Measuring the evolution of the star formation rate efficiency of neutral atomic hydrogen gas from z ~1– 4

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Galactic Scale Star Formation
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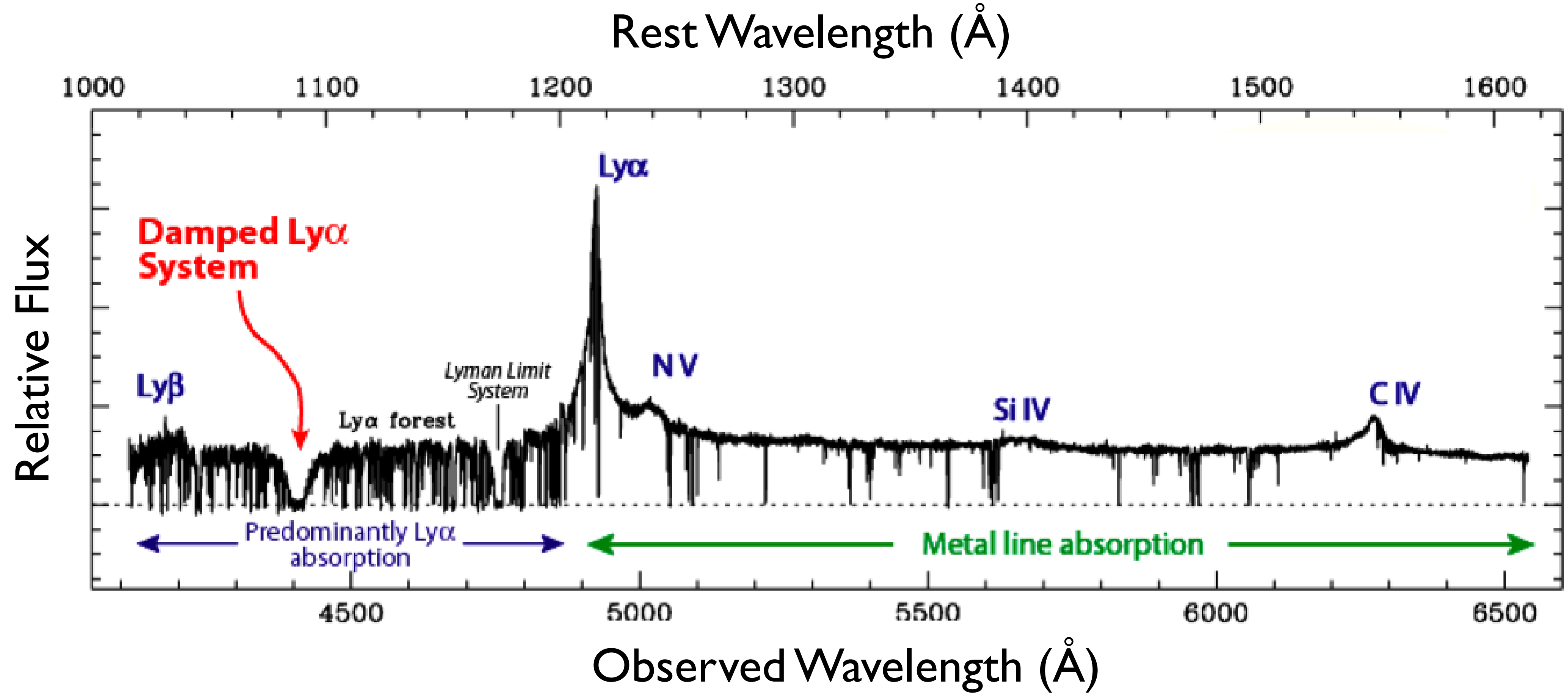
Damped Lyman Alpha Systems (DLAs)



- Definition of Damped Lyα System (DLA): $N(HI) \geq 2 \times 10^{20}$ cm^{-2}
- Distinguishing characteristics of DLAs :
  - (1) Gas is Neutral
  - (2) Metallicity is low: [M/H]=-1.3 (more on this later)
  - (3) Molecular fraction is low: $f_{H2} \sim 10^{-5}$
- DLAs dominate the neutral-gas content of the Universe out to z~4.5
- DLAs cover 1/3 of the sky at z=[2.5,3.5]

Wolfe et al. 2005

Kennicutt-Schmidt (KS) Relation

$$\Sigma_{\mathrm{SFR}} = A\Sigma_{\mathrm{gas}}^{N}$$

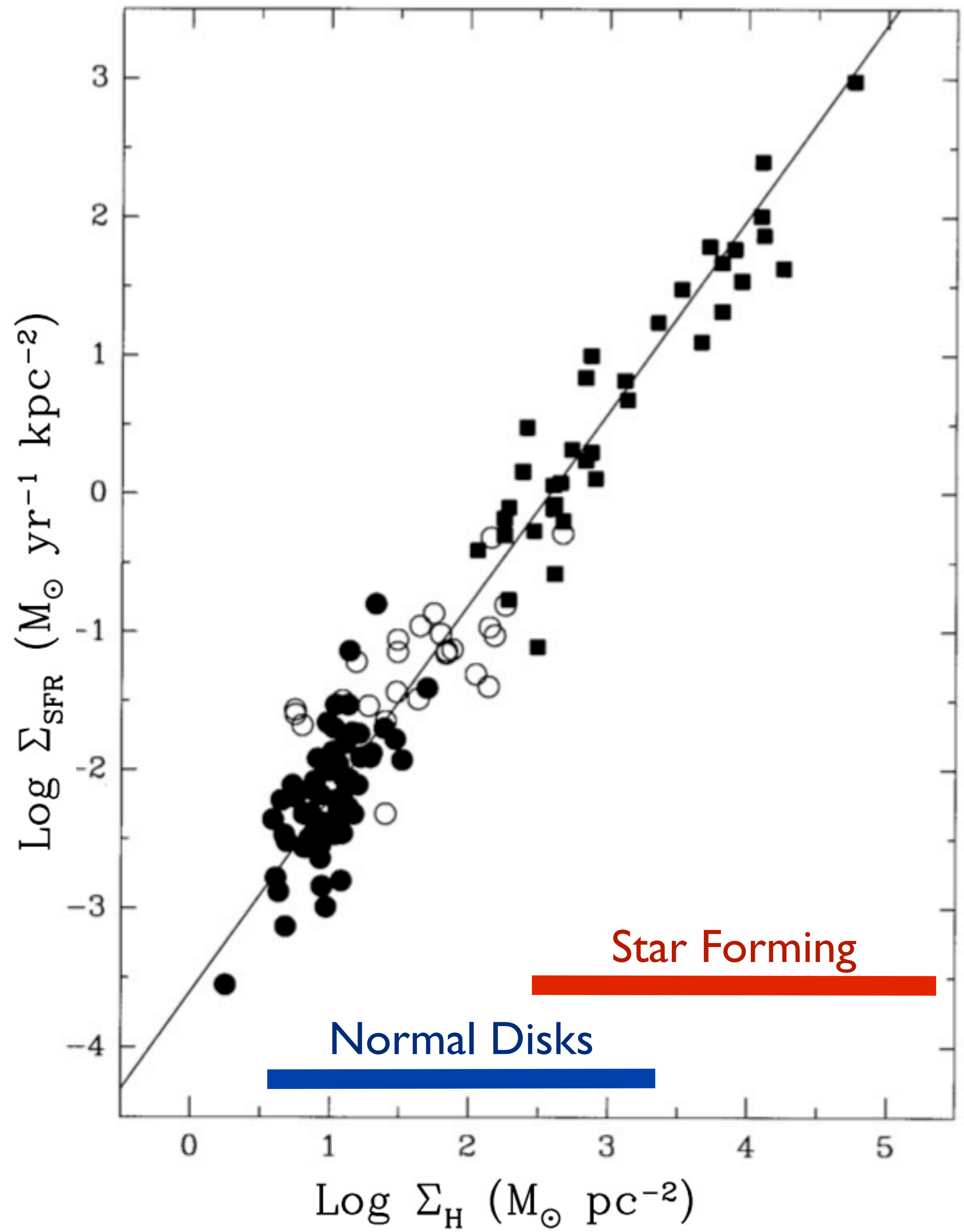
The Star Formation Rate (SFR) surface density goes as the total gas surface density to a power law

Can rewrite it with column density N:

$$\Sigma_{\mathrm{SFR}} = K \times (N/N_c)^{\beta}$$

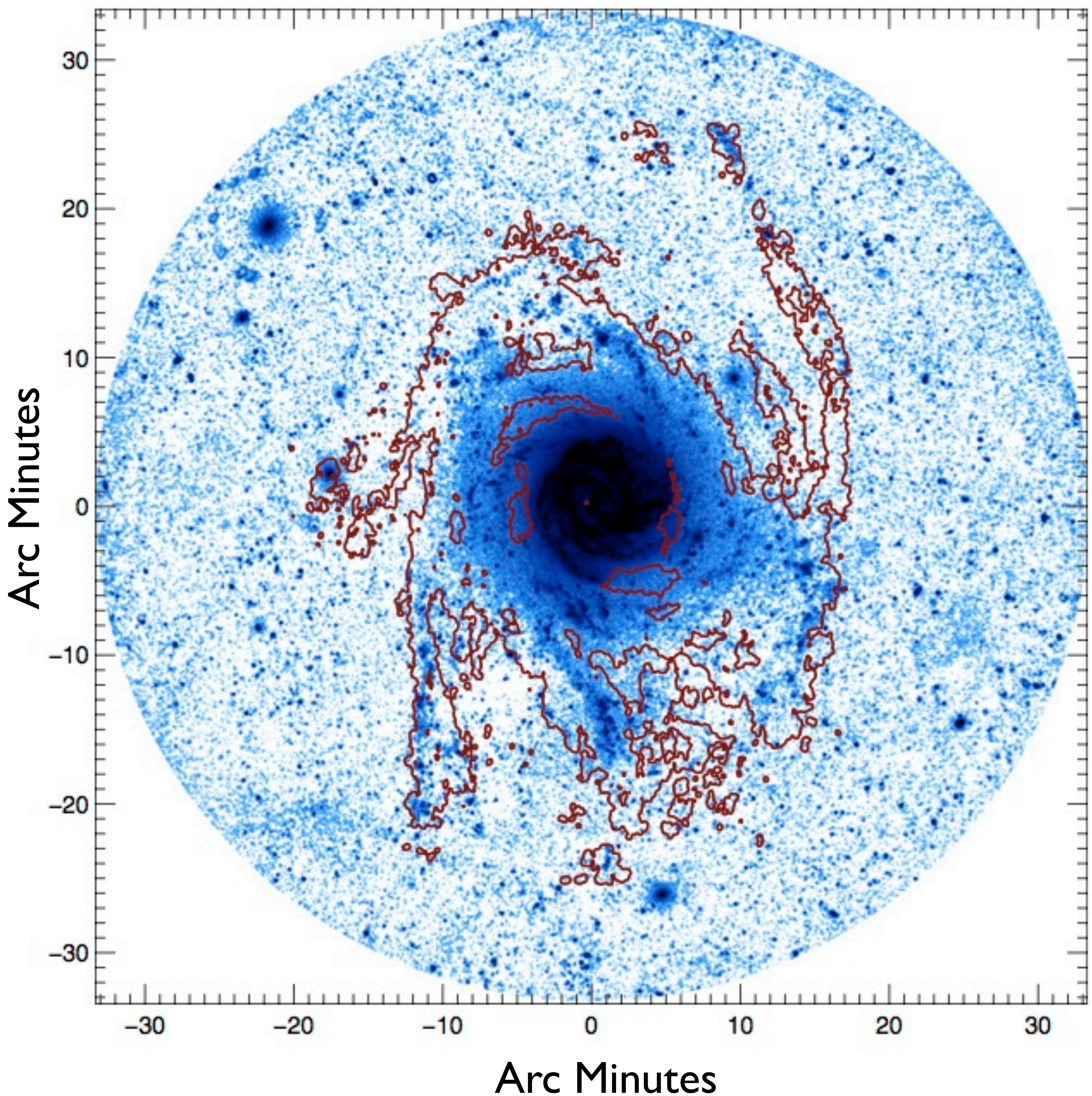
$N_c = 1.25 \times 10^{20}\ \mathrm{cm}^{-2}$ $\beta = 1.4 \pm 0.15$

$K = 2.5 \times 10^{-4} M_\odot\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$



Kennicutt, 1998

Tightly Correlated HI and FUV emission in M83



Blue: FUV map (GALEX)

Red: HI contours (THINGS)

Bigiel et al. 2010a

Can we see DLAs in emission at z~3?

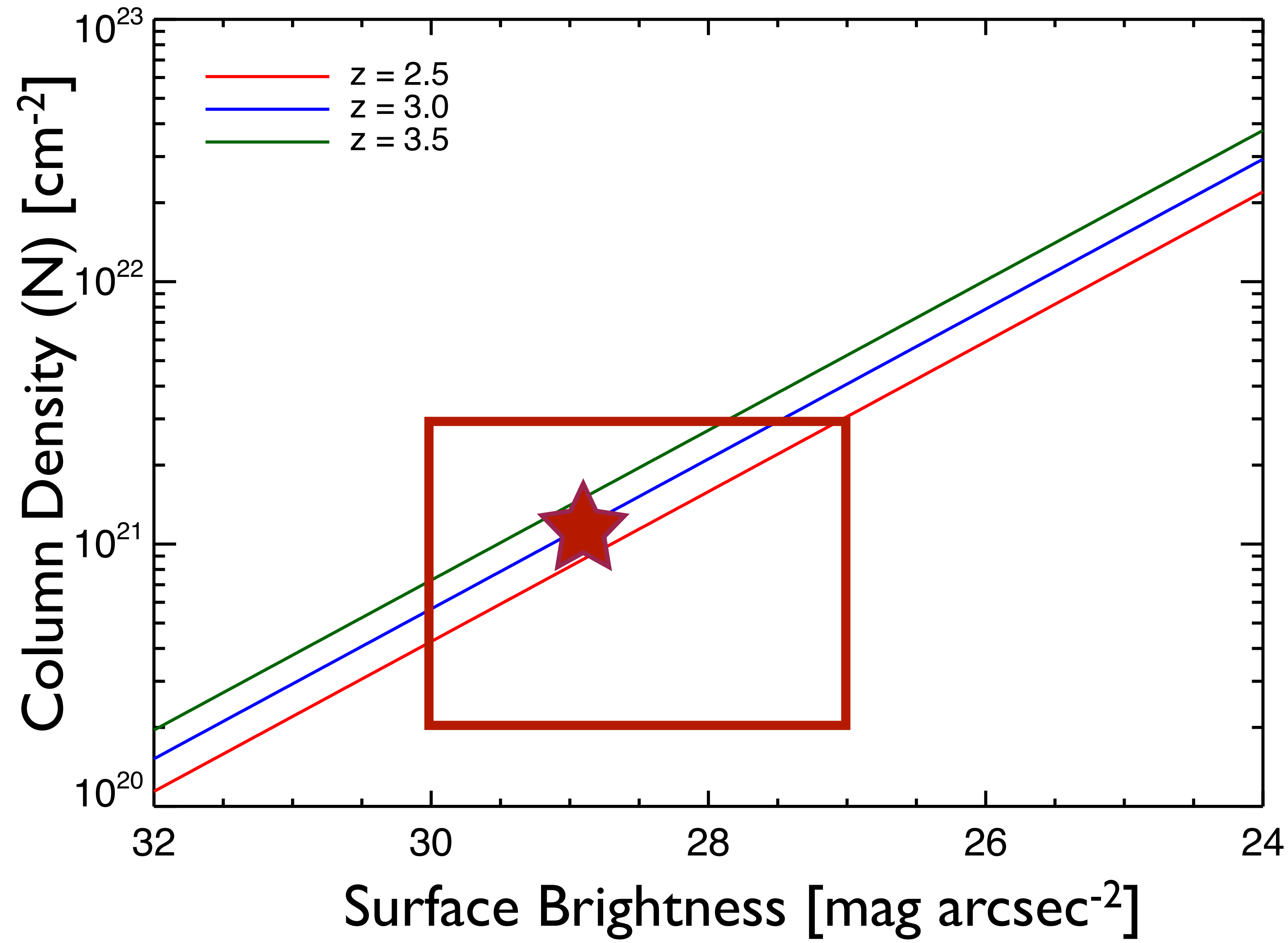
- Gas Density ↔ SFR (KS)
- SFR ↔ FUV L_ν

(Madau Kennicutt Calibration)

At z=3 1500 Å → 6000 Å
- This puts it in the visible!

- L_ν/area↔ Surface Brightness

- Most DLAs:
  $N \sim 2\times10^{20} \rightarrow 3\times10^{21}$ cm^{-2}
  $N_{avg} \sim 1\times10^{21}$ cm^{-2}

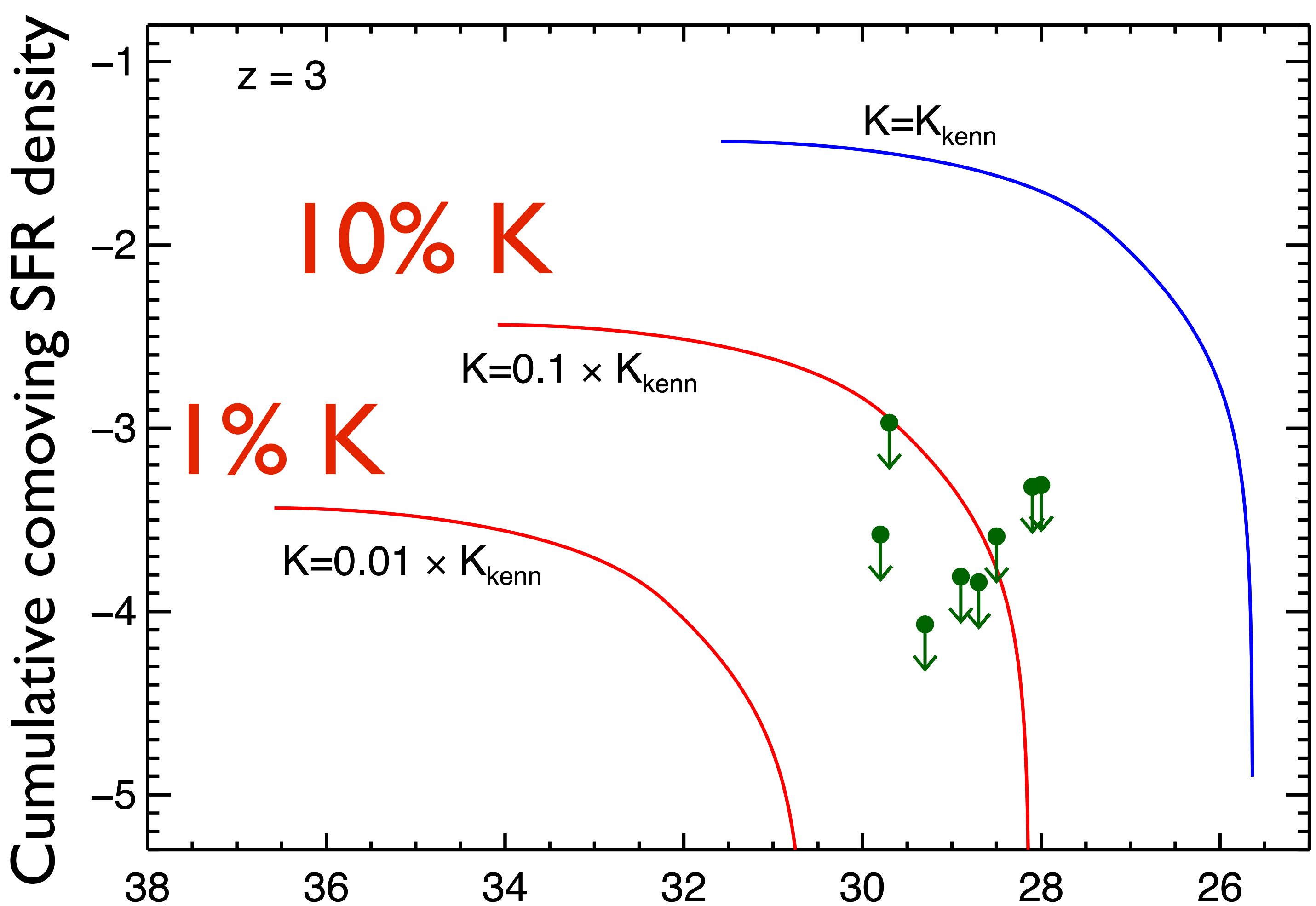


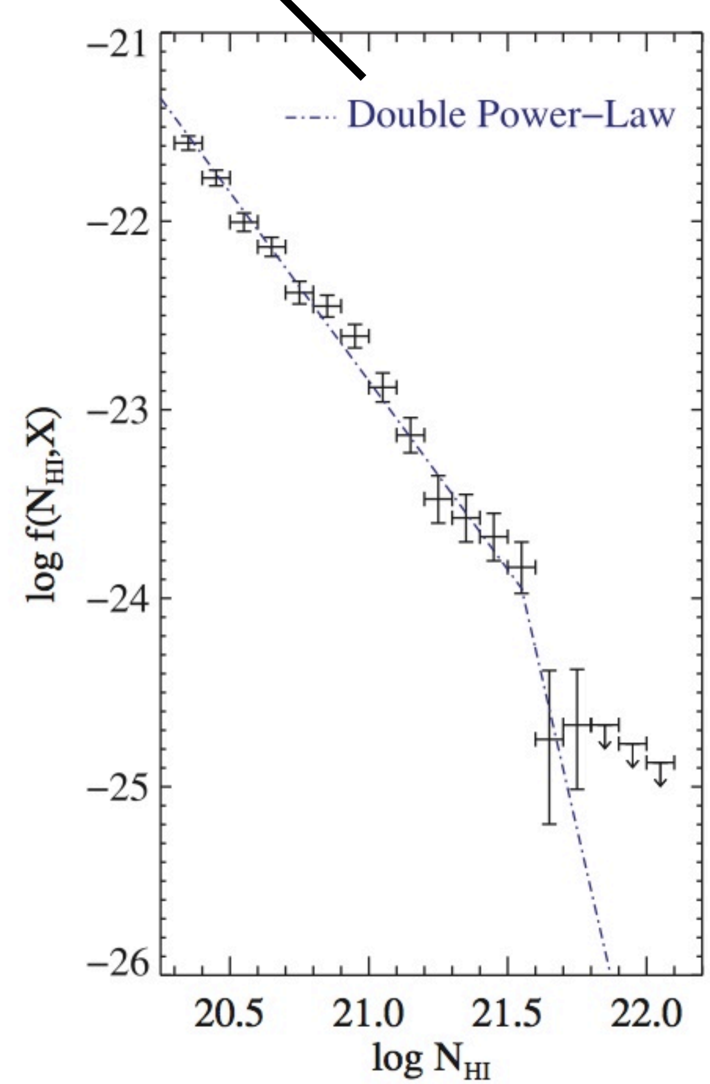
Only high resolution image sensitive enough is the Hubble Ultra Deep Field (UDF)

Cumulative comoving SFR density for DLAs

$$\Sigma_{\rm SFR}(N) = K(N/N_c)^{\beta}$$

$$\dot{\rho}_*(>N) = \int_N^{N_{\rm max}} \Sigma_{\rm SFR}(N') \frac{H_0}{c} f(N', X) dN'$$





Wolfe & Chen 2006

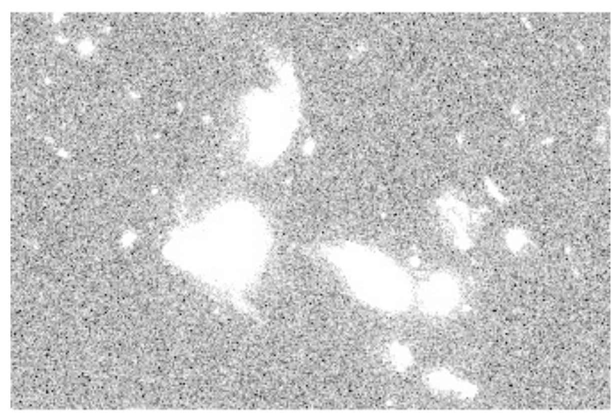
Wolfe & Chen 2006 result:

- SFR efficiency of DLAs is a factor of ≥10 below KS relation

Caveat:

- Wolfe & Chen 2006 search excluded objects with high surface-brightness cores ($\mu_V < 26.6$ mag/arcsec^2)

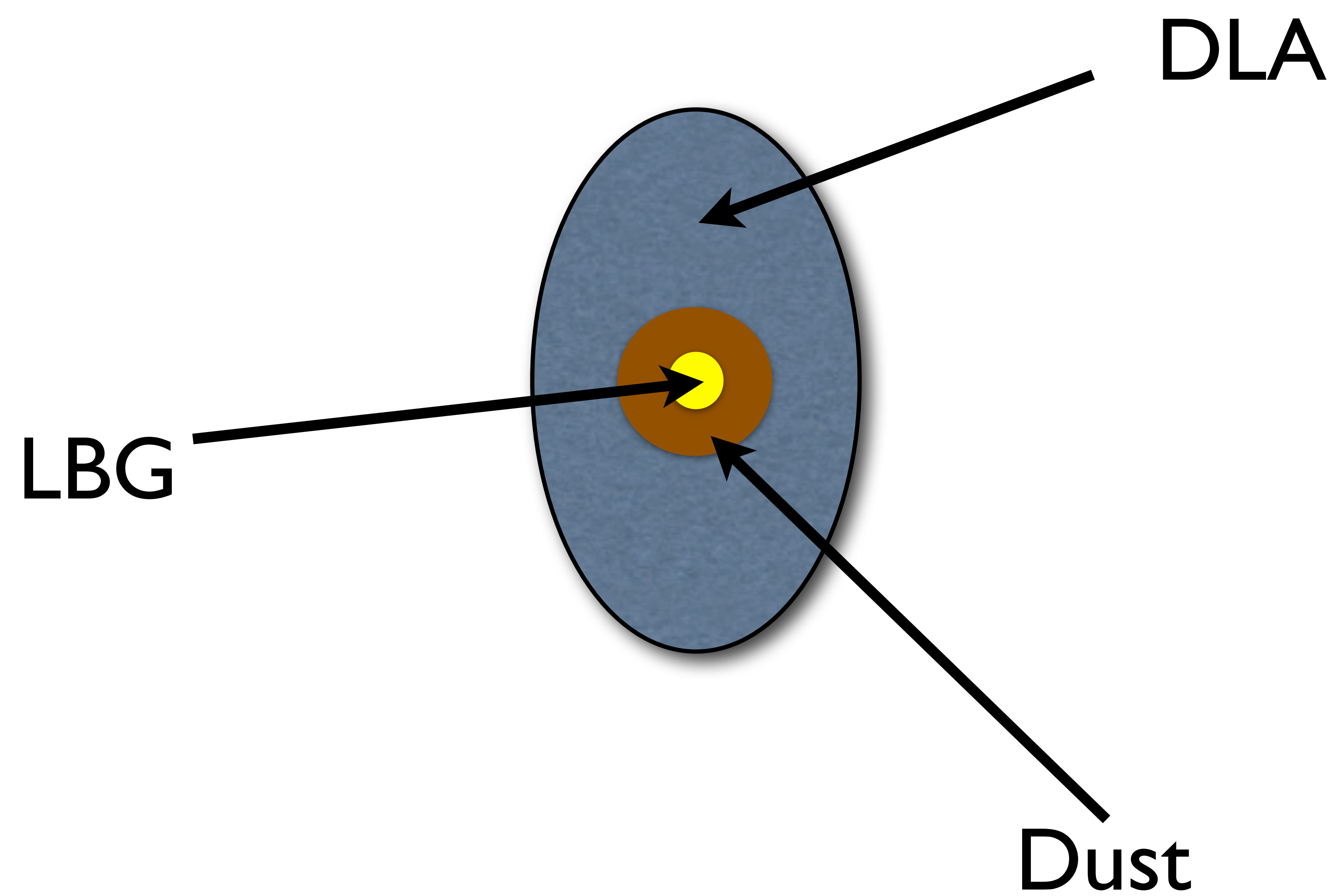
(i.e. LBGS)



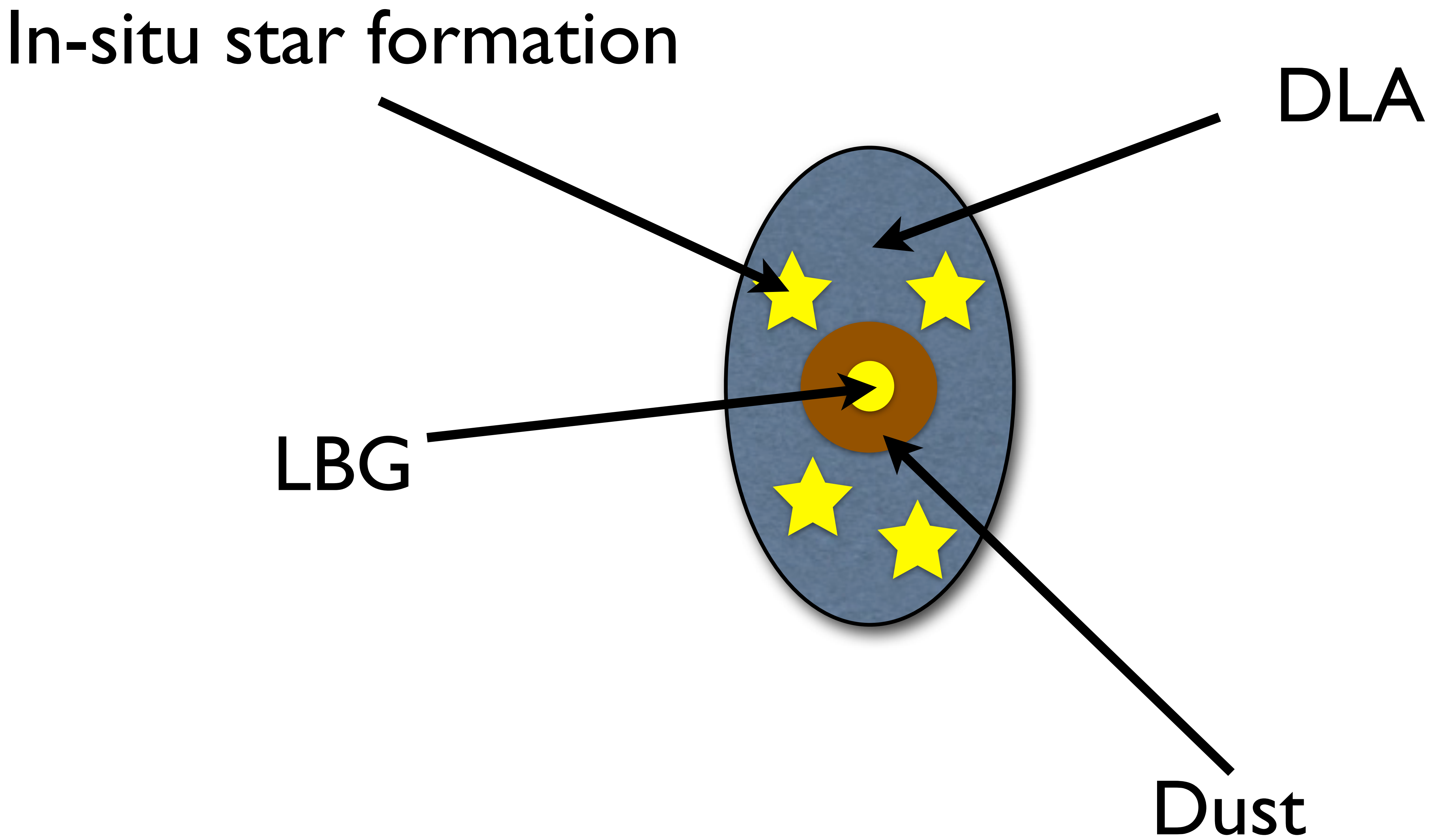
Another possibility:

- Lyman Break galaxy cores may be embedded in DLAs, and may themselves exhibit *in situ* star formation

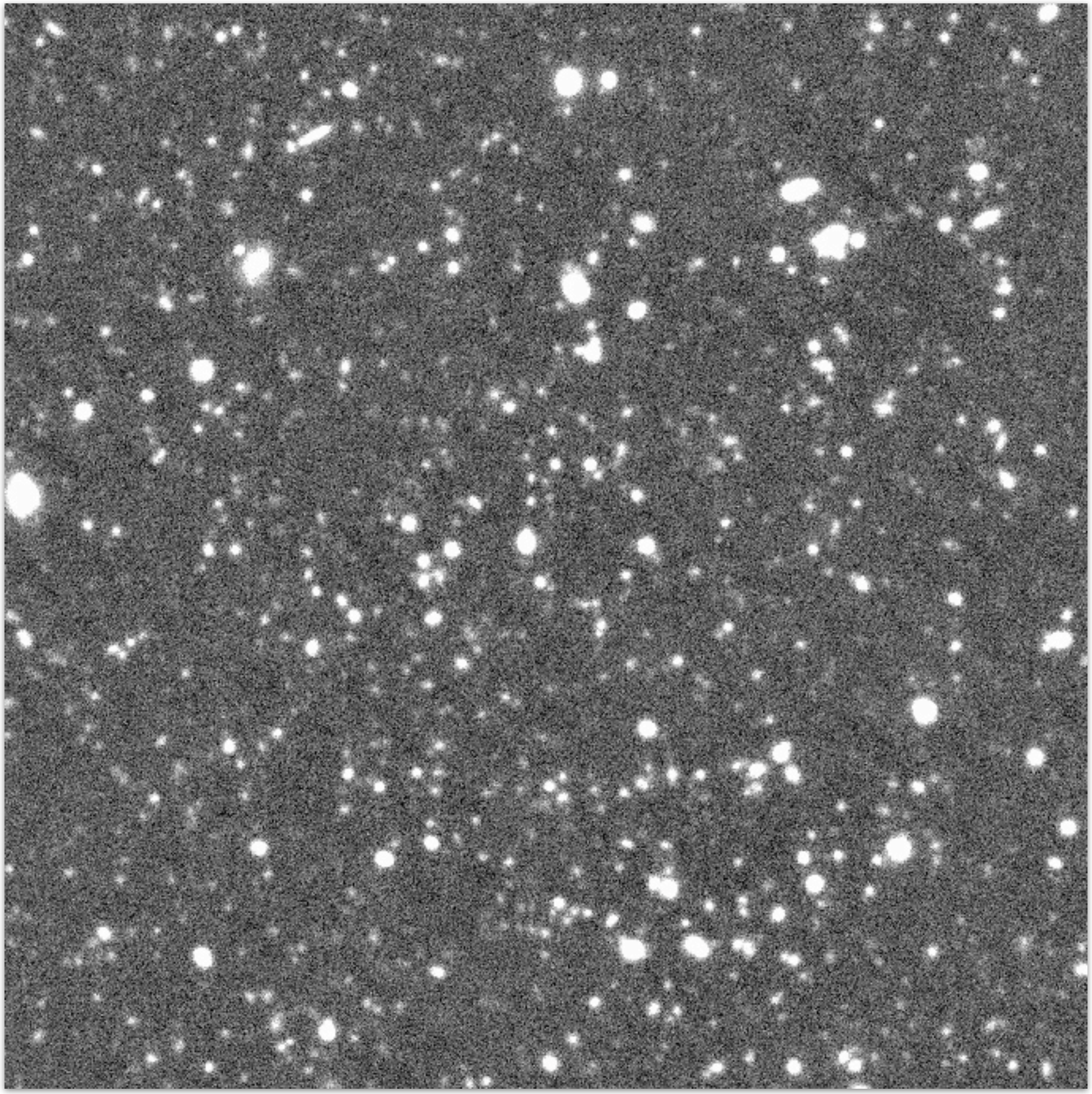
LBGs embedded in DLA Neutral Gas Reservoirs



In situ star formation in DLAs associated with LBGs



Solution: Ultra Deep u'-band image of UDF with Keck



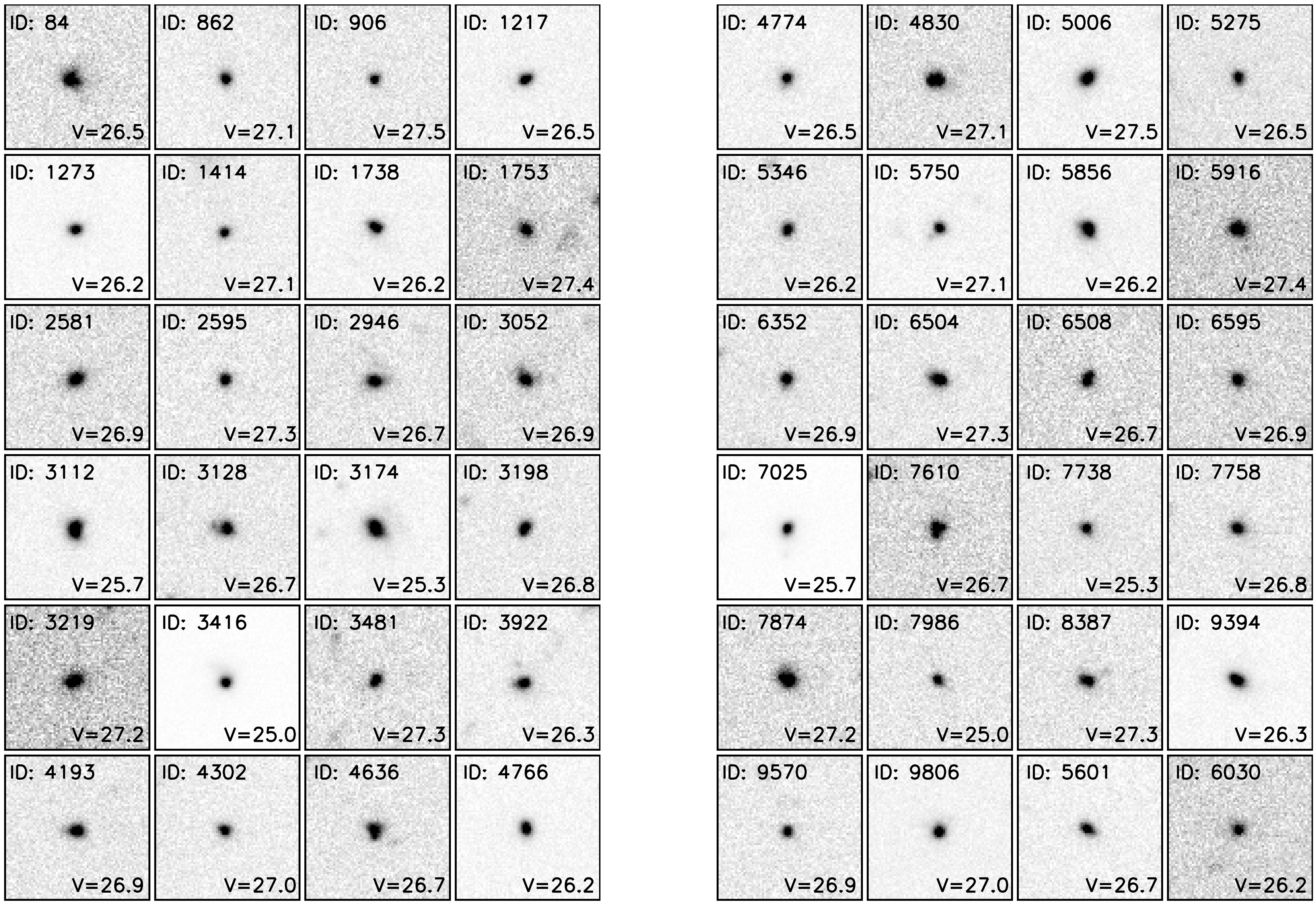
Rafelski et al. 2009

Keck Telescopes

1 σ depth = 30.7 mag/arcsec^2
Detection limit =27.6 mag/arcsec^2
FWHM = 1.3 arcsec

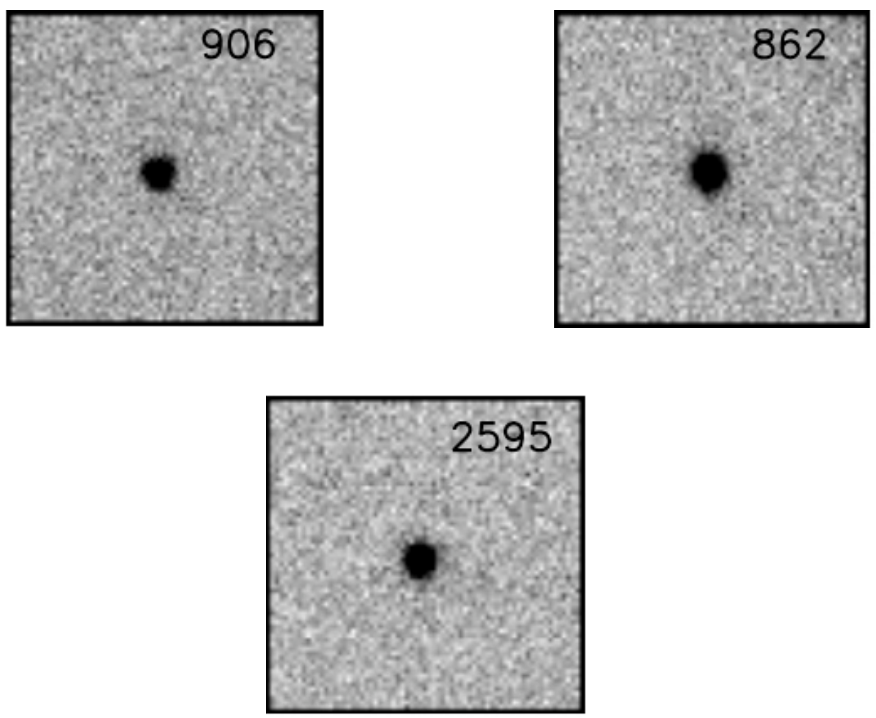
Use the u-band image to select 407 z~3 LBGS via their flux decrement from the Lyman break

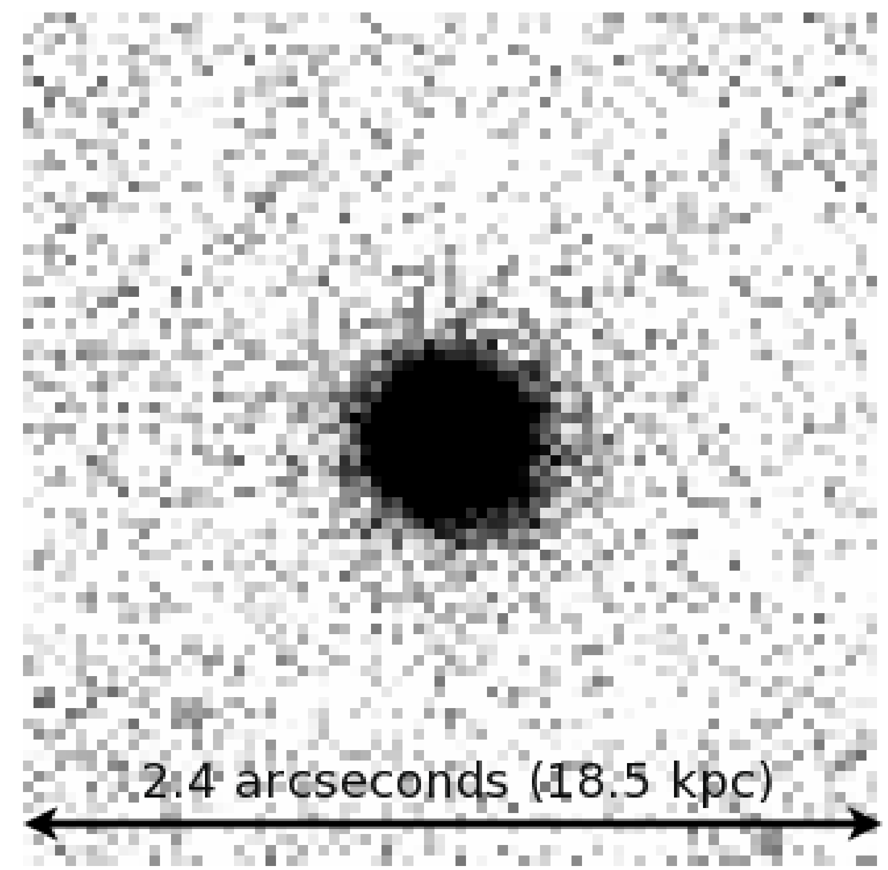
48 compact, symmetric, and isolated z~3 LBGs in V-band



Rafelski et al. 2011

Stack 48 isolated, compact, symmetric z~3 LBGs in the V-band (rest-frame FUV)



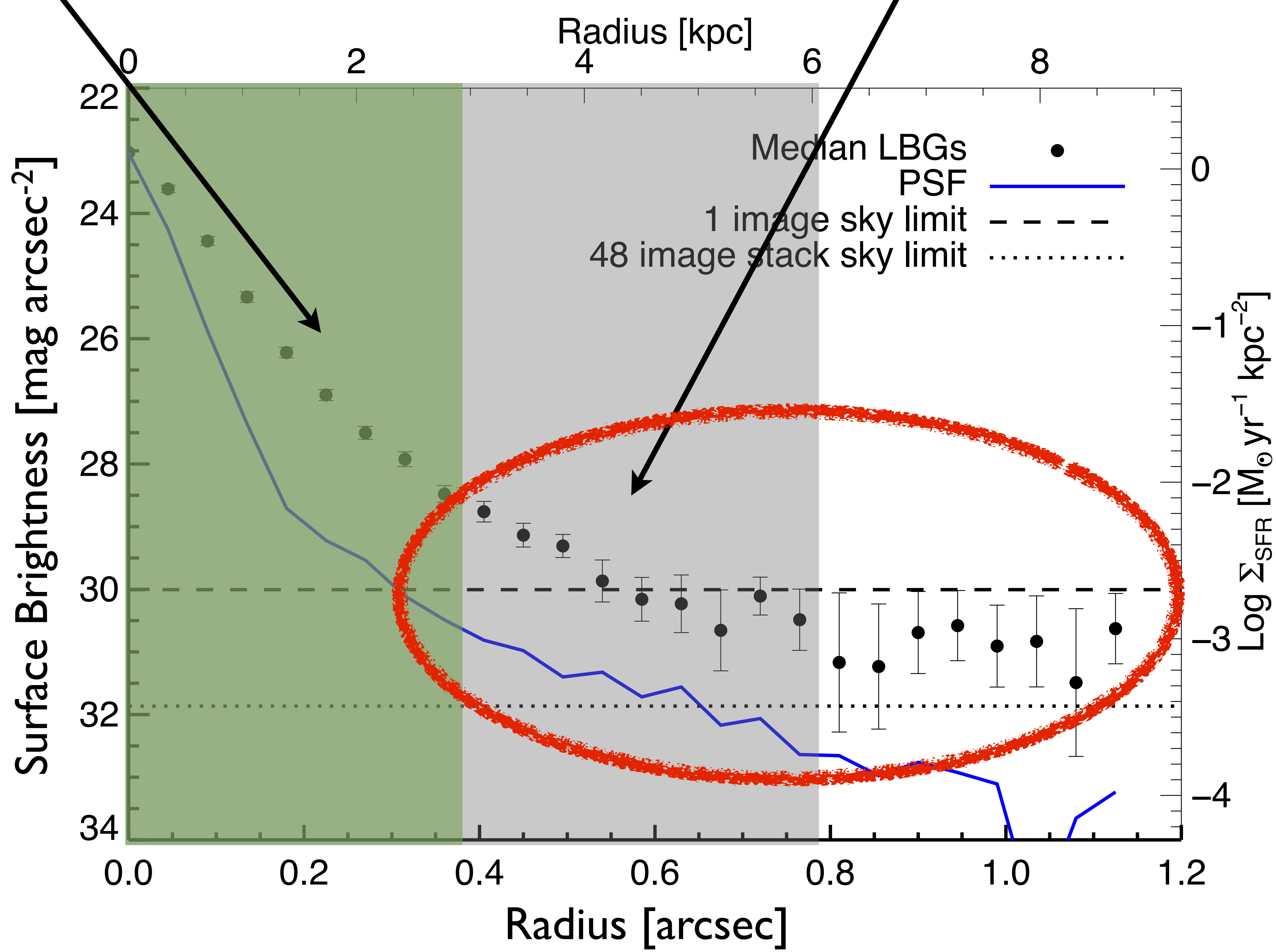


Rafelski et al. 2011

Radial surface brightness profile of stacked image

Inner core

Outskirts



Rafelski et al. 2011

Goal: compare comoving SFR density in outskirts of LBGs to DLAs to obtain a SFR efficiency

Column density of gas varies with radius, we need a differential version of the comoving SFR density $(\dot{\rho_*})$

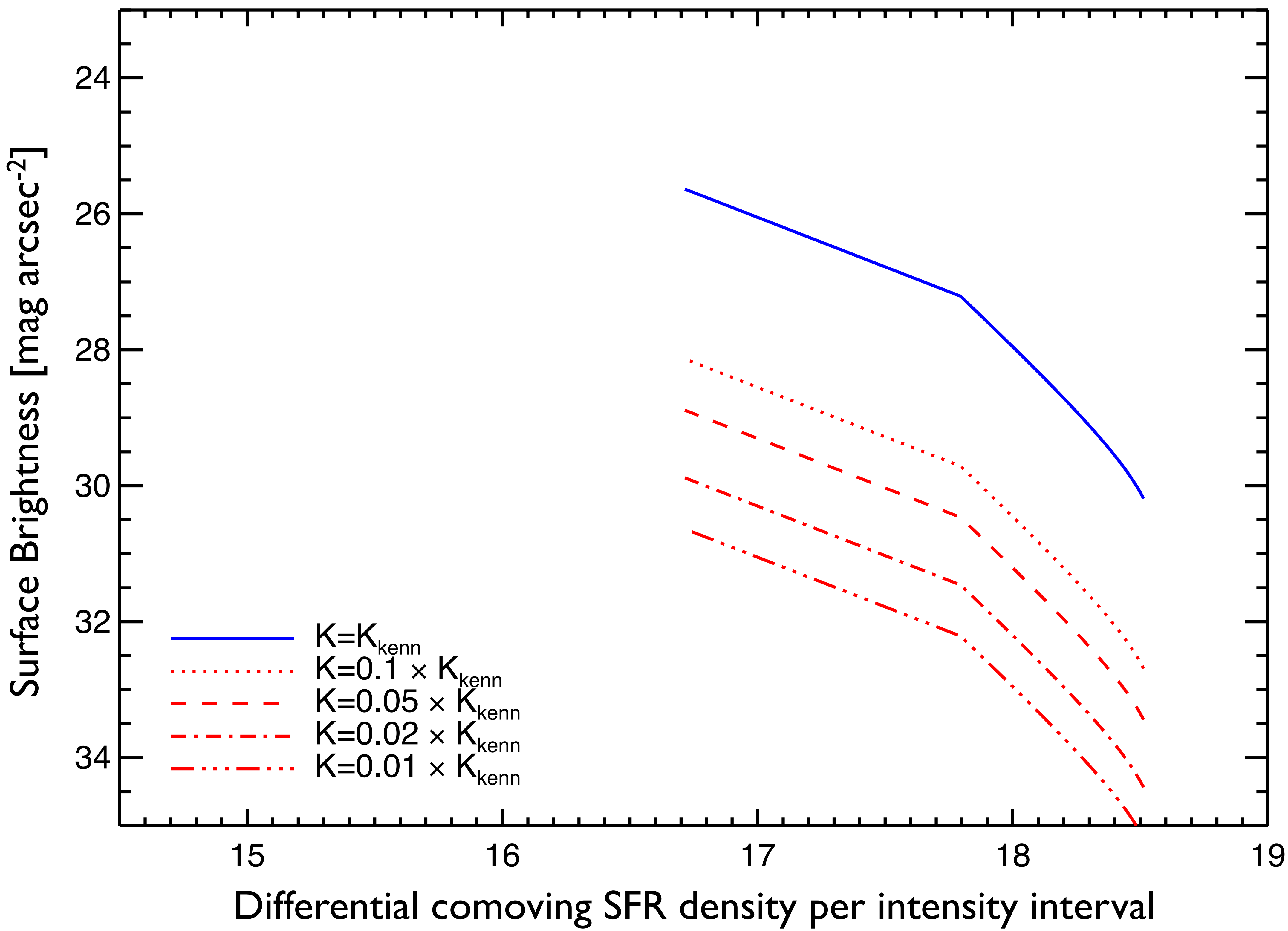
Previously:

$$\dot{\rho_*}(> N) = \int_N^{N_{\rm max}} \Sigma_{\rm SFR}(N') \frac{H_0}{c} f(N', X) dN'$$

Differential:

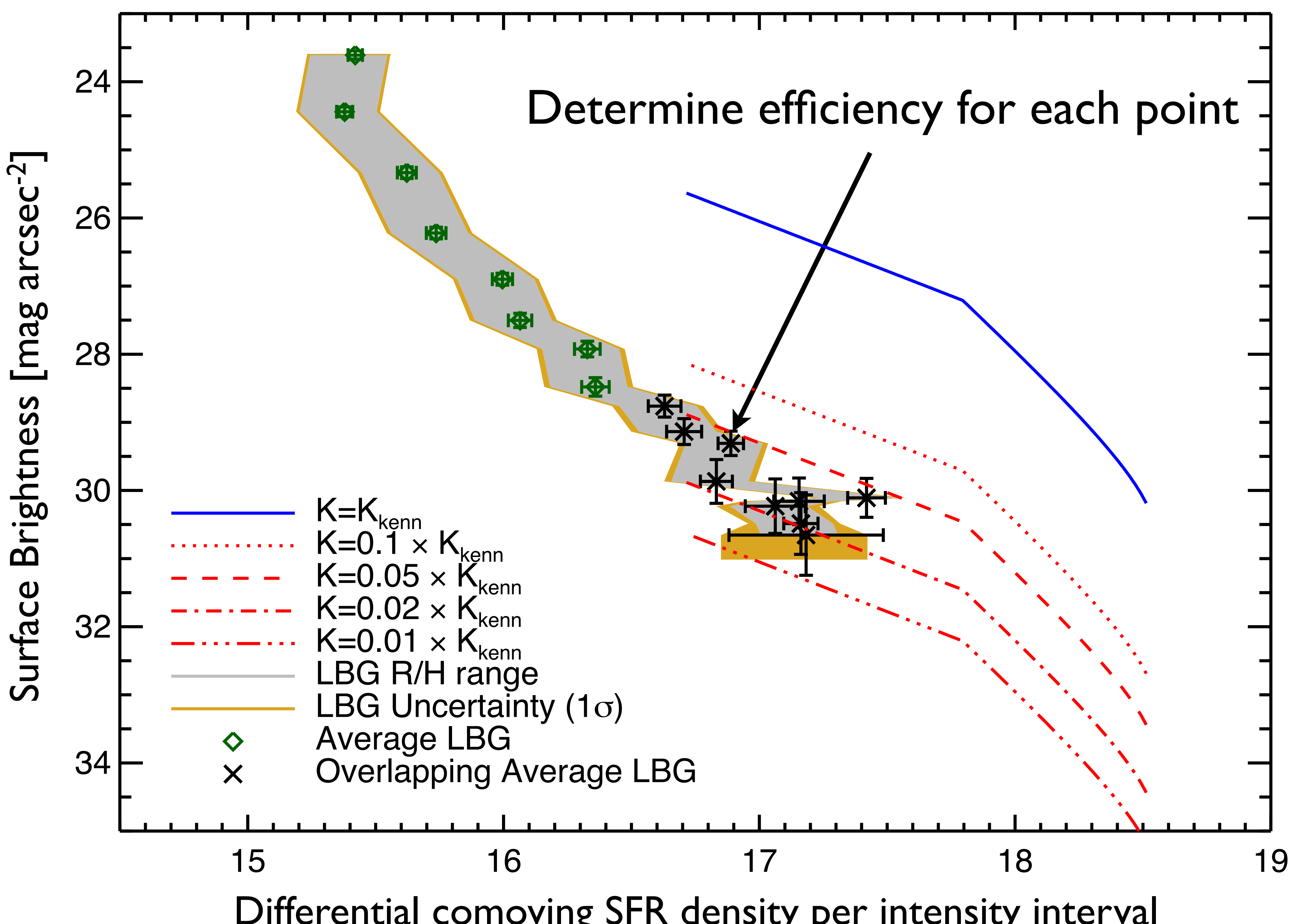
$$\frac{\Delta \dot{\rho_*}}{\Delta N} = \langle \Sigma_{\rm SFR}(N) \rangle \frac{H_0}{c} f(N, X) \quad \Rightarrow \frac{\Delta \dot{\rho_*}}{\Delta I}$$

Model differential comoving SFR density for DLAs



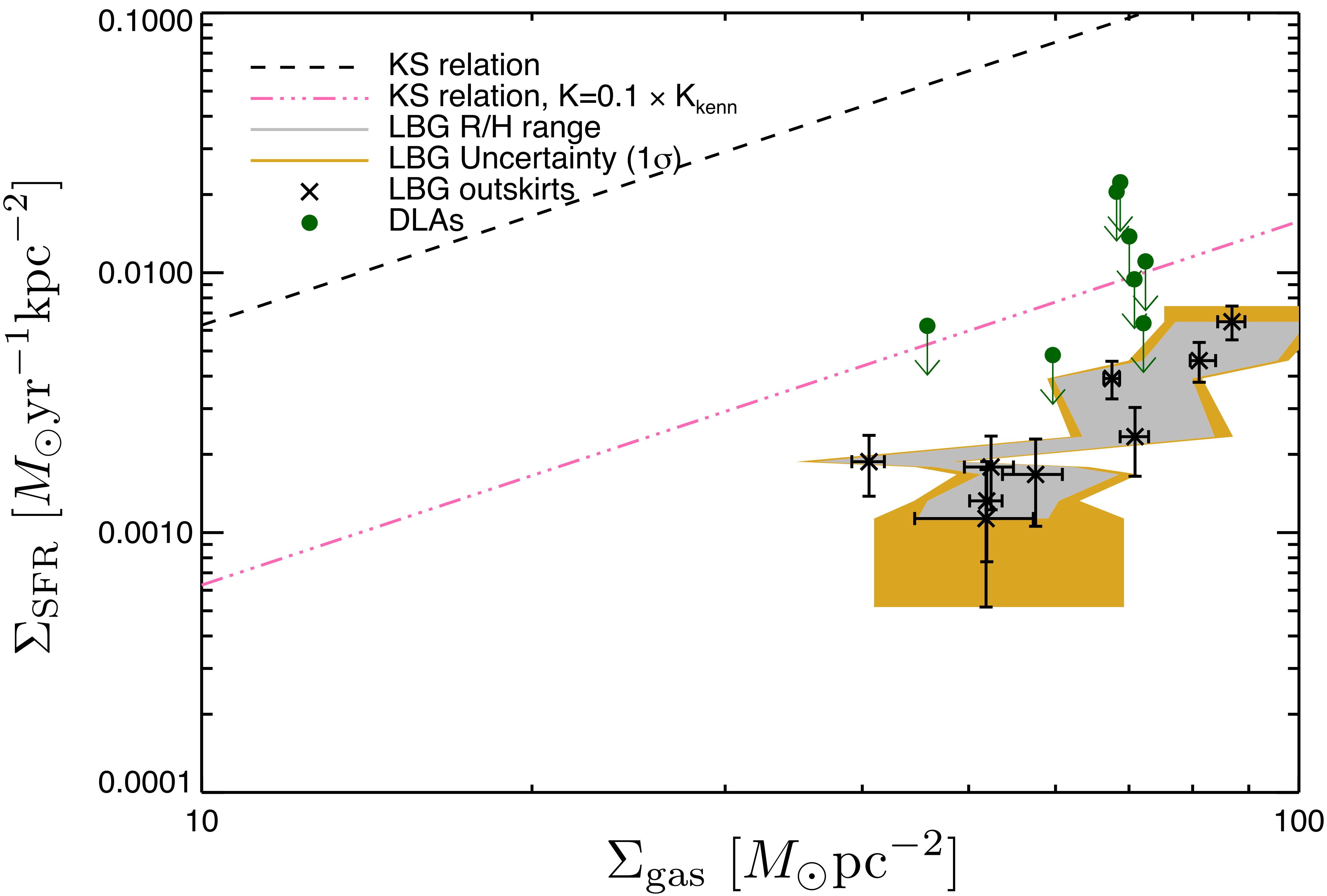
Rafelski et al. 2011

Comparison of model to data to determine efficiency



Rafelski et al. 2011

The KS relation for atomic dominated gas at z~3

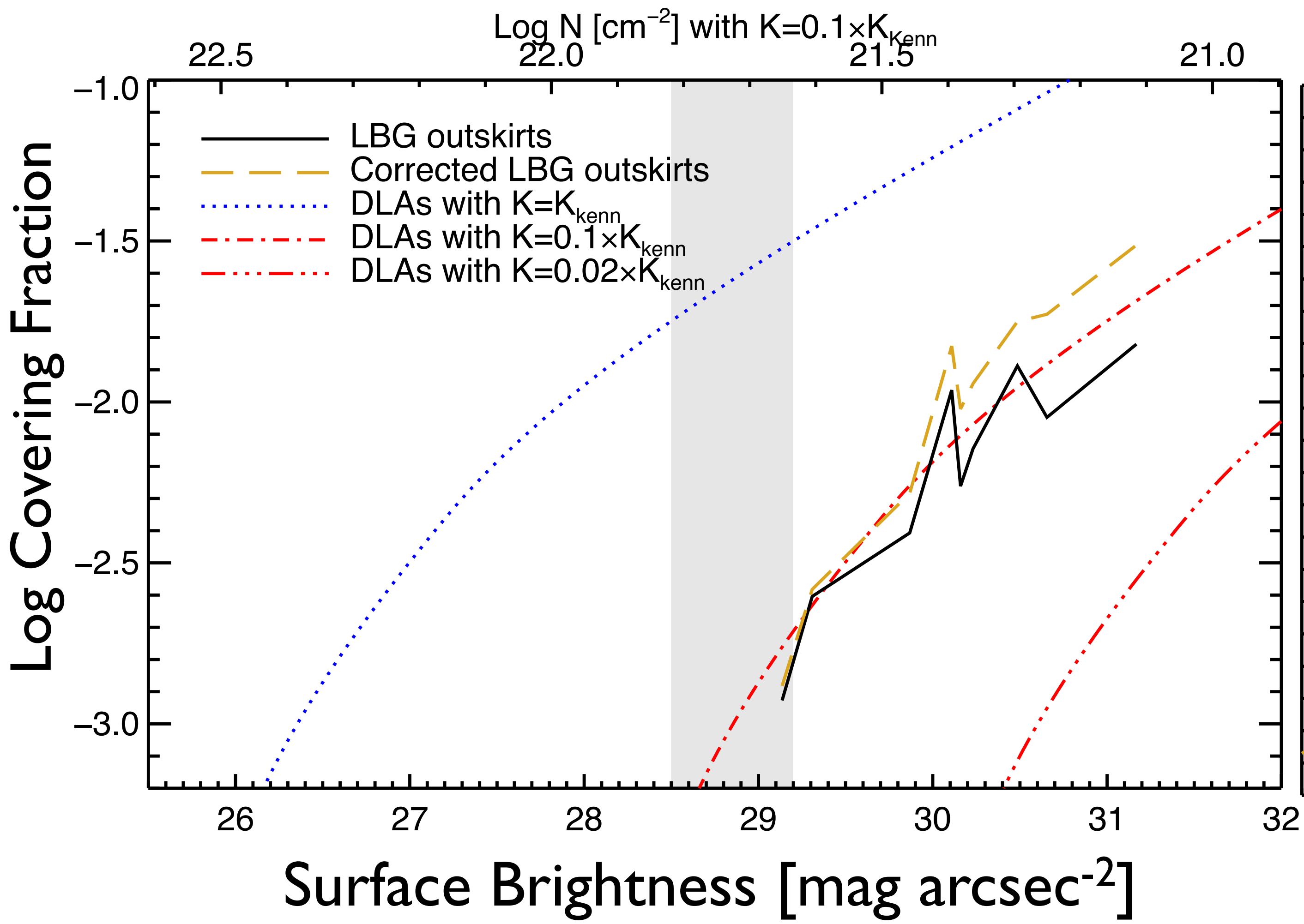


Rafelski et al. 2011

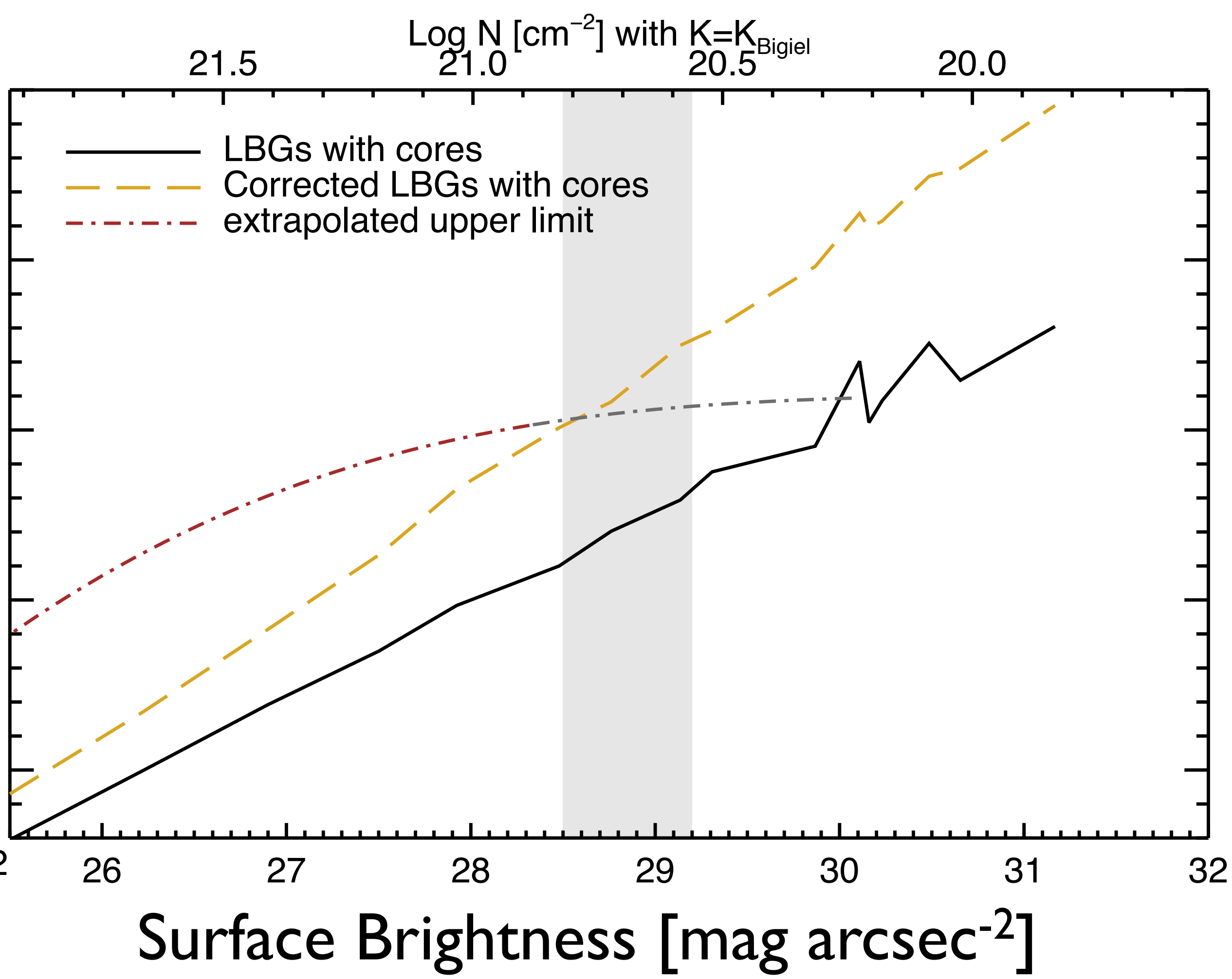
The covering fraction of the outskirts of LBGs is consistent with the DLA covering fraction

The emission unlikely to be from molecular-dominated gas

atomic-dominated gas



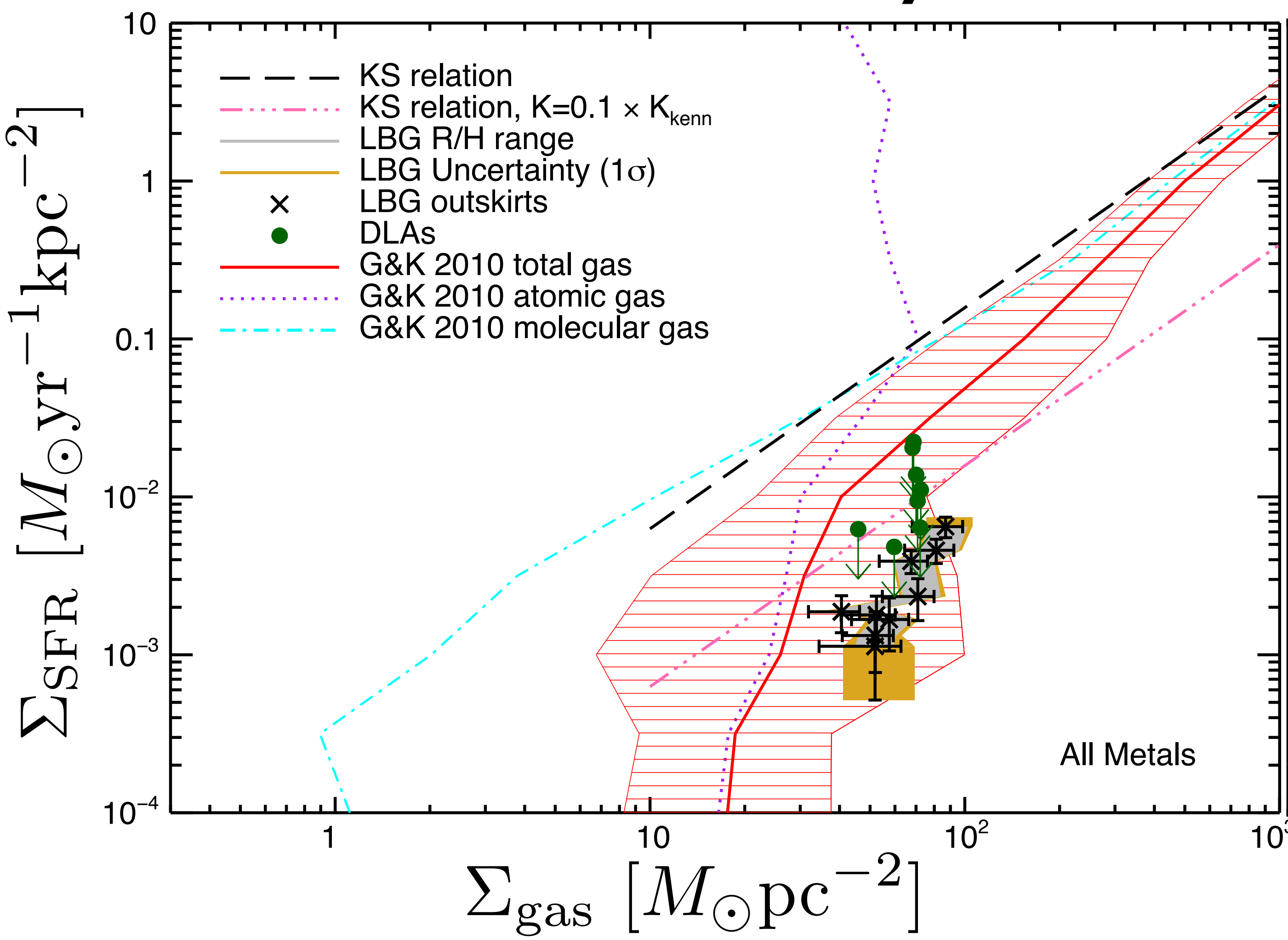
molecular-dominated gas



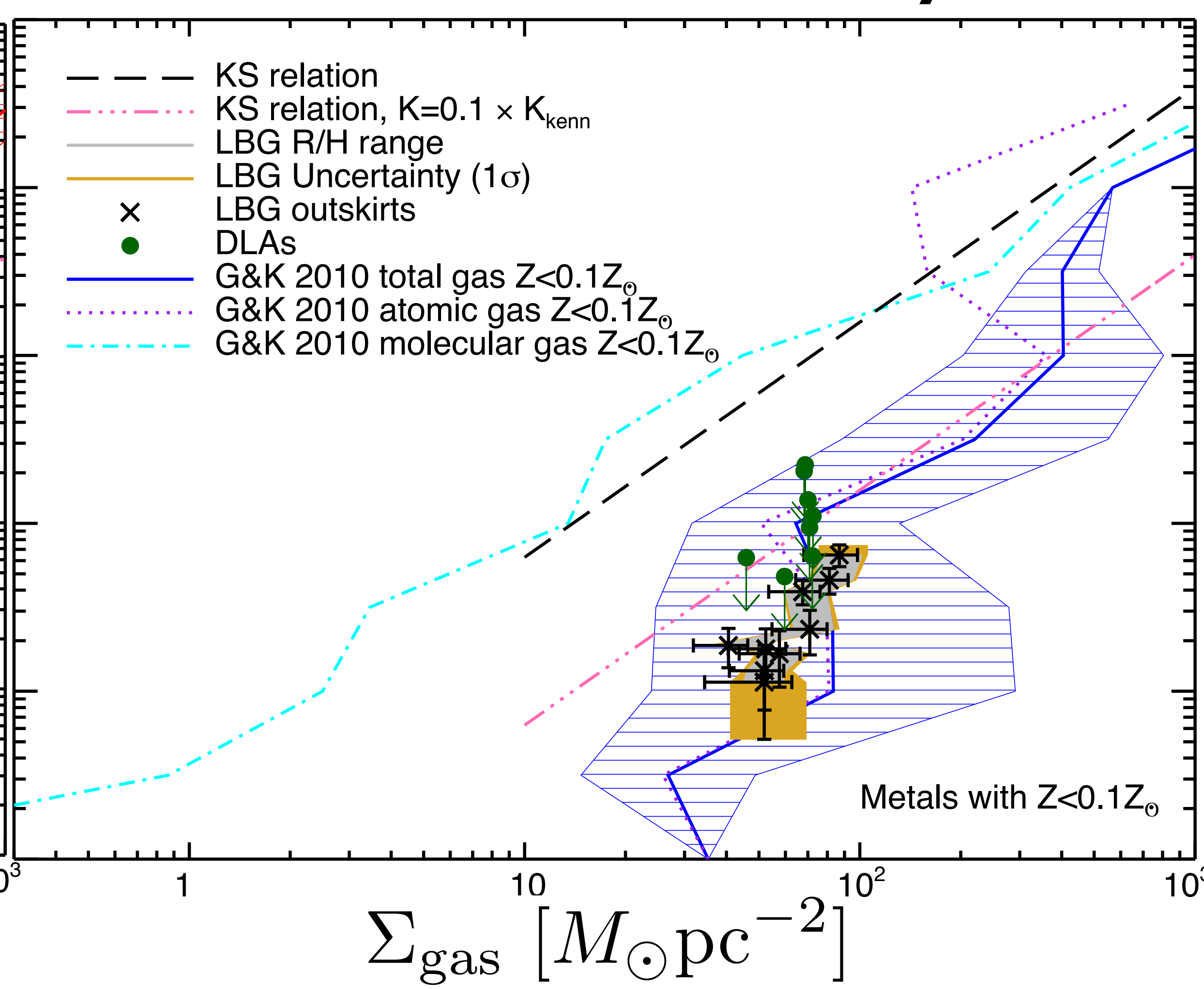
Rafelski et al. 2011

Comparisons to predictions from simulations (Gnedin & Kravtsov 2010)

LBG Metallicity



DLA Metallicity



Rafelski et al. 2011

What is responsible for the reduced SFR efficiency?

Metallicity of gas?

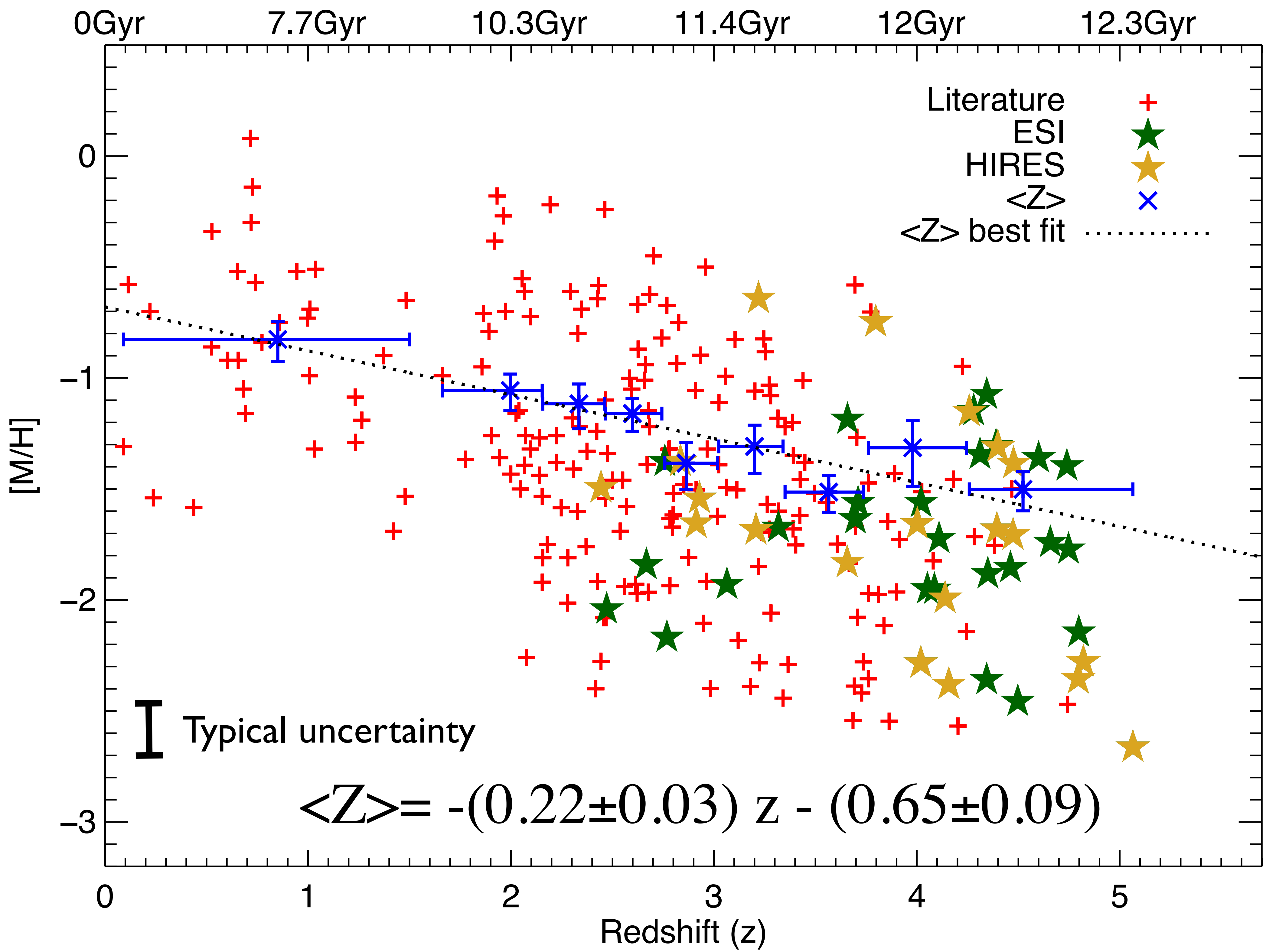
Background radiation field?

Role of molecular vs. atomic hydrogen gas?

Other possibilities?

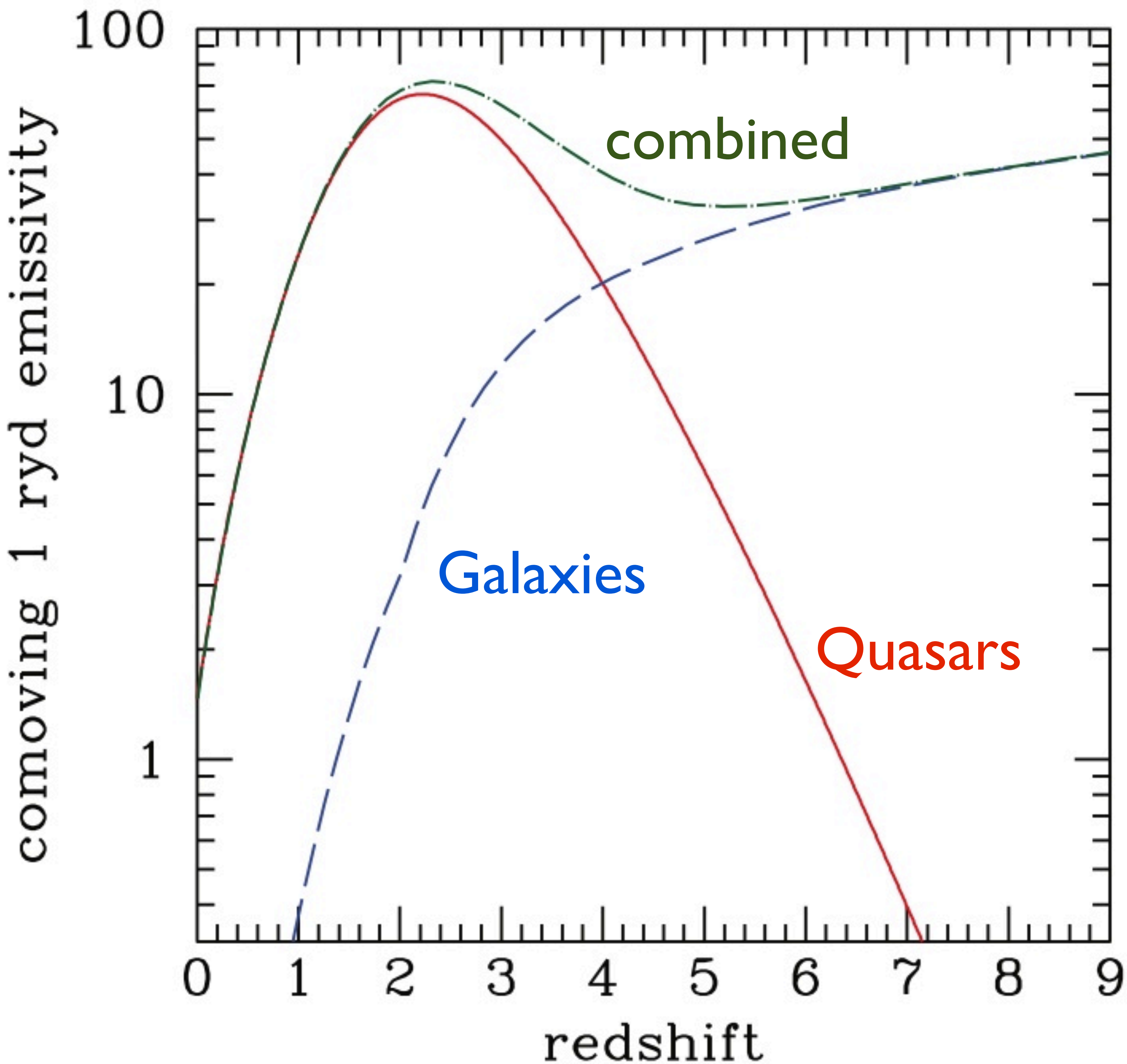
To better answer this question, would like to measure SFR efficiency for a range of redshifts

Metal Abundances versus redshift



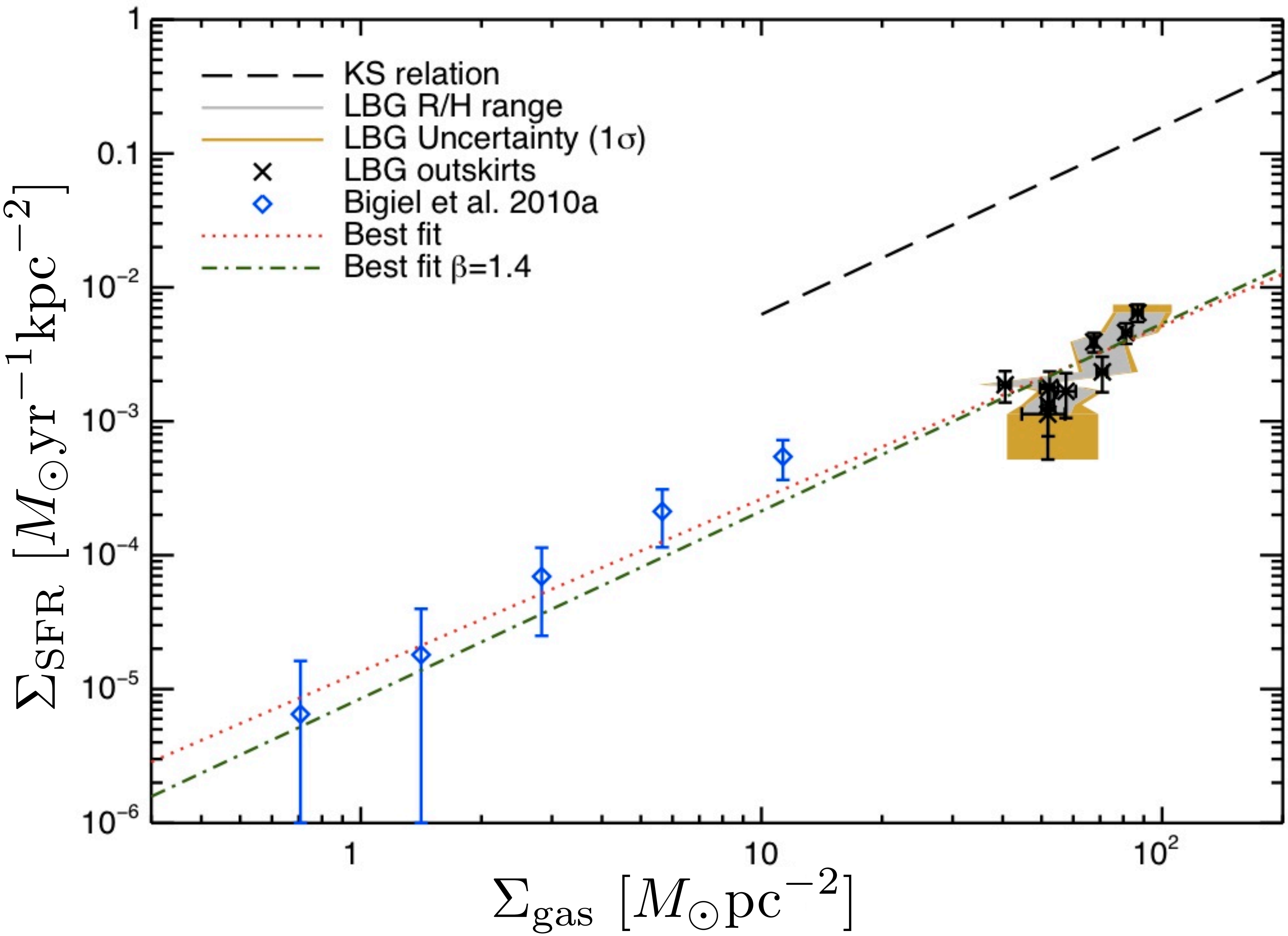
Rafelski et al. 2012 in press

Evolution of Background Radiation Field



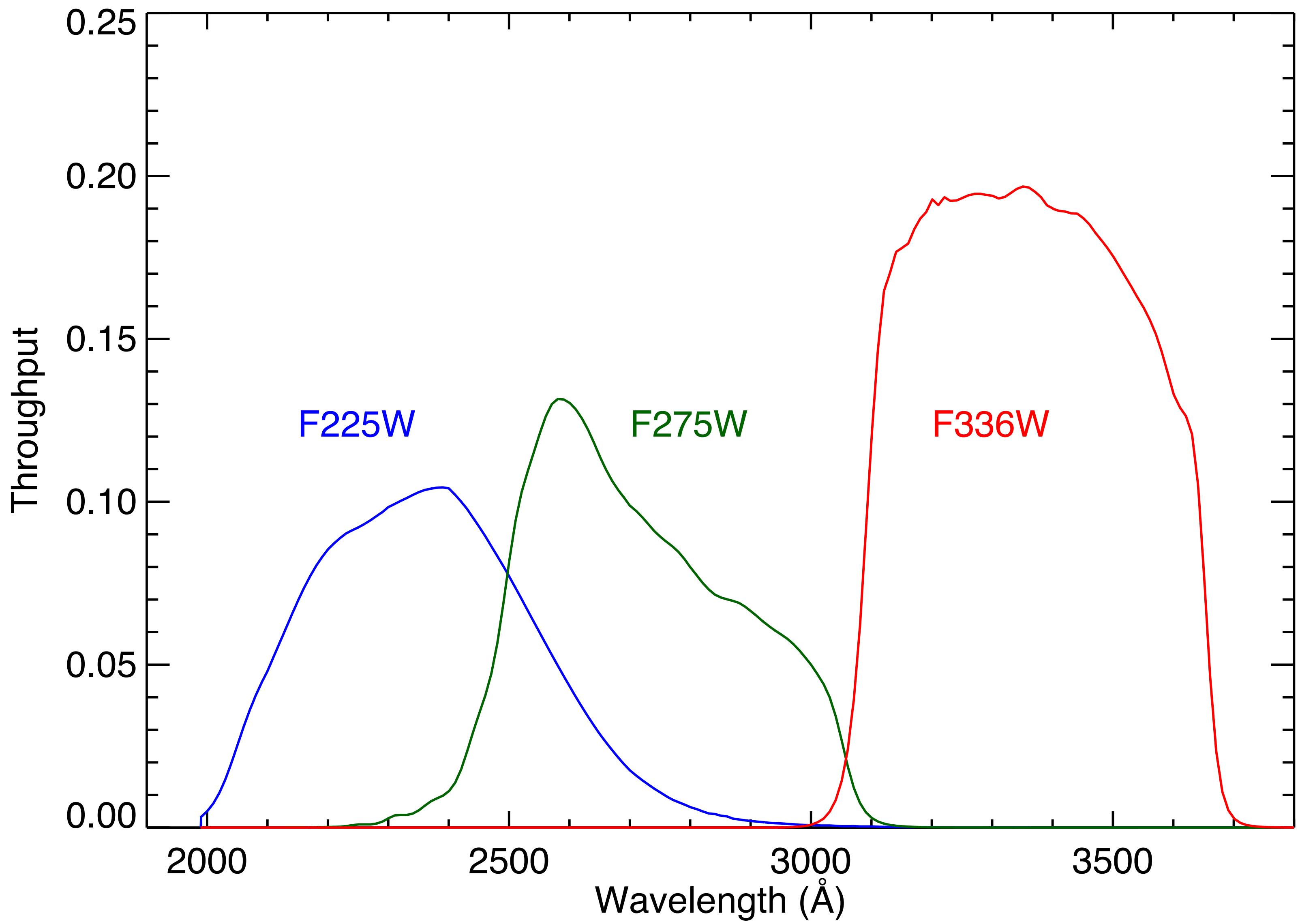
Haardt & Madau 2012

Comparison of z~3 outskirts with z=0 outskirts



Rafelski et al. 2011

The Ultraviolet Hubble Ultra Deep Field



UVUDF

ipac

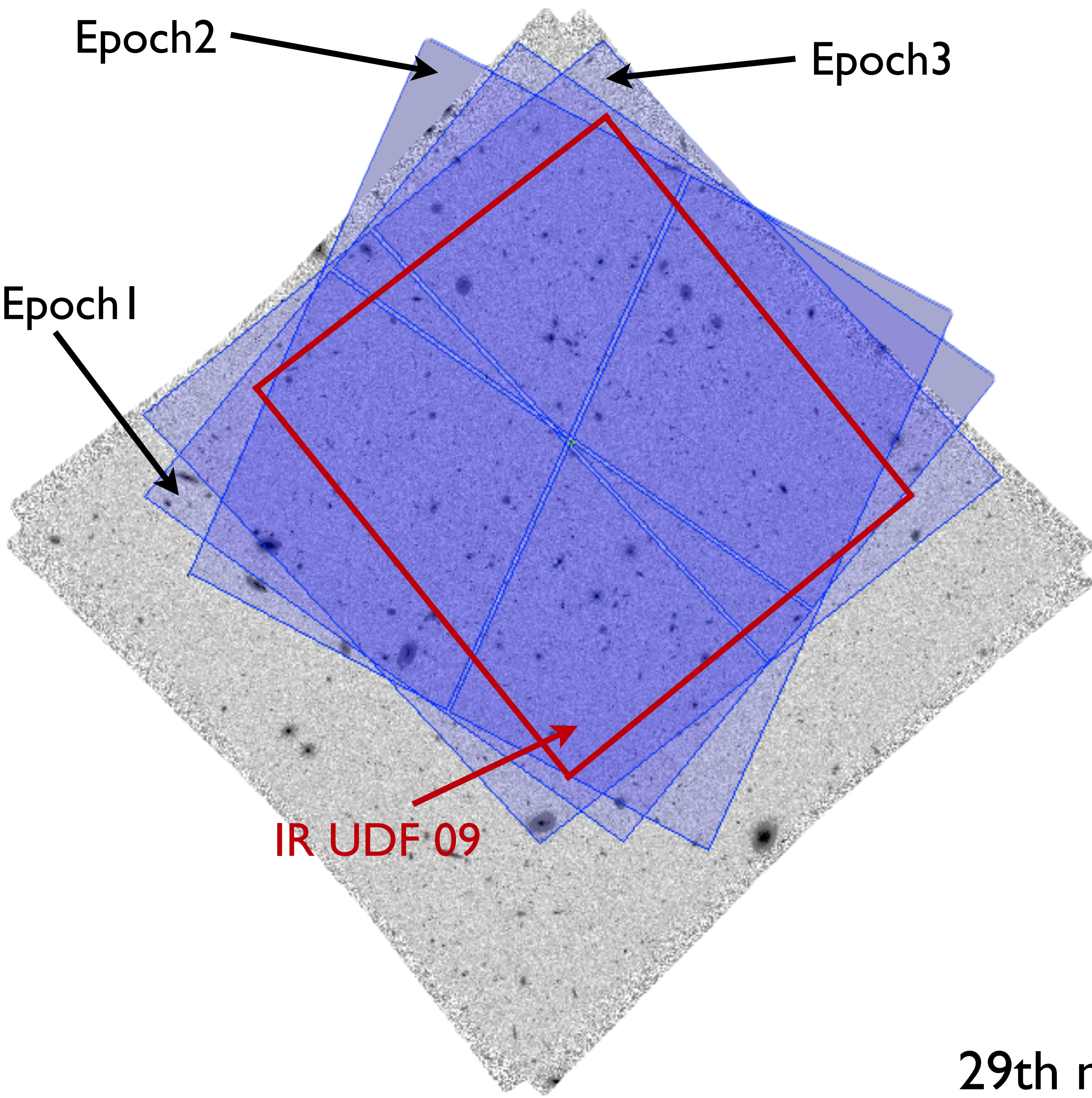
90 HST orbits:
30 F336W
30 F275W
30 F225W

Measure SFR efficiency at z~1 and z~2

Improve z~3 measurement with larger sample of LBGs

Use existing i' band UDF data for measurement at z~4

NUV Coverage of UDF with WFC3



Epoch 1:
- March 2 - March 11
- 6 Orbits / 12 exposures per filter

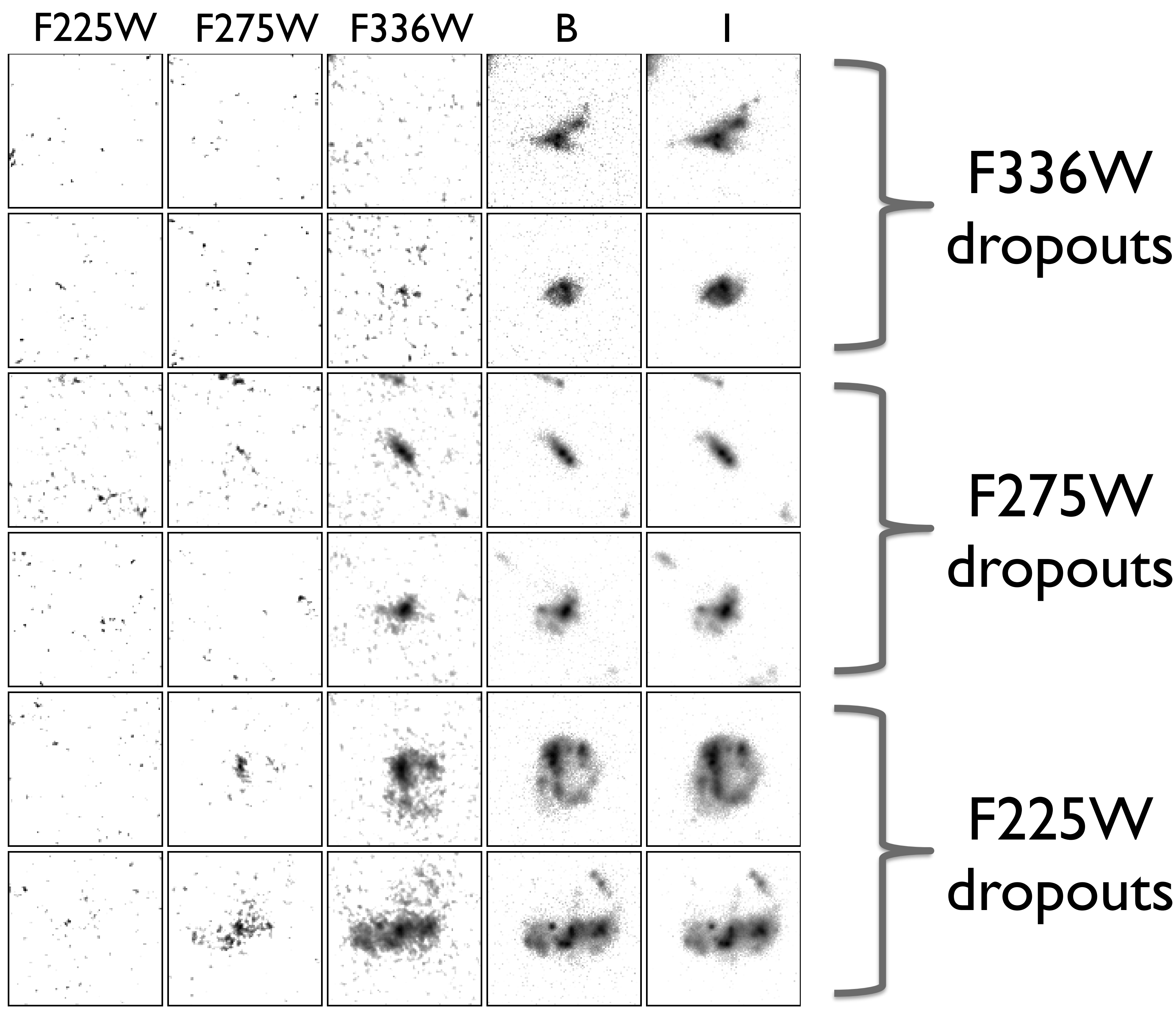
Epoch 2:
- May 28 - June 4
- 10 Orbits / 20 exposures per filter

Epoch 3:
- August 4 - September 19
- 14 Orbits / 28 exposures per filter
- + 2 failed orbits from above

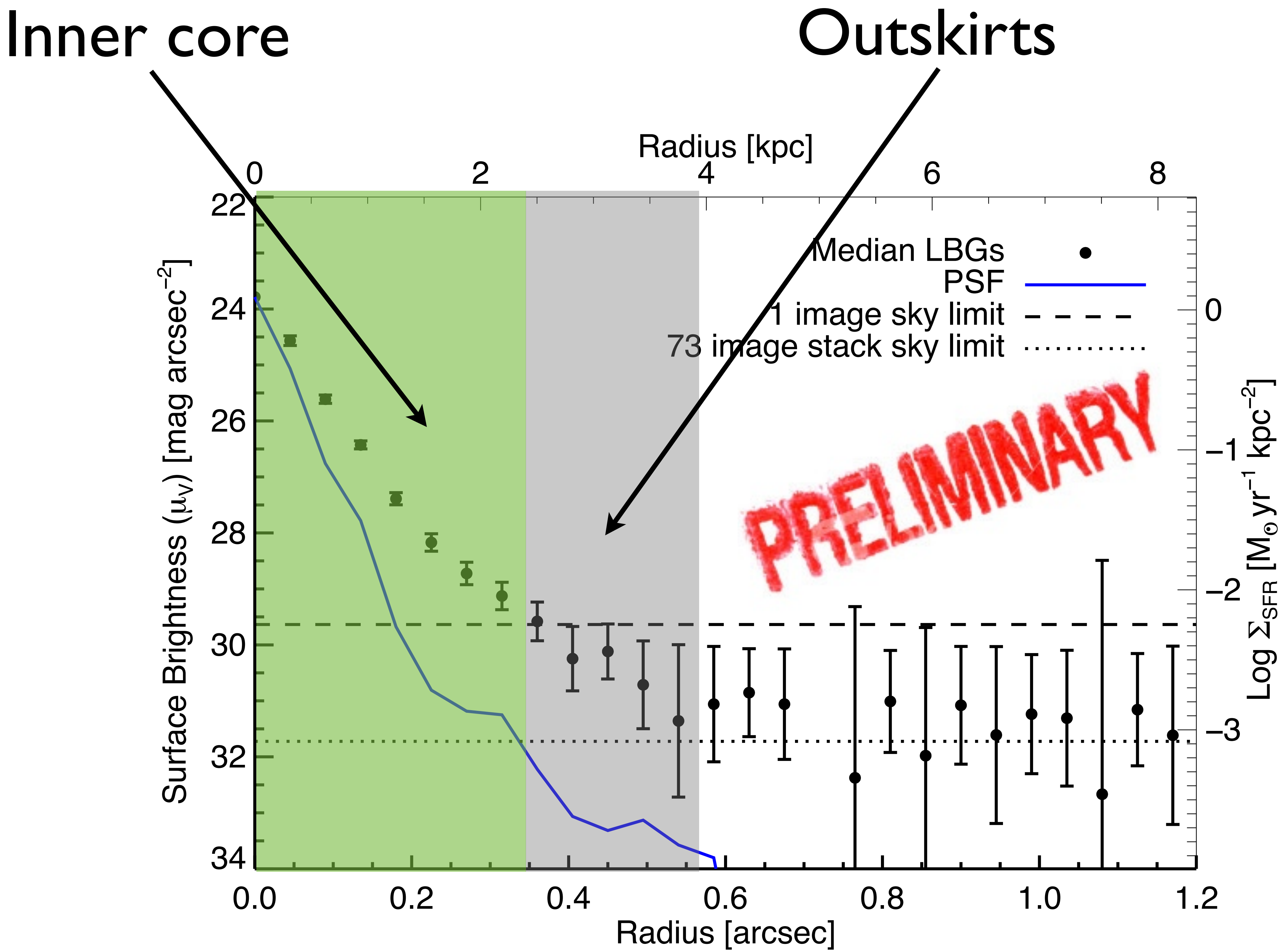
Total:
- 30 Orbits / 60 exposures per filter
- 90 Orbits in total by mid September

29th mag 10 sigma point source limit

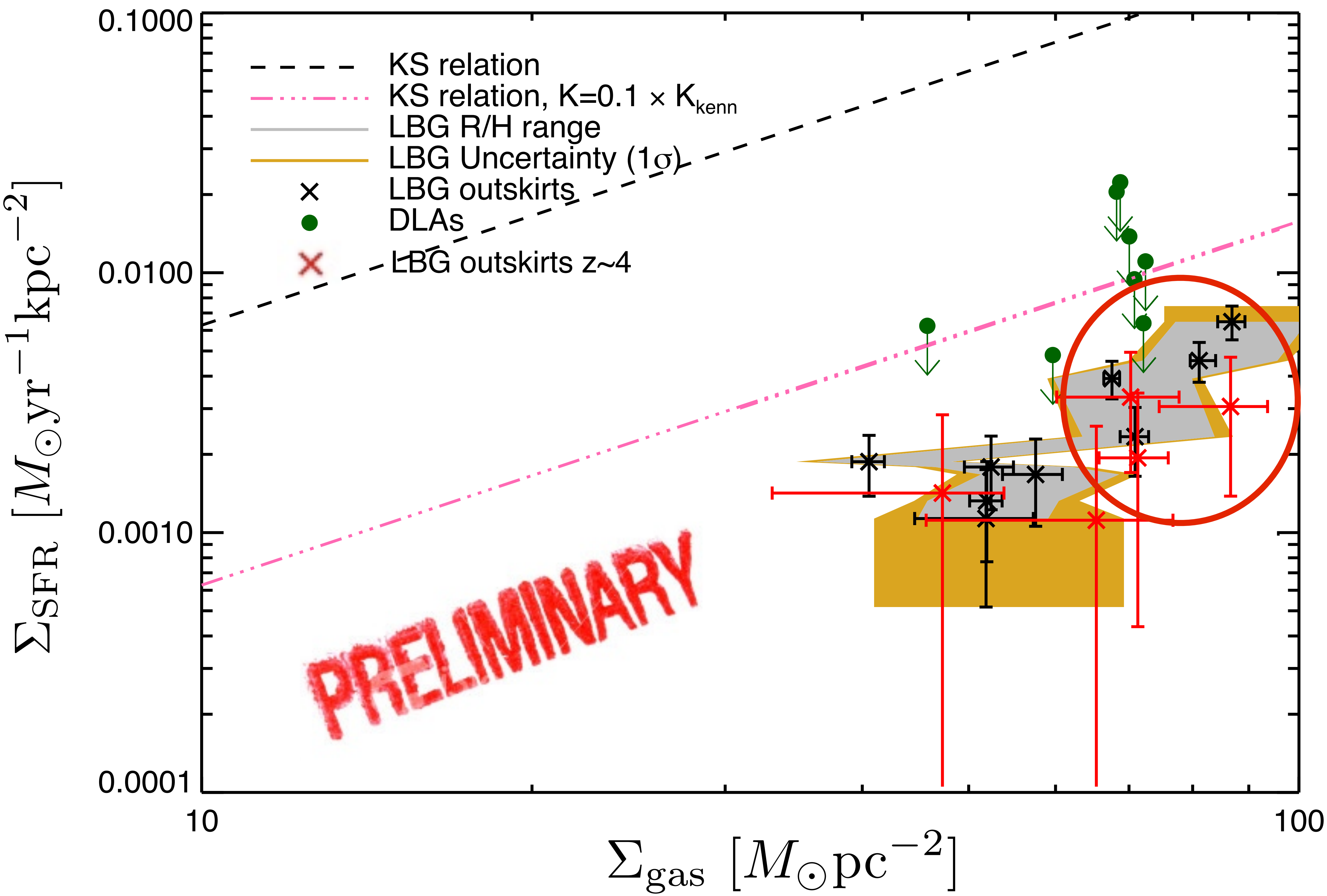
UV dropout galaxies at z~1-3



Radial surface brightness profile of stacked LBGs at z~4



How do things change at z~4?



Summary

- Measured extended rest-frame FUV emission in outskirts of z~3 LBGs
- Star formation rate efficiency of atomic-dominated gas at z~3 is a factor of ~10 lower than predicted by Kennicutt-Schmidt relation for local galaxies at z=0
- Covering fraction of DLA gas consistent with LBG outskirts, while molecular gas insufficient to cover the LBG outskirts.
- Consistent with predictions from Gnedin and Kravtsov 2010 suggesting the metallicity could be the driver for the lower SFR efficiency
- Measured the metallicity evolution of neutral hydrogen gas out to z~5
- Obtaining NUV data with HST to measure the SFR effiency at z~1 & 2
- Preliminary measurement of the SFR efficiency at z~4