Lyα radiation transfer in galaxies -- modelling and recent insight

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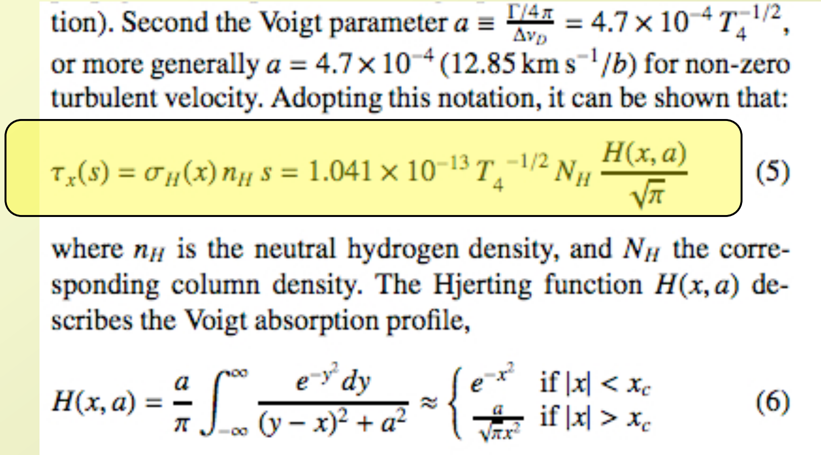
- Lya line: basics from emission to radiation transfer
- Transfer codes, predictions, confrontation with observations
- Radiation transfer modeling of z~3 LBG and LAE:
  results, insight, « unification » of LBG and LAE,…
- Connections with local galaxy observations, clumping?
- Conclusions

Why Lya transfer?



tion). Second the Voigt parameter $a \equiv \frac{\Gamma/4\pi}{\Delta\nu_D} = 4.7 \times 10^{-4}\, T_4^{-1/2}$, or more generally $a = 4.7 \times 10^{-4}\,(12.85\ \mathrm{km\,s^{-1}}/b)$ for non-zero turbulent velocity. Adopting this notation, it can be shown that:

$$\tau_x(s) = \sigma_H(x)\, n_H\, s = 1.041 \times 10^{-13}\, T_4^{-1/2}\, N_H\, \frac{H(x,a)}{\sqrt{\pi}} \tag{5}$$

where n_H is the neutral hydrogen density, and N_H the corresponding column density. The Hjerting function $H(x,a)$ describes the Voigt absorption profile,

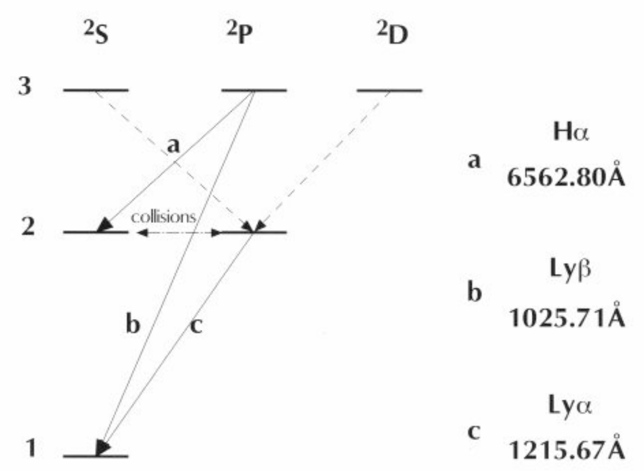
$$H(x,a) = \frac{a}{\pi} \int_{-\infty}^{\infty} \frac{e^{-y^2}\, dy}{(y-x)^2 + a^2} \approx \begin{cases} e^{-x^2} & \text{if } |x| < x_c \\ \frac{a}{\sqrt{\pi} x^2} & \text{if } |x| > x_c \end{cases} \tag{6}$$

Lyα optical depth (in convenient units)

<==> τ~1 at line center for N_H=3.10^{13} cm^{-2}

(and T=10^{4}K)

==> need radiation transfer!



GENERAL: fate of Lyα photons

Lyα
- **scattering until escape --> Lyα halo**
- **destruction by dust**
- destruction through 2 photon emission (only in HII region)

==> Need to follow transfer and interactions with HI and dust!

For comparison with observations: need line *and* continuum transfer

Lyα in galaxies: intrinsic line strength
What to start with…

Galaxies with intense star formation (starbursts):

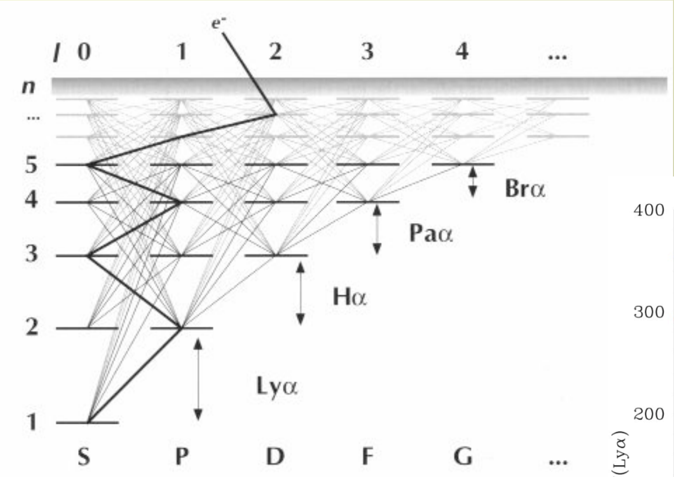
Intense UV radiation, ionising flux (>13.6 eV), and

emission lines from HII regions and diffuse ionised ISM

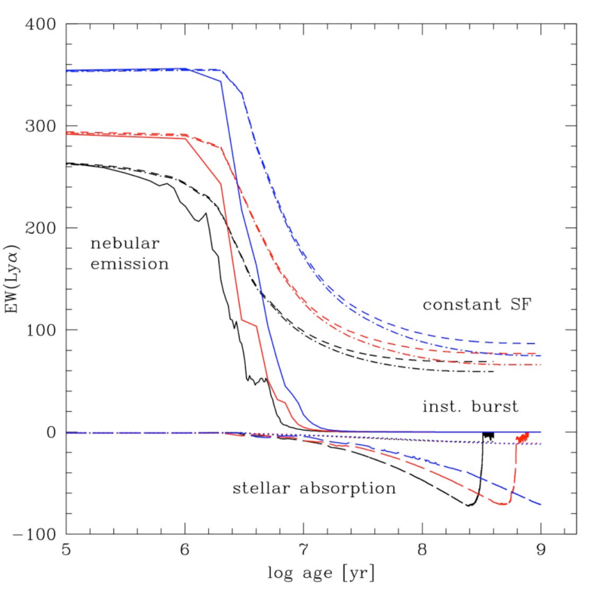
→ H, He recombination lines, [semi-]forbidden metal lines …

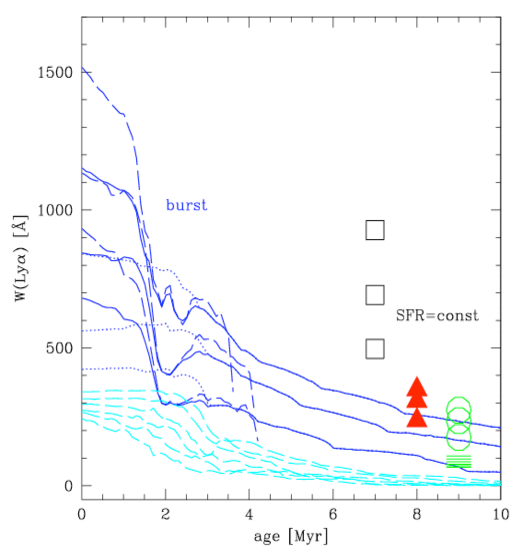
→ case B: **$L(\mathrm{Ly}\alpha, \mathrm{H}\alpha, \ldots) = c_l * Q_H$** and **$I(\mathrm{Ly}\alpha)/I(\mathrm{H}n) = c(T,n_e)$**

2/3 of recombinations lead to emission of 1 Lyα photon



Nebular emission: depends on age, metallicity, IMF





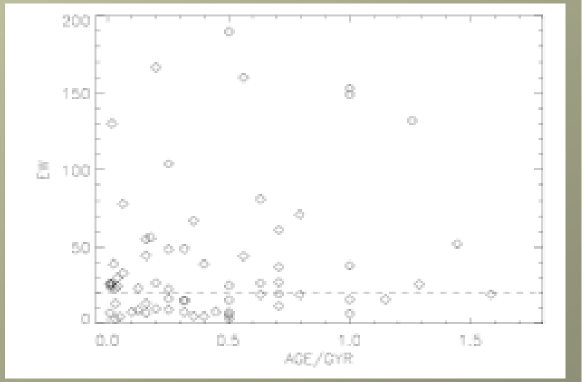
Schaerer (2003)

Lyα in galaxies: intrinsic line strength
What to start with…

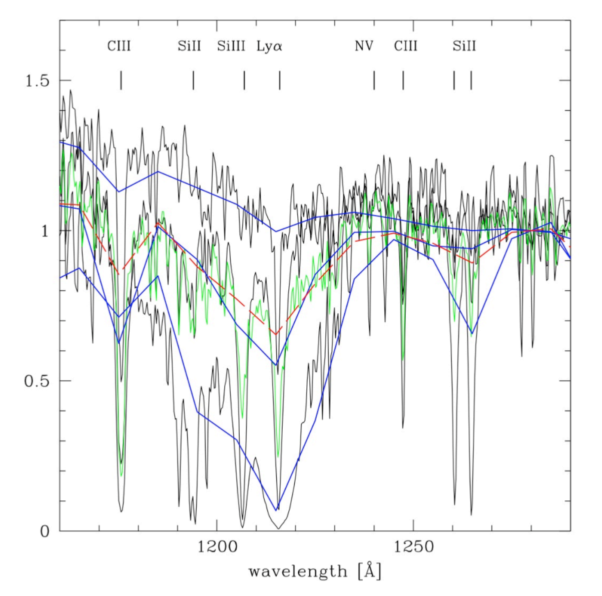
Also stellar absorption (cf. Valls-Gabaud 1993)

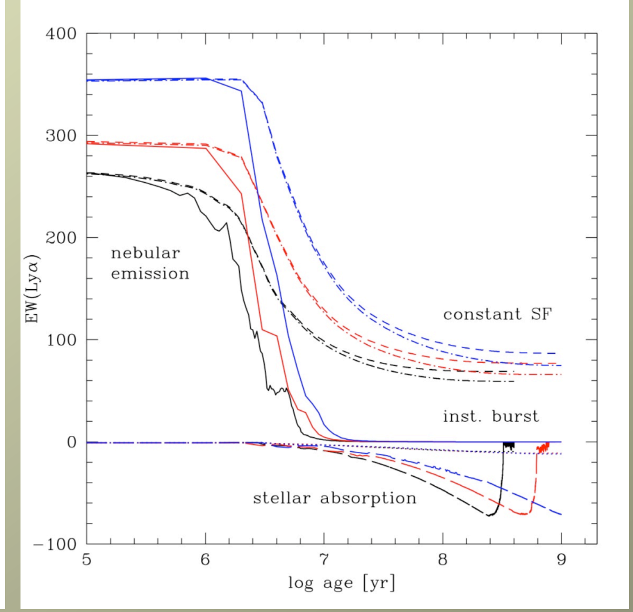
Expectations (intrinsic Lyα - before radiation transfer):

- EW>100 Å: recent SF (t<10-50 Myr) - burst or continuous
- Constant SF (or superposition of random bursts): EW ~60-100 Å
  --> I.e. no trend of EW(Lyα) with age for massively star-forming galaxies (but Shapley's talk?)
-Maximum EW depends on metallicity, IMF…
  +other effects (cooling radiation, …)



Pentericci et al. (2009)





Schaerer & Verhamme (2008)

Lya + continuum transfer: input physics

- Lya transfer:
  - Absorption cross section (H, also D cf. Dijkstra et al. 2006)
  - Frequency and angular redistribution
  - Recoil effect
  - HI distribution and velocity field
- UV continuum transfer:
  - dust properties (cross section…)
  - albedo, phase function
  - other opacity sources? (H2)
  - dust distribution

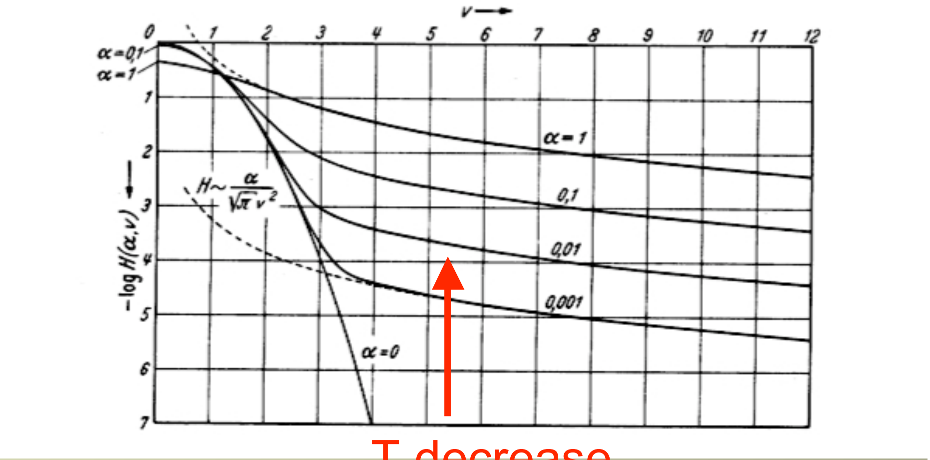
Other parameters:

- Distribution of sources
- Intrinsic spectrum (stars+nebula)
- Observers's parameter (direction, opening angle etc.)

Lyα transfer: basics

Lyα: not simple - coherent and isotropic - scattering

1) Absorption probability (=profile):
Voigt/Hjertig function



x=frequency shift from line center
(in Doppler width units)

3.12. *Radiation damping*.—In the case of radiation damping, substitution of (2.22.1) into (3.1.11) gives, for isotropic scattering,

$$R_{\text{II-A}}(x, x') = \pi^{-3/2} \int_{\frac{1}{2}|\bar{x}-\underline{x}|}^{\infty} e^{-u^2} \left[\tan^{-1}\frac{\underline{x}+u}{\sigma} - \tan^{-1}\frac{\bar{x}-u}{\sigma}\right] du. \qquad (3.12.1)$$

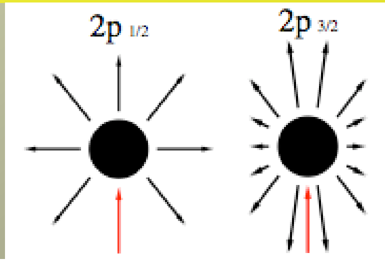
The corresponding result for the dipole phase function is

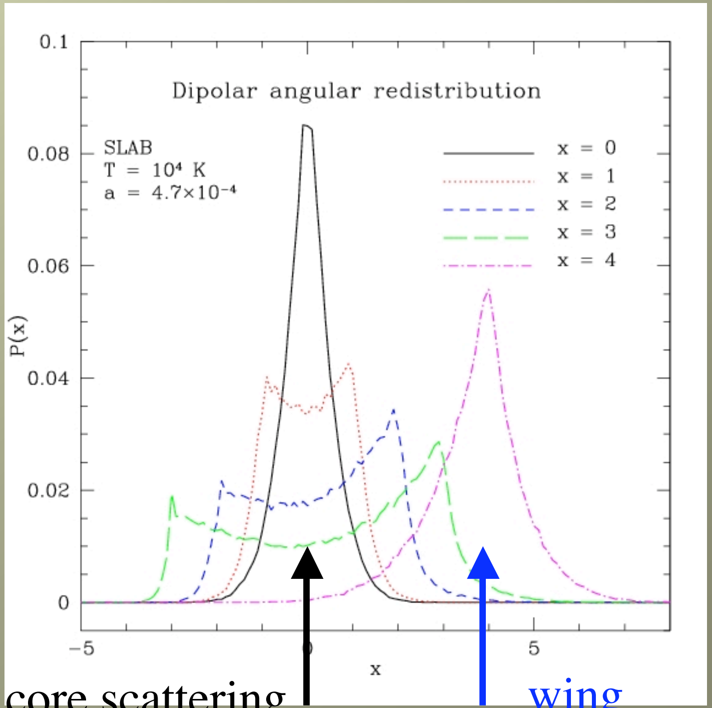
$$R_{\text{II-B}}(x, x') = \frac{3\pi^{-3/2}}{8}\sigma \int_{\frac{1}{2}|\bar{x}-\underline{x}|}^{\infty} e^{-u^2} \int_{\bar{x}-u}^{\underline{x}+u} \left[3 - \left(\frac{x-t}{u}\right)^2 - \left(\frac{x'-t}{u}\right)^2 + 3\left(\frac{x-t}{u}\right)^2 \left(\frac{x'-t}{u}\right)^2\right] \frac{dt\,du}{t^2+\sigma^2}. \qquad (3.12.2)$$

2) Angle averaged frequency redistribution functions R_{II} (Hummer 1962)

==> Close to core: **redistribution over ~[-x_{in},+x_{in}]**
==> Sufficiently far in wing: **photon re-emitted close to initial frequency (~coherent)**
(in comoving frame)

3) Angular redistribution





core scattering

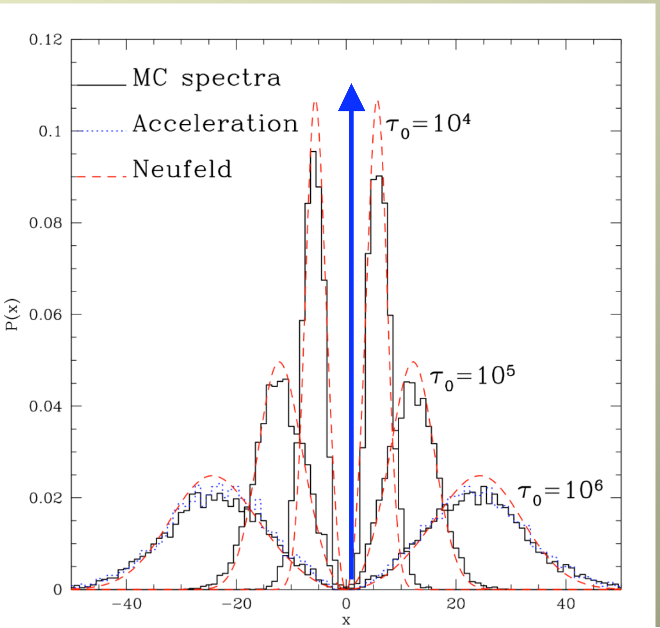
wing

Lyα transfer: Example

Source inside homogeneous static slab emitting monochromatic line at line center

Static case + symmetric Lyα emission profile ==> double-peaked profile

Separation increases with column density (opt.depth)



Emission frequency shifting from line center to wing -

Equivalent to approaching/receeding screen

--> blue/red-shifted peak

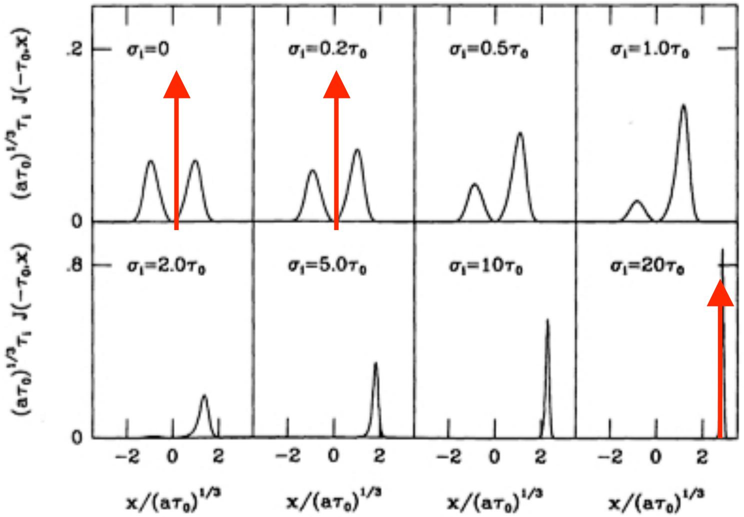


FIG. 6.—Intensity of the transmitted radiation for a slab illuminated isotropically by external radiation at various

Neufeld (1990)

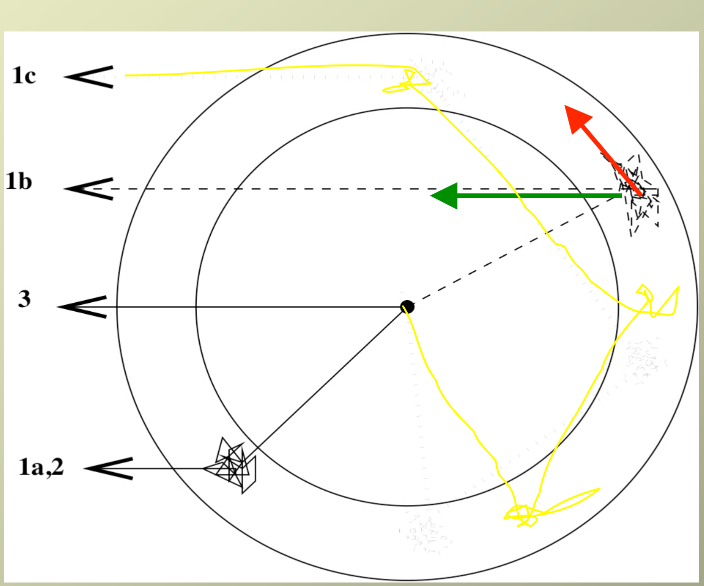
Lyα transfer: Example

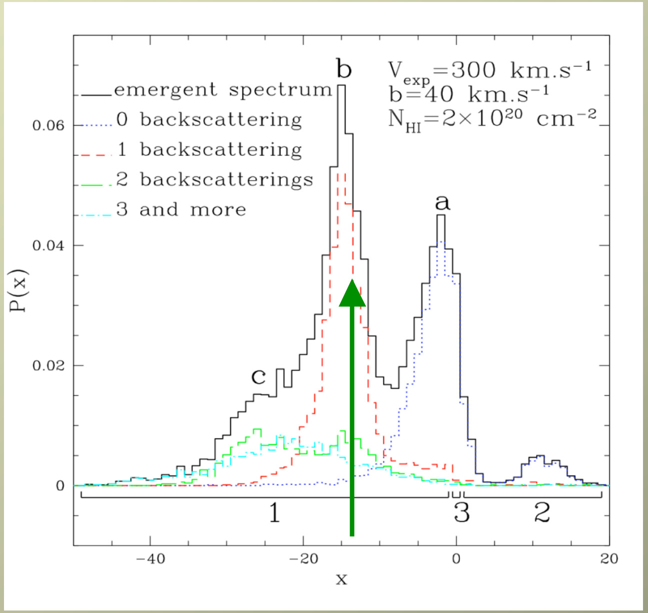
Lyα emission inside expanding shell with velocity v_{exp}

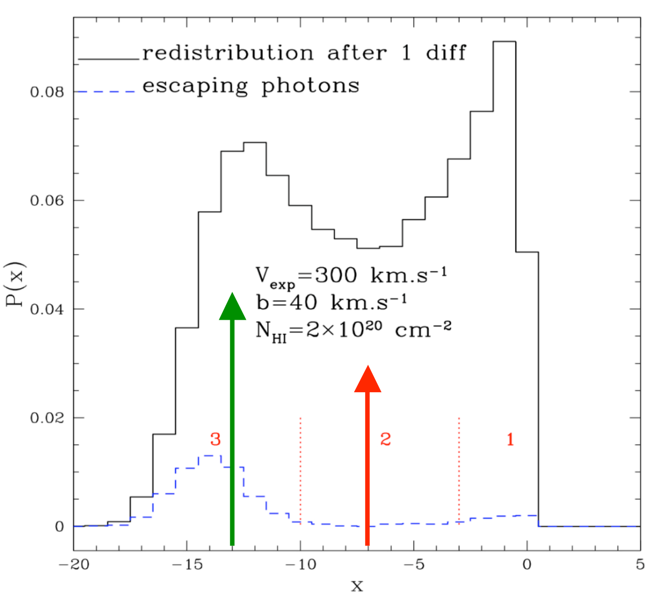
==> asymmetric redshifted line

(single or double-peaked) profile + faint blue part

==> Main peak situated « in general » at 2*v_{exp} **,** or higher velocity for high N(HI)



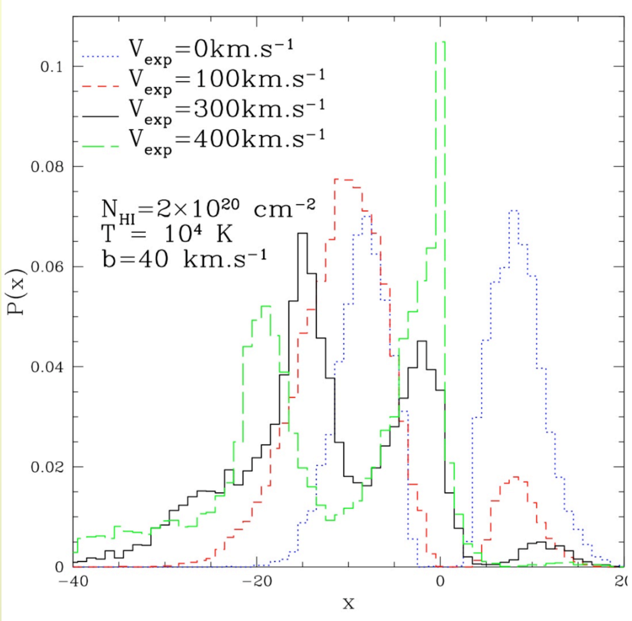




Verhamme et al. (2006)

Lyα transfer: Example

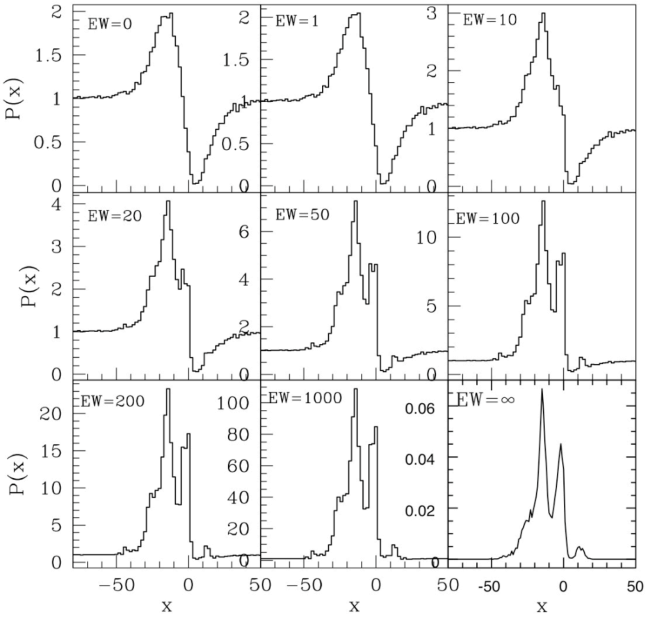
Lyα emission inside expanding shell with v_{exp}

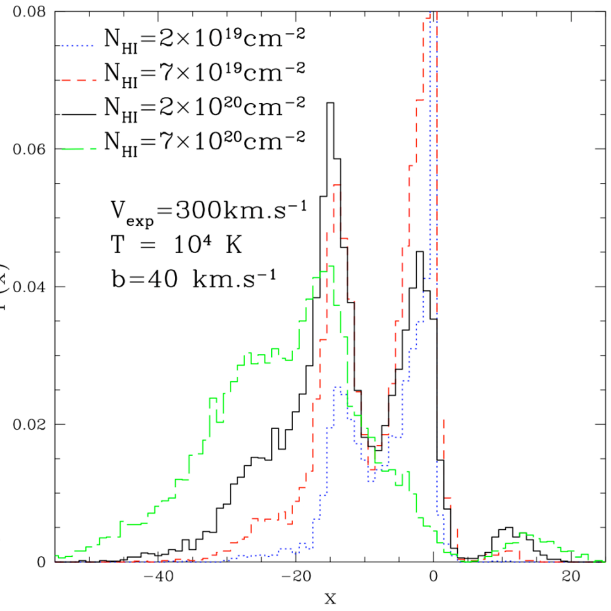


Dependence on v_{exp}

Emission line + continuum for varying EW(Lyα):

--> from P-Cygni to asymmetric line profiles





Dependence on N_H

Verhamme et al. (2006)

Lyα transfer with dust

Dust:

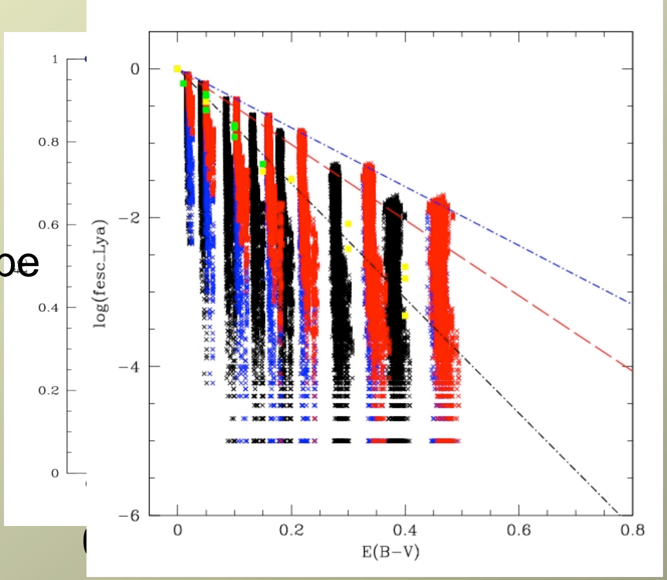
- scattering and absorption
- properties described by albedo, angular redistribution function (e.g. Henyey-Greenstein), cross section
- main modeling parameter: dust optical depth

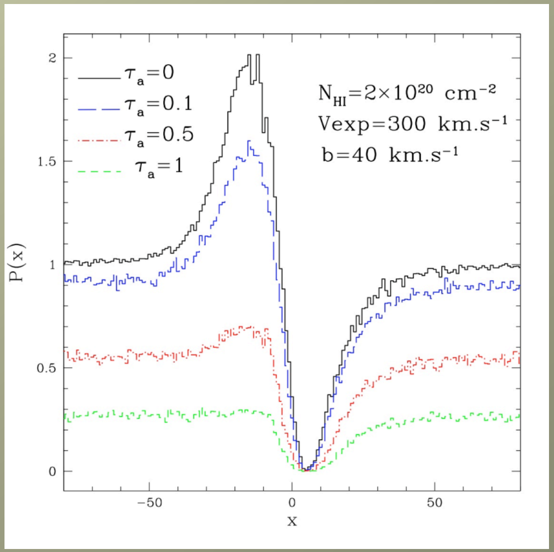
Within Lyα line: **interaction with dust** negligible at line center ($\sigma_H >> \sigma_d$!) **possible in wings due to multiple scattering**

==> Efficient destruction of Lyα photons by dust!
NOTE depends also on HI kinematics!

==> Line profiles also affected by dust

Lyα escape fraction





Lyα TRANSFER: ISM GEOMETRY?!

Lya transfer depends strongly on geometry
--> photons follow « path of least resistance »

Expectations:

•Inhomogeneous ISM:
UV continuum photons
penetrate more than Lya photons
--> higher EW(Lya)

Neufeld 1991, Haiman & Spaans 1999, Haiman et al. 2000, Hansen & Oh 2006

•Outflows & galactic winds ubiquitous in starburst galaxies --> complex geometries and velocity structures with « open » directions …

==> Orientation effects expected…

BUT: **importance of these effects remains to be established!**

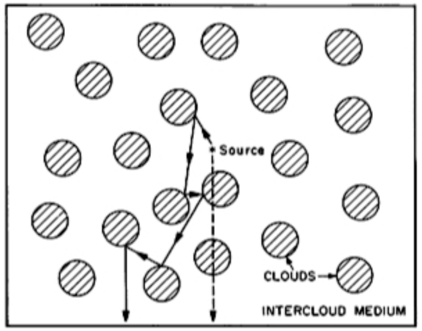
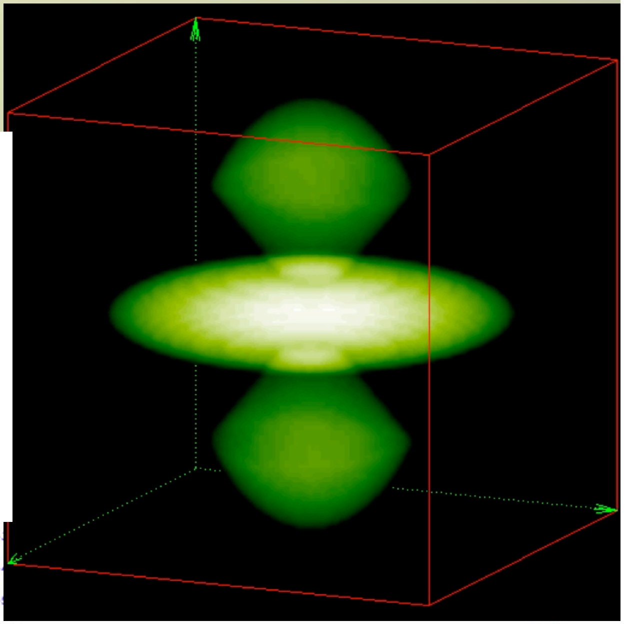
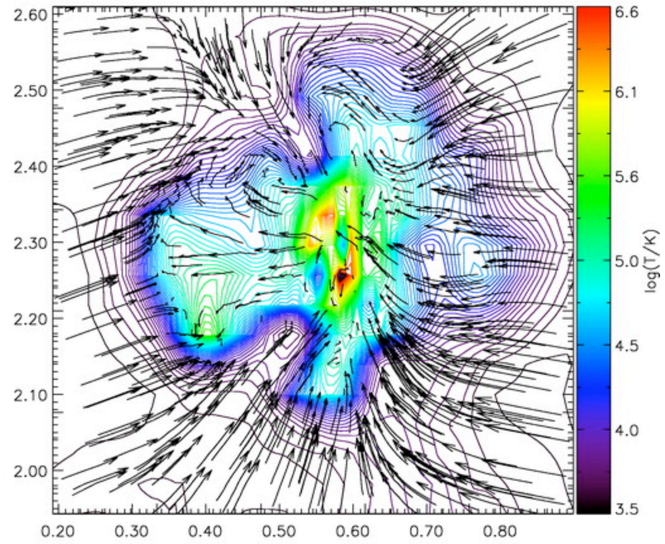


FIG. 1.—Escape of radiation from a two-phase medium. *Solid line:* typical path of a Lyα photon; *dashed line:* path of an unscattered photon.

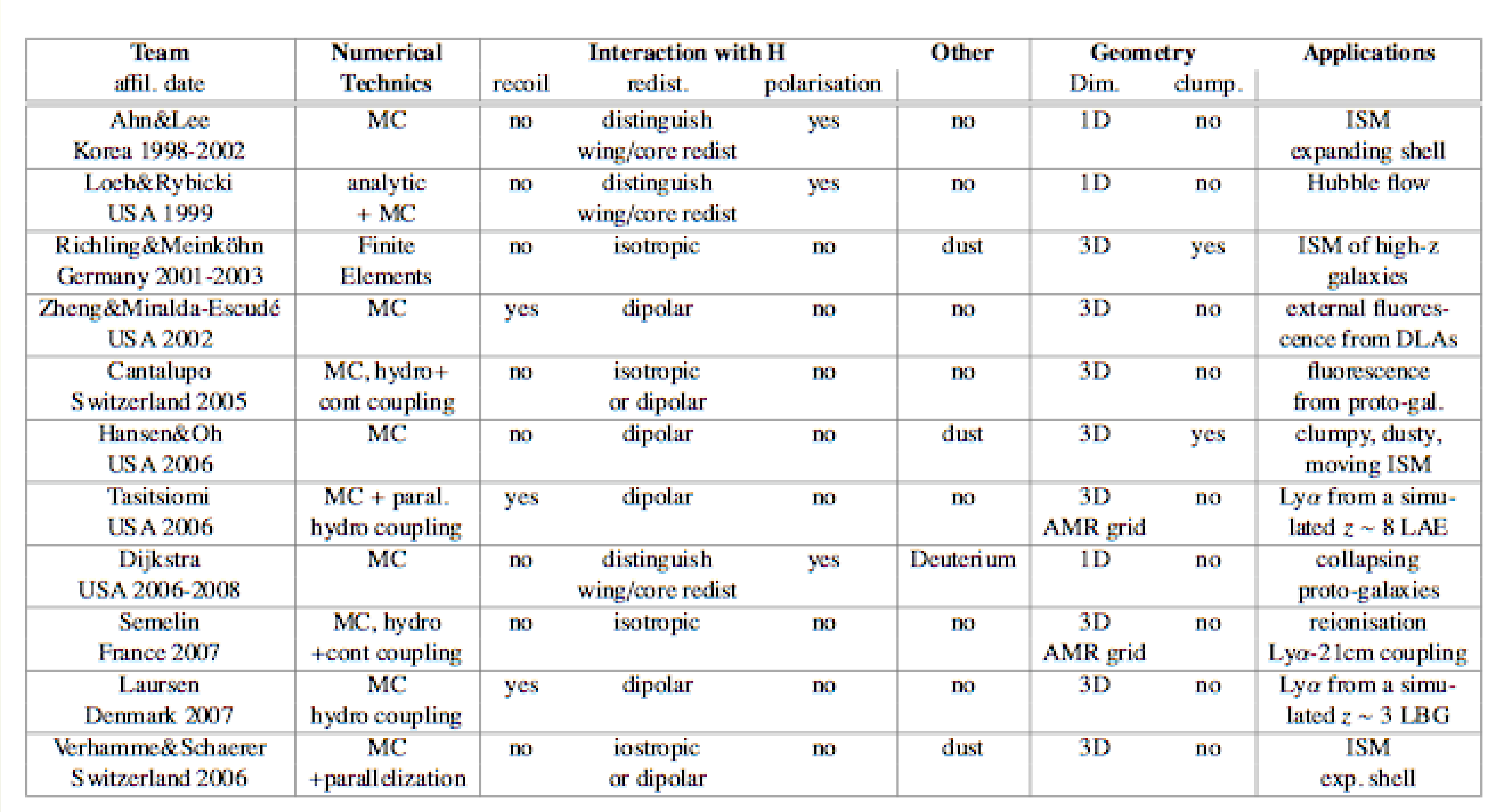




Lya transfer codes

==> **Analytical results** for simple cases in Neufeld (1990), Loeb & Rybicki (1999), Dijkstra et al. (2006)

Verhamme (2008, PhD)



Team affil. date	Numerical Technics	Interaction with H recoil	 redist.	 polarisation	Other	Geometry Dim.	 clump.	Applications
Ahn&Lee Korea 1998-2002	MC	no	distinguish wing/core redist	yes	no	1D	no	ISM expanding shell
Loeb&Rybicki USA 1999	analytic + MC	no	distinguish wing/core redist	yes	no	1D	no	Hubble flow
Richling&Meinköhn Germany 2001-2003	Finite Elements	no	isotropic	no	dust	3D	yes	ISM of high-z galaxies
Zheng&Miralda-Escudé USA 2002	MC	yes	dipolar	no	no	3D	no	external fluorescence from DLAs
Cantalupo Switzerland 2005	MC, hydro+ cont coupling	no	isotropic or dipolar	no	no	3D	no	fluorescence from proto-gal.
Hansen&Oh USA 2006	MC	no	dipolar	no	dust	3D	yes	clumpy, dusty, moving ISM
Tasitsiomi USA 2006	MC + paral. hydro coupling	yes	dipolar	no	no	3D AMR grid	no	Lyα from a simulated $z \sim 8$ LAE
Dijkstra USA 2006-2008	MC	no	distinguish wing/core redist	yes	Deuterium	1D	no	collapsing proto-galaxies
Semelin France 2007	MC, hydro +cont coupling	no	isotropic	no	no	3D AMR grid	no	reionisation Lyα-21cm coupling
Laursen Denmark 2007	MC hydro coupling	yes	dipolar	no	no	3D	no	Lyα from a simulated $z \sim 3$ LBG
Verhamme&Schaerer Switzerland 2006	MC +parallelization	no	iostropic or dipolar	no	dust	3D	no	ISM exp. shell

See also: talks by Cen, Laursen, Verhamme and
posters by Forero-Romero, Zheng

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: parallelised automatic profile fitting tool (Hayes et al. 2009)

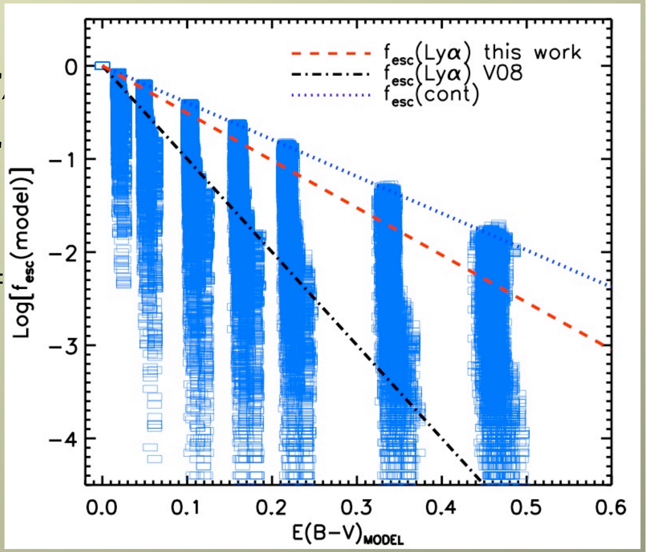
→ currently most complete Lyα + dust transfer code

First simulations: homogeneous density distributions

In preparation: clumpy/fractal structures

MCLya code + fitting engine

- Extended model grid calculations: (Hayes, Schaerer,
  - Full MCLya (cont + line + dust) radiation transfer
    No acceleration used (caution!)
  - Shell geometry: 4D grid with v=0..600 km/s, N_H=
    b=0..100 km/s, dust optical depth=0..4
  - 5200 models computed, approx. 20 CPU years!



- Automatic Lya profile fitting engine (Hayes, Schaerer, Verhamme 2009):
  - For shell models: fits in 6D parameter space (v, N_H, b, τ_{dust}, EW, FWHM)
  - → first automatic Lya fits
  - → Quantification of degeneracies, uncertainties,…

→ Many interesting applications…

→ currently most complete Lyα + dust transfer code

First simulations: homogeneous density distributions

In preparation: clumpy/fractal structures

Lya + continuum transfer modelling

Simple approach:

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

1) Expanding spherical shell - Parameters:

* If possible contrained by observations:

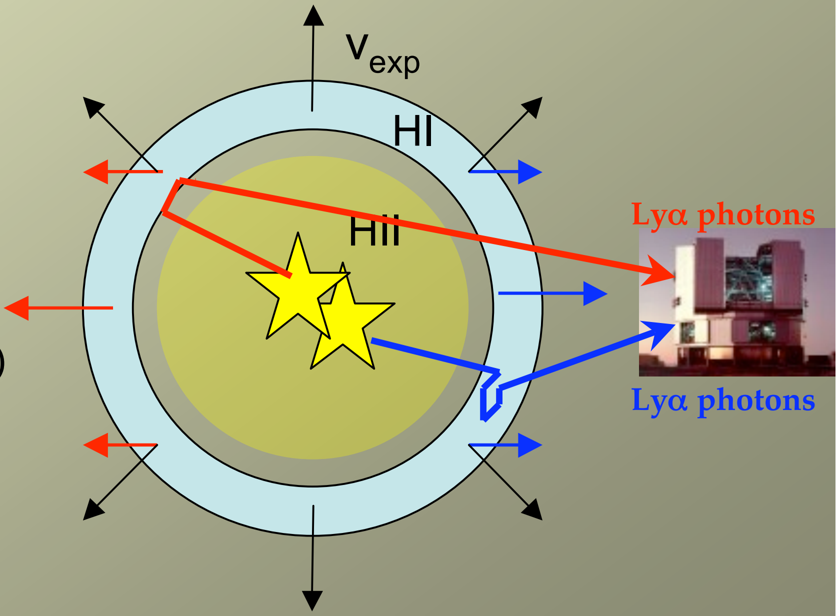
velocity v_{exp}, b, FWHM(emission)

* Constrained or free:

column density N(HI), extinction

* free: W(Lyα)

→ Richling et al. (2006), Dijkstra etal. (2006+), Schaerer & Verhamme (2008), Verhamme et al. (2008)



2) Other geometries (slabs…)

--> Atek et al. (2009)

3) Using structures from hydrodynamic simulations

--> Laursen et al. (2007, 2009), Verhamme, Devriendt+ (2009)

Why spherically expanding, homogeneous geometry?

- Simple geometry, few parameters…
- Reasonable, at least for z~3 LBGs

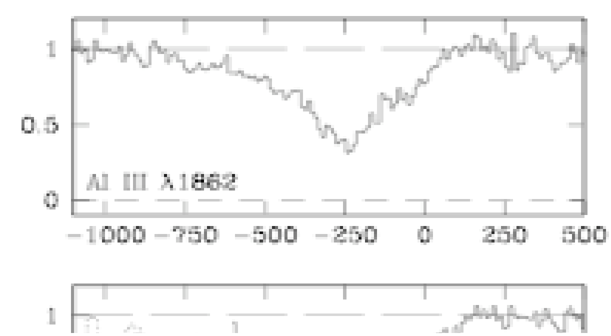
* **Expanding spherical shell** motived by:

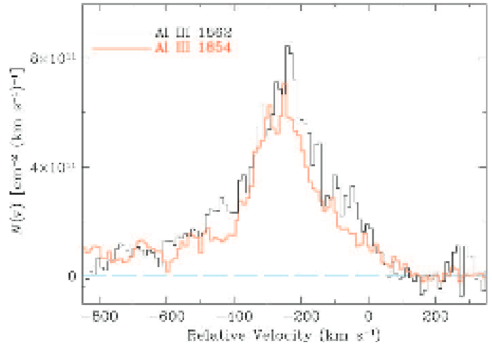
- Shift $-v_{exp}$ between IS and photospheric lines (Shapley et al. 2003)
- Shift $+2^*v_{ex}$ between photospheric lines and Lyα
- Radiation transfer modeling ==> ~spherical symmetry

- Outflow signatures ubiquituous (out to large distances)
- Very few double-peak (~static) Lya profiles observed
  -- would be expected in biconical structures (e.g. M82)!

* **Quasi-homogeneous shell / large covering factor**
motived by observations of strong IS lines---> black profiles
(e.g. Heckman et al. 2001, cb58 Pettini et al. 2002)

* **Constant expansion velocity approximation**:
column density weighted velocity spread << velocity range of IS abs. lines



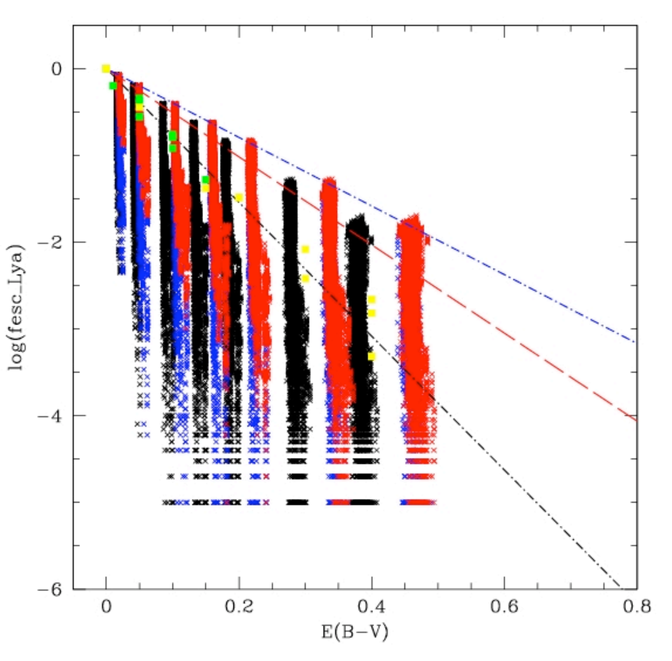


Predictions from Lya model grids

For given vexp, N(HI), dust content, b -->

- continuum escape fraction
- Lya escape fraction
- detailed Lya line profile for arbitrary input spectra

Verhamme et al. (2008)
Hayes et al. (2009)



==> **fesc(Lya) decreases with extinction**, but also dependence on vexp, dust/gas ratio, N(HI)

$EW^{obs}(Lya) = fesc(Lya)/fesc(cont)*EW^{intrinsic}$

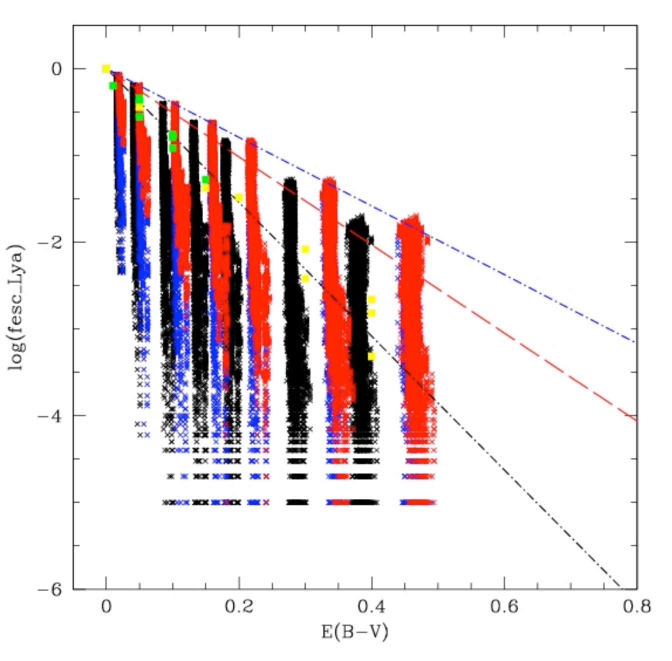
==> **max EW decreases « on average » with E(B-V)**

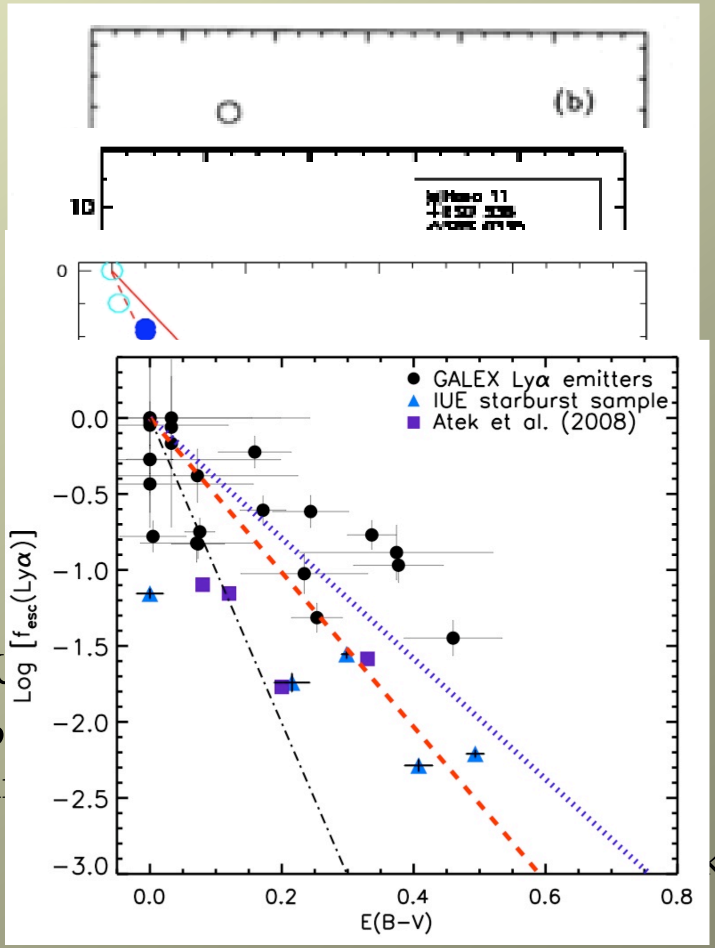
==> but « normal » EW possible at any fesc(Lya)

- E(B-V) from UV continuum attenuation (currently assuming attenuation law)
- dependence on vexp (blue, red)

Predictions from Lya model grids - compared to observations

==> **fesc(Lya) decreases with extinction**, but also dependence on vexp, dust/gas ratio, N(HI)





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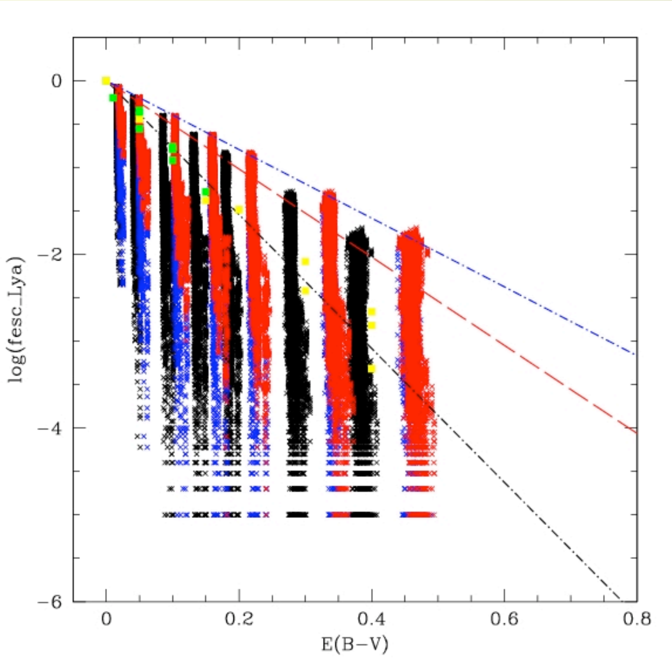
Empirical fesc determination of z~0-0.2 galaxies (Atek et al. 2009)

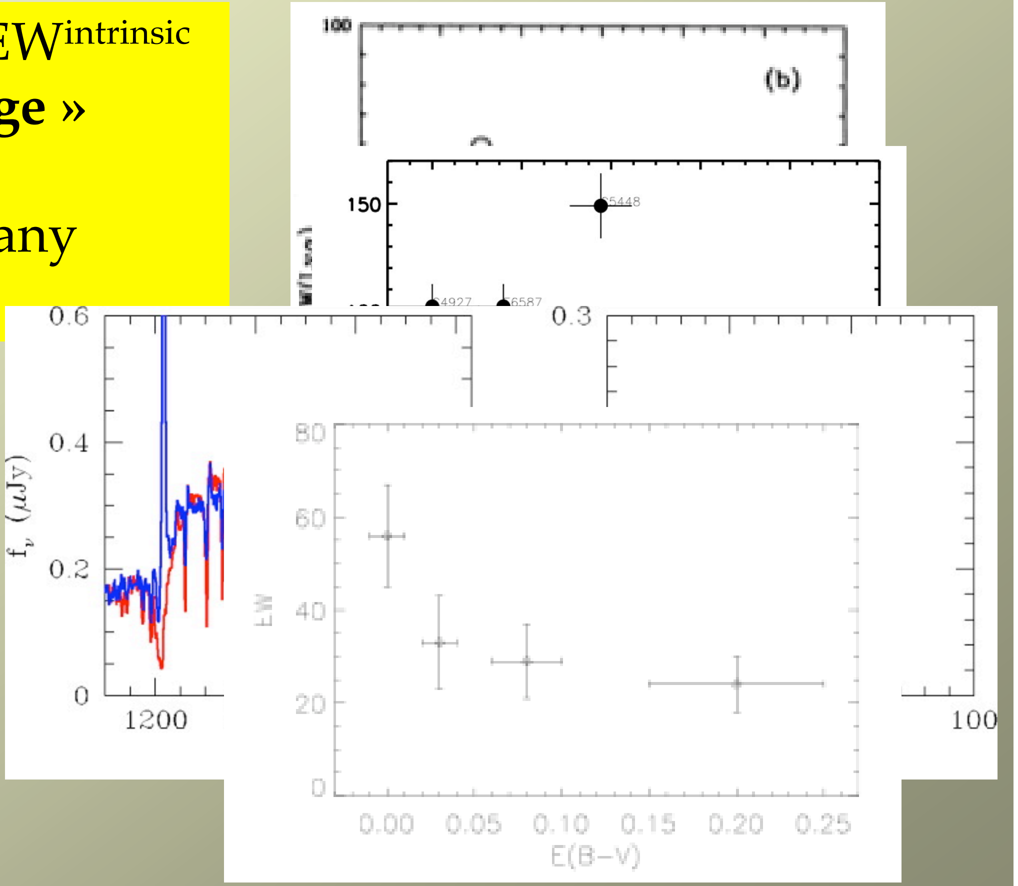
Predictions from Lya model grids - compared to observations

EW^{obs}(Lya) = fesc(Lya)/fesc(cont)*$EW^{intrinsic}$

==> **max EW decreases « on average » with E(B-V)**

==> but « normal » EW possible at any fesc(Lya)





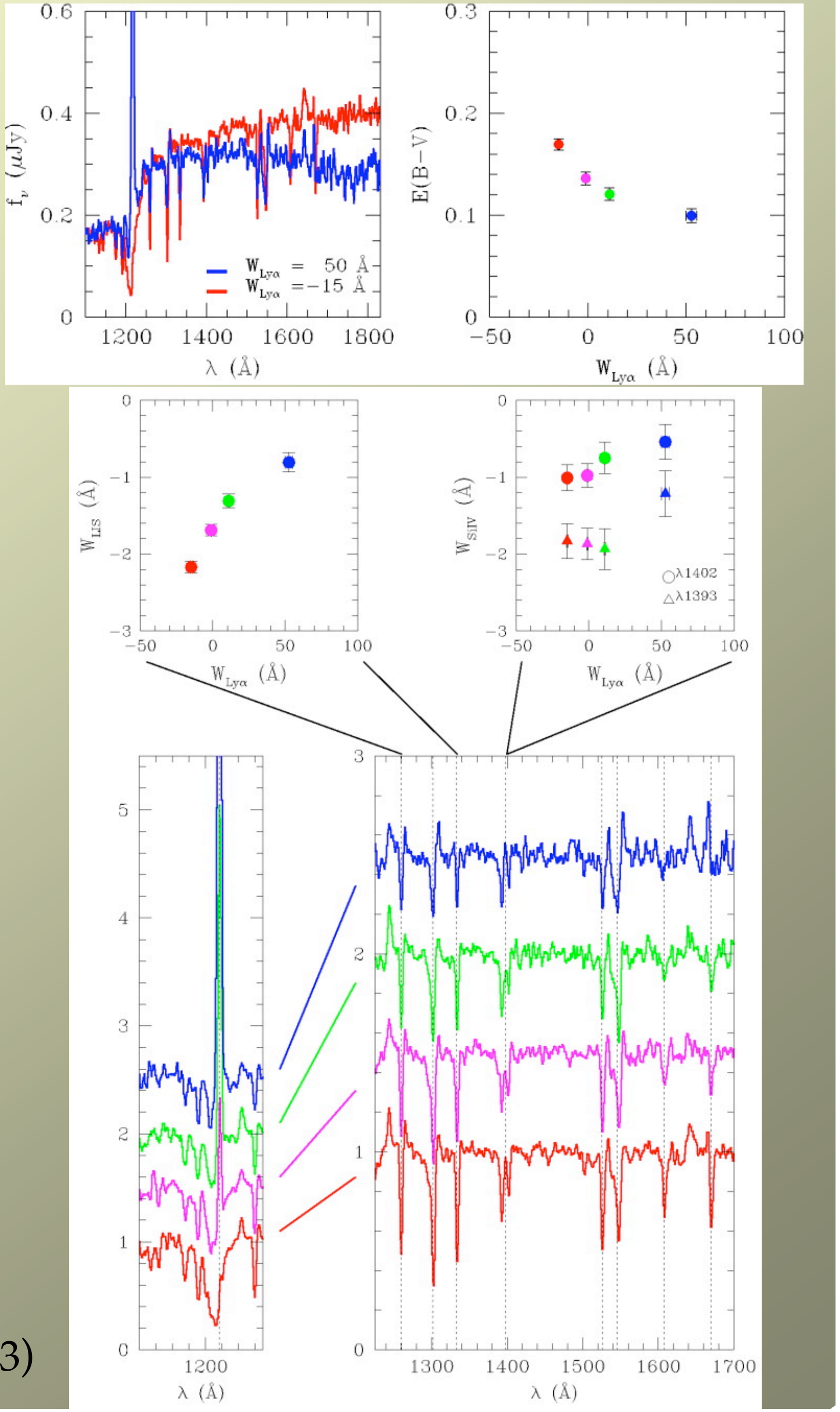
z~3-6 LBGs with Lya emission (Pentericci et al. 2009)

Quantitative analysis of Lya in LBG and LAE - Main objectives

- Quantitative use of Lya to constrain starburst properties
- Understanding observed Lya profile diversity
- Explain observed correlations between Lya and E(B-V), IS lines …
- Clarify links between different Lya emitting objects and different galaxy populations (LAE, LBG, and others)

Reminder:

- LAE and LBG = UV selected SF galaxies
- Subset of LBG shows strong Lya emission
- Intrinsically: LAE should show LyBreak

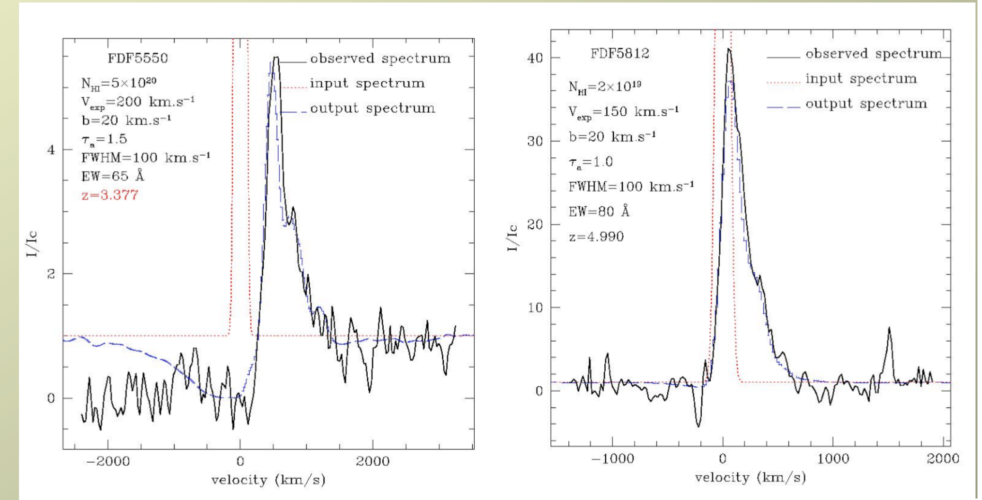


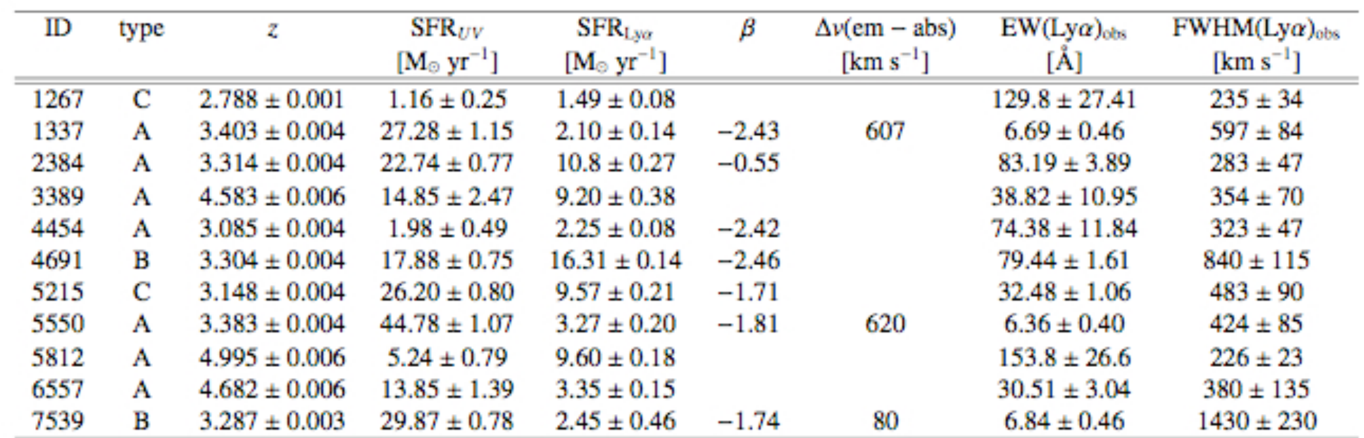
Shapley et al. (2003)

1) Lya emitting LBGs at z~3

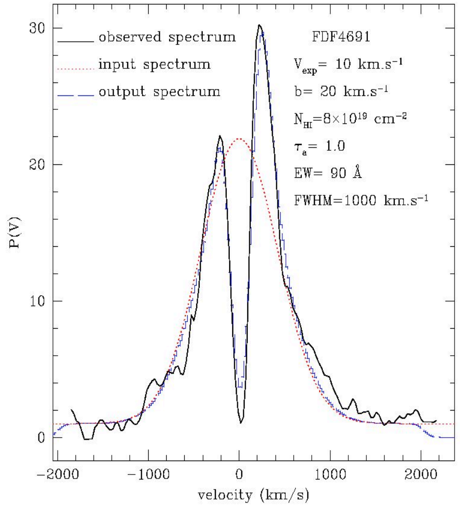
- modeling of **11 LBGs with Lyα emission** from the FORS Deep Field (Tapken et al. 2007)
- 8 objects @ z~2.7-3.4, 3 @ z~4.5-5
- Variety of profiles and EW

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





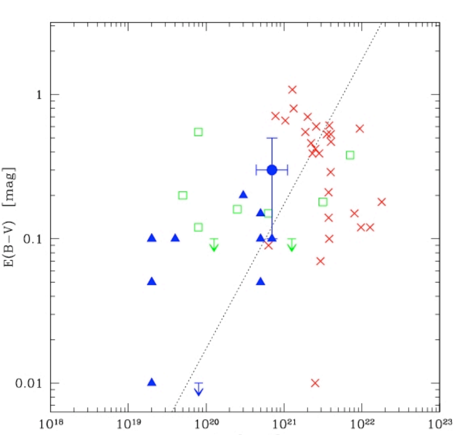
ID	type	z	SFR_{UV} [$M_\odot$ yr^{-1}]	$SFR_{Ly\alpha}$ [$M_\odot$ yr^{-1}]	β	Δv(em − abs) [km s^{-1}]	EW(Lyα)$_{obs}$ [Å]	FWHM(Lyα)$_{obs}$ [km s^{-1}]
1267	C	2.788 ± 0.001	1.16 ± 0.25	1.49 ± 0.08			129.8 ± 27.41	235 ± 34
1337	A	3.403 ± 0.004	27.28 ± 1.15	2.10 ± 0.14	−2.43	607	6.69 ± 0.46	597 ± 84
2384	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

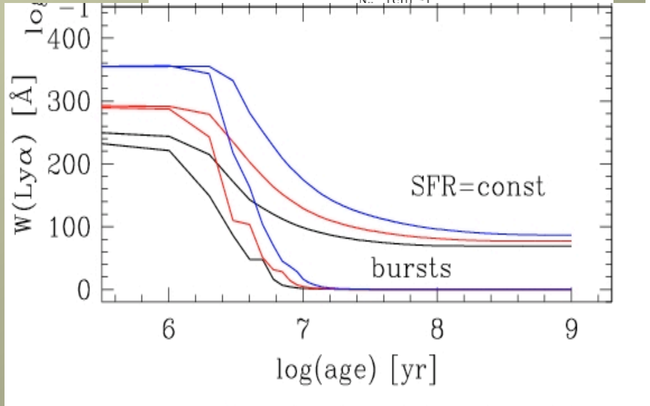


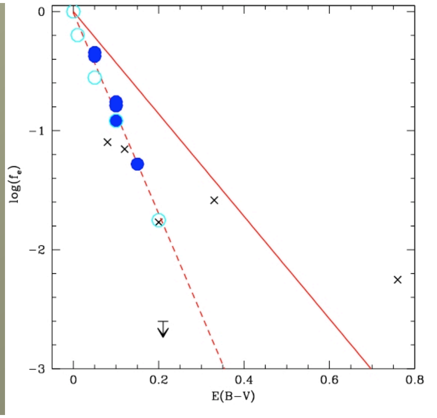
Verhamme et al. (2008)

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**
- Correlation of shift Lya-IS lines with EW does **not** reflect ouflow velocity variations







Verhamme et al. (2008)

2) LBGs at z~3 with Lya absorption

- 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)

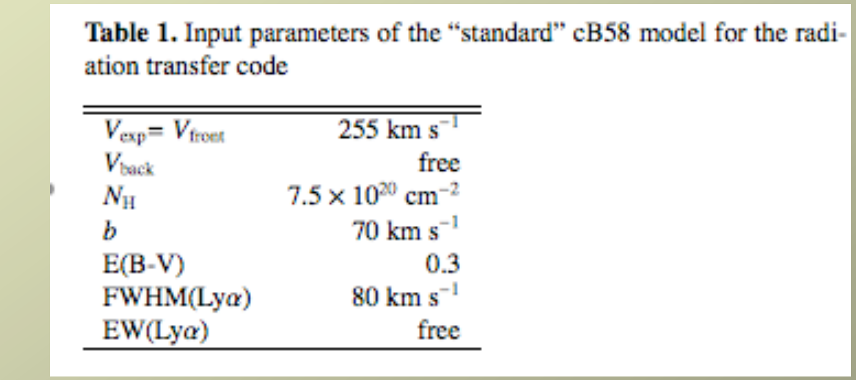
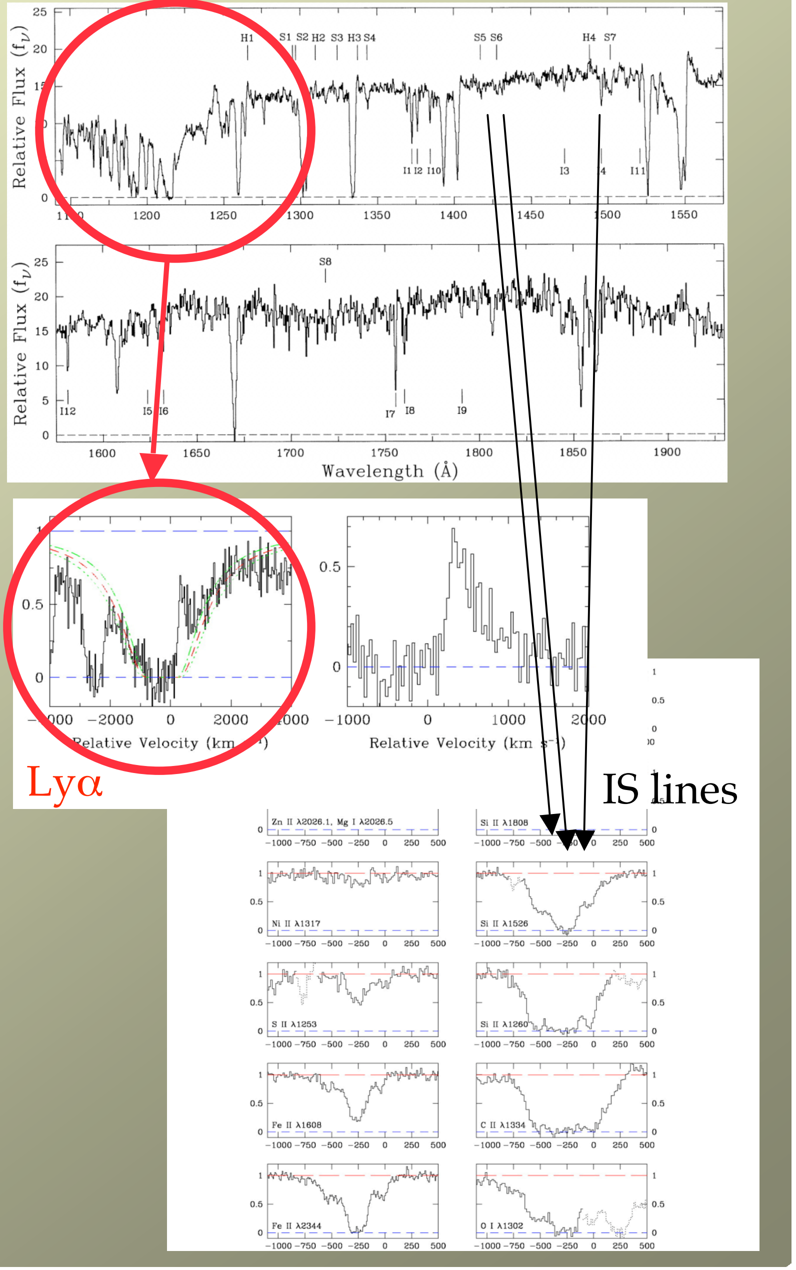


Table 1. Input parameters of the "standard" cB58 model for the radiation transfer code

$V_{\mathrm{exp}} = V_{\mathrm{front}}$	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



Lyα

IS lines

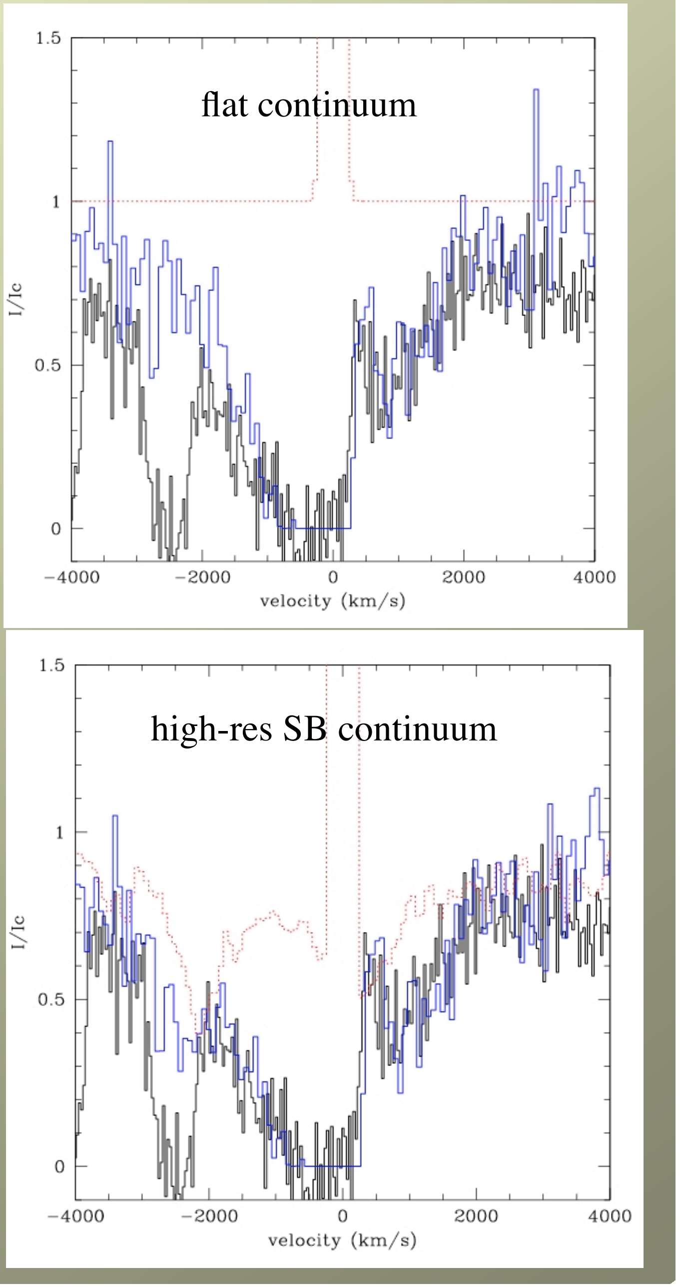
2) LBGs at z~3 with Lya absorption (cB58)

Geometry: two moving slabs (or asymmetric shell)
v_{front}=255 km/s (fixed by IS lines),
v_{back}~140 km/s yield excellent fit!
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 !



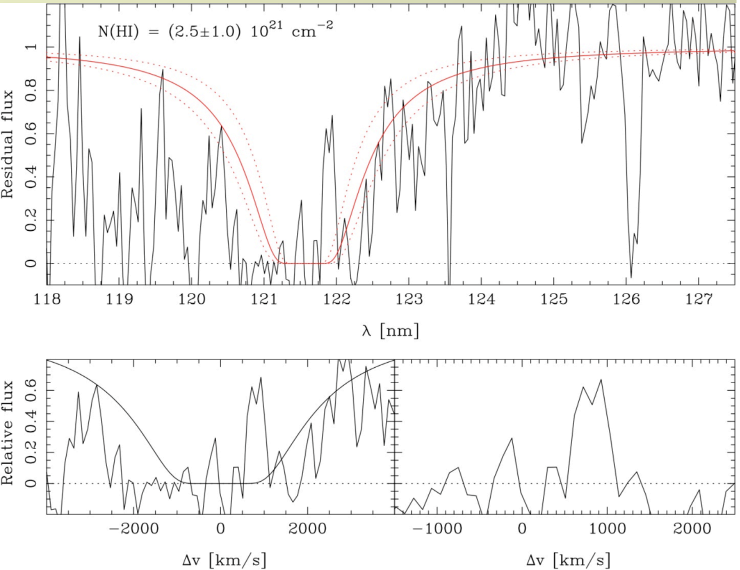
Schaerer & Verhamme (2008)

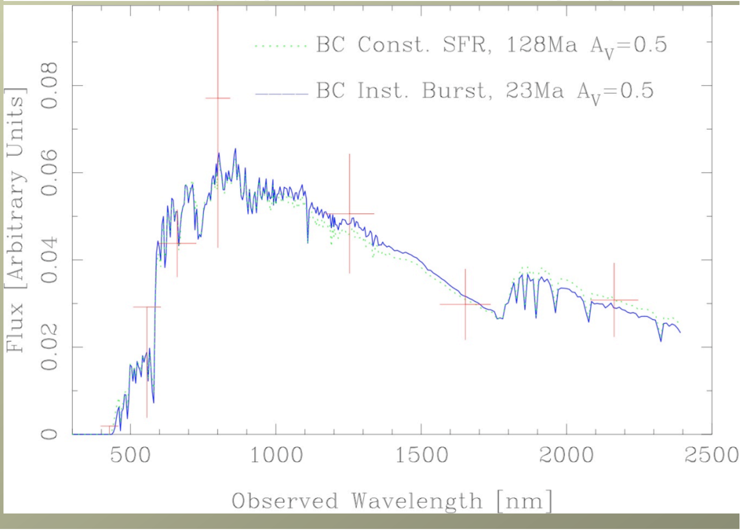
2) LBGs at z~3 with Lya absorption (continued)

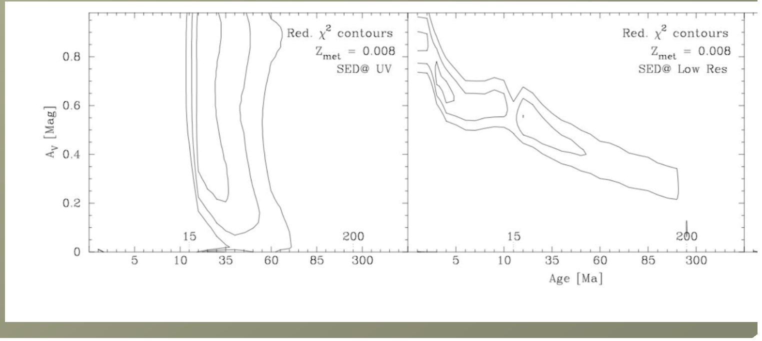
- Strongly lensed z=3.7 LBG discovered by Cabanac et al. (2005)
- Deep FORS2 medium-res spectroscopy and SED analysis: Cabanac et al. (2008)

☐ extinction: A_V~0.5
☐ Low IS lines - photospheric: outflow~110 ±30 km/s
☐ Lya emission peak at ~800-900 km/s
☐…

--> see Poster Cabanac







2) LBGs at z~3 with Lya absorption (continued)

- ❑ Extinction: A_V~0.5
- ❑ Low IS lines - photospheric: outflow~110 ±30 km/s
- ❑ Lya emission peak at ~800-900 km/s

Lya fit results:

→A_V~0.4-1.6

→N(HI)~(2-5) 10^{21} cm^{-2}

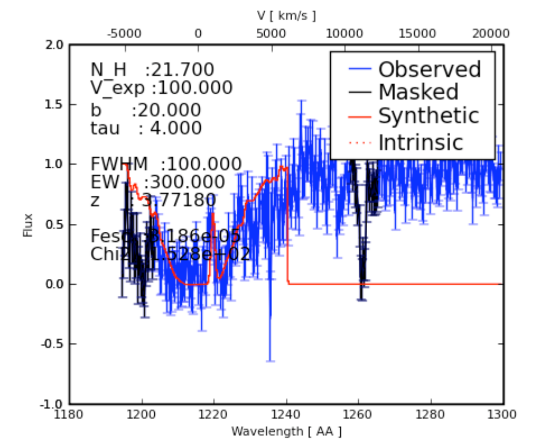
→High intrinsic EW

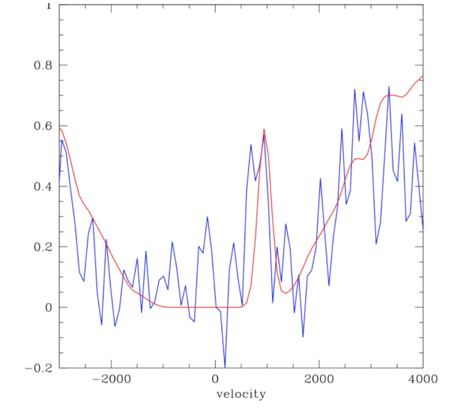
- ➢ Confirms results from cB58

→Large v shift of Lya peak due to high N(HI). Compatible with low outflow velocity

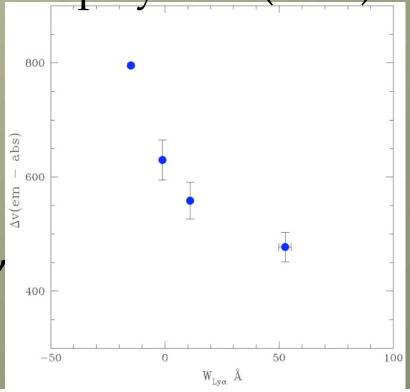
- ➢ **Observed correlation of Lya-IS shift in LBGs does NOT trace true outflow velocity variations**

Cf. LBG wind models: Ferrara & Ricotti (2007), Nath & Silk (2009)

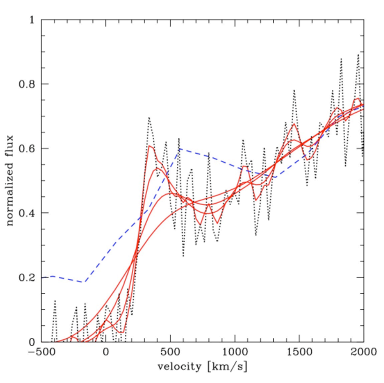




Shapley etal. (2003)



Verhamme etal. (2008)



LBGs and LAEs at z~3: a consistent scenario

Scenario proposed from analysis of cB58, Cabanac and FDF objects:

- **All LBGs have an intrinsic emission of W(Lyα)~60-100 Å (SFR~const) or higher (up to ~200-400 Å for ages <~10 Myr - some LAE)**

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

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

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

LBGs and LAEs at z~3: a consistent scenario

Implications for LBGs and LAEs:

- **No correlation between Lyα and age expected for EW<~100 Å**
- **EW>~100 Å ==> young population (<~10 Myr) dominates UV emission**

- Lya escape fraction is not constant

On average:

- **LAE: lower extinction expected than for LBG**
- **LAE: lower mass expected than for LBG**

Other implications:

- **Observed W(Lyα), LF(Lyα) distributions ≠ intrinsic distributions!** Number of galaxies with weak W(Lyα), L(Lyα) must be overestimated.

Other studies

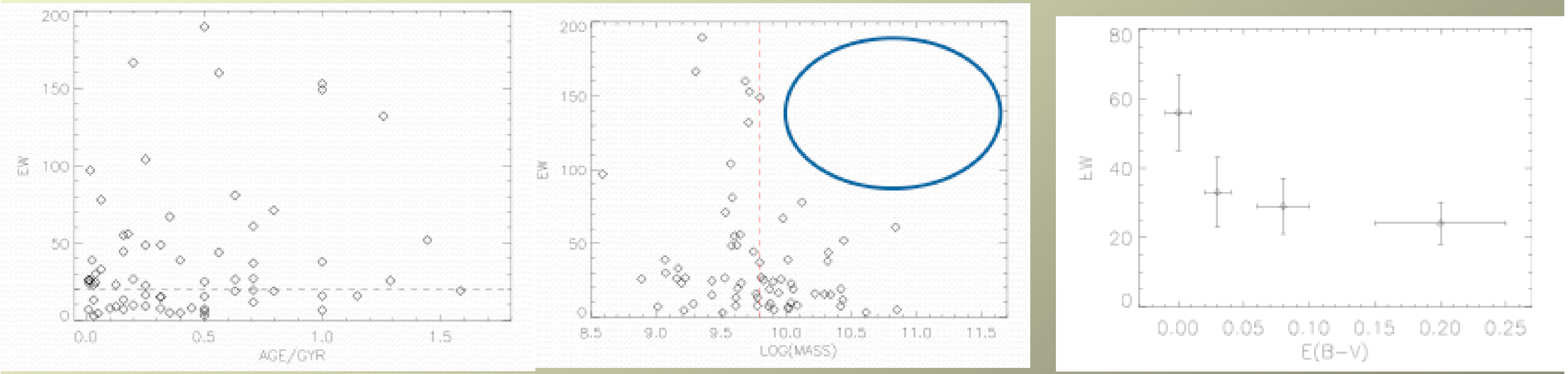
Pentericci et al. (2009): *LBG + Lyα selection*

- Selection of ~70 B,V,i dropouts with U to 8.8mu photometry (GOODS-MUSIC) and Lyα in emission (~50% have EW>20Å)
- SED fits: mass, SFR, age, extinction

==> No correlation of Lyα with age

==> absence of high EW for massive gals

} agree with our scenario



Increase of SFR, metallicity, extinction, … with galaxy mass observed in many samples

Reddy et al. (2006, 2008), Burgarella et al. (2006), Noeske et al. (2007), Elbaz et al. (2007) …

cf. talks of Reddy, Sawicki, Illingworth, + Ferrara

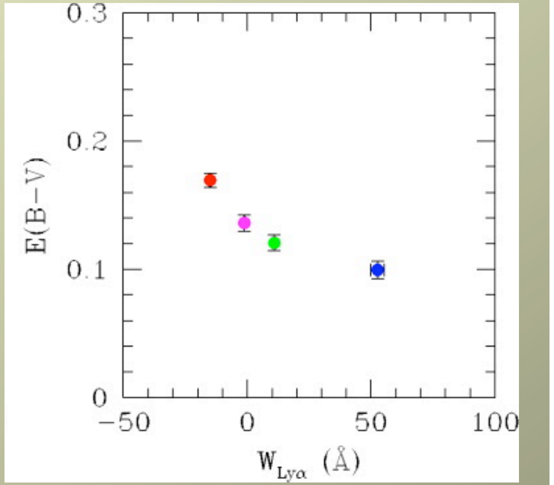
LBGs and LAEs at z~3: a consistent scenario

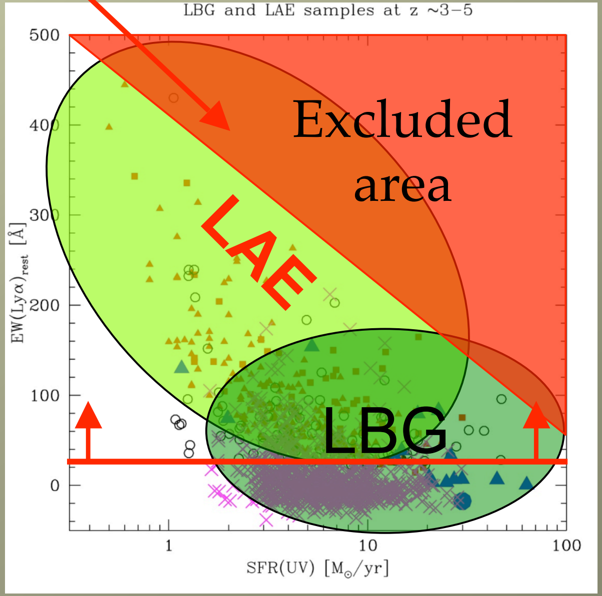
Our scenario:

✓ **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)

LBGs and LAEs at z~3: a consistent scenario

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(Ando et al. 2004, Yamada et al. 2005, Tapken et al. 2007…)

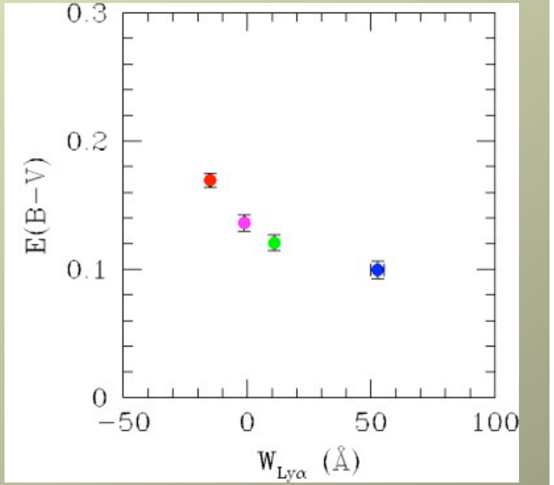
…

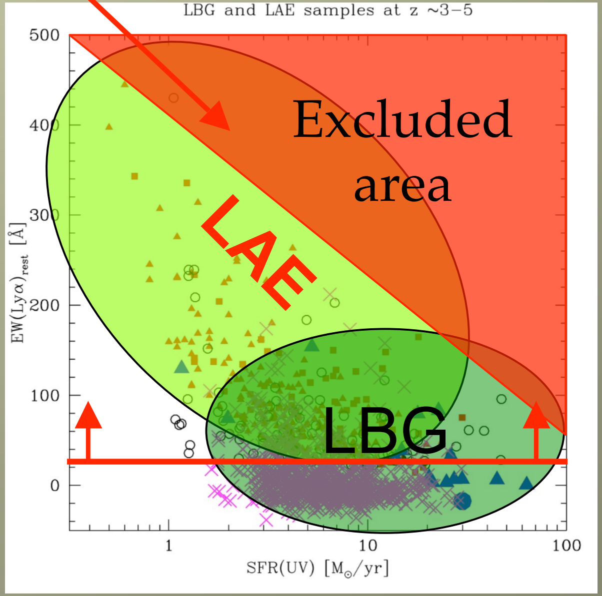
✓**allows consistent diagnostic between Lyα and UV:**
SFR=const, age ~30-100 Myr

✓**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)

Unification of LBGs and LAEs at z~3

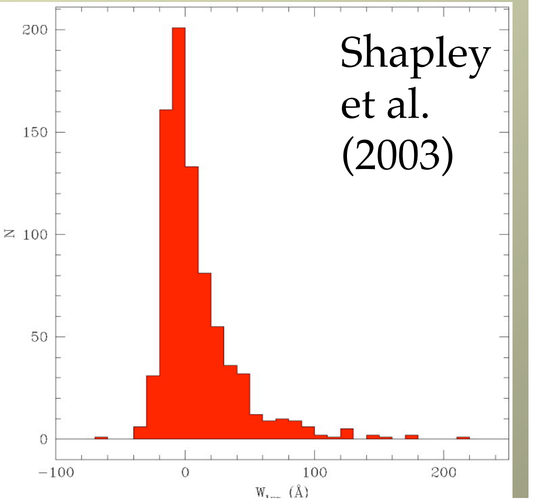
➢ EW(Lyα) distributions of LBG and LAE apparently different (Gronwal et al. 2007)

➢ However: most LAE fainter than LBG

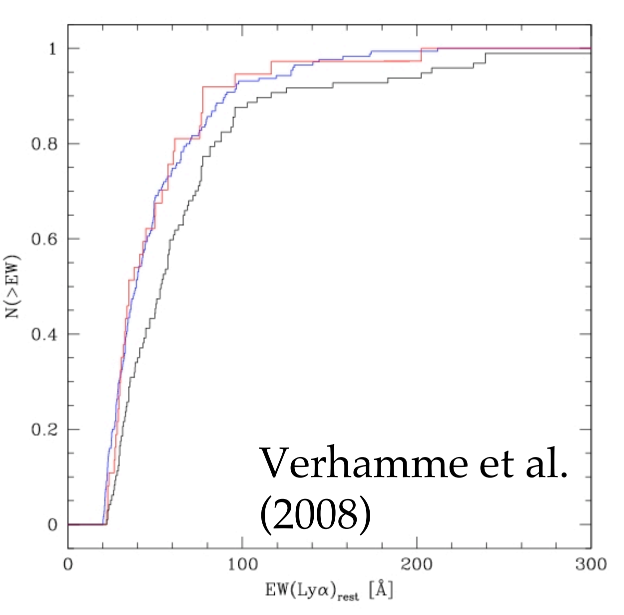
With same criteria (EW^{rest}>20 Å, R_AB<25.5):

- **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



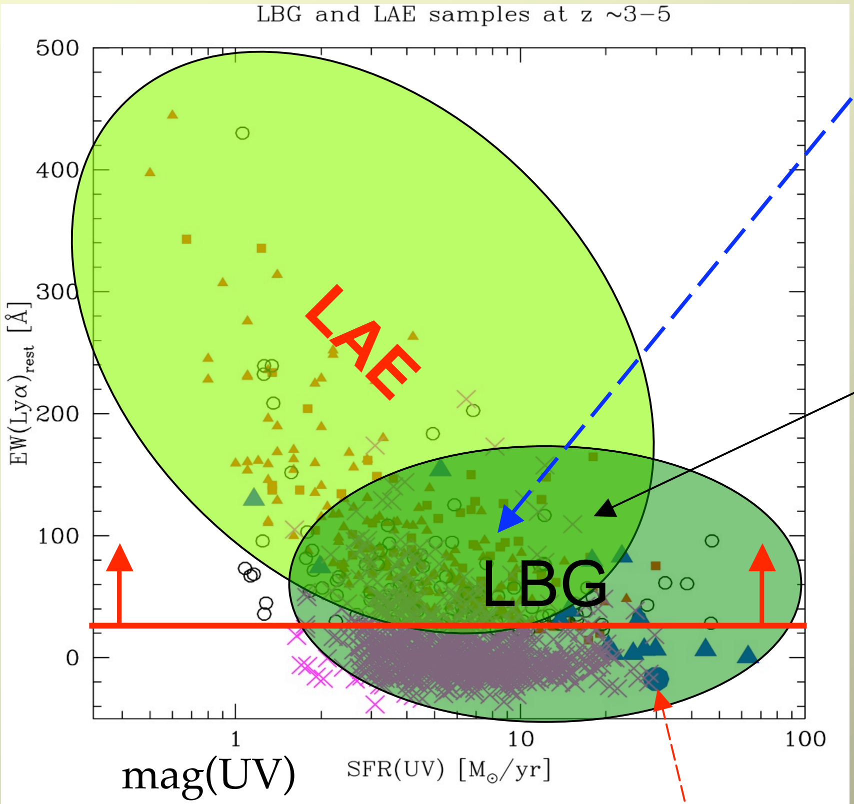
Shapley et al. (2003)



Verhamme et al. (2008)

Unification of LBGs and LAEs

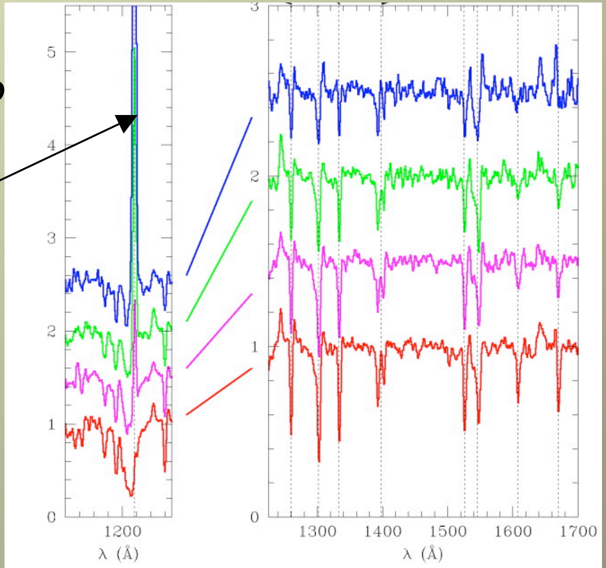
Verhamme et al. (2008)



e.g. FDF objects

overlap
~25%

~25%
~25%
~25%



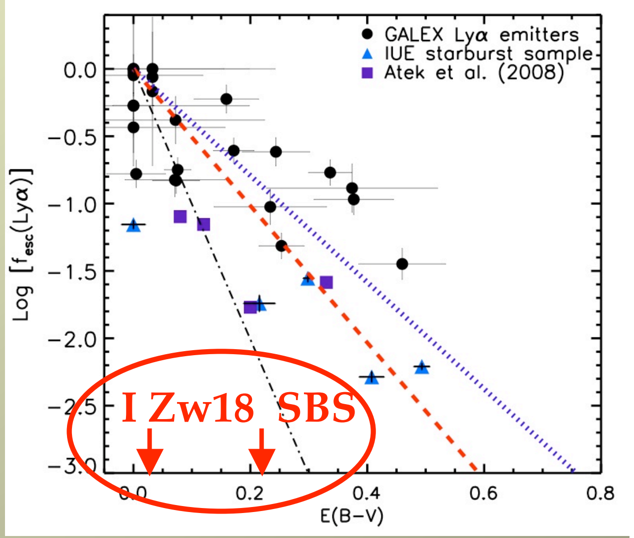
Shapley et al. (2003)

cB58, Cabanac

==> *Remaining ~77% of LAEs:*
should behave like « scaled down » LBGs

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

Questions / tests for our scenario

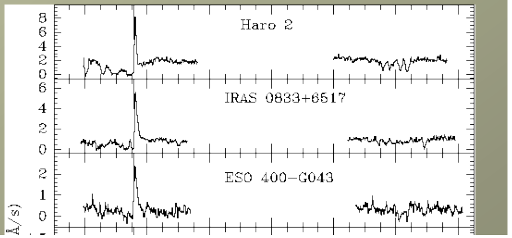


Are the Lya observations of local/nearby objects compatible with our models/scenario?

- Global (integrated) properties of local SB with *Lya emission* - yes

- What about objects with strong ***Lya absorption*** (SBS 0335-052, I Zw 18…) ?

Kunth et al. (1998)

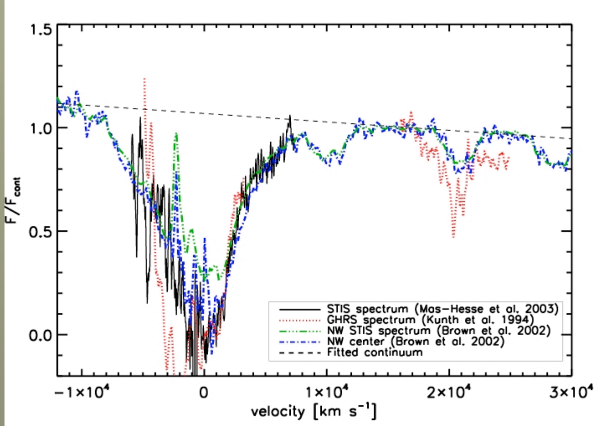


Objects with Lya absorption show ~static ISM
(Kunth et al. 1998)

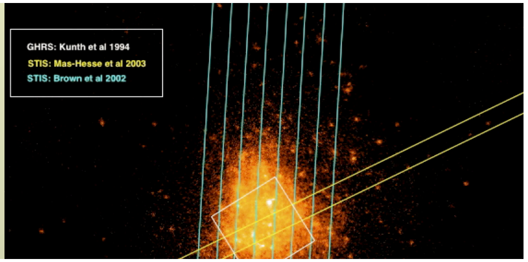
--> increases scattering --> higher dust abs.probility

But, What about **very low/zero extinction** objects ?

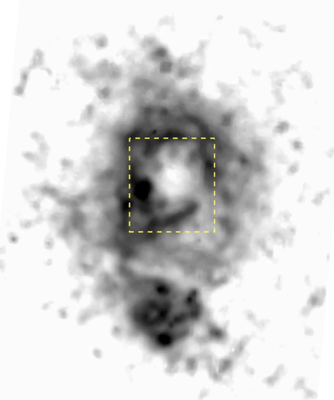
Prototype I Zw 18: among most metal-poor galaxies known. E(B-V) in NW region~0-0.05
(Cannon et al. 2002)



I Zw 18 -- how to transform strong emission into absorption without dust?



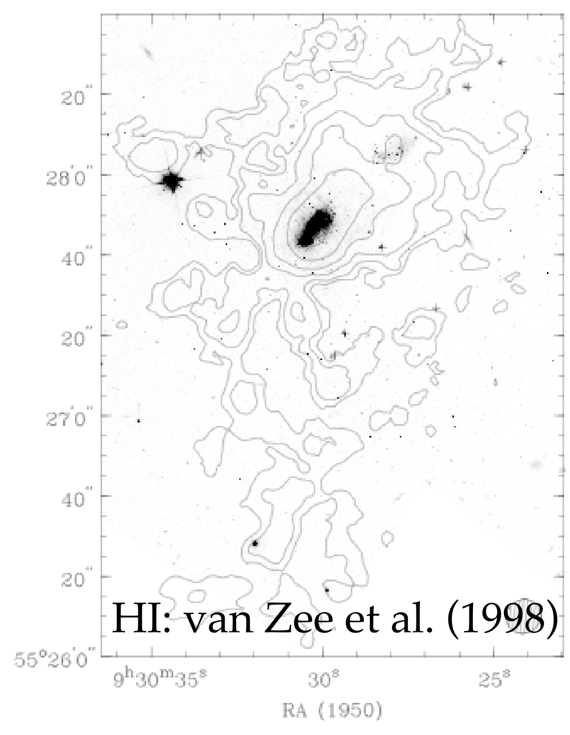
Atek,
Schaerer,
Kunth
(2009)



HST: ACS + STIS data

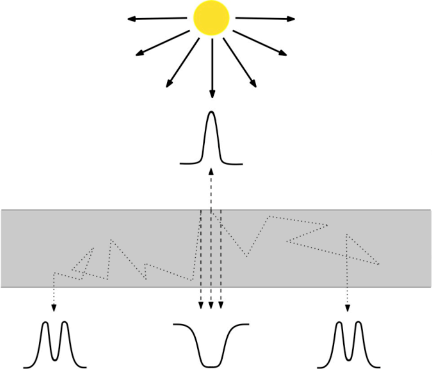
Intrinsic Lya emission ma
(from Ha + extinction)

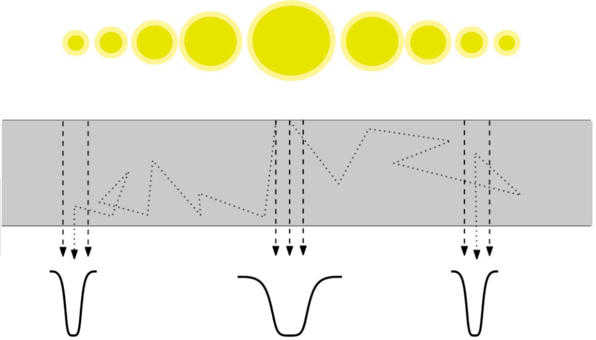
Observed spectra across
NW region

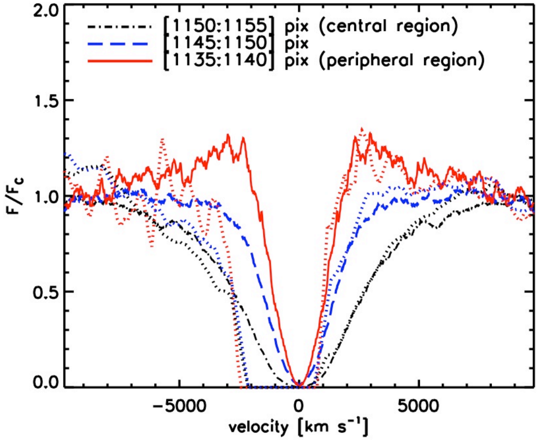


HI: van Zee et al. (1998)

- Absorption profile explained by:
  - Very high N_H (3e21 cm^{-2}) + static + little dust, or
  - Very high N_H + static+ scattering into diffuse halo
- Spatial variation of Lya profile consistent with observed distribution of UV continuum and Lya emission







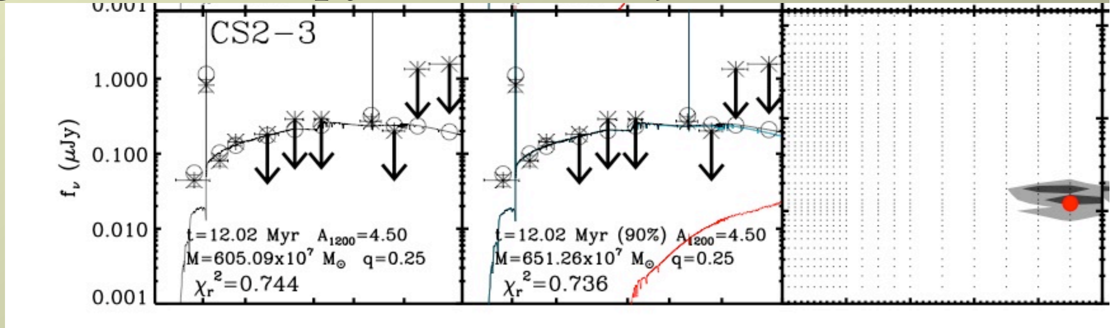
Evidence for clumping?

* Clumping invoked to explain high EW(Lya) objects

Finkelstein et al. (2008,9): *analysis of 14 LAE at z~4.5* (CDFS)

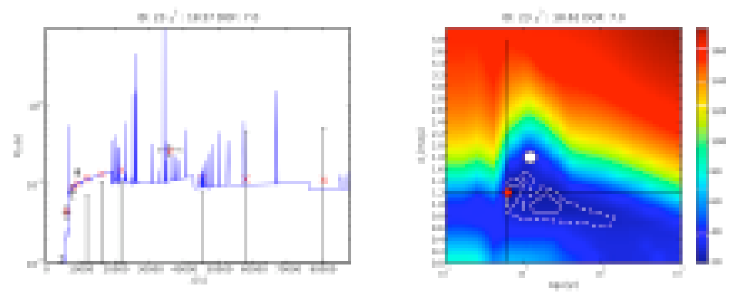
==> 6-7 of 14 objects have $A_V>0.8$ ($E_{B-V}>0.2$)

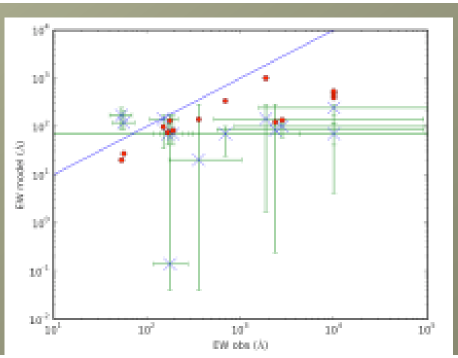
==> evidence for Lyα boosting due to clumpy ISM in 8 objects



Are the results robust?
Do they make sense?

- High extinction:
  - –Large uncertainties
  - –Few bands with detections, short leverage arm --> need deeper JHK
  - –Multiple populations?
- Lyα boost:
  - –Only for objects with large EW(Lyα) uncertainties!
  - –Only in faintest objects. Physical reason?
  - –Assumes also half of Lyα flux is lost in IGM





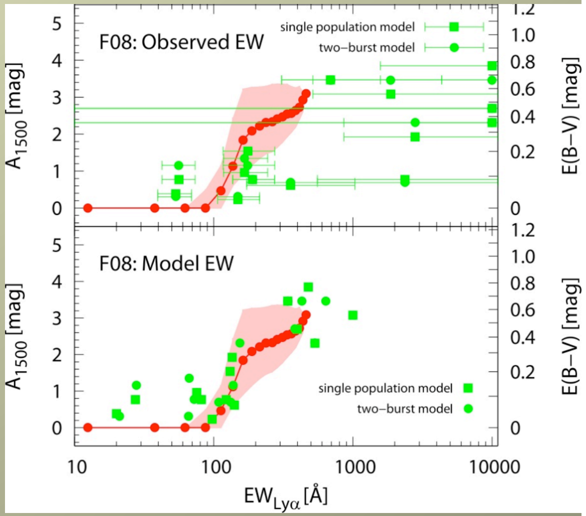
--> Poster de Barros

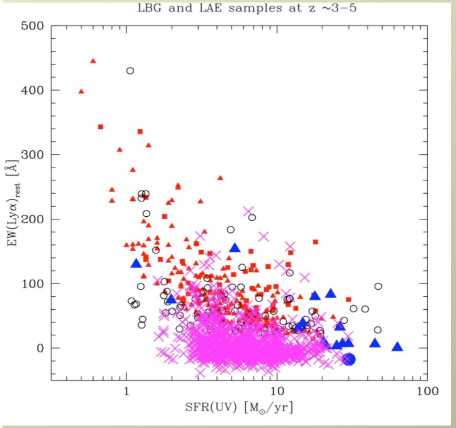
Evidence for clumping?

Are the results robust? Do they make sense?

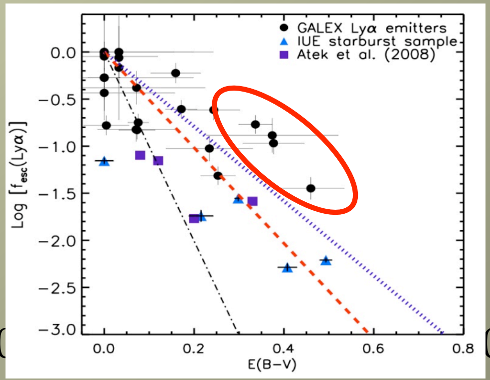
[Finkelstein et al. (2009), Kobayashi etal. (2009)]

- High extinction (mean A_V=0.9) in z~4.5 LAE:
  - **opposite** to conclusions from z~5 LBGs (Verma et al. 2007) and trends of decreasing extinction with increasing z (Bouwens+, Reddy+)
- Trend of EW(Lyα) *increasing* with extinction:
  - **opposite** to observed trend in z~3 LBGs (Shapley et al. 2003+), not seen in GALEX z~0.2 LAE (Atek et al. 2009)
- **Opposite** explanation for « Ando-effect » (Kobayashi et al. 2009):
  - due to *increase* of dust with *decreasing* mag/SFR?

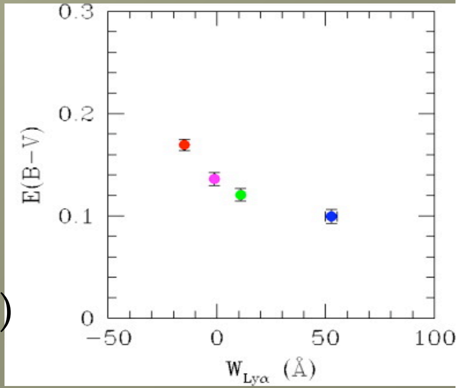




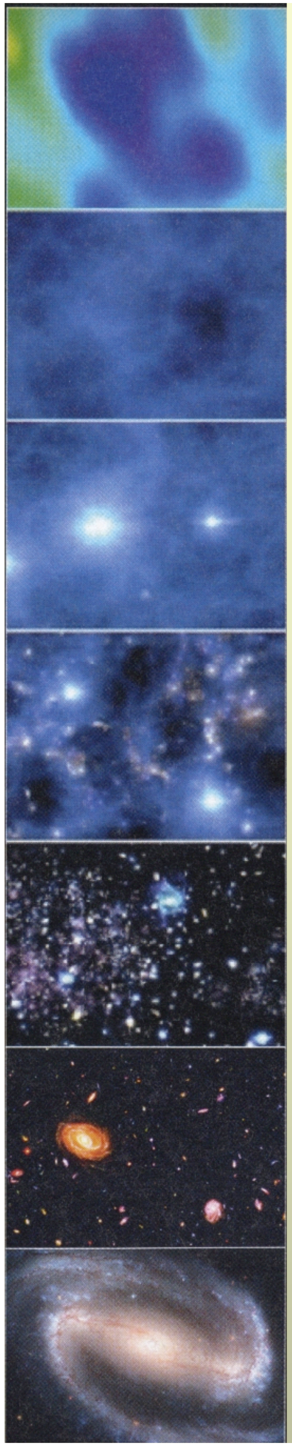
No clear evidence for effect of clumping on Lya (yet!?)



GALEX sample (Atek et al. 2009, Scarlata talk)



z~3 LBGs (Shapley et al. 2003)



Conclusions

- 3D Lya transfer codes: many new developments
  - ➢Must include Lya+ dust + continuum transfer for comparison with galaxies
  - ➢ Predict dependence of fesc(Lya) on E(B-V) + other parameters

- MCLya: successful modeling of Lya profiles of LAEs and LBGs covering a diversity of line profiles
  - ➢**Main factor explaining transition from abs to emm: dust**
  - ➢Models explain many (all?) observed correlations

==> Unification of LBGs and LAEs:

❖ All LBGs are intrinsically LAE. Increase of dust with galaxy mass + transfer effects explain the differences.

❖ At z~3: 20-25 % of LBG = 23% of LAEs.
Other LAEs = less luminous than LBGs

❖ Increase of LAE/LBG with redshift naturally explained

- 3D Lya models (so far) also consistent with local starbursts

→Simulations using more sophisticated structures upcoming…
→Need to couple transfer models at galaxy and IGM scales