# 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*
- Conclusions

→ 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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# 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

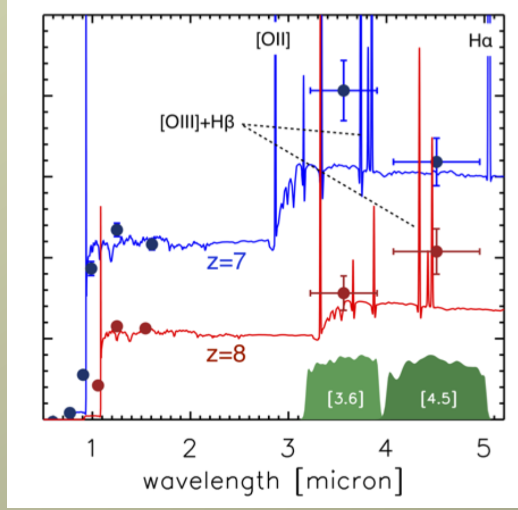
# Physical properties of high redshift star-forming galaxies

- 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

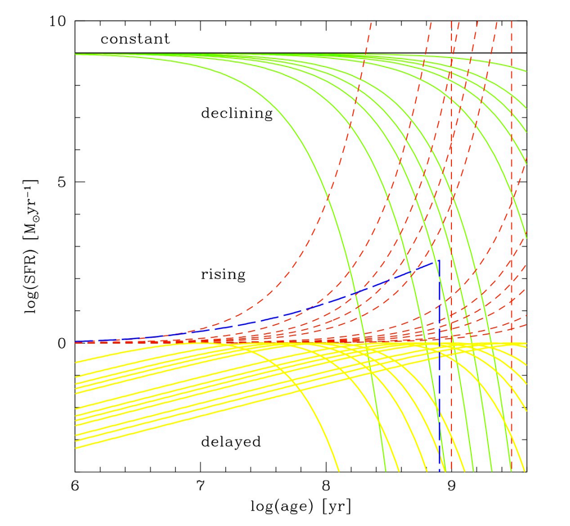



- **LBGs at z~7-8**: excess at 3.6 micron due to [OIII]+Hβ
  (Labbé et al. 2012, Smit et al. 2013)
- **LBGs at z~4**: excess at 3.6 micron due to H$\alpha$
  (Shim et al. 2011, de Barros et al. 2011, Stark et al. 2012)
- Broad-band excess in **z~2 LBGs** with strong H$\alpha$
  (Erb et al. 2006, Reddy 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-$\alpha$ 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)
- …

# 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 (2014)

# 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. …

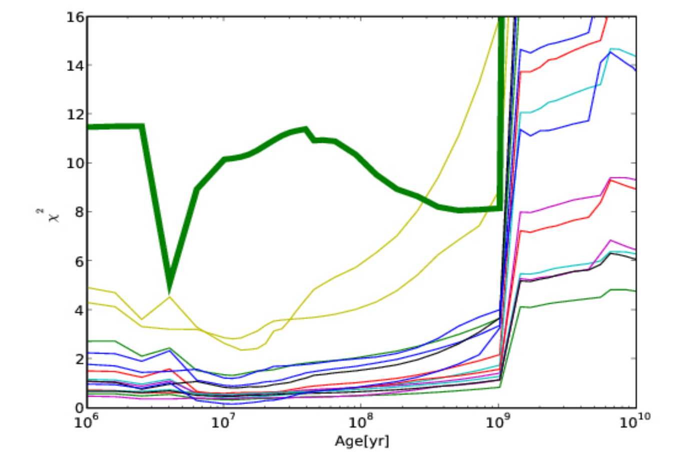
# 1. Age of high-z LBGs (dominant population)

**« Old » galaxies in the high-z universe ? high formation redshift?**

(cf. Eyles et al. 2005, 2007, Yan et al. 2006, Labbé et al. 2010)

- Age estimated from Balmer break
- **Emission lines can mimick large break**

(Schaerer & de Barros 2009)

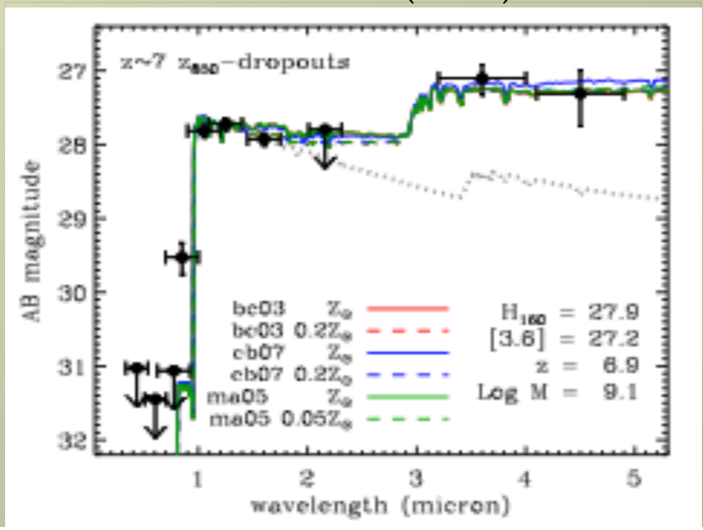



Schaerer & de Barros (2010)

Stacked SED (14 objects @ z~7) :
*classical SED fits*
- Weighted age ~350 (+30-170) Myr

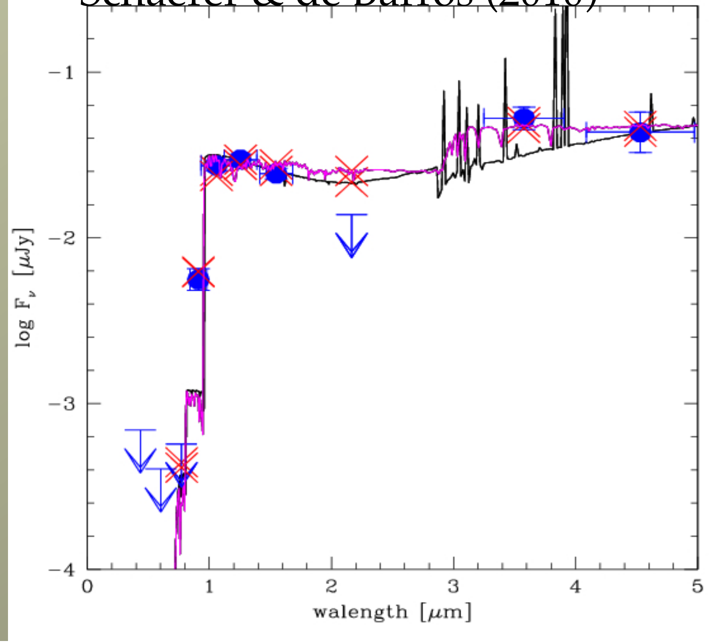
--> onset of SF at z~30 (+30-19) !?

Labbé et al. (2010)




*Models including nebular lines:*

- Age~4 Myr
- $A_V$~0.2
- M*~5. $10^7$ $M_\odot$

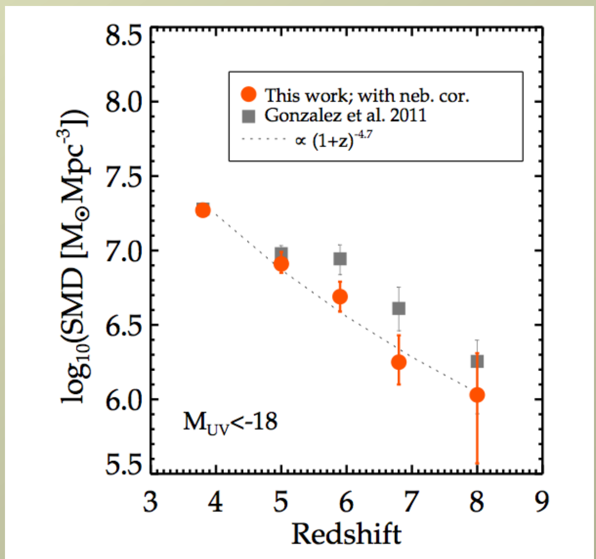


# 2. Properties of high-z galaxies: stellar mass and implications

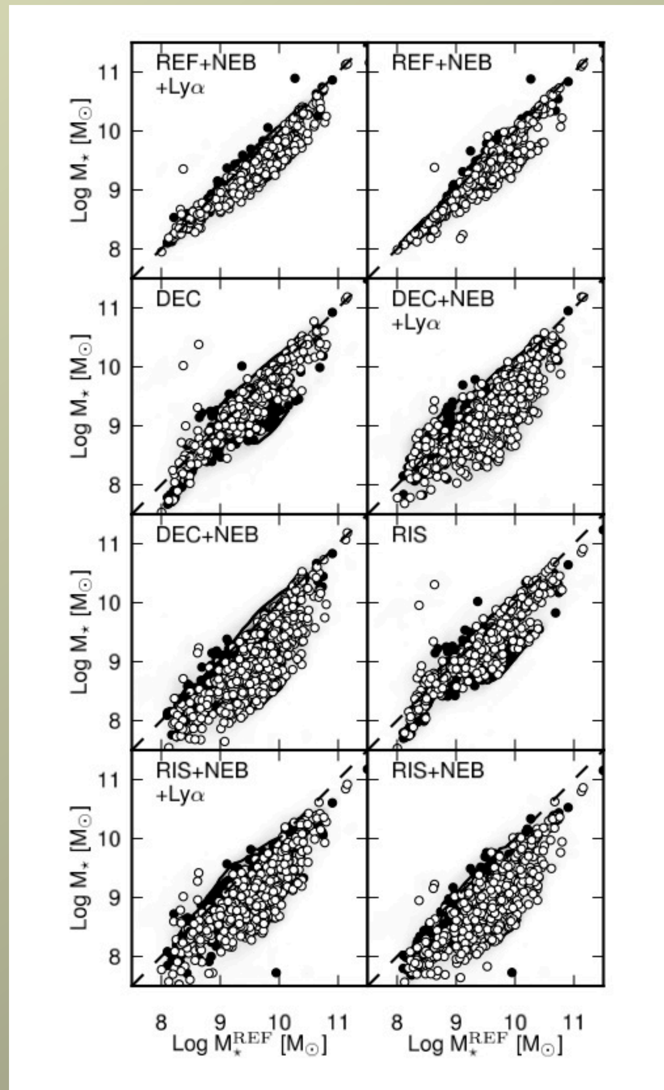
**stellar masses systematically lower** (than SFR=const) with nebular emission and for variable SF histories:

*typically ~2-3 times lower mass*

➔ Reduced stellar mass density at high-z



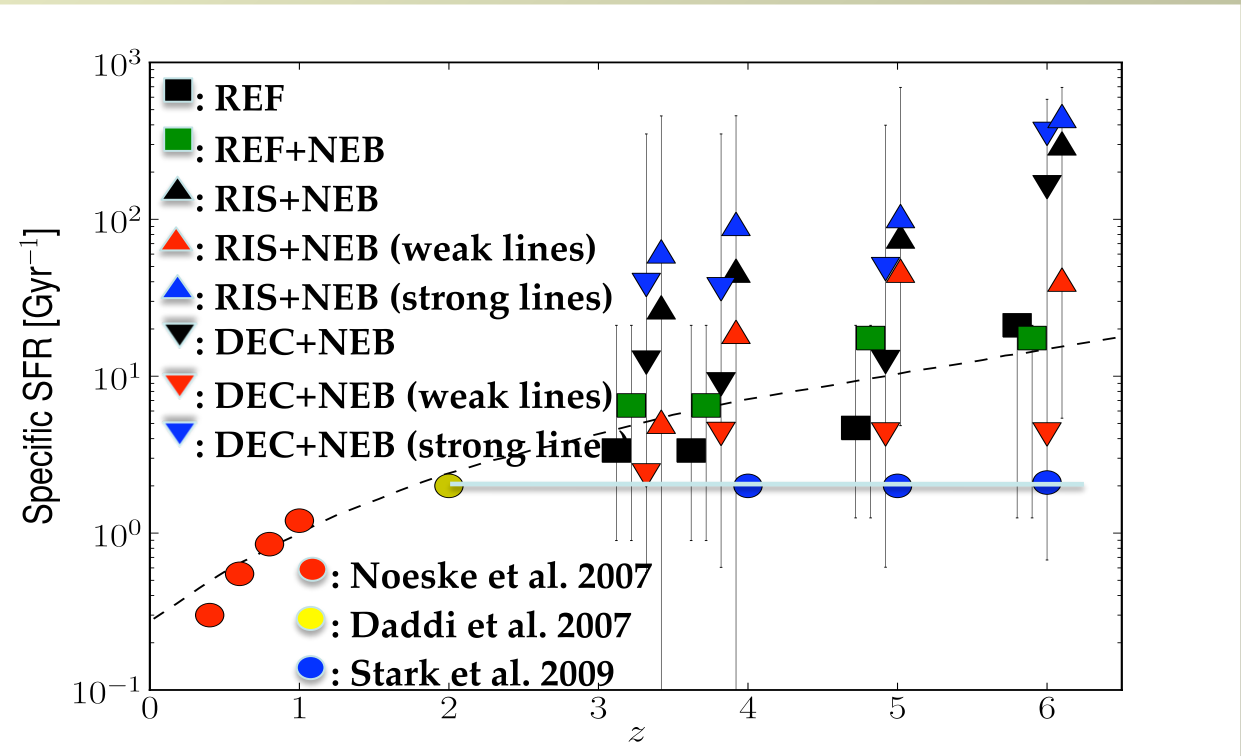

Stark et al. (2012)



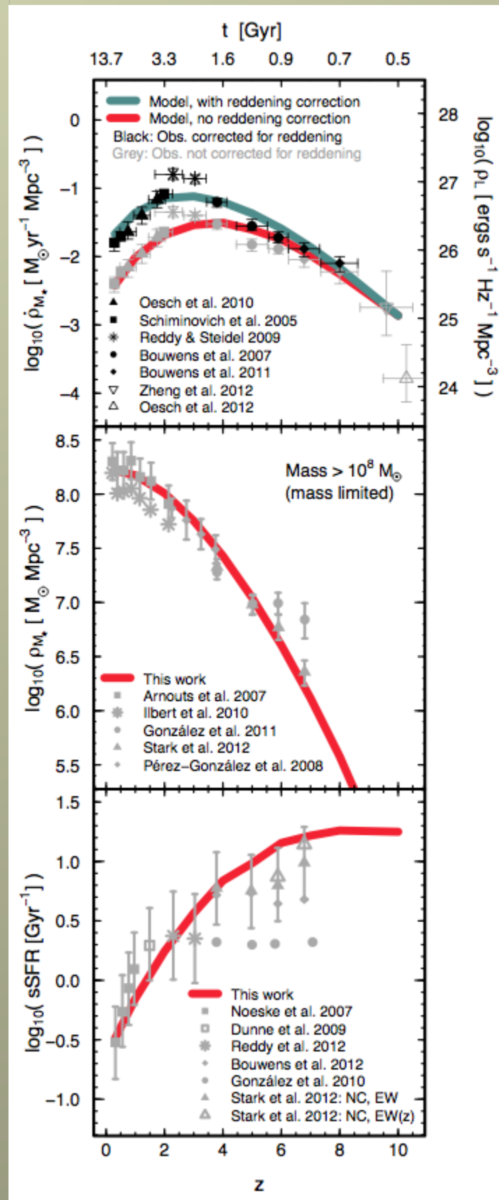

de Barros et al. (2012)

# 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)

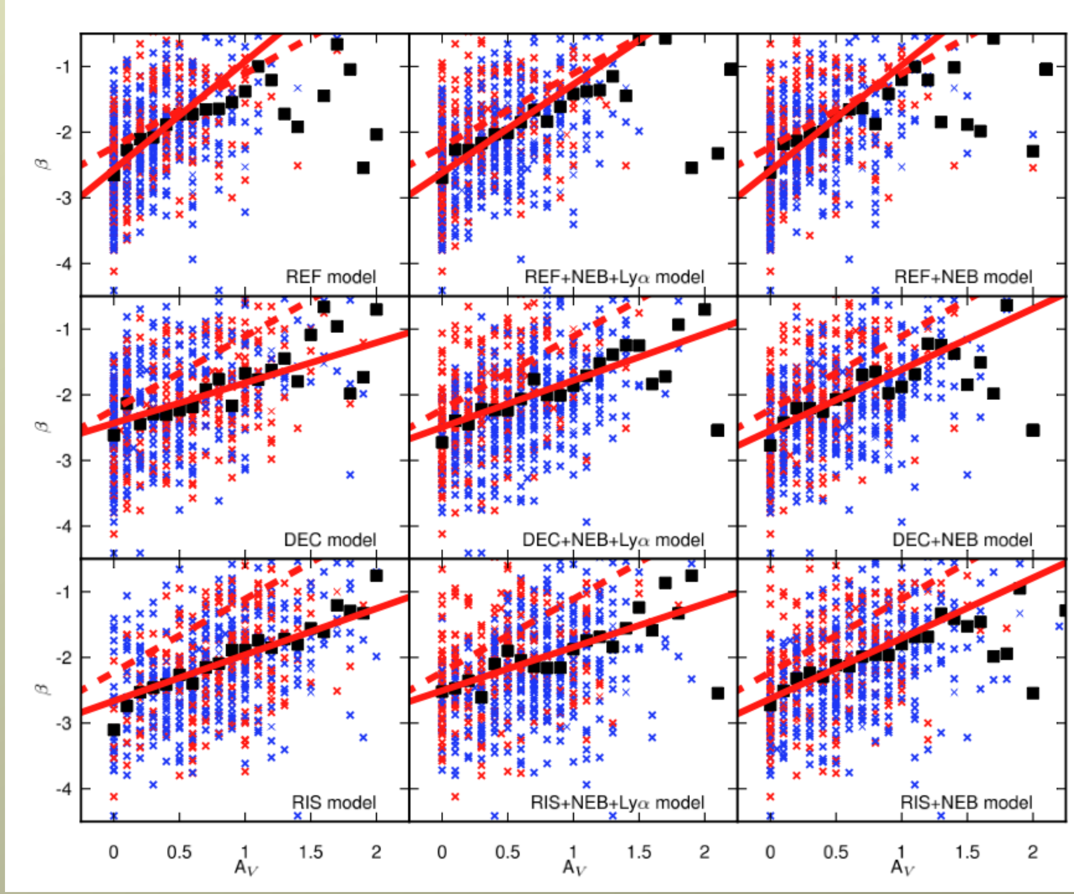



Tacchella et al. (2012)

# 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)

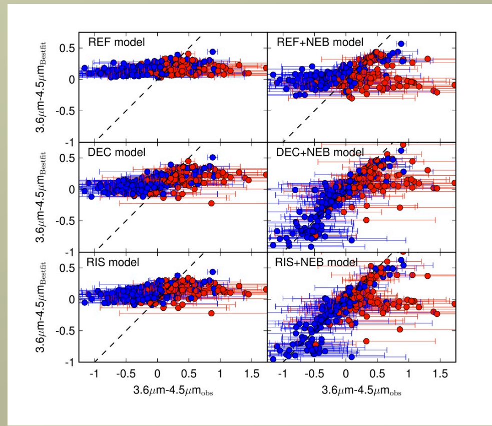



de Barros, Schaerer, Stark (2014)

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

# 5. Variable star formation histories – shorter SF timescales

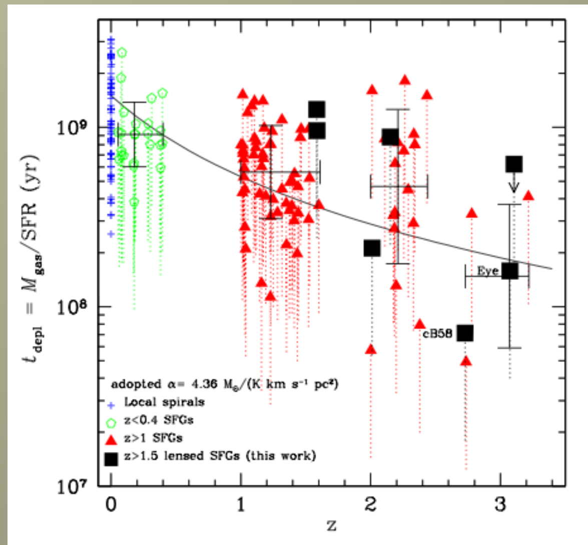
- Redshift non-evolution of M*-M_UV from z~5 to 3
  ➔ **SFR=const or fastly rising SFH excluded**
  ➔ **episodic SF favoured**
  (cf. Stark et al. 2009)




de Barros, Schaerer, Stark (2012, 2014)

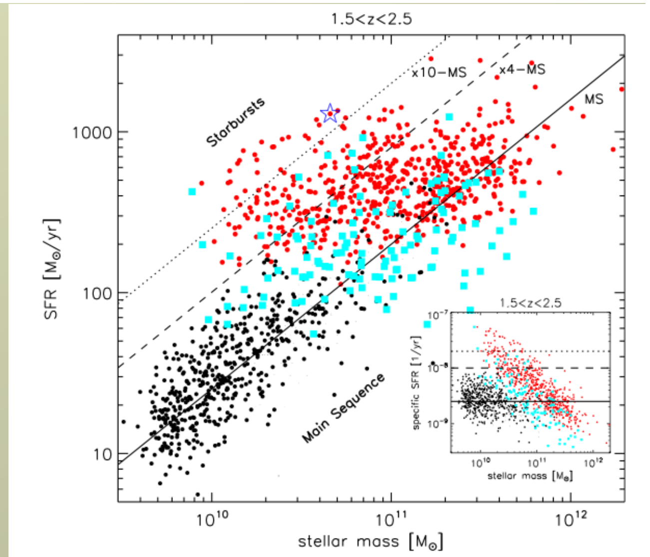
- **Slowly rising SF** (e.g. Papovich et al. 2012) **not applicable to individual galaxies**
  → need to turn-off SF

- 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 ?**

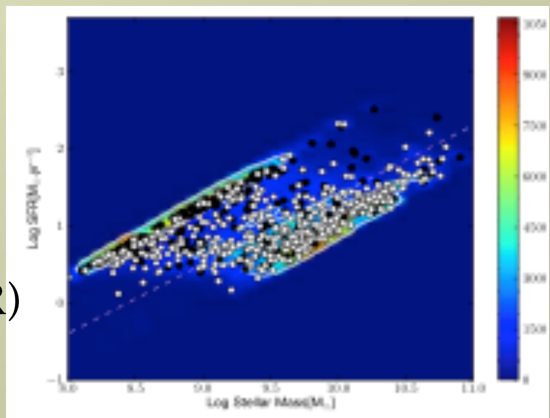
  Scatter may be large!

  Caution: selection effects!

$A_V$ **free**

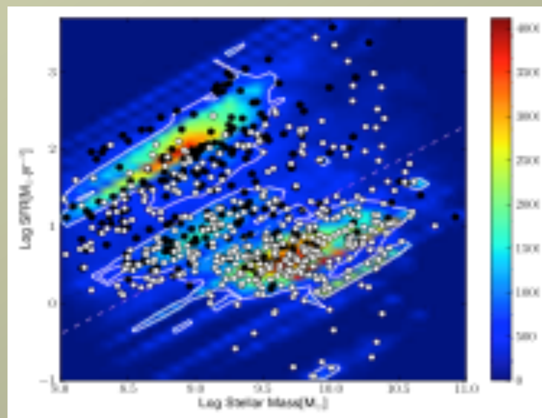
log(SFR)

SFR=const, age>50Myr



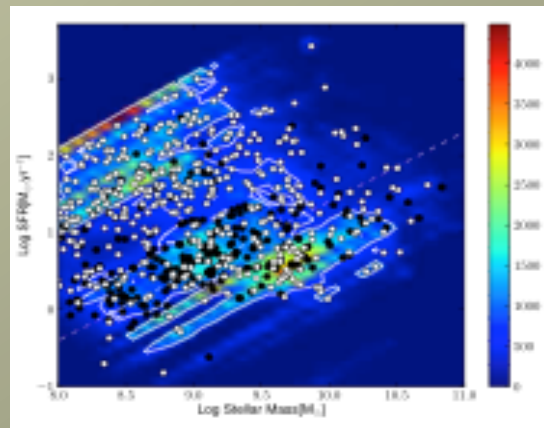
log(M*)

variable SF histories



log(M*)

**variable SF histories + nebular**



log(M*)

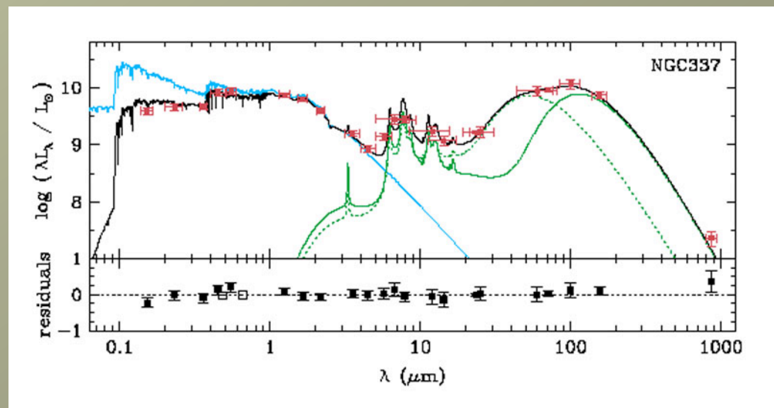
**Caution:** biases, selection criteria+ can severely affect the possible correlations (e.g. Dunne et al. 2009, Stringer et al. 2011)

# 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.)**

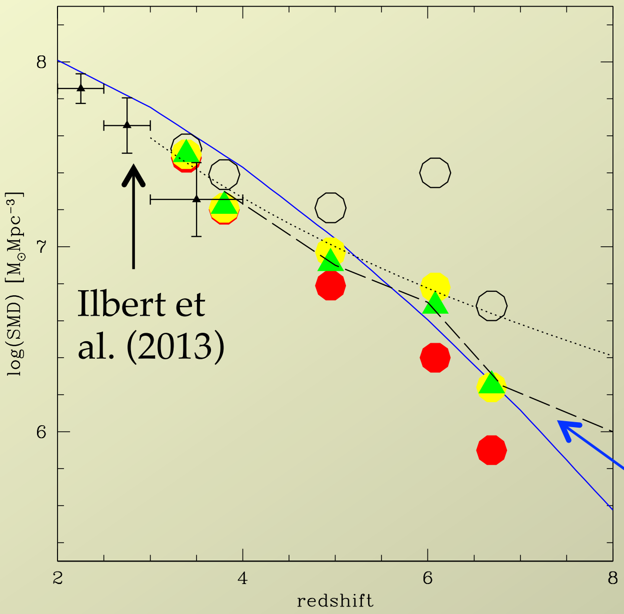
  → **Main quantities: SFRD, SMD, LIRD …**

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

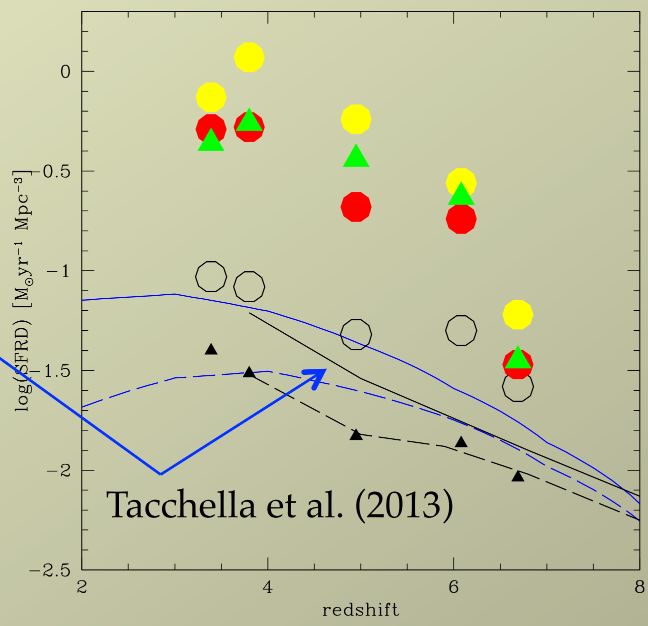


# Evolution of the LBG population with redshift

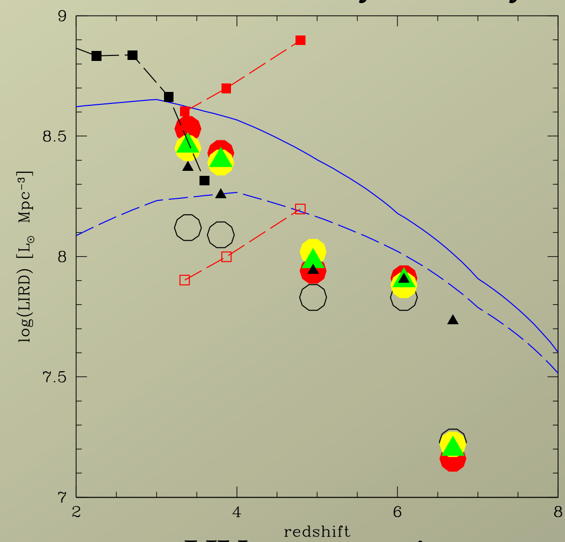
## Stellar mass density



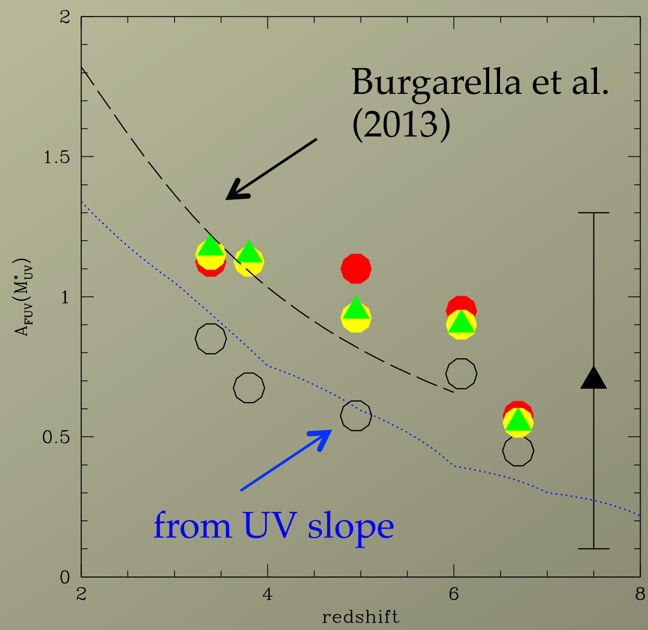

## Star formation rate density




## IR luminosity density




## UV attenuation



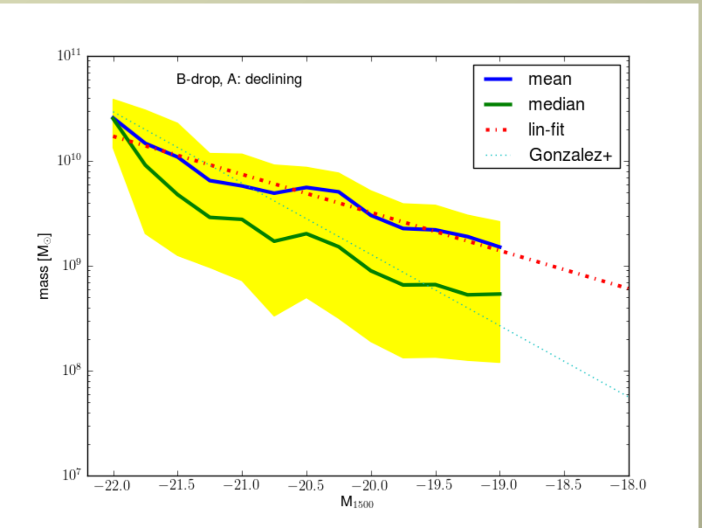

Schaerer & de Barros (2015)

# Evolution of the LBG population with redshift

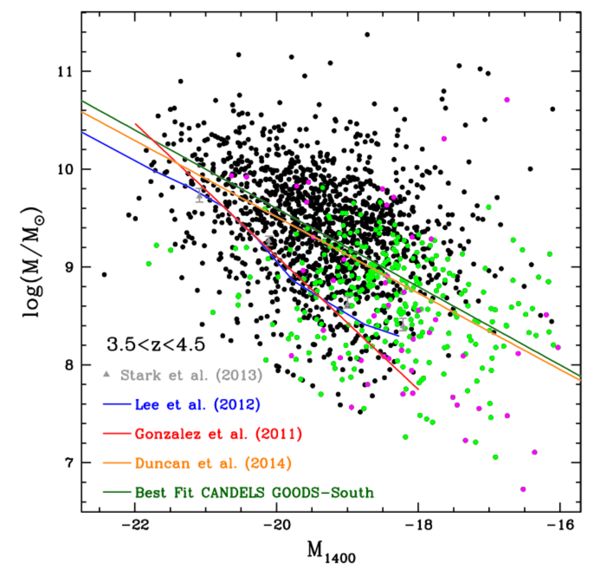
Stellar masses as fct. of UV magnitude:

- M/L(UV) fairly constant
- M*(M_UV) relation flatter than Gonzalez et al. (2011)

- broad agreement between different studies: e.g. de Barros et al. (2012, 2014), Duncan et al. (2014), Salmon et al. (2014), Grazian et al. (2014), Schaerer & de Barros (2015)



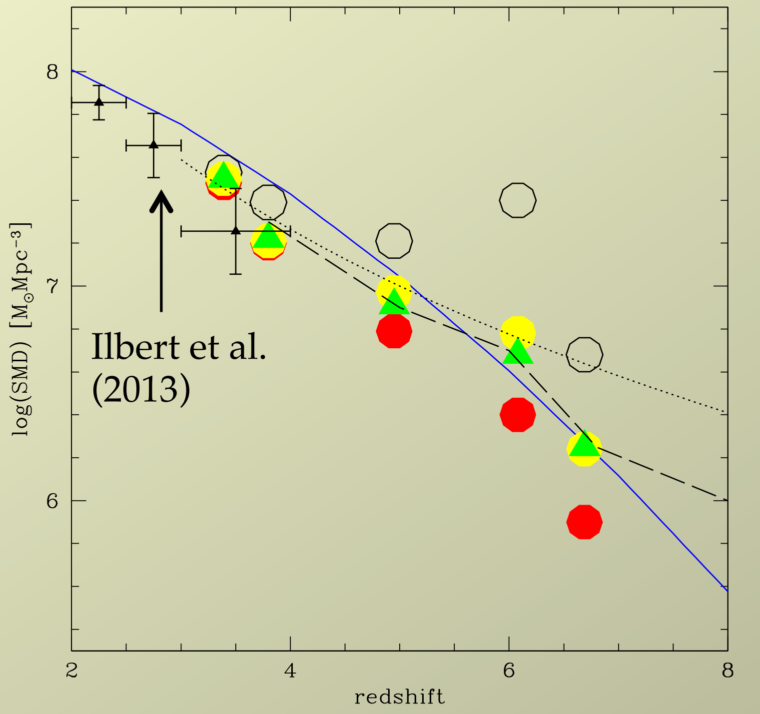

Schaerer & de Barros (2015)




Grazian et al. (2014)

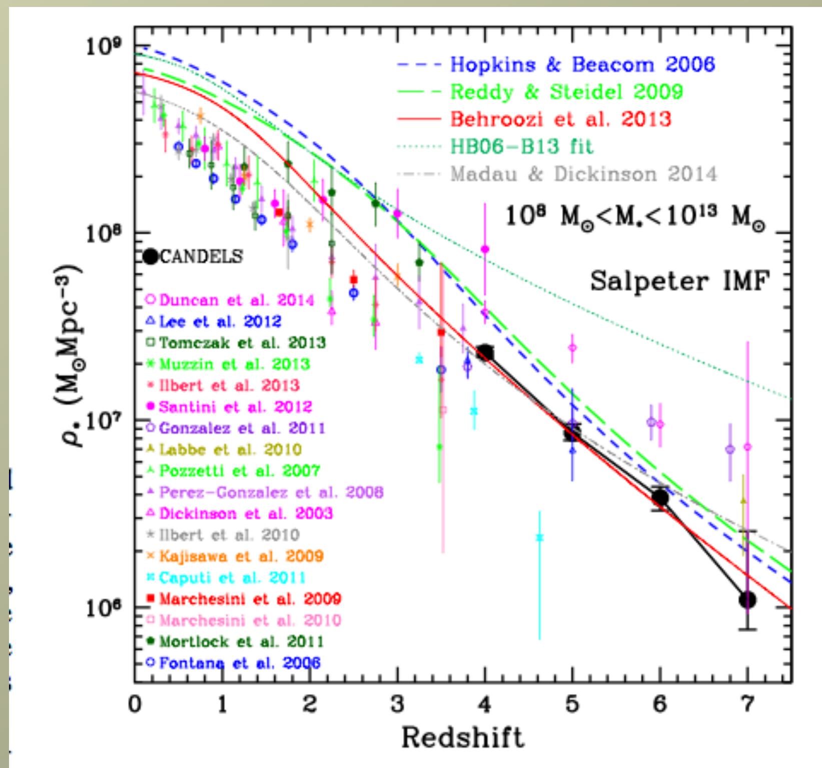
# Evolution of the LBG population with redshift

*Stellar mass density*




SMD integrated down to M_UV=-18
assuming different SFHs

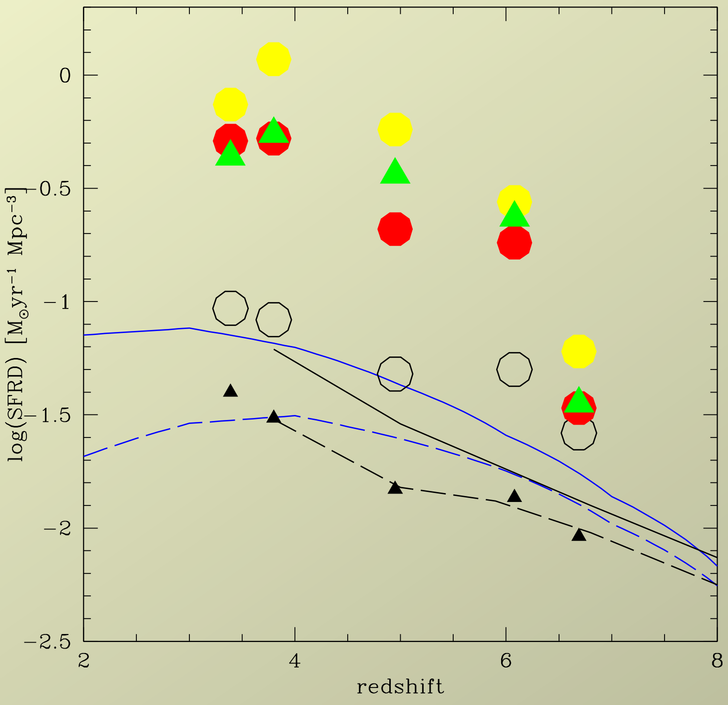
Schaerer & de Barros (2015)




Grazian et al. (2014)

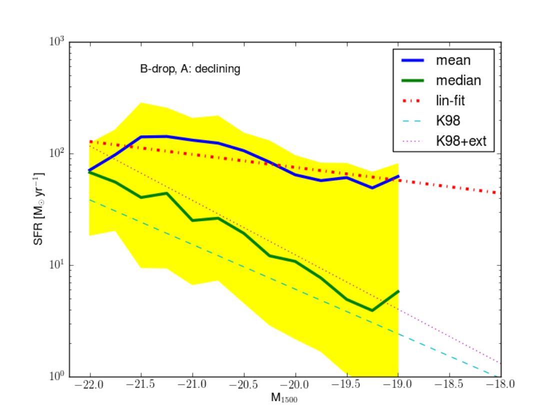
# Evolution of the LBG population with redshift

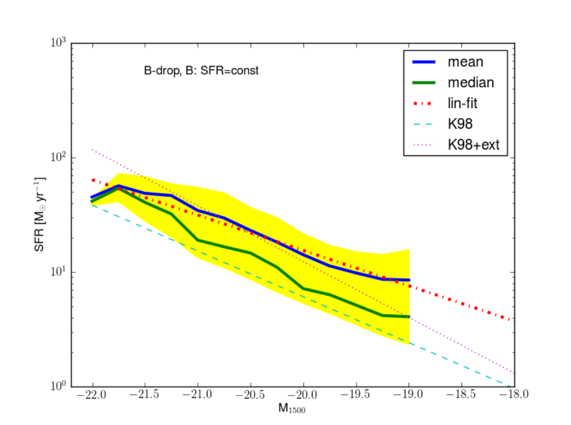
*Star formation rate density*




- Higher « instantaneous » SFRD than usual, due to variable SFHs

- Fully consistent with observed UV luminosity density

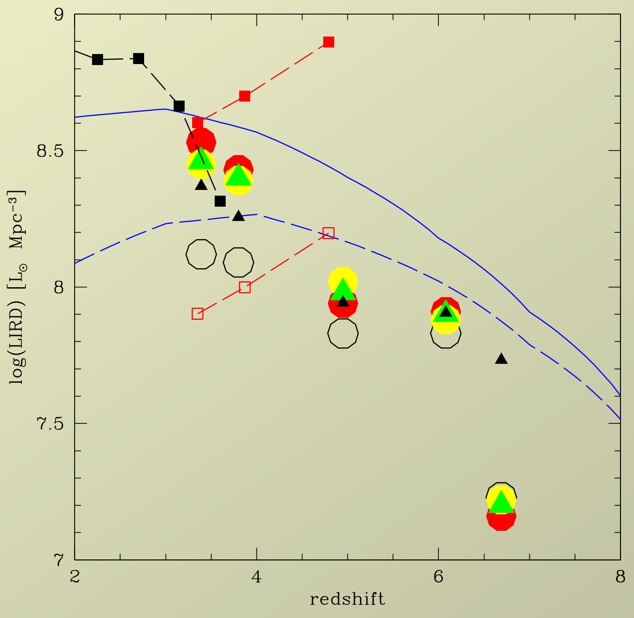



Schaerer & de Barros (2015)

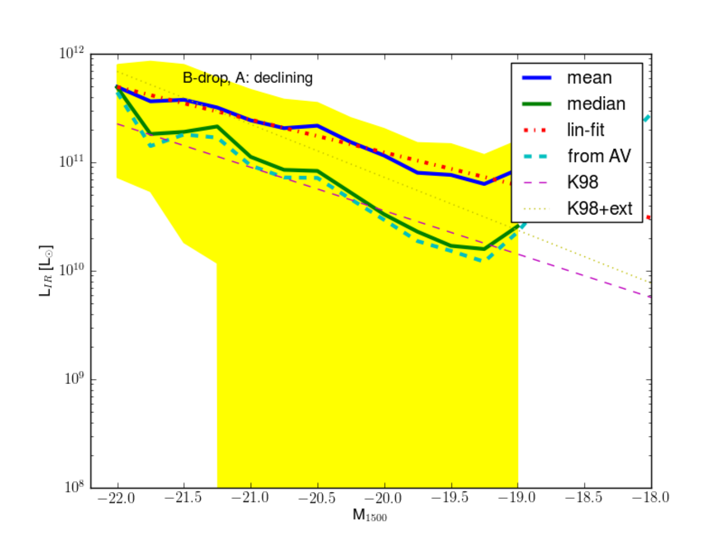
# Evolution of the LBG population with redshift

*Infrared luminosity density*

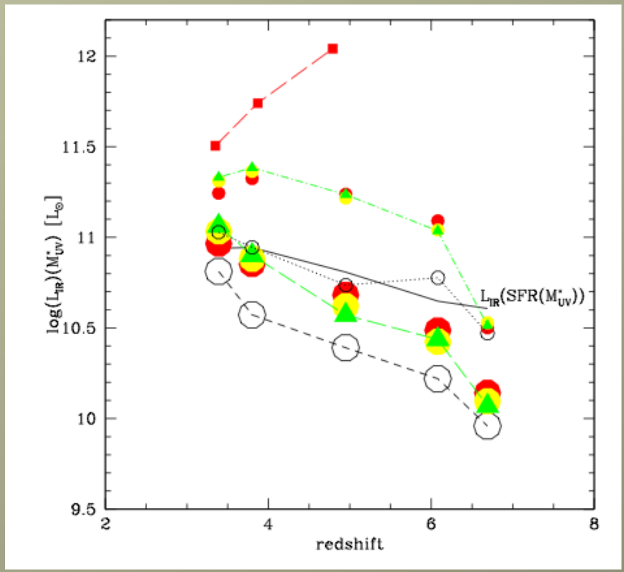



- Rapid decline of the LIRD with redshift expected
- Simple Kennicutt relation is not appropriate to predict LIR

Schaerer & de Barros (2015)

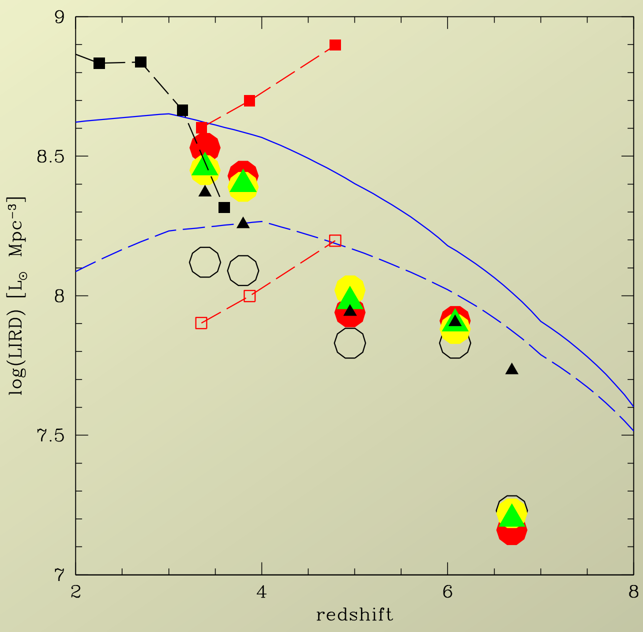



S & de Barros (2015), Schaerer et al. (2013)



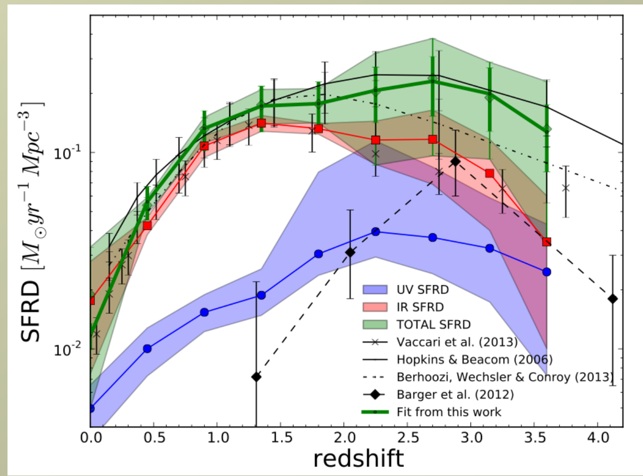
# Evolution of the LBG population with redshift

*Infrared luminosity density*

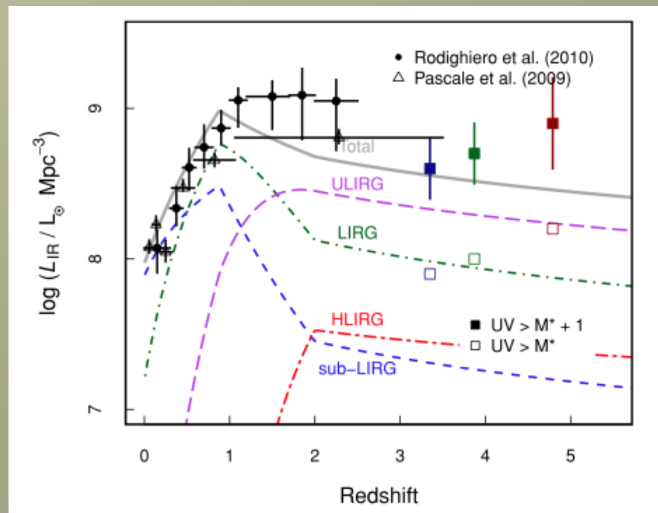



Schaerer & de Barros (2015)

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




Burgarella et al. (2014)

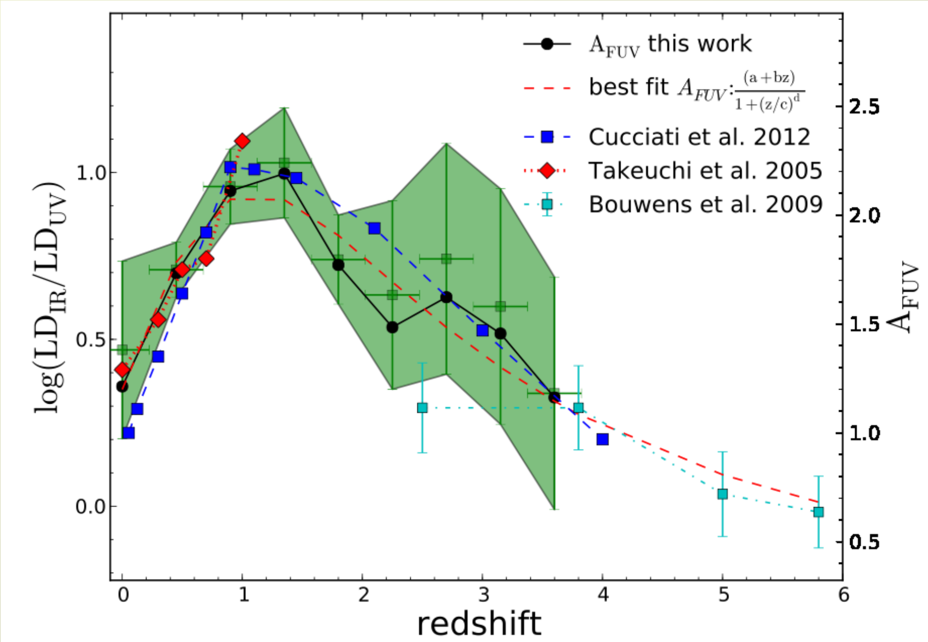


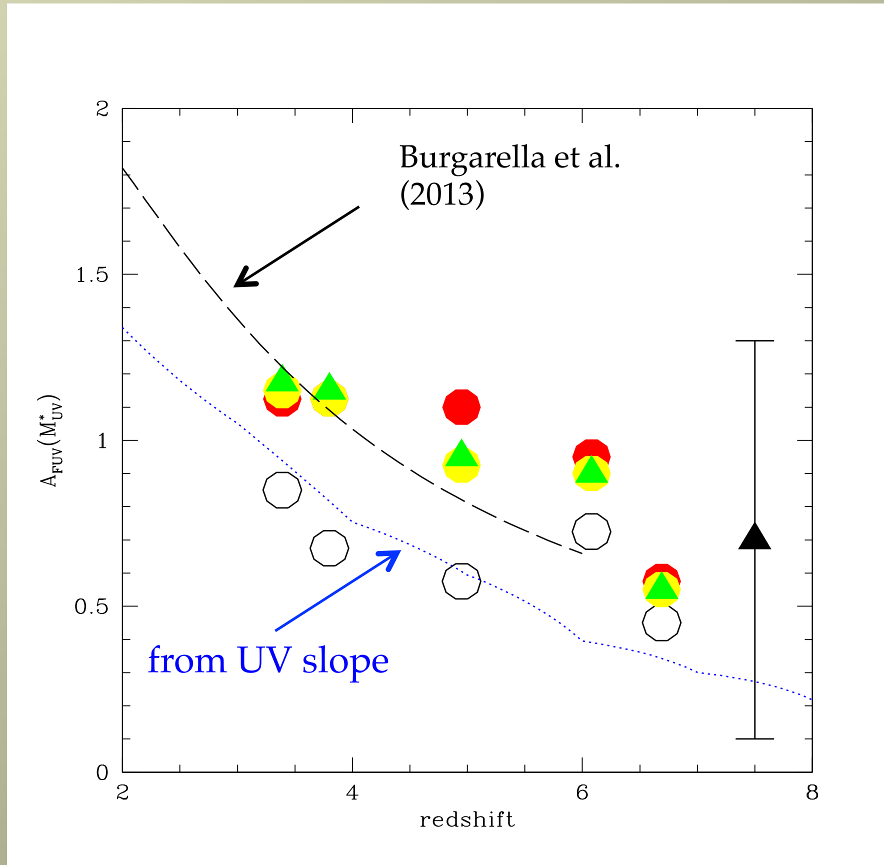

Coppin et al. (2015)

# Evolution of the LBG population with redshift

*Mean UV attenuation*

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



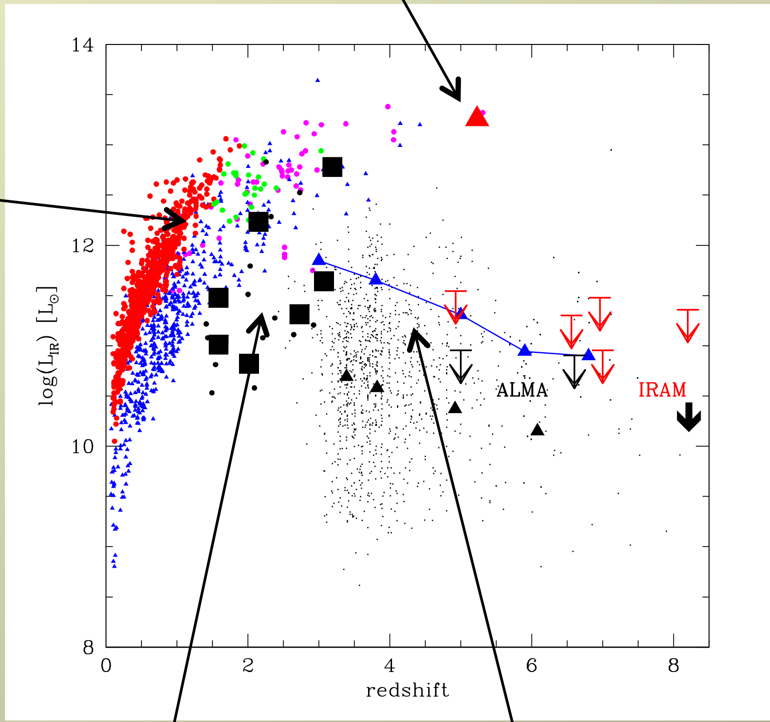

Schaerer & de Barros (2015)

# Evolution of the LBG population with redshift

*Observed and predicted IR luminosity*

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

Herschel blank fields (Elbaz+ 2011, Symeonidis+ 2013)

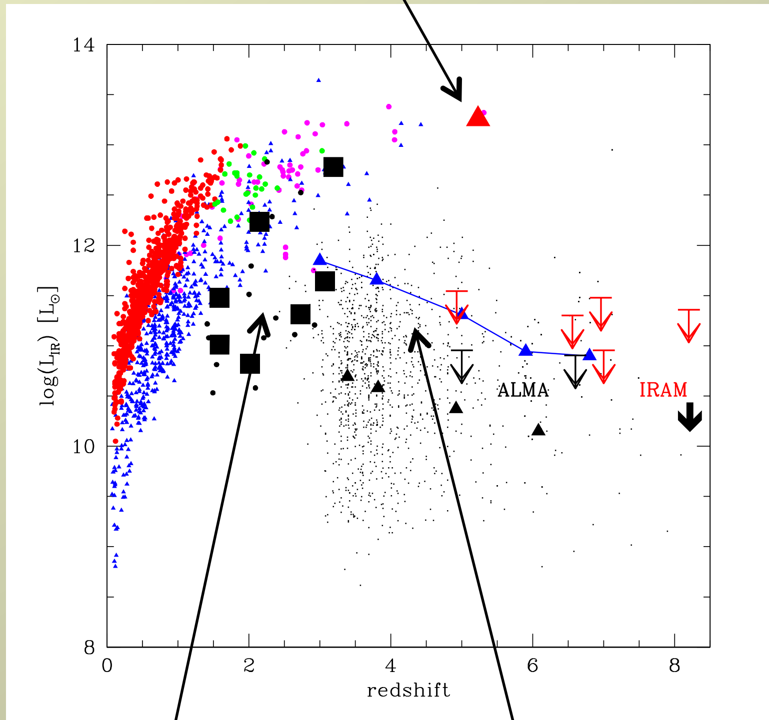



Strongly lensed objects from Herschel Lensing Survey (Sklias et al. 2014)

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

# 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)*

# Our sample

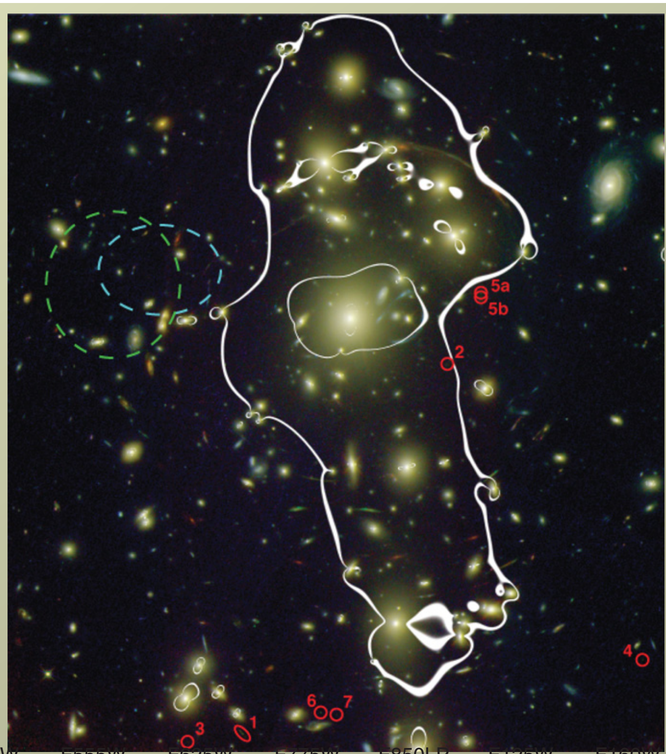
Lensed galaxies:
- z=6.56 HCM6A μ=4.5: Boone+2007
- z=7 LBG in Abell 1703 μ=9, from Bradley+ 2012

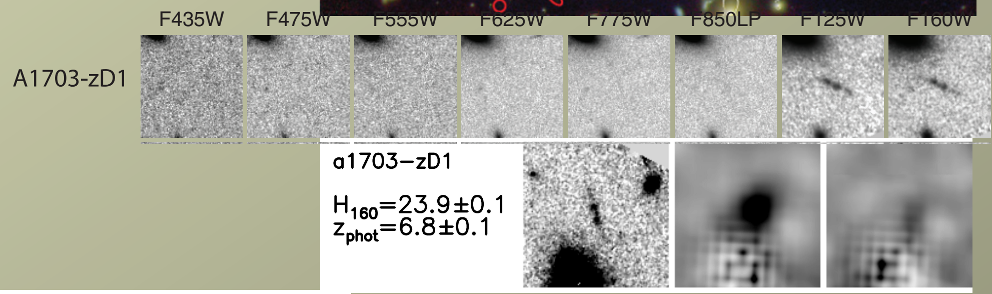
Blank fields:
- z=7.5078 LBG from Finkelstein+2013

→ New IRAM observations

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

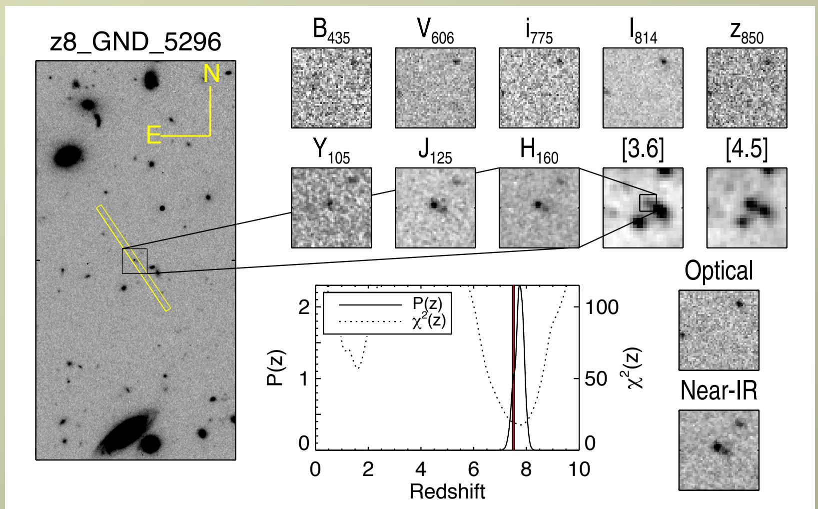
→ Recent ALMA observations

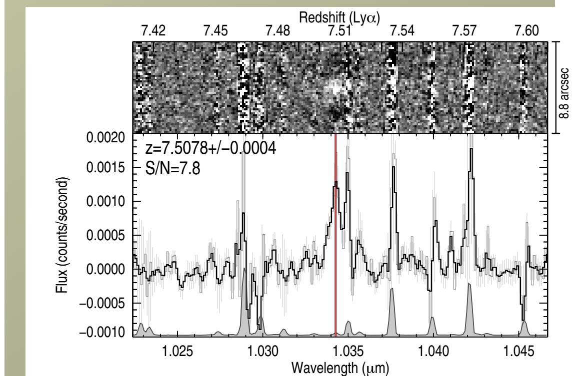



Bradley+ 2012

Finkelstein+ 2013



# IRAM and ALMA observation

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

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

➔ No detection in continuum and [CII] 158micron

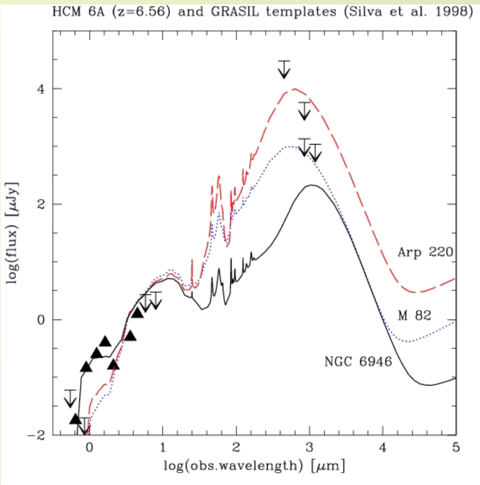
→ **Limits on IR luminosity and dust mass**: assuming T_d=35 K, β=2,
including correction for CMB heating

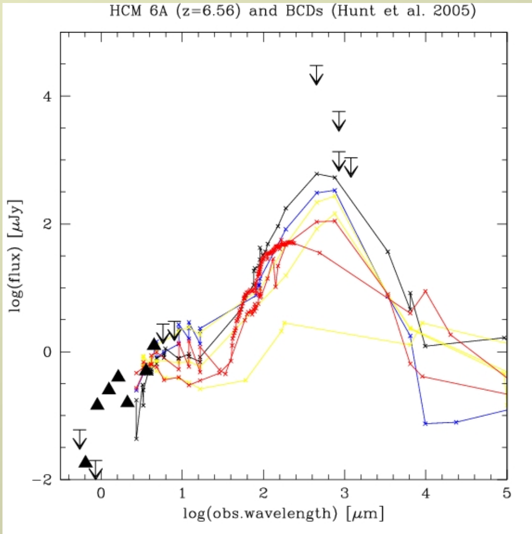
**Table 1.** Summary of millimeter observations and derived quantities. All luminosity upper limits are 3 $\sigma$ and are *not* corrected for lensing. For A1703-zD1 and HCM6A the true luminosity limits are therefore lower by the magnification factor $\mu$. The dust temperature $T_d$ indicated here is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

| Source | $z$ | $\nu$ [GHz] | $\mathrm{rms_{cont}}$ [mJy beam$^{-1}$] | $\sigma_{\mathrm{line}}$ [mJy beam$^{-1}$]$^{e}$ | $L_{[\mathrm{CII}]}$ $10^8$ [$L_\odot$] | $L_{\mathrm{IR}}(T_d=25)$ $10^{11}$ [$L_\odot$] | $L_{\mathrm{IR}}(T_d=35)$ $10^{11}$ [$L_\odot$] | $L_{\mathrm{IR}}(T_d=45)$ $10^{11}$ [$L_\odot$] | $\mu$ |
|---|---|---|---|---|---|---|---|---|---|
| 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.

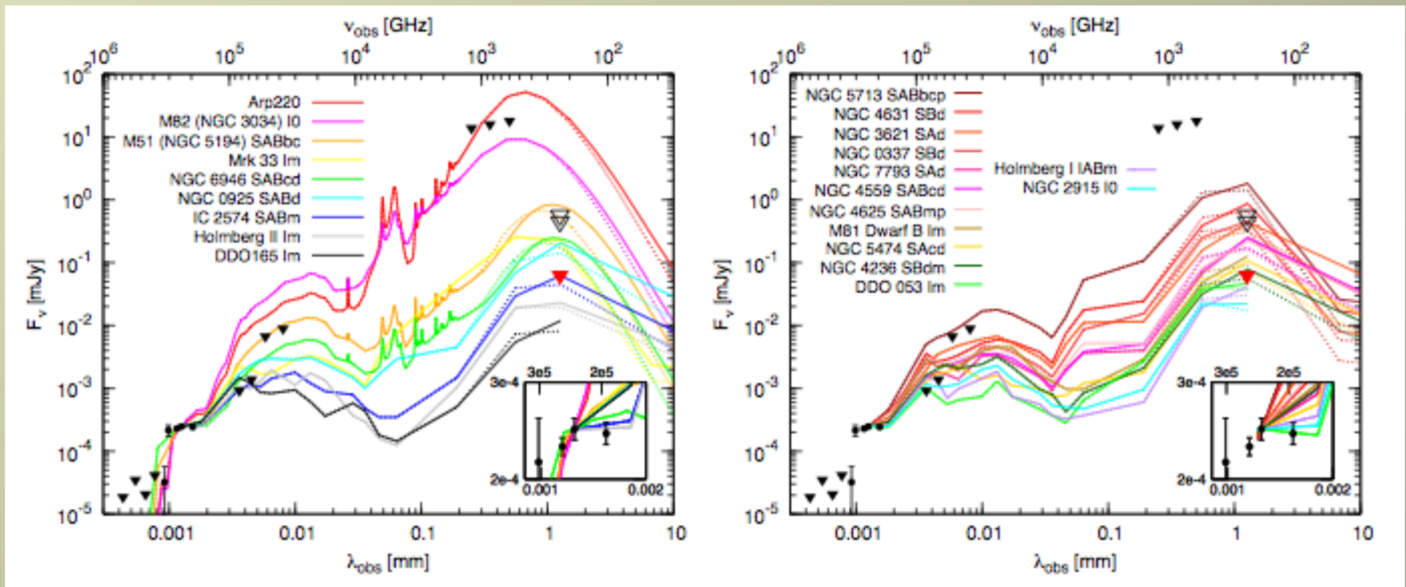
# IR-mm SED of « normal » z>6 galaxies from IRAM and ALMA



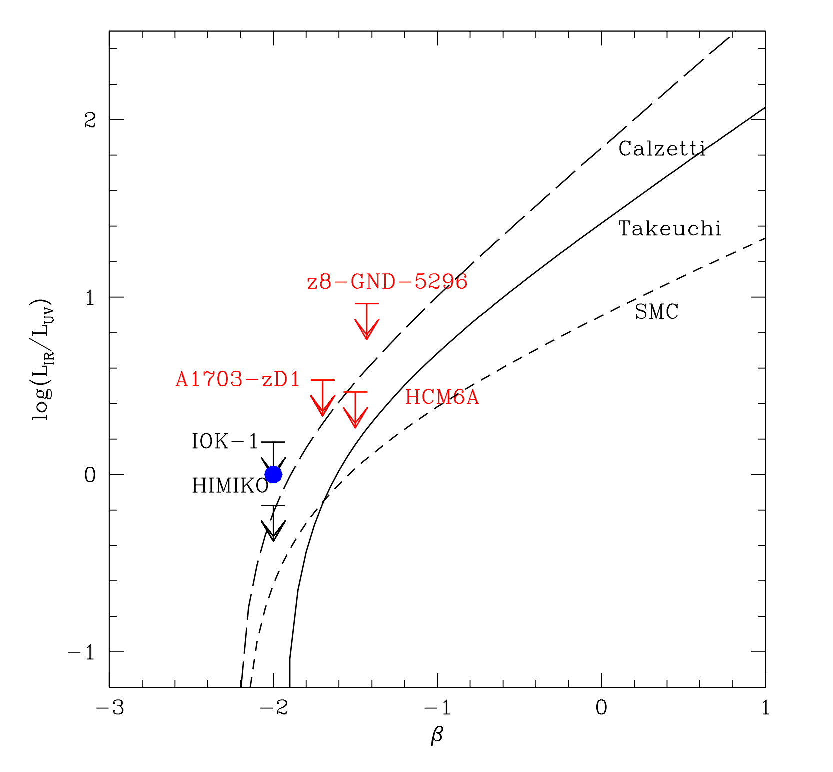

Boone et al. (2007):

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



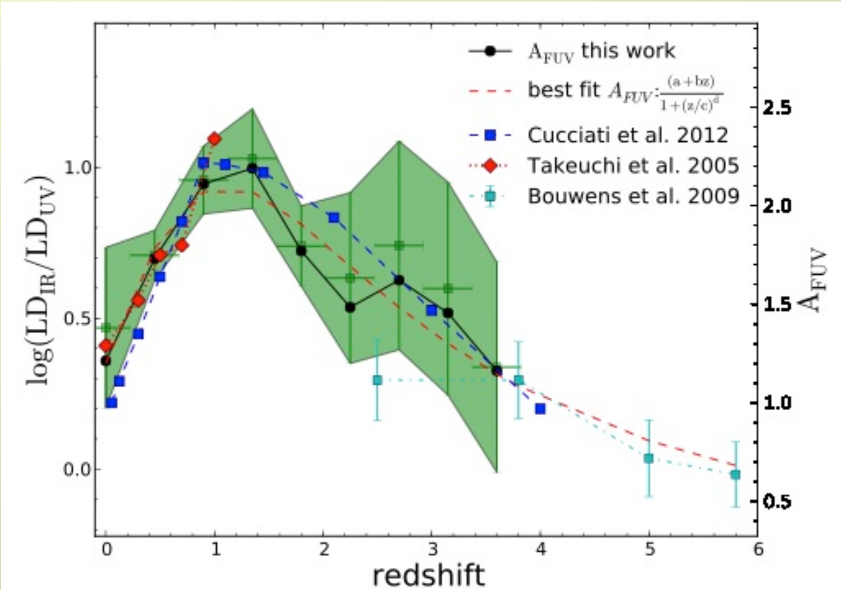

Ota et al. (2014):
SED compatible with nearby irregulars or dwarf galaxies

# 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

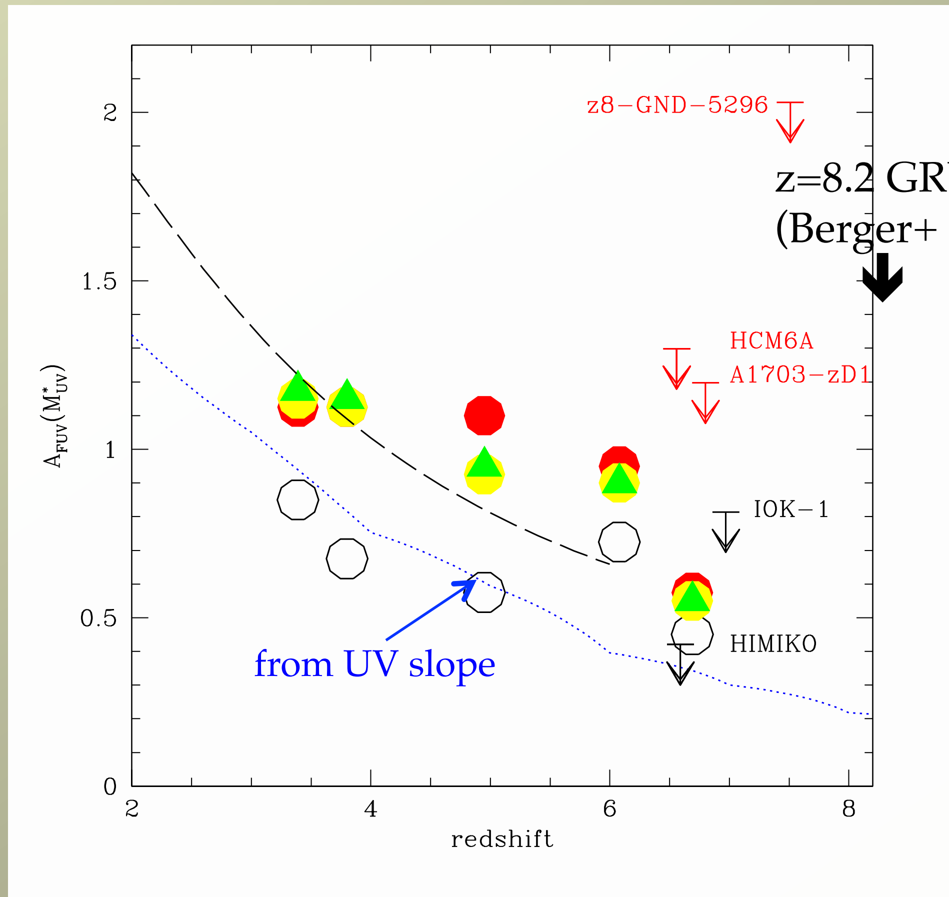



Burgarella et al. (2014)

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)

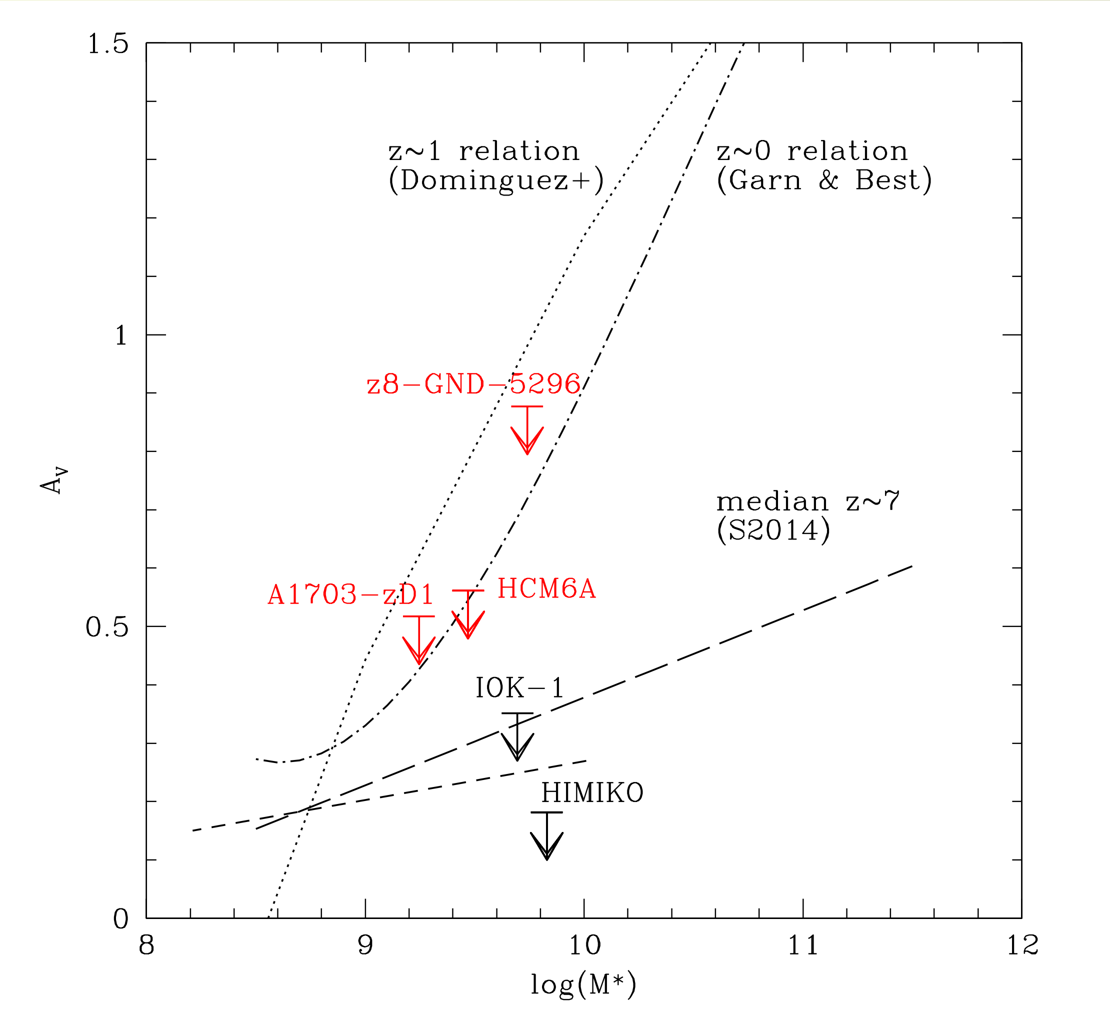



z=8.2 GRB
(Berger+ 2014)

5
3
2
0.8
0.3

Schaerer et al. (2014)

# Mass – dust attenuation relation

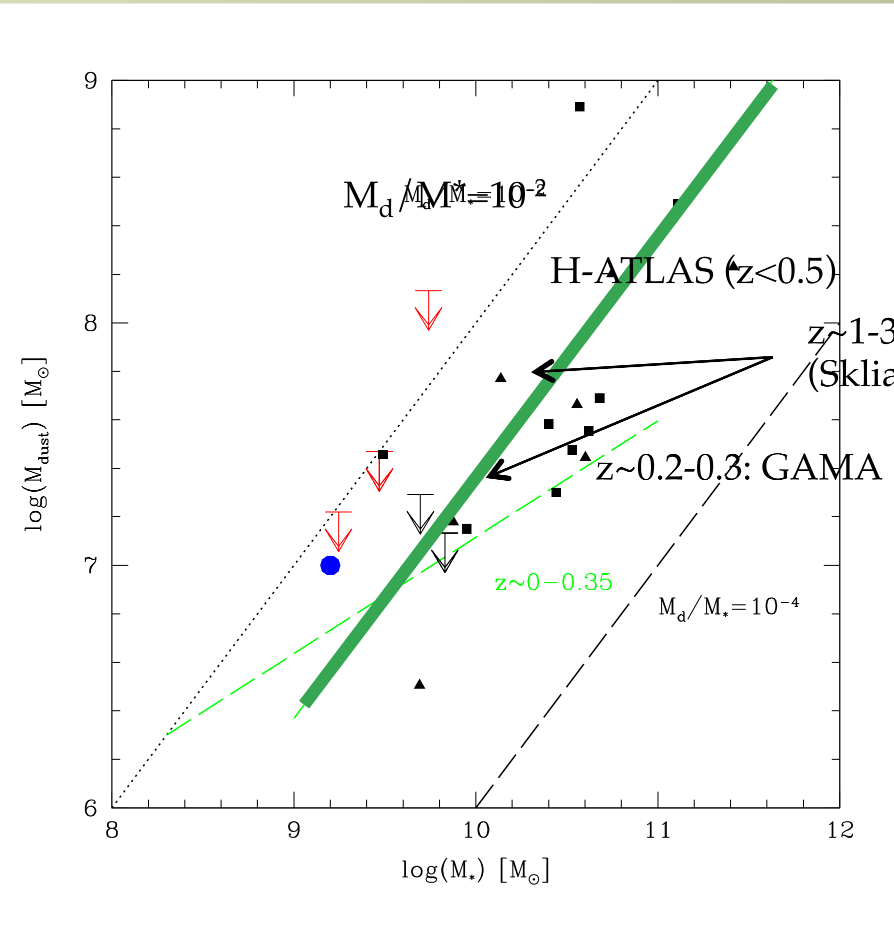


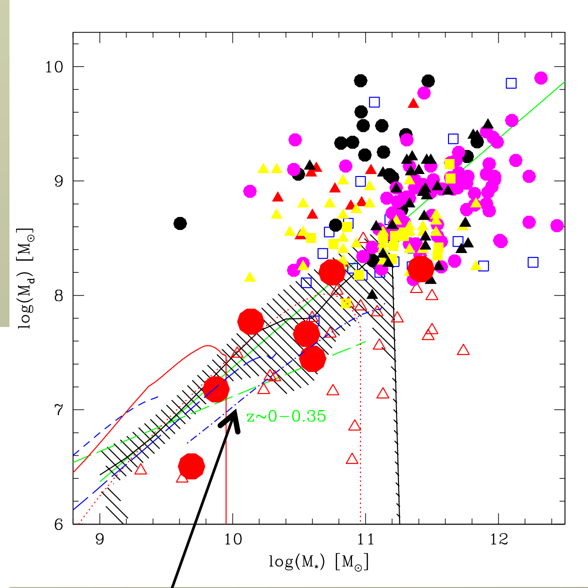

- ≥ 2 objects: less attenuation than expected from relation at lower redshift
- Compatible with *flatter mean relation for z~7 LBGs*
(Schaerer & de Barros 2014)

# 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)

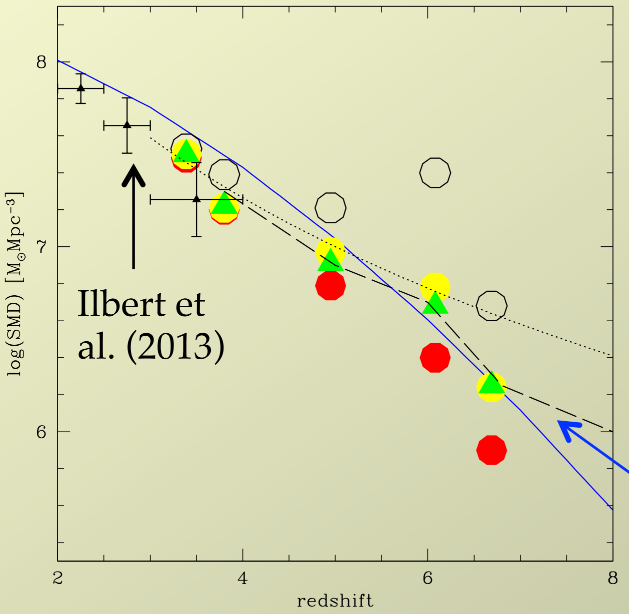


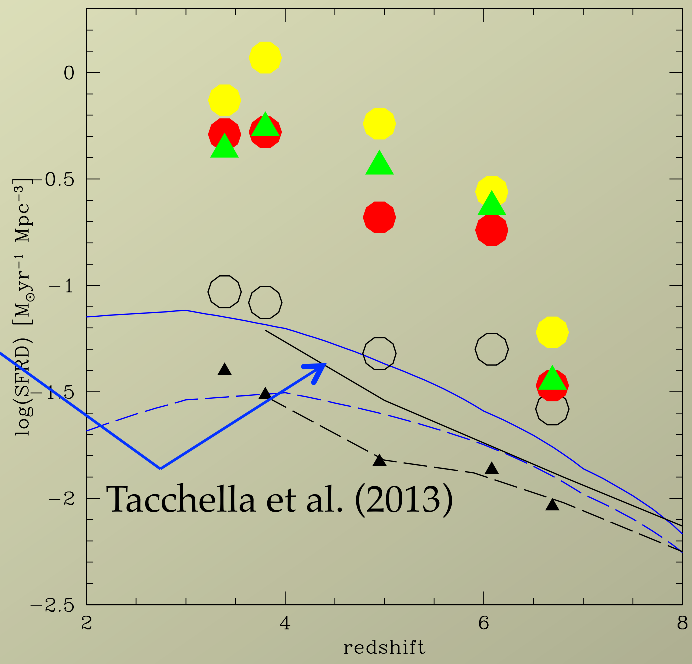

Schaerer al. (2014)

# Implications

Stellar mass density



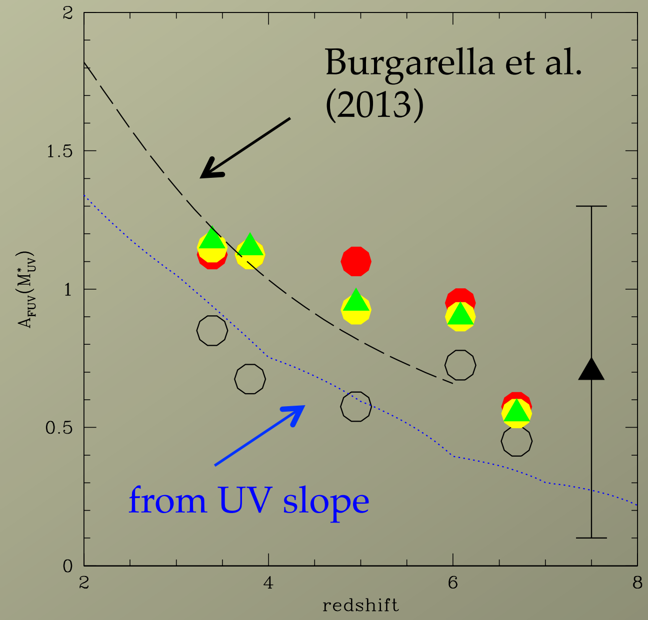

Star formation rate density



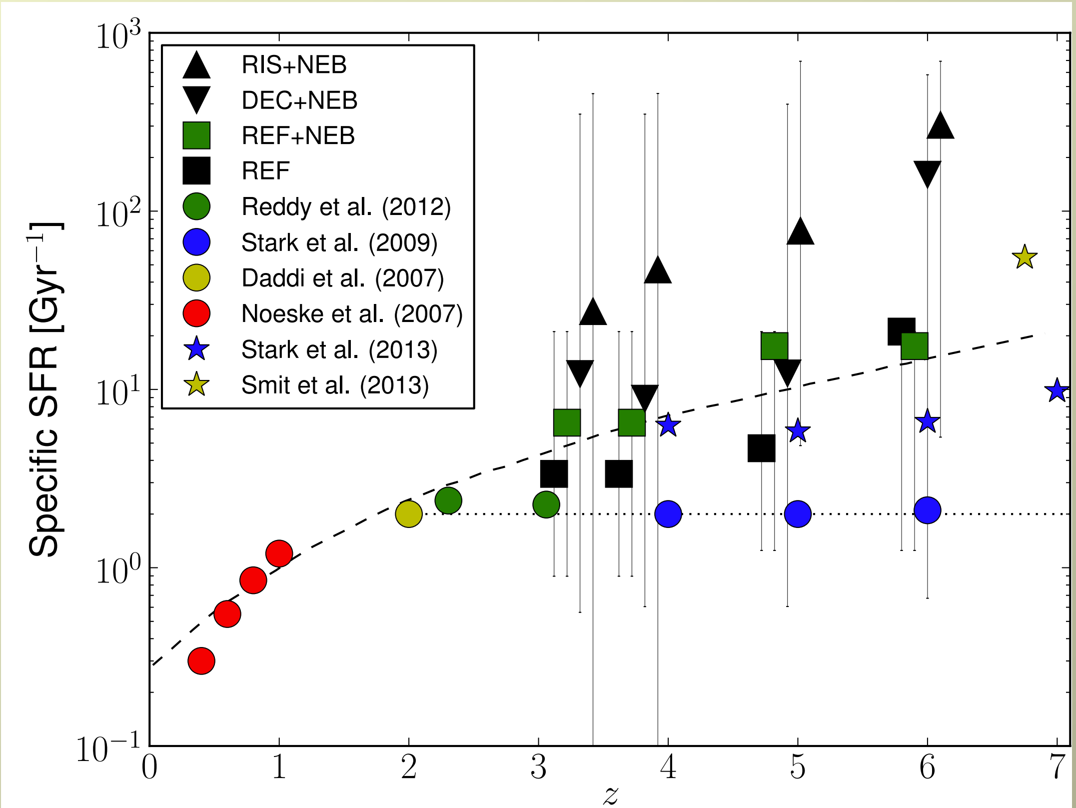

Current inferences from LBGs are compatible with latest mm observations

Schaerer & de Barros (2014)

UV attenuation



# Implications



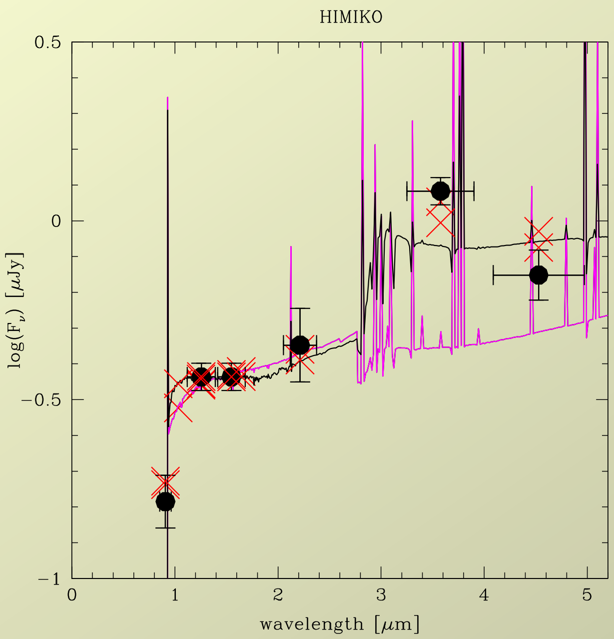

Analysis of large LBG sample with SED models allowing for:

- nebular emission
- variable SF histories

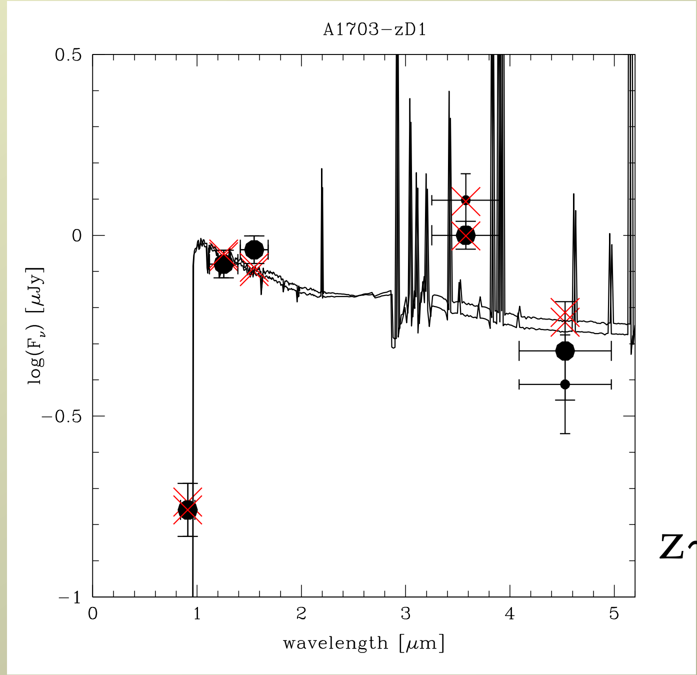
➔ sSFR rising with redshift
➔ Large scatter expected

de Barros et al. (2014)

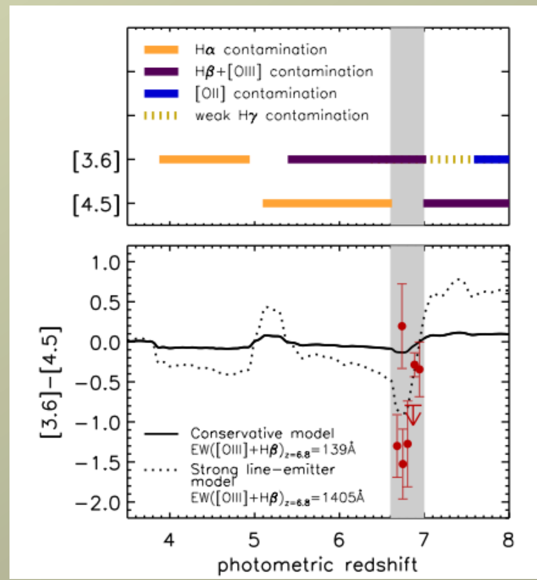
# Implications



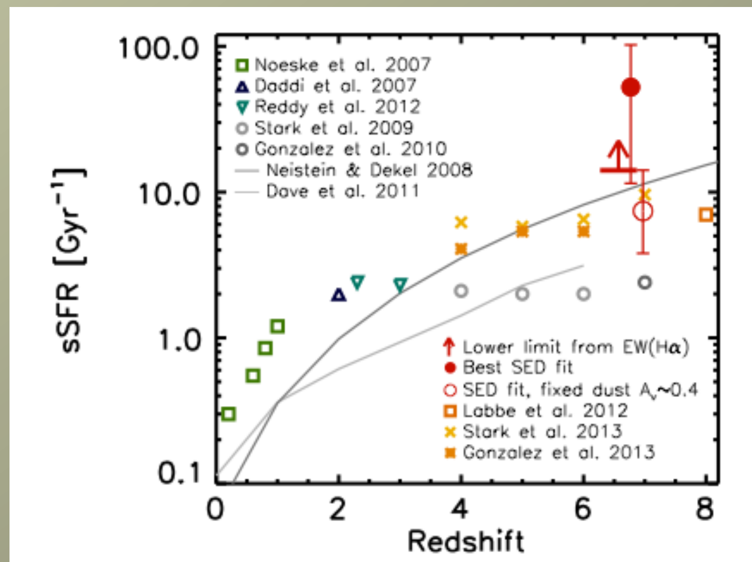

z=6.595




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!

# 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 $\mathrm{Gyr}^{-1}$ confirmed for 1 object

→ More deep IR-mm observations needed (ALMA …)

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