# Unveiling obscured star formation and dust attenuation up to z=4

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*And many other collaborators of Herschel surveys teams*


The unquiet Universe, Cefalu june 2014

# Accounting for (young) stellar & dust emissions

- A global point of view:

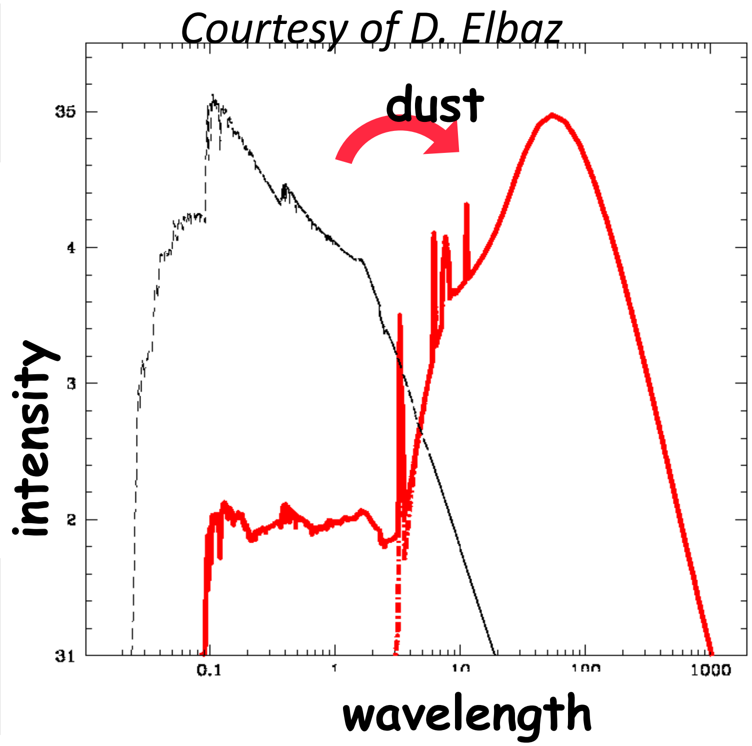
**UV and IR luminosity densities**

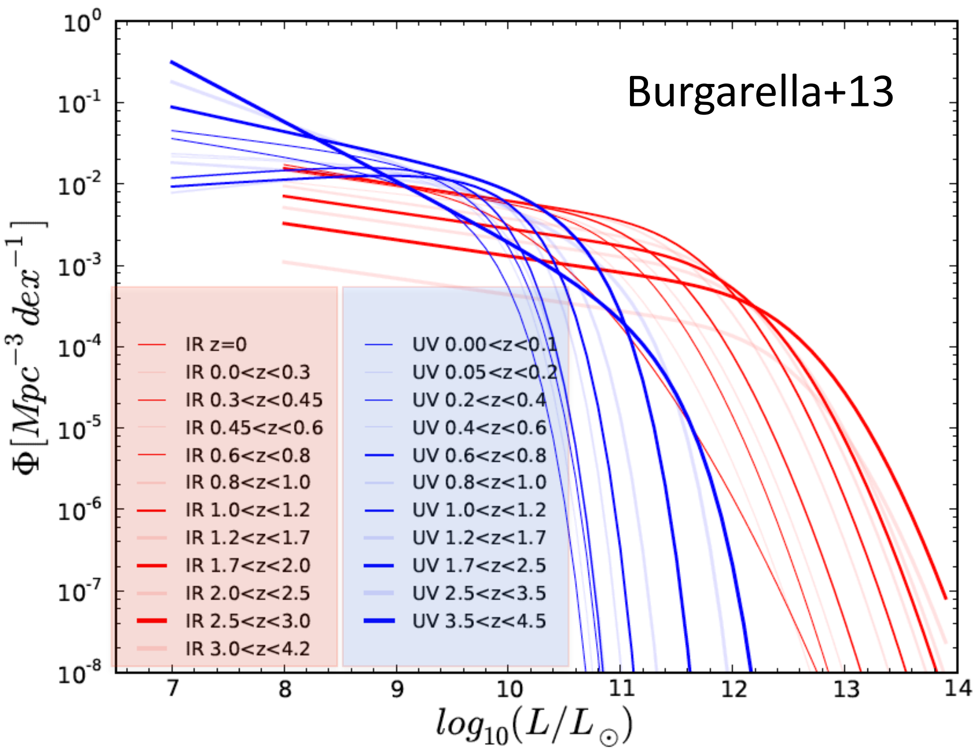
- UV emitting galaxies:

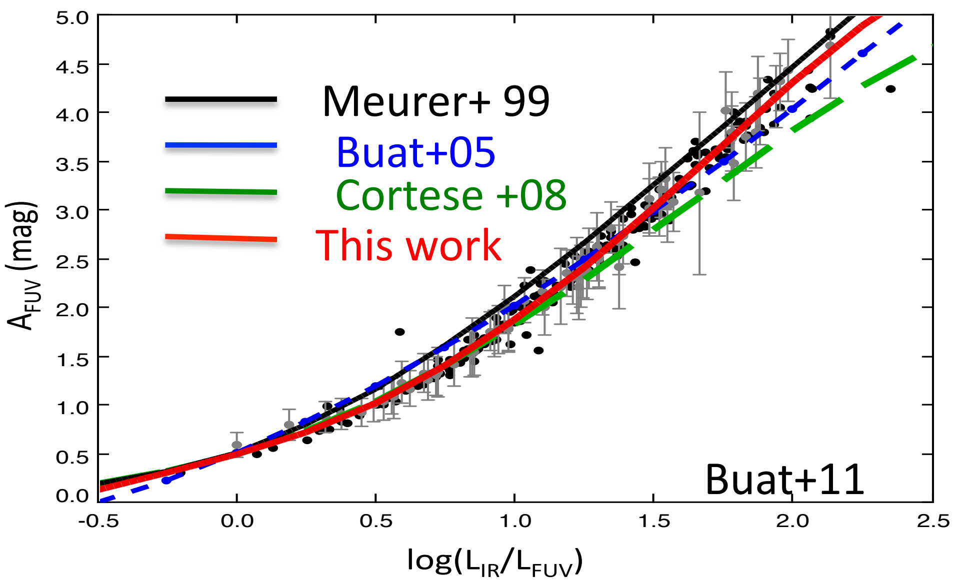
**Star formation history**

**Dust attenuation**

# General context




**Both UV and IR emissions are related to recent star formation**

**•They must be added to measure the star formation**

**•Their ratio is a tracer of dust attenuation**

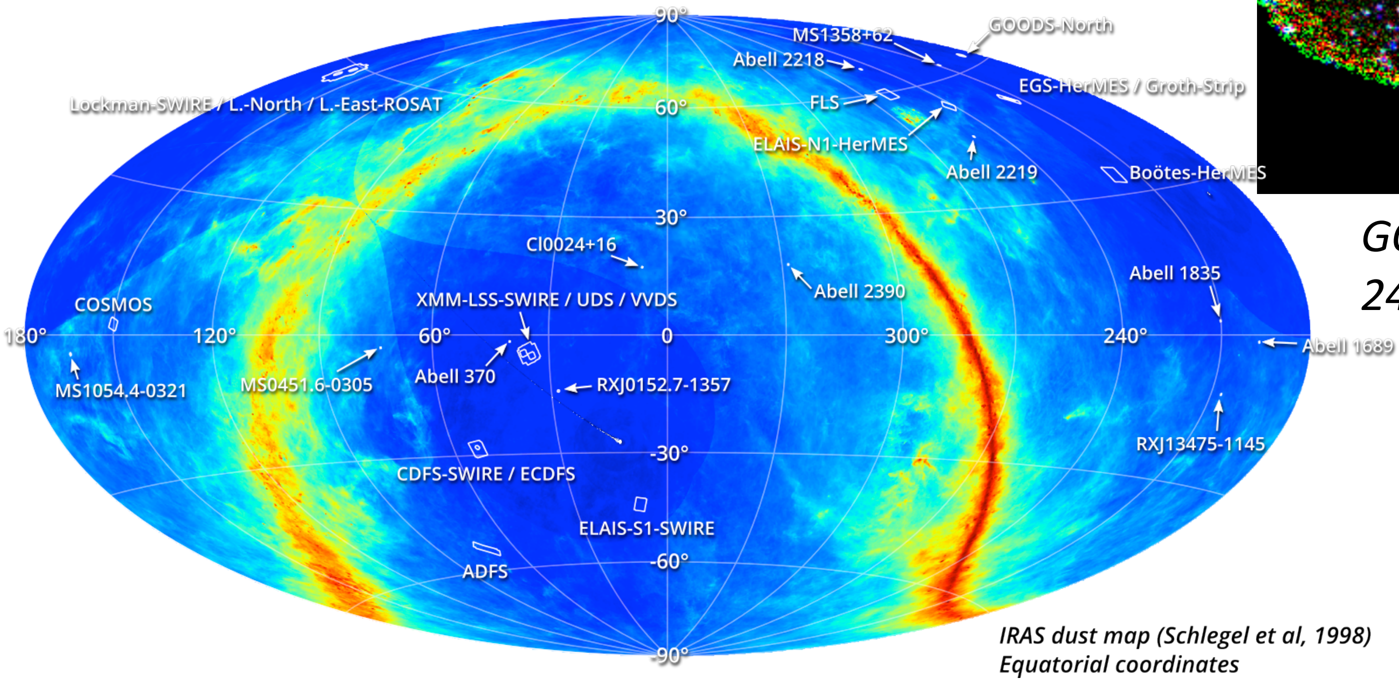
# Based on several Herschel surveys

- HerMES (P.I.: S. Oliver),
- GOODS-Herschel (P.I.:D. Elbaz)

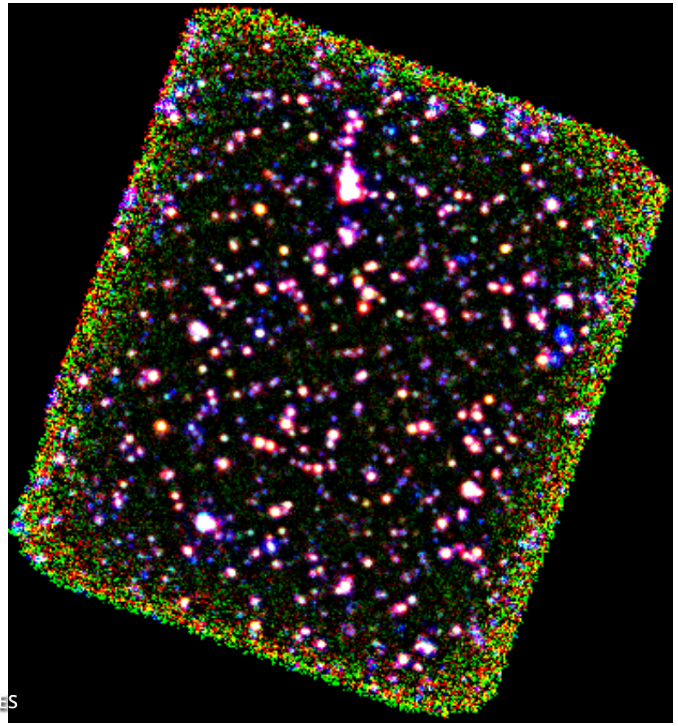
  + PEP (P.I.: D. Lutz)

**COSMOS and CDFS fields**

**HerMES Data Release 2 Field Positions**




*IRAS dust map (Schlegel et al, 1998)*
*Equatorial coordinates*



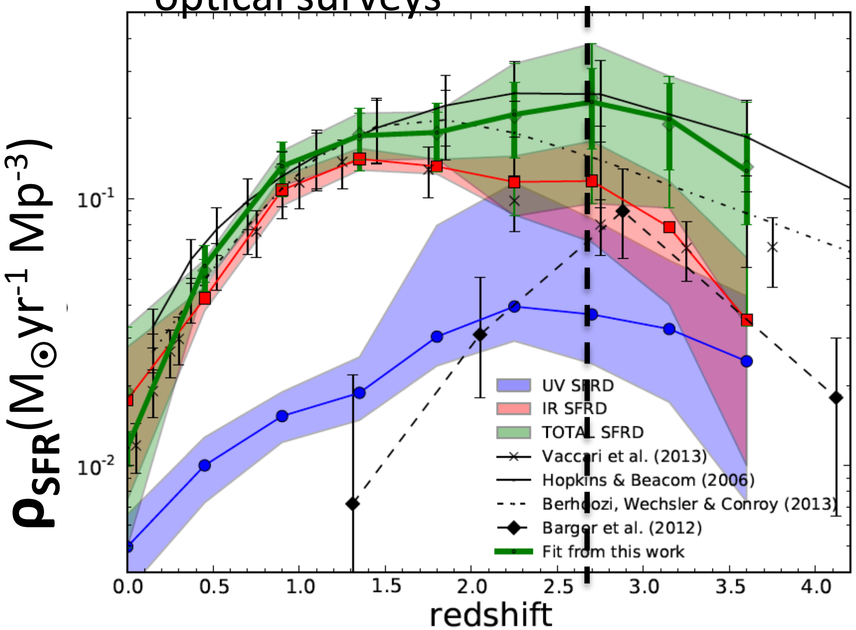
*GOODS-H-CDFS field at 24-100-160 μm*

# Accounting for (young) stellar & dust emissions

- **A global point of view**: UV and IR luminosity densities to measure the SFR density and the global dust attenuation

# Total SFR density and dust attenuation

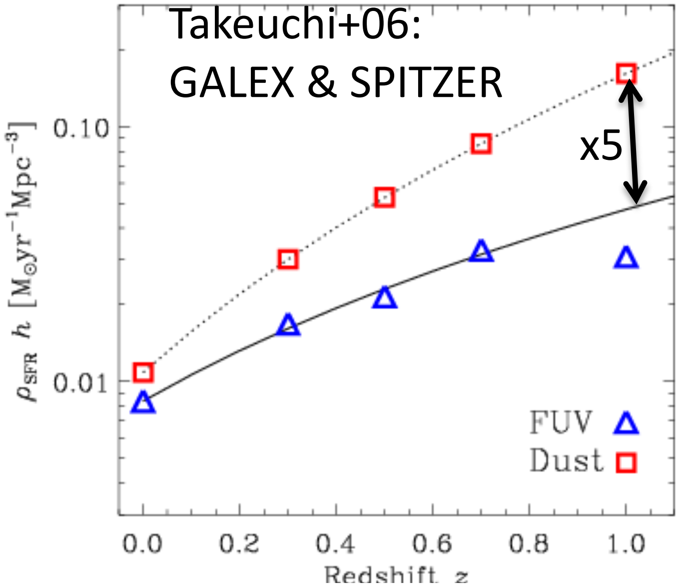
Burgarella+13 Herschel and optical surveys

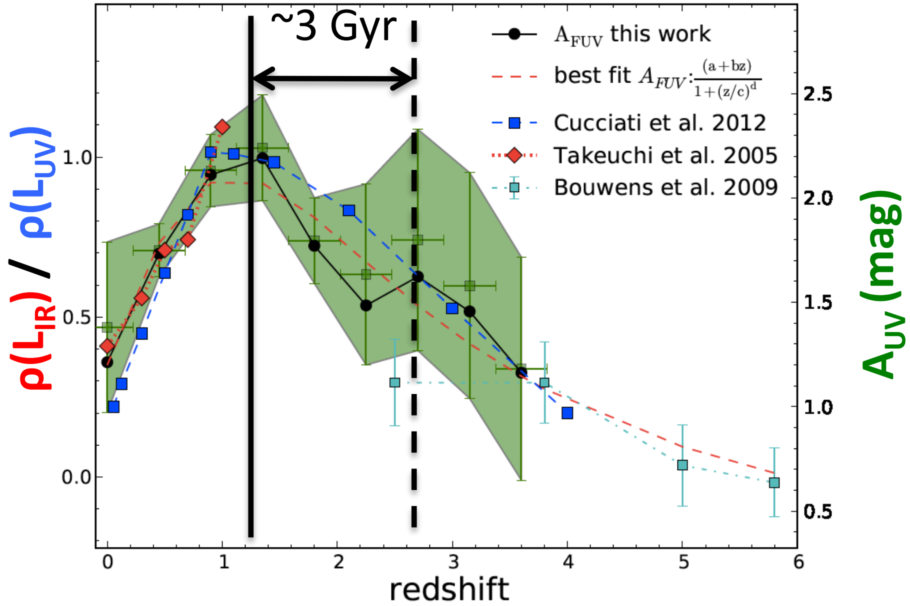



$\rho_{SFR}$ (tot) = $\rho_{SFR(UV)}$+$\rho_{SFR(IR)}$

$\rho_{SFR(IR)}$> $\rho_{SFR(UV)}$ at all redshifts (z<3.5)

A plateau (or slight increase) of $\rho_{SFR}$ at z>1




Attenuation increases up to z=1 and then decreases $A_{UV}(z=0)$ ~$A_{UV}(z=4)$

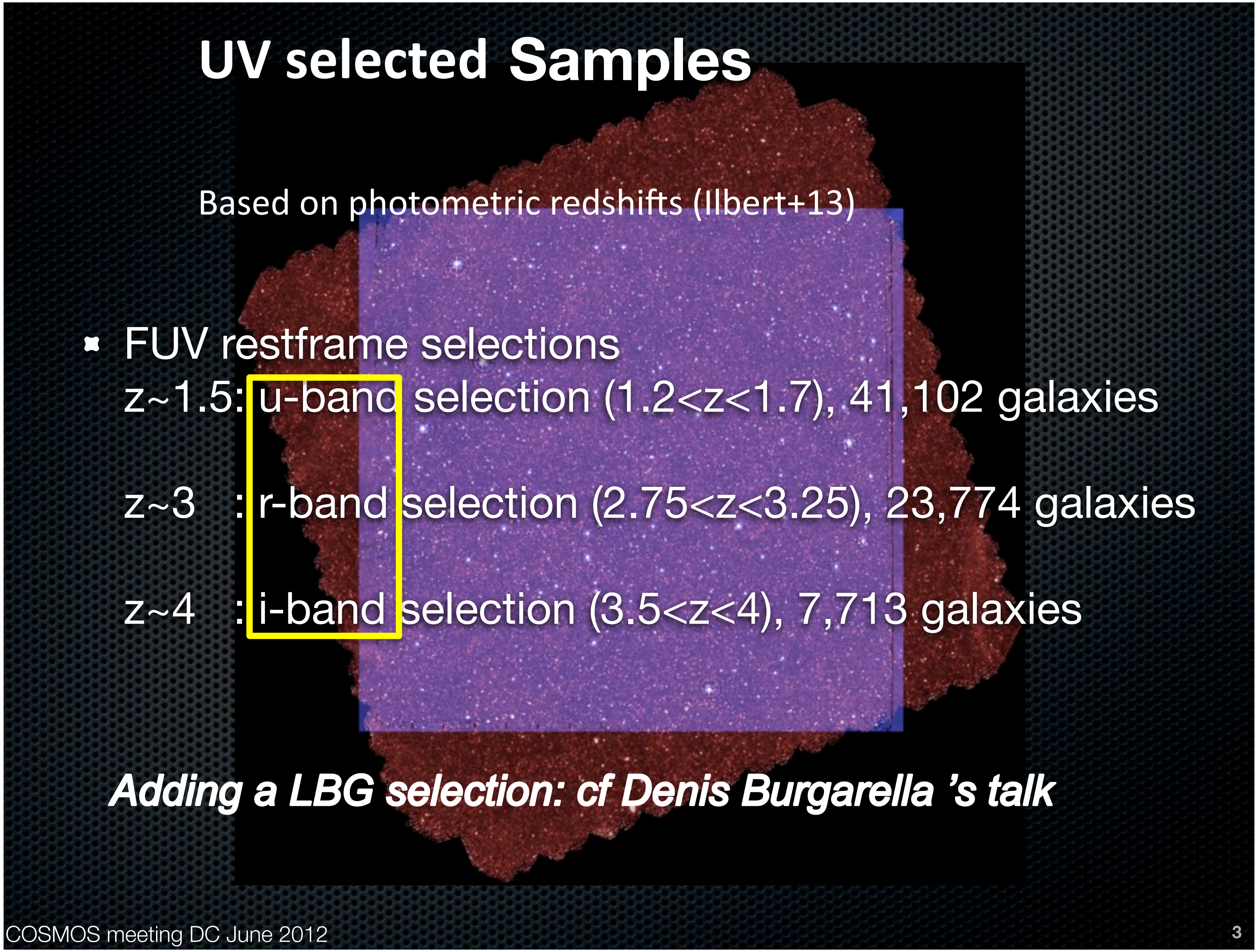
# Accounting for (young) stellar & dust emissions

- **UV emitting galaxies:**

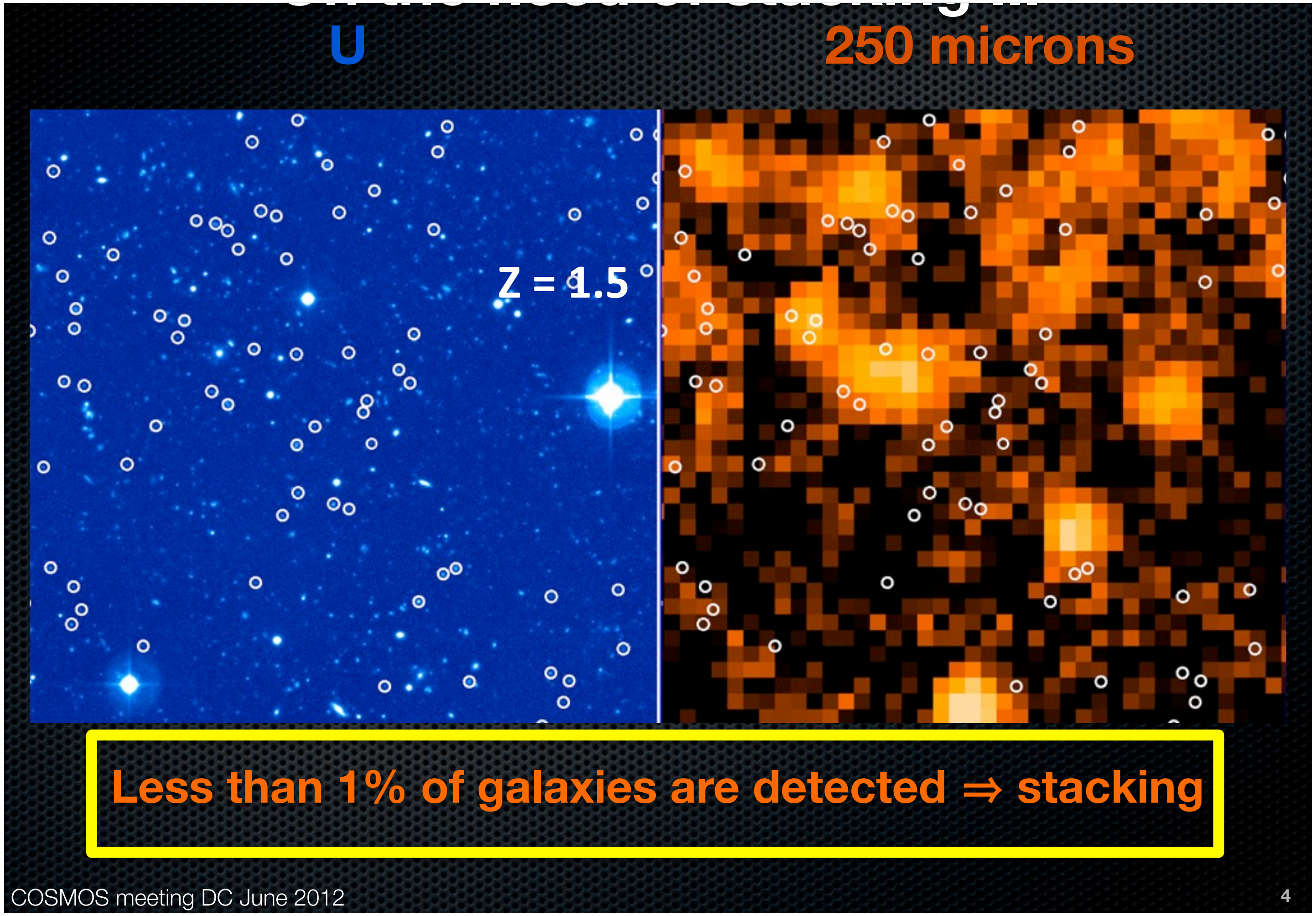
**Star formation history:** SFR-$M_*$ evolution with z

# Study of UV selected galaxies and LBGs in the COSMOS field @ z=1.5, 3 & 4

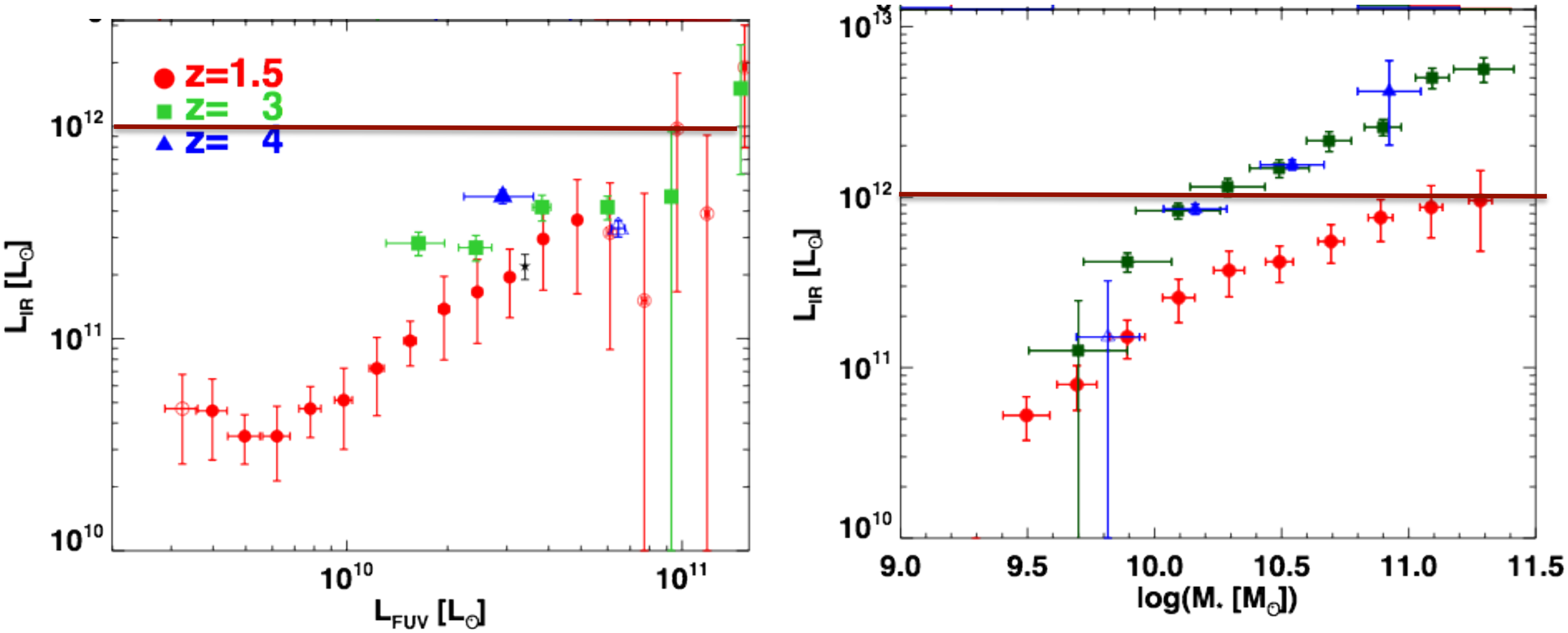
Heinis+13,+14, Alvarez-Marquez et al. in prep.



# Almost no counterpart of UV selected sources in Herschel images



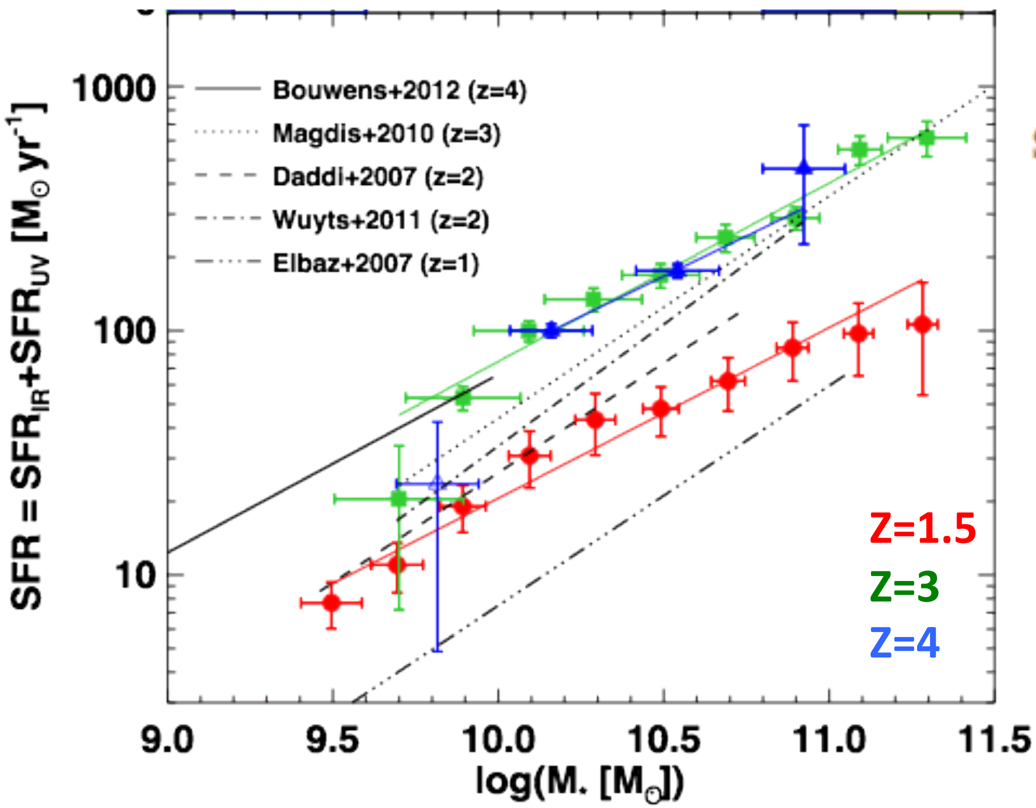
# Stacking per bin of $L_{FUV}$ and of $M_*$ for the UV selection (Heinis+13, 14)




$L_{IR}$ measured by fitting Dale & Helou (2002) templates on SPIRE data

**Higher IR luminosities are reached when the stacking is performed by bins of $M_*$**

# SFR versus M* : a well defined 'Main Sequence' for star-forming galaxies




$$\mathrm{SFR_{IR}}[\mathrm{M_\odot yr^{-1}}] = 1.09 \times 10^{-10} L_{\mathrm{IR}}[\mathrm{L_\odot}]$$
$$\mathrm{SFR_{UV}}[\mathrm{M_\odot yr^{-1}}] = 1.70 \times 10^{-10} L_{\mathrm{FUV}}[\mathrm{L_\odot}]$$

*(from Kennicutt, 98)*

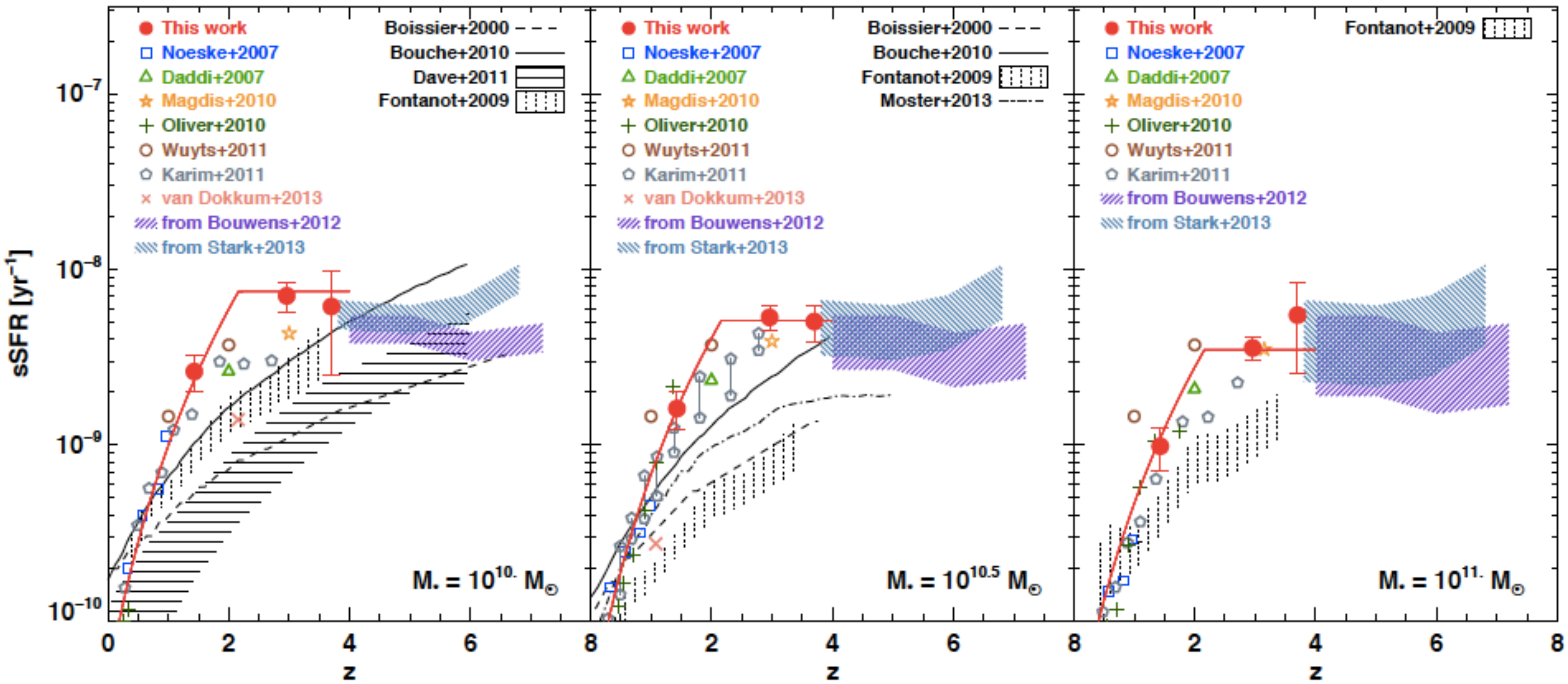
$\mathrm{SFR} = \mathrm{SFR}_0\ M_*^{0.7}$

→ slope< 1, low dispersion because of stacked quantities

see also e.g. Noeske+07, Oliver+10, Whitaker+12

slope~1 found by Elbaz+07, Daddi +07, Wuyts+11

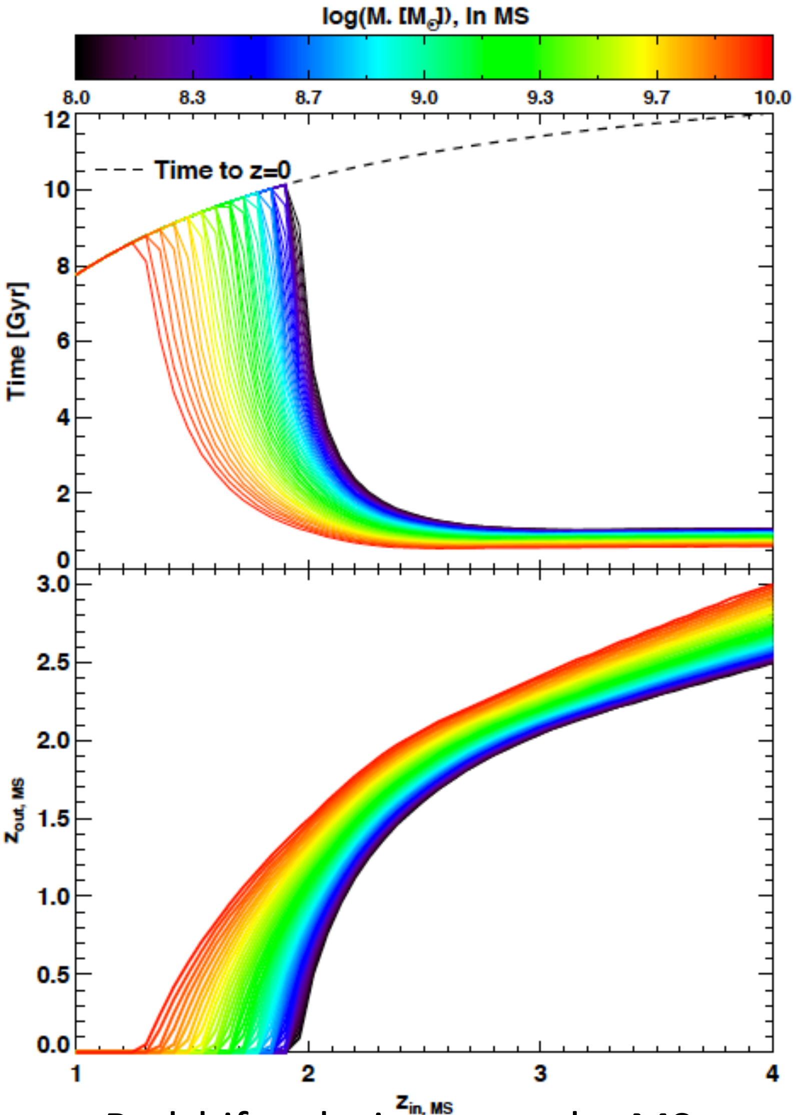
# Specific SFR (sSFR=SFR/M*) : very active galaxies at z =3 & 4, a challenge for the models




Consistent with **a plateau in sSFR for z>~2**

**High sSFRs**, in agreement with other measures at z=1.5 and consistent with the measures at higher redshifts

Models do not predict the high sSFRs found at z>1, the discrepancy is particularly high with our Herschel measures




Redshift (time) galaxies exit the MS (quenching)

Redshift galaxies enter the MS

## From the evolution of the sSFR with z and $M_*$ we can infer the time a galaxy stays on the MS

Defining a quenching mass varying with z:
(Ilbert+13 & Baldry+12)

$M_Q = 3.7\ 10^{10}\ (1+z)^{0.53}$

Galaxies reaching $M_Q$ exit the MS
We account for the return fraction (Conroy & Wechsler09)

Galaxies entering the MS at 2.5<z<4: stay ~1Gyr on it
Galaxies entering the MS at z<1.2: stay until z=0

# Accounting for (young) stellar & dust emissions

- **UV emitting galaxies:**

**Star formation history**

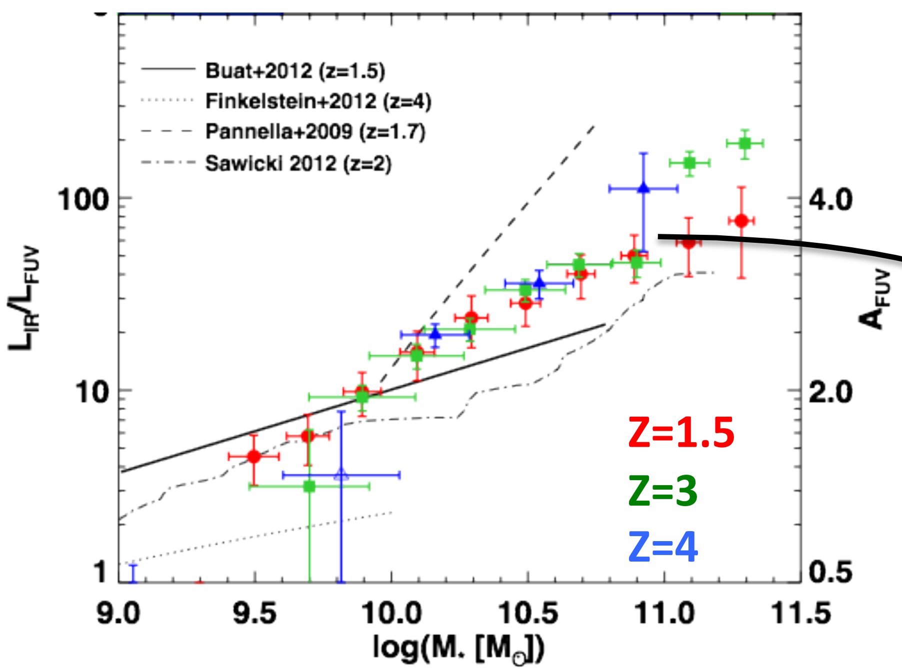
**Dust attenuation**: $L_{IR}/L_{UV}$= IRX

Variation with $M_*$,β (slope of the UV continuum)

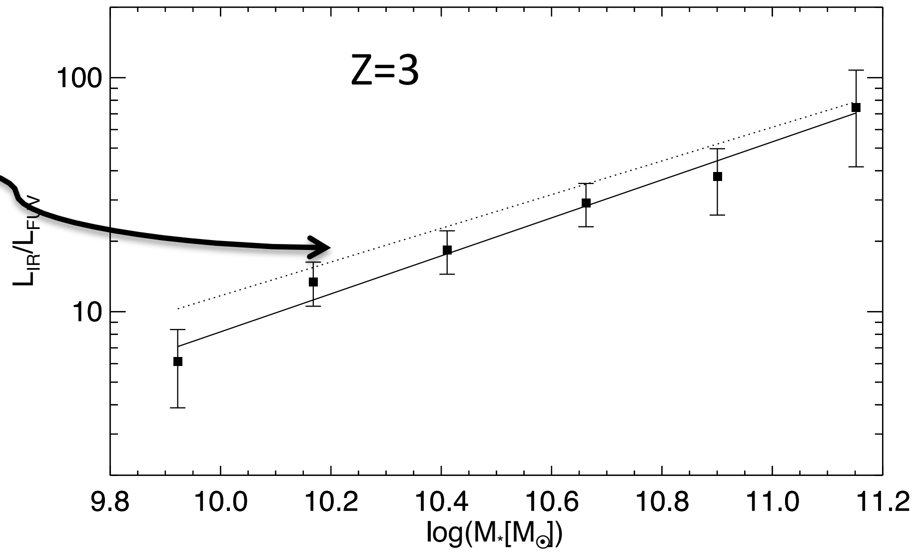
Attenuation curve

# Dust attenuation $L_{IR}/L_{FUV}$=IRX versus $M_*$ for UV selected galaxies and LBGs

**UV selected galaxies, Heinis+14**

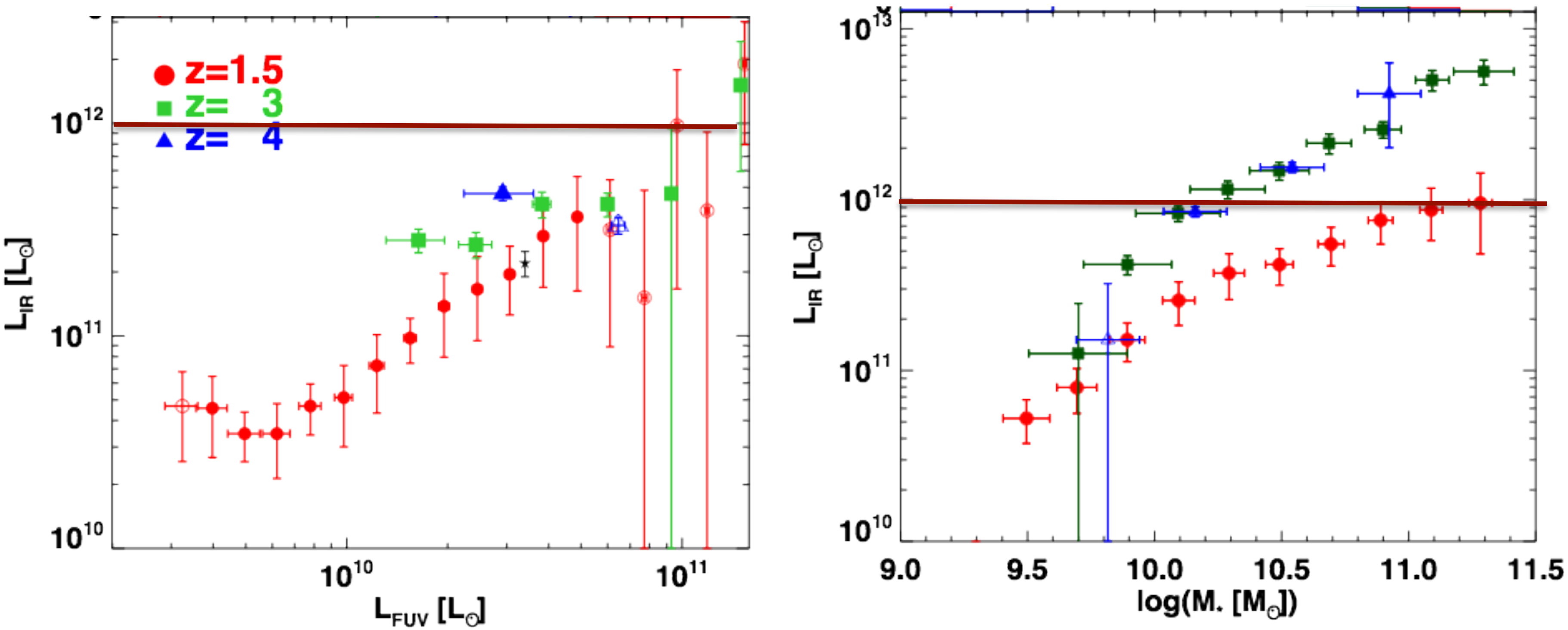



**Lyman-Break Galaxies**
**Alvarez-Marquez et al. in prep**



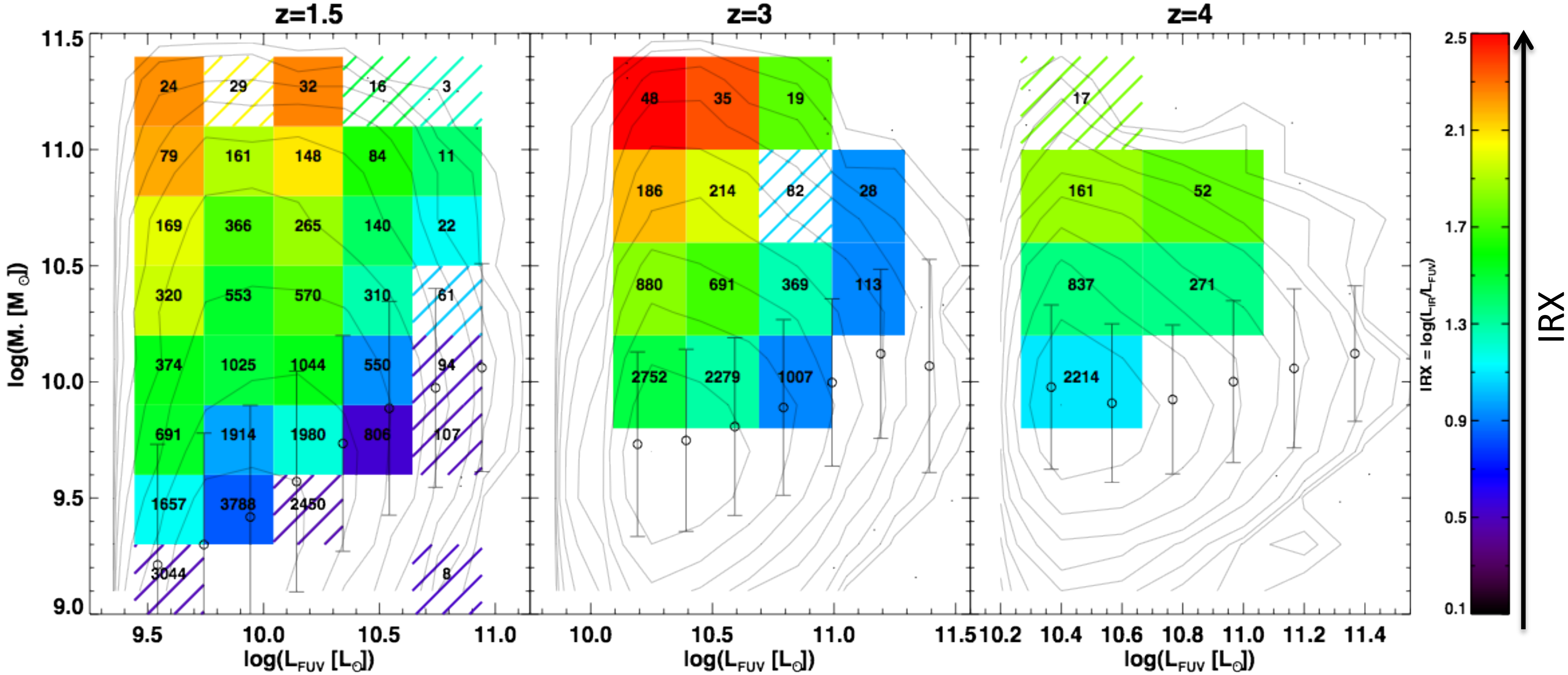

$L_{IR}$ measured by fitting Dale & Helou (2002) templates on SPIRE data
$A_{FUV} = f(L_{IR}/L_{FUV})$ (Buat+05)

Consistent results found by Panella et al.




**Higher IR luminosities are reached when the stacking is performed by bins of $M_*$**

→ Stacking per bin of ($L_{FUV}$,$M_*$)




•Dust attenuation increases with $M_*$ for a given $L_{FUV}$
•Dust attenuation decreases with $L_{FUV}$ for a given $M_*$
•The dispersion in dust attenuation decreases with $L_{FUV}$

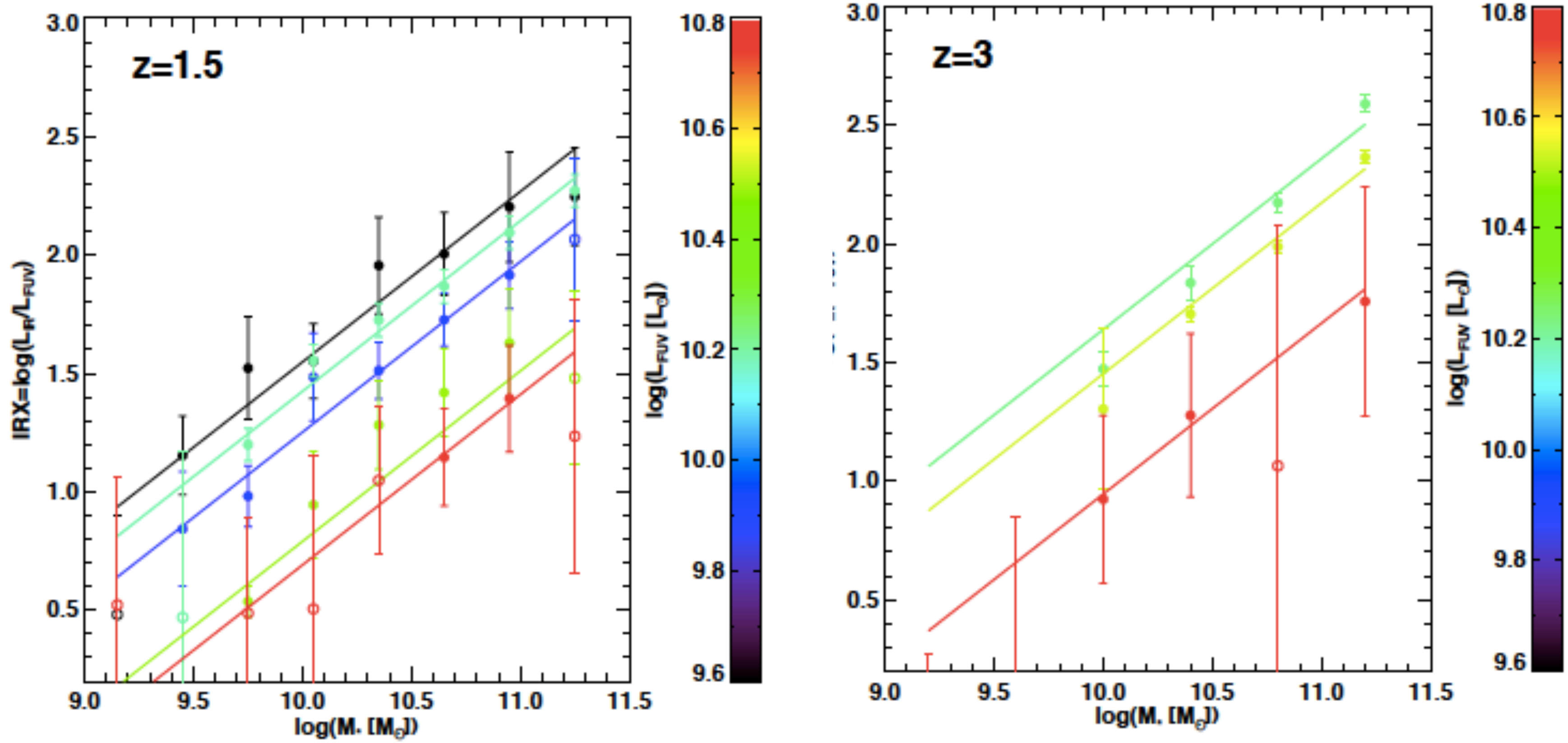
*See also Burgarella+06, Buat+09,12*

# A recipe to derive $L_{IR}/L_{FUV}$=IRX

*Heinis+14*

$$IRX=\log(L_{IR}/L_{FUV})=IRX_0(\mathbf{L_{FUV}})+0.72*\log(\mathbf{M_*}/10^{10.35})$$

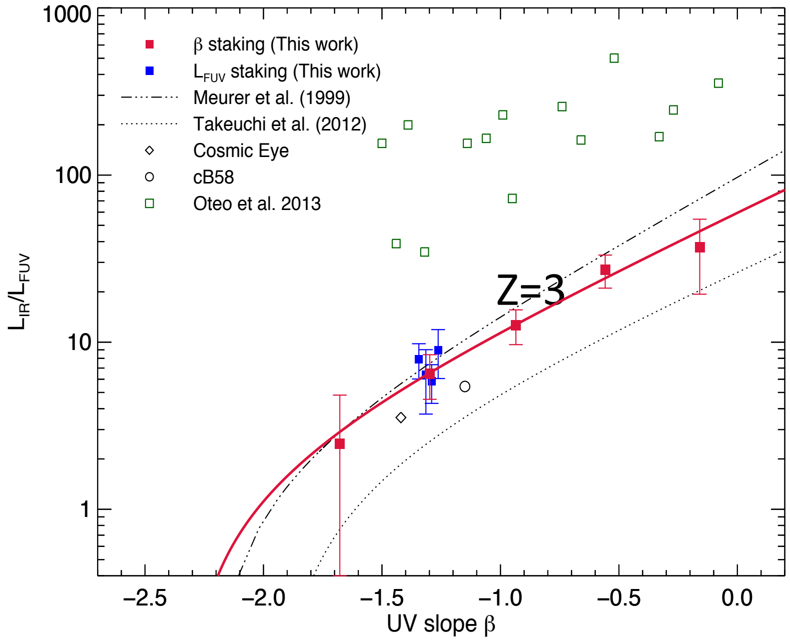
@z=1.5 & 3



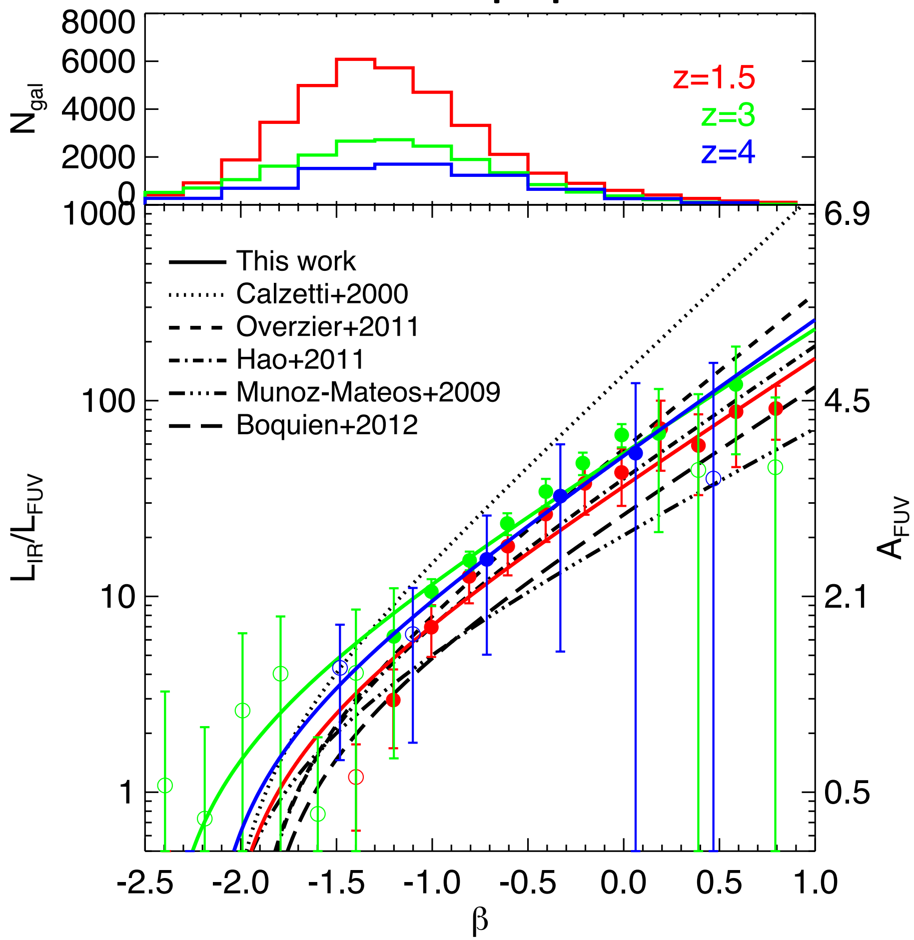
# IRX-β relations, UV selection & LBG

- ß estimated with intermediate band filters $f_\lambda \propto \lambda^\beta$ (1200-2500Å)
- Stacking per bins of Δß = 0.2

**Lyman-Break galaxies,**
**Alvarez-Marquez et al. In prep**




**UV selected galaxies**
**Heinis et al. In prep**



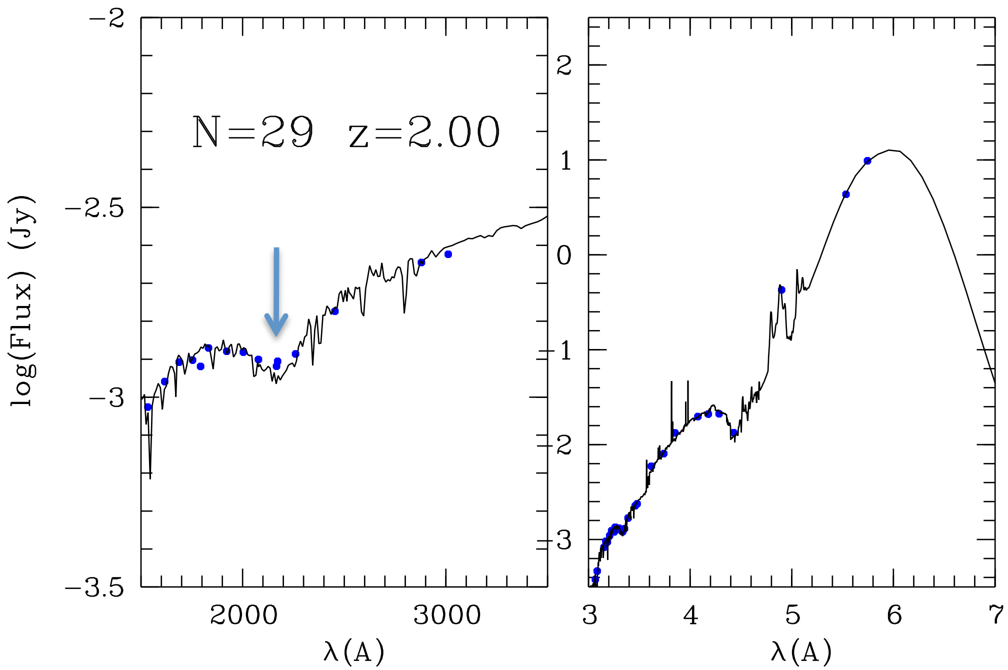

Lyman Break Galaxies closer to the local starburst law than purely UV selected objects

# Dust attenuation curve in « UV selected » galaxies 1<Z<2

**Buat+11,12**

**Subaru/MUSYC** broad and intermediate band filters (Cardamone+10)
+**IRAC & MIPS** data (Dickinson+03)
+**GOODS-Herschel/PACS** data

**751 galaxies,** **236 galaxies detected with MIPS,** **80 sources detected with PACS, upper limits for the other ones**




Fitted with CIGALE

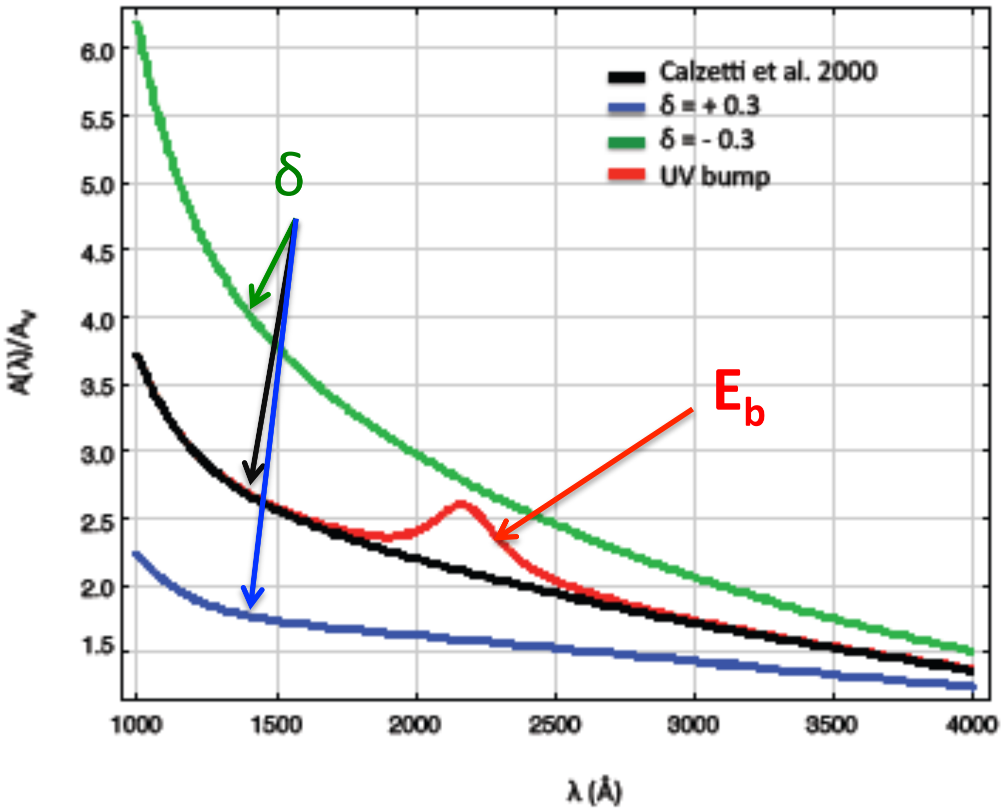
## Parametrization of the attenuation curve

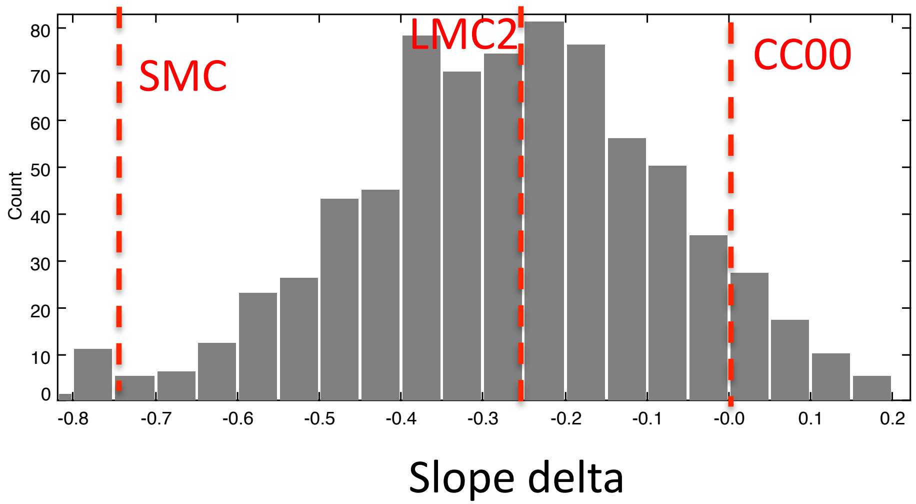
$$k(\lambda) = \left( \frac{A(\lambda)}{E(B-V)} + \frac{E_b \lambda^2 \gamma^2}{(\lambda^2 - \lambda_0^2) + \lambda^2 \gamma^2} \right) \left( \frac{\lambda}{\lambda_V} \right)^{\delta}$$

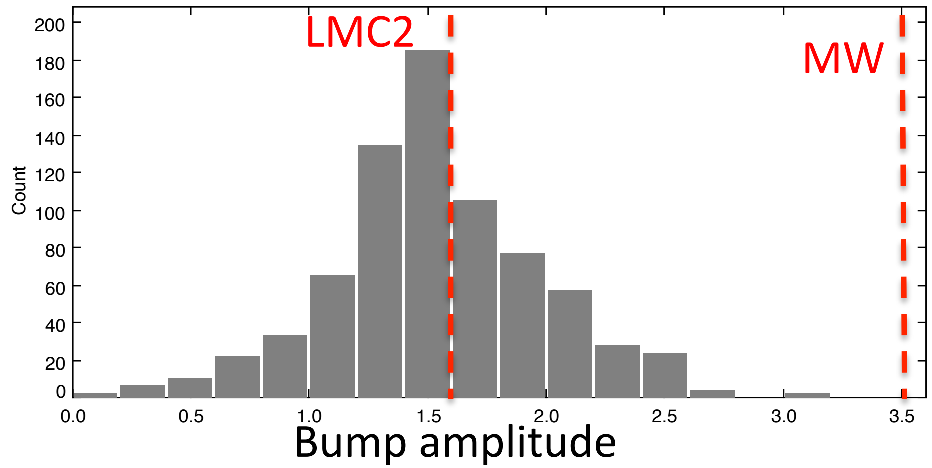
**Calzetti et al. (2000)**

**UV bump**
*Fitzpatrick & Massa formalism*

**power law**

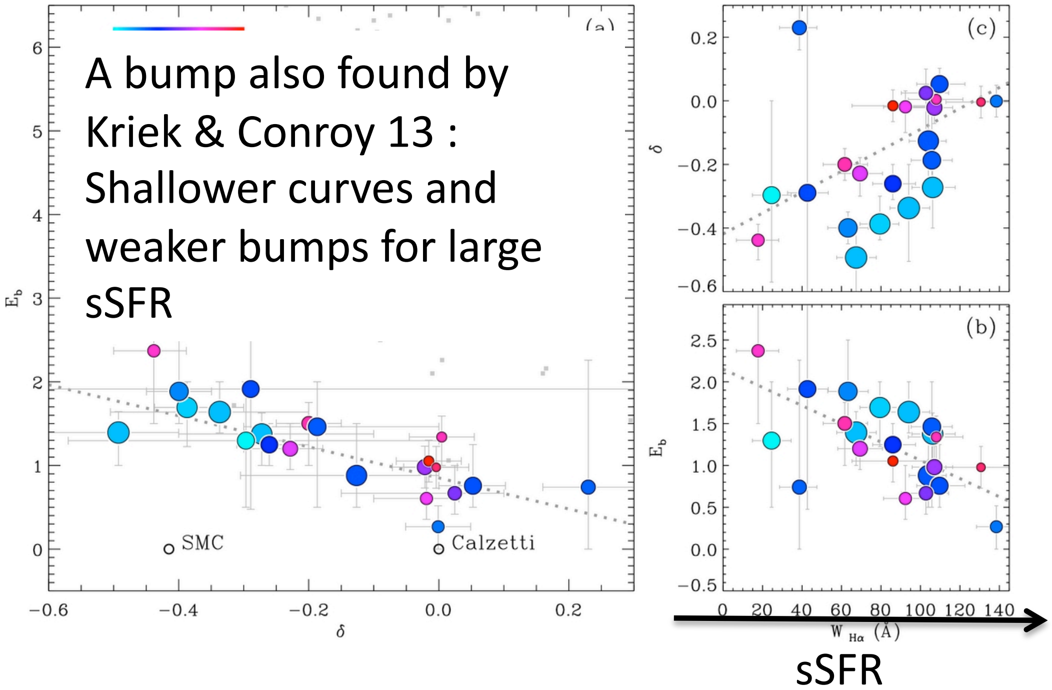




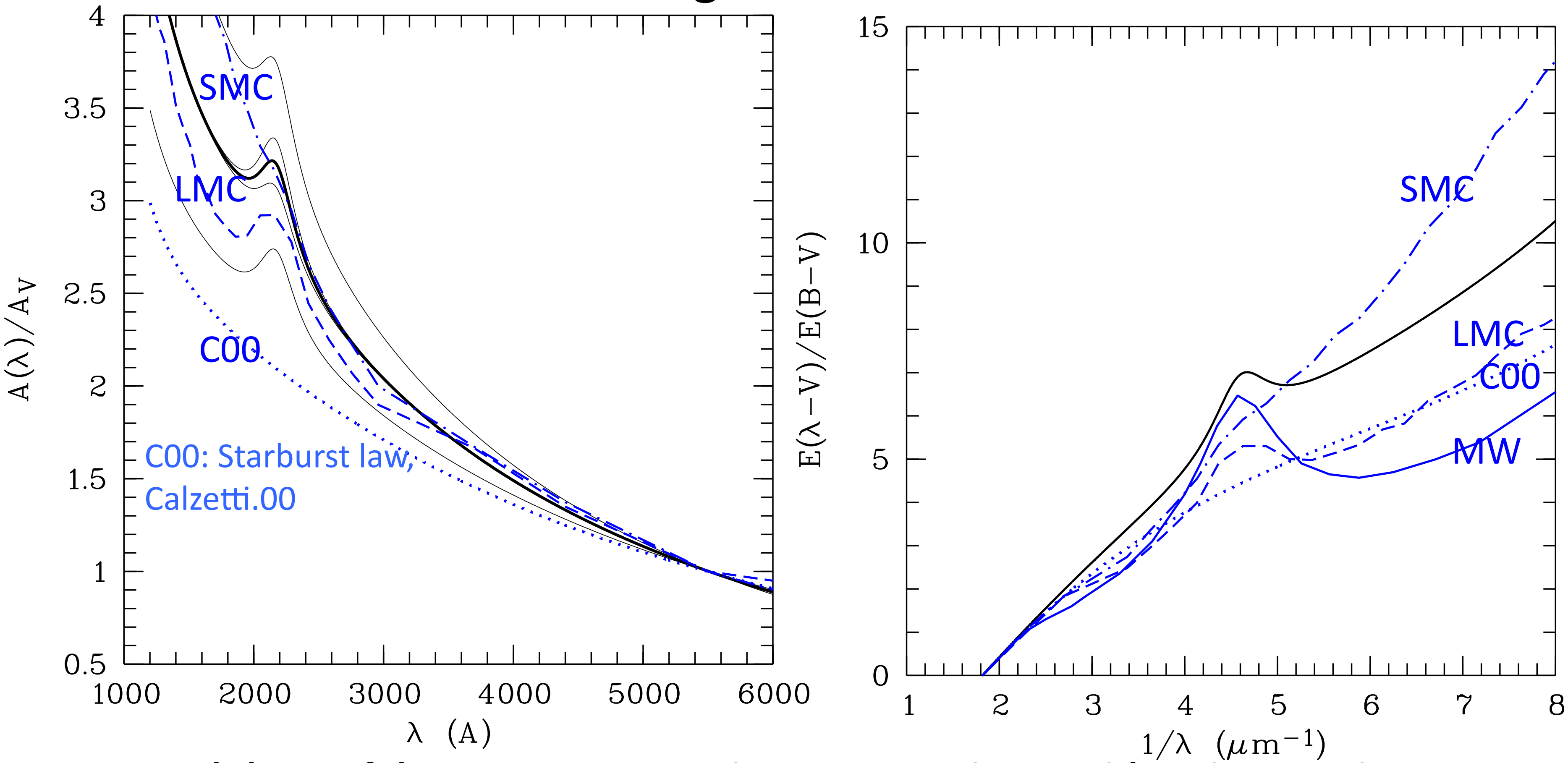




**$E_b$= 1.6 +/- 0.4 $\delta$ = -0.27 +/- 0.17**

**Close to the values of the LMC2 extinction curve**



# Derivation of a mean dust attenuation curve with a UV bump in the CDFS galaxies with 1<z<2




**General shape of the average attenuation curve consistent with an increase in UV similar to that of the LMC supershell extinction curve (steeper than the Calzetti curve on top of which there is a bump at 2175 A) whose amplitude is similar to that found in the LMC supershell, (45% that of the MW one) . BUT Large dispersions among galaxies**

# Summary

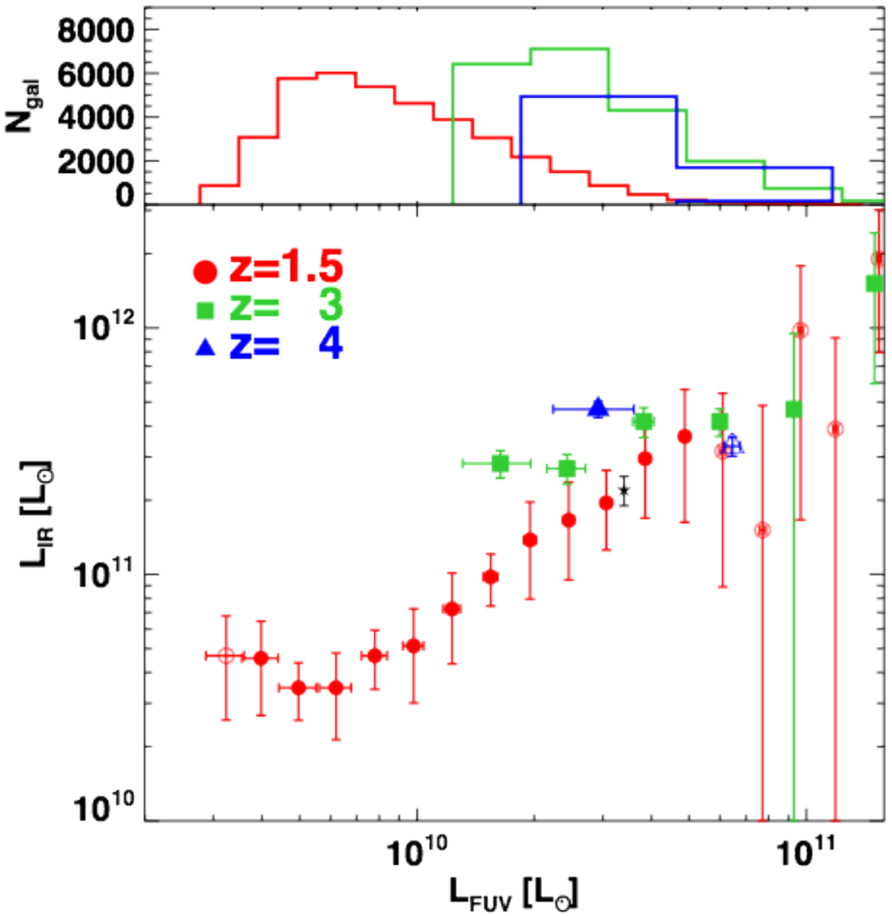
•The total dust attenuation measured with the IR an UV luminosity densities peaks at z~1.2, ~3 Gyr after the maximum of star formation.

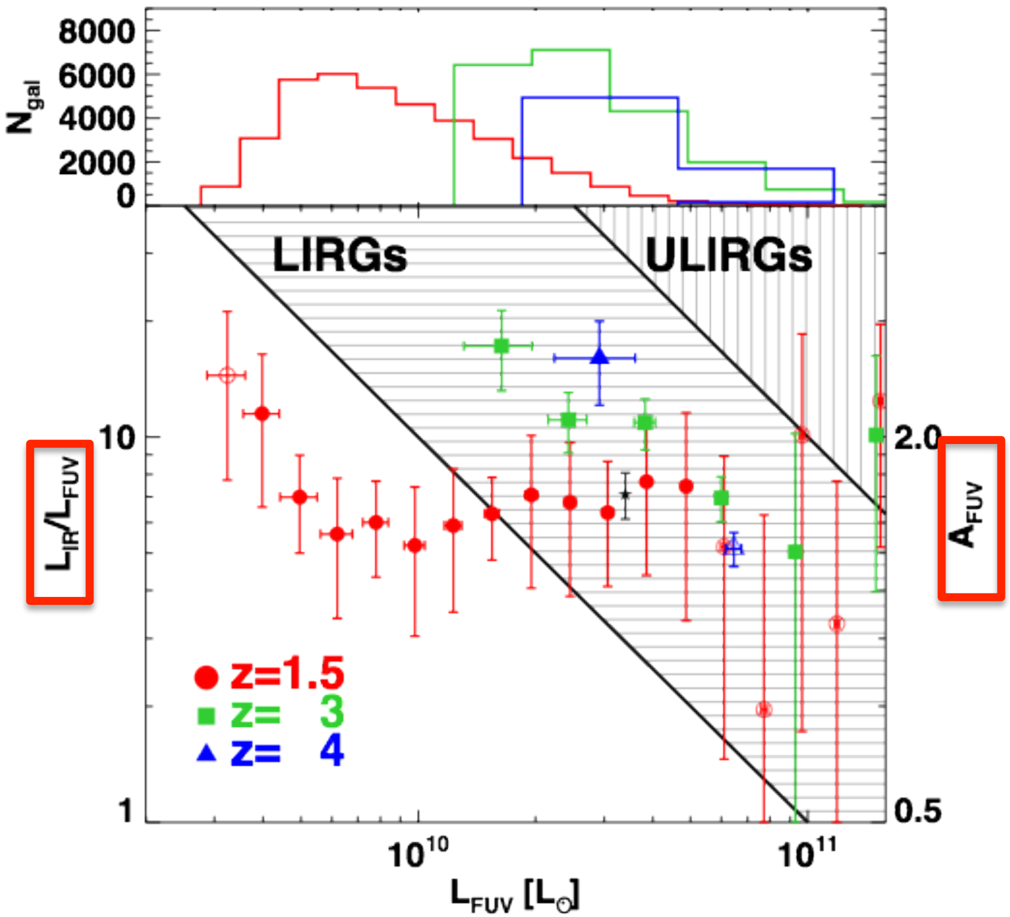
• UV selected  galaxies at z-3 are found with  a larger sSSFR than predicted by models.
→These galaxies cannot stay very long times  on the Main Sequence.

•Dust attenuation is found to depend on both M* and Luv (recipes).

•The dust attenuation curve of UV selected galaxies at 1<z<2 is found to be in average steeper than the Calzetti law and to exhibit a 2175A bump (close to the extinction law in the LMC).

# Stacking per bin of $L_{FUV}$

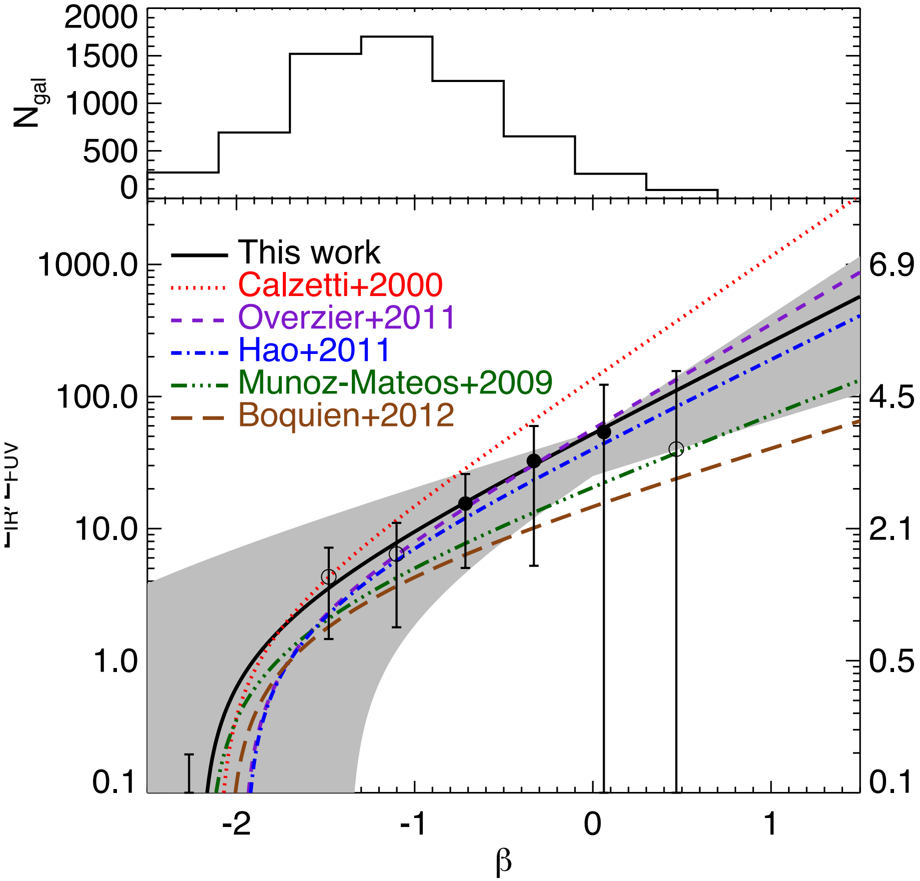


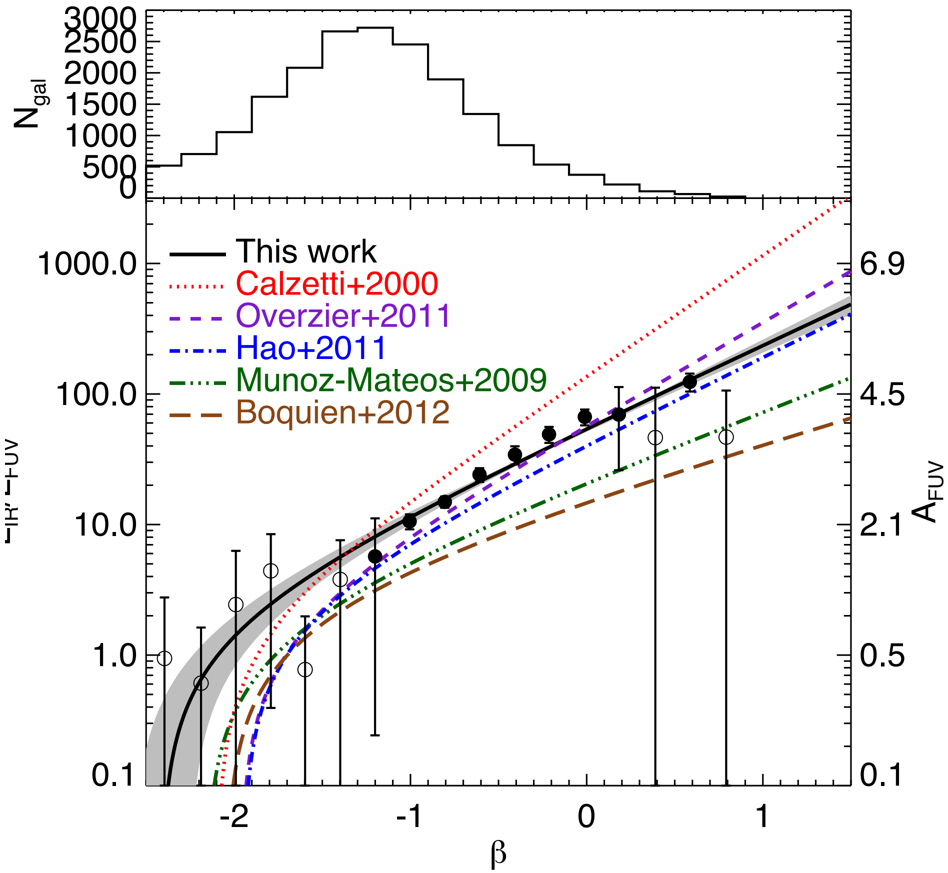

$L_{IR}$ measured by fitting Dale & Helou (2002) templates on SPIRE data

$A_{FUV} = f(L_{IR}/L_{FUV})$ (Buat+05)

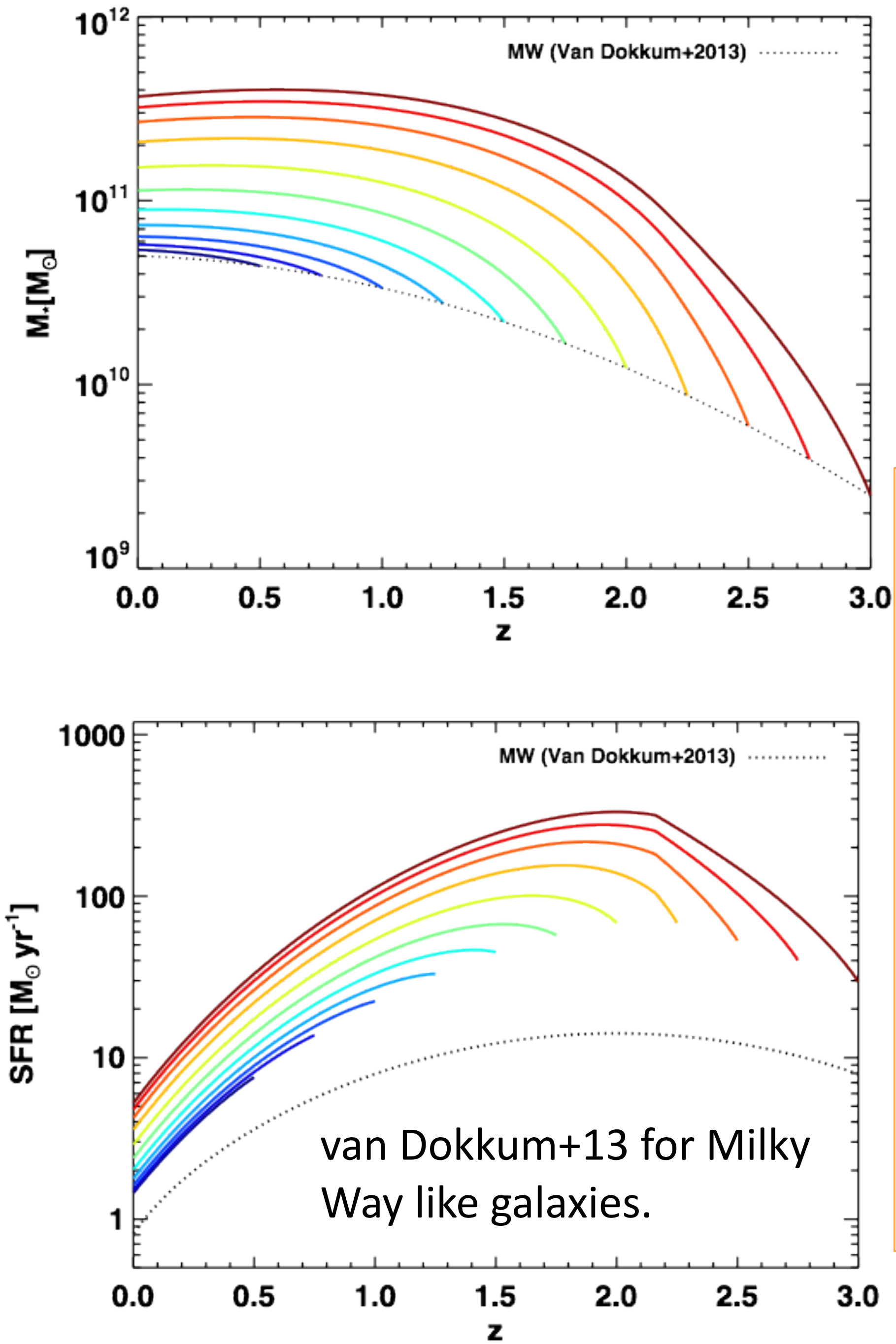
→ **LIRGs and sub-LIRGs**



N_gal
2000
1500
1000
500
0
This work
Calzetti+2000
Overzier+2011
Hao+2011
Munoz-Mateos+2009
Boquien+2012
1000.0
100.0
10.0
1.0
0.1
6.9
4.5
2.1
0.5
0.1
A_FUV
-2
-1
0
1
β

N_gal
3000
2500
2000
1500
1000
500
0
This work
Calzetti+2000
Overzier+2011
Hao+2011
Munoz-Mateos+2009
Boquien+2012
1000.0
100.0
10.0
1.0
0.1
6.9
4.5
2.1
0.5
0.1
A_FUV
-2
-1
0
1
β



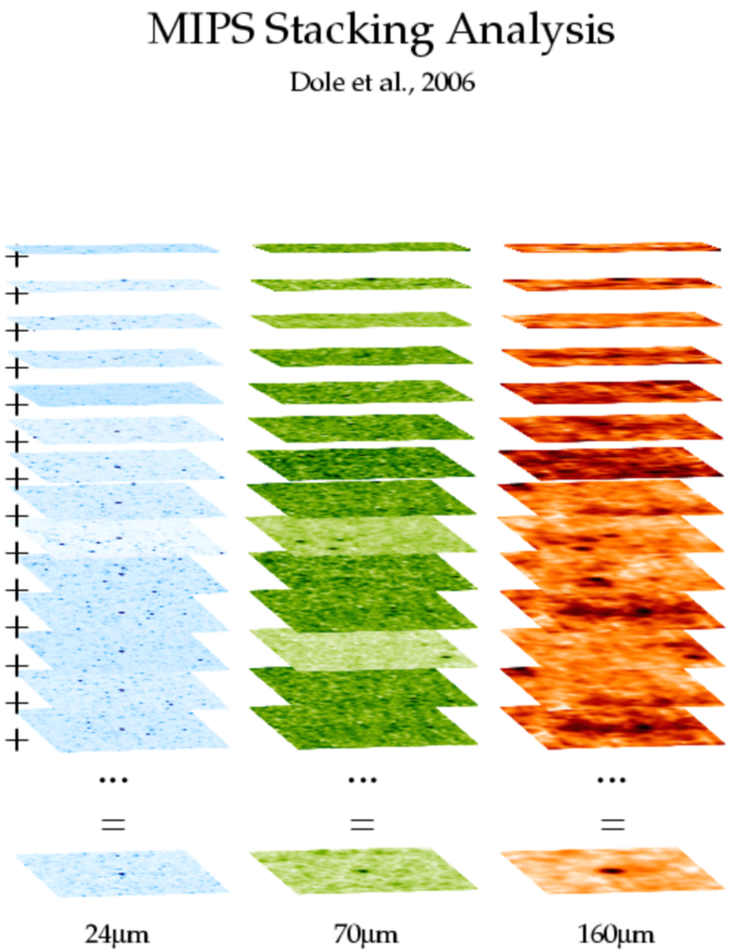

**From the evolution of the sSFR with z and $M_*$ we can infer the average star formation histories of galaxies**

Evolution of stellar mass and star formation rate for galaxies which have the same stellar mass as the Milky Way at a given redshift from z=3 to 0.5 (colour coded) and then remain on the Main Sequence

**The star formation history inferred from the evolution of the sSFR with z are inconsistent with the history expected for the Milky Way**

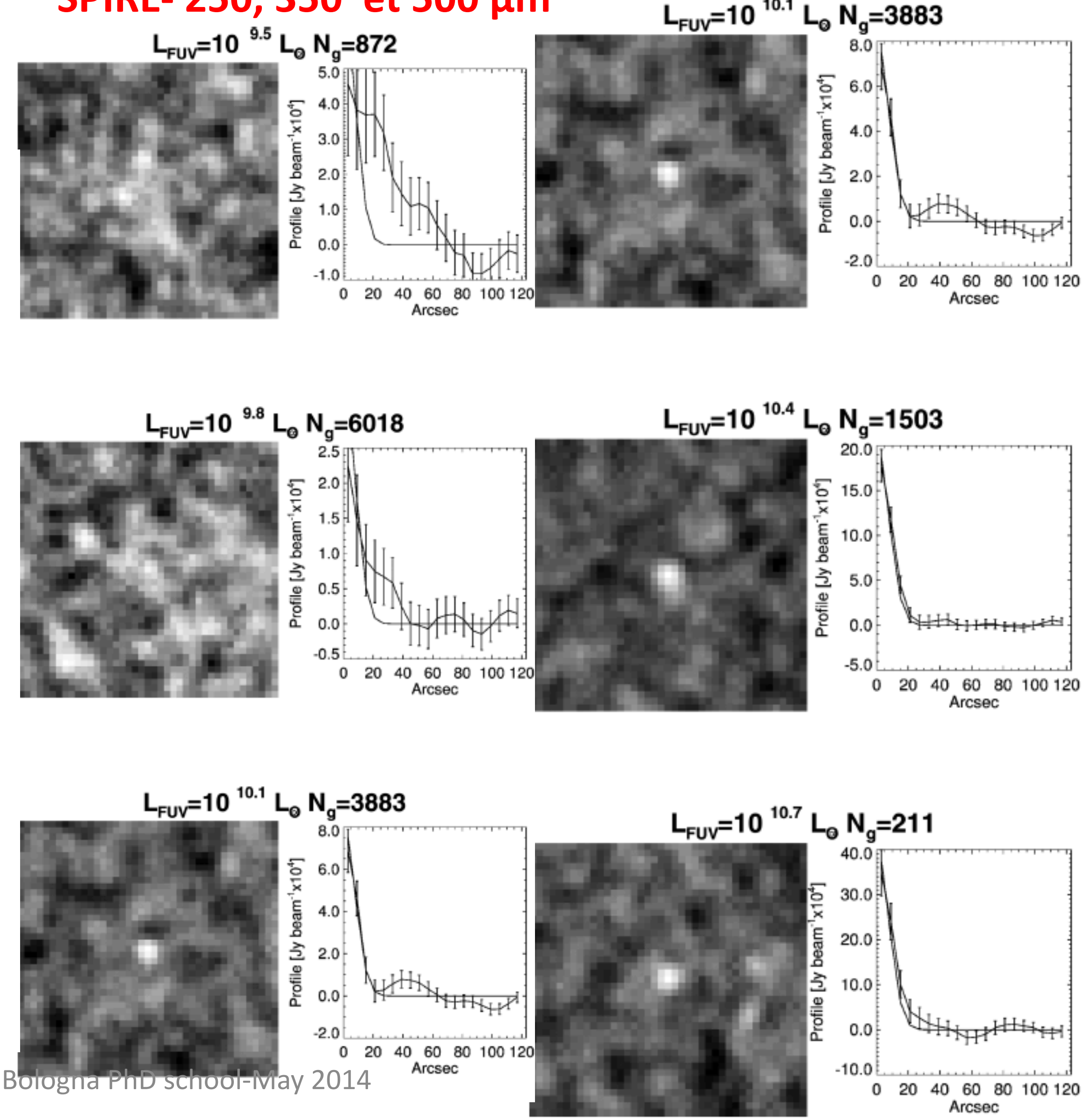
# A stacking technique is needed!

Method of Béthermin+10
Bavouzet 2008




**SPIRE- 250, 350 et 500 μm**

Heinis et al. 2013

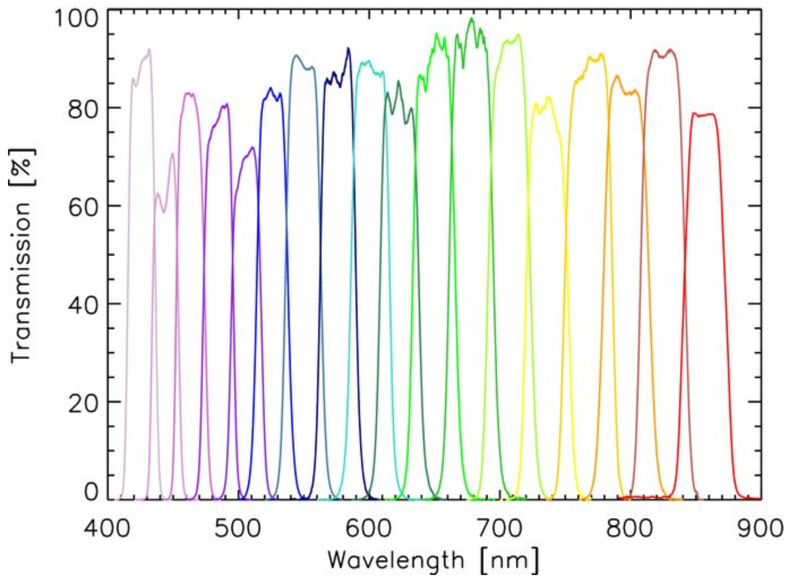


# Dust attenuation curve in « UV selected » galaxies 1<Z<3 Buat+11,12

Combining **GOODS-Herschel/PACS** data and
**Subaru/MUSYC** broad and intermediate band filters (Cardamone+10)
+**IRAC & MIPS** data (Dickinson+03)

**28 photometric bands**: SNR > 5 in optical and NIR + **SNR> 3 at 24 µm → 236 galaxies**

80 sources detected with PACS, upper limits for the other ones




*Subaru Intermediate band filters*

**An absorption feature at 2175 A rest frame** clearly seen and modeled with the SED fitting code CIGALE.