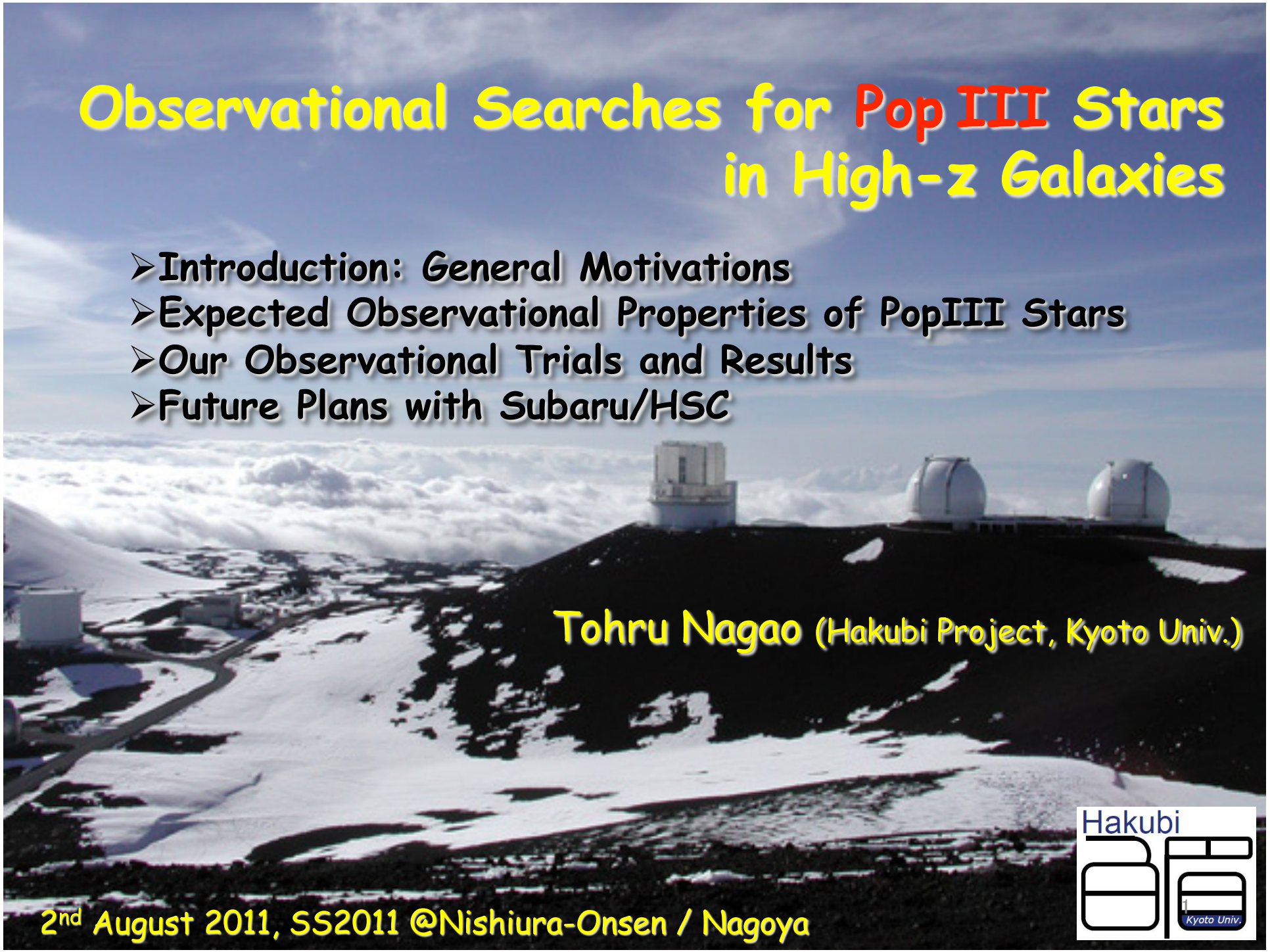
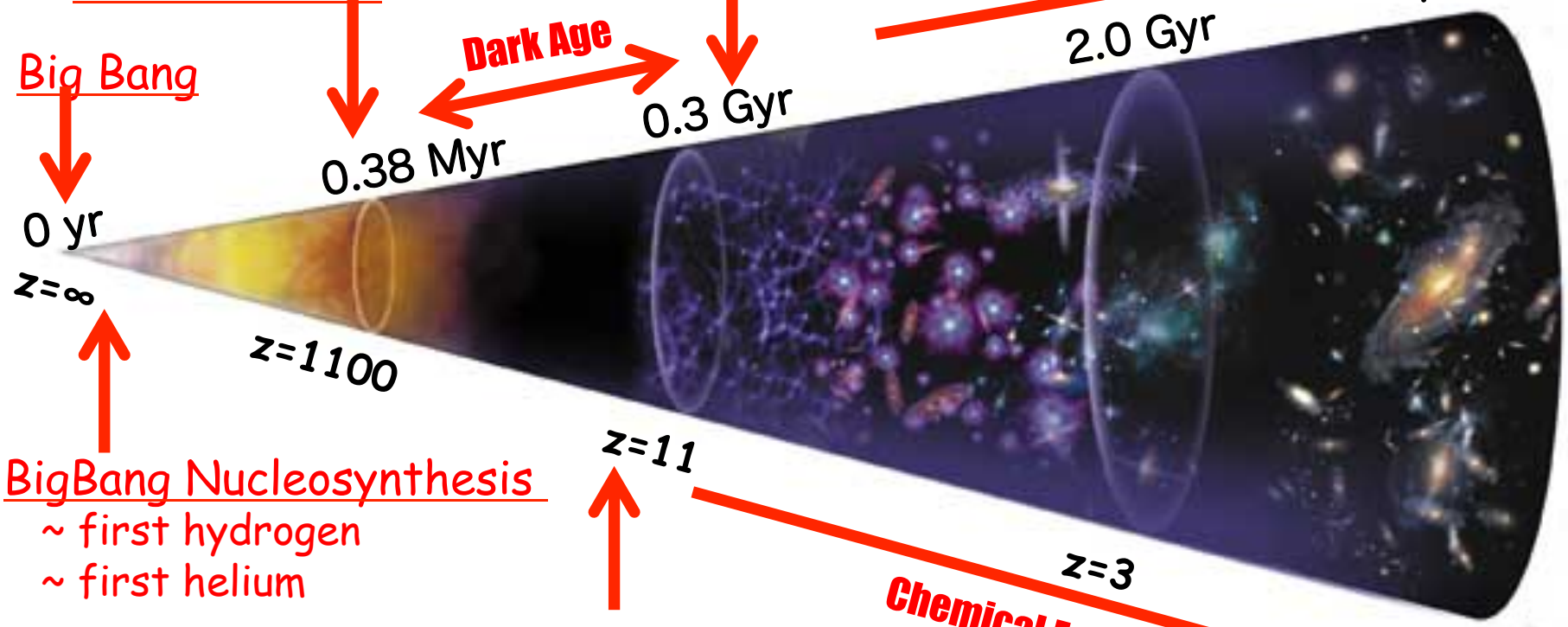

Observational Searches for Pop III Stars in High-z Galaxies
➢Introduction: General Motivations
➢Expected Observational Properties of PopIII Stars
➢Our Observational Trials and Results
➢Future Plans with Subaru/HSC
Tohru Nagao (Hakubi Project, Kyoto Univ.)
2nd August 2011, SS2011 @Nishiura-Onsen / Nagoya
Hakubi
Kyoto Univ.

Cosmic chemical evolution



Current Universe

Population III
& Reionization

Recombination

Galaxy Evolution

13.7 Gyr

Dark Age

2.0 Gyr

Big Bang

0.3 Gyr

0.38 Myr

0 yr

z=∞

z=1100

z=11

z=3

Chemical Evolution

z=0

BigBang Nucleosynthesis
- ~ first hydrogen
- ~ first helium

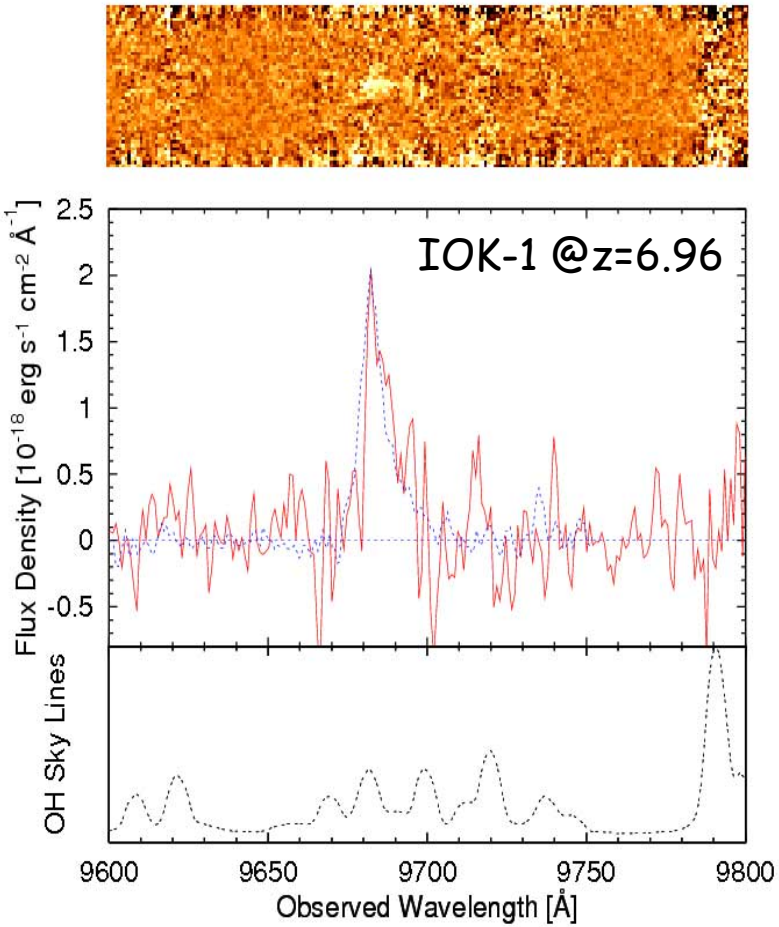
First Heavy Elements
- ~ first stars, first suparnovae
- ~ second generations
- ~ third, fourth, ...

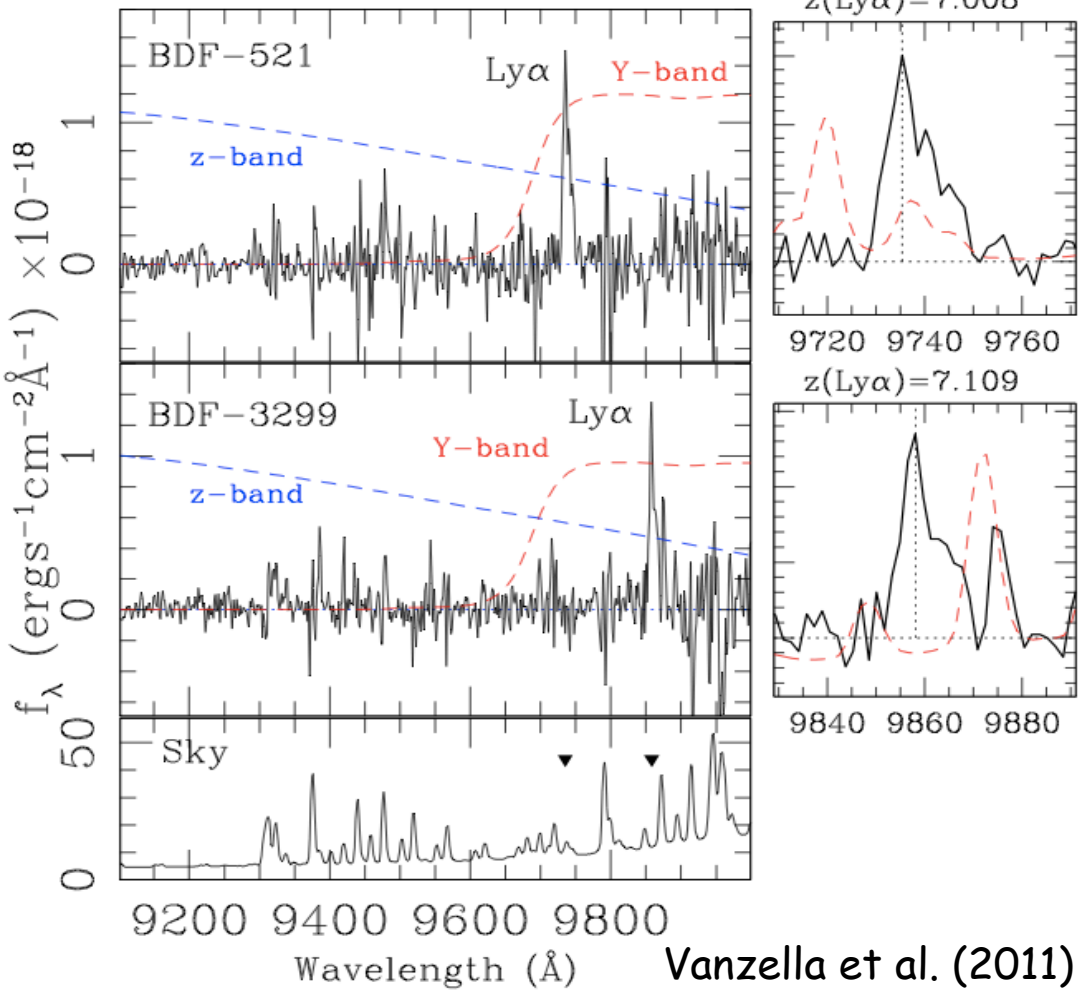
WHEN? WHERE? HOW MUCH?

- ~ earth-like planets
- ~ life, human, & you

Spectroscopic sample of very high-z galaxies

Iye et al. (2006)





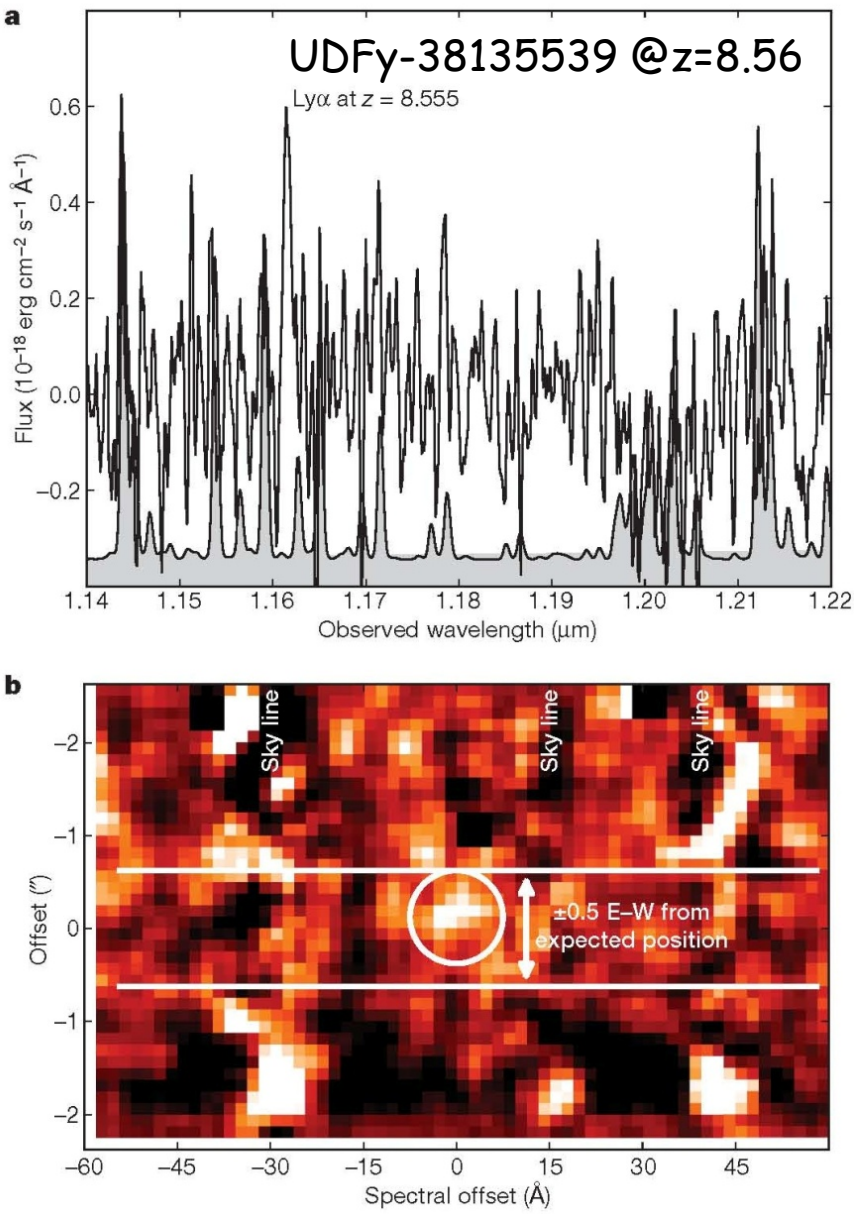
Vanzella et al. (2011)

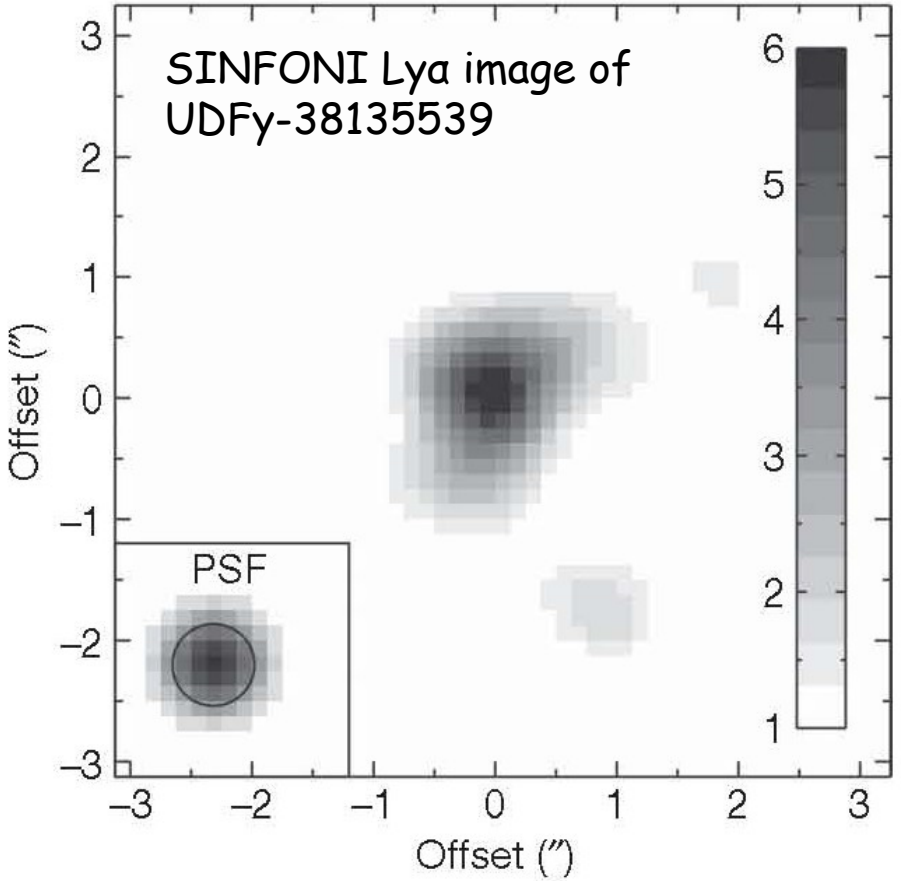
- NB973-selected LAE @SDF
- Subaru/FOCAS 8.5 hours (!!)
- あとでもう一度でてきます

- z'dropout-selected galaxies @GOODS-S
- VLT/FORS 15.9 hours (!!!)
- Simultaneously observed with MOS

Spectroscopic (??) sample of very high-z galaxies

Lehnert et al. (2010)

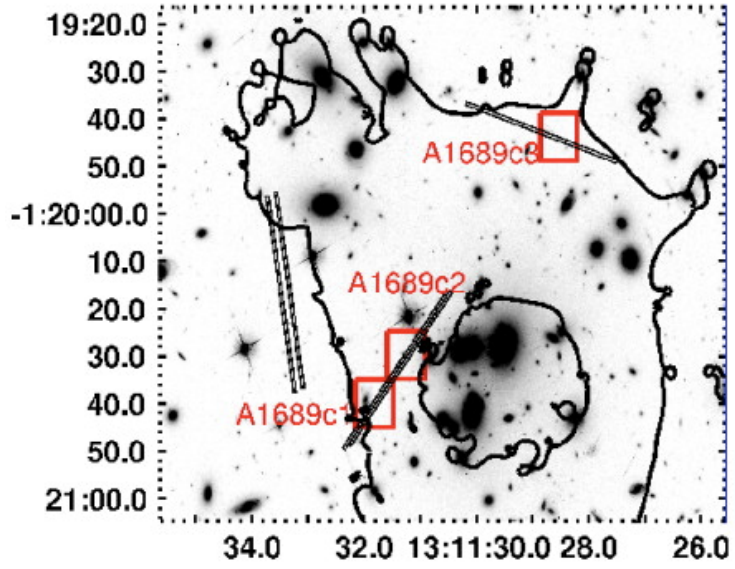


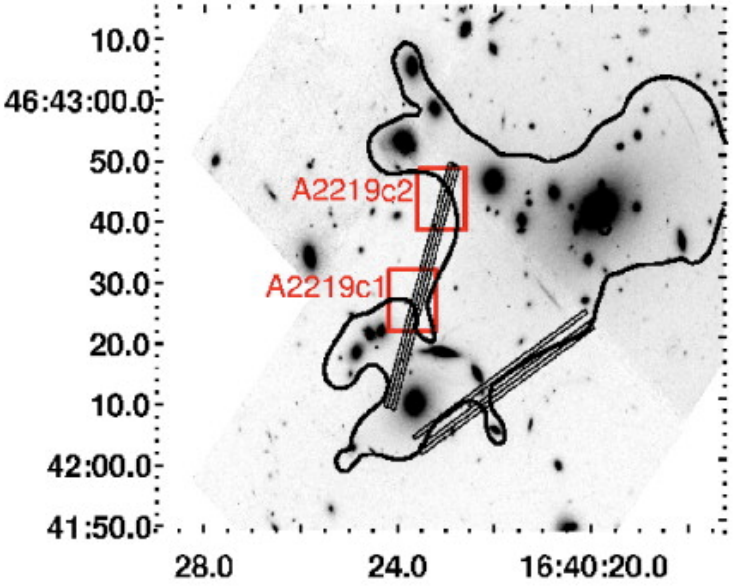


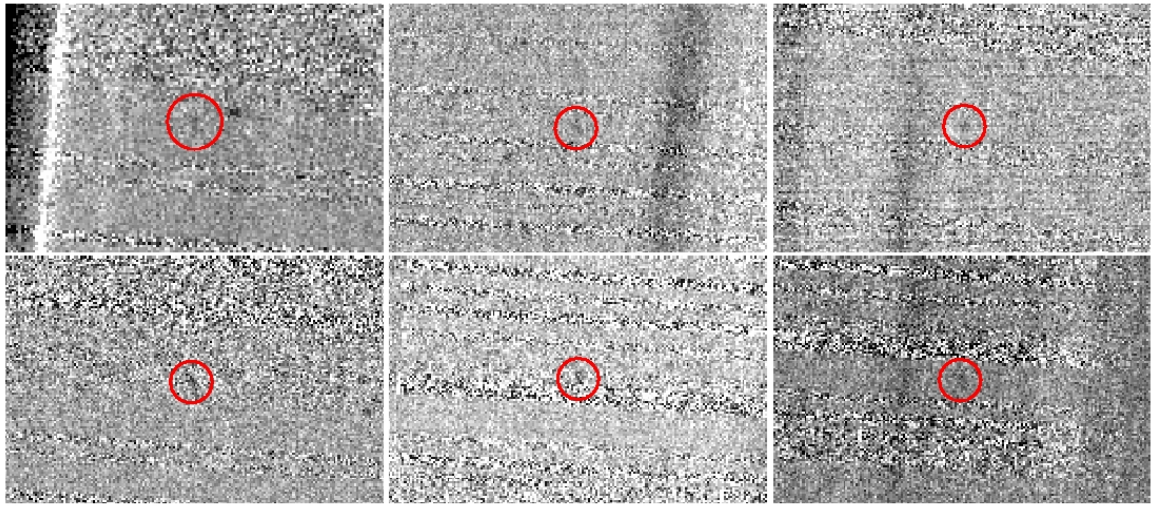
- Y-dropout galaxy @UDF
- VLT/SINFONI 14.8 hours in DDT (!!!!!)
- 3d spectroscopy in J-band
- 世論的には ok っぽい雰囲気か (?)

Spectroscopic (????) sample of very high-z galaxies

Stark et al. (2007)



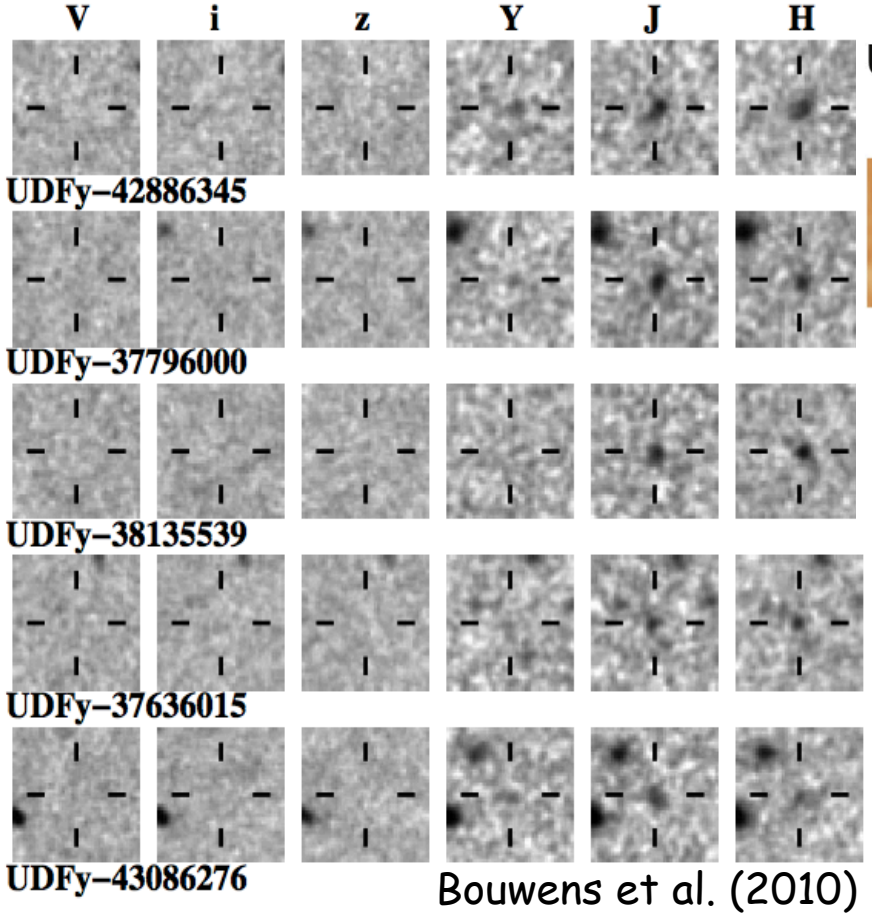




- Blind searches on "critical lines"
- Grav. magnification factor: x10-50
- Keck/NIRSPEC 5-15 hours for each slit pos.
- $8.6 < z_{sp\_lensed} < 10.2$

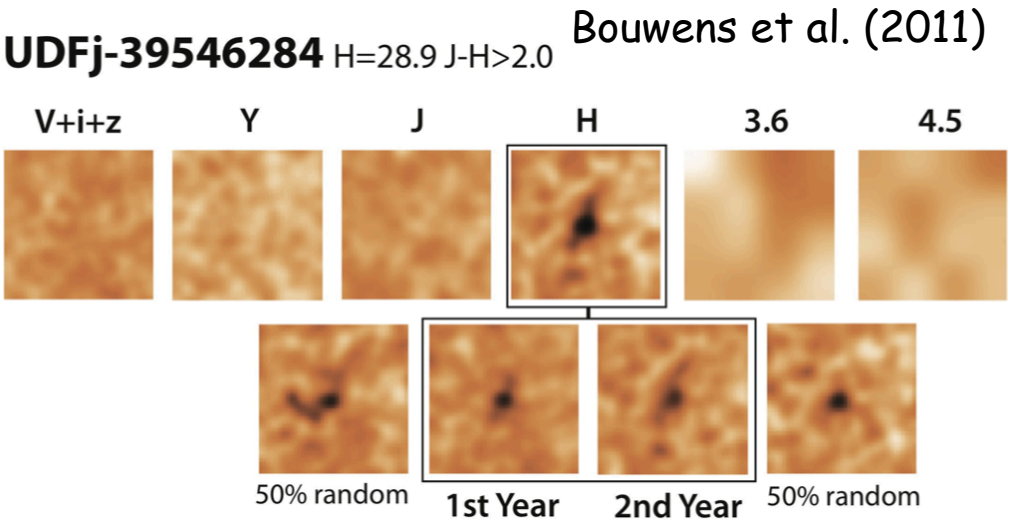
- いまいち世論的には受け入れられてない気が。
- 本当だと光度関数がかなり変になるからか？
- PhotometricにはBouwens+09等の観測もあり。
- 僕もMOIRCSでやろうとしたけど落ちました…

Photometric sample of very high-z galaxies



Bouwens et al. (2010)

- Y-dropout galaxies @UDF
- 8.0 < z_{ph} < 8.5
- 3rd one was spec-confirmed (?)



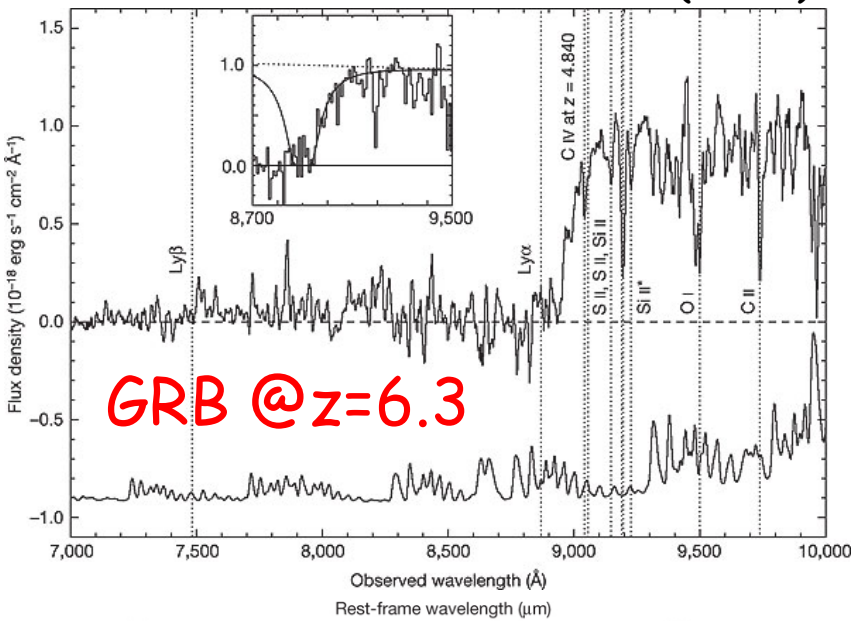
Bouwens et al. (2011)

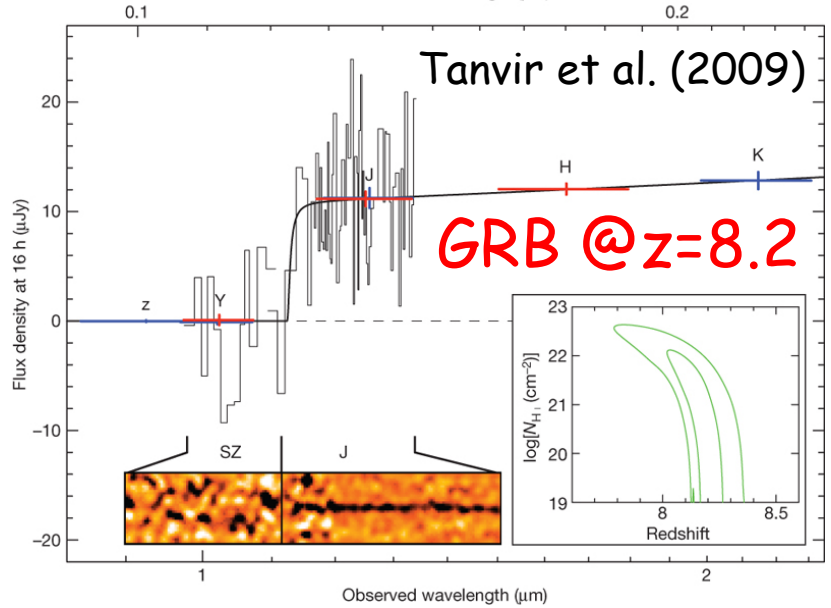
- J-dropout galaxy @UDF
- z_{ph} ~ 10
- Hバンドでしか受かってない…

- So, we now know many high-z galaxies.
- How about their stellar population?
- Are they hosting Population III stars?
- めっさ暗いんで、よく分かんない。

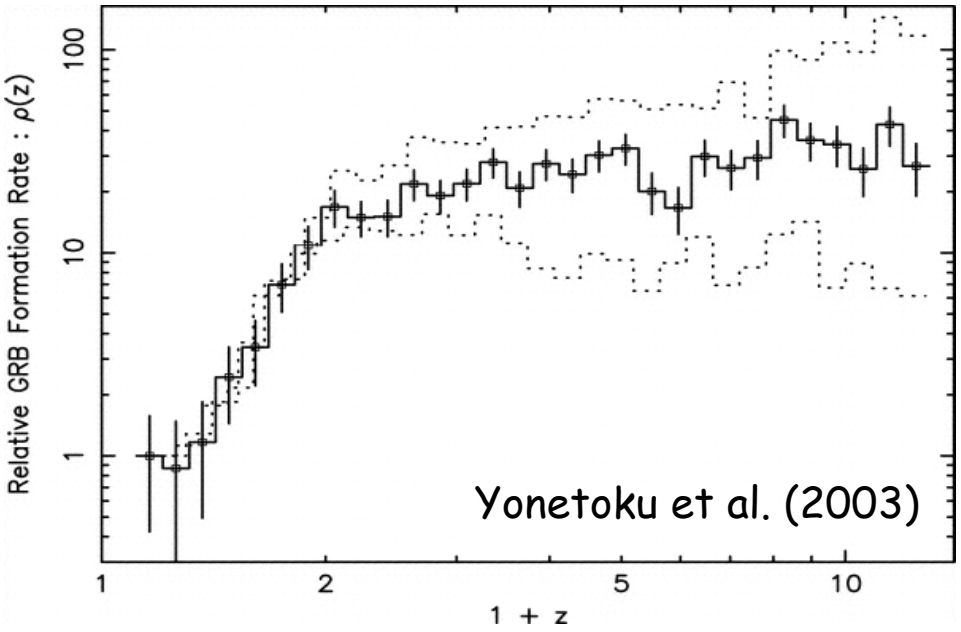
What's happening in such very high-z galaxies?

Kawai et al. (2005)





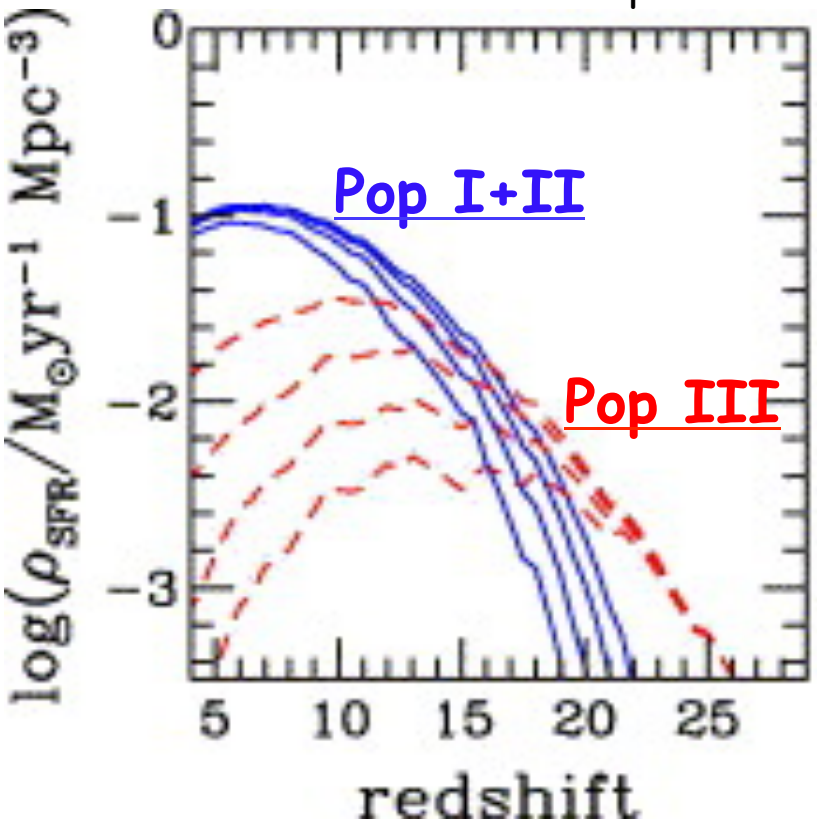
- GRBs also observed at z>6
- 少なくとも超新星爆発はぼんぼん起きてる。
- もちろんそれは当たり前の話だけど。



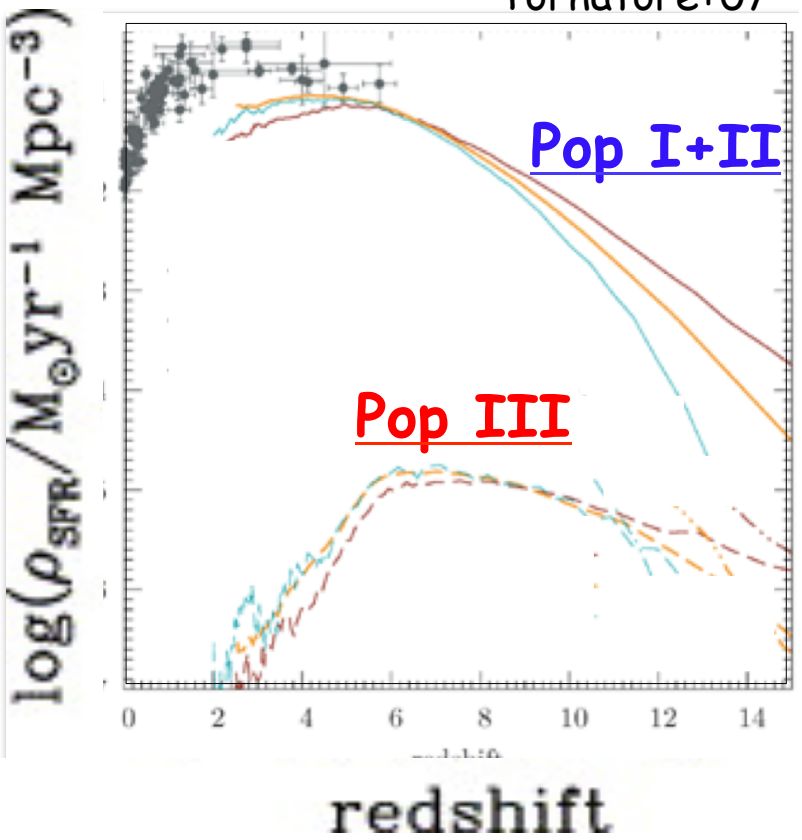
- Expected GRB rate: high even at z~10
- Population III explosions?

PopIII stars at z<10 !?

Scannapieco+03

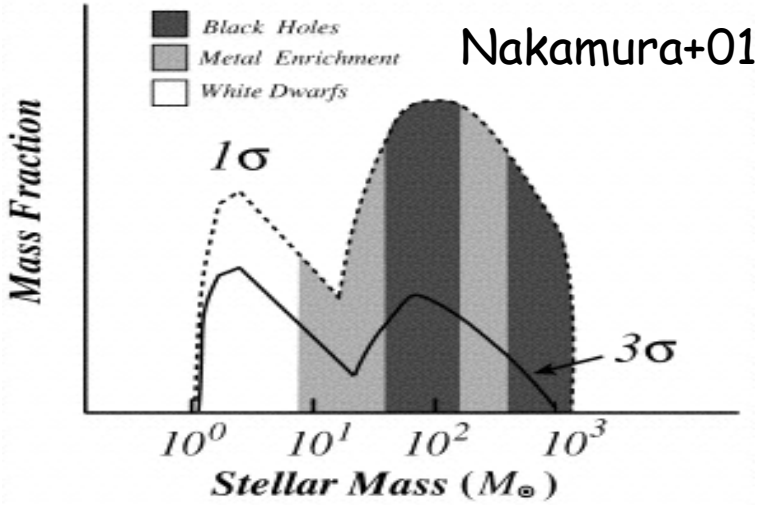


Tornatore+07



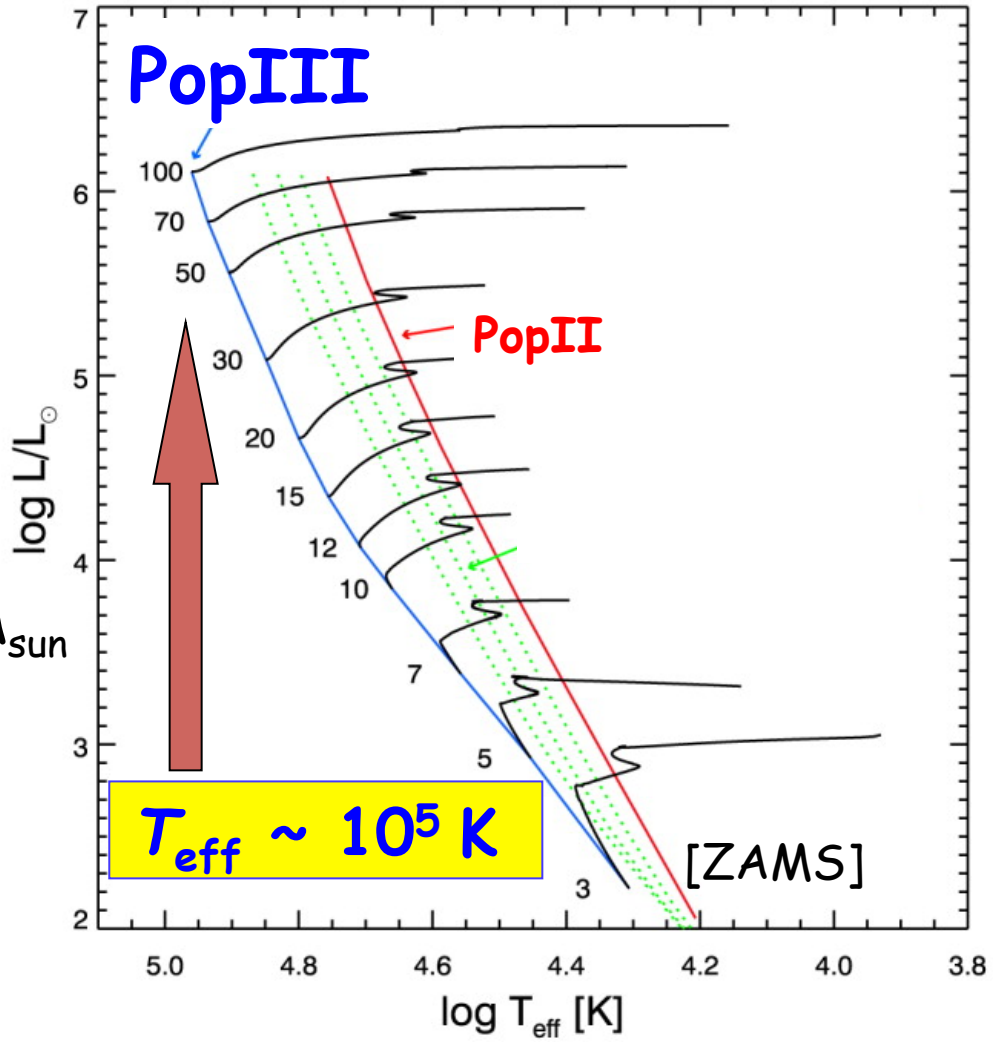
- Some models predict the PopIII presences even at z~4-6.
- Currently accessible redshifts… Why not search for PopIIIs?
- How to distinguish PopIII-hosting galaxies observationally?

Properties of Population III stars



Nakamura+01

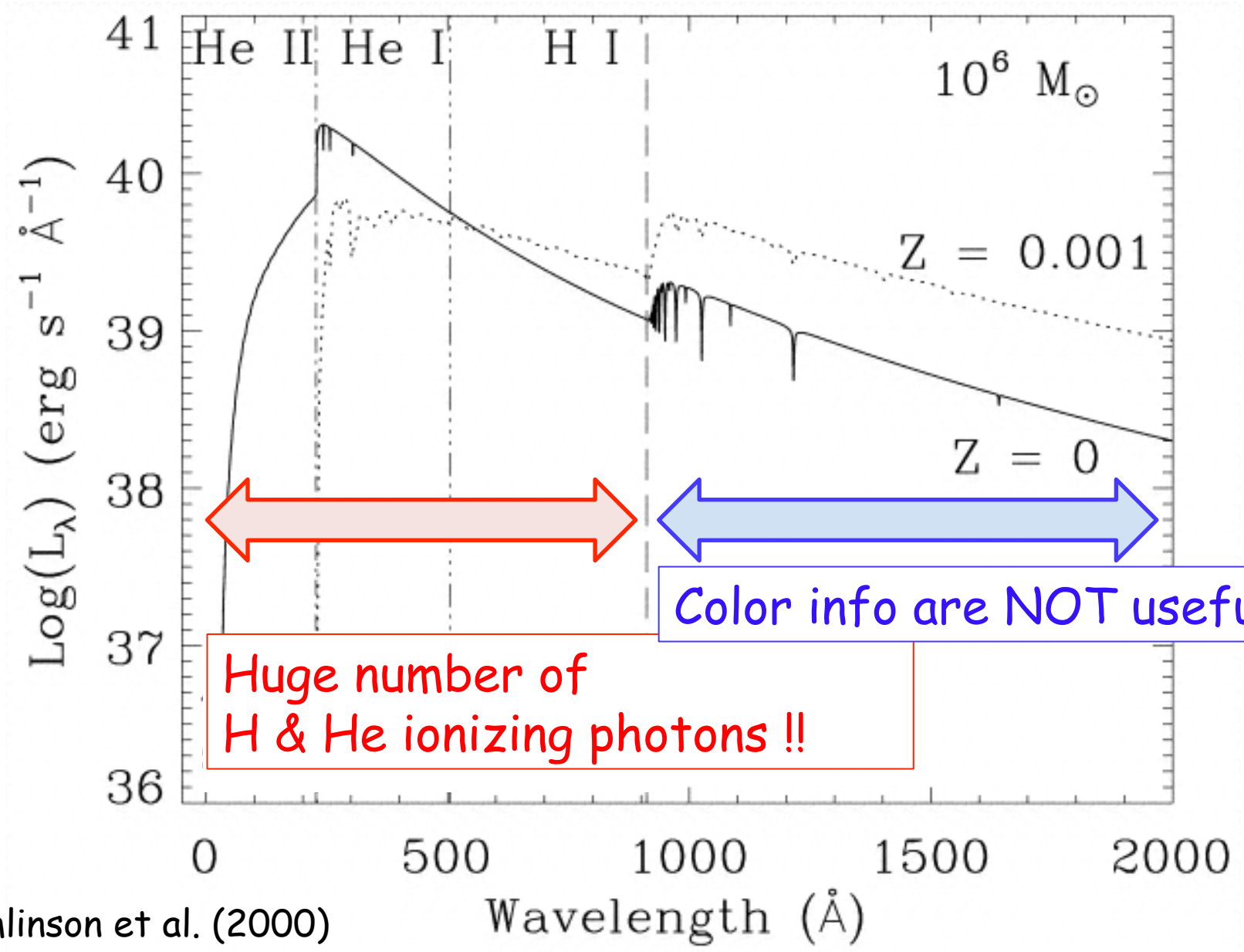
Tumlinson+03



- Very top-heavy IMF
  reaching up to a few 100M_{sun}
- Very high T_{eff}
  due to low opacity
  even below M=100M_{sun}
- Very hard SED
  especially at FUV

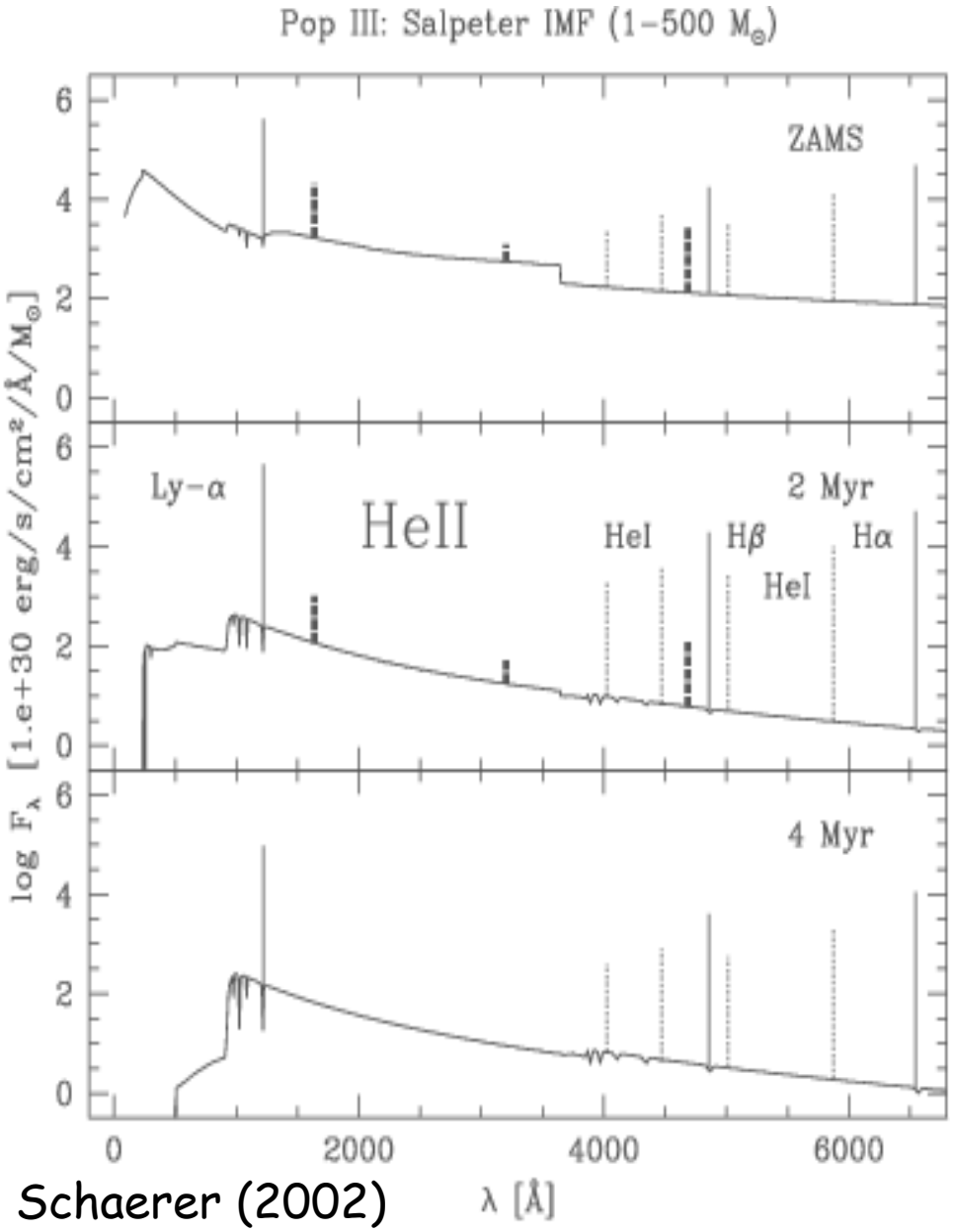
…could be diagnostics for PopIII stars!?

SED of PopIII stellar clusters (= PopIII galaxies)



Tumlinson et al. (2000)

Expected spectrum of PopIII galaxies

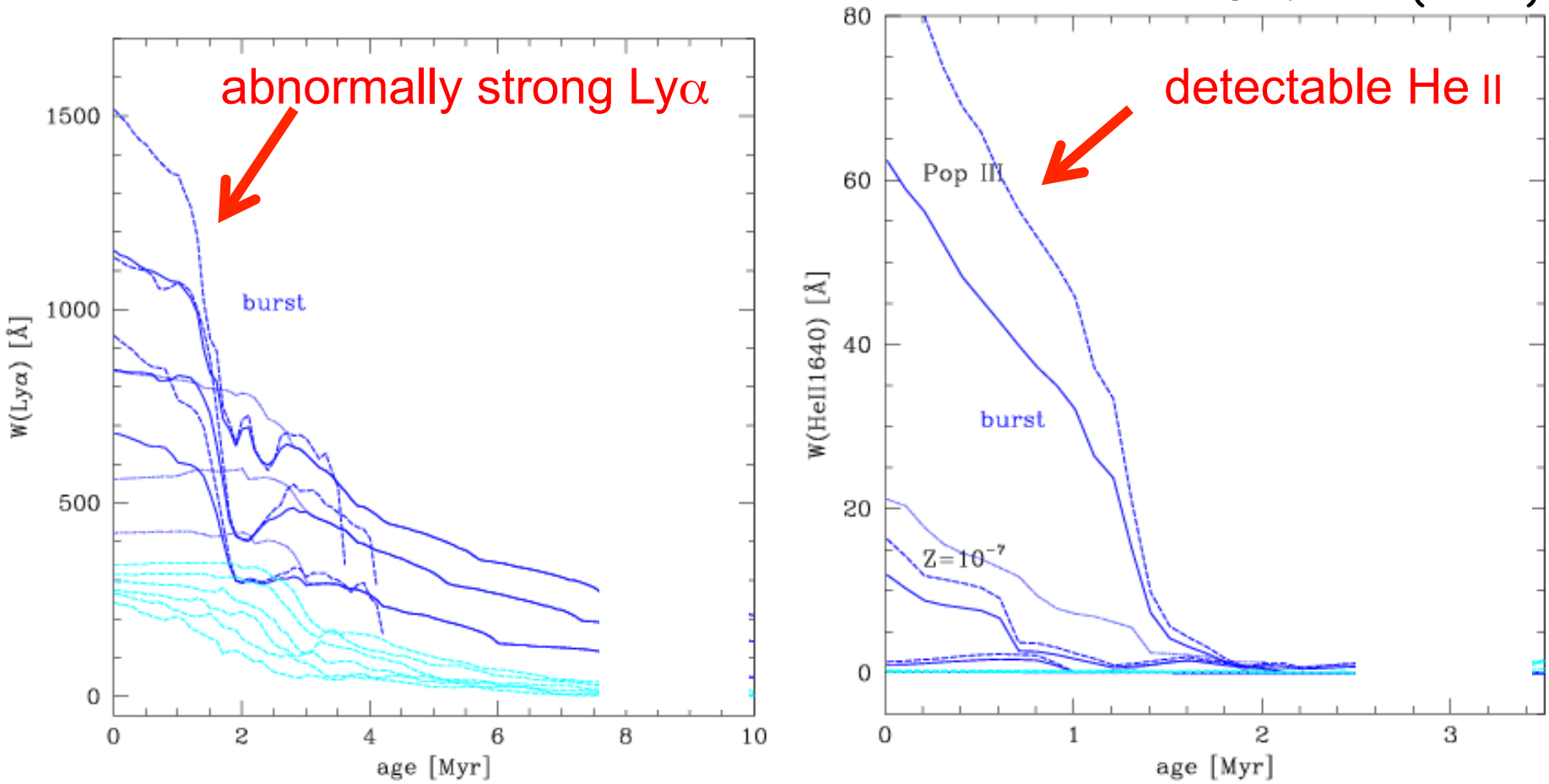


Schaerer (2002)

- Strong HI and HeII
  discriminating from PopI/II
- Especially HeII 1640
  accessible even at high-z
  no resonance effects
- No metal lines
  discriminating from AGN

Expected strengths of emission lines

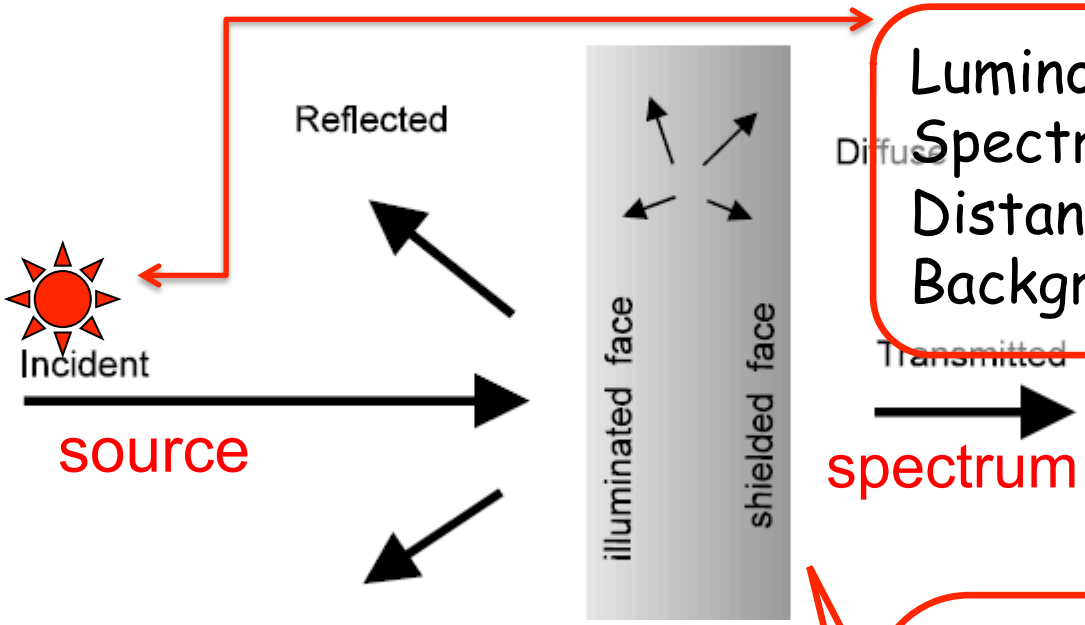
Schaerer (2003)



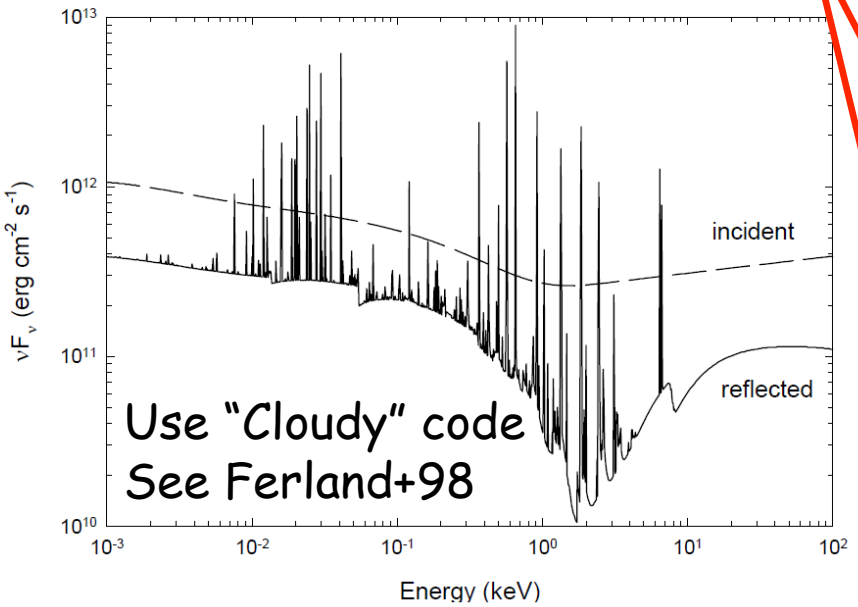
Possible strategy for PopIII searches:

1) search for strong "**Lya** emitters"
2) identifying **He II** line among them

Note: Simulating Emission-Line Spectra



Luminosity (or Flux)
Spectral energy distribution
Distance to clouds
Background radiation

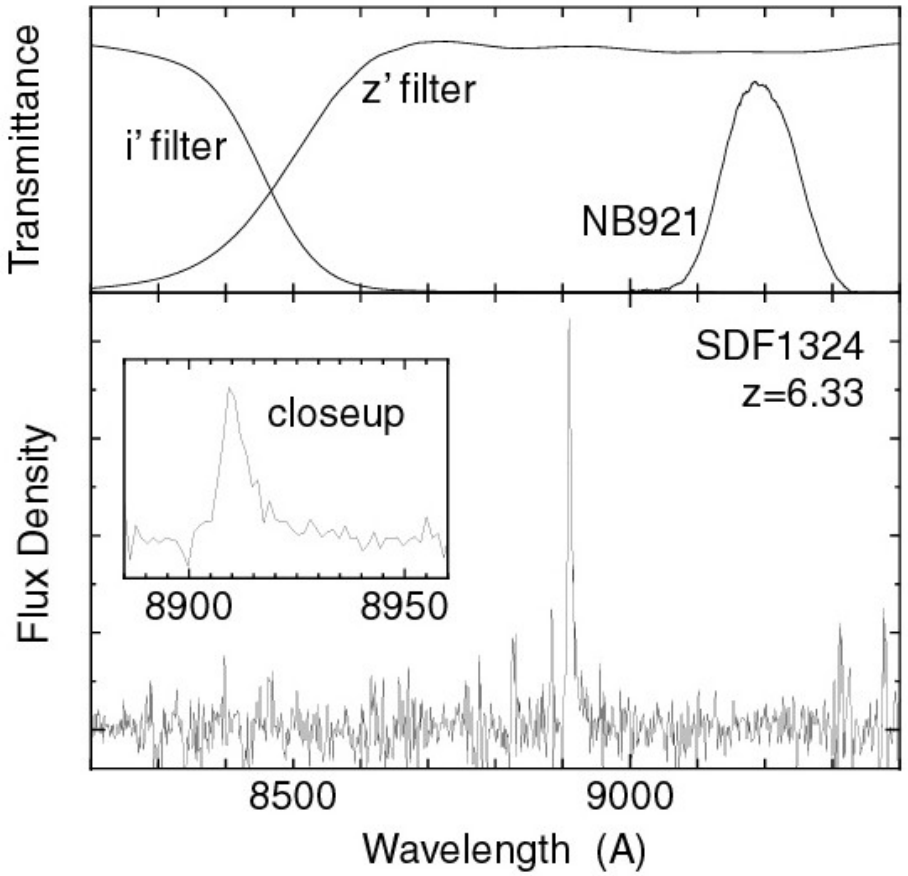


Use "Cloudy" code
See Ferland+98

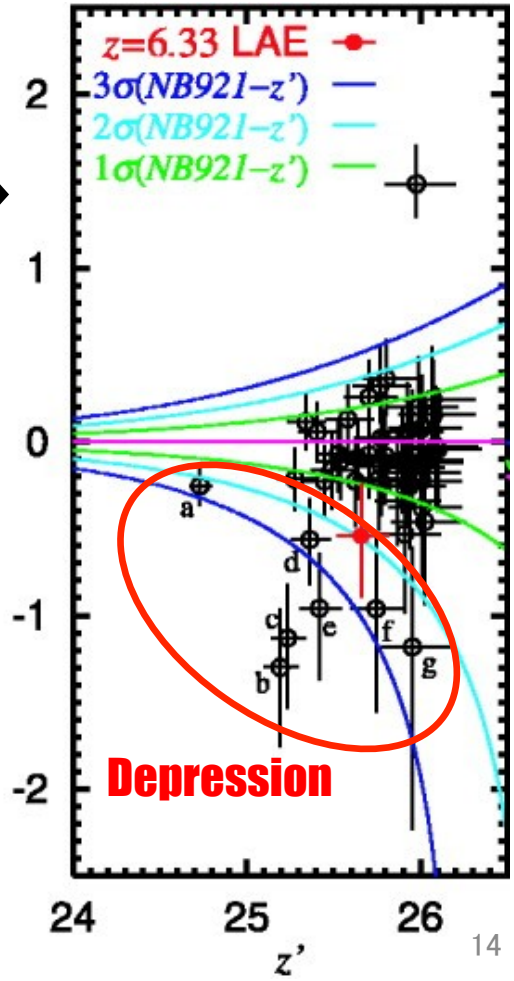
Hydrogen number density
Column density (thickness)
Metallicity (abundance ratios)
Dust grains (and molecules)
Ionization parameter (U)
Geometry (gas distribution)
etc…

Our searches for “extreme” Ly alpha emitters

Nagao et al. (2004)



Extremely strong LAEs at 6.0<z<6.5 cause a “NB921-depression” with respect to z’-band magnitude



Eight NB921-depressed objects among 48 i’-dropout galaxies in the Subaru Deep Field (deep & very wide!)

Further optical spectroscopy

Nagao et al. (2005)

Using Subaru/FOCAS & Keck/DEIMOS

Among 8 photometric candidates…

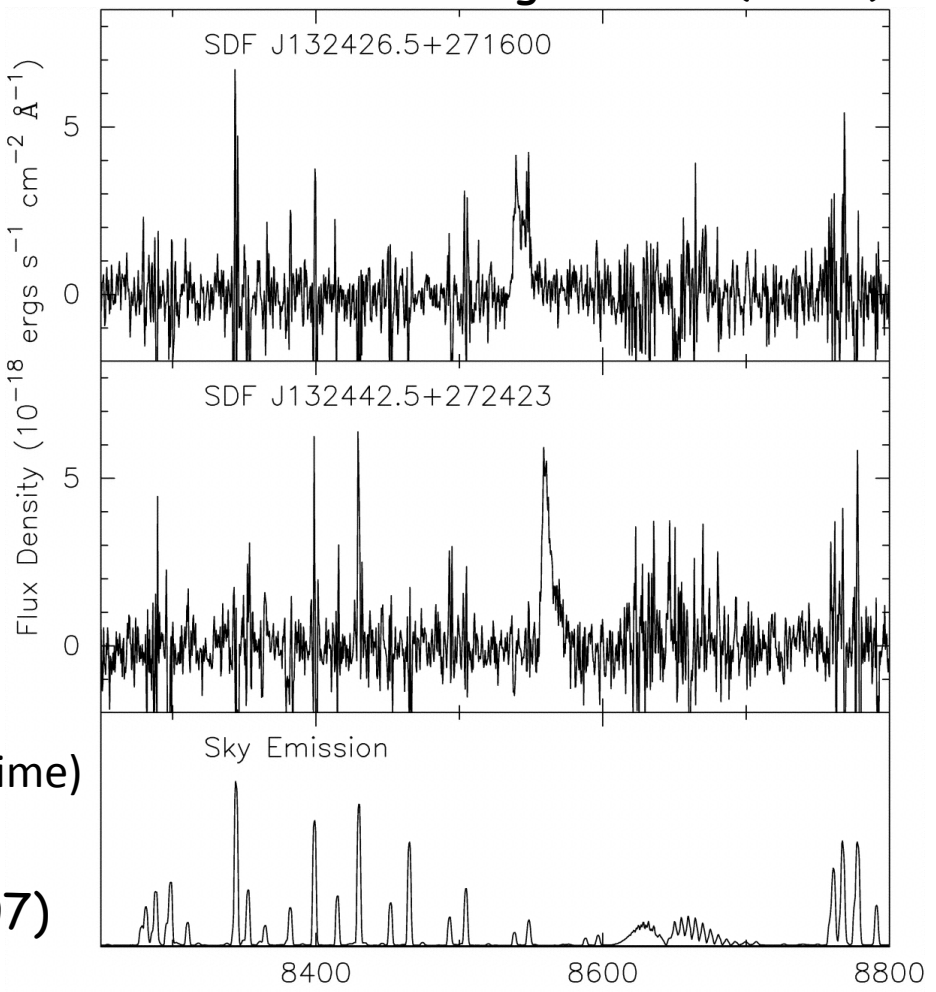
5 LAEs with a large EW (>100A !!)
- ~ z_{spec} =6.00, EW_{rest}=114A
- ~ z_{spec} =6.03, EW_{rest}= 94A
- ~ z_{spec} =6.04, EW_{rest}=236A
- ~ z_{spec} =6.11, EW_{rest}=153A
- ~ z_{spec} =6.33, EW_{rest}=130A

2 no signal (slit acquisition failure?)

1 unobserved (due to limited observing time)

0 low-z interlopers

Nagao et al. (2007)

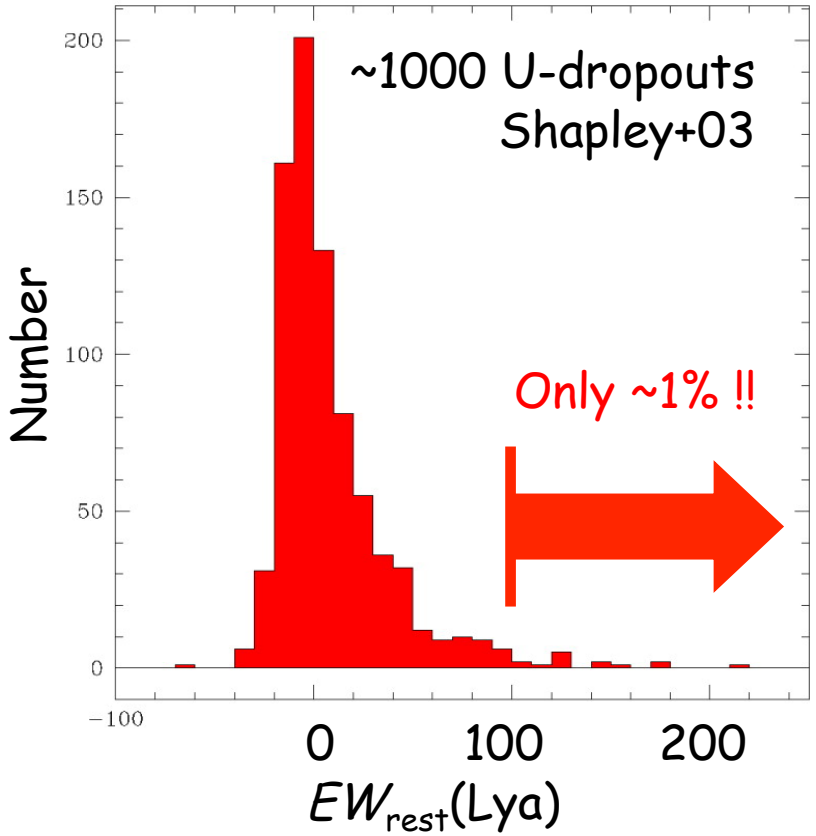


NB-depressed i-dropout method is very efficient to find large-*EW* LAEs
EW is accurately determined through *NB921* magnitude

Evolution of Ly alpha equivalent widths

The fraction of the *broad-band selected* galaxies with EW_{rest}(Lya) > 100A

i'-dropout at z~6 → (at least) 5/48 ~10%
U-dropout at z~3 → roughly ~1%



Significantly higher at z~6 than z~3

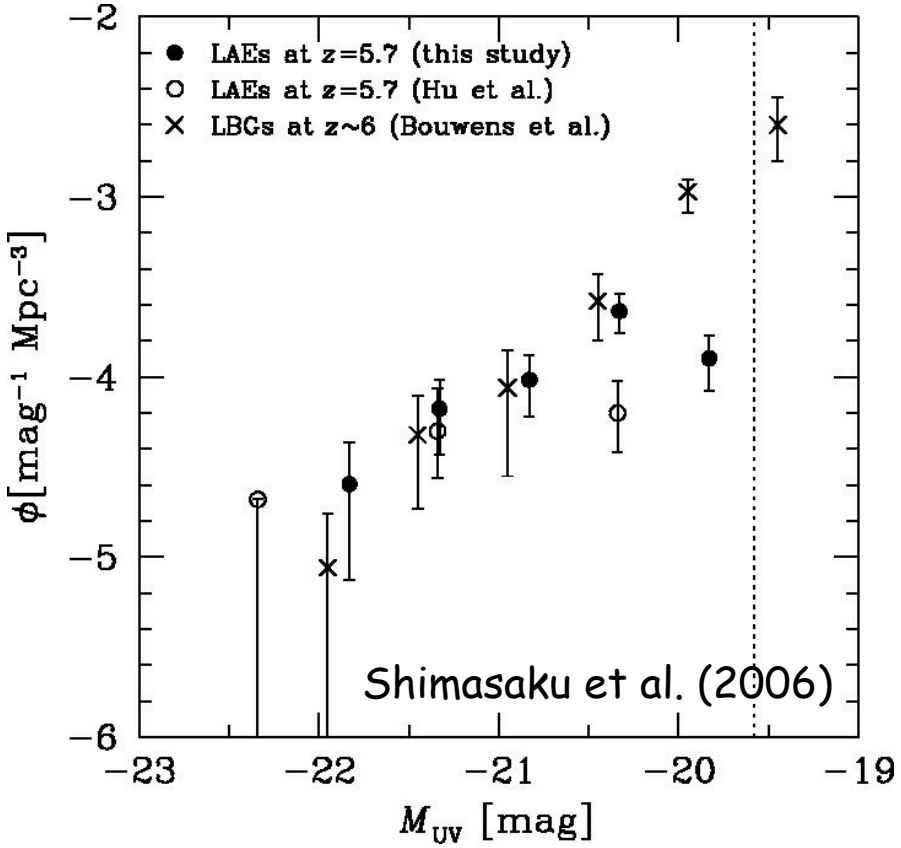
Evolution of the stellar population

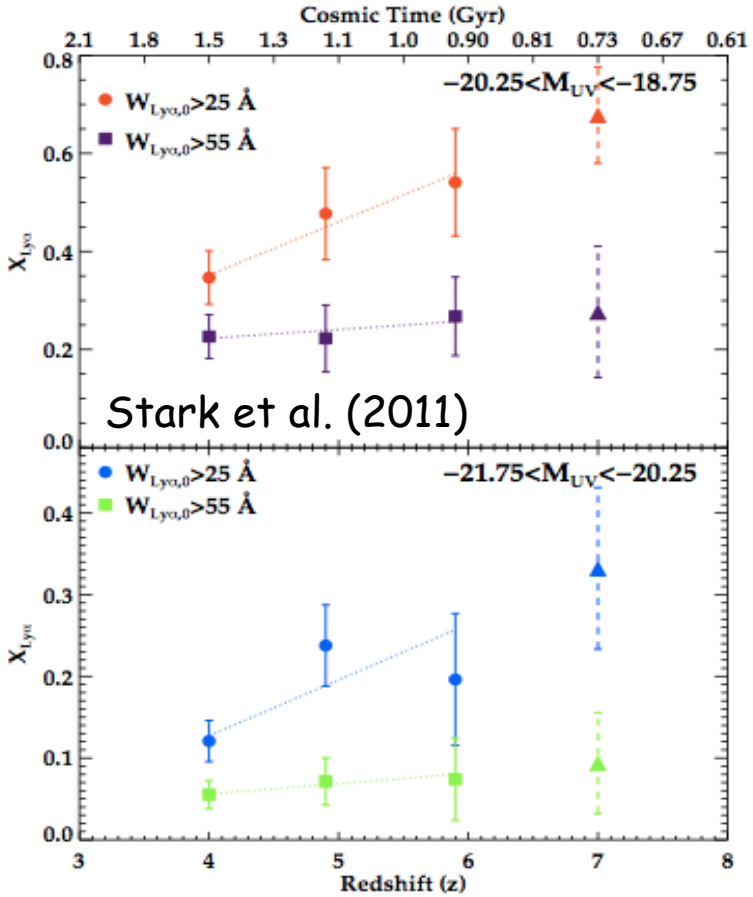
Possibilities:

~ Younger stellar pop. (<10^7yr)
~ Top-heavy IMF
~ Presence of PopIII

➔ Observational Test through He II !!

Evolution of Ly alpha equivalent widths (contd.)

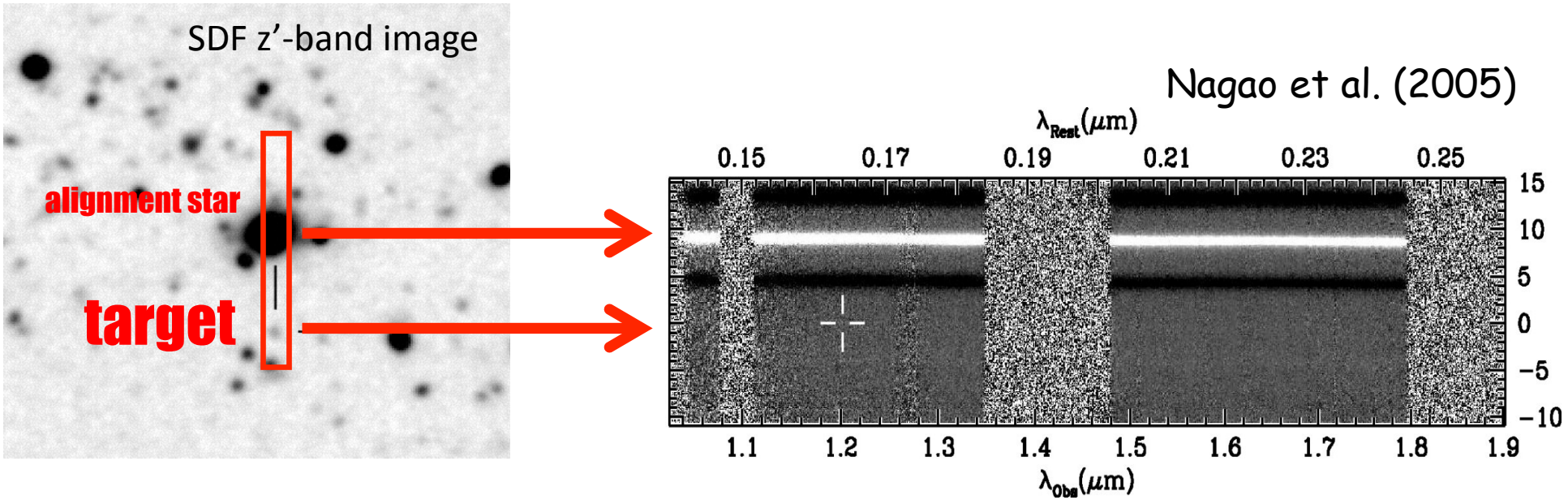




- UV LFs of LAEs & LBGs at z~6 @SDF
- Roughly comparable number density
- Suggesting a high fraction of LAEs

- Spectroscopic campaign @GOODS-N
- LAE fraction is increasing
- Suggesting evolution of stellar pop.

NIR deep spectroscopy to search for He II emission



Subaru/OHS (OH airglow suppressor)
54 ksec on-source exposure for
a LAE at z=6.33 with EW_{rest}=130A

→

only upper limit
~ F(He II) < 9.1e-18 ergs/s/cm^2
~ SFR_{PopIII} < 1.8—13.2 M_{sun} /yr

Since F(Lyα) suggests SFR_{total} > 16 M_{sun} /yr,
the star formation in this LAE is not dominated by PopIII.

Possible implication

expected fractions of
PopIII-dominated galaxies (Scannapieco+03)

- as a function of mass and
  "energy input per gas mass" (← IMF)
- low feedback models might be
  disfavored by our result

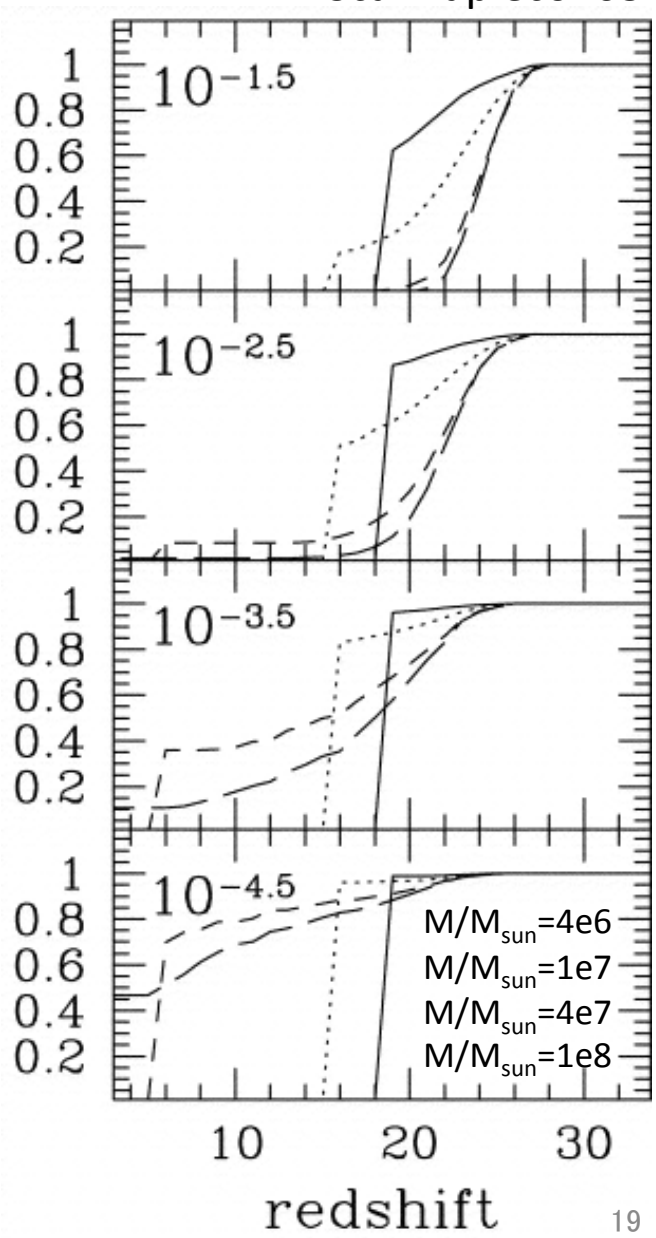
but no strong constraints…

- ***only 1 target*** has been examined…

⬇

Further observations are crucial.

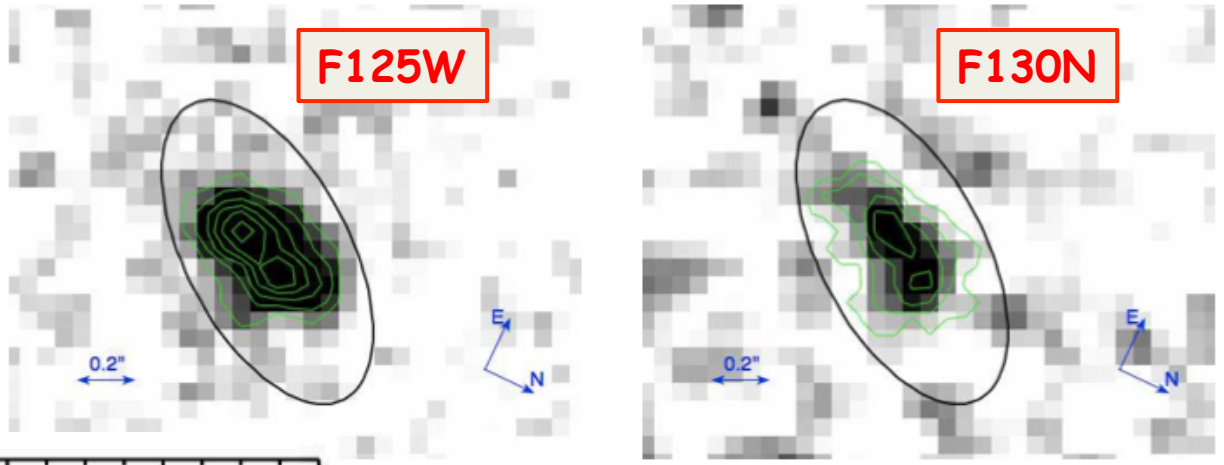
Scannapieco+03

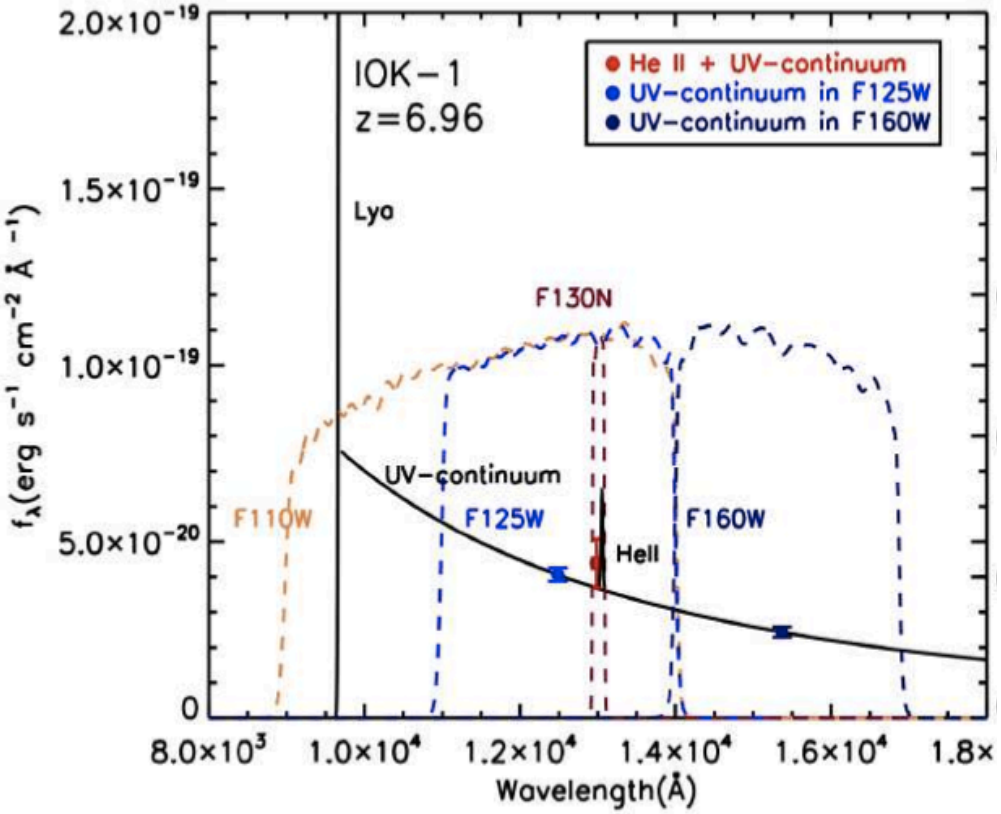


A further trial for the "direct" He II detection

Cai+11

- HST/ACS imaging obs.
- He II with NB filter (!)
- 5.6h (8 orbits) for NB
- 1.4h (2 orbits) for BB

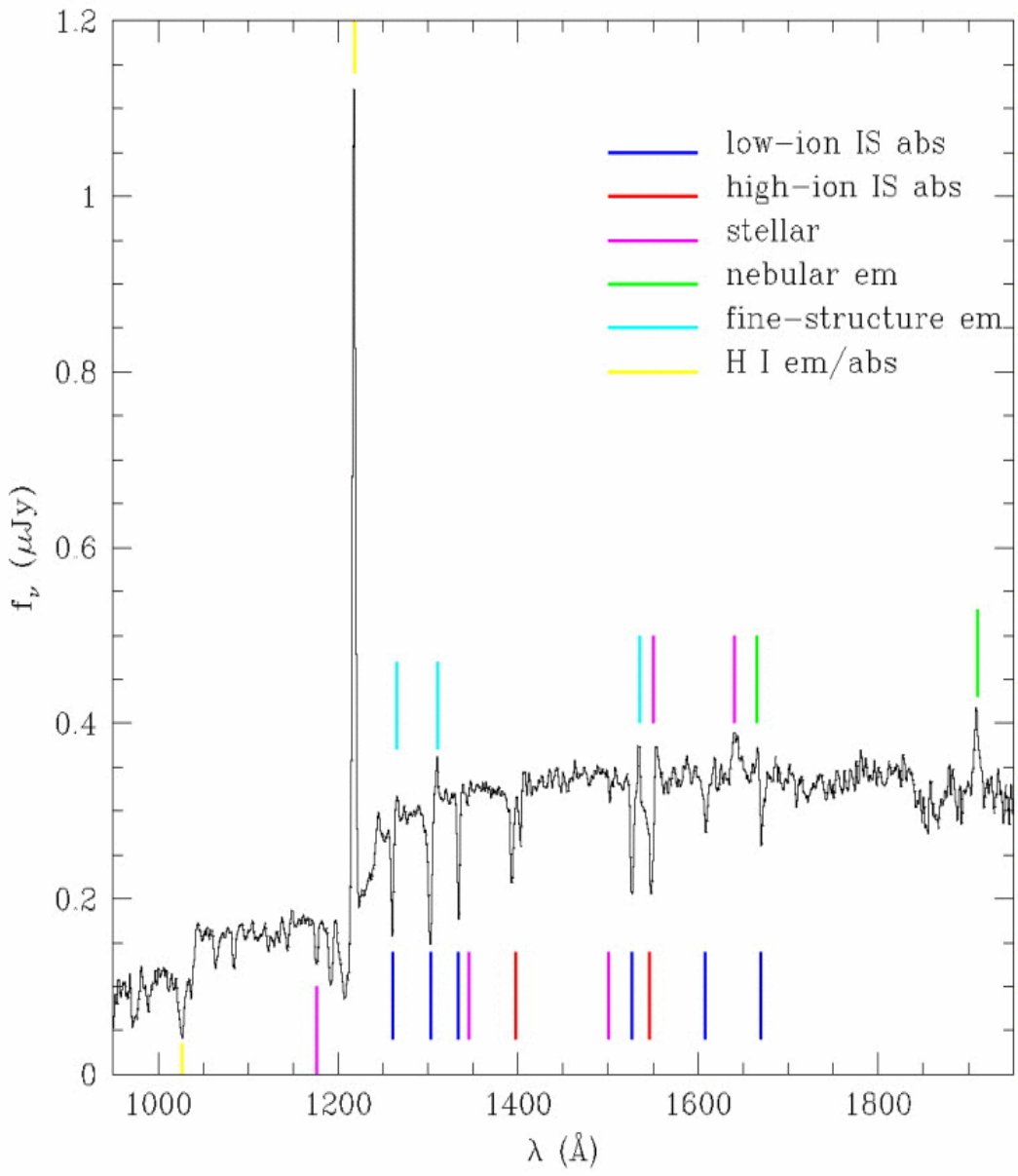




- 1.2 sigma excess in F130N (!?)
- F_{HeII} = 1.2 ± 1.0 x 10^{-18} cgs
- ~5 times deeper than our obs…
- SFR_{PopIII} < 0.5 M_{sun} yr^{-1}
- SFR_{PopIII}/SFR_{total} < 6%

- Detection with JWST is feasible

Stacking analysis

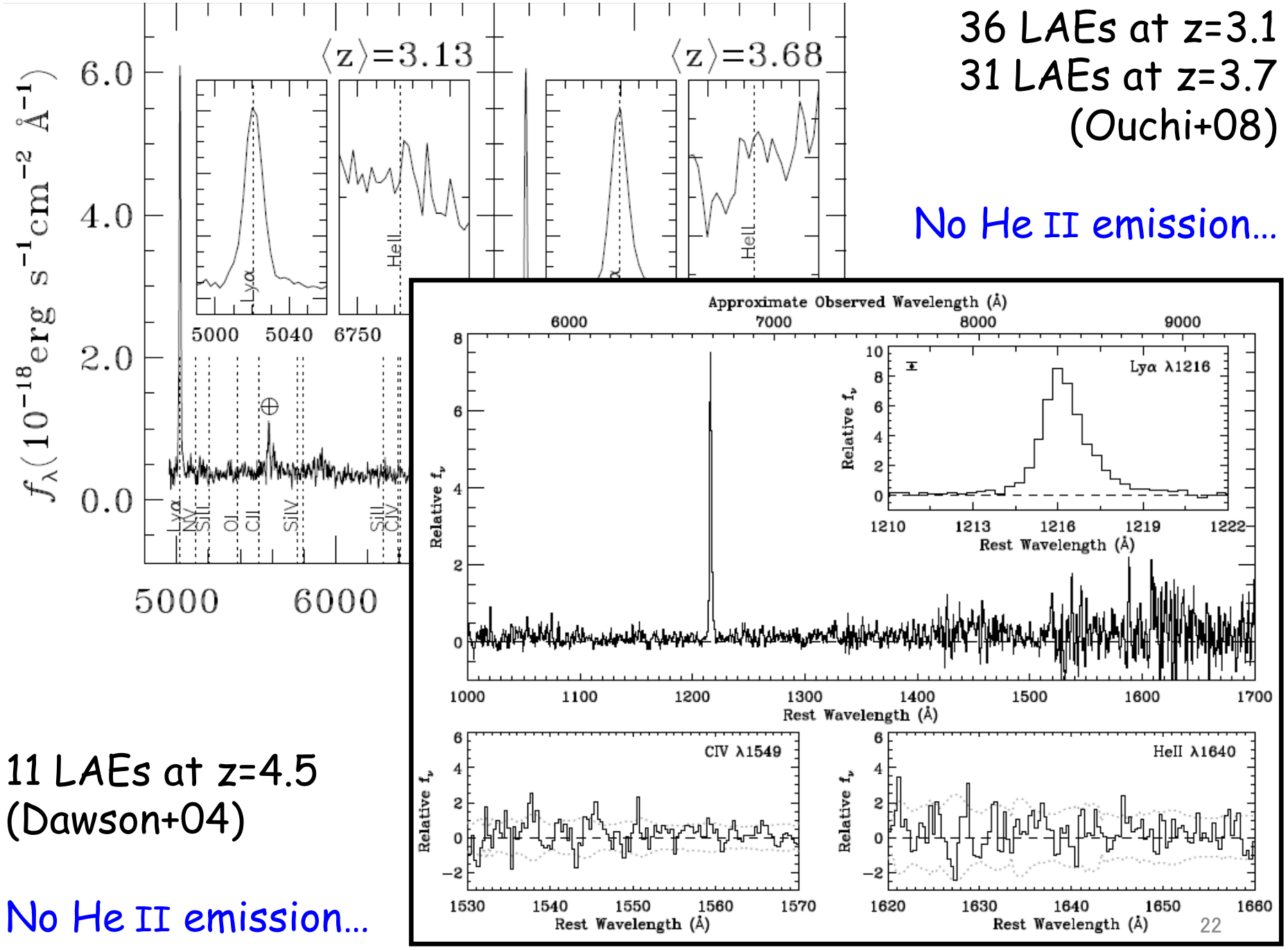


Stacked 811 LBGs
at z=3
(Shapley+03)

…He II emission !?

Evidence of PopIII !?
(Jimenez+06)

Just a stellar feature ?
(Shapley+03)



36 LAEs at z=3.1
31 LAEs at z=3.7
(Ouchi+08)

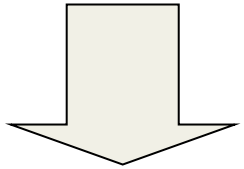
No He II emission…

11 LAEs at z=4.5
(Dawson+04)

No He II emission…

Our search for "Lyα-He II dual emitters"

- Spectroscopy? ...**not a bad idea, but too expensive**
  - ~ faint HeII emission at NIR (or red part in Opt)
  - ~ low number density of targets --> longslit obs.
- Narrow-Band Imaging?
  - ~ requiring "well-matched" combination of filters
  - ~ requiring huge FOV to search "rare" objects



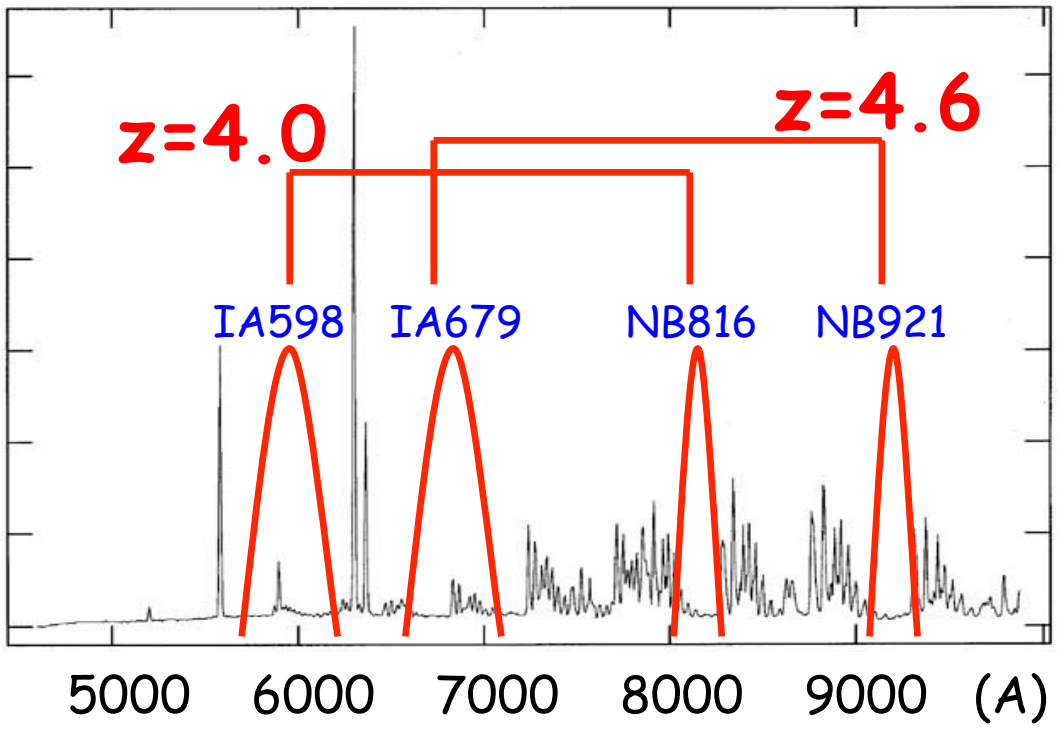
Subaru/Suprime-Cam + custom filter set

very wide FOV (27'x34')

For both Lyα @ λ_{rest} = 1216A & HeII @ λ_{rest} = 1640A

Observations

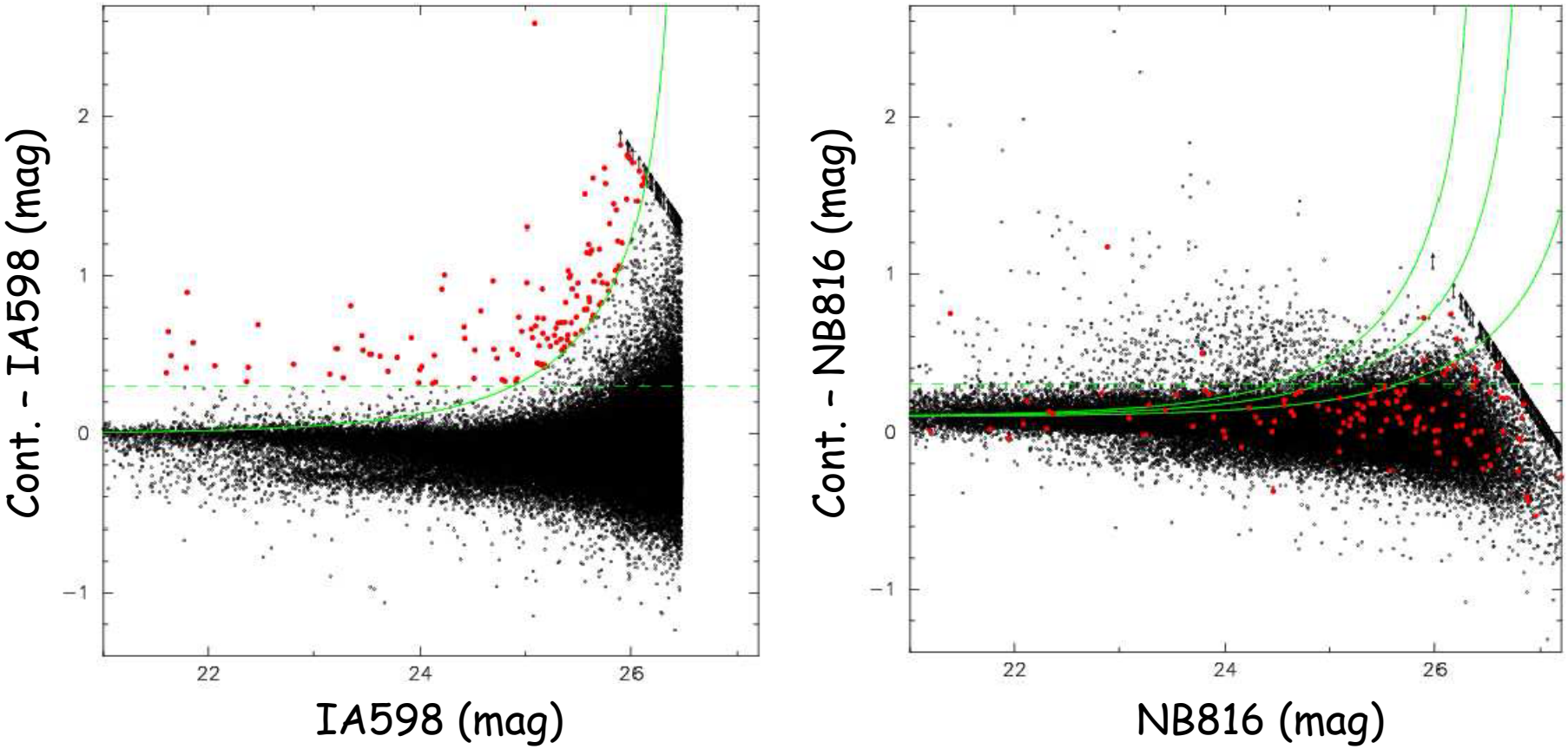
- z=4.0
  - ~ HeII@8200A: **"NB816"**
  - ~ Lya @6080A: **"IA598"**
- z=4.6
  - ~ HeII@9180A: **"NB921"**
  - ~ Lya @6810A: **"IA679"**



- NB816 & NB921
  - ~ originally for Lya emitters at z = 5.7, 6.5

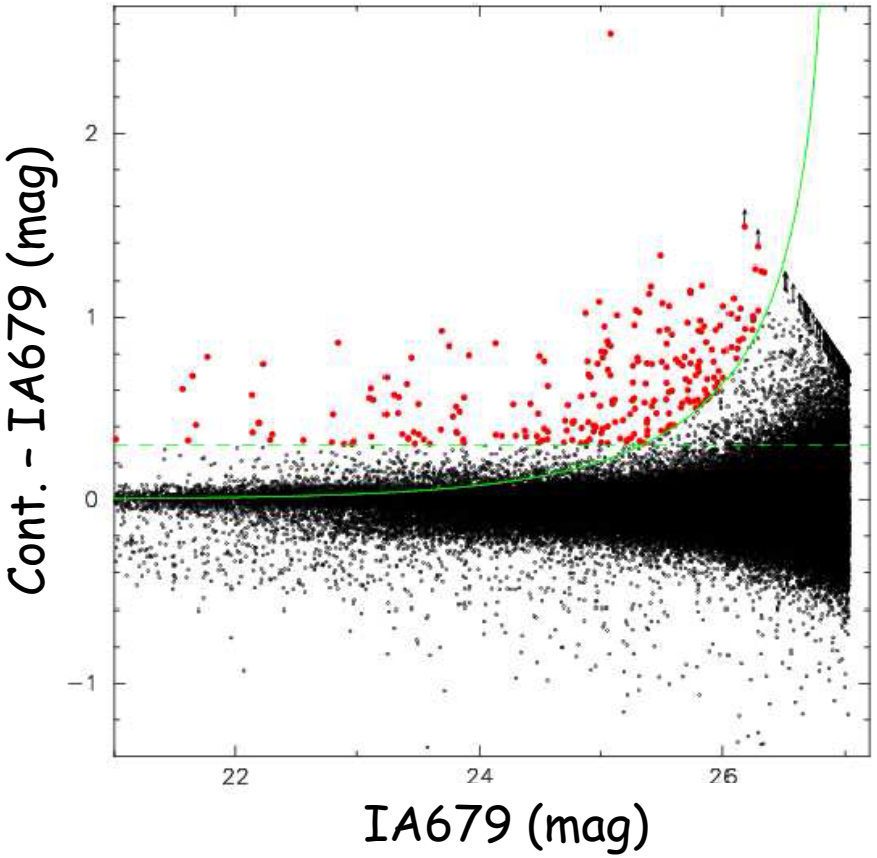
- IA598 & IA679
  - ~ wide bandwidth (Dl~300A): sensitive only to large-EW
    - … no problem for us, because our targets are PopIII !!

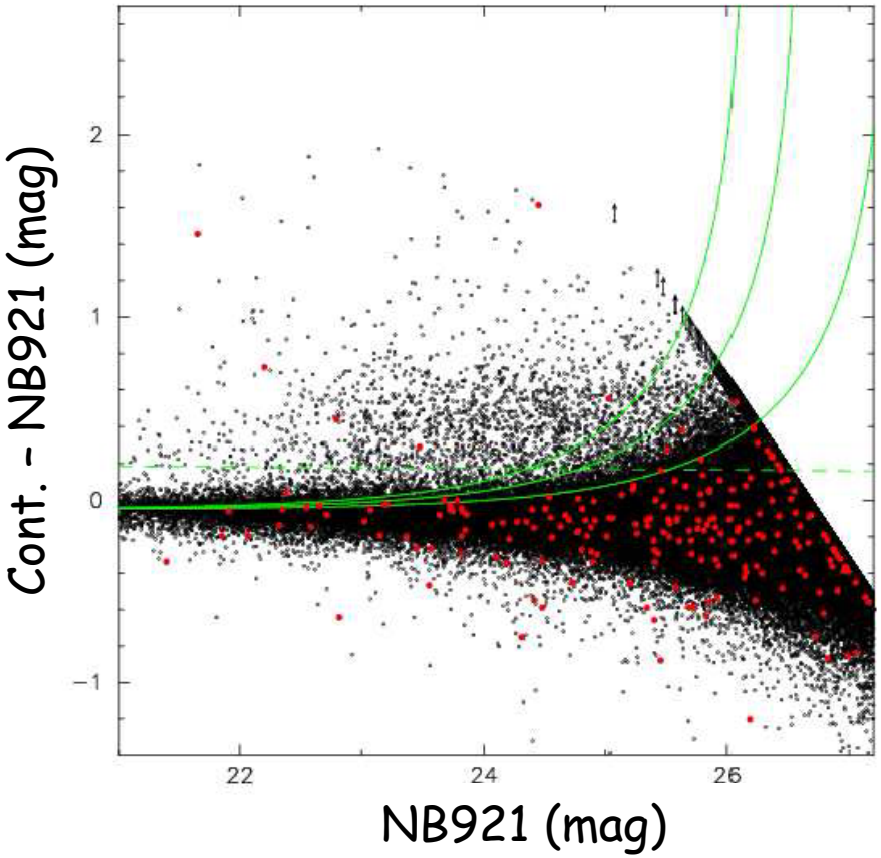
Selection of "IA598-NB816 dual emitters" (z~4.0)



- Cont. – IA598 > 0.3 mag ⇔ EW_{obs} > 114A
  (133 objects)

Selection of "IA679-NB921 dual emitters" (z~4.6)

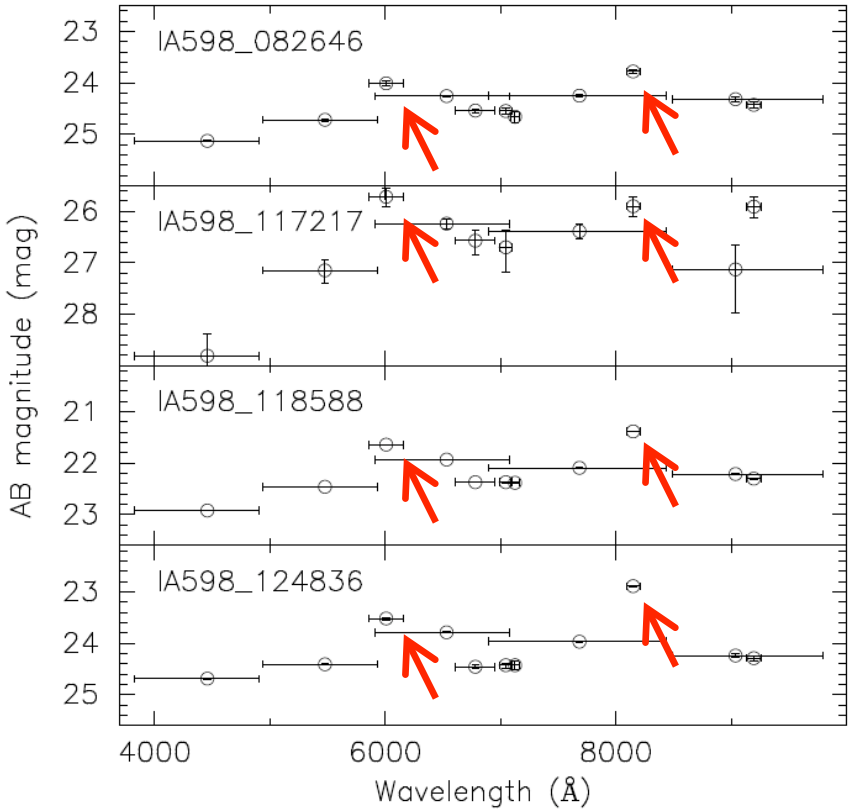


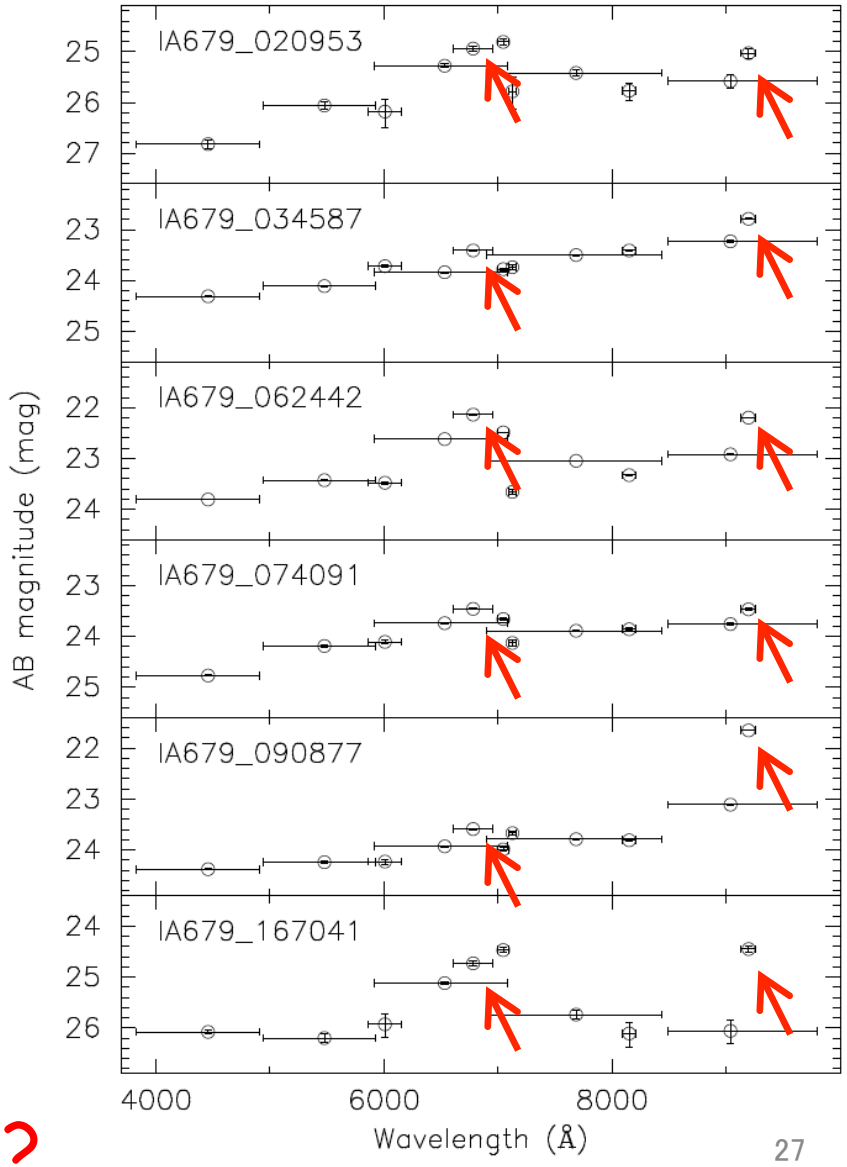


- Cont. – IA679 > 0.3 mag ⇔ EW_{obs} > 145A
  (234 objects)

Results: Discovery of “dual emitters” !?

Nagao et al. (2008)

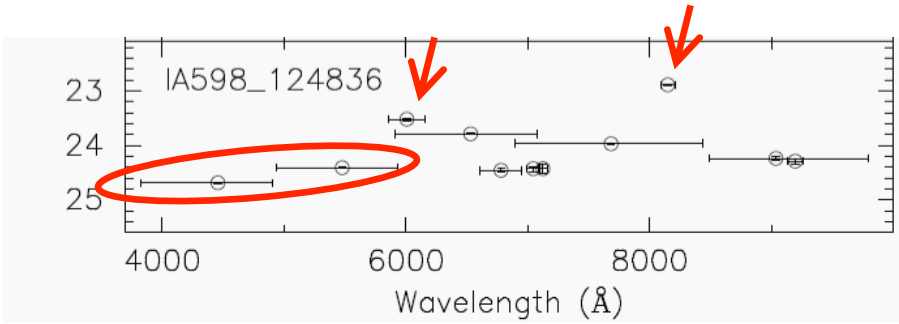




4 IA598-NB816 dual emitters
6 IA679-NB921 dual emitters

… candidates of PopIII !?

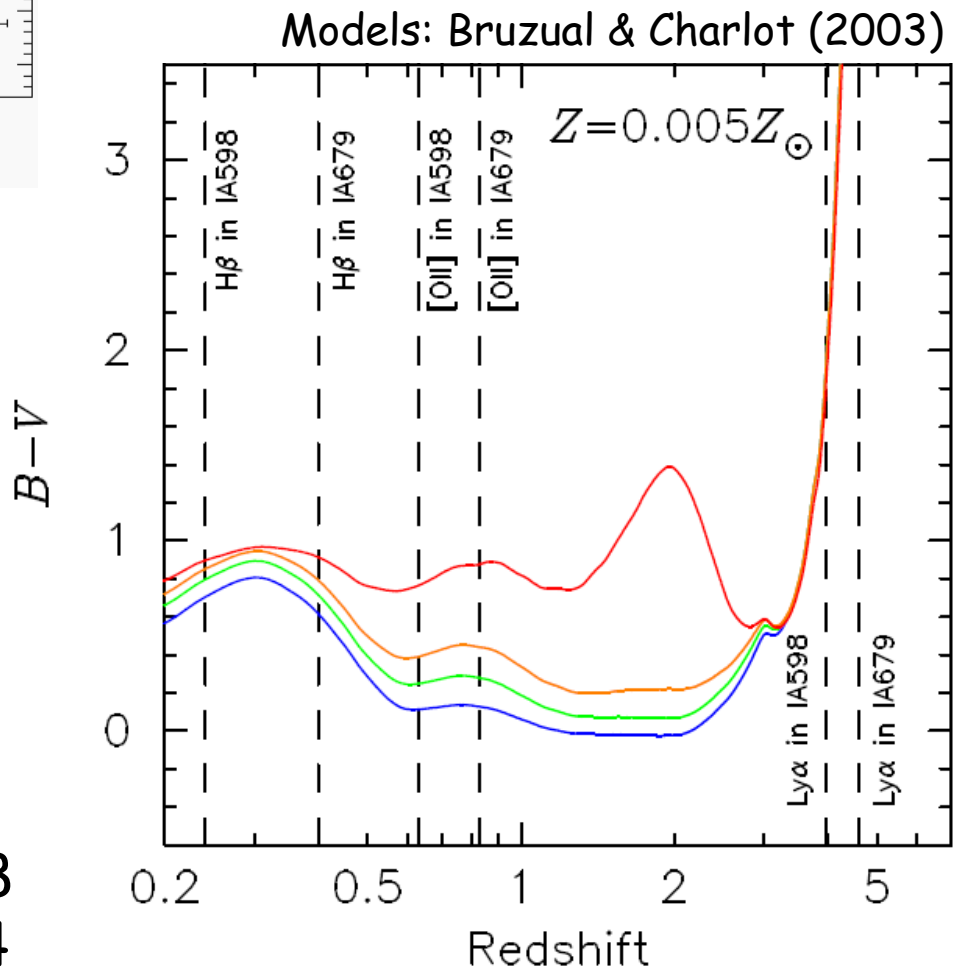
Results: No "Lyα-He II dual emitters" found...



All IA-NB dual emitters show "blue" B-V colors (B-V < 1.0)

Galaxies at z > 4 should show "red" B-V colors (B-V > 1.5)

IA-NB dual emitters : consistent to
[OII] & [OIII] at z=0.6/z=0.8
Hb & Ha+[NII] at z=0.2/z=0.4



➔ ***No "Lya-HeII dual emitters" found...***

Upper limit on the PopIII SFR density (SFRD)

- Our survey sensitivity on SFR_{PopIII}

$L(HeII) = f_{1640} \times SFR_{PopIII}$

~ f_{1640} : depends on model parameters, e.g., IMF
~ adopting f_{1640} reported by Schaerer (2003)
[assuming Salpeter IMF with $50 < M_{PopIII}/M_{sun} < 500$]

$[SFR_{PopIII}]_{lim} \sim 2\ M_{sun}/yr$

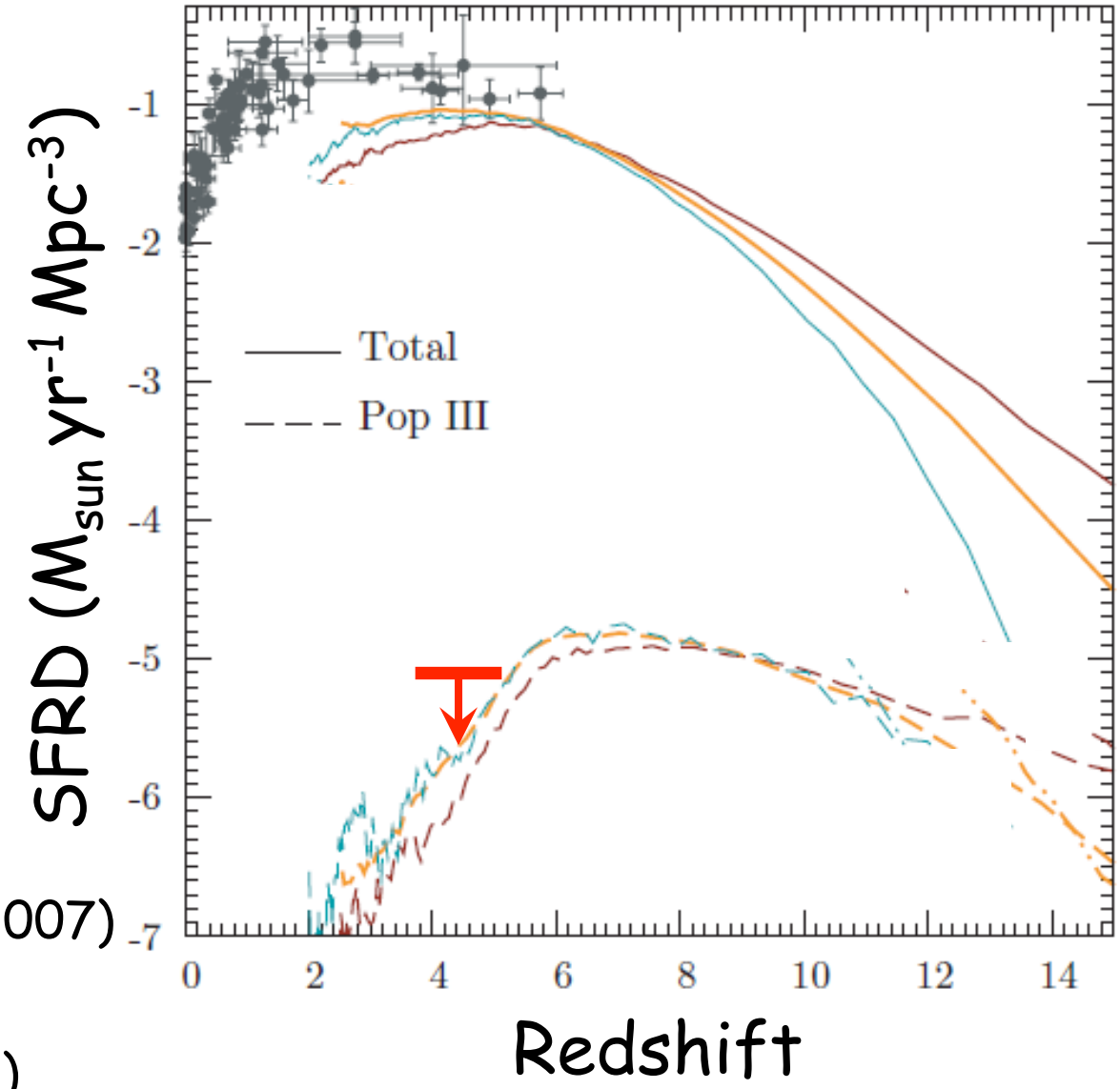
- Upper limit on the PopIII SFR density ($SFRD_{PopIII}$)

$V_{survey} = 4.03 \times 10^5\ Mpc^3$ ($3.93<z<4.01$ & $4.57<z<4.65$)

~ no galaxies with $SFR_{PopIII} > 2\ M_{sun}/yr$ were found
~ assuming no PopIII formation with low SFR_{PopIII}
~ $[SFRD_{PopIII}]_{lim} = [SFR_{PopIII}]_{lim} / V_{survey}$

$SFRD_{PopIII} < 5 \times 10^{-6}\ M_{sun}/yr/Mpc^3$

SFRD(PopIII): Comparison with a model prediction



SFRD model:
Tornatore et al. (2007)

Observational limit:
Nagao et al. (2008)

Summary

- Some models predict the presence of PopIII even at $4<z<7$
  ~ now accessible with large telescopes such as Subaru

- PopIII-hosting galaxies show an extreme Lyα and strong He II
  ~ due to the high effective temperature of PopIII stars

- Evolution of the Lyα EW distribution from z~6 to z~3
  ~ suggesting the presence of PopIII in galaxies at $z>4$?

- Our survey for "dual emitters" gave a constraint on $SFRD_{PopIII}$
  ~ still consistent with predictions, but あともうちょい。

- Future plans with the Subaru/HSC legacy survey
  ~ observational tests for PopIII models will be feasible soon!!