The Lyman Continuum Escape Fraction and the Legacy of Deep Extragalactic HST UV Imaging Surveys

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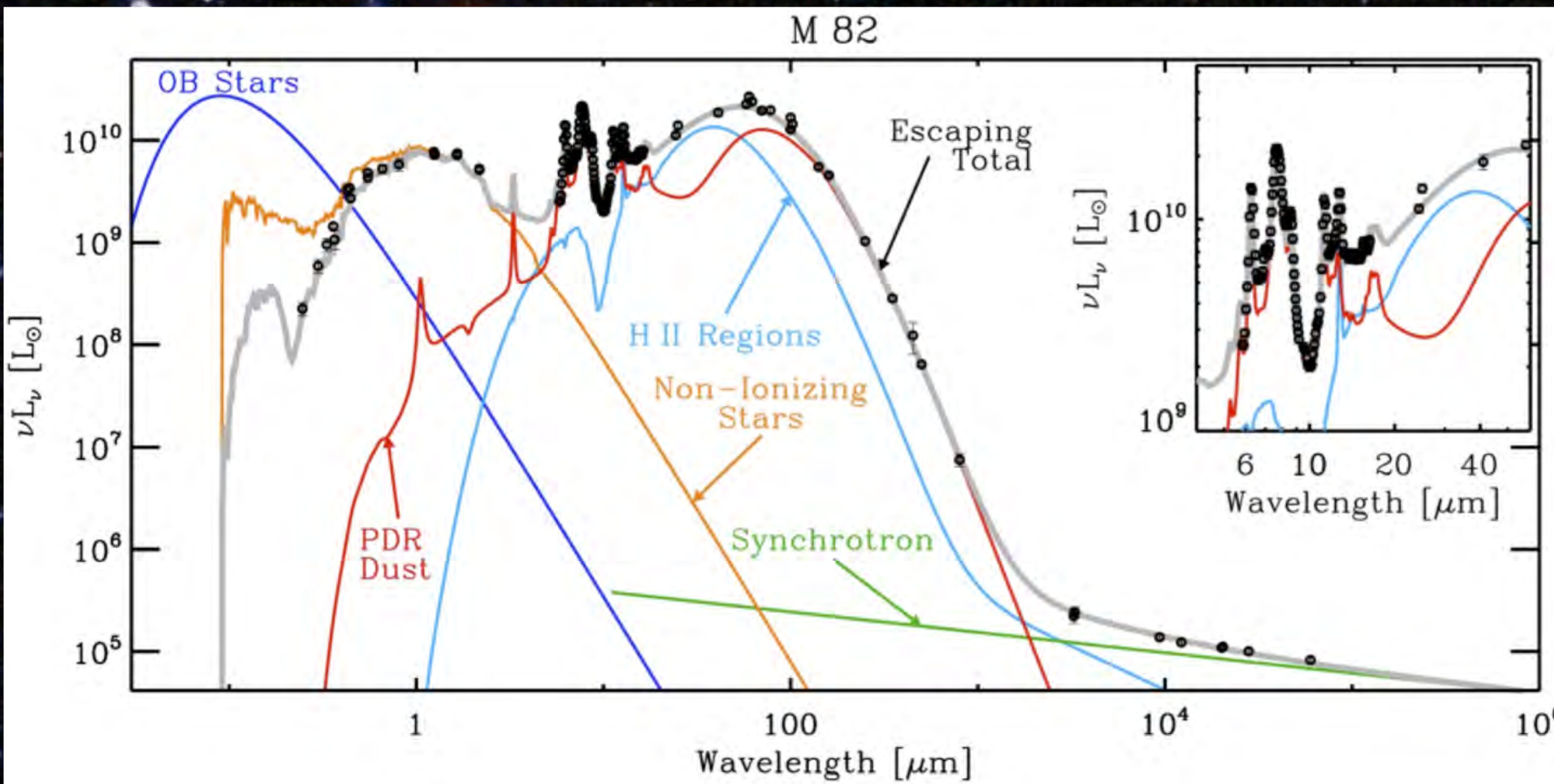
AND THE UVCANDELS TEAM


よろしくお願いします
ご招待有り難うございます

Rest-frame far-UV: vital tracer of star formation Directly Samples light from hot (O and B) stars

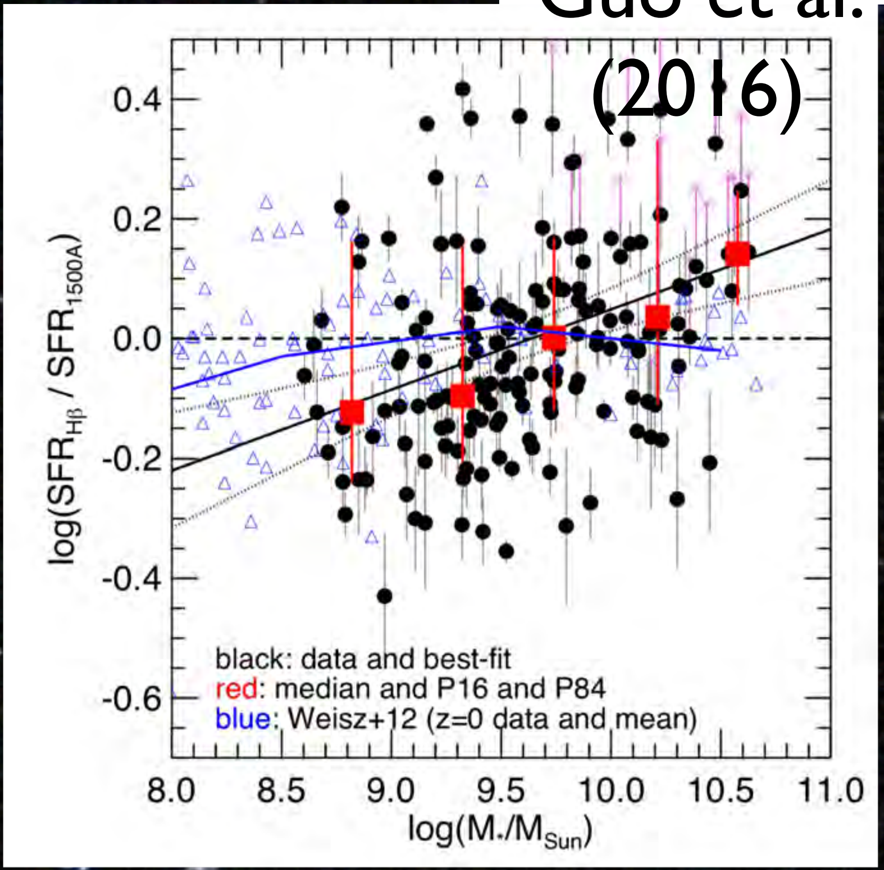


M82 SED fitting by DustPedia, using Galliano et al. (2008, 2011) model

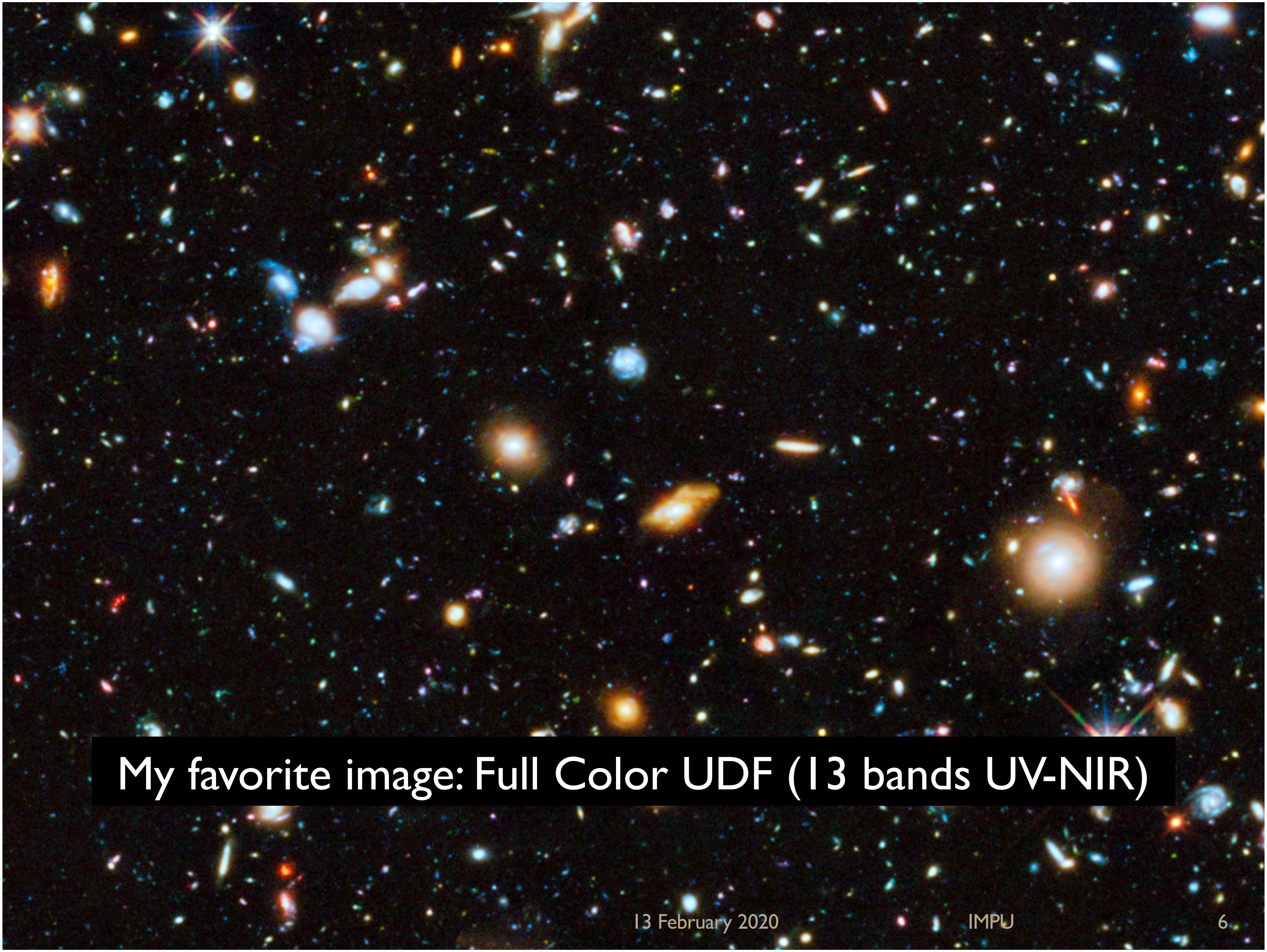
Time Scales

- Measure of star-formation on time scales of 100 Myr
- Necessary to understand star-formation history in combination with e.g. Balmer line measurements of instantaneous SFR
- Sensitive to continuous star formation scenarios

Guo et al. (2016)

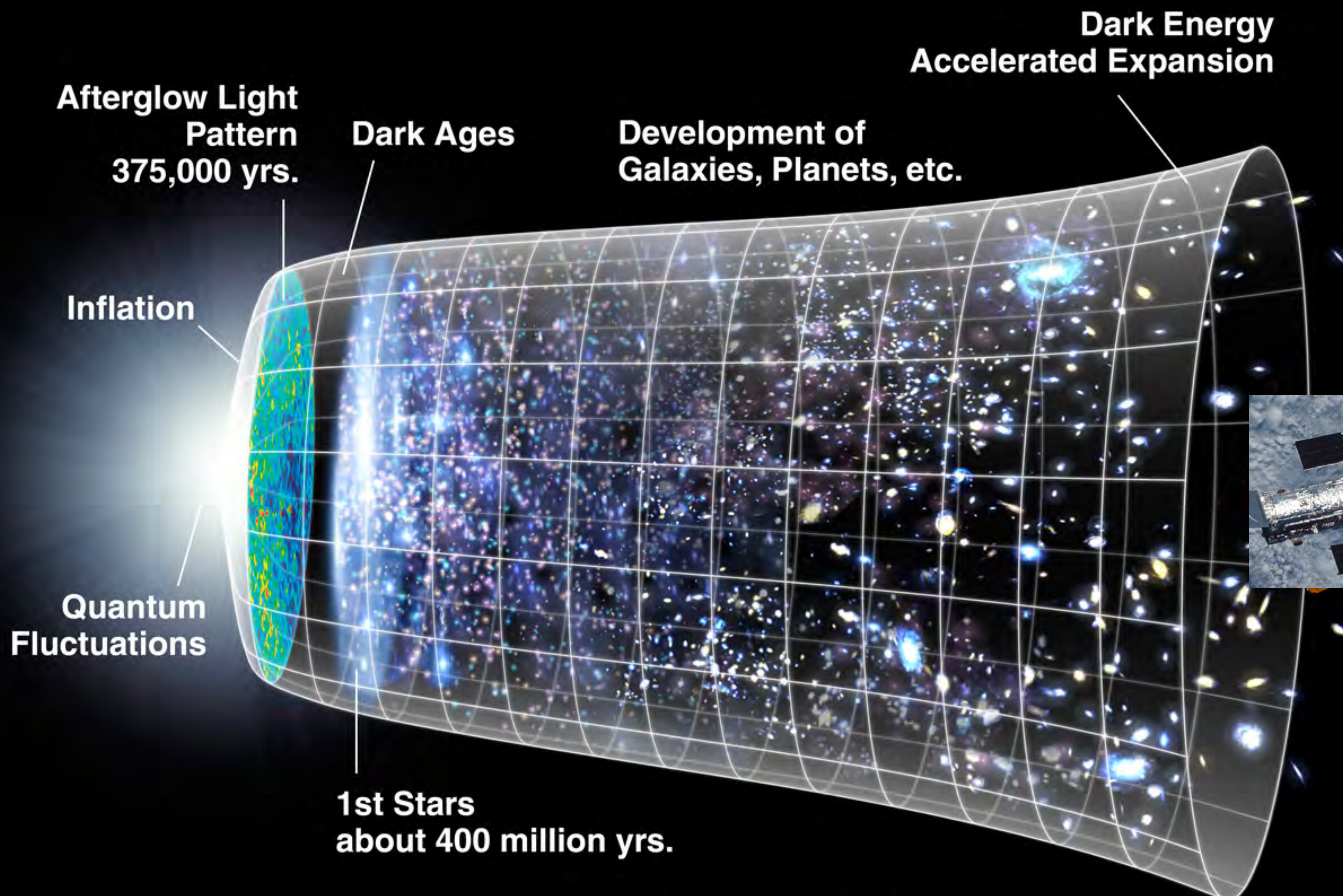


M33: GALEX (blue) and Spitzer (red)



My favorite image: Full Color UDF (13 bands UV-NIR)

HUBBLE UVUDF ULTRA DEEP FIELD


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.

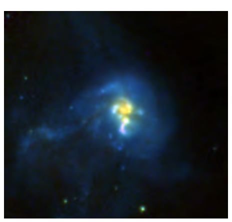
Reionization

neutral Intergalactic Medium (IGM)

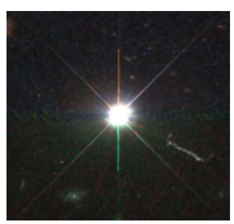
Ionizing sources - What are they?

- HI ionized by photons with energy greather than 13.6 eV
  - λ < 912 angstroms
  - "Lyman continuum"

    (LC or LyC)



Galaxies

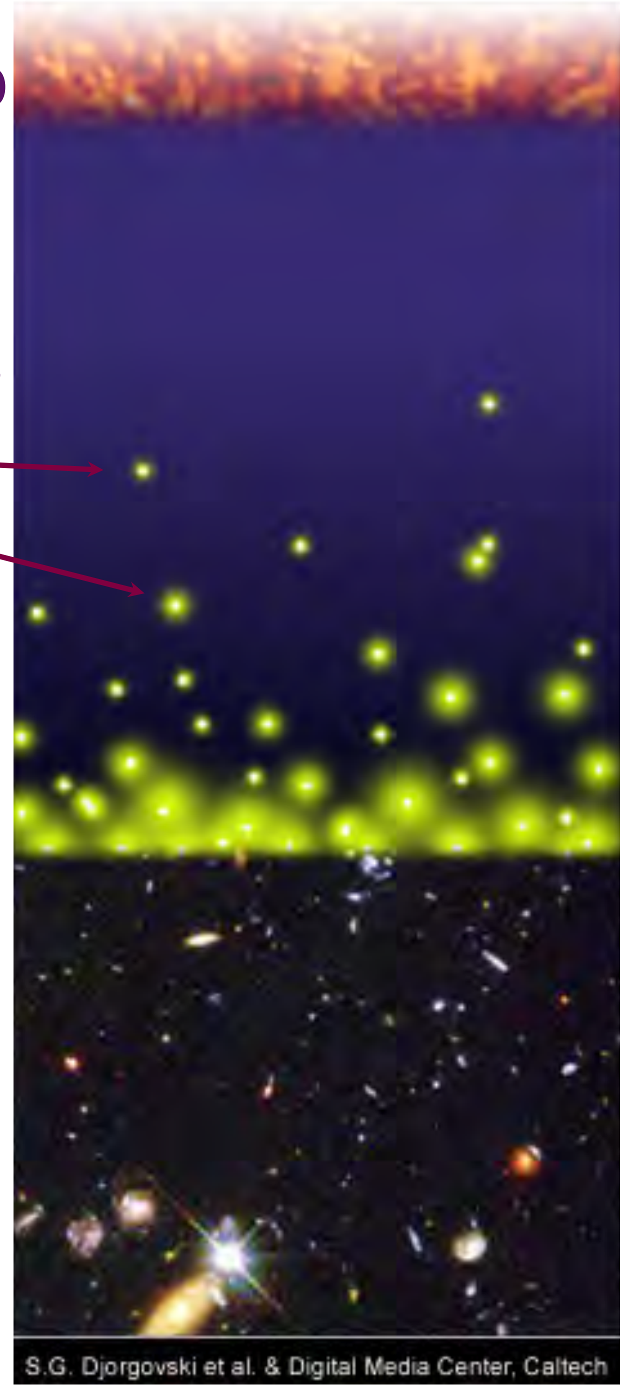


QSOs

z=1100 — Recombination

"Dark Ages"

z = ?



z=6 — Reionization

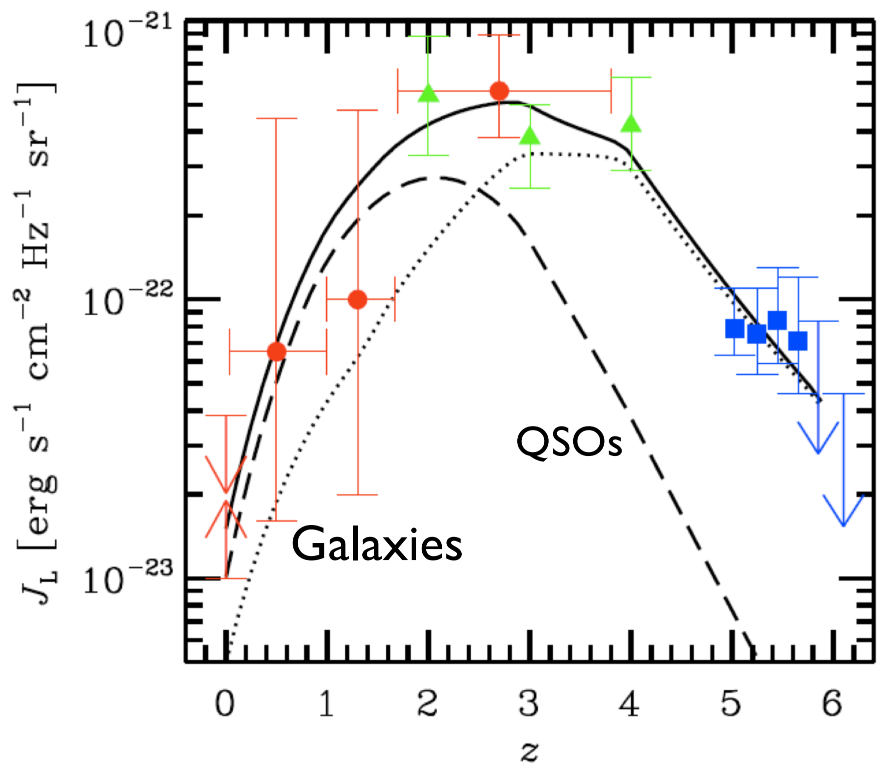
z=3 — He II Reionization

z=0 — Present Day

QSO Contribution to Ionizing Background

- QSOs are prodigious sources of ionizing radiation
  - Lyman Continuum (LC) λ<912 AA
- Dominate ionizing flux at z<2
- Steep decline in number of QSOs at z>3
- Star formation probably caused reionization

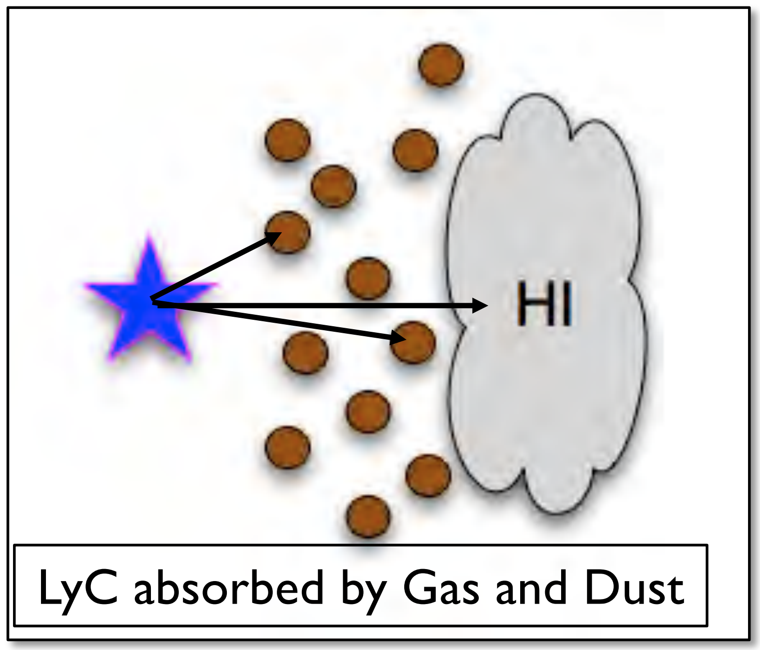
Data points are measurements from Lyman-α forest.



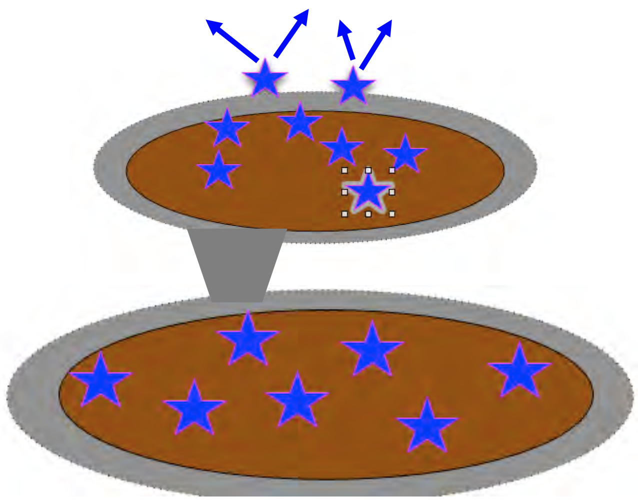
- - - QSO contribution from LF
— Total ionizing bg from
  Lya forest opacity
  QSO proximity effect
········· Inferred stellar contribution

Inoue et al. (2006)

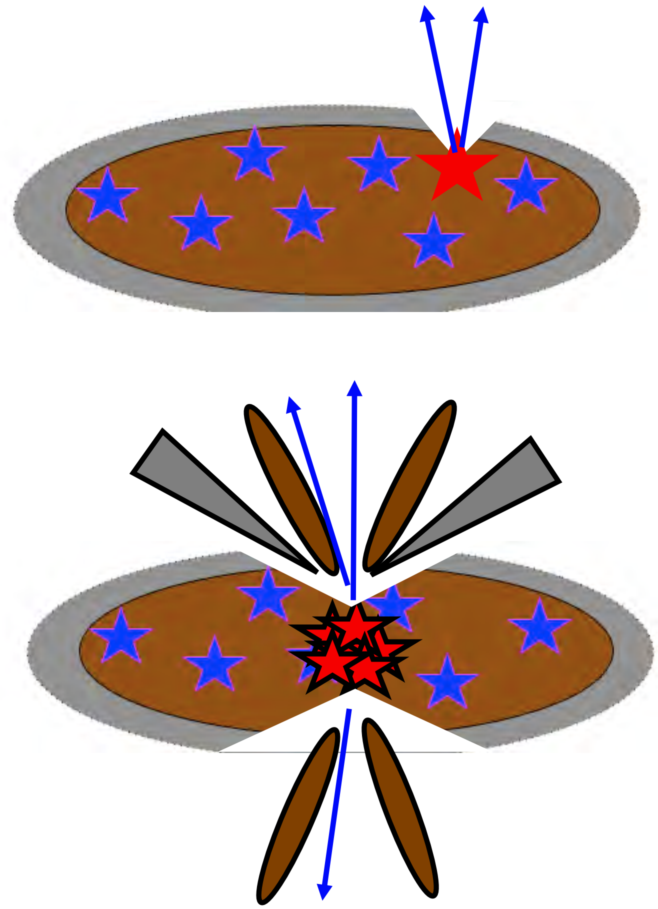
Galaxies contain lots of dust and HI: how can LC escape?



Galaxies contain lots of dust and HI: how can LC escape?

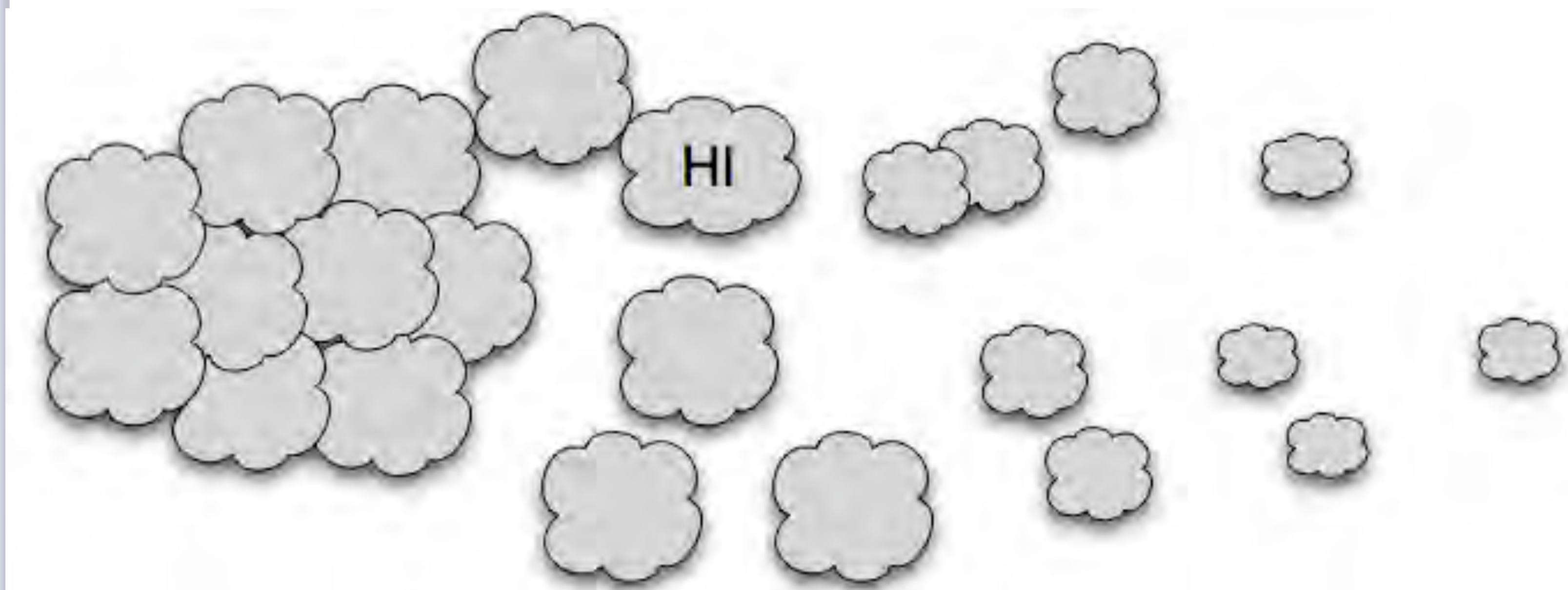


Interactions



Feedback

LyC absorbed by intervening HI

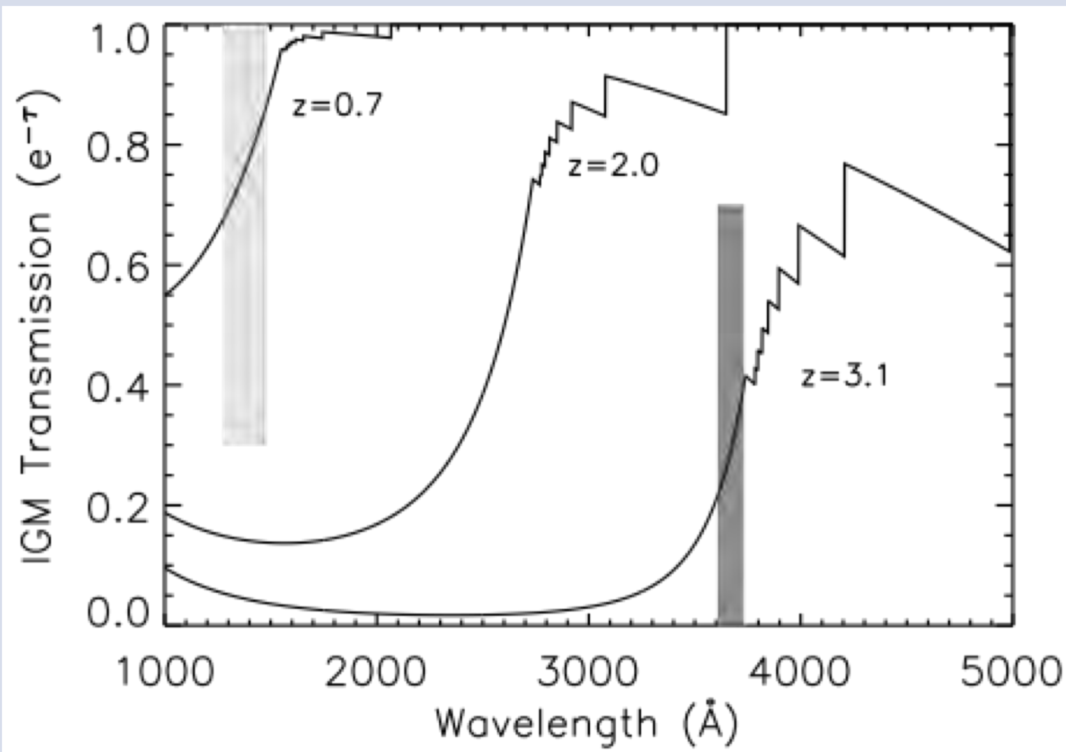


Z=6 Z=3 Z=1.3 Z=0.7

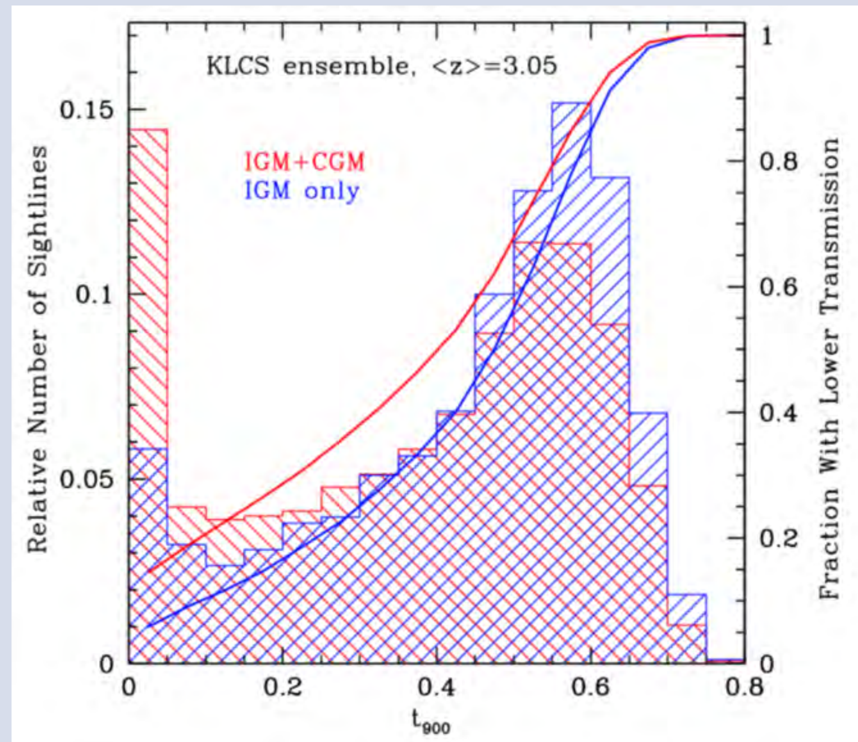
“Lyman Break Galaxies (LBGs)”

IGM Transmission

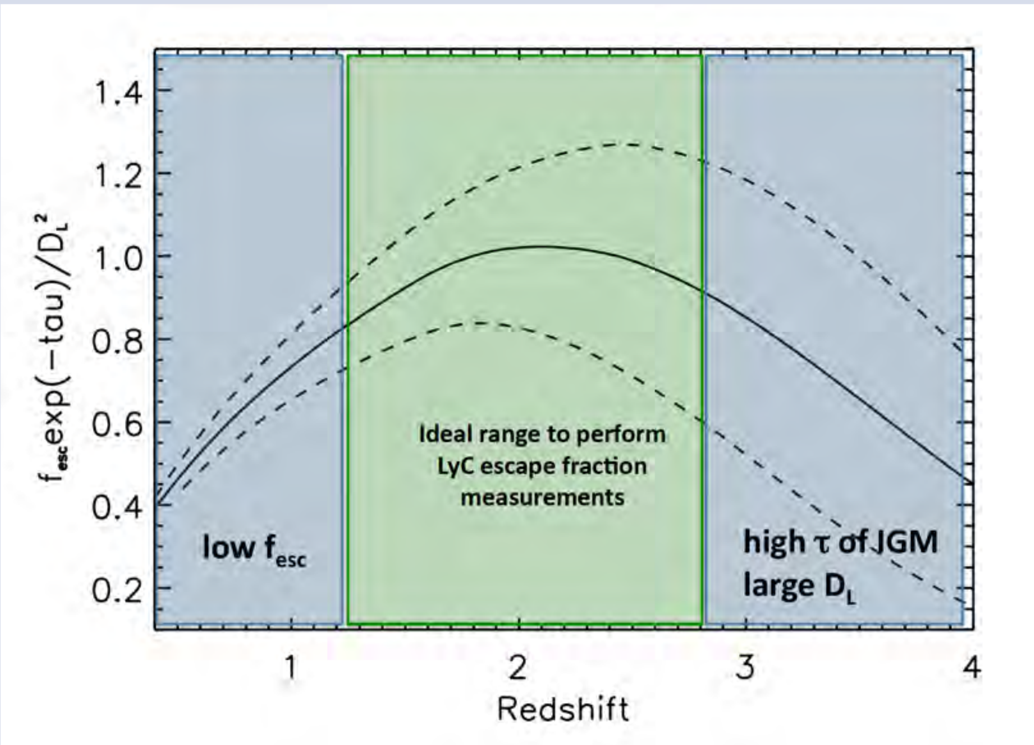
Madau (1995)



Steidel et al. (2018)



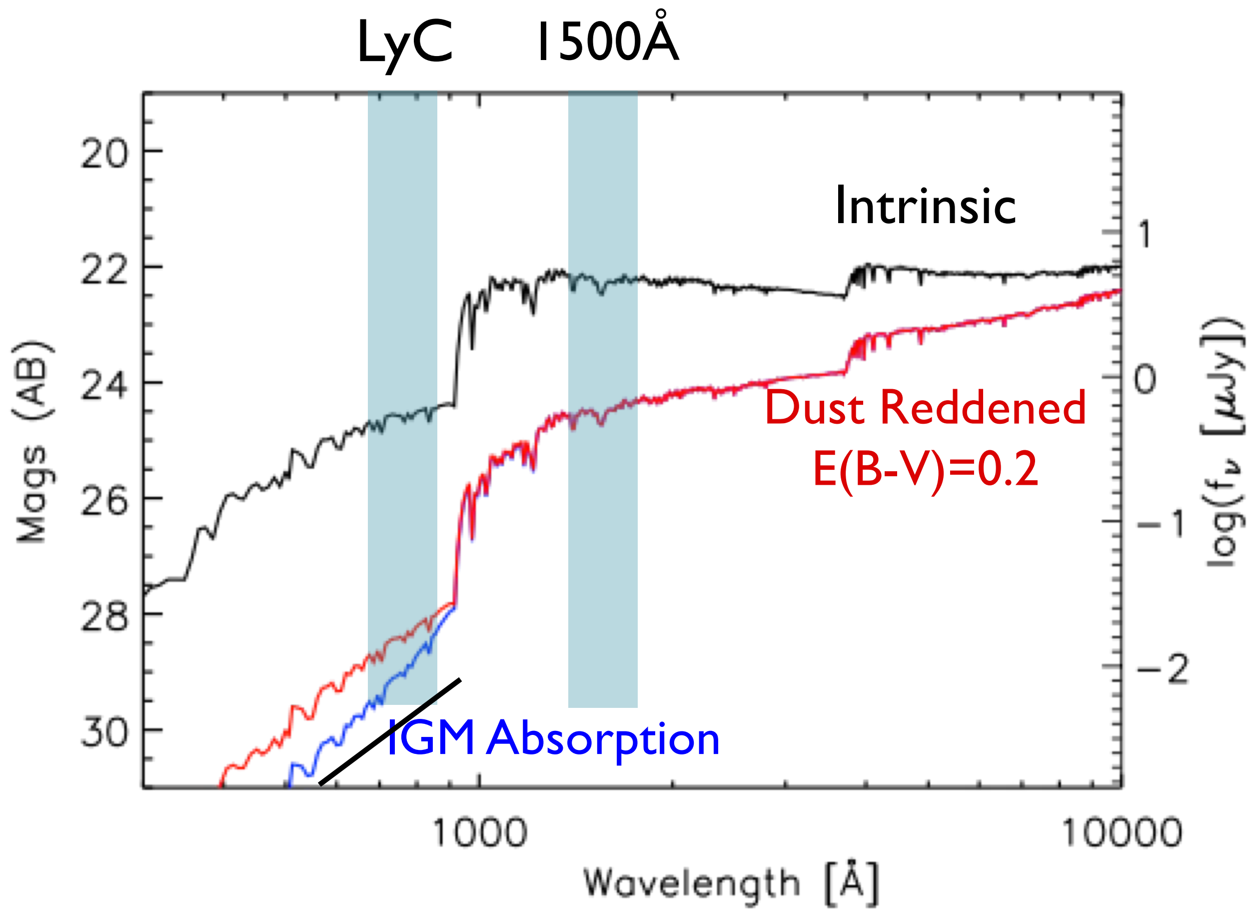
Measuring LyC at z=1-2



1. Can't measure f_{esc} at z~6 because of intervening IGM (very challenging at z>3.5)
2. Statistical problem with absorbers at z>2 (Steidel et al. 2018)
3. Lower z LC-emitters are easier to study
4. Evolution of typical $f_{esc}(z)$ means strong emitters are rare at z~0
5. At z<2, LC needs to be observed from space

The escape fraction: f_{esc}

	$\Delta(f_{\nu,1500}/f_{\nu,750})$
Intrinsic	3-10
Dust	~2
IGM	2
Total	20-50 3-4 mags



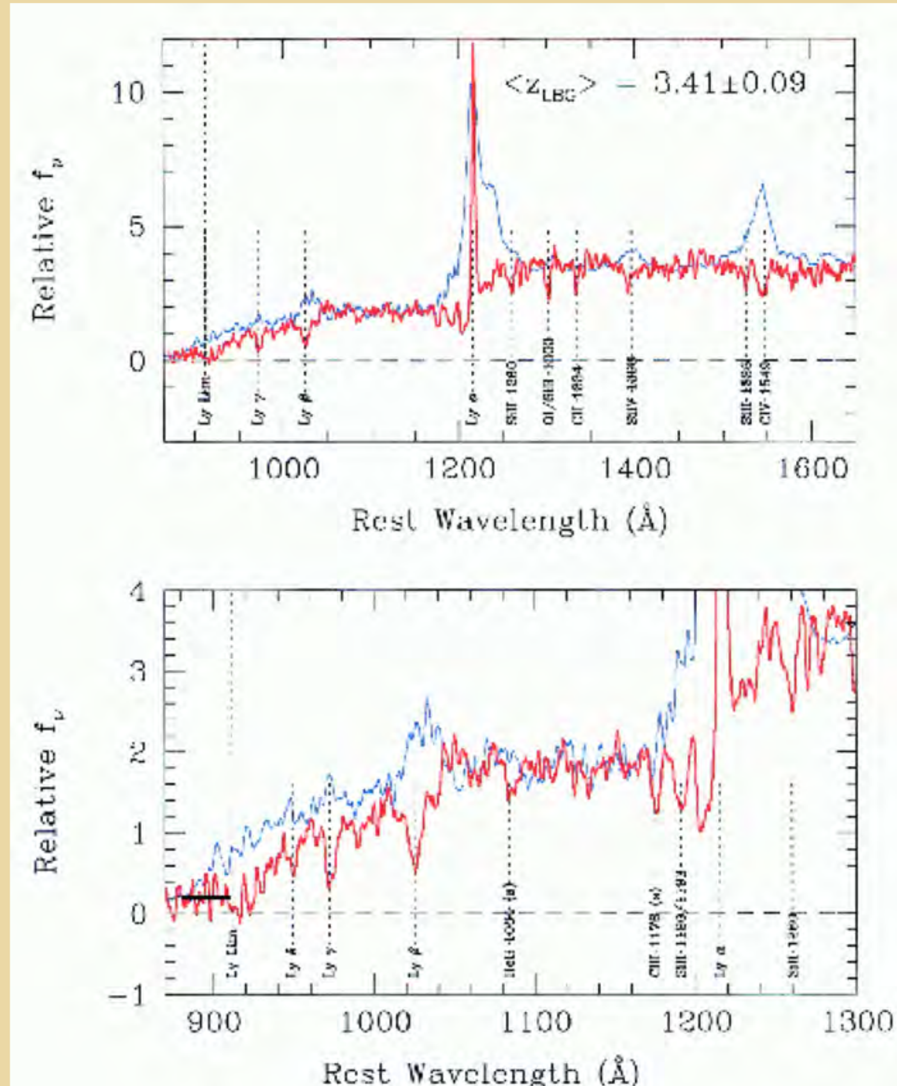
1. f_{esc} = fraction of lyman continuum photons which escape galaxy.
2. $f_{esc,rel}$ = fraction of lyman continuum photons which escape galaxy divided by fraction of 1500Å photons escaping galaxy.


10 years of searching for the Lyman Continuum

Early results:
z~3 Lyman Break Galaxies
Keck spectroscopy

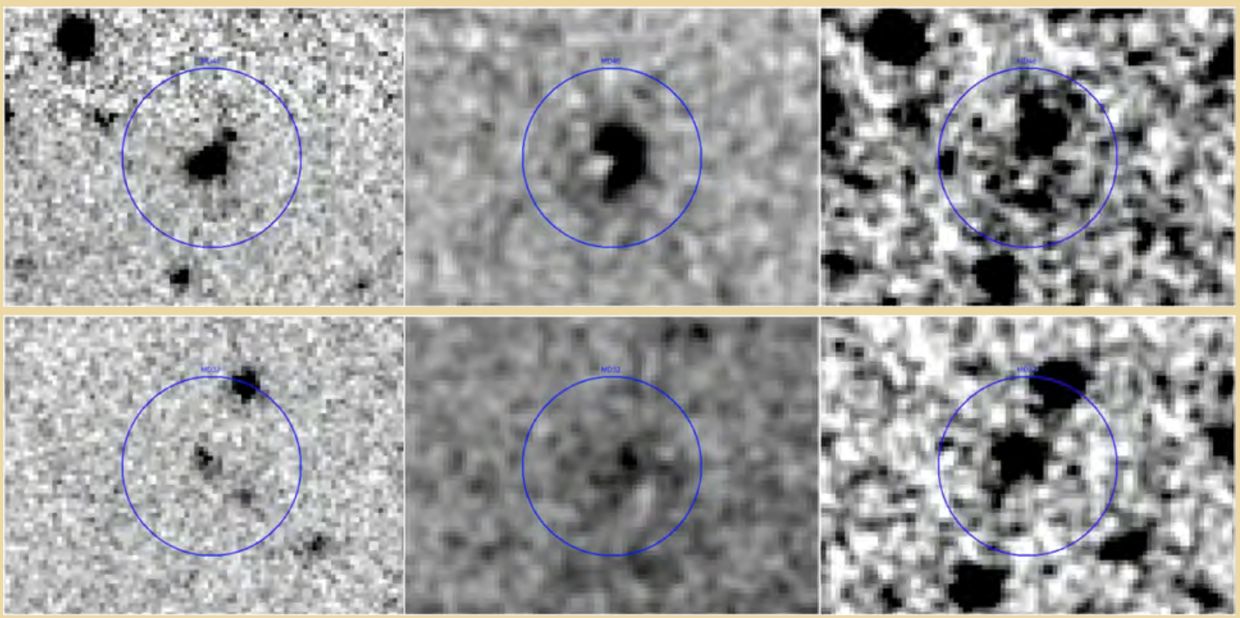
- Lyman Break Galaxies (LBGs): UV-selected, star forming galaxies at z>3
- Steidel et al. (2001) stack of 29 LBG spectra at <z>~3.4
  - Biased toward blue LBGs
  - Significant Ly-alpha emission
- Shapley et al. (2006) z~3 LBGs
  - 2/14 have high $f_{esc,rel}$ ~ 1
- Bogosavljevic et al. (2009) have many more spectra (100+), with ~10% fesc detected
- Shockingly high $f_{esc,rel}$ ~ 1

Steidel et al. (2001)

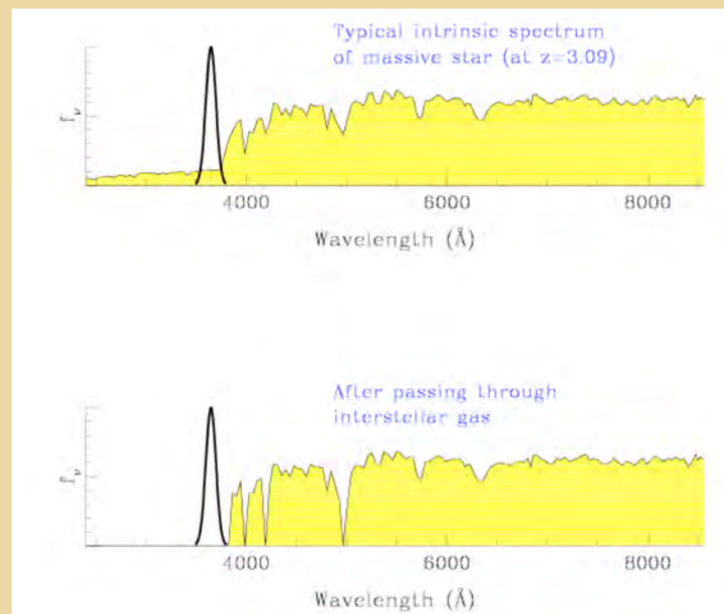


Early Results: Narrow-Band Imaging at Keck and Subaru telescopes

- Iwata et al. (2008), Shapley et al. (2009), Nestor et al.(2011, 2013)
- NB imaging of SSA22 field, many NB detections
- Possible spatial offset of LC from FUV
- Very high f_{esc} in Ly-a emitters

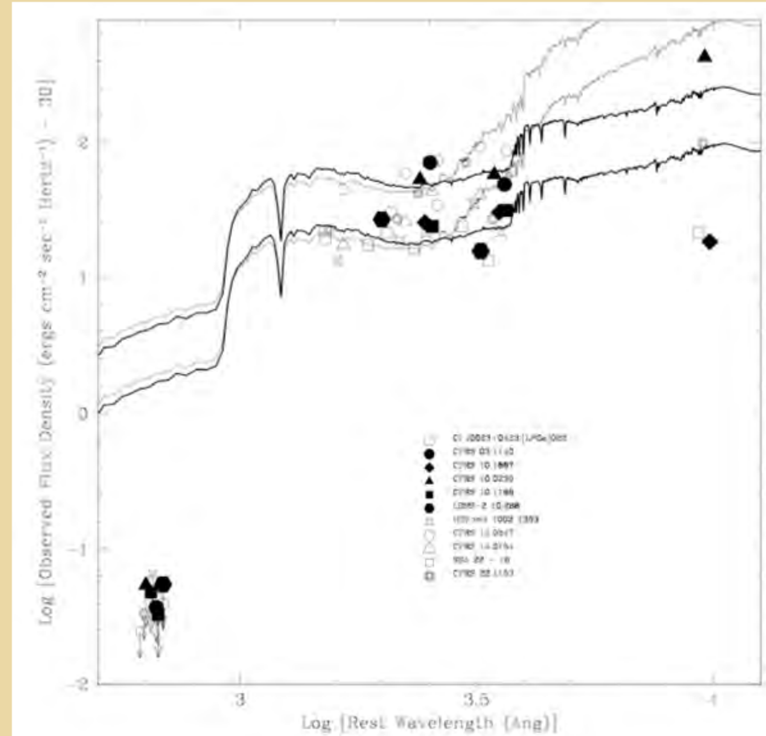


R-band Ly-a NB LC NB

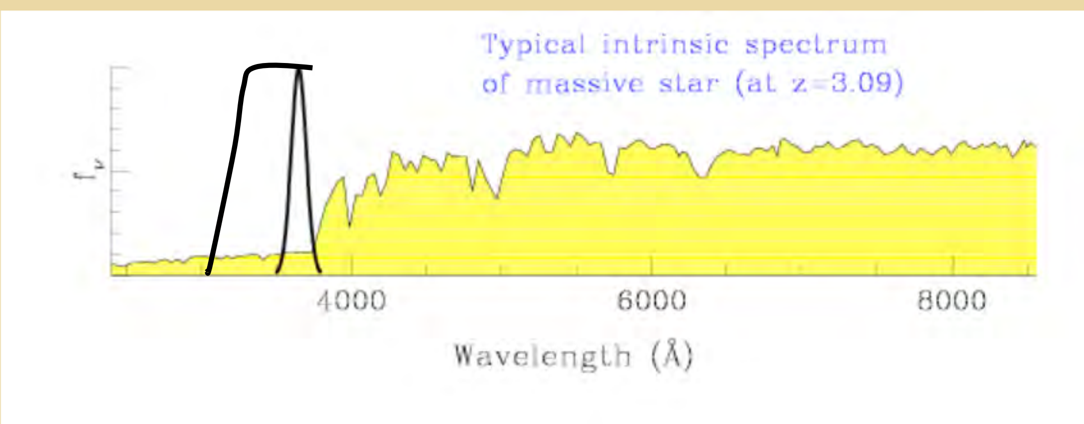


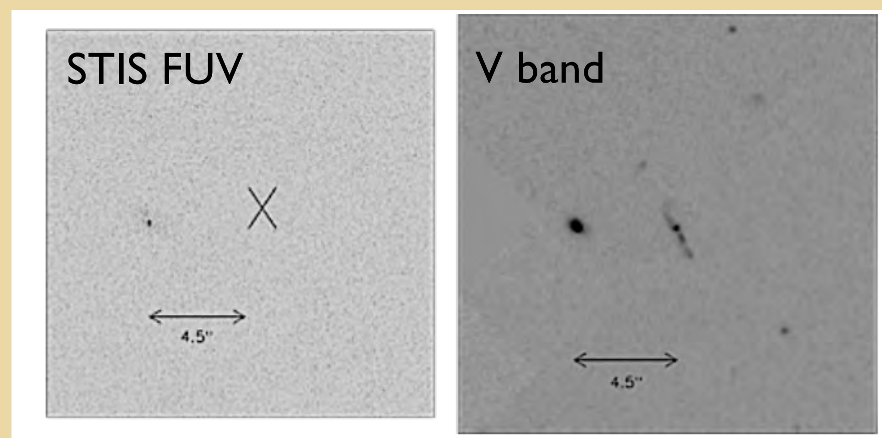
Early results: FUV Imaging from space (z~1.3)

Malkan, Webb, & Konopacky (2003)



- HST/STIS imaging of λ~1500Å (λ_{rest} ~ 700 Å)
- 11 Starbursts at z>1.1
- No Detections
- Similar limits obtained by stacking GALEX data (Cowie et al. 2008)

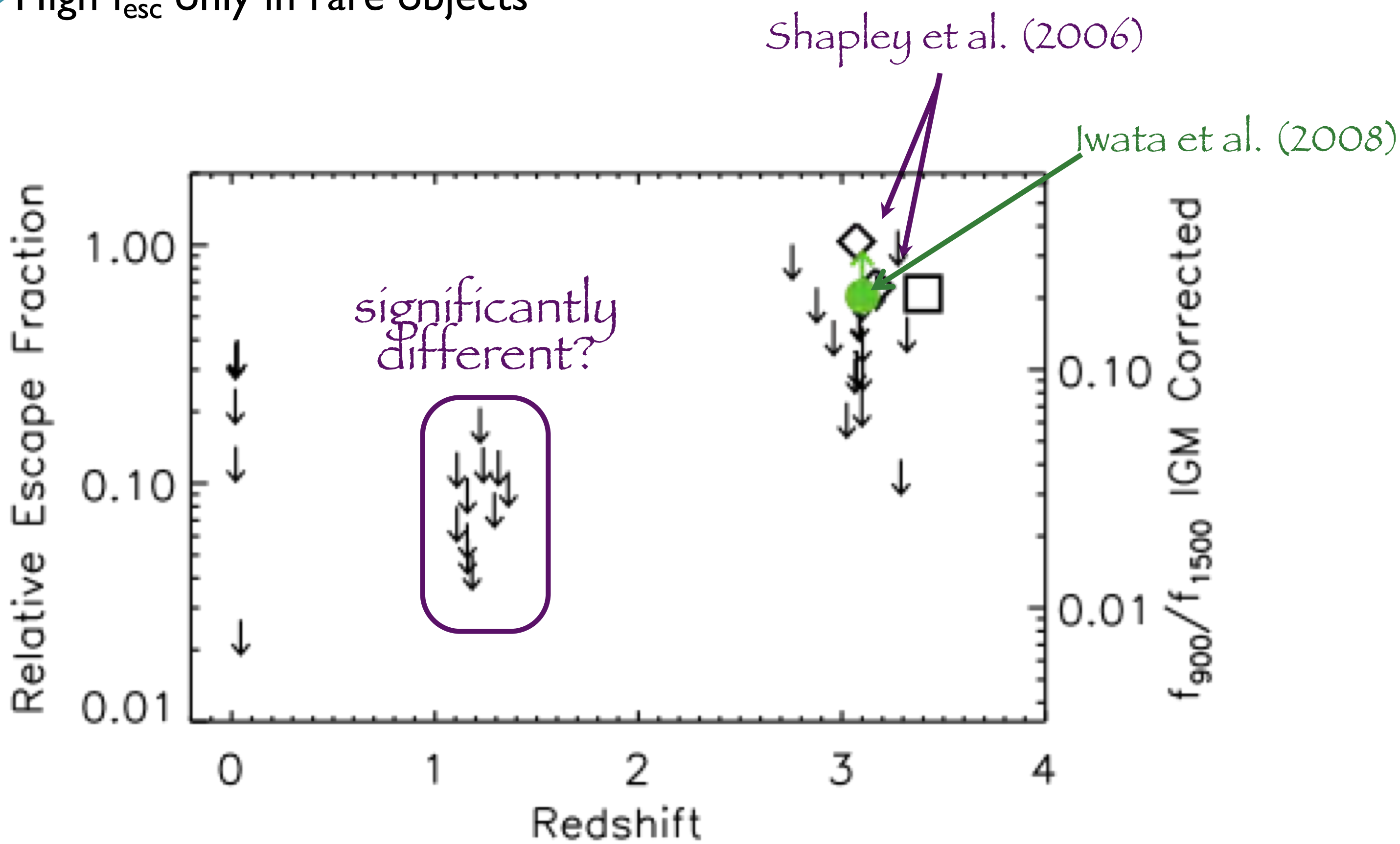




Summary of Previous f_{esc} Measurements when we started

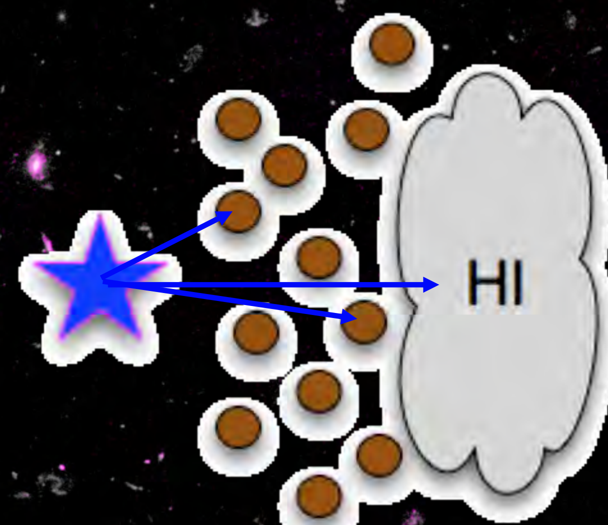
Spectroscopy at z~0, z~3, Imaging at z~1 with HST

⇒ High f_{esc} only in rare objects



Deepest UV observations with HST

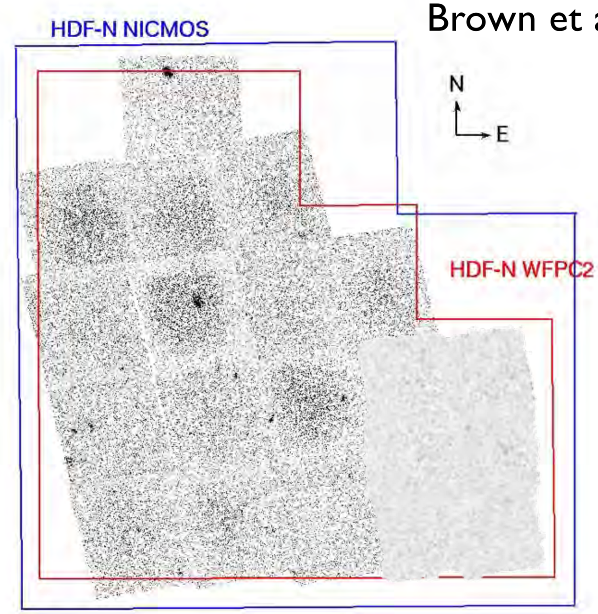
- Understanding the escape of Lyman continuum photons from galaxies
- 350 orbits in 6 programs (Teplitz & Siana)



LyC absorbed by Gas and Dust

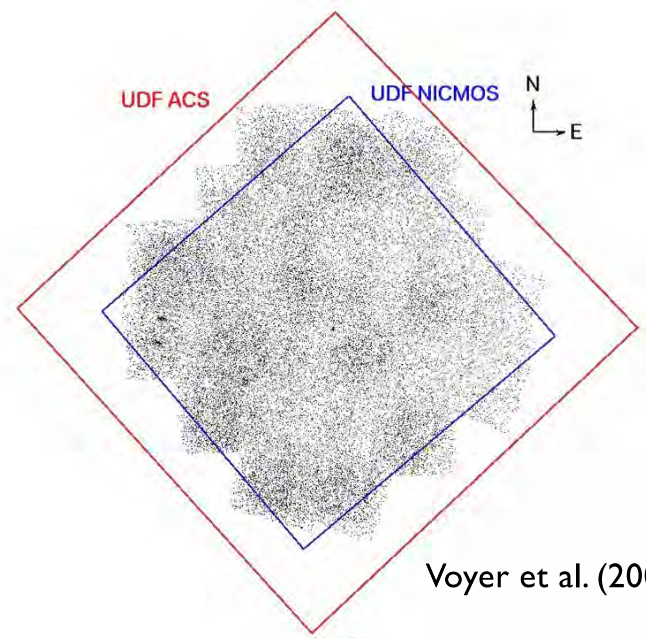
FUV Imaging of the Hubble Deep Fields

Teplitz et al. (2006)
Gardner, et al. (2000)
Brown et al. (2000)



- HDF and UDF
- ACS/SBC (1600 AA)
- 3 sigma AB=27 to 29

- $f_{es,c,rel}$ limits <0.5 to <0.1 in individual objects
- Stack limit, $f_{esc,rel}$ < 0.08
- Siana et al. (2007)



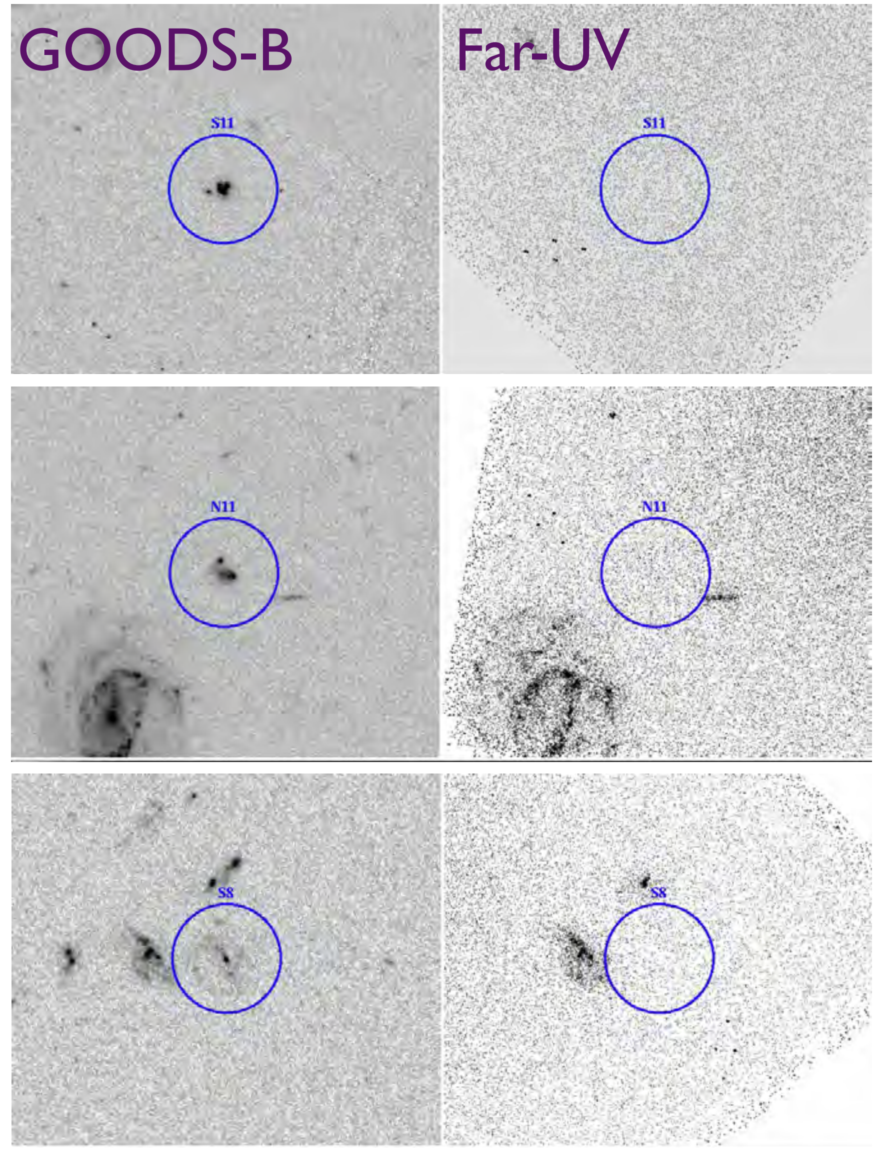
Voyer et al. (2009, 2011)

New Survey: brighter sources, deeper images

- Imaging of 14 blue galaxies at z~1.3 as luminous as LBGs
- 5 orbits/target; AB>29, 3σ

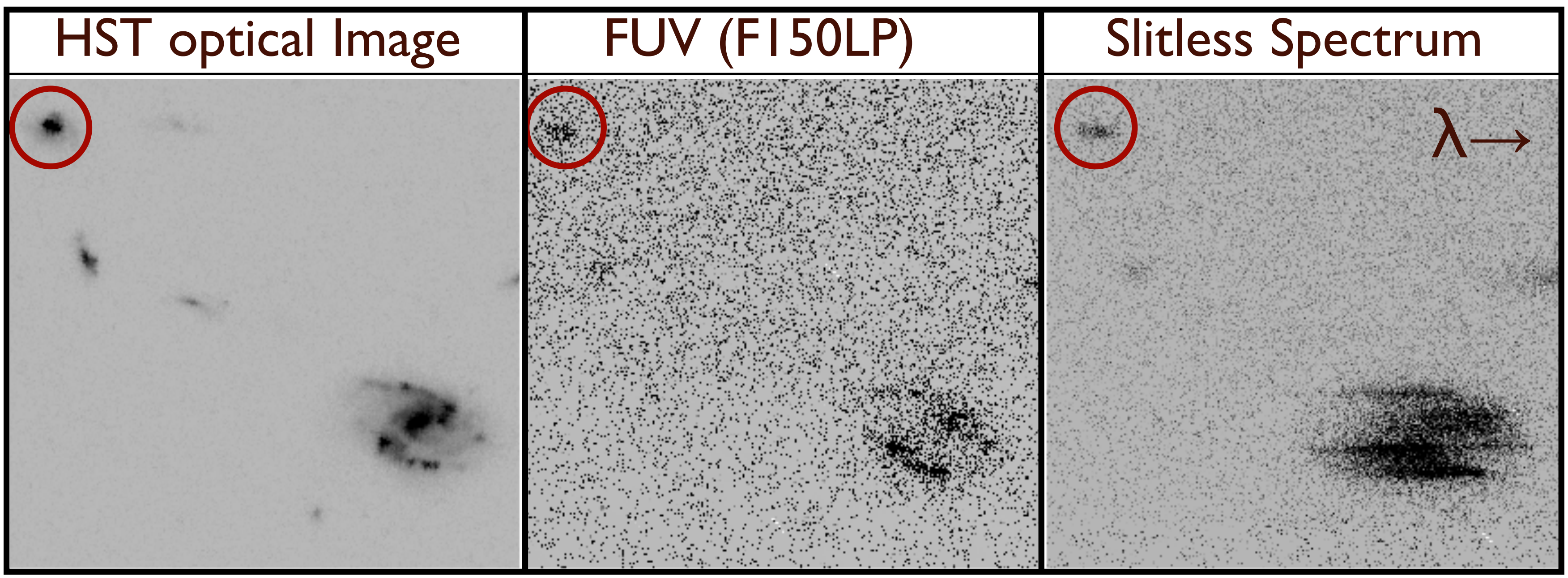
⇒deepest f_{esc} survey to at z~1

- Detect $f_{esc,rel}$ down to ~3%,
- But <u>no detections</u>! (0/15)
- new stack limit $f_{esc,rel}$ < 1.8%
- Siana et al. (2010)

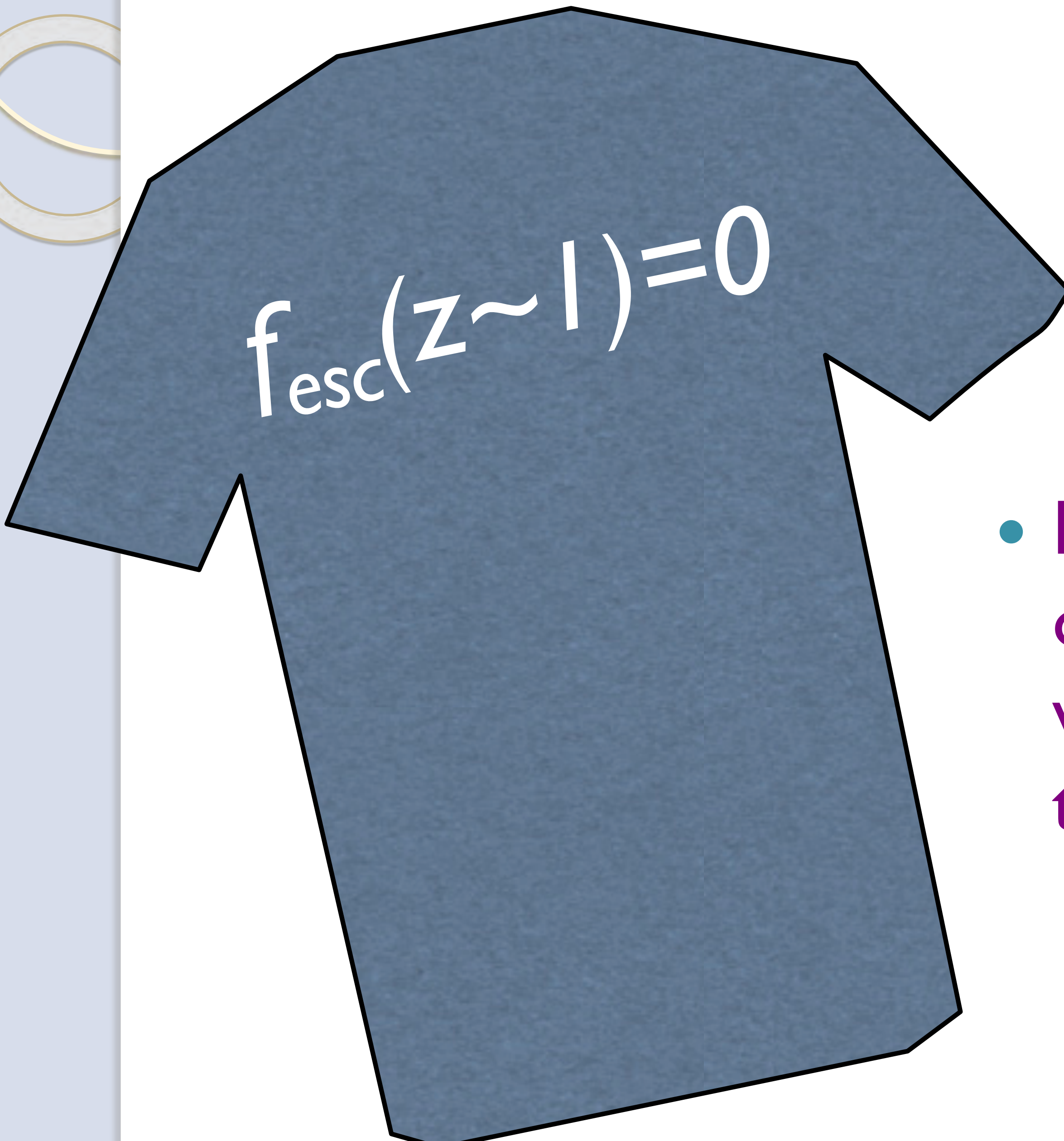


HST Far-UV Prism z=0.7 LBG Analogs

- 22 SBC prism spectra near 912AA
- Rare objects with high escape fractions ($f_{esc,rel}$ > 20%)?
- 115 orbits; No detections
- Bridge et al. (2010)

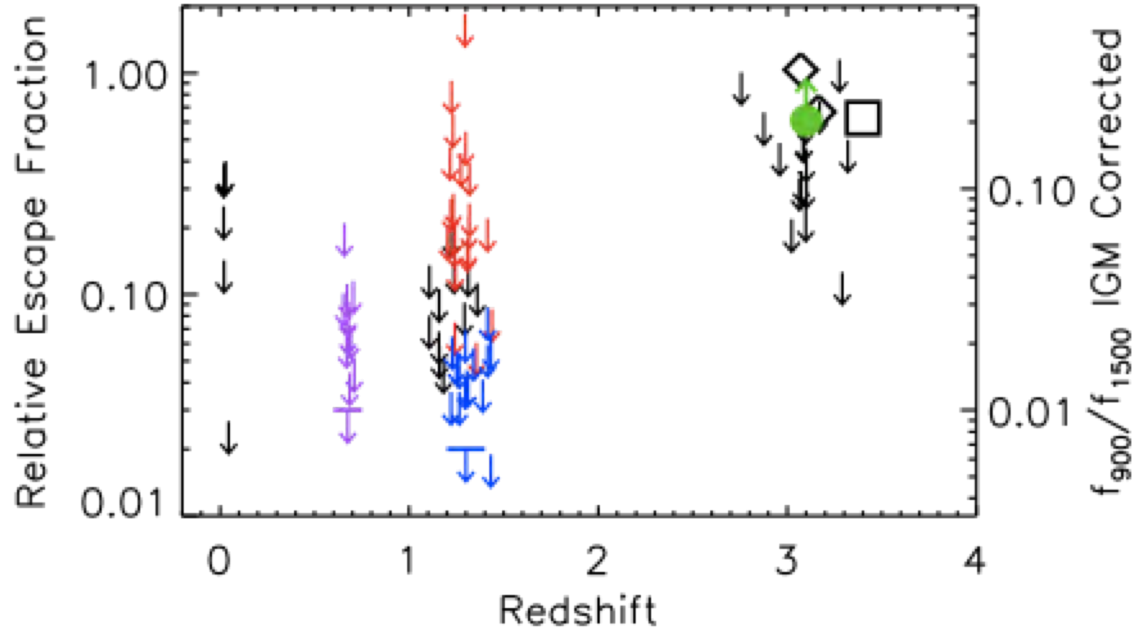


Summary of z~1 Results



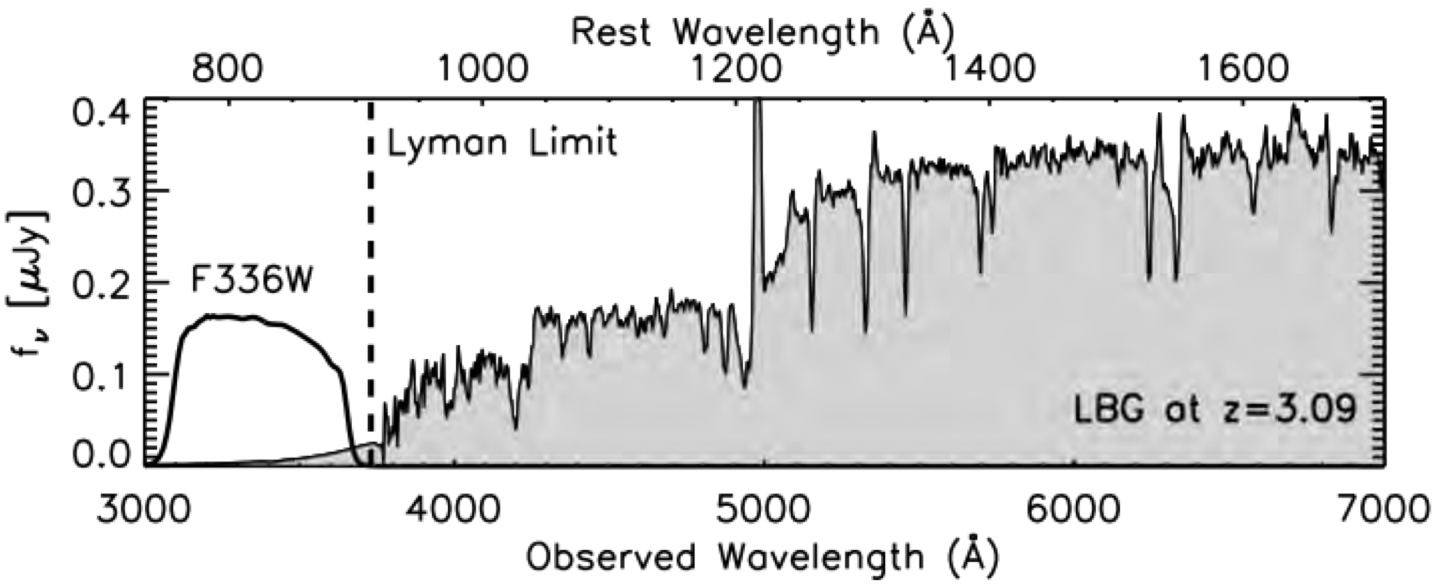
- HST gave me 300 orbits and all I got was this lousy tshirt….

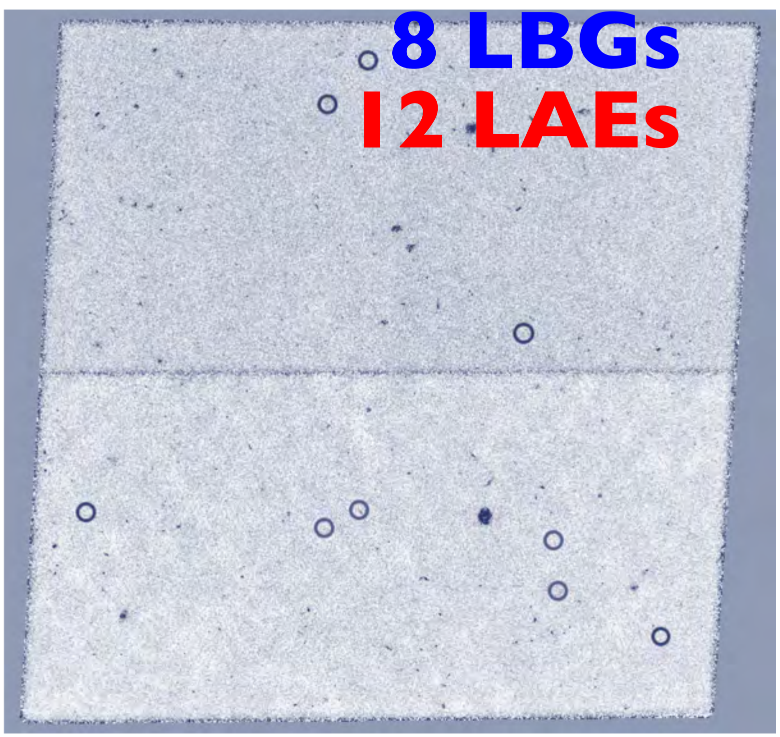
f_{esc} evolves with redshift



- High-z galaxy density suggests f_{esc}>20% to reionize the Universe
- Multiple detections of high f_esc at z~3
    - How does LyC escape in these galaxies?

Ultradeep Imaging of LyC at z~3.1

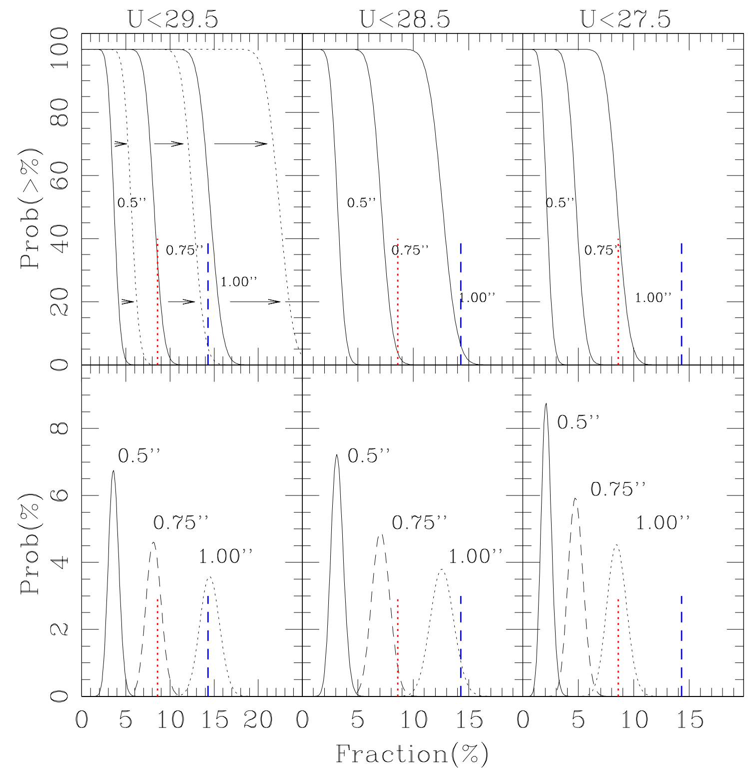




- Follow-up Keck NB detections (Shapley et al.)
- 32 Orbits - WFC3/UVIS F336W; 30.0 mag/arcsec^2 (1σ, AB)
  - Deepest U-band image ever!
- PI = Siana

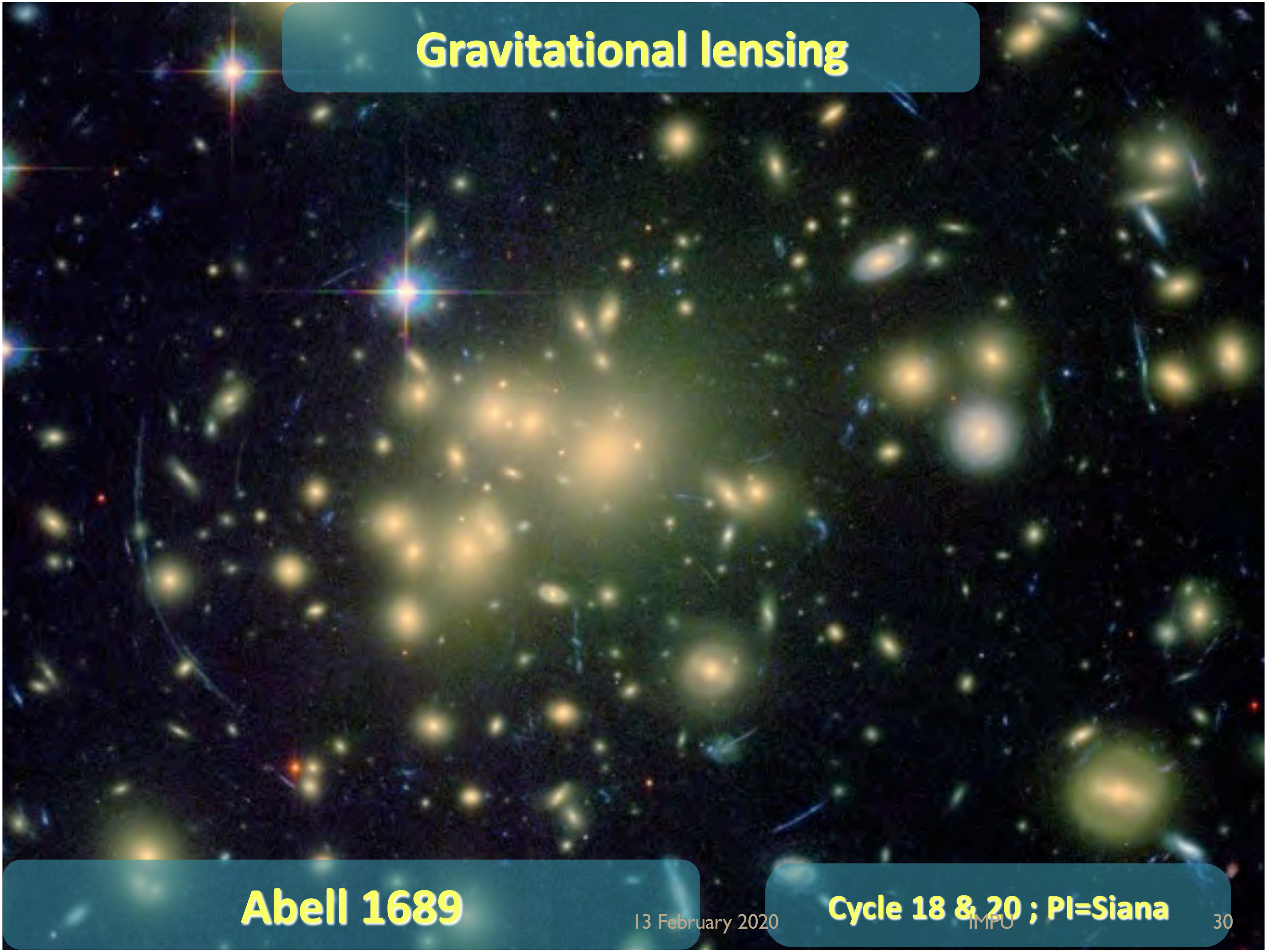
Lessons learned from Ultradeep Imaging

- We (Siana et al. 2015) resolve F336W from galaxies identified as candidate LyC emitters in Keck NB imaging
- Yielded more accurate slit position for spectra to identify interlopers
  - Keck spectroscopy rules out all 6 detections!
  - In a separate study, Mostardi et al. (2015) confirm 1/16 candidates
- Conclusion: LyC rarely comes from these bright LBGs
- Warning: HST resolution needed to confirm ground-based candidates!



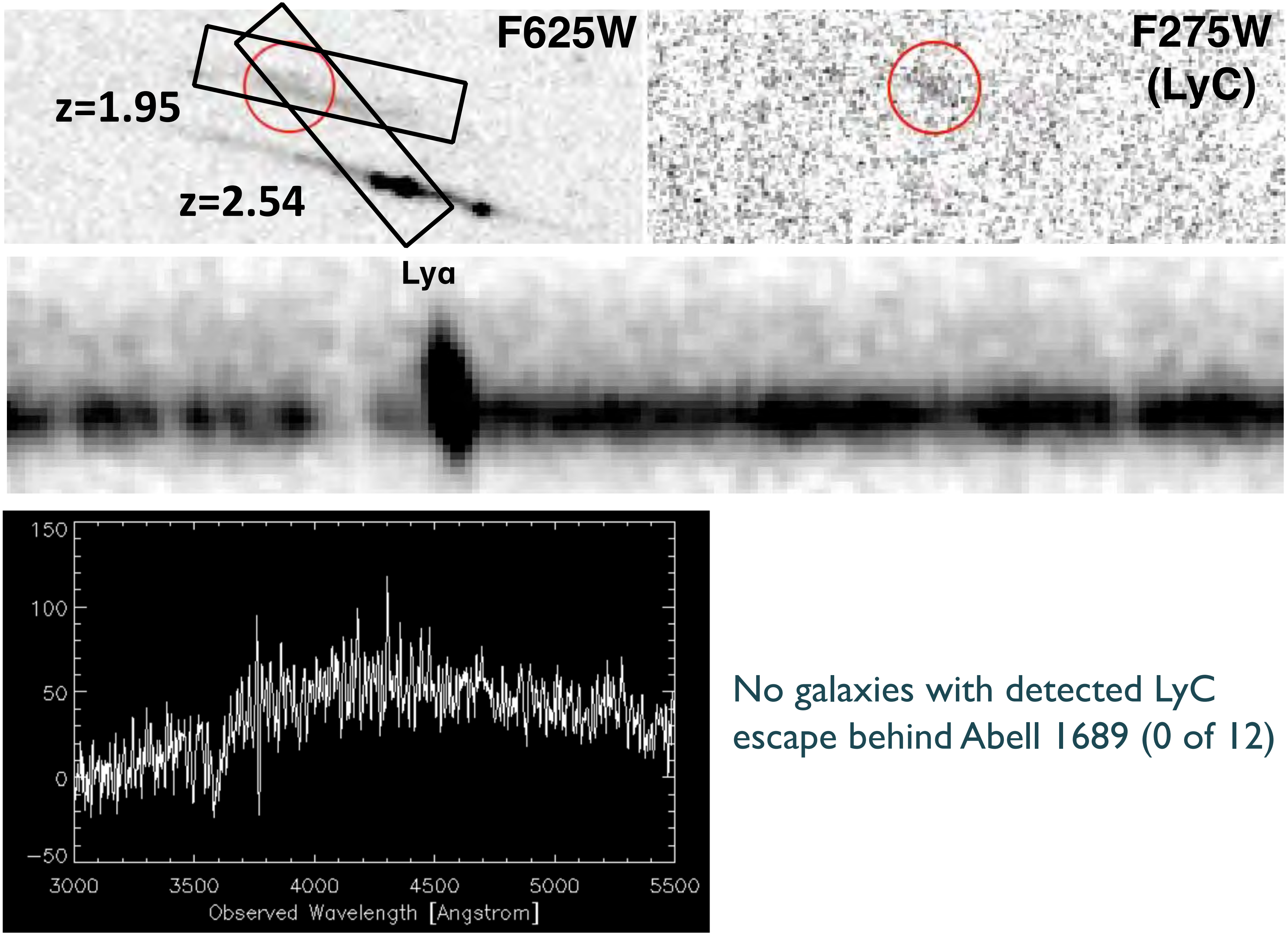
Vanzella et al. (2010) show a significant probability of low-z contamination of z~3 LyC detections: analysis of the GOODS-S field predicting the probability of contamination (y-axis) as a function of the fraction of the same (x-axis)

Gravitational lensing



Abell 1689

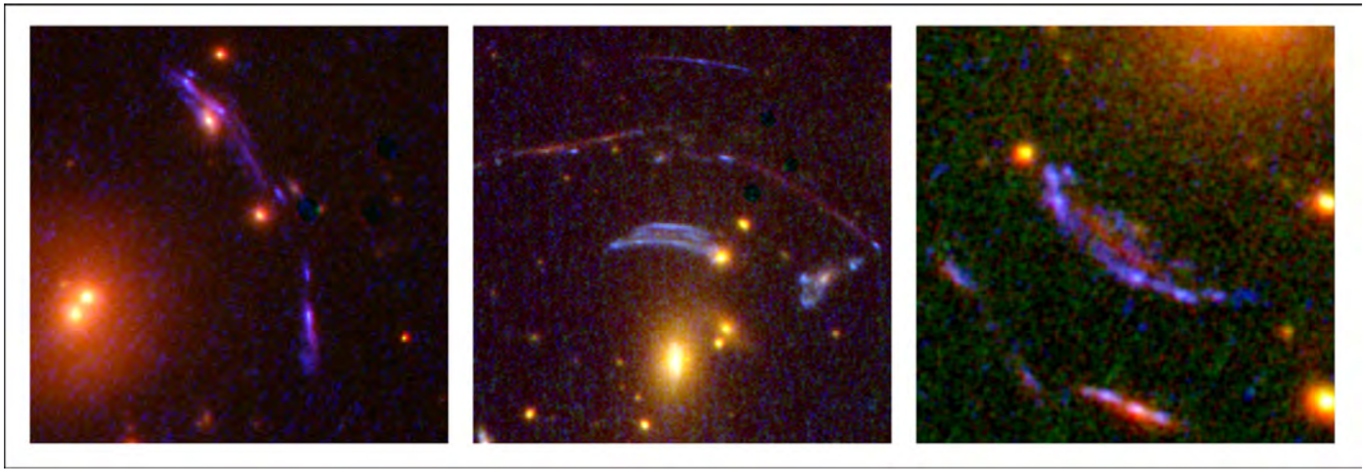
Cycle 18 & 20 ; PI=Siana



No galaxies with detected LyC escape behind Abell 1689 (0 of 12)

Strongly Lensed Low-Luminosity Galaxies at redshifts z=1.3-3

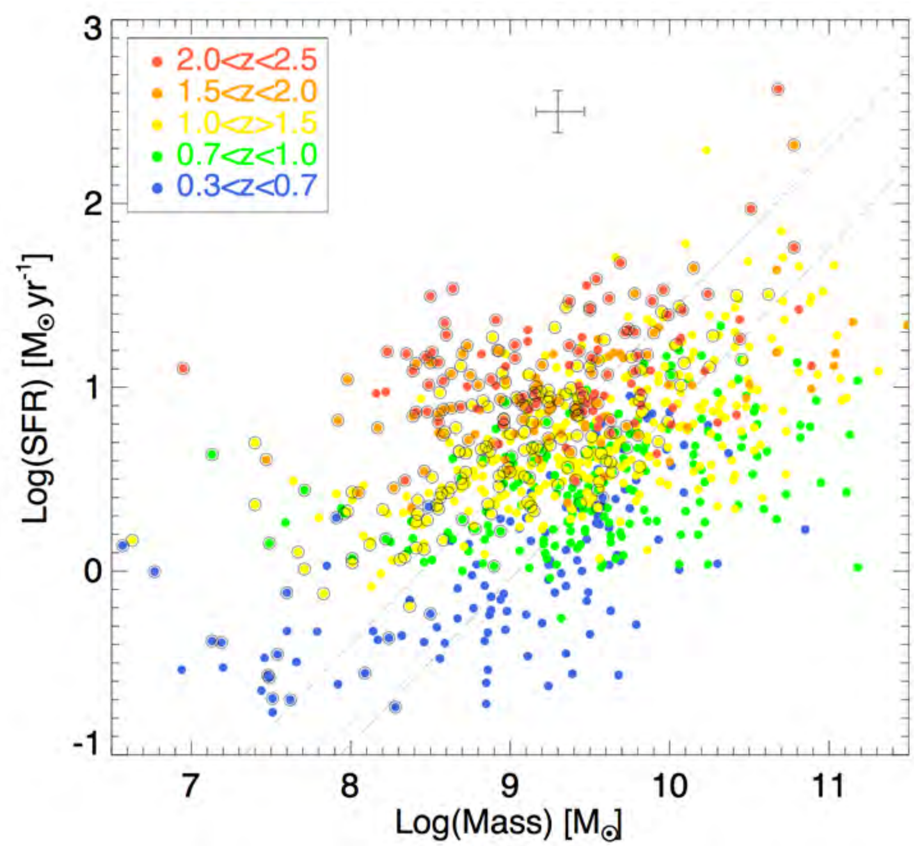
Riley, et al. (2020)



- Lensed sources at 1.3<z<3.1, observed with ACS/SBC F150LP and WFC3 UVIS F390W
- No detections (f_{esc} < 5%) from 7 sources

Targeting high-EW sources at z~1.3 with HST

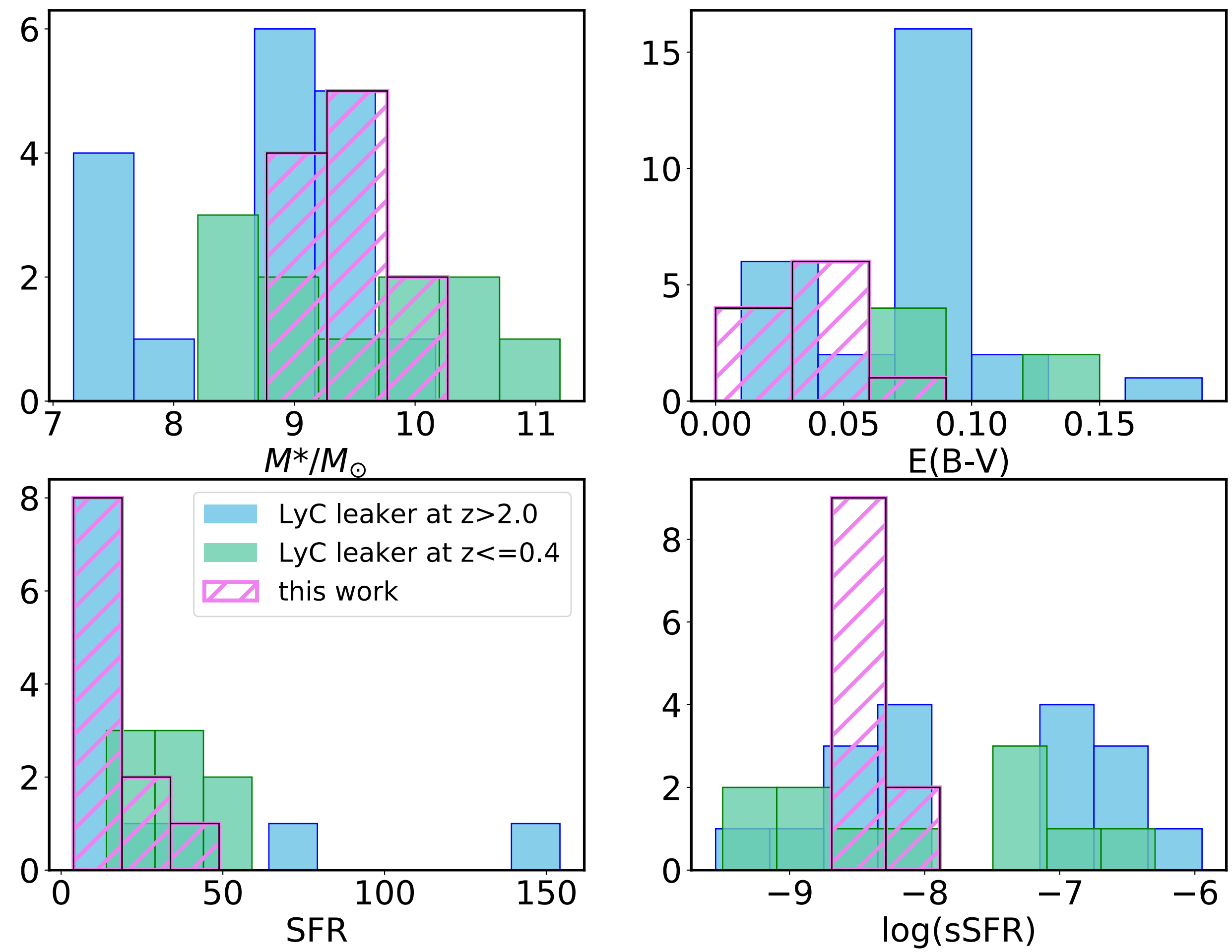
- Cycle 23 program
- 8 targets, z~1.3, ACS/SBC imaging
- Selected from 3D-HST to have high-EW
- Would detect fesc in individual sources
- No detections



Atek et al. 2014; ELGs in 3DHST+WISPs; high EW (>200 AA) indicated by black circles

Comparison with other samples

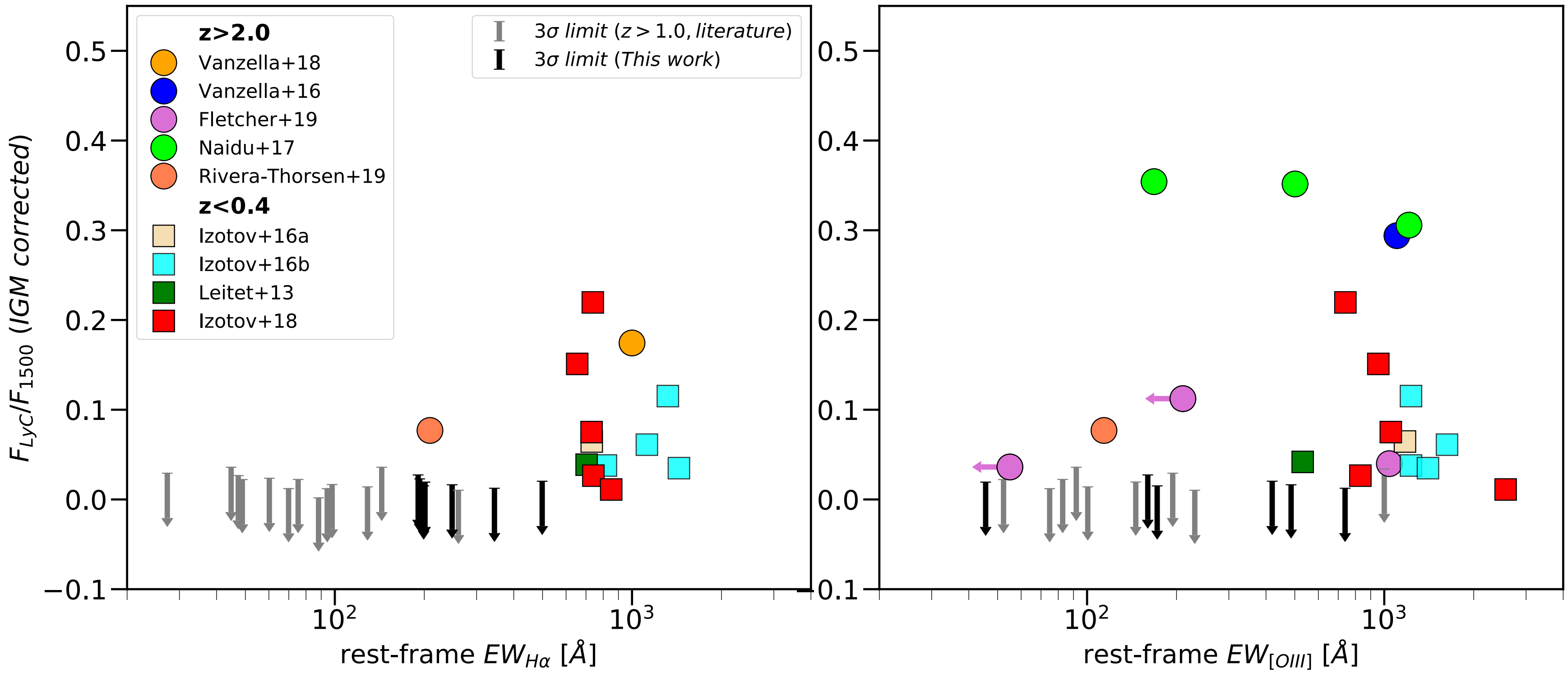
Alavi et al. (2020)



Comparison with other surveys

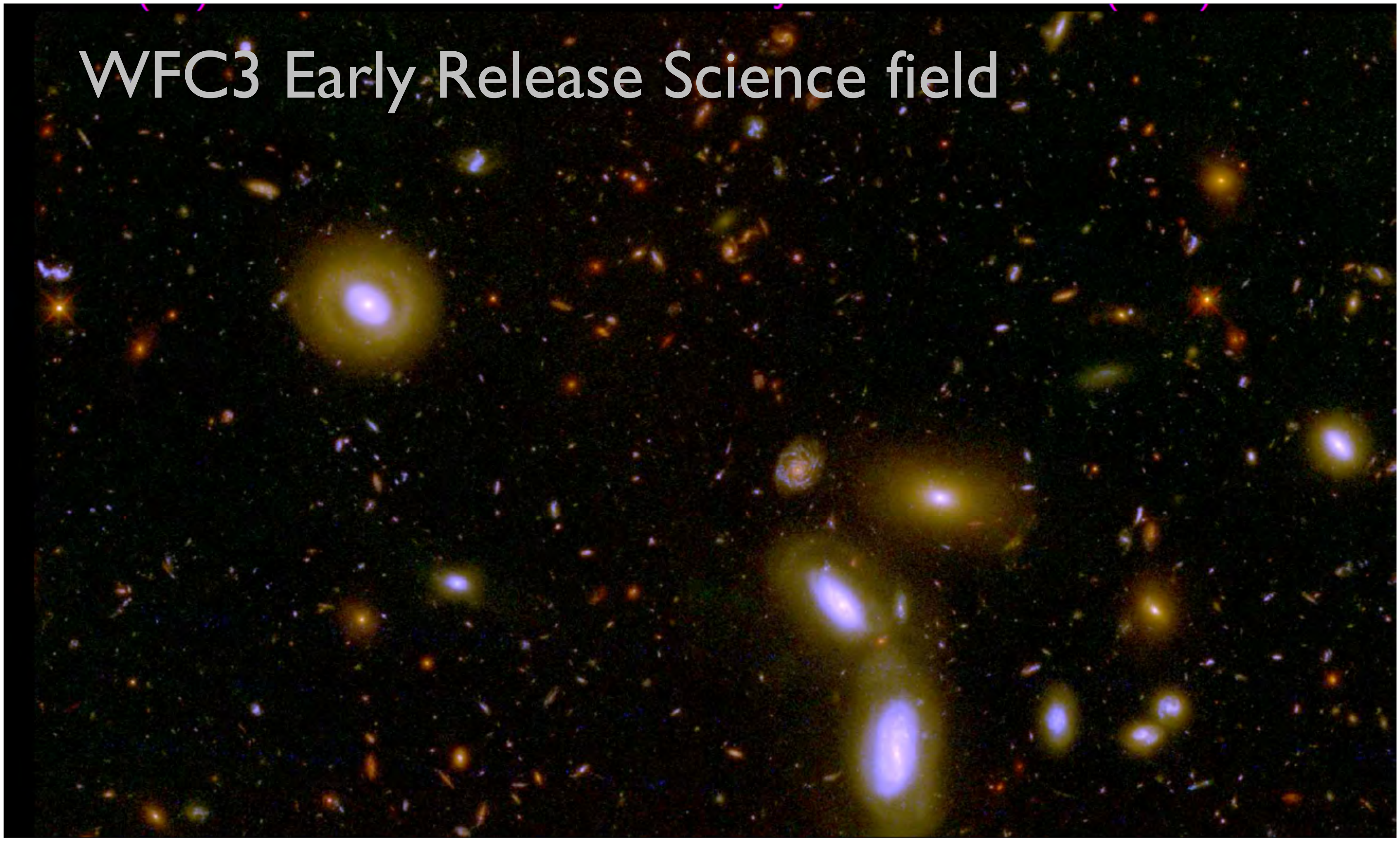
Non-detections PROBABLY span the same range of moderate Hα EW values as some of the LyC leakers

Non-detections span the same range of OIII EW as LyC leakers

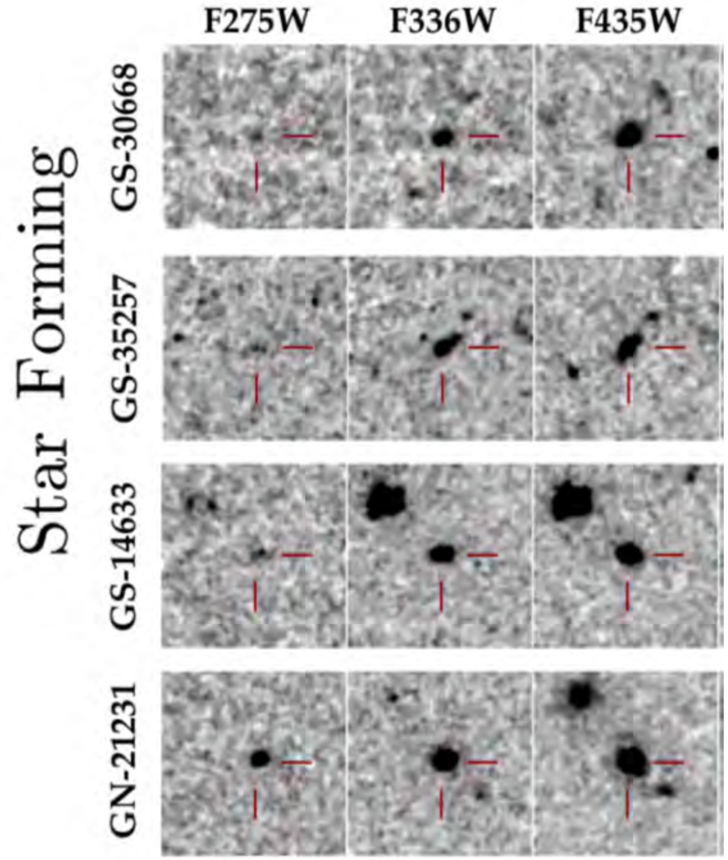


Hα EW **[OIII] EW**

HST results by other groups

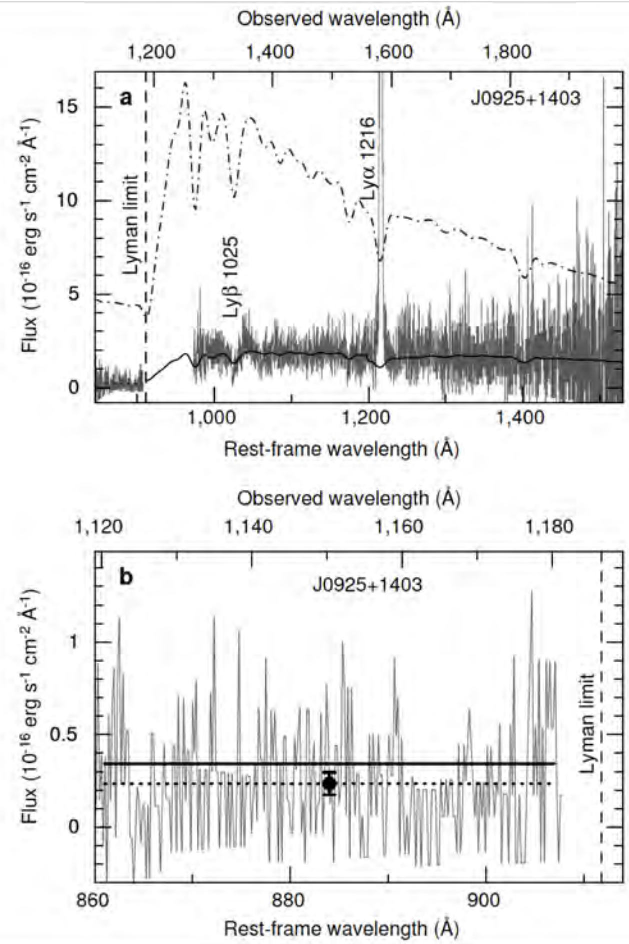


Detections of Individual Sources



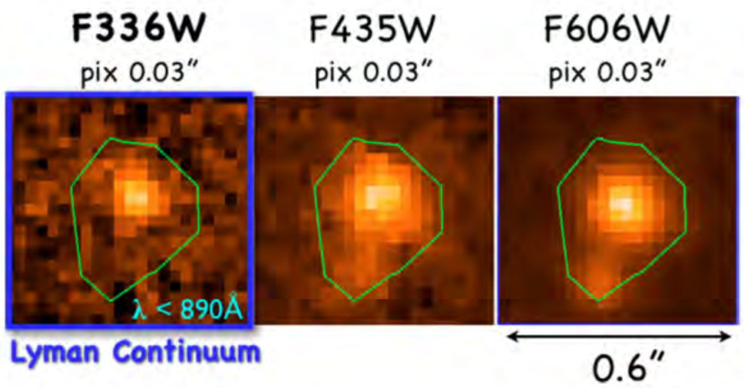
- Naidu et al. (2017)
- 4 non-AGN candidates at z~2.4 in F275W from HDUV
- High fesc (~60%)

z~0.3-0.4 (Izotov et al. 2016,2018)

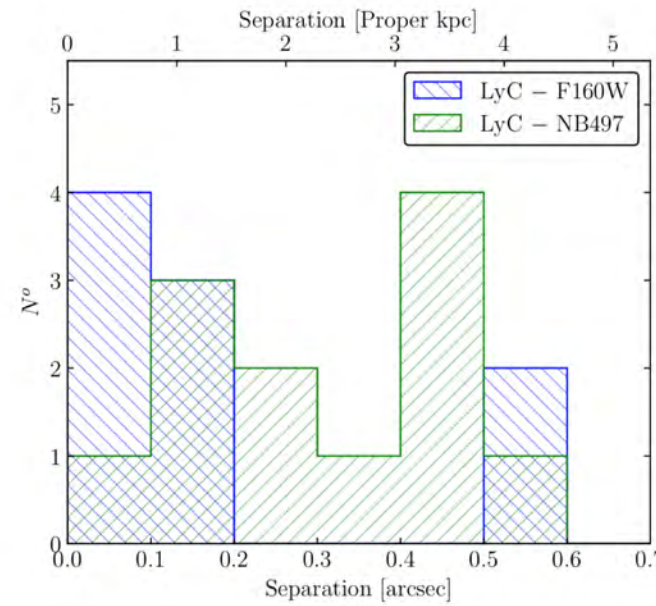


- COS spectrum of "green pea"-like galaxies
- Range of f_{esc} (few % up to 70%

Detections of Individual Sources at z>3



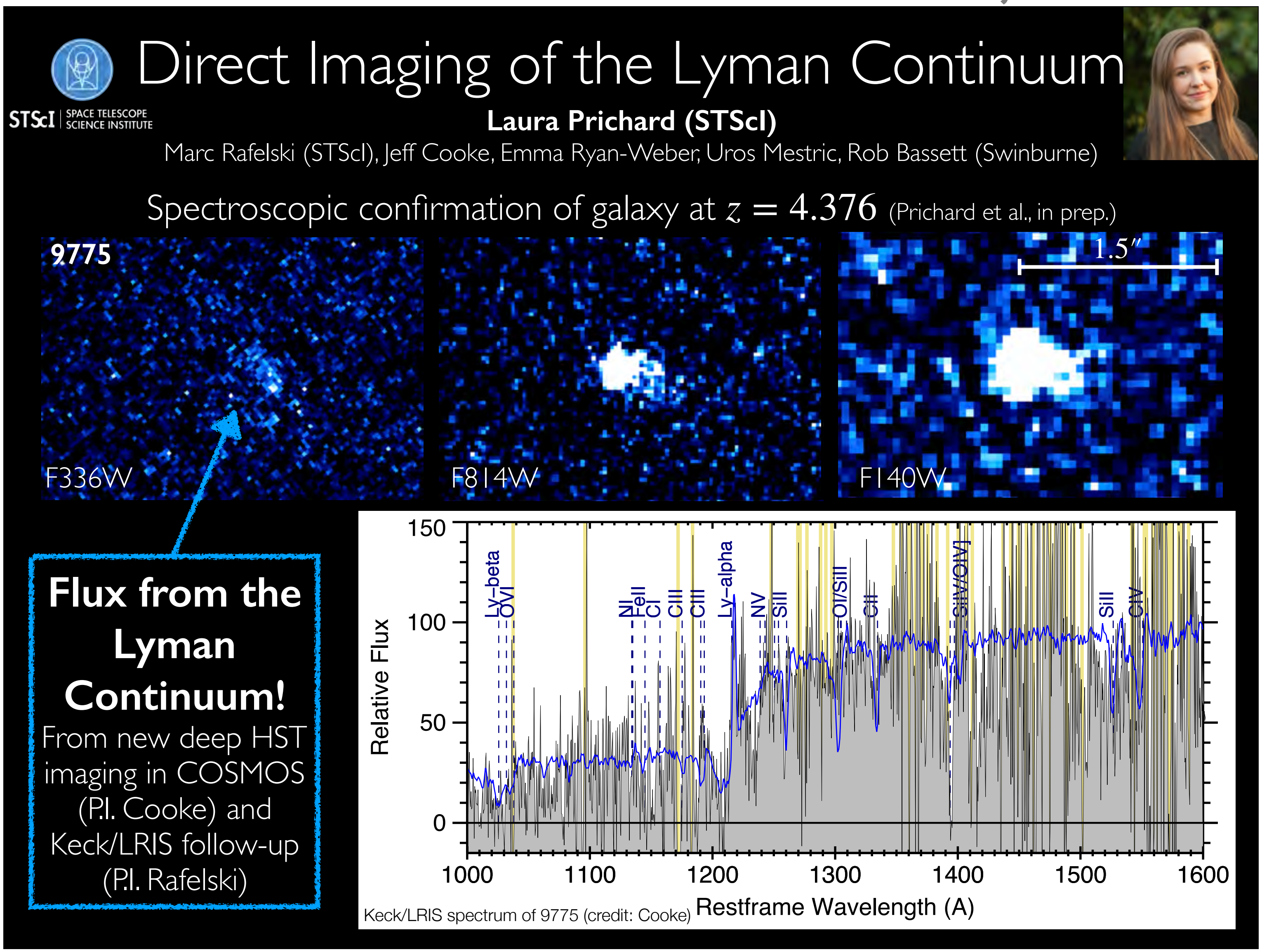
- HST follow-up of candidates (Vanzella et al. 201, 2016, 2018; Ji et al. 2020)
- z=3.212, 3.794, 4.0
- High [OIII]λ5007/[OII]λ3727 and [OIII]+Hbeta EW
- "ion1" LyC is spatially offset
- Includes S/N~10 detection, spatially unresolved
- High escape fraction depends upon unknown IGM transmission



- Detection of 20% of sources in sample of 61 Lyα emitters at z=3.1 (Fletcher et al. 2019)
- f_{esc} ranges 15-60%, with 20% for stack
- LyC peak separated from Lyα peak

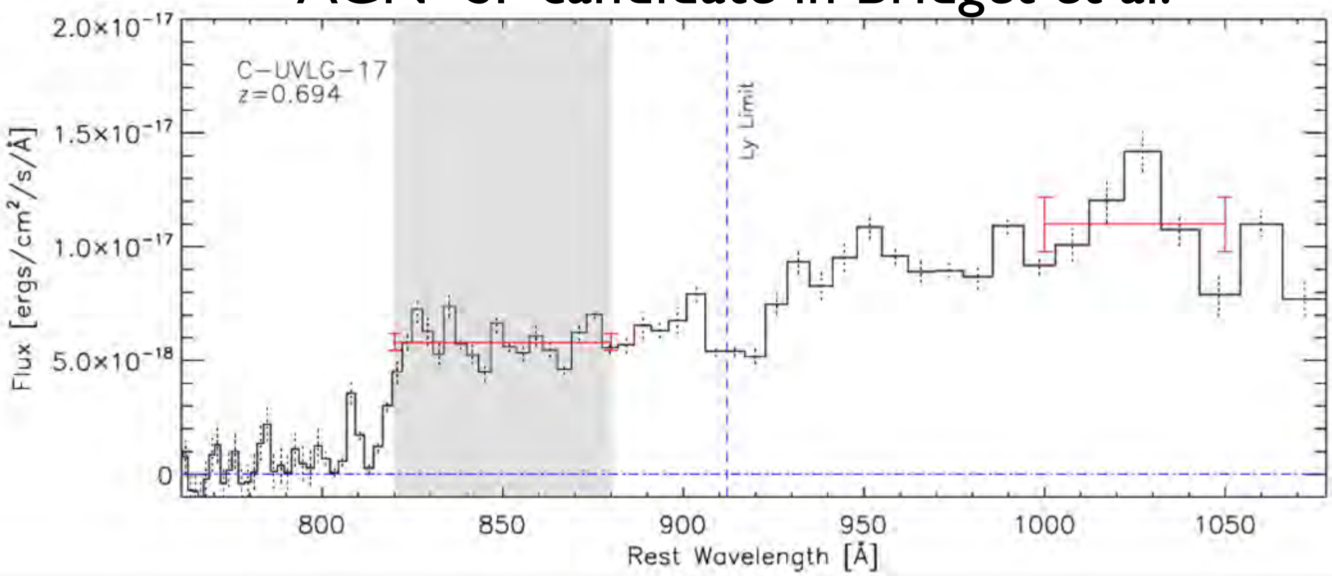
Rare, very high redshift detections

Second object at z=4.4



Weak AGN?

AGN+SF candidate in Bridget et al.

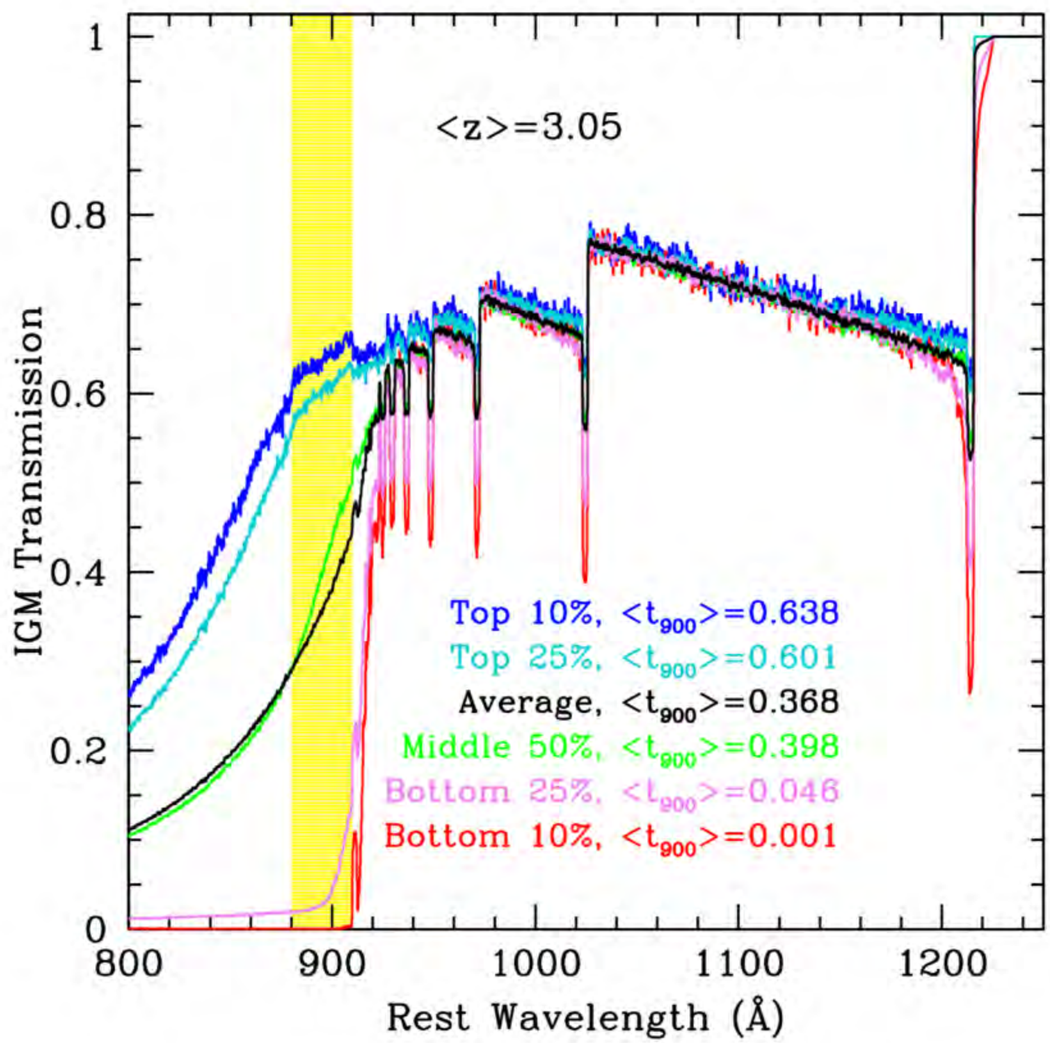


- Some studies suggest faint AGN at z>3 imply QLF with much higher source density at high redshift (e.g. Giallongo et al. 2015,2019; but see Parsa et al. 2018)
- Khaire et al. (2016) suggest this higher density would be enough to explain AGN-driven reionization
- Smith et al. (2020, in press) find significant LyC detection from weak AGN in ERS field within GOODS-S

Statistically significant samples needed

- Steidel et al. (2018) Figure 11: "*transmission spectra, in the rest frame of the source, for ⟨z⟩ = 3.05 for an ensemble of 10000 lines of sight assuming the CGM+IGM opacity model. The various color-coded spectra represent averages within per- centile ranges of t900.*"
- Bottom 25% of sightlines are opaque to LyC
- The paper suggests that >30 sightlines need to be considered together in order to reduce systematic IGM correction uncertainty to 10%

(Steidel et al. 2018)



Implications

- Our group did not make an unambiguous detection of escaping LyC radiation from this z~1 sample,
- Non-detections constrain the absolute Lyman continuum escape fraction, fesc < 3%
- We measure an upper limit of fesc< 9: 6% from a sample of SFGs selected on high Hα equivalent width (EW> 200A), which are thought to be close analogs of high redshift sources of reionization.

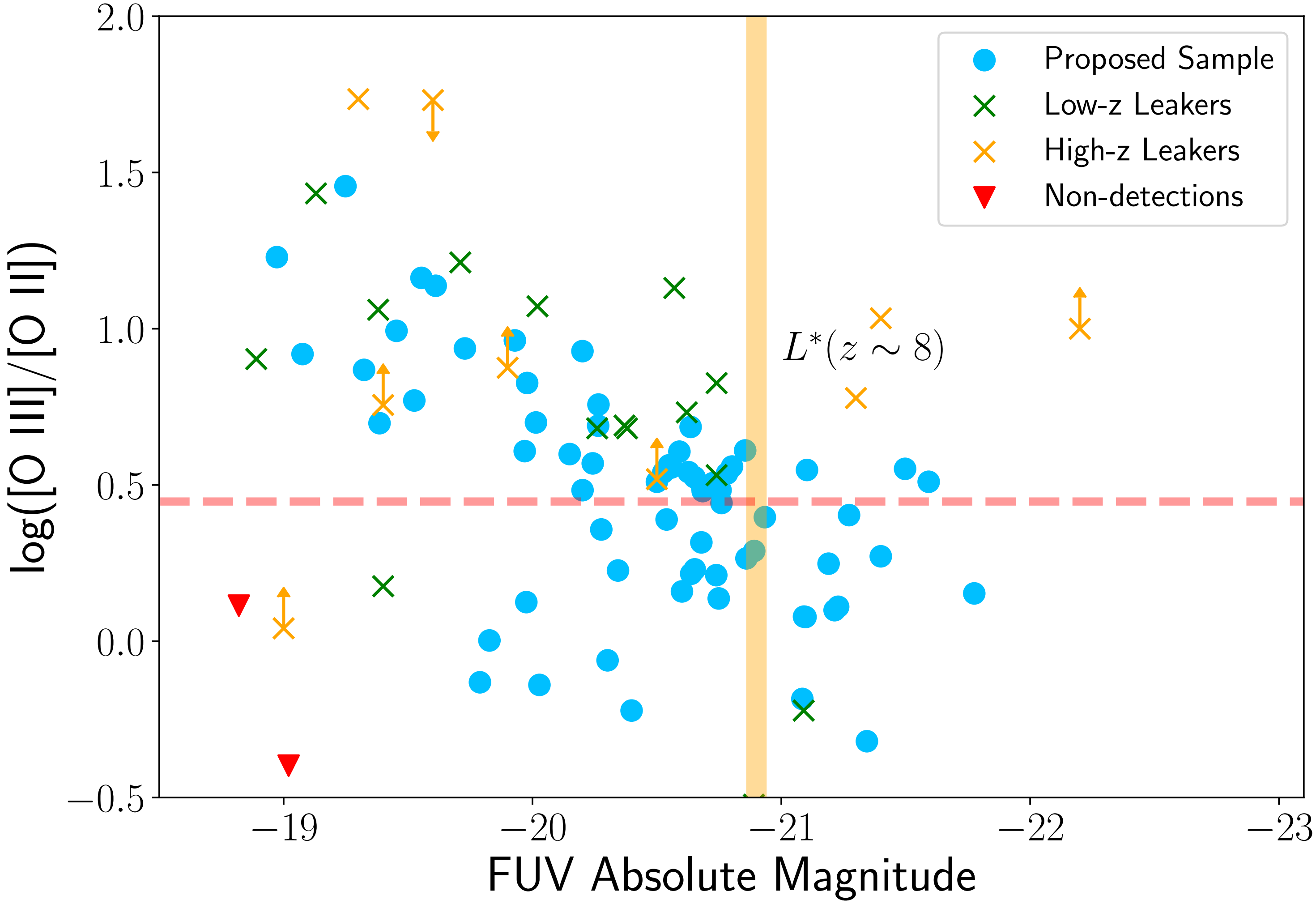
- Other surveys have more success
- If the LyC escape fraction increases with redshift, SFGs remain plausible candidates for reionization
- Some indication that high [OIII]/[OII] ratio predicts LyC escape
- Strong Hα EW (~100-500 Å), on its own is insufficient diagnostic tool for the leakage of LyC photons, but extreme values (>1000 Å) may be indicative

HST's final years: the UV initiative

Introducing:
The *HST* Low-Redshift Lyman Continuum Survey

134 orbits, 66 new galaxies
100 low-z LyC measurements
Radiation-hydro simulations
PI: Jaskot

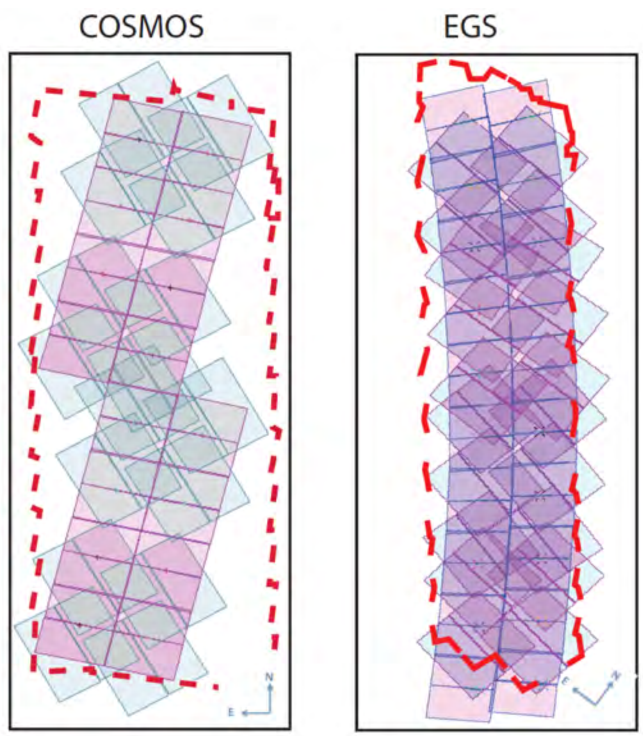
HST Low-Redshift Lyman Continuum Survey

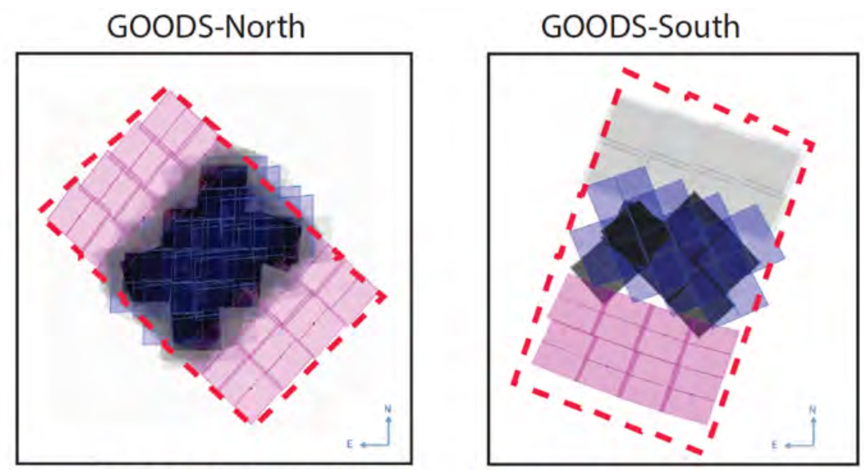


UVCANDELS

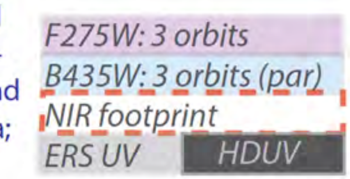
- Definitive extragalactic UV imaging of the four premier HST deep-wide survey fields best suited to JWST observations.
- Targets the key processes of galaxy evolution during the epoch of vigorous star formation at $0.5 < z < 3$:
  - Study the structural evolution of galaxies and create 2D maps of their star-formation history.
  - Combine UVCANDELS with Herschel legacy data to trace the evolution of the dust content of moderate z galaxies.
  - Probe the role of environment in the evolution of low-mass star-forming galaxies.
  - Investigate the decay of star-formation in massive early type galaxies and the role of minor mergers.
  - Stack images to constrain the escape fraction of ionizing radiation from galaxies at $z \sim 2.5$ to better understand how star-forming galaxies reionized the Universe at $z > 6$.

UVCANDELS

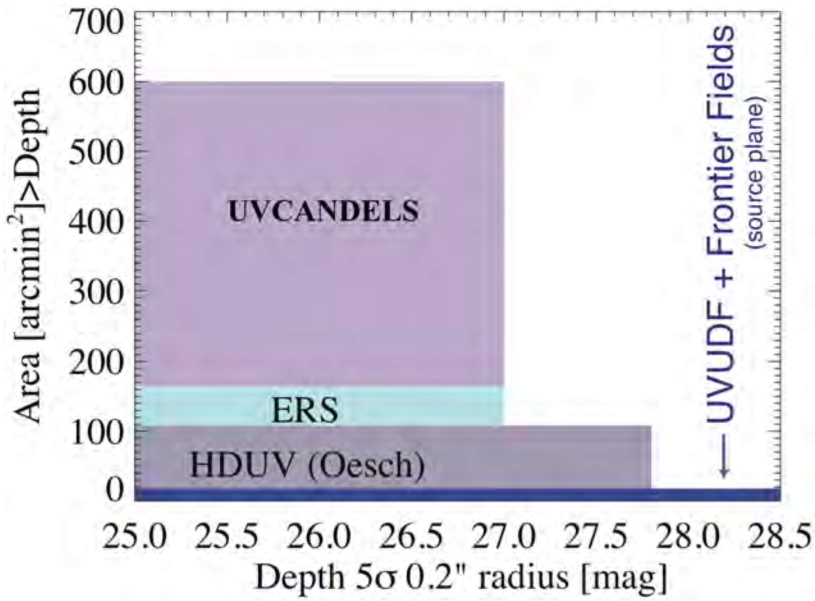


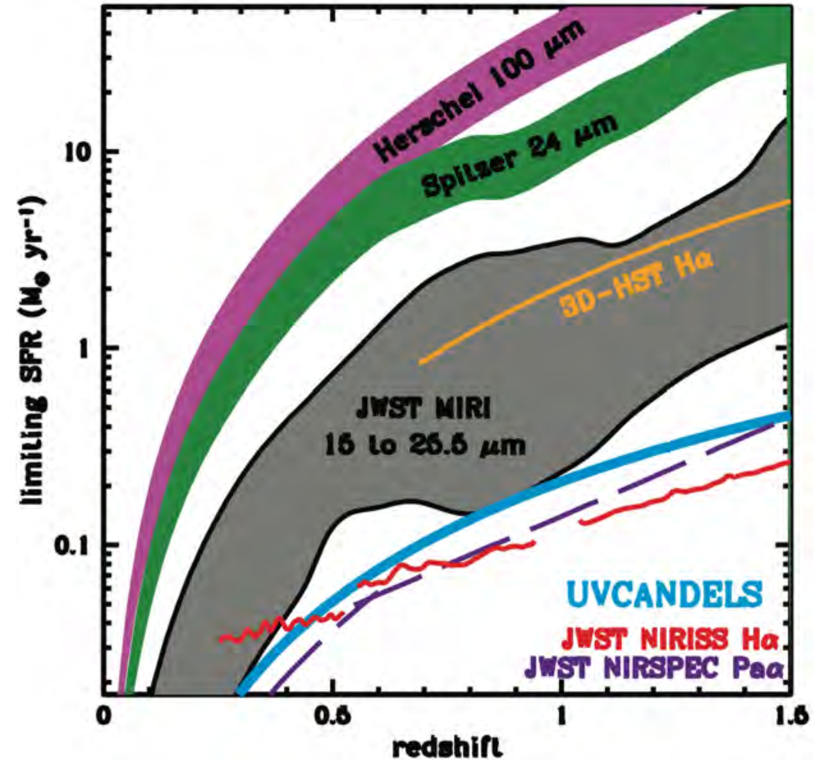


Note: (1) GOODS already has B-band coverage, but COSMOS and EGS do not; UVCANDELS will obtain deeper F435W images in the CANDELS-Deep regions of GOODS where previous UV and NIR are deeper, rather than in the new UV area; (2) In EGS, we will target the area with full NIR+ACS/V+I coverage, as shown by the red



UVCANDELS





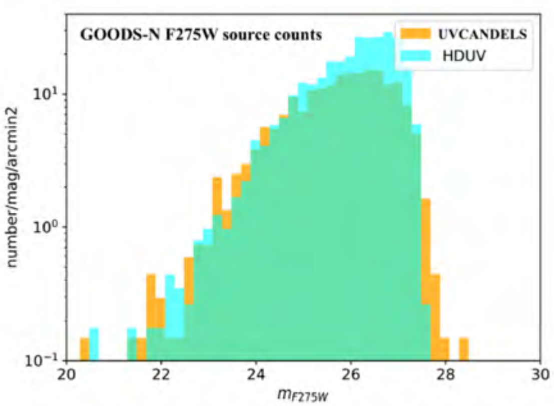


Figure 7: differential number density for objects detected at $\geq 3\sigma$ in GOODS-N F275W from *UVCANDELS* and HDUV.

Figure 7 shows the number counts in F275W from the published HDUV catalog (Oesch+18) and our *UVCANDELS* catalog. The measurements are in good agreement up to $m_{\mathrm{F275W}} \sim 26$. The number counts from *UVCANDELS* are slightly below those from HDUV at fainter magnitudes because of the deeper F160W and F275W data in the GOODS-N Deep region. The numbers of detections at very faint magnitudes slightly increases for *UVCANDELS*, since we adopt the hot+cold mode photometry approach which is more robust in segmenting very faint sources (Barden+12).

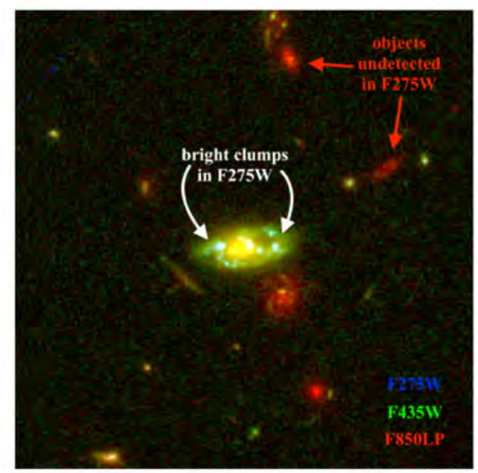
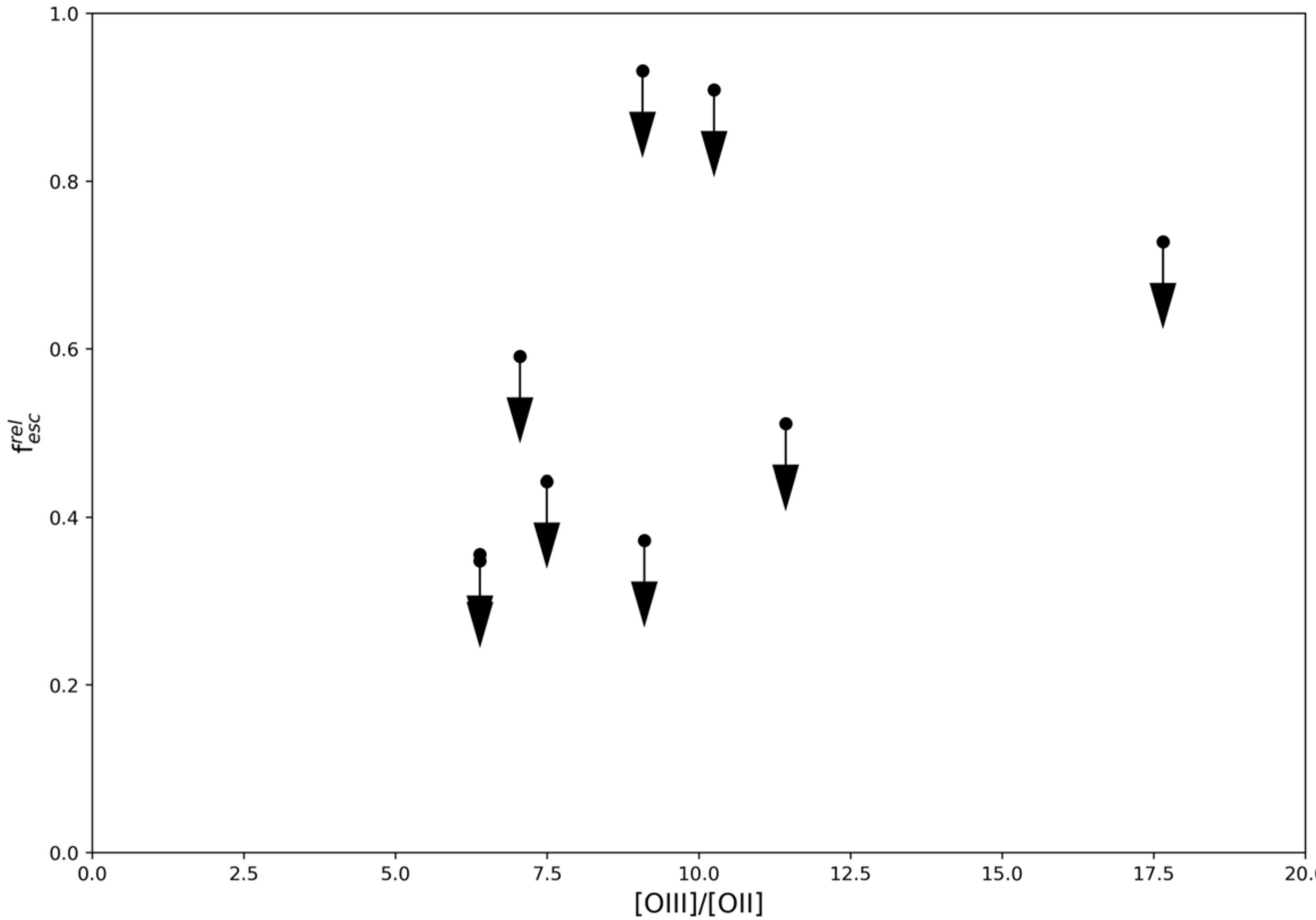


Figure 8: RGB image of a 25″ ×25″ region in GOODS-N.

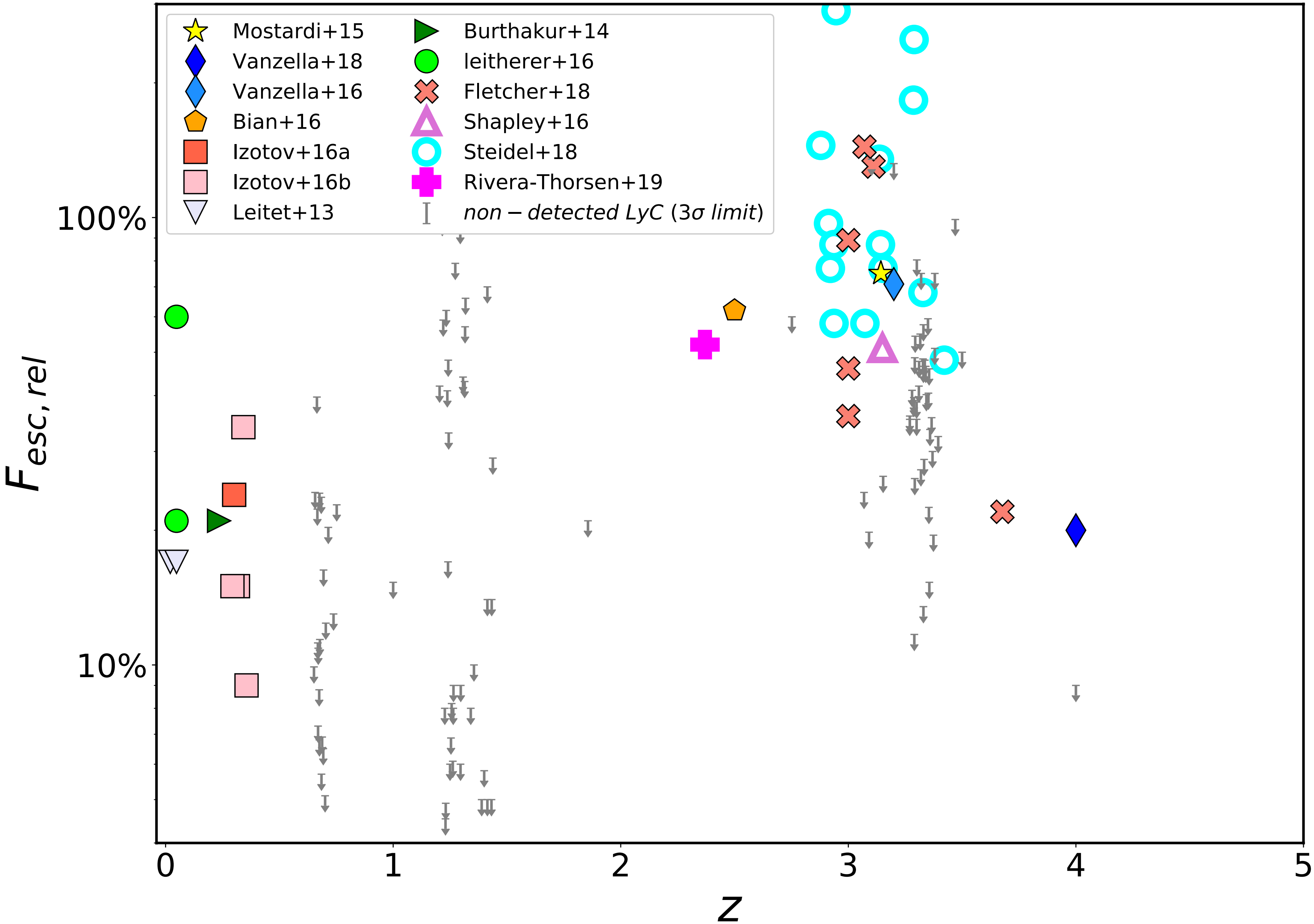
UVCANDELS: preliminary results

Individual $f_{esc,rel}$ limits for galaxies in GOODS-N with strong [OIII]/[OII] (Rutkowski et al., in prep)

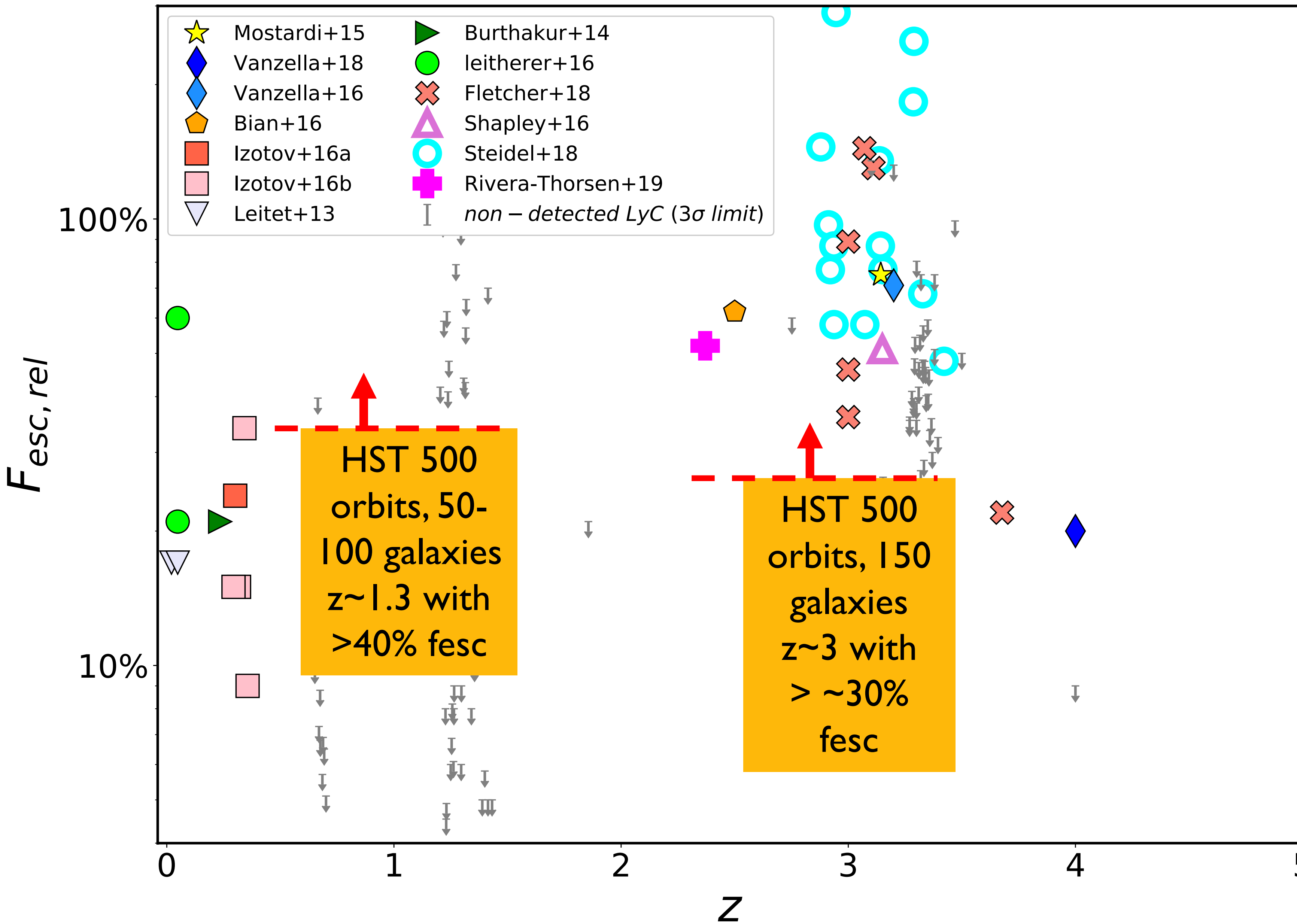


The limits of what HST can do

F_esc > 100% depends on assumption of IGM and intrinsic flux ratio



F_esc > 100% depends on assumption of IGM and intrinsic flux ratio



Conclusions/Summary

- LyC escape is important factor in understanding reionization.
- Requires UV observations & space-quality imaging (to rule out contamination)
- Detections support star-forming galaxies producing sufficient ionizing photons
- Strong evidence that the LyC escape fraction evolves with redshift
- Low luminosity (low metallicity) galaxies are focus of LyC observations
  - High [OIII]/[OII] may predict LyC escape
  - High EW lines may not be enough
- Lensing may offer new way advantage, but need more data
- Differential sightlines require statistically significant sample
- We need more UV data!