Direct constraints on UV attenuation, dust-obscured star formation, and dust mass of z=6.5-7.5 galaxies

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- Introduction, motivation
- New constraints on z>6 star-forming galaxies
- Conclusions

→ Schaerer et al. 2014, A&A in press; arXiv:1407.5793
→ de Barros, Schaerer, Stark, 2014, A&A 563, A81
→ Schaerer & de Barros 2014, in prep

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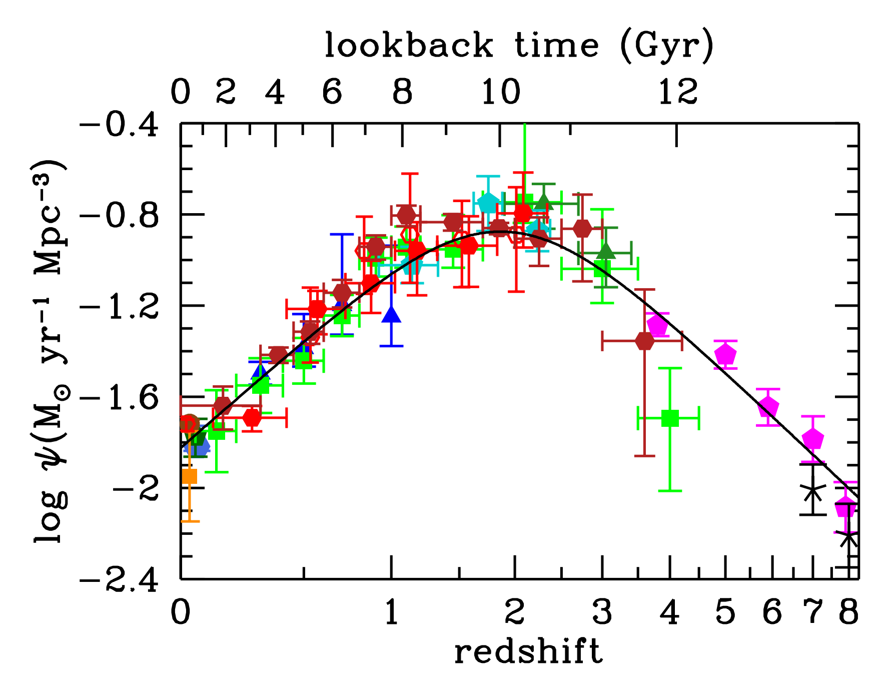
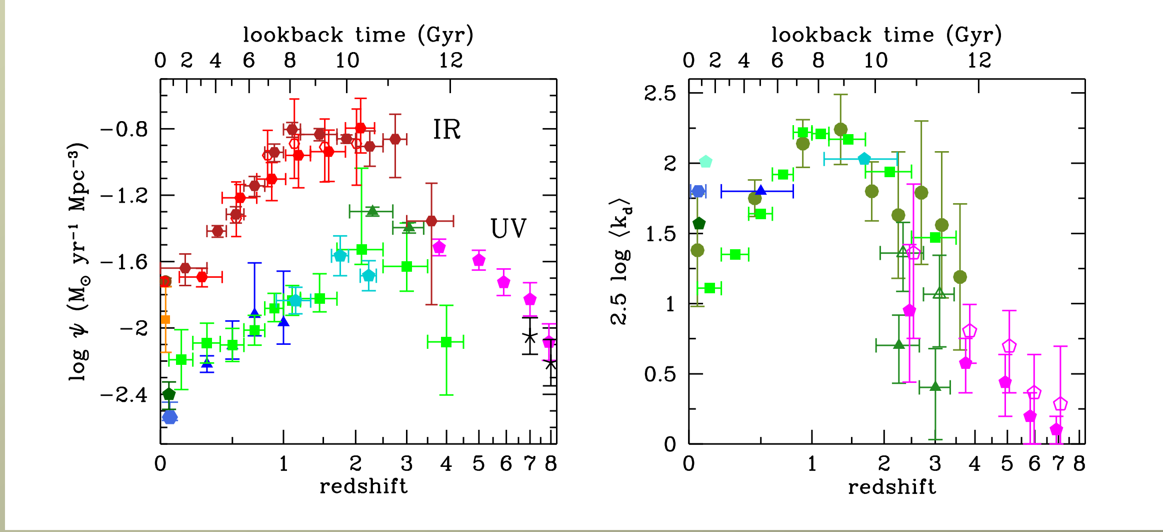
Introduction



Cosmic star formation rate history

→ review of Madau & Dickinson (2014)

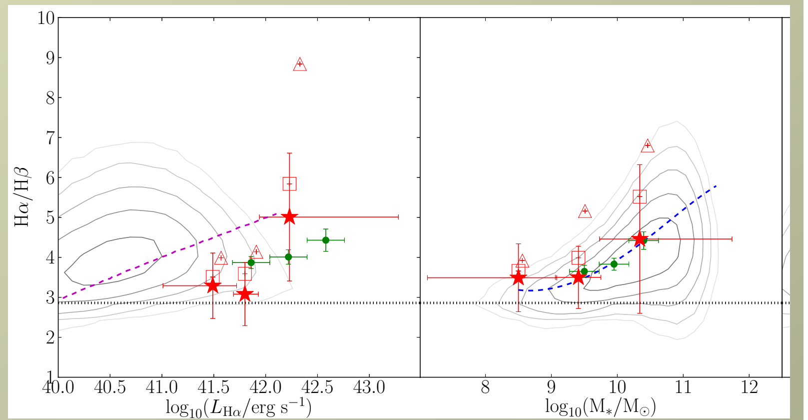


Major unknowns:

- contribution of different galaxy populations
- dust-obscured star formation
- attenuation correction

Introduction

Dominguez et al. (2013)

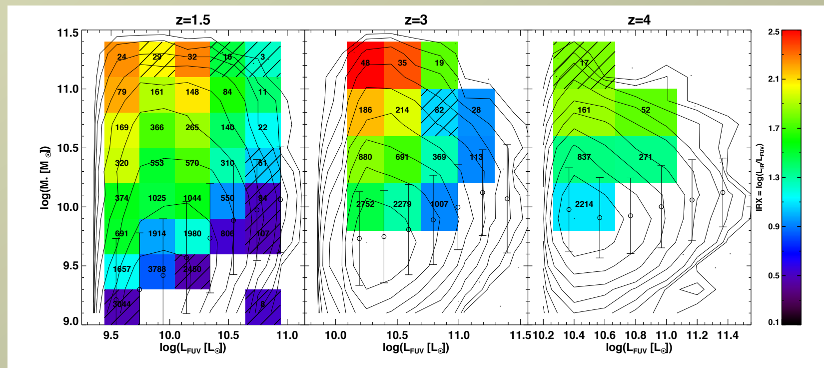


Measurement of dust attenuation

Main methods:

1. Balmer decrement: Hα/Hβ ratios measured out to z~2 (ground-based + HST WFC3 grism)

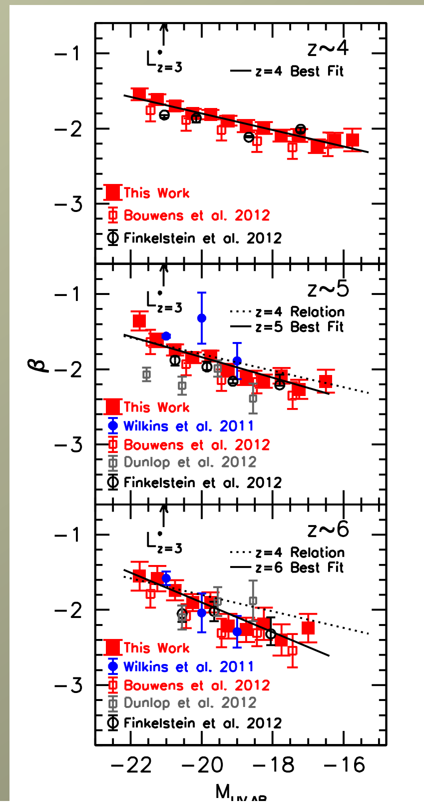
Heinis et al. (2013)



2. IR/UV ratio

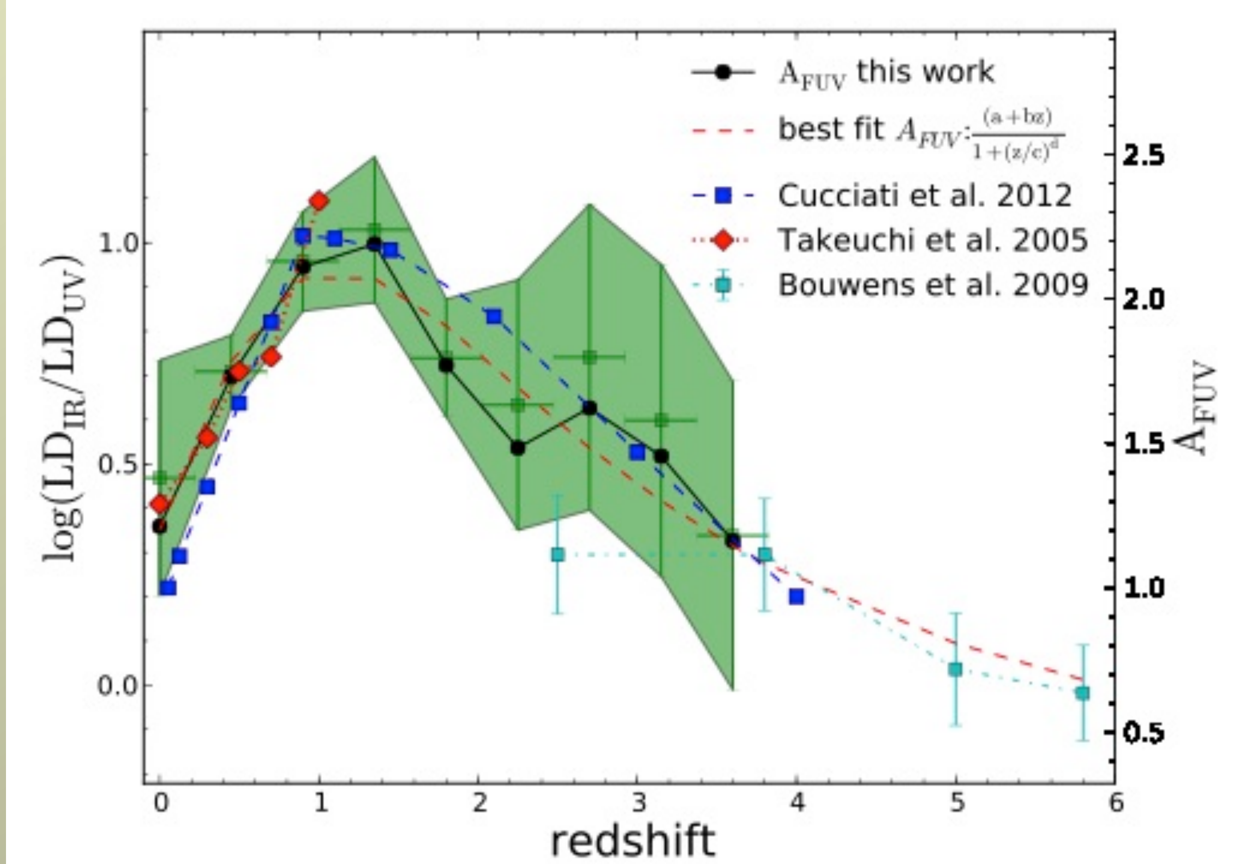
3. UV slope β: only method so far at high redshift (LBGs, LAEs)

Bouwens et al. (2014)



Results from IR / Herschel

Mean attenuation as function of redshift

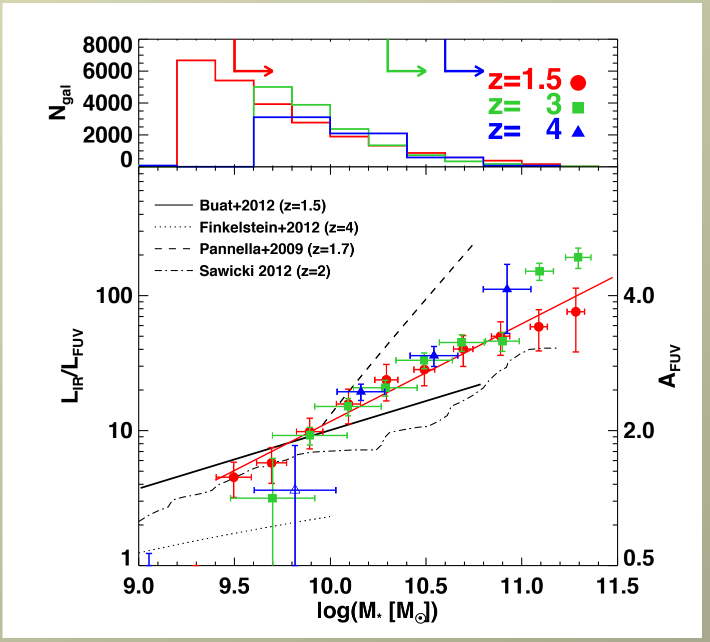


Burgarella et al. (2014)

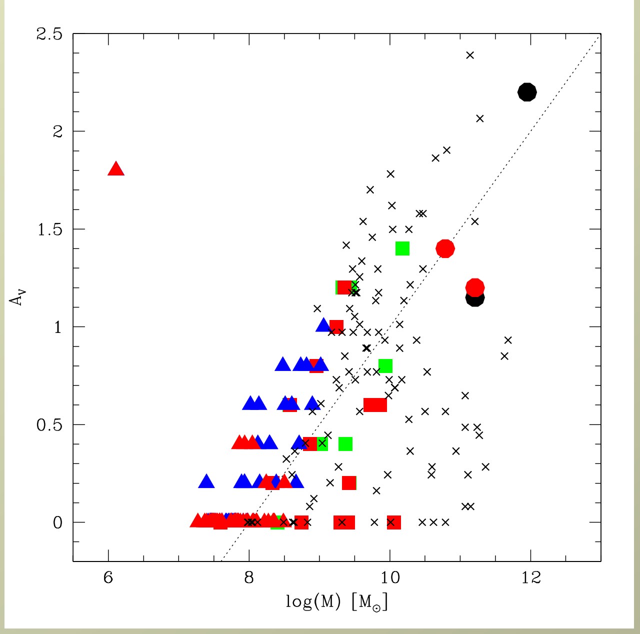
Results from IR / Herschel

Stellar mass -- dust atttenuation correlation

- «universal » for all galaxy types?
- also valid at high z?



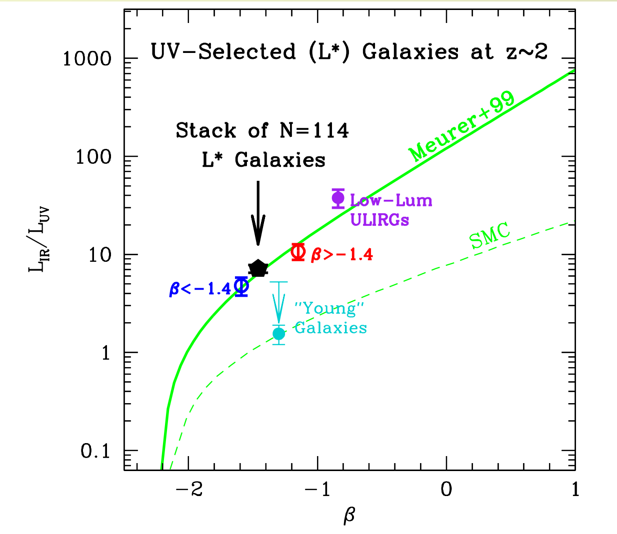
Heinis et al. (2014)
Pannella et al. (2014)
+ many others



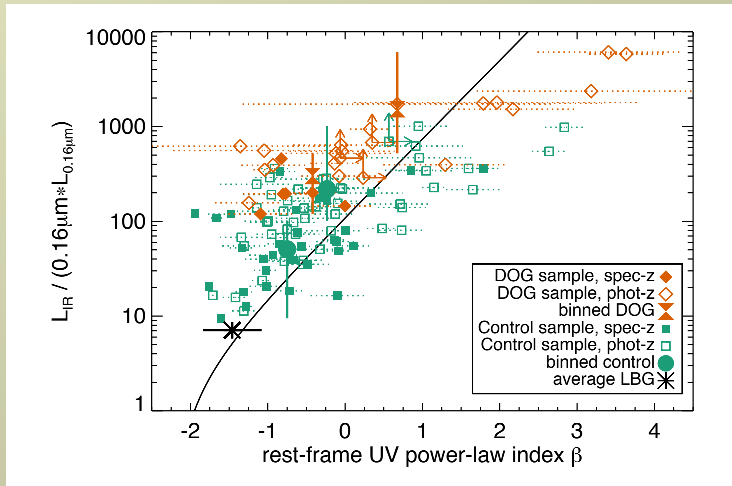
Tentative relation for LBGs @ z~6-8 !?
Schaerer & de Barros (2010)

Results from IR / Herschel

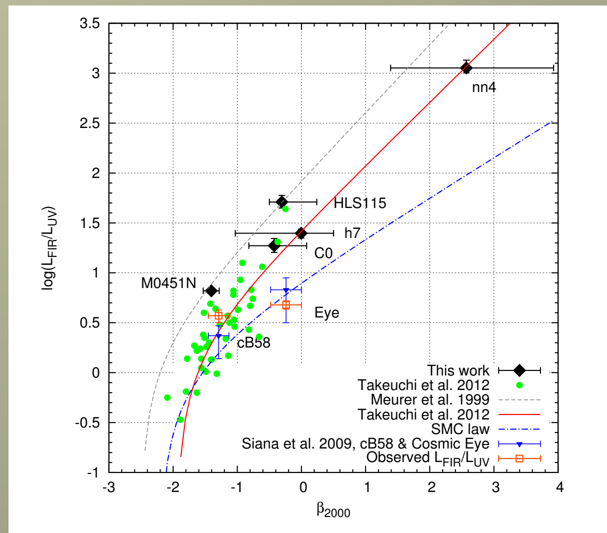
IRX – beta relation



z~2 LBGs: Reddy et al. (2012)



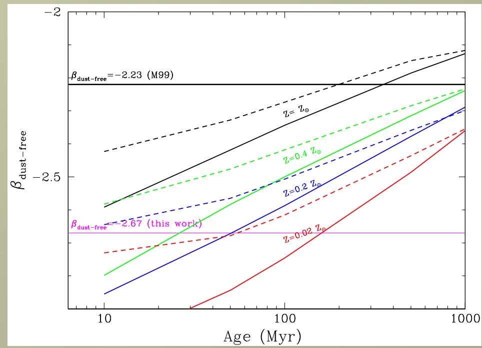
z~2 DOGs: Penner et al. (2012)



Lensed z~2-3 SFGs: Sklias et al. (2014)

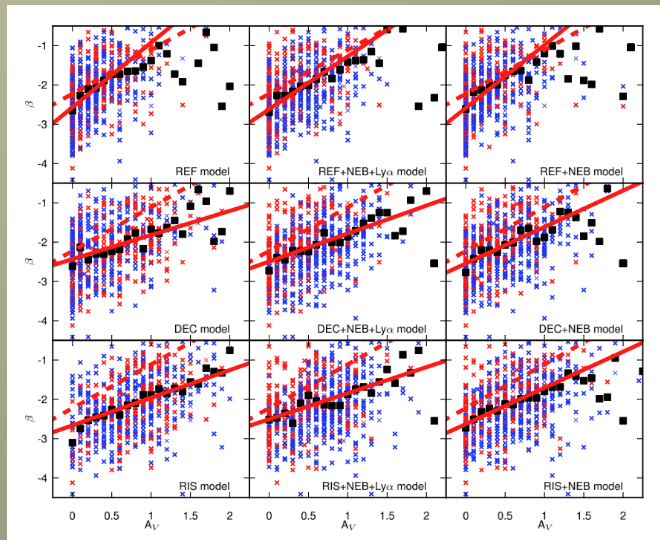
Adequacy of the UV slope method at high-z?

- Empirical correlation of IRX (=IR/UV) versus UV slope β in nearby star-forming galaxies: « Meurer law » (Meurer et al. 1992, Takeuchi et al. 2012)
- Correlation is reproduced by models with:
  - *SFR=const, age>100 Myr & solar metallicity*
    ➔ *Intrinsic slope* β_0=-2.23
  - Calzetti attenuation law



- Assumptions probably invalid for high-z galaxies:
  - Younger populations on average
  - Non-uniform/burtsty SF histories
  - Metallicity < solar

➔ **Revised « Meurer law »**
➔ **Higher UV attenuation for given slope β**



de Barros et al. (2014), Castellano et al. (2014 + Poster)

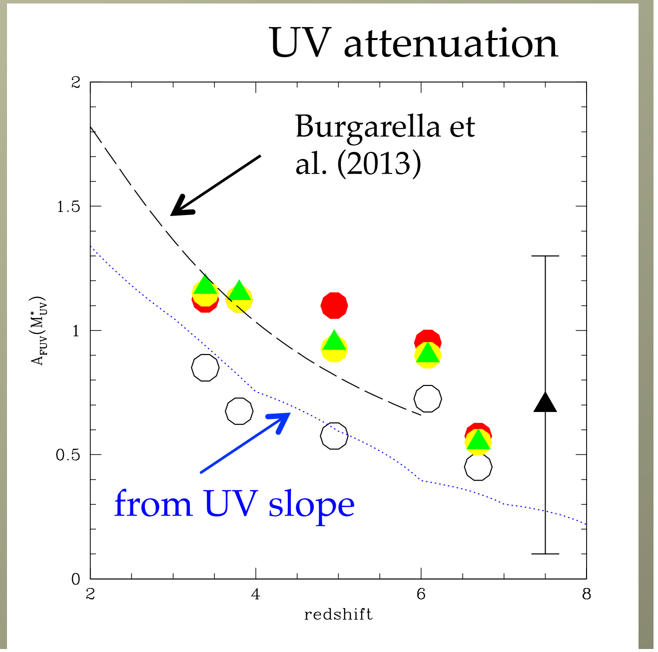
InAdequacy of the UV slope method at high-z:
→ Higher UV attenuation at high-z?

LBGs at z~3-7:

- Large LBG sample from z~3-6: SFR increased by ~2-3 (de Barros et al. 2014)
- z_{spec}~2.8-3.8 sample (14 objects with known metallicity):
  SFR higher by factor 2-4 (Castellano et al. 2014)

- SFR density increased by factor ~1.2 – 4 between z~7 and 3 (Schaerer & de Barros 2014)
- UV attenuation versus z in agreement with extrapolation of IR/UV measurement at z<3 (Burgarella et al. 2014)

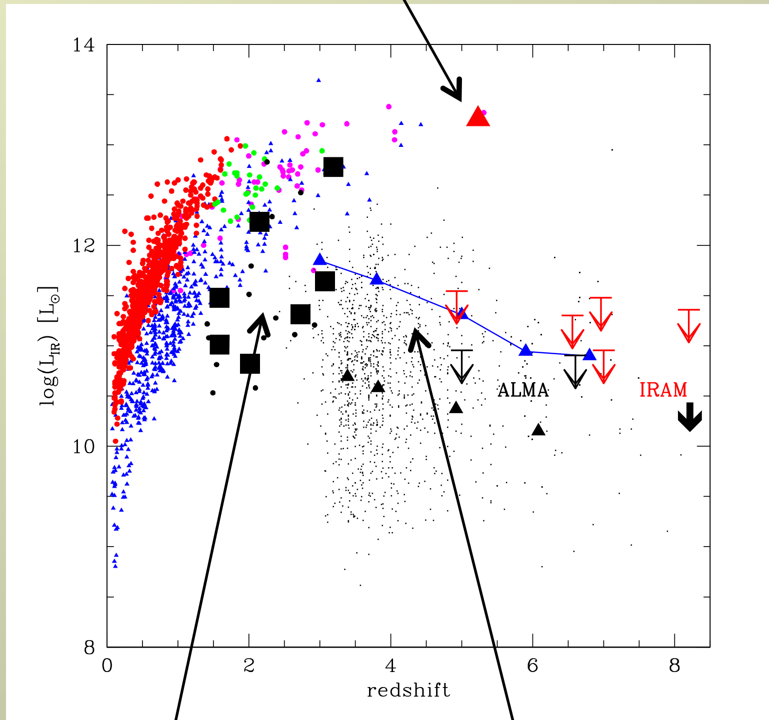
→ Next step: direct measurement of IR emission



Schaerer & de Barros (2014)

First hints on dust in « normal » z>6 galaxies with IRAM and ALMA

z=5.2 Herschel Lensing Survey (Combes et al. 2012)



Strongly lensed objects from Herschel Lensing Survey (Sklias et al. 2014)

Predicted L_{IR} of ~1400 LBGs from z~3.4 – 7 (Schaerer+ 2013)

Lensed galaxies:

- z=4.9 MS1248arc: Livermore+ 2012
- z=6.56 HCM6A: Boone+2007
- z=7 A1703: Schaerer+2014

Blank fields:

- z=6.56 LAE Himiko: Ouchi+2013
- z=6.96 LAE IOK-1: Ota+2014
- z=8.2 GRB090423: Walter+2012 Berger+ 2014
- z=7.5 Finkelstein+2013 object

Our sample

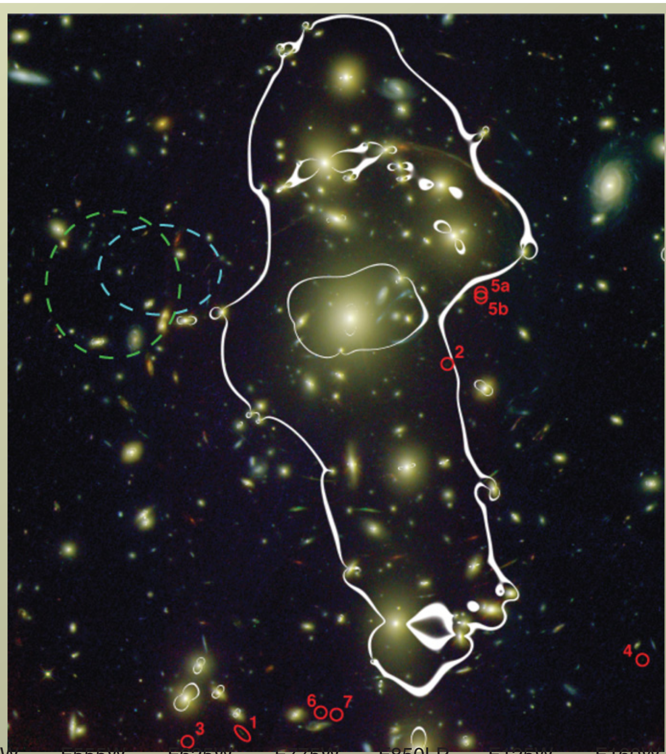
Lensed galaxies:
- z=6.56 HCM6A μ=4.5: Boone+2007
- z=7 LBG in Abell 1703 μ=9, from Bradley+ 2012

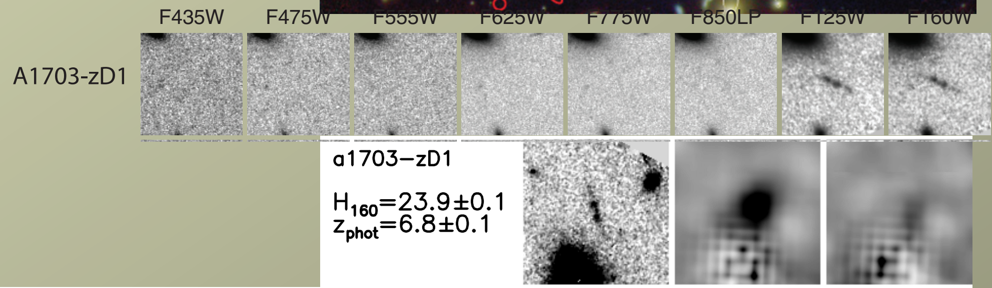
Blank fields:
- z=7.5078 LBG from Finkelstein+2013

→ New IRAM observations

- z=6.56 LAE Himiko: Ouchi+2013
- z=6.96 LAE IOK-1: Ota+2014

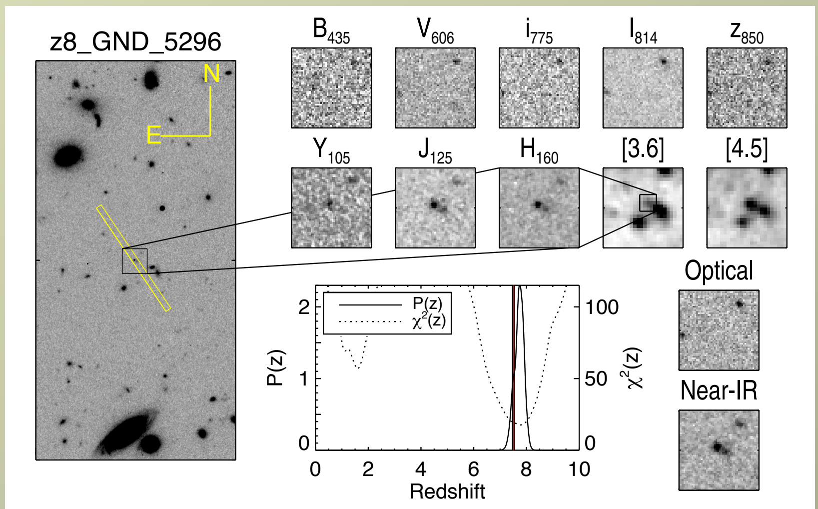
→ Recent ALMA observations

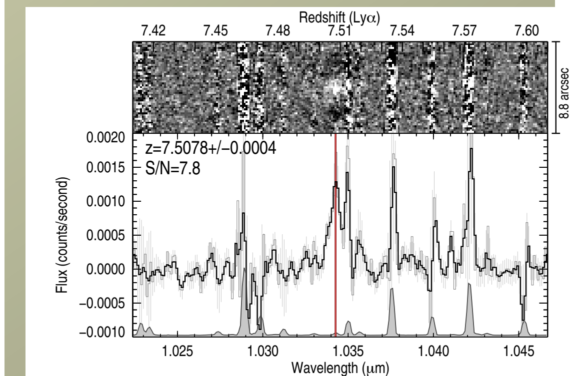




Bradley+ 2012

Finkelstein+ 2013





IRAM and ALMA observation

- MAMBO-2 @30m, 1.2mm: σ=0.36 mJy, 4h on-source (Boone+2007)
- WIDEX@PdBI: σ_{cont}=0.09, 0.12, 0.16 mJy/beam (Walter+2012, Schaerer+2014)
- GISMO@30m, 2mm: σ_{cont}=0.15 mJy (Schaerer+2014)

- ALMA band 6, cycle 0 data: σ_{cont}=0.017 – 0.021 mJy/beam (Ouchi+2013 Ota+2014)

➔ No detection in continuum and [CII] 158micron

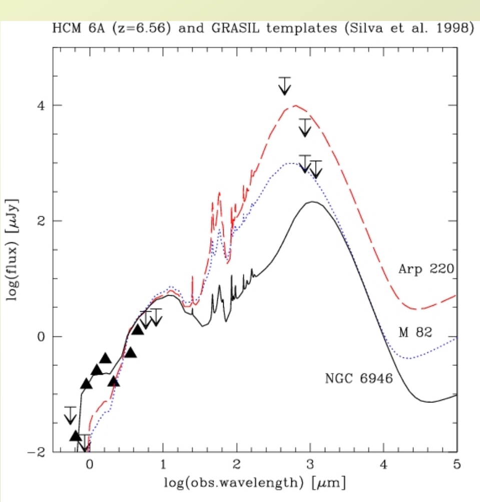
→ Limits on IR luminosity and dust mass: assuming T_d=35 K, β=2,
including correction for CMB heating

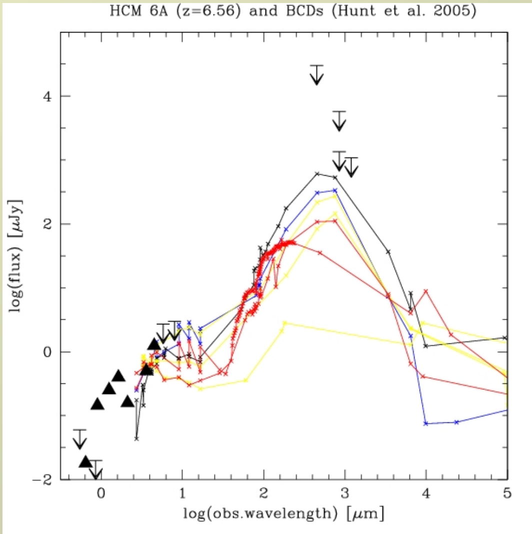
Table 1. Summary of millimeter observations and derived quantities. All luminosity upper limits are 3 σ and are *not* corrected for lensing. For A1703-zD1 and HCM6A the true luminosity limits are therefore lower by the magnification factor μ. The dust temperature T_d indicated here is corrected for the CMB heating, i.e., it corresponds to the temperature dust would have if it were heated by stars alone.

Source	z	ν [GHz]	$\mathrm{rms_{cont}}$ [mJy beam^{-1}]	σ_{line} [mJy beam^{-1}]^e	$L_{[\mathrm{CII}]}$ 10^8 [$L_\odot$]	$L_{\mathrm{IR}}(T_d=25)$ 10^{11} [$L_\odot$]	$L_{\mathrm{IR}}(T_d=35)$ 10^{11} [$L_\odot$]	$L_{\mathrm{IR}}(T_d=45)$ 10^{11} [$L_\odot$]	μ
A1703-zD1	6.8[a]	241.500	0.165	1.517	$< 2.55/\mu$	$< 3.96/\mu$	$< 7.32/\mu$	$< 14.38/\mu$	9.
z8-GND-5296	7.508	223.382	0.124	1.824	< 3.56	< 3.84	< 6.65	< 12.67	
IOK-1[b]	6.96	238.76	0.021	0.215	< 0.38	< 0.53	< 0.96	< 1.87	
HCM6A[c]	6.56	251.40	0.16	0.849	$< 1.36/\mu$	$< 3.47/\mu$	$< 6.49/\mu$	$< 12.81/\mu$	4.5
Himiko[d]	6.595	250.00	0.017	0.167	< 0.28	< 0.36	< 0.67	< 1.30	

[a] Approximate photometric redshift (cf. text). [b] Observations from Ota et al. (2014). [c] Observations from Kanekar et al. (2013).
[d] Observations from Ouchi et al. (2013). [e] In $\Delta v = 50$ km s^{-1} channels.

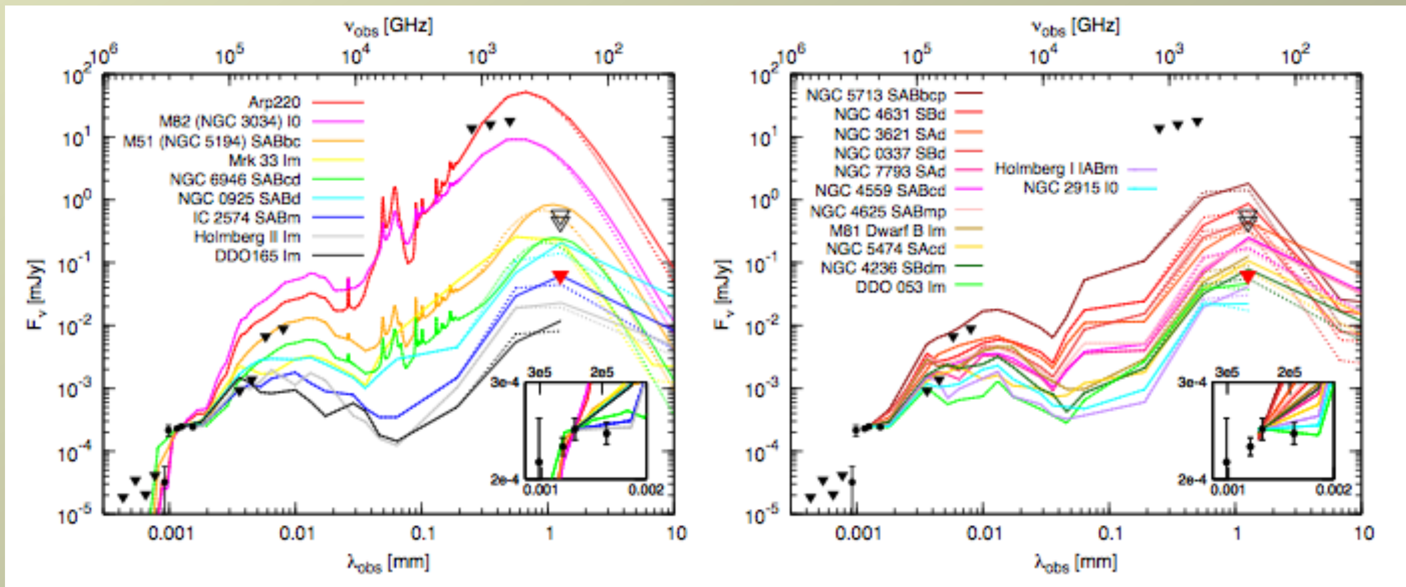
IR-mm SED of « normal » z>6 galaxies from IRAM and ALMA





Boone et al. (2007):

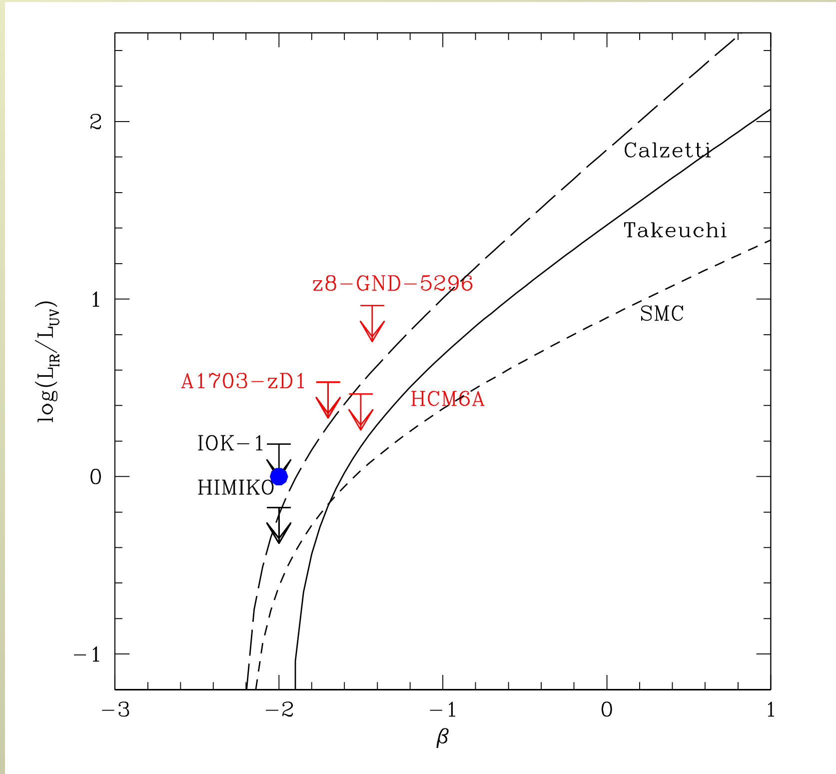
- SEDs of Arp220, M82-like objects excluded
- SED compatible with nearby spirals or dwarf galaxies



Ota et al. (2014):

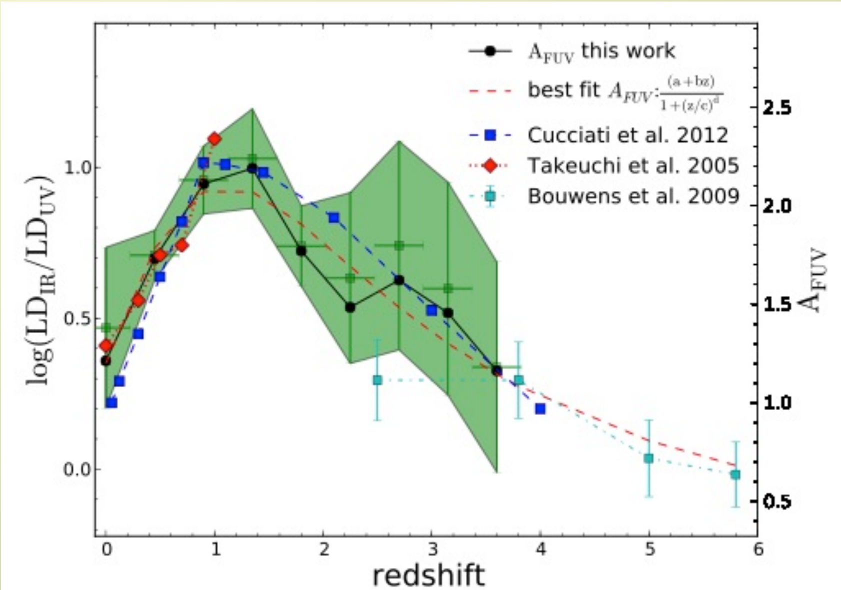
SED compatible with nearby irregulars or dwarf galaxies

IRX-beta relation of « normal » z>6 galaxies from IRAM and ALMA



IRX-beta relation compatible with nearby starbursts

Mean attenuation as function of redshift

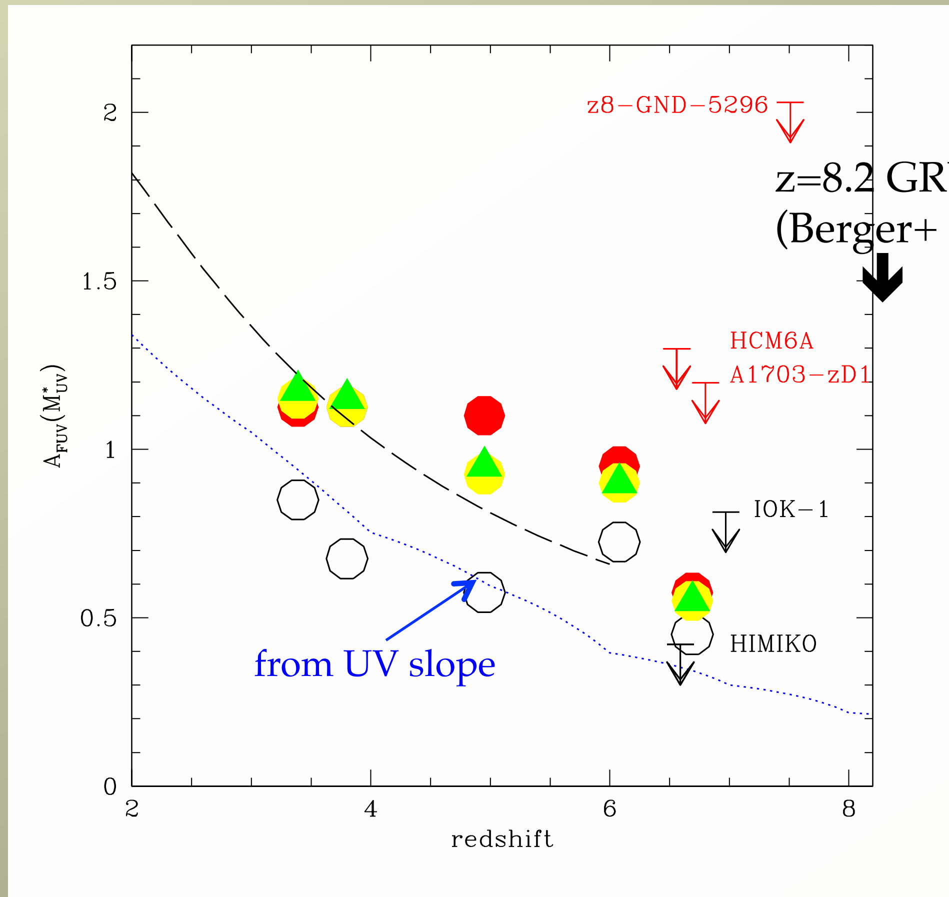


Burgarella et al. (2014)

UV attenuation compatible with:

- (higher) attenuation from SED fits
- extrapolation of IR/UV results from z<3.5

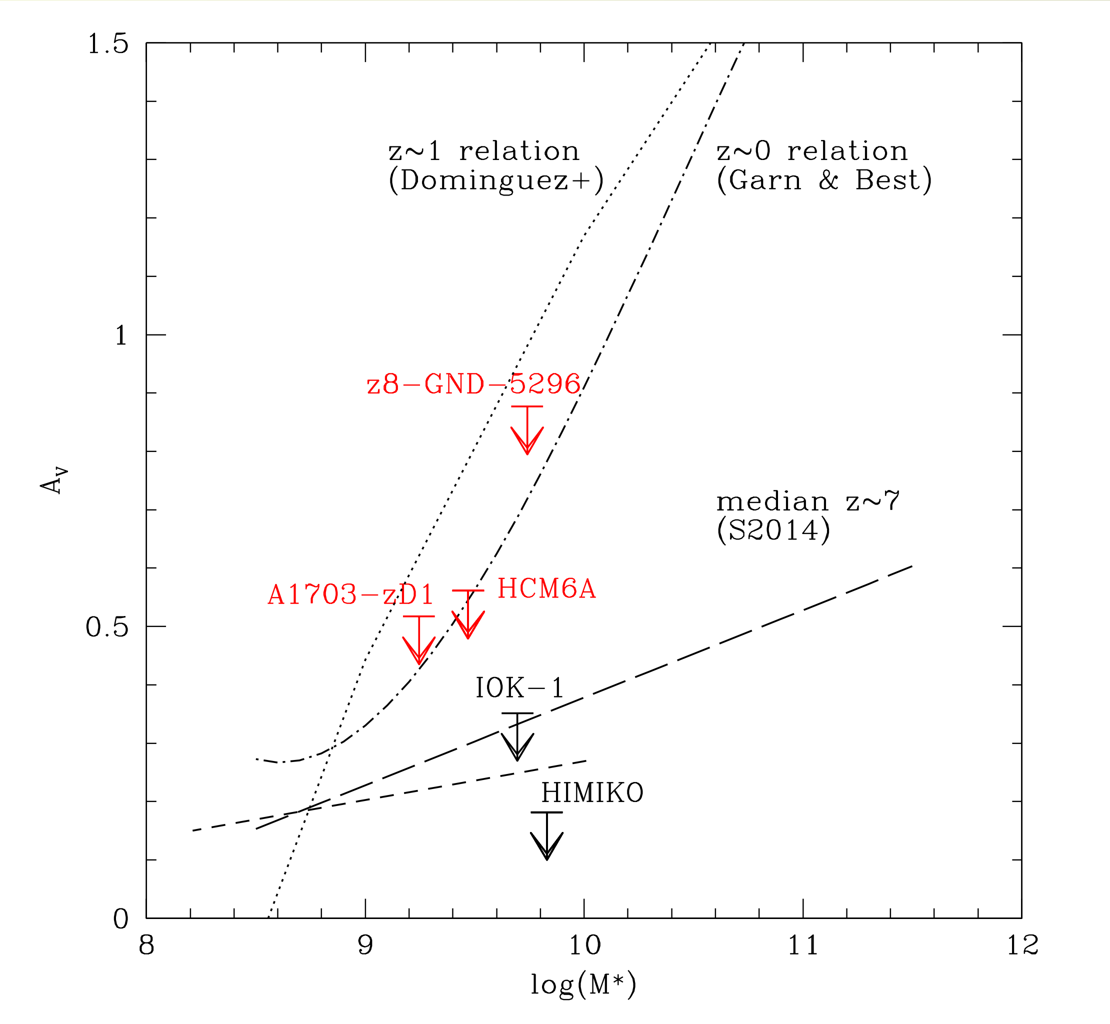
Dust-obscured SF:
SFR(IR)/SFR(UV)



5
3
2
0.8
0.3

Schaerer et al. (2014)

Mass – dust attenuation relation



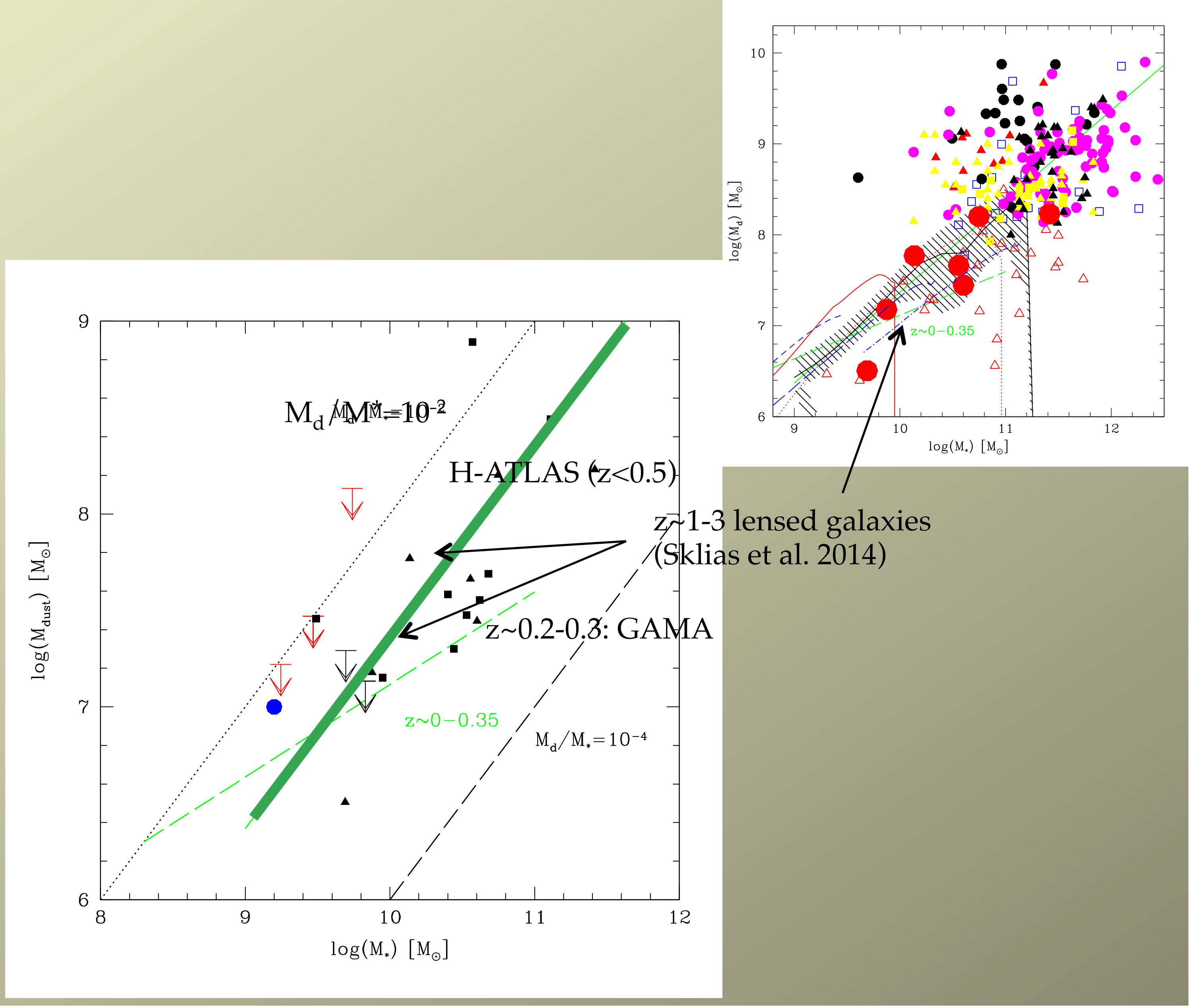
- ≥ 2 objects: less attenuation than expected from relation at lower redshift
- Compatible with *flatter mean relation for z~7 LBGs*
  (Schaerer & de Barros 2014)

Dust masses of « normal » z>6 galaxies with IRAM and ALMA

Dust masses at z>6 :

- Current upper limits are compatible with normal dust/ stellar mass ratios
- No indication for redshift evolution of M_d/M^* from z~0 to 3 and at z~7
- Dust production per SN ~0.15-0.45 $M_\odot$ (Hirashita+ 2014)

Schaerer al. (2014)



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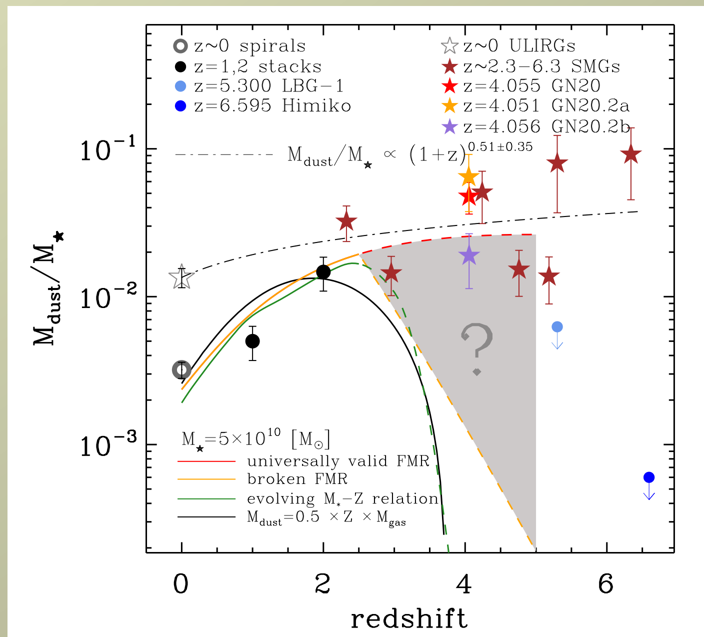
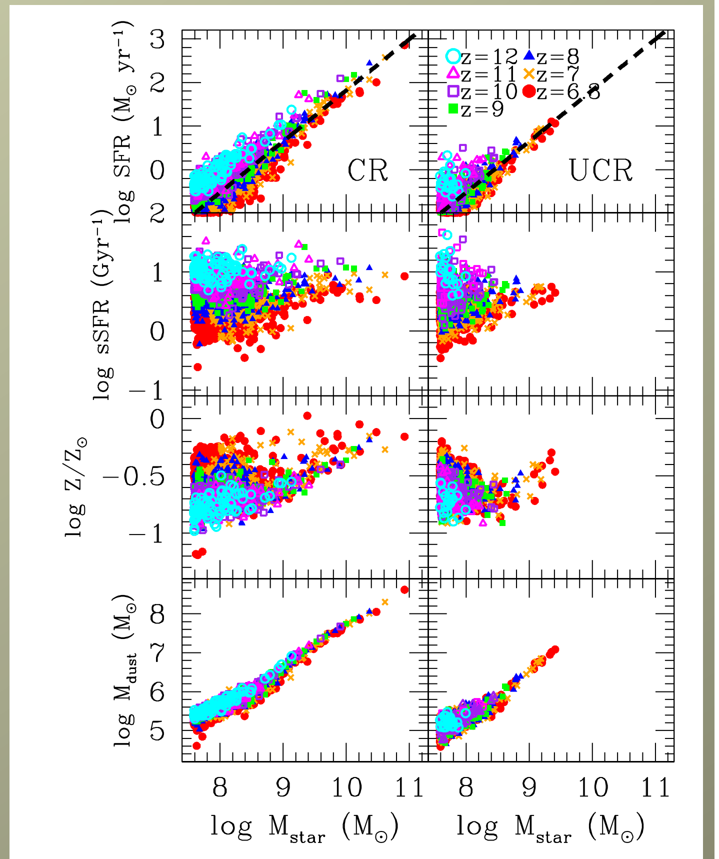
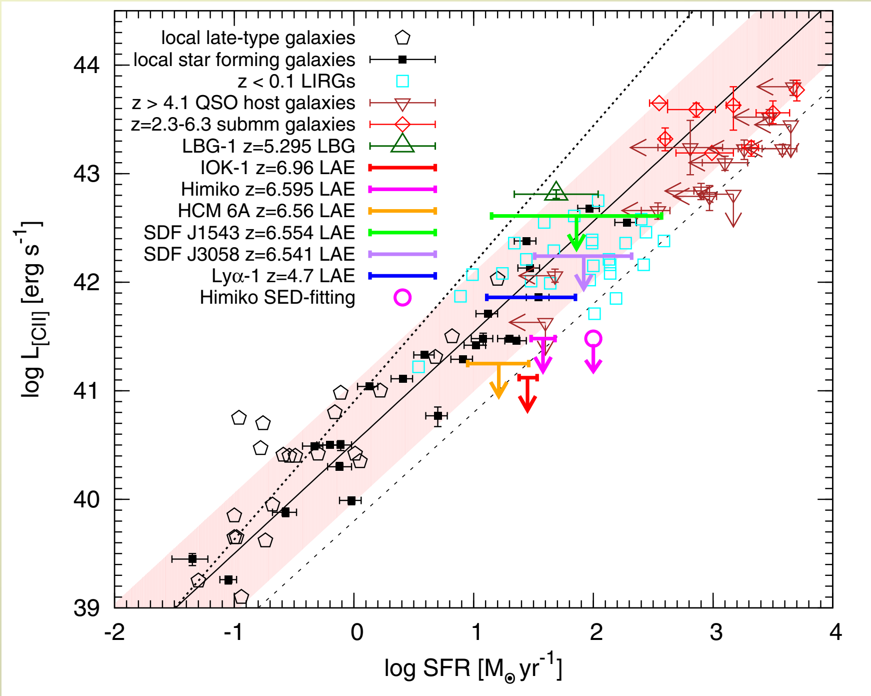


Tan al. (2014)

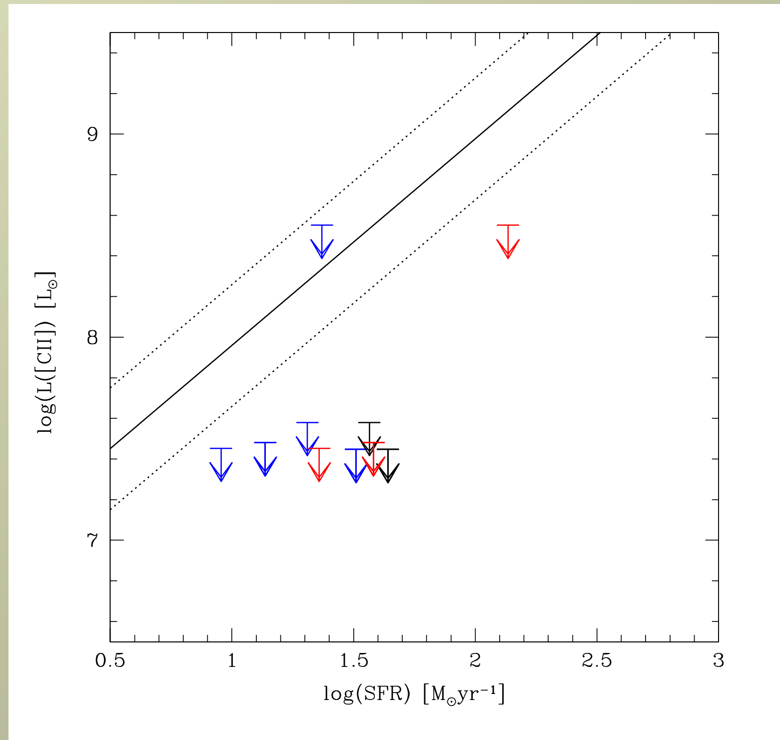


Yajima al. (2014)

[CII] emission from « normal » z>6 galaxies with IRAM and ALMA



Ota et al. (2014)

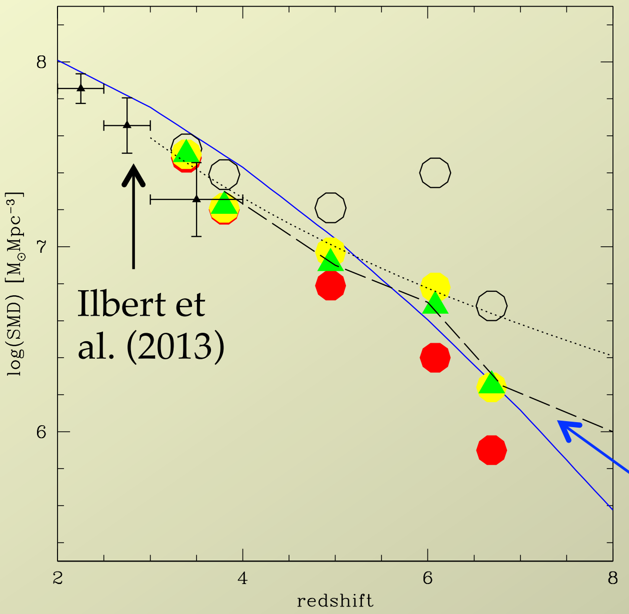


Schaerer et al. (2014)

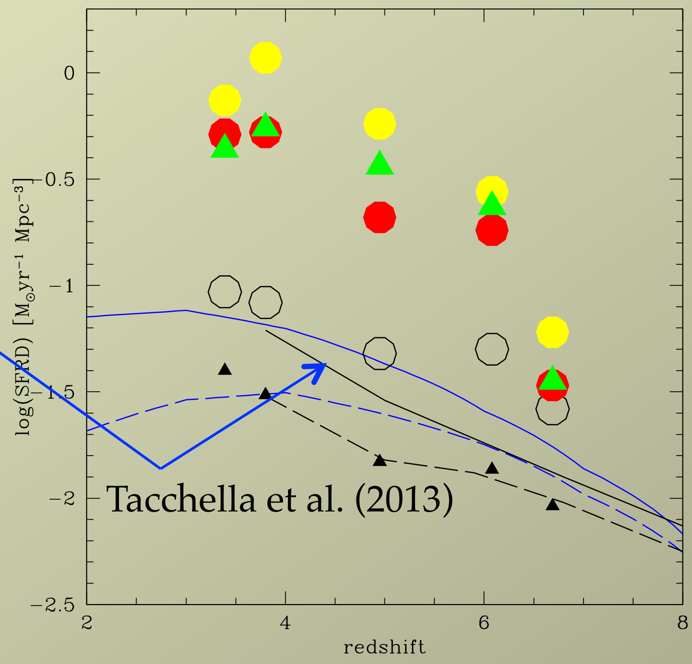
- [CII] not detected (so far) in z>6 galaxies
- L([CII]) below local correlation with SFR (de Looze et al. 2012, 2014)
- Explanation for weak [CII] emission debated
  (Stacey+2010, Vallini+2013, Garcia-Lopez+ 2013, …)

Implications

Stellar mass density



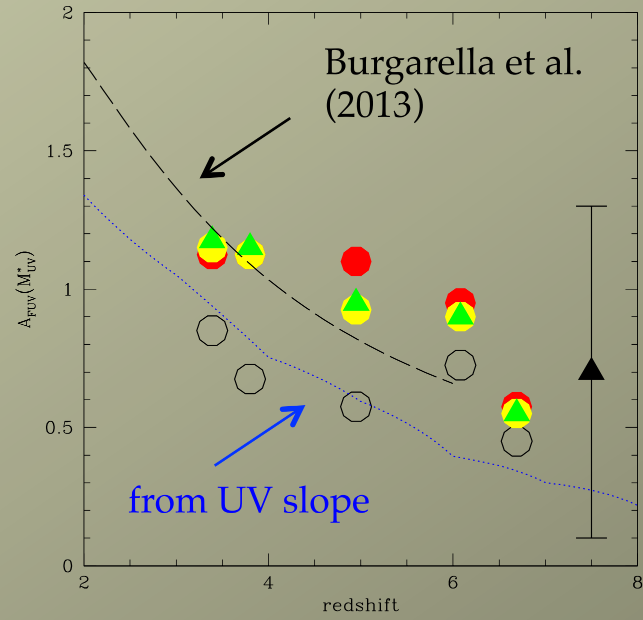
Star formation rate density



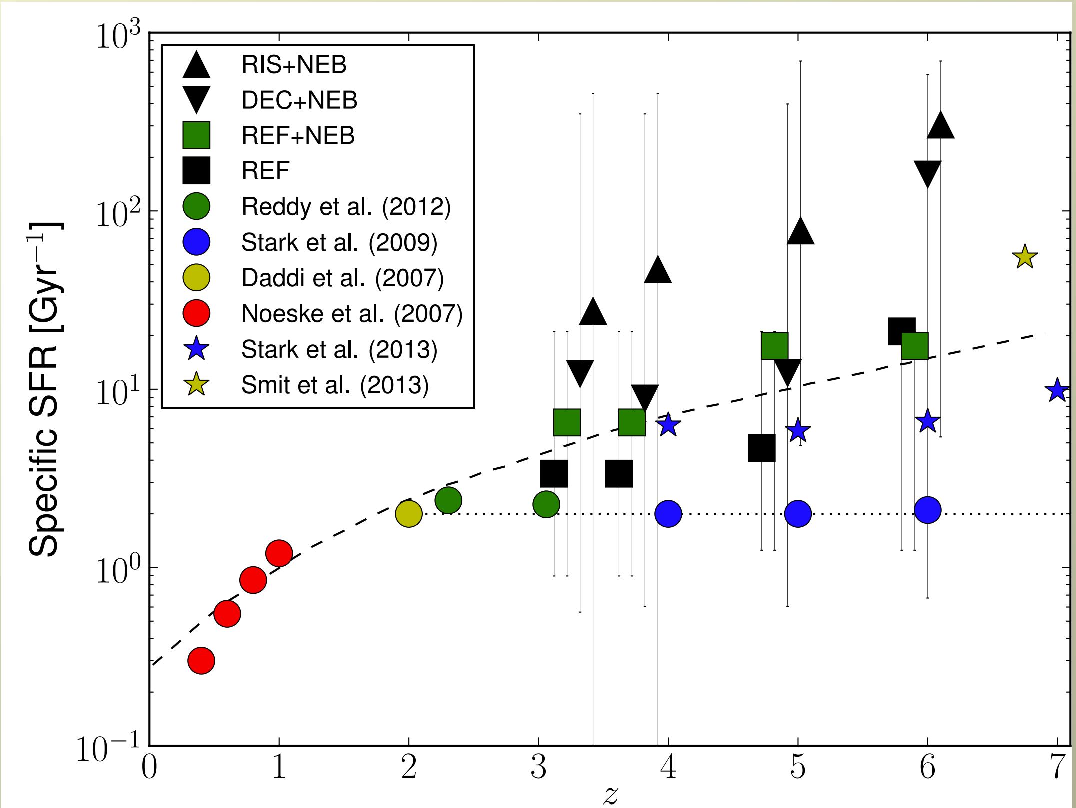
Current inferences from LBGs are not incompatible with latest mm observations

Schaerer & de Barros (2014)

UV attenuation



Implications



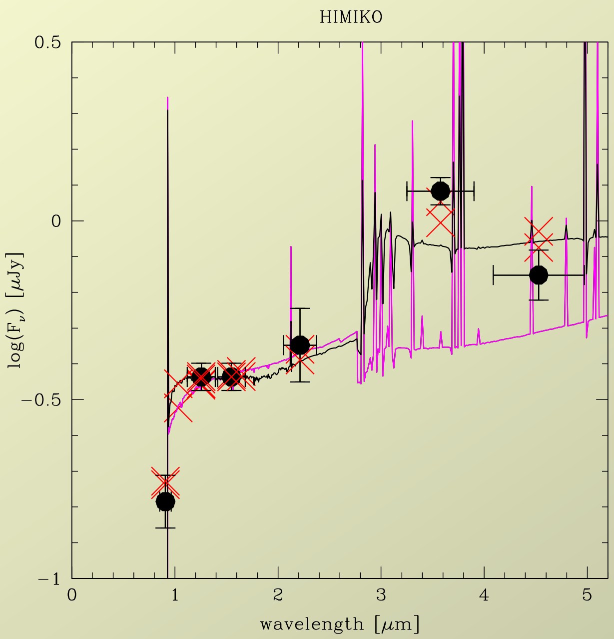
Analysis of large LBG sample with SED models allowing for:

- nebular emission
- variable SF histories

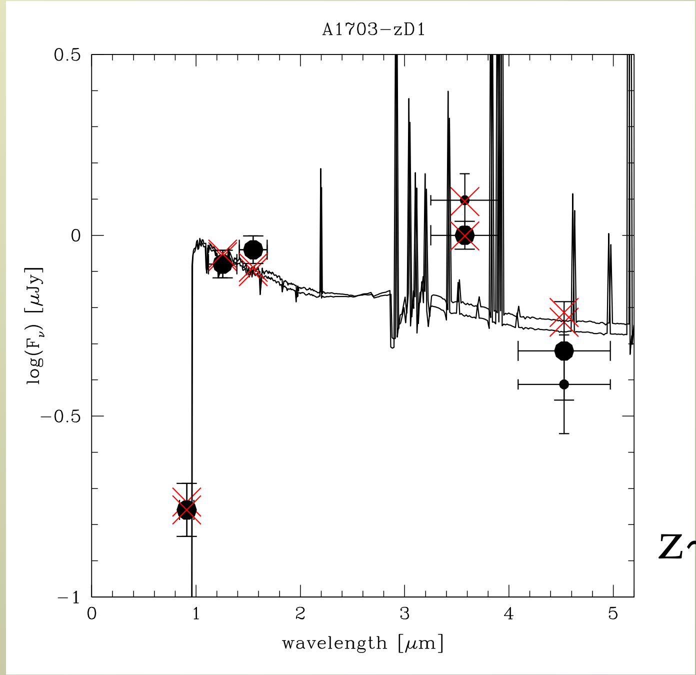
➔ sSFR rising with redshift
➔ Large scatter expected

de Barros et al. (2014)

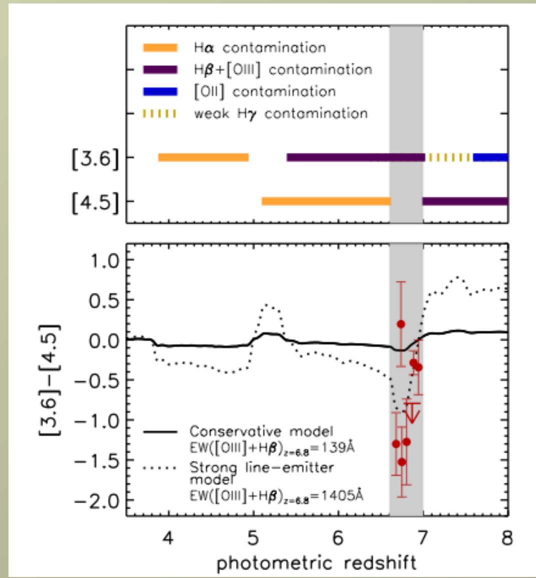
Implications



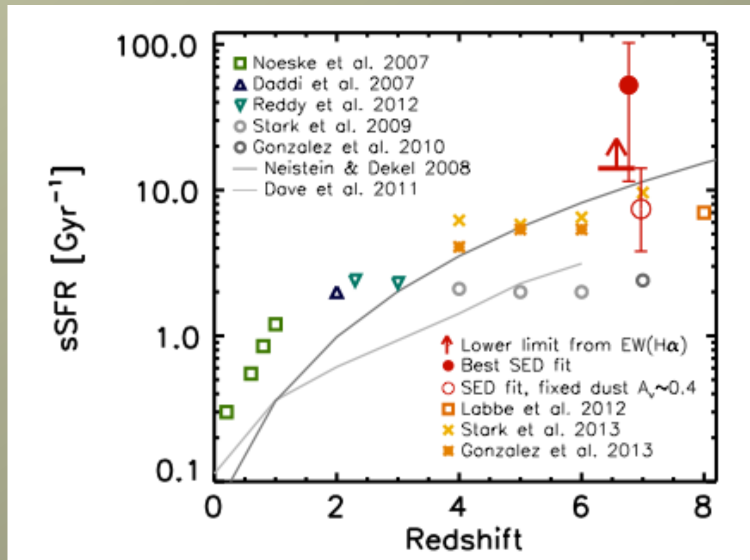
z=6.595



z~7



Smit et al. (2014)



- Rising SF histories excluded for Himiko
- Poor constraint on sSFR

- Abell 1703-zD1: **high sSFR ~20-90 Gyr^{-1}**

→ More statistics needed!

SF galaxies @ z~6.5-7.5: conclusions

- New deep IRAM PdBI 1.2mm observations of two z=7 and 7.5 LBGs + 3 Lyman-alpha emitters at z=6.5-7 previously observed (IRAM + ALMA)
- [CII] + dust continuum undetected

  → limits on dust mass, IR luminosity, UV attenuation, dust-obscured SF

- SED compatible with nearby spirals, irregulars or dwarfs; not M82-like
- IRX-beta relation: objects compatible with local relation
- Limits on UV attenuation compatible with UV slope and SED fits
- UV attenuation versus redshift:
  - OK with extrapolation from z<3.5 (Burgarella et al. 2013)
  - **Can be higher by factor 2 estimated from UV slope**
- *Attenuation – stellar mass*: probably flatter at z~7
- *Dust/stellar mass ratio*: universal. No evidence (yet) for difference with z~0-3
- High sSFR~20-90 Gyr^{-1} confirmed for 1 object

→ More deep IR-mm observations needed: ALMA, …