High-z Galaxies at the epoch of reionization

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Outline

- Galaxy contributions to hydrogen reionization
- Reionization probed by LyA emission line
- Search for the first stars
- Future high-z galaxy survey
- Summary

High-z universe

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

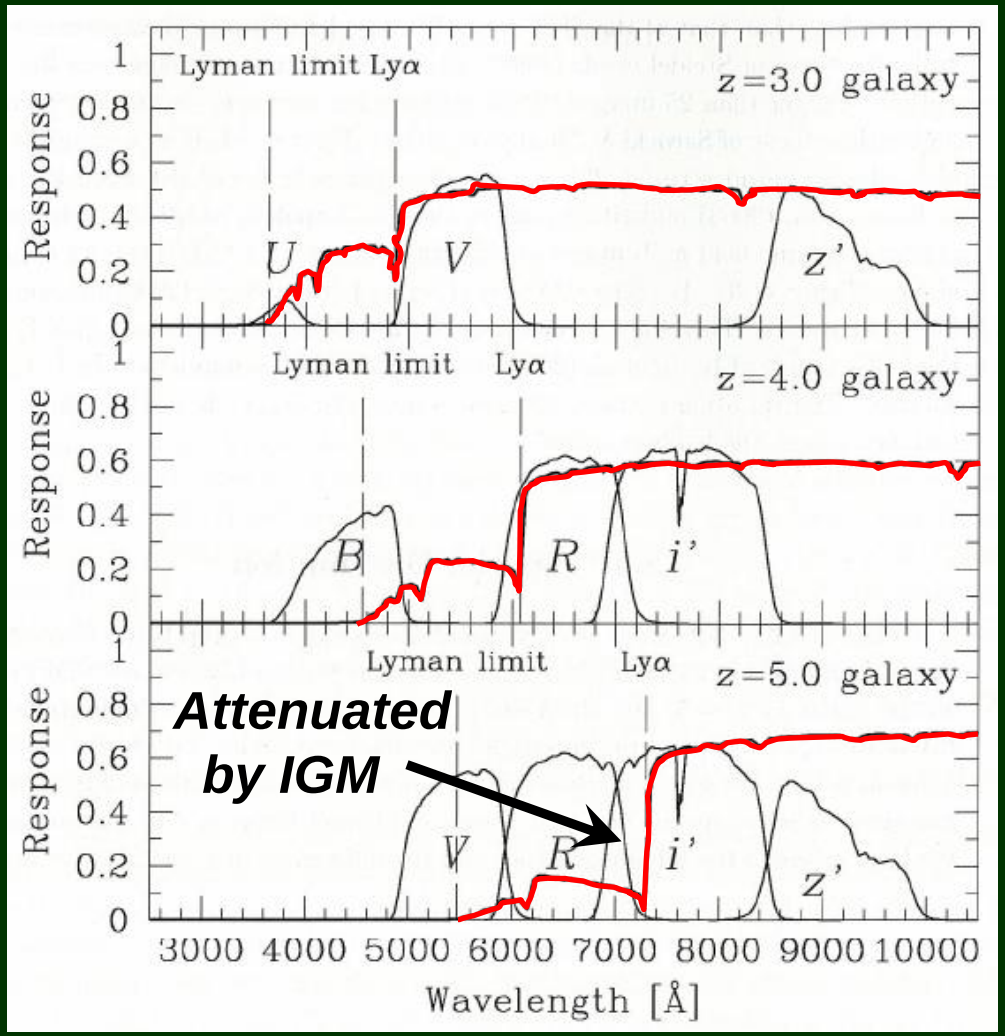
- **The epoch of first generation of galaxies**
  - Early star formation history
  - Initial structure formation
- **History of cosmic reionization**
  - **When** did the reionization take place ?
  - **What** ionized the universe ?
  - **How** was the reionization process ?
  - Complement to QSO / WMAP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

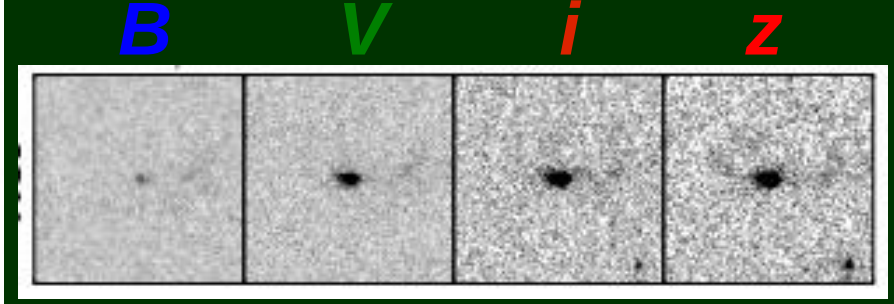
Galaxy contributions to hydrogen reionization

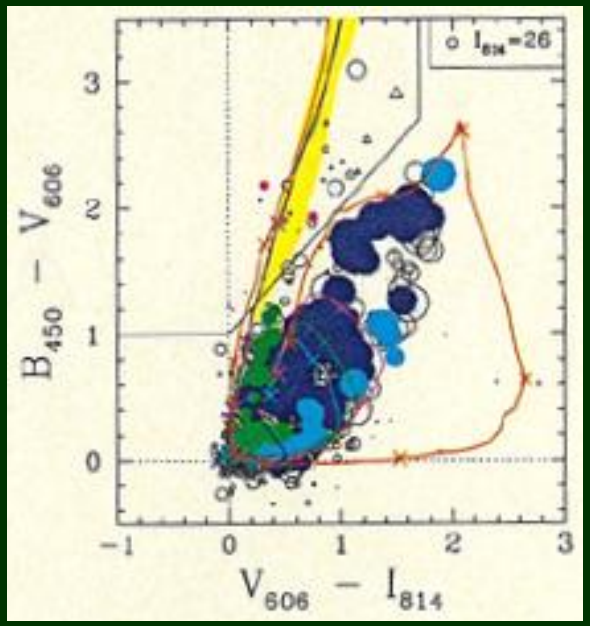
What ionized the universe ?

Lyman Break Galaxy (LBG)

- Lyman break --- sharp drop in continuum flux below Lyα
- ~2000LBGs have been spec. identified at z~3

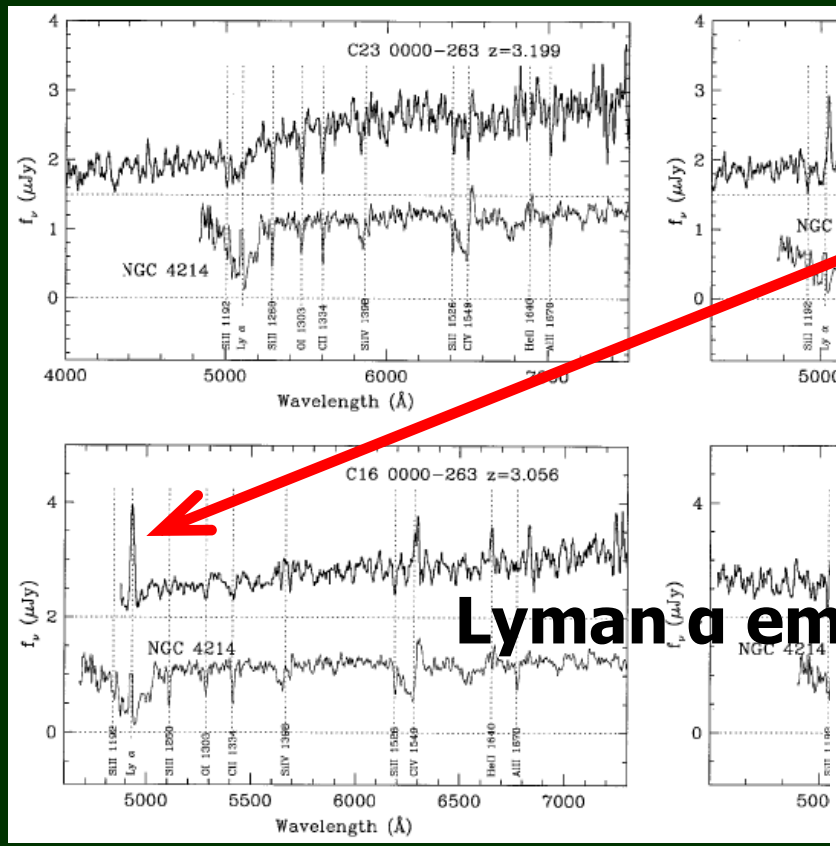






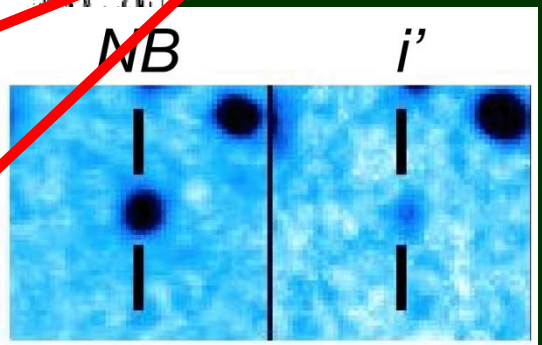
Lyman Alpha Emitter (LAE)

- Some LBGs have strong Lyman α emissions
- Discoveries of LBGs/LAEs → One of the important milestones of 10m telescopes

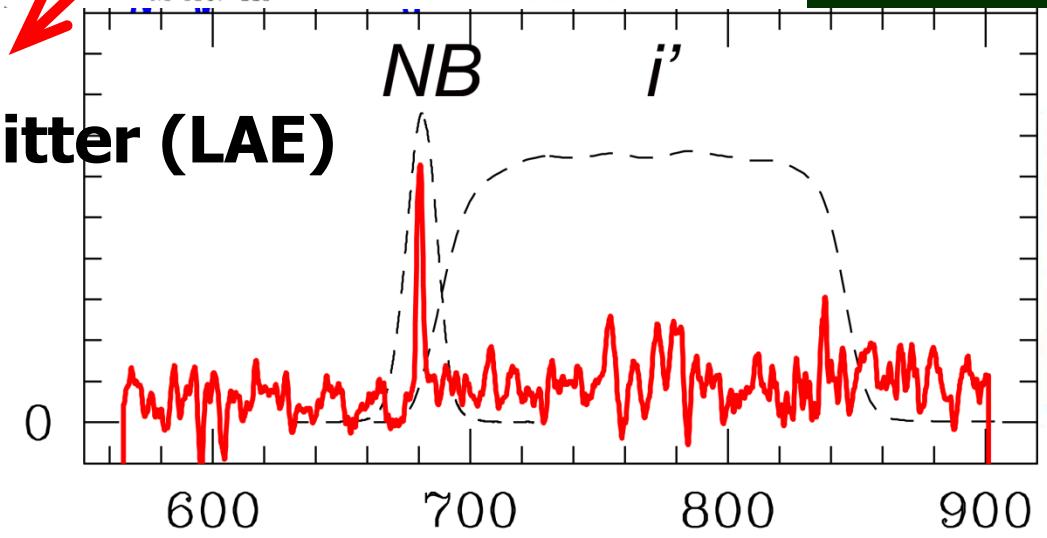


Steidel+ 96

Lyman α emission



Lyman α emitter (LAE)



Differences with or without Lyα

- Stellar mass
  LBG: 10^{9}-$10^{10}M_{\odot}$
  LAE: few x $10^{8}M_{\odot}$
- Age
  LBG: 10^{6}-10^{9}yr
  LAE: 10^{6}-10^{8}yr
- Av
  LBG: <1
  LAE: <0.1 (but see Finkelstein+ 07)

Ref.:
- LBG z=2; Erb+, z=3; Shapley+ 01, Papovich+ 01, Iwata+ 05, Rigopoulou+ 06, z=4; Pentericci et al. 07, z=5; Verma+ 07, z=6; Yan et al. 06, Eyles et al. 05, z=7; Egami+ 05
- LAE z=3.1 Gawiser+ 06, Nilsson+ 07, z=4; Overzier+ 06, Finkelstein+ 07,08, z=5; Lai+ 06, Pirzkal+ 07

⇒ LBGs are massive, older, and more dusty than LAEs

… but still large uncertainty in the staked analysis.

- Dark halo mass
  LBG: $10^{11\text{-}12}M_{\odot}$ (Giavalisco+ 98, NK+ 06, Ouchi+ 06, …many)
  LAE: $10^{11}M_{\odot}$??? (z=3.1; Gawiser+ 07)

Photon Budget

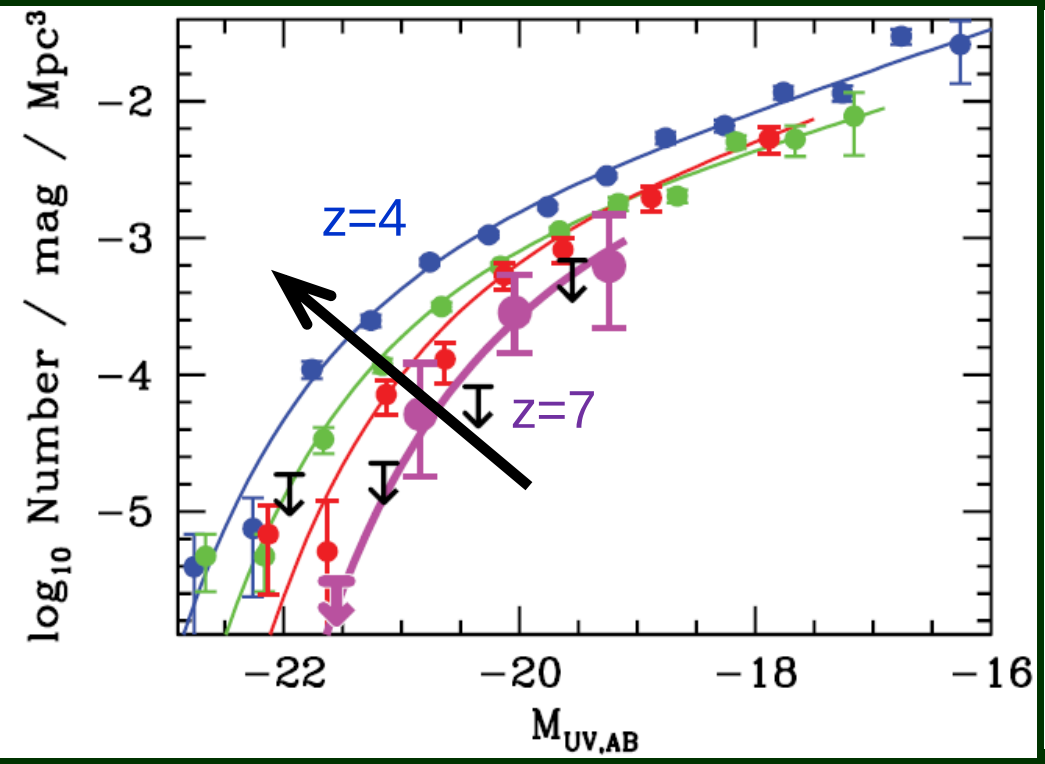
$$\dot{\rho}_{\rm SFR} \approx 0.013 f_{\rm esc}^{-1} \left(\frac{1+z}{6}\right)^3 \left(\frac{\Omega_b\, h_{50}^2}{0.08}\right)^2 C_{30}\, M_\odot\, {\rm yr}^{-1}\, {\rm Mpc}^{-3}$$

- Star formation rate density (SFRD) required to fully reionize the universe (Madau , Haardt & Rees 99, Bunker+ 04)
  - f_{esc}: escape fraction (see Iwata's talk)
  - C_{30}: IGM clumping factor=$\langle n_H^2 \rangle / \langle n_H \rangle^2$
- Observed SFRD (= integration of LF) of galaxies (LBGs) put constraint on the photon budget of the reionization
- Critical observation: Precise determination of the faint-end slope of the UV(ionizing radiation) continuum LF at z>6
- uncertainty: dust extinction

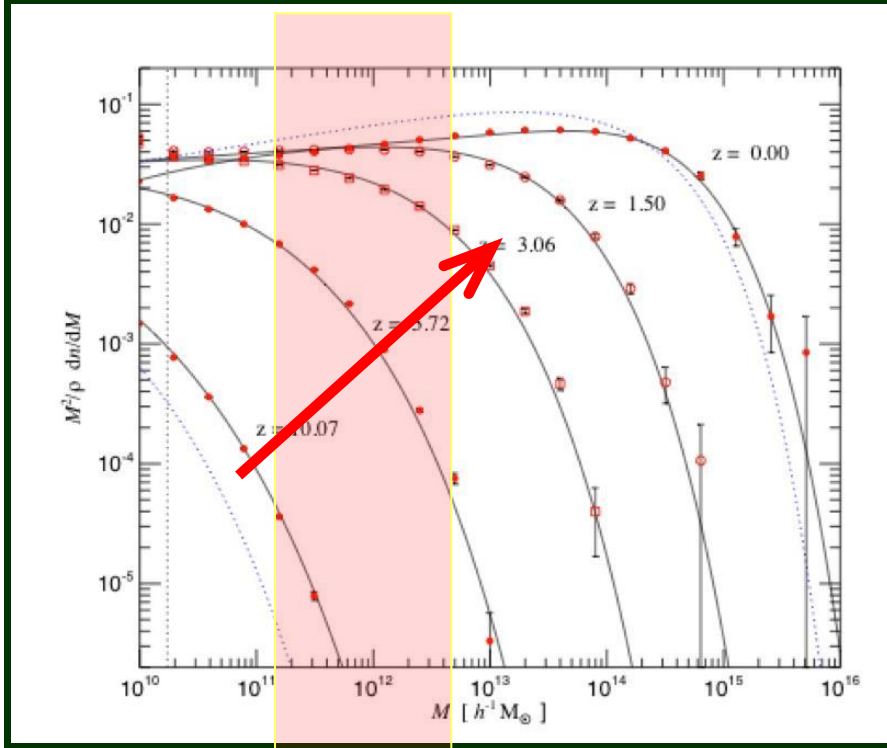
Evolution of UV LF

- rest-UV LF evolution of LBGs
- Significant number evolution at the bright end at z=7→3
- Consistent w/Yoshida+06, Shimasaku+05; but see Sawicki+06

Rapid Buildup of L* galaxies



Bouwens+ 08

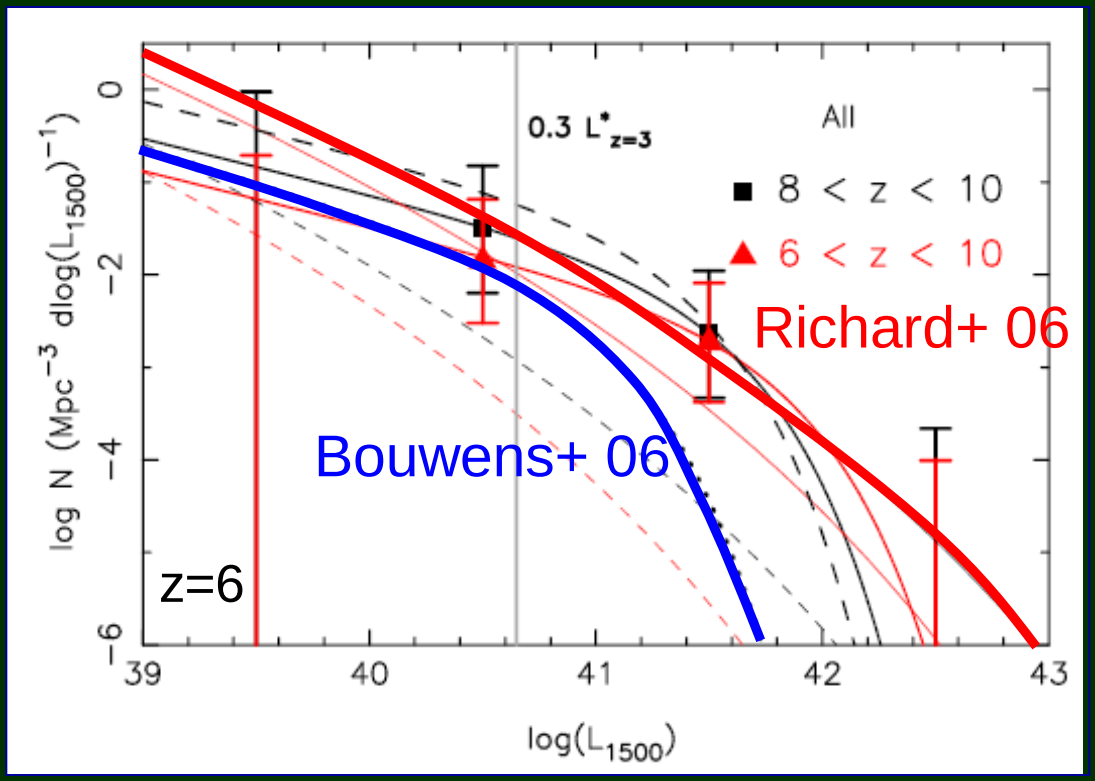


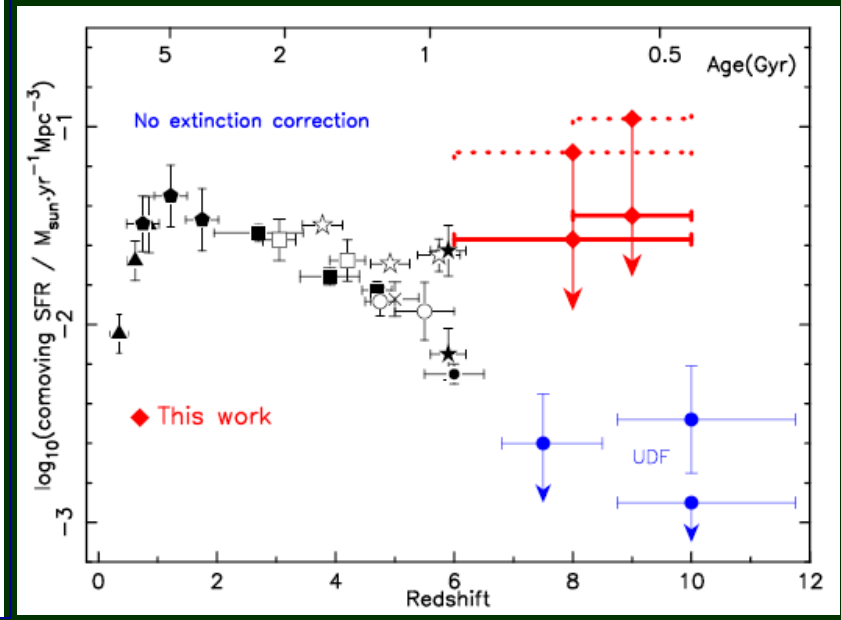
Mass of ~L* galaxies

Springel + 05

UV LF at z~6

- Discrepancy of the results
- Statistically weak, cosmic variance, no spec. sample → limit of current observational facilities



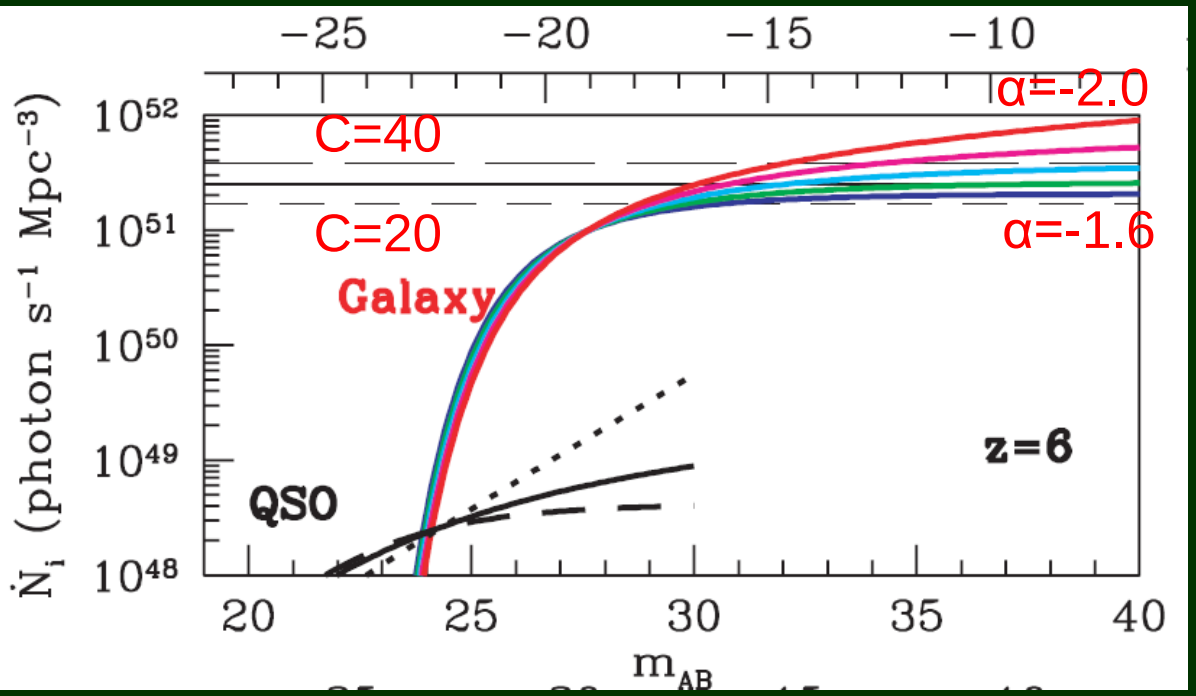


Richard+ 06 VLT/grav.L 12arcmin^2

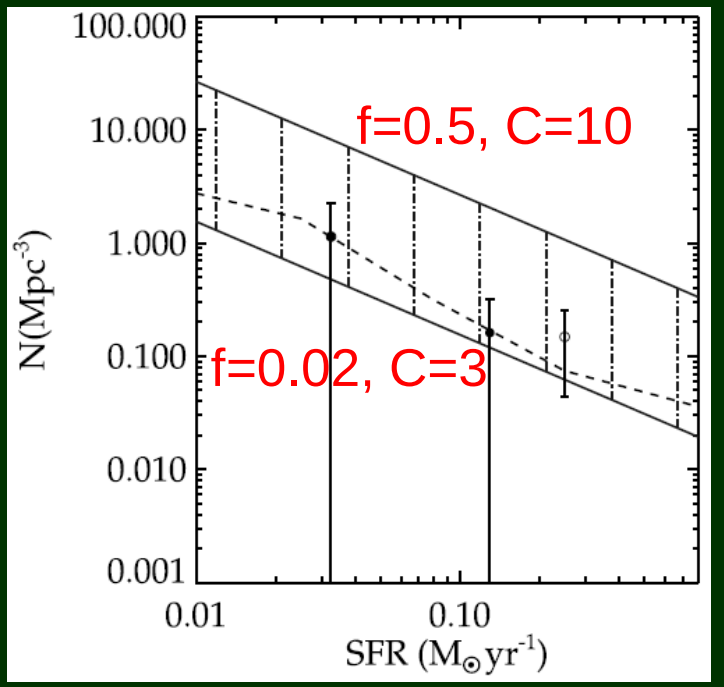
Bouwens+ 06 UDF 5arcmin^2

Photon Budget

- Yan & Windhorst 04; z=6, fesc=0.1, C_{30}=20-40
- Stark+ 07; 8.5<z<10.4
- Richard+ 08; z>7, fesc=0.5, C_{30}=2-10
- sub-L* galaxies predominantly contribute to the photon budget (but see Bunker+ 04)



Yan & Windhorst 04

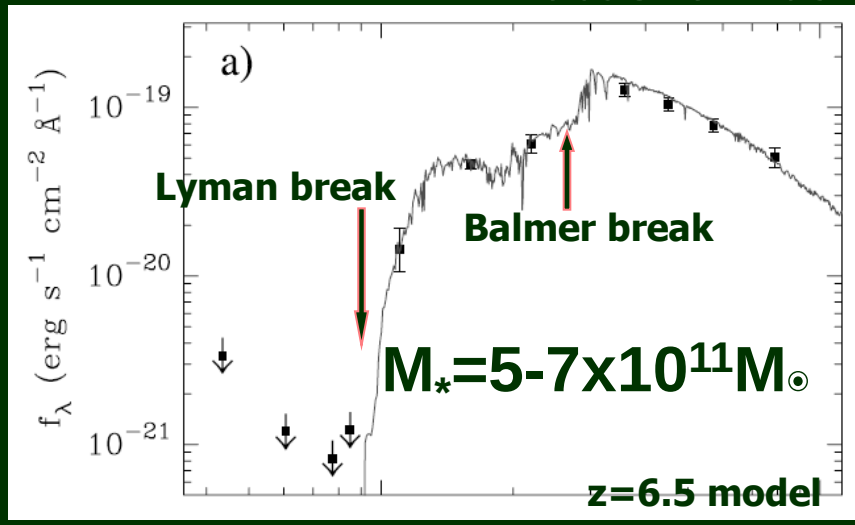


Stark + 07

Old & massive galaxy at z=6.5 ?

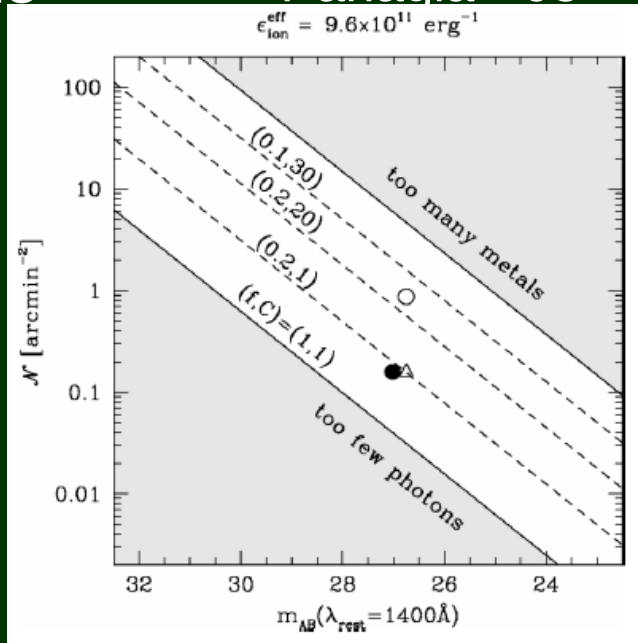
- Old & massive galaxy at z=6.5 ?
  - HUDF-JD2
  - M_*=5-7x$10^{11}M_\odot$!!!
  - 4x nearby L*gal, 50x L*LBG@z=3!
  - z_f>9
  - Derived by photo-z、no spec. confirm.

Mobasher+ 05



- HUDF-JD2-like population only can reionize the universe w/(f,c)=(0.2, 20)

Panagia+ 05



- Very dusty galaxy at z=6.5 ? A_V～1, z_f～20 (Chary+ 05)
- No LBGs >3x$10^{11}M_\odot$ at z=5 (McLure+ 06)
- HUDF-JD2 at z~3 w/another photo-z code (Rodighiero+ 07)

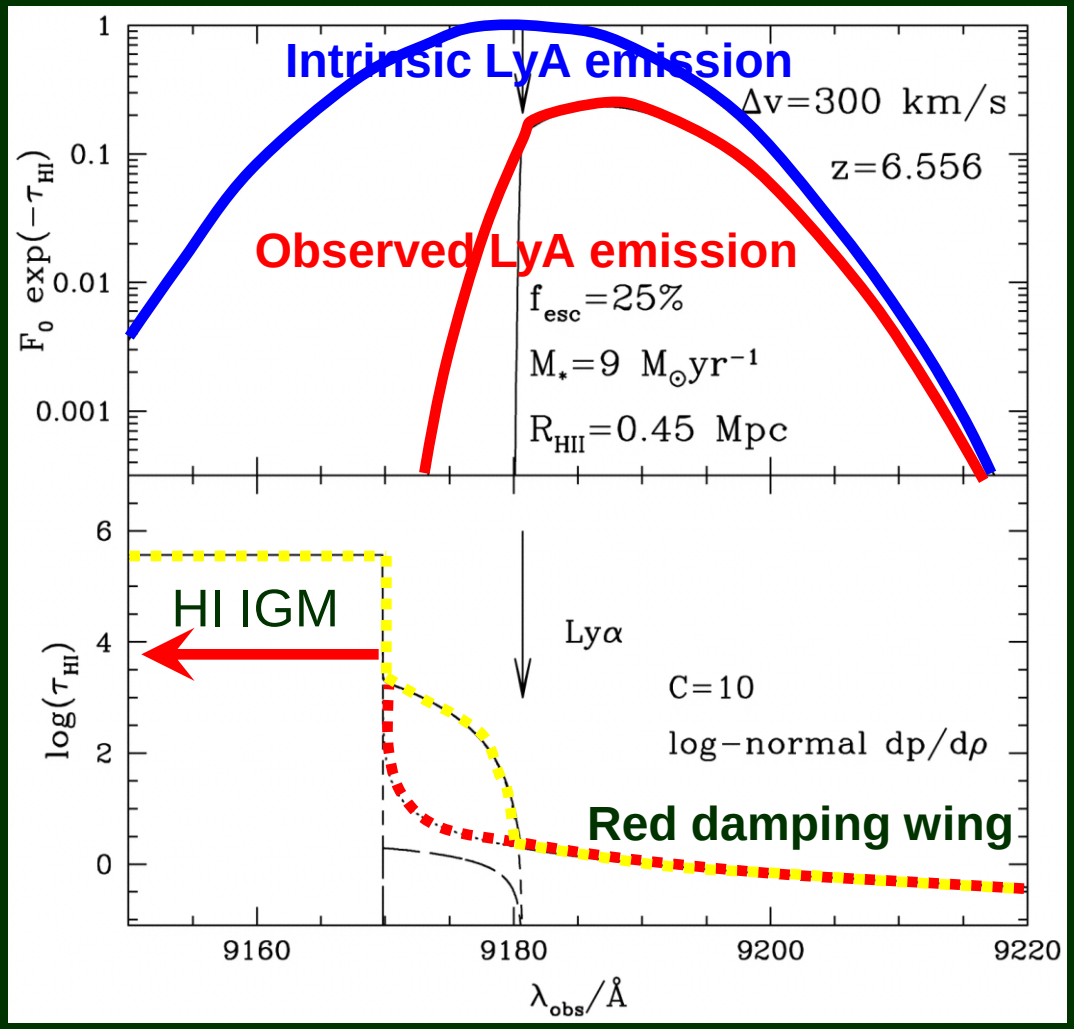
Reionization probed by LyA emission line

When did the reionization take place ?

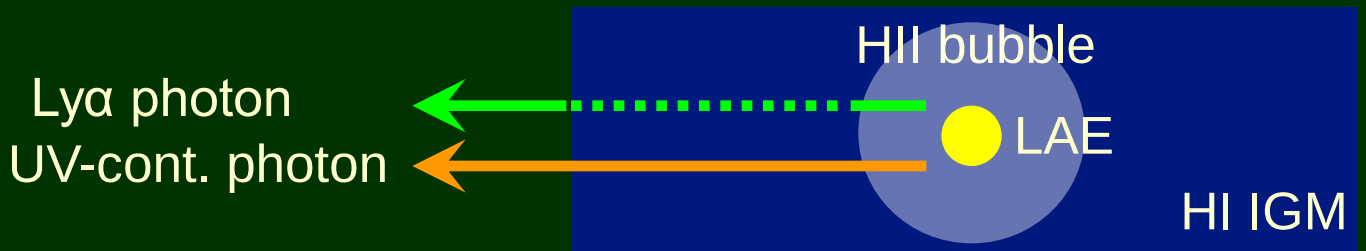
Reionization proved by LAEs

Lyα emission line profile

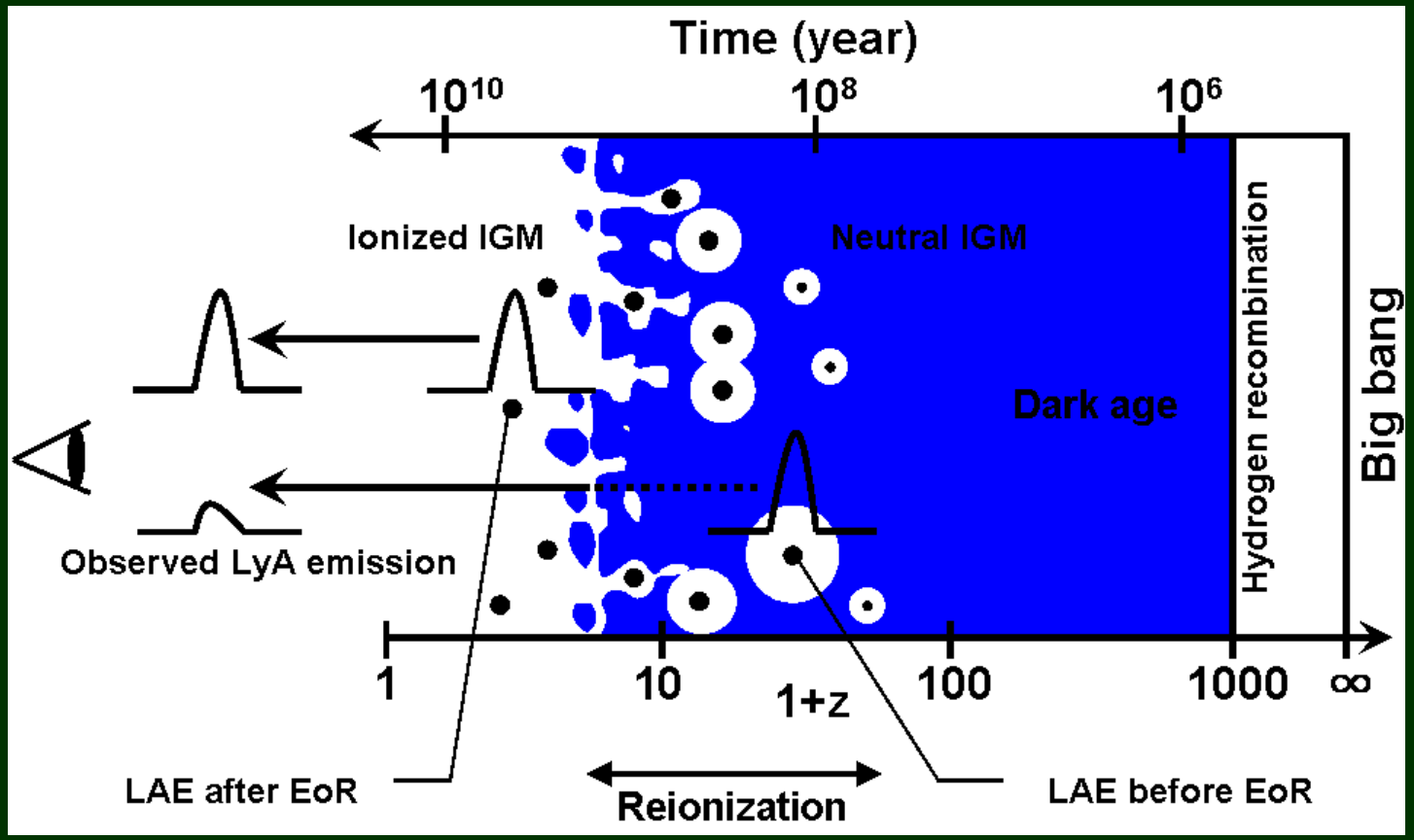
Optical depth distribution



Haiman+ 02



Reionization proved by LAEs

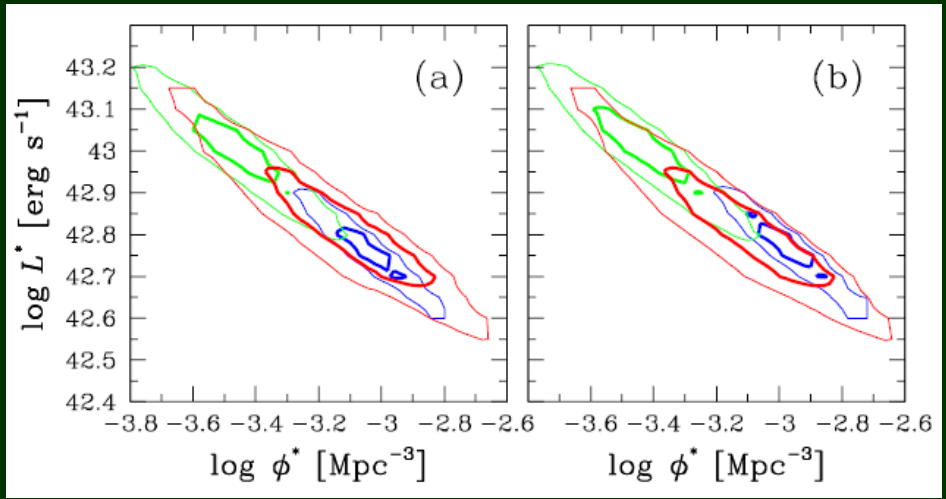


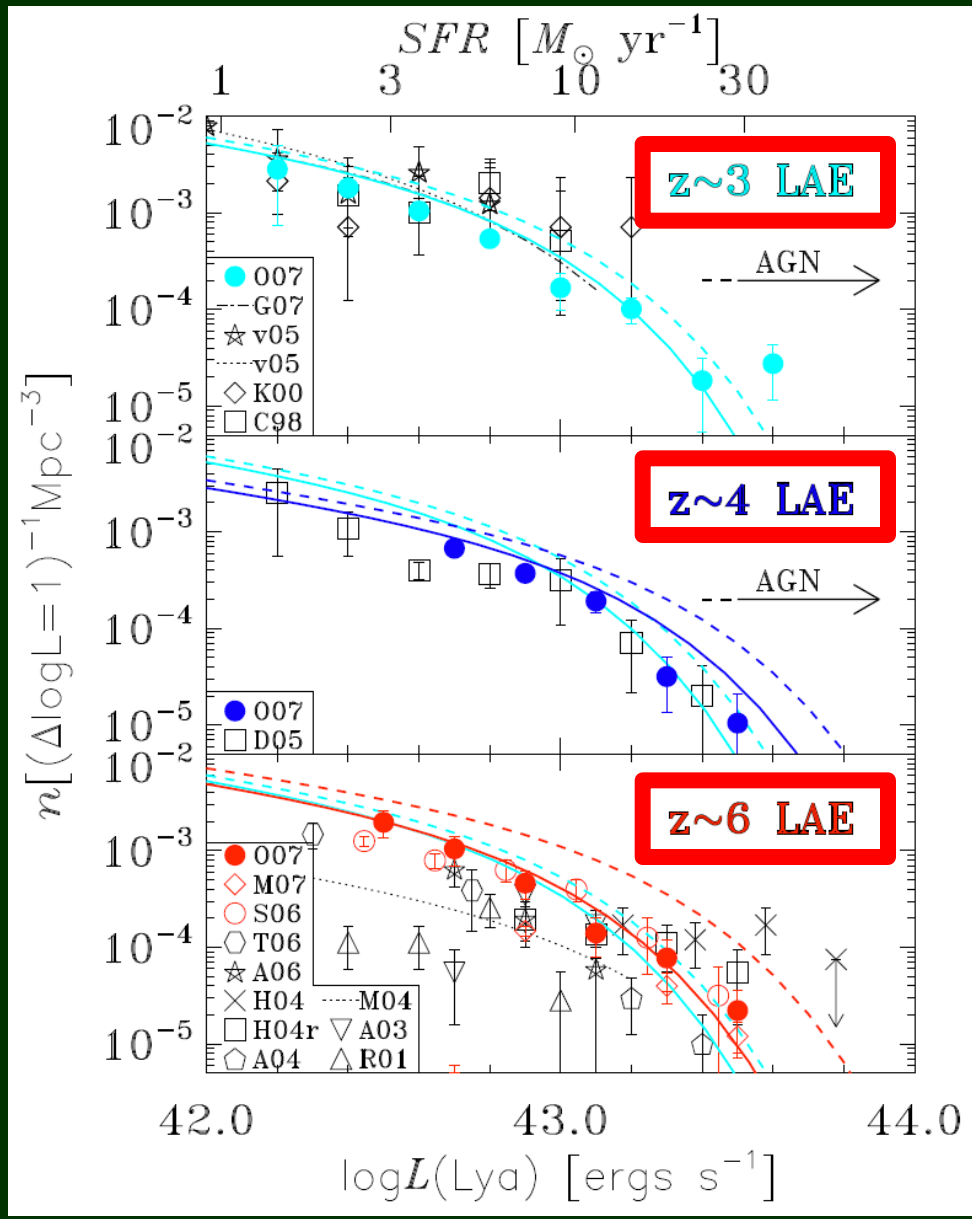
- Significant decline of LAE-LF suggests IGM attenuation
  (Haiman & Spaans 99, Malhotra & Rhoads 04)

- 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



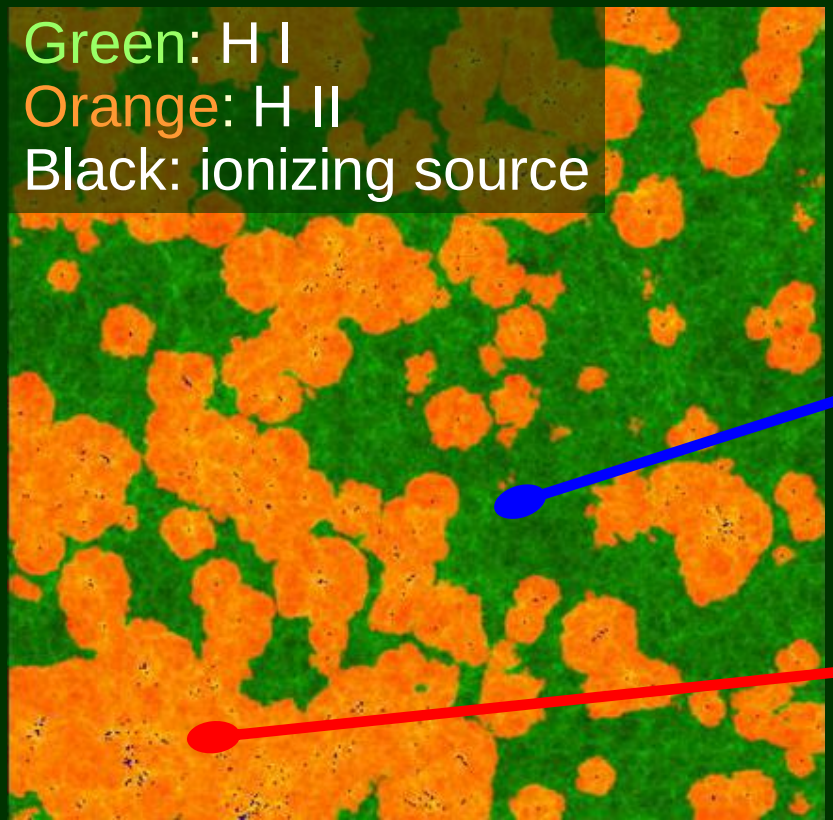


Ouchi+ 08

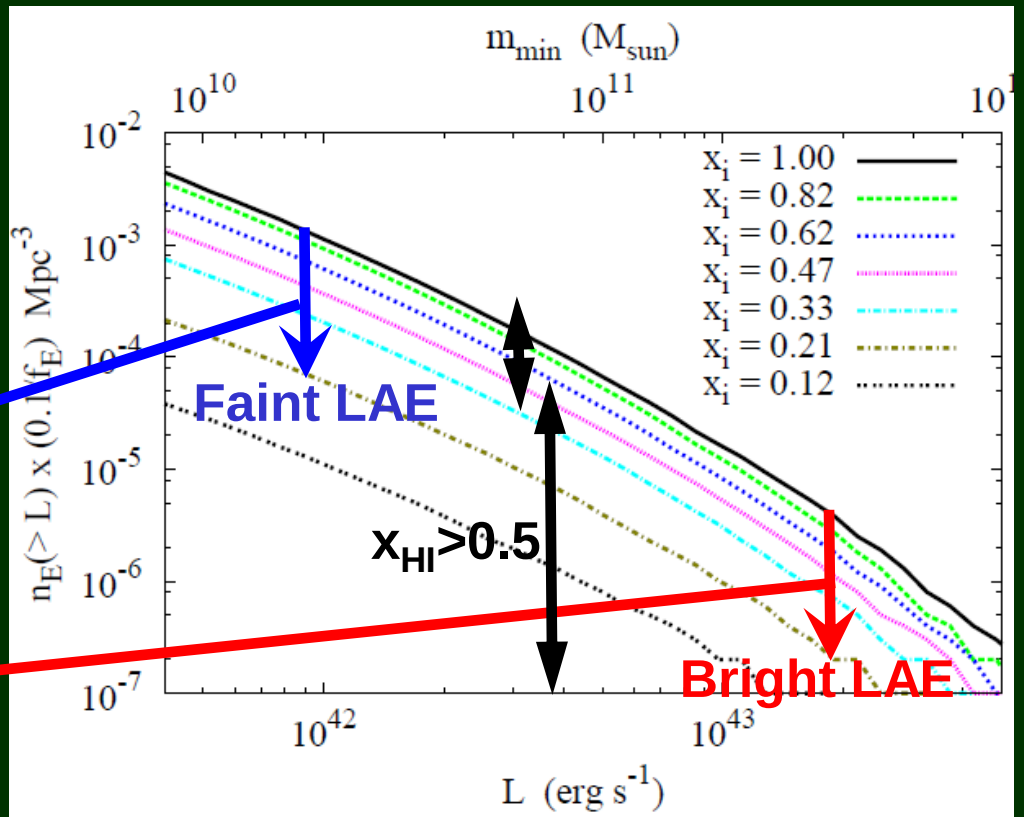
Theoretical predictions

- 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, Kobayashi+ 07, Iliev+ 08, Dayal+ 09

Iliev+ 06

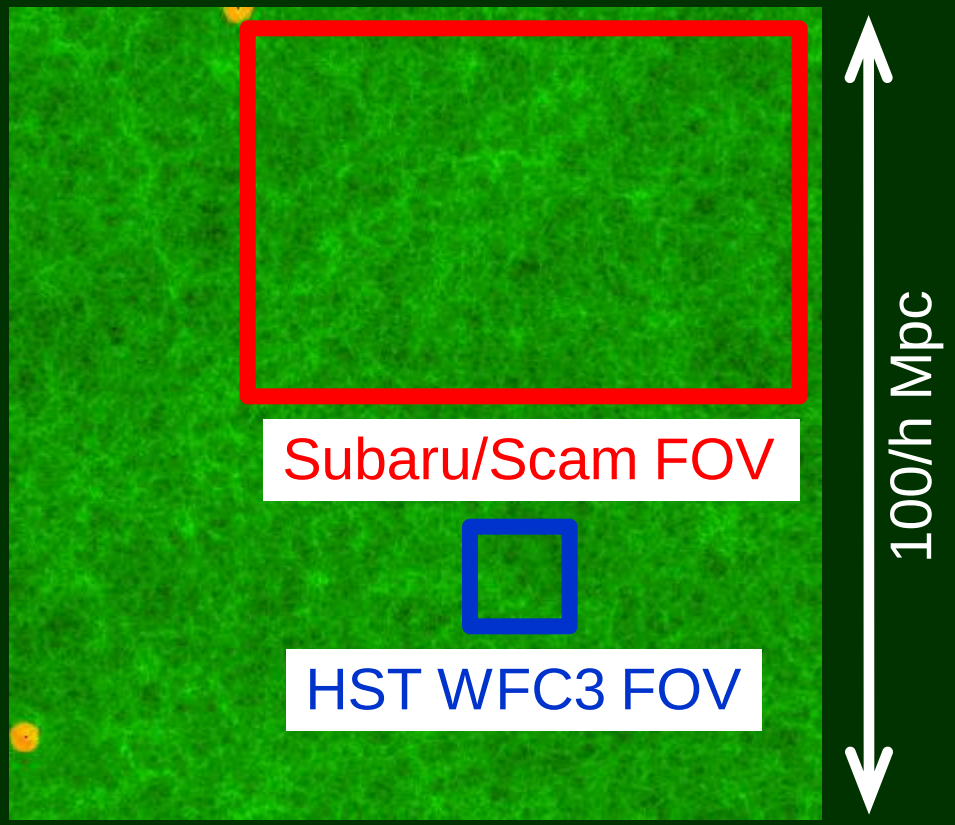


McQuinn+ 07

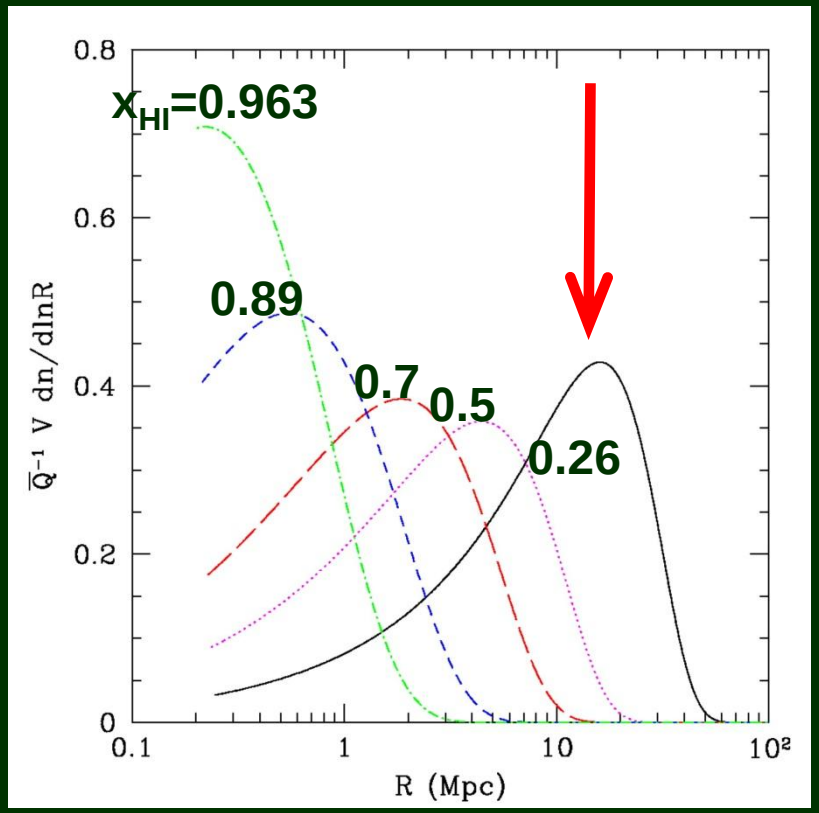


Large FOV is required — scale of reionization

- 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

Comparison of Lyα LF between z=6.5 and 5.7

- Apparent deficit compared w/ z=5.7

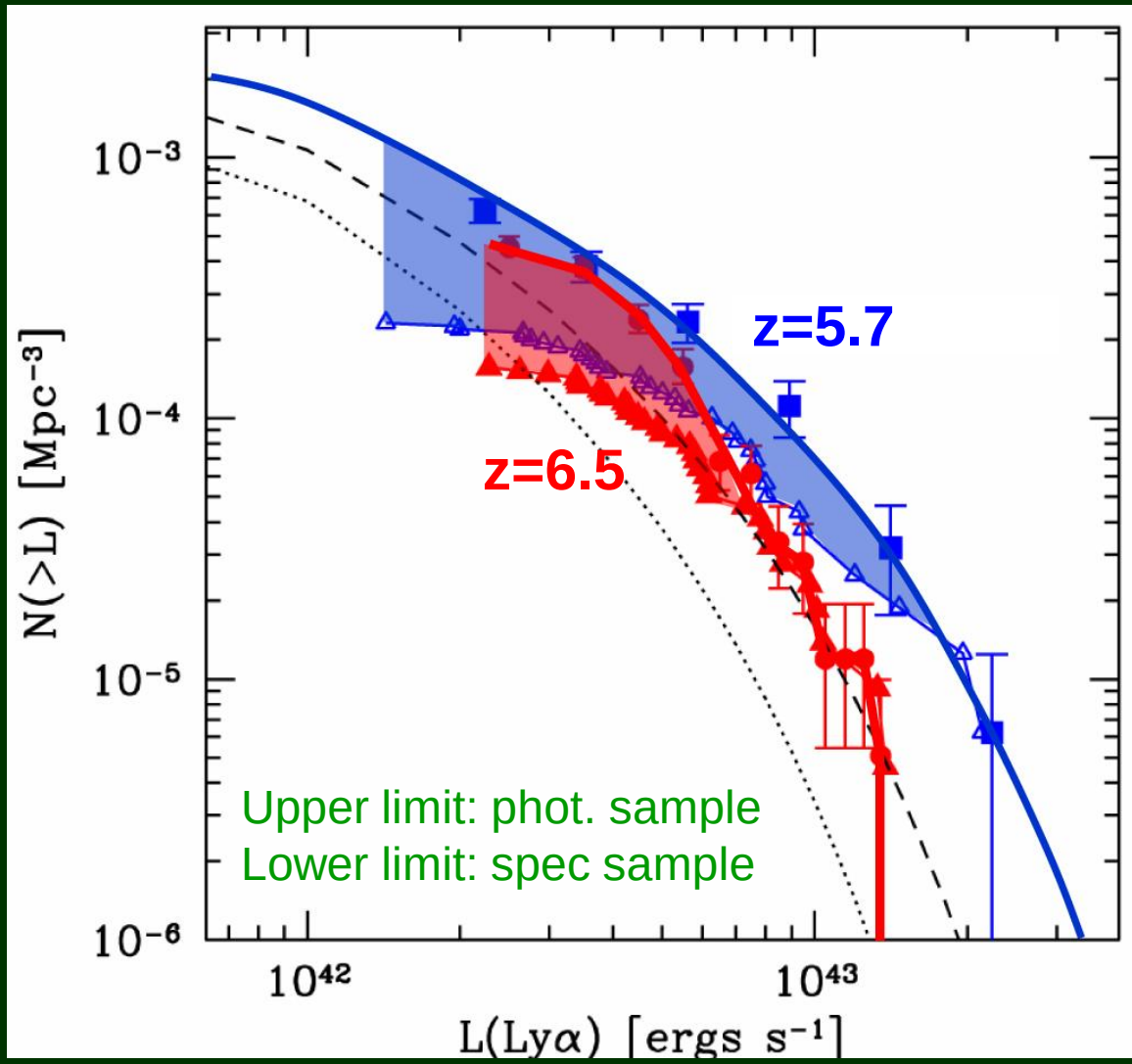
- Based on large volume, homogeneous sample in a general field
- Almost all of bright LAEs have been spec. identified.
- L(LyA) of z=6.5LAEs in other fields w/o grav.L

  -Kurk 04 1.1×10^{43} erg/s

  -Rhoads 04 1.1×10^{43}

  -Stern 05 1.04×10^{43}

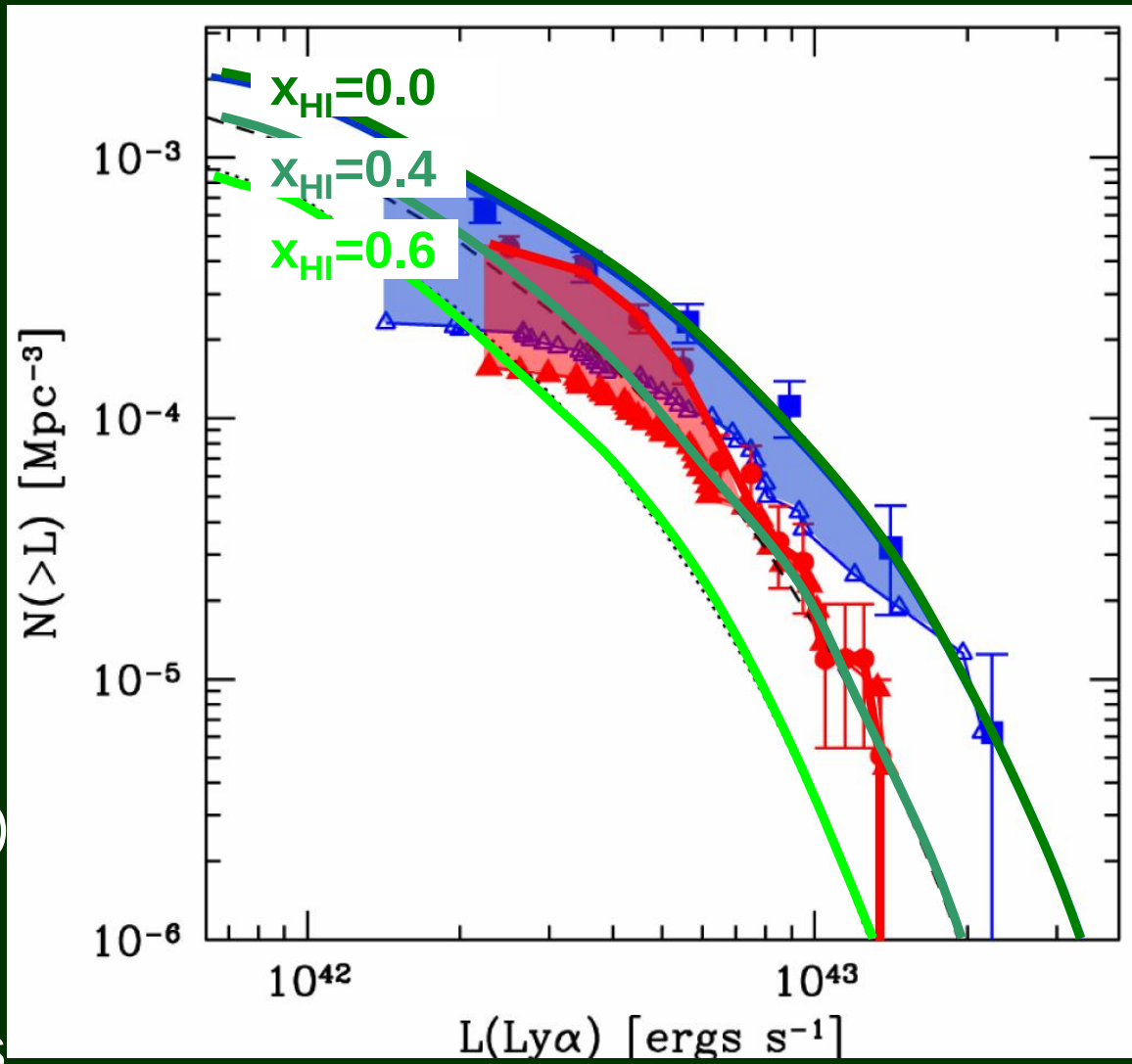
→ consistent w/ our bright end



NK+ 06 updated

Comparison of Lyα LF between z=6.5 and 5.7

- 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)
- Uncertain for the faint end difference → needs more spectroscopy



NK+ 06 updated

Comparison of the rest-UV LF of LAEs

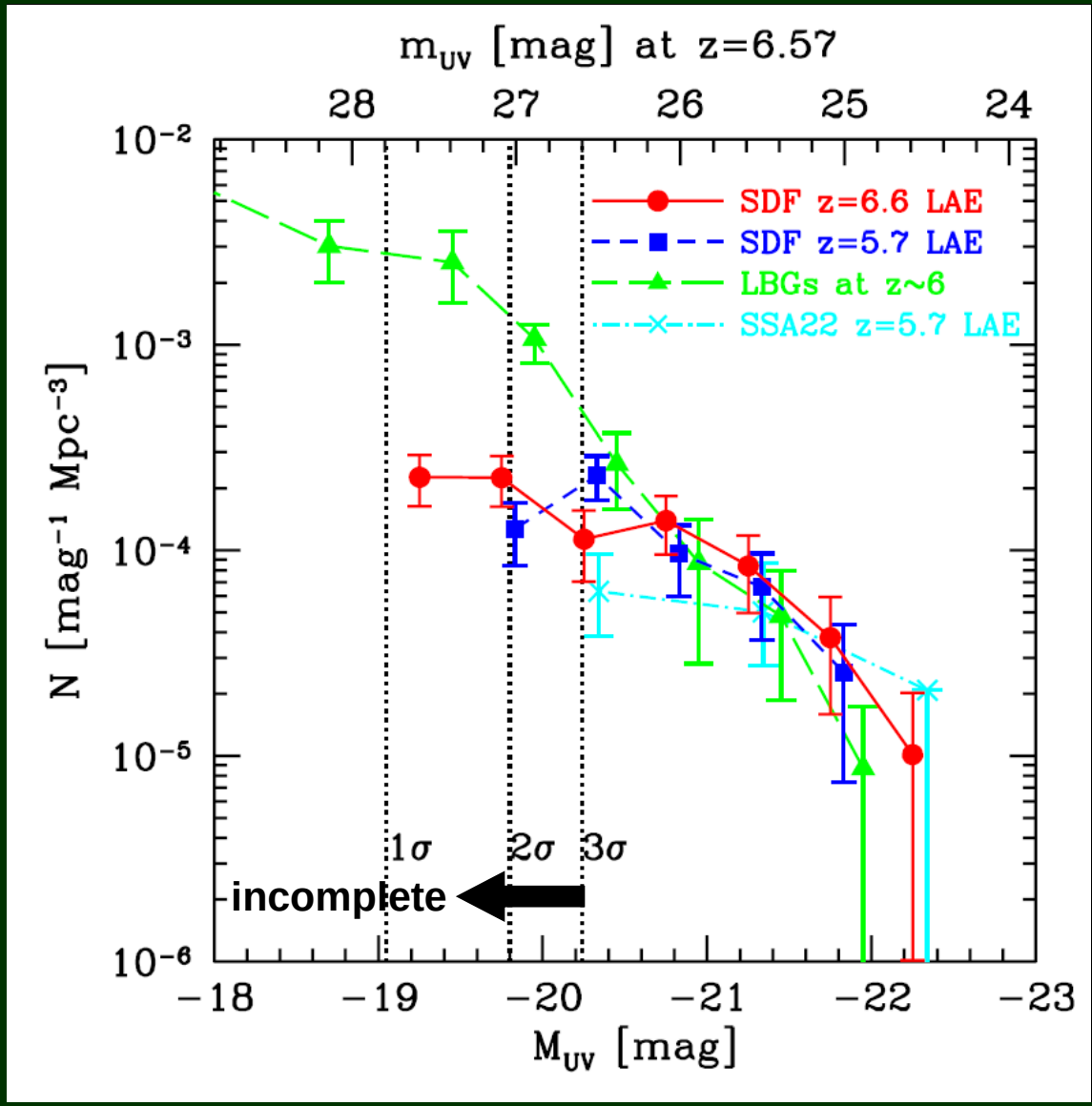
- LyA LF difference is caused by

  IGM attenuation ?

  vs.

  galaxy evolution ?
- The rest UV (1255A) flux is not sensitive to neutral IGM

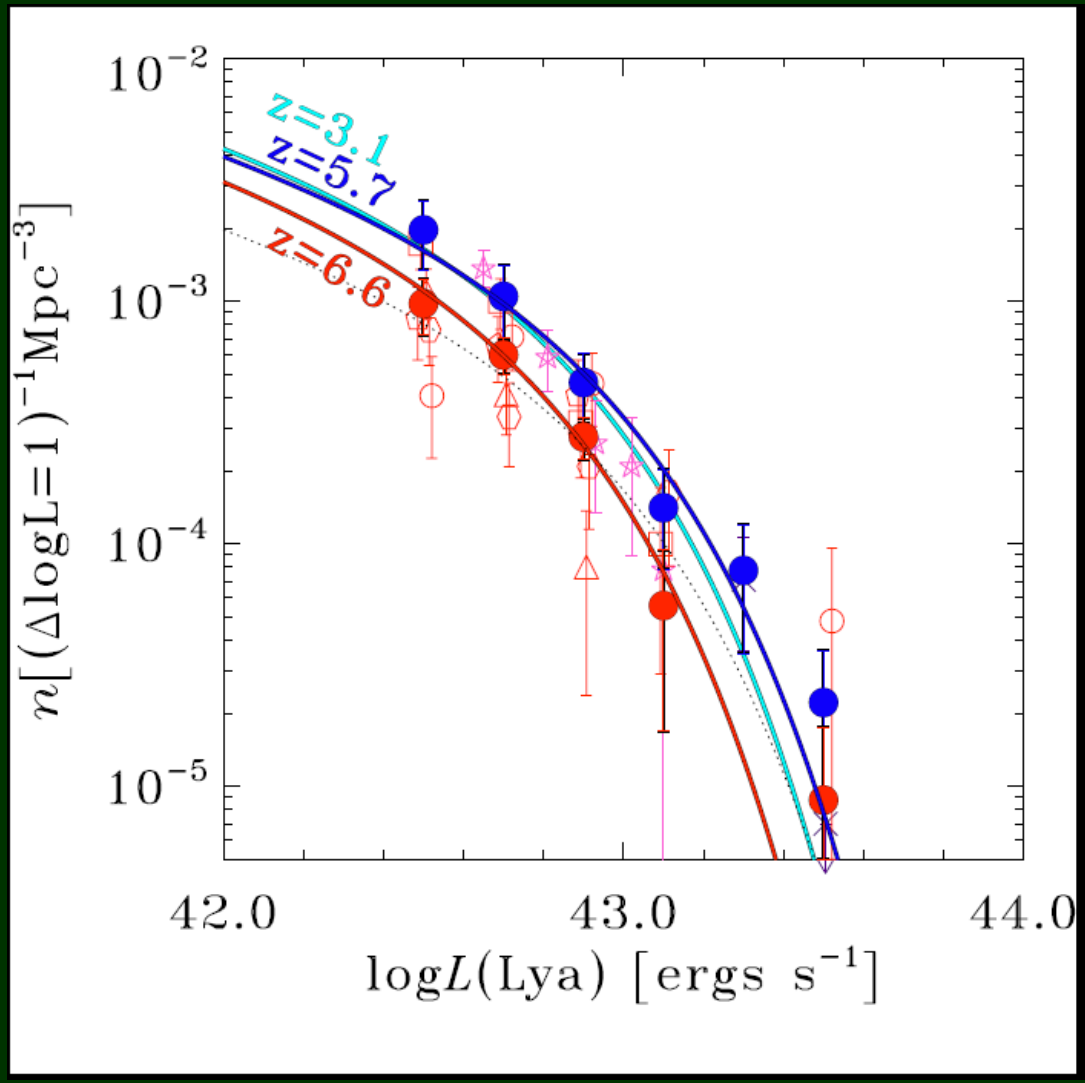
- The rest-UV LF of LAE at z=6.5 agrees w/ LAEs at z=5.7



Comparison of Lyα LF between z=6.5 and 5.7

- New independent result based on 1sqdeg survey
- Much less affected by cosmic variance than the previous survey

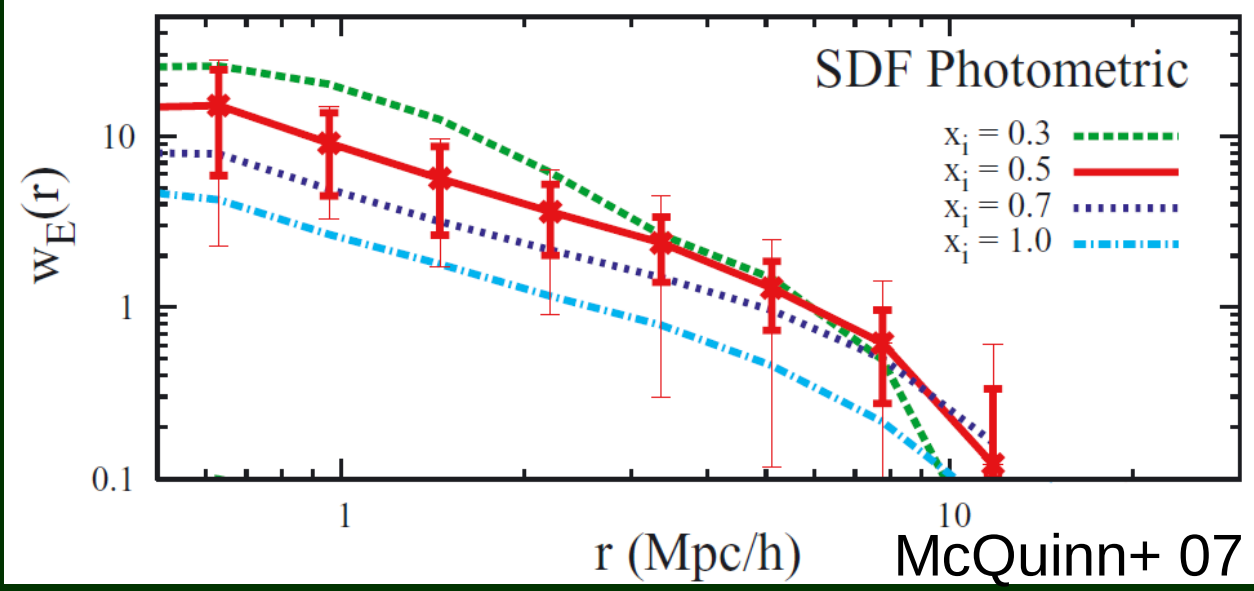
- 30% decline of LF amplitude from z=5.7 to 6.5
- Consistent support from 5x wider FOV survey
- Decline also at the faint end?



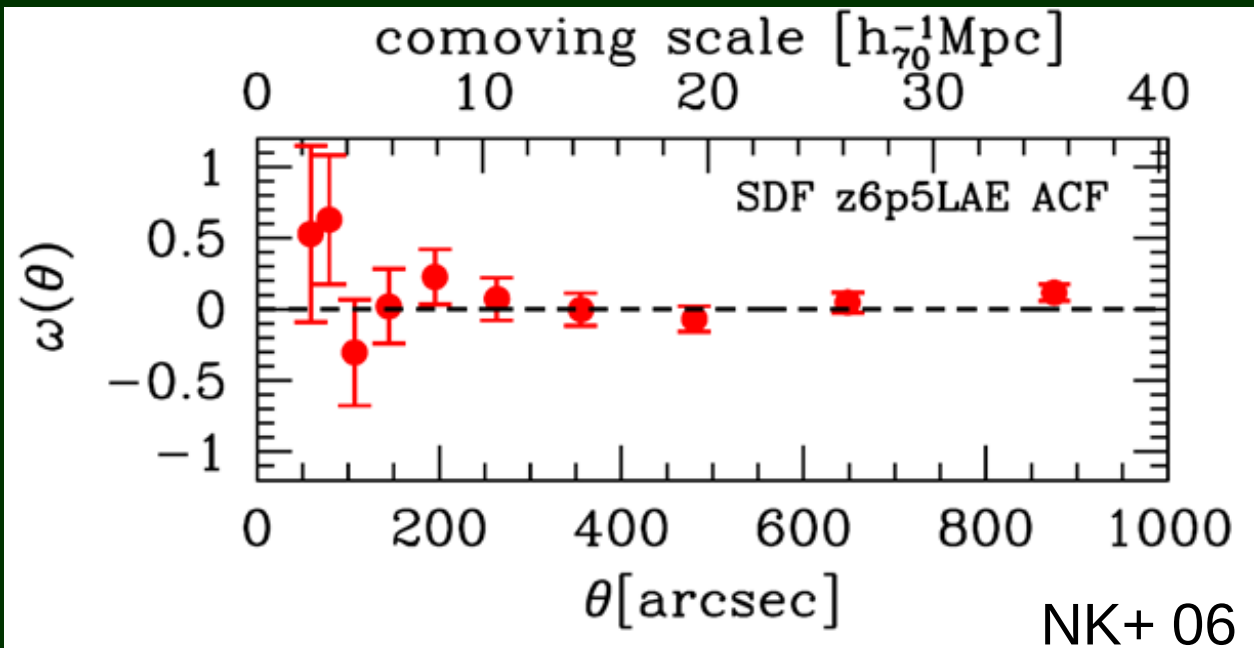
Ouchi+ in prep. (very preliminary)

Clustering of z=6.5 LAEs

- Theory: Enhanced clustering signature during reionization. (see also Orsi+ 08, Nagamine+ 08)
- Observation: LAE at z=6.5 has a homogeneous distribution ~40Mpc
- consistent w/x_{HI}<0.5
- Cosmic variance ?



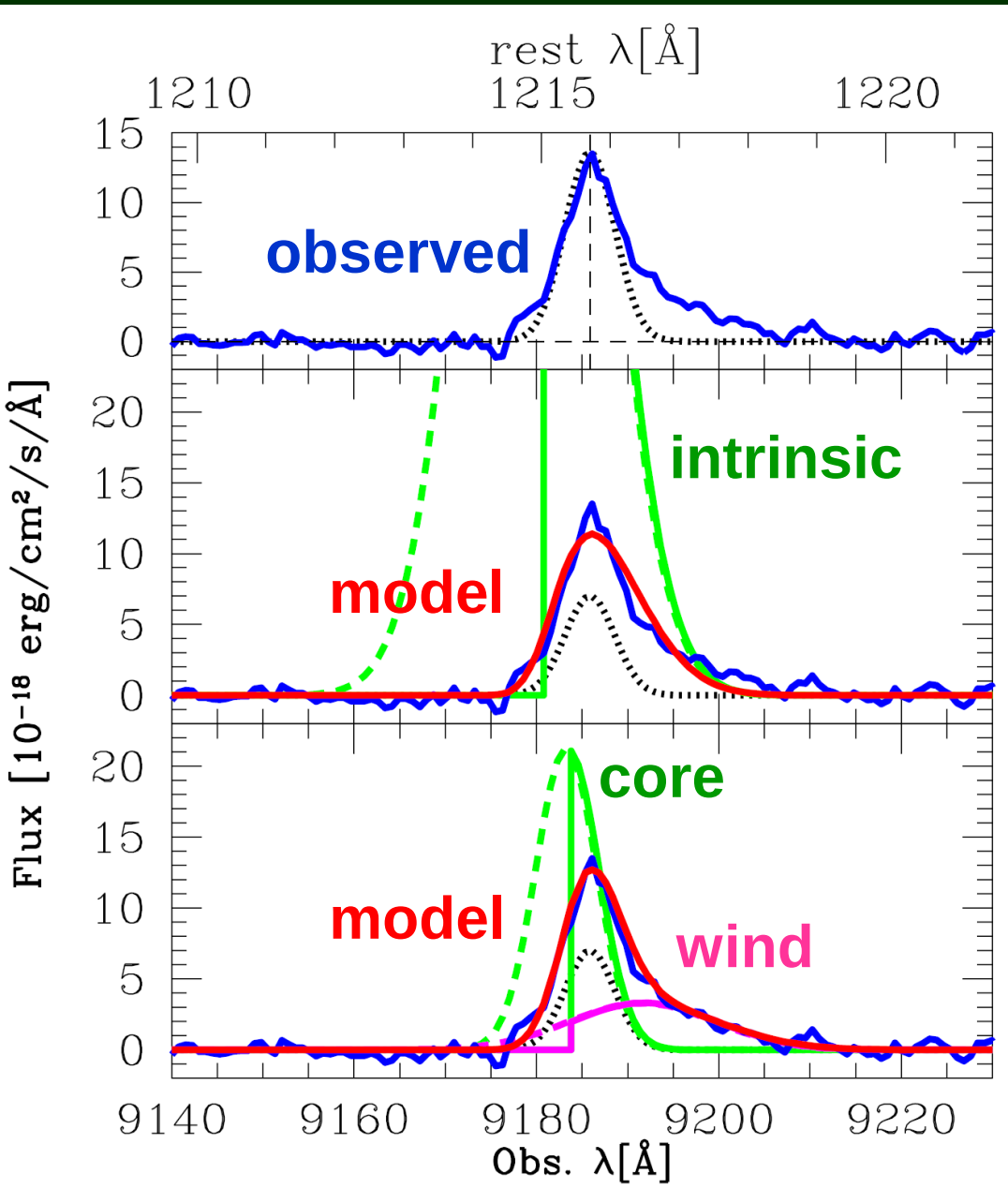
McQuinn+ 07



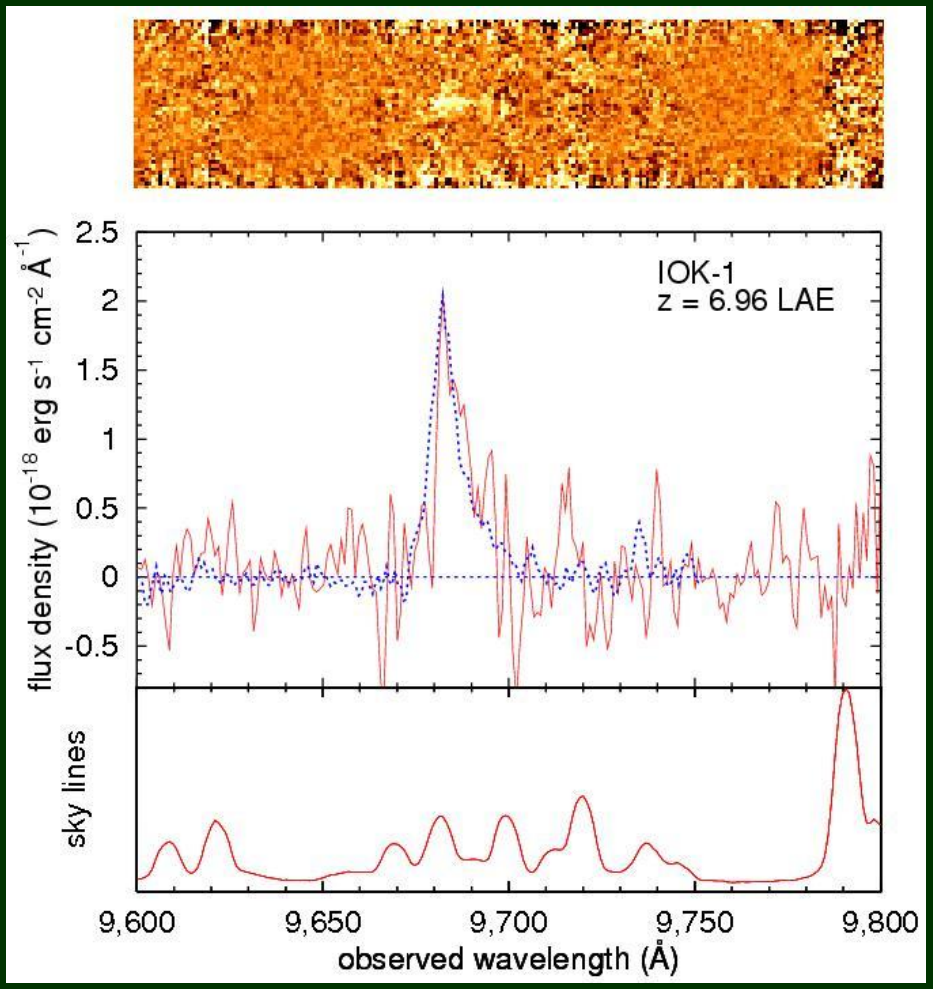
NK+ 06

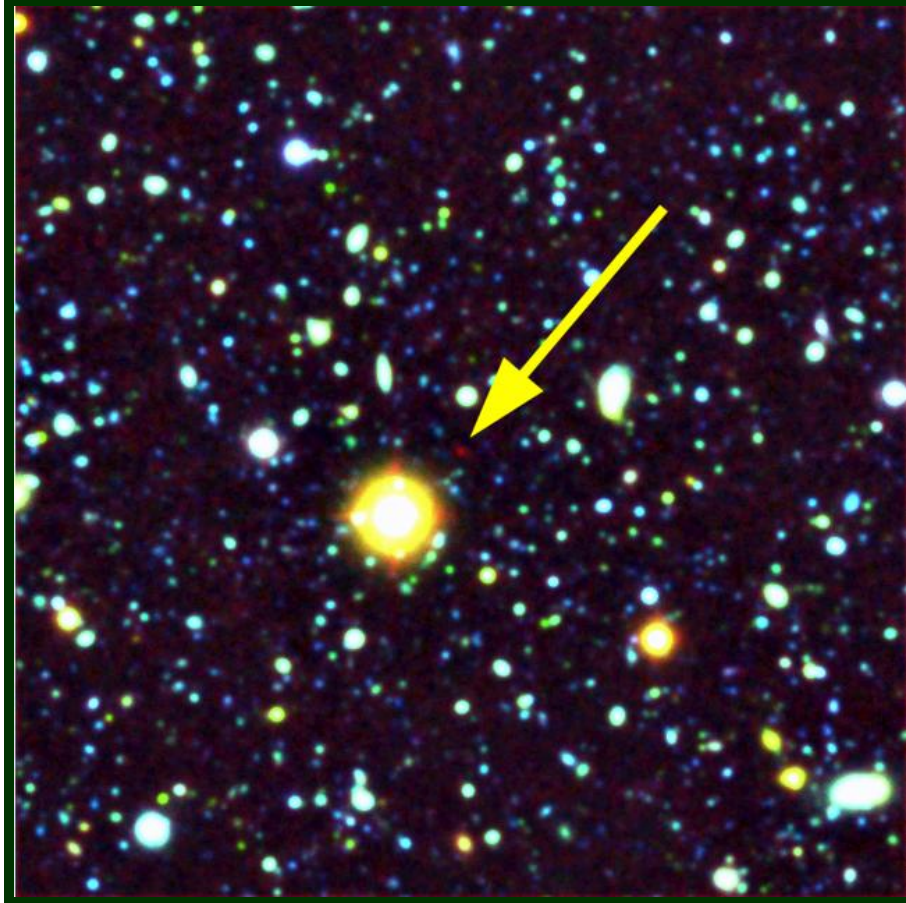
composite spectrum of z=6.5 LAEs

- 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

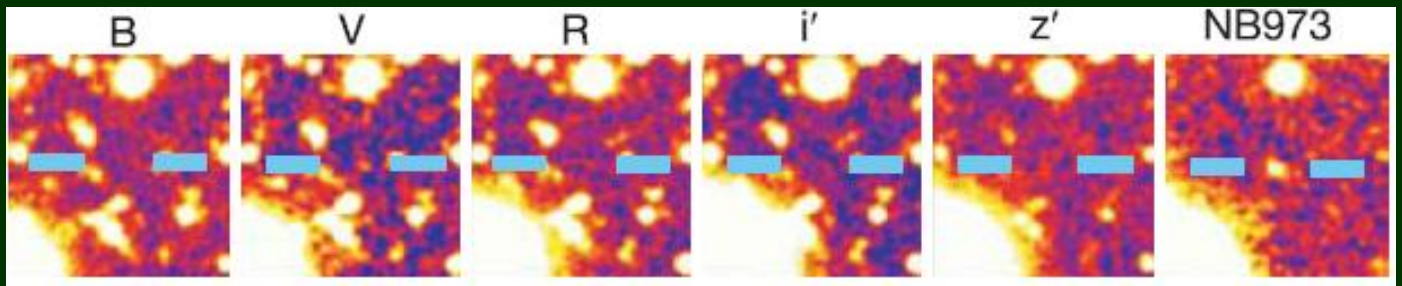


A LAE at z=6.96 in the SDF





Iye, Ota, NK+ 06

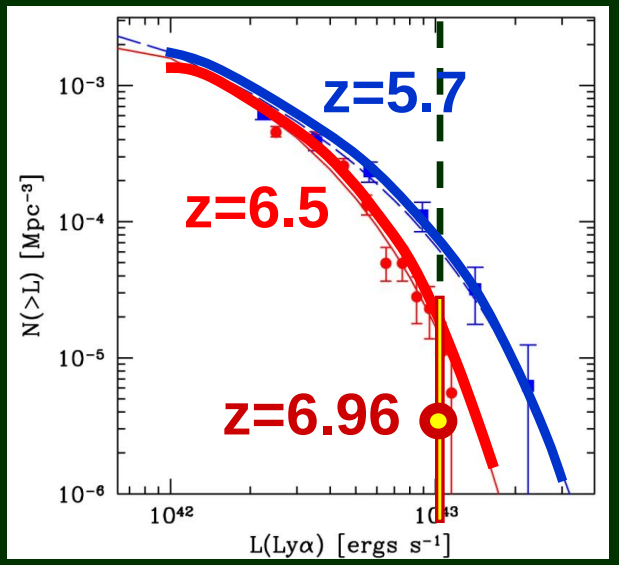


The Madau plot of LAEs

- The only one galaxy at z=7 hardly constrain the LyA-LF, but…
- The LAE number density at high-L end decreases:

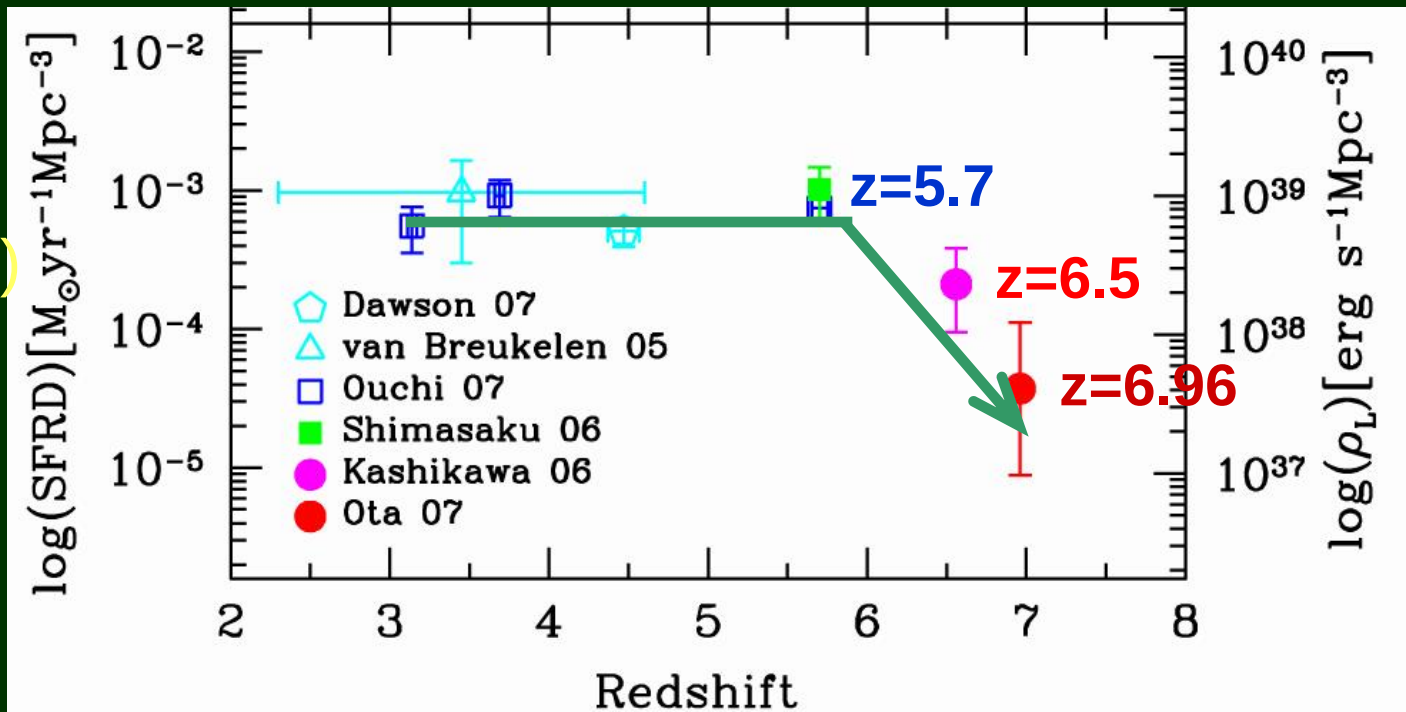
  1.00 → 0.24 → 0.04

  (z=5.7 z=6.5 z=7.0)



Ota, NK+ 07

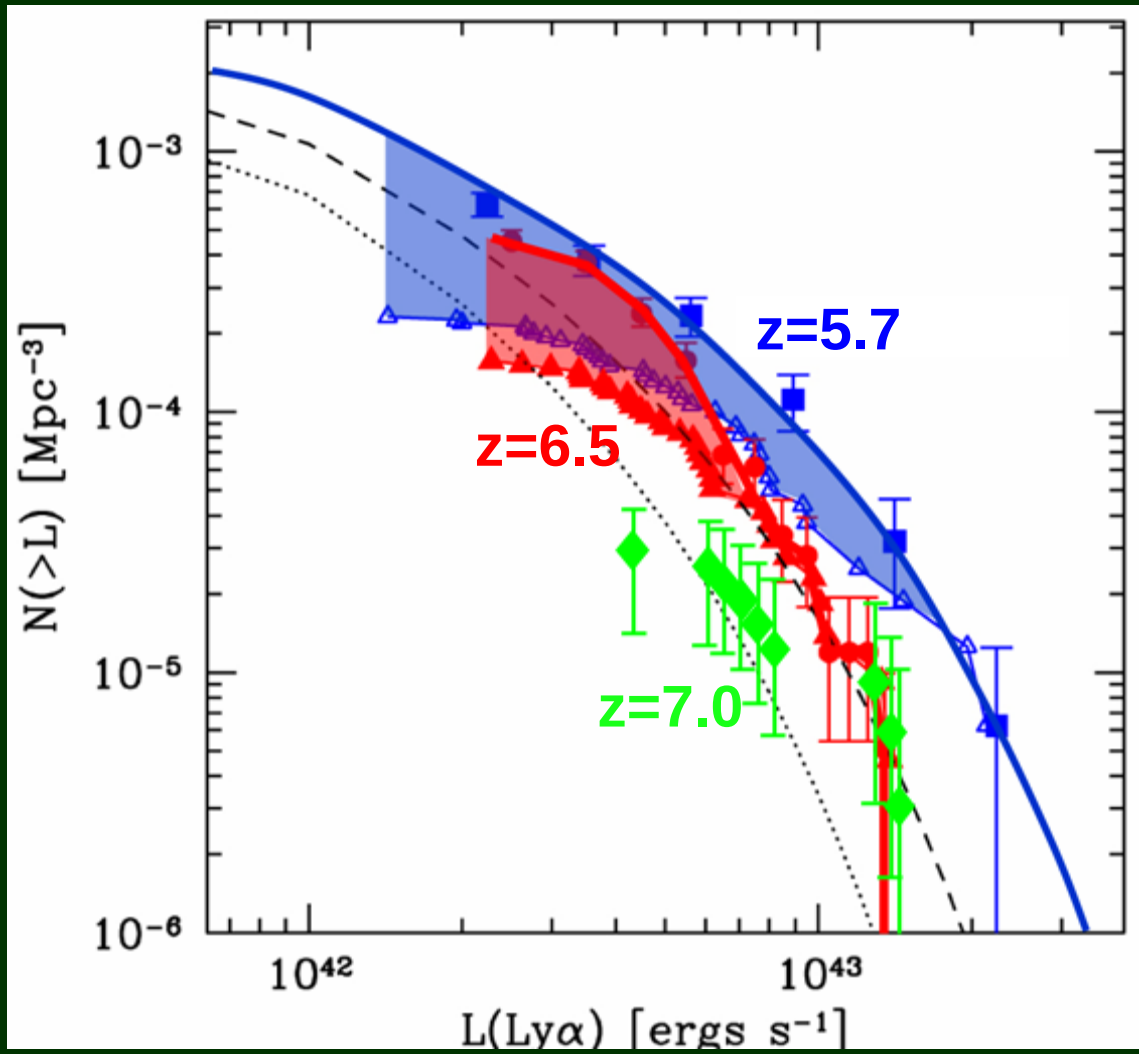
- The LyA luminosity density ($L>1\times10^{43}$erg/s) of LAEs gradually decreases from z=5.7 to 7.0



Updated z=7.0 survey

- New red-sensitive (x2 QE at 9730A) CCDs are installed in Subaru/Scam.
- 13hrs integration w/NB973
- 5σ lim mag=25.4 (←24.9)

- 9 candidates
- Decline of Lyα LF from z=6.5
- Need spec. confirmation

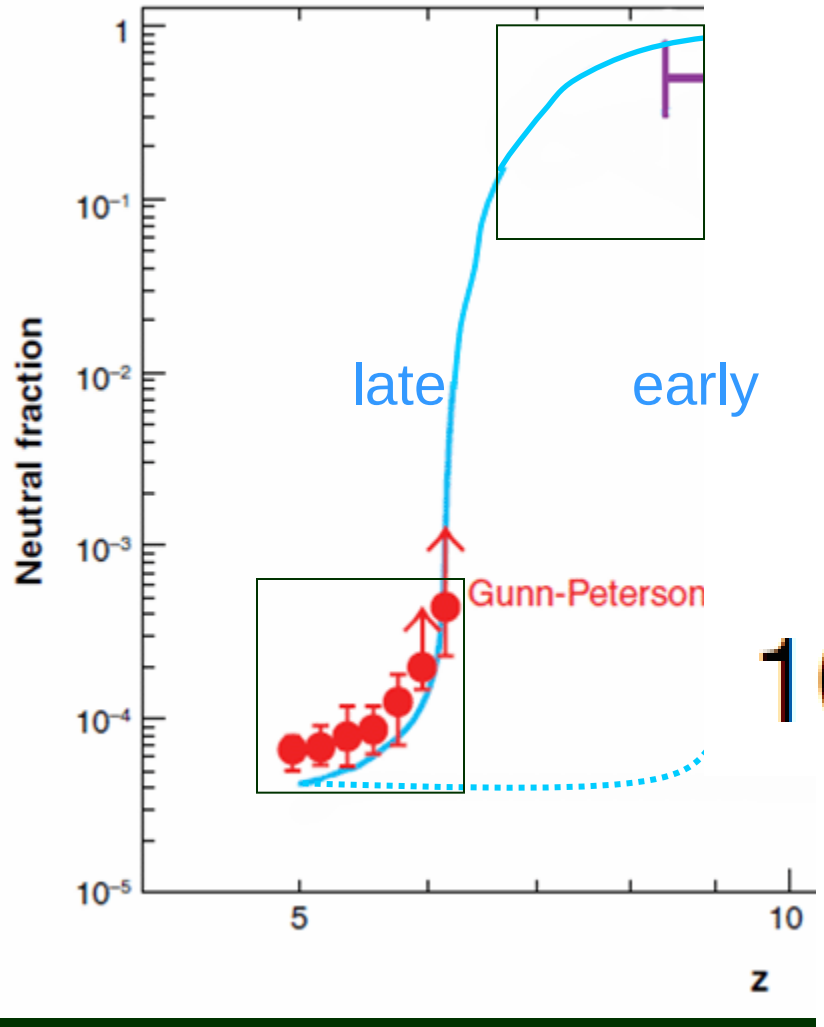


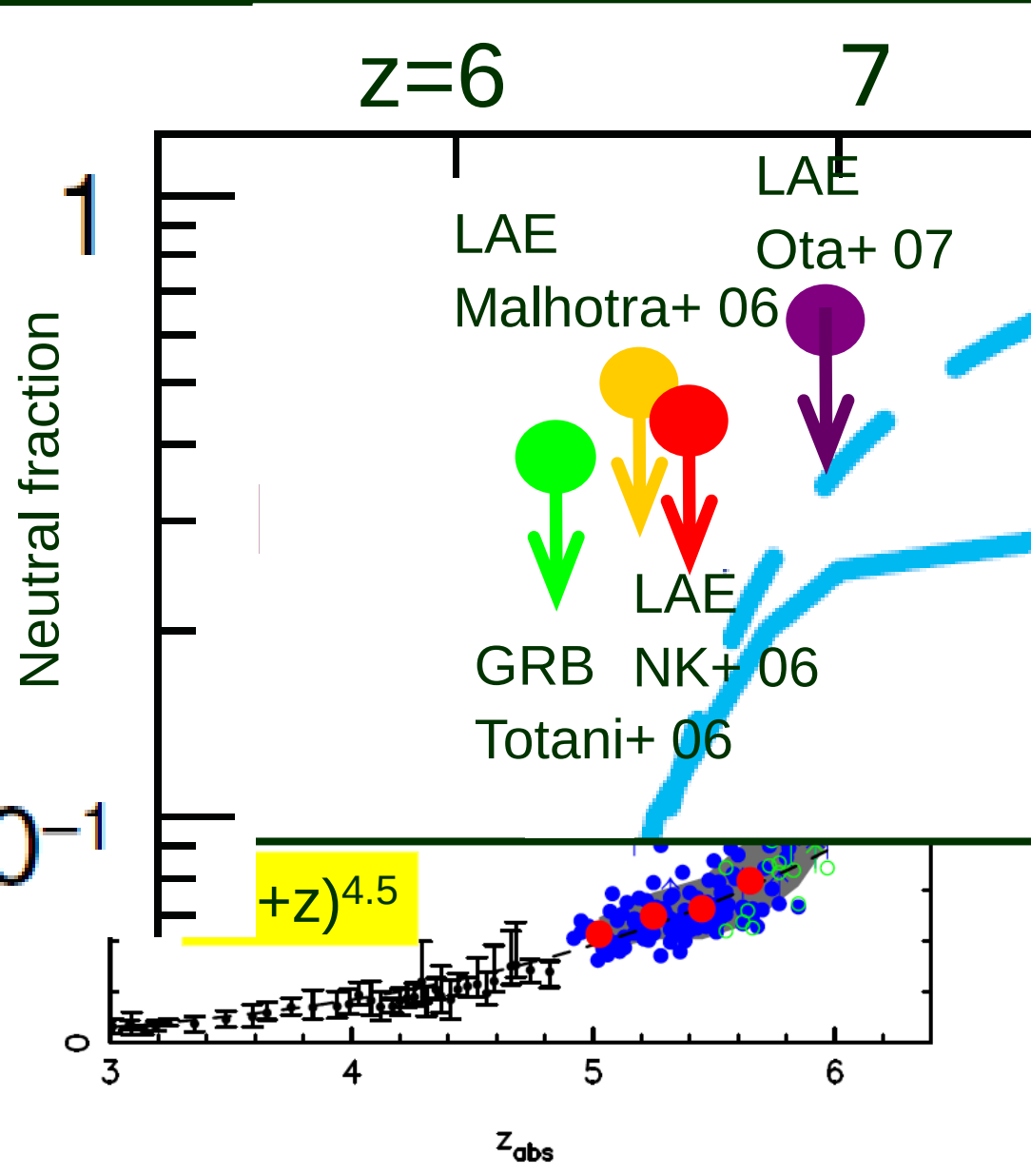
Ota, NK+ in prep. (preliminary)

- See also Hibon+ 09, 7 candidates at z=7.7

Rapid evolution of the ionizing state?

The history of neutral fraction





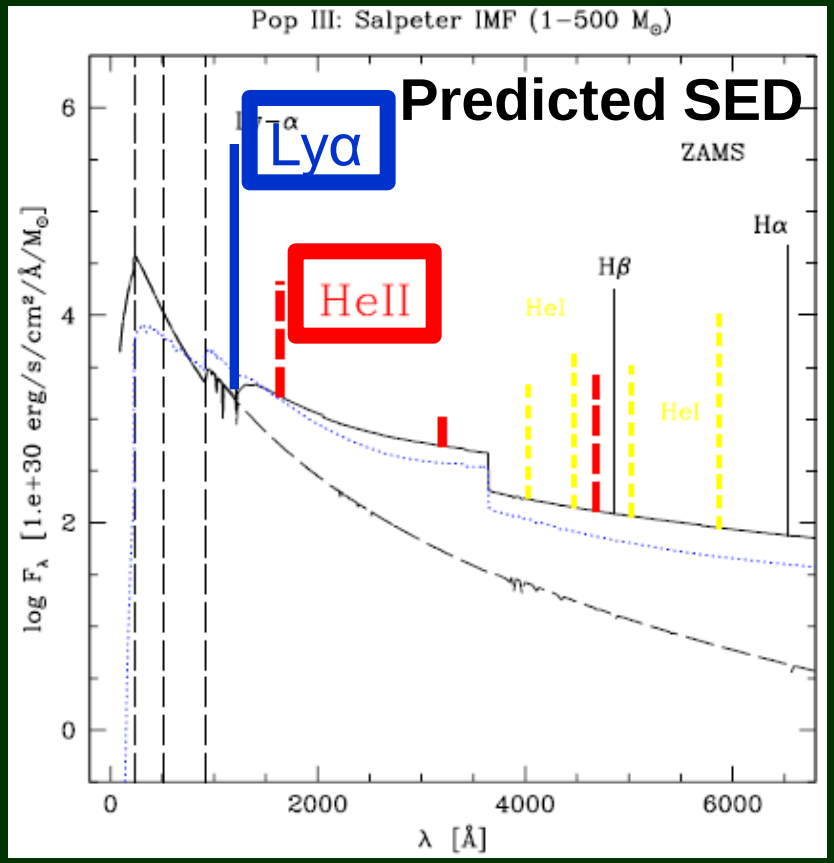
Uncertainties of Lyα-test … too many

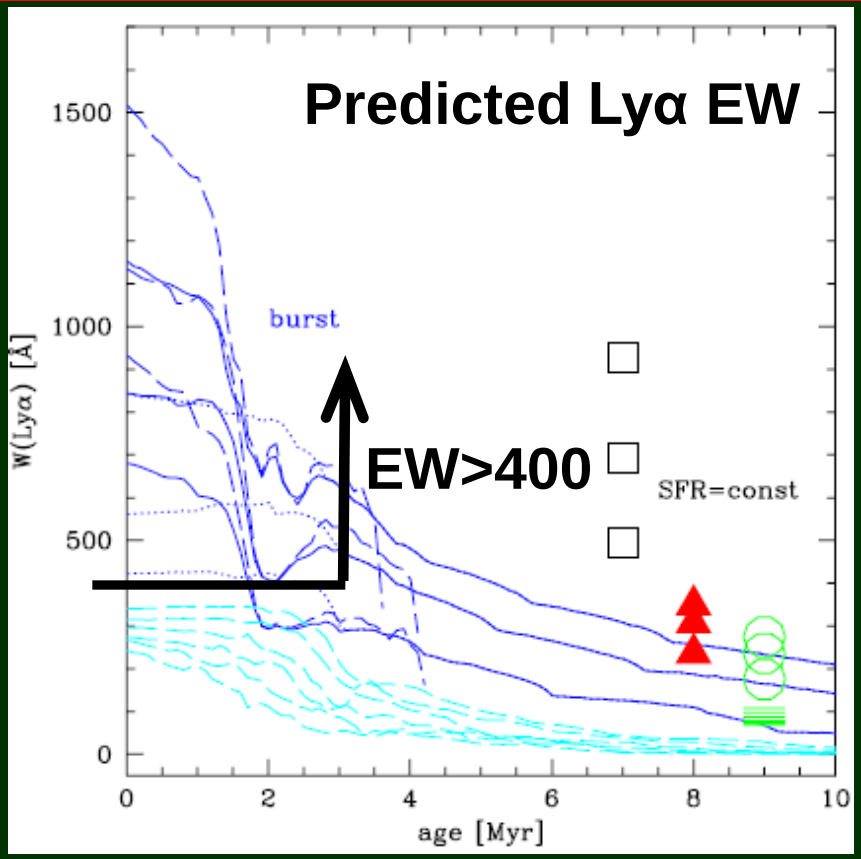
- Intrinsic properties of LAEs
  - Does LAE really have no LF evolution ?
  - Does LAE trace large-scale structure ?
  - Is L(LyA) of LAE proportional to its mass ?
  - How large the effect of dust is ?
  - What is the escape mechanism of LyA photons ?
- Internal structure of LAE
  - How internal density 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

Searches for the Population III objects

Where are the first stars ?

PopIII





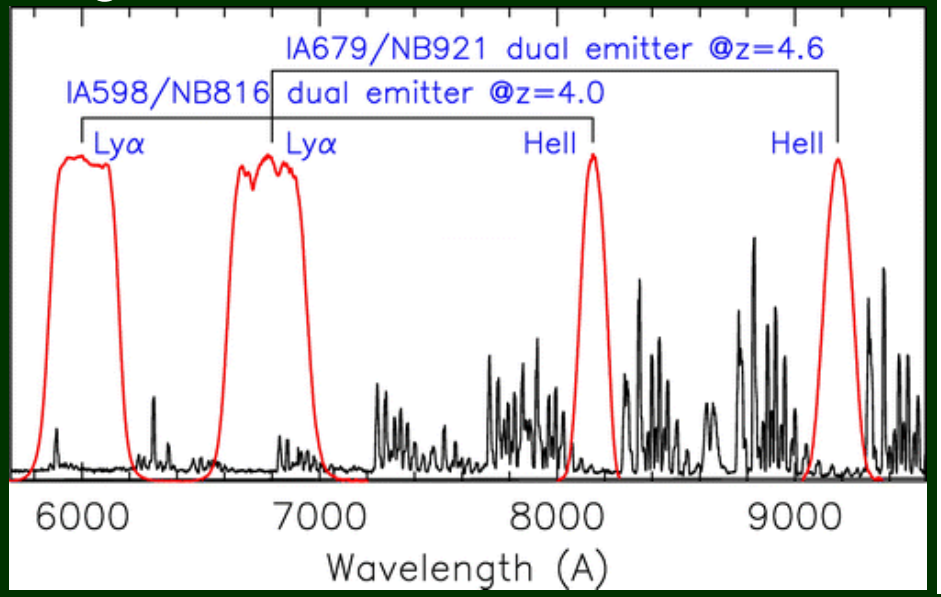
Shaerer+ 02,03

- 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

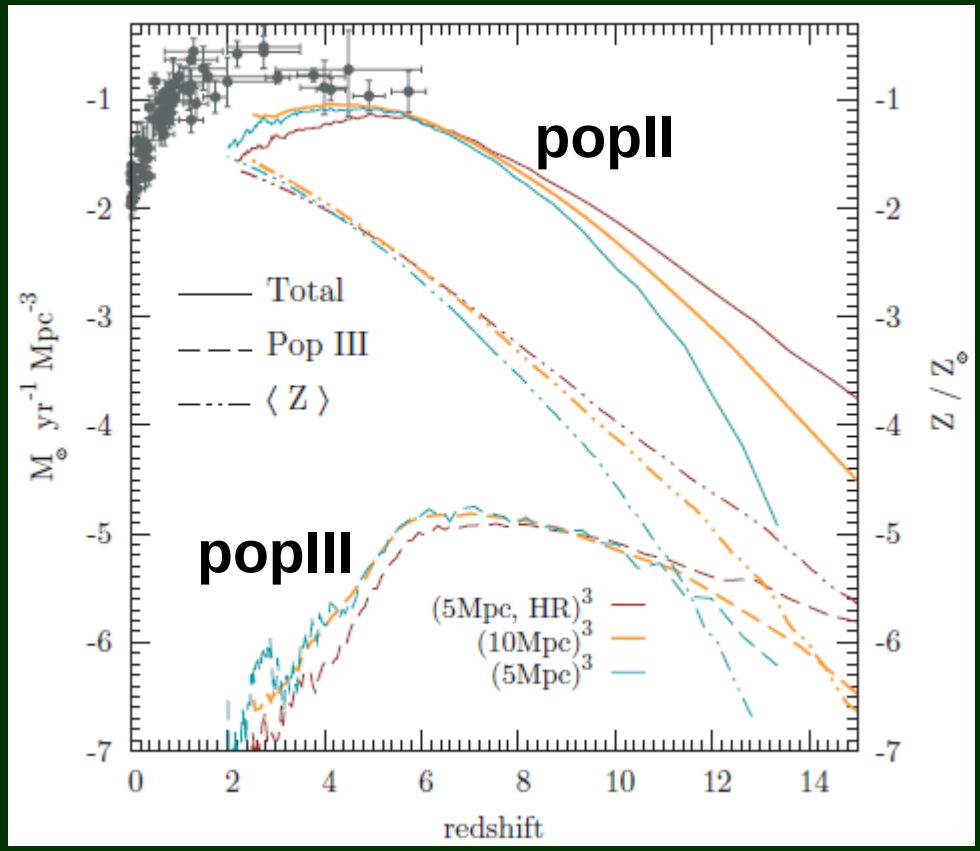
PopIII

- popIII direct searches for strong Lyα+HeII; all negative results
  - Double NB search @z=4 (Nagao+ 08)
  - Stacked spectrum @z=4.5 (Dawson+ 04)

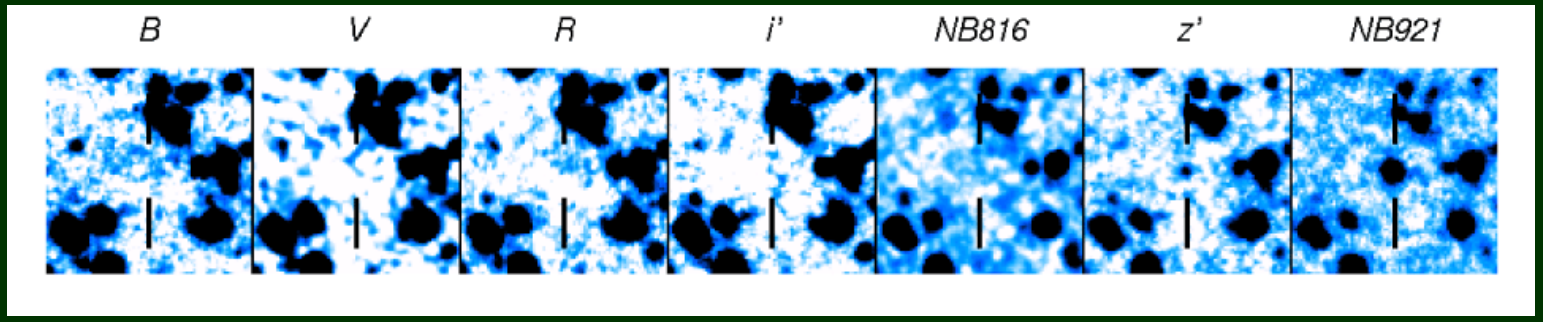
Nagao+ 08

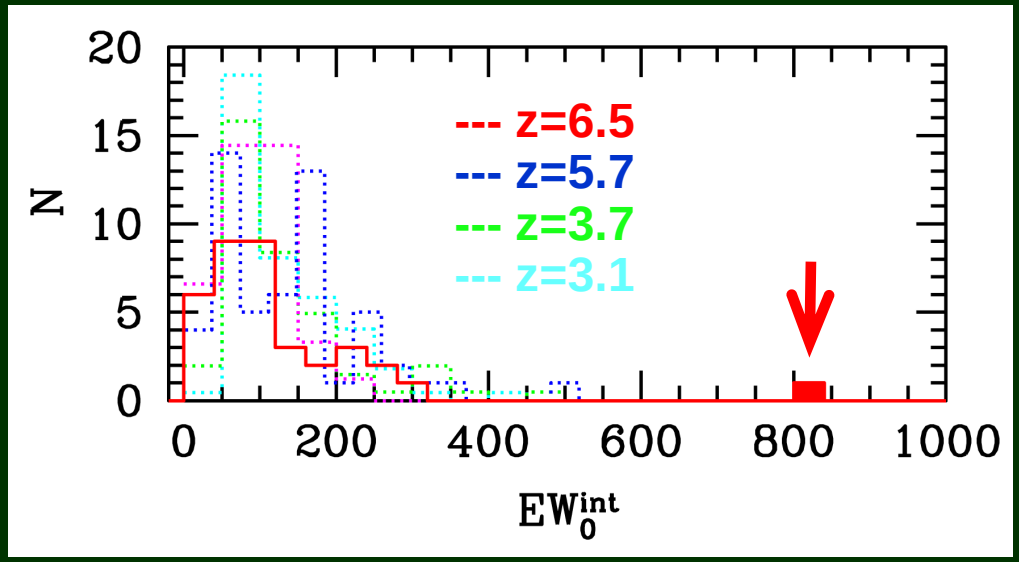


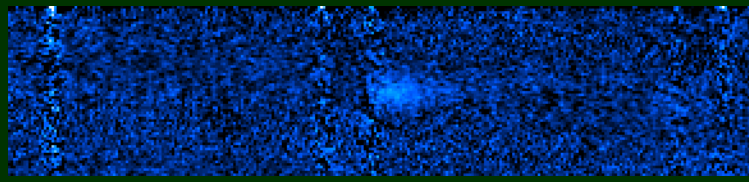
Tornatore+ 07

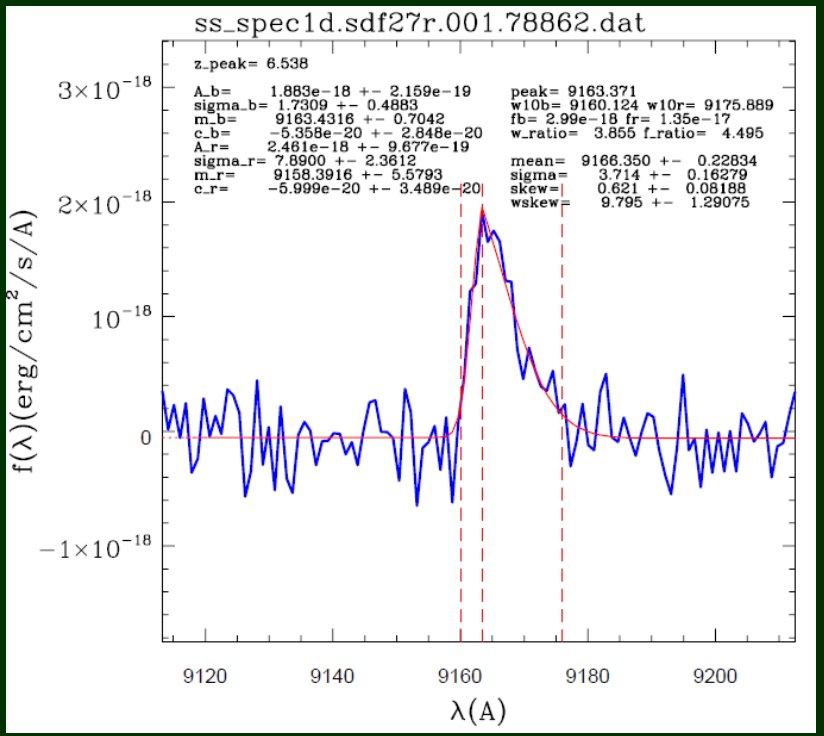


PopIII candidate with EW~800!



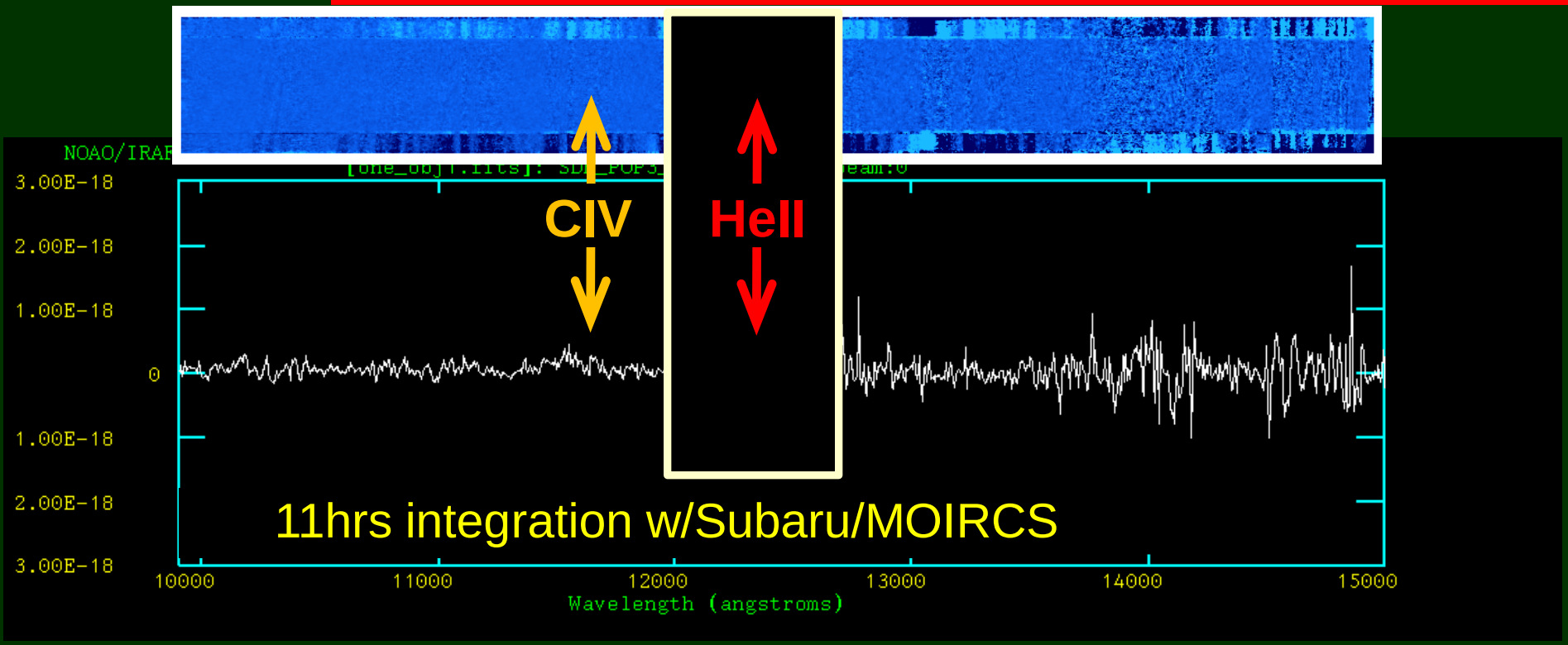






- SDF-popIII-1
  - z=6.545 LAE
  - Continuum flux is detected (28mag)
  - EW=812$^{+116}_{-122}$A (rest) !!!

PopIII candidate with EW~800!



NK+ in prep.

- No detections of HeII nor CIV
  - < 3σ=3.88e-19 ergs/s/cm^2/A
  - Neither popIII nor AGN ??
  - LyA is enhanced by clumpy dust clouds (Hansen&Oh 06) ??
  - HeII emission of popIII is fainter than expected ??

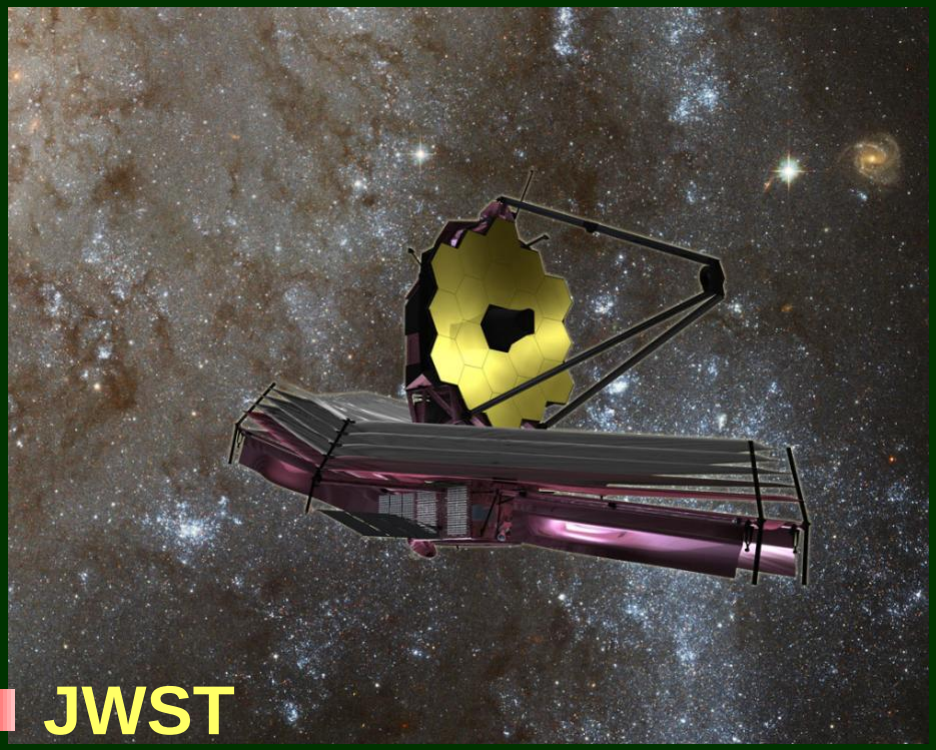
High-z galaxy survey in the next Decade

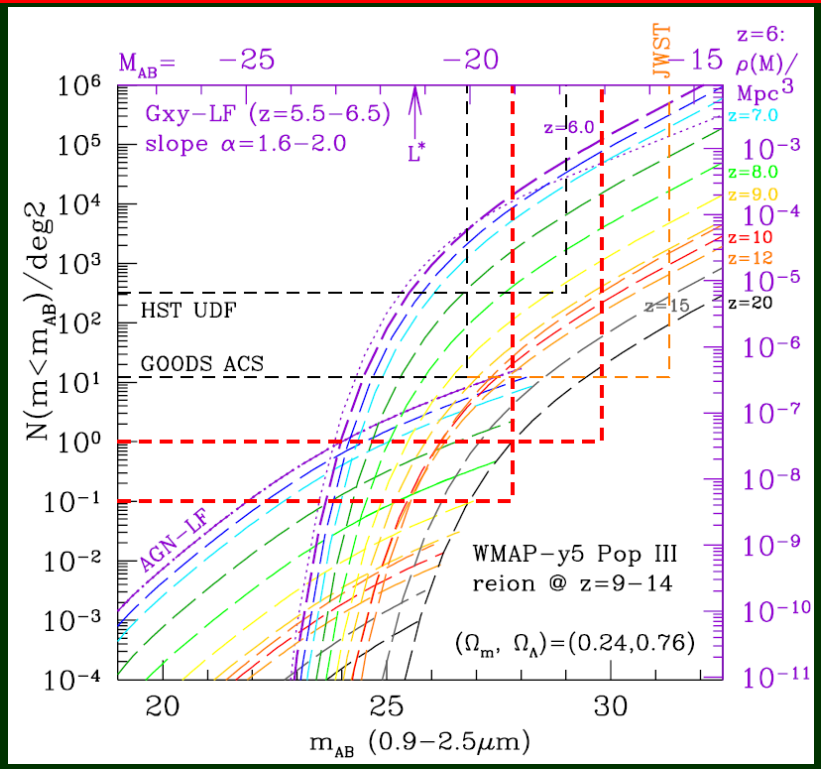
How we can learn the early universe?

What's next ?

- **Galaxy contributions to hydrogen reionization**
  What ionized the universe ?
  - Faint-end slope of the LF of LBGs
  - Deep BB survey to measure the faint-end slope — **JWST**
  - Wide BB survey to overcome CV — **HSC**
- **Reionization probed by LyA emission line**
  When did the reionization take place ?
  - LF, clustering, line profile of LAEs
  - Deep NIR NB survey for higher-z
  - Wide NB survey for clustering — **HSC**
- **Searches for the Population III objects**
  Where are the first stars ?
  - Detect LyA+HeII lines to confirm popIII
  - Deep spectroscopy — **ELTs**

Deep survey w/JWST



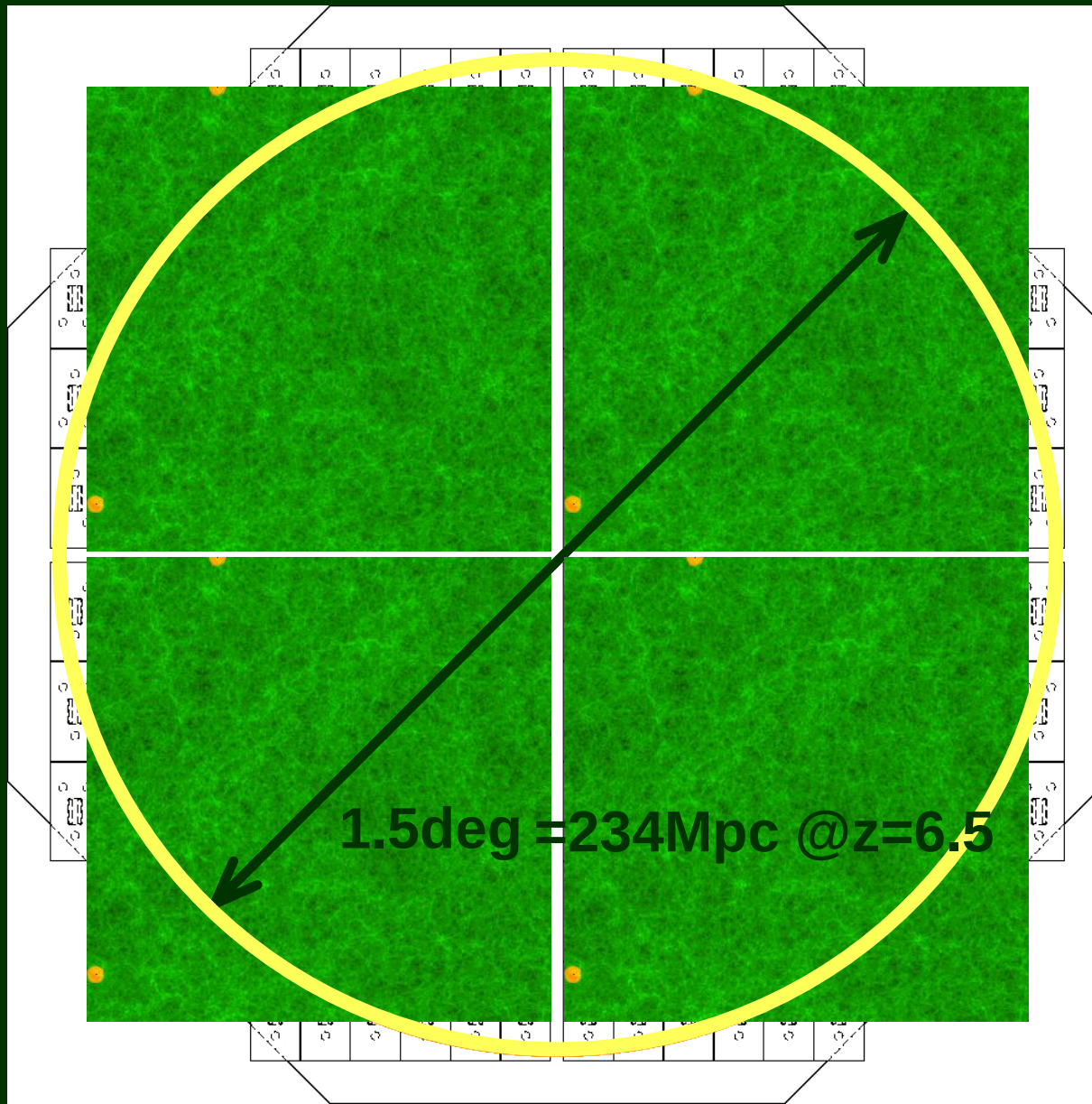


Jansen+ 09

- **JWST**
  - ~100 high-z sources at z=9-20
  - faint sources (x10 fainter, >SFR~0.1M⊙/yr) at z=6-9
- **Photon budget**
  - Accurate measurement of faint-end slope
- **Lyα LF**
  - Higher-z → Lyα-LF is sensitive in early reionization

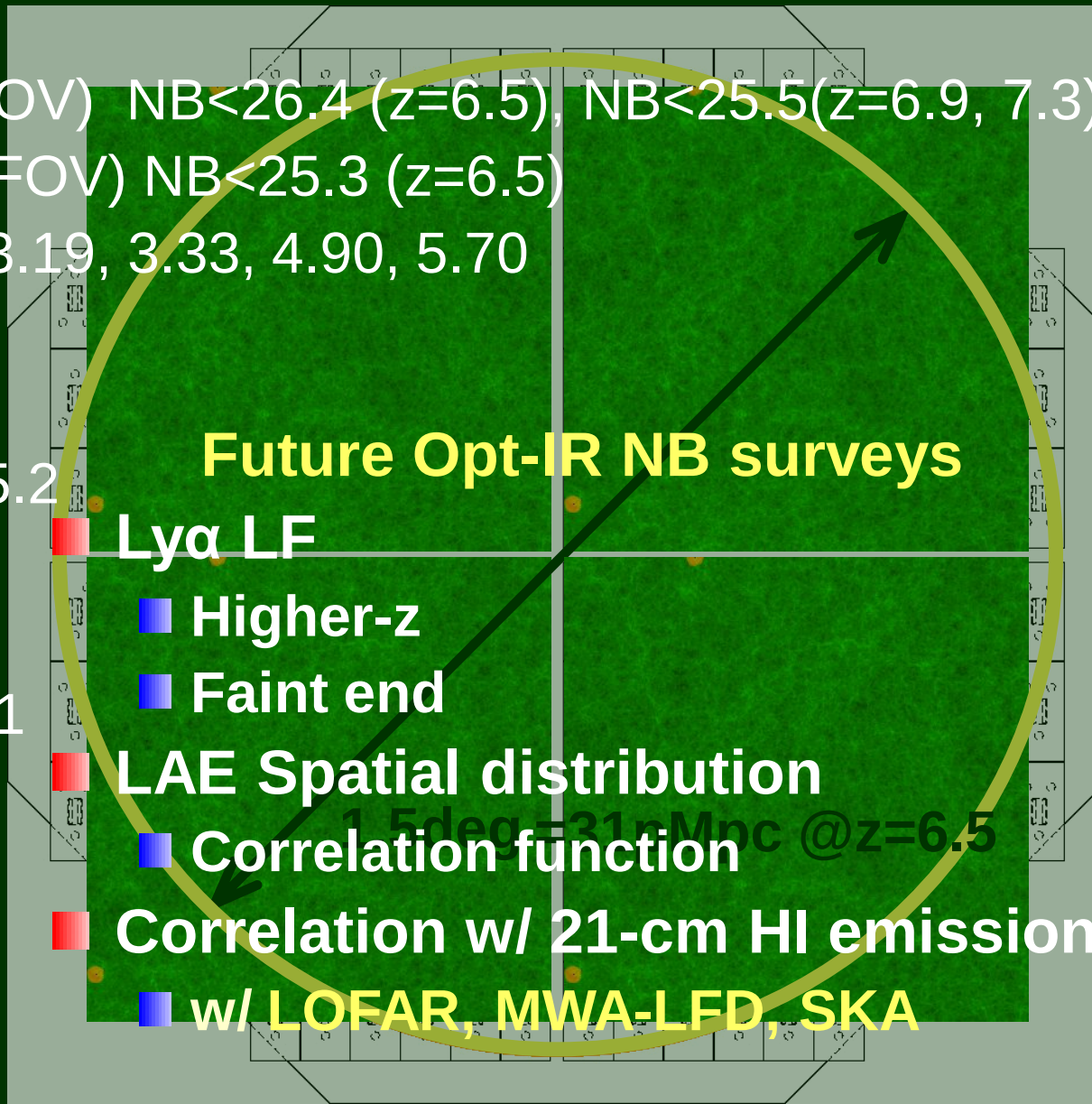
Hyper Suprime-Cam

- HSC
  - 1.5degφ
  - 116 CCDs (1Gpix)
  - Red-sensitive CCDs
    ～1.1μm
- Powerful tool for
  - Larger sample
    of high-z galaxies
  - Spatial distribution
  - Patchy reionization



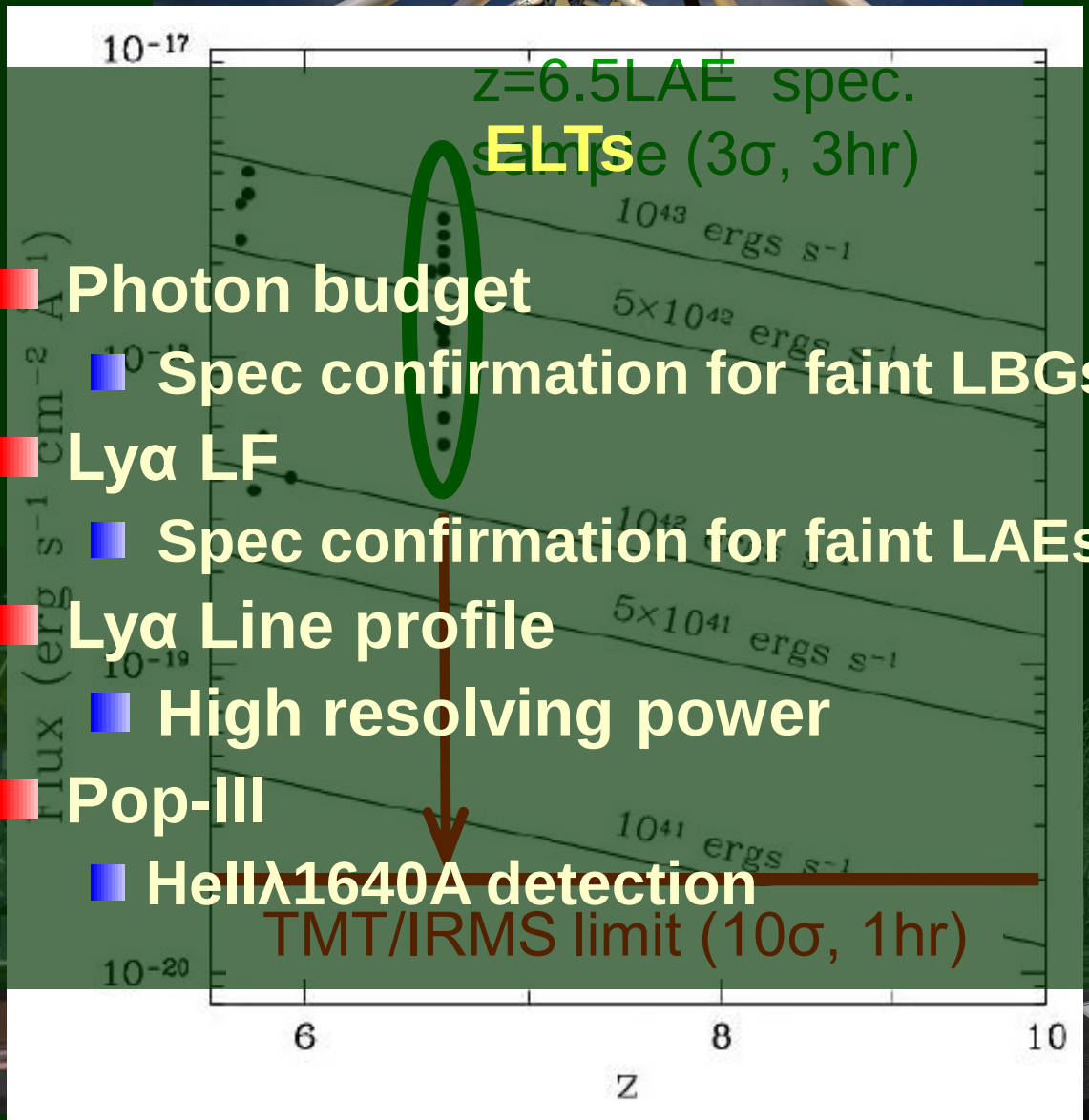
Future NB surveys

- HSC survey(TBD)
  - UDS 3.5sqdeg(2FOV) NB<26.4 (z=6.5), NB<25.5(z=6.9, 7.3)
  - Deep 41sqdeg(23FOV) NB<25.3 (z=6.5)
  - Lower-z LAEs; z=3.19, 3.33, 4.90, 5.70
- WIRCAM
  - z=7.7
  - >0.1sqdeg, NB<25.2
- UltraVista
  - z=8.8
  - 0.7sqdeg, NB<24.1
- DAzLE
  - 9.95<z<10.05
- HAWK-I/WFC3 ?
- …



Opt-IR giant telescopes in next generation

TMT 30m



z=6.5LAE spec. sample (3σ, 3hr)

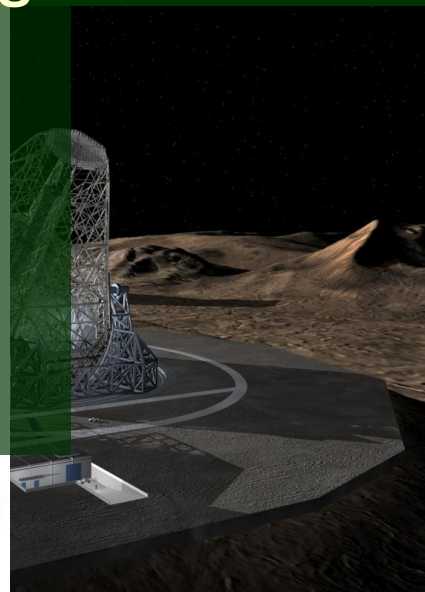
ELTs

- Photon budget
  - Spec confirmation for faint LBGs
- Lyα LF
  - Spec confirmation for faint LAEs
- Lyα Line profile
  - High resolving power
- Pop-III
  - HeIIλ1640A detection

TMT/IRMS limit (10σ, 1hr)

GMT 27m

E-ELT 42m



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