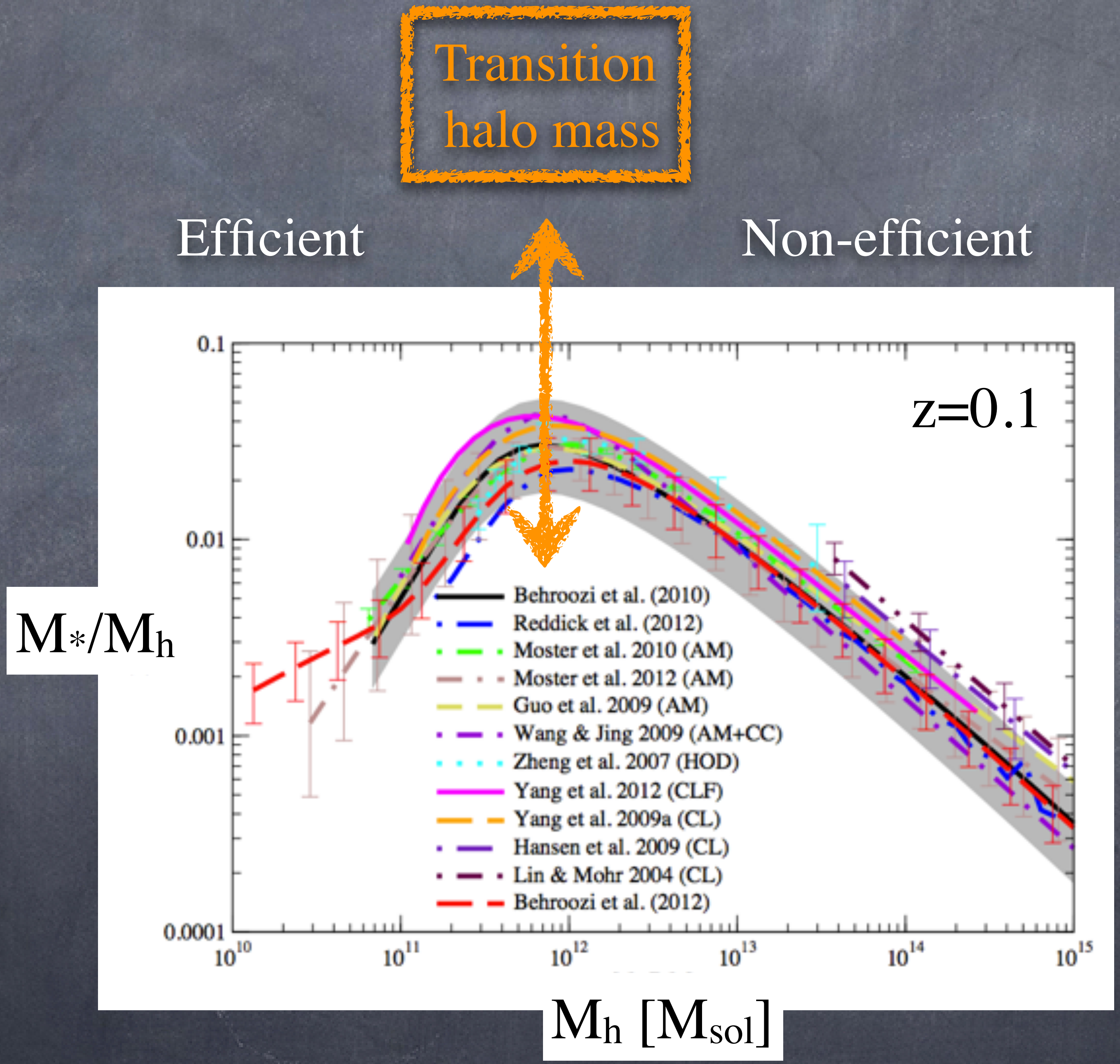
The bispectrum of the Cosmic Infrared Background : a new insight on the link between star formation and dark matter

Aurélie Pénin
ACRU/ UKZN

Lacasa, Pénin & Aghanim 2014
Pénin, Lacasa, Aghanim 2014

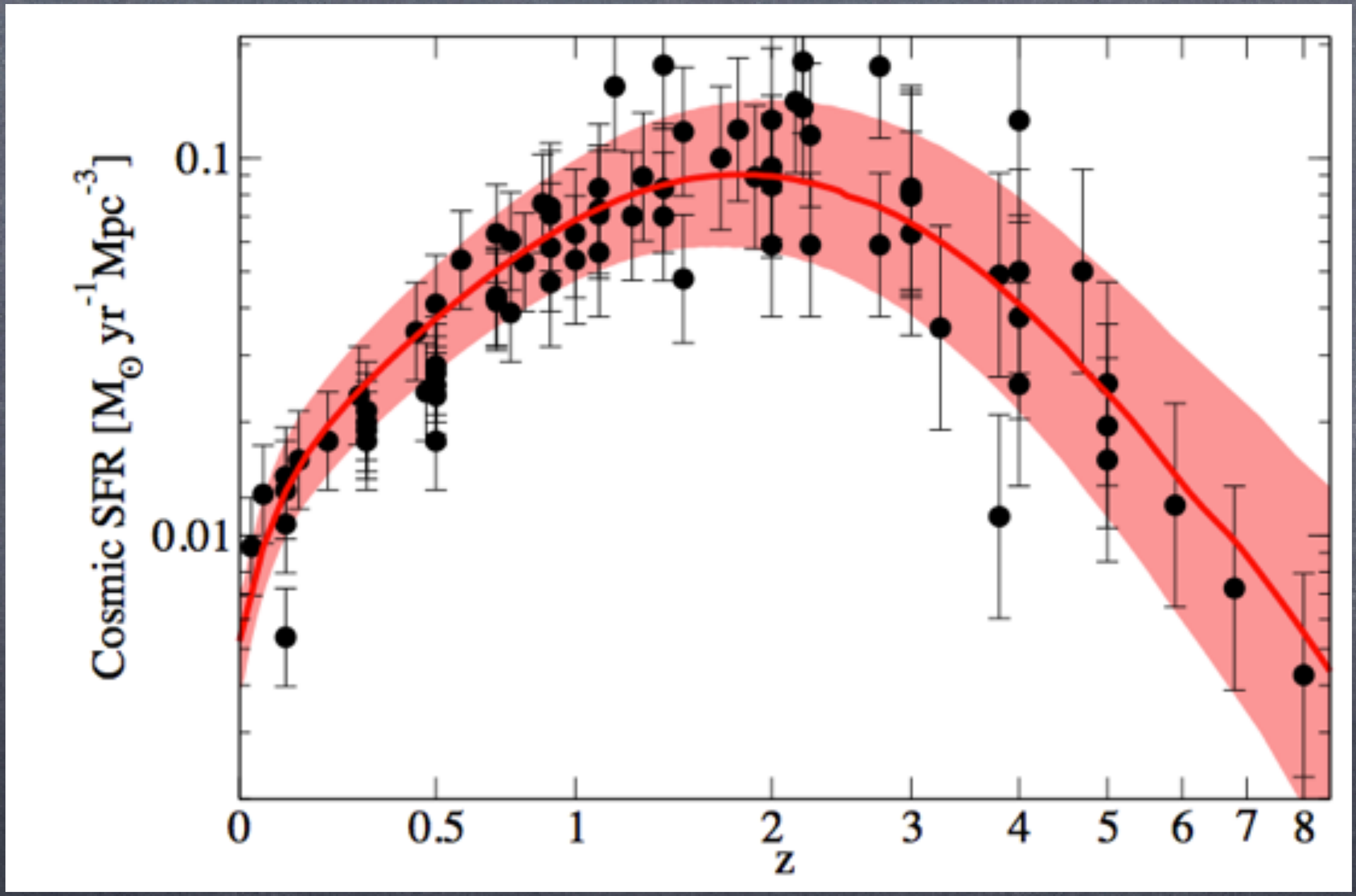
Star formation within dark matter halos



Behroozi+2012

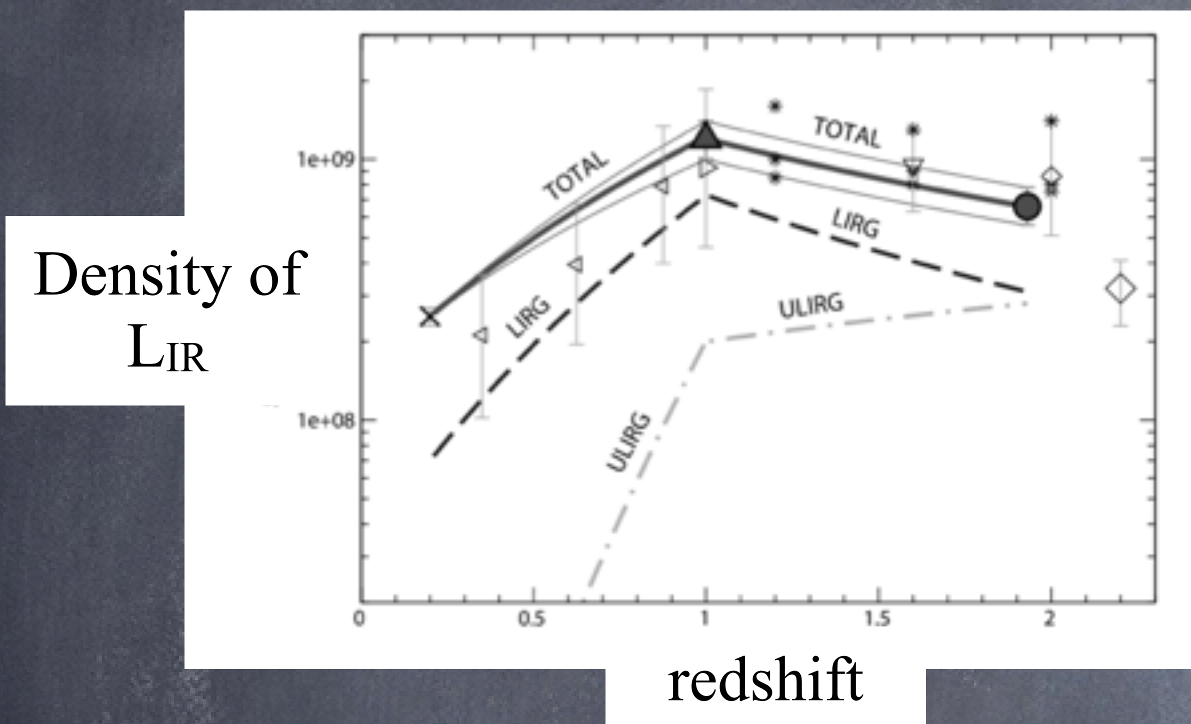
The global star formation rate

Intense episode of star formation at z~1-2

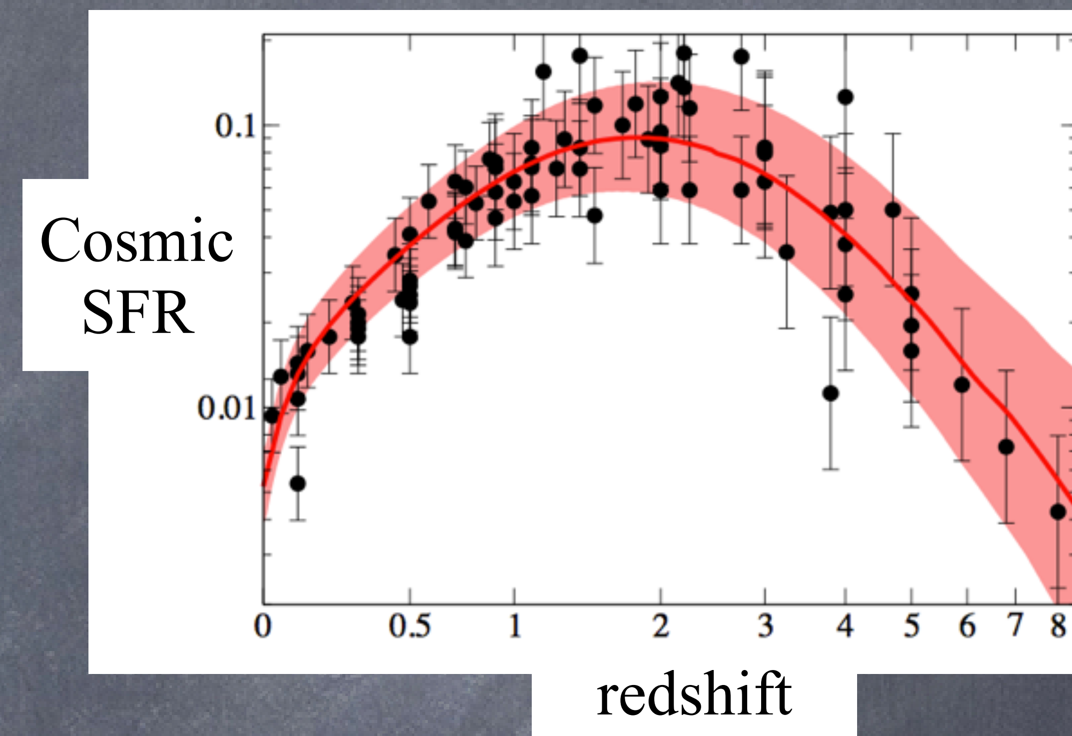


Behroozi+2012

The infrared point of view



$\propto$



Caputi+2007

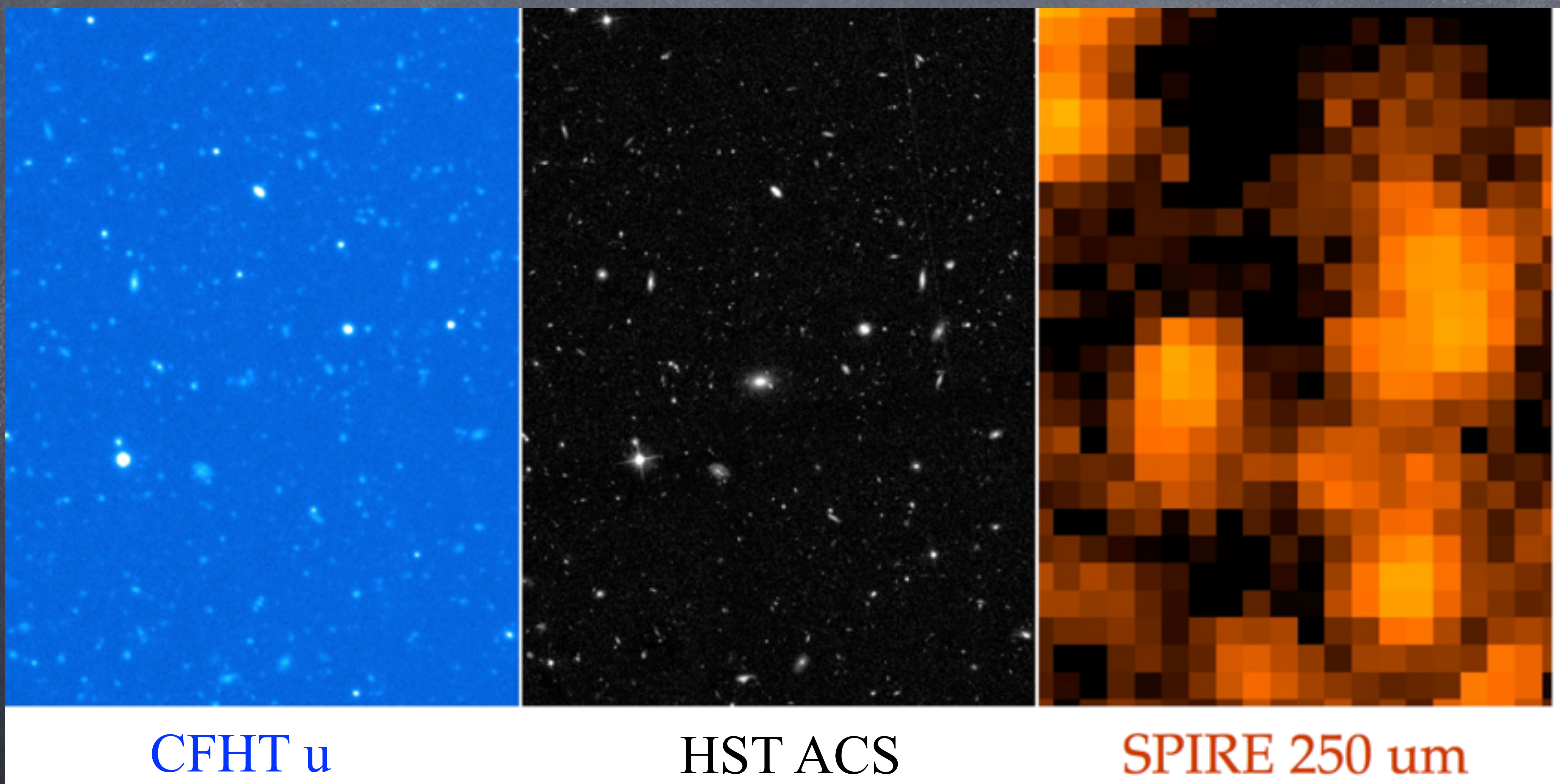
Behroozi+2012

IR : Preferential probe of star formation

But a background in the IR

Because of confusion :

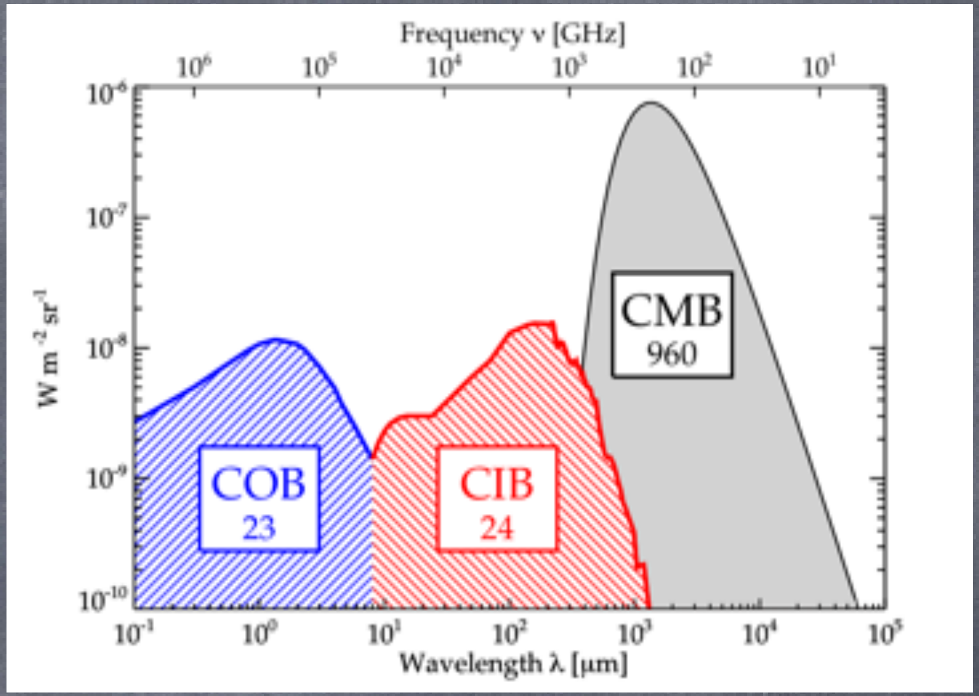
Extragalactic sources under the limit of detection lead to brightness fluctuations because of the low resolution of the instruments.



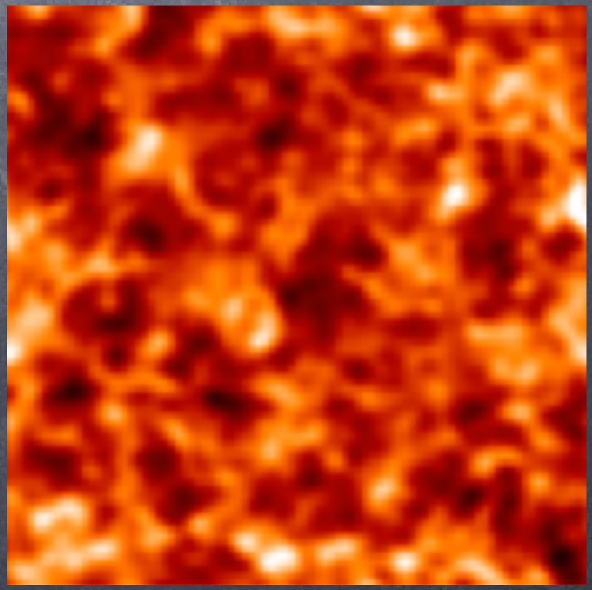
With the courtesy of Sebastien Heinis

The Cosmic Infrared Background

- 8 um to 1.3 mm
- Continuous and integrated field
- Encodes all the processes of galaxy evolution since the decoupling
- Its bulk : z ~ 1-2
- Its source : dusty star-forming galaxies = locus of star formation in the Universe
- Spatial structure : image of the density field of dusty-star forming galaxies



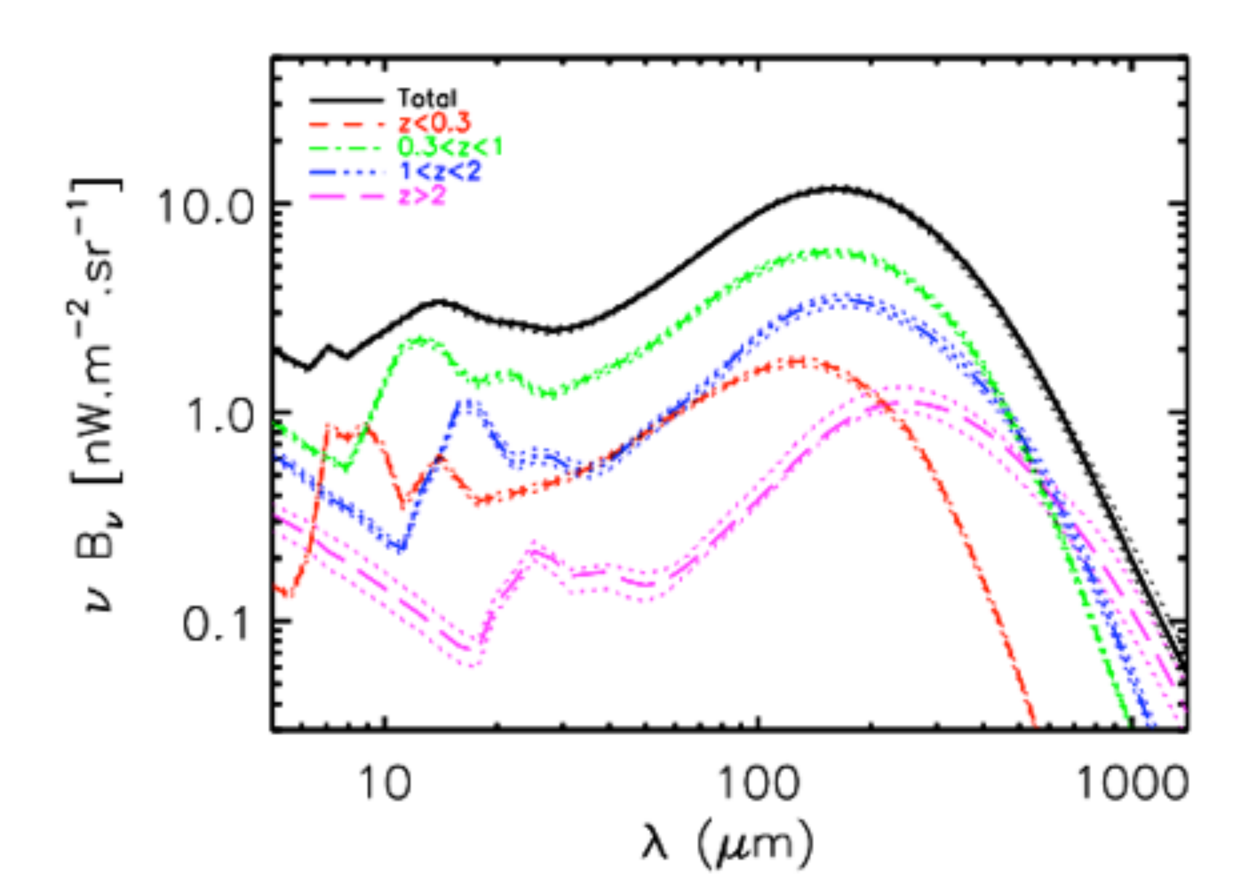
Dole+2006



Planck 350 um

Evolution in redshift

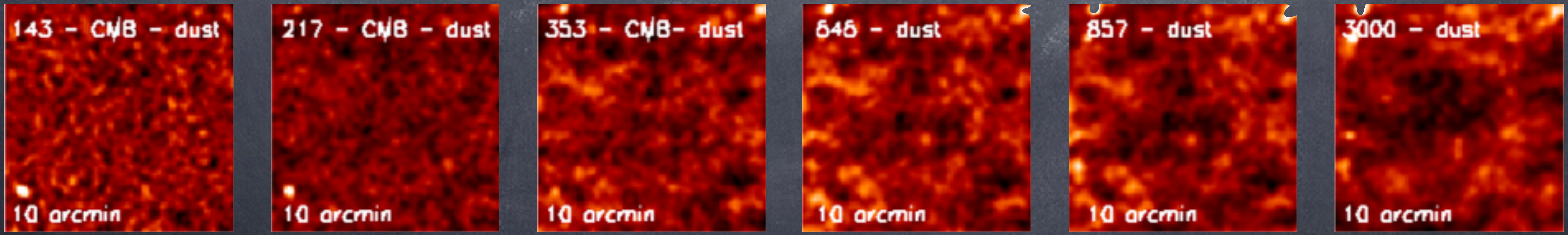
Béthermin+2011



Longer wavelengths probe higher redshift galaxies

Redshift

2 mm	1.4 mm	850 um	550 um	350 um	100 um



The Planck Collaboration XXX

The anisotropies of the CIB

Preferential probe of
star formation within large scale structure
and of its evolution over z ~ 1 - 4

Large scales : linear bias

$$\frac{\delta \rho_g}{\bar{\rho}_g} = b \frac{\delta \rho}{\bar{\rho}}$$

Fluctuations of
the galaxies
density field

bias

Fluctuations of
the dark matter
density field

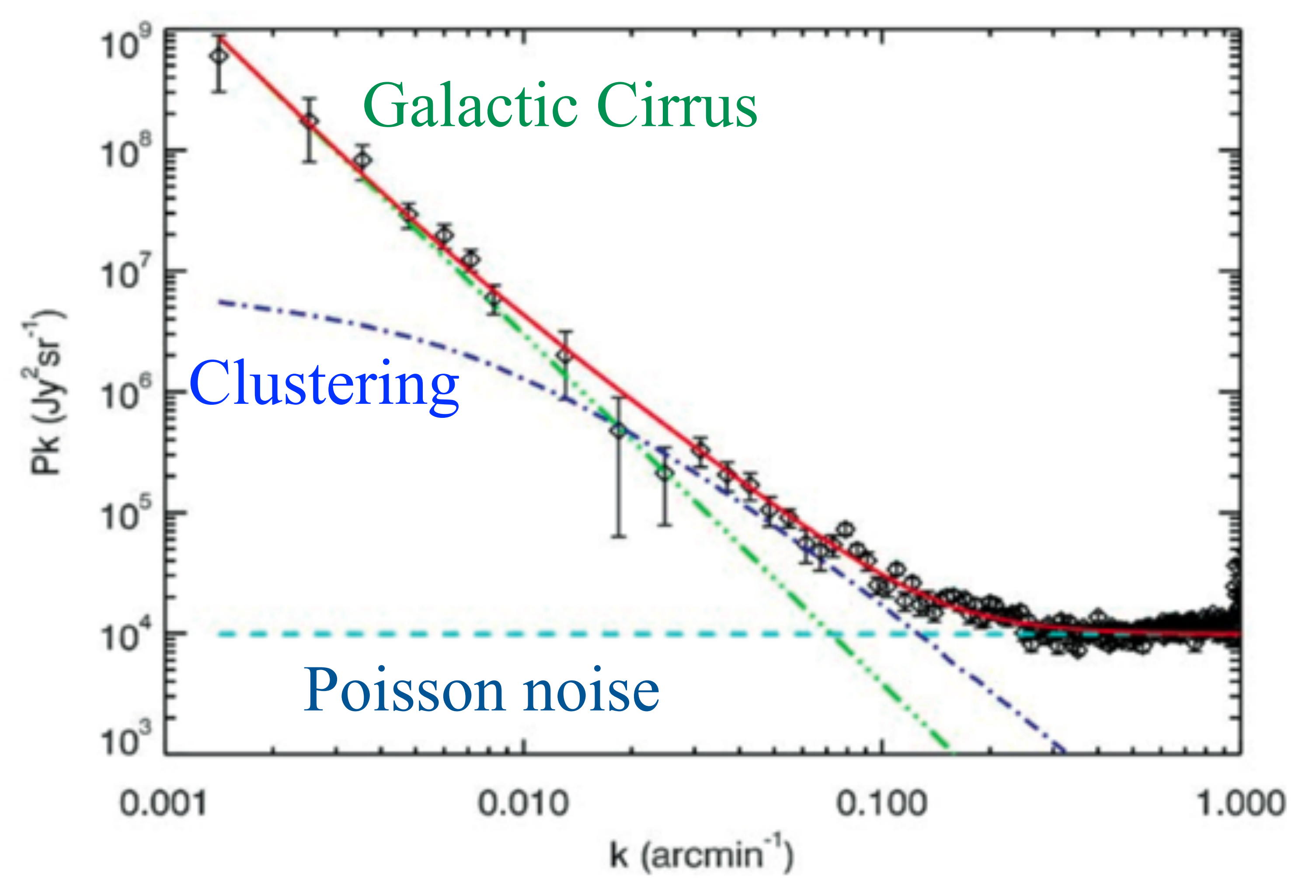
Small scales

depends on the intrinsic
properties of galaxies

Baryonic processes
occuring within galaxies

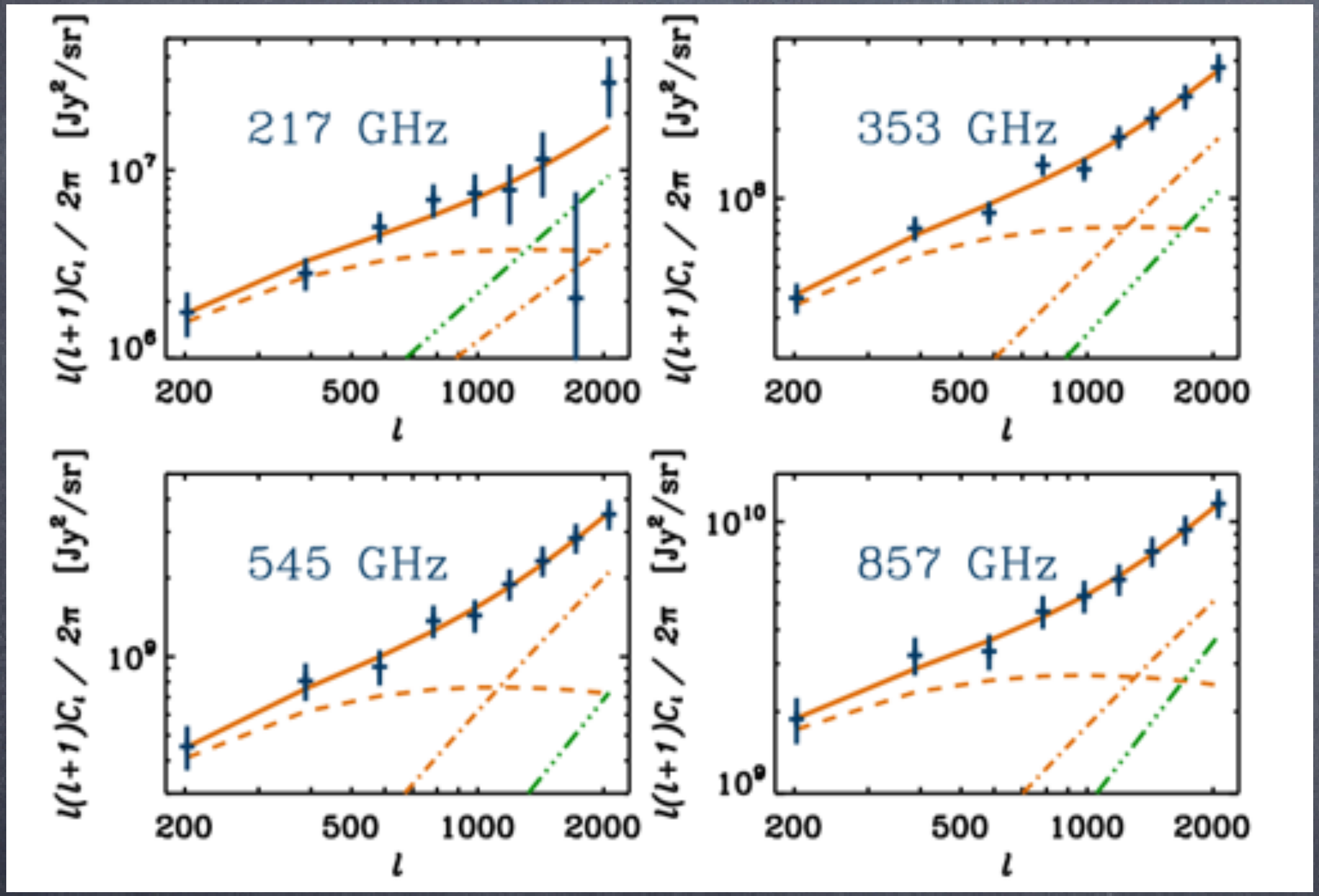
Before Planck and Herschel

Spitzer/MIPS
160 um

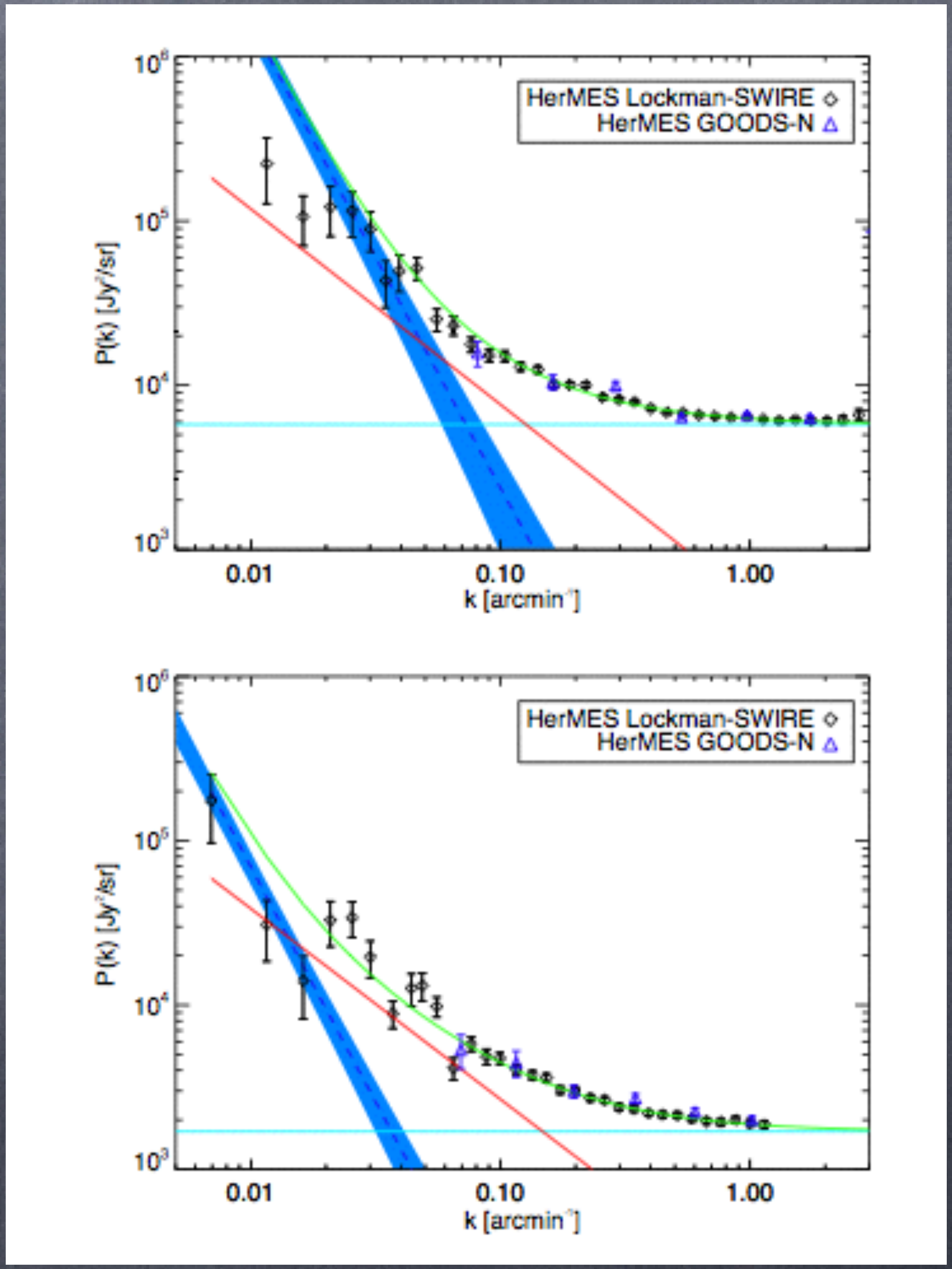


Lagache+2007

Planck and Herschel I



Planck Early Results XVIII



Amblard+2011

Modelling the power spectrum of CIB anisotropies

$$C_\ell^\lambda = \int \frac{\mathrm{d}z}{r^2}\frac{\mathrm{d}r}{\mathrm{d}z} a^2(z)\bar{j}_\lambda^2(z) P_{\mathrm{gal}}(k,z)$$

Galaxies emissivities

3D power spectrum
of the galaxies

Model of evolution of galaxies

Halo model + HOD

Ingredients of the 3D power spectrum

- The Halo Model :
  - Halo mass function, 1st and 2nd order biases of the halos, halo density profile (NFW)
- The Halo Occupation Distribution

M_{sat} = minimum mass of the halo to contain one satellite galaxy

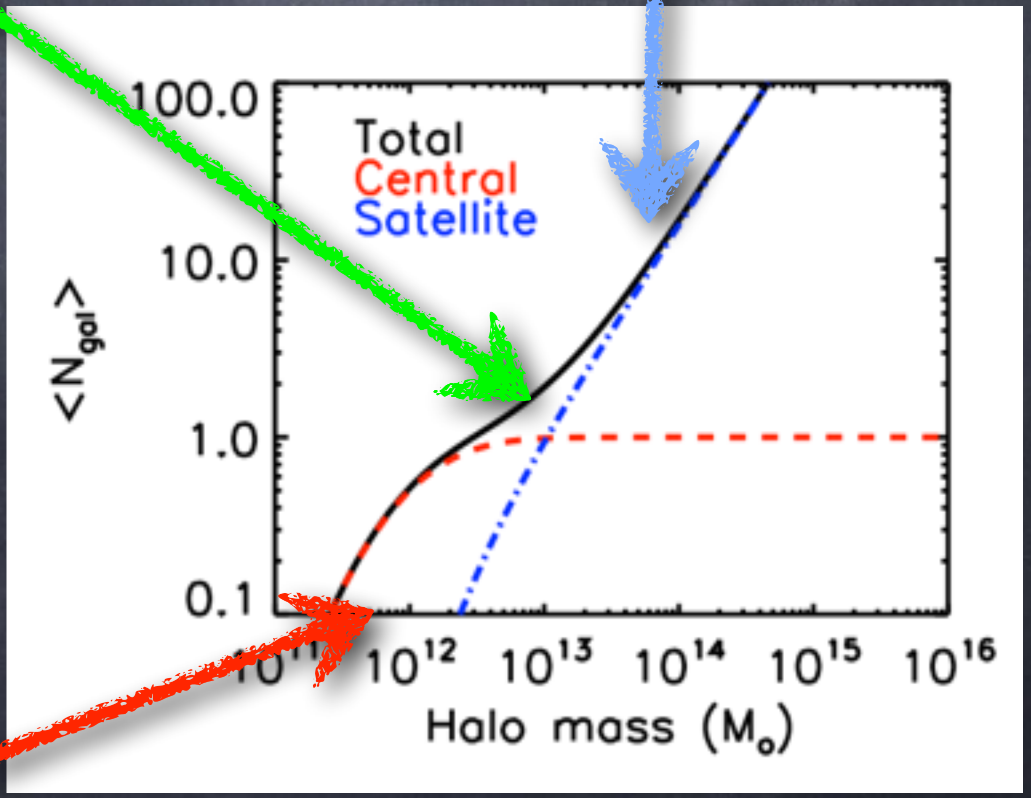
alpha = slope of the number of satellites

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

Number of central galaxies

Number of satellite galaxies

M_{min} = minimum mass of the halo to contain a central galaxy



The 3D power spectrum

$$P_{\rm gg}(k,z) = P_{\rm gg}^{\rm clus}(k,z) + P_{\rm gg}^{\rm shot}(k,z)$$

Clustering

Shot noise

The 3D power spectrum

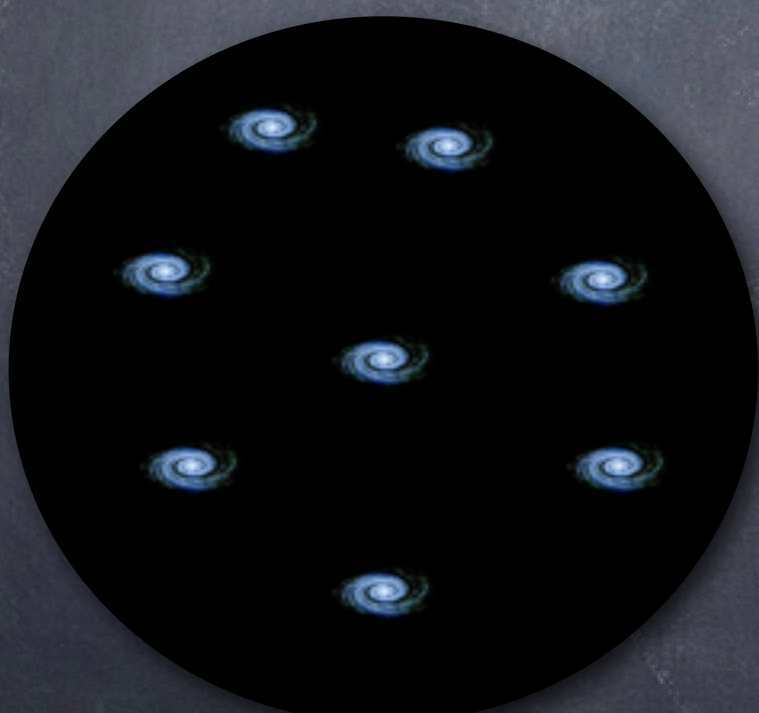
$$P_{\rm gg}(k,z) = P_{\rm gg}^{\rm clus}(k,z) + P_{\rm gg}^{\rm shot}(k,z)$$

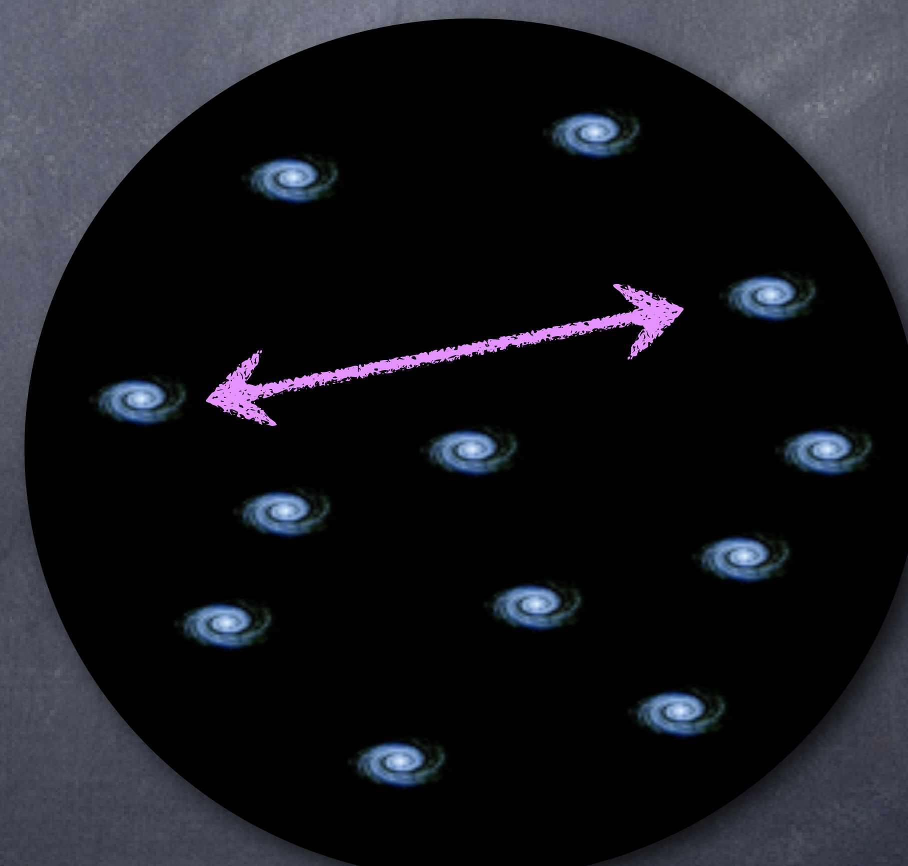
$$P_{\rm gg}^{\rm clus}(k,z) = P_{\rm 1h}(k,z) + P_{\rm 2h}(k,z)$$

The 3D power spectrum

$$P_{\mathrm{gg}}(k,z) = P_{\mathrm{gg}}^{\mathrm{clus}}(k,z) + P_{\mathrm{gg}}^{\mathrm{shot}}(k,z)$$

$$P_{\mathrm{gg}}^{\mathrm{clus}}(k,z) = P_{1\mathrm{h}}(k,z) + P_{2\mathrm{h}}(k,z)$$

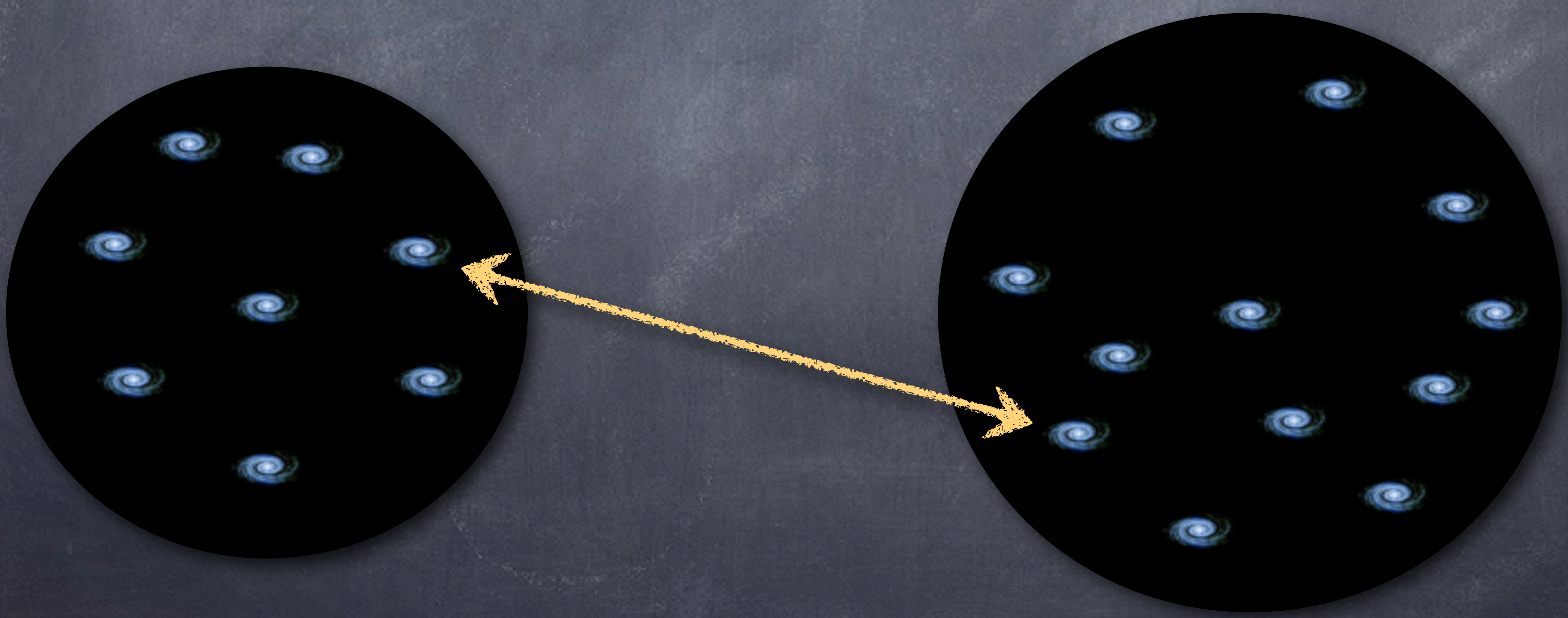




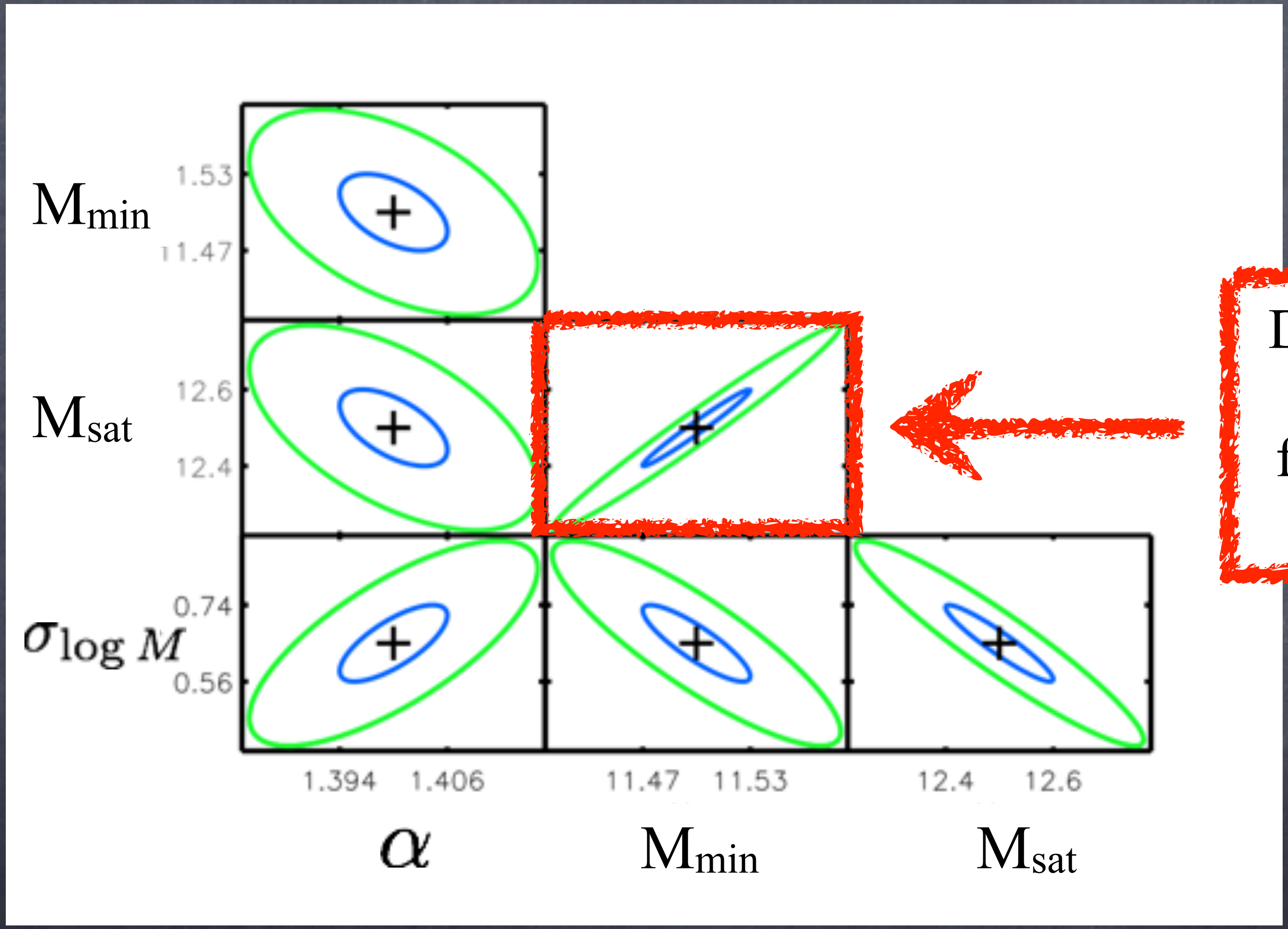
The 3D power spectrum

$$P_{\rm gg}(k,z) = P_{\rm gg}^{\rm clus}(k,z) + P_{\rm gg}^{\rm shot}(k,z)$$

$$P_{\rm gg}^{\rm clus}(k,z) = P_{\rm 1h}(k,z) + P_{\rm 2h}(k,z)$$



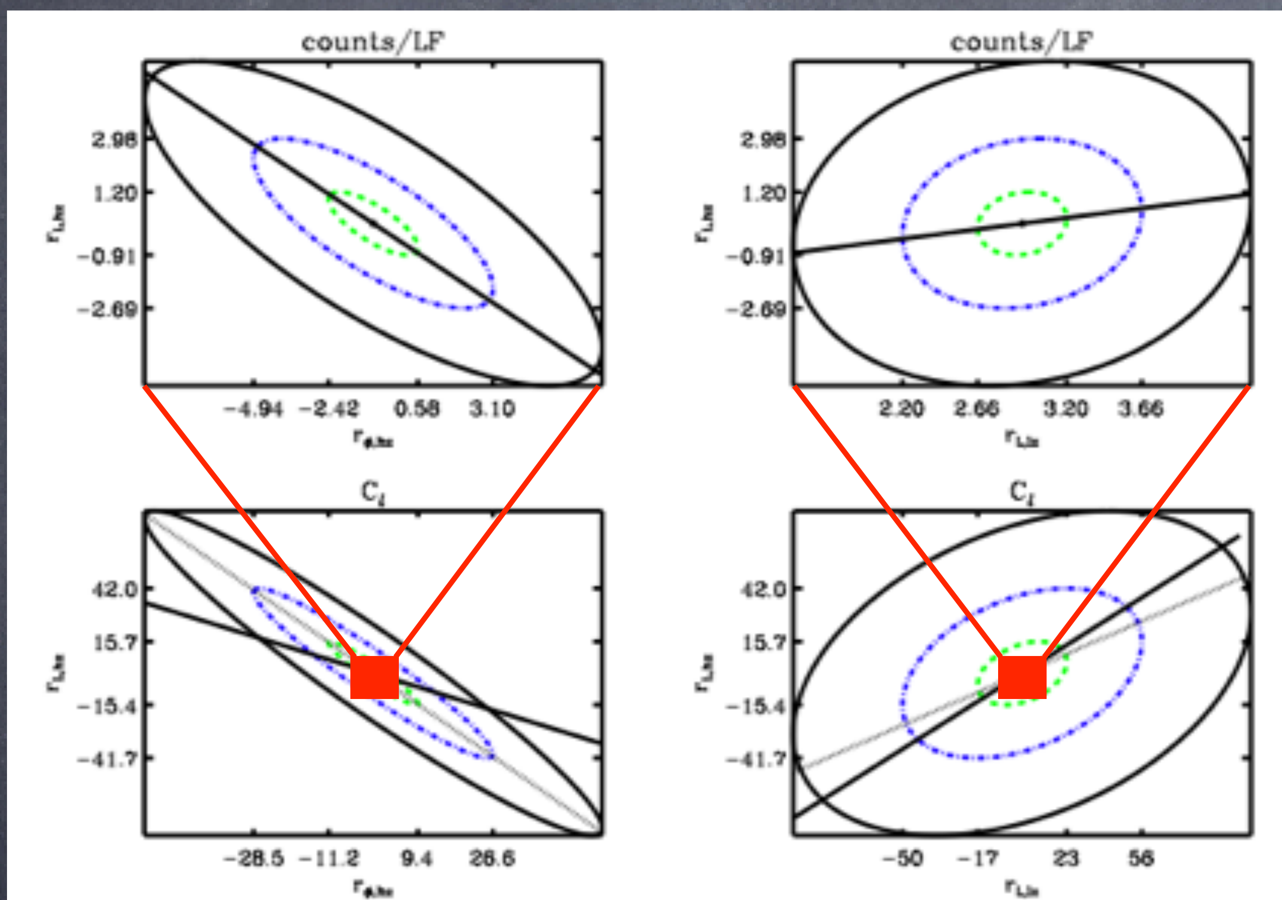
Constraining HOD parameters with the power spectrum only



Degeneracy induced by 2-point correlation function/power spectra studies

Pénin+2012a

Constraining the evolution of galaxies with power spectra only



Pénin+2012a

Power spectra alone cannot constrain the evolution of galaxies

$$C_\ell^\lambda = \int \frac{\mathrm{d}z}{r^2}\frac{\mathrm{d}r}{\mathrm{d}z} a^2(z)\bar{j}_\lambda^2(z) P_{\mathrm{gal}}(k,z)$$

Integration over the redshift

Clustering at higher orders

- Galaxy distribution : non-Gaussian
- Additional information is contained in high order moments

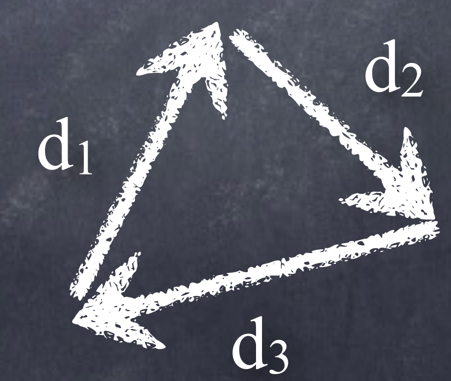
Power spectrum

- 2-point correlation function
- Probability that 2 galaxies are separated by a distance d

- Measures the power of fluctuations

Bispectrum

- 3-point correlation function
- Probability that 3 galaxies are separated by distances d_1, d_2, d_3

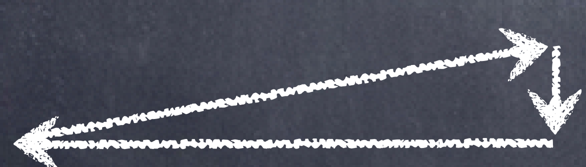


- Depends on the configuration of the triangle
- Tool to measure non-Gaussianity

Displaying a bispectrum

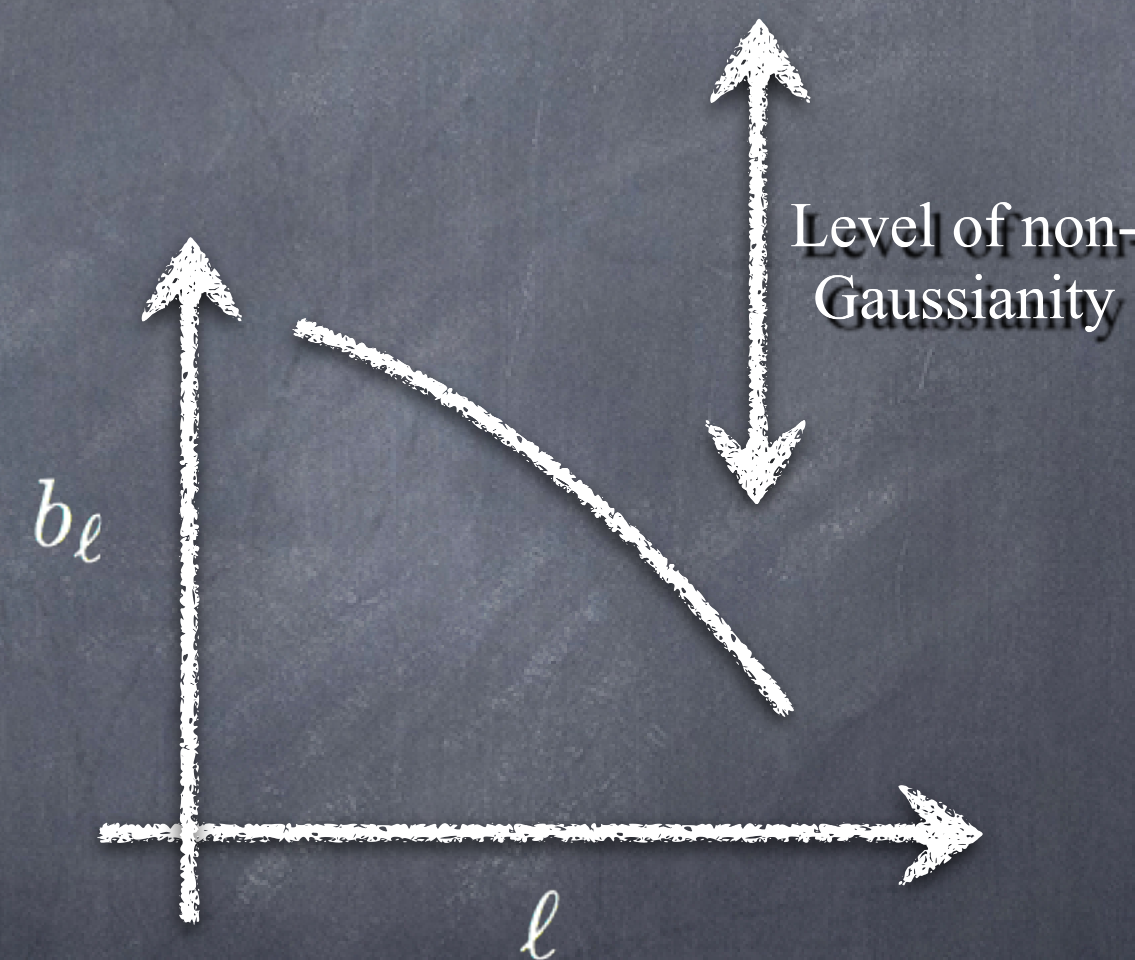
$$\ell_1 = \ell_2 = \ell_3$$

Equilateral



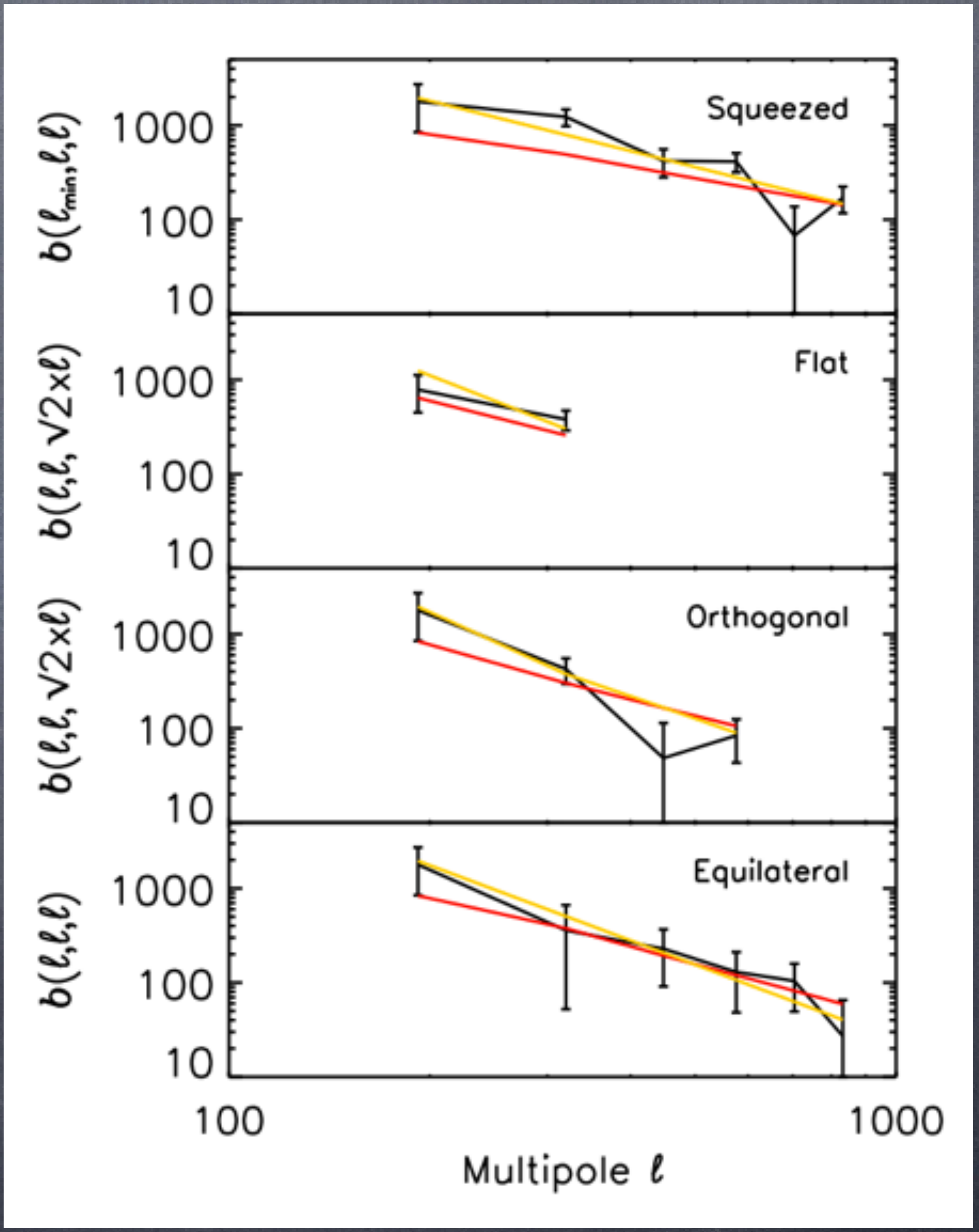
$$\ell_1 = \ell_2$$
$$\ell_3 = \ell_{min}$$

Squeezed



The bispectrum of the CIB

- CIB anisotropies : non-Gaussian
- Additional information : better contraints on models
- CIB : a foreground to the CMB
    - Knowledge of the non-Gaussianity of the CIB is required to determine that of the CMB
- Prescription : Lacasa+2012
- Measurements :
    - The Planck Collaboration XXX
    - 850 um, 4000 deg^2



The Planck Collaboration XXX

Modelling the bispectrum of the CIB anisotropies

$$C_\ell^\lambda = \int \frac{\mathrm{d}z}{r^2}\frac{\mathrm{d}r}{\mathrm{d}z} a^2(z)\bar{j}_\lambda^2(z) P_{\mathrm{gal}}(k,z)$$

$$b_{\ell_1\ell_2\ell_3}^\lambda = \int \frac{\mathrm{d}z}{r^4}\frac{\mathrm{d}r}{\mathrm{d}z} a^3(z)\bar{j}_\lambda^3(z) B_{\mathrm{gal}}(k_1,k_2,k_3,z)$$

Galaxies emissivities

3D bispectrum of the galaxies

Model of evolution of galaxies

Halo model + HOD

The 3D bispectrum of the galaxies

$$B_{\rm gal}(k_{123},z) = B_{\rm gal}^{\rm clus}(k_{123},z) + B_{\rm gal}^{shot}(k_{123},z)$$

The 3D bispectrum of the galaxies

$$B_{\rm gal}(k_{123}, z) = B_{\rm gal}^{\rm clus}(k_{123}, z) + B_{\rm gal}^{shot}(k_{123}, z)$$

$$B_{\rm gal}^{\rm clus}(k_{123}, z) = B_{\rm gal}^{\rm 1h}(k_{123}, z) + B_{\rm gal}^{\rm 2h}(k_{123}, z) + B_{\rm gal}^{\rm 3h}(k_{123}, z)$$

The 3D bispectrum of the galaxies

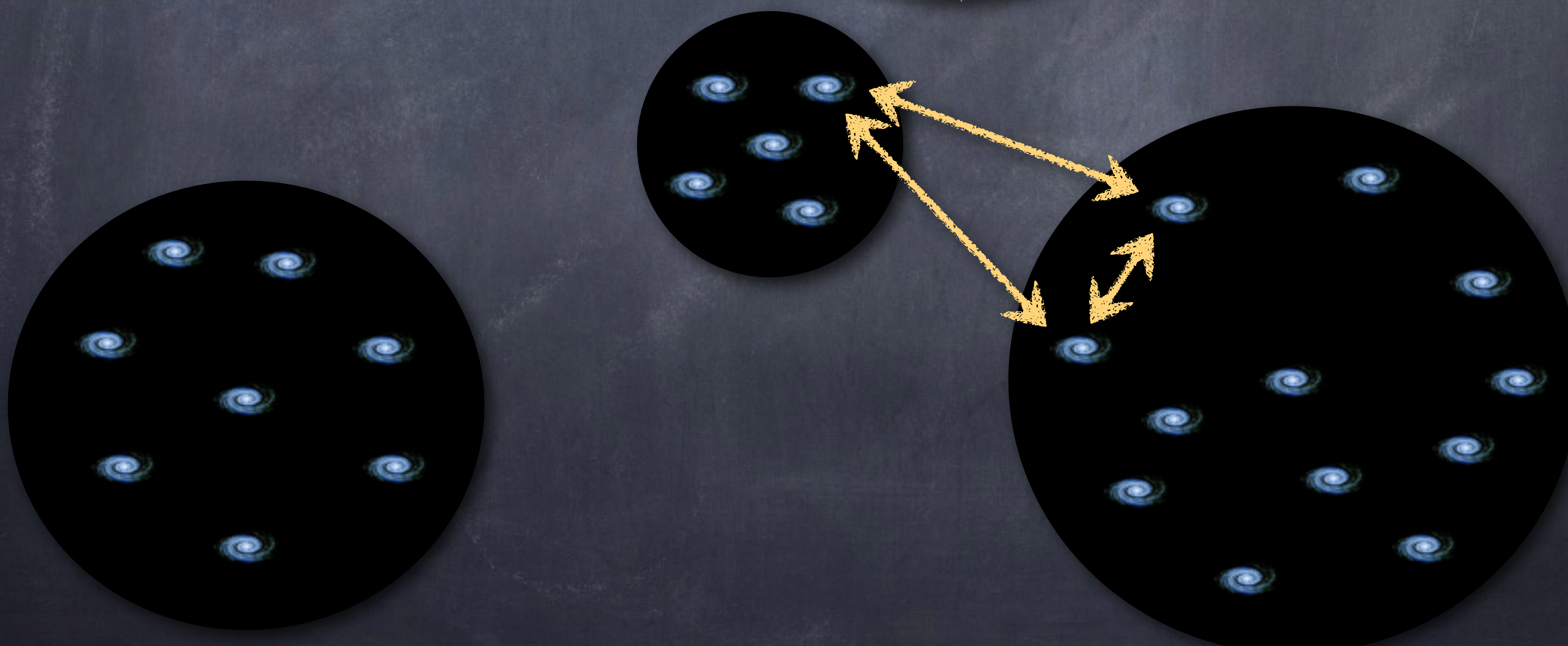
$$B_{\rm gal}(k_{123}, z) = B_{\rm gal}^{\rm clus}(k_{123}, z) + B_{\rm gal}^{shot}(k_{123}, z)$$

$$B_{\rm gal}^{\rm clus}(k_{123}, z) = B_{\rm gal}^{\rm 1h}(k_{123}, z) + B_{\rm gal}^{\rm 2h}(k_{123}, z) + B_{\rm gal}^{\rm 3h}(k_{123}, z)$$

The 3D bispectrum of the galaxies

$$B_{\mathrm{gal}}(k_{123}, z) = B^{\mathrm{clus}}_{\mathrm{gal}}(k_{123}, z) + B^{shot}_{\mathrm{gal}}(k_{123}, z)$$

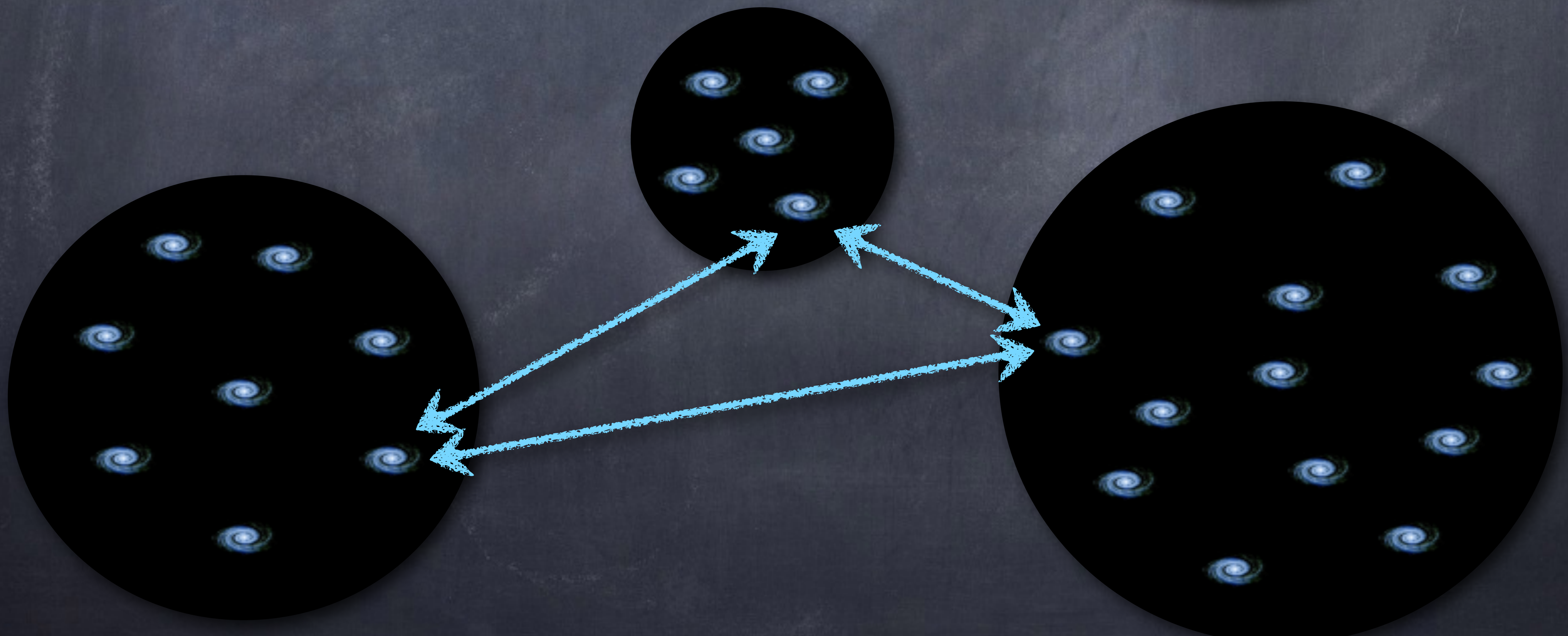
$$B^{\mathrm{clus}}_{\mathrm{gal}}(k_{123}, z) = B^{\mathrm{1h}}_{\mathrm{gal}}(k_{123}, z) + B^{\mathrm{2h}}_{\mathrm{gal}}(k_{123}, z) + B^{\mathrm{3h}}_{\mathrm{gal}}(k_{123}, z)$$



The 3D bispectrum of the galaxies

$$B_{\rm gal}(k_{123},z) = B_{\rm gal}^{\rm clus}(k_{123},z) + B_{\rm gal}^{shot}(k_{123},z)$$

$$B_{\rm gal}^{\rm clus}(k_{123},z) = B_{\rm gal}^{\rm 1h}(k_{123},z) + B_{\rm gal}^{\rm 2h}(k_{123},z) + B_{\rm gal}^{\rm 3h}(k_{123},z)$$



The 3D bispectrum of the galaxies

$$B_{\rm gal}(k_{123},z) = B_{\rm gal}^{\rm clus}(k_{123},z) + B_{\rm gal}^{shot}(k_{123},z)$$

$$B_{\rm gal}^{\rm clus}(k_{123},z) = B_{\rm gal}^{\rm 1h}(k_{123},z) + B_{\rm gal}^{\rm 2h}(k_{123},z) + B_{\rm gal}^{\rm 3h}(k_{123},z)$$

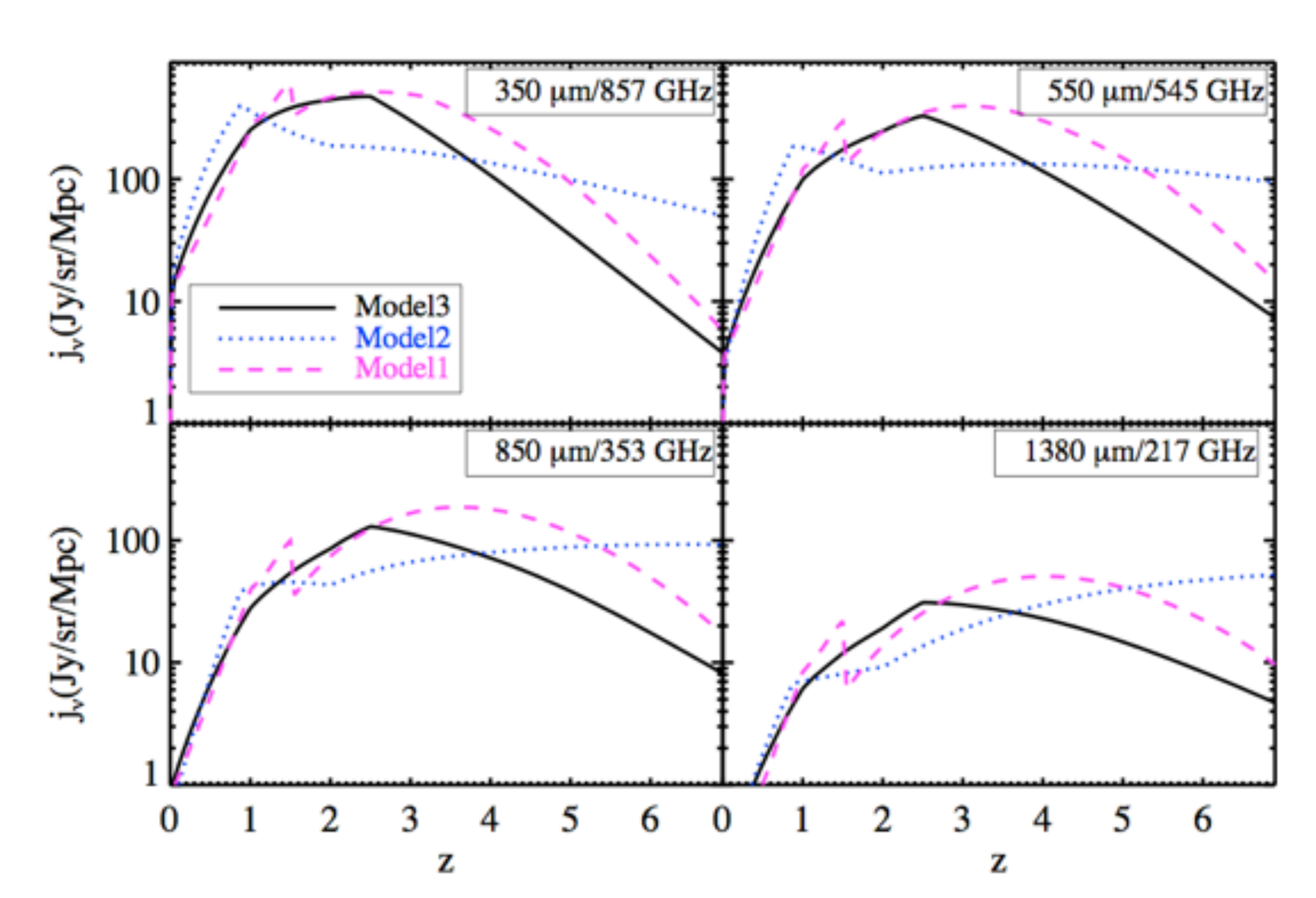
$$b_{\ell_1\ell_2\ell_3}^{\rm shot} = b_{\ell_1\ell_2\ell_3}^{\rm shot1g} + b_{\ell_1\ell_2\ell_3}^{\rm shot2g}$$

1-galaxy term

2-galaxy term

Models of evolution of galaxies

- 3 models of evolution of galaxies
  - Negrello+2007 : semi-analytical (Model1)
  - Béthermin+2011 : parametric luminosity function (Model2)
  - Béthermin+2012 : split between main sequence/starbursts (Model3)



Predictions of the bispectrum of CIB anisotropies

Degeneracy between the model of evolution of galaxies & HOD parameters

For each wavelength and for each model of galaxy

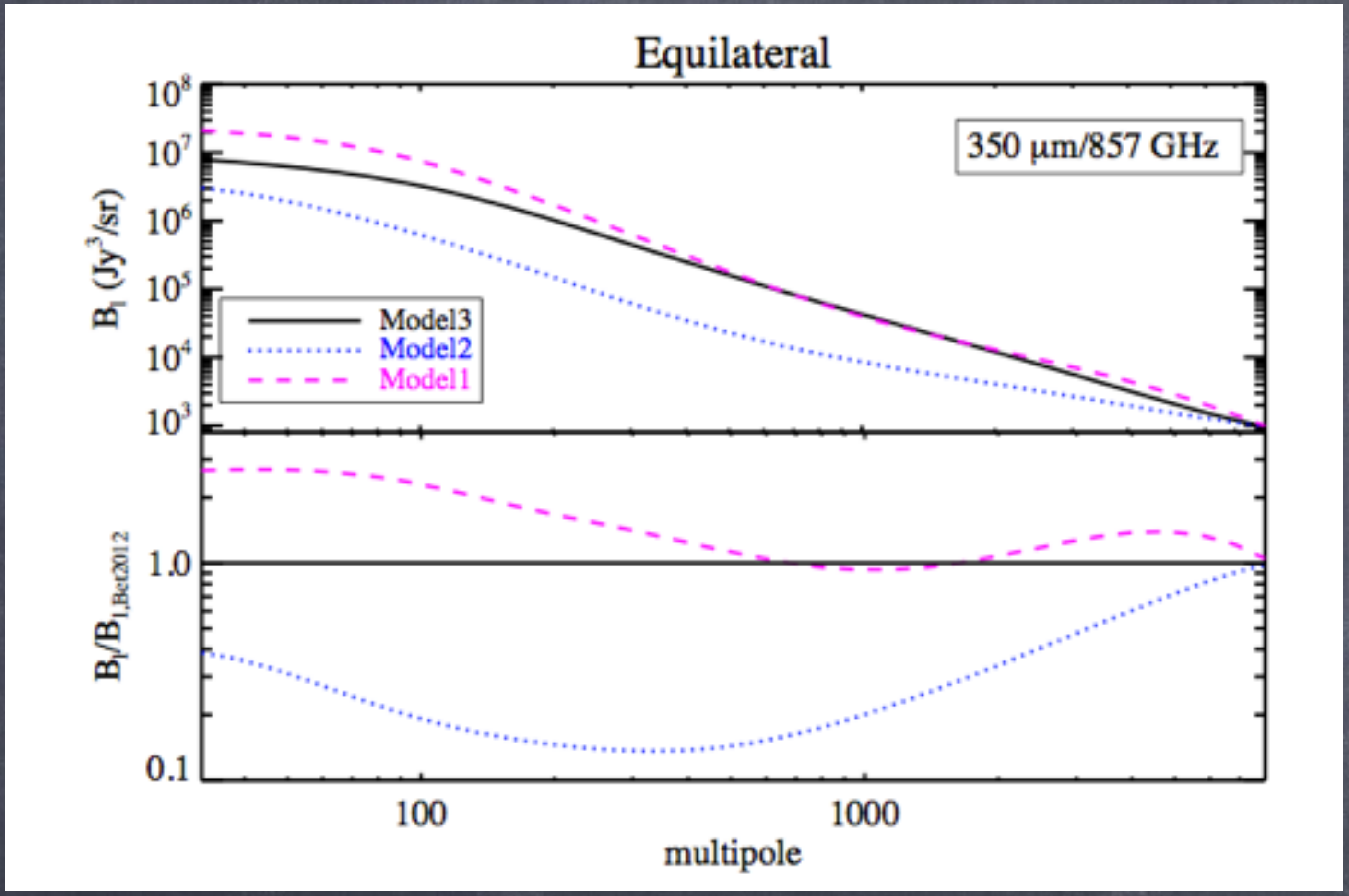
Power spectrum
Planck Early Papers

$\xrightarrow{\text{Fit of the HOD parameters}}$

Bispectrum

Variations of the bispectrum with the model of galaxies

350 um
850 GHz

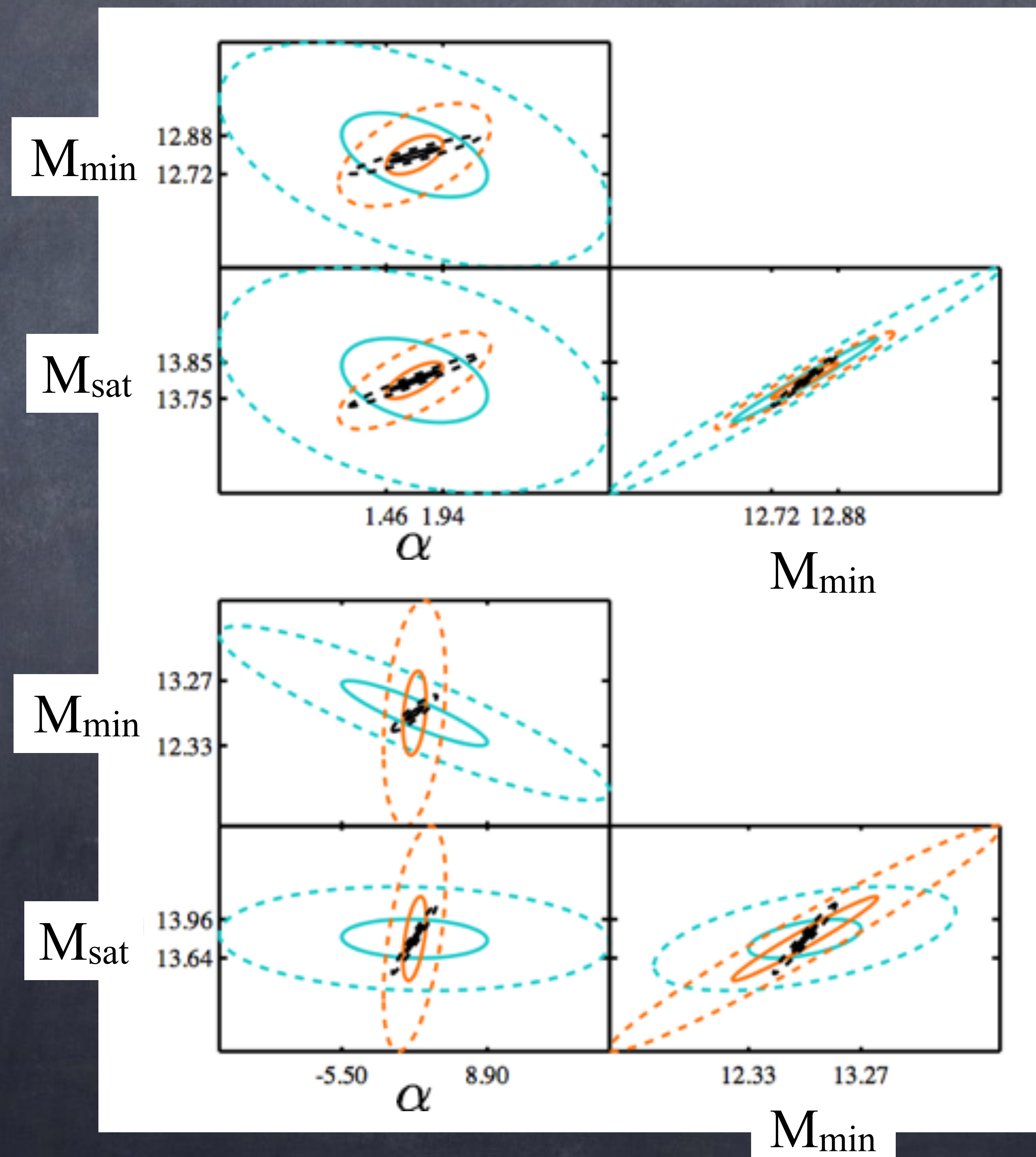


Variations depend on the scale : factor 5 at l ~ 300

Power spectrum + bispectrum
Constrain models of evolution of galaxies

Constraining HOD parameters by combining power spectrum and bispectrum

- 350 um
- 50 % of the sky



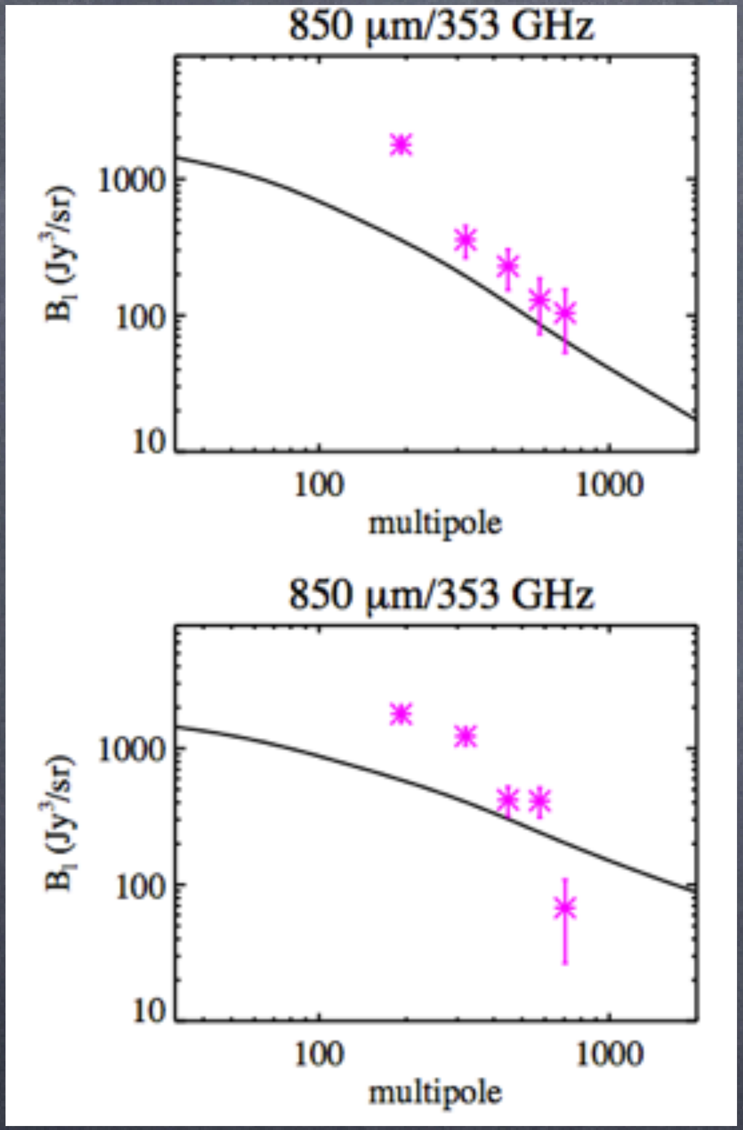
Ideal case : only CIB anisotropies

Realistic case : with foregrounds residuals (CMB, Galactic dust)

Power spectrum
Bispectrum
Combination

——— : 1 sigma
- - - - : 2 sigma

Comparison with measurements



Measurements are steeper than the model

The main assumption

$$C_\ell^\lambda = \int \frac{\mathrm{d}z}{r^2} \frac{\mathrm{d}r}{\mathrm{d}z} a^2(z) \bar{j}_\lambda^2(z) P_{\mathrm{gal}}(k, z)$$

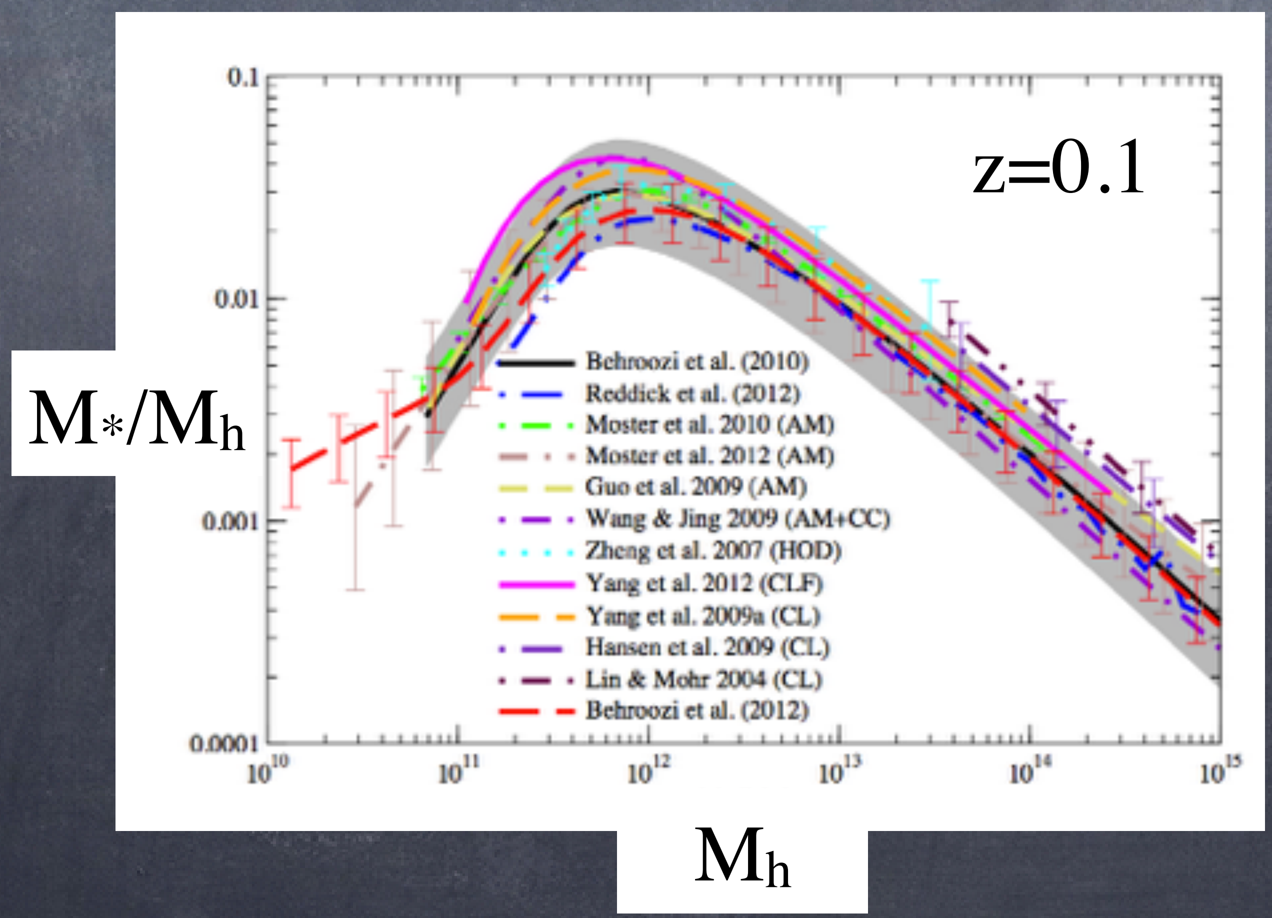
$$b_{\ell_1 \ell_2 \ell_3}^\lambda = \int \frac{\mathrm{d}z}{r^4} \frac{\mathrm{d}r}{\mathrm{d}z} a^3(z) \bar{j}_\lambda^3(z) B_{\mathrm{gal}}(k_1, k_2, k_3, z)$$

No dependence of the galaxy luminosity on the halo mass :
All galaxies have the same luminosity

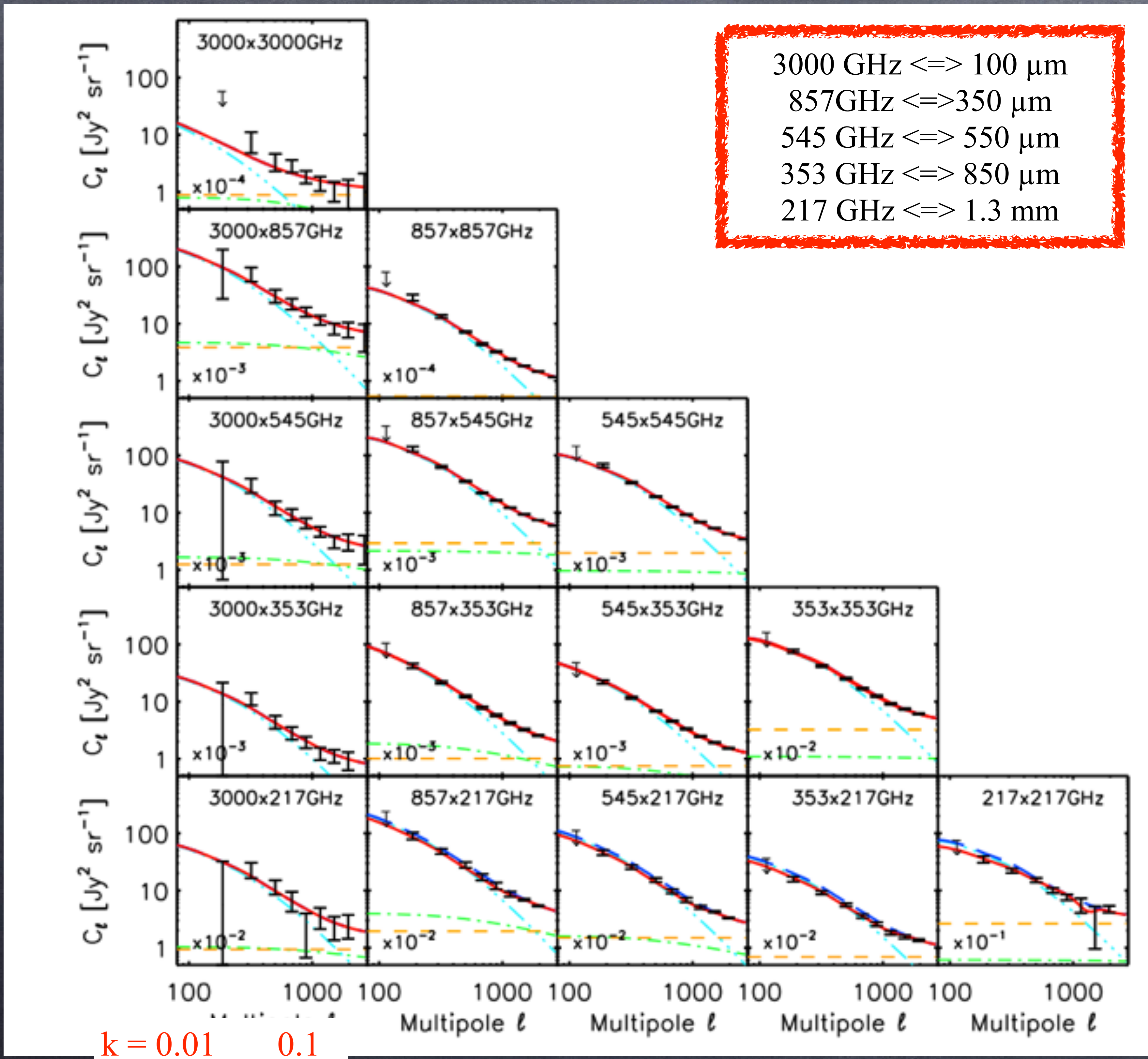
Caveats :
Unrealistic : in more massive halos galaxies are more massive and more luminous
Interpretation : overabundance of satellite halos
No simultaneous fit of measurements at several wavelengths

The Luminosity - Halo mass relation

$$L_{\mathrm{IR}}(M_h) \propto \frac{M_h}{\sqrt{2\pi\sigma^2_{L_{\mathrm{IR}}/M_h}}} \exp\left[-\frac{(\log_{10} M_h - \log_{10} M_{\mathrm{eff}})^2}{2\sigma^2_{L_{\mathrm{IR}}/M_h}}\right]$$



Application to the latest measurements

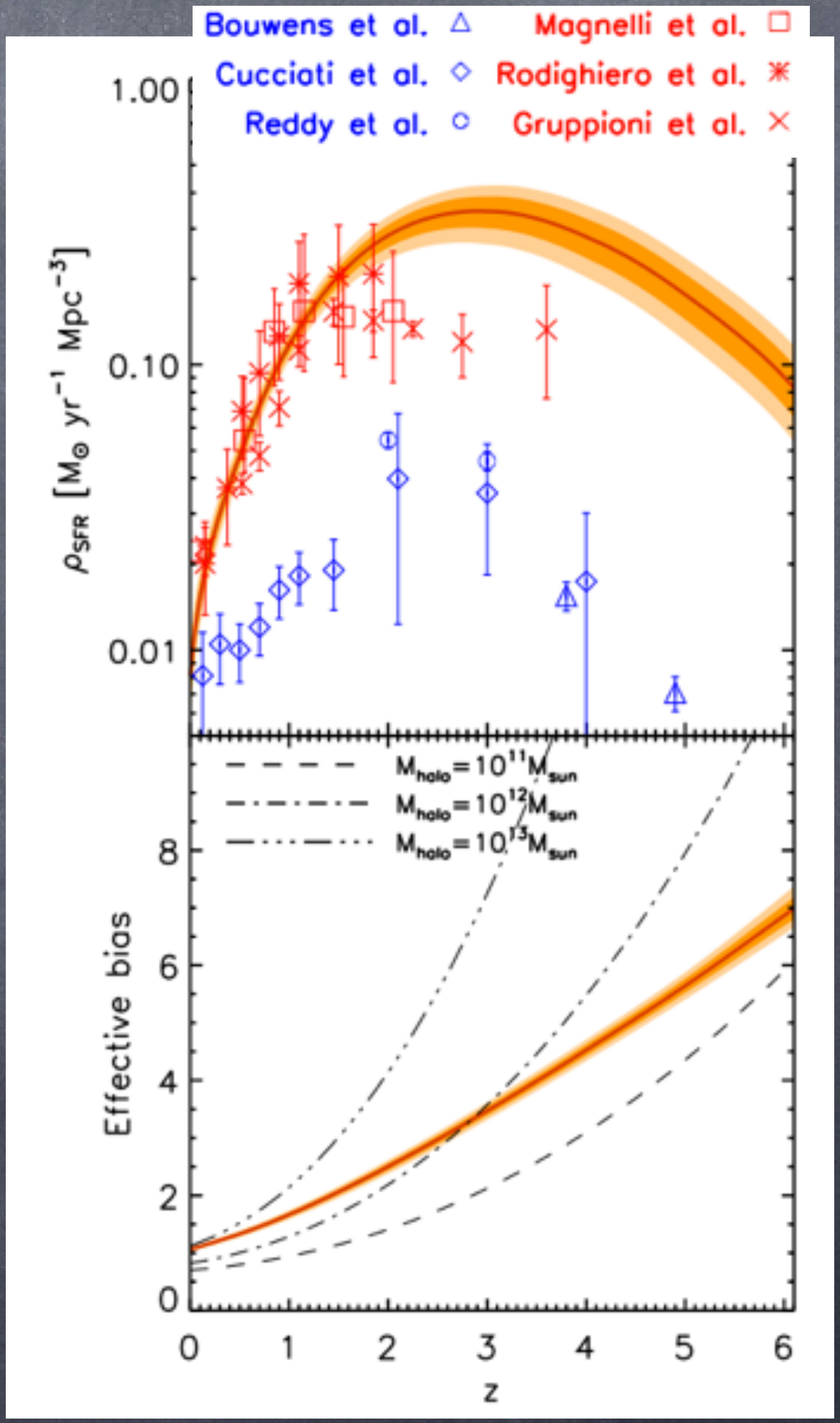


Simultaneous fit of auto and cross power spectra

The Planck Collaboration XXX

A new insight on dusty star-forming galaxies

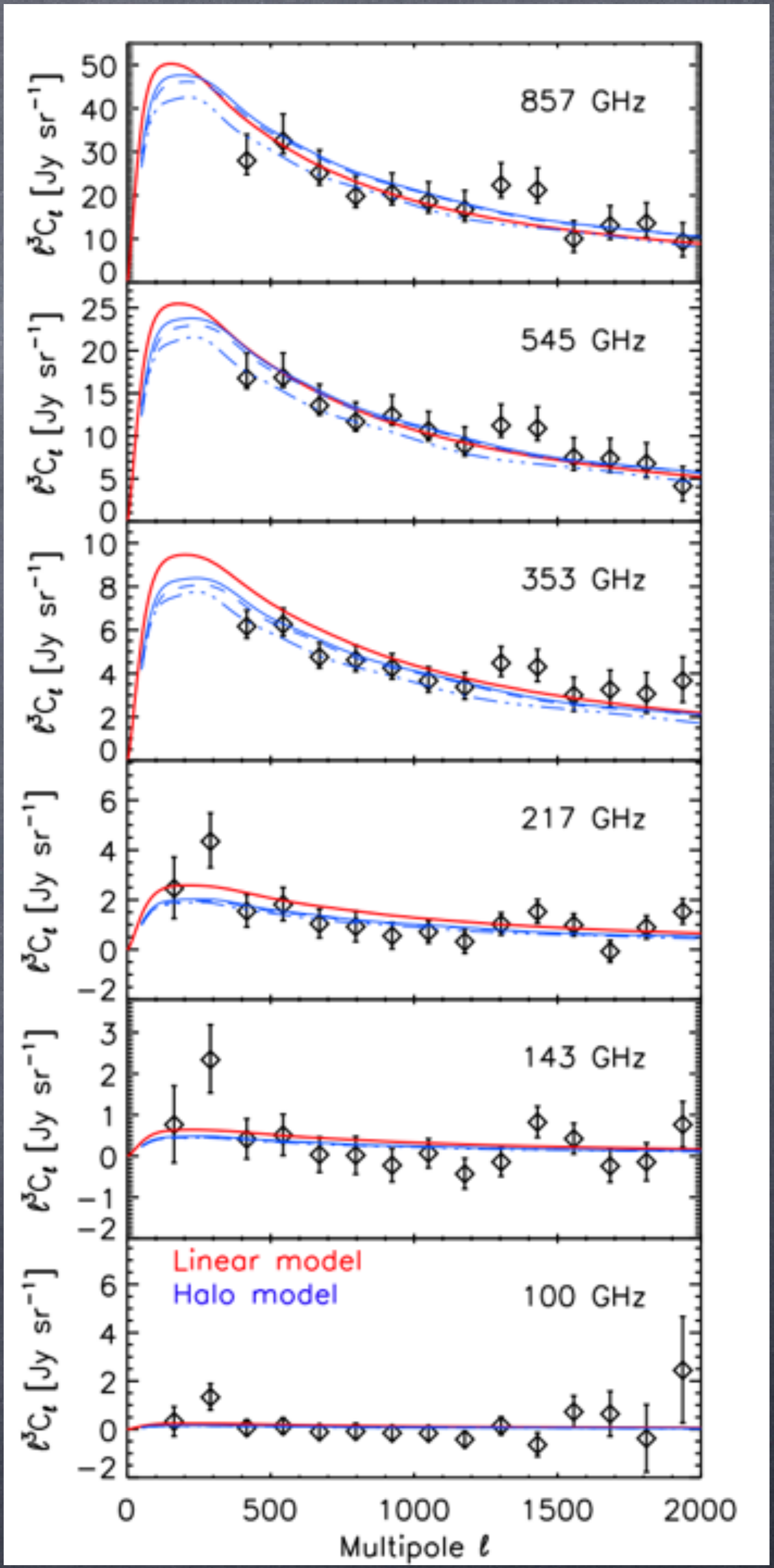
- Most efficient halo mass for galaxies generating the CIB
  - log M_{halo} = 12.6
- SFR density up to z~2.5
- CIB source : main sequence galaxies and not mergers



The Planck Collaboration XXX

CIB x CMB Lensing

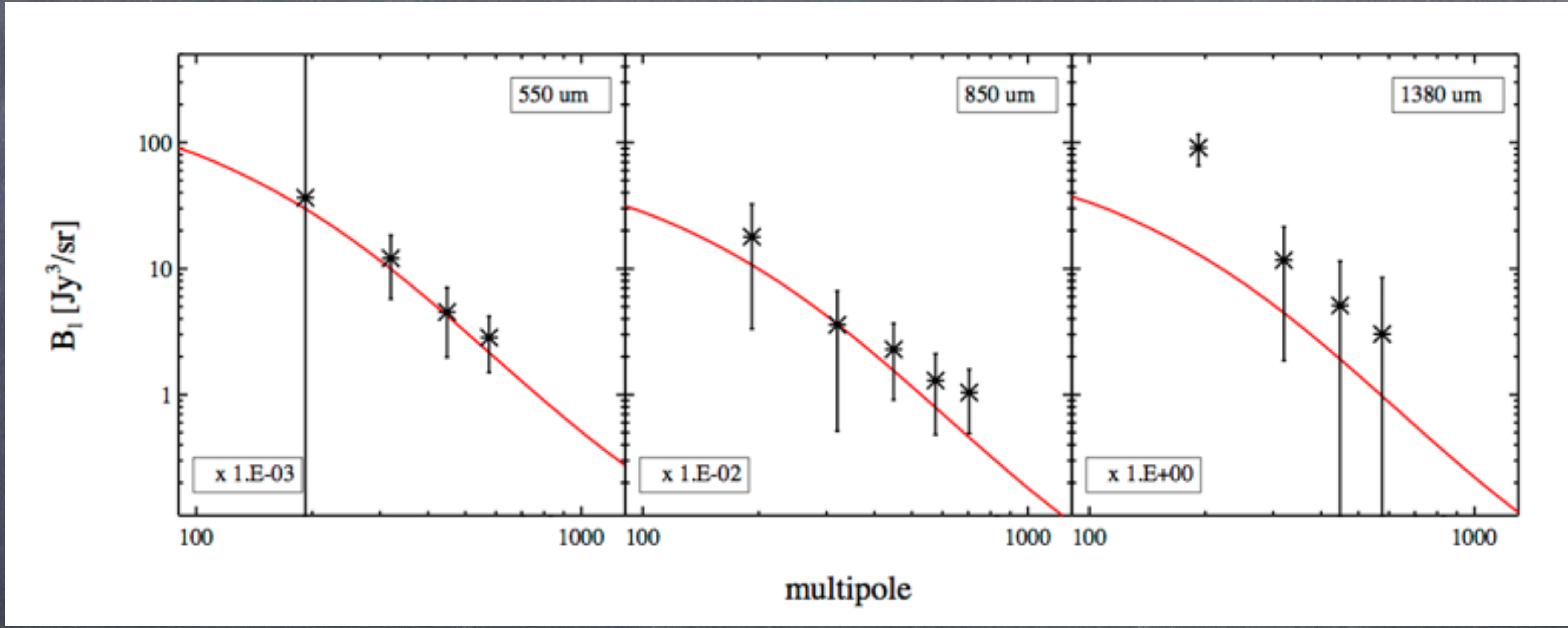
- CMB lensing : CMB photons are deflected by gravitational potentials before reaching us
- Probe of large scale structure at $1 < z < 3$
- Used their best fits
- Excellent agreement



The Planck Collaboration XXX

The bispectrum

Best fits parameters coming from Planck power spectra



550 and 850 um : remarkable agreement
1380 um : less remarkable

A work in progress

- Carry best fits of bispectra measurements with this model
- Constrain the SFRD at $z > 2.5$?
- Constrain the redshift evolution of the effective mass?
- Best fits consistent with those coming from the power spectrum?
- Known limitation : the locality and determinism of the bias

Conclusion & Perspectives

- CIB anisotropies : preferential probe of star formation within large scale structures at the peak of the Universe SFR
- New insight on the relation between galaxies and dark matter : the galaxy bias
- New insight on the relation between star formation and dark matter
- Complete modelling of the CIB anisotropies
- Main uncertainties : SED
- Requires new measurements of SEDs at high redshift ($z > 4$)