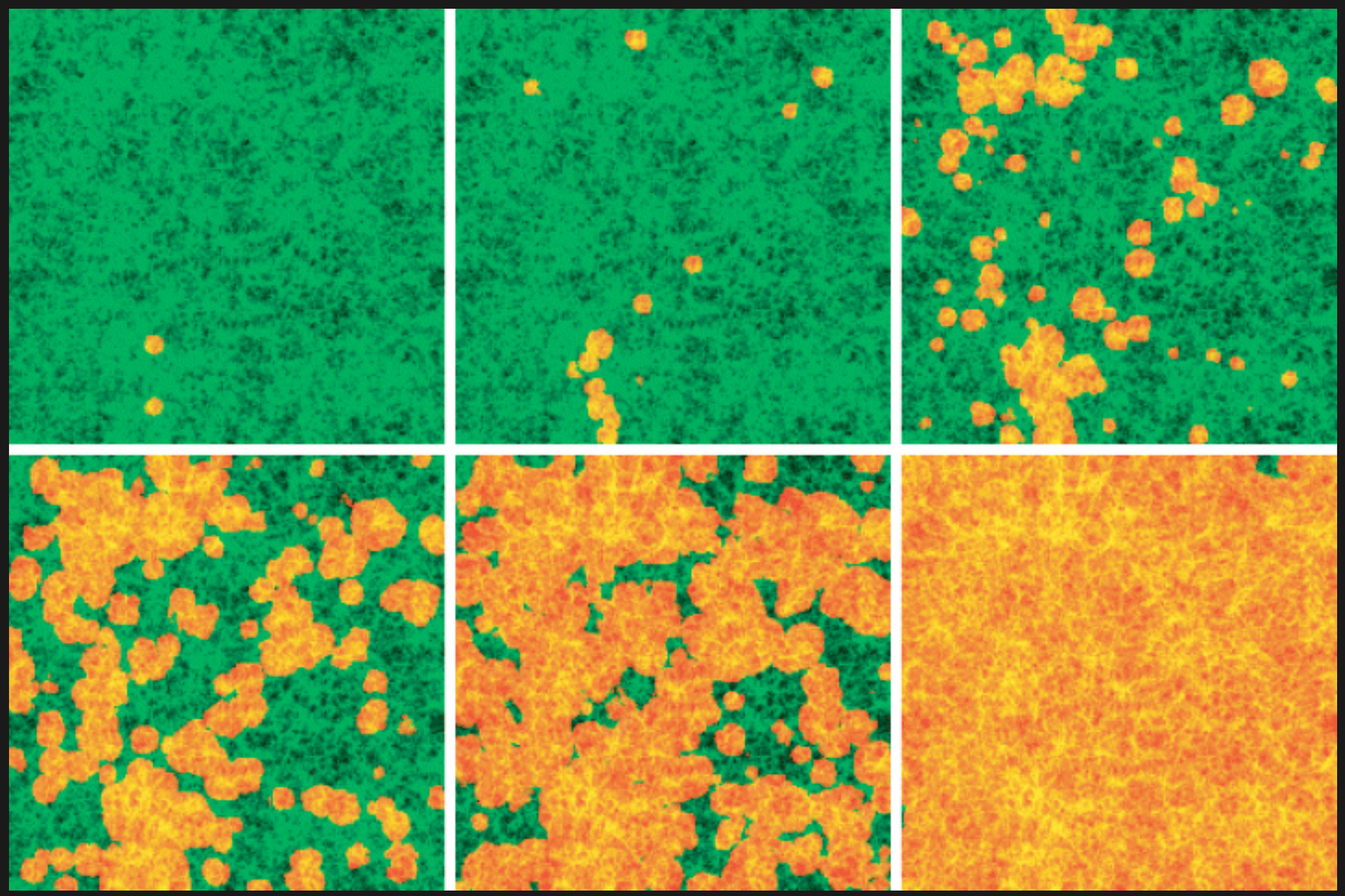
Detections of Ionizing Radiation from High-z Galaxies

I. Iwata (NAOJ)
with A. K. Inoue, Y. Matsuda, K. Kousai, T. Hayashino, T. Yamada,
H. Furusawa, M. Akiyama, D. Burgarella, J.-M. Deharveng,
J. P. U. Fynbo, N.-E. Kofod, P. Moller, C. Ledoux

Cosmic Reionization in Numerical Simulations

z=18.5

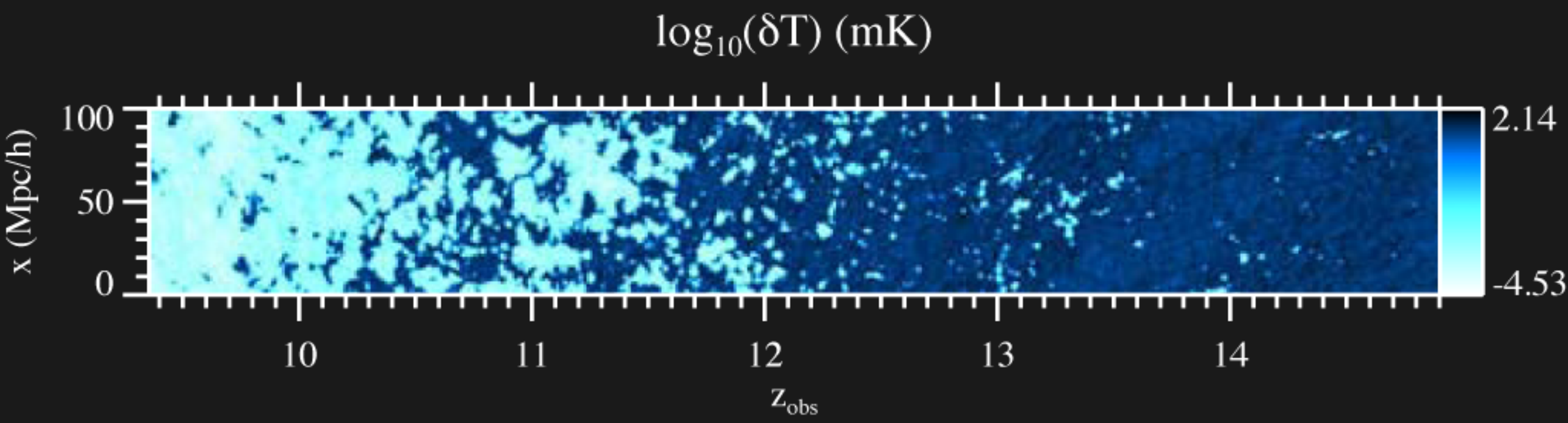
100h^{-1} Mpc



Iliev et al. MN 369, 1625 (2006)

z=11.3

Cosmic Reionization in Numerical Simulations



Mellema et al. MN 372,679(2006)

Ying and Yang in the Cosmic Dawn

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- ***Ying***(陰): Shadow, Darkness - Neutral Hydrogen Probed by HI 21cm Line with Radio Missions

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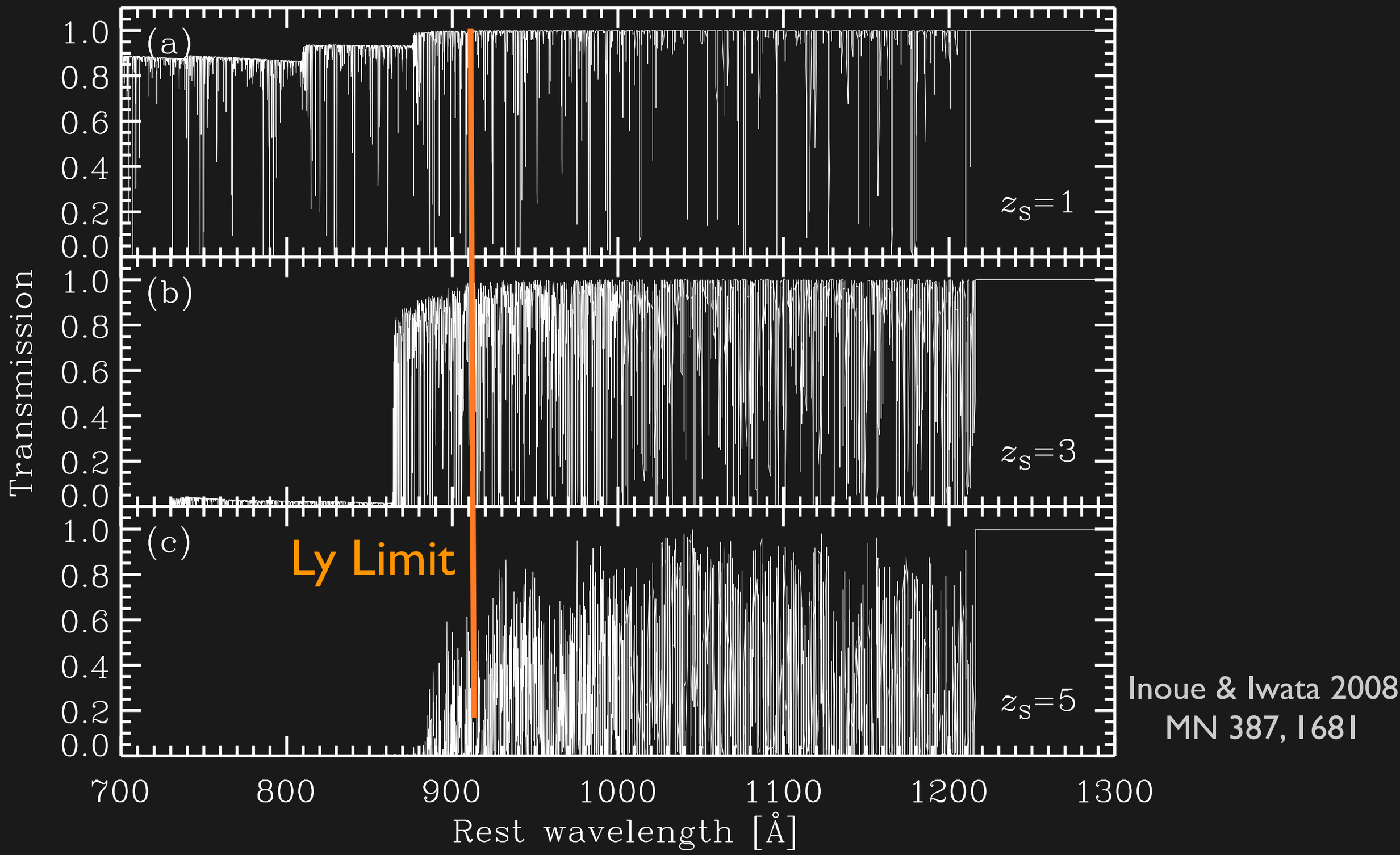
Ying and Yang in the Cosmic Dawn

- ***Ying***(陰): Shadow, Darkness - Neutral Hydrogen Probed by HI 21cm Line with Radio Missions
- ***Yang***(陽): Light, Brightness - UV Sources to Ionize Hydrogen, Probed by Optical and Infrared Observations
- Ying and Yang are NOT Against Each Other; Both (Observations) are Cooperative to Clarify the Process of Reionization

What is the Primary Source of Ionizing Photons?

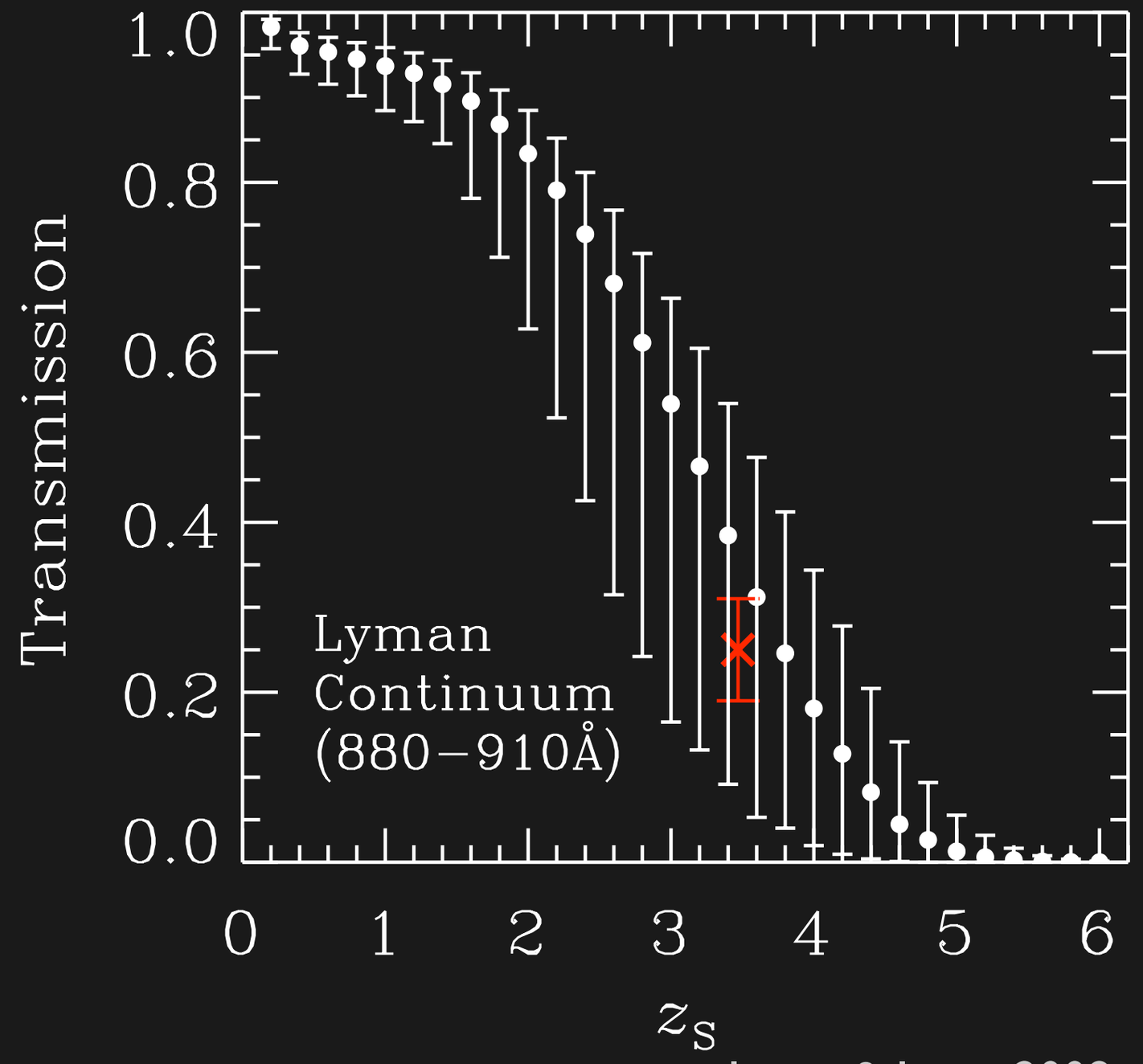
- Galaxies Have Been Thought To Be Primary Sources of Ionizing Photons at z>3
- Actual Contribution is Still Poorly Constrained
  - Difficulty in Observation of Ionizing Photons
  - Difficulty in Modeling Ionizing Photon Escaping From Galaxies into IGM - Depends on Location and Geometry of Star-forming Regions and Surrounding Neutral ISM

IGM Attenuation Grows Rapidly at Higher Redshift



Inoue & Iwata 2008
MN 387, 1681

Ionizing Photons in the EoR are Invisible



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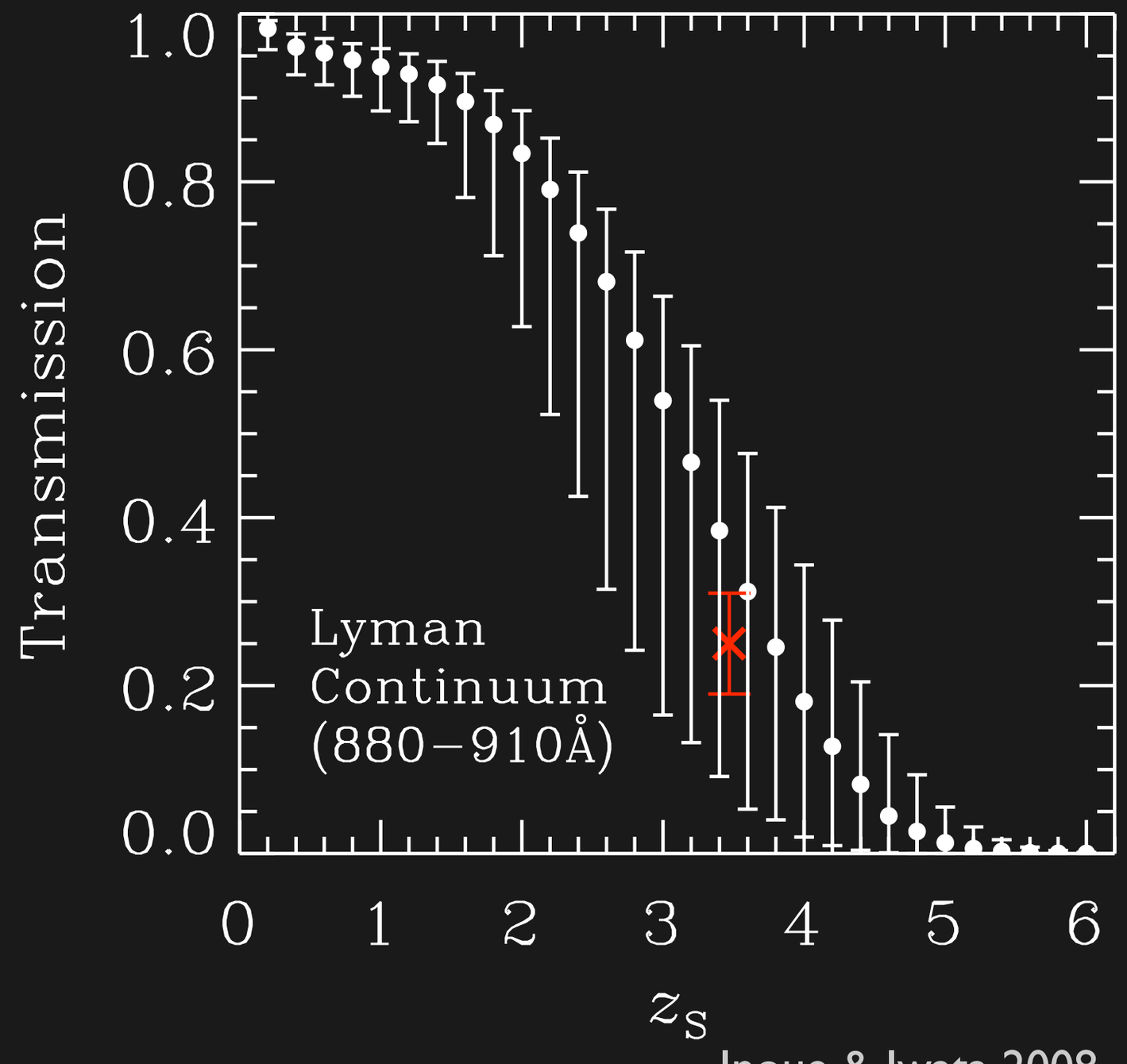
- It is Virtually Impossible to Observe LyC from Galaxies at z>5, Even with Next-Gen Extremely Large Telescopes



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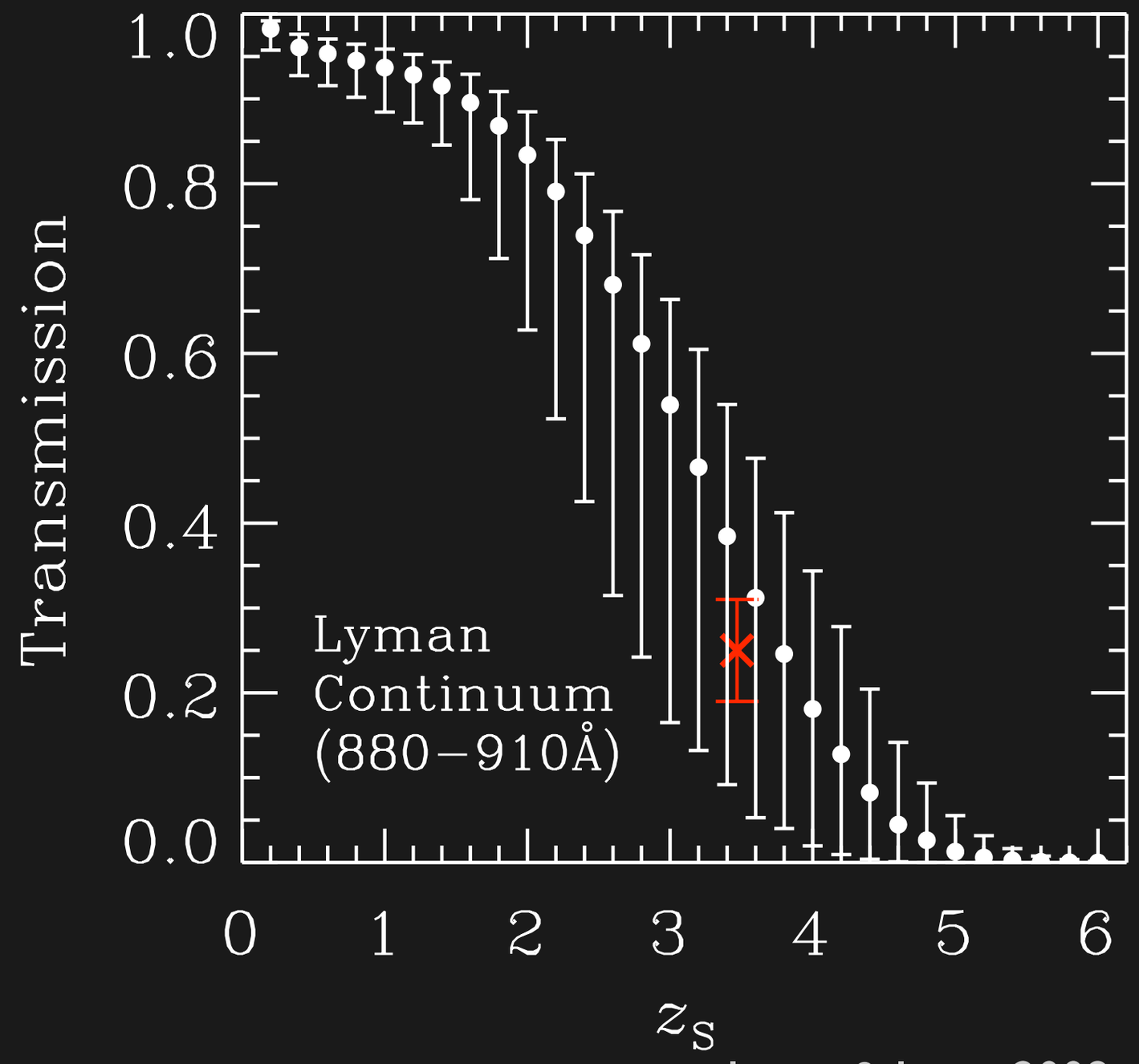

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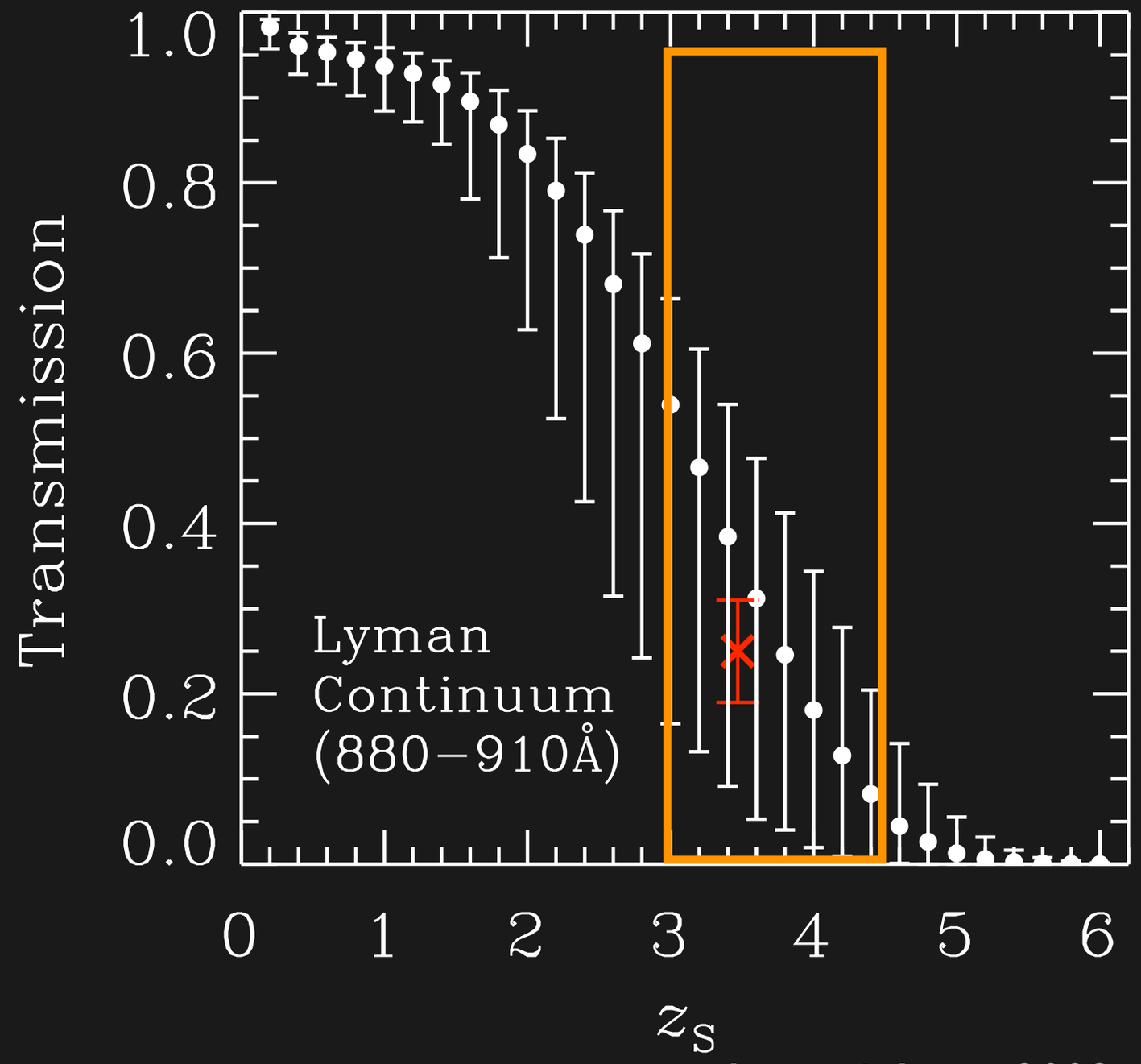
- At z<3 We Need Spacebourne Facility to Detect LyC
- 3<z<5 is the Unique Window to Search for LyC from High-z Galaxies

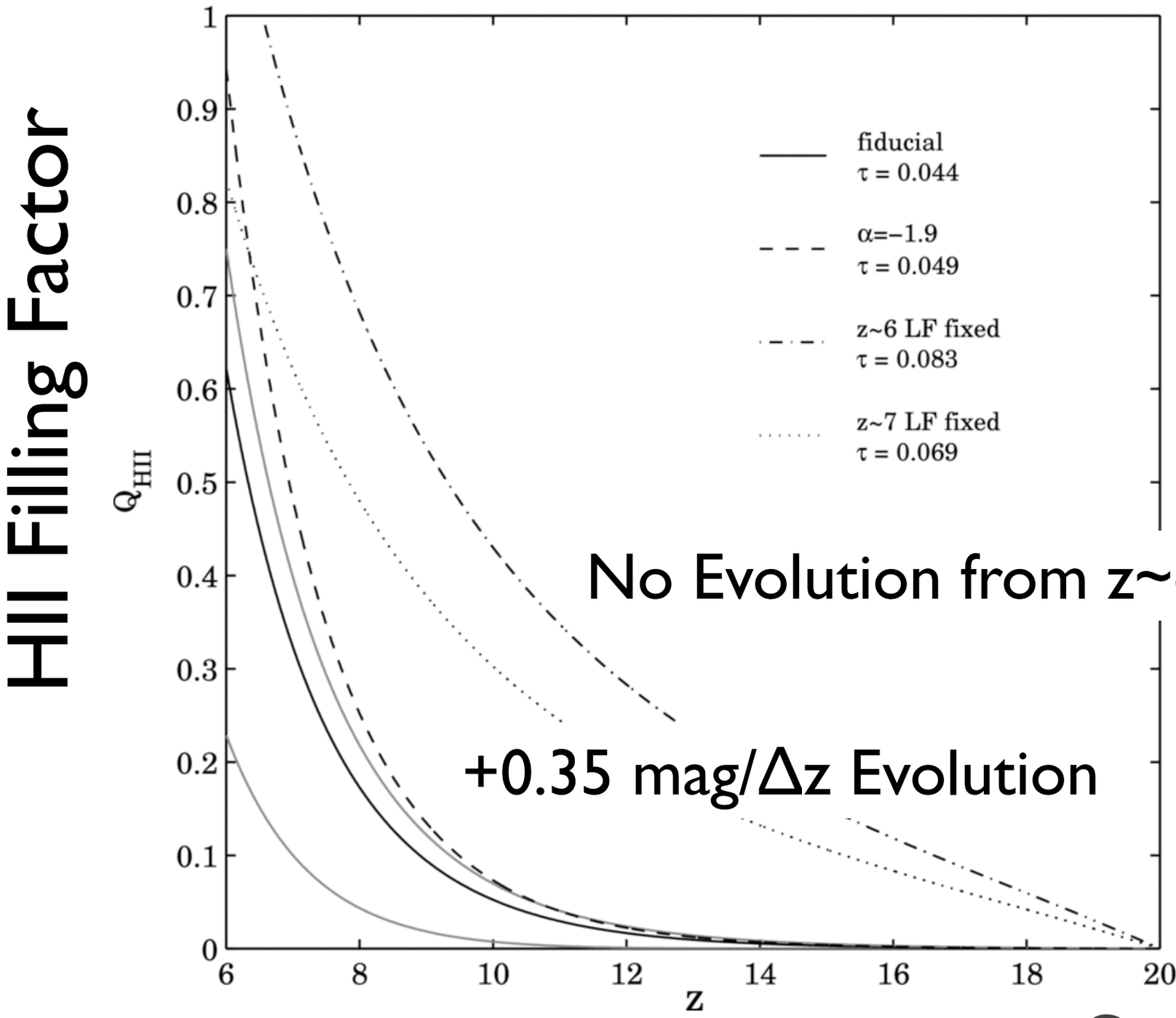


Inoue & Iwata 2008
MN 387, 1681

What We Really Want to Know Is ..

- Lyman Continuum Luminosity, Emissivity (per Volume)
  - Required to Quantify Contribution to the Reionization or Cosmic Ionizing Background
- "Intrinsic" Escape Fraction of Ionizing Photons
  - $f_{esc} \equiv L_{LC,out} \,/\, L_{LC,int}$
  - To Understand How LyC Escapes from Galaxies
- Direct Detection of Ionizing Photons From Star-Forming Galaxies

Are Observed Galaxies Able to Reionize the Universe?



Oesch+09 ApJ 690, 1350

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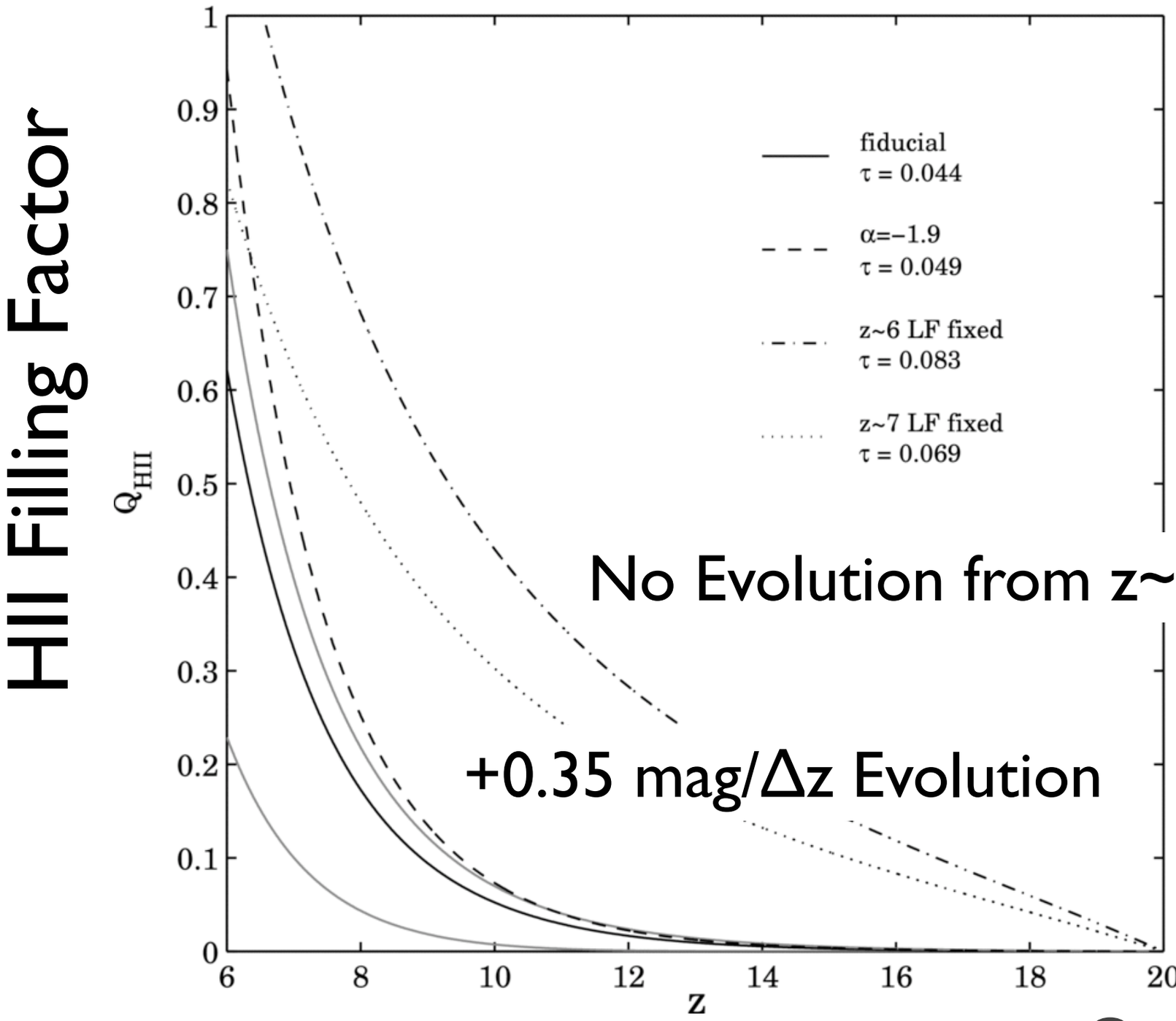


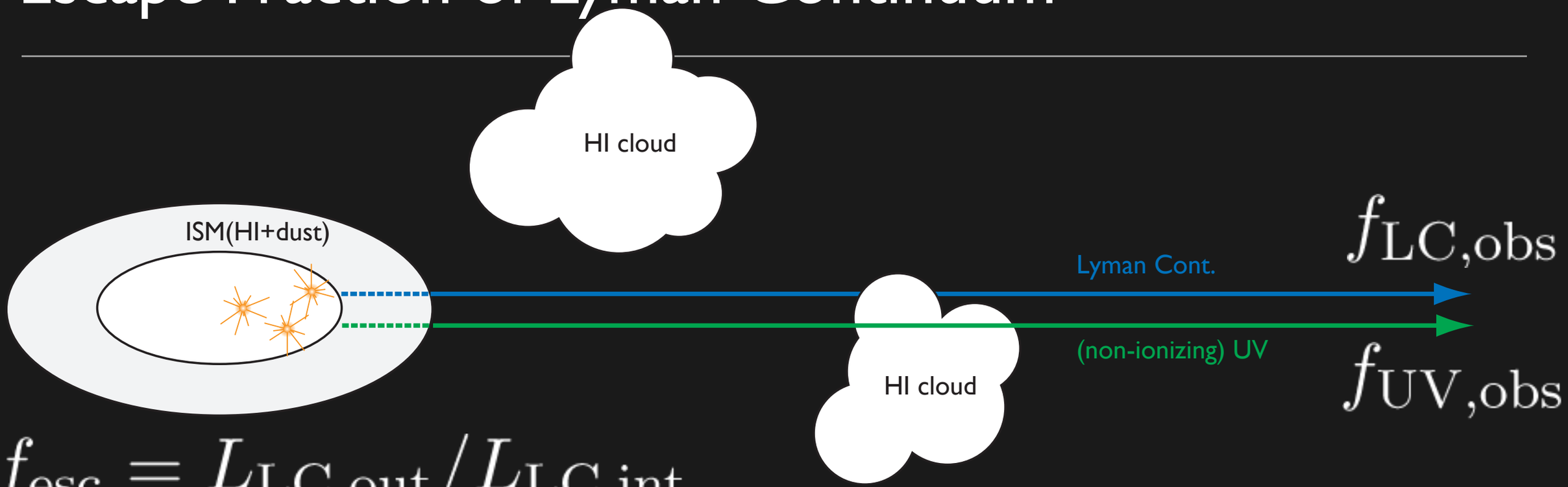
No Evolution from z~6 or 7

+0.35 mag/Δz Evolution

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

Oesch+09 ApJ 690, 1350

Escape Fraction of Lyman Continuum



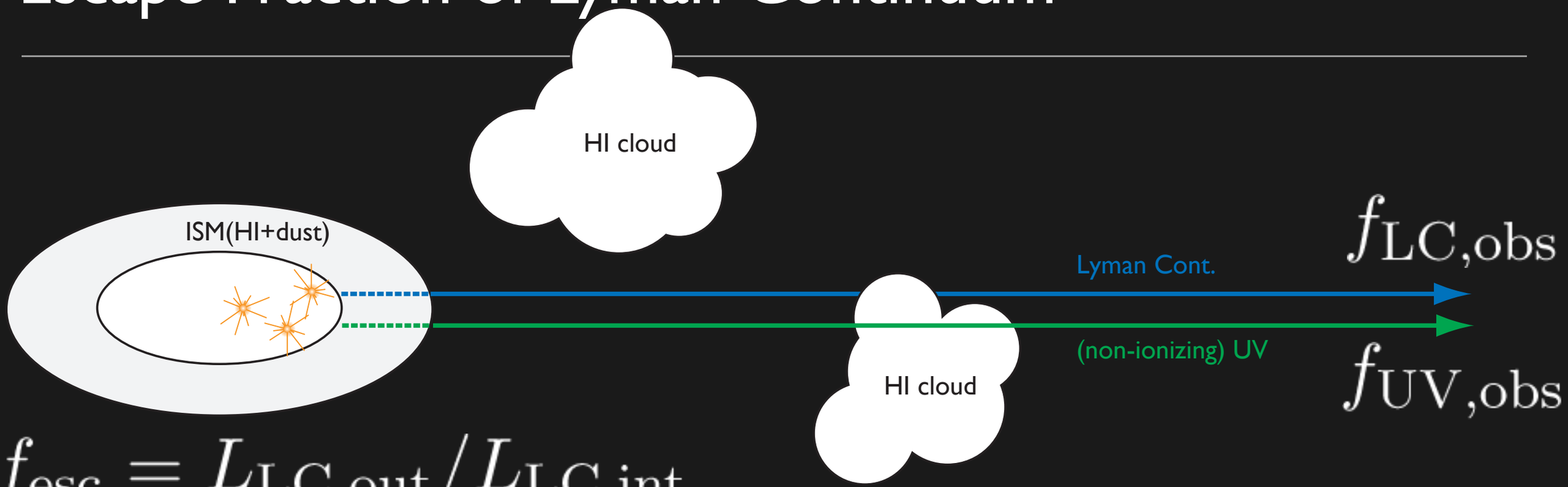
$$f_{\rm esc} \equiv L_{\rm LC,out}/L_{\rm LC,int}$$

$$f_{\rm esc} = 10^{-0.4A_{\rm UV}} f_{\rm esc,rel}$$

$$f_{\rm esc,rel} = \frac{(L_{\rm LC,out}/L_{\rm LC,int})}{(L_{\rm UV,out}/L_{\rm UV,int})}$$

$$= \frac{(L_{\rm UV}/L_{\rm LC})_{\rm int}}{(f_{\rm UV}/f_{\rm LC})_{\rm obs}} \exp(\tau_{\rm IGM,LC})$$

Escape Fraction of Lyman Continuum



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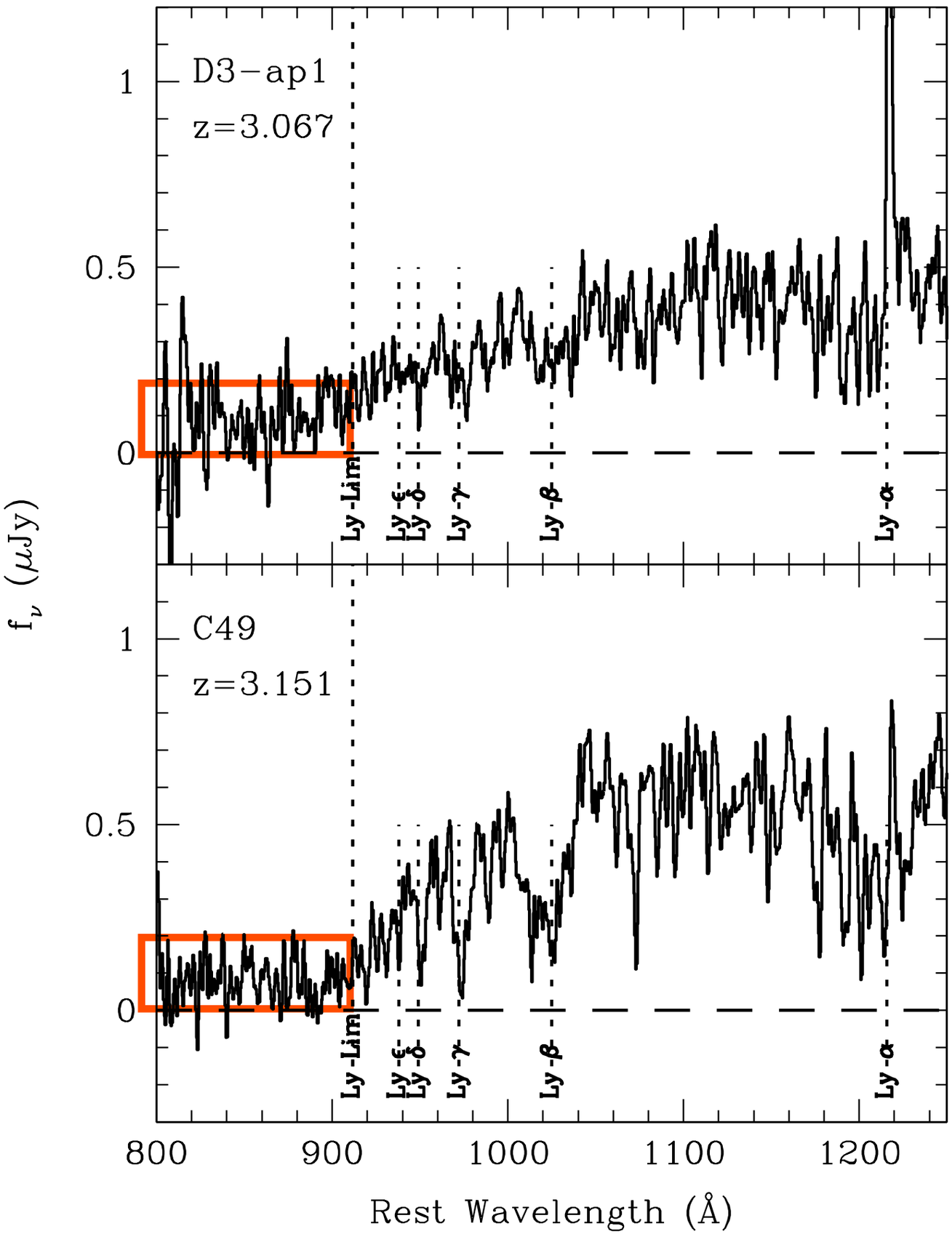


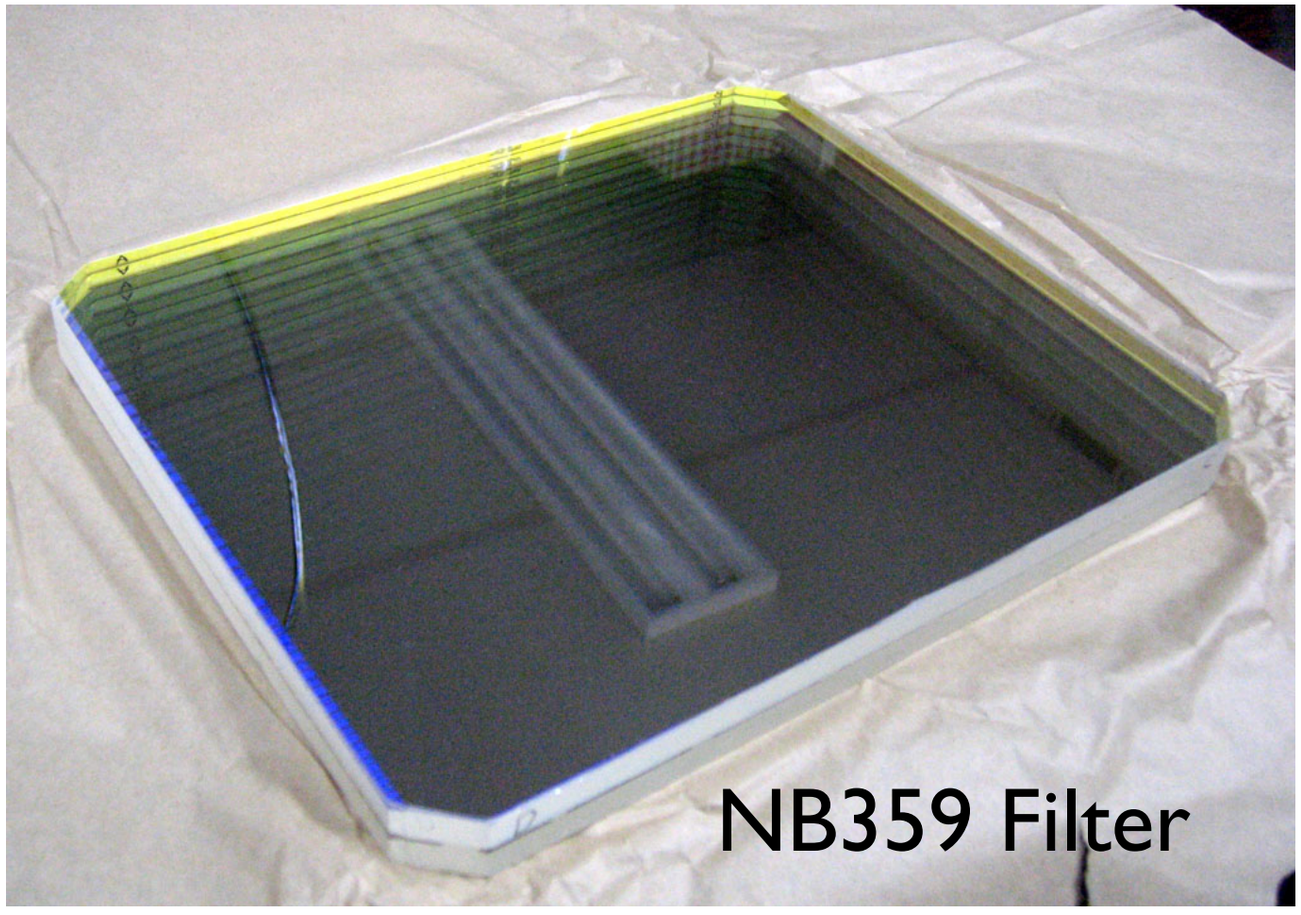
Shapley+ 2006 ApJ 651, 688

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

Recently Shapley+ reports More LyC Detections at z~3 Through Deep Spectroscopy

A New Trial with Subaru

- Special Narrow-Band Filter for Suprime-Cam



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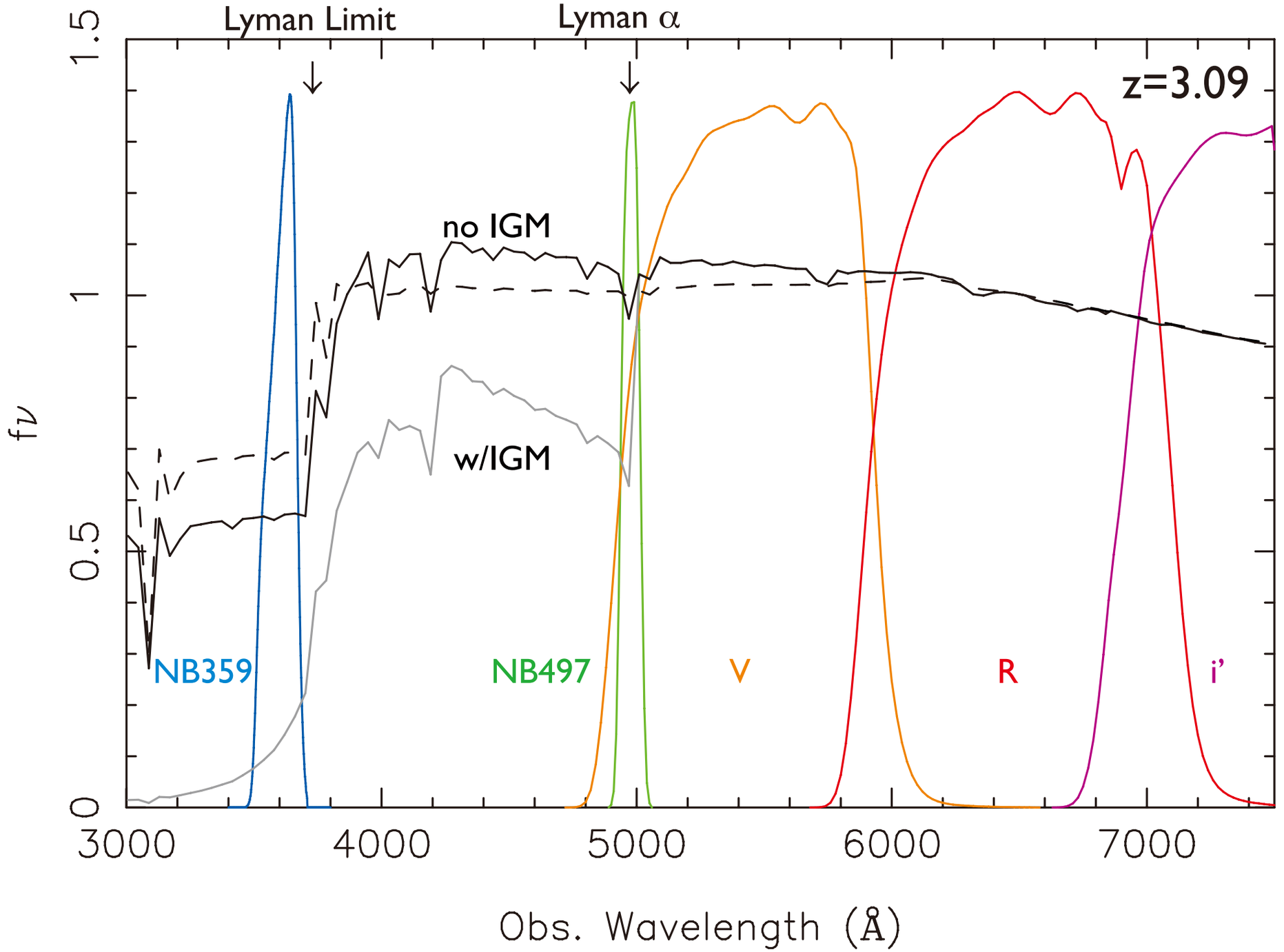
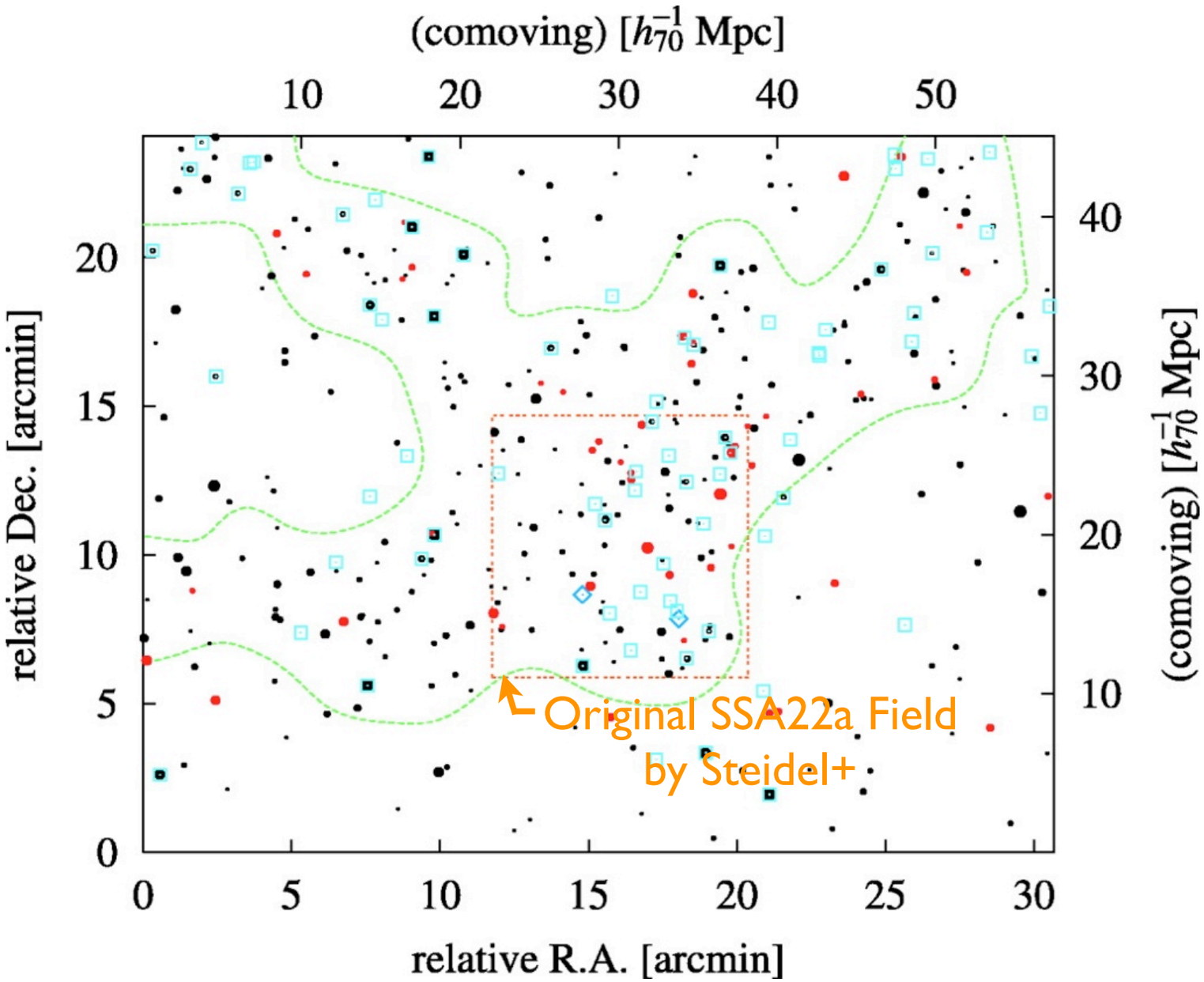


Power of Narrow-Band Imaging

- Wide-Field Narrow-Band Imaging with Subaru / Suprime-Cam Enables Us to Search for Ionizing Radiation from Large Number of Galaxies at Specfic Redshift Range
- No Light Loss with Slit
- We Can Also Examine Spatial Offset Between Ionizing and Non-ionizing Radition

SSA22: Proto-Cluster at z=3.09



Matsuda et al. AJ 128, 569 (2004)

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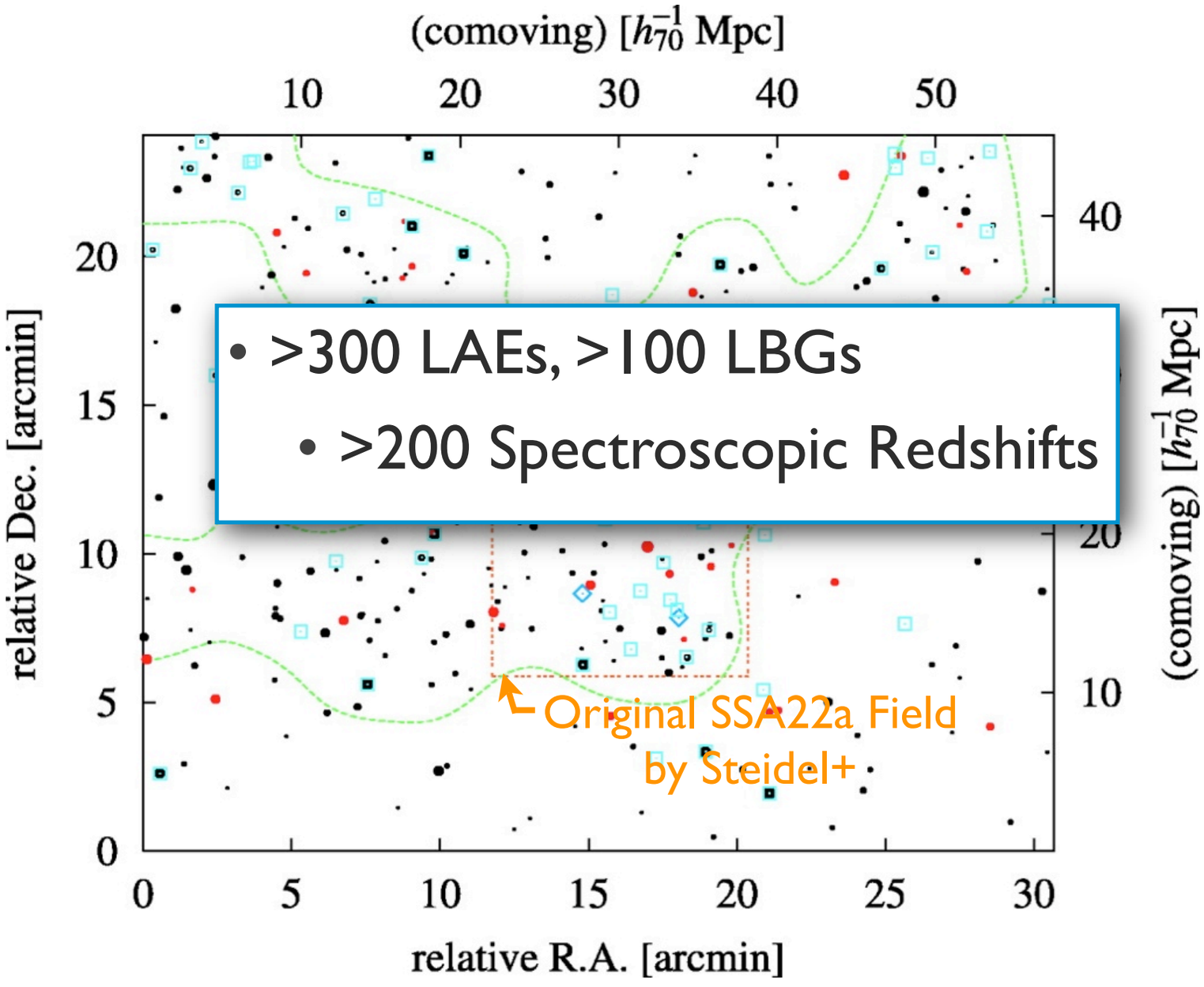

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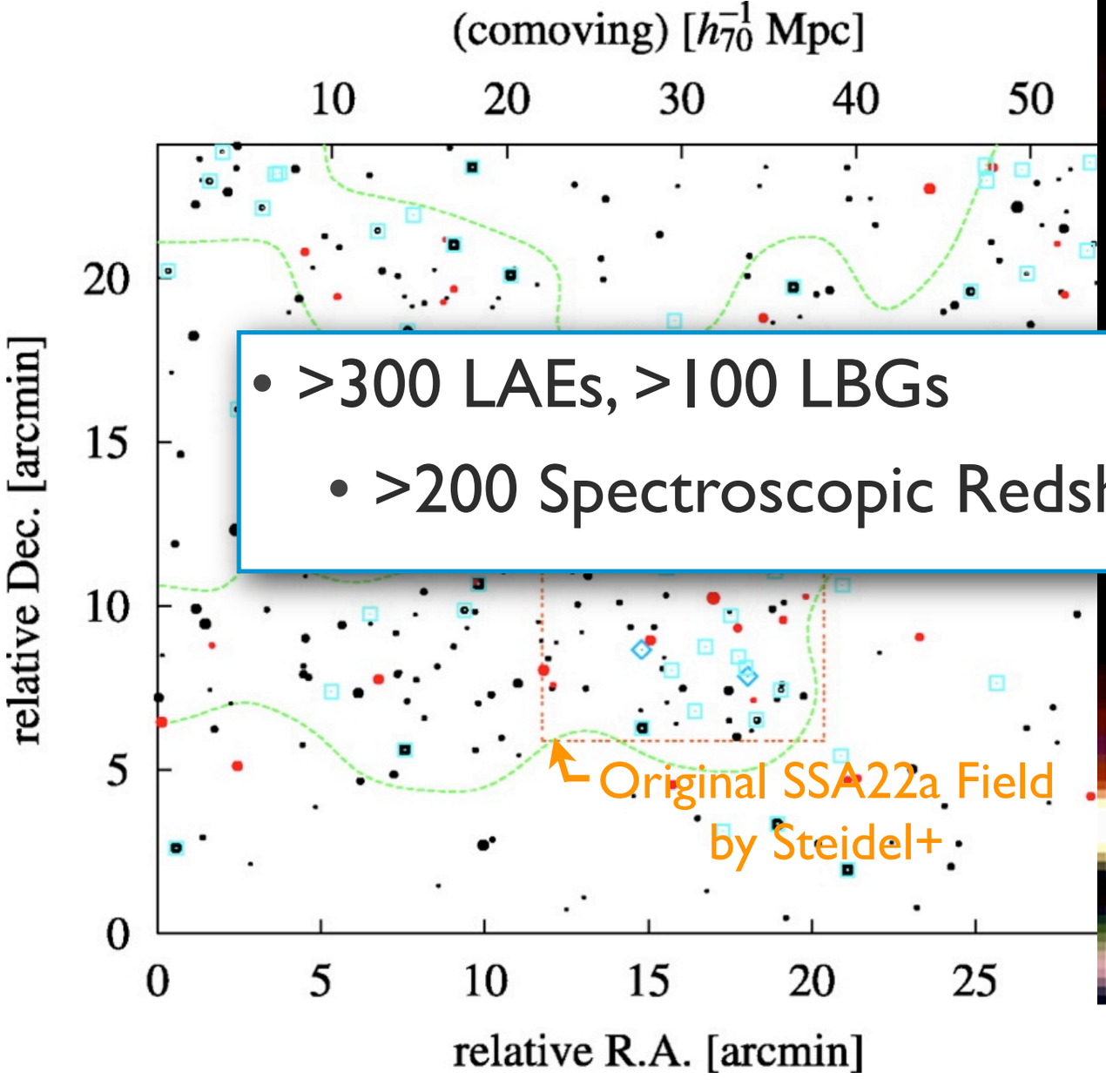
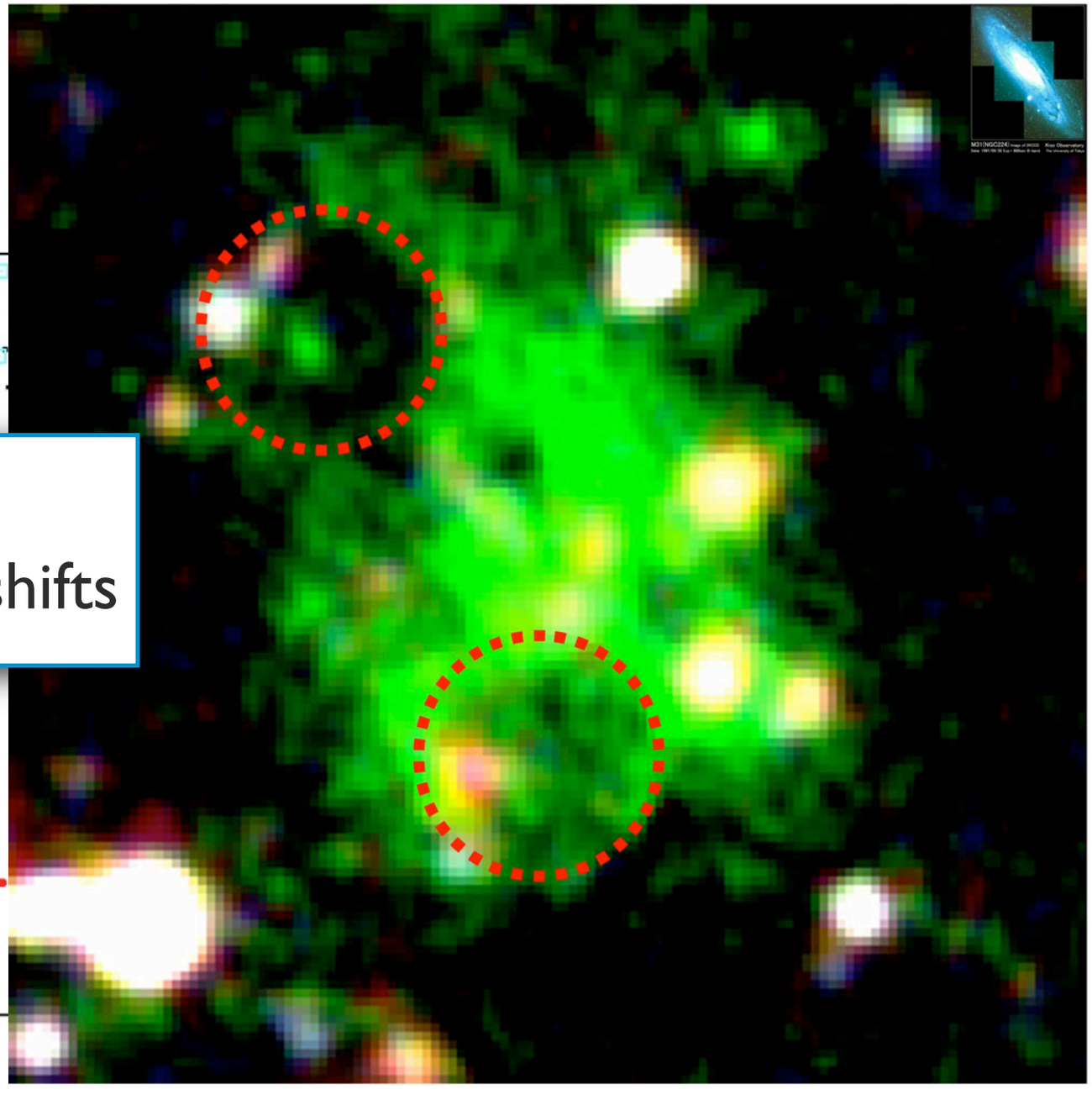


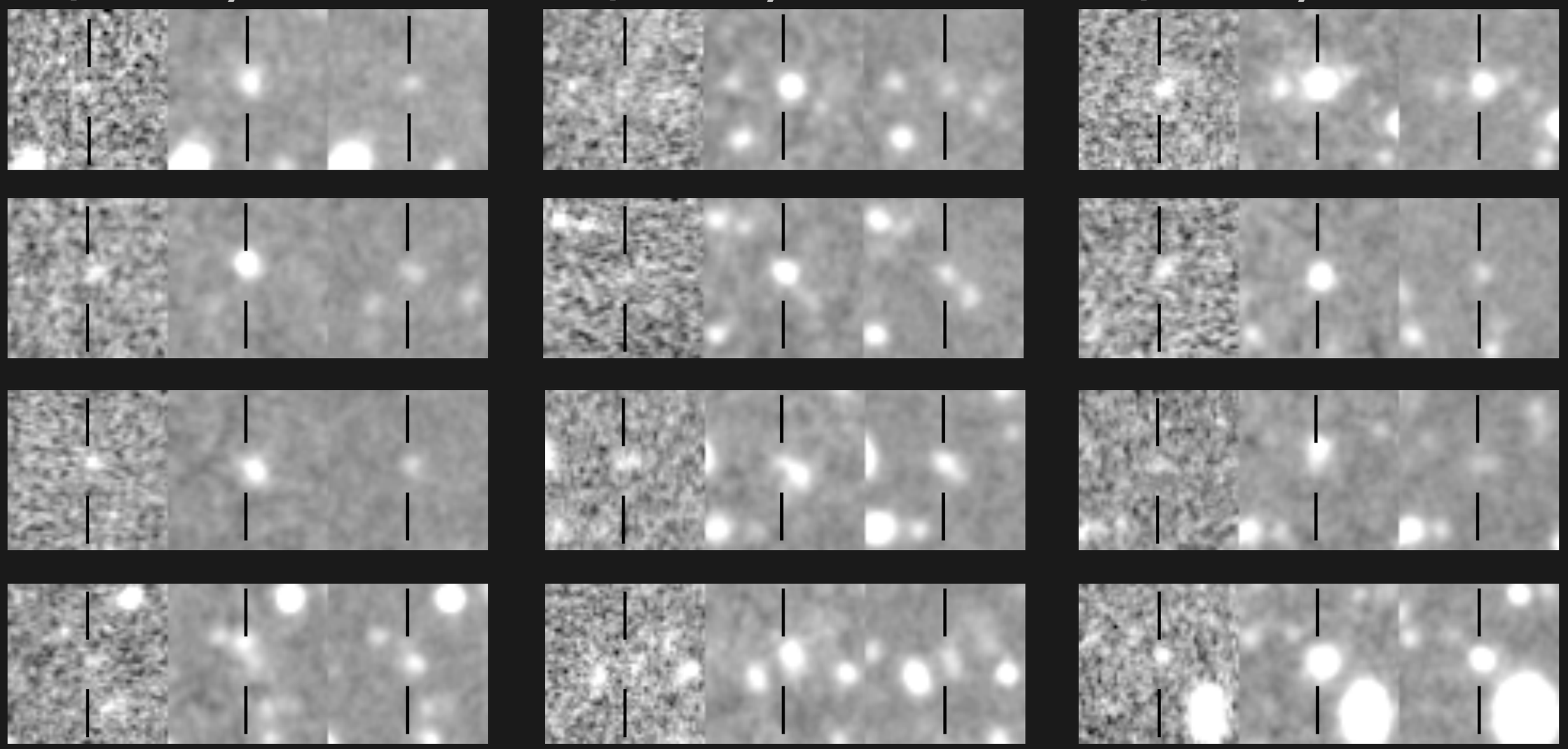


Matsuda et al. AJ 128, 569 (2004)

Detections of Ionizing Radiation

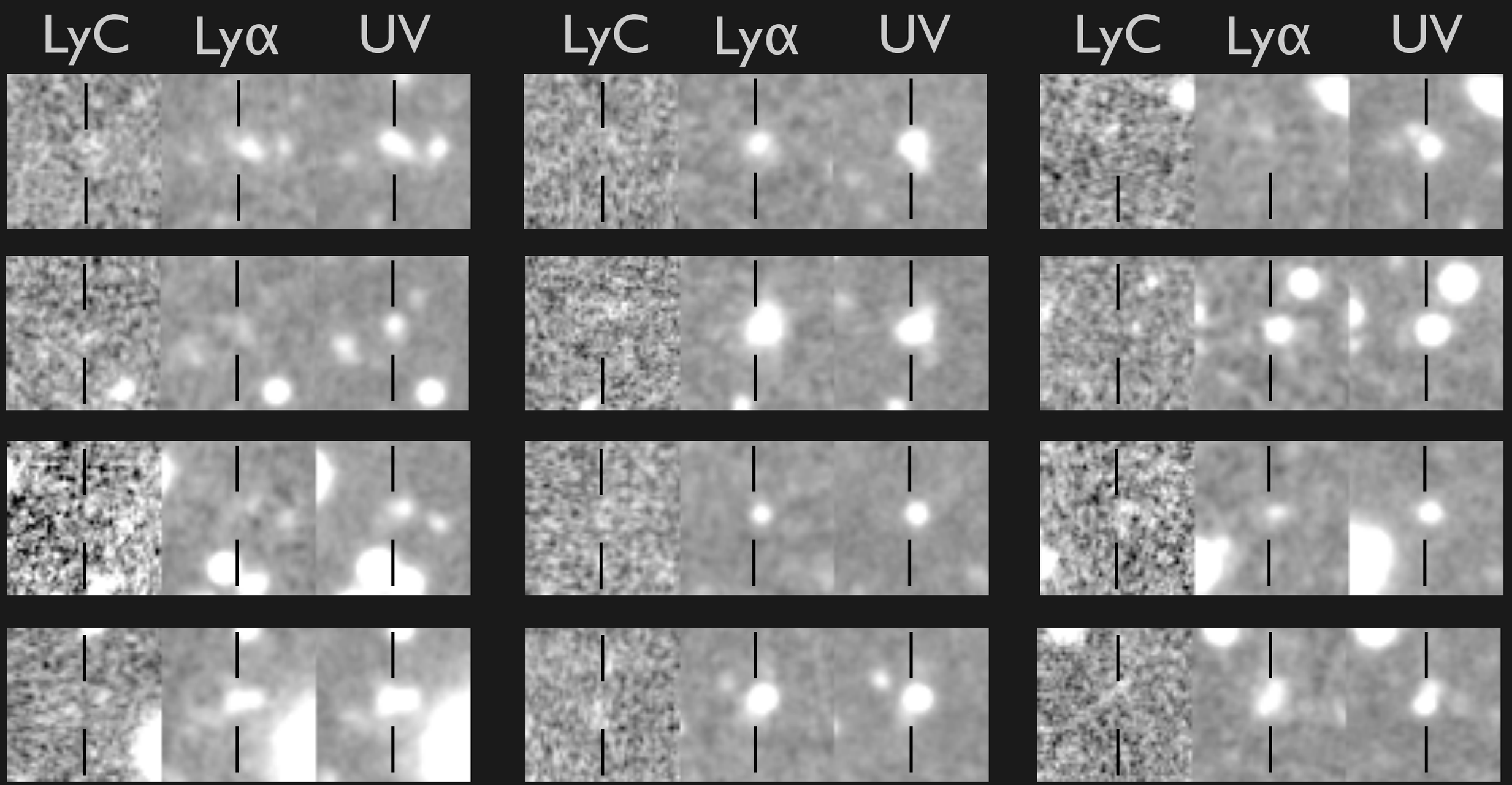
- >3σ Detections for 24 Galaxies among 264 Galaxies with z_{spec}>3.05
  - 12 Lyman Break Galaxies (LBGs)
  - 12 Lyman-α Emitters (LAEs)
- Increased from Iwata et al. ApJ 692, 1287 (2009) by Spectroscopic Follow-up and Reanalysis

LyC Detected Lyα Emitters



FoV: 10”x10”

LyC Detected Lyman Break Galaxies



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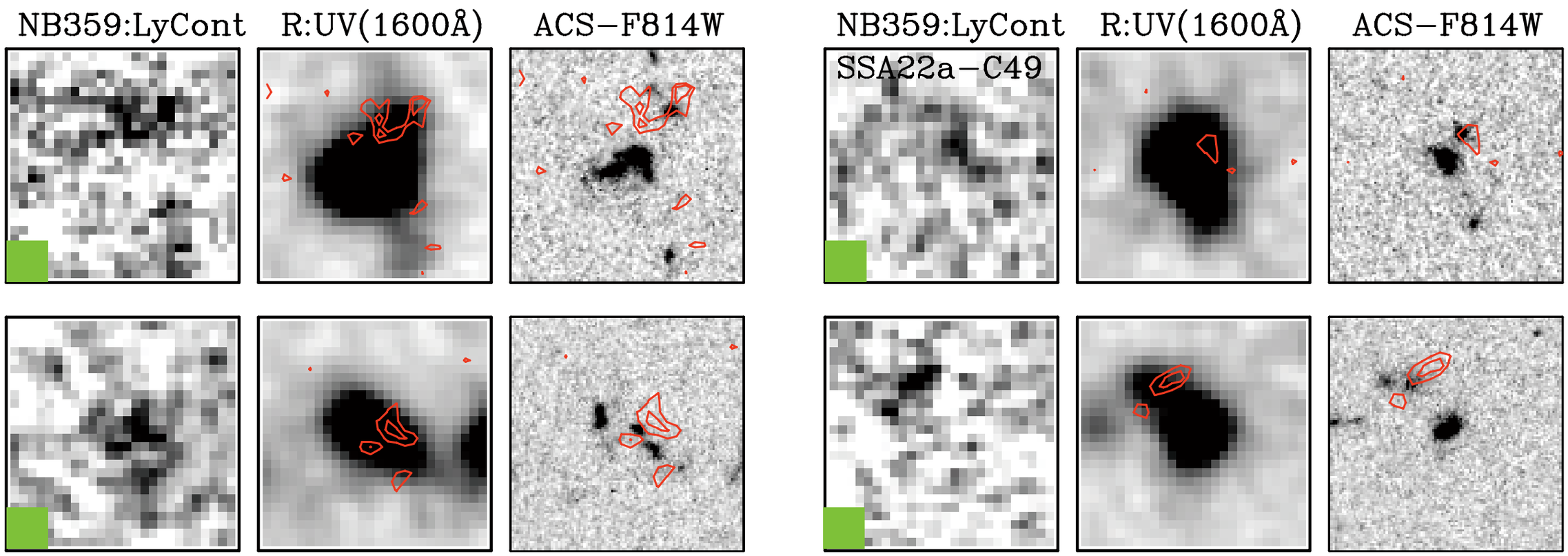
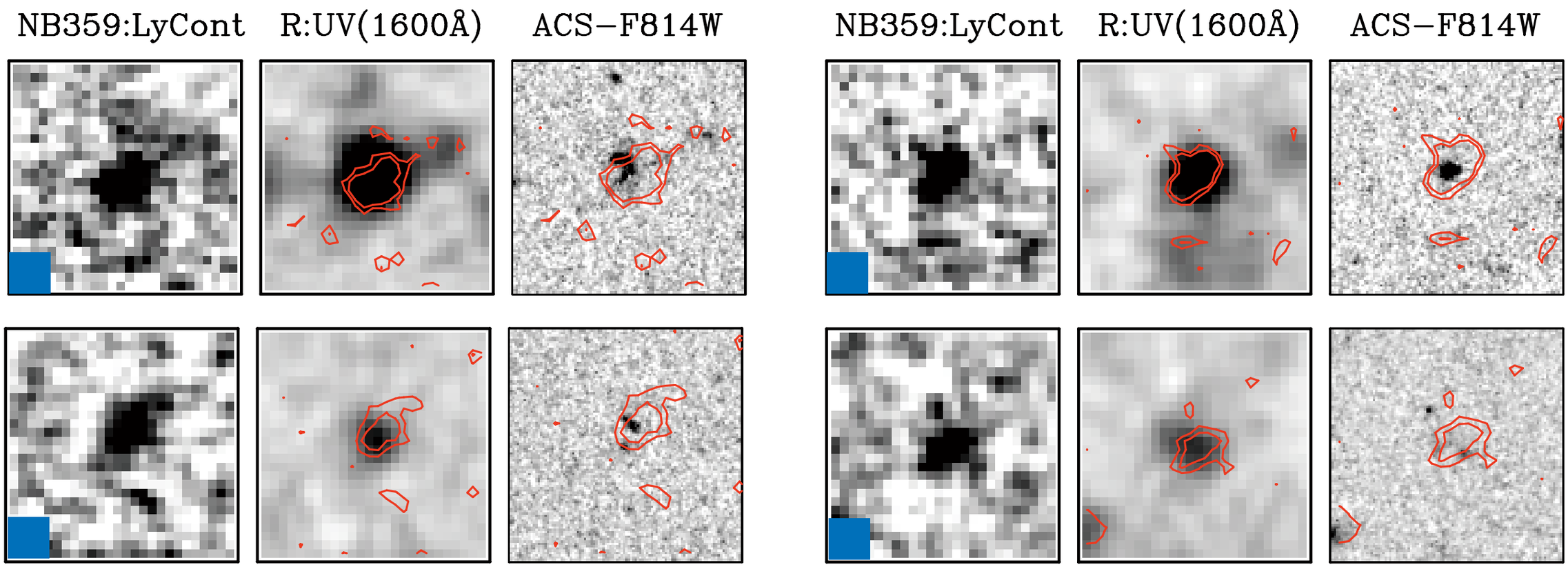
HST/ACS Images - LyC Offset from non-ionizing UV for LBGs



FoV: 5”x5”

HST/ACS Images - But No Offset for LAEs



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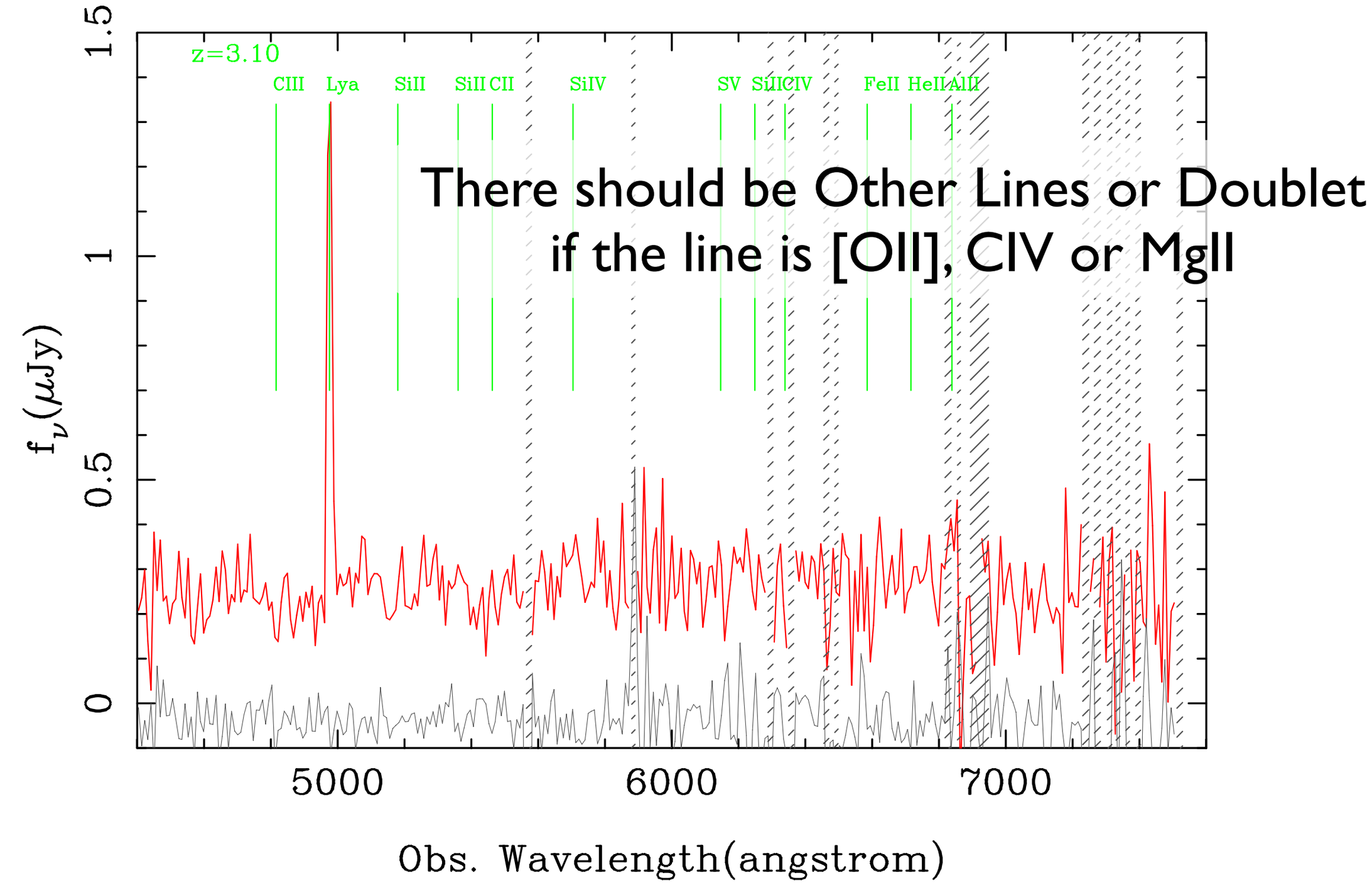
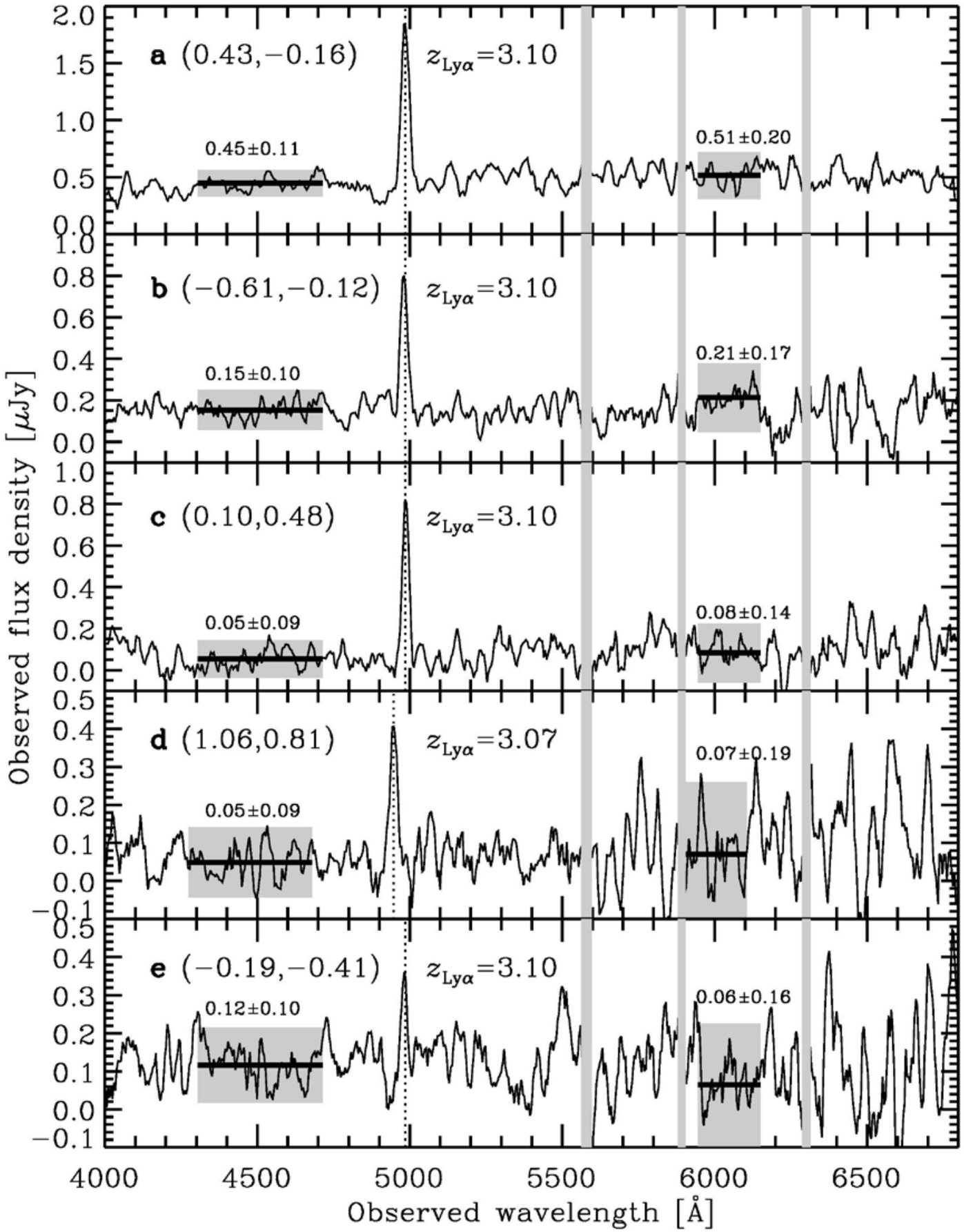
Are They Really at z~3.1?

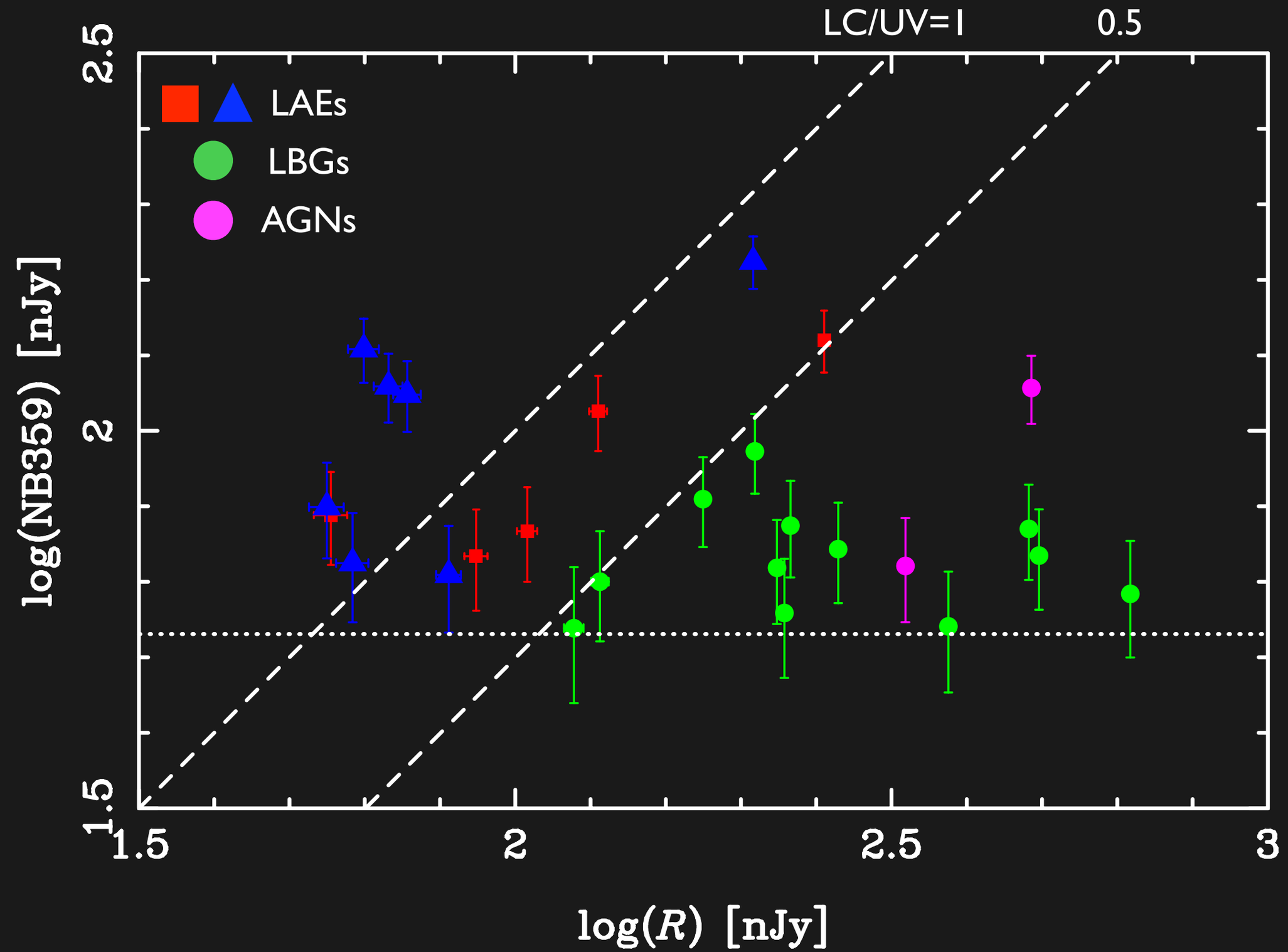


- Follow-up Spectroscopy with VLT/ VIMOS and Subaru/ FOCAS Confirmed that At Least Some Galaxies with Strong LyC Emission Are Really at z~3.1



Kousai et al. in Prep.

Strong "LyC Emitters"



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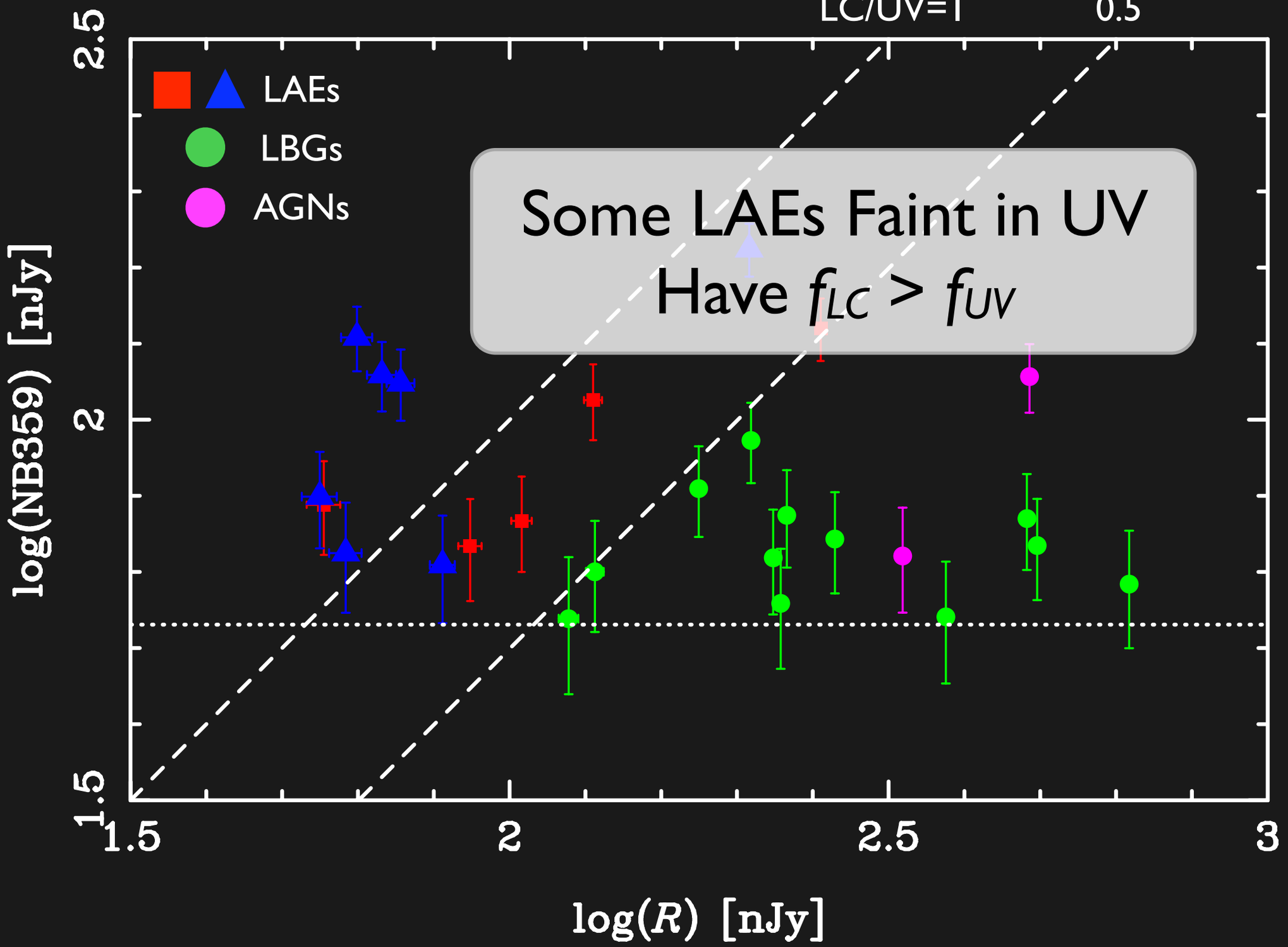
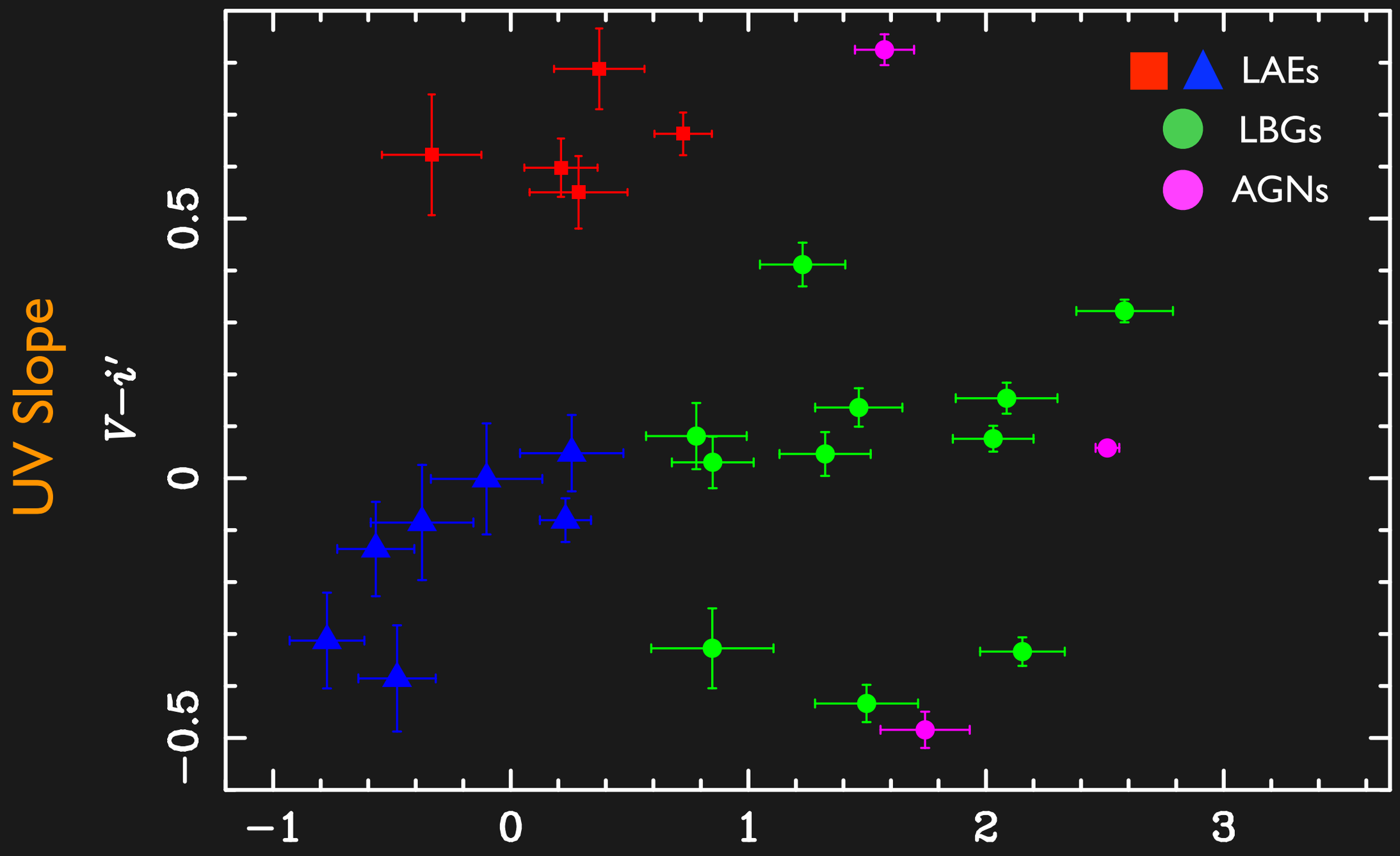


Two-Color Diagram



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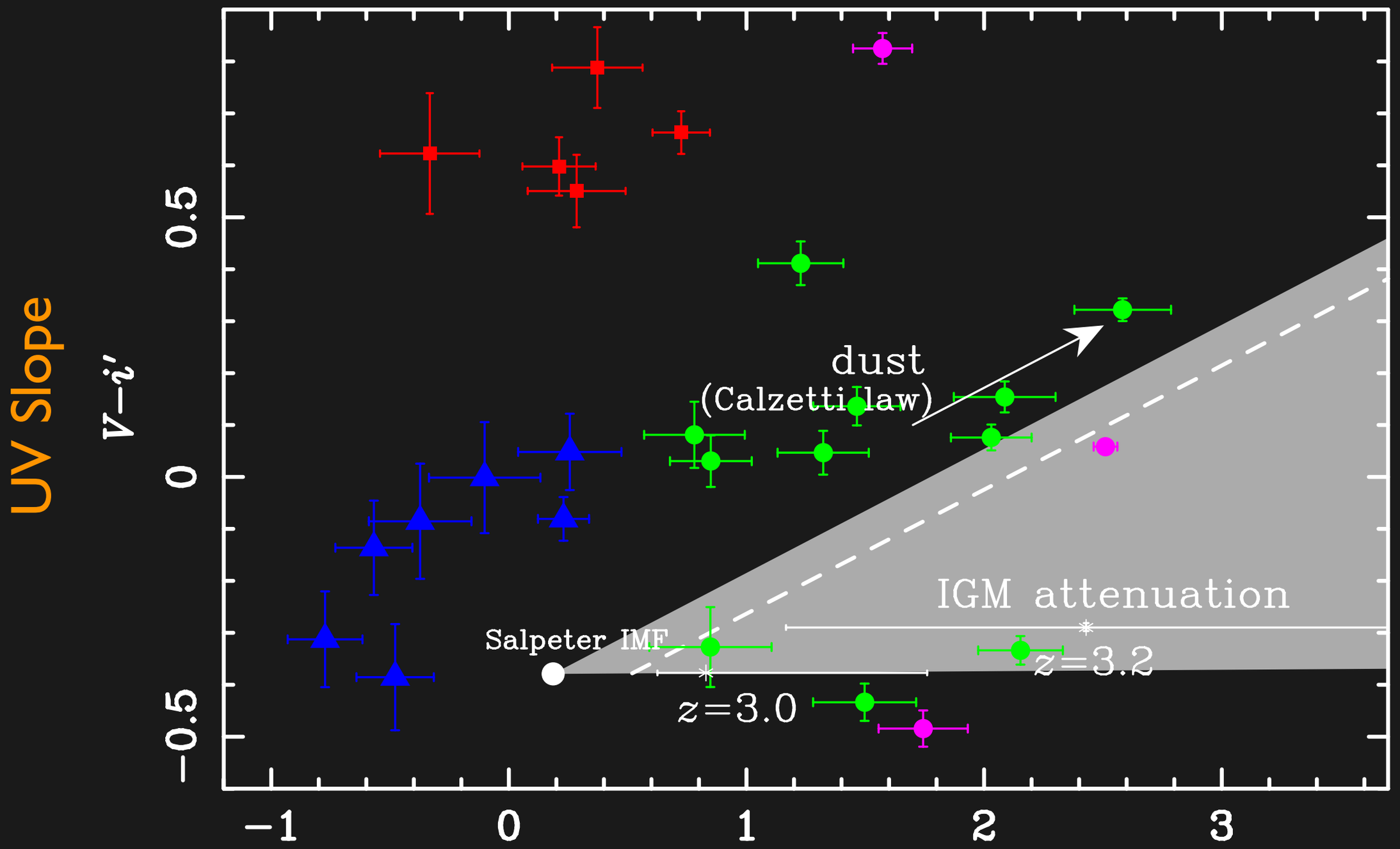

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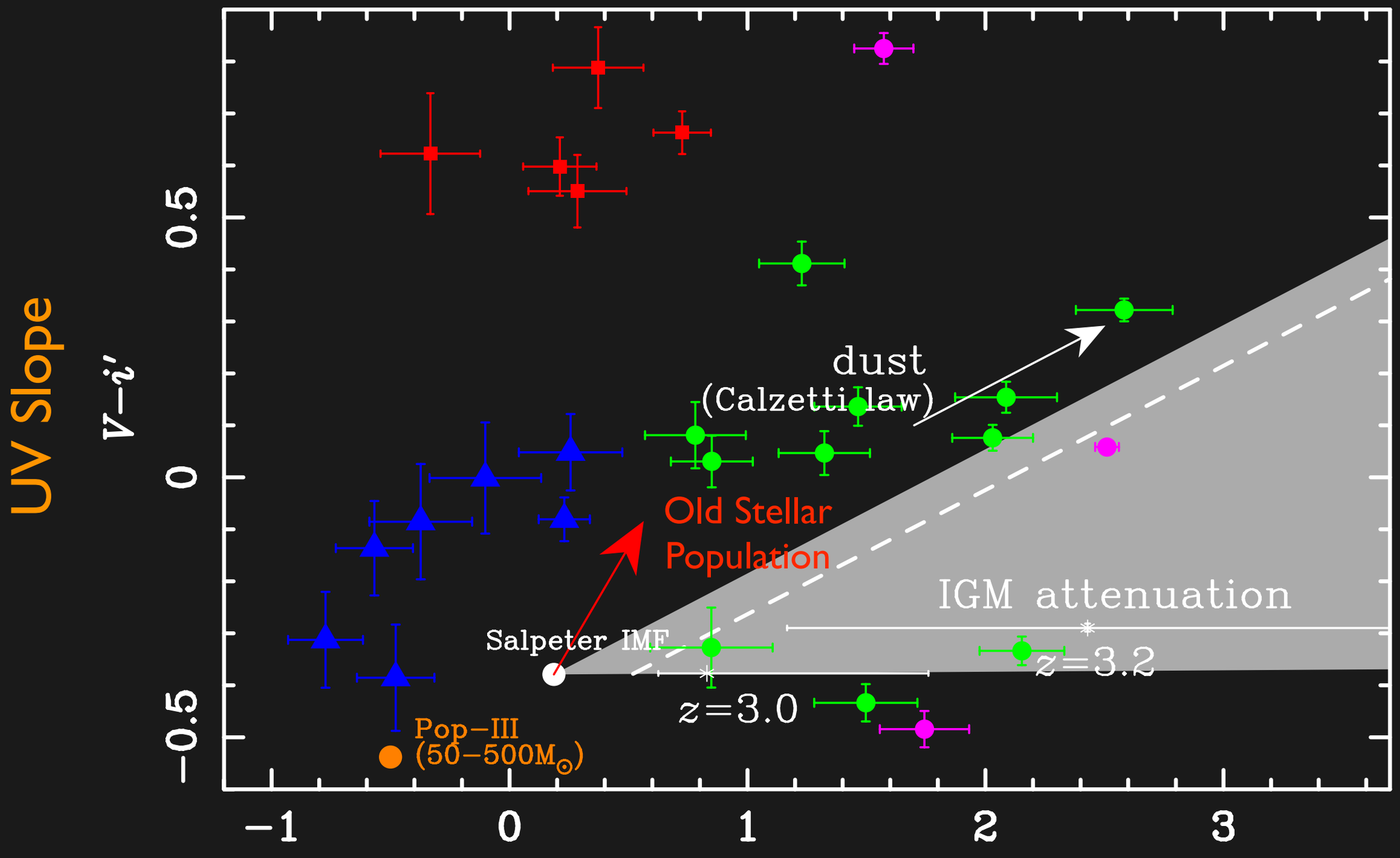

More Detections from Lyα Emitters in a Blank Field

- VLT/FORS Narrow-Band Imaging
- Compared to Subaru/Suprime-Cam
  - Narrower Field of View but Higher Sensitivity at <4000Å
- Target Field: BR1202-0725 Field
  - "Building the Bridge" Survey by Fynbo et al.
  - 18 LAEs with z_{spec}=3.2 (Grove et al. 2009)
- >3σ Detections for 2 (+ Possible 1) LAEs

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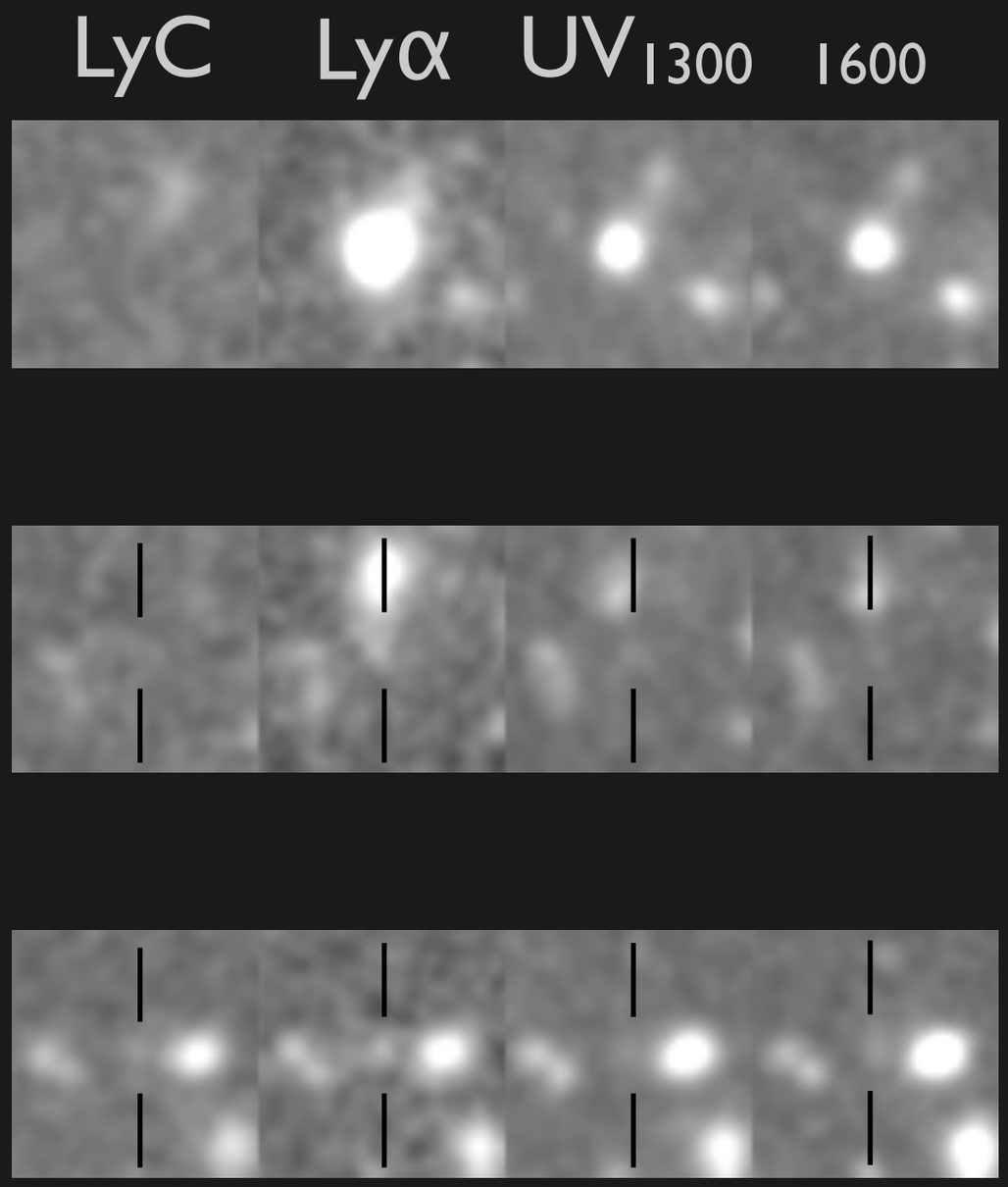
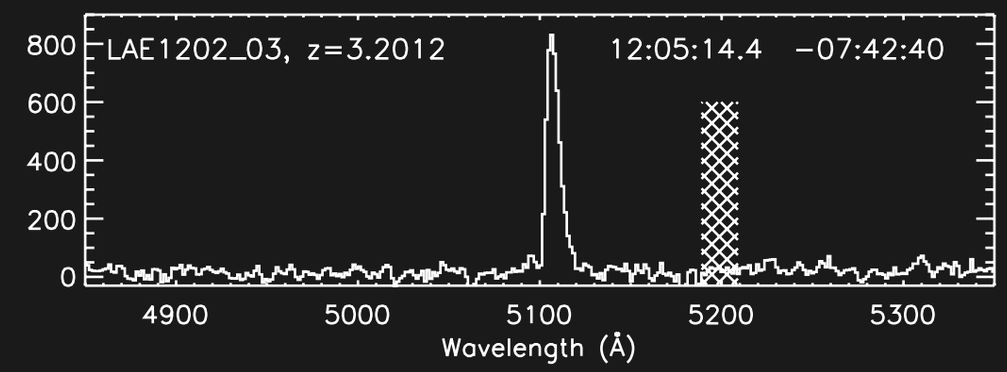
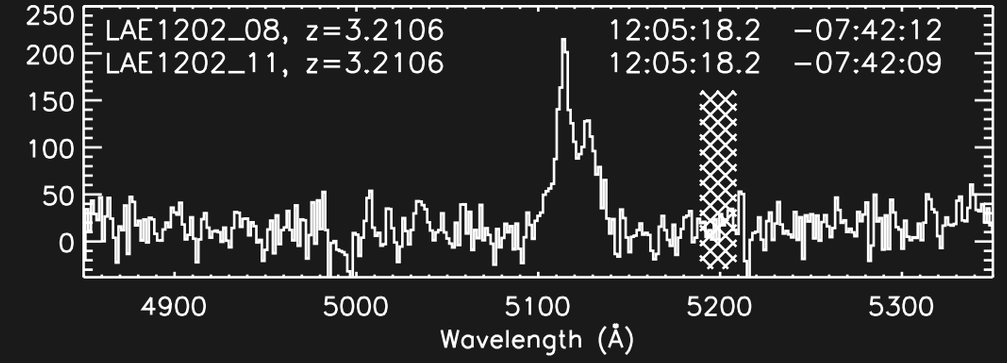
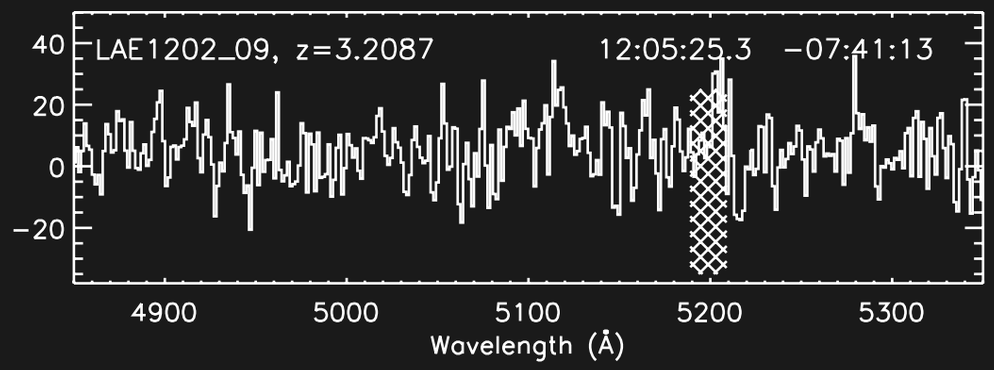




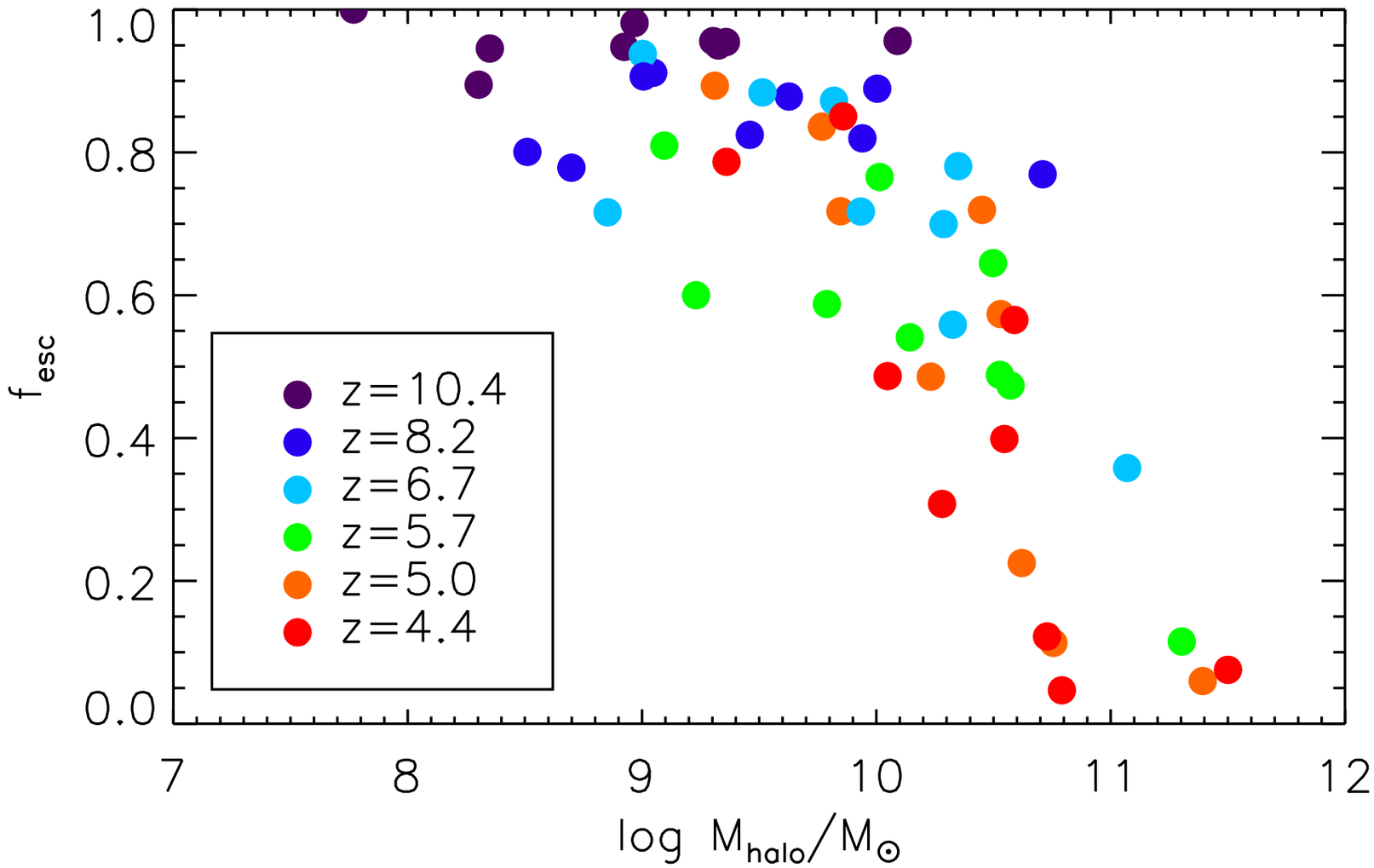




FoV: 10”x10”

Grove et al. A&A 497, 689 (2009)

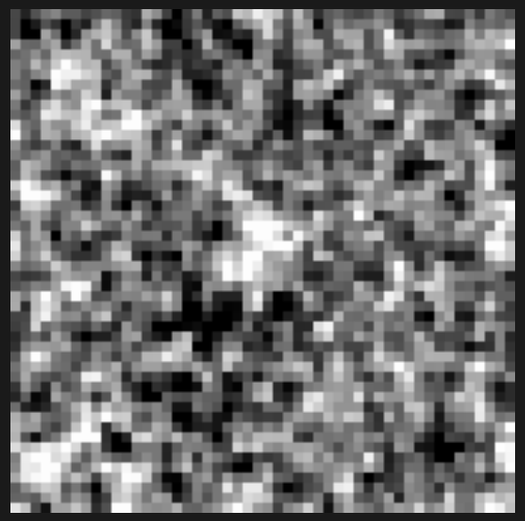
High LyC Escape Fraction?



- 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

Composite Image - Average Escape Fraction

LyC

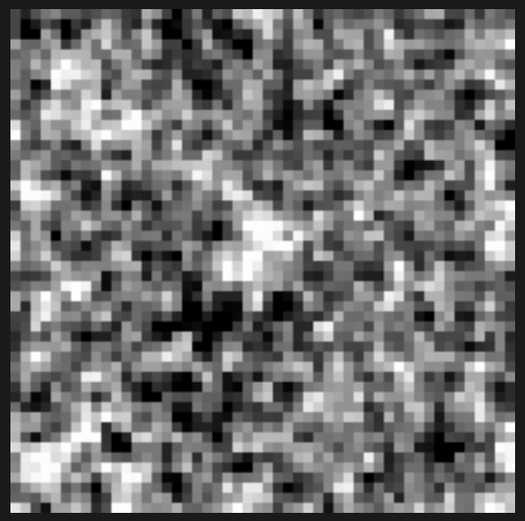


UV

- Composite of All 193 Galaxies in SSA22 with z_{spec}>3.05 and R>26.4 AB
  - Normalized with R-band flux density
- $\langle f_{LC}/f_{UV} \rangle$ = 0.03

Composite Image - Average Escape Fraction

LyC



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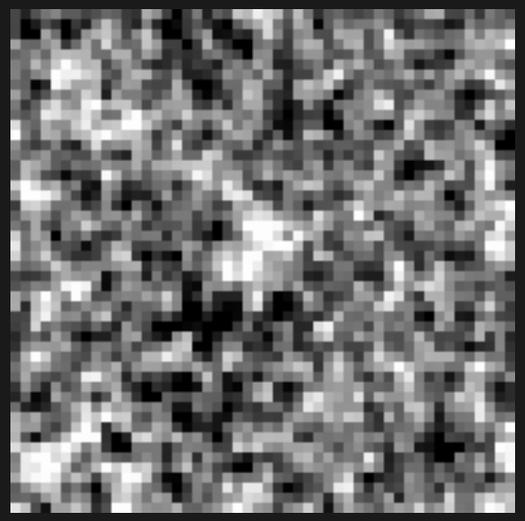
  (assuming $(L_{UV}/L_{LC})_{int}$=3 and average IGM opacity)

Composite Image - Average Escape Fraction

LyC



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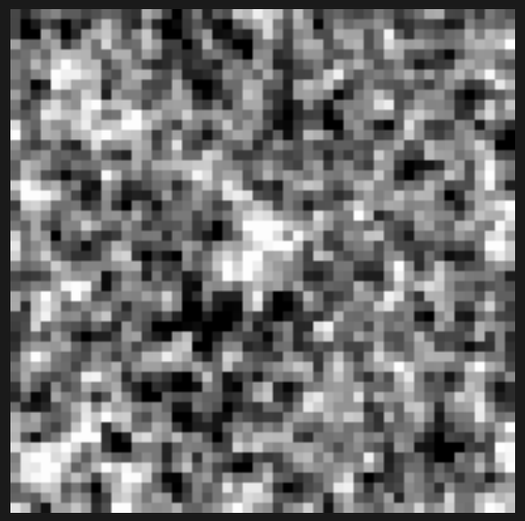
  = 0.04±0.01

Composite Image - Average Escape Fraction

LyC



UV

- Depends on Assumptions on Intrinsic UV/LC ratio, IGM Opacity, Dust Attenuation
- No Care for LyC Offsets from UV Peak

- Composite of All 193 Galaxies in SSA22 with z_{spec}>3.05 and R>26.4 AB
  - Normalized with R-band flux density
- $\langle f_{LC}/f_{UV} \rangle = 0.03$
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  (assuming $(L_{UV}/L_{LC})_{int}$=3 and average IGM opacity)
- $f_{esc} = 10^{-0.4 A_{UV}} f_{esc,rel}$

  = 0.04±0.01

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- Existence of Strong LyC Sources - “Ionizers”
  - They Appear to be Ubiquitous at z~3
  - Candidate of Primary Sources Responsible to EoR

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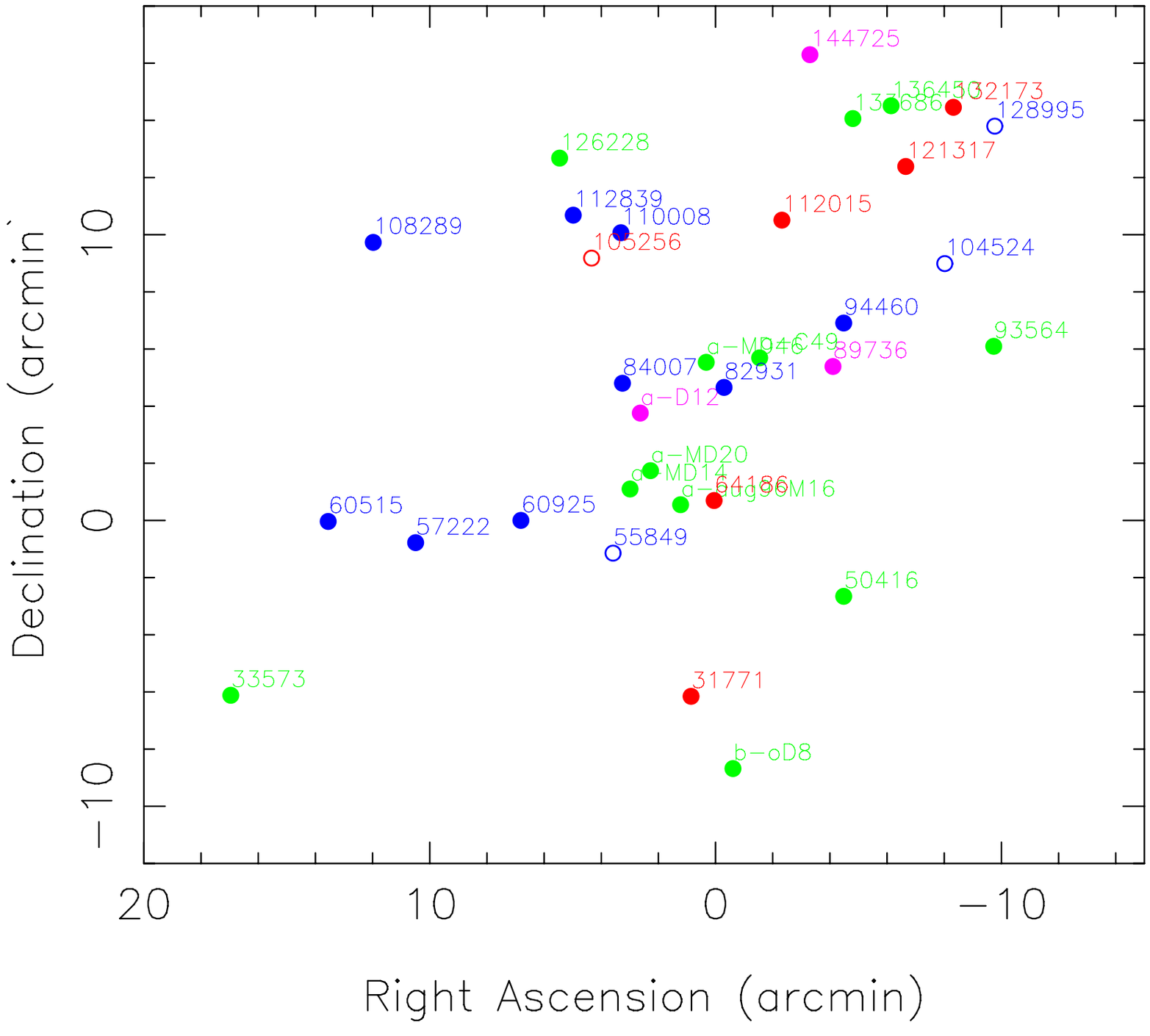
- Average f_{esc} Estimate ~ 4% at z=3.1

Spatial Distribution for LyC Sources in SSA22



Colors vs. Rest-UV mag.