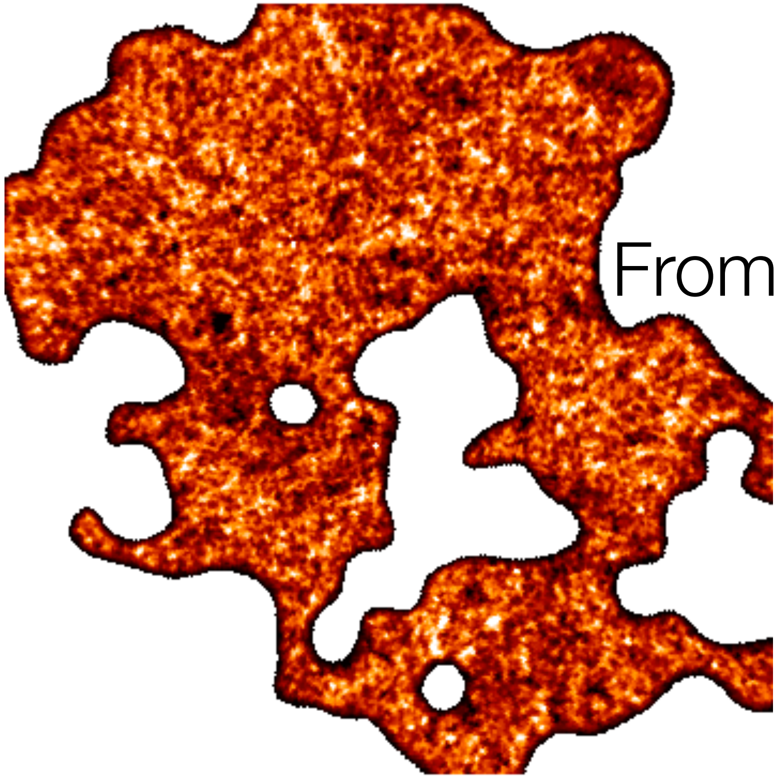


From Cosmic Microwave Background to Cosmic Infrared Background: dusty star-formation in the making

Honolulu, August 2015

Guilaine Lagache

Laboratoire d'Astrophysique de Marseille, France

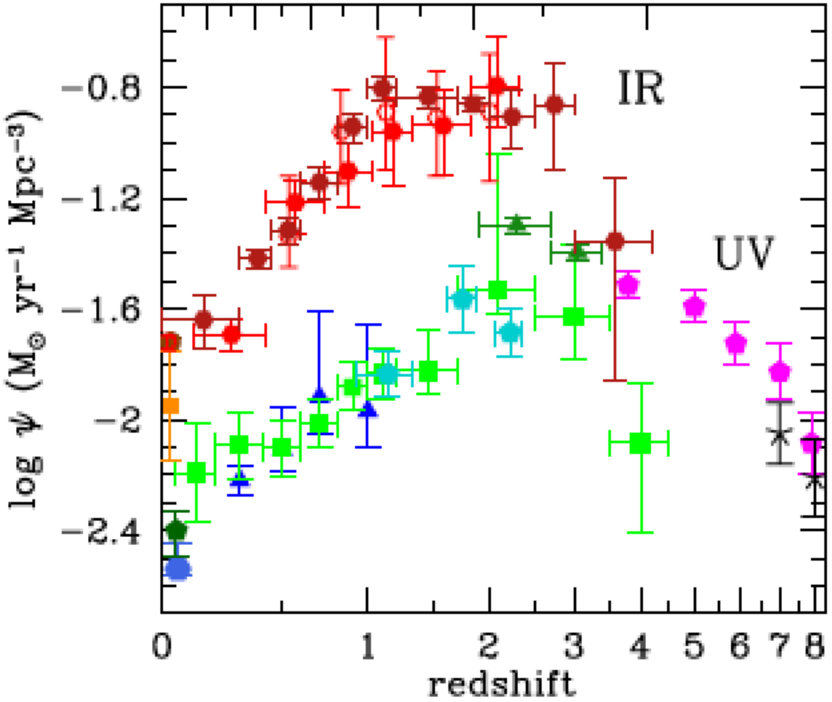
HFI PLANCK

Dusty star-formation at high redshift

- One of the most pressing questions of modern Cosmology: How the clumpy structured universe that we see today evolved from the smoothly distributed matter that existed during the dark ages?

- Dusty star-forming galaxies (DSFG) are participating to this major change

Cosmic Star Formation Rate Density



Madau & Dickinson, 2014

Critical player in the assembly of stellar mass
and the evolution of massive galaxies

« IR » = 1- 1000 μm / 300 THz – 300 GHz

Dusty star-formation at high redshift

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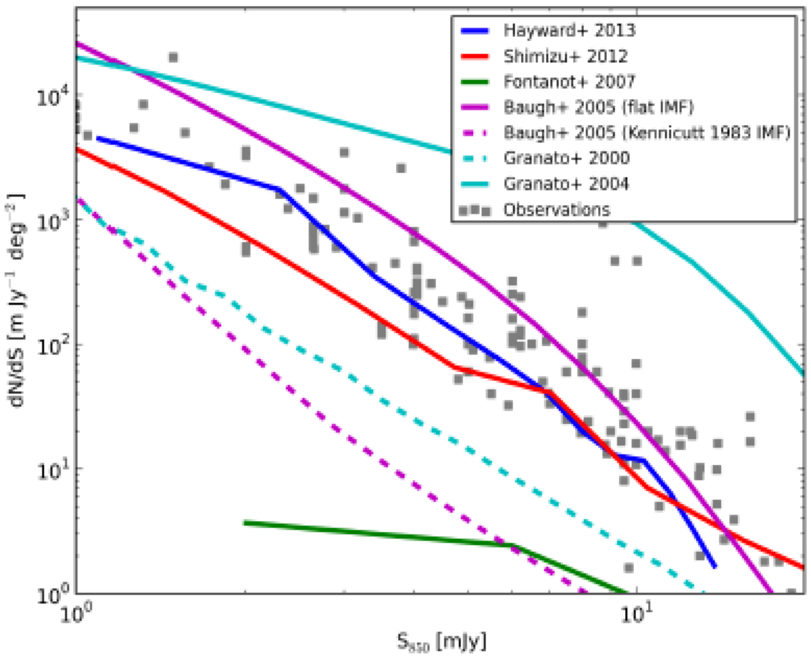
- Dusty star-forming galaxies (DSFG) are participating to this major change

850 μm number counts / theoretical models



Forming dusty galaxies at high-z: confounding problem for theorists across the board

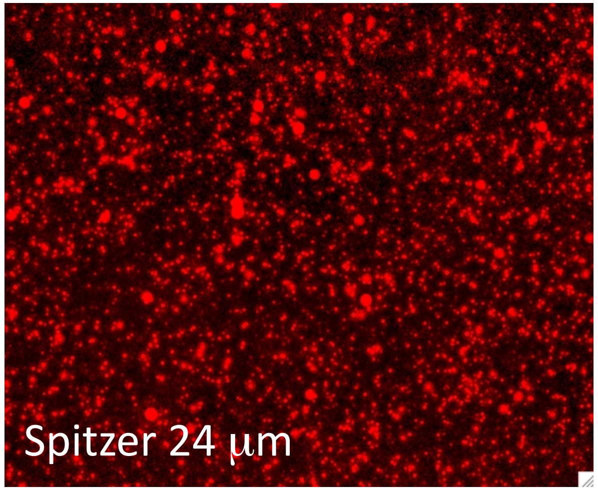
To date: no model simultaneously matches the observed number counts of bright DSFG while also matching their inferred physical properties, as well as the z=0 stellar mass function in an *ab* initio manner

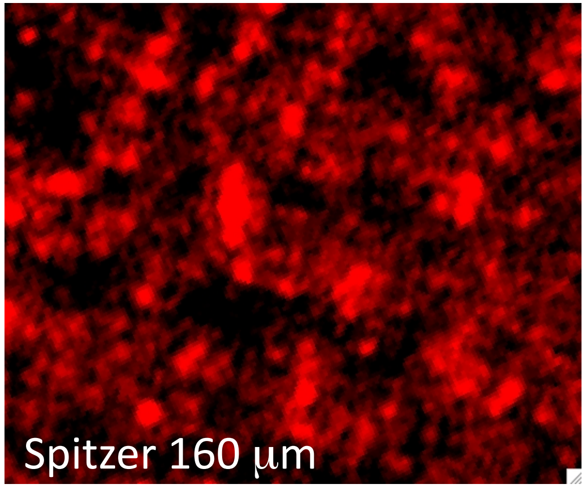
Casey et al. 2014

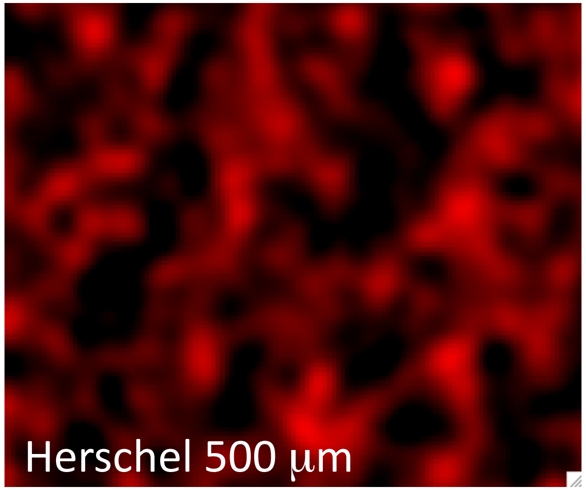
Dusty star-formation at high redshift

- Observe the dusty star-formation at high redshift => (sub-)mm experiments

- Very difficult to detect DSFG at high redshift
  - so faint and numerous (compared to the angular resolution achievable in the far-IR to mm), that confusion plagues observations substantially







Dusty star-formation at high redshift

- Observe the dusty star-formation at high redshift => (sub-)mm experiments

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- CMB experiments, such as Planck, or far-IR/mm experiments (e.g., Herschel, SCUBA-2) can only see the brightest objects that represent the tip of the iceberg in terms of galaxy mass halos and star formation rates.
  - Only ALMA can see *all* of them (but very small areas)

- Fortunately, CMB experiments are sensitive enough to measure the cumulative IR emission from all galaxies throughout cosmic history

=> Cosmic IR Background and its anisotropies.

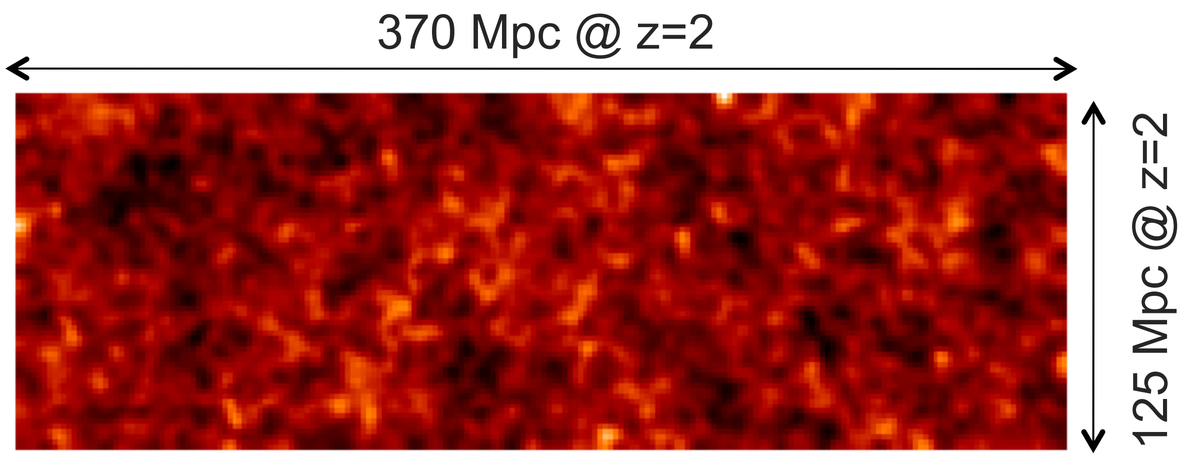
CIB anisotropies

- So bright (δI/I~10-15%) that they represent (together with the shot noise) the main foreground contaminant to CMB temperature maps at small scales.

- Distinct frequency-redshift dependance (from 3000 GHz to 100 GHz):
  => probe a large span of redshifts (0.5<z<4)

- An important tracer of large-scale structures

Bootes
12 deg x4 deg



- Derive information on the physical processes governing the star formation and galaxy evolution

- Probe the cosmology

Outline

I. Current measurements of CIB anisotropies

II. What have we learned from these measurements in the framework of galaxy evolution, dusty-star formation at high redshift ?

III. CIB as a tracer of dark matter field => Cross correlating cosmic fields

- Learn more on the CIB (e.g., tomography)
- Probe cosmology (e.g., B-mode and dark energy)

IV. The Legacy of Planck

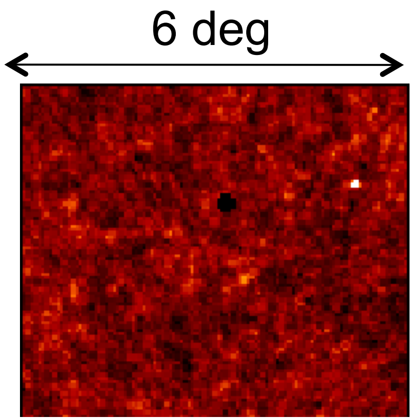
I. Current measurements of CIB anisotropies: maps, power spectra, bispectra

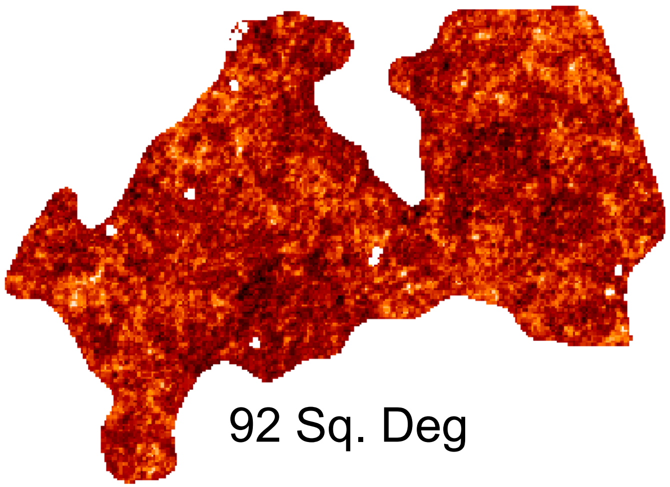
Difficult problem of component separation

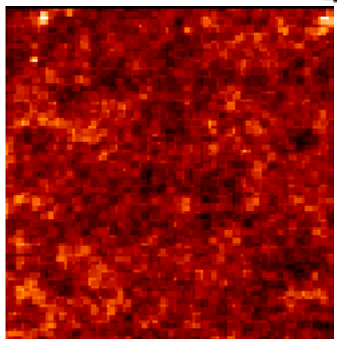
- Galactic dust, CMB, SZ
- Map-based or C_l-based component separation

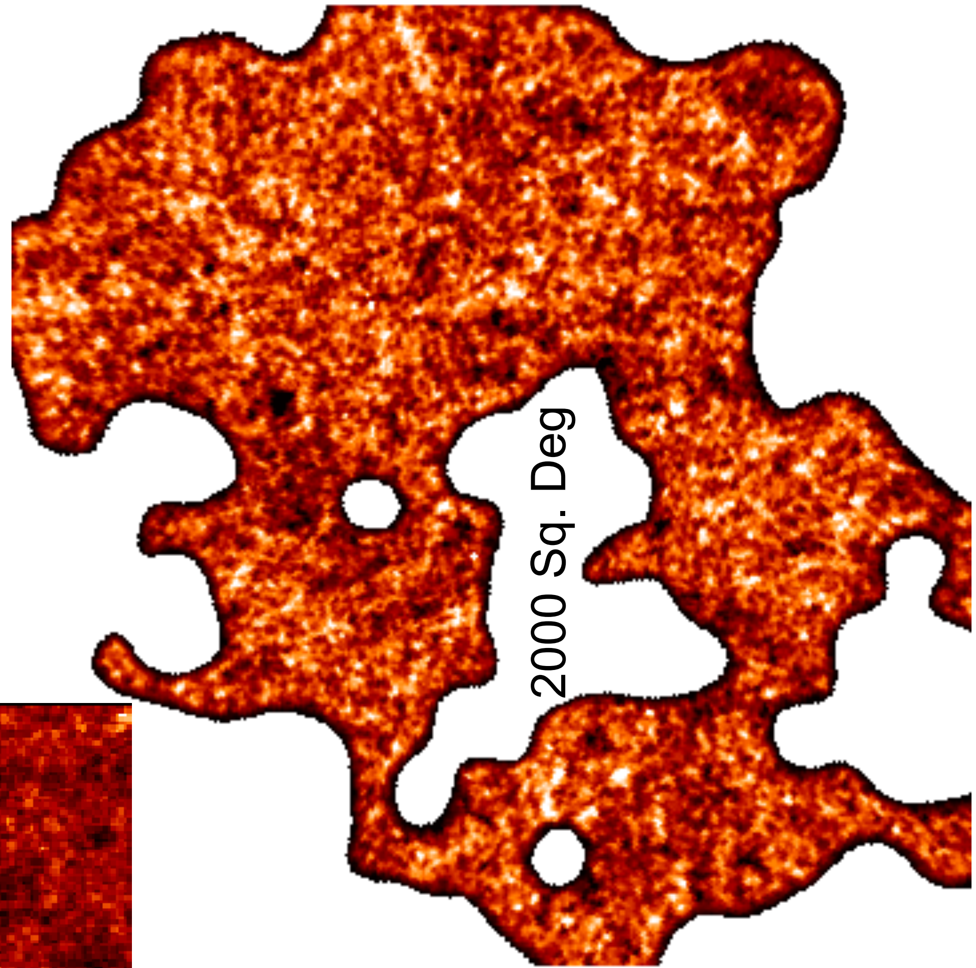
CIB anisotropies: maps

- Need CMB maps and Galactic dust template maps
  - Only successfully attempted in Penin+12 (Spitzer + IRAS) and Planck collaboration XVIII 2011 and XXX 2013 from 143 to 3000 GHz using:
    - HI maps as dust template
    - HFI maps as CMB template



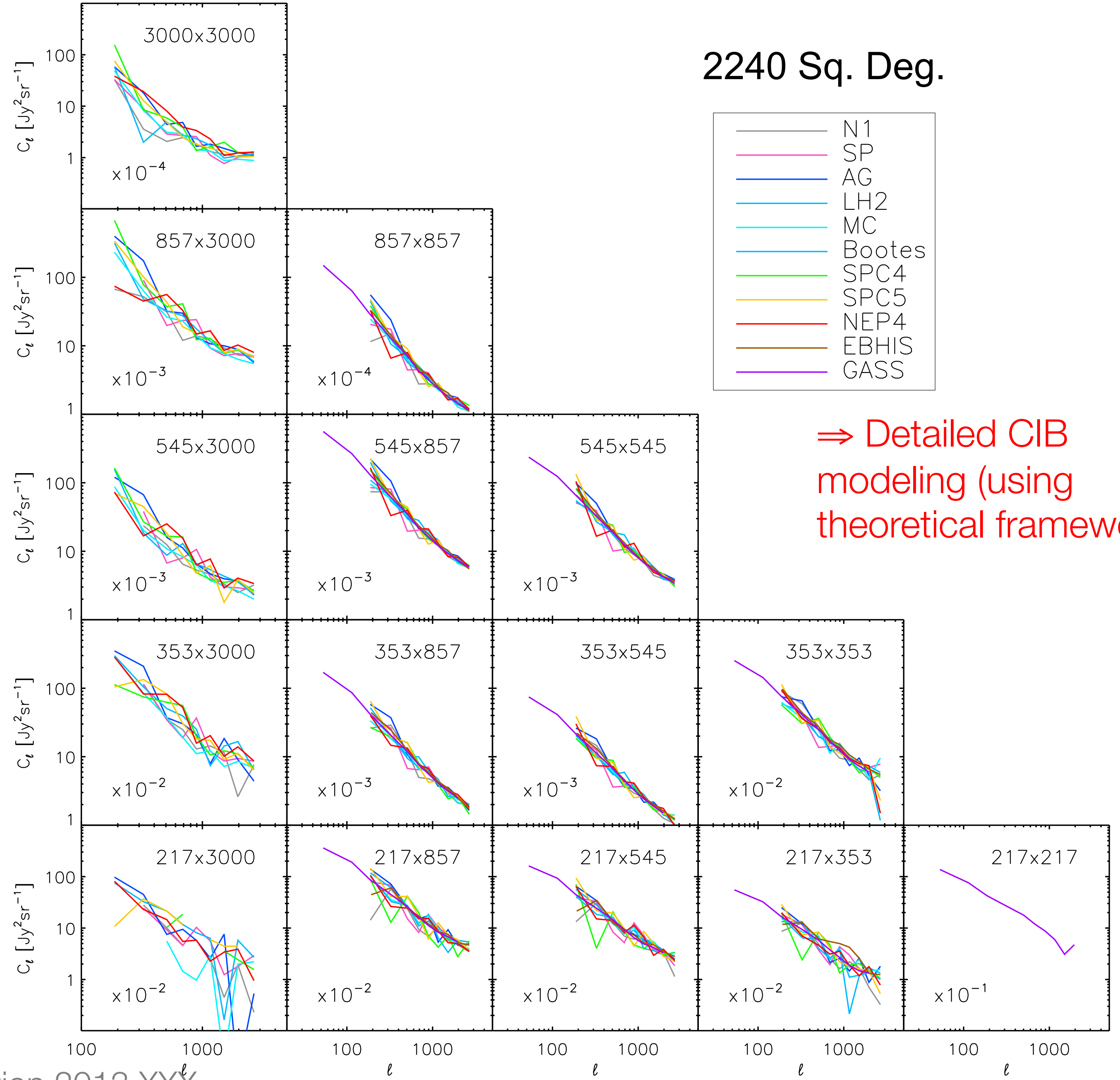






Angular power spectrum: 11 fields

2240 Sq. Deg.



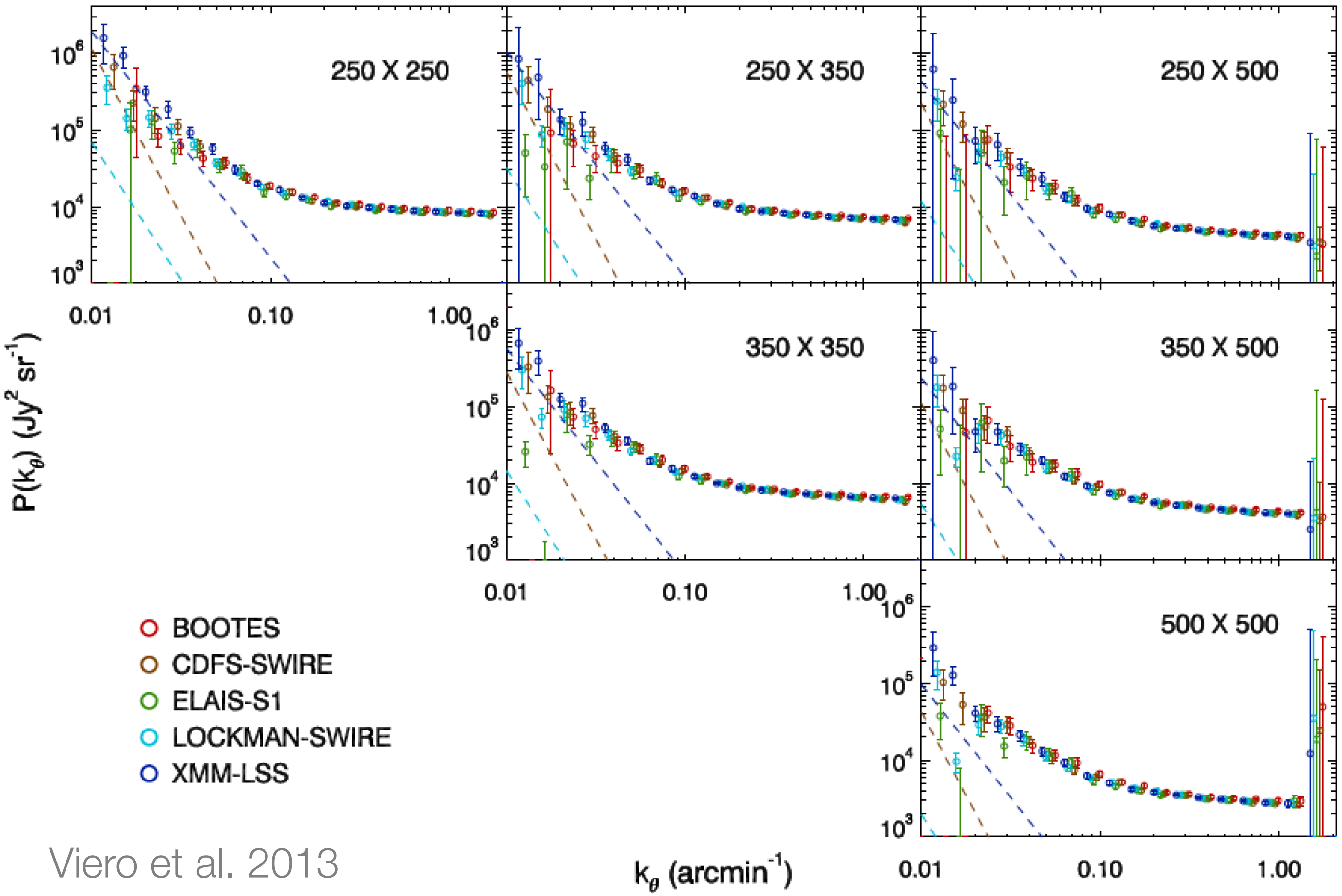
⇒ Detailed CIB modeling (using theoretical framework)

Planck collaboration 2013 XXX

CIB anisotropies: power spectra

- High-frequency (Spitzer/MIPS, Herschel/SPIRE)
  - 1871, 1200, 600, 857 and 1200 GHz (160, 250, 350 and 500 microns)
  - Fitting for cirrus component at large-scale in power spectra

    Lagache+07, Amblard+11, Viero+13, Thacker+13



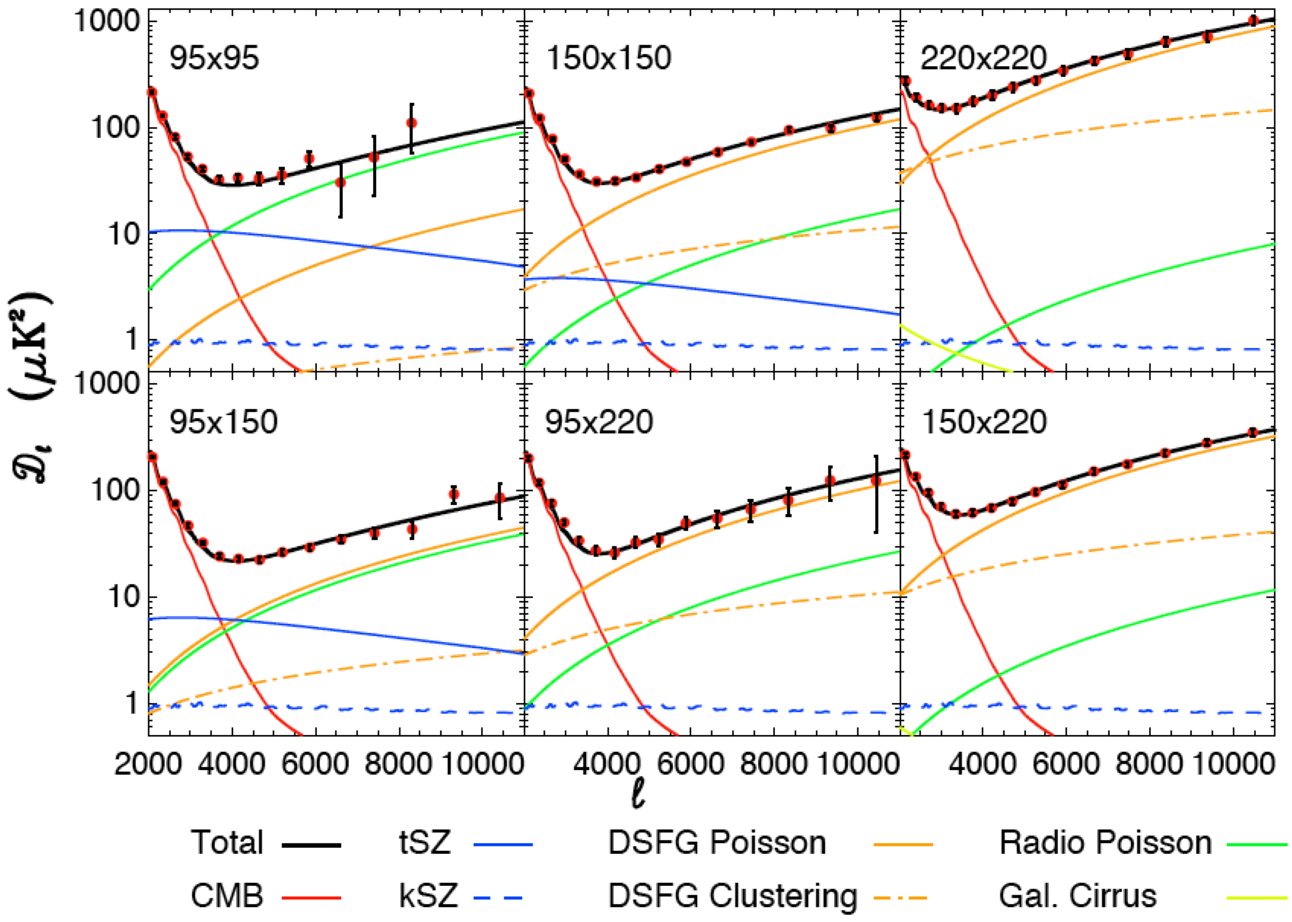
Viero et al. 2013

⇒ Detailed CIB modeling (using theoretical framework)

CIB anisotropies: power spectra

- Low-frequency (Planck, ACT, SPT)
  - From 100 to 220 GHz
  - Complete likelihood, including all components

    Hall+10, Reichardt+12, Dunkley+13, Planck collaboration 2015, XI & XIII

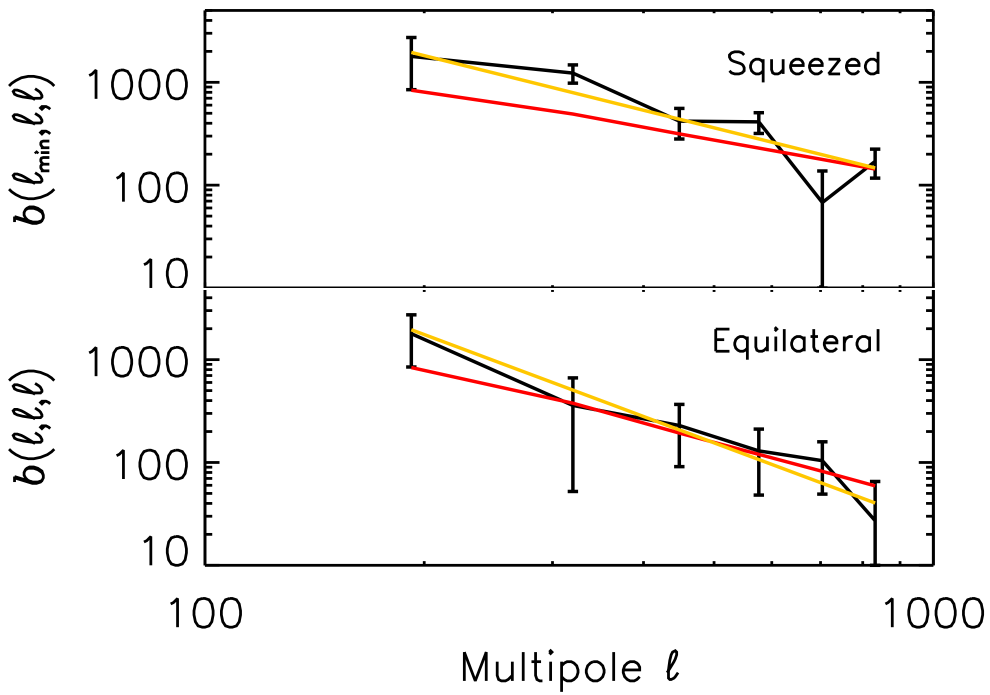


⇒ Poor CIB modeling (power laws or templates)

George et al. 2015

CIB anisotropies: bispectra

- 3-point correlation function in harmonic space, lowest order indicator of the non-Gaussianity of the field
- Planck/HFI 217, 353, 545 GHz (Planck collaboration XXX 2013) and SPT 95, 150, 220 GHz (Crawford+14)
- Multi-frequency fitting to separate clustered CIB, Poisson and tSZ effect; or CIB maps and tSZ decontamination



⇒ Comparison with model expectations

Planck collaboration XXX 2013

II. CIB anisotropies

Probe the clustering properties of dusty, star-forming galaxies

Constrain the relationship between star formation and dark matter distribution (mean halo mass which is most efficient at hosting star formation M_{eff})

Measure the cosmic abundance of dust

Measure the star formation rate density

Derive mean spectral energy distributions of galaxies

Basics of CIB modeling

- Angular power spectrum (Haiman & Knox 2000)

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

Where $P_{j,\nu\nu'}$ is the 3-D power spectrum of the emissivity:

$$<\delta j(\vec{k},\nu)\delta j(\vec{k}',\nu')> = (2\pi)^3 \bar{j}(\nu)\bar{j}(\nu')P_{j,\nu\nu'}(\vec{k})\delta^3(\vec{k}-\vec{k}')$$

- Existing models: $P_j = P_{gg}$

Assuming the CIB is sourced by galaxies, and that the spatial variations in the emissivity trace the galaxy number density:

$$\delta j/\bar{j} = \delta n_{gal}/\bar{n}_{gal}.$$

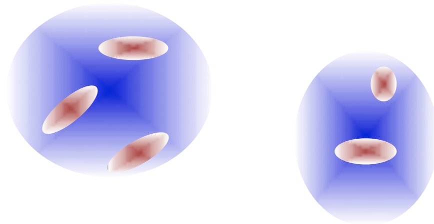
(all galaxies contribute equally to the emissivity density, irrespective of the mass of their host halos)

An improved model for CIB

- Extended halo model (eHOD), introduced for CIB by Shang+12 or conditional luminosity functions (CLF, Amblard & Cooray 07)

- In the framework of the halo model:

$$P_{gg}(k,z) = P_{2h}(k,z) + P_{1h}(k,z)$$



- The assumption of a mass-independent luminosity is abandonned :

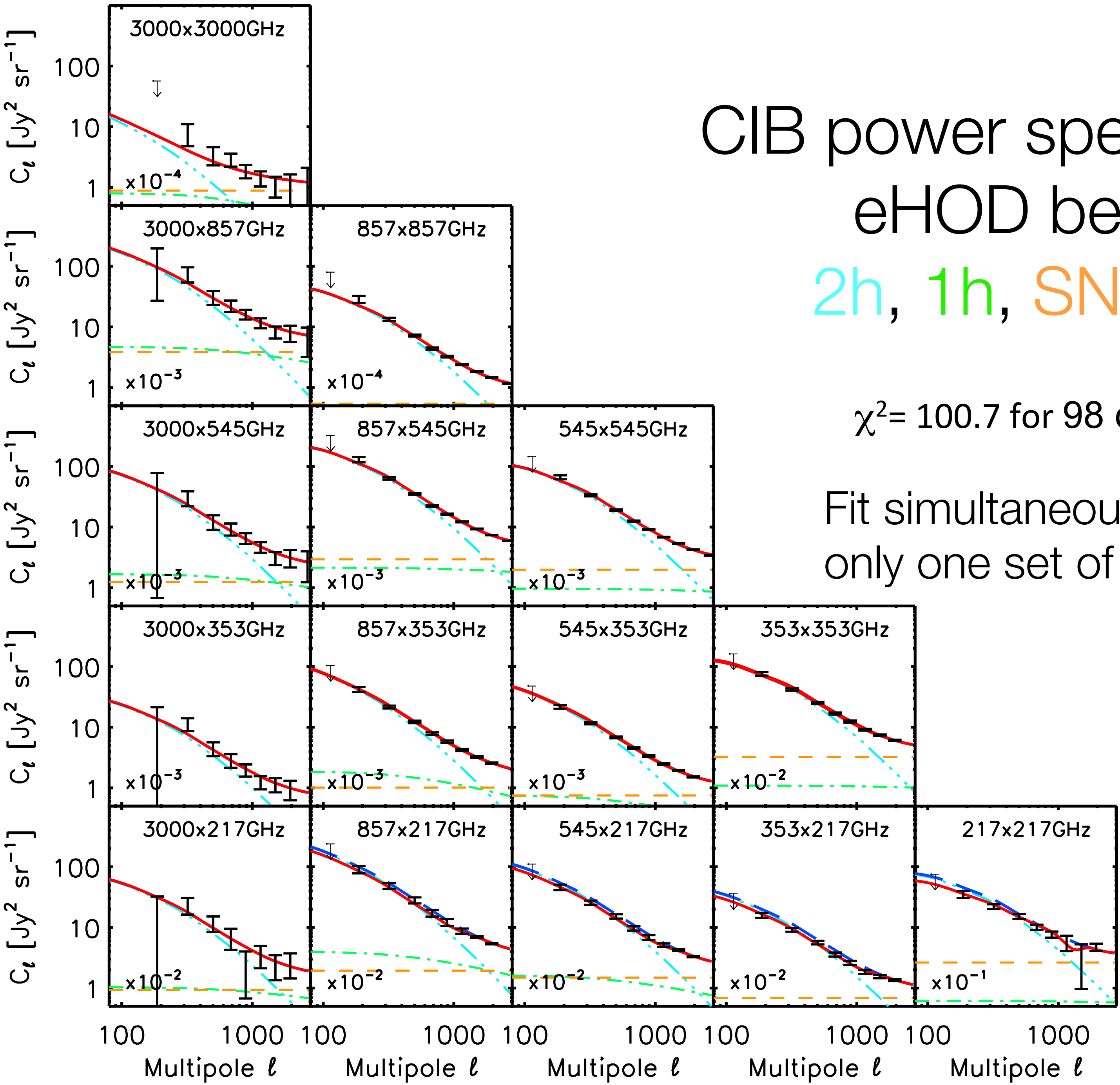
$$j_\nu(z) = \int dM \frac{dN}{dM}(z) \frac{1}{4\pi} \left[N_{cen} L_{cen,(1+z)\nu}(M,z) + \int dm \frac{dn}{dm}(M,z) L_{sat,(1+z)\nu}(m) \right]$$

with: $$L_{(1+z)\nu}(m,z) = L_0 \Phi(z) \Sigma(m) \Theta[(1+z)\nu].$$

Redshift evolution

SFR-halo mass relation (log-normal)

SED shape



CIB power spectra with eHOD best fit

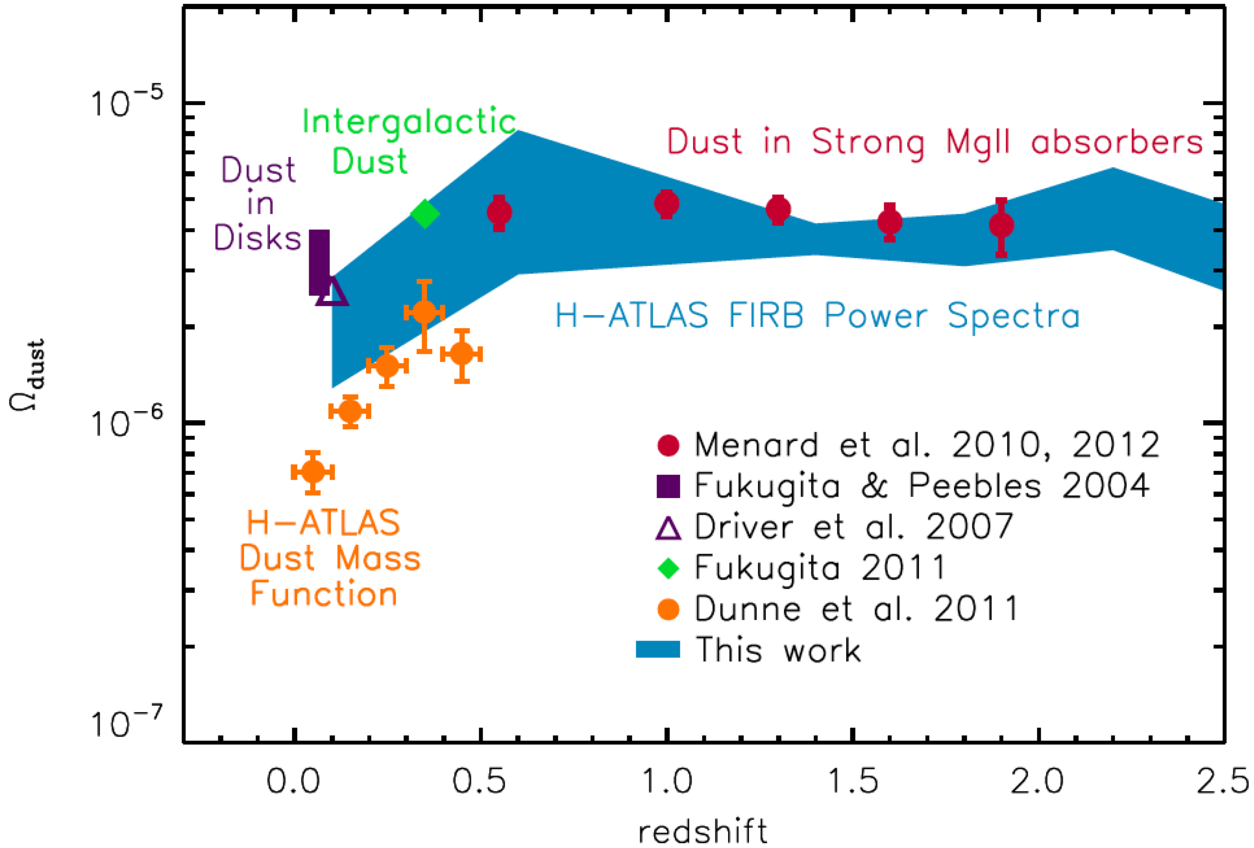
2h, 1h, SN, total

χ^2= 100.7 for 98 degrees of freedom

Fit simultaneously all ν with only one set of parameters

Cosmic Dust Abundance

- From CLF in HOD (Thacker+2013): $$\Omega_{\rm dust}(z) = \frac{1}{\rho_o}\int_{\rm L_{min}} dL\phi(L,z)M_{\rm dust}(L)$$
  with $$M_{\rm dust}(L) = \frac{L}{\kappa_d(\nu)B([1+z]\nu,T)}$$
- Or using directly the emissivities : $$\Omega_{\rm dust}(z) = \frac{1}{\rho_o}\frac{\bar{j}_{\nu_0}}{\kappa_d(\nu_0)B([1+z]\nu_0,T)}$$



From Thacker+13
(see also Schmidt+15)

Adding the contribution « Dust in Disks » to extinction measurements

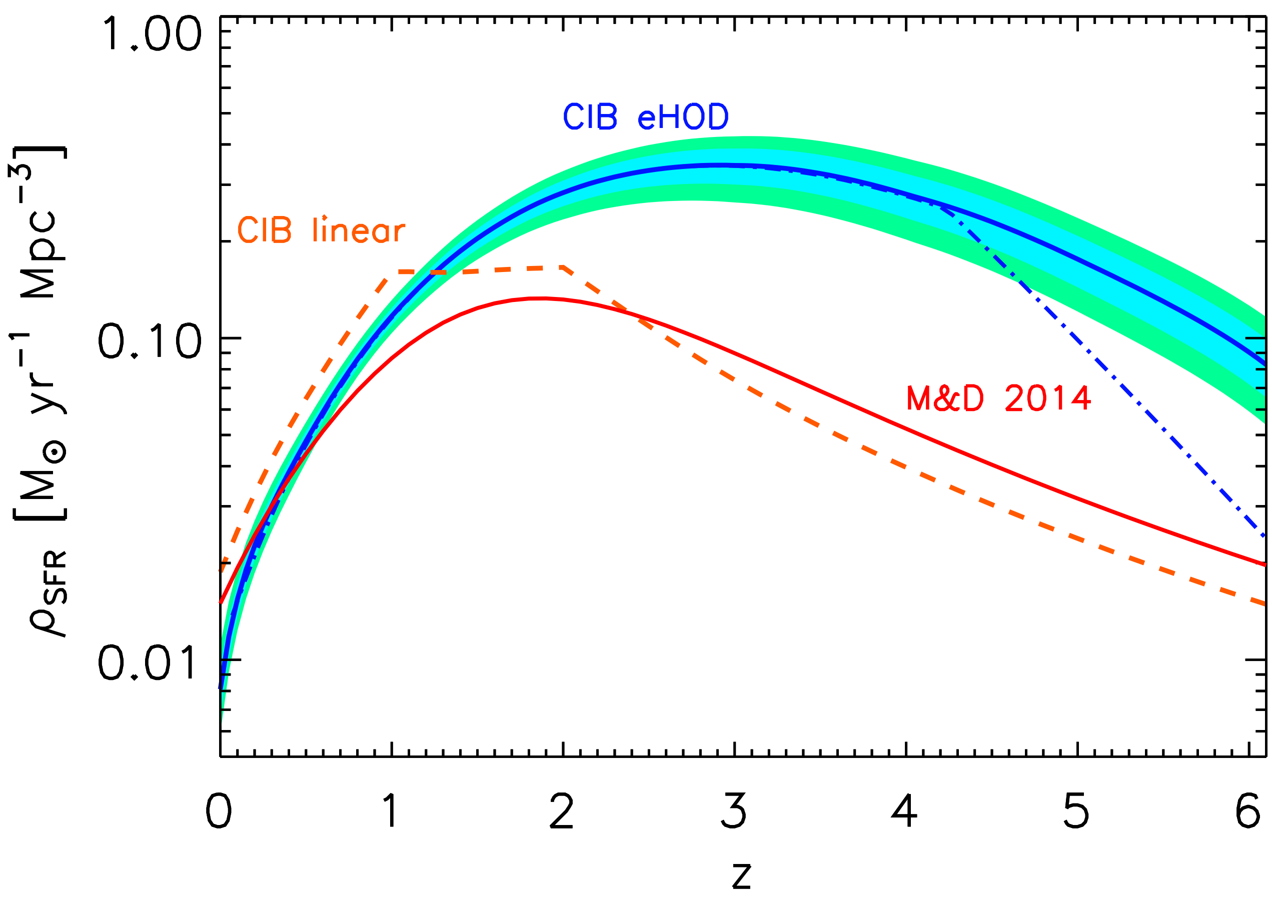
z=0: $\Omega_{\rm dust}$ ~ 0.2% Ω_{M^*}
z~2: $\Omega_{\rm dust}$ ~ 1% Ω_{M^*}

Star formation rate density

- A robust census for star-forming galaxies at $z \gg 2$ selected on the basis of dust emission alone does not exist.

  => the total amount of SF that is missed from UV surveys at such high *z* remains uncertain.

- With their redshift depth, CIB anisotropies can give strong constraints… but… :



CIB eHOD:
- Standard (continuous)
- Break in L/M relation (dash-dot)

CIB linear:
- SEDs fixed (Berthemin+12)
- Pj = beff^2 x Plin

Madau & Dickison 2014:
- Compilation UV+IR

Mean spectral energy distribution

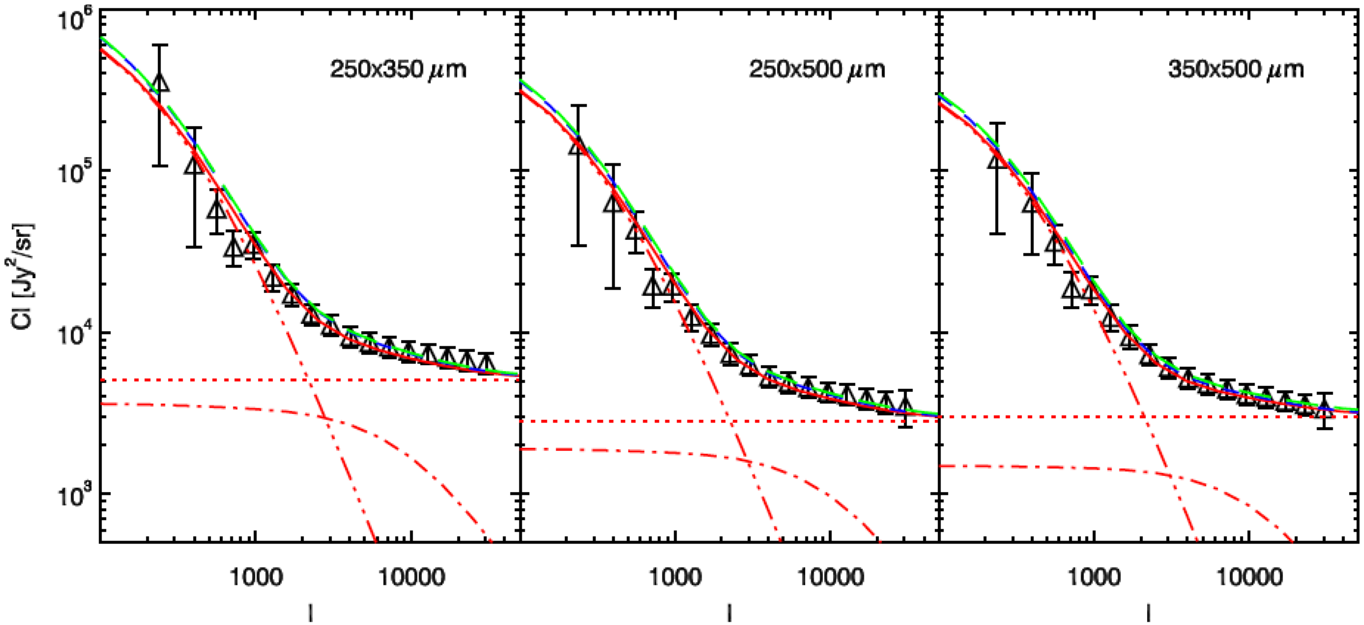
- Results on e.g., SFRD, Ω_{dust} drastically depend on SED parametrisation
- In SPIRE only or Planck only high-frequency data (e.g. Thacker+13, Schmidt+15):
  - T constant with redshift provides good fit
  - Strong degeneracies between the SED parameters T, β, and temperature evolution
- In eHOD Planck + IRIS (Planck collaboration XXX 2013):
  - Dust spectral index: $\beta = 1.75 \pm 0.06$
  - Variation of temperature with redshift $T = T_0(1+z)^{\alpha}$ with $T_0 = 24.4 \pm 1.9$K, $\alpha = 0.36 \pm 0.01$
- Independent analysis of main sequence galaxies (e.g., Magdis+12, Béthermin+15):
  - Average SED(z) using stacking analysis of Spitzer, Herschel, LABOCA, and AzTEC
  - A harder interstellar radiation field up to z~4 : $U = U_0(1+z)^{1.8}$ consistent with temperature evolution from Planck XXX.
  - Consistent with a decrease in the gas metallicity with redshift

An alternative model

- A relation between SFR and M* (main sequence)
- An evolution of the stellar mass function with redshift for star forming galaxies
- Mean SED(z)
- A relation between M* and Mhalo from abundance matching (including a fraction of quenched galaxies)

  => a relation between emissivities and dark-matter halo mass

- Compute CIB power spectra using a method similar to Shang+12
- Very successful: CIBA, w(θ), number counts, CIBxlensing, N(z)

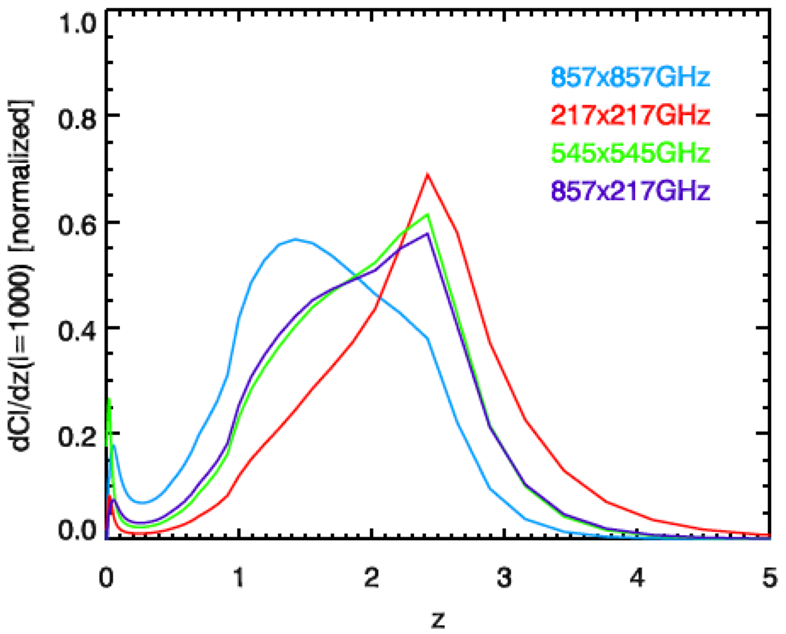


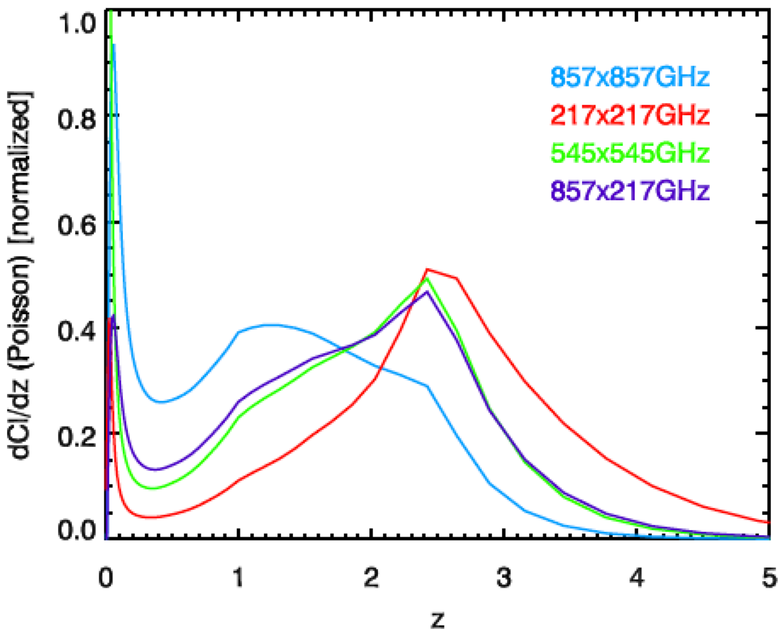
Béthermin+13

An alternative model

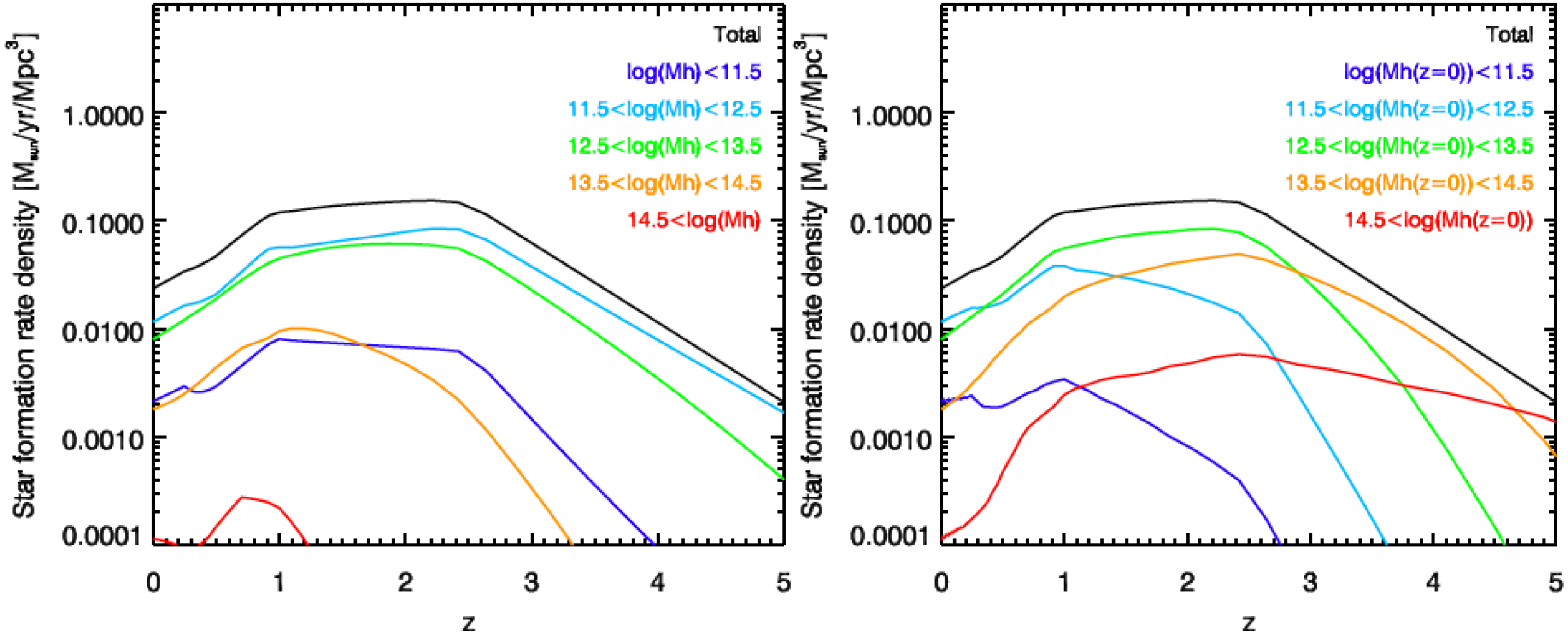
Correlation between bands on small scales (Poisson)							
	3000 GHz	857 GHz	545 GHz	353 GHz	217 GHz	143 GHz	100 GHz
3000 GHz	1.000						
857 GHz	0.599	1.000					
545 GHz	0.407	0.916	1.000				
353 GHz	0.310	0.830	0.962	1.000			
217 GHz	0.277	0.785	0.920	0.968	1.000		
143 GHz	0.279	0.745	0.894	0.963	0.958	1.000	
100 GHz	0.333	0.743	0.881	0.940	0.921	0.988	1.000

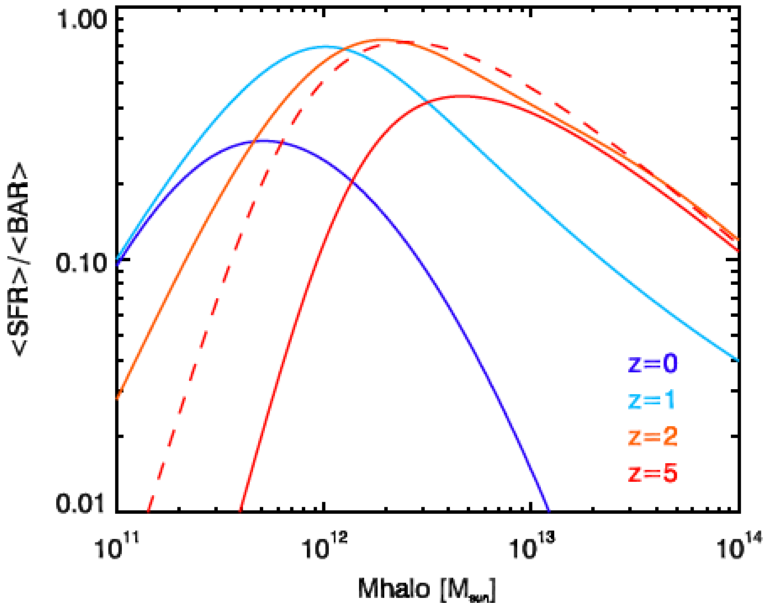
Correlation between bands on large scale (l=1000)							
	3000 GHz	857 GHz	545 GHz	353 GHz	217 GHz	143 GHz	100 GHz
3000 GHz	1.000						
857 GHz	0.766	1.000					
545 GHz	0.636	0.971	1.000				
353 GHz	0.555	0.925	0.988	1.000			
217 GHz	0.529	0.902	0.975	0.997	1.000		
143 GHz	0.538	0.904	0.975	0.996	0.999	1.000	
100 GHz	0.575	0.919	0.981	0.996	0.997	0.999	1.000





An alternative model





Instantaneous star formation efficiency:
(… far from the universal Log normal relation used in eHOD)

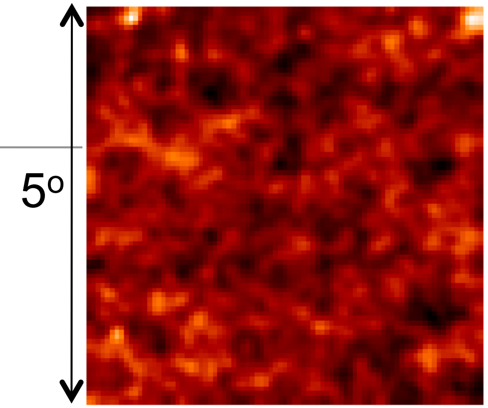
III. Cross-correlating cosmic fields

Learning on the CIB (e.g. tomography), galaxy formation & evolution

Use CIB anisotropies as an integrated mass tracer (useful for CMB B-mode)

Use the CIB to derive constraints on dark energy

Cross-correlations



- CIB anisotropies are a very good LSS tracer but:
  - Redshift distribution not so well-known
  - Emissivity is dark-matter halo mass dependent and not well-known
  - Intensity maps are highly contaminated

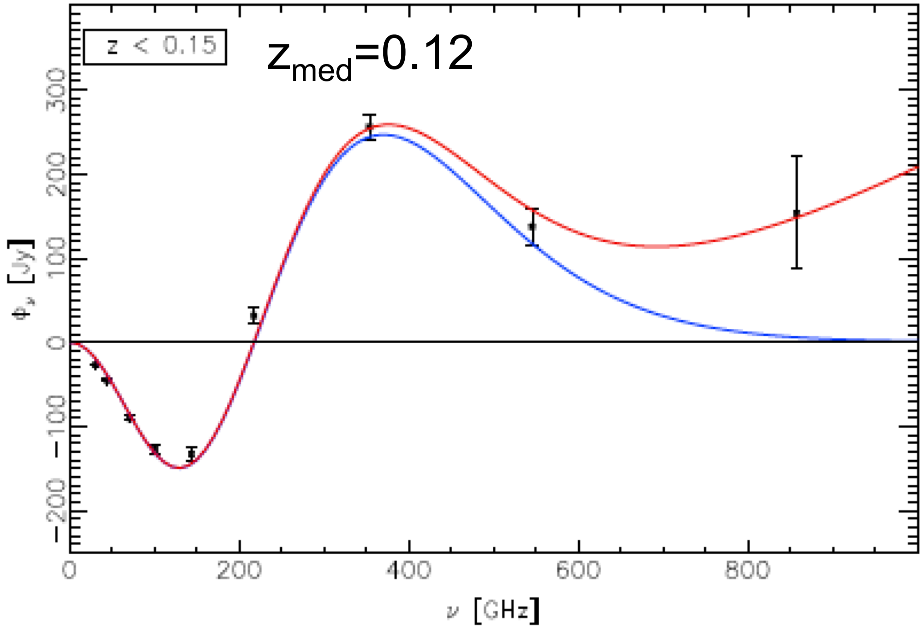
- Learn on the CIB, galaxy formation & evolution
  - CC with the lensing map (Song+03, Holder+13, Planck collaboration XVIII 2013)
  - CC with LRGs ($z<1$, Serra+14)
  - CC with SDSS QSOs at $0<z<5$ (Schmidt+15)
  - CC with NIR Background (Thacker+14)
  - CC with MaxBCG galaxy clusters at $0.1 < z < 0.3$ (Hincks+13)
  - CC with tSZ (predicted Addison+12, measured Planck collaboration 2015 XXIX)
- Use CIB Anisotropies as an integrated mass tracer
  - Useful for CMB B modes! (delensing: Sherwin & Schmittfull 15, Simard+15; detection of lensing B-mode: Hanson+13)
- CMB-CIB cross-correlation for ISW
  - Prediction: Ilic+11

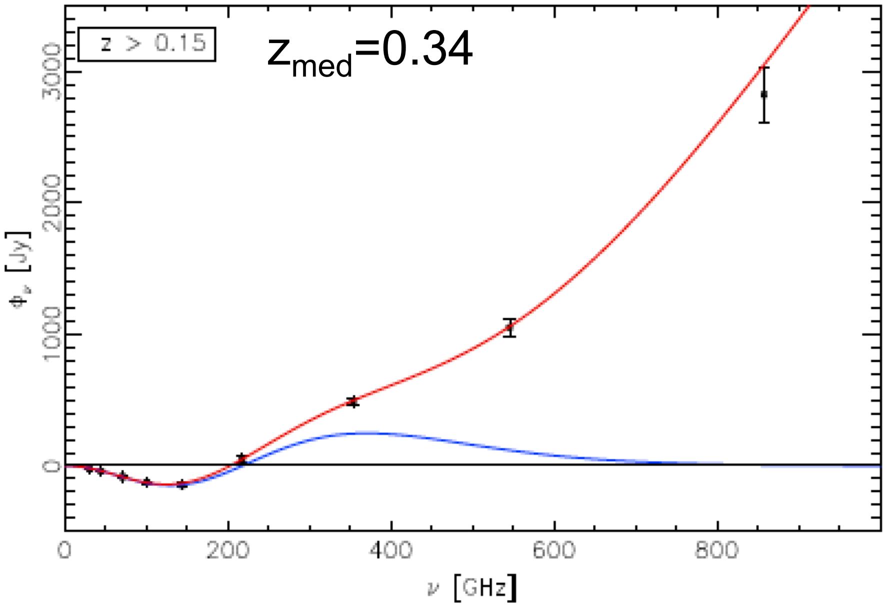
- And much more to come….

CIB-tSZ cross-correlation

- Uncertainty in the CIB-tSZ power significantly degrades constraints on the kinematic SZ (Reichardt+12)
- How and why star formation in massive systems has evolved over cosmic time

SED of stacked Planck clusters from 30 to 857 GHz in two redshift bins



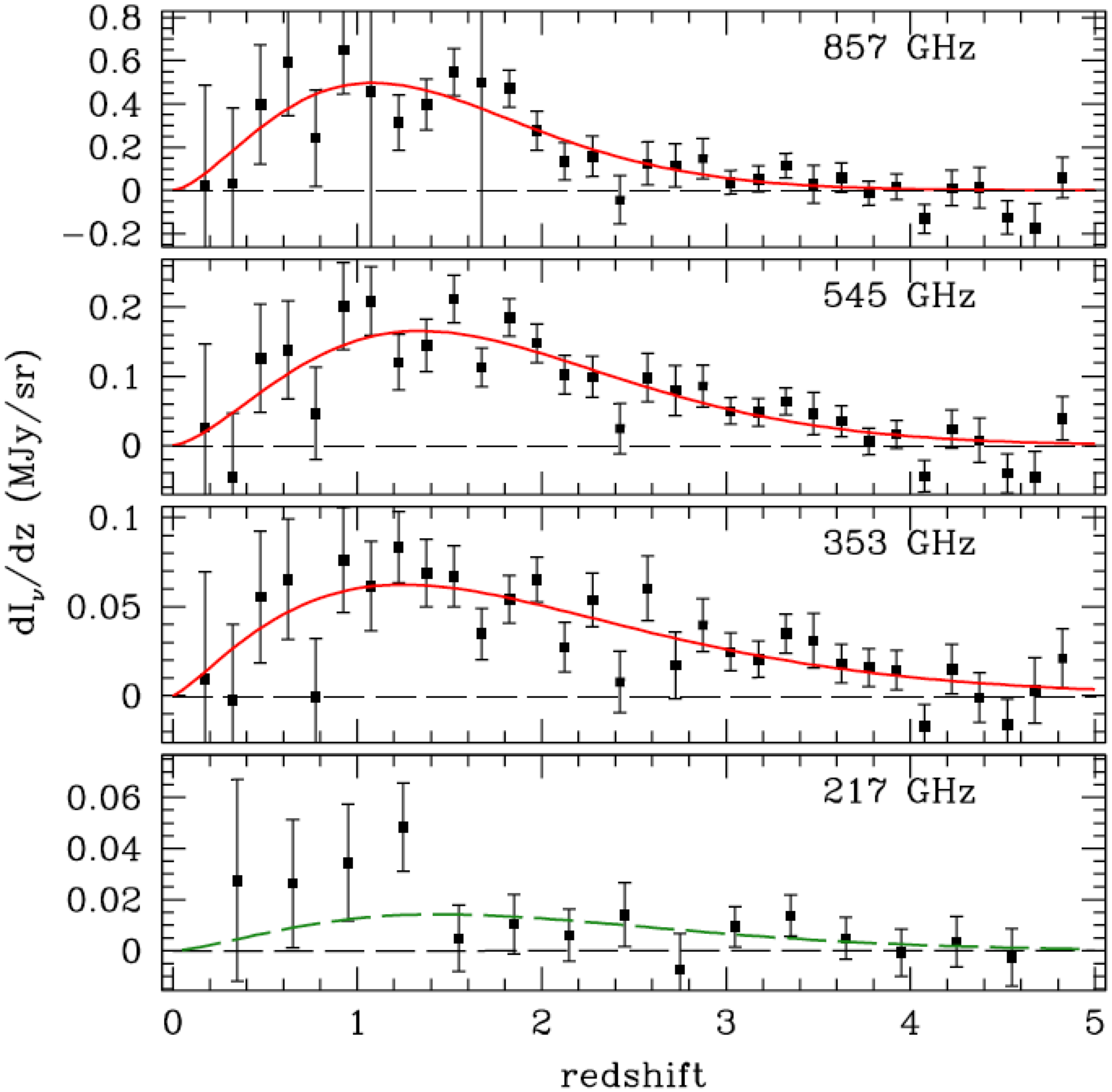


Spatial extension of the stacked signal => dust emission comes from the outskirts of the clusters

Planck collaboration 2015 XXIX, to be submitted

CIB tomography

- SDSS DR7 quasars
  - 5364 square degrees
  - 63,995 quasars 0<z<5



Schmidt+15

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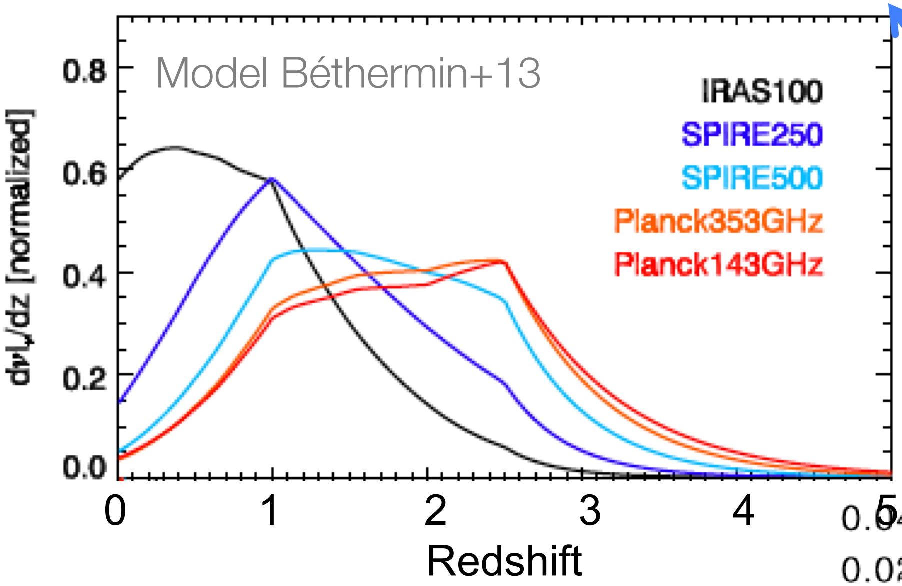
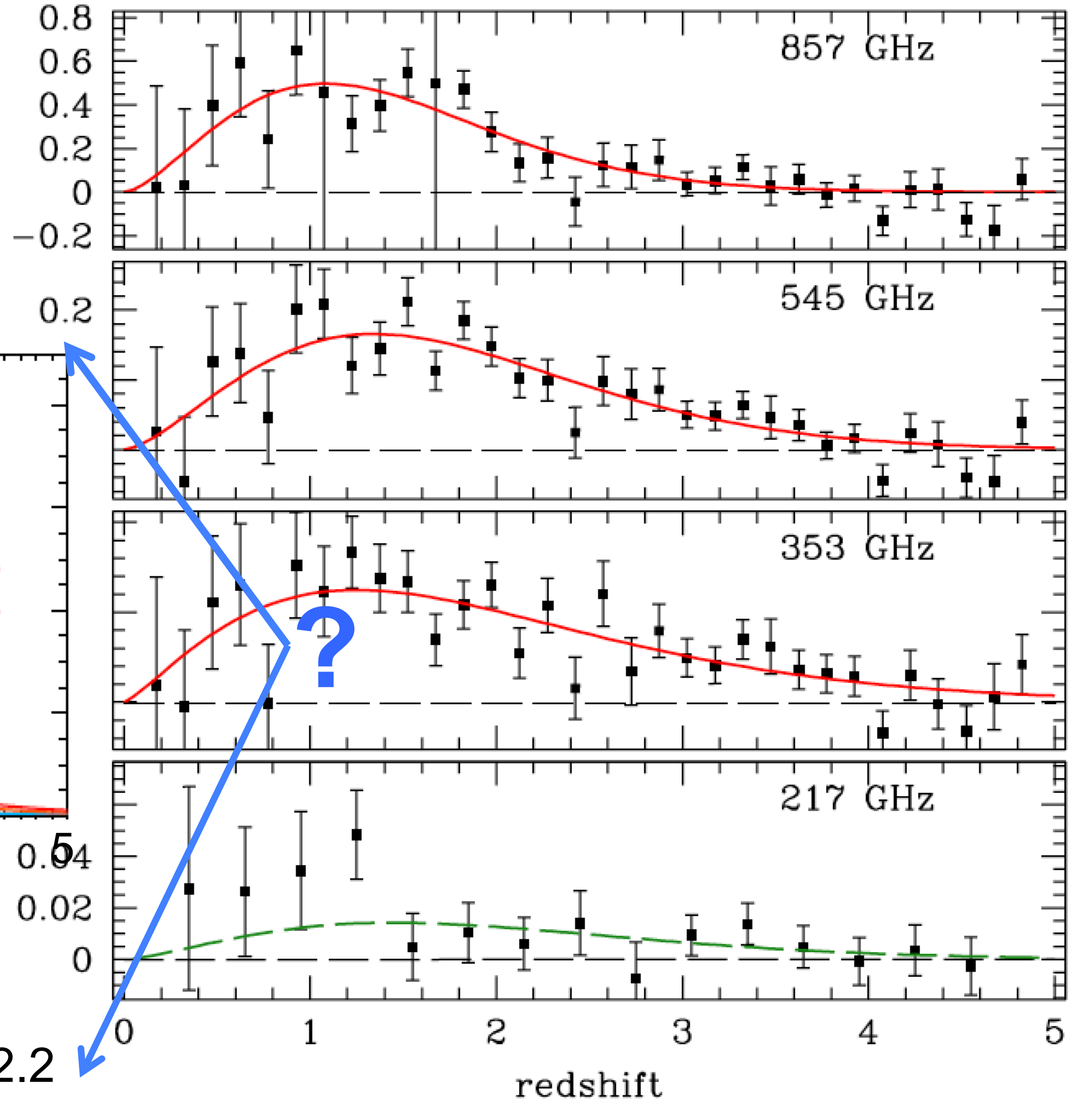




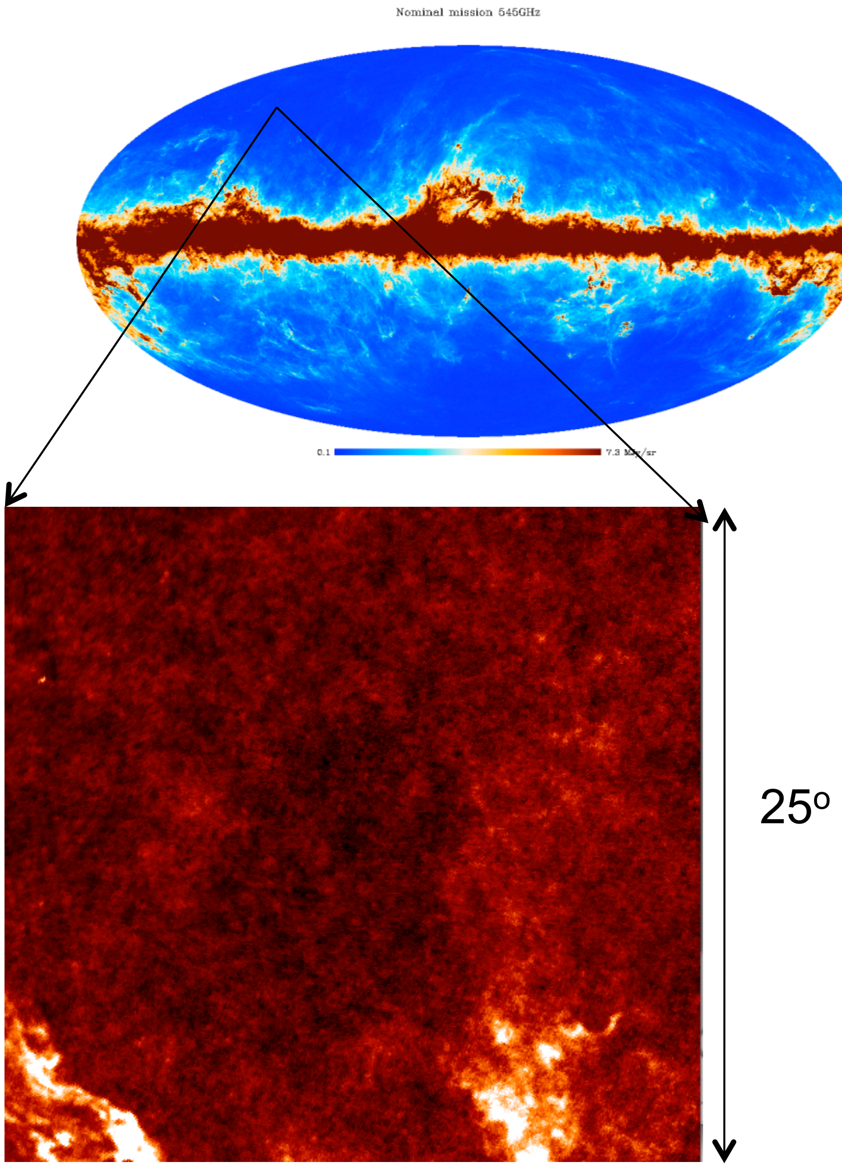
+

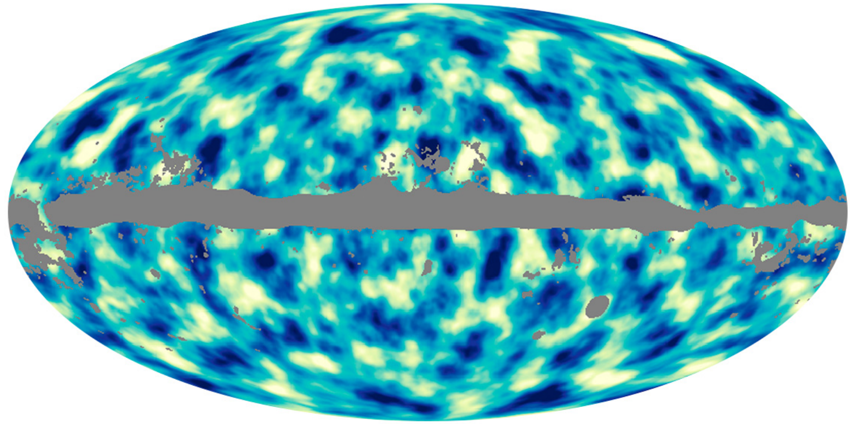
DSFG selected at 353 GHz: <z> ~2.2

Schmidt+15

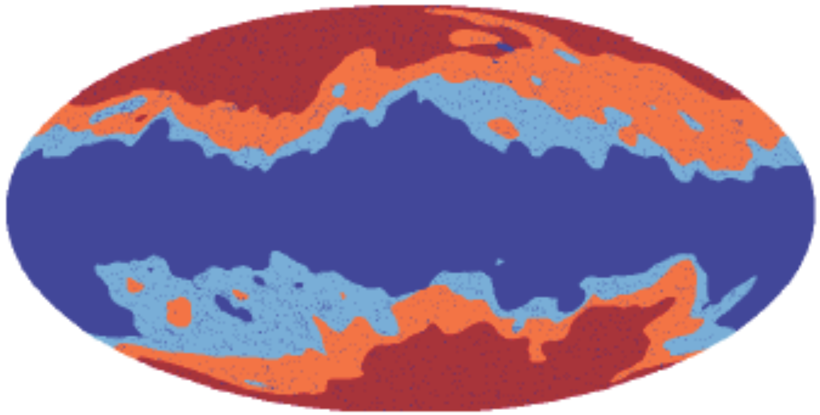
CIB-Lensing cross-correlation: ingredient

A frequency map (HFI)





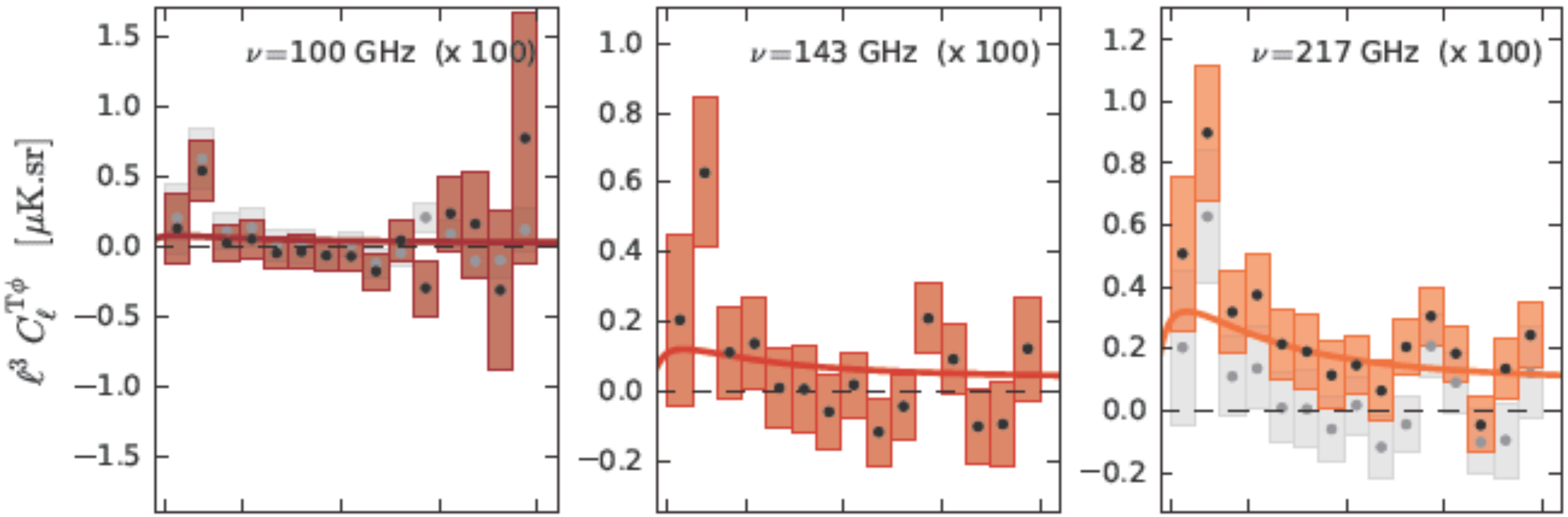
A Lensing map (HFI)
Projected mass distribution



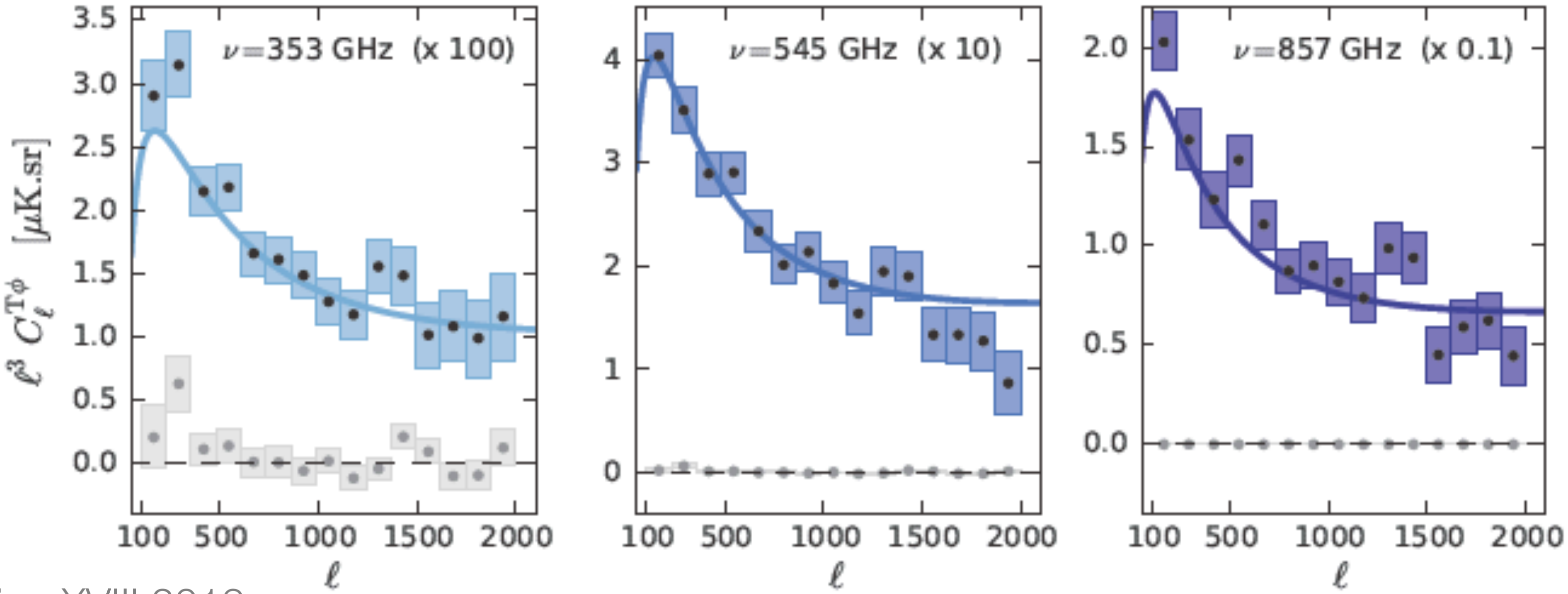
A mask (fsky=31%)

Planck collaboration XVIII 2013

CIB-Lensing cross-correlations

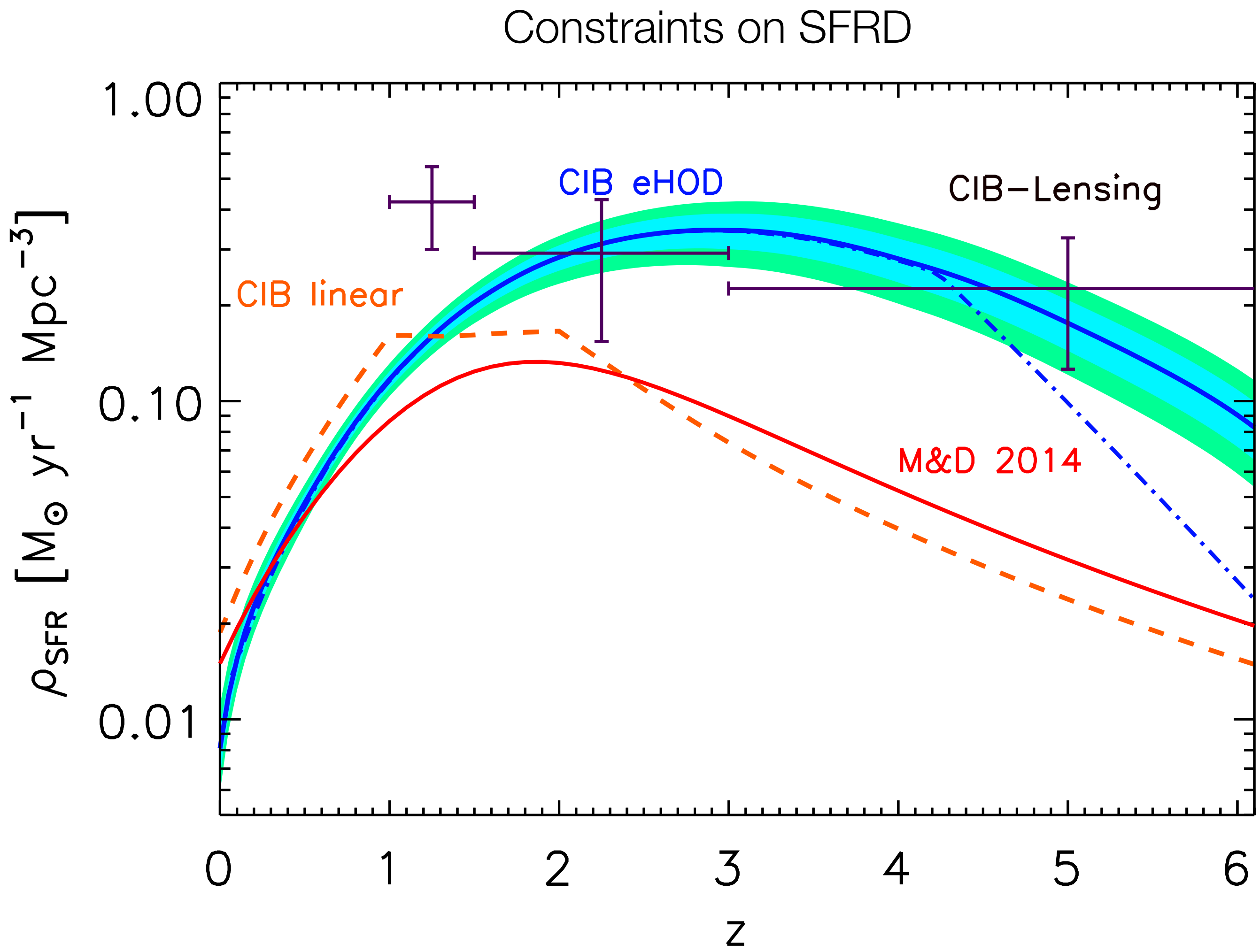


Detection significance with a peak value of 42σ/19σ (stat)/(stat+sys) at 545 GHz



Planck collaboration XVIII 2013

CIB-Lensing cross-correlations



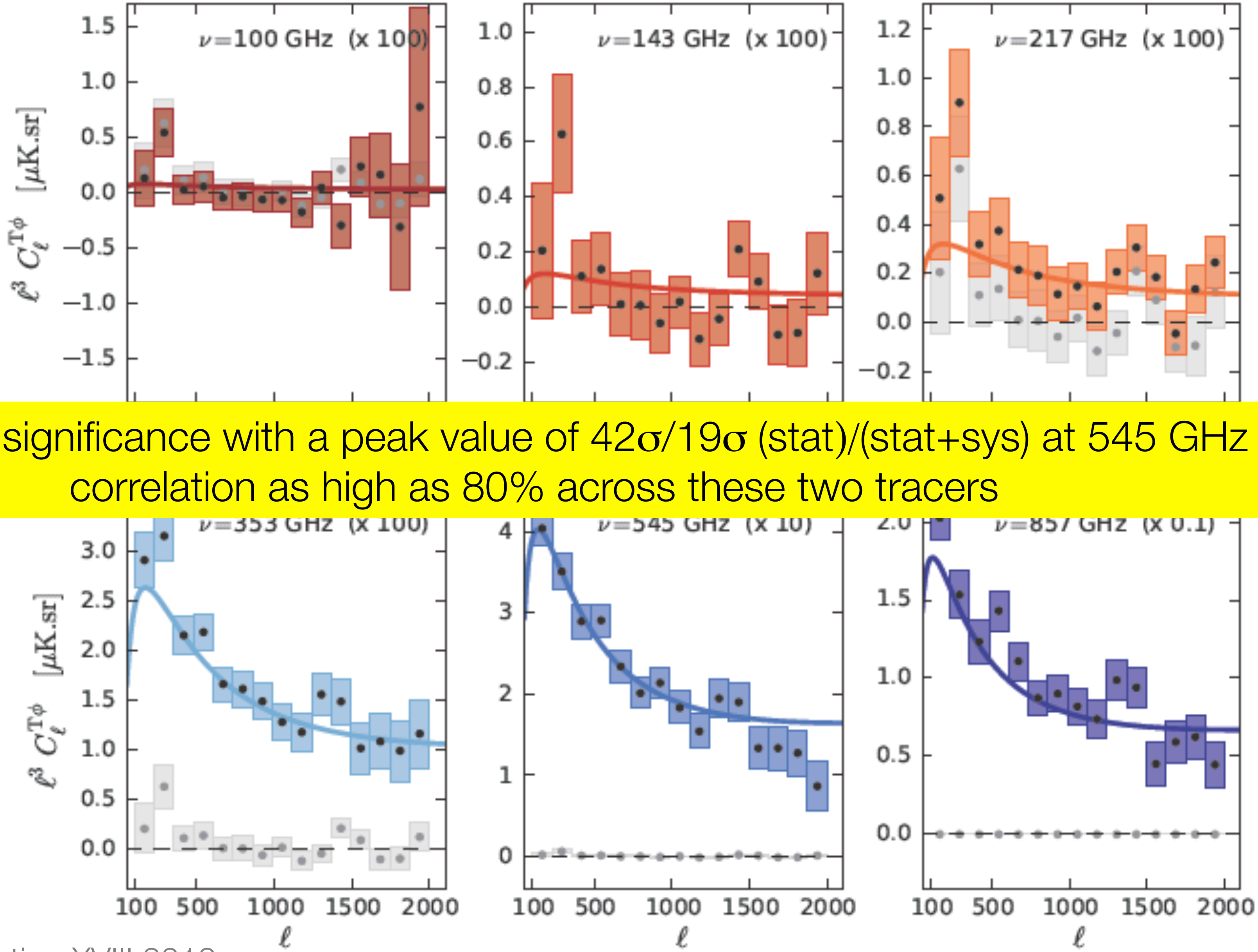
Cross-correlations: learning on CIB, galaxy formation & evolution

- … not yet there
  - Need to reduce the error bars
  - Systematic effects not always under control
  - Modeling very difficult
  - Modeling too focussed (for the purpose of the cross-correlation)

- As of now, adding current cross-correlation measurements *does not bring much*

- But consistency checks

CIB- CMB Lensing cross-correlations



Detection significance with a peak value of 42σ/19σ (stat)/(stat+sys) at 545 GHz correlation as high as 80% across these two tracers

Planck collaboration XVIII 2013

CIB anisotropies as an integrated mass tracer

Gravitational lensing remaps the observed position of CMB anisotropies as

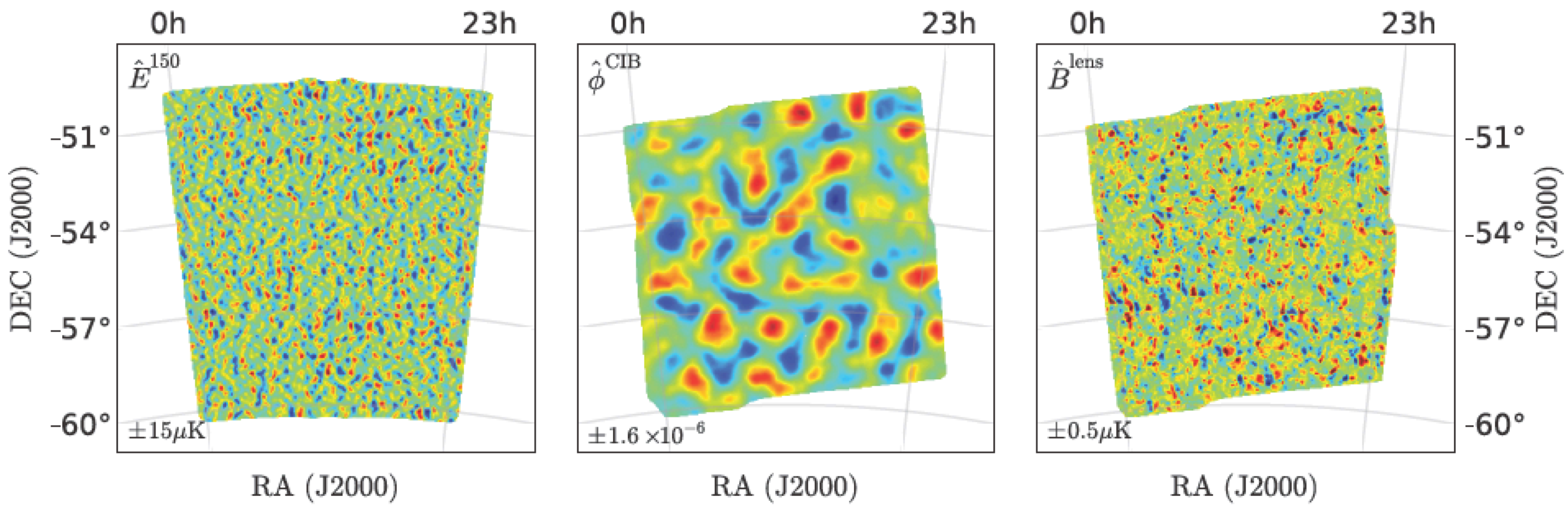
$$\hat{n} \rightarrow \hat{n} + \nabla\phi(\hat{n}),$$

where ϕ is the CMB lensing potential

This remapping mixes some of the (relatively) large E modes signal into B modes

=> induced B modes: $$B^{\mathrm{lens}}(\vec{l}_B) = \int d^2\vec{l}_E \int d^2\vec{l}_\phi W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi) E(\vec{l}_E)\phi(\vec{l}_\phi)$$

Hanson+13



E-modes from SPTpol + Φ-modes from Herschel/SPIRE → Synthesized lensing B-mode template.

CIB anisotropies as an integrated mass tracer

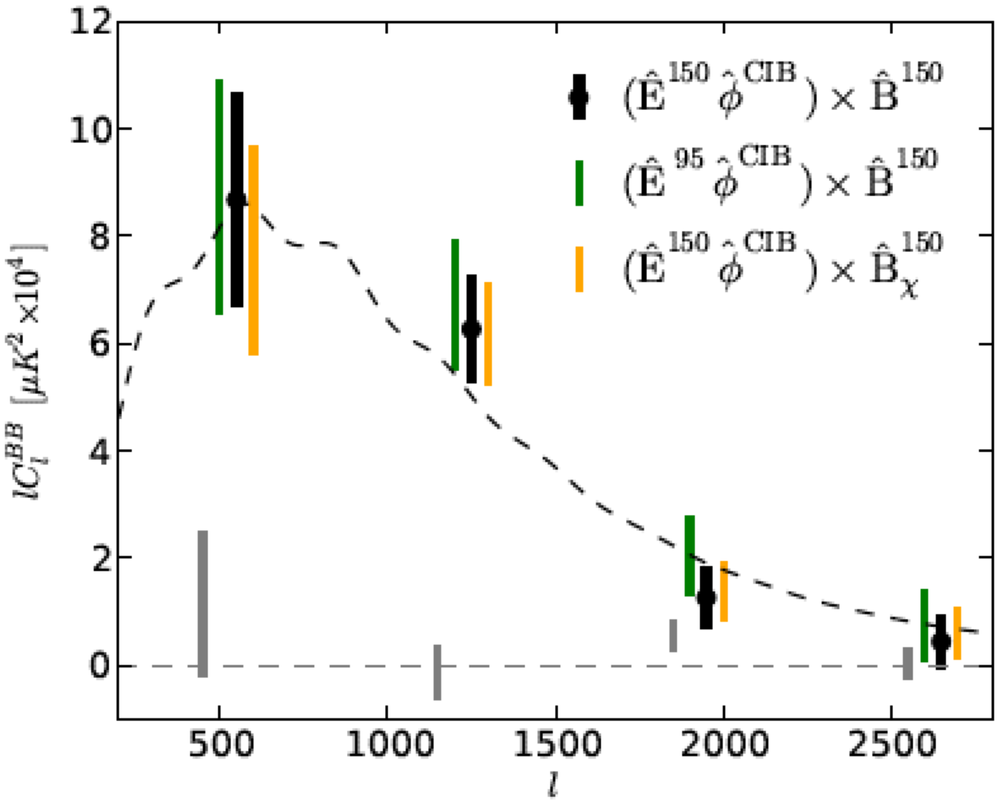
Gravitational lensing remaps the observed position of CMB anisotropies as

$$\hat{n} \rightarrow \hat{n} + \nabla\phi(\hat{n}),$$

where ϕ is the CMB lensing potential

This remapping mixes some of the (relatively) large E modes signal into B modes

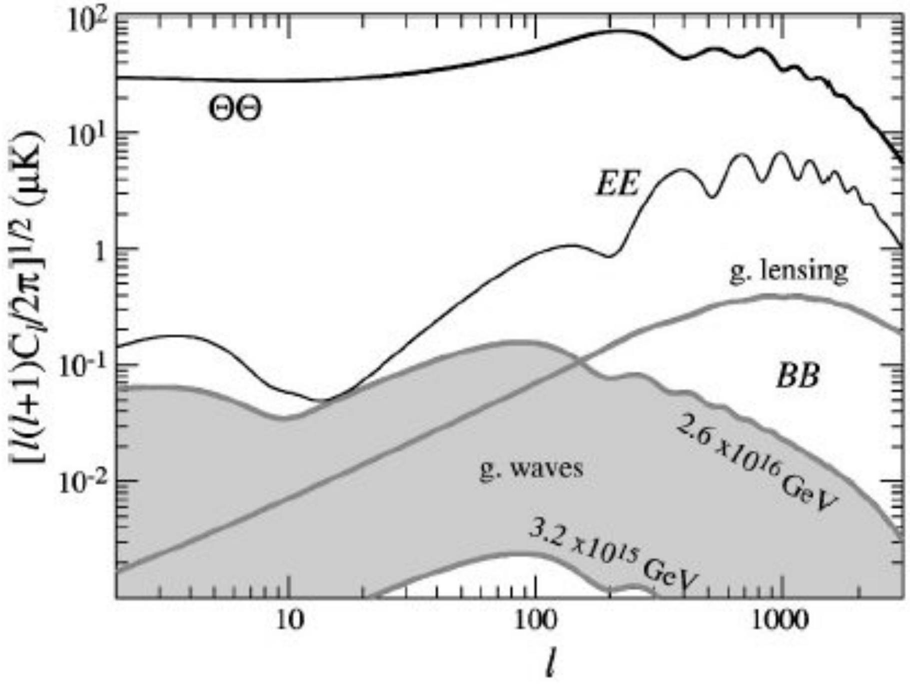
=> induced B modes: $B^{\rm lens}(\vec{l}_B) = \int d^2\vec{l}_E \int d^2\vec{l}_\phi W^\phi(\vec{l}_E, \vec{l}_B, \vec{l}_\phi) E(\vec{l}_E)\phi(\vec{l}_\phi)$

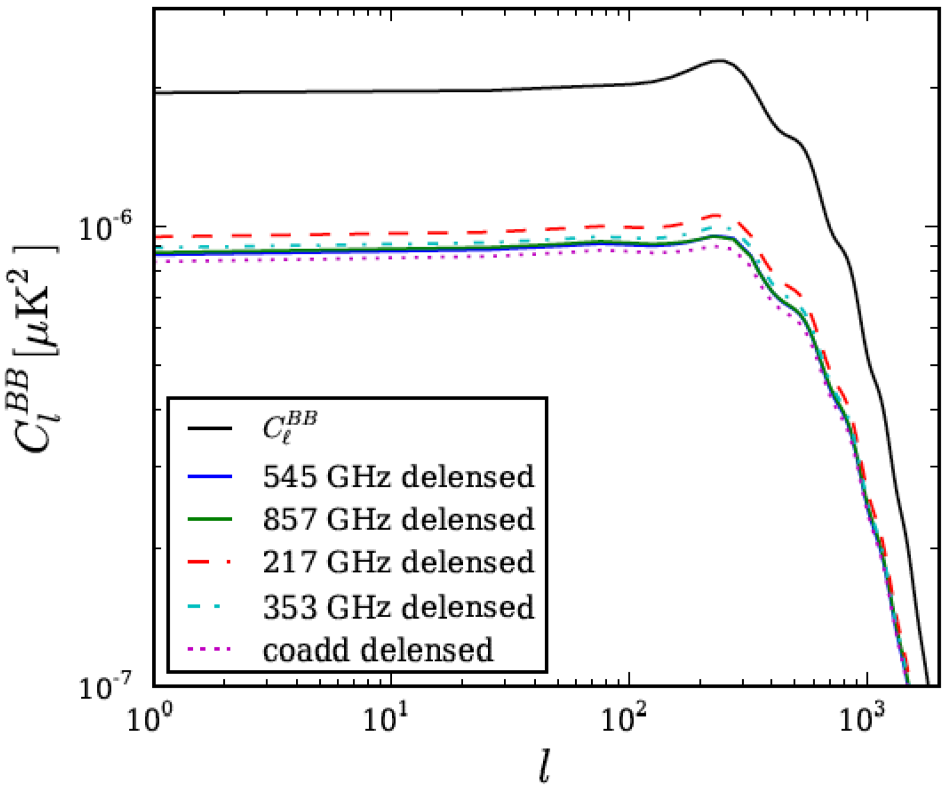


Hanson+13
(see also van Engelen+14)

Delensing the CMB with the Cosmic Infrared Background

Sherwin & Schmittfull 2015





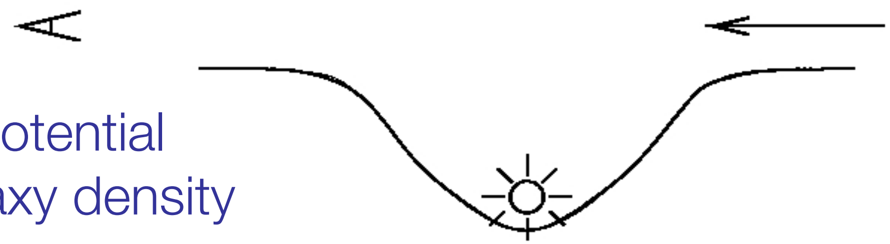
CIB delensing can remove more than 50% of the lensing power
=> lower the noise of a B-mode measurement by a factor of ≈ 2.2

Even for future experiments such as LiteBird, internal delensing by reconstructing the lensing field from the CMB itself does not perform much better than CIB delensing

ISW: Dark energy signature

Much like gravitational lensing the ISW effect is gravitational but instead of probing the gravitational potential directly, it measures its time dependence along the line of sight.

gravitational potential traced by galaxy density



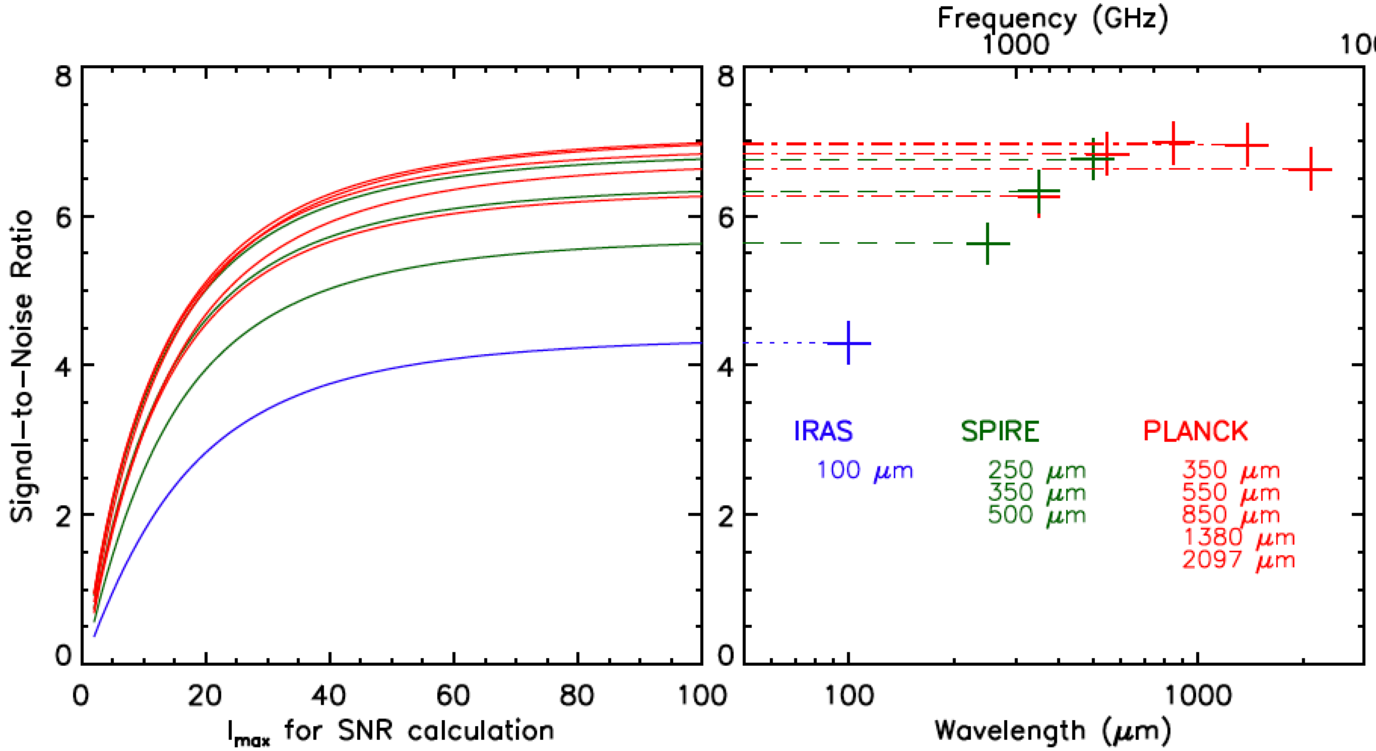
potential depth changes as CMB photons pass through

$$\frac{\delta T}{T} = -2 \int \dot{\Phi}(\tau) d\tau$$

The gravitational potential is actually constant in a matter dominated universe on large scales.

However, when the equation of state changes, so does the potential, and temperature anisotropies are created.

CMB x CIB for ISW: expected signal to noise



Frequency (GHz)	857	545	353	217
Wavelength (μm)	350	550	850	1380
Perfect Single SNR	6.26	6.83	6.98	6.95
Joint SNR	7.12			
Realistic Single SNR 1 ($f_{\rm sky} = 0.75$, $f_{\rm CMB} = 0.01$, $\mathcal{A}_{\rm fore.} = 0.01$)	5.36	5.73	5.39	3.56
Joint SNR	5.88			

Ilic+11

IV. The Legacy of Planck

The Legacy of Planck

- All-sky maps
  - For Cosmology
    - high-frequency maps (353-545-857 GHz) better suited for CIB template
    - Linear combination of dust (Gal + Xgal) maps to get the best CIB template
  - For CIB analysis
    - the area of your favorite best field or catalog has been covered! (check also Herschel coverage) => pursue cross-correlations

- CIB power spectra from 217 to 857 GHz (+ 3000 GHz) and cross-spec at 143 GHz (Planck collaboration 2014 XXX)

- Most accurate photometric absolute and relative calibration

- Your noise is my signal; your signal is my noise…
  - Planck/HFI sees all components but
    - Planck collaboration provides a CMB map
    - Can use dedicated component separation, e.g. tSZ (Planck collaboration 2015 XXII, Van Waerbeke+2014)
  - Most difficult is to separate Galactic dust from CIB anisotropies
    - All-sky HI at 10-15 arcmin
    - Work in progress in Planck collaboration using Generalised Needlet ILC

Conclusion

- A new breakthrough in CIB measurements with Planck
  - CIB maps on very large area (>2200 deg^2)
  - CIB angular power spectrum but also bispectrum
  - CIBxlensing measurements

- Some improvements to go one step further
  - Bispectra are not considered in the interpretation (comparison with model expectation but no “inversion”)
  - Low-freq (ν<300 GHz): need to do better than templates or power laws
    - Isolate the highest-z component?
  - Experiment “mixing”: need a global analysis from low to high-ell, and low to high-ν using Planck, Herschel, ACT, & SPT
  - Different models fit very well the data but give quite different answers, e.g., on Meff, redshift distributions
    - SEDs of galaxies at high redshift still uncertain
  - Galactic dust contamination: still a problem