Lyman Alpha Emitters, Damped Lyman Alpha Systems, and Faint Galaxies at High Redshift

M. Rauch (OCIW)

Collaborators

ESO data :

Haehnelt (IoA), Bunker (Oxford), Becker (KICC), Marleau (IPAC), Graham (UCB), Cristiani (Trieste), Jarvis (Hertfordshire), Lacey (Durham), Morris (Durham), Peroux (Marseille), Rottgering (Leiden), Theuns (Durham)

Keck data:

Becker (KICC), Sargent (CIT), Simcoe (MIT), Burles (MIT)

Two observational challenges in the high redshift universe:
Redshift limits and intrinsic flux limits.

The higher the redshift, the less likely we are to see typically galaxies

→

Much of cosmic structure at high redshift has not been detected in emission.

The Baryonic Universe at z ~ 3

The Intergalactic Medium

Damped Lyman alpha systems

Dwarf galaxies

Bright Lyman alpha emitters

Massively star forming (Lyman break) galaxies

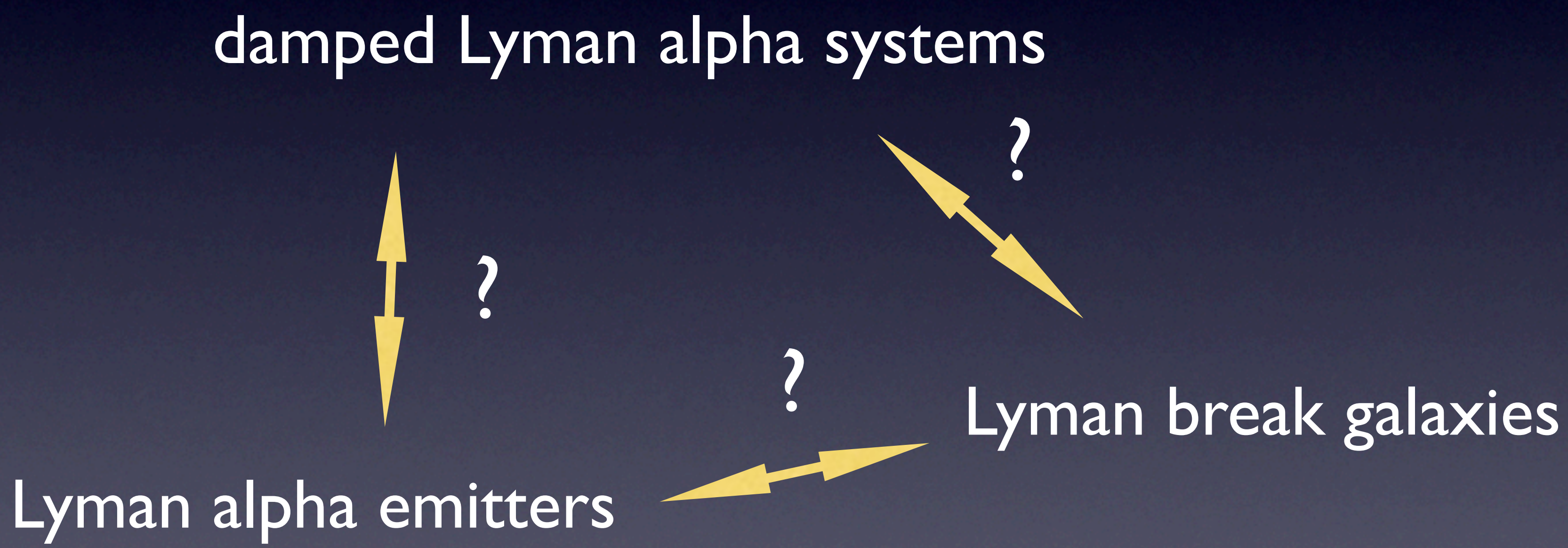
Big Questions:

1) Can we descend further into the dark abyss ?

- how can we observe the (hidden?) majority of galaxies ?
- is there a true faint end to the luminosity function ?
- can we observe dark (starless) baryonic halos ?

Big Questions:

2) Can we unify the observational zoo of galaxies ?



Big Questions:

3) How do Galaxies Form ?

- gas accretion from the IGM
- mergers
- evolution of the stellar population
- galactic outflows, feedback into the IGM

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Tough to observe by any means !

Study high z Lyman alpha emission

Multiple sources of Lyman alpha:

- Lya fluorescence from the IGM
- cooling radiation from gas accretion
- emission from wind shells
- Lya from star-formation
- AGN

How the current project started out

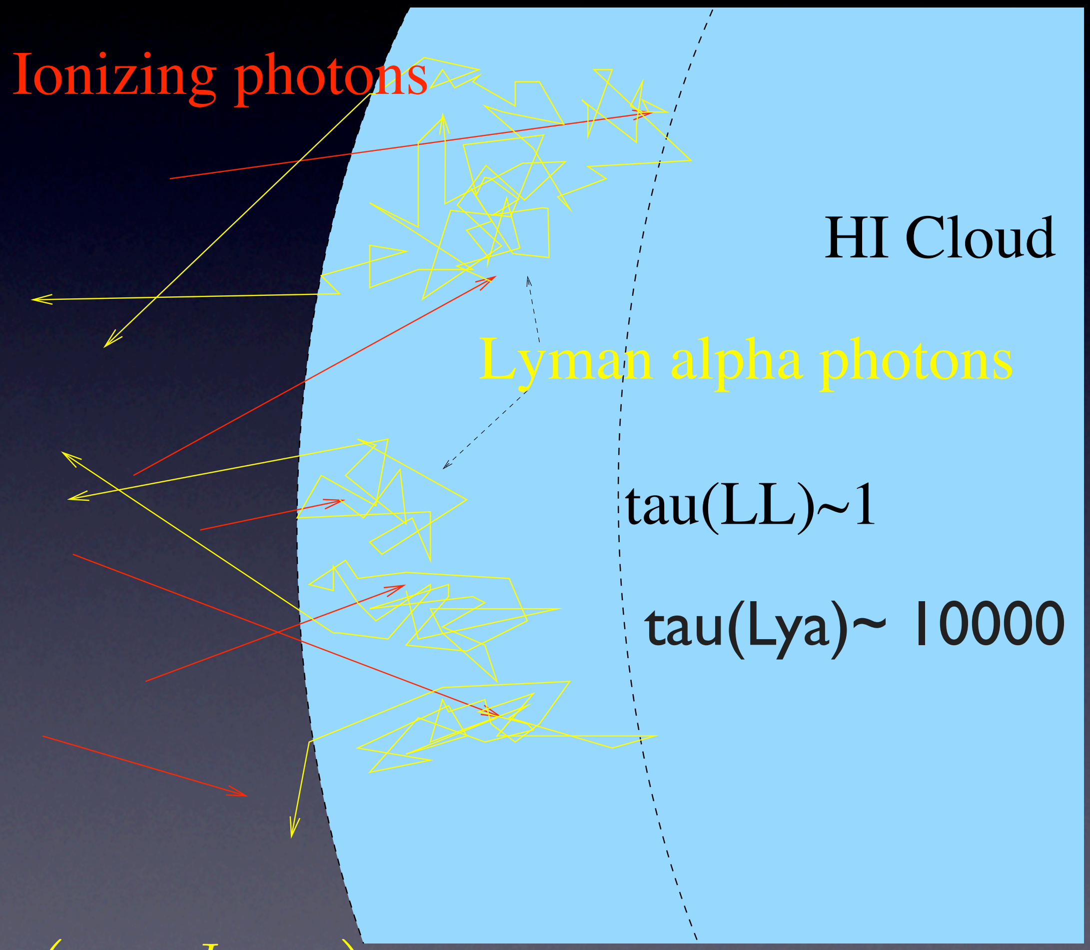
Map the Intergalactic Medium in Emission

Lyman alpha fluorescence induced by the ionizing background

Hogan & Weymann 1987

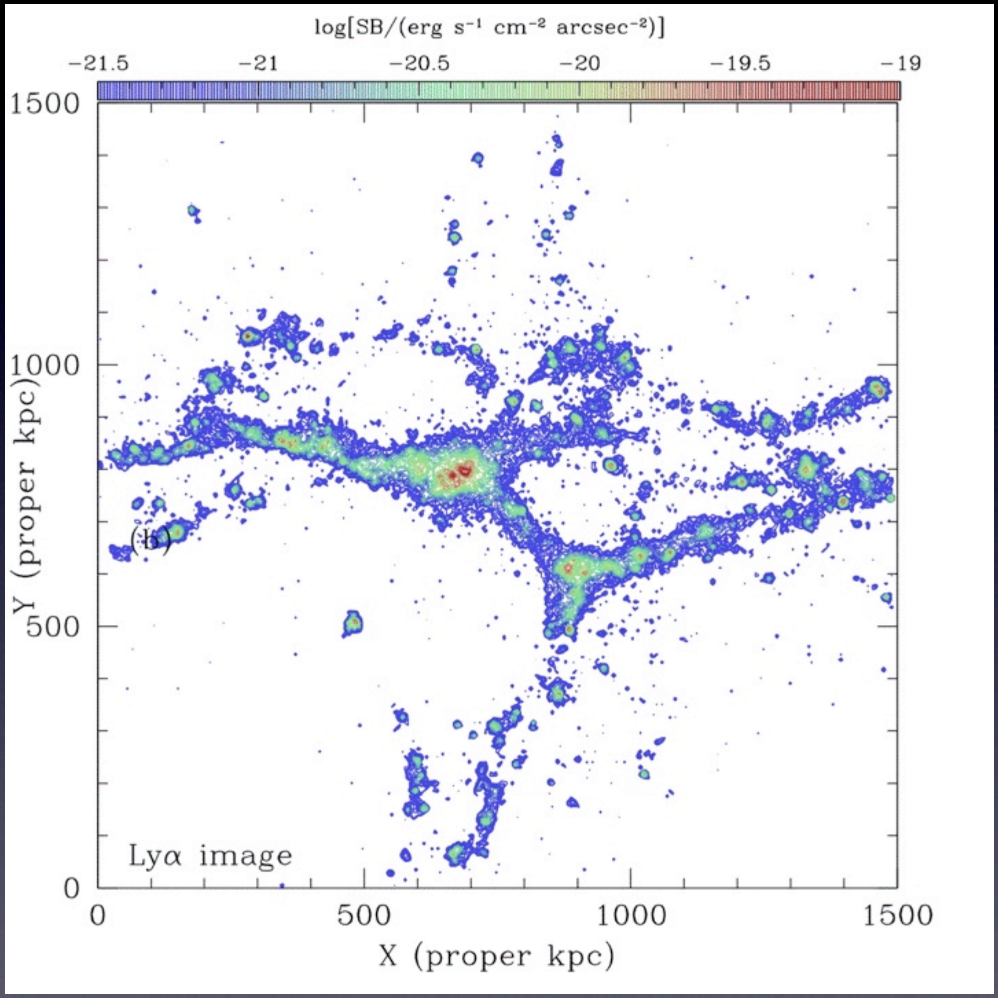
"Image" cosmic web in Lya glow:

2-d image of optically thick cosmic web !



Lyalpha intensity $9 \times 10^{-20} \left(\frac{\eta}{0.5}\right) \left(\frac{J}{4.3 \times 10^{-22}}\right)$ erg cm^{-2}s^{-1}arcsec^{-2}

z~3 Lyman alpha emission map



Kollmeier et al 2009

signal proportional to the intensity of the UV background

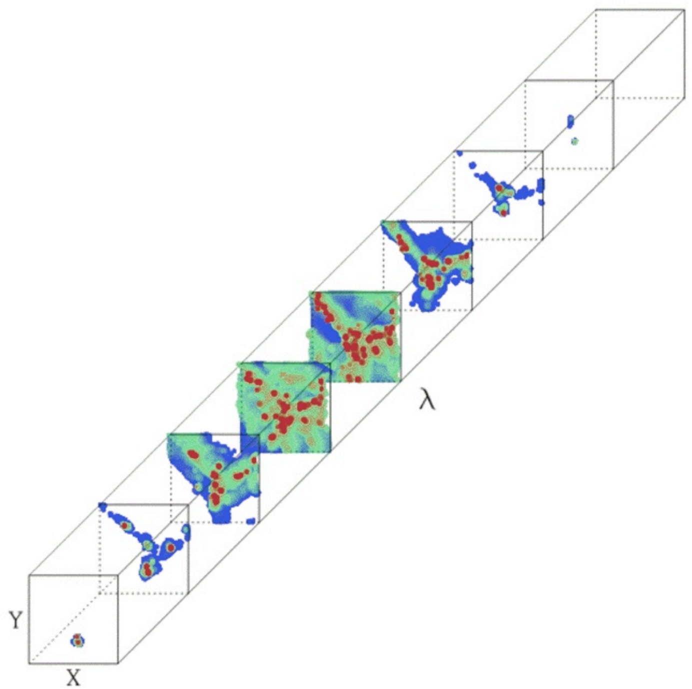
signal reaches a plateau for gas with N(HI) > 18.5

actual signal enhanced by cooling radiation, star-formation

Note the amount of detail; volume too small to contain even a single Lyman break galaxy

z~3 Lyman alpha emission map

use 2-D spectroscopy
to study velocity field
(e.g., with an IFU)

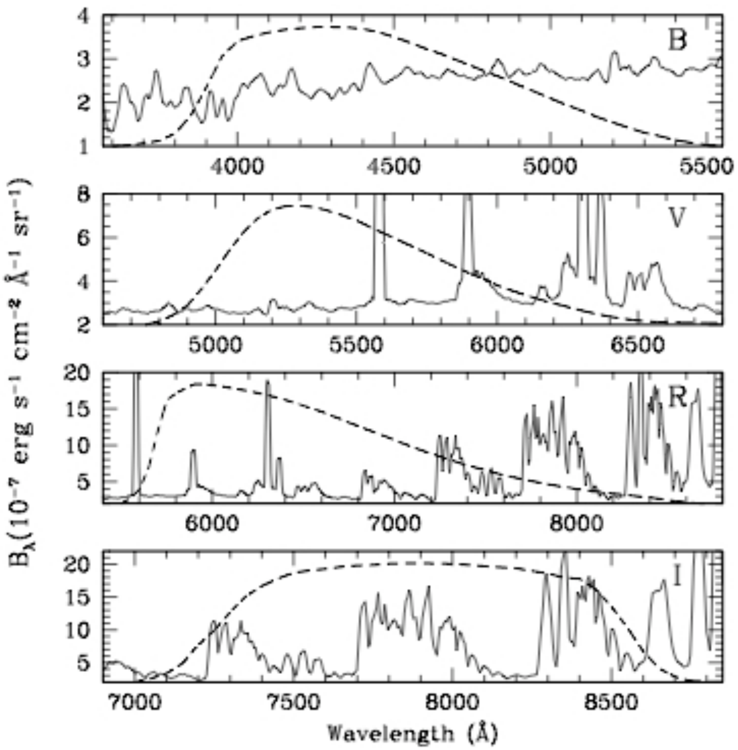


study in- and outflows of
optically thick gas

Kollmeier et al 2009

Problem: the signal is extremely faint.

Search for very low level light emission (~1% of night sky);



Patat 2002

1. $(1+z)^4$ dimming; z as low as possible

(but z > 2 to avoid declining UV background)

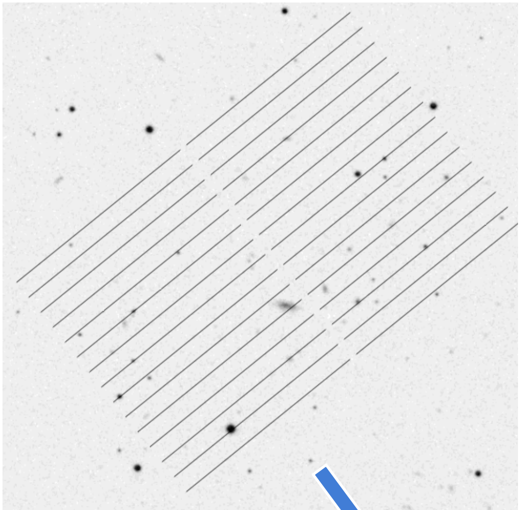
2. spectral range where sky background is low

observe in U or B band where sky faint

3. need to strongly suppress sky background !

usual narrow band filters too broad.
need spectroscopy or extremely narrow band pass (~ 5A) to suppress sky

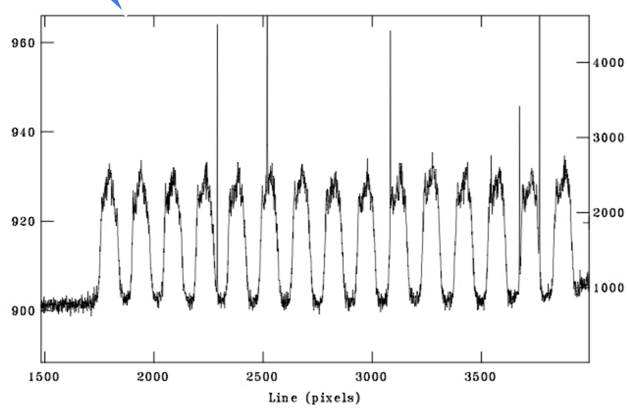
Various Approaches:

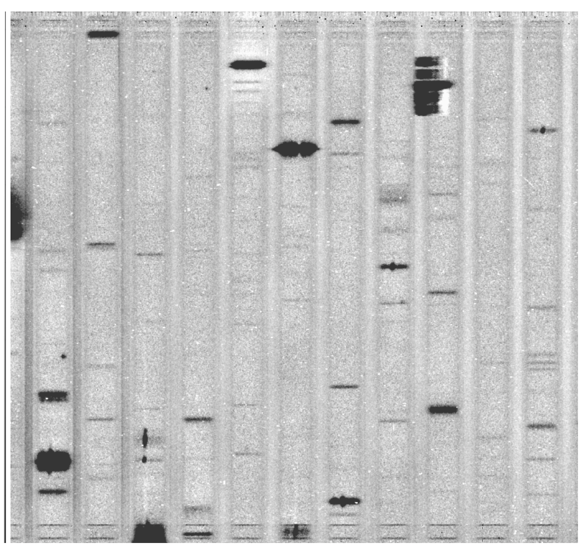


1) Venetian Blind Spectroscopy:

multi-longslit mask + filter + disperser

w. Sargent, Simcoe & Burles





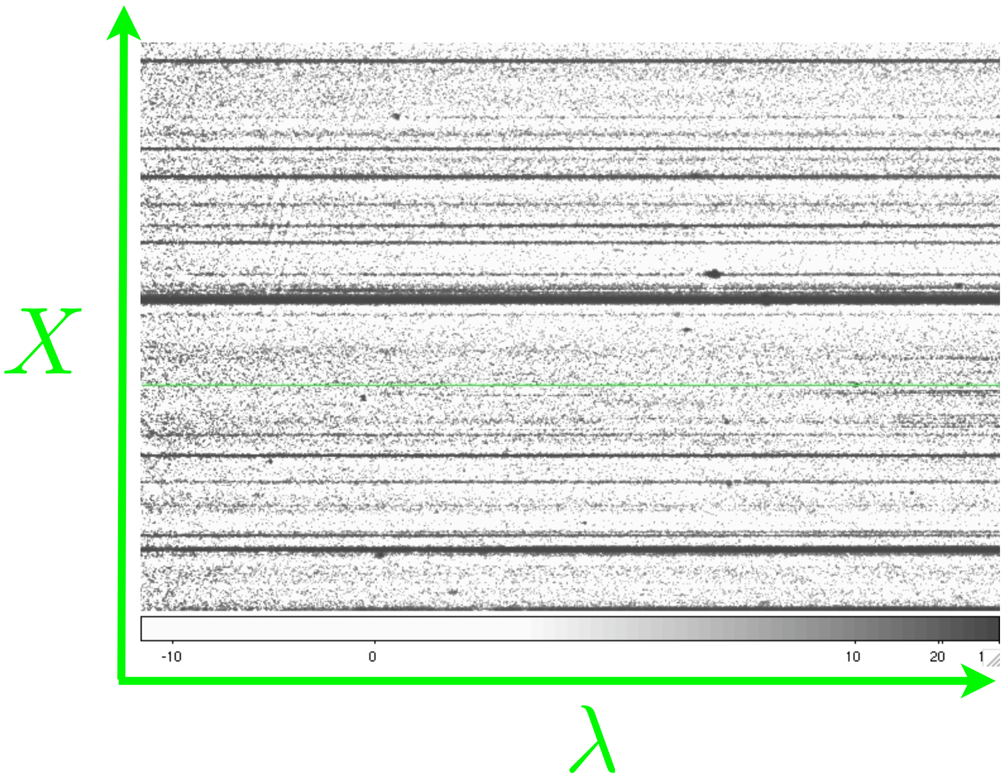
Pro : sky suppression + (sparsely sampled) 2-D image

Con: difficult to ID object w. short spectra; cosmic variance

Various Approaches:

2) Single Long Slit Spectroscopy:

longslit mask + disperser



Pro : highest sensitivity; long spectral coverage (helps to ID interlopers)
lower cosmic variance than NB approach

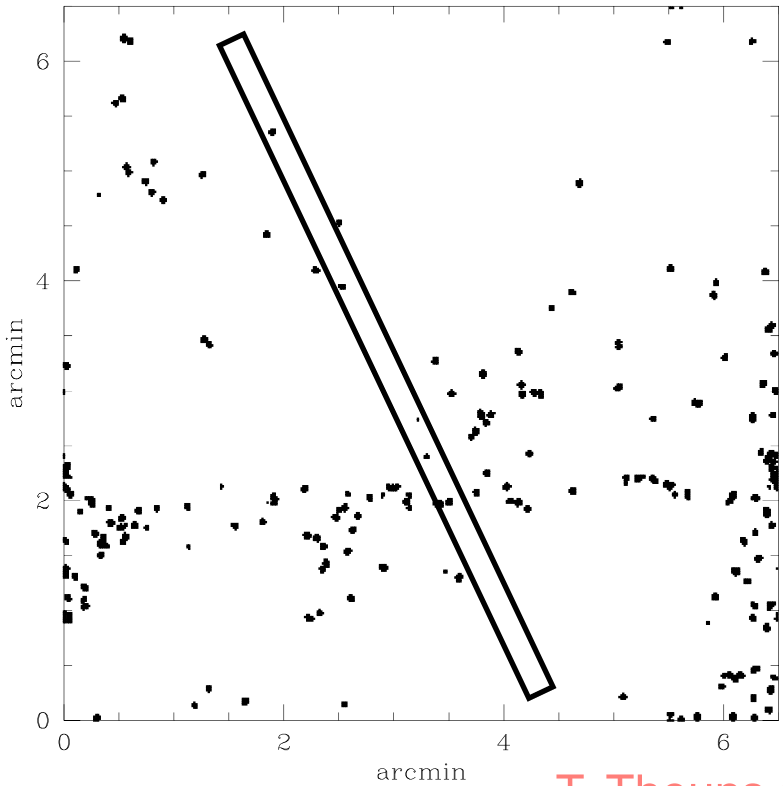
Con: lower dimensionality (essentially pencil-beam); “edge effects”

Put long slit on (judiciously chosen) blank piece of sky and expose for 100 hours !

LL emitters are much more numerous than, e.g., Lybreak galaxies

expect ~30 per unit redshift at z~3 on a typical long slit (Gould & Weinberg 1996)

need not worry about positioning the slit.

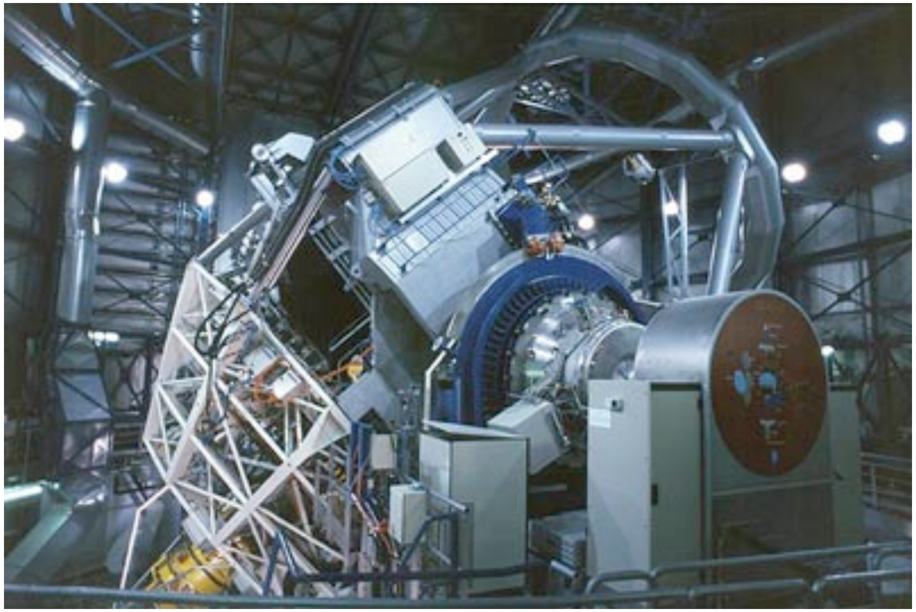


T. Theuns simulation

After several years of unsuccessful applications for observing time: ESO large program with VLT and FORS2 low resolution spectrograph (single 2” wide slit, VPH grism).

We are looking for extended emission:

insert in service mode and take advantage of bad seeing time (when nobody else wants the telescope).



ESO exposure resulted in 92 hours on source, median seeing 1.07”, 1σ surface brightness limit $8 \times 10^{-20} \mathrm{erg\ s^{-1} cm^{-2} arcsec^{-2}}$ in $1\ \mathrm{arcsec}$ aperture. Field of z=3.2 QSO previously observed by Bunker et al.

Unfortunately:

Prospects of detection based on ionizing UV background intensity of
J $\geq 10^{-21} \mathrm{ergs}^{-1} \mathrm{cm}^{-2} \mathrm{sr}^{-1}$

(from proximity effect (Scott et al 2000);
or escape fraction of ionizing photons from Lybreak galaxies (Steidel et al 2001))

but:

- Proximity effect measurements biased upwards

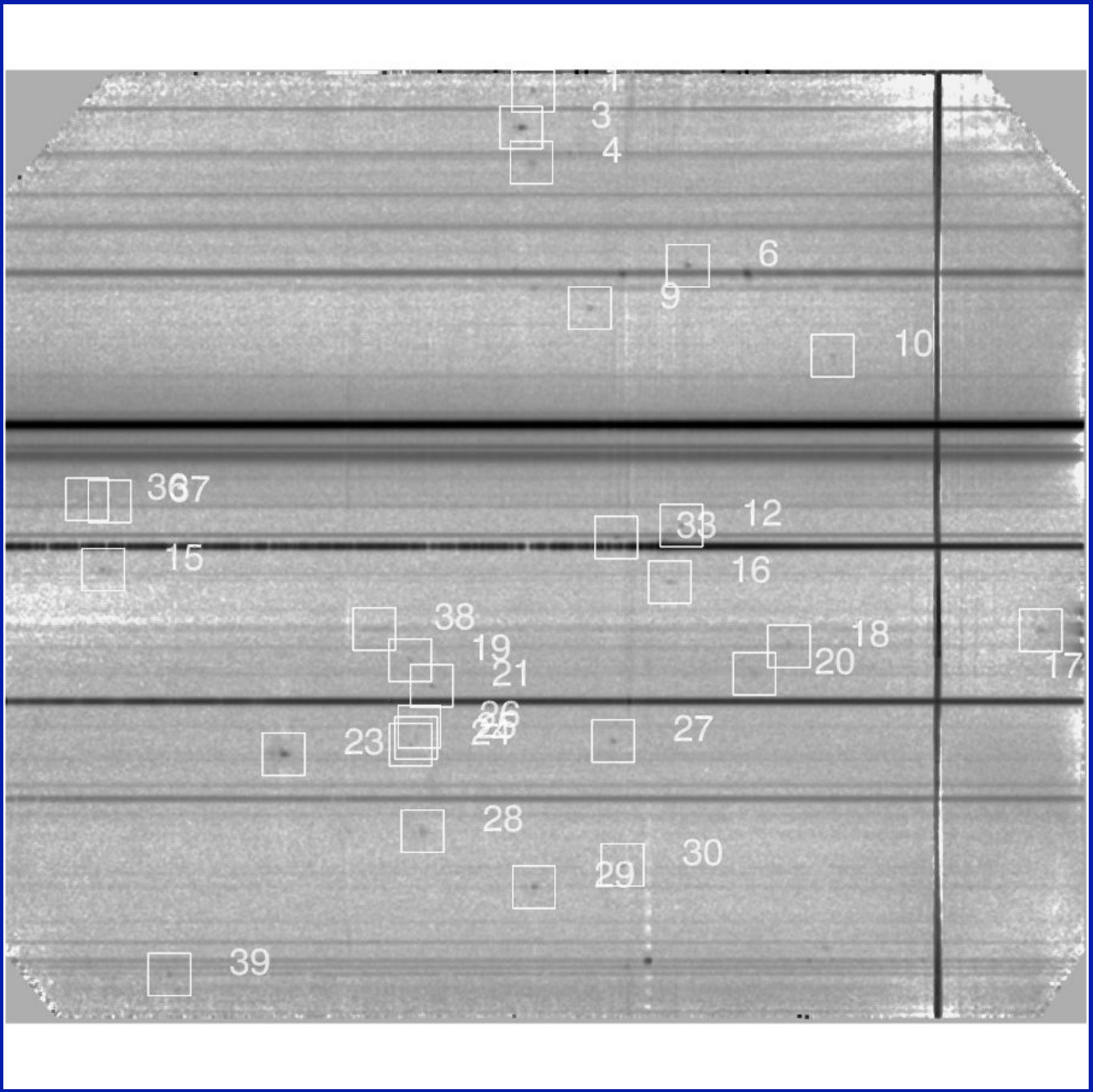
- Steidel et al result contradicted by more recent work.

Lyman alpha forest opacity suggest J only about 40% of the above value (Bolton et al 2005).

Cannot obtain a significant detection of the Ly alpha fluorescence signal !!

What we found instead ...

data reduction by
George Becker



27 single line emitters, mostly without detectable continuum, over 4457 - 5776 A.
Fluxes a few $\times 10^{-18} erg\ cm^{-2} s^{-1}$; mean redshift 3.2

expect 30 sources, find 27, BUT:

-SB higher by at least factors 2-4 and often much more than anticipated

-this is not the effect we were looking for

-evidence of outflows in some emission profiles

- no uniform glow - many profiles strongly peaked - internal source of UV ?

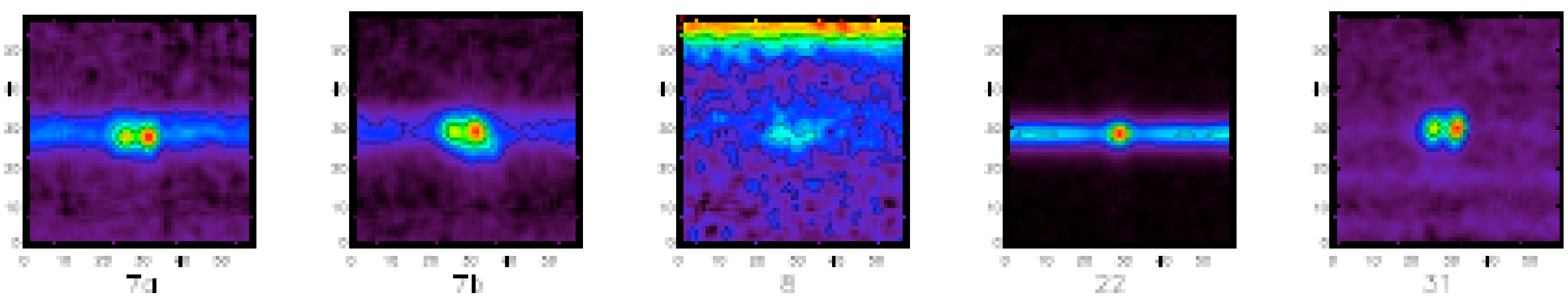
Optically thick HI regions already powered by star formation ?

Foreground galaxies, misidentified as high z Lyalpha ?

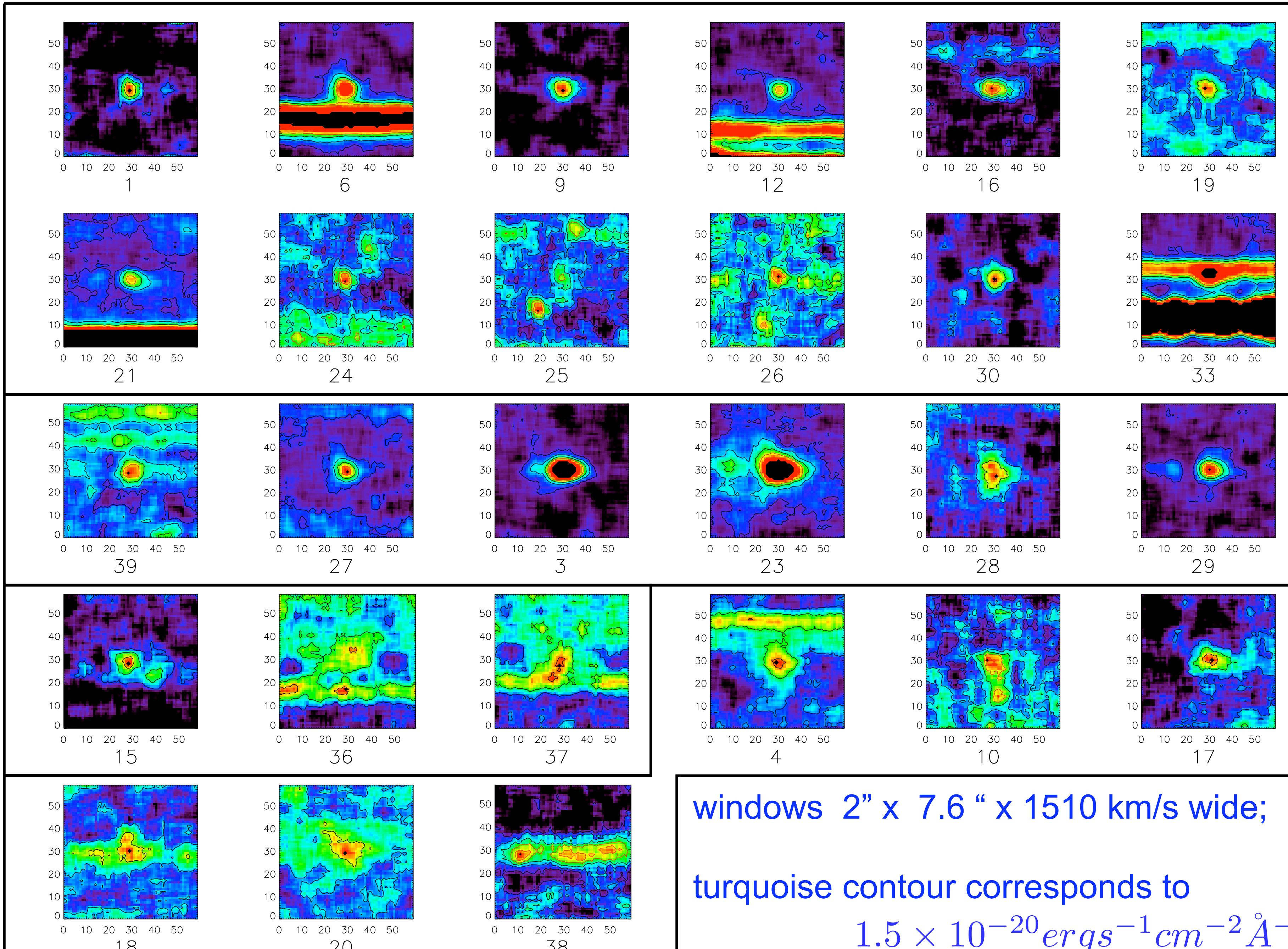
Identification of Lyman alpha emitters:

1) single emission line
2) none or point source continuum, discontinuity across emission line
3) co-incident with absorption redshift of background QSO in the field

Tricky, if faint.



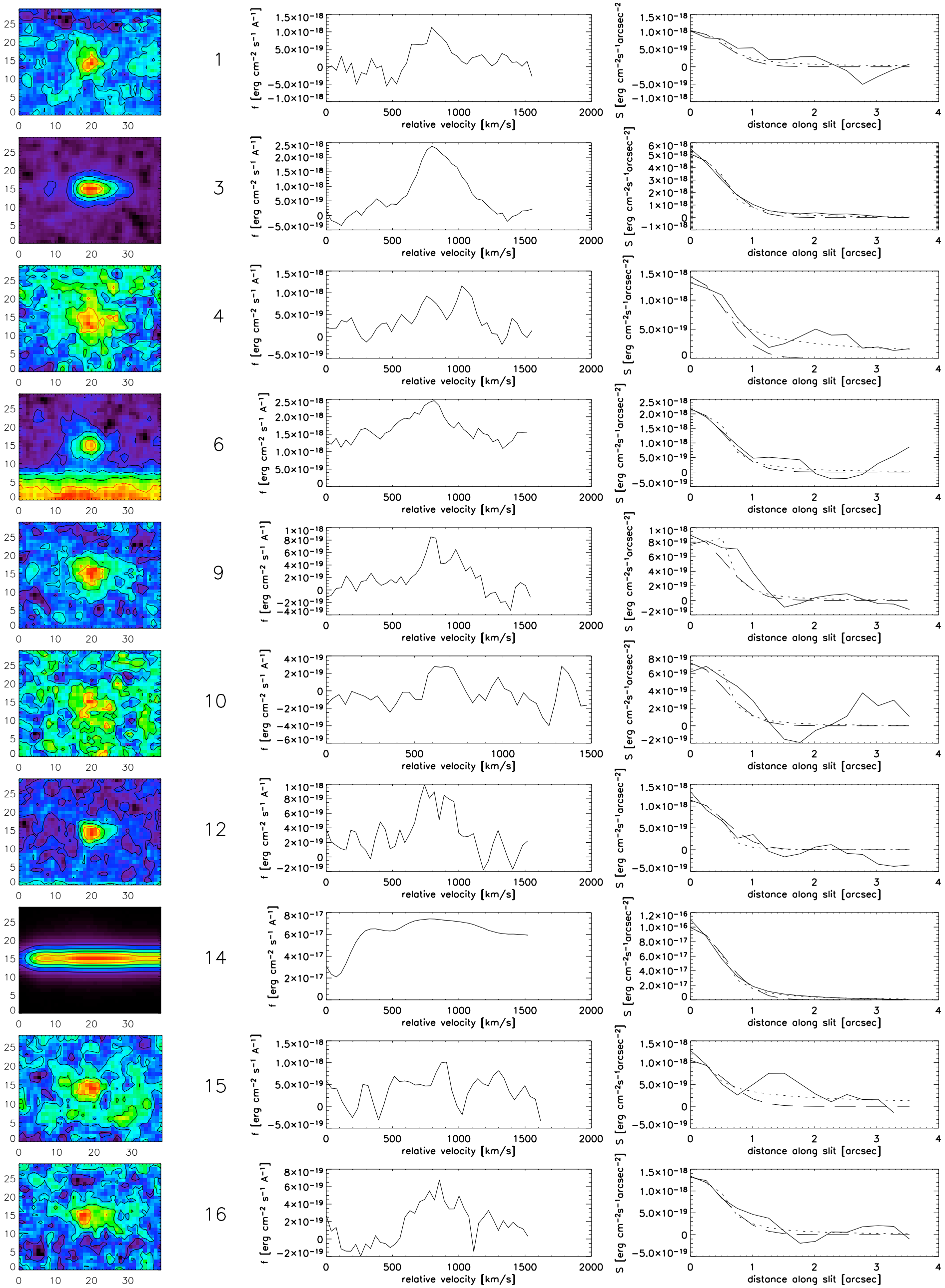
[OII] [OII] Hbeta Hgamma [OII]



windows 2” x 7.6 “ x 1510 km/s wide;

turquoise contour corresponds to

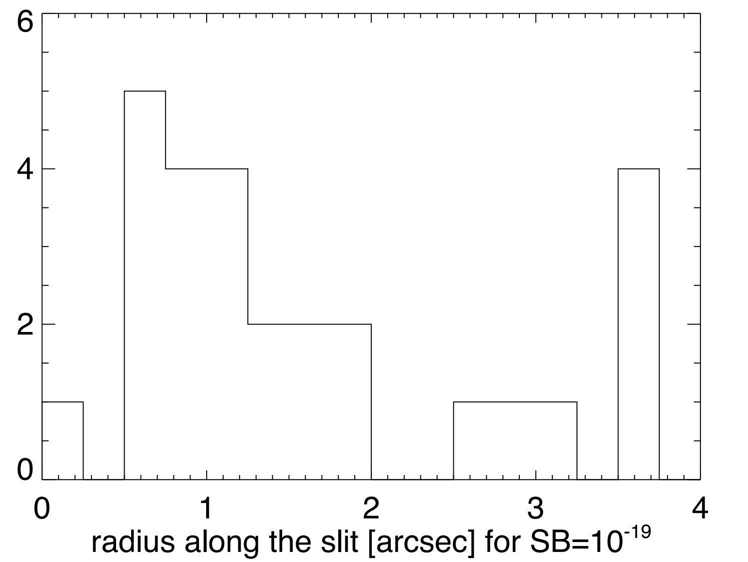
$$1.5 \times 10^{-20} ergs^{-1} cm^{-2} \text{Å}^{-1}$$



Objects often extended in velocity and space.

fit surface brightness profile with Gaussian w. power law tails

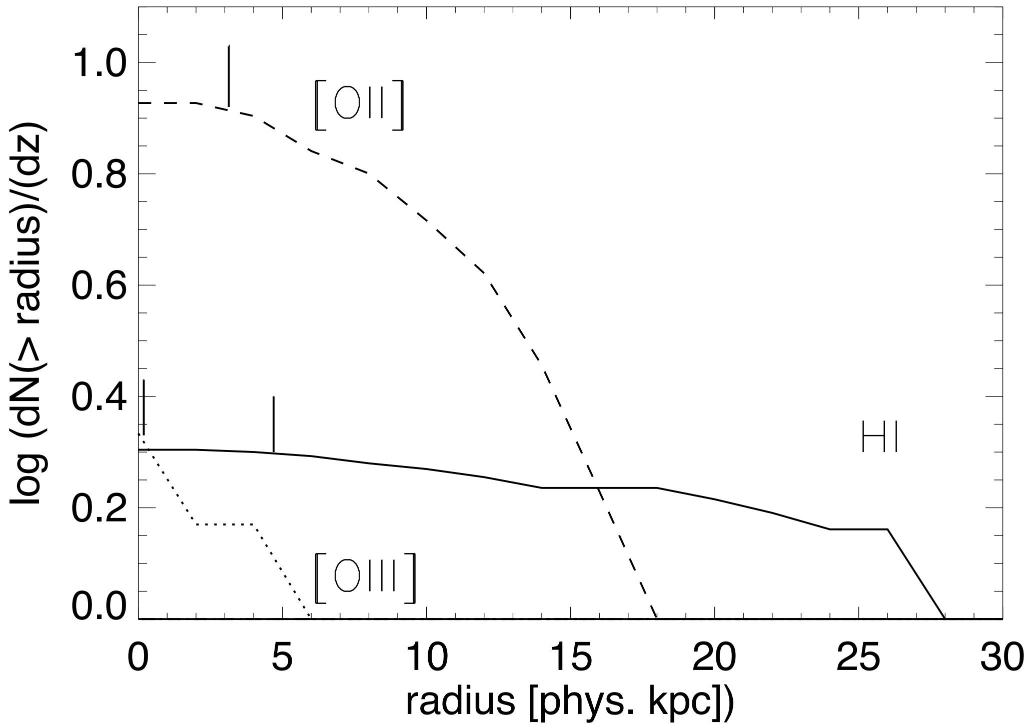
crude estimate of the radius := distance of the $1 \times 10^{-19} \mathrm{erg\ s^{-1} arcsec^{-2}}$ contour from the center.



Have comoving volume, number of objects, radius distribution, can compute

rate of incidence per unit redshift

$$\frac{dN}{dz} = \sum_i \frac{\sigma_i}{V_i} \frac{dl}{dz}$$



What are they ?

if [OII] 3726,3728 A ?: 0.2 < z < 0.55 $\frac{\partial^2 N}{\partial z \partial \Omega}$ = 302 arcmin^{-2}

$5 \times 10^{-3} \mathrm{M}_\odot\ \mathrm{yr}^{-1}$ < SF rate < $0.1\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$

- based on Trentham et al (2005) local LF for field dwarves, expect about one remaining object in our emitter sample.

- dN/dz of our emitters if [OII] is about 14 times that of local DLAS (e.g., Rao, Turnshek & Nestor 2006).

Unlikely that our sample is dominated by [OII], unless clustered.

if [OIII] 5007 A ? 0 < z < 0.16 $\frac{\partial^2 N}{\partial z \partial \Omega}$ = 412 arcmin^{-2}

- space density would be 40 times higher than that of local dwarf galaxies.

- dN/dz would be 7 times that of local DLAS.

-observed density of emitters in wavelength where [OIII] can and cannot be detected is similar.

Unlikely that our sample is dominated by [OIII].

What we think we are seeing ...

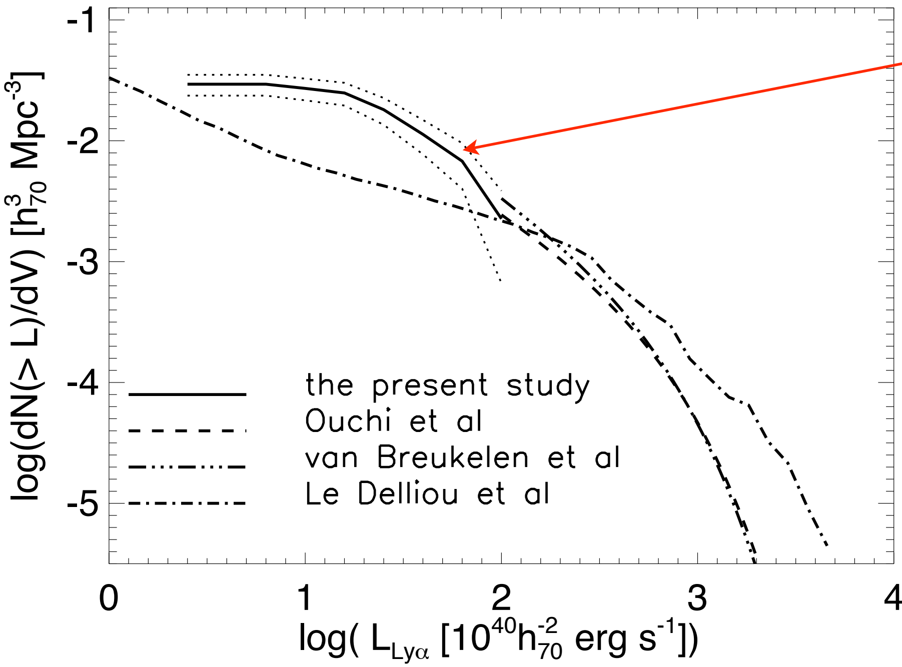
IF HI Lyalpha: (2.67 < z < 3.75) $\frac{\partial^2 N}{\partial z \partial \Omega}$ =98 arcmin^{-2}

- comoving density $3 \times 10^{-2} \mathrm{Mpc}^{-3}$

- total masses $> 3 \times 10^{10}\ \mathrm{M}_{\odot}$

- virial velocities $v_c > 50\ \mathrm{km\ s}^{-1}$ (Mo & White 2002, Wang et al 2007)

Cumulative Lyman alpha luminosity function:



Steepening of the luminosity function
wrt. shallower surveys
and modelling with constant Lya
escape fraction :

escape fraction (extinction) simply
may not be constant:

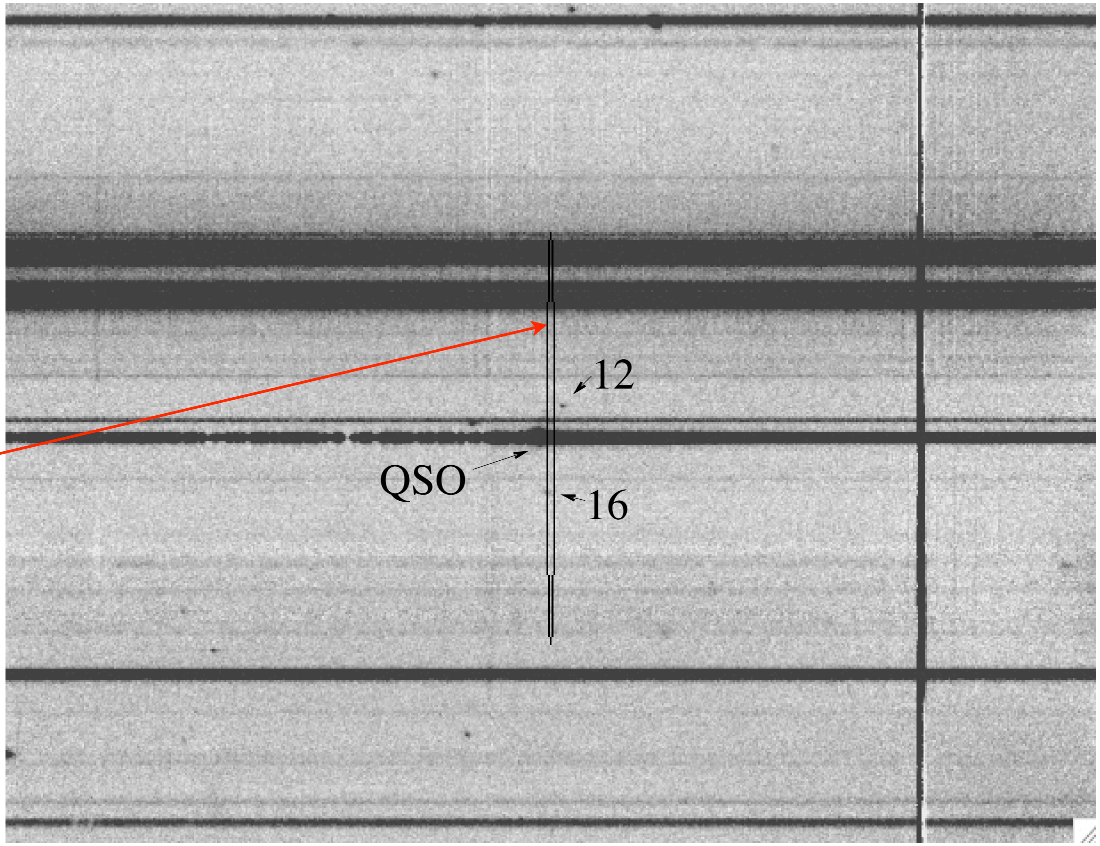
is dust diminishing towards fainter
objects?

What drives the emission ?

Global Lya fluorescence induced by UV background (Hogan & Weymann 1987) factor ten weaker (Gould & Weinberg 1996).

Fluorescence locally enhanced by the QSO in the field (e.g., Cantalupo 2005) explains at most 1-2 objects (QSO too faint).

“Zone of influence”



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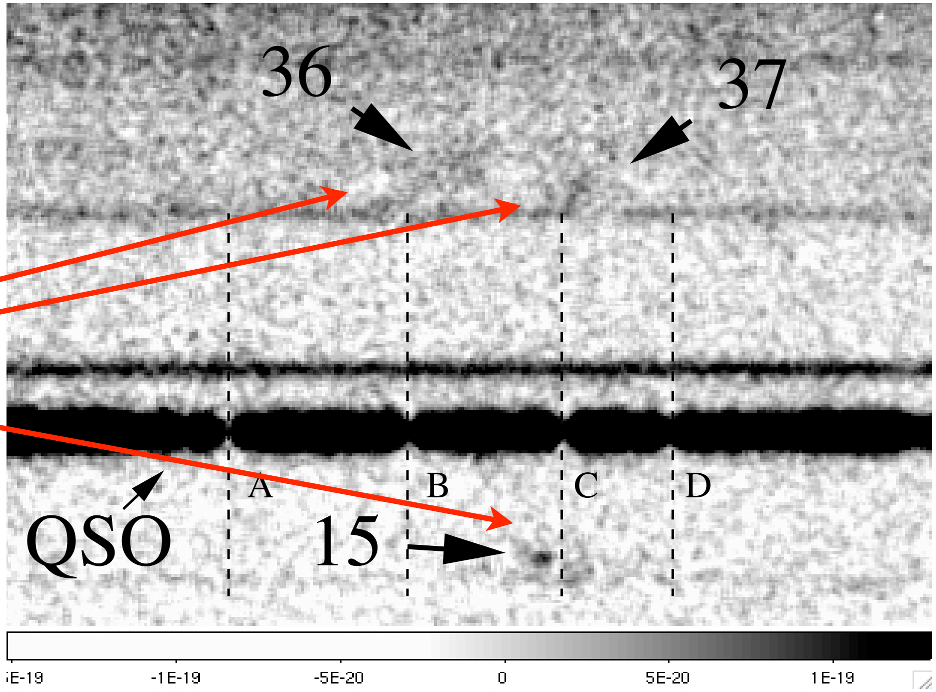
Cooling radiation (e.g., Dijkstra et al 2005) may explain a few objects, but most objects cannot be massive enough to be dominated by cooling radiation.

Star formation ok

Weird structures in emission and absorption

Cooling flows ? Outflows ?



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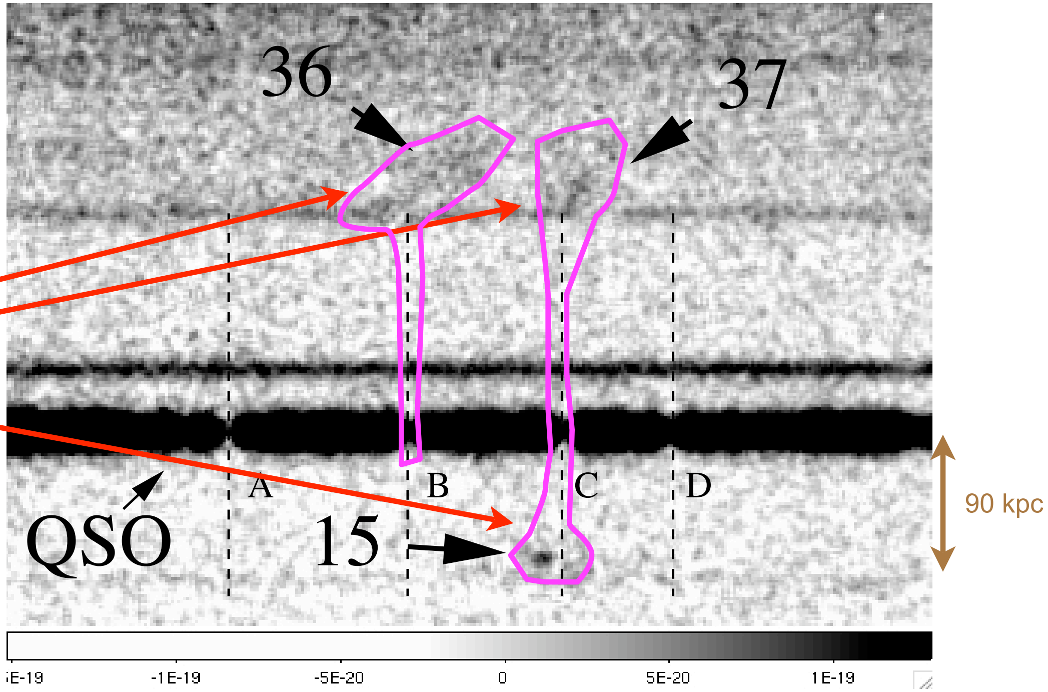


IF HI Lyalpha is induced by star-formation:

-- $7 \times 10^{-2} \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$ < SF rate < $1.5\ \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$

-SF rate density $1.2 \times 10^{-2}\ \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}\ \mathrm{Mpc}^{-3}$

- stellar mass within a Gyr $7 \times 10^{7}\ \mathrm{M}_{\odot} - 1.5 \times 10^{9}\ \mathrm{M}_{\odot}$

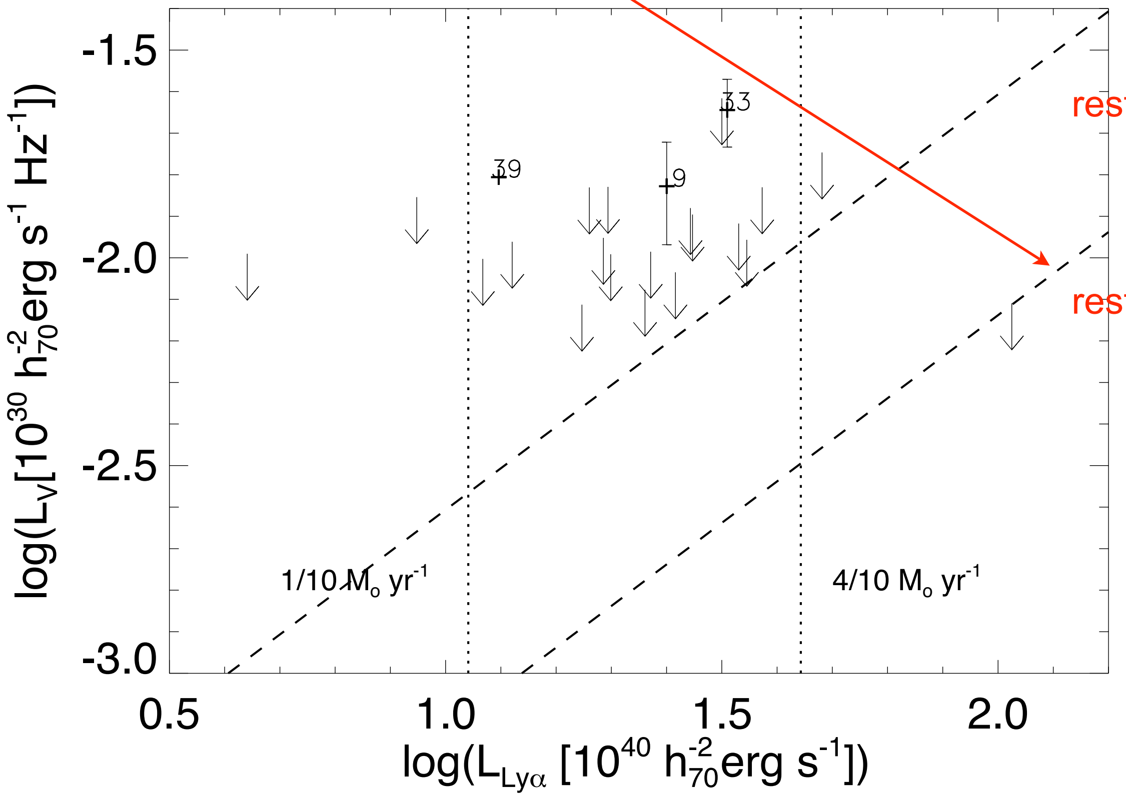
Have mostly only upper limits on continuum detections

Crude estimate of continuum based on conversion between SF rates and Lya, Luv fluxes:

$$L_{UV}(\mathrm{erg\ s^{-1}Hz^{-1}}) = 8 \times 10^{27}\ \mathrm{SFR}(\mathrm{M_\odot yr^{-1}})$$ Madau et al 2000

$$\mathrm{SFR}(\mathrm{M_\odot yr^{-1}}) = 9.1 \times 10^{-43} L_{Ly\alpha}(\mathrm{erg\ s^{-1}})$$ Kennicutt 1998, Brocklehurst 1971

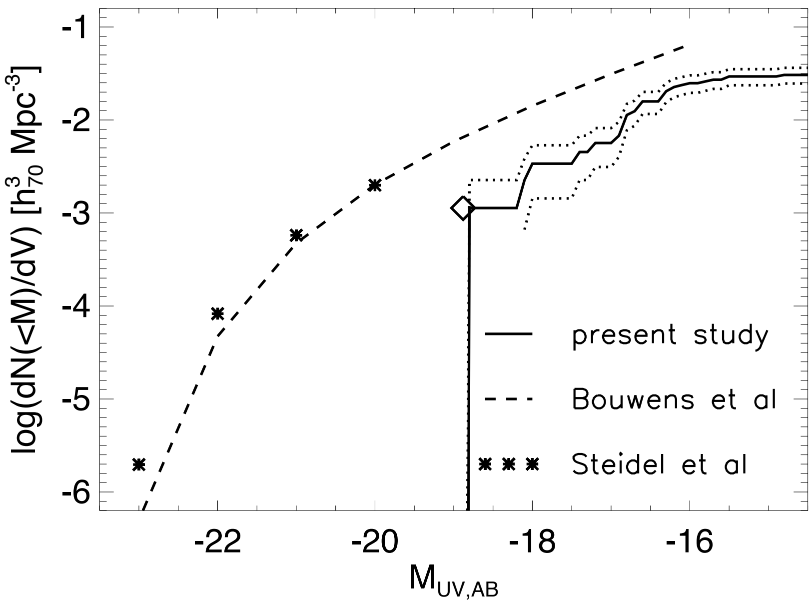
$$\log(L_{UV}) = -14.14 + \log(L_{Ly\alpha})$$



rest EW = 20 A

rest EW = 68 A

Convert Lya into “continuum magnitudes” and place objects into context of Hubble Ultra Deep Field (HUDF) (B band dropouts)



Little overlap with other ground based surveys

exactly one Lyman break galaxy in the field

account for 36 percent of B-dropout SF rate density.

Are we seeing the faint end of the HUDF high z population from the ground in Lya emission ?

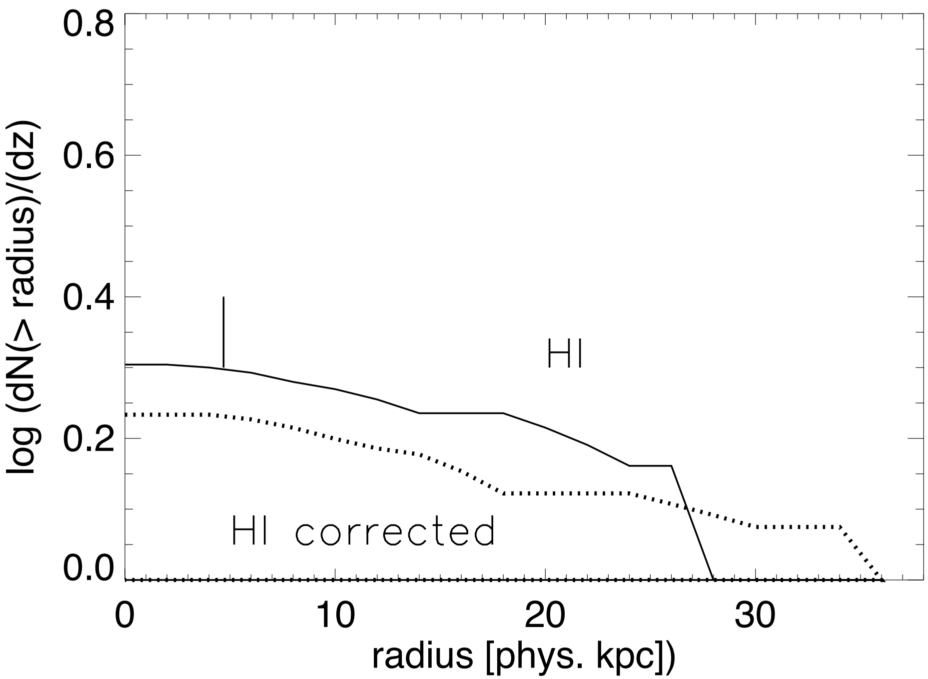
Caution: Plot only illustrative; precise magnitude range of our LF depends on EW width (logarithmically). Bouwens et al HUDF LF is for B-band dropouts, at somewhat higher redshift.

Rate of incidence dN/dz:

geometric cross section and number density

$$\frac{dN}{dz} = \sum_i \frac{\sigma_i}{V_i} \frac{dl}{dz}$$

(correct for finite sizes, slit losses)



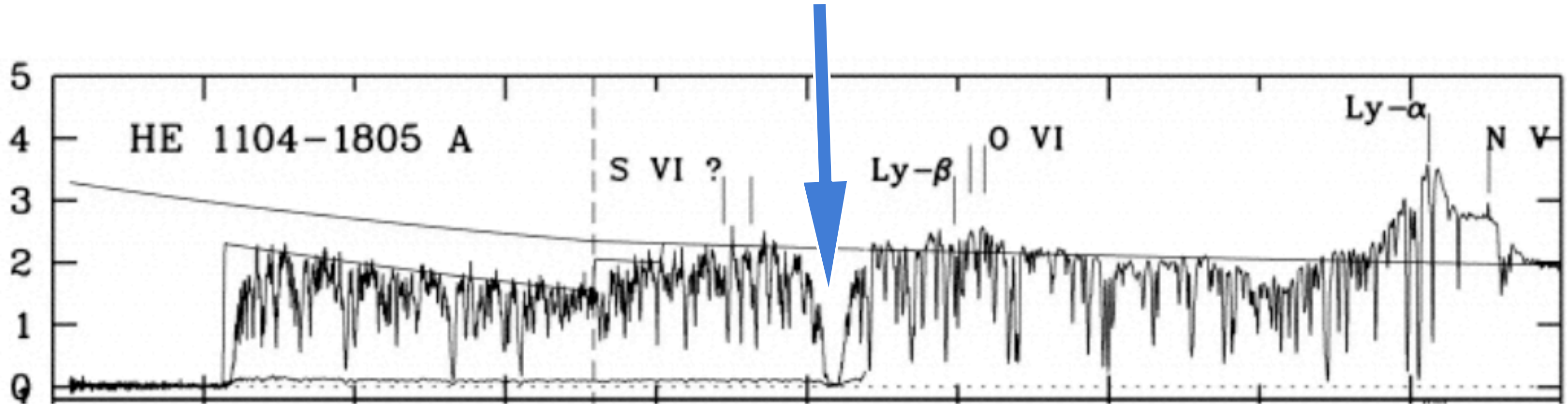
Find:

total dN/dZ = 0.23;

cf. dN/dz(DLAS)= 0.26 (e.g., Peroux et al 2005)

Are these the long-sought host galaxies of DLAS ?

What are Damped Lyman Alpha Systems ?

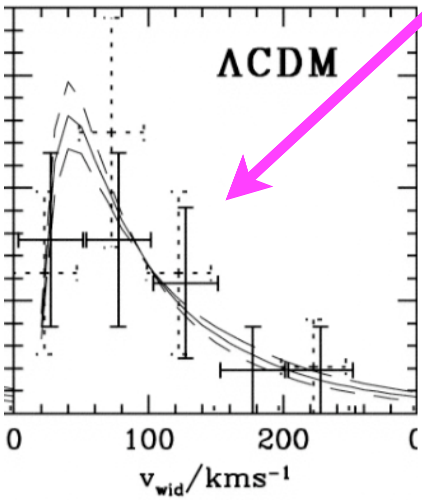


- First known population of high redshift galaxies (Wolfe & collabs.)
- dN/dz ~0.26 (e.g., Peroux et al 2005)
- main reservoir of neutral hydrogen (Wolfe & collabs)
- low metallicity (z ~ 1/10 - 1/100 solar) (many authors)
- very little dust (Murphy & Liske 2004)
- SFR comparable to Lybreak galaxies from [CII] 158um cooling (Wolfe et al 2003)
- surface density of star formation very low (i.e., star formation happens at best in a compact core (Wolfe & Chen 2006)

Kinematics and Modelling:

- large rotating disks (contradicting CDM) ? (Prochaska & Wolfe 1998)
- merging dwarf galaxies (in agreement with CDM) ? (Haehnelt, Steinmetz, MR 1998, 2000)
- winds from dwarf galaxies ? (Nulsen, Barcons & Fabian 1998)

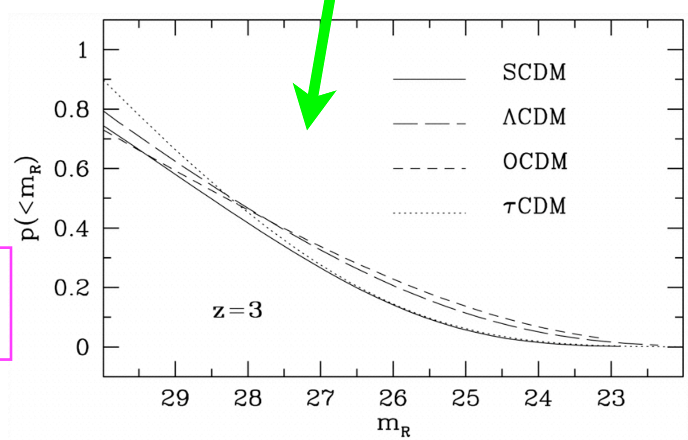
Fitting measured velocity widths of low ionization absorption complexes in DLAS

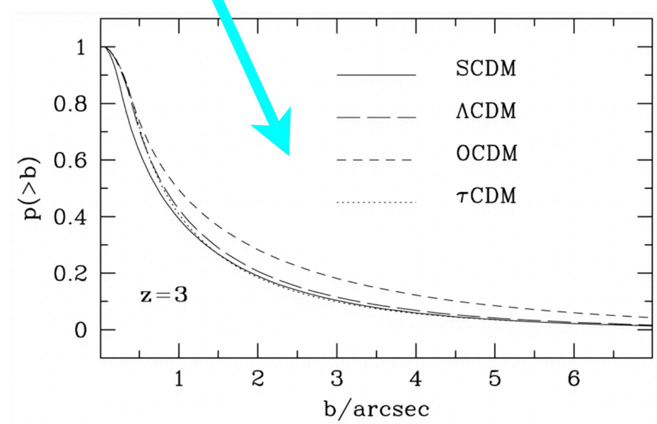


predict: - DLA cross section as a function of halo circular velocity

- luminosity and impact parameter distributions of DLAs

Haehnelt, Steinmetz, MR (1998,2000)





CDM predicts DLA host galaxies to be:

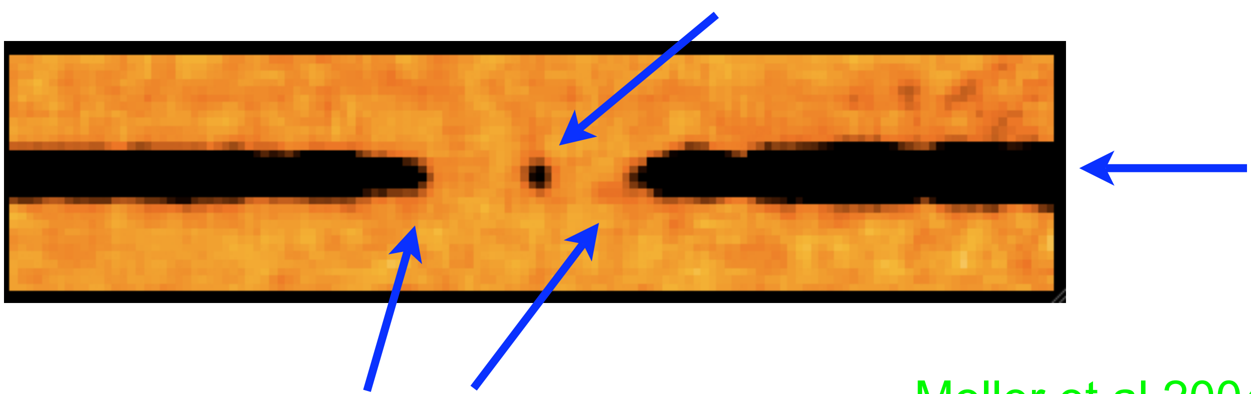
mostly small

mostly faint

mostly low mass

swamped by the light of the background QSO

The very few existing observations of DLA hosts bear this out:



Moller et al 2004

What Lya emitters and DLAS have in common

Close correspondence between emitters and DLAS:

both must be extended, optically thick gas

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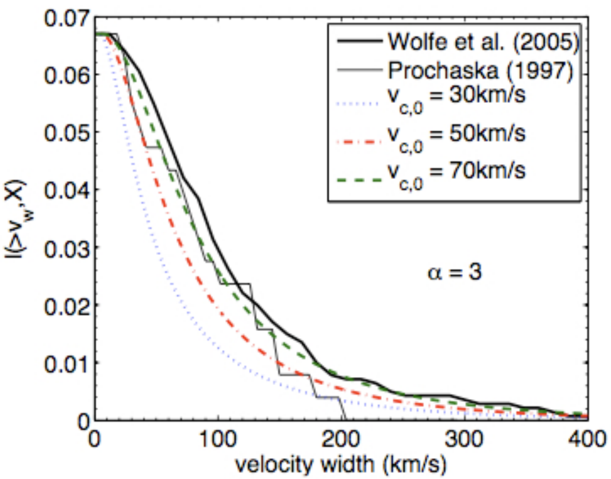
Confirms protogalactic clump model for high z QSO absorbers (MR, Haehnelt, & Steinmetz 1998, HSR 1998,2000), which are low mass, multiple objects later to merge into typical present day L* galaxies. (see also Barnes & Haehnelt).

Mutual constraints from Lya emission and damped Lya absorption properties:

Barnes & Haehnelt 2008

velocity width of DLAS

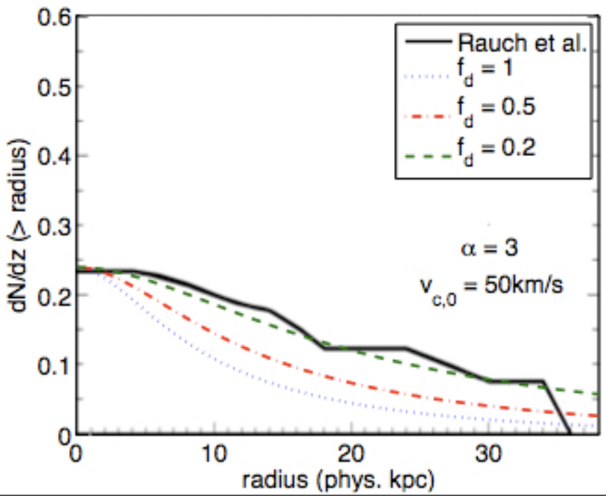


$$\sigma(v_c) = \pi r_0^2 \left(\frac{v_c}{200 \text{ kms}^{-1}} \right)^{\beta} \exp\left[- \left(\frac{v_{c,0}}{v_c} \right)^{\alpha} \right]$$

$\beta \approx 2.5$ (with help from hydro-symulations)

presence of tail of velocity width distribution tail requires that very small halos contribute little.

cumulative rate of incidence of Ly emitters vs absorbers



IF DLAS and Lya emitters are the same galaxies:

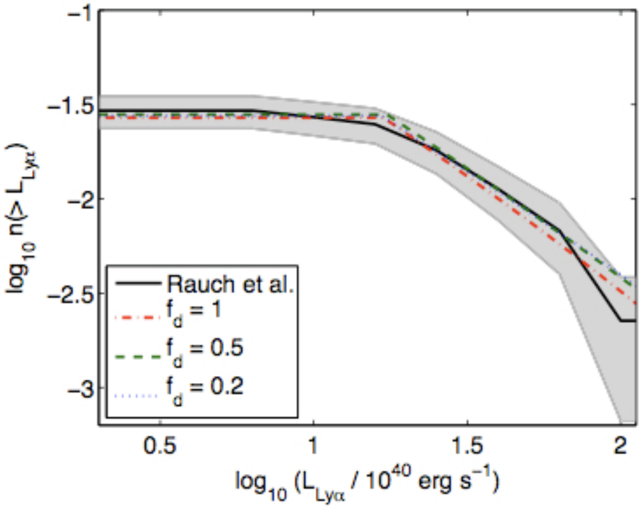
shape of observed dN/dz of Lya emitters as a function of size requires that Lya emitters are larger than DLAS (not surprising).

Then, at a given time only a fraction of DLAS can be active Lya emitters, to avoid having too many of them (duty cycle on the order of 20%).

Mutual constraints from Lya emission and damped Lya absorption properties:

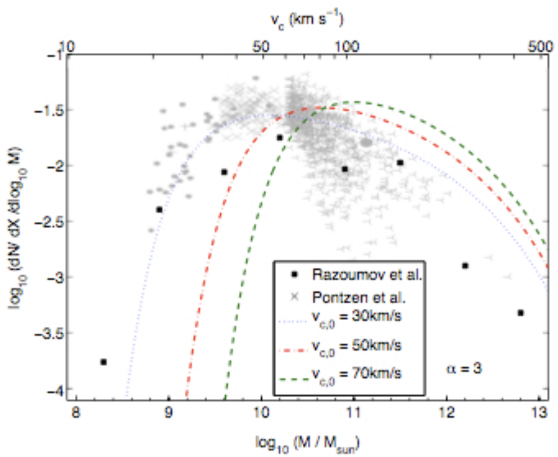
Barnes & Haehnelt 2008

Lya luminosity function



$$L \propto M, \text{cutoff } v_0 = 45 - 70 \text{ kms}^{-1}$$

dN/dz vs. halo mass



DLAS and Lya emitters can be made consistent with each other:

contribution of very low mass galaxies to cross-section and luminosity function is suppressed

duty cycle of 0.2 - 1 for Lya emission

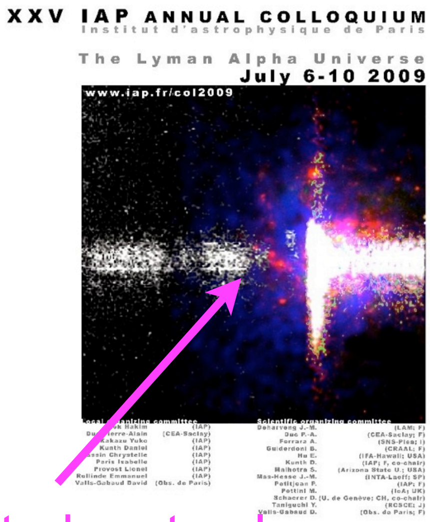
Lya emitters are somewhat bigger than DLAS

Results pose new questions:

What about outflows ? Are they important ?

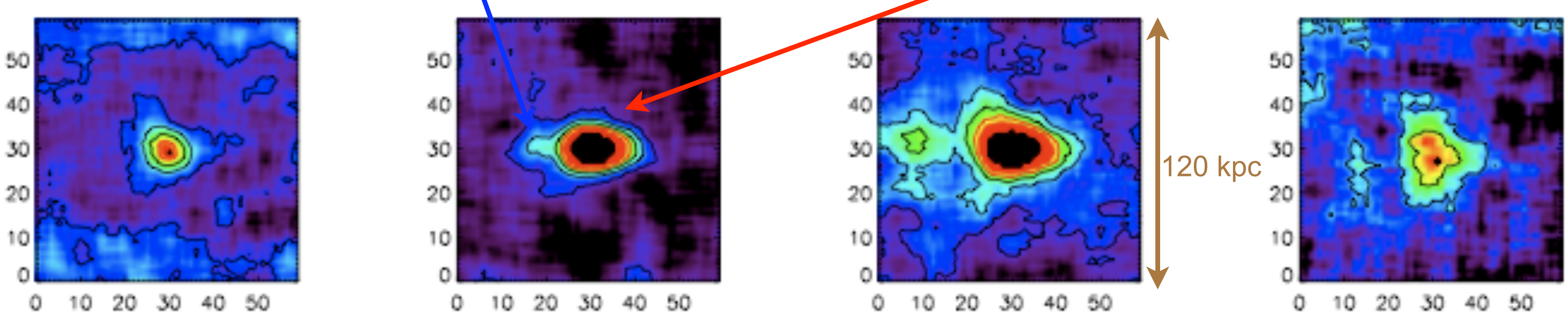
Increase the DLA cross-section? Spread metals ?
Suppress Lyalpha emission ?

Are these objects Lybreak gals w. superwinds ?

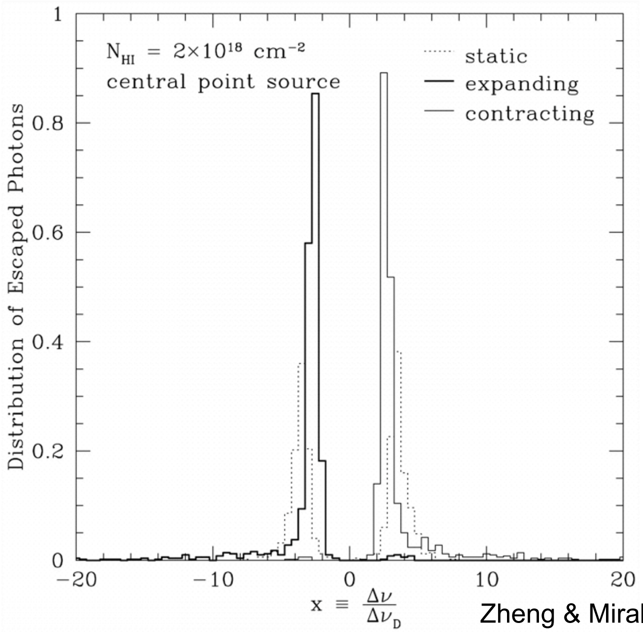


low z starburst galaxy

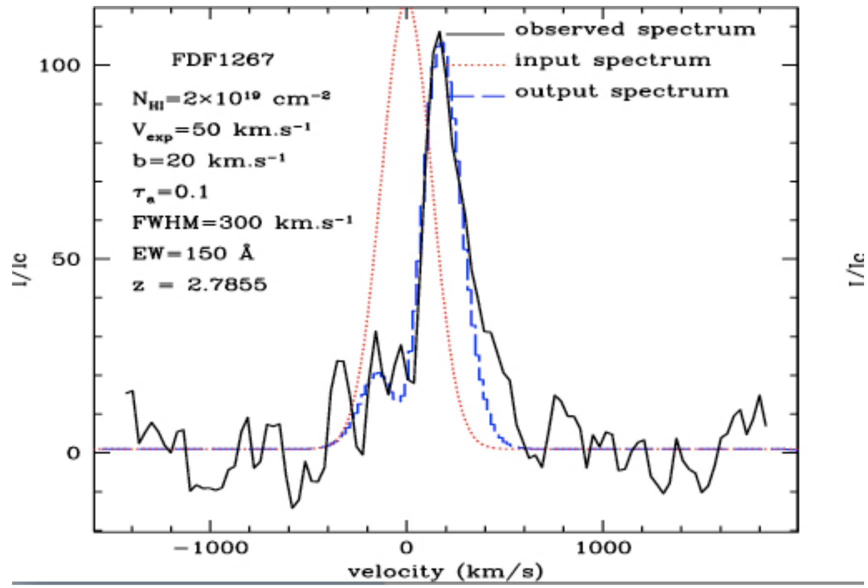
Four of the brightest of our objects:
Note small blue peak and dominant, anvil shaped red peak



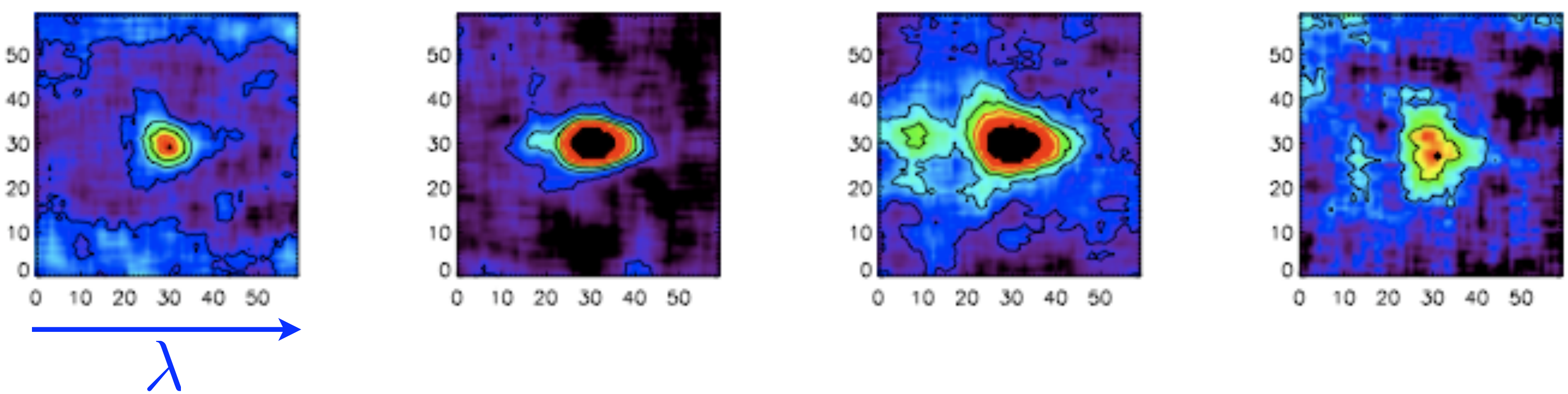
Simple radiative transfer models from the literature:



Zheng & Miralda-Escude 2002



Verhamme et al 2006



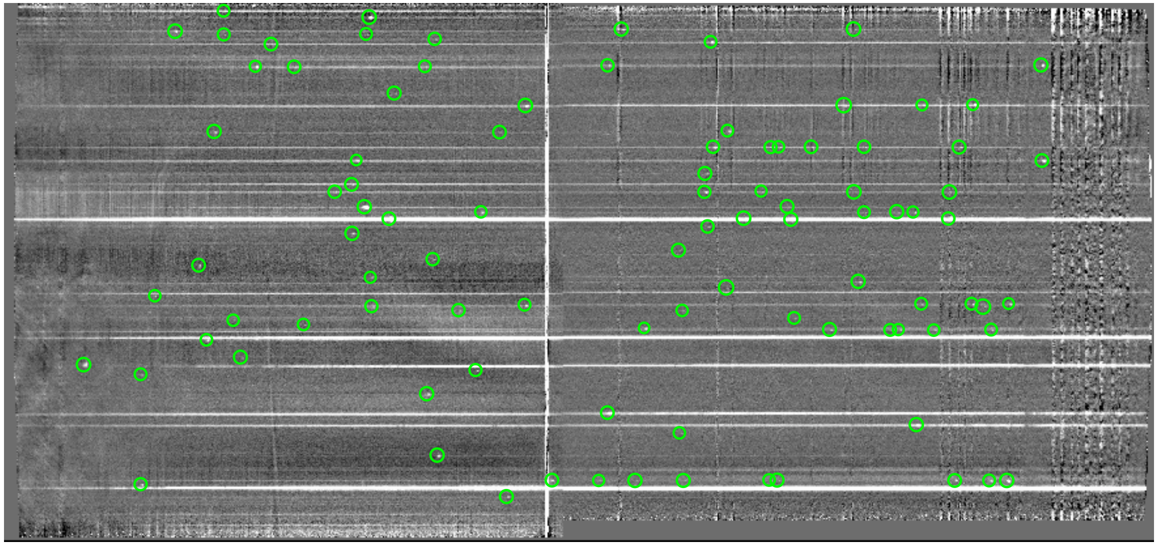
Models of slowly expanding shells appear to work for brighter objects

What Lya emitters and faint continuum sources have in common

How are Lya emitters related to continuum selected galaxies (i.e., stellar populations) ?

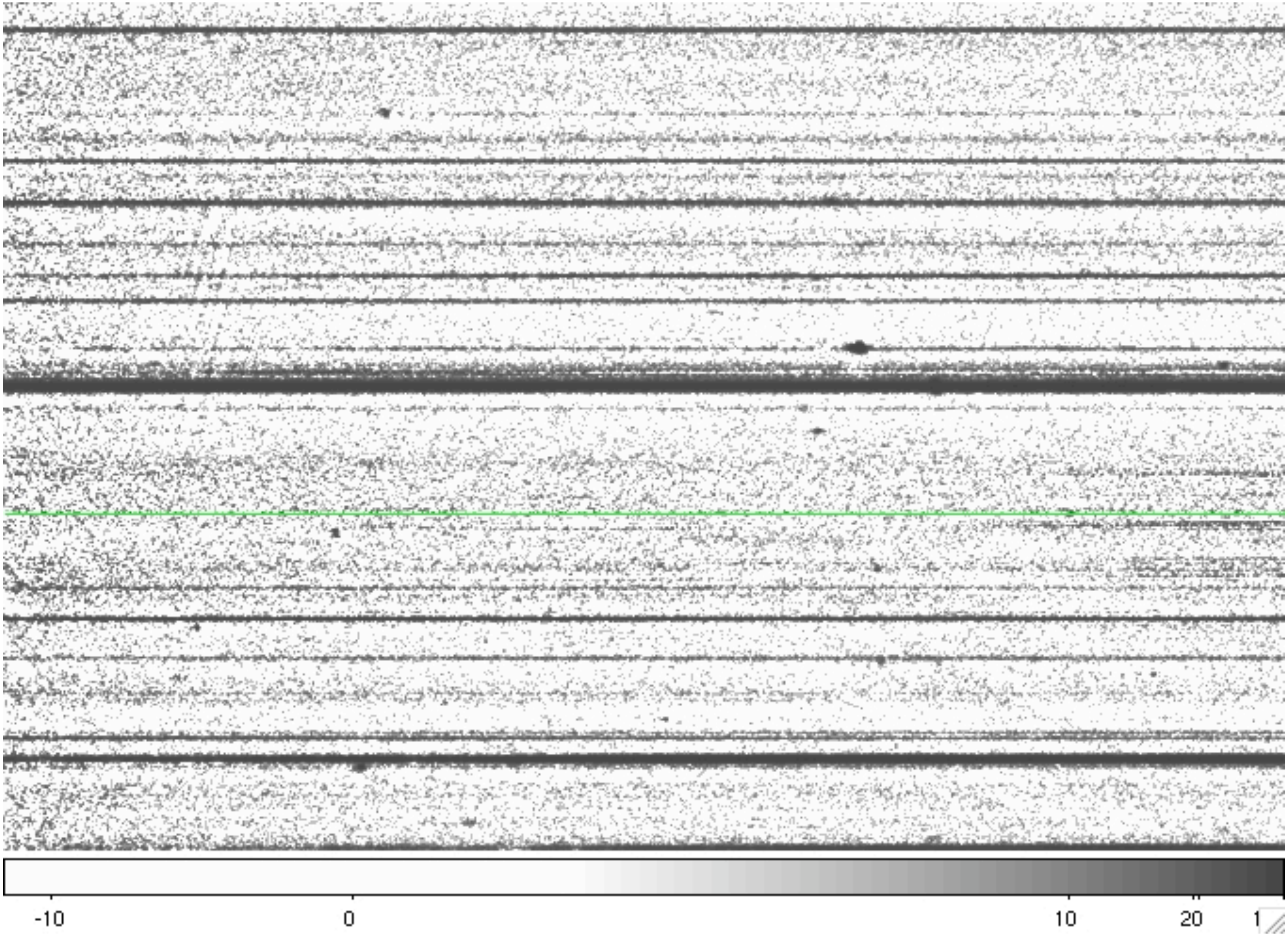
Link Lya to stellar populations:

perform longslit spectroscopy in fields with very deep broad band imaging (HDFN, HUDF) !

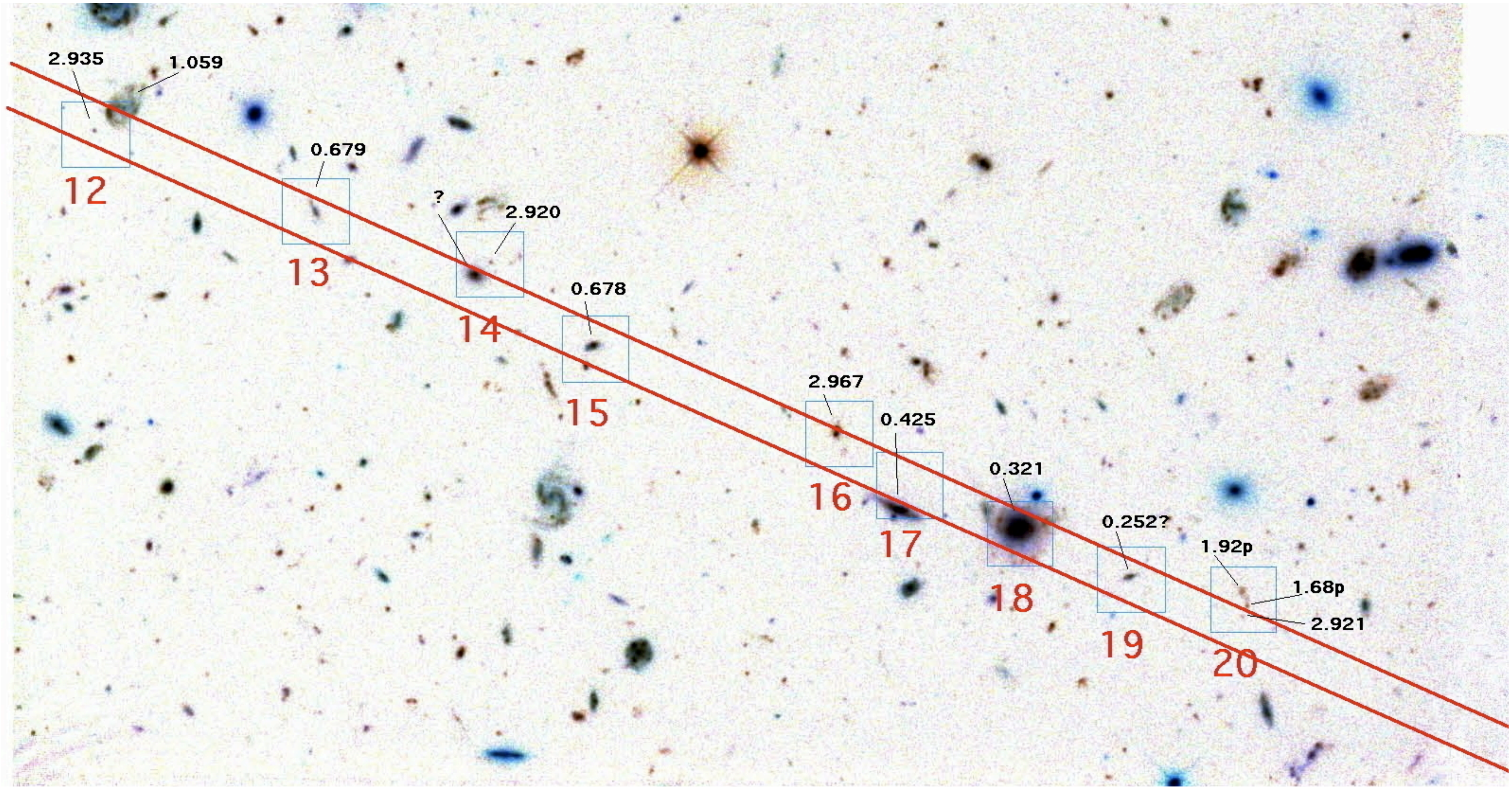


HDFN longslit with LRIS

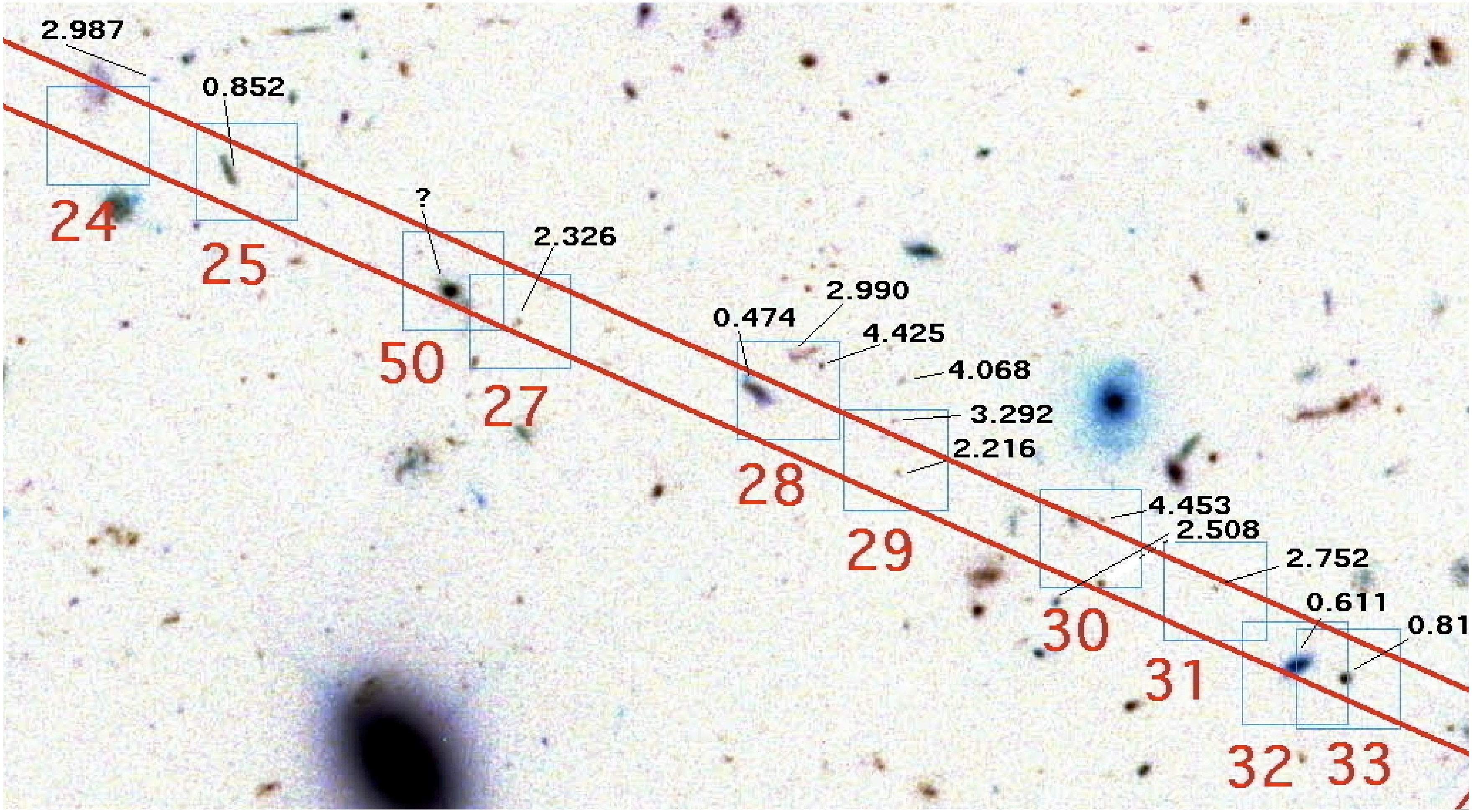
- Keck LRIS LS spectroscopy of the Hubble Deep Field North
- so far 20 hours on sky (w. Sargent & Becker)



Emission line selected continuum sources in the HDFN



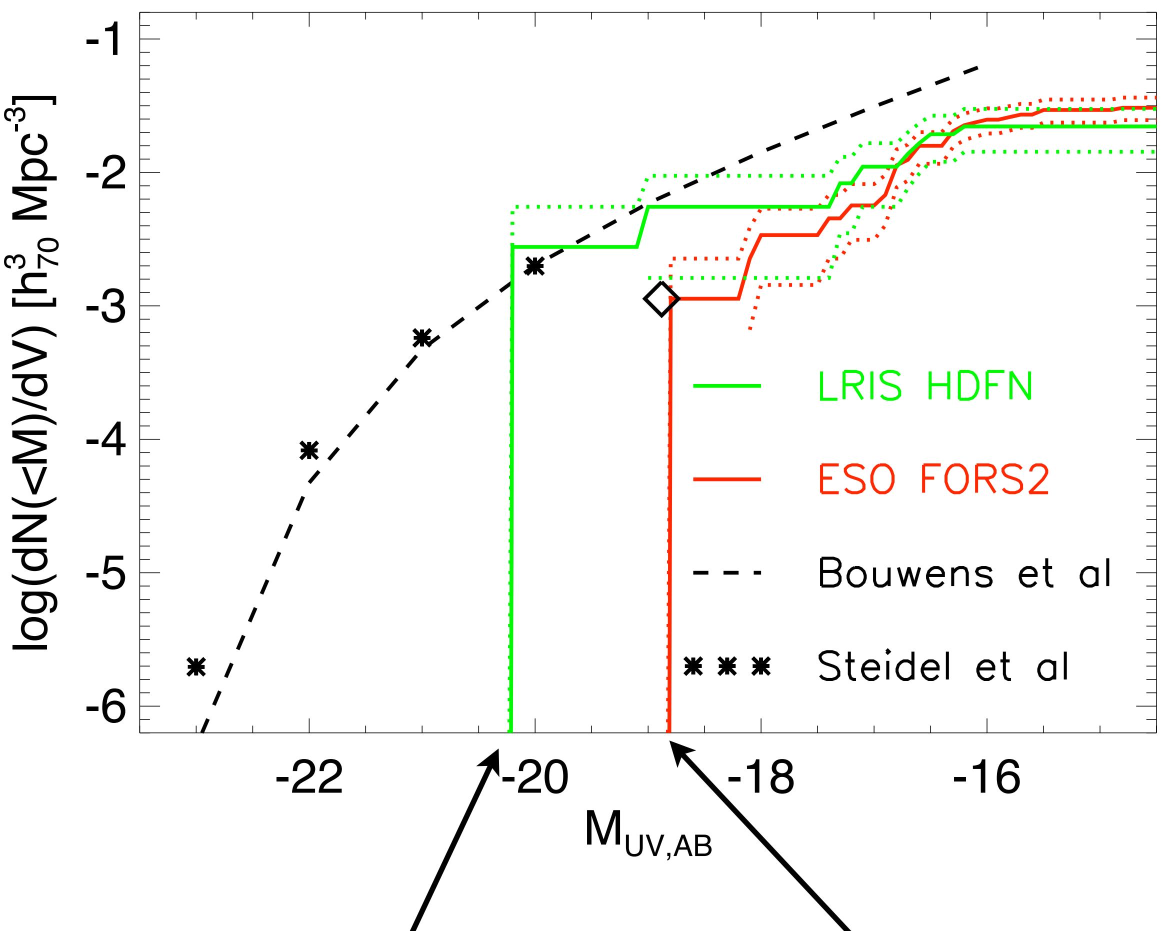
continuum counterparts, compact, faint;
truly high redshift sources.



8 secure Lya emitters in 2.2 < z < 3.7 on 165” long slit (362 comoving cubic Mpc).
Space density $> 2.2 \times 10^{-2} \mathrm{h}_{70}^{3} \mathrm{Mpc}^{-3}$!

None of them detected in U band, but all of them identified with compact faint broad band images. (F606 etc).

rest frame UV continuum magnitudes for Lyman alpha selected galaxies



magnitudes converted from Lyalpha

magnitudes directly from HDFN catalogs

Conclusions

We discovered a population of faint Ly alpha emitters with high space density (25x as common as all other galaxy types detected from the ground);
The objects have low star formation rates, and probable low masses, and stellar counterparts;

are we finally seeing typical high z starforming gals ?

Emitters are the likely counterpart of DLAS and optically thick QSO absorbers (cross-section, low metallicity, SF rate, heating rate)

map the bulk of the neutral hydrogen in the universe in emission!

progenitors of present day Milky Ways likely to be drawn from these objects.

Ground-based spectroscopy can (in principle) go deeper than space-based imaging (high sky-suppression, long exposure times are key)

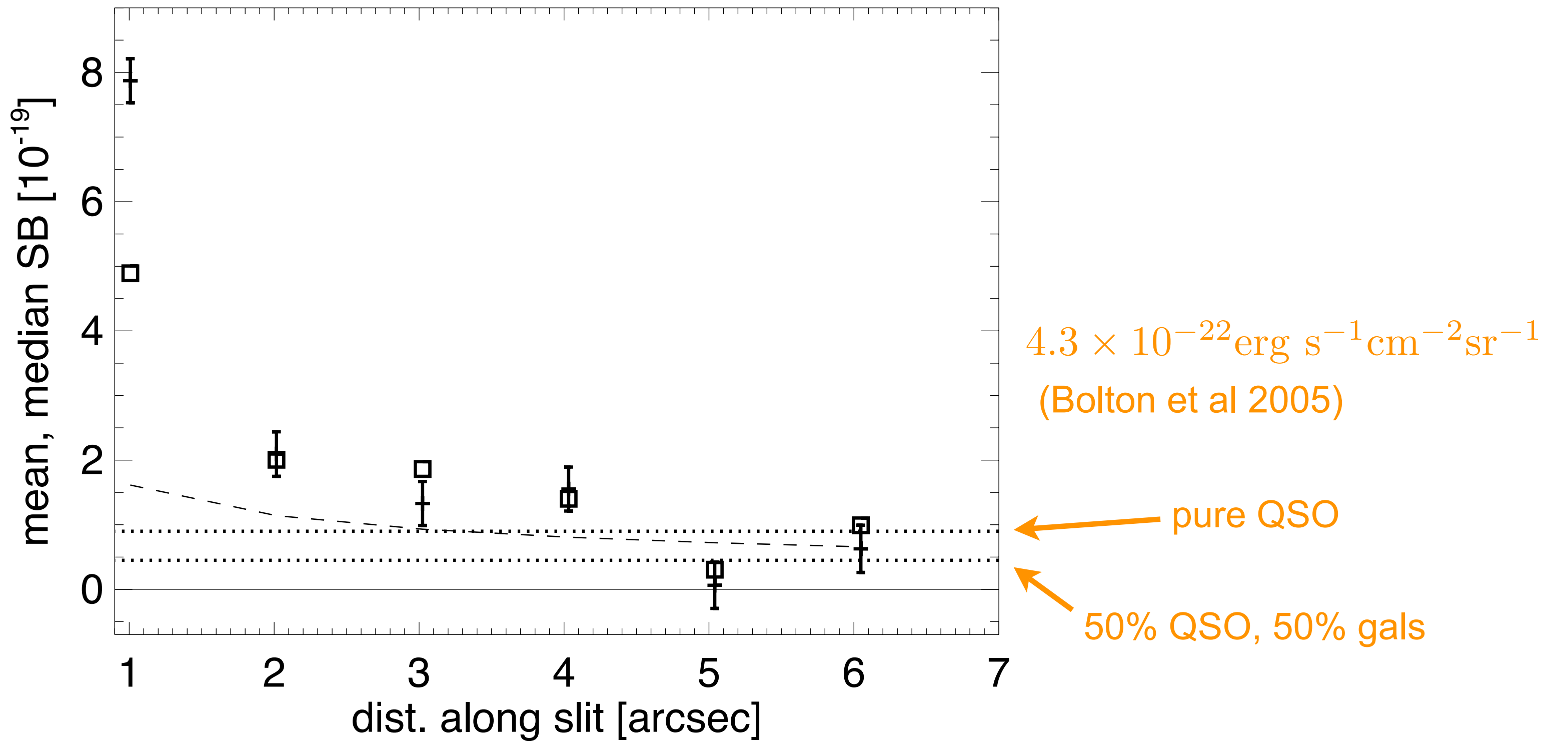
Will we soon be able to see “all” starforming galaxies ?

What about Lya fluorescence ?

found already ~30 objects but all factor > 2-4 brighter than expected

most Lyman limit patches have some star formation !?

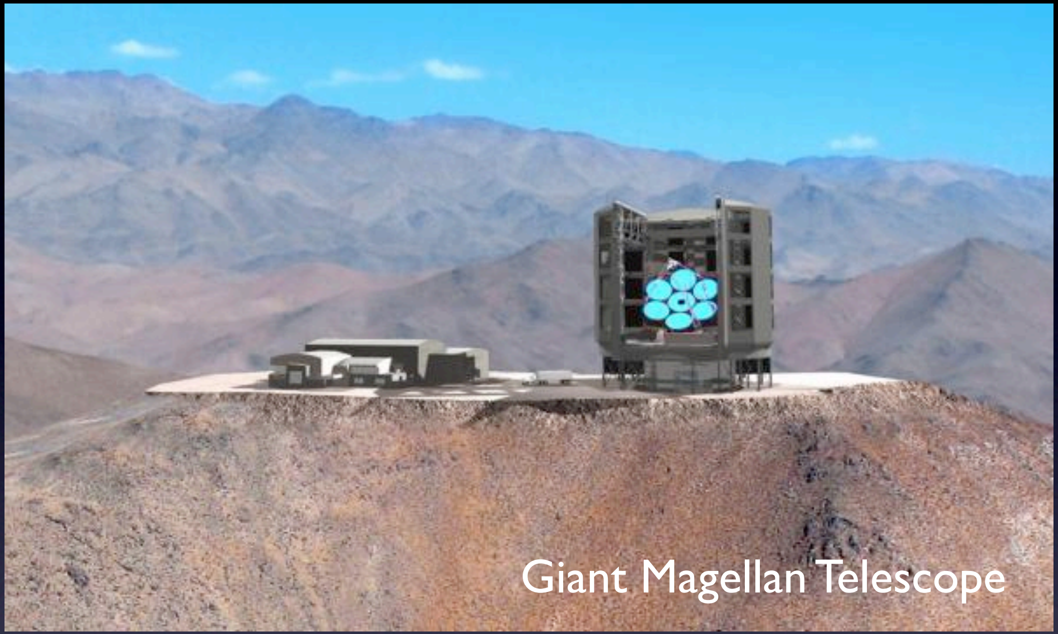
mean (error bars) and median surface brightness for stacked objects



extended emission out to r = 4” at $2 \times 10^{-19} erg\ cm^{-2} s^{-1} arcsec^{-2}$

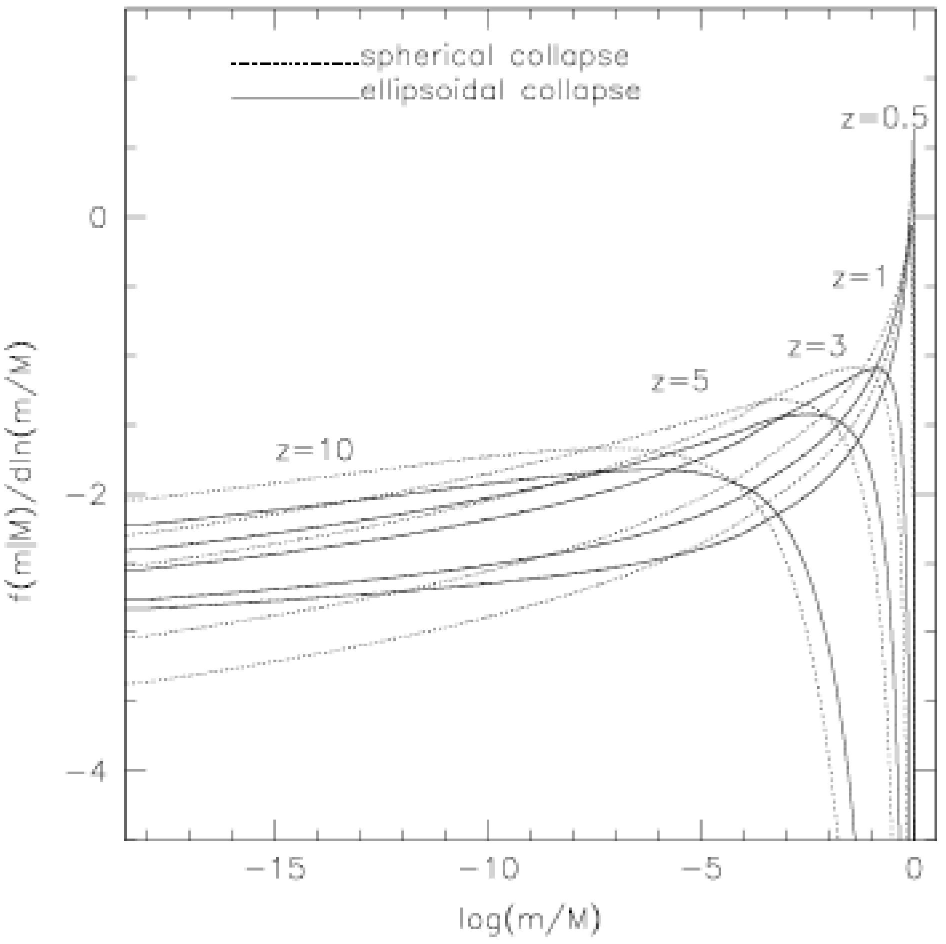
The Future

- longer exposure times
- bigger telescopes
- smarter spectrographs
- (IFU, tunable filters)



- cosmological simulations with radiative transfer
- understand star formation vs. Lya (duty cycle, Kennicutt relation)
- explore diagnostics of Lya emission (in/out flows, dust, spatial distrib.)

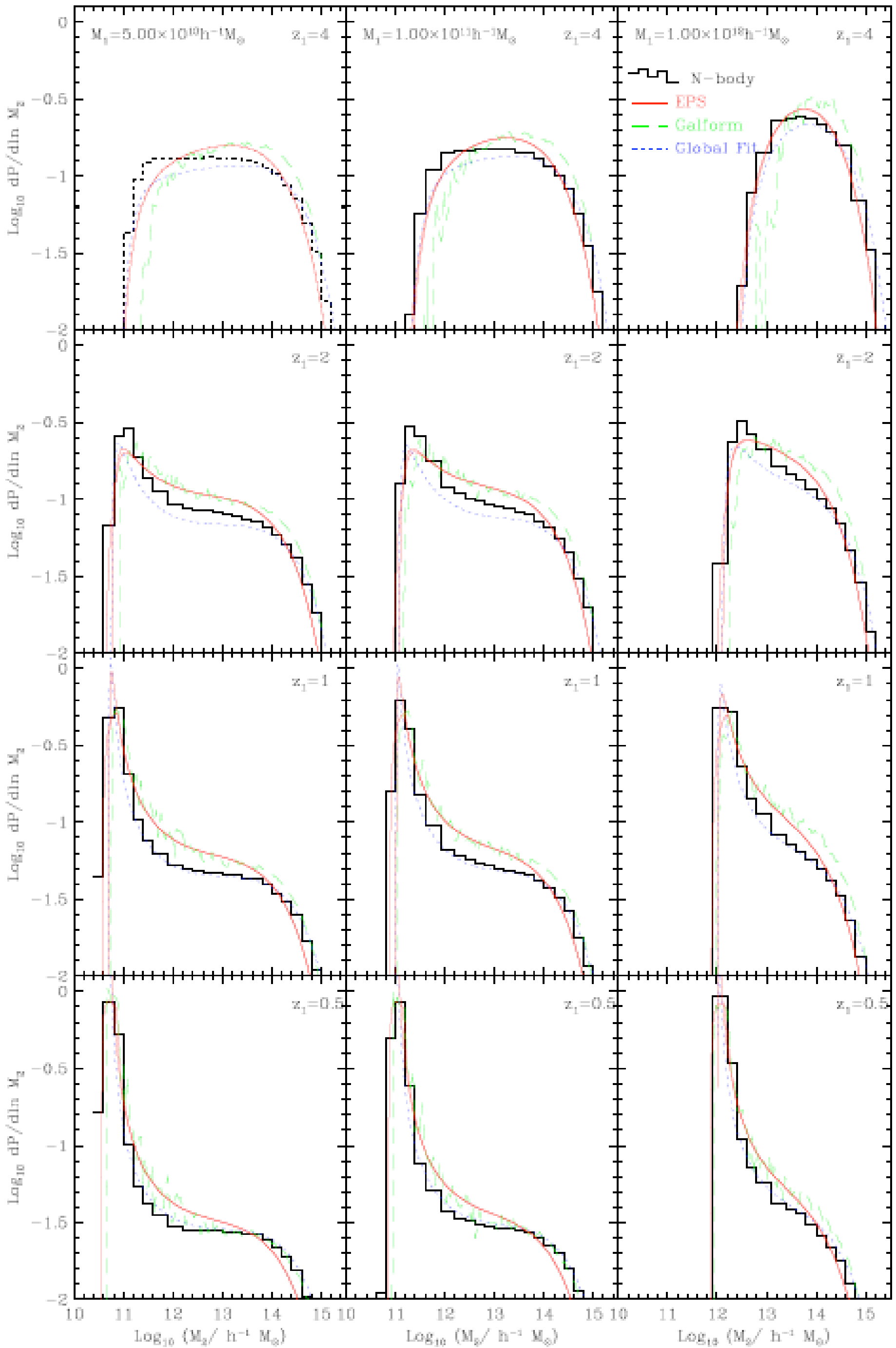
Giocoli et al 2007



conditional mass function for $10^{12} M_{\odot}$ halo

Distribution of final halo masses

Cole et al 2007



halos end up predominantly in present day halos less than 10-100 times more massive conditional mass function for halo

Cole et al 2007