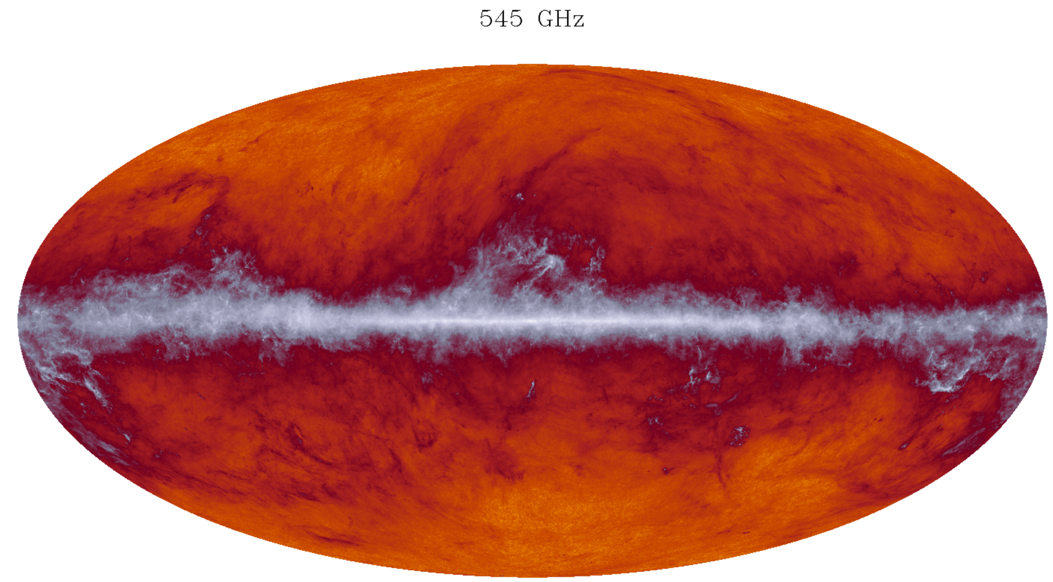
CIB Redshift and Mass Dependence

- 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

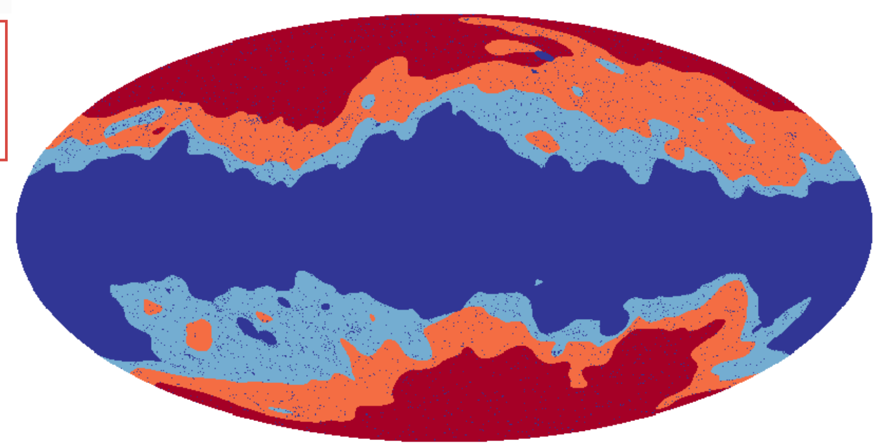




$$\sum_{\ell m} \tilde{\phi}_{\ell m} Y_{\ell m}(x) = \nabla^a \left[\alpha(x) \nabla_a \beta(x) \right]$$

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

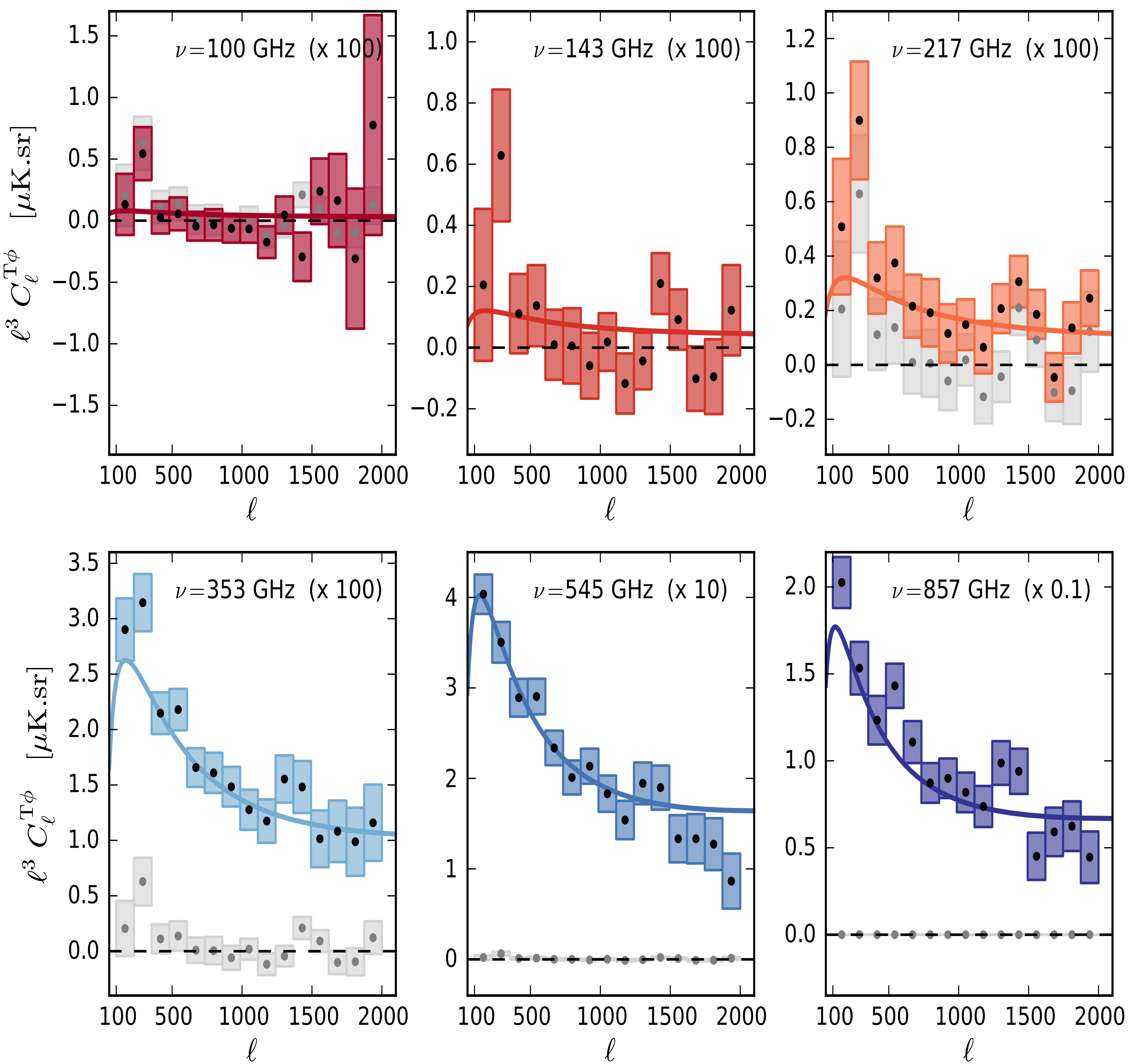
$$\beta(x) = \sum_{\ell m} C_\ell^{TT} \tilde{a}_{\ell m} Y_{\ell m}(x)$$



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

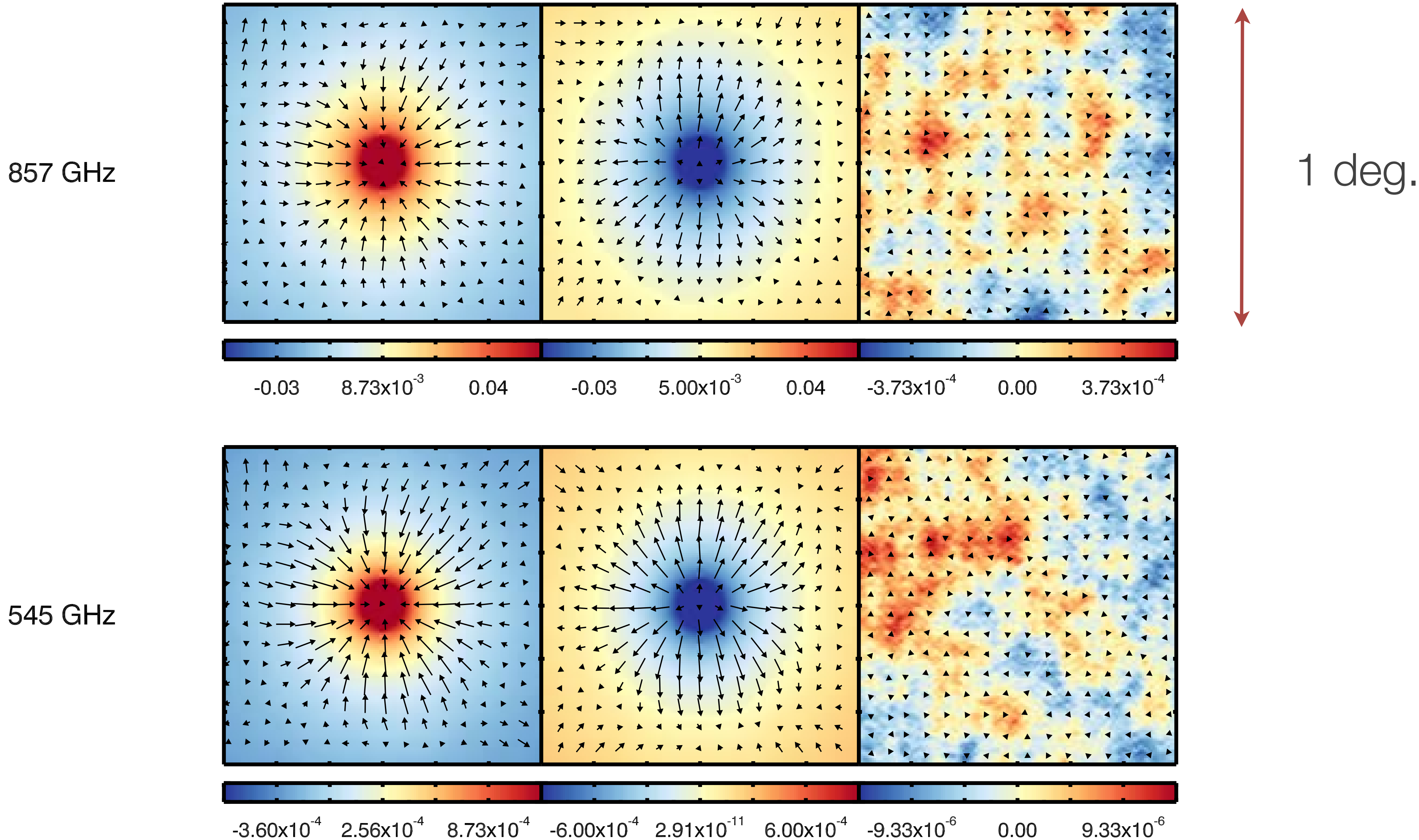
- The correlation of the inverse variance weighted reconstructed lensing potential with the temperature map is equivalent to the optimal bispectra (Smith++08).

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%).

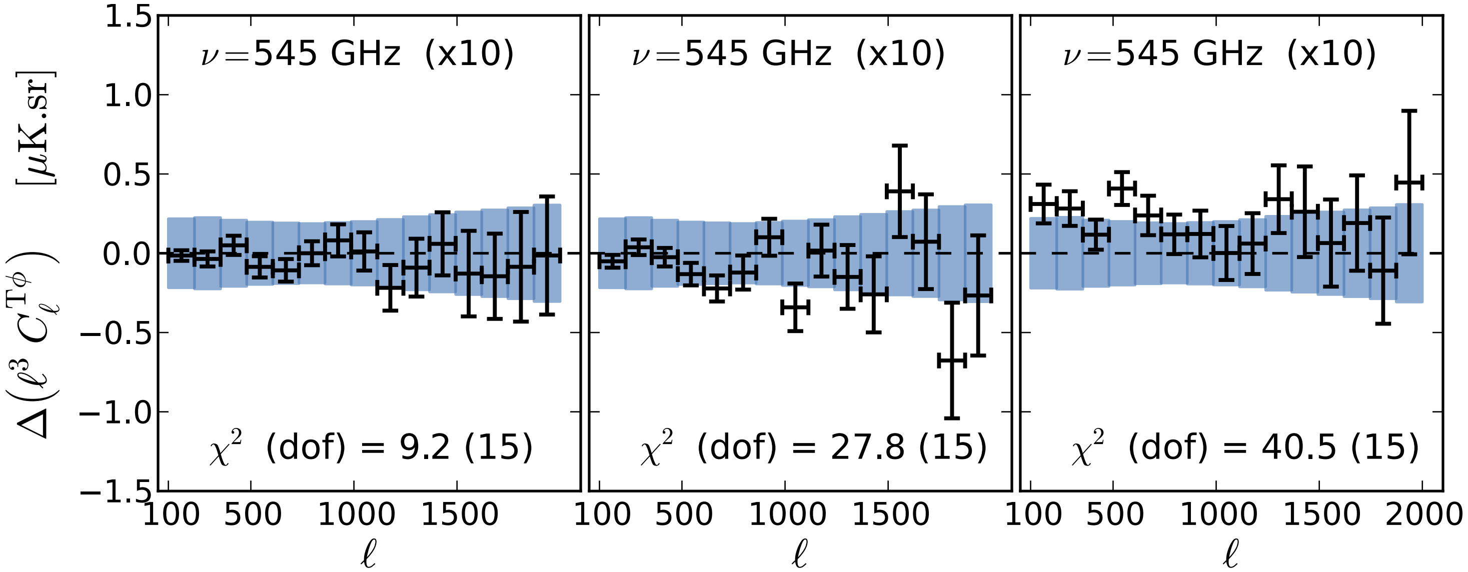
Using the CIB to "See" the Lensing of the CMB



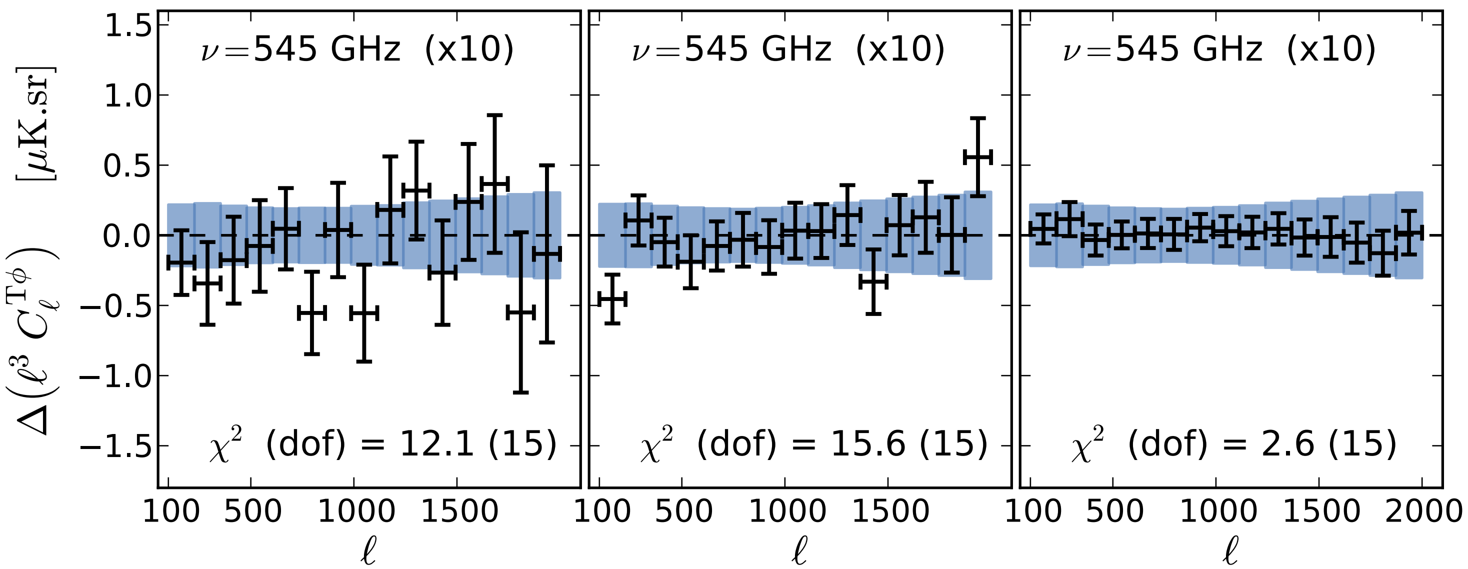
Stacking on: 20,000 T extrema | 20,000 T minima | Random location

- 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).

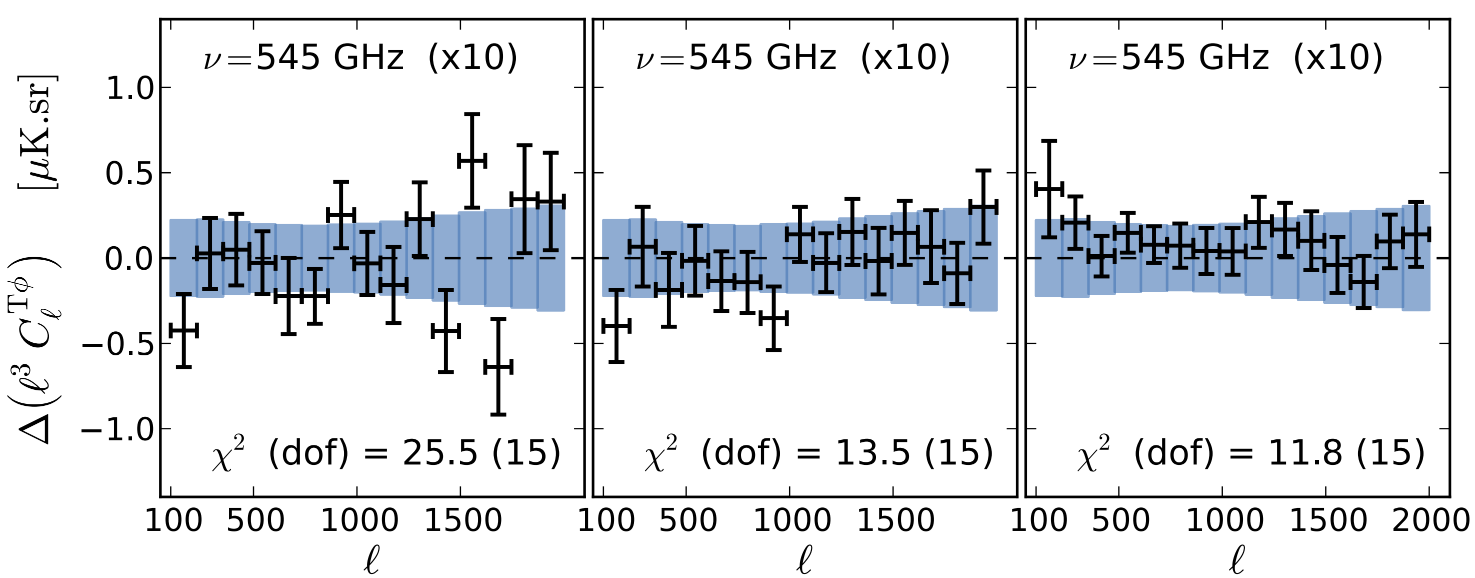
Null tests, null tests,and... more null tests...



- Null T(half ring) x Φ
- Null T(detset) x Φ
- Null T(survey) x Φ

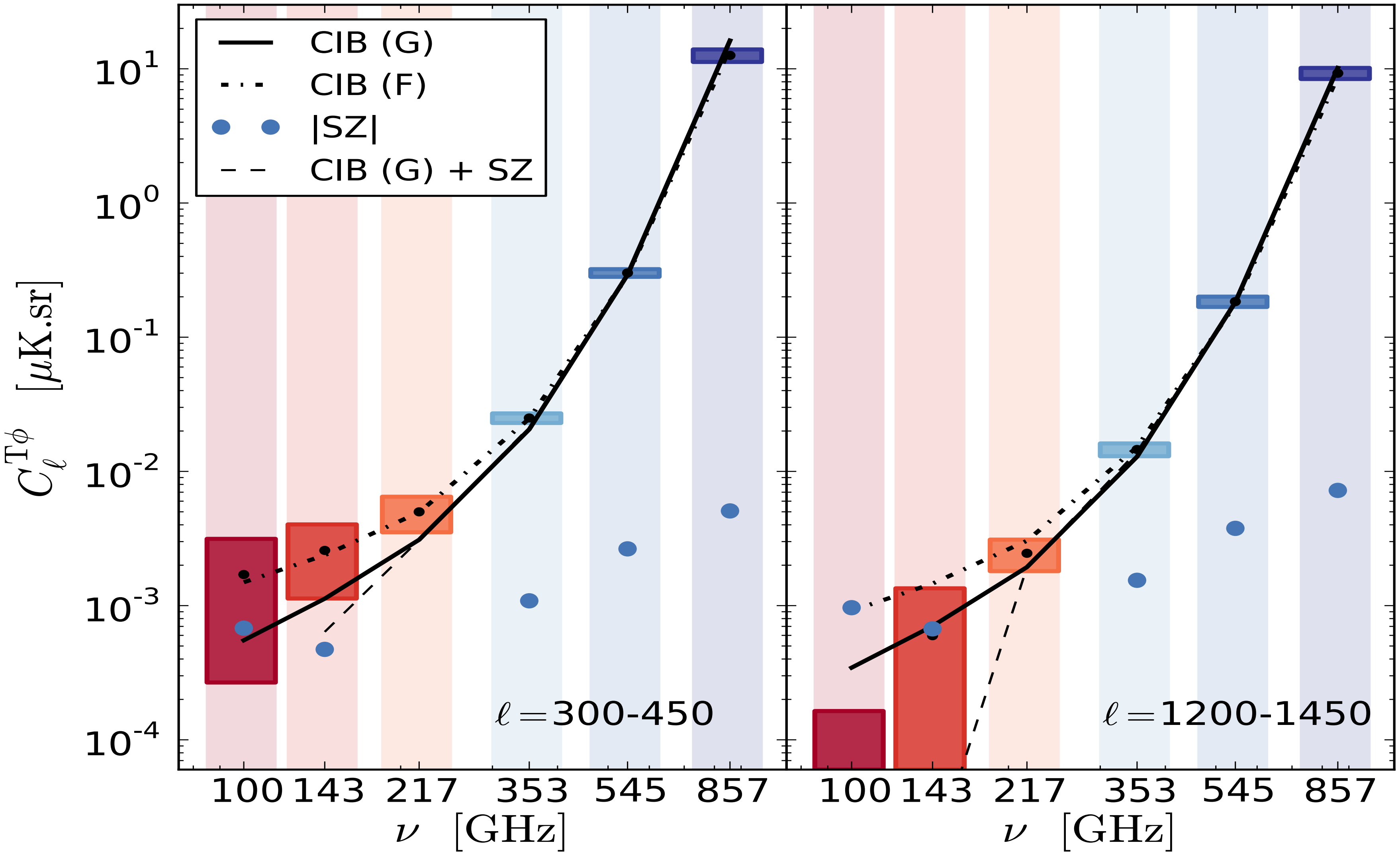


- Null T(20%-40% mask) x Φ
- Null T(60%-40% mask) x Φ
- Null T(w/ or wo/ HI cleaning) x Φ



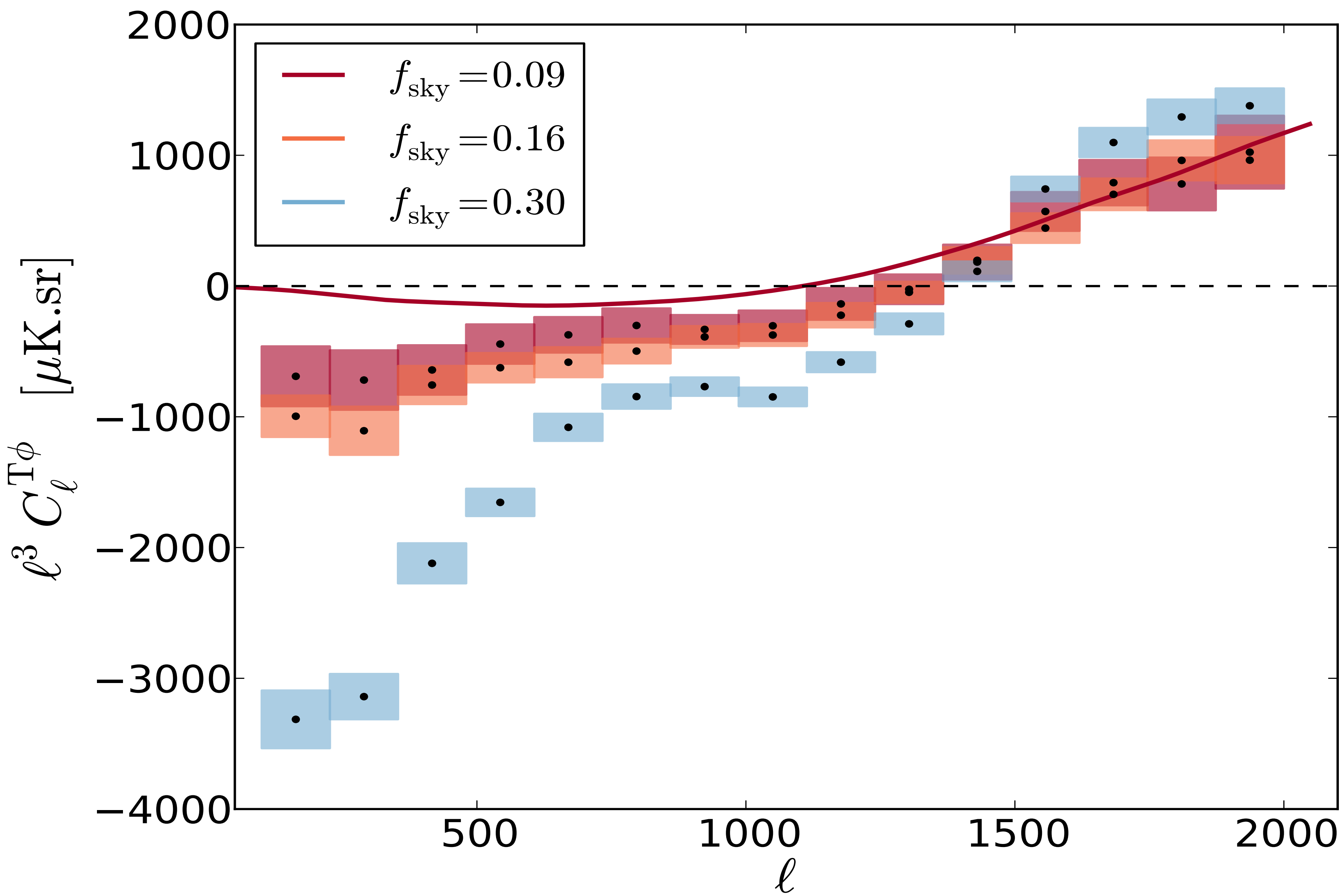
- Null Φ(100-143 GHz) x T
- Null Φ(217-143 GHz) x T
- Null Φ(20-40%) x T
- Same results hold at other frequencies

Is SZ Contamination Important?



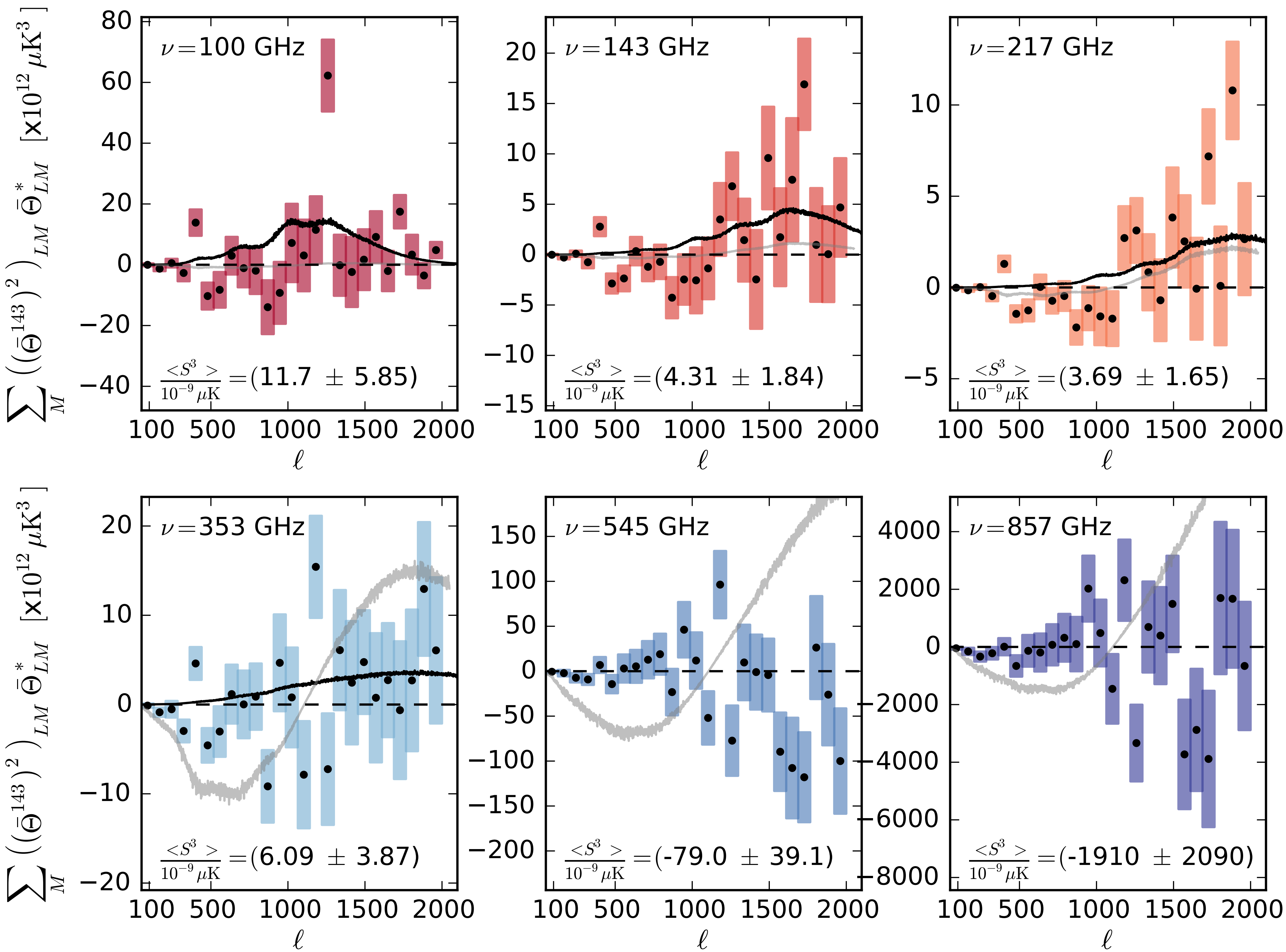
- Current models suggest SZ contribution is not important.
- To test this with our data nonetheless, we compare a "fit" using a CIB only SED (Fixsen++98 or Gispert++01) to a fit with an added SZ spectra:
  - The CIB only SED, without any fit, is a good match to the measured frequency dependence.
  - The data do not favor the inclusion of an extra SZ component, i.e., no significant ΔX^2.

Is the CIB Bispectrum Worrisome?

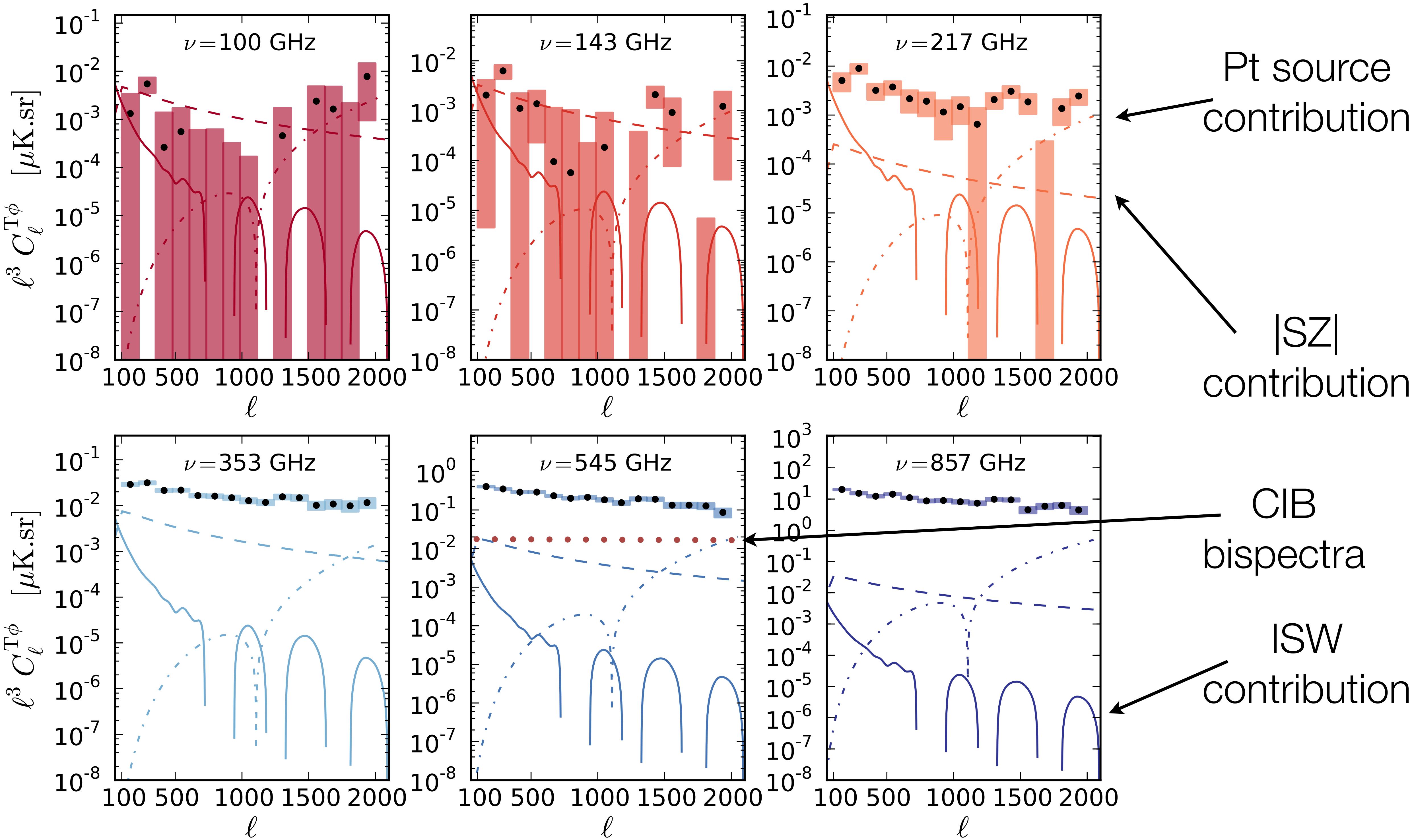


- CIB bispectrum detected by Crawford++12 but still largely uncertain.
- We use a lensing reconstruction at 545 GHz to set an upper limit on the CIB bispectrum contribution:
  - At l=400, the 1700 µK for Φ(545)xT(545) leads to a 0.02 µK signal for Φ(143)xT(545).

Evaluating Point Source Contamination



Summary of Possible Astrophysical Contaminants



- After having excluded substantial instrumental and astrophysics contaminants, we interpret the measured signal as the correlation between the CIB and CMB lensing.

Modeling the CIB x Lensing Correlation

planck

- We will model jointly the CIB autos and the CIB x Lensing angular spectra.

$$C_\ell^{XY} = \int_0^{\chi_*} d\chi \; W^X(\chi) W^Y(\chi) \; P_{\delta\delta}(k = \ell/\chi, \chi)$$

$$W^\nu(\chi) = b \frac{a \bar{j}_\nu(\chi)}{\chi};$$

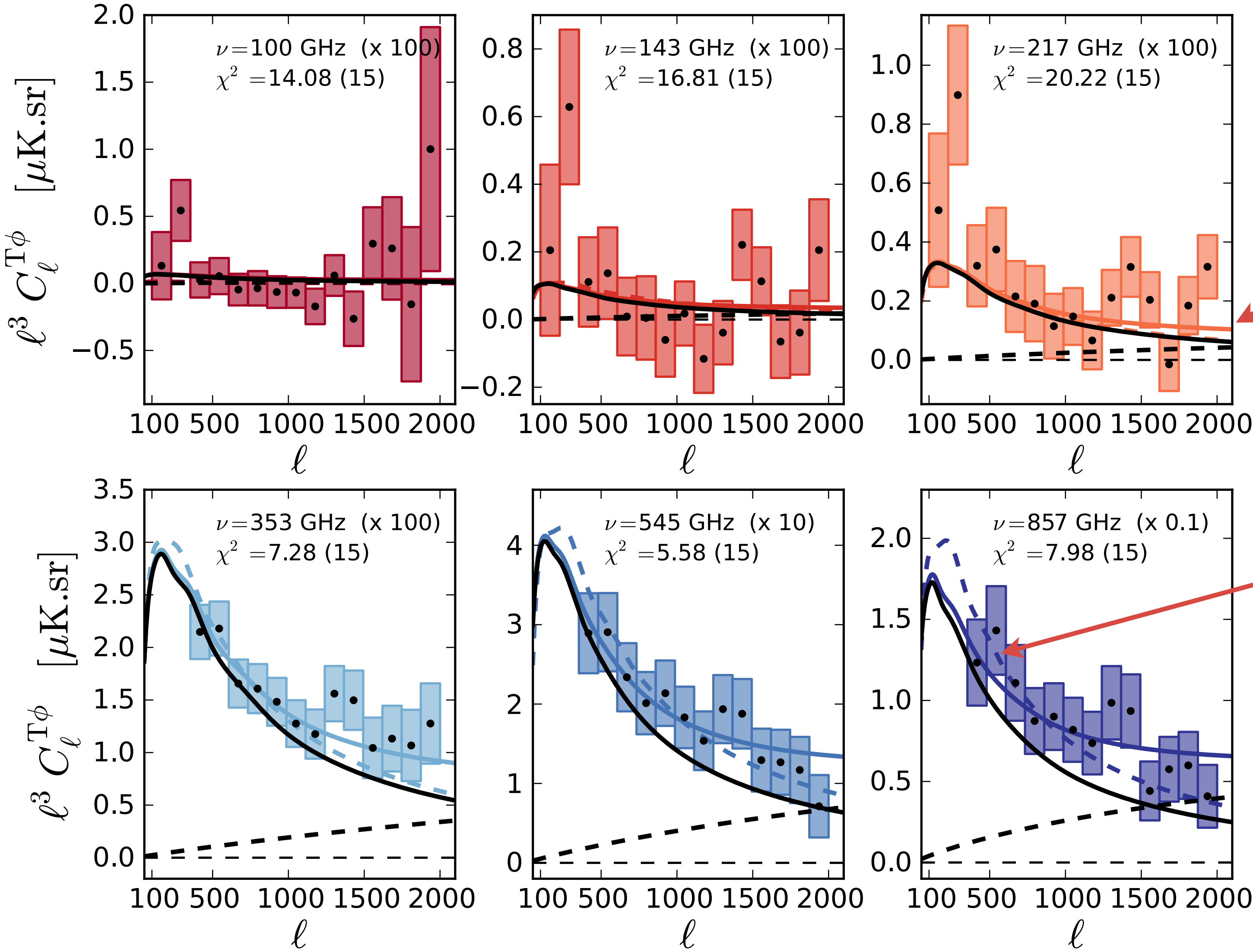
$$W^\phi(\chi) = -\frac{3}{\ell^2} \Omega_m H_0^2 \frac{\chi}{a} \left(\frac{\chi_* - \chi}{\chi_* \chi} \right)$$

Mean emissivity:

$$\bar{j}_\nu(z) = (1+z) \int_0^{S_{\rm cut}} dS \; S \; \frac{d^2 N}{dS \, dz}$$

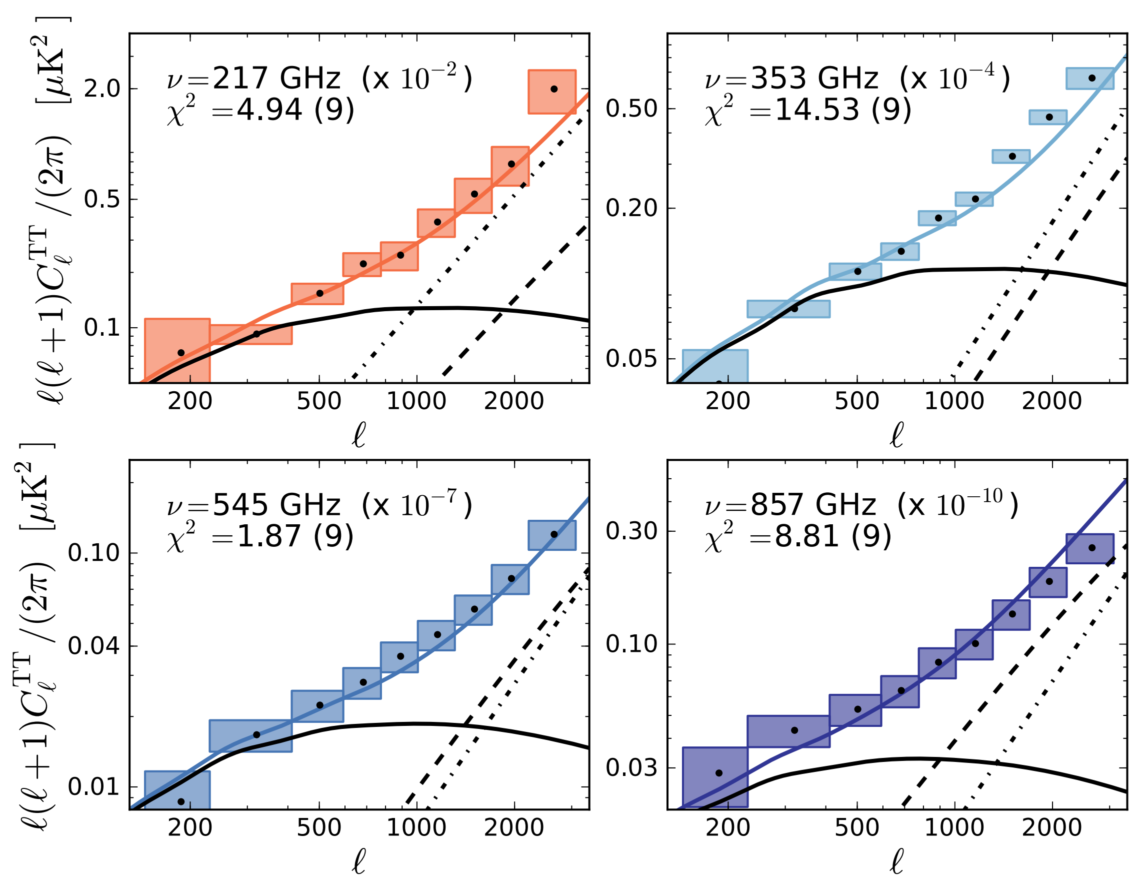
- We fix the cosmology to the Planck cosmology as we are dominated by galaxy modeling uncertainties.
- We consider two models:
  - A simple linear bias model with a "Gaussian" emissivity (inspired by Hall+12).
  - A Halo Occupation Density (HOD) model. We solve for two HOD parameters and the mean emissivity per frequency in 3 redshift bins. This is an extension from the Planck Early Paper XVIII analysis.
- A more thorough modeling is presented in the CIB focused Planck 2013 Results. XXX

Best Fit Auto- and Cross-Spectra

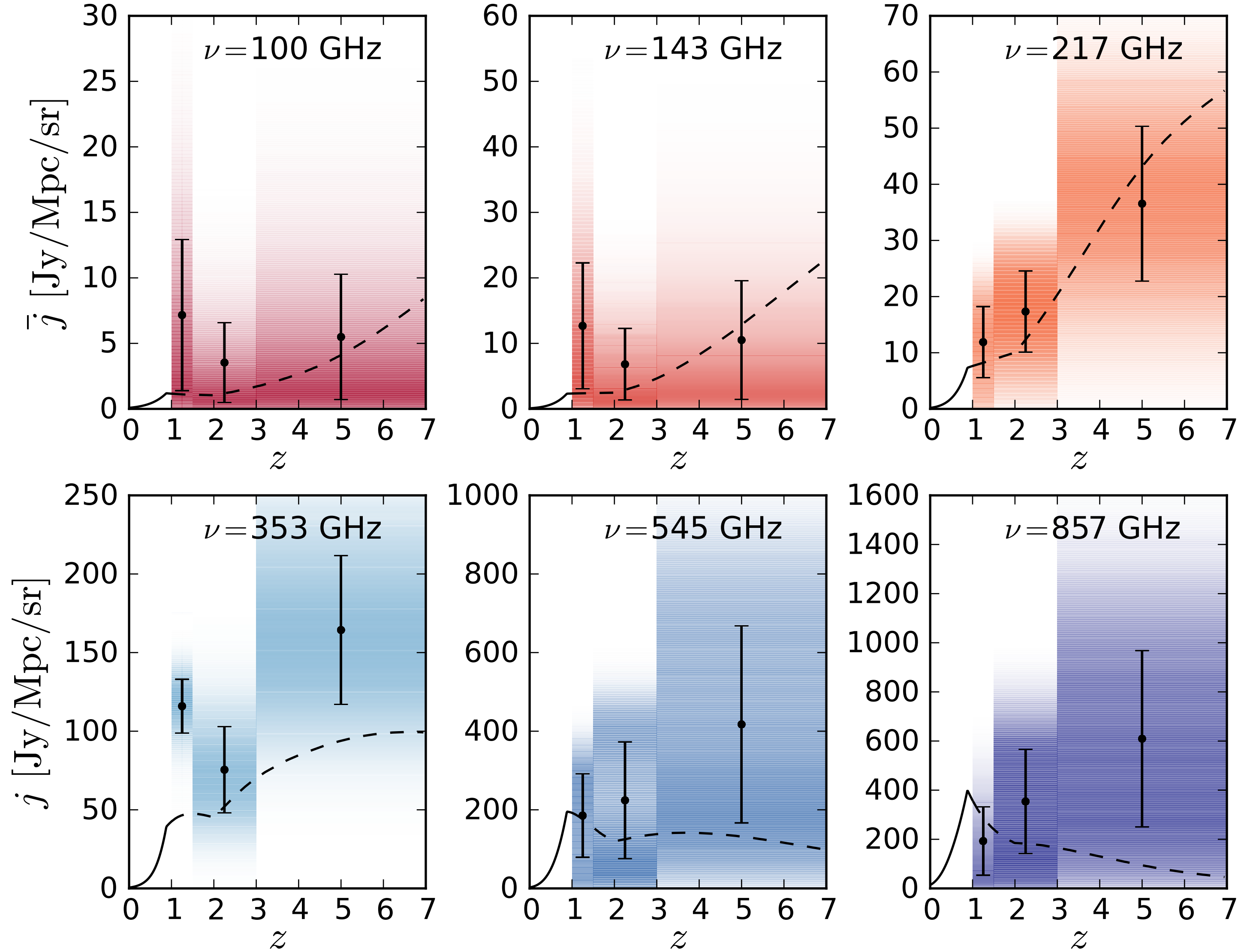


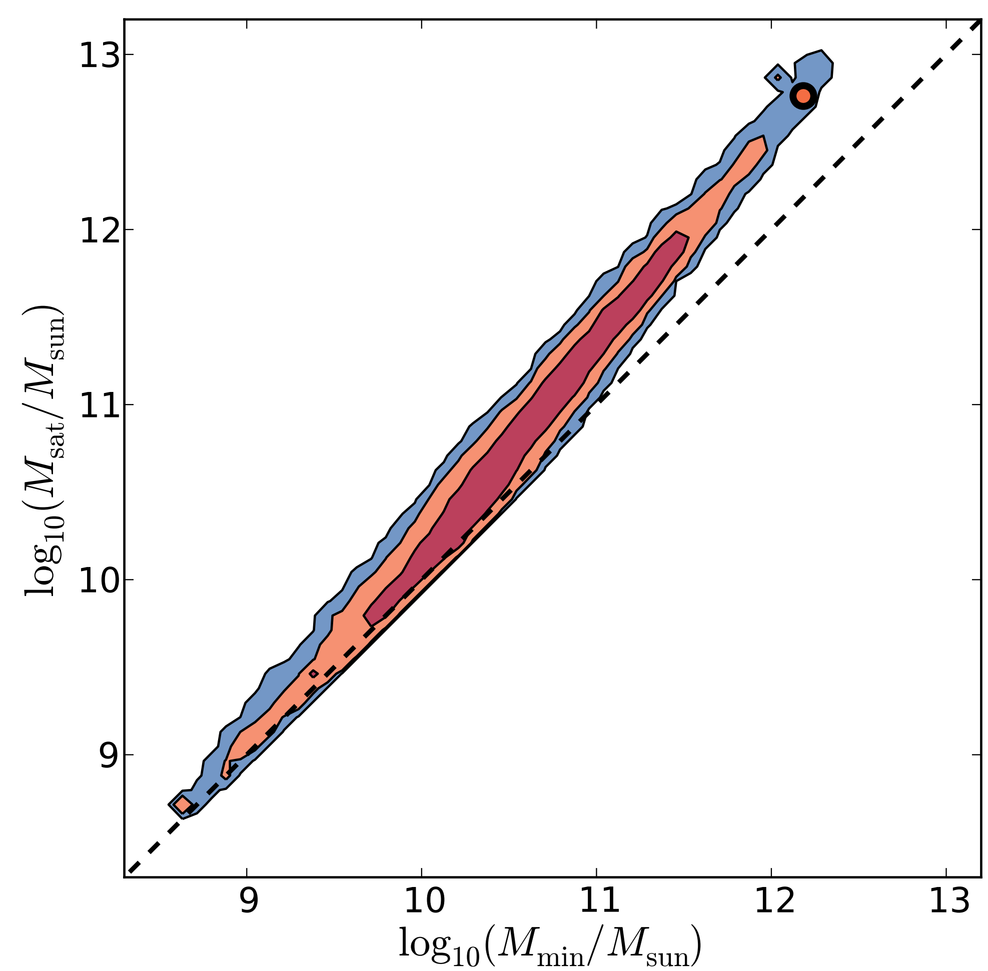
Reconstructed emissivities model

Linear bias model with b~2.4



Reconstructed Emissivities and HOD Masses





Each DM halo is populated with $N_{gal} = N_{cen} + N_{sat}$

$$N_{\rm cen} = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log M - \log M_{\rm min}}{\sigma_{\log M}}\right)\right]$$

$$N_{\rm sat} = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log M - \log 2M_{\rm min}}{\sigma_{\log M}}\right)\right]$$

Constraining the SFR at High Redshift

- Using the Kennicutt 98 law and an effective SED for our sources (Béthermin+12, Magdis+ +12), we can convert the measured emissivities into star formation densities as a function of z.

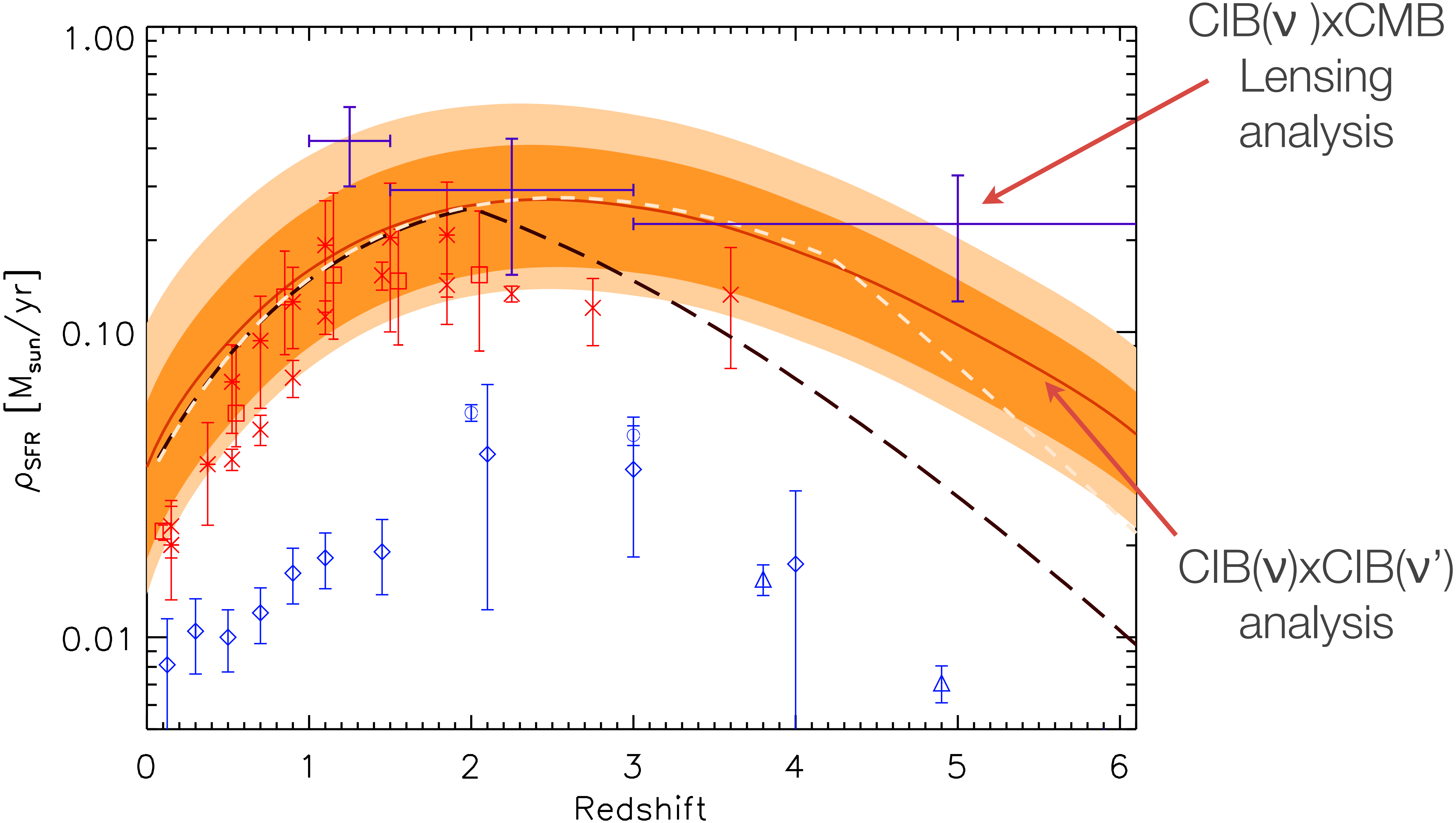
	$1 < z \leq 1.5$		$1.5 < z \leq 3$		$3 < z \leq 7$	
	$\bar{j}(z)$	ρ_{SFR}	$\bar{j}(z)$	ρ_{SFR}	$\bar{j}(z)$	ρ_{SFR}
100 GHz	7.16±5.77	1.96±1.58	3.53±3.05	0.655±0.564	5.49±4.78	0.271±0.236
143 GHz	12.7±9.60	1.37±0.964	6.82±5.46	0.438±0.351	10.5±9.05	0.178±0.153
217 GHz	11.9±6.33	0.310±0.165	17.3±7.23	0.282±0.118	36.6±13.8	0.182±0.068
353 GHz	116±17.1	0.671±0.099	75.5±27.5	0.286±0.104	164±47.3	0.320±0.092
545 GHz	185±106	0.320±0.183	224±148	0.317±0.210	417±251	0.659±0.396
857 GHz	193±139	0.144±0.104	354±212	0.317±0.190	609±359	1.37±0.809

j: [Jy/Mpc/sr]

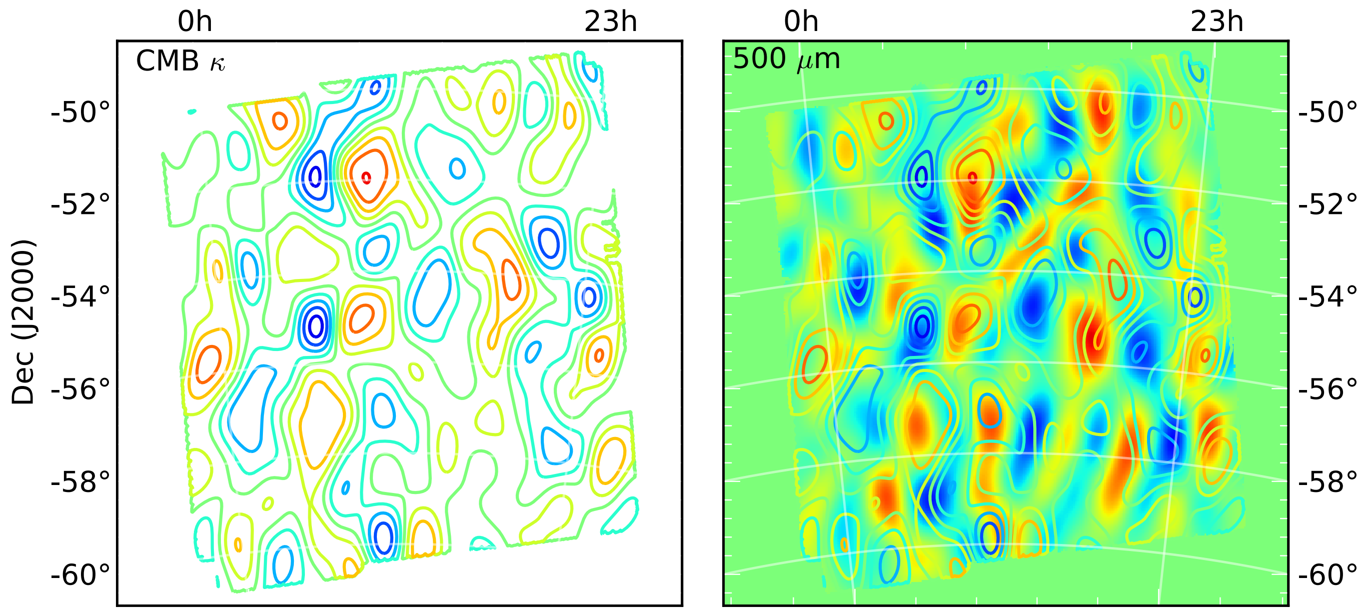
ρ_{SFR} : [$M_{sun}/Mpc^3/yr$]

- Adding the CMB lensing x CIB correlation helps constrain the high z contribution
- Combining these constraints lead to ρ_{SFR} = 0.423 ± 0.123, 0.292 ± 0.138 and 0.226 ±0.100 $M_{sun}/Mpc^3/yr$ for each z bin.

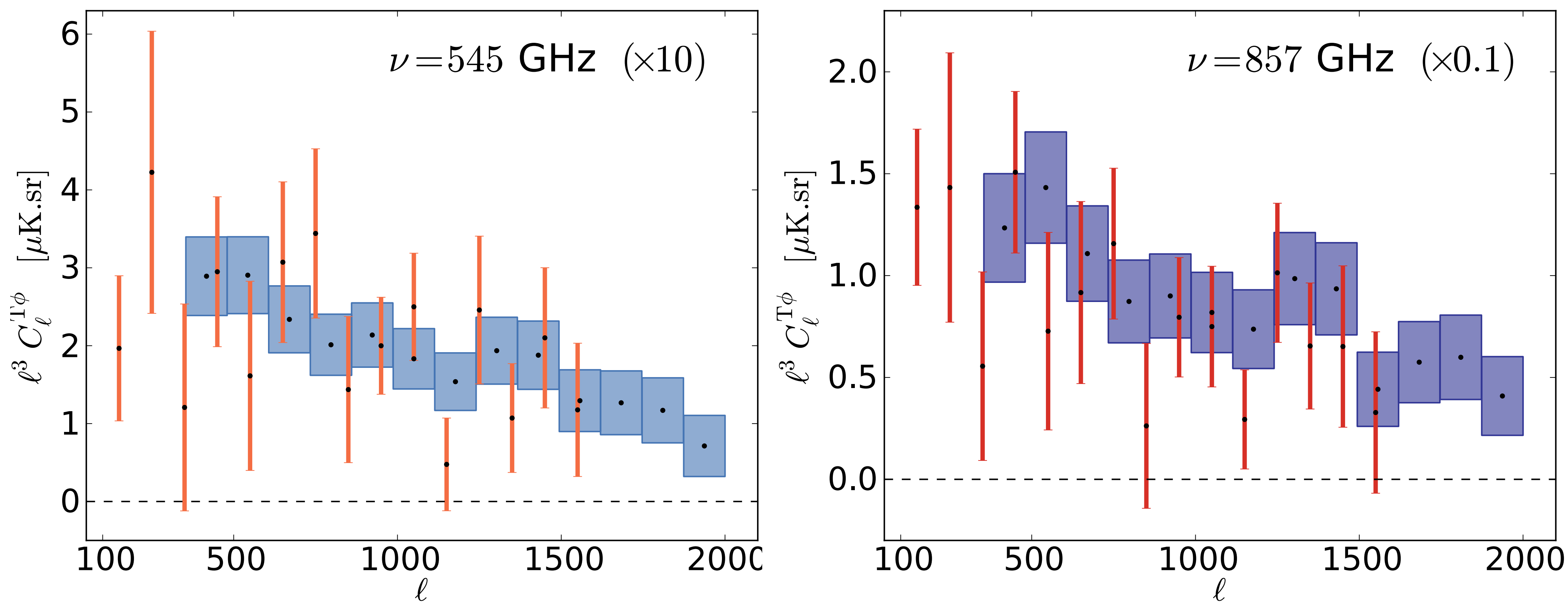
Star Formation Rate Constraints



SPT x Herschel vs Planck x Planck



- 90 sq. deg of overlapping SPT and Herschel observations.
- Leads to a 6.6-8σ detection.
- It will take CCAT to resolve these objects



Point and error bars from Holder++13
(No color correction included)

Summary

- Using Planck data alone, we report a strong correlation between the CMB lensing gravitational potential and all temperature maps at frequencies above 217 GHz, and marginal significance at 100 and 143 GHz.
- This measurement is interpreted as the correlation between the CMB lensing and the CIB.
  - Using an extensive set of null tests, we exclude substantial instrumental systematic effects.
  - Using various masks and frequencies for Φ and T, we exclude any substantial galactic contamination.
  - Using targeted tests for known astrophysical foregrounds, we exclude a strong contamination by the SZ effect, the CIB bispectrum and we remove a small point source contamination.
- The detection levels reach 3.6 (3.5), 4.3 (4.2), 8.3 (7.9), 31 (24), 42 (19), and 32 (16) σ statistical (statistical and systematic) at 100, 143, 217, 353, 545 and 857 GHz, respectively.
- We built two models and inferred constraints on the star formation density at high redshift, leading to a measurements in 3 large redshift bins, up to z<6.
- The high degree of correlation measured (around 80 %) allows for unprecedented visualization of lensing of the CMB.
- This correlation holds great promise for novel CIB and CMB focused science.
  - CMB lensing appears promising as a probe of the origin of the CIB.
  - The CIB is now established as an ideal tracer of CMB lensing.
- Good consistency with the Hershel (550μm and 350 μm) x SPT results from Holder++13.

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.

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