Star-forming galaxies at high-z with the JWST

Daniel Schaerer (Geneva Observatory, CNRS)

- *Motivation + open question*
- *Physical properties of high-z star-forming galaxies*
  - → *need for direct emission line measurements*
- *New method to identify the sources of reionisation*

→ 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
→ Izotov et al. 2015, Nature

UNIVERSITÉ DE GENÈVE

irap astrophysique & planétologie

Motivation / questions

Fundamental properties of galaxies at high-z and their evolution

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

Dust evolution with redshift?

Is SF universal/uniform??

- 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

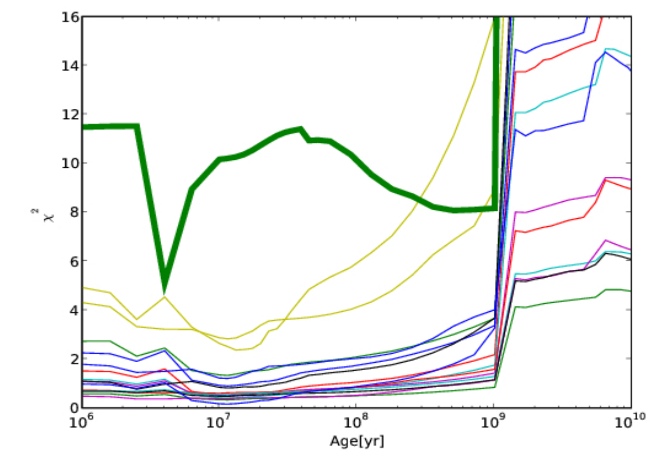
Ages of high-z star-forming galaxies

« 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)

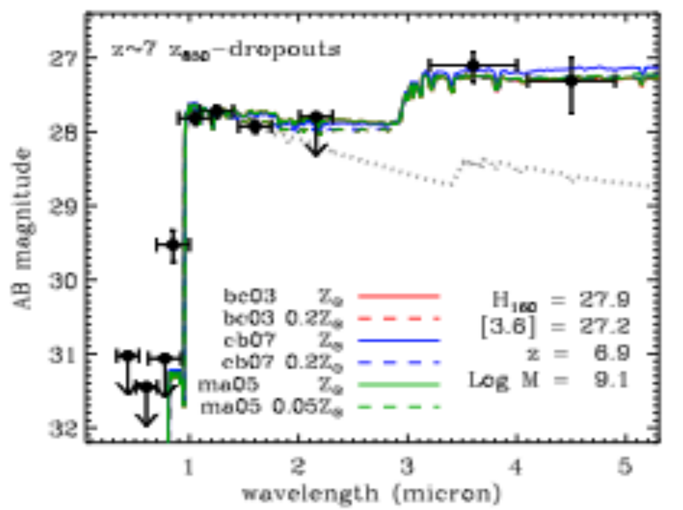


Schaerer & de Barros (2010)

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

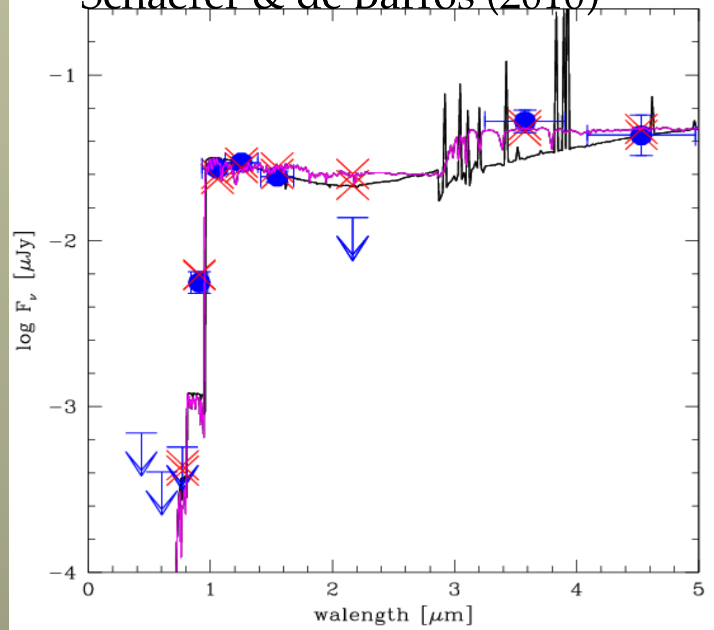
--> onset of SF at z~30 (+30-19) !?

Labbé et al. (2010)



Models including nebular lines:

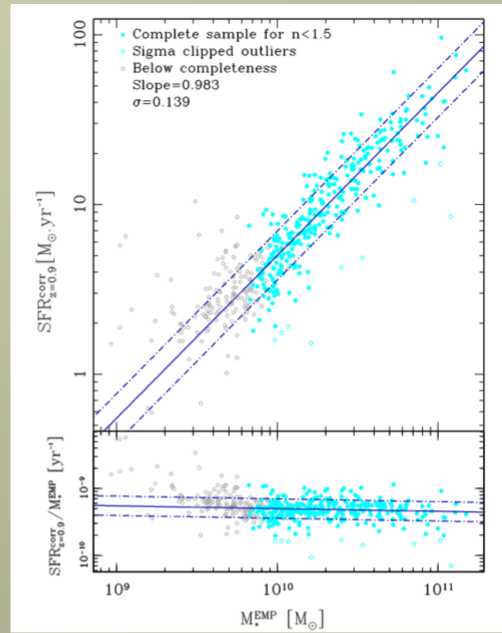
- Age~4 Myr
- A_V~0.2
- M*~5. 10^7 $M_\odot$



Universal star formation?

→ **Is SF universal/uniform??**

- What is the timescale of star formation?
  Long/short/universal/redshift dependent?



Small dispersion in SFR-M* relation at low redshift (z=0…2): e.g. Salmi et al. (2012), K. Guo et al. (2015)

Extending also to higher-z ? E.g. Speagle et al. (2014)
→ **steady, environment-independent mode of star formatio**

Q Dispersion identical at all redshift? Also valid at z>3?

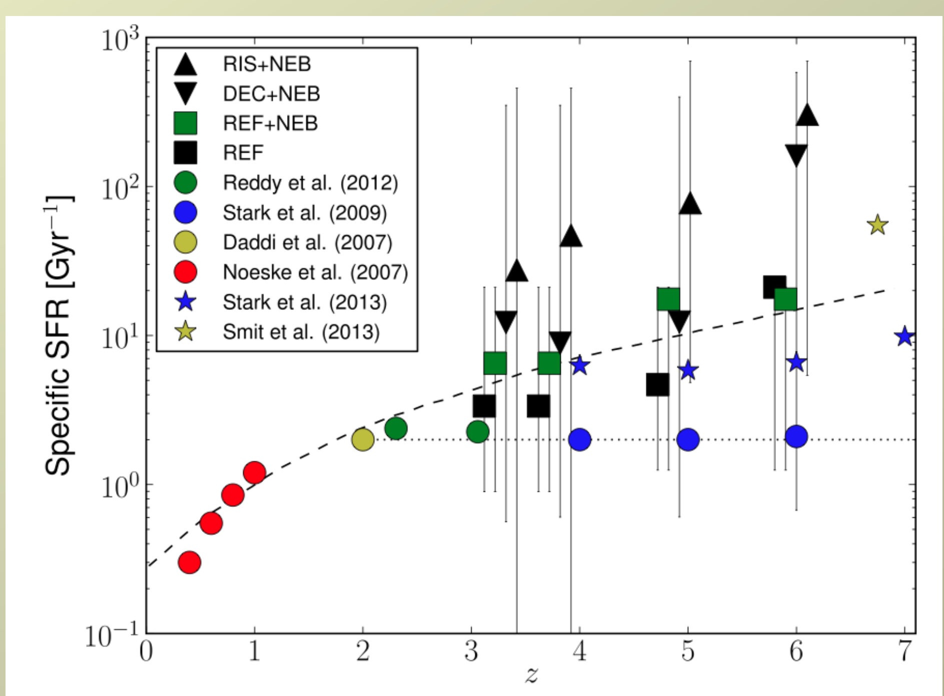
If SFR not ~constant and timescale <~0.1 Gyr
→ common SFR(UV), SFR(IR) indicators are not valid

→ consistent analysis needed!

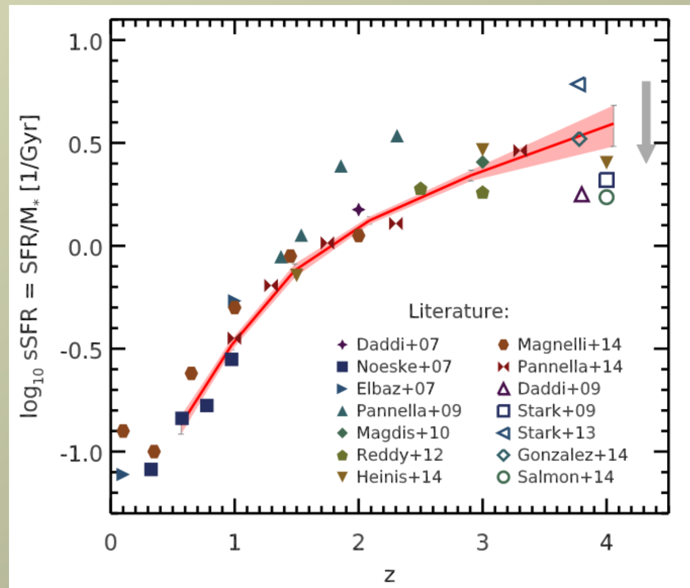
→ **Emission lines measurements needed**

Specific star formation rate evolution

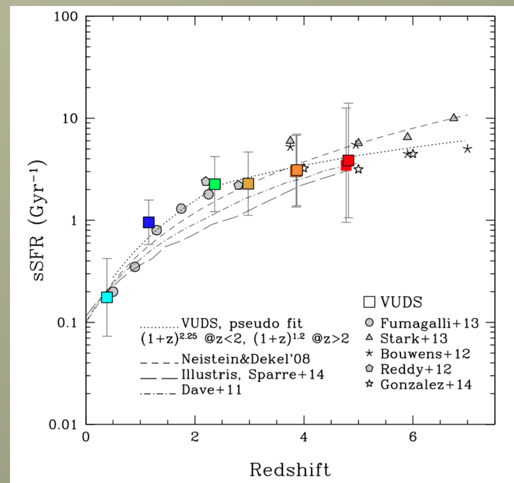
Rising but how strongly?
Scatter?
Smooth accretion versus bursty histories?
→ **Emission lines measurements needed**



de Barros et al. (2012, 2014)



IR view: Schreiber et al. (2014)

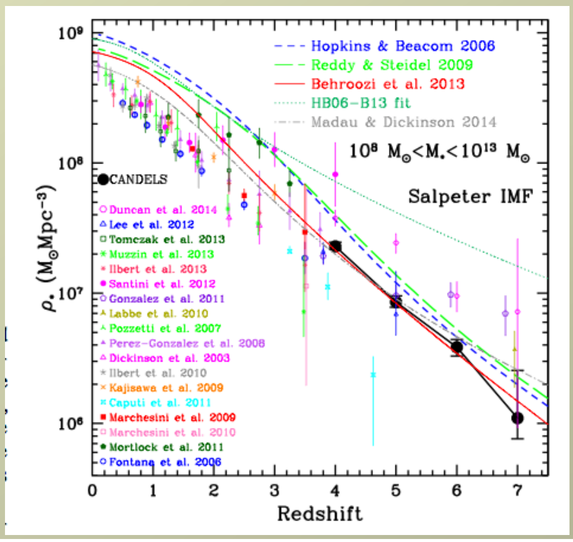


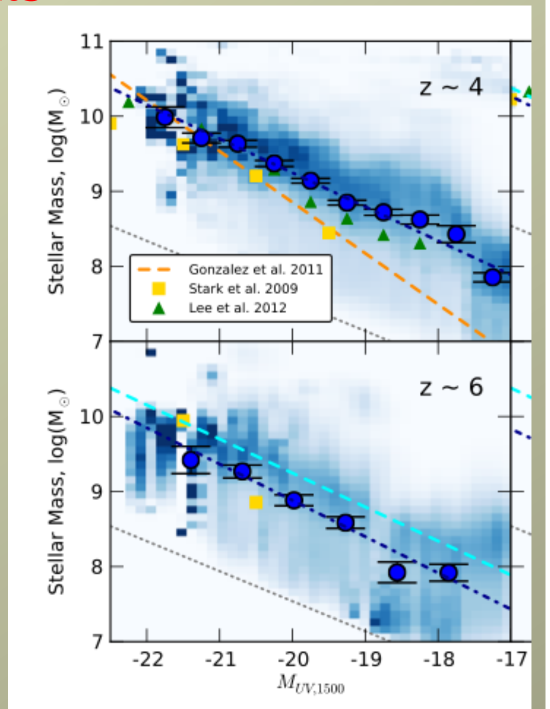
VUDS: Tasca et al. (2015)

Stellar masses at high redshift

Spitzer photometry → stellar mass estimates
stellar masses systematically lower (than SFR=const) with nebular emission and for variable SF histories: *up to ~2-3 times lower mass*
→ **Emission lines measurements needed for better accuracy**

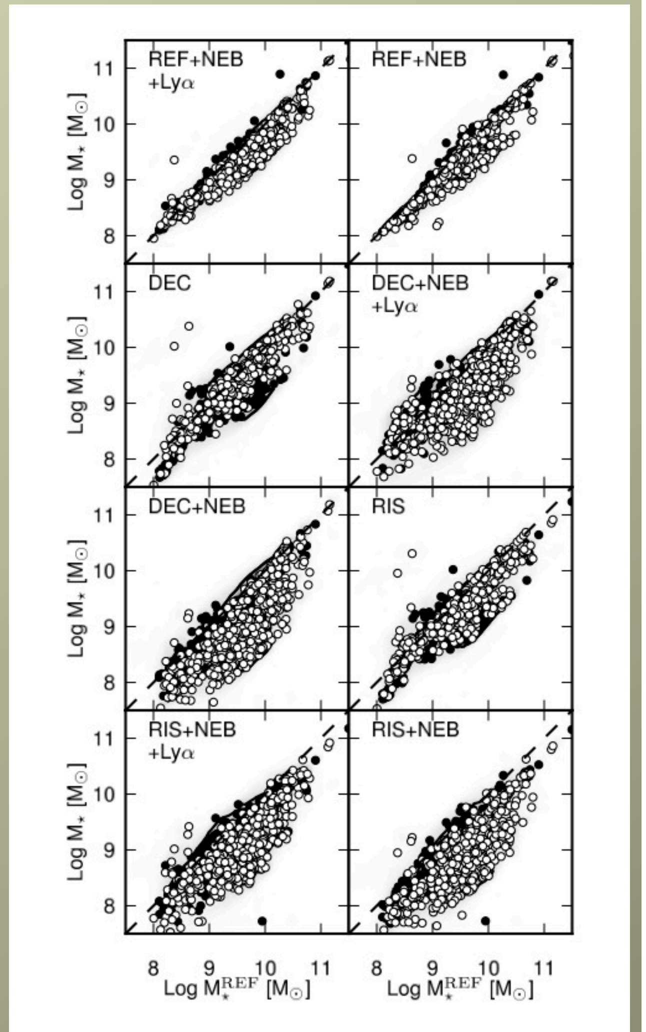
→ Reduced stellar mass density at high-z





Duncan et al. (2014)

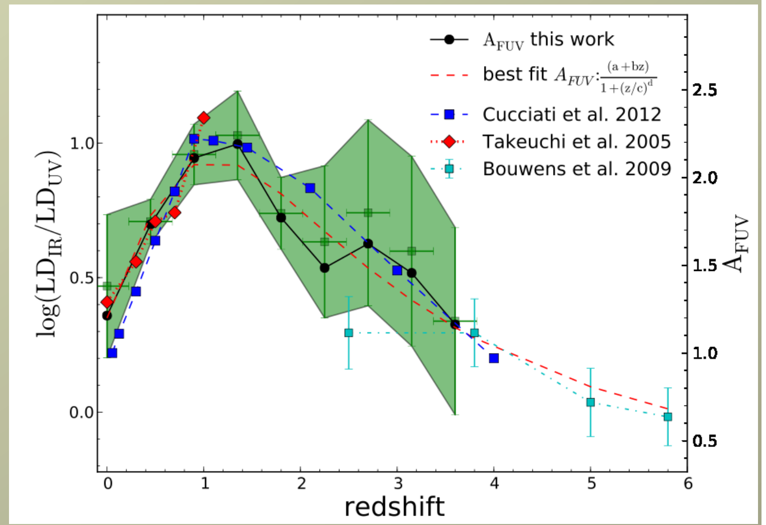
Grazian et al. (2014) + many others



de Barros et al. (2012, 2014)

LBG populations at high redshift – dust attenuation

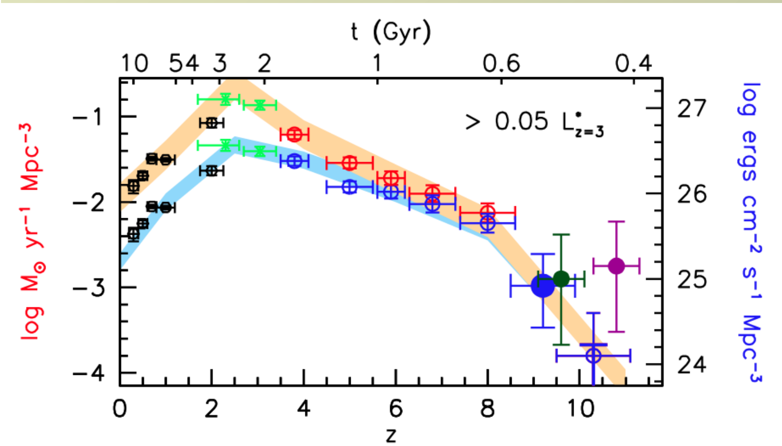
Mean attenuation from IR/UV:
Burgarella et al. (2013)

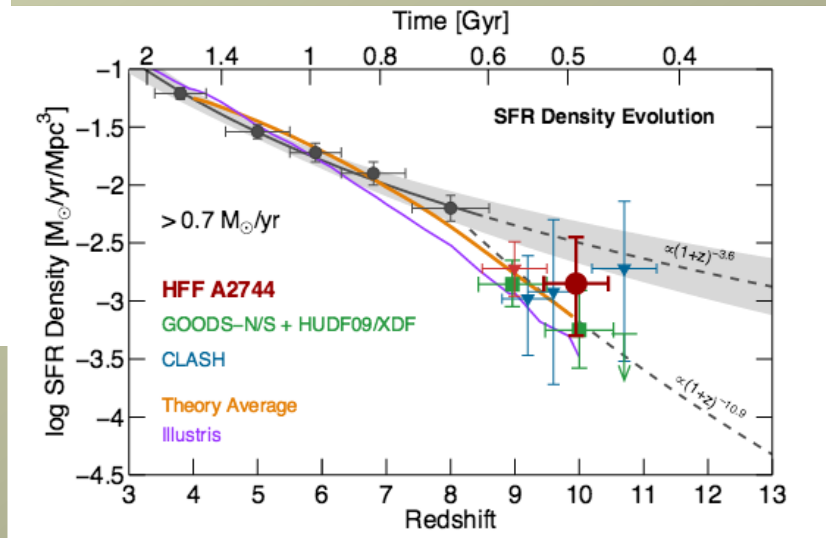


From integral over UV LF compute

→ **total (extinction corrected) UV** ***star formation rate density as a fct redshift***

→ Correction of dust extinction currently based on UV slope for z>3. Direct measurements needed!





Bouwens et al. (2012…), Oesch et al. (2015)

Physical properties of high redshift star-forming galaxies

(Strong) emission lines are ubiquitous (at z~3-7)
& affect the determination of the physical parameters (age, mass, SFR, specific SFR …)
→ widely accepted

→ **Models with nebular emission now « standard »**

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

Ono et al. (2010)
Acquaviva et al. (2012)
Finkelstein et al. (2013)
Robertson et al. (2013)
Duncan et al. (2014)
Castellano et al. (2014)
…

Consistent SED modeling/fitting of z~2-7 star-forming galaxies

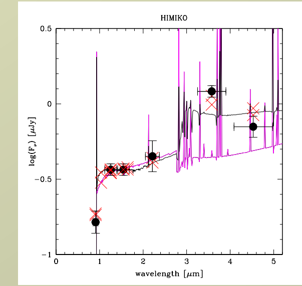
SED modeling

- 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 with same code (modified Hyperz code)

Observational constraints

- broad-band photometry → stellar populations ← HST, Spitzer, **JWST**
- IR/mm emission → dust attenuation ← **ALMA, JWST**
- Nebular emission lines → youngest population, SFR ← **JWST**

Consistent SED modeling of LBGs at high-z: implications



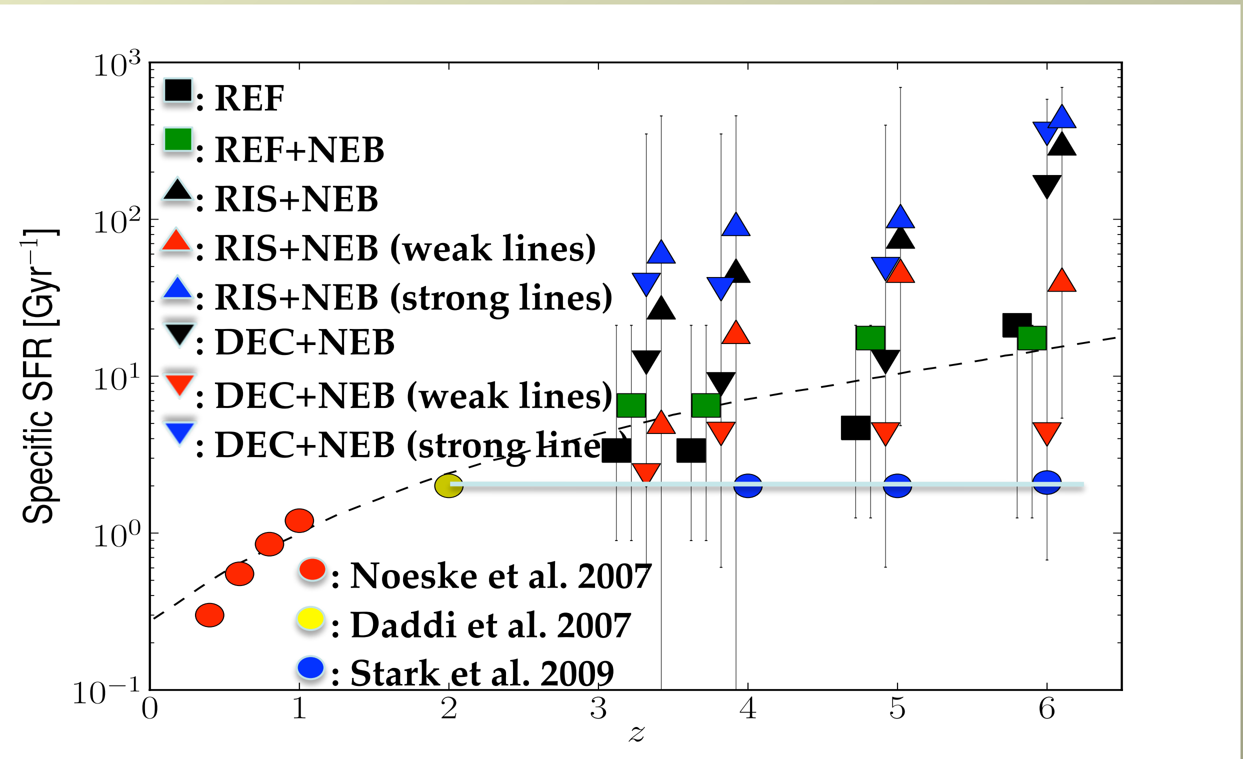
1. Younger galaxy ages
2. Lower stellar masses
3. Specific SFR (sSFR=SFR/M*) increases with redshift (@ z>2-3)

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

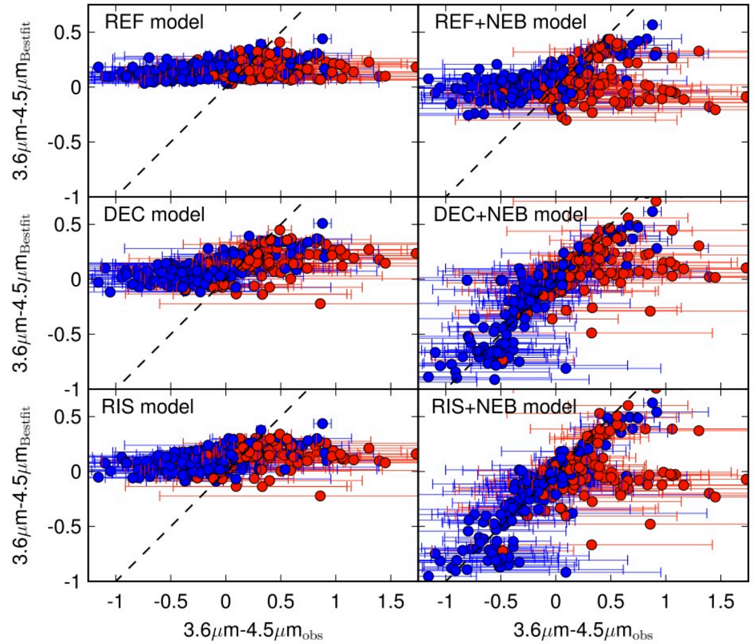


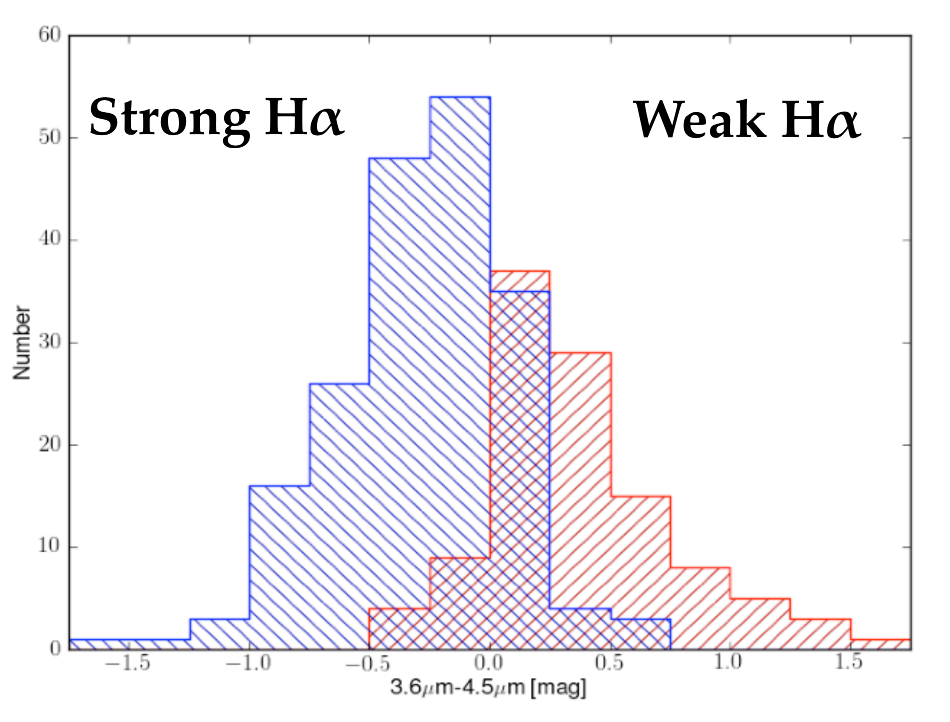
de Barros, Schaerer & Stark (2012, 2014)

4. LBGs @ z=3.8 to 5: support for variable SF histories

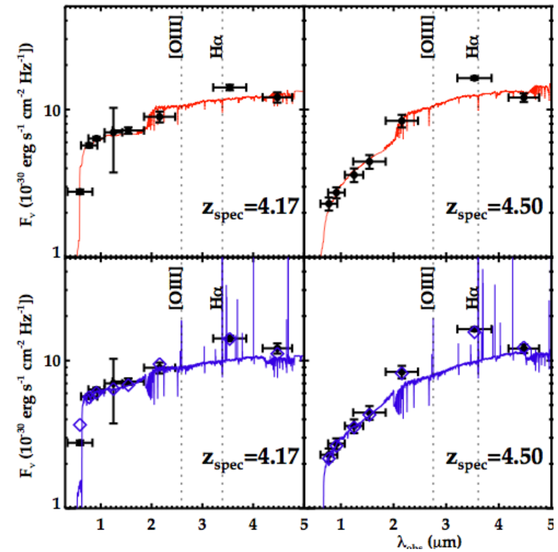
- **(3.6-4.5) color only recovered by models including nebular emission**
- **constant SFR + age>50 Myr: unable to reproduce observed range of (3.6-4.5) colors**

de Barros, Schaerer, Stark (2012, 2014)





« Empirical » distinction of Hα-emitters and non-emitters
cf. Shim et al. (2011)
Stark et al. (2012)



5. SFR – mass relation

Difficulties:

- **Concept of SF-main sequence misleading at high redshift ?**

  Scatter may be large!

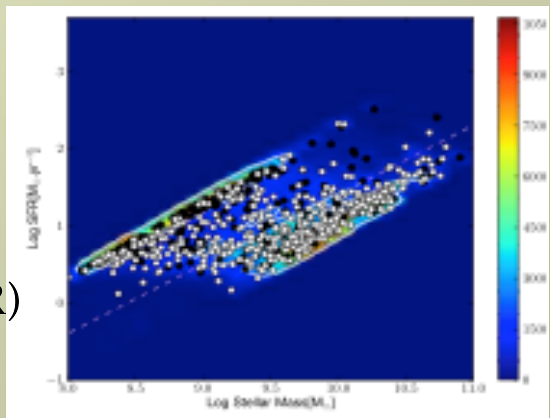
  Caution: selection effects!

Example: z~4 LBGs

A_V free

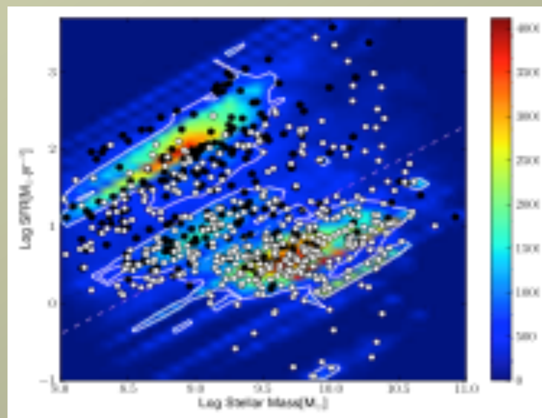
SFR=const, age>50Myr

log(SFR)



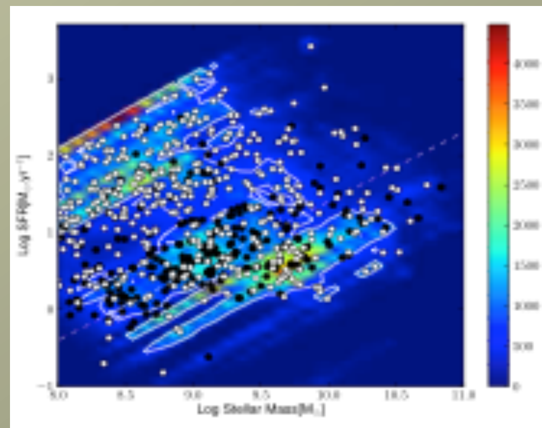
log(M*)

variable SF histories



log(M*)

variable SF histories + nebular

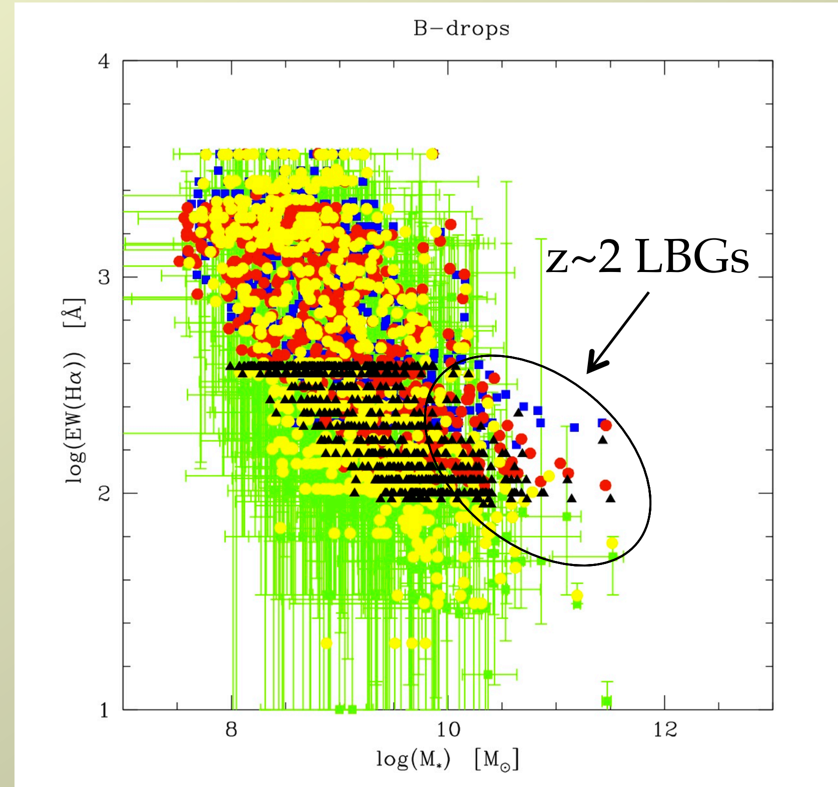


log(M*)

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

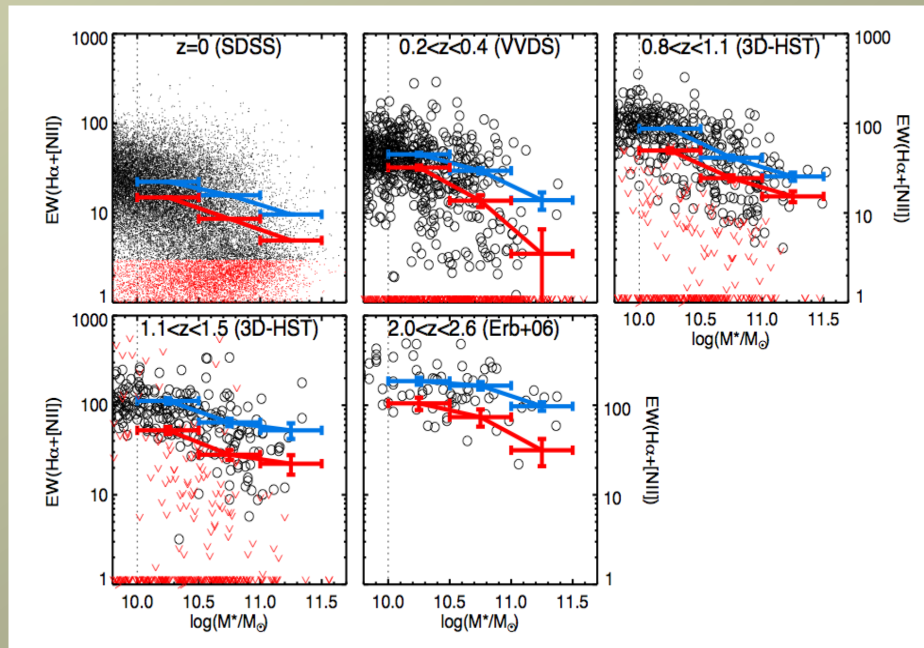
What JWST can do for this …

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



Schaerer et al. (2013)

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

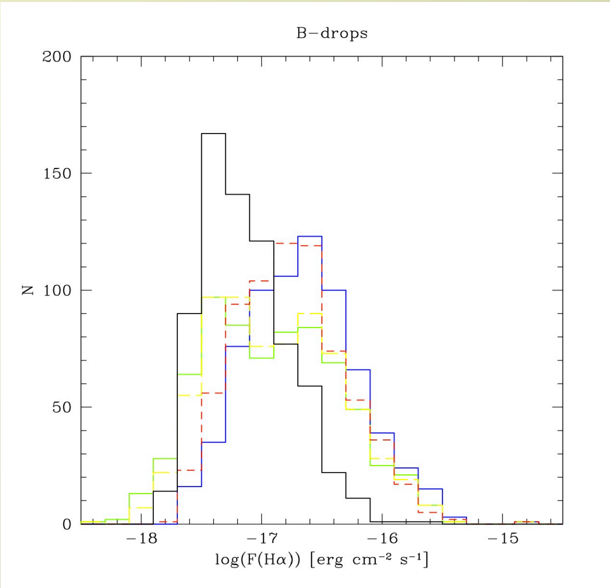


Fumagalli et al. (2012)

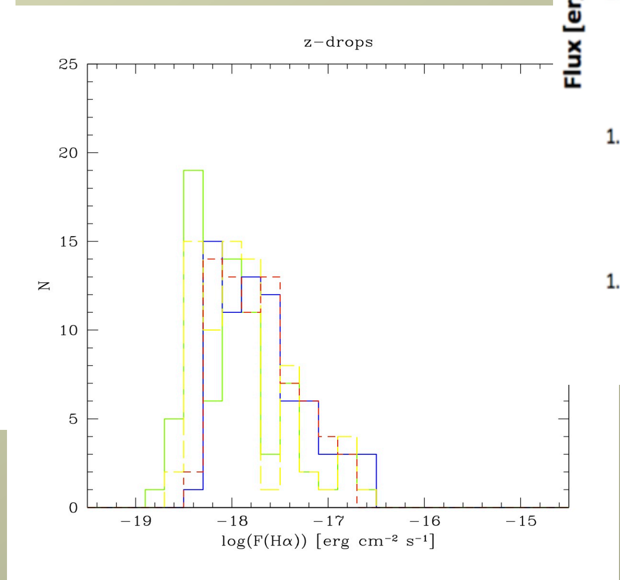
What JWST can do for this …

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

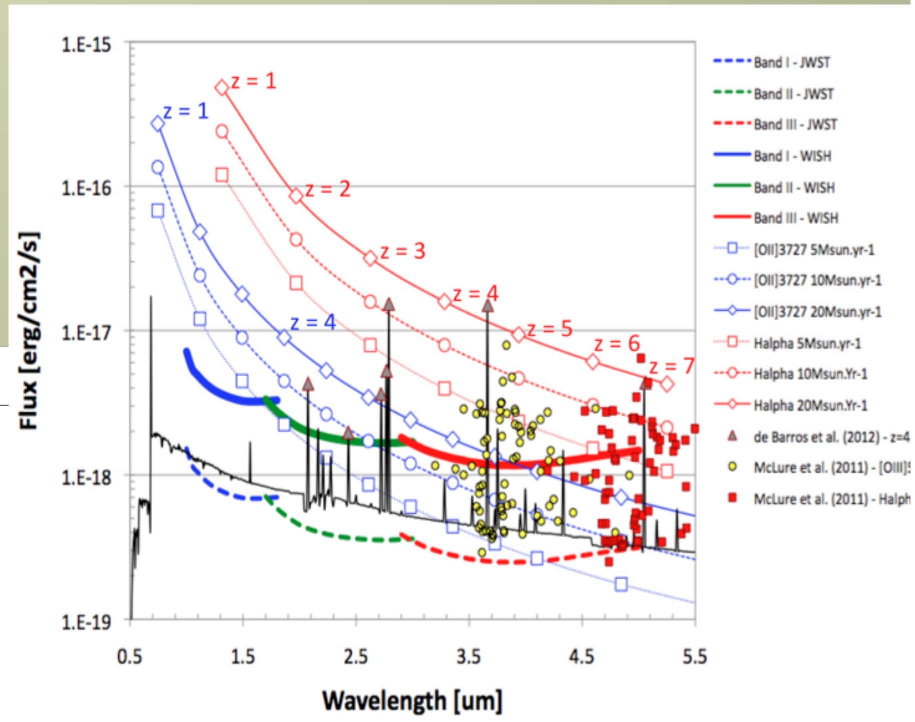
Expected Hα fluxes



z~4



z~7



Courtesy of Burgarella (2014)

from Schaerer et al. (2013)

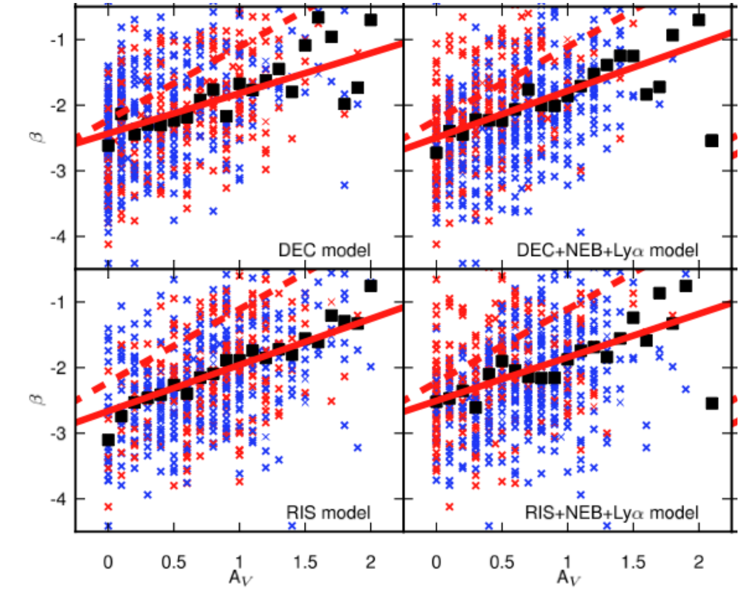
6. Higher dust attenuation

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

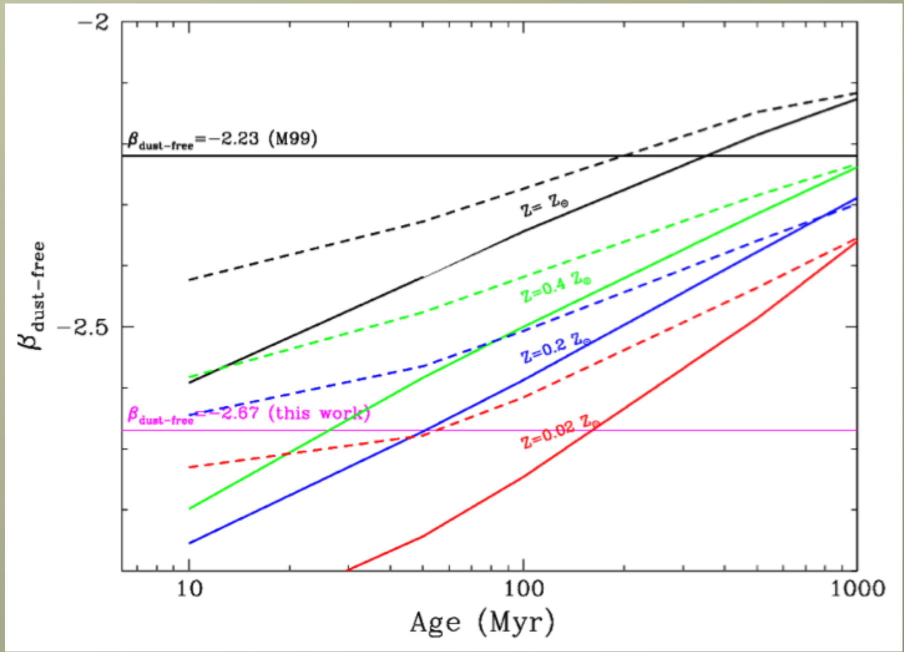
- Assumptions SFR=const and age>100 Myr may break down
- → Different relation β – E(B-V)

- 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)

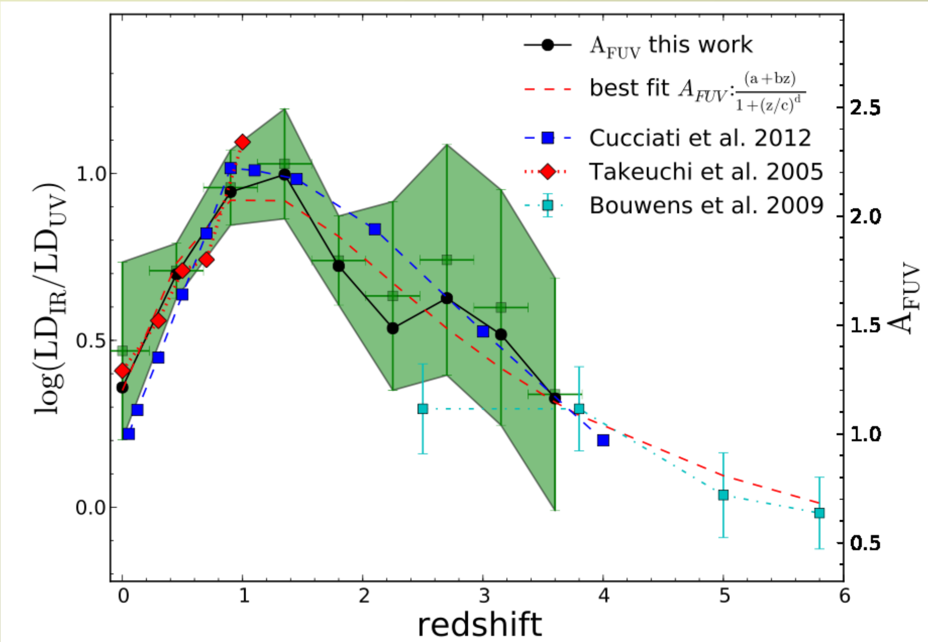


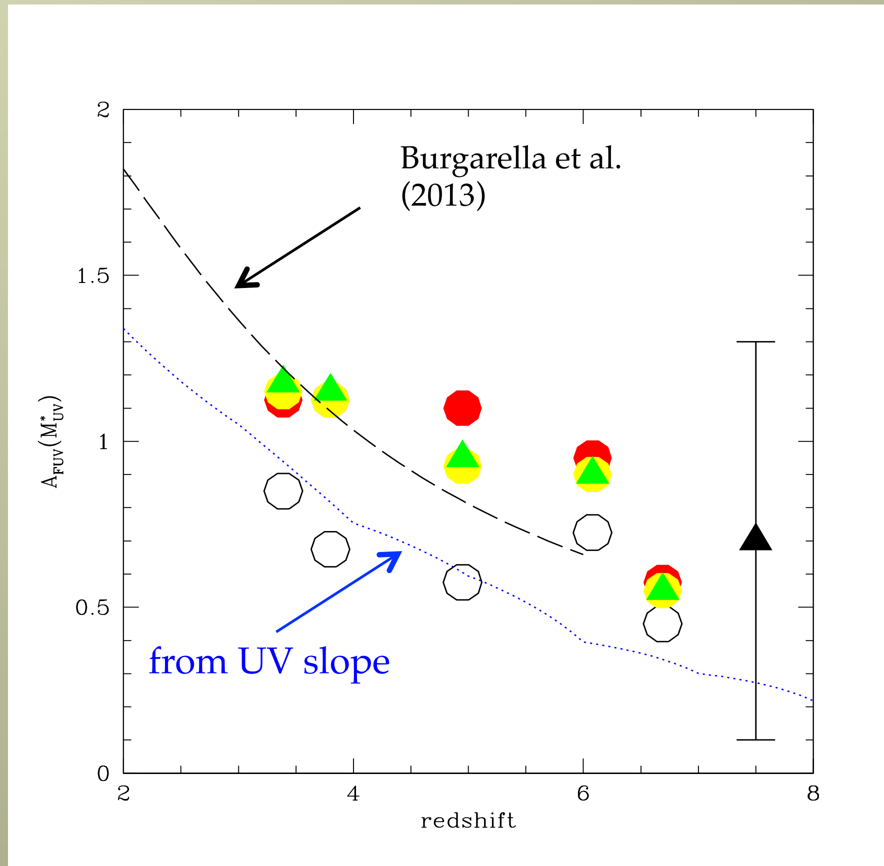
Castellano et al. (2014)

Evolution of the LBG population with redshift

Mean UV attenuation

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

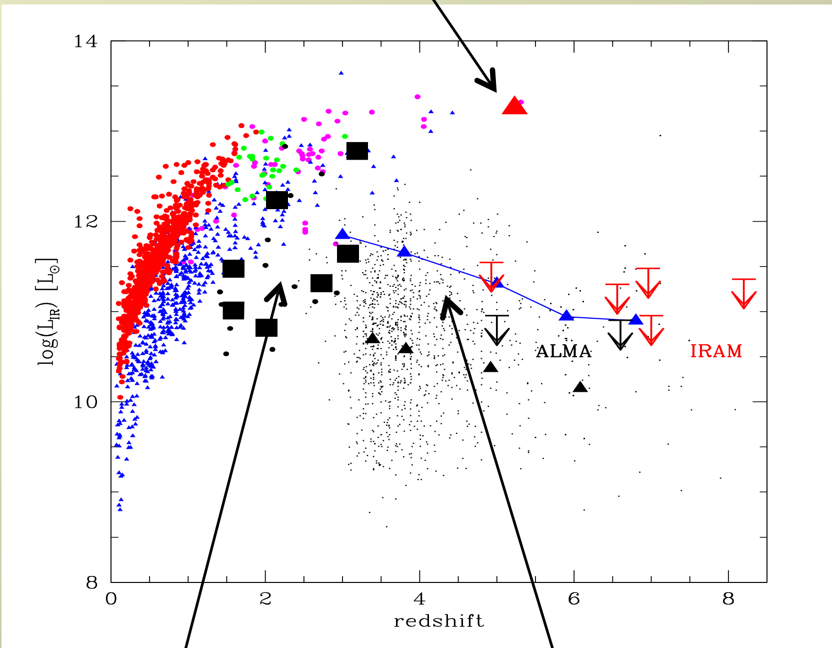




Schaerer & de Barros (2015)

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:

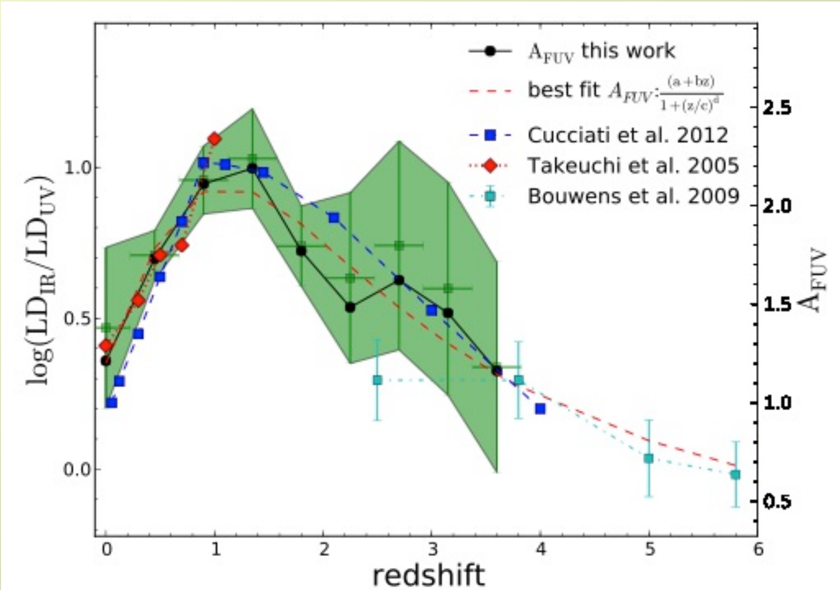
- z=6.56 HCM6A: Boone+2007
- z=7 A1703: Schaerer+2014

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

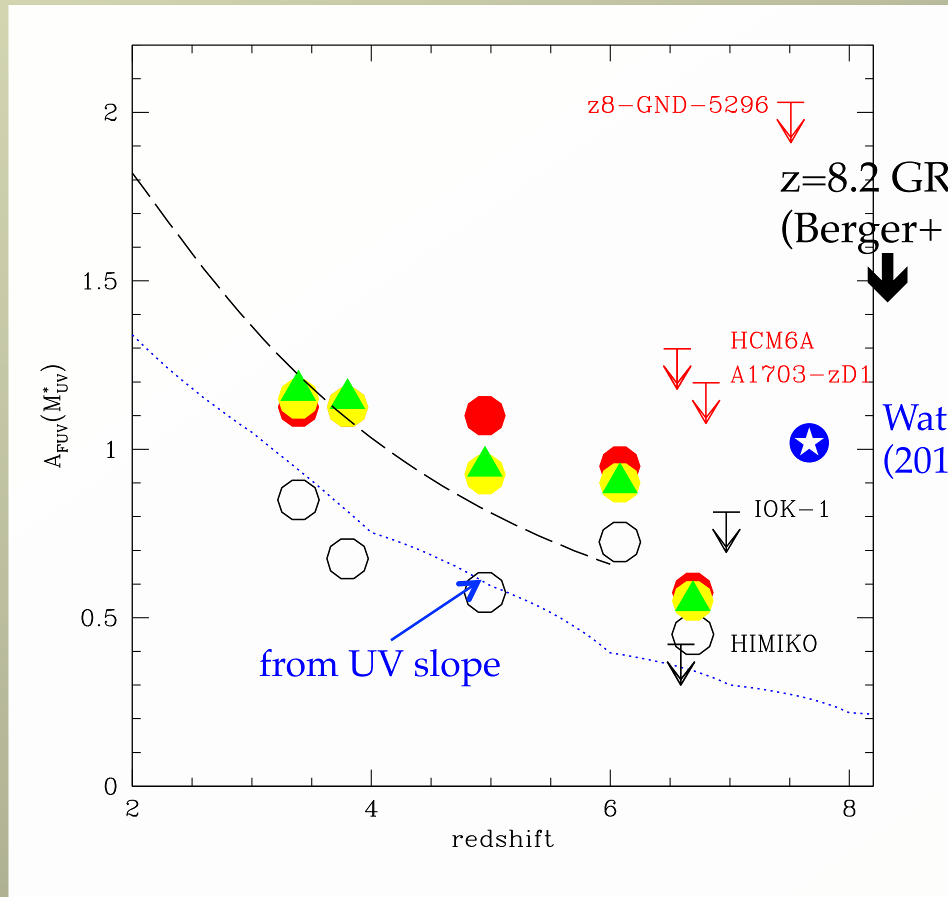
➔ 2 new non-detections at 1.2 and 2 mm (~0.1 mJy rms)

Mean attenuation as function of redshift



Burgarella et al. (2014)

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



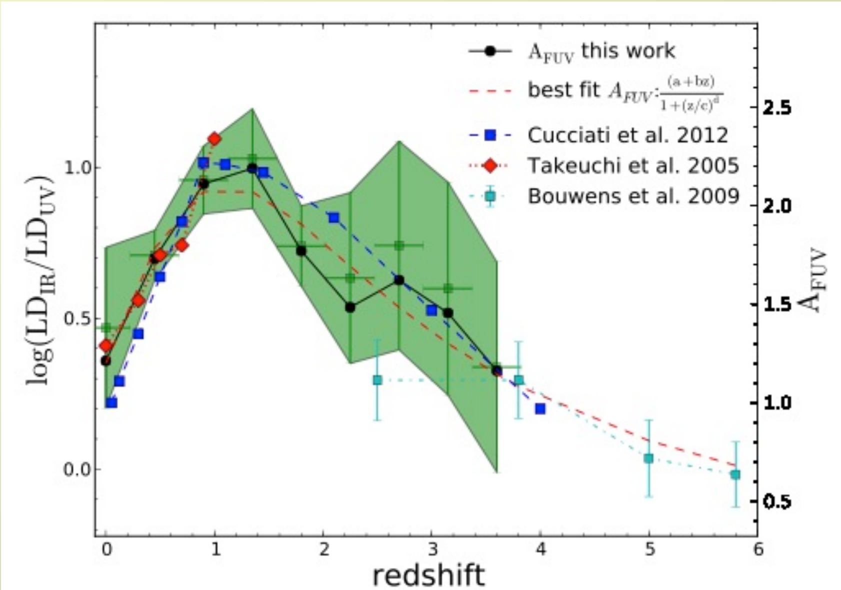
5
3
2
0.8
0.3

Schaerer et al. (2014)

UV attenuation compatible with:

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

Mean attenuation as function of redshift



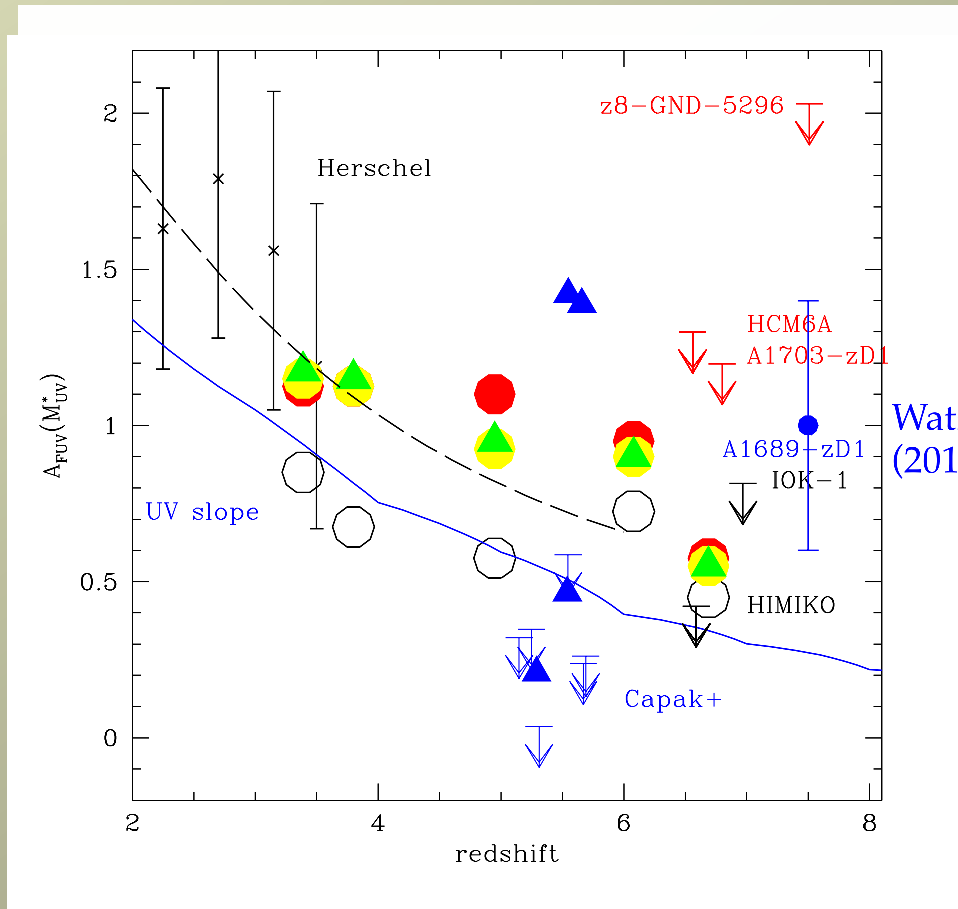
Burgarella et al. (2014)

UV attenuation compatible with:

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

With new objects from Watson et al. + Capak et al. (2015)

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



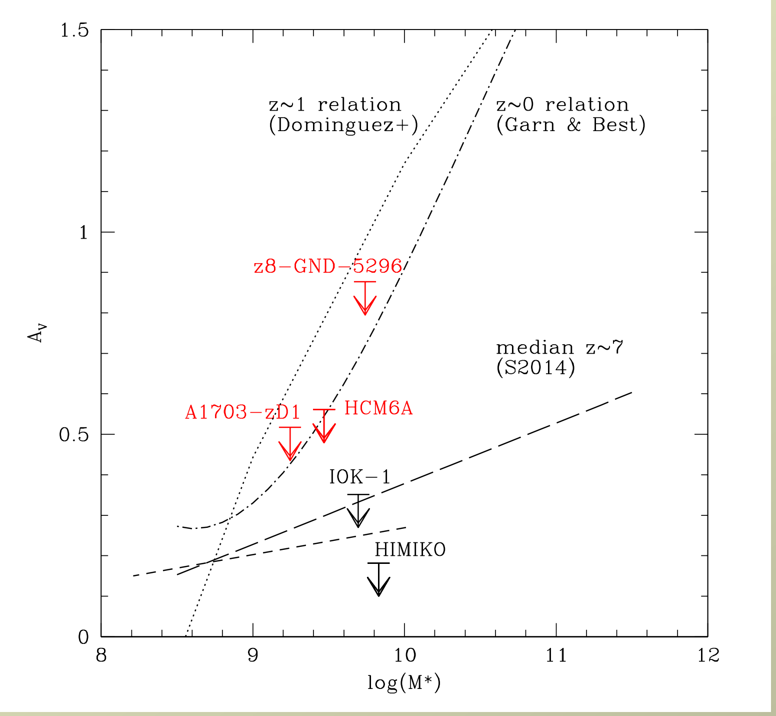
Watson et al. (2015)

5
B
2014)
3
2
0.8
0.3

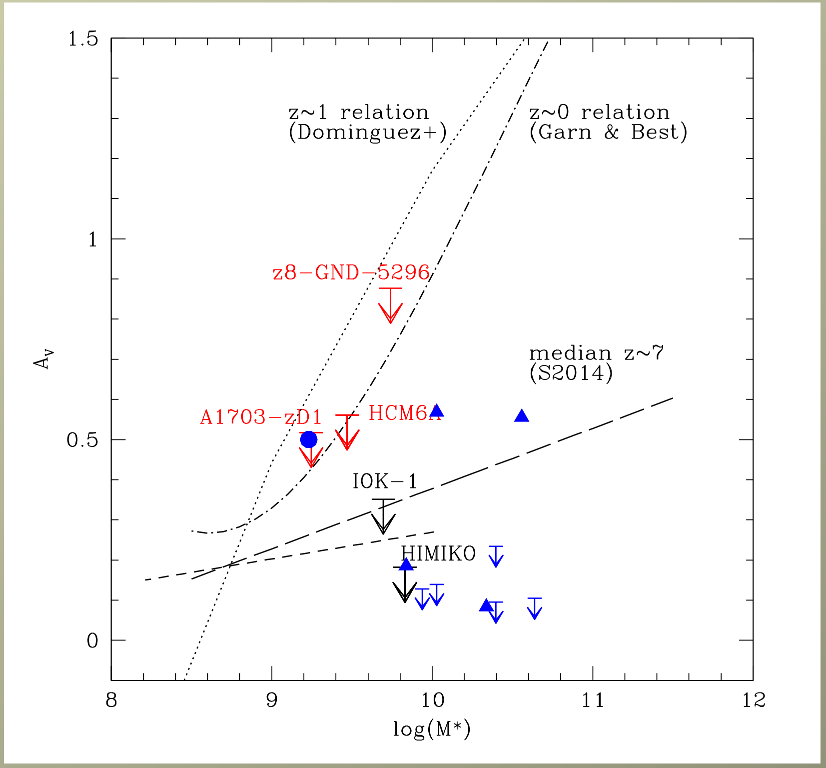
Schaerer et al. (2014)

Mass – dust attenuation relation

Schaerer et al. (2015)

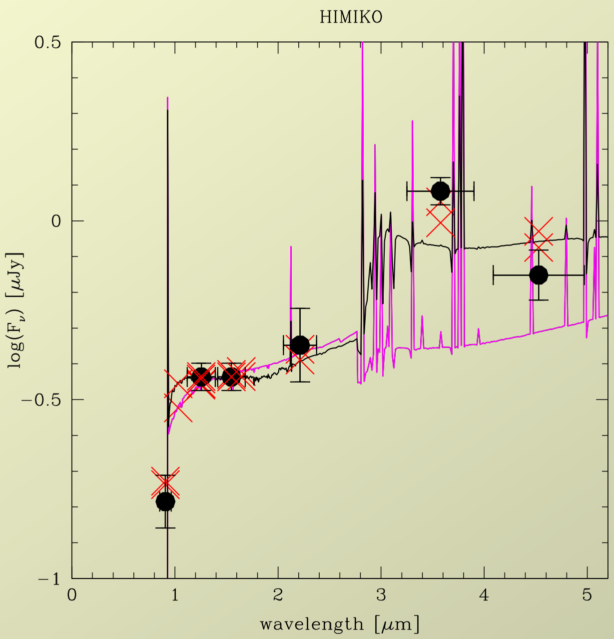


With new objects from
- Watson et al. (2015), z=7.5
- Capak et al. (2015), z~5

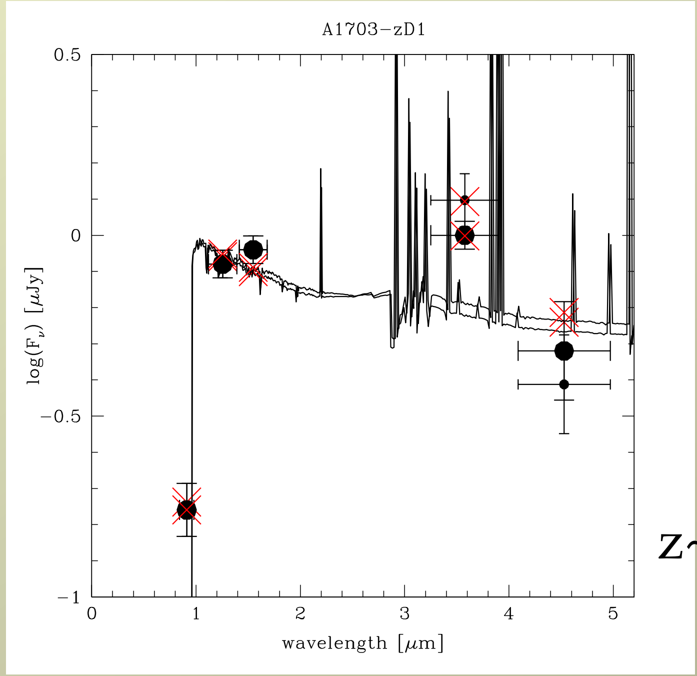


- z ≥ 2 objects: less attenuation than expected from relation at lower redshift
- Compatible with *flatter mean relation for z~7 LBGs* (Schaerer & de Barros 2014)

Feeding back IRAM/ALMA limits to SED fits: implications

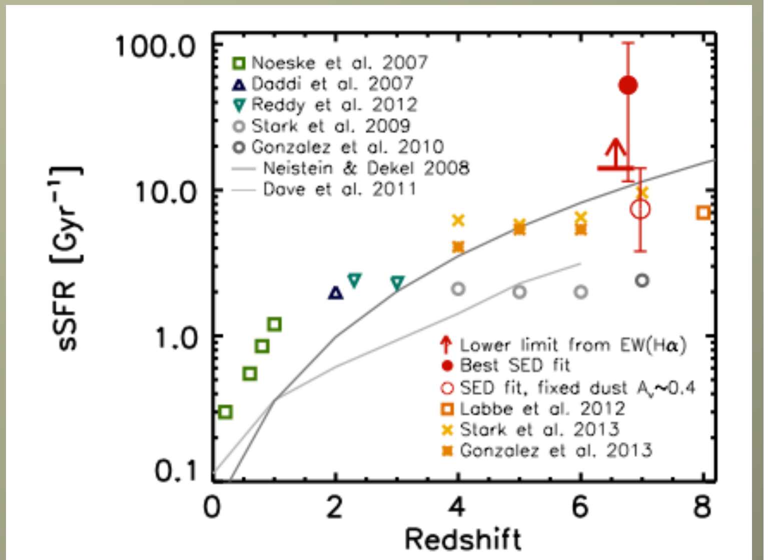


z=6.595



z~7

Smit et al. (2014)



Himiko:

- **Rising SF histories excluded**
- Poor constraint on sSFR

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

Strong [OIII]+Hb emission at z~7! Universal?

→ More statistics needed!

Conclusions

A) Consistent analysis of observations needed to address several questions:
SF properties, timescales, SFR, SFR-M dispersion…*

B) Physical parameters of LBGs affected by emission lines and SF histories:
* **Masses ↘, ages ↘, sSFR ↗ increases with z**
* Data favours variable SF histories
* UV attenuation higher than usual (Meurer law)

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

→ **Rest-frame optical emission line measurements with JWST will provide fundamental new constraints on high-z SF galaxies**

The quest for the sources of cosmic reionisation

- Numerous searches for « Lyman continuum leakage » from star-forming galaxies at low and high-z
  → sources elusive, so far!

- Faint, low mass galaxies thought to be main contributors to cosmic reionization

→ **JWST spectroscopy to identify/characterise LyC leaking galaxies**

The quest for the sources of cosmic reionisation

Criteria to identify Lyman continuum emission

DIRECT:

- Imaging or spectroscopy across the Lyman break (HST, FUSE, … ground-based)
  Many searches/surveys → very few candidates
  (cf. Malkan+, Steidel+, Cowie+ …, Siana et al. 2015, Vanzella et al. 2015, Grazian et al. 2015)

INDIRECT:

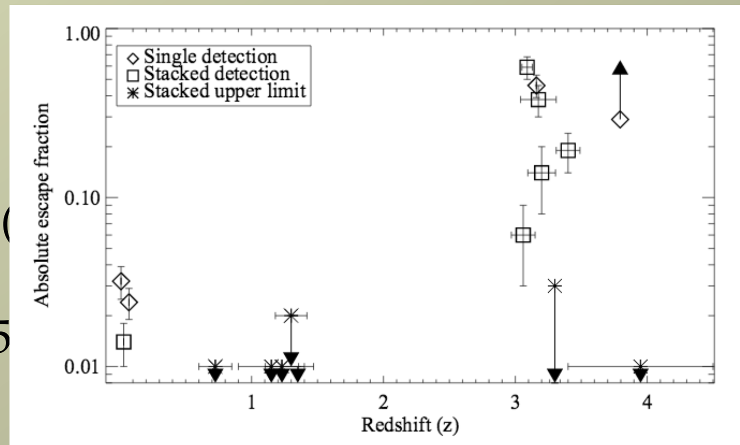
- UV **low ionisation absorption lines** → *low covering factor of the UV continuum* source (Heckman et al., Jones et al. 2013)
- High **[OIII]/[OII] ratio** → *density bounded HII regions*
  (Nakajima & Ouchi 2014, Jaskot, Oey+ collaborators)
- **Lyman-alpha line profile** → signature of *low HI column density* and/or holes in the cold ISM (Verhamme et al. 2015)

The quest for the sources of cosmic reionisation

Criteria to identify Lyman continuum emission

DIRECT:

- Imaging or spectroscopy across the Lyman break (
Many searches/surveys → very few candidates
(cf. Malkan+, Steidel+, Cowie+ …, Siana et al. 2015
al. 2015)



Bergvall+ 2013

INDIRECT:

- UV **low ionisation absorption lines** → *low covering factor of the UV continuum* source (Heckman et al., Jones et al. 2013)
- High **[OIII]/[OII] ratio** → *density bounded HII regions* (Nakajima & Ouchi 2014, Jaskot, Oey+ collaborators)
- **Lyman-alpha line profile** → signature of *low HI column density* and/or holes in the cold ISM (Verhamme et al. 2015)

The quest for the sources of cosmic reionisation

*Best **high-z** Lyman continuum source:*

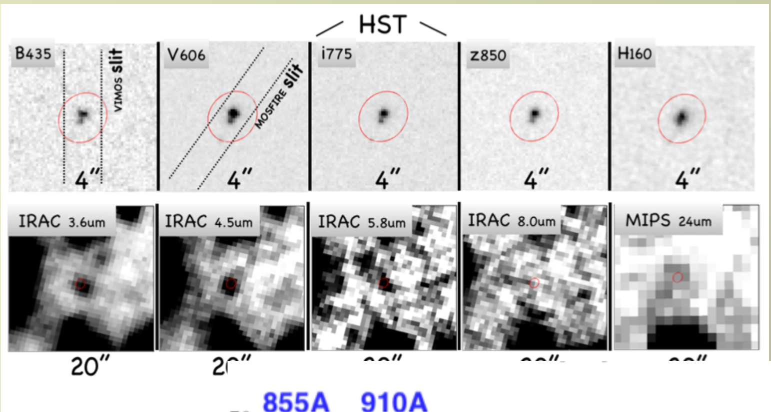
z=3.218 galaxy « Ion2 »in GOODS-S/Candels

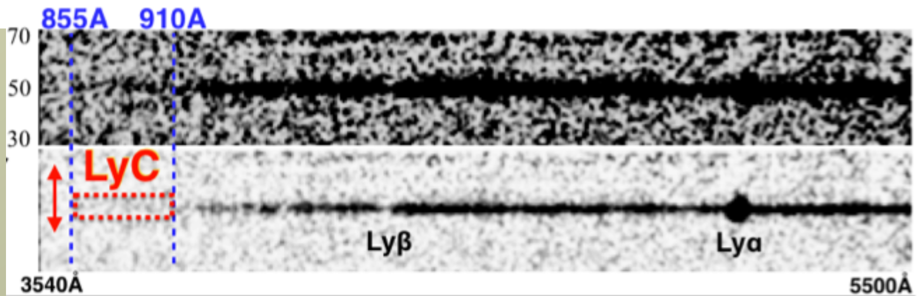
UV rest-frame mag_AB~24.5-25

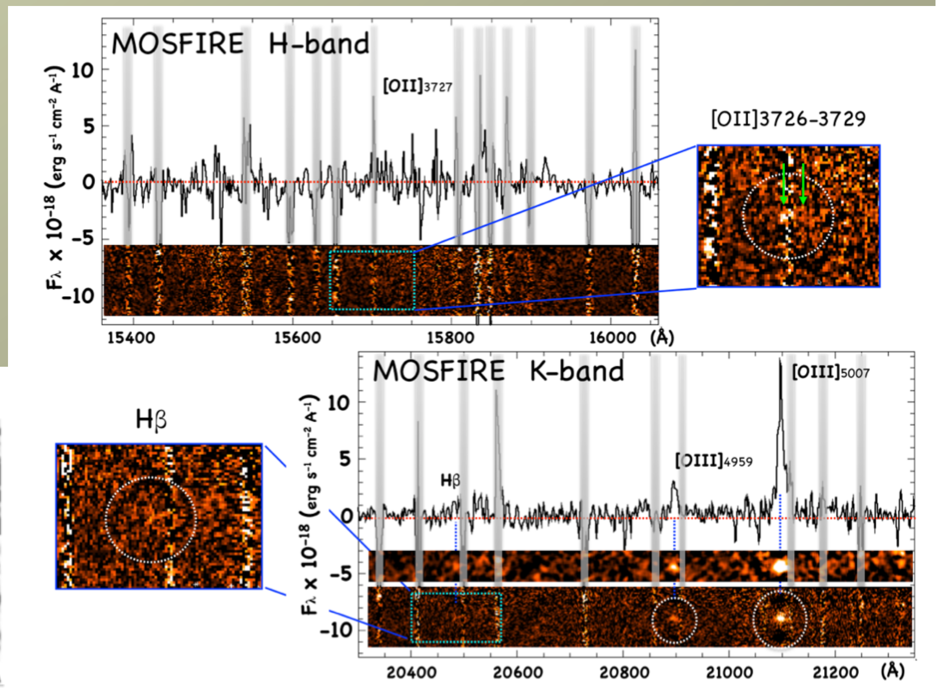
→ Low metallicity (1/6 $Z_{\odot}$), ~low mass (1.6 10^9 $M_{\odot}$)

→ **High ratio [OIII]/[OII]>10, high [OIII]+Hb equivalent width (~1600 Ang)**

Vanzella et al. (2015), de Barros et al. (2015)



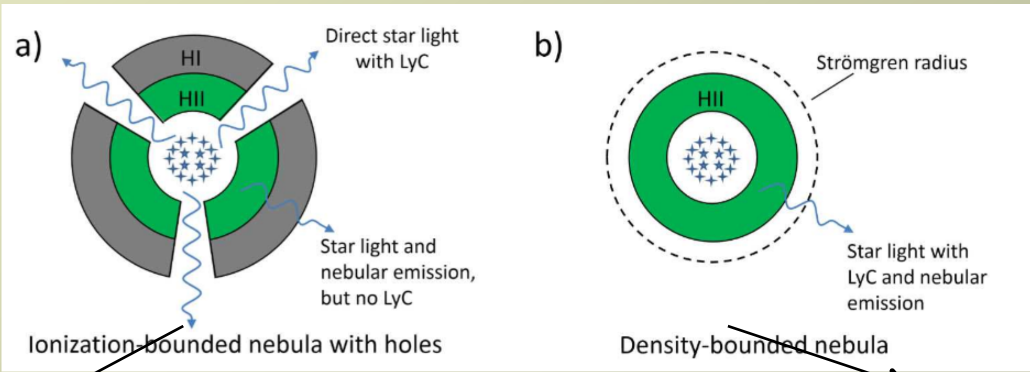




The quest for the sources of cosmic reionisation

New (indirect) indicator the Lyman continuum escape:

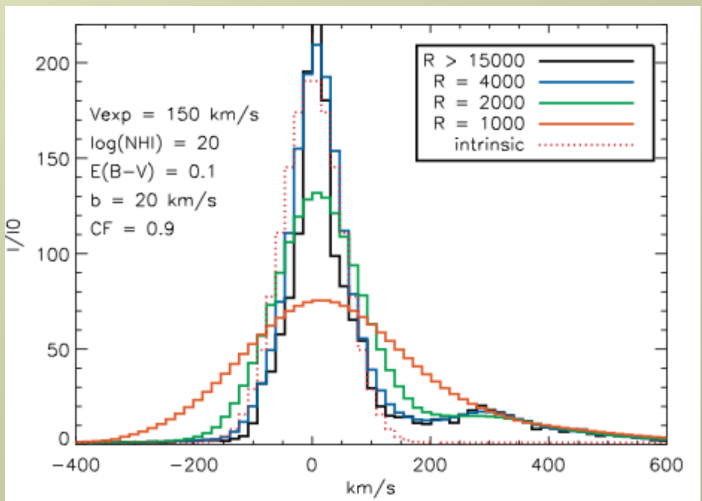
narrow Lya line profile, small separation of peaks

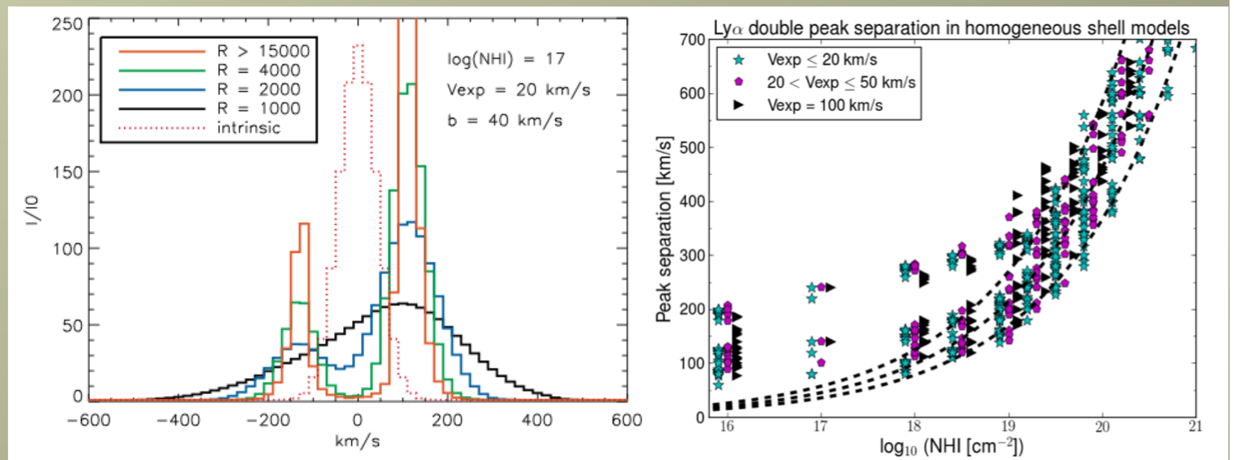


Zackrisson et al. (2013)

clumpy ISM

homogeneous medium or
large covering fraction





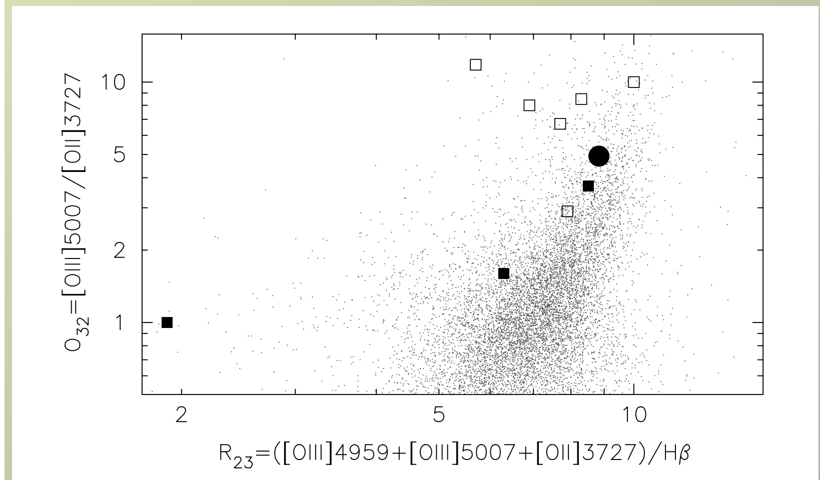
Verhamme et al. (2015)

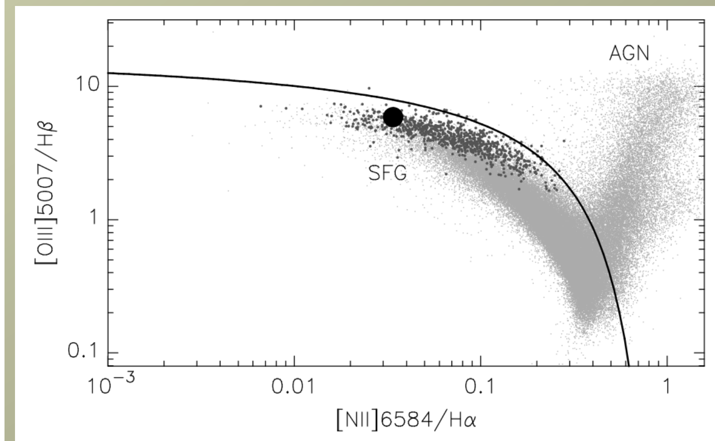
The quest for the sources of cosmic reionisation

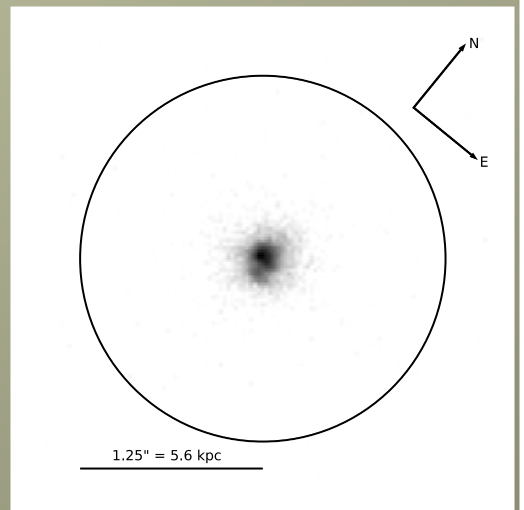
New COS-HST program: *measure Lyman continuum and test indirect indicators* (Thuan, Izotov, Orlitova, Verhamme, Schaerer, Guseva)

Object selection (from Sloan):

- High [OIII]/[OII] ratio
- Compact SF galaxy – « Green Pea » like
- z~0.3 and UV-bright for « easy » Lyman-continuum detection with COS

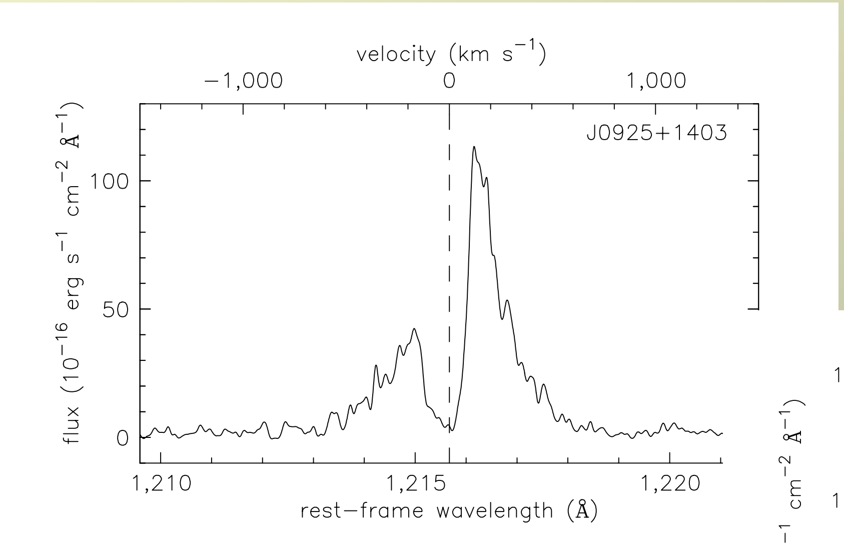


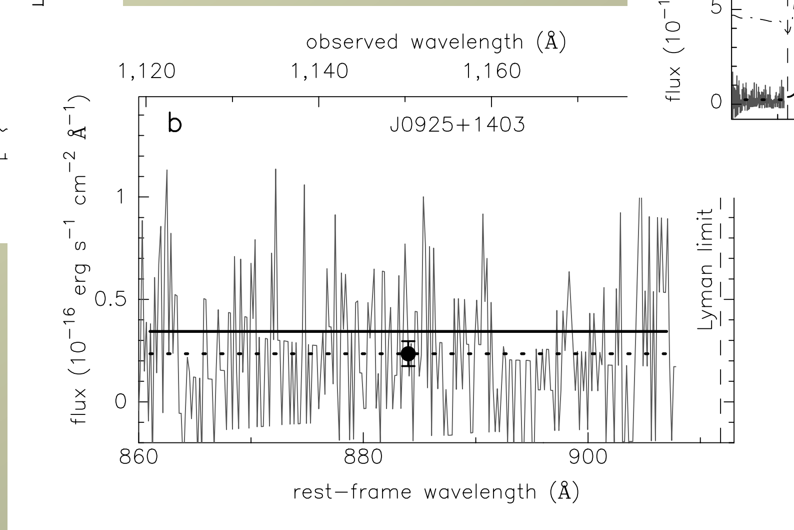


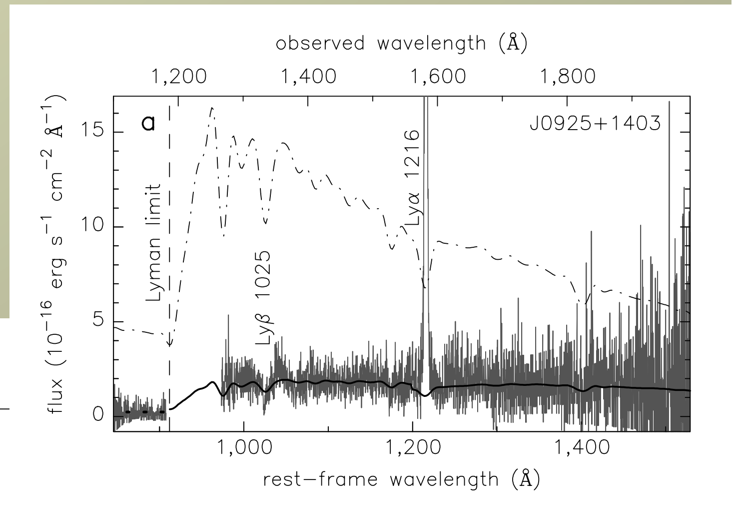


The quest for the sources of cosmic reionisation

New COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2015)







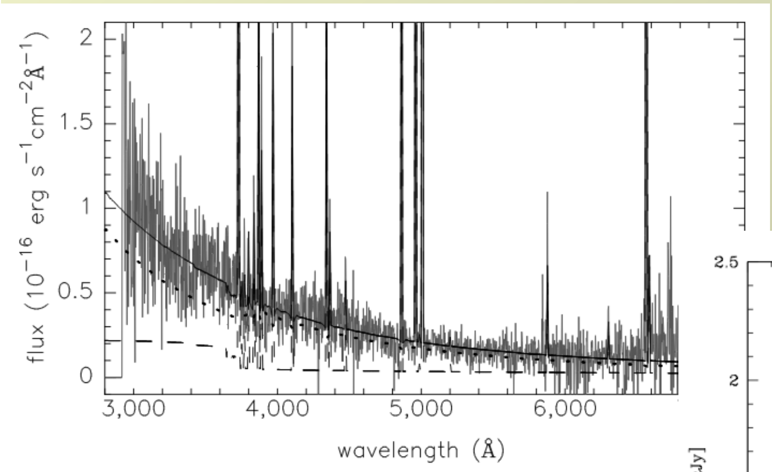
- ✔ High [OIII]/[OII]
- ✔ Narrow Lya profile

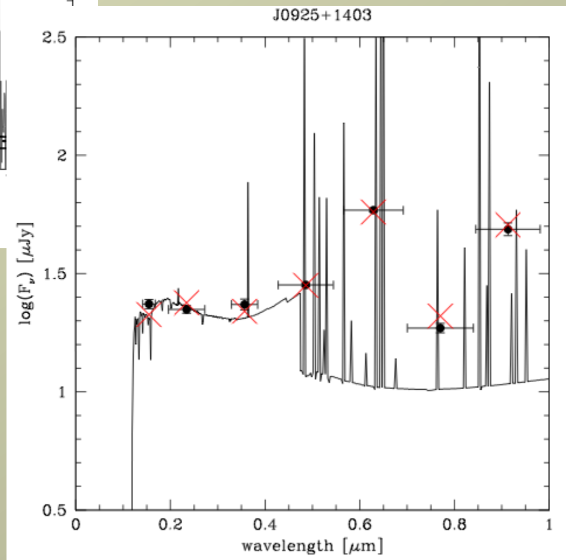
✔ Lyman continuum leakage

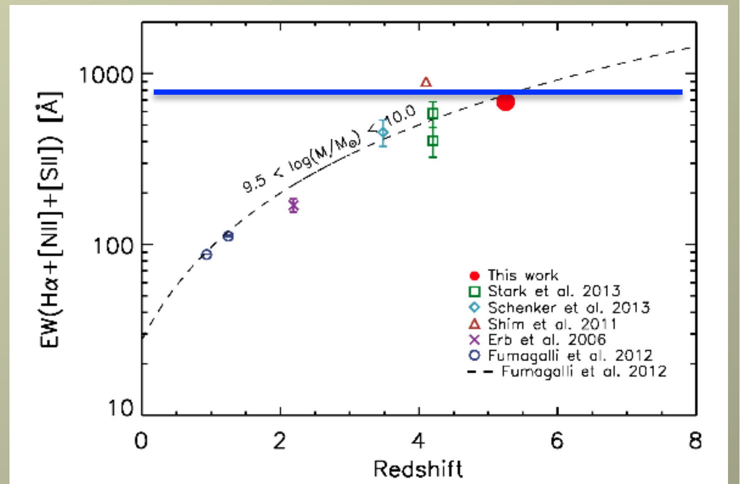
- 11.8 sigma detection (3.43±0.29)×10^{-17} erg s^{-1} cm^{-2} $Å^{-1}$
- Absolute fesc=7.8±1.1 % (highest so far at low redshift)

The quest for the sources of cosmic reionisation

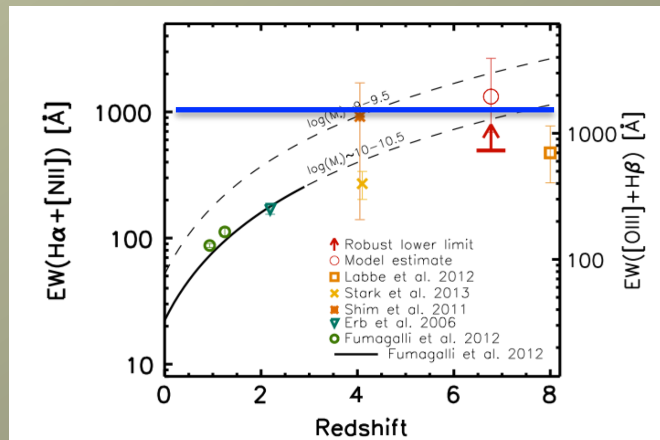
New COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2015)







z~5: Rasappu+ (2015)

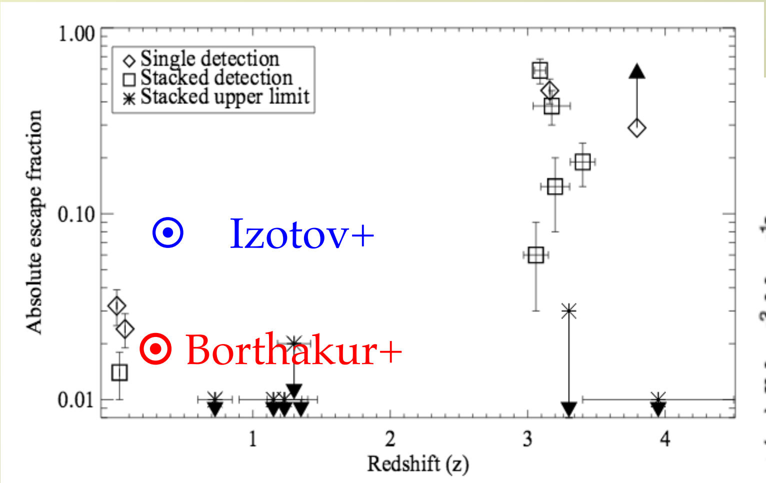


High equivalent widths:
EW(Ha)=730 Å
EW([OIII]4959+5007)=1480
…
➠ Comparable to high-z galaxies

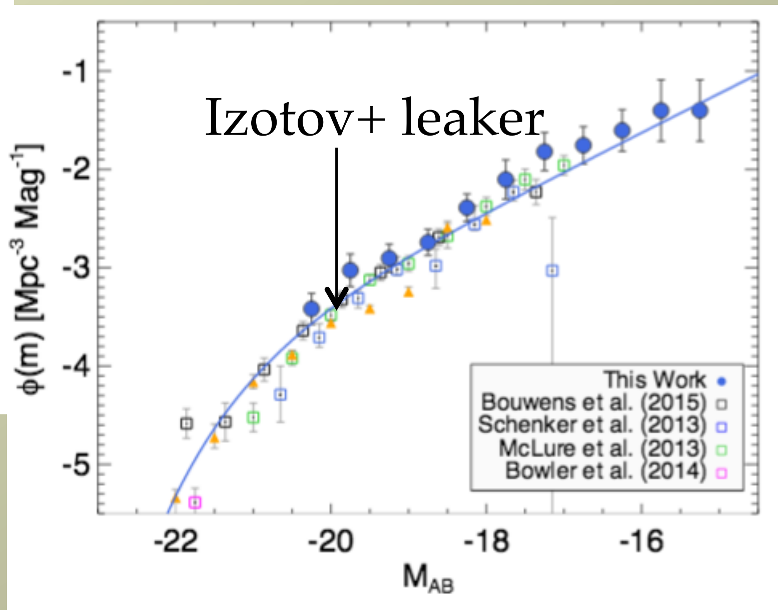
z~7: Smit+ (2014), Roberts-Borsani+ (2015)

The quest for the sources of cosmic reionisation

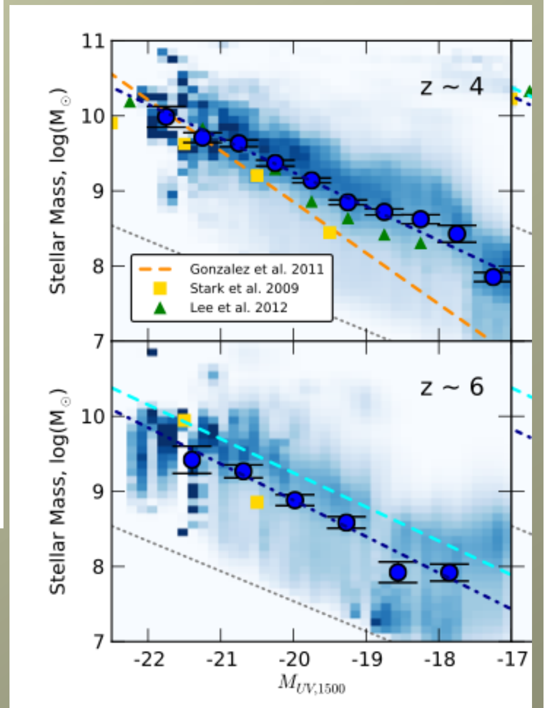
New COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2015)



High escape fraction



Atek+ (2015)



Relatively bright source
Stellar mass ~2 10^9 Msun

Duncan et al. (2014)

The quest for the sources of cosmic reionisation

With JWST spectroscopy + imaging
+ ground-based Lya spectra

Indirect indicators for Lyman-continuum leakage

- *JWST:* **UV low ionisation absorption lines** → *low covering factor of the UV continuum* source (Heckman et al., Jones et al. 2013)

- *JWST:* **High [OIII]/[OII] ratio** → *density bounded HII regions* (Nakajima & Ouchi 2014, Jaskot, Oey+ collaborators)
- *Ground-based:* **Lyman-alpha line profile** → signature of *low HI column density* and/or holes in the cold ISM (Verhamme et al. 2015)

JWST: **Related to high SFR/surface ?** (compact galaxies)

Cf. Heckman+, Theuns talk

Conclusions

A) Consistent analysis of observations needed to address several questions:
SF properties, timescales, SFR, SFR-M dispersion…*

B) Physical parameters of LBGs affected by emission lines and SF histories:
* **Masses ↘, ages ↘, sSFR ↗ increases with z**
* Data favours variable SF histories
* UV attenuation higher than usual (Meurer law)

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

→ **Rest-frame optical emission line measurements with JWST will provide fundamental new constraints on high-z SF galaxies**

C) New observational criteria to identify sources of cosmic reionisation

→ **Characterisation/identification of reionisation sources with JWST**