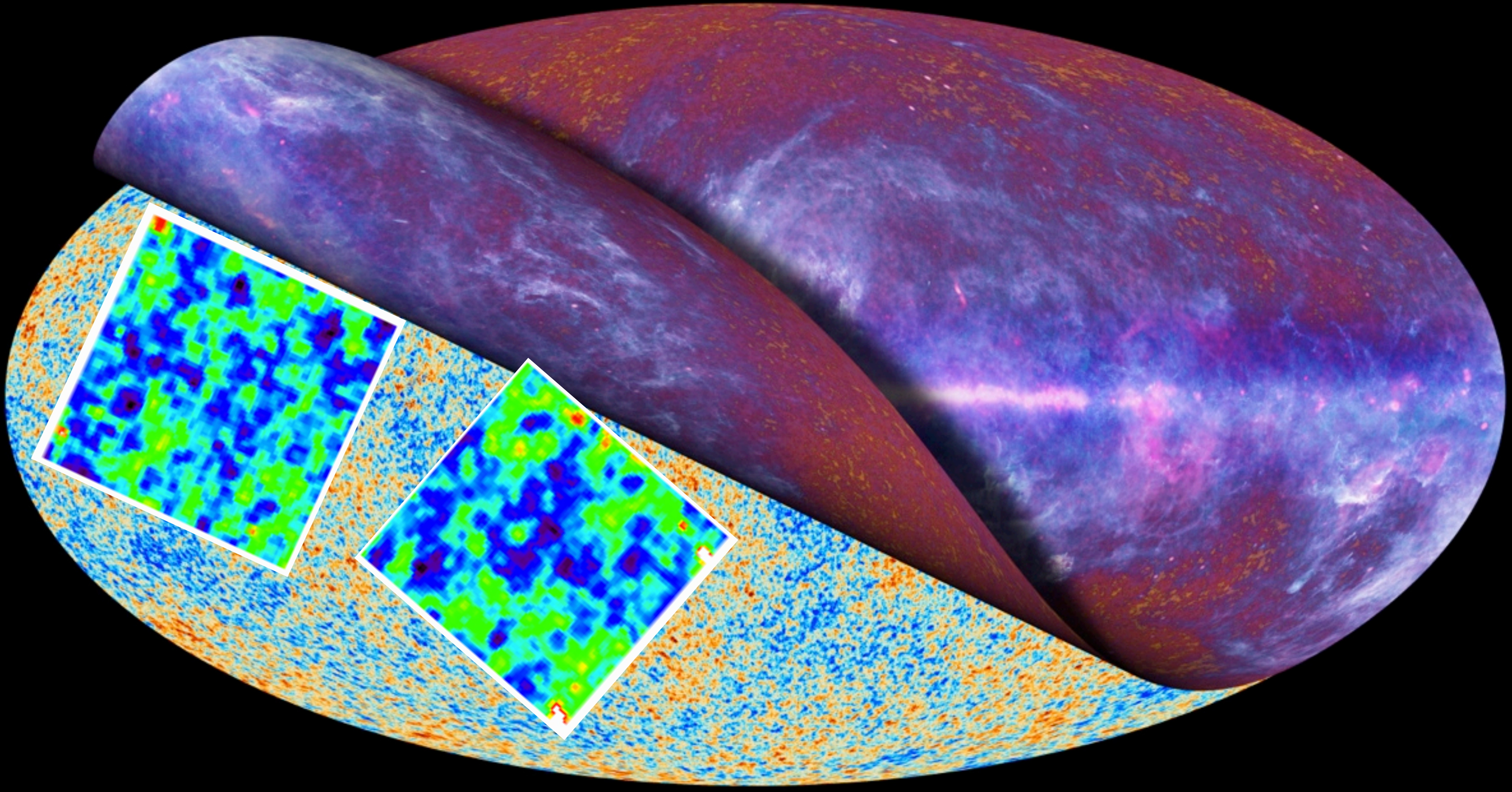


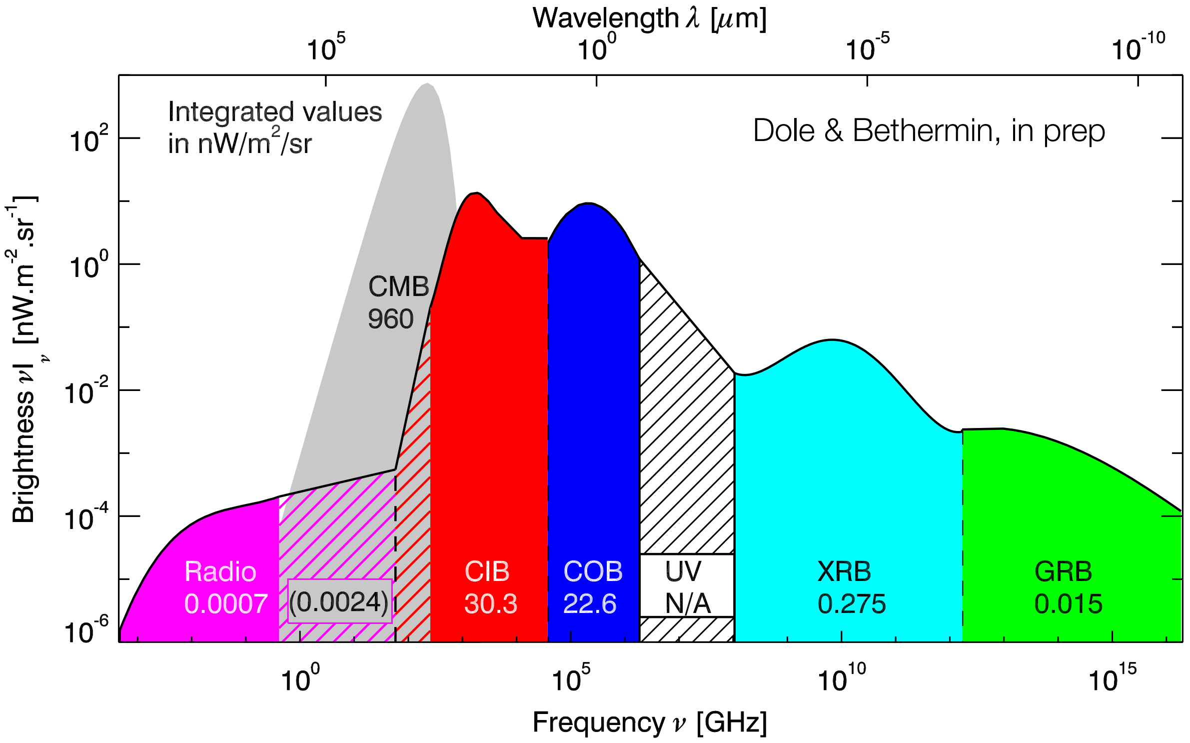
Planck unveils the Cosmic ~~Microwave~~ Infrared Background

Cosmic Infrared Background measurement and Implications for star formation

Guilaine Lagache
Institut d'Astrophysique Spatiale
On behalf of the Planck collaboration

Cosmic Infrared Background

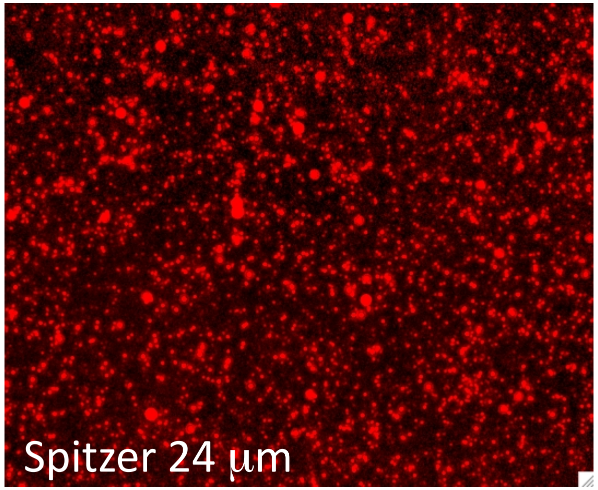
- Cosmological, diffuse, background light produced by the integrated emission from galaxies formed throughout cosmic history



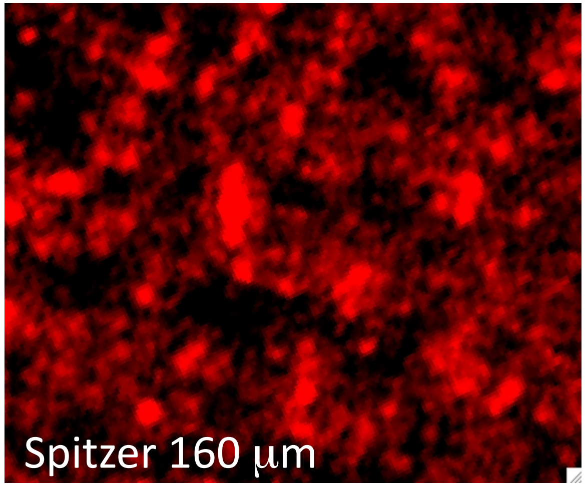
- CIB (8-3000 mm or 100-4 10^4 GHz) : star-heated dust within galaxies => wealth of information about the processes of star formation therein.
- CIB = a way to study statistically dusty-galaxy evolution.

Origins of CIB anisotropies

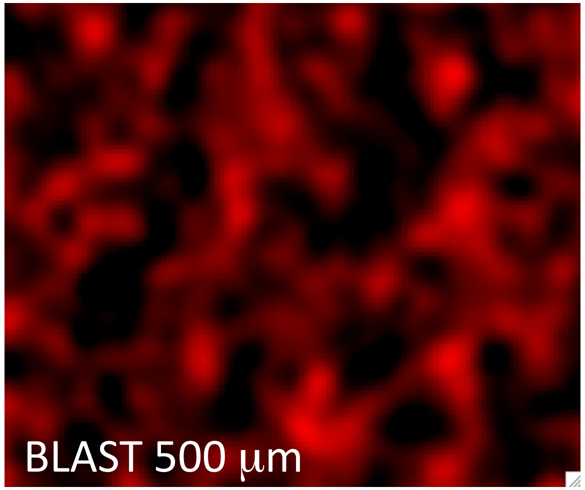
Extragalactic-sources confusion: our « business »



Resolved CIB: 80%



Resolved CIB: 15%



Resolved CIB: <1%

In the far-IR, submm and mm:

- Maps of diffuse emission: a web of structures, characteristic of CIB anisotropies
- P(D) analysis, stacking of known populations, angular power spectrum and bispectrum
- CIB anisotropies = a way to study statistically dusty-galaxy evolution AND clustering.

Images from M. Béthermin

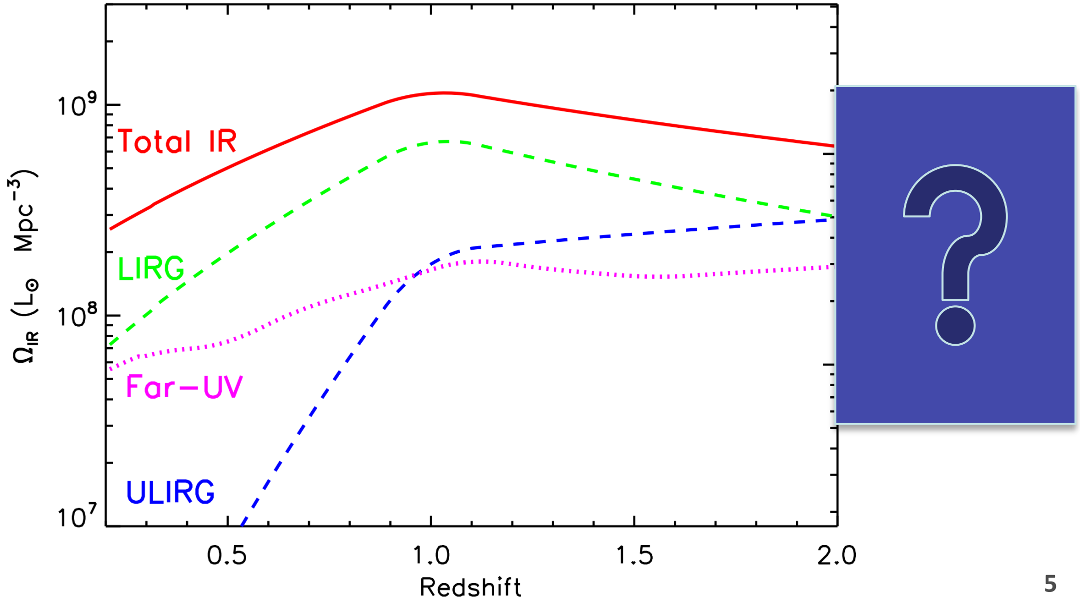
CIB anisotropies and structure formation

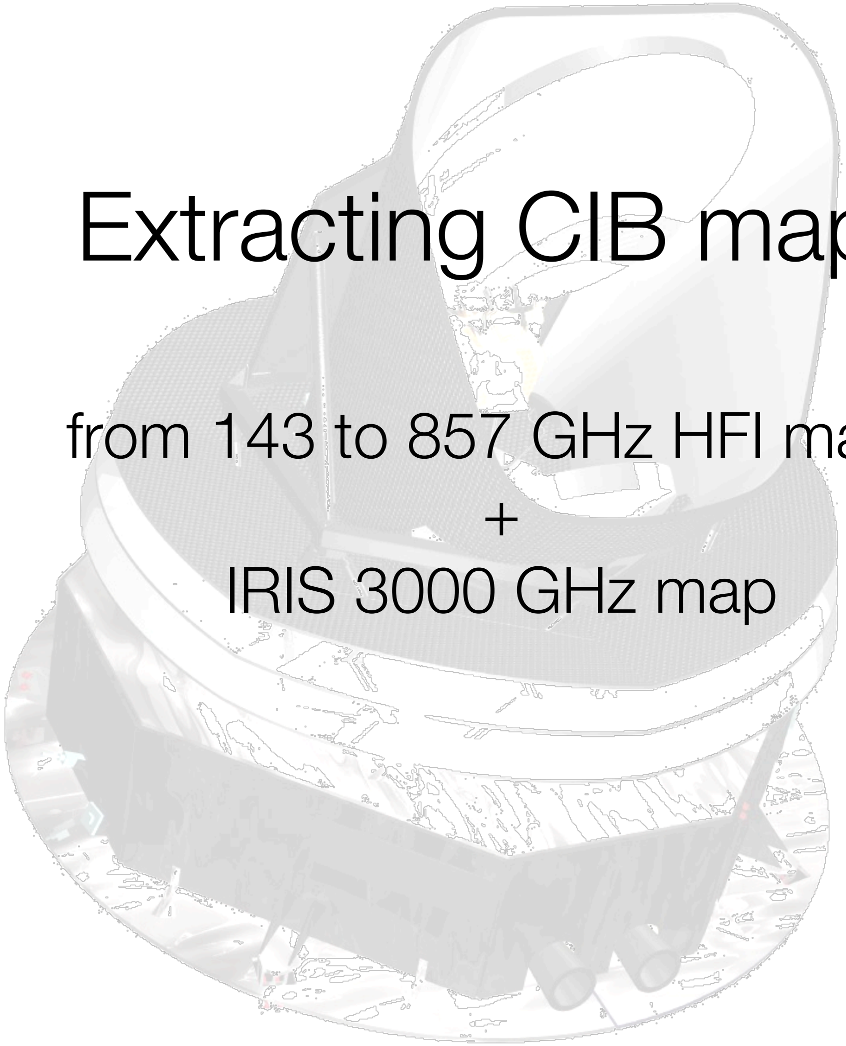
- Angular power spectrum and bispectrum
  - A white-noise component due to shot noise

    (sampling of a background composed of a finite number of sources)
  - A correlated component due to spatial correlations between the sources of the CIB

- Correlated anisotropies:
  - Expected to trace large-scale structures
  - Probe the clustering properties of dusty, star-forming galaxies
  - Constrain the relationship between dusty galaxies and dark matter distribution

  - Constrain the star formation history at high redshift





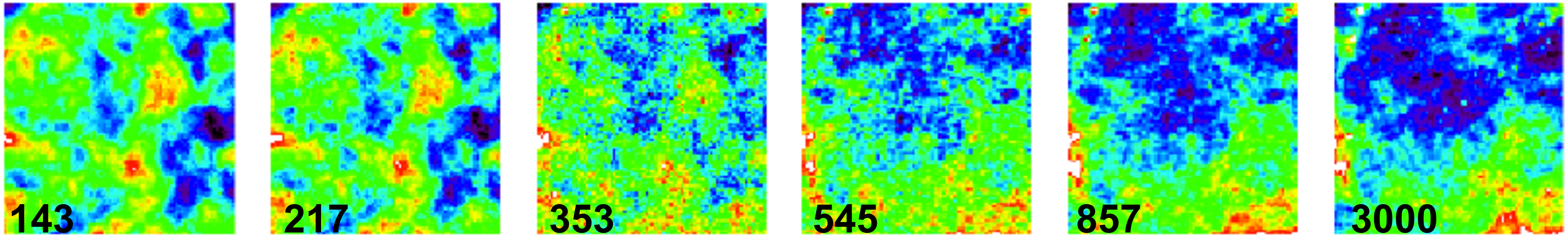
Extracting CIB maps

from 143 to 857 GHz HFI maps

+

IRIS 3000 GHz map

Component separation



5^{o}x5^o field

- Removing the background CMB
- Removing the foreground Galactic dust
- Correcting for the SZ contamination
- Masking point sources
  - *Use the PCCS (and IRAS FSC) to mask sources up to 80% completness*

Removing Galactic dust

- No Galactic dust frequency-map without extragalactic dust contamination

- Galactic dust and CIB:
  - SEDs too close, power spectra with no features (power laws with index~-2.7 versus ~-1)

- Use of « modern » methods promising but give biased results (CIB leakage in dust map)

- Template removal is currently the best approach
  - well established dust/HI correlation

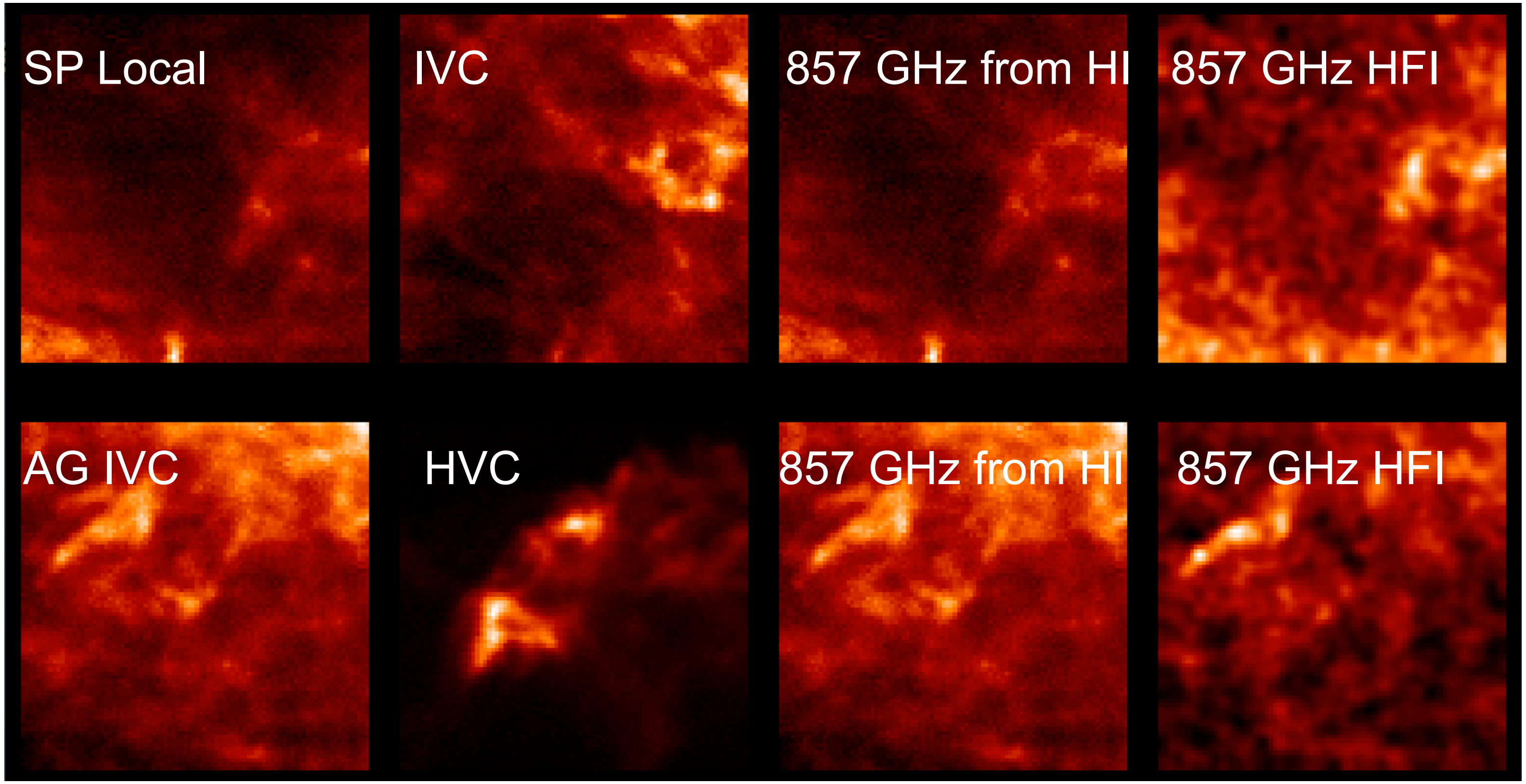
- Need high angular resolution HI data to separate CIB from dust

- Improve also the extraction of the CMB

IR-HI correlation

HI: best tracer of dust emission in the diffuse sky

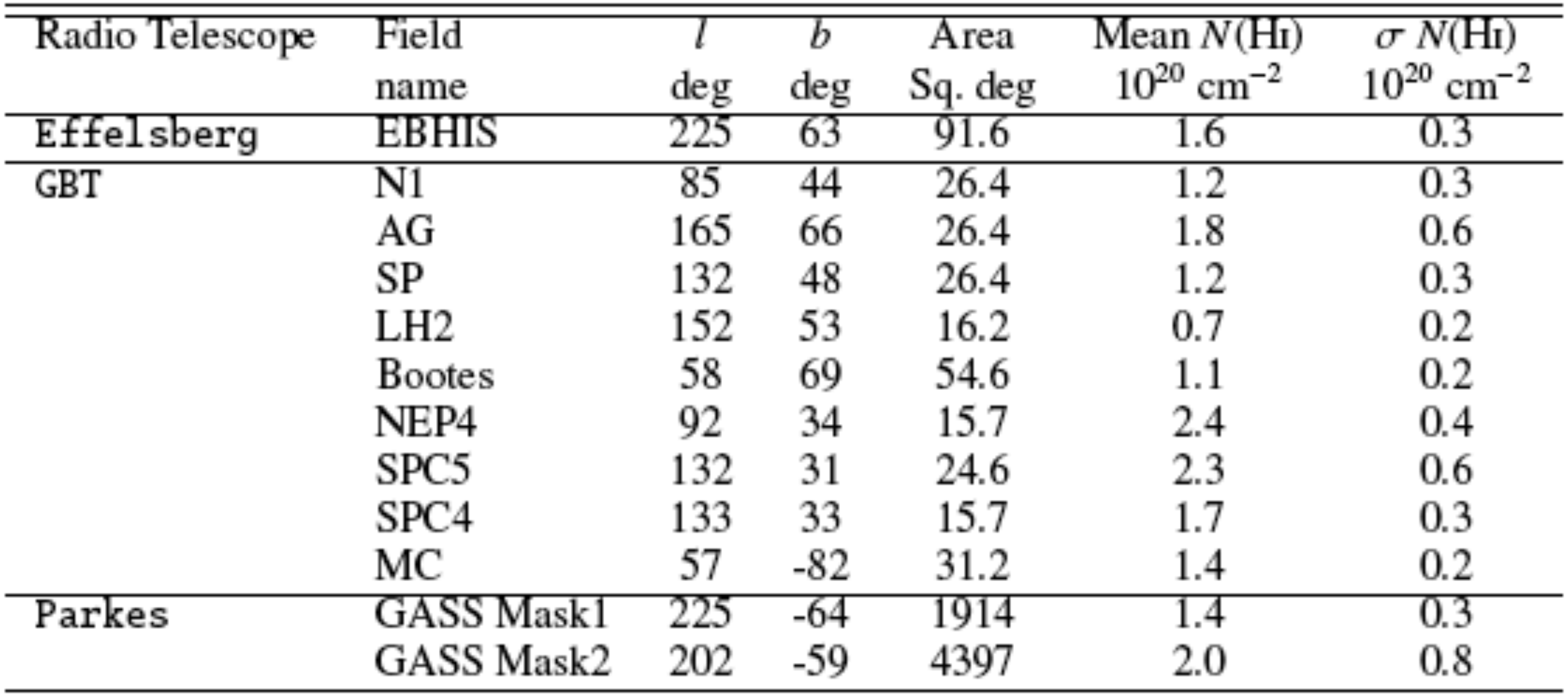
- HI data in each field: different velocity components (local, IVC, HVC)



(See Planck collab XVIII, 2011)

- Model: Planck/HFI at each ν $I_\nu(x,y) = \sum_i \alpha_\nu^i N_{HI}^i(x,y) + C_\nu(x,y)$

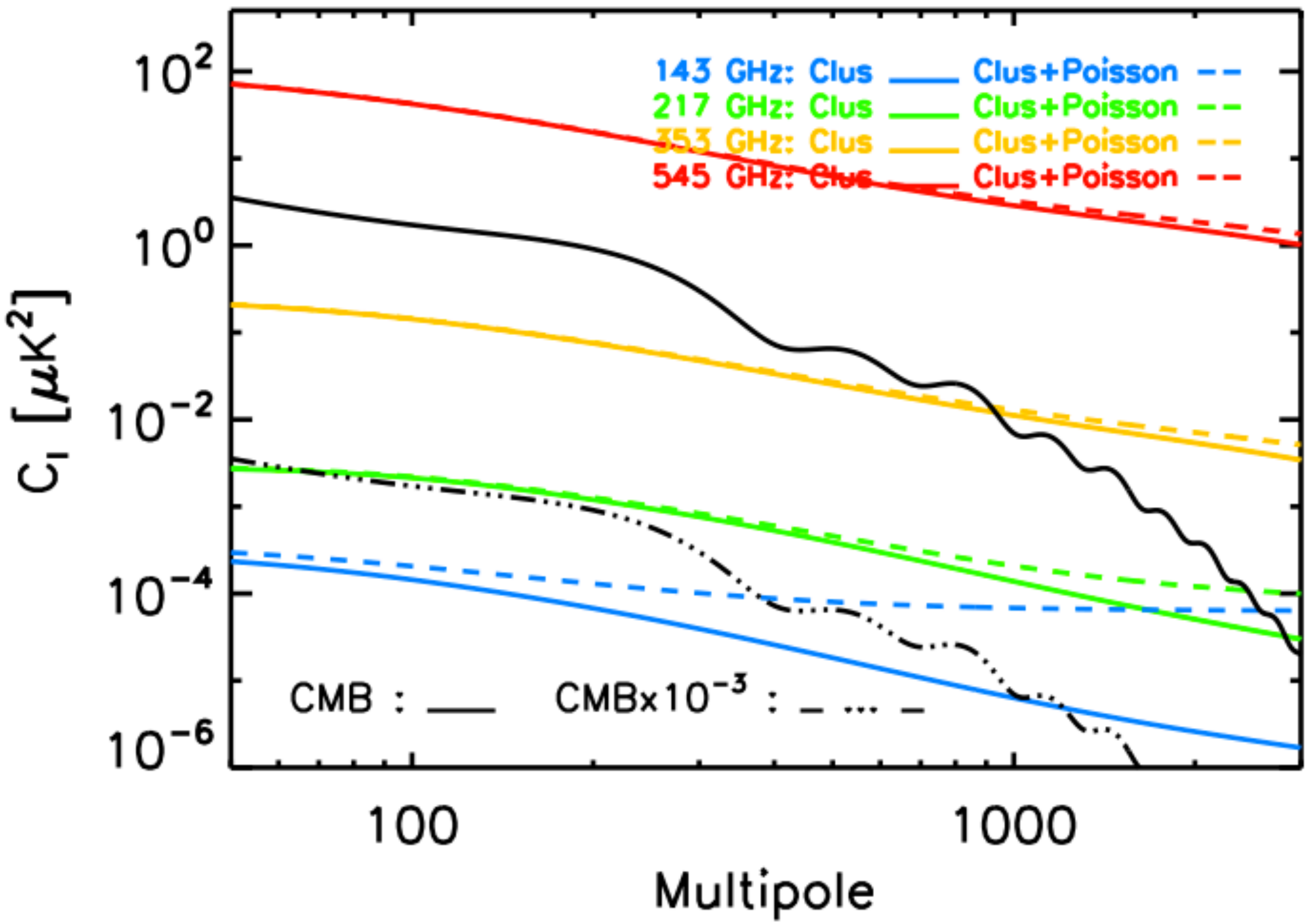
Selected fields



Radio Telescope	Field name	l deg	b deg	Area Sq. deg	Mean $N(\mathrm{HI})$ 10^{20} cm^{-2}	σ $N(\mathrm{HI})$ 10^{20} cm^{-2}
Effelsberg	EBHIS	225	63	91.6	1.6	0.3
GBT	N1	85	44	26.4	1.2	0.3
	AG	165	66	26.4	1.8	0.6
	SP	132	48	26.4	1.2	0.3
	LH2	152	53	16.2	0.7	0.2
	Bootes	58	69	54.6	1.1	0.2
	NEP4	92	34	15.7	2.4	0.4
	SPC5	132	31	24.6	2.3	0.6
	SPC4	133	33	15.7	1.7	0.3
	MC	57	-82	31.2	1.4	0.2
Parkes	GASS Mask1	225	-64	1914	1.4	0.3
	GASS Mask2	202	-59	4397	2.0	0.8

- CIB power spectrum: ~2240 deg^2
  - Improves by a factor >16 over previous analysis
- CIB bispectrum: ~4400 deg^2
  - increases the S/N, but prevents the use of the 857 GHz

Removing CMB



CMB/CIB power spectrum ratio at ℓ=100:

~5000 at 143 GHz

~1000 at 217 GHz

Any hope to measure the CIB at 143 GHz?

Which CMB for CIB analysis?

- Look at CIB using various component separation CMB-removed maps
  - No problem at 353 GHz: CIB power spectrum very stable w.r.t. CMB
  - 217 GHz: variation of CIB Cl by factor 4 at $\ell \sim 100$
  - 143 GHz: variation of CIB Cl by factor more than 10 at $\ell \sim 100$

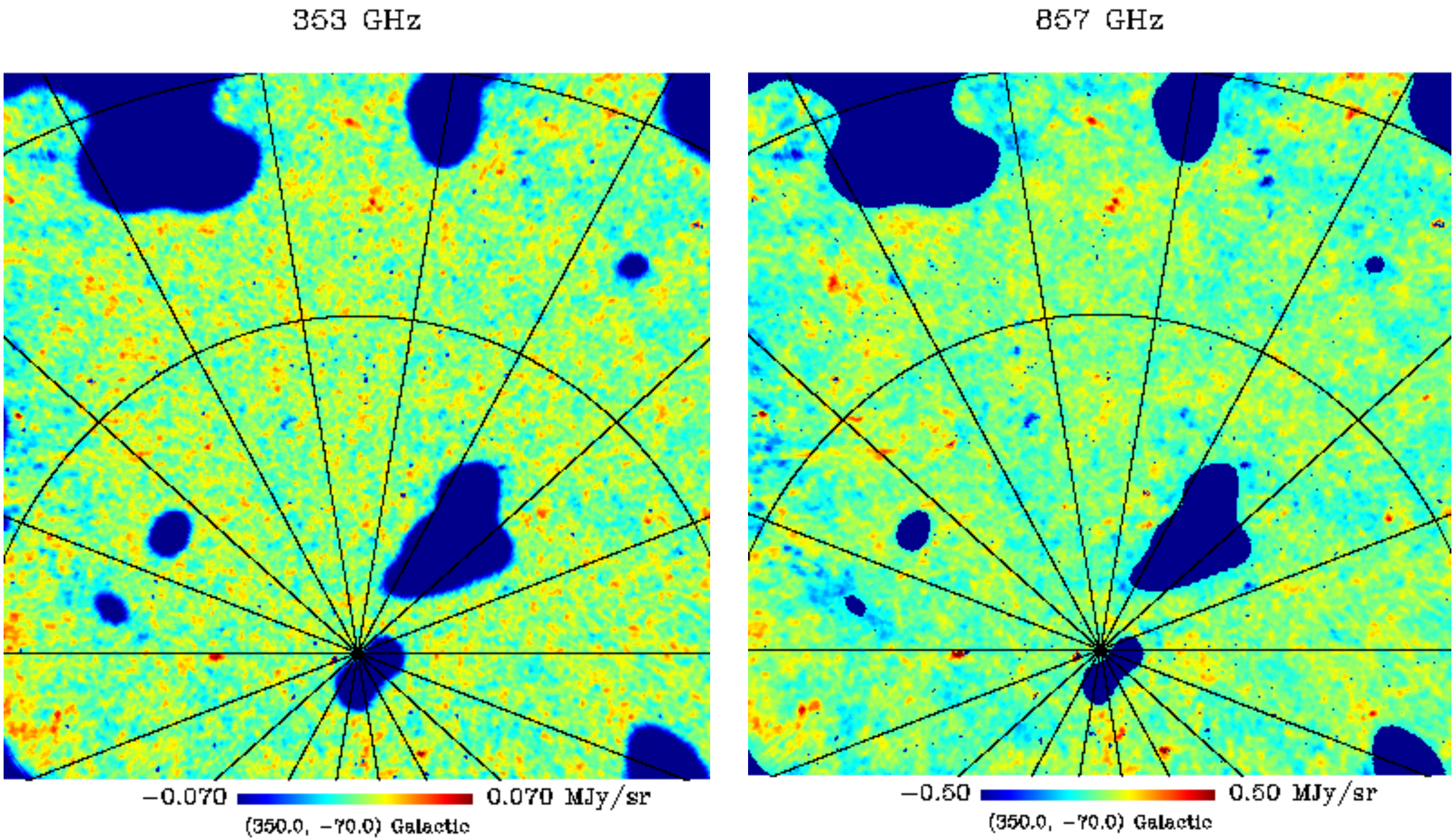
=> Among others: CIB leakage in CMB map

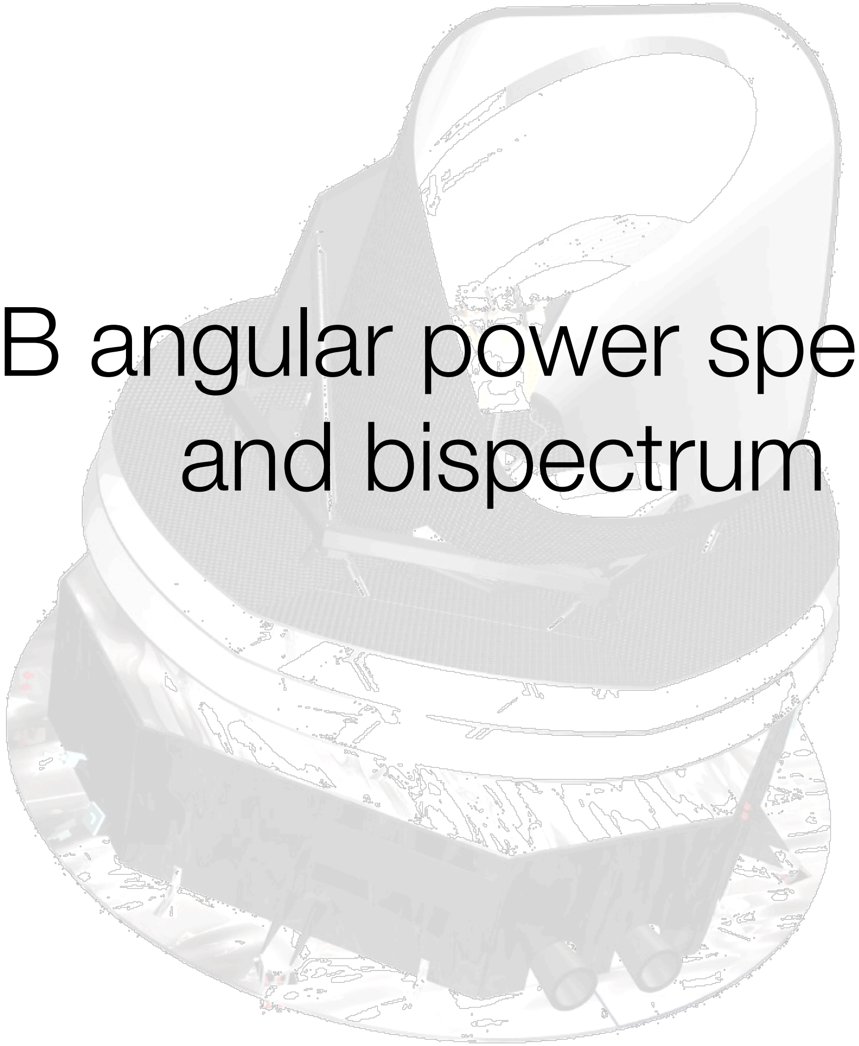
For CIB, we need a dedicated CMB map

- HFI 100 GHz map: a good template for the CMB
  - Advantages:
    - "internal" template, meaning its noise, data reduction process, photometric calibration, and beam are well known,
    - angular resolution close to the higher frequency channels
  - Galactic dust removed, PS masked
  - Instrument noise supressed (maps are wiener filtered)
  - Drawback: tSZ signal and spurious CIB

Dust and CMB-free maps

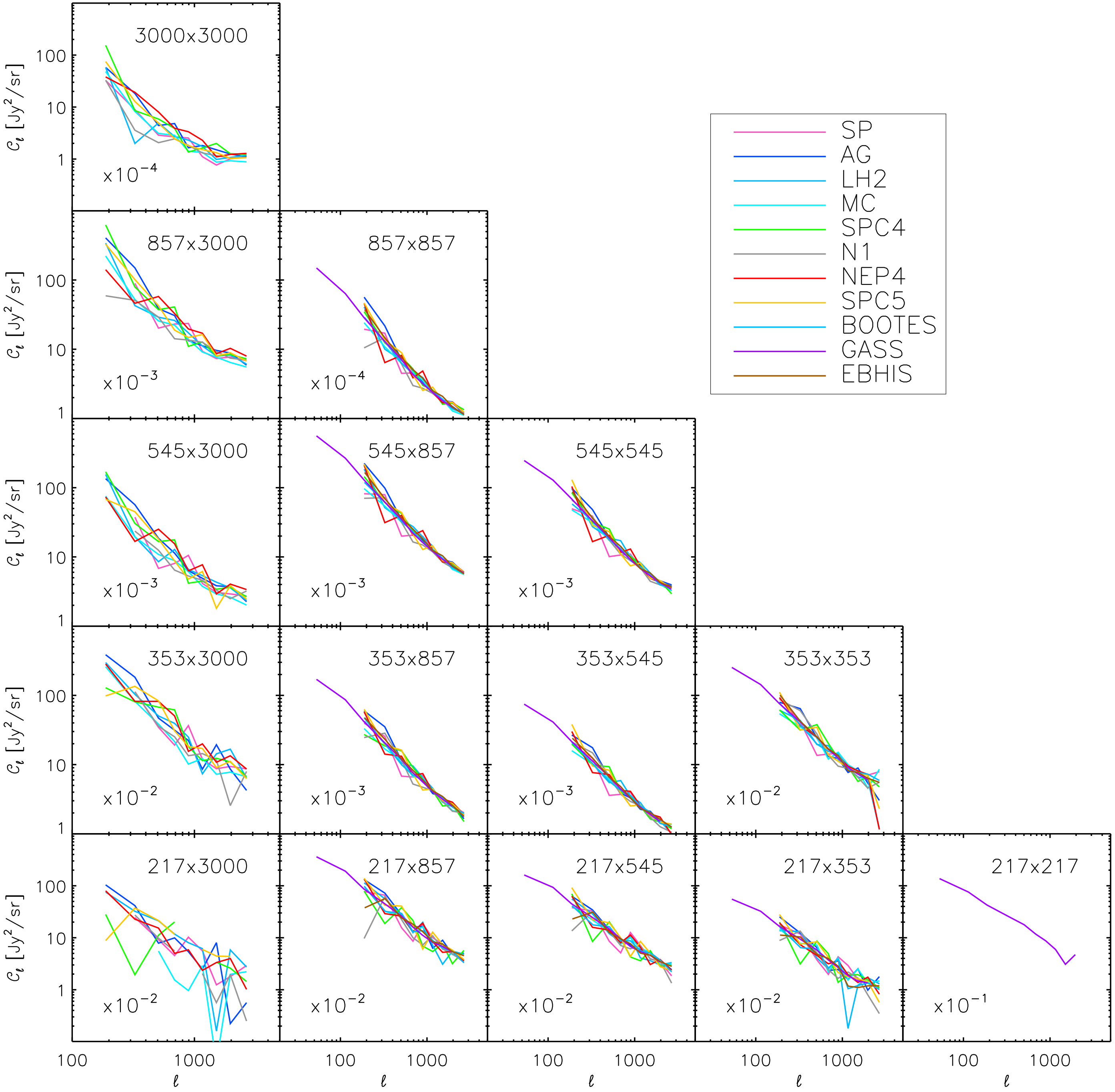
A 65x65 deg^2 patch





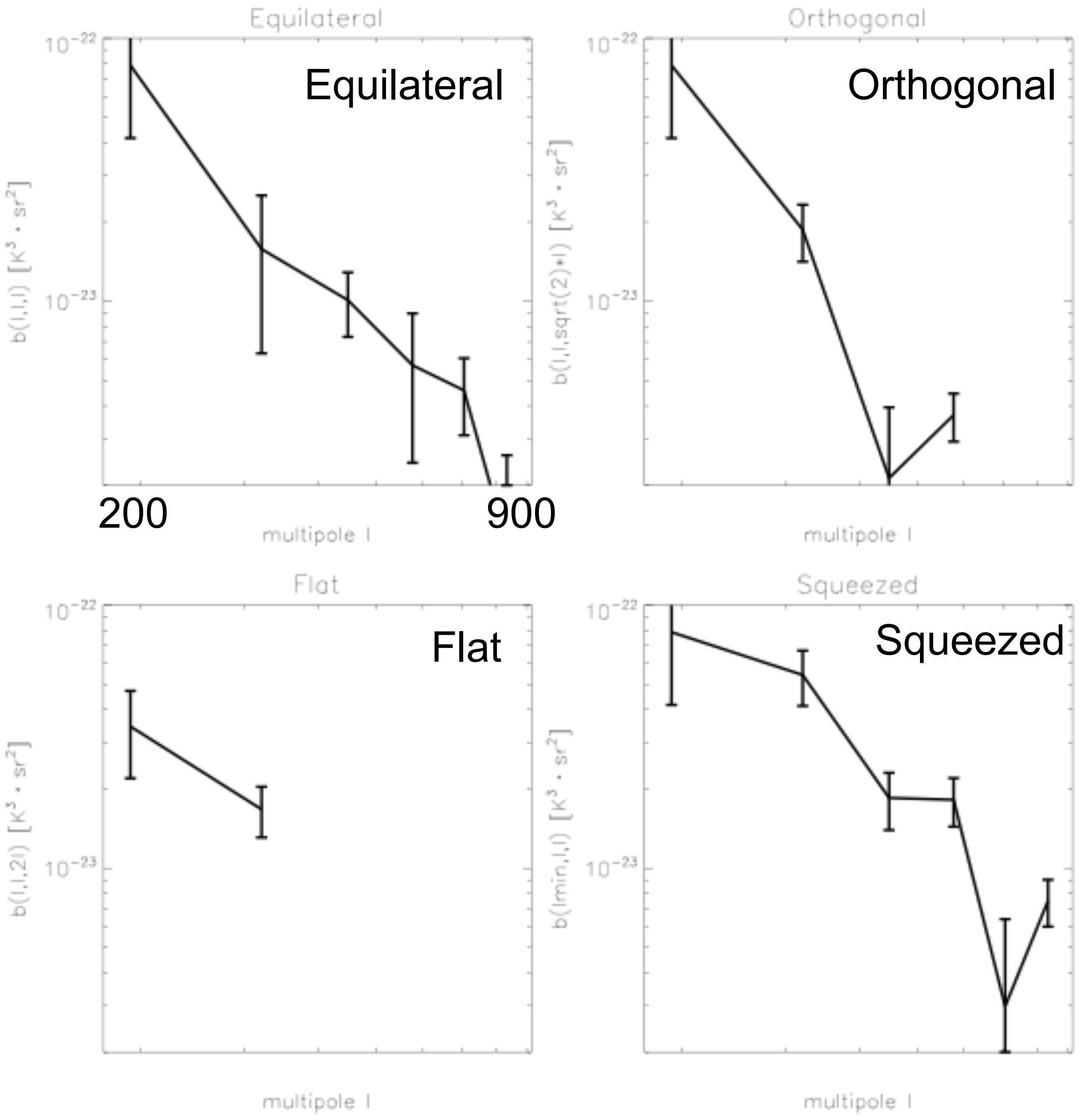
CIB angular power spectrum and bispectrum

Agular power spectrum: all fields



(plot from N. Ponthieu)

And the bispectrum!



(plot from F. Lacasa)

- GASS Mask2, ~4400 deg^2
- 3-point correlation function in harmonic space
- Lowest order indicator of the non-Gaussianity of the field.
- For $130<\ell<900$, 6 multipole bins and 43 bispectrum configuration (ℓ_1,ℓ_2,ℓ_3)
- At 545GHz:
  - SNR per config=5.7
  - SNR tot=32.7
- At 353 GHz:
  - SNR per config=3.9
  - SNR tot=24.8

Further corrections to CIB measurements

- Cross-spectra of CIB maps:

$$a^{\nu}_{\ell m} \times a^{\nu' *}_{\ell m} = \left[a^{CIB,\nu}_{\ell m} + a^{SZ,\nu}_{\ell m} - w_{\nu}\left(a^{CIB,100}_{\ell m} + a^{SZ,100}_{\ell m}\right)\right] \times \left[a^{CIB,\nu'}_{\ell m} + a^{SZ,\nu'}_{\ell m} - w_{\nu'}\left(a^{CIB,100}_{\ell m} + a^{SZ,100}_{\ell m}\right)\right]^{*}$$

- CIBxCIB spurious correlation

$$C^{\nu\times\nu'}_{\mathrm{CIBcorr}} = -w_{\nu} C^{100\times\nu'}_{\mathrm{CIB}} - w_{\nu'} C^{100\times\nu}_{\mathrm{CIB}} + w_{\nu} w_{\nu'} C^{100\times 100}_{\mathrm{CIB}}$$

- tSZxtSZ

$$C^{\nu\times\nu'}_{\mathrm{SZcorr}} = C_{\mathrm{SZ}}\left[g_{\nu} g_{\nu'} + w_{\nu} w_{\nu'} g^{2}_{100} - g_{100}(w_{\nu'} g_{\nu} + w_{\nu} g_{\nu'})\right].$$

- tSZXCIB:

$$\begin{aligned} C^{\nu\times\nu'}_{\mathrm{CIB\times SZcorr}} = \; & C^{\nu\times\nu'}_{\mathrm{CIB\times SZ}} + C^{\nu'\times\nu}_{\mathrm{CIB\times SZ}} - w_{\nu} C^{100\times\nu'}_{\mathrm{CIB\times SZ}} - w_{\nu'} C^{100\times\nu}_{\mathrm{CIB\times SZ}} \\ & - w_{\nu} C^{\nu'\times 100}_{\mathrm{CIB\times SZ}} - w_{\nu'} C^{\nu\times 100}_{\mathrm{CIB\times SZ}} + 2 w_{\nu} w_{\nu'} C^{100\times 100}_{\mathrm{CIB\times SZ}} \end{aligned}$$

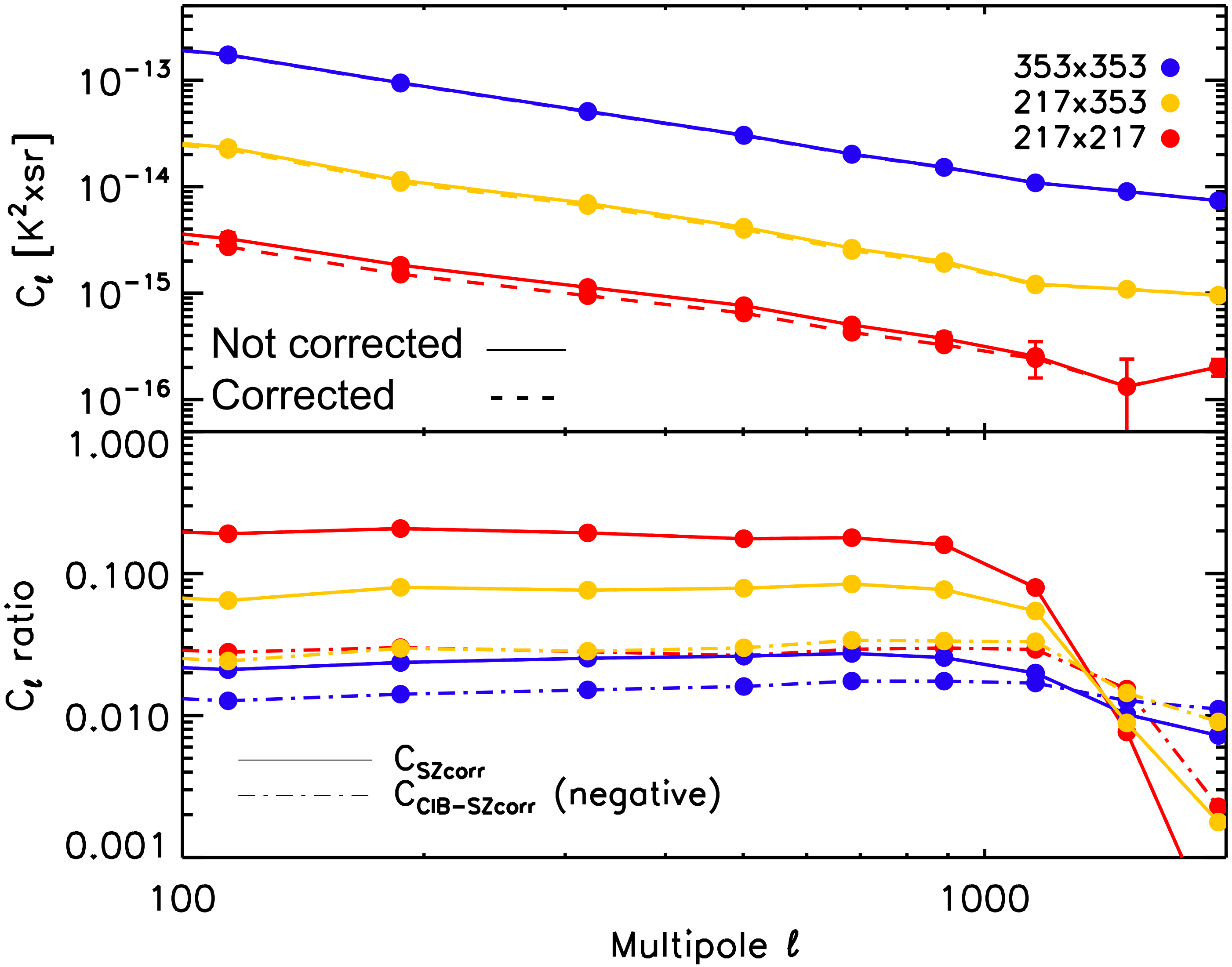
Further corrections to CIB measurements

- CIBxCIB spurious correlation
  - Need a CIB model
  - Compute the correction using our model in the fitting procedure
  - Factor of ~1.15 for $50<\ell<700$ at 217 GHz

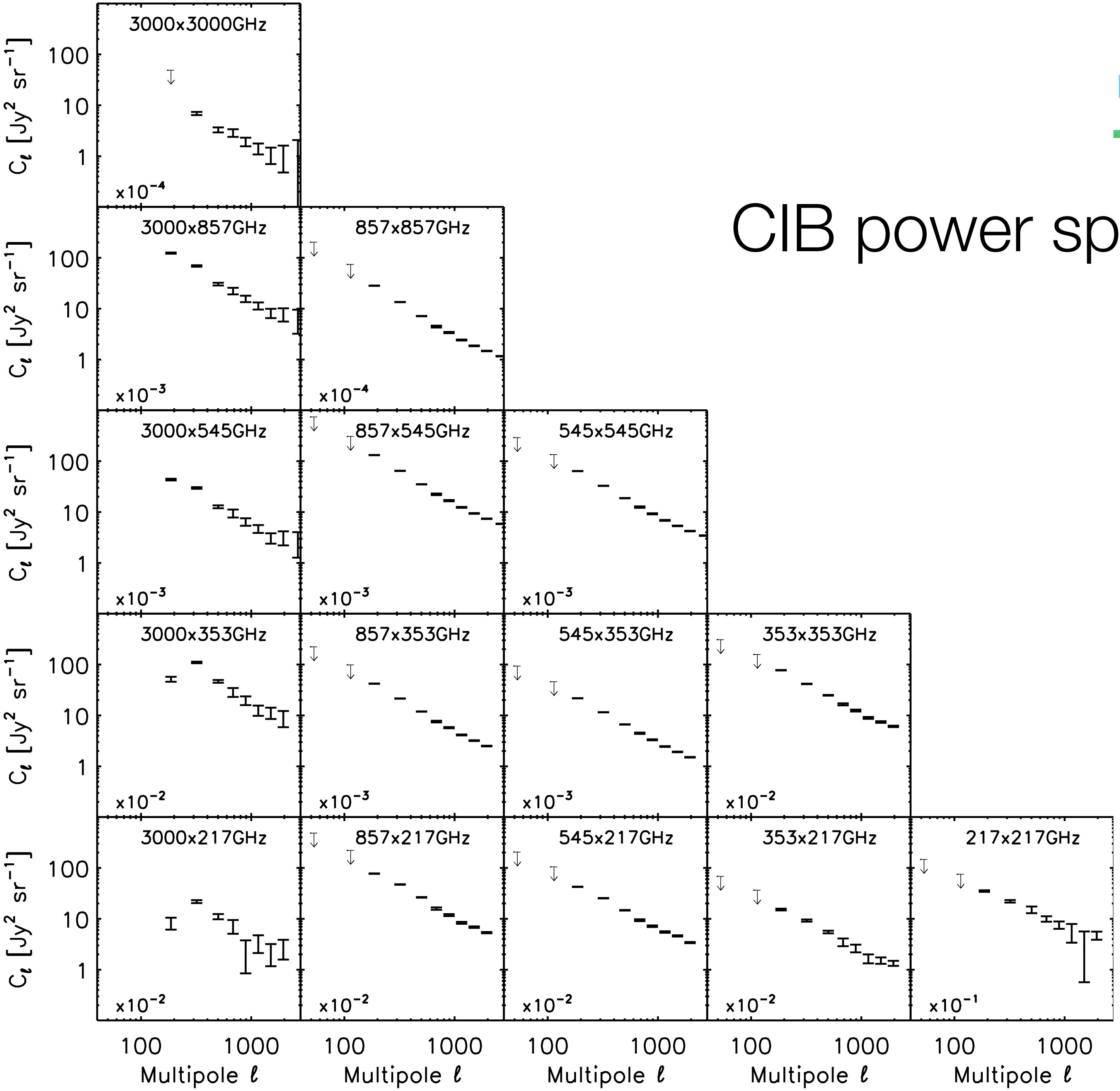
- tSZxtSZ
  - Compute the correction at the power spectrum level
  - Use Planck collab 2013 (XXI) tSZ power spectrum
  - Uncertainty = 10%

- tSZXCIB:
  - Compute the correction at the power spectrum level
  - Use Addison et al. (2012) model
  - Uncertainty = factor of 2

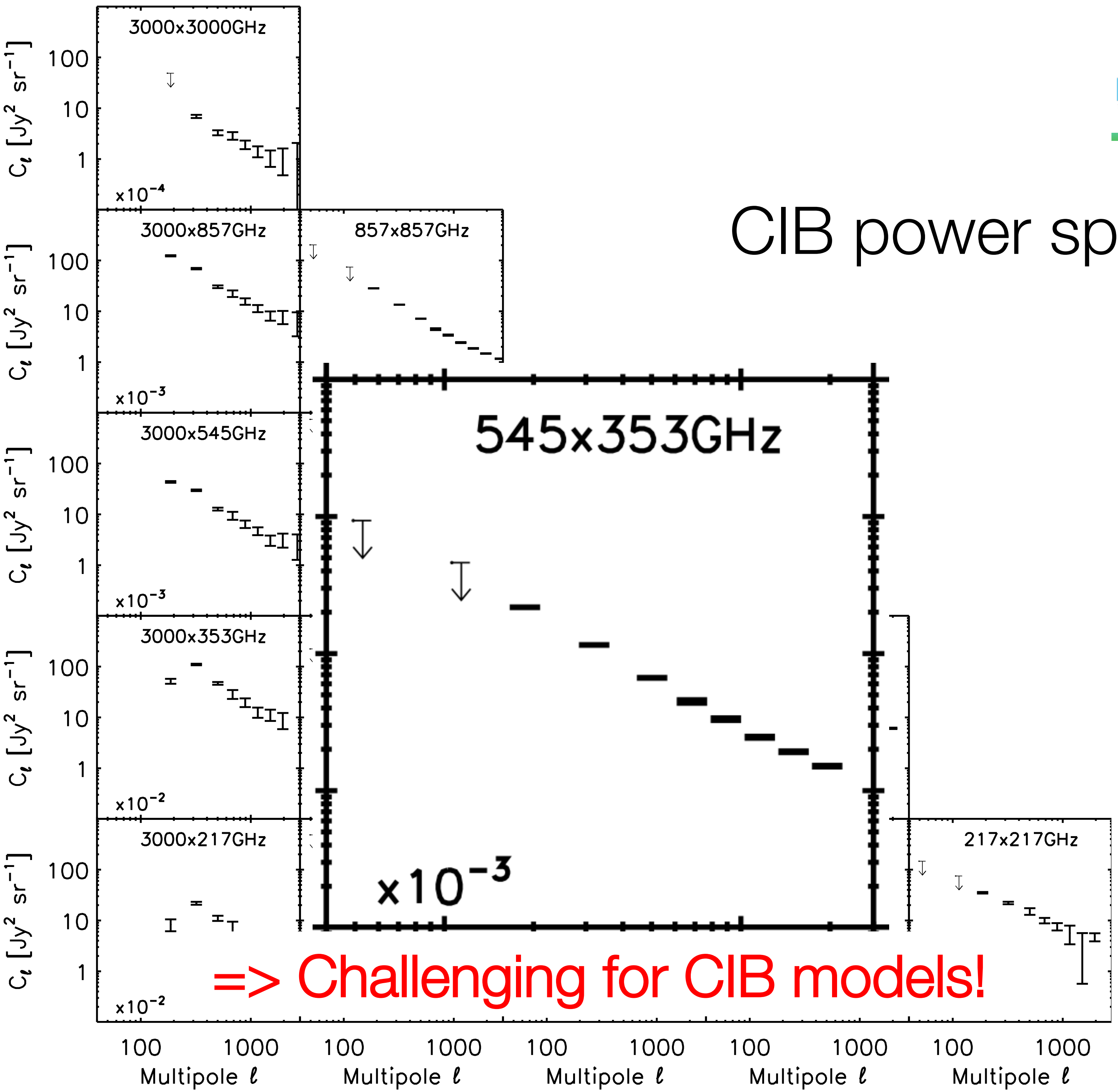
SZ-related corrections



CIB power spectra

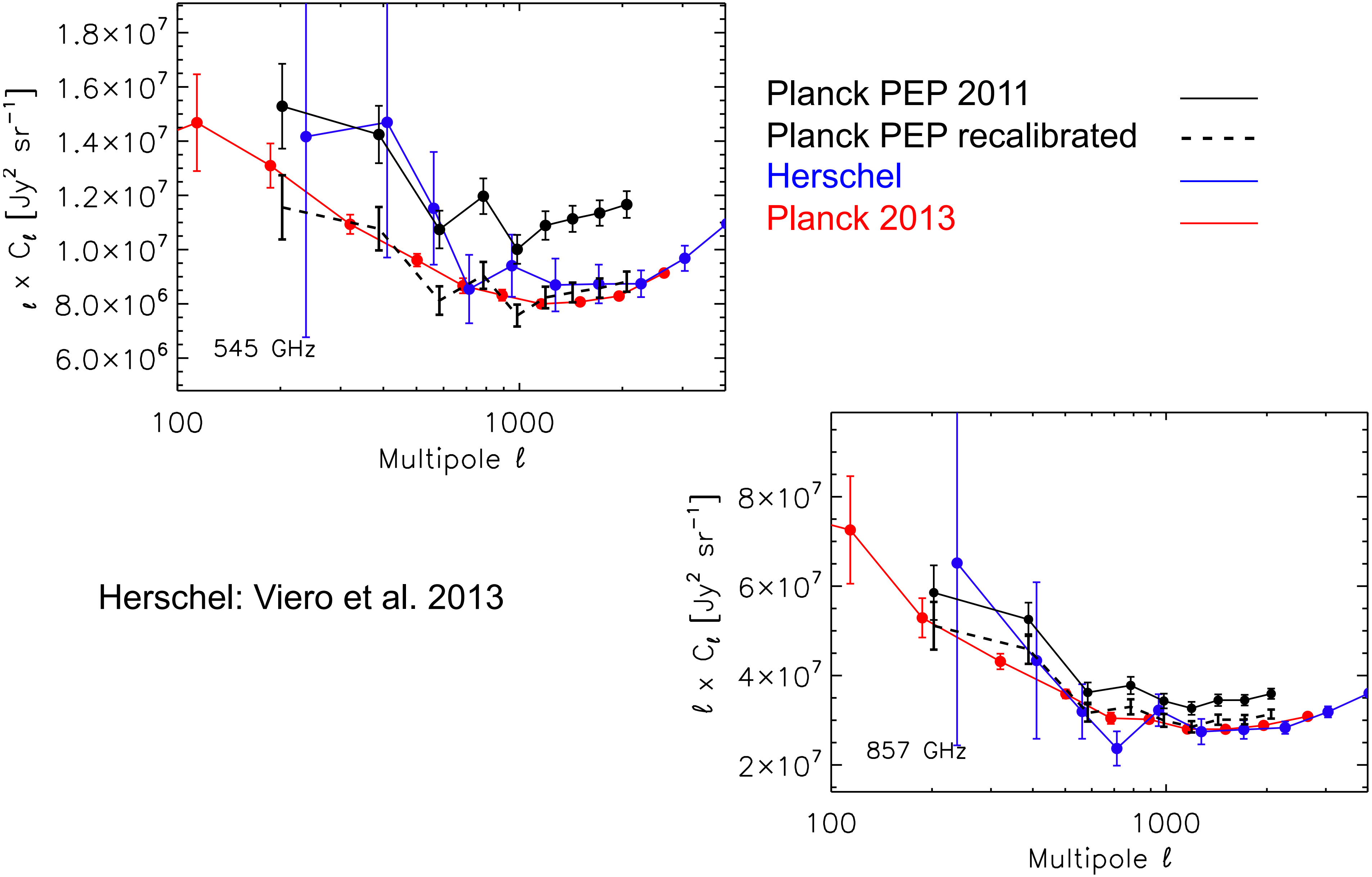


CIB power spectra

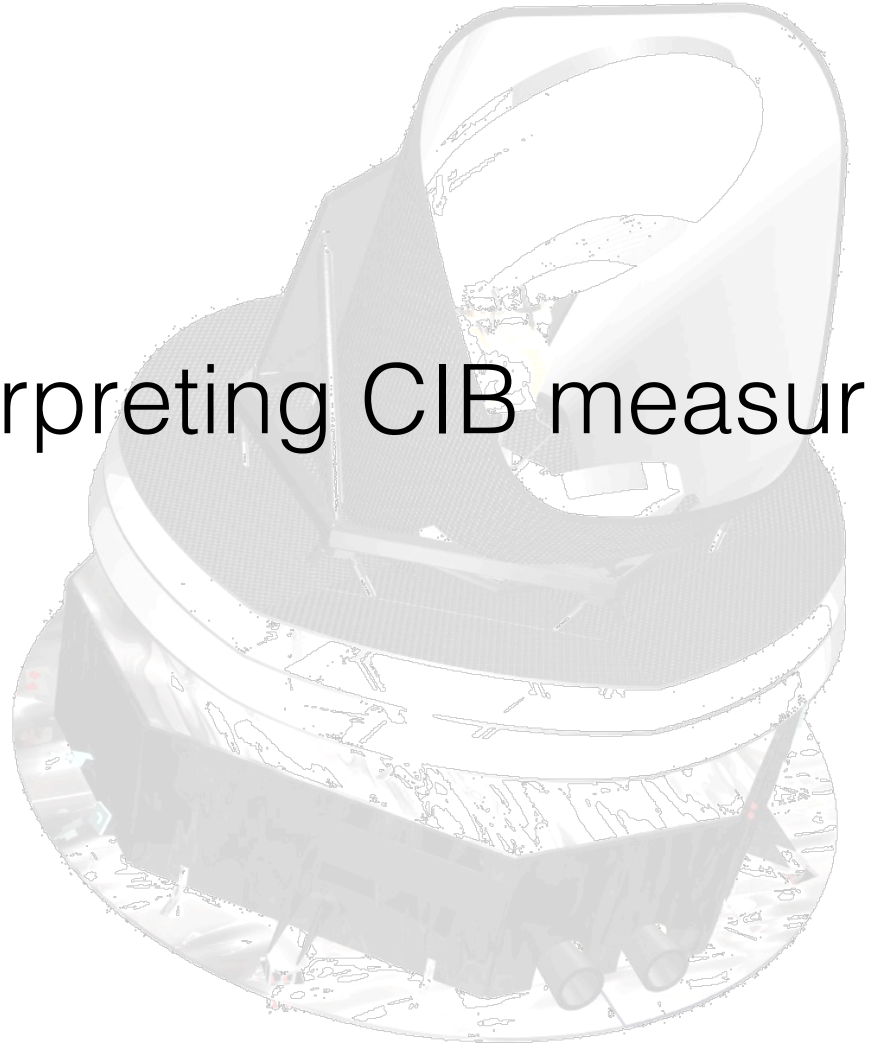


=> Challenging for CIB models!

Comparison with recent Herschel measurements



Herschel: Viero et al. 2013



Interpreting CIB measurements

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 masses of their host halos)

A simple linear model

- On large scales, in the linear regime, $P_{gg}=b_{eff}^2P_{lin}$

  Where b_{eff} is the mean bias of dark matter halos hosting dusty galaxies at a given z, weighted by their contribution to the emissivities.

- The emissivities are computed from the star formation rate density:

$$\bar{j}(\nu, z) = \frac{\rho_{\mathrm{SFR}}(z)(1+z)s_{\nu,eff}(z)\chi^2(z)}{K},$$

  - K is the Kennicutt (1998) constant
  - $S_{\nu,\mathrm{eff}}(z)$ are the effective SED of dusty galaxies at a given redshift, deduced from Béthermin et al. (2012) model

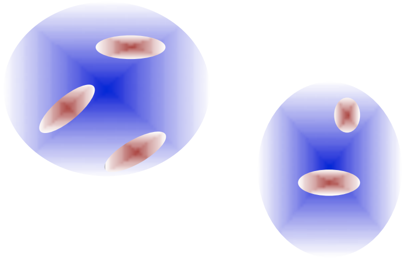
    Mix of secularly-star-forming galaxies and starburst galaxies

    Increase of T with z following the measurements of Magdis et al. (2012)

An extended halo model for CIB

- Introduced for CIB by Shang et al. 2011
- In the framework of the halo model:

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



- We abandon the assumption of a mass-independent luminosity:

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

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

SED shape

Redshift evolution

SFR-M relation (log-normal)

Parameters

Linear model

- b_0, b_1, b_2
- ρ_{SFR} (z=0, 1, 2, 3, 4)
- Calibration factors

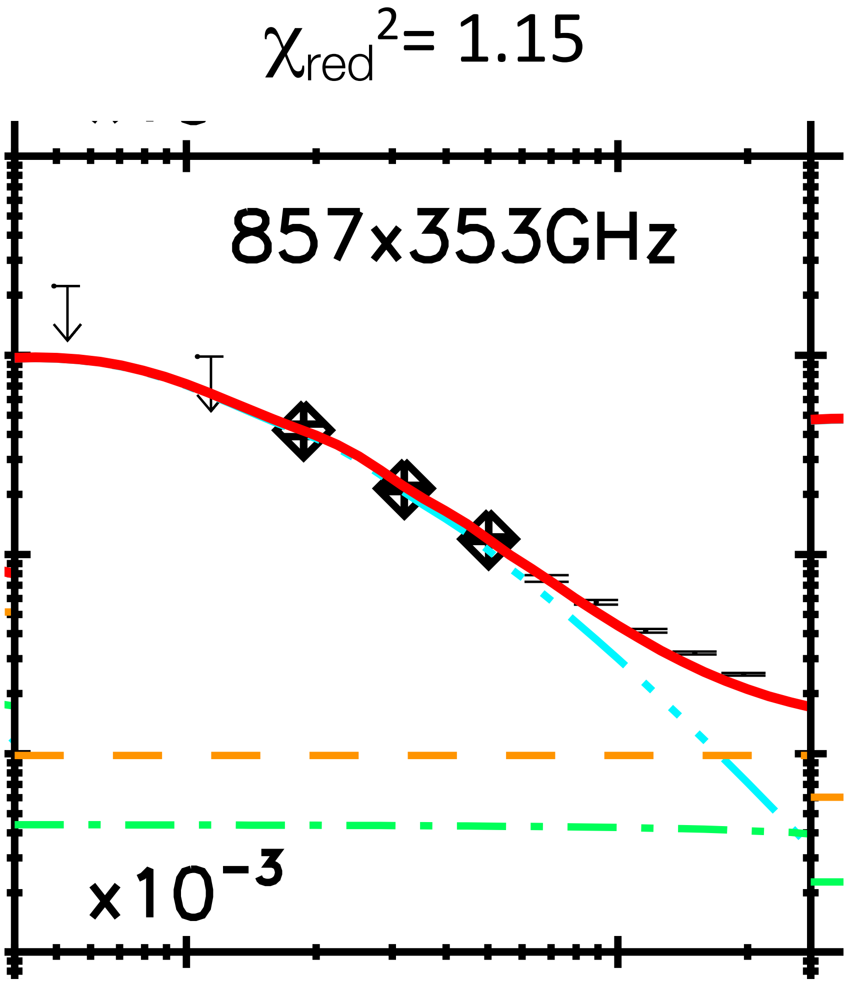
- Priors:
  - b_0 and ρ_{SFR} (z=0)
  - CIB mean
  - Photometric calibration errors

Extended Halo model

- Global normalisation of the L-M relation $(1+z)^{\delta}$
- M_{eff}
- SED:
  - modified BB with $T=T_0(1+z)^{\alpha}$
  - β, α, ν^*, $T_{0,}$ γ
- All Shot noises

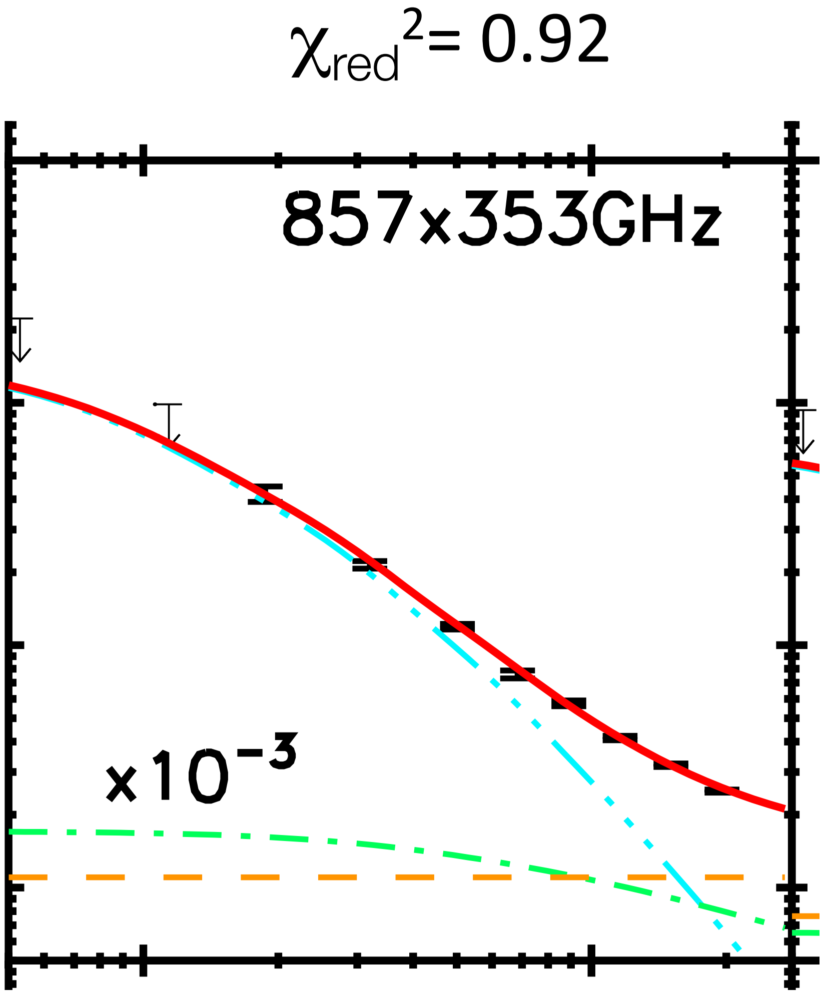
- Priors:
  - T_0 € [20,60] ; β € [1.5,2]
  - δ € [0,7]
  - SN: 20% error

Equally good fits…



Linear

(plot from M. Béthermin)

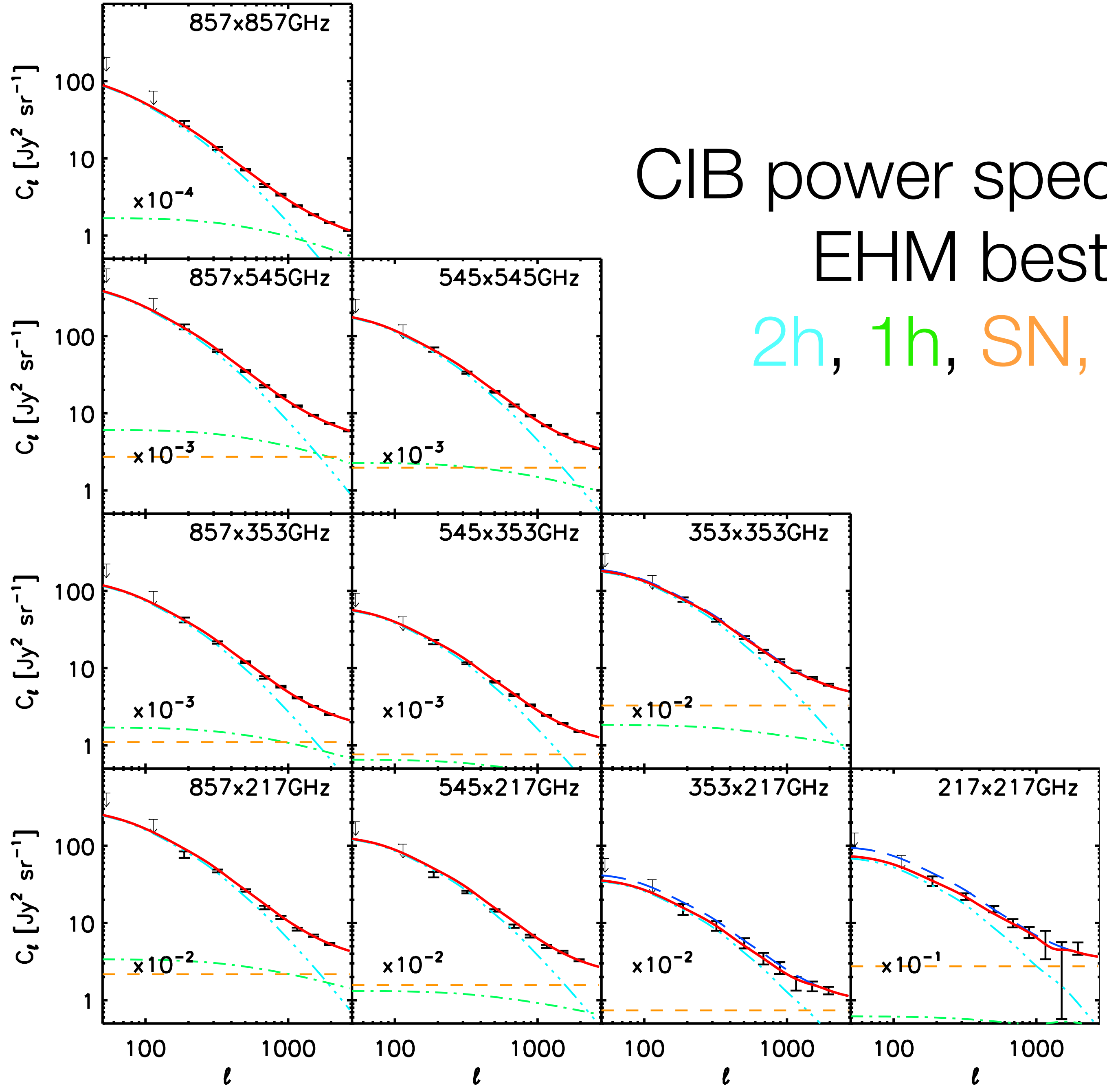


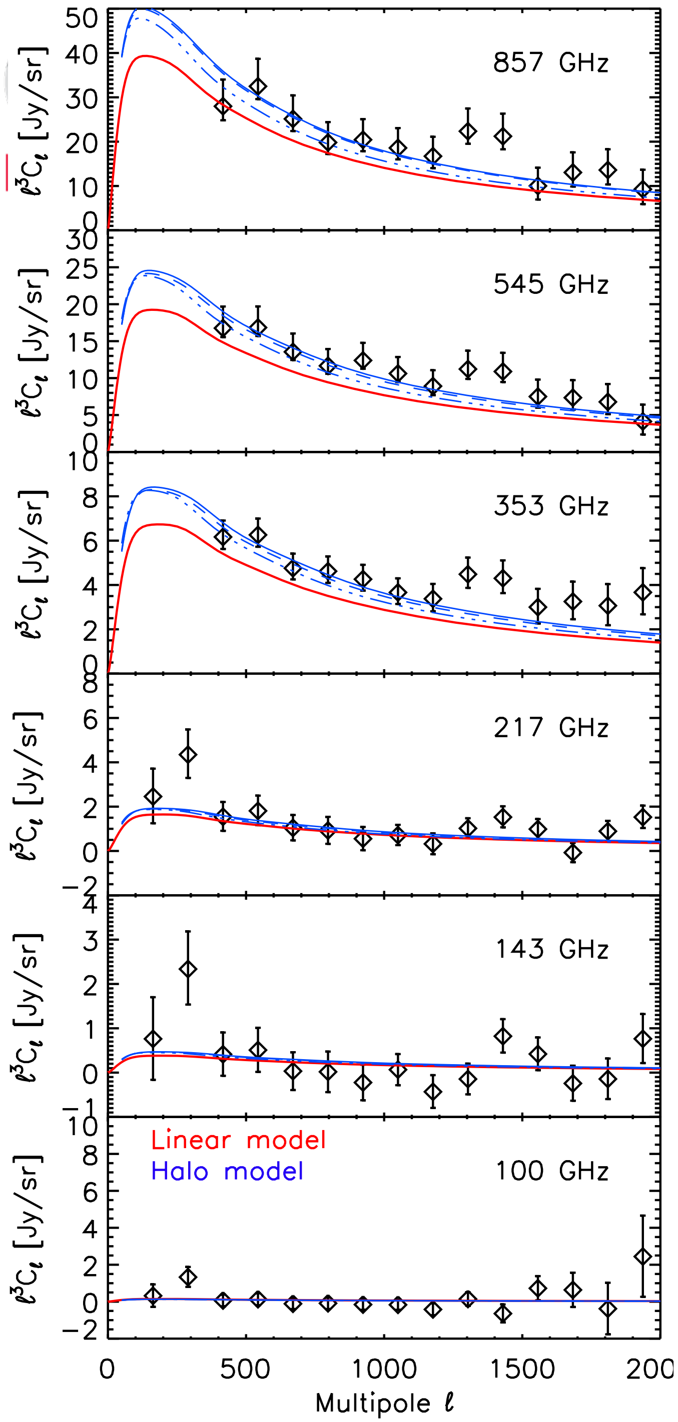
Extended Halo Model

(plot from P. Serra)

CIB power spectra with EHM best fit

2h, 1h, SN, total





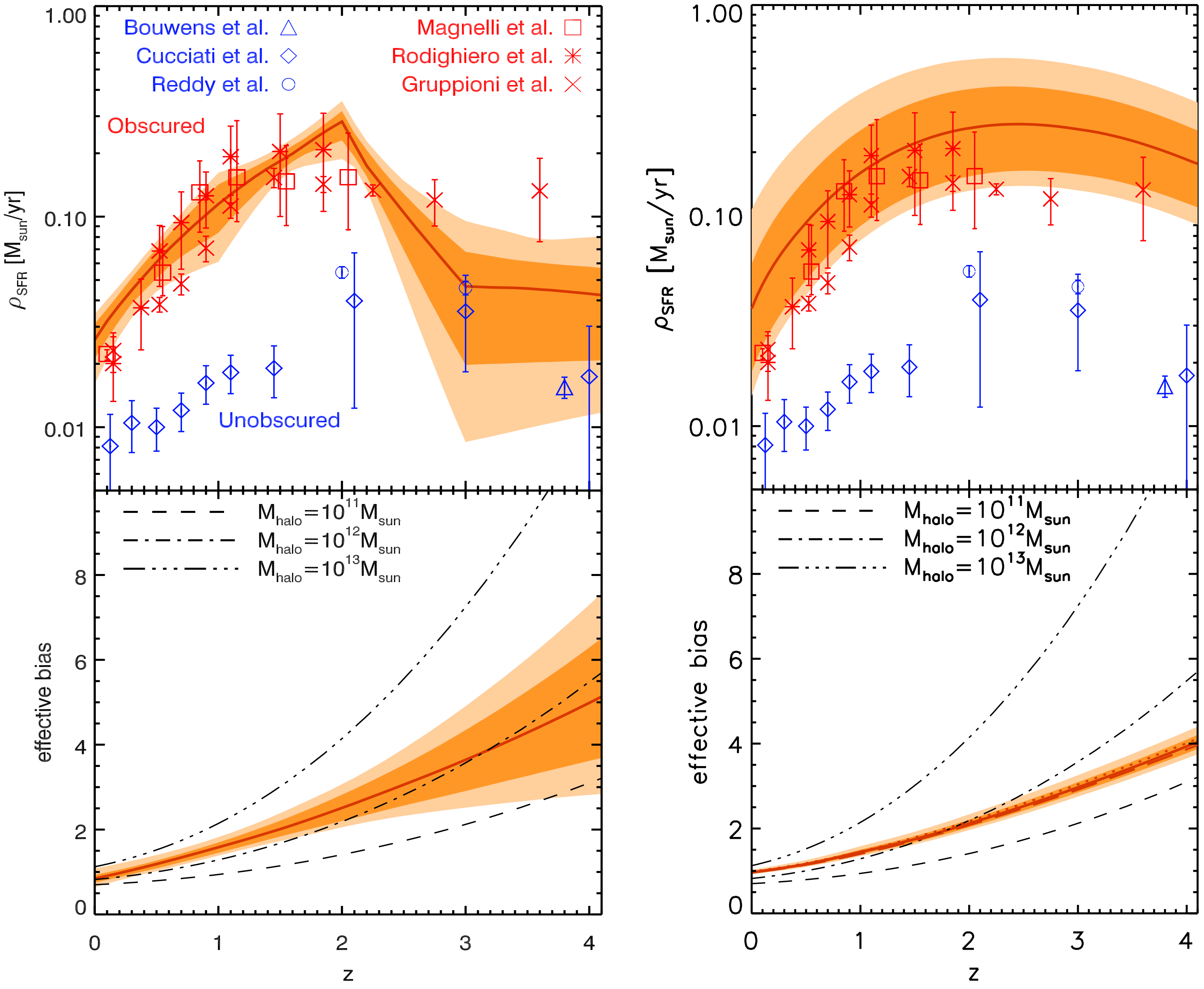
…. that are consistent with CIBxCMB lensing measurements

(Planck collab, XVIII, 2013)

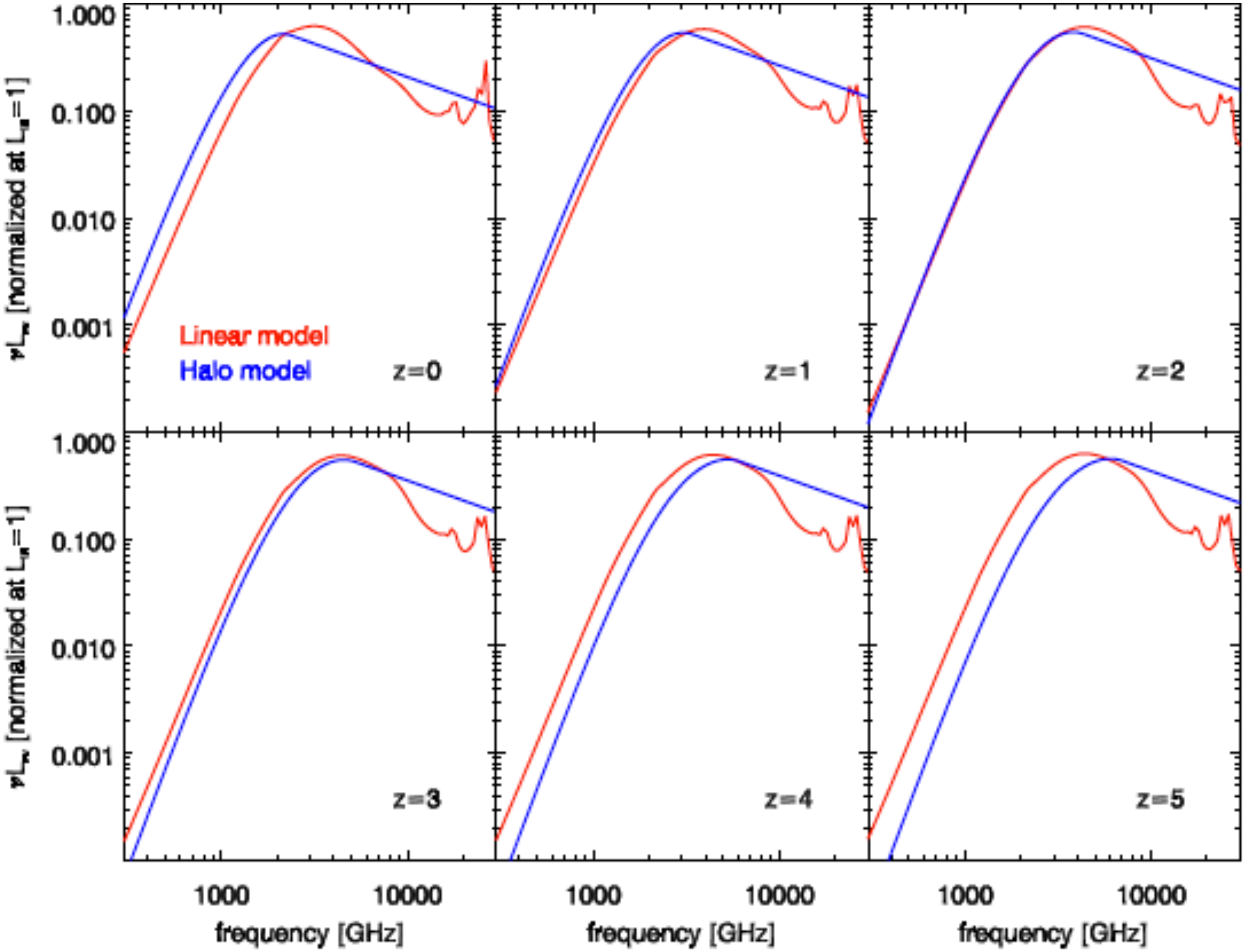
…. but give different ρ_{SFR} and bias at high z

Linear Model

Extended Halo Model



…. due to different SEDs



Linear model:
- SEDs fixed
- Magdis et al. 12 T(z) up to z=2
- Extrapolation at higher z

Extended HM:
- Shape fixed by the modified BB

Good agreement for $1 \leq z \leq 3$

Which ones are the best??

Changing the parametrisation of the EHM…

… to see the effect on ρ_{SFR}

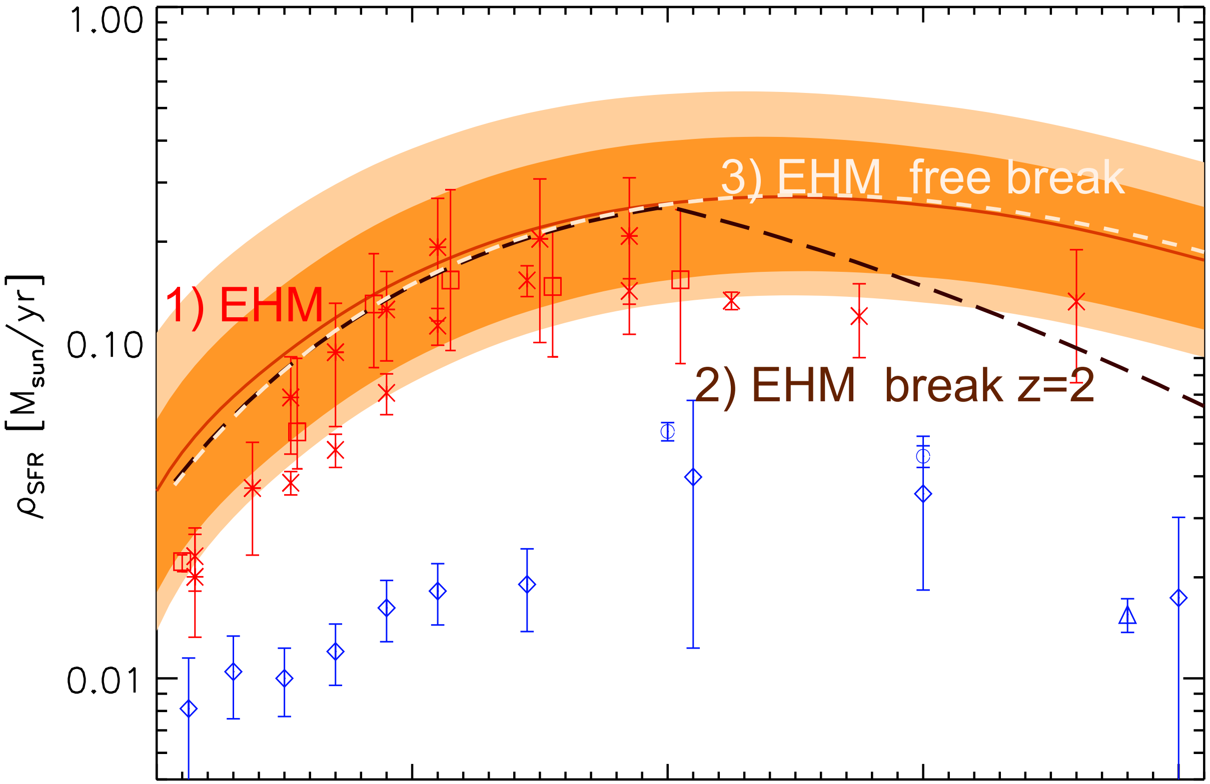
1) « Nominal » EHM

2) Imposing a break at z= 2 in the redshift normalization parameter of the L-M relation (as in Shang et al. 2012)

=> Degrade the quality of the fit

3) Fitting for a break in both the L-M relation and T(z)

=> find z_{break}>2.9



The extended halo model

- Most efficient mass Meff
  - $\log(M_{eff}/M_{\odot}) = 12.2\pm0.13$
  - Redshift evolution compatible with zero

- Variation of temperature with redshift
  - Dust spectral index: $\beta = 1.85\pm0.06$
  - Unavoidable, $T_0<21.9$K, $\alpha=0.71\pm0.1$ (very satisfactory but with z_{break}!)
  - A harder interstellar radiation field up to z~2.5 (Magdis et al. 2012)

- Fit simultaneously all frequencies with only one set of parameters

- Was not able to find a good solution when:
  - The CMB was not corrected for 217x545
  - The SZ was not corrected for 217x217
  - Dust residuals were left at low ell
  - … (the cosmological parameters were set to wmap9 rather than planck1!)

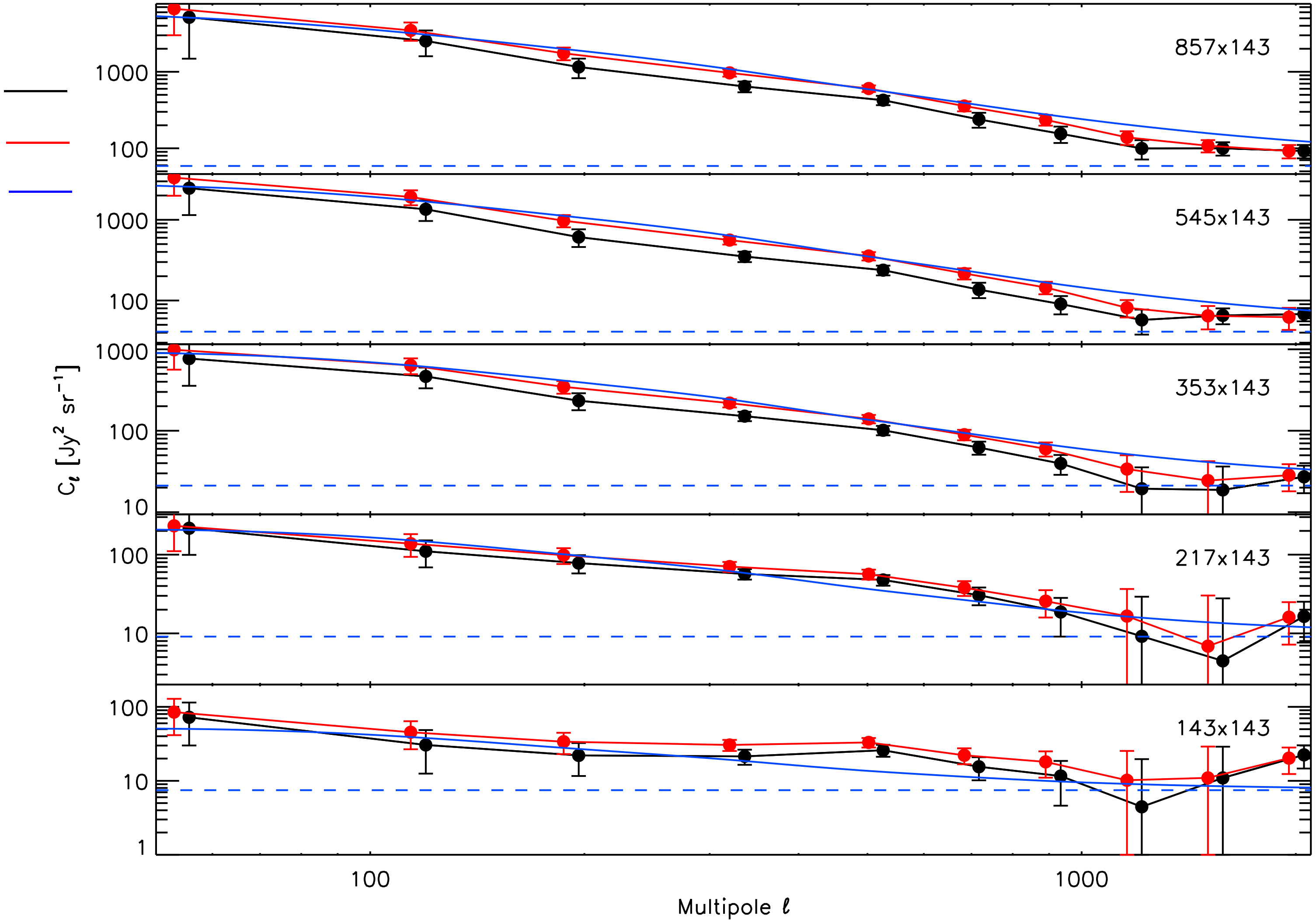
=> We reach the time when the models start to be predictive!!

What about the 143 GHz ?

Not corrected

Corrected

EHM Predictons



Clear detection and nice measurements!

BUT large corrections due to spurious CIB and SN important

SO very model-dependent

Conclusion

- A new breakthrough in CIB measurements
  - Very large area (>2200 deg^2)
  - Angular power spectrum but also bispectrum
  - All corrections: dust, CMB, point sources, SZ, spurious CIB
  - Dedicated analysis and simulations for error bars

- A successful modeling
  - Extended halo model
    - One set of parameters for all frequencies (auto- and cross-spectra)
    - Dust spectral index and most efficient mass: compatible with “standard” values
    - Clear evolution of the dust temperature with redshift
    - Unprecedent constraints on the SFR density and bias evolution
  - Linear Model
    - Take advantage of the unique measurements of HFI at large scales
    - Framework more limited (imposed SED, priors on local values and CIB)
    - Nice cross-checks on the SFRD and bias evolution
  - Limited by our knowledge of SEDs of galaxies at high redshift

- Stay tuned: on astroph in ~1 month

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

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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.