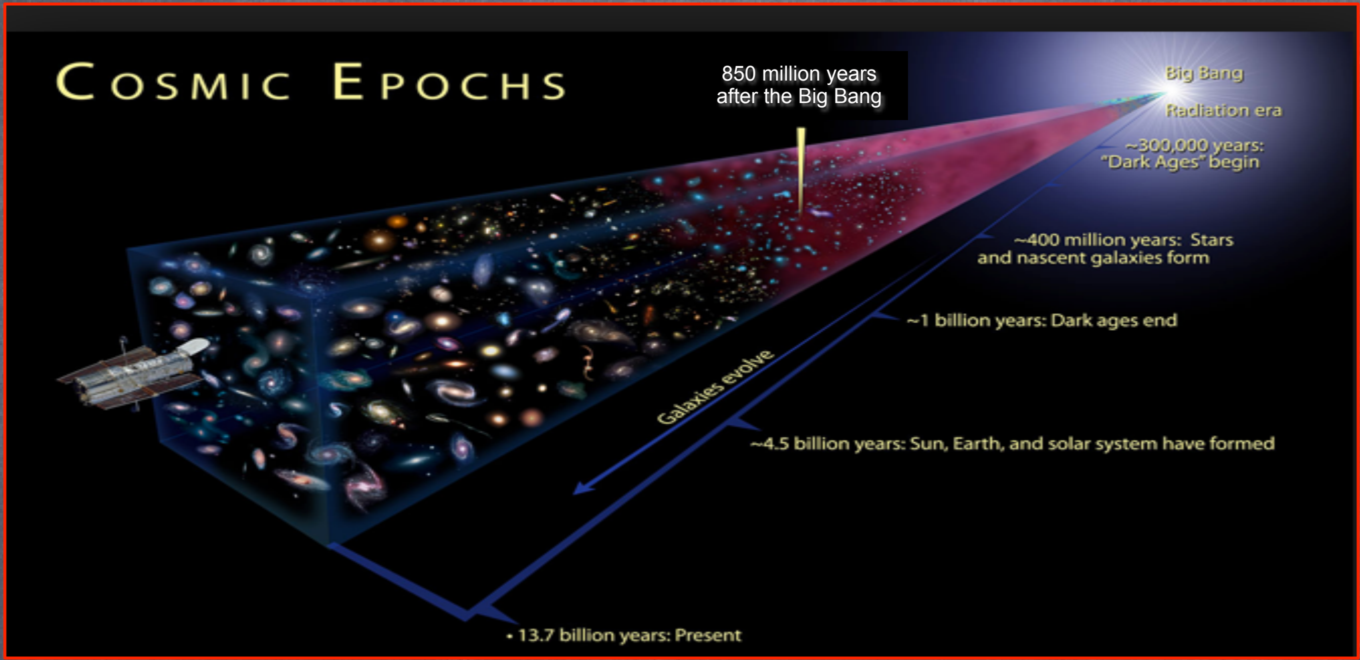
Probing the earliest galaxies and reionization

Eros Vanzella

INAF - Astronomical Observatory of Bologna



Lecture #3

Lectures

Lecture 1
Monday 2hr
Ionized IGM
Deep surveys
UV LFs

Cosmic reionization: how was the IGM reionized?
Probes of cosmic reionization (and ionization)
Selection techniques of high-redshift galaxies
Redshift evolution of the UV luminosity function

Lecture 2
Tuesday 1hr
Escaping ion. radiation

Is all cosmic reionization made by galaxies ?
Issues on the escape fraction

Lecture 3
Thursday 1hr
Spectr. observations

Exploring the farthest and faintest galaxies with deep spectroscopy: the first two Gyrs after the Big-Bang

Lecture 4
Friday 1hr
Current limitations: the future

Next generation optical/near-IR facilities: JWST and ELT

Cosmic hydrogen reionization: who, when, how ...

Design Panchromatic Surveys to search for faint (L<<L*) and distant sources (z<20)

Strong observational effort in the last 20 years

count galaxies/ AGNs; compute UV LFs

Search for the farthest sources ?
... ongoing ...

Compute ionizing UV luminosity density

Compare with UVB 0<z<6
post-reionization

Approaching EoR z>6-7
reionization

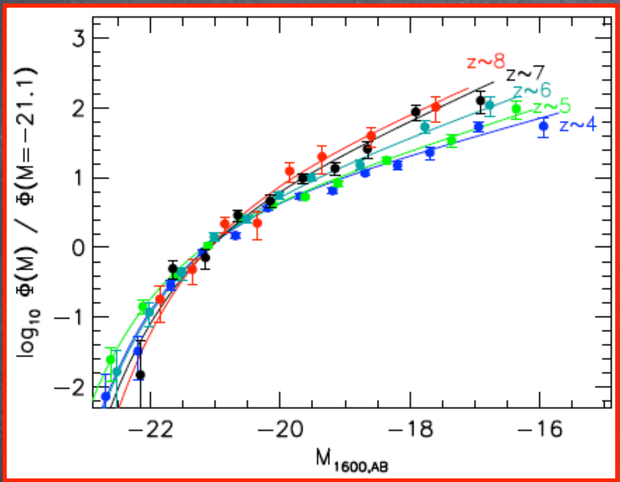
Problem Solved
? No

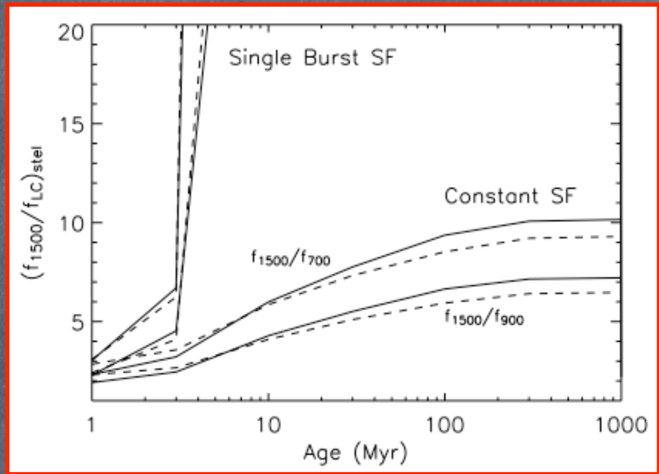
Investigate ionizing emission: physics, feedback
... ongoing ... ?

Connection with IGM physics ?
... ongoing ...

Ionizing sources

$$\phi(M_{1400}) \xrightarrow[\text{assume } M_{\rm lim}]{\text{integrate;}} \rho_{L_{1400}} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma 1400}\rangle]{} \dot{N}^{int}_{ion} \xrightarrow[f_{esc,rel}]{} \dot{N}_{ion}$$





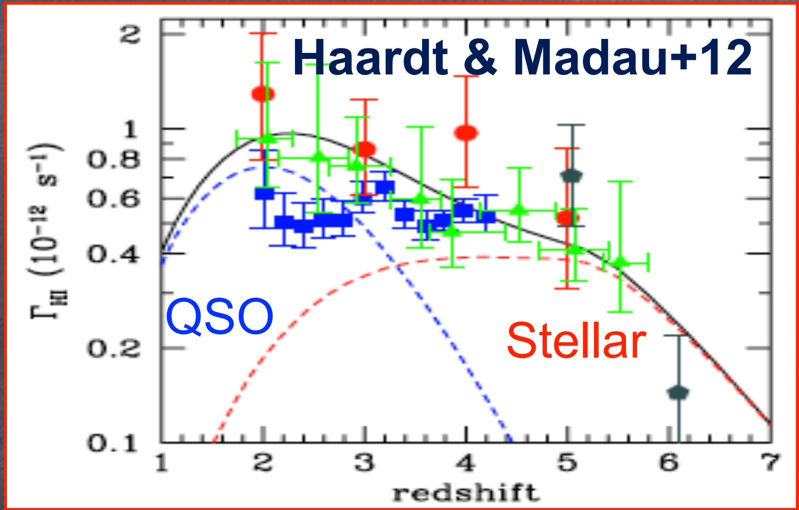
?

$\rho_{1500} = \int_{L_{min}}^{\infty} L\ \phi(L)dL$

- LyC from young stars
- intrinsic ratio depends on SFH

Focusing on star-formimg galaxies

Galaxies leading candidates @ z>3



But see Madau & Haardt 2015 - AGN

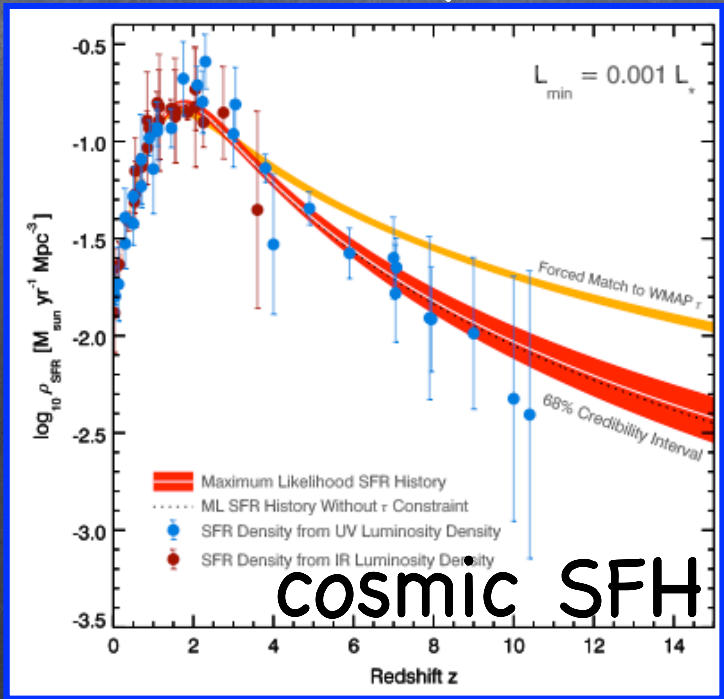
Pawlik et al. (2009)

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

$$\dot{\rho}_c(z) = \frac{0.027\, M_\odot}{\mathrm{Mpc}^3\,\mathrm{yr}} \frac{\mathcal{C}/f_{esc}}{30} \left[\frac{1+z}{7}\right]^3 \left[\frac{\Omega_b}{0.0465}\right]^2$$

Minimum SFRD needed to keep the Universe ionized

Cosmic SFH - UV photons



UV LFs,

lum. density (1500A)

fesc

critical parameter in any model of EoR

Madau & Dickinson+14

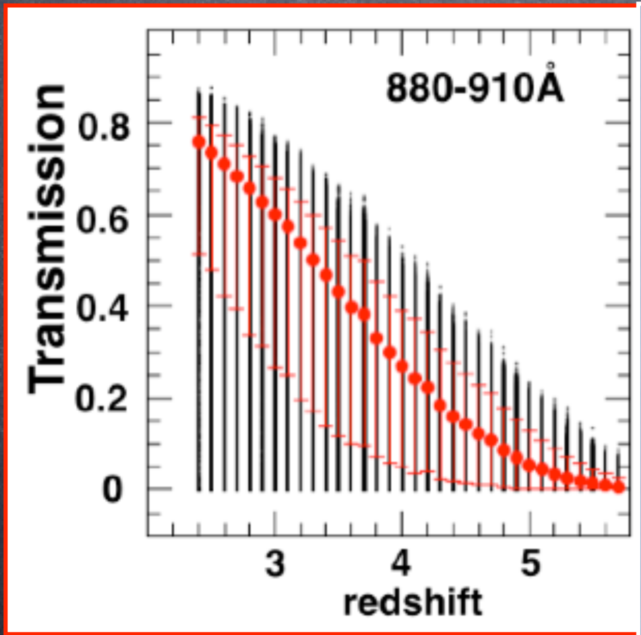
Robertson+15

How many ionizing photons escape from galaxies ?

fesc

First: we cannot directly observe Lyman continuum radiation (<912A) at z>4.5;

by definition reionization happens if LyC photons are "used": the mean free path is very short during EoR

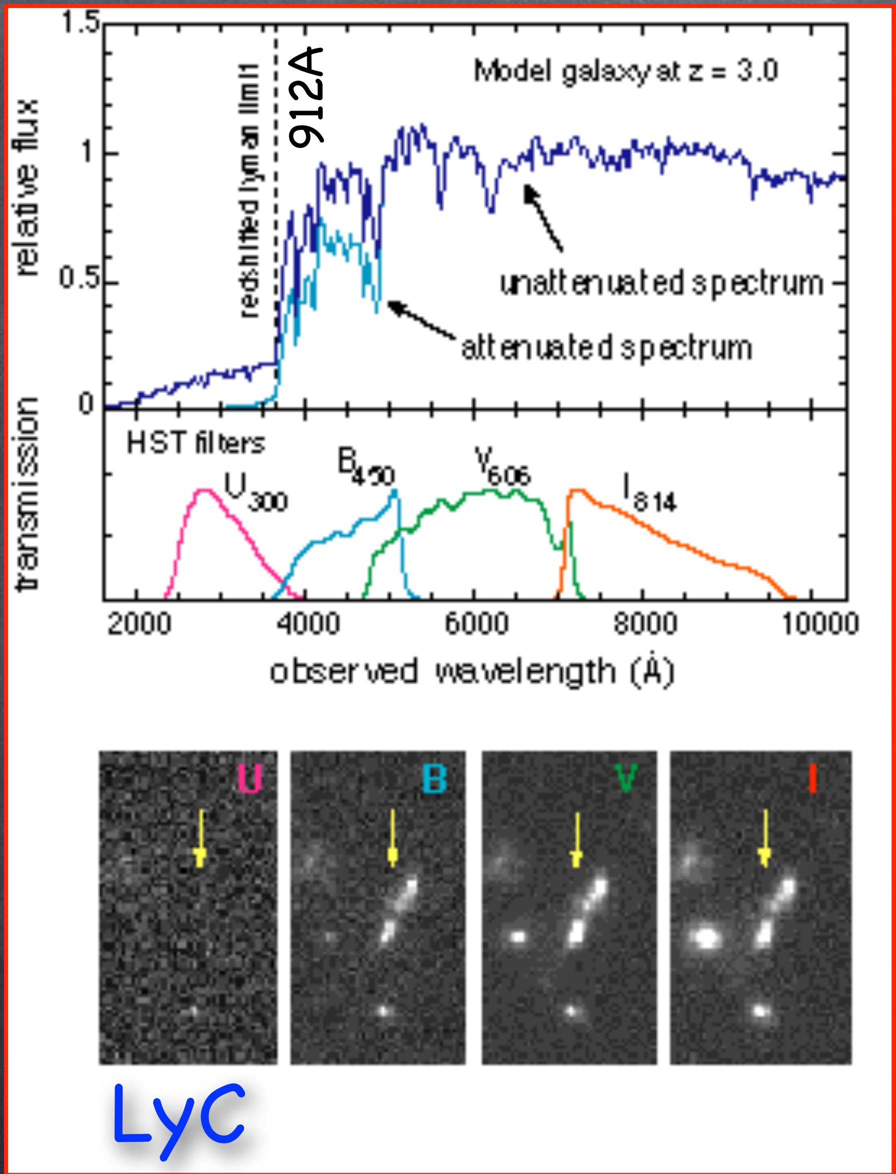


A way is to look at properties of z<4.5 LyC emitters, learn, and investigate if at z>6 such properties are more common, eventually identifying reionizing sources

$N_{HI} > 1.7 \times 10^{17} cm^{-2}$ $\tau_{(LyC)} > 1$

Trying to observe directly LyC at low redshift (z<4.5)

However, galaxies are selected with dropout techniques ...

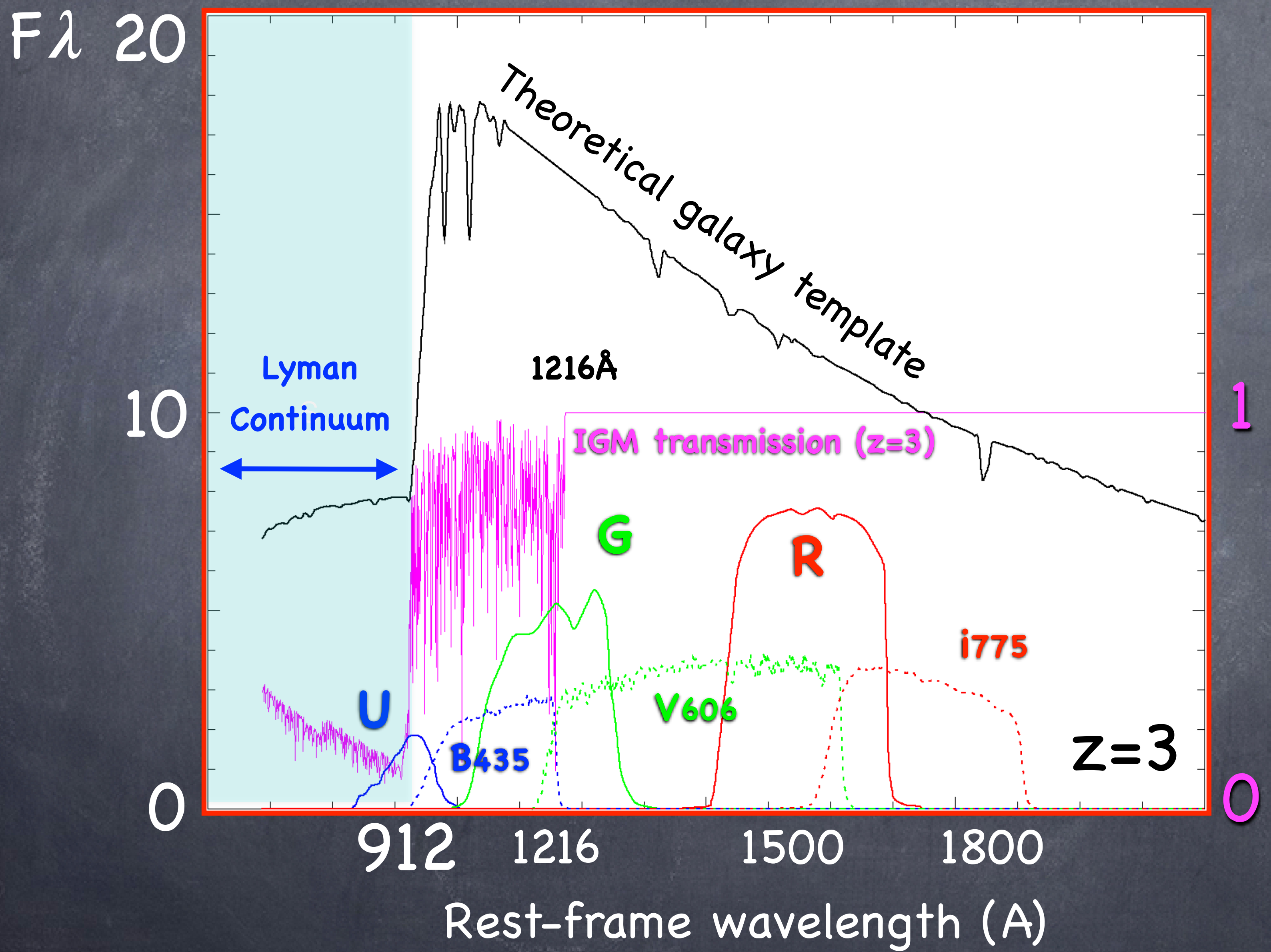


Counter-intuitive ?

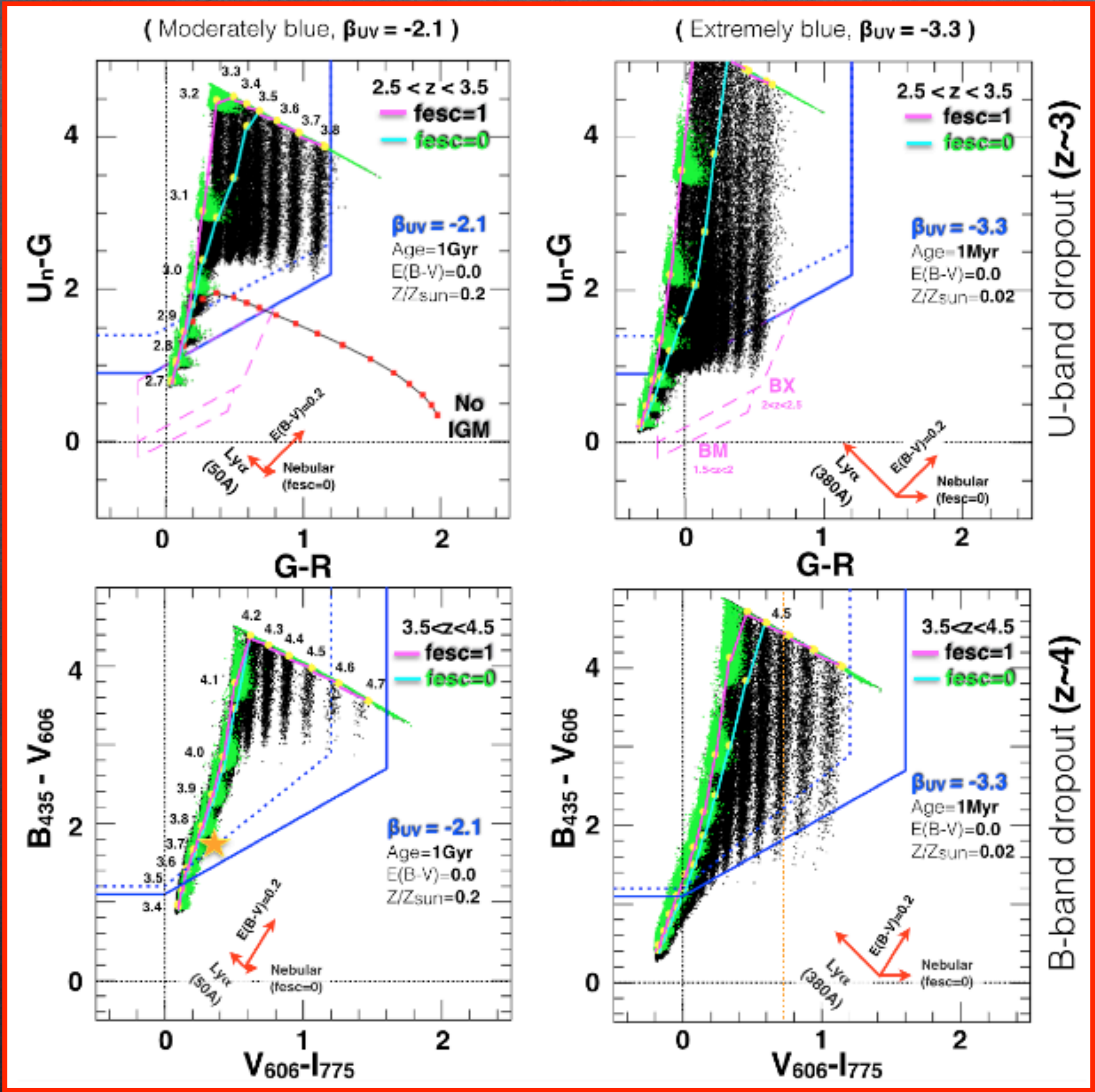
We select high-z galaxies with the dropout technique, is the required drop biasing our search for Lyman continuum emission ? I.e. are we missing them ?

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

What is the color of a stellar "ionizer" ?
Do we miss it ?



What is the color of a stellar ionizer ?
Do we miss it ?



In case of stellar emission there is not a significant effect in the color selection: **we don't miss them**. Why ?

Two reasons:
1) IGM mean free path
2) Intrinsic spectrum
both introduce a drop even if fesc=1

Vanzella+15

Note: for AGNs the effect can be not negligible

Before measuring fesc...

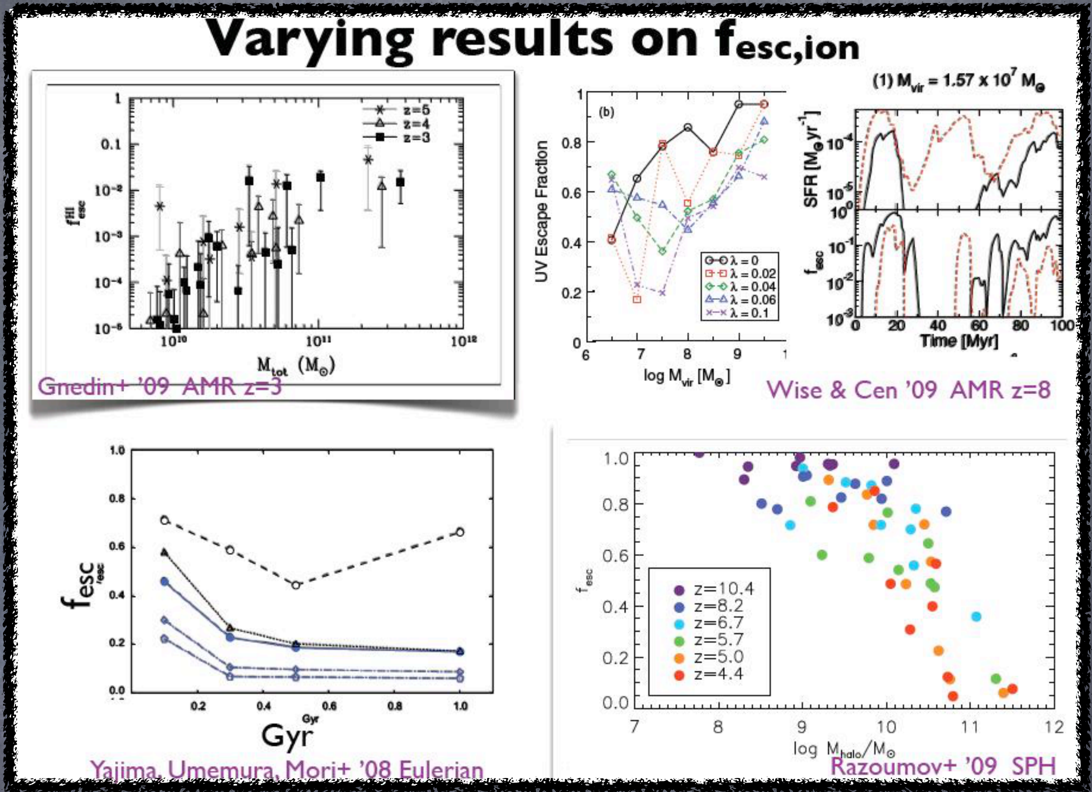
Theoretical modeling: SFH, RT, feedback, kinematics, geomerty of the gas/dust - complex problem

- 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)

- fesc ↑ if (↓L OR ↓Mass)
  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 / luminoisties
2) may increases with redshift

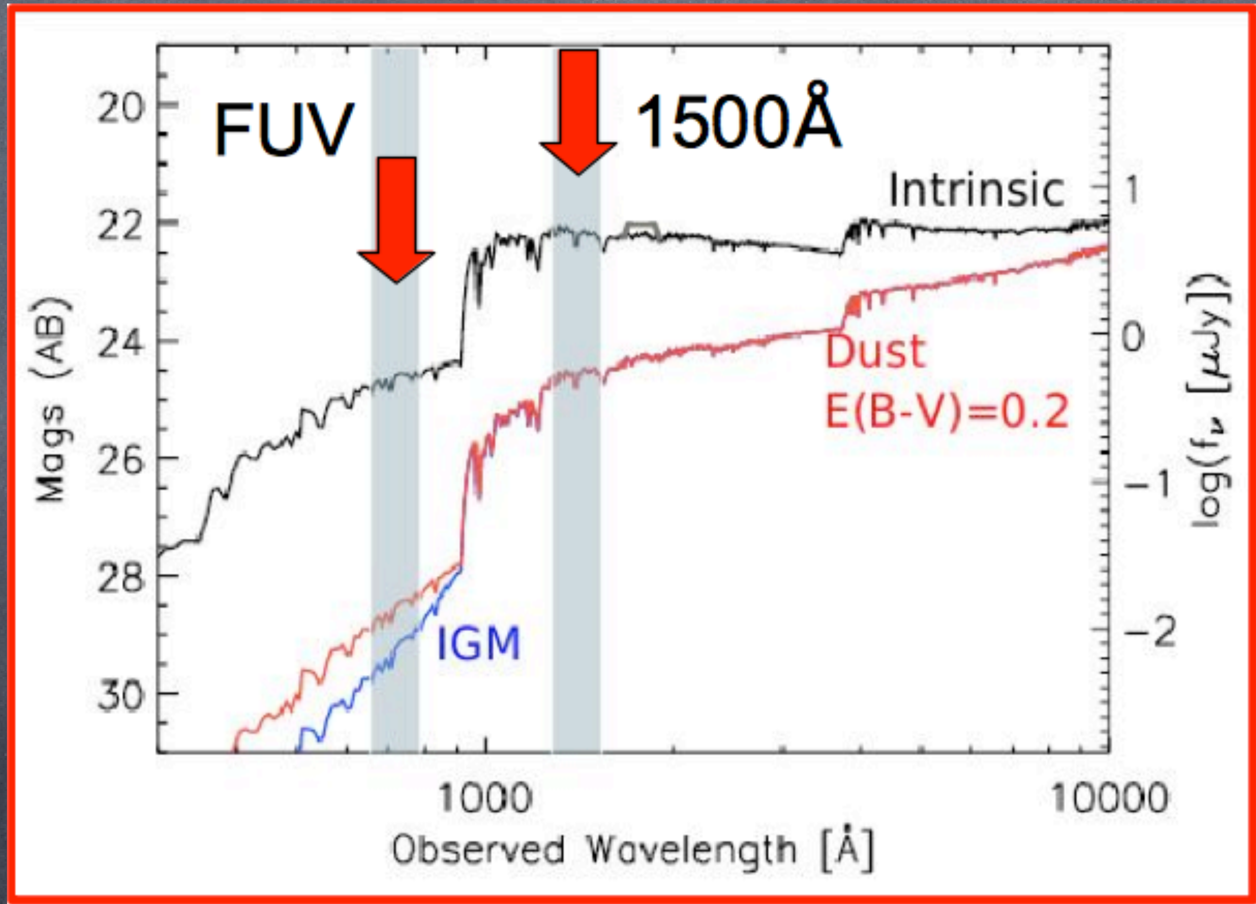
This typically requires very high resolution simulations, capable of resolving details in the interstellar medium (ISM).

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)



The escape fraction of ionizing radiation (LyC)

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

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

fesc,rel

fesc

fesc: is smaller than 1 by definition

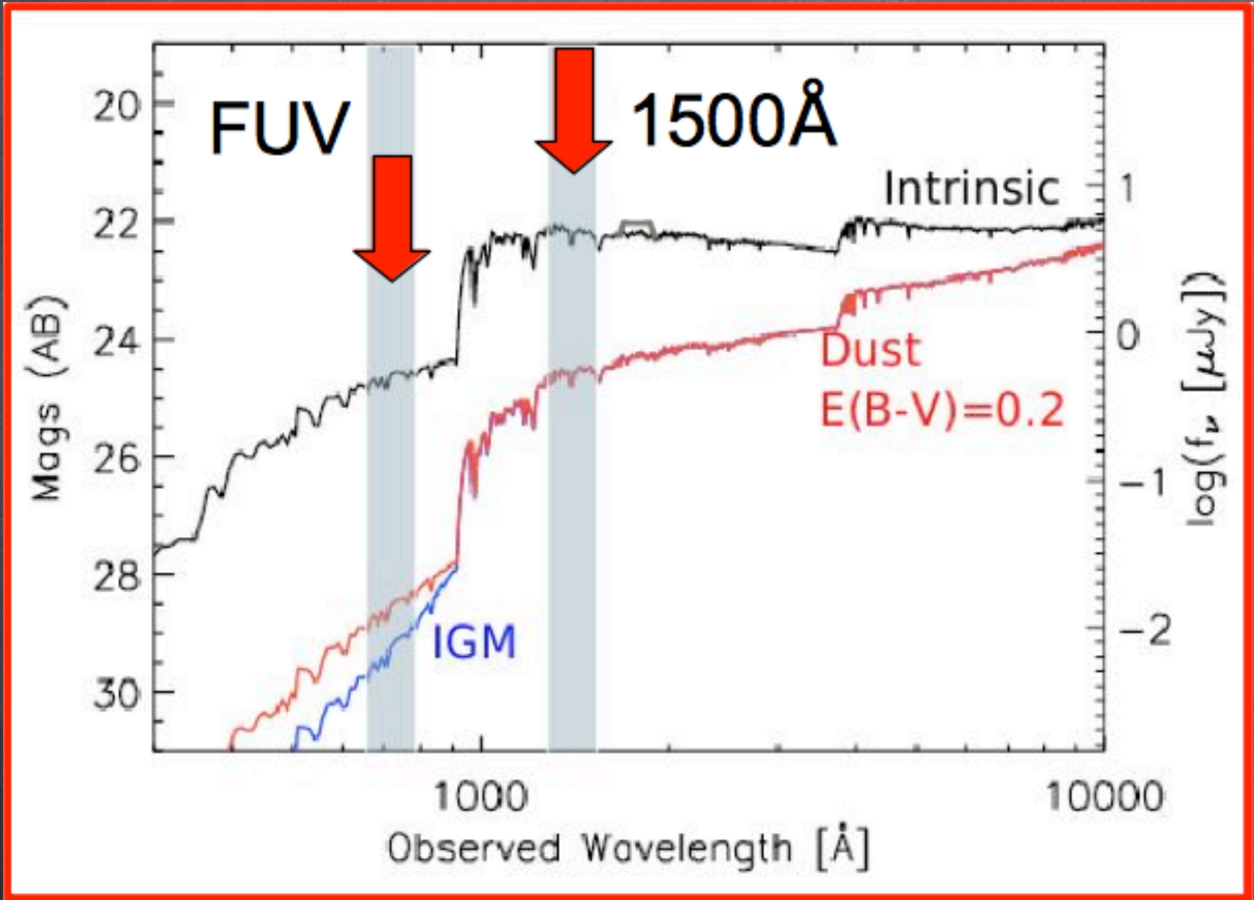
$T_{LyC}=e^{-\tau(LyC)}$ $\tau(LyC)=N_{HI}\sigma_{LL}$ $\sigma_{LL}=6.28\times10^{-18}$ cm^{-2}

$\tau(LyC)>1$ $N_{HI}>1.7\times10^{17} cm^{-2}$

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 ($m_{1500} \approx 24.5$)

=> $m_{900} \approx 30$ (AB) !

$\Delta m=5$ (e.g., i-U>5).

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

Observing Lyman continuum leakage / fesc

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

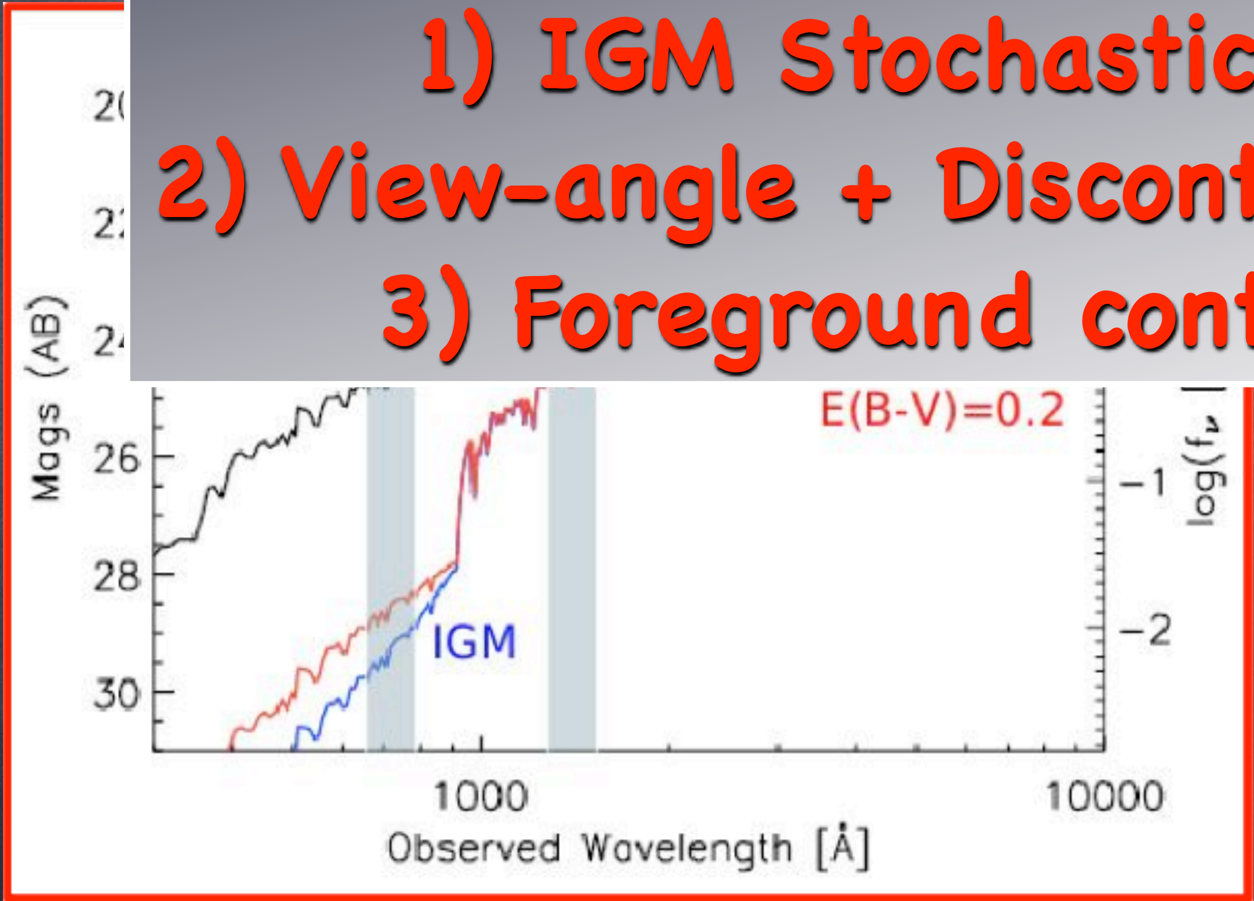
2) ne

Caveats:

1) IGM Stochasticity (mfp)

2) View-angle + Discontinuous in time

3) Foreground contamination

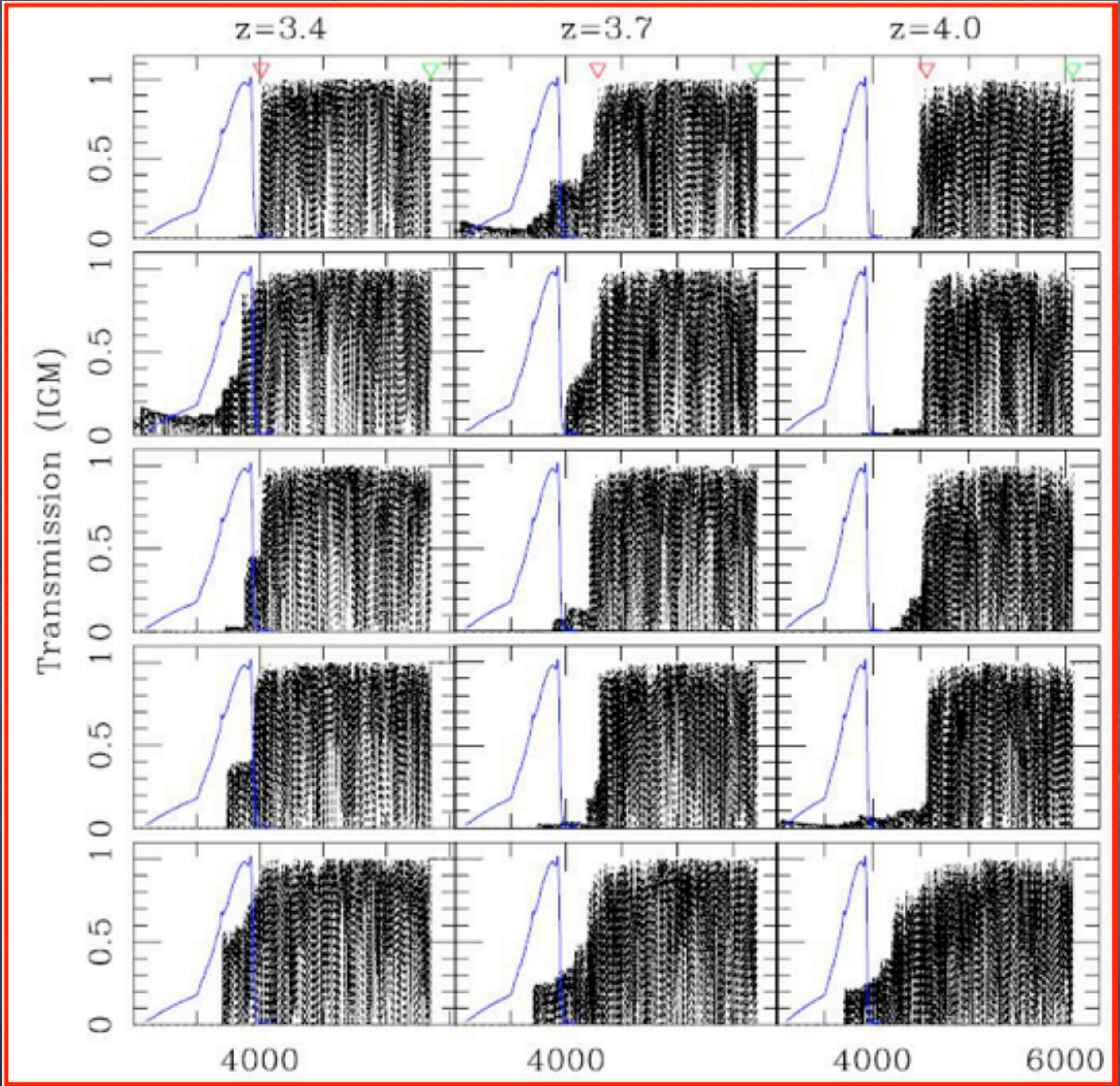


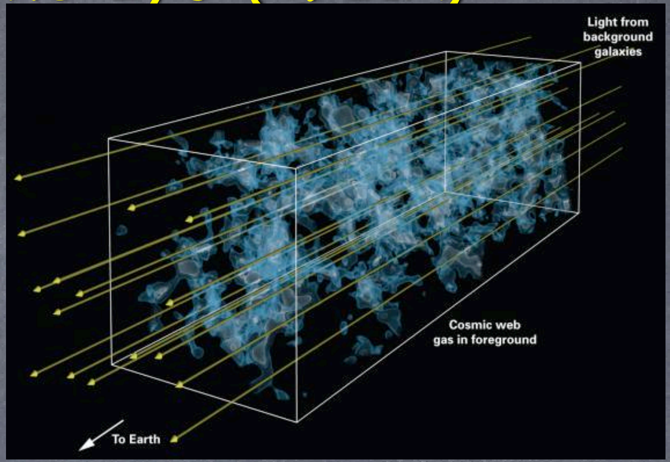
=> m_{900} ≈30 (AB) !

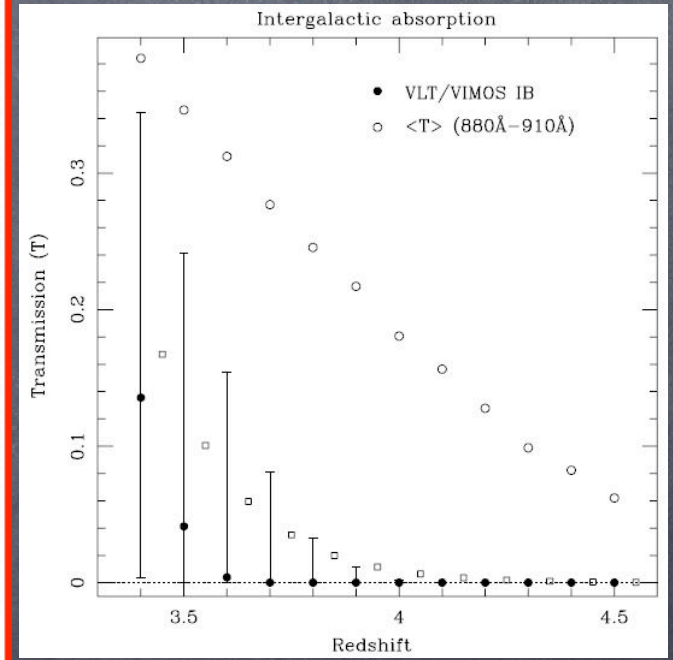
Δm=5 (e.g., i-U>5).

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

Stochasticity of the **IGM absorption** at the LyC (<921A)







Well measured and simulated

Inoue et al 2008,2014

Paresce+08

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

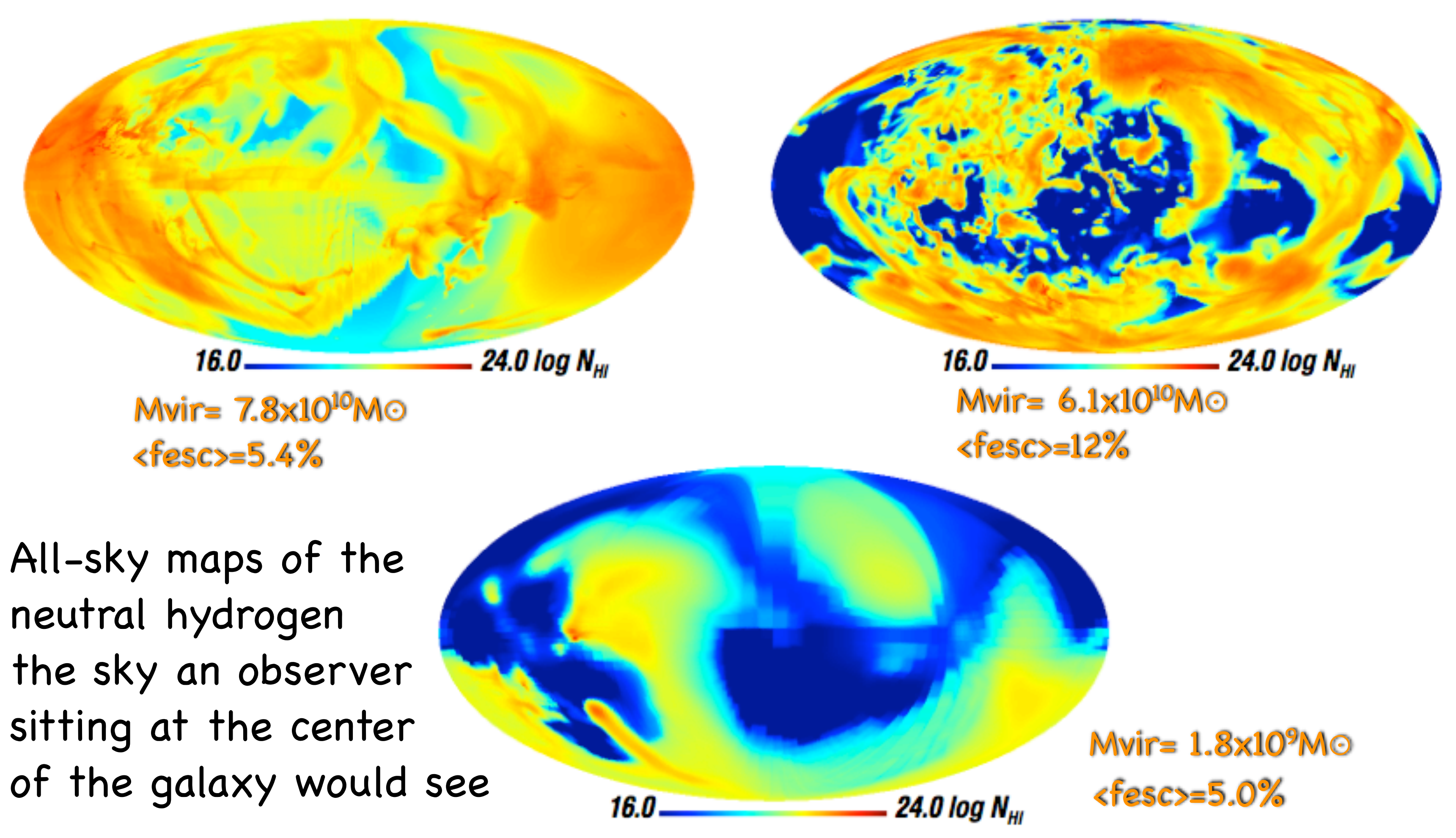
n.abs per unit z and N_{HI}

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

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

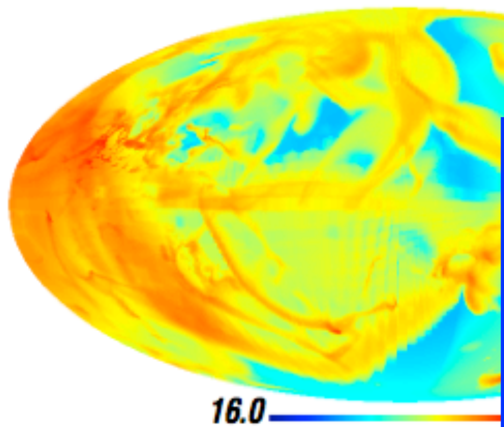
$f_{esc} \sim T_{LyC} = e^{-\tau(LyC)}$ $\tau(LyC) = N_{HI}\sigma_{LL}$ $\sigma_{LL} = 6.28 \times 10^{-18}$ cm^{-2}

=> this implies N_{HI} > 5×10^{17} cm^{-2}, fesc<5%

... result: stacking of ≃ 100 galaxies is needed to obtain a good estimate of fesc within 20% uncertainty

View angle effects ...

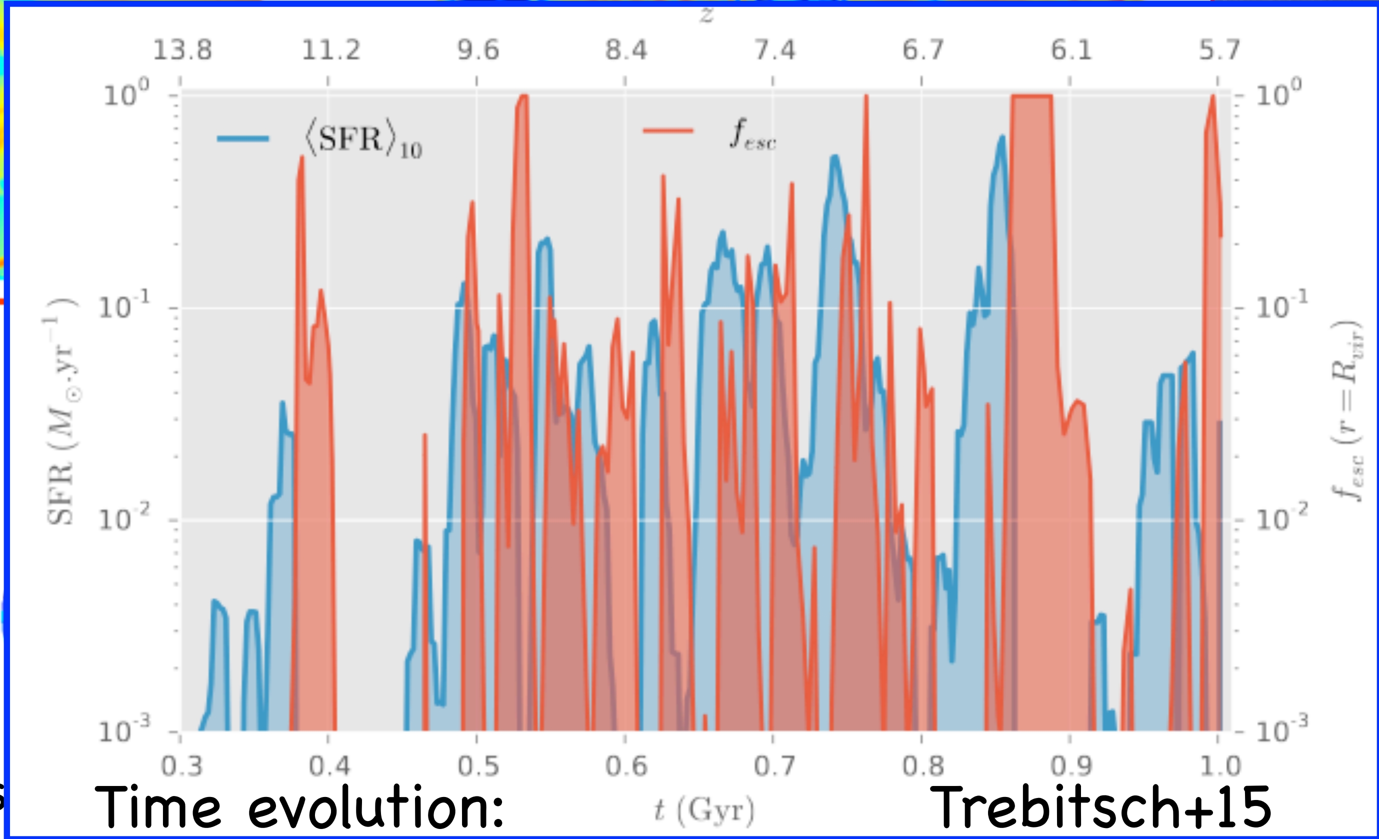
Cosmological radiation hydrodynamic simulation (Cen & Kimm 2015)



Mvir= $7.8\times10^{10}M_\odot$

<fesc>=5.4%

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



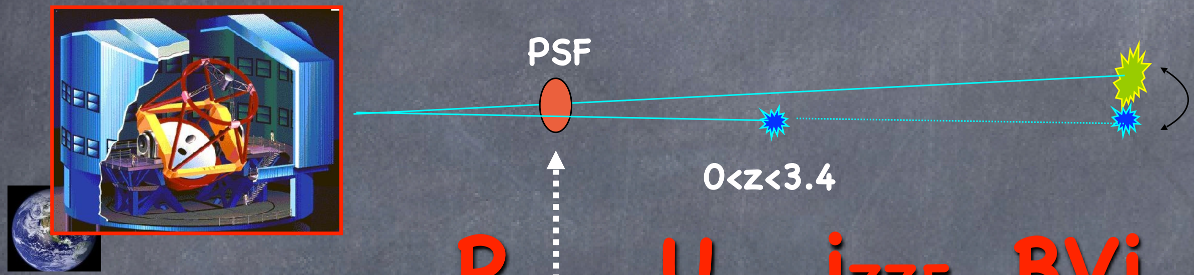
$f_{esc} \sim T_{LyC} = e^{-\tau(LyC)}$ $\tau(LyC) = N_{HI}\sigma_{LL}$ $\sigma_{LL} = 6.28\times10^{-18}$ cm^{-2}

=> this implies N_{HI} > 5×10^{17} cm^{-2}, fesc<5%

... result: stacking of ≃ 100 galaxies is needed to obtain a good estimate of fesc within 20% uncertainty

Foreground contamination (I)

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



z=3.41
$\Delta\theta$=0.3"

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

Ground based:
fesc ≈ 30%

From HST:
fesc > 433%

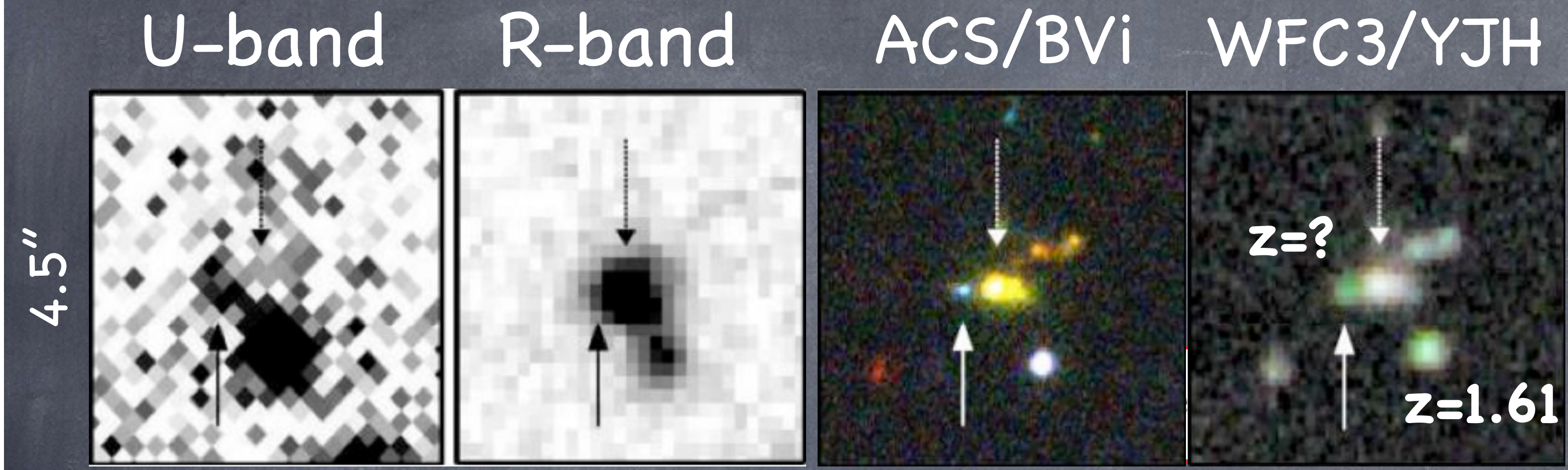
Recent NIR spectroscopic observations confirm our warnings raised in 2010 (Siana+15)

Statistical study on this effect (EV+10; Nestor+11)

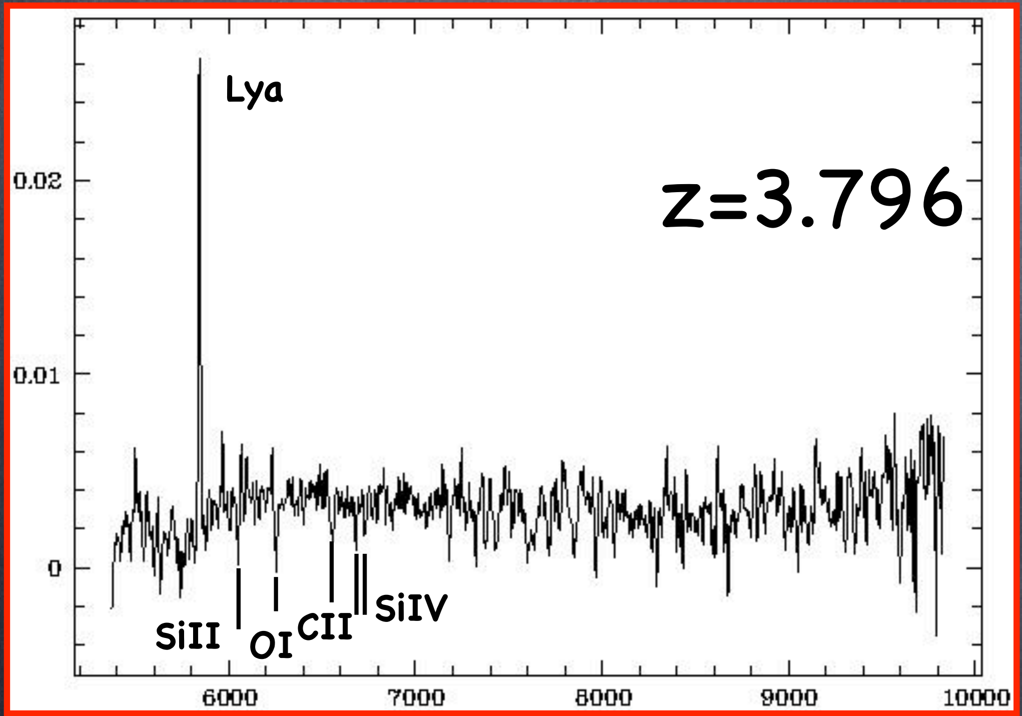
- critical for ground-based observations (spatial resolution)
- increases with redshift
- increases with increasing depth

Critical analysis based on GOODS+CANDELS , EV+12 (tricks to limit the contamination)

Foreground contamination (II): example (EV+12)

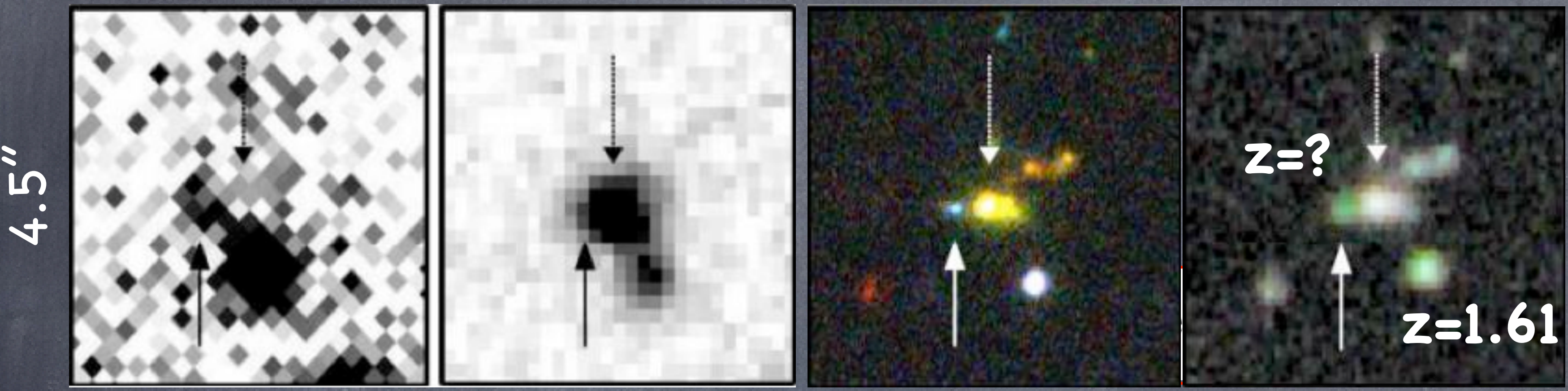


Y → B
J → G
H → R

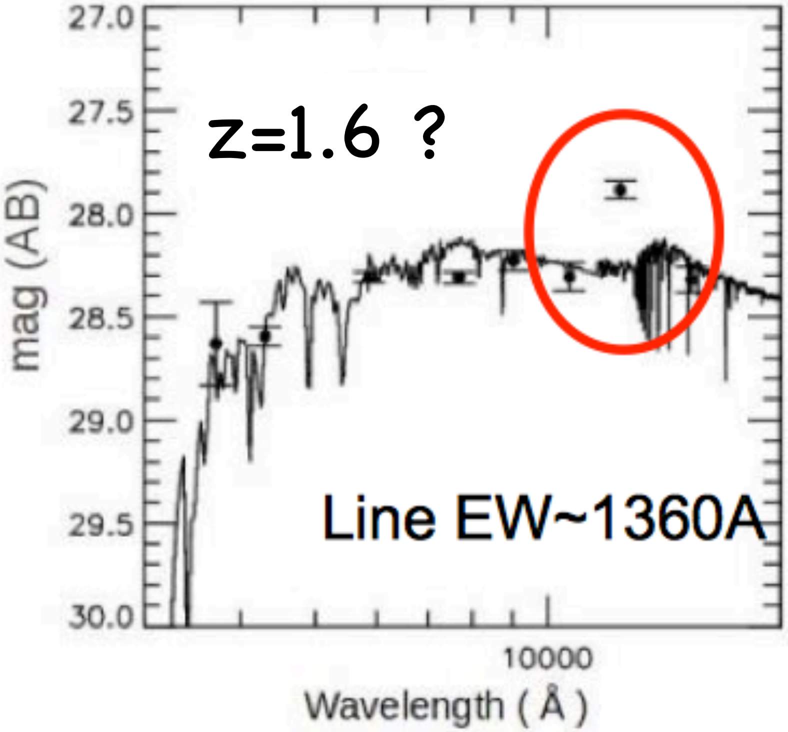


Foreground contamination (II): example (EV+12)

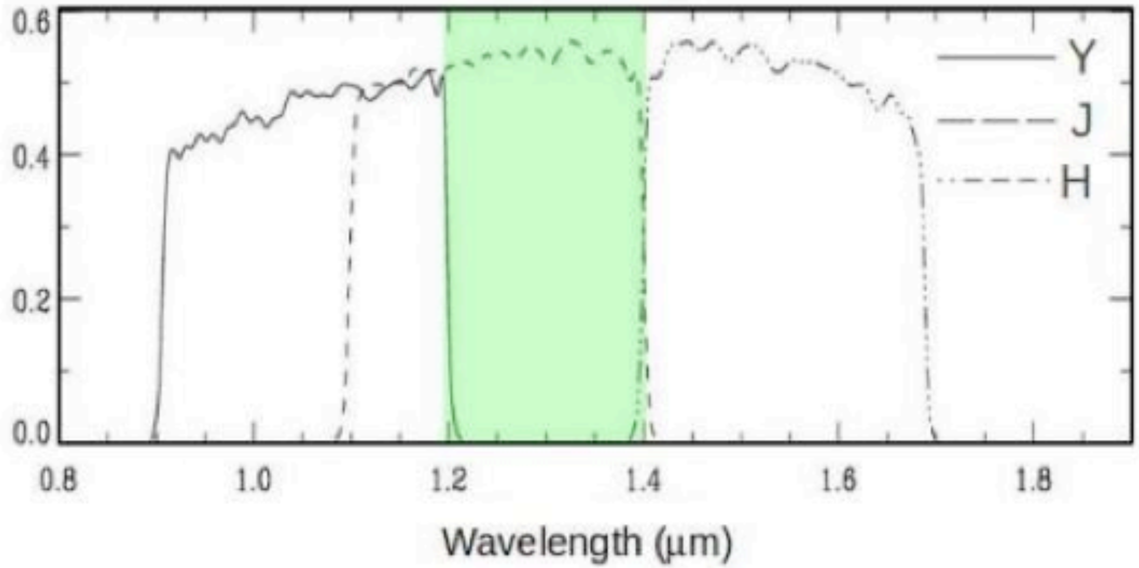
U-band R-band ACS/BVi WFC3/YJH



Y → B
J → G
H → R

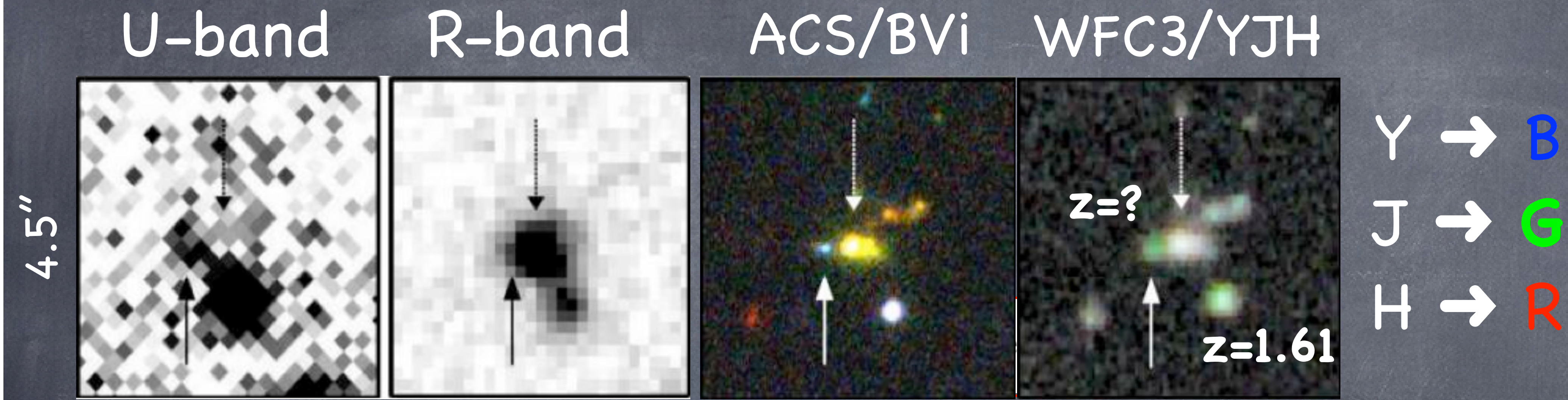


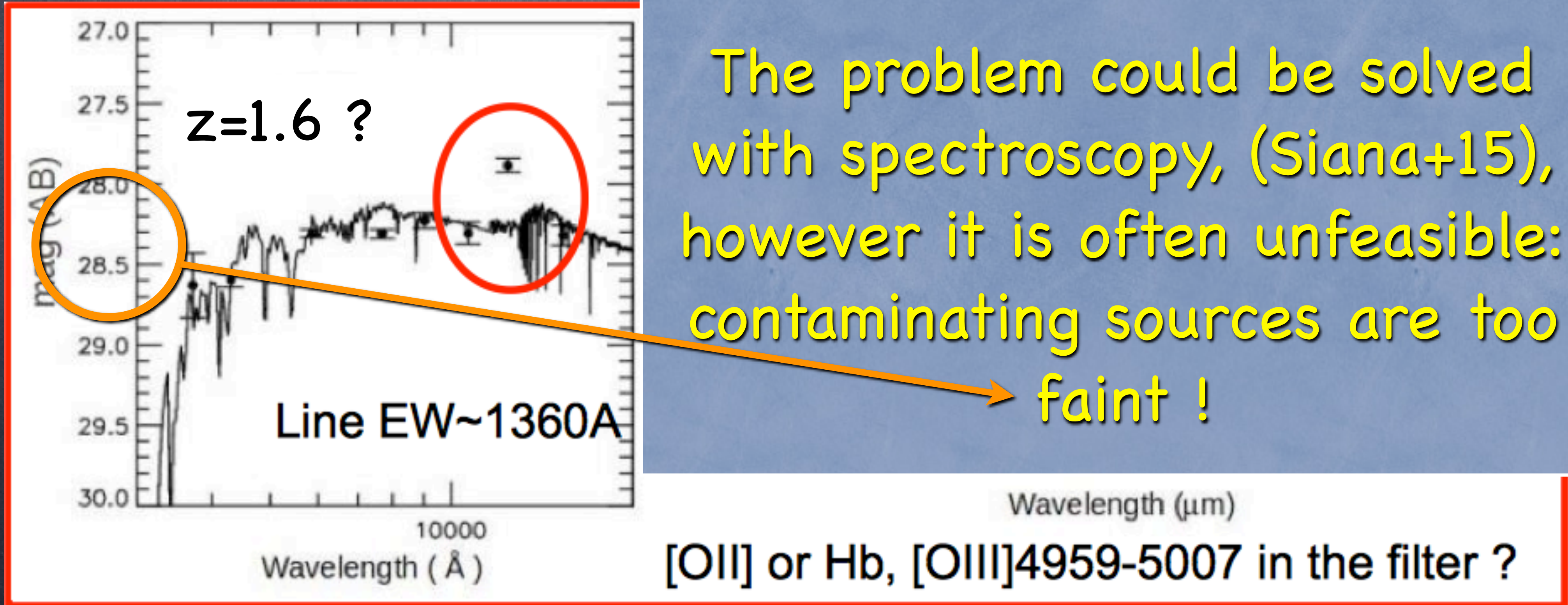
2500 2900A @ z=3.8



[OII] or Hb, [OIII]4959-5007 in the filter ?

Foreground contamination (II): example (EV+12)

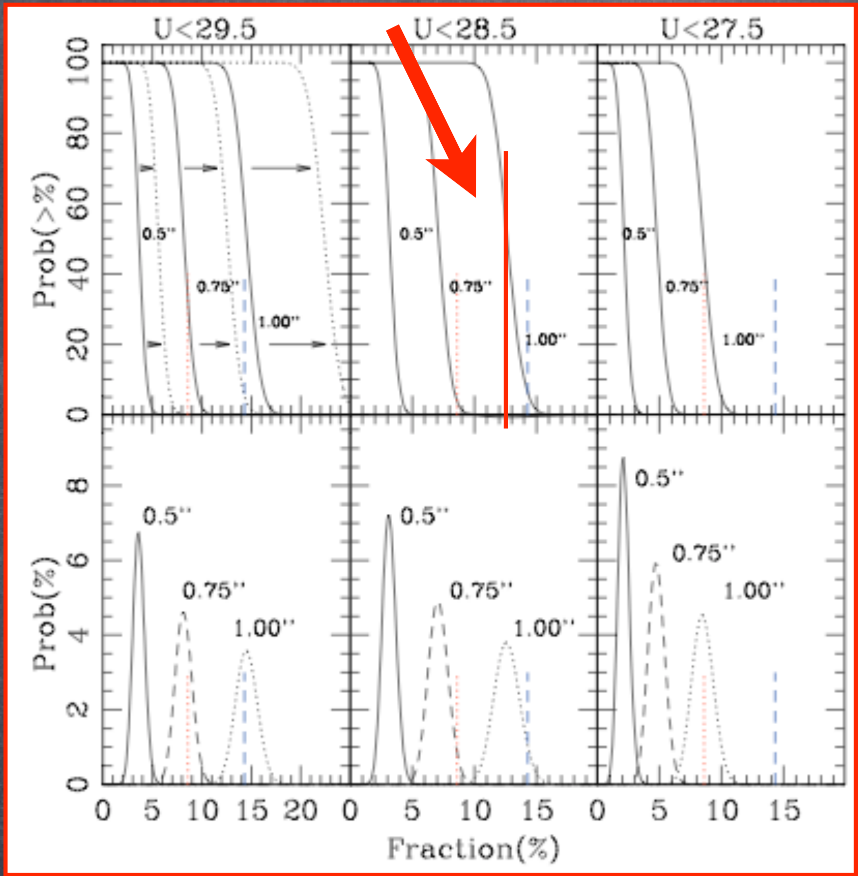




The problem could be solved with spectroscopy, (Siana+15), however it is often unfeasible: contaminating sources are too faint !

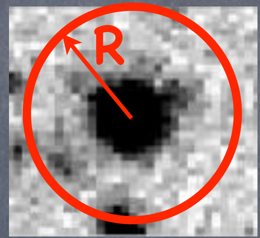
Foreground contamination, statistical correction

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**

... past claimed LyC detections have been revised (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 measurments: caveats under control ?

Intrinsic

View angle effects + intermittent behavior

Increase sample size

External

IGM absorption stochastic

Modeled

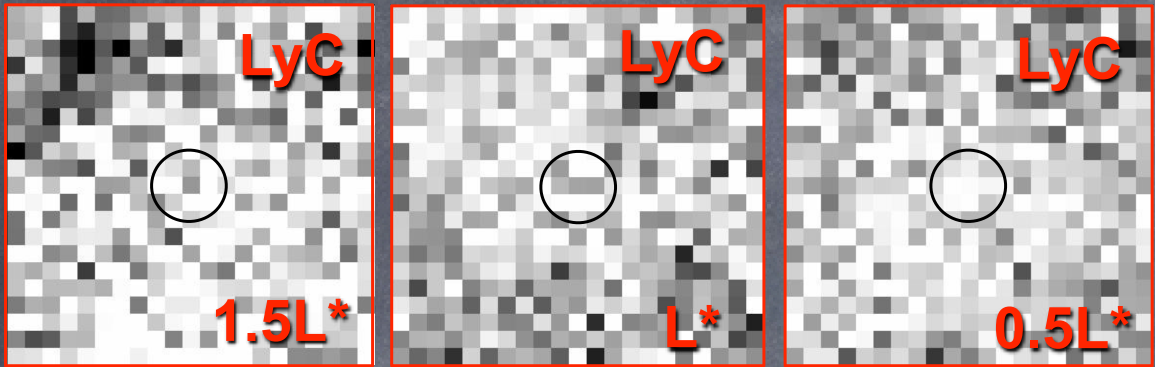
Foreground contamination

Statistical correction
Individual investigation (spectroscopy)

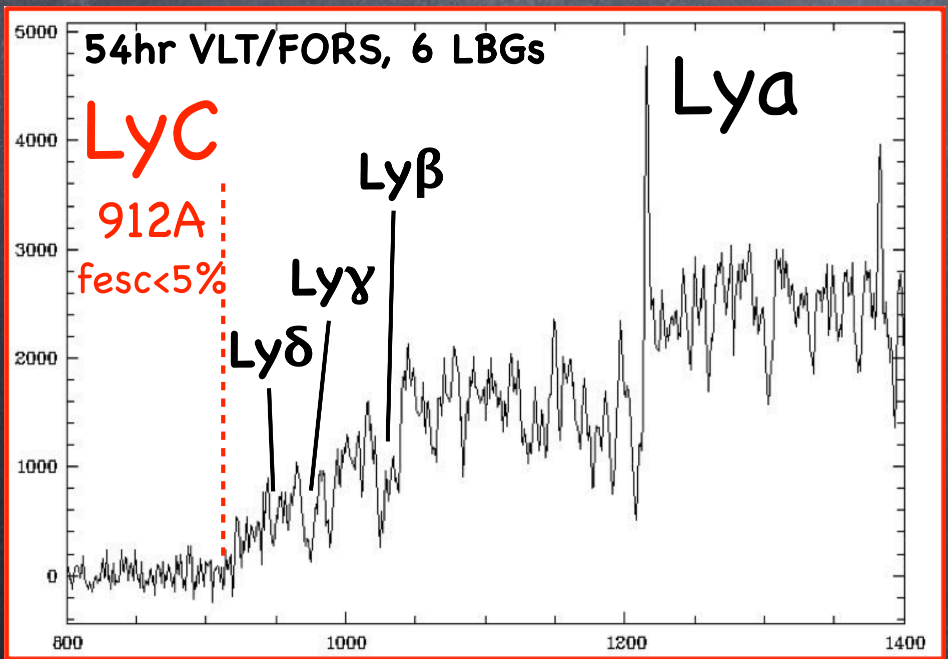
Looking directly at ionizing emission from z≈3.3-3.5

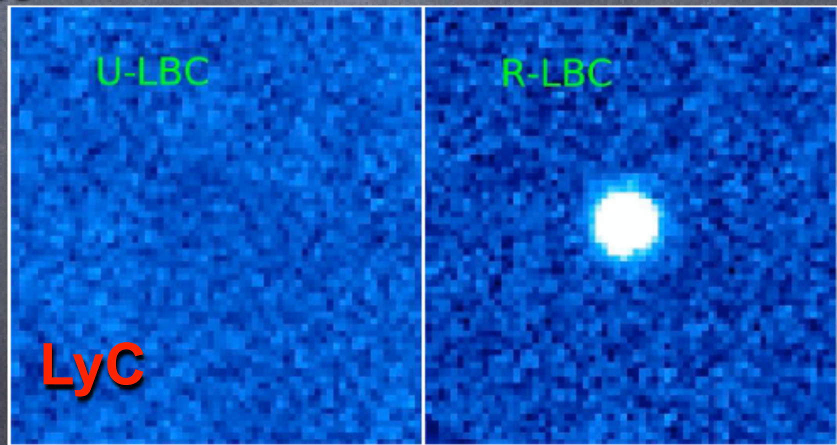
102 LBGs from GOODS-S (EV+10,12)

(GOODS+CANDELS)



22 LBGs	25 LBGs	20 LBGs
$\langle\Delta m\rangle$=7.5	$\langle\Delta m\rangle$=6.1	$\langle\Delta m\rangle$=6.6
fesc,rel < 3%	fesc,rel < 9%	fesc,rel < 5%





Grazian et al. (2015) - COSMOS

37 galaxies, fesc,rel < 3%

(see also Boutsia+11; Guaita+15

Giallongo 2002; Siana+10; Siana+15)

LyC measurments: caveats

Intrinsic

View angle effects + intermittent behavior

Increase sample size

External

IGM absorption stochastic

Modeled

Foreground contamination

Statistical correction

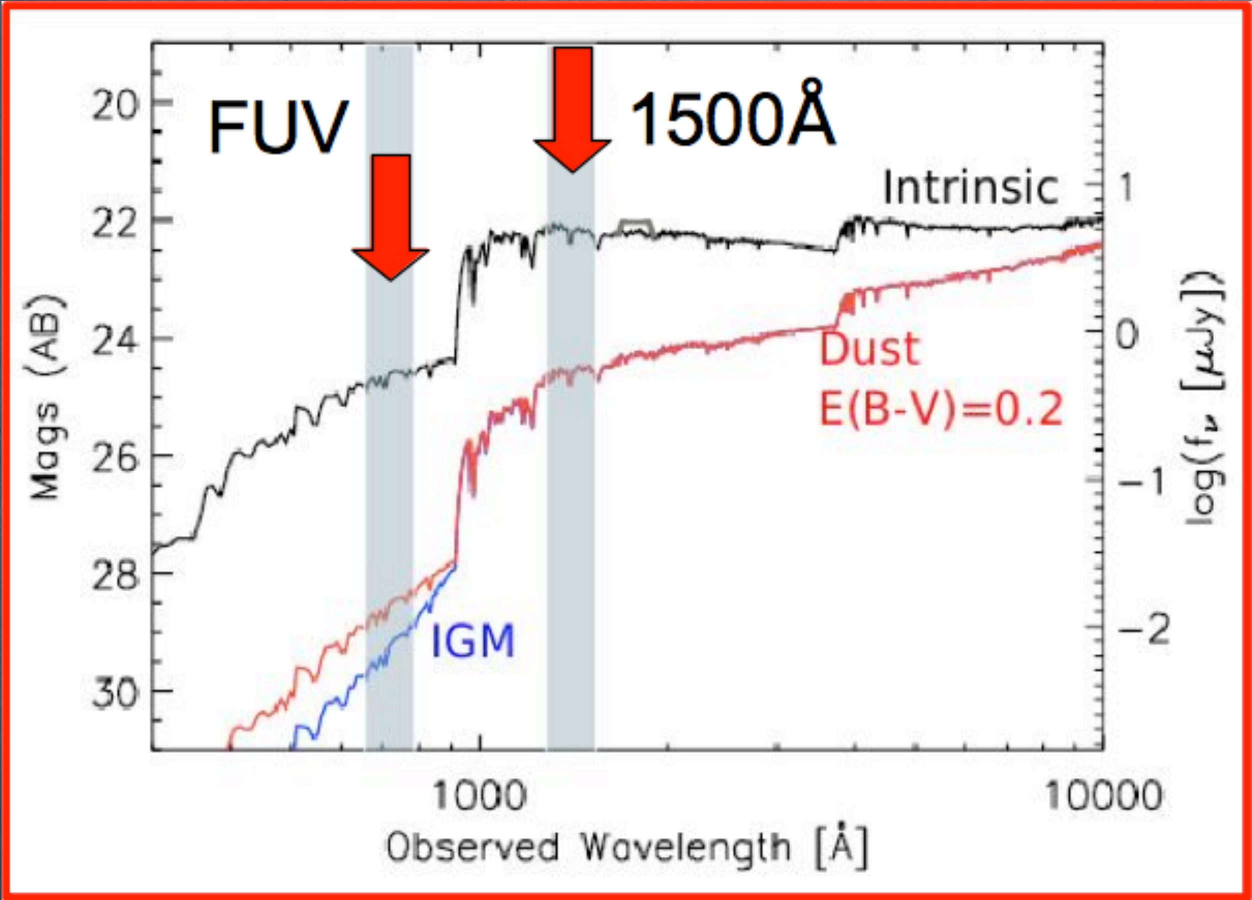
Individual investigation (spectroscopy)

In Addition

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

Need to access fainter sources

… however, investigate faint regime is challenging



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

CHALLENGING!

It is FAINT! e.g.,

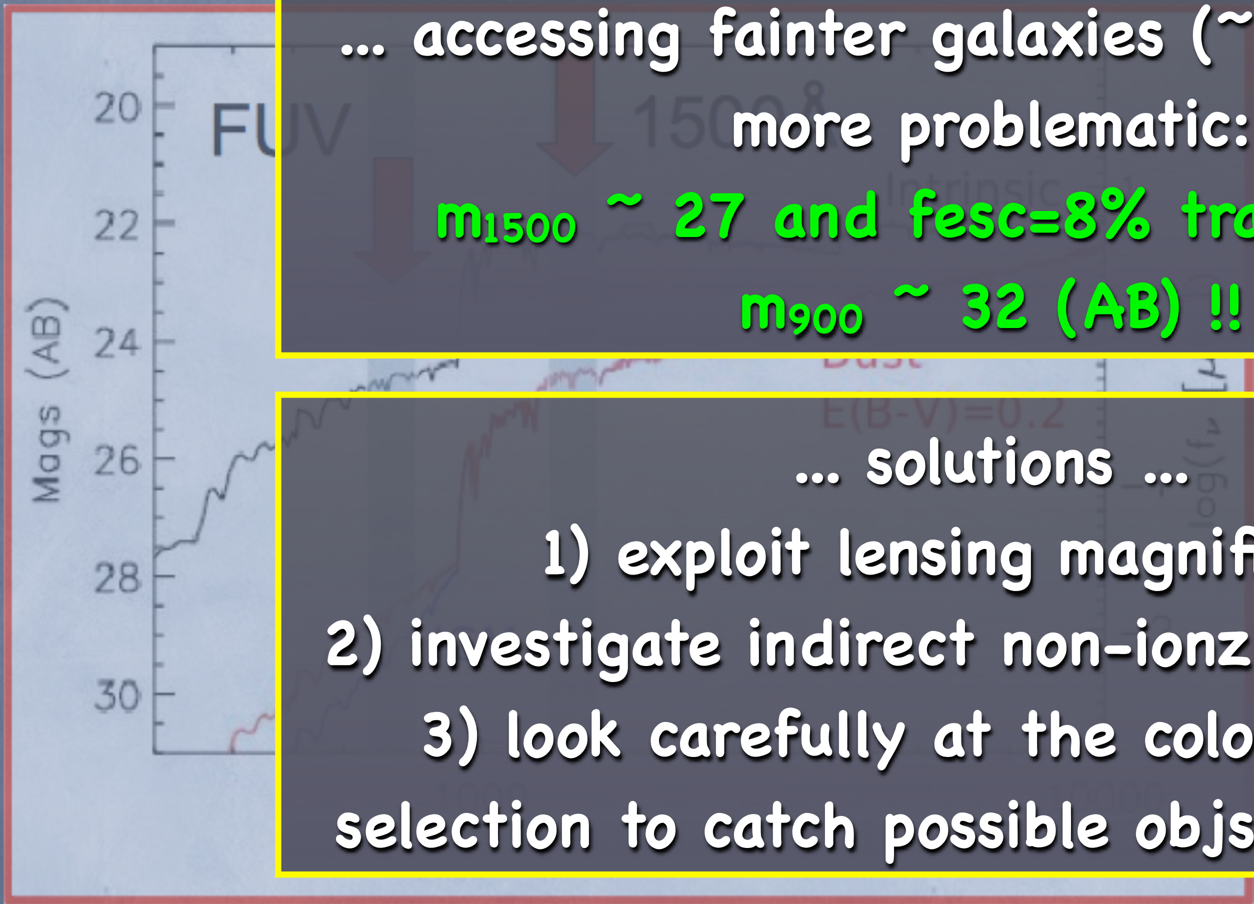
fesc=8% at z=3

L* galaxy (m_{1500}≈24.5)

=> m_{900} ≈30 (AB) !

Δm=5 (e.g., i-U>5).

… however, investigate faint regime is challenging



… accessing fainter galaxies (~0.1L*) is even more problematic:

m_{1500} ~ 27 and fesc=8% translates to m_{900} ~ 32 (AB) !!

… solutions …

1) exploit lensing magnification

2) investigate indirect non-ionzing signatures

3) look carefully at the colors, refined selection to catch possible objs with fesc >0

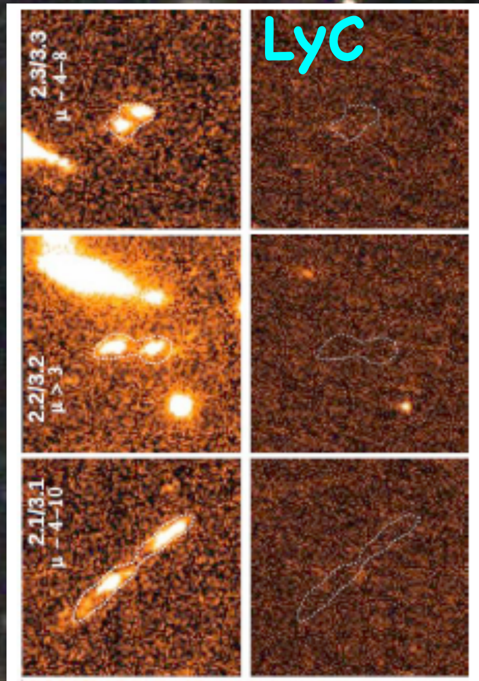
$$f_{esc,rel} \equiv \frac{(L1500/L_{LyC})_{int}}{(F1500/F_{LyC})_{obs}} \exp(\tau^{IGM}_{LyC}), \qquad (2)$$

Probing LyC emission at z~2-3 for sub-L* (L<0.5L*) LBGs with strong lensing

Vanzella 2012

Expect to probe fesc<15% for 0.05-0.1L* galaxies with 5 galaxy clusters and U-band imaging U~30 (assuming LFs, magnification maps, U-band depth, IGM ...

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



z=3.03

Ongoing programs:
e.g., HST/UV survey on lensed clusters (PI Siana, 90 orbits)

Non-ionizing (>912A) signatures of LyC leakage

escape fraction of ionizing radiation

λ <912A gas abs. dust. abs

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

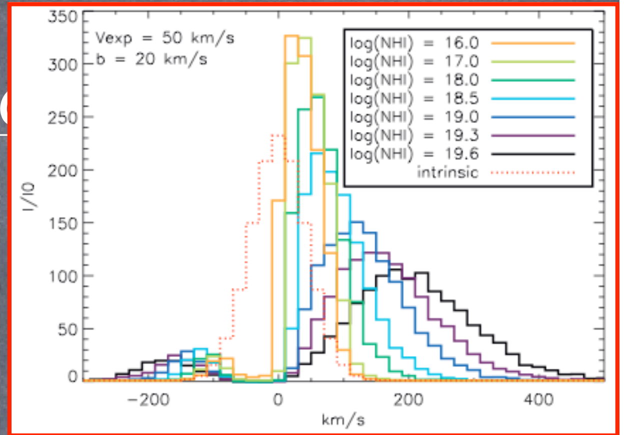
NHI dust

$T_{LyC} = e^{-\tau(LyC)}$ $>1.7 \times 10^{17} cm^{-2}$

$\tau(LyC) = N_{HI} \sigma_{LL}$ $\tau(LyC) > 1$

$\sigma_{LL} = 6.28 \times 10^{-18}$ cm^{-2}

From photoionization, RT models and indire



NHI

1) non-zero Lya flux at the systemic redshift

(Schaerer+11; Berhens+14; Verhamme+14)

Covering fraction

2) weak Carbon Silicon low-ionization absorption lines

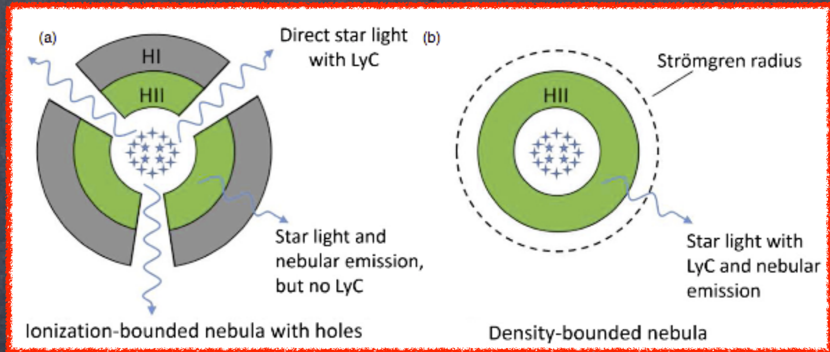
(CII,SiII), low covering fraction (Jones+14; Heckman+11)

Density bounded nebula ?

3) large O32=[OIII]4959-5007 / [OII]3727 (> 10)

O32 index positively correlates (also) with fesc

(Nakajima & Ouchi 2014; Jaskot & Oey 2013;but see Stasinska+15)



Non-ionizing (>912A) signatures of LyC leakage

escape fraction of ionizing radiation

λ <912A gas abs. dust. abs

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

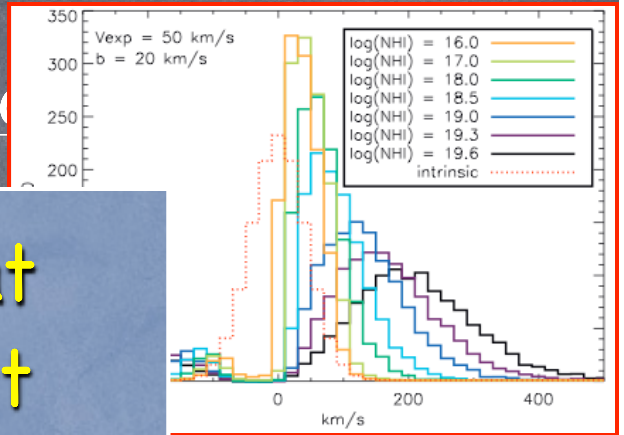
NHI dust

$T_{LyC}=e^{-\tau(LyC)}$ $>1.7\times10^{17}\,cm^{-2}$

$\tau(LyC)=N_{HI}\sigma_{LL}$ $\tau_{(LyC)}>1$

$\sigma_{LL}=6.28\times10^{-18}\ cm^{-2}$

From photoionization, RT models and indire



NHI 1) n

Covering fraction 2) ines

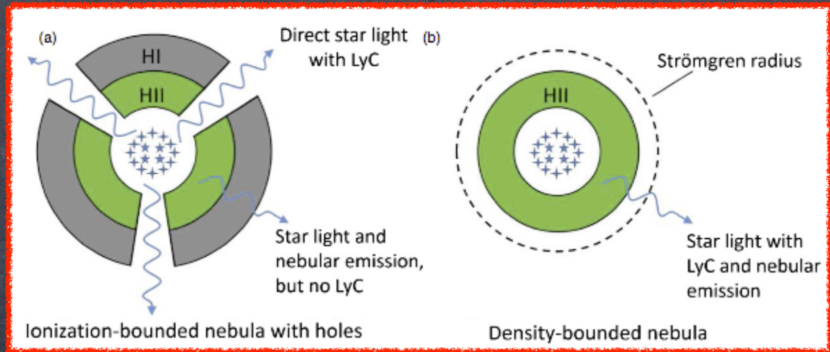
han+11)

This is very promising but eventually requires direct LyC confirmation for validation

Density bounded nebula ?

3) large O32=[OIII]4959-5007 / [OII]3727 (> 10)

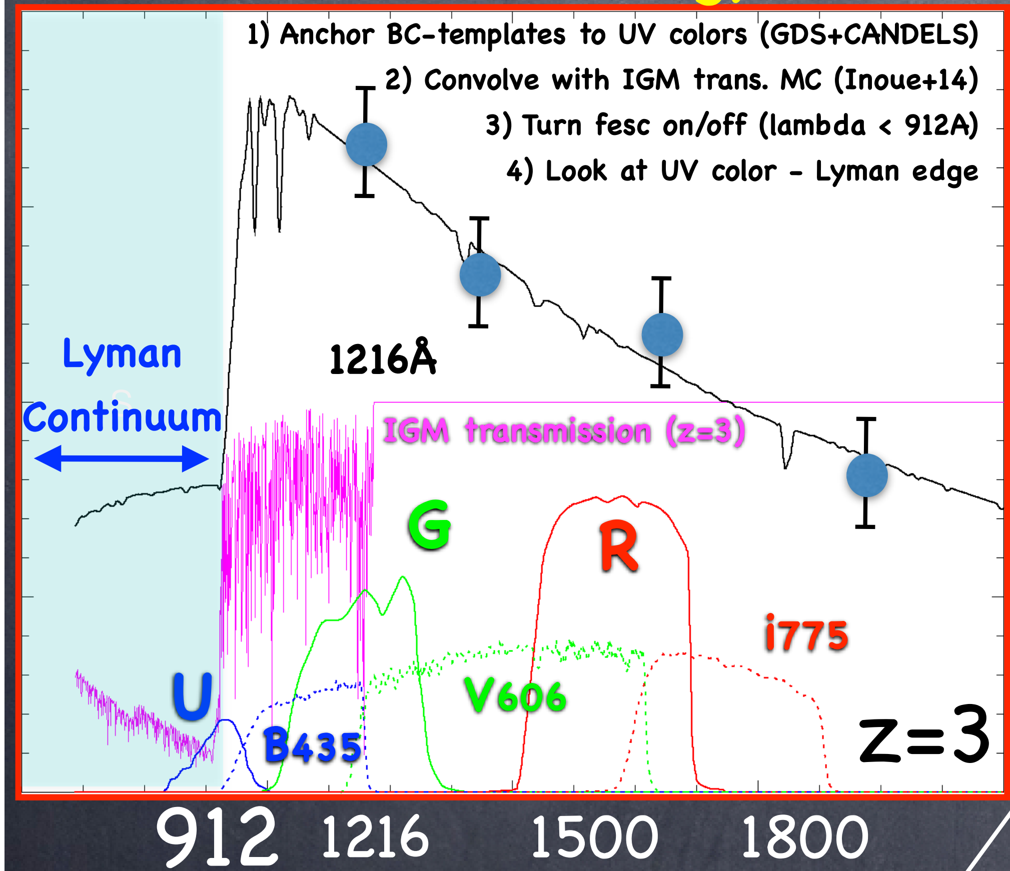
O32 index positively correlates (also) with fesc (Nakajima & Ouchi 2014; Jaskot & Oey 2013;but see Stasinska+15)

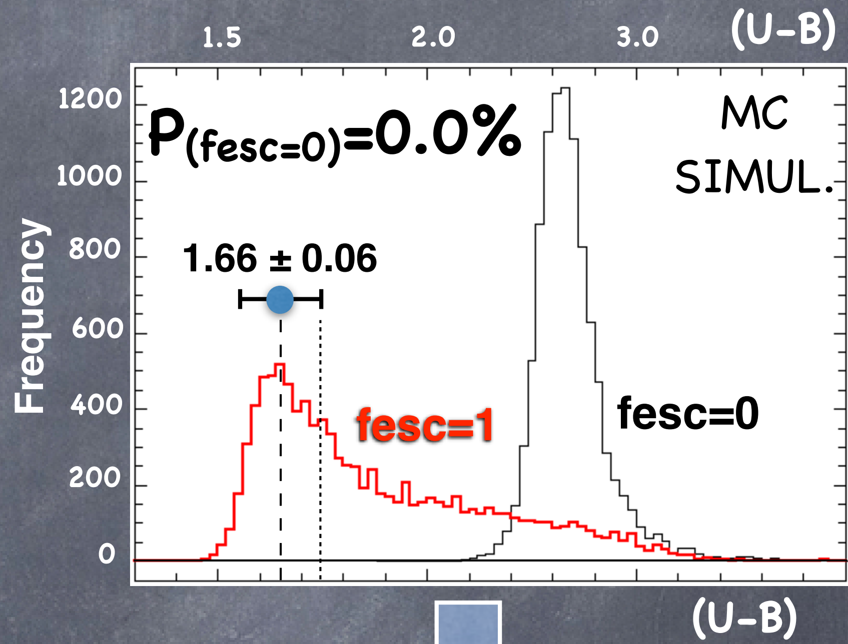


Trying to select LyC emitters at z<4
a complementary approach (EV+15)

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

New Methodology

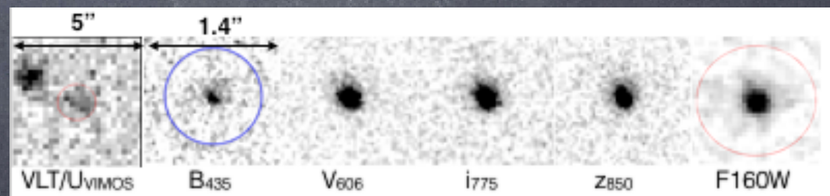




<830A

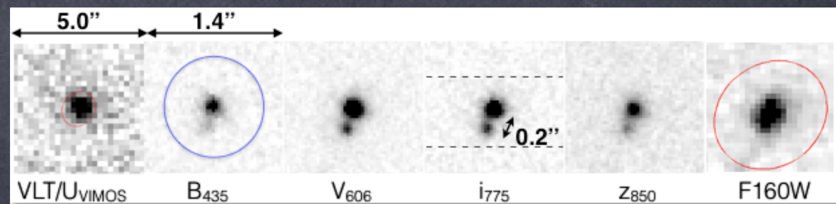
Ion1

z=3.795



Ion2

z=3.213



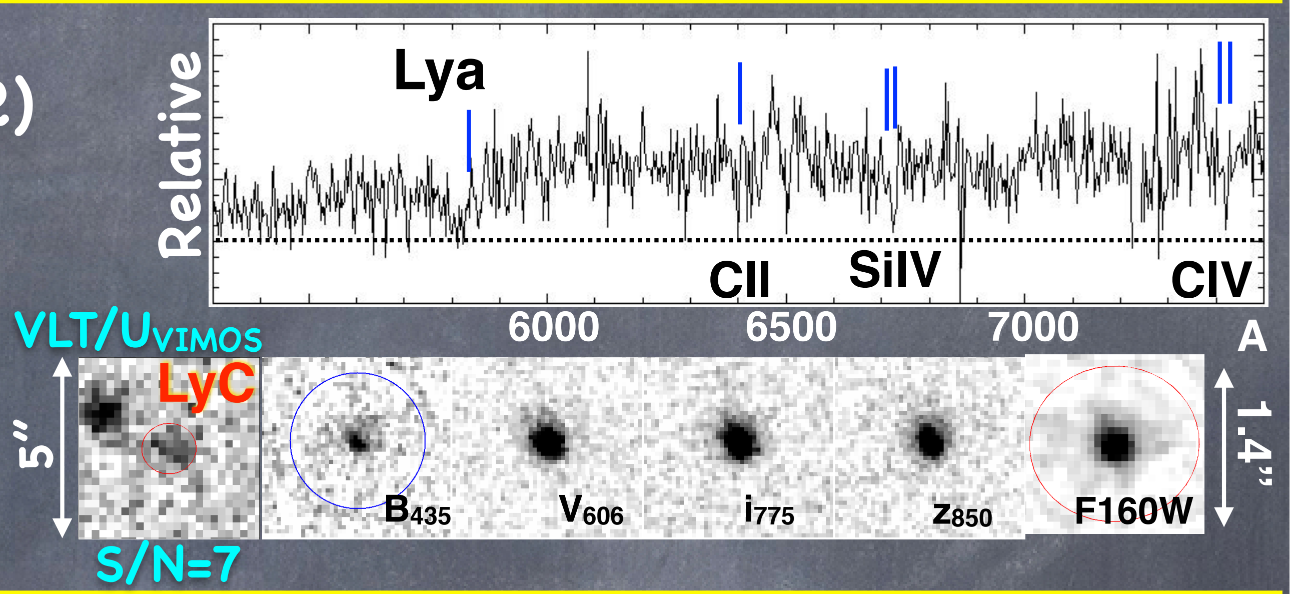
<938A

Two candidates LyC-emitters
spatially resolved Re≃250pc

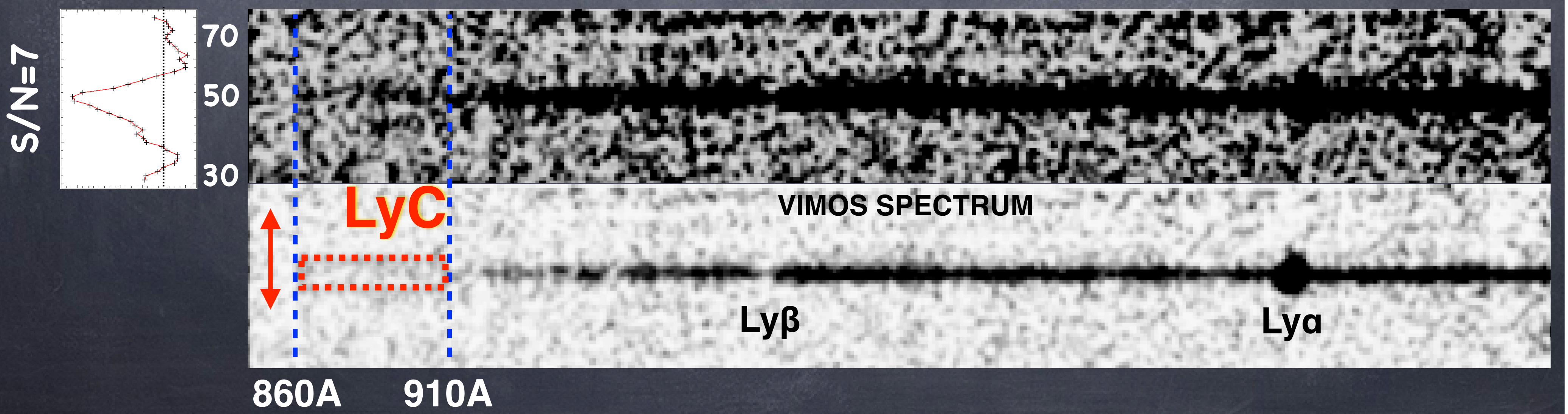
Two LyC sources with direct LyC detection !?

- No X-ray (6Ms)
- No high-ionization lines (CIV, NV...)
- Nucleated, but spatially resolved Re~250pc
- No mid/far-IR
- Lya yes/no
- SFR 20-30 Msol/yr
- $M^* \approx 10^9$Msol
- UV slope ≈ -2

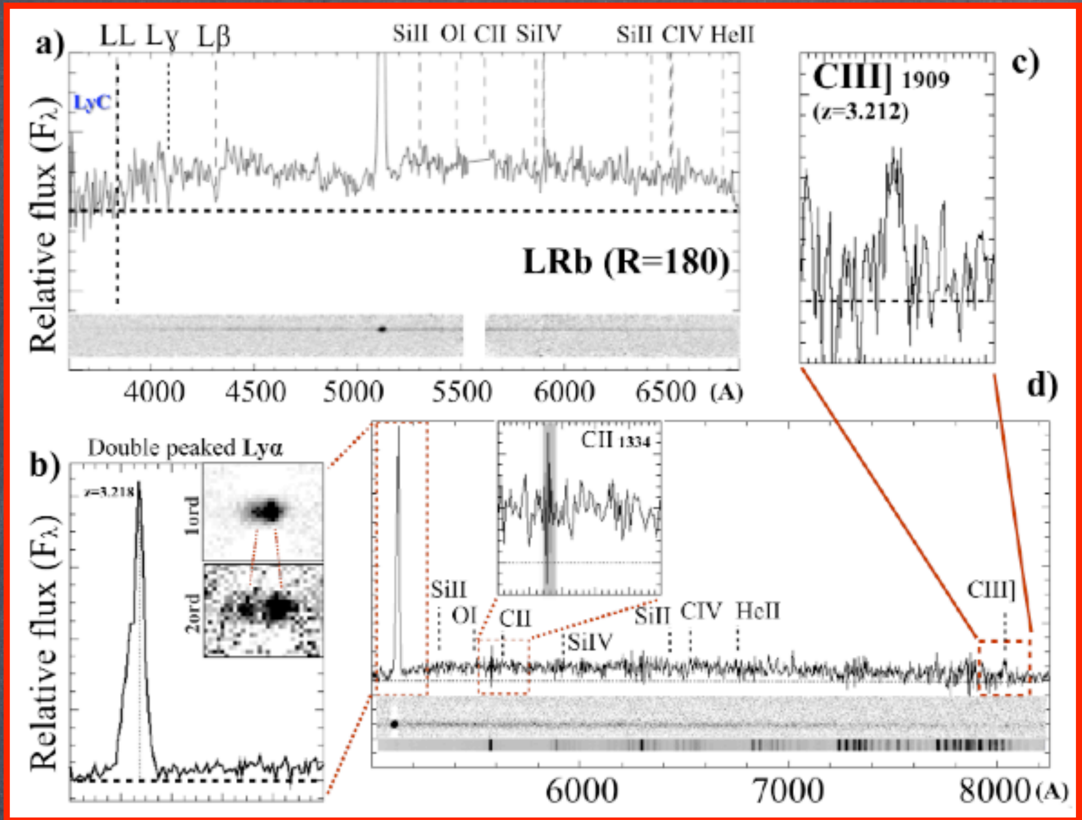
Ion1: (z=3.795, i_{775}=24.82)

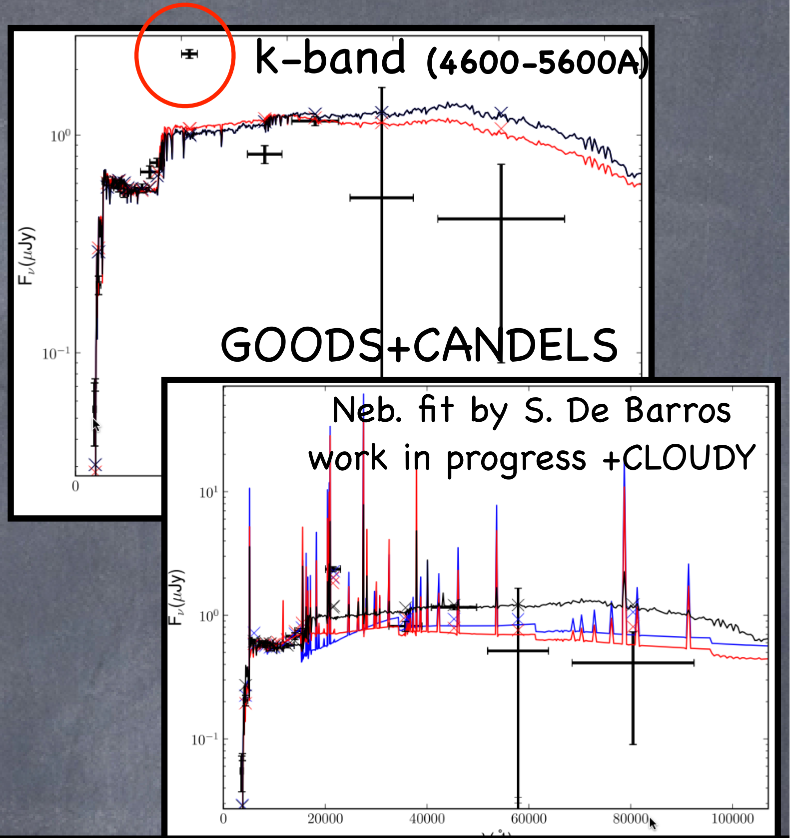


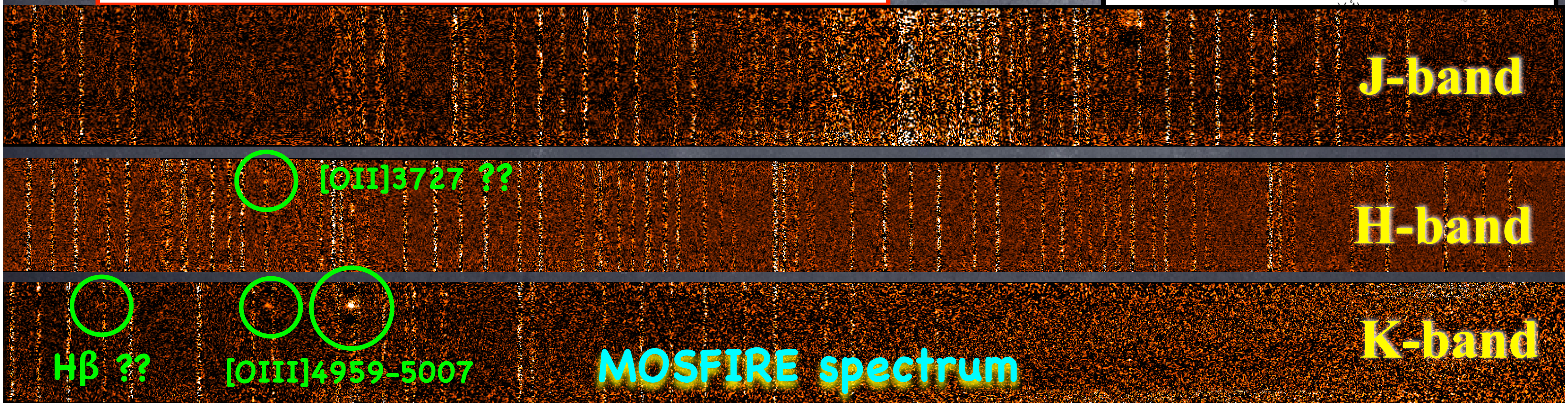
Ion2: (z=3.213, i_{775}=24.50)



A plausible ionizer : Ion2 (z=3.213)

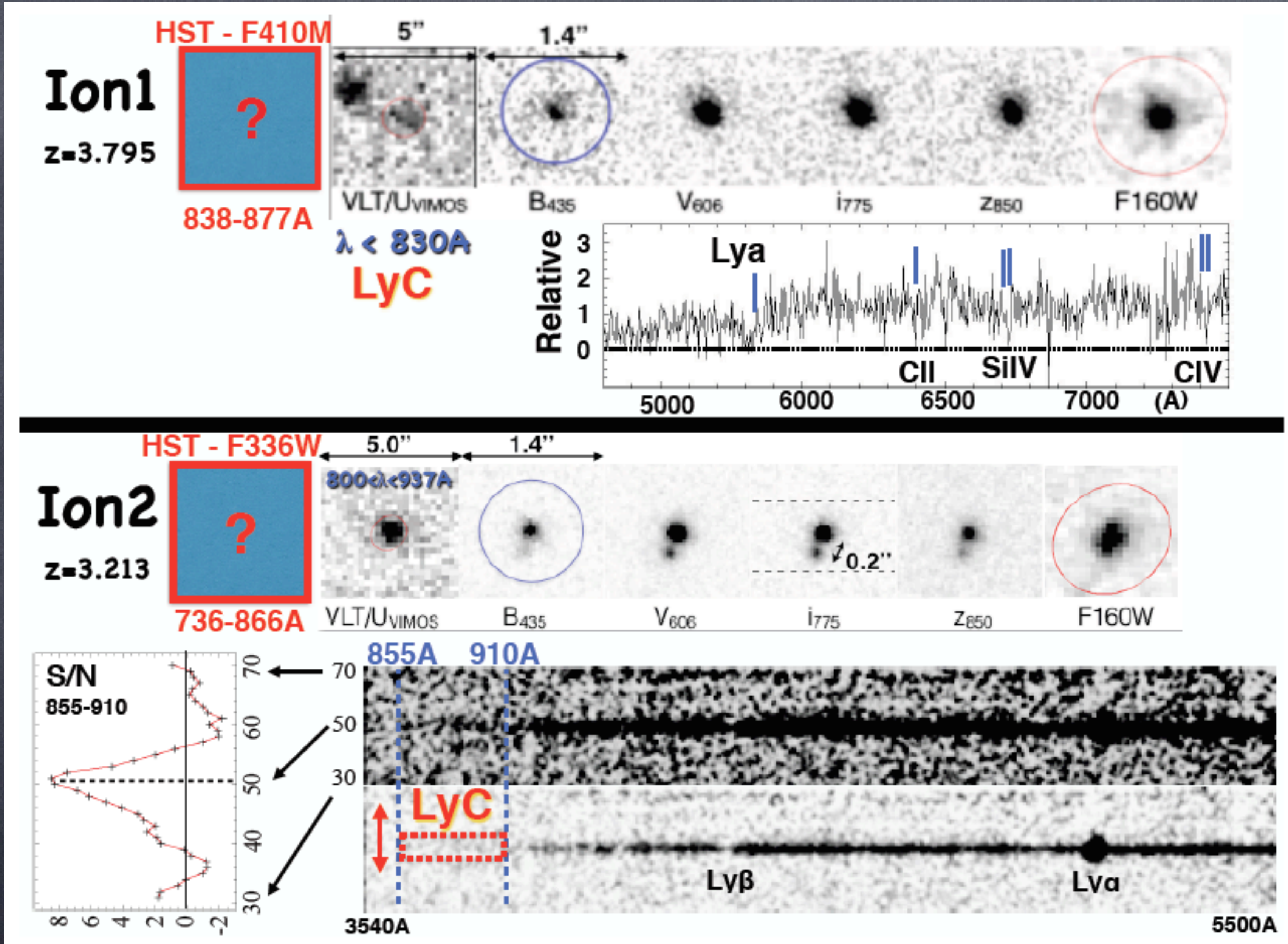






Spectrum: courtesy Guenther Hasinger

Observing LyC with HST

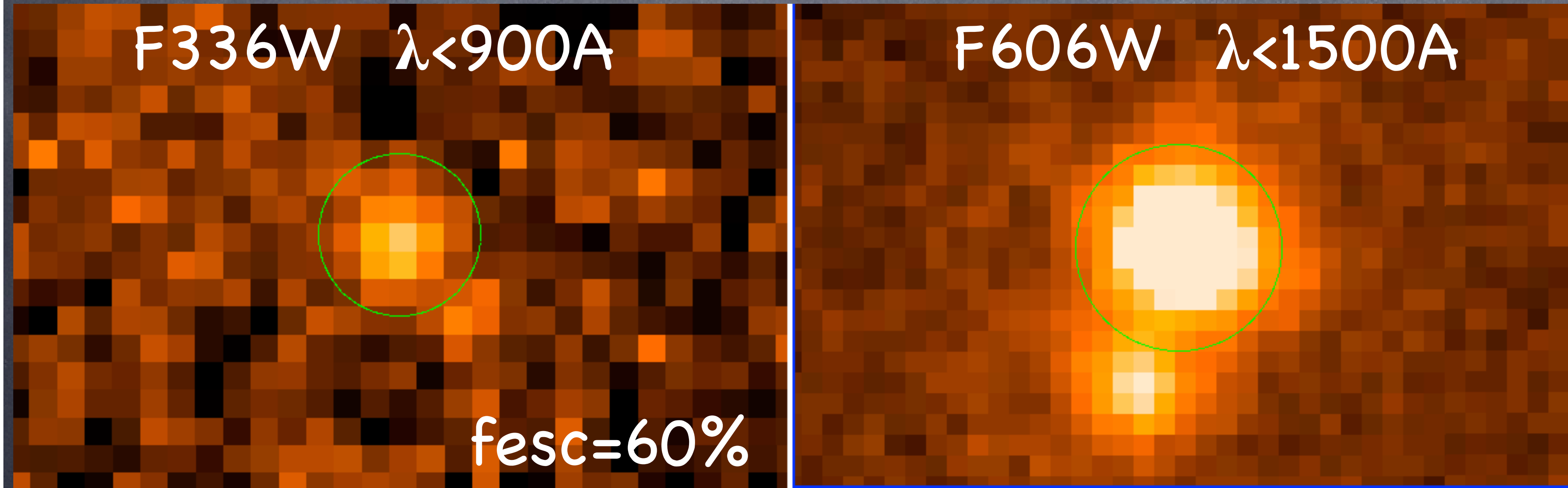


HST
WFC3/UV

... data acquisition for Ion2: ongoing these days...

confirmed !

A ~~plausible~~ ionizer : Ion2 (z=3.213) <2Gry after BB

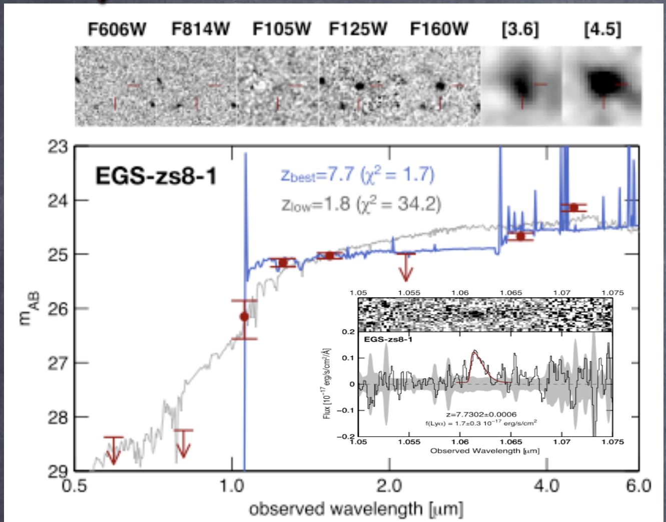


Very informative on the physical mechanisms that allow ionizing photons to escape and reach the IGM, irrespective to the nature of ionizing radiation

Study z~3-4 galaxies, analogs of z>7 ?

ISM conditions & ionization

zspec=7.73 (Oesch+15)



EW([OIII]+Hb)

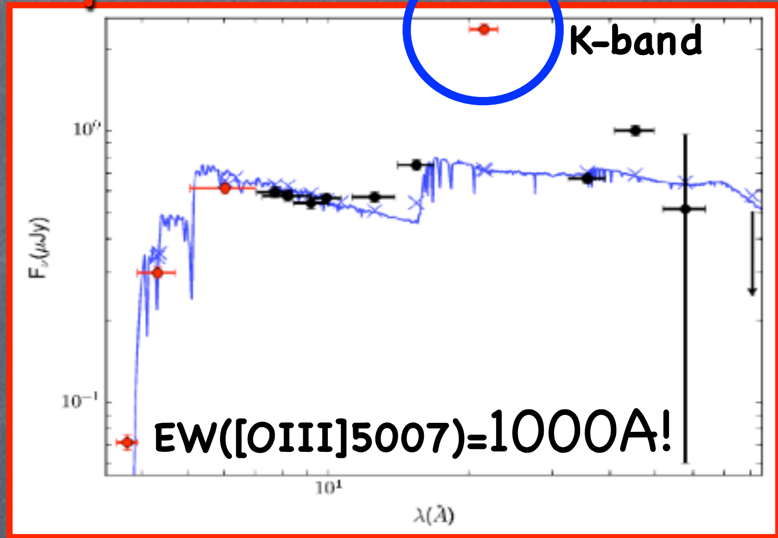
6200A observed

720 rest-frame

Density-bounded condition??

Transparent ISM ?

zspec=3.216 De Barros+15



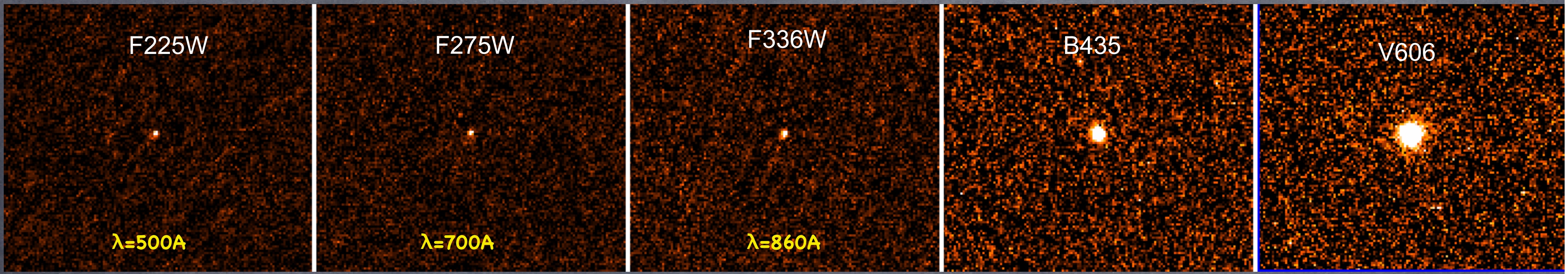
Finkelstein et al. (2014) z=7.5
Oesch et al. (2015) z=7.73
Zitrin et al. (2015) at z=8.5
all with similar strong rest-frame nebular emission

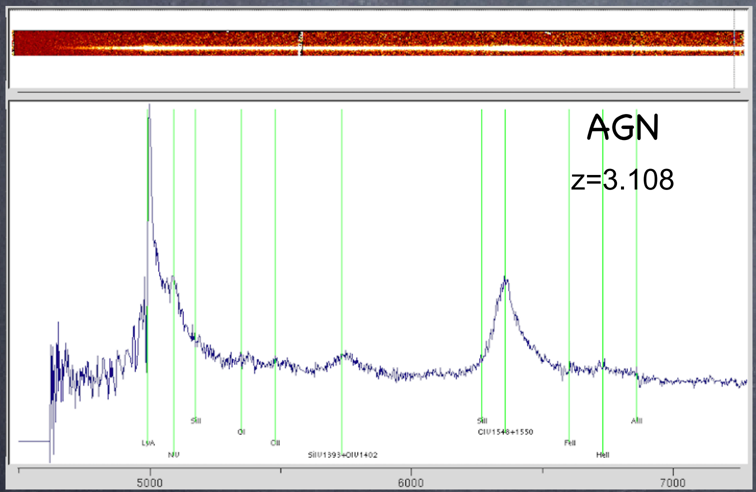
Two relevant facts:

1) LyC leakage
2) Strong nebular emission

are “Ion2-like” sources more frequent at z>6 ??

What is the fesc of AGNs ?? ... work in progress





Fram CLASH-VLT spectroscopic survey

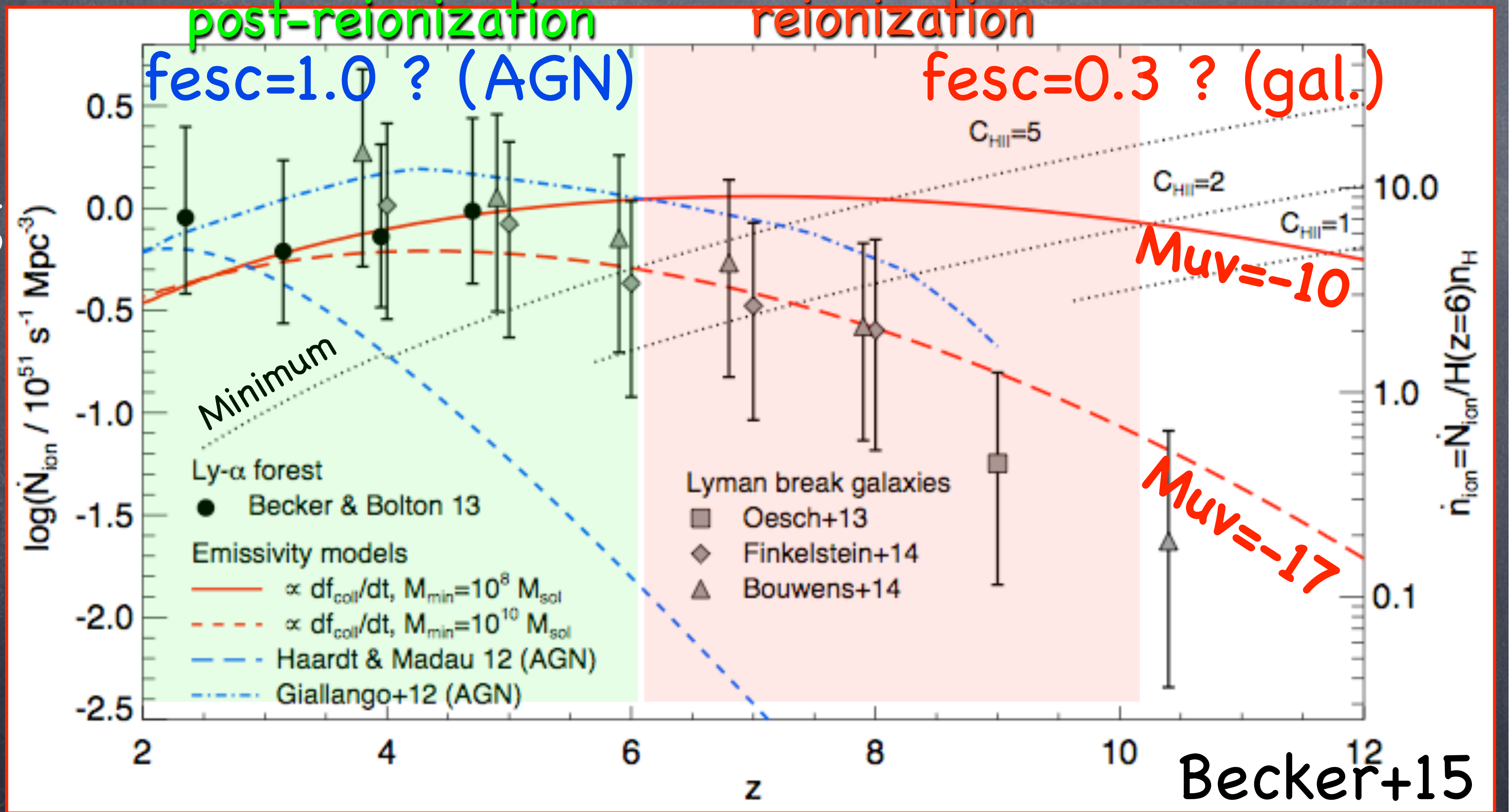
we know fesc in AGN can be > 0,

but how many AGNs do we observe at high-z ?

Who is responsible for the ionization ?

$$\phi(M_{1400}) \xrightarrow[\text{integrate; assume } M_{lim}]{} \rho_{L_{1400}} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma 1400}\rangle]{} \dot{N}_{ion}^{int} \xrightarrow[f_{esc,rel}]{} \dot{N}_{ion}$$

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



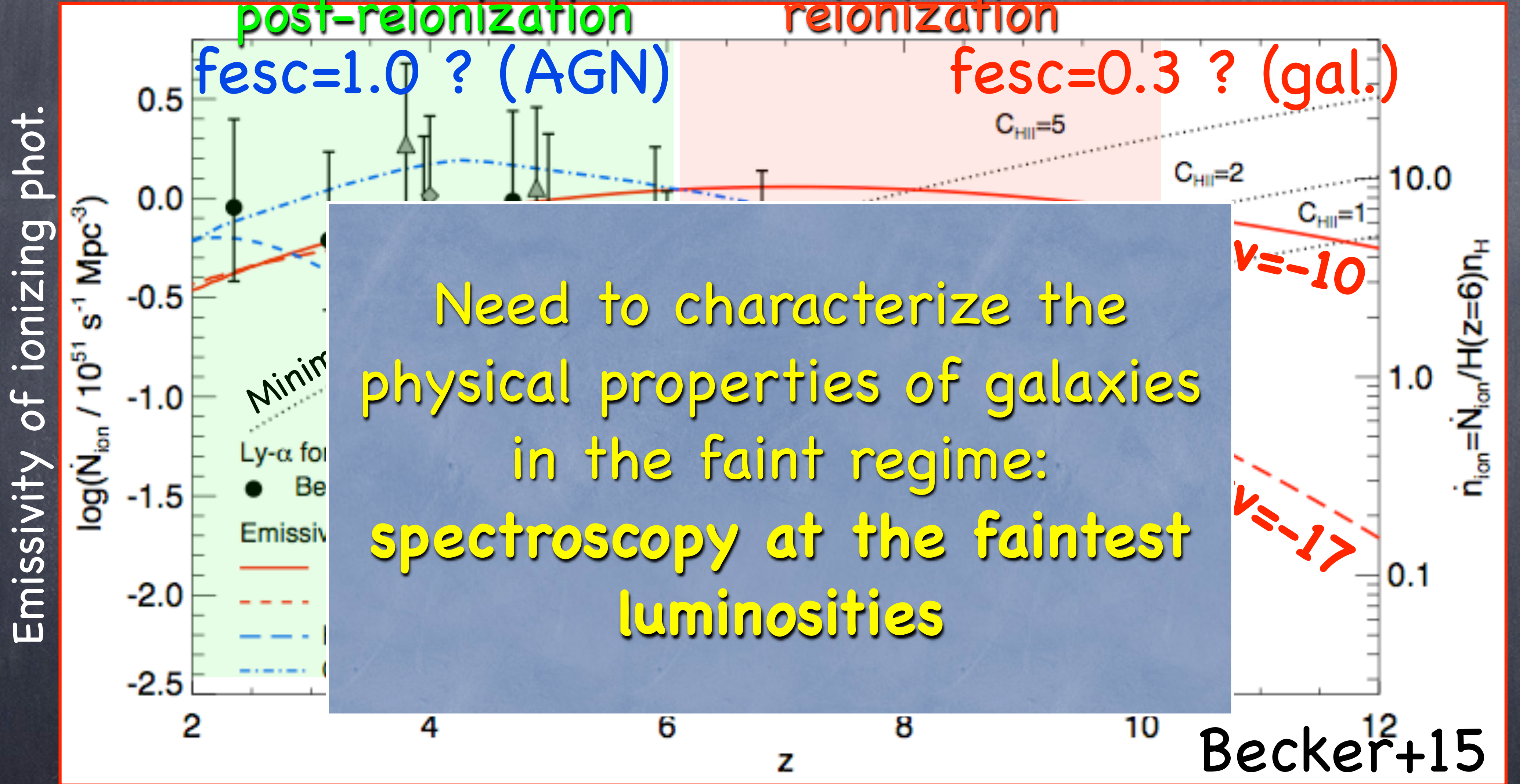
AGNs - select AGNs from X, challenging
- faint-end LFs ? Uncertain (zspec)
- fesc ? Helium reionization ?

SF-galaxies - faint-end LFs ? Ok, there are many!
Some with zspec (Alavi 2014)
-fesc ? (low for bright...)

Who is responsible for the ionization ?

$$\phi(M_{1400}) \xrightarrow[\text{integrate; assume } M_{\lim}]{} \rho_{L_{1400}} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma 1400}\rangle]{} \dot{N}^{int}_{ion} \xrightarrow[f_{esc,rel}]{} \dot{N}_{ion}$$

$$\frac{dQ_{\mathrm{H\,II}}}{dt} = \frac{\dot{n}_{\mathrm{ion}}}{\bar{n}_{\mathrm{H}}} - \frac{Q_{\mathrm{H\,II}}}{\bar{t}_{\mathrm{rec}}}$$



Need to characterize the physical properties of galaxies in the faint regime: **spectroscopy at the faintest luminosities**

AGNs - select AGNs from X, challenging
- faint-end LFs ? Uncertain (zspec)
- fesc ? Helium reionization ?

SF-galaxies - faint-end LFs ? Ok, there are many!
Some with zspec (Alavi 2014)
-fesc ? (low for bright...)

Questions