Dust attenuation in the Universe: what do we know about its variation with redshift and from galaxy to galaxy

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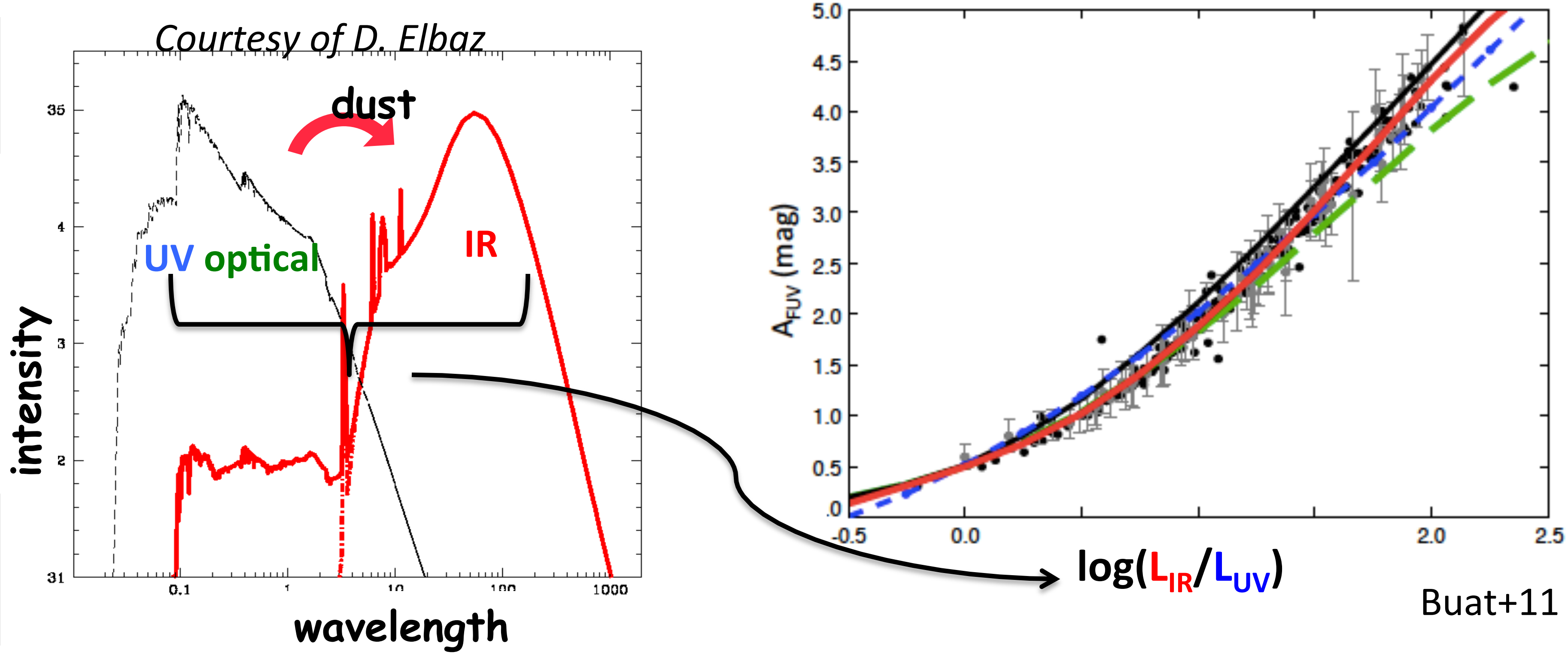
And many collaborators from Herschel and AKARI surveys teams and the HELP european network

SISSA, May 3, 2016

General context

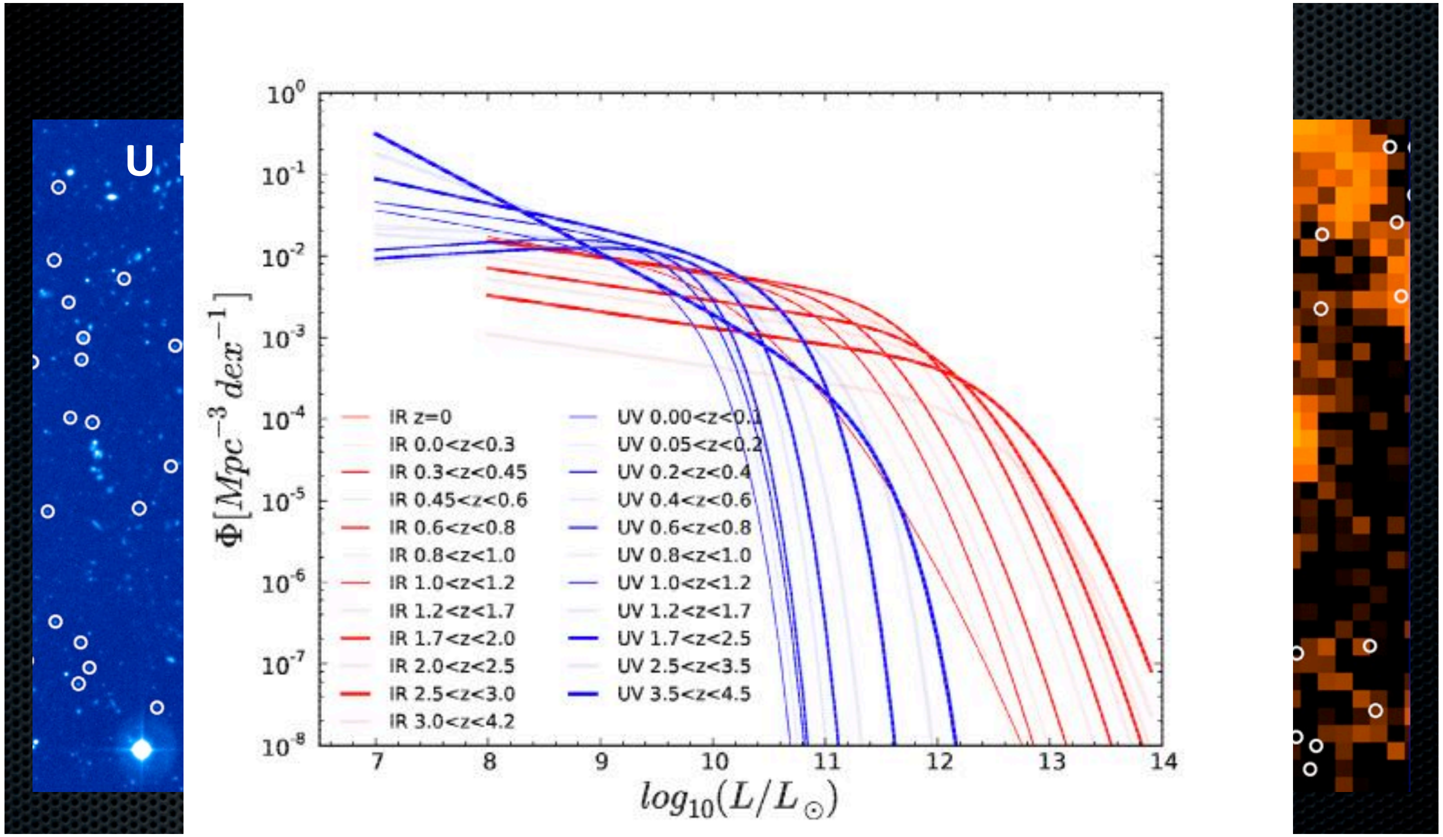


Both UV and IR emissions are related to recent star formation and to dust attenuation

The only relatively reliable measure for the UV attenuation factor for single galaxies was found in the ratio of the integrated far-IR flux to the far-UV flux, measured near 1600 Å, requiring the measurement of the entire spectral energy distribution of galaxies.

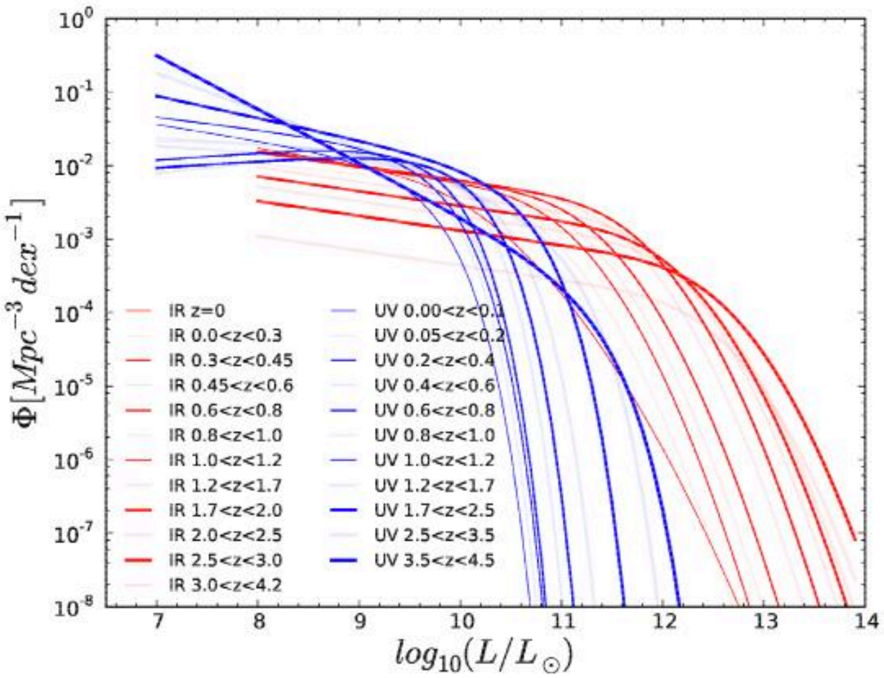
Witt & Gordon 2000

COSMOS field:
Almost no counterpart of UV-rest frame selected sources in Herschel images

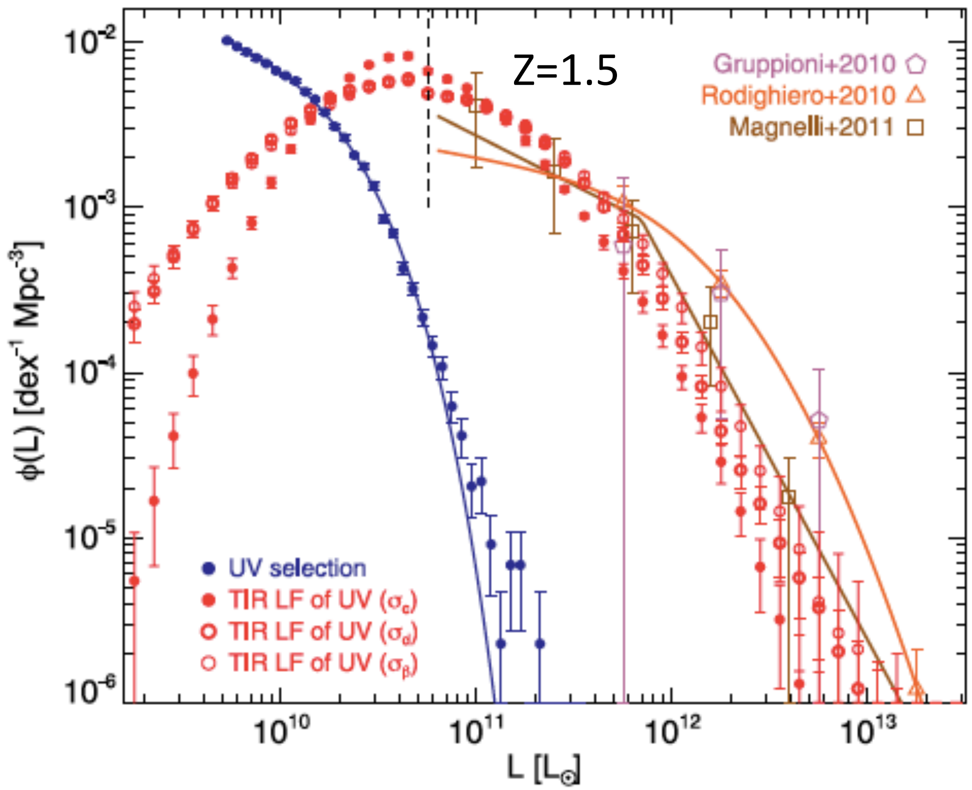


Heinis+13

Are we able to 'see' all the universe in UV?

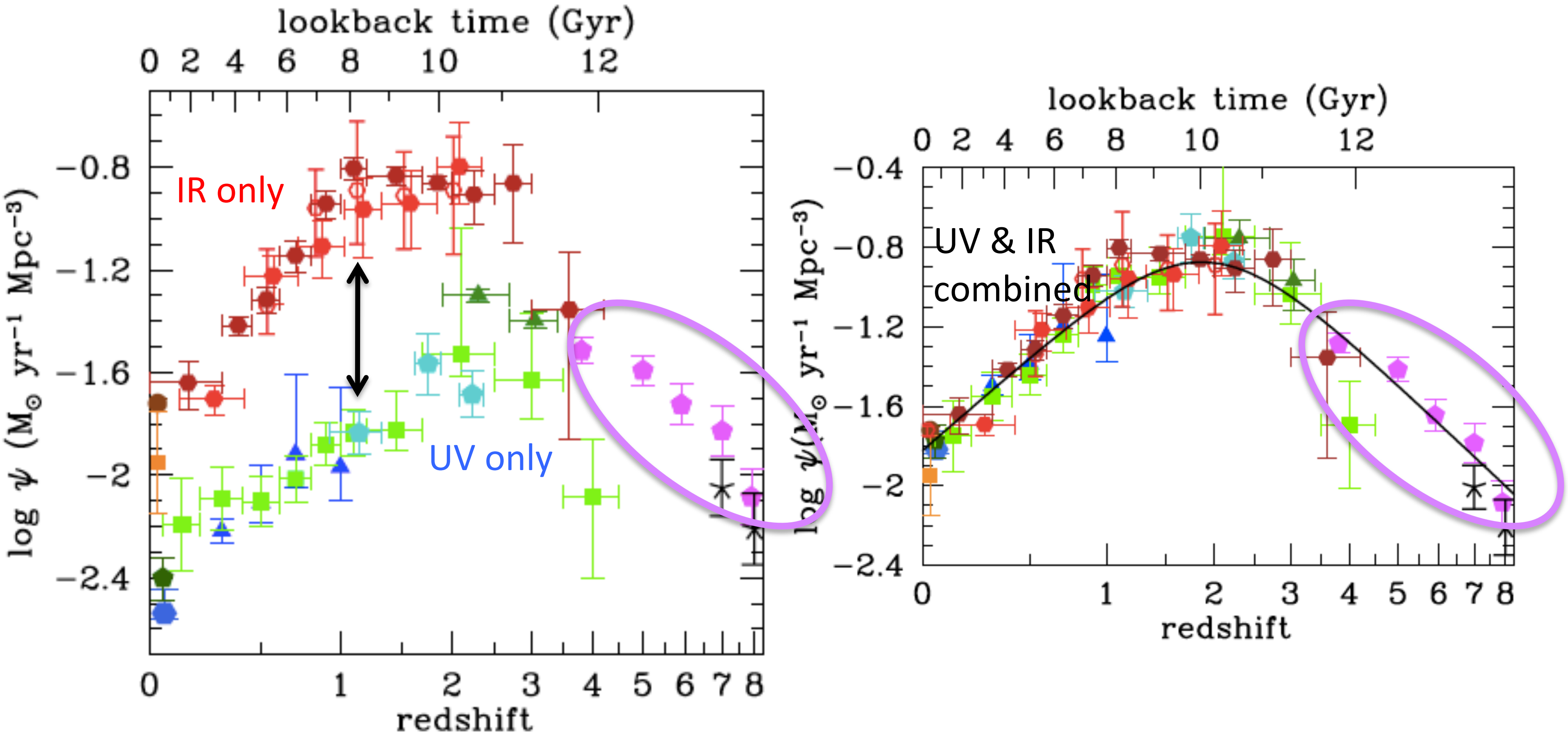


Burgarella+13



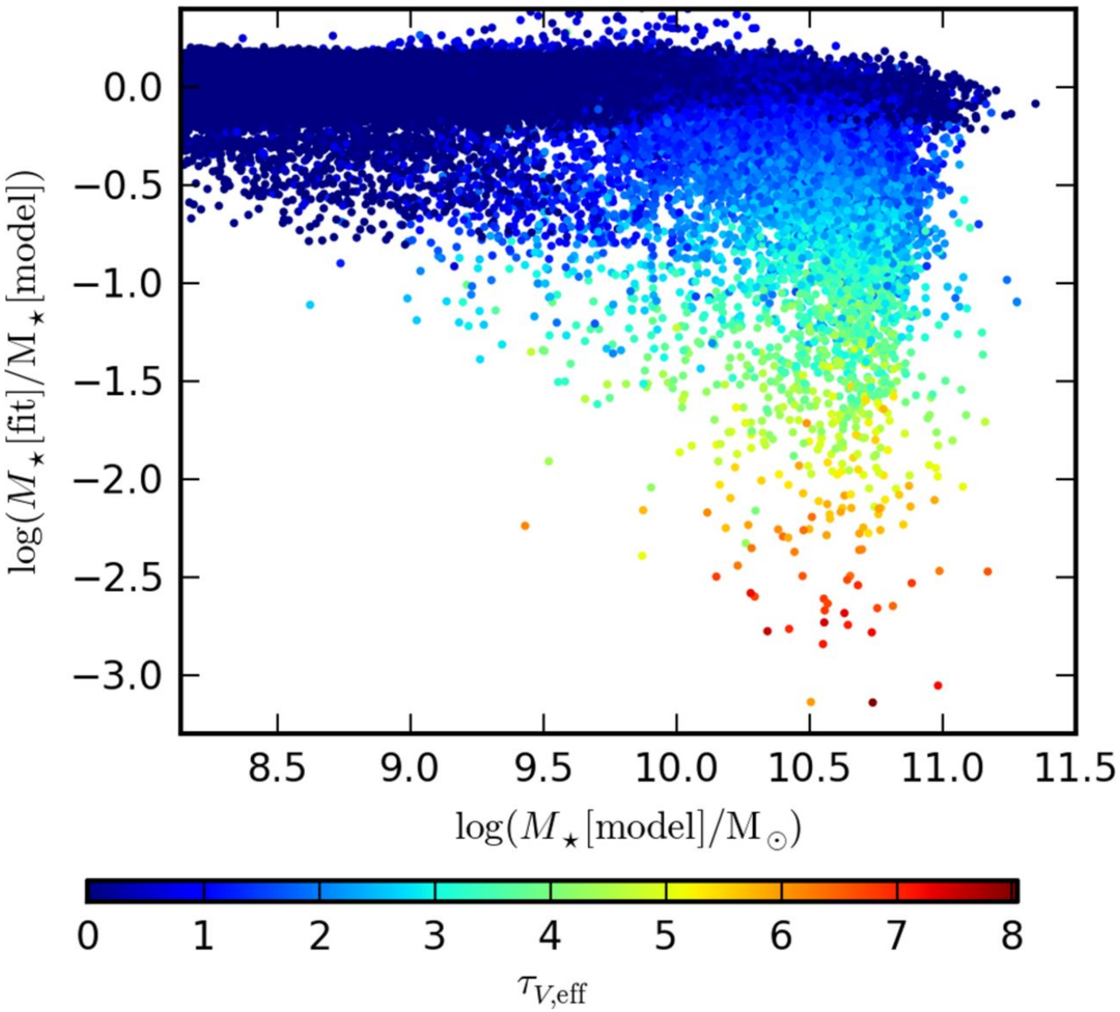
Heinis+13

SFR measurements need corrections for attenuation



Madau & Dickinson 2014

Dust attenuation has also an impact on M_* determination



Model: GALFORM semi-analytical modelling
Fit: SED fitting with standard recipes: BC03 SPS, Calzetti att. Law, exponentially declining SFR Without FIR/ submm data

Mitchell+ 2013

About dust attenuation in the universe:
outline

- The global amount of attenuation in the universe: UV and IR luminosity densities
- Attenuation in samples of single galaxies:

  -UV emitting galaxies:

  -IR selected galaxies

→ A consistent picture with the stellar mass as main driver of dust attenuation

- The attenuation law: a universal one ?→ NO

About dust attenuation in the universe

- **The global amount of attenuation in the universe: UV and IR luminosity densities**
- Amount of attenuation for:

-UV emitting galaxies:

Z=1.5, 3 & 4 COSMOS field with Herschel (HERMeS data)

-IR selected galaxies

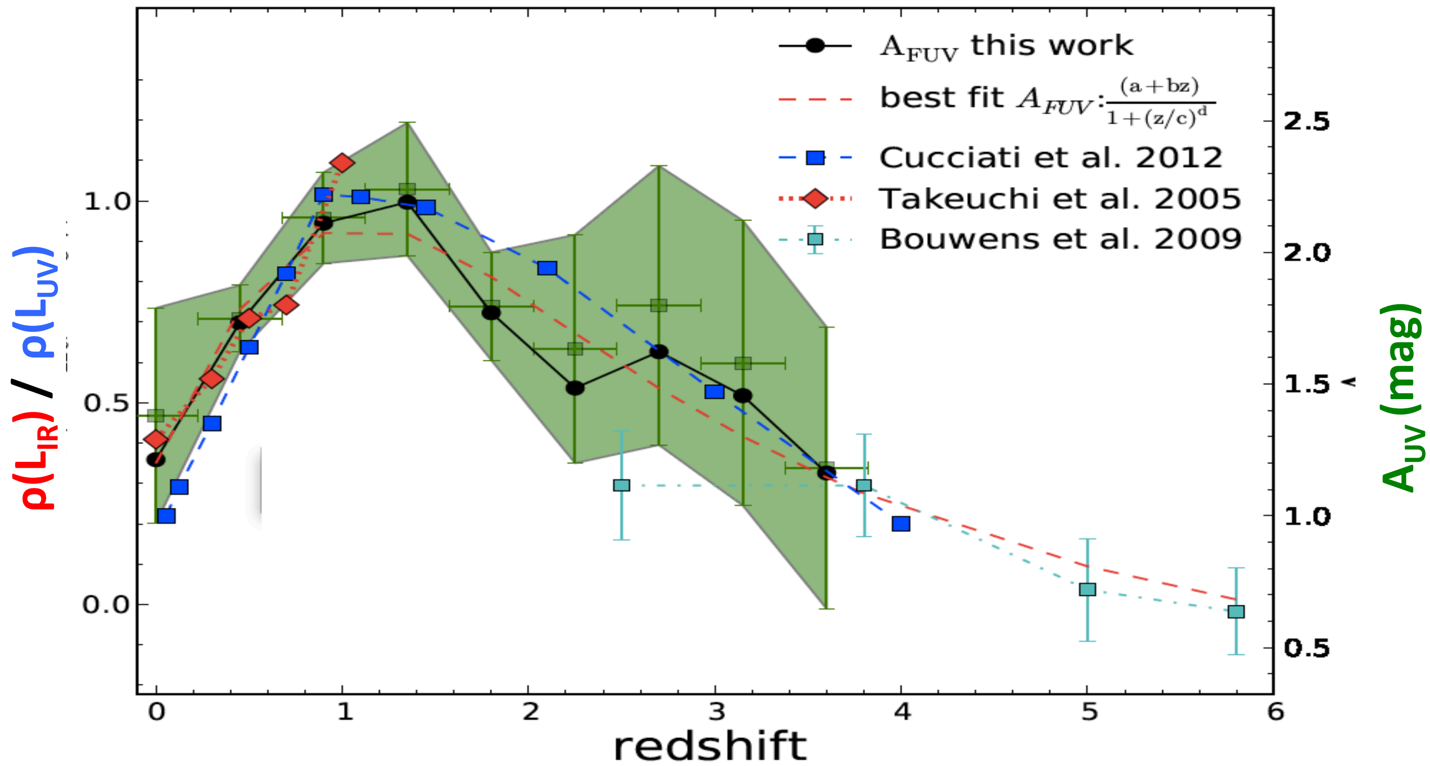
NEP-AKARI field, 0<z<2

- The attenuation law: a universal one → NO

ρ(L_{IR}) / ρ(L_{UV}) as a measure of <A(UV)> in the universe

Burgarella, Buat et al. +13 (& Takeuchi, Buat & Burgarella+05)

Herschel (IR) and optical surveys (UV)



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

About dust attenuation in the universe

- The global amount of attenuation in the universe: UV and IR luminosity densities
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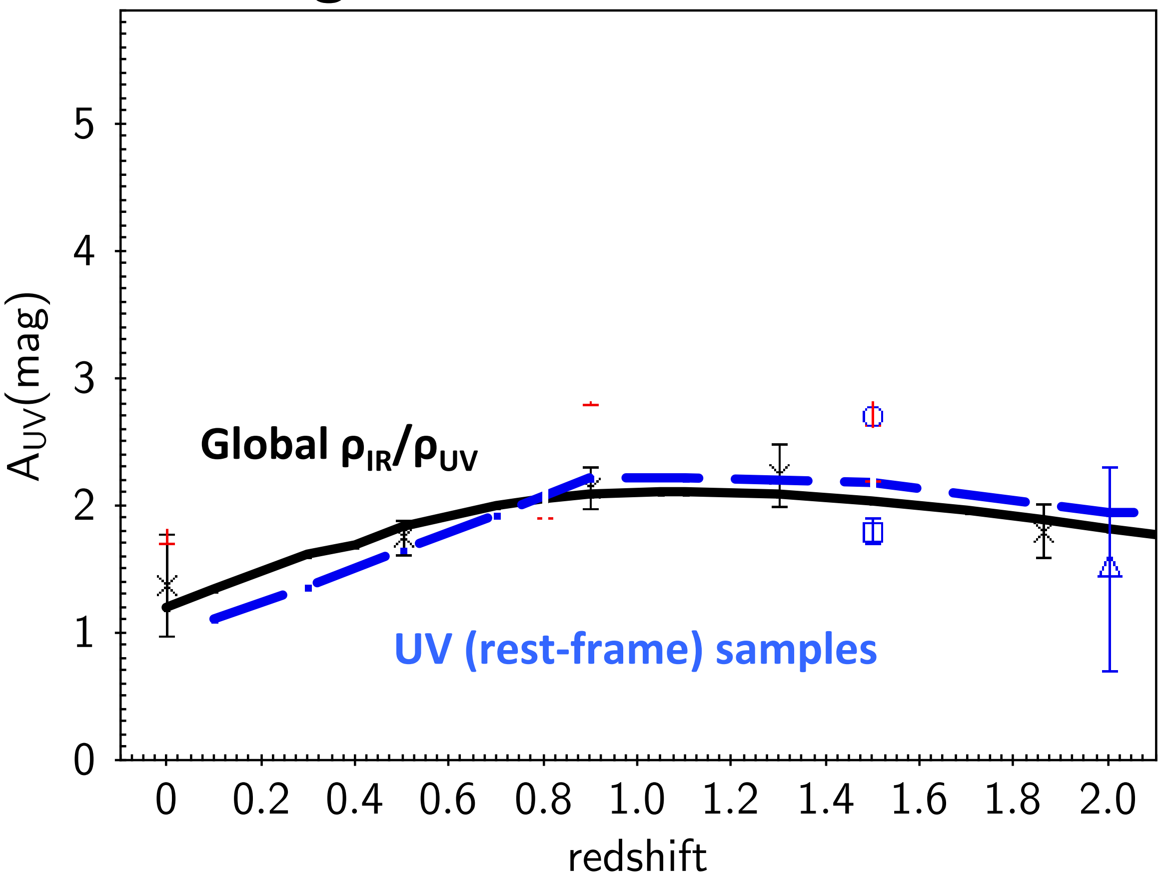
NEP-AKARI field, 0<z<2

- The attenuation law: a universal one → NO

Evolution of dust attenuation with z: global and UV selection



UV selected samples

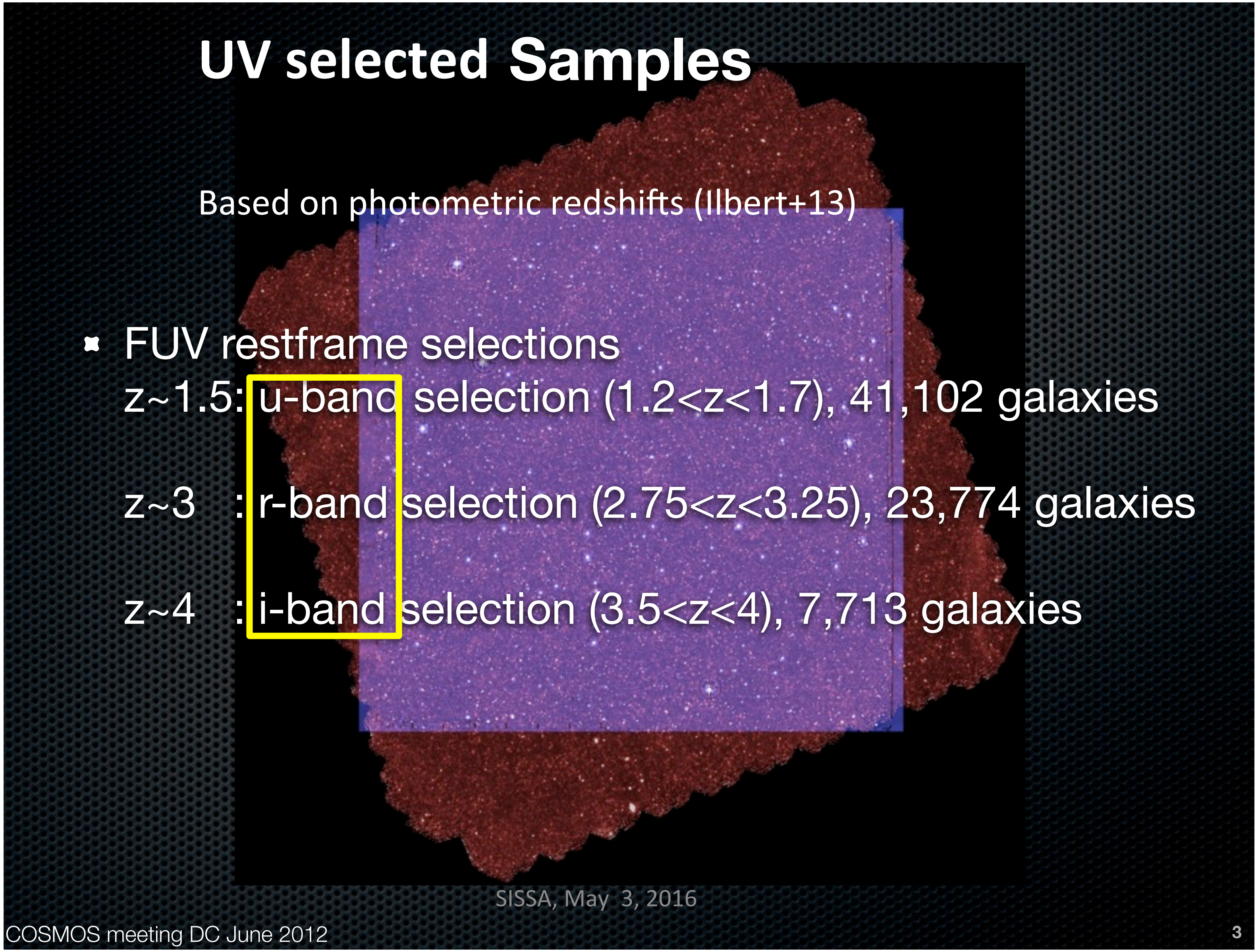
---Cucciati+12, VVDS+CFHT survey: attenuation from SED fitting

Heinis+13 , □ COSMOS
Ibar+13: ○ Hα emitters
Reddy+08: △

Buat+15

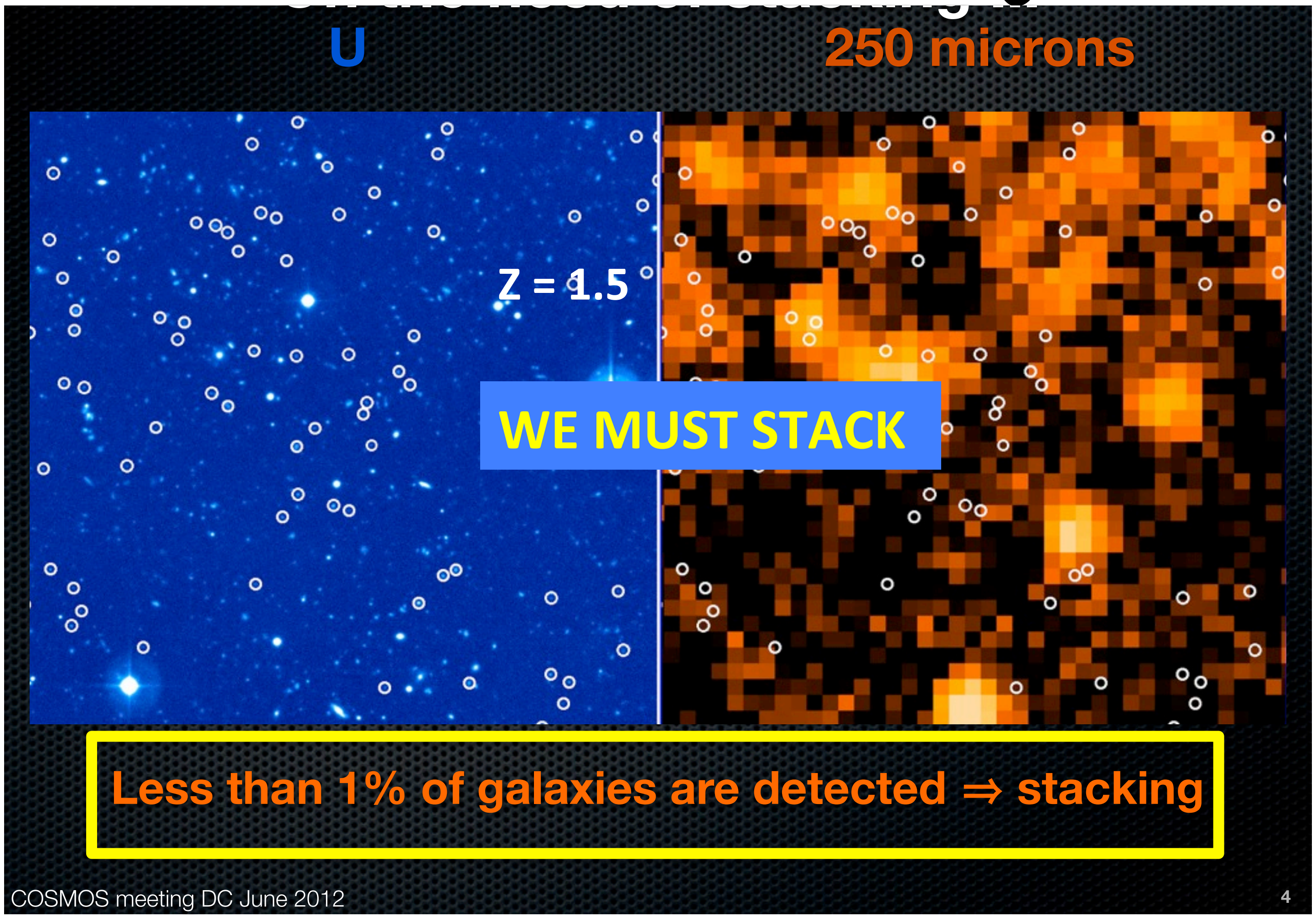
UV selected samples: similar to the global one measured with ρ_{IR}/ ρ_{UV}

Study of UV selected galaxies
in the COSMOS field @ z=1.5, 3 & 4
Heinis+13,+14 HerMES project

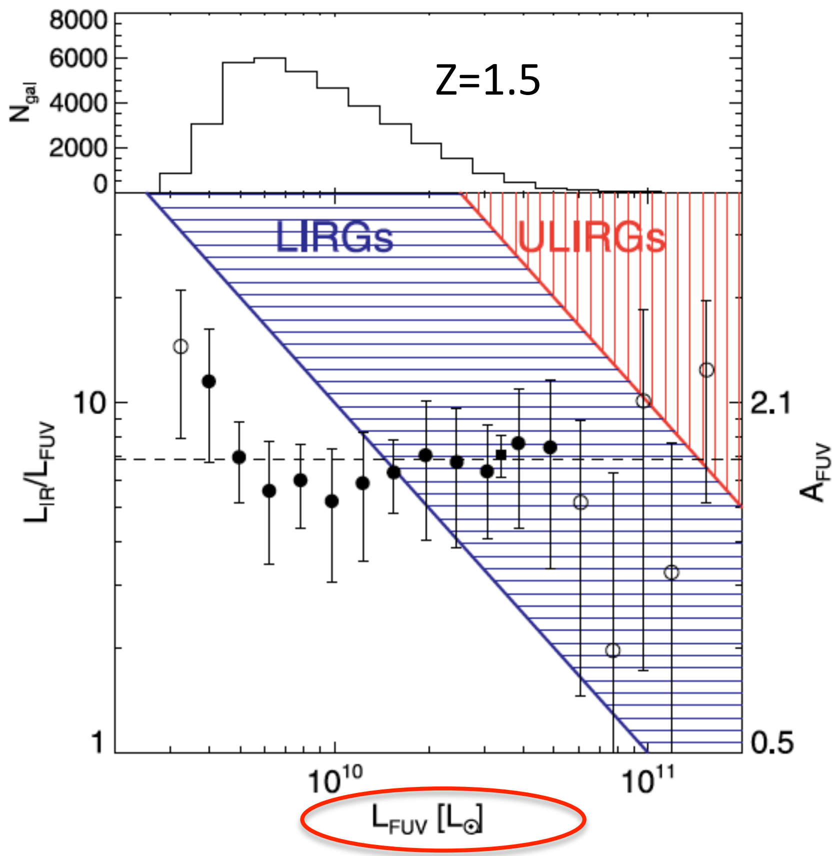


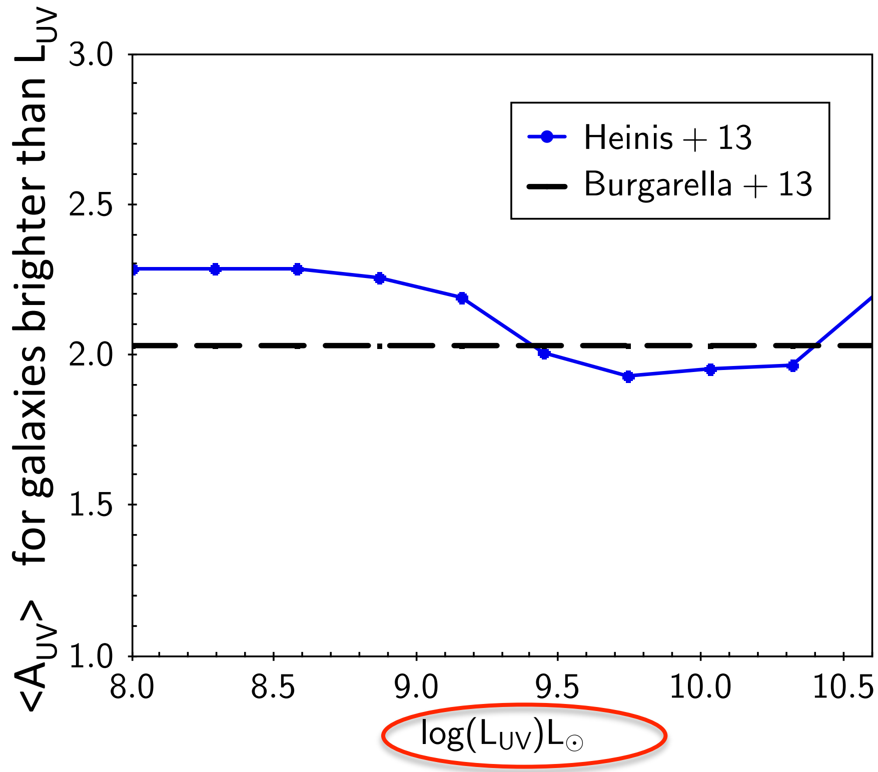
Adding the IR to the UV:

Almost no counterpart of UV selected sources in Herschel images!!



Heinis+13,+14





No trend of L_{IR}/L_{UV} with L_{UV}
→The same average L_{IR}/L_{UV}
is measured for any cut in L_{IR}

→ **$<A_{UV}>$ in any UV selection is similar to the average attenuation**

About dust attenuation in the universe

- The global amount of attenuation in the universe: UV and IR luminosity densities
- Amount of attenuation for:

-UV emitting galaxies:

-IR selected galaxies

NEP-AKARI field, $0<z<2$

- The attenuation law: a universal one → NO

A 8 µm rest-frame selection in the NEP-AKARI deep field

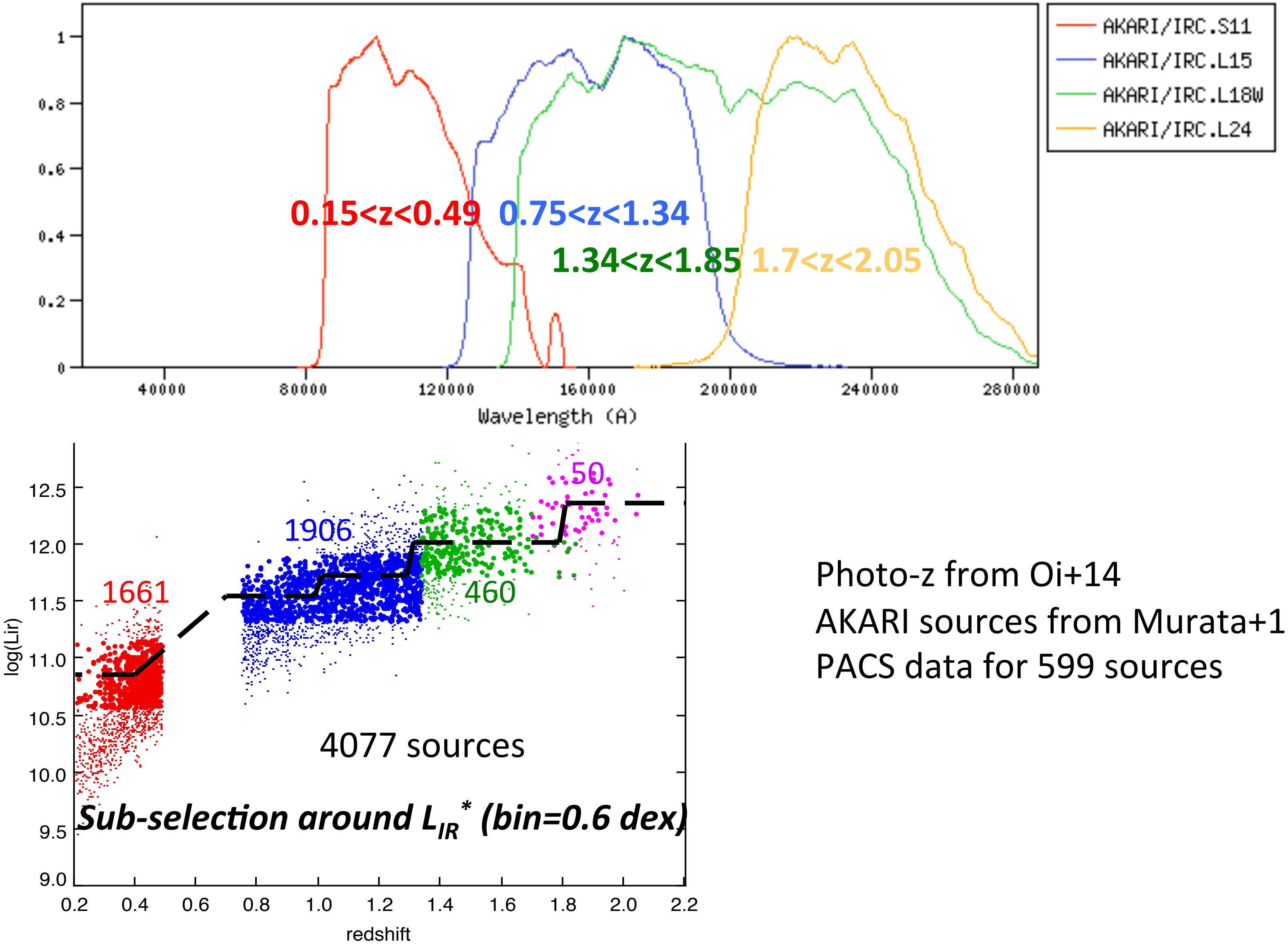
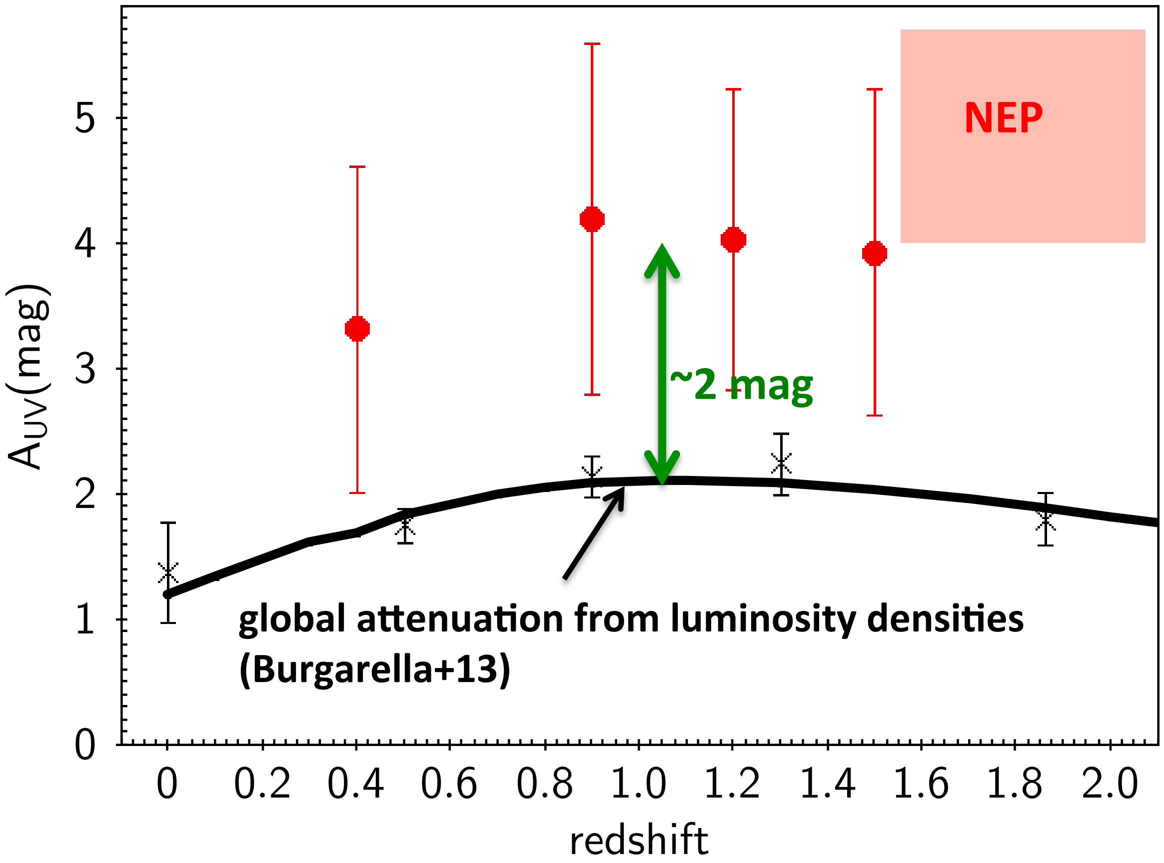


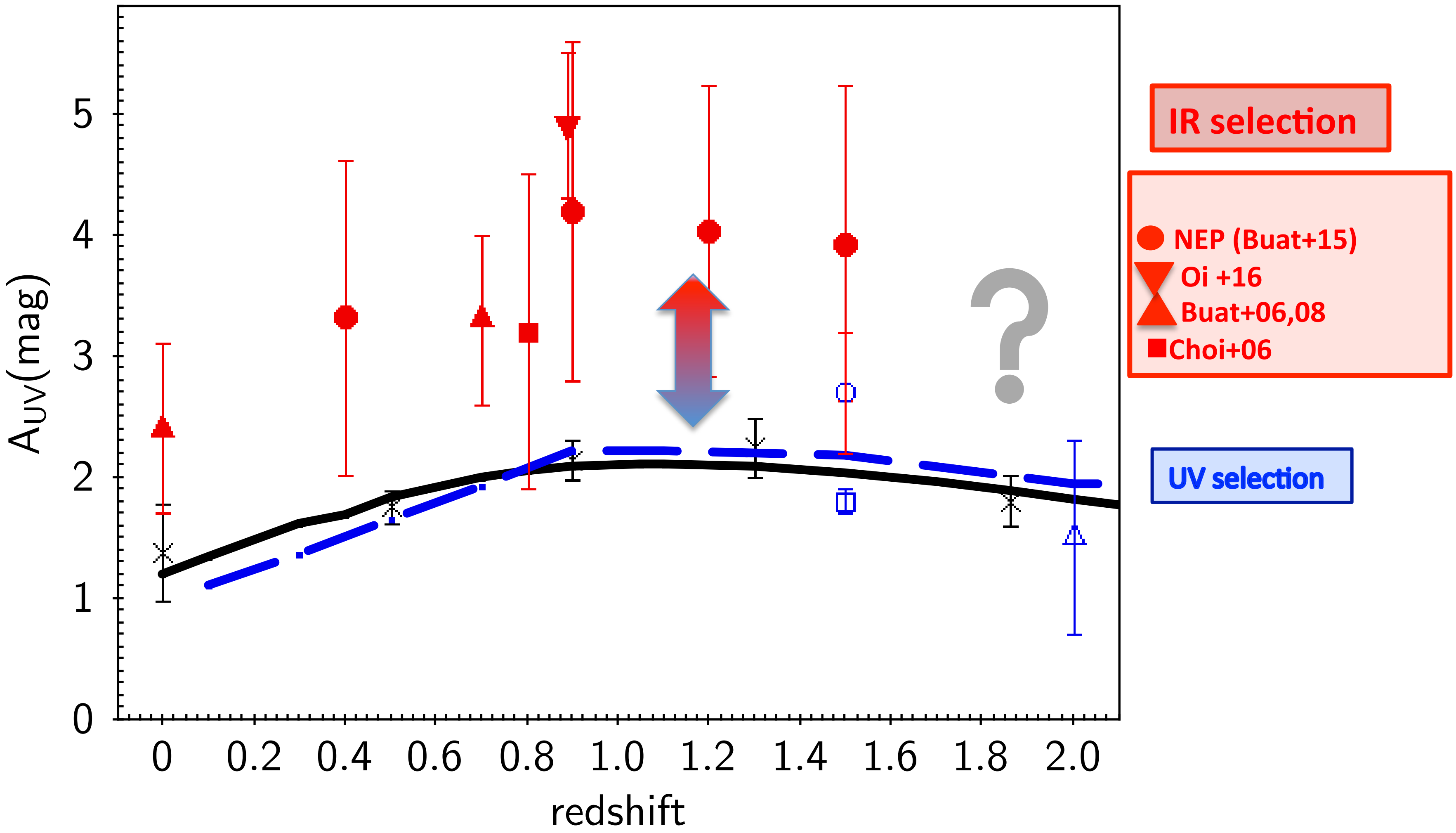
Photo-z from Oi+14
AKARI sources from Murata+13
PACS data for 599 sources

Going back to the evolution of dust attenuation (A_{UV}) with z



Attenuation in IR selected galaxies ~2 mag higher than the average of the universe

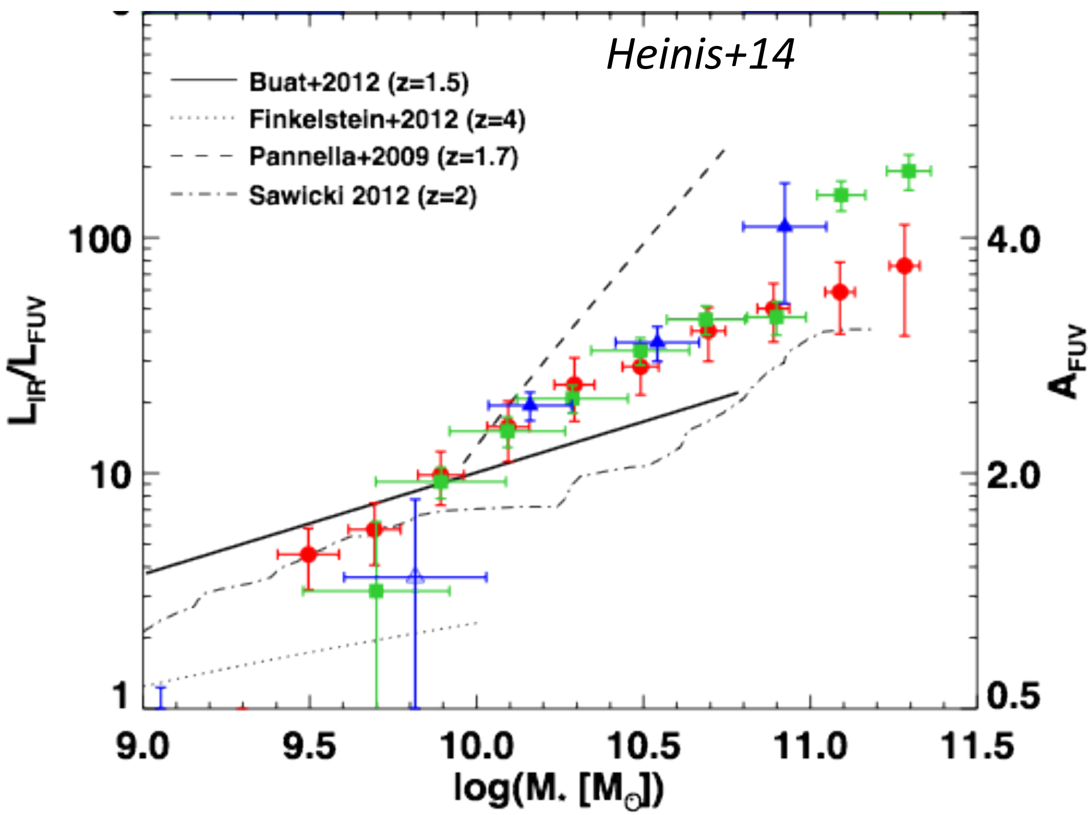
Evolution of dust attenuation with z



IR selected samples :

Slight increase of the attenuation with redshift for galaxies producing the bulk of the IR energy (L_{IR}^* galaxies)

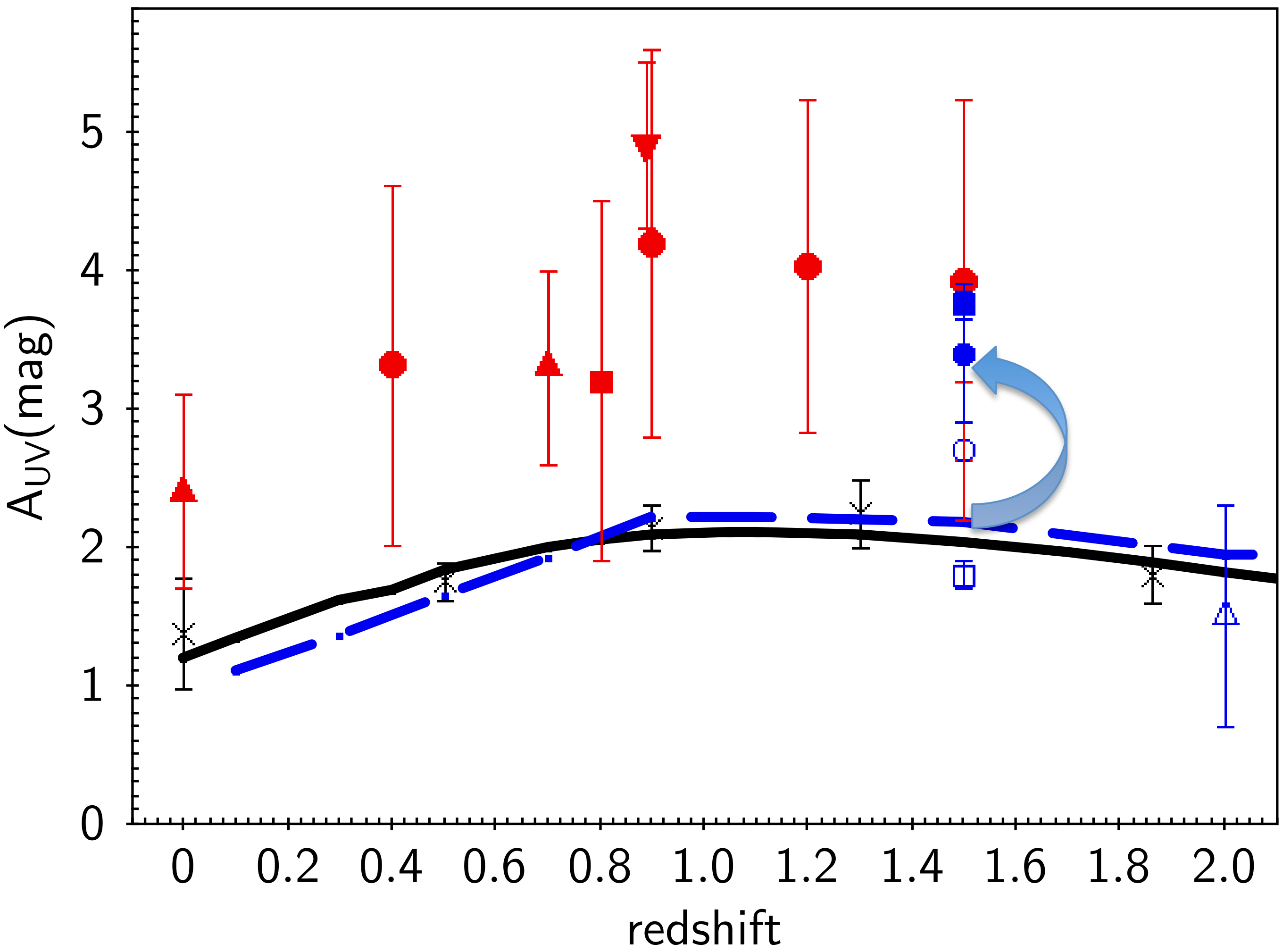
UV selected samples: much lower attenuation, similar to the global one measured with ρ_{IR}/ρ_{UV}



Dust attenuation increases with M_*, a universal correlation?

Garn & Best 2010 Ibar+2013, Heinis+2014, Price+2014, Panella+2015

Evolution of dust attenuation with z

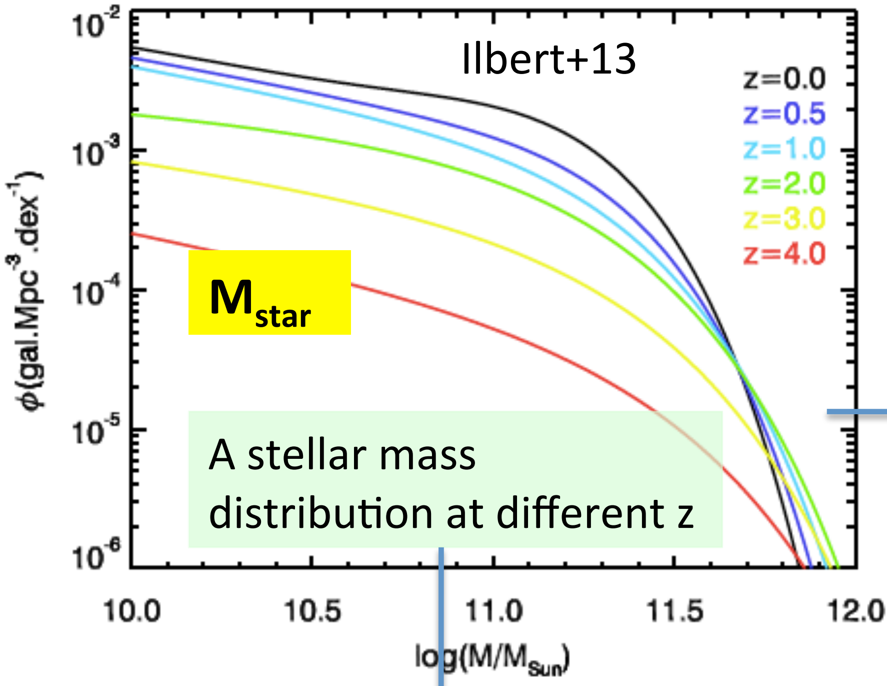


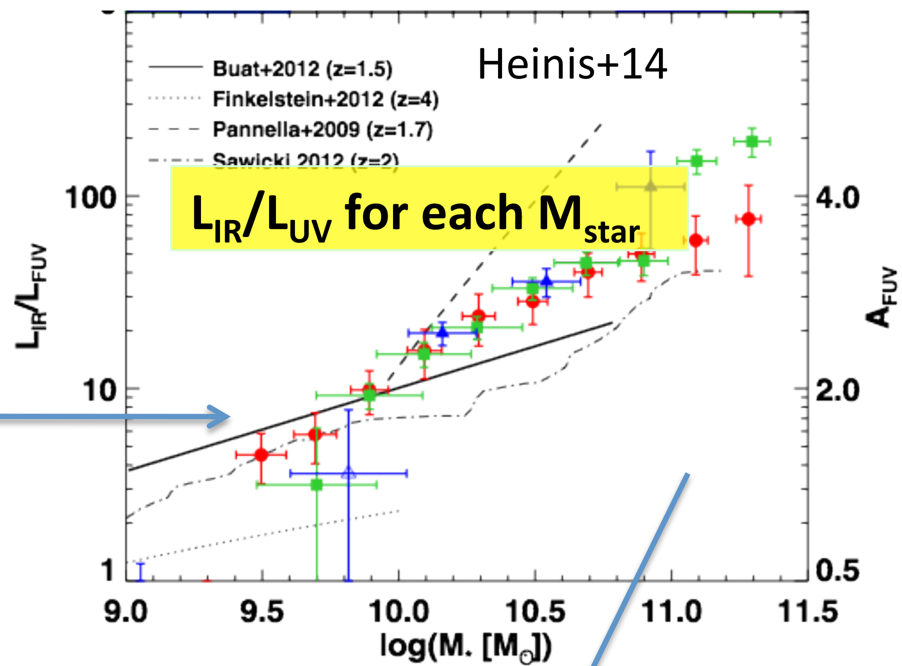
UV selections

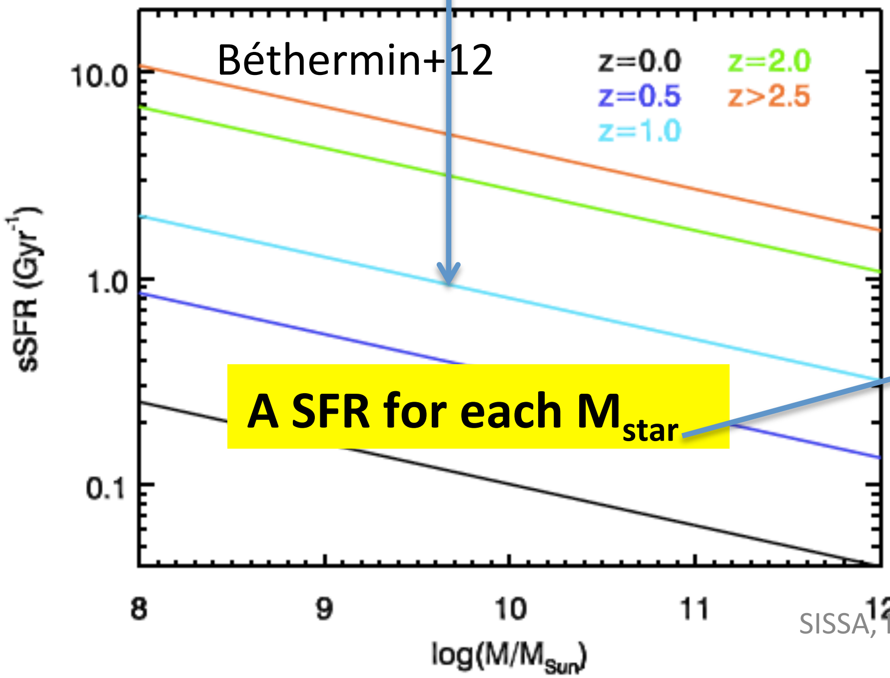
→ If we select galaxies with the same stellar mass as in the IR selection

→ Similar attenuation

Towards a consistent model?





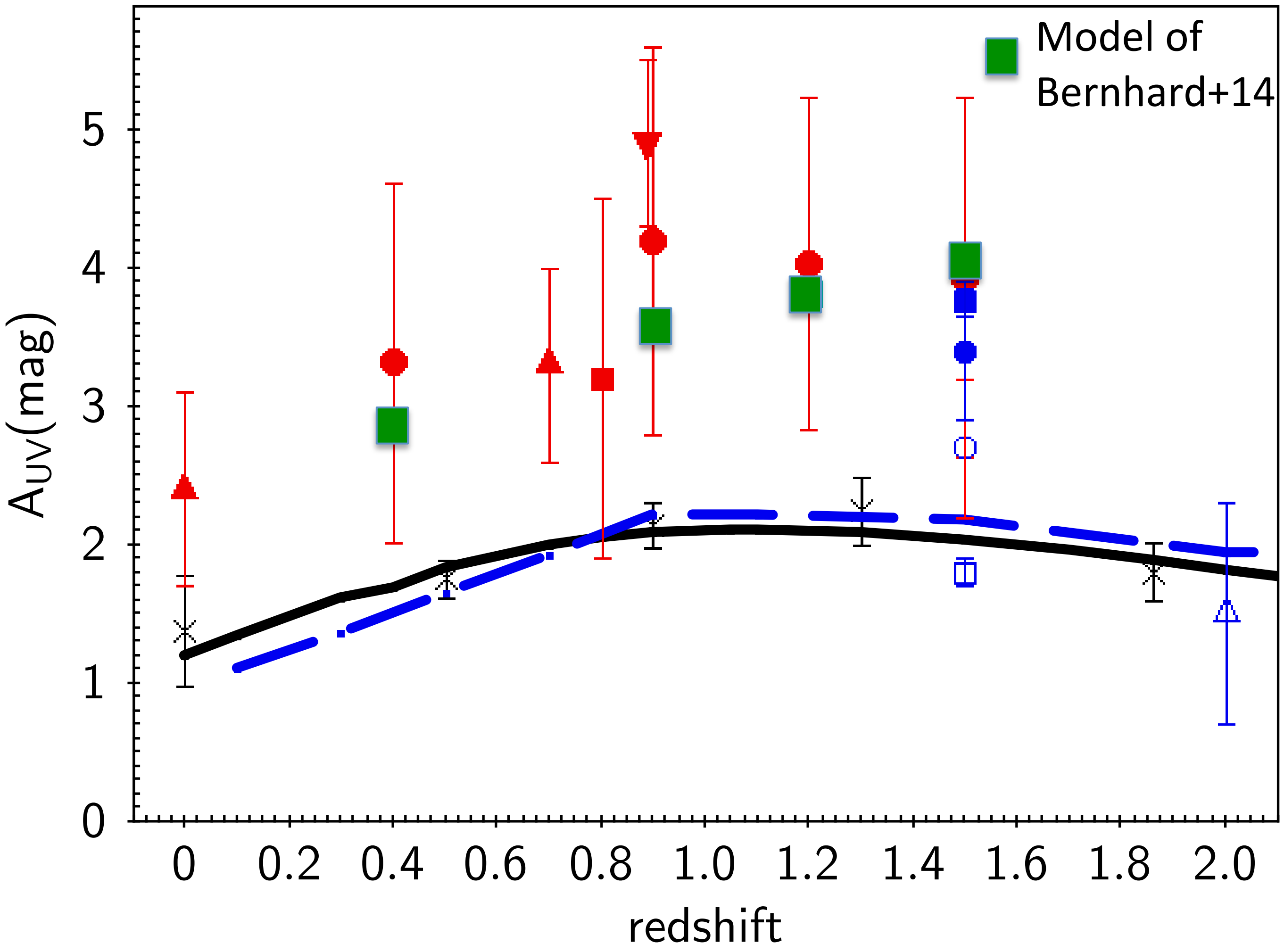


MOCK
CATALOGUE
Bernhard+14

For each $\mathbf{M_{star}}$ at any z

- SFR = SFR(IR)+SFR(UV)
  $= k_{IR}\, \mathbf{L_{IR}} + K_{UV}\, \mathbf{L_{UV}}$
- $\mathbf{L_{IR}/L_{UV}}$

→ $\mathbf{L_{IR}}$ **&** $\mathbf{L_{UV}}$



Model of
Bernhard+14
A_UV(mag)
redshift
0
1
2
3
4
5
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0

About dust attenuation in the universe

- The global amount of attenuation in the universe: UV and IR luminosity densities
- Amount of attenuation for single galaxies:

-UV emitting galaxies:

-IR selected galaxies

→ A consistent model based on stellar mass to reproduce the attenuation found in UV and IR selected samples

About dust attenuation in the universe

- The global amount of attenuation in the universe: UV and IR luminosity densities
- Amount of attenuation for:

-UV selected galaxies:

Z=1.5, 3 & 4 COSMOS field with Herschel (HERMeS data)

-IR selected galaxies

NEP-AKARI field, 0<z<2

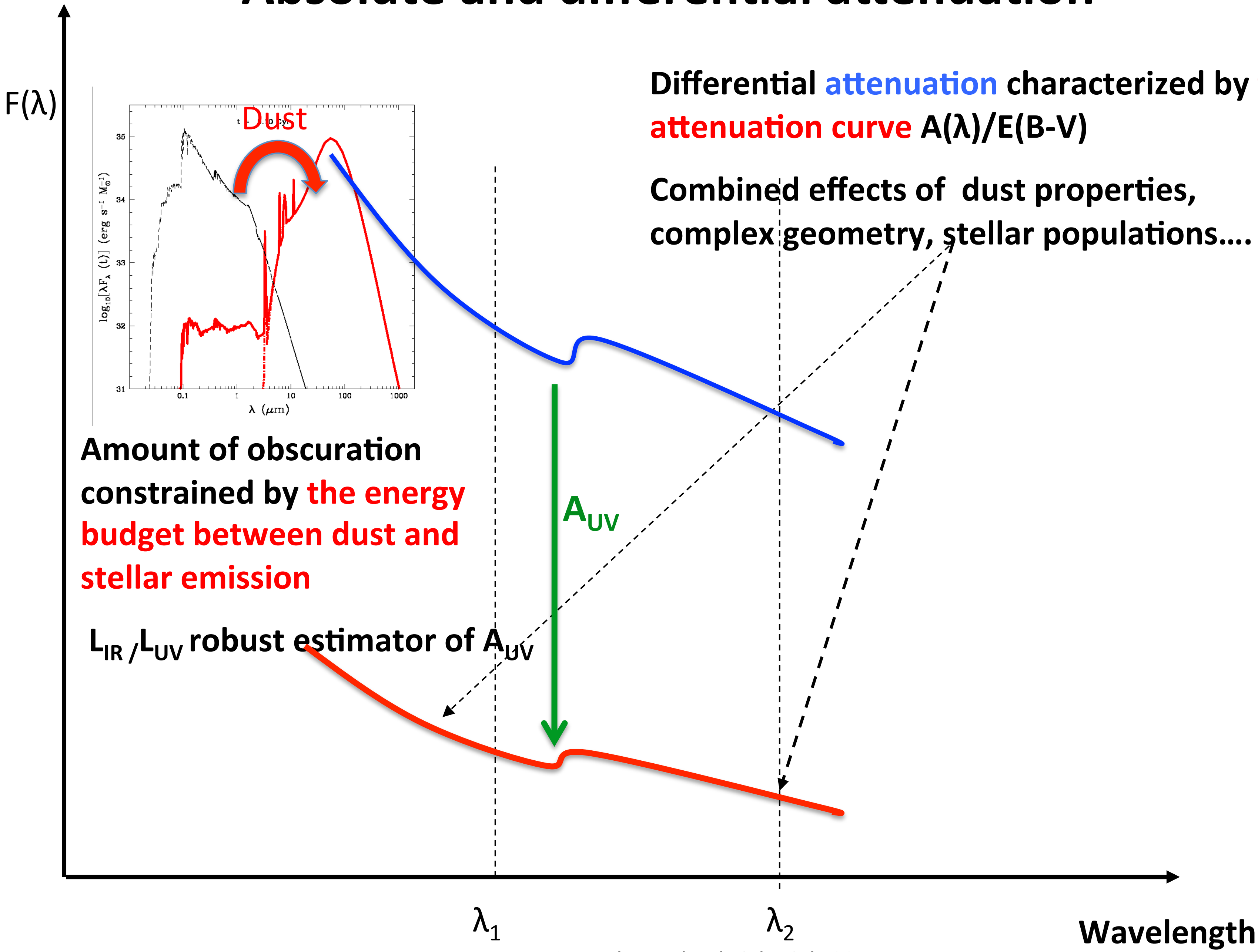
- **The attenuation law: a universal one?**

-UV emitting galaxies

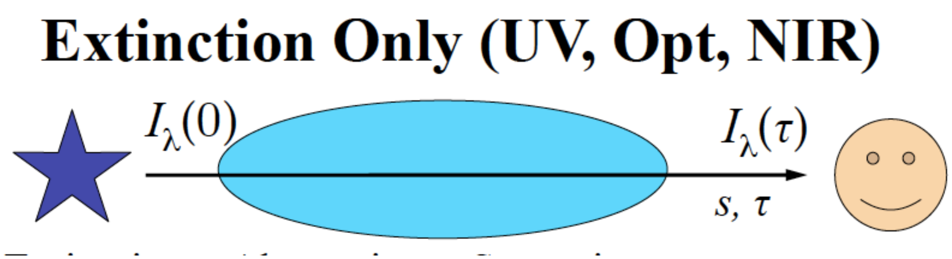
-IR bright massive galaxies

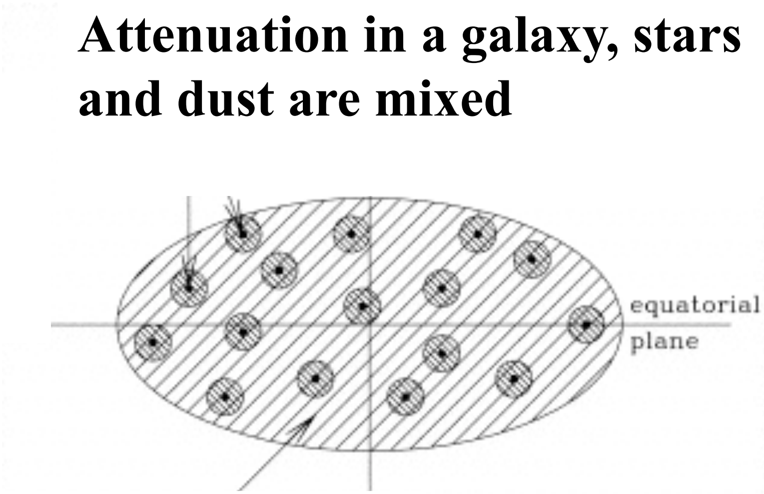
Witt & Gordon 00 No justification was found for the use of a universal attenuation function for the analysis of a large sample of galaxies.

Absolute and differential attenuation



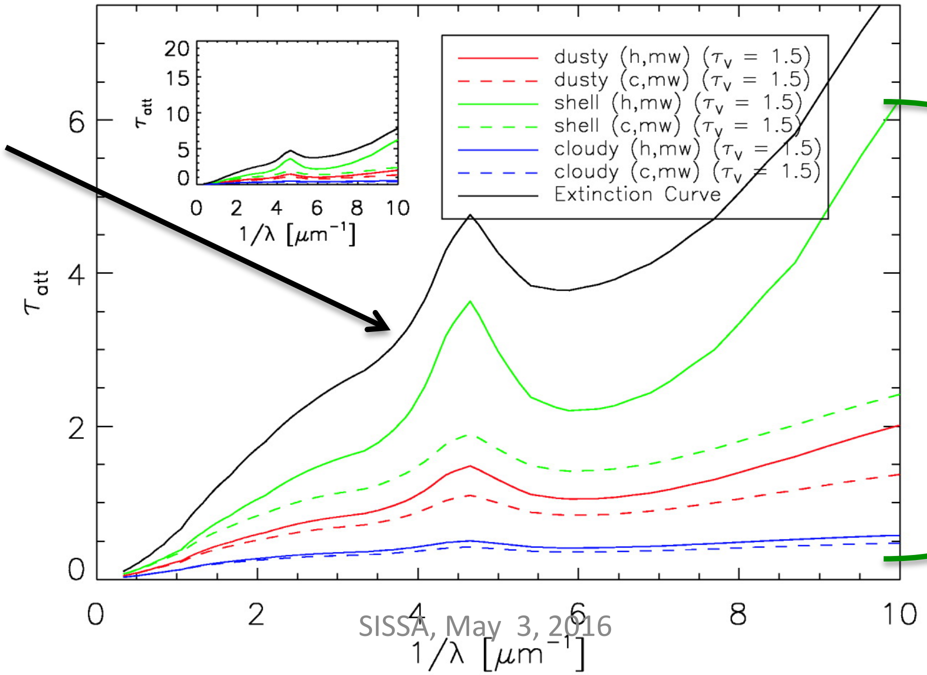
Attenuation ≠ extinction





MW Extinction curve along one ligne of sight, depends on dust properties only

Witt & Gordon 2000



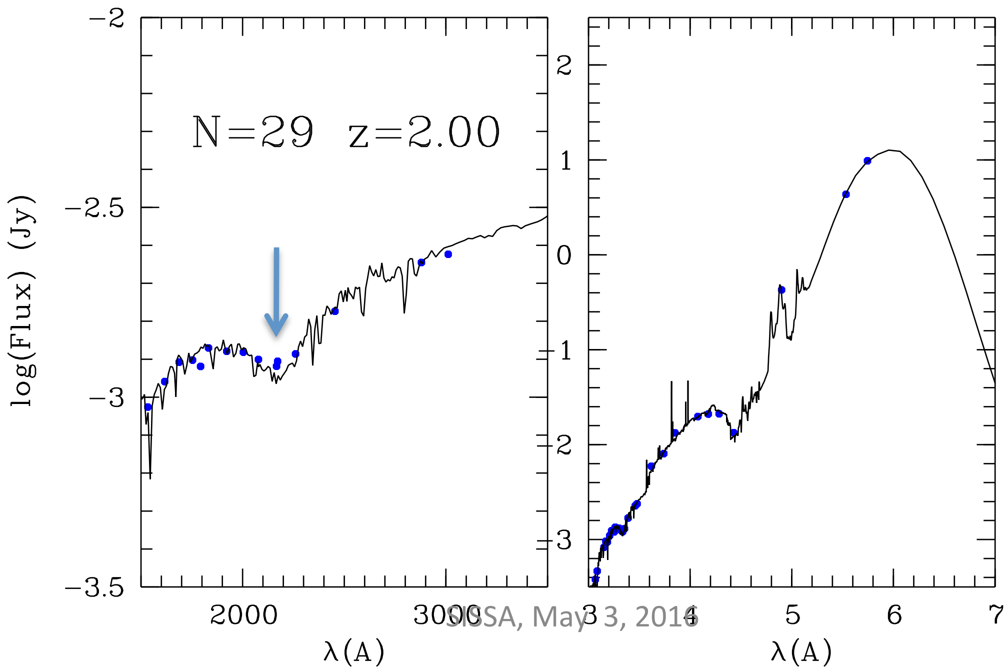
Attenuation law for extended objects depends on dust properties and dust-stars geometry

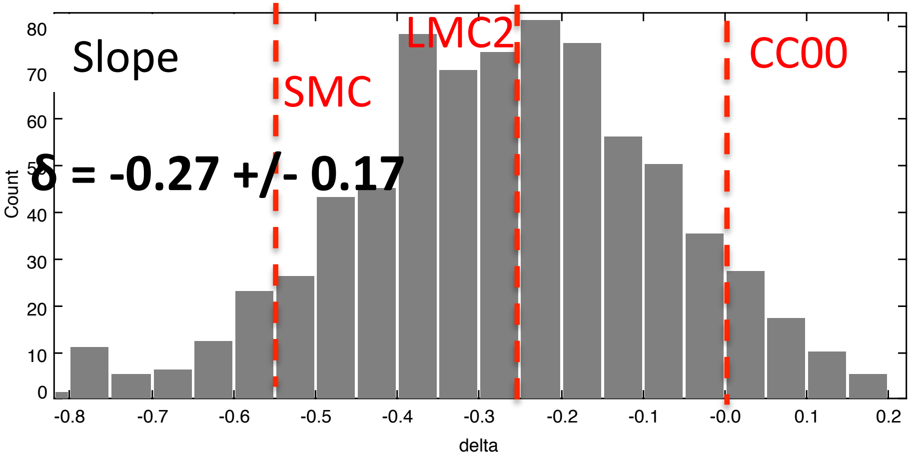
Dust attenuation curve in « UV emitting » galaxies 1<Z<2

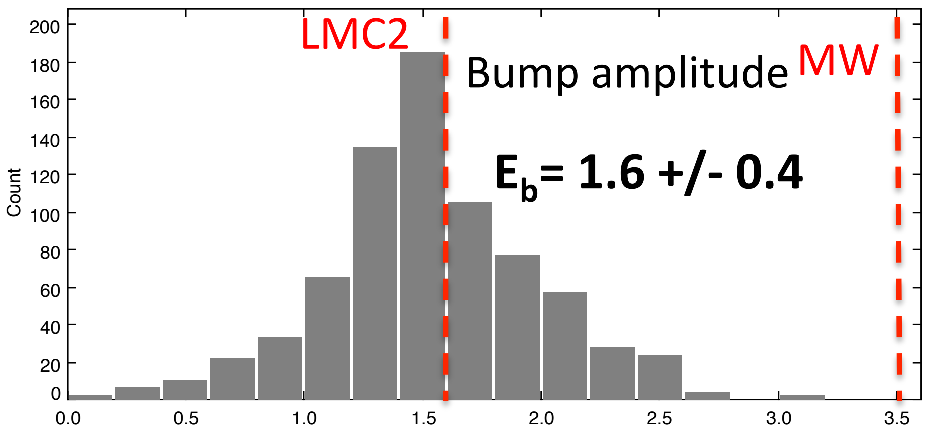
Buat+11,12

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**





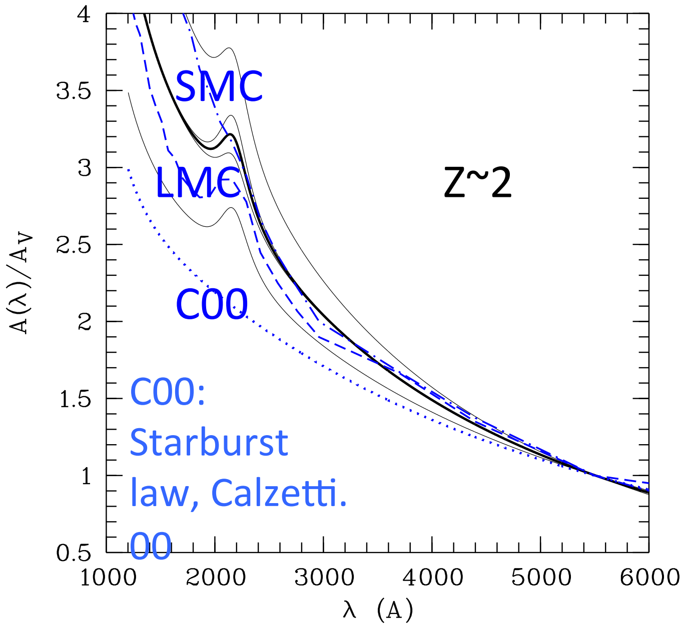


Close to the values of the LMC2 extinction curve

Bumps confirmed in ~20% of the global sample and ~40-50 % of galaxies observed in mid and far IR

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

Calzetti law

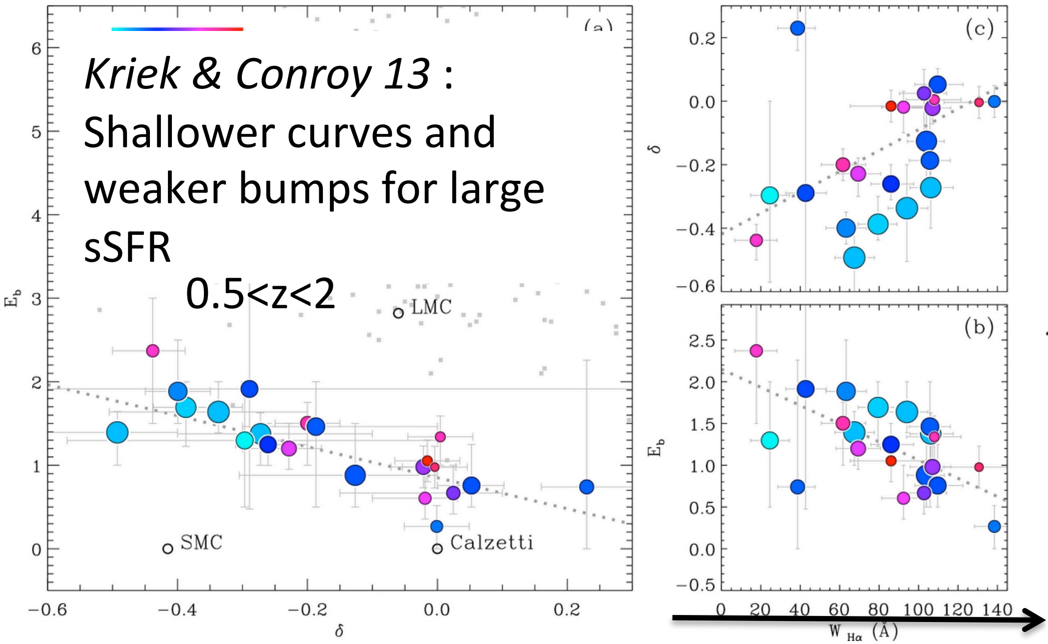


E_b= 1.6 +/- 0.4 δ = -0.27 +/- 0.17

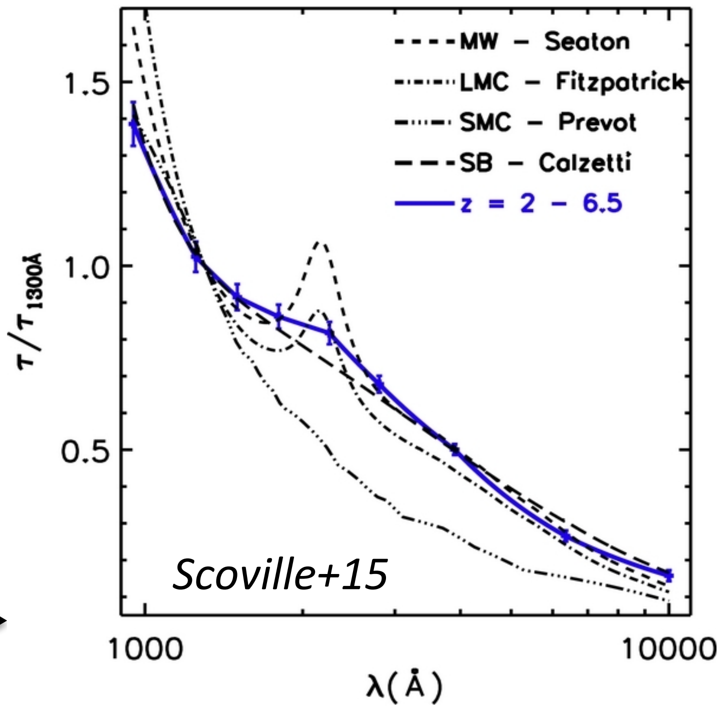
Buat+11,12

Kriek & Conroy 13 : Shallower curves and weaker bumps for large sSFR

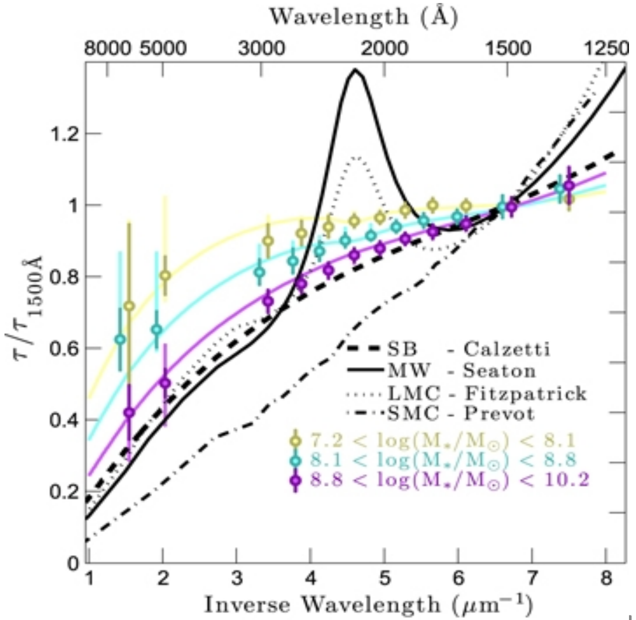
0.5<z<2

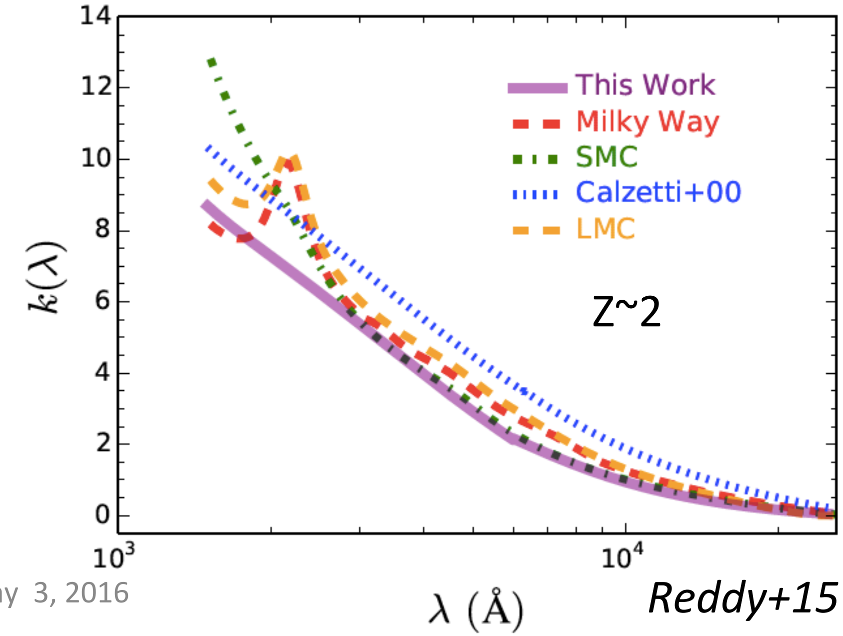


W(Hα) ≈ sSFR



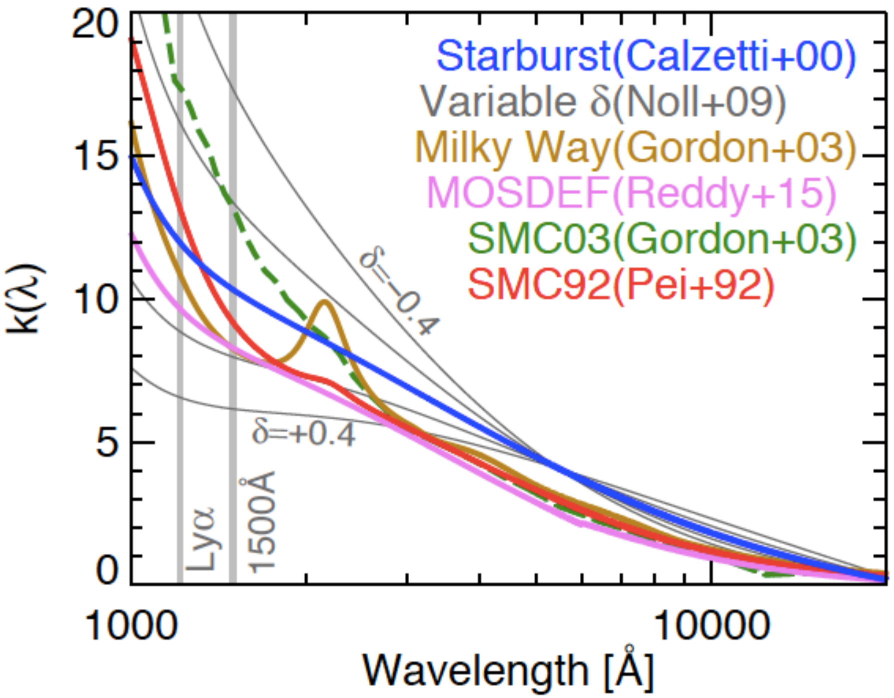
Zeimann+15: Emission line galaxies: Shallower curves than Calzetti's one, steepening when M* increases

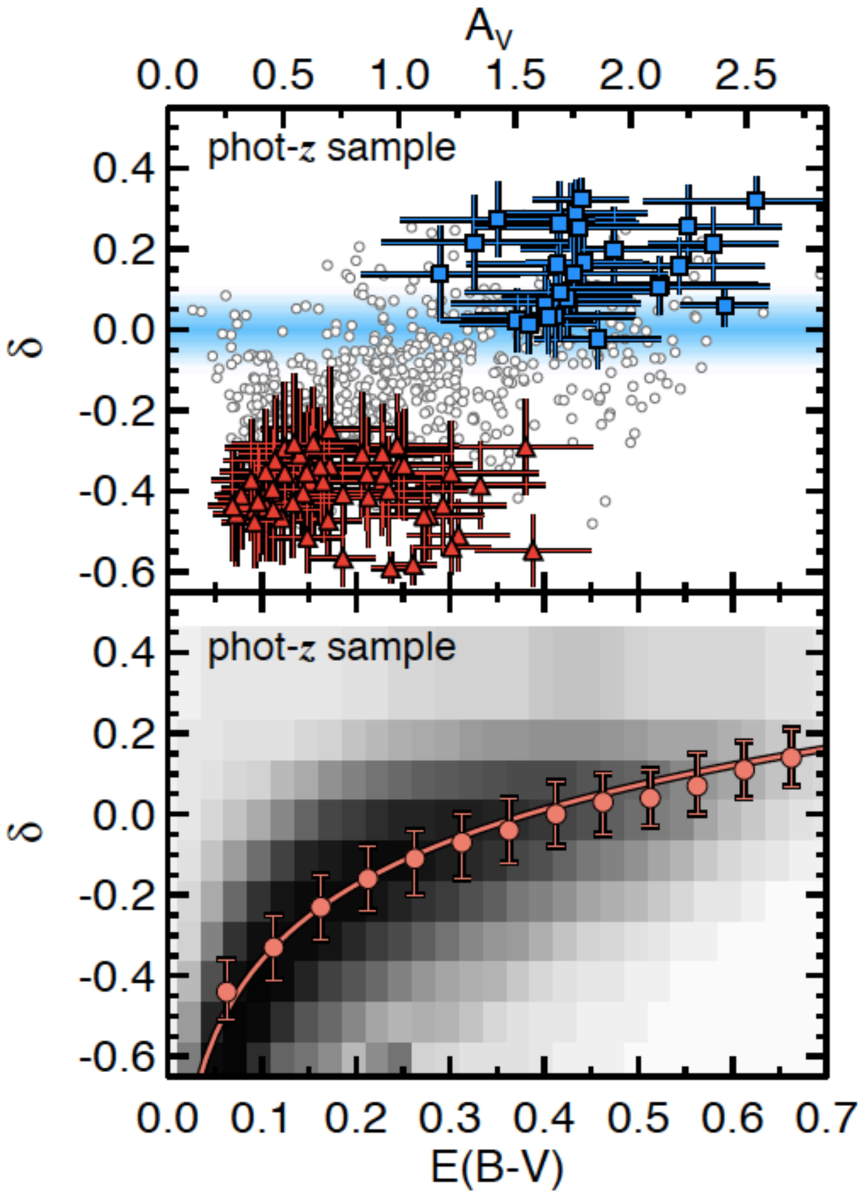




Reddy+15

Salmon+15, CANDELS data, 1.5<z<3 galaxies detected with **MIPS/24 µm**





$\delta = (0.62 \pm 0.05)\ \log(E_{B-V}) + 0.26 \pm 0.02$

(Very) tentative conclusion?

An attenuation curve Calzetti like or steeper (LMC like)
with bumps @ 215 nms present in >20% of galaxies
flattening when the sSFR and E(B-V) increases?
BUT
Likely to be also dependent on the selection of the targets
(UV (first selection) + IR data if any)

Going from a **UV-optical/IR selection** to **a far-IR selection**
--> A more complicated situation!

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**

Lo Faro et al. In prep

TO INVESTIGATE THE DUST ATTENUATION PROPERTIES OF IR-SELECTED GALAXIES AT LOW AND HIGH-z

UV-to-FIR SED fitting

Physically-motivated SED modelling

CIGALE, MAGPHYS (like)
cigale.lam.fr

Radiation transfer SED modelling

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

ON

WELL KNOWN SAMPLE FOR WHICH A WEALTH OF DATA IS AVAILABLE &
RT-based solutions have been already computed in detail

Z~1 LIRGs and Z~2 ULIRGs) (from Lo Faro+13,15).

- **nearby (U)LIRGs from GOALS** (Armus et al. 2009) **sample**

The attenuation laws considered in the work

Charlot & Fall 2000
and Magphys recipes

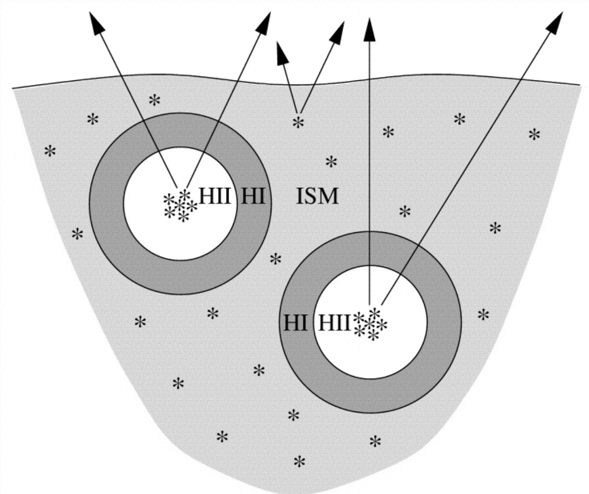
$$\tau_\lambda(t') = \begin{cases} \tau_\lambda^{\rm BC} + \tau_\lambda^{\rm ISM} & \text{for } t' \leqslant t_0 \\ \tau_\lambda^{\rm ISM} & \text{for } t' > t_0. \end{cases} \quad = 10^{7}\ \textit{years}$$

$$\tau_\lambda^{BC} = (1-\mu)\tau_V(\lambda/5500\text{Å})^{\delta_{BC}}$$

$$\tau_\lambda^{ISM} = \mu\tau_V(\lambda/5500\text{Å})^{\delta_{ISM}}$$

$$A_\lambda^{BC} = A_V^{BC}(\lambda/5500\text{Å})^{\delta_{BC}}$$

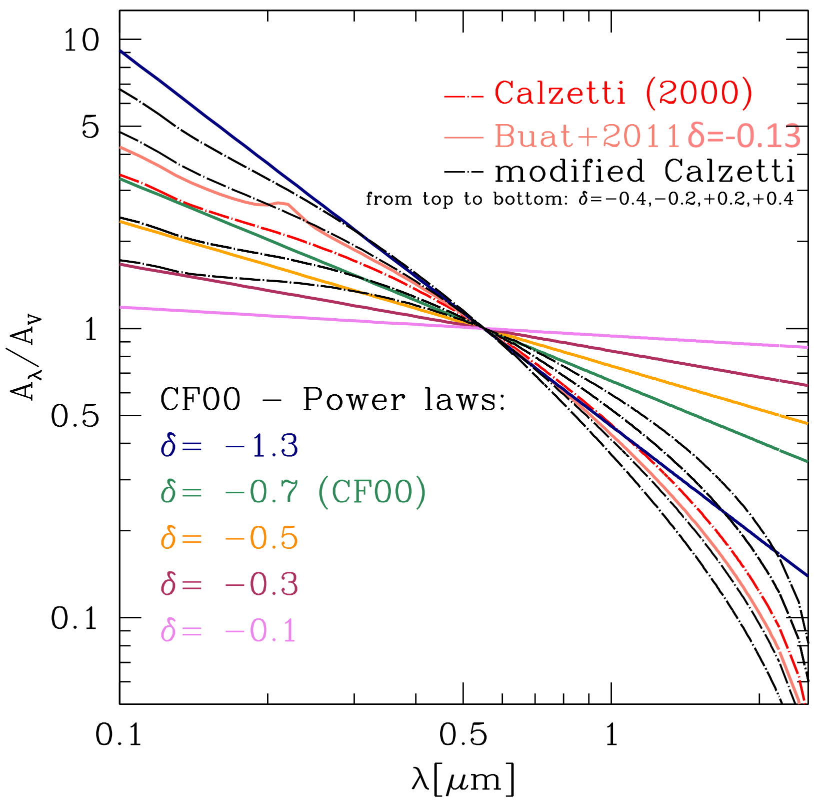
$$A_\lambda^{ISM} = A_V^{BC} f_{att}(\lambda/5500\text{Å})^{\delta_{ISM}}$$



Calzetti and Calzetti modified laws

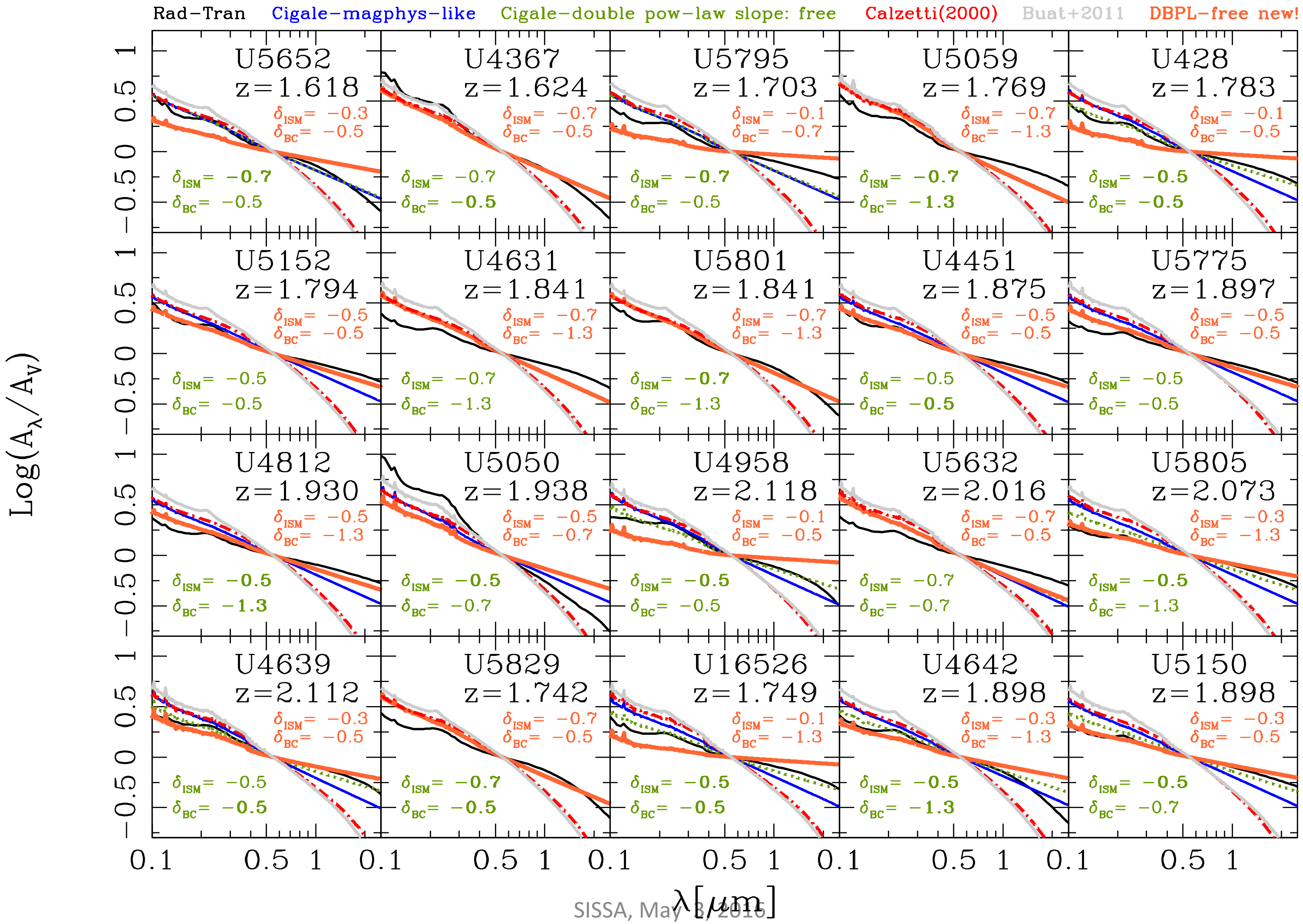
$$k(\lambda) = \left(\frac{A(\lambda)}{E(B-V)} + \frac{E_b\lambda^2\gamma^2}{(\lambda^2-\lambda_0^2)+\lambda^2\gamma^2}\right)\left(\frac{\lambda}{\lambda_V}\right)^\delta$$

$+ f_{att}$

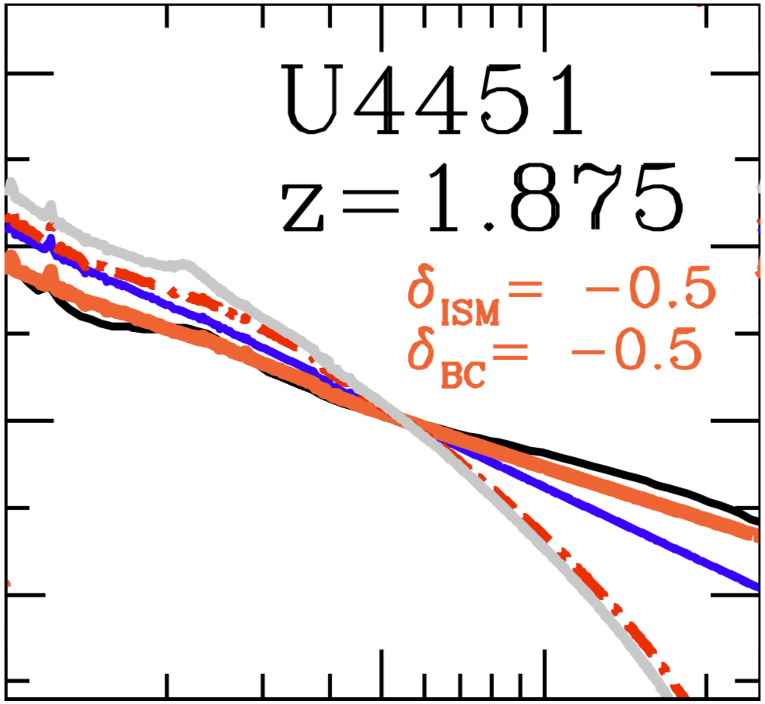


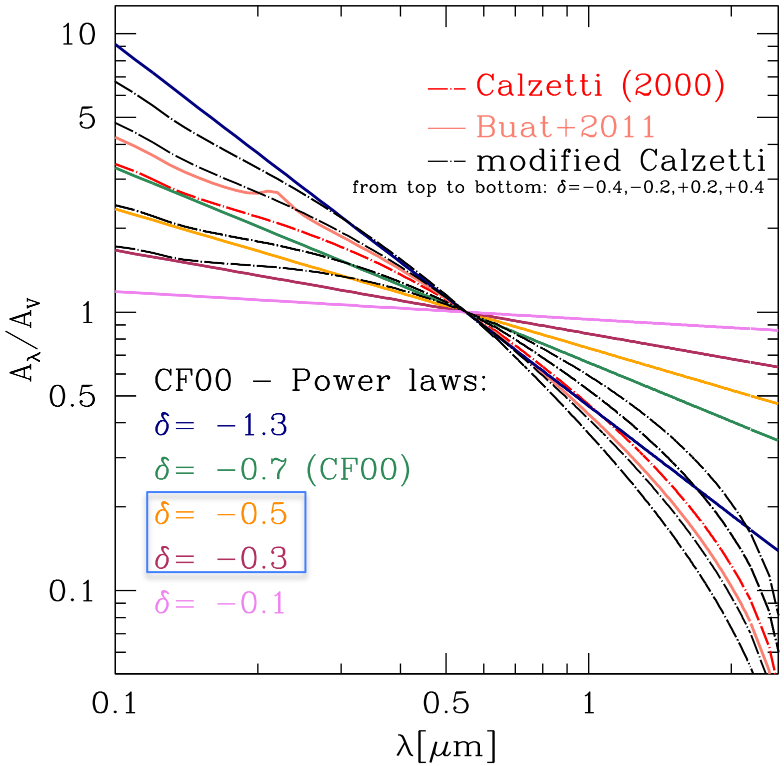
Courtesy of Barbara Lo Faro

Comparison of different attenuations curves: SED modelling with Cigale, Magphys and Grasil *Lo Faro+16: (in prep)*



IR luminous galaxies (LIRGs and ULIRGs): a flatter attenuation curve, not only in UV, not reproduced by starburst like attenuation curves.





For the whole sample of ULIRGs → $<\delta_{ISM}> \cong -0.4$

Chevallard et al. 2013:
Attenuation in optical-NIR
0.55<λ<1.6 μm

Compilation of Radiative Transfer modeling results
→ All predict a grayer attenuation for an increasing attenuation

$\delta_{ISM} \rightarrow -n^{ISM}$

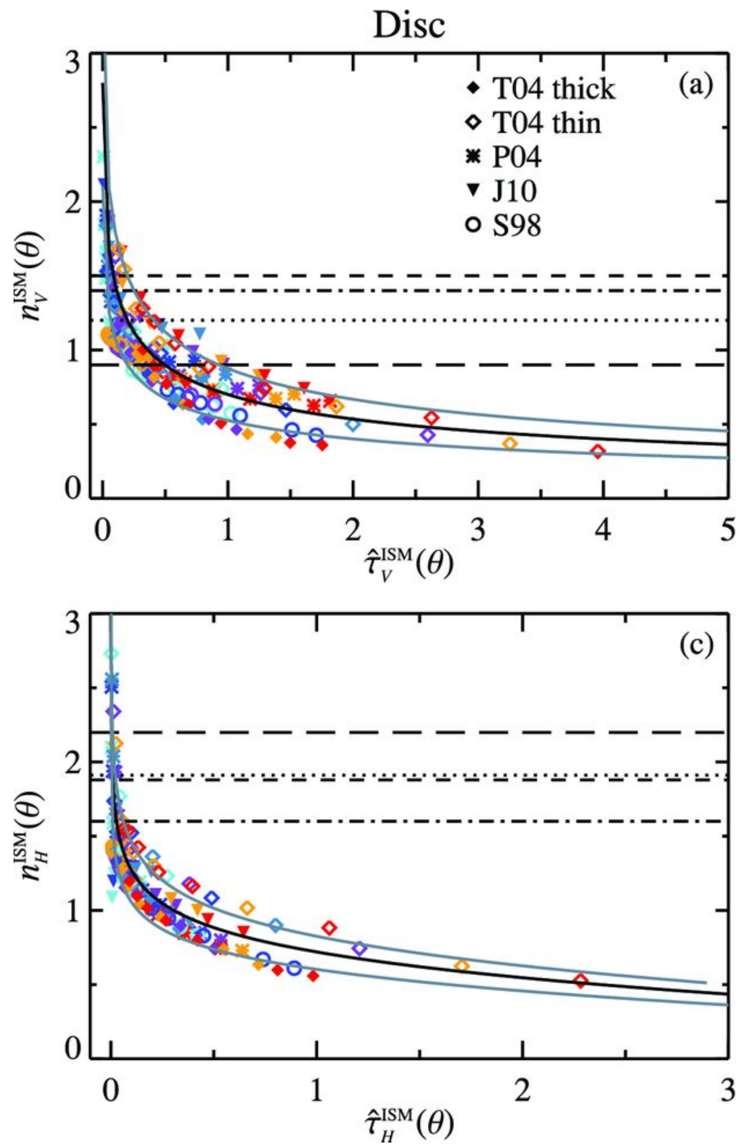
$$n_\lambda^{\rm ISM}(\tau_V) = n_V^{\rm ISM}(\tau_V) + b(\tau_V) \quad (\lambda/\mu{\rm m} - 0.55)\,,$$

with

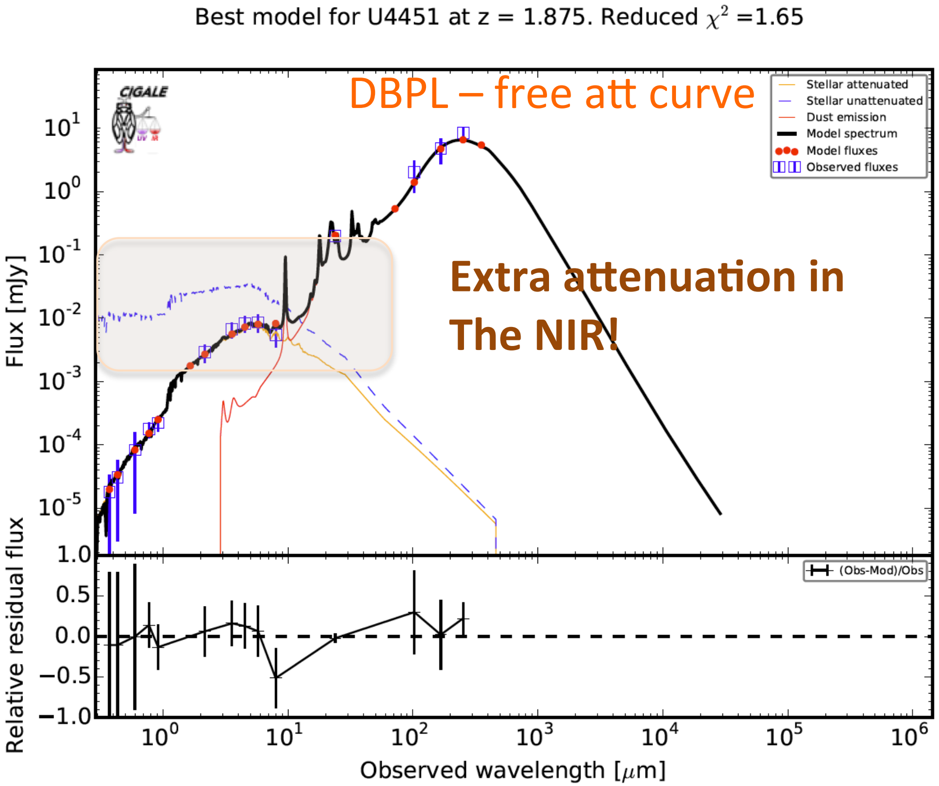
$$n_V^{\rm ISM}(\tau_V) = \frac{2.8}{1 + 3\sqrt{\tau_V}} \qquad (\pm 25\ {\rm per\ cent})$$

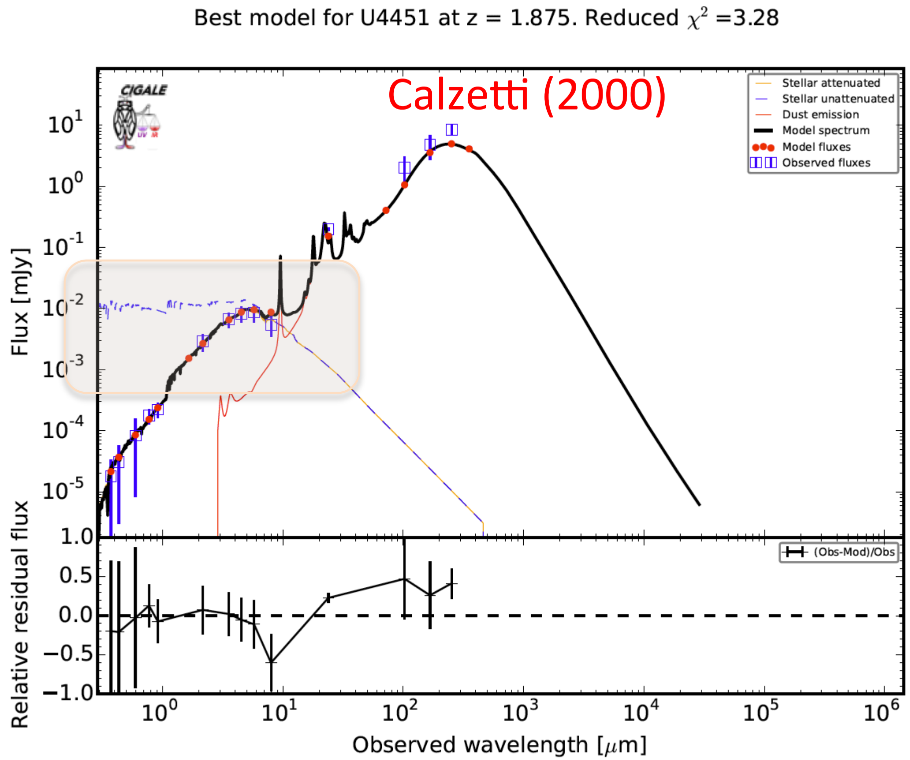
and

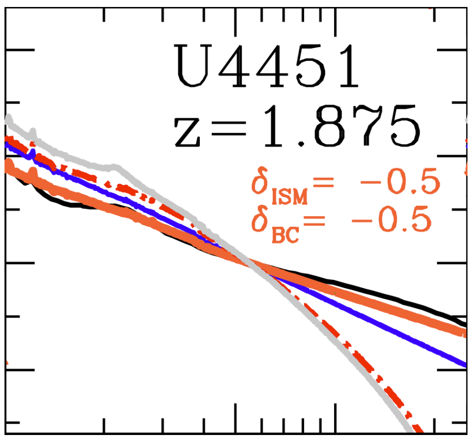
$$b(\tau_V) = 0.3 - 0.05\,\tau_V \qquad (\pm 10\ {\rm per\ cent})\,,$$



How do these ``flatter'' attenuation curves affect the NIR-to-FIR SED ?



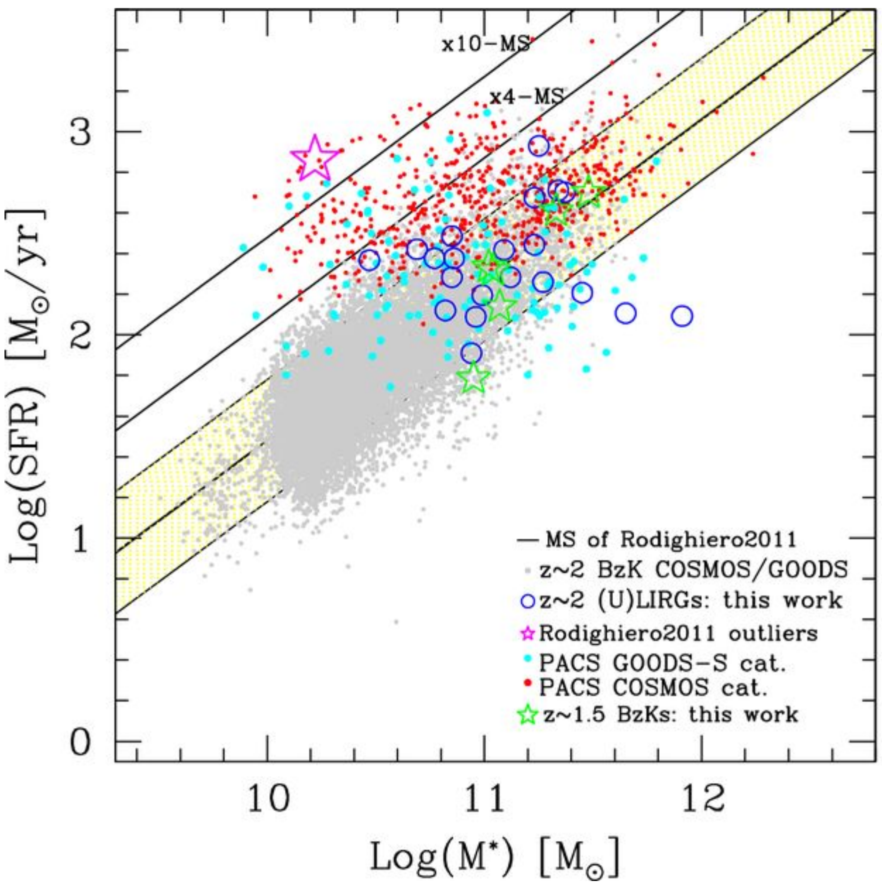


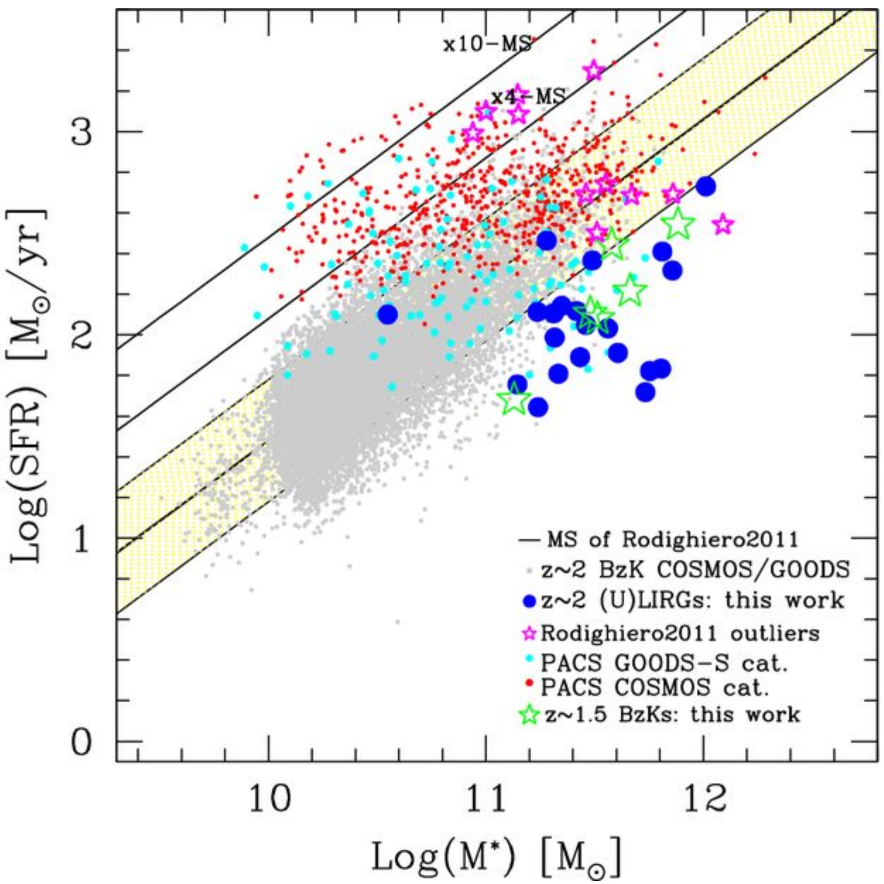


A larger amount of attenuation at longer wavelengths (NIR) than allowed by Calzetti(2000) att. law. (*Mitchell (2013), Da Cunha(2010)*)

→ Affects the determination of the stellar mass

As a consequence → impact on the position of the « Main Sequence »





Lo Faro+2015

Few words to conclude

- **The absolute amount of attenuation:**

  well determined when **far-IR data** are available

  A good and universal (?) correlation **with the stellar mass**: reconcile UV and IR selections

- **The differential attenuation**: depends on the attenuation curve which **is not universal**, may flatten for IR bright galaxies and galaxies with a large sSFR, dust attenuation….

  more work and statistics is needed, variation with the ISM properties, redshift, sSFR

Dust evolution in high-z quasars

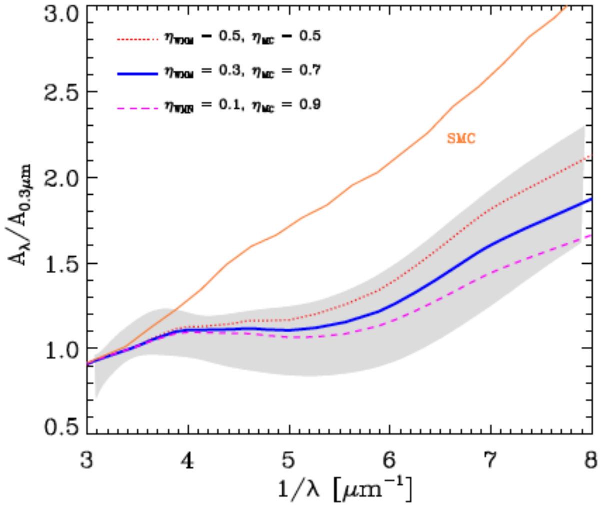


Figure 4. UV extinction curves ($A_V/A_{0.3\,\mu m}$) at $t = 1$ Gyr derived with the optical constants of amorphous carbon for carbonaceous grains. The dotted, thick solid and dashed lines show the cases with (η_{WNM}, η_{MC}) = (0.5, 0.5), (0.3, 0.7), (0.1, 0.9), respectively. The hatched region is the range of the extinction curve including the uncertainty derived for the quasar J1048+4637 at $z = 6.2$ (Maiolino et al. 2004). The SMC extinction curve is drawn by the thin solid line.

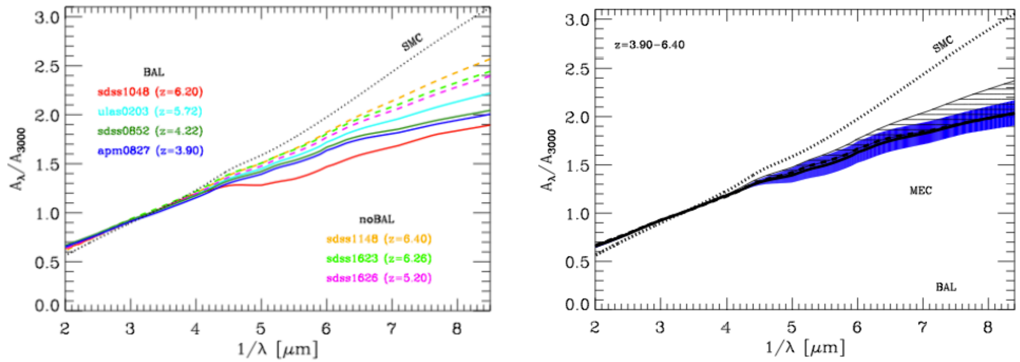
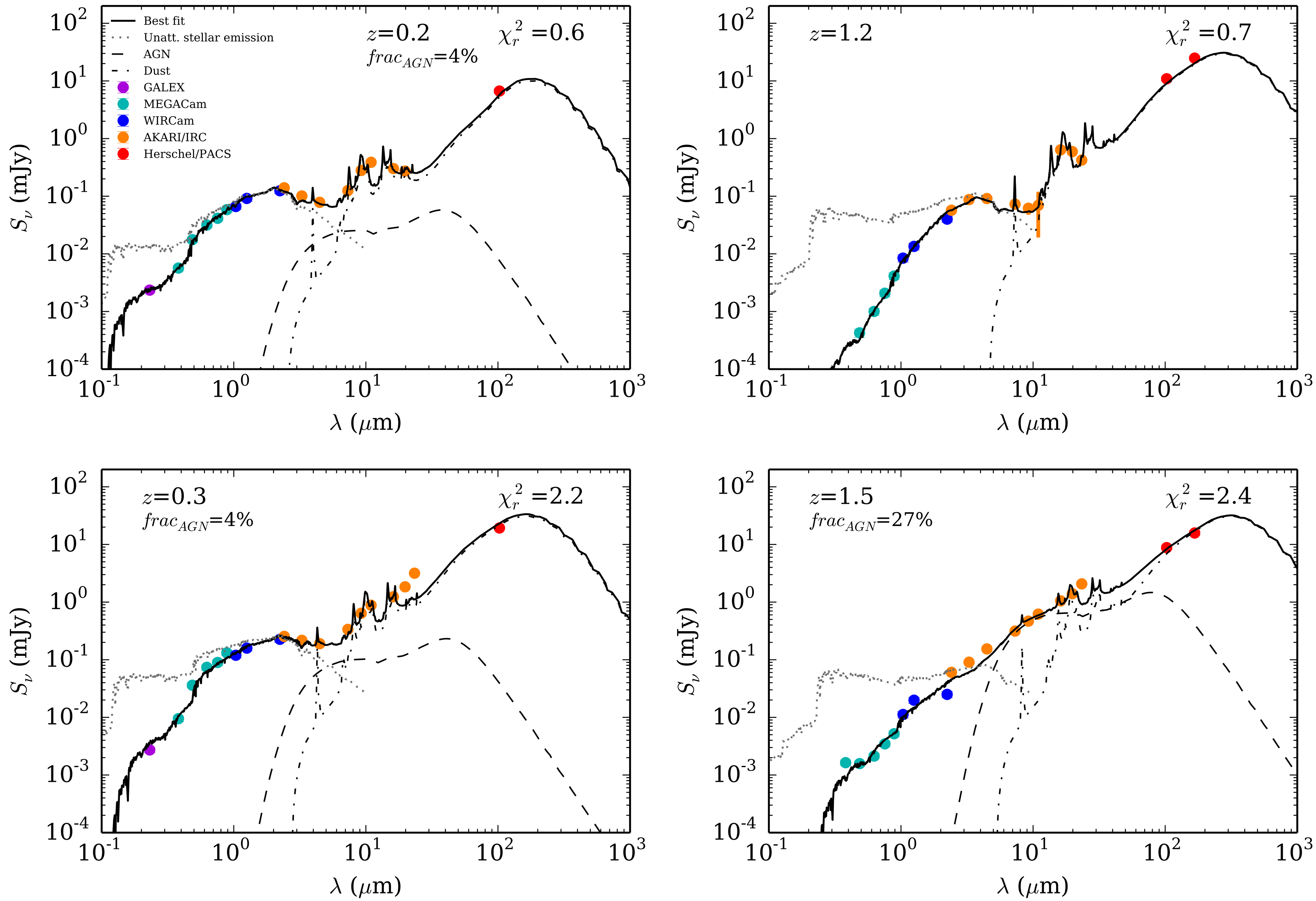


Figure 2: Left panel: Best fit extinction curves of reddened quasars. The solid lines are for BAL quasars, while dashed lines are for non-BAL quasars. For comparison, the SMC extinction curve is also shown and labeled in the figure (dotted black line). Right panel: The solid line shows the mean extinction curve (MEC) computed by averaging the results obtained for BAL reddened quasars, while the shaded region shows the dispersion. The dashed line shows the extinction curve obtained by the simultaneous fit of all the BAL quasars, while the hatched area shows the 68% confidence limit.

Conclusion: an attenuation curve Calzetti like or steeper (SMC like) with bumps present in >20% of galaxies

BUT, not so simple

Fitting the full SED with Cigale



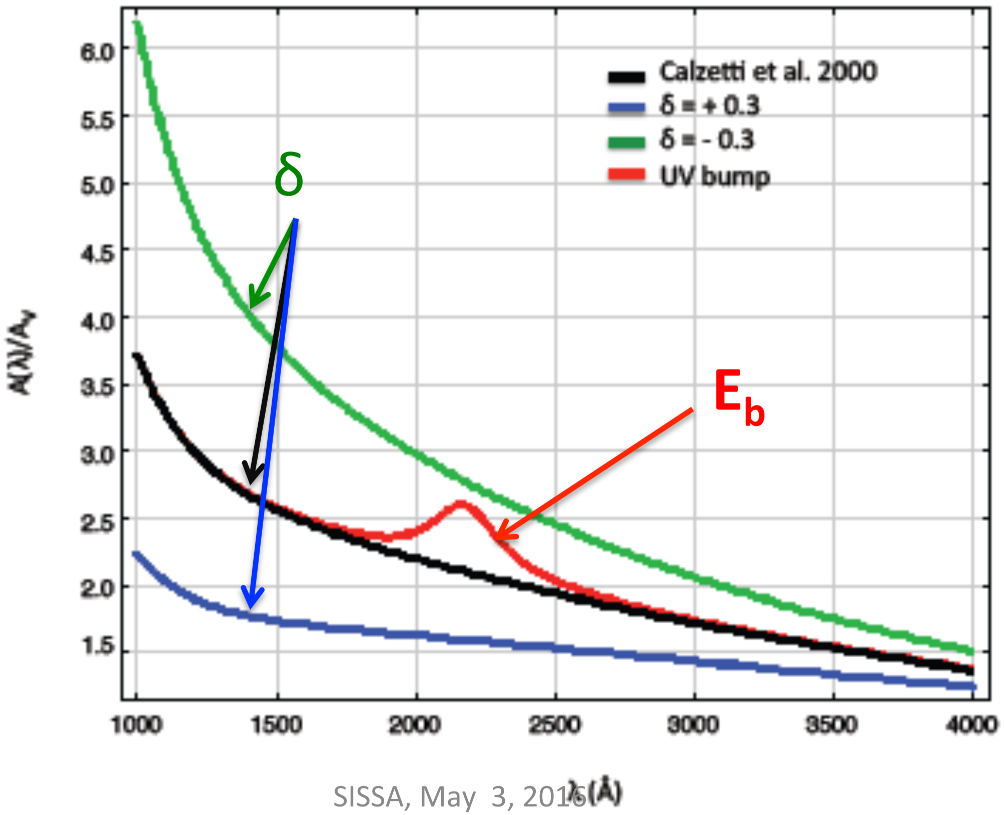
Parametrization of the attenuation curve

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

Calzetti et al. (2000)

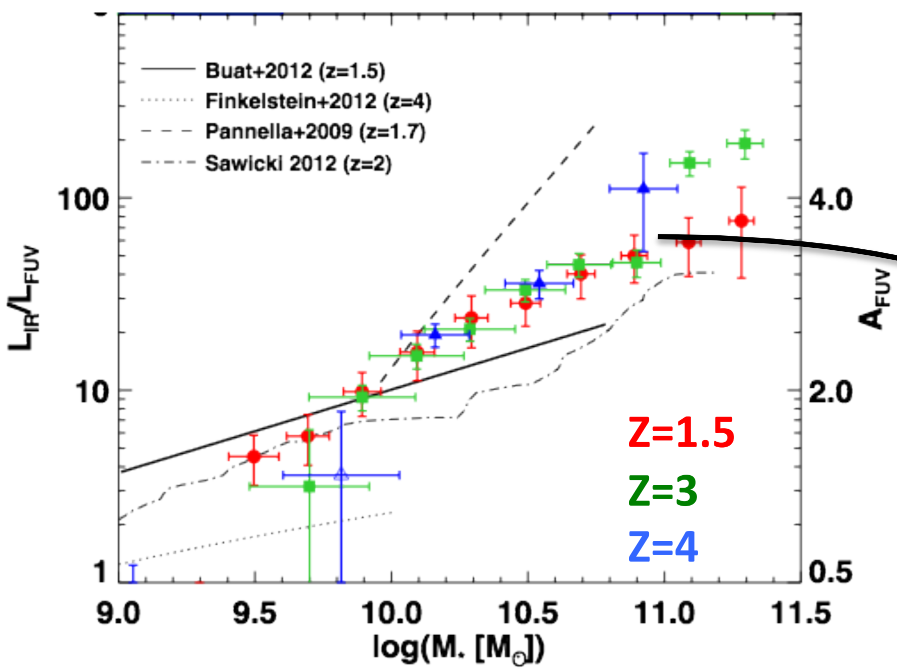
UV bump
Fitzpatrick & Massa formalism

power law



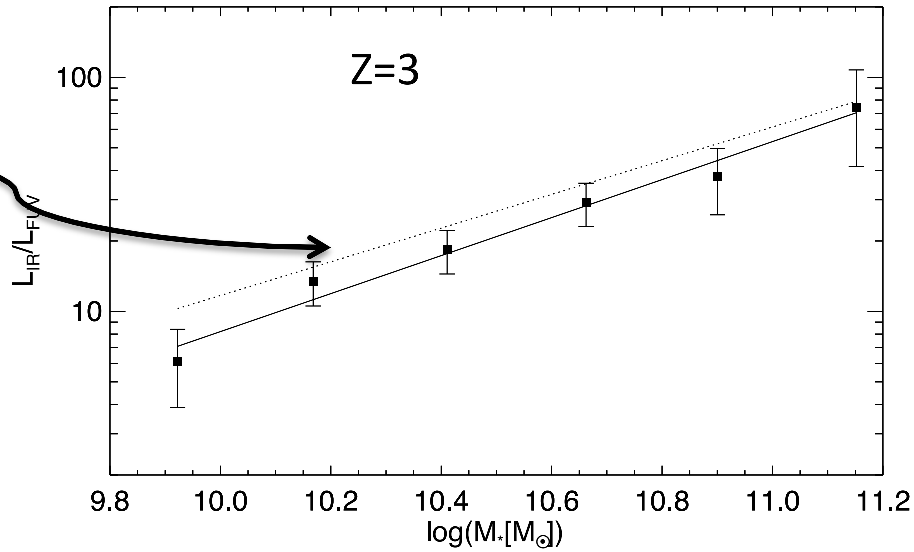
Dust attenuation L_{IR}/L_{FUV} versus M_* for UV selected galaxies

Heinis+14



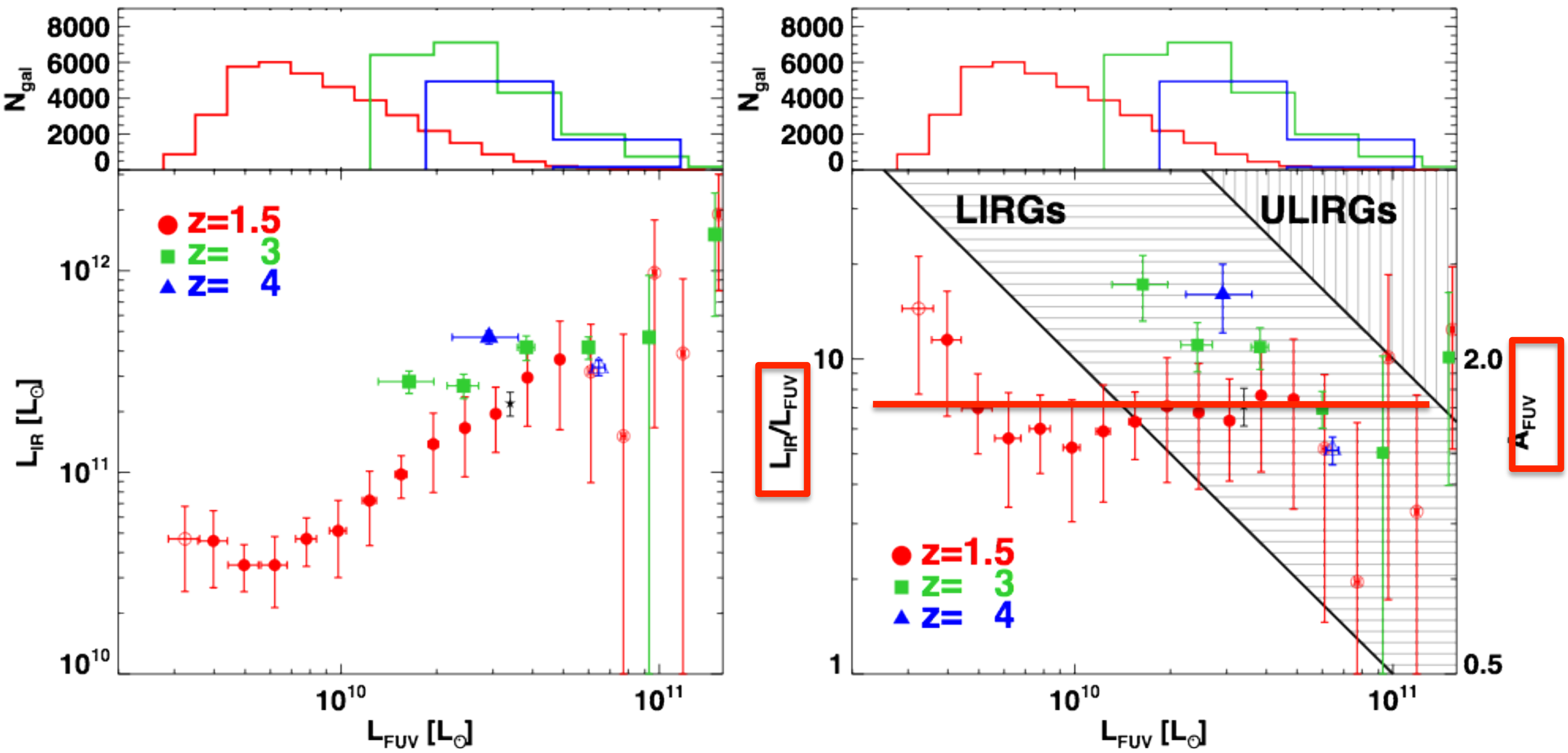
Lyman-Break Galaxies

Alvarez-Marquez et al. 2015



A (L_{IR}/L_{FUV}, M_*) correlation which does not seem to vary with z

Consistent results found by Panella+14 for a mass selection



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

Heinis+13,14

UV selected galaxies → <u>LIRGs and sub-LIRGs</u>

<u>Flat distribution of L_{IR}/L_{UV} versus L_{UV}</u>