The Lyman Continuum Escape Fraction and Other Curiosities in HST Deep Surveys

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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

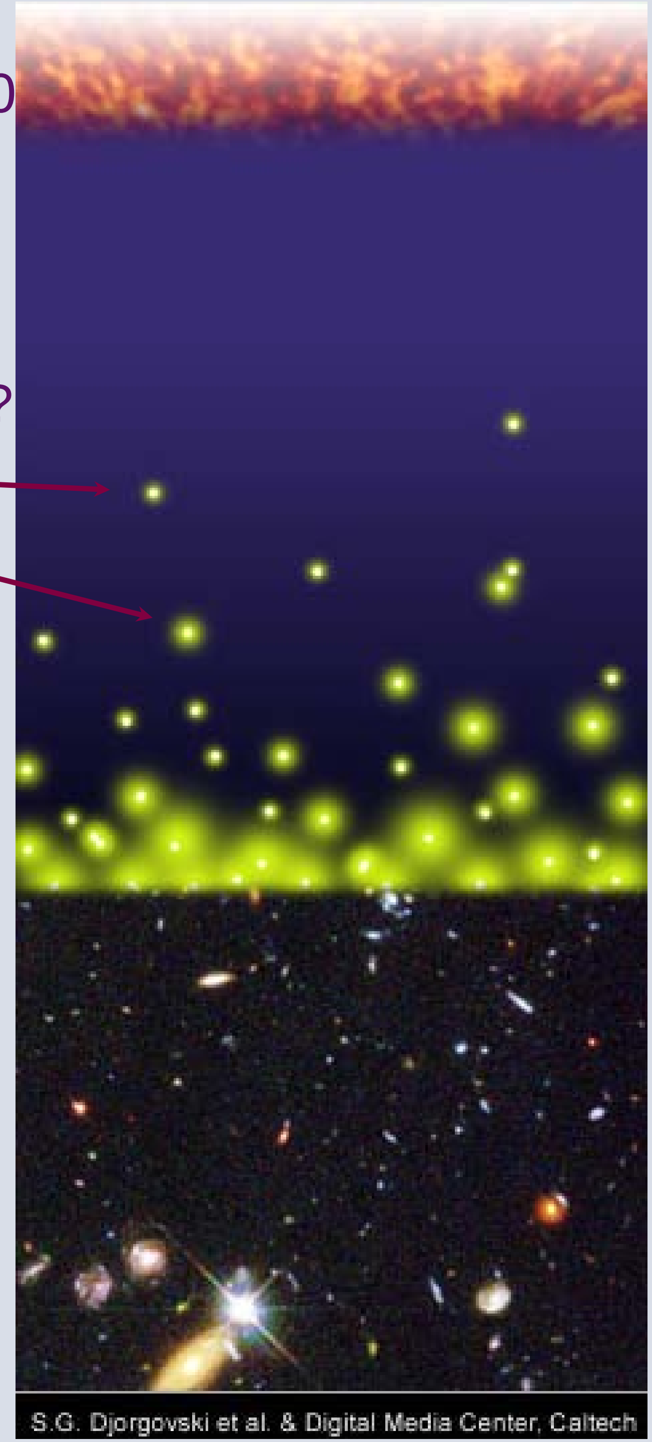
“Dark Ages”

z = ?

z=6 Reionization

z=3 He II Reionization

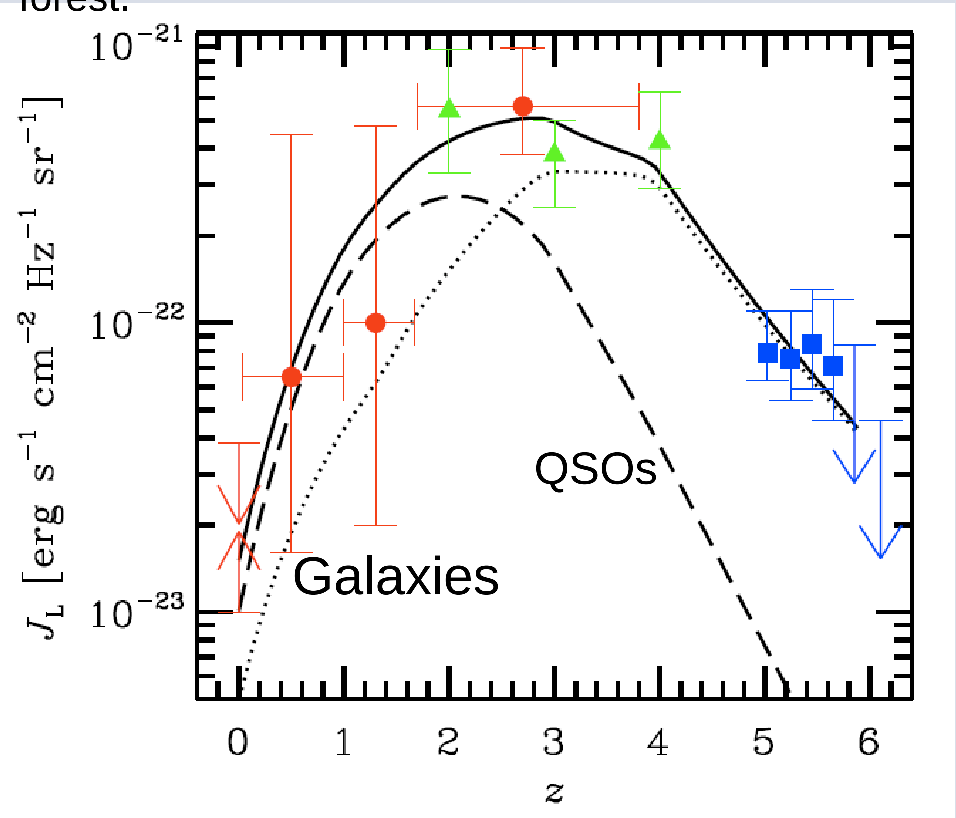
z=0 Present Day



QSO Contribution to Ionizing Background

- QSOs are prodigious soures 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!

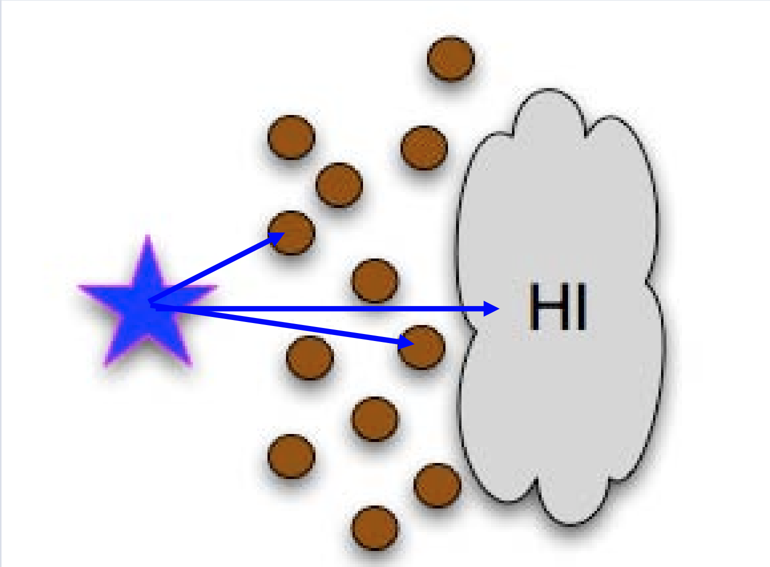
Data points are measurements from Lyman-α forest.



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

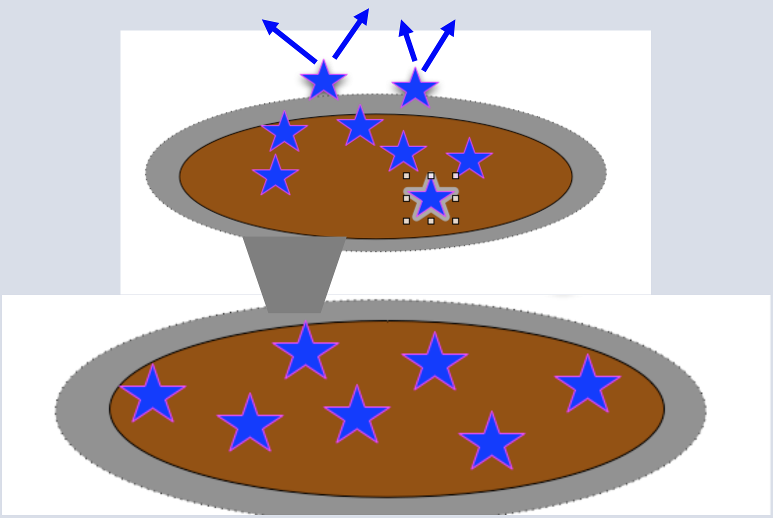
Inoue et al. (2006)

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

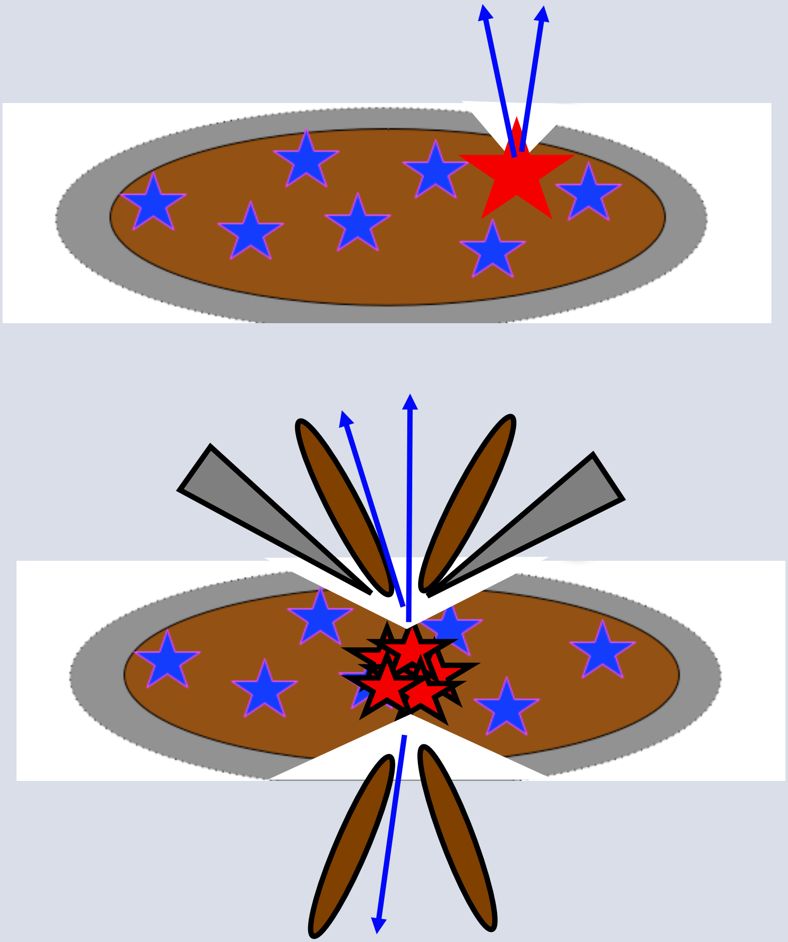


LyC absorbed by Gas and Dust

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

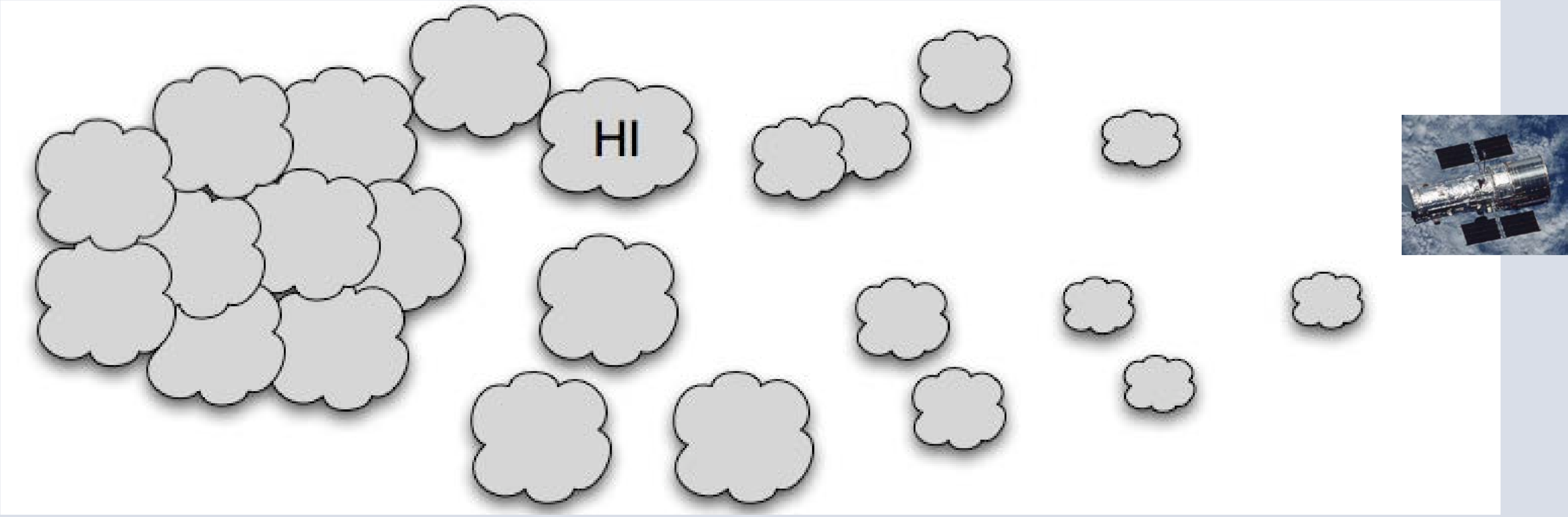


Interactions



Feedback

LyC absorbed by intervening HI



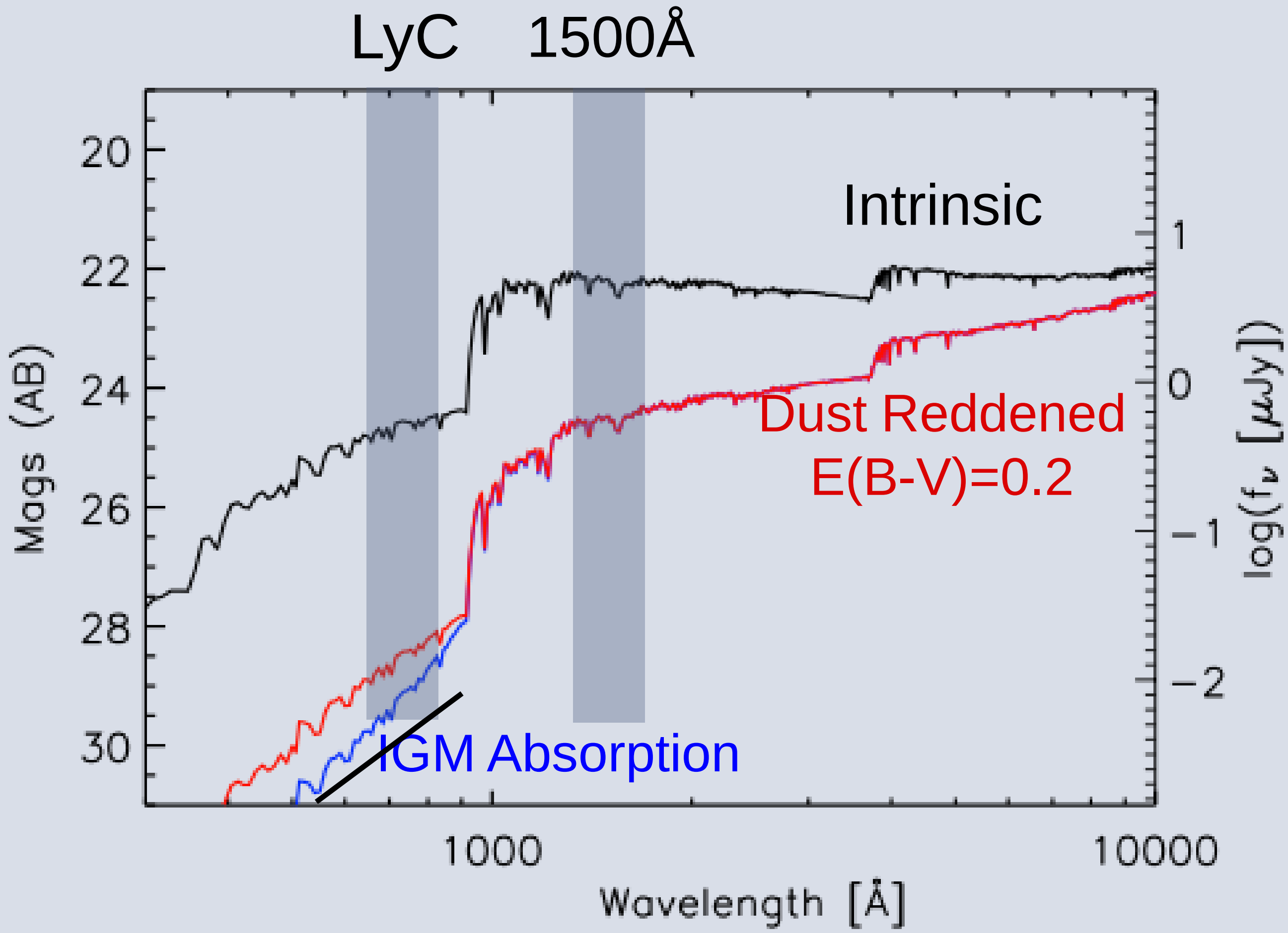
Z=6 Z=3 Z=1.3 Z=0.7

“Lyman Break Galaxies (LBGs)”

The escape fraction: f_{esc}

"The UV escape fraction remains problematic" (Fan et al. 2006)

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



f_{esc} Definitions

1. f_{esc} = fraction of lyman continuum photons which escape galaxy.
    - Includes dust absorption and HI
    - Useful when starting from theoretical SFR (semi-analytic models)
2. $f_{esc,rel}$ = fraction of lyman continuum photons which escape galaxy divided by fraction of 1500Å photons escaping galaxy.
    - No need to quantify dust absorption (difficult to constrain at high-z)
    - Observationally useful (rest-frame 1500 Å easy to measure at z>1, becasuse it redshifts into the optical)

$$f_{\mathrm{esc,rel}} = \frac{(L_{1500}/L_{900})_{\mathrm{int}}}{(f_{1500}/f_{900})} \exp(\tau_{\mathrm{IGM},900})$$

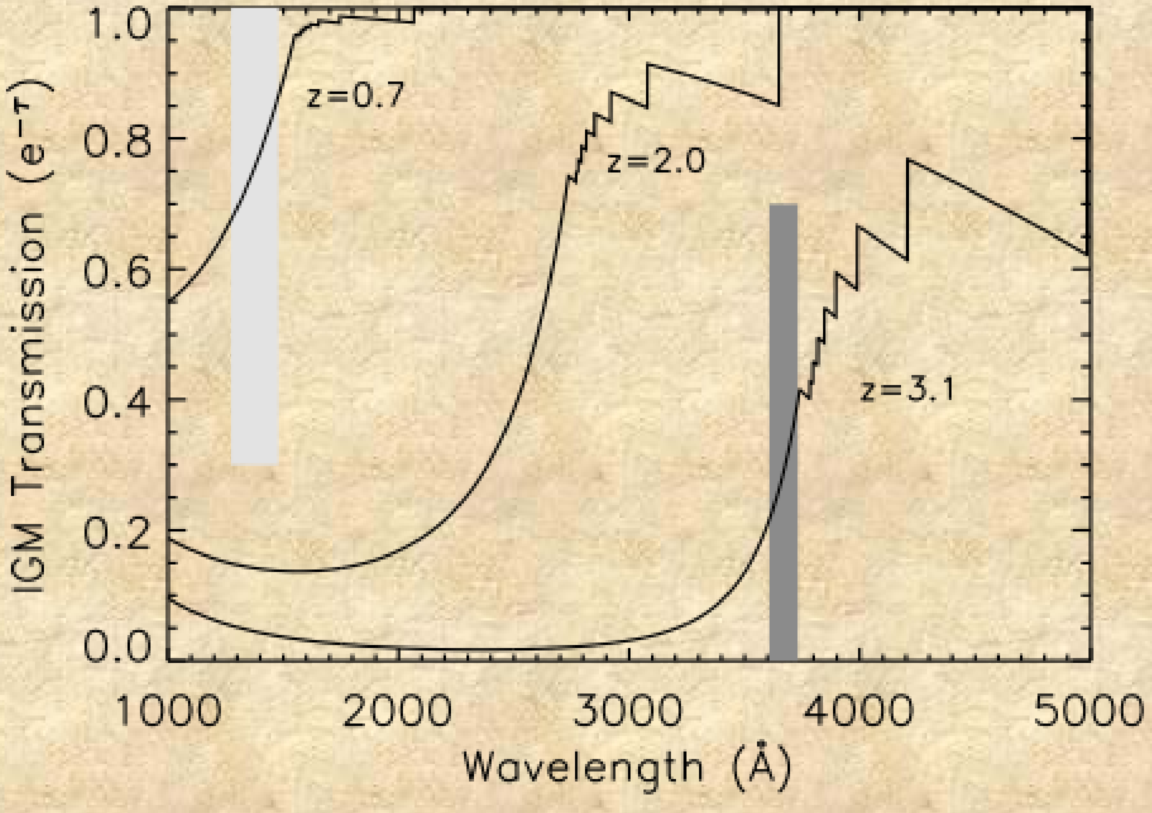
- **f_{esc} ~ 3-10x lower than $f_{esc,rel}$**

Measuring f_{esc}

1. Can't measure f_{esc} at z~6 because of intervening IGM (or even z>3.5)

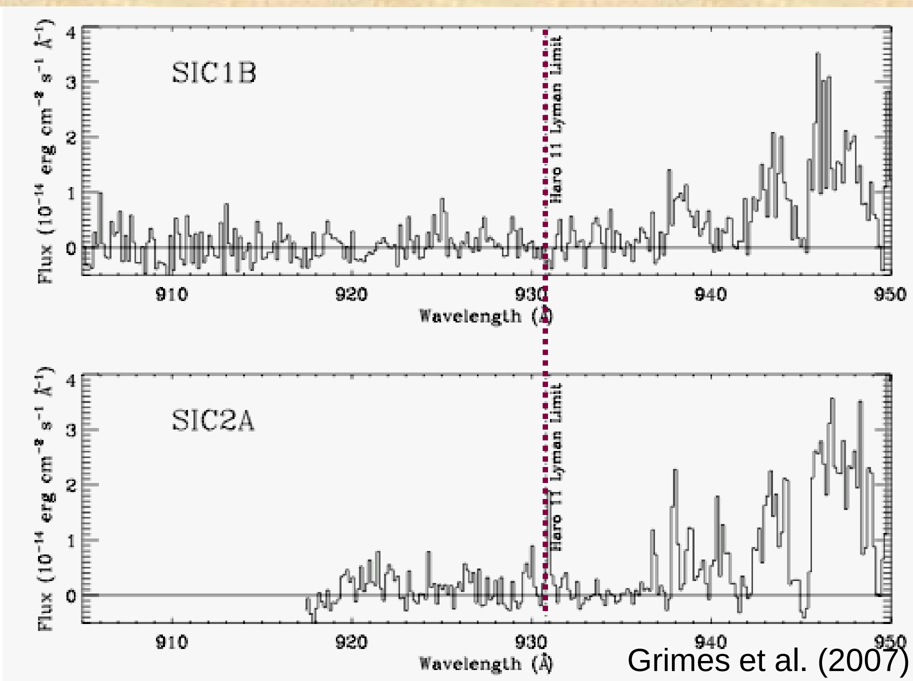
2. Lower z LC-emitters would be easier to study

3. At z<2, LC needs to be observed from space

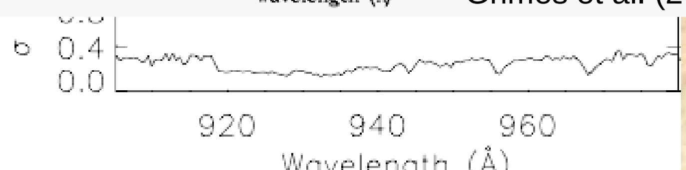


z ~ 0
FUV spectrscopy from space

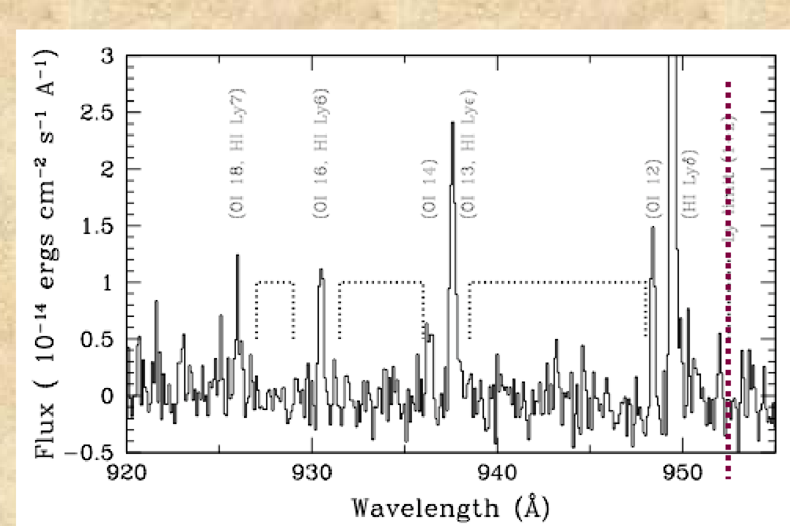
- 6 objects, no LC detected
- Far-UV not sensitive
- HI, dust absorption in MW



Grimes et al. (2007)



Bergvall et al. (2006)



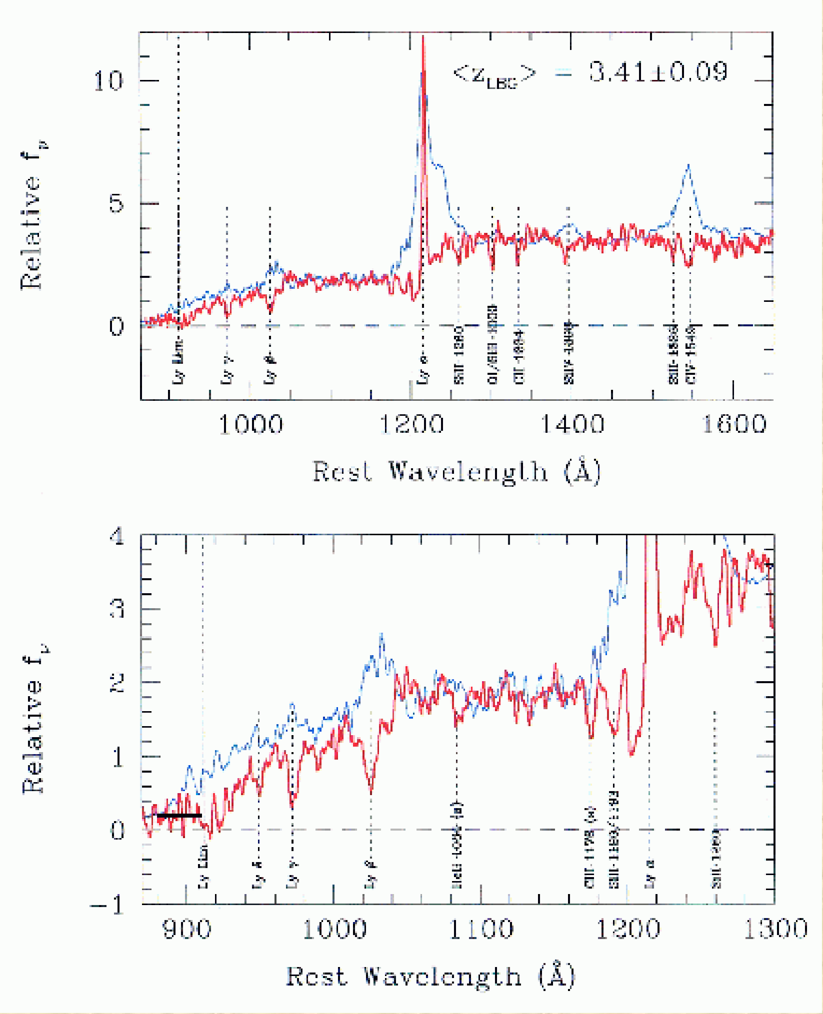
Deharveng et al. (2001)
Leitherer et al. (1995)

z~3 Lyman Break Galaxies
Keck spectroscopy

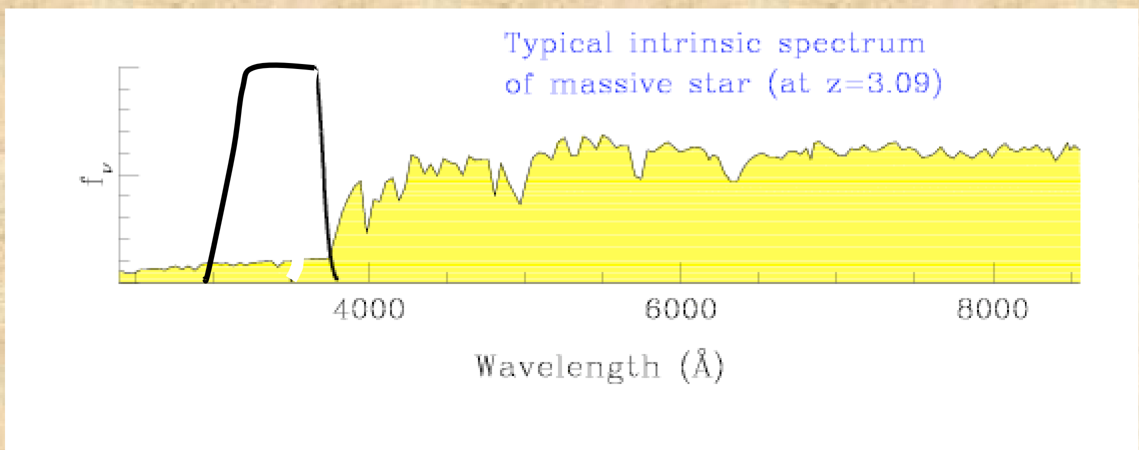
Steidel et al. (2001)

- 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) 14 spectra of 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



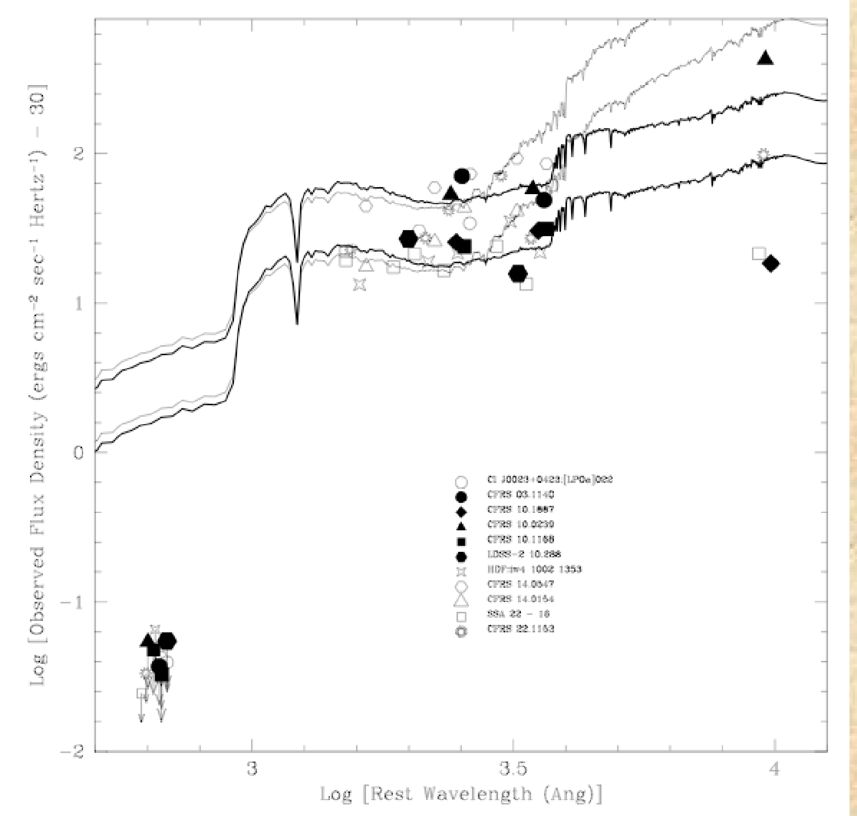
Imaging Below the Lyman Limit

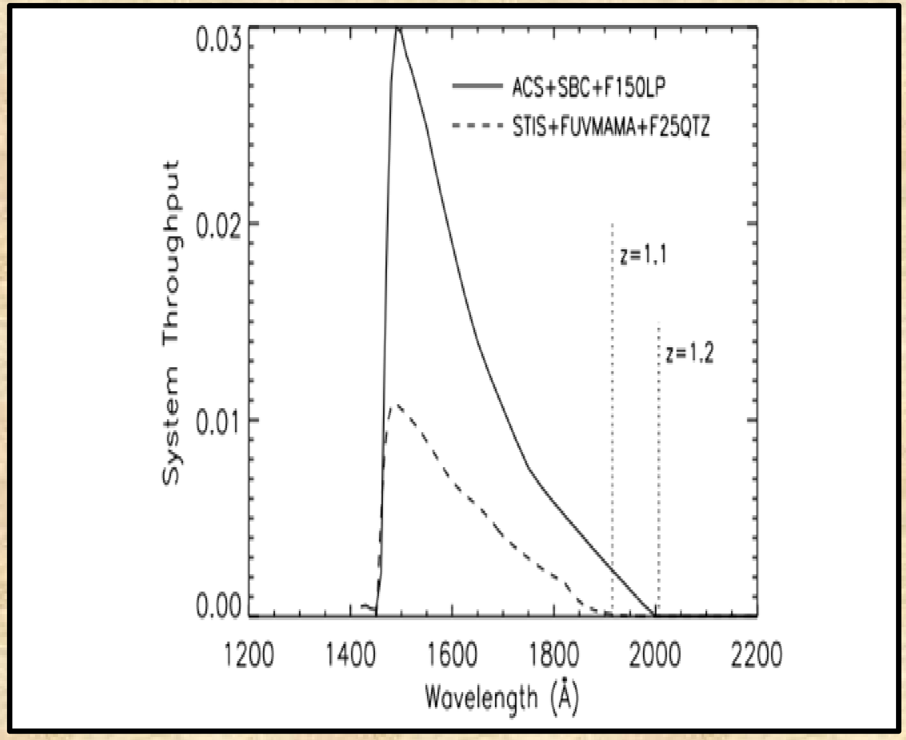


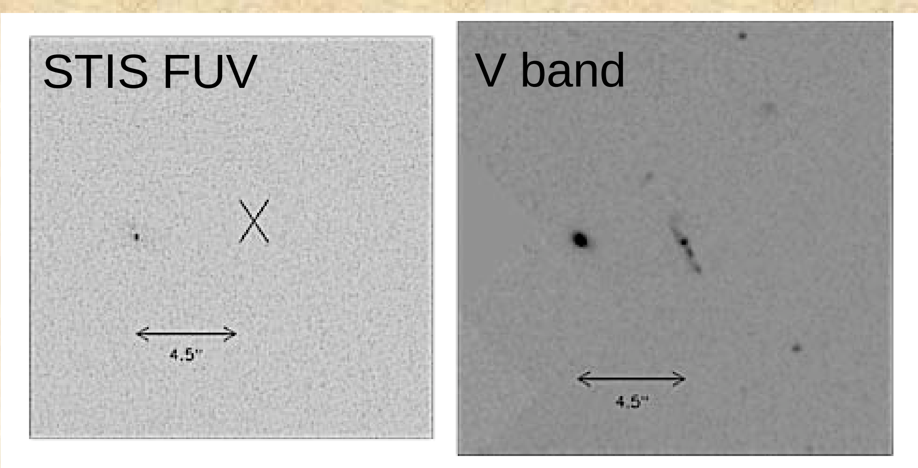
z~1.3
FUV Imaging from space

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)

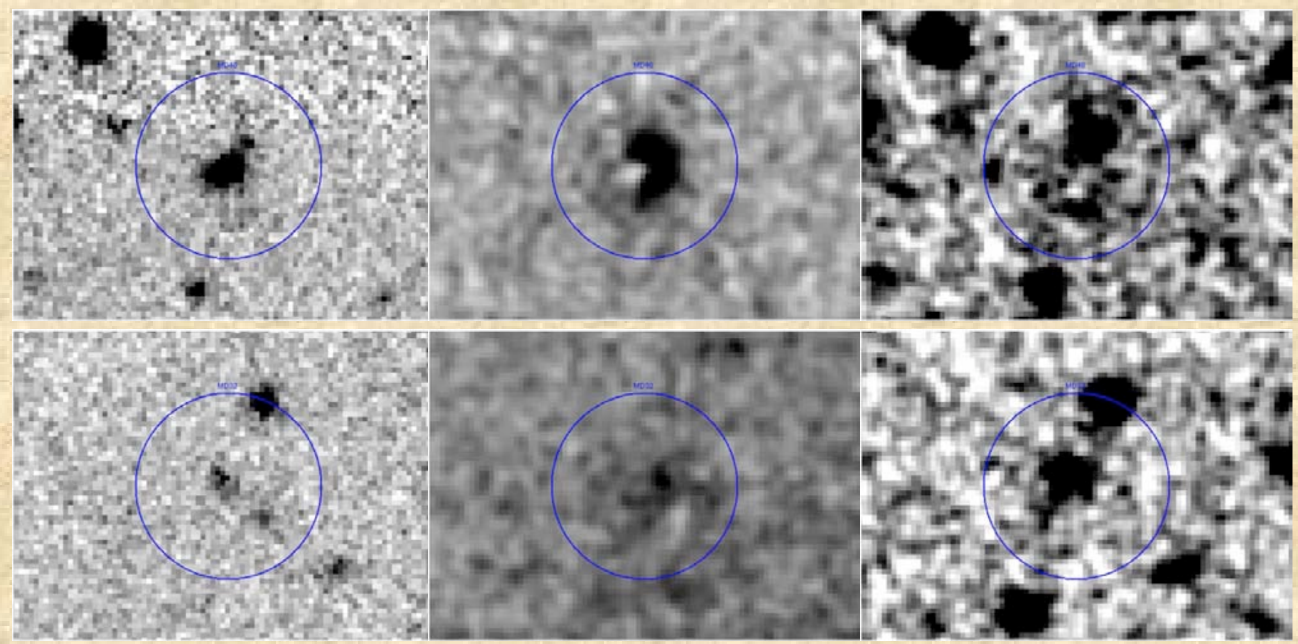




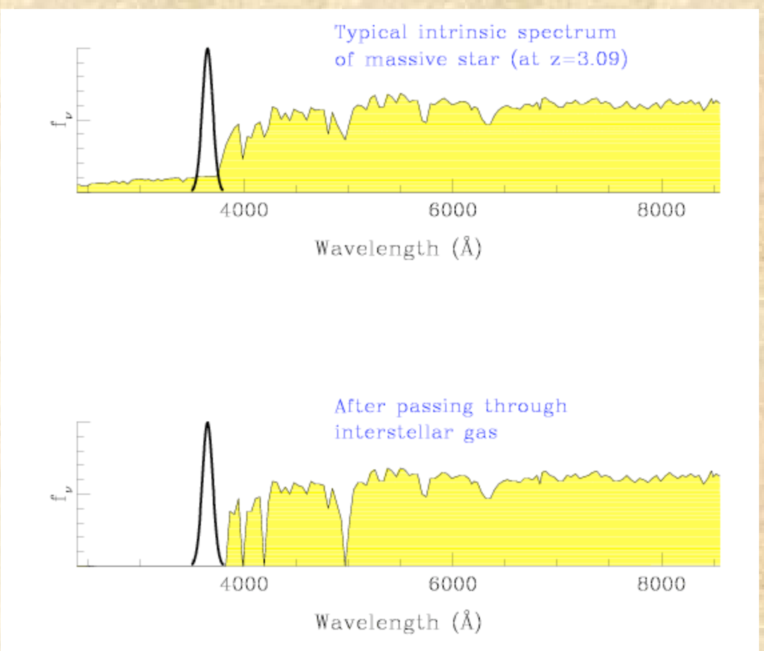


Narrow-Band Imaging at Keck and Subaru telescopes

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



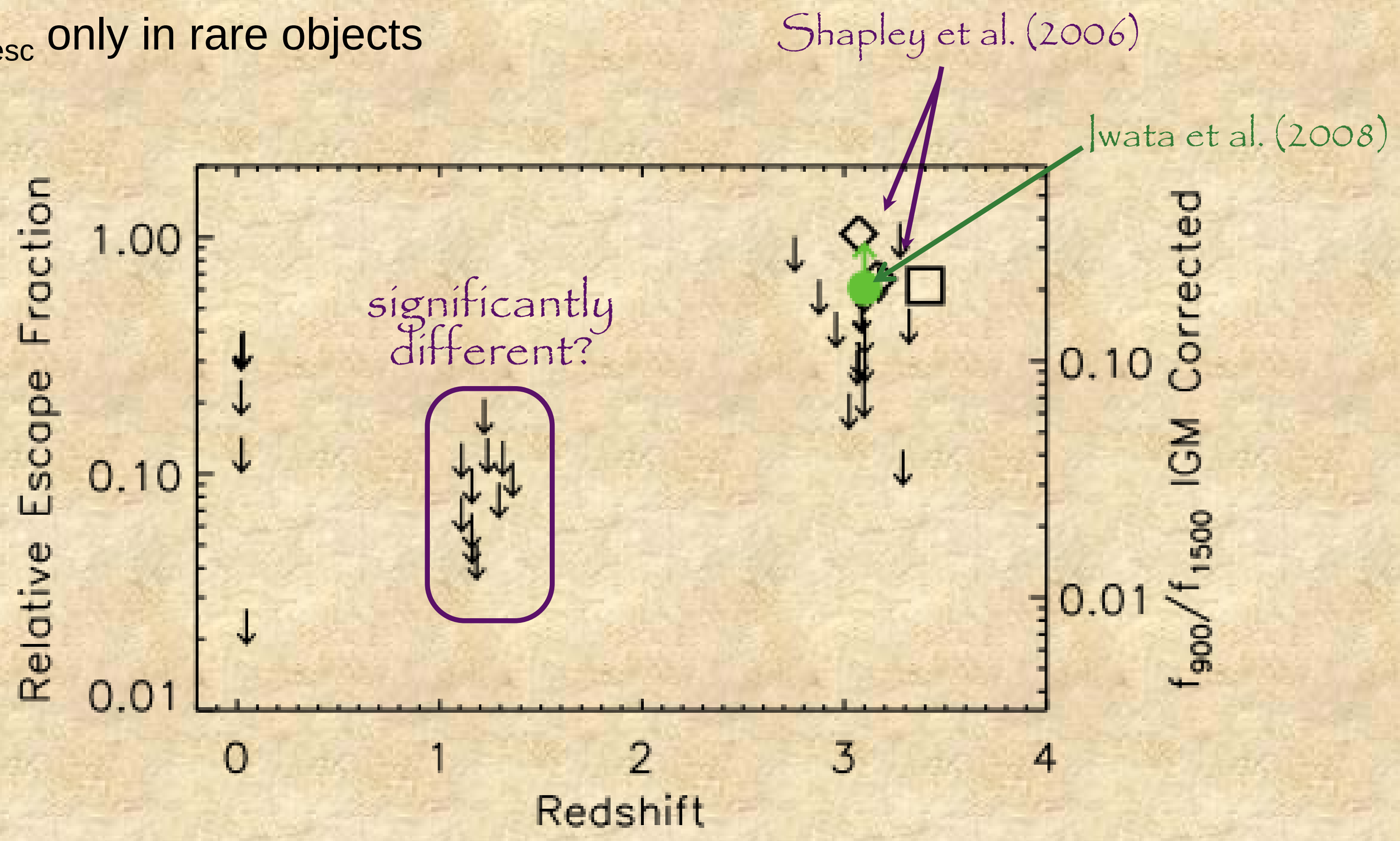
R-band Ly-a NB LC NB



Summary of Previous f_{esc} Measurements

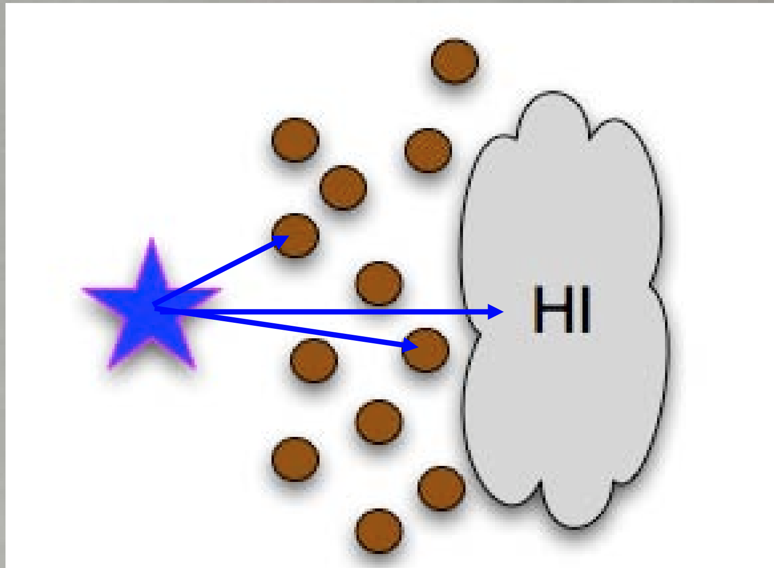
Spectroscopy at z~0, z~3, Imaging at z~1 with HST

$\Longrightarrow$ High f_{esc} only in rare objects



The deepest UV observations with HST

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

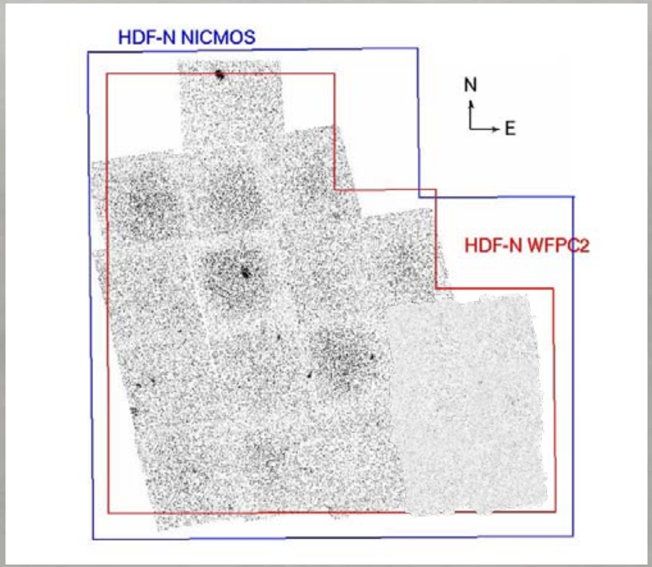


LyC absorbed by Gas and Dust

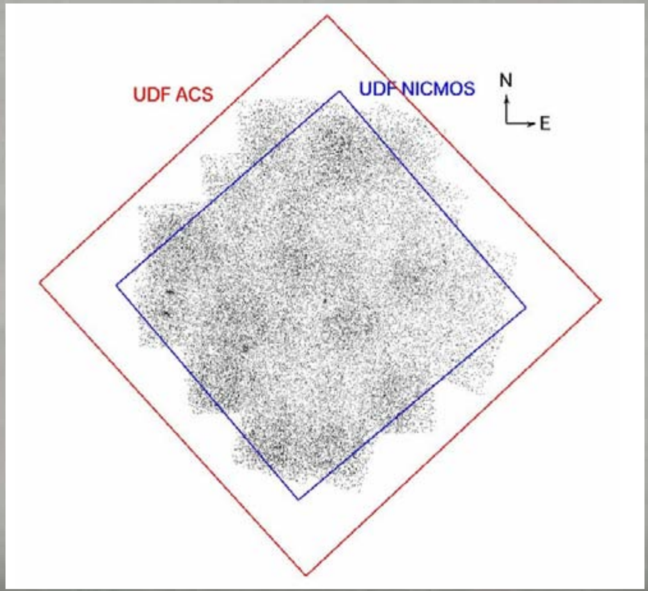
FUV Imaging of the Hubble Deep Fields

- 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)



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



Voyer et al. (2009, 2011)

New Survey: brighter sources, deeper images

Imaging of 14 luminous, blue galaxies at z~1.3 as luminous as LBGs

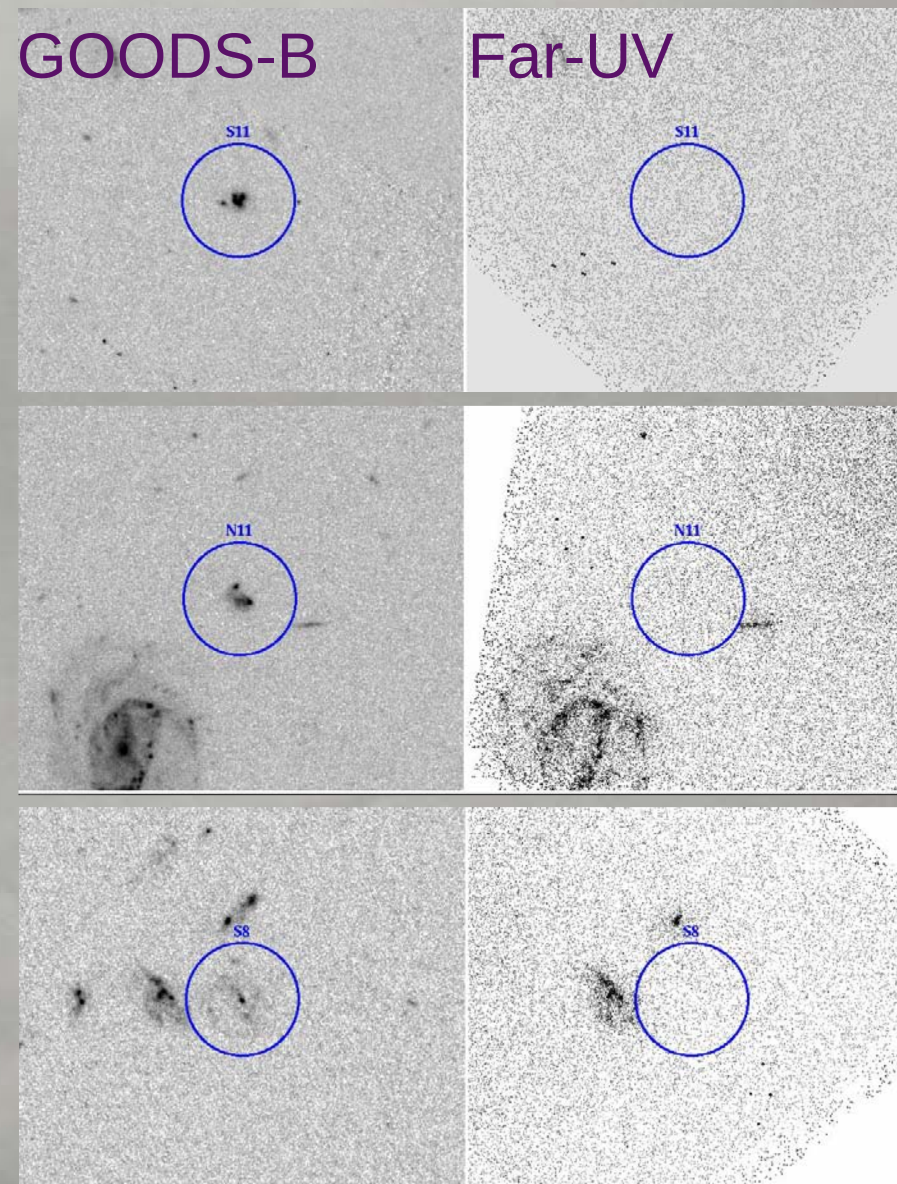
5 orbits per target; AB>29, 3sigma

$\Rightarrow$ deepest f_{esc} survey to date

Would detect $f_{esc,rel}$ down to ~3% but no detections out of 15 objects!

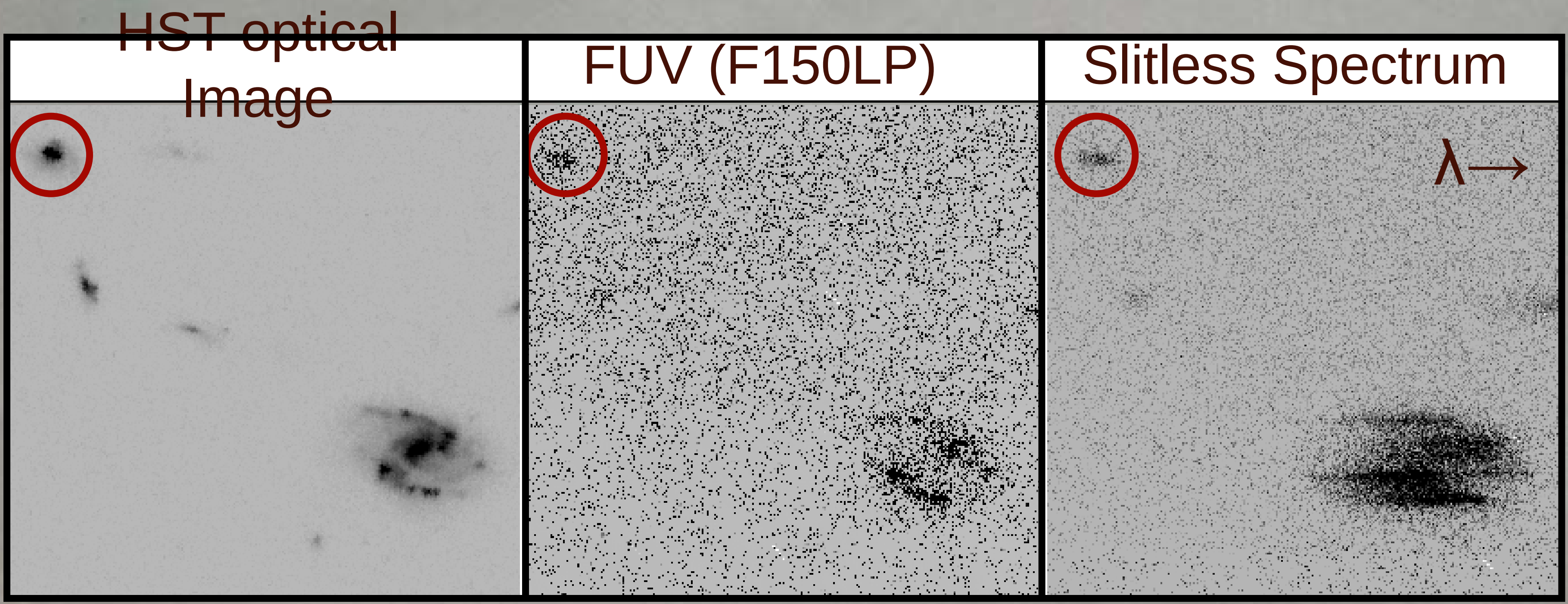
new stack limit fesc,rel < 1.8%

Siana et al. (2010)



HST Far-UV Prism z=0.7 LBG Analogs

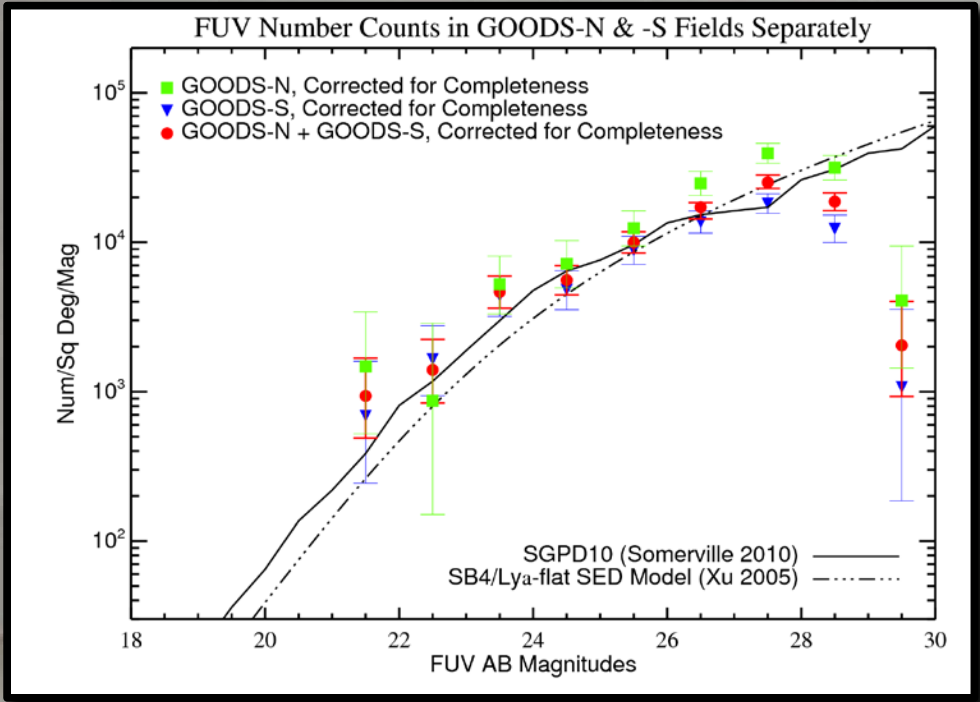
- 22 SBC prism spectra near 912AA
- Look for rare objecs with high escape fractions ($_{fesc,rel}$ > 20%)
- 115 orbits; No detections
- Bridge et al. (2010)

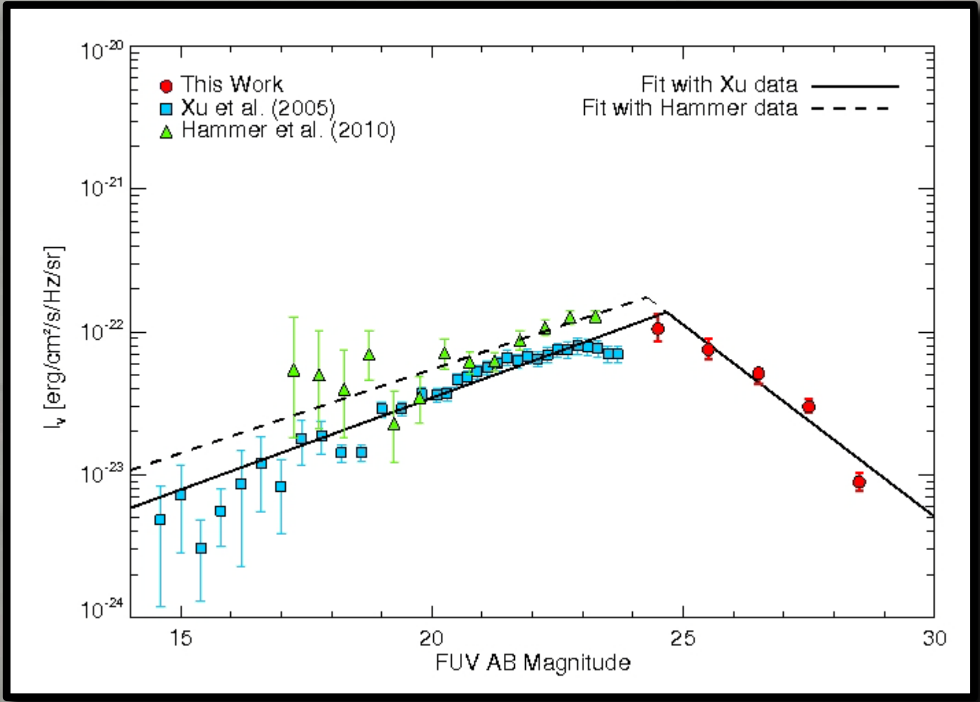


FUV Number Counts

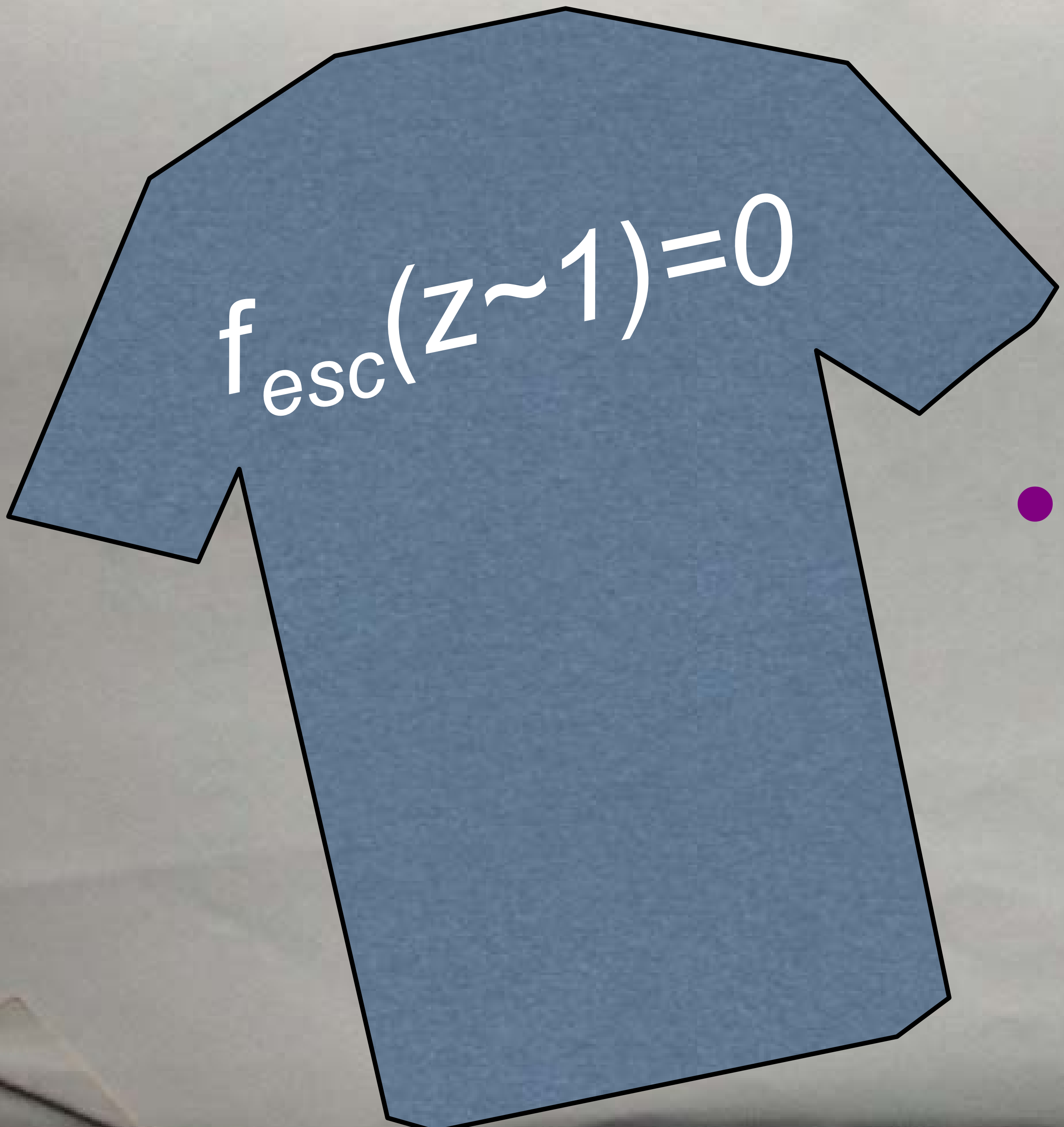
- Voyer et al. (2011)
- Mitigate for cosmic variance
- Good agreement with semi-analytic models

- New measurements show clear turn over in integrated light
- New limit on the resolved UV Extragalactic Background Light



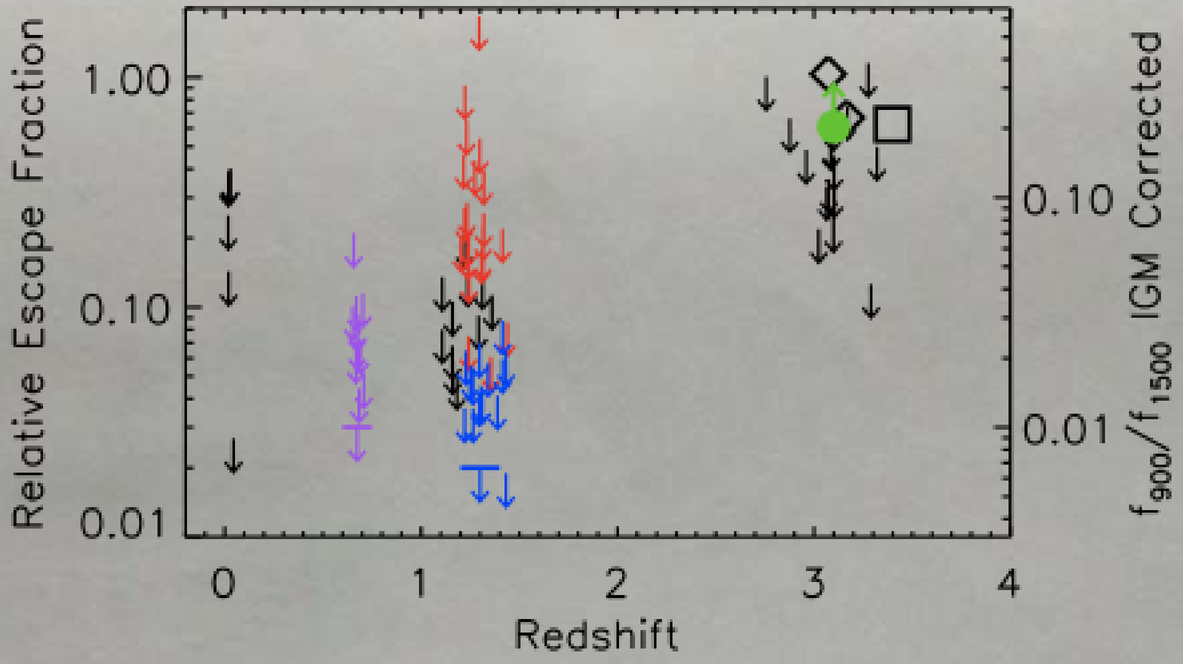


Summary of z~1 Results



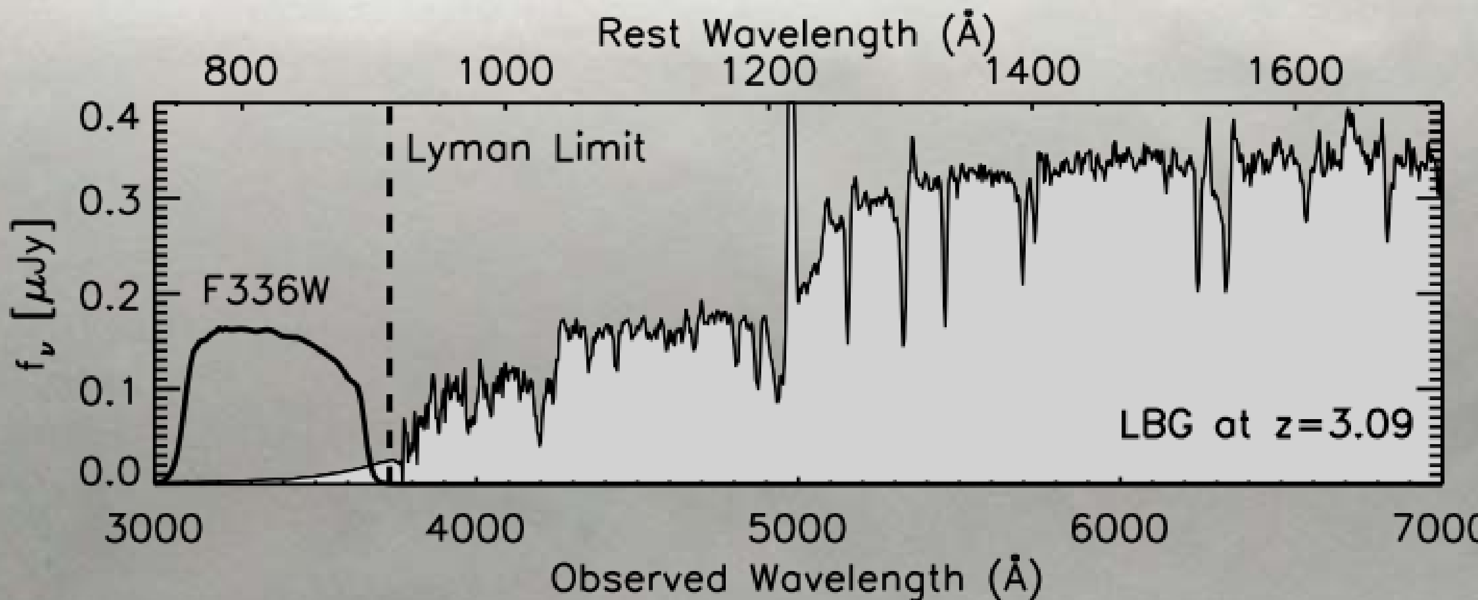
- HST gave me 300 orbits and all I got was this lousy tshirt….

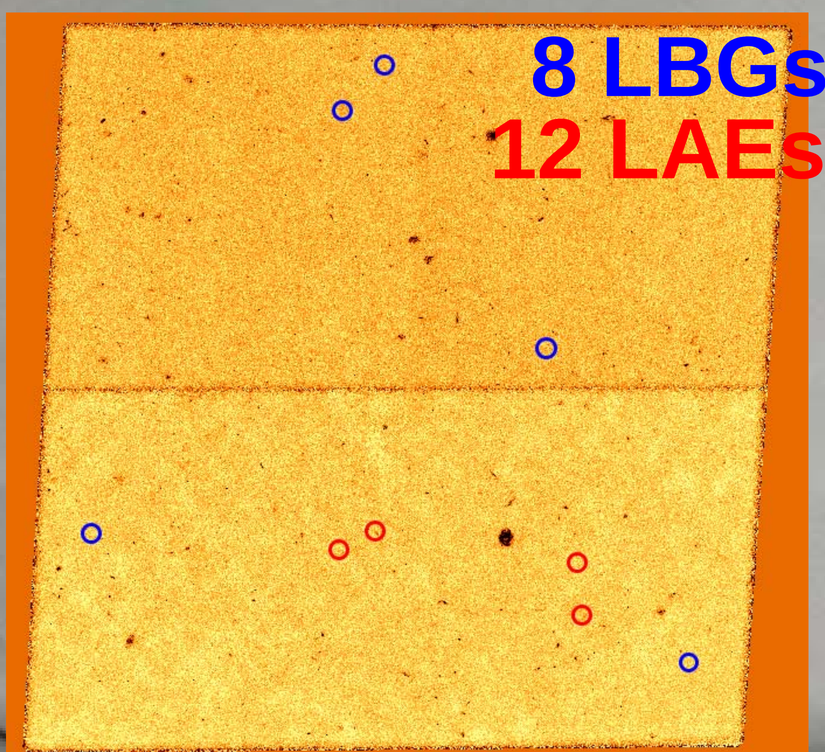
f_{esc} evolves with redshift



- 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?

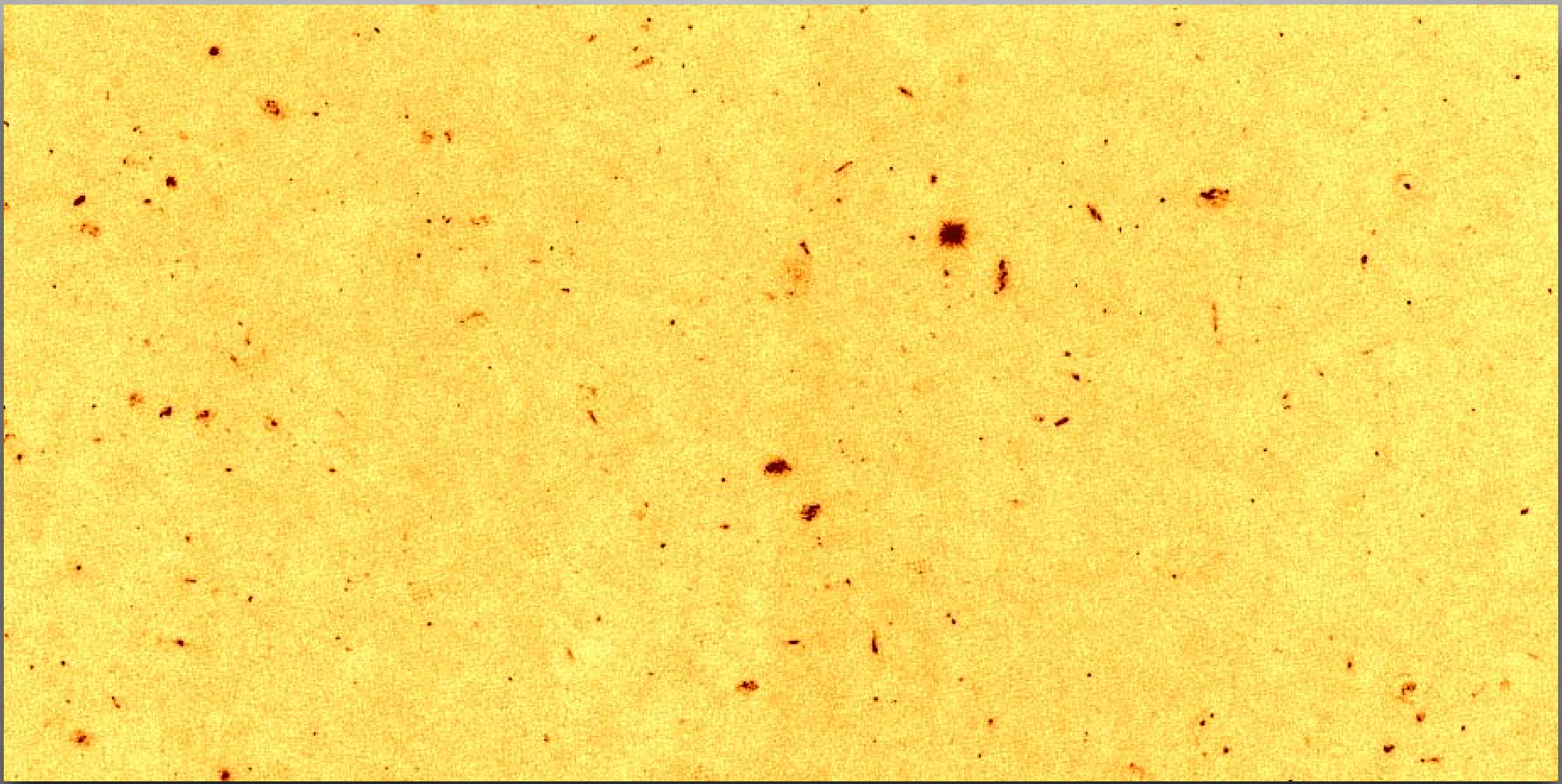
Ultradeep Imaging of LyC at z~3.1





- 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

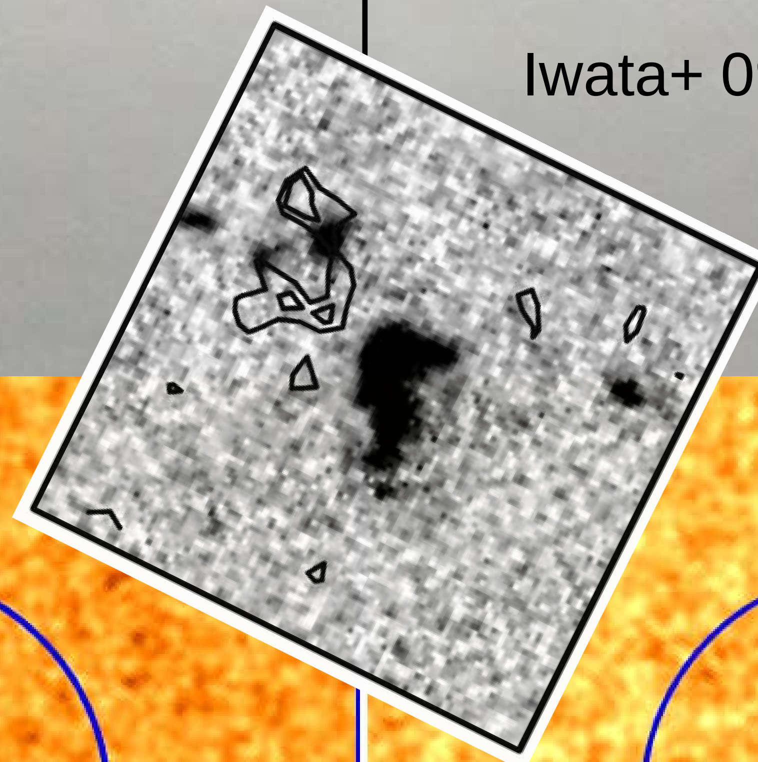
Deepest U-band Image Ever : 30.0 mags/arcsec^2 (1σ, AB)



UV Continuum

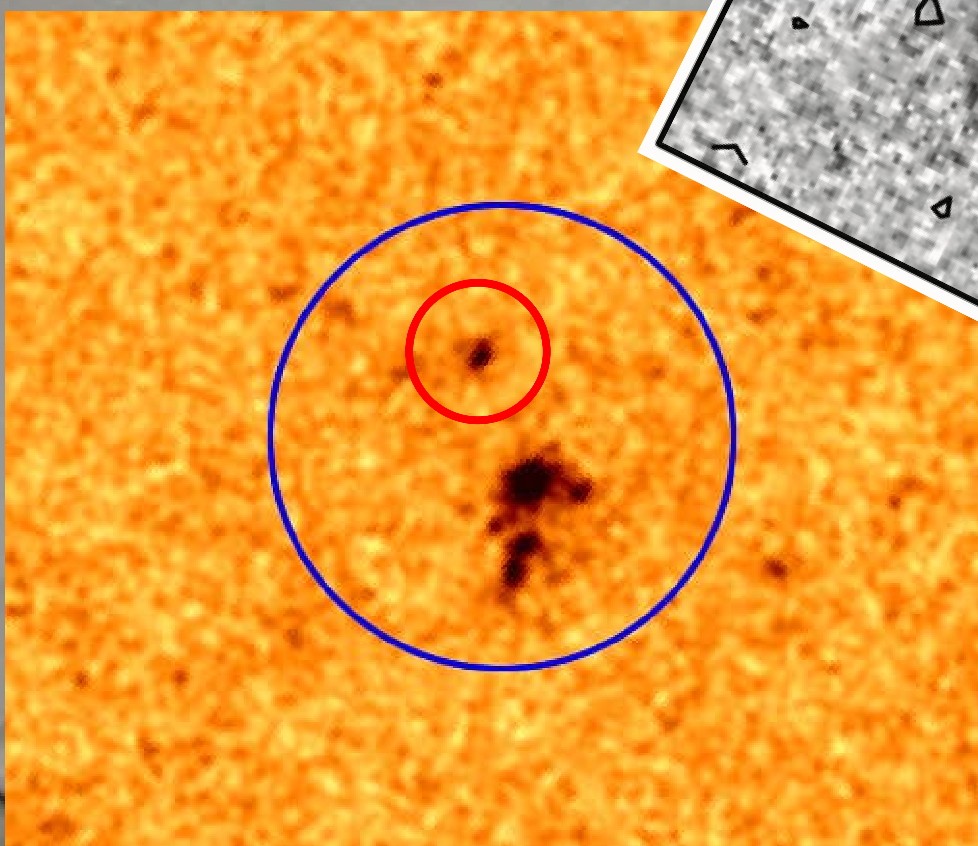
Ly Continuum

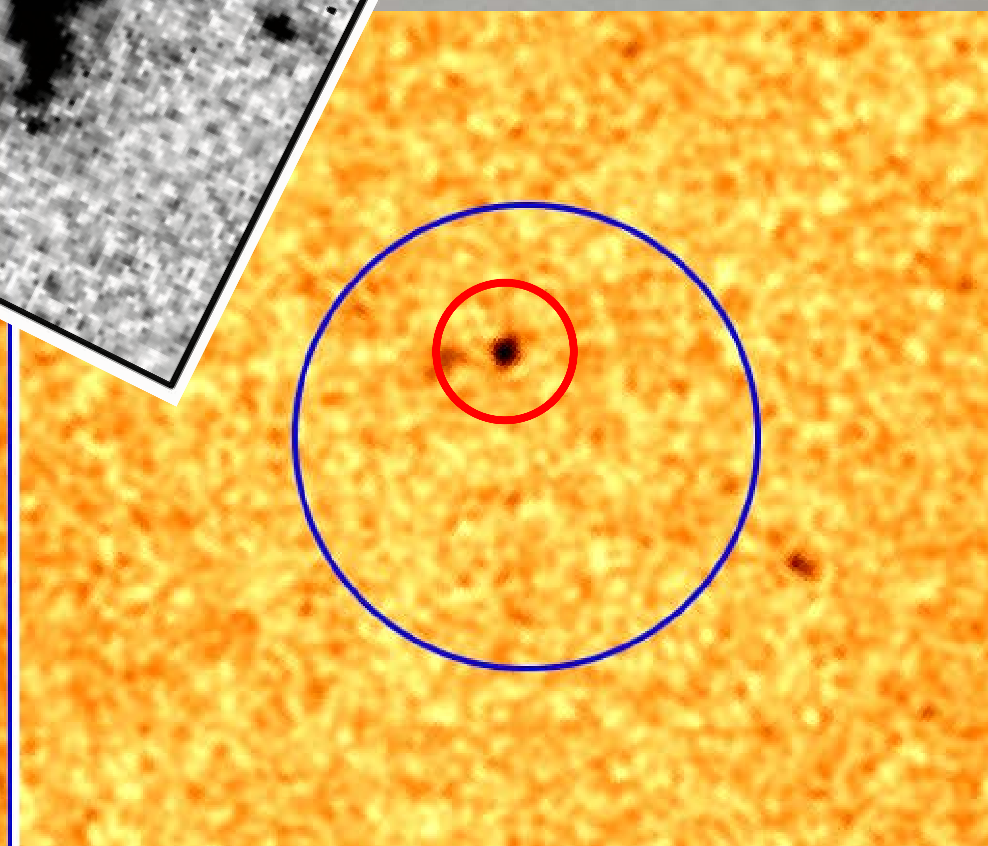
Iwata+ 09



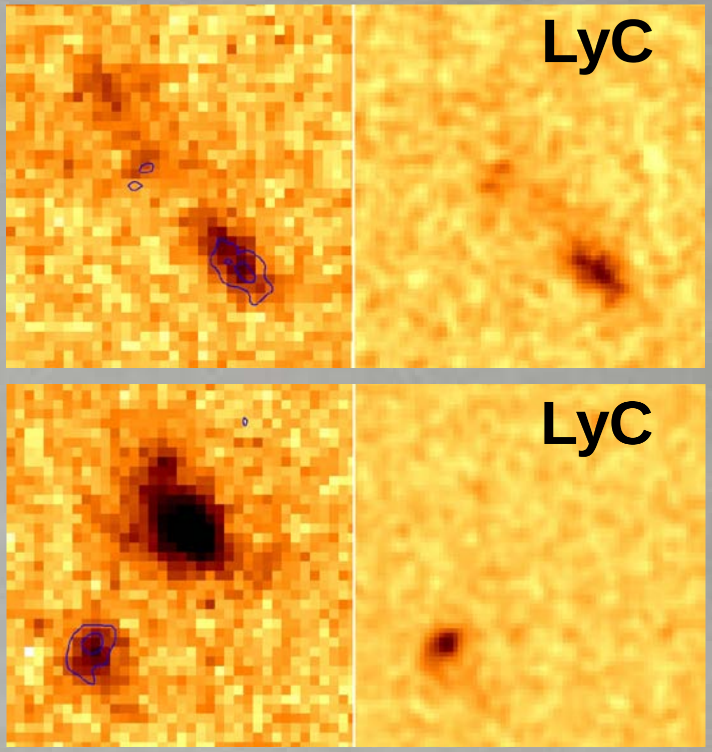
26.4 AB

27.4 AB





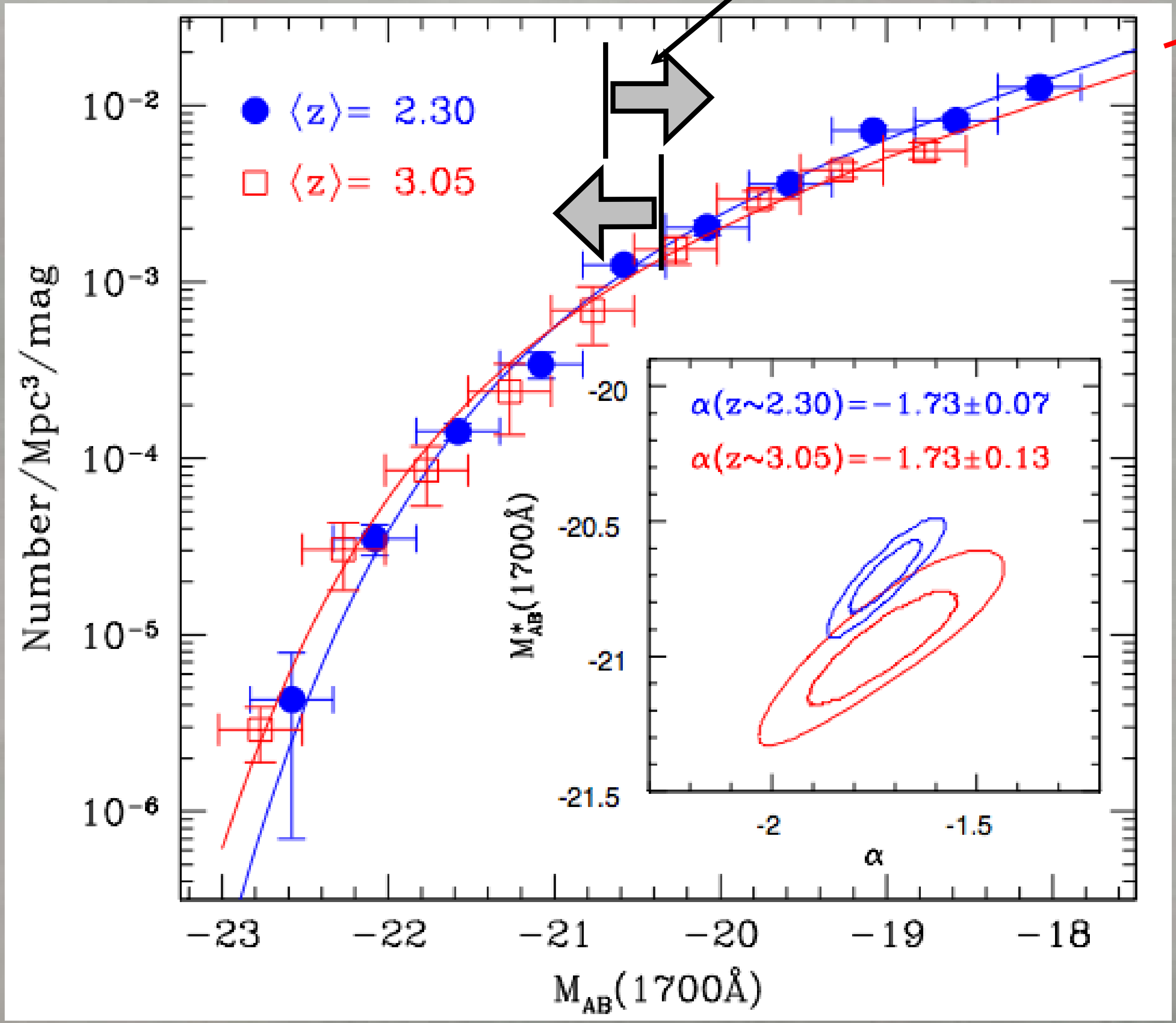
- Can now resolve LyC escaping from galaxies.
  - 6 of 20 candidate detections
  - 2 NOT confirmed
- Not from brightest galaxies
  - But LyC emissivity VERY high in some regions, contrary to models
- LyC not coming from bright LBGs



- Stay Tuned! (Siana et al. 2011, in prep)

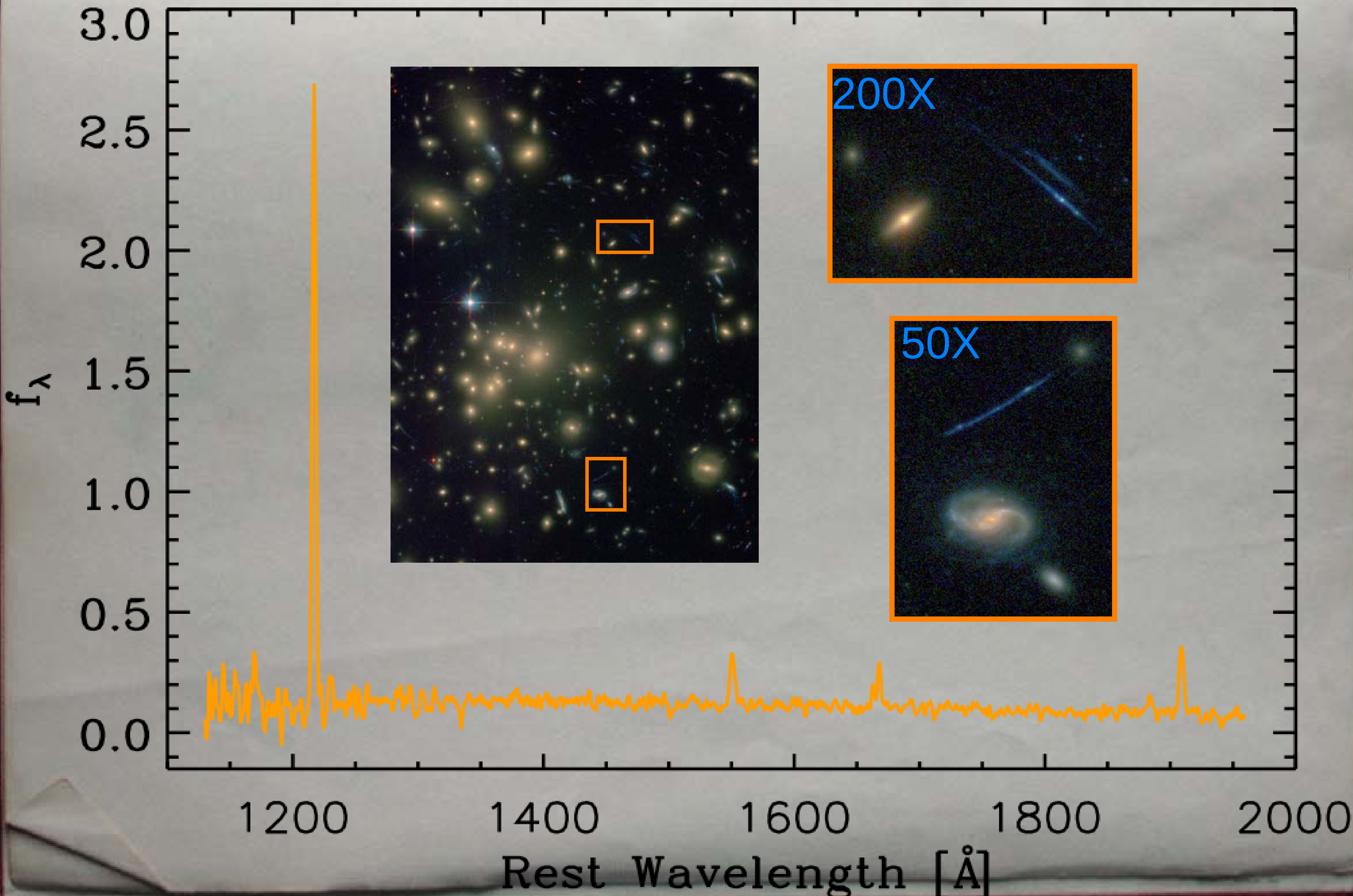
The Real Action

97% of unobscured UV luminosity density



Reddy & Steidel 2009

A1689


3.0
2.5
2.0
1.5
1.0
0.5
0.0
f_λ
200X
50X
1200
1400
1600
1800
2000
Rest Wavelength [Å]

CANDELS

Cosmic **A**ssembly **N**ear-infrared **D**eep **E**xtragalactic **L**egacy **S**urvey

Co-PIs:
S. Faber

University of California Santa Cruz

H. Ferguson

Space Telescope Science Institute

And 100 co-Is !!

CANDELS Overview

- WFC3 Imaging Survey + Supernova Search
- Wide + Deep Wedding Cake Strategy
  - Wide – 2 orbit depth covering ~0.2 sq. deg.
  - Deep – 12 orbit depth covering ~0.04 sq. deg.
- Covering 5 SEDS Fields
  - Wide: EGS, COSMOS, & UDS
  - Deep: GOODS-S + GOODS-N
- 902 orbits allocated, 152 for SNe follow-up

“Documenting the first third of galactic evolution”

- Imaging data for 250,000 galaxies from z=1.5-8
- Detect at least ~8 high-z supernovae (z>1.5)

<u>Wide Science</u>

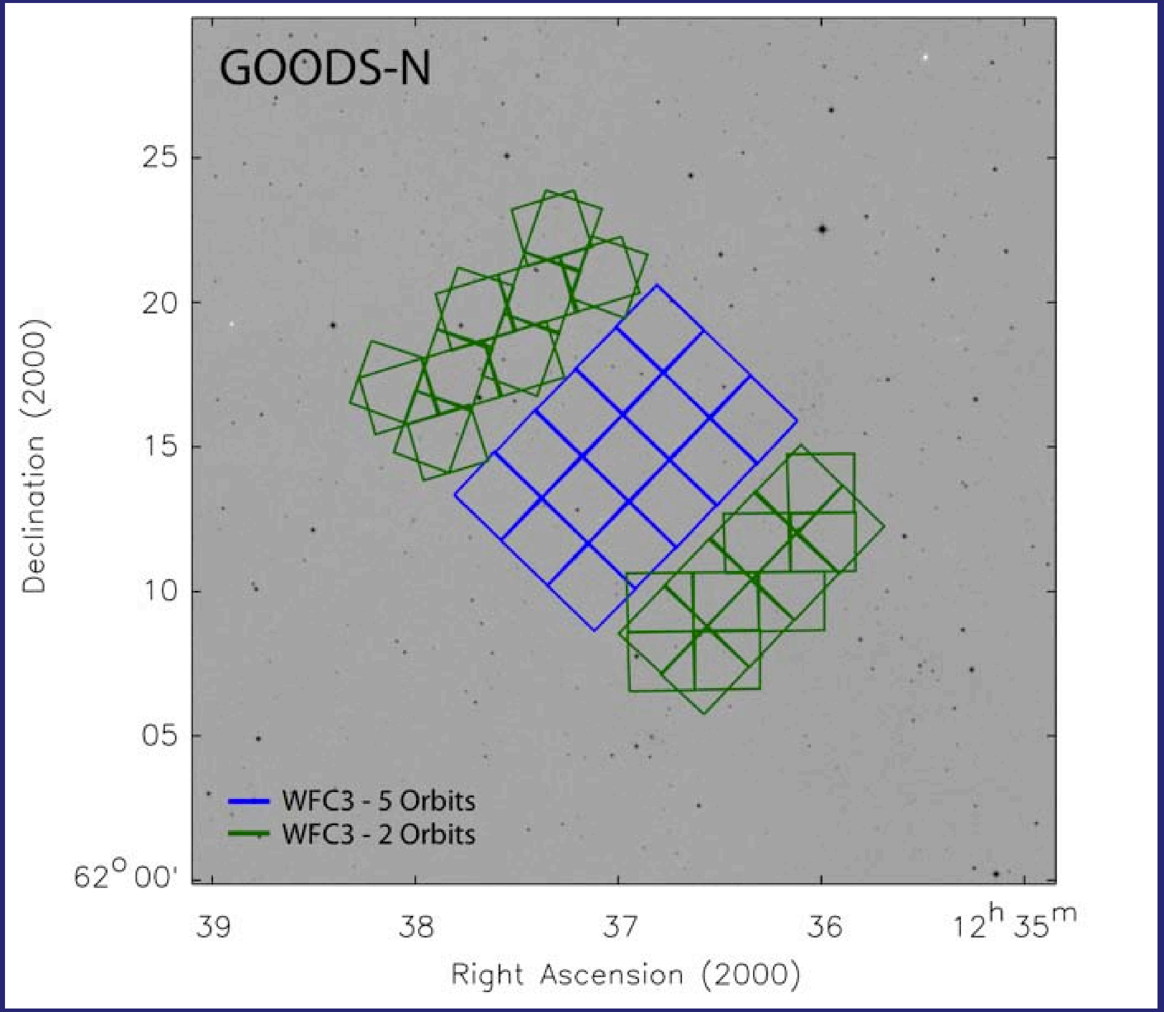
- Measure the growth and evolution of spheroids, bulges and disks.
- Quantify merger activity at z~2 for the first time.
- Properties of AGN hosts and triggering mechanisms
- Supernova search.

<u>Deep Science</u>

- Assess contribution of faint galaxies to reionization
- Properties of the earliest star-forming regions & galaxy interactions
- Structural properties, stellar masses, and environments of earliest identifiable non-QSO AGN.
- Supernova search.

UV observations

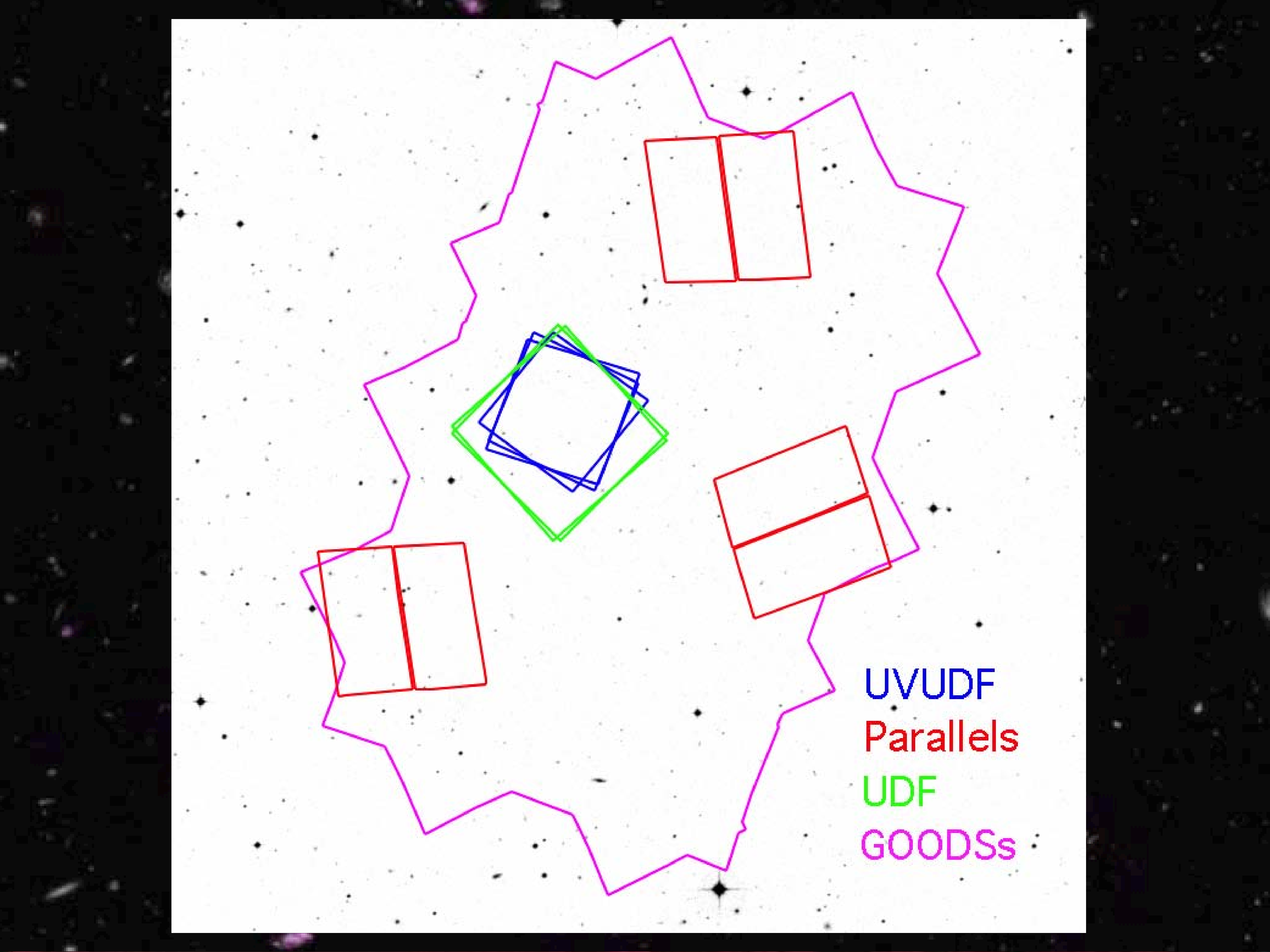
- Day-side UV obs
- 100 orbits
  - F275W, F336W



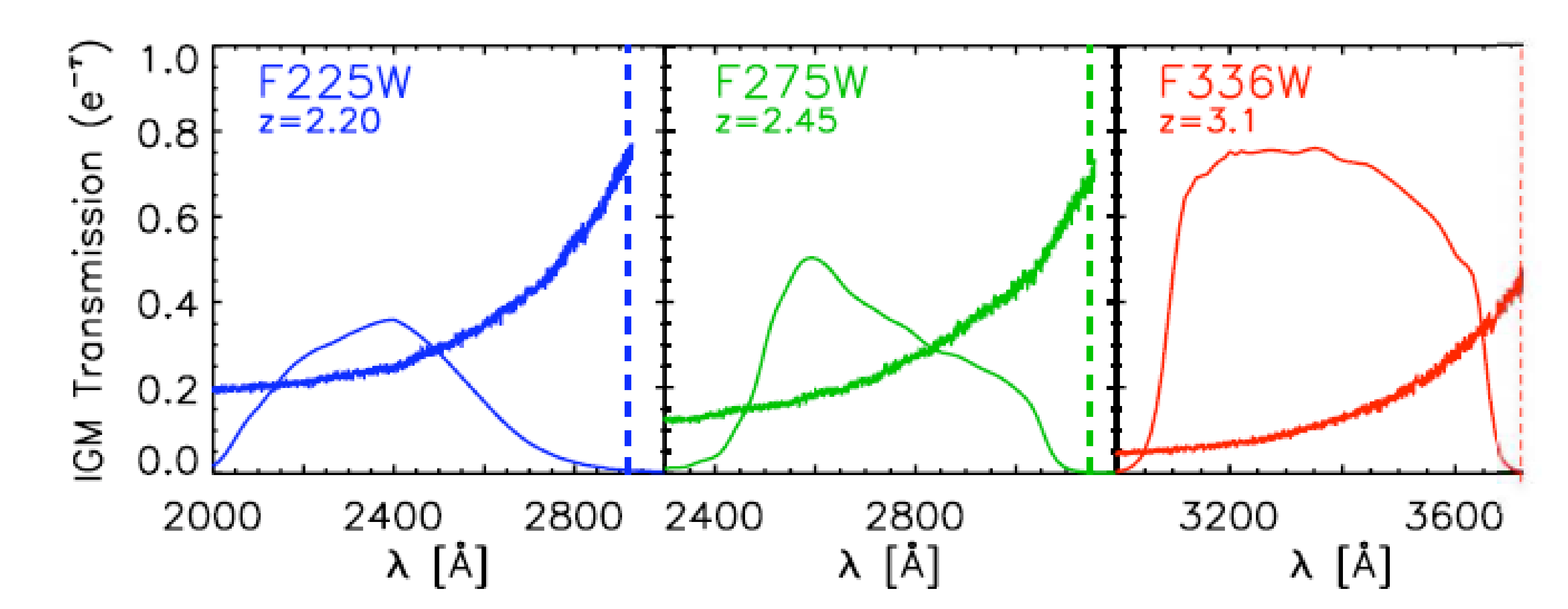
- Constrain the *absolute* Lyman-continuum escape fraction for galaxies at z~2.5, with resolved imaging of LyC

The Ultra-violet Ultra-deep Field

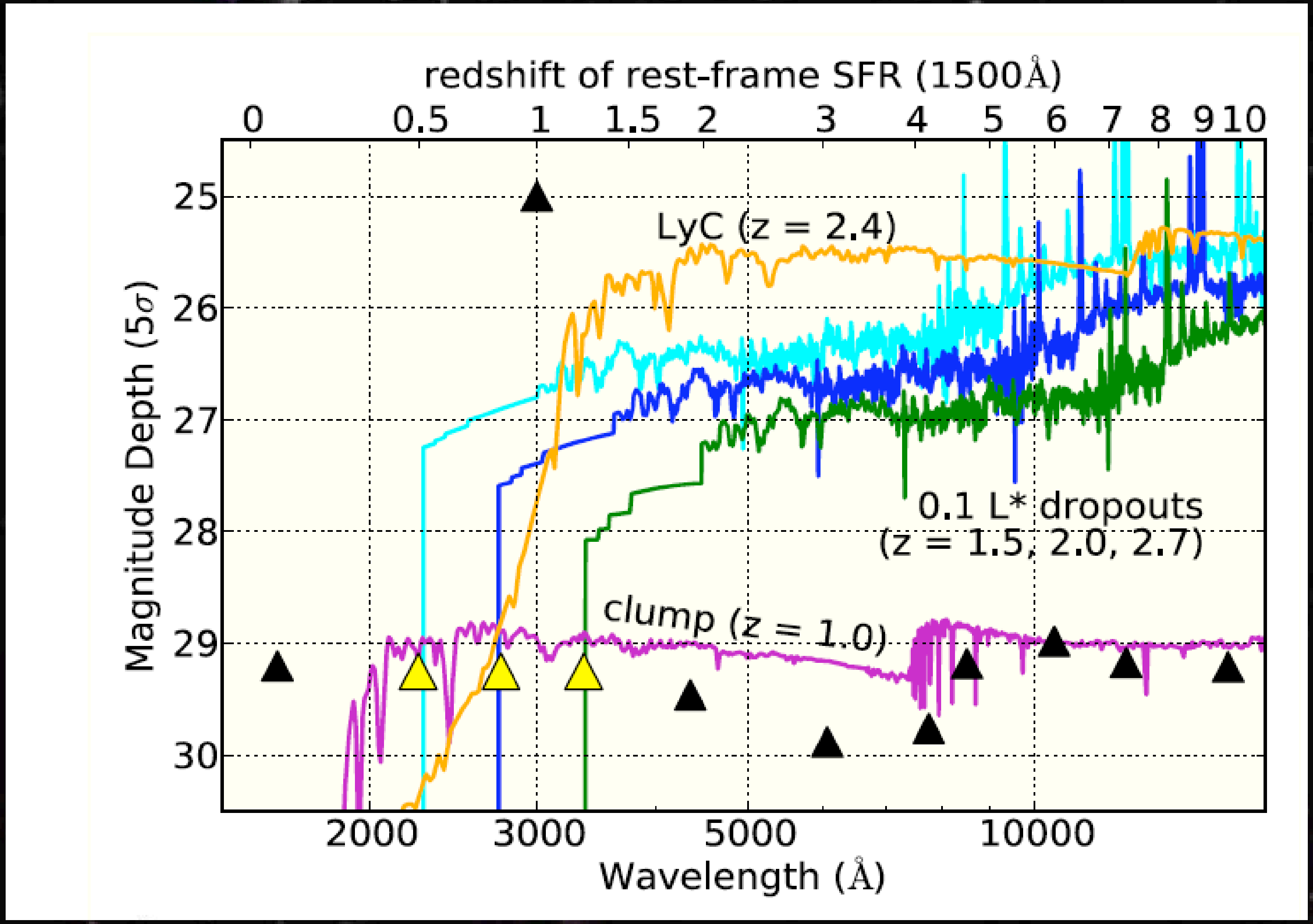
- WFC3/UVIS F225W, F275W, F336W
  - 90 orbits in Cycle 19 (February – October 2012)
  - 2x2 binning of the CCD in F225W & F275W
  - covers NIR FOV; 3 separate ORIENTs
- Treasury science benefits
  - **f(esc) at z~2**
  - greatly improved photo-z
  - Sub-galactic clumps at z~1
  - Star formation efficiency in LBGs


UVUDF
Parallels
UDF
GOODSs

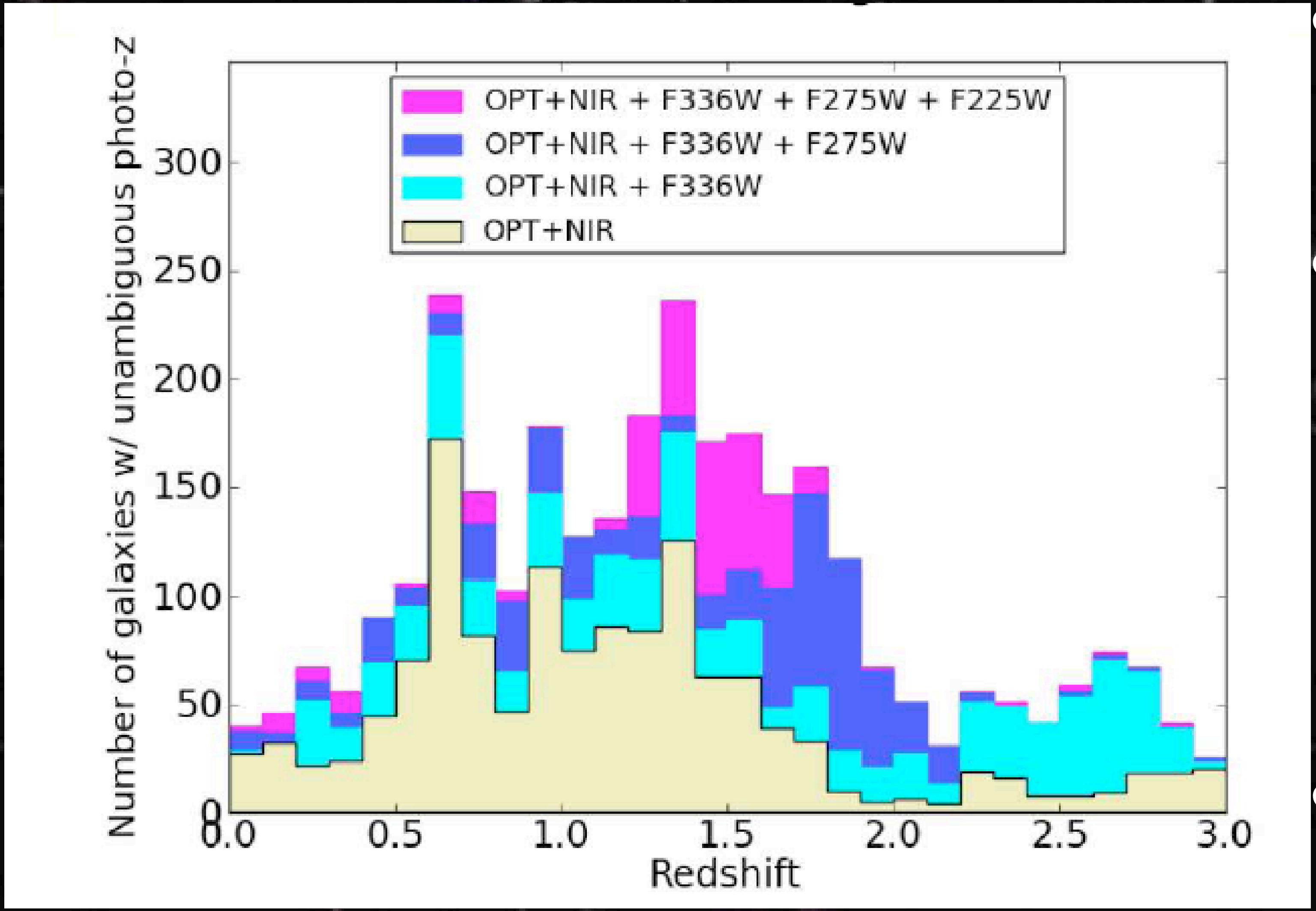
The Ultra-violet Ultra-deep Field



The Ultra-violet Ultra-deep Field

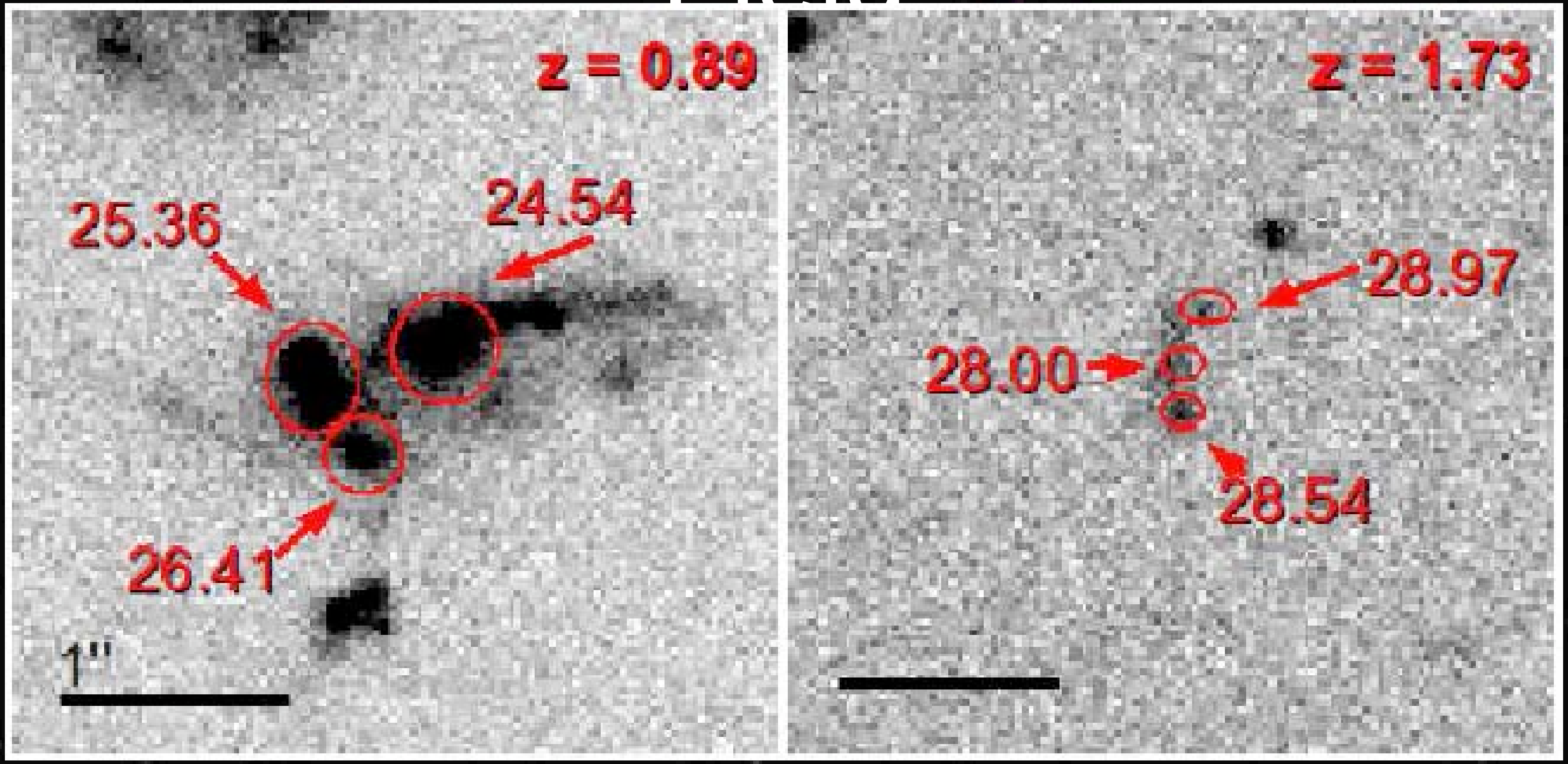


The Ultra-violet Ultra-deep Field



- Resolve redshift ambiguities for >1000 galaxies
- NUV filters needed to sample Lyman break
- Predictions based on Coe et al. (2006)

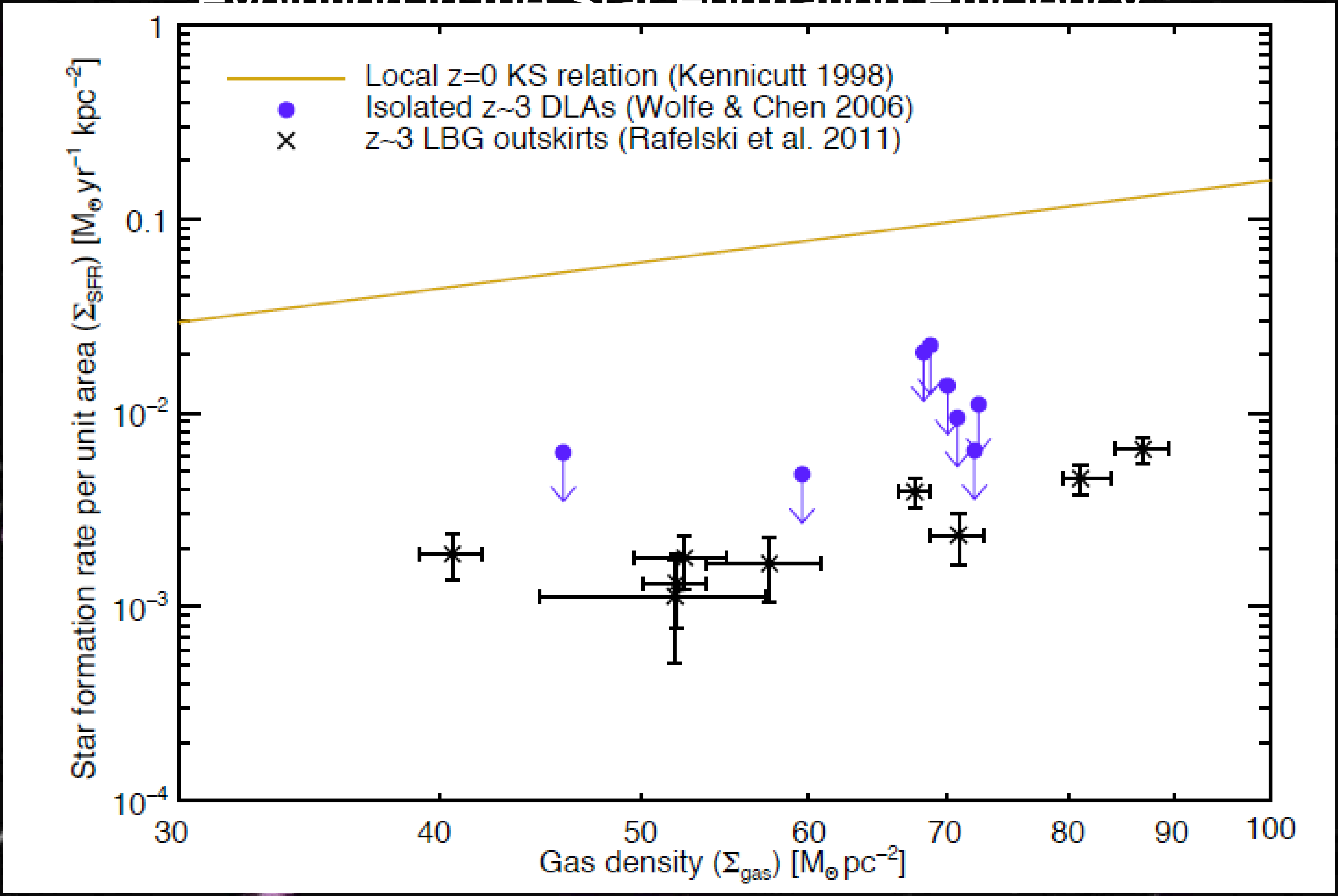
The Ultra-violet Ultra-deep Field



- Sub-galactic clumpy structure: signatures of disks in formation (e.g. Elmegreen et al. 2008)
- NUV data will allow us to trace clump evolution to later time
  - (700 pc resolution at $0.5 < z < 1.5$)
- WFPC2 U-band UDF hints at larger clumps at $z<1$ (Voyer et al. 2012, in prep)

The Ultra-Violet Ultra-deep Field

Evolution in the Star Formation Efficiency

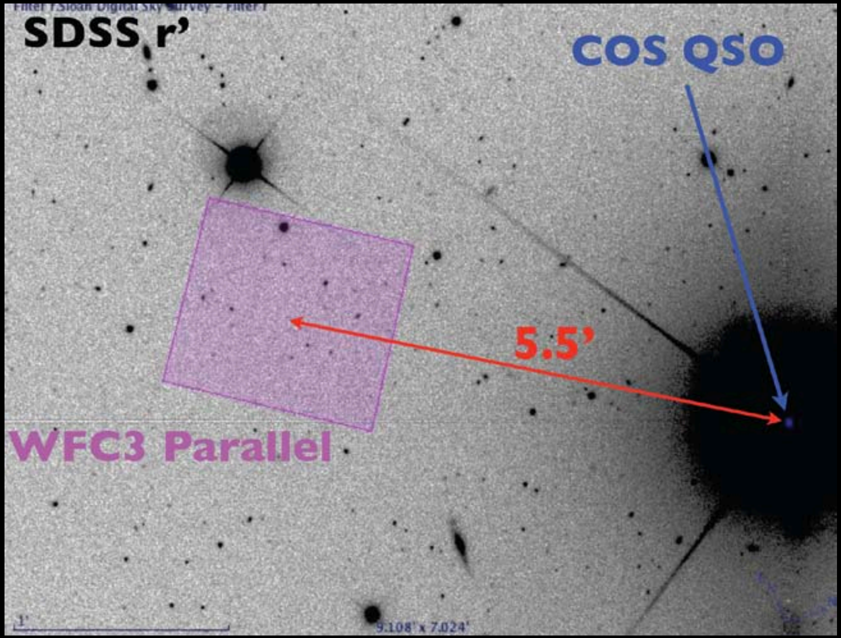


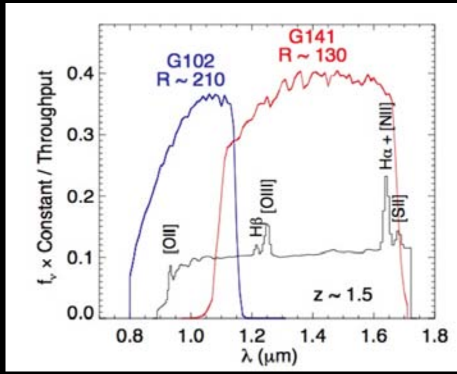
WFC3 Infrared Spectroscopic Parallel Survey (WISP)

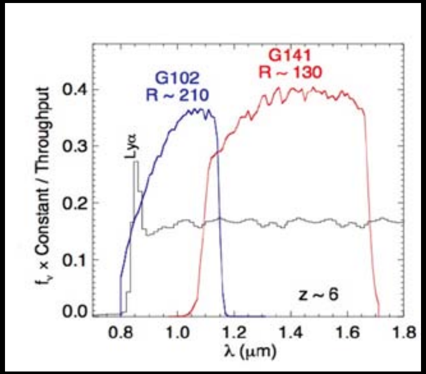
Malkan (PI), McCarthy, Teplitz, Atek, Colbert, Henry, Rafelski, Ross, Siana, Scarlata, Dressler, Martin, Fosbury, Bunker

WISP
WFC3 Infrared Parallel Survey

The strategy







1. Pure parallel IR search: diagnostic lines accessible at higher redshifts;

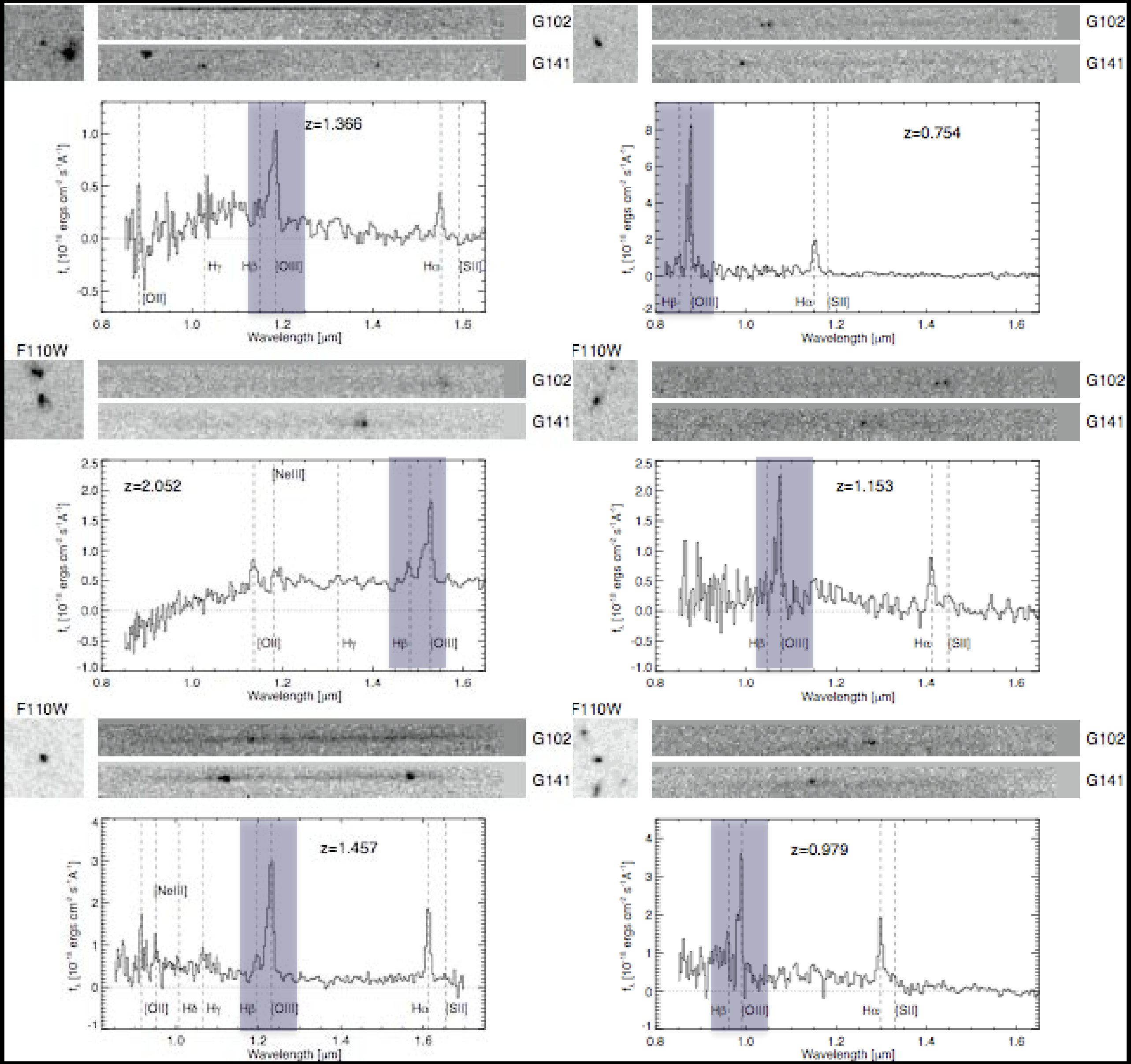
2. Both grisms, IR+UVIS B/I in long visits (>5 orbits) G141 only, otherwise;

3. Continuous spectral coverage samples large 3D volume in multiple lines (~1Mpc^3 @ z=1-2)

WISP

WFC3 Infrared Parallel Survey

The Data

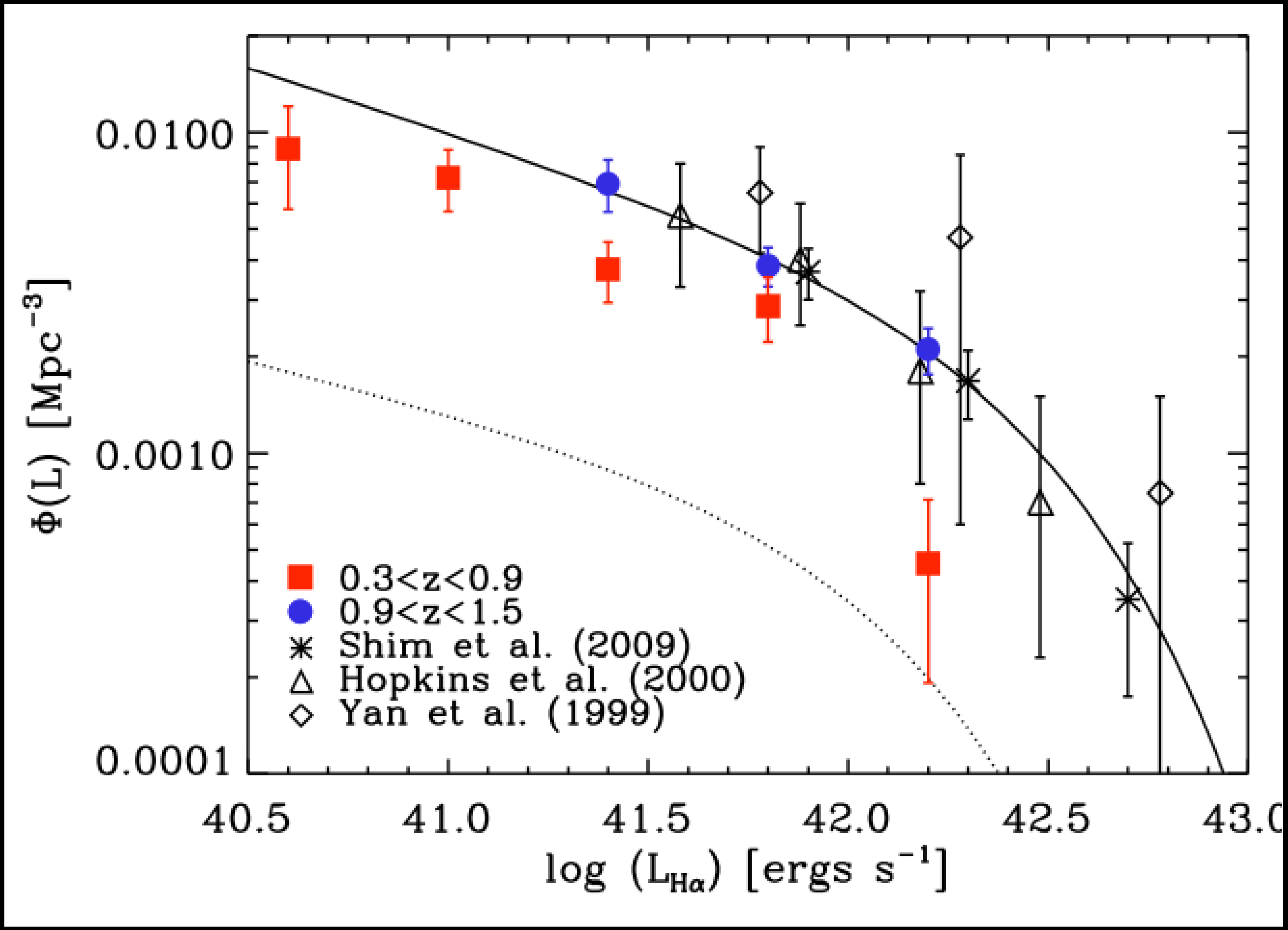


Combination of two (overlapping) grisms gives wide spectral coverage (0.8--1.7μm)

Excellent focus (~2 pixels) means that we resolve [OIII]5007/4959 lines
 in compact galaxies

We project the survey will detect 2000 Ha emitters, 750 [OIII] emitters

The depth



Colbert et al. & Bunker et al in prep

WISP is so sensitive to faint Hα at z=0.9--1.3 (Red) that it reaches the same dwarf starbursts at the bottom of the *local* (z~0) LF

Useful predictions for future wide-area IR surveys

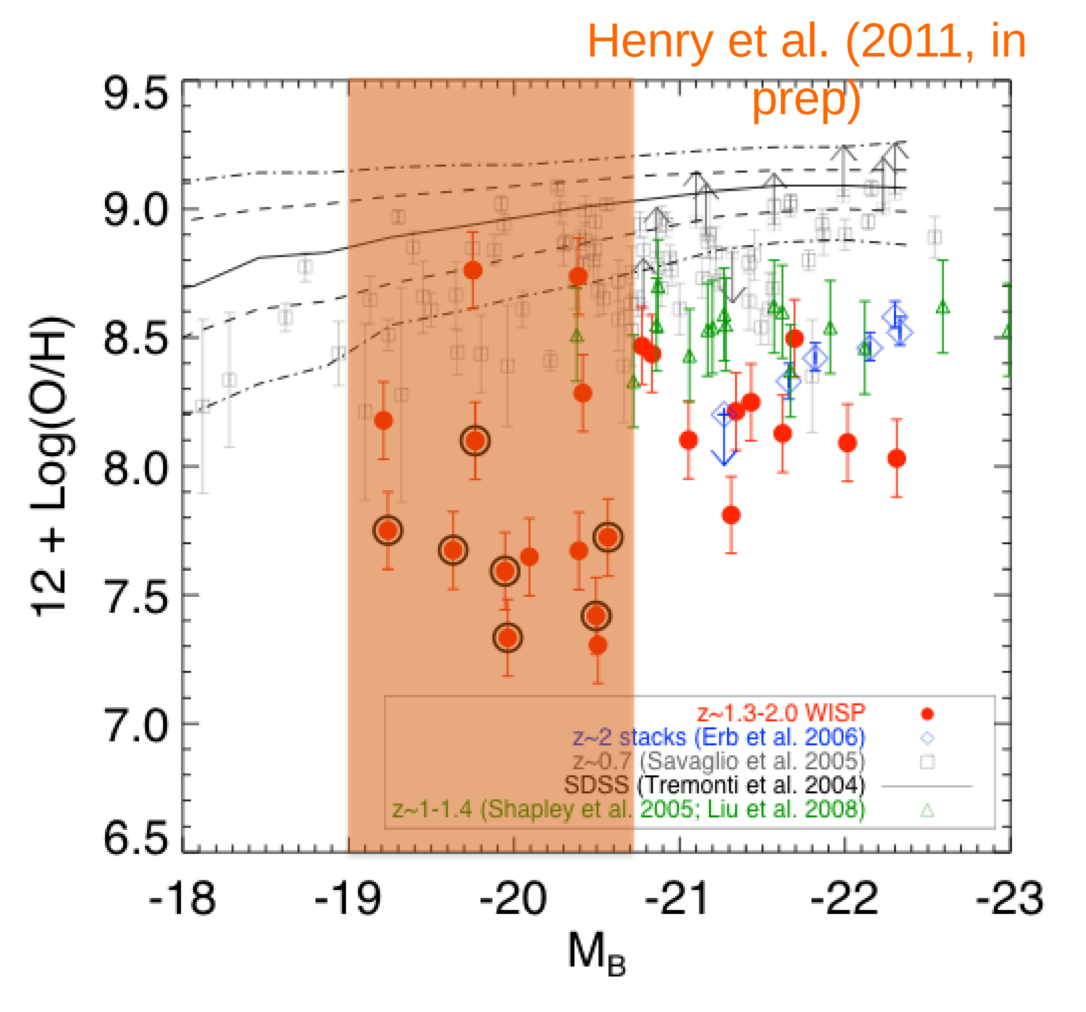
Luminosity-metallicity

WISP
WFC3 Infrared Parallel Survey

WISP will measure R_{23} for ~70 galaxies in the 1.3<z<2, and will extend the metallicity measurements to much lower masses, and metallicities.

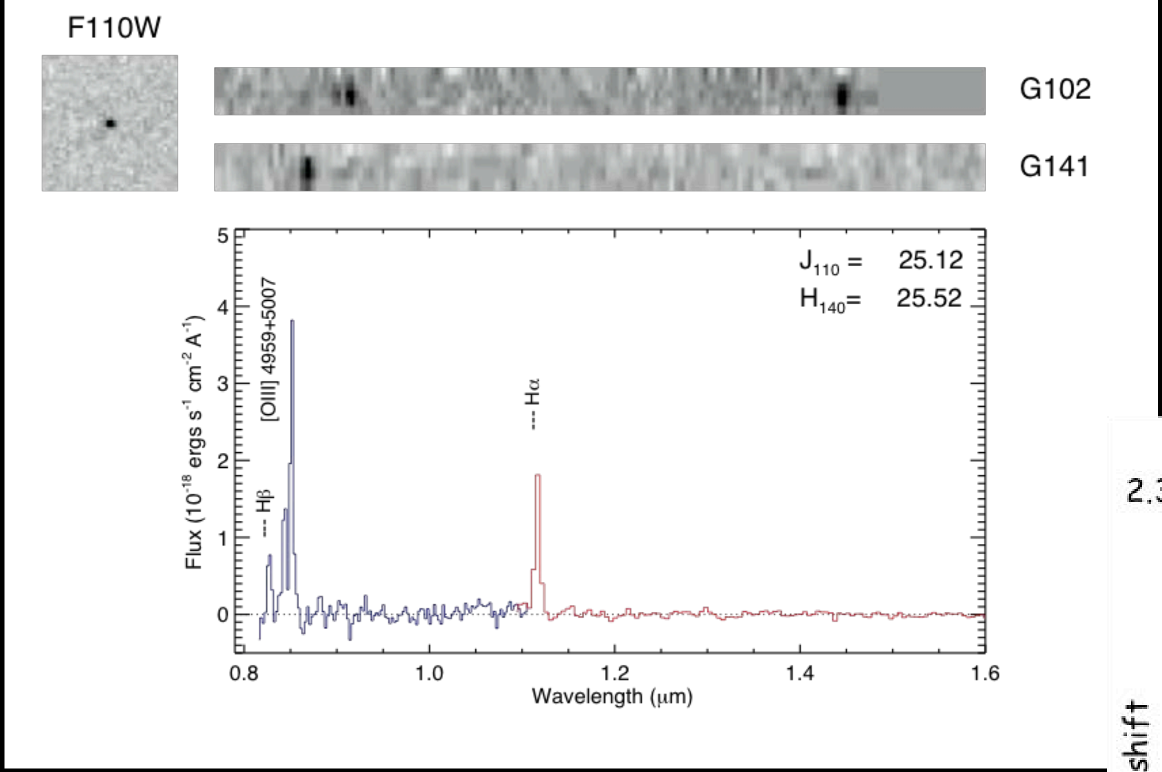
Measure the evolution of the mass/metallicity/SSFR fundamental plane (Mannucci et al. 2010)

Black circles identify highest-EW starforming galaxies

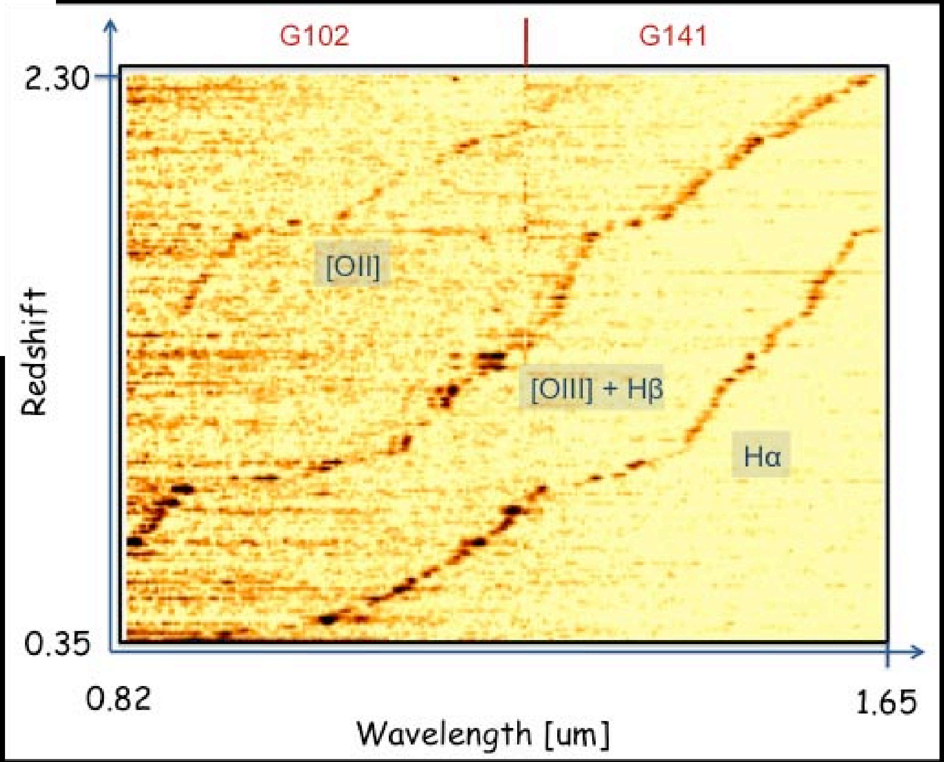


24 galaxies in 30 fields

High EW sources



Montage of 180 spectra of High-EW galaxies

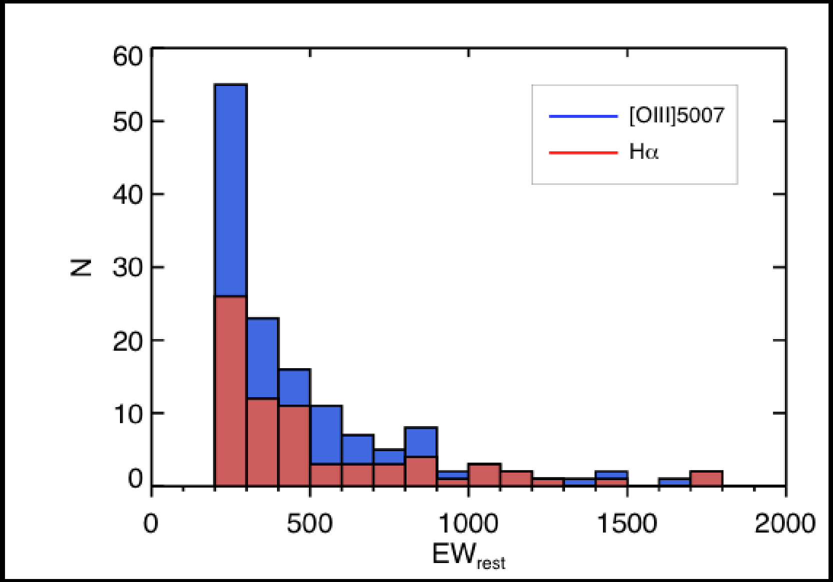


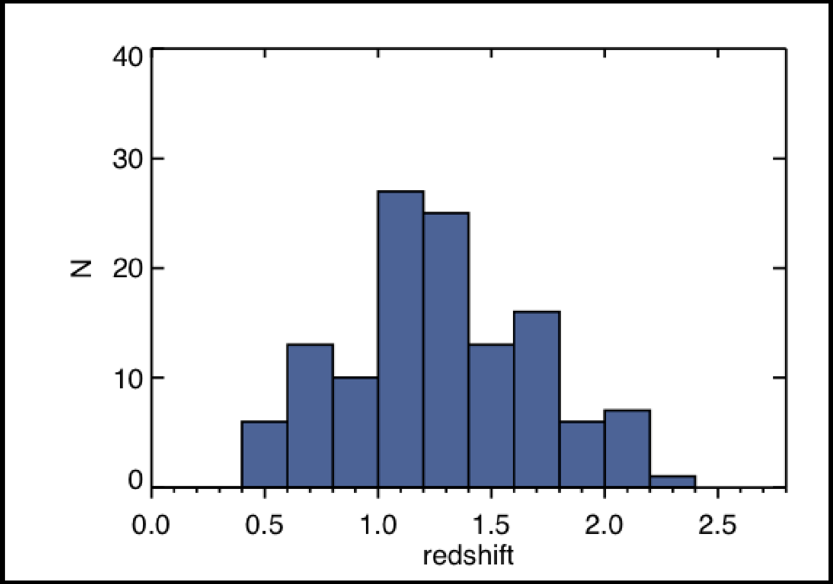
WISP

WFC3 Infrared Parallel Survey

High EW sources

WISP surveys galaxies down to emission line flux limits. We uncover a population of extremely strong emission-line galaxies with rest-frame equivalent widths much higher than 200 Å and a surface density of 1 arcmin^{-2} .WISPS covers a broad and continuous redshift



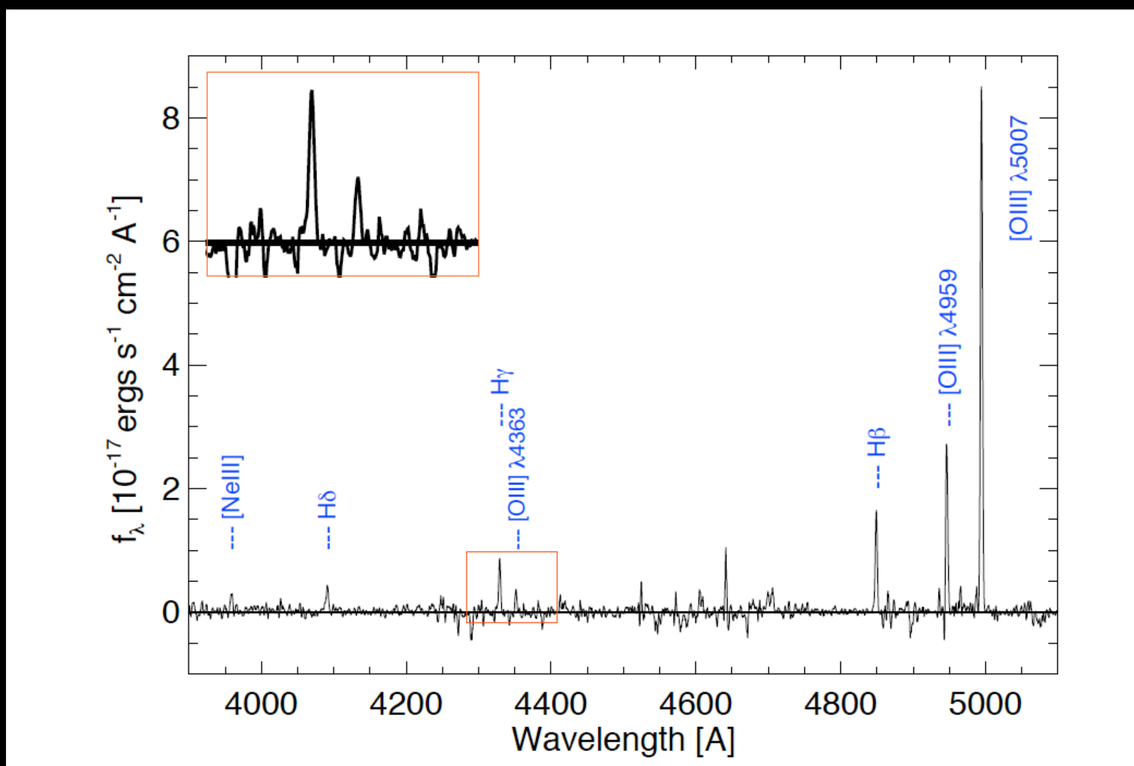


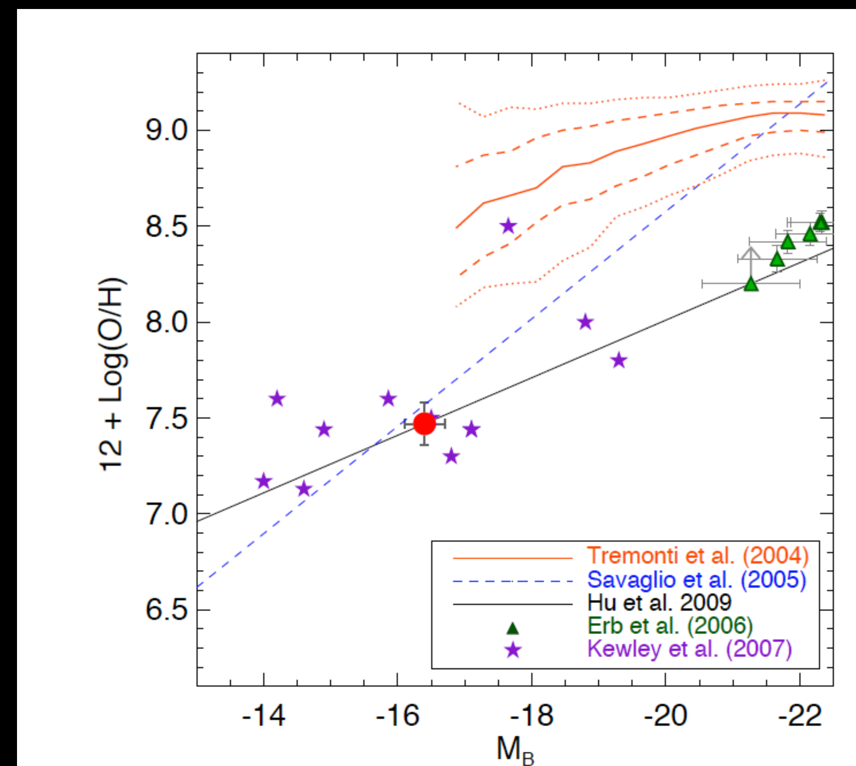
WISP

WFC3 Infrared Parallel Survey

High EW sources

The emission-line selection allows an efficient search for extremely low metallicity galaxies (XMPGs)



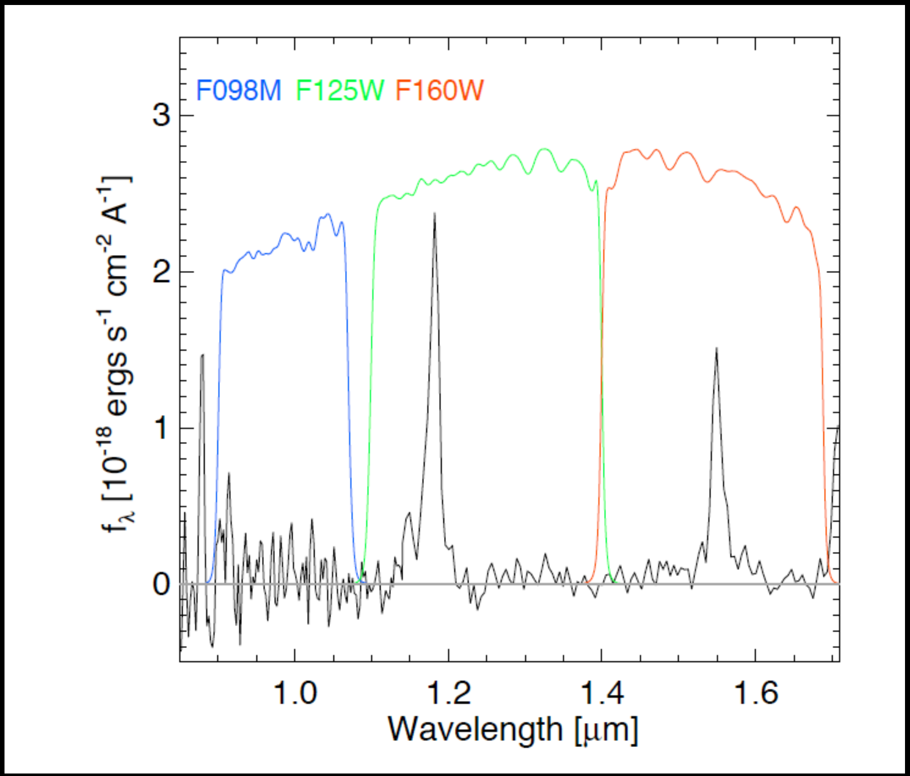


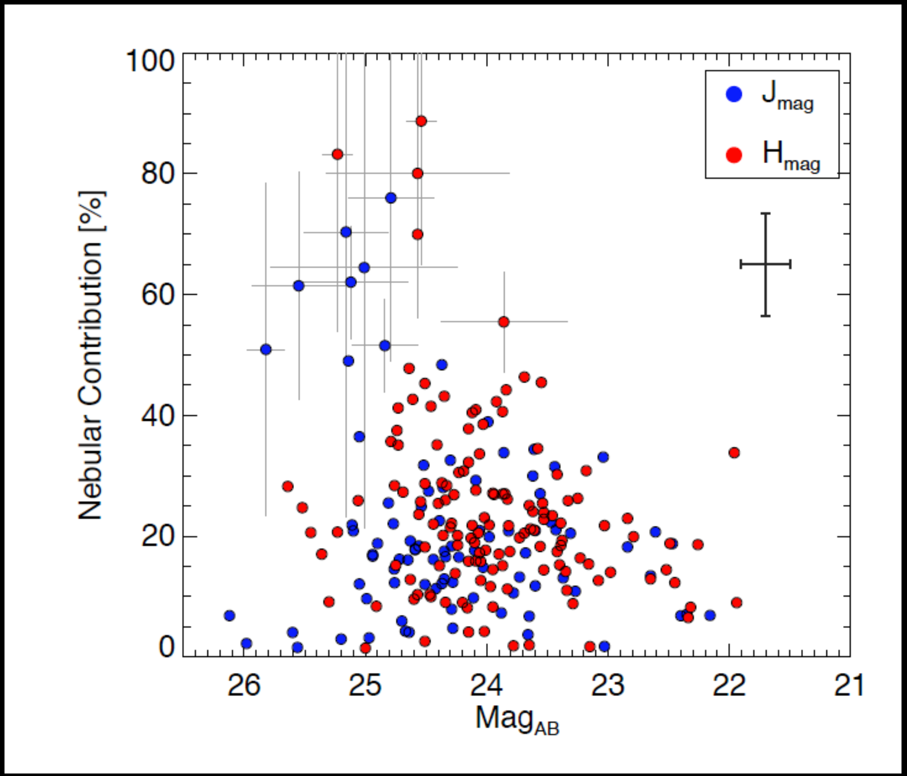
WISP

WFC3 Infrared Parallel Survey

High EW sources

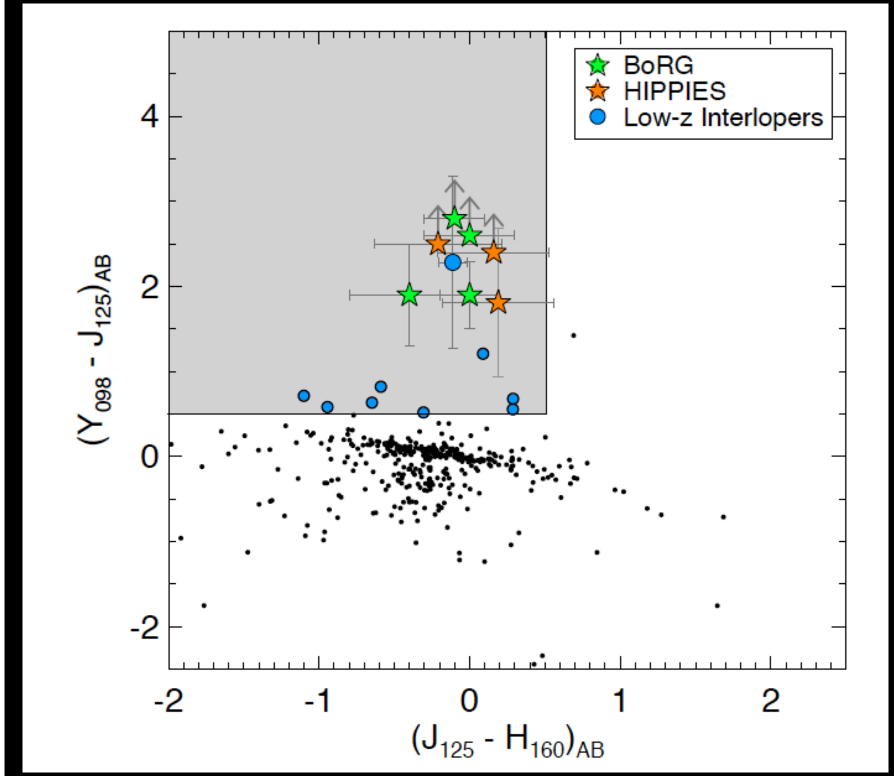
A significant number of galaxies have their nebular flux contributing to more than 20% of the total flux For some galaxies, the Hα line increases the J_{110} *flux by 1 mag.*





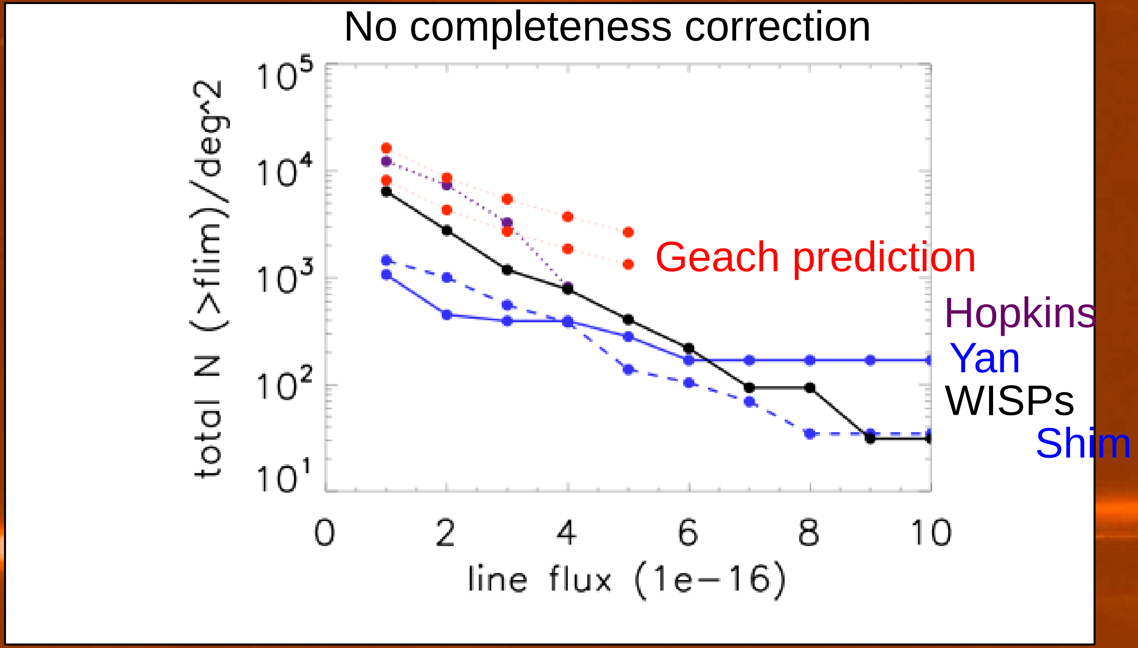
High EW sources

- The presence of strong emission lines in the dropout selection filters can mimic the Y-J and J-H colors of z~8 galaxies
- About 10% of the high-EW sample satisfy these criteria
- But, our data are not as deep as the HUDF



Predictions for Wide-field NIR Grism Surveys

- WFC3/IR grism surveys provide the best prediction of performance by future large area slitless spectroscopic surveys.



- We do not confirm the predictions based on NICMOS surveys (e.g. Geach et al.); caution is warranted.
- Stay tuned for more results at AAS!

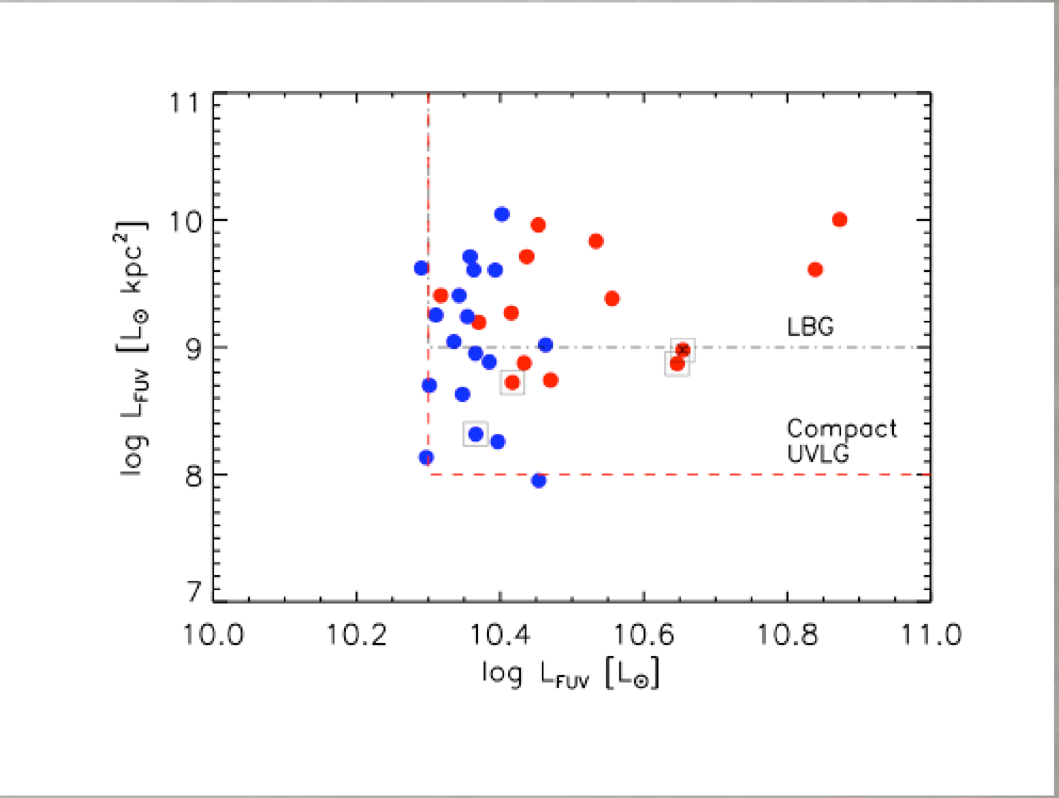
Conclusions/Summary

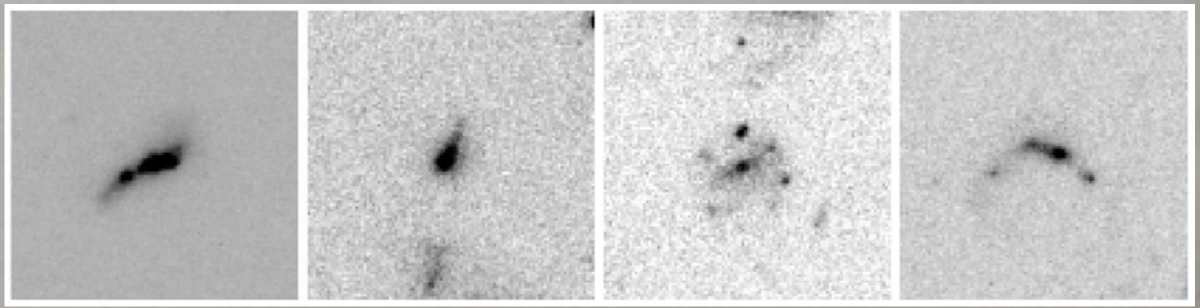
- Strong evidence that the LyC escape fraction evolves with redshift
- Low luminosity (and low metallicity) galaxies are important focus for LyC observations
- Upcoming observations will measure the *absolute* escape fraction at z~2
- HST slitless spectroscopy is discovering a population of very strong line-emitting sources, including low metallicity galaxies
- HST provides the best prediction of future large-area NIR slitless spectroscopic surveys

Backup Slides

HST Far-UV Prism z=0.7 LBG Analogs

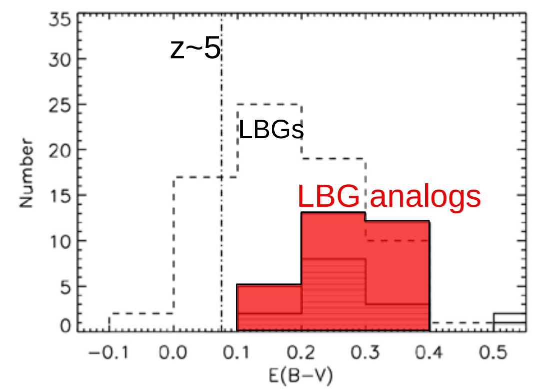
- LBG Analogs (L_{UV} and Surface Brightness, Hoopes et al. 2006)
  - GALEX luminosities
  - HST sizes
  - Selected with photo-z, confirmed at Palomar
- Target selection
  - 32 Objects (3-5 orbits each) selected in COSMOS
  - Range of morpohologies
- Measure f_{850}/f_{1050}
  - scale FUV to f_{1500} with fit to SED
- No detections in 30 objects

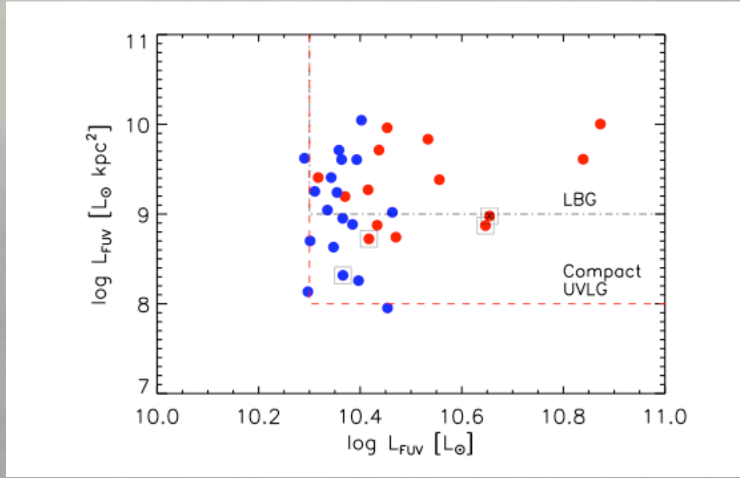




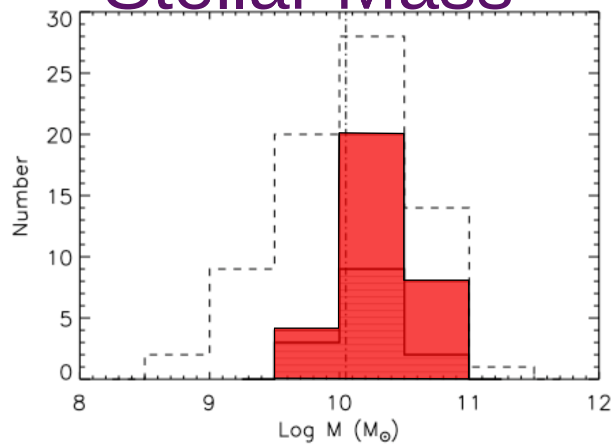
Comparison of z~1 sample with z~3 LBGs

Extinction

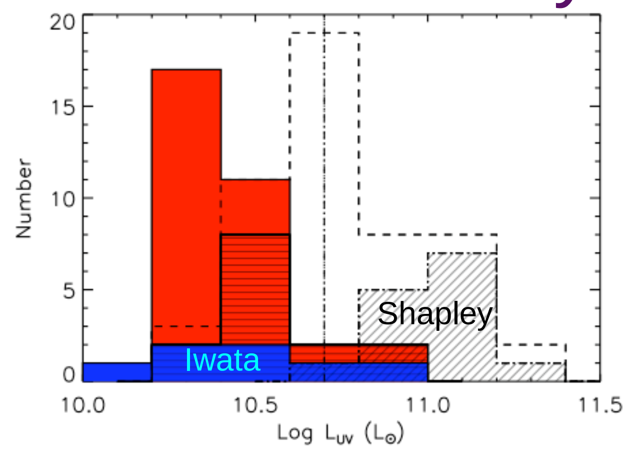




Stellar Mass



FUV Luminosity



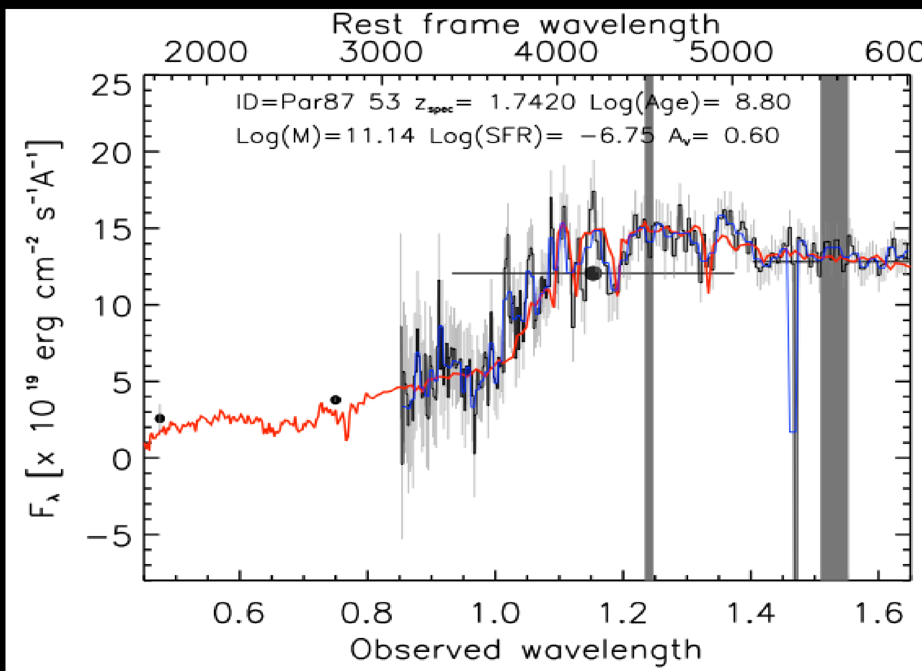
Note: Bogosavljevic et al. (2009) suggest that fesc is higher in lower luminosity LBGs (still very luminous to be in LBG sample)

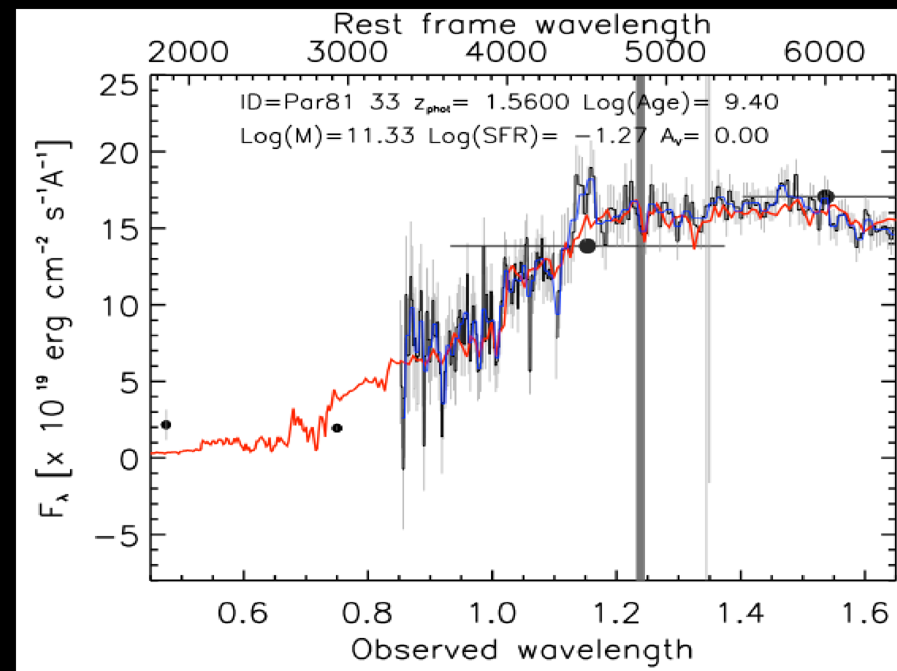
WISP

WFC3 Infrared Parallel Survey

Passive Galaxies

Among the ‘brighter’ WISP galaxies, MANY have Identifiable *absorption line spectra*, especially the HK/Balmer break, so our survey will not miss the massive ‘red/dead’ population.

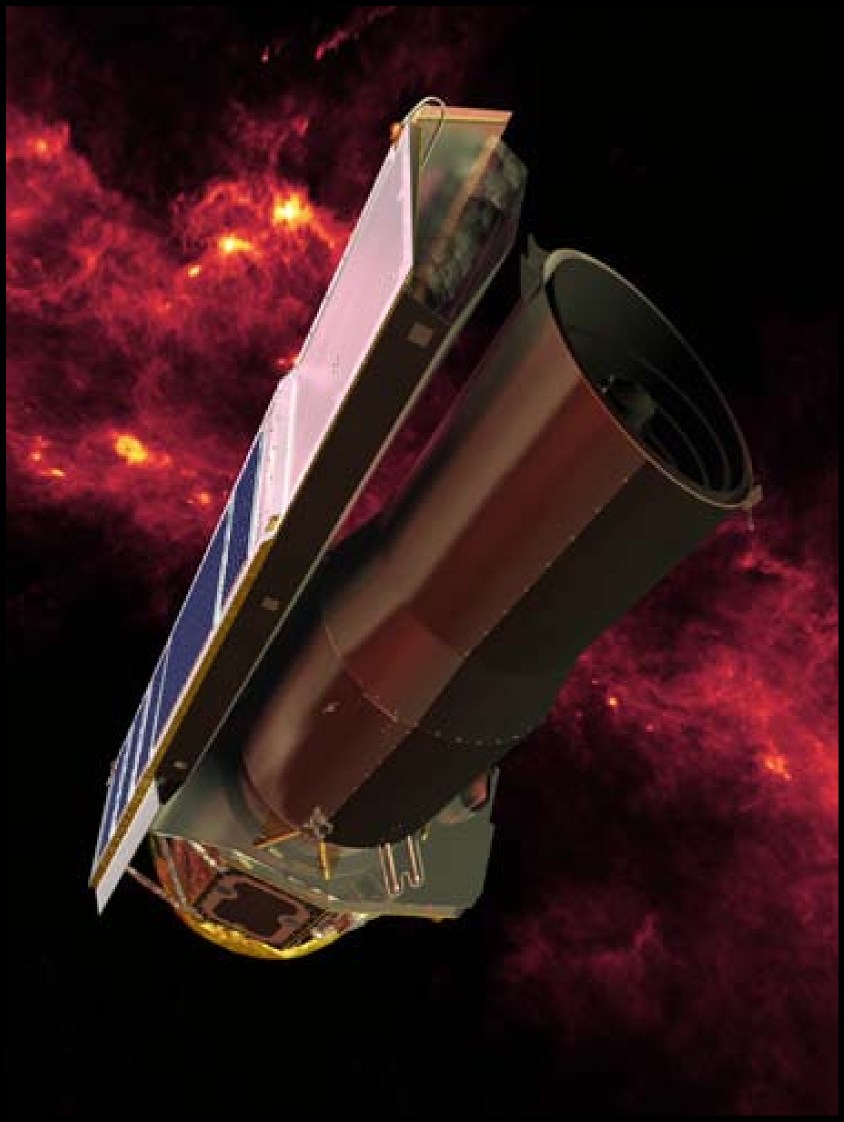




Scarlata et al 2011, in prep

We can now derive accurate parameters for the stellar population ➔ ages, masses, dust content, star-formation histories

Spitzer Follow-up



IRAC 3.6 micron imaging of 60 fields that have G102 and G141 spectroscopy

30 minutes integration per field

Greatly improves mass estimation