期待されるLAE 検出数 :準解析的モデルからの見積り

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Mock Catalog for High-z Galaxies

○ ベース＝準解析銀河形成モデル（三鷹モデル Nagashima & Yoshii 04）

・任意の z の銀河の物理量（星形成史、金属量、星･ガス質量など）を計算

○ ＋ 最新の種族合成モデル（Schaerer 03）

・低金属量星（$Z < 10^{-4}$）の進化トラックの最新モデル

・三鷹モデルの星形成史と convolve → N_{LyC}、$L_{Ly\alpha}$、L_{1500} など

○ ＋ Lyα 離脱率の現象論的モデル（MARK+ 07, 10）

・Lyα 輻射輸送の理論計算･近傍銀河の観測からの示唆を考慮

・z=3-7 LAE の Lyα･UV 光度関数、Lyα 等価幅分布を再現

○ ＋ nebular emission（Schaerer & de Barros 09）

・continuum + lines (H, He, C, N, O, S, etc.：金属量に依存)

Mock Catalog の補足

○ 近傍銀河で得られた星形成などの経験則を、そのまま high-z に適用

・ダスト減光曲線＝MW、metal-to-dust mass ratio＝MW

➔ high-z での星形成が本質的に変わる場合もありうる

○ 個々の銀河は、個数ではなく個数密度

➔ サーベイ体積を与えれば、その中の銀河の個数が求まる

・銀河 “1つ” の個数密度はホストハローの質量に依存

○ Schaerer 03 には限られた情報（N_{LyC}、UBV… mag など）しかない

➔ 他のバンドにおける等級は、Kodama & Arimoto (1997) から計算

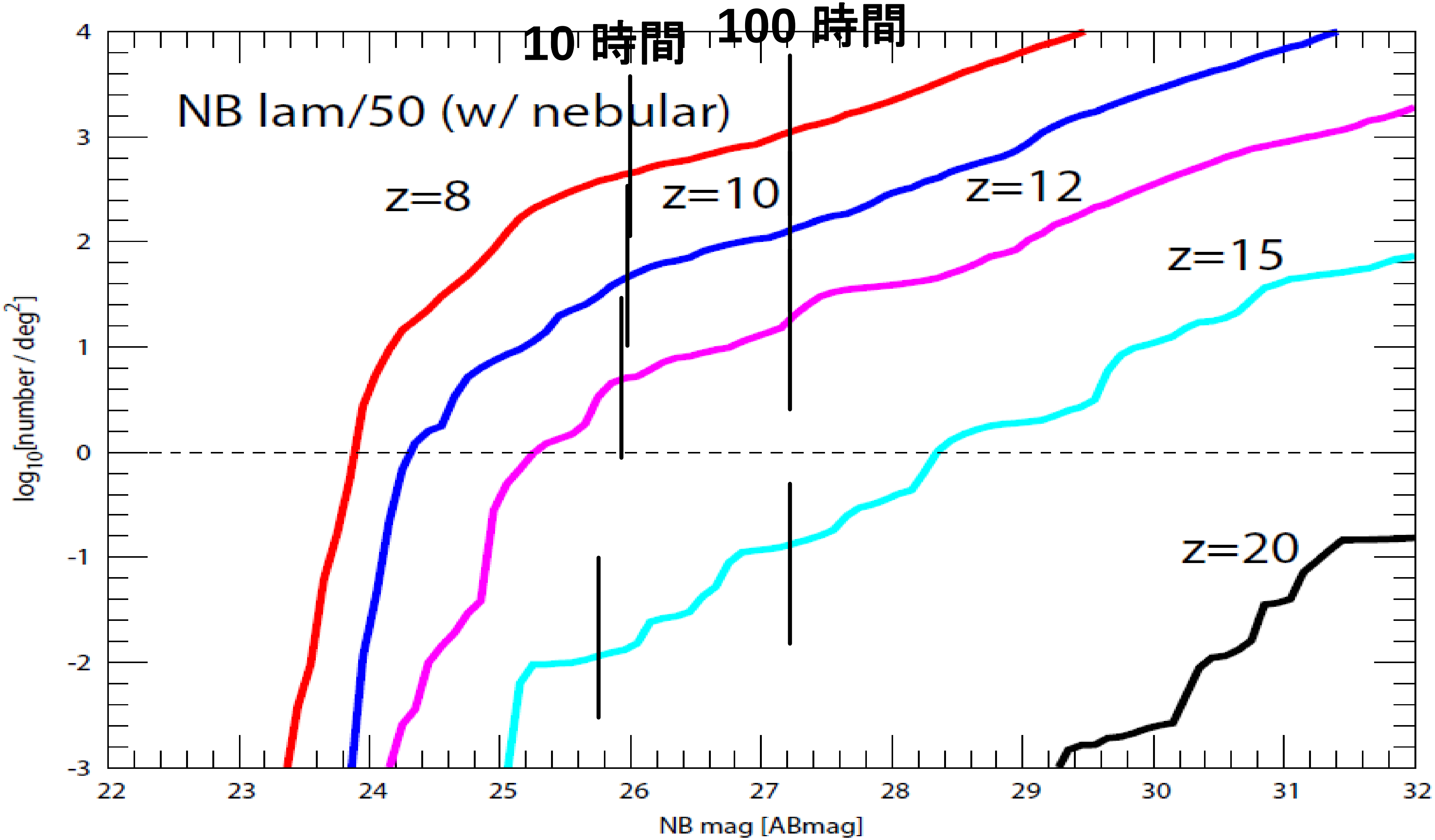
任意のバンドが選べるため、今回 WISH BB filters (Set 3, 4, 3e, 4e)、

NB filters (FWHM=100A, 300A, λ/100, λ/50) を全て計算

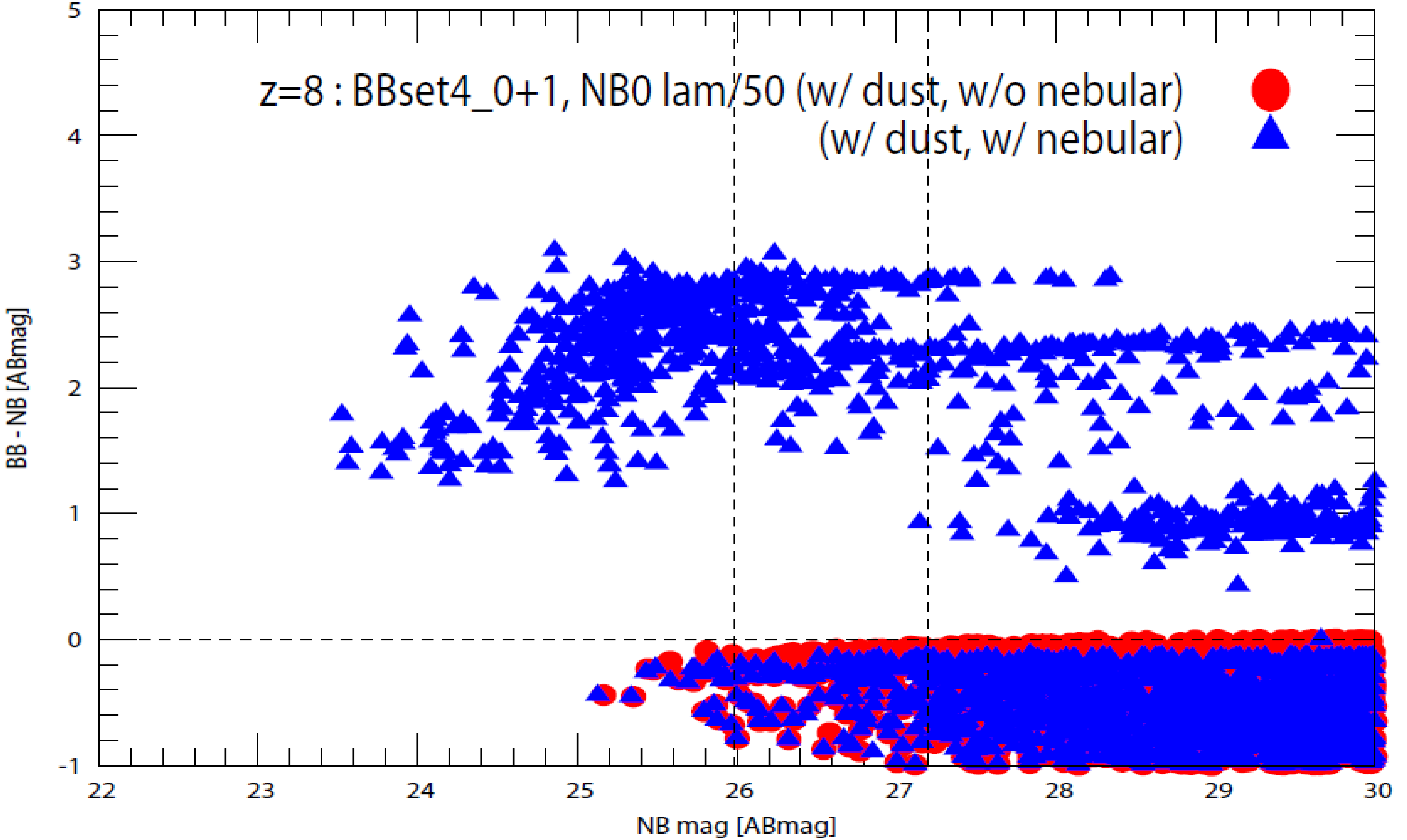
○ 主に計算＆解析に使っていた PC が 2010/02/19 に死亡

➔ 廃棄予定だった PC（5年前の製品）を譲り受けたが、セットアップに時間を取られ、その後も低スペックに苦しめられている。。。

z > 8 NB Number Count



z = 8 NB vs. BB-NB CMD



~まとめ~

○ **1 deg² を各 NB (FWHM=λ/50) で掃けば･･･**

･10 hour exp.(S/N > 3)
z=8: ~ 500 個、z=10: ~ 50 個、z=12: ~ 5 個、z=15: ~ 0.01 個
･10 hour exp.(S/N > 3)
z=8: ~1,000個、z=10: ~ 100個、z=12: ~ 10個、z=15: ~ 0.1個
↑ Lyα の IGM 吸収が z=5.7 と同じ場合

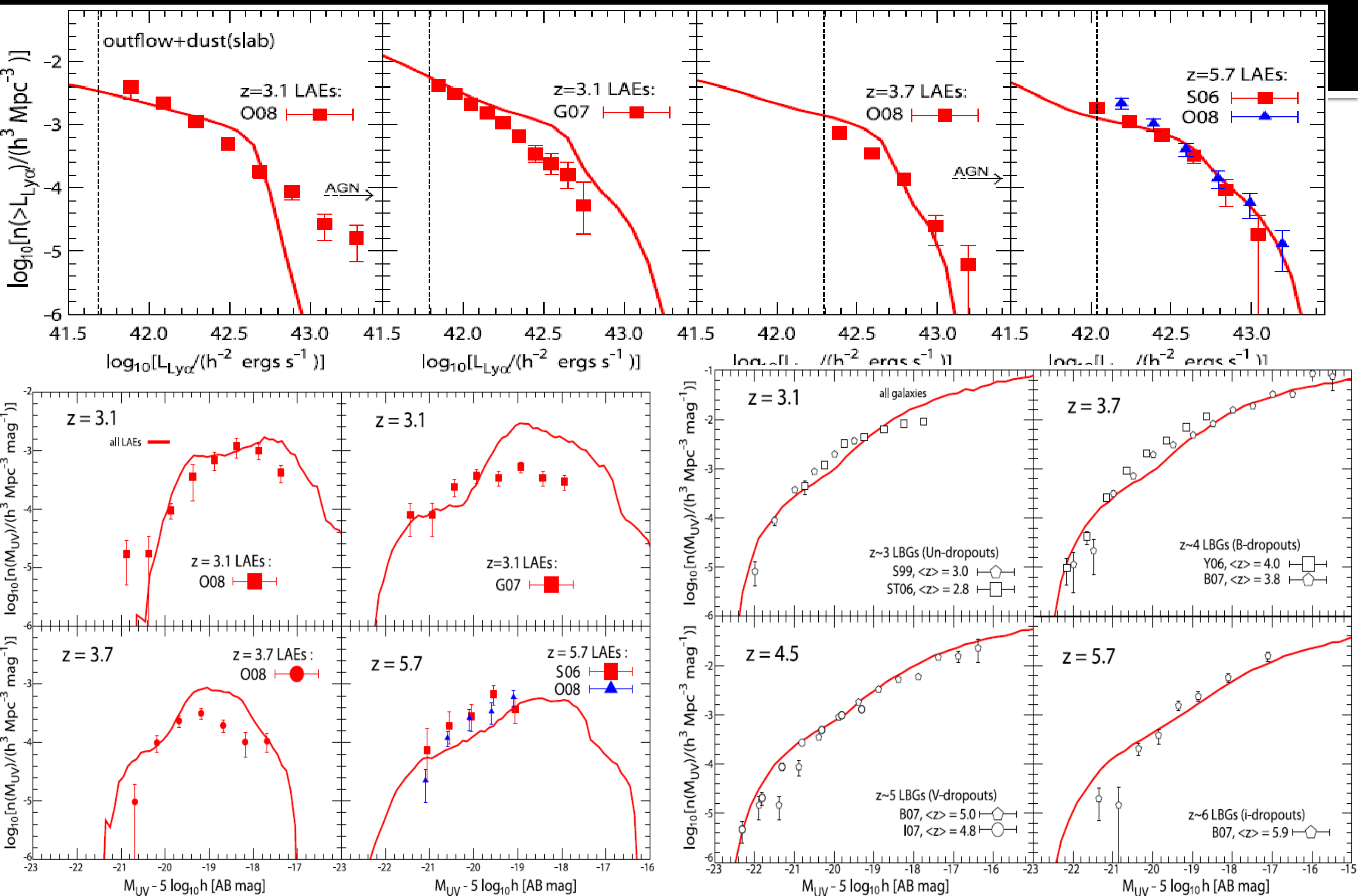
○ **EW(Lyα) に閾値を設ければ検出数は減るが、コンタミも減る**

➔ mock catalog の CMD 上の分布から評価

○ **理論的な high-z galaxies の不定性（IMF、ダスト減光）は上記見積もりを増やす方向**

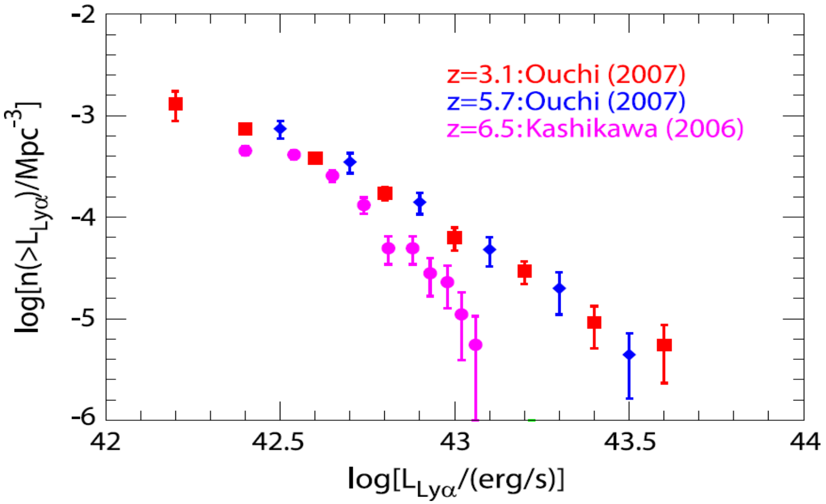
➔ LAE @ z > 8 の実際の検出数がこれより少なければ、再電離の効果と考えられる

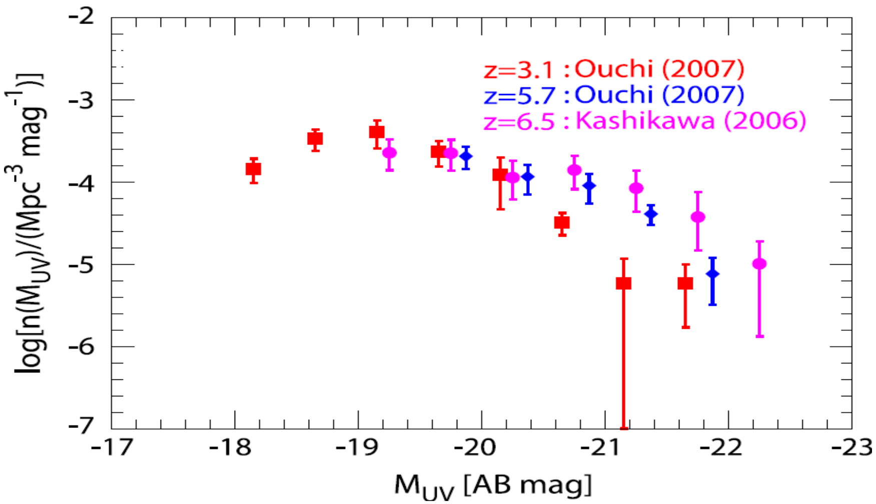
既存の LAE・LBG 観測データとの比較



→ LAE luminosity functions (LFs): Lya LF & UV LF

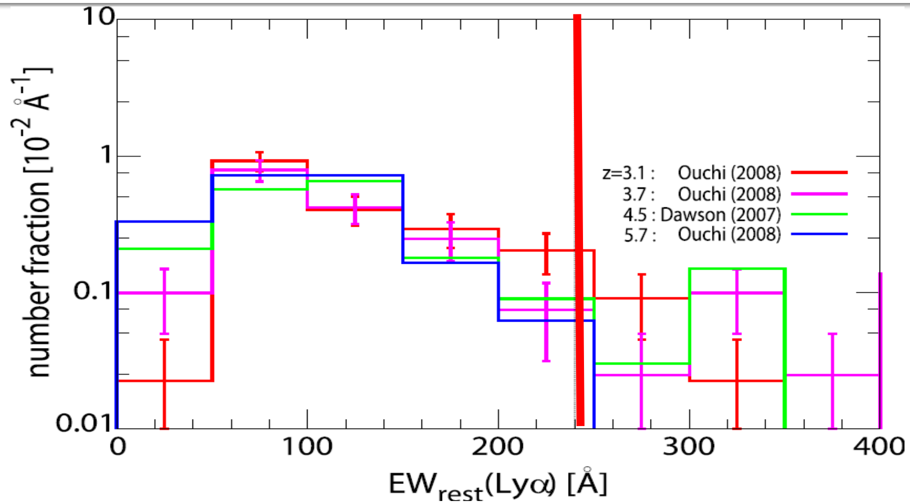
(1) UV LF: almost no-evolution @ z = 3-7
or somewhat brighter at higher-z
(2) Lya LF: no-evolution @ z < 6, decrease @ z > 6
→ Lya extinction in IGM (= cosmic reionization)?





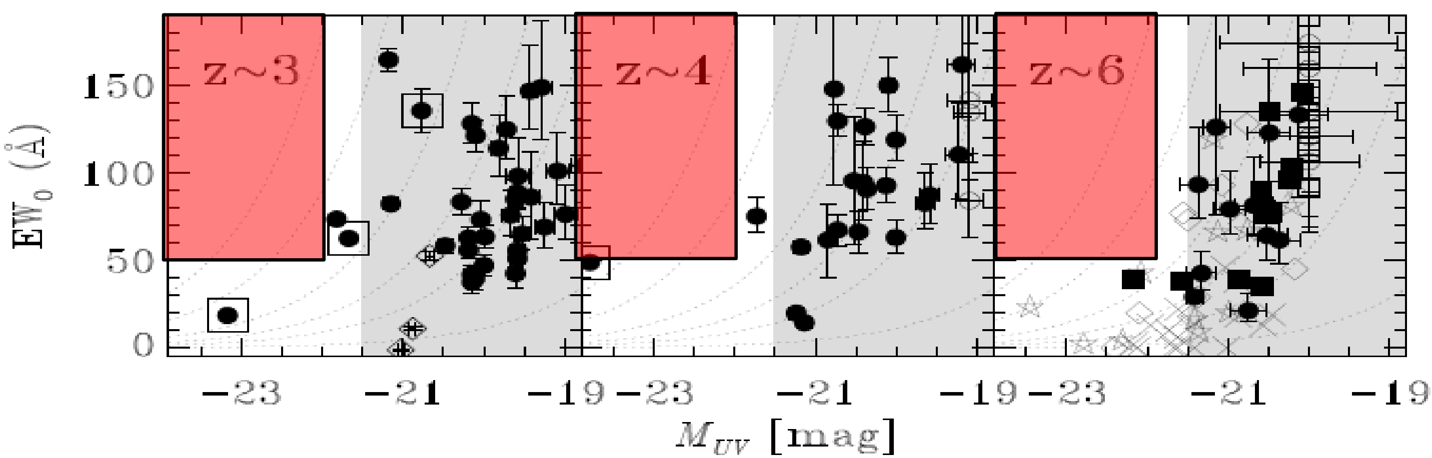
Important information about LAEs is imprinted in these obs. LFs

❖ Lya Equivalent Width (EW) Distribution



some LAEs @ z = 3-6 have EW(Lya) > 240 A
➔ include Pop III stars and/or top-heavy IMF?

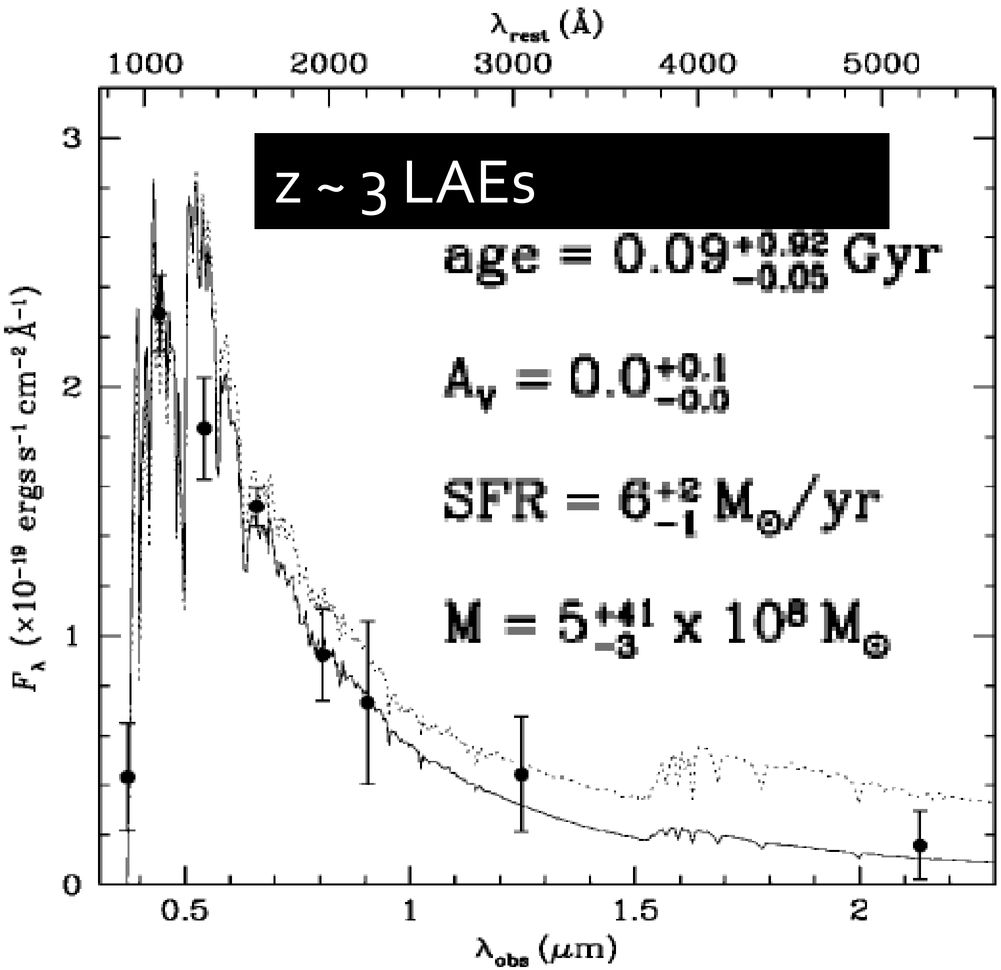
◆ Distribution in M(UV)-EW(Lya) plane



deficiency of UV-bright LAE w/ large-EW

Physical properties of LAEs@high-z

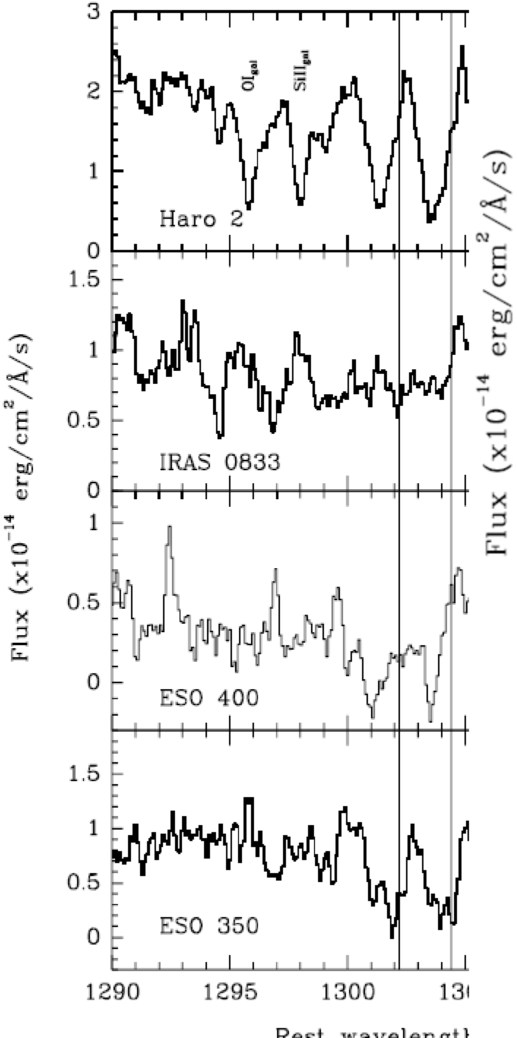
- stacking broad-band fluxes (Gawiser+ '06)

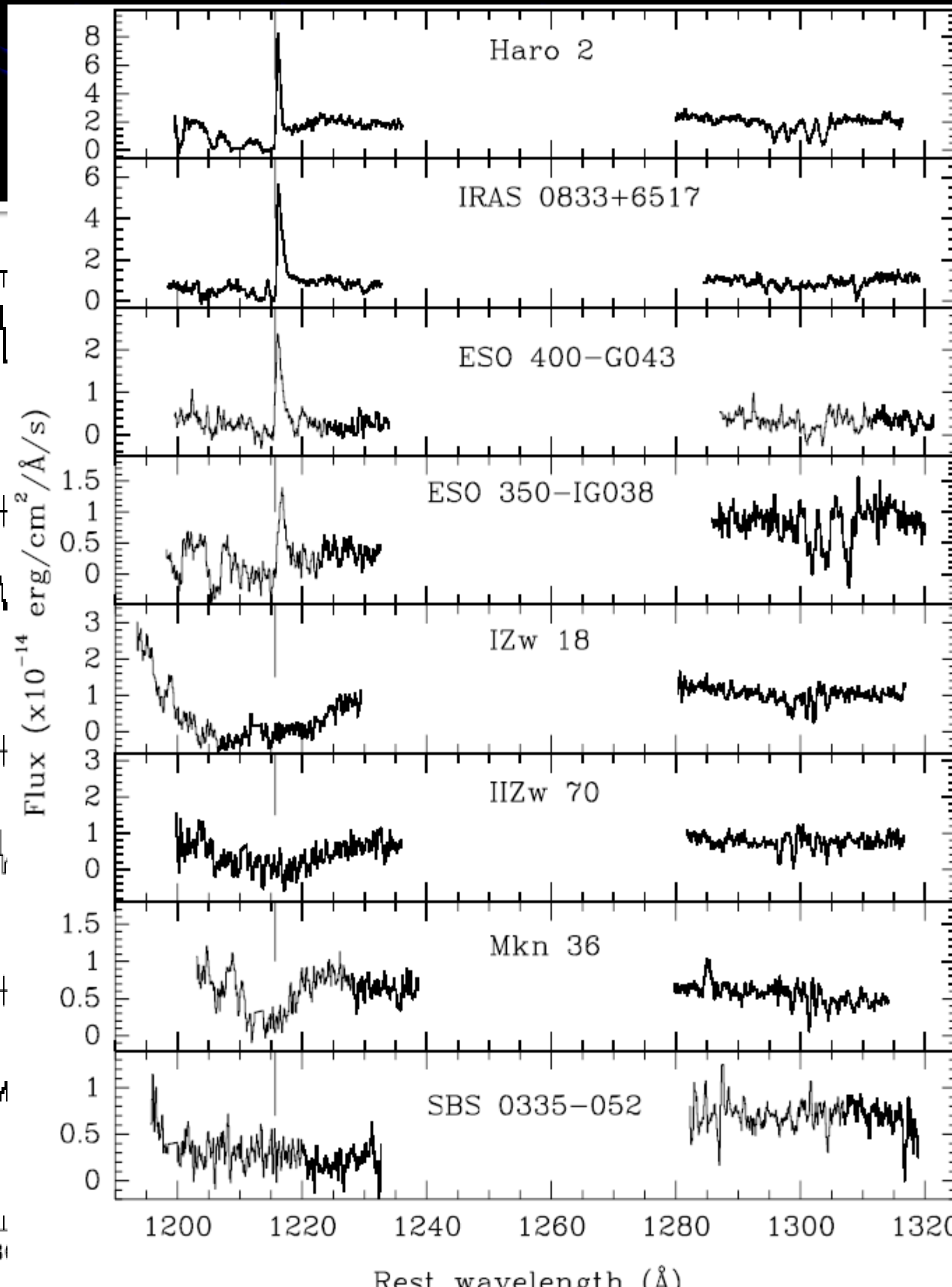


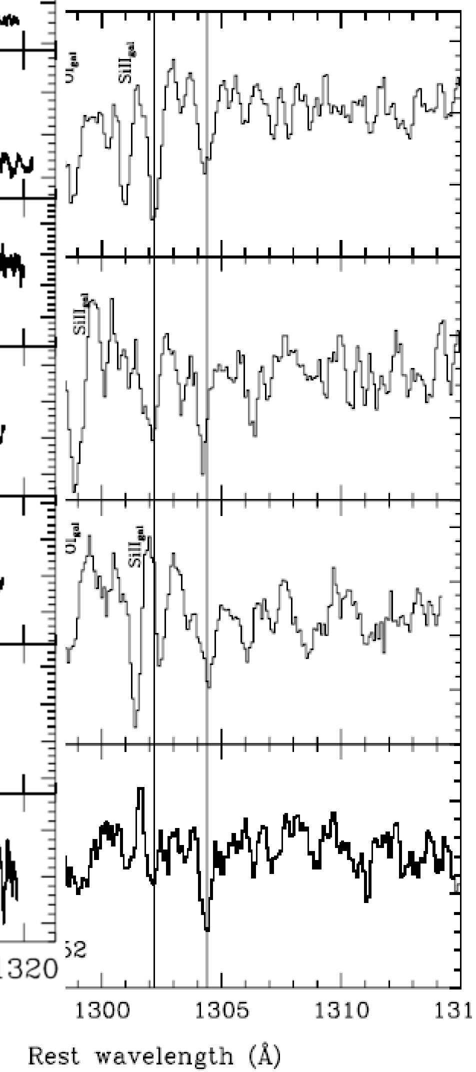
- high SFR
- young (10-100 Myr)
- almost dust-free
- low stellar mass

Lyα Emis… …laxies

- interstellar … + '98)







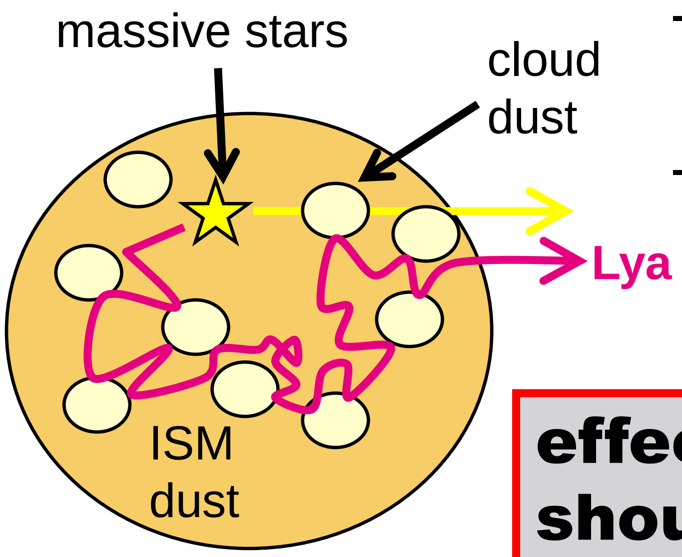
➢ Several models with different approaches exist

- analytic: e.g., Haiman & Spaans '99, Dijkstra+ '07
- semi-analytic: Le Delliou+ '05 & '06, Orsi+ '08
- SPH: e.g., Barton+ '04, Nagamine+ '08

*** in all model, Lya escape fraction f_{esc}^{Lya} is oversimplified**

f_{esc}^{Lya} = const or $\exp(-tau_d)$ ← tau_d : dust opacity for continuum

◆ Implications for f_{esc}^{Lya} from theories of Lya transfer



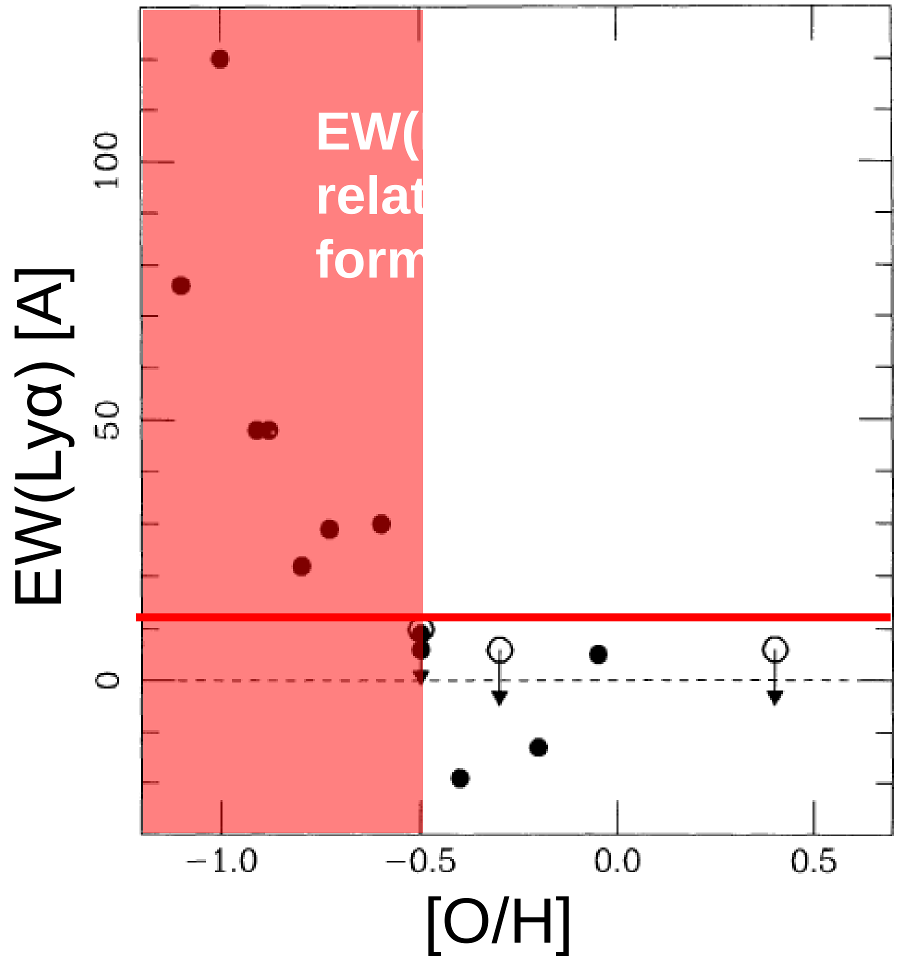
- Lya: a resonance line of HI
  → random-walk before escape
- f_{esc}^{Lya} is highly sensitive to dust geometry & ISM dynamics; f_{esc}^{Lya} is not constant and not equal to $\exp(-tau_d)$

effects of dust geometry & outflow should be incorporated in f_{esc}^{Lya}

[redacted]

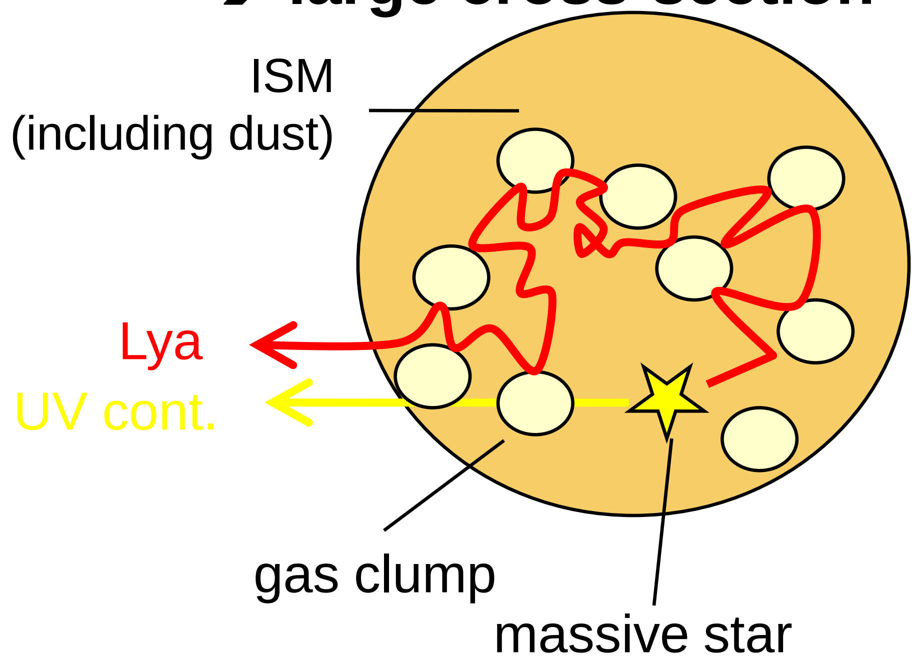
◆ Metallicity Dependence
(Charlot & Fall ’93)

⇨ **high f^{Lya}_{esc} at low-metallicity (⇔ low-dust content)**



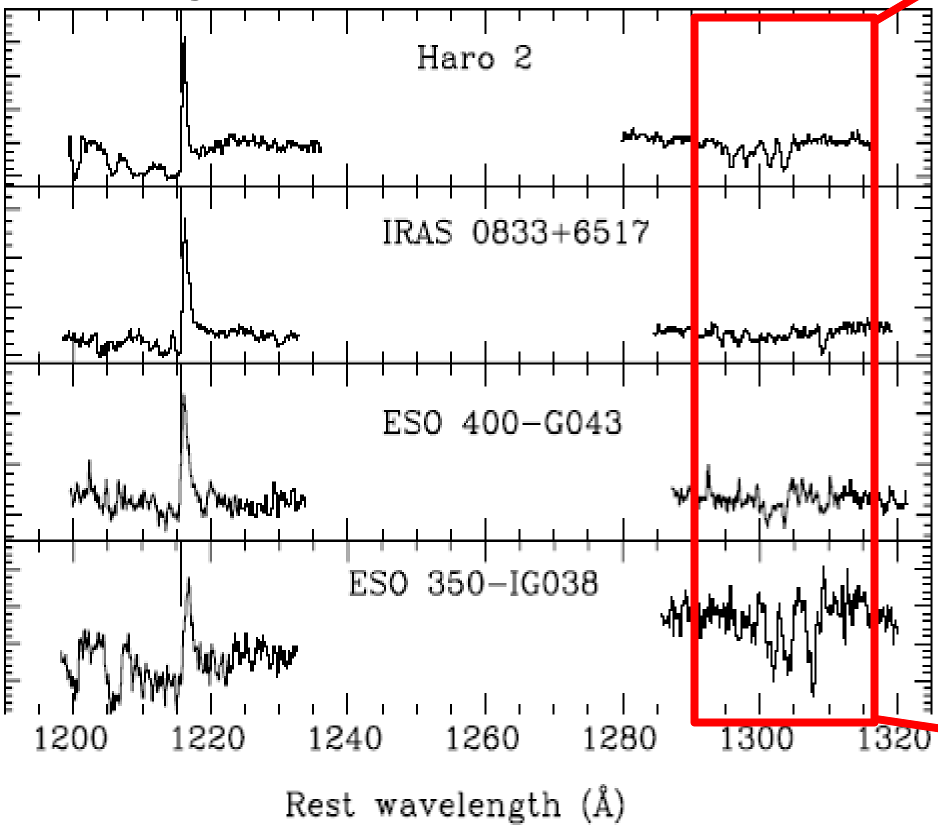
- consistent with theoretical expectation (Neufeld ’90)

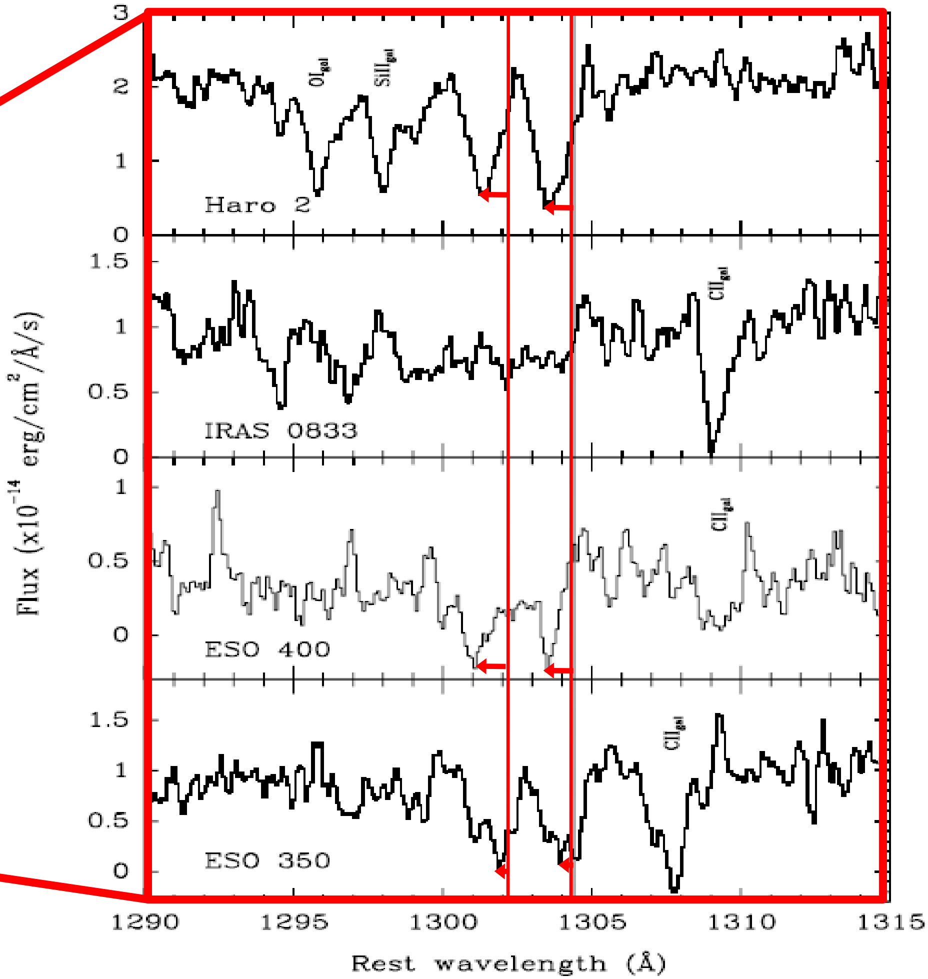
Lya: resonance line of H I
➔ large cross-section



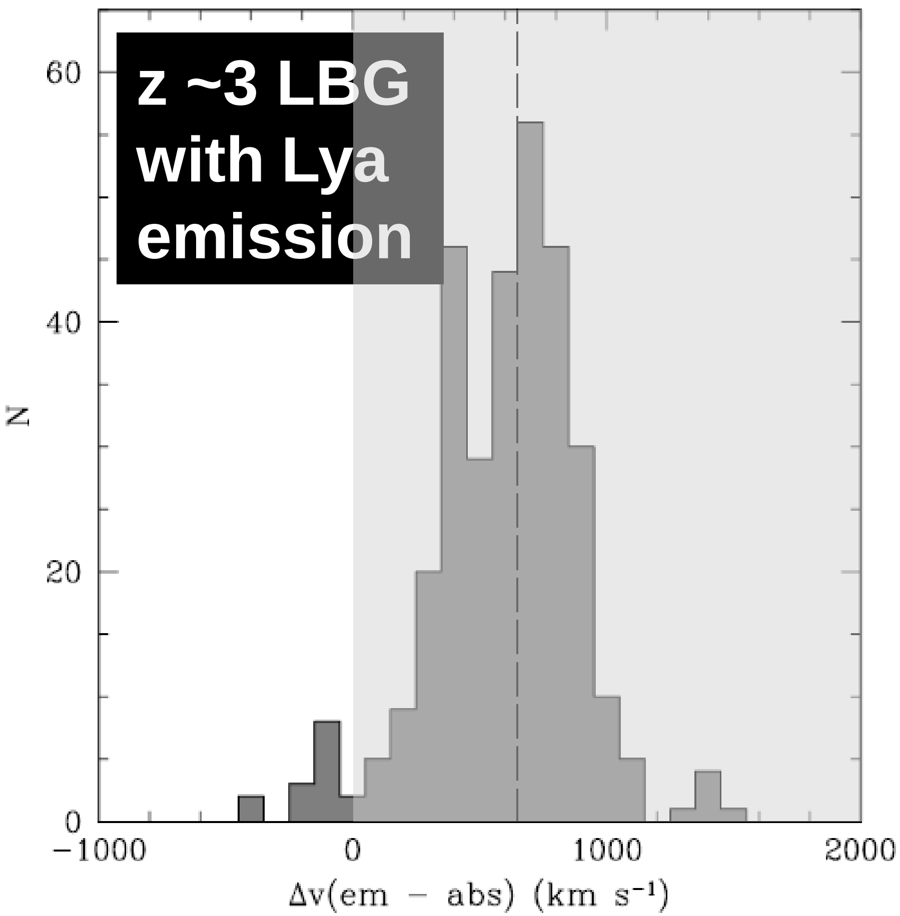
✓ gas-dynamics (outflow) (Kunth+ '98) ⇒ **high f_{esc}^{Lya} in outflowing condition**

UV spectra of local galaxies with Lya emission

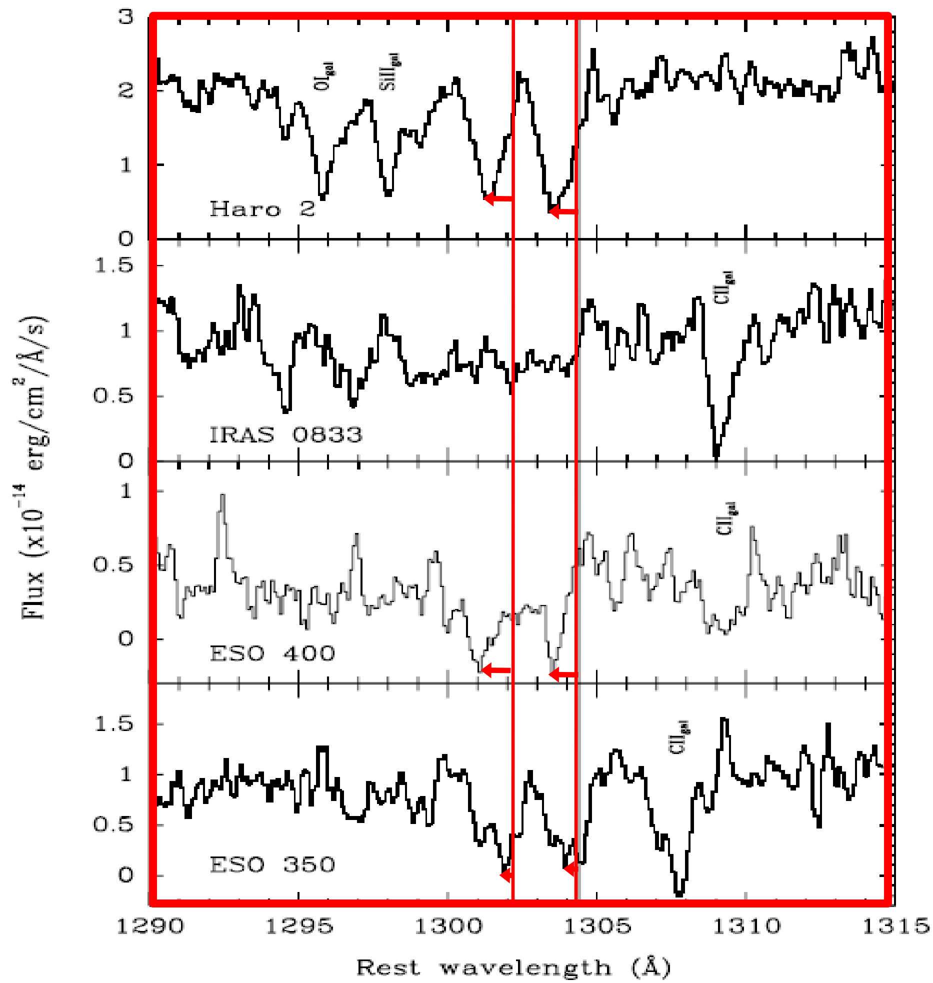




✓ gas-dynamics (outflow) (Kunth+ '98) ⇨ **high f_{esc}^{Lya} in outflowing condition**

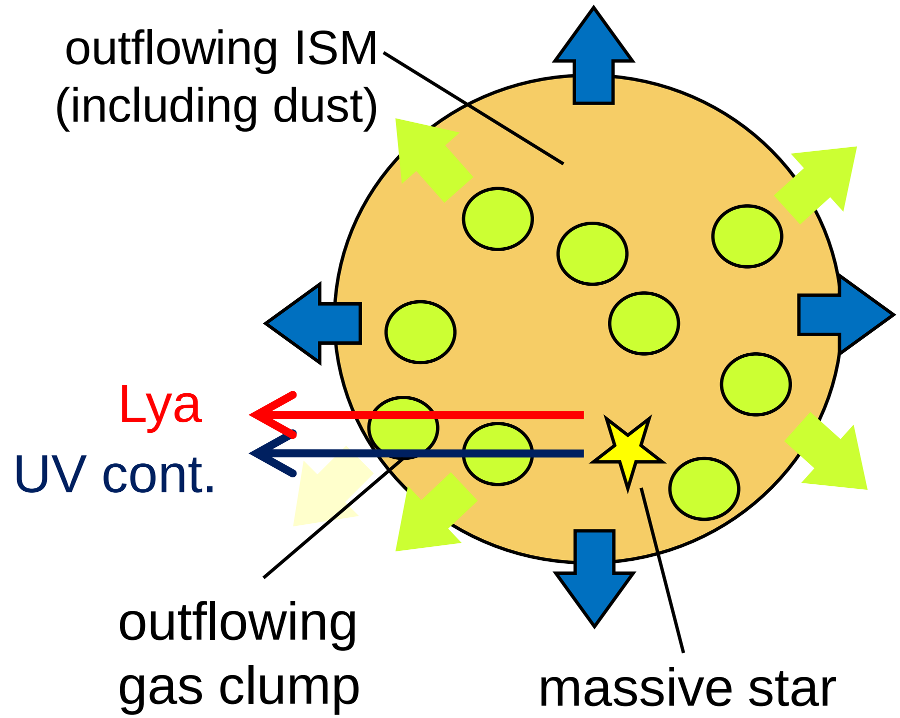


Shapley+ '03



✓ gas-dynamics (outflow) (Kunth+ '98) ⇨ **high f_{esc}^{Lya} in outflowing condition**

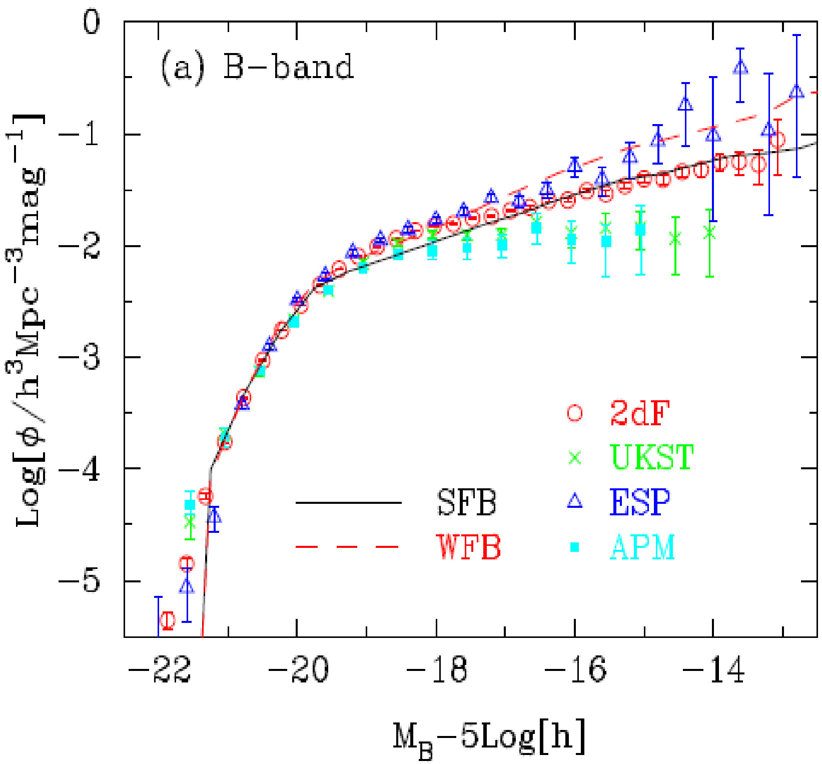
- consistent with theoretical expectation
  ➔ galactic-scale outflow drastically reduce the effective opacity of Lya (Hansen & Oh '05)



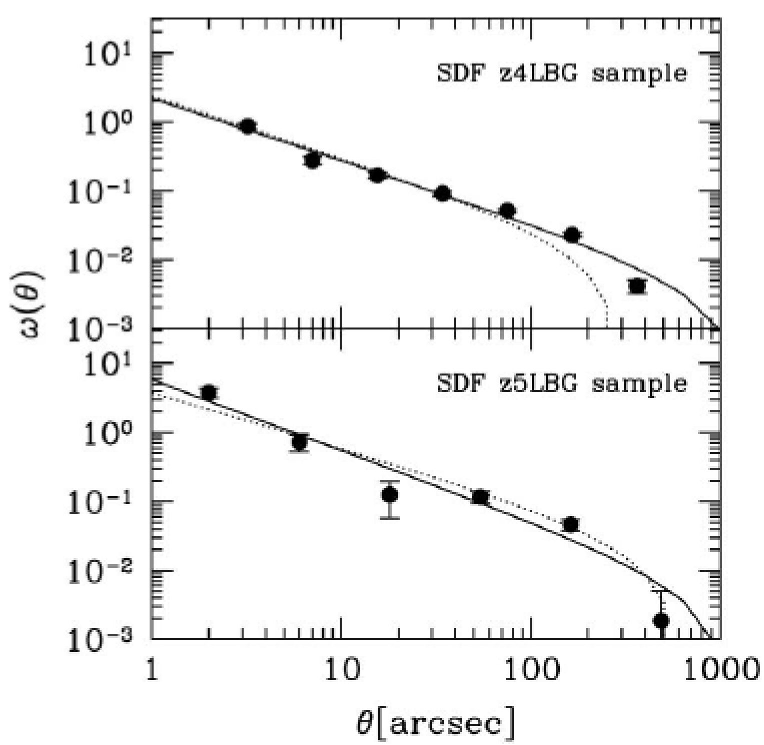
interstellar dust extinction & outflow effect should be incorporated into f_{esc}^{Lya} model

➢ semi-analytic model of hierarchical galaxy formation

- reproduce most of the obs. properties of local galaxies (Nagashima & Yoshii '04; Nagashima+ '05),
and UVLFs & ACFs of LBGs @ z=4, 5 (Kashikawa+ '06)



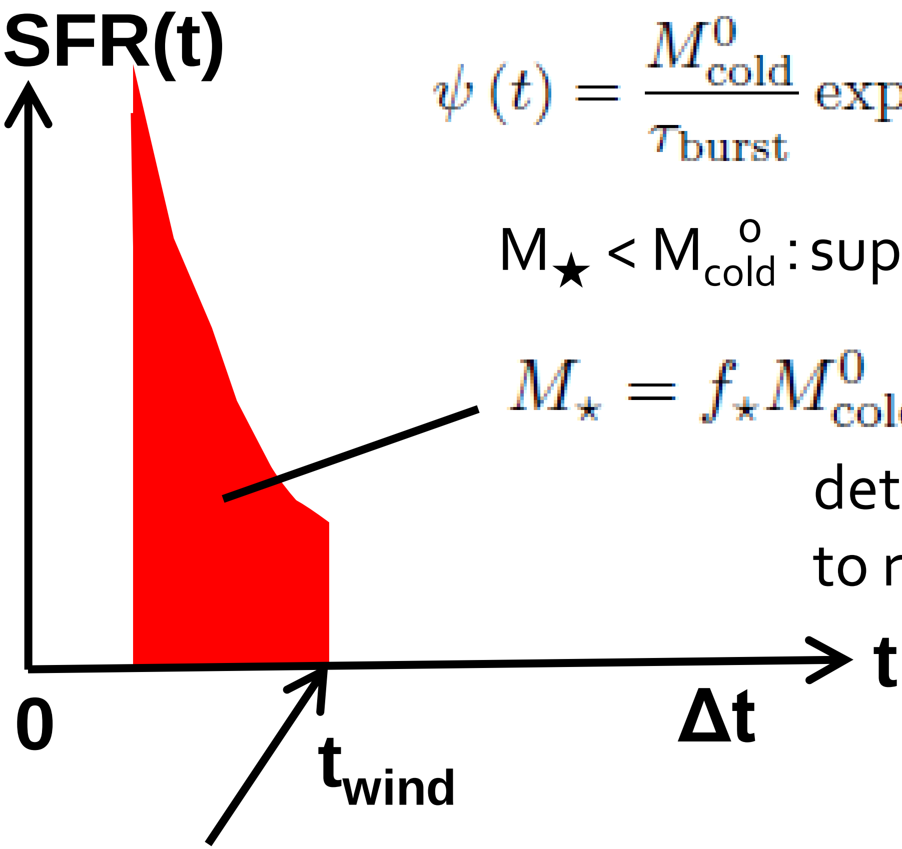
Nagashima+ '05



Kashikawa+ '06

Extension of the Mitaka Model for LAE

SFR in starburst galaxies



$$\psi(t) = \frac{M^0_{\rm cold}}{\tau_{\rm burst}} \exp\left[-\frac{t}{\tau_{\rm burst}}\right] \qquad \tau_{\rm burst} = f_{\rm dyn}\tau_{\rm dyn}$$

$M_\star < M^{o}_{cold}$: supernova (SN) feedback

$$M_\star = f_\star M^0_{\rm cold} \qquad f_\star = f_\star(V_{\rm c})$$

determined by the Mitaka model to reproduce the local LFs

galactic wind blows and SF is terminated: similar to the traditional picture of galactic wind (Arimoto & Yoshii '87)

- Lya line luminosity emitted from each galaxy L_{Lya}

$$L^{\rm emit}_{\rm Ly\alpha} = L^{\rm max}_{\rm Ly\alpha}(1 - f^{\rm Lyc}_{\rm esc}) f^{\rm Ly\alpha}_{\rm esc}$$

escape fraction of Lyman cont.
➔ f^{LyC}_{esc} = 0 (fiducial)

escape fraction of Lya

the maximum possible Lya line luminosity:
L_{Lya} in the case of f^{LyC}_{esc} = 0 & ionization equilibrium (case B)
← determined by using SFR, metallicity, age & SSPs of Schaerer (2003)

- observed Lya line luminosity L^{obs}_{Lya}

$$L^{\rm obs}_{\rm Ly\alpha} = L^{\rm emit}_{\rm Ly\alpha} T^{\rm IGM}_{\rm Ly\alpha}$$

IGM transmission to Lya emission
➔ T^{IGM}_{Lya} = 1 (fiducial)

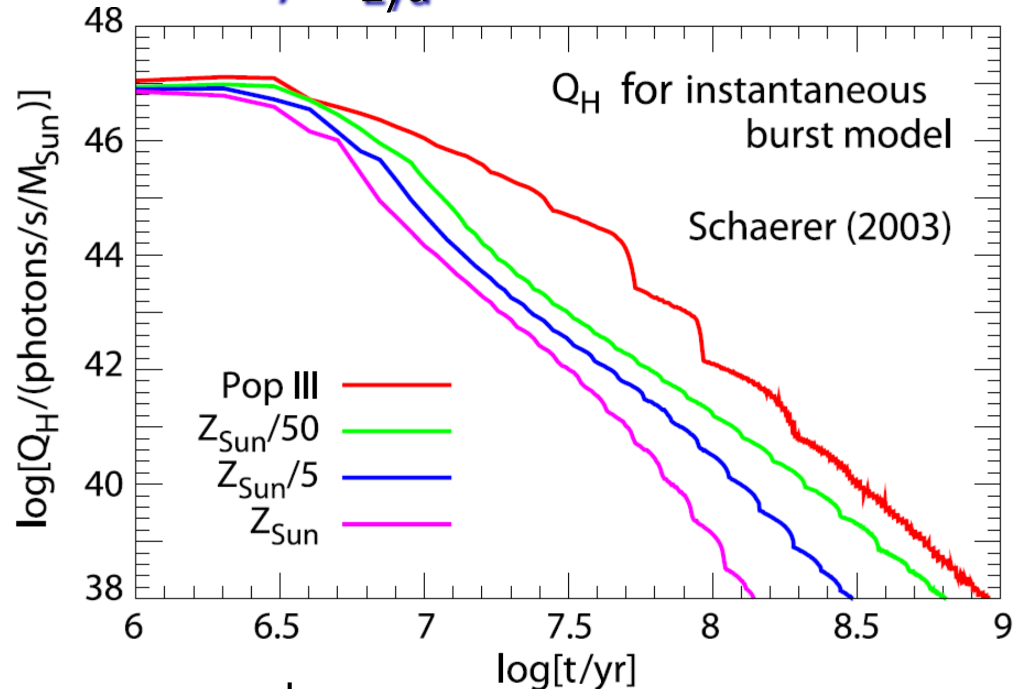
Calculate Lya Line Luminosity

$$L_{\mathrm{Ly}\alpha}^{\mathrm{emit}} = L_{\mathrm{Ly}\alpha}^{\mathrm{max}} f_{\mathrm{esc}}^{\mathrm{Ly}\alpha}$$

- **maximally possible Lyα luminosity L_{Lya}^{max}**

$$L_{\mathrm{Ly}\alpha}^{\mathrm{max}}(t) \propto \int_0^t \psi(t') Q_{\mathrm{H}}\left(t - t', Z_\star(t')\right) \mathrm{d}t'$$

convolution of SFR with HI ionizing photon emission rate Q_H



- **observed Lyα line luminosity L_{Lya}^{obs}**

$$L_{\mathrm{Ly}\alpha}^{\mathrm{obs}} = L_{\mathrm{Ly}\alpha}^{\mathrm{emit}} T_{\mathrm{Ly}\alpha}^{\mathrm{IGM}} = L_{\mathrm{Ly}\alpha}^{\mathrm{max}} \left(1 - f_{\mathrm{esc}}^{\mathrm{LyC}}\right) f_{\mathrm{esc}}^{\mathrm{Ly}\alpha} T_{\mathrm{Ly}\alpha}^{\mathrm{IGM}}$$

IGM transmission to Lya emission

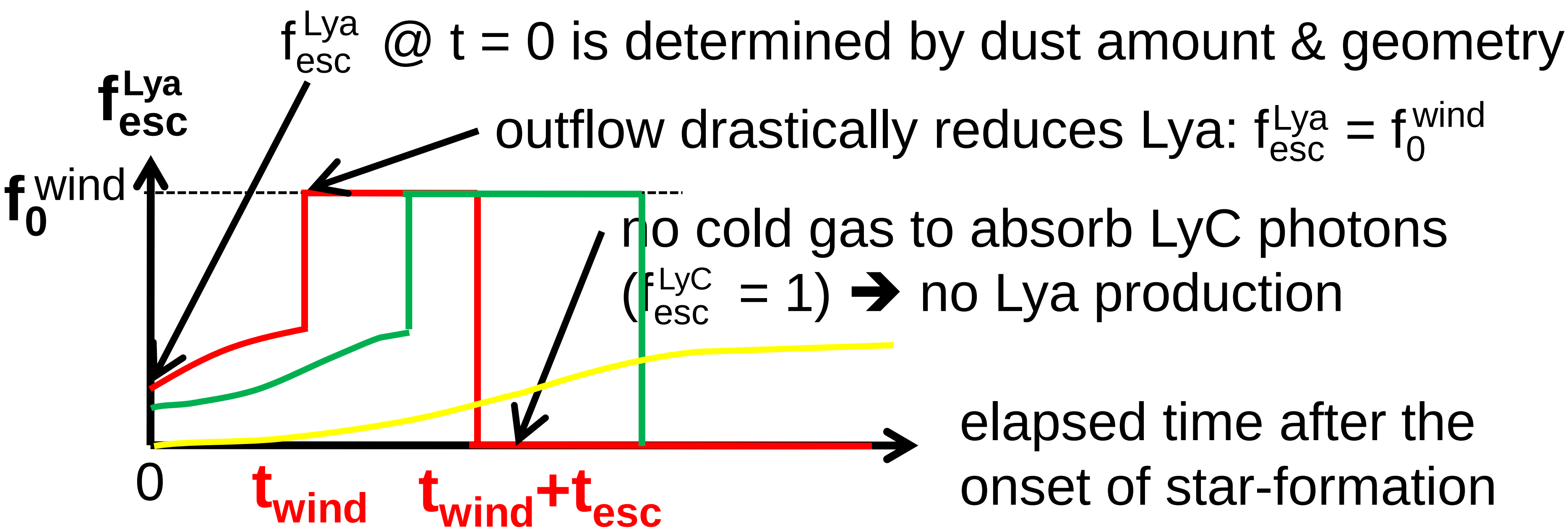
◆ **simply proportional model** (e.g., Le Delliou+ '06):

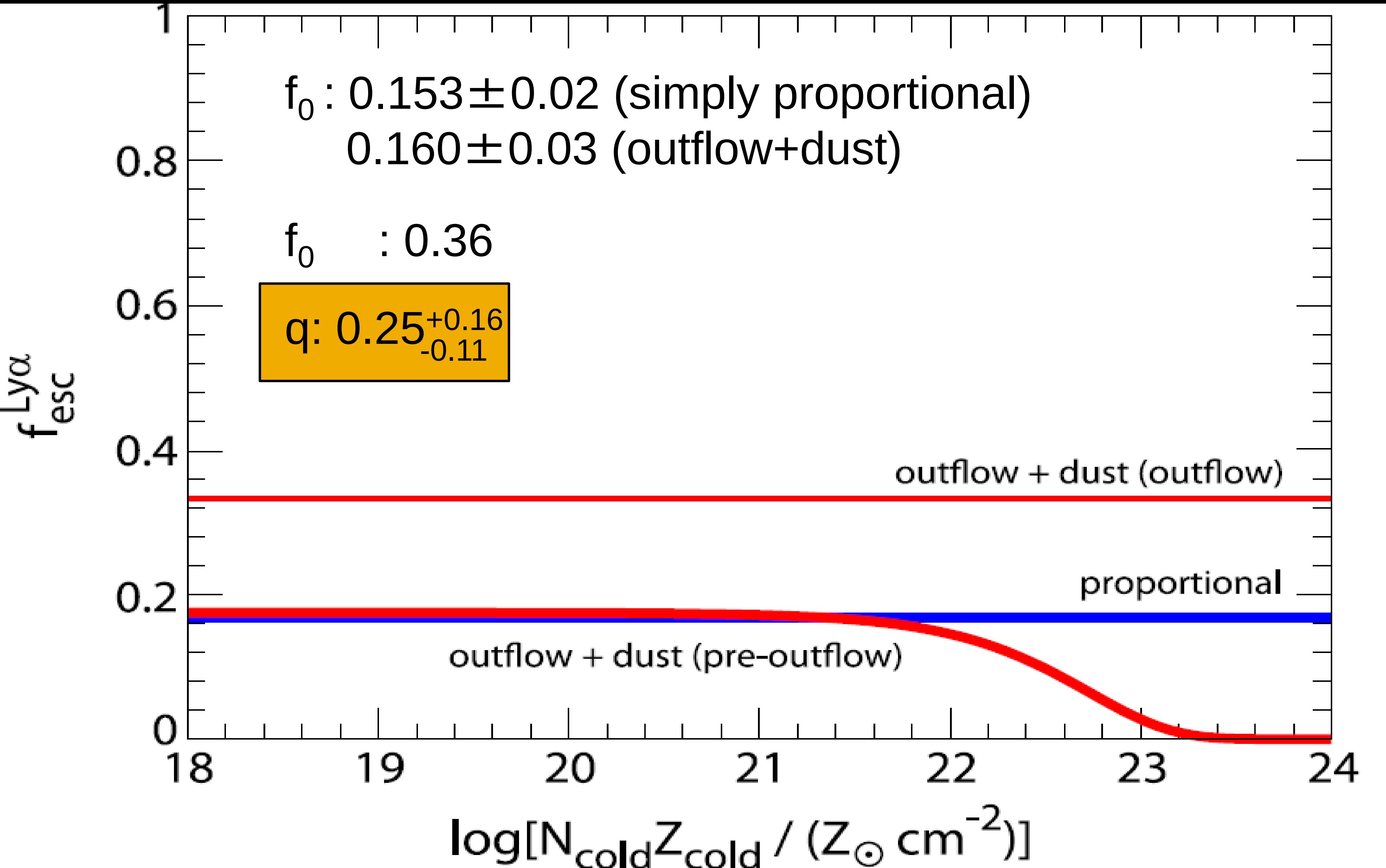
constant f_{esc}^{Lya} regardless physical properties of each galaxy

◆ **the outflow + dust model**:

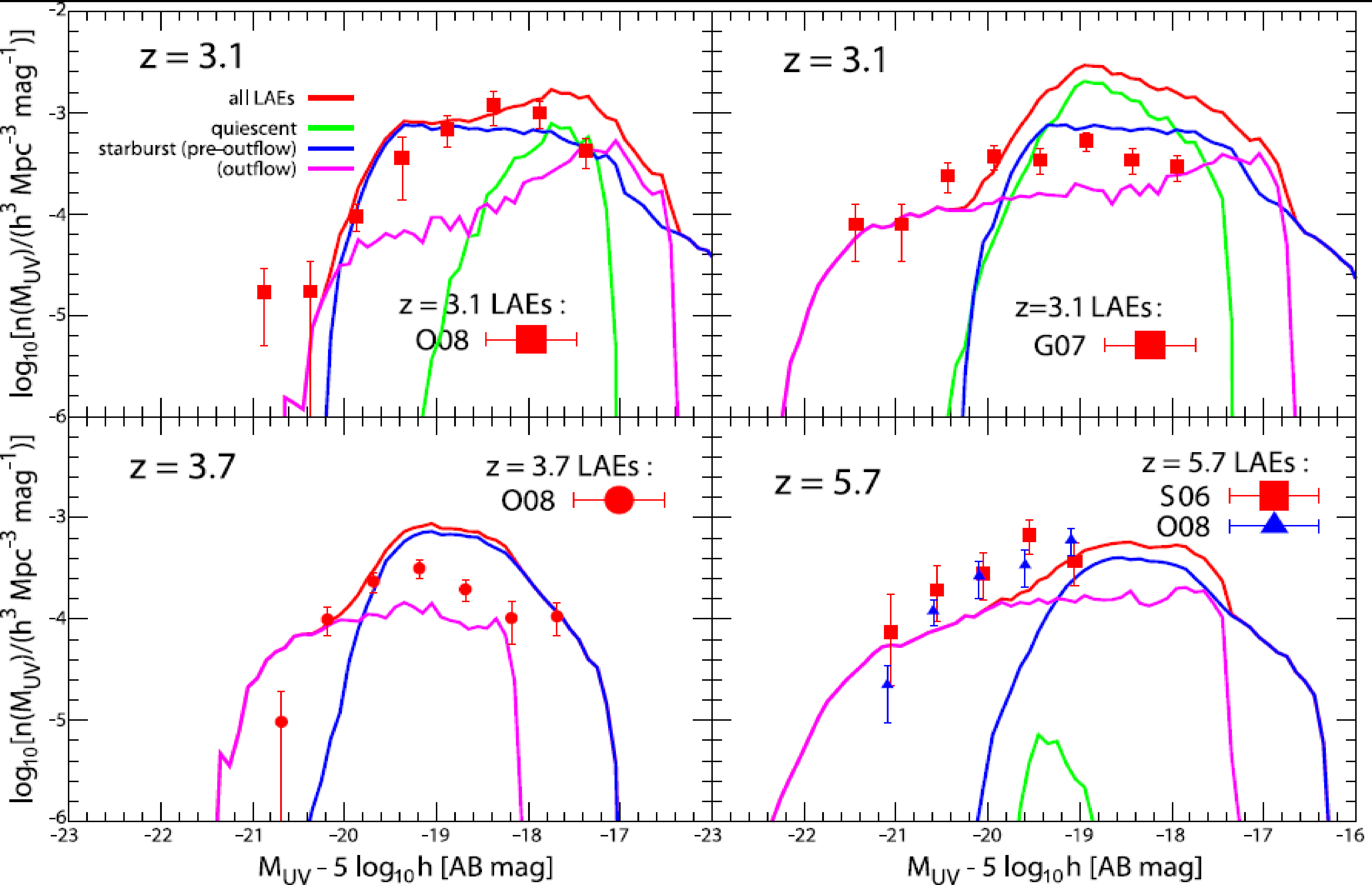
including interstellar dust extinction (next slide)

& galaxy-scale outflow induced as supernova feedback

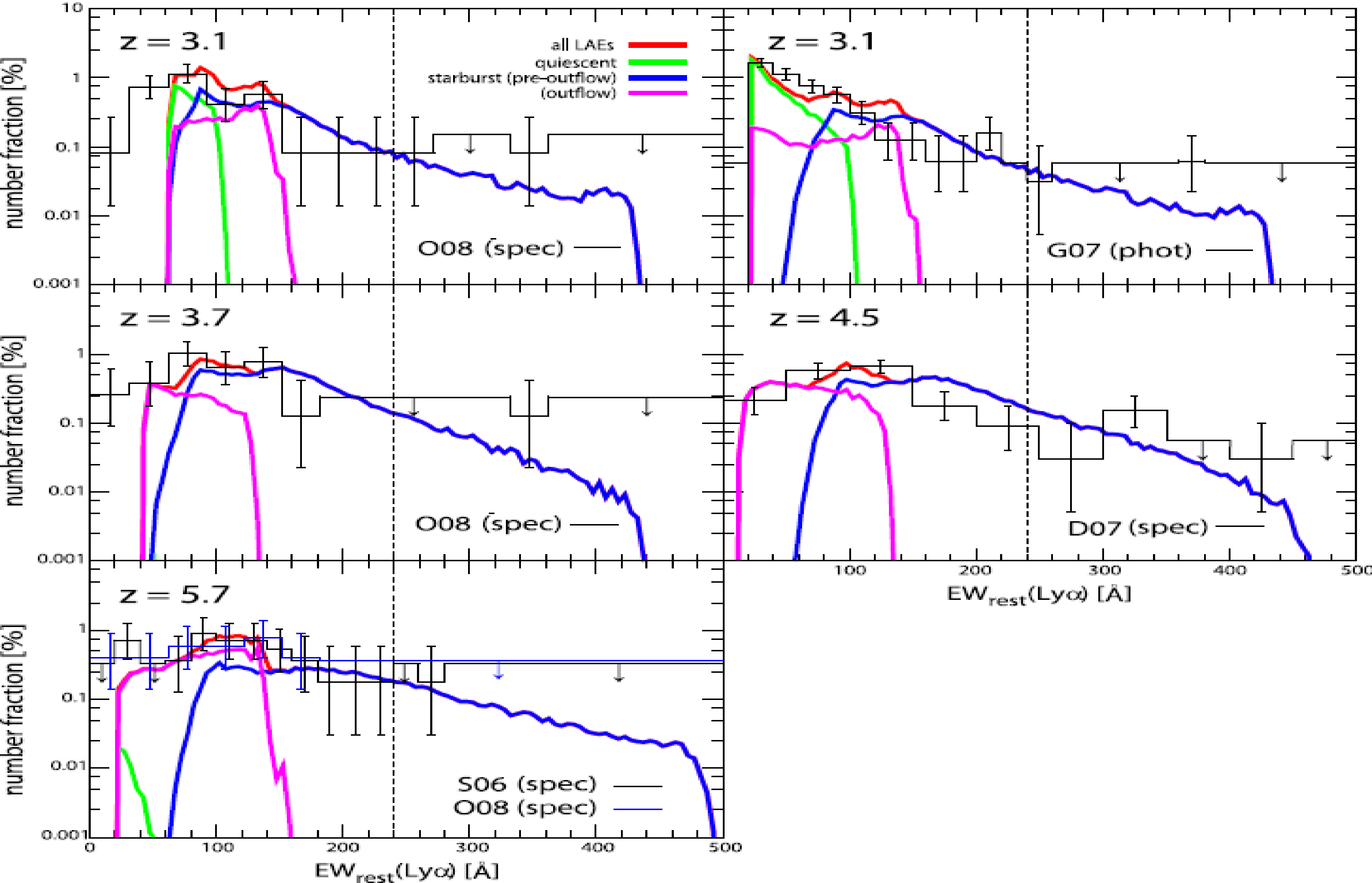




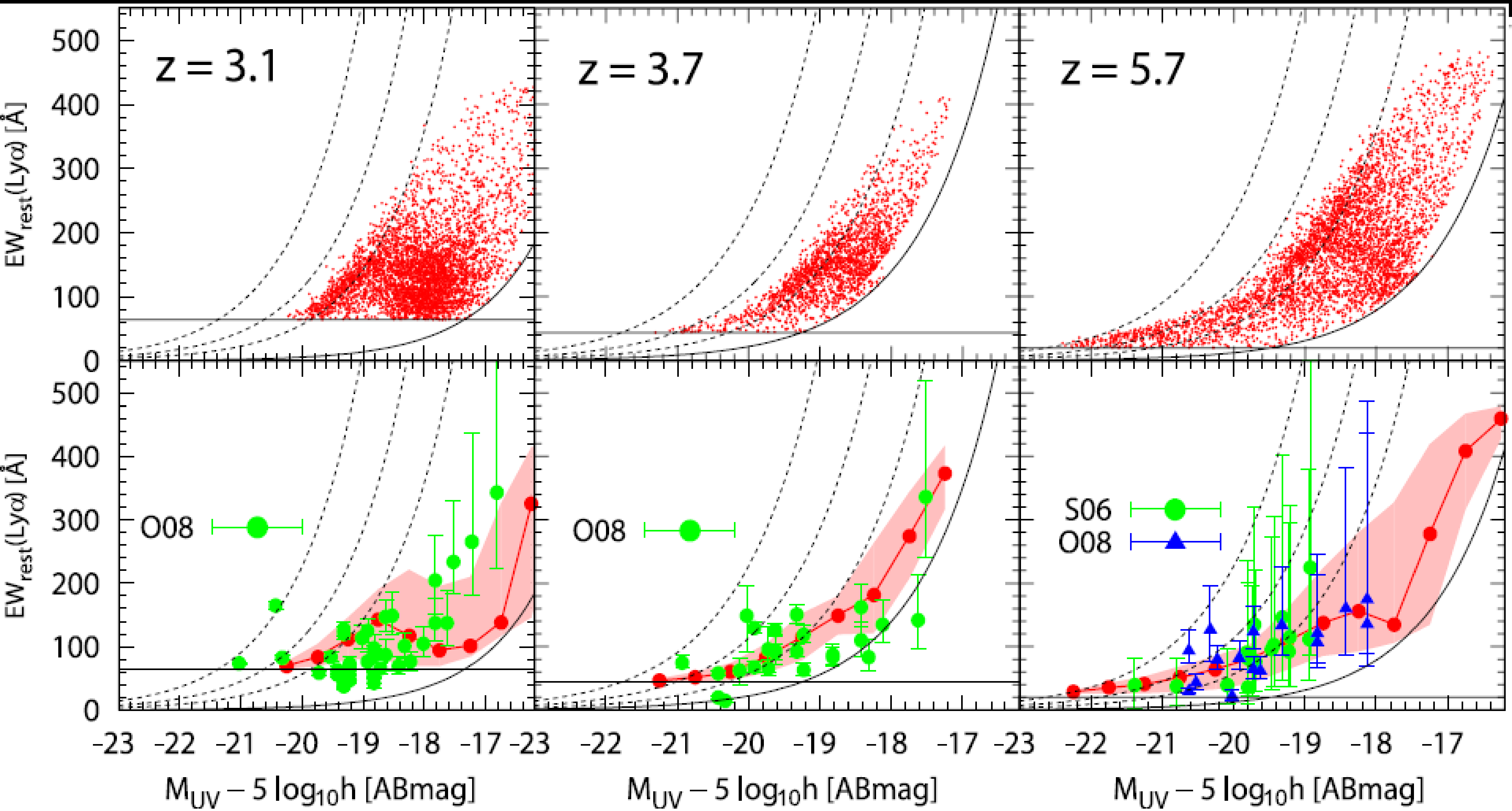
f0 : 0.153±0.02 (simply proportional)
0.160±0.03 (outflow+dust)
f0 : 0.36
q: 0.25+0.16 -0.11
outflow + dust (outflow)
proportional
outflow + dust (pre-outflow)
f esc Lyα
log[N cold Z cold / (Z⊙ cm-2)]
1
0.8
0.6
0.4
0.2
0
18
19
20
21
22
23
24



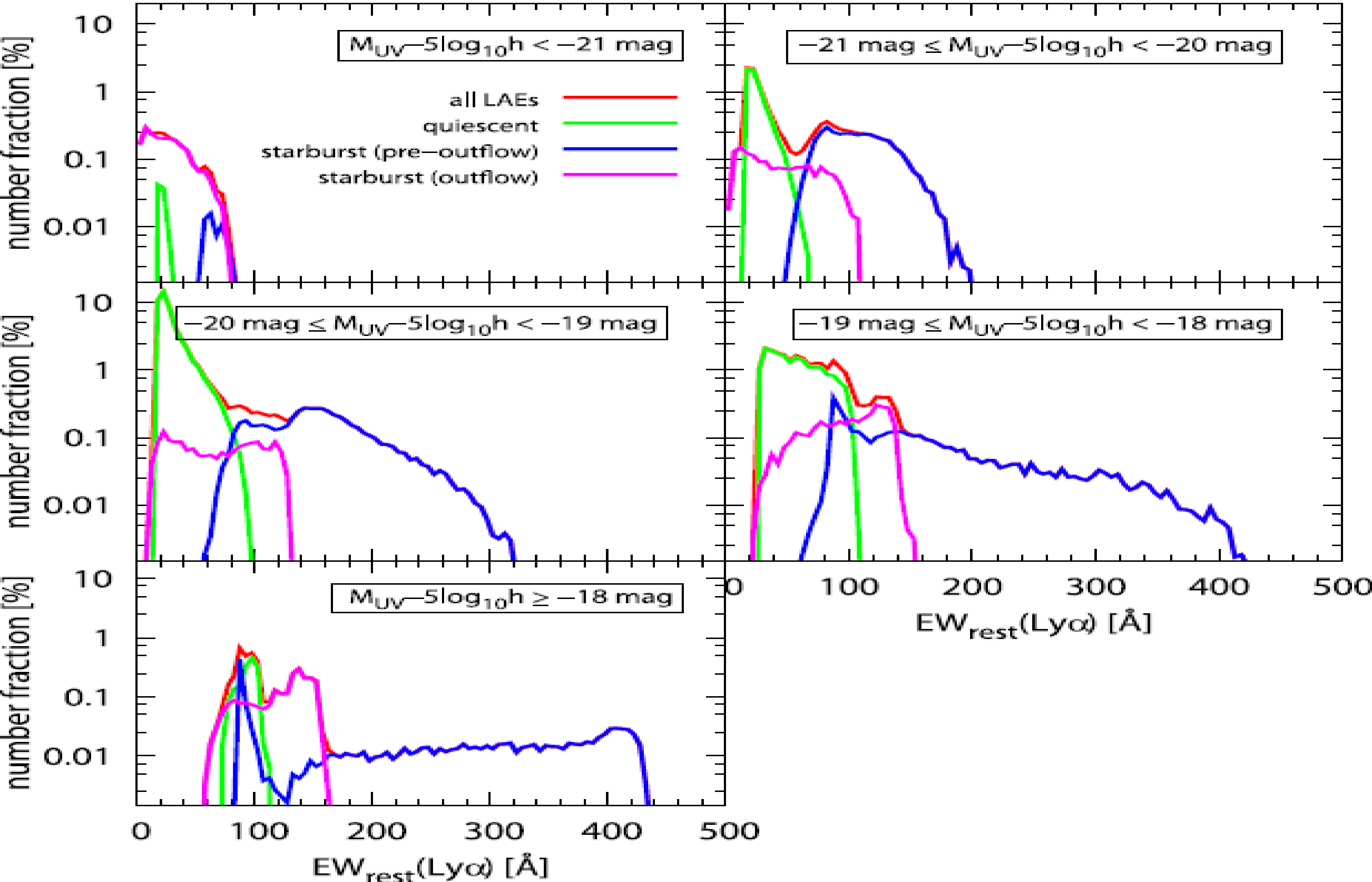
z = 3.1
all LAEs
quiescent
starburst (pre-outflow)
(outflow)
z = 3.1 LAEs :
O08
z = 3.1
z=3.1 LAEs :
G07
z = 3.7
z = 3.7 LAEs :
O08
z = 5.7
z = 5.7 LAEs :
S06
O08
log10[n(MUV)/(h3 Mpc-3 mag-1)]
MUV - 5 log10h [AB mag]
-2
-3
-4
-5
-6
-23
-22
-21
-20
-19
-18
-17
-16



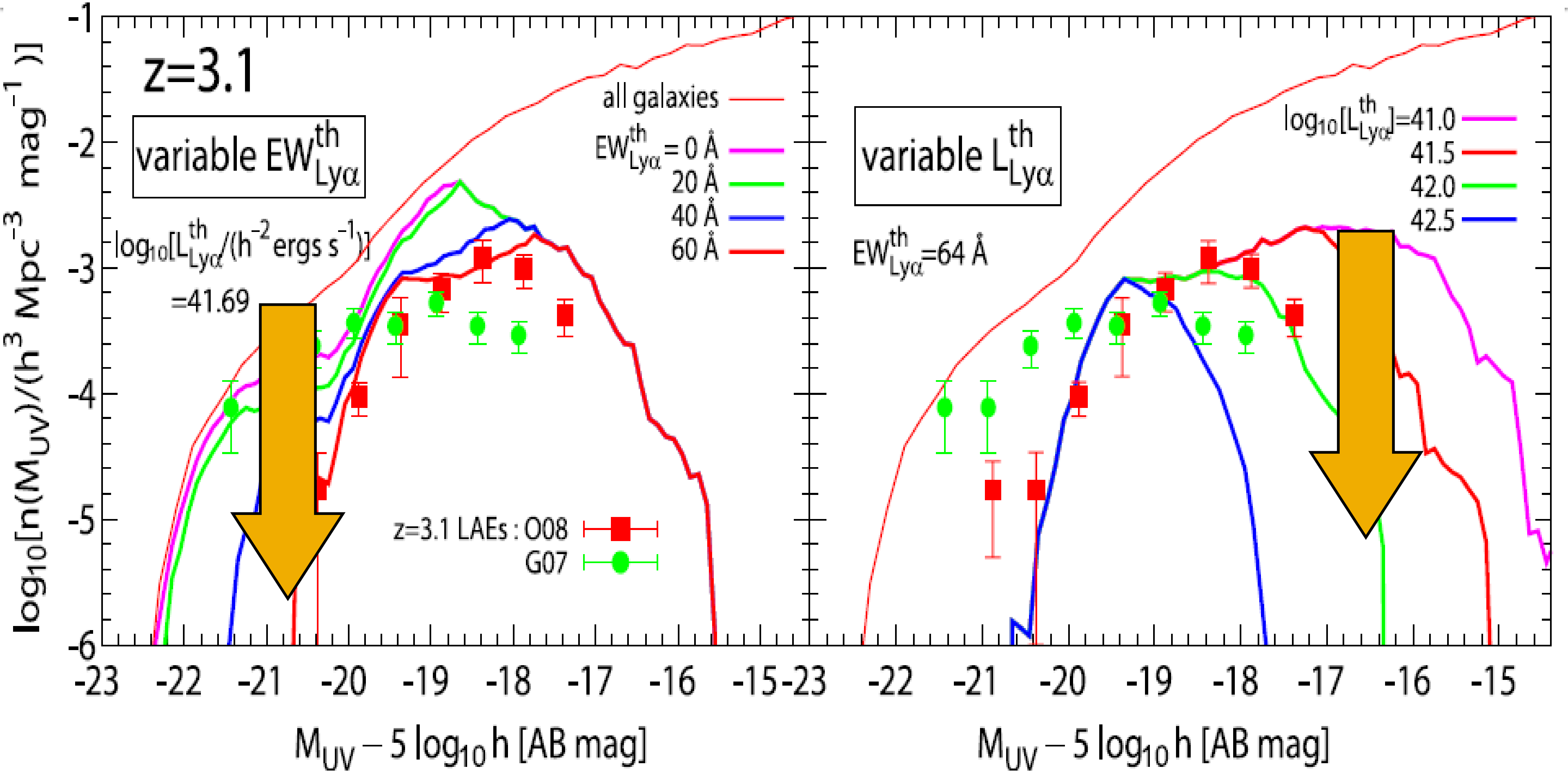
z = 3.1
all LAEs
quiescent
starburst (pre-outflow)
(outflow)
O08 (spec)
z = 3.1
G07 (phot)
z = 3.7
O08 (spec)
z = 4.5
D07 (spec)
z = 5.7
S06 (spec)
O08 (spec)
number fraction [%]
EWrest(Lyα) [Å]
10
1
0.1
0.01
0.001
0
100
200
300
400
500



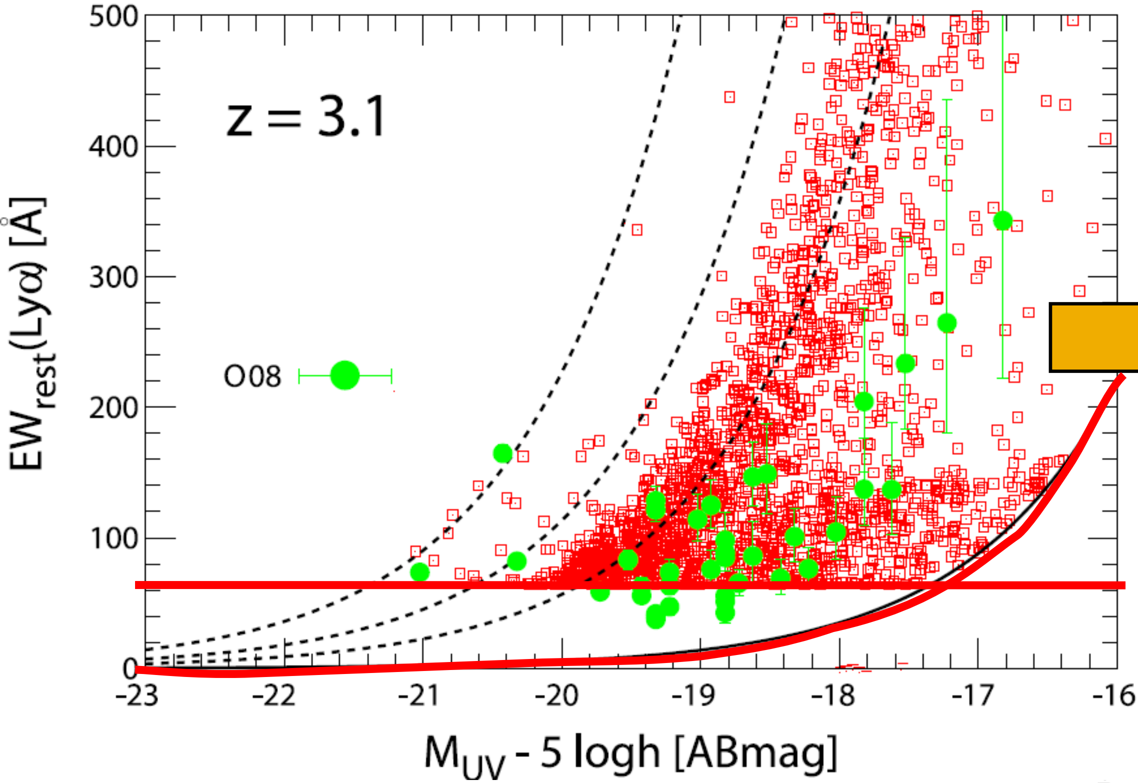
z = 3.1
z = 3.7
z = 5.7
O08
O08
S06
O08
$EW_{rest}(Ly\alpha)$ [Å]
$M_{UV} - 5 \log_{10}h$ [ABmag]



$M_{UV}-5\log_{10}h < -21$ mag
-21 mag $\leq M_{UV}-5\log_{10}h < -20$ mag
-20 mag $\leq M_{UV}-5\log_{10}h < -19$ mag
-19 mag $\leq M_{UV}-5\log_{10}h < -18$ mag
$M_{UV}-5\log_{10}h \geq -18$ mag
all LAEs
quiescent
starburst (pre−outflow)
starburst (outflow)
number fraction [%]
10
1
0.1
0.01
0
100
200
300
400
500
EW_{rest}(Lyα) [Å]

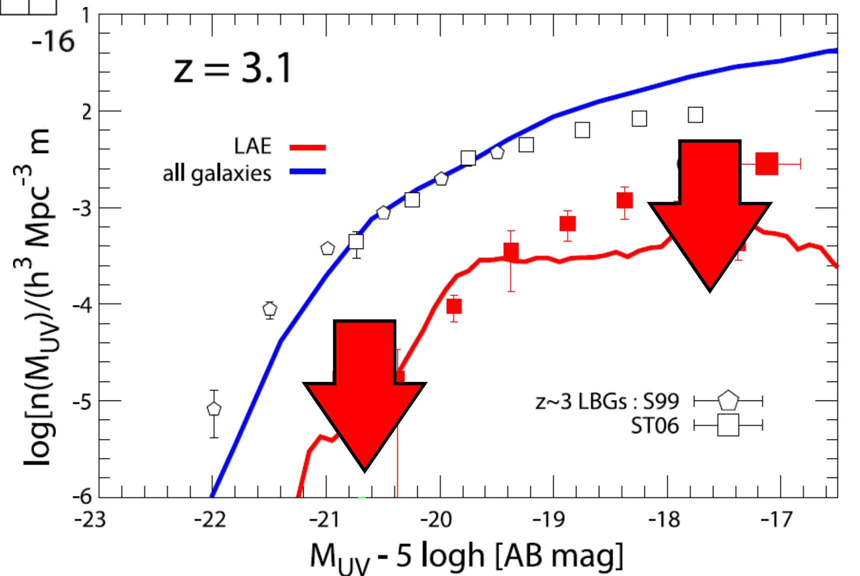


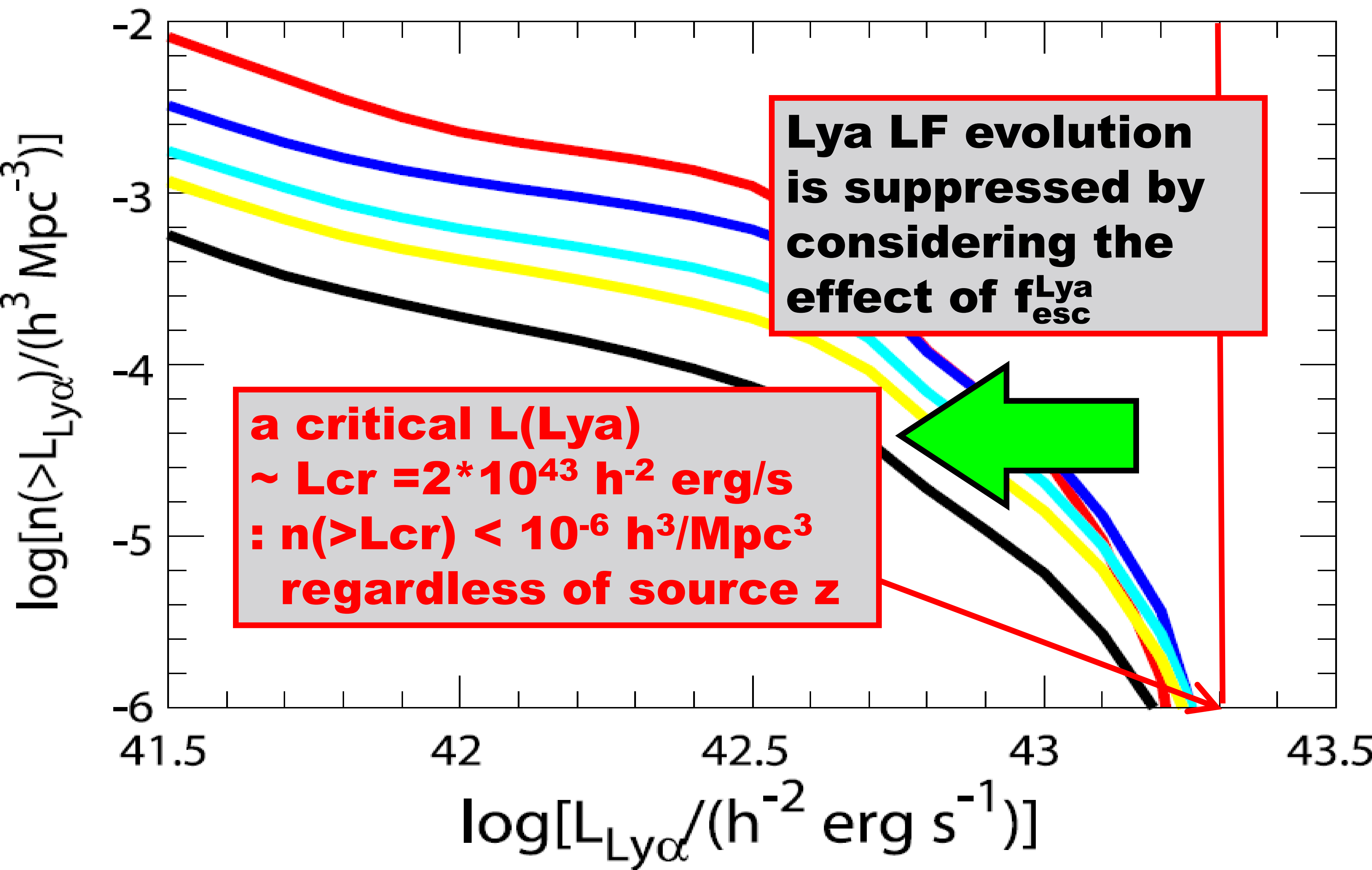
z=3.1
variable $EW^{th}_{Ly\alpha}$
$\log_{10}[L^{th}_{Ly\alpha}/(h^{-2}$ ergs $s^{-1})]$
=41.69
all galaxies
$EW^{th}_{Ly\alpha}$ = 0 Å
20 Å
40 Å
60 Å
z=3.1 LAEs : O08
G07
variable $L^{th}_{Ly\alpha}$
$EW^{th}_{Ly\alpha}$=64 Å
$\log_{10}[L^{th}_{Ly\alpha}]$=41.0
41.5
42.0
42.5
$\log_{10}[n(M_{UV})/(h^3$ Mpc^{-3} mag^{-1})]
$M_{UV} - 5 \log_{10} h$ [AB mag]



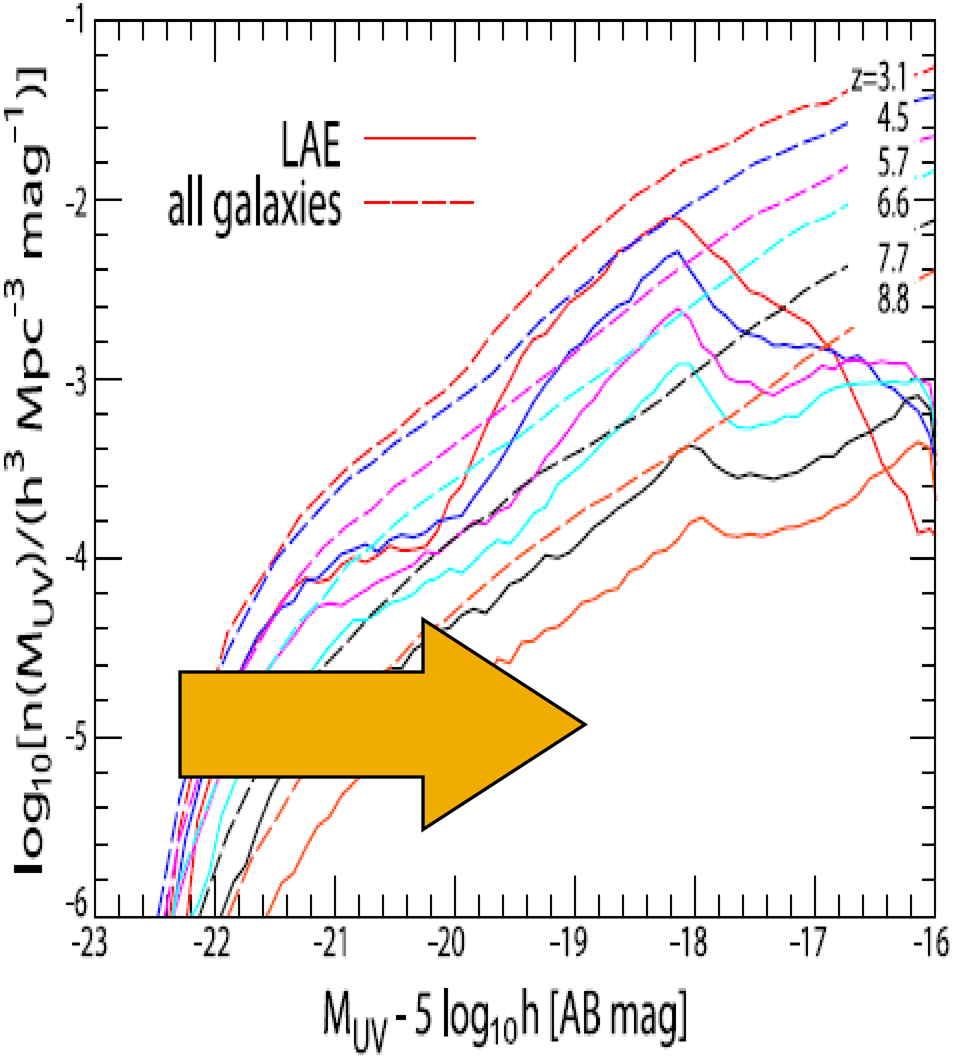
EW(Lya) dist

UV LF

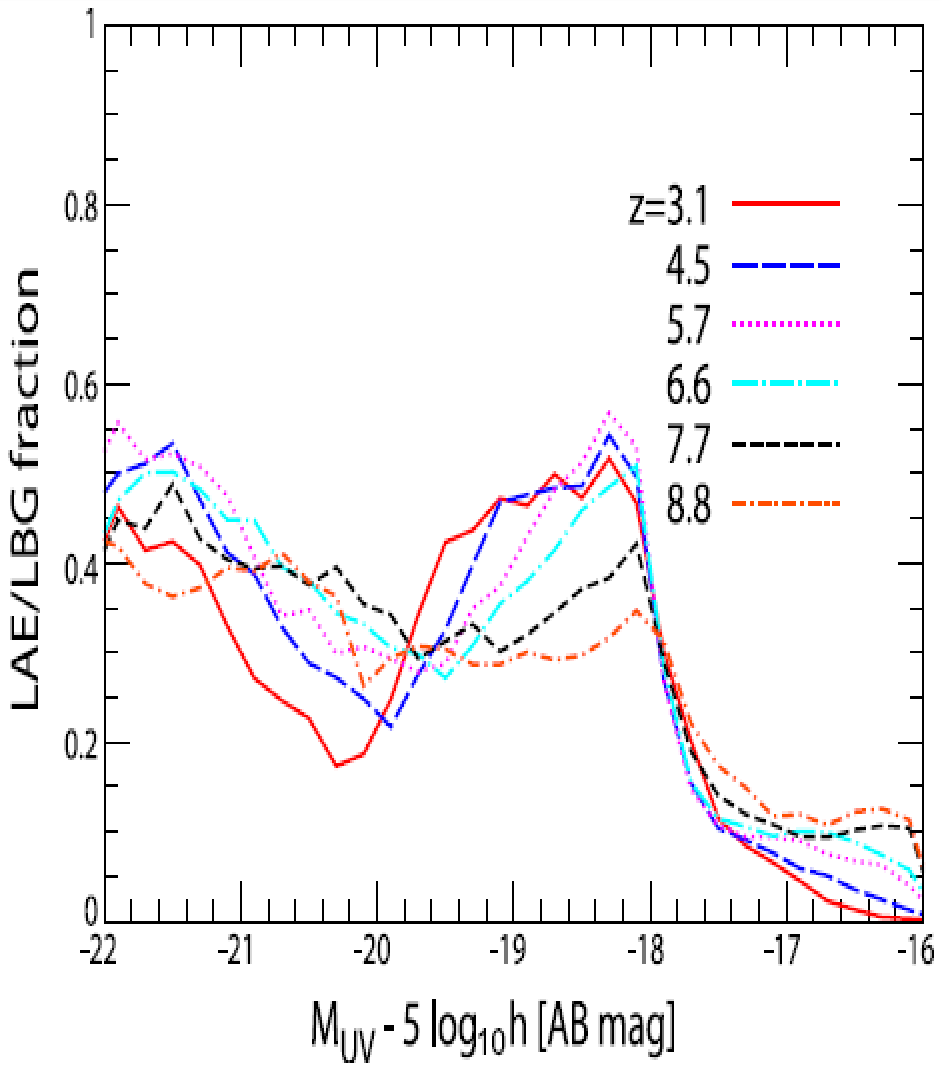




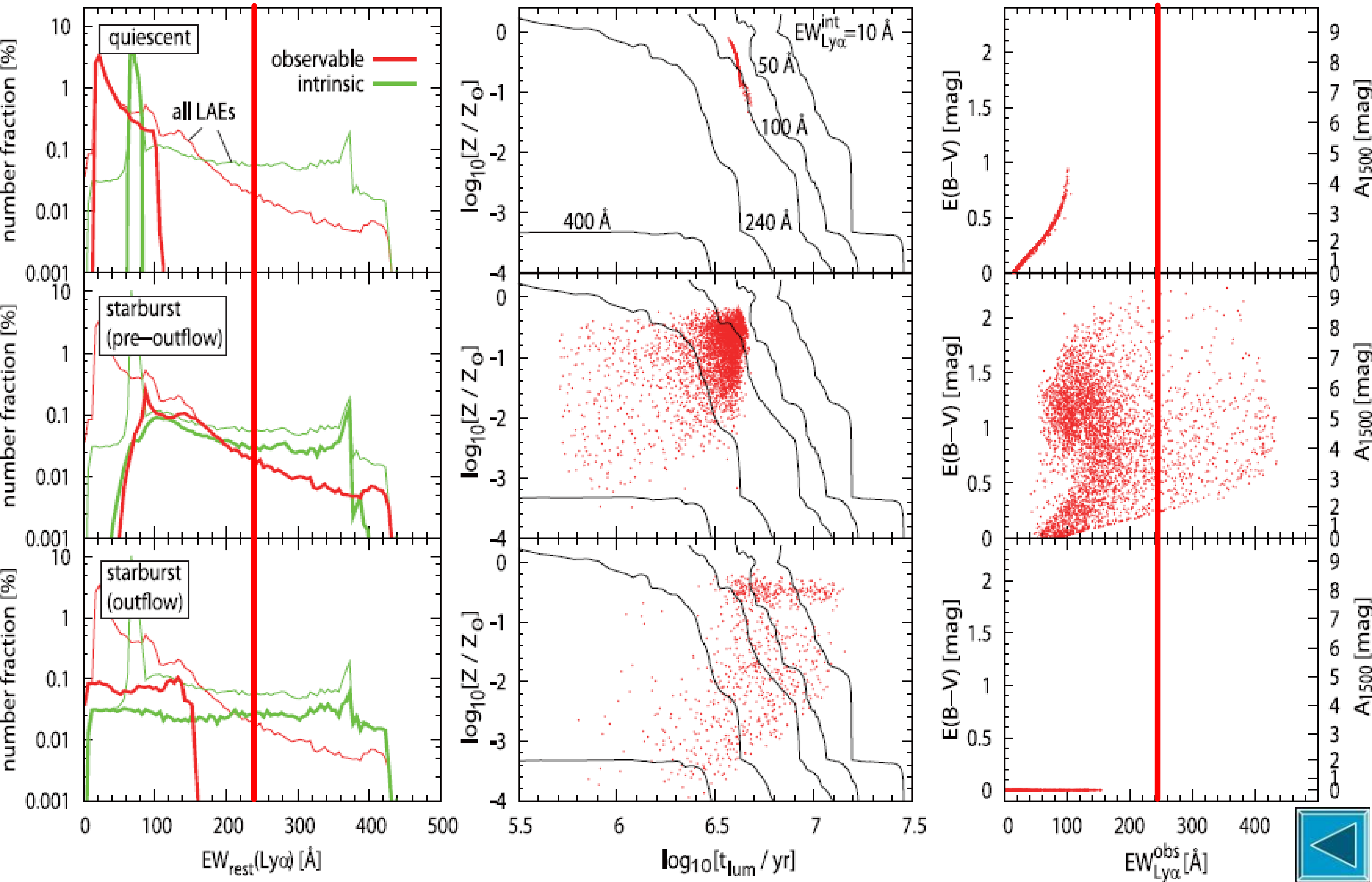
Lya LF evolution is suppressed by considering the effect of f_{esc}^{Lya}
a critical L(Lya)
~ Lcr =2*10^{43} h^{-2} erg/s
: n(>Lcr) < 10^{-6} h^{3}/Mpc^{3}
regardless of source z
-2
-3
-4
-5
-6
41.5
42
42.5
43
43.5
log[n(>L$_{Ly\alpha}$)/(h^{3} Mpc^{-3})]
log[L$_{Ly\alpha}$/(h^{-2} erg s^{-1})]



z=3.1
4.5
5.7
6.6
7.7
8.8
LAE
all galaxies
log10[n(MUV)/(h3 Mpc-3 mag-1)]
MUV - 5 log10h [AB mag]



z=3.1
4.5
5.7
6.6
7.7
8.8
LAE/LBG fraction
MUV - 5 log10h [AB mag]



quiescent
observable
intrinsic
all LAEs
starburst (pre–outflow)
starburst (outflow)
number fraction [%]
$EW_{rest}(Ly\alpha)$ [Å]
$EW^{int}_{Ly\alpha}$=10 Å
50 Å
100 Å
240 Å
400 Å
$\log_{10}[Z / Z_\odot]$
$\log_{10}[t_{lum}$ / yr]
E(B−V) [mag]
A_{1500} [mag]
$EW^{obs}_{Ly\alpha}$ [Å]

[redacted]

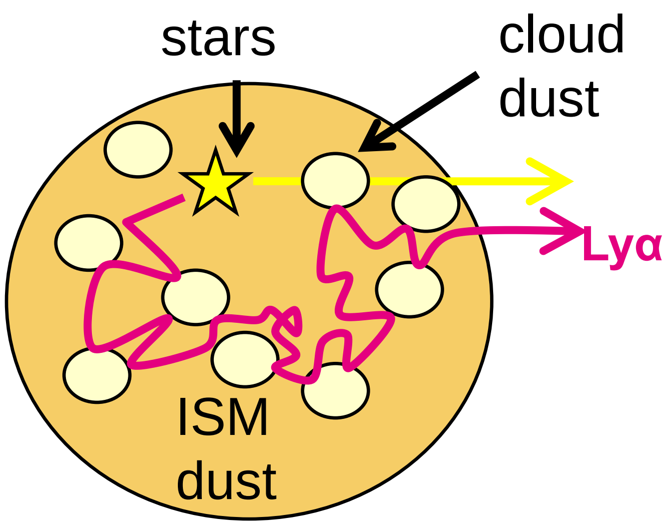
← Lyα 光度関数とのフィットで決めた

○ τ_c:Lyα 波長付近の連続光に対する dust opacity

← 近傍銀河の観測量とのフィットで決めた（三鷹モデル）

➔ $\boldsymbol{\tau_{Ly\alpha} / \tau_c} \equiv$ **q:geometry parameter** (Finkelstein+ 08)

$$\tau_{Ly\alpha} = q\tau_c$$



- q >> 1:homogeneous ISM
- q << 1: clumpy interstellar dust

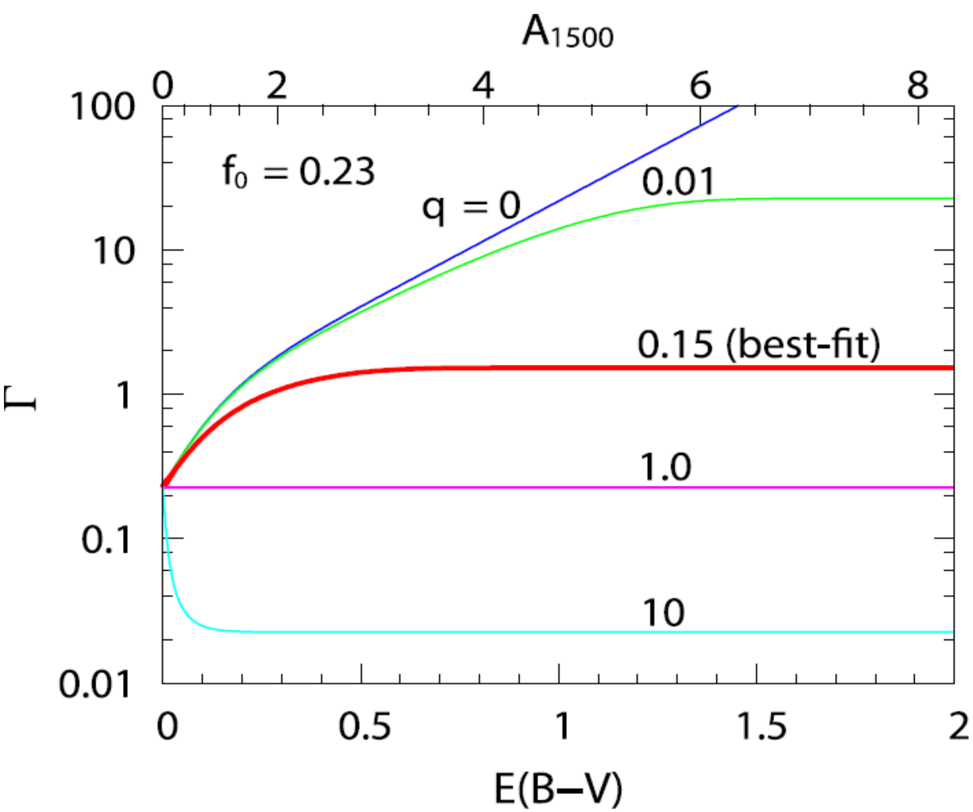
[redacted]

EW(Lyα) は変わる : **EW_{dust} / EW_{int} ≡ $\Gamma(\tau_c)$**

$$\Gamma(\tau_c) = (f_0 / q) \times [1 - \exp(-q\tau_c)] / [1 - \exp(-\tau_c)]$$

for quiescent and pre-outflow starburst

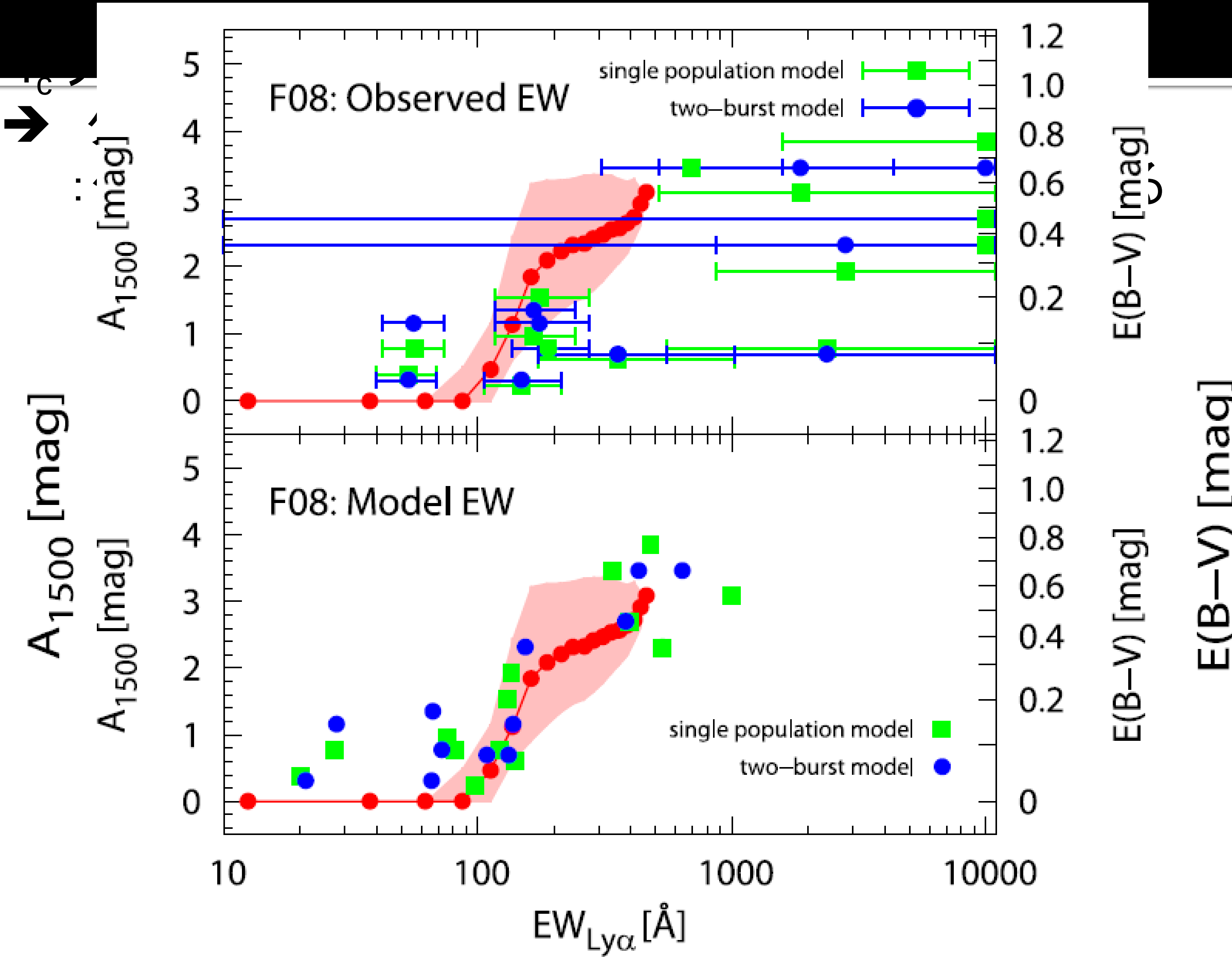
f_0 / q_{wind} for outflow starburst



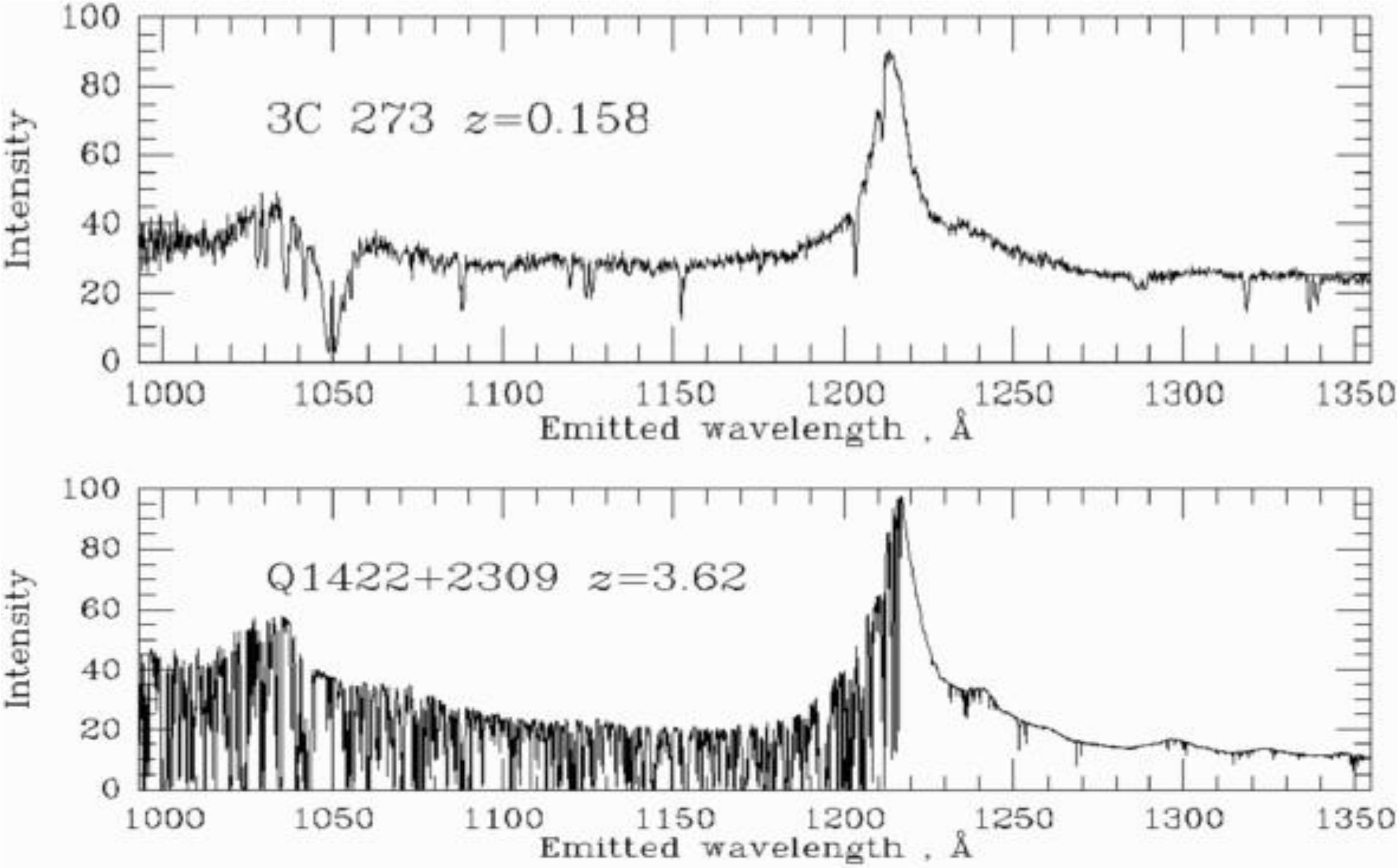
- best-fit : $q = 0.15 < 1$
  ➔ **clumpy ISM を示唆**

- best-fit : $q = 0.15$
  ➔ **ダスト減光が大きいほど Γ 大**

  $\Gamma \rightarrow (f_0 / q) = 1.5$
  for $E(B-V) \rightarrow \infty$


F08: Observed EW
single population model
two–burst model
F08: Model EW
single population model
two–burst model
A_{1500} [mag]
E(B–V) [mag]
$EW_{Ly\alpha}$ [Å]
10
100
1000
10000

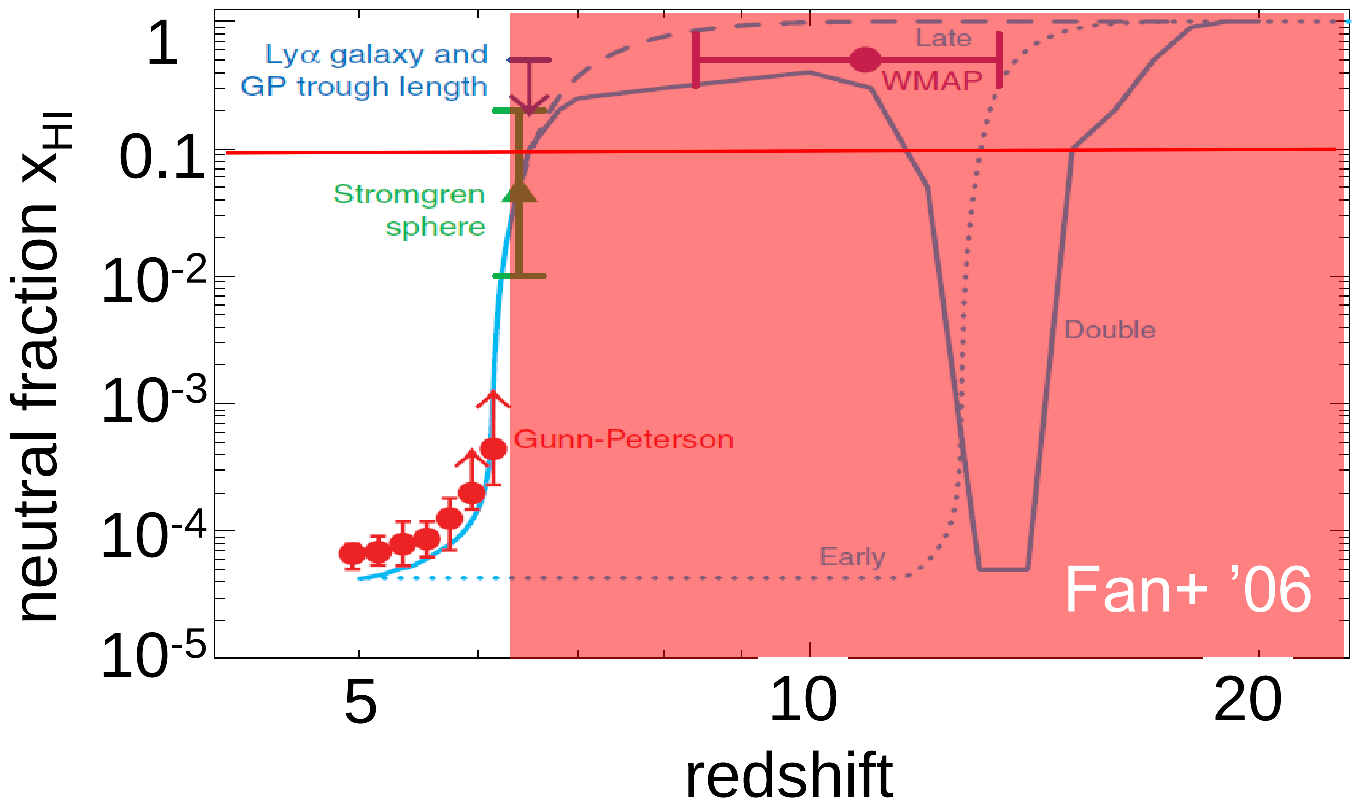
[redacted]



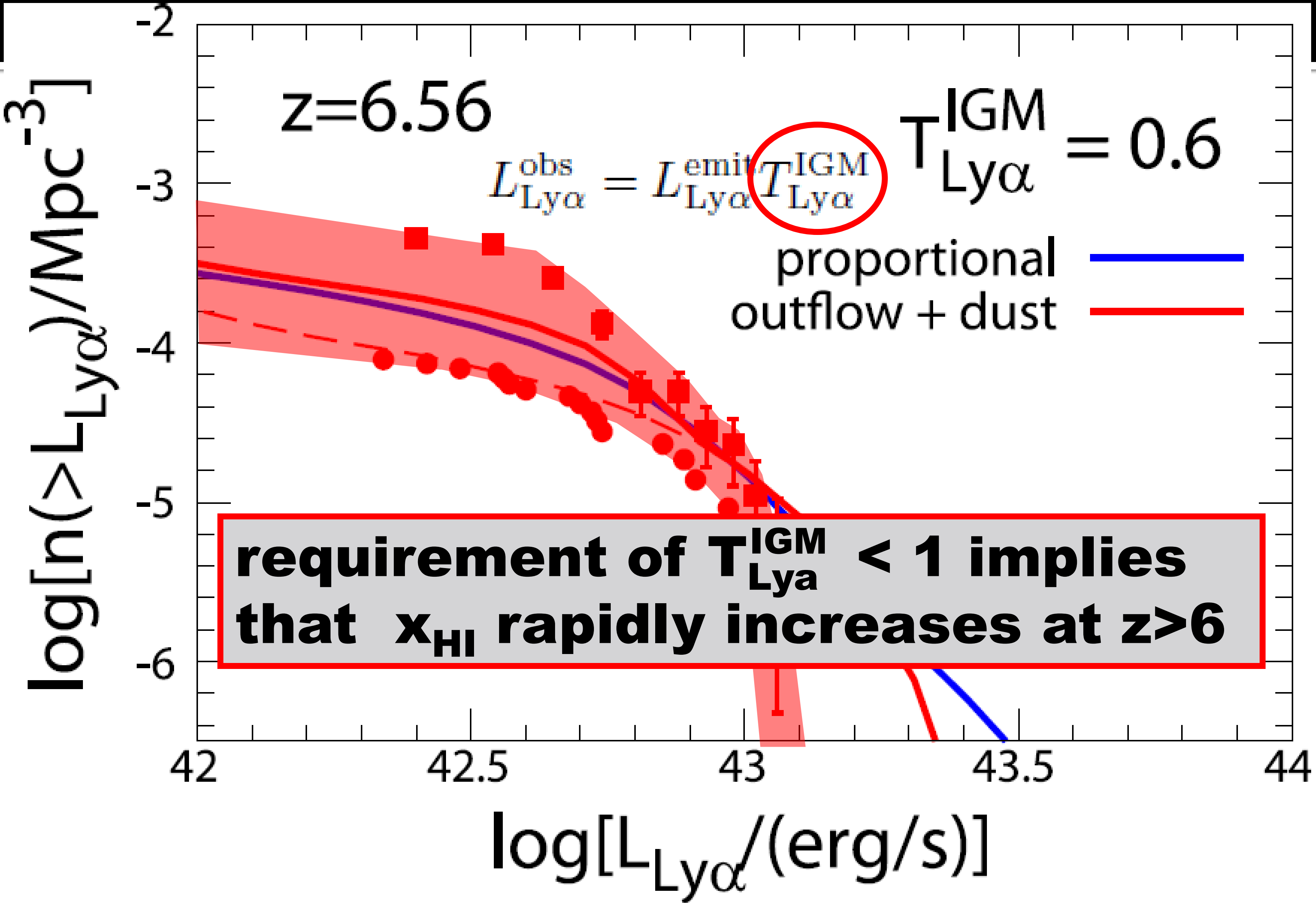
Bill Keel’s website：http://www.astr.ua.edu/keel/agn/

[redacted]

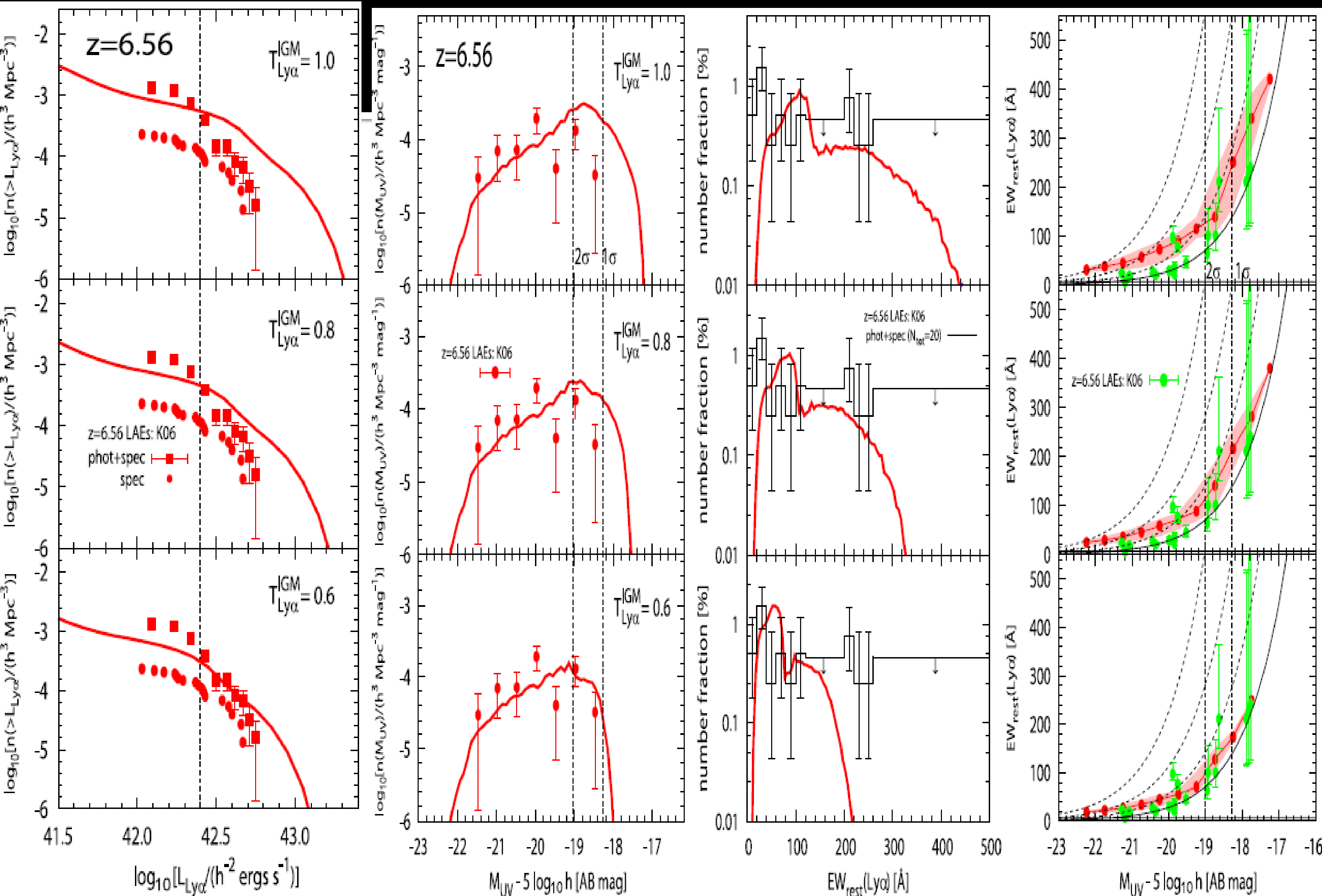
IGM neutral fraction (x_{HI}) > 0.1 (Santos ’04)



observed LAE Lya LF will be dimmer @ z > 6.5 than those at z < 6



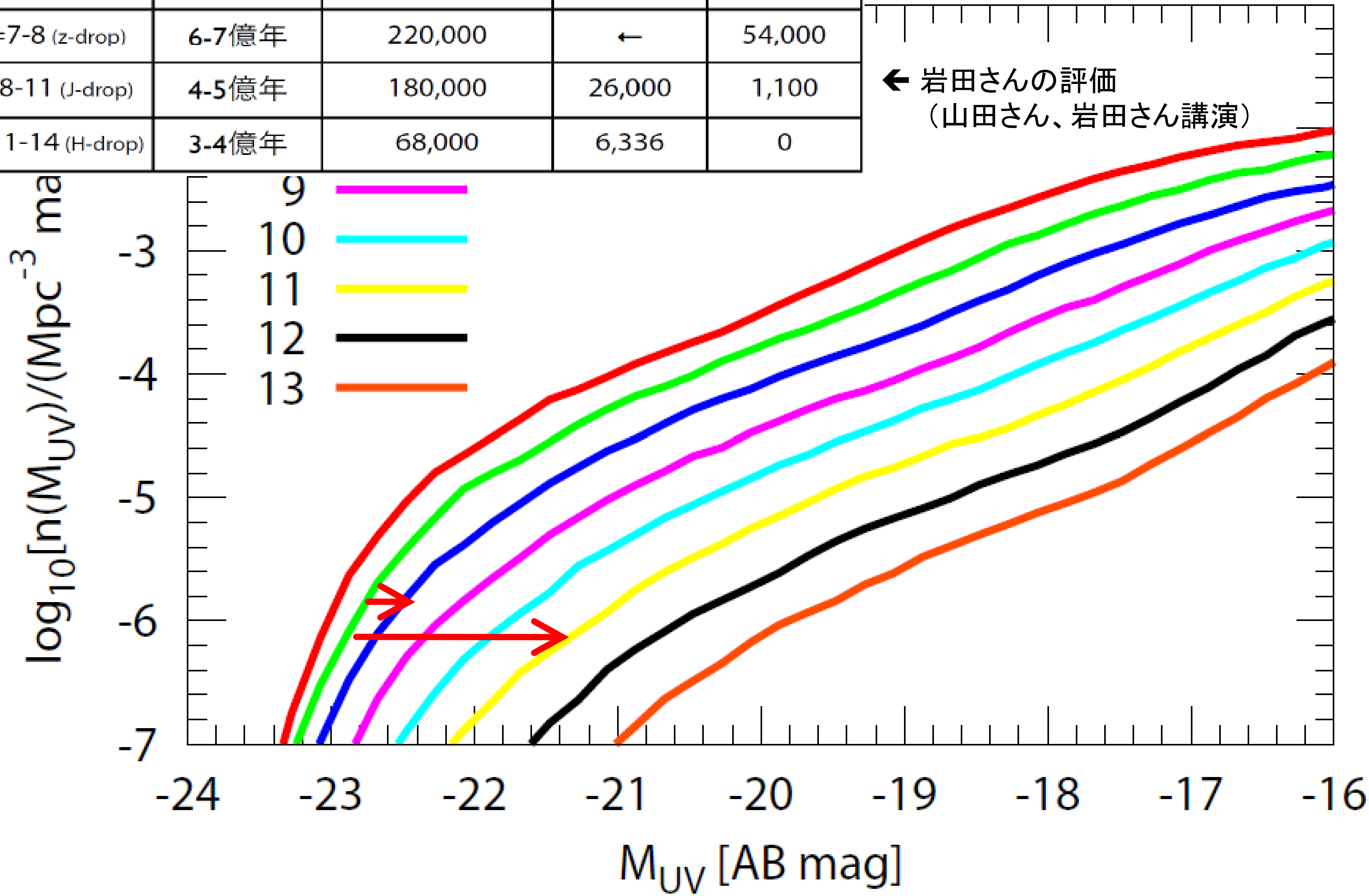
z=6.56
$L^{obs}_{Ly\alpha} = L^{emit}_{Ly\alpha} T^{IGM}_{Ly\alpha}$
$T^{IGM}_{Ly\alpha} = 0.6$
proportional
outflow + dust
requirement of T^{IGM}_{Lya} < 1 implies
that x_{HI} rapidly increases at z>6
log[n(>L$_{Ly\alpha}$)/Mpc^{-3}]
log[L$_{Ly\alpha}$/(erg/s)]
-2
-3
-4
-5
-6
42
42.5
43
43.5
44



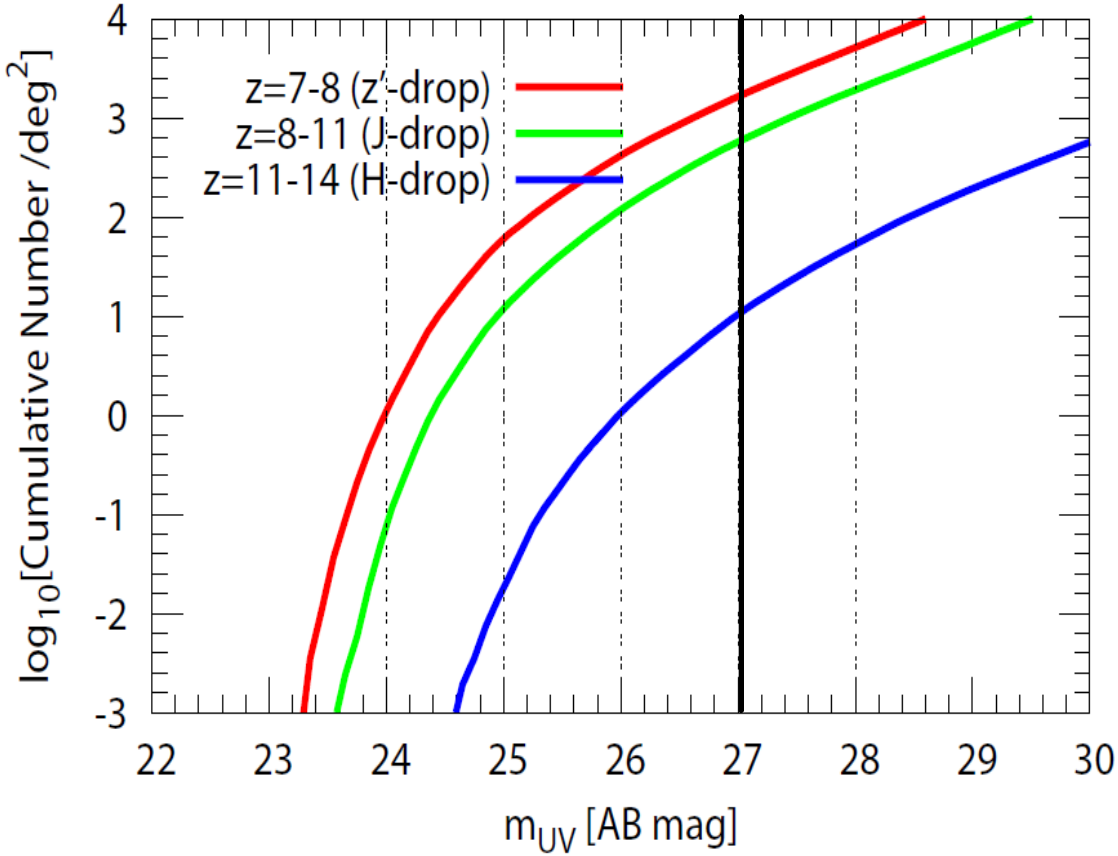
z=6.56
$T^{IGM}_{Ly\alpha}$ = 1.0
$T^{IGM}_{Ly\alpha}$ = 0.8
$T^{IGM}_{Ly\alpha}$ = 0.6
$\log_{10}[n(>L_{Ly\alpha})/(h^3\ Mpc^{-3})]$
$\log_{10}[L_{Ly\alpha}/(h^{-2}\ ergs\ s^{-1})]$
z=6.56 LAEs: K06
phot+spec
spec
$\log_{10}[n(M_{UV})/(h^3\ Mpc^{-3}\ mag^{-1})]$
$M_{UV} - 5\log_{10}h$ [AB mag]
2σ
1σ
number fraction [%]
$EW_{rest}(Ly\alpha)$ [Å]
phot+spec (N_{tot}=20)

z > 6 LBG UV 光度関数

	宇宙年齢	z=7から無進化	z>7で減少	DM進化
z=7-8 (z-drop)	6-7億年	220,000	←	54,000
z=8-11 (J-drop)	4-5億年	180,000	26,000	1,100
z=11-14 (H-drop)	3-4億年	68,000	6,336	0



[redacted]



○ 100 deg^2 で $m_{UV} < 27$ mag な LBG 検出数

- z=7-8：163,422 個
- z=8-11：57,646 個
- z=11-14：1,014 個

	宇宙年齢	z=7から無進化	z>7で減少	DM進化
z=7-8 (z-drop)	6-7億年	220,000	←	54,000
z=8-11 (J-drop)	4-5億年	180,000	26,000	1,100
z=11-14 (H-drop)	3-4億年	68,000	6,336	0

← 岩田さんの評価
（山田さん、岩田さん講演）