Lyman-α emitters --- Lyα in SF galaxies

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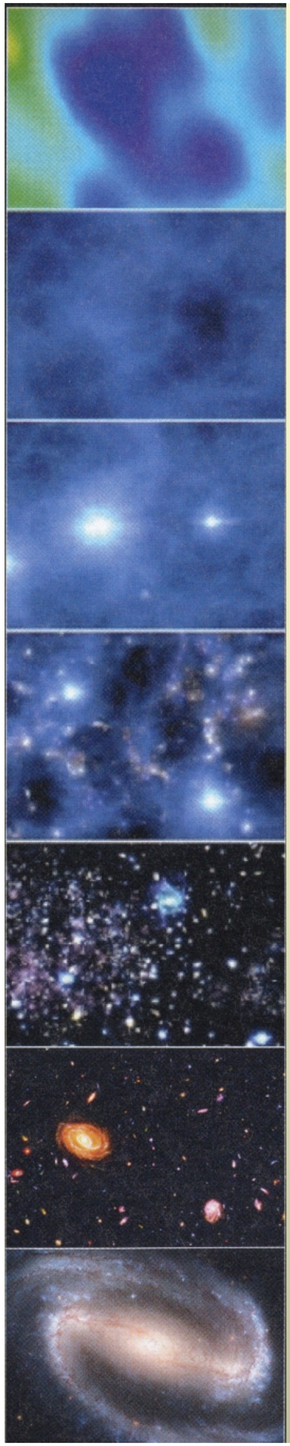
Main collaborators: Anne Verhamme (ObsGE), Hakim Atek (IAP), Christian Tapken (MPIA)

- Overview:
  - –high-z star forming galaxies, LAE samples
  - –LAE, LBG populations at different redshift
  - –LAE properties (stellar populations, age, dust…)
- LBG and LAE at z~3: a unifying scenario
- Insight from radiation transfer modeling
- Conclusions and perspectives

- Verhamme, Schaerer, Maselli (2006, A&A 460, 397)
- Schaerer (2007, arXiv0706.0139S)
- Schaerer & Verhamme (2008, A&A, 480, 396)
- Verhamme, Schaerer, Atek, Tapken (2008, arXiv:0805.3601)



Sources of Lyα emission

Observed in:

- AGN
- Radiogalaxies
- Sub-mm galaxies
- Lyman Break Galaxies
- Lyα Emitters (LAE, >20
- DLA
- Lya blobs (LAB)
- Nearby starburst galax
- …

What todo with Lya ?

-Redshift

-SFR

-Stellar populations

-Peculiar EW --> PopIII?

-ISM/outflow properties

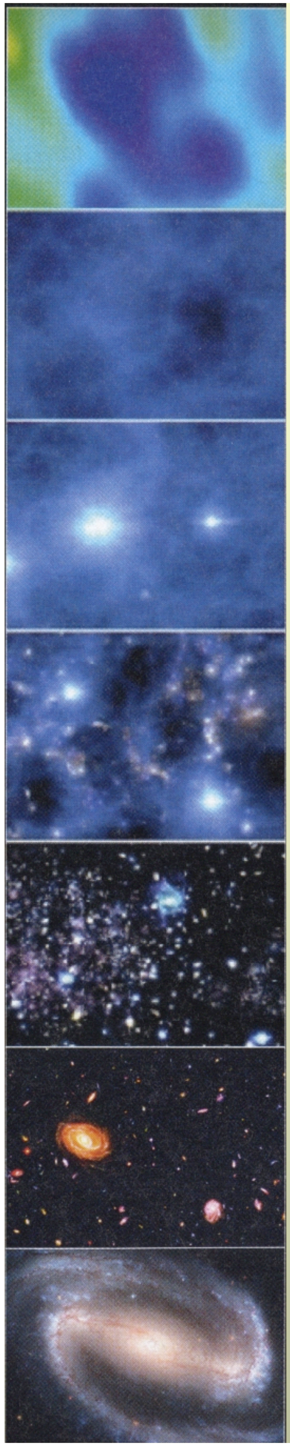
-IGM

-LF --> reionisation

…

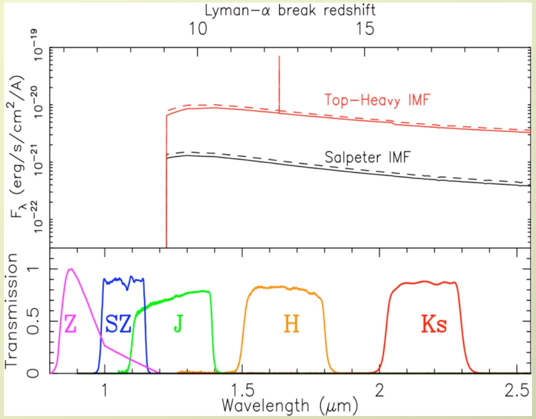
Origin:

- Recombination radiatio
  from stellar photoionisation --> starbursts
  or non-thermal radiation
- Cooling radiation from cold accretion
  (protogalaxies?)
- Fluorescent radiation (IGM?)



High-z starburst samples

Lyman Break Galaxies (LBG)

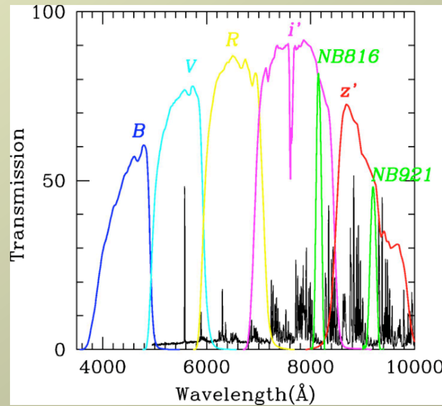


Selection: 1) Lyman discontinuity

• Broad-band (continuum) selection

• Spectroscopic follow-up

Lyα Emitters (LAE)



2) Strong Lyα line

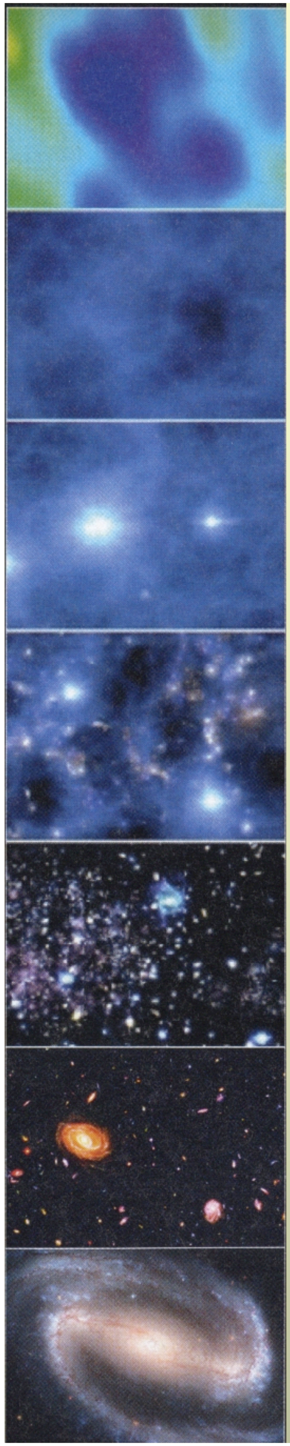
• Narrow-band excess + drop-out (most surveys)

Other techniques:

• blind spectroscopic searches (***longslit***: e.g. Ellis et al. 2001, Stark et al. 2007; ***large IFUs***: e.g. van Breukelen et al. 2005)

• Combined NB+multi-slit spectroscopy (Crampton & Lilly 1999, Stockton 1999, Martin et al. 2008)

• Grisms: e.g. ACS, GALEX



(Large) LAE samples - after long searches…

Hawaii group:

• Cowie & Hu (1998), Hu et al. (1998)…

z=5.7 Hu et al. (2004) - 26 LAE (22 confirmed spectro)

LALA (Rhoads, Malhotra + >2000, Finkelstein et al. 2008)

• z=4.5, 5.7, 6.5 - ~160 LAE at z=4.5

SUBARU:

• z=3.1, 3.7., 5.7: …Ouchi et al. (2007), SXDS, 1deg^2 - 356, 101, 401 LAE

•z=5.7 Ajiki et al. (2003)… Shimasaku et al. (2006) - 89 LAE (28 confirmed spectro)…Murayama et al. (2007) - COSMOS field (1.95deg^2)

• z=6.5: Kodaira et al. (2003), Taniguchi et al. (2005)

Kashikawa et al. (2006) - 58 LAE (17 confirmed spectro)

CTIO 4-m:

• z=3.1 Gronwal et al. (2007), CDFS, 0.28deg^2 -162 LAE

GALEX:

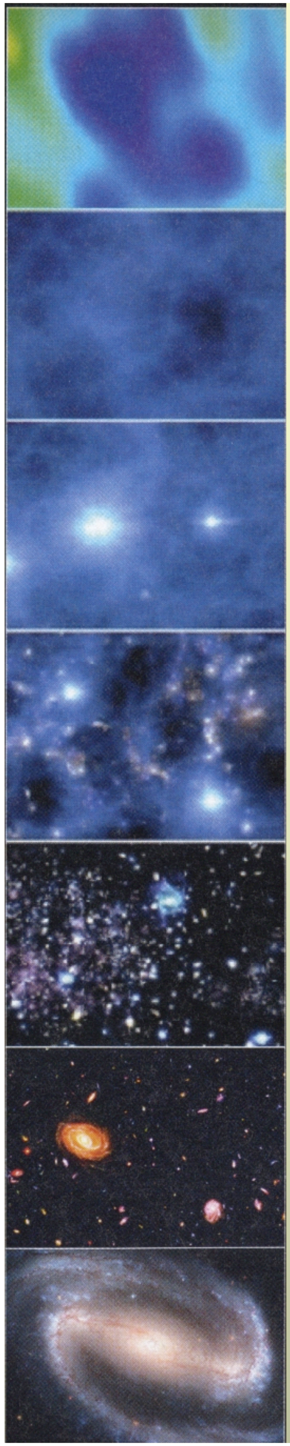
• z~0.2-0.35 Deharveng et al. (2008), 5.65 deg^2 - 96 LAE

Local starbursts: systematic Lyα study still missing! (but cf. Kunth, Mas-Hesse, Leitherer, Oestlin, Hayes …) --> see Poster H. Atek

Other groups:

• Stiavelli et al. (2001), Venemans et al. (2005+), Nilsson et al. (2007), Westra et al., …

High-z record(s): z=6.96 Iye et al. (2006), z~9-10 candidates Stark et al. (2007)



LAE population at z≥3

Flux limits:

-spectroscopic: 3e-18 erg

-narrow-band: typically

down

EW limits:

-SUBARU: 64, 44, 27 Å (r

-MUSYC, z~3.1: ~20 Å (

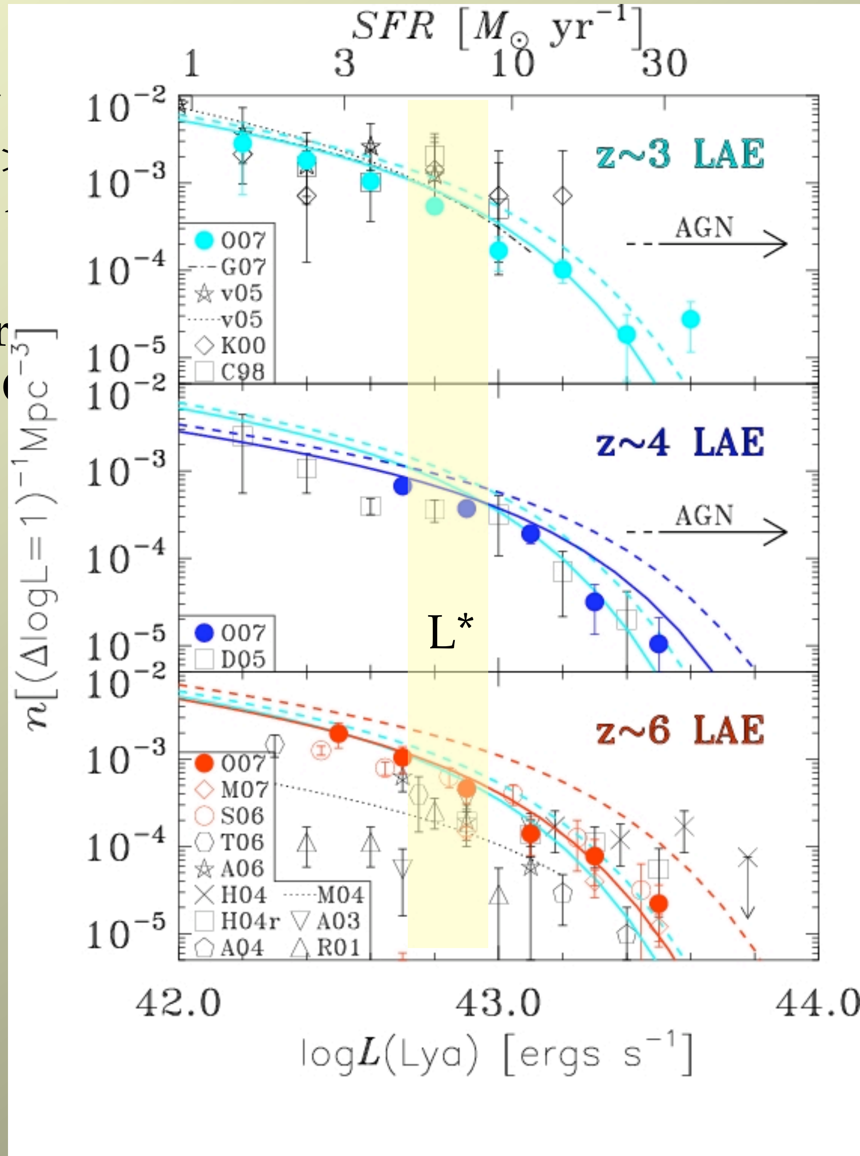
Number densities, Lyα luminosity functions:

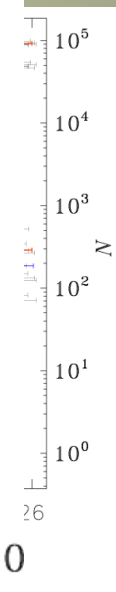
* little/no evol. of L* and number density from z~3.1 to 5.7

* evolution at z>6

(due to IGM? mass fct.?)

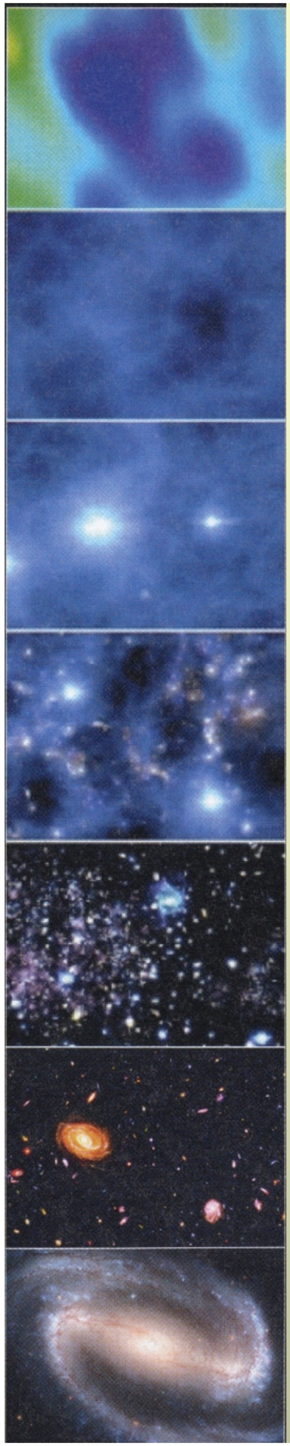
Fainter samples with strong lensing: e.g. Santos et al. (2004)



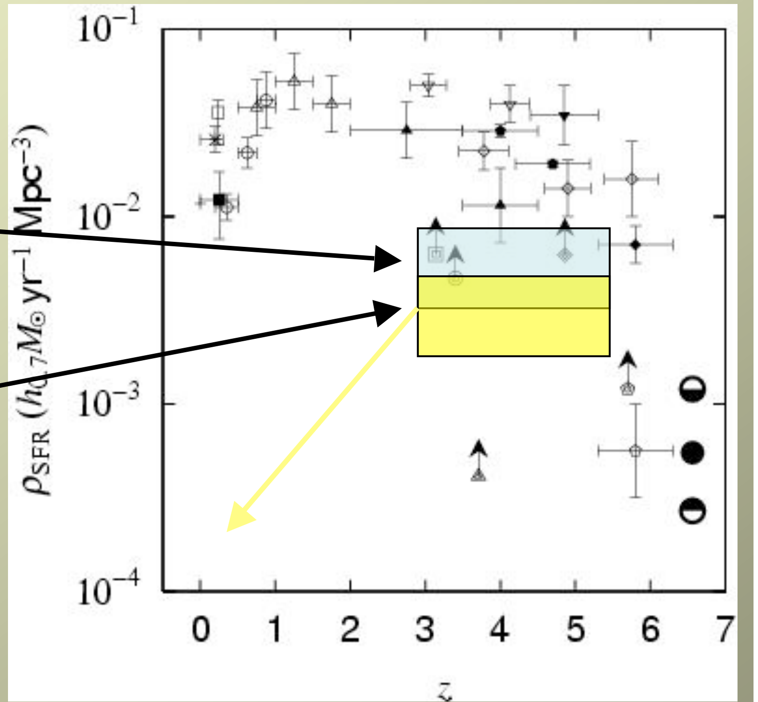


2007)

More on LF(Lya) --> talks by R. Siriand, J. Rhoads, K. Nilsson, J.-M. Deharveng



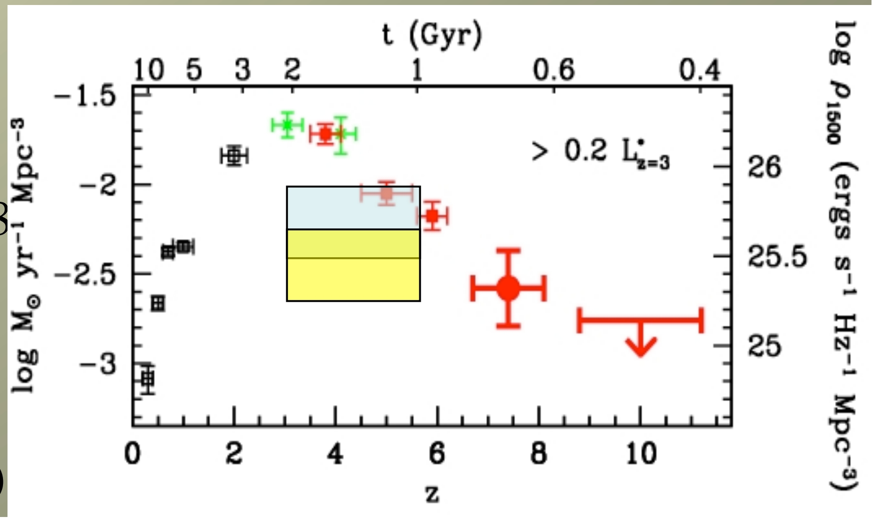
LAE population at z≥3



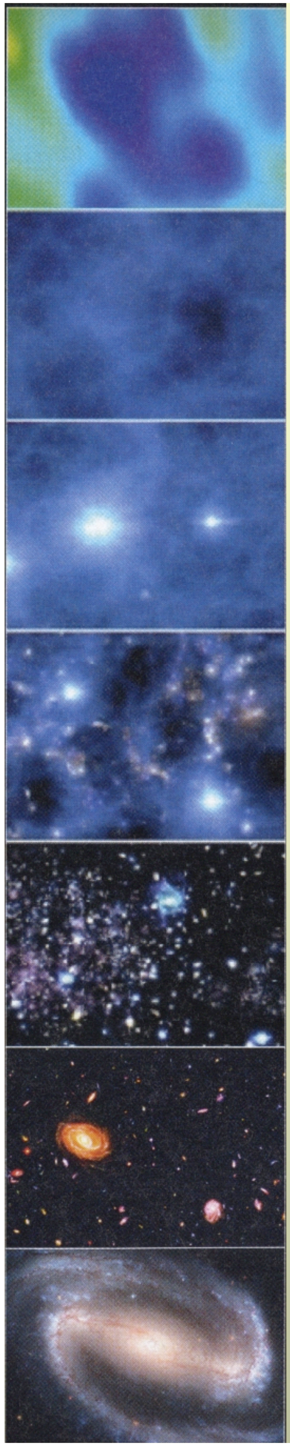
SFR density of LAE:
z~3.1 to 5.7: Ouchi et al. (2007)
- estimate from extrapolation of LF(Lya) and LF(UV): (5-9)*10^{-3} $M_\odot$ yr^{-1} Mpc^{-3}
-factor 2 lower (down to det.limit)
- Consistent with earlier results (Kudritzki et al. 2000, Cowie & Hu 1998, Ouchi et al. 2003, Taniguchi et al. 2005, Gronwal et al. 2007)

z≥6.5:
Apparent decrease of SFRD (partly ?) due to IGM
(cf. Ota et al. 2008)

z~0.2-0.4: Deharveng et al. (2008)
- SFRD decrease by factor ~16 from z~3 (more rapid than SFRD(UV) decrease)



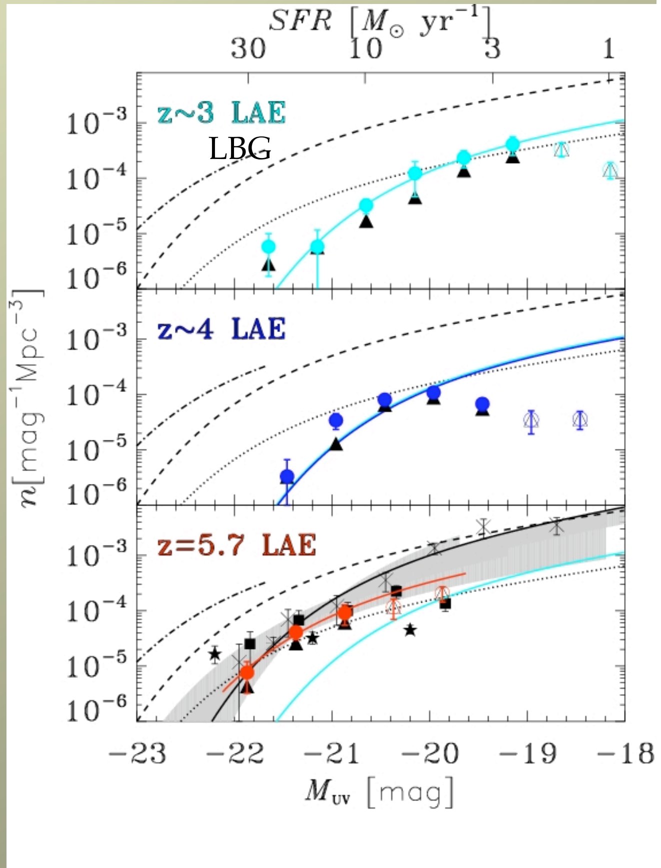
Bouwens et al. (2008)



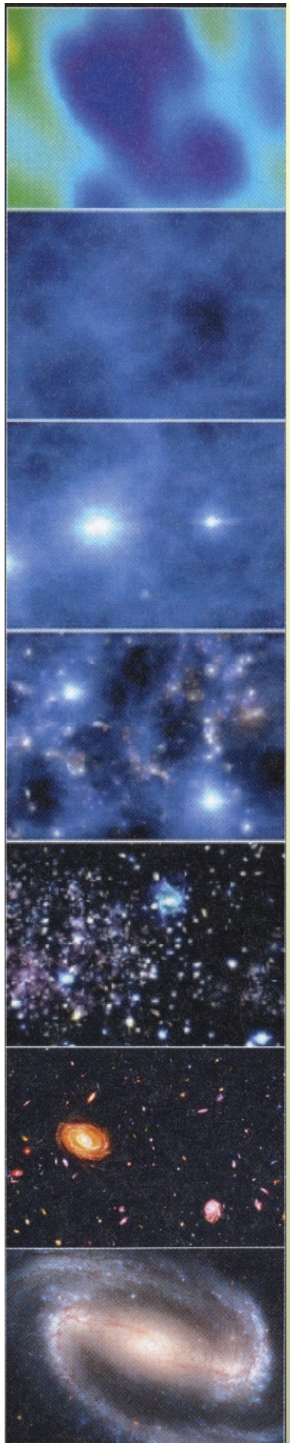
LAE and LBG populations at z≥3

- LBG dominate number of galaxies and star formation at z~3 … 6
- Increasing role of LAE with z:
  - Density LAE/LBG ↗ from ~25% to ~50% between z~ 3 and 5.7
  - SFRD multiplied by ~2
- **Converging importance of LBG and LAE at z≥6?**

==> Same type of galaxies ? Same populations?



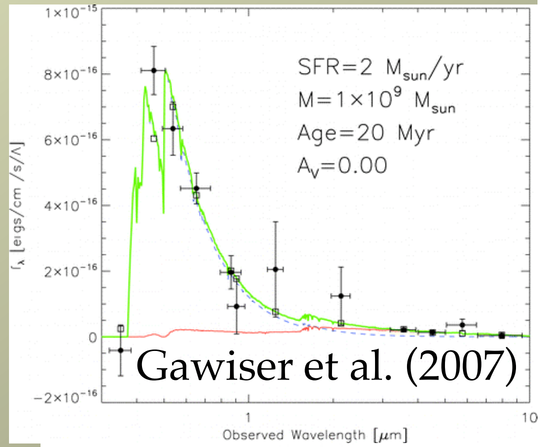
Ouchi et al. (2007)



Stellar populations in LAE

Few stellar population studies yet!

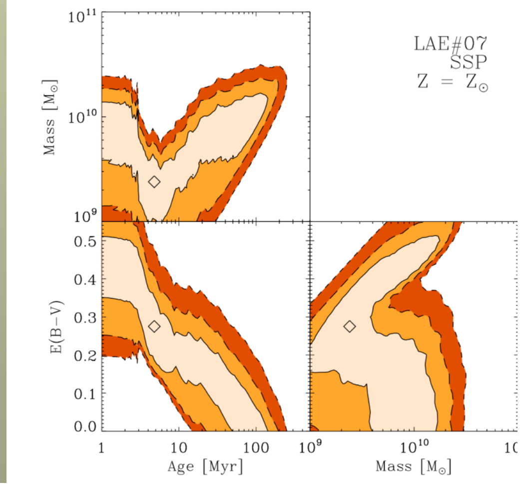
Schaerer & Pelló (2005), Chary et al. (2005), Lai et al. (2007, 2008), Gawiser et al. (2006, 2007), Pirzkal et al. (2007), Nilsson et al. (2007), Finkelstein et al. (2007, 2008)

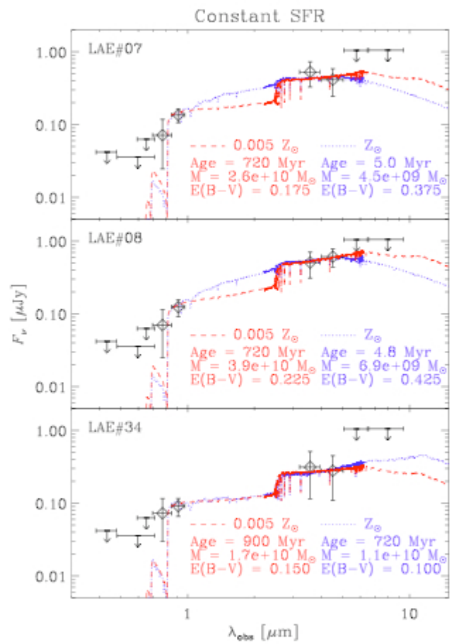


Gawiser et al. (2007)

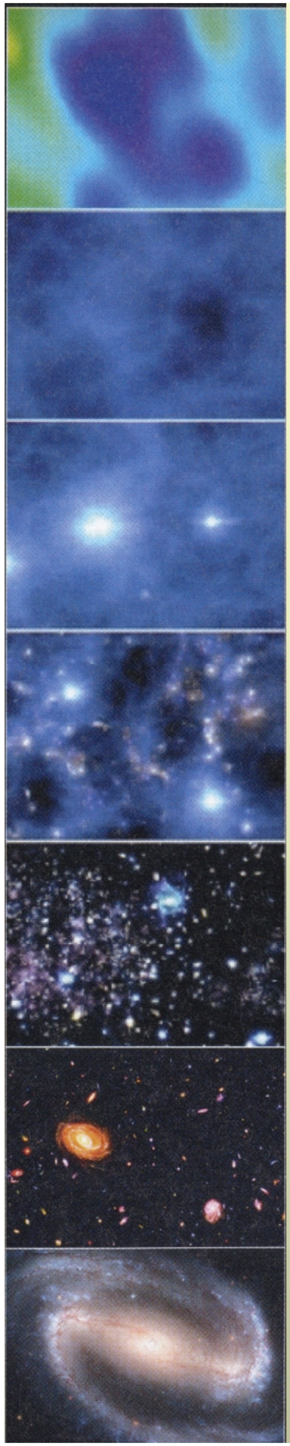
* Some objects detected at ≥3.6μm (~0.5-1 μJy level) with Spitzer
* Other: stacked analysis

General picture:
- wide range of ages: few to several 100 Myr
- masses typically 10^8-10^9 $M_\odot$ (some 10^7 and few*10^{10} $M_\odot$ or less)
- little/no extinction





3 GOODS LAE @ z=5.7
Lai et al. (2007)



Stellar populations in LAE

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- little/no extinction

==> properties of LAE comparable to LBG at z~5 (Verma et al. 2008)

==> younger, less massive, less dusty than z~3 LBGs

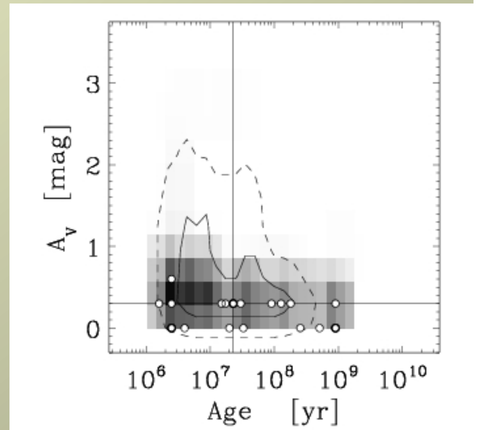
Possibly some quite dusty LAE:

❖ 1 z=6.56 lensed LAE (Abell 370):
Schaerer & Pelló (2005), Boone et al. (2007) - A_V <~1

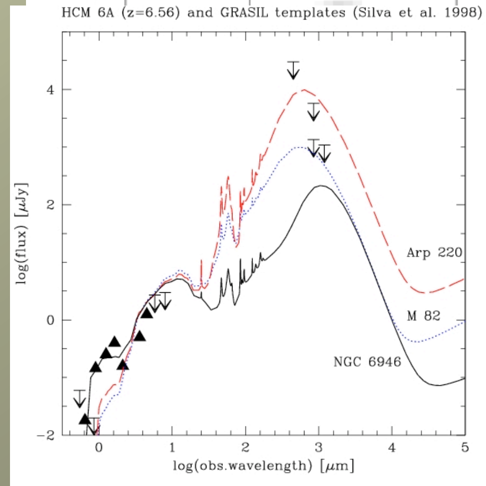
❖ 3 z=5.7 LAE: Lai et al. (2007): A_V~0.6 to 1.4

❖ Finkelstein et al. (2008): 9/15 LAE at z~4.5 with A_V>0.8 !?

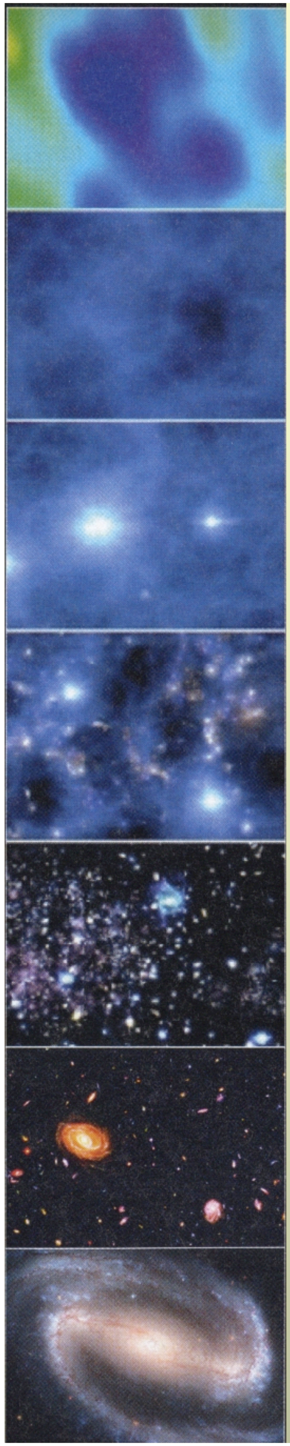
→cf. S. Finkelstein poster and talk S.Malhotra



(Verma et al. 2008)



Boone et al. (2007)



LAE population models

Many mod.Press-Schechter and semi-analytical models:
Haiman & Spaans (1999), Le Delliou et al. (2005, 2006), Thommes&Meisenheimer (2005), Mao et al. (2006), Dijkstra et al. (2007), Kobayashi et al. (2007), Blaizot et al. (2008), Srianand et al. …
Linked to cosmological simulations:
e.g. Barton et al. (2004), Davé et al. (2006), Nagamine et al. (2008)…

Predict various observables:
- LF(Lyα), LF(UV), …EW(Lyα)
- also stellar populations…

→cf. talks by R. Srianand, J. Rhoads

Main parameters:
- Lyα escape fraction
- duty cycle
- extinction, …

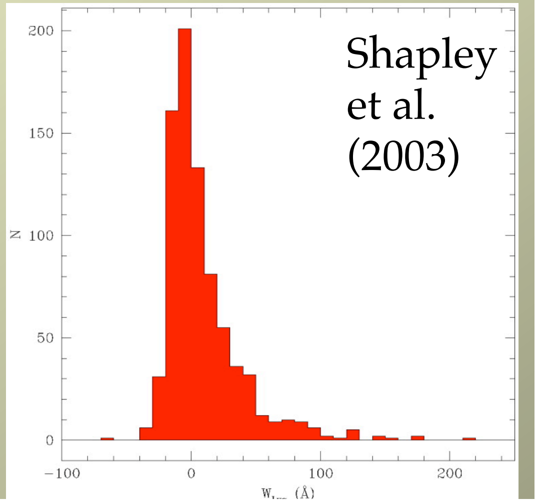
No treatment of Lyα physics ==> **need for radiation transfer models and detailed understanding of individual objects + observed trends!**

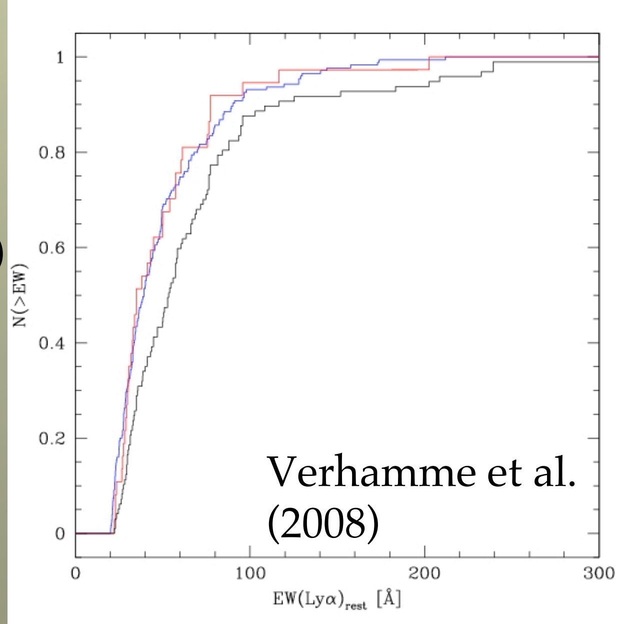
LBGs and LAEs at z~3: different populations?

➢ EW(Lyα) distributions of LBG and LAE apparently different (Gronwal et al. 2007)
➢ However: most LAE fainter than LBG

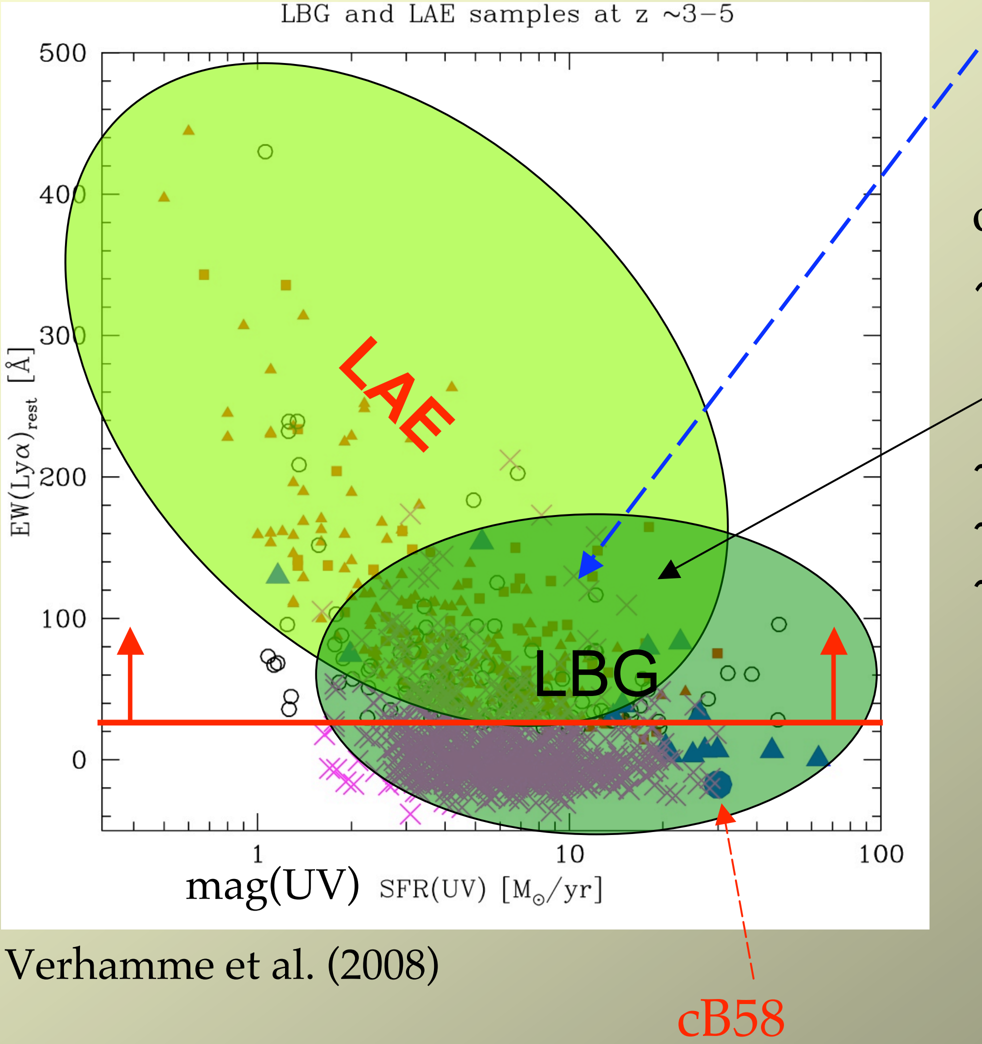
With same criteria (EW^{rest}>20 Å, R_AB<25.5):
• **Distribution of EW(Lya) compatible between LAEs and LBGs**
• **Number density of LBGs identical to LAEs**
(cf. Gronwall et al. 2007)
• **Correlation length of populations compatible** (cf. Adelberger et al. 2005, Gawiser et al. 2007)
• Many properties in common (mags, colour, SFR, etc.)

==> Unification of LBGs and LAEs at z~3:
~ 20-25 % of LBG = 23% of LAEs
Other LAEs = less luminous starbursts





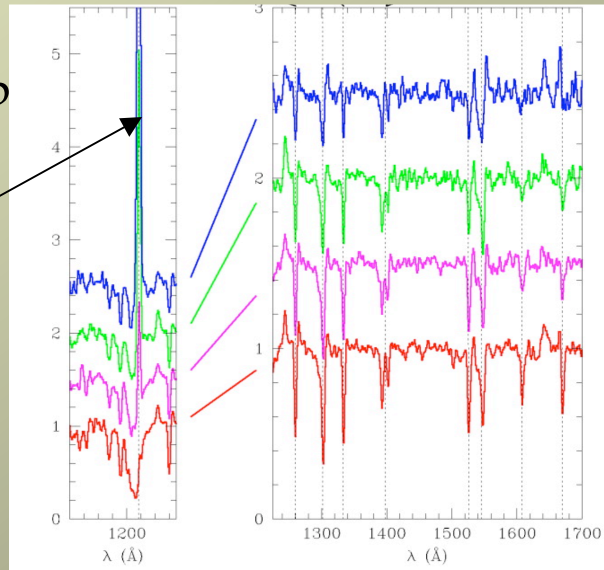
Unification of LBGs and LAEs



Verhamme et al. (2008)

overlap
~25%

~25%
~25%
~25%



Shapley et al. (2003)

==> *Remaining ~75% of LBGs:*
Lyα strength and profile diversity understood by radiation transfer effects

MCLya code

General 3D UV + Lya radiation transfer code:

- Arbitrary geometry + velocity field
- Arbitrary source distribution + input spectra
- Monte Carlo line and continuum radiation transfer
- Scattering on HI
- Dust scattering + absorption

→ Verhamme et al. (2006, A&A 460, 397)

New:

- Deuterium (cf. Dijkstra et al. 2006)
- QM redistribution (cf. Stenflo 1981)
- Dust: Henyey-Greenstein phase fct., different albedo
- Recoil effect

→ code parallelised (OpenMPI)

→ Also: automated profile fitting tool (Hayes et al. 2008)

→ currently most complete Lyα + dust transfer code

First simulations: homogeneous density distributions

In preparation: clumpy/fractal structures

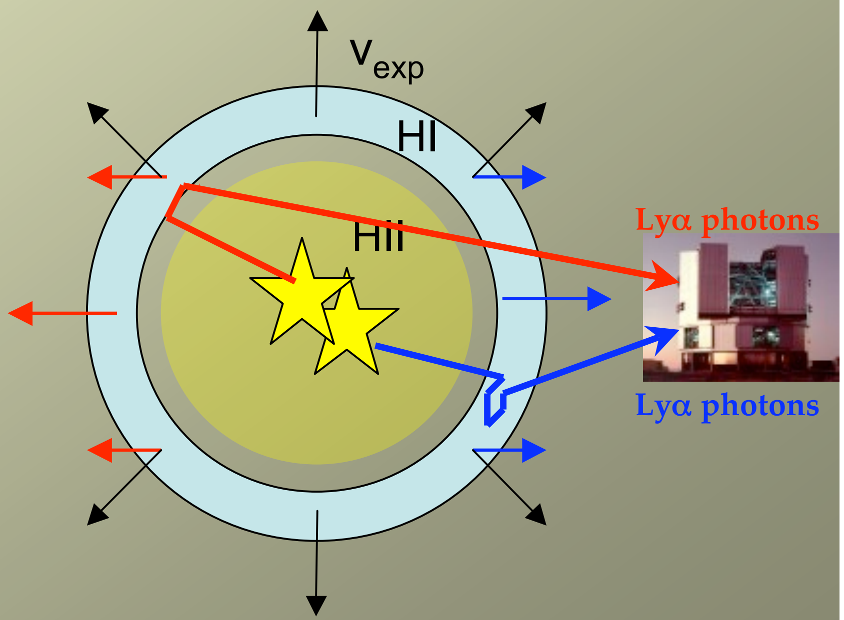
LBG at z~3: a coherent analysis

Our approach:

- modeling of: starburst (stars), emission lines and ISM (outflow with dust)
- **3D radiation transfer code: Lyα + UV (line, continuum, dust)**
  (Verhamme, Schaerer, Maselli 2006) with input from synthesis models (Starburst99, Schaerer 2003, Gonzalez-Delgado et al. 2005)

Geometry:

1) expanding spherical shell
2) bipolar flow (2 faces in expansion)
3) foreground screen



Parameters:

* If possible contrained by observations:
Velocity v_{exp}, b, FWHM(emission)
* Contrained or free:
column density N(HI), extinction
* free: W(Lyα), [back-gd velocity]

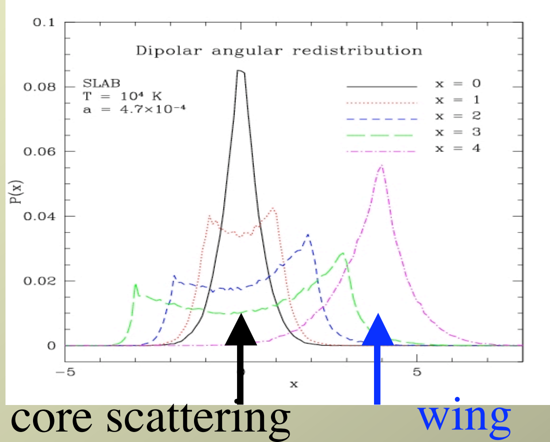
LBG - constraints on outflow geometry:

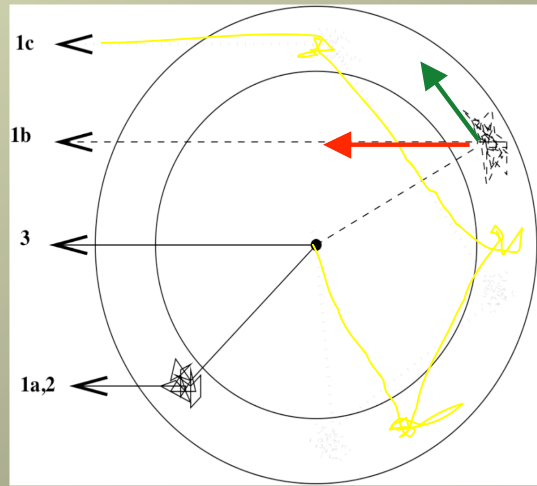
1) Expanding spherical shell motived by:

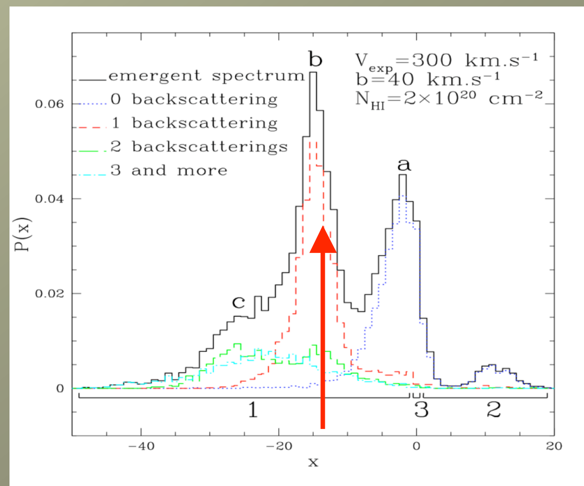
- Shift $-v_{exp}$ between IS and photospheric lines
- Shift $+2^*v_{ex}$ between photospheric lines and Lyα
- Radiation transfer modeling ==> ~spherical symmetry

2) Quasi-homogeneous shell / large covering factor

motived by observations of strong IS lines- --> black profiles (e.g. Heckman et al. 2001)





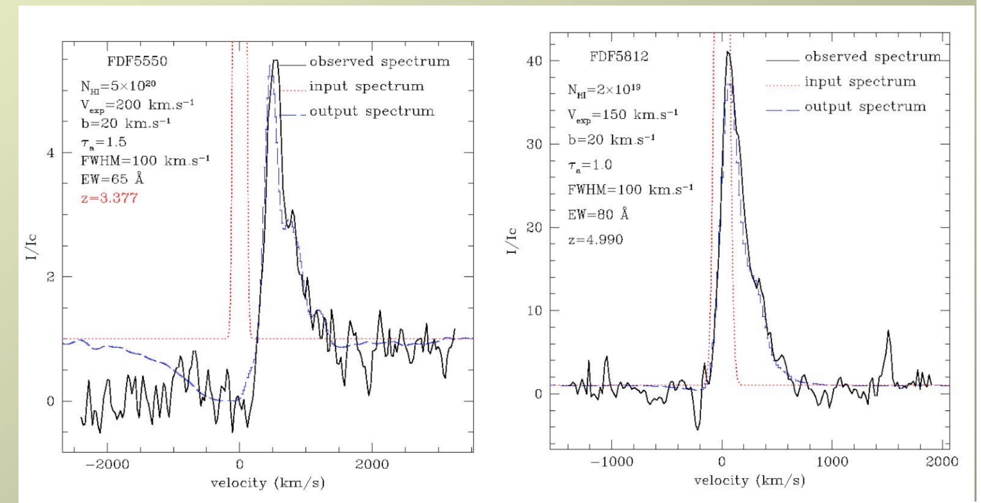


Verhamme et al. (2006)

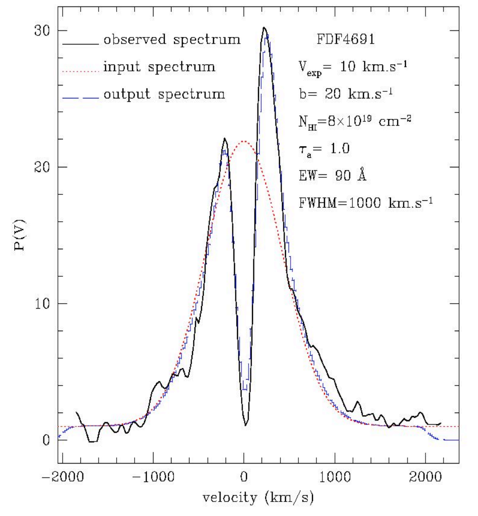
LBGs at z~3: a coherent analysis (FDF)

- modeling of **11 LBGs with Lyα emission** from the FORS Deep Field (Tapken et al. 2007)
- 8 objects @ z~2.7-3.4, 3 @ z~4.5-5
- Variety of profiles and EW

- *geometry:* expanding shell
- *free parameters (5-6):* N(HI), v_{exp}, E(B-V), b, W(Lyα), FWHM

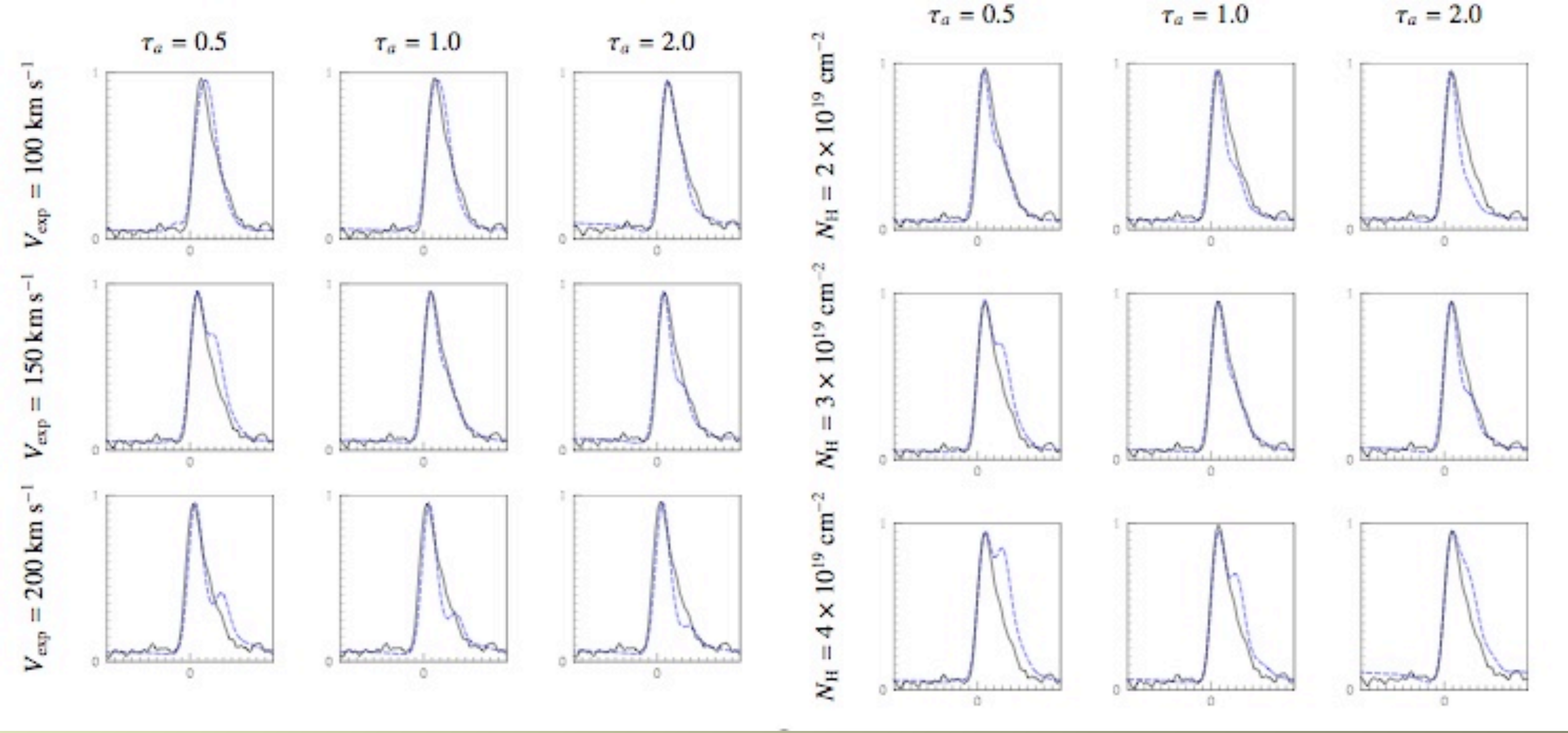


ID	type	z	SFR_{UV} [$M_\odot$ yr^{-1}]	$SFR_{Ly\alpha}$ [$M_\odot$ yr^{-1}]	β	Δv(em – abs) [km s^{-1}]	$EW(Ly\alpha)_{obs}$ [Å]	$FWHM(Ly\alpha)_{obs}$ [km s^{-1}]
1267	C	2.788 ± 0.001	1.16 ± 0.25	1.49 ± 0.08			129.8 ± 27.41	235 ± 34
1337	A	3.403 ± 0.004	27.28 ± 1.15	2.10 ± 0.14	−2.43	607	6.69 ± 0.46	597 ± 84
2384	A	3.314 ± 0.004	22.74 ± 0.77	10.8 ± 0.27	−0.55		83.19 ± 3.89	283 ± 47
3389	A	4.583 ± 0.006	14.85 ± 2.47	9.20 ± 0.38			38.82 ± 10.95	354 ± 70
4454	A	3.085 ± 0.004	1.98 ± 0.49	2.25 ± 0.08	−2.42		74.38 ± 11.84	323 ± 47
4691	B	3.304 ± 0.004	17.88 ± 0.75	16.31 ± 0.14	−2.46		79.44 ± 1.61	840 ± 115
5215	C	3.148 ± 0.004	26.20 ± 0.80	9.57 ± 0.21	−1.71		32.48 ± 1.06	483 ± 90
5550	A	3.383 ± 0.004	44.78 ± 1.07	3.27 ± 0.20	−1.81	620	6.36 ± 0.40	424 ± 85
5812	A	4.995 ± 0.006	5.24 ± 0.79	9.60 ± 0.18			153.8 ± 26.6	226 ± 23
6557	A	4.682 ± 0.006	13.85 ± 1.39	3.35 ± 0.15			30.51 ± 3.04	380 ± 135
7539	B	3.287 ± 0.003	29.87 ± 0.78	2.45 ± 0.46	−1.74	80	6.84 ± 0.46	1430 ± 230



Verhamme et al. (2008)

* Fits with varying: velocity, dust content, column density
* Constant: b = 20 km/s, FWHM = 100 km/s, EW = 80 Å

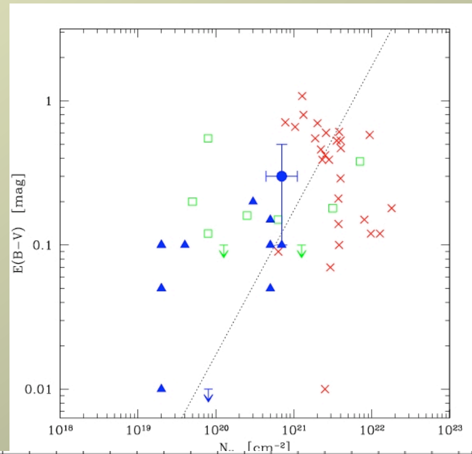


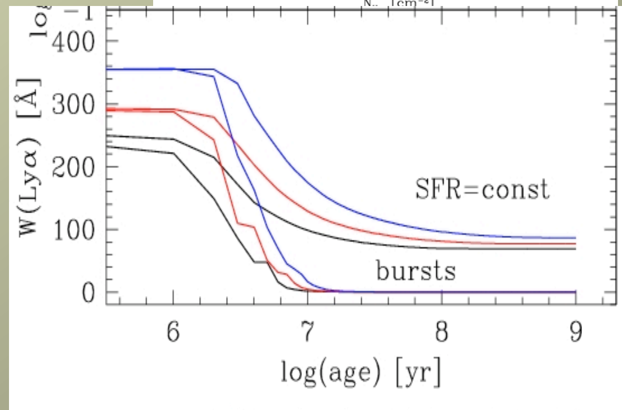
==> few degeneracies for:

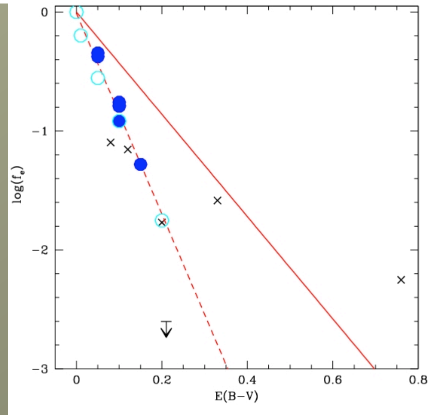
- objects with accurate redshift (from stellar lines)
- sufficient spectral resolution (here R~2000)

Main results from Lyα profile fits

- Most objects: ~150-200 km/s, some ~static
- **~Low HI column densities** (N(HI)~10^{19} to $7*10^{20}$ cm^{-2})
- **Extinction from Lya profile reasonable** cf. to SED fits. LBGs: E(B-V)~0 to 0.2
- **Dust/gas ratio somewhat higher than Galactic. Quite large scatter.**
- Low intrinsic FWHM~100 km/s
  -- not related to mass!
- **~High intrinsic EW(Lyα)** (~50-200 Å)
  --> **as expected for SFR~const**
- **Lyα escape fraction depends mostly on extinction.** Good agreement with local starbursts for E(B-V)<~0.2 (cf. Atek et al. 2008)







Verhamme et al. (2008)

LBG at z~3: a coherent analysis (cB58)

- MS 1512-cB58: bright LBG (R~20) at z=2.73 (Yee et al. 1996)
- Best studied LBG! Multi-λ observations , rich UV spectrum: stellar and IS lines
- Representative of LBGs with strong Lyα absorption (Shapley et al. 2003)

- Detailed analysis of stellar content, IS kinematics, abundances… (Ellington et al. 1996, Pettini et al. 2000, 2002, de Mello et al. 2002, Savaglio et al. 2002)

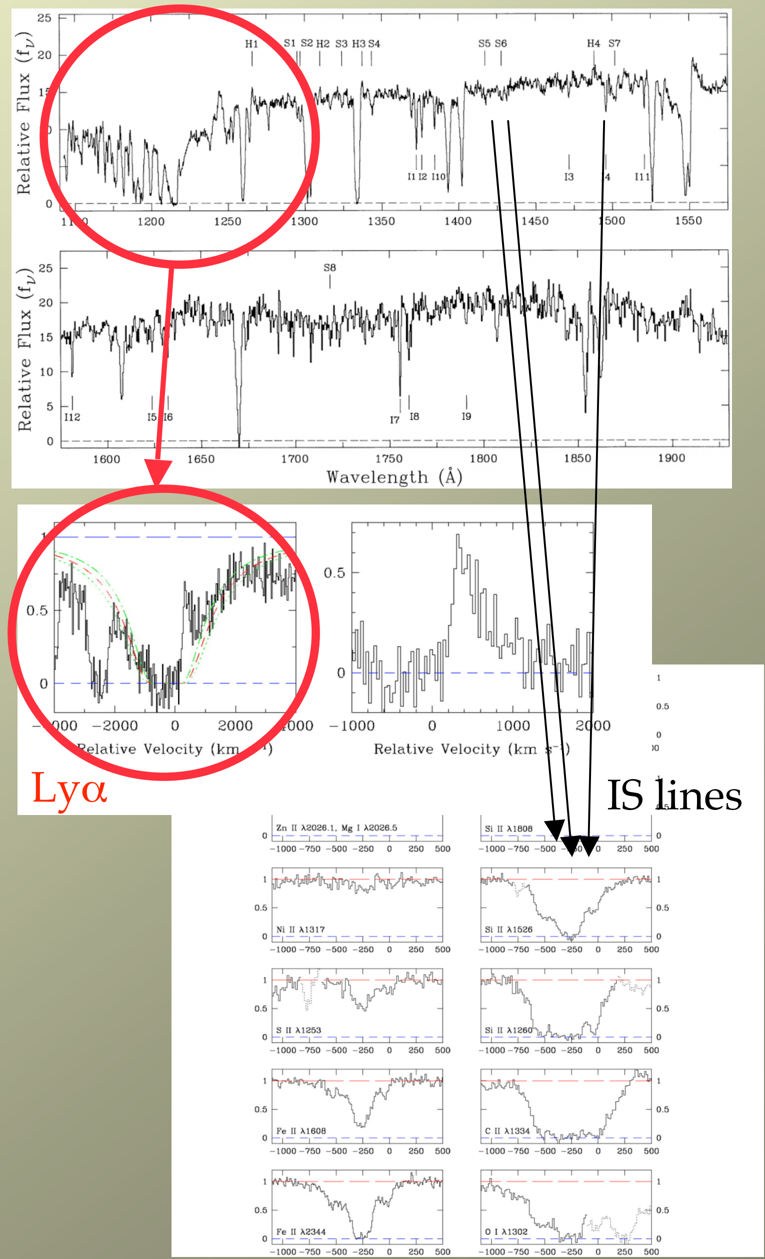


Table 1. Input parameters of the "standard" cB58 model for the radiation transfer code

$V_{exp} = V_{front}$	255 km s^{-1}
V_{back}	free
N_H	7.5×10^{20} cm^{-2}
b	70 km s^{-1}
E(B-V)	0.3
FWHM(Lyα)	80 km s^{-1}
EW(Lyα)	free

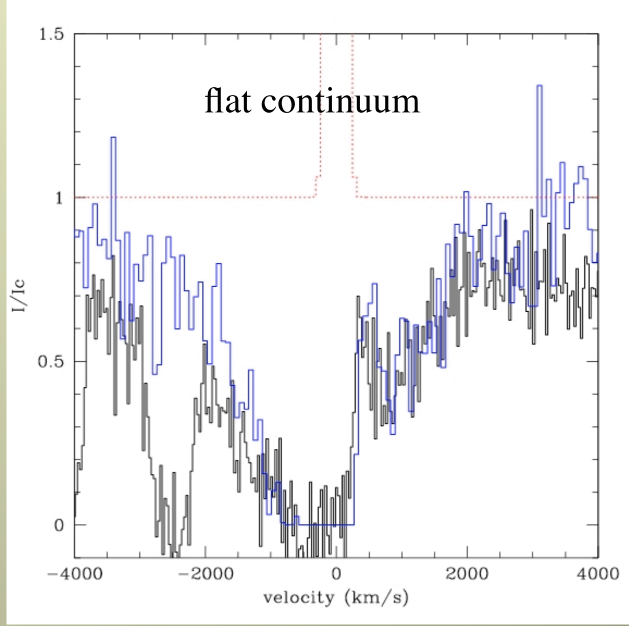
Modeling the z~3 LBG cB58

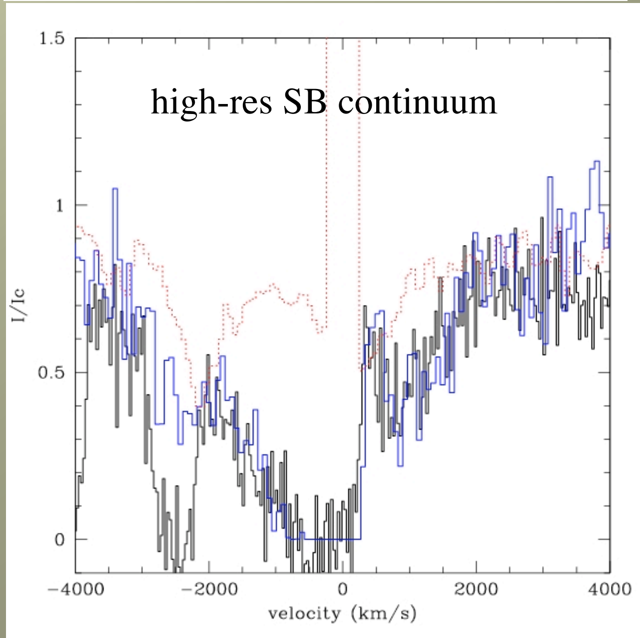
3) Two moving slabs:
v_{front}=255 km/s (fixed by IS lines),
v_{back}~140 km/s yield excellent fit!
(for flat continuum or « true » starburst spectrum + line)

Result ~independent of other properties of background « mirror » (only $b^{1/2}$).

Requires strong intrinsic Lyα emission:
W(Lyα)>60 Ang
==> compatible with high W(Lyα), as expected for SFR=const ! (and indicated by UV stellar pop. analysis)

==> Observed Lyα profile of cB58 = strong intrinsic Lyα emission (~SFR=const) + radiation transfer and dust effects !





Schaerer & Verhamme (2008)

LBGs and LAEs at z~3: a consistent scenario

Scenario proposed from analysis of cB58 and FDF objects FDF:

- **All LBGs have an intrinsic emission of W(Lyα)~60-80 Å (SFR~const) or higher**

- **Observed diversity** of Lyα strength and profiles **due to**: **different column densities N(HI) and concomitant change of dust with N(HI)**

- **N(HI) increases mainly with galaxy mass** (small increase of dust/gas ratio with M_{galaxy})

- **LBGs and LAEs:**
  - strong overlap of populations (at z~3: LBG(EW>20) = LAE(R<25.5))
  - low luminosity LAEs = less massive than LBGs

Schaerer & Verhamme (2008)
Verhamme, Schaerer et al. (2008)

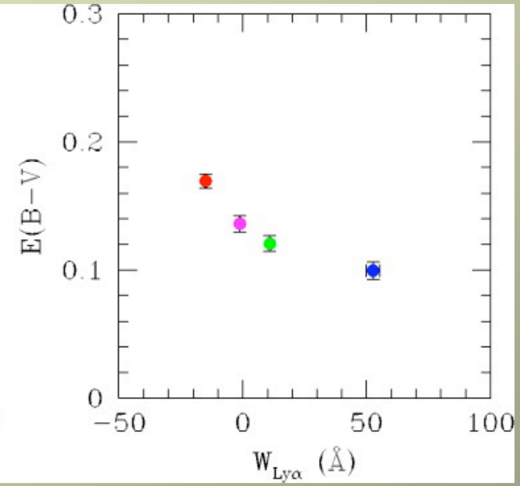
LBGs and LAEs at z~3: a consistent scenario

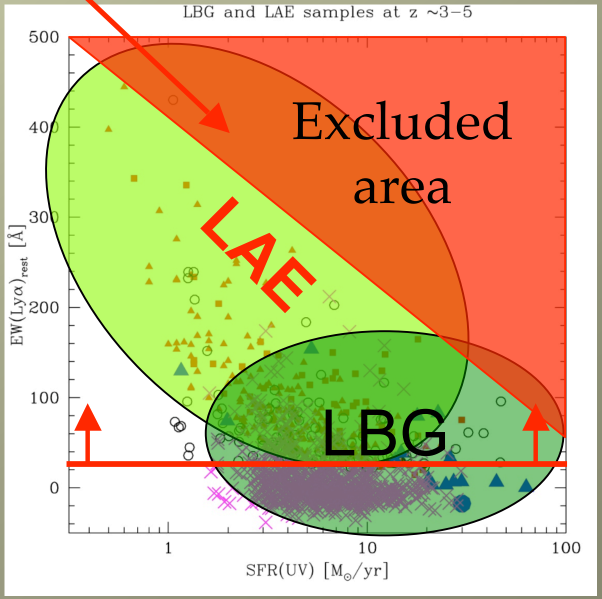
Our scenario:

✓ **reproduces observed correlations:**
E(B-V) vs. W(Lyα) and others (Shapley et al. 2003)

✓ **predicts absence of strong W(Lyα) for massive galaxies** -- in agreement with observations
(Ando et al. 2004, Yamada et al. 2005, Tapken et al. 2007…)

…





Schaerer & Verhamme (2008)
Verhamme, Schaerer et al. (2008)

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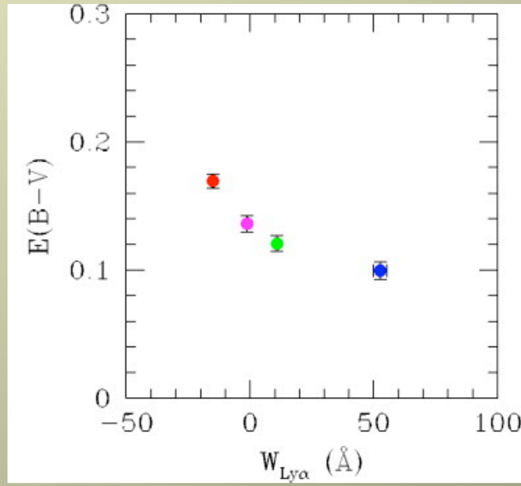


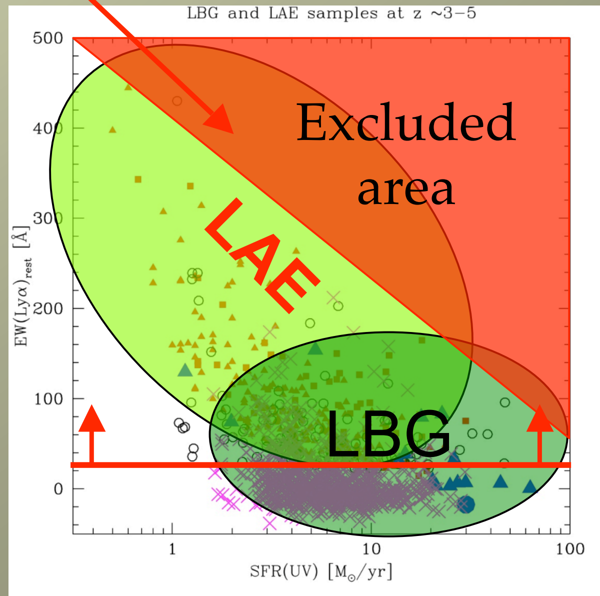
✓ **predicts absence of strong W(Lyα) for massive galaxies** -- in agreement with observations
(Ando et al. 2004, Yamada et al. 2005, Tapken et al. 2007…)

…

✓**allows consistent diagnostic between Lyα and UV:**
SFR=const, age ~30-100 Myr

✓**no need for short star formation time scales** (« duty cycles ») Ferrara & Ricotti (2006)

✓ **allows unification of LBG and LAE:**
e.g. at z~3**:** ~ 20-25 % of LBG and 23% of LAEs



✓ **explains naturally observed increase of LAE/LBG ratio with redshift** if (average) extinction decreases.
(cf. observations of Noll et al. 2004, Shimasaku et al. 2006, Ouchi et al. 2007, Reddy et al. 2007, Deharveng et al. 2008)

Schaerer & Verhamme (2008)
Verhamme, Schaerer et al. (2008)

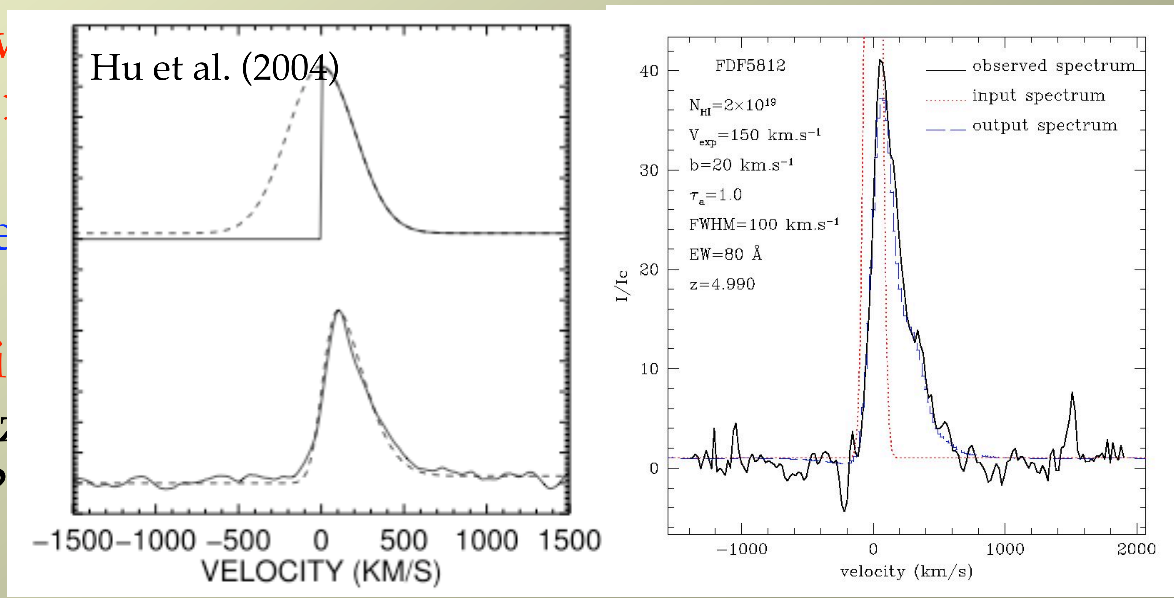
(some) open questions

- ❑ *Lyα transfer modeling*: geometry ? Clumpy ISM?
- ❑ How general are ~spherical outflows in LBGs?

- ❑ What about outflov
- ❑ Do SF galaxies at z

- ❑ Where are the expe

- ❑ Are there dusty (hi
gas and dust in high-z
- ❑ What metallicities?



- ❑ High-z objects: what fraction of Lyα line is really « absorbed » by the IGM?
- ❑…

Future observations

*** Spectroscopic follow-up of high-z galaxies**
-- rest UV:

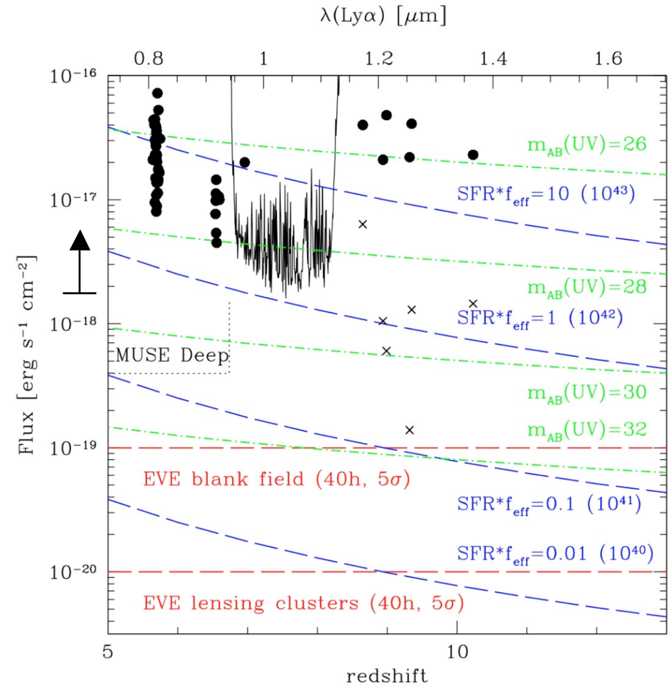
- $z_{spectro}$
- Lyα flux, EW, profile --> reionisation
- IS lines… --> outflows?
- HeII1640 --> PopIII?

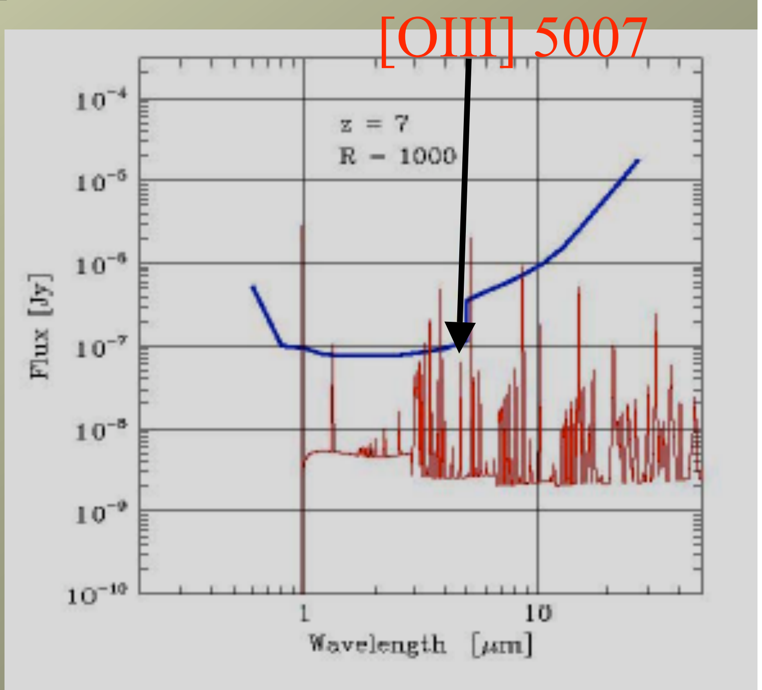
==> near-IR multi-object spectrographs (EMIR, KMOS…)

*** (multi)IFU searches for EL objects:** e.g. MUSE

*** Later: rest-frame optical spectroscopy**

- metallicities, O/H … ==> JWST
  feasible, but very difficult…!





10^6 Msun burst, Z=10^{-3} Zsun
Sensitivity for t_{exp} = 111 hour, S/N=10

Future observations

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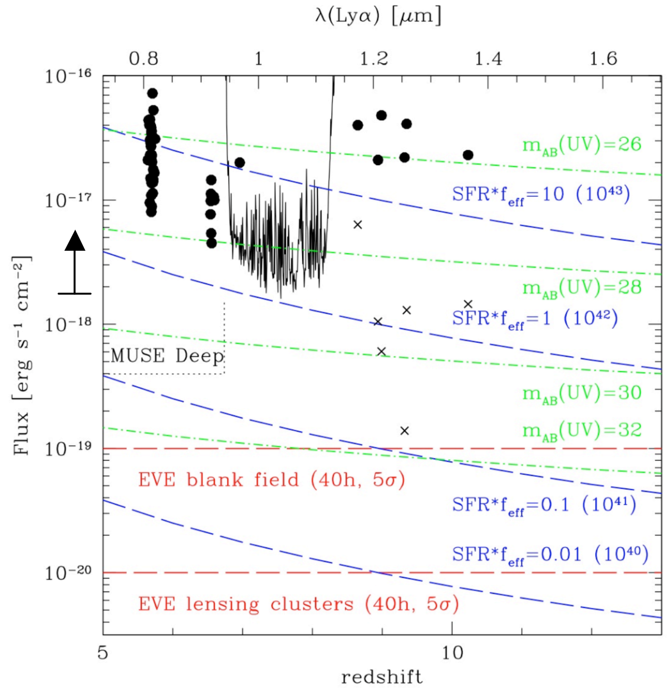
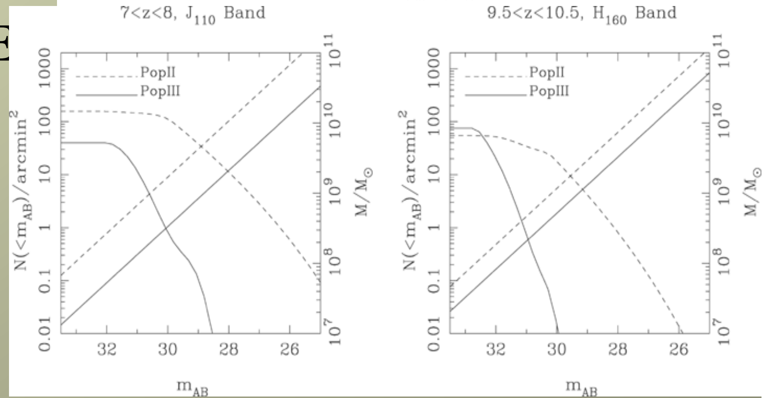
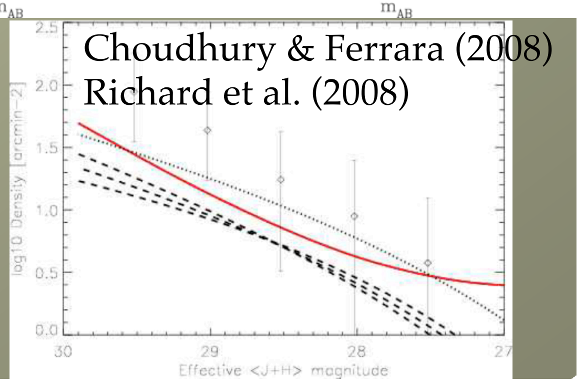
*** JWST + ELT:**

==> e.g. E-ELT Visual Explorer (EVE): optical-IR high multiplex spectrograph (~600 spectra, FOV 20-80 arcmin^2, R>6000)

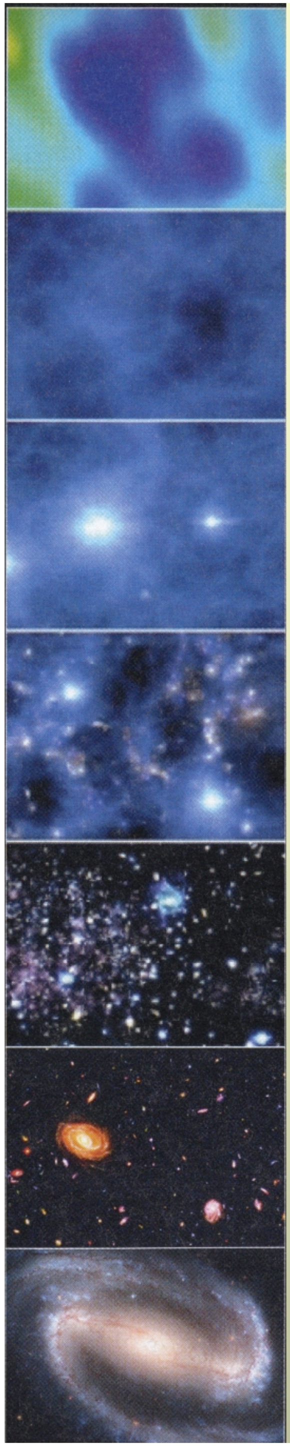
- Lyα from m_{AB}=30-32 objects up to z~13!
- HeII1640 up to z~10
- **High number density of faint objects expected!**







Choudhury & Ferrara (2008)
Richard et al. (2008)



Conclusions

- Large samples of LAE available now at z>~3
- LAE used for many purposes (SF, clustering, reionisation,…)

- SFR density of LAE < LBG and depending on z
- Importance of LAE compared to LBG increases with z

- *Stellar populations of LAE:*
  - wide range of ages: few to several 100 Myr
  - masses typically 10^8-10^9 $M_\odot$
  - little/no extinction -- but also (some?) dusty objects

- *Unification of LBGs and LAEs:*
  - At z~3: 20-25 % of LBG = 23% of LAEs
  - Other LAEs = less luminous than LBGs
  - Observed trends of Lyα strength and profile due to radiation transfer effects --> increasing N_{HI} and/or dust with galaxy mass
  - Increase of LAE/LBG with redshift naturally explained

END