[WISH Science Workshop @ 国立天文台三鷹　2009/04/08]

期待されるLBG･LAE 検出数 :準解析的モデルからの見積り

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我々の銀河形成モデル

MARK, Totani, & Nagashima (2007, 2009)

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

・近傍銀河の観測量を再現

・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）

・低金属量星の進化トラックの最新モデル

・各銀河の星形成史、金属量 など（三鷹モデルから）

➔ UV 連続光、HI 電離光子放射数（intrinsic Lyα 輝線光度）などを計算

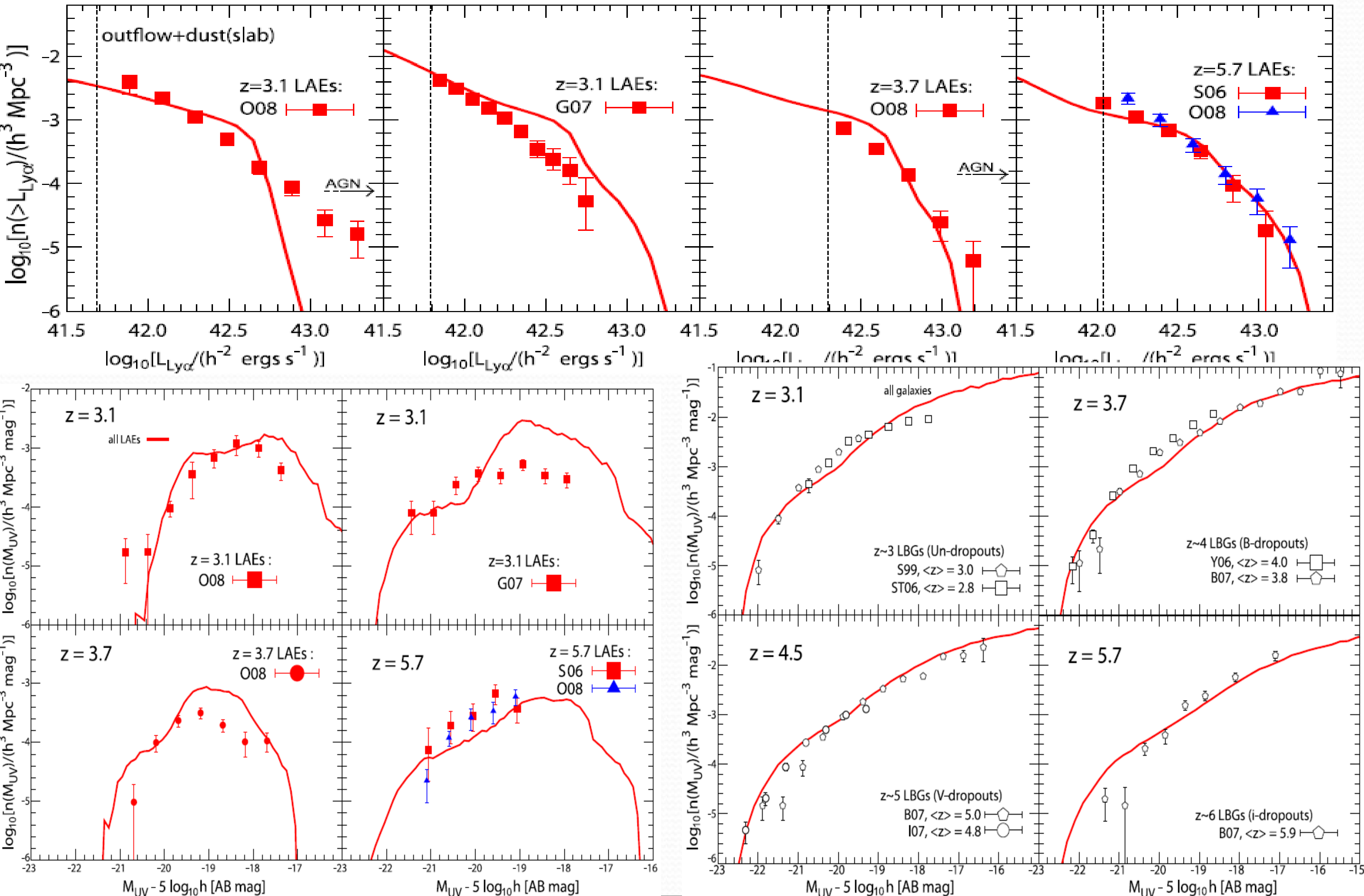
○ ＋ Lyα 離脱率の現象論的モデル

・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

・各銀河の UV 連続光、intrinsic Lyα 輝線光度

➔ 観測される Lyα 輝線光度、Lyα 等価幅を計算

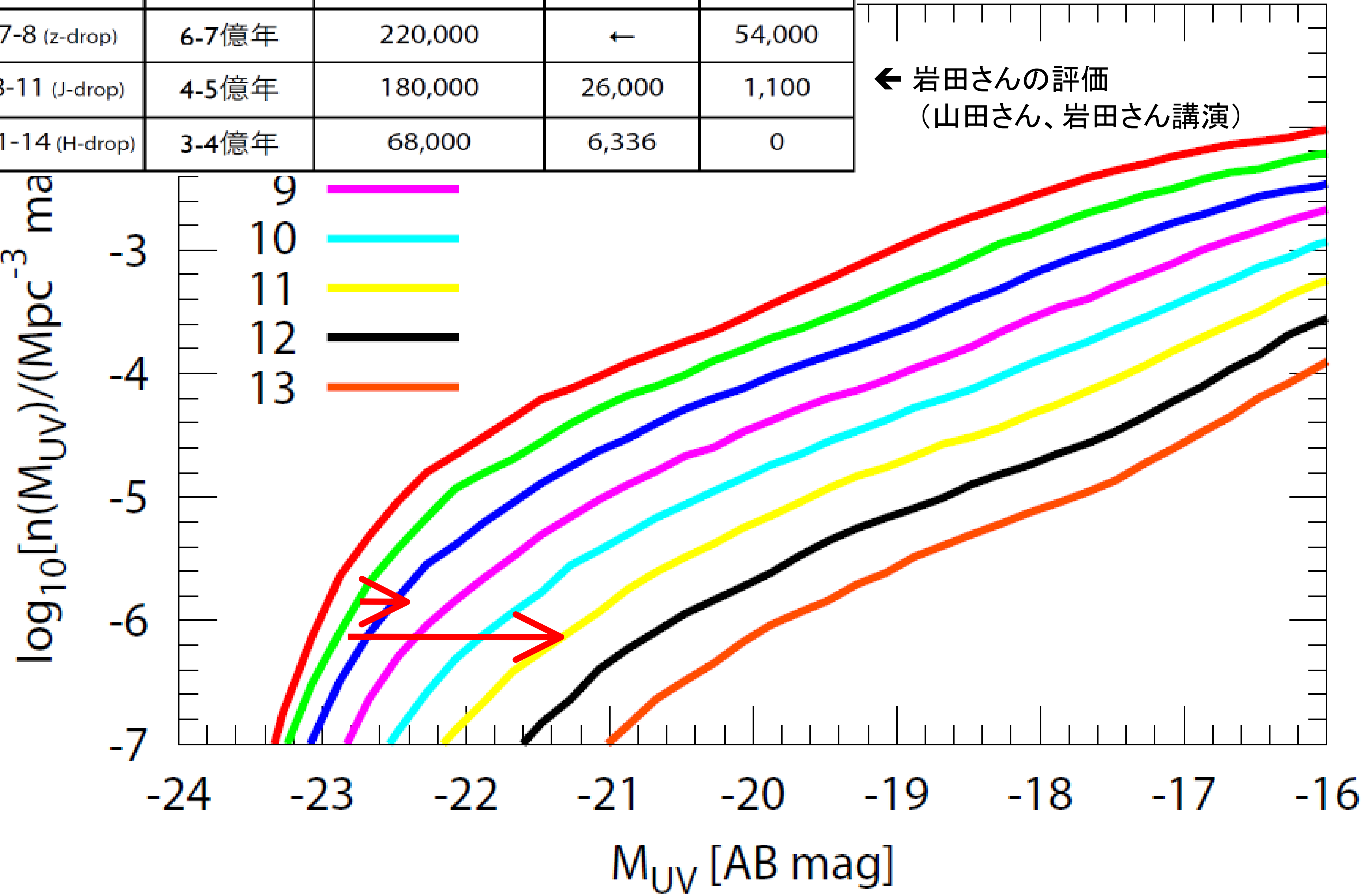
既存の LAE･LBG 観測データとの比較



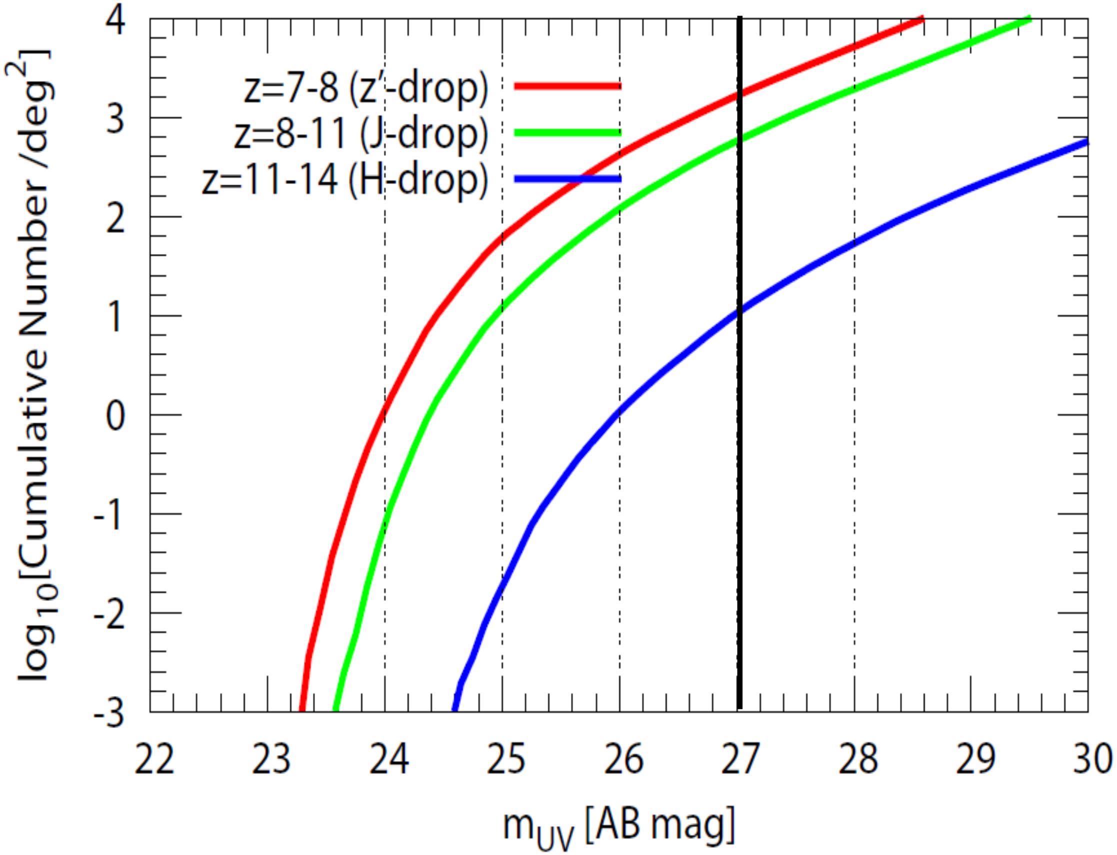
z > 6 LBG UV 光度関数

	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

← 岩田さんの評価
（山田さん、岩田さん講演）



z > 6 LBG Number Count



○ **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
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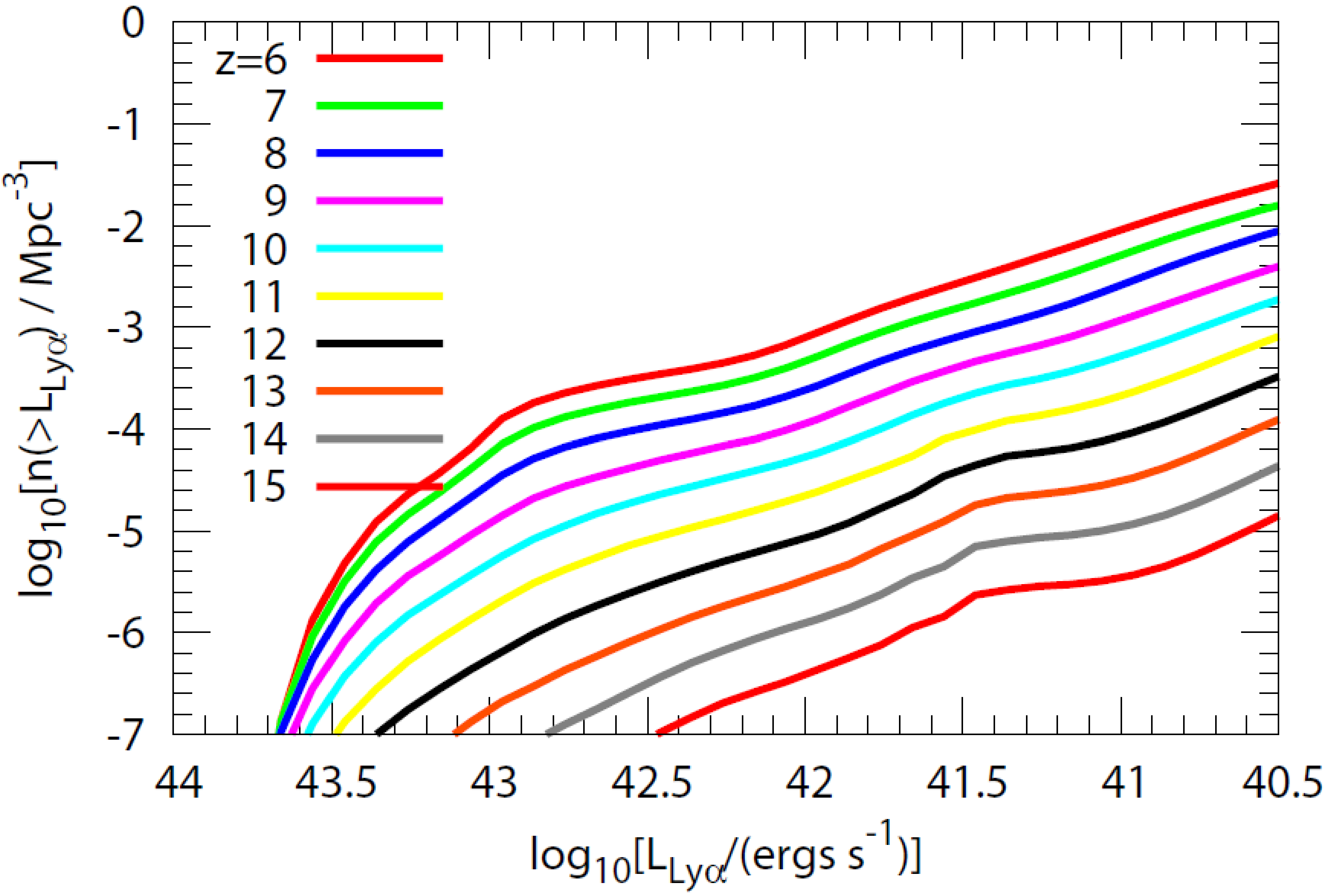
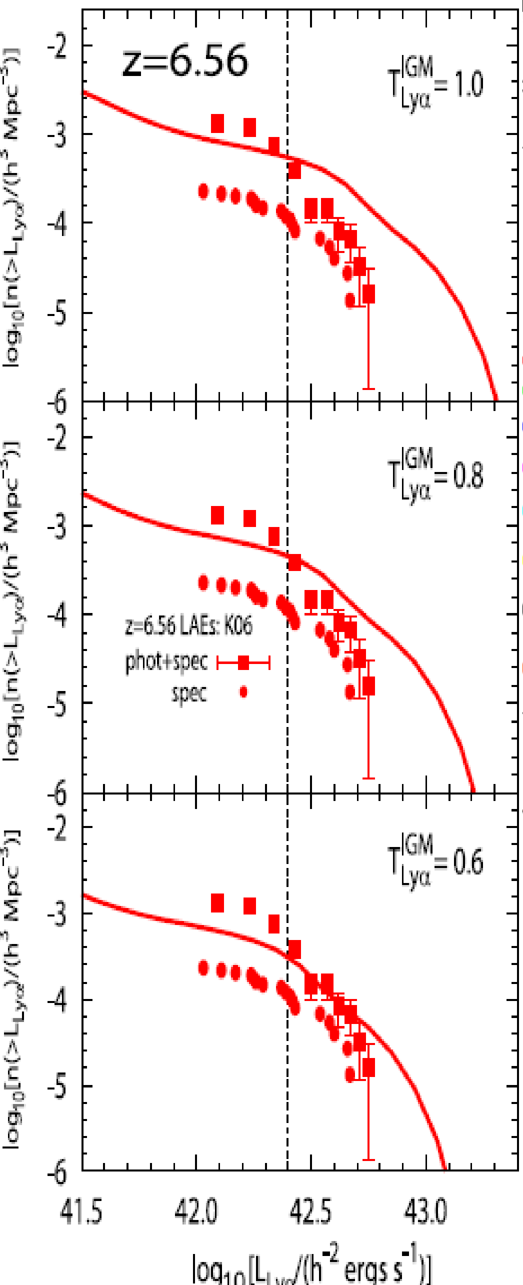
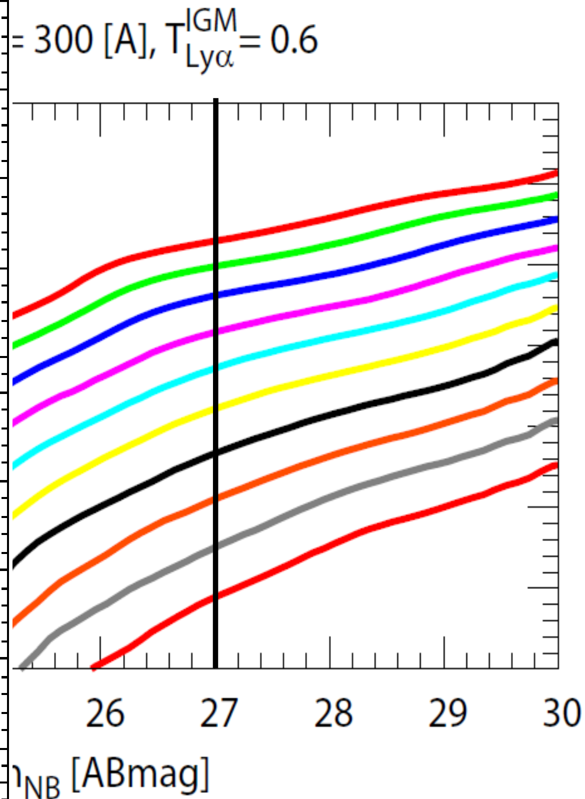
z > 6 LAE Lyα 光度関数



z > 6 LAE Number Count





- ○ 100 deg^2 で $m_{NB} < 27$ mag な LAE (EW > 20 A) 検出数
  - ➔ FHWM 大ほど多
  - ☆ FWHM = 100 A → Δz = ±0.04
- ○ 再電離の効果も加味した LAE (EW > 20 A) 検出数
  - ➔ z=5.7 に比べた Lyα 透過率 $T^{IGM}_{Ly\alpha}$ による

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

~まとめ~

○ 100 deg^2 を 27 mag まで掃けば・・・

LBG：~ 160,000 個（z ~ 7-8）、~ 60,000 個（z ~ 8-11）、
~ 1,000 個（z ~ 11-14）

LAE：~ 4,000 個（z ~ 8）、~ 700 個（z ~ 10）、
~ 80 個（z ~ 12）
↑ Lyα の IGM 吸収が z=5.7 と同じ場合

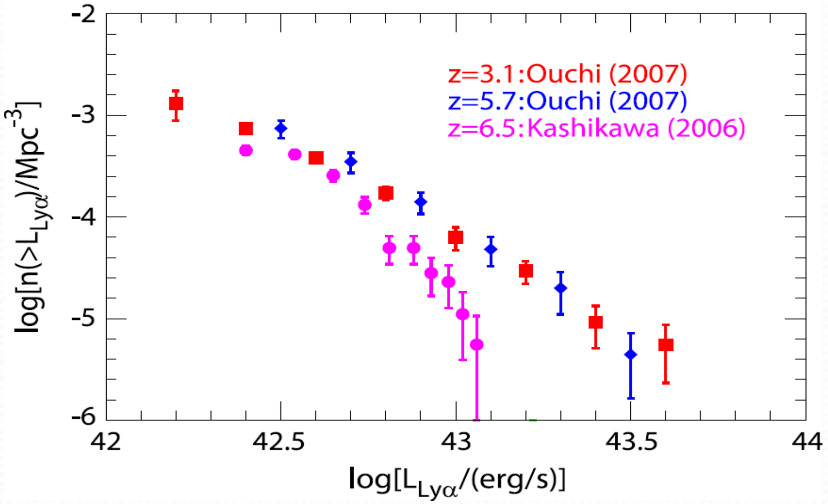
○ IMF、ダスト減光曲線の不定性もあるが、これらによってこの評価より少なくなることは多分ない

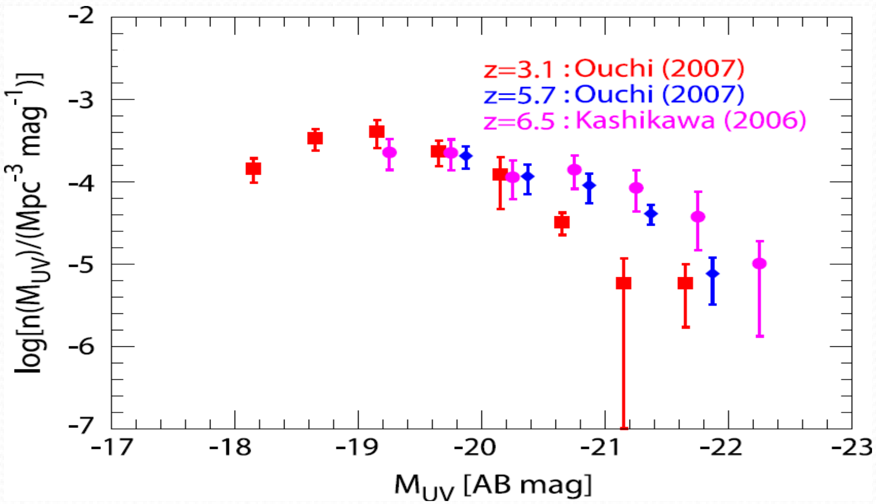
○ LAE @ z > 8 の実際の検出数がこれより少なければ、
再電離の効果と考えられる

Observational Data of LAEs (1)

◆ 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)?

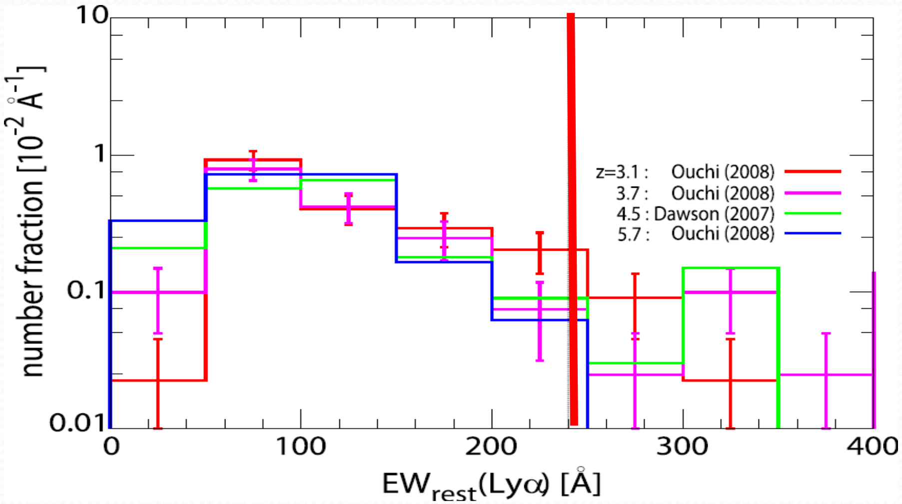




Important information about LAEs is imprinted in these obs. LFs

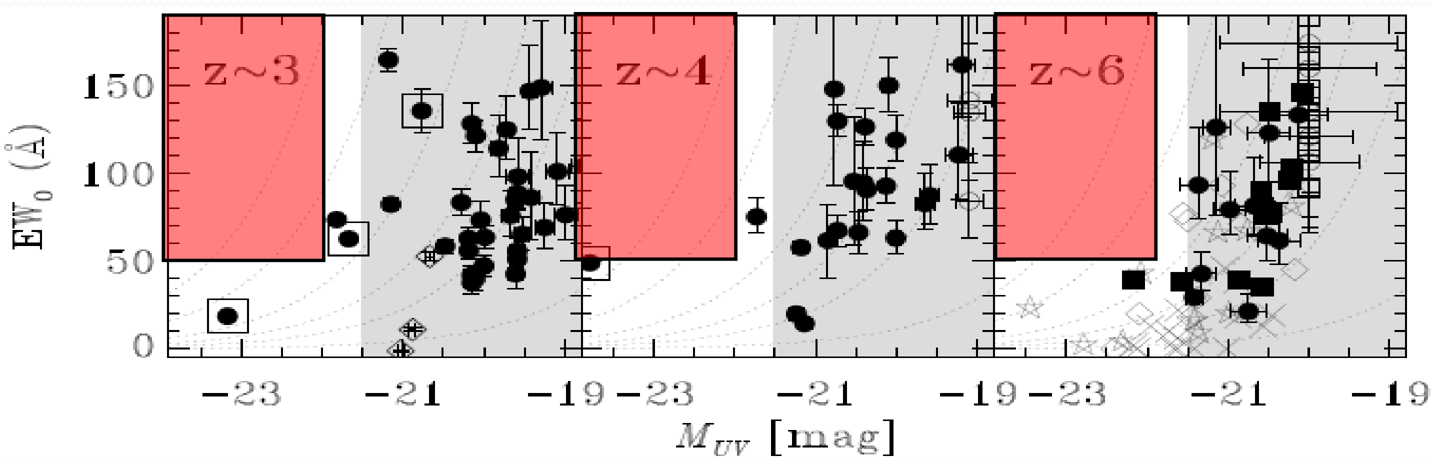
Observational Data of LAEs (2)

◆ Lya Equivalent Width (EW) Distribution



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

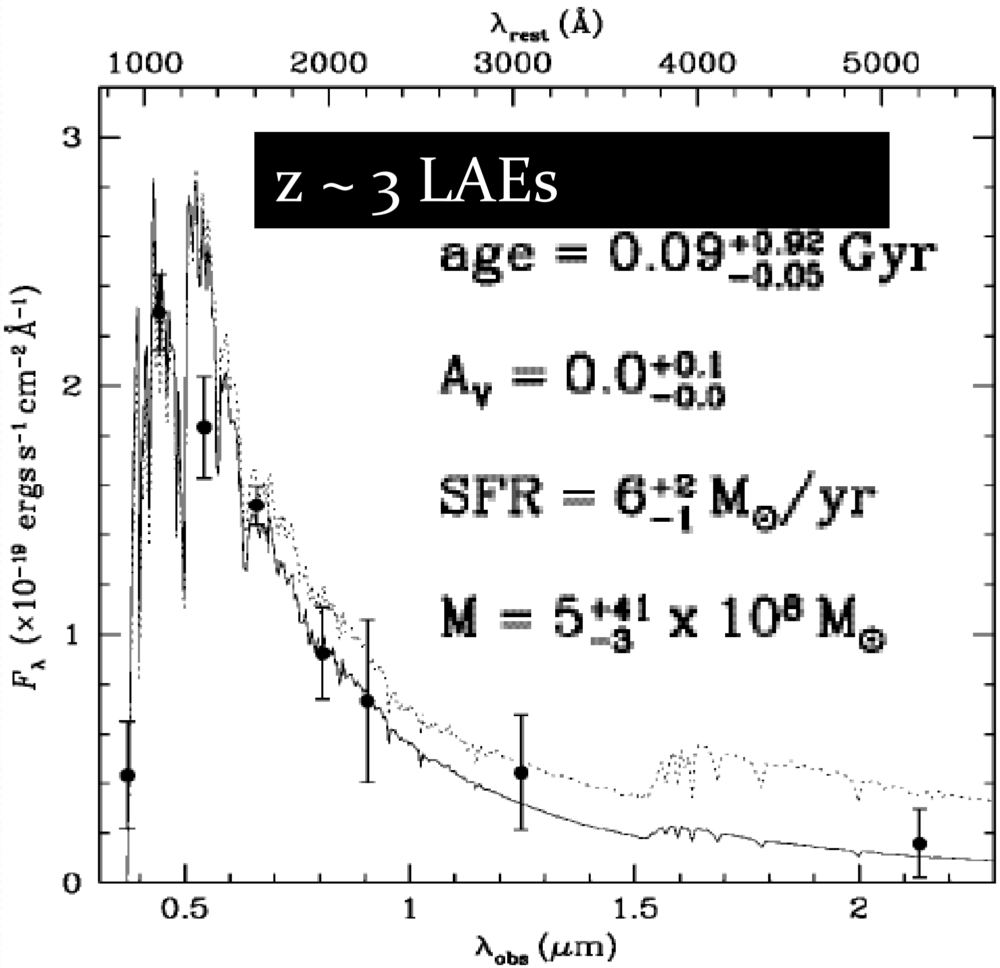
◆ Distribution in M(UV)-EW(Lya) plane



deficiency of UV-bright LAE w/ large-EW

Physical properties of LAEs@high-z

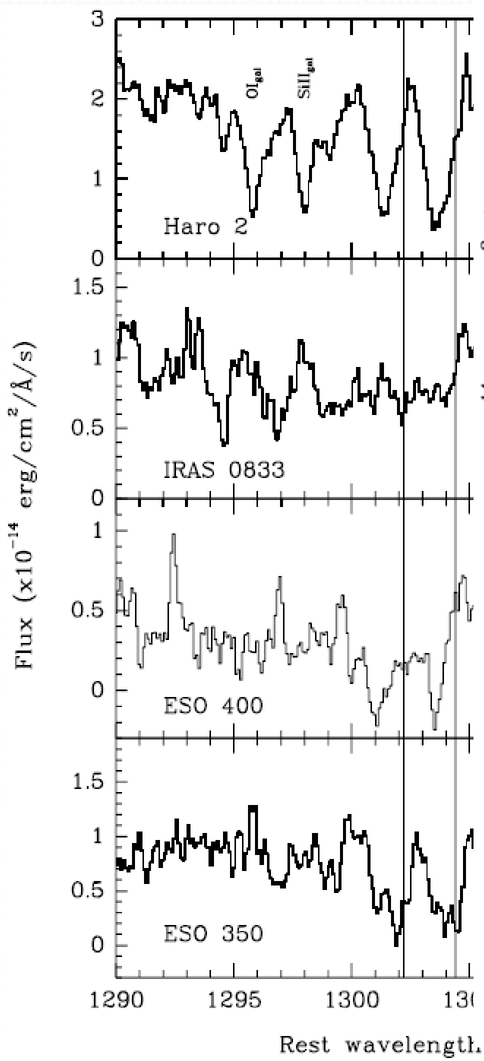
- stacking broad-band fluxes (Gawiser+ ’06)

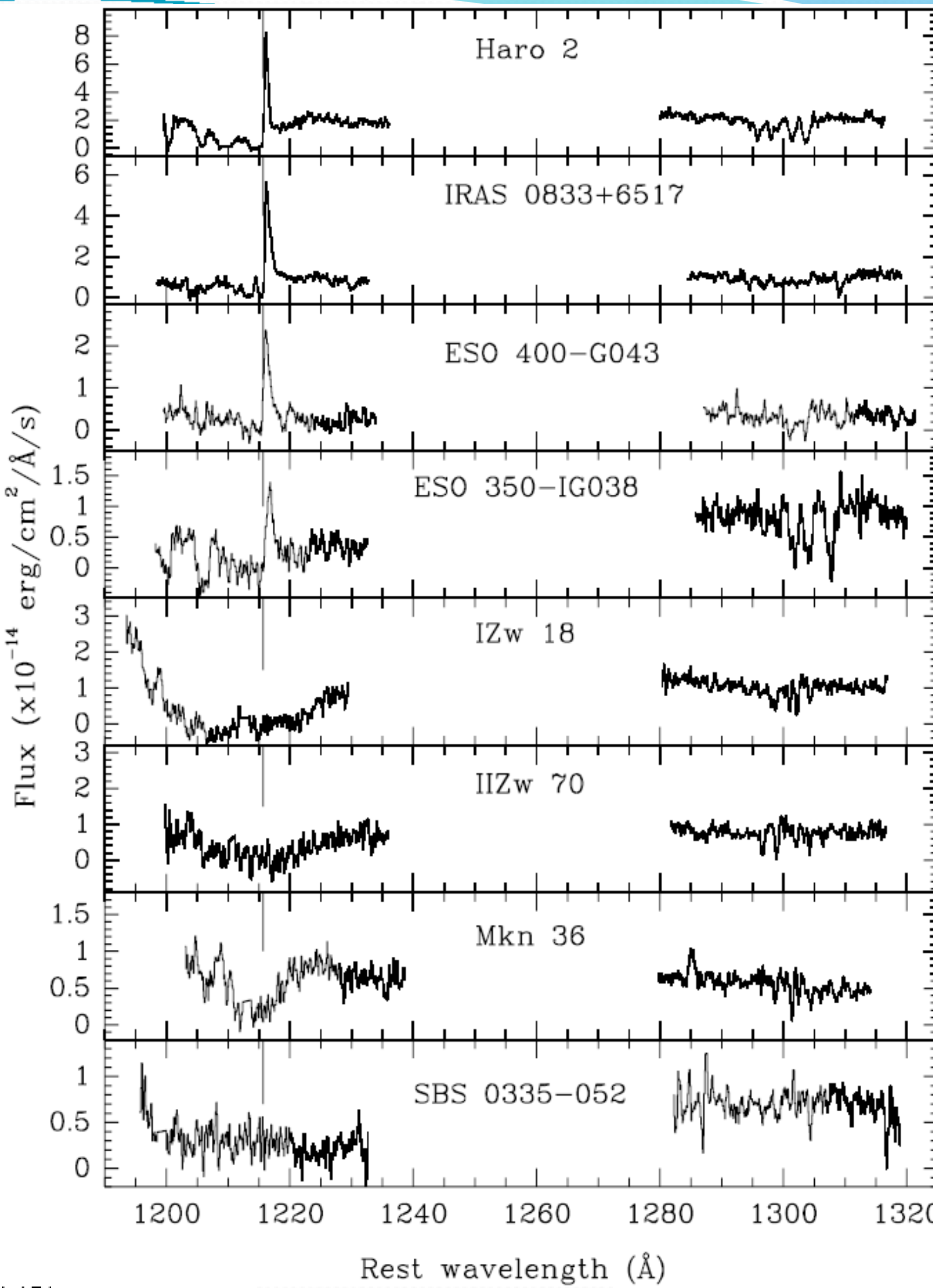


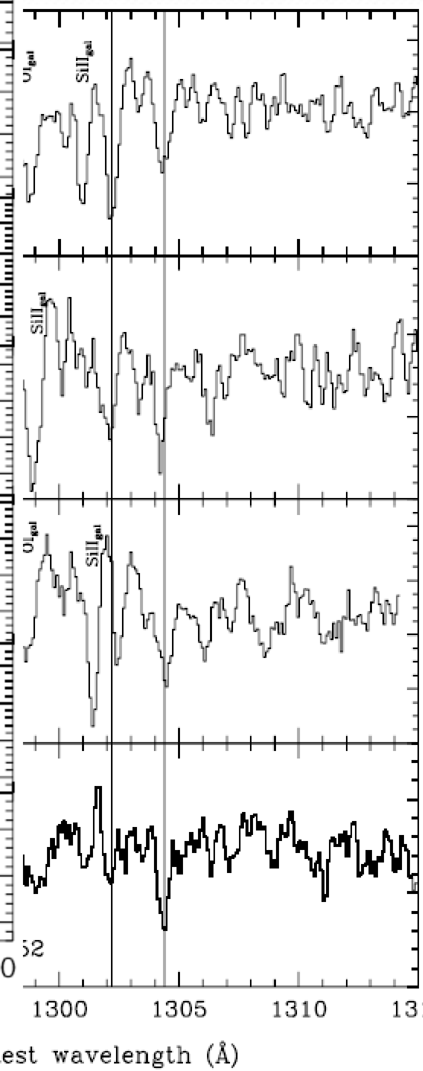
- high SFR
- young (10-100 Myr)
- almost dust-free
- low stellar mass

Lyα Emis laxies

- interstellar th+ ’98)







Theoretical Works & f_{esc}^{Lya}

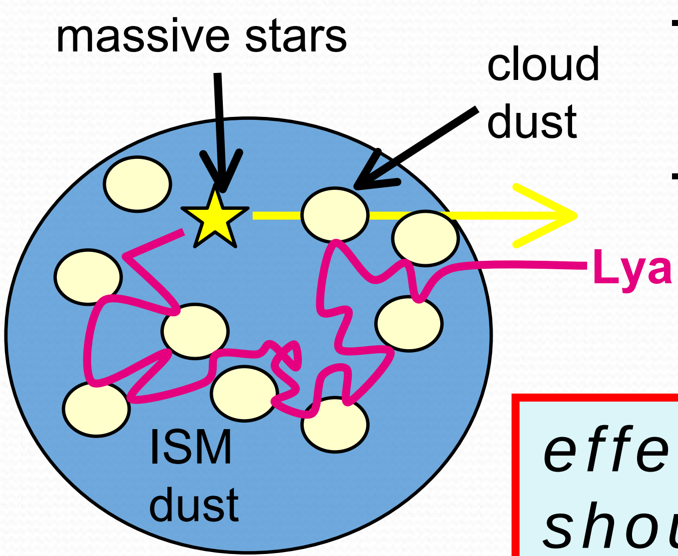
◆ Several models with different approaches exist

- 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



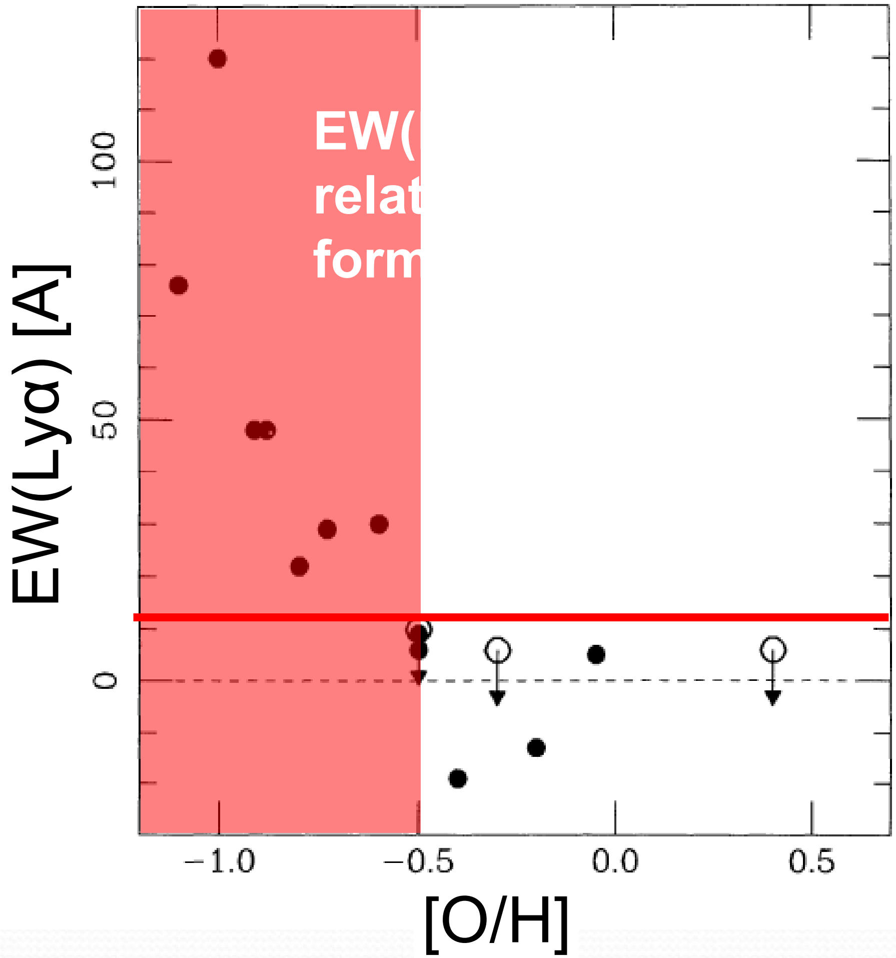
- Lya: a resonance line of HI
  → random-walk before escape
- f_{esc}^{Lya} is highly sensitive to dust geometry & ISM dynamics; f_{esc}^{Lya} is not constant and not equal to exp(-tau_d)

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

Implications for f_{esc}^{Lya} from Observations (1)

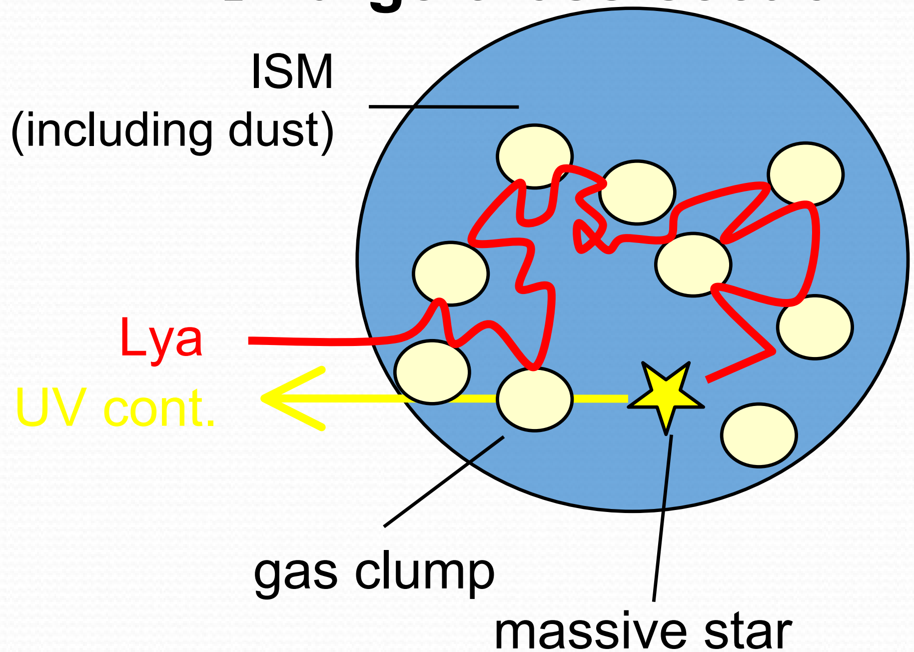
◆ Metallicity Dependence
(Charlot & Fall '93)

➩ **high f_{esc}^{Lya} at low-metallicity (⇔ low-dust content)**



- consistent with theoretical expectation (Neufeld '90)

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

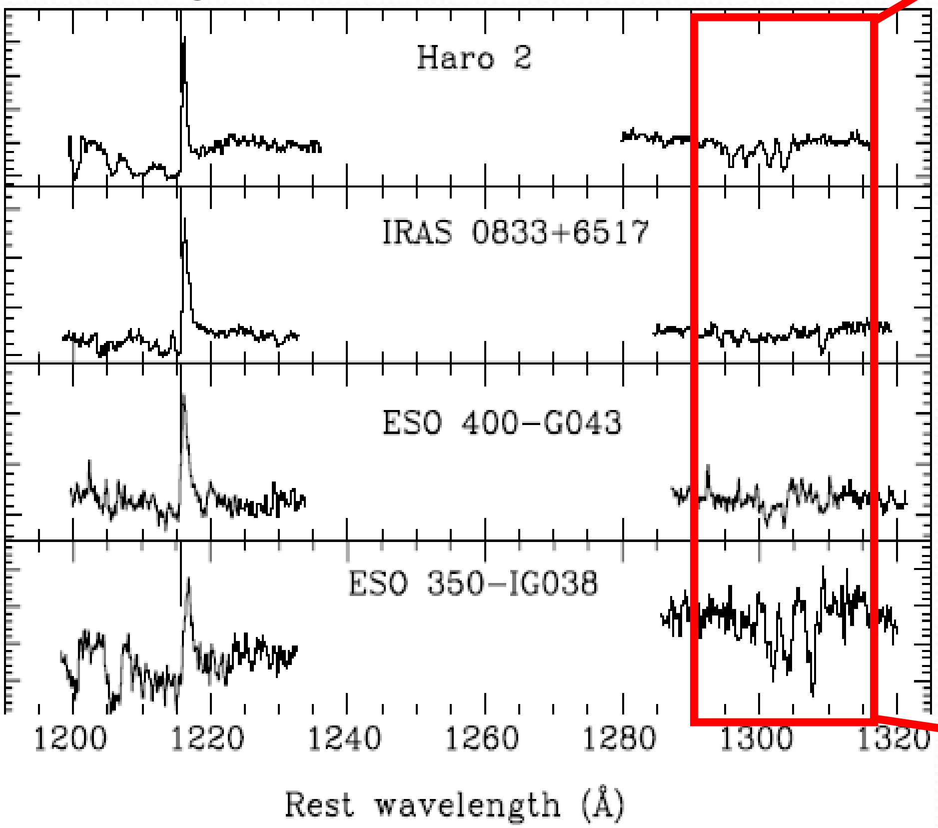


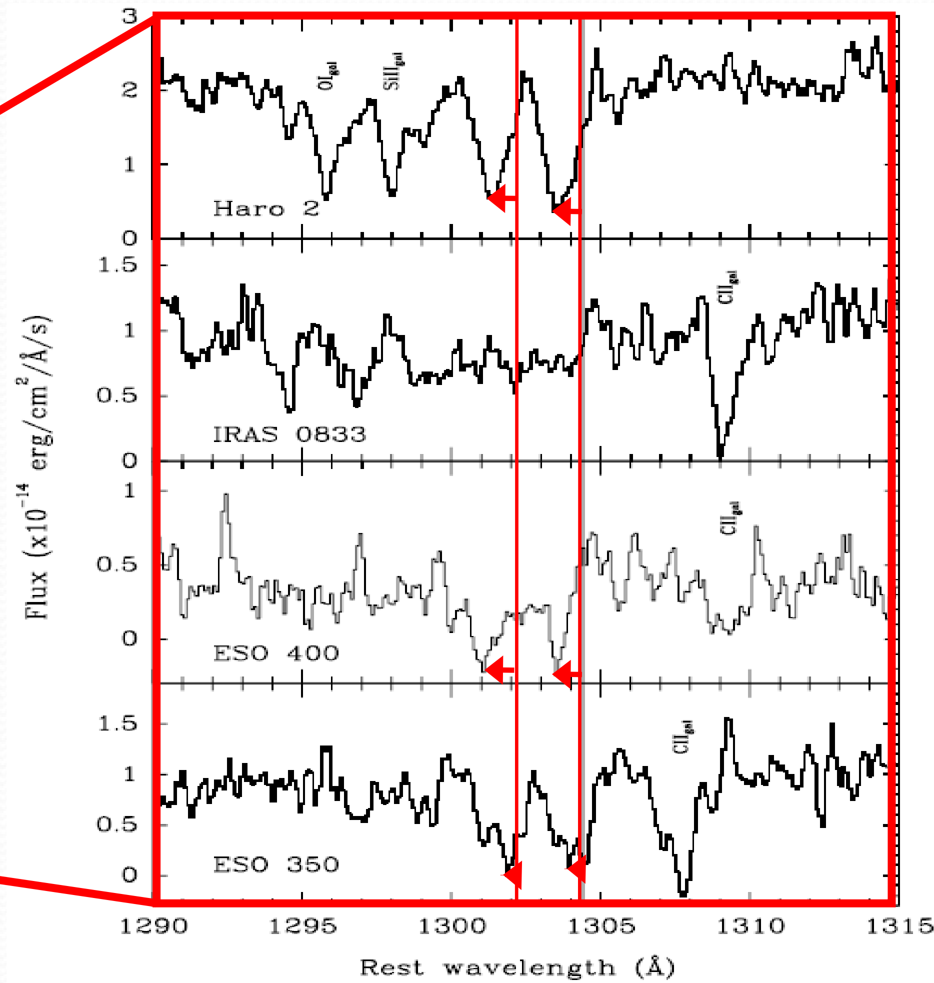
Implications for f_{esc}^{Lya} from Observations (2)

- gas-dynamics (outflow) (Kunth+ '98)

⇨ **high f_{esc}^{Lya} in outflowing condition**

UV spectra of local galaxies with Lya emission





Implications for f_{esc}^{Lya} from Observations (2)

- gas-dynamics (outflow) (Kunth+ '98)

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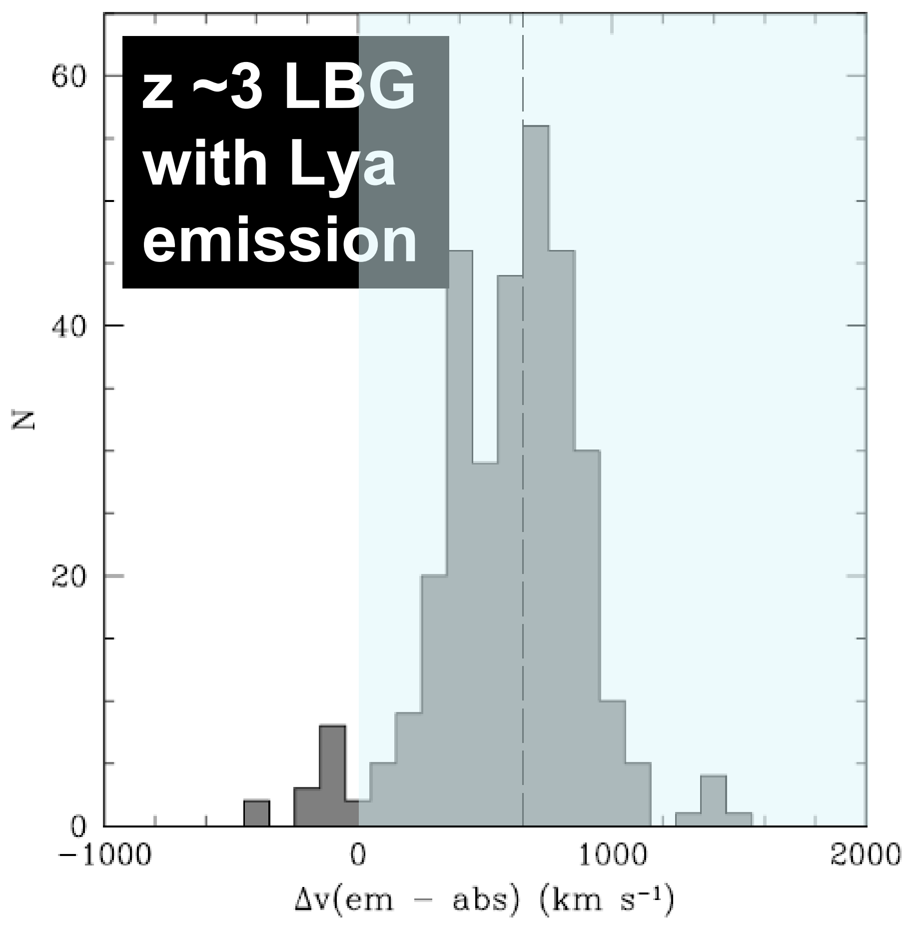
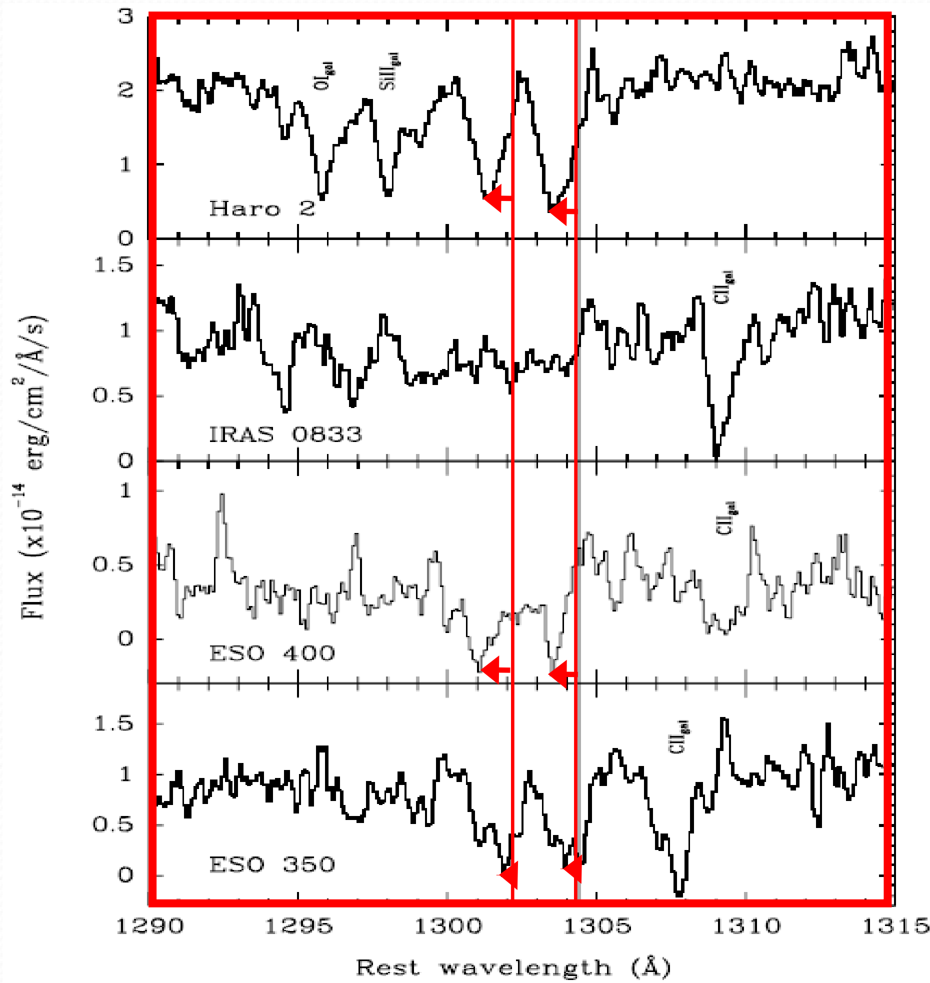


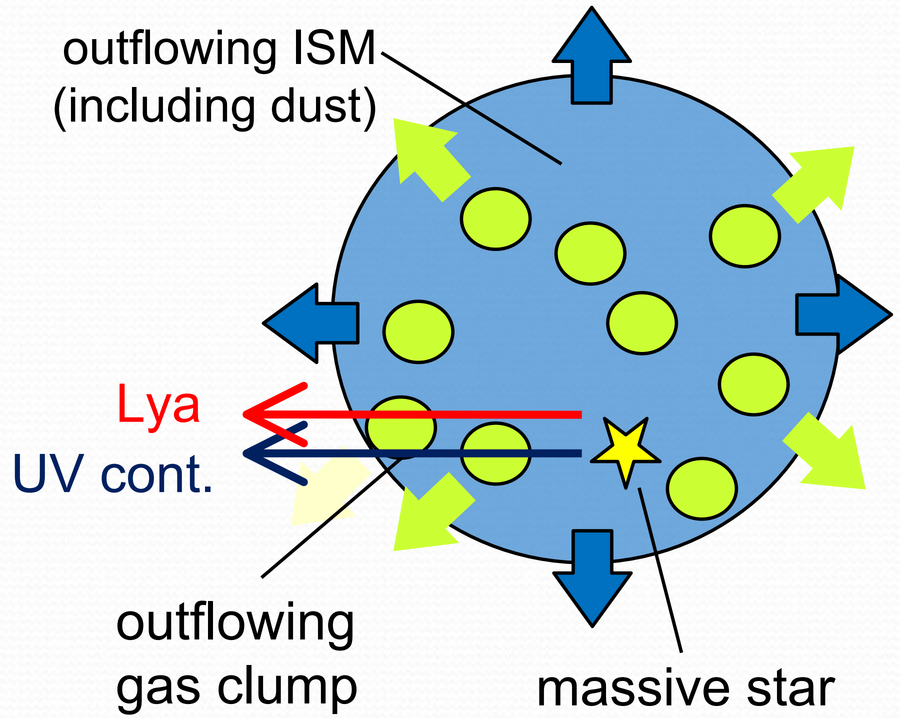
Shapley+ '03



Implications for f_{esc}^{Lya} from Observations (2)

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

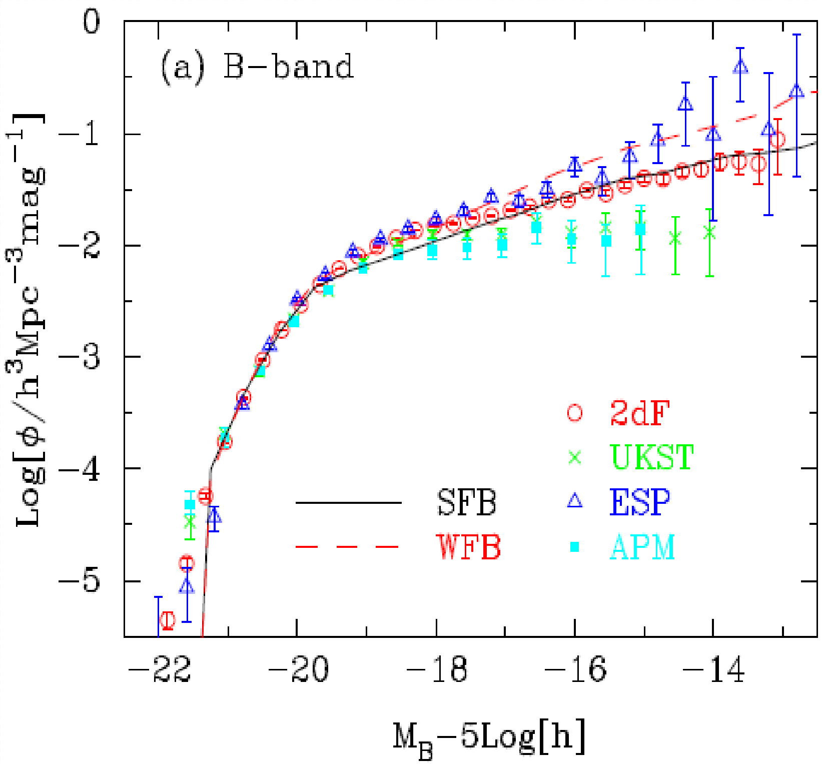
- consistent with theoretical expectation
  ➔ galactic-scale outflow drastically reduce the effective opacity of Lya (Hansen & Oh '05)



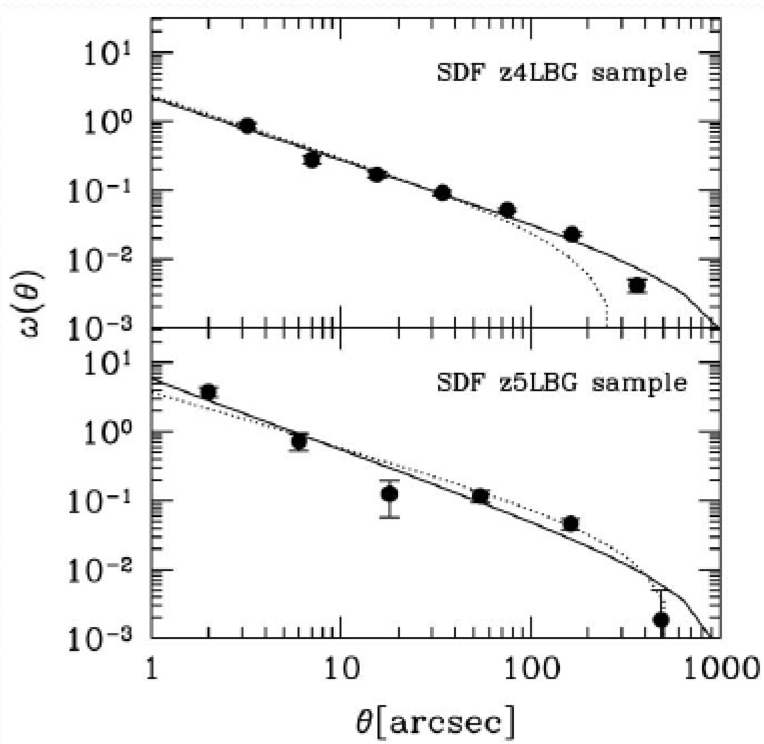
interstellar dust extinction & outflow effect should be incorporated into f_{esc}^{Lya} model

Base of Our Theoretical 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)



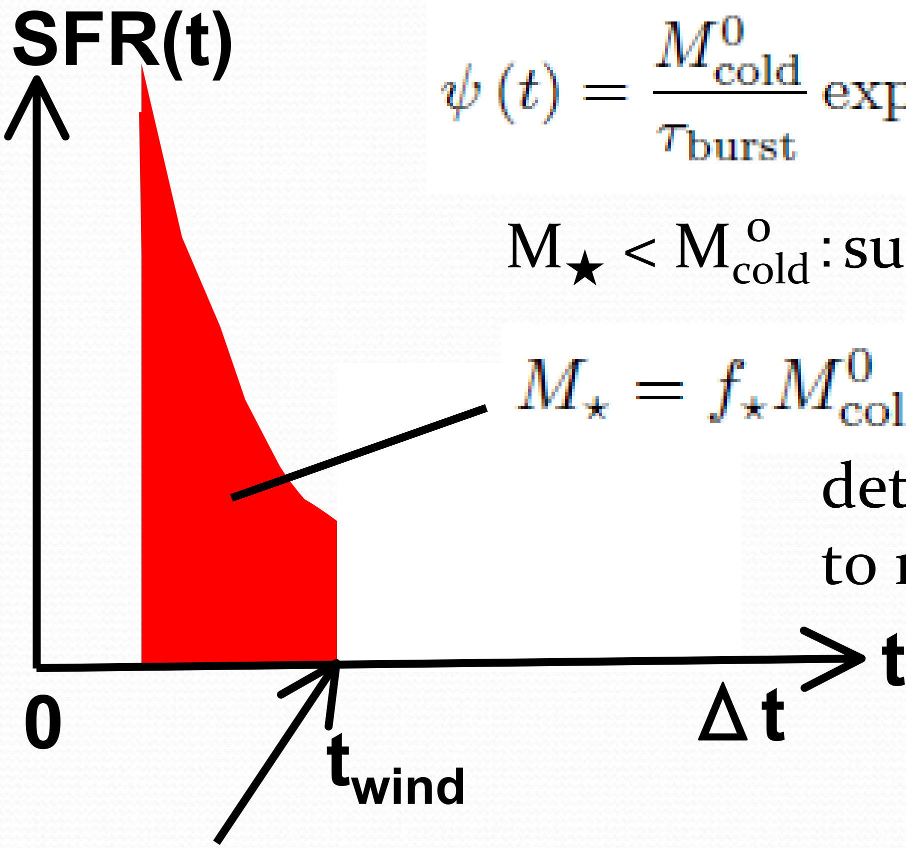
Nagashima+ ’05



Kashikawa+ ’06

Extension of the Mitaka Model for LAE

◆ SFR in starburst galaxies



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

$M_\star < M^0_{\rm cold}$: 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)

How to Calculate L(Lya)

- Lya line luminosity emitted from each galaxy $L_{\rm Lya}^{\rm emit}$

$$L_{\rm Ly\alpha}^{\rm emit} = L_{\rm Ly\alpha}^{\rm max}(1 - f_{\rm esc}^{\rm Lyc}) f_{\rm esc}^{\rm Ly\alpha}$$

escape fraction of Lyman cont.
➔ $f_{\rm esc}^{\rm LyC}$ = 0 (fiducial)

escape fraction of Lya

the maximum possible Lya line luminosity:
$L_{\rm Lya}$ in the case of $f_{\rm esc}^{\rm LyC}$ = 0 & ionization equilibrium (case B)

← determined by using SFR, metallicity, age & SSPs of Schaerer (2003)

- observed Lya line luminosity $L_{\rm Lya}^{\rm obs}$

$$L_{\rm Ly\alpha}^{\rm obs} = L_{\rm Ly\alpha}^{\rm emit} T_{\rm Ly\alpha}^{\rm IGM}$$

IGM transmission to Lya emission
➔ $T_{\rm Lya}^{\rm IGM}$ = 1 (fiducial)

Calculate Lya Line Luminosity

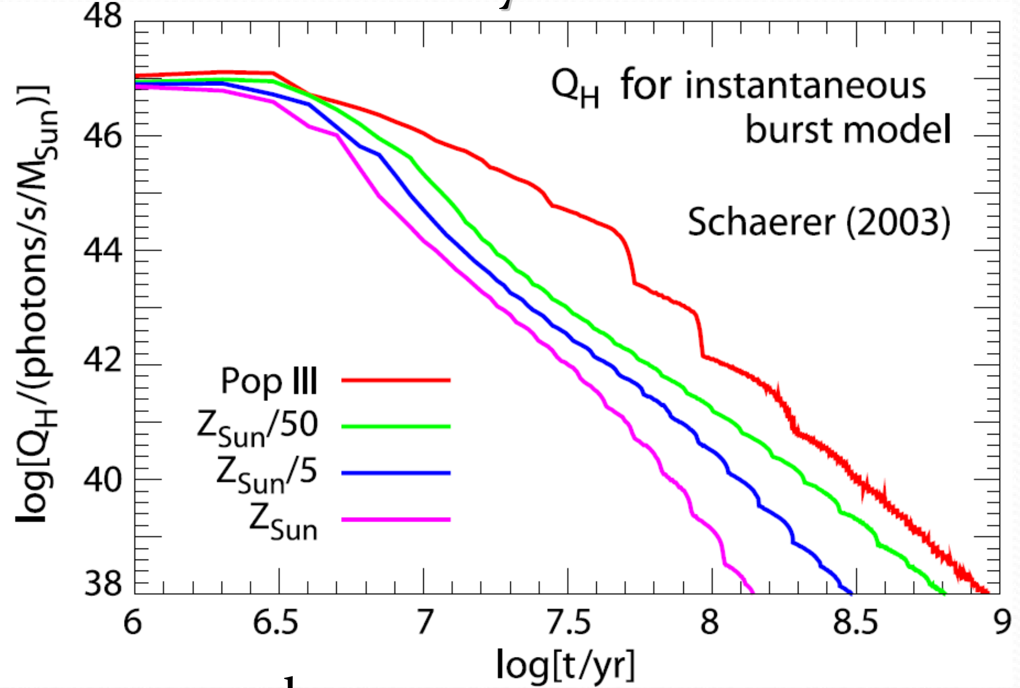
$$L_{\mathrm{Ly}\alpha}^{\mathrm{emit}} = L_{\mathrm{Ly}\alpha}^{\mathrm{max}} f_{\mathrm{esc}}^{\mathrm{Ly}\alpha}$$

escape fraction of Lya photon

- maximally possible Ly α luminosity $L_{\mathrm{Lya}}^{\mathrm{max}}$

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

convolution of SFR with HI ionizing photon emission rate Q_H



- observed Ly α line luminosity $L_{\mathrm{Lya}}^{\mathrm{obs}}$

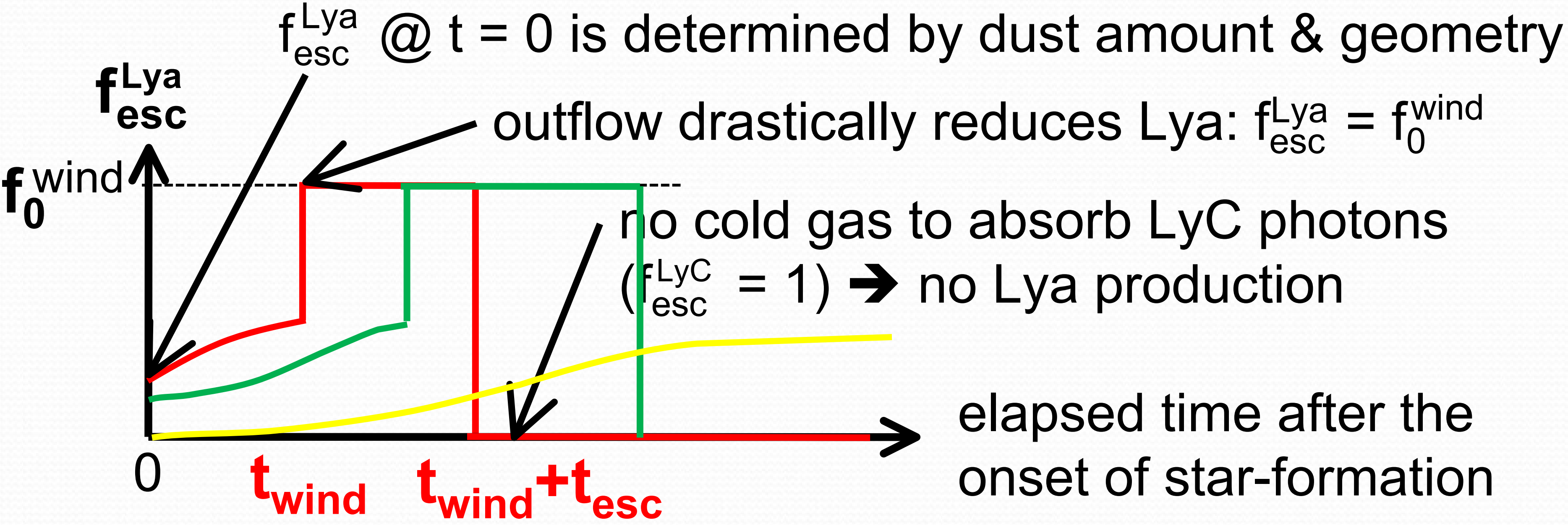
$$L_{\mathrm{Ly}\alpha}^{\mathrm{obs}} = L_{\mathrm{Ly}\alpha}^{\mathrm{emit}} T_{\mathrm{Ly}\alpha}^{\mathrm{IGM}} = L_{\mathrm{Ly}\alpha}^{\mathrm{max}} \left(1 - f_{\mathrm{esc}}^{\mathrm{LyC}}\right) f_{\mathrm{esc}}^{\mathrm{Ly}\alpha} T_{\mathrm{Ly}\alpha}^{\mathrm{IGM}}$$

IGM transmission to Lya emission

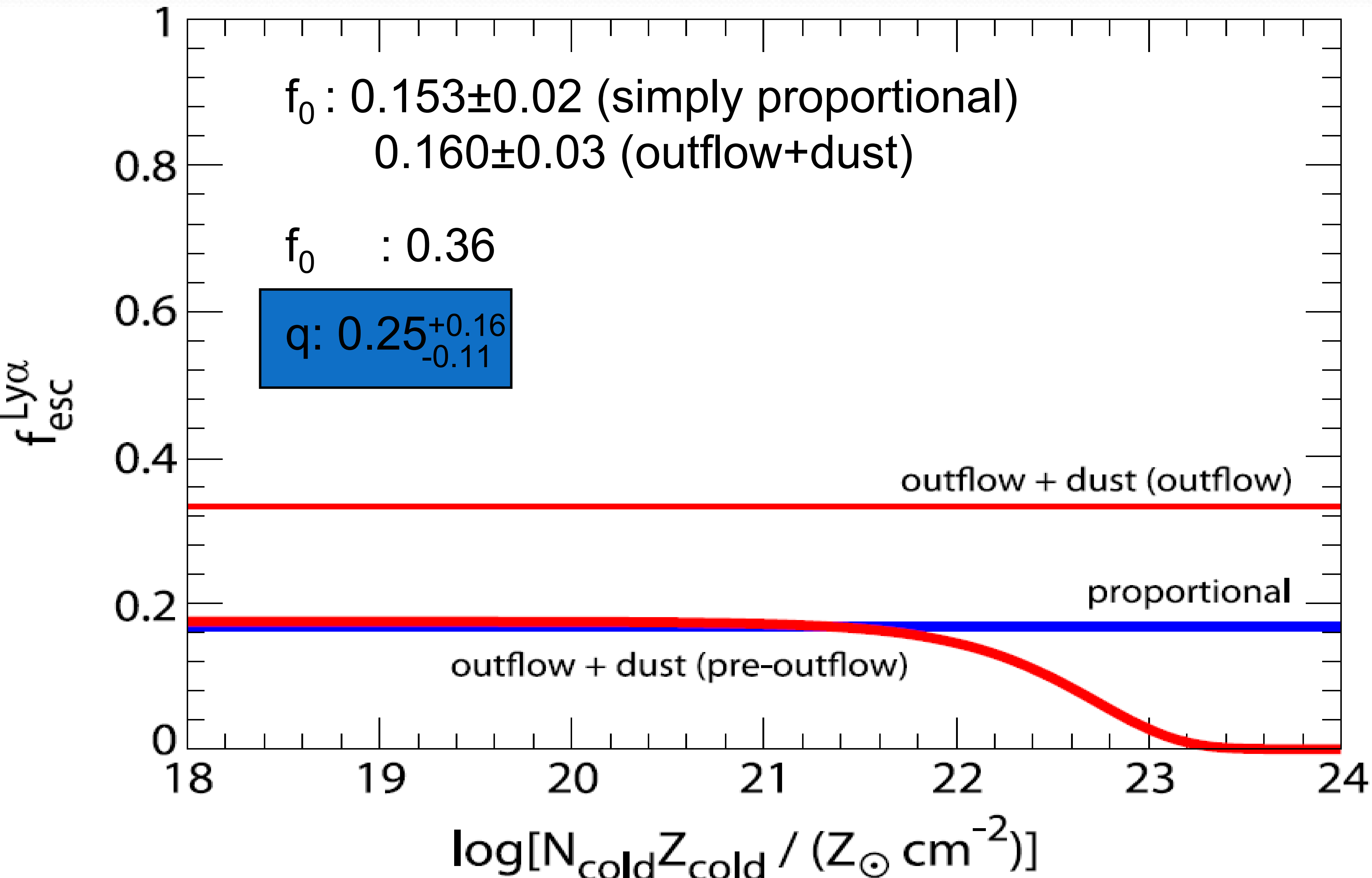
Our Model for f_{esc}^{Lya}

◆ **simply proportional model** (e.g., Le Delliou+ '06):
constant f_{esc}^{Lya} regardless physical properties of each galaxy

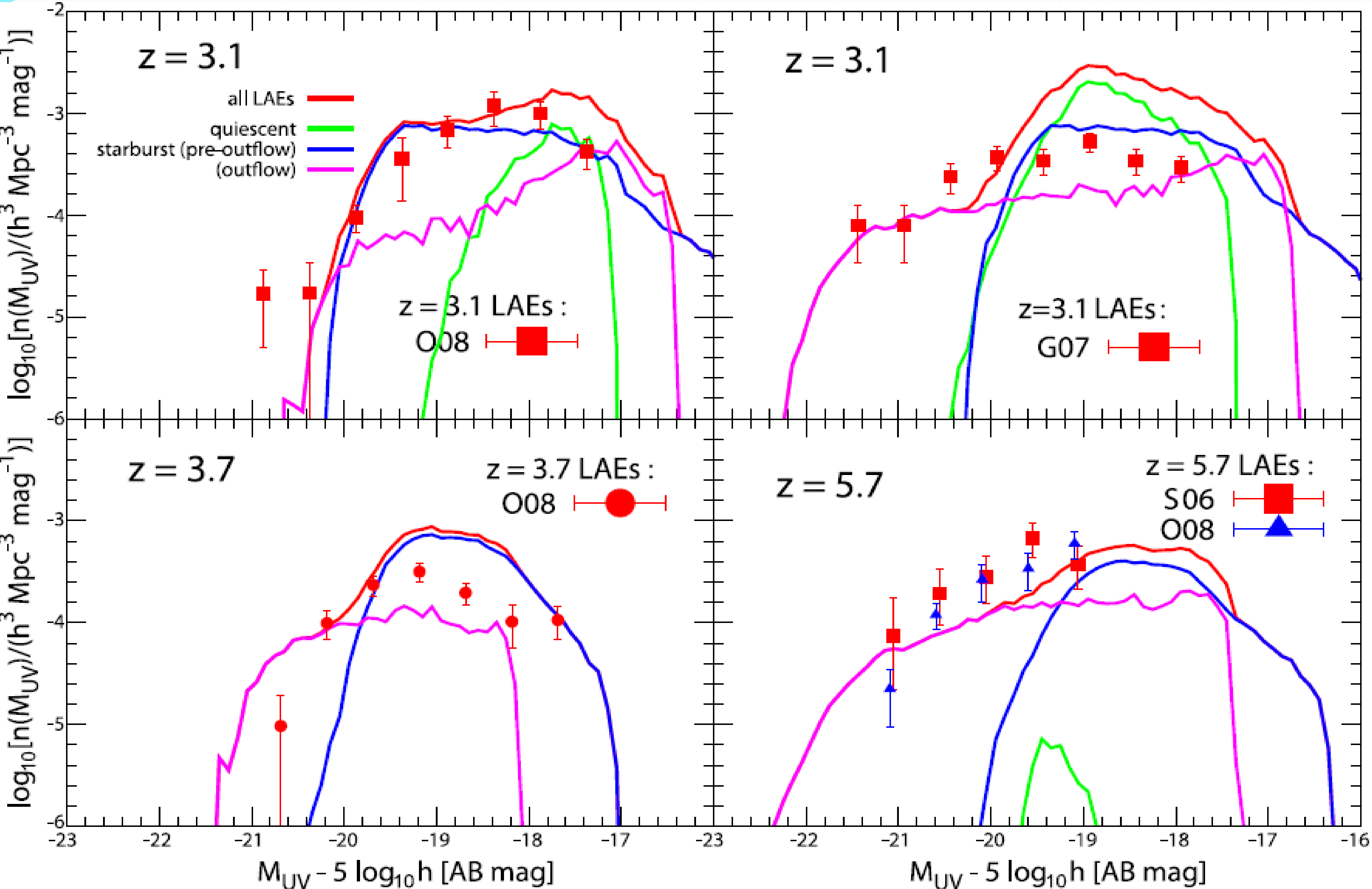
◆ **the outflow + dust model**:
including interstellar dust extinction (next slide)
& galaxy-scale outflow induced as supernova feedback



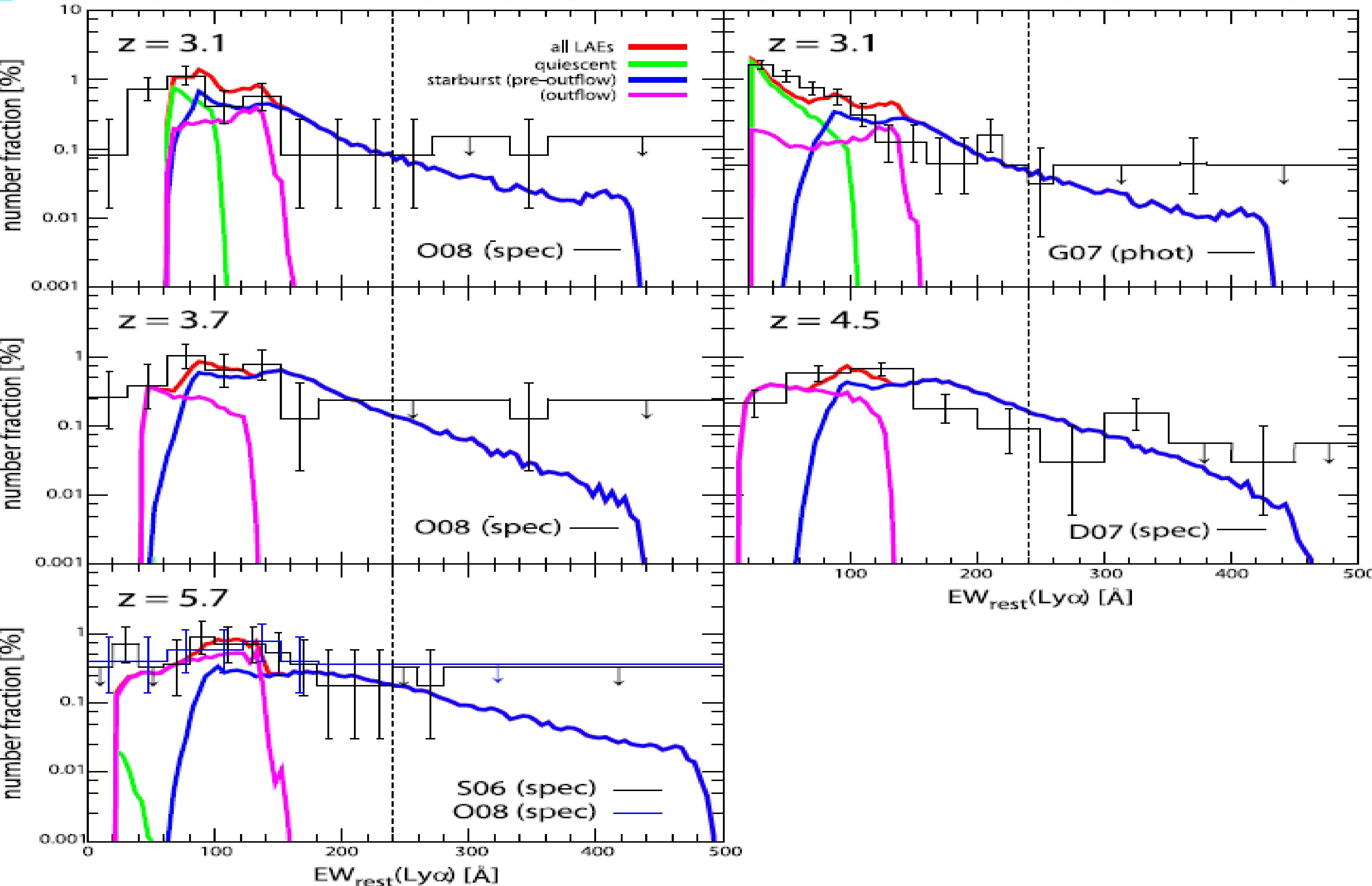
Resultant Lya Escape Fraction



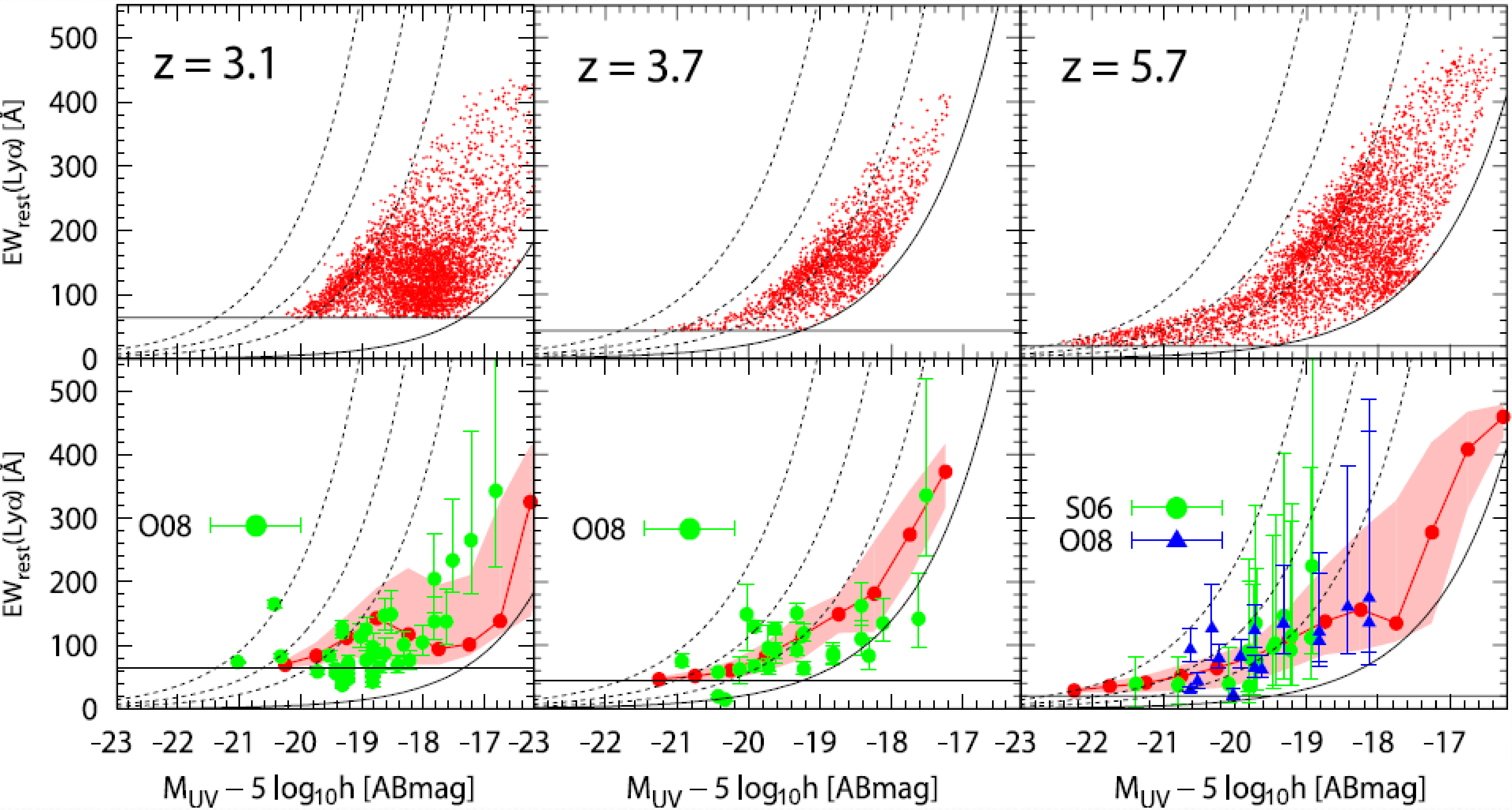
Comparison with LAE UV LF @ z<6



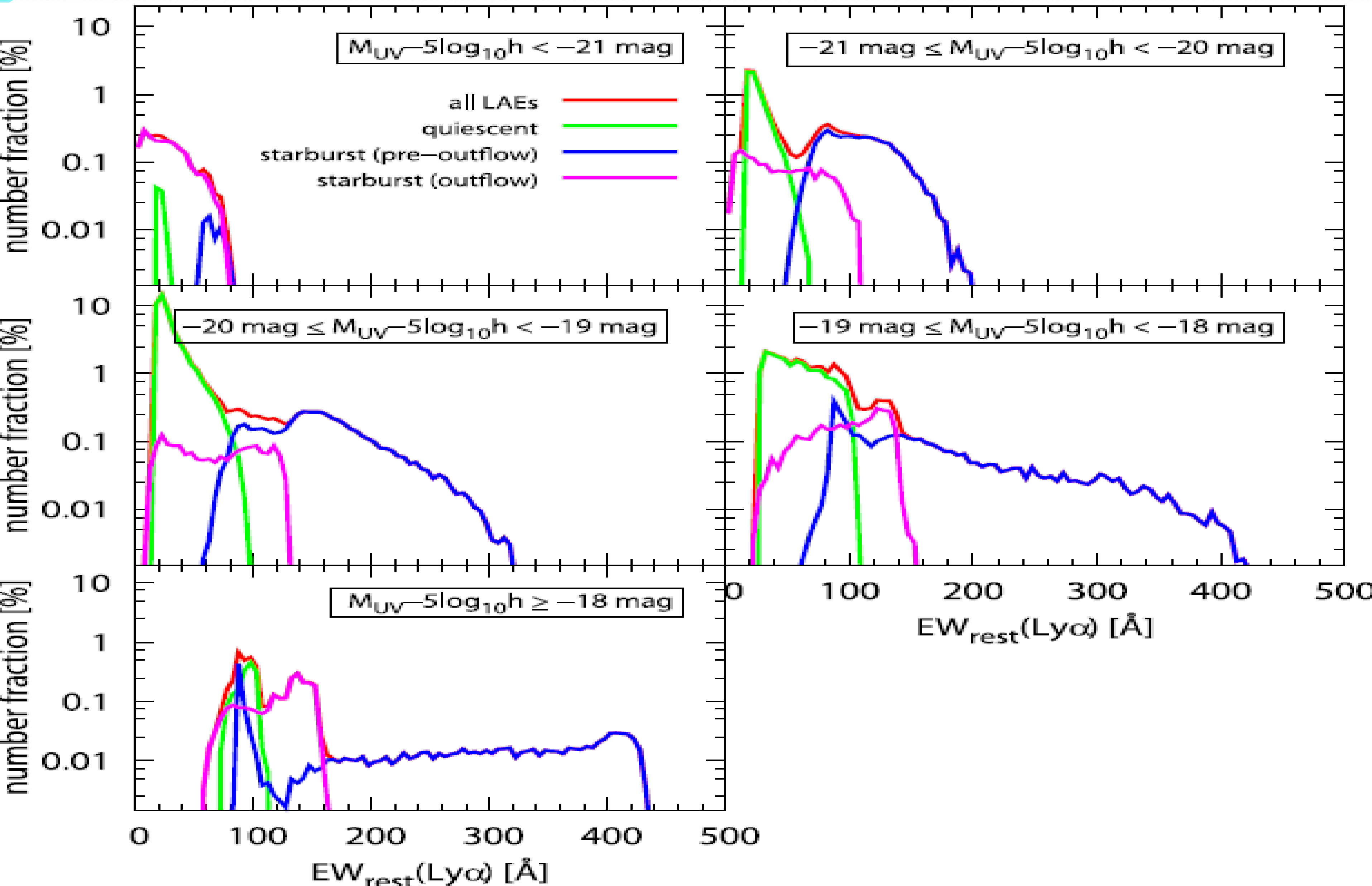
Comparison with LAE EW dist. @ z < 6



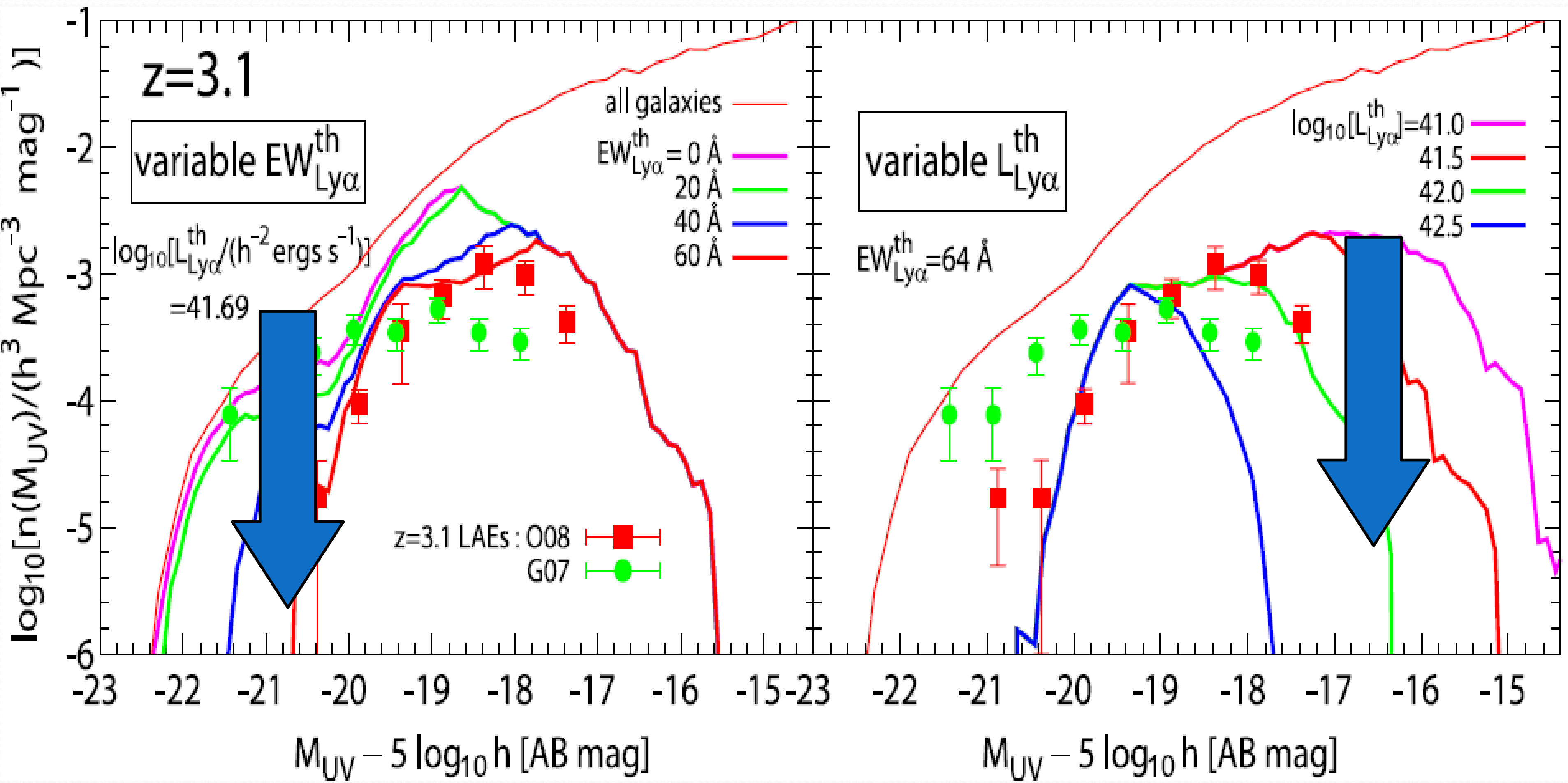
Comparison in M(UV)-EW(Lya) plane @ z < 6



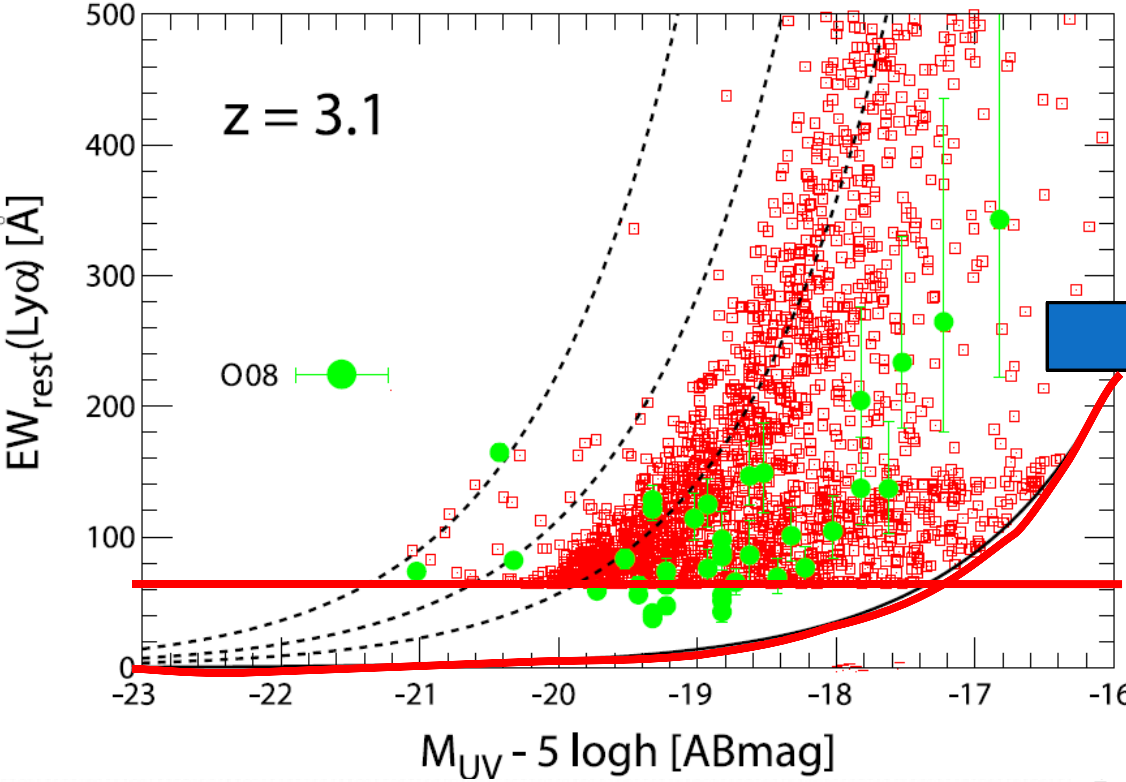
Comparison in M(UV)-EW(Lya) plane @ z < 6



Characteristics in LAE UVLF

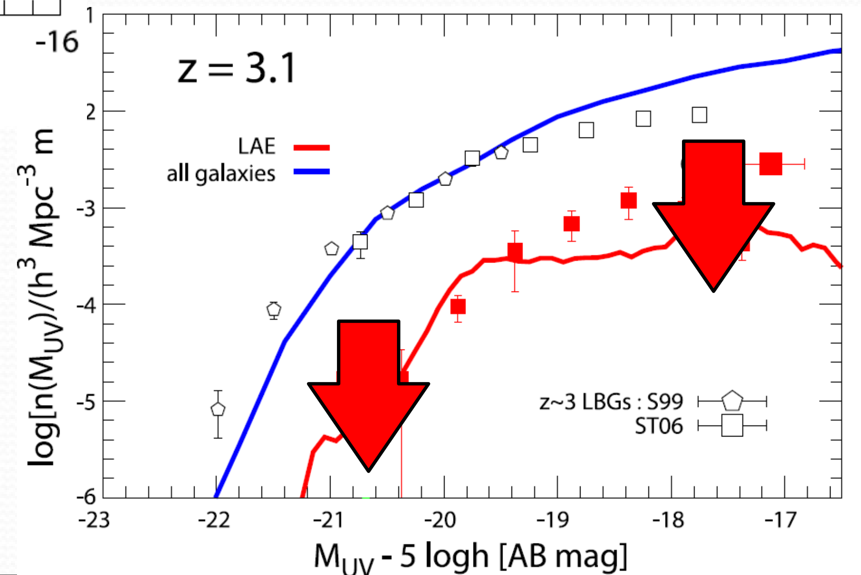


Characteristics in UV LF

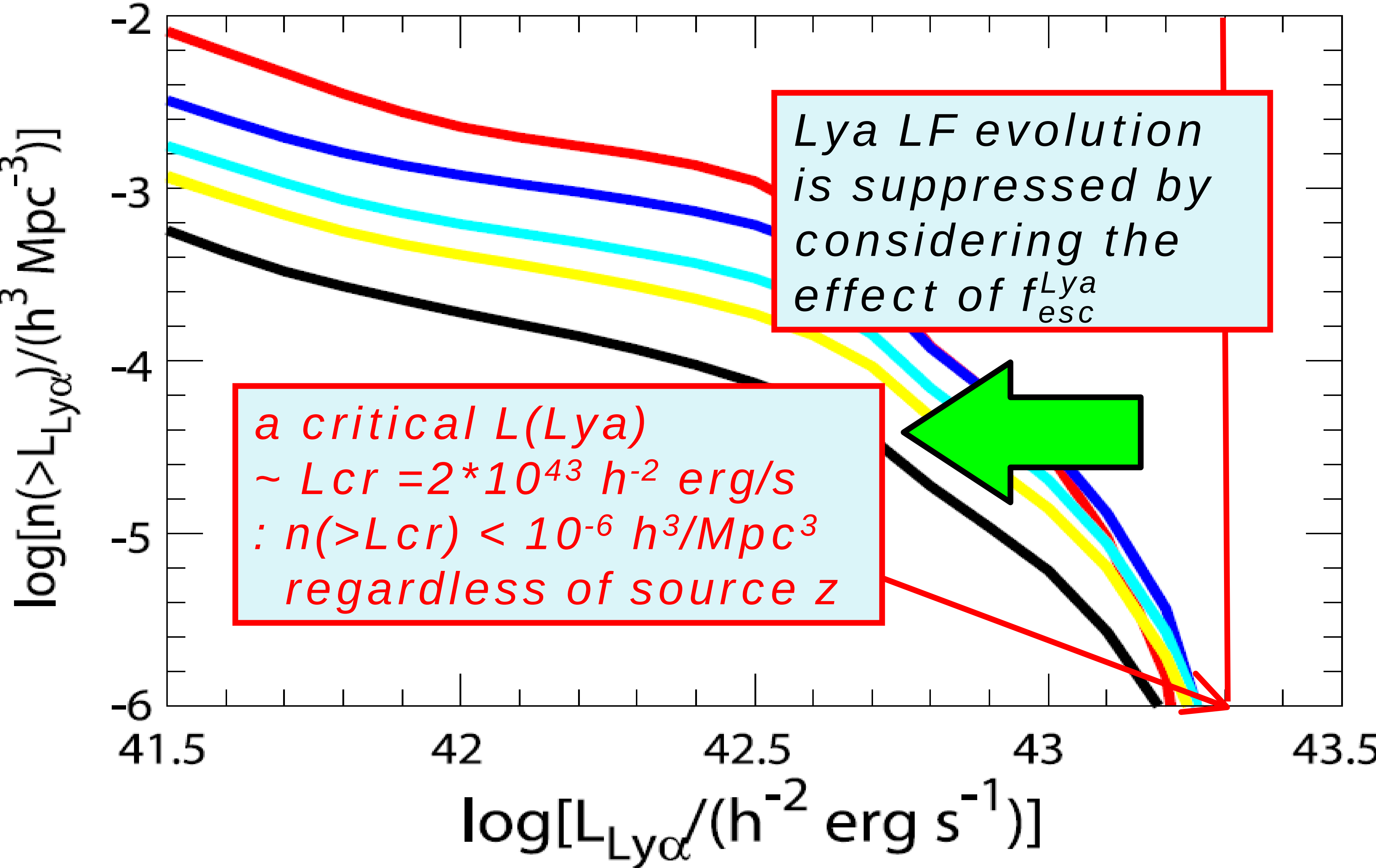


EW(Lya) dist

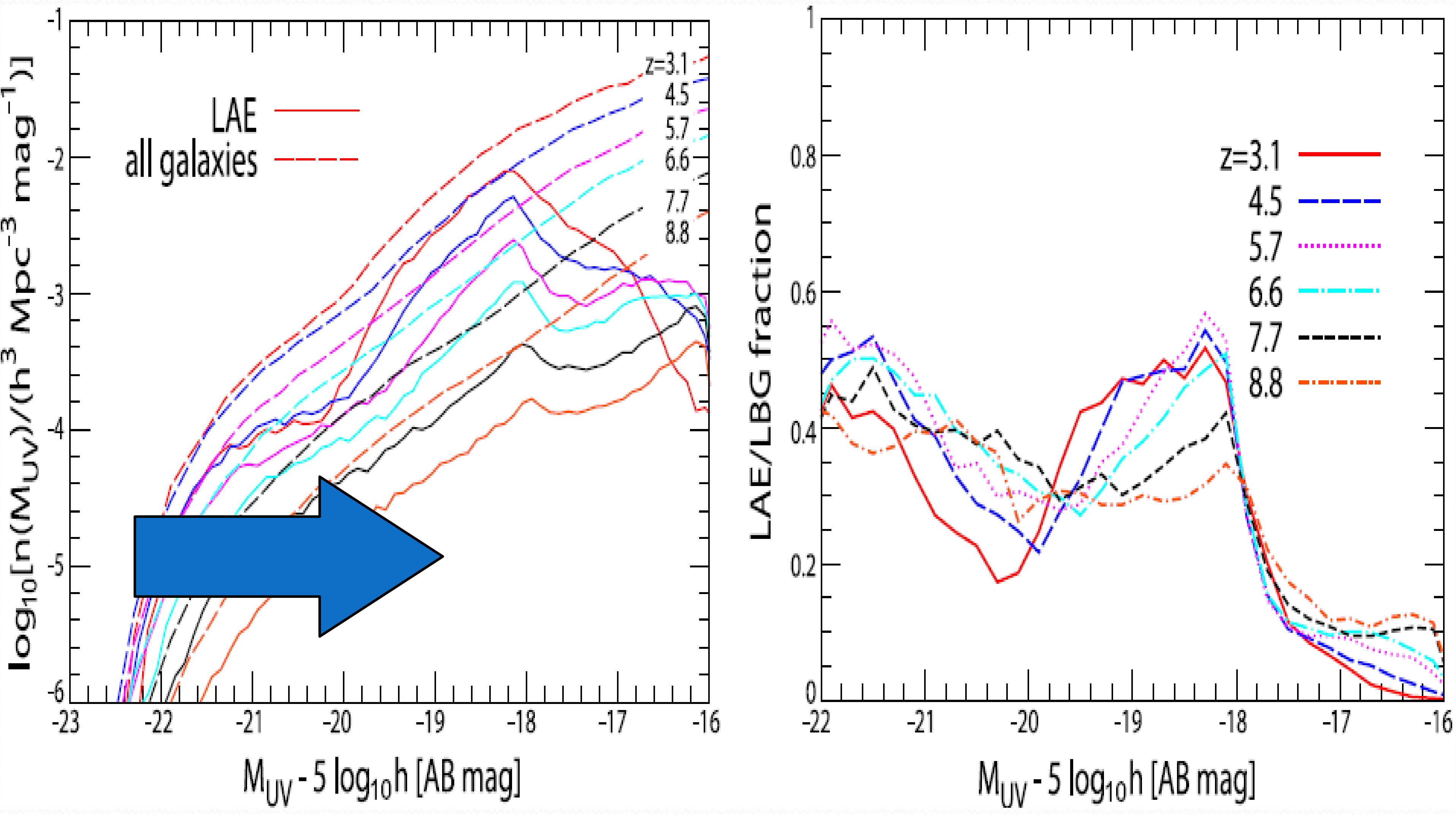
UV LF



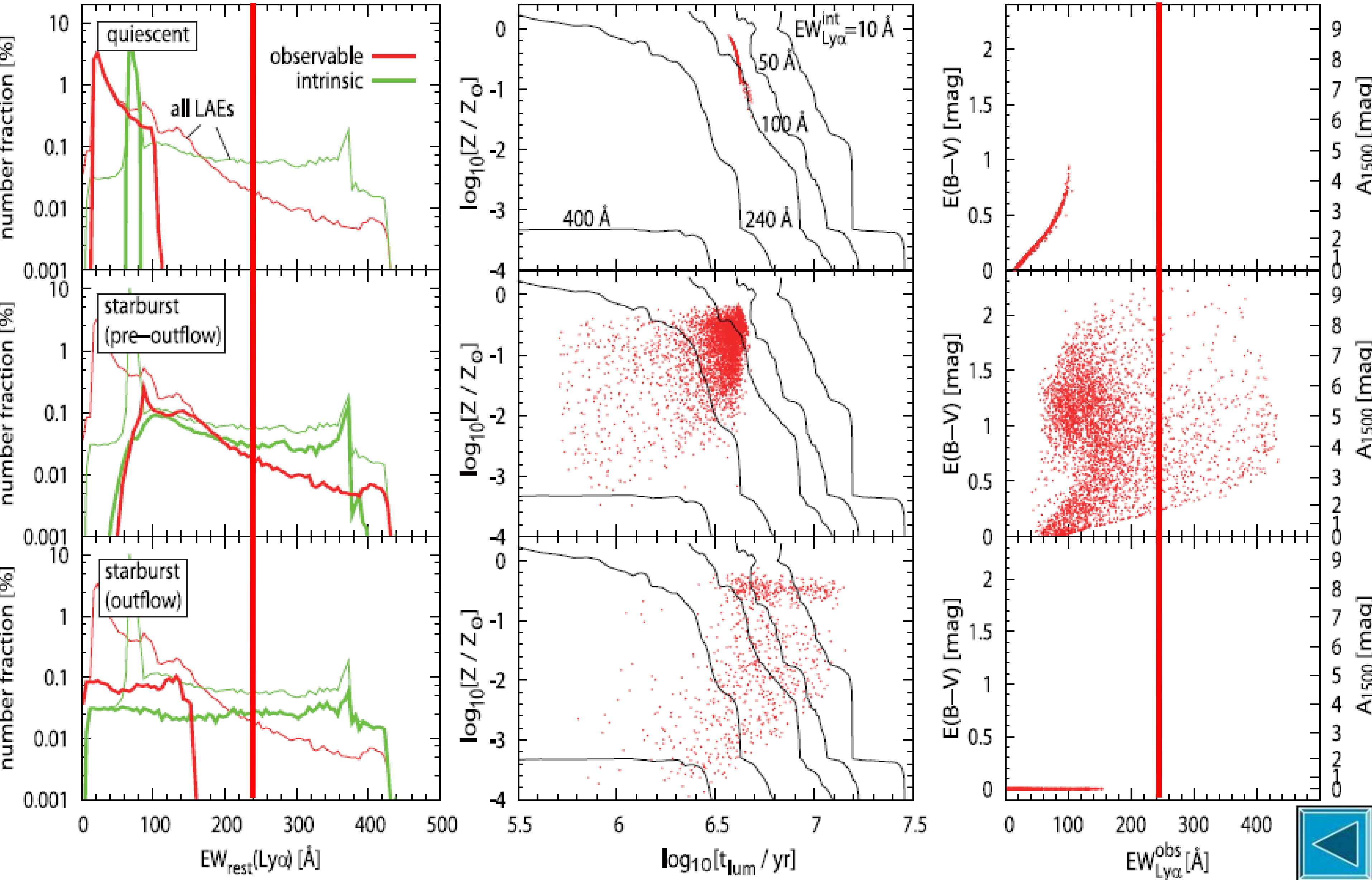
Prediction to Redshift Evolution of Lya LF



Redshift Evolution of LAE UVLF



Nature of LAEs with EW > 240 A



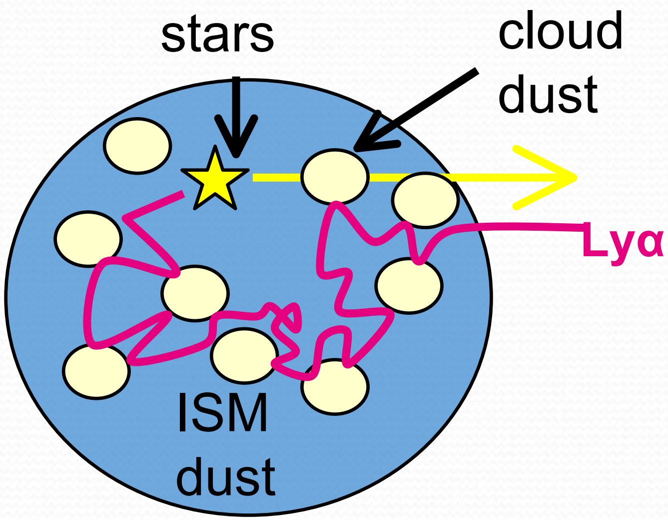
Lyα と UV 連続光の dust opacity

○ $\tau_{Ly\alpha}$:Lyα line に対する dust opacity
　← 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）

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

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



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

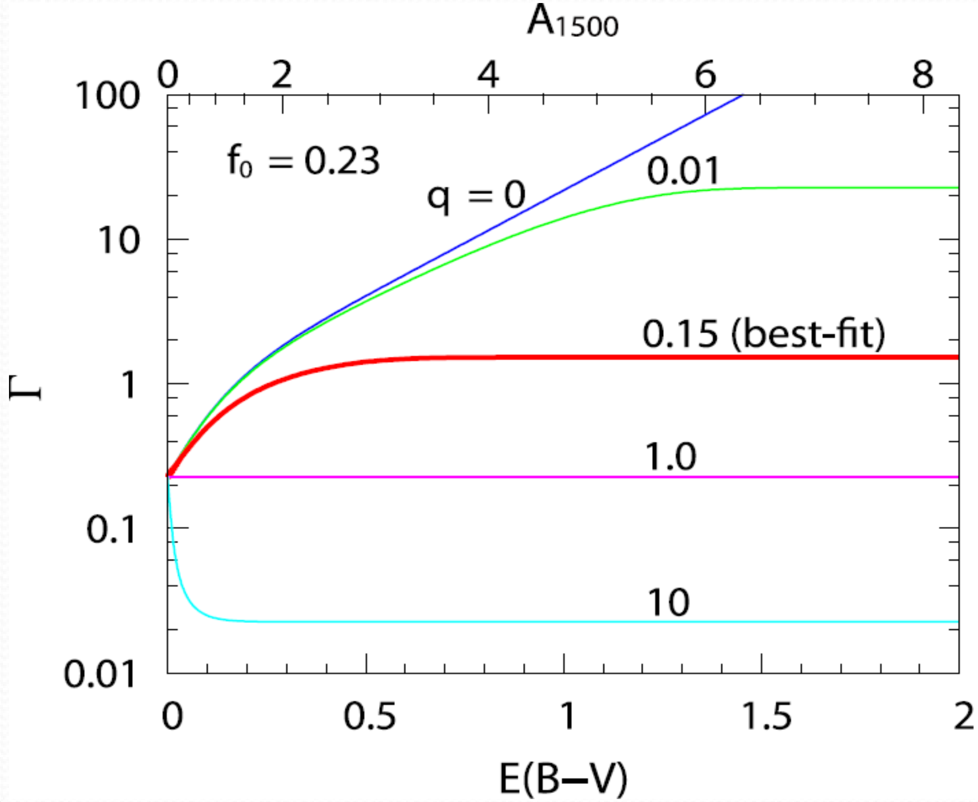
geometry parameter q と EW(Lyα)

○ q＝1 でなければ、dust extinction を受ける前後で EW(Lyα) は変わる: $\mathbf{EW_{dust} / EW_{int} \equiv \Gamma(\tau_c)}$

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

for quiescent and pre-outflow starburst

f_0 / q_{wind} for outflow starburst

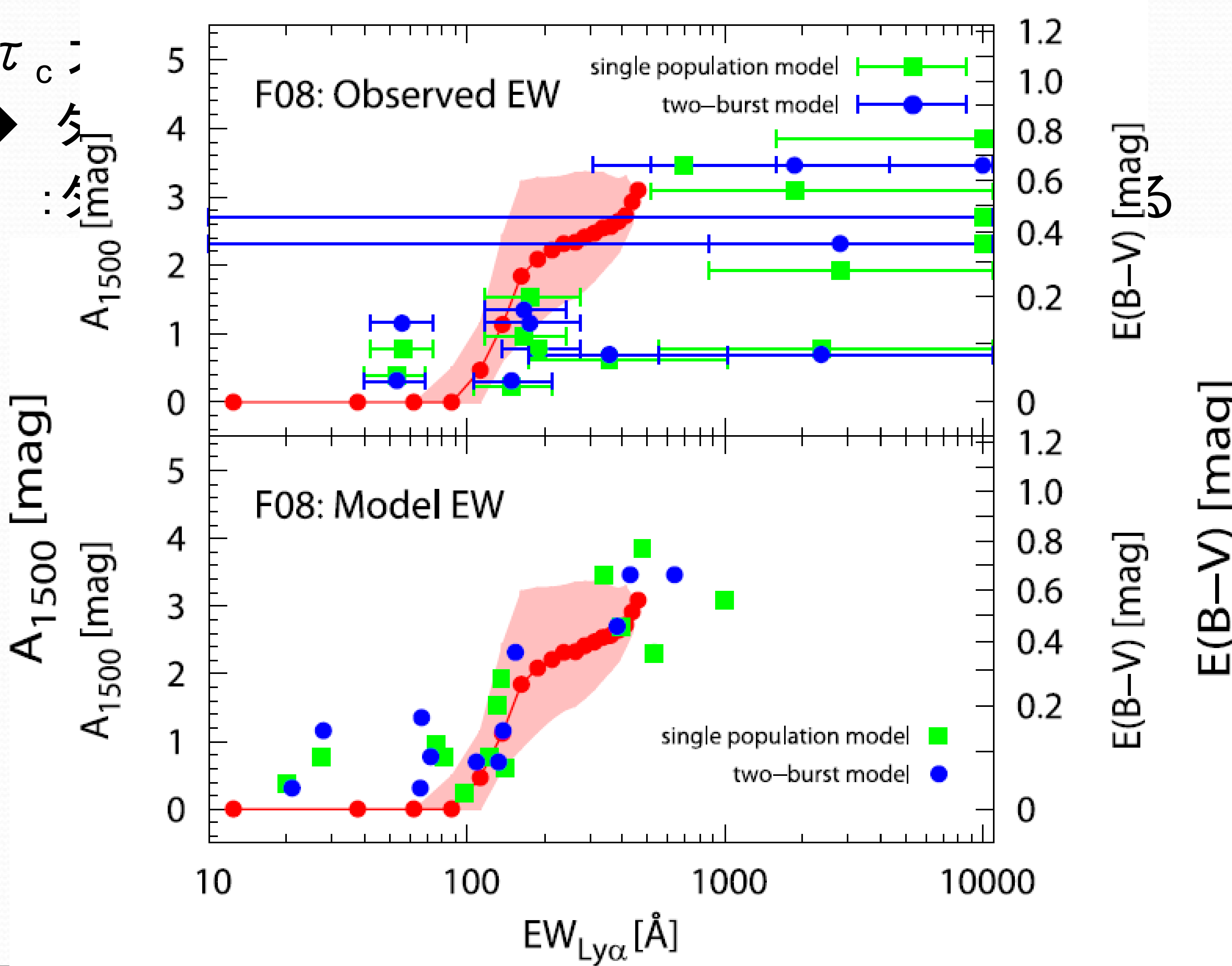


- best-fit : q = 0.15 < 1
  ➔ **clumpy ISM を示唆**

- 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) $\rightarrow \infty$

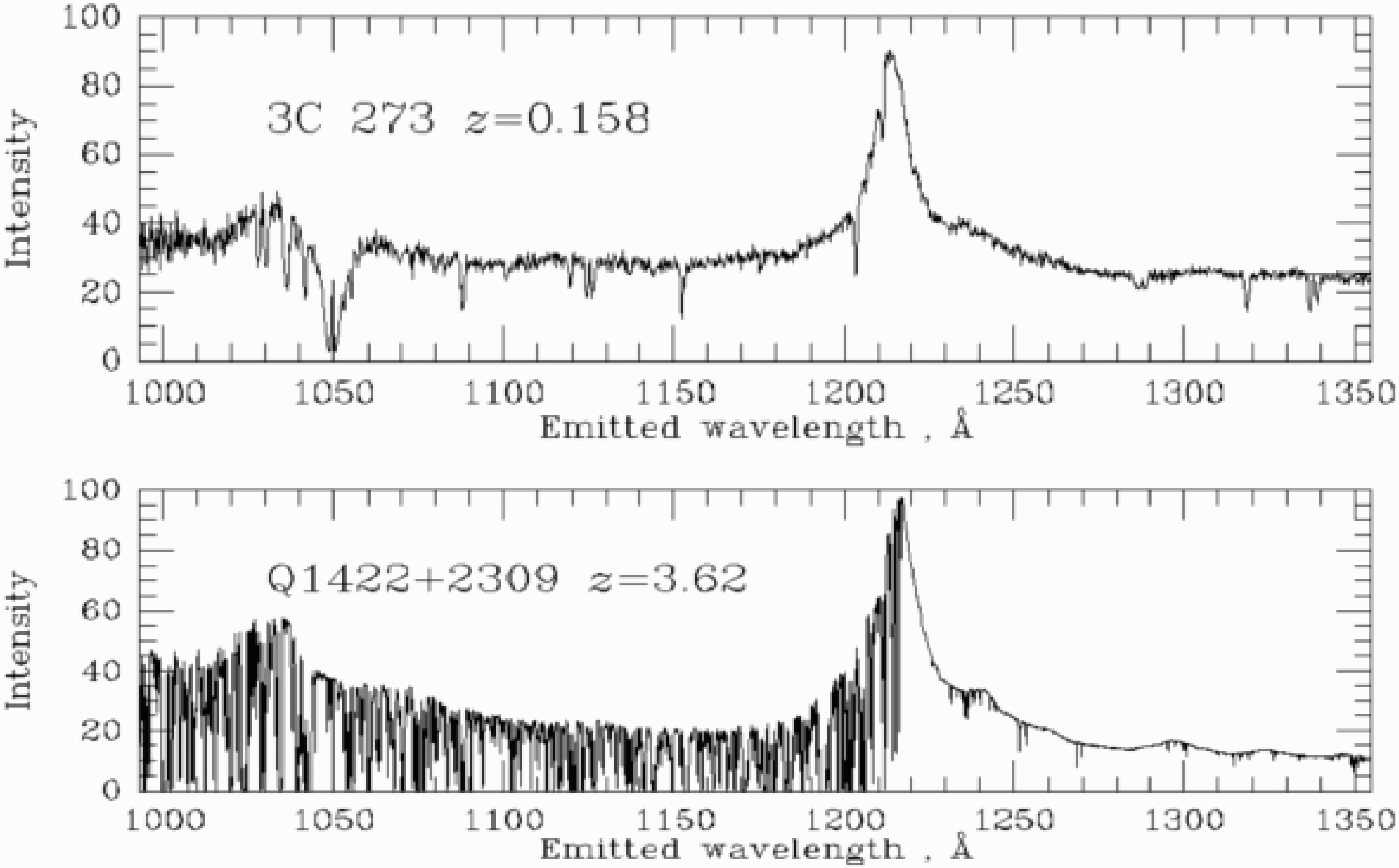
Model Prediction

○ τ_c



Cosmic Reionization

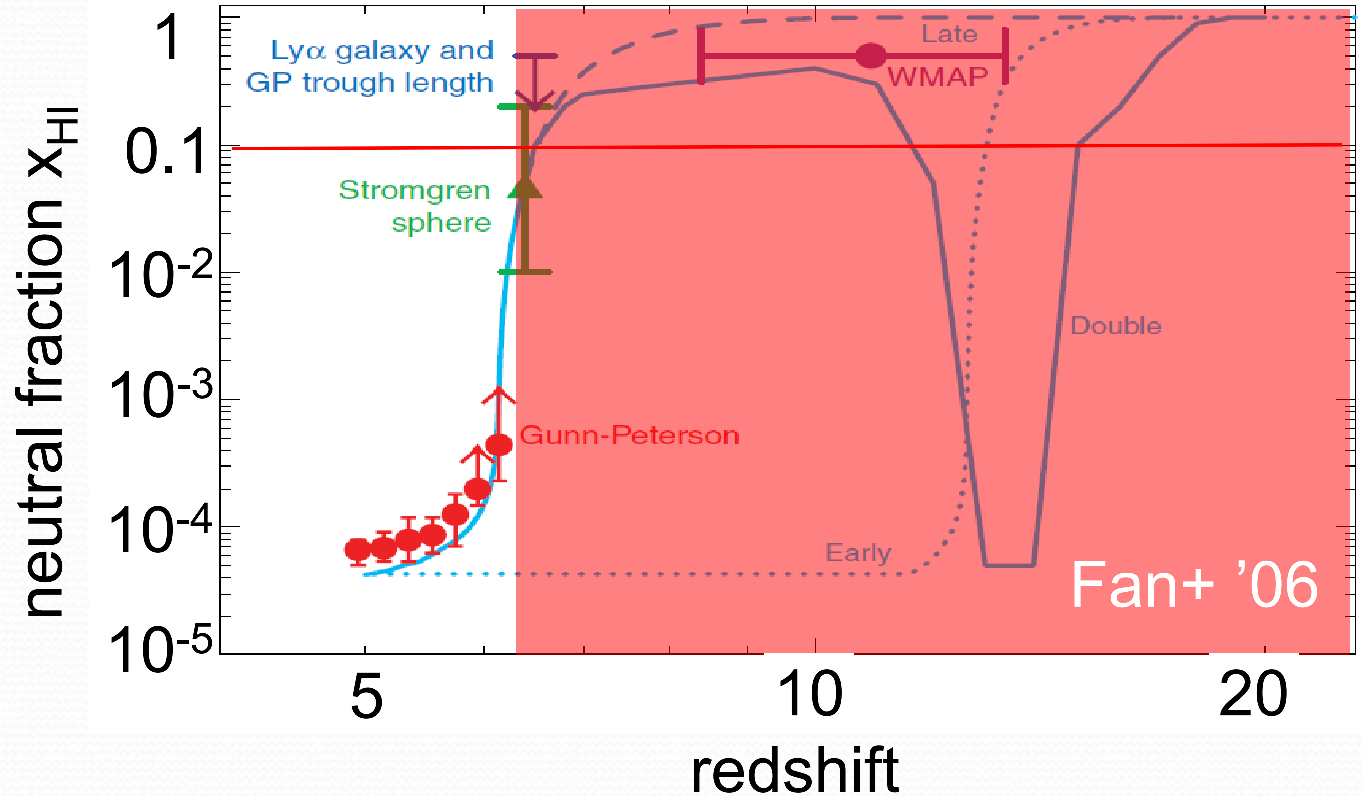
◆ Gunn-Peterson test (Gunn & Peterson 1968)



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

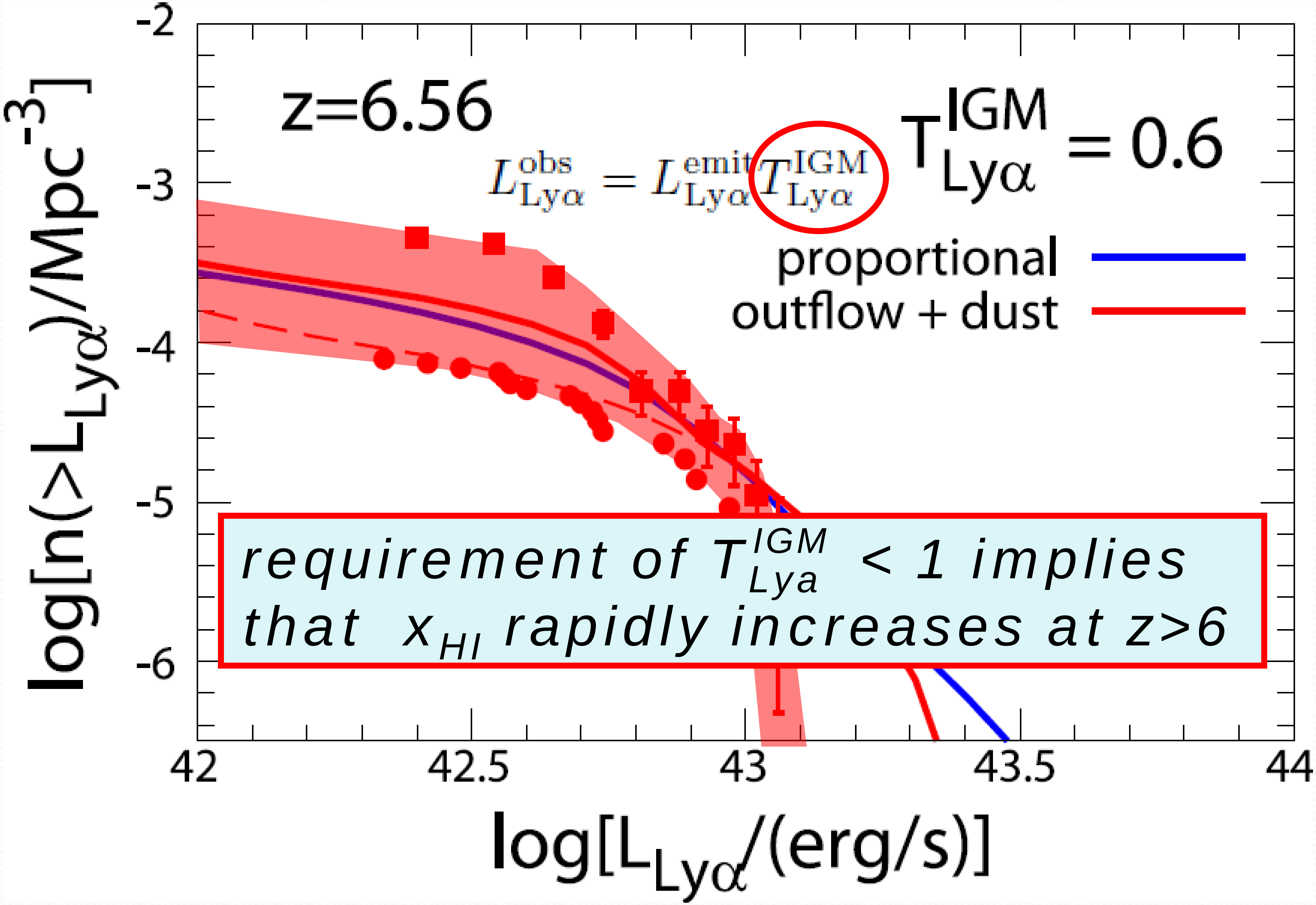
Cosmic Reionization

- Lya emission from LAE is attenuated in IGM where IGM neutral fraction (x_{HI}) > 0.1 (Santos '04)



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

Comparison with Lya LF: z > 6



requirement of $T_{Lya}^{IGM} < 1$ implies that x_{HI} rapidly increases at z>6

LAE Statistical Quantities @ z > 6