Observations of Forming Galaxies at z>4 and Cosmic Reionization

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Collaborators

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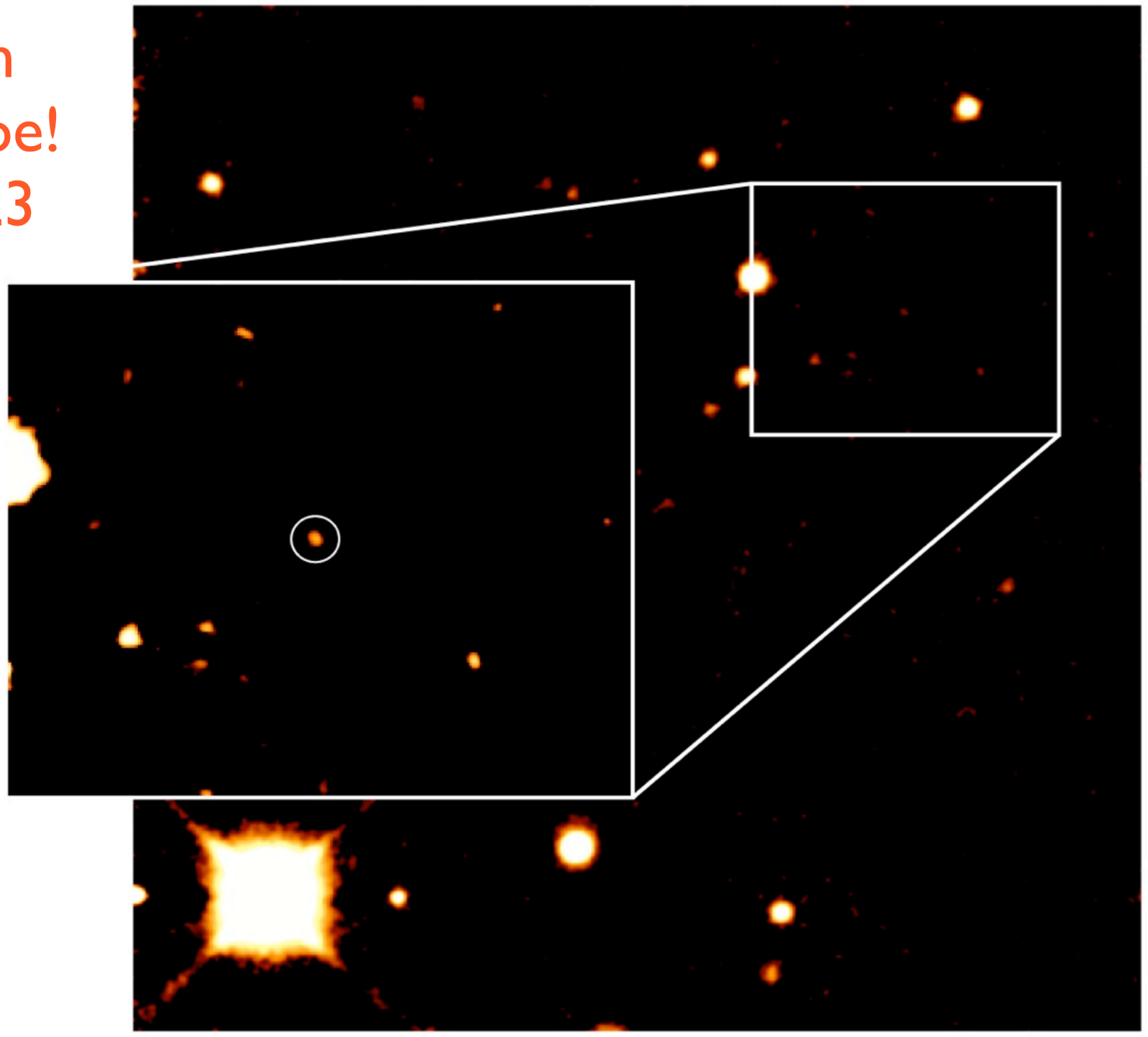
- A. K. Inoue (Osaka Sangyo Univ.)
- N. Tamura, K. Aoki, H. Furusawa (NAOJ)
- M. Akiyama, Y. Matsuda, T. Yamada, T. Hayashino, K. Kousai (Tohoku Univ.)
- J.-M. Deharveng, D. Burgarella (LAM, France)

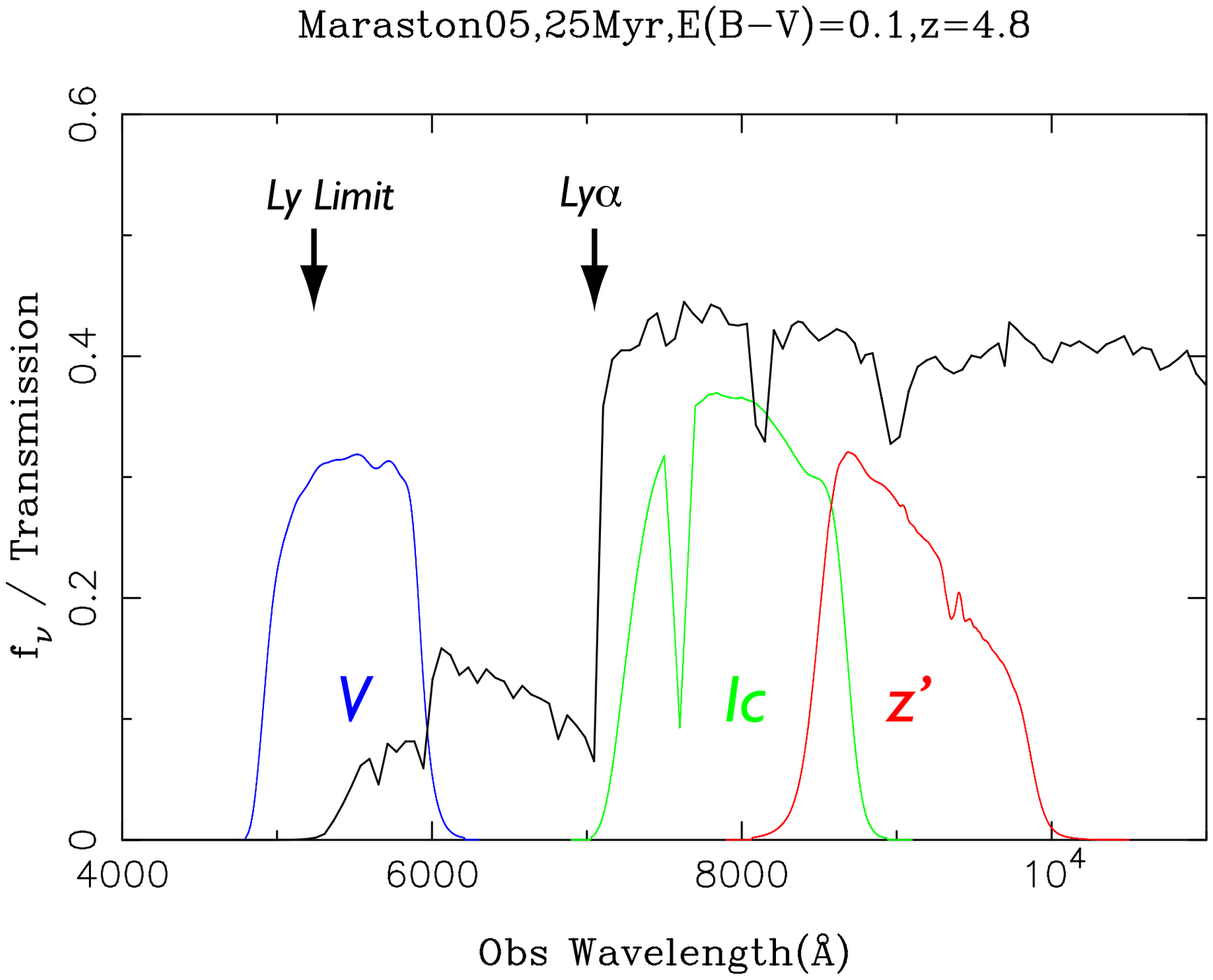
z~8.2 with 2m Telescope! GRB090423



Yanagisawa, Yoshida, Kuroda et al.
Okayama Astrophysical Observatory, NAOJ

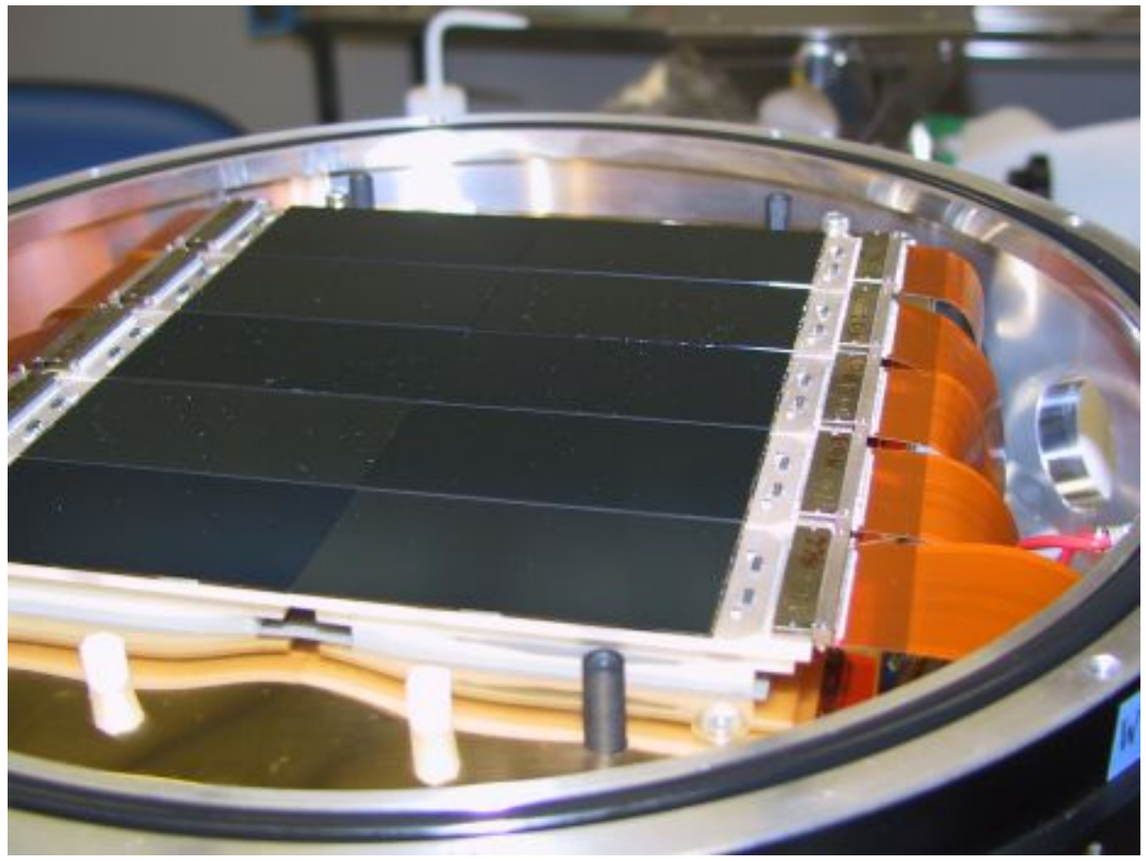
- Observations of High-Redshift Star-forming Galaxies
  - Lyman Break Galaxies (LBGs)
- Cosmic Reionization

Lyman Break Galaxies

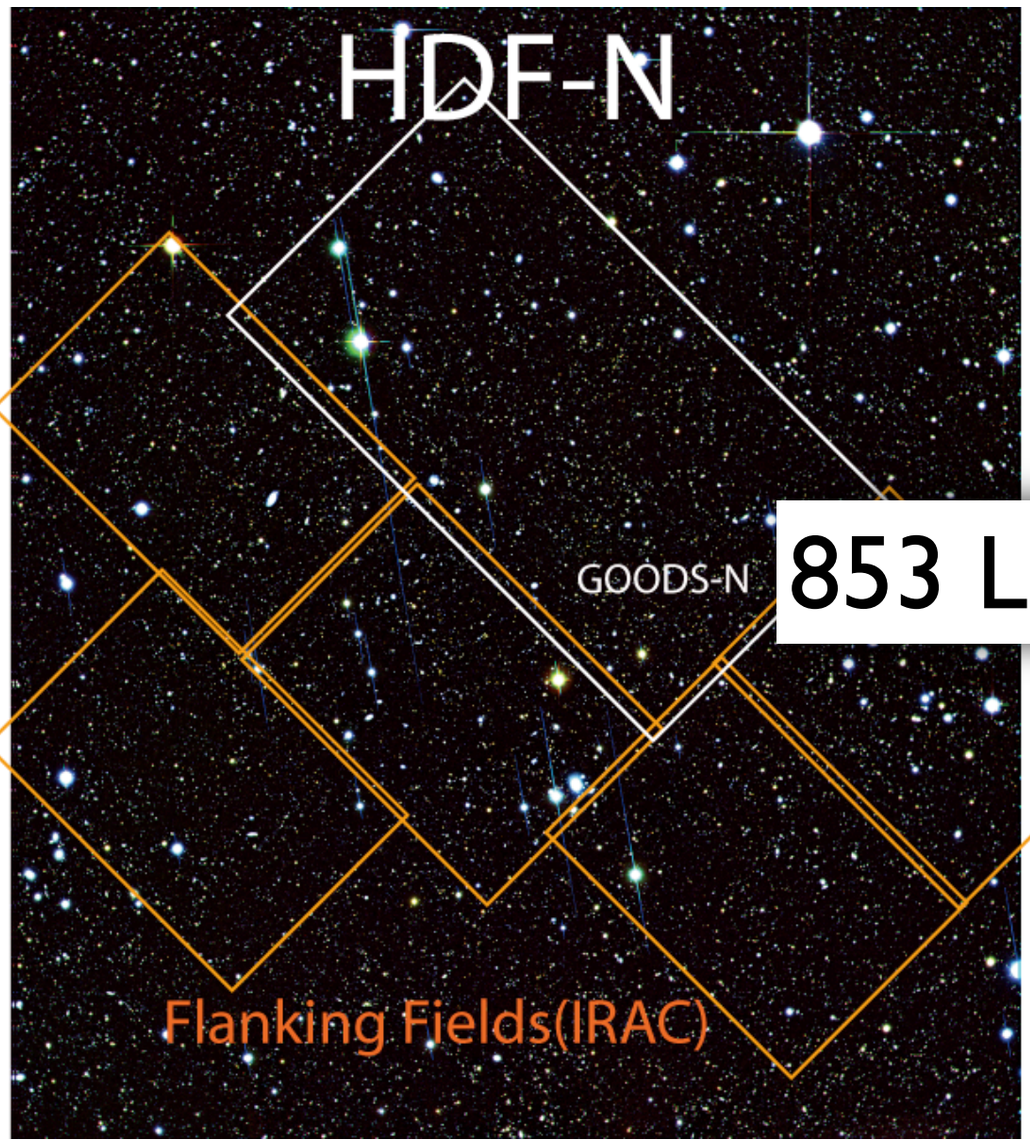


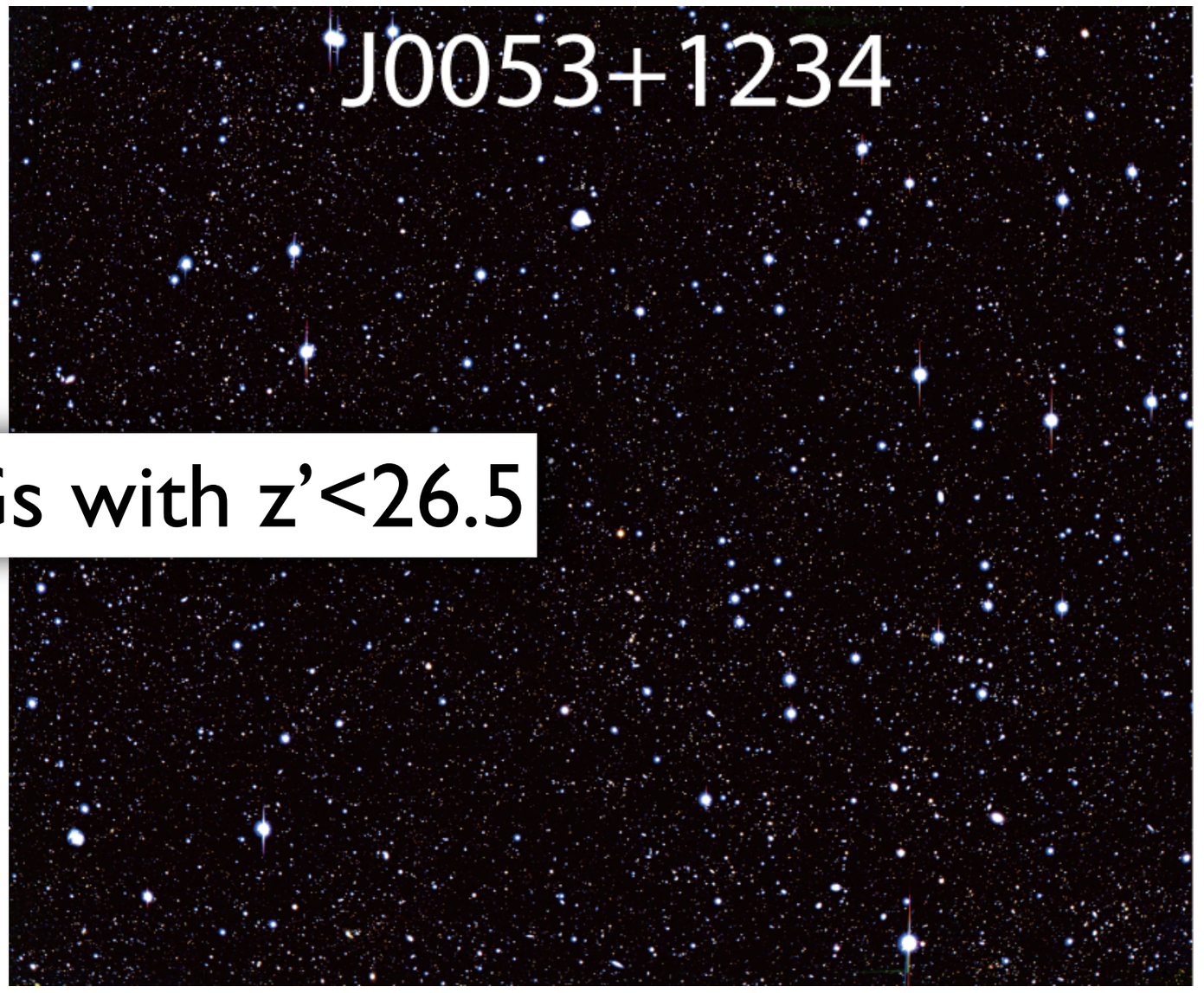
Suprime-Cam

- Unique Instrument with 30’ FoV + 8m Mirror
- LBG Searches with Subaru:
  - Subaru Deep Field
  - Subaru-XMM Deep Survey



Subaru Suprime-Cam z~5 LBG Search





853 LBGs with z'<26.5

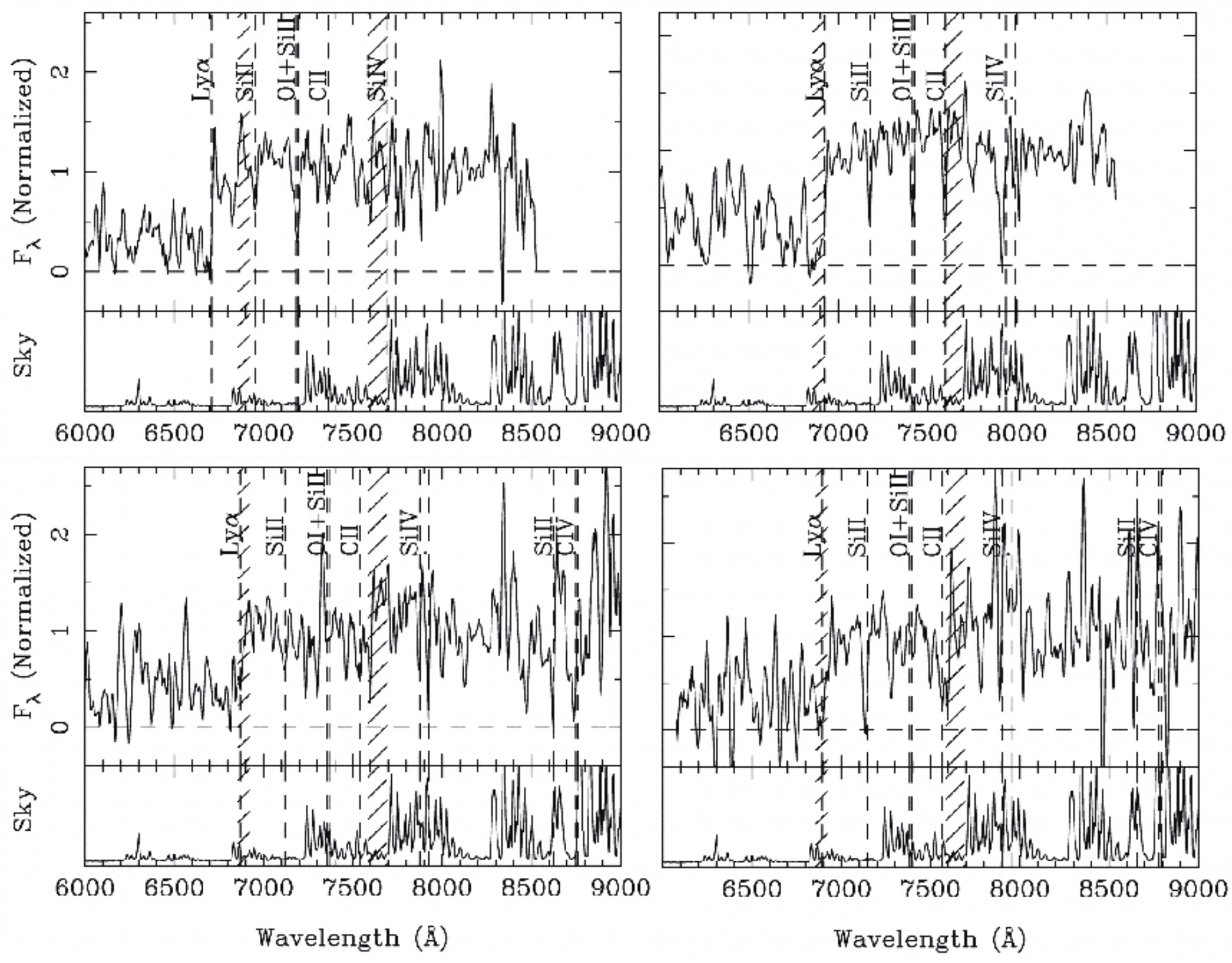
508 arcmin^2

781 arcmin^2

Spectroscopic Follow-up of LBG Candidates

- Subaru / FOCAS: Ando et al. (2004, 2007)
- Gemini / GMOS-N and S (using Nod & Shuffle): Kajino et al. submitted to ApJ
- So Far 16 (North) + 7 (South) Objects Have Been Confirmed to be at z~5
- Color Selection Works Very Well

FOCAS Spectroscopy

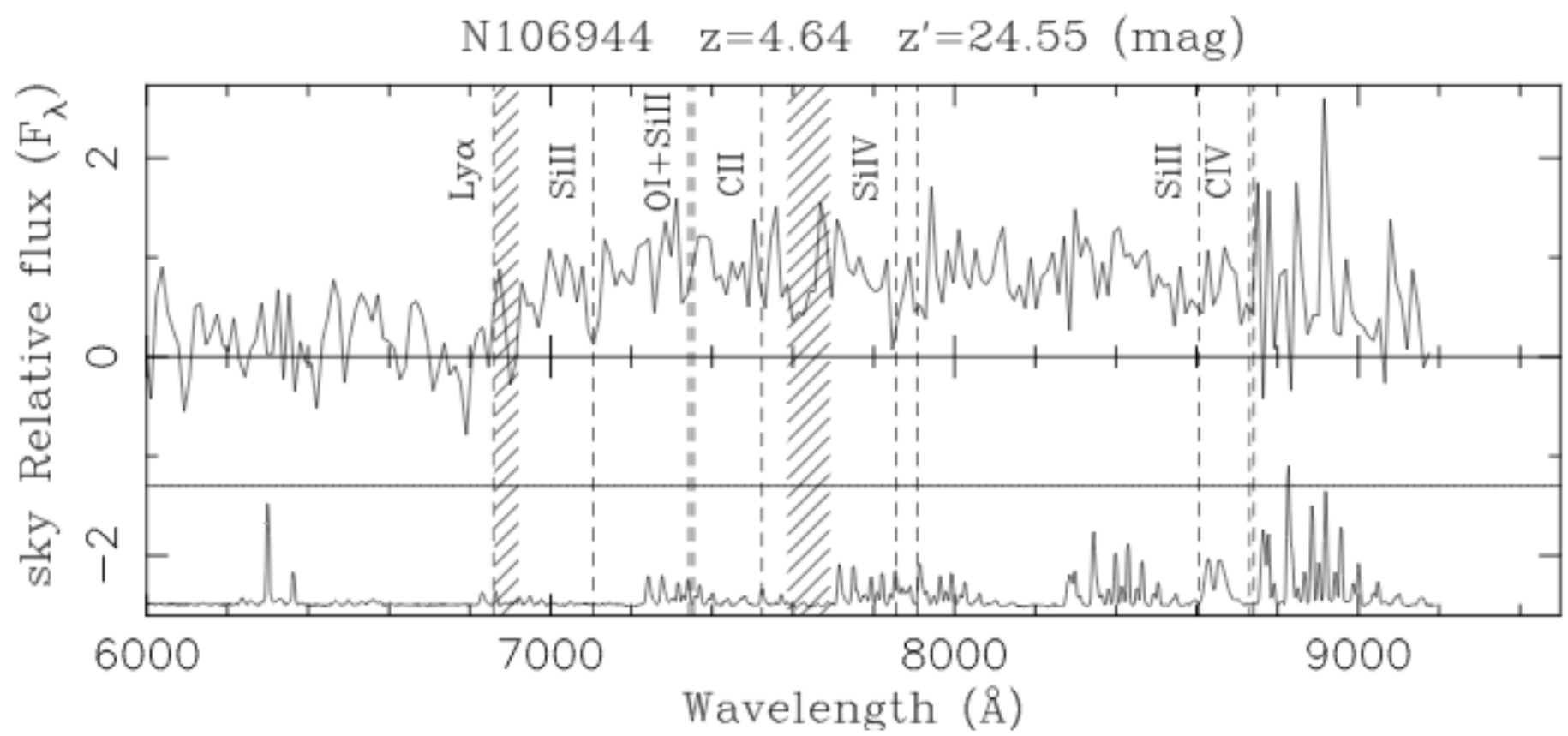


Ando+ 2004 ApJ 610, 635

GMOS Spectroscopy

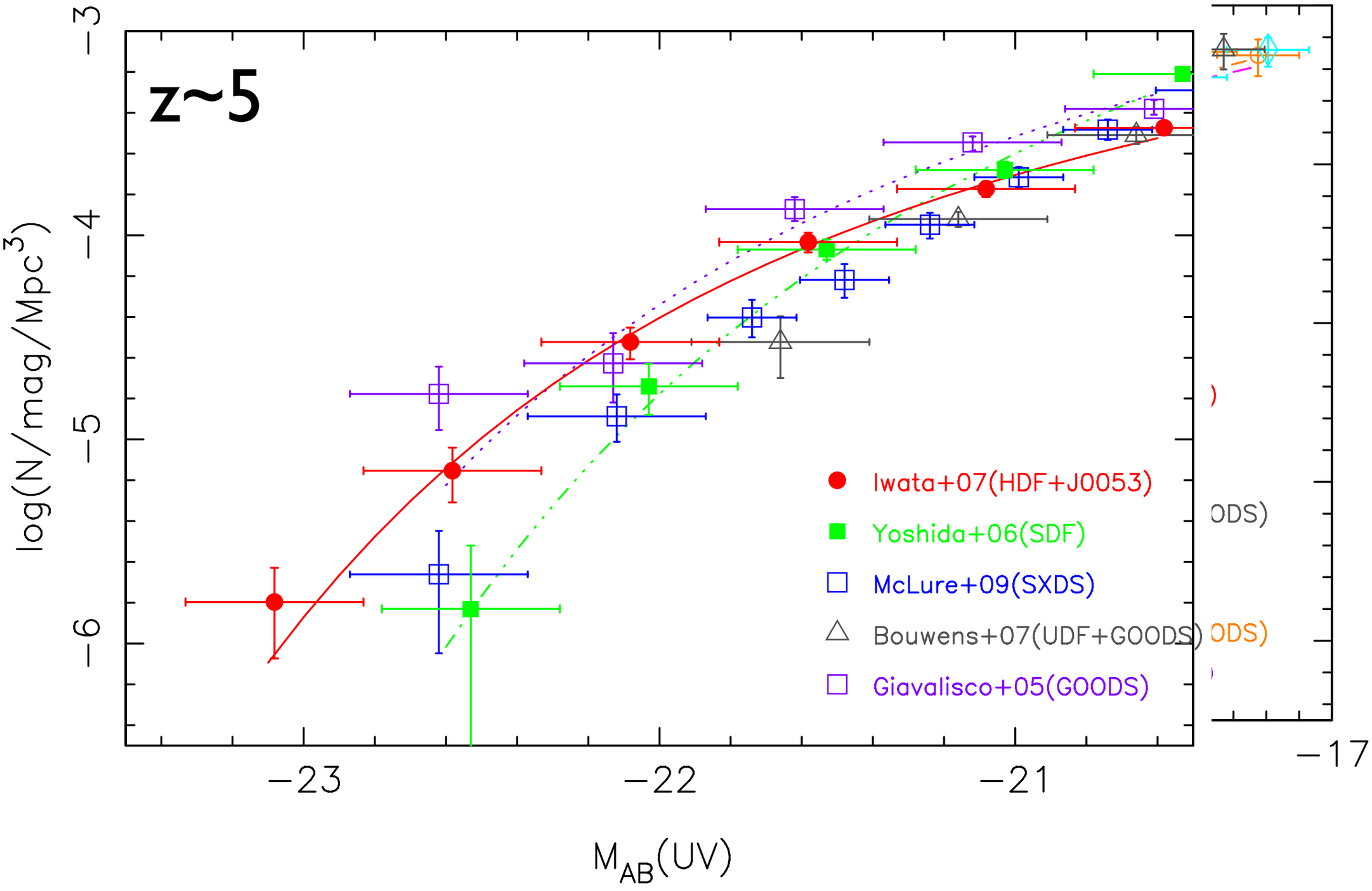
2D Nod-and-Shuffle Spectrum

z=4.64

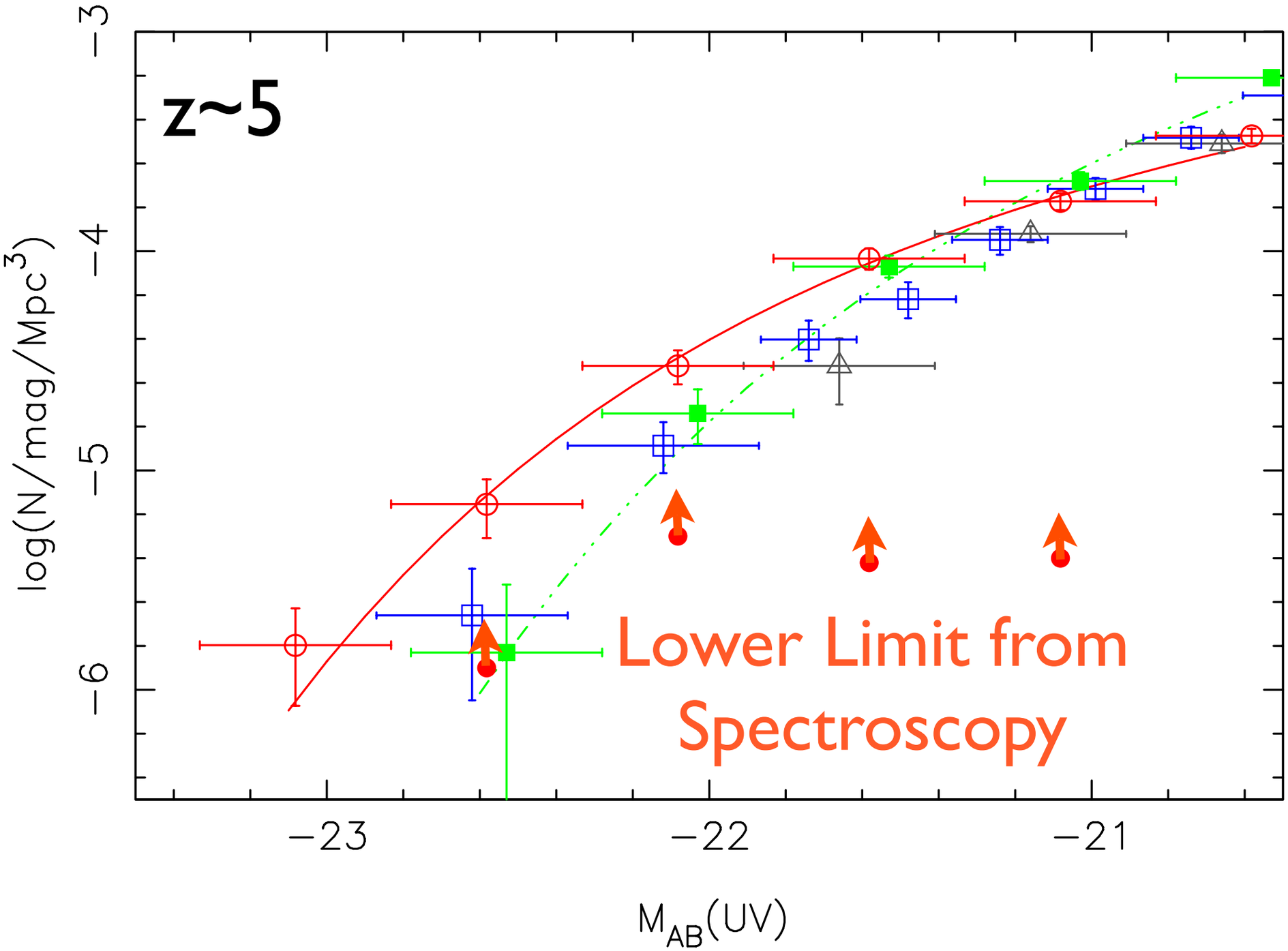


Kajino+ submitted to ApJ

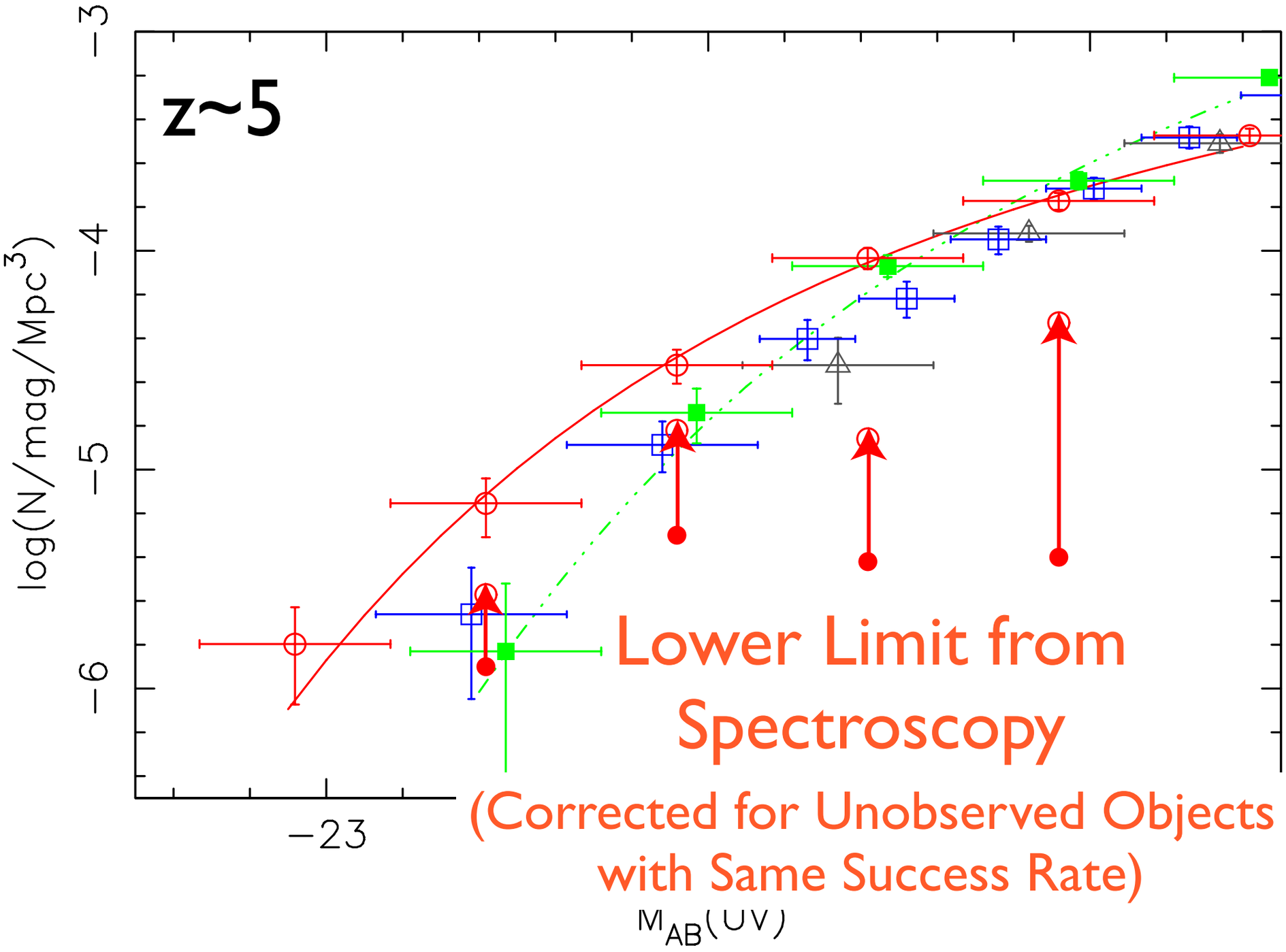
UV Luminosity Function

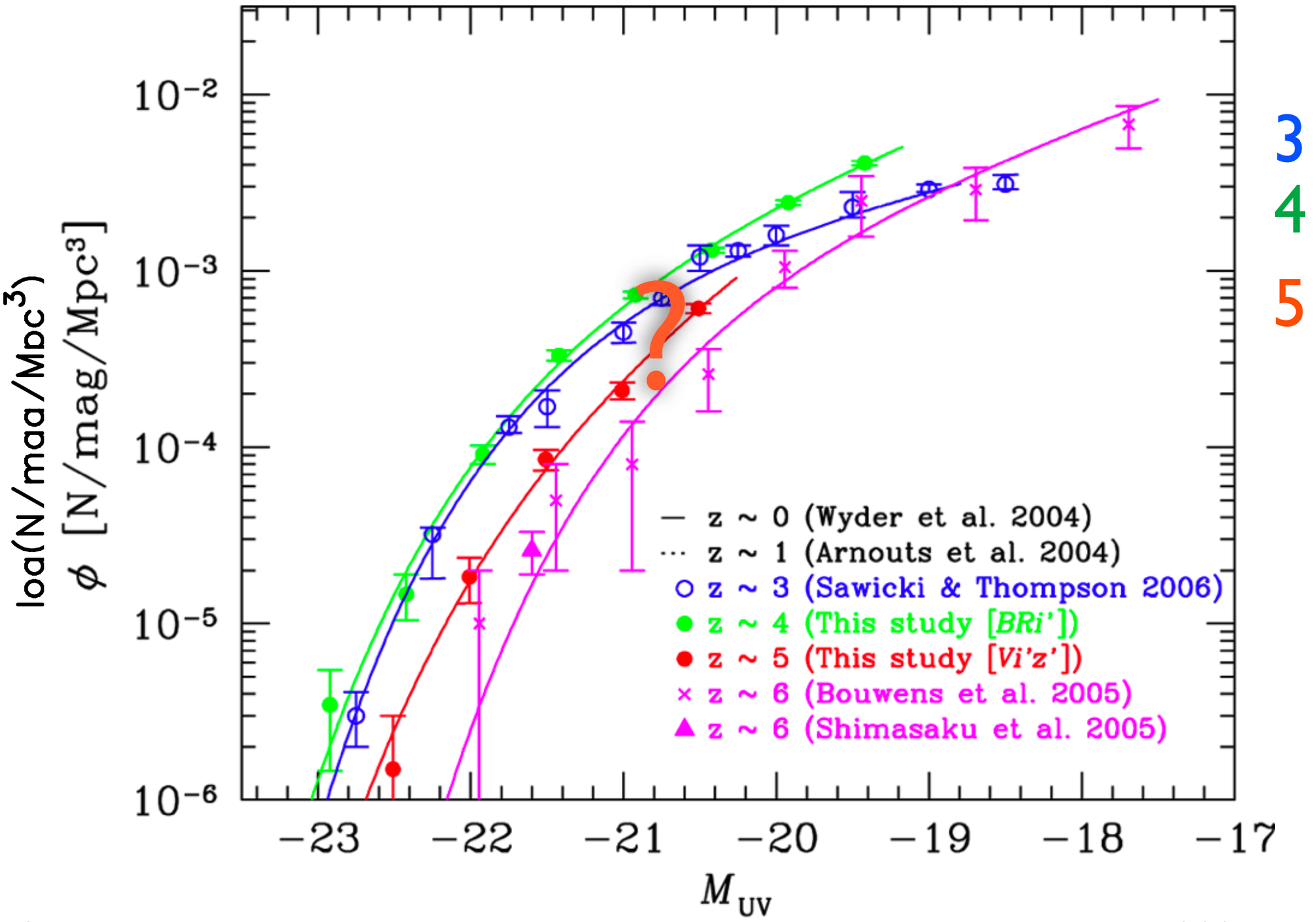


UVLF: Constraints from Spectroscopy



UVLF: Constraints from Spectroscopy



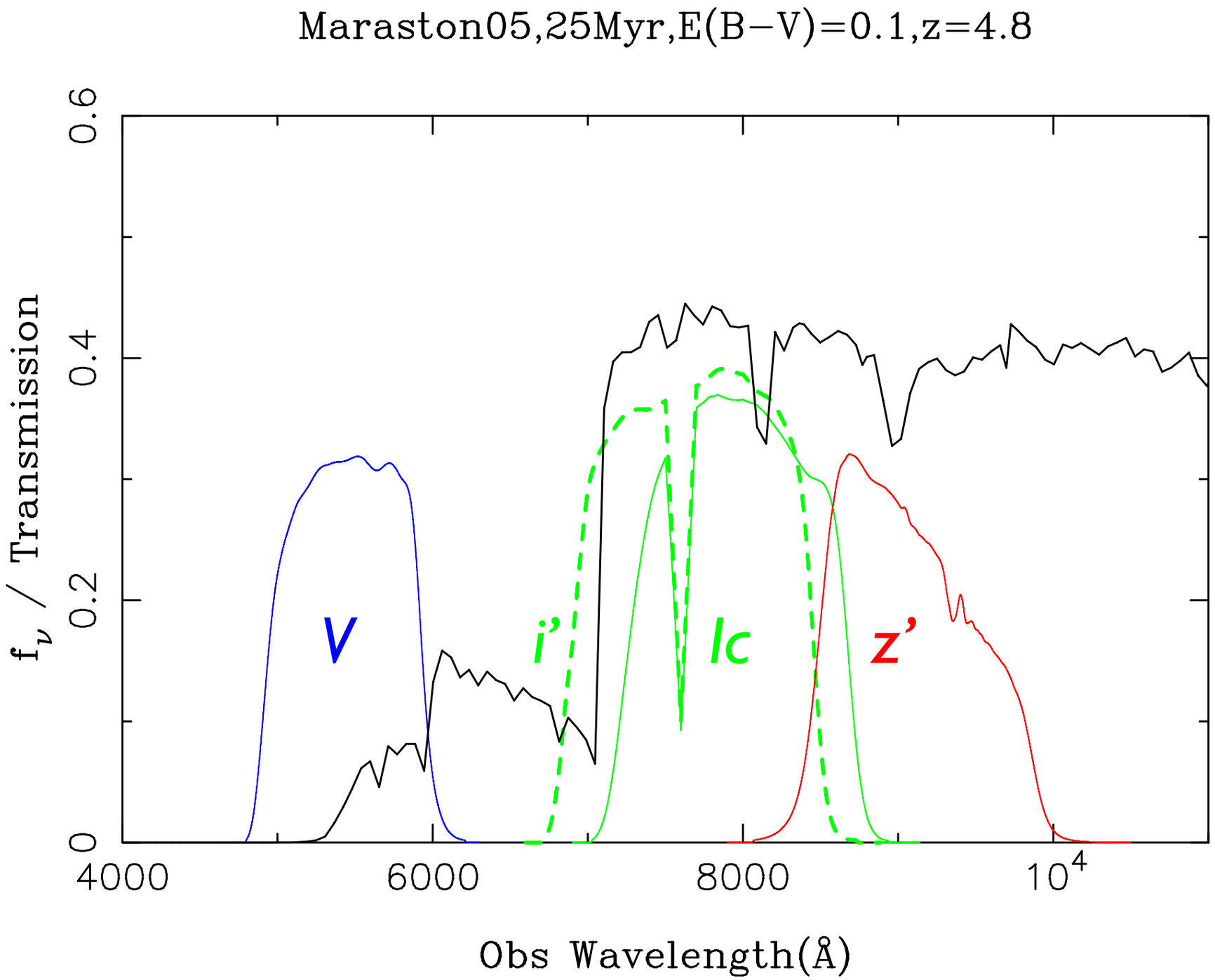


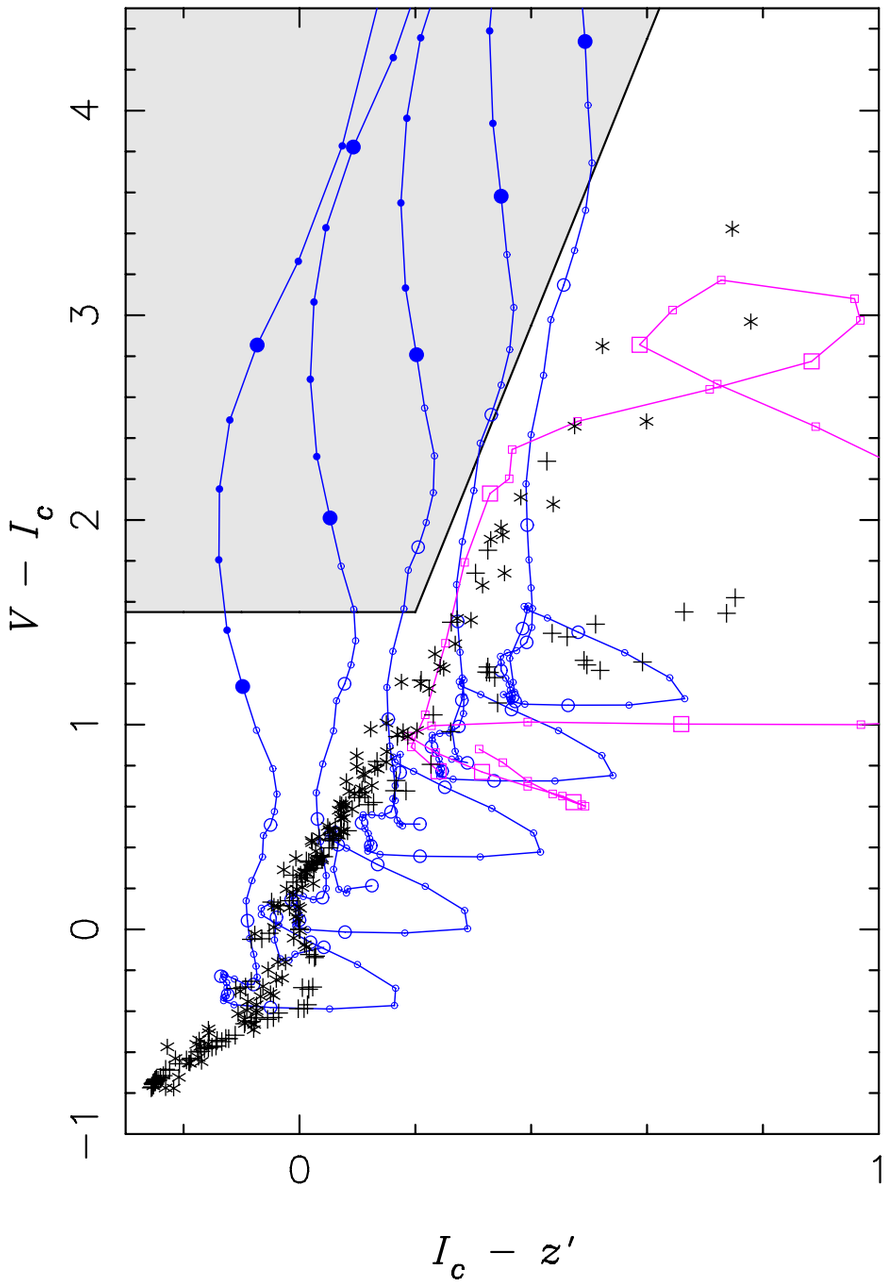
Iwata+ 2007 PASJ 59S, 1337

Yoshida+ 2006 ApJ 653, 988

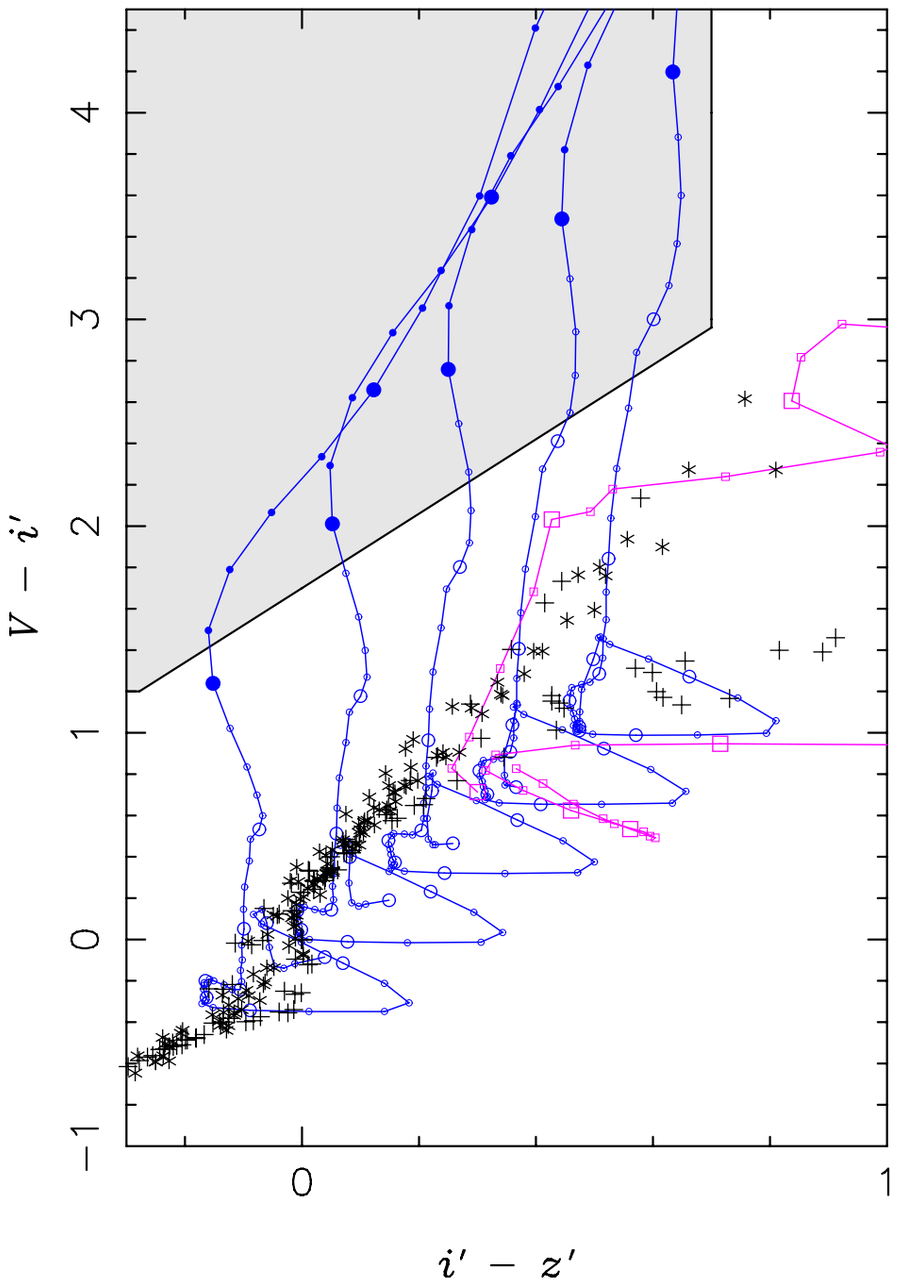
Do We See the Same Population?

Filters Used by Us and Subaru Deep Field





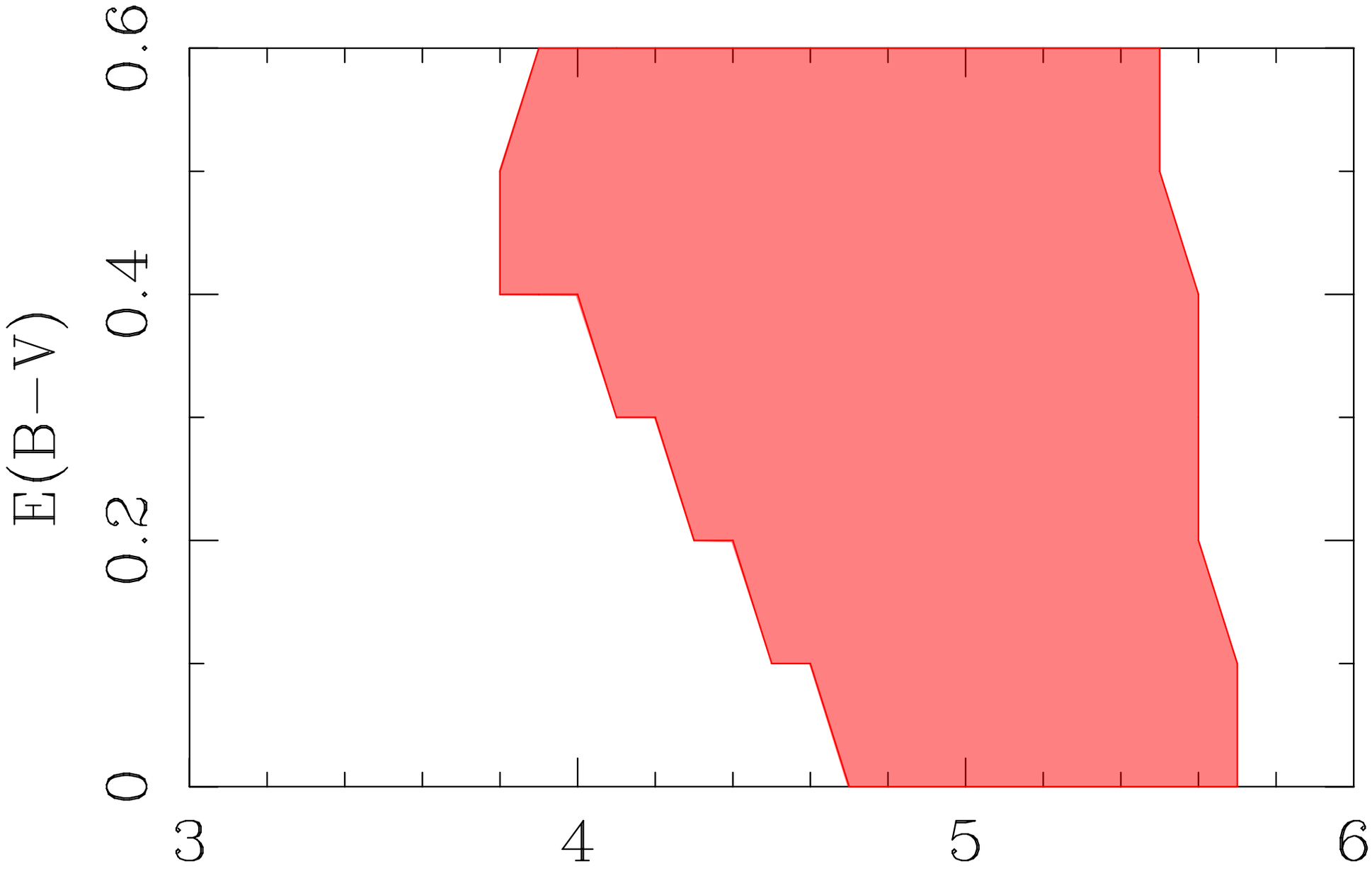
VIcz' (Ours)



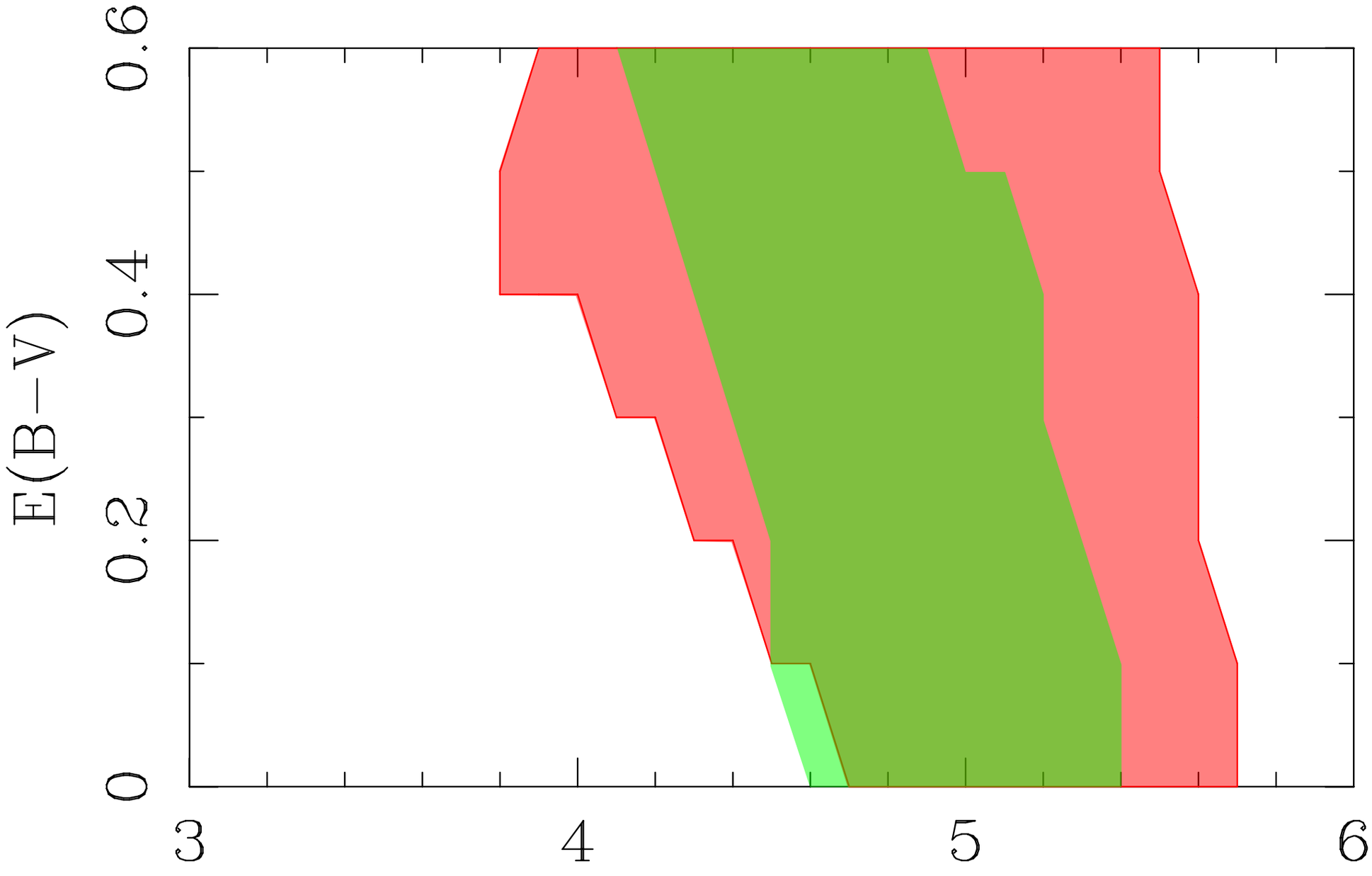
Vi'z' (SDF)

Model: Maraston05, Const. SFR, Salpeter IMF, Z=0.5Zsun, age=25 Myr, Calzetti Dust, IGM Attenuation (Inoue+05)

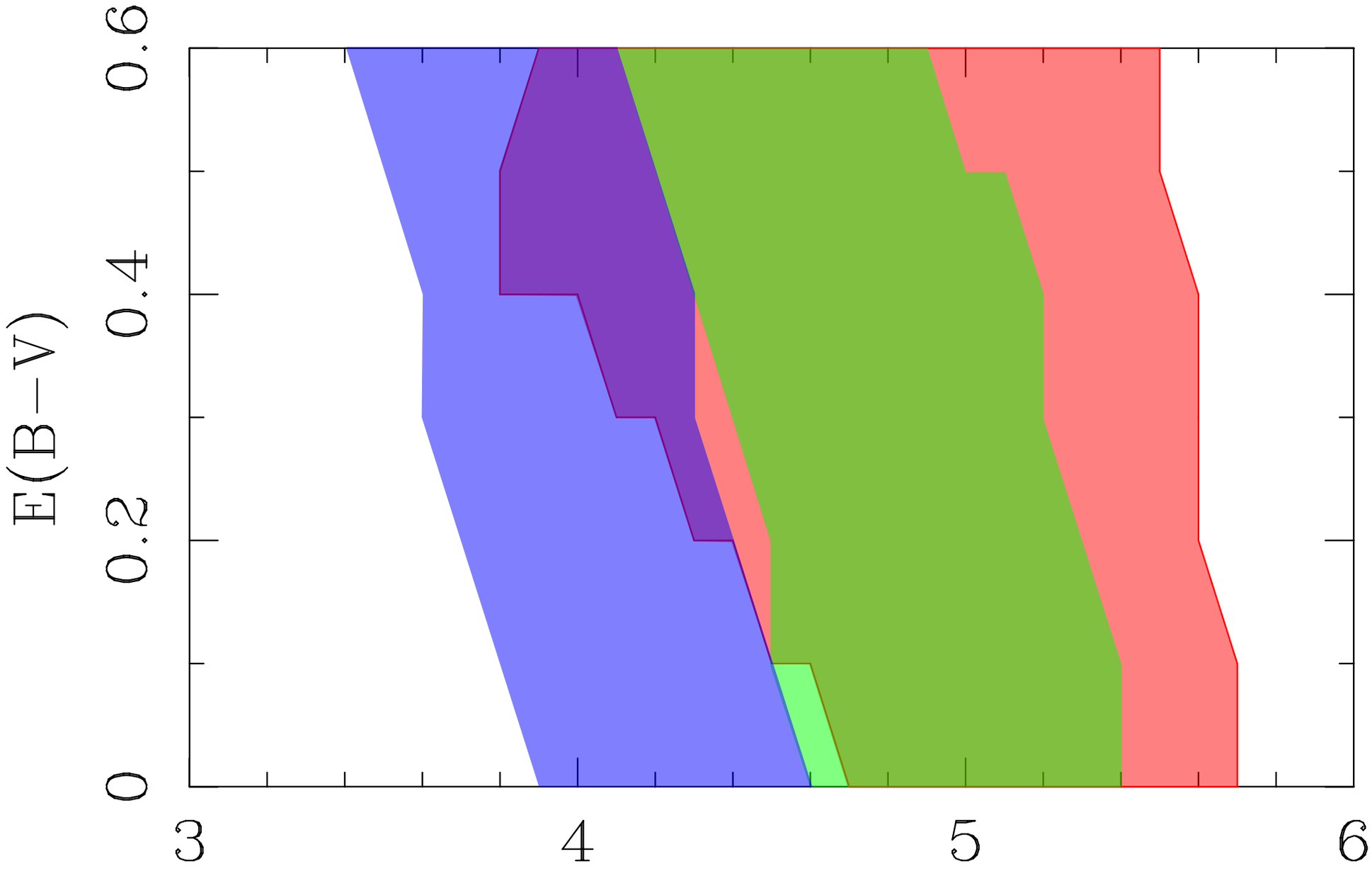
Populations Covered by Vlz Selection



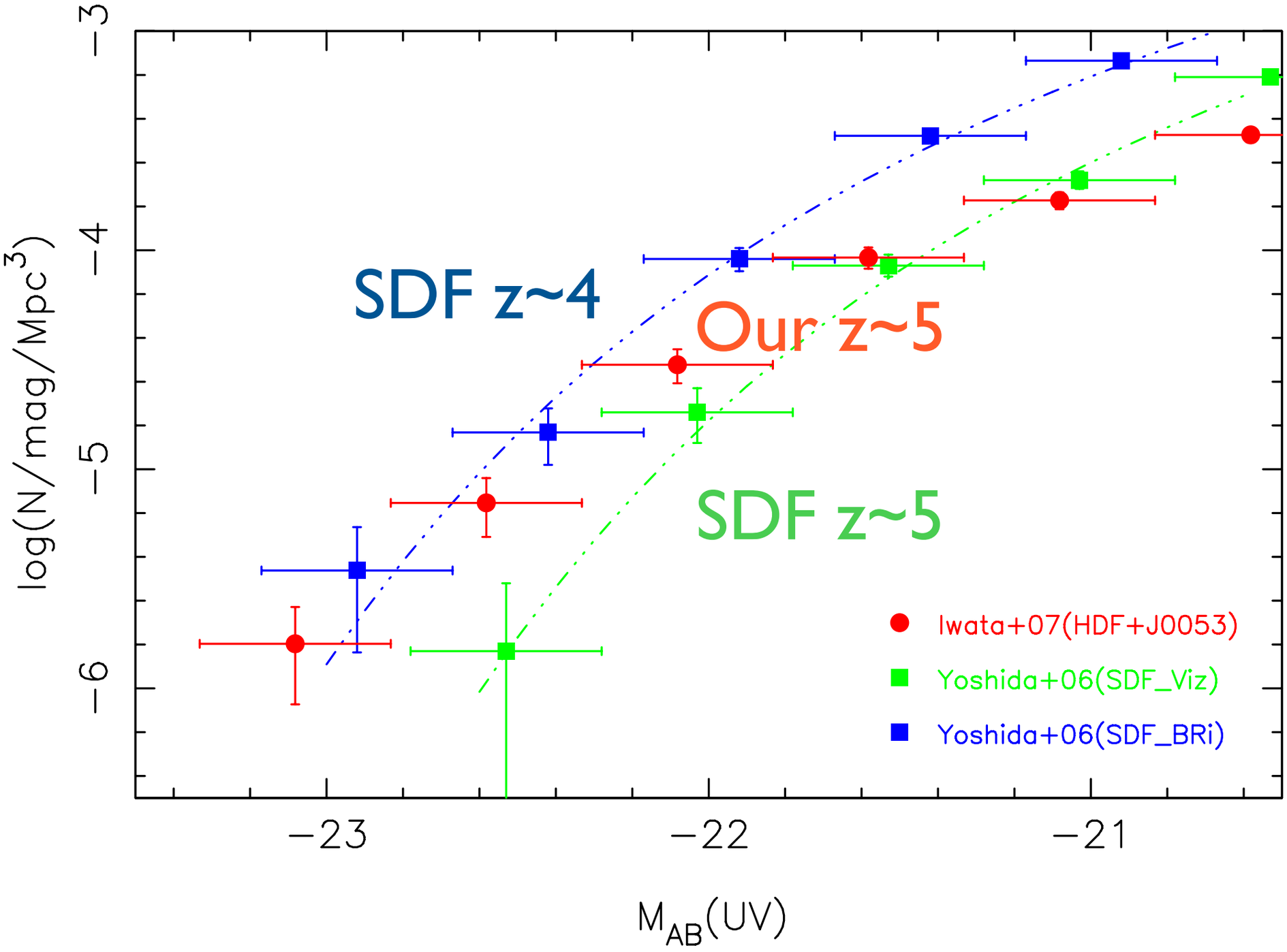
Populations Covered by VIz and Viz Selections



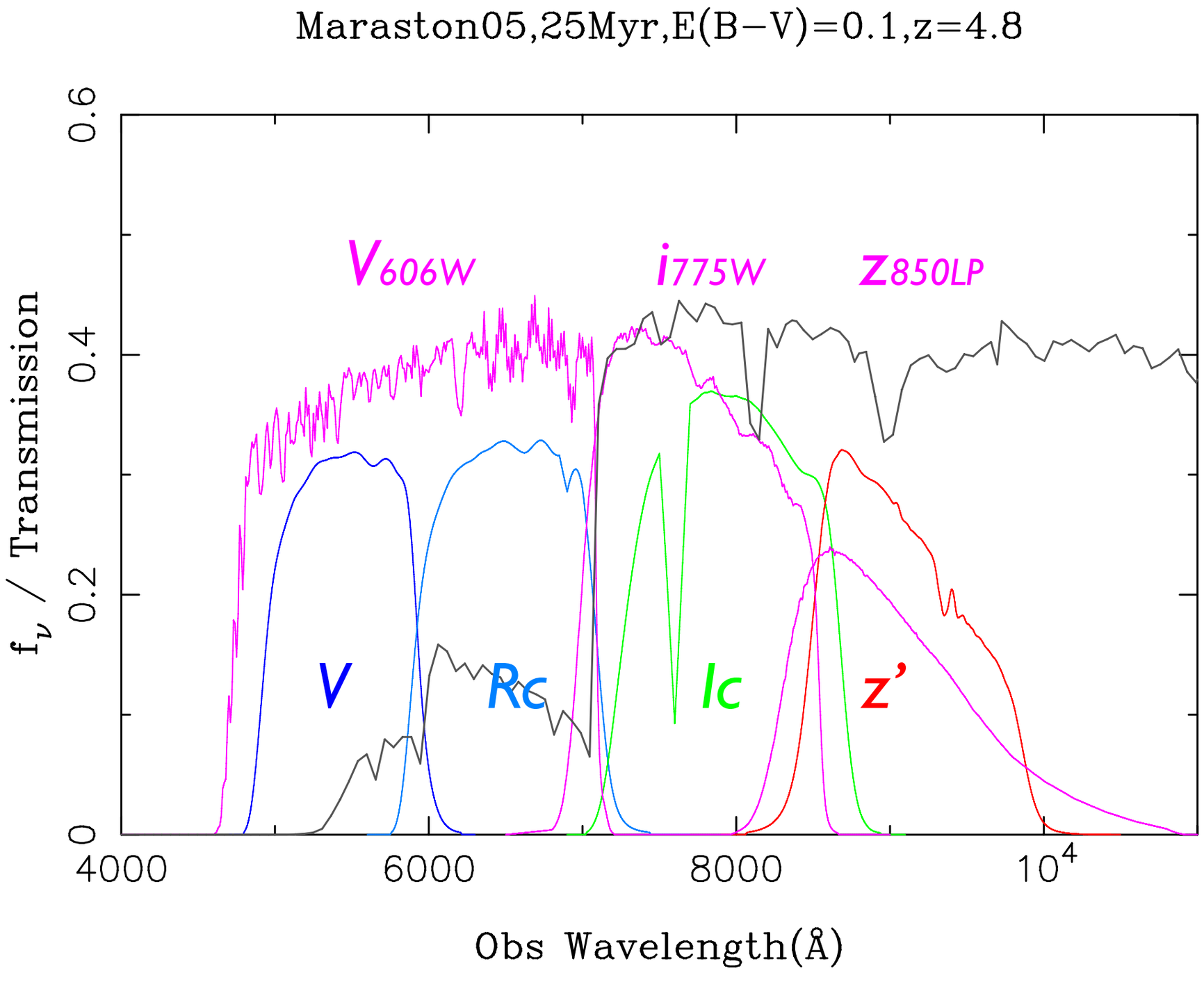
Populations Covered by VIz, Viz and BRi Selections

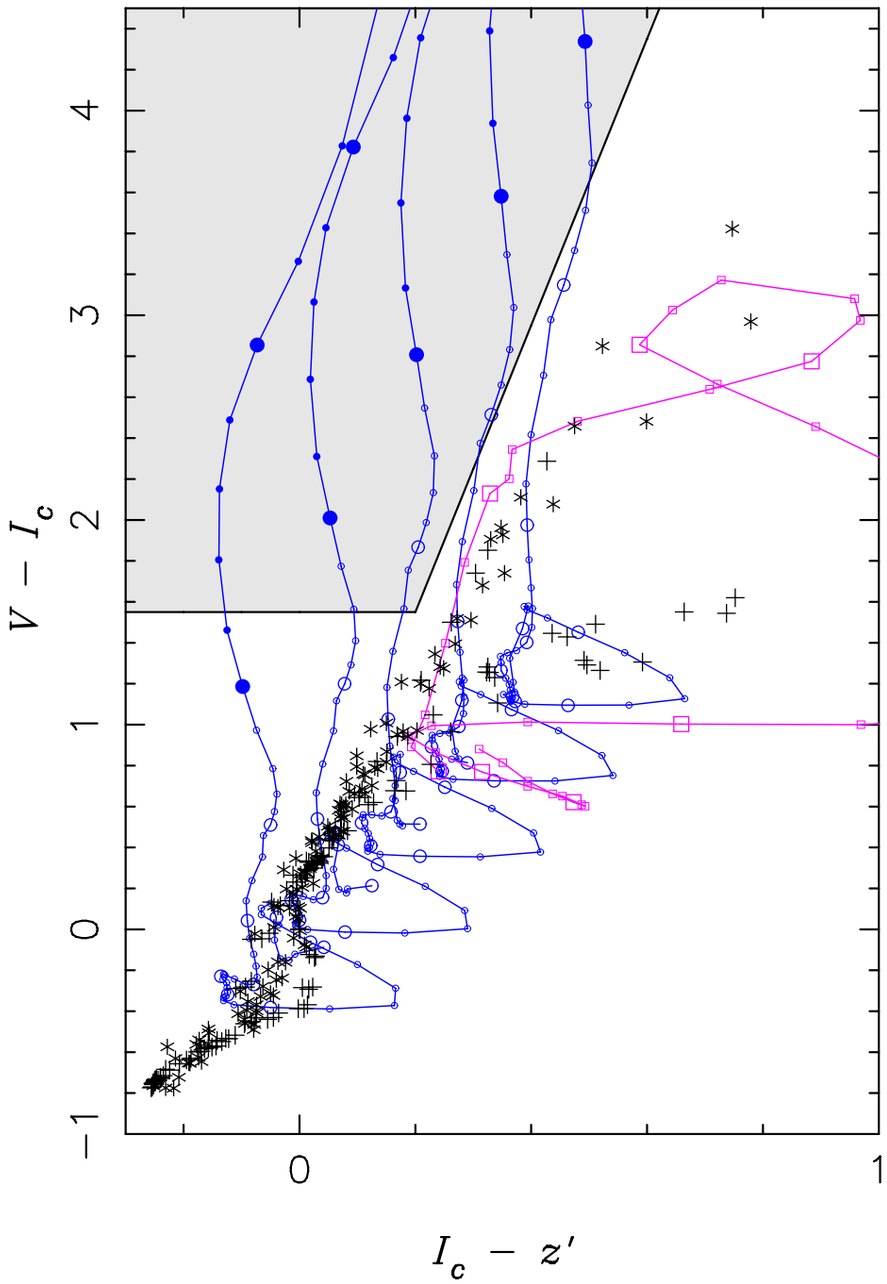


Bright-End of UVLF: Possible Explanation of Discrepancy?

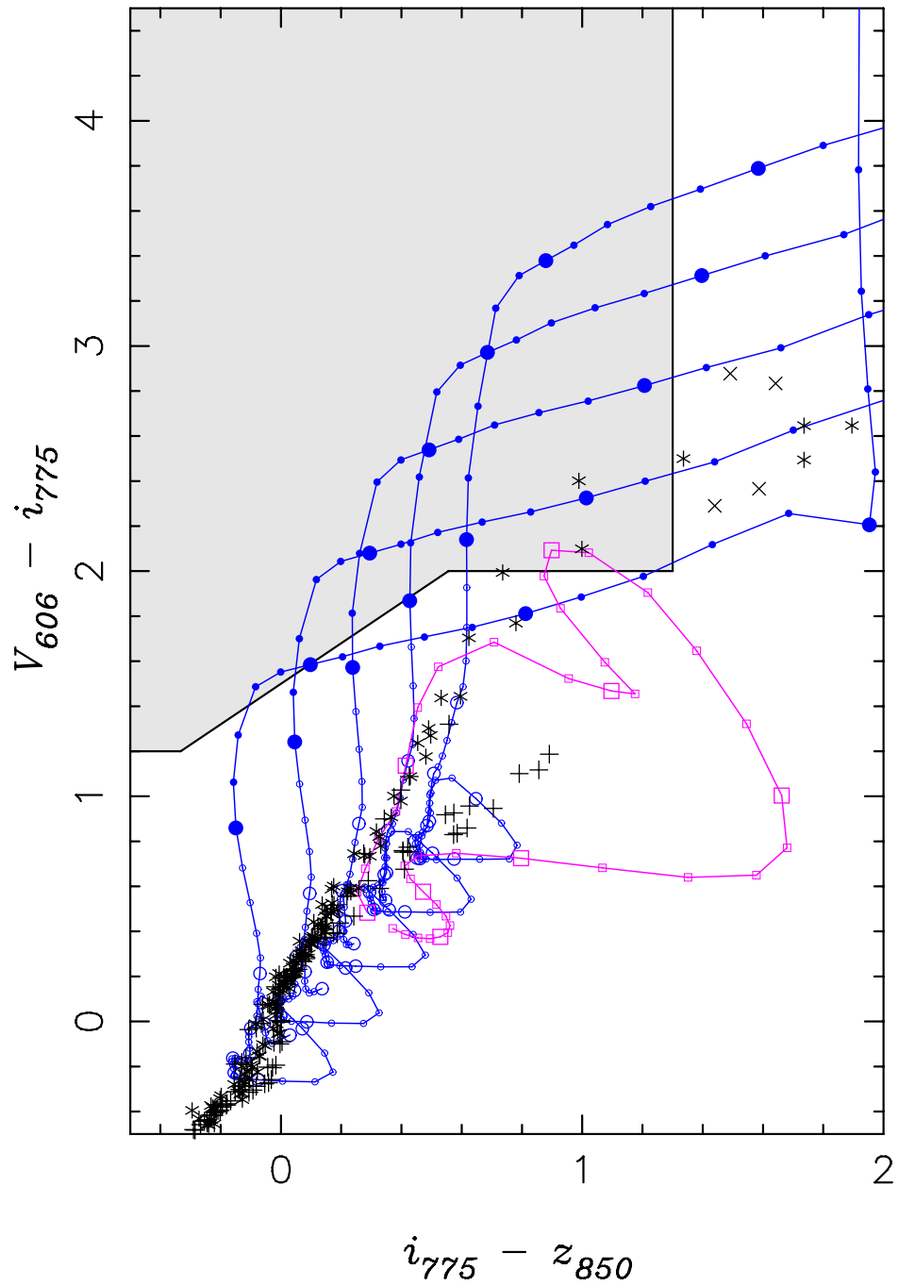


Filters Used by Us and HST/ACS GOODS



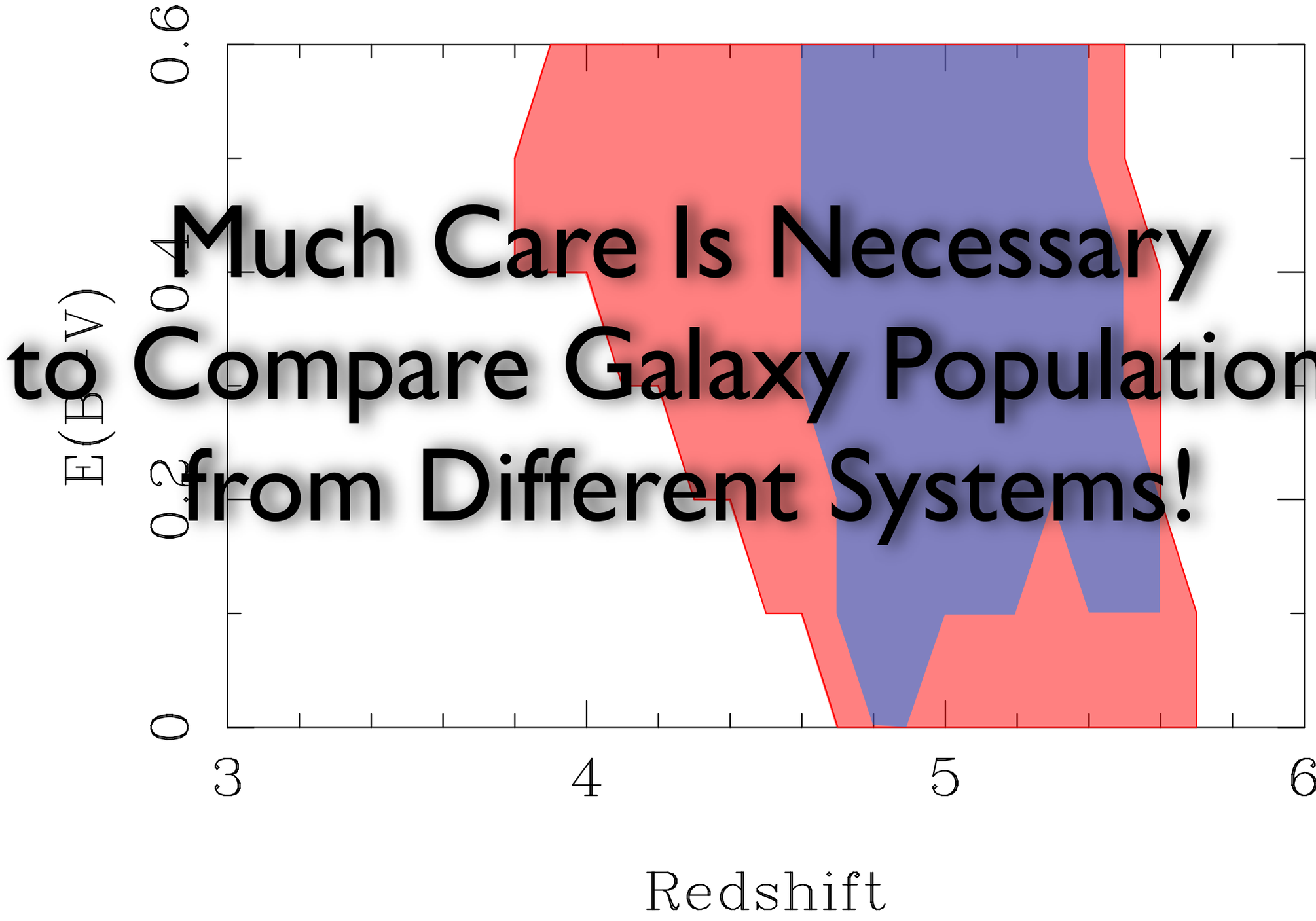


VIcz' (Ours)



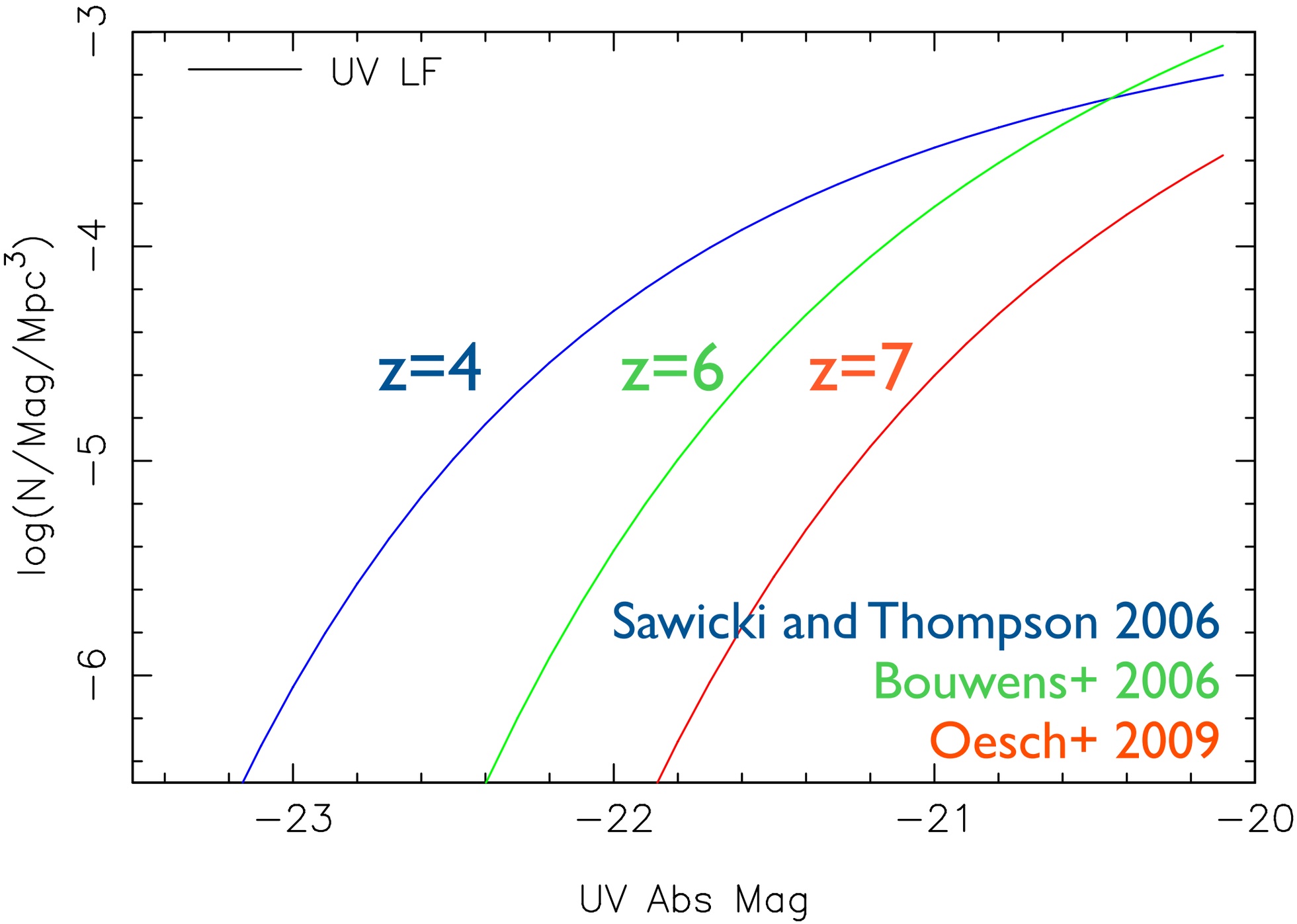
HST/ACS

Populations Covered by VIz and HST/ACS Selections

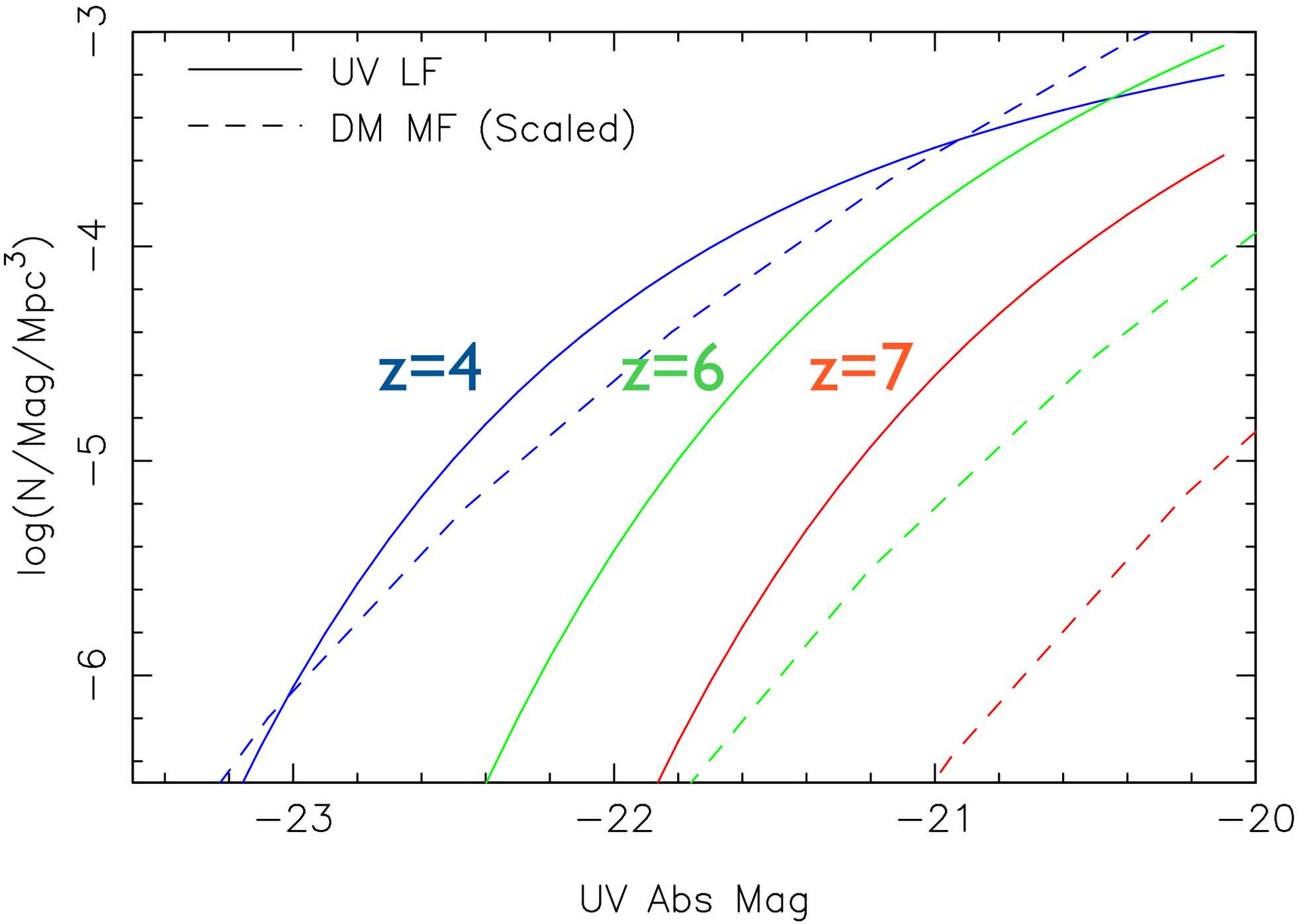


Much Care Is Necessary to Compare Galaxy Populations from Different Systems!

Evolution of UV Luminosity Function

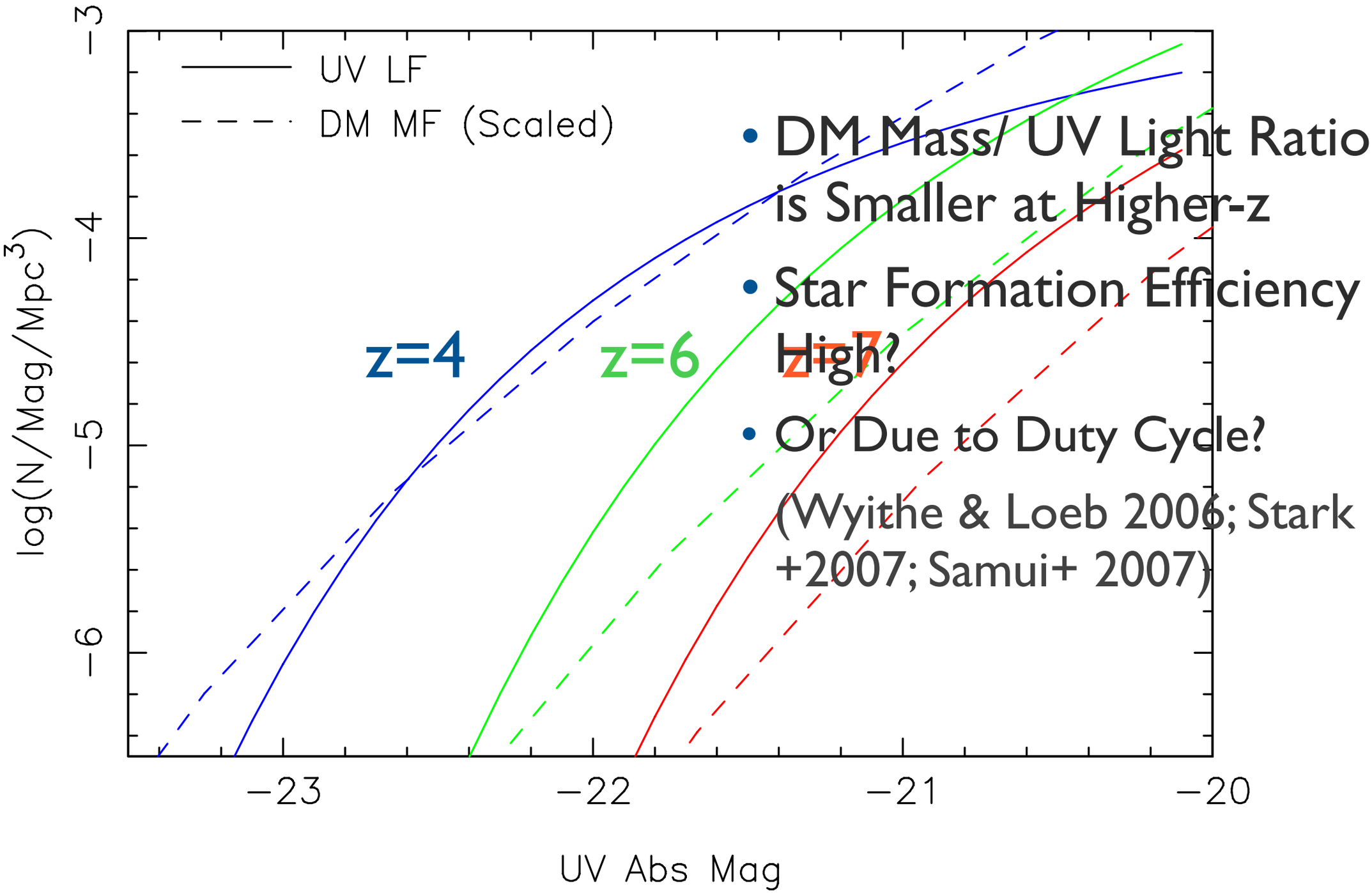


Evolution of UV LF and Dark Matter Mass Function



Assuming Constant Mass/Light

Evolution of UV LF and Dark Matter Mass Function



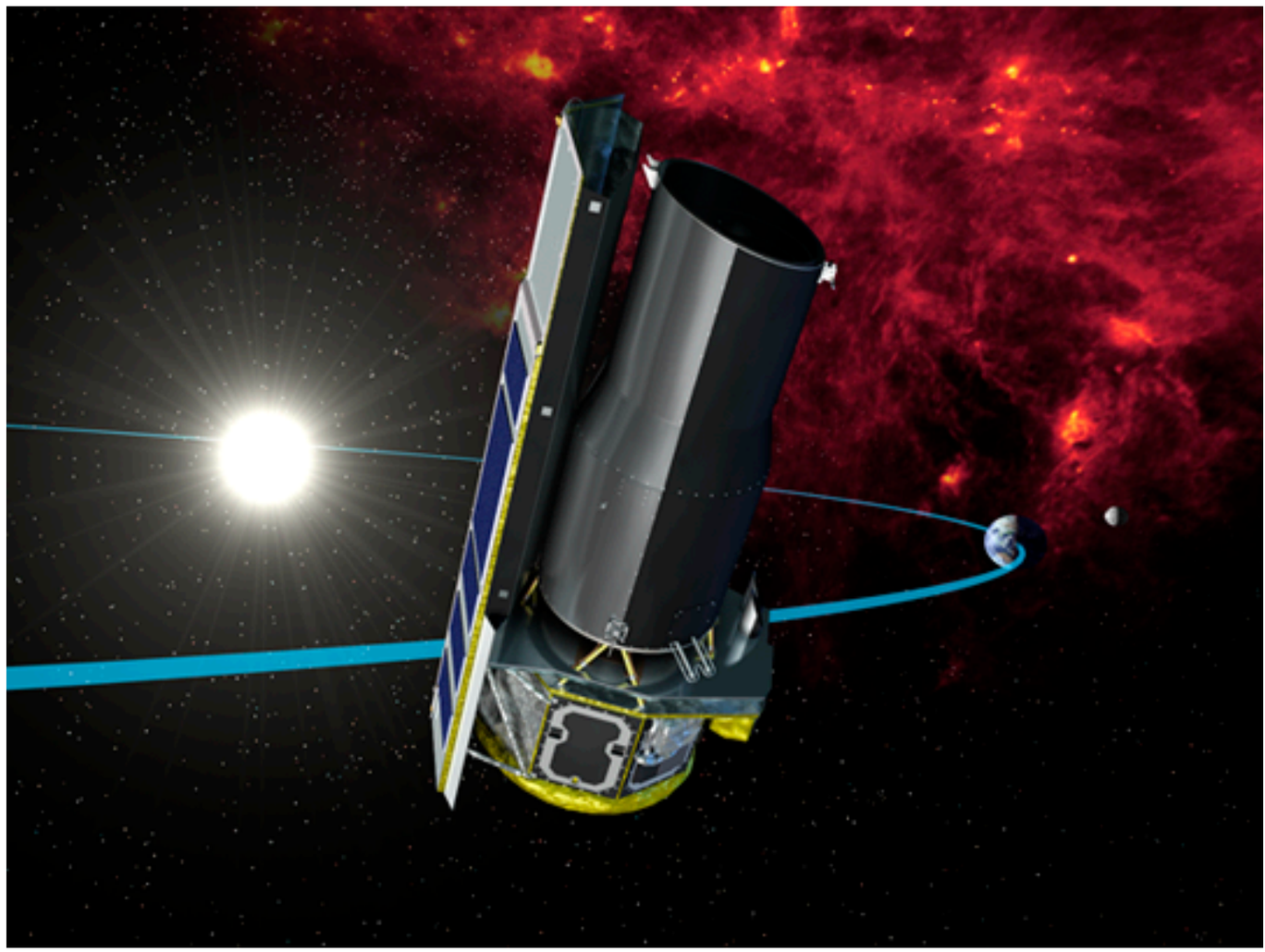
- DM Mass/ UV Light Ratio is Smaller at Higher-z
- Star Formation Efficiency is High?
- Or Due to Duty Cycle?

(Wyithe & Loeb 2006; Stark +2007; Samui+ 2007)

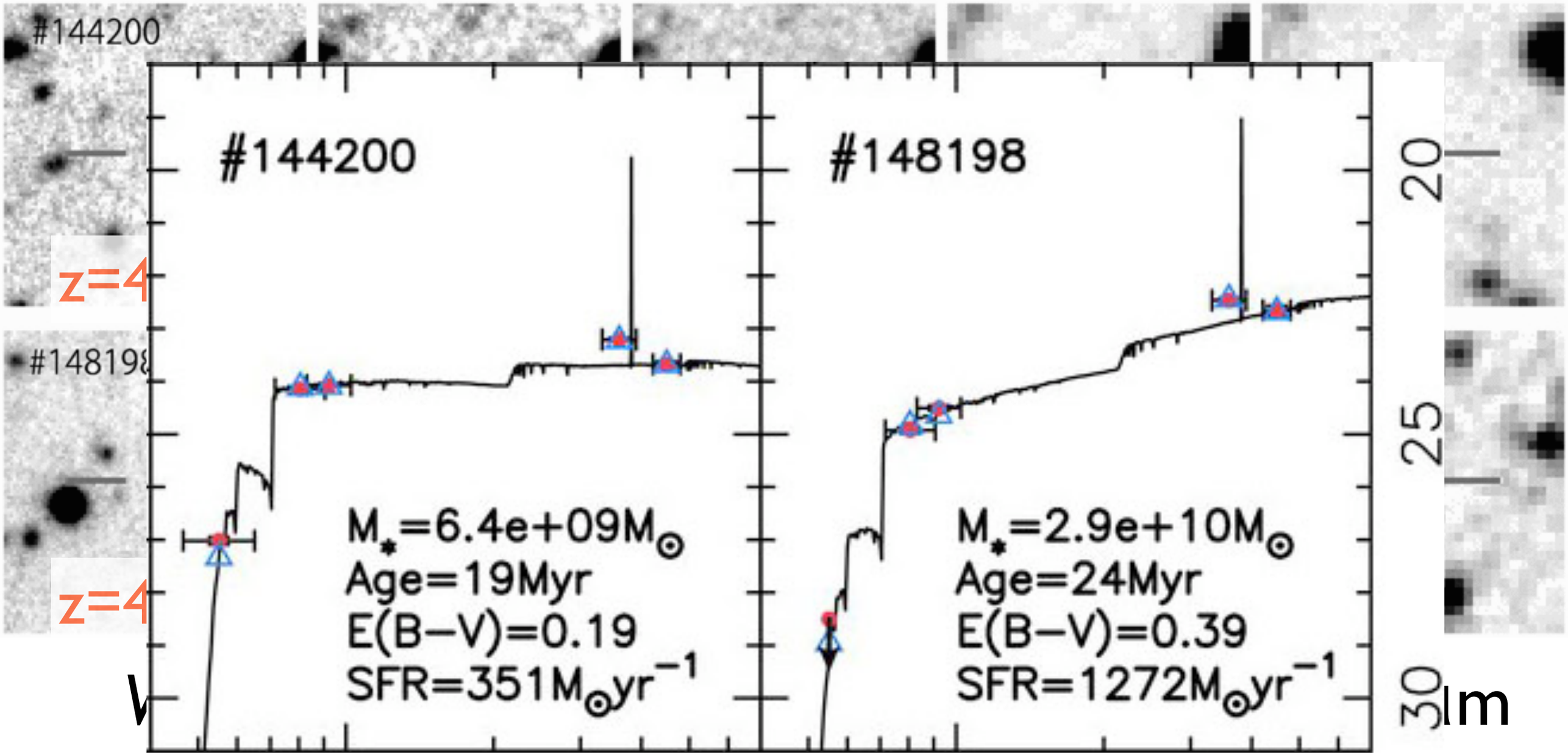
Assuming Mass/Light Evolve as $(1+z)^{-1}$

Stellar Population Estimates from SED Fitting

- Spitzer / IRAC: Imaging in Rest-Frame Optical Wavelengths
  - GOODS (Legacy Survey) + Our Own Flanking Fields Observations



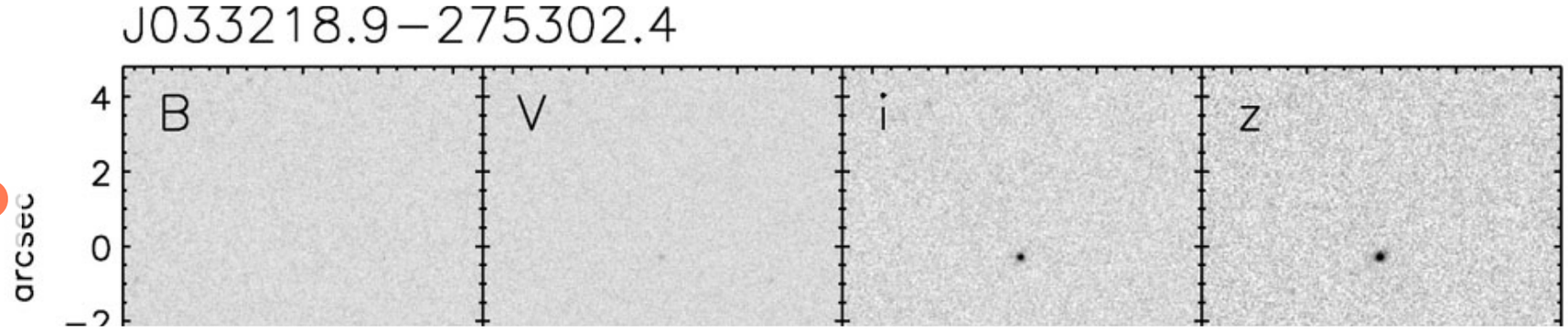
SED Fitting Using Rest-Frame UV to Optical Images

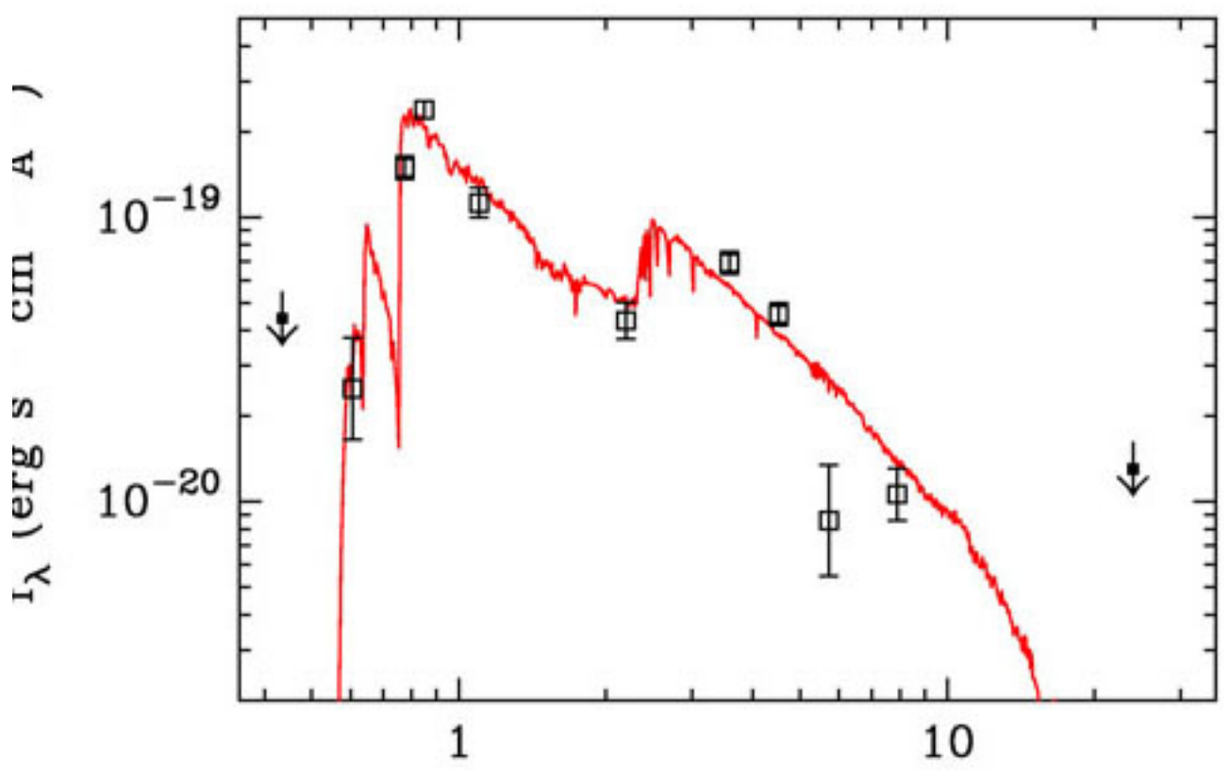


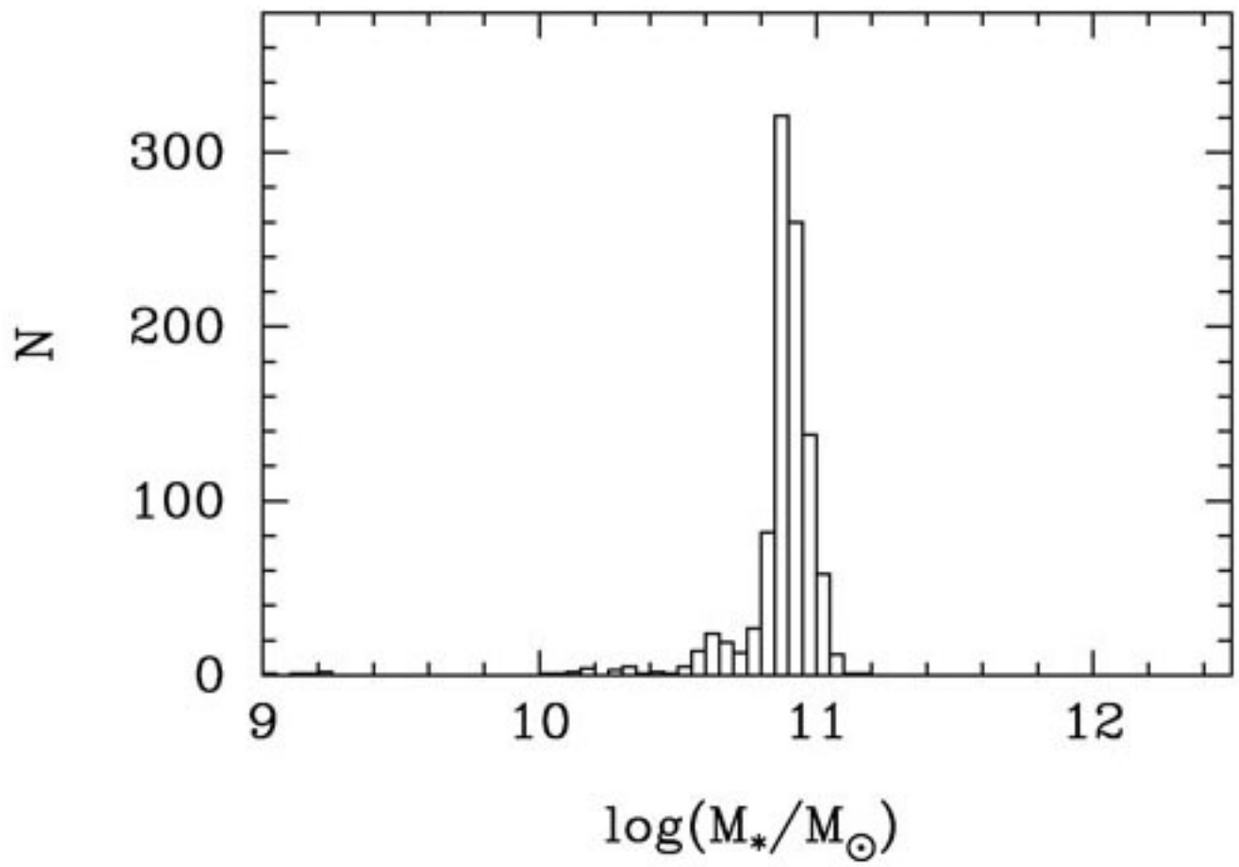
See Poster by Yabe et al. for Updates

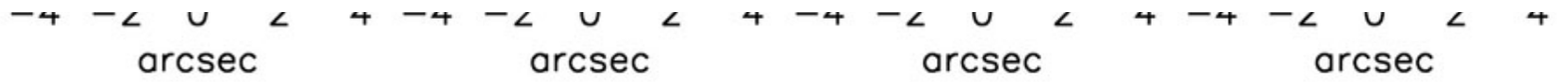
Massive Galaxies When the Universe is <1.2 Gyr

z=5.56





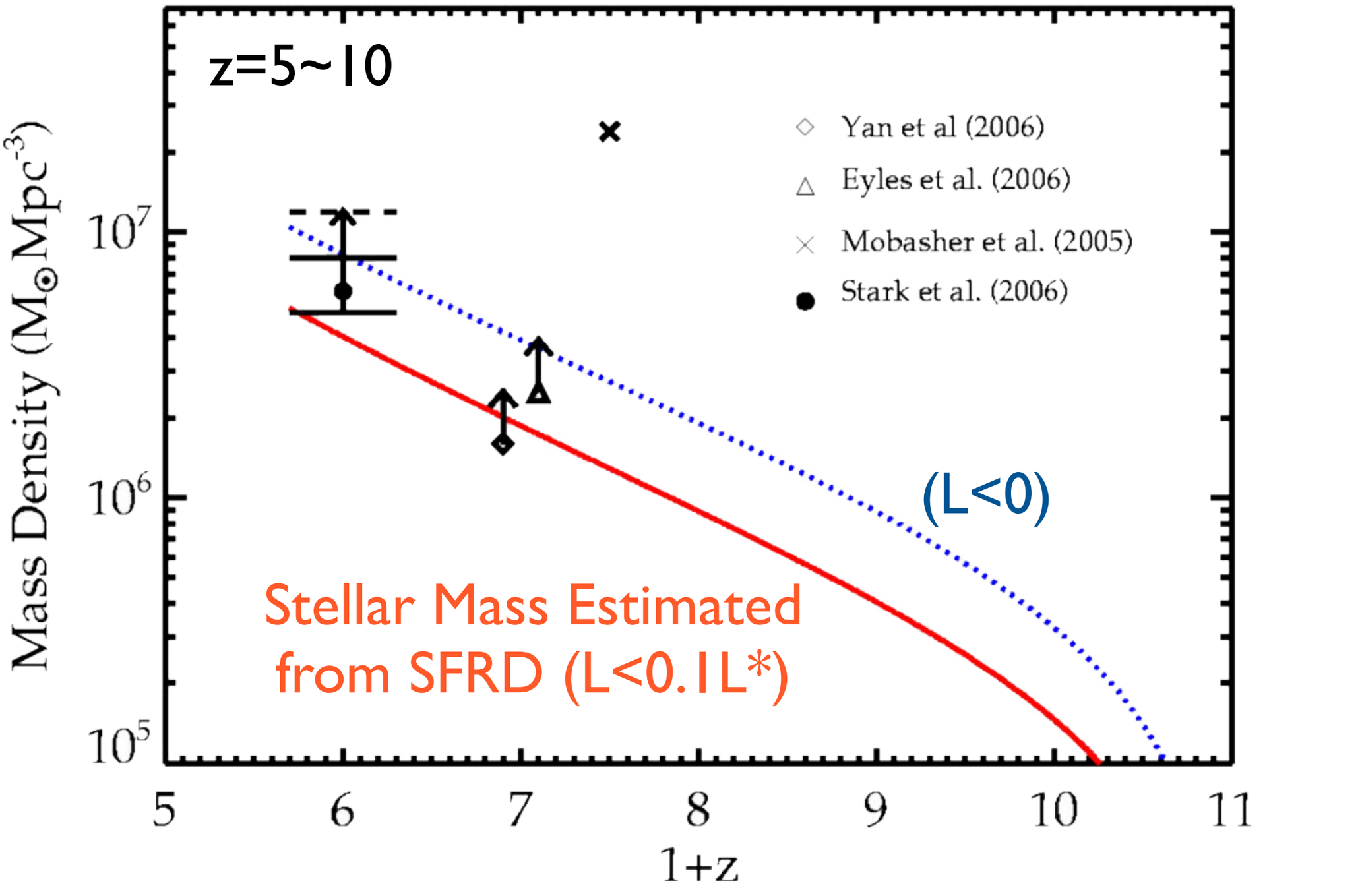




"Balmer Break Galaxies"
Wiklind+ 2008, ApJ 676, 781

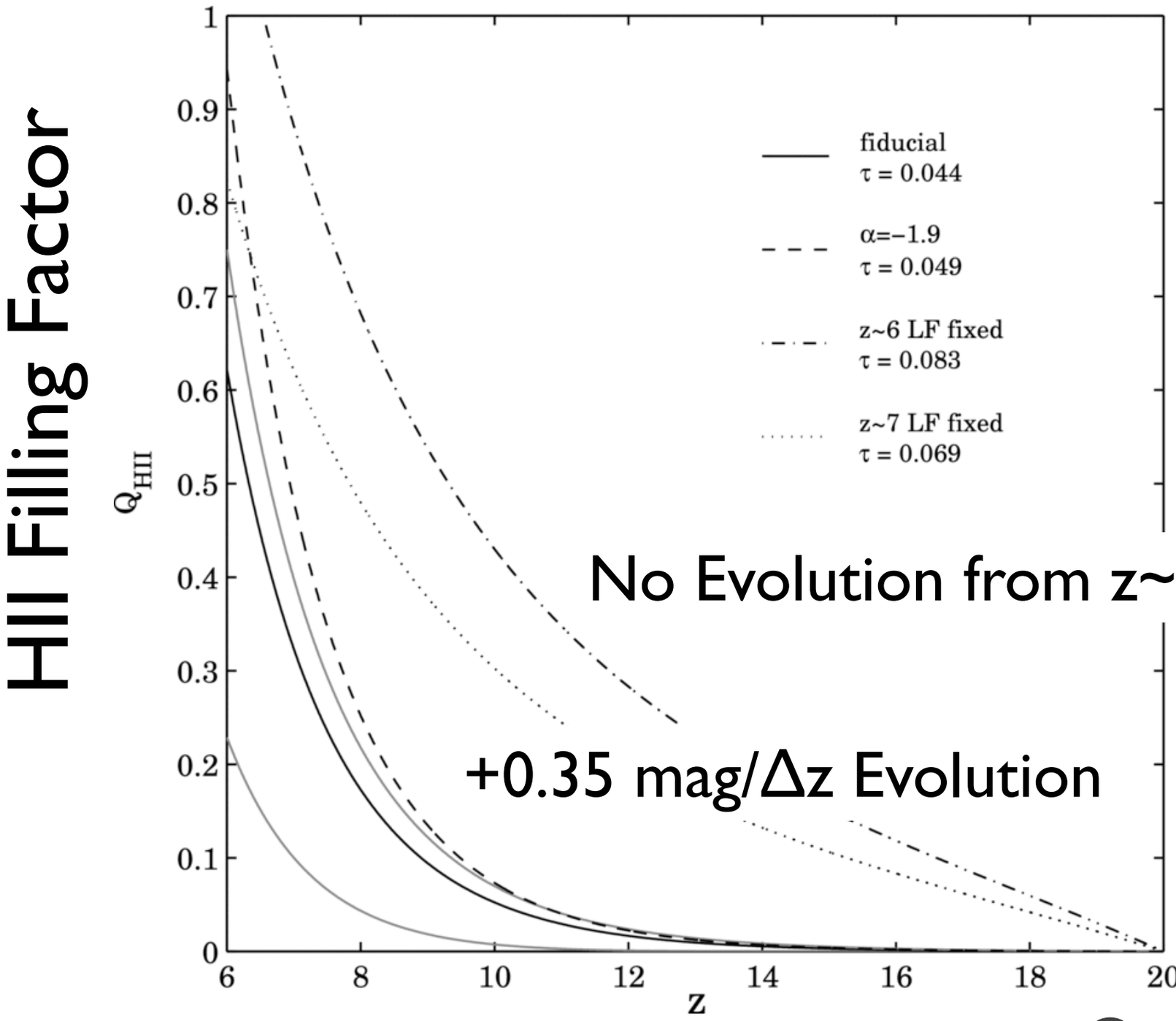
See also Dunlop+2007 MN 376, 1054

Discrepancy in Stellar Mass Function



Stark+07 ApJ 695, 84

Are Observed Galaxies Able to Reionize the Universe?



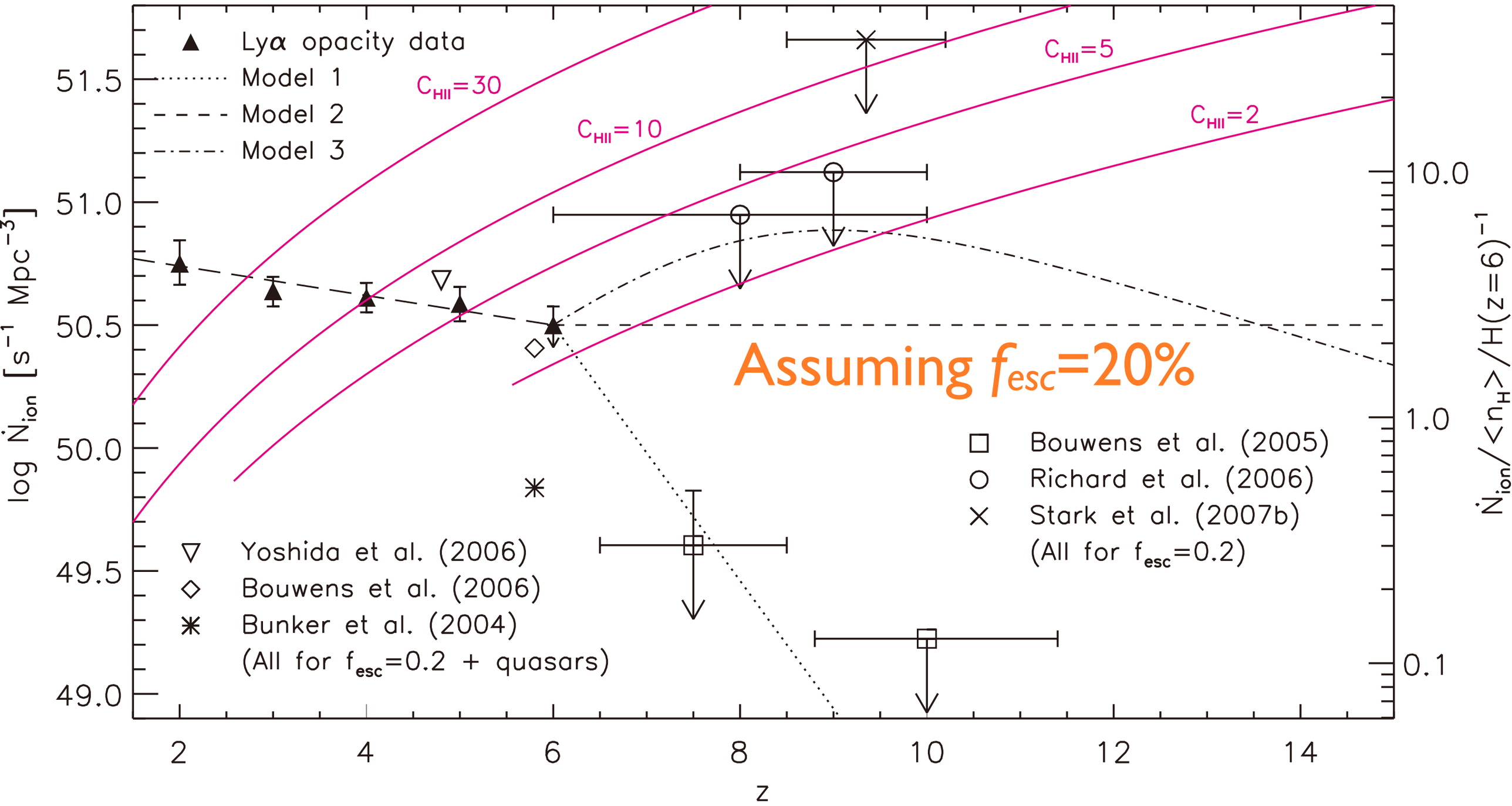
No Evolution from z~6 or 7

+0.35 mag/Δz Evolution

Assuming f_{esc}=20% and C=2

Oesch+09 ApJ 690, 1350

Are Observed Galaxies Able to Reionize the Universe?



Bolton & Haehnelt 2007, MNRAS 382, 325

Parameters to Clarify Reionization Process

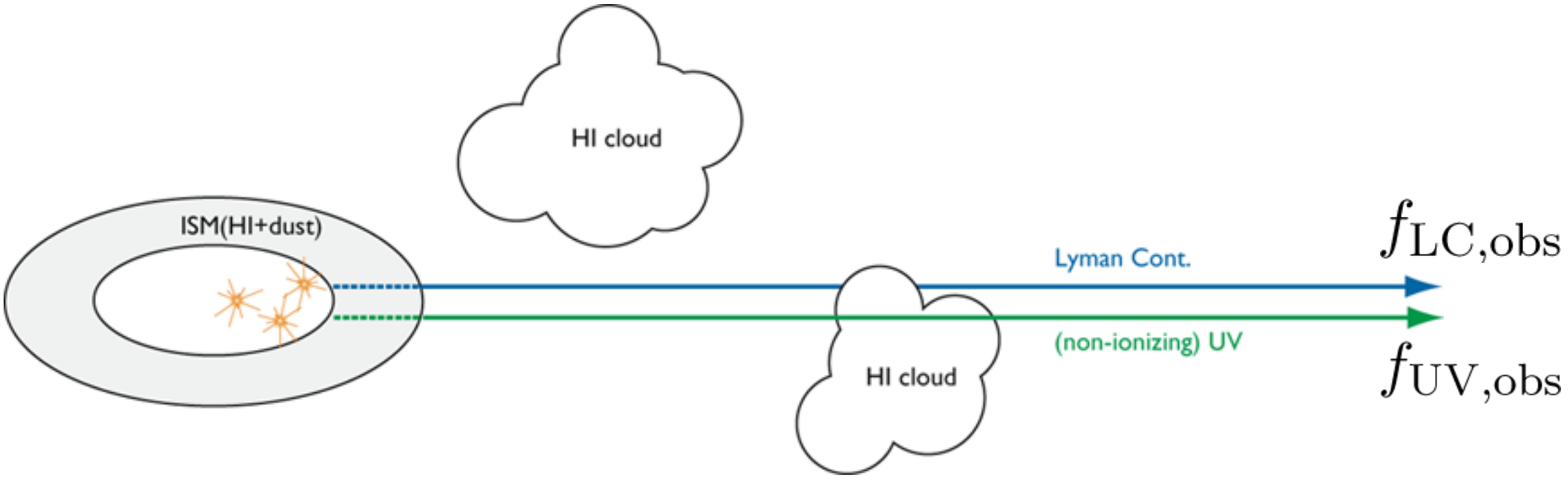
HII Clumping Factor $C \equiv \langle \rho^2 \rangle_{IGM} / \langle \rho \rangle^2$

UV Emissivity of Ionizing Sources

f_{LC} / f_{UV}: Intrinsic
Lyman Continuum / UV Flux Ratio

f_{esc}: Escape Fraction of Lyman Continumm
from Galaxies Out to IGM

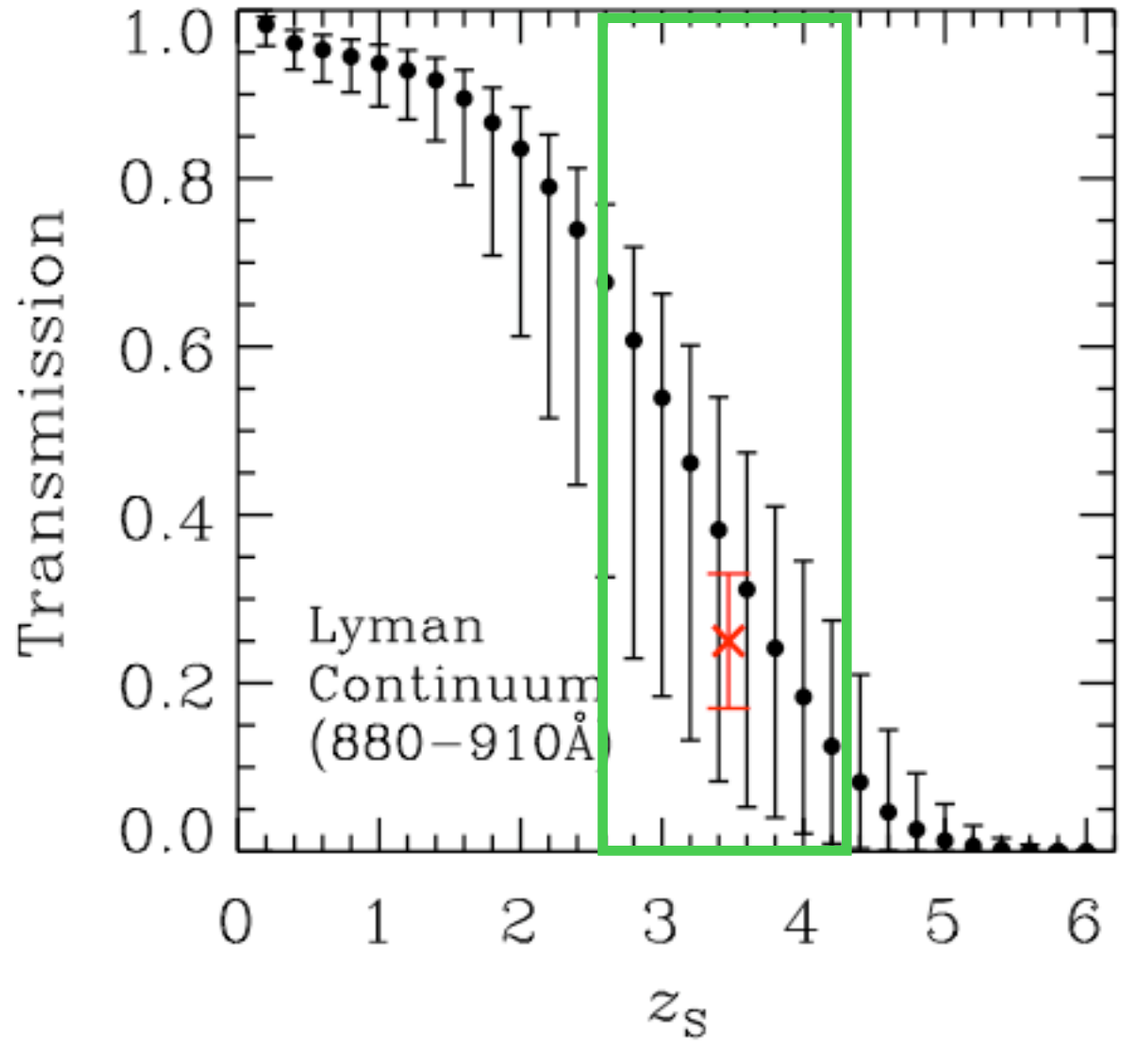
Escape Fraction of Lyman Continuum



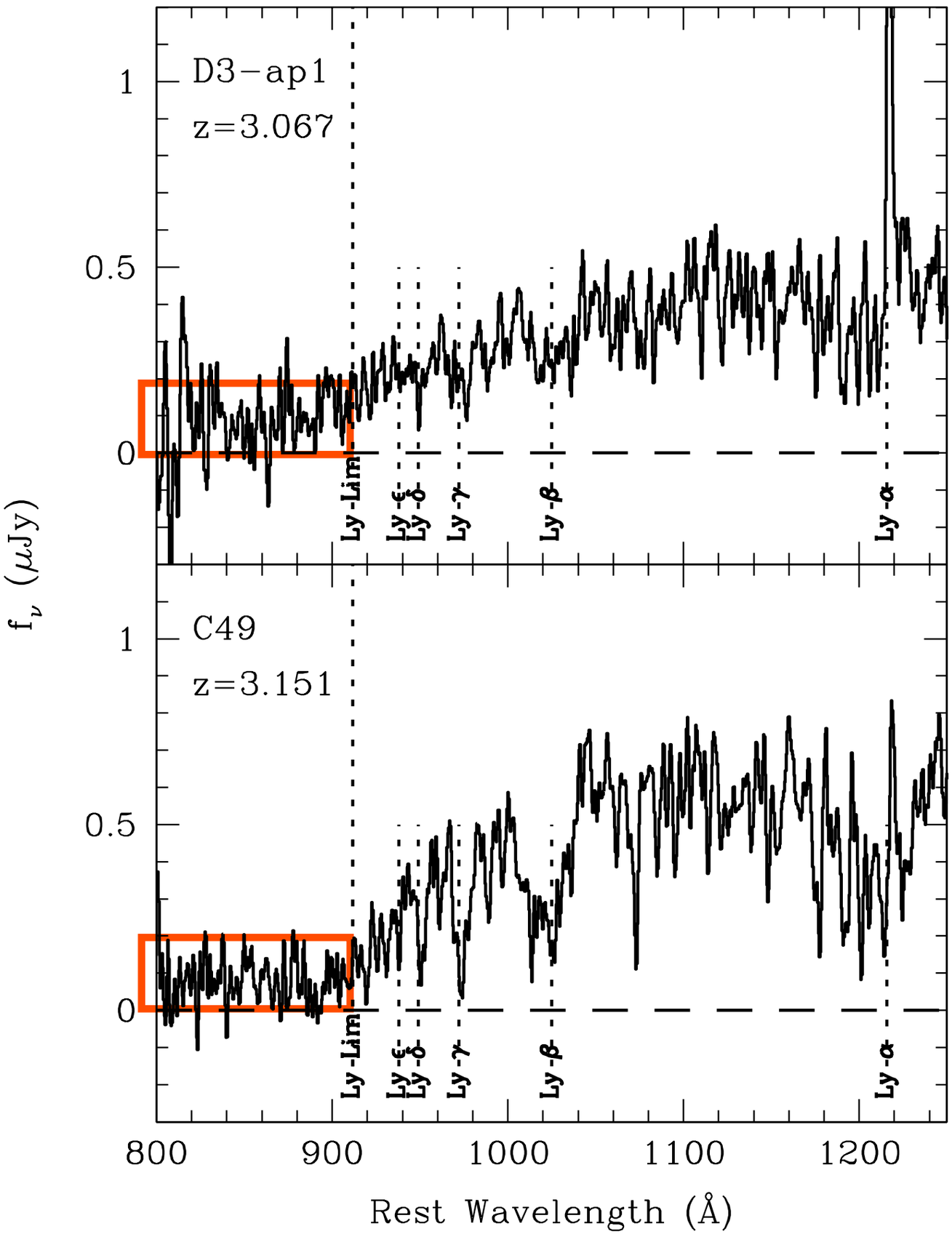
$$F_{obs} = F_{int} \times f_{esc} \times e^{-\tau(IGM)}$$

Detection of Lyman Continuum From Galaxies

- Lyman Continuum from Galaxies at z>5 is Virtually Invisible Due to Strong Intergalactic Absorption
- Observation at z<5 is Required



Inoue &I wata 2008, MN 387, 1681

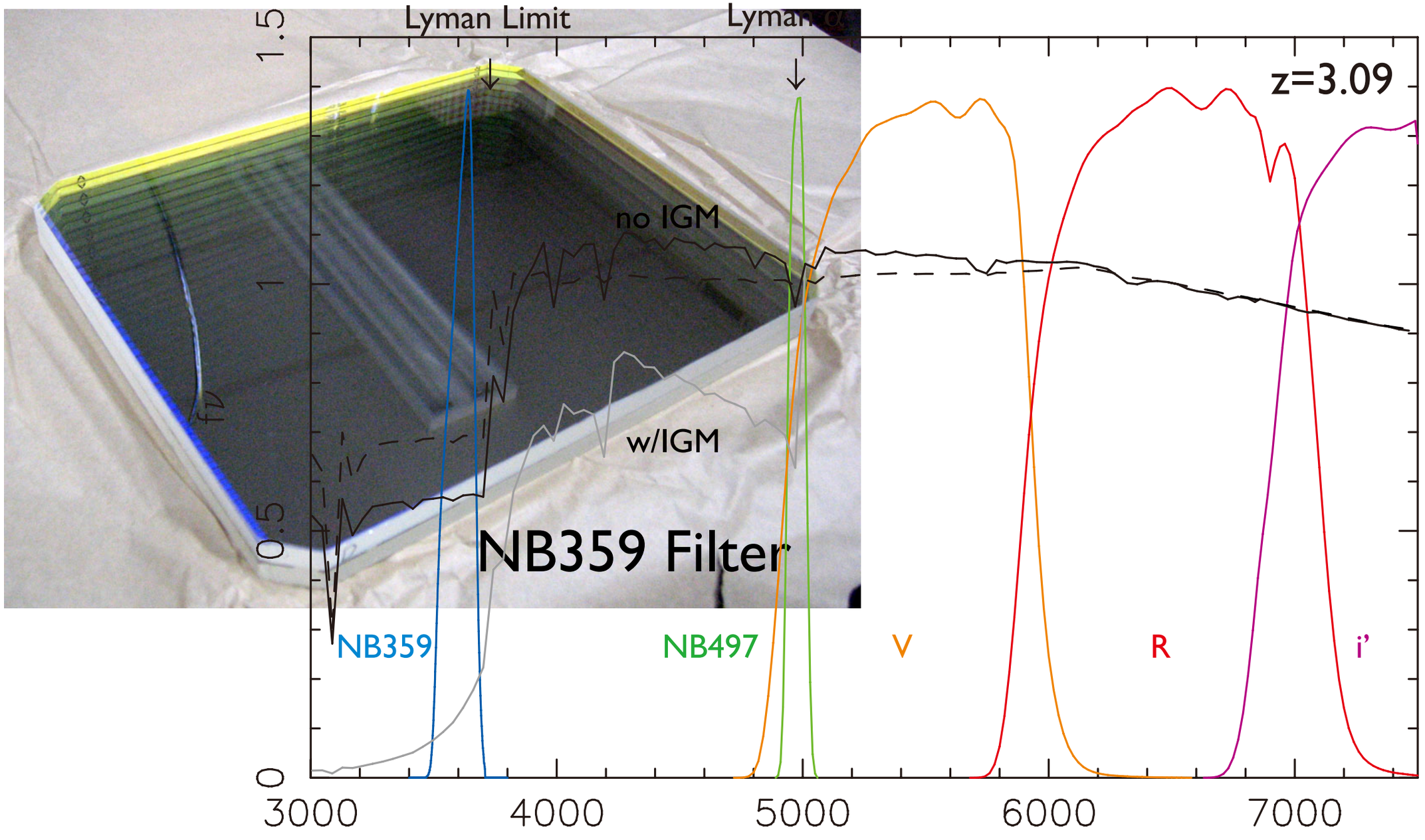


Shapley+ 2006 ApJ 651, 688

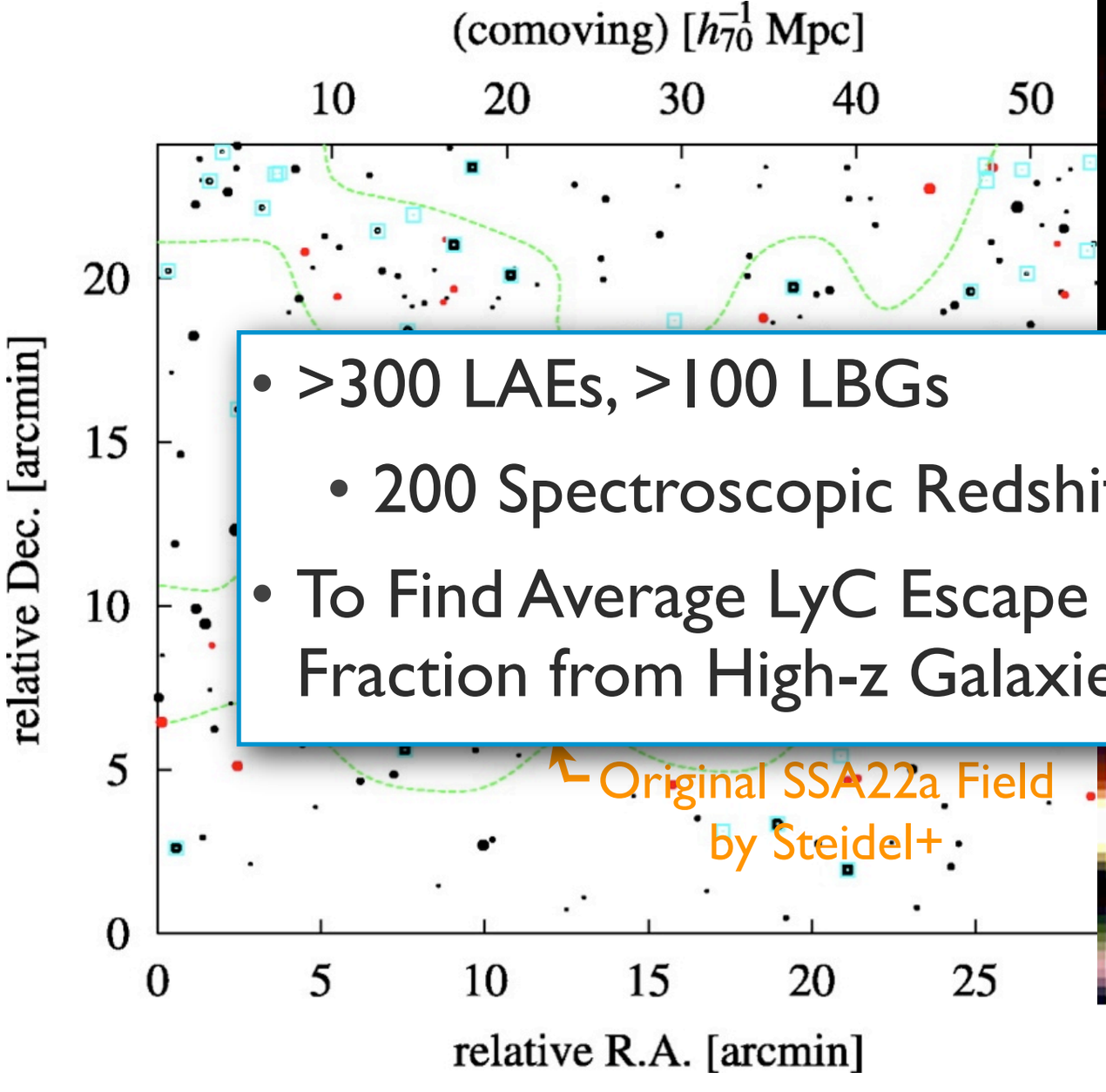
- Detected ionizing radiation from two z~3 LBGs (L>L*), among 14 spectroscopically observed.
- Average escape fraction was suggested to be less than 10%

A New Trial with Subaru

- Special Narrow-Band Filter for Suprime-Cam

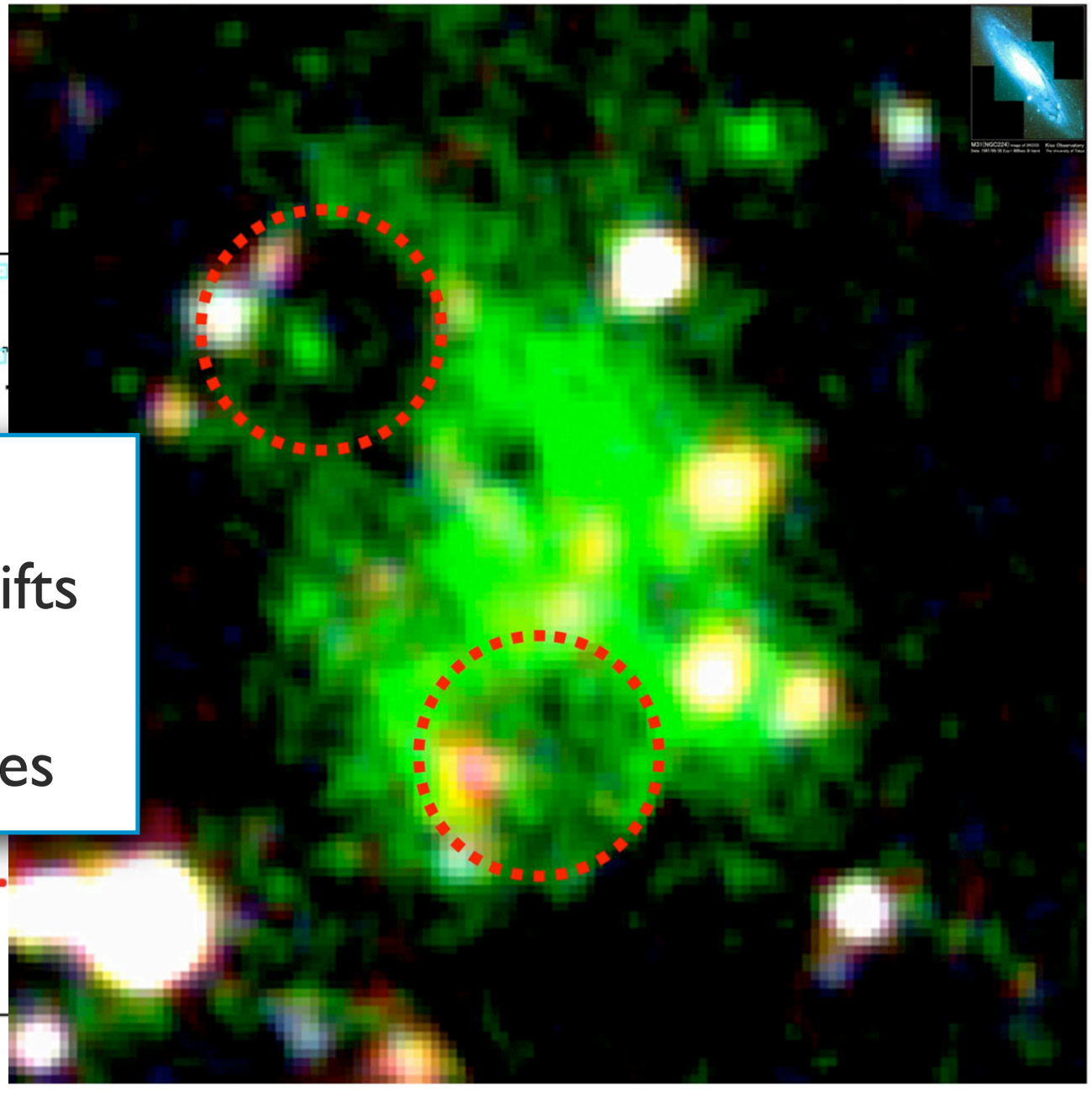


SSA22: Proto-Cluster at z=3.09

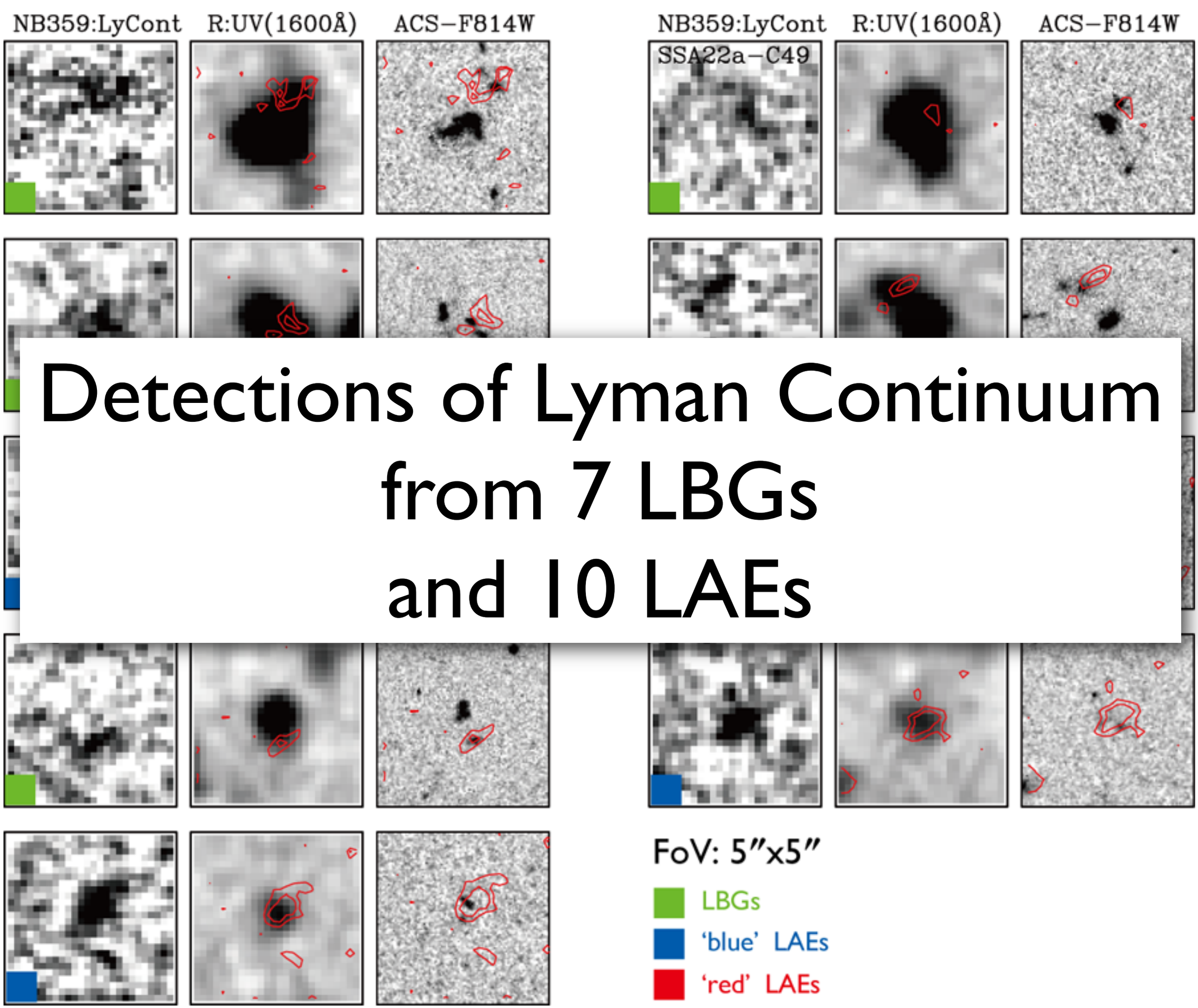


- >300 LAEs, >100 LBGs
  - 200 Spectroscopic Redshifts
- To Find Average LyC Escape Fraction from High-z Galaxies

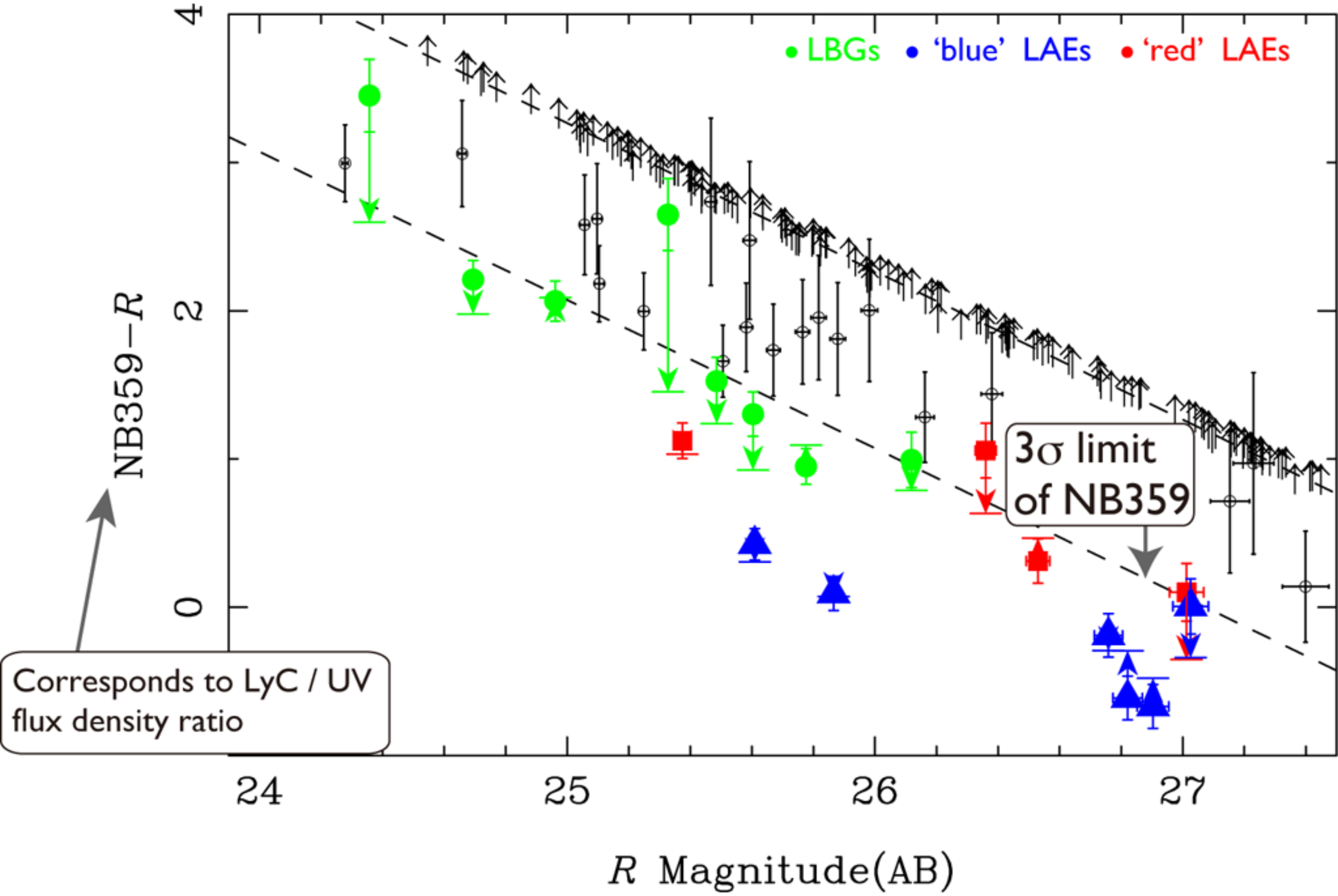
Original SSA22a Field by Steidel+



Please Refer Talk by Y. Matsuda



Detections of Lyman Continuum from 7 LBGs and 10 LAEs



Iwata+ 2009, ApJ 692, 1287

(UV slope)

'red' LAEs

'blue' LAEs

LBGs

$V-i'$

0.5

0

−0.5

0

1

2

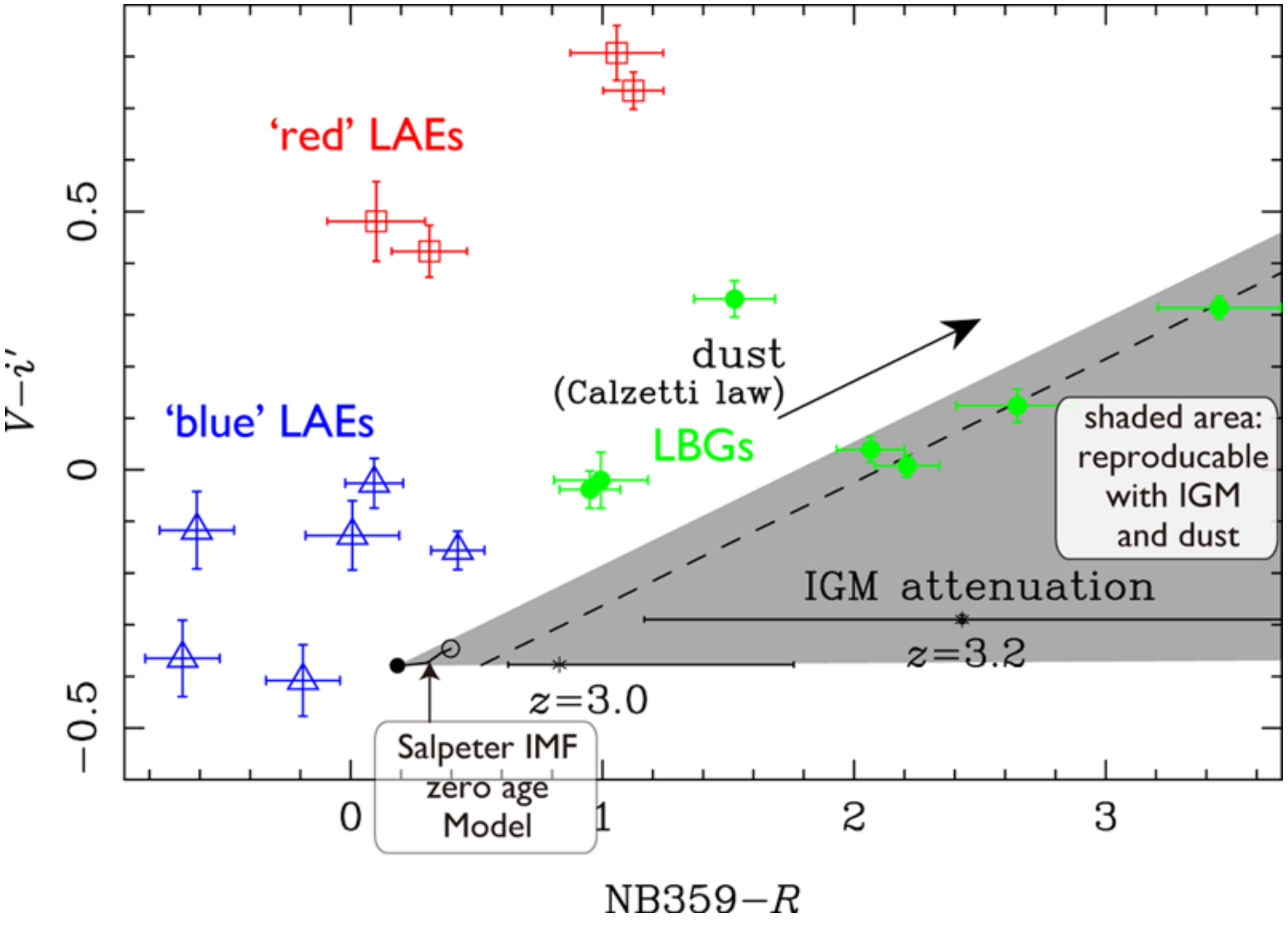
3

NB359−R

Strong LyC

(f_{LC}/f_{UV})

(UV slope)



(f_{LC}/f_{UV})

(UV slope)

'red' LAEs

'blue' LAEs

dust
(Calzetti law)

LBGs

IGM attenuation

z=3.2

z=3.0

Addition of
Old Stellar Population

$V-i'$

NB359$-R$

(f_{LC}/f_{UV})

(UV slope)

$V-i'$

0.5

0

−0.5

'red' LAEs

'blue' LAEs

dust
(Calzetti law)

LBGs

shaded area:
reproducable
with IGM
and dust

IGM attenuation

z=3.2

z=3.0

Pop−III
(1−100M$_\odot$)

0

1

2

3

NB359−R

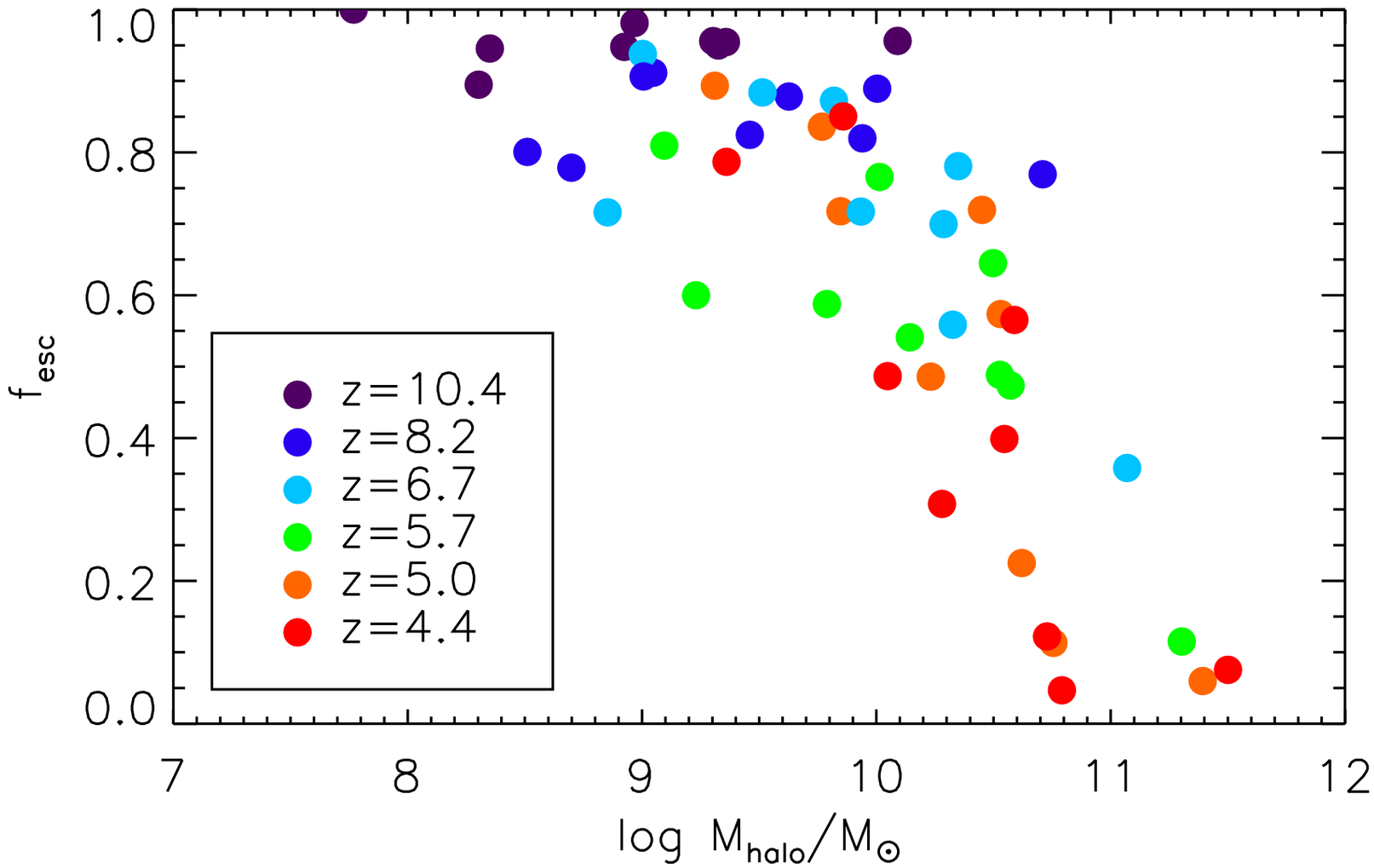
LyC Stronger
Than Pop-III!

(f_{LC}/f_{UV})

Escape Fraction of Lyman Continuum

- LBGs: f_{esc} (median) = 4% - 20% Depending of Assumptions on IGM Opacity and Intrinsic Lyman Continuum Luminosity
- LAEs: Unable to Explain Their Lyman Continuum Luminosity with Standard Stellar Population Models, Even If We Assume f_{esc}=100%
  - Note: No Signature of AGN
- Follow-up Observations to Investigate Their Nature Are Required

High LyC Escape Fraction?



- Razoumov and Sommer-Larsen (arXiv:0903.2045): High-resolution Cosmological Simulation
- f_{esc}>0.8-1.0 at z>8
- Halo-Mass dependent Escape Fraction
- See also: Wise & Cen 2009, Yajima 2009

Summary

- High-redshift Star-forming Galaxies
  - Need of Careful Treatment in Comparison of Different Data Sets
  - Existence of Very Massive (>10^{10} Msun Stars) Galaxies at z≥5

    - High Efficiency at Higher Redshift
    - Numerous Dwarf Galaxies Beyond Current Detection Limit?

      or Massive Star Formation at z>10?
    - Are Observed Galaxies Sufficient for Reionization?

      - Large Uncertainties Both in Observations and Models
- Lyman Continuum Escape Fraction
  - Subaru / Suprime-Cam Wide-field Survey Detected Ionizing Photons at z~3
  - Surprisingly High Escape Fraction - “Ionizers”?

Prospects for Future

- We Need More Photons!
  - Wide-Field Imager: Hyper Suprime-Cam
  - Larger Mirror: ELTs such as TMT
- Near-Infrared Observations
  - Space-Based Observations: JWST and WISH*
  - High Throughput Spectrograph in Near-Infrared for Subaru or Gemini?

*http://www.wishmission.org