Lyα輝線銀河から探る宇宙再電離と初代天体

柏川伸成
(国立天文台)

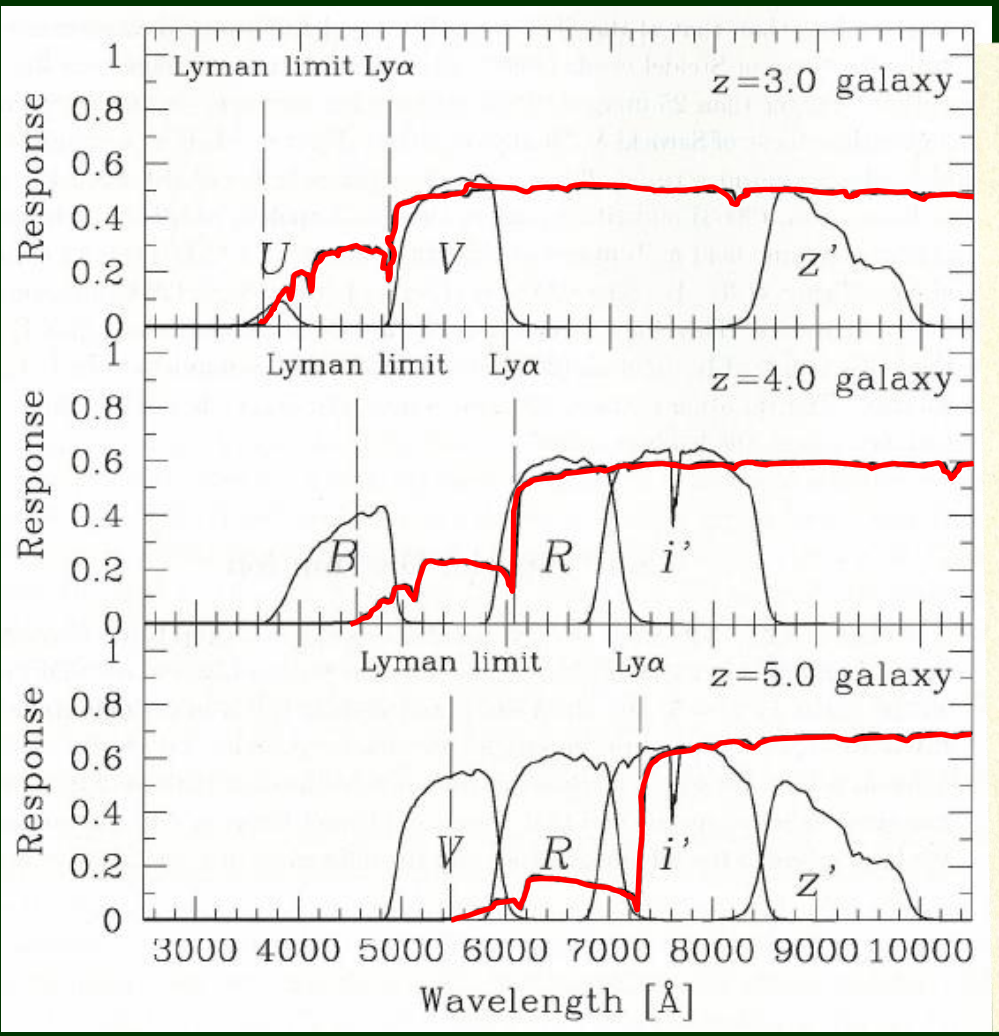
High-z universe

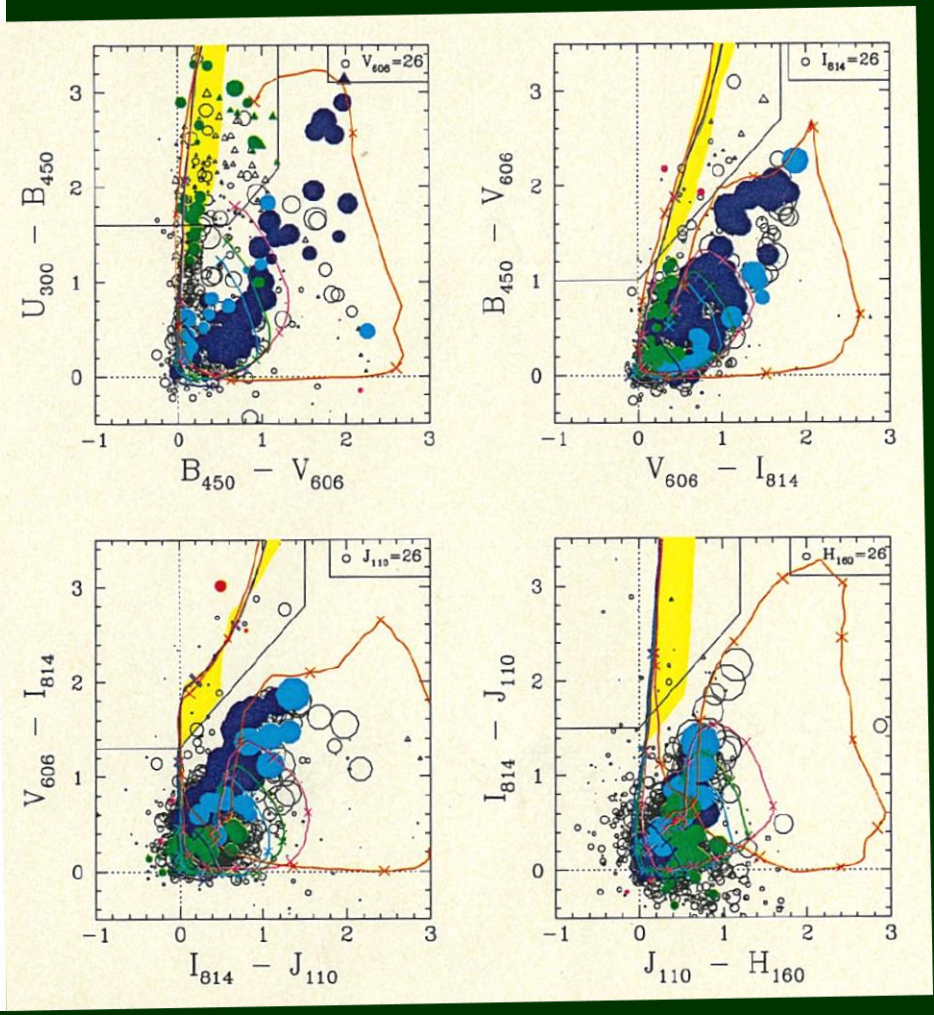
The study of the highest-z (z>6) galaxies probes:

- **The epoch of first generation of galaxies**
  - Early star formation history
  - Initial structure formation
- **History of cosmic reionization**
  - **When** did the reionization take place ?
  - **What** ionized the universe ?
  - **How** was the reionization process ?
  - Complement to QSO / WMAP / GRB / 21cm…

Lyman Break Galaxy(LBG)

- Lyman breakをはさむようにフィルターを選択すれば、z=3,4,5,6…のLBGを2色図上で検出することができる。



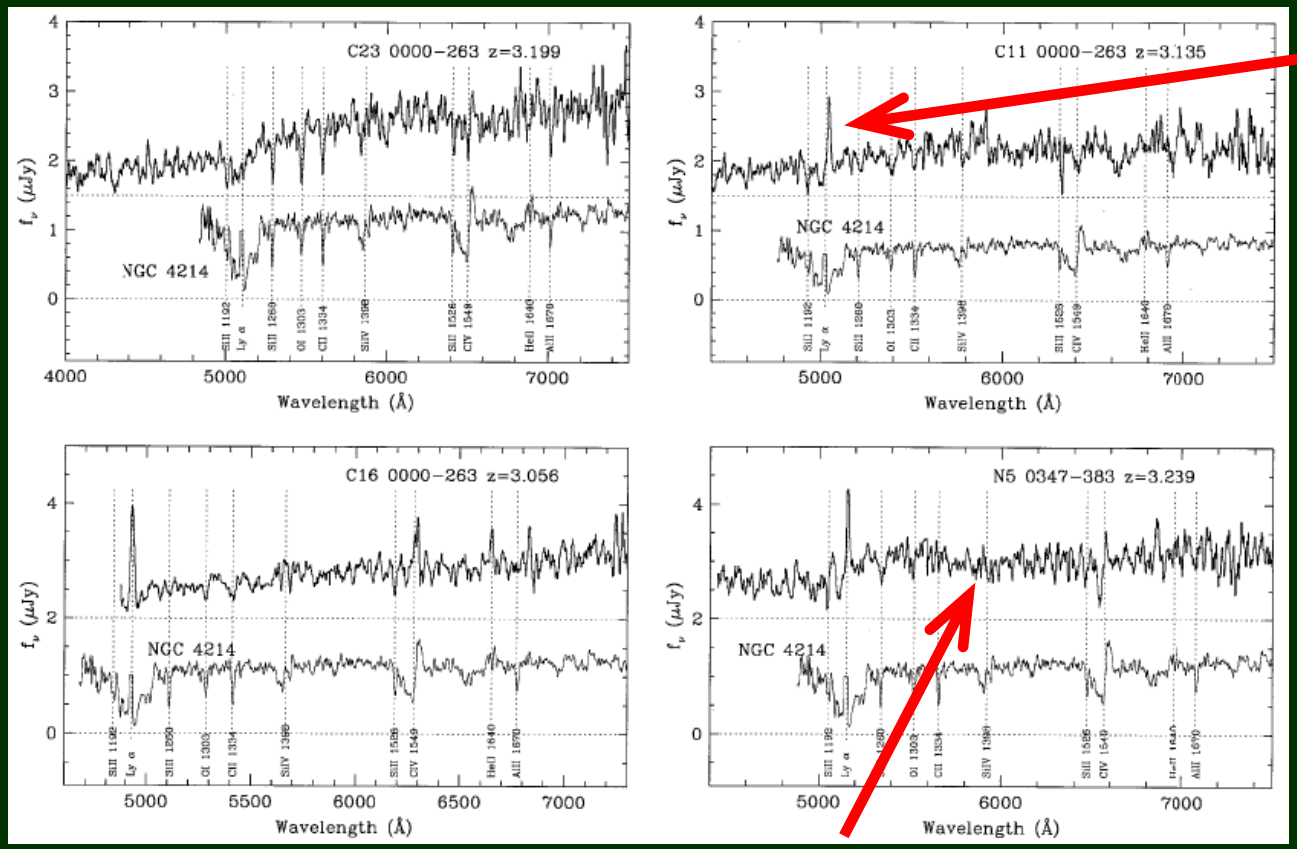


Yoshida+ 07

Dickinson+ 03

Spectroscopic confirmations of LBGs

- 実際分光してみると確かにz>3の銀河
- すべてm_R~25と非常に暗い→10m望遠鏡でなければ分光できない。
- LBGの発見→10m望遠鏡の金字塔的観測の1つ。



いくつかのものについては強い
Lyman α輝線

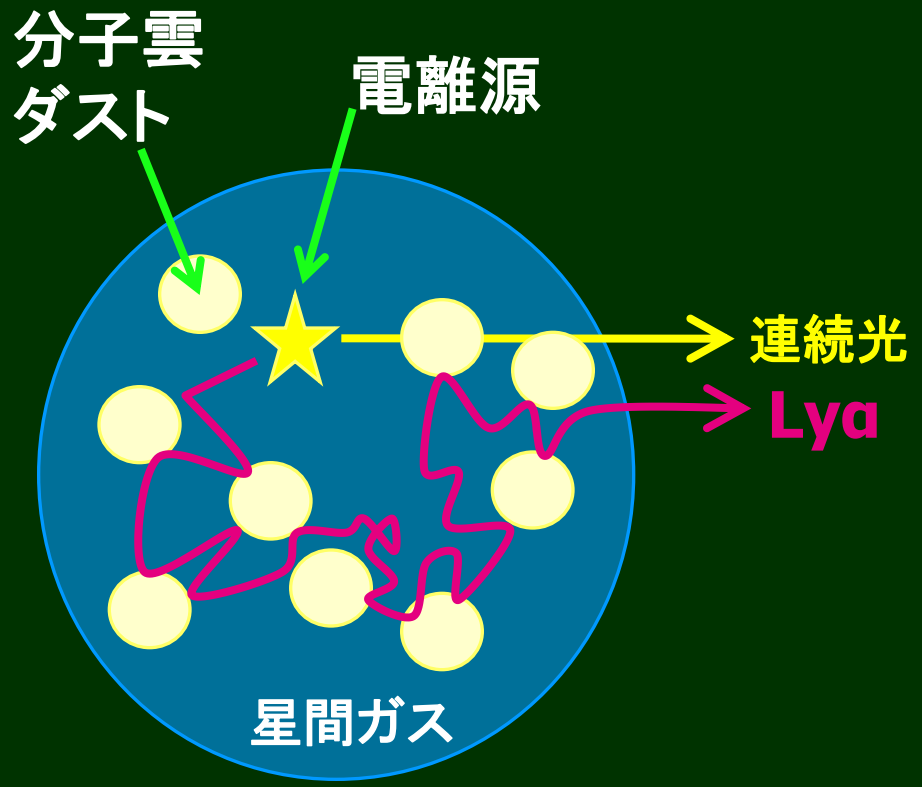
Lyman α emitter (LAE)

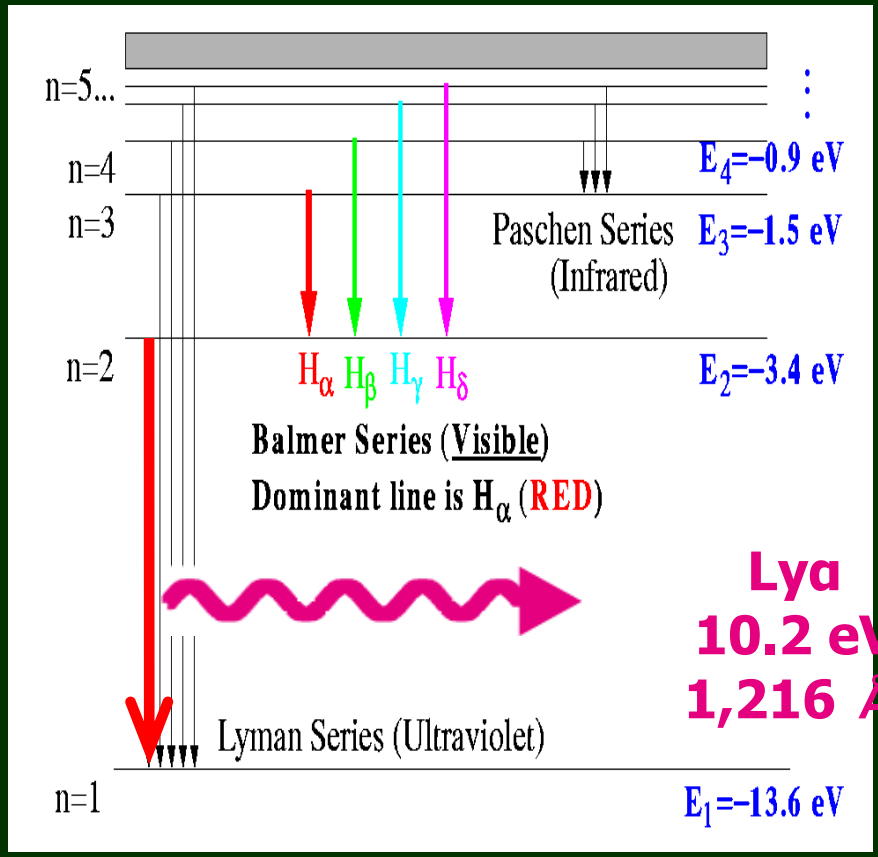
Steidel+ 96 APJ 462, L17

rest-紫外域にある多くの星間ガス吸収線

Lyman alpha emission

- ライマンα線：水素のn=1(基底準位) とn=2の間の遷移に伴う共鳴線（resonance line）
- 銀河内部の中性水素・ダストに吸収・散乱されやすい（実際は複雑）。
- ダストをまだ大量に持たない若い銀河からの光。





LBG/LAEの違いについて

- Stellar mass
  LBG: > $10^{10}M_{\odot}$ (Shapley+ 01),
  LAE: 5 x $10^{8}M_{\odot}$ (z=3.1 Gawiser+ 06), a few x $10^{8}M_{\odot}$ (z=4.1: Overzier+ 06), 5-10 x $10^{8}M_{\odot}$ (z=7: Egami+ 05)
- Age
  LBG: > 10^{9}yr (Shapley+ 01)
  LAE: ～10^{8}yr (Gawiser+ 06)
- Av
  LBG: <1
  LAE: <0.1 (but see Finkelstein+ 07)

  ⇒ LBGに比べてLAEは星も**ダスト**も少なくて若い。

- Dark halo mass
  LBG: $10^{11\text{-}12}M_{\odot}$ (NK+ 06, Ouchi+ 04)
  LAE: $10^{11\text{-}12}M_{\odot}$??? (Hamana+ 05), ただし不定性大きい。

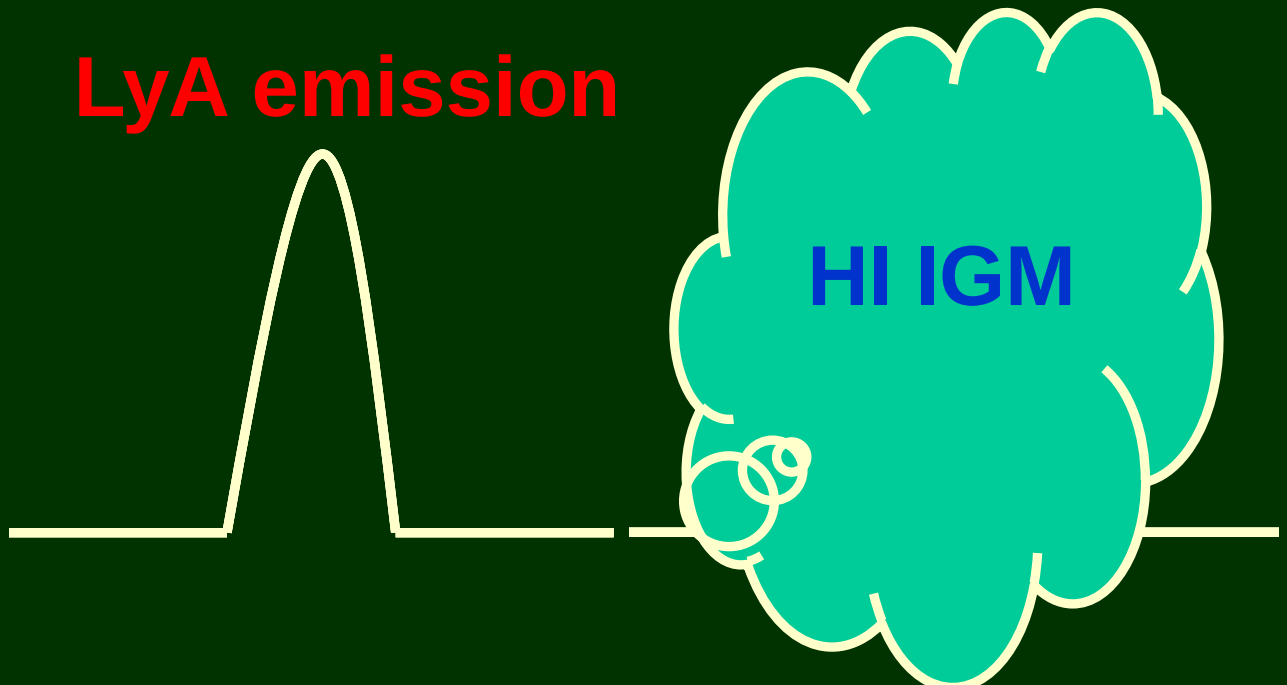
40 years ago…

Partridge & Peebles (1966) "Are young galaxies visible?"

"…most of the radiation from young galaxies would arrive at wavelengths of 1-3μ where detection is difficult. However, it seems possible that the Lyman-α line might be detected if it is a strong feature of the spectra of young galaxies."

Reionization proved by LAEs

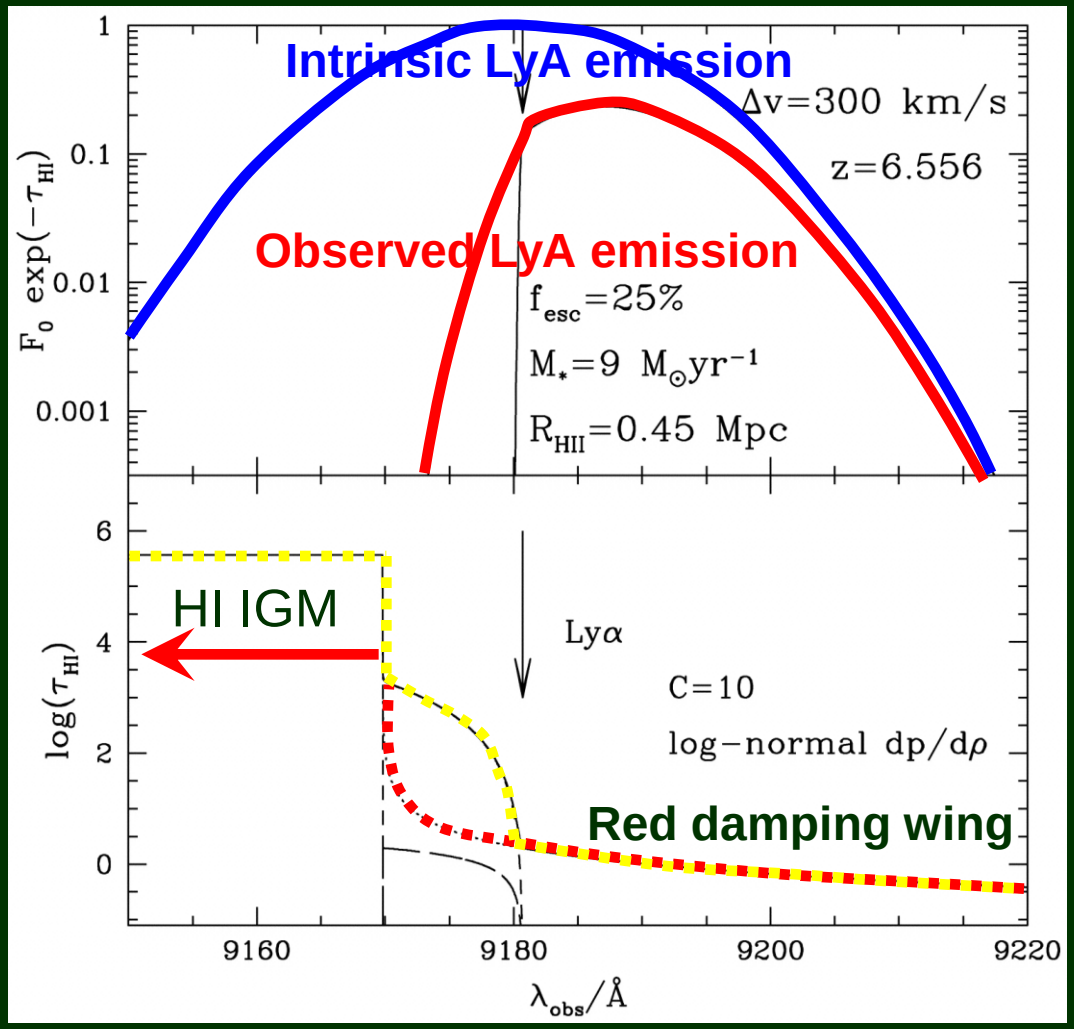
- Lyman α emitters (LAEs)
  - High-z star-forming galaxies, and would dominant at the faint end of LF of ionizing sources in reionization era
  - Easy to detect w/ narrow-band filter
  - Neutral IGM would change its line property



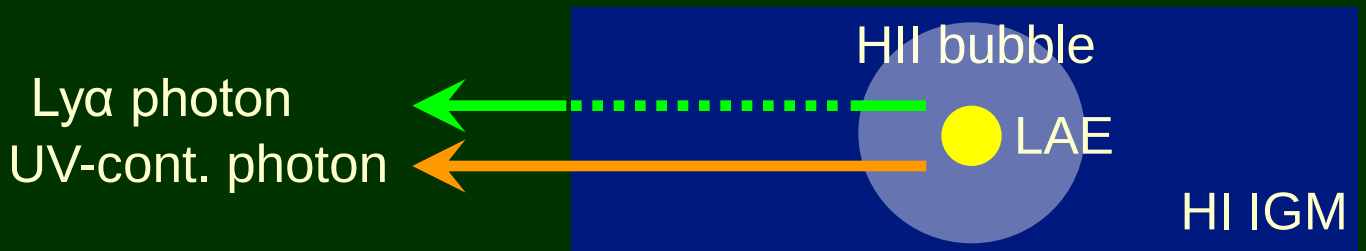
Reionization proved by LAEs

Lyα emission line profile

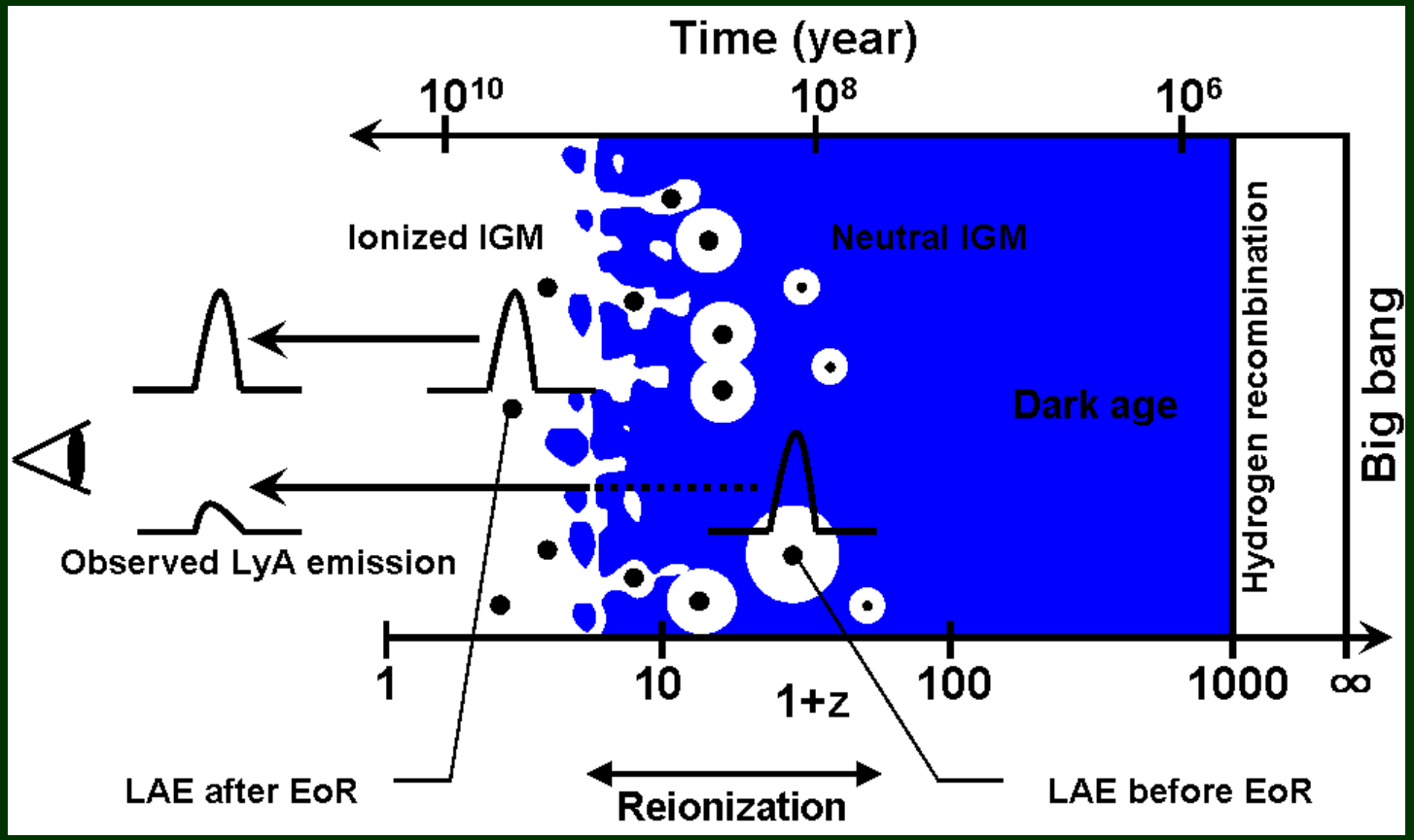
Optical depth distribution



Haiman+ 02



Reionization proved by LAEs

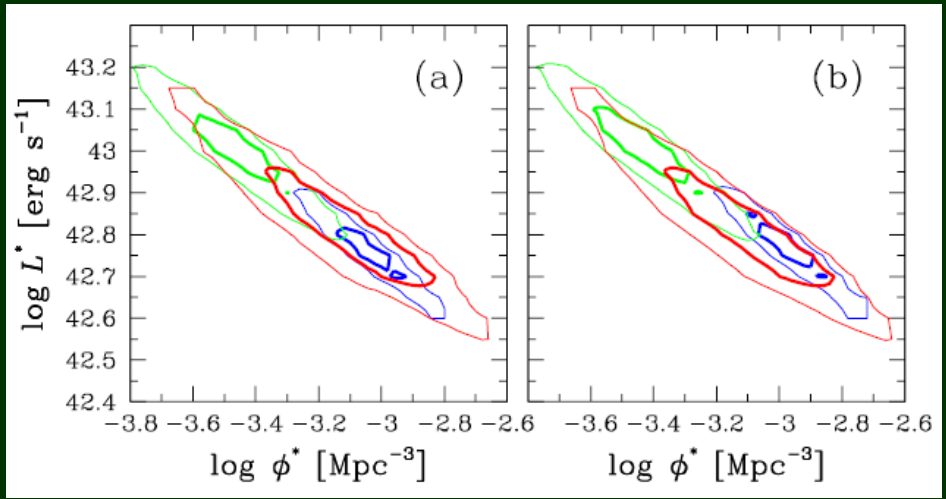


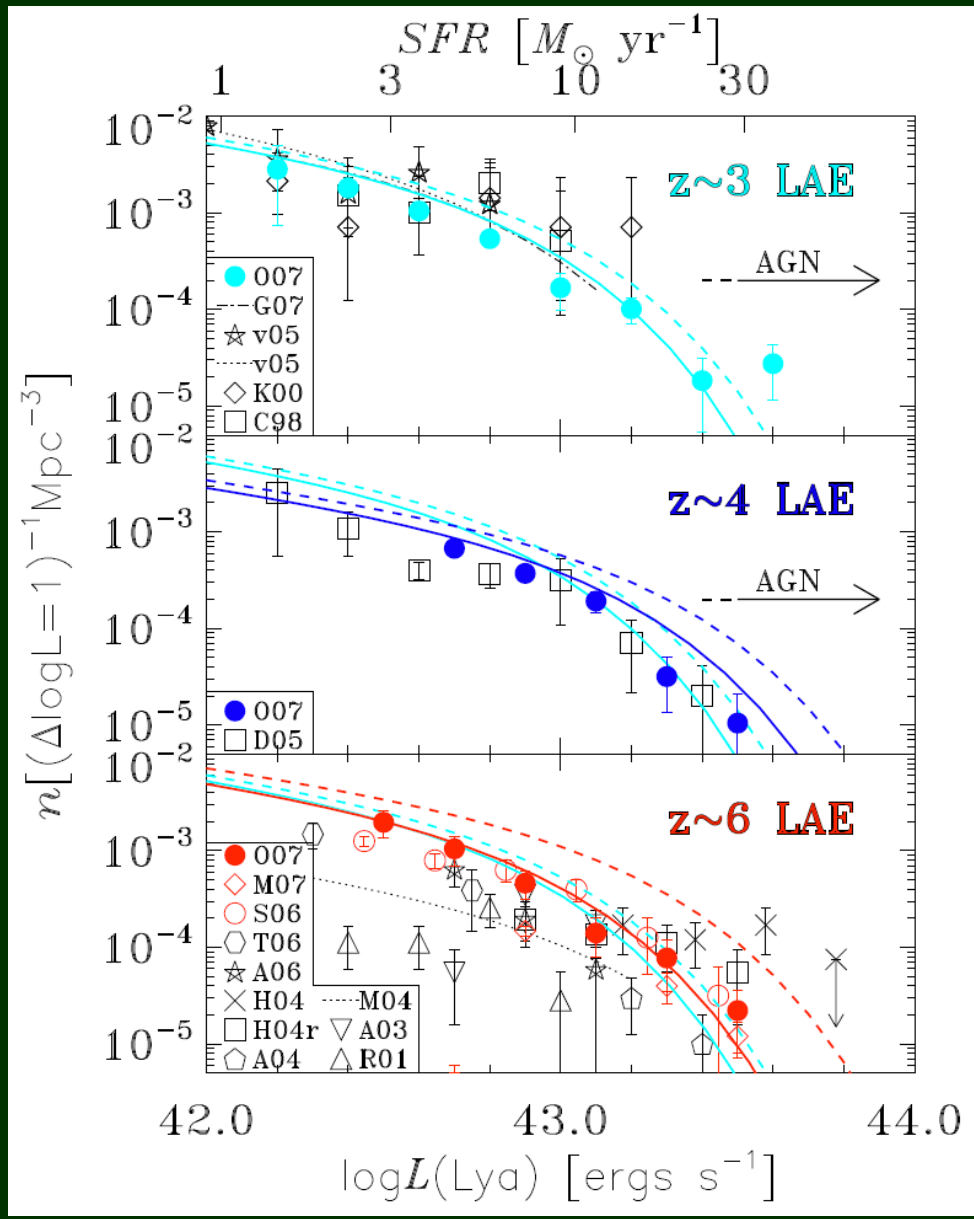
- Significant decline of LAE-LF suggests IGM attenuation
  (Haiman & Spaans 99, Malhotra & Rhoads 04)

- Advantages
  - Sensitive at $x_{HI}<10^{-3}$（⇔GP test）
  - Statistical estimate（⇔GRB）
- Disadvantages
  - Hard to distinguish w/ LAE evolution
  - Hard to distinguish internal attenuation

Lyα LF at 3<z<5.7

- Lyα LF at 3<z<5.7
  No evolution
  - Systematic LAE survey at z=3.1/3.7/5.7
  - 1sqdeg survey
  - Contrary to LBG evolution
  - See also
    Dawson+ 07
    Gronwall+ 07
    van Breukelen+ 05



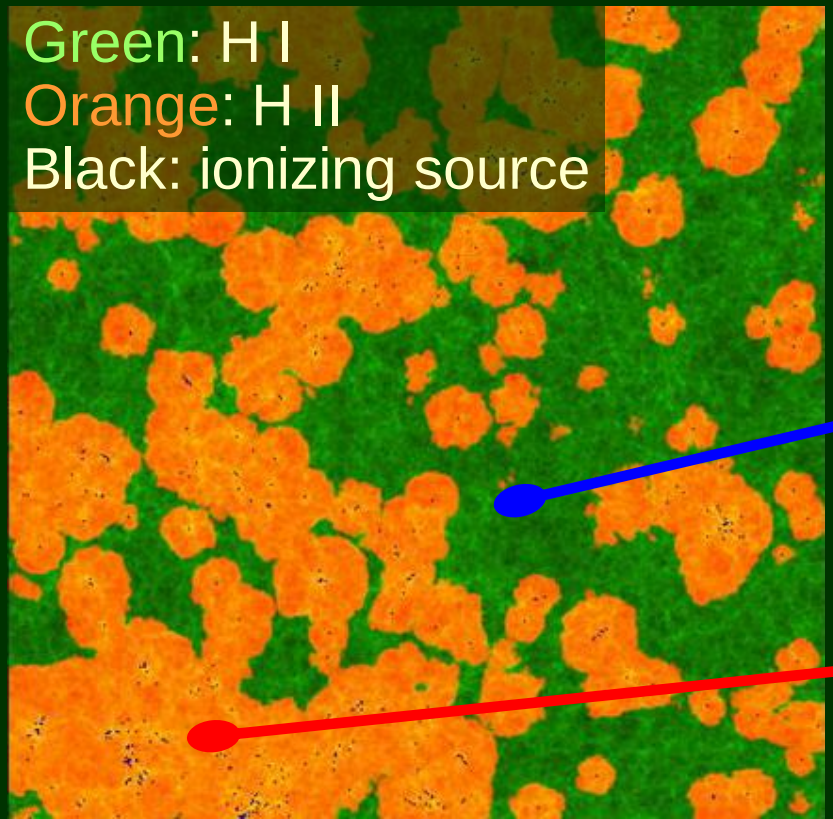


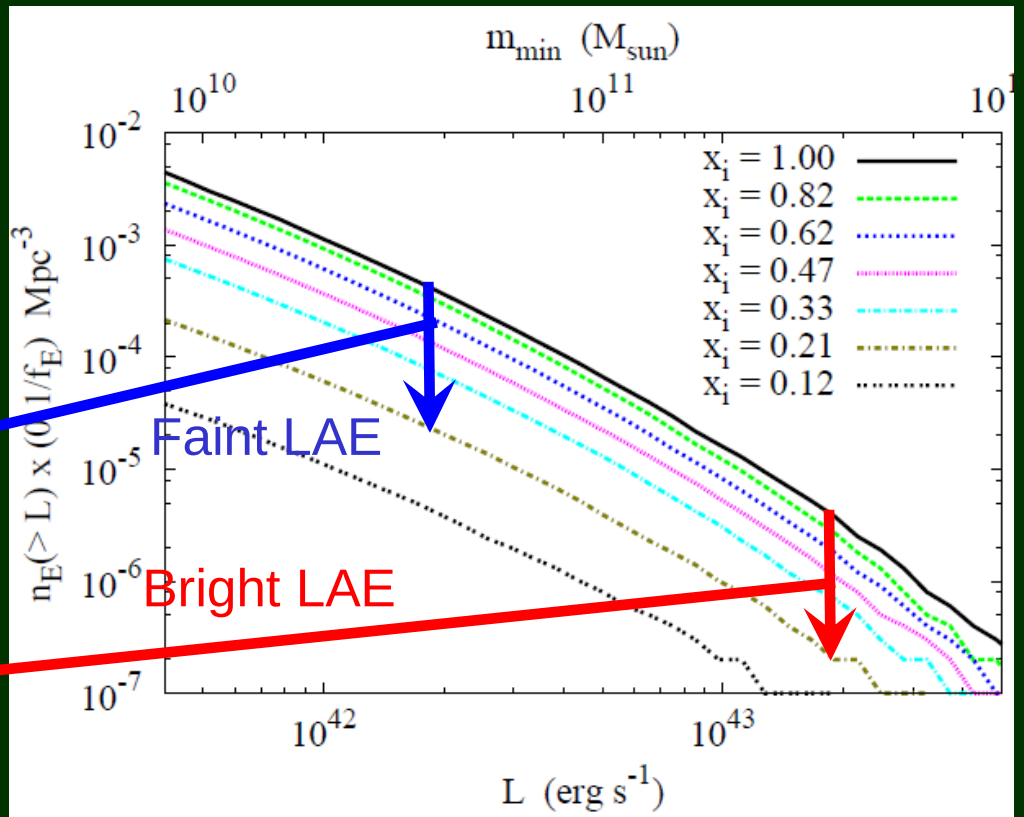
Ouchi+ 07

Theoretical predictions

- Model predictions on Lyα LF
  - Bright LAE → easy to observe, Faint LAE → difficult to observe
  - The amplitude of LF decreases according to x_{HI}, irrespective of L (or mass).
  - See also Haiman & Cen 05, Le Delliou+ 05, Dijkstra+ 06, Mesinger & Furlanetto 07

McQuinn+ 07

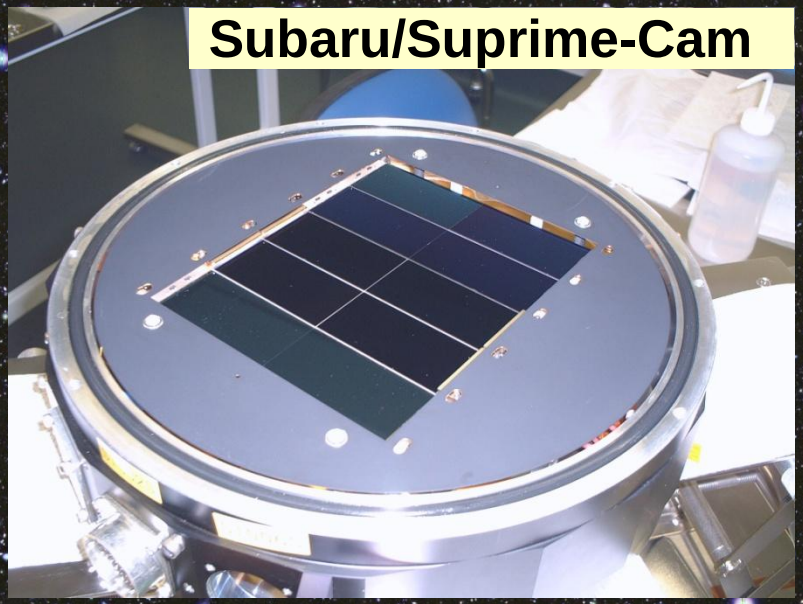




Subaru Deep Field (SDF)

Subaru Deep Field (SDF)

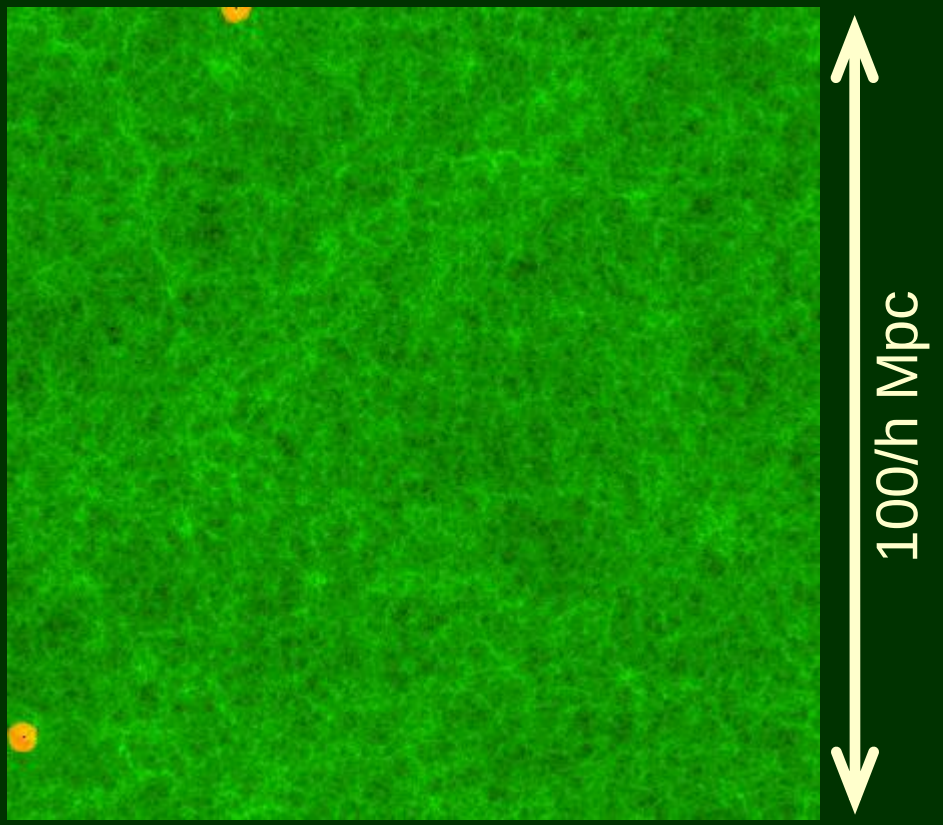
- RA 13:24:21.38 DEC +27:29:23.0
- Subaru/Prime-focus camera has 10 2kx4k CCDs
- 34'x27' wide FOV 876 arcmin^2 ← 5 x GOODS
- **public data --- http://soaps.naoj.org/sdf/**
- see NK+ 04



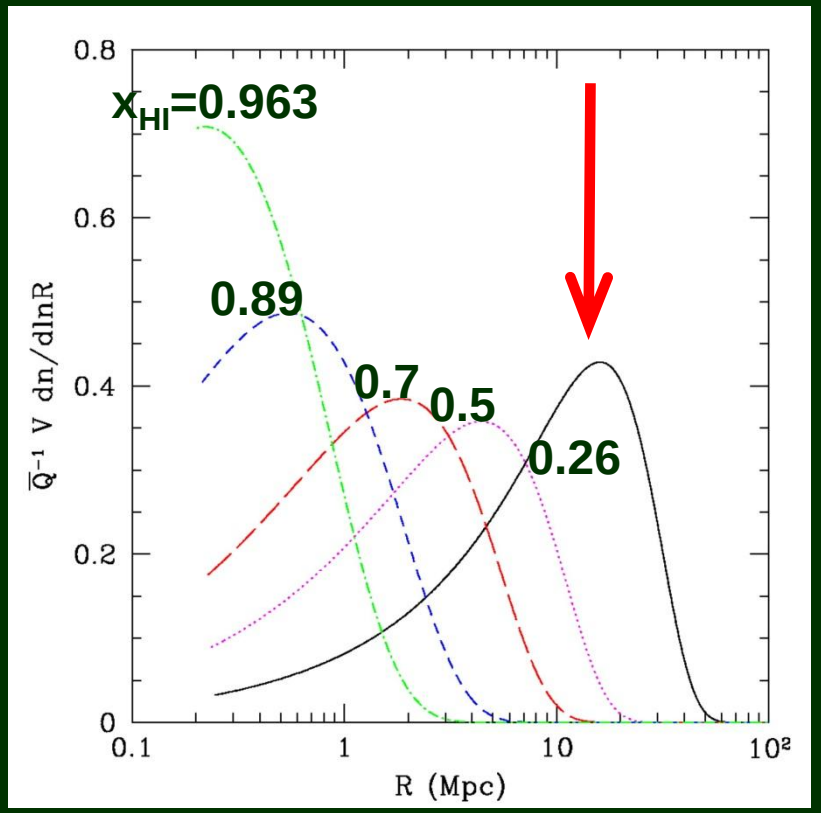
real SDF image

Panoramic view is required !! — scale of reionization

- Cosmological HII region ~ 0.45pMpc ~1.3'@ z=6.5 (Haiman 02)
- Overlapped HII region ~8.6pMpc ~24'@z=6 (Wyithe & Loeb 04)

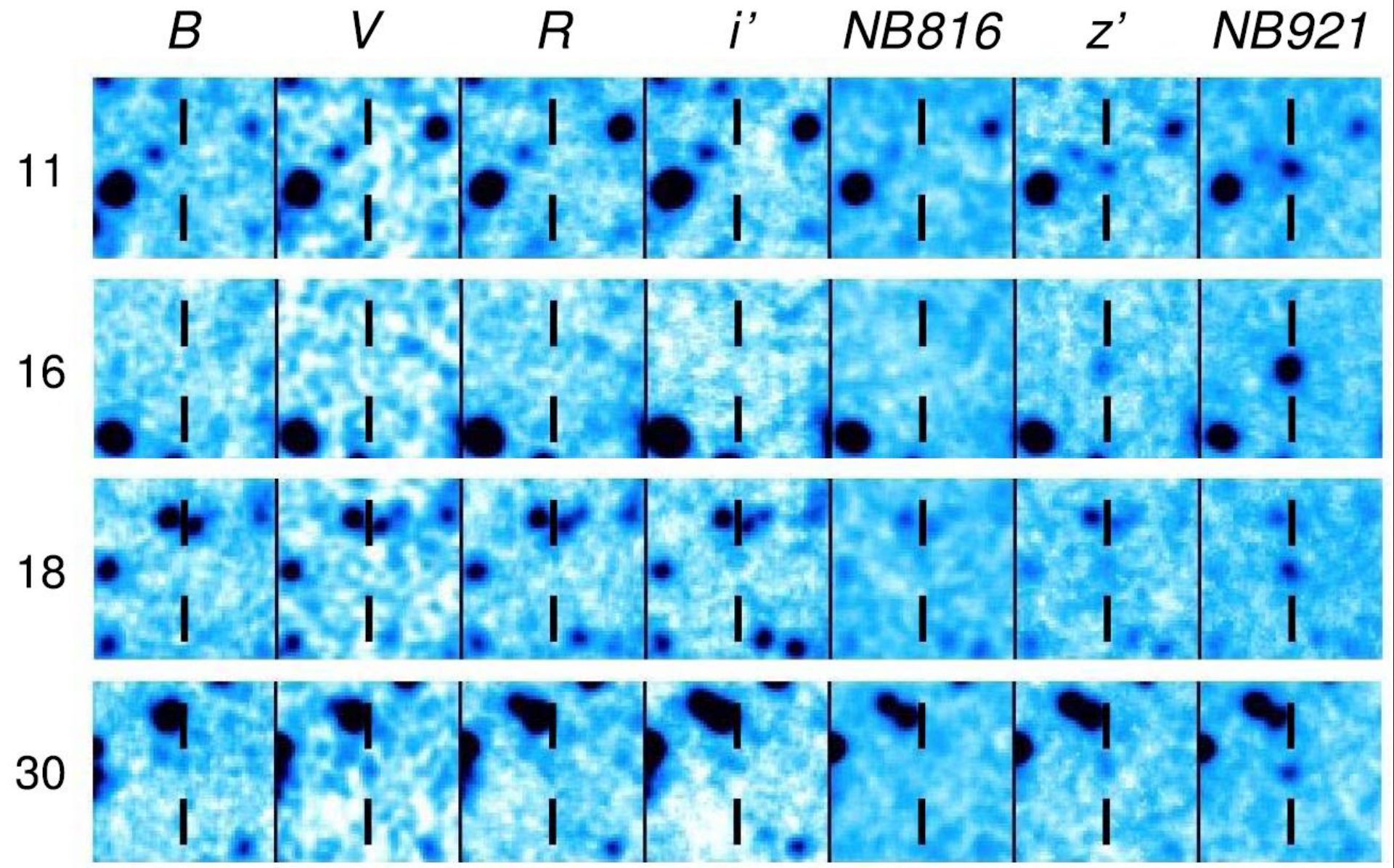


Iliev+ 06
Green: H I
Orange: H II
Black: ionizing source

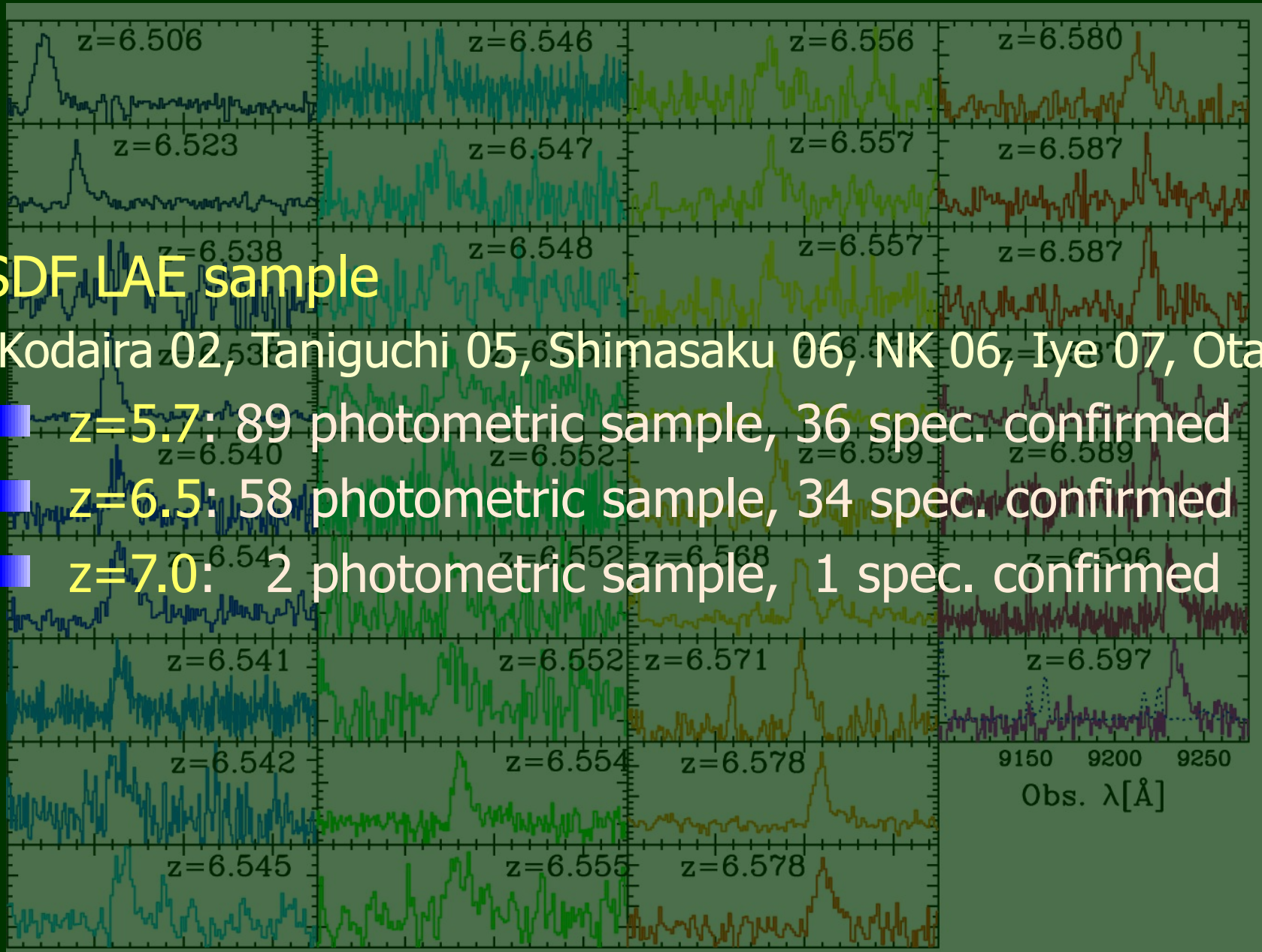


Furlanetto+ 04
Ionized bubble~10pMpc @EoR

Thumbnails of z=6.5LAE in the SDF



LAEs at z=5.7, 6.5, & 7.0 in the SDF



- SDF LAE sample

(Kodaira 02, Taniguchi 05, Shimasaku 06, NK 06, Iye 07, Ota07)

  - z=5.7: 89 photometric sample, 36 spec. confirmed
  - z=6.5: 58 photometric sample, 34 spec. confirmed
  - z=7.0: 2 photometric sample, 1 spec. confirmed

The Lyα LF of z=6.5LAEs in the SDF

- Apparent deficit compared w/ z=5.7

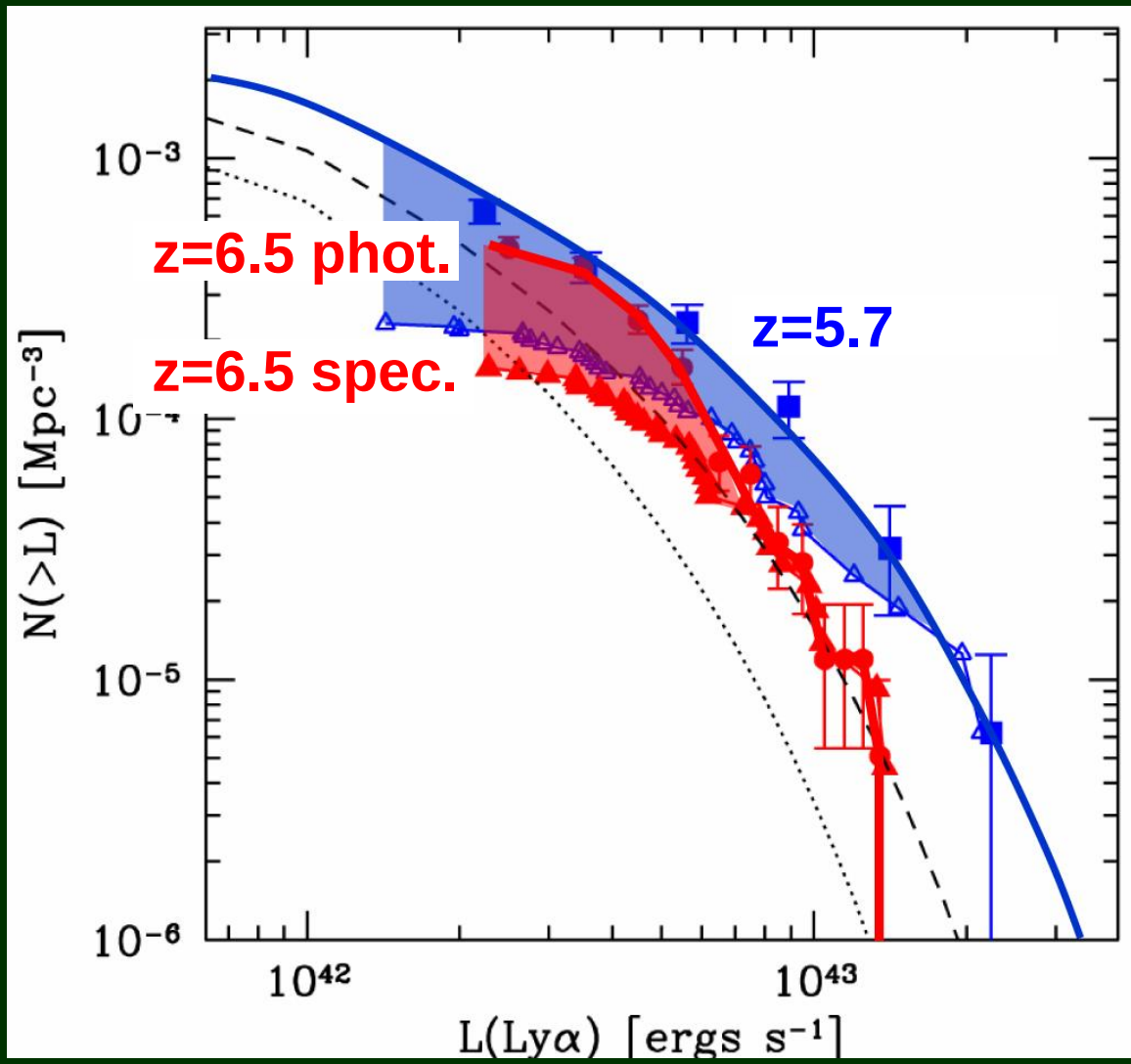
- Based on large volume, homogeneous sample in a general field
- Almost all of bright LAEs have been spec. identified.
- L(LyA) of z=6.5LAEs in other fields w/o grav.L

  -Kurk 04 1.1×10^{43} erg/s

  -Rhoads 04 1.1×10^{43}

  -Stern 05 1.04×10^{43}

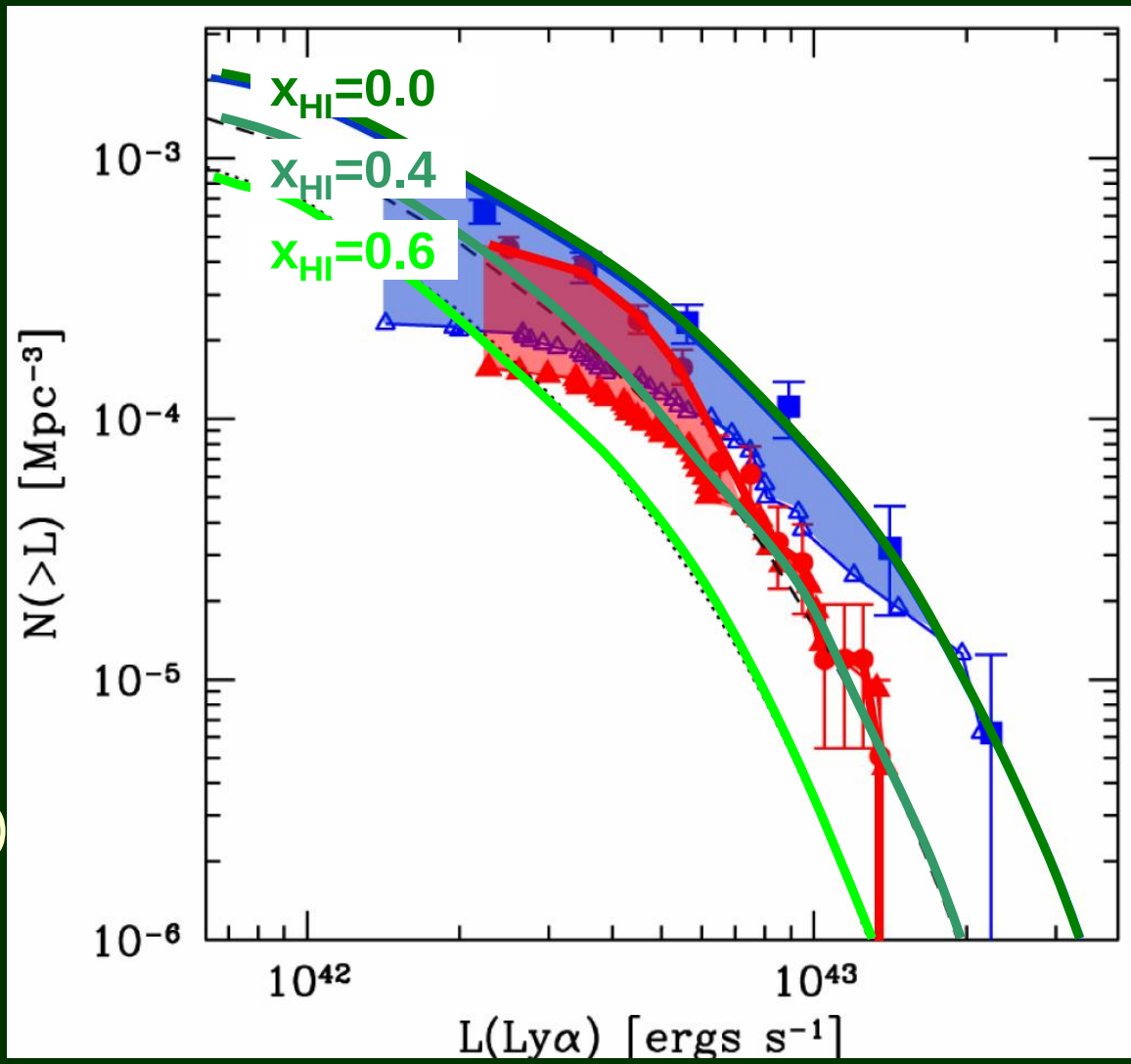
→ consistent w/ our bright end



NK+ 06 updated

The Lyα LF of z=6.5LAEs in the SDF

- Apparent deficit compared w/ z=5.7
- Reionization has not completed at z=6.5
  - L*=0.75 mag difference
  - →x_{HI}<0.45 at z=6.5 (Santos 04)
  - →x_{HI}=0.30 at z=6.5 (Kobayashi+ 07)
  - →x_{HI}<0.50 (Dijkstra+ 07)
  - →x_{HI}<0.38 (McQuinn+ 07)
- Faint end slope cannot be determined
  - → photon budget for reionization



NK+ 06 updated

Follow-up spec. status at 2008 Sep.

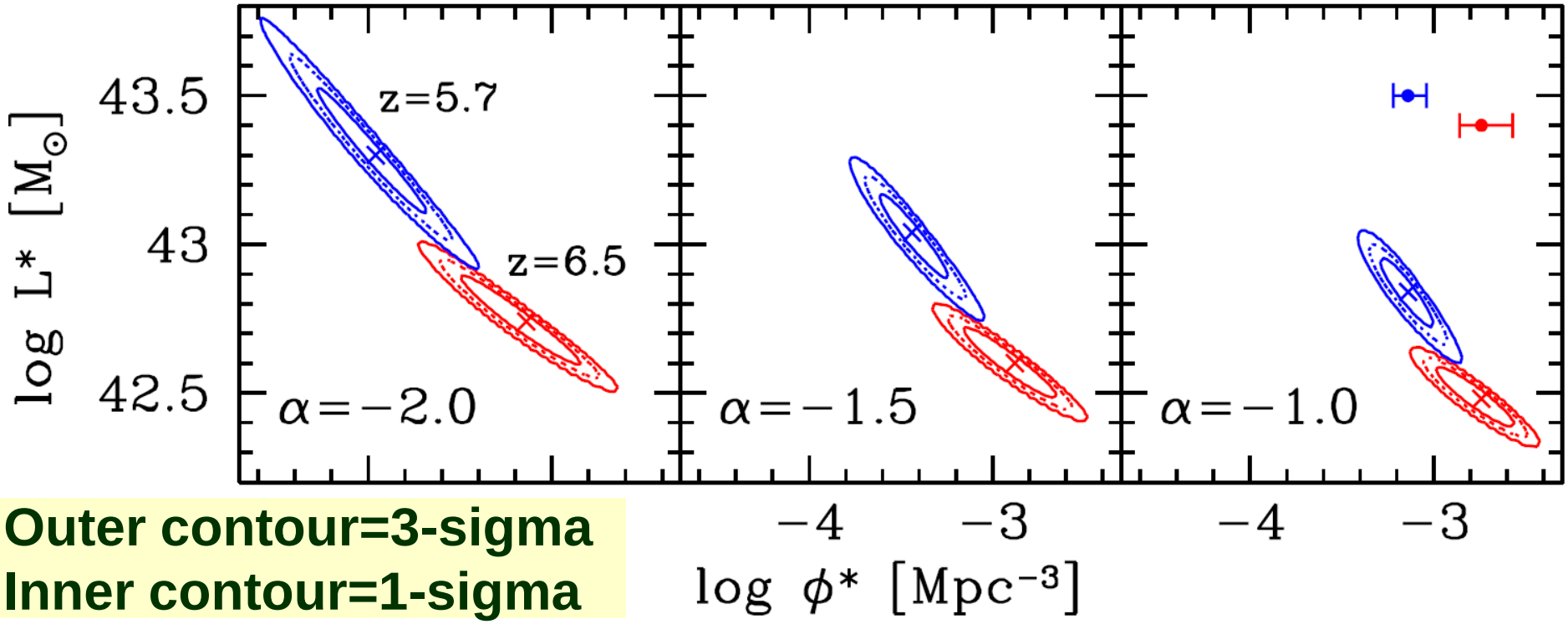
- 2007: 3nights: Subaru/FOCAS --- cloudy/TOO

  17 new data
- 2008: 2nights: Keck/DEIMOS --- cloudy

  No new data
- 2009?

Significance of the LF difference

- Error contours of Schechter parameters (φ^*,L^*)
  - The LF difference is 3-sigma significance
  - The cosmic variance (Somerville+ 04) ~30% reduces the significance to 2-sigma

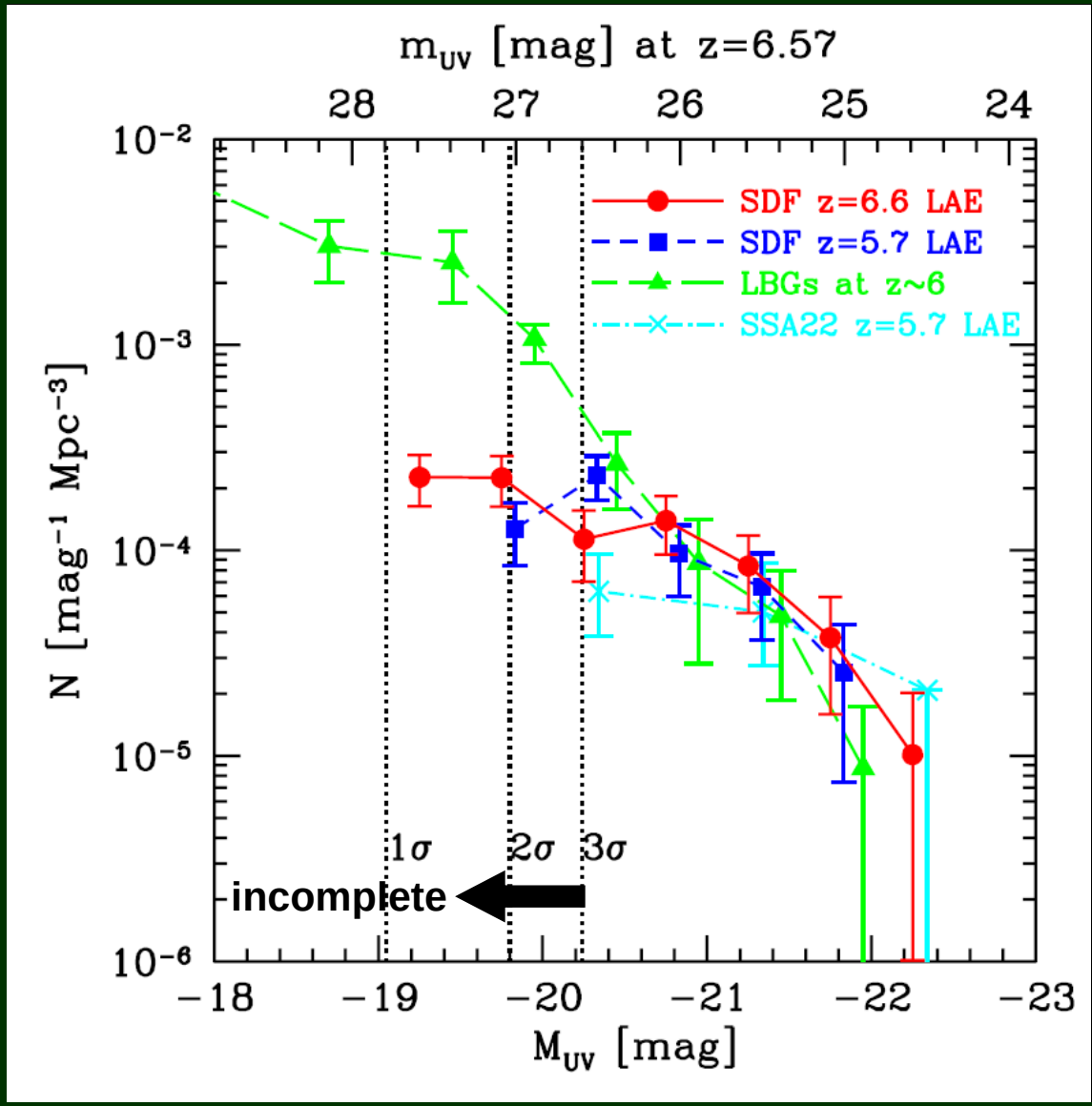


Outer contour=3-sigma
Inner contour=1-sigma

The rest-UV LF of z=6.5LAEs

- LyA LF difference is caused by
  IGM attenuation ?
  vs.
  galaxy evolution ?
- The rest UV (1255A) flux is not sensitive to neutral IGM

- The rest-UV LF of LAE at z=6.5 agrees w/
  LAEs at z=5.7 &
  i-dropouts at z~6 (Bouwens+ 06)

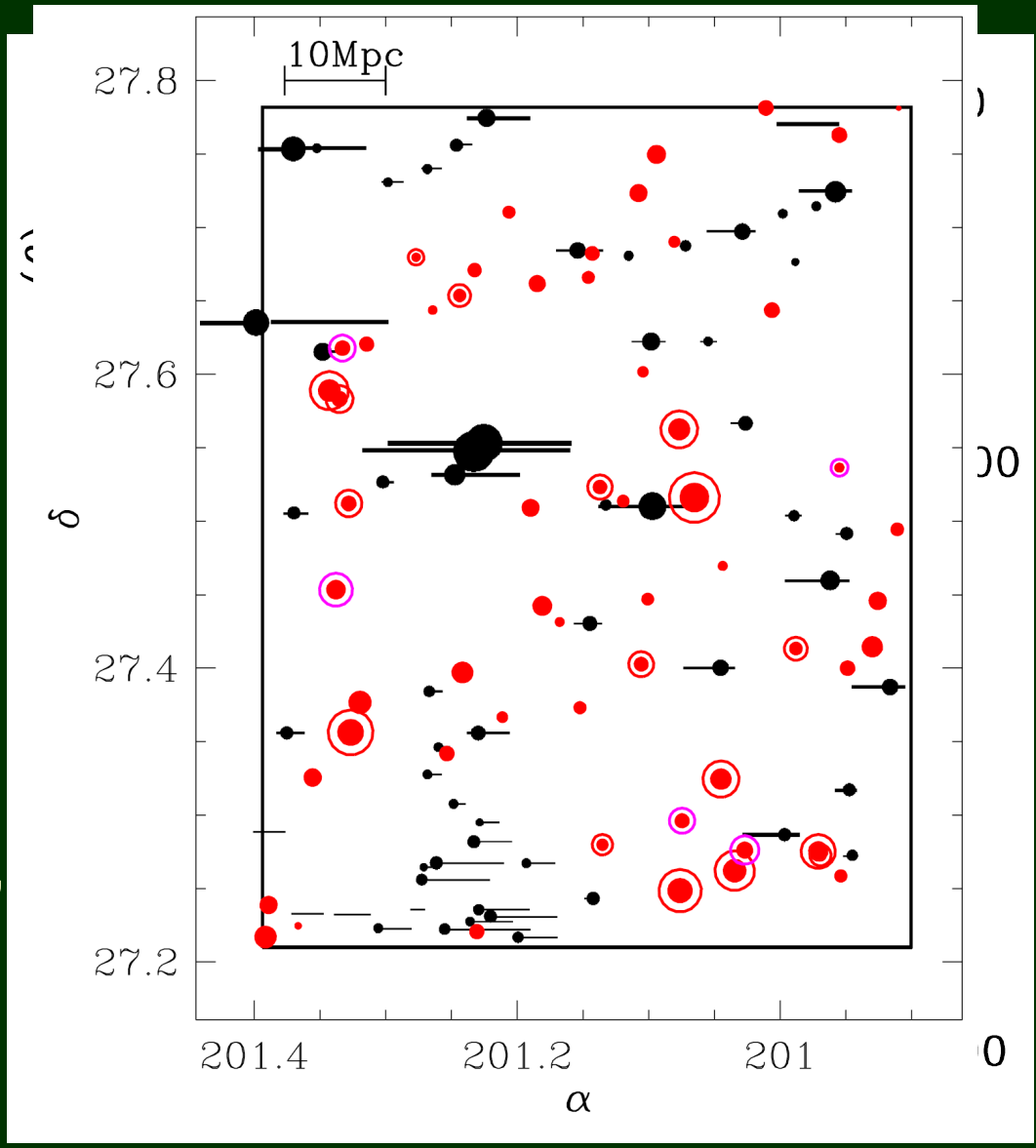


Spatial distribution of z=6.5 LAEs

- 3 independent tests
  - ACF
  - VPF
  - 2d-KS test
- LAE at z=6.5 has a homogeneous distribution ~40Mpc
- Spatial homogeneous also in LyA luminosity/ EW
- In general, low-z LAEs are sensitive to LSS

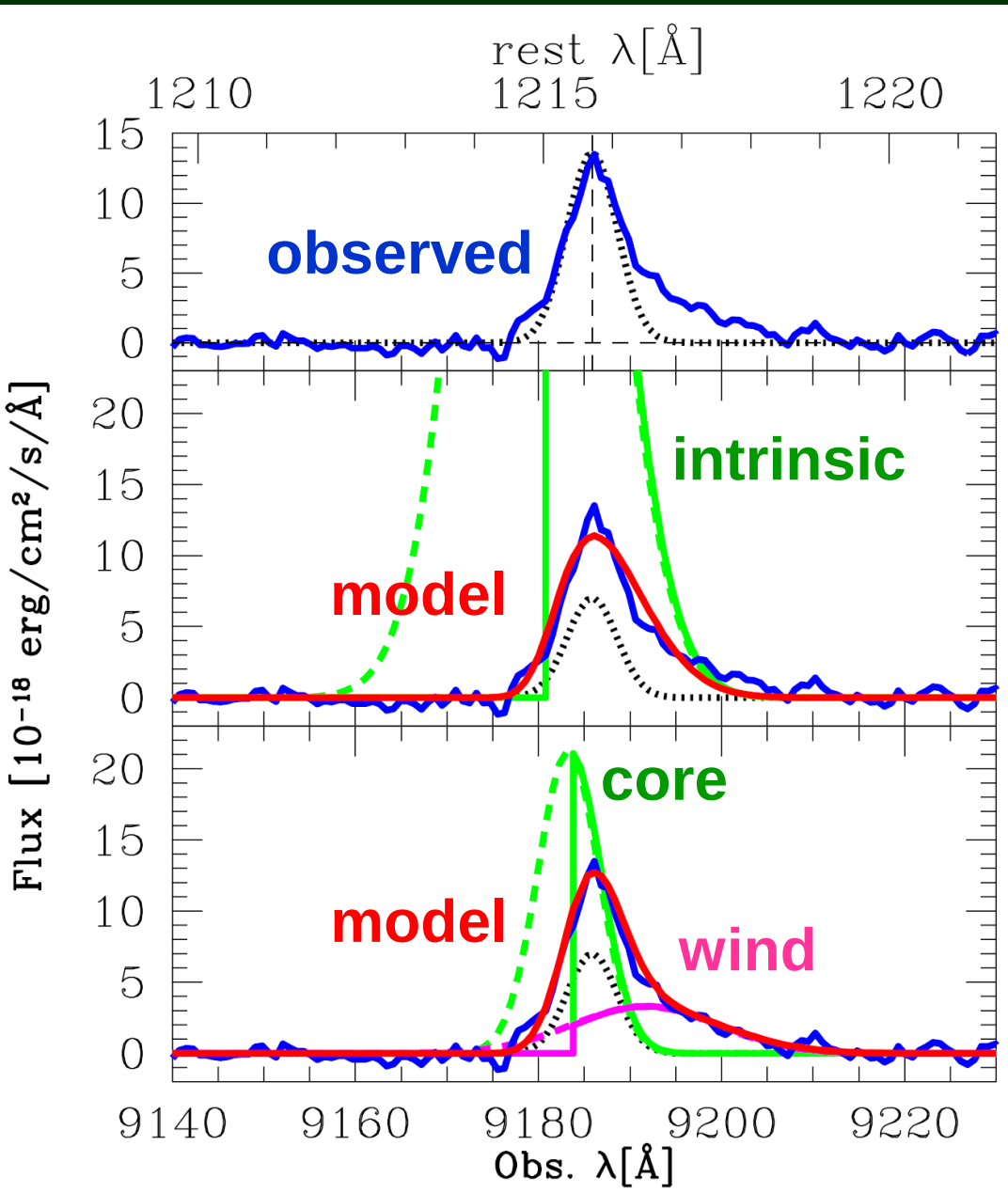
  (Shimasaku+03, Ouchi+ 05, Malhotra+ 05)
- Cosmic variance ?

  see Hu+ in prep.



composite spectrum of z=6.5 LAEs

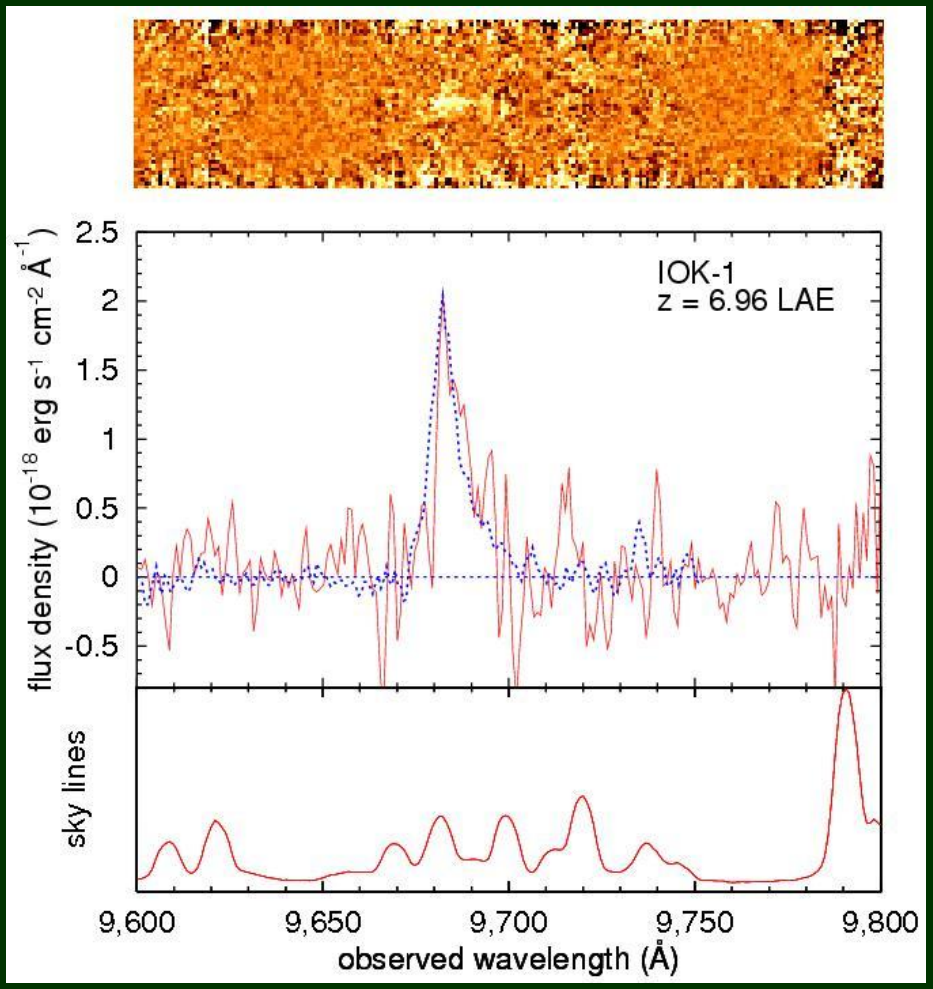
- composite spectrum has an apparent red wing
- Reionization model
  - red damping wing
  - R_{HII}=0.45Mpc
- Galactic wind model
  - double gaussian comp.
  - wind=200km/s

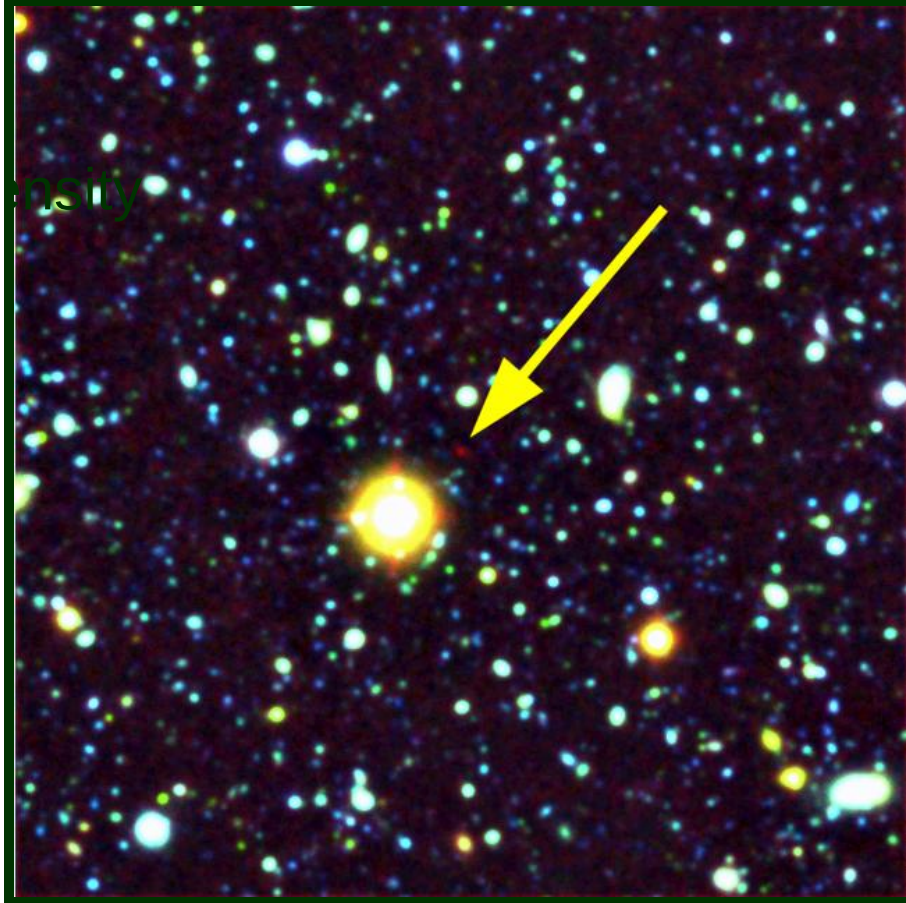


FAQ

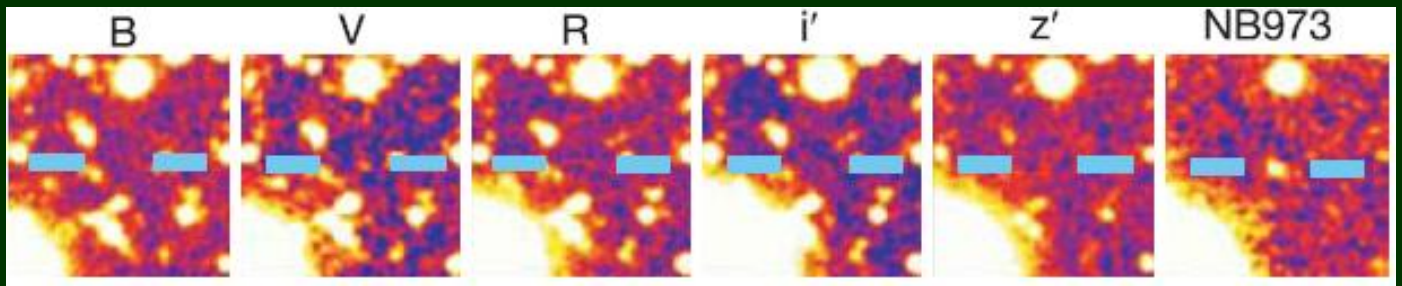
- Lyα-LFの変化は銀河進化で説明できるのでは？(Dijkstra+, McQuinn+)
  - z=3-6で無進化。z>6で急に進化？
  - UV-LF はz=5.7と6.5で変わらない。
- ●hotra & Rhoads, ●u et al.とは結果が違うじゃん。
  - データクオリティが全然違う。
  - LF導出の方法は極めていい加減。
- Cosmic varianceじゃないの？
  - そうかも。
  - 標準的なCDMではcosmic varianceは30%→Lyα LFの違いは説明できない。
  - そもそも空間的に非一様な再電離プロセスでcosmic varianceができているのかも。
  - もっと広い観測、low-zの観測が必要。

A LAE at z=6.96 in the SDF





Iye+ 06



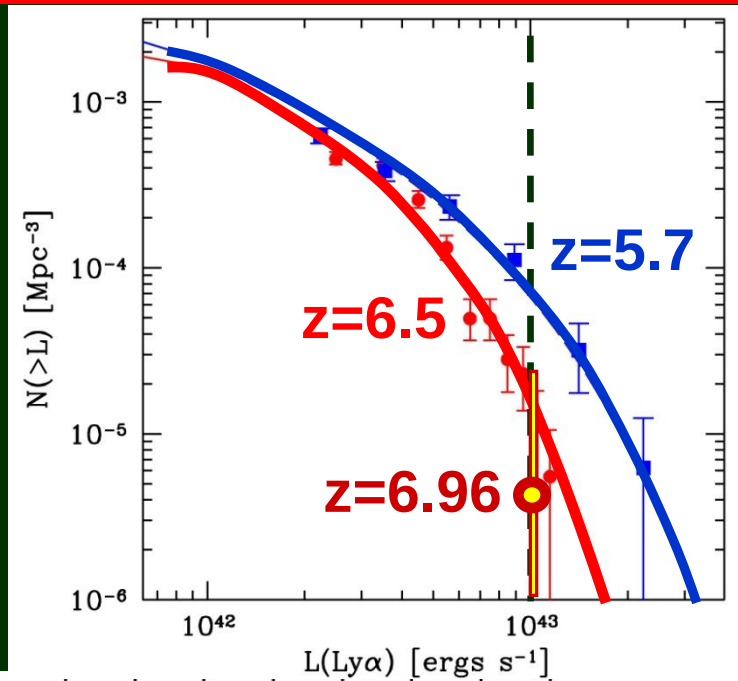
The Madau plot of LAEs

- The only one galaxy at z=7 hardly constrain the LyA-LF,

  but…
- The LAE number density at high-L end decreases:

  1.00 → 0.24 → 0.04

  (z=5.7 z=6.5 z=7.0)



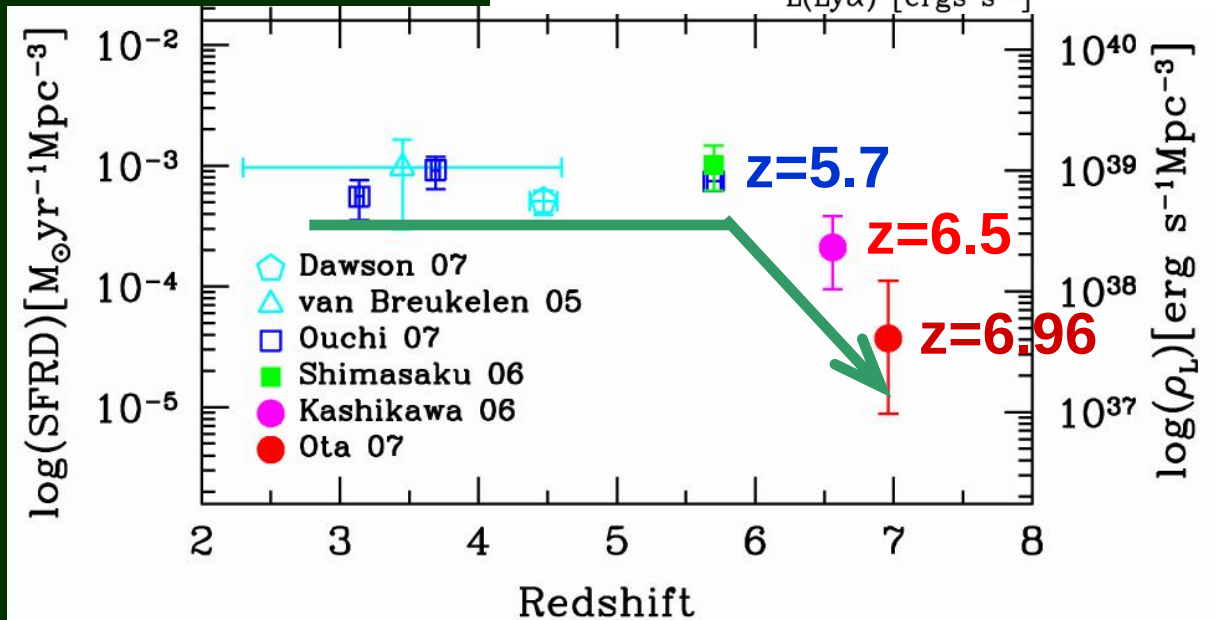
Ota+ 07

- The LyA luminosity density

  ($L>1\times10^{43}$erg/s)

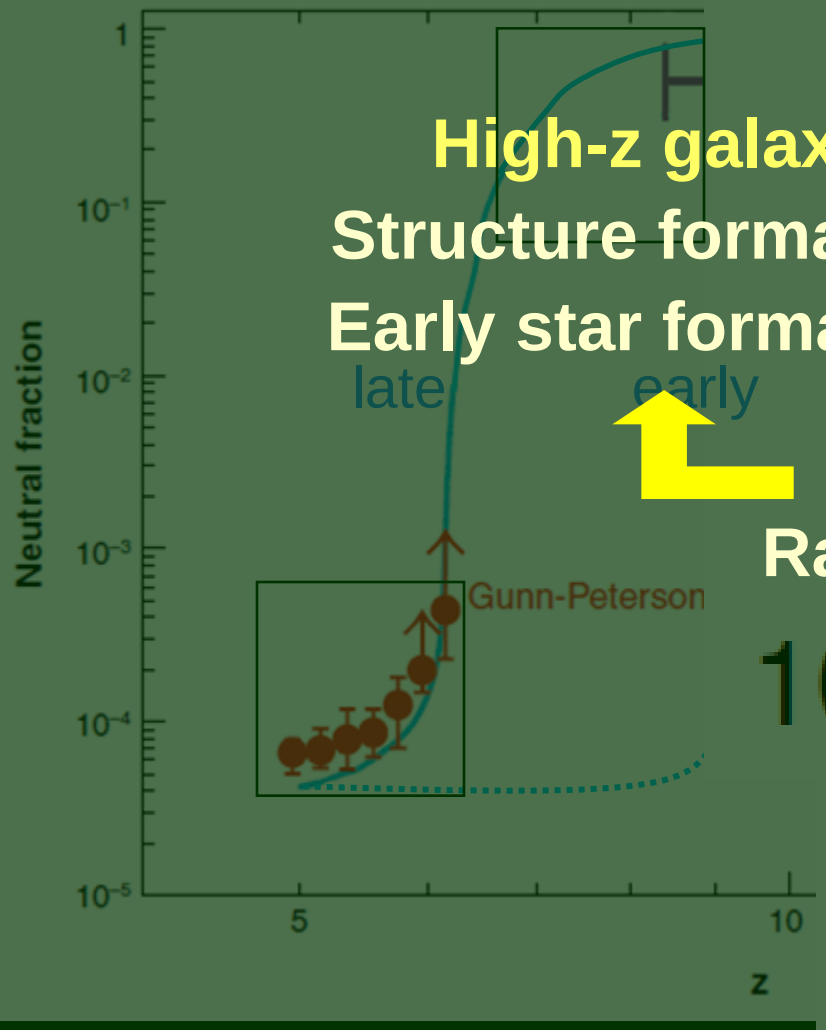
  of LAEs gradually decreases

  from z=5.7 to 7.0



Rapid evolution of the ionizing state?

The history of neutral fraction



High-z galaxy

Structure formation

Early star formation

late early

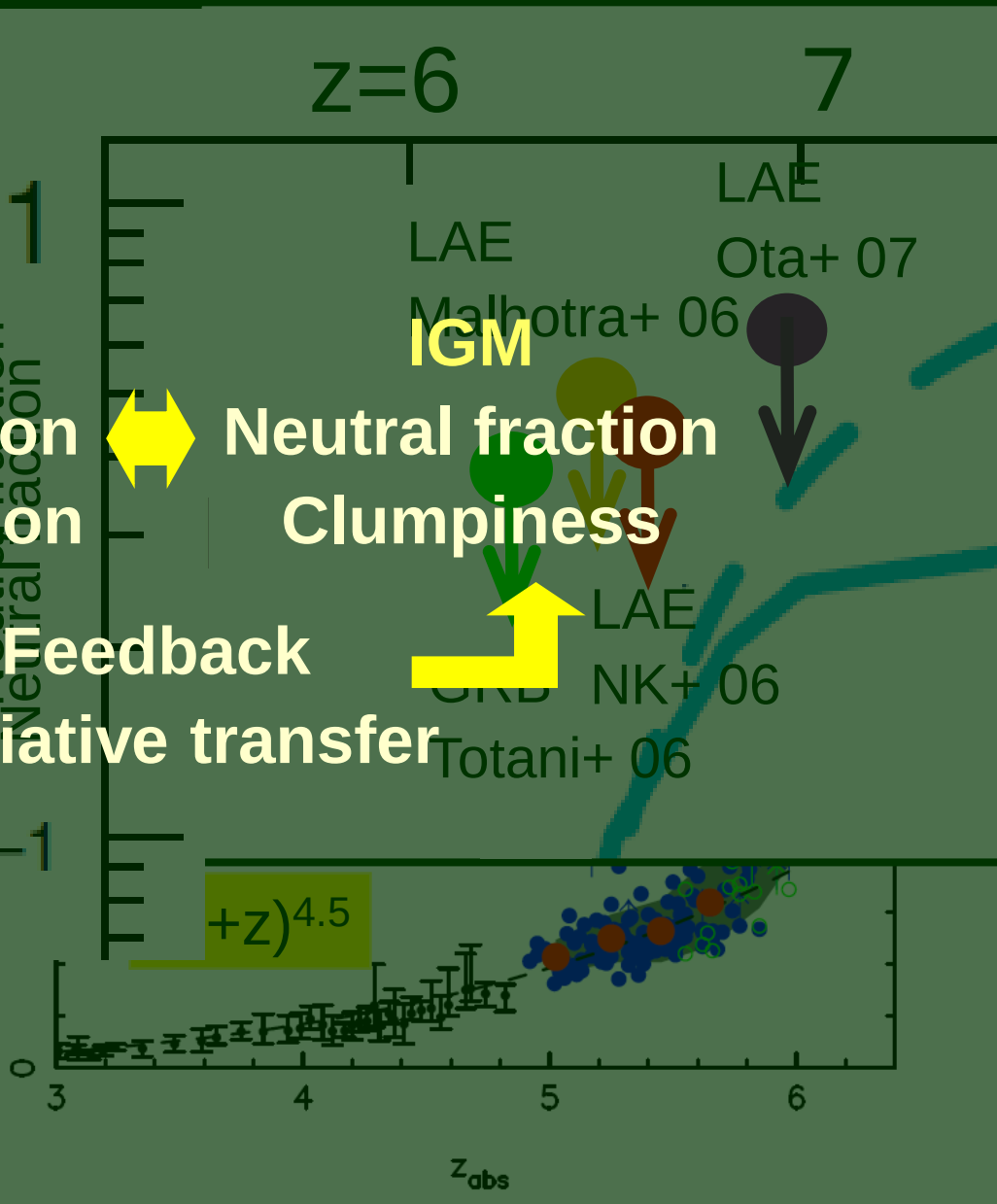
Feedback

Radiative transfer

IGM

Neutral fraction

Clumpiness



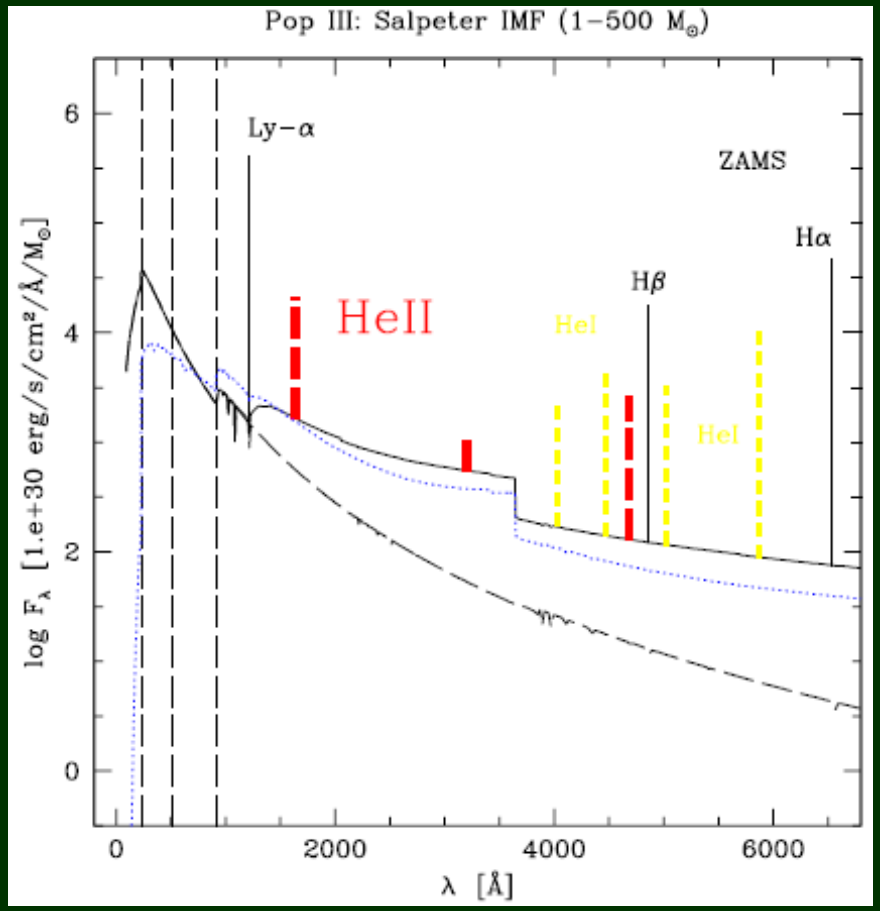
Uncertainties of Lyα-test … too many

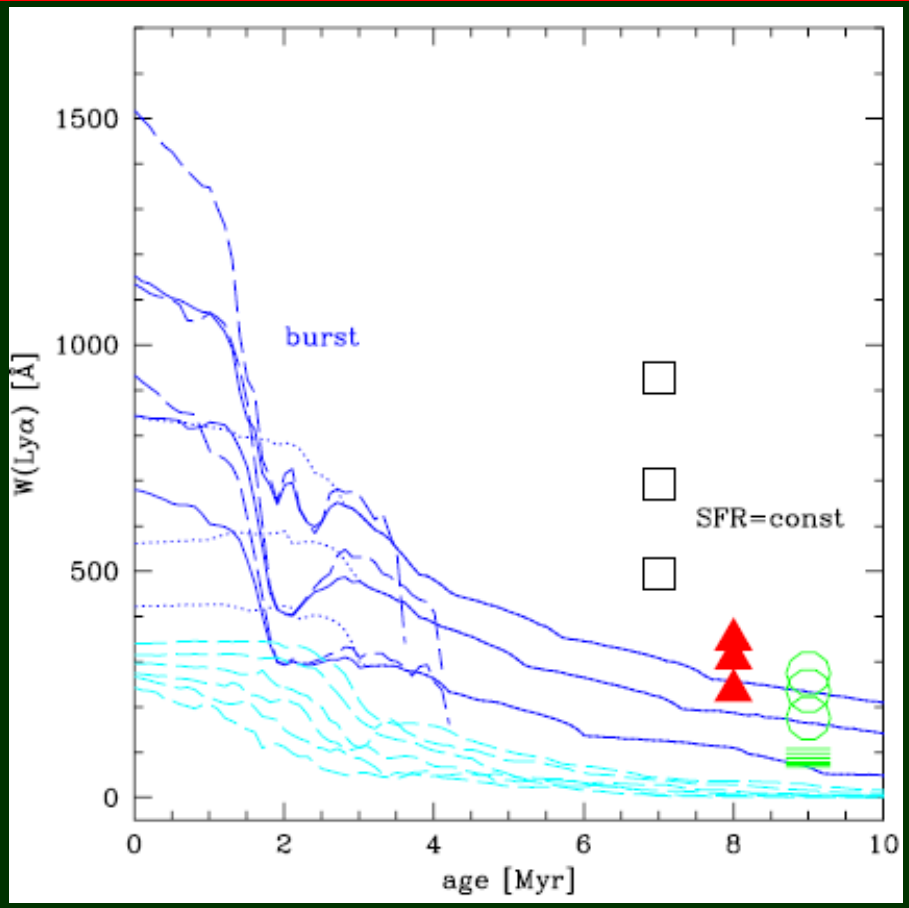
- Intrinsic properties of LAEs
  - Does LAE really have no LF evolution ?
  - Does LAE trace large-scale structure ?
  - Is L(LyA) of LAE proportional to its mass ?
  - How large the effect of dust is ?
  - What is the escape mechanism of LyA photons ?
- Internal structure of LAE
  - How internal density profile of HI does LAE have ?
  - Does LAE have galactic wind ?
- IGM physics
  - How large the typical density of IGM ?
  - How large the clumping factor of IGM ?
  - Does LAE really have cosmological HII region ?
- cosmic variance

Lyα-test: Future

- LF
  - Higher-z → Lyα-LF is sensitive in early reionization
    w/ on-going NIR survey, JWST, TMT
- Spatial distribution
  - Correlation function
    w/ HSC, JWST
  - Counts-in-cell (Mesinger&Furlanetto 07)
    w/ JWST
- Line profile
  - w/ TMT (Haiman+ 02, Dijkstra+ 07)
- Correlation w/ 21-cm HI emission
  - w/ MWA-LFD, LOFAR (Wyithe&Loeb 07)
- Pop-III candidates
  - LAEs w/ large EW → HeIIλ1640A detection (Shaerer+ 03)

もし本当に銀河形成の現場が見れるとすれば...

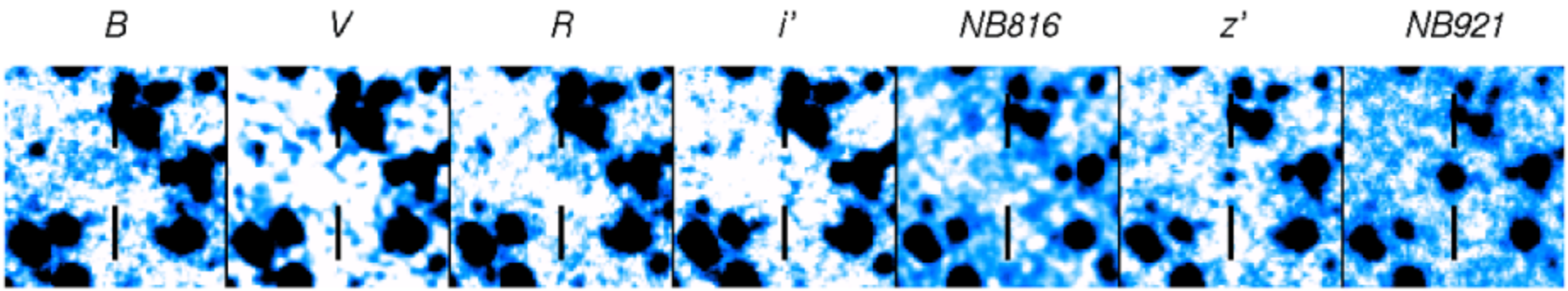


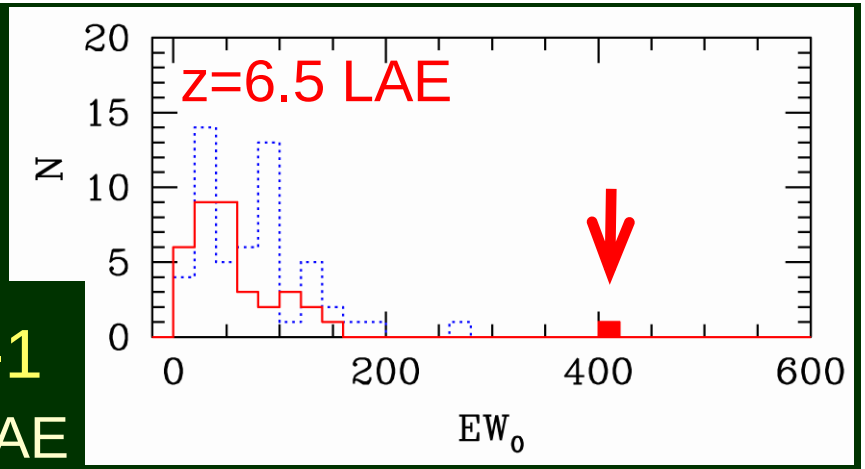


Shaerer+ 02,03

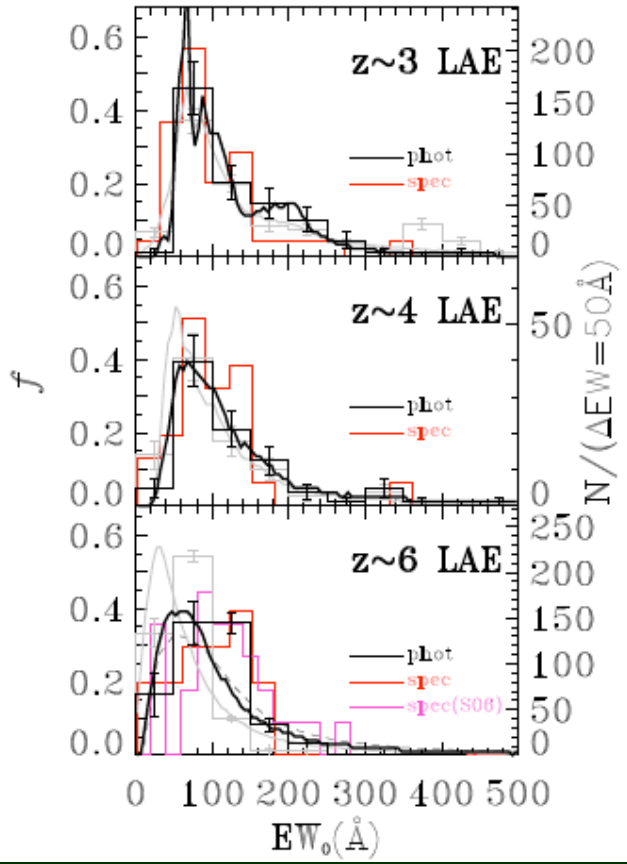
- popIII
  - Low-metal $Z<10^{-5}Z_{\odot}$ High effective temperature, hard SED
  - Large EW of Lyα+ HeIIλ1640A emission
  - Feedback from popIII will have strong impact on initial galaxy formation and the subsequent SFH+ IGM evolution (Ciardi+ 07)

PopIII candidate with EW=800!



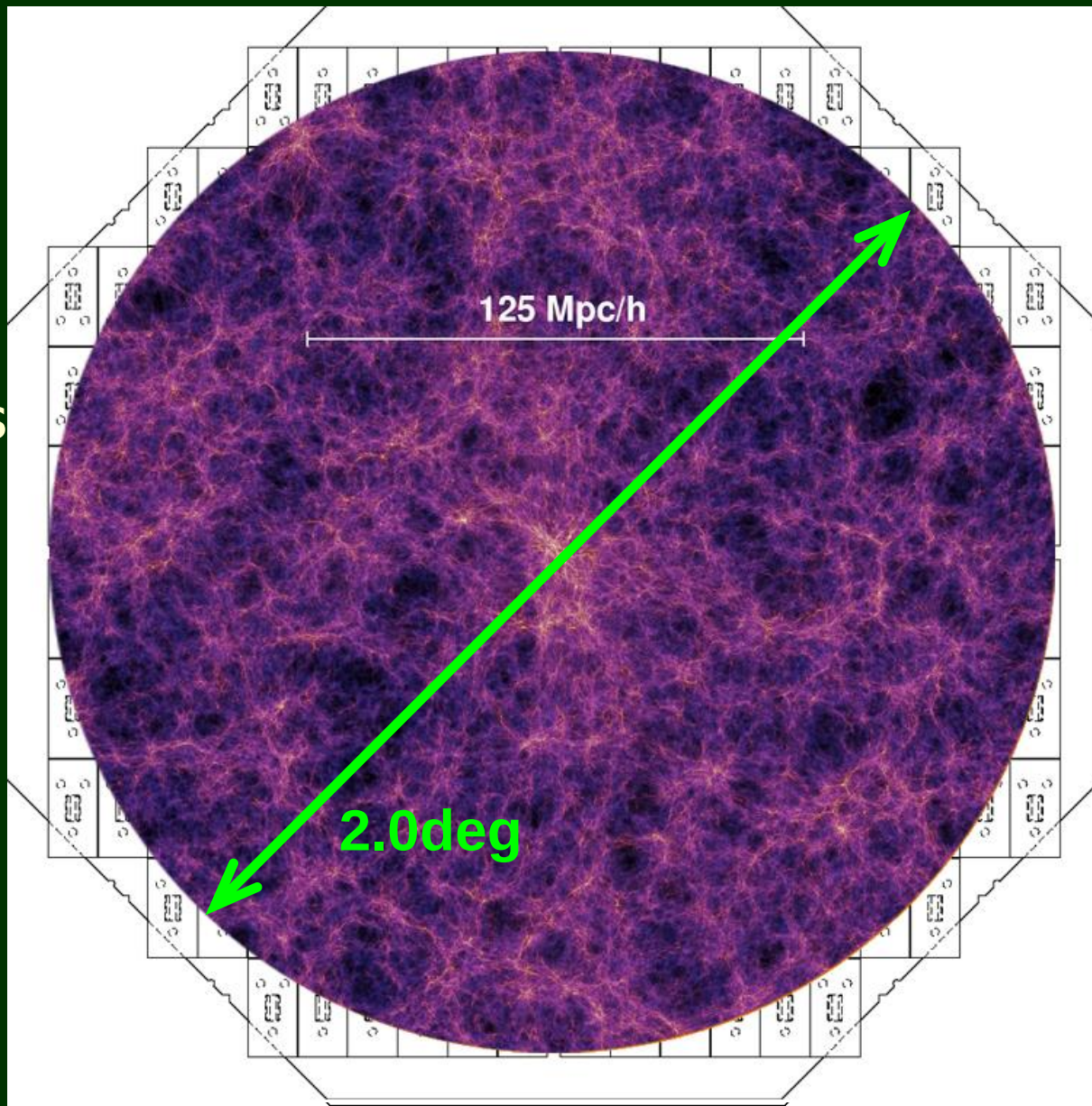


- SDF-popIII-1
  - z=6.545 LAE
  - Continuum flux is detected (28mag)
  - EW=406^{+58}_{-61}A (rest)
  - Intrinsic EW~800A
  - Need NIR spec. to detect HeII emission
  - See also; Nagao+ 08

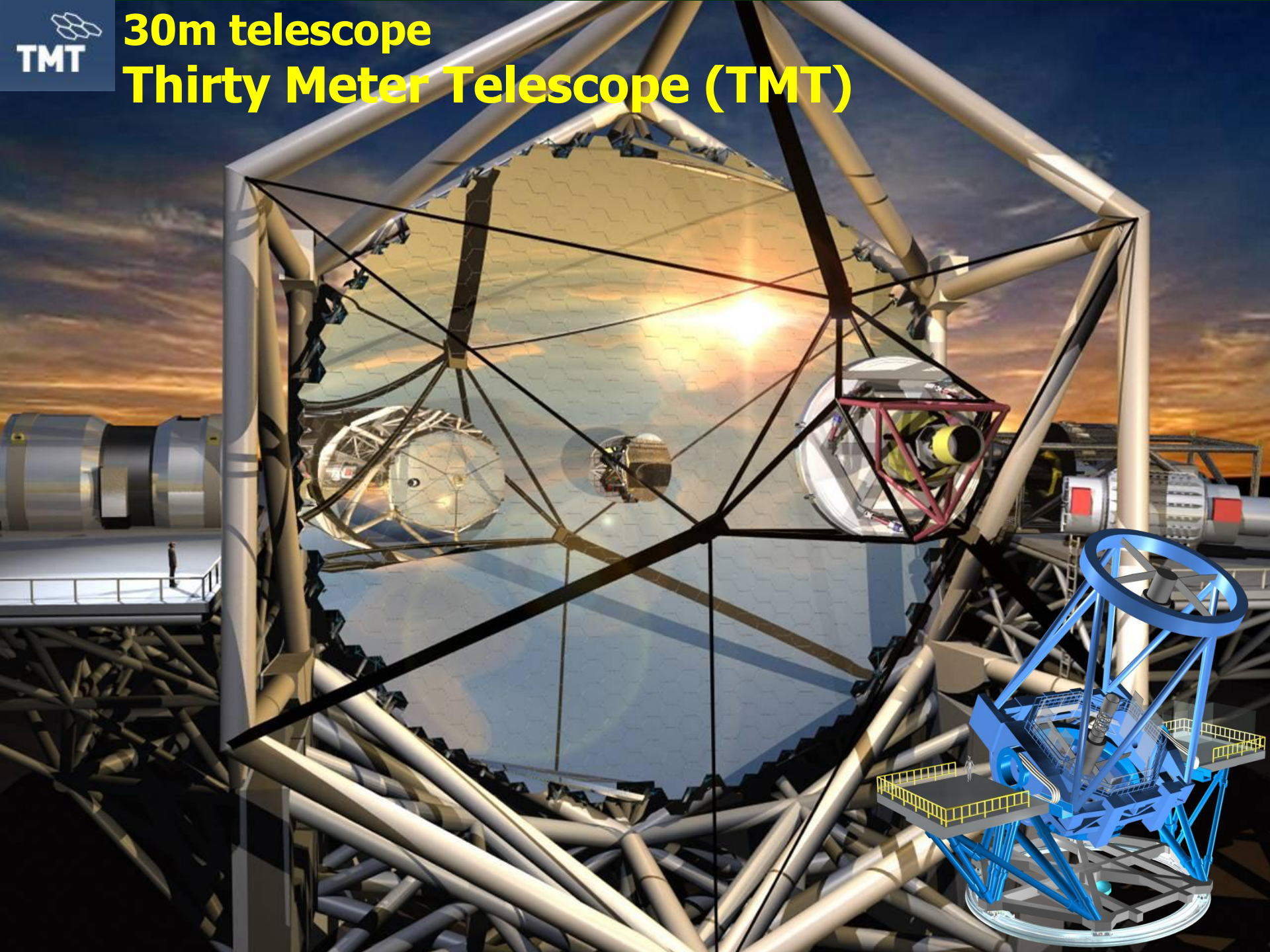


Subaru's next step: Hyper Suprime-Cam

- HSCAM
  - 2.0degφ
  - 120~180 CCDs (1.0~1.4 Gpixels)
  - 0".16 / pixel
  - Red-sensitive CCDs ~1.1μm
- Powerful tool for
  - Larger sample of high-z LAEs
  - Spatial distribution
  - Patchy reionization



30m telescope
Thirty Meter Telescope (TMT)



Summary

The LyA-LF at z=6.5 has an apparent deficit compared w/5.7

The LyA luminosity density gradually decreases from z=5.7 to 7.0

- Reionization has not completed at z=7.0-6.5
  - x_{HI}=0.52 at z=7.0, x_{HI}=0.30 at z=6.5 (exc. galactic evolution)
- Galaxy evolution?
  - Abrupt Lyα-LF evolution at z~6 ??
  - The UV-LF has almost unchanged: LAEs might have little intrinsic evolution from z=7.0 to 5.7
- Cosmic variance?
  - Larger cosmic variance in LAEs than general population ?
  - Inhomogeneous reionization / High clumping factor of IGM ?

Looking at the final stage of the reionization by LAEs