Observatoire astronomique de Strasbourg | ObAS

AstroParticle Symposium 2024, Orsay, 15 Nov 2024 (remote)

Cosmic far-infrared background: links between star formation and dark-matter halos

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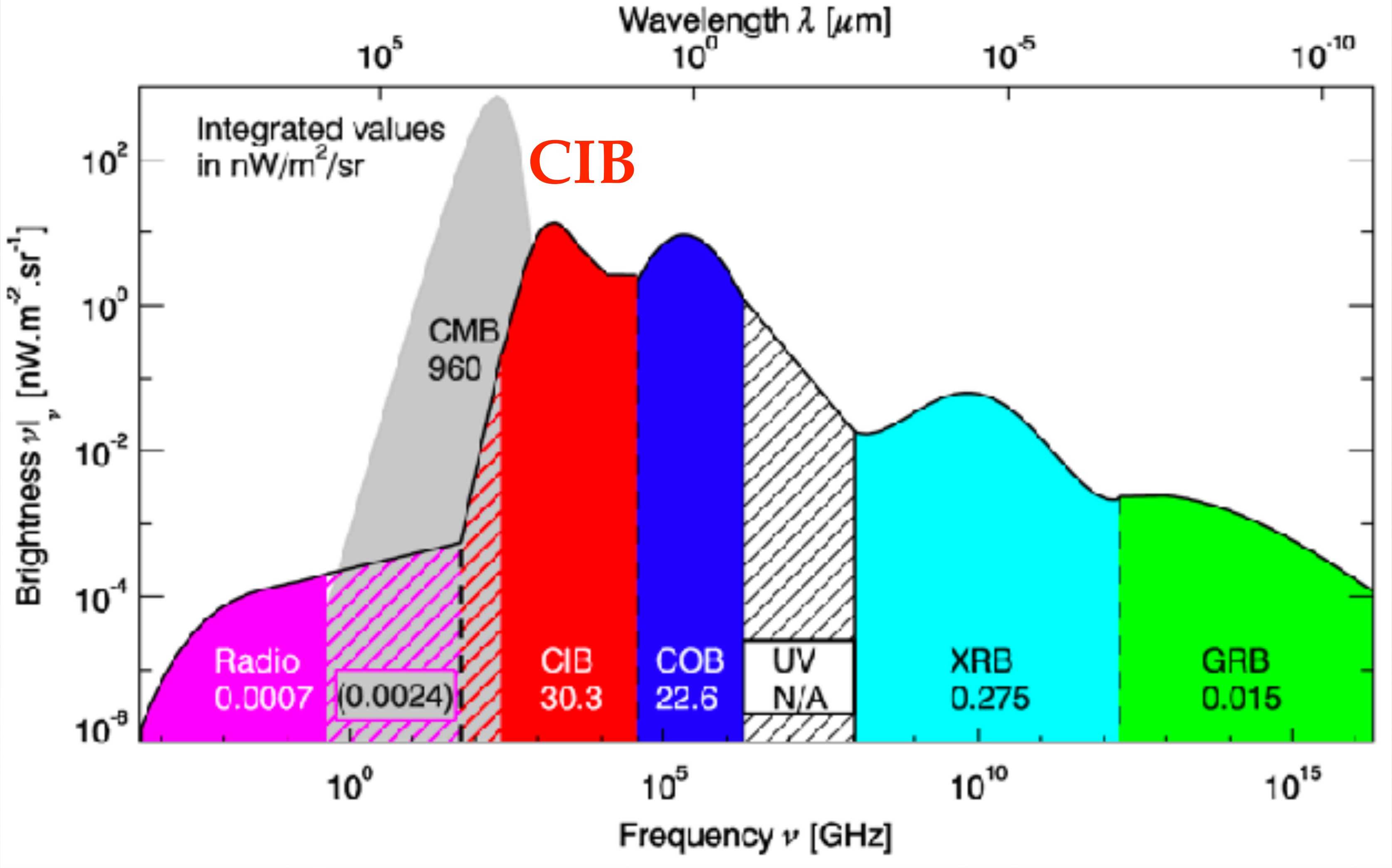
Origin of the cosmic infrared background

- Half the light emitted during galaxy formation in the cosmic infrared background (CIB)

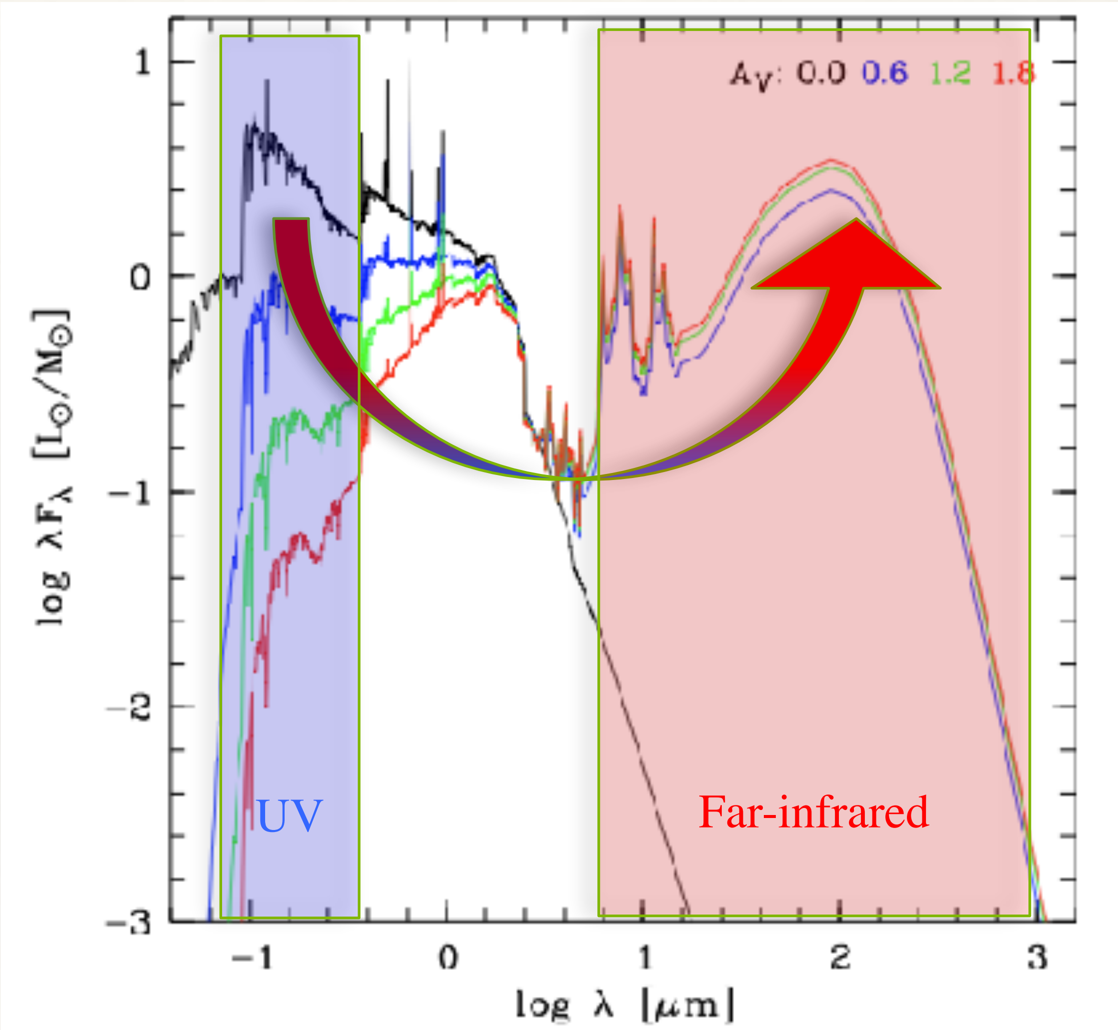


Spectral energy distribution of extragalactic background

- Where does the CIB comes from?
- What does it teach us about galaxy evolution?

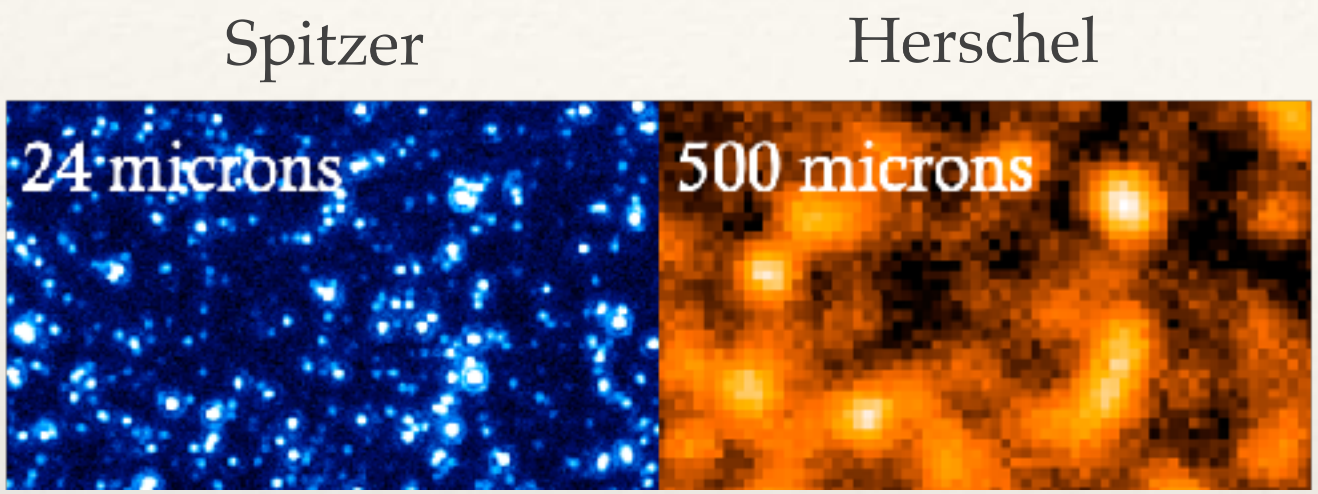
Dusty star formation

- UV emissions of galaxies dominated by massive, hot, short-lived stars
- But UV strongly absorbed by dust and re-emitted in the far-IR
- We need both to get a full picture of the star formation history in the Universe



Spectral energy distribution of a galaxy (Noll+09)

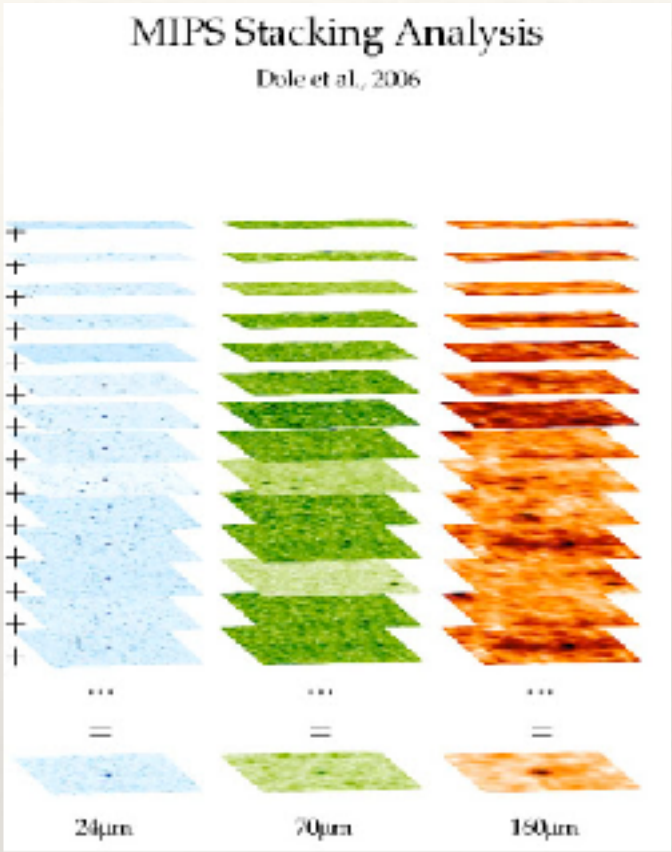
Which sources emit the CIB?



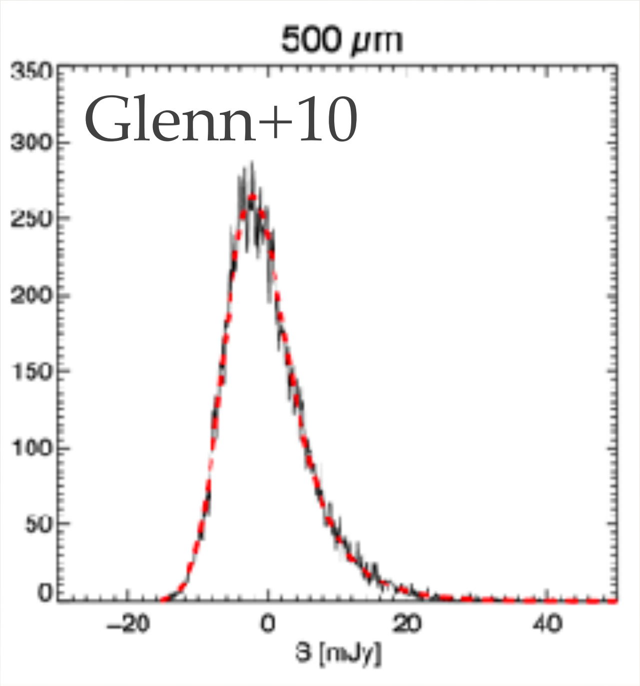
Individual detections account for ~80% of the CIB

Individual detections account for ~5% of the CIB

Stacking at known galaxy positions to beat confusion



The full CIB can be extrapolated from the faint-end slope (e.g., Béthermin+10a)



Pixel histogram (P(D) analysis)
Mathematical link between the histogram and the flux distribution

Estimated total contribution from galaxies

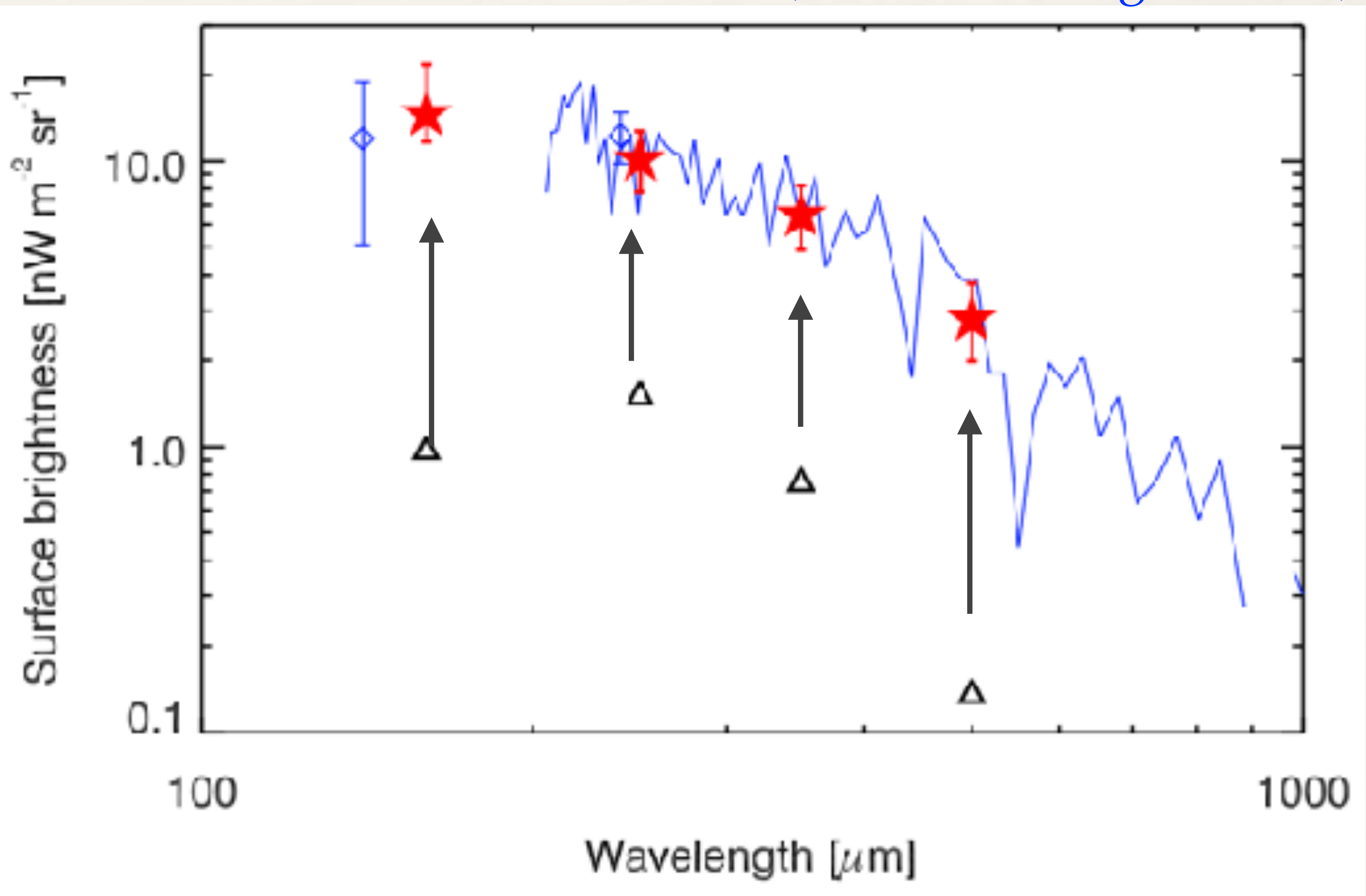
The origin of the CIB resolved

★ Total from all galaxies (stacking, P(D))

△ Individual detections

Absolute CIB level
(Fixsen+98, Lagache+00)

- Individually detected sources (△) account for only a small fraction of the CIB
- The estimated total emission from galaxies ~ absolute CIB level



CIB spectral energy distribution
(adapted from Béthermin+12b)

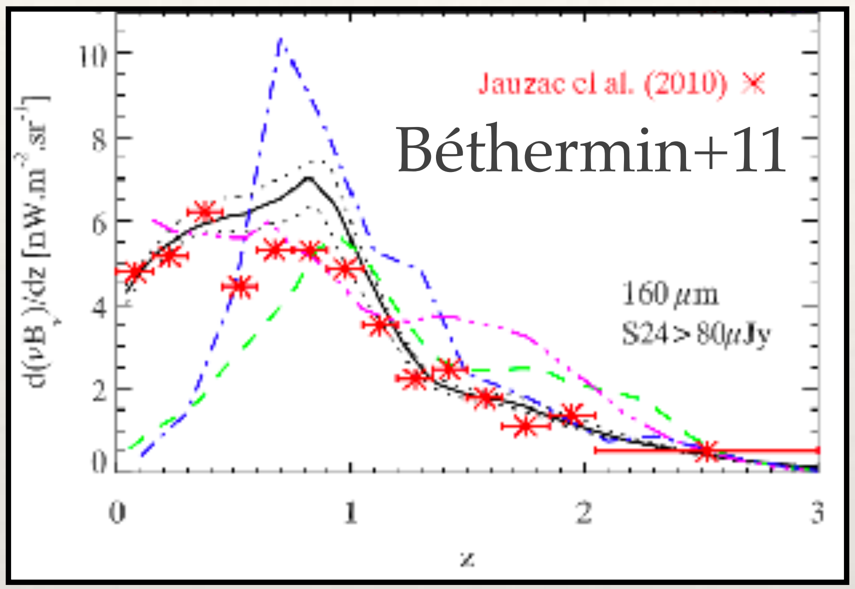
See also Berta+11, Vieiro+13b, Leiton+15

Caveat: at these wavelengths, source sources ≠ galaxy counts (e.g., Béthermin+17)

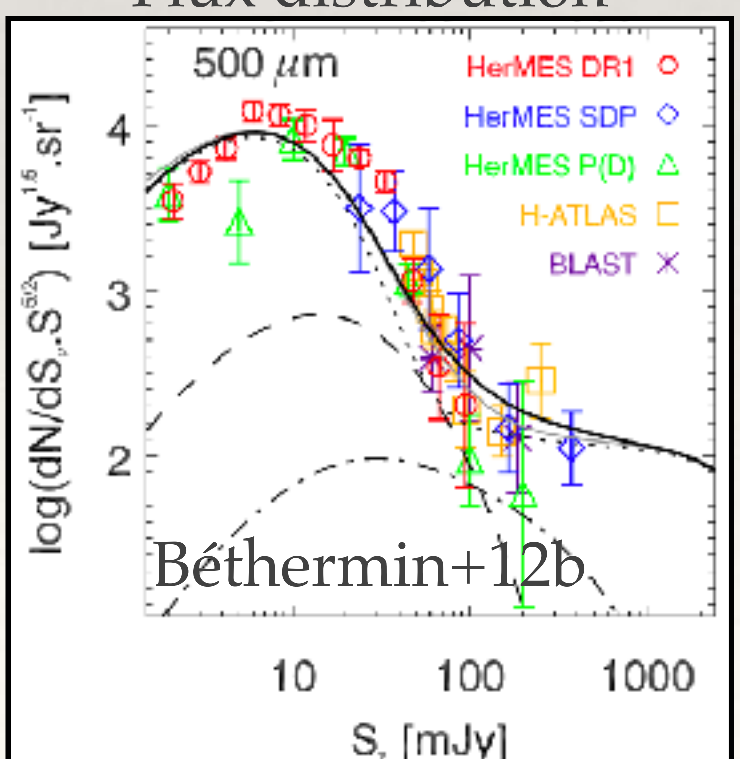
Modeling the CIB constraints

OBSERVATIONAL CONSTRAINTS

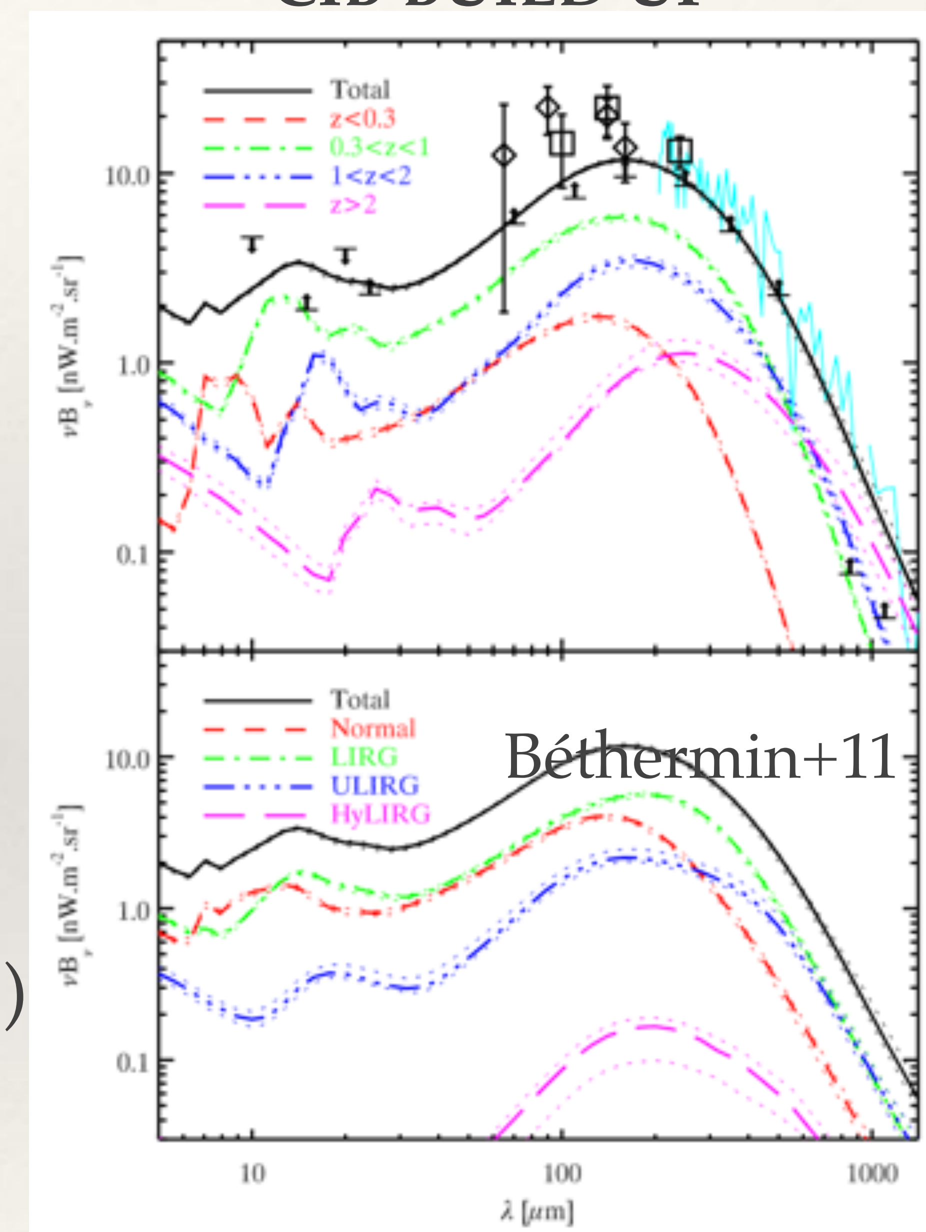
Redshift distribution



Flux distribution



CIB BUILD UP



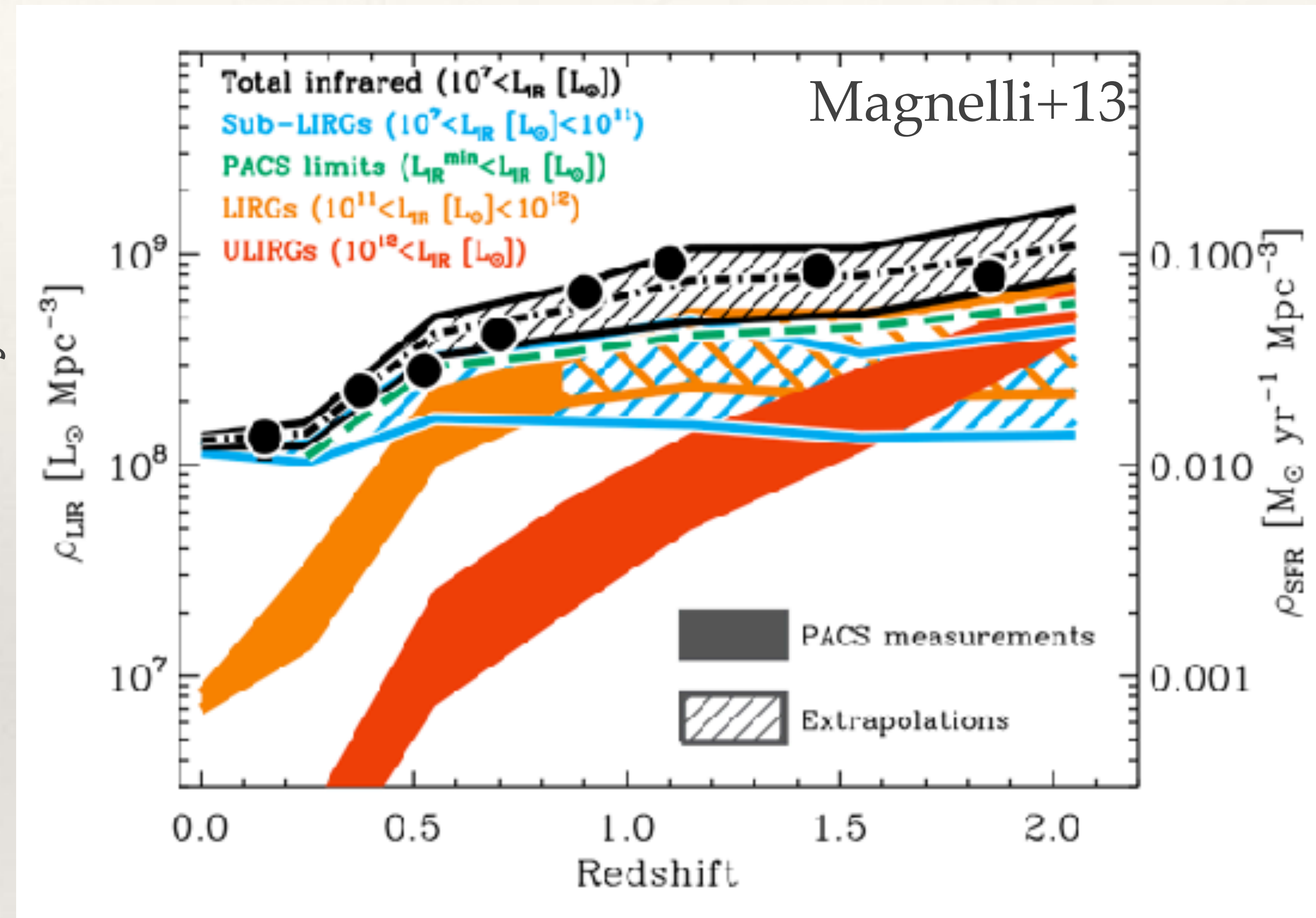
Modeled using:
- evolving luminosity function (free parameters)
- spectral energy distribution
- geometry of the Universe

+ STAR FORMATION HISTORY (see next slide)

Dusty star formation at high z: significant contribution of rare dusty monsters

- Both observations and models: large contribution of galaxies forming >100 M☉/yr at z>2
- Extreme galaxies formed early
  => non intuitive in the hierarchical scenario!
- Higher mergers fraction at high redshift => are they analogous to local ULIRGs (>100 Msun/yr, major mergers)?

SFR density

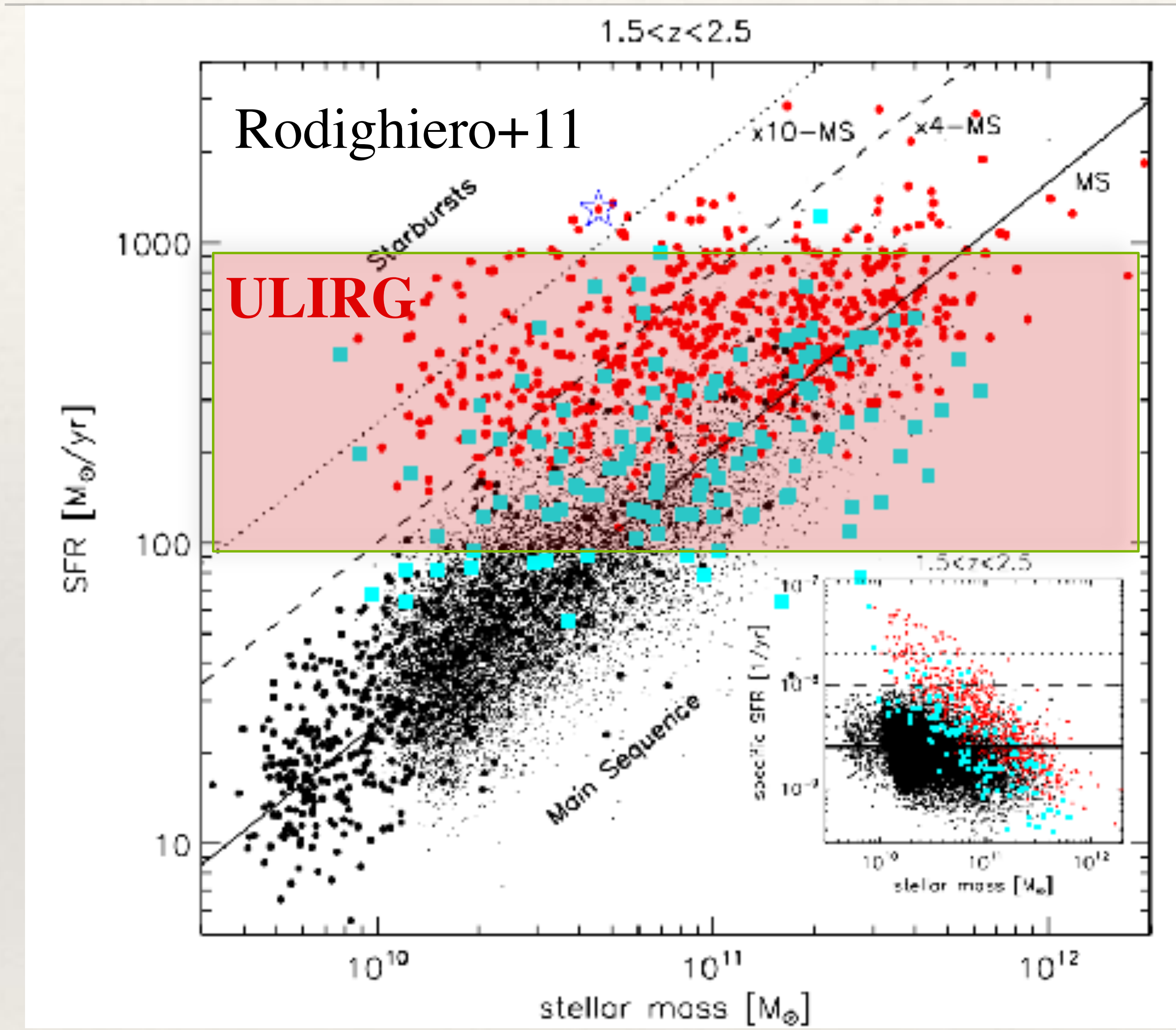


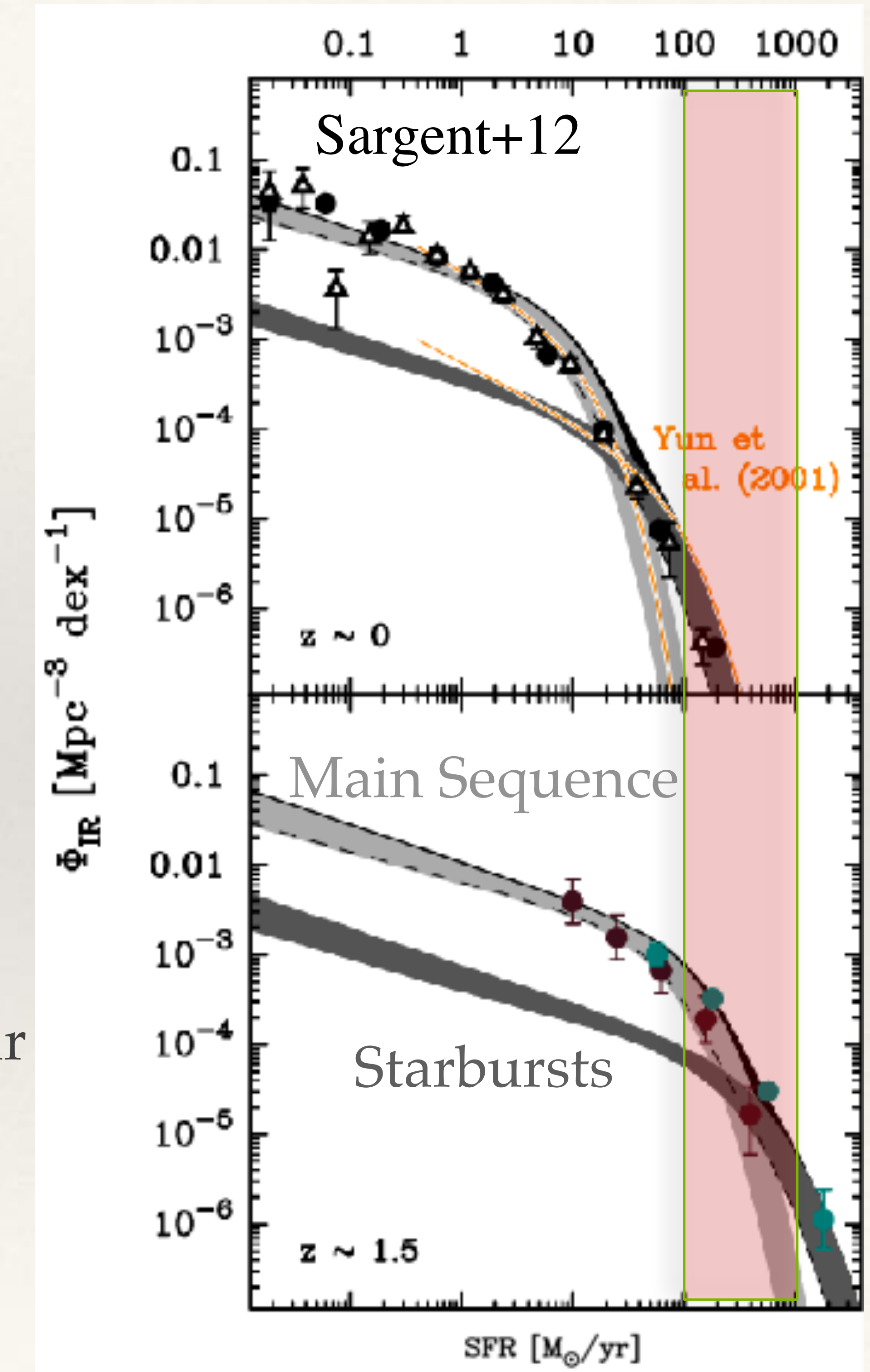
Total	<10 M☉/an
10-100 M☉/an. (LIRGs)	>100 M☉/an (ULIRGS)

See also Caputi+07, Le Borgne+09, Béthermin+11, Gruppioni+13, Viero+13

For reference, Milky Way SFR

… which are massive main-sequence galaxies



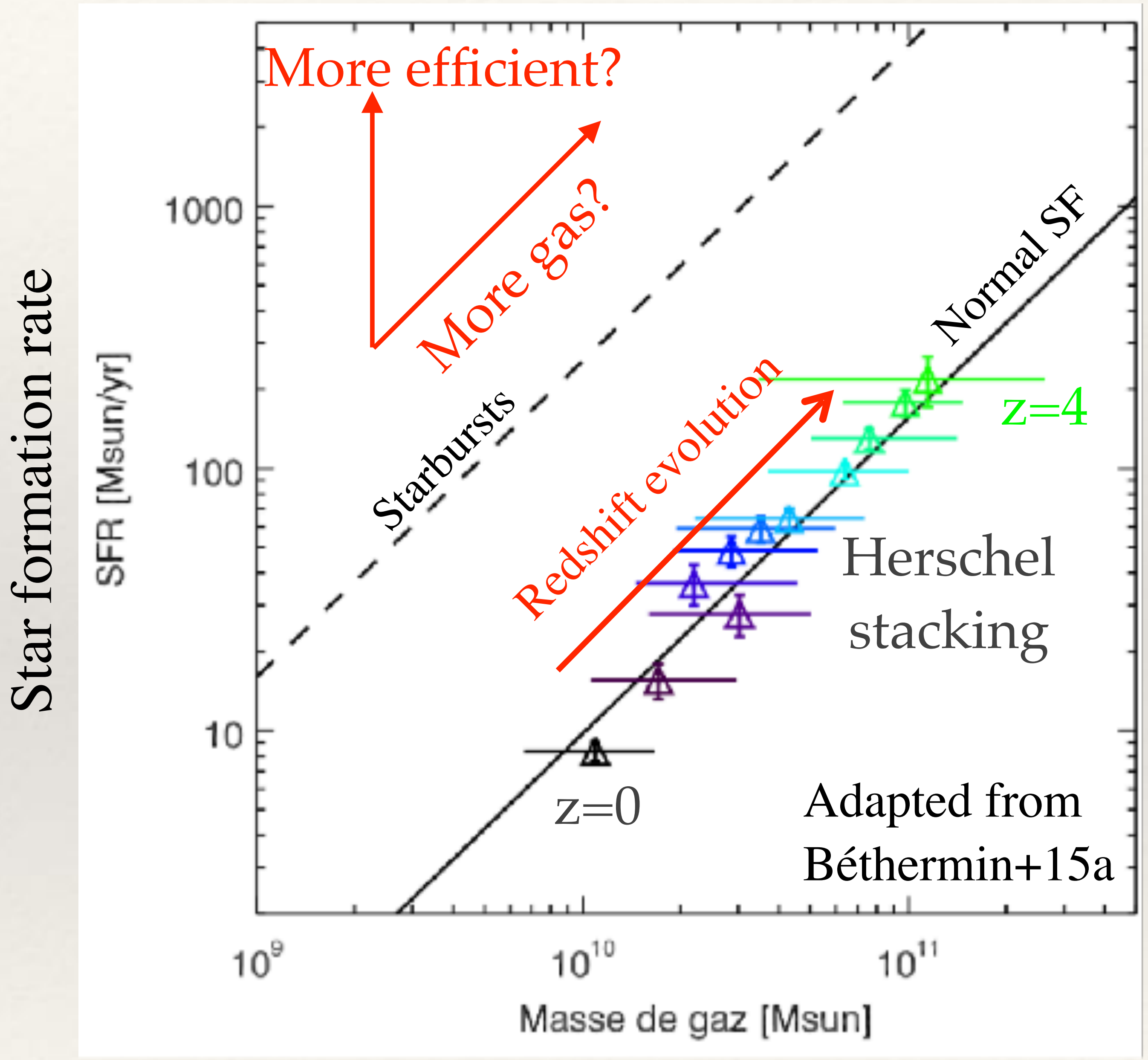


Main-sequence of star-forming galaxies: correlation SFR-Mstar (suggest a smooth star formation history)

z=0: ULIRGS are starbursts (usually merger driven)
z>1.5: ULIRGs are mainly on the main sequence

… full of gas!

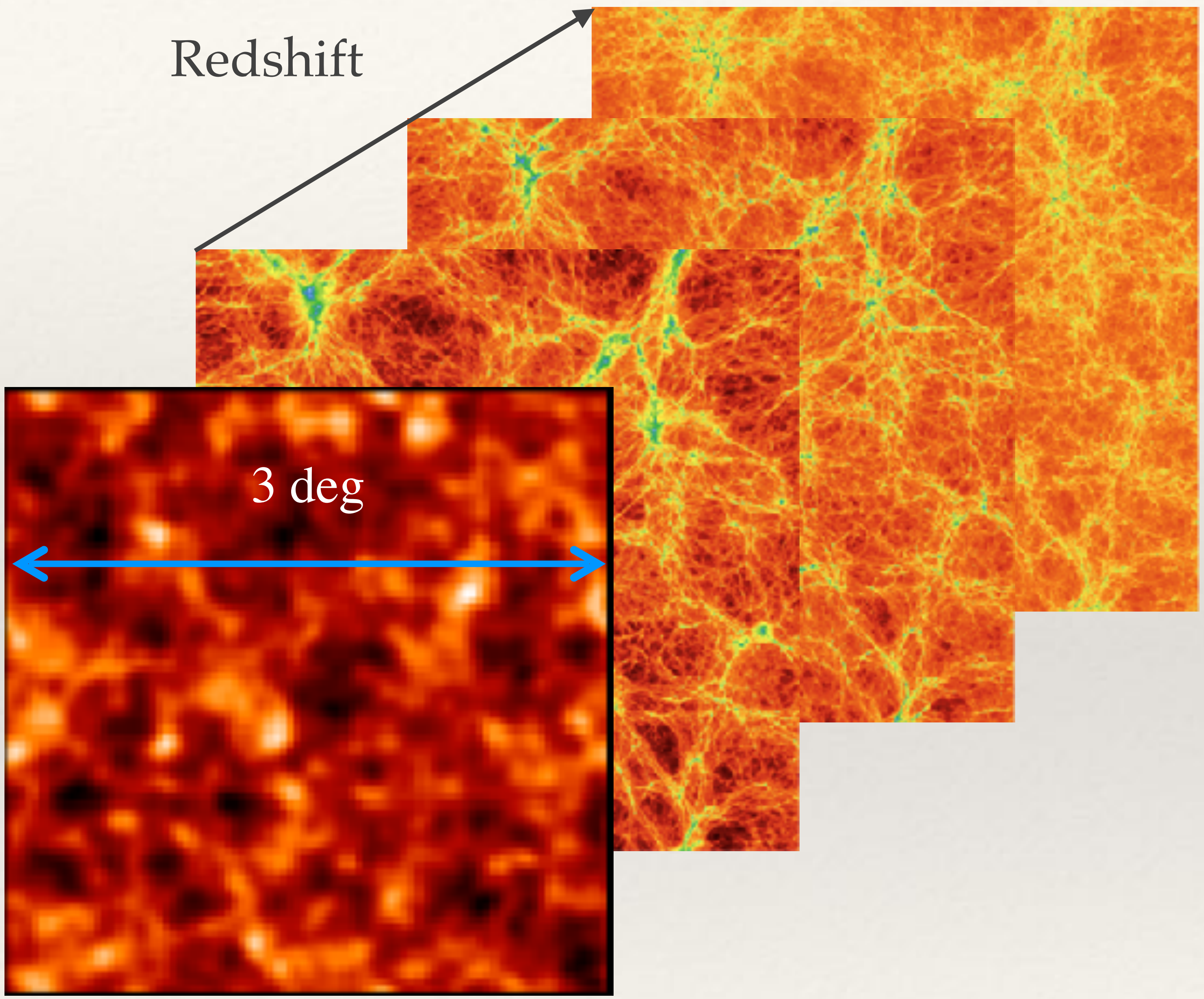
- Cold gas is the full of star formation
- Local Universe: high SFR usually associated to merger-driven starbursts
  => high SFE (=SFR/Mgas)
- High-z: more mergers, but also stronger diffuse accretion (i.e., larger gas reservoirs)
- Gas reservoirs seem to be the main driver of the high SFRs



See also Daddi+10, Magdis+12, Tacconi+13, Dessauges-Zavadsky+15, Genzel+15

Cosmic infrared background (CIB) anisotropies

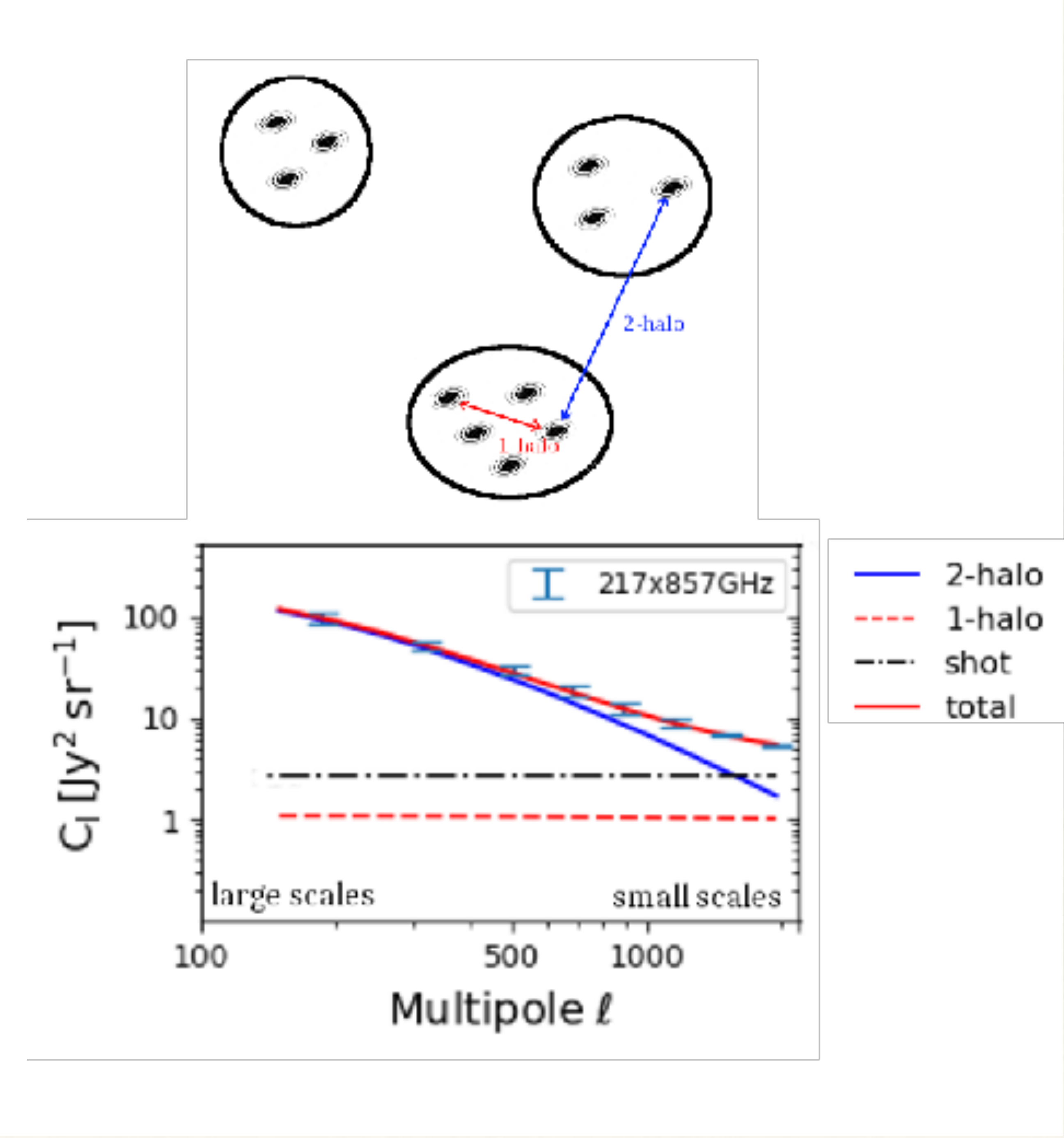
- How is the star formation distributed into the large-scale structure?
- Hard to measured clustering of individual galaxies (confusion)
- CIB anisotropies: information about the clustering of star formation, but degeneracies between redshift



Fluctuations of the cosmic infrared background (Planck collaboration et al.)

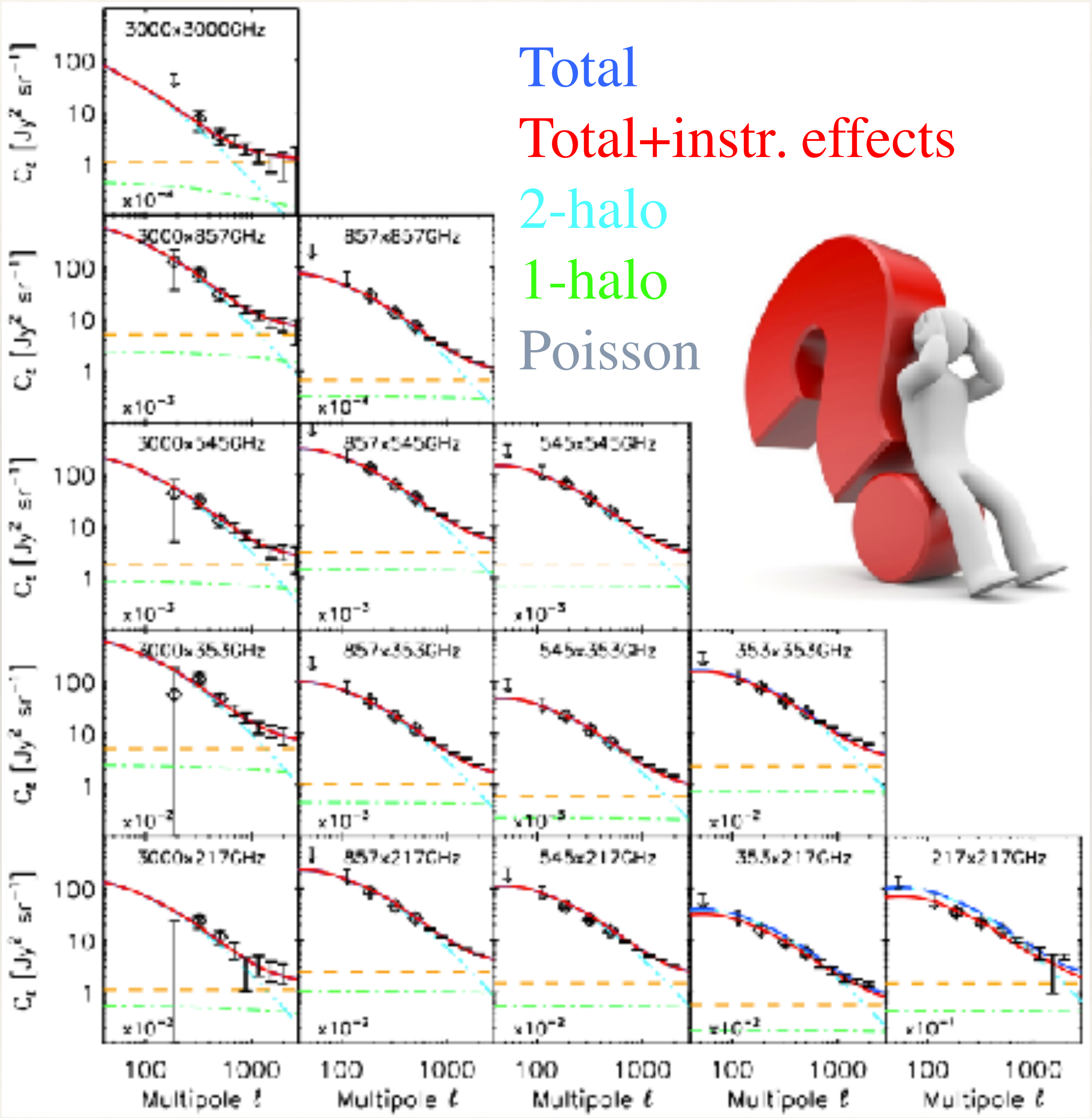
Power spectrum of the CIB

- **Power spectrum:** statistical tools measuring the level of the fluctuations in a map at the various scales
- **2-halo term:** correlation between galaxies in two different halos, dominate large scales
- **1-halo term:** correlation between galaxies in the same halo, mainly intermediate scales
- **Shot noise (Poisson):** fluctuation expected from random fluctuation of the number of sources, small scales



CIB anisotropies with Planck

- Fluctuations between bands measured between 100 and 1400 microns (3000 to 217 GHz).
- PROBLEM: how to break the degeneracies between redshift?
- Longer wavelengths are dominated by higher redshift.
- Cross-correlations provide additional constraints



Modeling CIB anisotropies

At large scale, a linear model is sufficient

CIB anisotropies — Clustering — Matter distribution

$$C^{2h}_{\ell,\nu,\nu'} = \int \frac{dz}{\chi^2}\frac{d\chi}{dz} a^2 b^2_{\rm eff}(z)\bar{j}(\nu,z)\bar{j}(\nu',z)P_{\rm lin}(k=\ell/\chi, z)$$

Galaxy emissivity

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

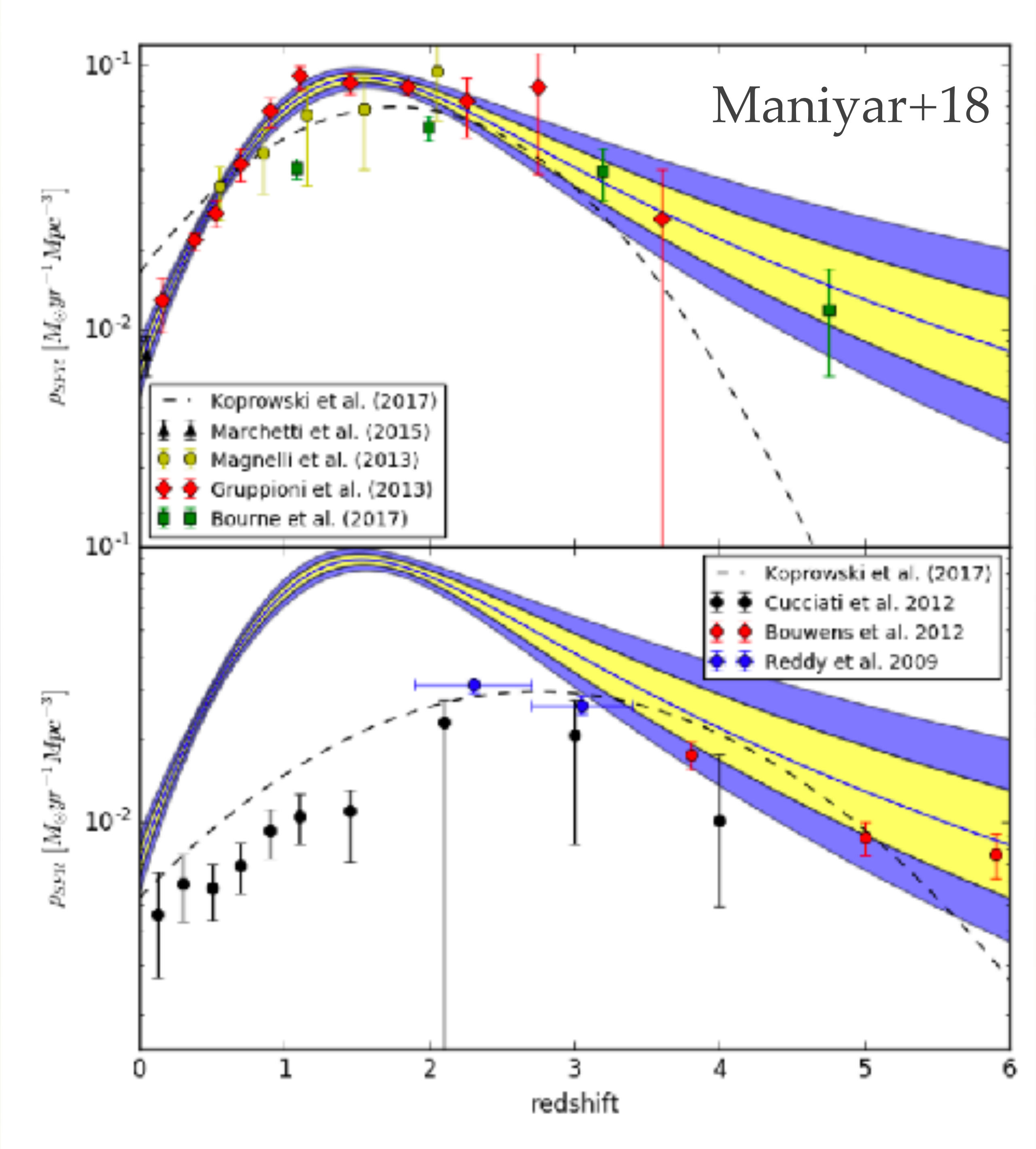
Star formation history

Mean spectral energy distribution of galaxies

Planck collaboration et al. 2014, XXX

Star formation history and host halos

- Star formation history:
  - good agreement with extrapolation of Herschel far-infrared luminosity functions
  - Uncorrected UV significant at z>3
- Clustering of galaxies dominating the CIB compatible with halos of few 10^{12} $M_{\odot}$



See also Planck collaboration 2014 XXX, Béthermin+13

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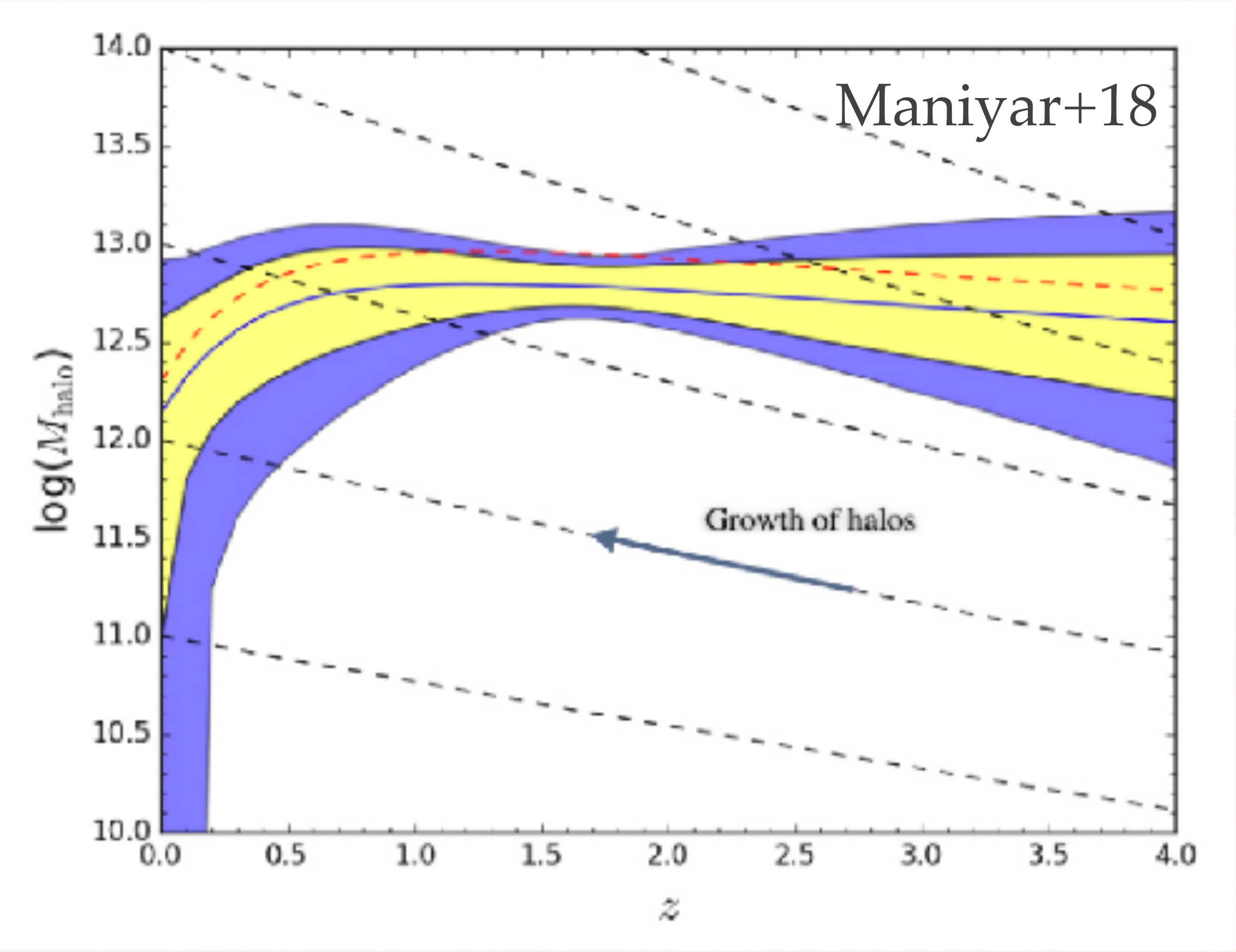
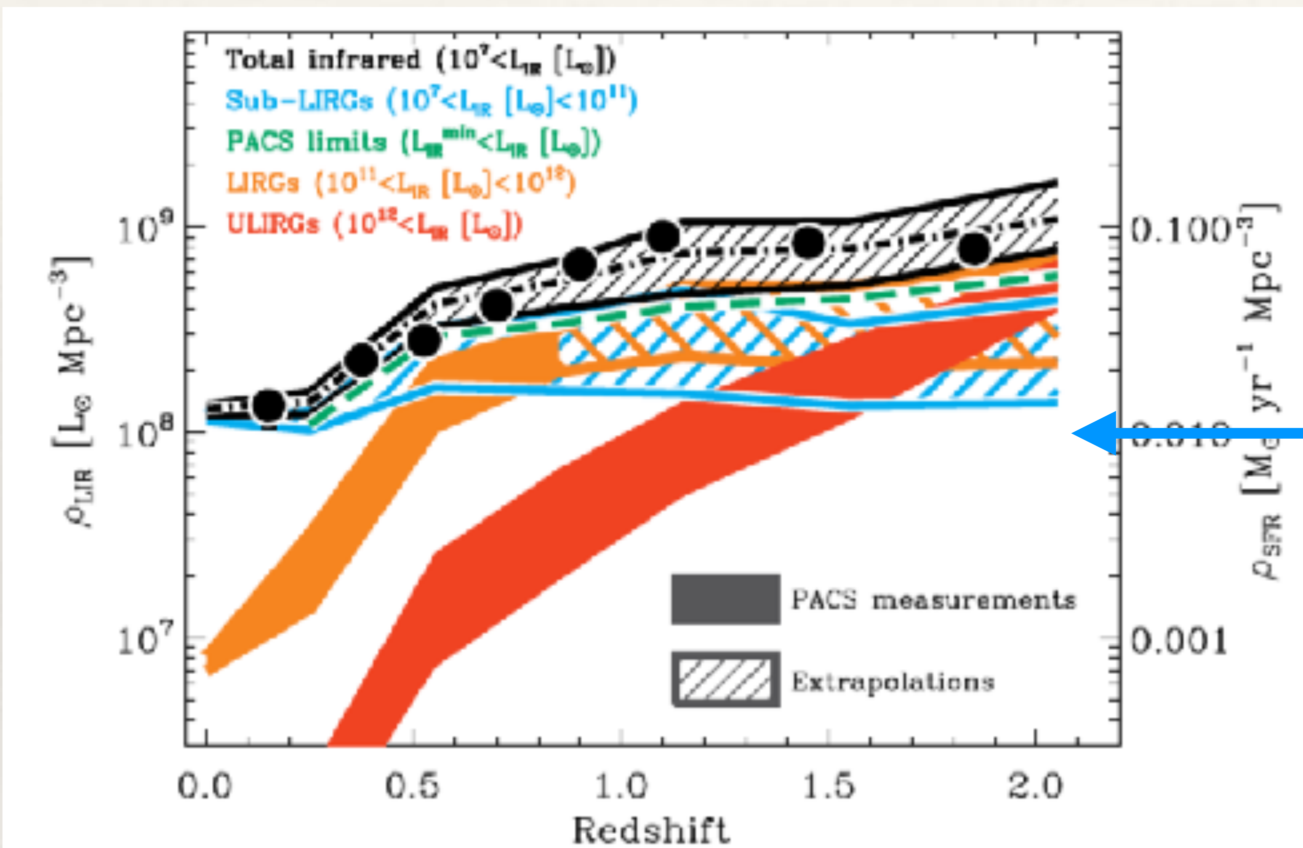
Mass of host dark-matter halos from *Planck* CIB anisotropies

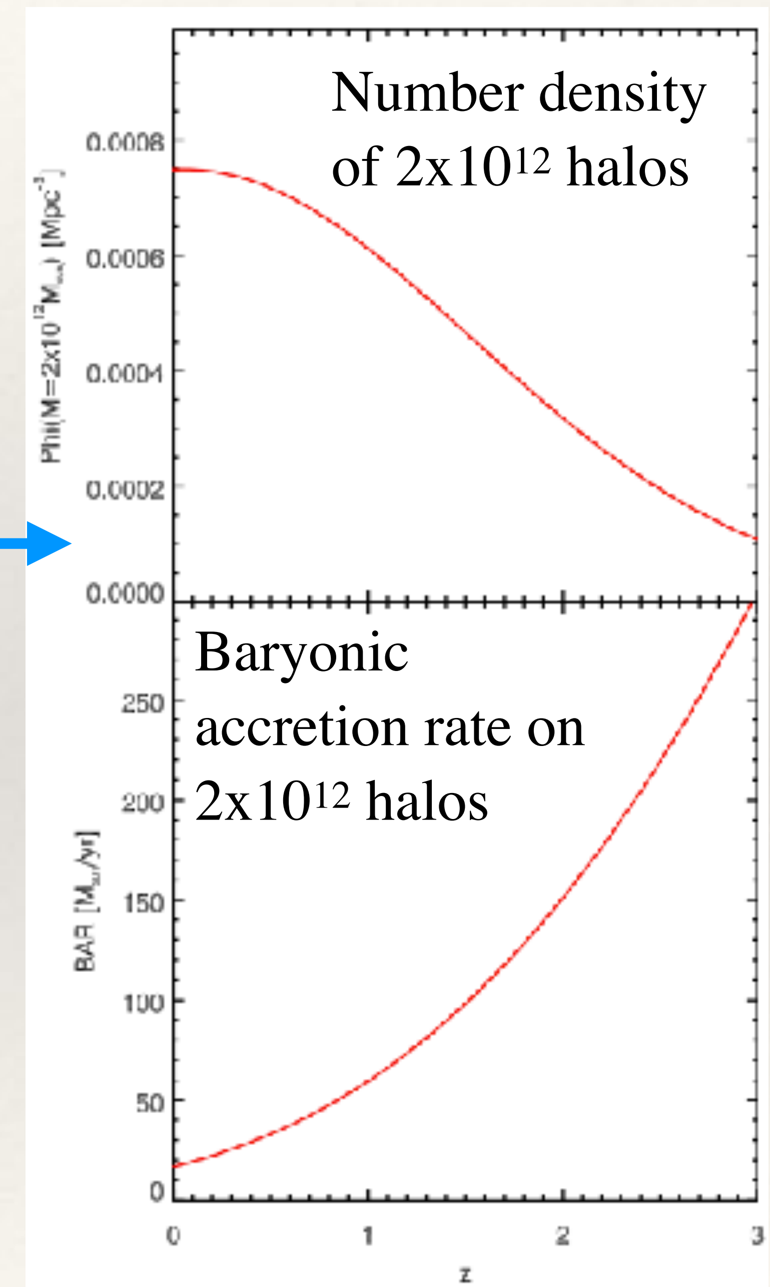


Interpreting the evolution of far-IR galaxies at first order

See a more formal discussion in Béthermin et al. (2013)



Evolution of the star formation rate density and contribution of various infrared luminosities (Magnelli+13)

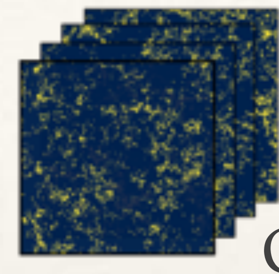


Redshift

The SIDES simulation

SIDES

Two light cones are available:
- SIDES-Bolshoi (2 deg², Béthermin+22)
- SIDES-Uchuu (118 deg², Gkogkou+22)



[CII] emission

Line fluxes

Observed SFR-luminosity relation

CO SLED templates

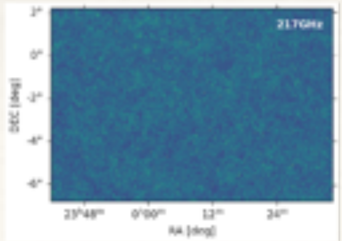
Abundance matching

Dark matter halo catalog → Galaxy catalog (Stellar masses) → Galaxy properties (passive/normal/starburst, SFR)

Observed scaling relations:
- fraction of passive galaxies
- main-sequence and scatter

SED templates

Béthermin+13, Béthermin+17, Béthermin+22, Gkogkou, Béthermin+22 (PhD paper)

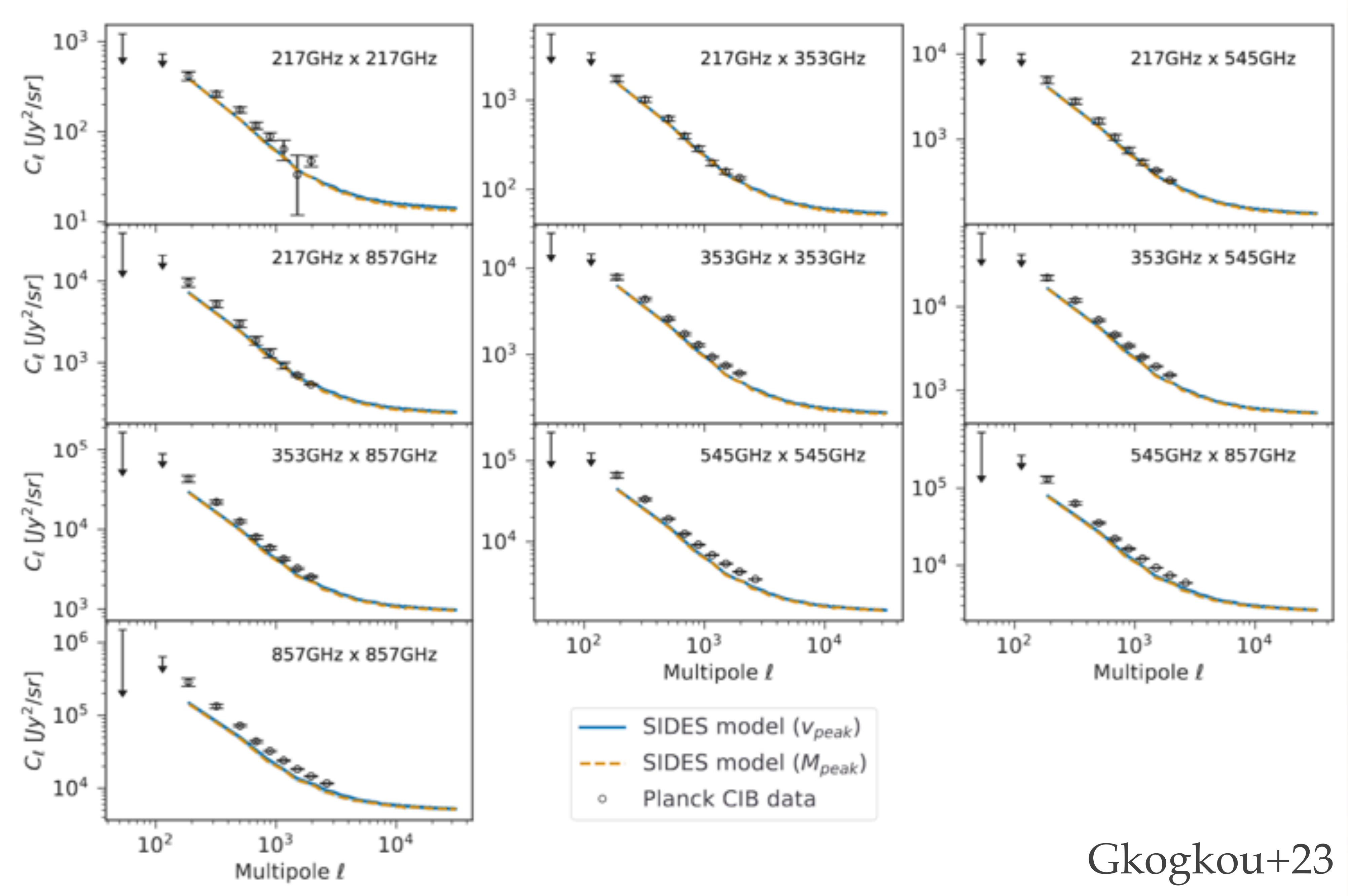


Continuum emission
Planck 217GHz

Continuum fluxes

Agreement between simulations and observations

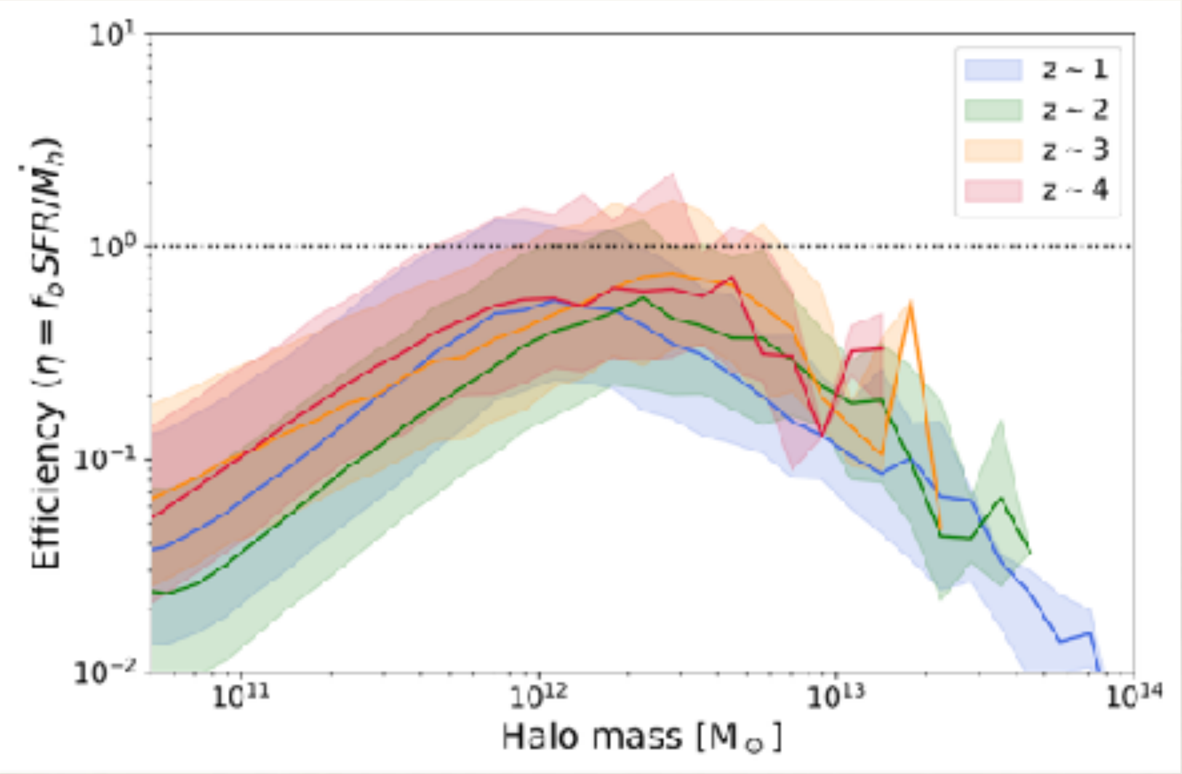
- We produced a new 117 deg² simulation based on the Uchuu dark matter light cone (Gkogkou+23).
- Without any tuning, SIDES is very close from Planck CIB anisotropies.



Gkogkou+23

Simple halo models based on star formation efficiency

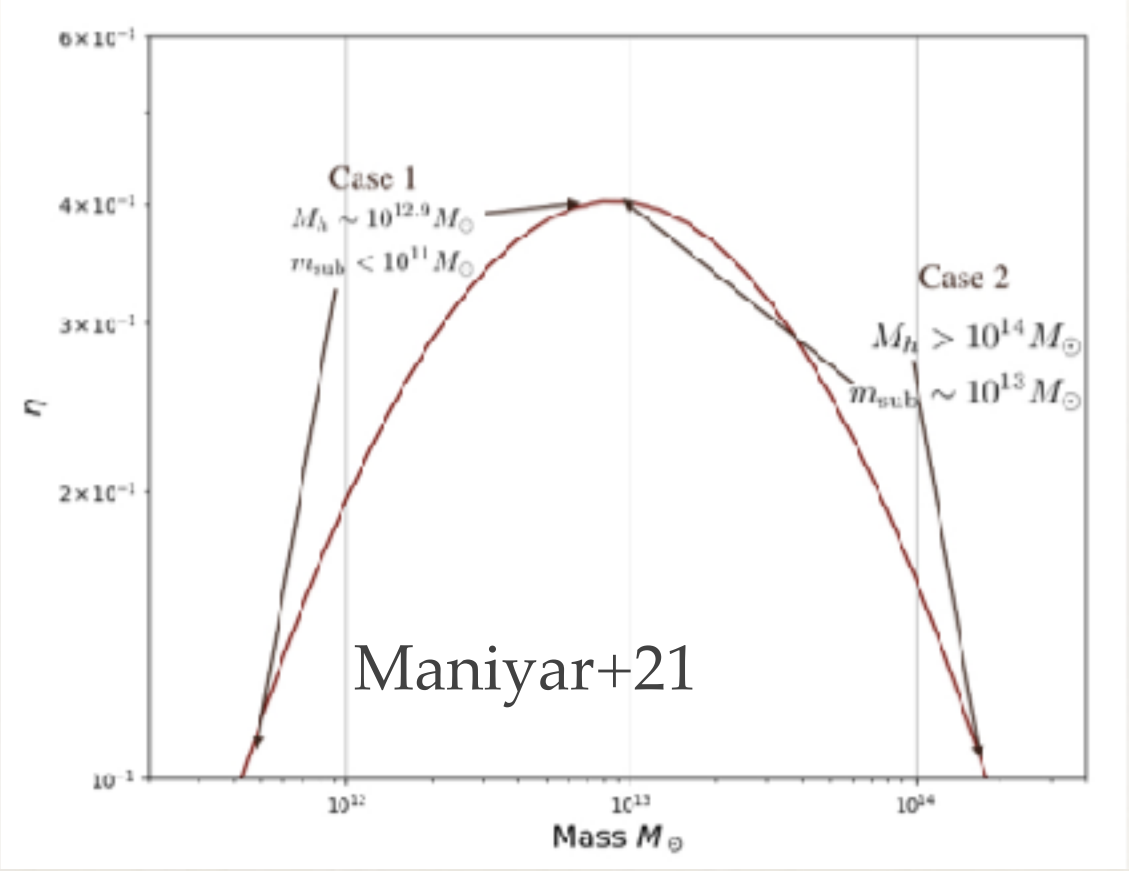
Simulations: SFR / baryon accretion rate



Update of Béthermin+13 with SIDES

Motivates →

New generations of HOD model (Maniyar+21) based on star formation efficiency depending on the halo mass

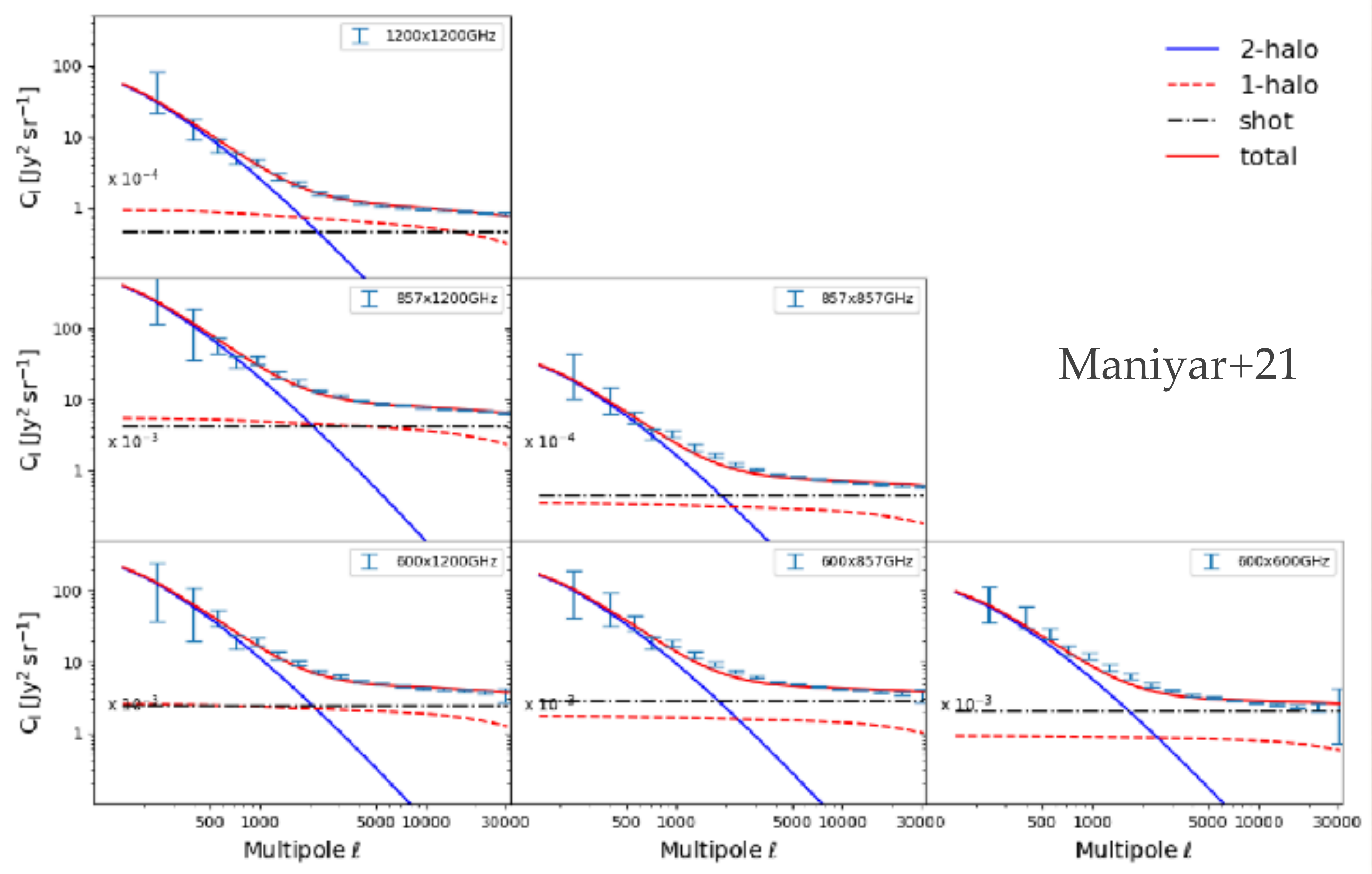


$$\frac{\rm SFR}{\rm BAR}(M_h, z) = \eta = \eta_{\rm max}\, e^{-\frac{(\log M_h - \log M_{\rm max})^2}{2\sigma^2_{M_h}(z)}}$$

Only 3+1 free parameter (1 parameter describing a z-dependant sigma)

Simple halo models based on star formation efficiency

Excellent fit with only four free parameters
- maximum efficiency
- halo mass of max efficiency
- width of the efficiency bump
- effective parameter for the quenching at low redshift and high mass)

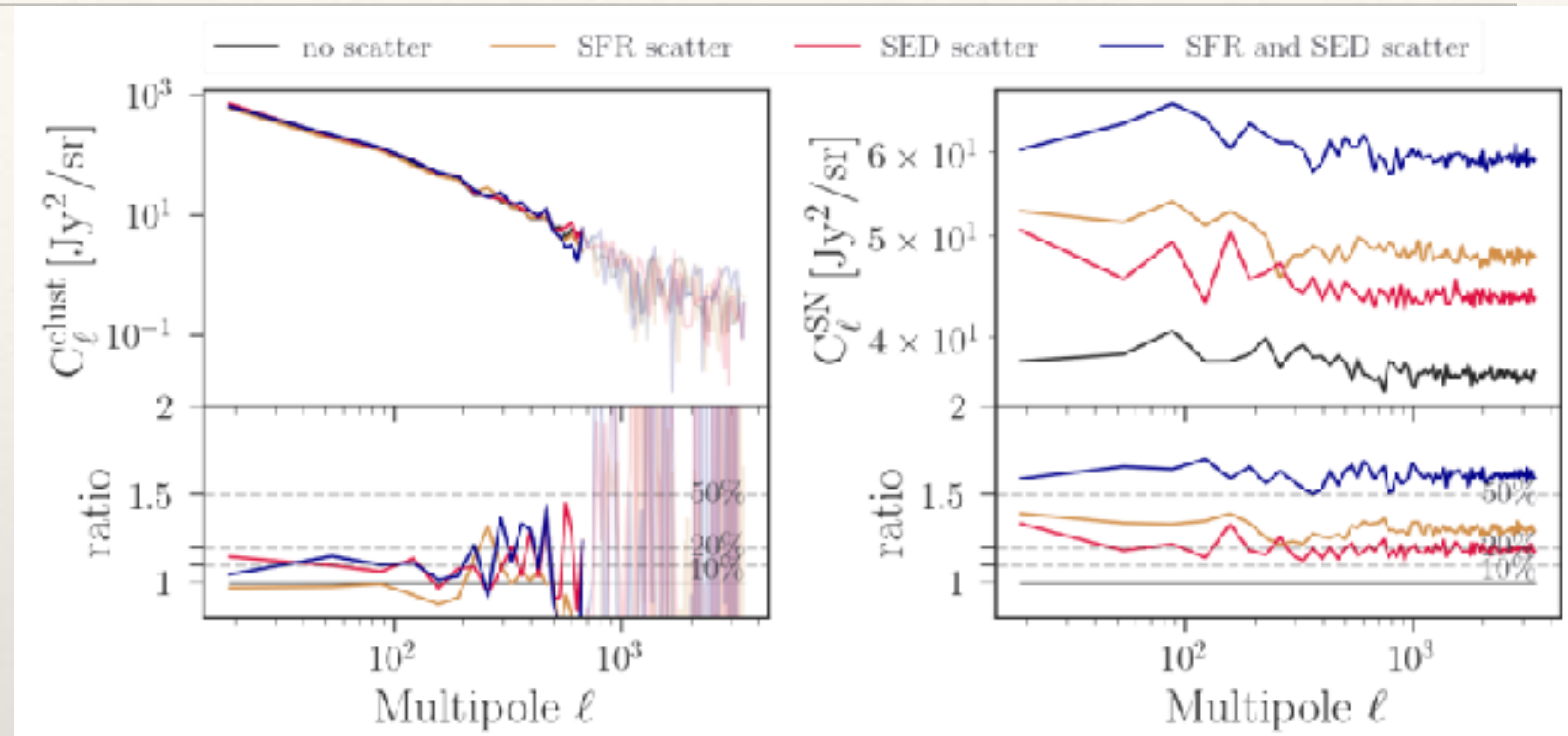


Maniyar+21

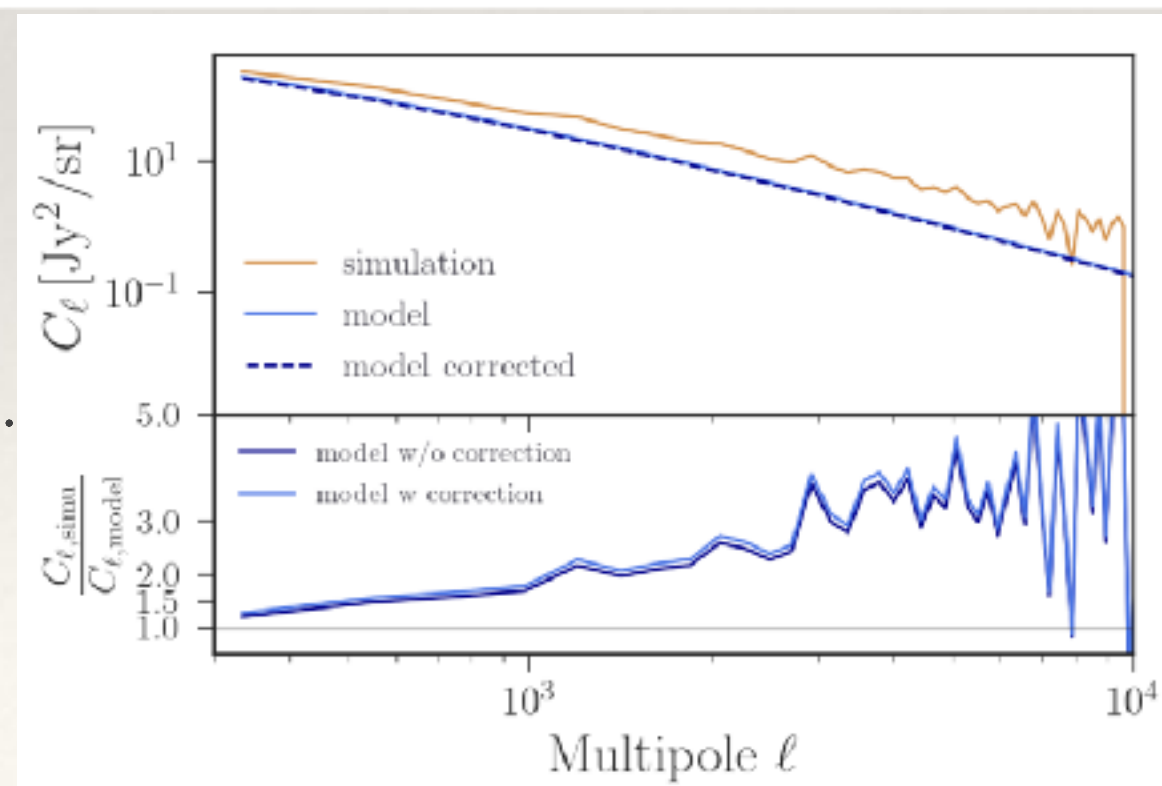
Caveat: the shot noise is not included in the model and a constant is fitted in the power spectra.

Limits of HOD models

- We produced alternative versions of SIDES following exactly the prescription of the HOD model to test its reliability.
- Scatter in the galaxy properties: no impact on the clustering, but strong impact on the Poisson term.
- Deficit of power at small scale with our HOD with a linear bias
  => need for better modeling of the non-linear (scale-dependent) bias



Gkogkou+ in prep.



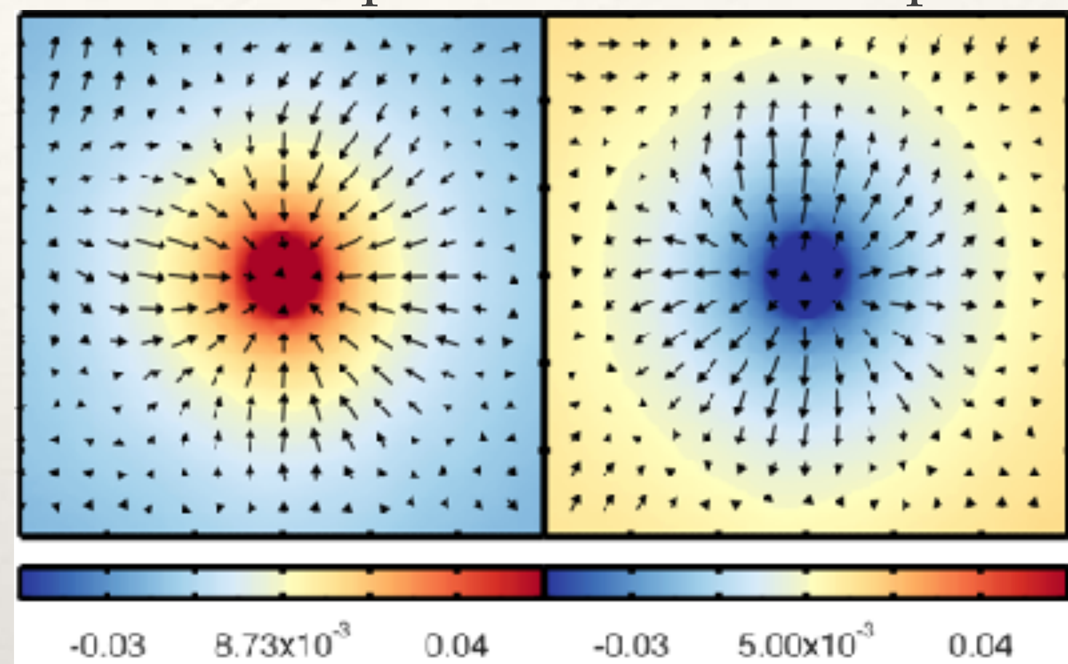
CIB x CMB lensing

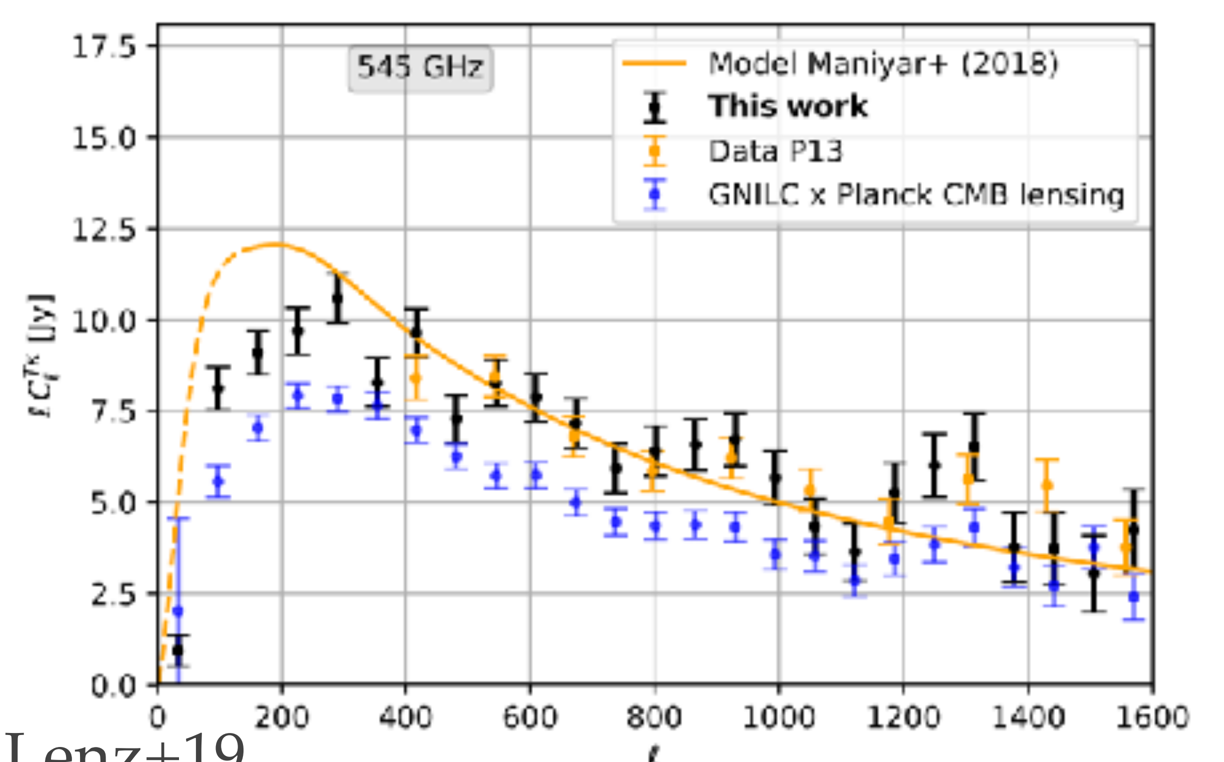
- We can probe more directly the link between the LSS and the star formation using the cross-correlation between CIB and CMB lensing.
- A booming signal was detected by Planck.
- This signal is used to constrain CIB anisotropy models.

Arrows: lensing deflection angle

Planck 2013 XVIII

CIB hot spot CIB cold spot

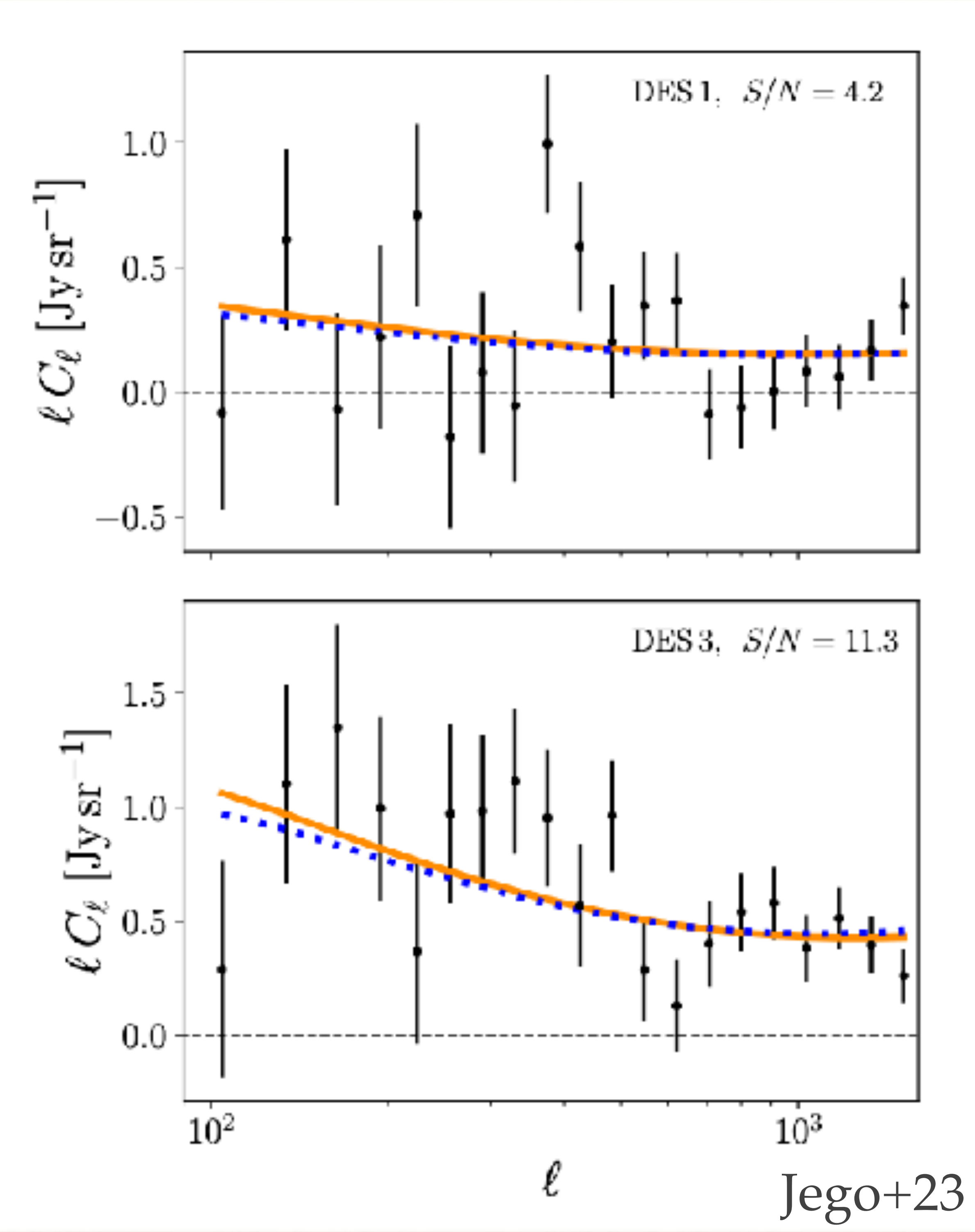




Lenz+19

CIB x galaxy lensing

- CIB x CMB lensing comes from the full line of sight.
- Weak lensing measurements from galaxies in various redshift bins allow a tomography of the CIB.
- Signal detected using DES and KIDS, but limited S/N.
- Huge improvement expected with Euclid!

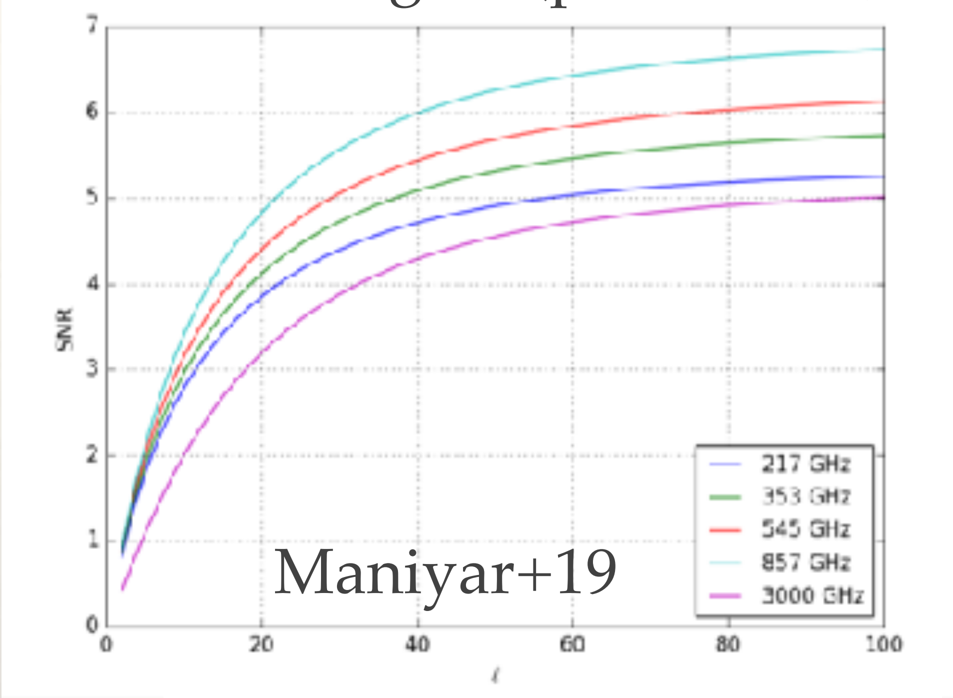


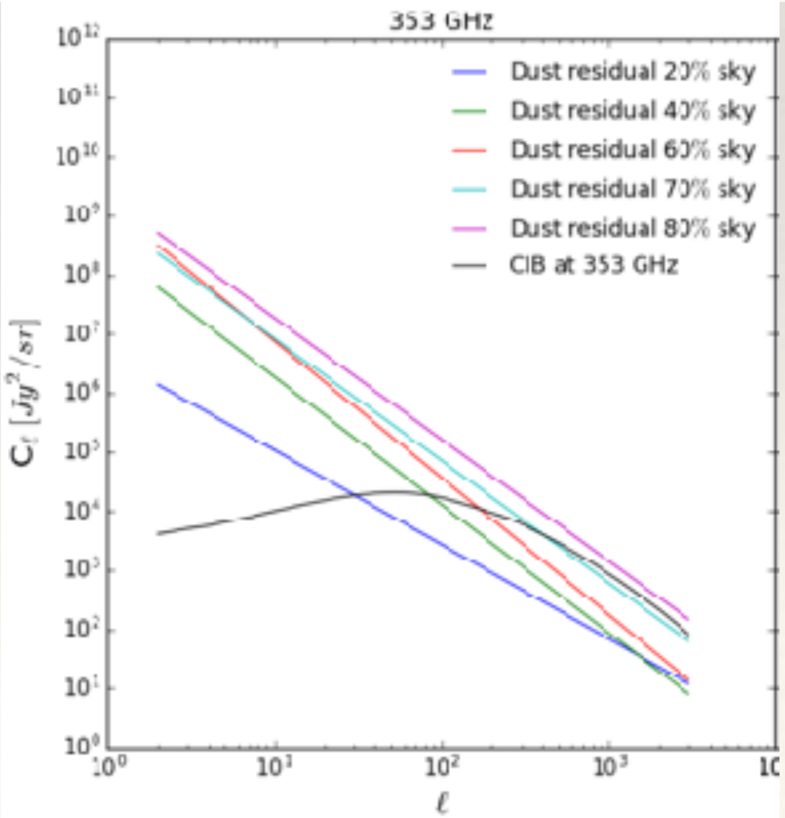
Jego+23

CIB as a cosmological tool?

- CIB anisotropies traces the large-scale structures over a large volumes.
- Theoretically, they could be used in cross-correlation with the CMB to detect the ISW effect (impact of the massive structures on the CMB).
- However, the galactic dust residuals in the CIB maps remain too high to actually detect something reliably.

Expected CIB x ISW signal (perfect CIB, full sky)

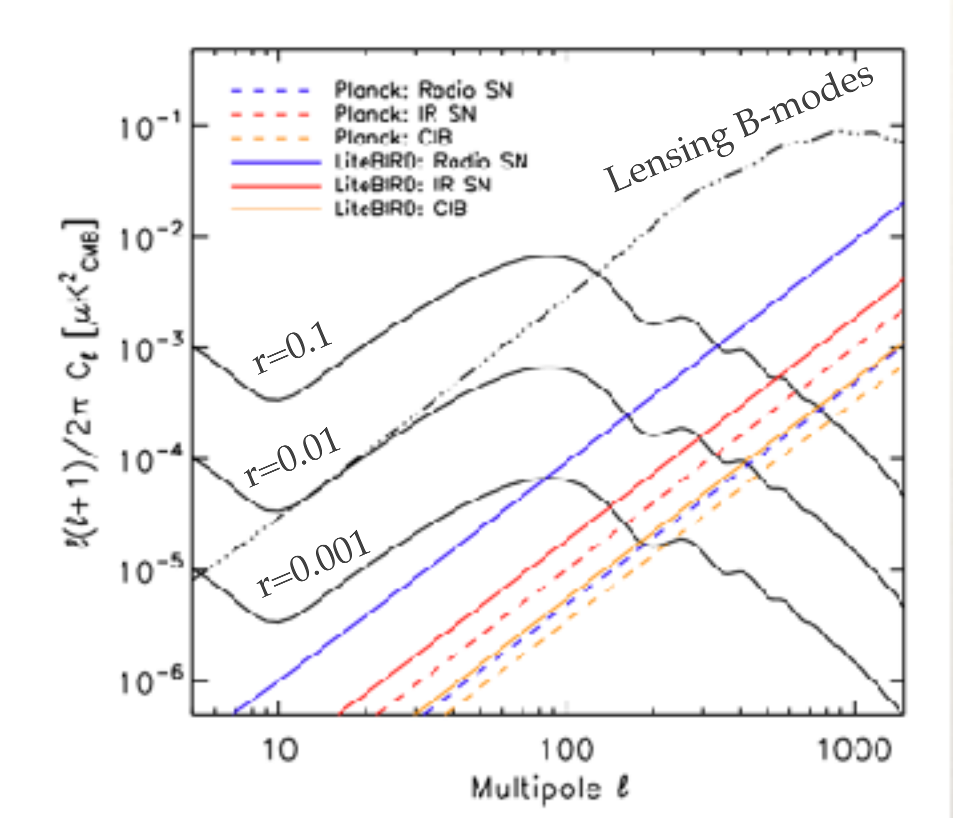




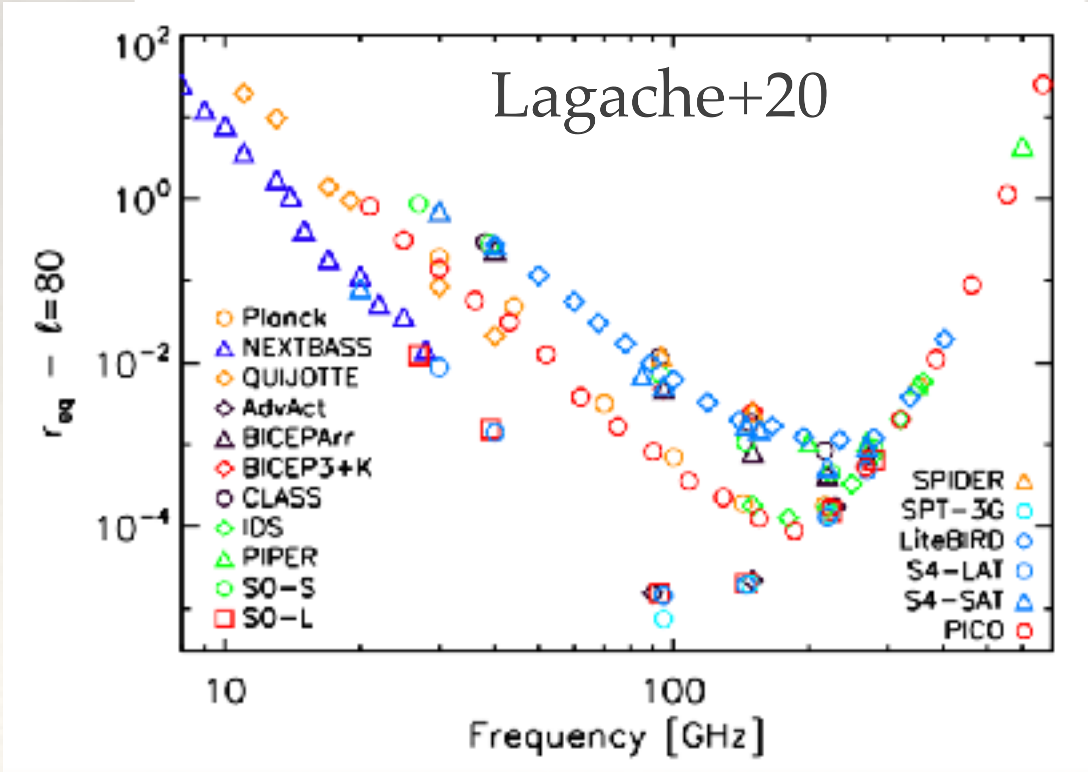
Polarized CIB as a cosmological nuisance

- The integrated dust emission from a galaxy is expected to be polarized at the level of 1%.
- Since galaxies are not supposed to be aligned, this leads to a shot-noise signal.
- This signal will impact the CMB B-mode measurements and set a limit on the scale-to-tensor ratios accessible (but not a problem for the next generation).

See also Béthermin+24 about future galaxy survey in polarization.



Equivalent scalar-to-tensor ratio from the foreground contamination



Conclusion

- Far-IR CIB is mainly emitted by gas-rich dusty galaxies during the peak of star formation of the Universe (z~1-3).
- Far-IR CIB anisotropies: galaxies producing the CIB are hosted by dark-matter halos of ~$10^{12.5}$ Sun.
- Far-IR CIB could also be used to probe cosmology (after progressing on component separation), but it can also be a nuisance.

Impact of the parametrization of the efficiency