Theme 2:
science with the FLARE spectroscopic survey

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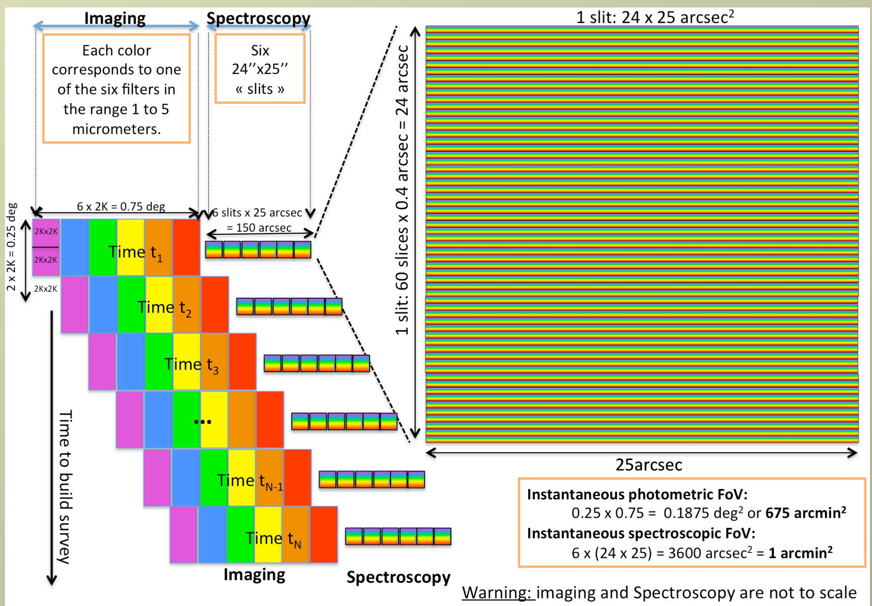
- for the SWG2

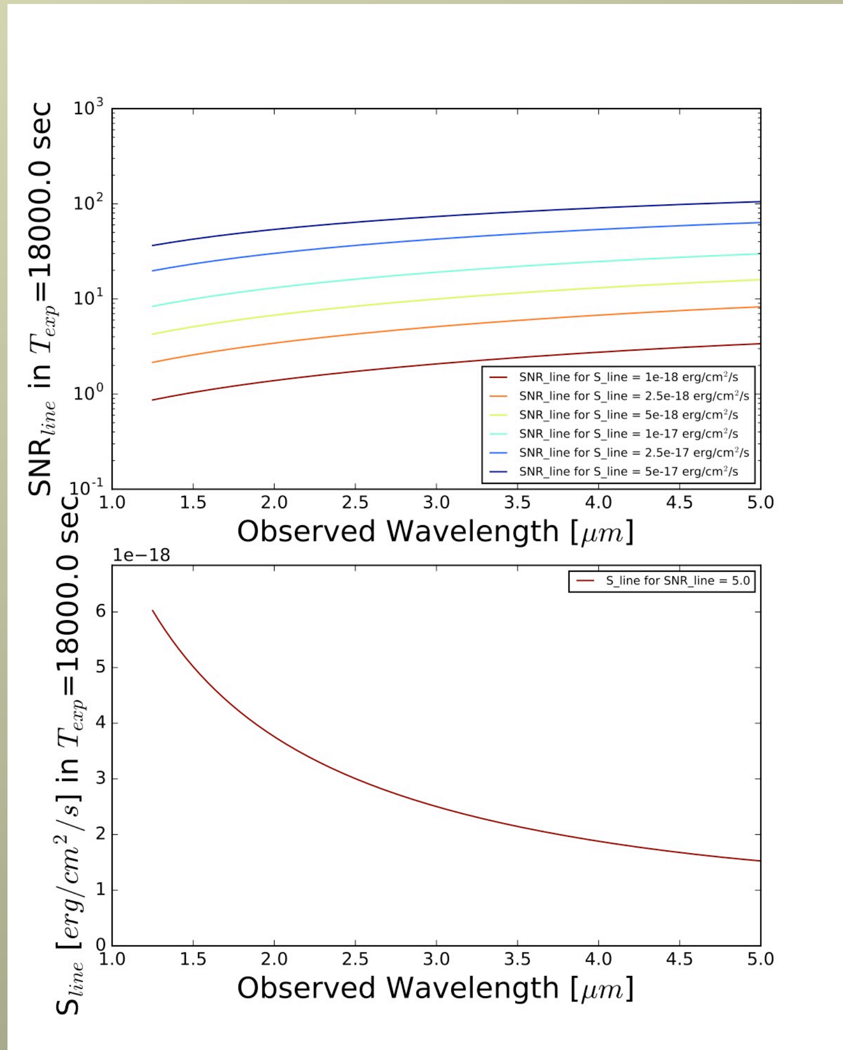
- Overview
- Selected science cases

Specifications of the FLARE spectro survey

IFU
1-5 micron
Instantaneous FOV 1 arcmin^2
Total survey area 1-2 deg^2
Line sensitivity~ 5e-18 erg/cm2/s to S/N~5-15

→ Unbiased emission line survey
+ with photometric coverage down to m_{AB}~28





Specifications of the FLARE spectro survey

IFU
1-5 micron
Instantaneous FOV 1 arcmin^2
Total survey area 1-2 deg^2

Rest-frame optical lines:

- From [OII]3727… [OIII]5007, to Hb, Ha

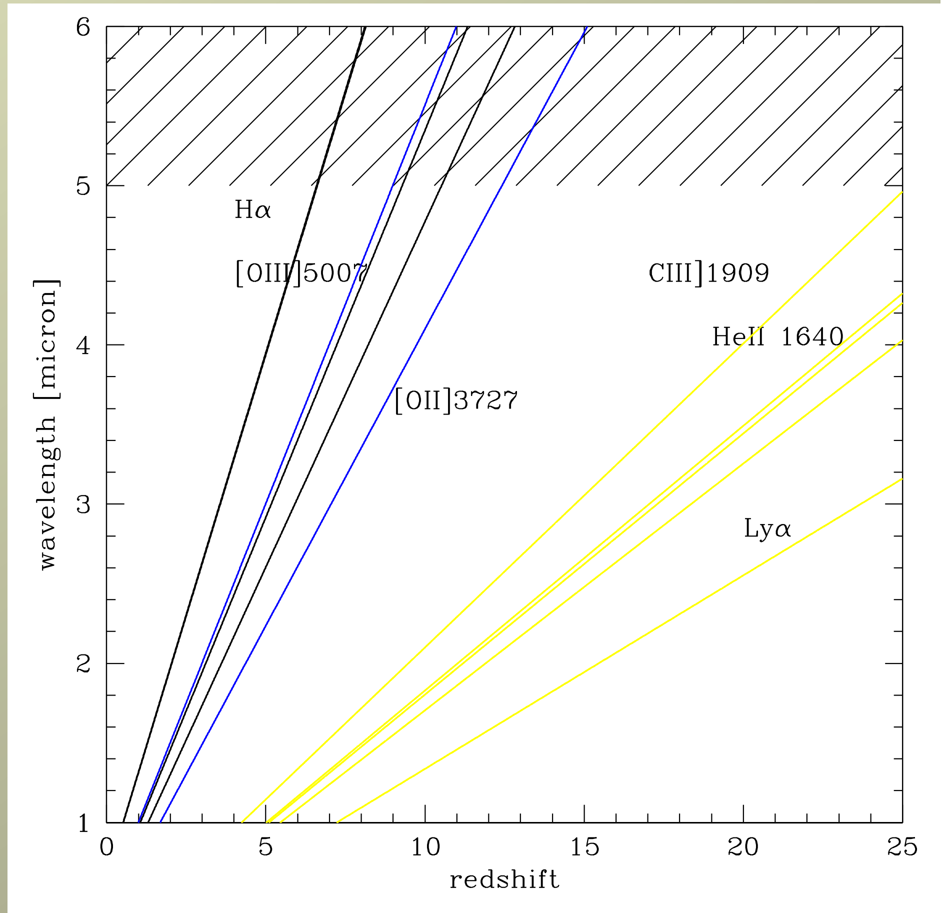
→ Ha out to z~6 (z~8 for 6 micron)

→ [OIII],[OII], Hb to z~9 (11)

Rest-frame UV lines:

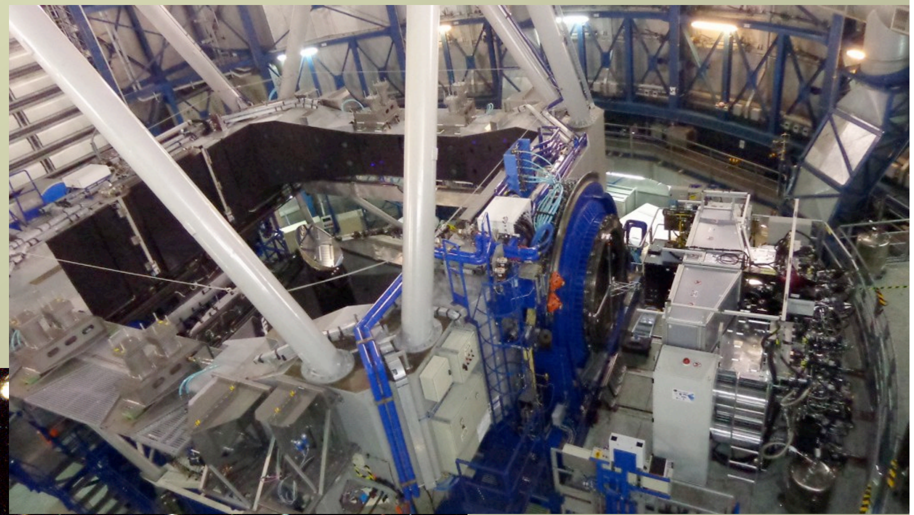
- Lya, HeII1640
- CIII]1909, CIV 1550
- OIII]1663

→ z~7 to 25 – all lines from Lya to CIII]1909!



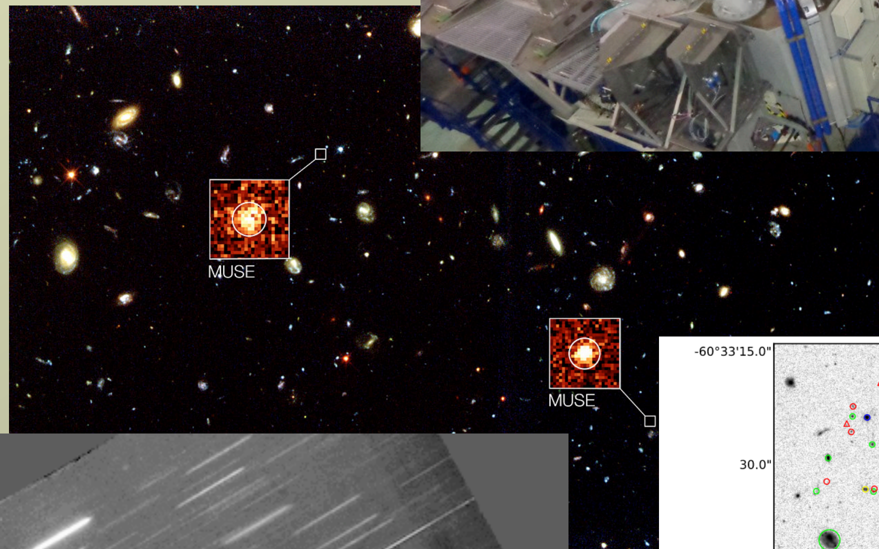
FLARE spectro survey – science cases

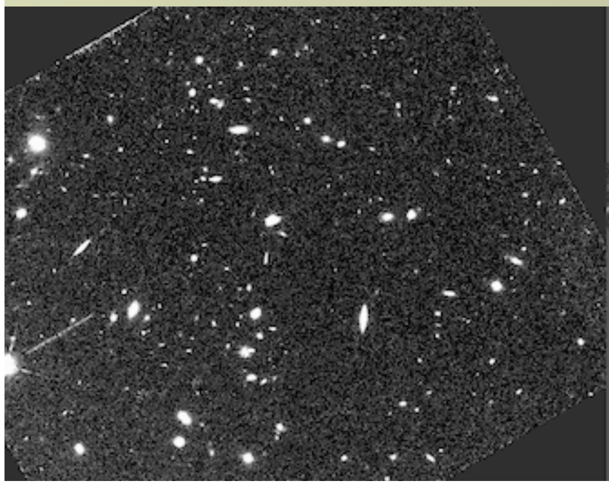
MUSE @ VLT: 1′x1′, optical

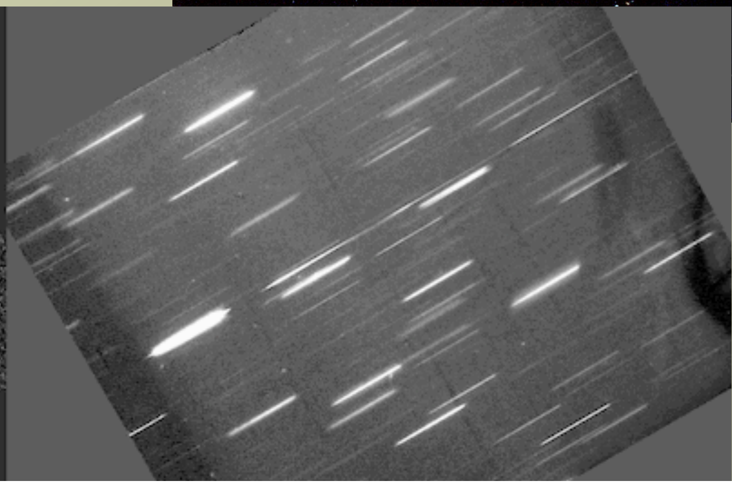


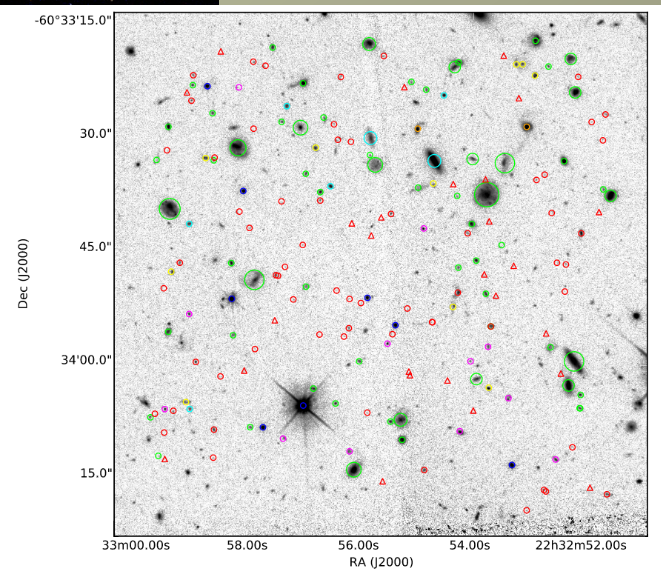
WFC3 grism: up to 1.6 micron

3D-HST survey 600 arcmin^2
Sensitivity 2.5e-18 erg/s/cm^2 (1σ)
→ 10000 galaxies at z~1 to 3









FLARE spectro survey – science cases

- **An unbiased Ha luminosity function evolution (from z~0.5 to 6-8)**
- **Are we missing dusty sources? Are we missing SF in the Universe?**
- **Dust attenuation in SF galaxies from z~1 to 6 (8)**
- Physics of high-z galaxies and SF (up to z~6-8):
  Stellar masses, SF histories, mass-metallicity
- **Very high-z galaxies (z~7 to 40):**
  redshift confirmation, physical properties …
- Evolution of the bright-end of the Lya LF from z~6 to 30
  inferences on cosmic reionisation
- **Sources of cosmic reionisation**
- **Exotic objects – PopIII, direct-collapse BH, …**
- Lyman-alpha blobs ?
- High-z galaxy clusters
- « Pointed » IFU observations of lensing clusters → probing fainter galaxies
- ….

YOUR FAVOURITE science case !? Suggestions welcome!

Hα surveys up to z~7: 13 Gyrs, same method

Are we missing SF in the Universe and how much?

What we need:

Improve SFH

- A **good (single)** star-formation tracer that can be applied from z=0 up to ~13 Gyrs ago (z~7 or more)
- Well calibrated/understood + sensitive

Understand the SFH

- Able to **uniformly** select large samples so you can directly identify/measure evolution
- **Different epochs** + **Large areas** + **Best-studied fields**
- **Wide parameter range: Masses, Environments, Galaxy properties**

What we need:

Improve SFH

Understand the SFH

- A goo… …e applied from z=0 u…
- Well c…
- Able … …n directly identi…
- Differ… …elds
- Wide parameter range: Masses, Environments, Galaxy properties

First Light And Reionization Explorer

FLARE

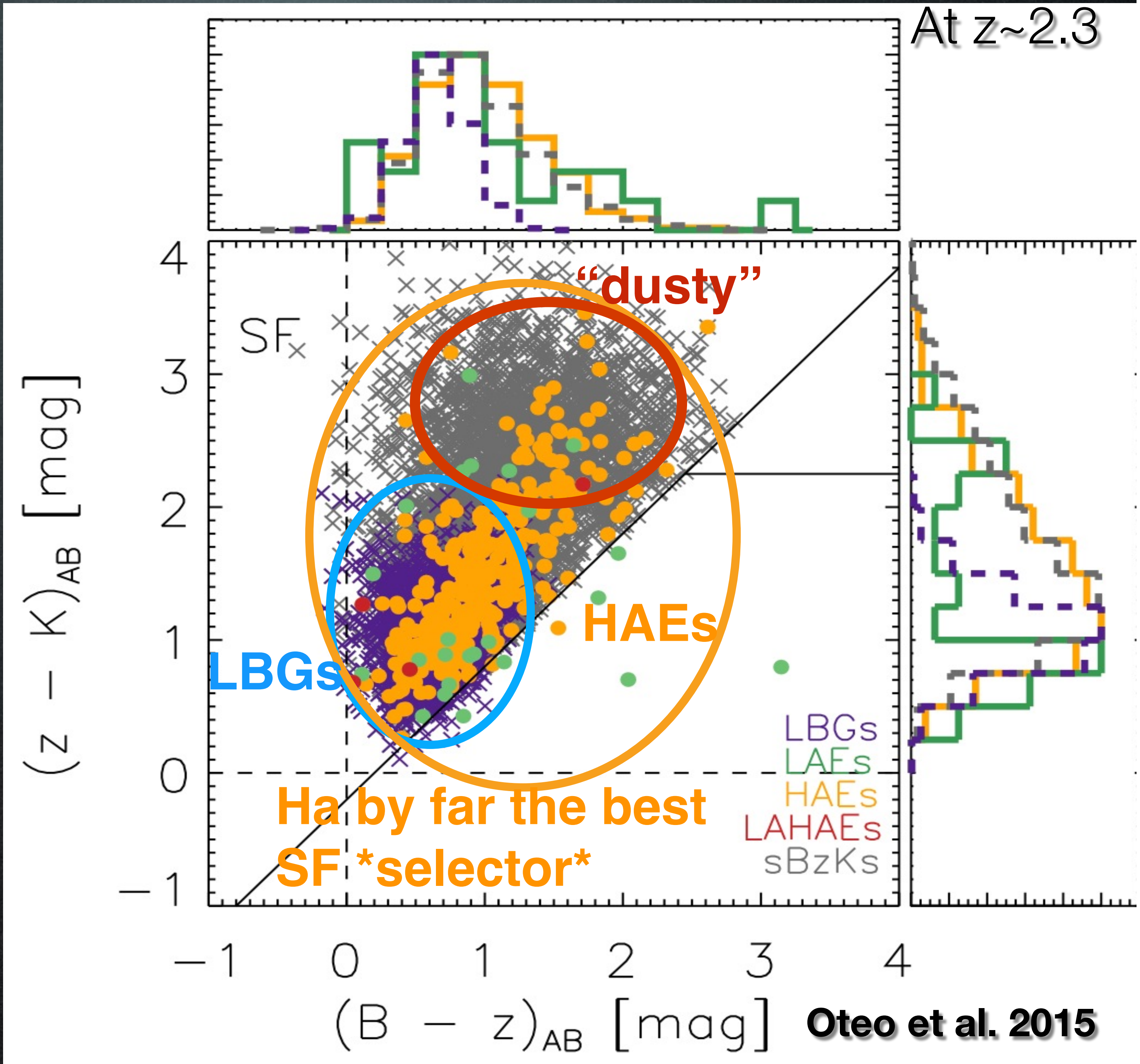
Selection really matters at z=2!

Lyman-break/UV selection: **misses ~65-70%** of star-forming galaxies! (metal-rich, dusty) (+ systematics)

LAEs: **miss** ~80% of star-forming galaxies

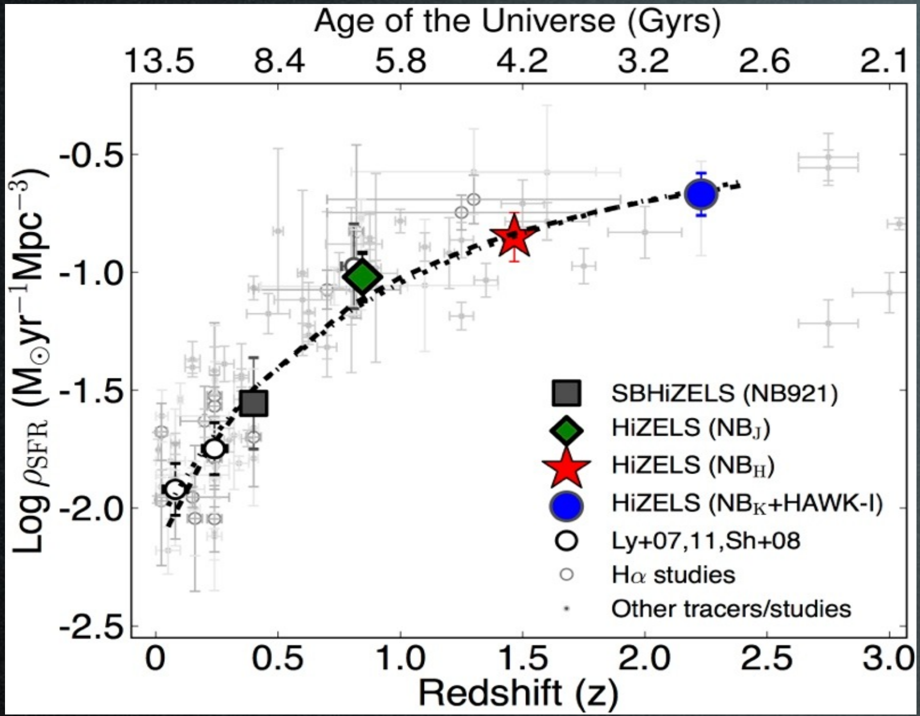
HAEs get ~100% down to the Ha flux limit they sample

See also Hayashi et al. 2013 for [OII]



Oteo et al. 2015

Star formation History

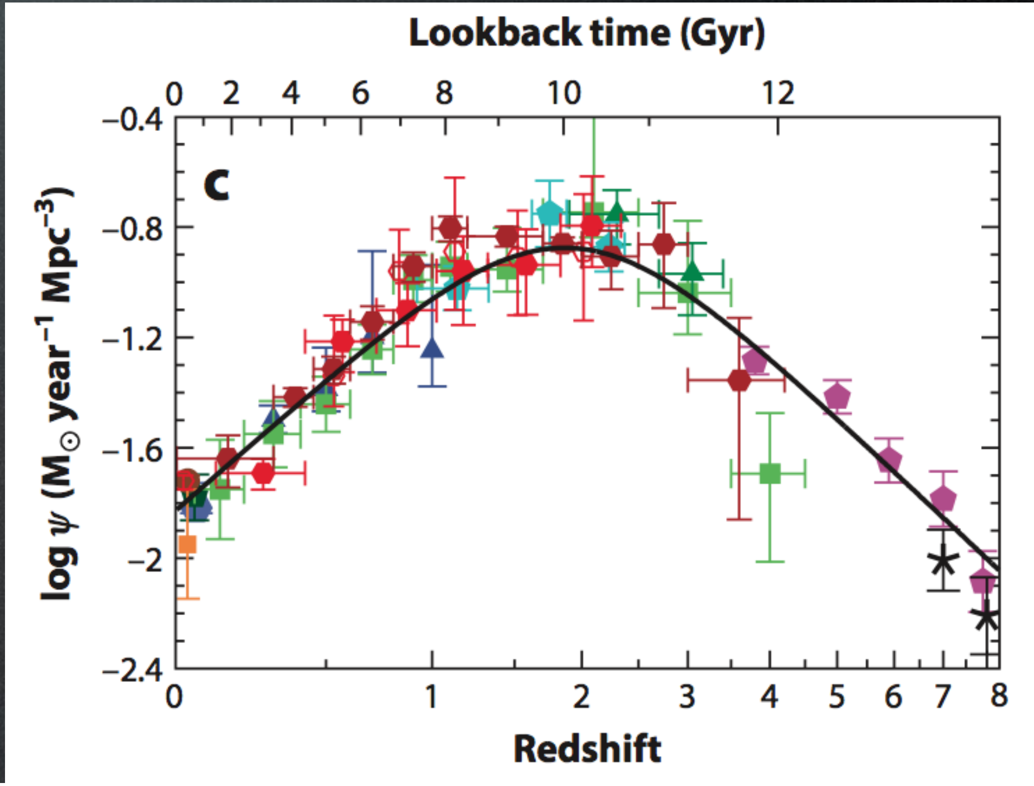


Strong decline with cosmic time

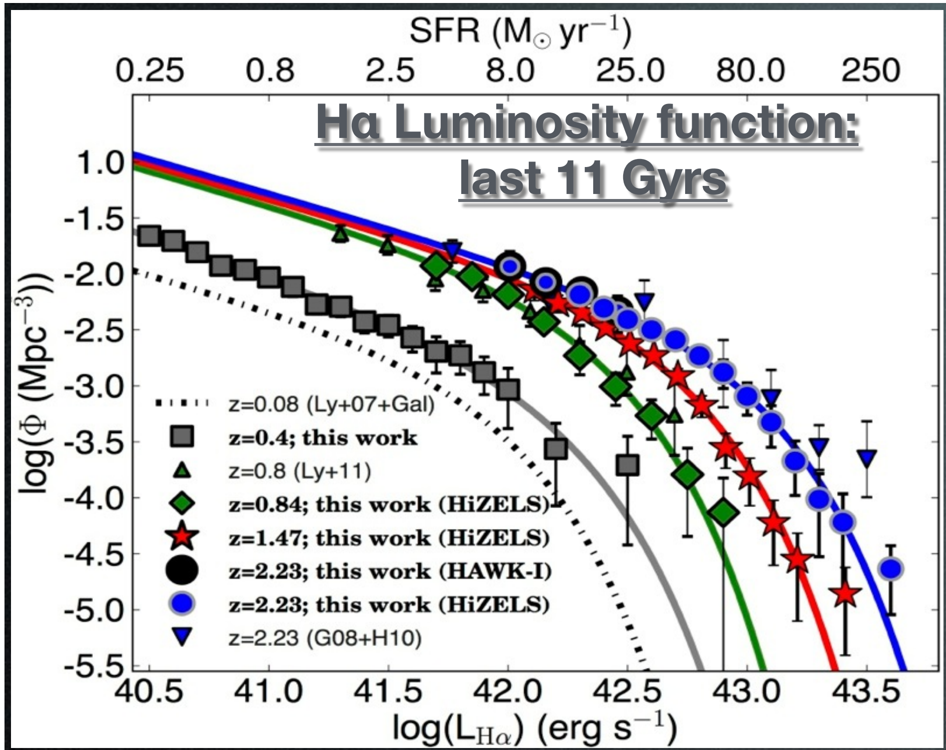
Sobral+13a

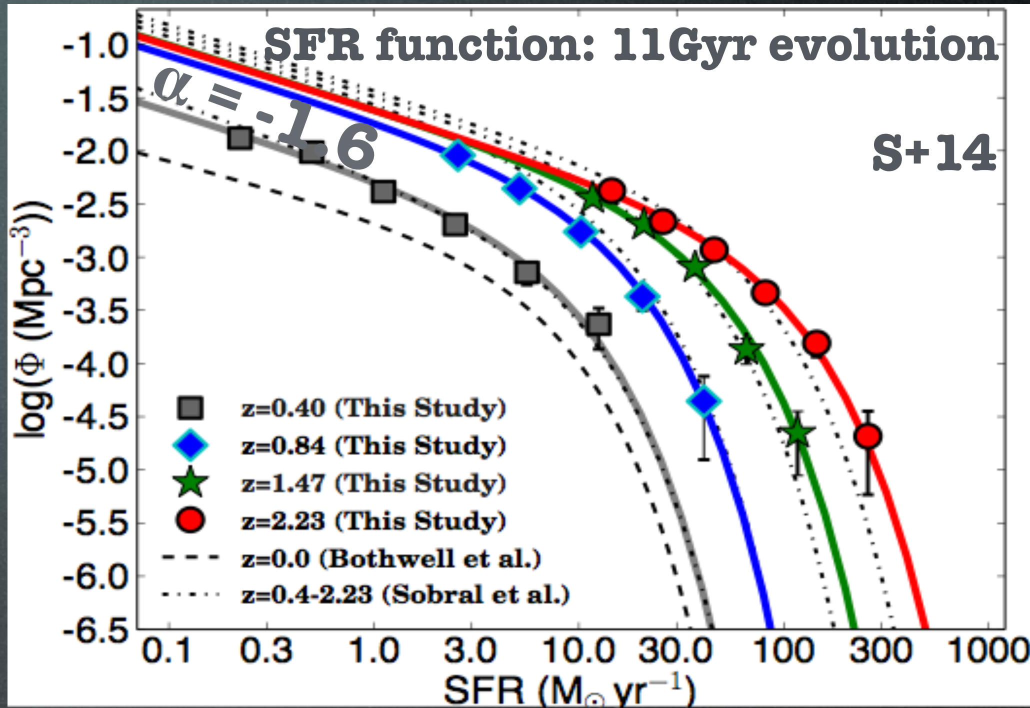
+ e.g. Lilly+96, Hopkins04, Karim+11

Madau& Dickinson 14

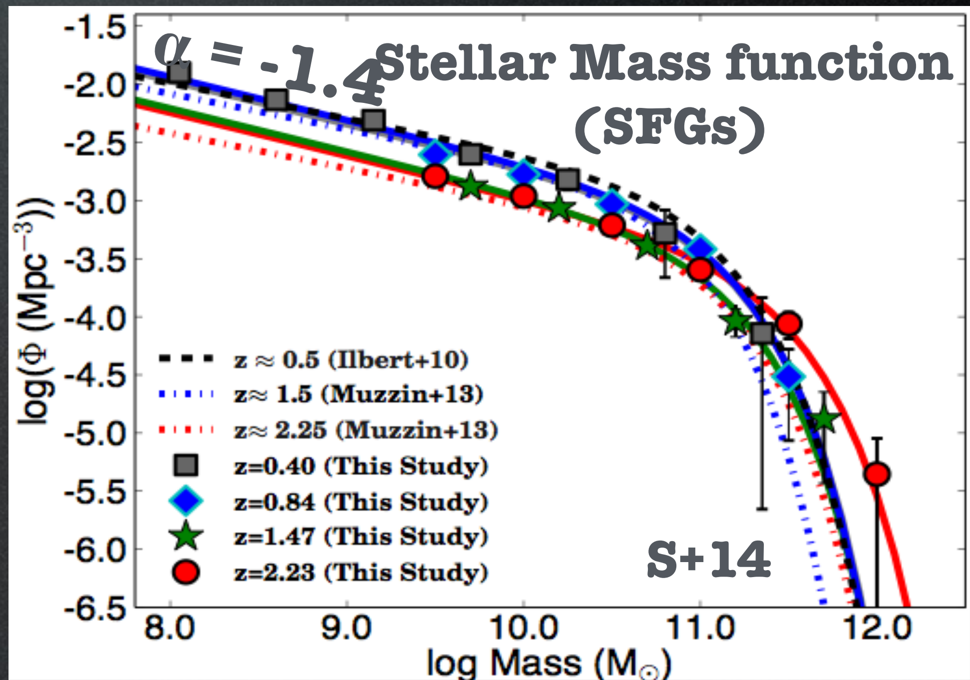


→ FLARE will measure cosmic SF history beyond the peak with uniform probe (Halpha)





Sobral et al. 2013a, 2014



Same selection: evolution of LF, SFR function, Mass function

Up to z~2.5 OK

A Big step forward :
Beyond K band

Let's really solve the biggest problems in a completely alternative, very robust way:

SFRs, sSFRs, EWs, Complete self-consistent samples across 13 Gyrs

Evolution in: metallicities, environment, masses, dust extinction, clustering + re-ionisation

+ ideal follow-up samples!

A Big step forward :
Beyond K band

Is it realistic? Why would you need to do it?

Hα star-forming galaxies $2<z<7$

Same robust selection

Full galaxy population: 13 Gyrs!

IFU spectroscopy of the unexplored: >2 um to 5 um

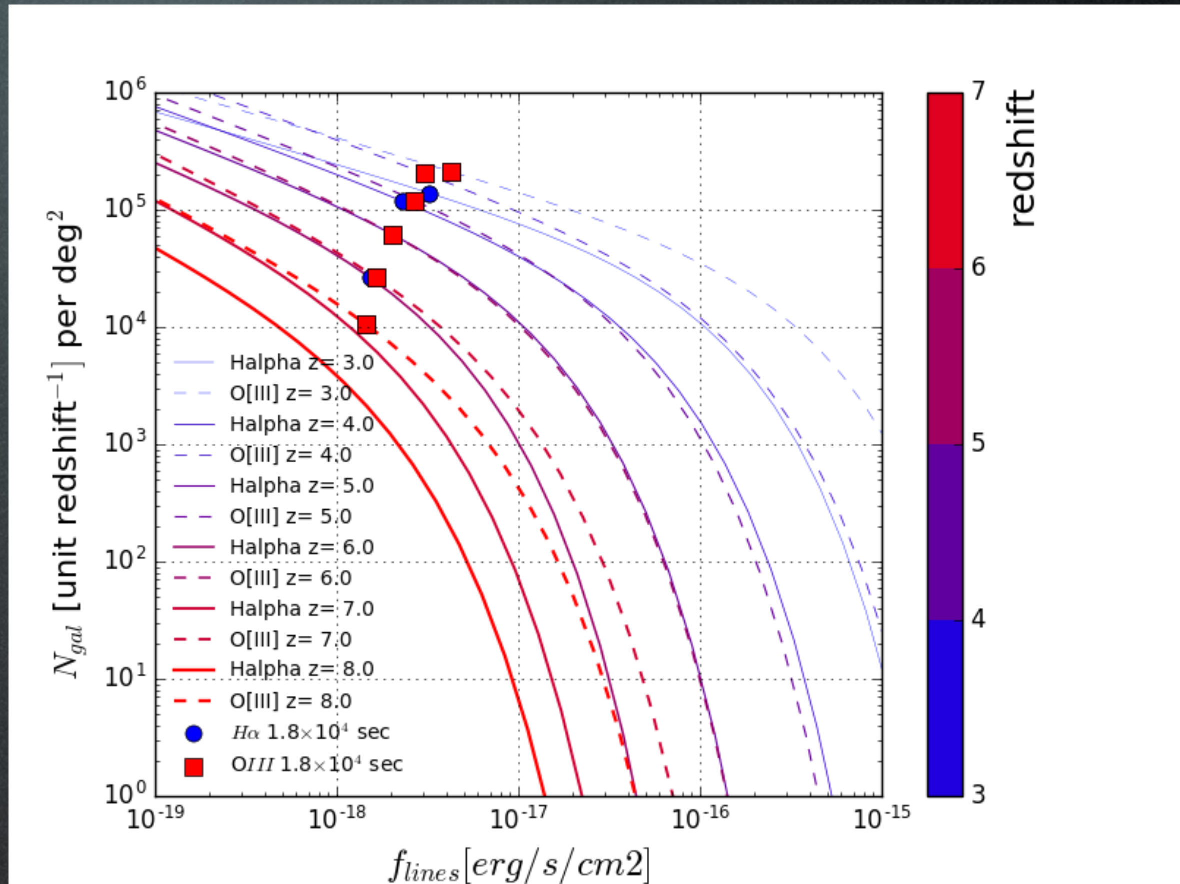
SFH and full census of *star-forming* galaxies ($H\alpha$ selected)

Direct comparison to UV and Lyman-α: re-ionization

Clustering, metallicity evolution, mass function

Morphologies, size evolution

Realistic predictions: Hα emitters



Burgarella 2016
Based on UV luminosity fcts
-- UV selection

f>2x10^{-18} erg/s/cm^2

L(Hα) limit ~10^{41} erg/s

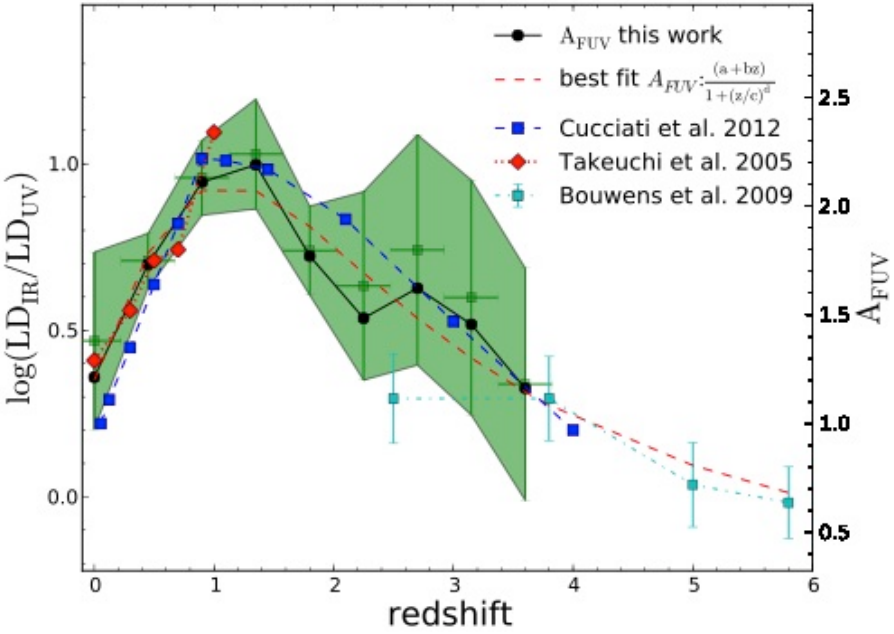
SFRs (Hα) >0.5 $M_\odot$/yr

Science goals:

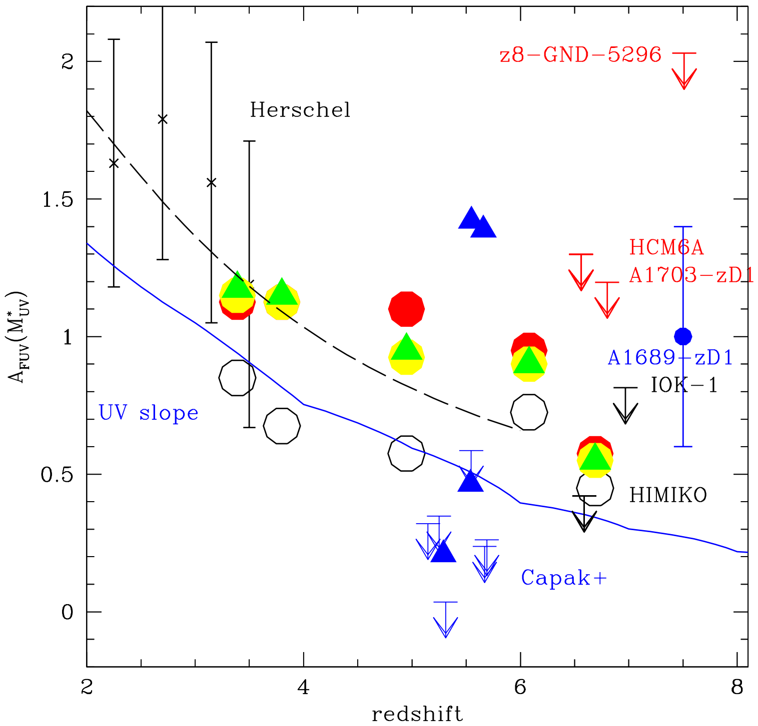
- Robust Star formation history of the Universe in multiple slices (spaced by <1Gyr) in the last 13 Gyrs
- Evolution of: SFR-Mass, Mass Function
- Clustering and evolution: DM halo masses - evolution
- Morphologies, sizes, dynamics (follow-up)
- Metallicity evolution with the same, robust selection
- Comparison/calibration with UV to better extend to z>7

- Re-ionisation: .e.g Ha-Lya matched surveys z=2.2 to 6.6

SC: Dust attenuation from z~3 to 6



Burgarella et al. (2014)



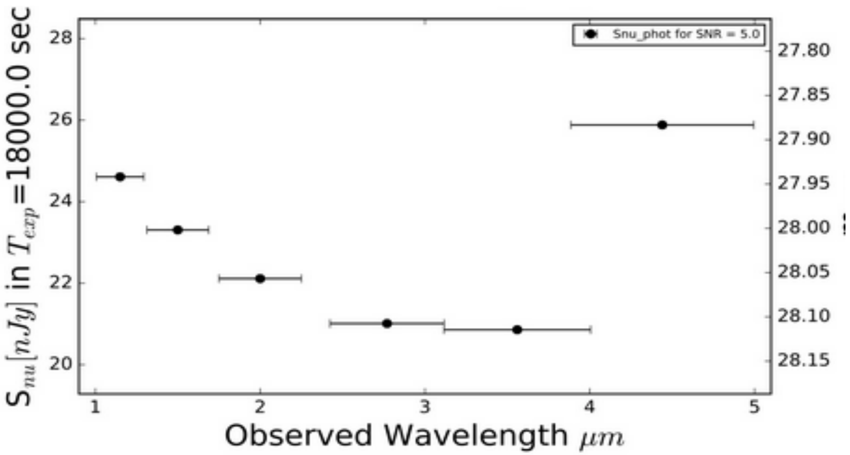
Schaerer et al. (2015)
+Capak et al. (2015) data

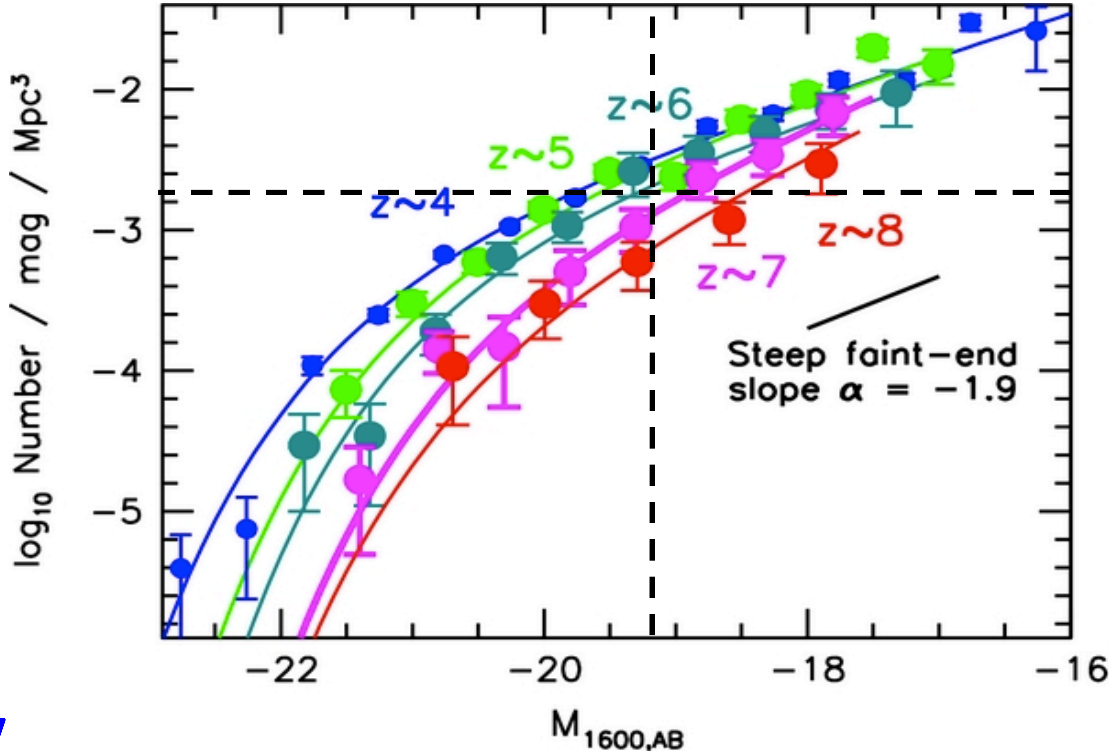
- Direct measure of UV attenuation (from IR/UV) with Herschel limited to z~3.5
- At z>3: UV slope used to estimate attenuation
- BUT: indications for deviations from std assumptions → higher attenuation
  Cf. de Barros+2014, Castellano+2014

➔ **Direct measurements needed!**

→ALMA, JWST, FLARE

Which sources at z=6 ? Starting from the UV LFs





Bouwens et al. 2012

At z=6 in photometry

Limiting magnitude: $\mathbf{m_{AB} = 28}$ **mag**

→$\mathbf{M_{AB}}$**(UV rest-frame) = -18.7**

→**1.5 M⦿/yr assuming no attenuation**

≈30 000 galaxies/deg^2 (Δz=1)

Spectroscopic sensitivity: Hα line

For which galaxies at z=6 will we be able to detect the Hα line?

From Kennicutt (1998) relations (SFR ~ Luminosity):

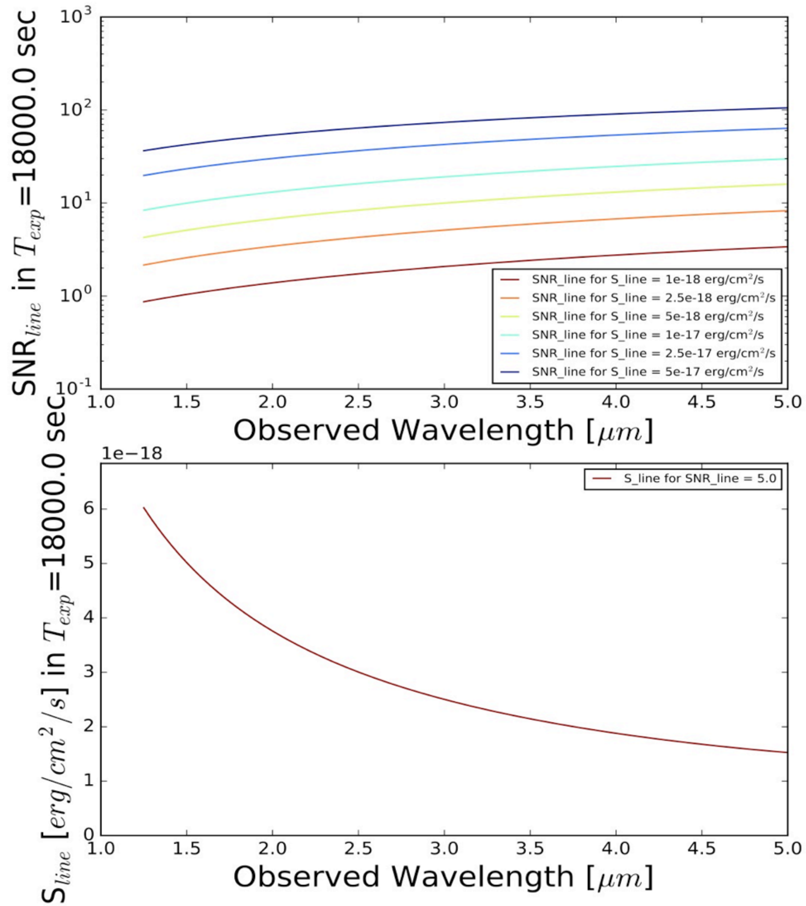
At z=0 $L(H\alpha)/L_\nu$ (UV) = 1.8 10^{13} Hz

→ At z=6 L_{line}/L_ν = 2.6 10^{12} Hz

Limiting sensitivity at 4.6 μm: ~1.5 10^{-18} erg $cm^{-2}s^{-}$

→ m_{AB}(UV)= 27 mag

→ **9000 gal/deg² (Δz=1)**



A conservative calculation?

Larger equivalent width at high z:

$L(H\alpha)/L_\nu$ (UV) boosted by a factor 1 to 5

we may assume a factor 3 (0.5 dex)

→ m_{AB}(UV)= 27.5 mag

~14000 galaxies/deg²

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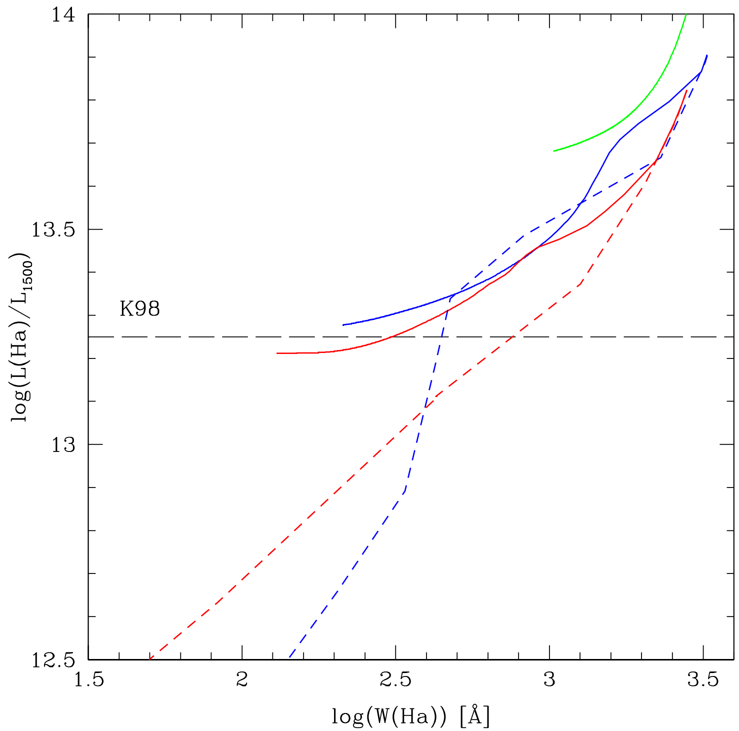


Attenuation: Balmer decrement

- Balmer decrement: $R\alpha\beta_{int}$ = F(Hα)/F(Hβ)=2.86
- Applying a standard extinction curve and a screen geometry:

  $E(B\text{-}V)_{gas} = 2.34\ (R\alpha\beta_{obs} - R\alpha\beta_{int})$

  $A(H\alpha) = 2.52\ E(B\text{-}V)_{gas}$
- To the UV continuum (0.15 μm)

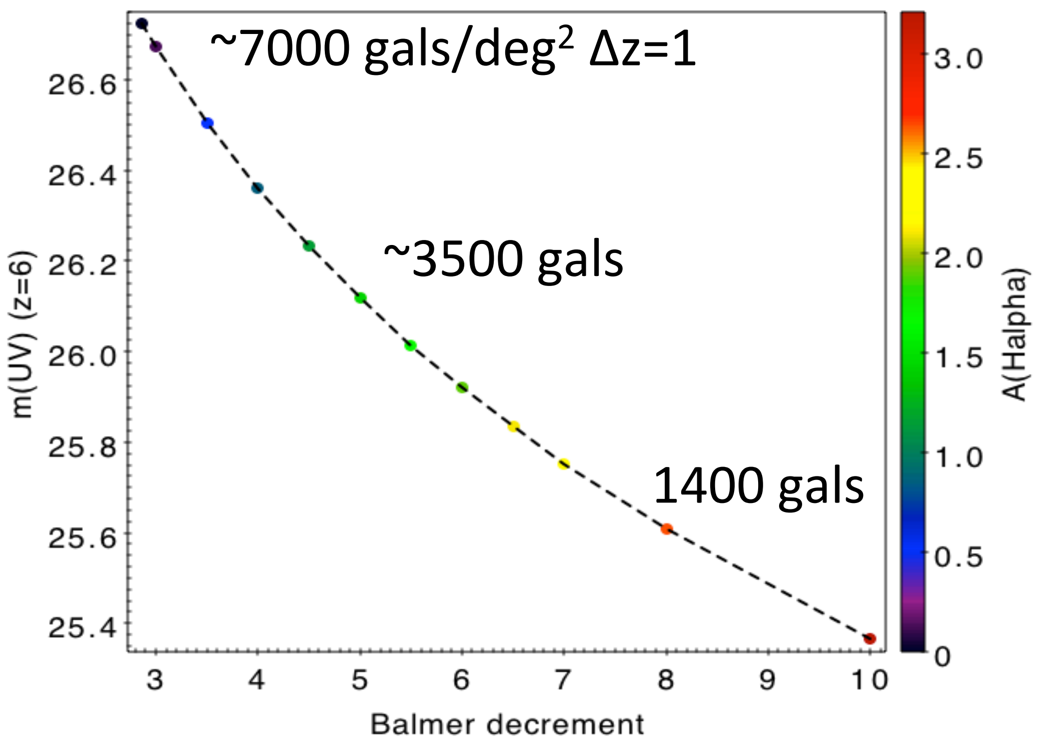
  $E(B\text{-}V)_{stars} = X * E(B\text{-}V)_{gas}$
  X from ~0.5 (Calzetti) to 1 (high z galaxies?) and Calzetti or SMC laws?
  $A(UV) = 10\ E(B\text{-}V)_{stars}$ (Calzetti+00)

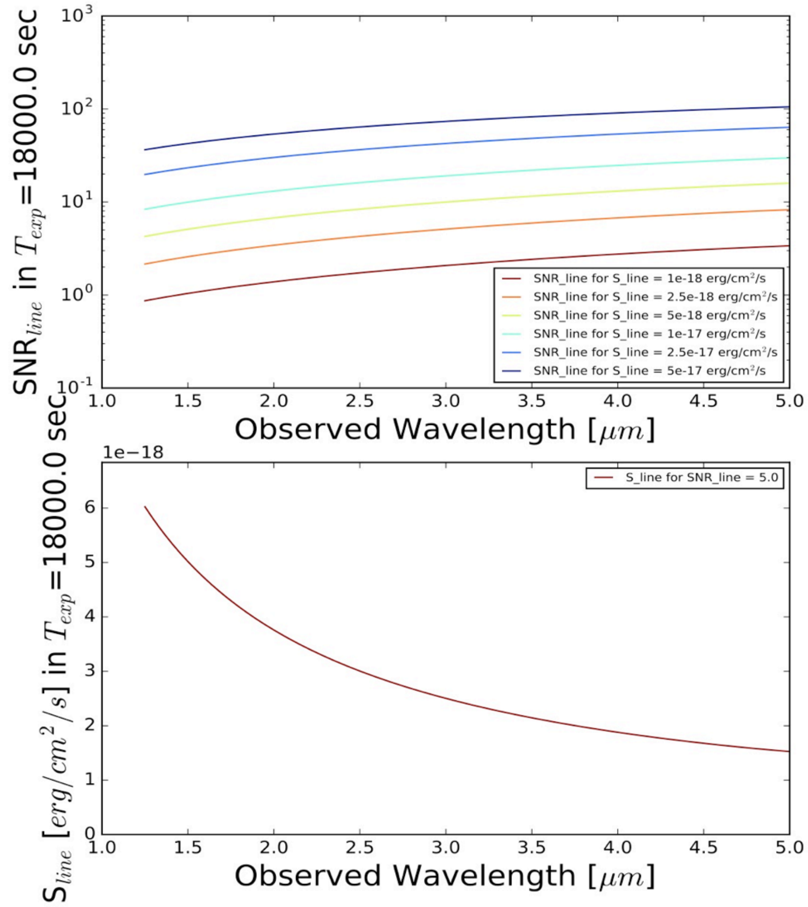
--> **A(UV)= 4* X* A(Hα) ($0.5<X<1$)**

Limiting sensitivity **in the Hβ line**

~2 10^{-18} erg $cm^{-2}s^{-1}$

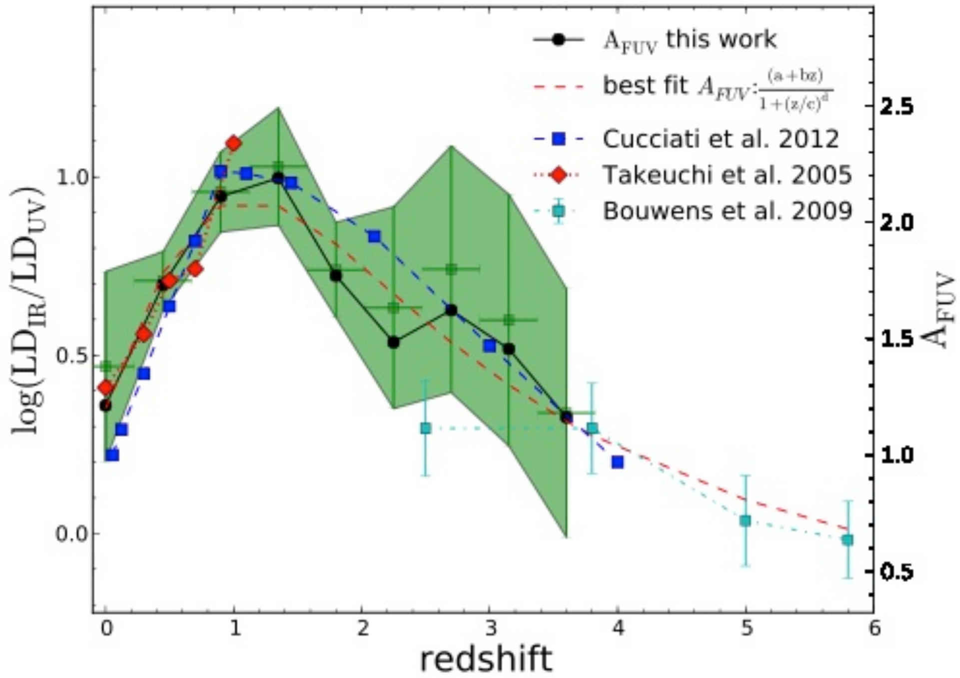
L(Hα)/L_ν (UV) assumed to be constant, very conservative; expected to increase with dust attenuation (A(UV)=2-4 A(Ha))



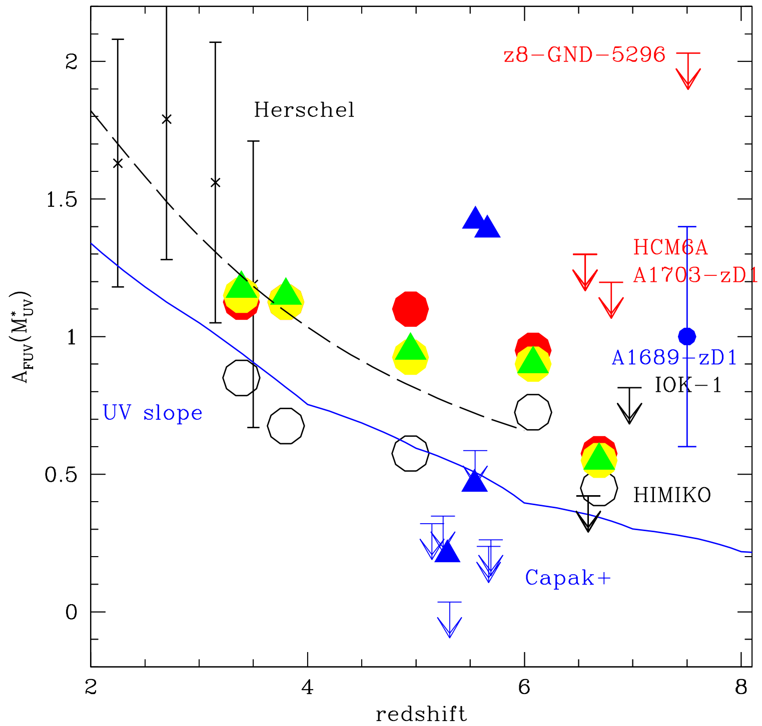


→ **Good statistics even for moderate/high attenuation**

Dust attenuation from z~3 to 6



Burgarella et al. (2014)



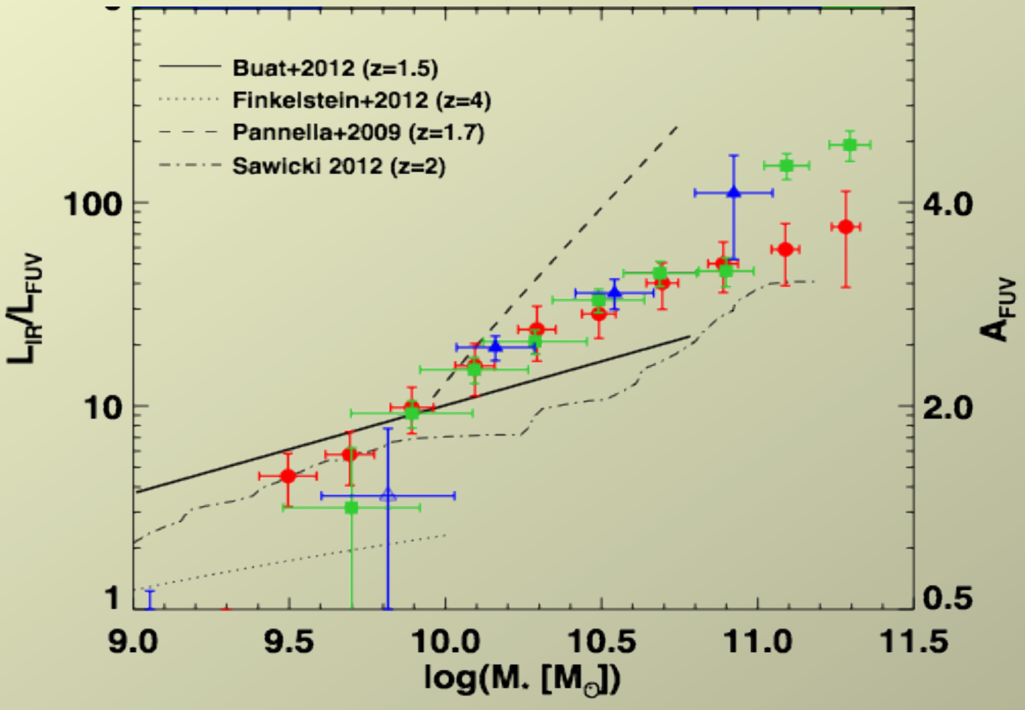
Schaerer et al. (2015)
+Capak et al. (2015) data

➔ **Direct measurements needed!**
→ALMA, JWST, FLARE

Is FLARE competitive with JWST and ALMA?
→ more quantitative comparison needed

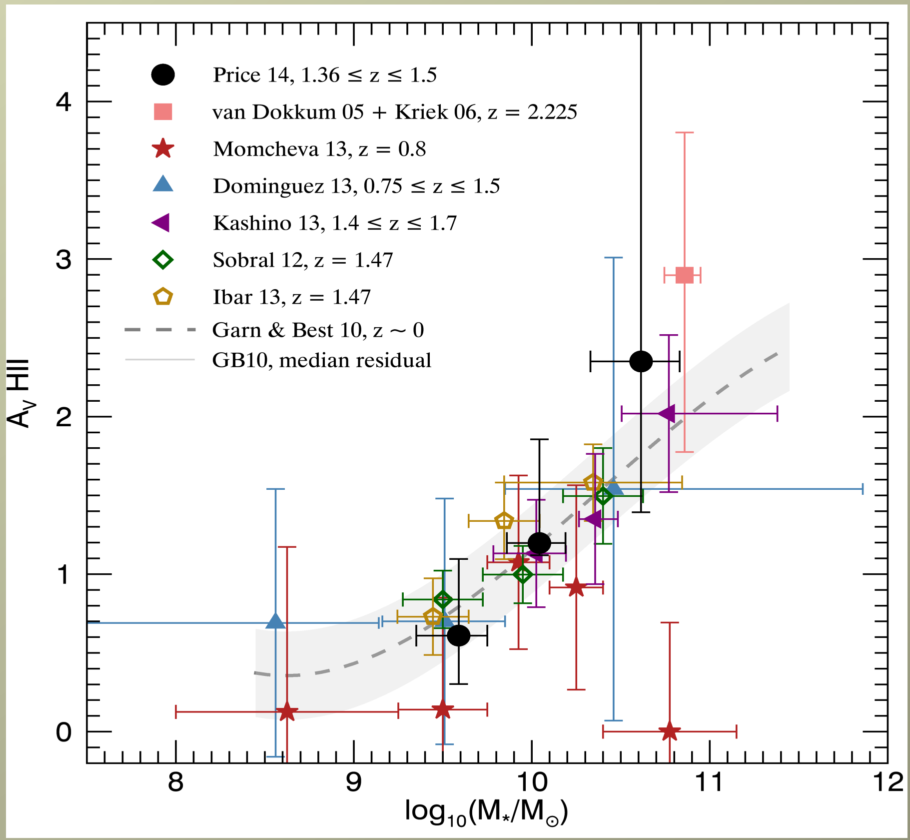
SC: Is there a universal Attenuation-Stellar mass relation?

UV continuum



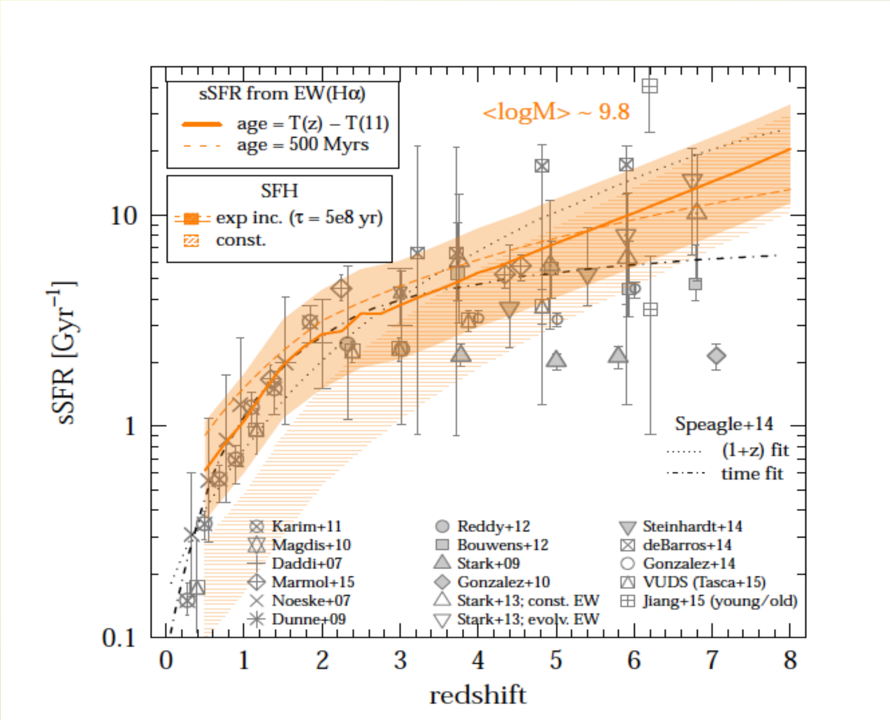
Heinis+14, see also Pannella +14

Nebular lines



Price+14, see also Ibar+13

SC: Is there a universal Attenuation-Stellar mass relation?



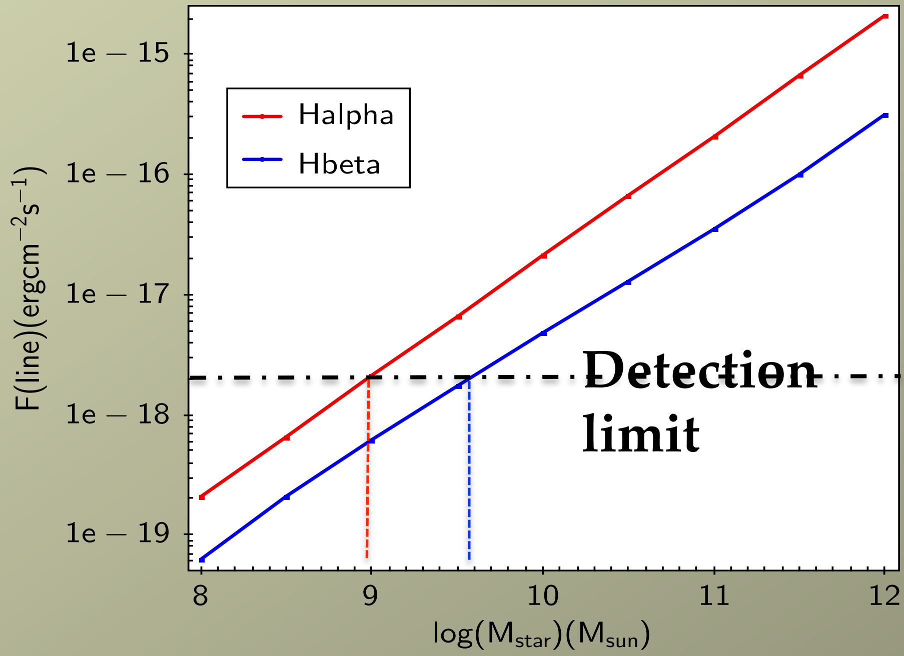
Faisst+ (2016)

M* ----------> SFR

sSFR → F(Hα), F(Hβ)

M*-----------> A(Hα)

M*--A_V

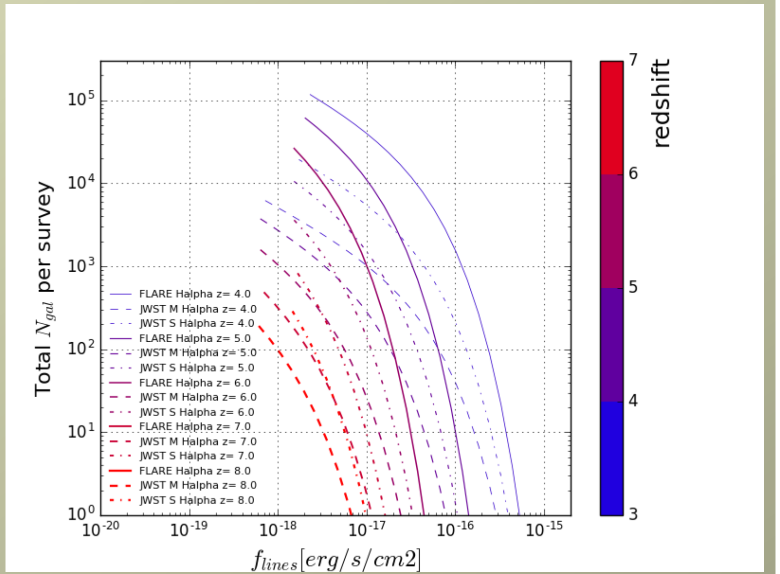


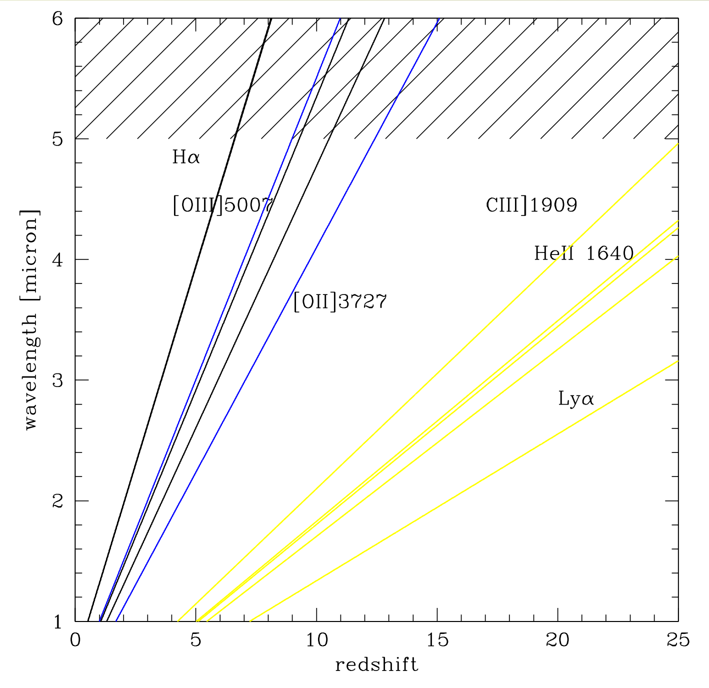
FLARE survey:

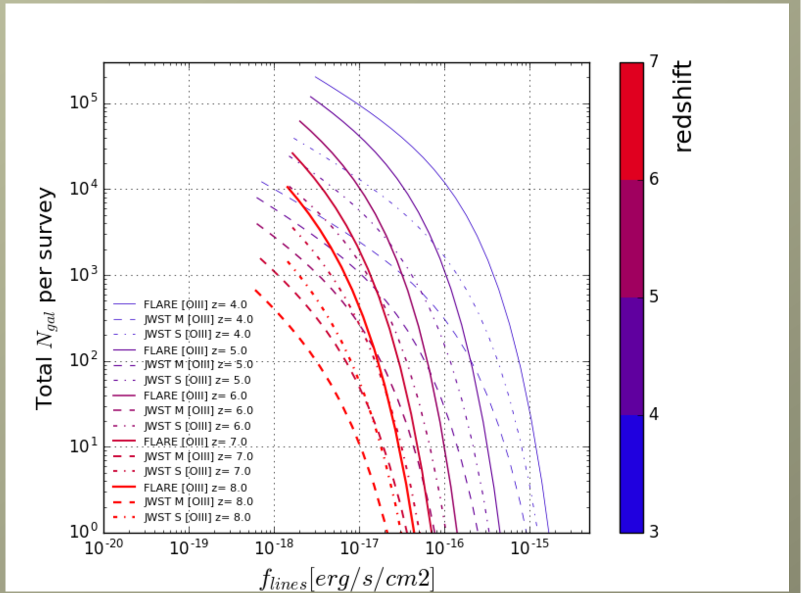
- Hα detected down to 10^9 M_{sun} at z~6
- Att-M* relation measured with the Balmer decrement down to $10^{9.5}$ M_{sun}
- Same depth from z~2 to 6 → measure evolution of M*-attenuation relation
- Competition / complementarity with ALMA !?

SC: Very high-z galaxies (z~7 to 40)
- redshift confirmation, physical properties …

Beyond z>7:
- High source density
- Ha unobservable
- [OIII], [OII] up to z~12
- Rest-frame UV lines between Lya and CIII]1909



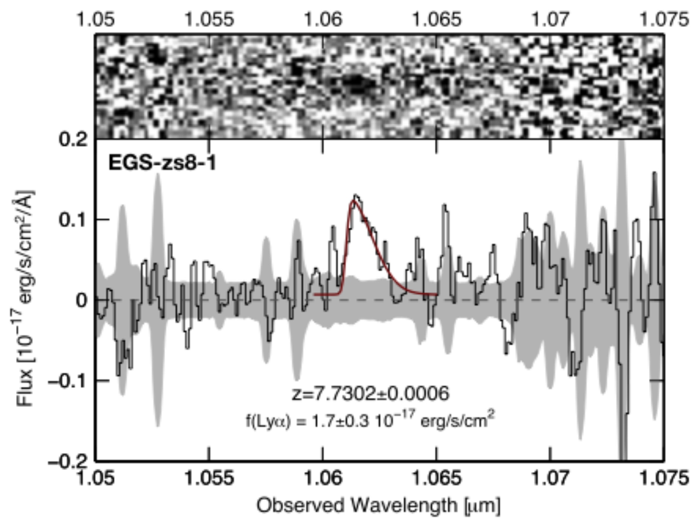




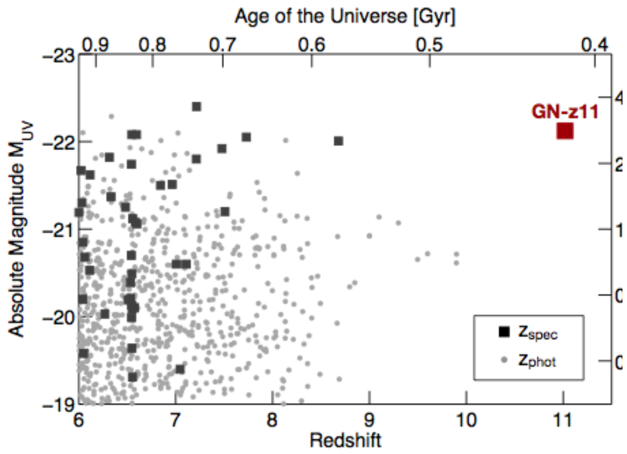
SC: Very high-z galaxies (z~7 to 40)
- redshift confirmation, physical properties …

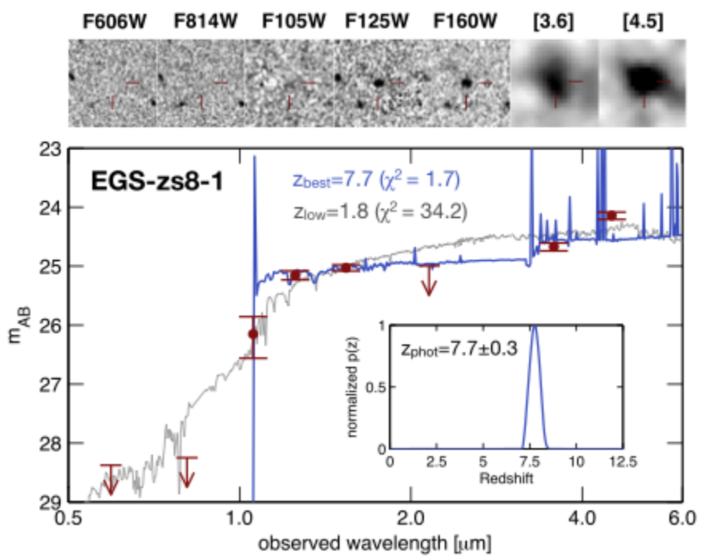
Some bright objects with Lya:

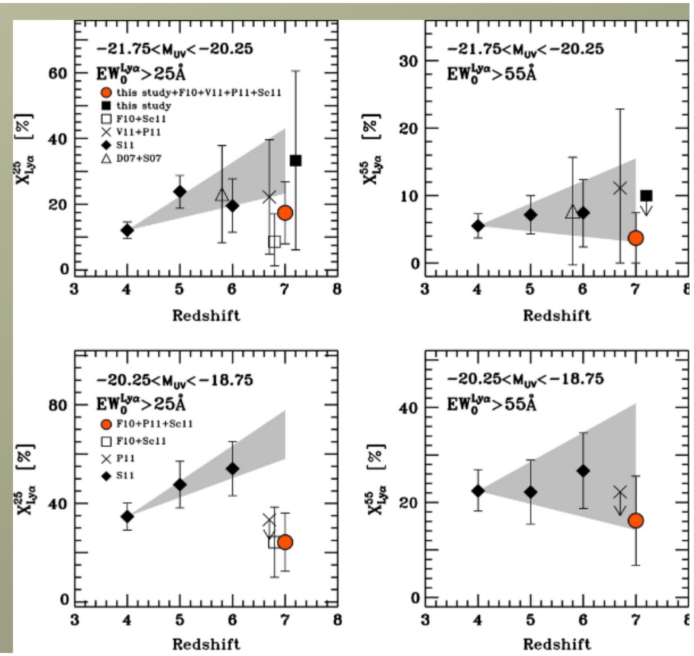
- Finkelstein+ 2013, Oesch+, Roberts-Borsani+ 2015
- F(Lya)~(0.3-2)-17 erg/s/cm2



Oesch et al. (2015) z=7.73







BUT: Overall Lya line decreases above z>6

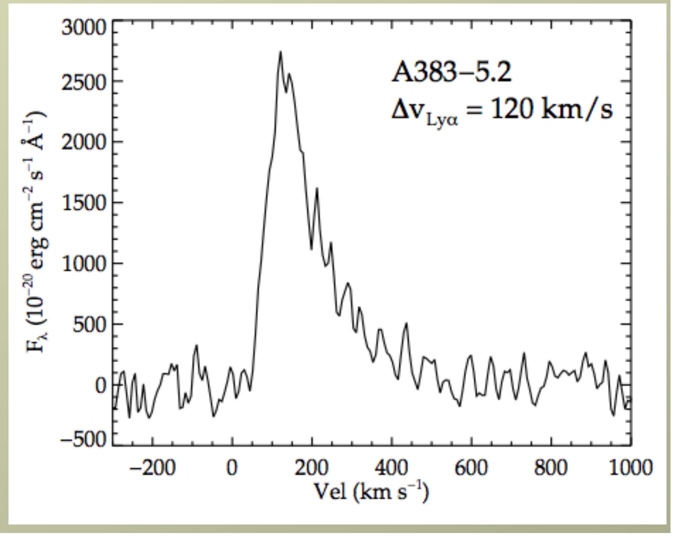
Cf. Stark+2010, 2012, Pentericci+2011, Vanzella+, Schenker+ 2012, Cassata+2014

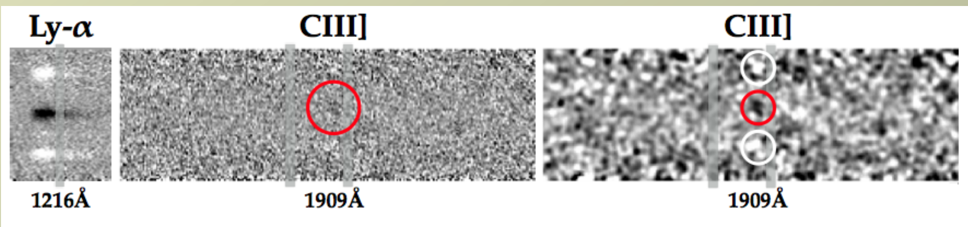
Very high-z galaxies (z~7 to 40)

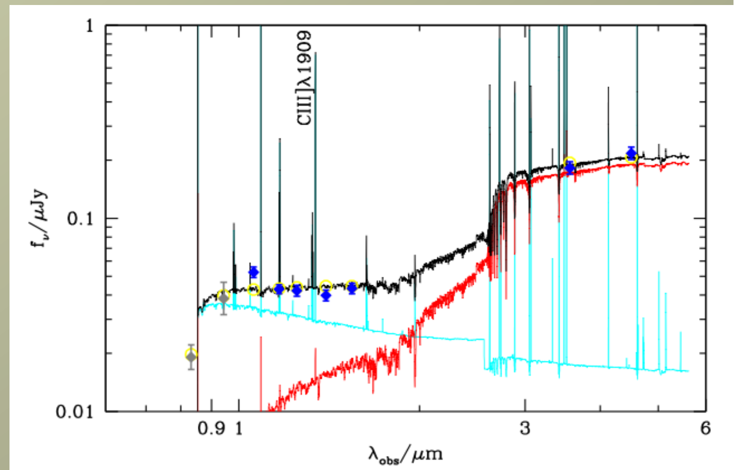
- **CIII] line for redshifts if Lya strongly depressed**
- Probes of outflows
- First attempts to derive physical parameters (ISM, stellar populations,…)

Current detection at z=6.0:

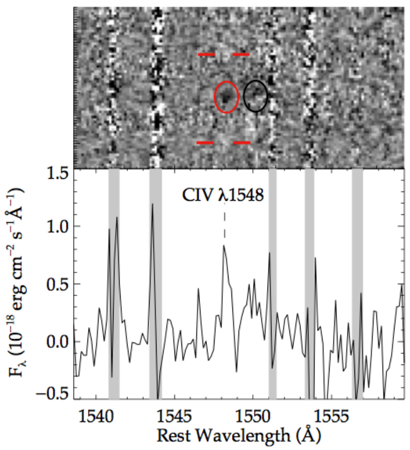
CIII] ~2e-18 erg/cm2/s, Lya=1.e-16 erg/cm2/s

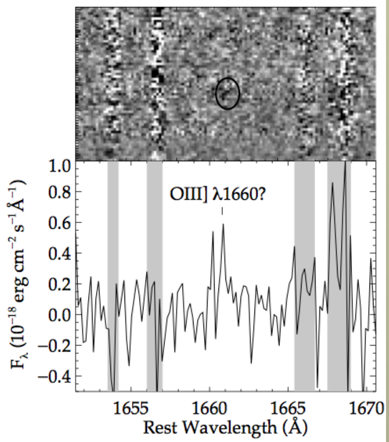






Other examples: CIV, OIII] in z=7.045 galaxy





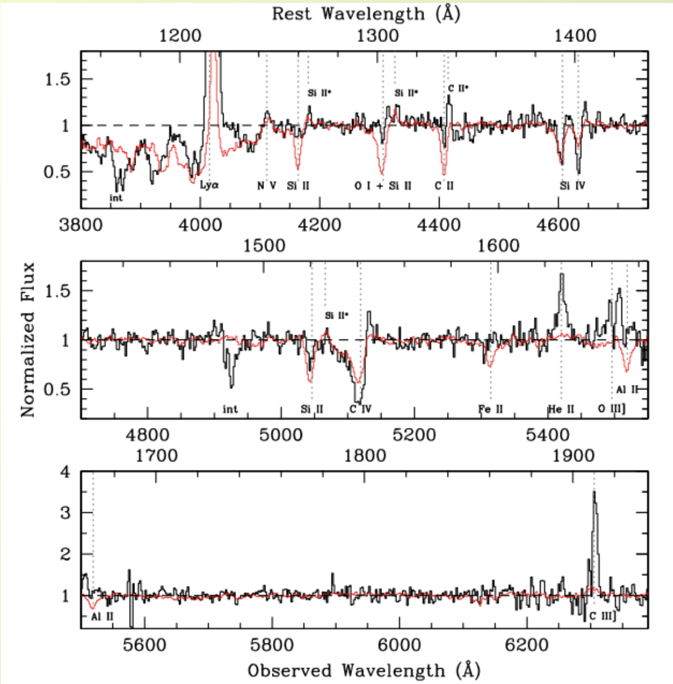
f~(2-4)e-18 erg/cm2/s

Model fit to A383.5.2

$\log U$	$-1.70^{+0.49}_{-0.64}$
$\log(M_{*,young}/M_{*,tot})$	$-2.99^{+0.04}_{-0.03}$
$\log(Z/Z_\odot)$	$-1.33^{+0.27}_{-0.20}$
log(C/O)	$-0.58^{+0.06}_{-0.06}$
log(age/yr)	$8.72^{+0.10}_{-0.10}$
$\log(M_{*,tot}/M_\odot)$	$9.50^{+0.10}_{-0.10}$
$\log(SFR/M_\odot yr^{-1})$	$0.29^{+0.08}_{-0.08}$
$\hat{\tau}_V$	$0.05^{+0.05}_{-0.05}$

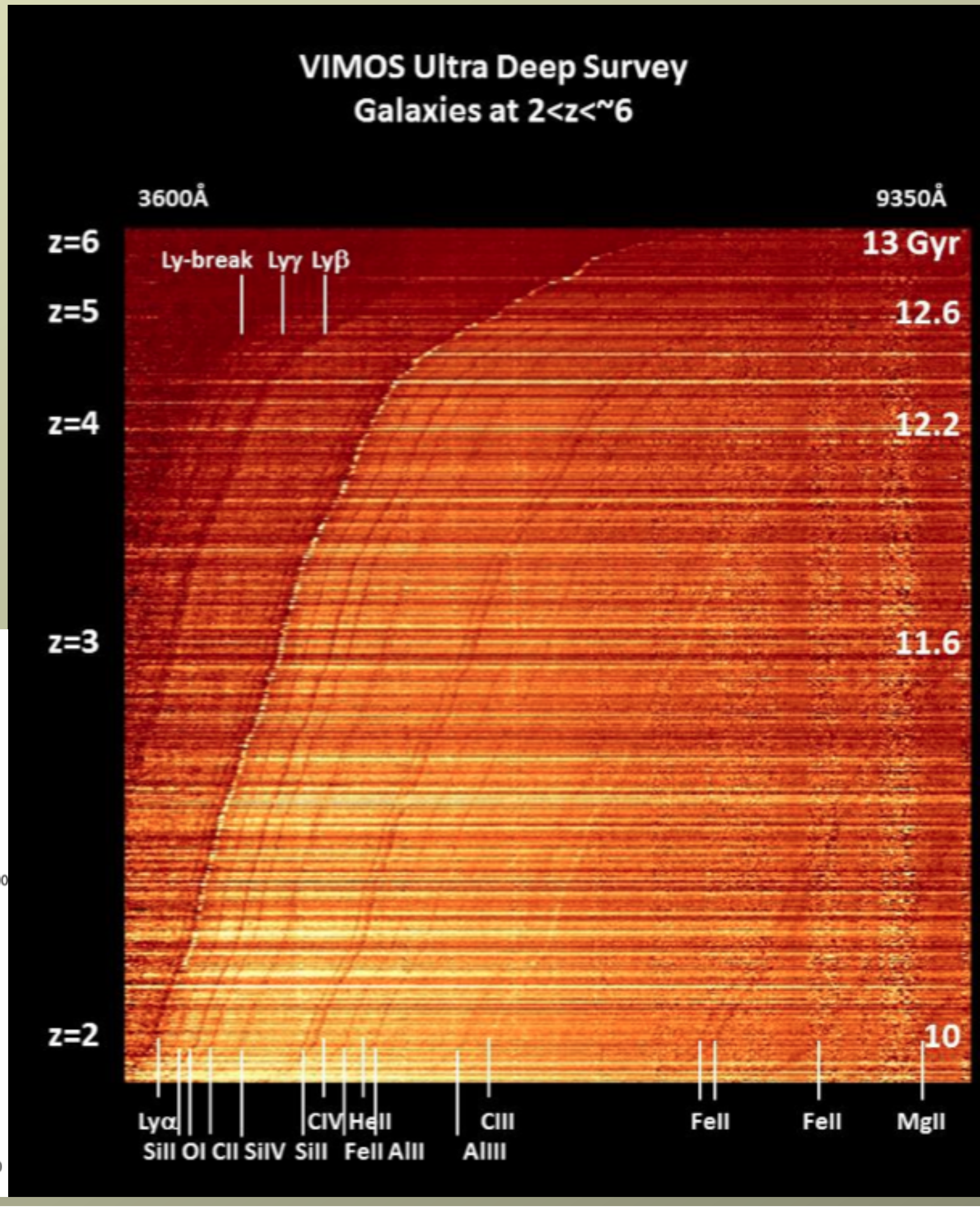
Stark et al. (2014, 2015)

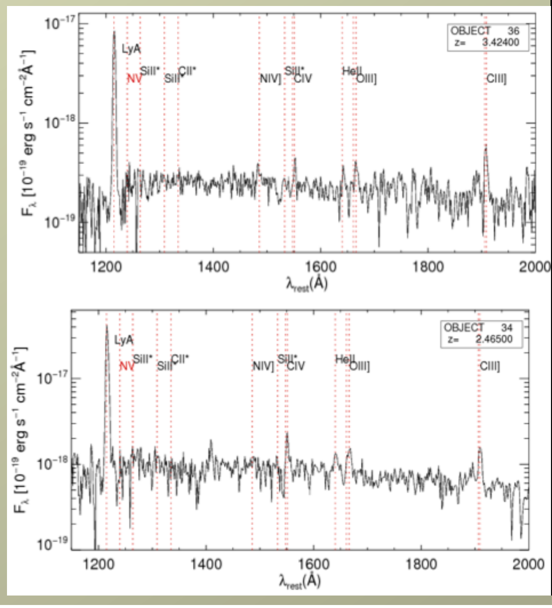
UV emission lines in z>4 galaxies



Erb et al. (2010)

Lefèvre et al. (2014)





Amorin et al. (2015)

SC: Very high-z galaxies (z~7 to 40)
- redshift confirmation, physical properties …

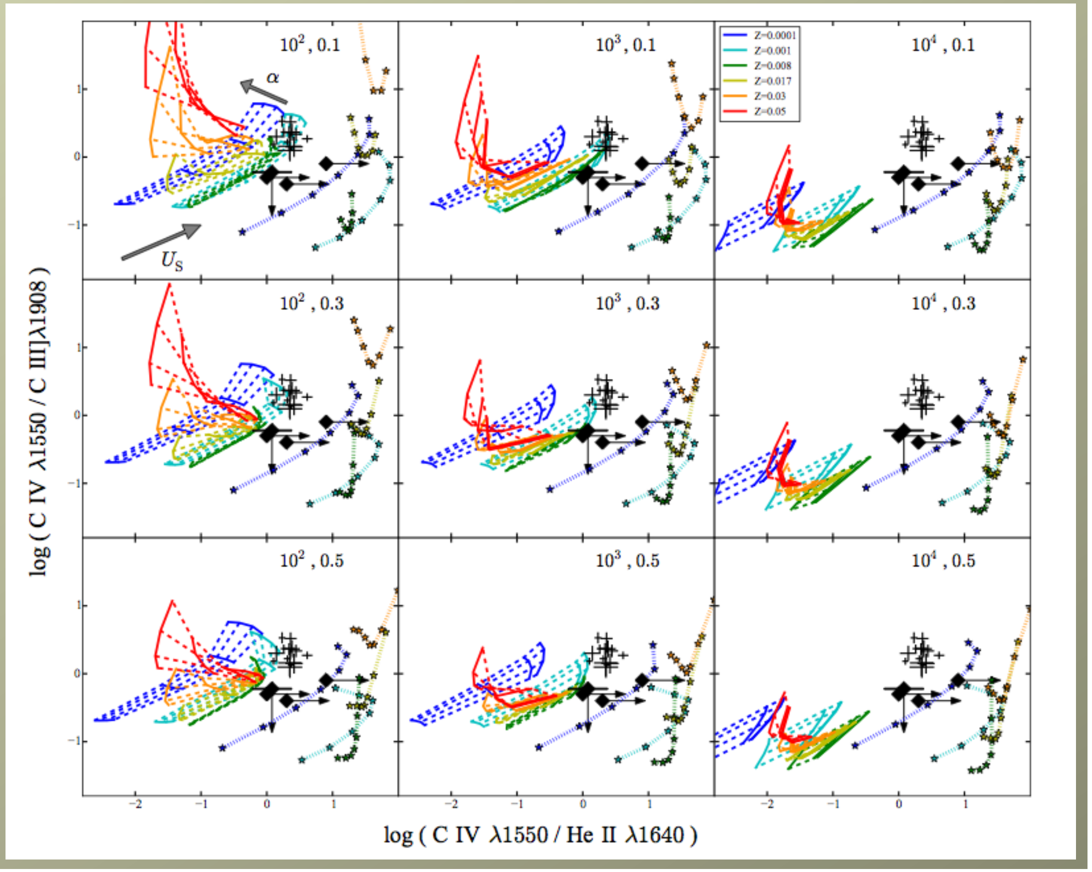
Rest-frame UV lines between Lya and CIII]1909 as diagnostics:

- Star formation versus AGN diagnostics
  cf. Nagao+, Feltre+ 2015, Nakajima+2016

- Hardness of ionizing spectrum
- Hotter stars at high-z?
- Higher ionization parameter?

Also:
- C/O abundances up to z~8
- …

Feltre+ 2015



SC: 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

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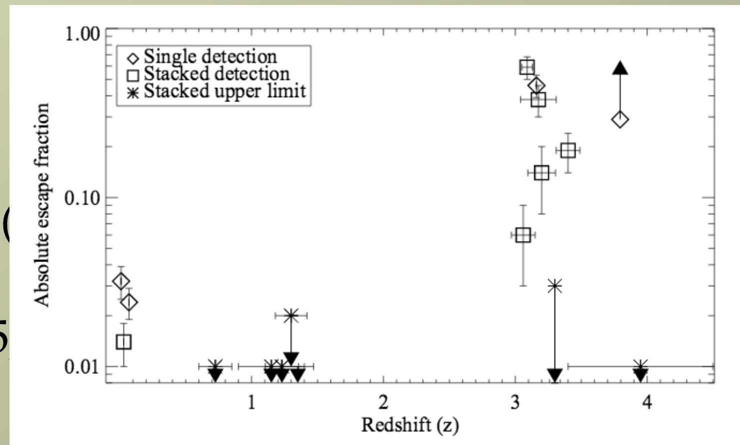

Bergvall+ 2013

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The quest for the sources of cosmic reionisation

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

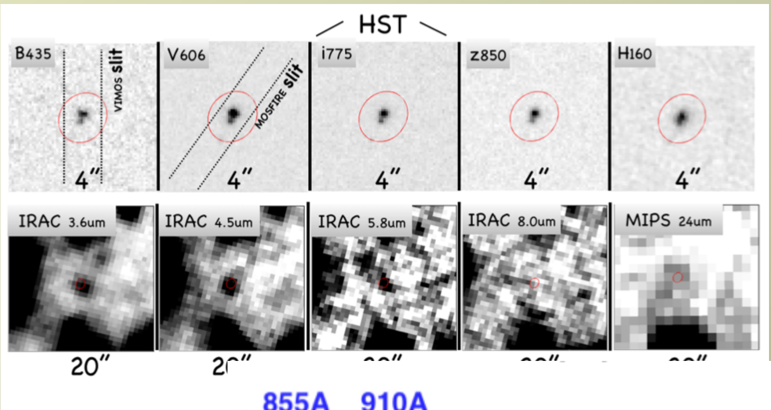
z=3.218 galaxy « Ion2 »in GOODS-S/Candels

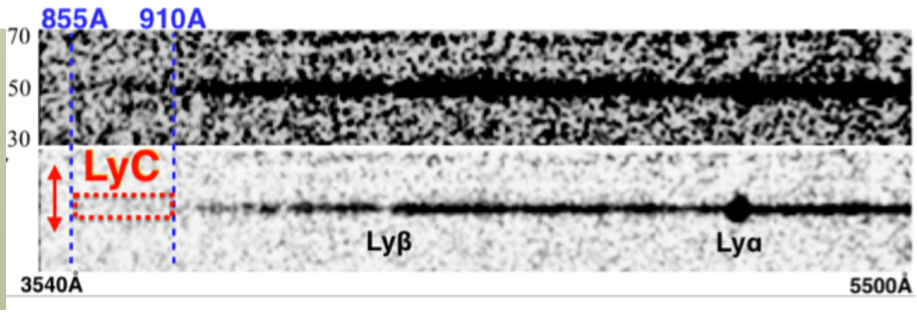
UV rest-frame mag_AB~24.5-25

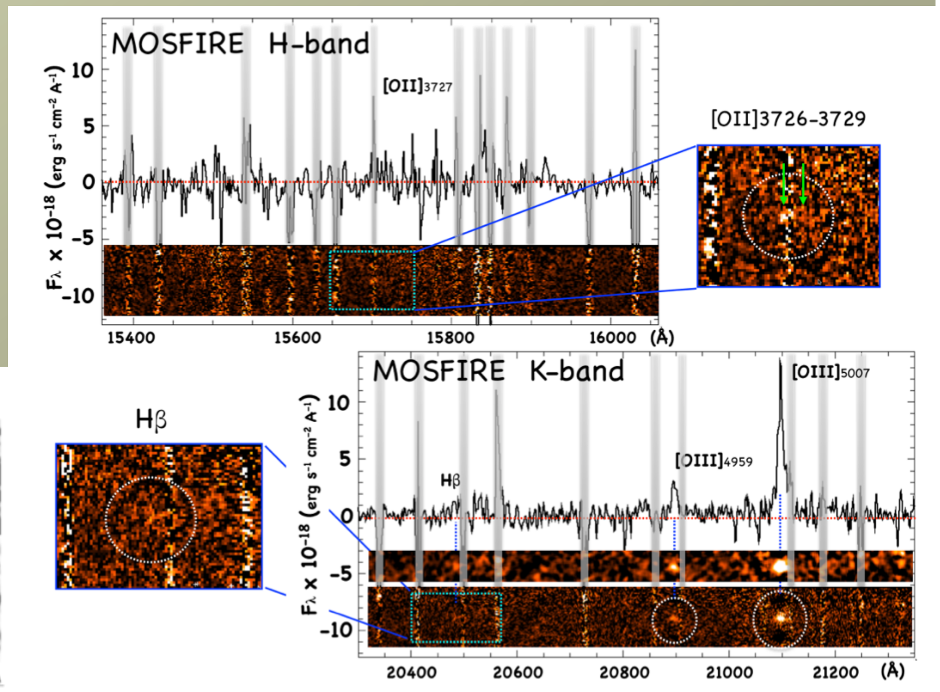
→ Low metallicity (1/6 $Z_{\odot}$), ~low mass (1.6 10^9 $M_{\odot}$)

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

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





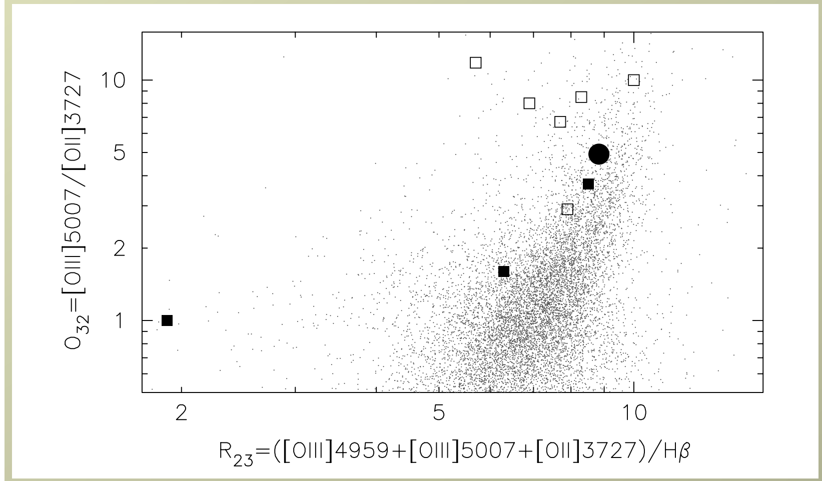


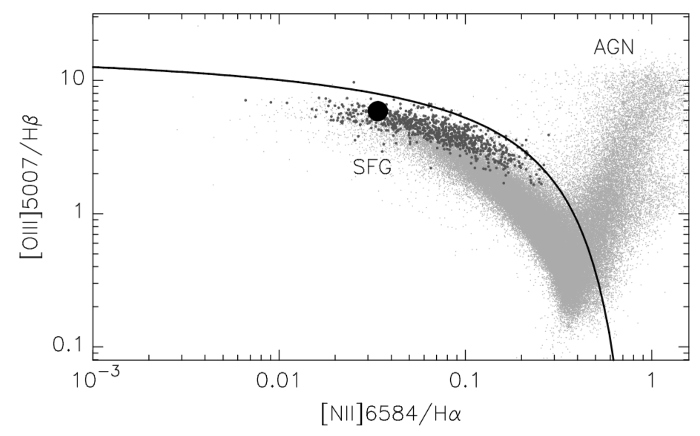
The quest for the sources of cosmic reionisation

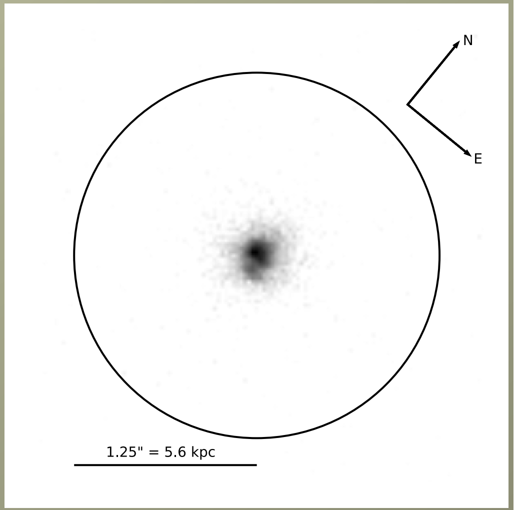
New COS-HST program: *measure Lyman continuum and test indirect indicators*
(Thuan, Izotov, Orlitova, Verhamme, Schaerer, Guseva)

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

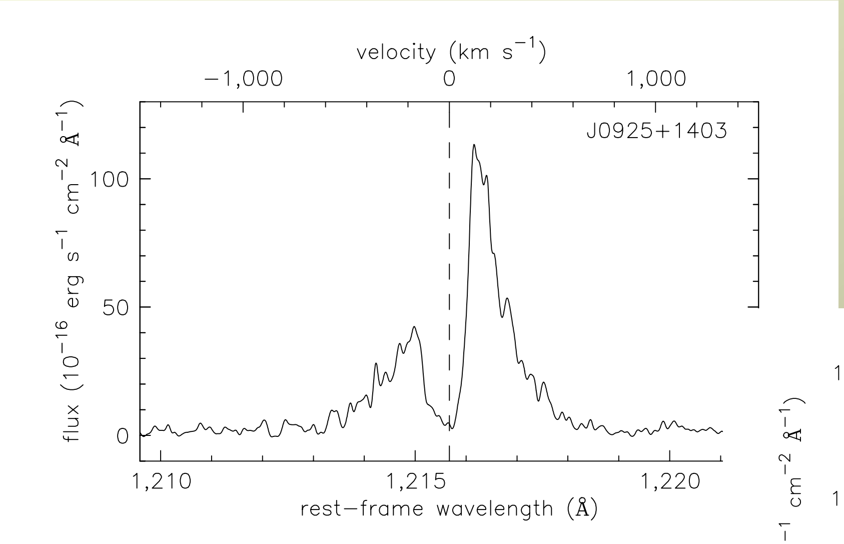


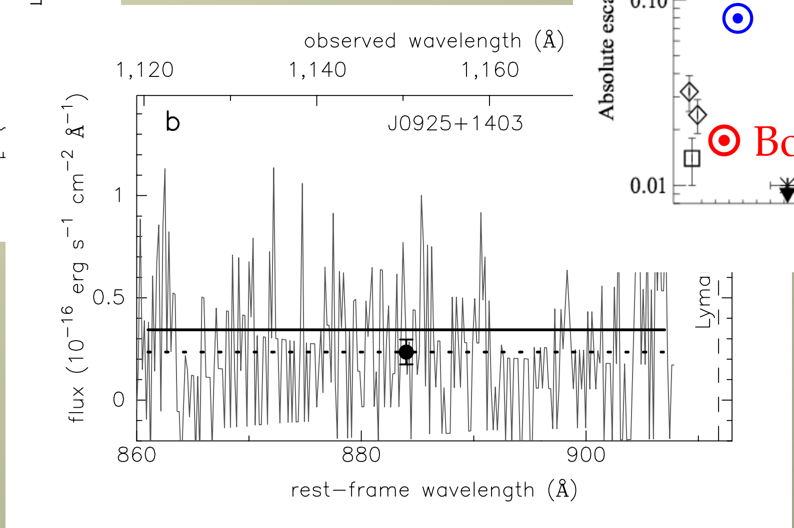


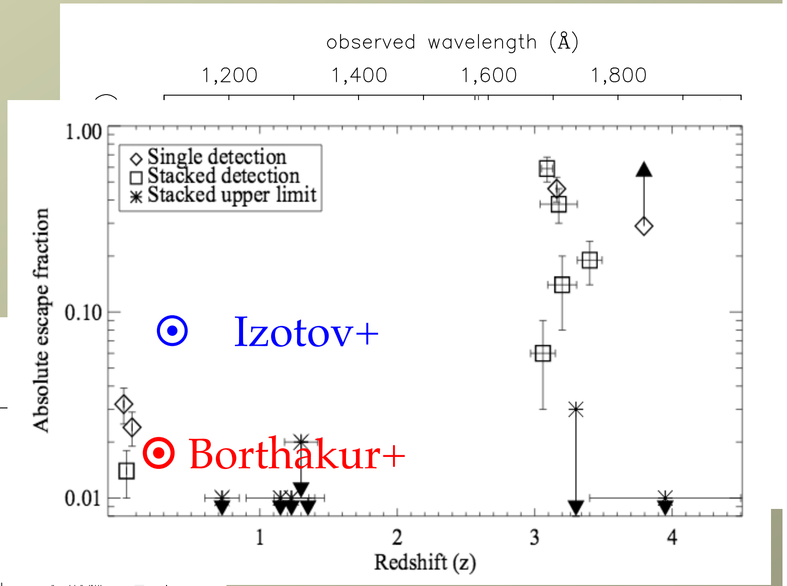


The quest for the sources of cosmic reionisation

New COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (Nature, 2016)







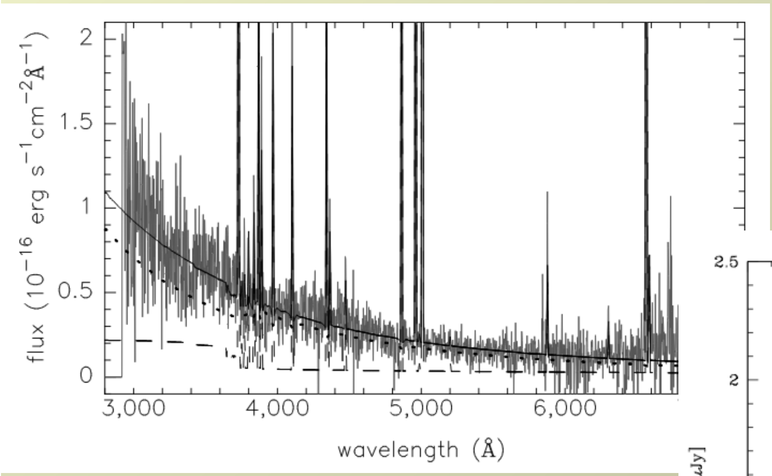
✔ High [OIII]/[OII]
✔ Narrow Lya profile

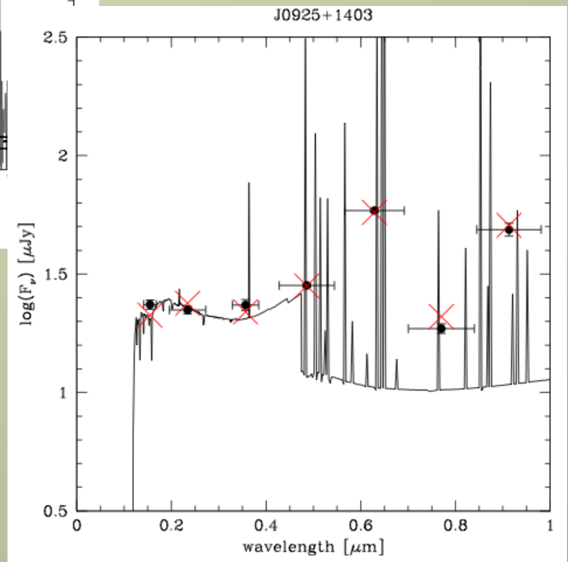
✔ Lyman continuum leakage

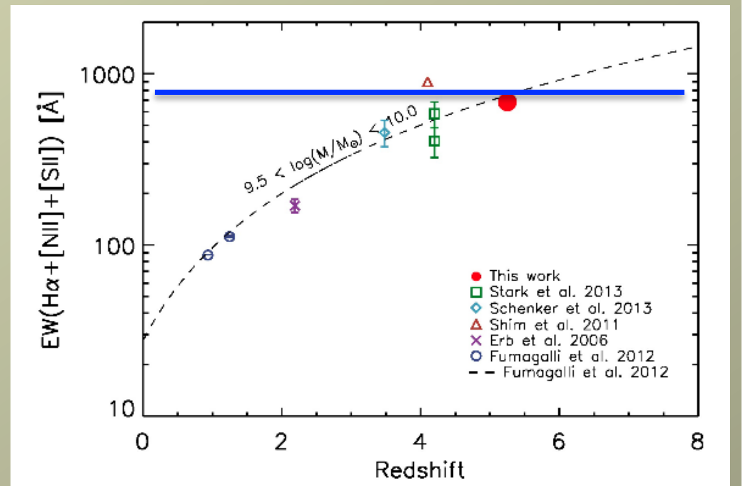
- 11.8 sigma detection (3.43±0.29)×10^{-17} erg s^{-1} cm^{-2} Å^{-1}
- **Absolute fesc=7.8±1.1 % (highest so far at low redshift)**

The quest for the sources of cosmic reionisation

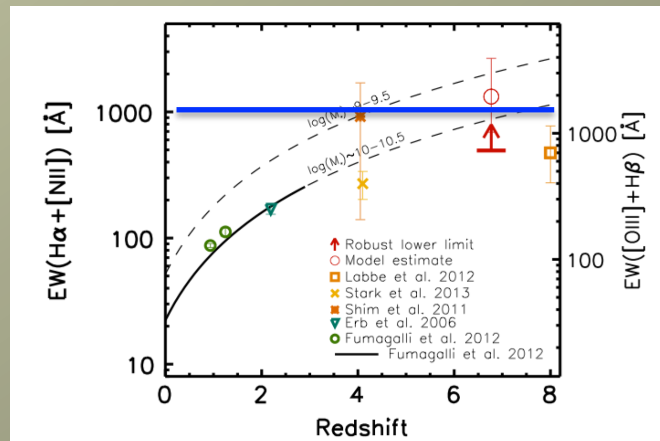
New COS-HST program: *measure Lyman continuum and test indirect indicators*
Izotov, Orlitova, Schaerer, Thuan, Verhamme, Guseva, Worseck (2015)







z~5: Rasappu+ (2015)

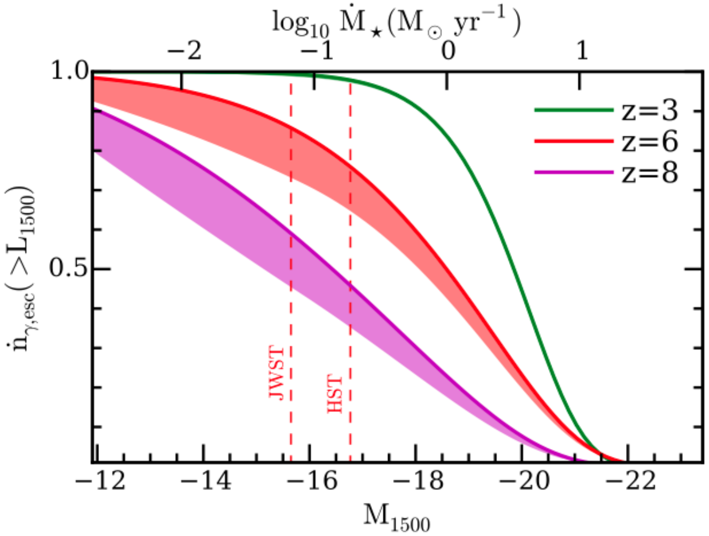


High equivalent widths:
EW(Ha)=730 Å
EW([OIII]4959+5007)=1480
…
➠ Comparable to high-z galaxies

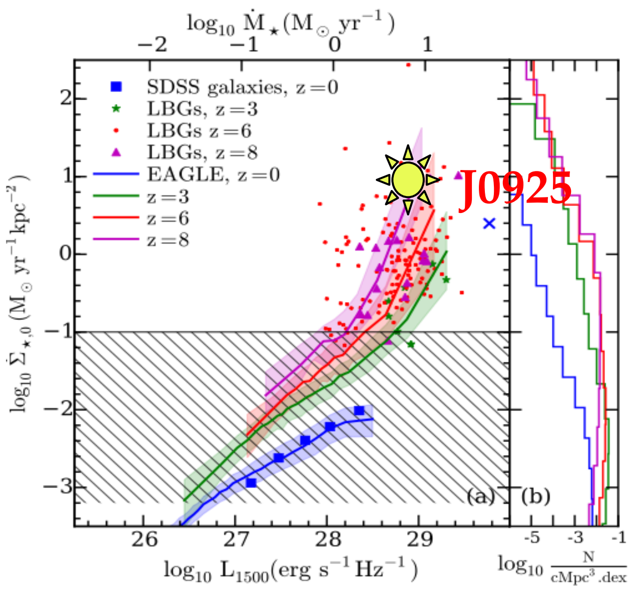
z~7: Smit+ (2014), Roberts-Borsani+ (2015)

SC: The quest for the sources of cosmic reionisation

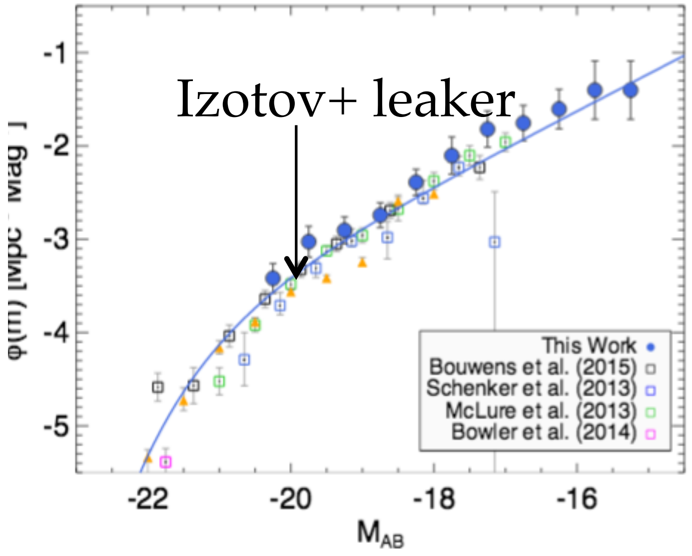
Did brighter galaxies reionise the Universe?

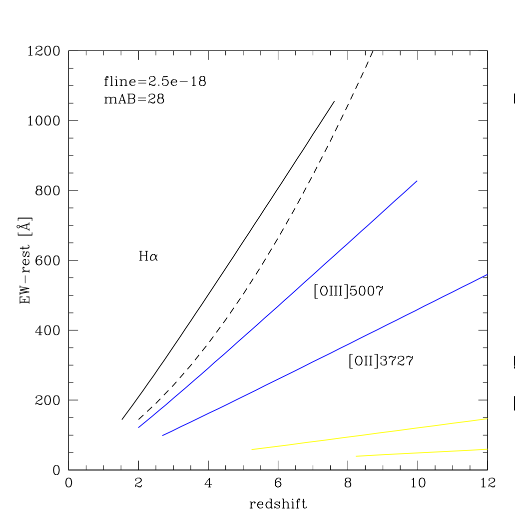


Sharma et al. (2015)



Quite bright source
Stellar mass ~2 10^9 Msun

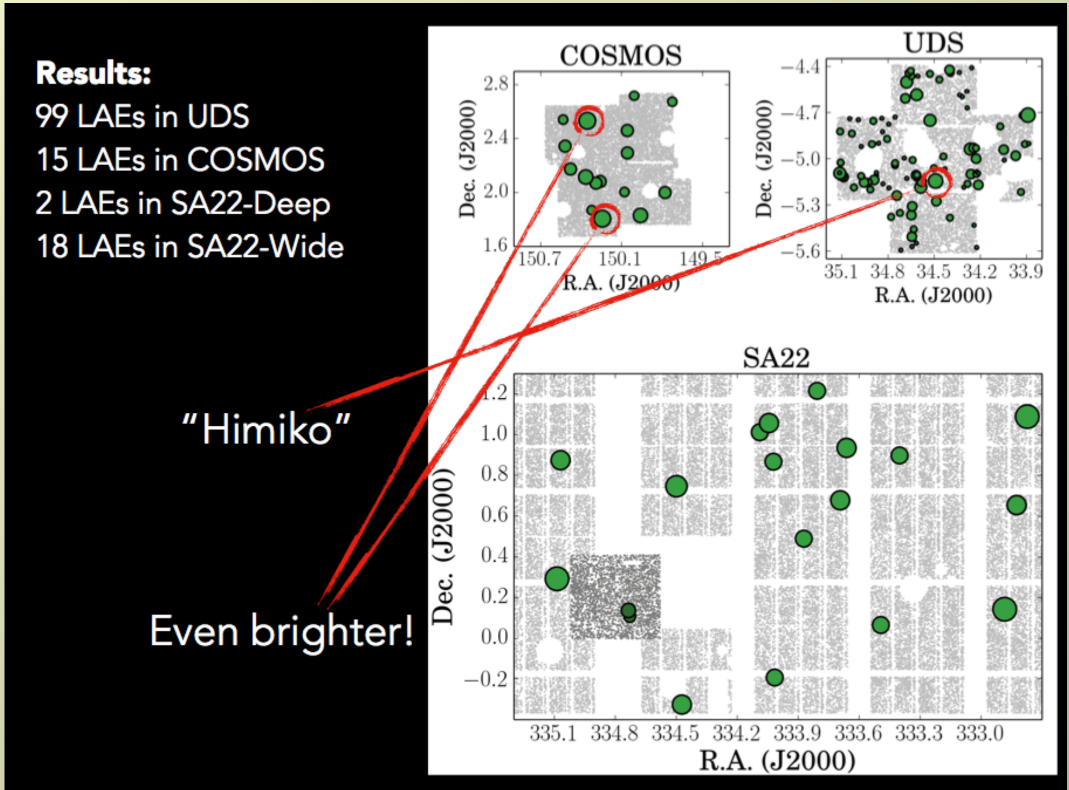




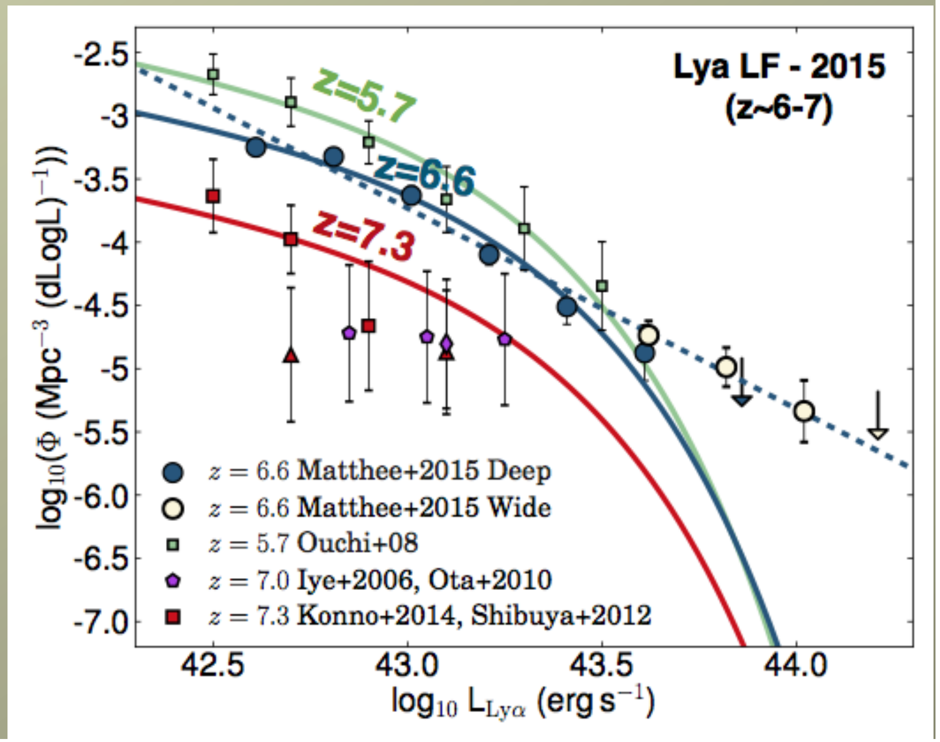
➔ Observable with FLARE
([OII] and [OIII] up to z~9)

SC: Exotic objects (PopIII, …)

Wide field surveys needed



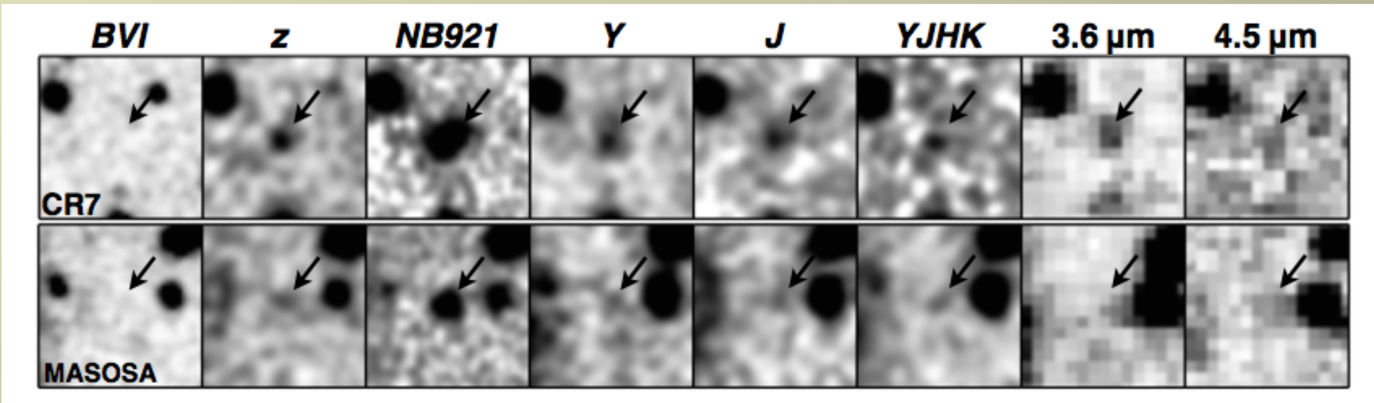
E.g.: narrow-band survey over 5 deg^2 in UDS, COSMOS, SA22



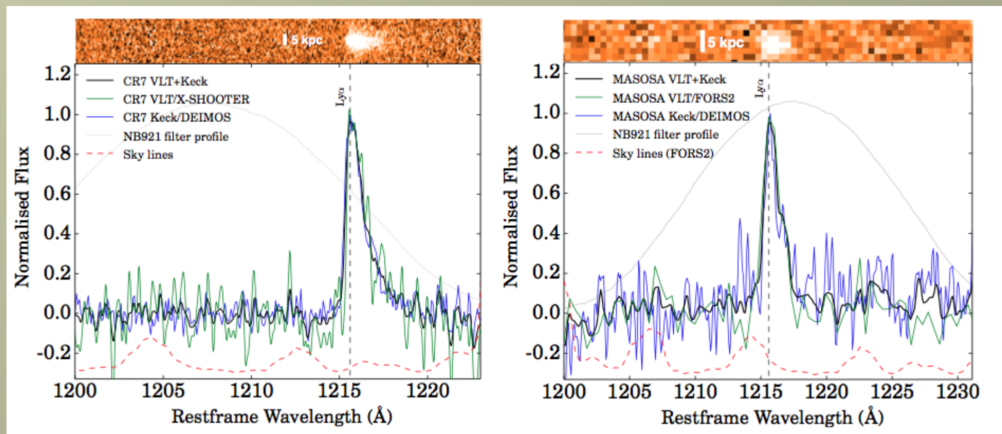
Matthee, Sobral et al. (2015)

Possible detection of PopIII signatures at z=6.6

Wide-field, narrow-band imaging for LAEs @ z=6.6:
3 very bright LAEs Matthee et al. (2015)



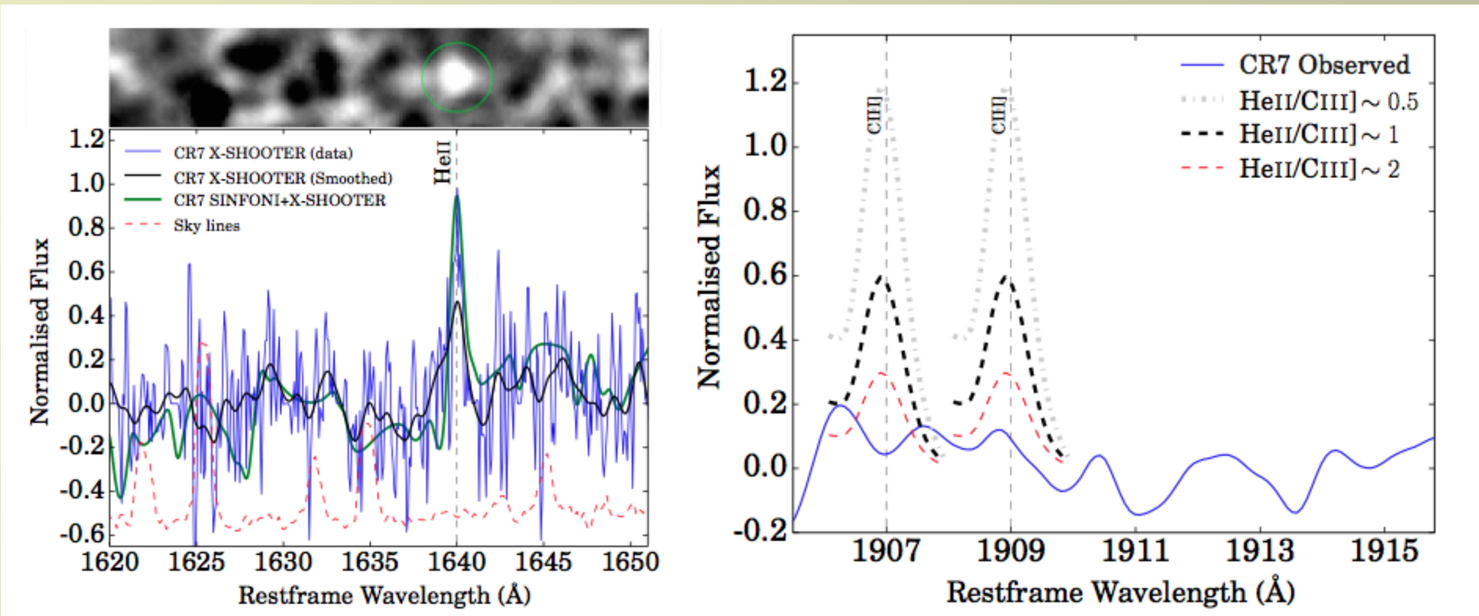
Spectroscopic confirmation



Sobral et al. (2015)

Possible detection of PopIII signatures at z=6.6

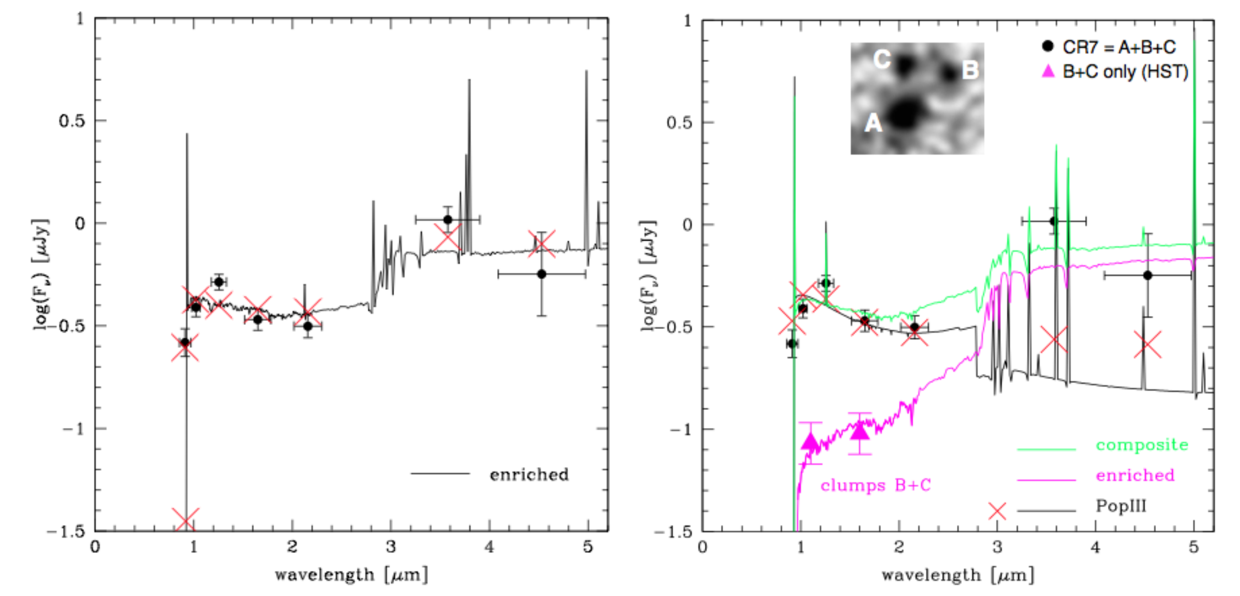
CR7: Detection of HeII 1640 Ang line + limits on metal lines (C, N, O)



→ 'CR7' source: best case for metal-free / PopIII stars so far!
Sobral et al. (2015)

Bright emission lines:
→ HeII~4e-17 erg/cm2/s, Lya=4*HeII

Possible detection of PopIII signatures at z=6.6

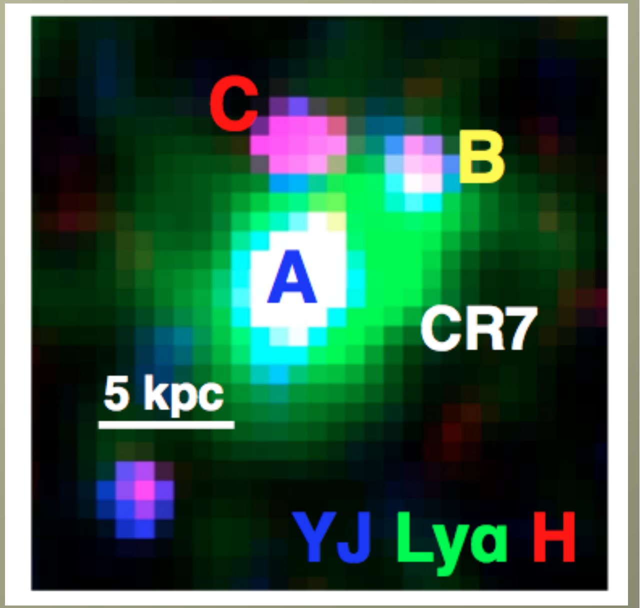


→ 'CR7' source: best case for metal-free / PopIII stars so far!

- PopIII dominated cluster A
- Older « normal » populations in B+C

→ Sobral et al. (2015)

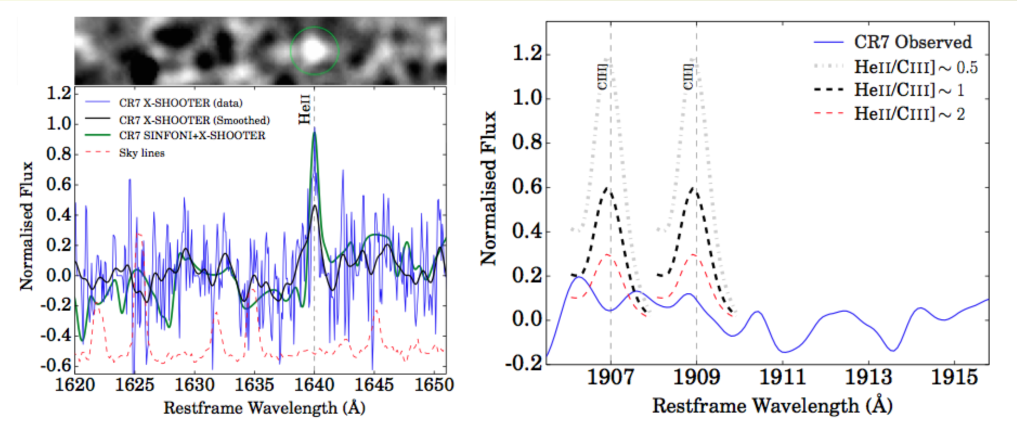
Cf Visbal+2016



Alternative explanations: *Direct collapse black hole*

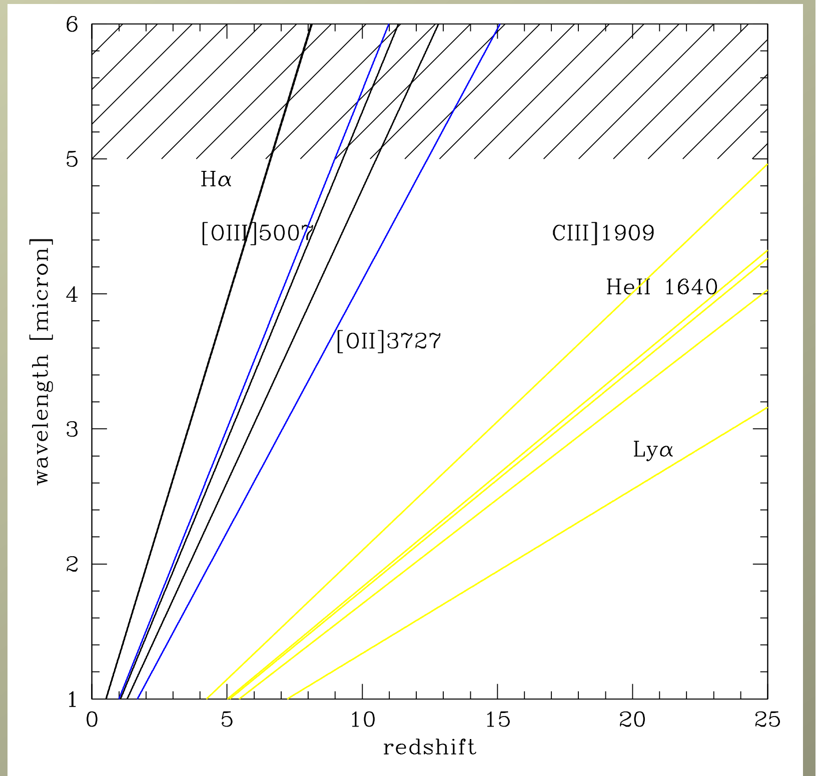
cf. Pallottini+2015, Agarwal+2015, Smit+2016, Smith+2016, …

SC: Exotic objects (PopIII, …)



CR7 shows bright emission lines:
→ HeII~4e-17 erg/s/cm2, Lya=4*HeII
→ continuum mag~25 (rest-UV)

Found from small survey volume (NB, Δz~0.1)
- Survey depth: (1-10)e-17 erg/s/cm2
  (from UDS to SA22 wide)



→ Vast discovery space for FLARE!
deeper and over wide redshift range

FLARE spectro survey – science cases

- **An unbiased Ha luminosity function evolution (from z~0.5 to 6-8)**
- **Are we missing dusty sources? Are we missing SF in the Universe?**
- **Dust attenuation in SF galaxies from z~1 to 6 (8)**
- Physics of high-z galaxies and SF (up to z~6-8):
  Stellar masses, SF histories, mass-metallicity
- **Very high-z galaxies (z~7 to 40):**
  redshift confirmation, physical properties …
- Evolution of the bright-end of the Lya LF from z~6 to 30
  inferences on cosmic reionisation
- **Sources of cosmic reionisation**
- **Exotic objects – PopIII, direct-collapse BH, …**

- Lyman-alpha blobs ?
- High-z galaxy clusters
- « Pointed » IFU observations of lensing clusters → probing fainter galaxies
- ….

YOUR FAVOURITE science case !? Suggestions welcome!

FLARE spectro survey – many science cases!

Unique of FLARE spectroscopy:

- large IFU in space with 1-5 micron coverage -- extension to longer λ!?
- large discovery space
- ~large survey field

Competitors for z>3-6 studies:

- JWST (2018-2023 or 2028)
- ALMA

Complementary facilities:

- JWST
- ALMA
- ELTs