Planck Early Results:
The Power Spectrum of the Cosmic Infrared Background

(Probing high-z galaxy clustering and star formation with Planck)

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on behalf of
the Planck
Collaboration

arXiv:1101.2028

Outline

1) Planck mission: quick introduction and update

2) The Cosmic Infrared Background

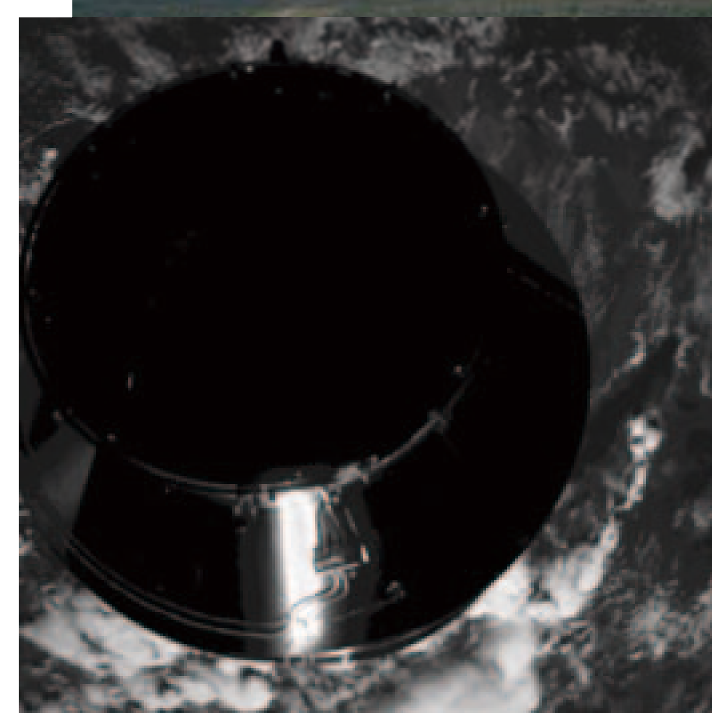
3) Planck measurements of the *Cosmic Infrared Background Power Spectrum* (arXiv:1101.2028)

4) Present and future synergies between CMB and large Infrared Surveys

The scientific results that we present today are a product of the Planck Collaboration, including individuals from more than 50 scientific institutes in Europe, the USA and Canada

Planck is a project of the European Space Agency -- ESA -- 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.

Launched on May 14th 2009...

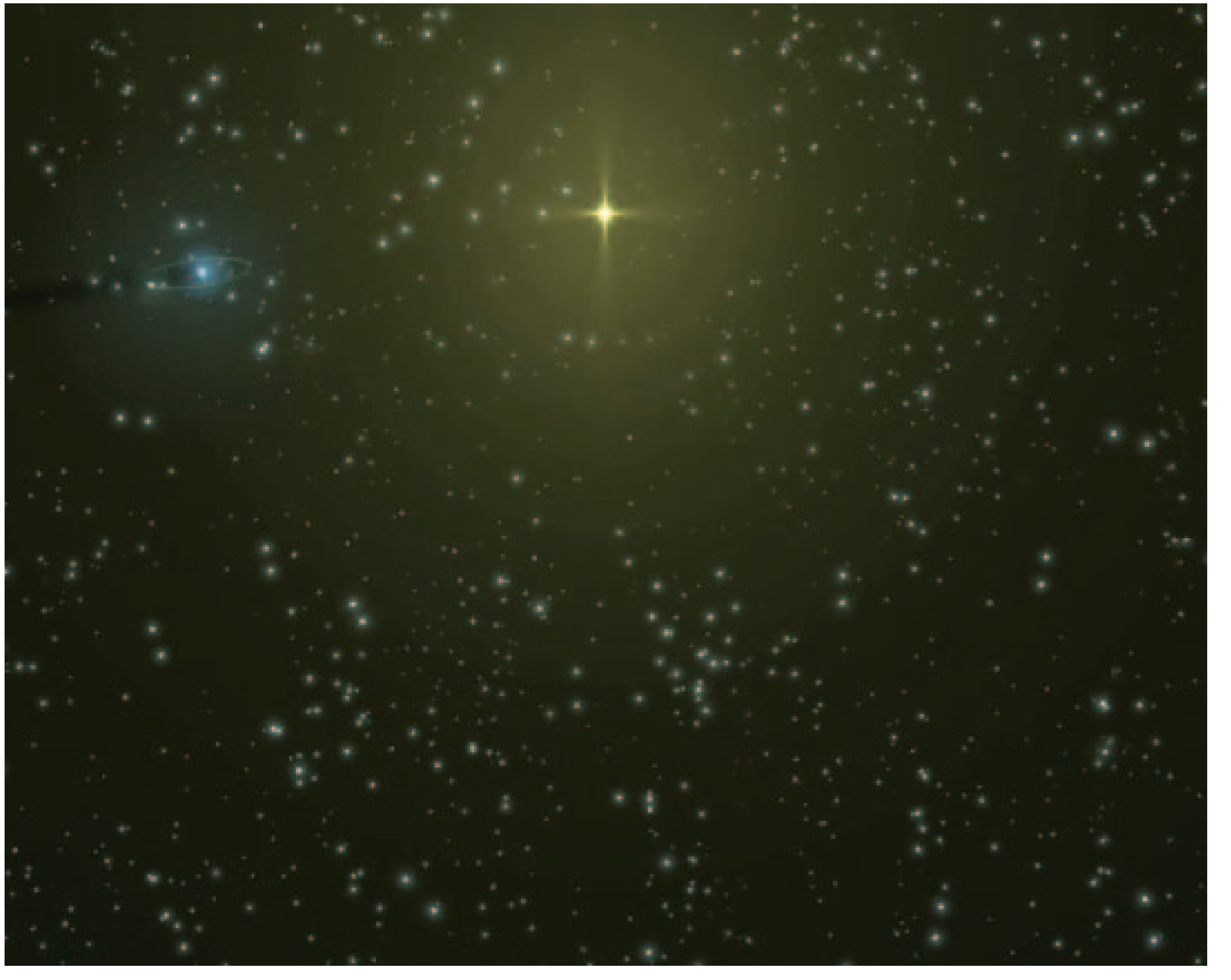


View from Herschel

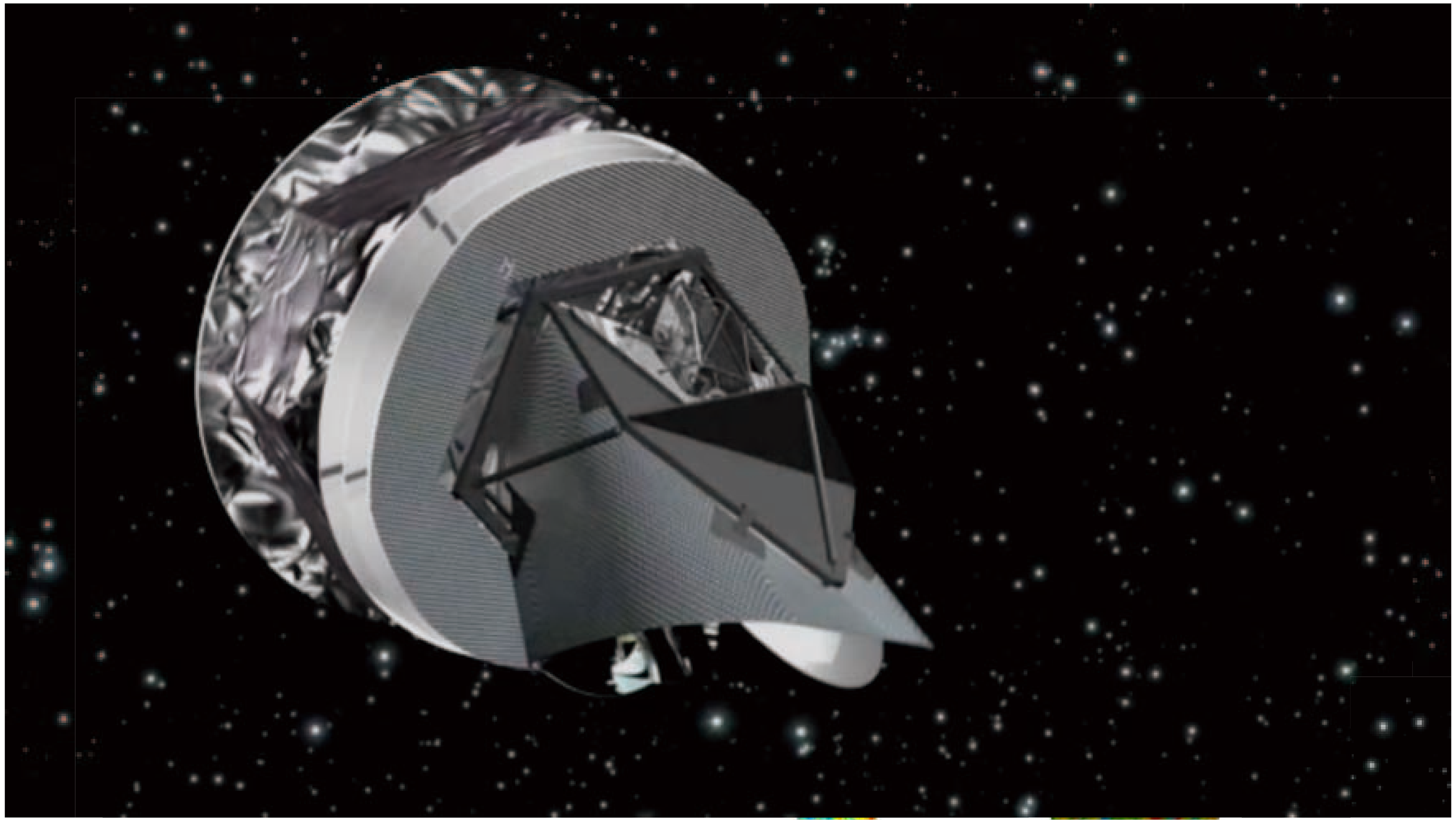
- Launched by ESA from Kourou in French Guiana
- Herschel and Planck were launched together using a Ariane V rocket (total payload about 5700 kg)
- Separation between Planck and Herschel occurred about 26 minutes after launch

... and entered L2 orbit on July 3d 2009

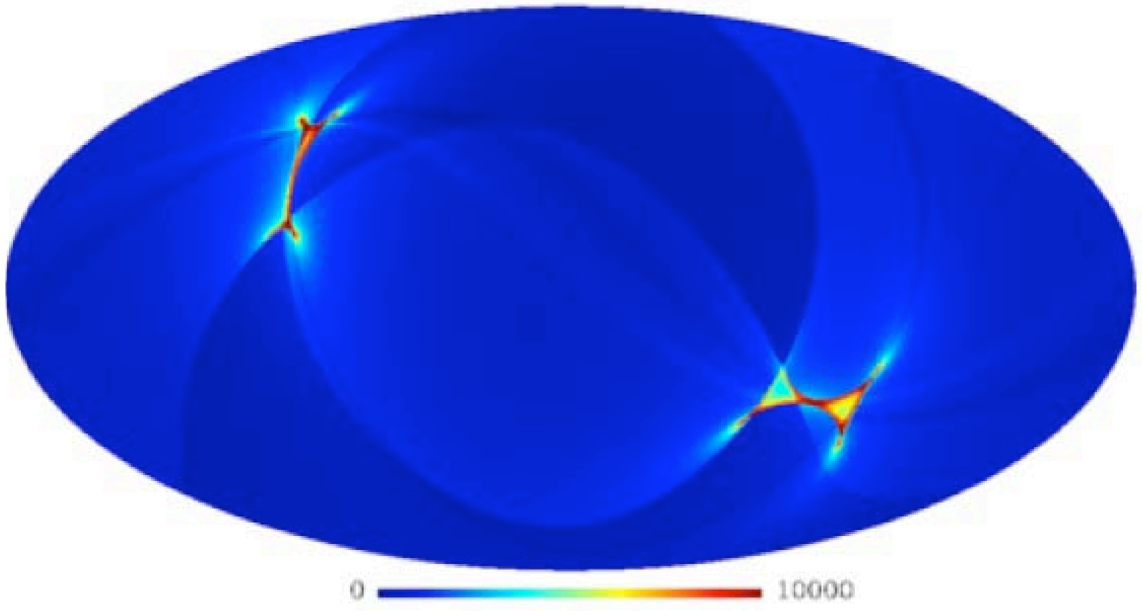
- Both Herschel and Planck traveled to L2 separately and were injected into different orbits around L2
- L2 is about 1.5 millions km from earth
- L2 offers great thermal stability and constant survey mode
- Joined WMAP in orbit around L2



Scanning strategy



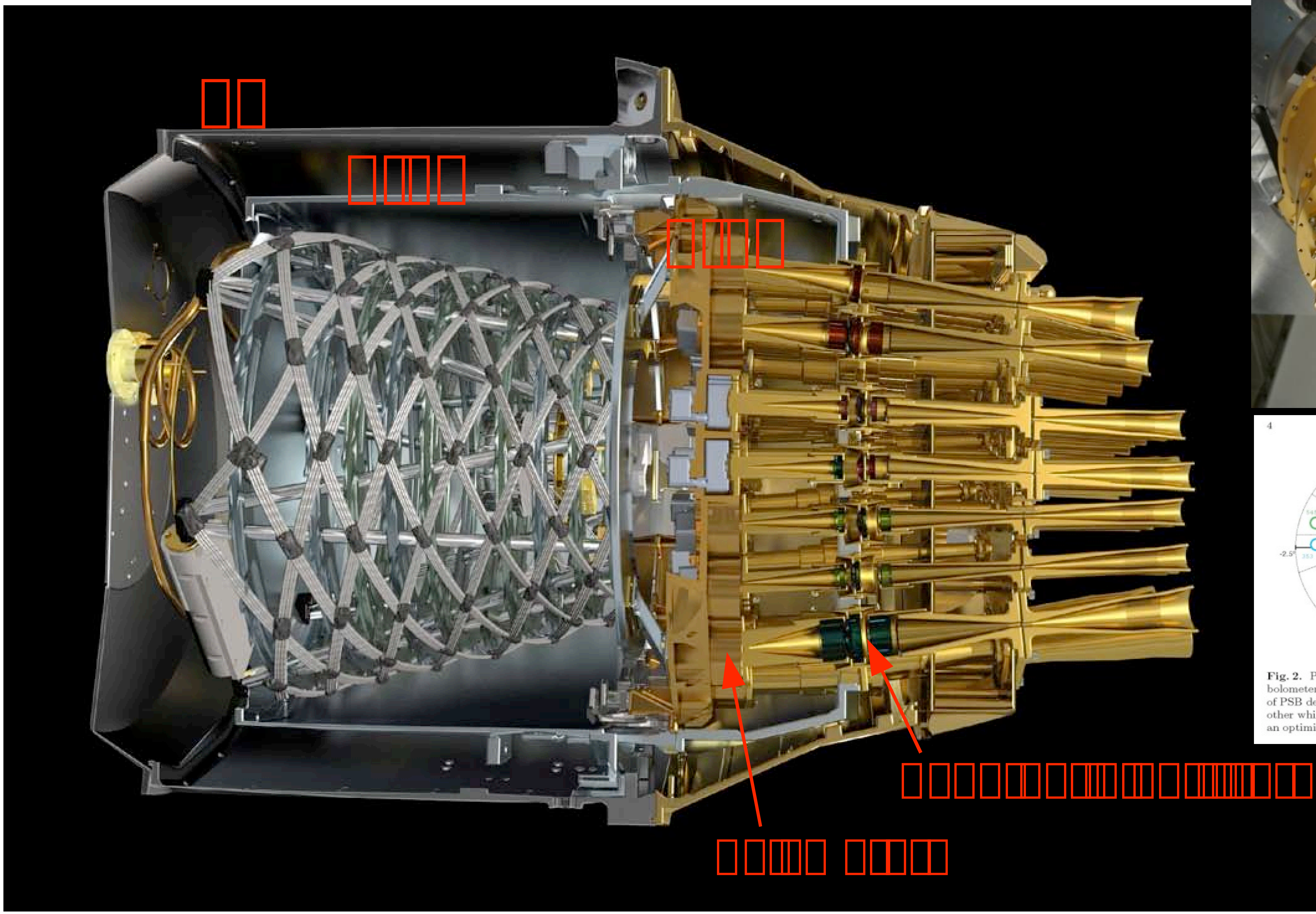
Hit counts for early papers

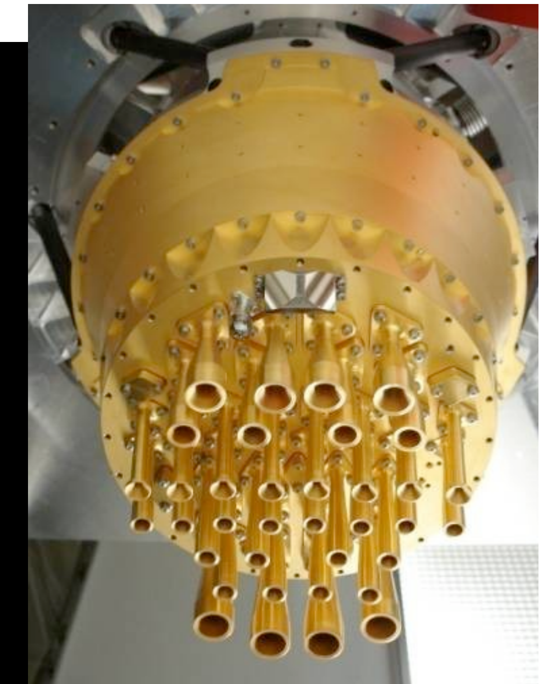


- Spin at 1 rpm
- Repoints spin axis by 2' every 40 minutes
- Additional slow modulation of spin axis for full sky coverage at every frequency
- Full sky observed every 6 months (half an orbit around the sun)
- 5 full sky surveys will be ultimately available

Planck: the 3rd generation space CMB experiment

- Planck Primary goal is to measure the temperature anisotropies of the CMB to fundamental limits down to 5 arcminutes *and* to measure the Polarization of the CMB
- Planck will be nearly photon noise limited in the CMB channels (100-200 GHz)
- This translates into a factor 2.5 in angular resolution and 10 in instantaneous map sensitivity with respect to WMAP
- HFI detectors are cooled to 100 mK, 6 bands 100 to 857 GHz, read in total power mode with a white noise from 10 mHz to 100 Hz (no 1/f noise from readout electronics in the signal range)
- The temperature stability of the 100 mK stage must be better that 20 nK$\sqrt{}$Hz in the same band not to affect the sensitivity





4 C. Rosset et al.: Beam mismatch

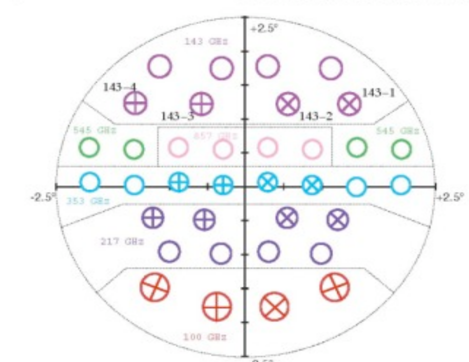
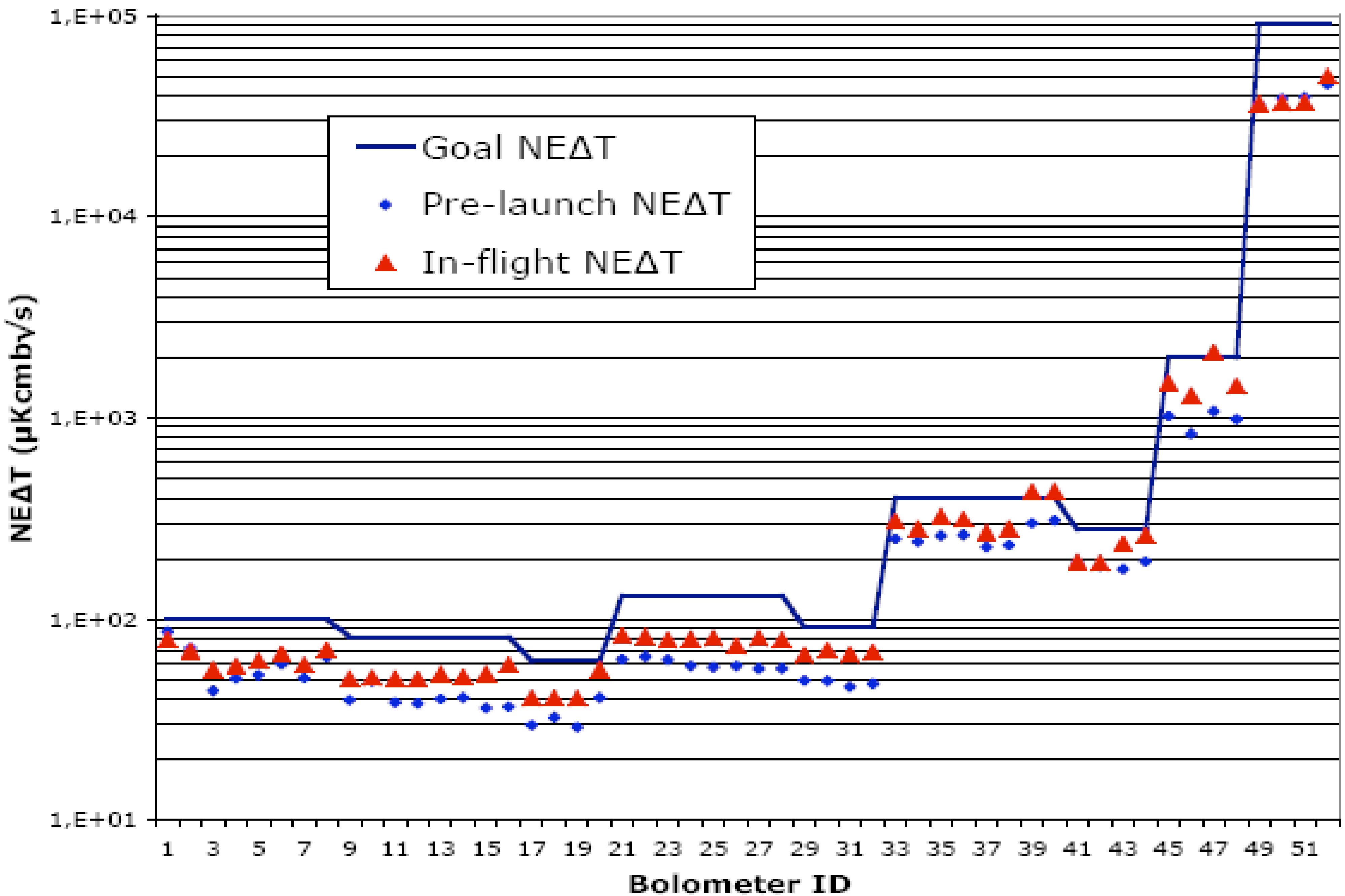


Fig. 2. Planck focal plane with polarization sensitive bolometers as seen from the sky. Complementary pairs of PSB detectors are arranged in two horns following each other while scanning the sky so that four detectors are in an optimized configuration for polarization measurement.

- Coolest point in outer space...

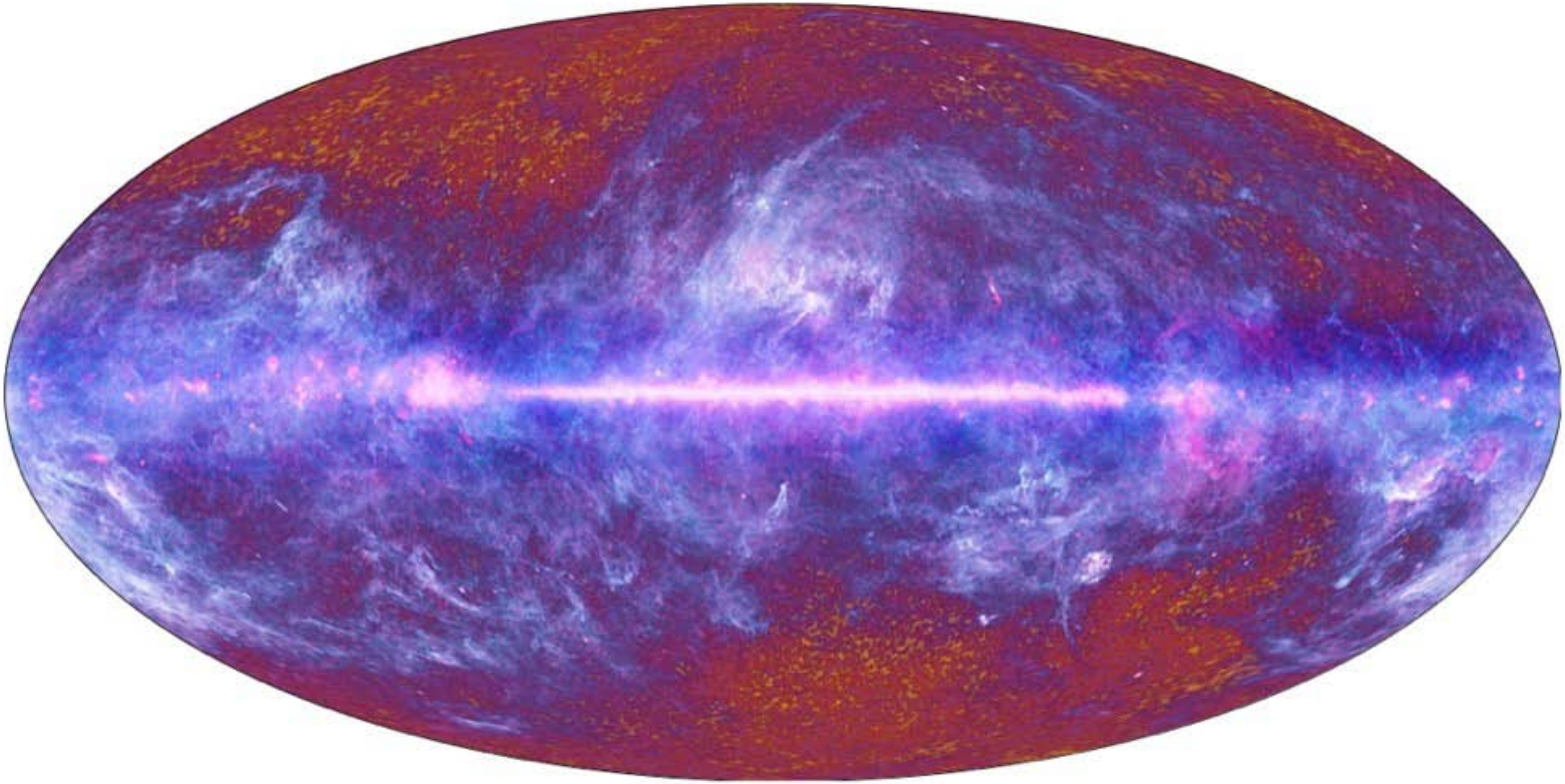
Overall sensitivity vs expectations



- White noise level in the 0.6-2.5 Hz range

Planck Early Results: First Assessment of the High Frequency Instrument In-flight Performance, arXiv:1101.2039

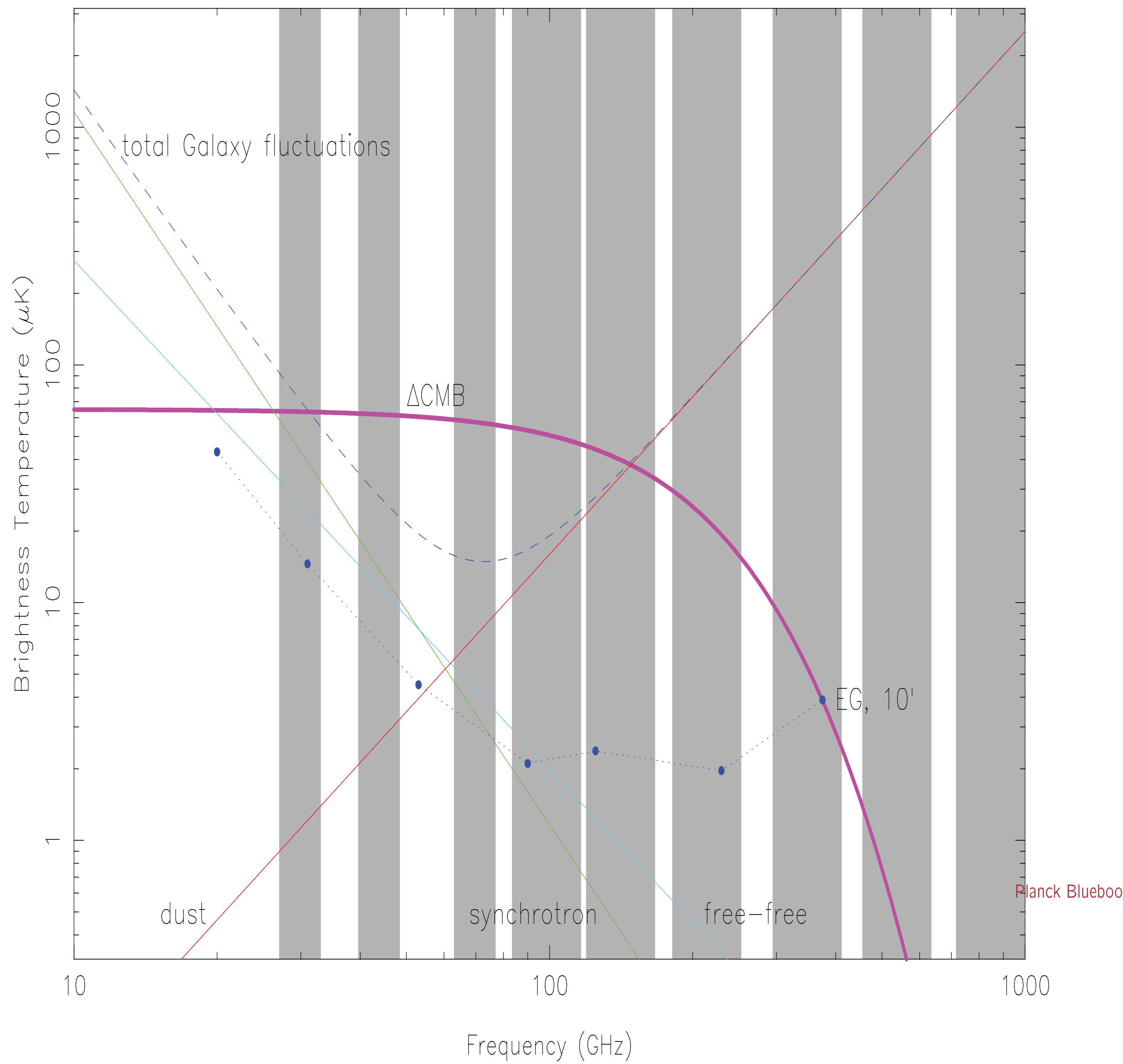
Planck's view of the universe



- First full sky survey image released in July 2010
- RGB color encoding using 143, 30 and 353 GHz

Planck Frequency Coverage

- Temperature and polarization power spectrum sensitivity should be limited by the ability to remove foregrounds (thus a very broad frequency coverage: 30 GHz-1 THz)
- Temperature measurements at nine frequencies: 30, 44, 70, 100, 143, 217, 353, 545, 857 GHz
- Polarization measurements at seven frequencies: 30, 44, 70, 100, 143, 217, 353 GHz
- Of necessity, we measure the foregrounds very well: lots of astrophysics!



Planck's Early Results

- The Planck collaboration is releasing
  - The Early Release Compact Source Catalogues (ERCSC): the first data product from Planck
  - Based on 1.6 sky surveys (10 months of observations) and 3 months of validation
- 7 papers describing the performance of the Planck mission and instruments in space, and the data processing that went into the ERCSC and the science results
- 18 papers reporting on early Galactic and extragalactic science results from Planck
  - 5 on Sunyaev-Zeldovich clusters
  - 3 on extragalactics radio sources
  - 1 on Cosmic Infrared Background
  - 2 on dusty galaxies, including the Magellanic Clouds
  - 5 on dust in the Milky Way, including spinning dust
  - 2 on cold cores or clumps
- First CMB results will come in January 2013

Outline

1) Planck mission: quick introduction and update

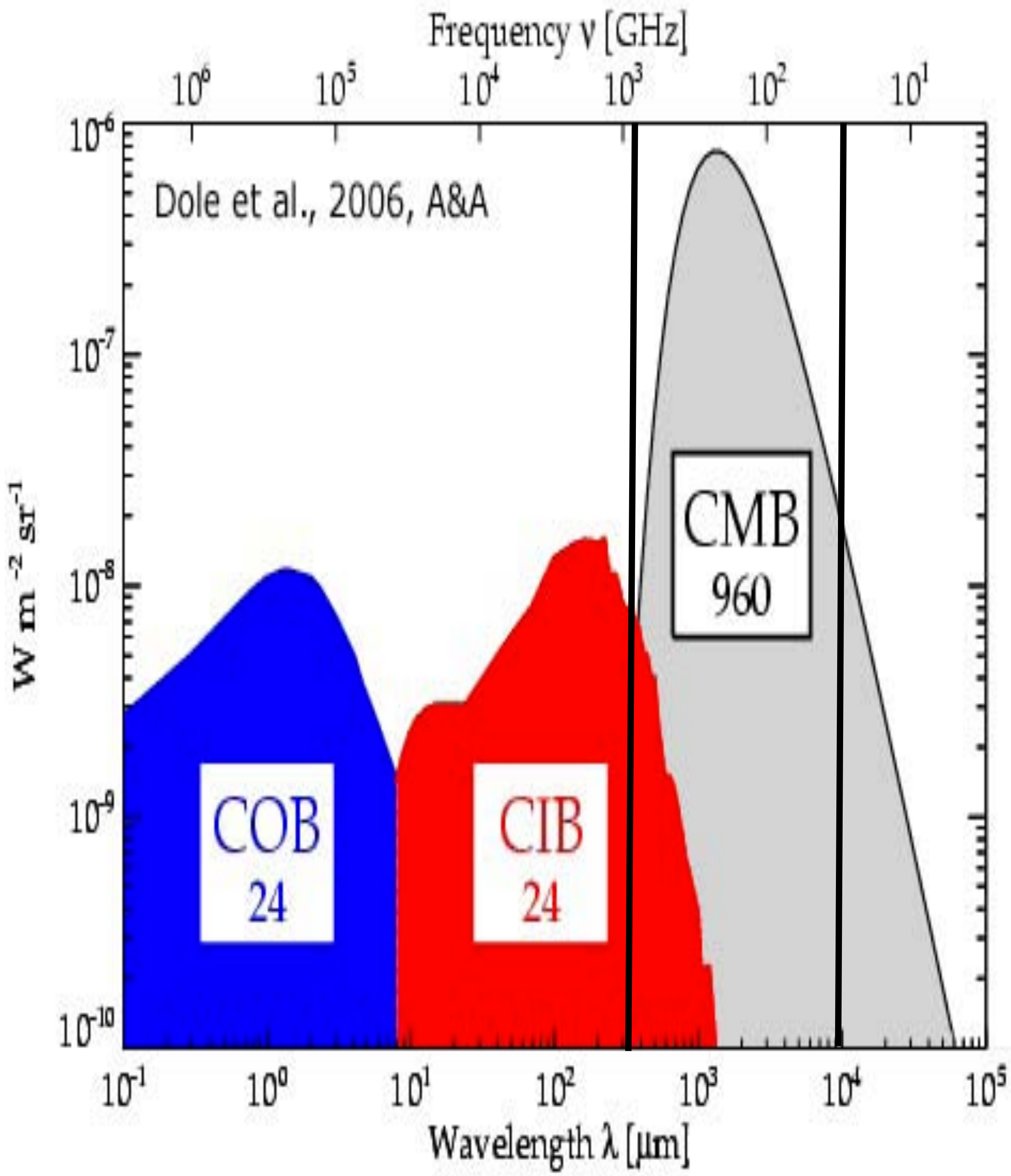
2) Planck measurements of the *Cosmic Infrared Background Power Spectrum* (arXiv:1101.2028)

- CIB introduction
- Planck analysis

3) Present and future synergies between CMB and large Infrared Surveys

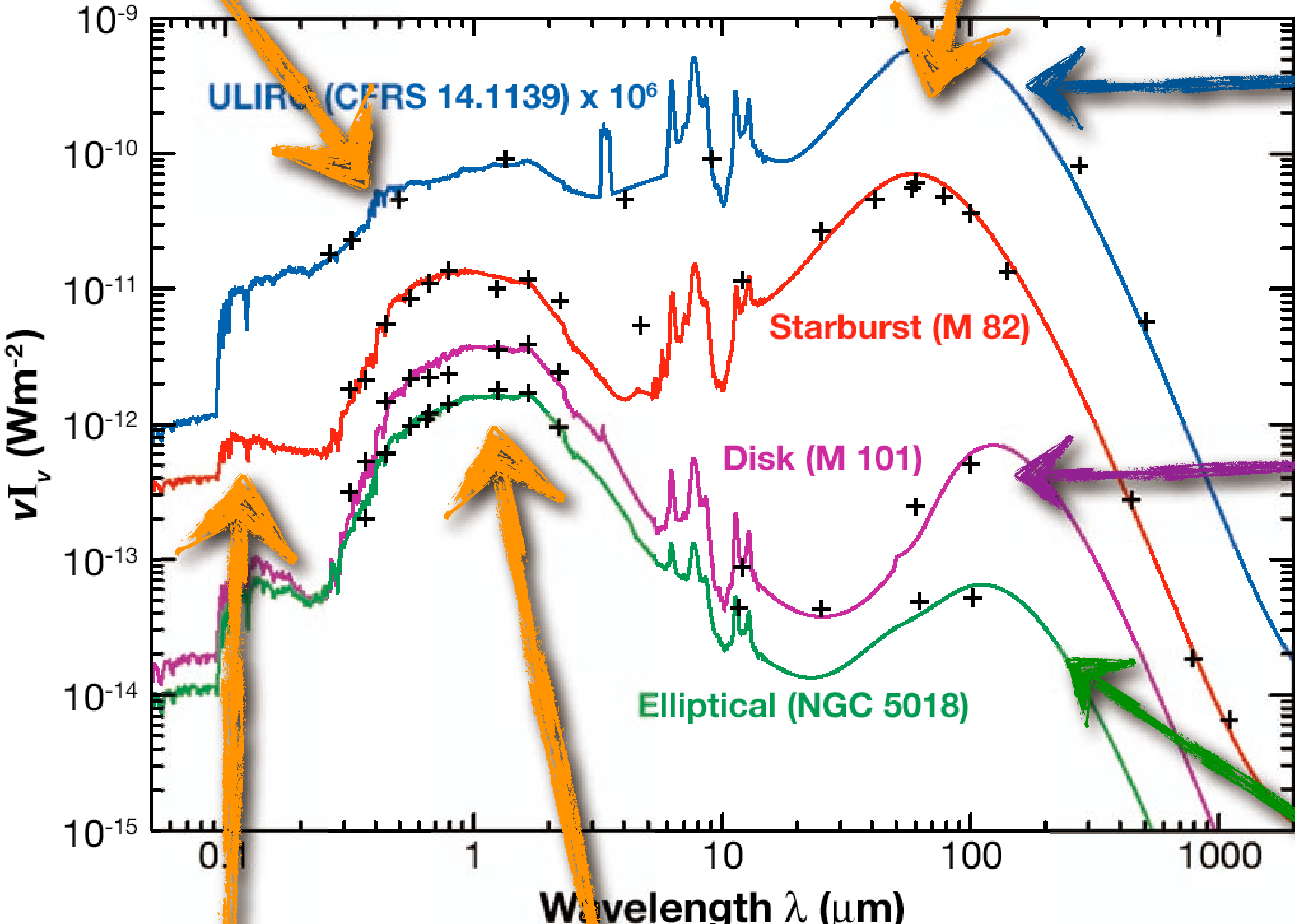
Mean sky brightness in IR important

- The extragalactic background brightness is dominated by the CMB...
- ... but the CIB and the COB have equal contribution
- Different than local measurements where it is ~1/3
    - IR gals contributions increases with z faster than optical ones
    - Slopes of the CIB part suggests that different galaxies contribute at different redshifts
- Over half of the energy produced since the surface of last scattering has been absorbed and re-emitted by dust.



Dust re-emits in the FIR

Starlight absorbed by dust



UV from young, hot stars

Lagache+ 2005

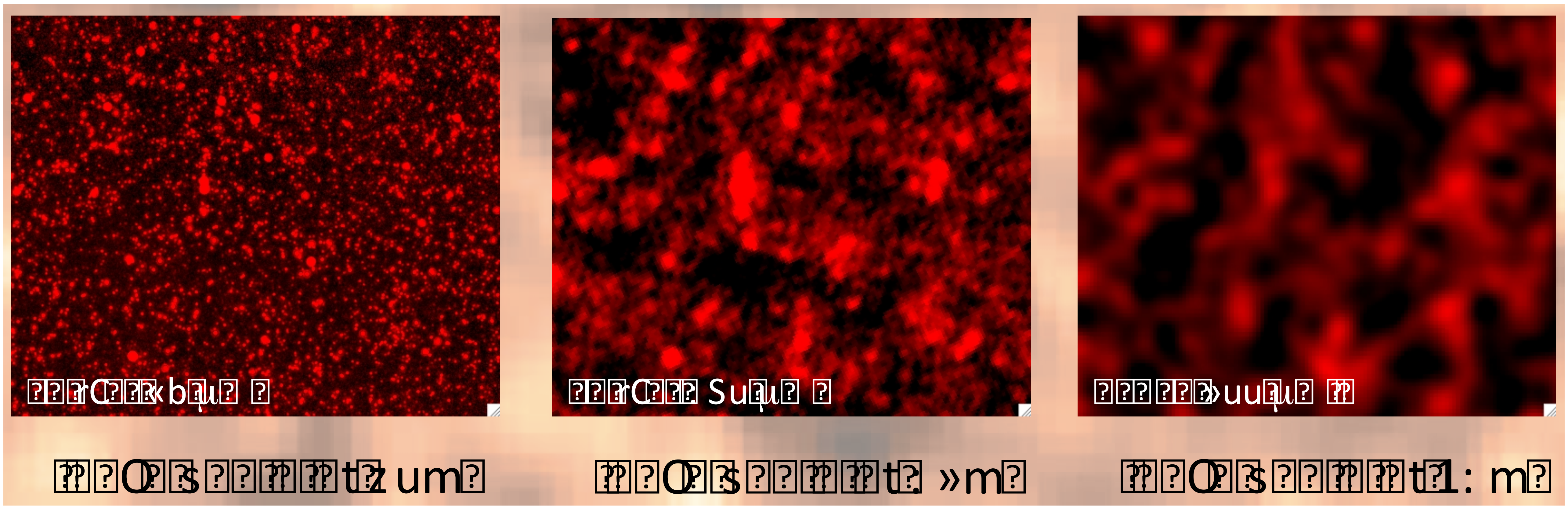
Stellar bump from old stars

Lagache et al. 2004
Gispert et al. 2001

Slides from J.Viera

Fluctuations: working in the confusion limit

- CIB is basically the extra-galactic confusion noise: it represents the cumulative emission of high-z, dusty, star forming galaxies

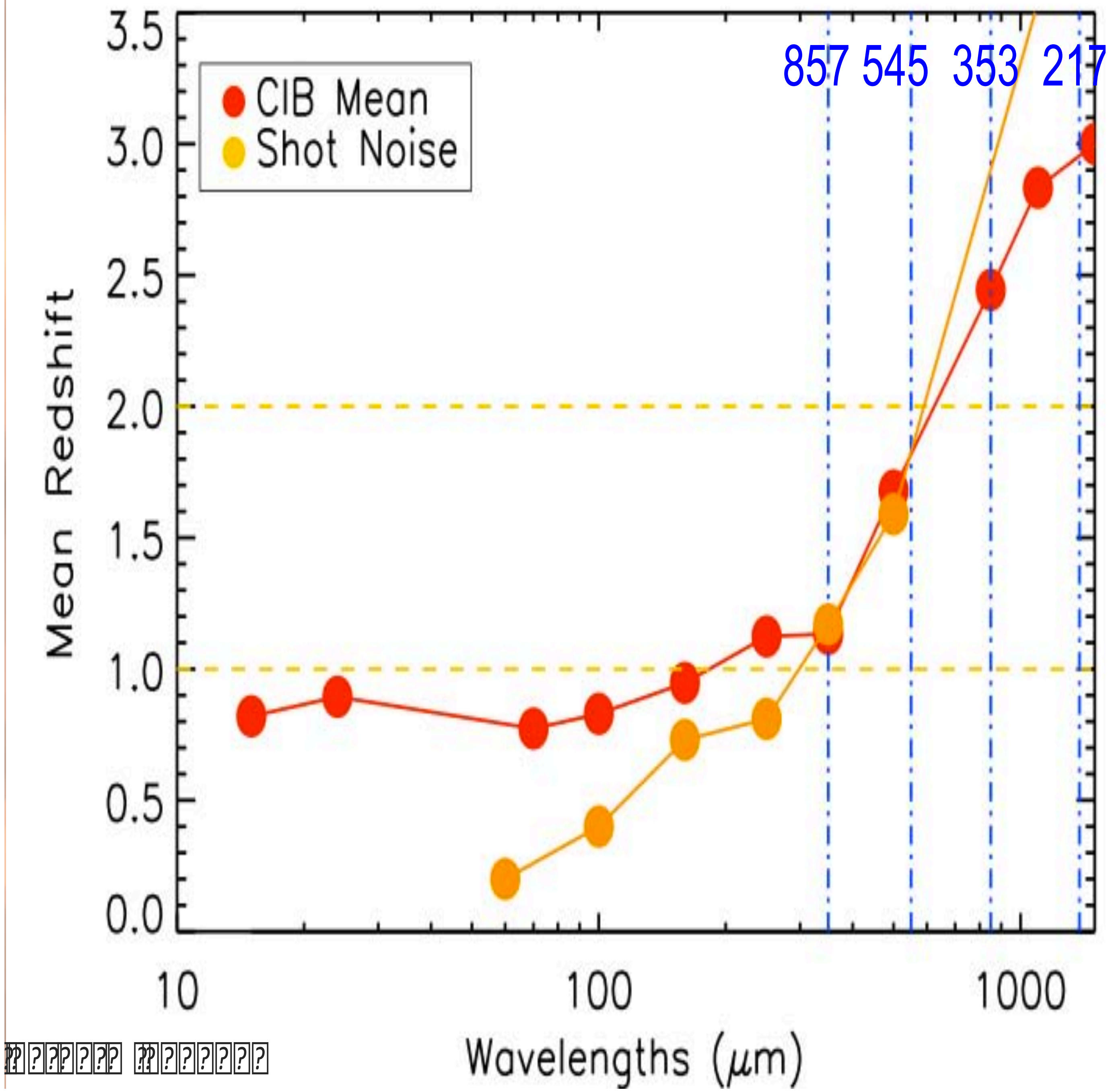


G. Lagache

- Clustering in CIB detected by Spitzer (fwhm~10”), Blast, ACT/SPT (~2’) and Herschel (~7” at 100mu).
- Planck adds large scales (linear regime) and high frequencies (higher redshifts)
- We will learn about SFR and more generally the interplay between baryons and dark matter at at high-z

Redshift dependance

- Longer wavelengths probes higher redshift



Mean: $$I_{CFIRB} = \int_0^{S_{max}} \frac{dN}{dS} S dS$$

Shot noise: $$C_\ell^{\text{shot}} = \int_0^{S_{\text{cut}}} S^2 \frac{dN}{dS}\, dS$$

Béthermin et al. 2011

CIB in a nutshell

- CIB is produced by star-heated dust in galaxies, thus is sensitive to the SFR at high redshift
- These IR galaxies are difficult to observe so that the CIB is a very unique window to study them
- The fluctuations in this background trace the large-scale distribution of matter, and so, to some extend the clustering of matter at high-z
- Planck adds high z and large scales
- Interest highlighted early on by Partridge & Peebles 1967 and discovered by Puget et al. 1996 (FIRAS) and Hauser et al. 1998 (DIRBE)

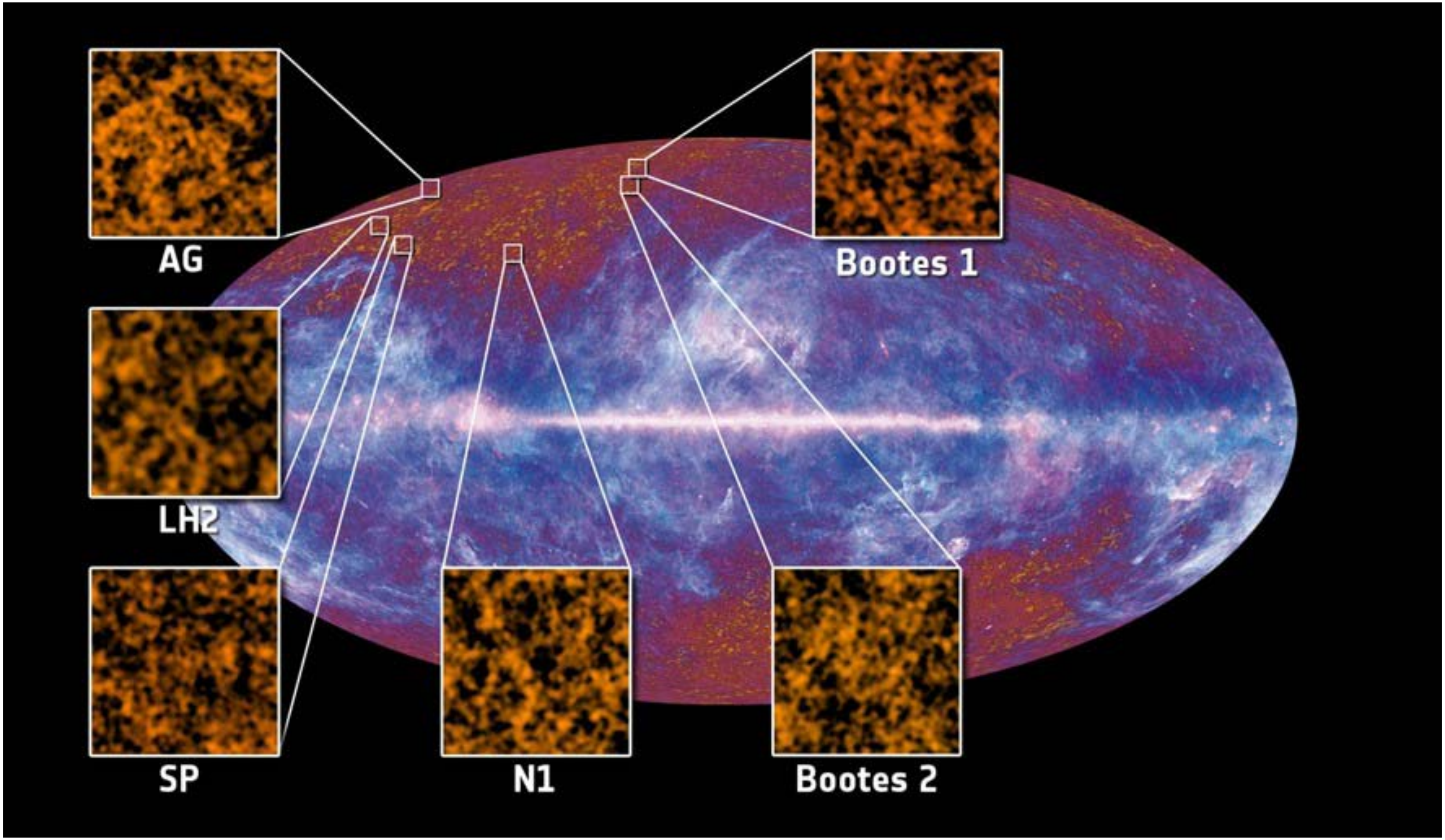
ARE YOUNG GALAXIES VISIBLE? II. THE INTEGRATED BACKGROUND

R. B. PARTRIDGE AND P. J. E. PEEBLES
Palmer Physical Laboratory, Princeton University
Received September 26, 1966

ABSTRACT

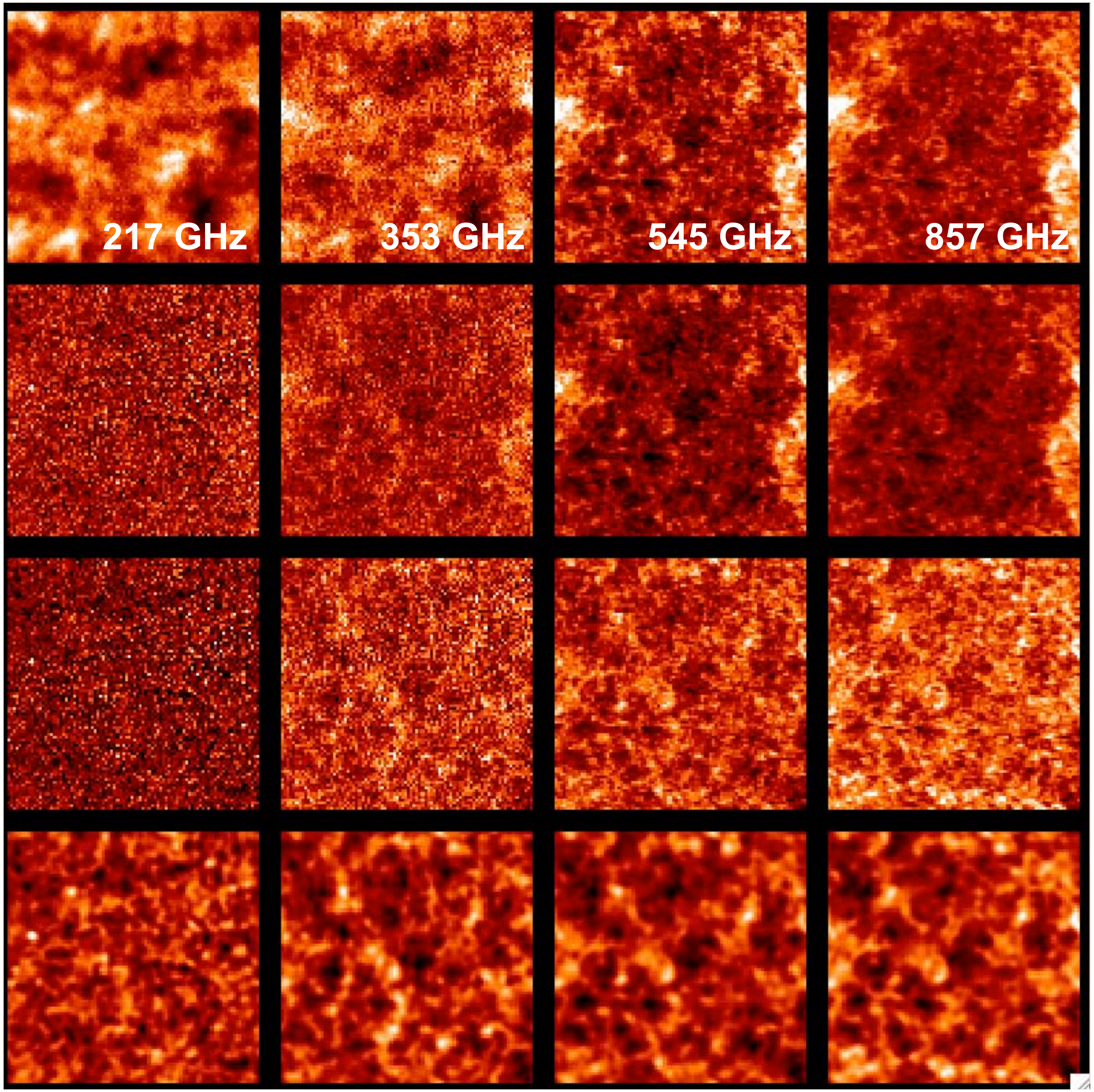
In a previous publication we presented a model for the formation of galaxies and for the properties of the young galaxies. In this article the time variation of the luminosity and spectrum of the model galaxy is used to compute the integrated background radiation due to the highly redshifted starlight from all the galaxies. This background is compared with the contribution from other sources, local and extragalactic. It is concluded that in the wavelength range from 5 to 15 μ it may be possible to pick out the integrated light of the distant galaxies. The intensity is within reach of present detection techniques.

Planck CIB Analysis



- 6 fields totaling 140 sq. deg.
- CIB maps = Raw map - CMB - Pt sources - Cirrus (HI maps from Martin et al. 2011)
- Lots of details on systematics and measurement in the paper

CIB maps



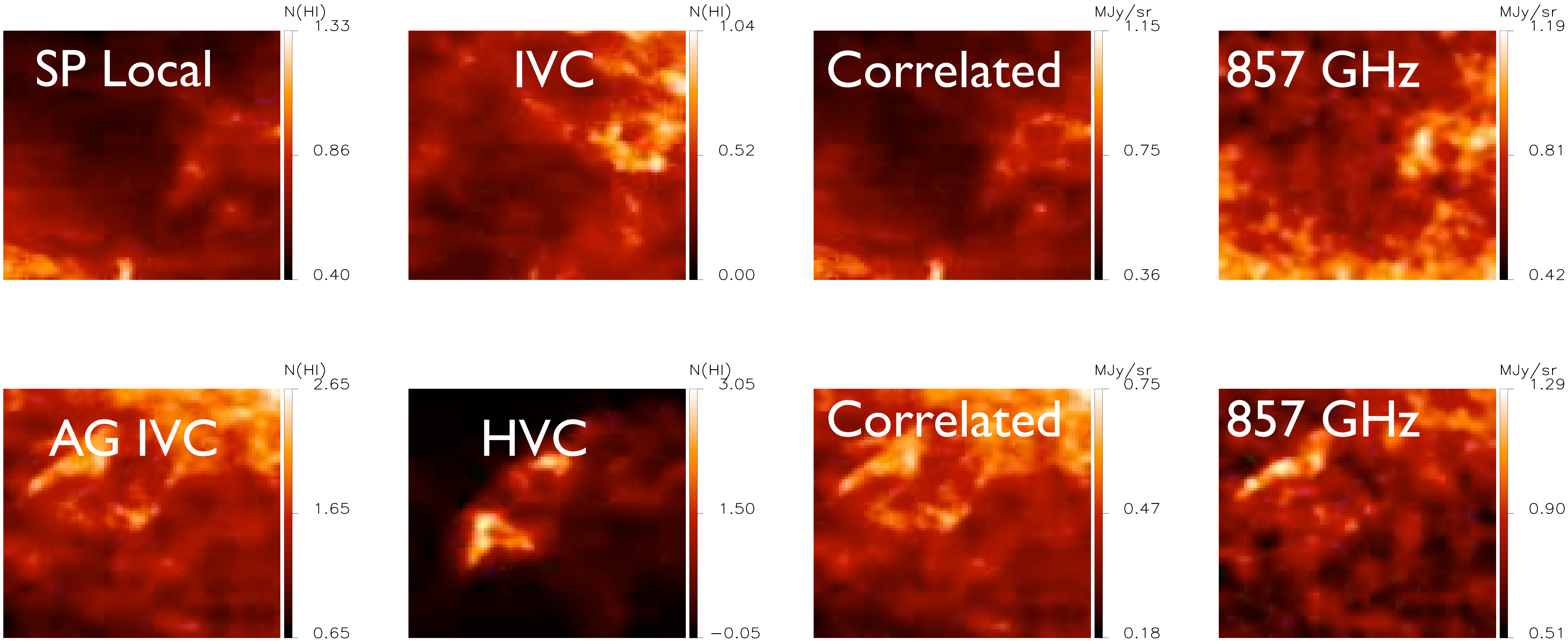
Raw

- CMB (143GHz)
- Pt sources

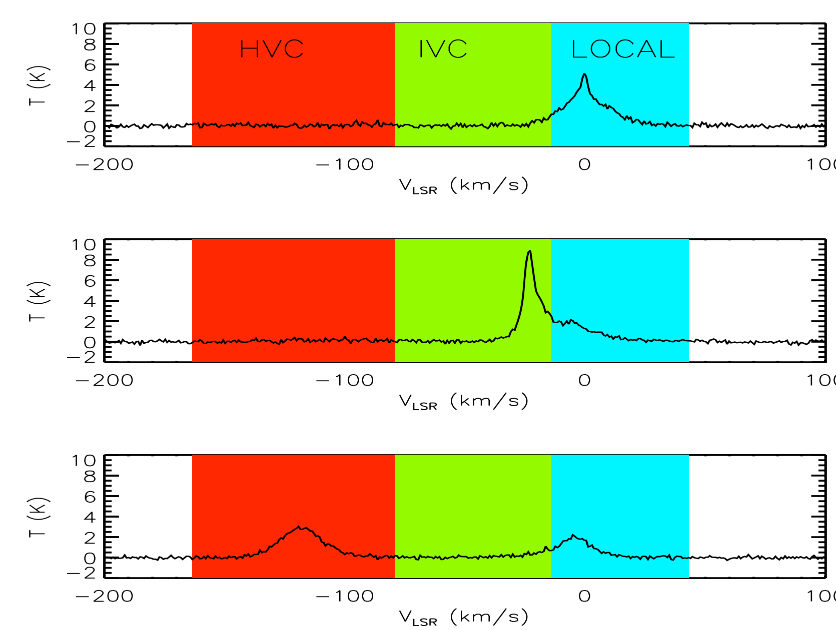
- Galactic dust

Smoothed at 10’

Dust cleaning with local 21cm maps

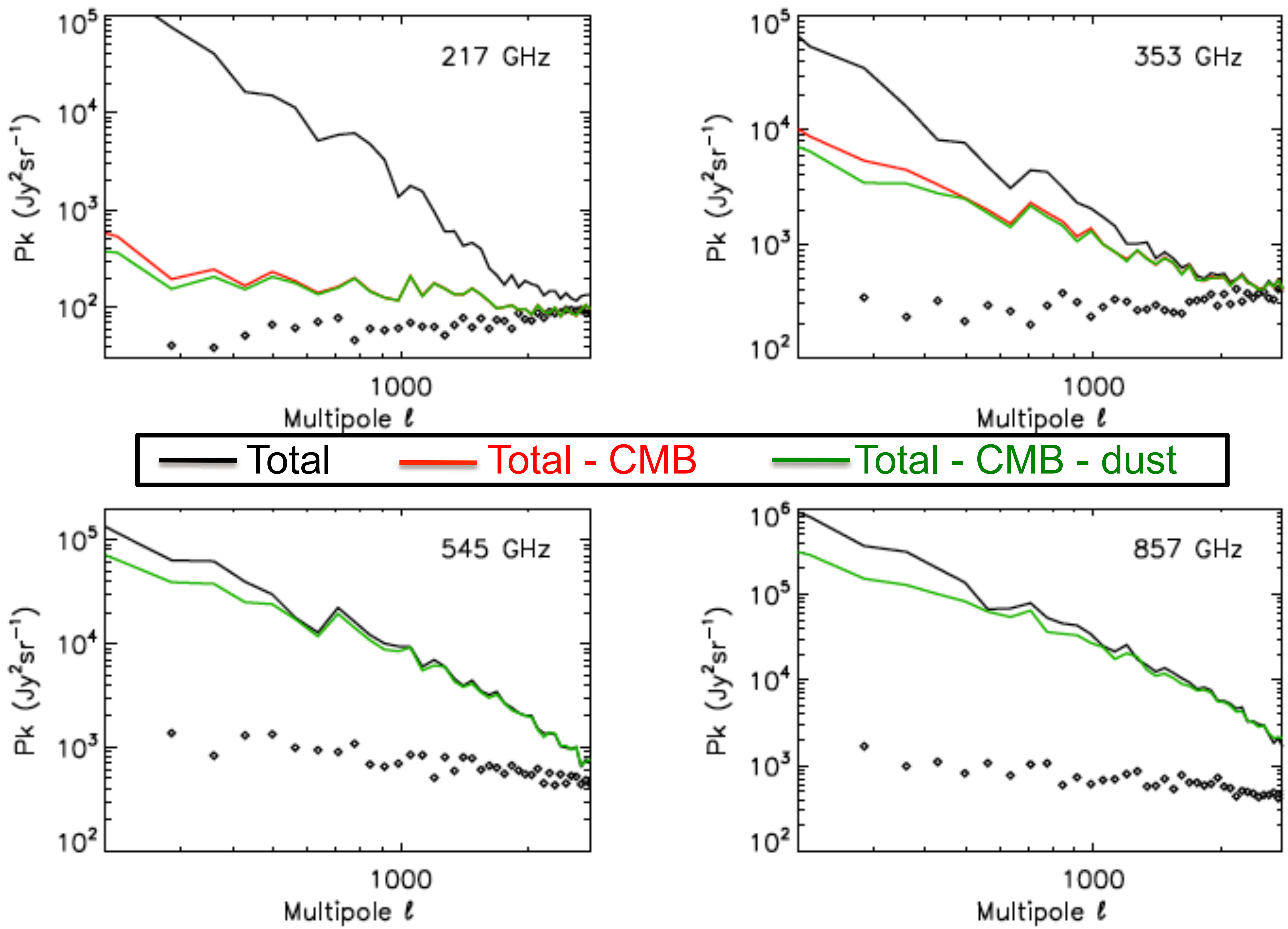


- HI best tracer of galactic dust in diffuse sky
- Important to decompose the HI observations in three different components corresponding to three different gas velocities
- Data from GBT (Martin et al. 2010)
- Relation between HI and dust is mostly empirical

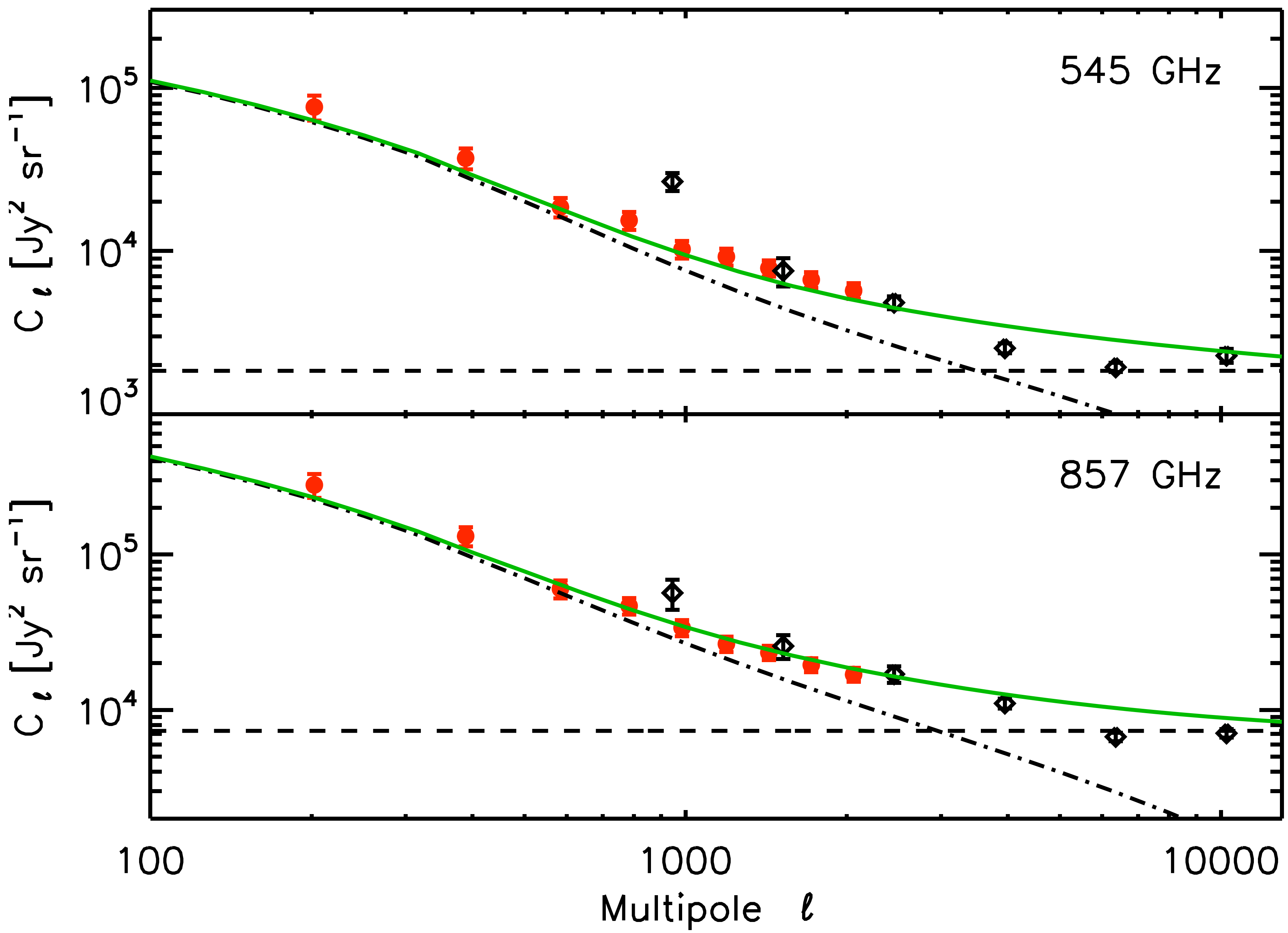


Pénin et al. 2011

Residual Power Spectra



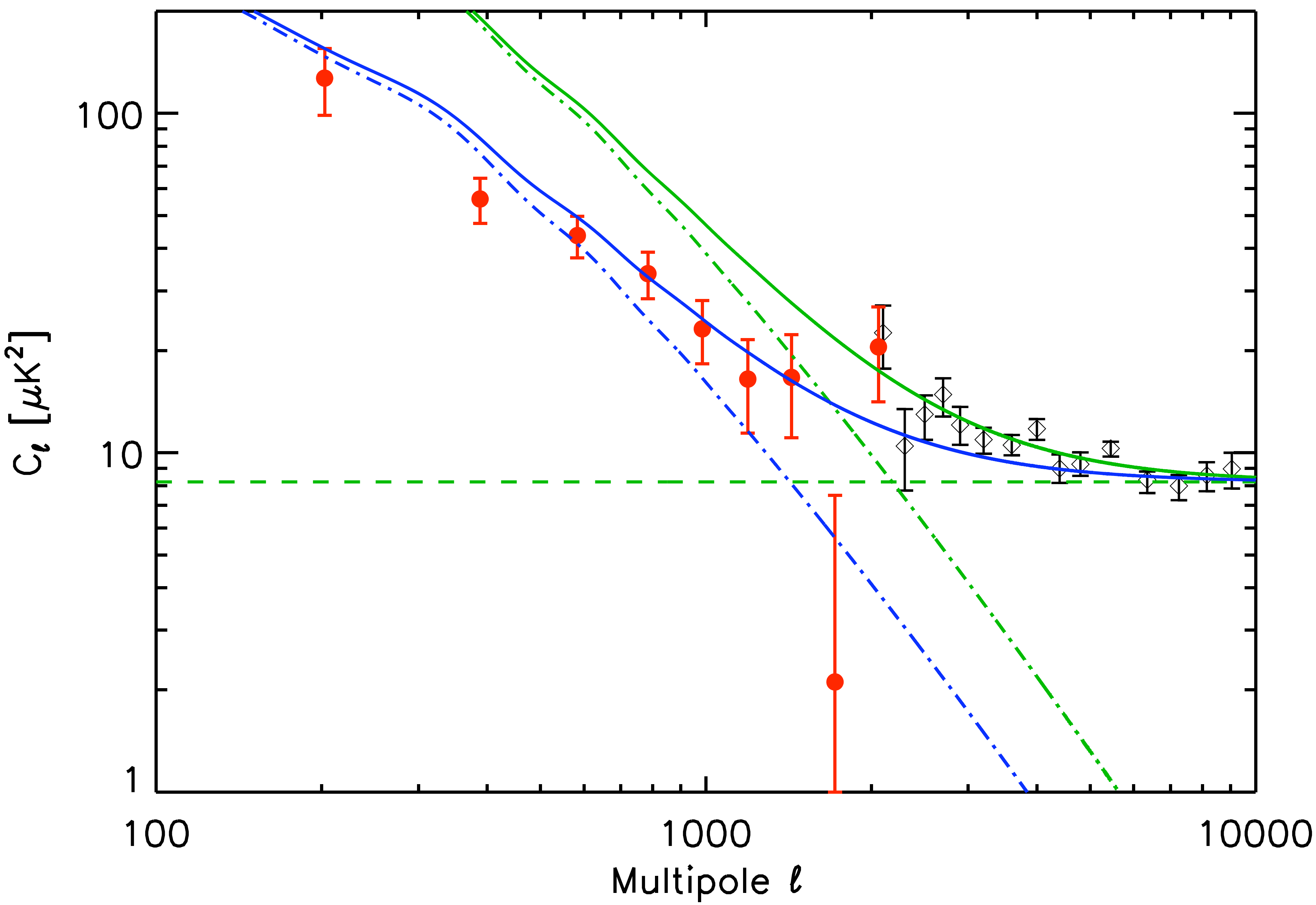
Comparison with Blast



- Almost the same flux cut, thus same shot noise

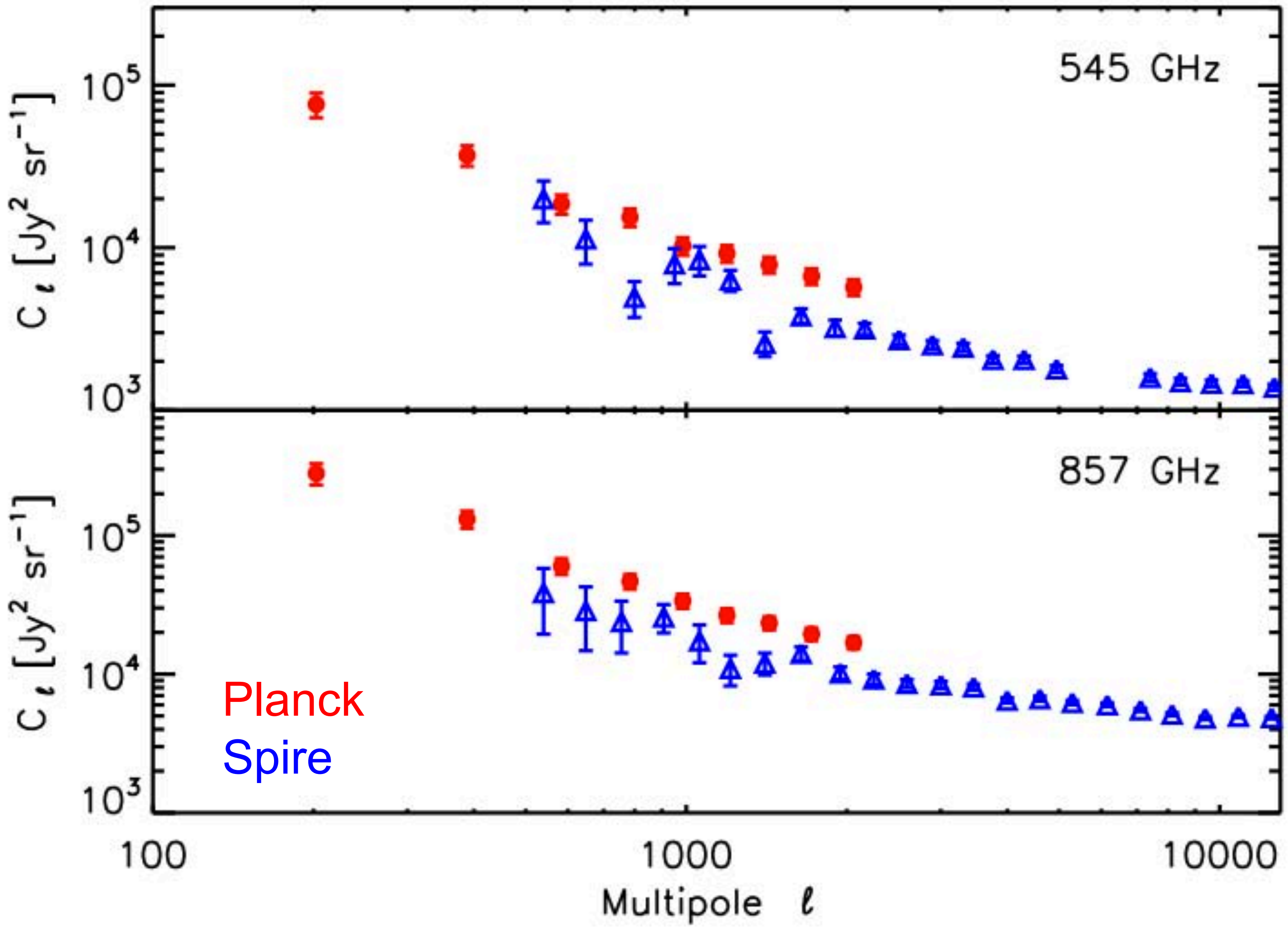
Viero et al. 2009

Comparison with SPT



Hall et al. 2010

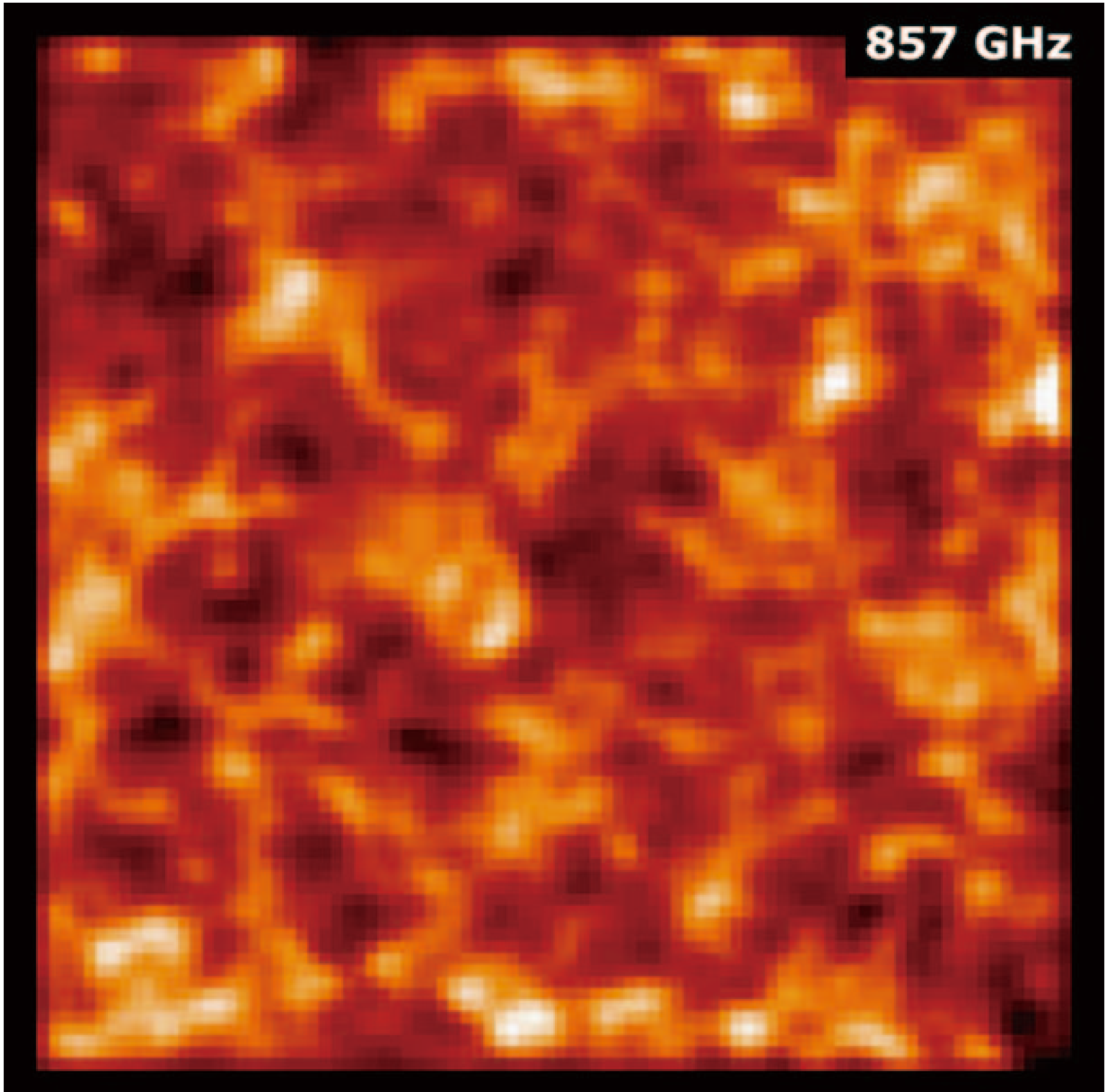
Comparison with Herschel Spire



- Comparison is subtle because of different flux cut level and color corrections
- Detailed study suggests issue with cirrus subtraction and beam solid angle (calibration)
- Joint analysis will be very potent when feasible, including cross power spectra

Amblard et al. 2011, arXiv:1101.1080

Planck maps at 217, 353, 545 and 857 GHz



- High SNR sub-degree structures at all frequencies
- Assuming sources at z~2, we are measuring clustering at 30 Mpc/h (k~0.03 h/Mpc) or less scales
- Structures partially correlated across frequencies
- Obviously cosmologically very interesting! What can we learn from these maps?

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: $P_{gg}(k,z)$

We consider either:

- 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

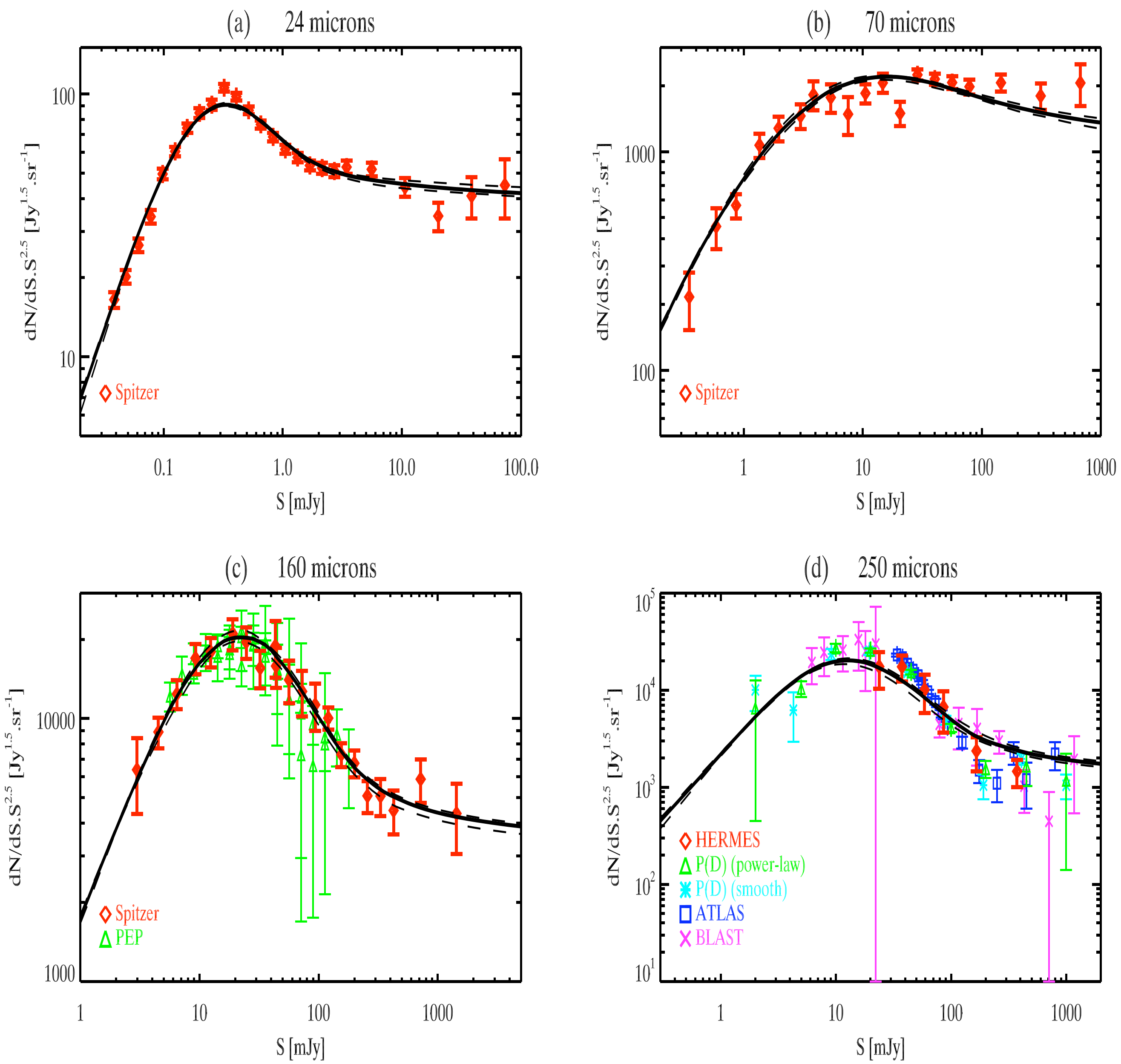
(3) Luminosity function and its redshift evolution for the relevant galaxies: $j(z)$

- We use the parametric (backward) model of Béthermin et al. 10
- Novelty of our approach: we can handle self-consistently and in a statistically sound manner all relevant observations (number counts, LF measurements, CIB mean, and redshift evolution)

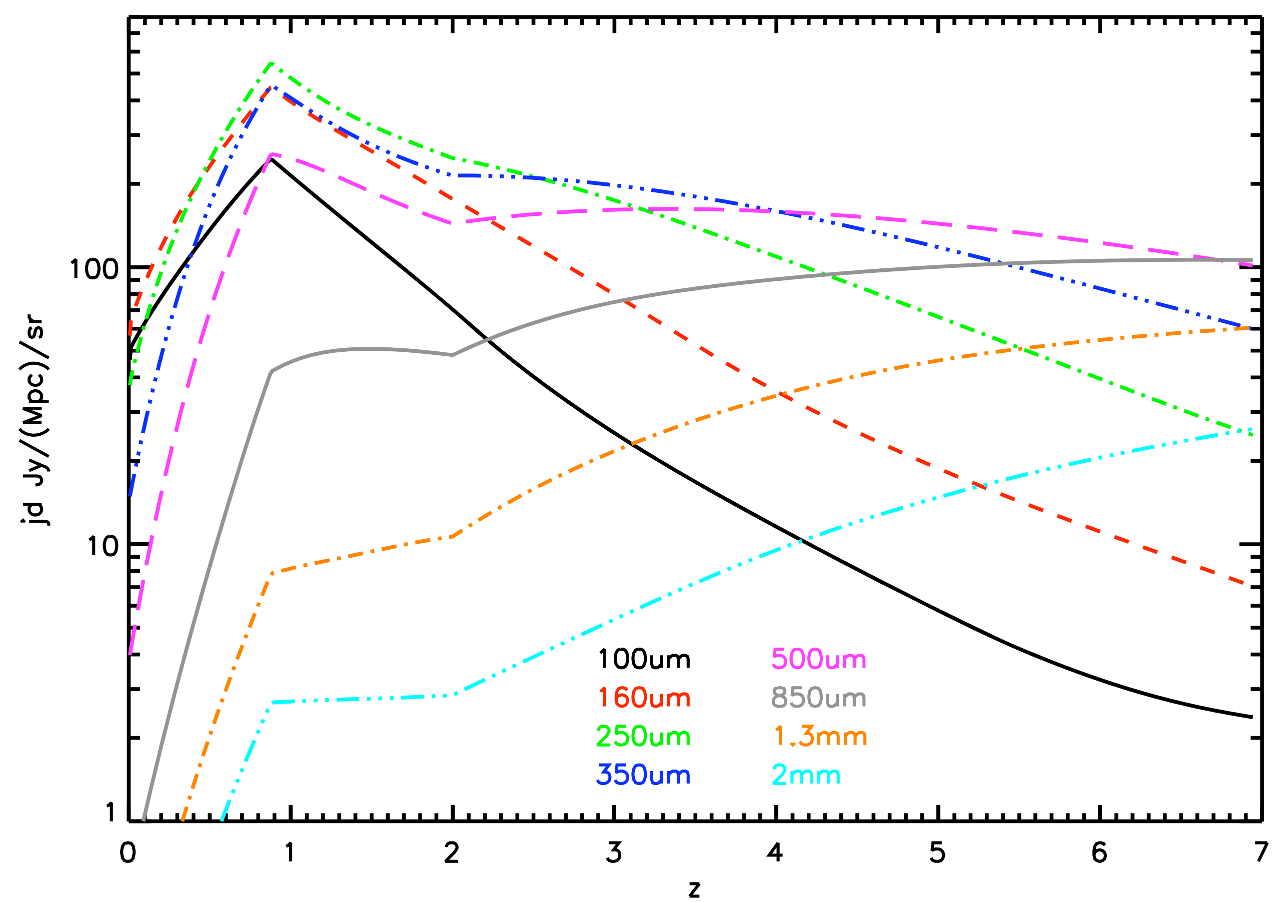
$$\bar{j}_\nu(z) = (1+z)\int_0^{S_{\rm cut}} dS\; S\; \frac{d^2N}{dS\,dz}$$

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

Differential counts and emissivities



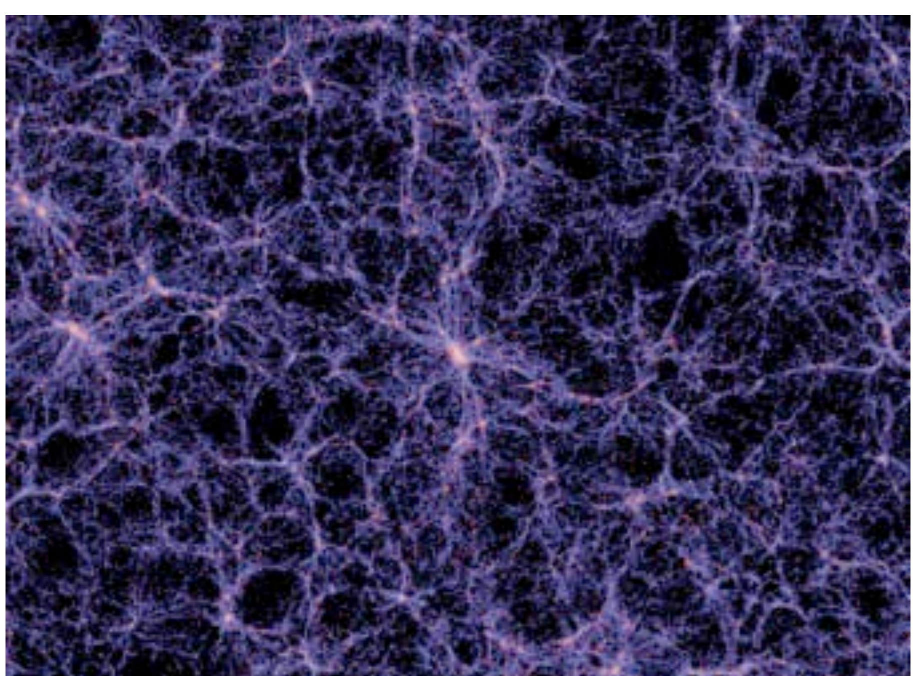
$$\bar{j}_\nu(z) = (1+z) \int_0^{S_{cut}} dS\ S\ \frac{d^2N}{dS\, dz}$$

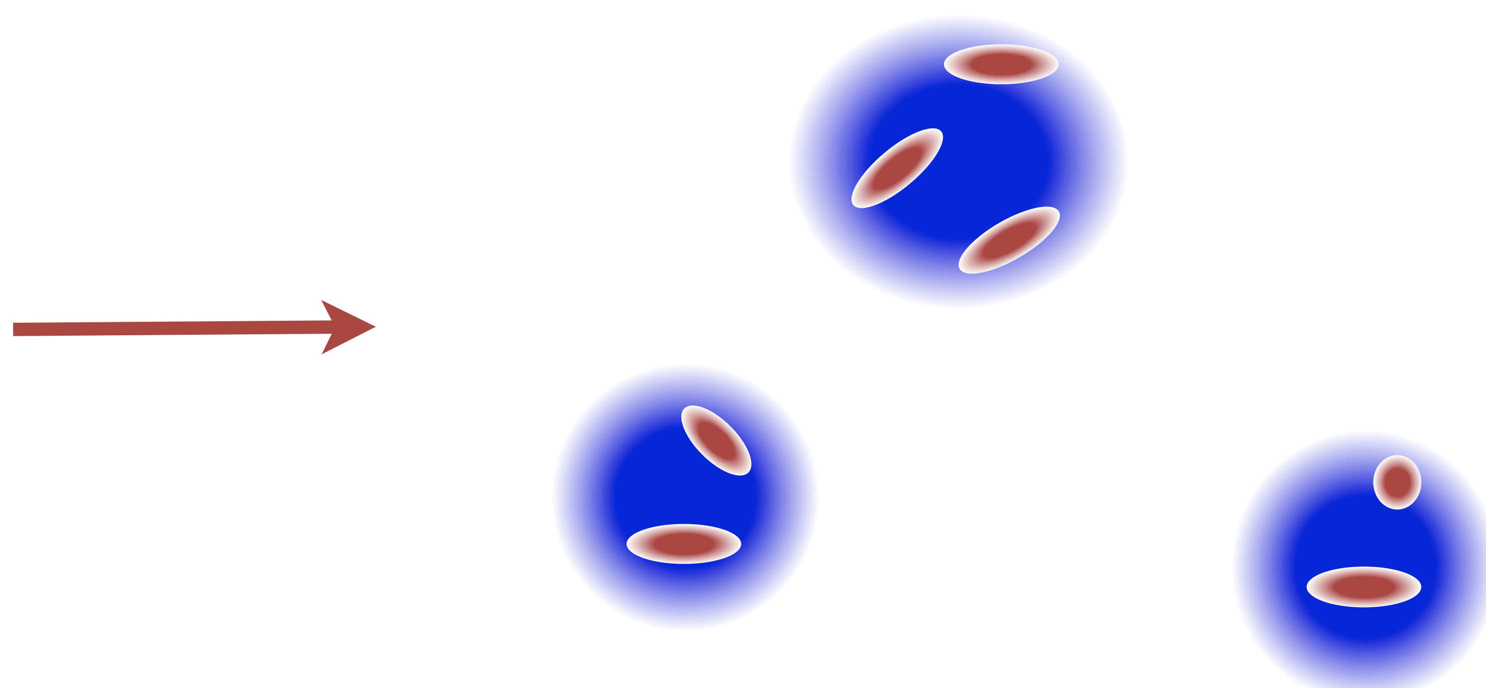


Matthieu Béthermin et al. 2011

HOD modeling - I

- Halo model: dark matter resides in spherical halos
- HOD: galaxies live in halos with a density fixed by the halo mass.
- The probability of having N galaxies in a halo of mass M is given by the halo occupation density (hod).
- Small scale clustering determined by galaxy distributions; large scale clustering determined by halo clustering
- Halo clustering follows DM clustering (with a cut-off due to halo exclusion) up to a multiplicative bias





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

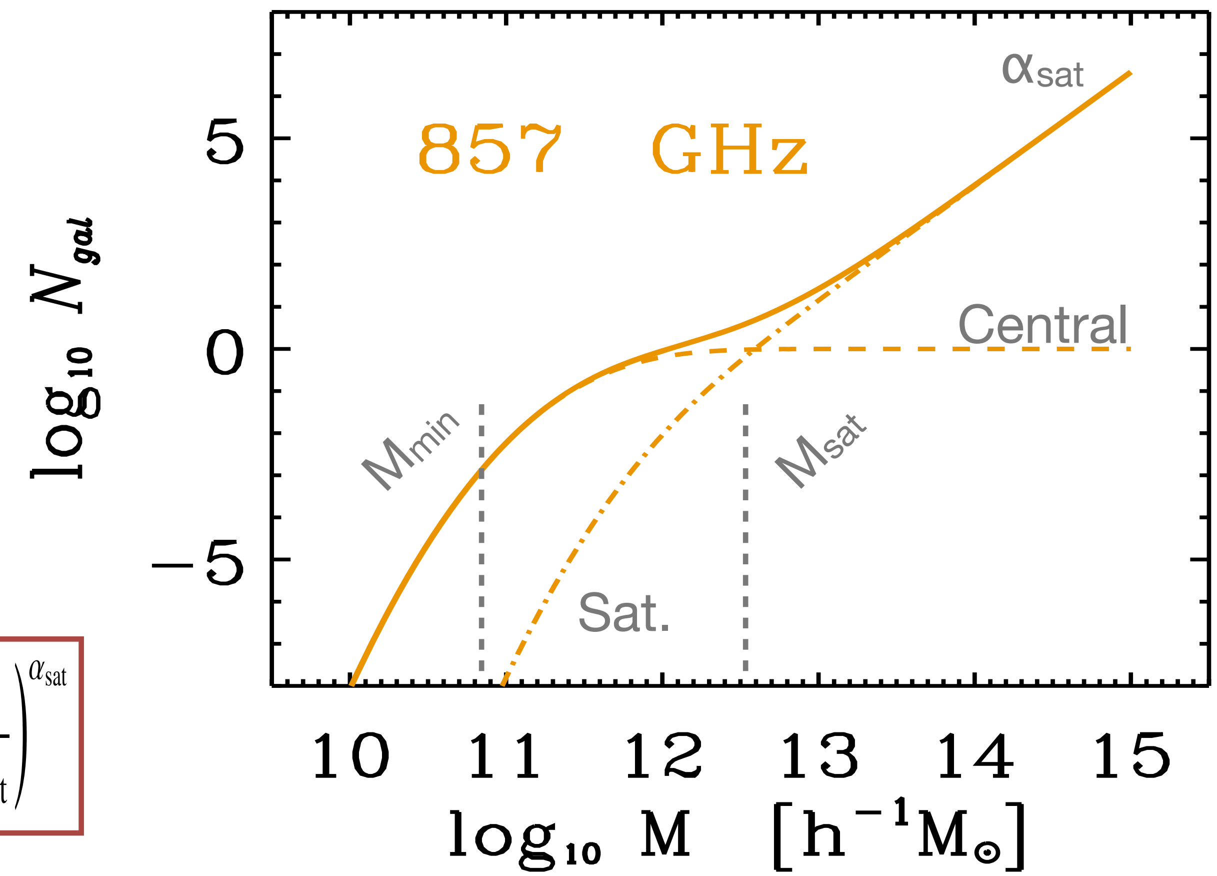
$$P_{1h}(k) = \int dM \frac{dN}{dM} \frac{\langle N_{\rm gal}(N_{\rm gal}-1)\rangle}{\bar{n}_{\rm gal}^2} u^2(k,M)$$

$$P_{2h}(k) = P_{\rm lin}(k)\left[\int dM \frac{dN}{dM} b(M) \frac{\langle N_{\rm gal}\rangle}{\bar{n}_{\rm gal}} u(k,M)\right]^2$$

$$\langle N_{\rm gal}\rangle = N_{\rm cen} + N_{\rm sat}$$

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

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



- The Halo Occupation Distribution defines the clustering of galaxies (bias) and its redshift evolution
- We use an ansatz from Zheng et al. 05 and Tinker et al. 08 validated on N-boby simulations and optical data (z~<2)
- A full study of the parameter space suggests that current CIB clustering data alone can neither constrain cosmology nor the galaxy evolution model. The latter is mostly constrained by number counts and redshift evolution
- We restrict ourselves to two HOD parameters: M_{min} and α_{sat}. We set M_{sat} = 10 M_{min} and $\sigma_{\log M}$=0.65 . We assume Poissonian distribution for N_{gal} .
- M_{min} roughly corresponds to the smallest halo mass hosting a CIB contributing galaxy. α_{sat} fixes the total number of galaxies and the ratio of contributing high/low mass halos

Pénin, O.D., Lagache, Béthermin, 2011, in prep.

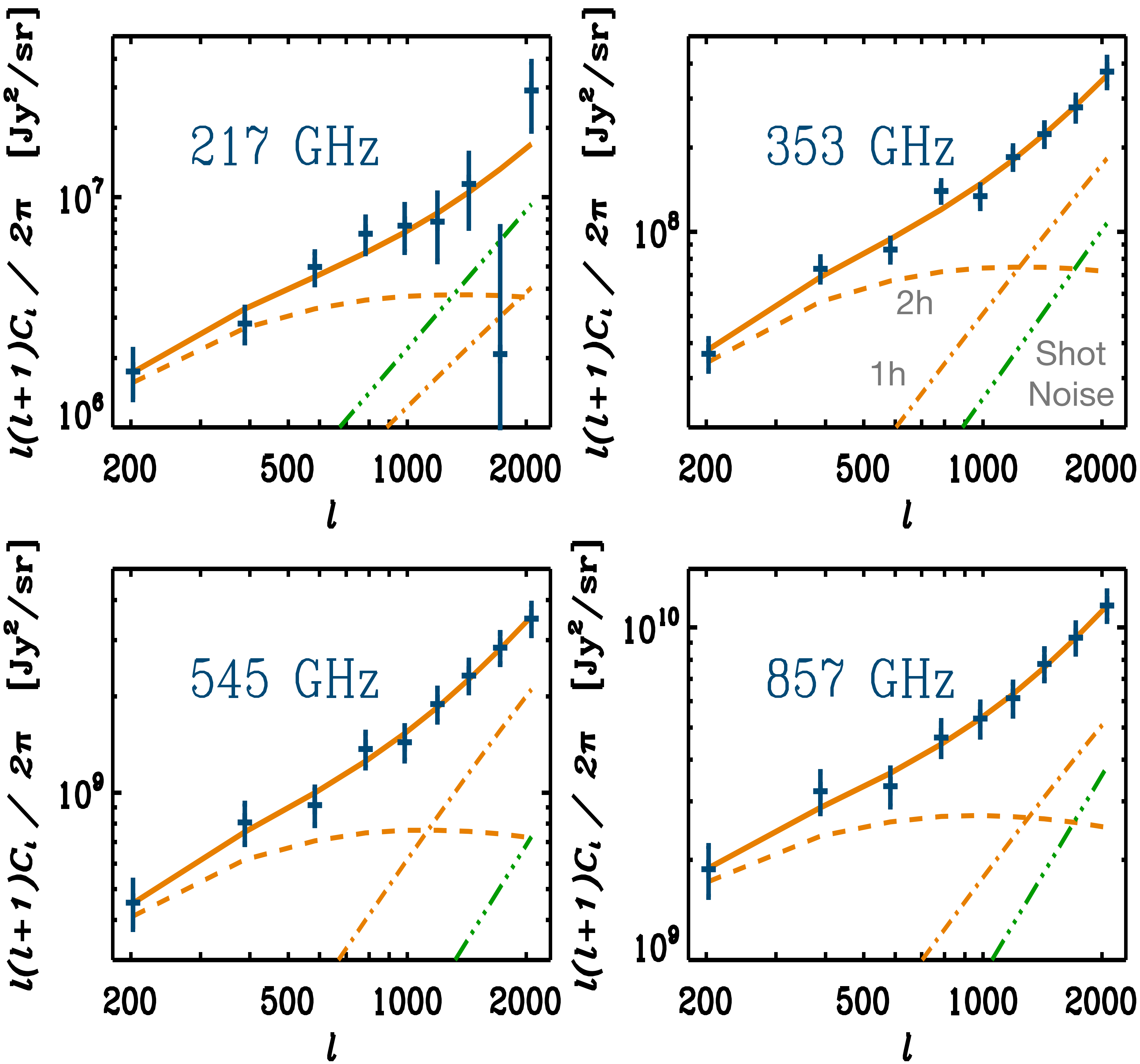
Caveat

- The Béthermin et al. 10 model has very little predictive power for z>~3.5 by lack of observations

- The only robust constrain we have is on the CIB mean as measured by FIRAS (Fixsen et al 98) that we use as a prior or not. (Mean CIB ∝ ∫ j dz)

$$C_\ell^{\nu\nu'} = \int_0^{3.5} dz \frac{d\chi}{dz}\frac{a^2}{\chi^2}\bar{j}_\nu(z)\bar{j}_{\nu'}(z)P_{gg}(k=\ell/\chi, z)$$
$$+ \left(j_{\rm eff}^{\nu\nu'}\right)^2 \int_{3.5}^{7} dz \frac{d\chi}{dz}\frac{a^2}{\chi^2}P_{gg}(k=\ell/\chi, z)$$

HOD model fits



- Varying two HOD parameters (and optionally one j bin for z>3.5) per frequency provides excellent fits (χ^2/dof~1)
- The angular scales we probe clearly require a careful modeling of the 1h and 2h terms
- Clear degeneracy between shot-noise level and 1-halo term. It explains the unphysical linear model results

HOD modeling best fit parameters

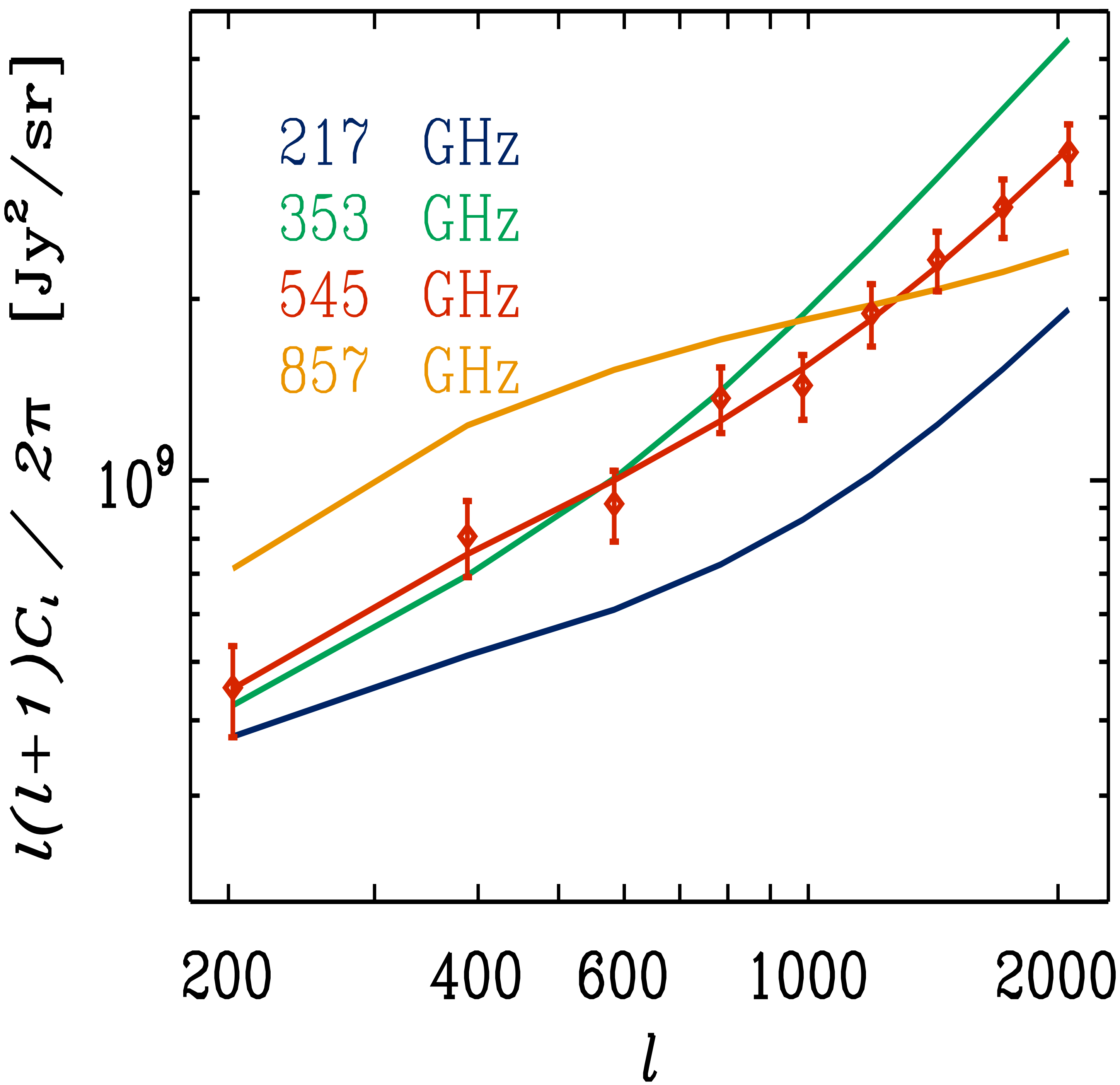
Frequency (GHz)	$\log_{10} M_{\rm min}$ [h^{-1}M$_\odot$]	$\alpha_{\rm sat}$	$j_{\rm eff}$ [Jy/Mpc/sr]	Reduced χ^2 (χ^2/dof)
217	11.95 ± 2.10	1.30 ± 1.16	7.51 ±0.75 × 10^1	2.68 (16.1/6)
353	12.49 ± 0.42	1.39 ± 0.42	2.00 ±0.29 × 10^2	2.42 (14.5/6)
545	12.35 ± 1.01	1.17 ± 0.65	3.11 ±3.85 × 10^2	0.50 (3.04/6)
857	12.20 ± 0.51	1.02 ± 0.87	3.14 ±17.0 × 10^2	0.73 (4.40/6)
217	11.82 ± 1.92	1.17 ± 2.38	N/A	1.14 (7.96/7)
353	12.50 ± 0.09	1.35 ± 0.20	N/A	0.80 (5.64/7)
545	12.35 ± 0.94	1.17 ± 0.45	N/A	0.35 (2.46/7)
857	12.21 ± 1.23	0.96 ± 0.73	N/A	0.60 (4.22/7)

solving for $j_{\rm eff}$

setting j to model extrapolation

- We observe a strong $M_{\rm min}$ - $j_{\rm eff}$ degeneracy limit our interpretative power
- This greatly limits what we can tell about the the clustering of “CIB-contributing” galaxies
- Consistently requires a higher $\alpha_{\rm sat}$ than optical data

Does one single HOD fit all frequencies?



- For each best fit model at each frequency, we are comparing here the *prediction* at 545GHz
- The uncertainties associated to each curve are not represented here but it hints at the fact each frequency requires a different HOD
- In general, we failed to find a multifrequency fit, even allowing for relative freedom at z>2.5
- This suggests that we are looking at somewhat different populations at different redshifts

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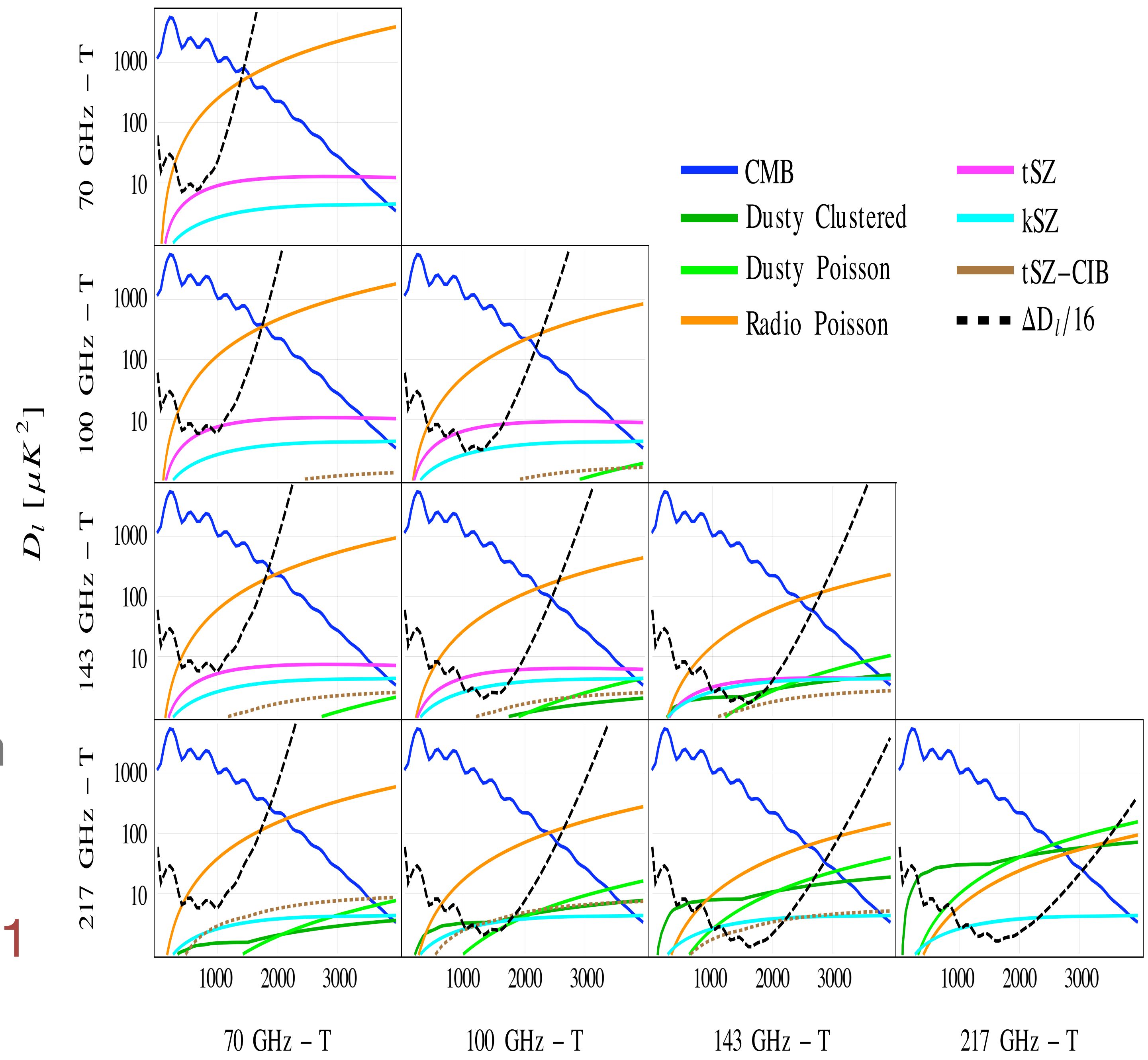
1) Planck mission: quick introduction and update

2) Planck measurements of the *Cosmic Infrared Background Power Spectrum* (arXiv:1101.2028)

3) Present and future synergies between CMB and large Infrared Surveys

CIB is becoming a critical issue in current CMB analysis

- Dominant foregrounds at high *l* for CMB temperature analysis, after the thermal SZ effect
- Potential dangerous bias to cosmological parameters thus requires an accurate model
- Will benefit from any information about and multiple cross-correlations with large sub-mm survey, eg Hajian & Viero et al. 11

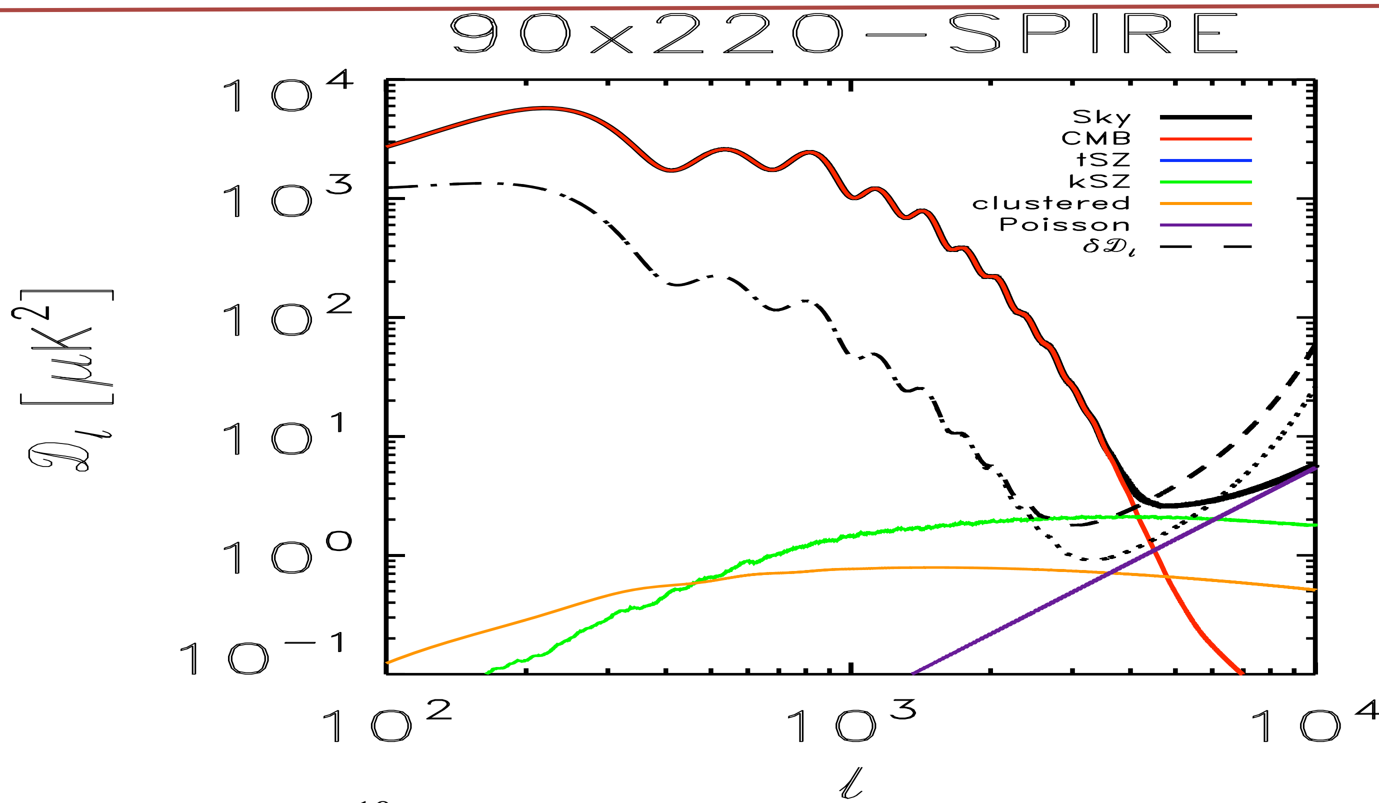


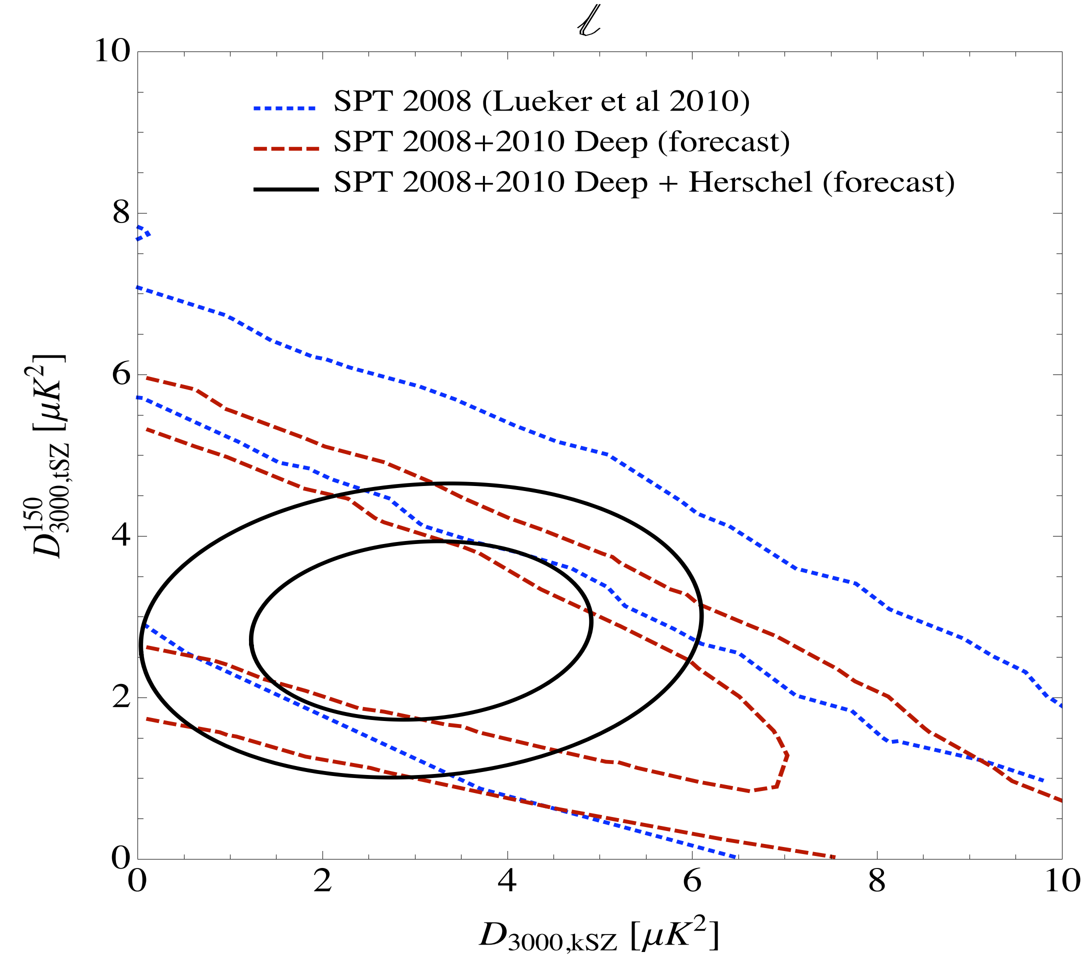
Millea, O.D., Dudley, Holder, Knox, Shaw, Song & Zahn, 2011

The new and ambitious SPT x Herschel program

- The measurement of kSZ from which we can constrain ionization history of the Universe (e.g. Pen & Zhang 99)

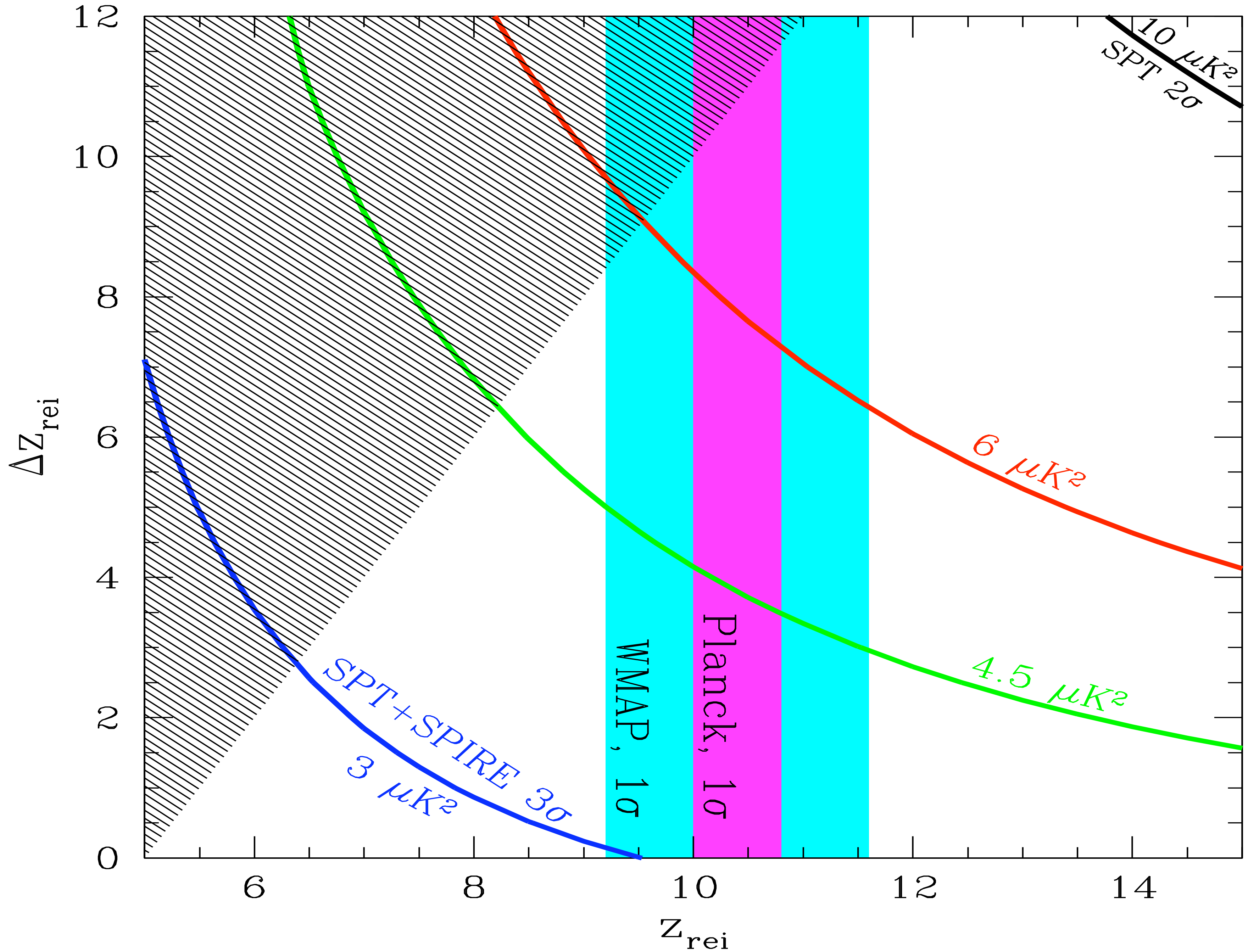
- New idea promoted by Joaquin Vieira and the SPT collaboration *(full disclosure: JV bought me lunch today)* : to use ~80 hours of Herschel/SPIRE time to map ~100 sq. deg. to remove CIB and isolate kSZ





Plot by Marius Millea and Lloyd Knox

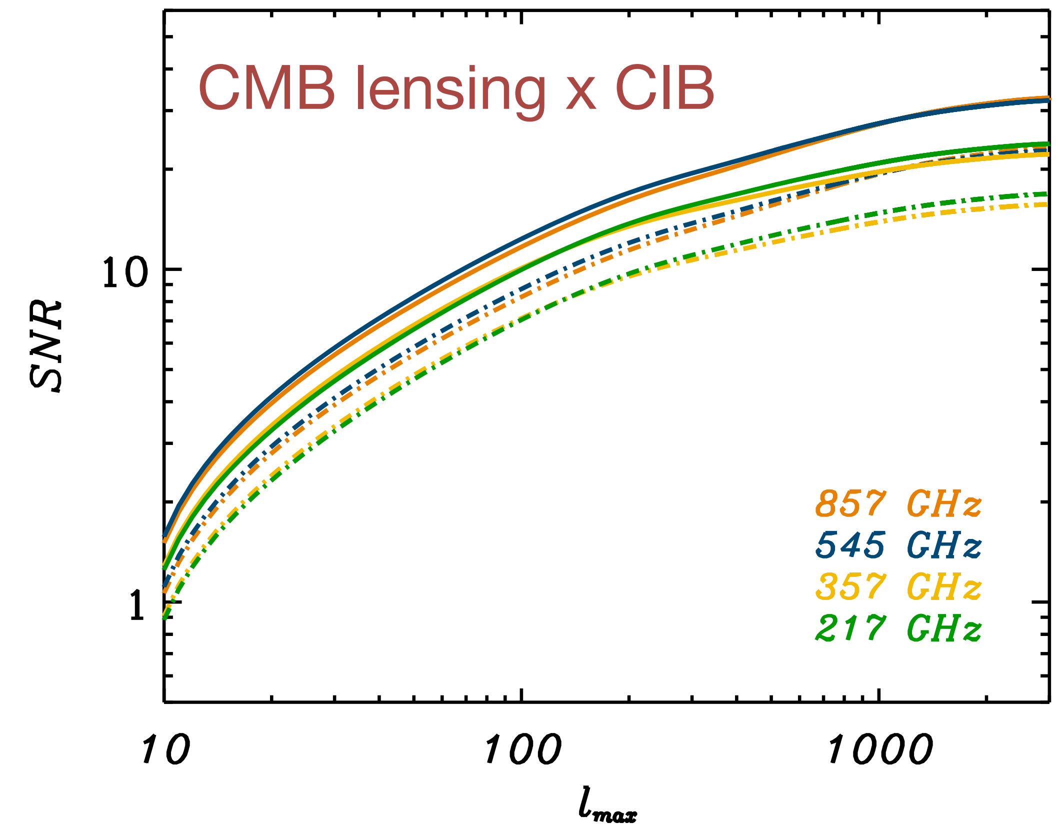
The new and ambitious SPT x Herschel program

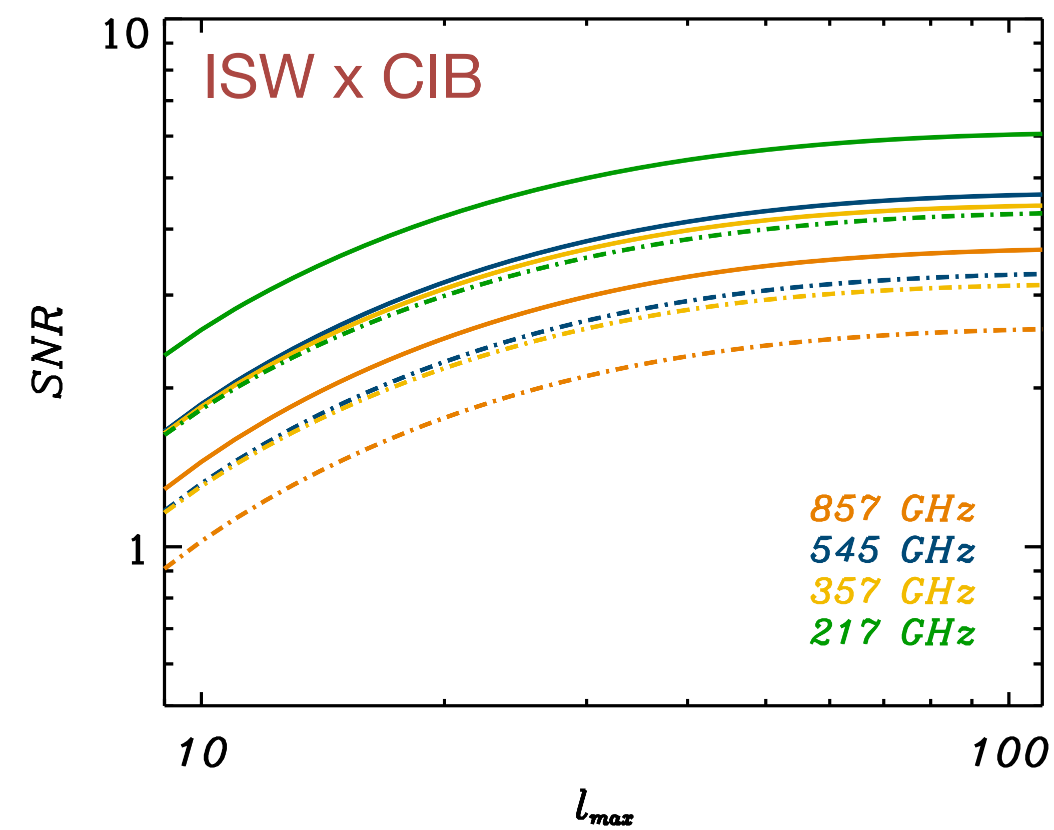


- This constraint on reionization are complementary AND independent from the "usual" ones coming from large scale polarization

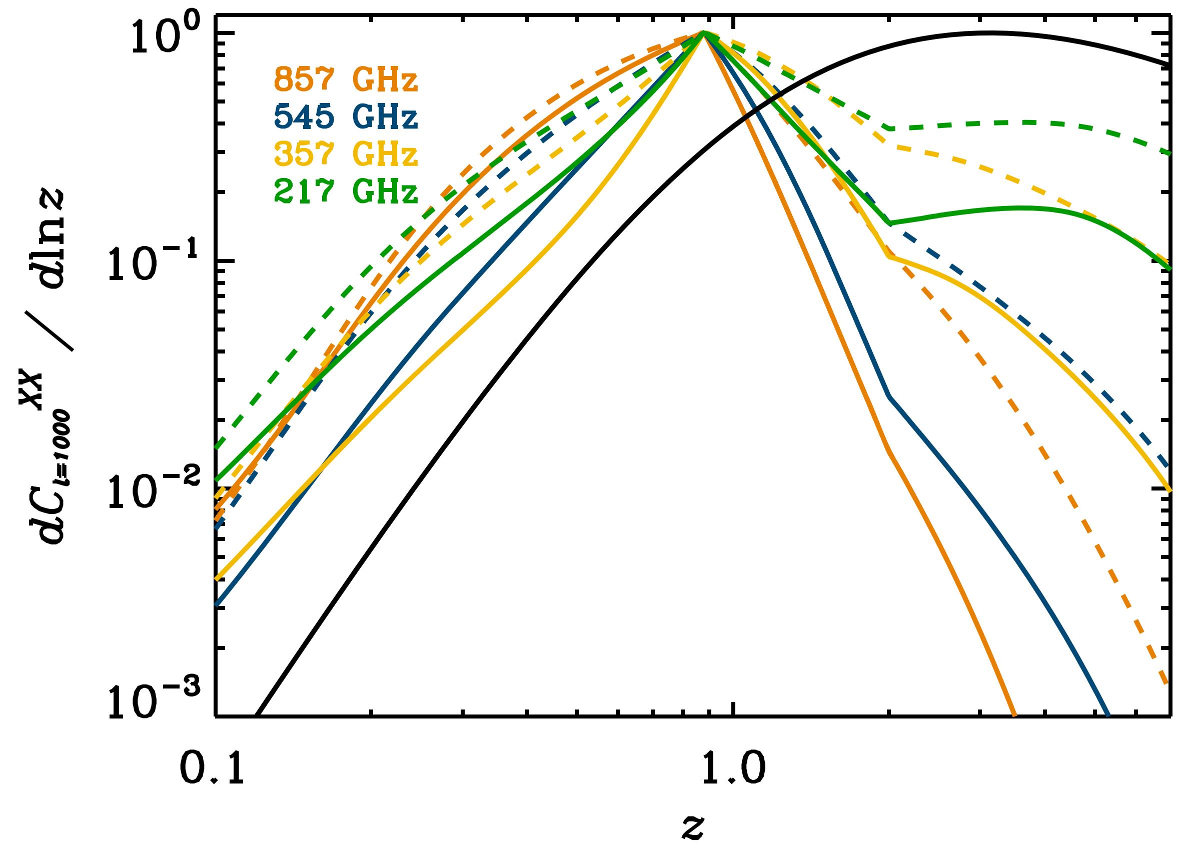
How are we going to learn more?

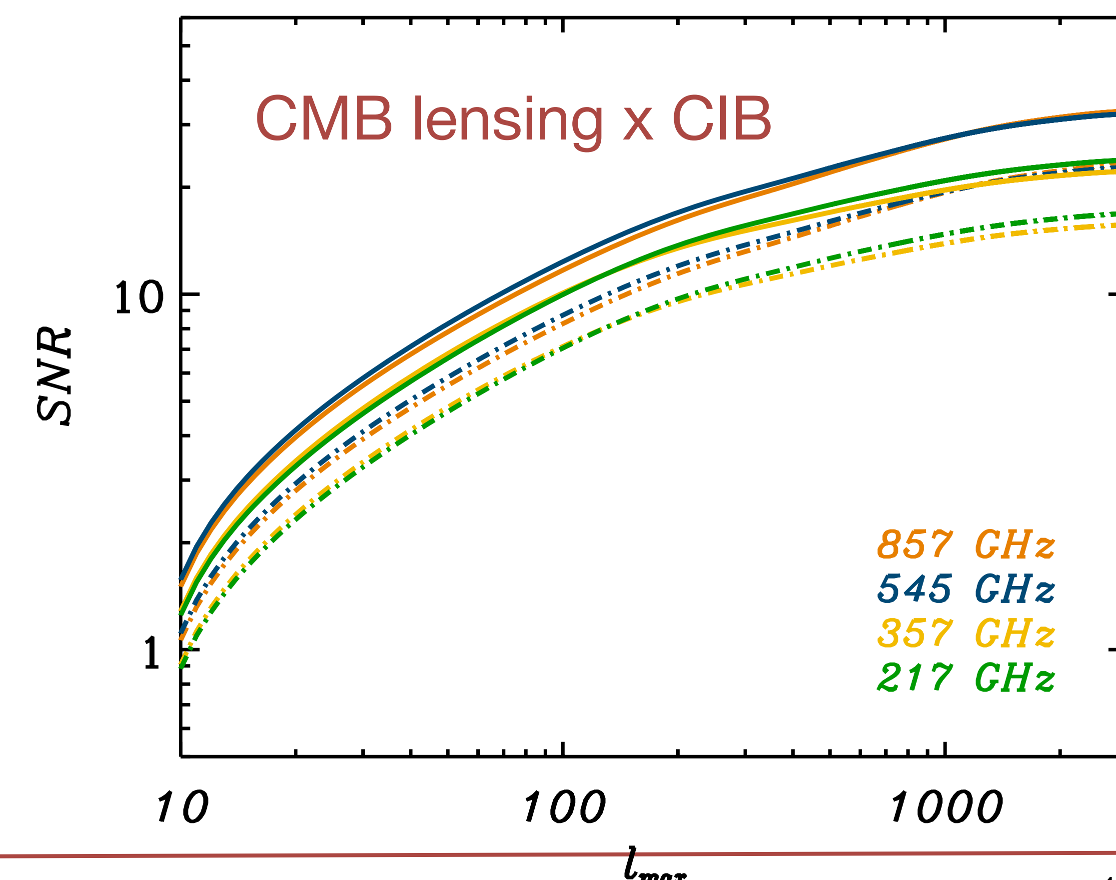
- By combining other data-sets, mostly Herschel (when fixed), but also SPT, ACT for extra angular coverage but also other wavelength for extra redshift coverage
- But also new probes:
  - From Planck only, CMB lensing cross-correlation is going to give us an unique leverage
  - Also incidentally a good probe of ISW (not including magnification bias)
  - Cross-correlations with QSOs, etc
- Better modelization now motivated by the new generation of experiments





- The CMB lensing has a perfectly matching kernel in *z* (Song et al. 99).
- CIB is in fact and ideal tracer of density field to cross-correlate with CMB lensing
- Unique direct probe of the CIB bias at z~2 at each frequency.
- But can also be done internally from Planck (SNR~20-30)
- And will also be done with SPT x SPIRE





Conclusions

- Planck has been operating flawlessly since the beginning of the science survey on August 13, 2009
- Built for cosmology, Planck has capabilities to pursue many interesting astrophysical investigations: Full sky, 9 frequencies, limited angular resolution (~4') but excellent sensitivity
- First CMB results and public data release in January 2013
- We have a robust measurement of CIB clustering from 10' to 2 deg at 217, 343, 545 and 857 GHz
- We develop a HOD inspired model using a self-consistent IR galaxy evolution model that provides us with a very good fit to the data
- Robust "model independent" physical interpretation is however still hard because of severe degeneracies and modeling uncertainties
- The CIB is emerging as a crucial elements in all current CMB data analysis
- We will benefit from a joint analysis with other data-sets and more data (if consistent) and new probes of the CIB as CMB lensing (and ISW) that Planck/SPT/ACT/Herschel/MUSIC/CCAT will enable
- The cross-benefits of large overlapping CMB and sub-mm surveys are obvious and numerous.

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INFLATIONARY THEORY AND ITS CONFRONTATION WITH DATA IN THE PLANCK ERA

With upcoming new data from the Planck satellite and other CMB experiments, but also from the next generation Large Scale Structure surveys, our capabilities to explore the beginning of the universe and the theory of Inflation will undergo a major improvement in the coming years. In this light, it is timely to gather together observers and theorists to discuss, explore and develop the theoretical signatures of the Physics of the early universe as well as the associated new observational or data analysis techniques required to make the best of upcoming data.

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