Models of clustering in the framework of the halo model

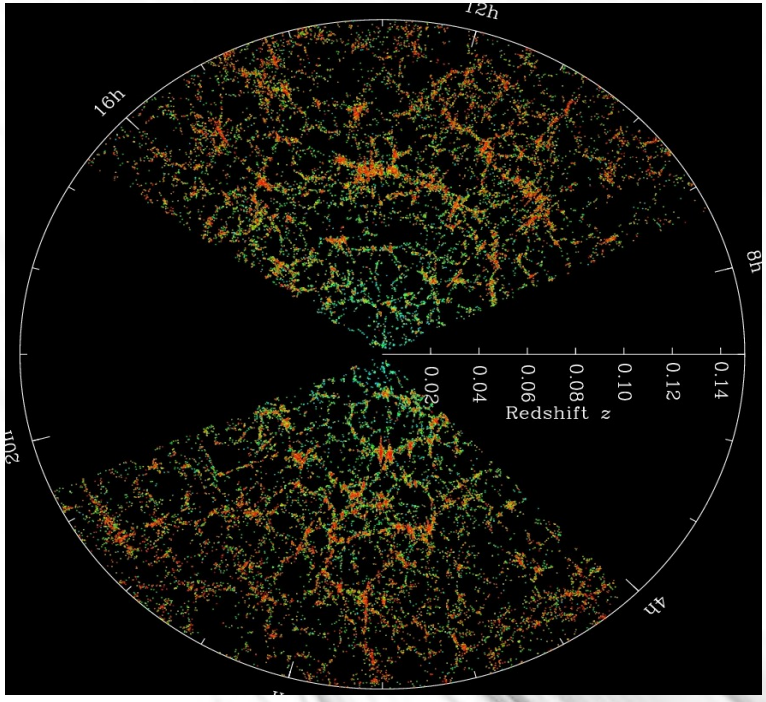
Aurélie Pénin
Laboratoire d'Astrophysique de Marseille, France

In collaboration with Eric Jullo, Johan Comparat, Jean-Paul Kneib
Guilaine Lagache, Olivier Dore, Matthieu Bethermin

Santa Fe Cosmology Workshop

The clustering of galaxies

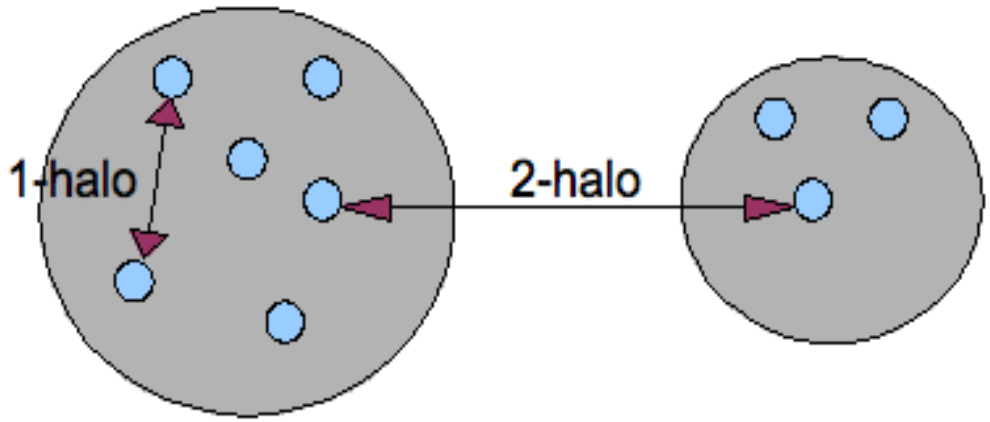
- In the optical : SDSS
- Galaxies are not distributed randomly : f laments, voids, knots
- Study of the clustering
  - Understand the distribution of dark matter and its link with galaxies
  - Understand the formation of galaxies



Blanton et al 2006

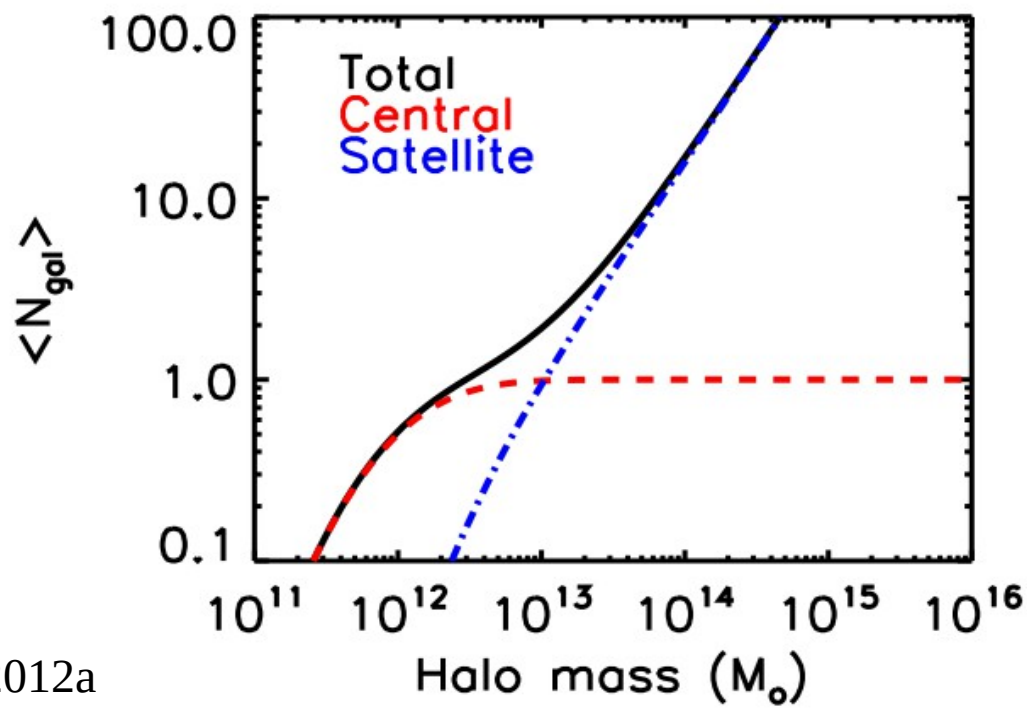
The halo model

- Main assumption : all DM is bound up into halos
- Halo : virialised object ~200 denser than the background
- Split into two terms
  - 1-halo : 2 galaxies in the same halo
  - 2-halo : 2 galaxies in two different halos



The halo occupation distribution

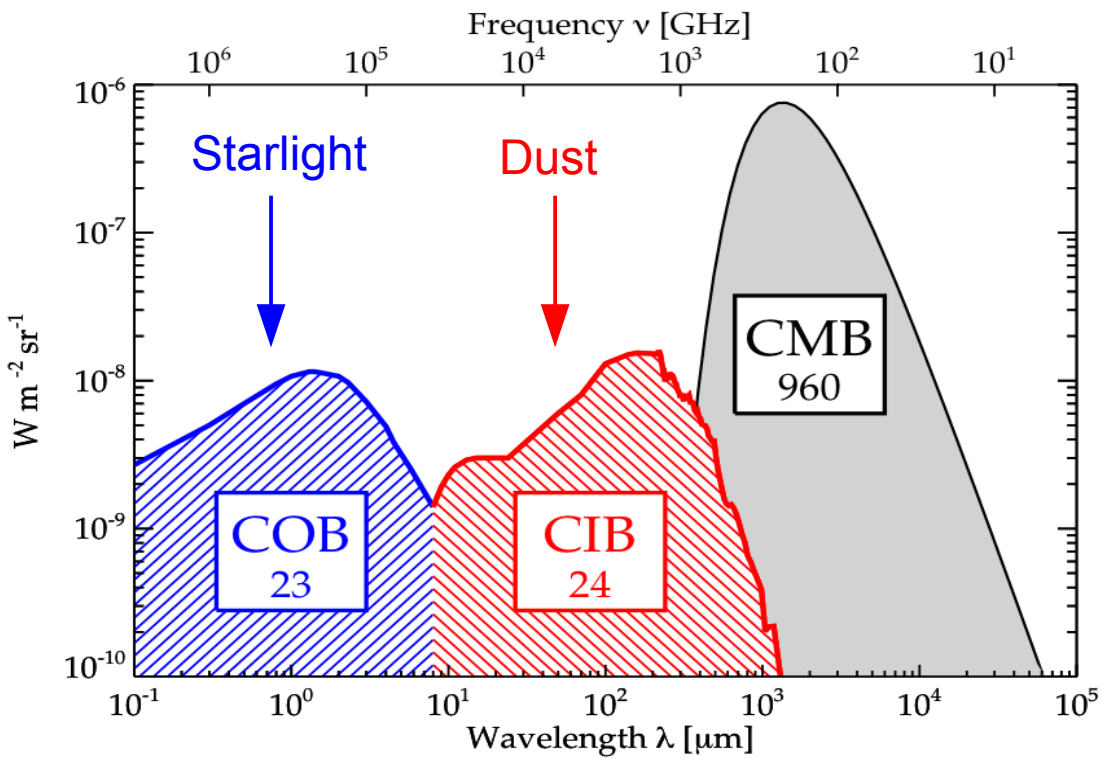
- Statistical approach
- Number of galaxies in a halo of mass M
- Split into two terms $\langle N_{gal} \rangle = \langle N_{cen} \rangle + \langle N_{sat} \rangle$
- Satellite : power law
- Central : step function
- The overall is parametric
- Only dependance :
  - Halo mass



Penin+2012a

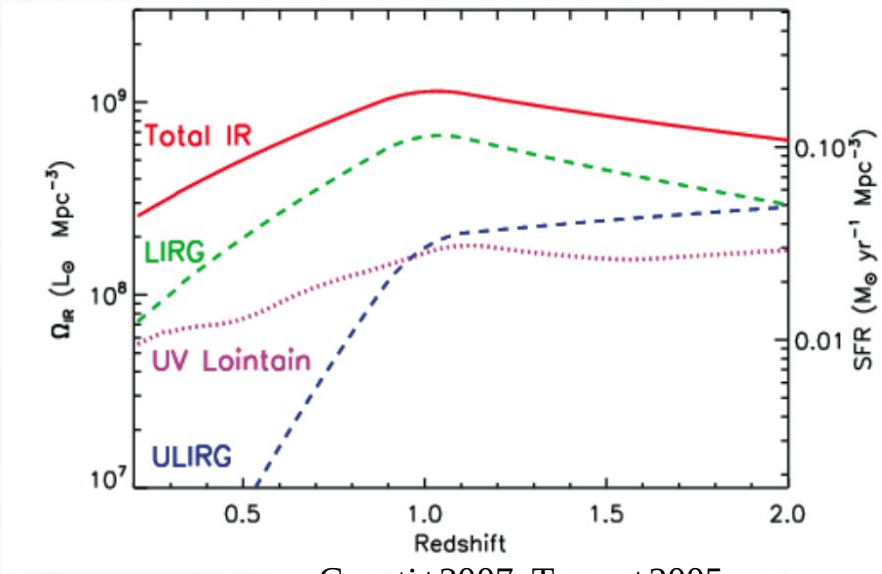
The extragalactic background light

- Contains the history of the energy production in the post-recombination Universe
  - Amplitude : formation and evolution of objects
  - Spatial fluctuations (10-15%) : spatial distribution of the objects

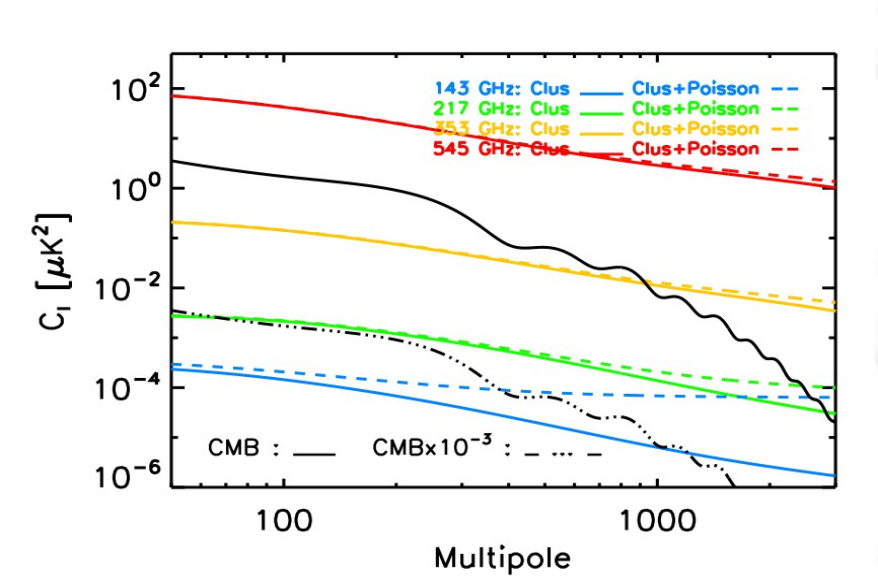


The cosmic infrared background

- Contribution of star-forming galaxies integrated on the whole history of the Universe
- Star-forming galaxies : high star formation rates
- **Evolution with the redshift**
  - CIB/COB~1
  - In the local Universe IR/OP~1/3
  - Increase of the energy emitted in the IR with z
- **Spatial structure**
  - Clustering
  - Strong contaminant to the CMB
- **High wavelengths probe high redshift galaxies**



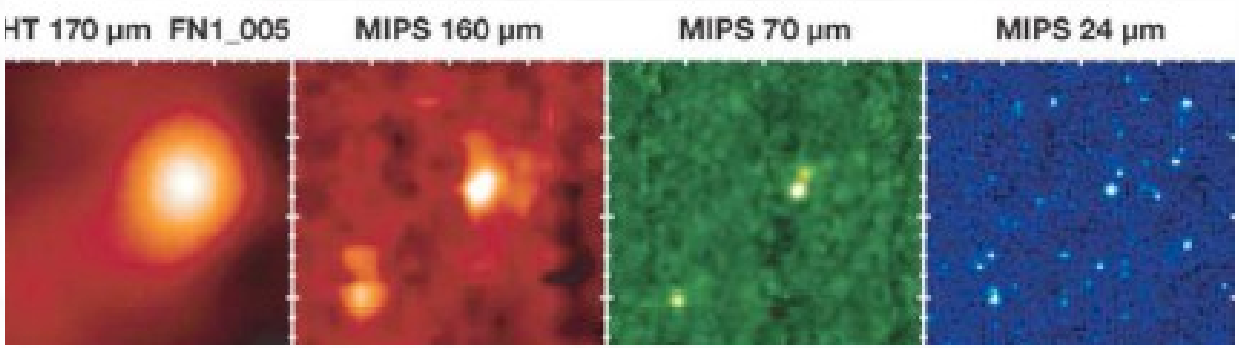
Caputi+2007, Tresse+2005



Planck early papers

CIB & Confusion

- Loss of small spatial scales at long wavelength due to a bad resolution of the instruments

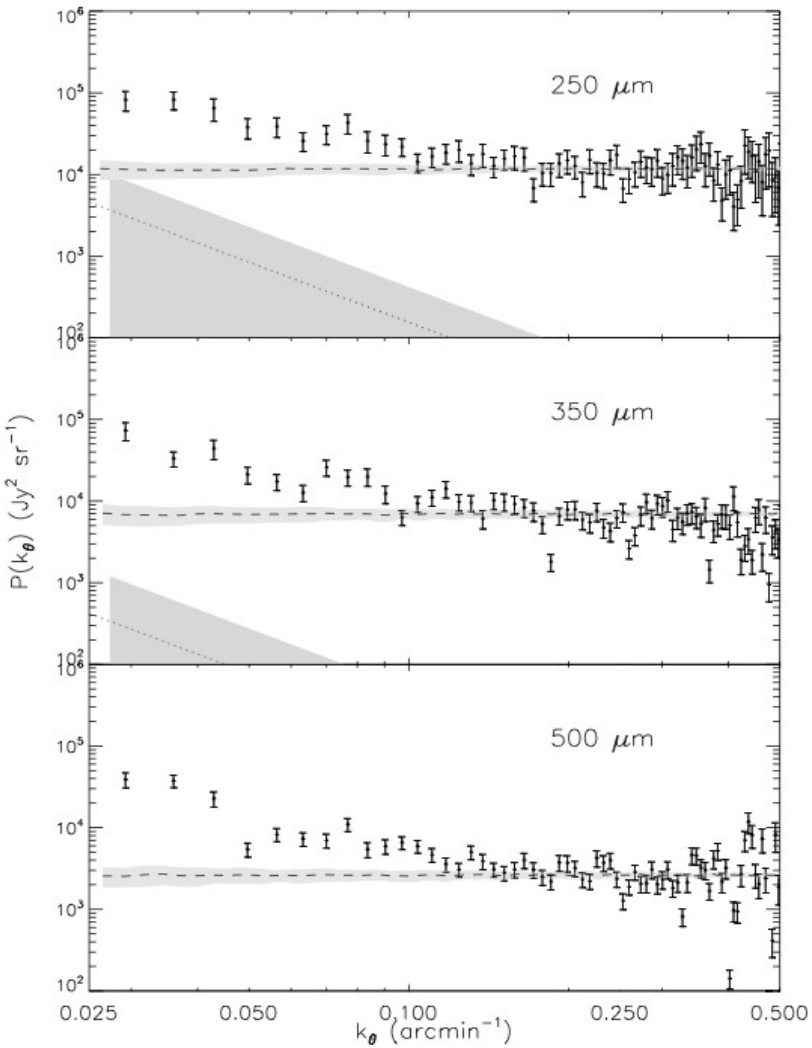


wavelength (μm)	S_{lim}	fraction of resolved CIB	Reference
ISOCAM/ISO 15μm	50 μJy	80 %	Elbaz et al. (2002)
Spitzer/MIPS 24 μm	60 μJy	70 %	Papovich et al. (2004)
Spitzer/MIPS 70 μm	1.2 mJy	60 %	Frayer et al. (2006)
Herschel/PACS 100 μm	3 mJy	45 %	Berta et al. (2010)
Herschel/PACS 160 μm	5.7 mJy	52 %	Berta et al. (2010)
Herschel/SPIRE 250 μm	20 mJy	15 %	Oliver et al. (2010)
Herschel/SPIRE 350 μm	20 mJy	10 %	Oliver et al. (2010)
Herschel/SPIRE 500 μm	20 mJy	6 %	Oliver et al. (2010)
SCUBA 850 μm	1 mJy	65 %	Smail et al. (2002)

- Use of statistical methods (P(D), stacking, power spectrum)

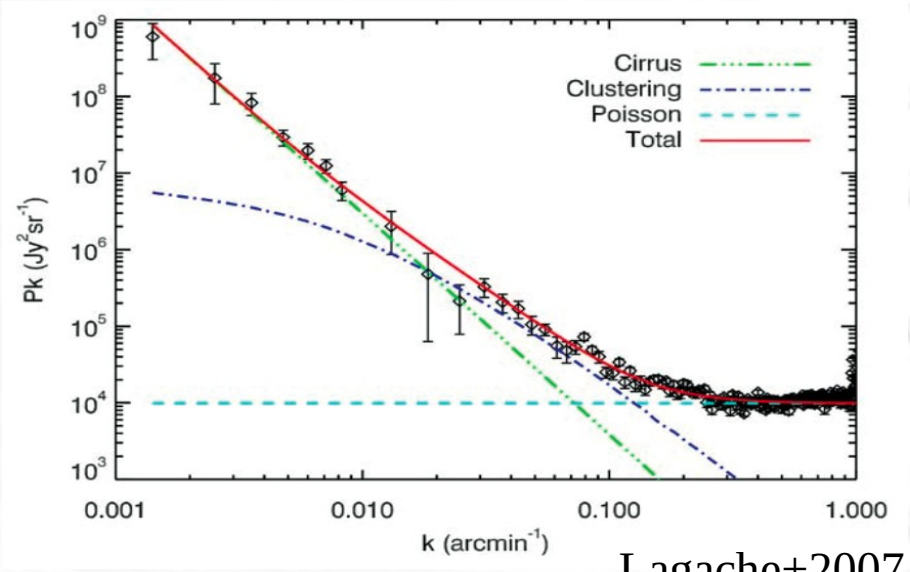
Clustering in the Cosmic Infrared Background

BLAST



Viero+2009

Spitzer MIPS 160 um



Lagache+2007

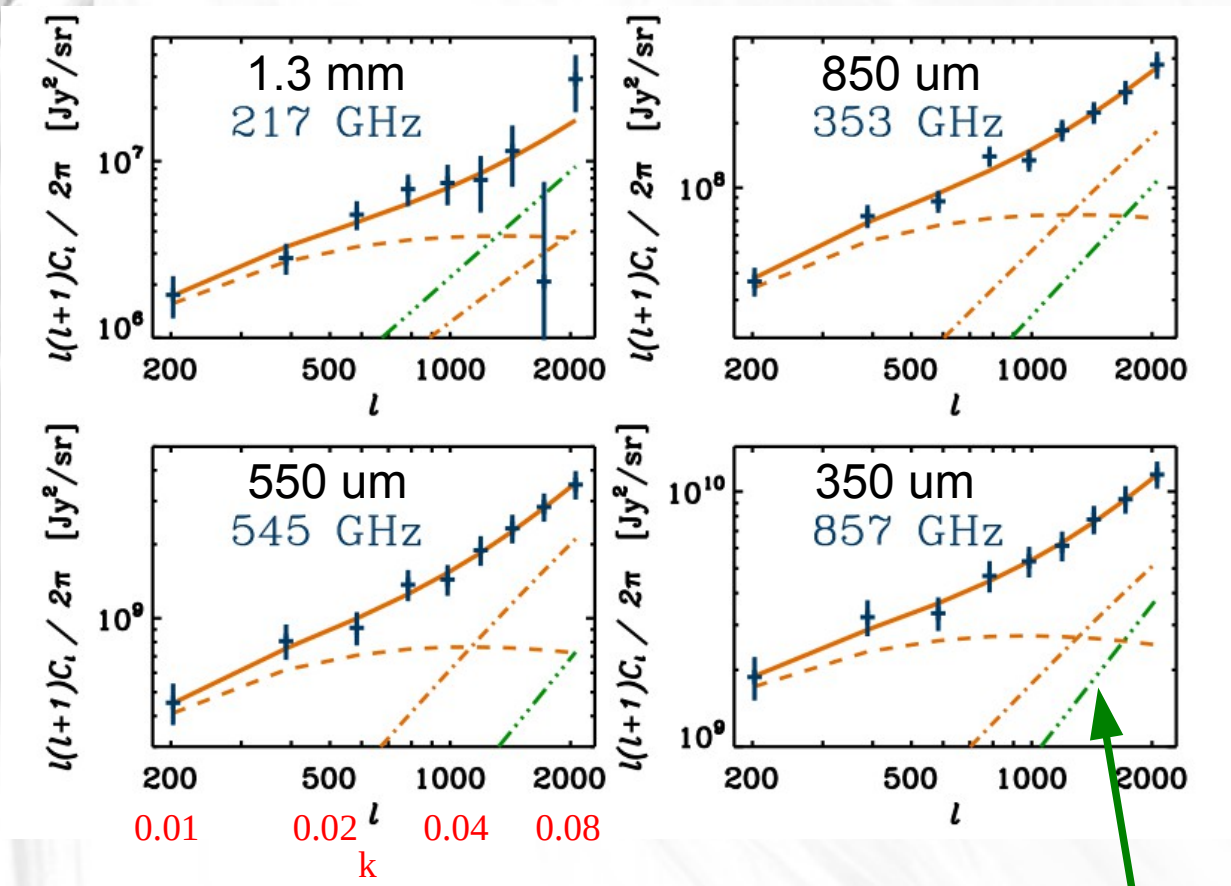
3 astrophysical components :

- Clustering
- Poisson noise
- Cirrus contribution

Excess of power at intermediate scales due to dusty star-forming galaxies clustering

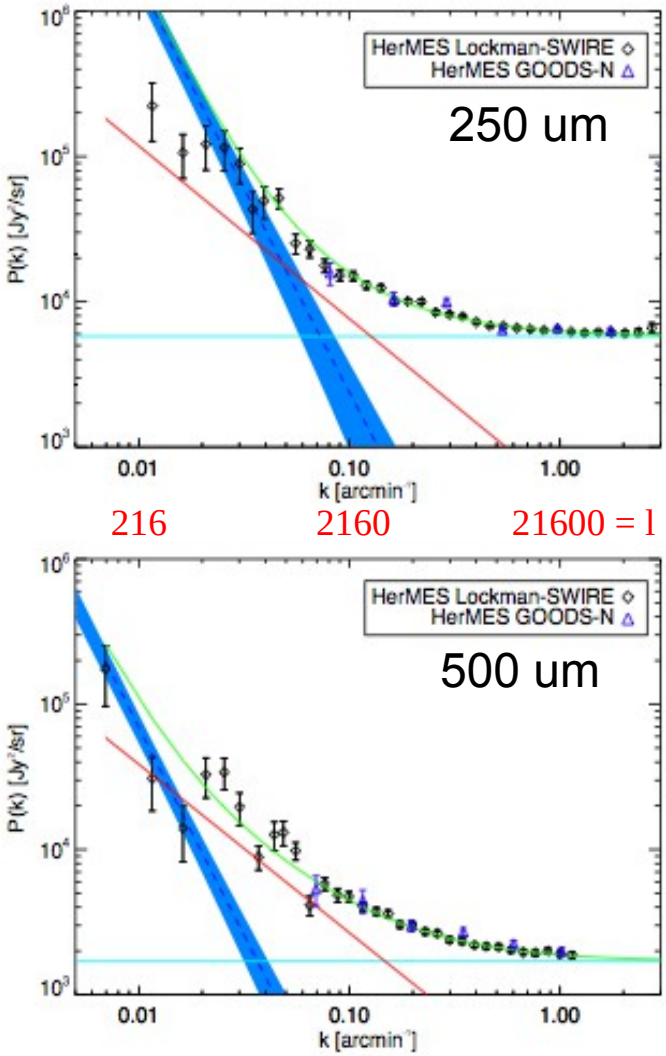
Latest measurements

Planck



The Planck Collaboration XVIII

Herschel



Amblard+2011

Why a new model of galaxies clustering?

- Need of one model to analyse all available measurements
- Common way : use of 2 models
  - Galaxies evolution
  - dark matter distribution
- Model of evolution of star-forming galaxies
  - Lagache+2004 :
    - used to be the most up to date model
    - does not reproduce Herschel differential number counts and the redshift distribution of the CIB
  - considered as free parameters (Amblard+2011)
- Distribution of DM
  - halo model (Viero+2009, Amblard+2011, Xia+2012)
  - biased linear power spectrum (Lagache+2007)

Power spectrum of the CIB anisotropies

- Galaxies : Béthermin+2011
- Dark matter : halo model (HOD, Tinker & Wetzel 2010)

$$C_\ell^{\lambda\lambda'} = \int dz \frac{dr}{dz} \frac{a^2(z)}{d_A^2} \bar{j}_\lambda(z) \bar{j}_{\lambda'}(z) P_{ss}(k = \frac{l}{d_A}, z)$$

IR galaxies emissivites

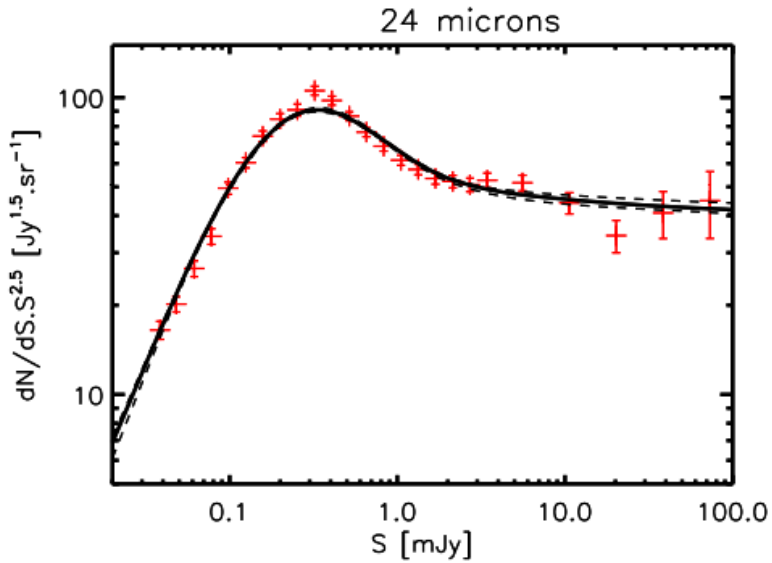
Model of evolution of IR galaxies

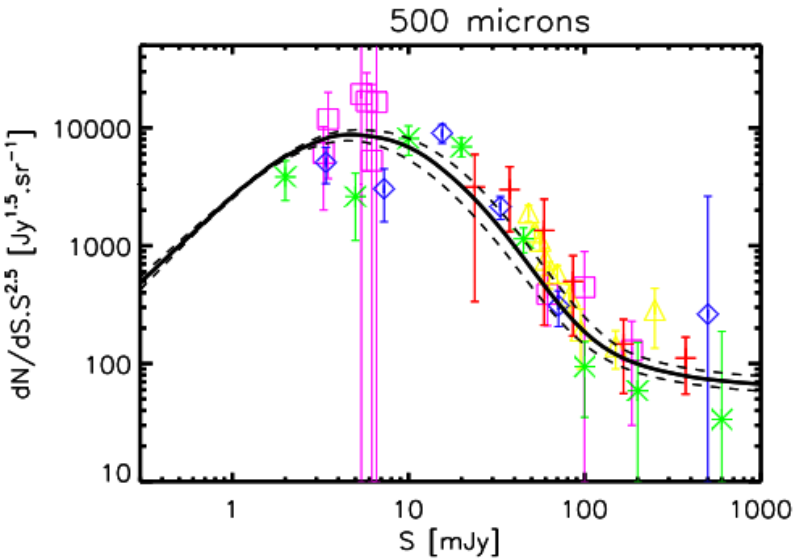
3D power spectrum of the galaxies

Halo model

Evolution model of IR galaxies

- Bethermin et al. 2011
- Parametric luminosity function
- 13 parameters
- Fitted to data
  - Luminosity functions
  - Differential number counts
  - CIB levels

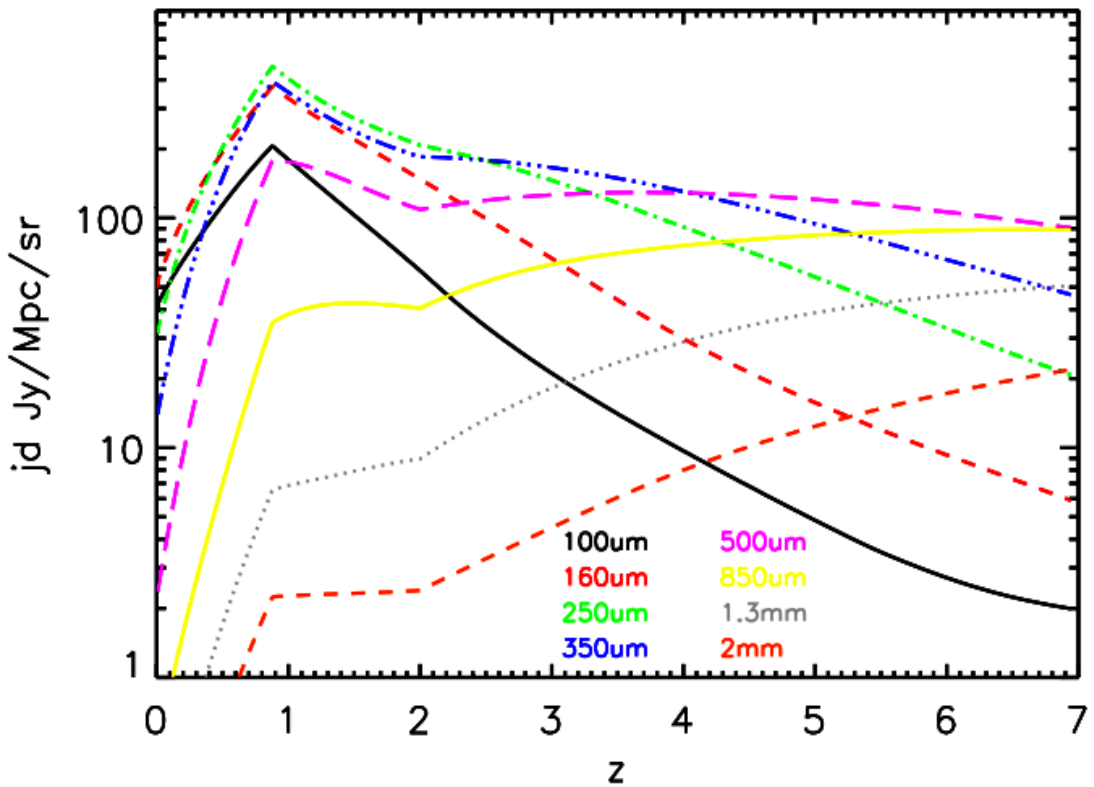




Evolution model of IR galaxies

- Use of the best f t to compute emissivities

$$j_\nu(z) = \left(a\frac{d\chi}{dz}\right)^{-1} \int_L S \frac{dN}{dz d(lnL)} d(lnL)$$



Halo Occupation Distribution (HOD)

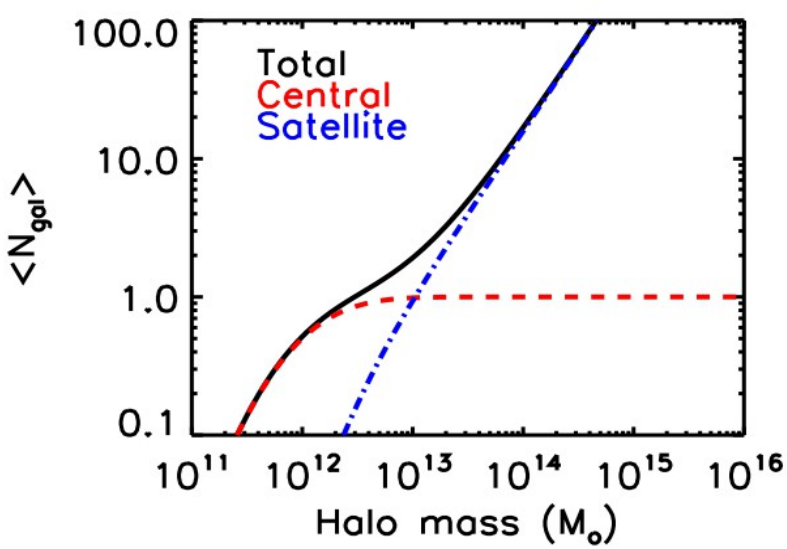
$$\langle N_{gal} \rangle = \langle N_{cen} \rangle + \langle N_{sat} \rangle$$

Number of central Galaxies

Number of satellite galaxies

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

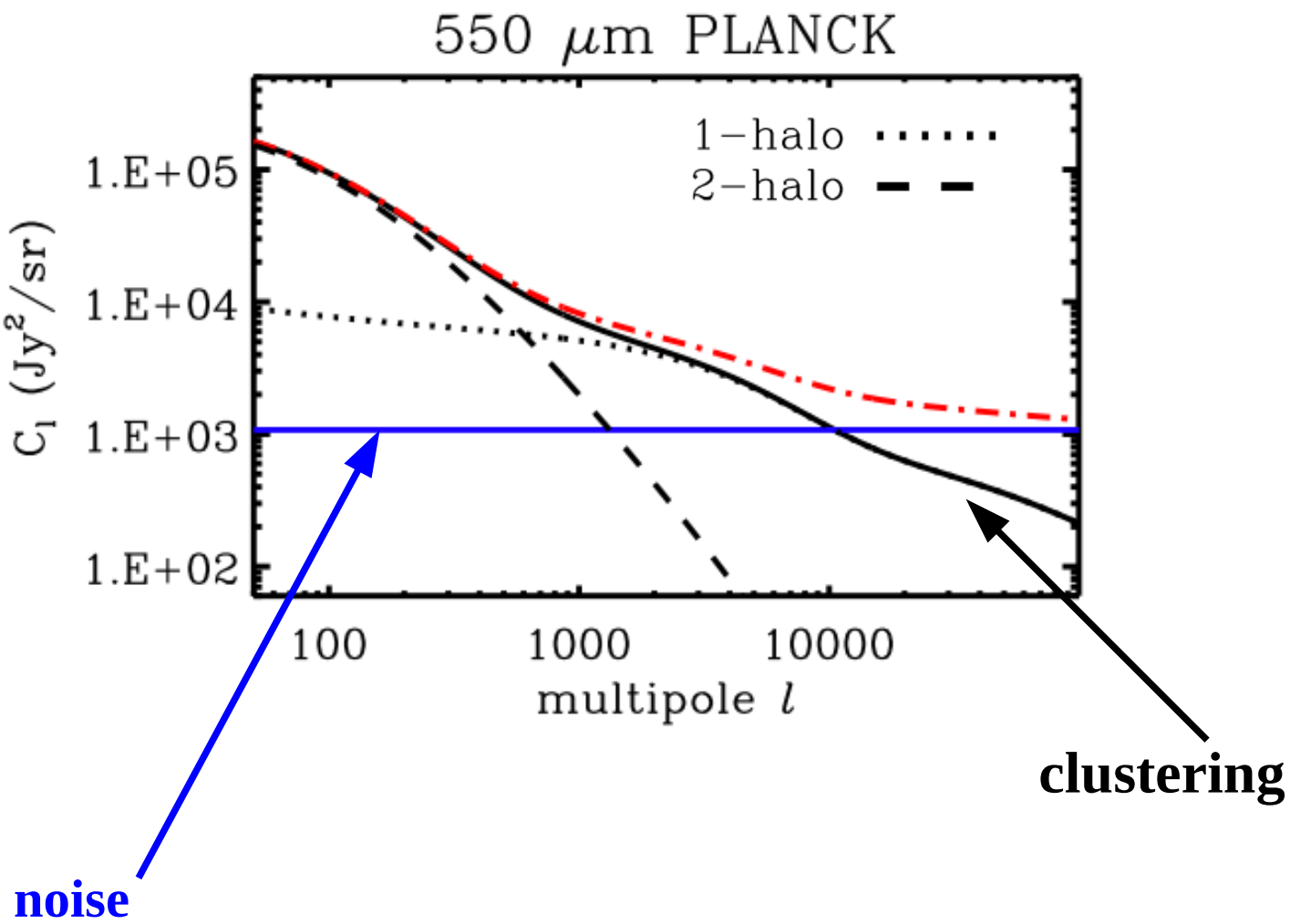
$$\langle N_{sat} \rangle = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\log M - \log 2M_{min}}{\sigma_{\log M}}\right)\right]\left(\frac{M}{M_{sat}}\right)^{\alpha_{sat}}$$



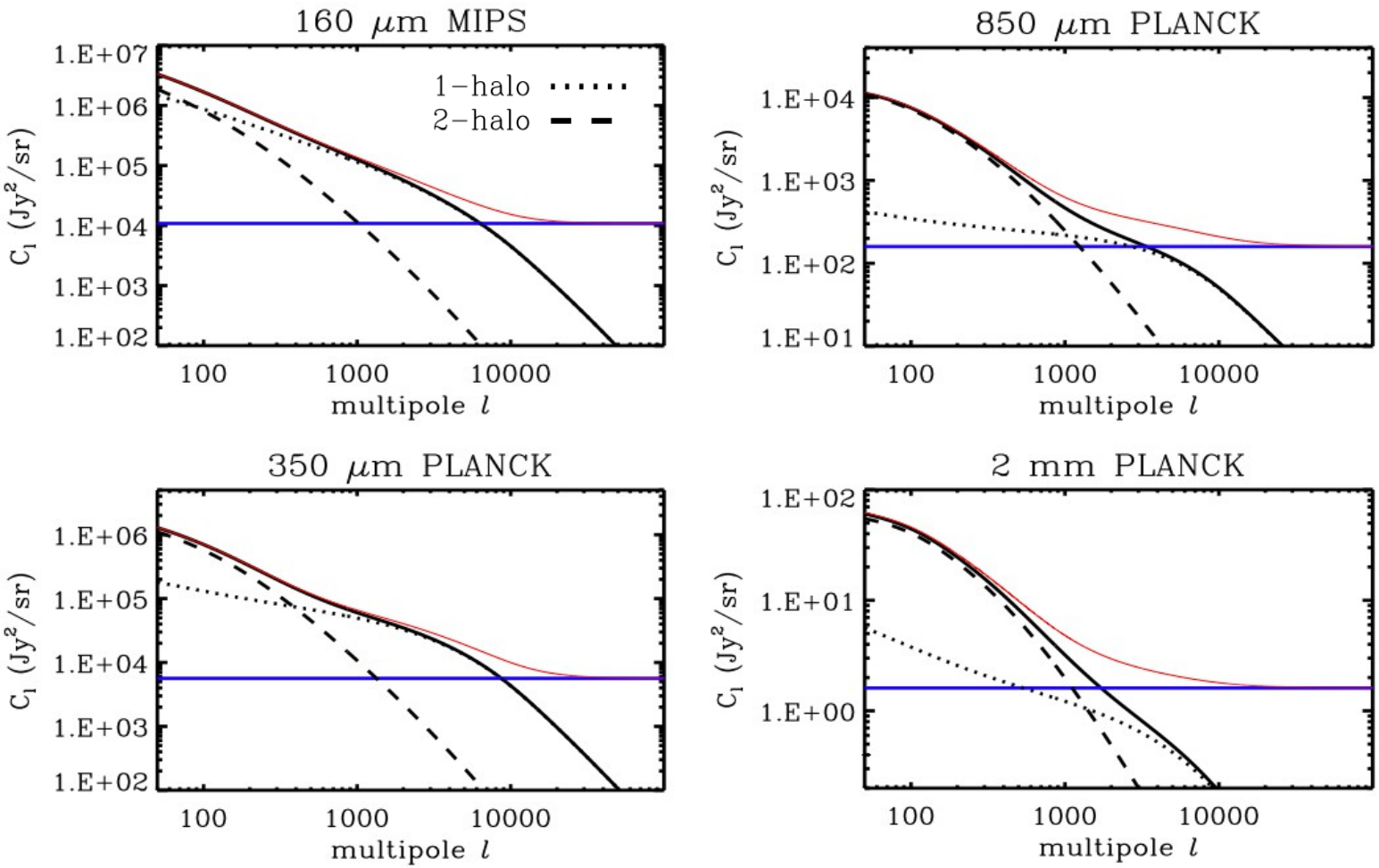
- **<u>Parameters of the HOD:</u>**
- M_{min} minimum halo mass in which a SB galaxy lies
- M_{sat} normalisation mass
- $_{sat}$ slope of the number of satellites
- $_{logM}$ the width of the transition between 0 central galaxy and 1

Power spectra

Addition of the Poisson noise (Béthermin+2011)



Power spectra



- 1h decreases with the wavelength => can be mistaken for the poisson noise
- 160 um : 1h can be measured accurately

Penin+2012

Degeneracies & constraints

- Fisher analysis :

$$F_{ij} = \sum_{\lambda} \sum_{\ell} \frac{1}{\sigma_{\ell}^{\lambda 2}} \frac{\partial C_{\ell}^{\lambda}}{\partial \theta_i} \frac{\partial C_{\ell}^{\lambda}}{\partial \theta_j}$$

Instrumental noise level

- Uncertainties :

$$\sigma_l^2 = \left(C_l + \frac{N_l}{B_l^2} \right)^2 \frac{2}{f_{sky}(2l+1)}$$

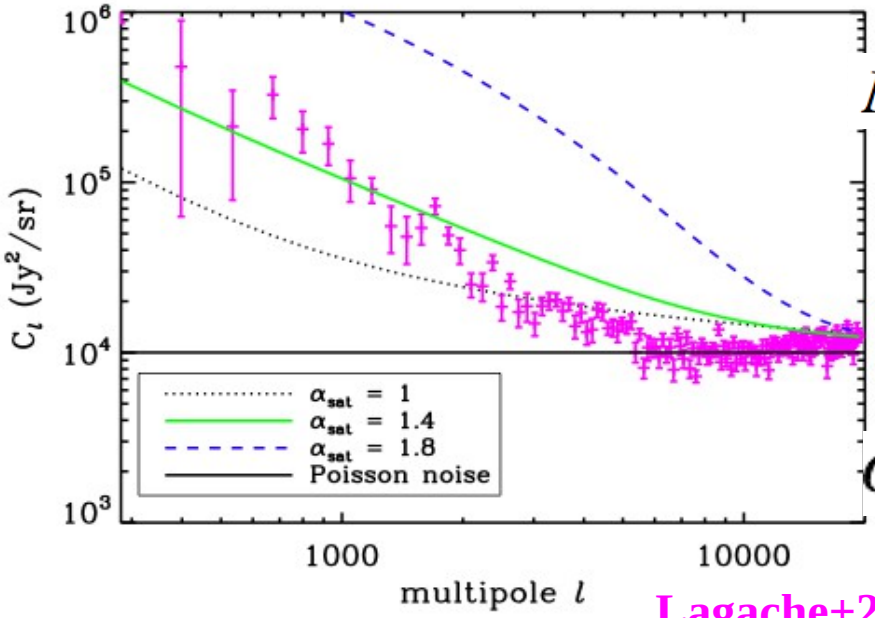
PSF power spectrum

Sky fraction

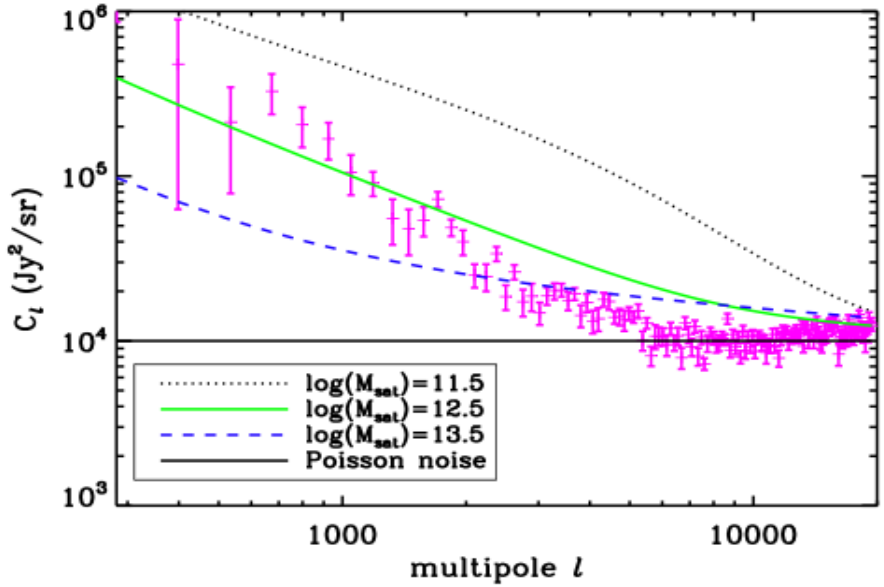
- Mock data : one set of parameters for all the wavelengths

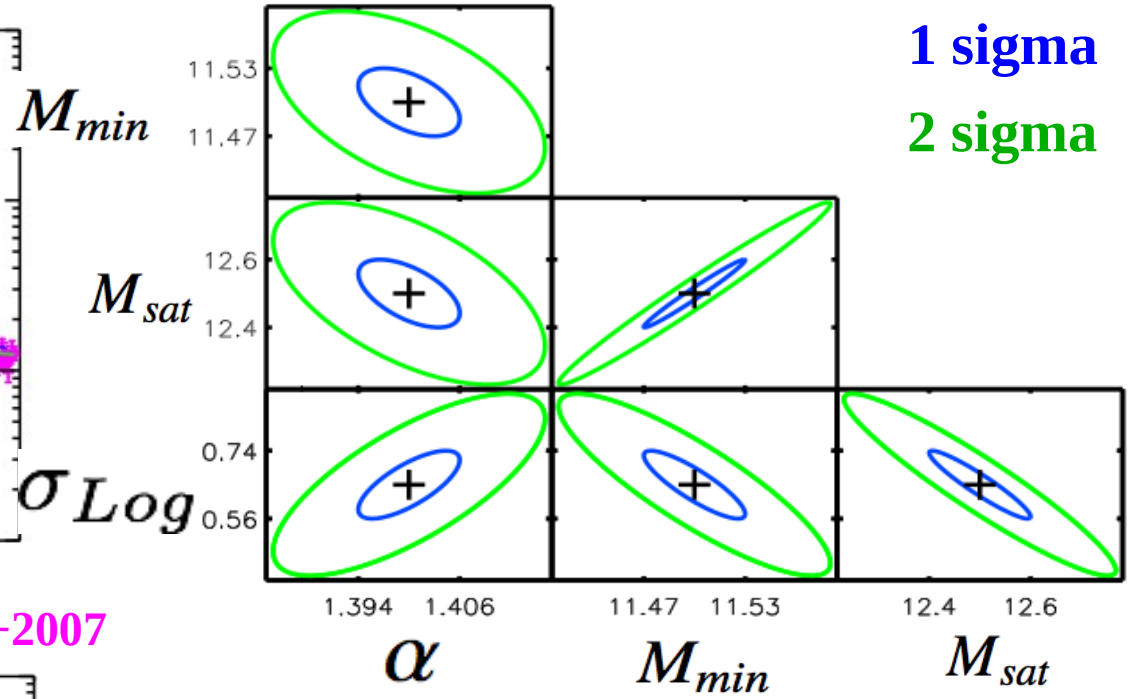
  IRIS 100 um , MIPS 160 um , Herschel & Planck 250 um, 350 um, 500/550 um, 850 um, 1.3 mm

Halo model dependencies



Lagache+2007





1 sigma

2 sigma

- Msat = 3.3 Mmin
- Parameters are well constrained

Penin+2012

Galaxy model dependencies

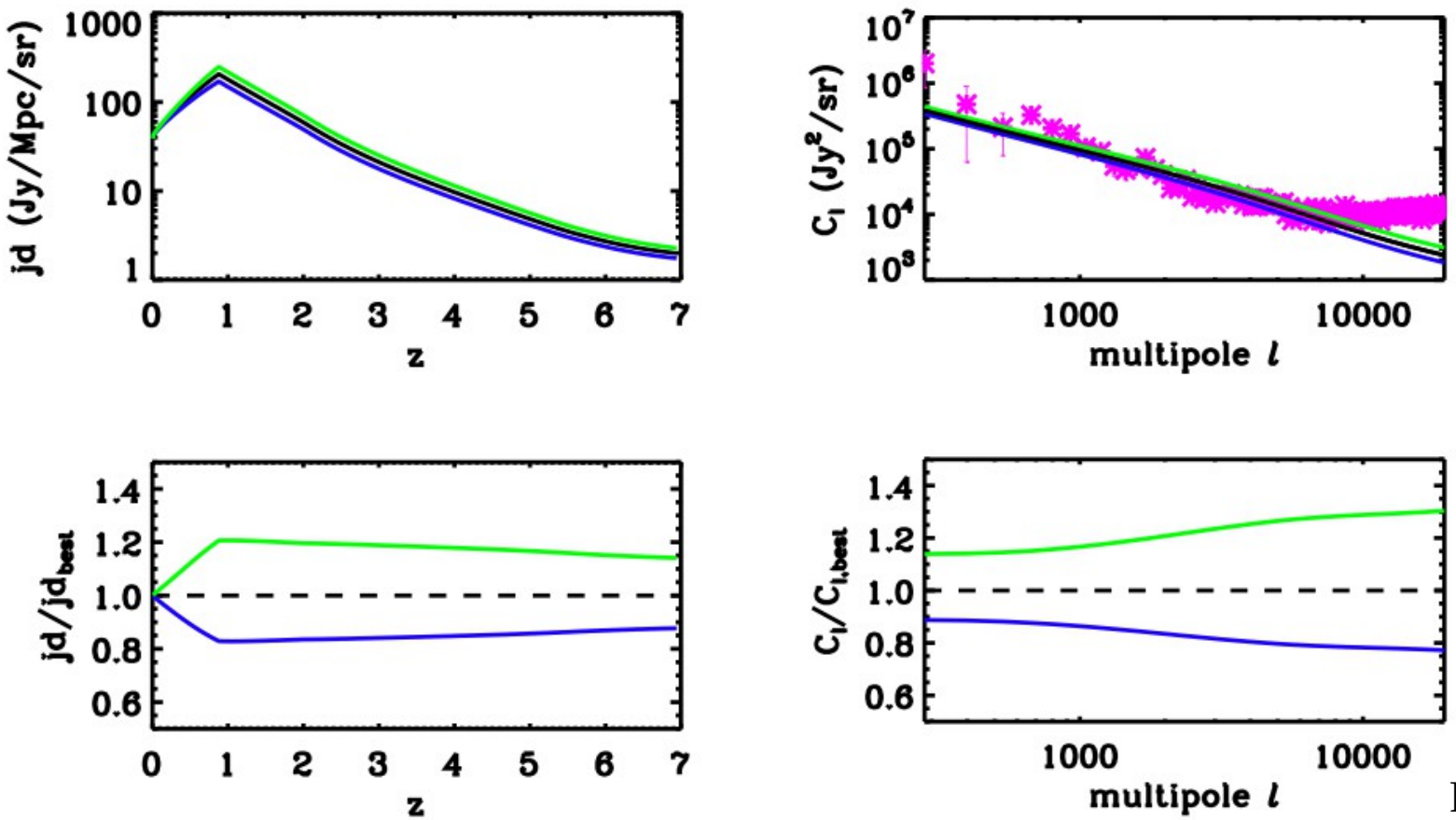
$$L^\star(z) = L^\star(z=0)(1+z)^{r_L}$$

$r_{L,\ \mathrm{low}\ z} = 2.93$

$r_{L,\ \mathrm{low}\ z} = 2.93 + 2\sigma$

$r_{L,\ \mathrm{low}\ z} = 2.93 - 2\sigma$

- Parameter ruling the redshift evolution of the luminosity function at 0<z<0.9
- At 160 um



Penin+2012

Degeneracies

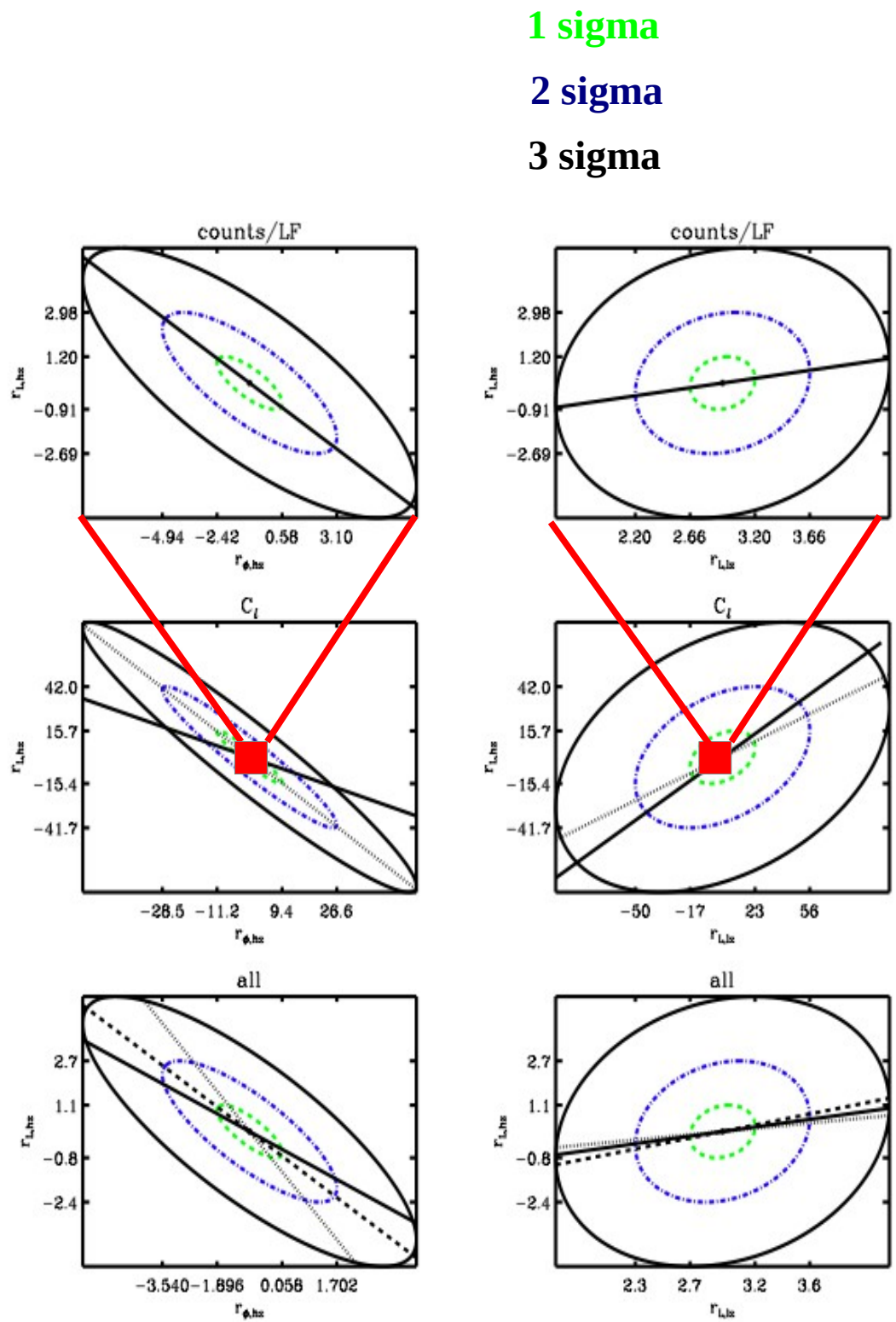
- Parameters that constrain the redshift evolution
- Counts/LF

$$r_{L^\star,lz} = 2.93 \pm 0.27$$

- Cl :

$$r_{L^\star,lz} = 2.93 \pm 20.0$$

- Counts/LF + Cl
  - Same error $r_{L^\star,hz}$
  - Better error $r_{\phi^\star,hz}$



Penin+2012

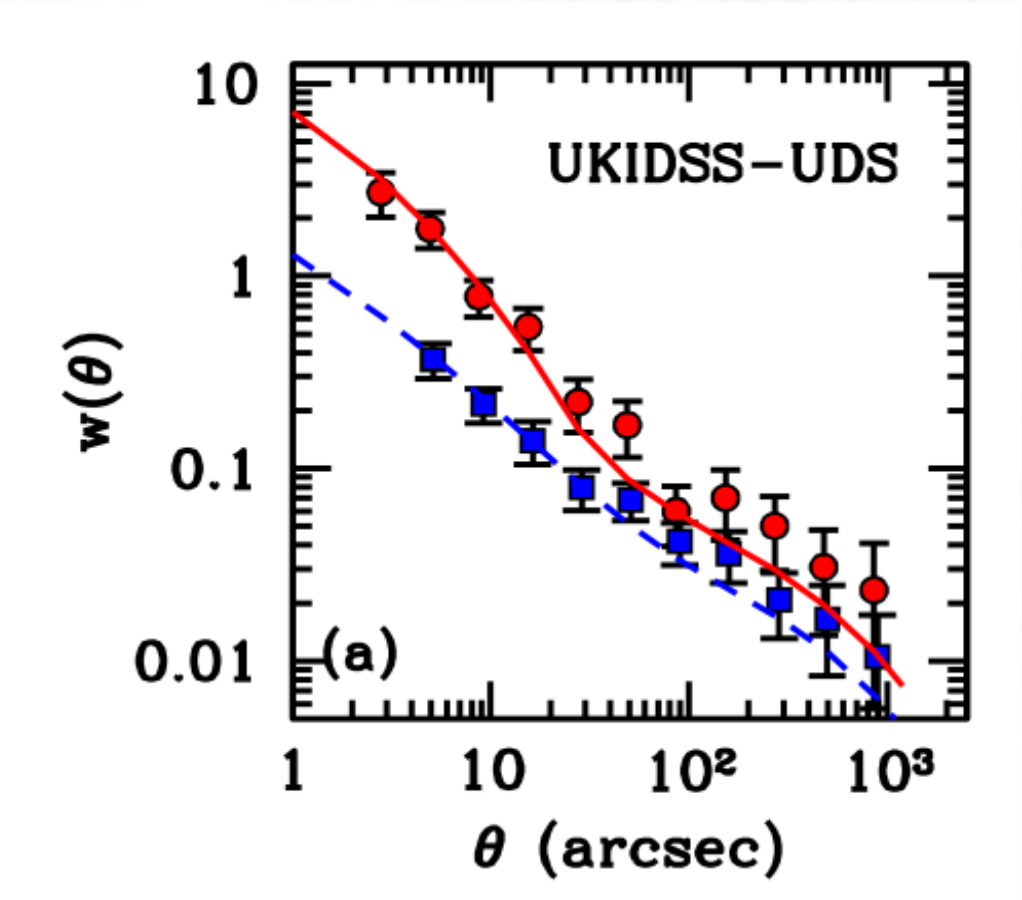
Modeling of the clustering

- Derive physical properties of galaxies: the mass of the halo in which galaxies reside as a function of the redshift, bias...
- The inf uence of the galaxies evolution model
- Successfully used to analyse Planck data (Planck Collaboration XVIII)
- Caveats :
  - Each wavelength has to be f tted separately
  - The emissivities only depend on the redshift
  - No dependence on the mass of the halo (strong approximation)
- The HOD only depends on the halo mass : need to depend on other observables

Dependencies of the clustering

- Luminosity (Meneux+2009)
- Color (De La Torre+2011)
- Redshift (Meneux+2009)
- Stellar mass (Meneux+2009)
- Morphology
- Early/Late type (Tinker+2009)
- ...

Dependance of clustering on evolution type



Quiescent galaxies

Star-forming galaxies

Williams+2009

Dependance of clustering on stellar mass

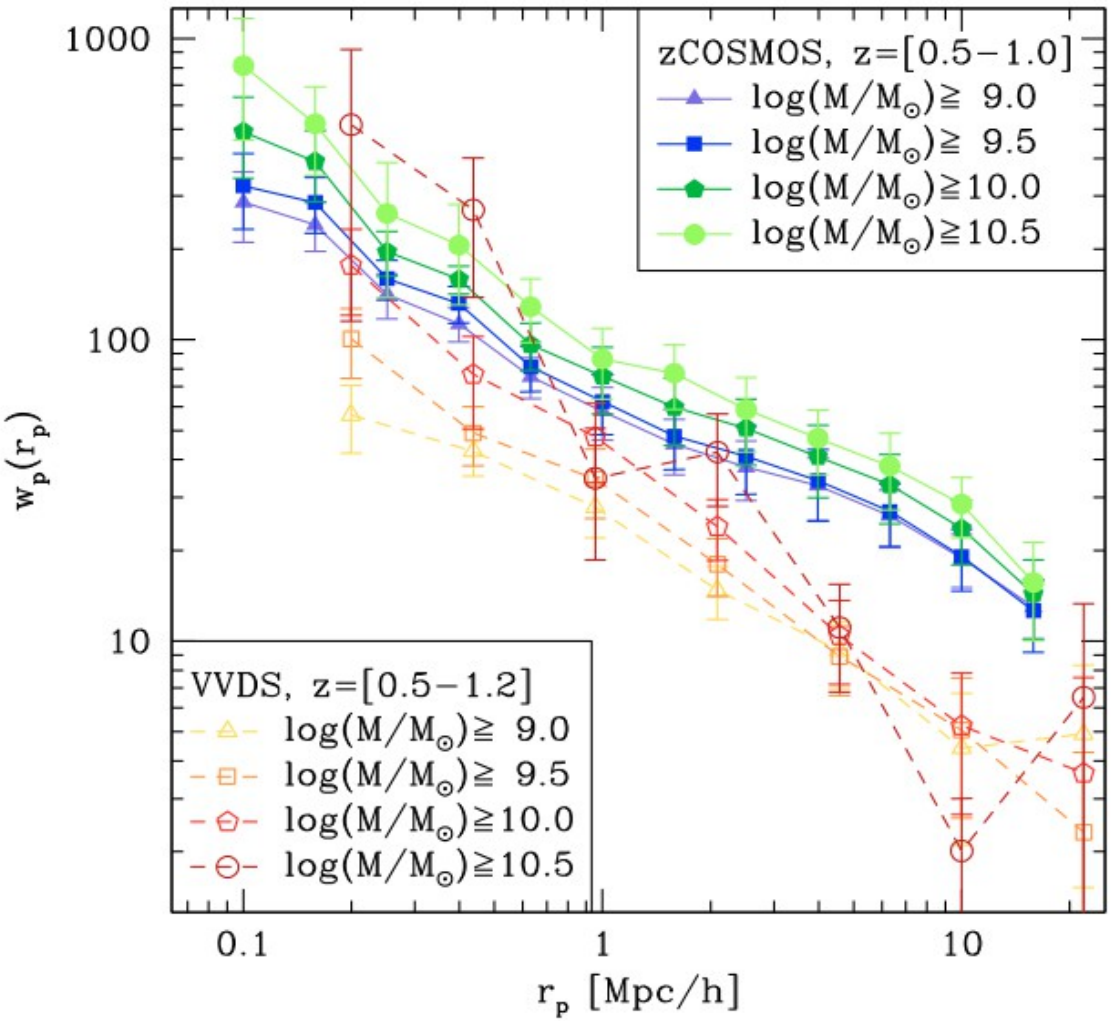


Fig. 18. Direct comparison of the dependence of clustering on stellar mass in the VVDS-Deep and zCOSMOS samples, over a similar redshift range.

Meneux+2009

Conditional Functions

- Of other observables :
  - Luminosity
  - Stellar mass

$$\Phi(m_\star|M_{halo}) = \Phi_{central}(m_\star|M_{halo}) + \Phi_{satellite}(m_\star|M_{halo})$$

Moster+2010

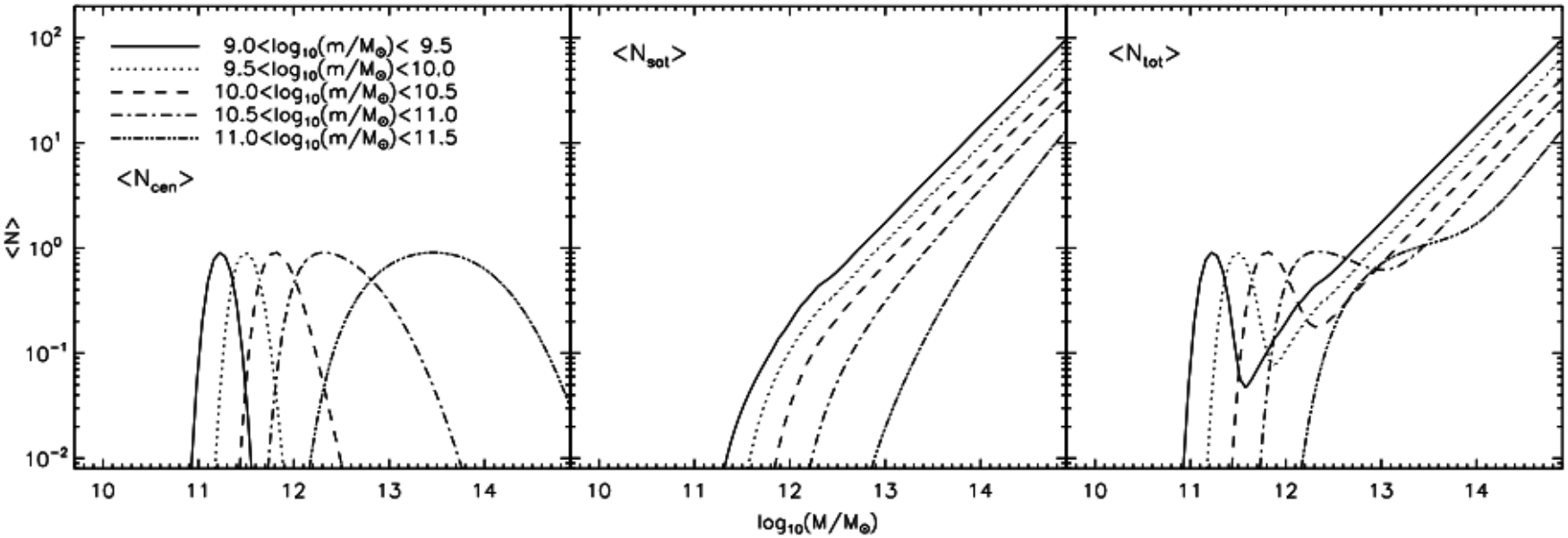


Figure 9. Occupation numbers as function of halo mass in stellar mass bins, derived using the conditional mass function. The left, middle, and right panels show the average number of central, satellite, and total galaxies per halo, respectively.

Conditional functions of SSFR

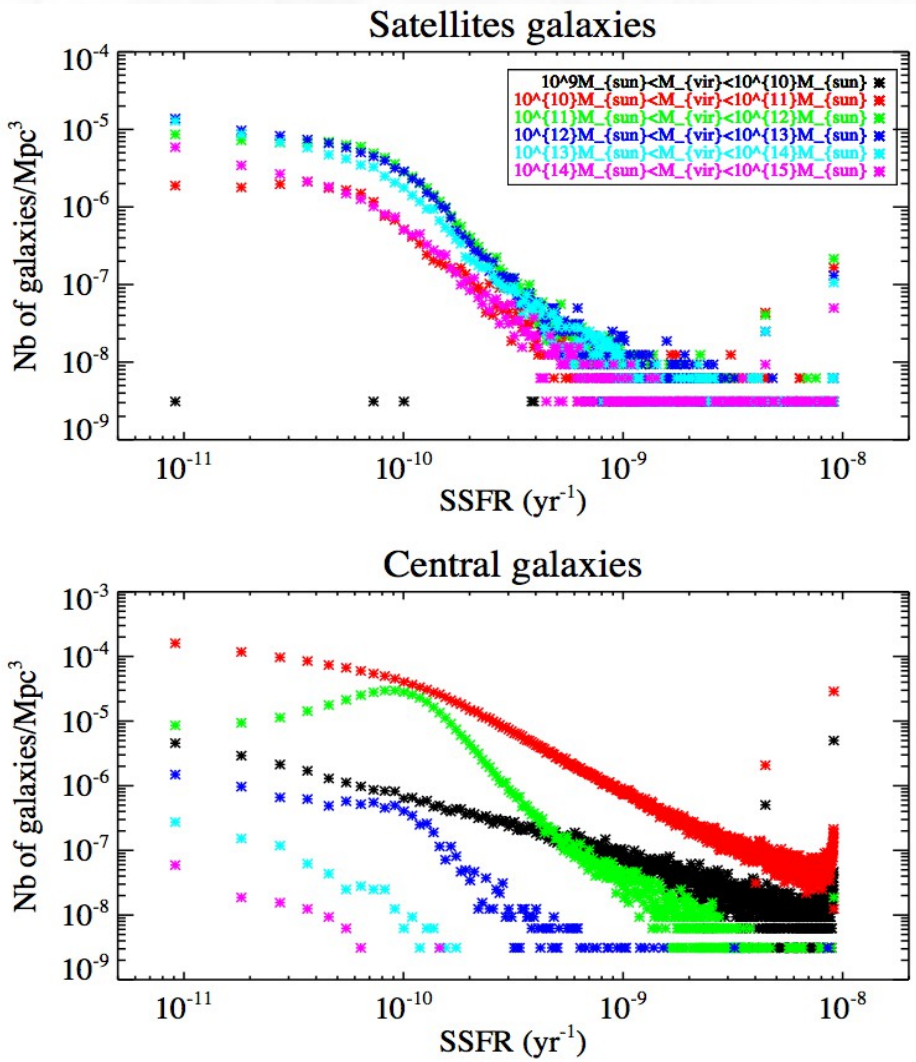
$$\Phi(SSFR|M_{halo}) = \Phi_{central}(SSFR|M_{halo}) + \Phi_{satellite}(SSFR|M_{halo})$$

The simulation Guo+2011

- Based on the Millenium simulation (MS)
- Volume = 685 Mpc3
- Implement galaxy formation recipes on the subhalos merger trees coming from the MS
- Fits well observations at low redshift (clustering, stellar mass function)
- Use the snapshot at z = 0

Conditional functions of SSFR

$$\Phi(SSFR|M_{halo}) = \Phi_{central}(SSFR|M_{halo}) + \Phi_{satellite}(SSFR|M_{halo})$$



Conditional functions of SSFR

$$\Phi(SSFR|M_{halo}) = \Phi_{central}(SSFR|M_{halo}) + \Phi_{satellite}(SSFR|M_{halo})$$

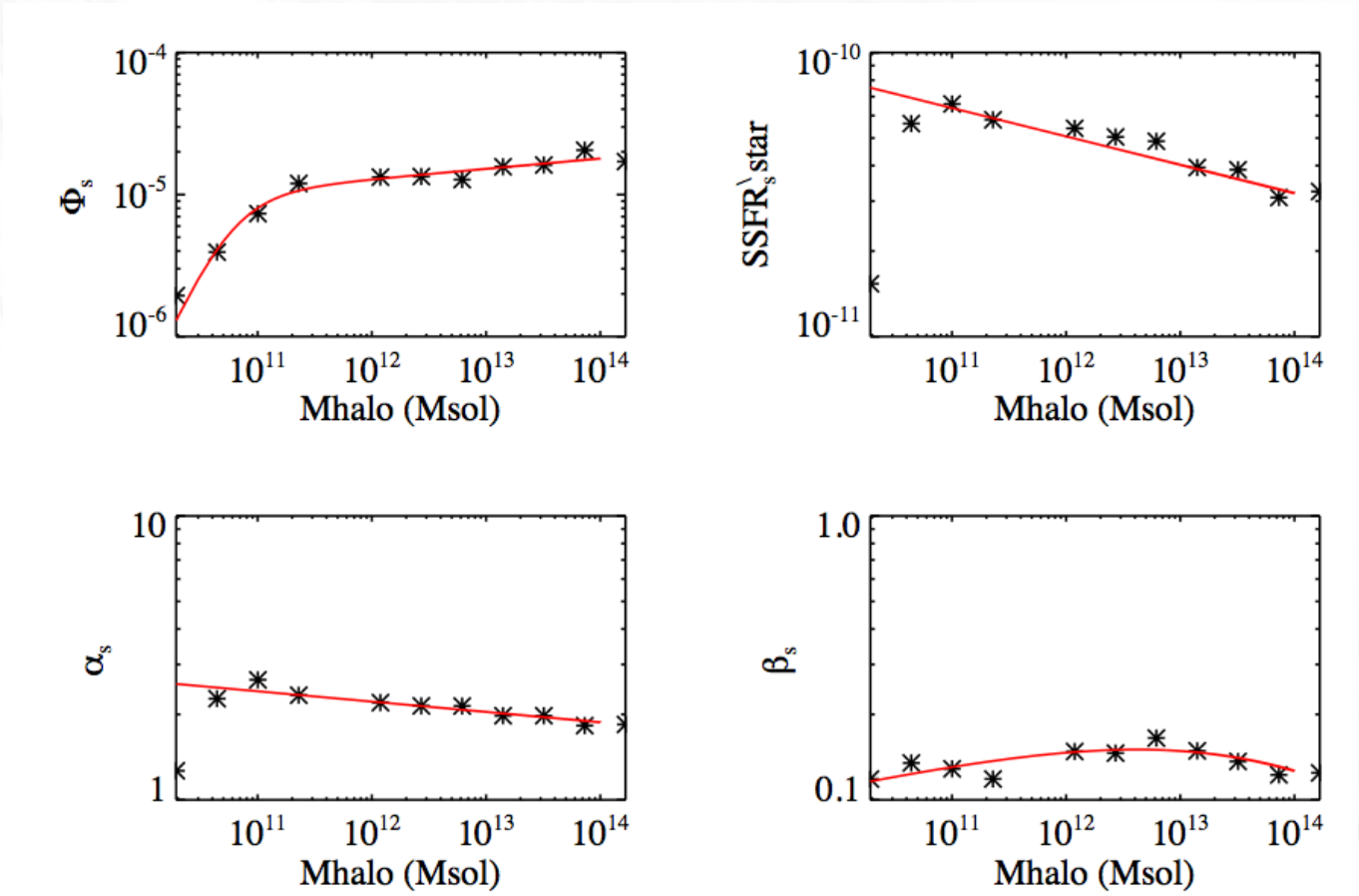
$$\Phi_{satellite}(SSFR|M_{halo}) = \Phi_s \left(\left(\frac{SSFR}{SSFR_s^\star} \right)^{\alpha_s} + \left(\frac{SSFR}{SSFR_c^\star} \right)^{\beta_s} \right)^{-1}$$

$$\Phi_{central}(SSFR|M_{halo}) = \Phi_c \left(\left(\frac{SSFR}{SSFR_c^\star} \right)^{\alpha_c} + \left(\frac{SSFR}{SSFR_c^\star} \right)^{\beta_c} \right)^{-1}$$

=> 8 parameters that depend on the halo mass

Dependance on the halo mass

- Simple power law
- Double power law
- For satellite galaxies :



Conclusion & Perspectives

- The overall is parametric
- Evolution in redshift will be added
- Parameters will be f tted on data:
  - Distribution of SSFR
  - Stellar mass function
  - Clustering measurements
  - Galaxy-galaxy lensing
- Cosmos f eld at f rst

Dependance of clustering on observables

- Luminosity meneux 2009
- Color
- Early type/late type, tinker 2009
- Mettre des plots

Modeling of the clustering

- j

Modeling of the clustering

- j

Modeling of the clustering

- j

Modeling of the clustering

- j

Conditional functions of SSFR

$$\Phi(SSFR|M_{halo}) = \Phi_{central}(SSFR, M_\star|M_{halo}) + \Phi_{satellite}(SSFR, M_\star|M_{halo})$$

$$\Phi_{satellite}(SSFR|M_{halo}) = \Phi_s \left(\left(\frac{SSFR}{SSFR_s^\star} \right)^{\alpha_s} + \left(\frac{SSFR}{SSFR_c^\star} \right)^{\beta_s} \right)^{-1}$$

$$\Phi_{central}(SSFR|M_{halo}) = \Phi_c \left(\left(\frac{SSFR}{SSFR_c^\star} \right)^{\alpha_c} + \left(\frac{SSFR}{SSFR_c^\star} \right)^{\beta_c} \right)^{-1}$$

=> 8 parameters that depend on the halo mass