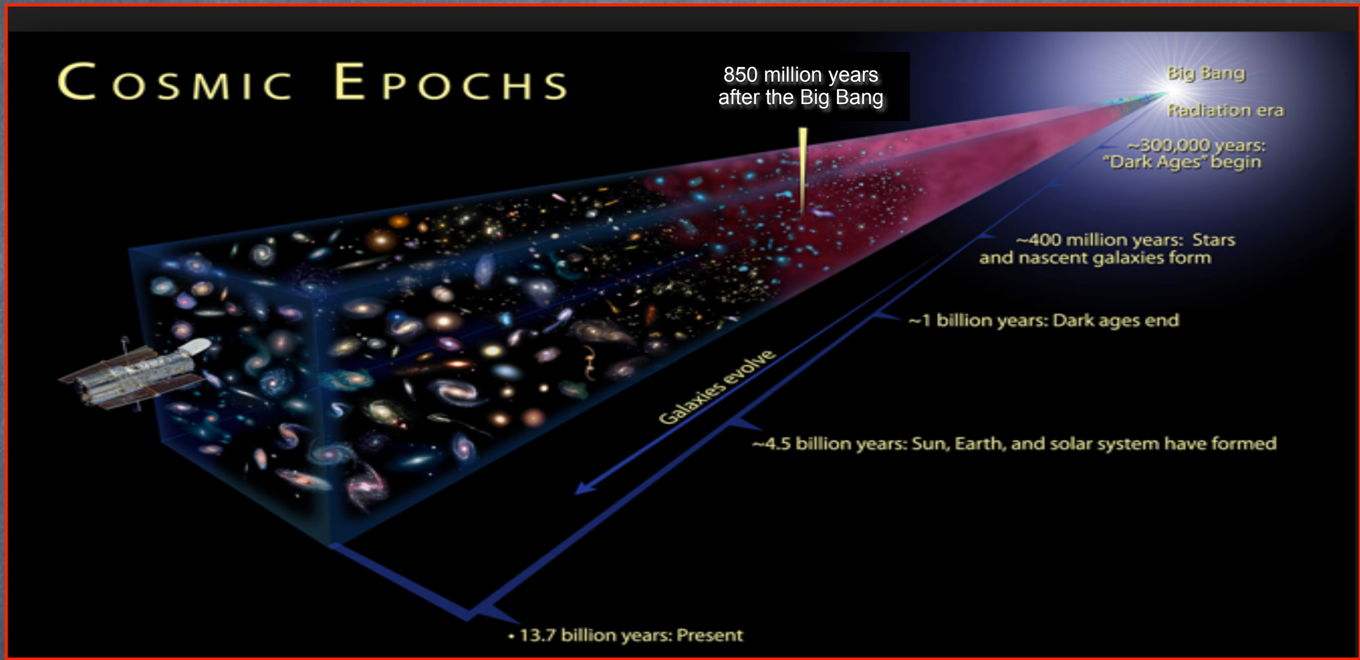
And there was (ionizing) light: ancient clues to reionization

Eros Vanzella

INAF - Astronomical Observatory of Bologna

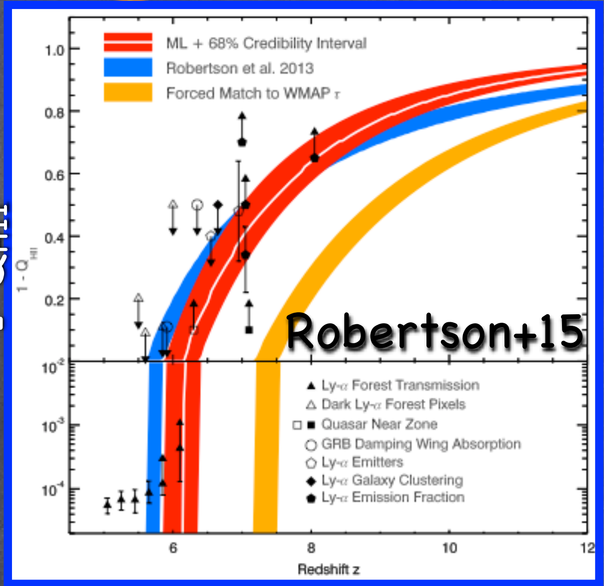


Collaborations:

CLASH and CANDELS Teams, + INAF, UMASS, University of Ferrara, California (Riverside), Kapteyn, +

Ingredients in the (re)ionization modeling

1−Q_{HII}



Redshift

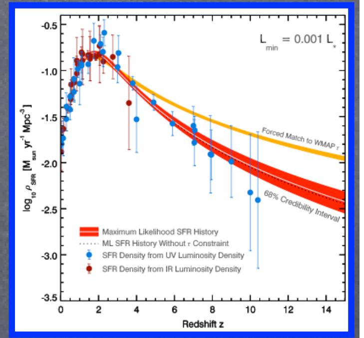
UV lum. funct. (N/mag/Mpc3)

ioniz. luminosity (phot/s)

(spectrum of sources)

escape fraction ion. photons: transmission

$$\dot{n}_{\rm ion}^{\rm com} = \int_{M_{\rm lim}}^{\infty} {\rm d}M_{\rm UV}\, \phi(M_{\rm UV}) \gamma_{\rm ion}(M_{\rm UV})\, f_{\rm esc}$$



Cosmic SFH

Volume filling factor:

Volume(HII) / Volume Universe

$$\frac{{\rm d}Q_{\rm H\,II}}{{\rm d}t} = \frac{\dot{n}_{\rm ion}}{\bar{n}_{\rm H}} - \frac{Q_{\rm H\,II}}{\bar{t}_{\rm rec}}$$

Q_{HII}=1 ionized

$Q_{HII}(z)$<1 neutral

mean comoving hydrogen number density

$$\bar{t}_{\rm rec} = \frac{1}{C_{\rm H\,II}\alpha_{\rm B}(T_0)\,\bar{n}_{\rm H}(1+Y/4X)(1+z)^3}$$

$$\approx 0.93\ {\rm Gyr} \left(\frac{C_{\rm H\,II}}{3}\right)^{-1} \left(\frac{T_0}{2\times 10^4\ {\rm K}}\right)^{0.7} \left(\frac{1+z}{7}\right)^{-3}$$

$$C_{\rm HII} \equiv \langle n_{\rm HII}^2 \rangle / \langle n_{\rm HII} \rangle^2$$

Hui (2012)

$$C_{\rm H}(z) = (2.9)\left[\frac{(1+z)}{6}\right]^{-1.1}$$

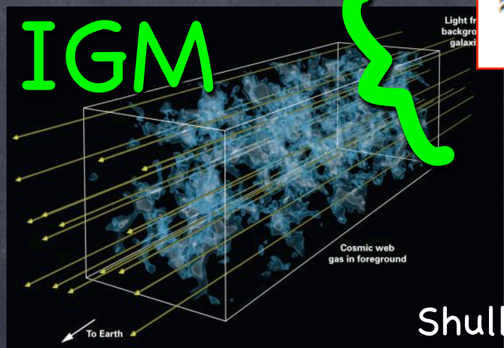
$z \sim 8.8^{+1.2}_{-1.1}$ CMB

Thomson optical depth to electron scattering τ=0.066+/-0.012 Planck Collaboration (2015)

$$\tau_e(z) = \int_0^z c\,\langle n_{\rm H}\rangle\, \sigma_T\, f_e\, Q_{\rm HII}(z') \frac{(1+z')^2 dz'}{H(z')}$$

Kimm & Cen (2014)

IGM



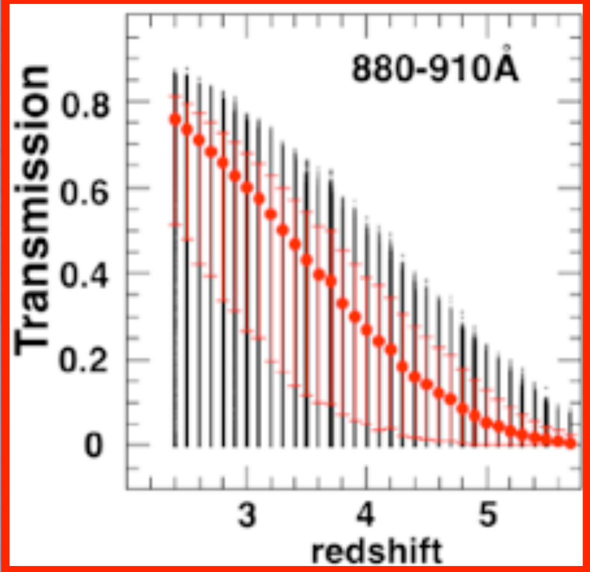
Shull et al. (2012)

Vanzella - IAP - 2016

Ingredients in the (re)ionization modeling

Critical parameter
in any reioniz. model
f_{esc}

... how can we infer the escaping ionzing radiation from z>6 sources ?
(LyC not visible directly at z>6)
Reliable indirect signatures are needed, calibrated to lower-z (z<4) analogs having fesc>0 ...



Theory (fesc...)

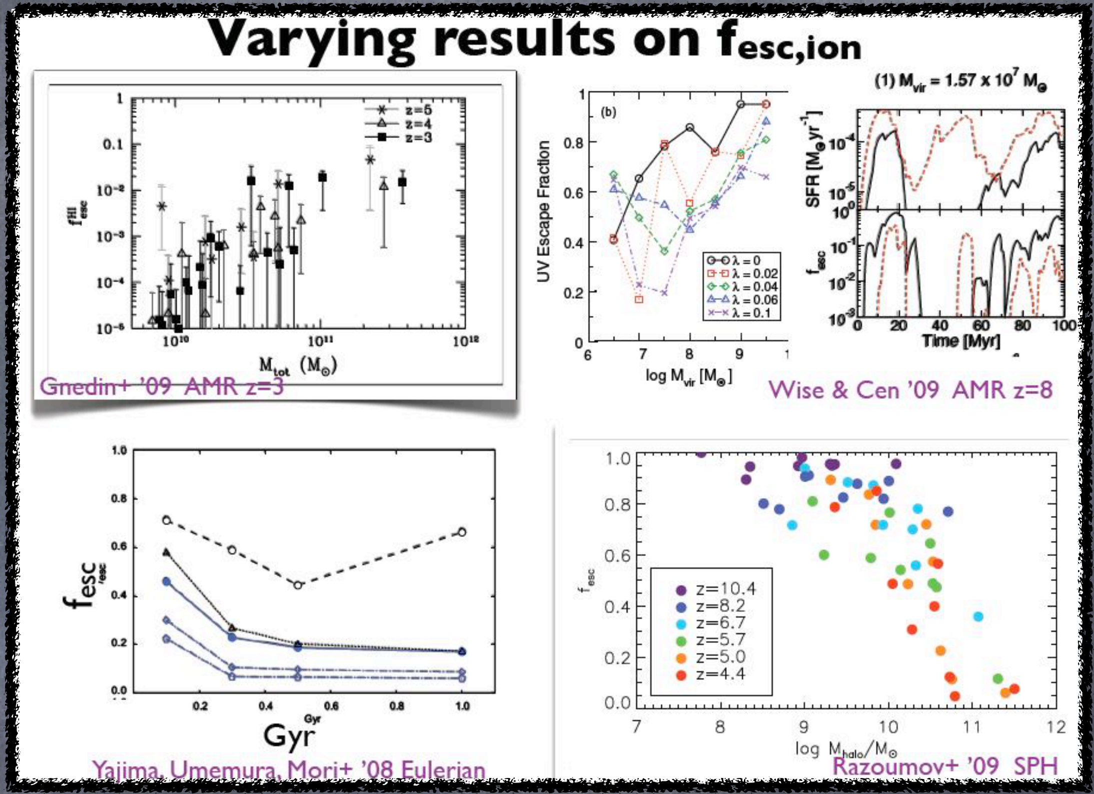
Theoretical modeling: SFH, RT, feedback, kinematics, geometry of the gas/dust - complex problem

- fesc ↓ if redshift ↑ (Wood & Loeb+00)
- fesc ↑ if redshift ↑ (Razoumov+06,+10)
- fesc ~ with redshift
  (Yajima+10; Ma et al. 2015; Gnedin+08)

- fesc ↑ if redshift ↑ [phenomenological models]
  Haardt & Madau (2012), Kuhlen & FG (2012), Alvarez+12, Fontanot+14

- fesc ↓ if halo mass ↑
  (Wood & Loeb+00, Ricotti & Shull+00
  Yajima+10, Razoumov+10)
- fesc ↓ if halo mass ↓ (Gnedin+08a,b)
- fesc ~ with halo mass (Ma et al. 2015)
- fesc ~ ↑ with halo mass (Trebitsch 2015)
  ↑ for bright galaxies (Sharma 2016)

- fesc ↑ if (↓L OR ↓Mass - faint, small, little)
Anderson, Governato et al. (2016)
Wise & Cen+09; Kimm & Cen (2014);
Wise et al. (2014); Paardekooper et al. (2015);
Roy et al. (2015); Fernandez & Shull+11;
Choudhury & Ferrara 07, Ferrara & Loeb 2012



Large variance in the predictions :

1) may increases for low mass halos / luminosities
2) may increases with redshift

Modeling typically requires very high resolution simulations capable to follow the details of the ISM.

Measuring fesc: Not an easy task

looking for λ<912A photons

Searching for LyC 0<z<4

Steidel et al. (2001)
Giallongo et al. (2002)
Malcan et al. (2003)
Shapley et al. (2006)
Siana et al. (2007,2010)
Iwata et al. (2009)
Cowie et al. (2009)
Bridge et al. (2010)
Vanzella et al. (2010a,b)
Nestor et al. (2013)
Siana et al. (**2015**)
Mostardi et al. (**2015**)
Grazian e al. (**2016**)
Guaita e al. (**2016**)
Vanzella et al. (2012a,b)
Vanzella et al. (2014a,b)
Vanzella et al. (2015)
De Barros et al. (2016)
Izotov et al. (2016)
Vanzella et al. (2016a,b)

Escape fraction of ionizing radiation (LyC) gas transmission, dust extinction (+ geometry)

Intrinsic ionizing photons unknown: commonly adopted strategy is to compare the observed flux at LyC to the observed flux at a frequency where the intrinsic emissivity can be inferred.

Ionizing photons UV (λ<912A) LyC

Attenuation by ISM (HI , dust)

Attenuation by the IGM (LAF, LLS, DLAs)

NON-ionizing photons UV (λ~1500A)

Attenuation by ISM (dust)

$$\left(\frac{f1500}{f_{LyC}}\right)_{OBS} = \left(\frac{L1500}{L_{LyC}}\right)_{INT} \times 10^{-0.4(A1500-A_{LyC})} \times e^{\tau_{HI,IGM}(LyC)} \times e^{\tau_{HI,ISM}(LyC)}, \quad (1)$$

Siana+07

Vanz+12

$$f_{\rm esc,rel} \equiv \frac{(L1500/L_{LyC})_{\rm int}}{(F1500/F_{LyC})_{\rm obs}} \exp(\tau^{\rm IGM}_{LyC}), \quad (2)$$

Steidel+01

$$f_{\rm esc} = 10^{-0.4A_{1500}} f_{\rm esc,rel}$$

$$f_{\rm esc} = \exp\left[-\tau_{HI,ISM}(LyC)\right] \times 10^{-0.4(A_{LyC})}, \quad (3)$$

< 1   < 1

$$10^{-0.4(A_{1500}-A_{LyC})} \times f_{\rm esc,rel} = \exp\left[-\tau_{HI,ISM}(LyC)\right] \quad (4)$$

< 1

fesc : is smaller than 1 by definition,

fesc,rel : would be < 1, otherwise $A_{900} < A_{1500}$

$$f_{\rm esc} = \exp[-\tau_{\rm H\,I,ISM}({\rm LyC})] \times 10^{-0.4(A_{\rm LyC})}$$

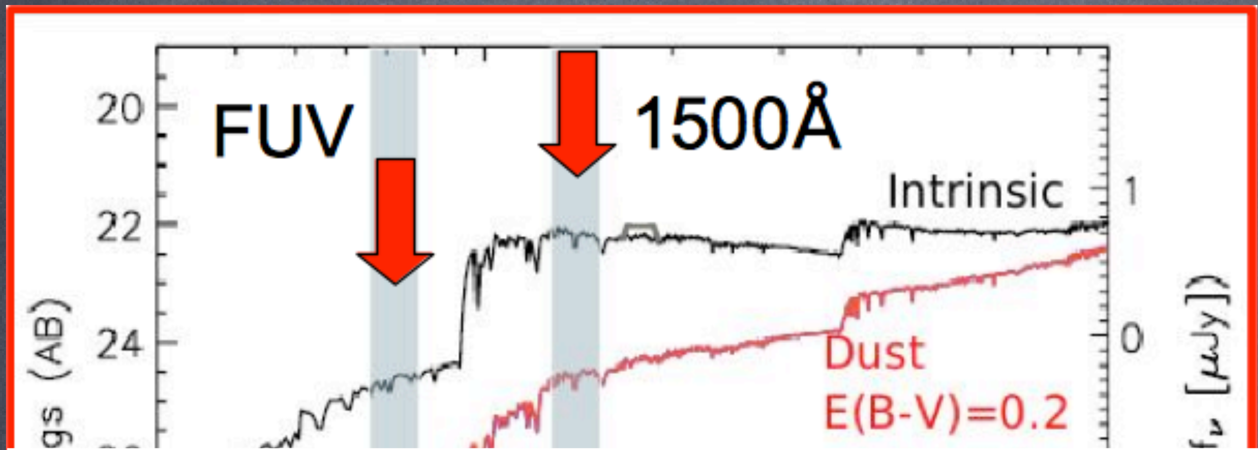
$fesc \sim T_{LyC} = e^{-\tau(LyC)}$ $\tau_{(LyC)} = N_{HI}\sigma_{LL}$ $\sigma_{LL} = 6.28\times10^{-18}$ cm^{-2}

=> this implies $N_{HI} > 5\times10^{17}$ cm^{-2}, fesc<5%

Observing Lyman continuum leakage / fesc

1) understand the physical mechanisms that allow ionzing photons to escape, apply to z>6 during EoR

2) need to observe z<4 (i.e. < 4500A)



CHALLENGING!

It is FAINT! e.g.,

fesc=8% at z=3

L* galaxy (m_{1500}≈24.5)

=> m_{900} ≈30 (AB) !

Δm=5 (e.g., i-U>5).

Observing LyC, caveats:

1) IGM Stochasticity (mfp)

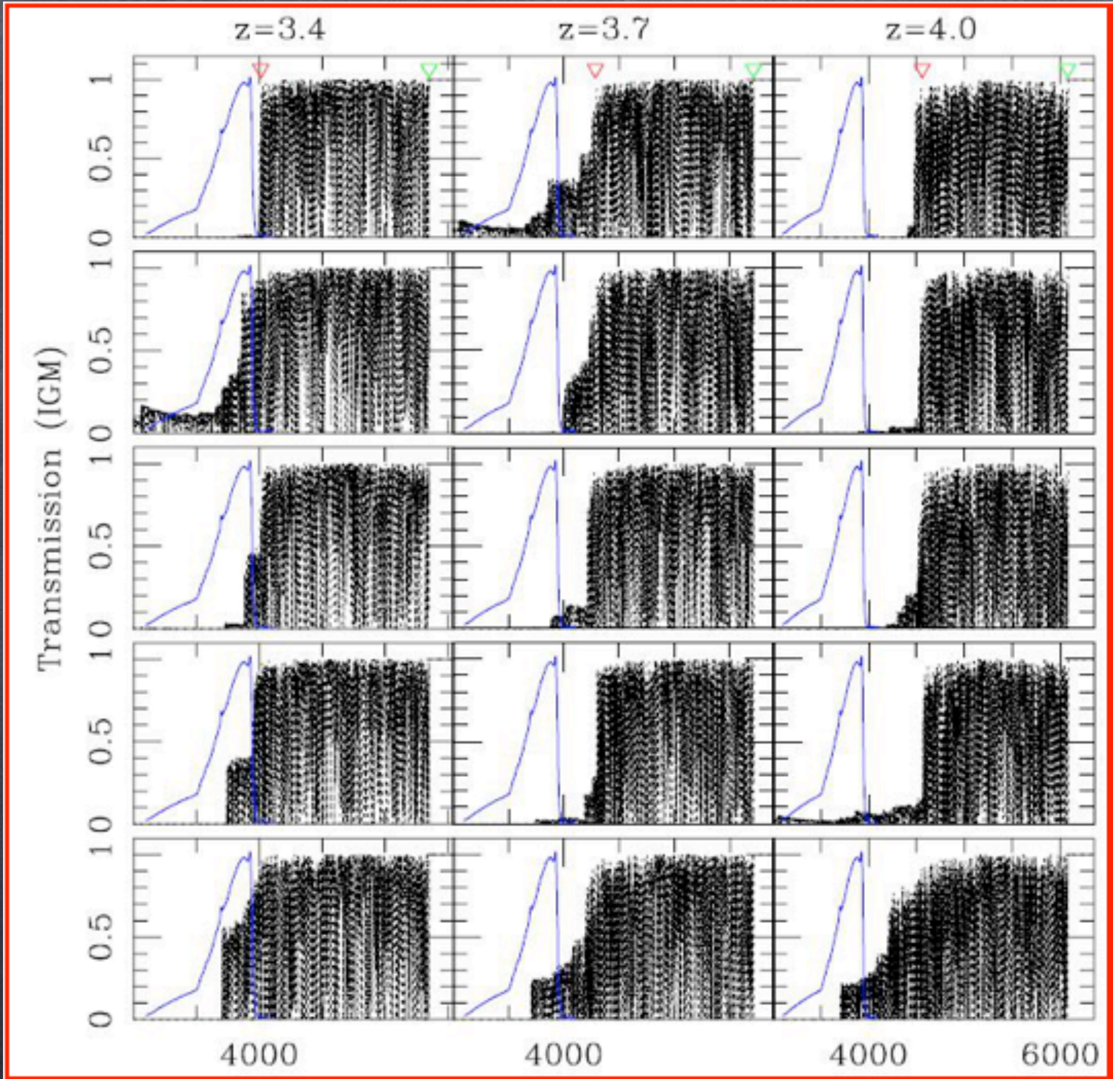
2) View-angle + Discontinuous in time

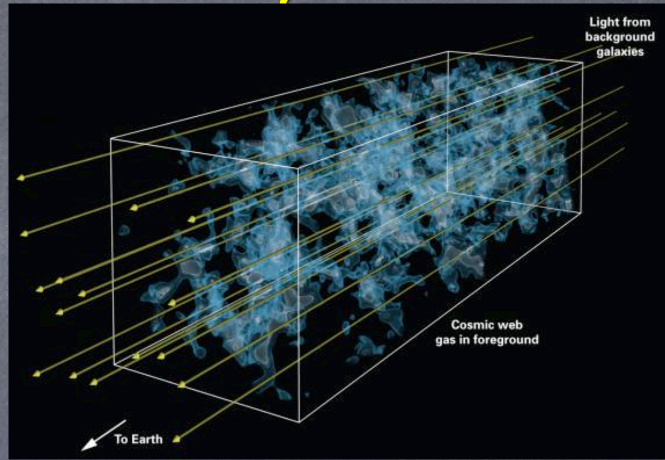
3) Foreground contamination

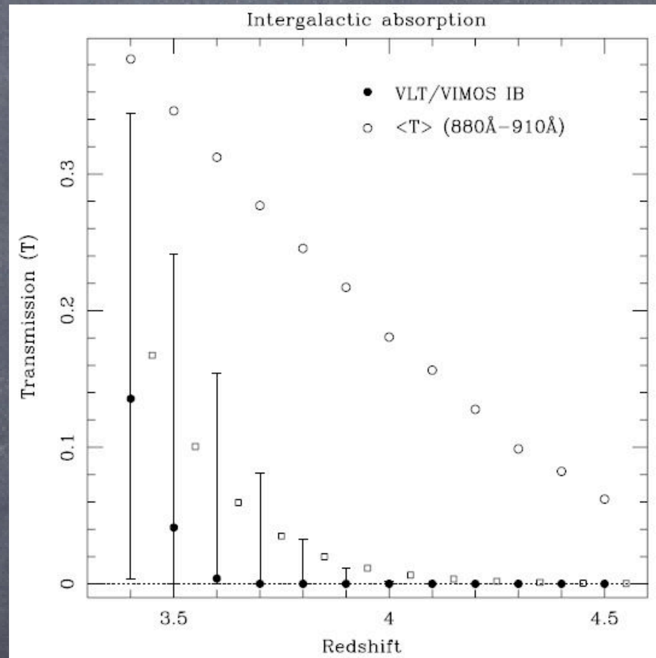
$(F1500/F_{LyC})_{obs}$

Stochasticity of the **IGM absorption** at the LyC

Vanz+10; Inoue et al 2008,2014







Well measured and simulated

Inoue et al. 2008, 2014

Meiksin 2006

Madau 1999

$$\tau_{\rm eff}(\nu_S, z_S) = \int_0^{z_S} dz \int_{N_l}^{N_u} dN_{\rm HI} \frac{\partial^2 \mathcal{N}}{\partial z \partial N_{\rm HI}} (1 - e^{-\tau_{\rm cl}})$$

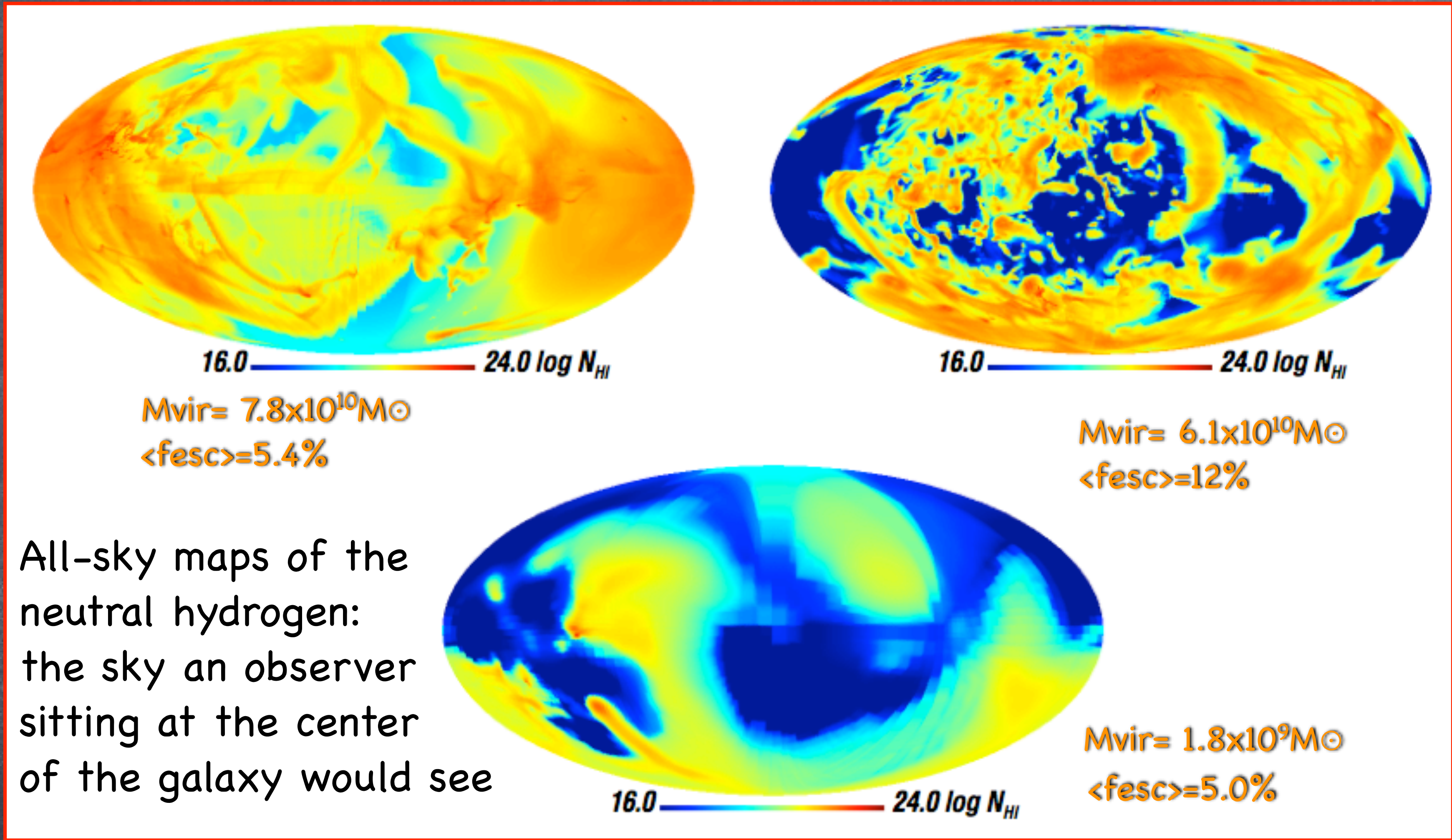
n.abs per unit z and N_{HI} Paresce+08

$$\tau_{\rm cl} = \sigma_{\rm HI}(\nu_S(1+z)/(1+z_S))N_{\rm HI}$$

Opt. depth of an abs. at z and NHI

View angle effects ...

Cosmological radiation hydrodynamic simulation (Cen & Kimm 2015)

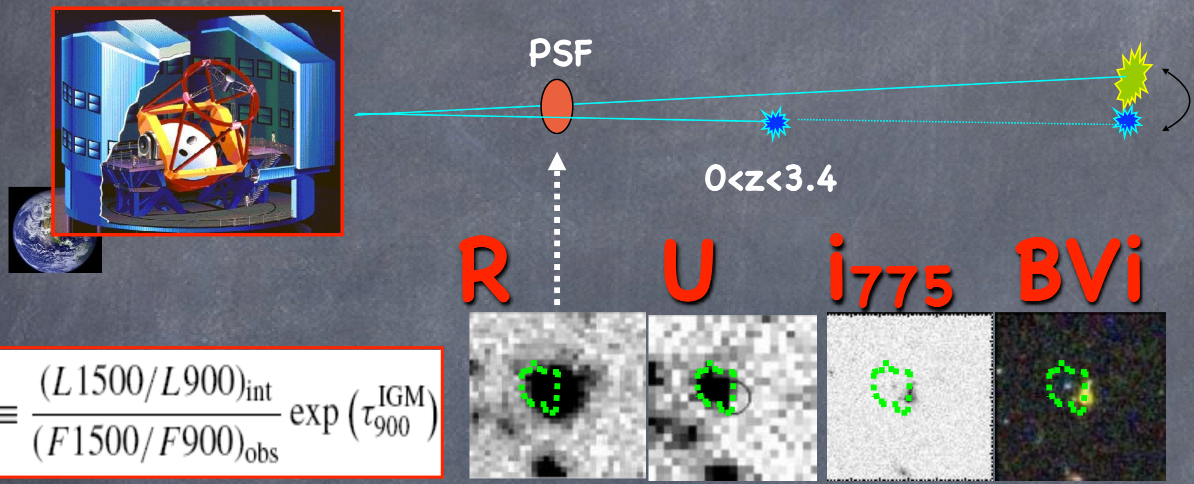


All-sky maps of the neutral hydrogen: the sky an observer sitting at the center of the galaxy would see

... result: stacking of ≥ 30-50 galaxies is needed to obtain a good estimate of fesc within 20% uncertainty

Foreground contamination: an example

Example (GOODS-S) z=3.41 (Vanzella+12)



z=3.41

$\Delta\theta$=0.3"

$$f_{\mathrm{esc,rel}} \equiv \frac{(L1500/L900)_{\mathrm{int}}}{(F1500/F900)_{\mathrm{obs}}} \exp\left(\tau_{900}^{\mathrm{IGM}}\right)$$

Ground based: fesc ≈ 30%

From HST: fesc > 433%

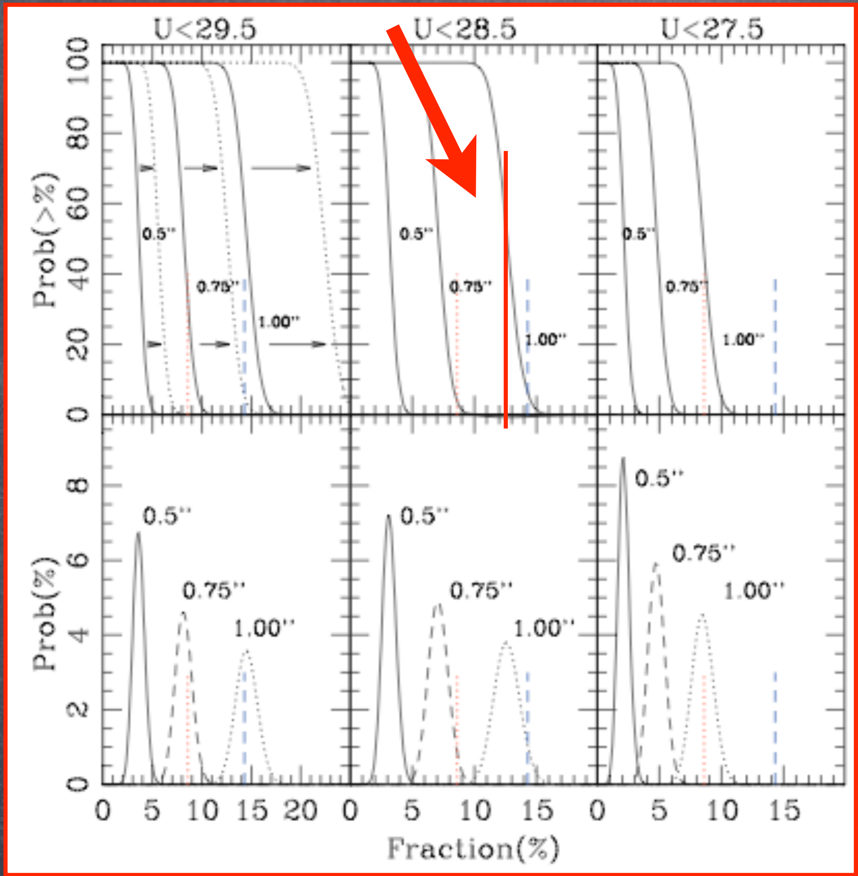
Statistical study

- critical for ground-based obser
- increases with redshift
- increases with increasing depth

Spectroscopy is needed, however it is often unfeasible: foreground sources are faint !

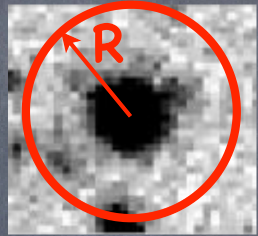
Foreground contamination, statistical correction (Vanz+10)

50% probability that at least 13% of N sources is contaminated



1) Given number counts at deep mags (assuming uniform surface density)

2) Consider a separation **R** or minimum spatial resolution (e.g. seeing)



we can calulate the probability **p** that a foreground obj. falls within radius **R**

... several LyC detections have been revised,

some with unphysical fesc (>>1) and contaminated (see Vanz+12; Siana+15)

Probability to observe **K** contaminated sources **f(K)** or at least **K** contaminated sources **P(>K)** in a sample of **N** high-z galaxies, given the probability **p** of the single case

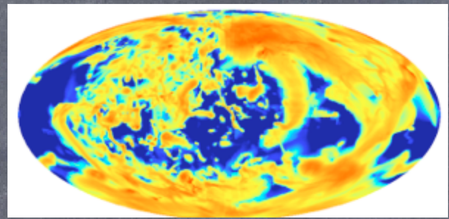
$$f(K) = \binom{N}{K} p^K (1-p)^{N-K}; \qquad P(\geq K) = \sum_{i=k}^{N} f(i).$$

Vanzella+10a

LyC measurements: caveats under control ?

Intrinsic

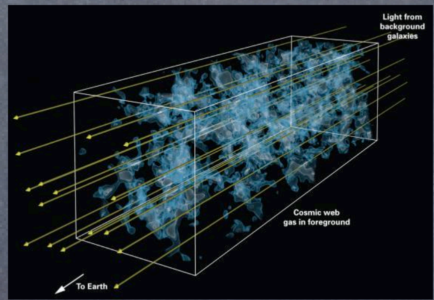
View angle effects +
intermittent behavior



Increase sample size ✓

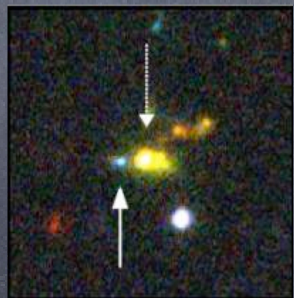
External

IGM absorption
stochastic



Modeled ✓

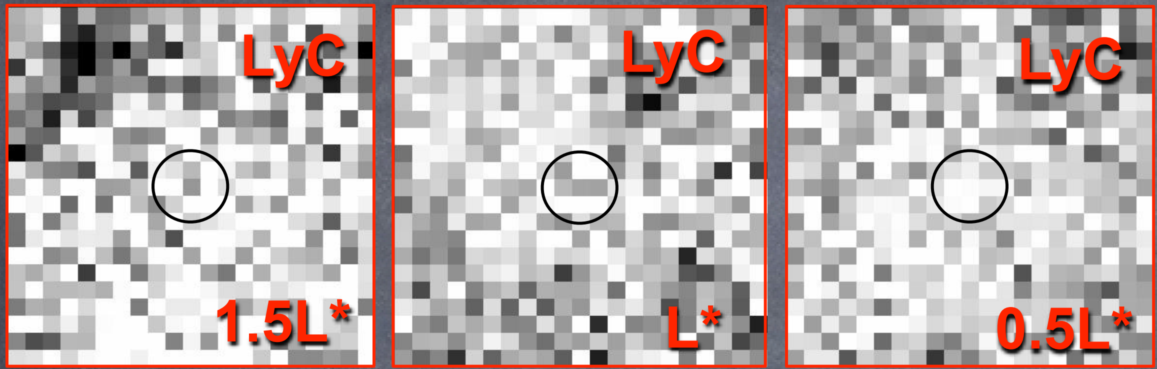
Foreground contamination



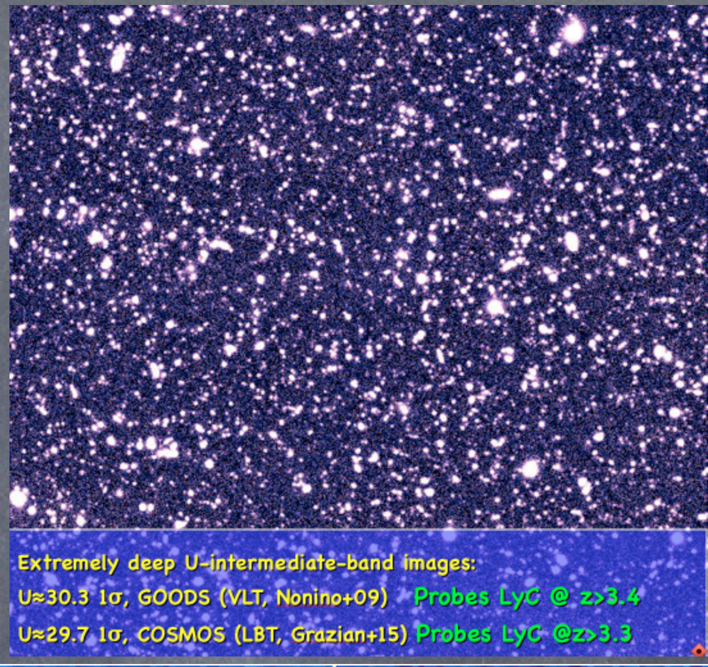
Statistical correction
Individual investigation
(spectroscopy) ✓

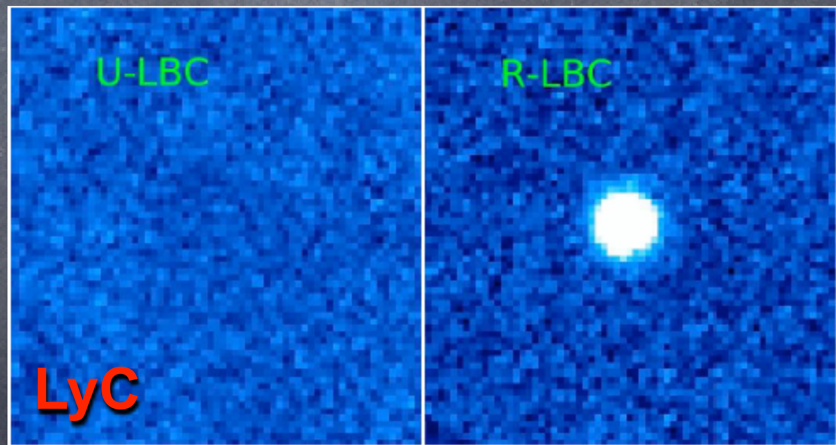
Looking directly at LyC emission z≈3.3-3.5, ~100 L>0.5L* LBGs, (CANDELS)

Vanzella et al. 2010, 2012 (GOODS+CANDELS)



22 LBGs	25 LBGs	20 LBGs
<Δm>=7.5	<Δm>=6.1	<Δm>=6.6
fesc,rel < 3%	fesc,rel < 9%	fesc,rel < 5%



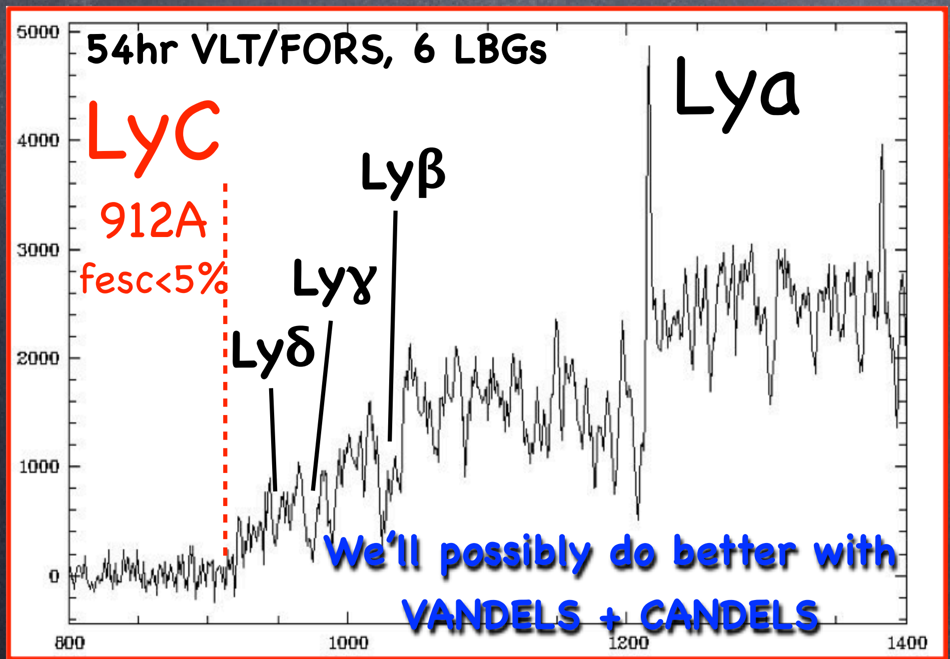


Grazian et al. (2016) - COSMOS

45 galaxies, fesc,rel < 3%

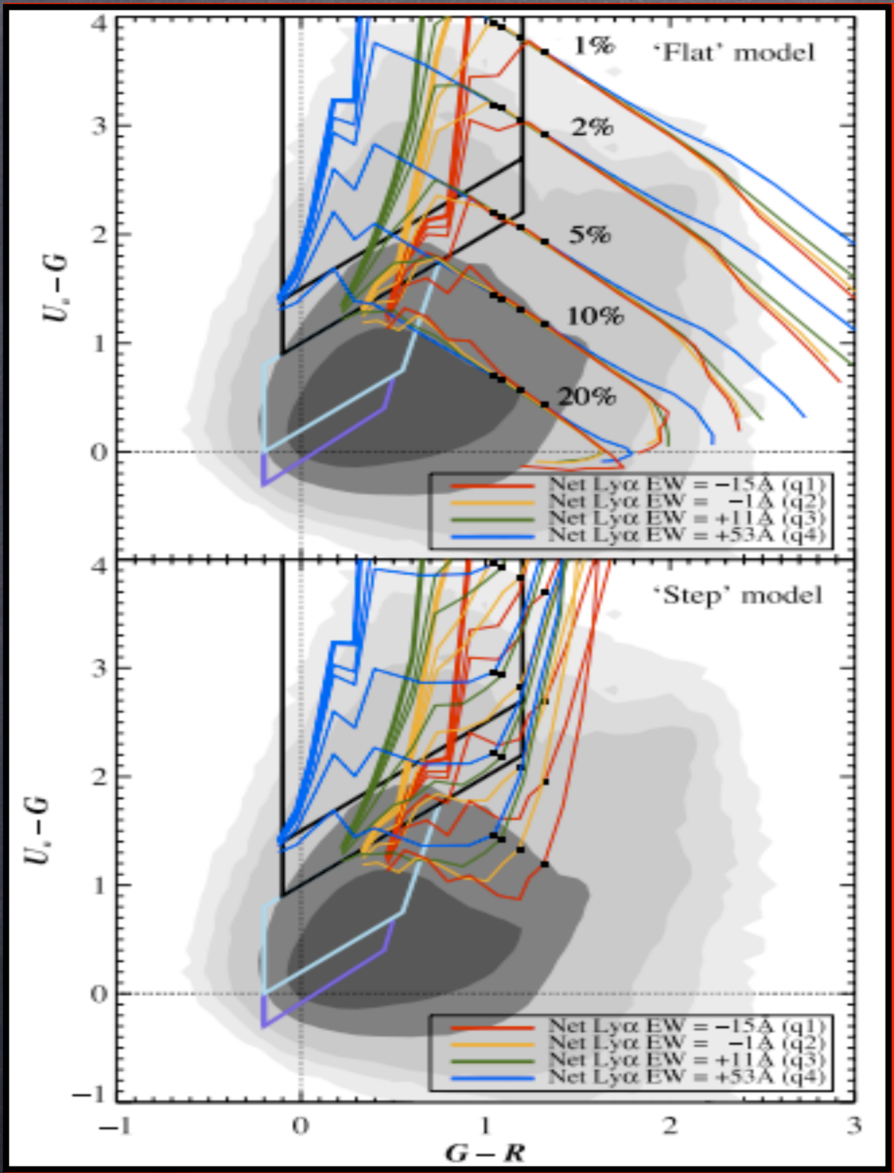
(see also Boutsia+11; Guaita+16;

Grazian et al. 2016)



Trying to observe directly LyC at z<4 (≳1Gry after EoR)

However, galaxies are selected with the "dropout" technique …



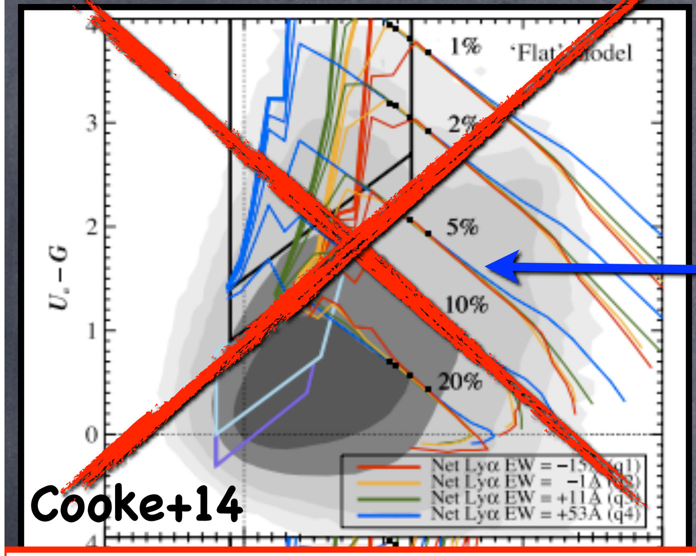
Cooke et al. 2014

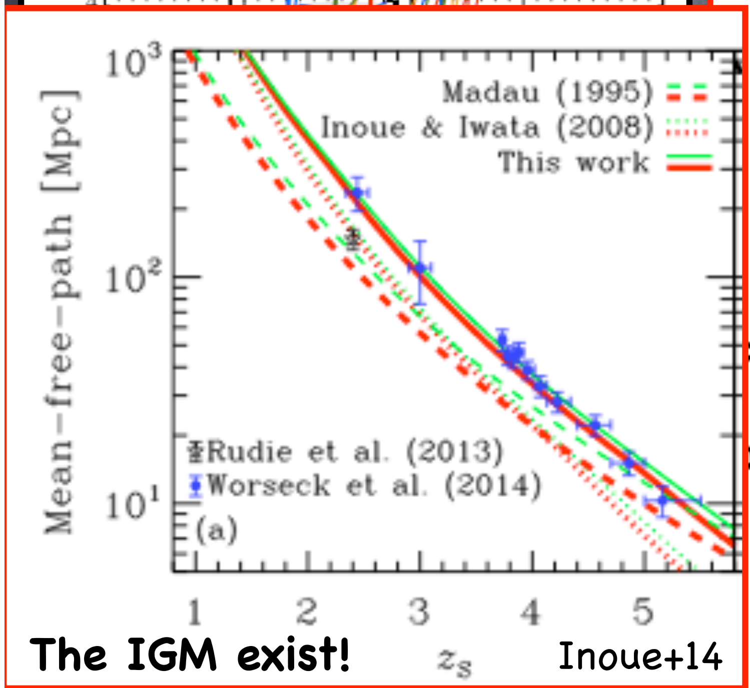
Counter-intuitive ?

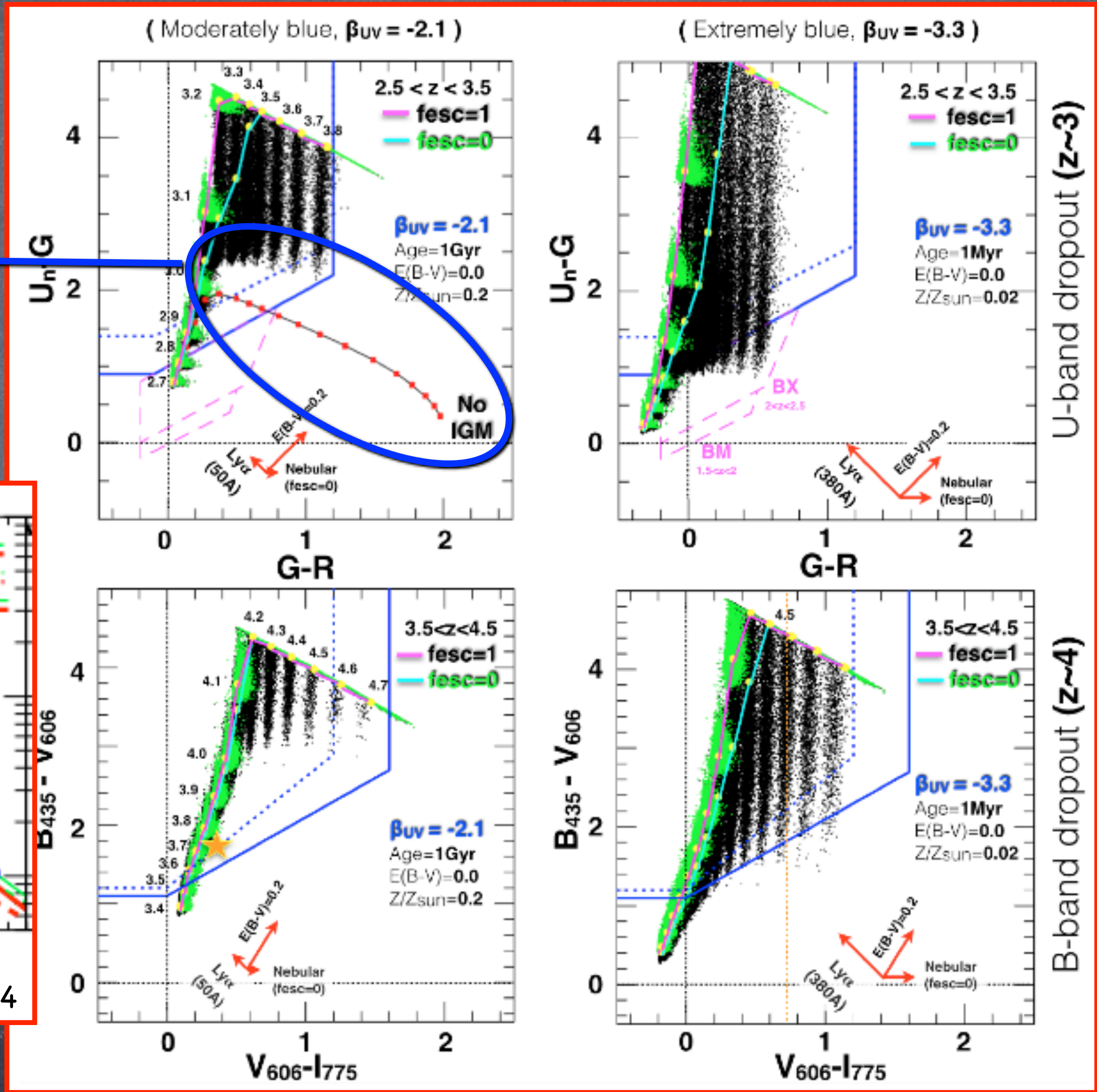
We select high-z galaxies with the dropout technique, is the required "Lyman-drop" biasing our search for Lyman continuum emission ?

Is there a selection effect (Suggested by Cooke et al. 2014) ?

Colors of a "stellar ionizer": do we miss it ? Vanzella+15



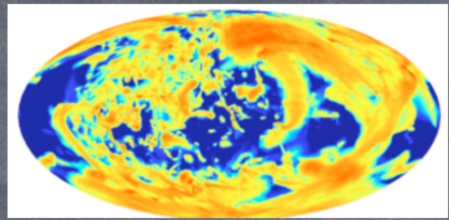




LyC measurements: caveats under control ?

Intrinsic

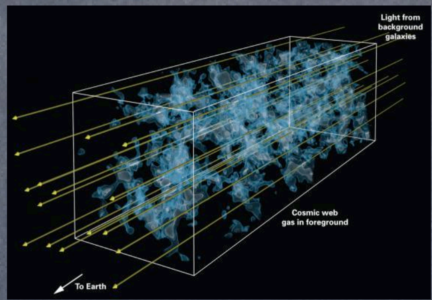
View angle effects +
intermittent behavior



Increase sample size ✓

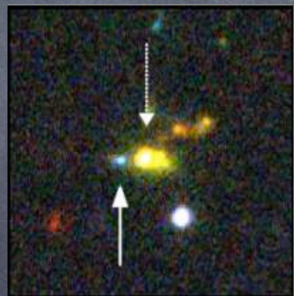
External

IGM absorption
stochastic



Modeled ✓

Foreground contamination



Statistical correction
Individual investigation
(spectroscopy) ✓

In Addition

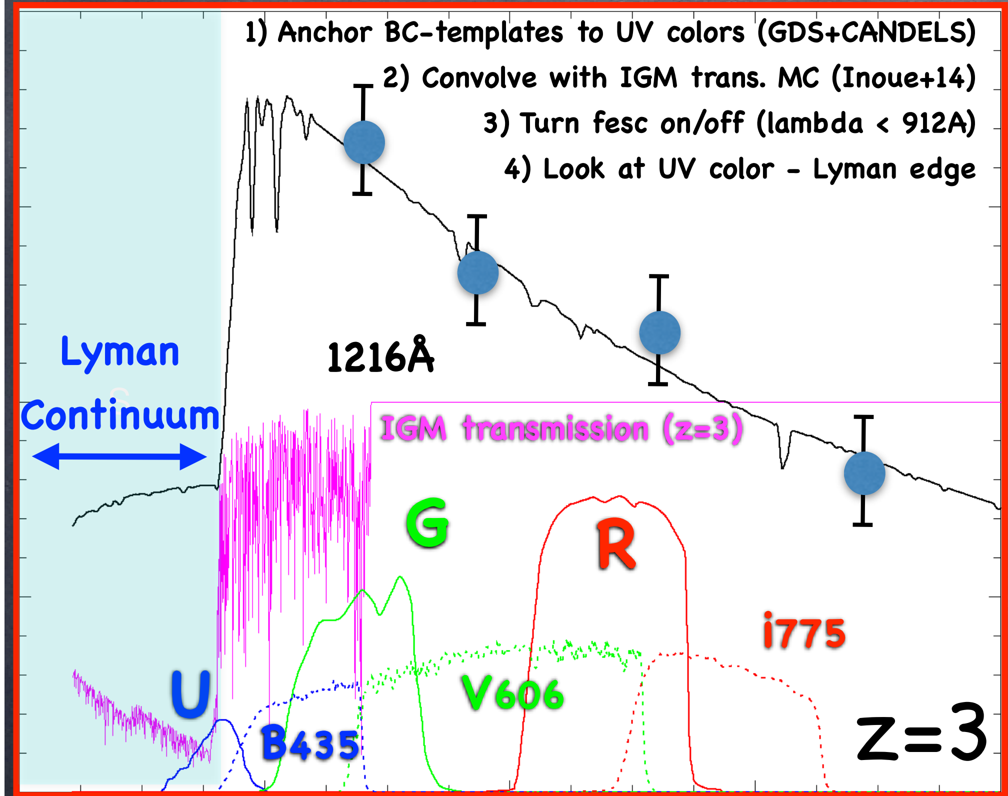
Intrinsically low <fesc>
at $L>0.5L^*$??

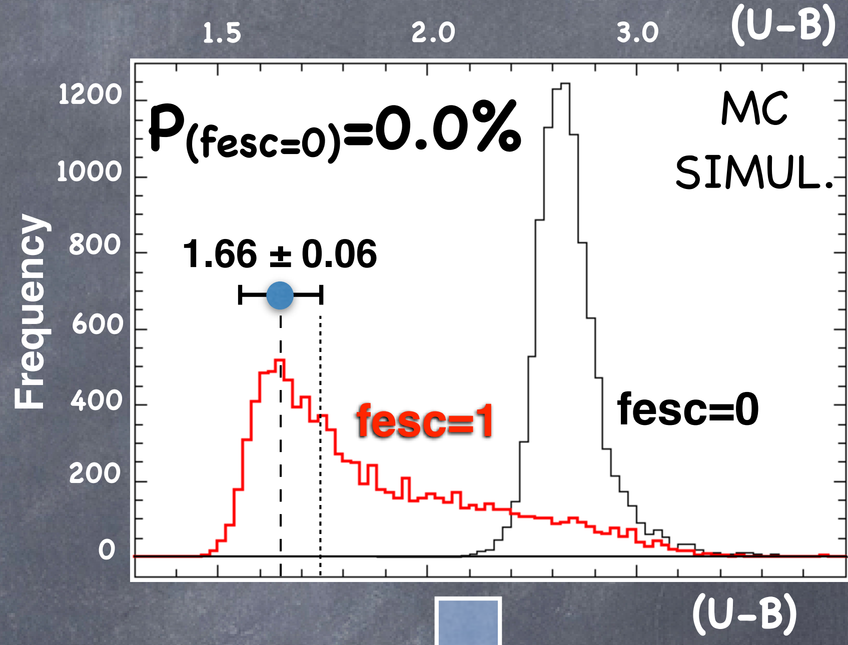
fesc>>0 is **rare**
at $L>0.5L^*$ (?)

Selecting LyC sources at moderate redshift, a different approach (z<4) (EV+15)

Looking for **non**-ionizing signatures of LyC leakage at L>0.5L*, very RARE objects , at z<4 (candidate "ionizers")

Methodology

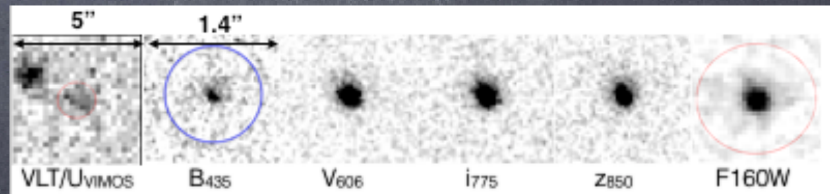




<830A

Ion1

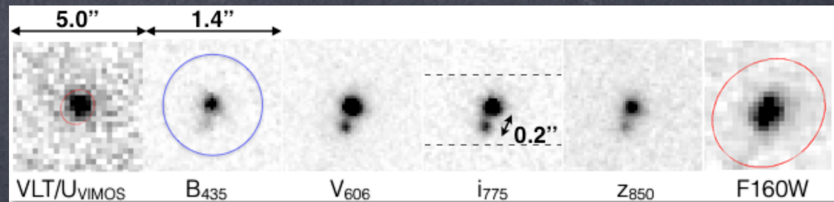
z=3.795



Two candidates LyC-emitters
spatially resolved Re≃300pc
HST/ACS 1500A (V15)

Ion2

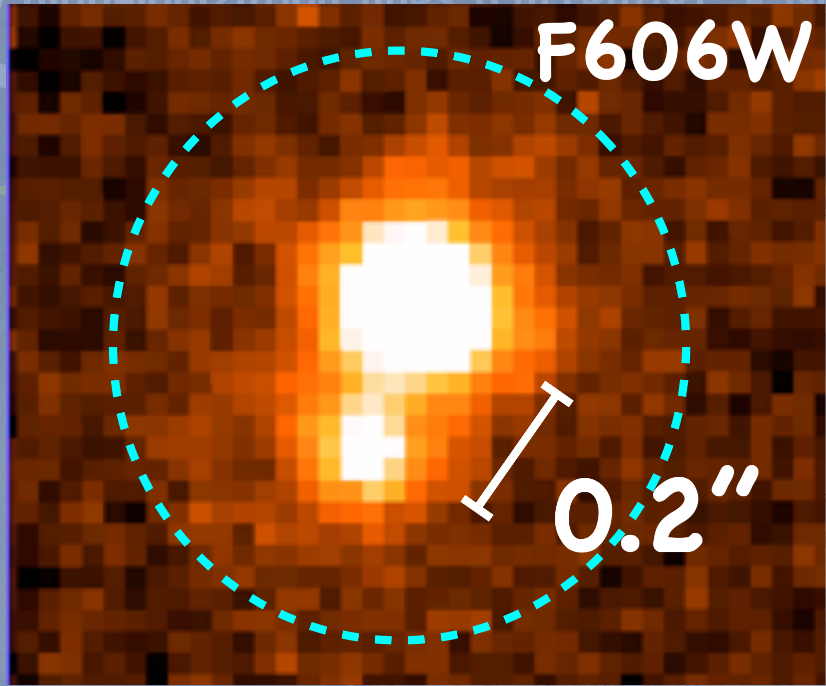
z=3.213



<938A

Two LyC sources with direct LyC detection !?

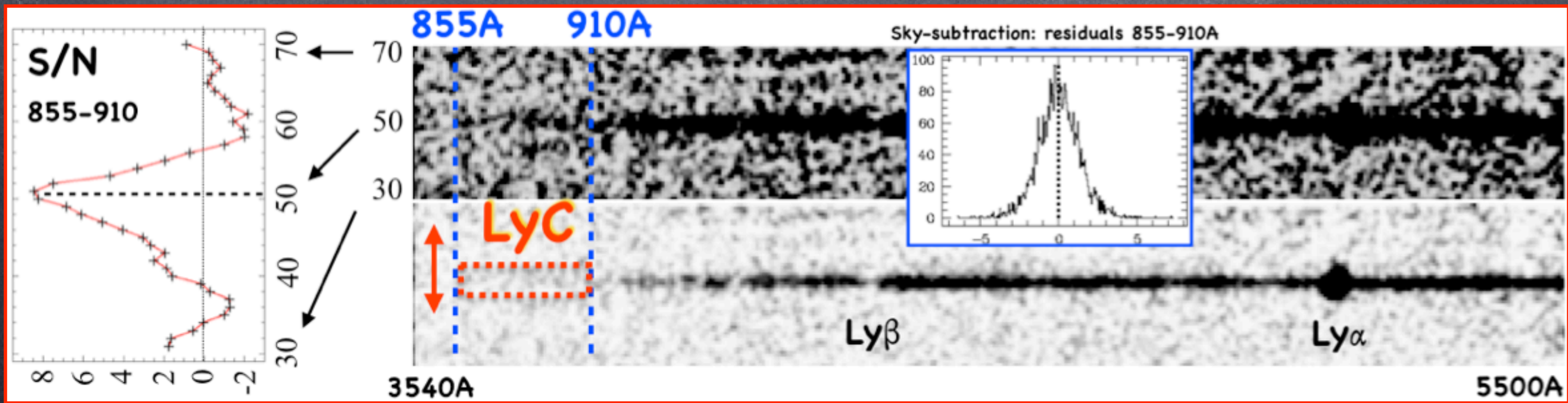
Ion2



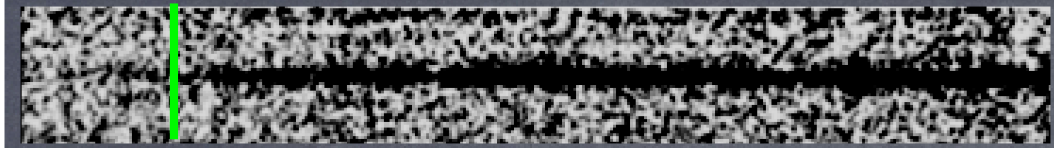
Two components!

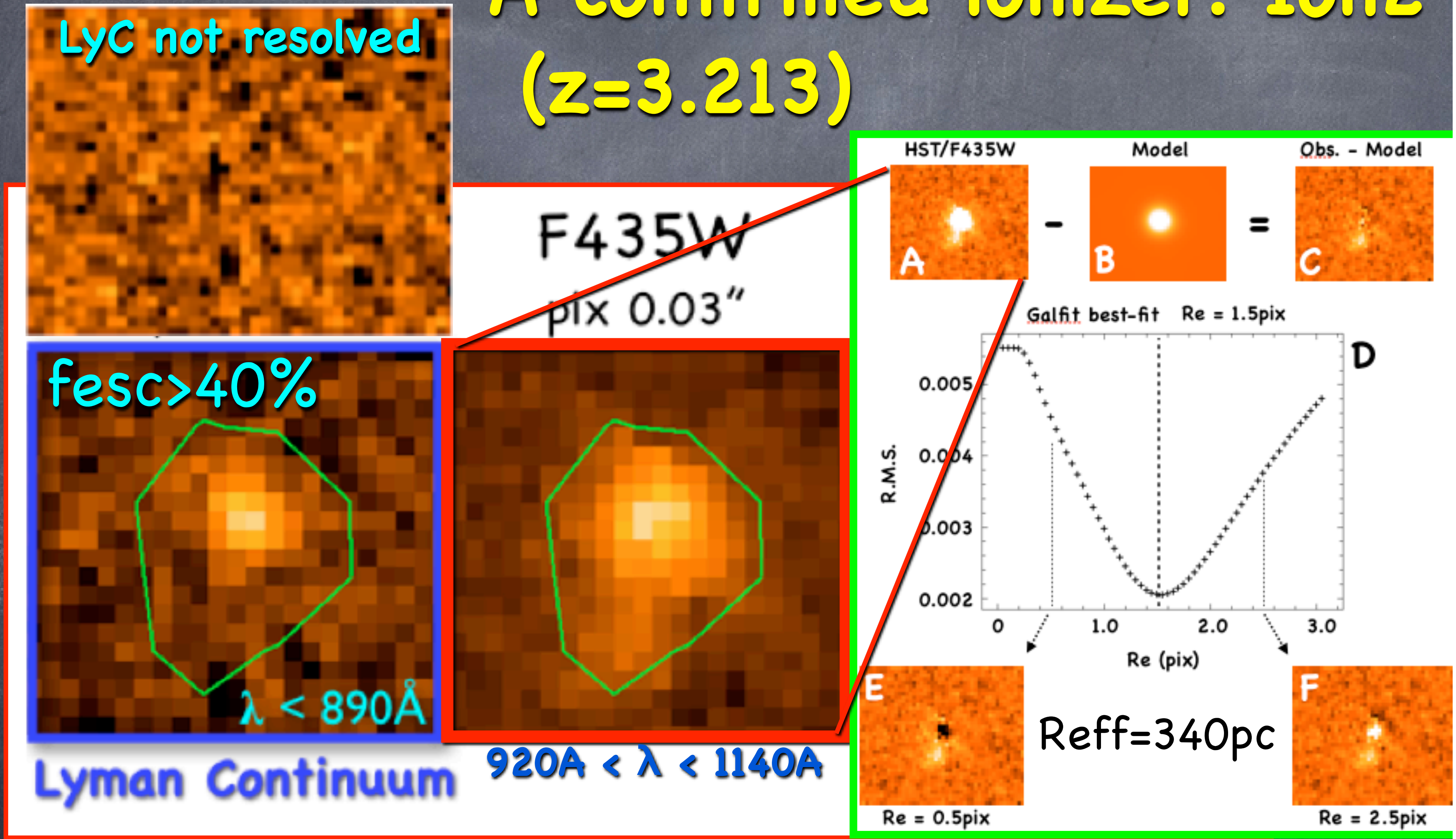
High spatial resolution imaging at the LyC is needed !!

Ion2: (z=3.213, i_{775}=24.50)



A confirmed ionizer: Ion2 (z=3.213)





1Gyr after Reionization ended

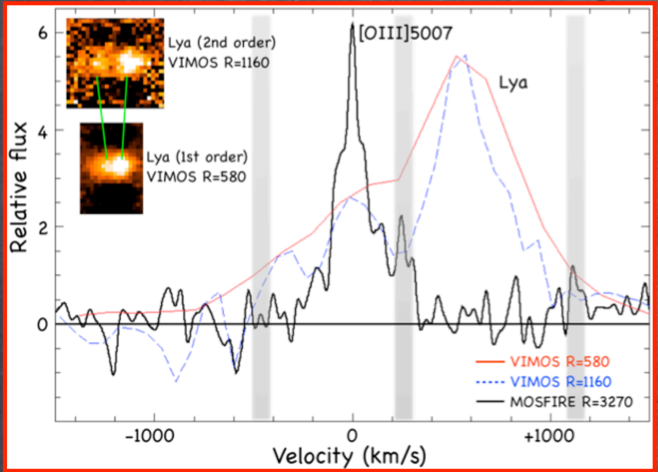
Vanzella et al. 2015; de Barros et al. 2016; Vanzella e al. 2016b

Thanks to Alavi, Vasei, Brian for fast data reduction

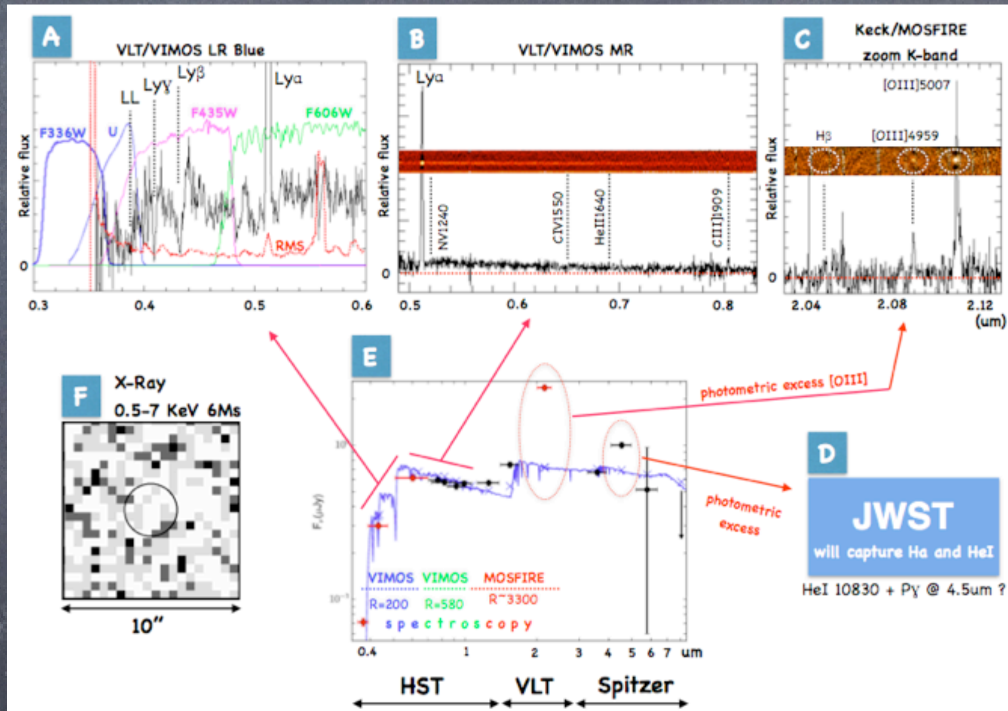
A panchromatic view of a LyC emitter

X-ray, UV spec, NIR spec, multi-frequency data -> big effort

1) **non-zero Lya flux** at the systemic redshift (Behrens +14;Verhamme+14; Henry+15)

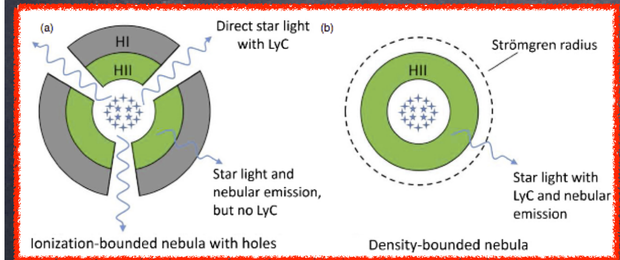


2) **weak** C, Si **low-ionization abs. lines** low covering fraction NHI (Jones+13,14; Heckman+11 Leethochawalit+16)



Radiation bounded

Density bounded



3) **large O32 > 10**

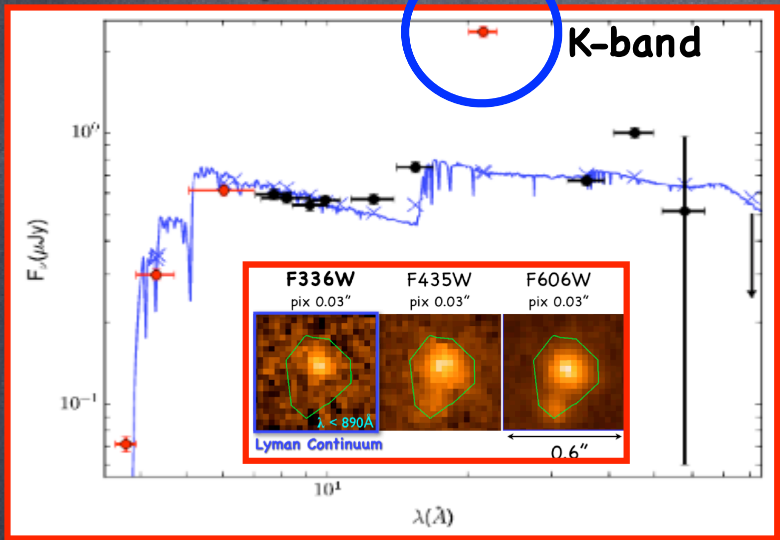
O32=[OIII]/[OII] positively correlates (also) with **fesc** (Nakajima & Ouchi 2014; Jaskot & Oey 2013)

4) **Blue + faint Hb equivalent width**, linked with ionizing photons (Zackrisson+13; Inoue+11)

Distant (z>7.5) spectroscopically confirmed L>L* galaxies

Lya+UV continuum (ELT);
Optical Oxygen+Balmer (JWST)

Ion2, zspec=3.212 Vanzella+16b



EW([OIII]+Hb)=1500A!

Two relevant facts:

1) LyC leakage

2) Strong nebular emission

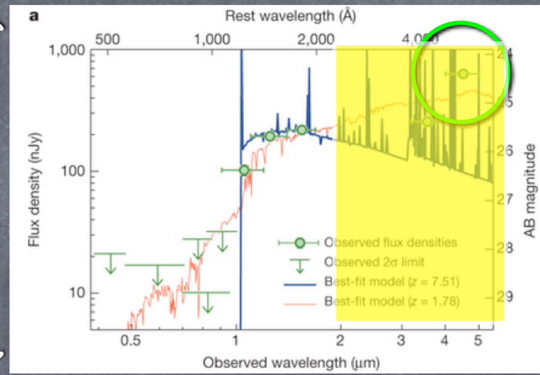
O32>10, density-bounded ISM?

JWST will eventually observe rest-frame optical lines at z>6 ISM conditions & ionization

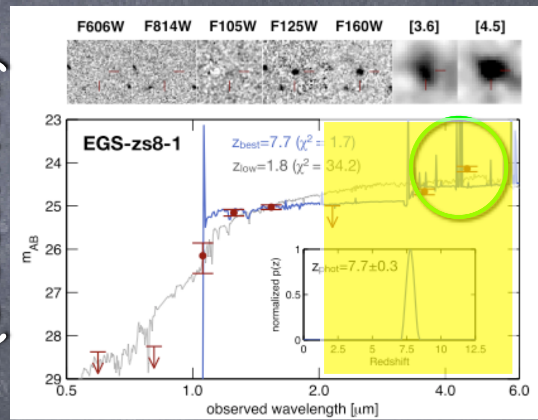
Are "Ion2-like" sources more frequent at z>6 ?? (Holden+16,see also Khostovan 2016; Stark et al. 2015)

Large EW([OIII]+Hb) ~ 600-1000A rest

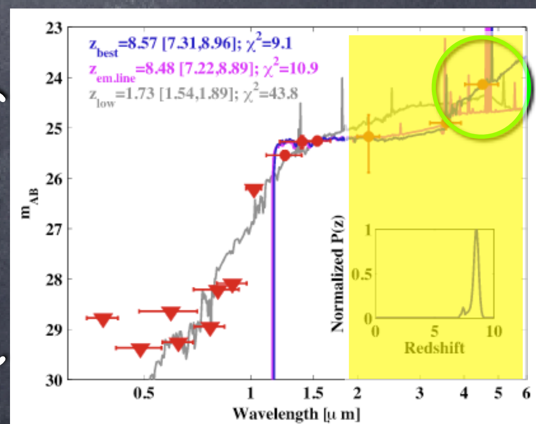
zspec=7.51 (Finkelstein+13)



zspec=7.73 (Oesch+15)

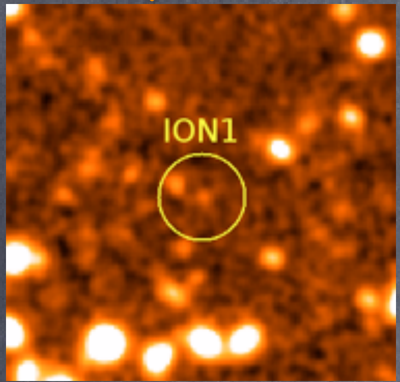


zspec=8.68 (Zitrin+15)

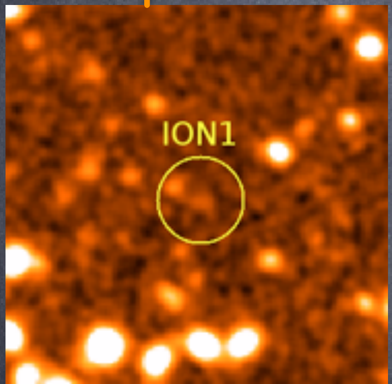


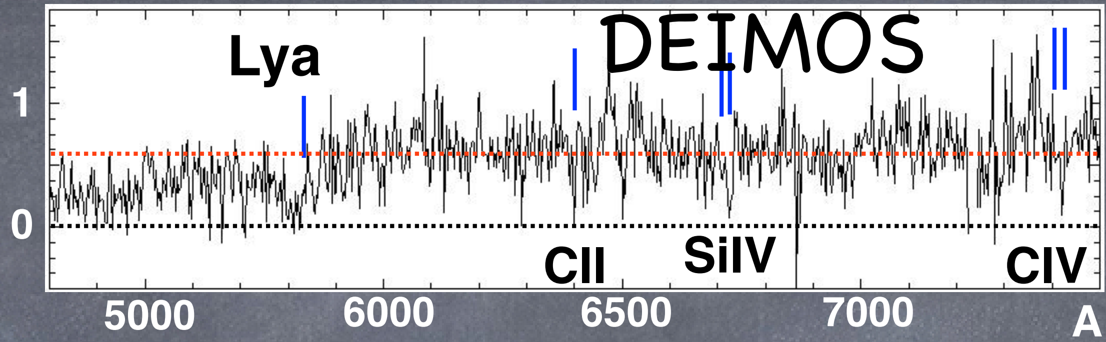
Another LyC source: Ion1 (in progress)

Group1 VLT/U



Group2 VLT/U





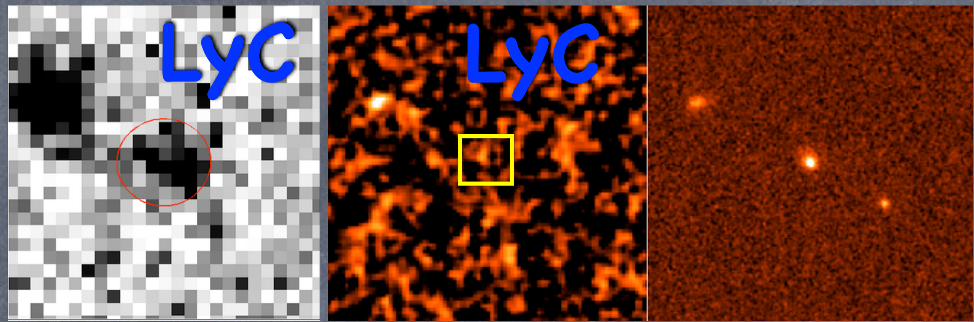
zspec=3.795

i_{775}=24.82

zphot=3.6

VLT/U_{VIMOS} HST/F410M F435W

5″

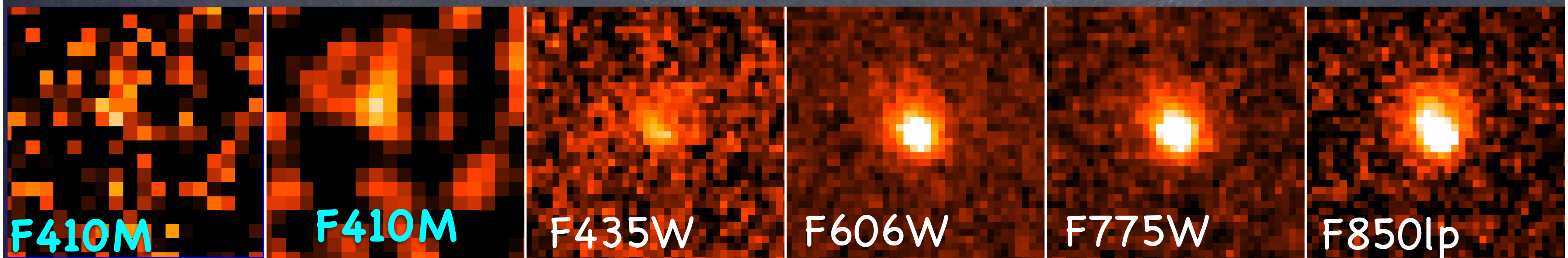


750-830A	834-876A	800-1000A
27.92±0.16	>28 1-sig	
S/N~6.7	(1.2″⊘)	

12 orbits, PI Vanzella

Spatially resolved LyC ?

1″



smoothed

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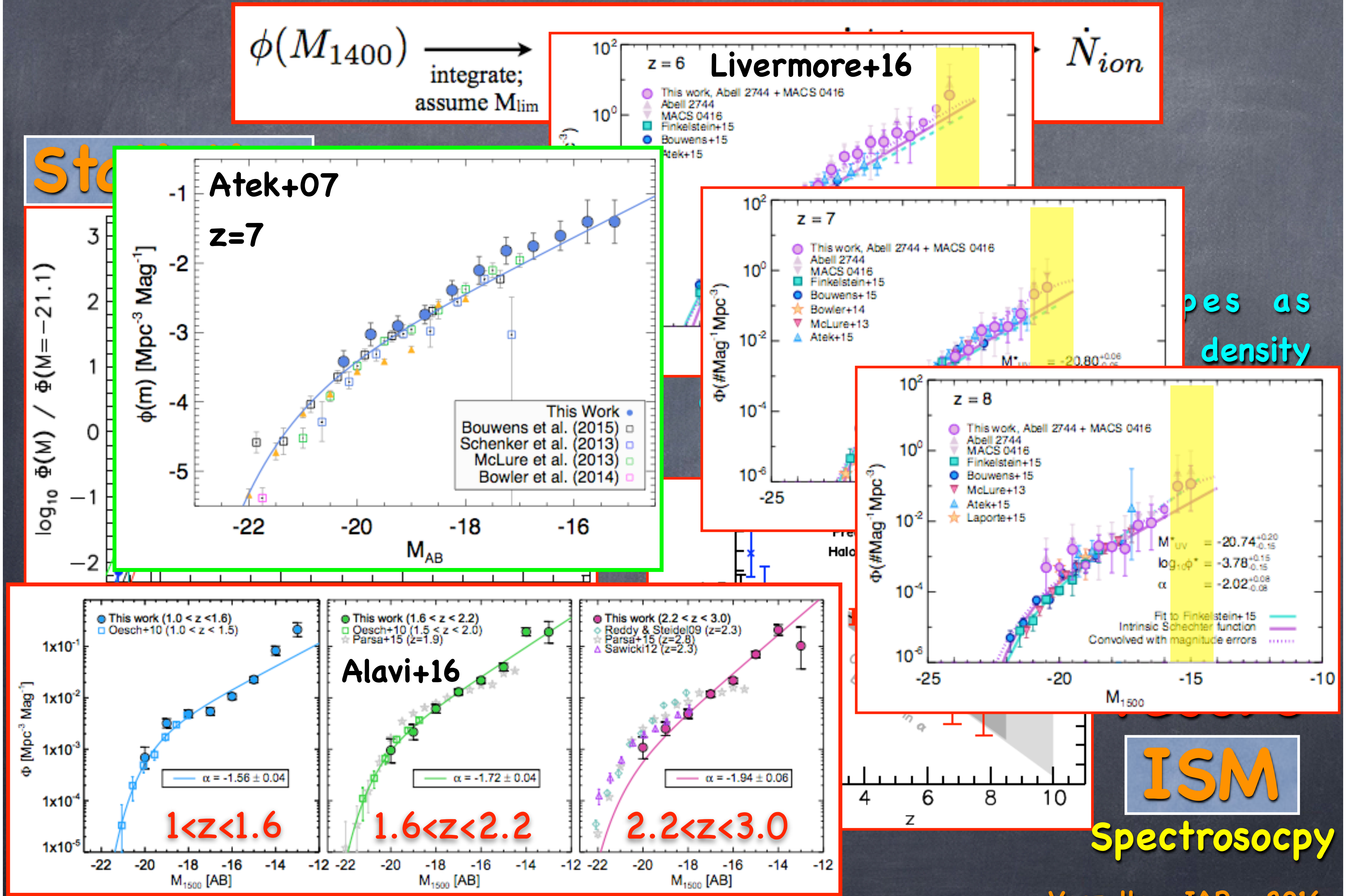
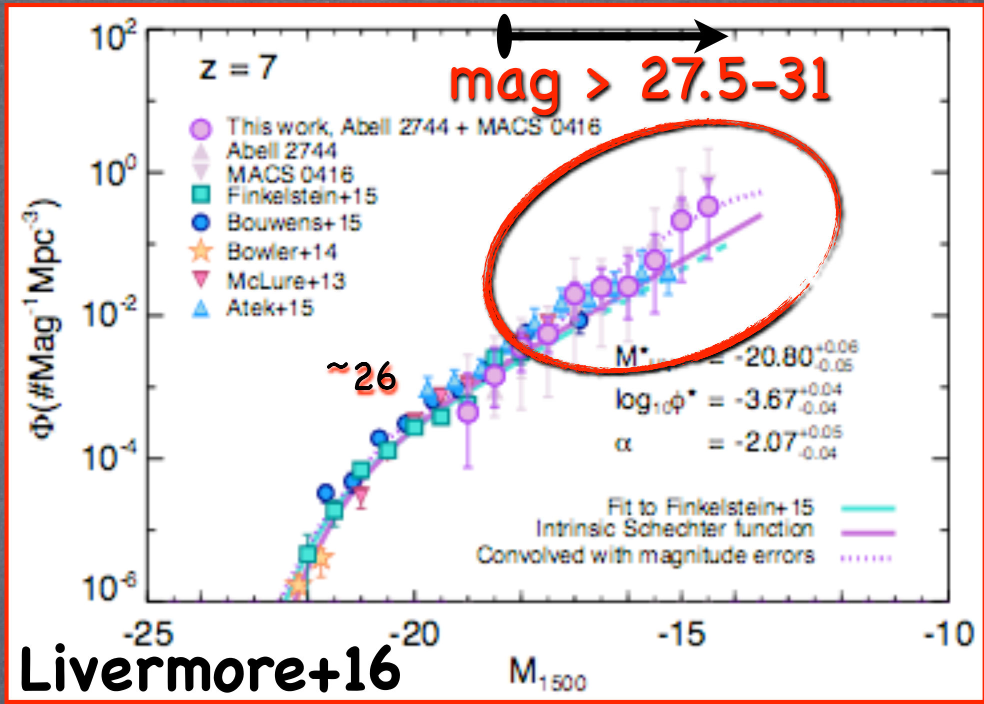
We need constraints at the deepest luminosity limits

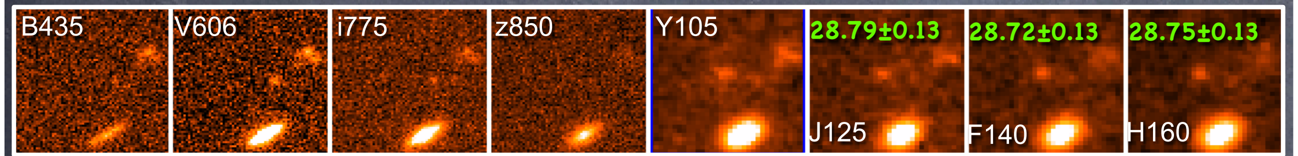


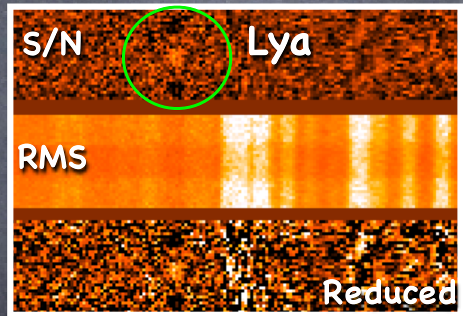
How can we access faint regimes with spectroscopy ??



Brute force (1)

VLT/FORS 30hr   m1500=28.80





HUDF

z=6.635

$f(Ly\alpha)=2\times10^{-18}$ erg/s/cm2 (S/N=7)

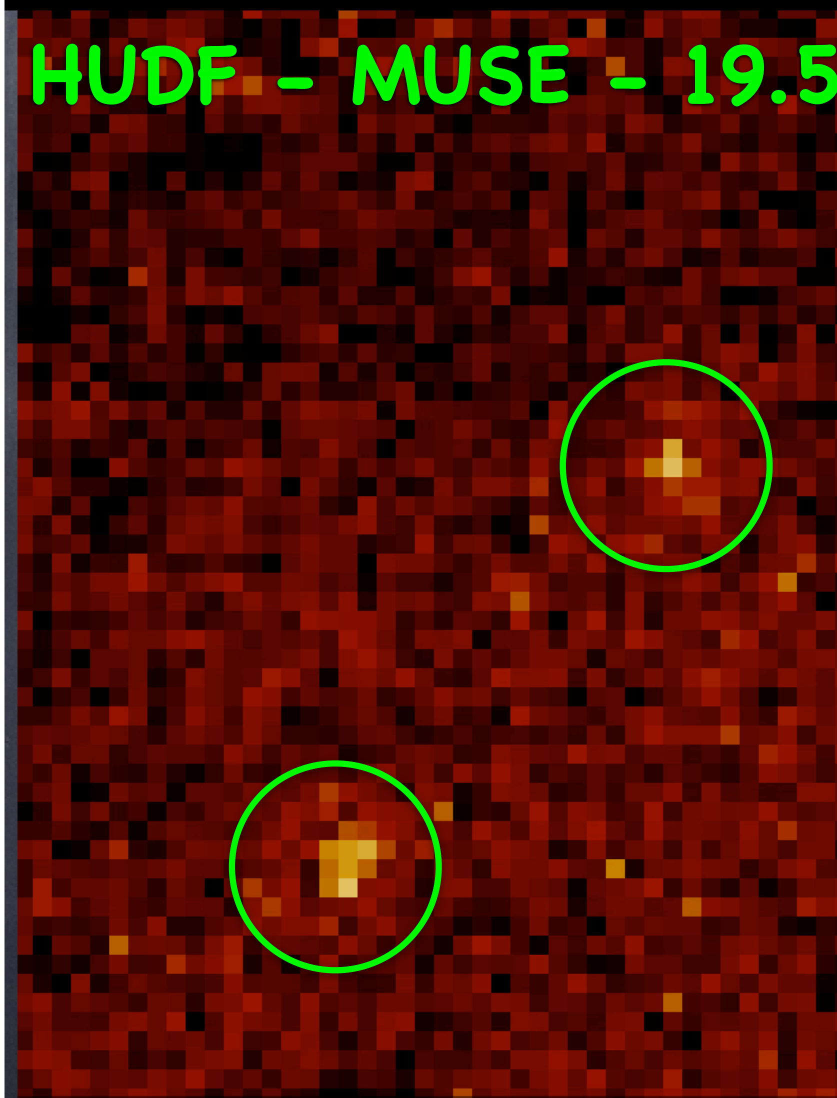
limitations: - low S/N also in the deepest fields (HUDF)

m>28.5 - low S/N in the spectrum

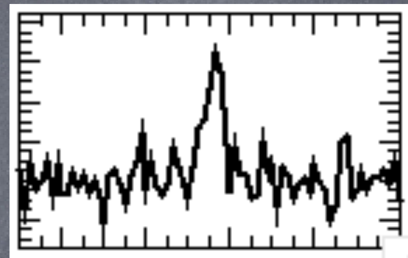
Brute force (3)

Low-luminosity galaxies: MUSE

Redshifts for faint (not lensed) galaxies



Amazingly faint, need JWST/ELT



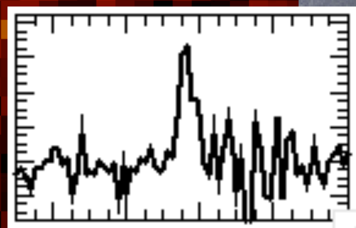
z=5.1330

Lya, z_{850}=

30.59±0.34

f(Lya) 1.5e-18cgs

photometry from Coe+06



z=5.1333

Muv -15.8

Lya, z_{850} = 30.75±0.52

f(Lya) 1.4e-18cgs

EW~200A rest-frame

if we could find something similar in a lensed field $m_{intr} = m_{obs} + 2.5\log_{10}(\mu)$

μ=15(10)(5) ➔ m_{intr} = 33(32.5)(31.7) !!

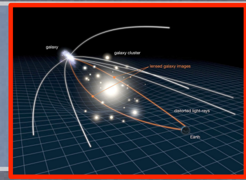
Muv -13.0 @ z 3-6.5

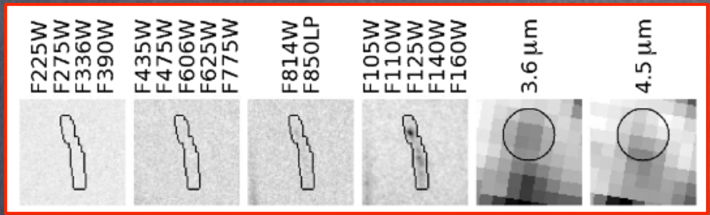
This is feasible now!

Investigating faint SF and blue galaxies @ z~6

Hubble Frontier Fields (P.I. Lotz) 6 galaxy clusters m≈28.7-29 5-sig

CLASH: 500 HST orbits (P.I Postman) 25 galaxy clusters m~27.5 5-sigma





z_{phot}=6.18

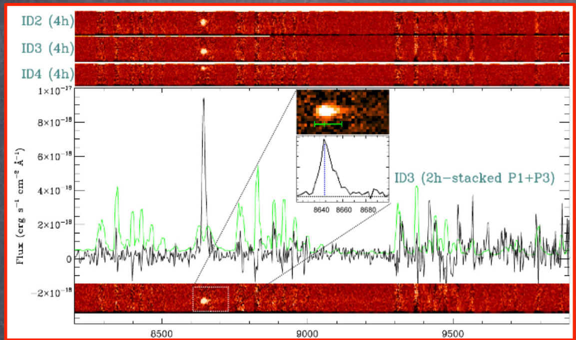
m1500~27.1

L~0.5L*

β = -2.6, Zitrin et al. (2012),

NO Lya from VIMOS spectrum (2hr)

Ongoing FORS2 spectroscopy, 15hr (PI Vanzella)



zspec=6.108

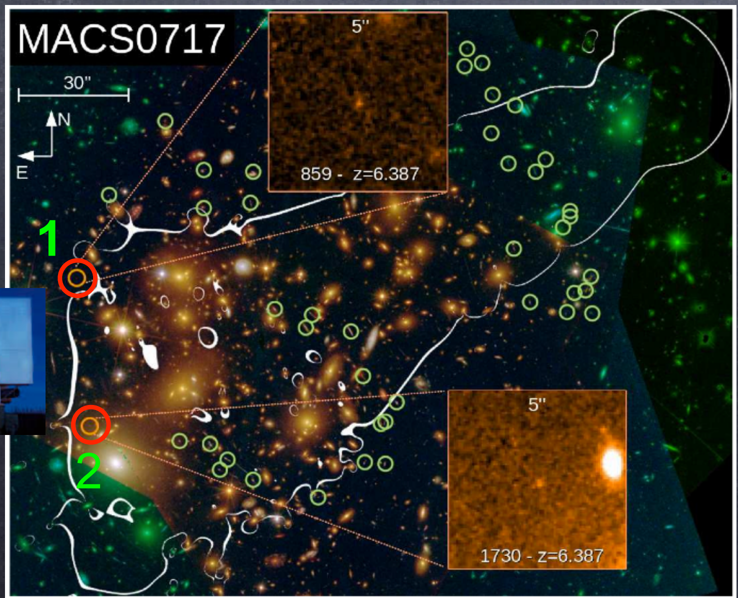
m1500~27.5

L~0.1L*

β = -2.8, Balestra+13; Karman+15

from VIMOS and MUSE

(Monna et al 2014)



zspec=6.387

m1500~29

L~0.04L*

β = -2.6, (EV et. 2014)

LBT/MODS

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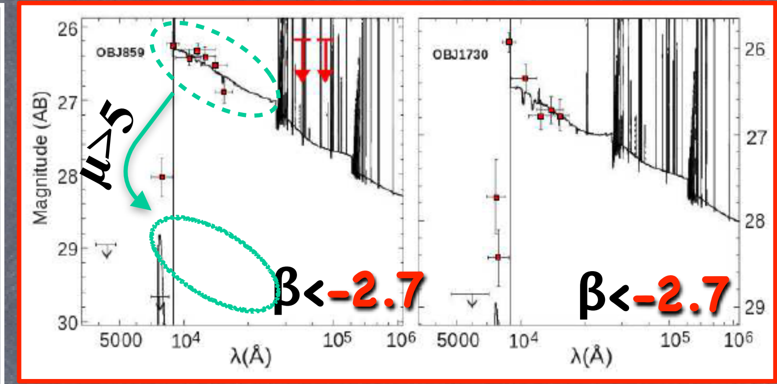
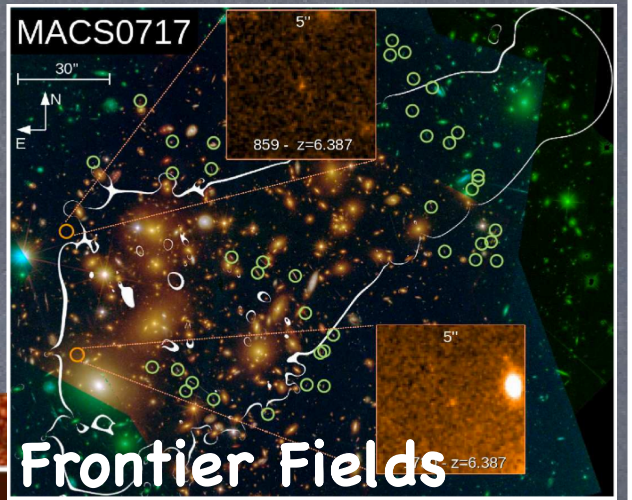
Small, blue, compact and low-mass galaxy at z=6.4 (EV+14)

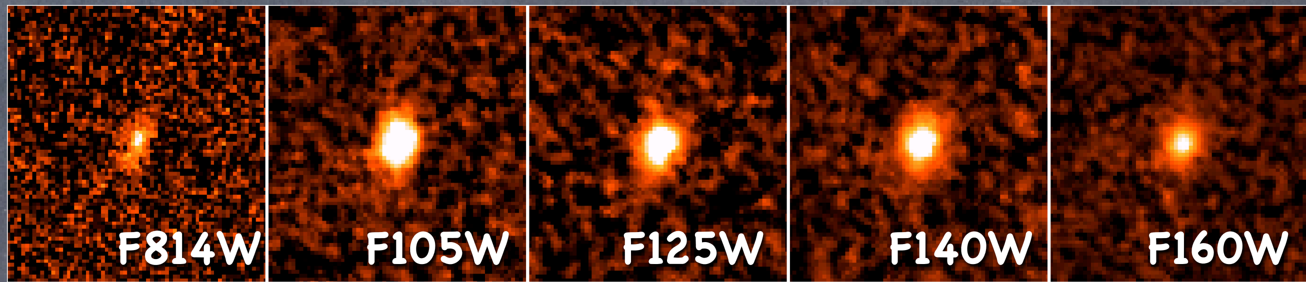
Newborn galaxy?
z=6.40
f(Lya)=2e-18cgs
m1500 ~ 29

Mabs = -17,
SFR<2 $M_\odot$/yr
size< 0.5 sq.kpc
M* ≈ $10^7 M_\odot$
E(B-V) ≈ 0
age ≈ 20Myr
Z < $0.02 Z_\odot$





NIR(HFF) S/N≈50
... in progress



Have we found a "(re)ionizer" ?

β = -2.7 +/-0.15

gas abs. dust. abs

λ <912A $f_{esc} = \exp[-\tau_{\mathrm{H\,I,ISM}}(\mathrm{LyC})] \times 10^{-0.4(A_{\mathrm{LyC}})}$ > 0 (possibly)

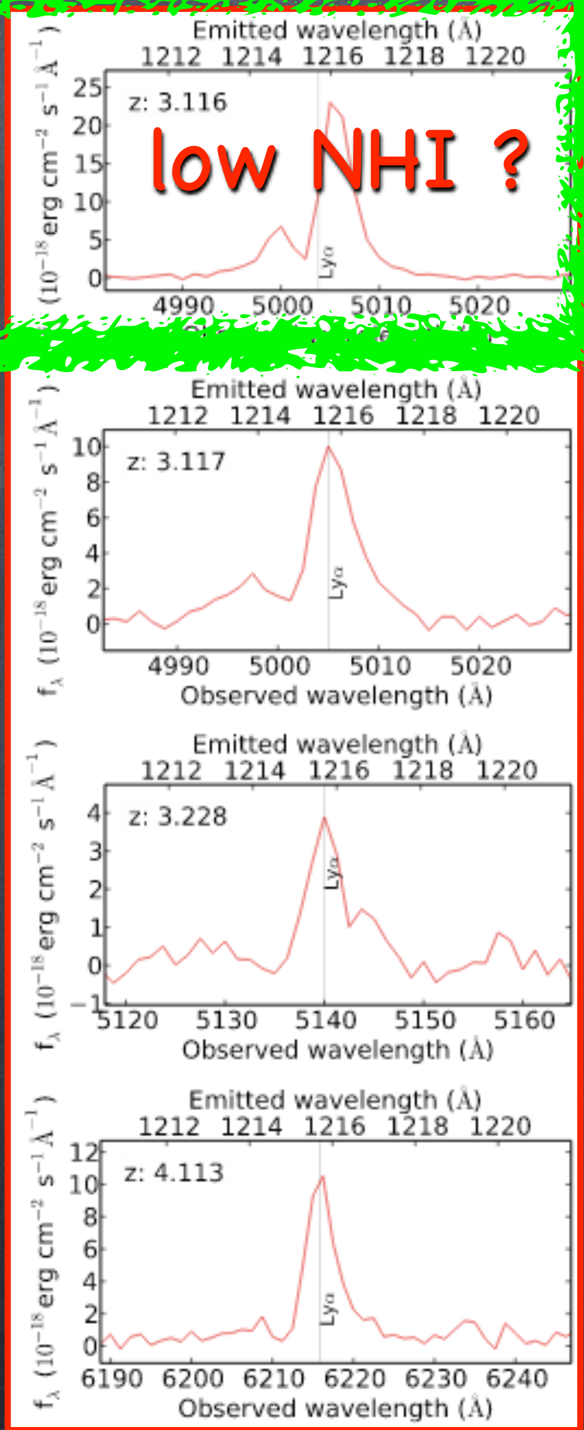
> 0 ? ≈1

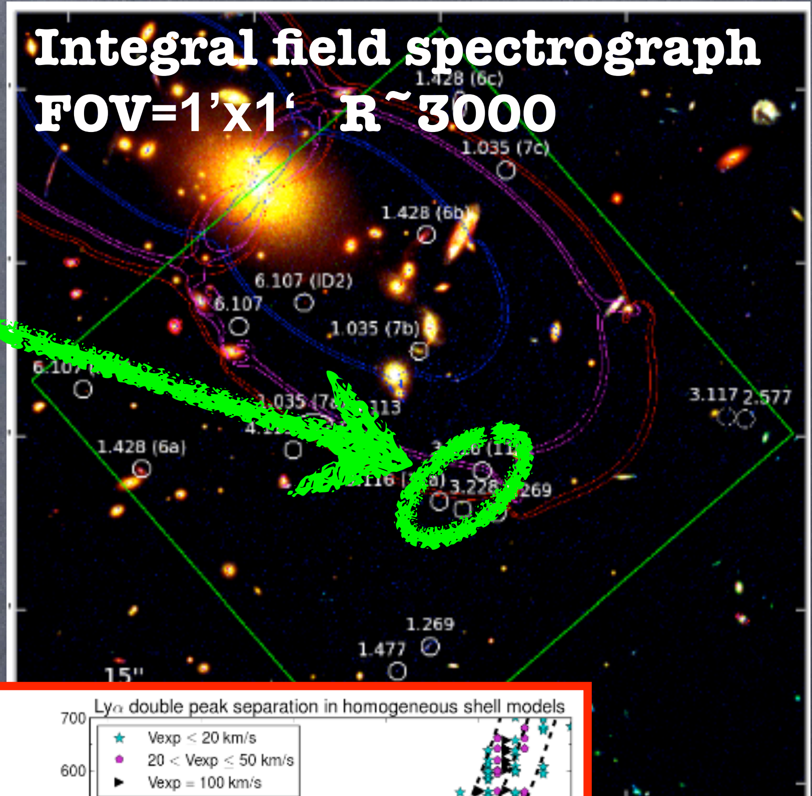
fesc <-> UV slope
Inoue +11
Zackrisson+13
Schaerer+11

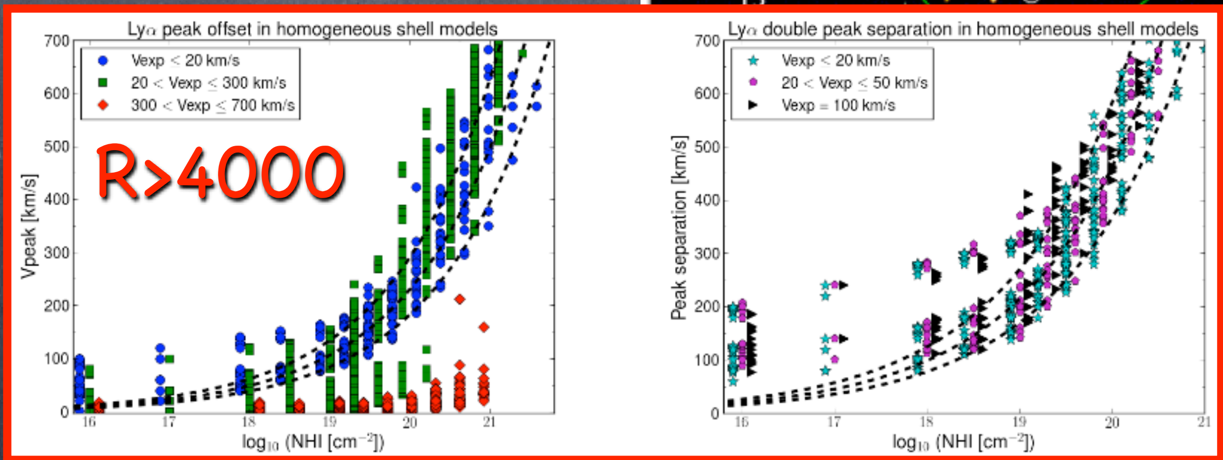
Spectroscopic investigation of faint galaxies @ z~3-6

we need a reference sample at moderate z in the low-L regime (Karman 2015,2016)

(Two MUSE pointings on AS1063)



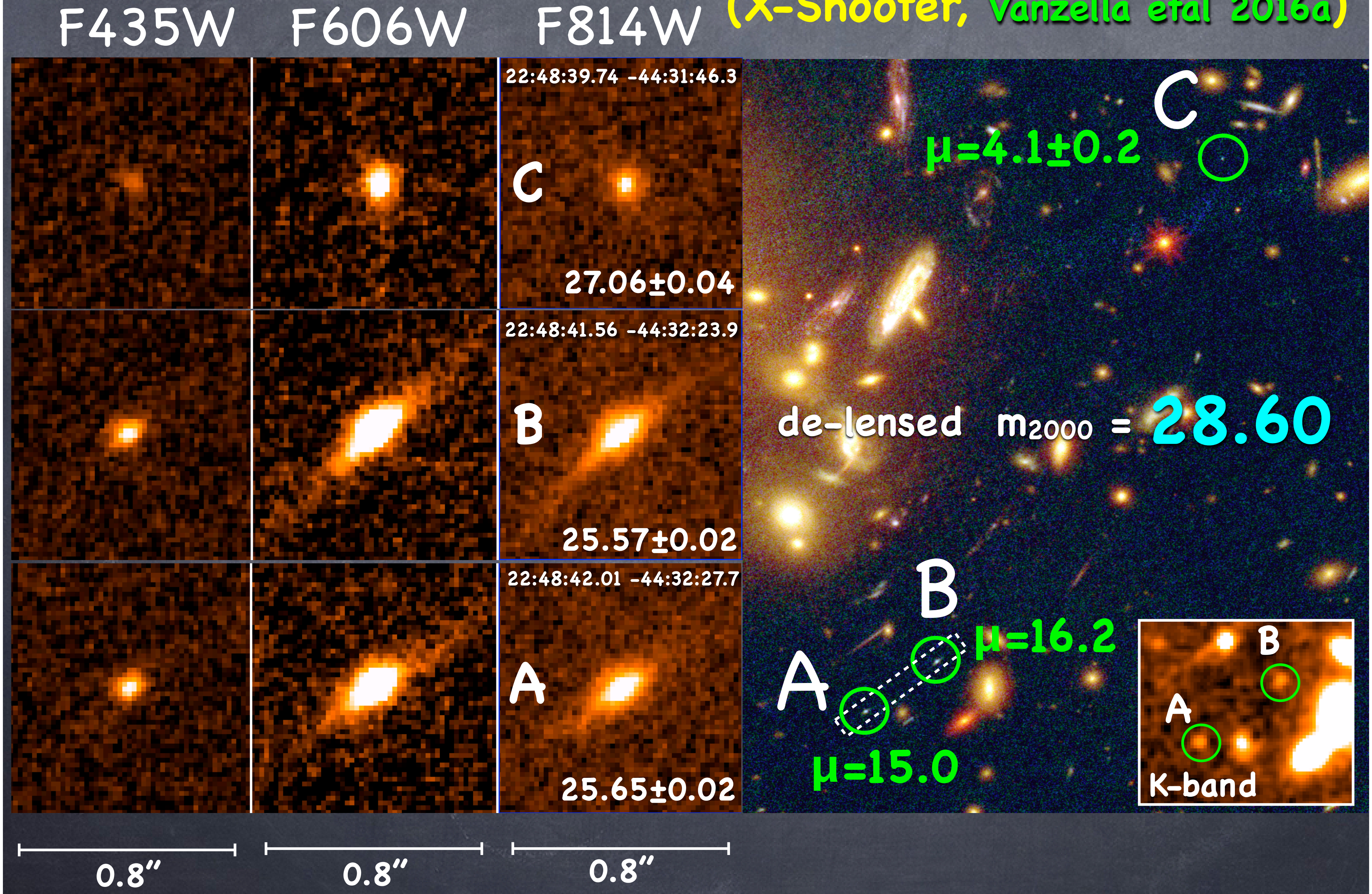




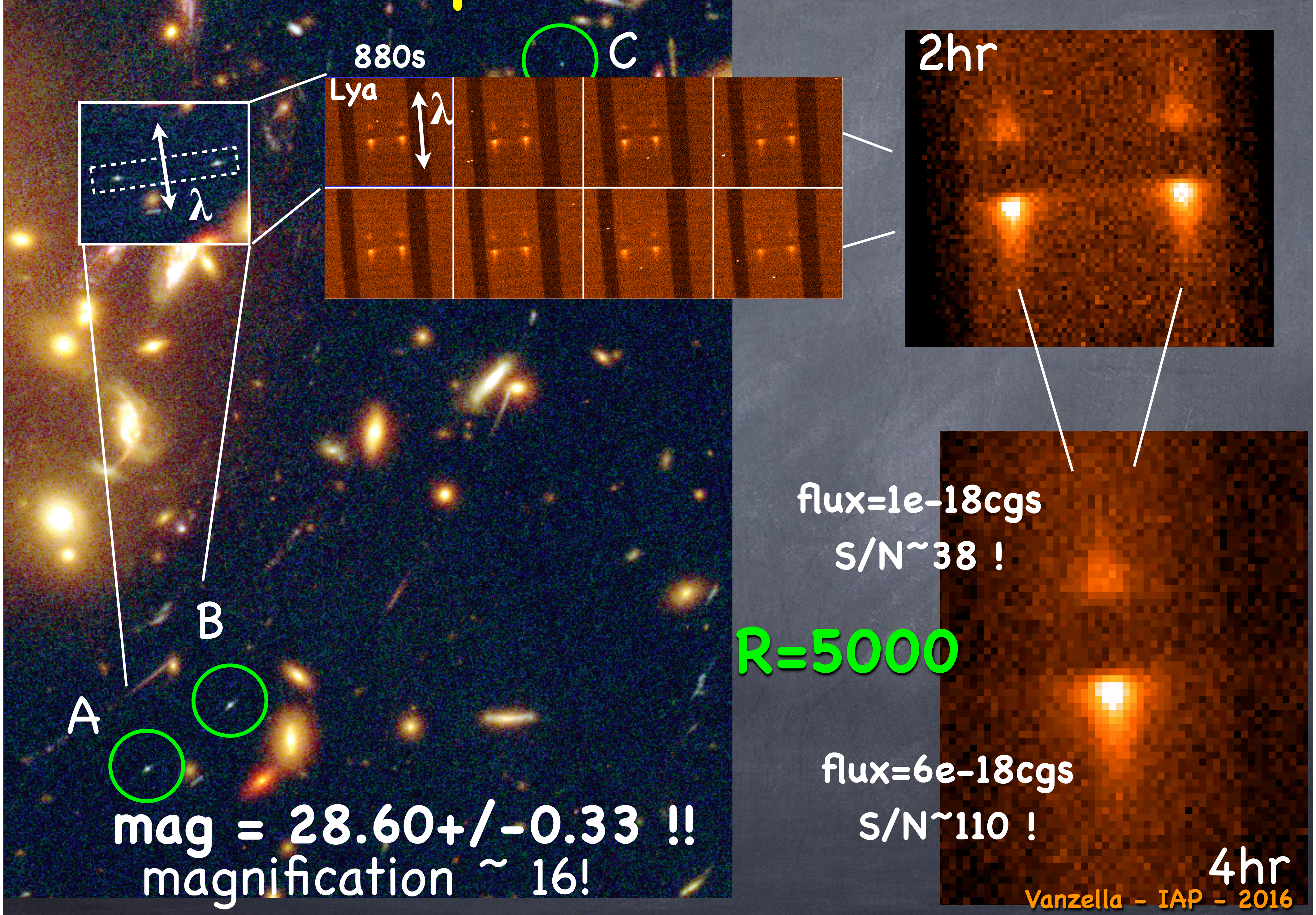
Verhamme+15

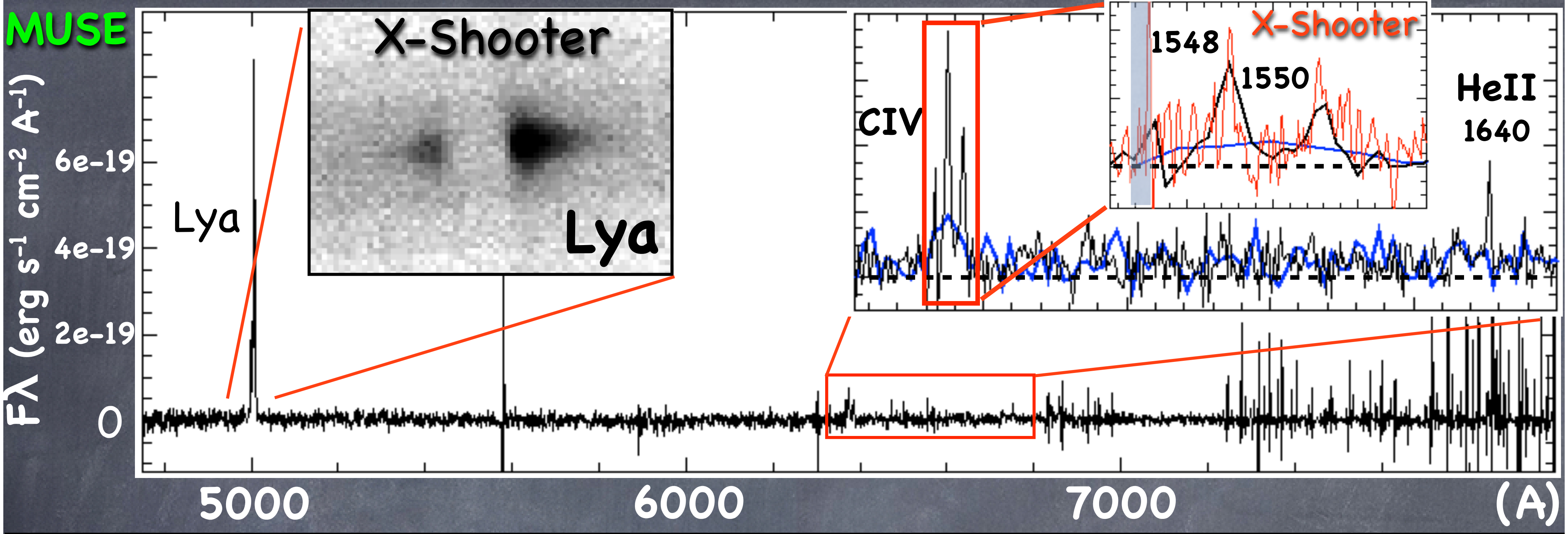
Pushing high resolution spectroscopy to the faintest limits

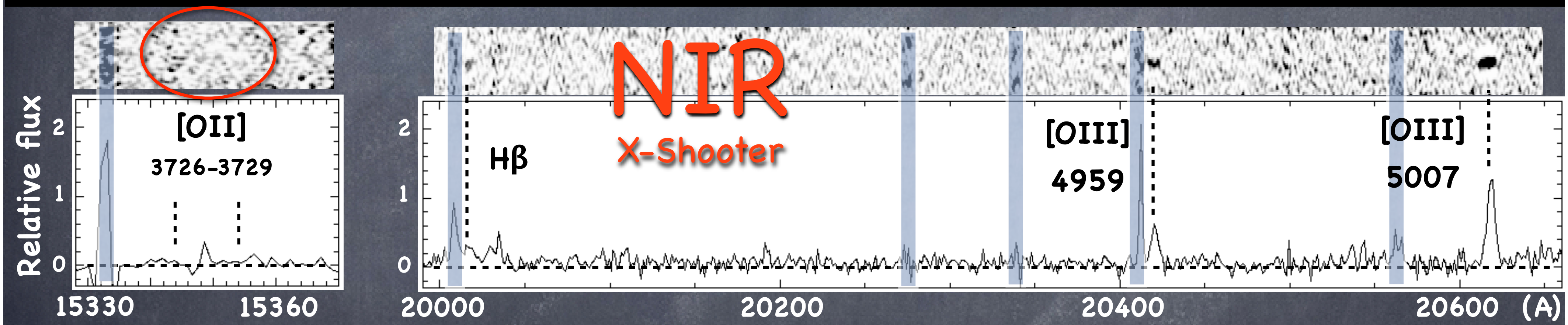
(X-Shooter, Vanzella etal 2016a)

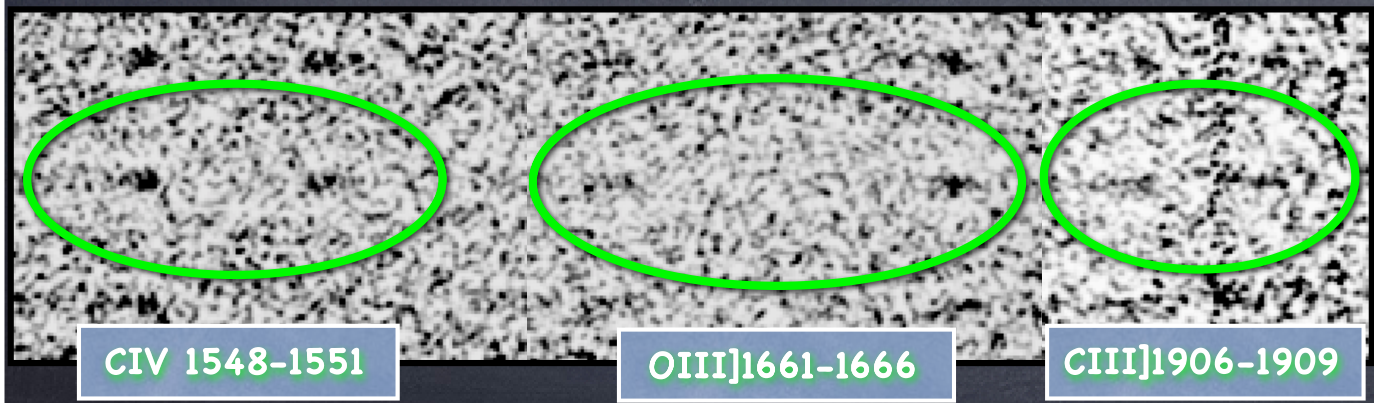


An "ELT-like" spectrum: X-Shooter (R~5000-7000)









HeII	1.3e-19	cgs	S/N=6
CIV_{1548}	3.1e-19	cgs	S/N=18
[OIII]	1.4e-18	cgs	S/N=33
Hb	1.9e-19	cgs	S/N=4

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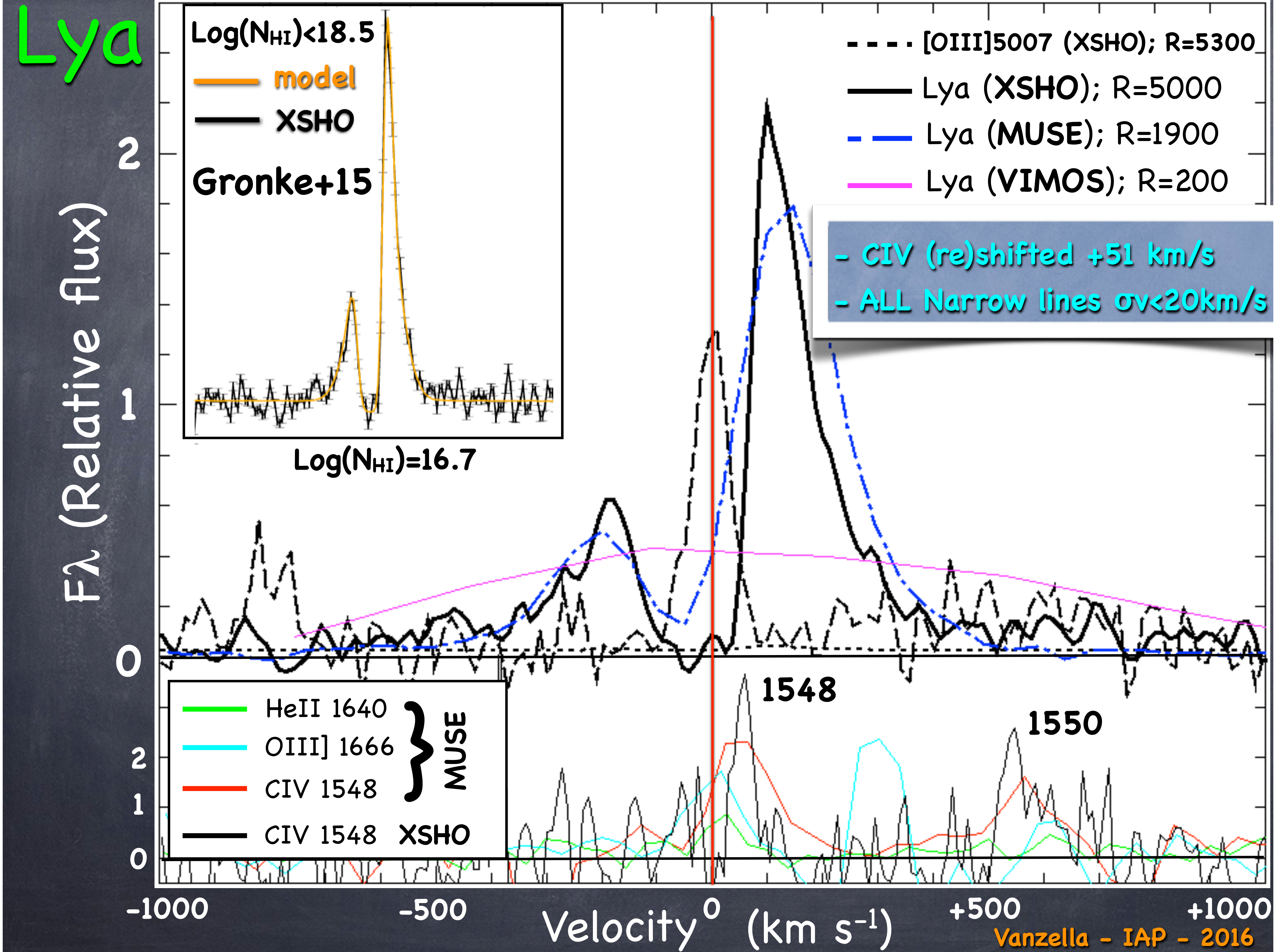
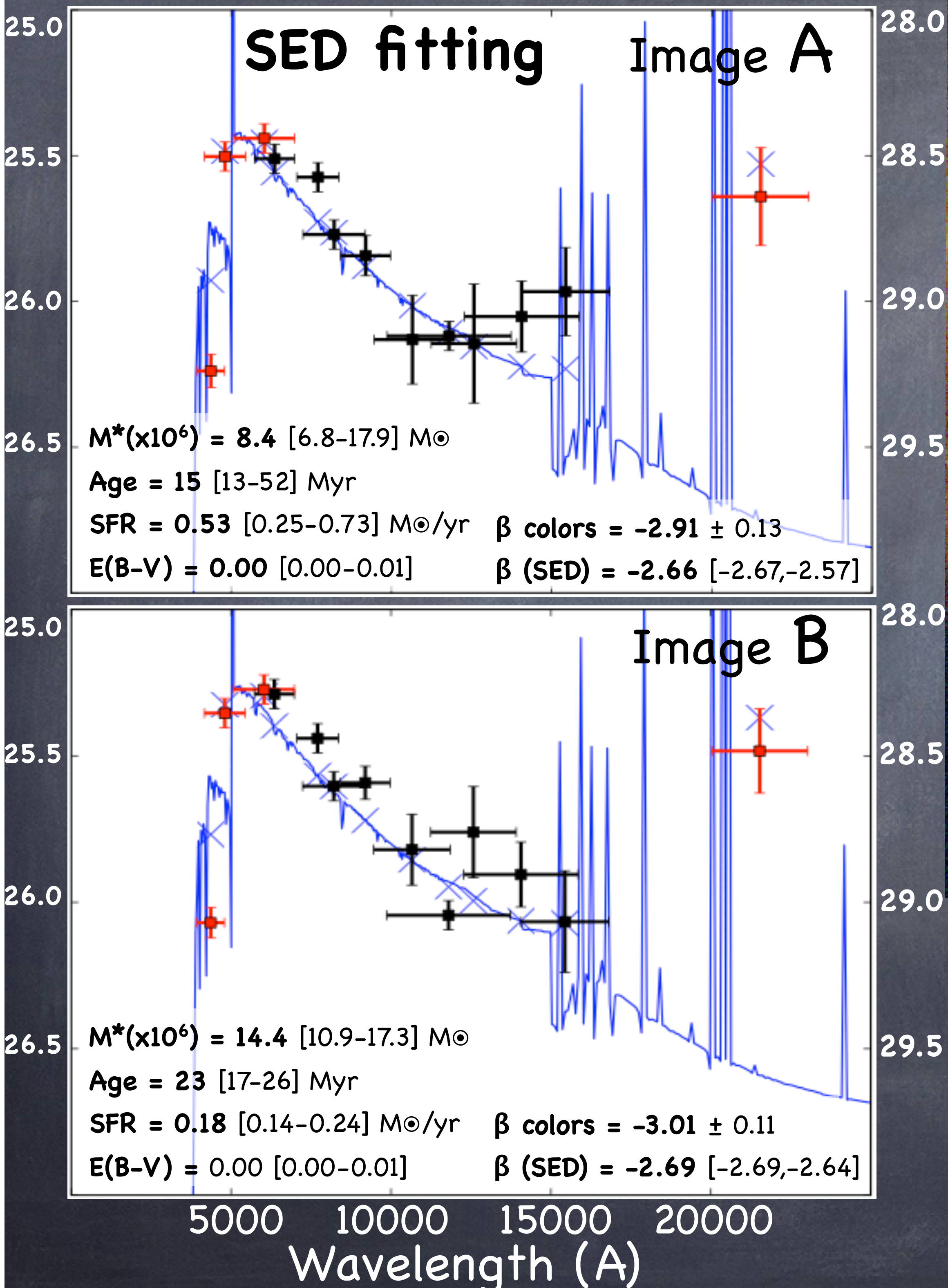
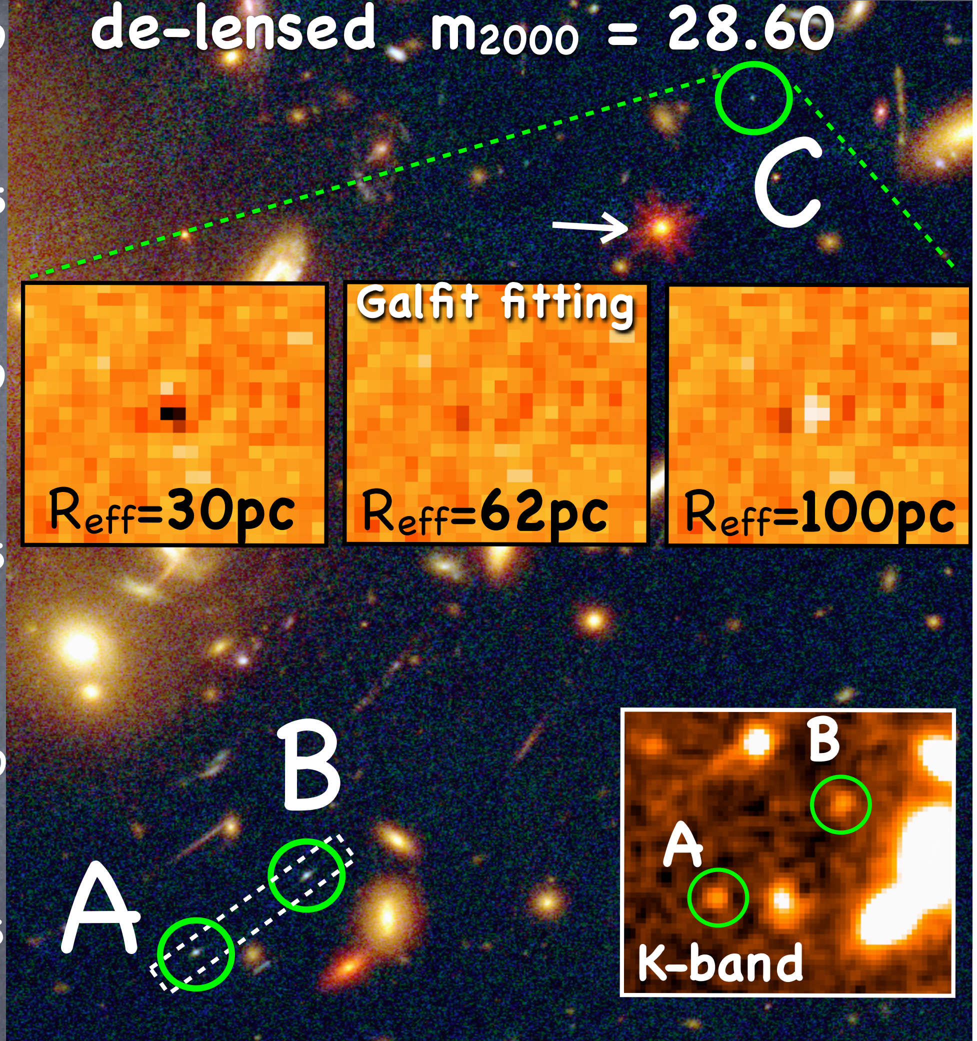


Lya
Log(NHI)<18.5
model
XSHO
Gronke+15
Log(NHI)=16.7
[OIII]5007 (XSHO); R=5300
Lya (XSHO); R=5000
Lya (MUSE); R=1900
Lya (VIMOS); R=200
- CIV (re)shifted +51 km/s
- ALL Narrow lines σv<20km/s
Fλ (Relative flux)
1548
1550
HeII 1640
OIII] 1666
CIV 1548
CIV 1548 XSHO
MUSE
-1000
-500
0
+500
+1000
Velocity (km s-1)
Vanzella - IAP - 2016



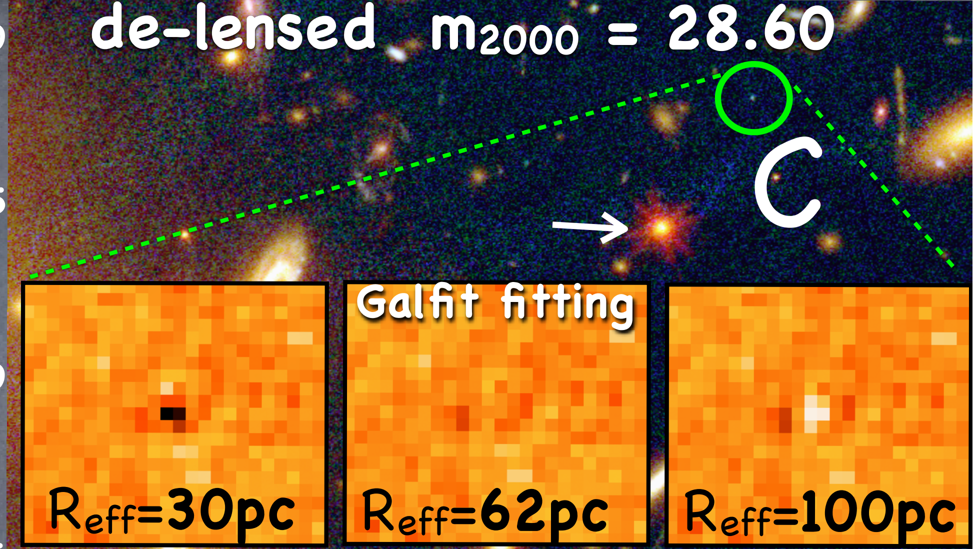


Extremely Blue, Small, Low mass,

optically thin galaxy

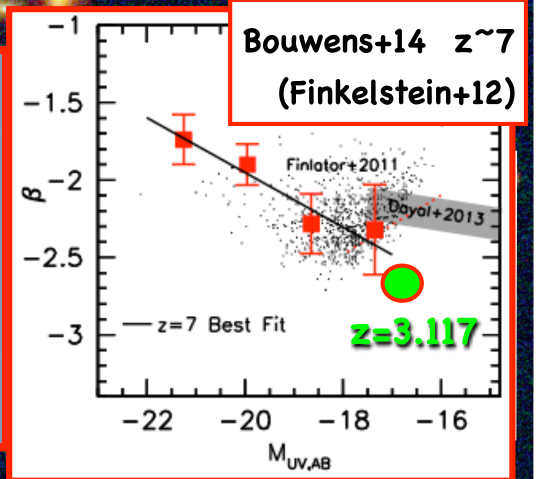
- Reff ~ 62pc (200 l.y.!), M<~1e7Msun
- O32>10, redshifted CIV1548-1550
- Narrow spectral features (σv<20km/s)
- Narrow Lya emission (dv 280km/s)
- 12+log(O/H) < 7.8

Vanzella - IAP - 2016



Are we approaching the conditions of an optically-thin system (log(NHI)<18.5) ?
Relevant for reionization at z~7-8

UV slope similar to z~7-8 galaxies at the same luminosity:



Extremely Blue, Small, Low mass, optically thin galaxy

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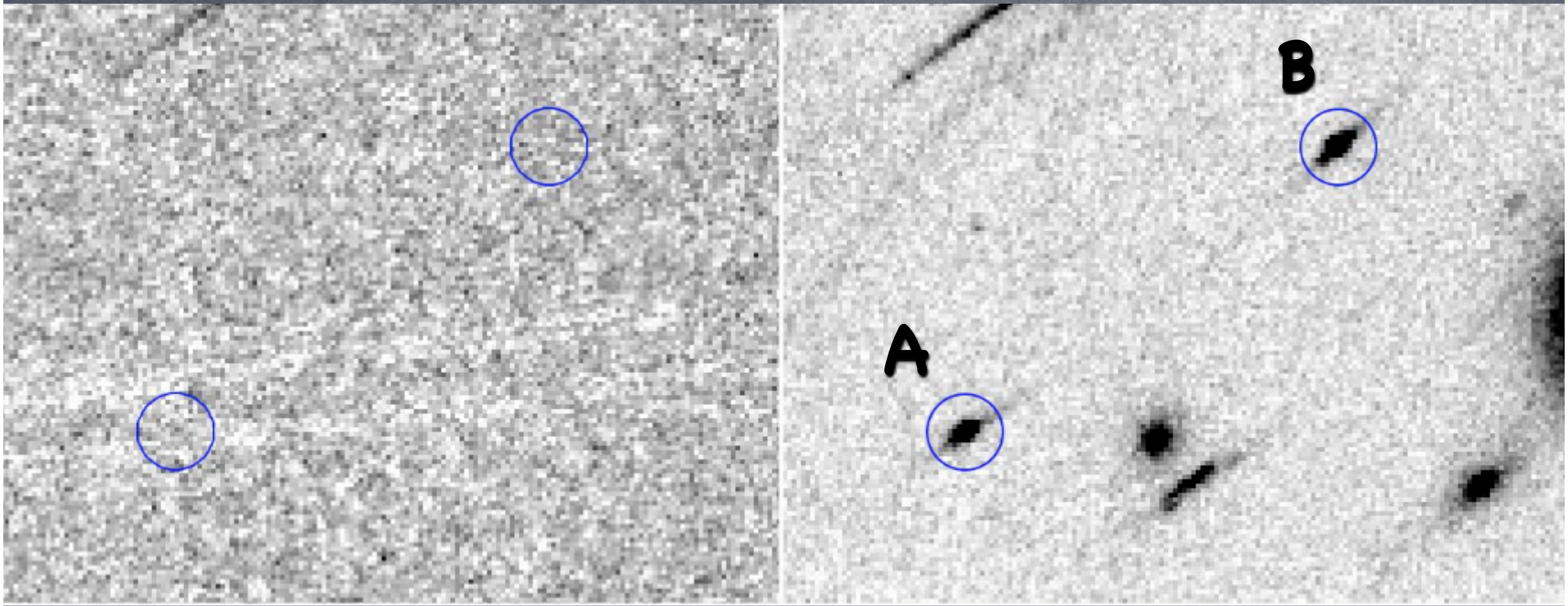
- O32>10, redshifted CIV1548-1550
- Narrow spectral features (σv<20km/s)
- Narrow Lya emission (dv 280km/s)
- 12+log(O/H) < 7.8

HST Lyman continuum imaging, preliminary (PI Siana)

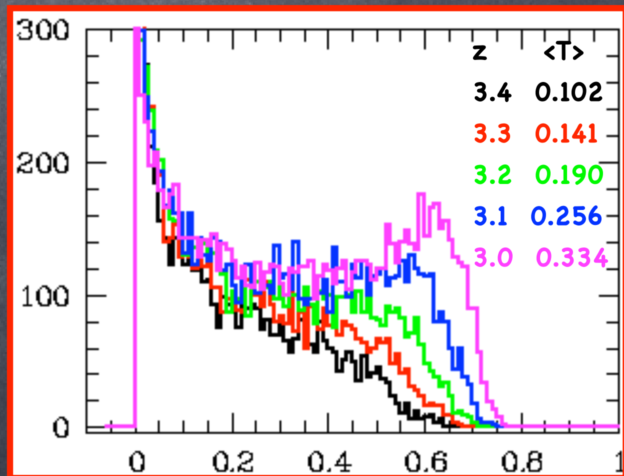


A+B
(3-sigma)

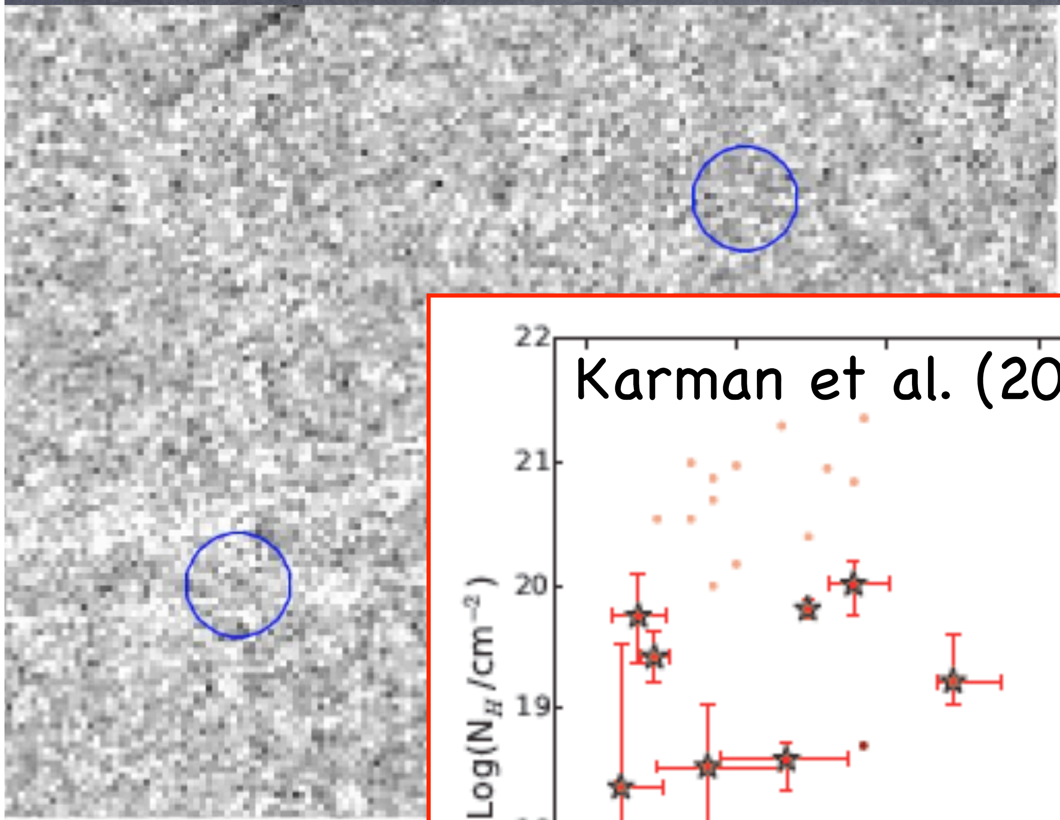
5	28.85
4	29.10
3	29.40

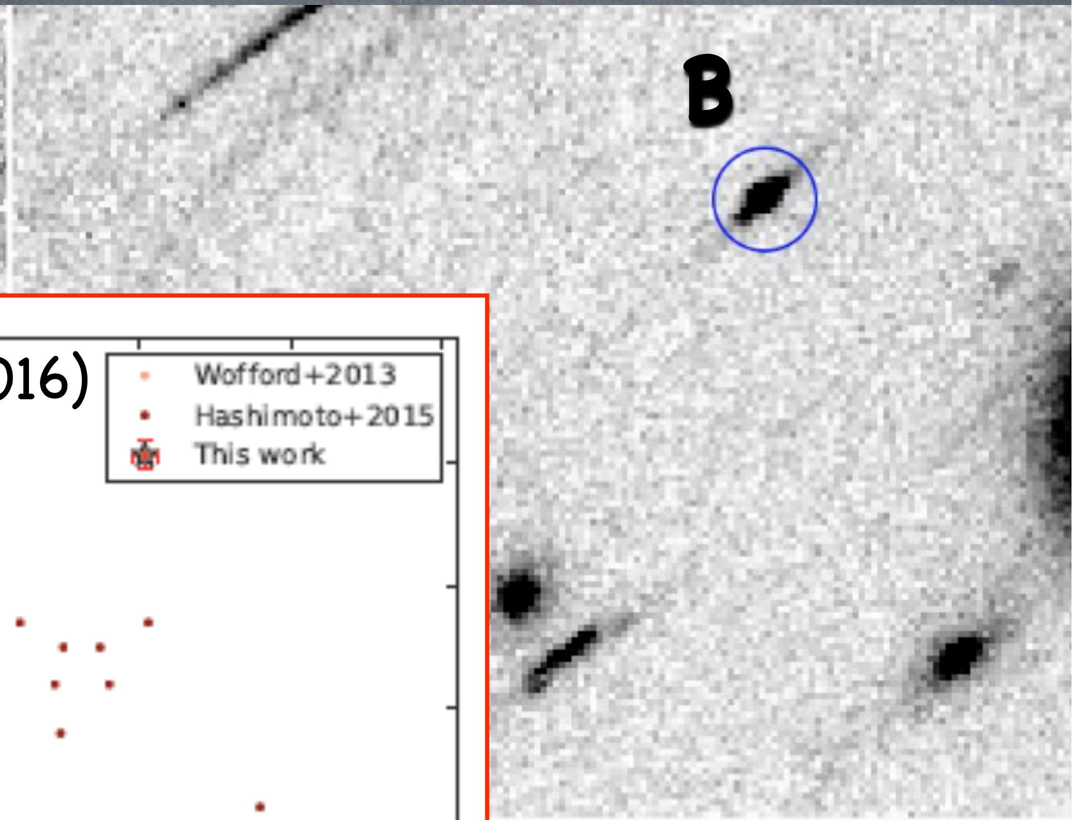
fesc,rel<0.3-0.5
(need spectroscopy
rememeber Alice's talk)

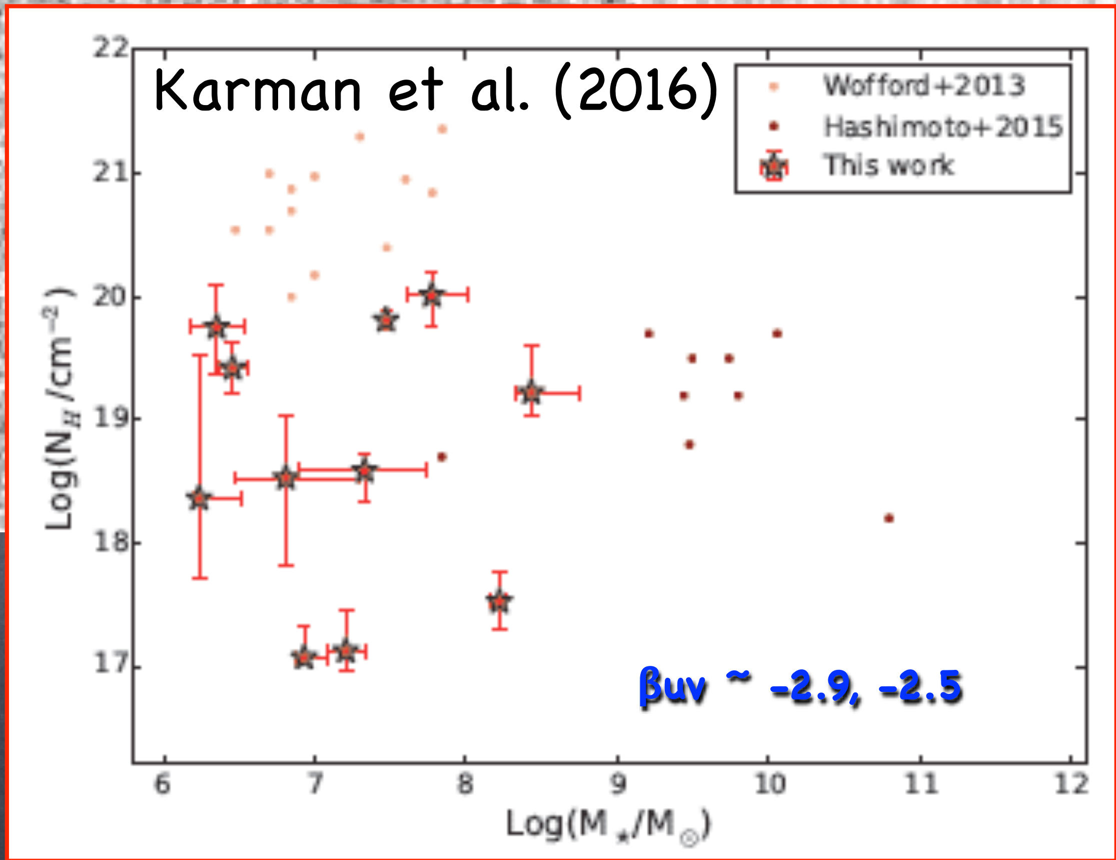
A statistical significant sample is needed



HST Lyman continuum imaging, preliminary (PI Siana)

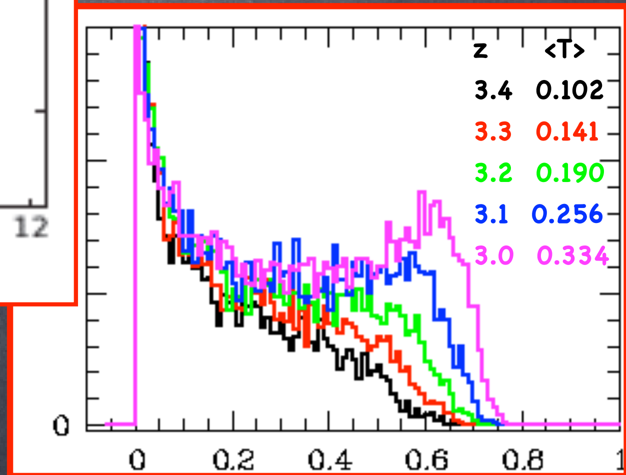






A+B
(3-sigma)

5 28.85
4 29.10
3 29.40

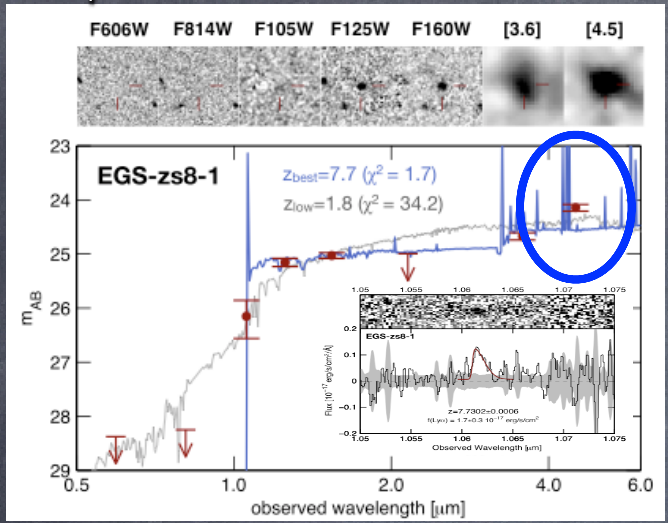


A statistical significant sample is needed

Studies at z<4 are crucial <-> JWST at z>6

ISM conditions & ionization

zspec=**7.73** (Oesch+15)



EW([OIII]+Hb)

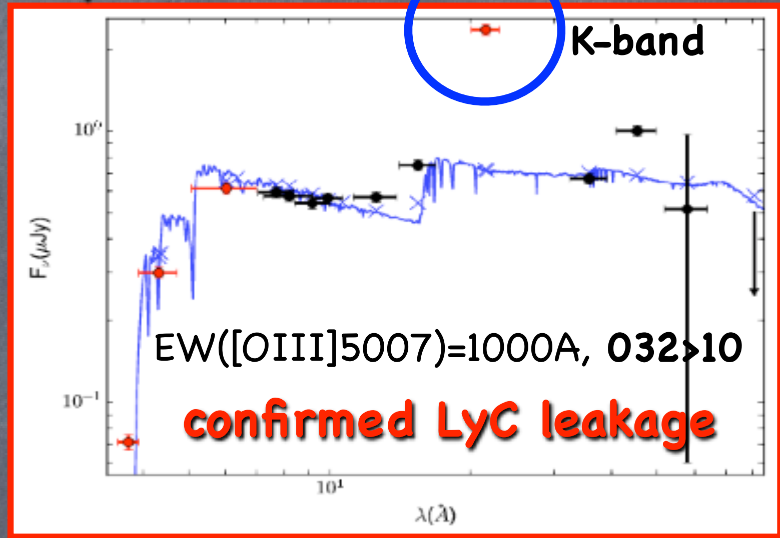
6200A observed

720 rest-frame

Density-bounded condition??

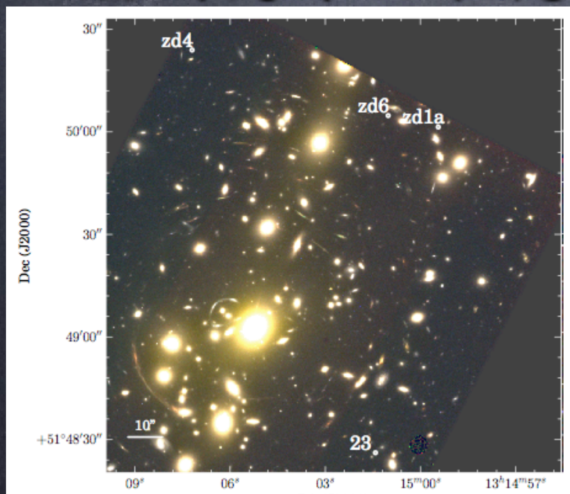
Transparent ISM ?

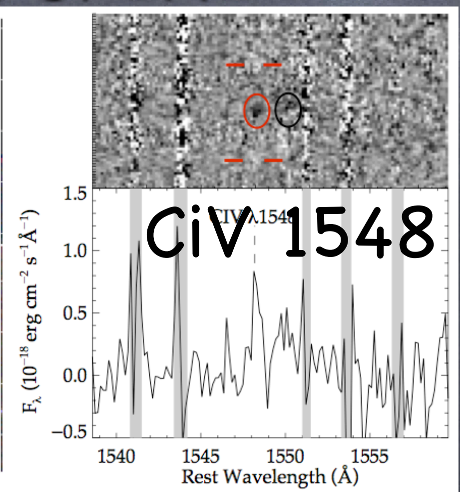
zspec=**3.212** Vanzella+16b



Nature of ionizing radiation - very narrow features - high ion. lines

z=7.04 - MOSFIRE

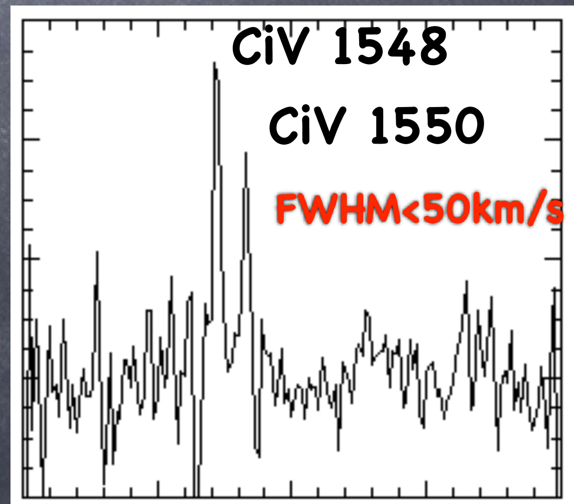




Stark et al. (2015)

Stellar/ nuclear origin ?

z=3.116 - MUSE/XShoot



Vanzella et al. (2016a)

Summary

- Dropout selection method **does not preclude** the inclusion of LyC galaxies (EV+15)

- LyC: On average, bright UV galaxies show low fesc < 5-10%
  - deep LBT+VLT U-band stacking + spectroscopy (Grazian+16;Guaita+16;EV10,12); see also Mostardi+15)

- LyC galaxies, bright-domain: a few discovered @ z~3 **(EV+16;deBarros+16;Shapley+16)**
  -> Ion2, L*, z=3.2, HST imaging S/N(LyC)=10, fesc>40%;
  Properties in line with expectation: large O32 (a posteriori), compact (340pc) faint UV abs lines, Lya blue@systemic; possible intense HeI10380 + Pγ ?
  -> Another L* LyC source (Ion1, z=3.8), no Lya, possible spatially resolved LyC
  ⇒ Rare, but very informative to find LyC emitters at z>5-6 with JWST, indirect signatures

- Attack the Faint luminosity domain (down to Muv ~-16):
  MUSE in fields and **lensed** fields (e.g., Karman+16); see also Alavi's talk
  An ELT-like spectrum: Detailed spectroscopy (R=5000-7000, m=28.60); extremely blue slope -2.7 … -3; low-mass <~1e7Msun; Reff=60pc;
  Are we approaching "ionizer-like" objects ?

  Faint galaxies (mag>27-30, de-lensed) show blue slopes, relatively low NHI (MUSE, Karman et al. 2016); several UV lines -> **need proper modeling !!**