Physical properties of the LBG population at z~3-7

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- *Physical properties of high-z star-forming galaxies*
- *Open questions and uncertainties*

- New constraints on *dust (and age) in z>6.5 star-forming galaxies*

- WISH to the rescue!
- Conclusions

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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

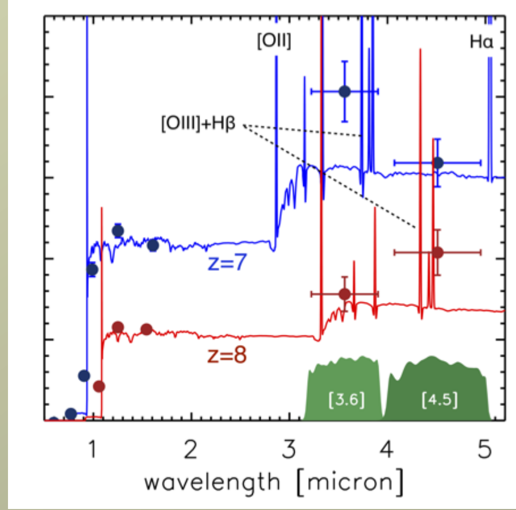
Physical properties of high redshift galaxies

- 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
Schaerer, de Barros, Sklias, 2013, A&A, 549, A4
Sklias et al., , 2014, A&A, 561, A149
Schaerer & de Barros, 2014, 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*α*

  (Shim et al. 2011, de Barros et al. 2011, Stark et al. 2012)
- Broad-band excess in **z~2 LBGs** with strong H*α*

  (Erb et al. 2006, Reddy et al.)
- **Lyman-alpha emitters (LAE) at z=3.1**: [OIII] lines dominate Ks band flux

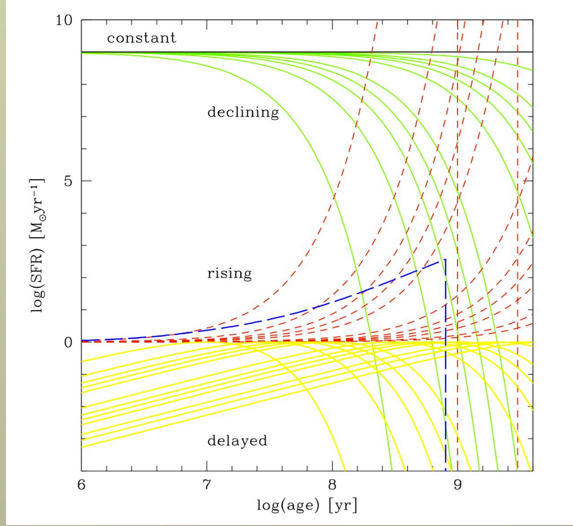
  (McLinden et al. 2011,)

- 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)
- …

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?

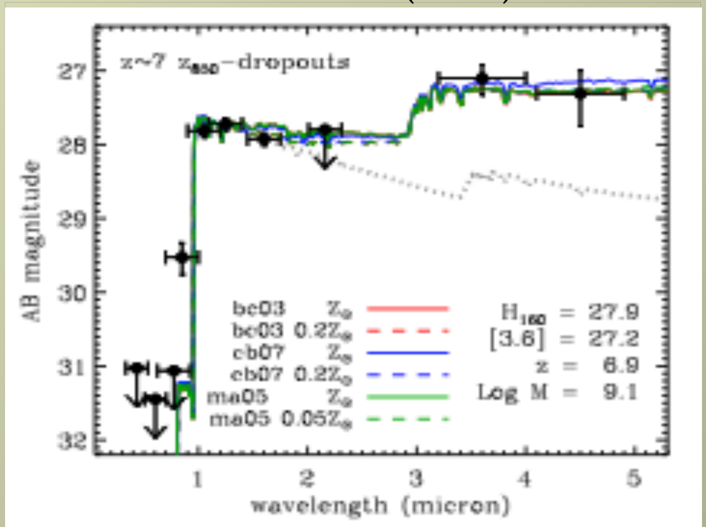
(cf. Eyles et al. 2005, 2007, Yan et al. 2006, Labbé et al. 2010)

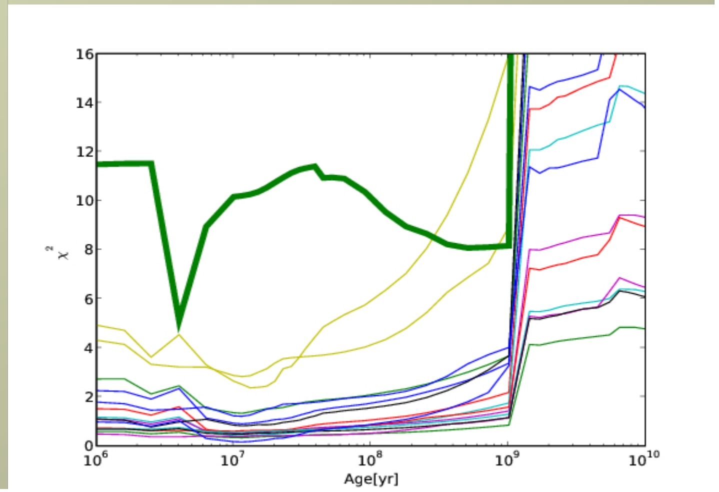
- Age estimated from Balmer break
- **Emission lines can mimick large break**

(Schaerer & de Barros 2009)

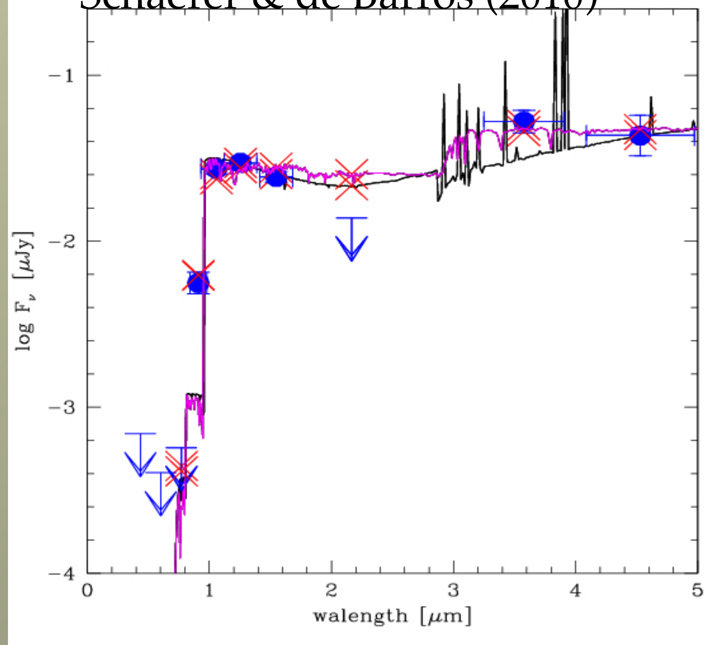
Stacked SED (14 objects @ z~7) :
classical SED fits
•Weighted age ~350 (+30-170) Myr
--> onset of SF at z~30 (+30-19) !?

Labbé et al. (2010)





Schaerer & de Barros (2010)



Models including nebular lines:

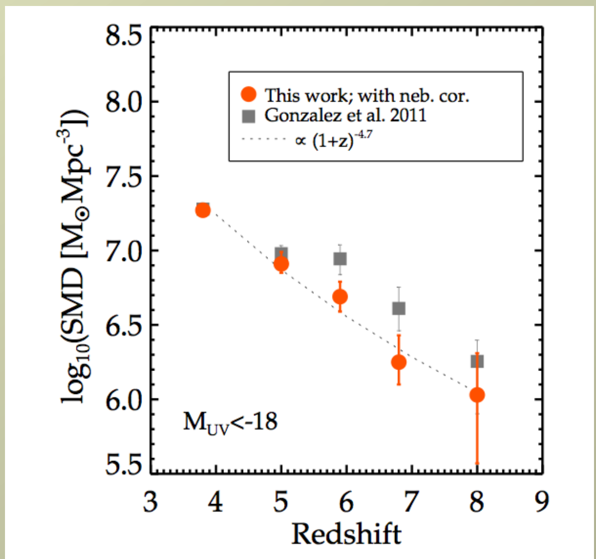
- Age~4 Myr
- A_V~0.2
- M^*~5. 10^7 $M_\odot$

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

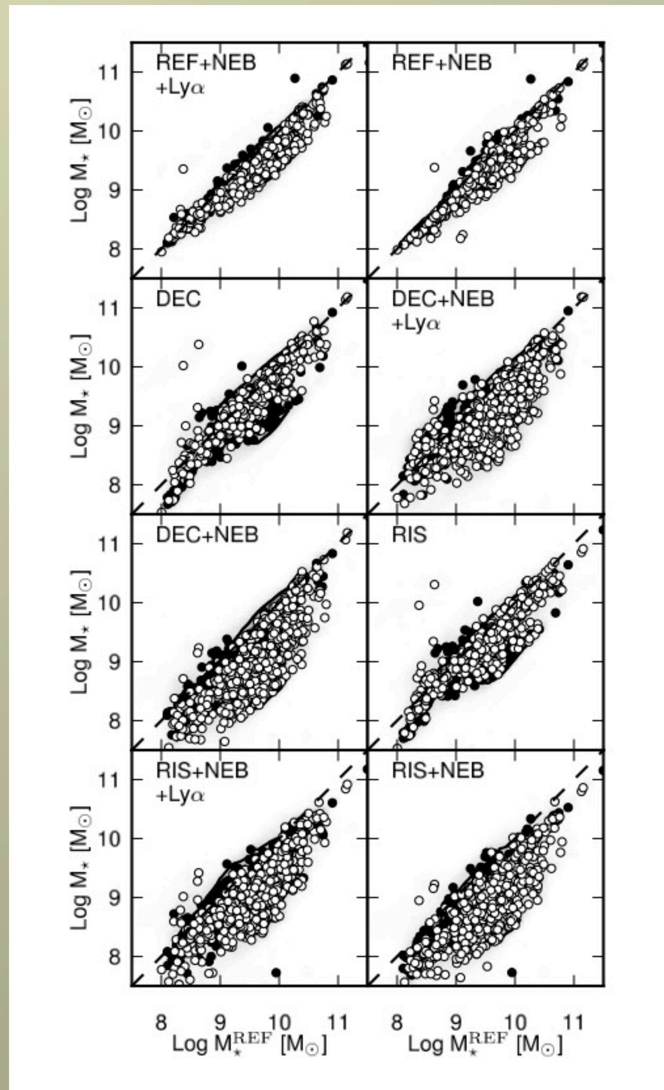
stellar masses systematically lower (than SFR=const) with nebular emission and for variable SF histories:

typically ~2-3 times lower mass

➔ Reduced stellar mass density at high-z



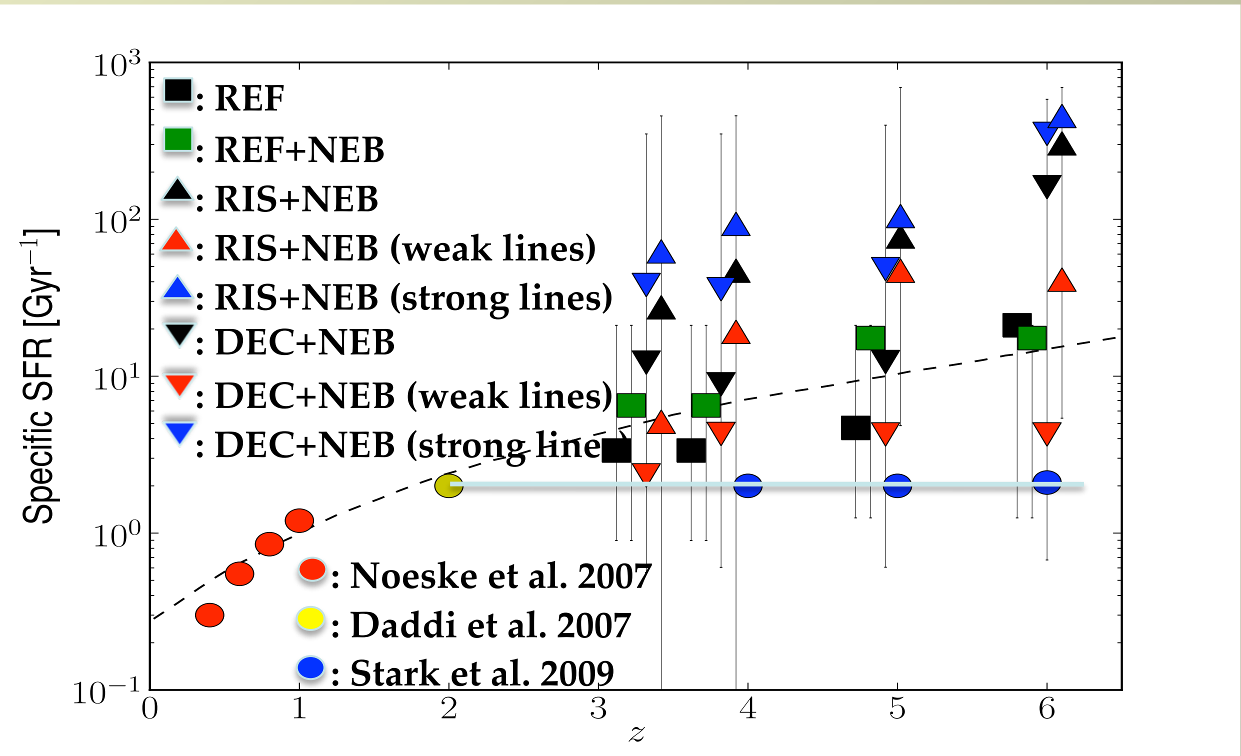
Stark et al. (2012)



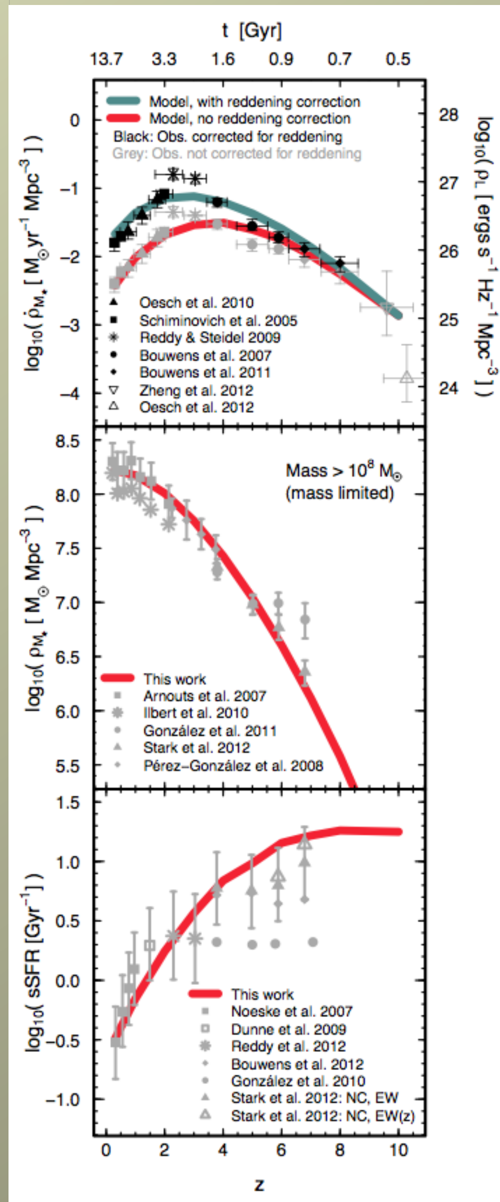
de Barros et al. (2012)

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)



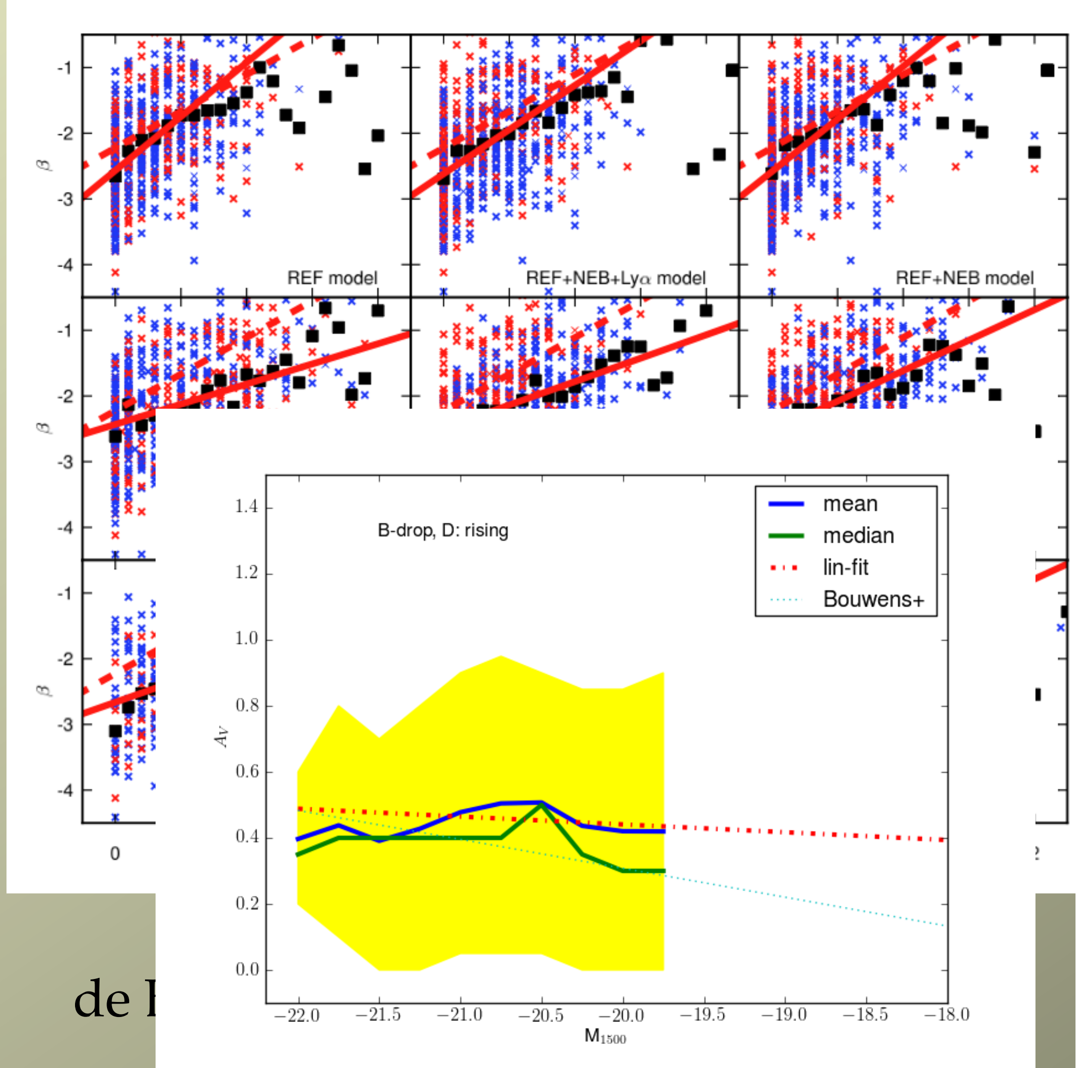
Tacchella et al. (2012)

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?
  (cf. also Castellano et al. 2014)

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

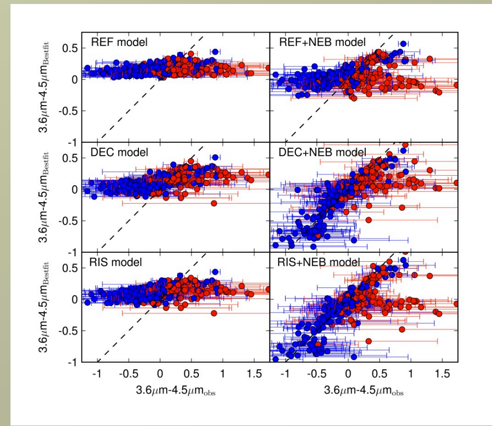


Schaerer & de Barros (2014)

5. Variable star formation histories – shorter SF timescales

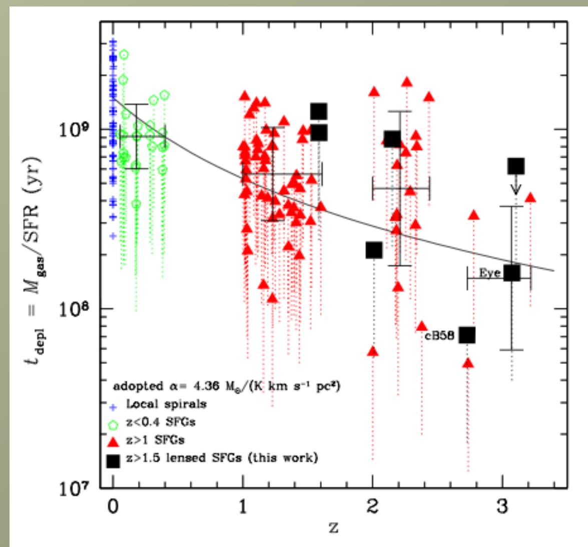
- Redshift non-evolution of M*-M_UV from z~5 to 3
  ➔ **SFR=const or fastly rising SFH excluded**
  ➔ **episodic SF favoured**
  (cf. Stark et al. 2009)

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



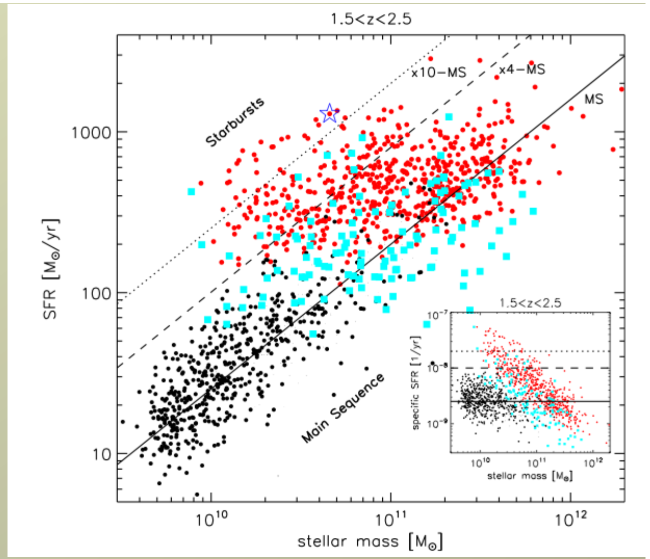
de Barros, Schaerer, Stark (2012)

- 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!

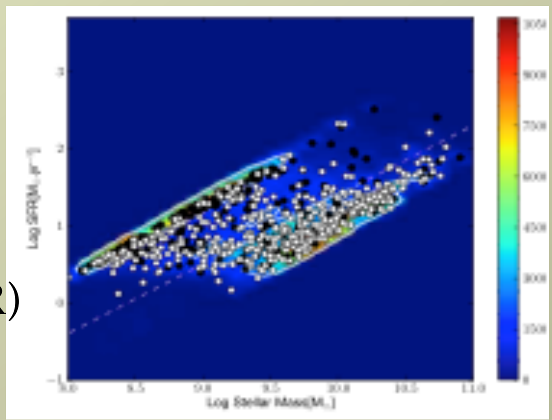
SFR=const, age>50Myr

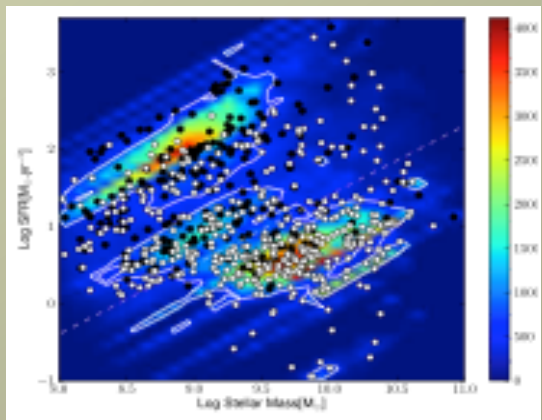
variable SF histories

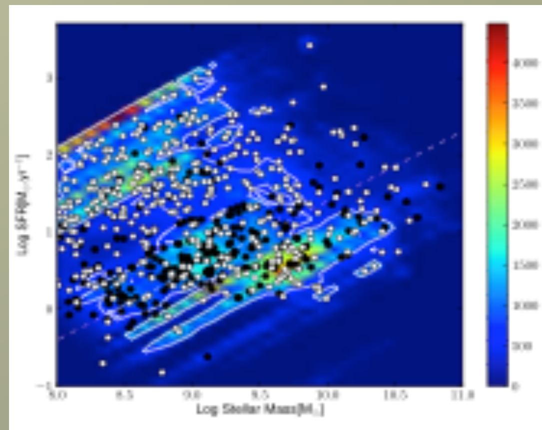
variable SF histories + nebular

A_V free

log(SFR)







log(M*)

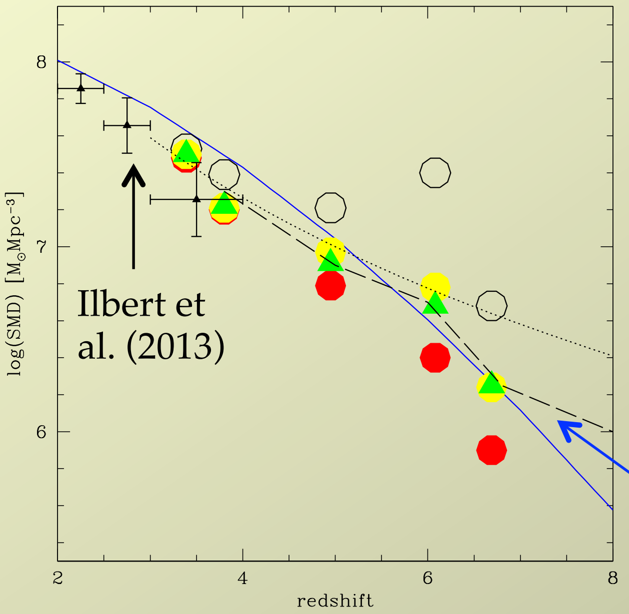
log(M*)

log(M*)

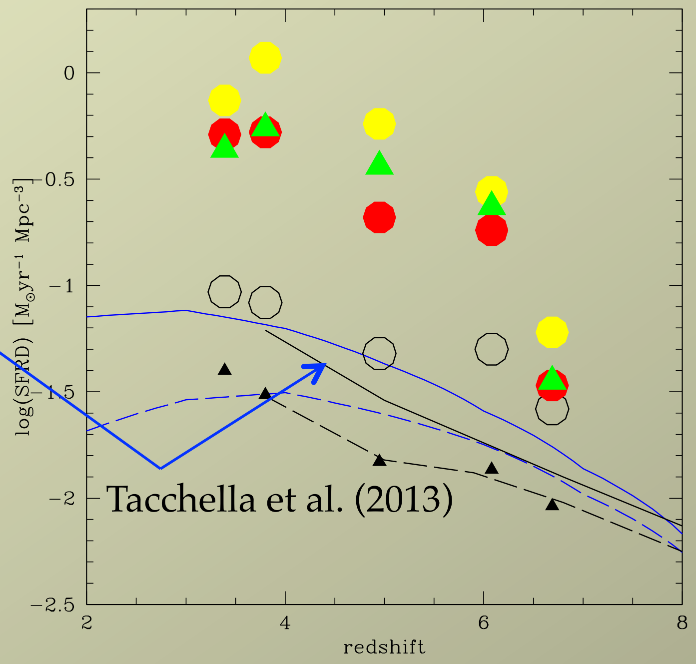
Caution: biases, selection criteria+ can severely affect the possible correlations (e.g. Dunne et al. 2009, Stringer et al. 2011)

Evolution of the LBG population with redshift

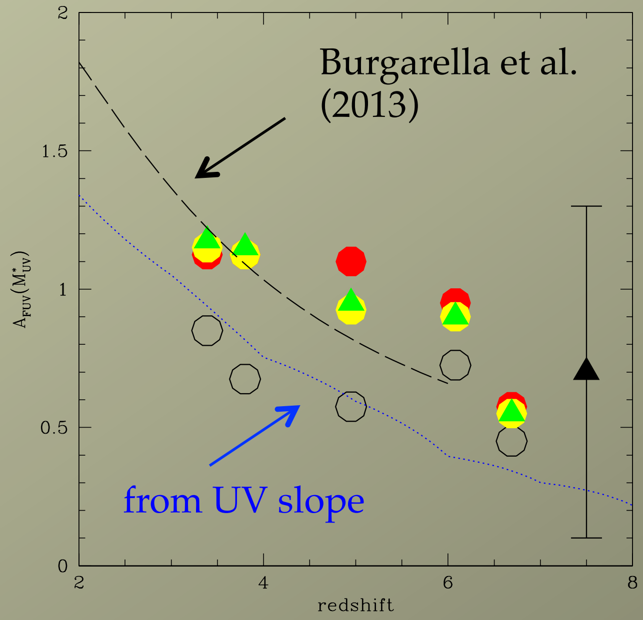
Stellar mass density



Star formation rate density



UV attenuation



Schaerer & de Barros (2014)

Open questions / uncertainties

- Galaxy ages (too) young?

  → Degeneracies between physical parameters (age, extinction)
  → SFR, M* depend also on age

- z~6-7: high sSFR typical? Mean sSFR and scatter not well established

- Complex SFH? More bursty for lower masses?
- Do quiescent galaxies exist at very high z ?

- Existence of SF main sequence at high-z? Interpretation of MS?

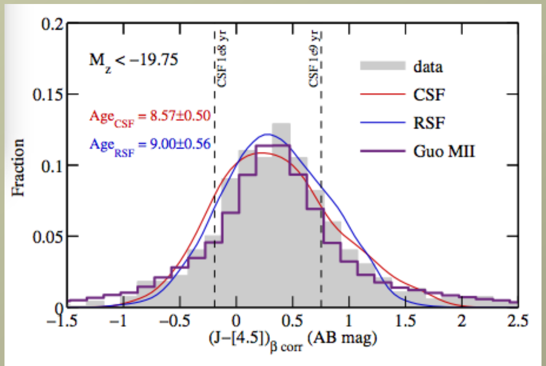
Open questions / uncertainties

- **Galaxy ages (too) young?**

  → **Degeneracies between physical parameters** (age, extinction)
  → SFR, M* depend also on age

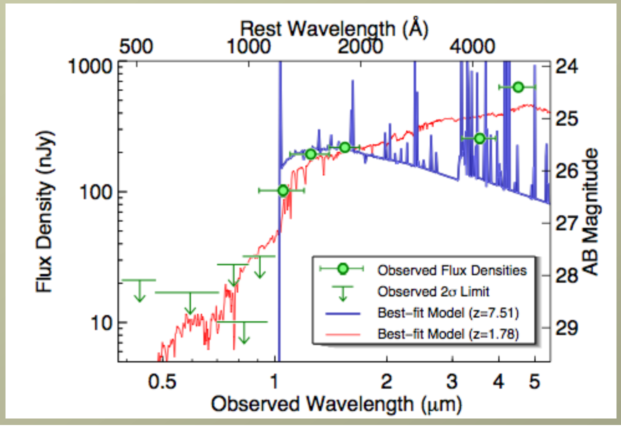
- Does Balmer break yields older age?

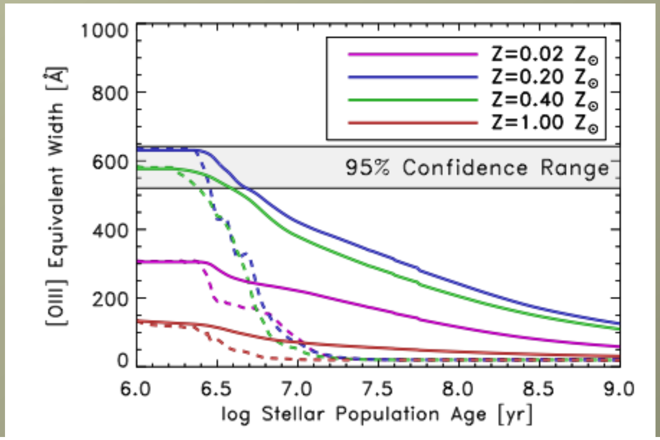
Oesch+ (2013)



- z~6-7 galaxies: very young? – Finkelstein+ object @ z=7.5
  Himiko (z=6.5)

Finkelstein+ (2013)





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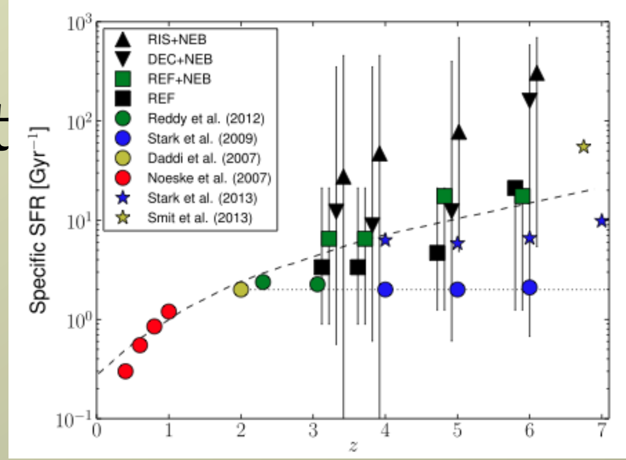
- z~6-7: very high sSFR typical? Mean sSFR and scatter not well established

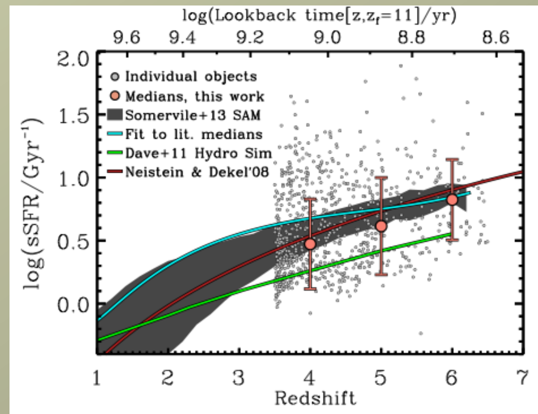
- Complex SFH? More bursty for lower masses?

- Existence of SF main sequence at high-z? Interpretation of MS?

E.g. Speagle+ (2014), Kelson (2014)

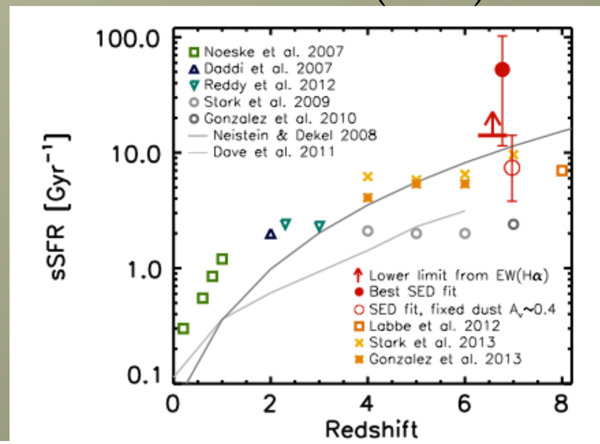


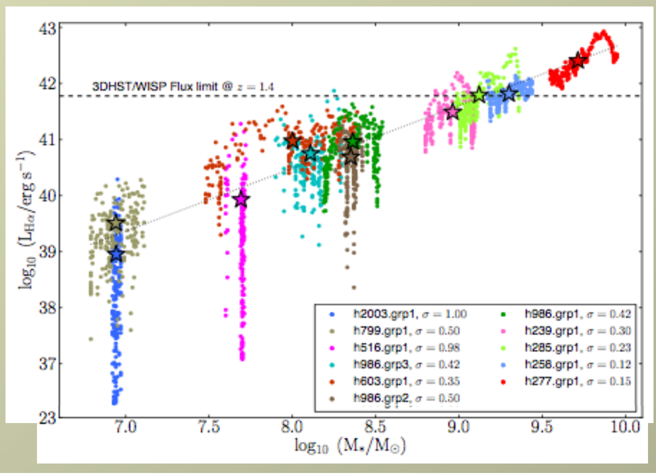
de Barros et al. (2012, 2014)



Salmon et al. (2014)

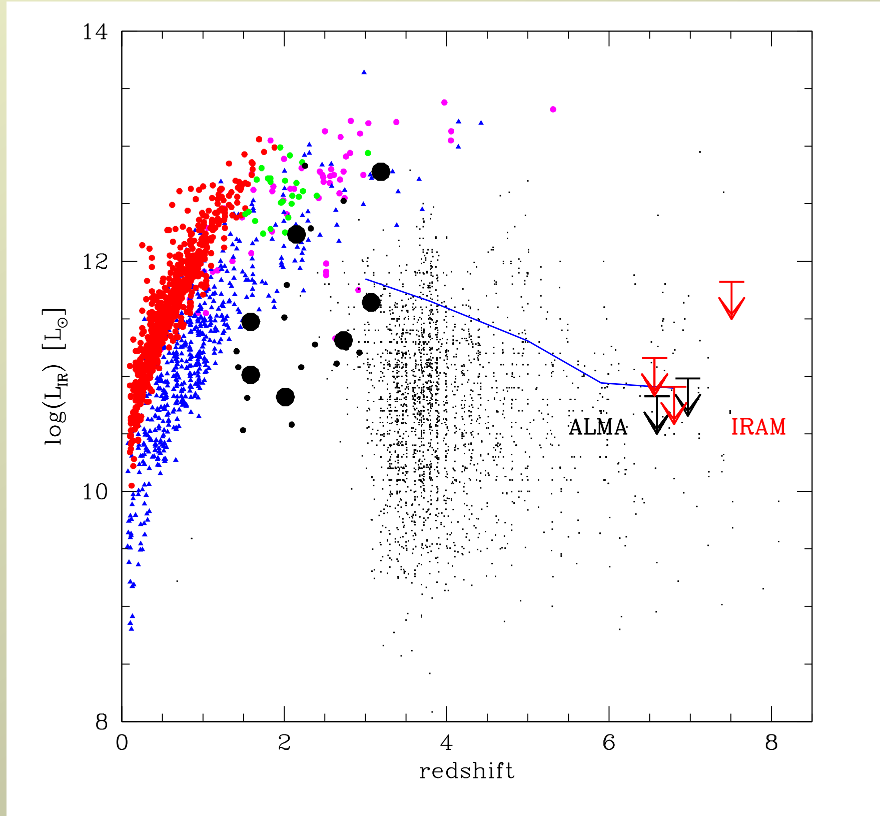
Smit et al. (2014)





Dominguez et al. (2014)

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



→ *Schaerer et al. (2014, arXiv: 1407.5793)*

Lensed galaxies:

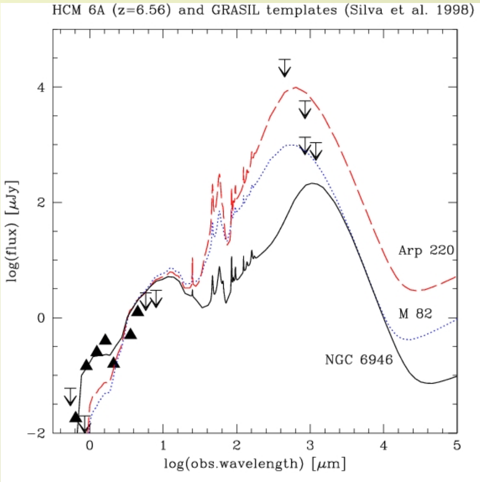
- z=6.56 HCM6A: Boone+2007
- z=7 A1703: Schaerer+2014

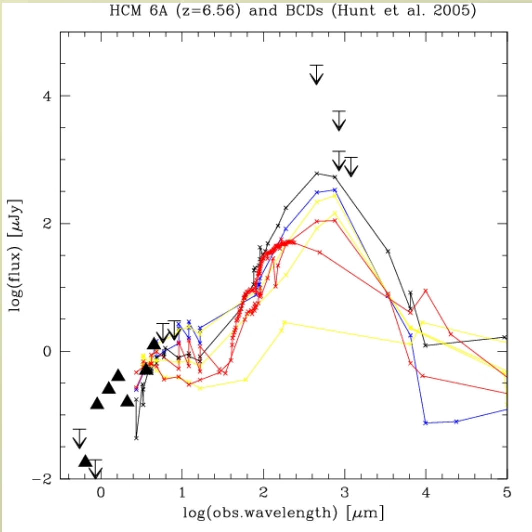
Blank fields:

- 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

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

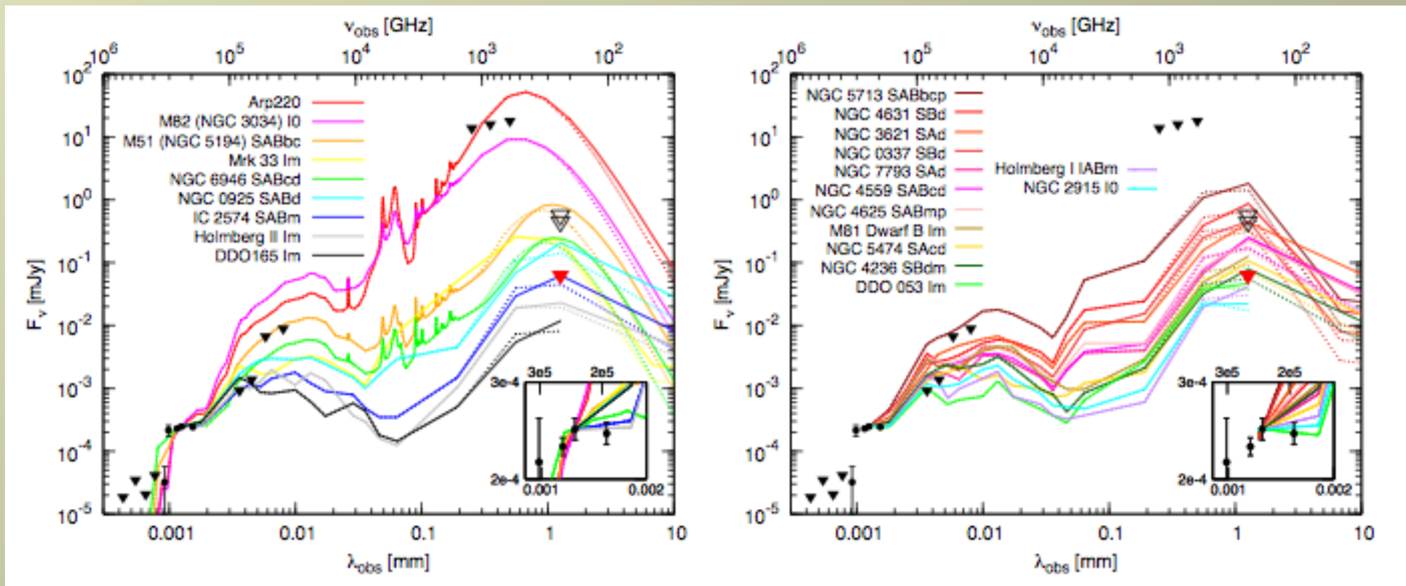
First hints on dust in « normal » z>6 galaxies with IRAM and ALMA





Boone et al. 2007:

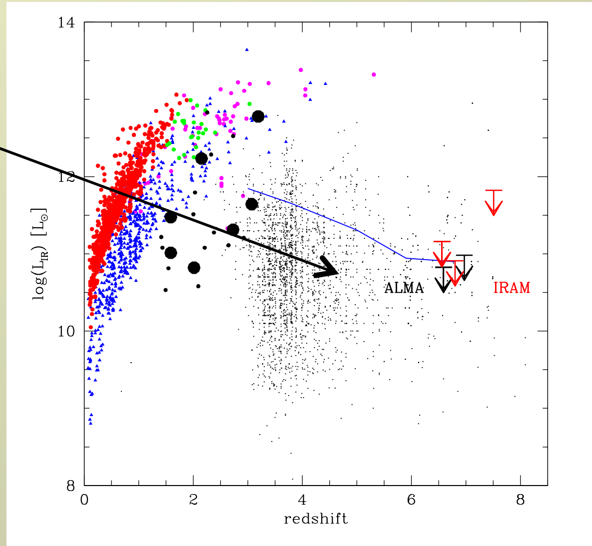
- SEDs of Arp220, M82-like objects excluded
- SED compatible with nearby spirals or dwarf galaxies



Ota et al. 2014

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

Predicted L_{IR} of ~1400 LBGs from z~3.4 – 7 (Schaerer & de Barros 2014)



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
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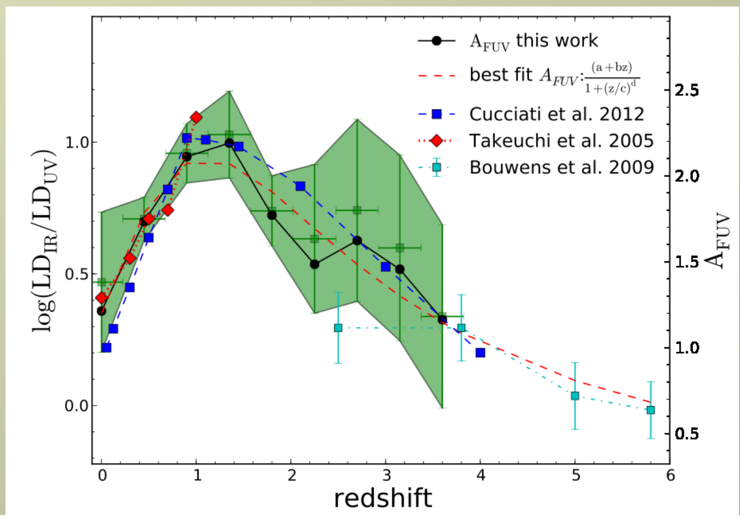
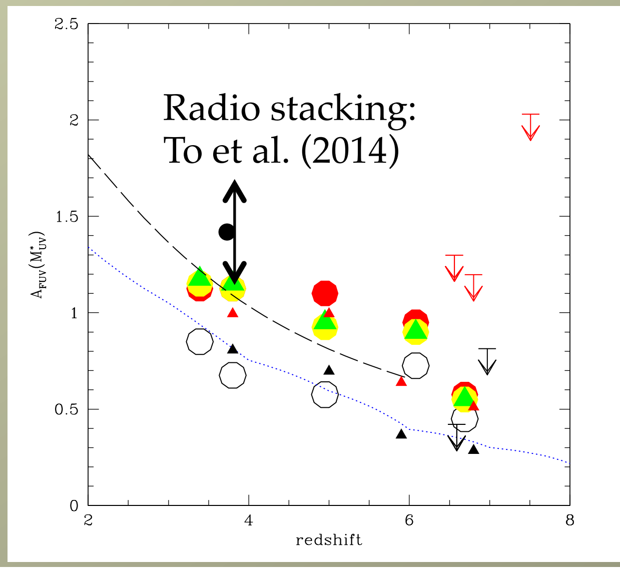
- z=7.5 Finkelstein+2013 object

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

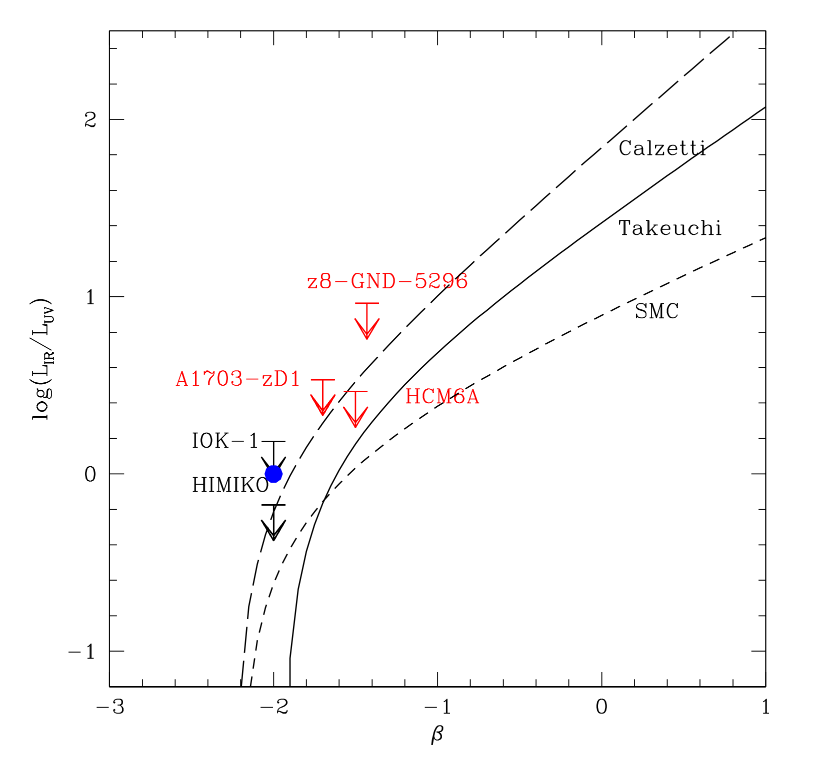


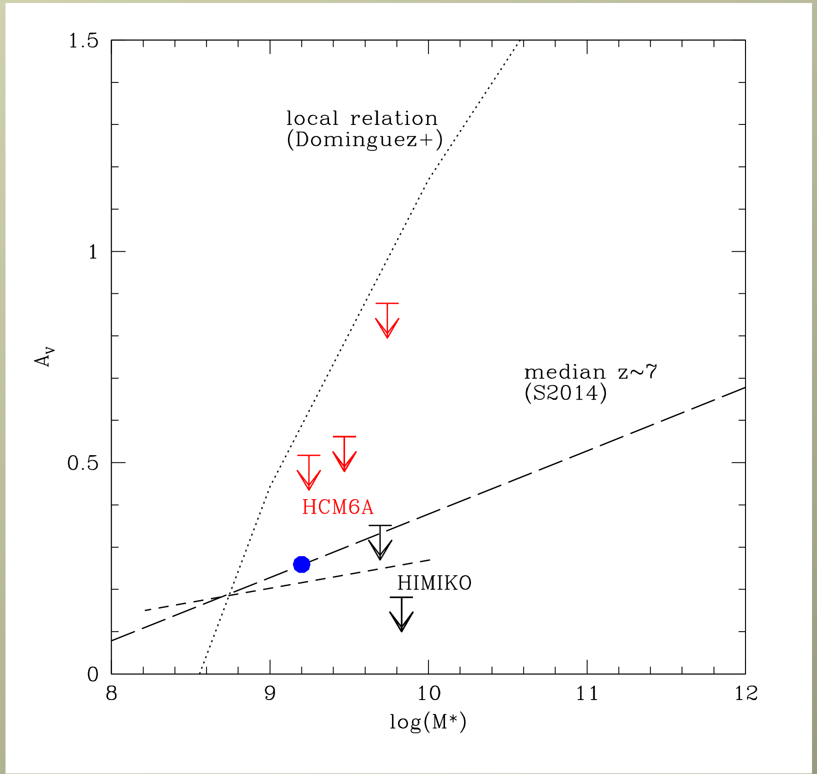


LBGs:

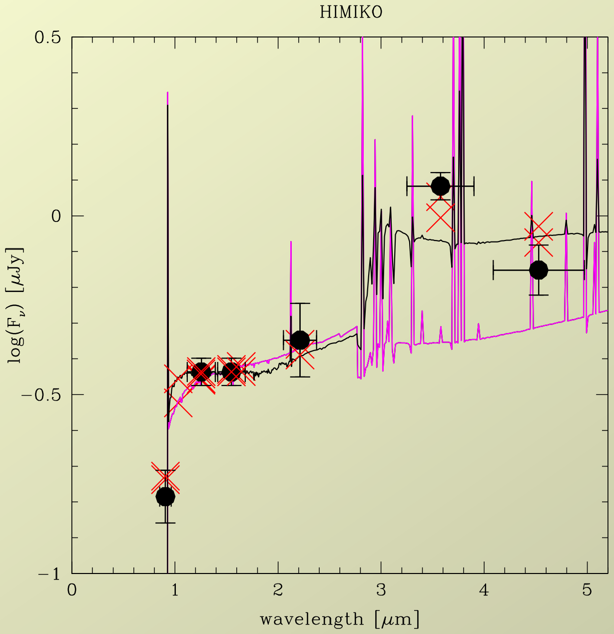
- IRAM / ALMA limits
- Attenuation from SED fits
  (Schaerer & de Barros 2014)

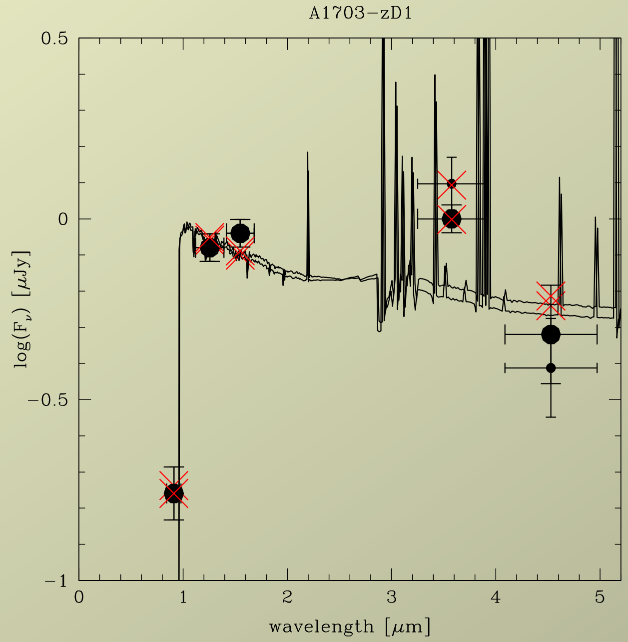
First hints on dust in « normal » z>6 galaxies with IRAM and ALMA





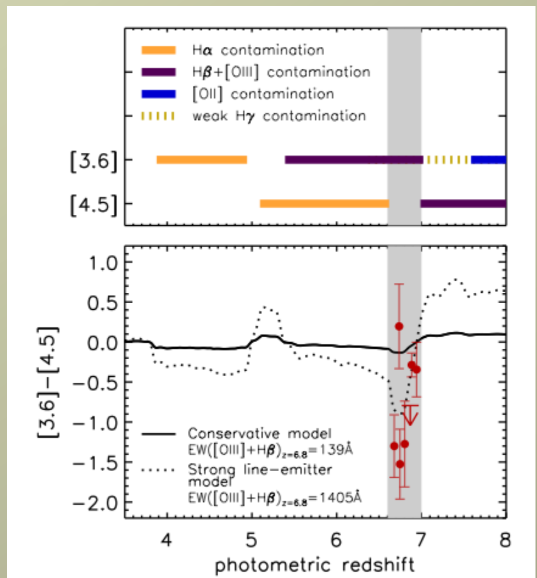
First hints on dust in « normal » z>6 galaxies with IRAM and ALMA

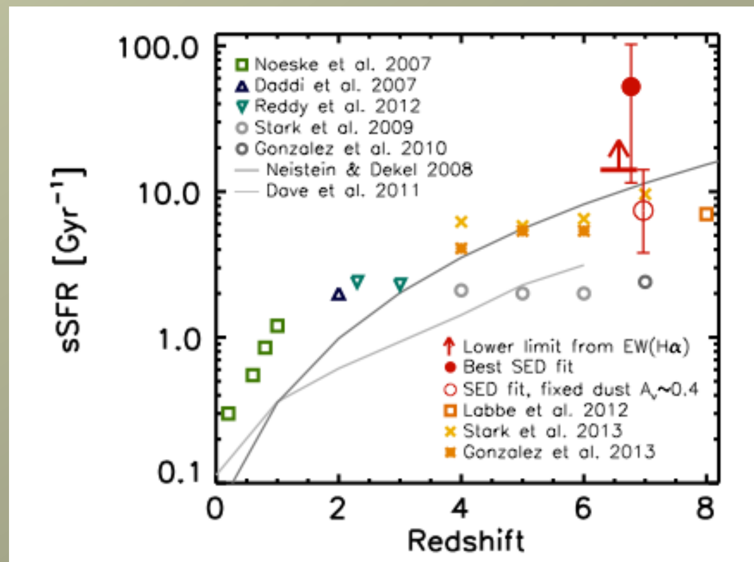




z=6.8

z=6.595

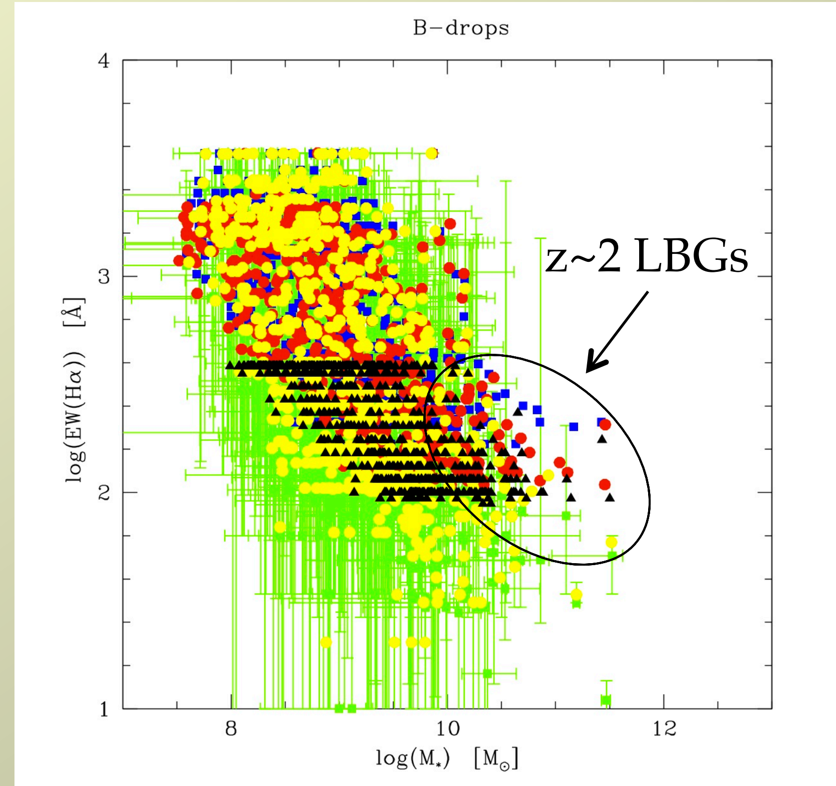




Smit et al. (2014)

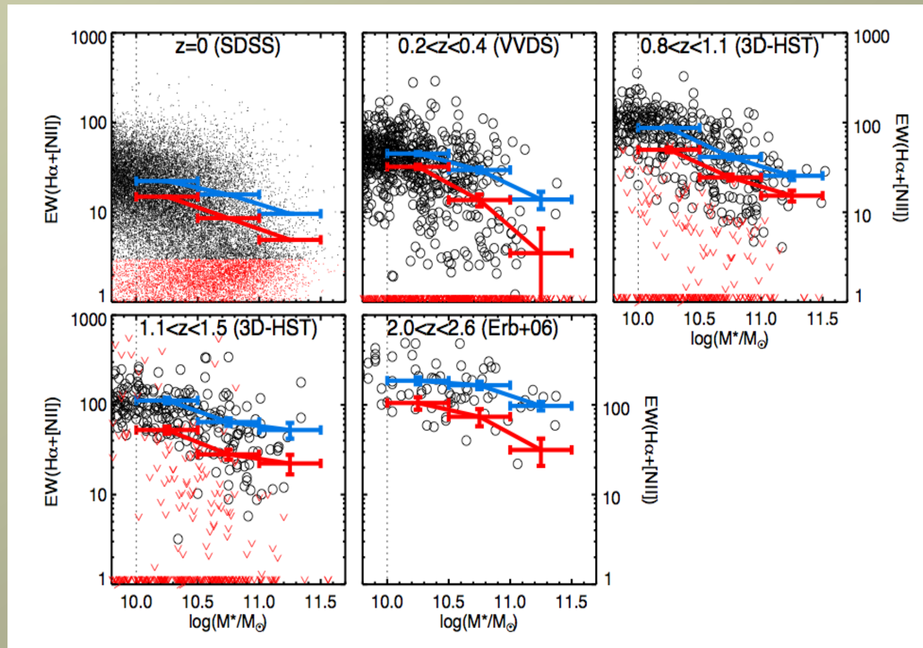
What WISH can do for this …

Different SFHs, scatter in SFR-mass and sSFR, SF timescales etc. are testable through emission line measurements @ highz!



de Barros et al. (2012)

SDSS, VVDS, 3D-HST, z~2 LBGs:
Observed Halpha equivalent widths at z~0 to 2



Fumagalli et al. (2012)

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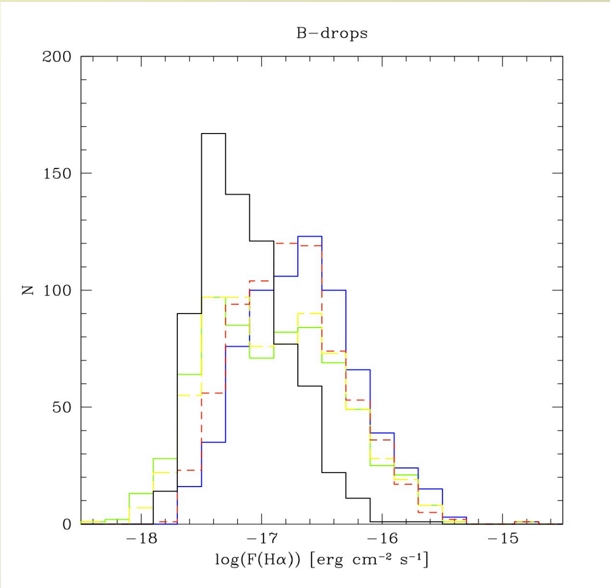
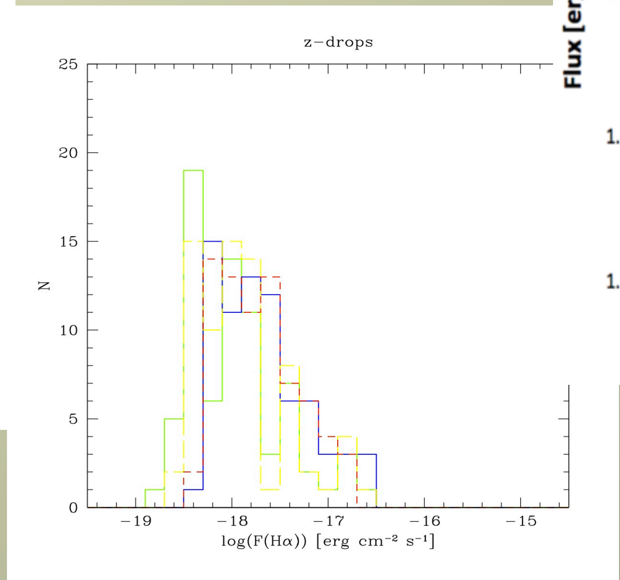
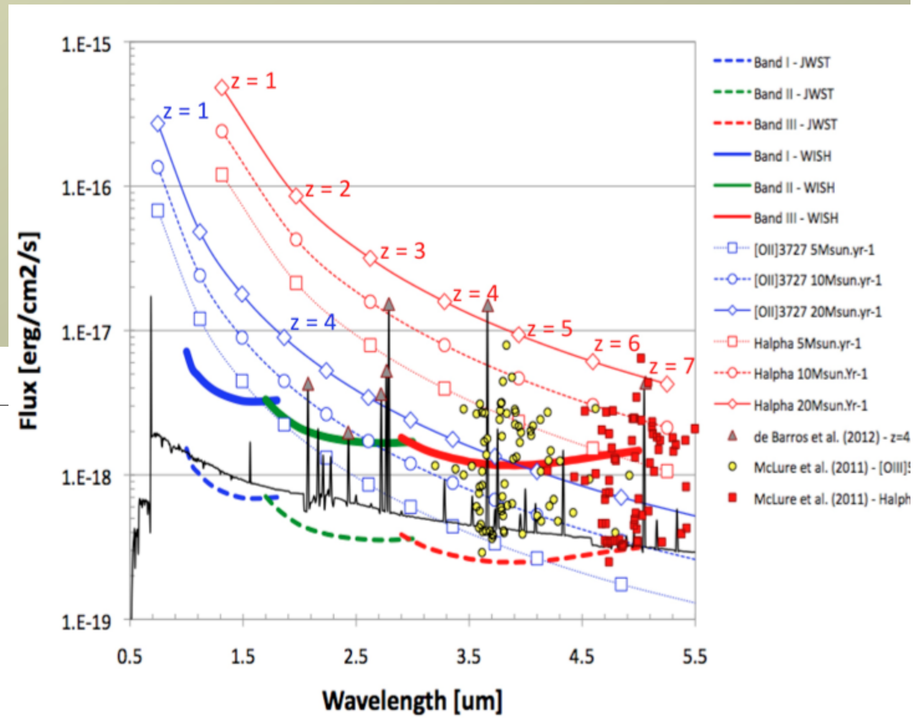
Expected Hα fluxes



z~4



z~7



Conclusions

- SED studies taking effects of nebular emission into account:
  - Stellar mass typically ↘ factor 2-3 → **rapid decrease of SMD with redshift**
  - Ages younger, **higher extinction**
  - **Specific SFR increases with redshift**
  - 2 groups of SF galaxies (65% with emission lines, 35% few/no lines) found at each redshift -- starburst/post-starburst!
- **Evidence for variable SF histories** and shorter SF timescale at z>3
- Successive/repetitive periods of SF observed between 1 - 2 Gyr after Big Bang – driven by feedback?
- **New constraints on dust attenuation at z>6** from IRAM+ALMA: compatible with higher extinction (cf. UV slope)
- WISH + spectroscopy can test/constrain these results
  → important new insight for early galaxy formation & evolution
- Statistics/ large samples probably needed!