Consistent physical properties of the LBG population at z~3-7 and new constraints from IR/mm

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Main collaborators: S. de Barros (Bologna), F. Boone (Toulouse)

- *Physical properties of high-z star-forming galaxies*
- *Properties of the LBG population*
- *New constraints on dust in z>6.5 star-forming galaxies*

→ de Barros, Schaerer, Stark, 2014, A&A 563, A81

→ Schaerer et al. 2015, A&A, 574, A19 (arXiv:1407.5793)

→ Schaerer & de Barros 2015, A&A, to be submitted

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irap astrophysique & planétologie

Motivation / questions

- Properties of high-z galaxies ? SFR, mass, age, extinction, metallicity etc.
- « Old » galaxies in the high-z universe ? Formation redshift?
- Are high-z galaxies dusty? Dust evolution with redshift?

- Typical timescales of star formation and SF histories?
- What drives SF in distant galaxies ? Cold accretion, mergers…? Importance of feedback?

- Cosmic star formation history and mass assembly

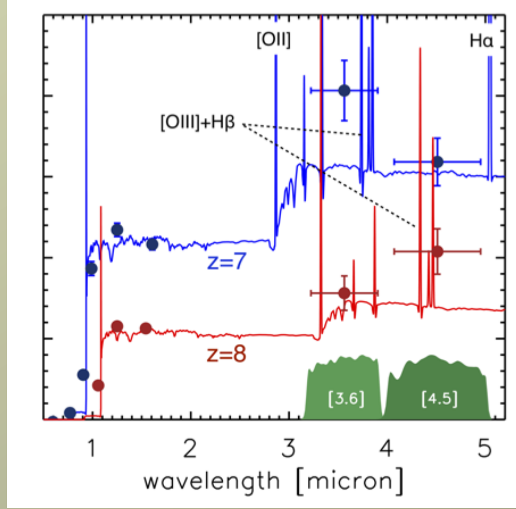
Physical properties of high redshift star-forming galaxies

• Physical parameters from SED models *including nebular emission*: implications on ages, masses, …, specific SFR, star-formation histories

(Strong) emission lines are ubiquitous (at z~3-7)
& affect the determination of the physical parameters
➔ now widely accepted

Schaerer & de Barros, 2009, A&A, 502, 423
Schaerer & de Barros, 2010, A&A, 515, 73
Schaerer, de Barros, Stark, 2011, A&A, 536, A72
de Barros, Schaerer, Stark, 2011, arXiv:1111.6057
de Barros, Schaerer, Stark, 2012, arXiv:1207.3663
de Barros, Schaerer, Stark, 2014, A&A, 563, A81
Schaerer, de Barros, Sklias, 2013, A&A, 549, A4
Sklias et al., 2014, A&A, 561, A149
Schaerer & de Barros, 2015, A&A, to be submitted

Evidence for (strong) emission lines at high-z

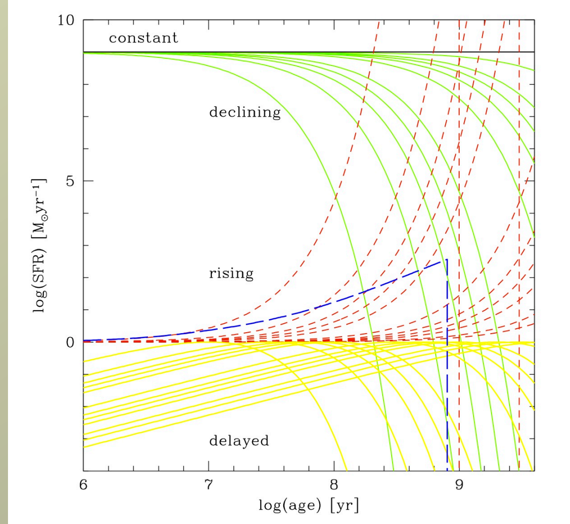


- **LBGs at z~7-8**: excess at 3.6 micron due to [OIII]+Hβ
  (Labbé et al. 2012, Smit et al. 2013)
- **LBGs at z~4**: excess at 3.6 micron due to Hα
  (Shim et al. 2011, de Barros et al. 2011, Stark et al. 2012)
- Broad-band excess in **z~2 LBGs** with strong Hα
  (Erb et al. 2006, Reddy et al.)
- **Lyman-alpha emitters (LAE) at z=3.1**: [OIII] lines dominate Ks band flux
  (McLinden et al. 2011,)

- Strong Halpha emission in **massive galaxies at z~1-1.5** (van Dokkum et al. 2011)
- **WFC3 grism surveys**: many strong emission line galaxies at z~1-2, whose photometry is/would be dominated by lines (e.g. Atek et al. 2011, Trump et al. 2011)

- Increasing fraction of LBGs with Lyman-α emission at high-z
  (Ouchi et al. 2008, Stark et al. 2010, Schaerer et al. 2011, …)
- Strong [OIII] lines detected in z~3.2-3.6 LBGs (Schenker et al. 2013, Holden+2014, Steidel+2014)
- …

Consistent modeling z~3-7 star-forming galaxies



- Extensive exploration of parameter space
  - Redshift
  - Attenuation
  - SF histories (SFR=const, exp. declining, delayed, exp. rising SFH)
  - Age
  - Metallicity
- Uncertainties determined from MC simulations
- Systematic study taking effects of nebular emission into account
- Uniform and consistent analysis of z~3 to 7-8 galaxies with same code (modified Hyperz code)
- Large sample (~1800) of UV selected drop-out galaxies with multi-band photometric data (GOODS-MUSIC V2 Santini et al. 2009, McLure et al. 2011)

➔ de Barros, Schaerer, Stark (2011, 2012, 2014)

➔ Schaerer & de Barros (2015)

Implications from (strong) emission lines at high-z

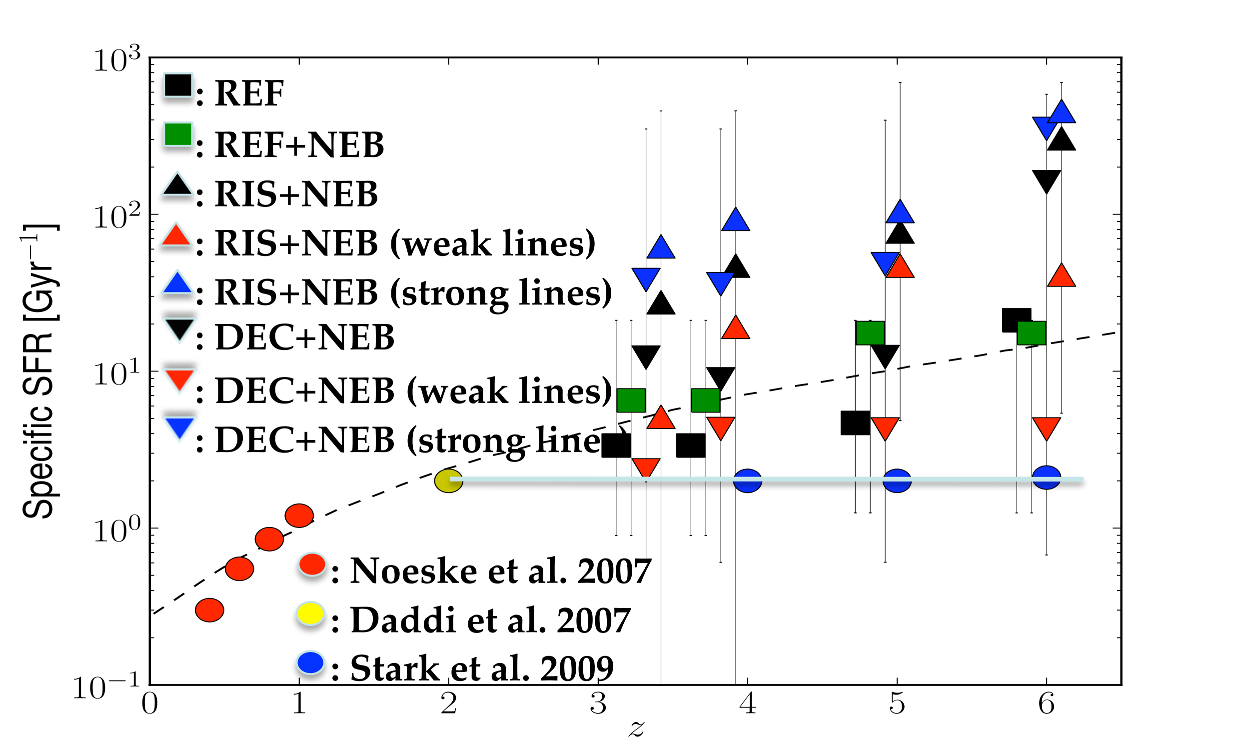
1. Younger galaxy ages
2. **Lower stellar masses**
3. Specific SFR (sSFR=SFR/M*) increases with redshift (@ z>2-3)

4. Higher dust attenuation (cf. inferences from UV slope)
5. Variable star formation histories – shorter SF timescales
6. Significant scatter in SFR-M*
7. …

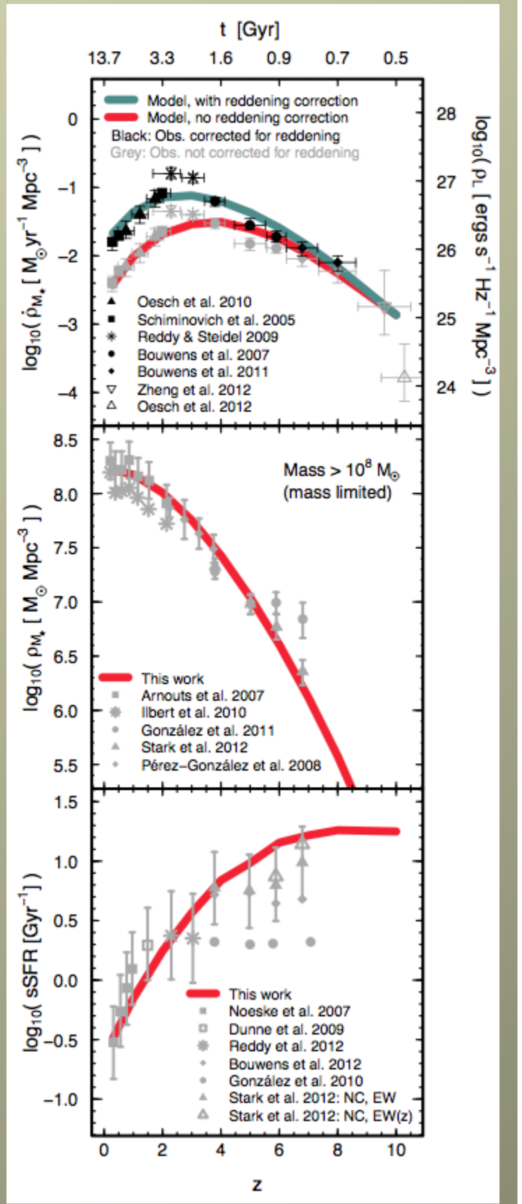
Schaerer & de Barros (2009, 2010, 2011), de Barros et al. (2011, 2014)
Also: Stark et al. (2013), Castellano et al. (2014), Duncan et al. (2014), Salmon et al. (2014), Grazian et al. (2015) …

3. Evolution of the specific SFR with redshift

- High sSFR=SFR/M* at high redshift
  (cf. Schaerer & de Barros 2010)
- sSFR increases with z. Agreement with simple galaxy formation models
- Large scatter expected – short SF timescales



de Barros, Schaerer & Stark (2012, 2014)



Tacchella et al. (2012)

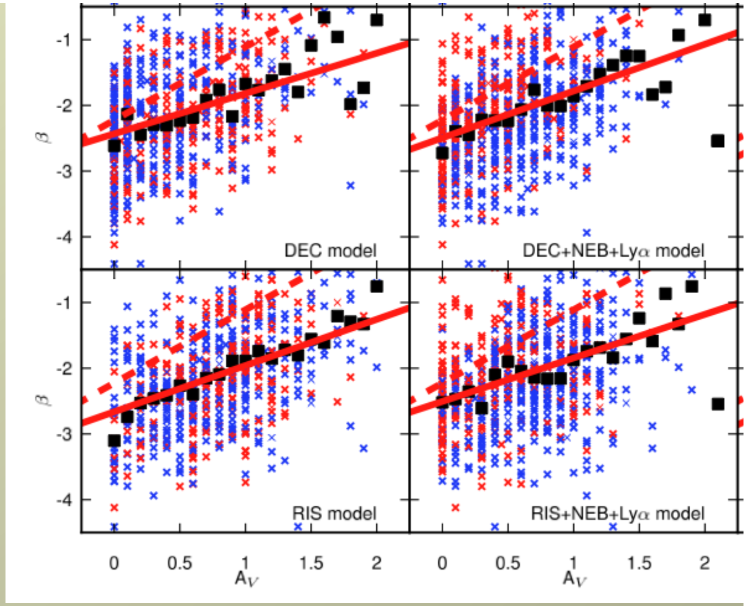
4. Higher dust attenuation

Use of UV slope to determine reddening/extinction is uncertain:

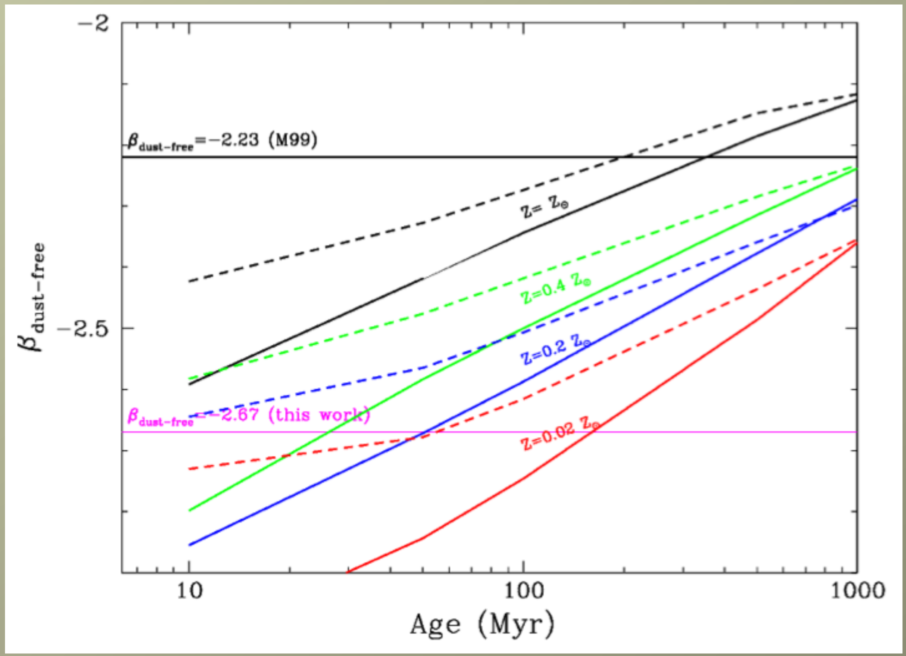
- Assumptions SFR=const and age>100 Myr may break down
- → Different relation β – E(B-V)

- Higher extinction than commonly thought
  → Revised « Meurer law »
  (cf. also Castellano et al. 2014)

➔ Next step: direct measurement of IR emission with ALMA
(cf. predictions in Schaerer et al. 2013)



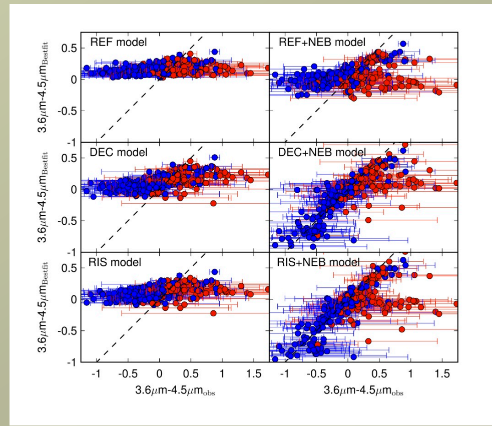
de Barros, Schaerer, Stark (2014)



Castellano et al. (2014)

5. Variable star formation histories – shorter SF timescales

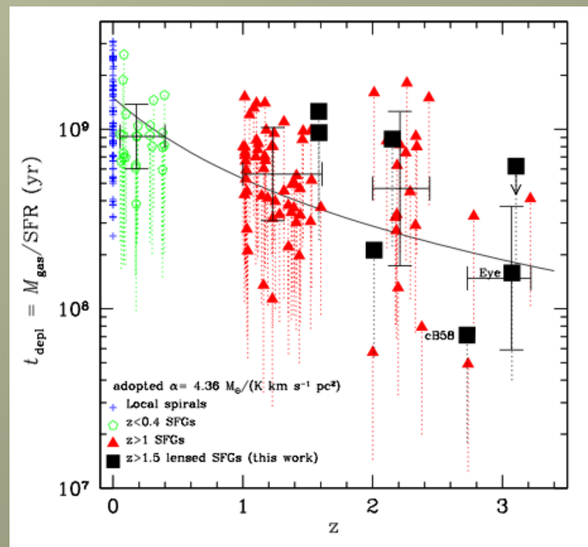
- Redshift non-evolution of M*-M_UV from z~5 to 3
  ➔ **SFR=const or fastly rising SFH excluded**
  ➔ **episodic SF favoured**
  (cf. Stark et al. 2009)



de Barros, Schaerer, Stark (2012, 2014)

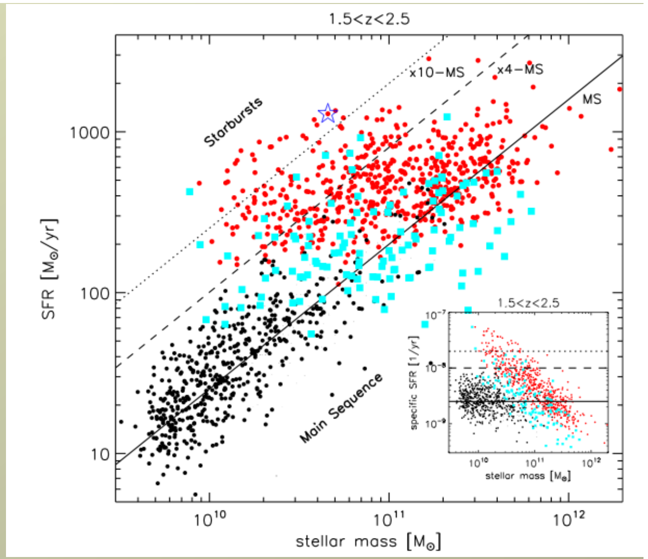
- **Slowly rising SF** (e.g. Papovich et al. 2012) **not applicable to individual galaxies**
  → need to turn-off SF

- Variable SF also supported by:
  - (3.6-4.5) color (EW(Ha)) distribution
  - Clustering of z~4 LBGs (Lee et al. 2009)
  - Galaxy models with feedback
    (Wyithe, Loeb+ 2011, 2014; Hopkins et al. 2014)
  - Decreasing SF timescale from z~0 to 3
    Saintonge et al. (2014), Dessauges-Zavadsky et al. (2014)



Dessauges-Zavadsky et al. (2014)

6. SFR – mass relation

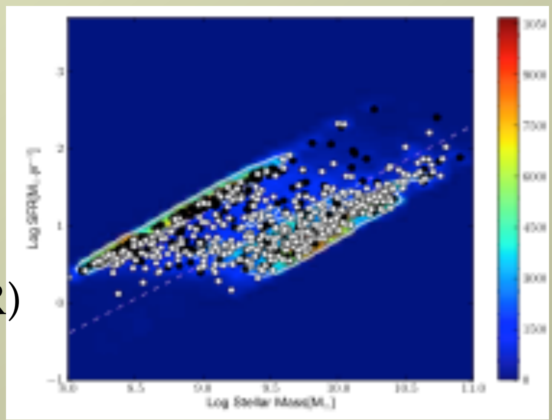


Rodighiero et al. (2011)

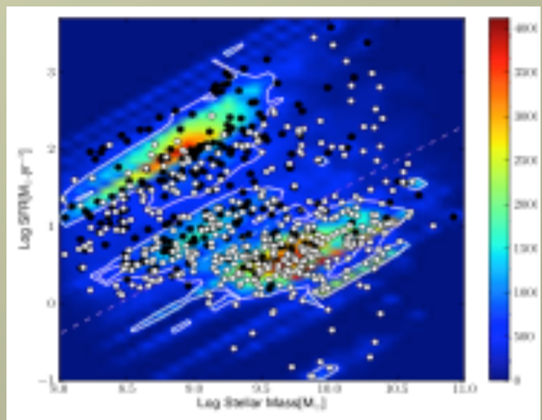
Difficulties:

- **Concept of SF-main sequence misleading at high redshift ?**
  Scatter may be large!
  Caution: selection effects!

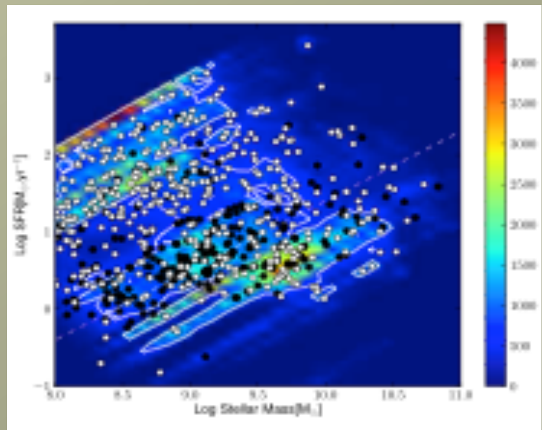
SFR=const, age>50Myr



variable SF histories



variable SF histories + nebular



A_V free

log(SFR)

log(M*) log(M*) log(M*)

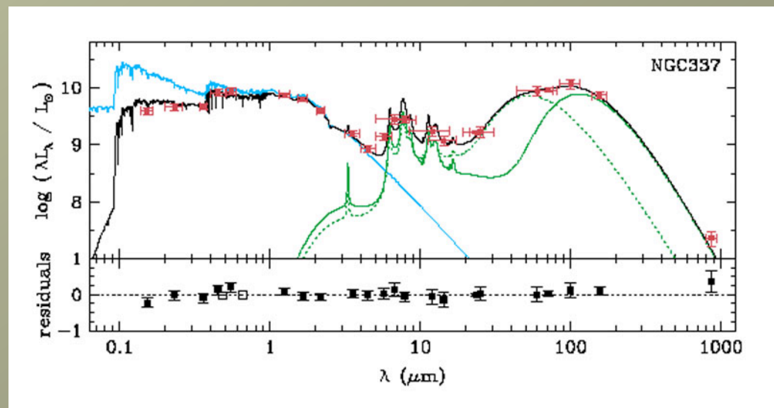
Caution: biases, selection criteria+ can severely affect the possible correlations (e.g. Dunne et al. 2009, Stringer et al. 2011)

Evolution of the LBG population with redshift

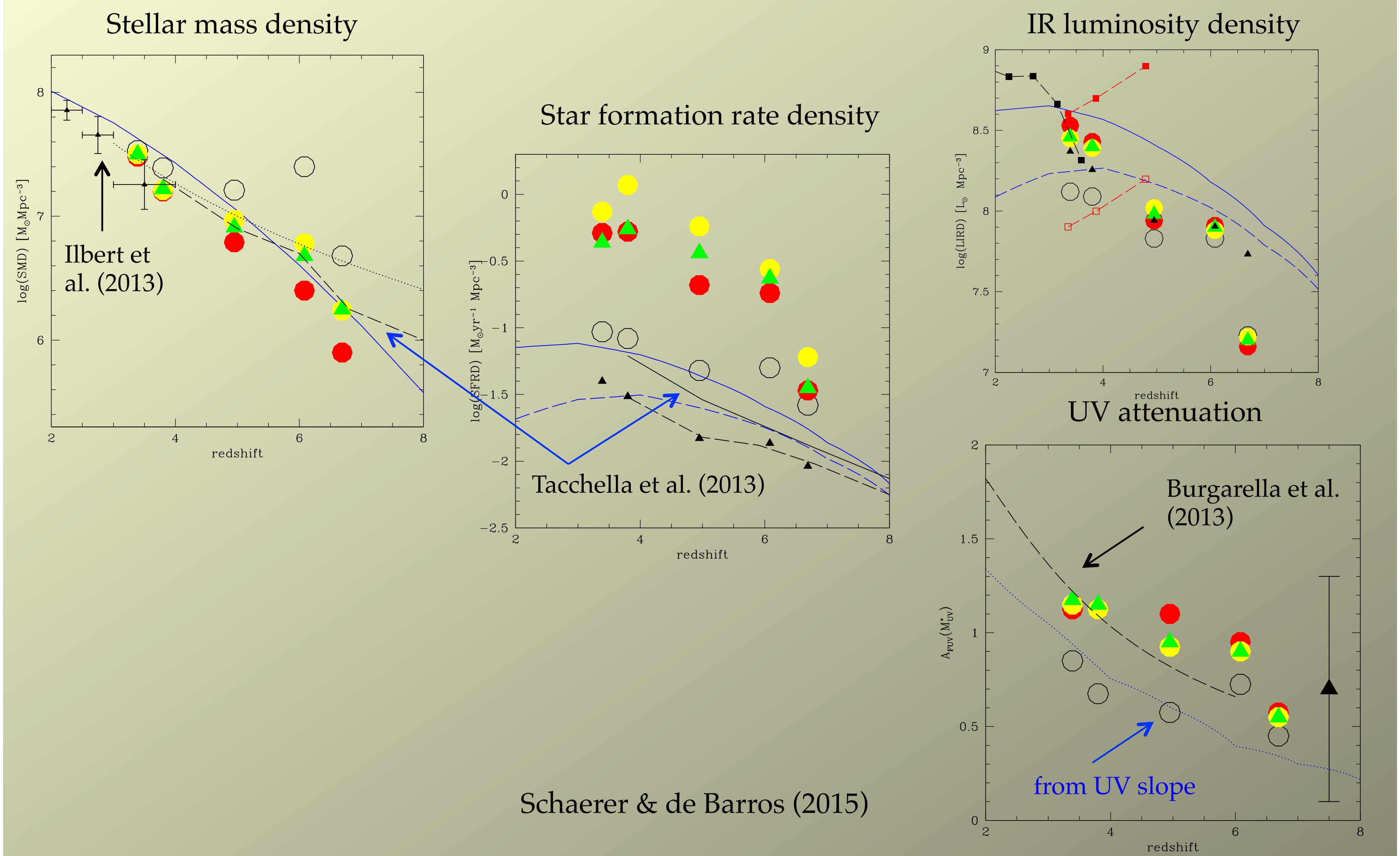
- Sample of z~3 to 7 LBGs (~1400 B,V,i,z-drop)
- Complete down to M_UV~ -19 .. -19.5
- Determine physical properties for set of SFHs and metallicities and statistical distribution as function of UV magnitude
  → Fits as fct of M_UV
- Convolve with observed UV luminosity function (Bouwens et al.)
  → **Integrated (« cosmic ») properties (SFR density, stellar mass density, etc.)**

  → **Main quantities: SFRD, SMD, LIRD …**

Total IR luminosity from energy conservation
(cf. da Cunha et al. 2008 etc.)

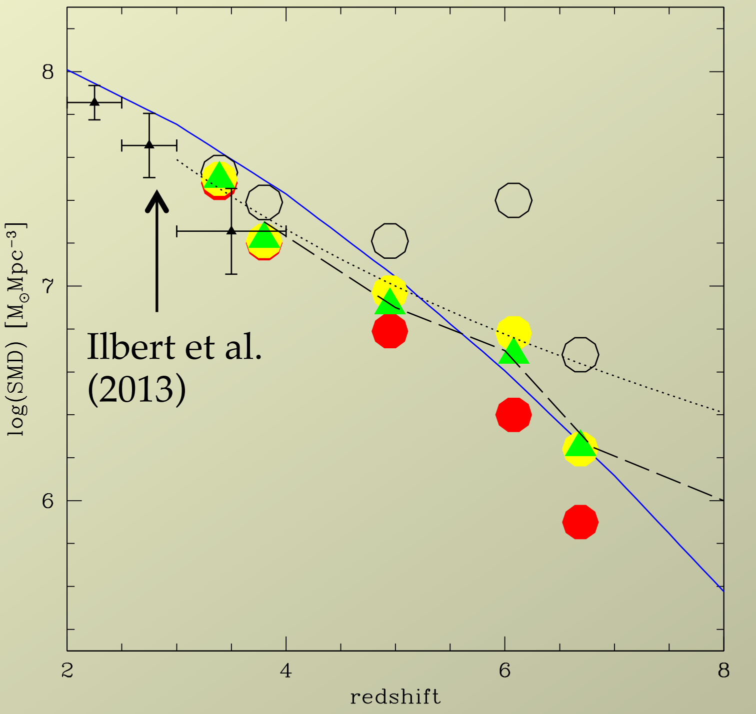


Evolution of the LBG population with redshift



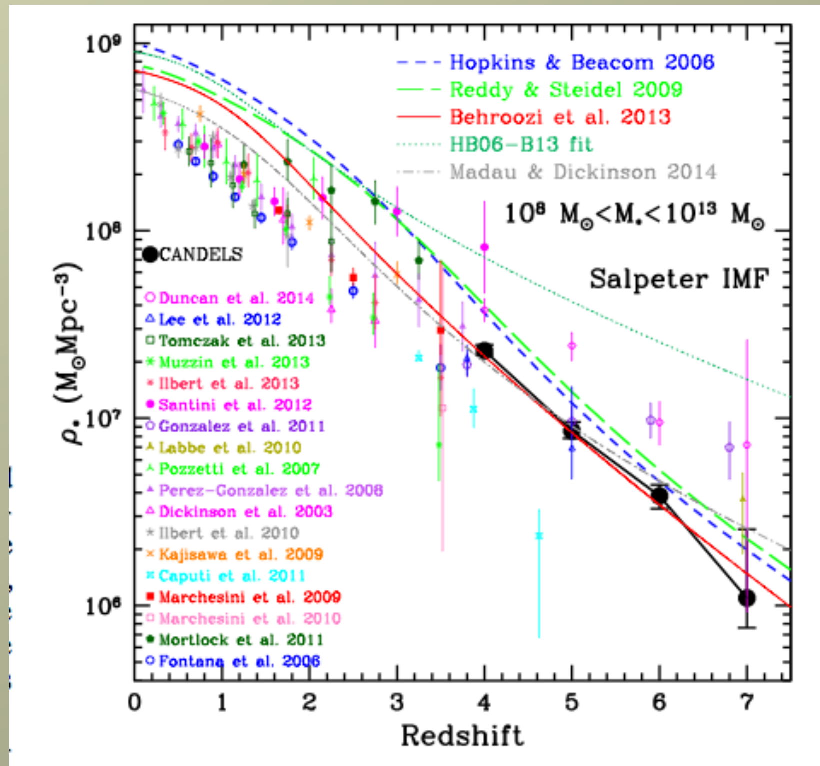
Evolution of the LBG population with redshift

Stellar mass density



SMD integrated down to M_UV=-18
assuming different SFHs

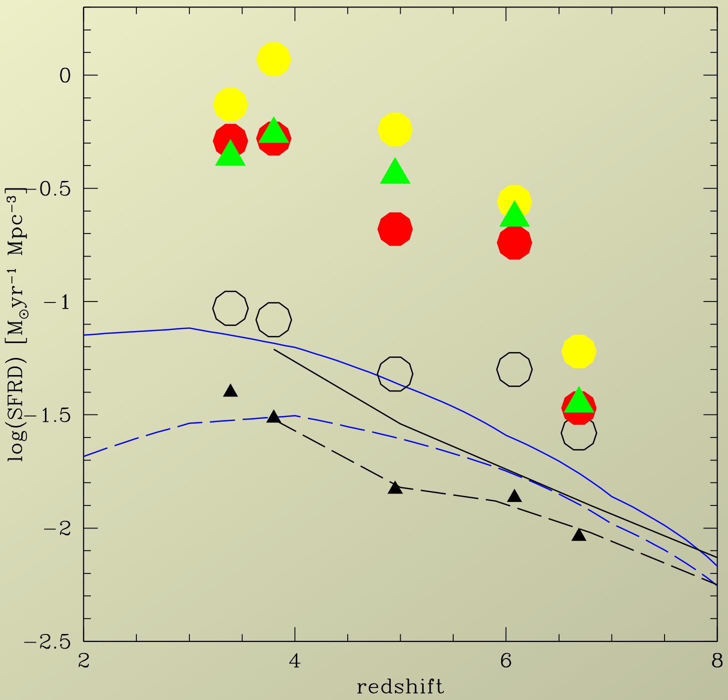
Schaerer & de Barros (2015)



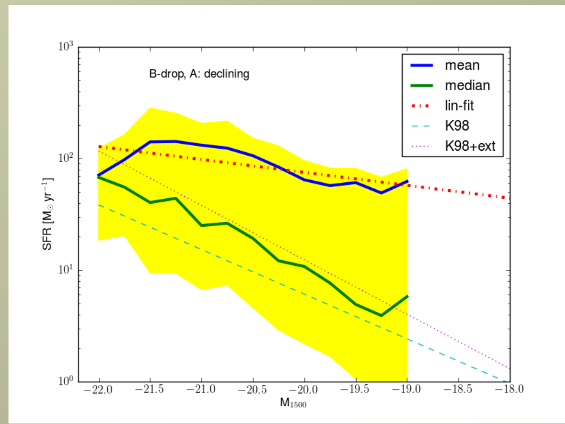
Grazian et al. (2014)

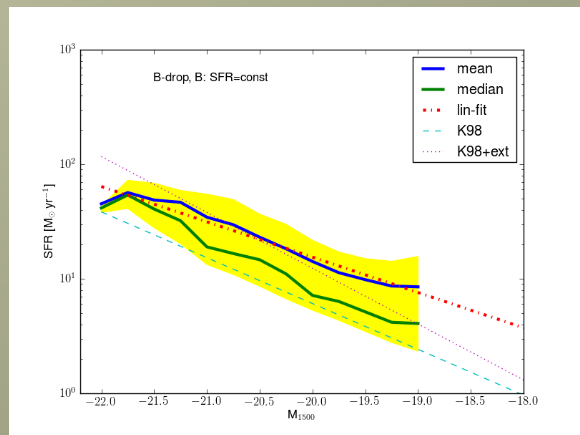
Evolution of the LBG population with redshift

Star formation rate density



- Higher « instantaneous » SFRD than usual, due to variable SFHs
- Fully consistent with observed UV luminosity density

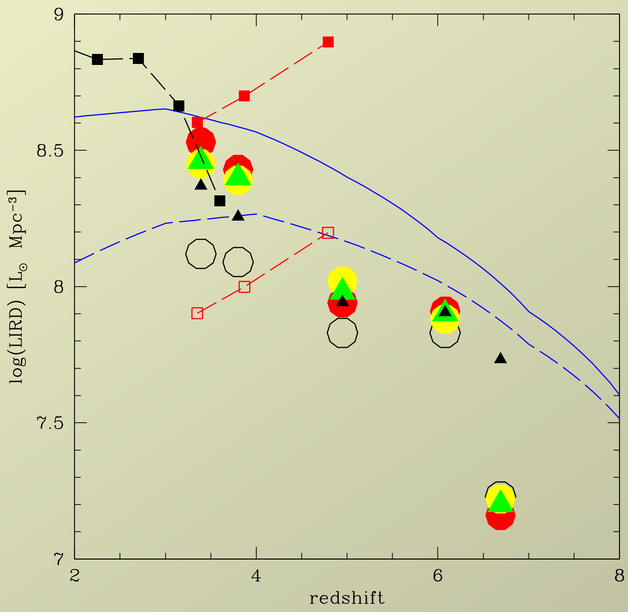




Schaerer & de Barros (2015)

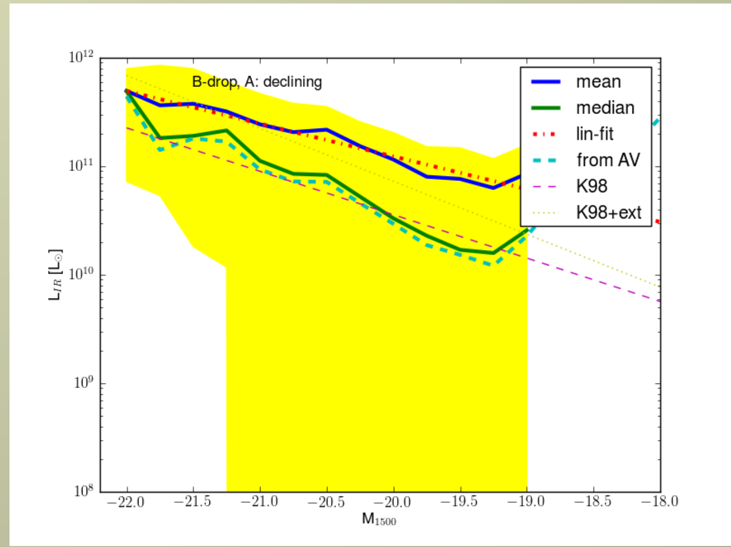
Evolution of the LBG population with redshift

Infrared luminosity density

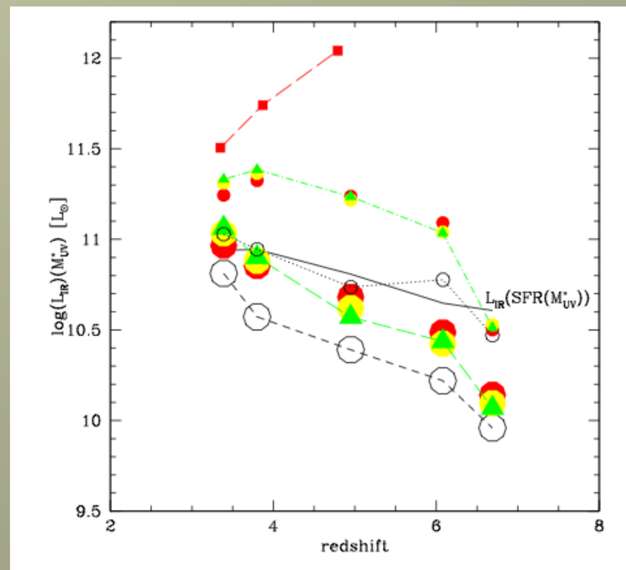


Schaerer & de Barros (2015)

- Rapid decline of the LIRD with redshift expected
- Simple Kennicutt relation is not appropriate to predict LIR
- Good agreement with LIRD from Herschel @ z~3.5



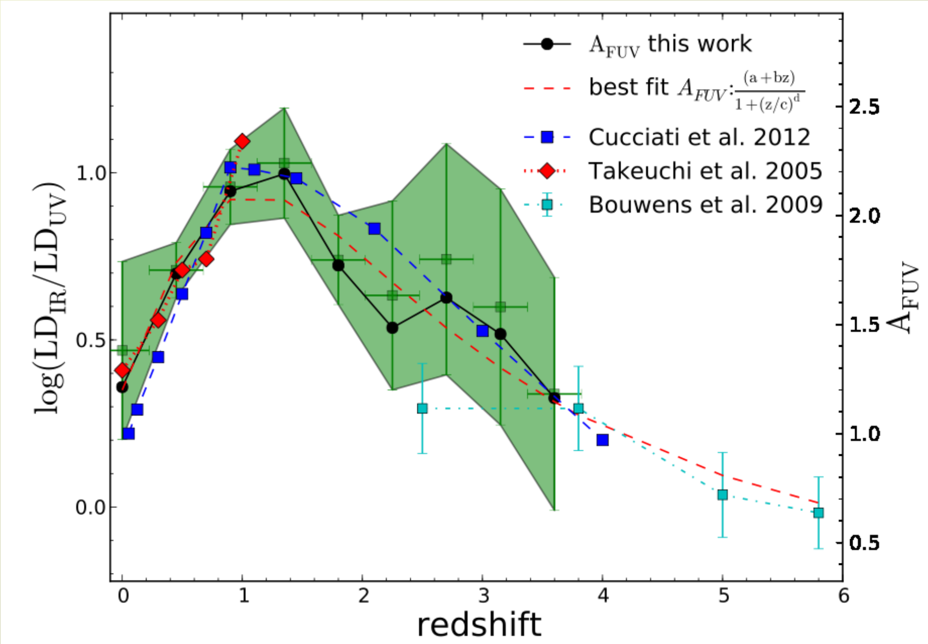
S & de Barros (2015), Schaerer et al. (2013)

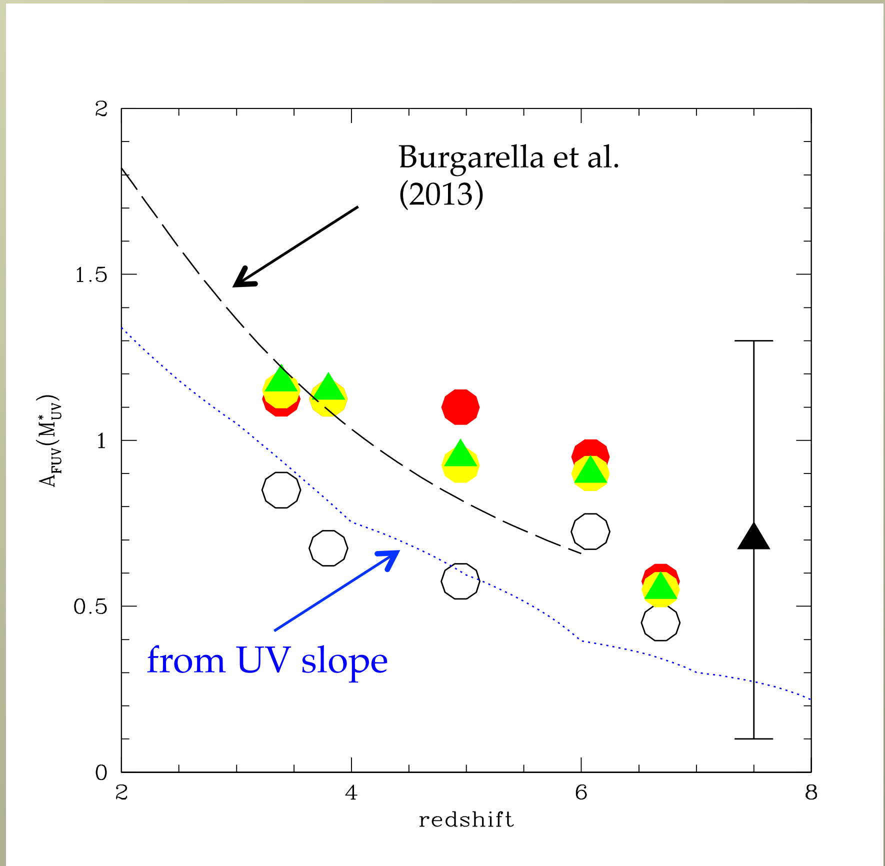


Evolution of the LBG population with redshift

Mean UV attenuation

Mean attenuation from IR/UV:
Burgarella et al. (2013)

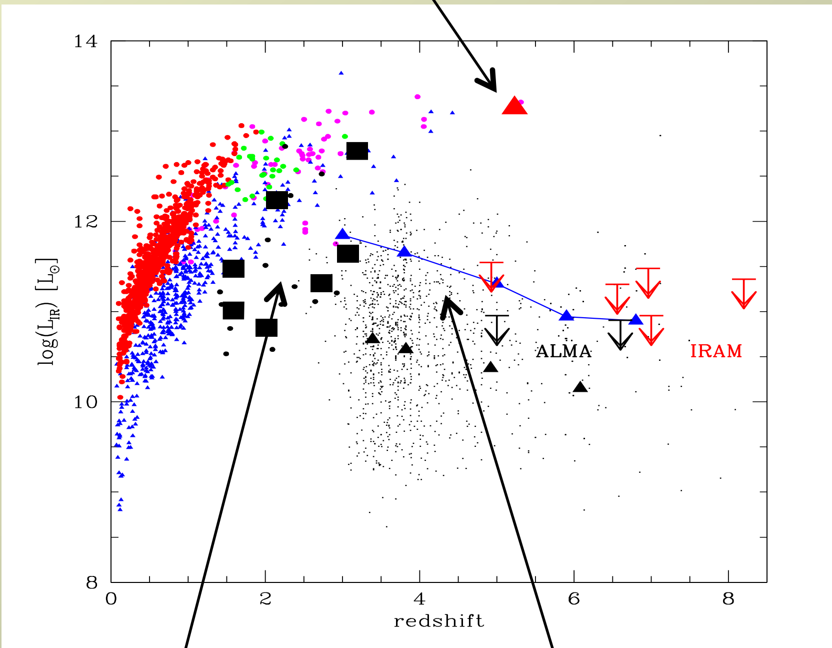




Schaerer & de Barros (2015)

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)

→ *Schaerer et al. (2015,A&A 574, A19; arXiv:1407.5793)*

Lensed galaxies:
- 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
- z=7.5 Finkelstein+2013 object

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

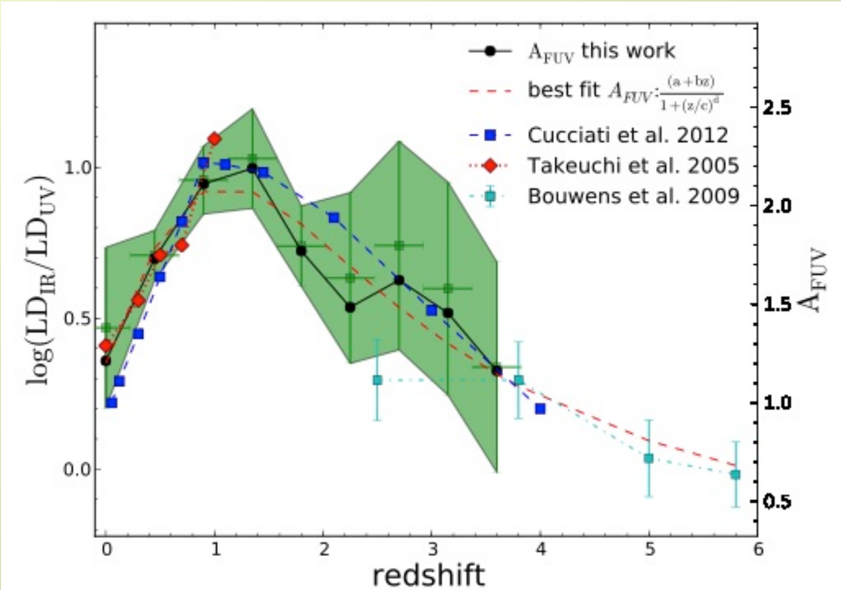
→ **Limits on IR luminosity and dust mass**: assuming T_d=35 K, β=2,
including correction for CMB heating

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]	rms_{cont} [mJy beam^{-1}]	σ_{line} [mJy beam^{-1}]^e	$L_{[CII]}$ 10^8 [$L_\odot$]	$L_{IR}(T_d = 25)$ 10^{11} [$L_\odot$]	$L_{IR}(T_d = 35)$ 10^{11} [$L_\odot$]	$L_{IR}(T_d = 45)$ 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 $\Delta\nu$ = 50 km s^{-1} channels.

Mean attenuation as function of redshift

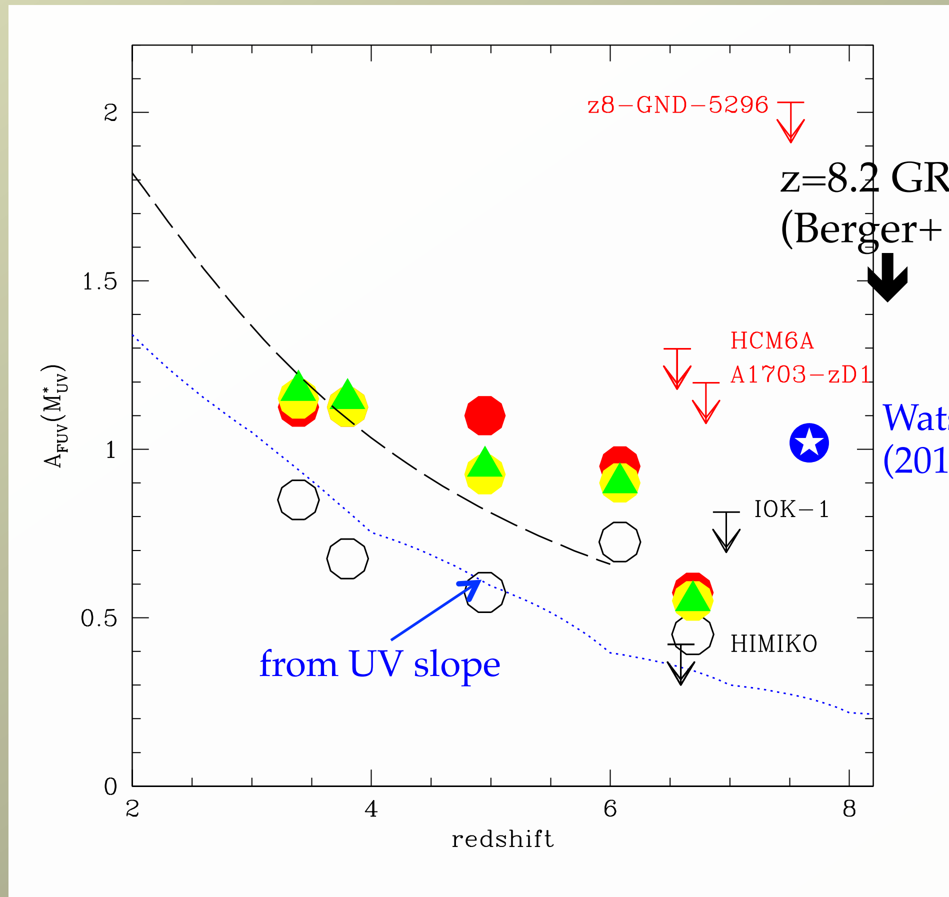


Burgarella et al. (2014)

UV attenuation compatible with:

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

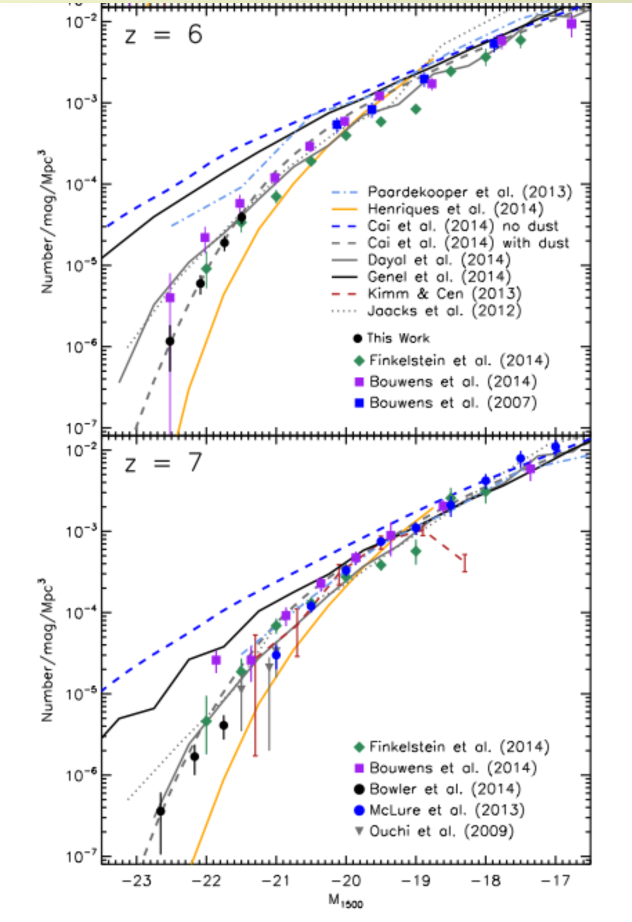
Dust-obscured SF:
SFR(IR)/SFR(UV)



5
3
2
0.8
0.3

Schaerer et al. (2014)

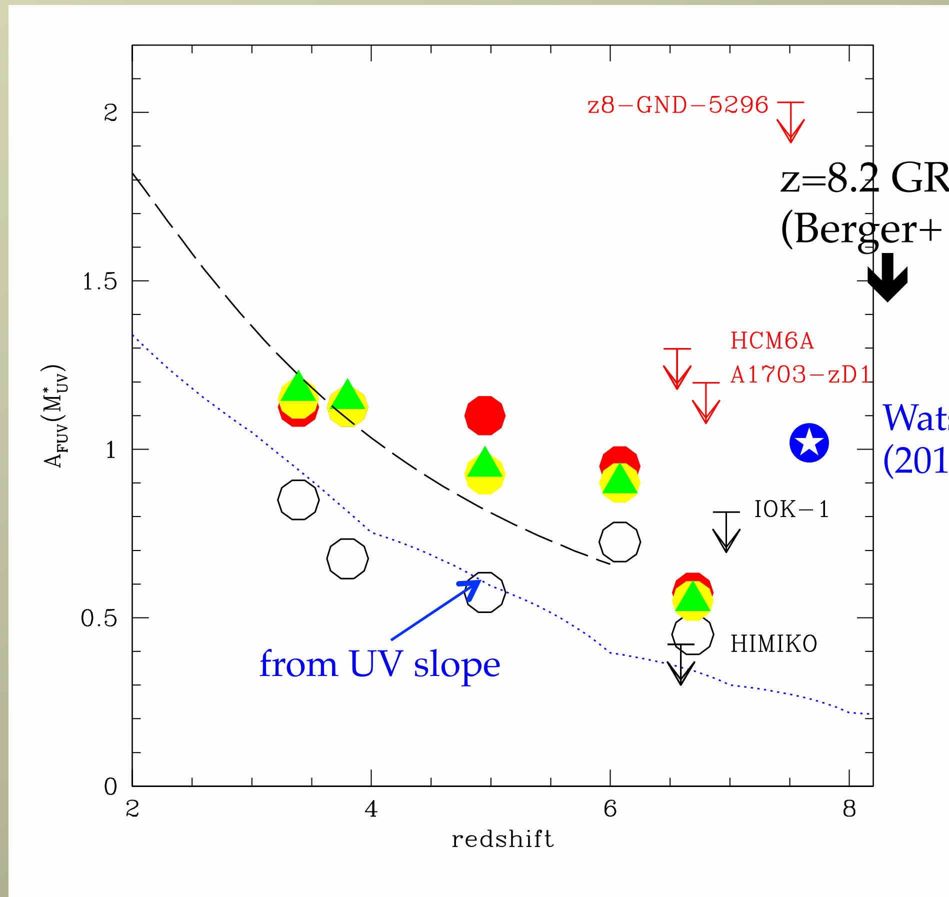
Mean attenuation as function of redshift



Bowler et al. (2015)

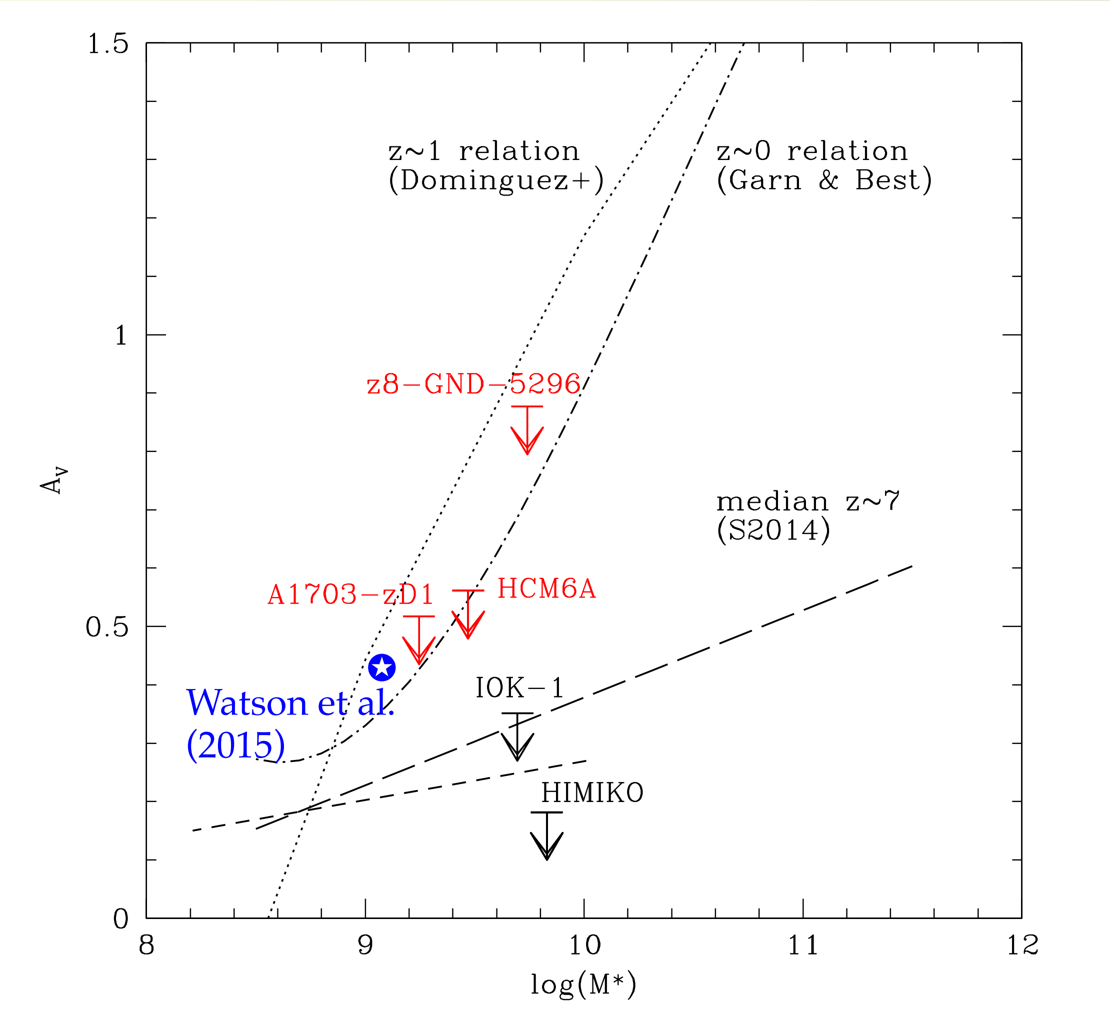
No evidence for very high UV attenuation

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



Schaerer et al. (2014)

Mass – dust attenuation relation

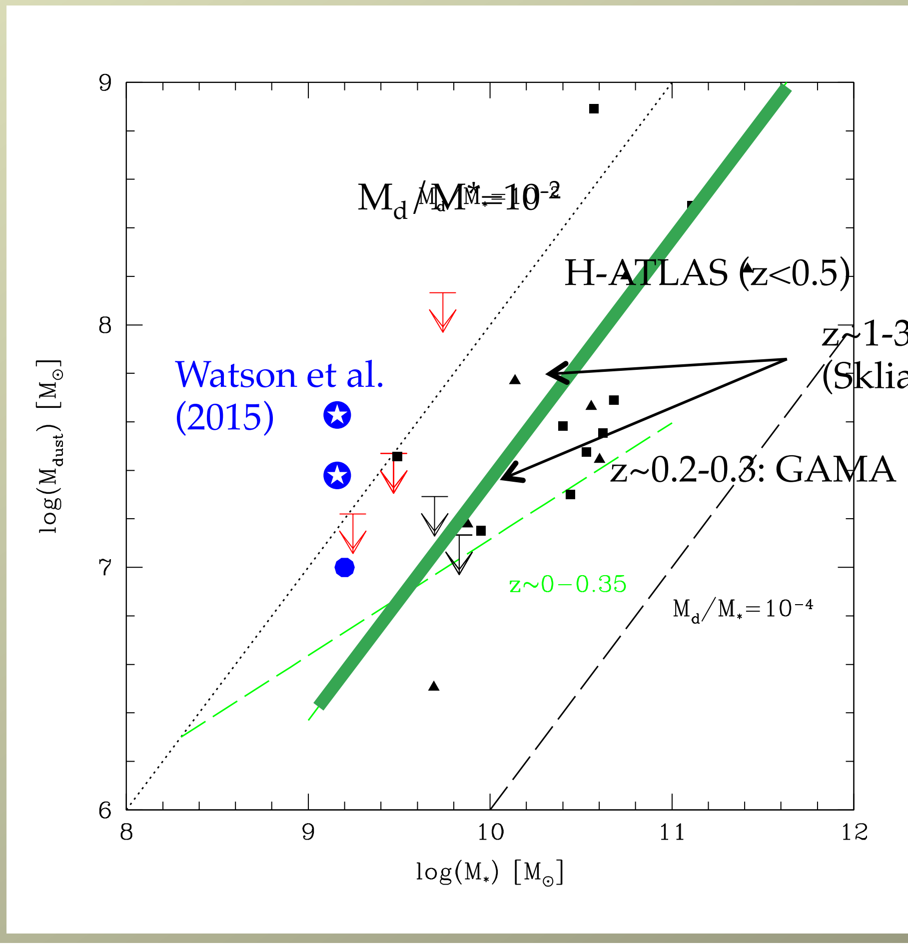


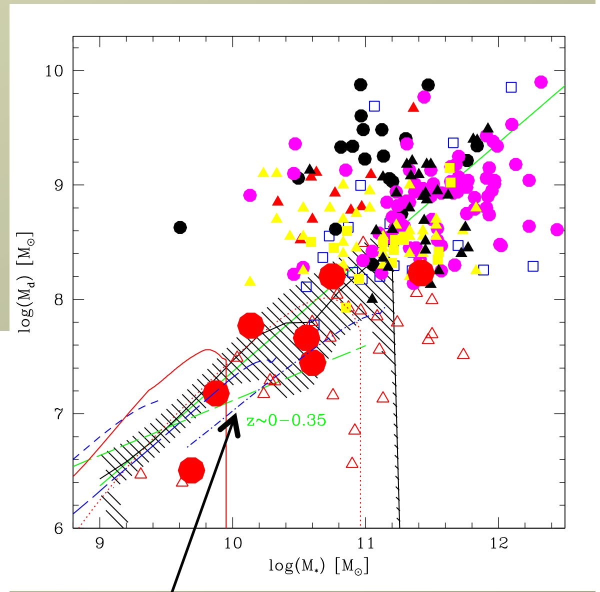
- ≥ 2 objects: less attenuation than expected from relation at lower redshift
- Compatible with *flatter mean relation for z~7 LBGs* (Schaerer & de Barros 2014)

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

Dust masses at z>6 :

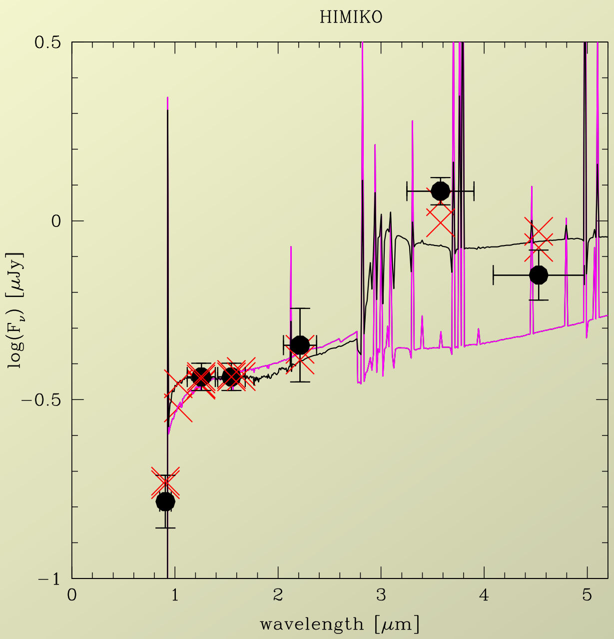
- Current upper limits are compatible with normal dust/ stellar mass ratios
- No indication for redshift evolution of M_d/M^* from z~0 to 3 and at z~7
- Dust production per SN ~0.15-0.45 $M_{\odot}$ (Hirashita+ 2014)



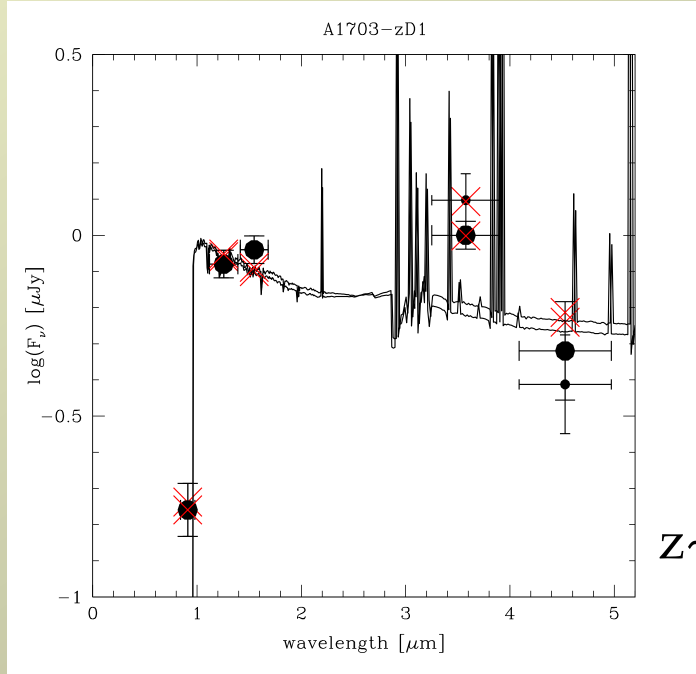


Schaerer al. (2014)

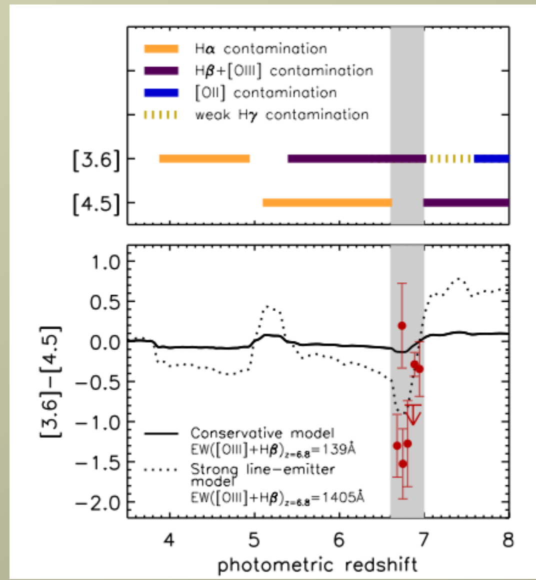
Implications



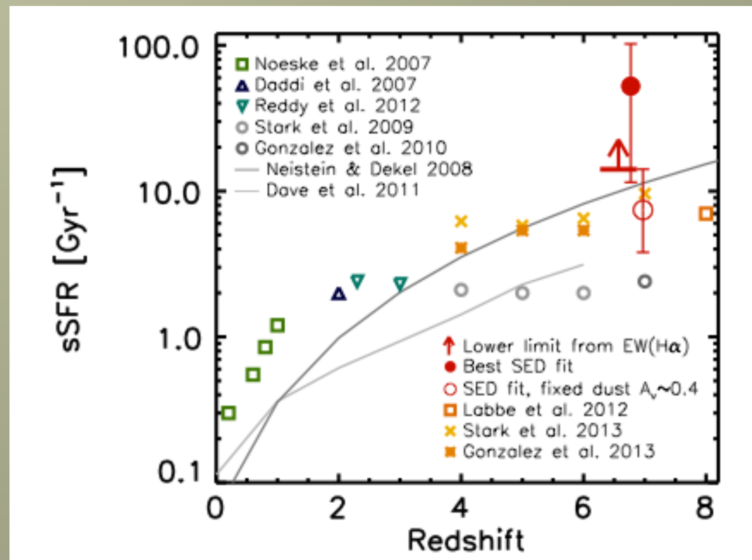
z=6.595



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!

Conclusions

A) Physical parameters of LBGs affected by emission lines and SF histories:

* Masses ↘, ages ↘, sSFR increases with z
* UV attenuation higher than usual (Meurer law)
* Data favours variable SF histories

B) Consistent derivation of cosmic density of SFR, M*, IR luminosity densities

C) 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)

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

- UV attenuation versus redshift:
  - OK with extrapolation from z<3.5 (Burgarella et al. 2013)
  - **Can be higher by factor 2 than estimated from UV slope**
- *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 …)

→ Emission line measurements at high-z (JWST…)