What do we know about the evolution with redshift of dust attenuation in galaxies?

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With the contribution of Barbara Lo Faro
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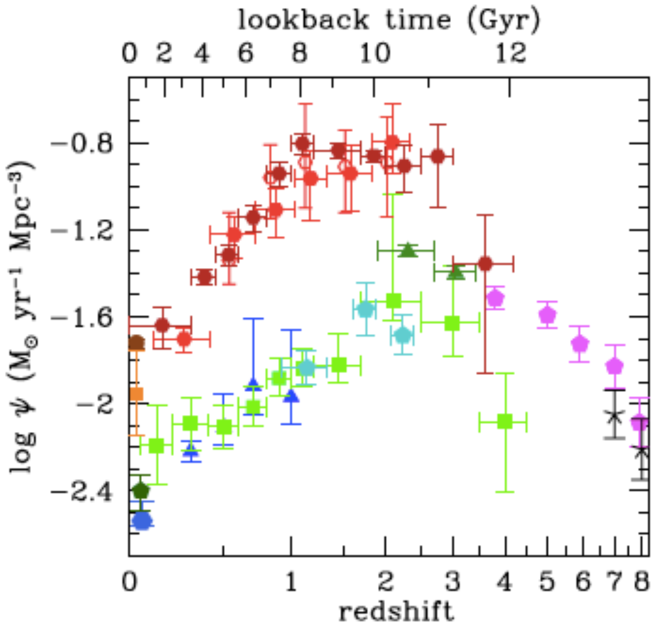
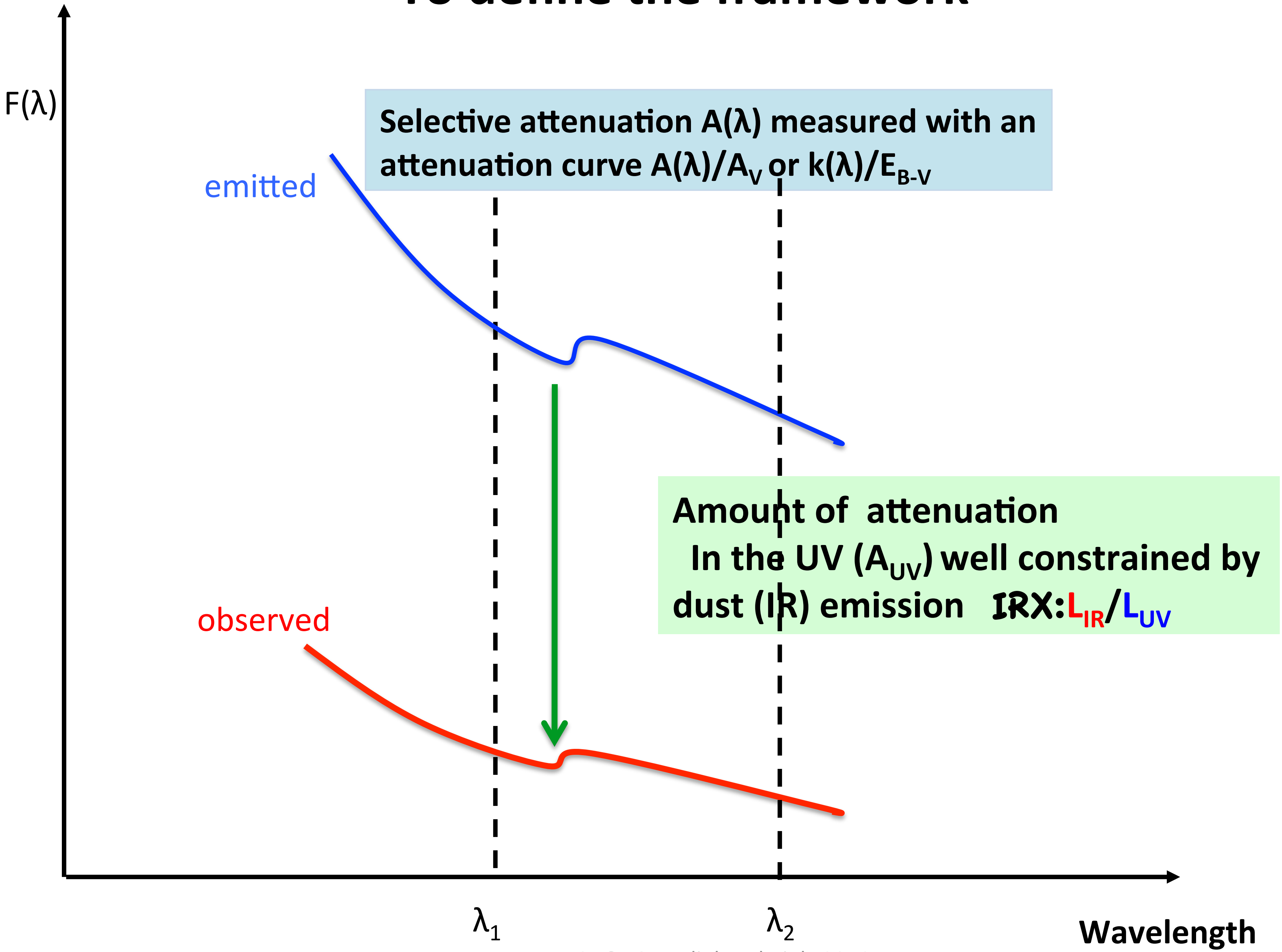


Madau & Dickinson, 2014

To define the framework



Outline

- The **attenuation law** from the local to the distant universe:
  - ✓ Formalisms and shapes of the laws
  - ✓ Attenuation laws for UV/optically selected galaxies
  - ✓ Attenuation laws for Dusty IR selected galaxies
- The measure of **the amount of dust attenuation**
  - ✓ Using the UV slope ß
  - ✓ Using optical/NIR colors
  - ✓ Using stellar masses

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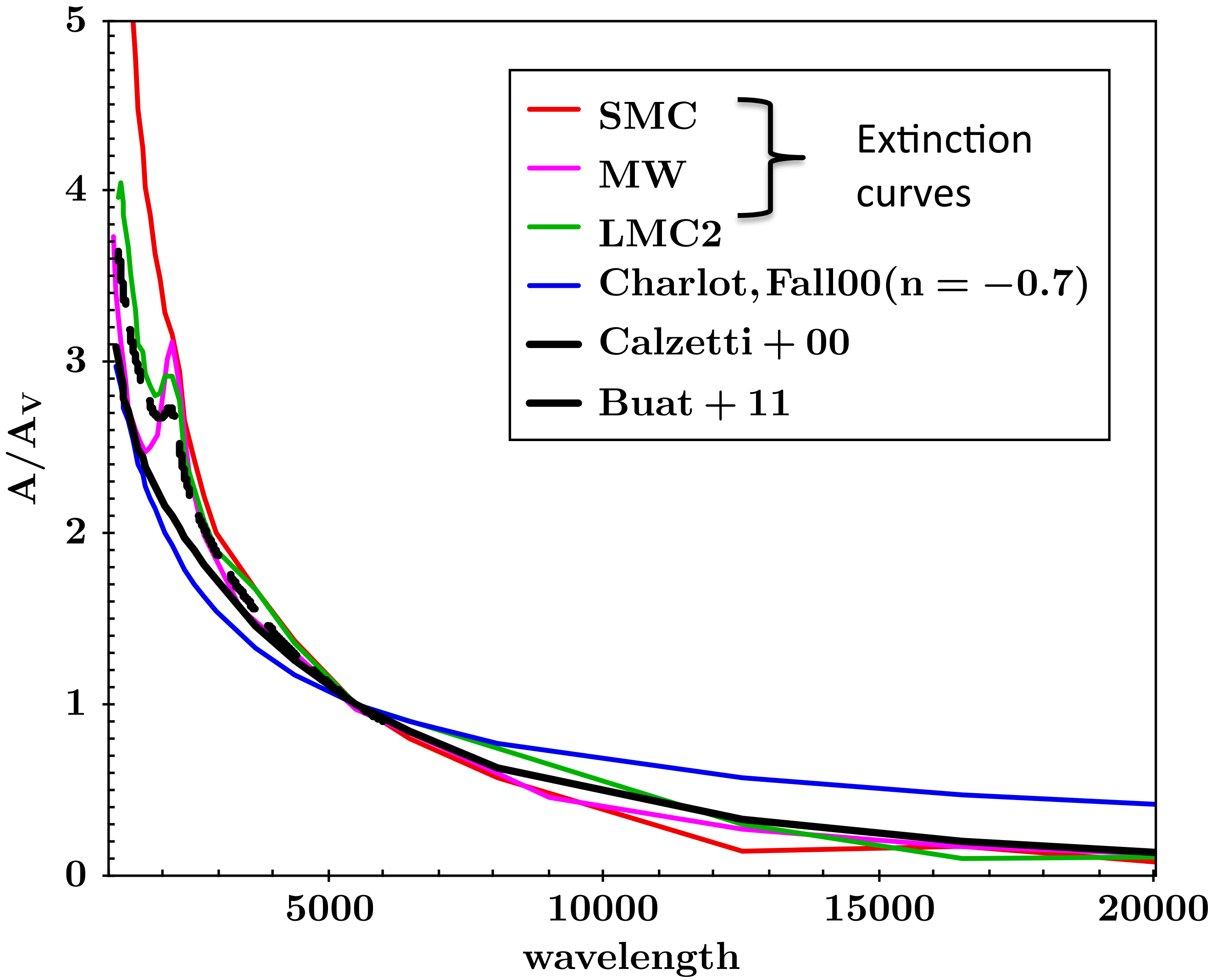
The shapes of some popular attenuation/extinction curves



The formalisms of the attenuation laws currently used

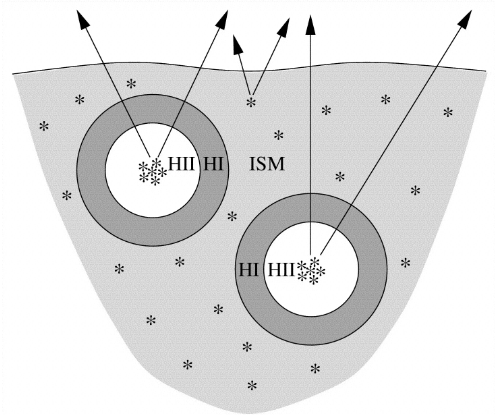
Charlot & Fall 2000: power laws

$$\hat{\tau}_\lambda^{BC} = (1-\mu)\,\hat{\tau}_V\,(\lambda/\lambda_V)^{n^{BC}}$$

$$\hat{\tau}_\lambda^{ISM} = \mu\,\hat{\tau}_V\,(\lambda/\lambda_V)^{n^{ISM}}$$

$$\hat{\tau}_\lambda(t) = \hat{\tau}_\lambda^{ISM} + \hat{\tau}_\lambda^{BC} \quad for\ t \le 10^7\ years$$

$$\hat{\tau}_\lambda(t) = \hat{\tau}_\lambda^{ISM} \quad for\ t > 10^7\ years$$



n^{BC} & n^{ISM} may be different and/or not fixed

(***Magphys code*** *(da Cunha+08), , Wild+11 Chevallard+13…*)

Calzetti and Calzetti modified laws

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

(Calzetti+00 + UV bump) X power law

CIGALE code's recipe *(Noll+09)*

$E(B\text{-}V)_{young}$ *for young stars*

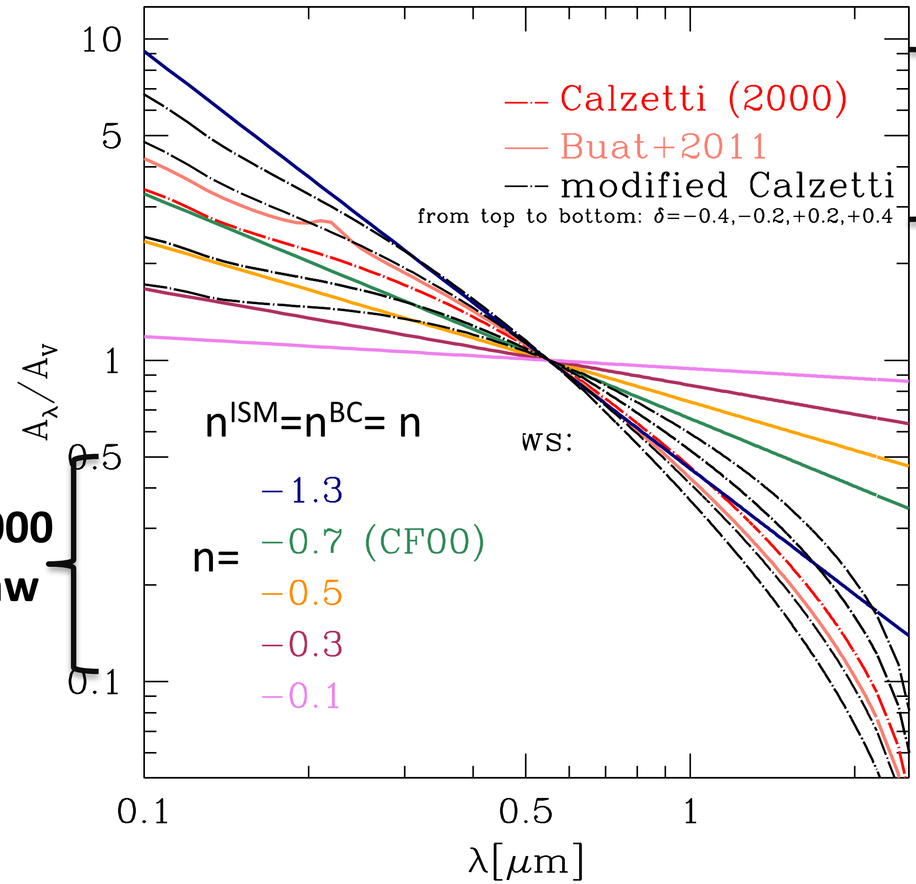
$E(B\text{-}V)_{old} = f_{att}\,E(B\text{-}V)_{young}$ *old stars*

$0<f_{att}<1$

Calzetti+00, Cigale code (Noll+09), Buat+11,12 Kriek&Conroy13, Zeimann+15, Salmon+15…

with or without f_{att}

The formalisms of the attenuation laws currently used induce different shapes in the optical-NIR



Calzetti+00 & modified Dashed lines

Charlot & Fall 2000 Double power law Solid lines

Courtesy of Barbara Lo Faro

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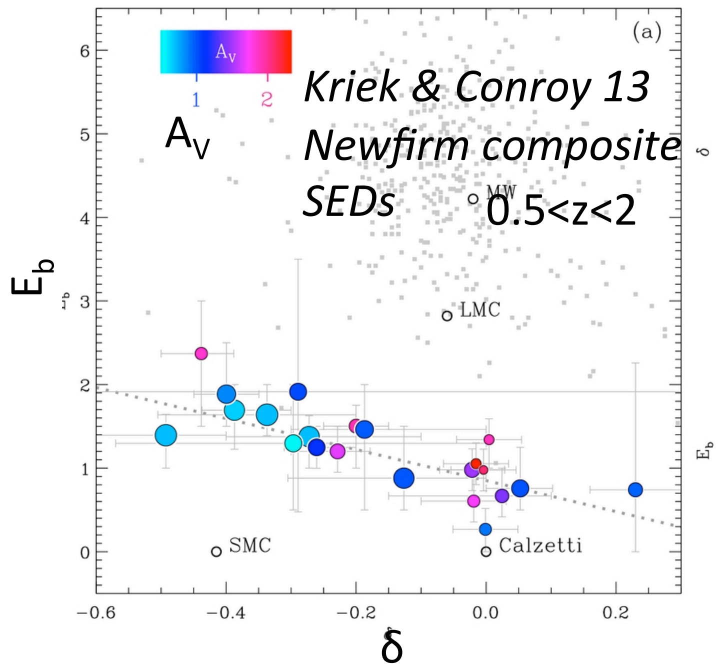
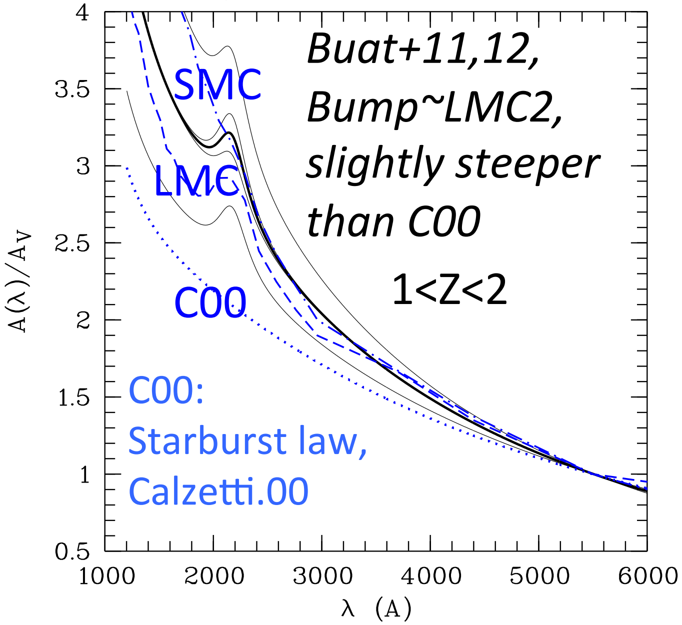
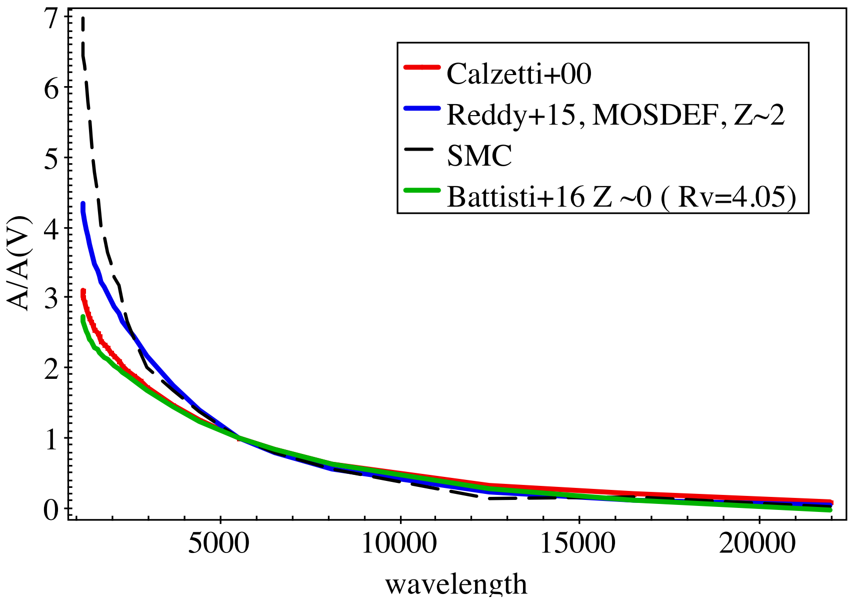
The variation of the attenuation curve in UV/optically (emission lines) selected star-forming galaxies

'Calzetti modified' formalism
or method

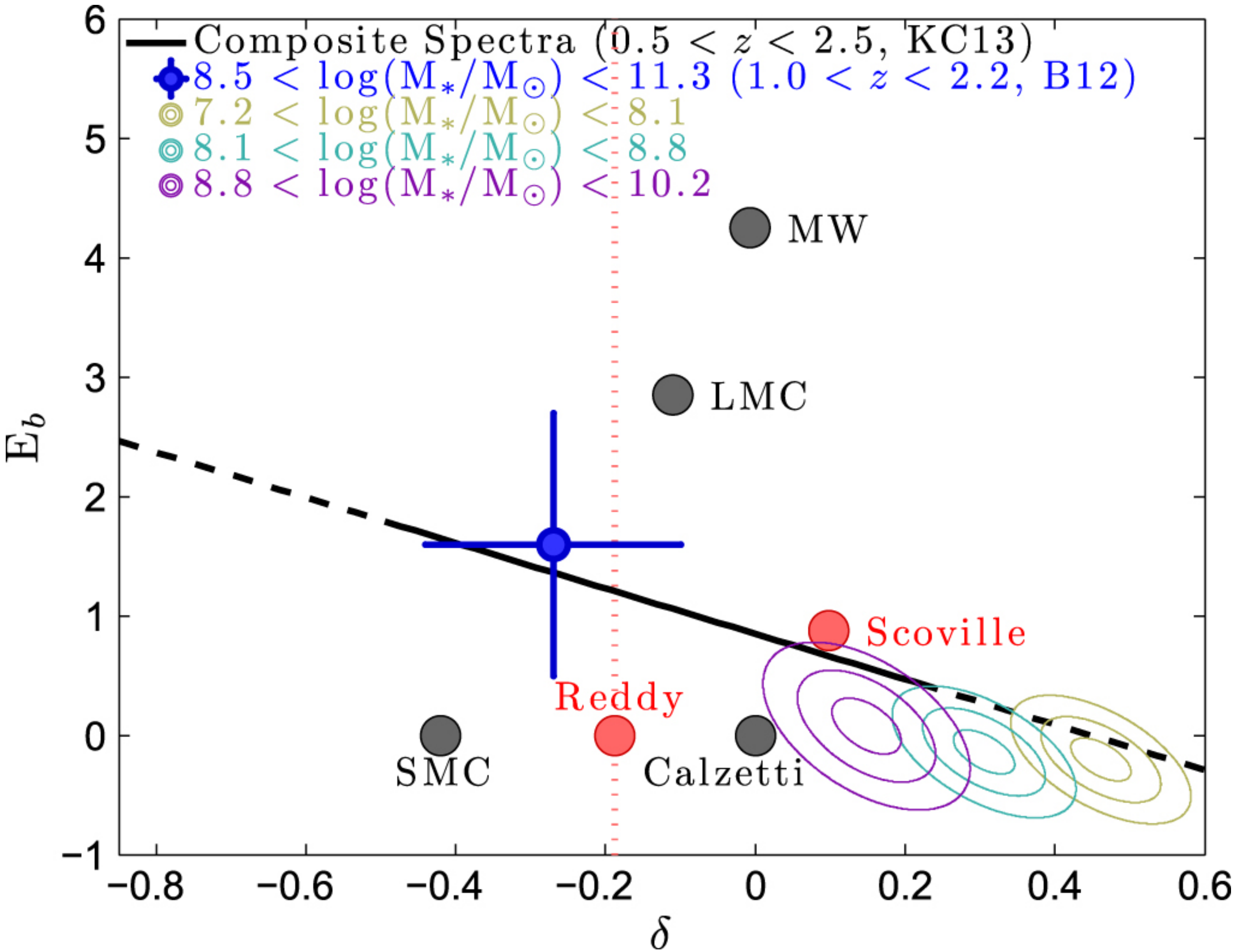


UV selected galaxies with IR detections

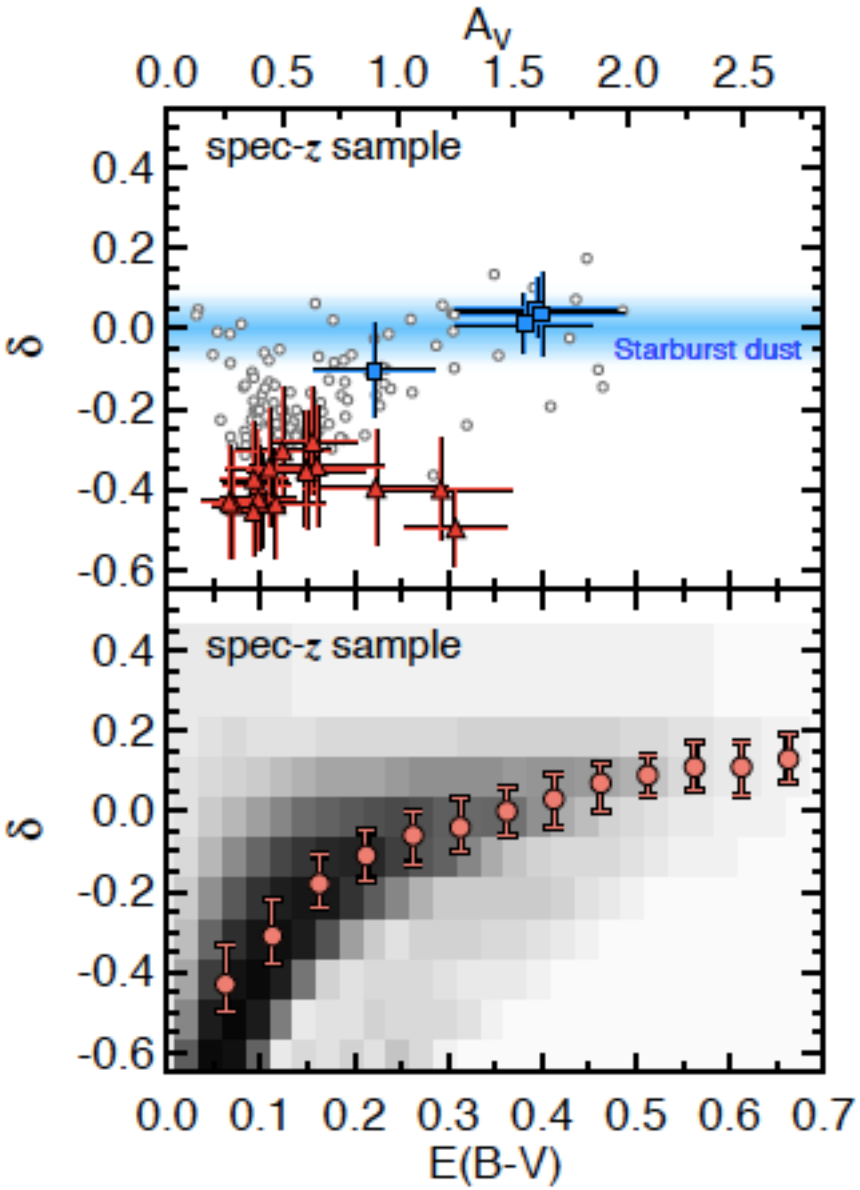




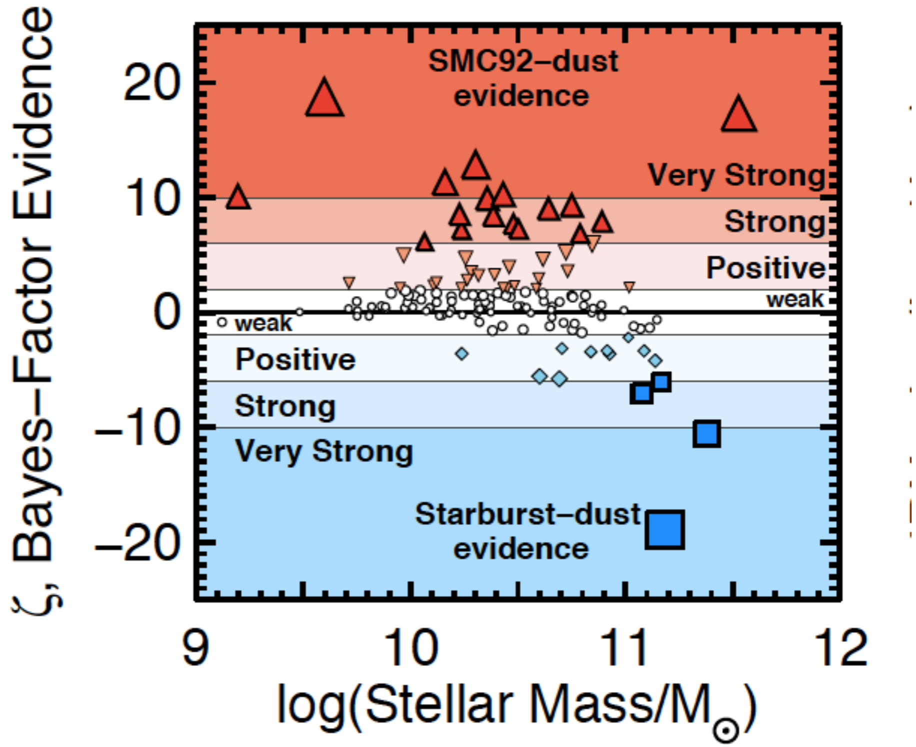
Calzetti+94 method



Zeimann+15, emission line galaxies



Salmon+15, arXiv, CANDELS data, 1.5<z<3 galaxies detected in the UV rest-frame and with SPITZER



Tentative conclusion?:

A shallower attenuation law for increasing attenuation and mass(?)

Attenuation laws which can be steeper than the Calzetti one with a moderate bump

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UNIVERSITY OF CAMBRIDGE

HELP

Herschel Extragalactic Legacy Project FP7/SPaCE

P.I. Seb Oliver

A census of galaxy populations and their star formation history from the local to the distant universe

« Ultimate « source extraction in all the cosmological Herschel fields (including HerMES and H-ATLAS surveys), UV to radio complementary data

→ photo-z, SFR, M_* for all the sources

UV-to-FIR SED fitting
comparison with radiative transfer modelling

Lo Faro et al. to be submitted

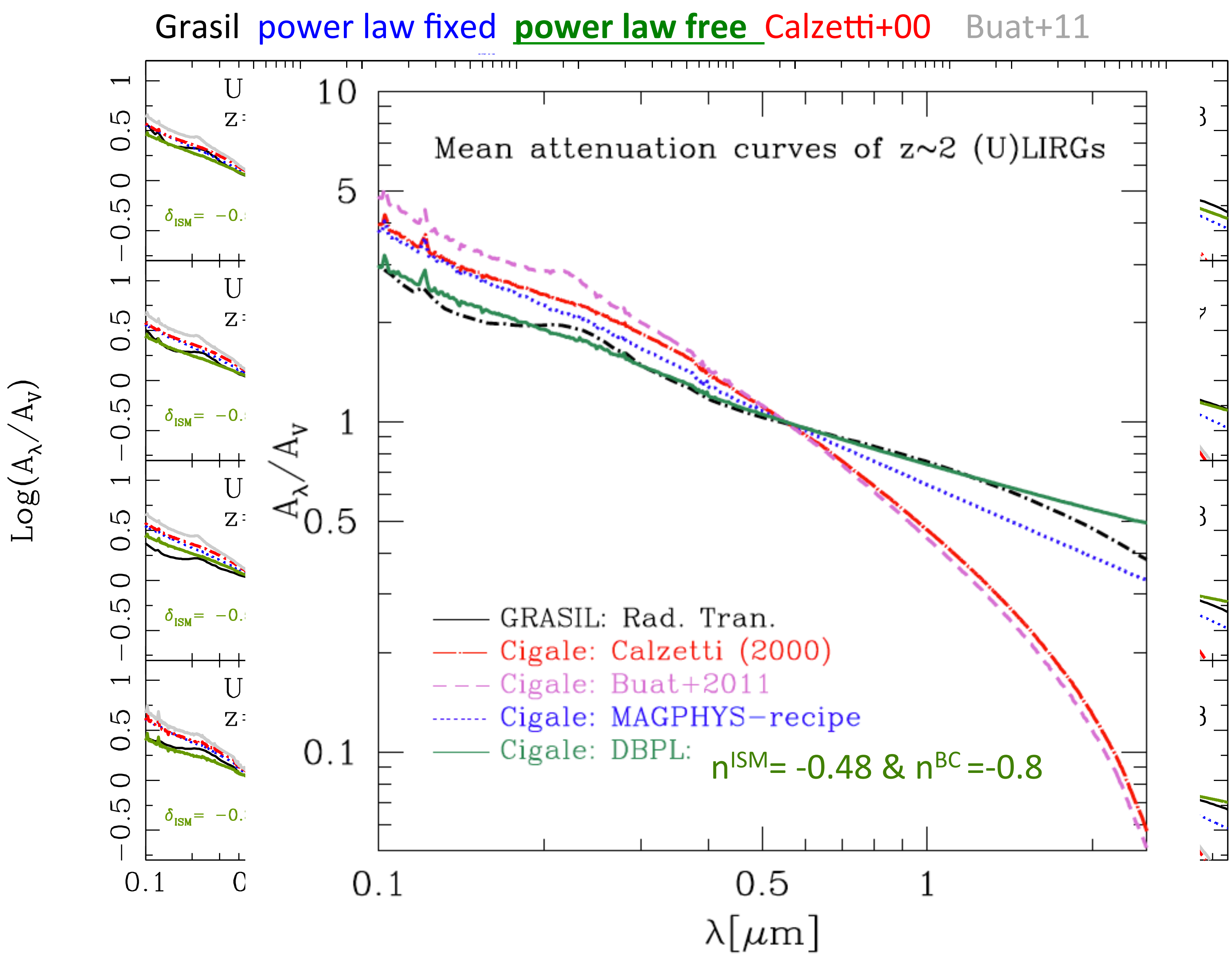
Physically-motivated SED modelling

Calzetti& modified, Double Power law
cigale.lam.fr

Radiation transfer SED modelling

GRASIL
adlibitum.oats.inaf.it/silva/grasil/grasil.html

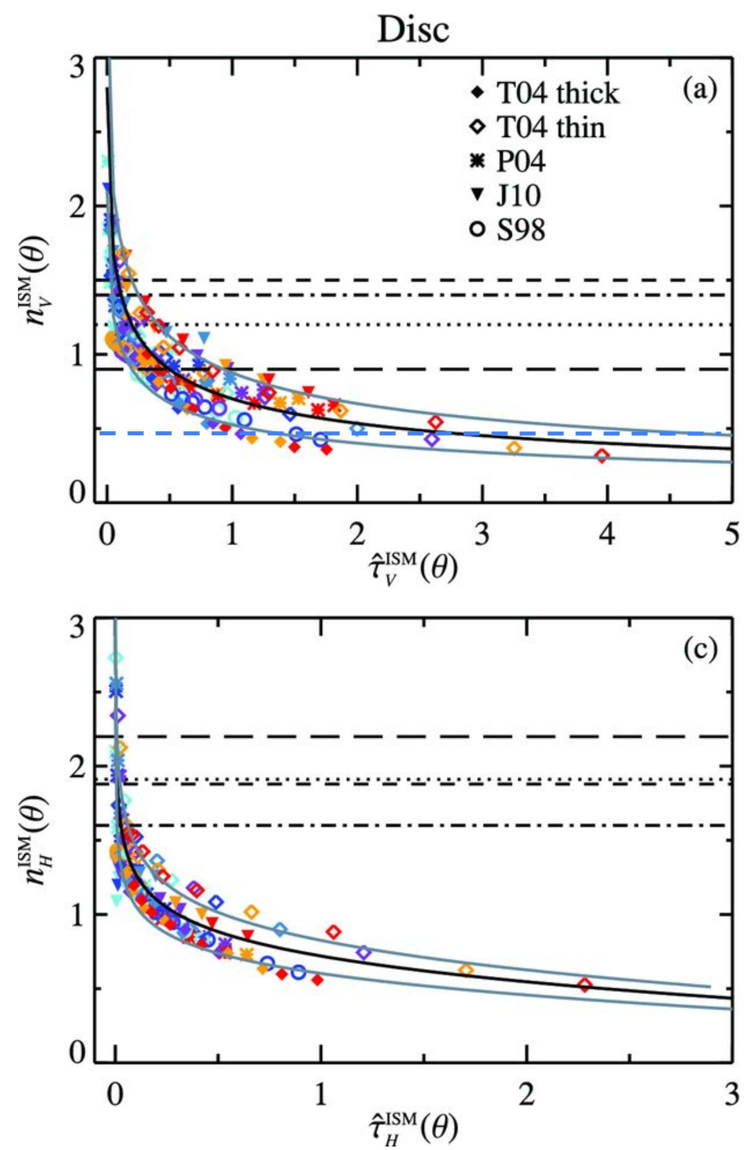
Z~1 LIRGs and Z~2 ULIRGs) (from Lo Faro+13,15)
Nearby (U)LIRGs from the GOALS sample (Armus+09)



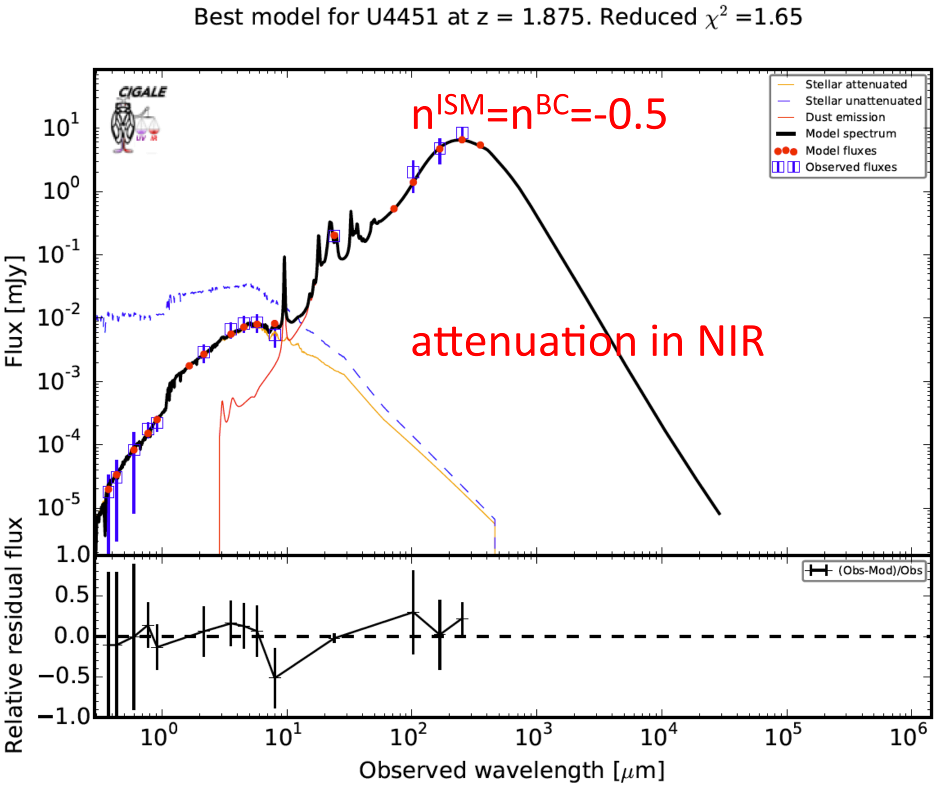
Grasil power law fixed power law free Calzetti+00 Buat+11
Mean attenuation curves of z~2 (U)LIRGs
GRASIL: Rad. Tran.
Cigale: Calzetti (2000)
Cigale: Buat+2011
Cigale: MAGPHYS−recipe
Cigale: DBPL:
n^ISM= -0.48 & n^BC =-0.8
A_λ/A_V
λ[μm]
Log(A_λ/A_V)

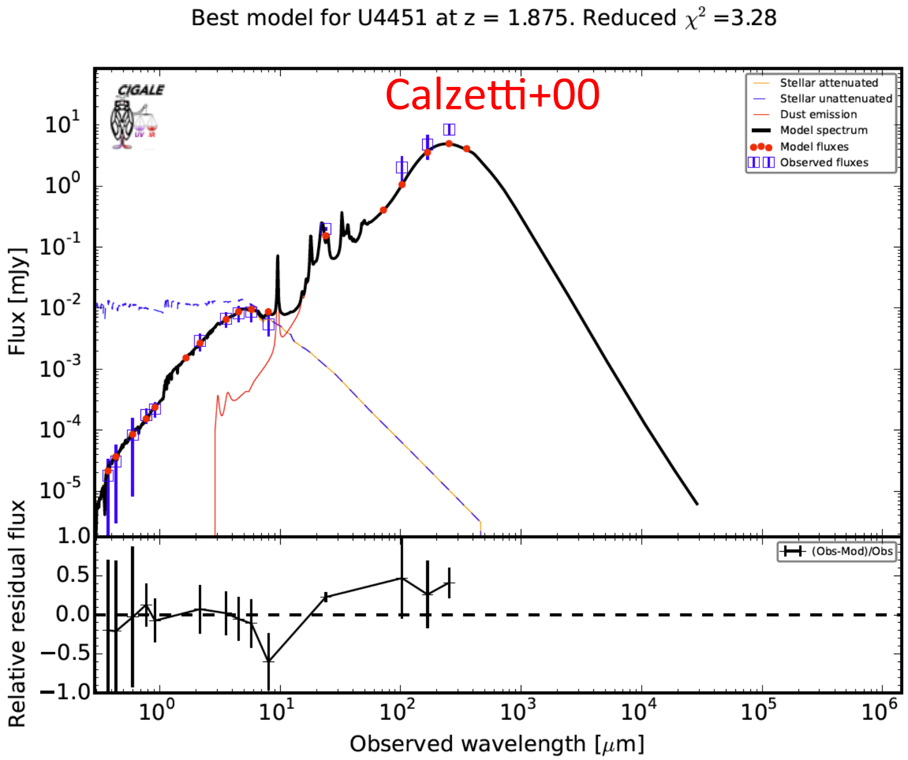
Flattening of the attenuation curve in high attenuated objects
→*In agreement with Chevallard et al. 2013*:

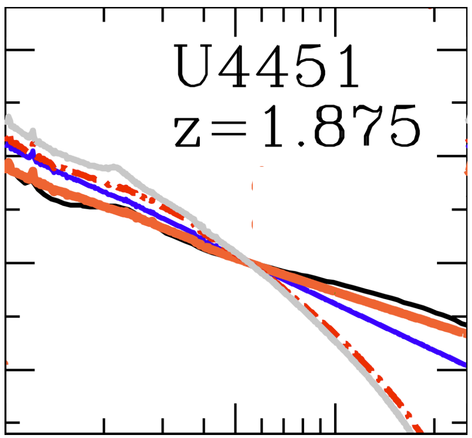
Compilation of Radiative Transfer modeling results, confirming GRASIL calculations
→ All predict a grayer attenuation for an increasing attenuation



How do these ``flatter'' attenuation curves affect the SED ?







A larger amount of attenuation at longer wavelengths (NIR) than allowed by Calzetti+00 att. law. (*Mitchell+13, Da Cunha+10*)

→Affects the determination of the stellar mass (*Mitchell+13, Lo faro+13*)

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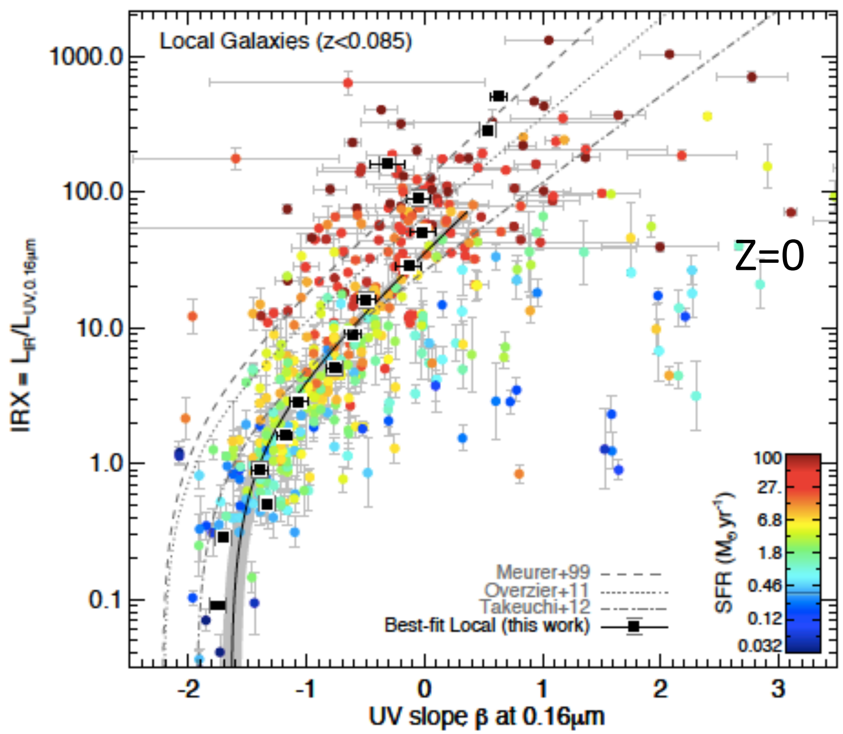
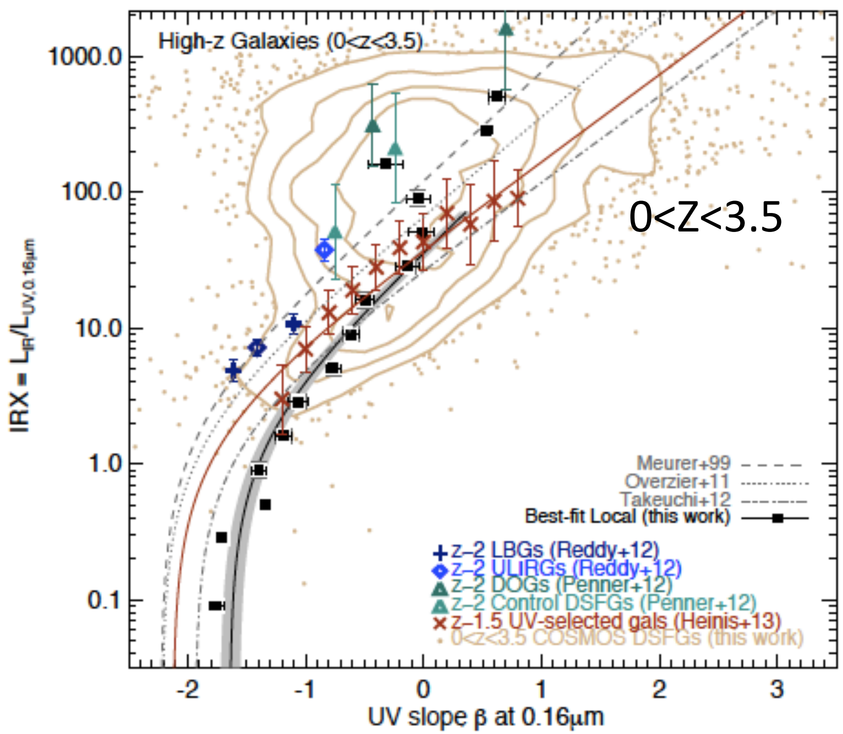
Measuring dust attenuation without IR data : the slope of the UV continuum: β

GALEX+IRAS



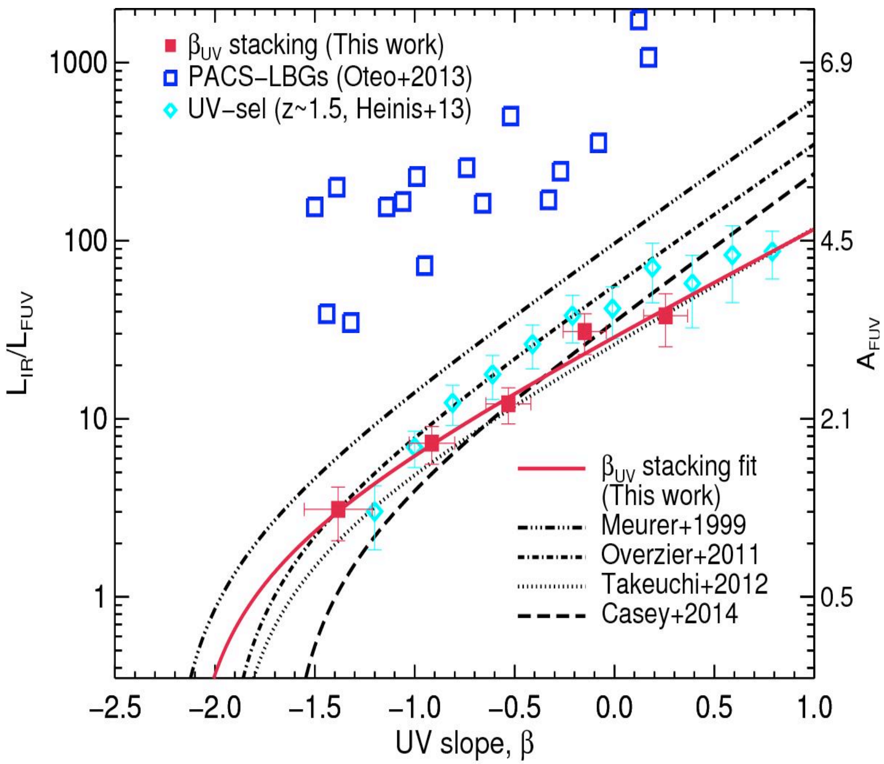
Cosmos field

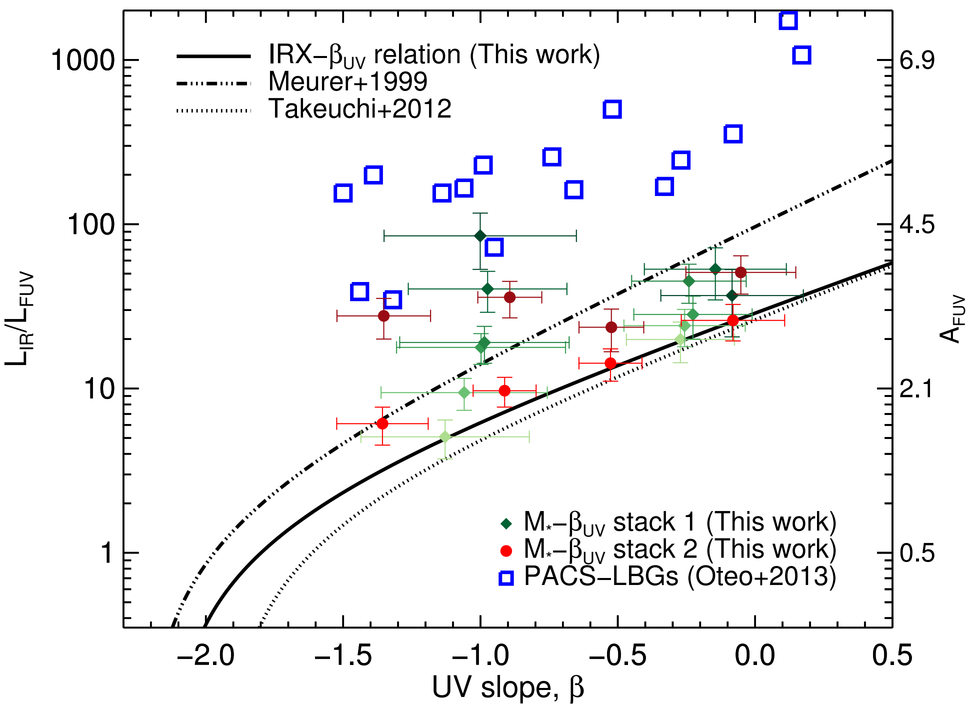


Casey+14

IRX-β : LBG selection at z~3 & stacking of Herschel data

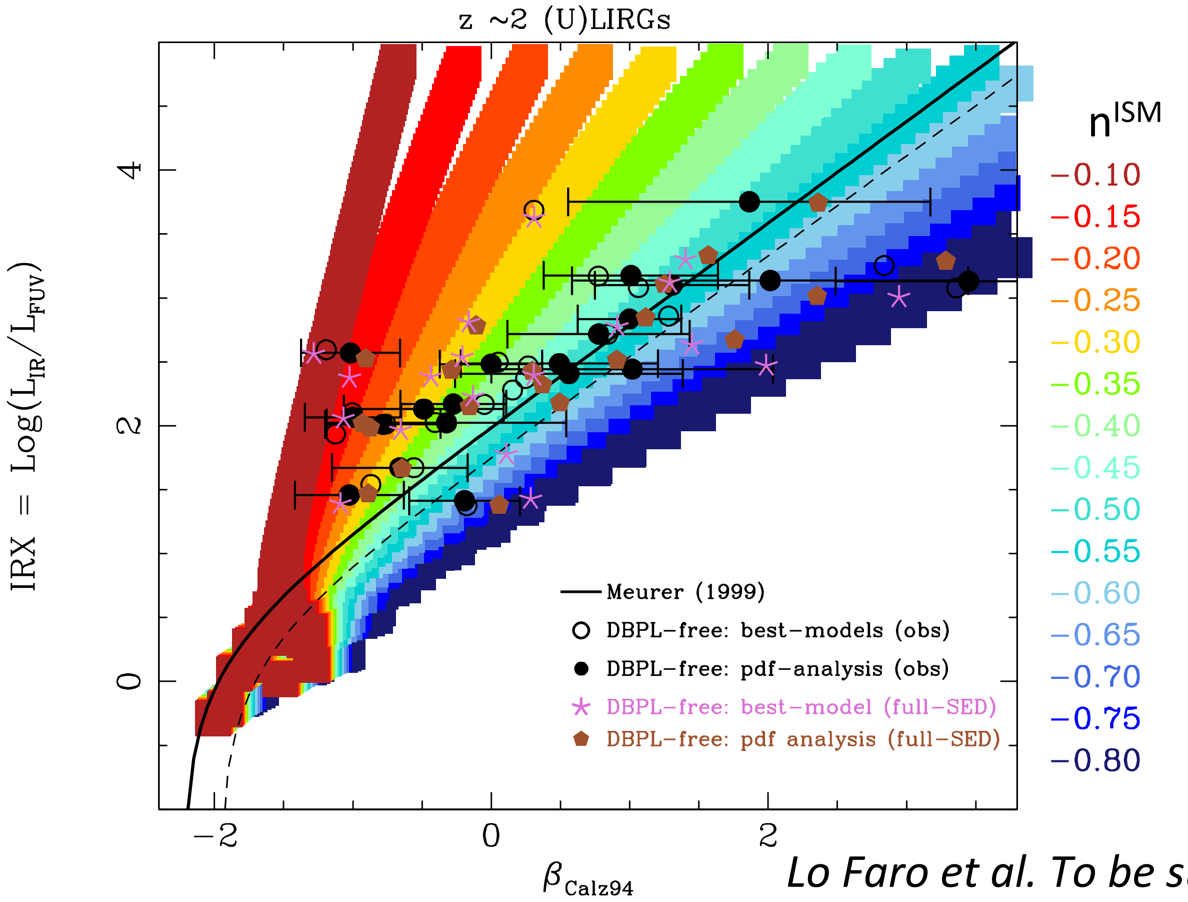
Alvarez-Marquez et al. 2016





The IRX-β plot is very sensitive to the shape of the attenuation curve in the UV

ULIRGs at z~2 detected by Herschel: a flatter curve in the UV



Lo Faro et al. To be submitted, see also Salmon+15, Safarzadeh+16

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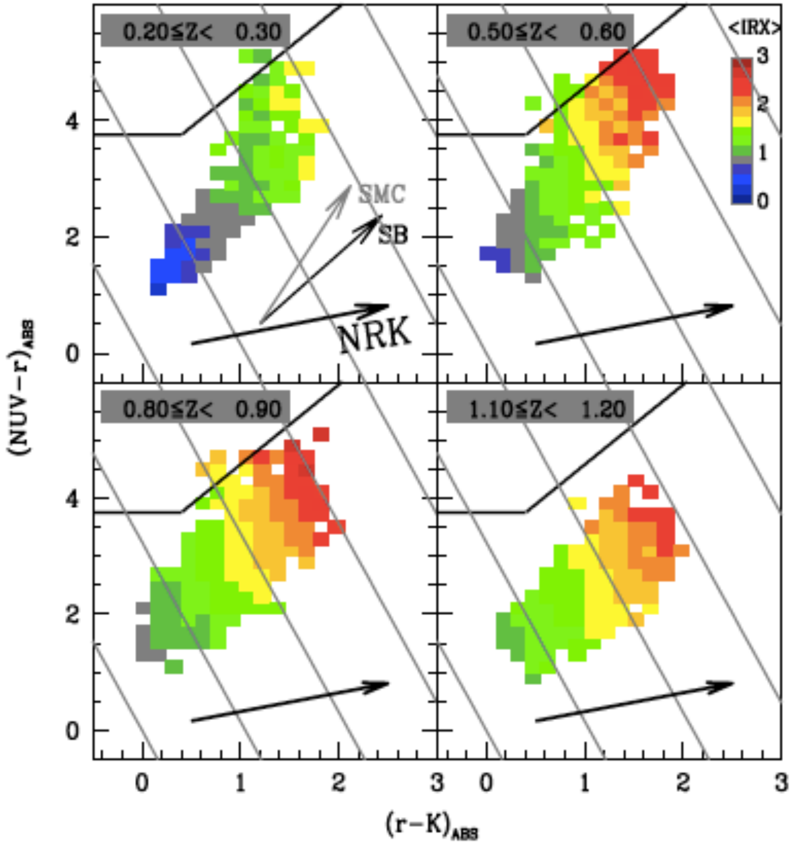
✓ Using rest-frame NIR optical colors

✓ Using stellar masses

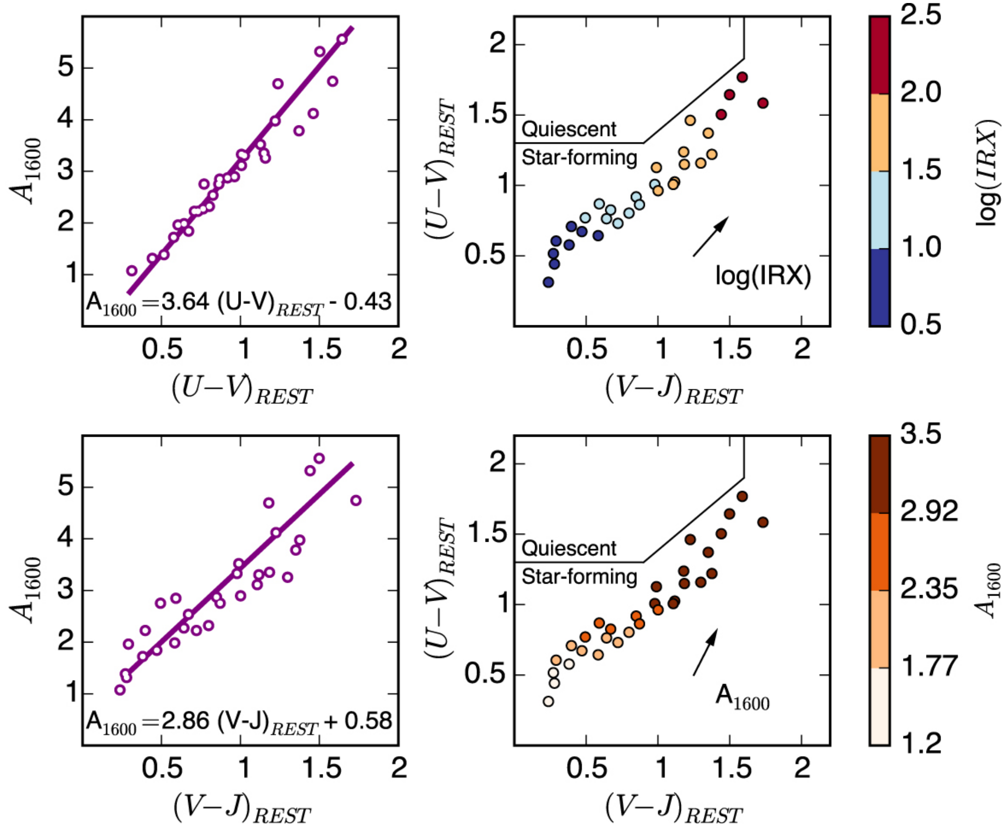
Using rest-frame colors to infer dust attenuation corrections

0<z<1



Arnouts+13 **NUV-R, R-K colors**

1<z<3



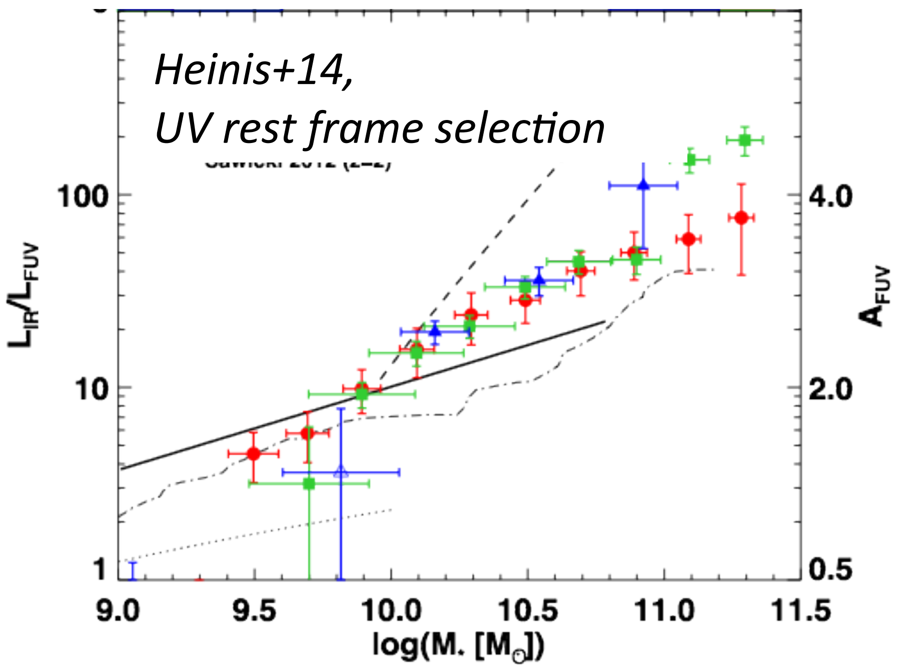
Forrest+13, **U-V, V-J colors**

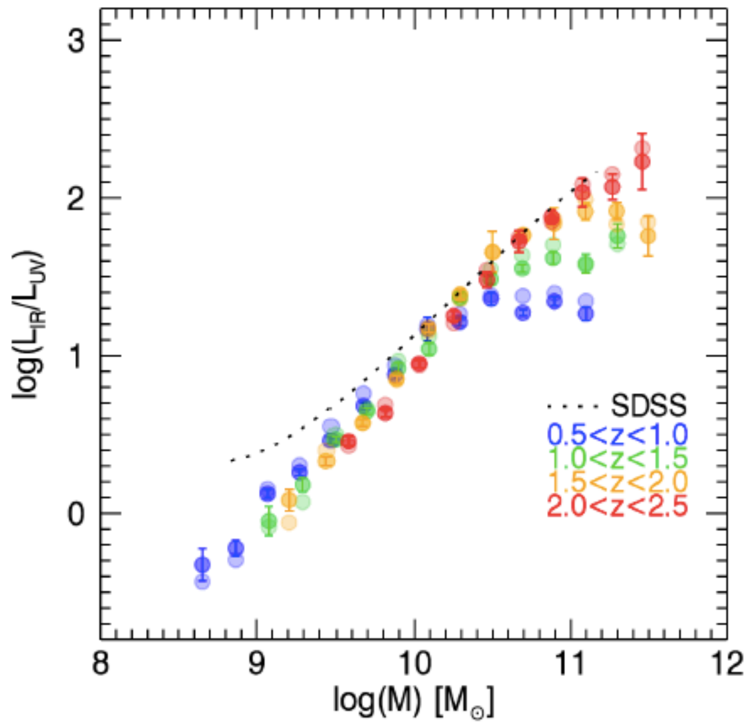
Needs to be calibrated to be used at higher/different redshifts

Attenuation-stellar mass relation on a large range of z

UV selected and star forming galaxies (Stacking of Spitzer/Herschel data)

Z=1.5, 3, 4

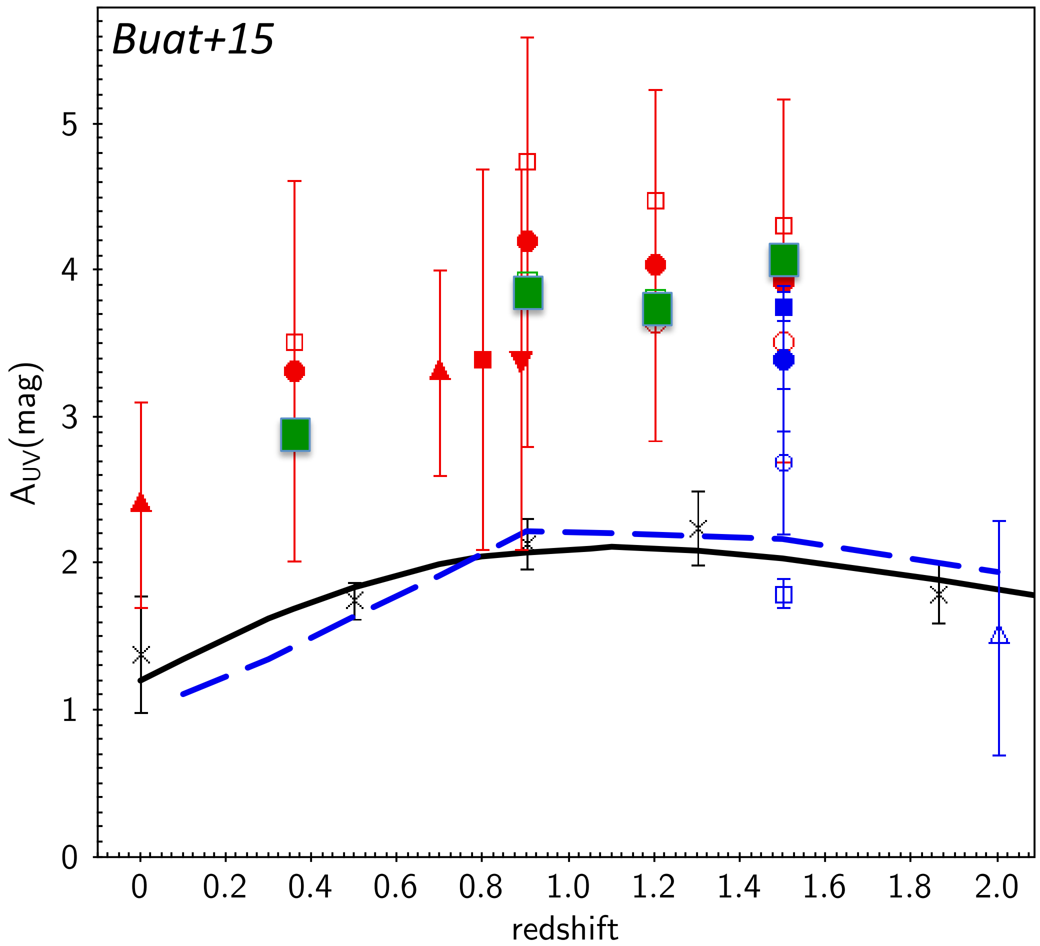




See also Oteo+14, Panella+15, Dunlop+16….

Whitaker+14, CANDELS , UVJ selection, MIPS stacking

Dust attenuation in IR and UV selected samples: a difference in stellar mass



IRX-M* relation assumed, Bernhard+14

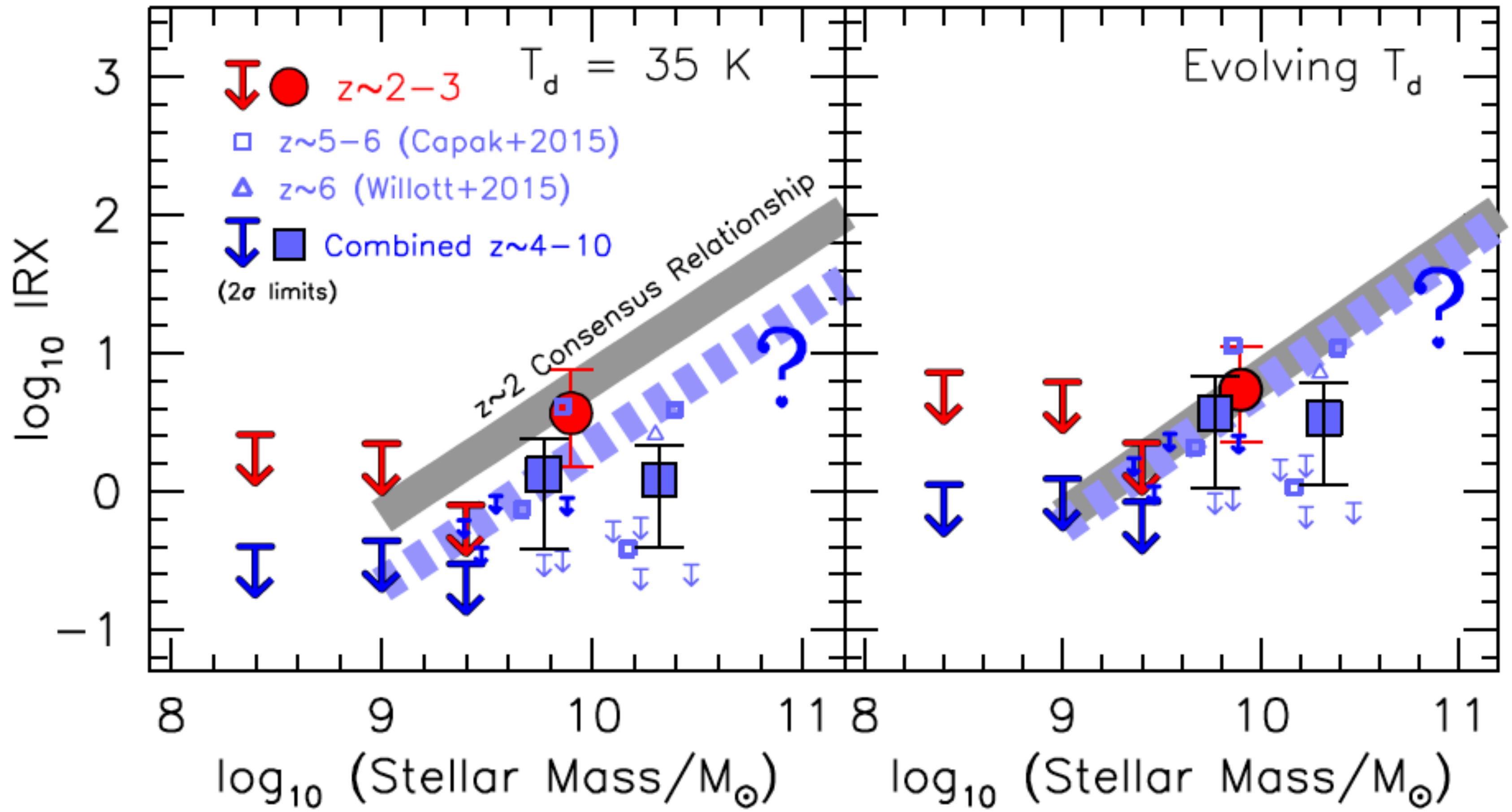
IR selected samples: IRAS/Spitzer/AKARI

UV rest-frame selections

At higher redshift: ALMA observations

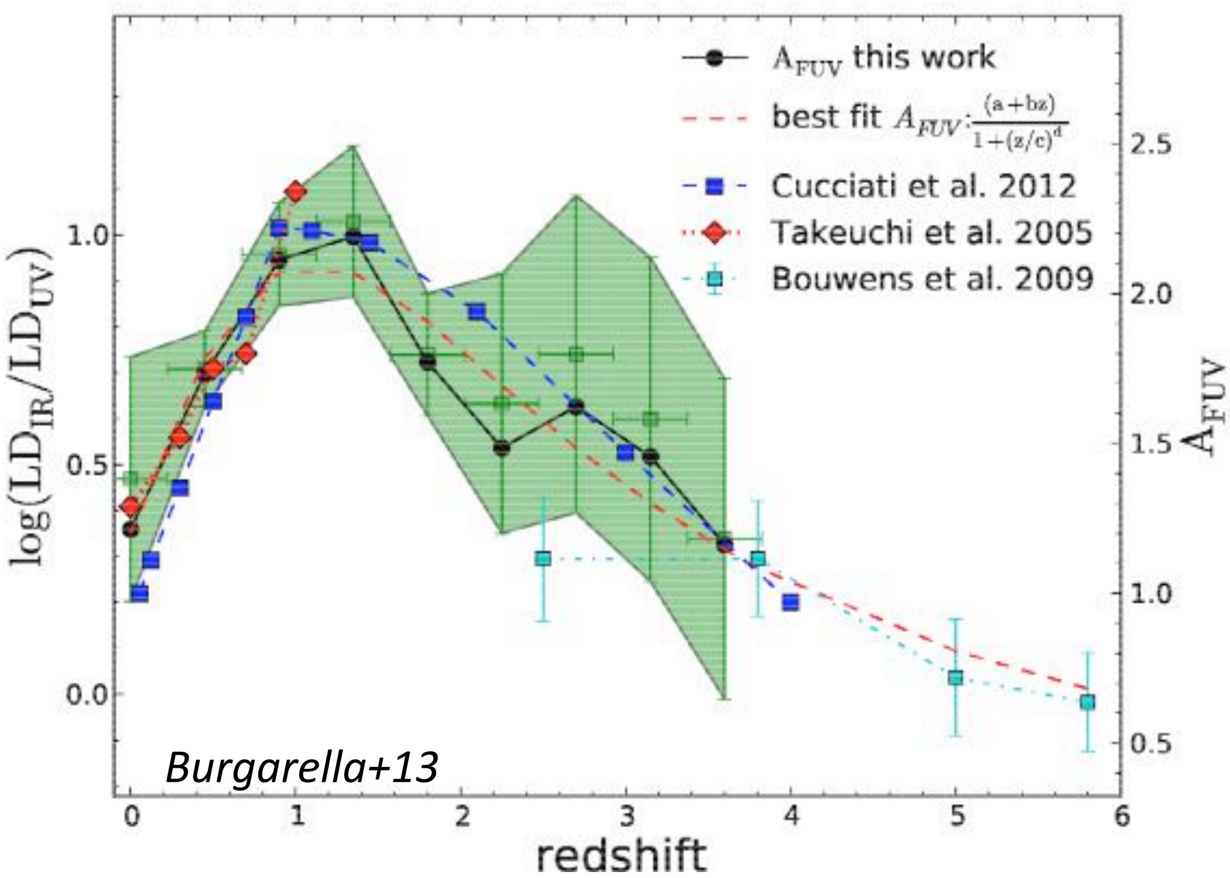
Either an evolution of the IRX-M* relation or an increase of T(dust) with z

HUDF-ASPECS, Bouwens+16 arXiv



An evolution of the IRX-M* relation is needed to understand the variation of IR to UV luminosity density ratio

Burgarella et al. in prep



To conclude

Witt & Gordon 00 . No justification was found for the use of a universal attenuation function for the analysis of a large sample of galaxies.

Only the measurement of the F_{FIR}/F_{F160BW} (IRX) flux ratio promises reasonable certainty for the determination of the UV attenuation correction factor in individual galaxies.

- ✓ **Confirmation of the variation of the attenuation curve among galaxies**: shape in UV/NIR, UV bump: as a function of the amount of attenuation, stellar mass, sSFR…→ sample selection)
- ✓ Fortunately, **some recipes seem reliable to measure the total amount of attenuation:** colors, stellar mass, but need to be well calibrated, at different redshifts
- ✓ The IRX-ß diagnostic is very sensitive to the attenuation curve and very likely to the stellar mass of galaxies