Lyman Alpha Emitting Galaxies at 2<z<3: Progenitors of Present-day L* Galaxies

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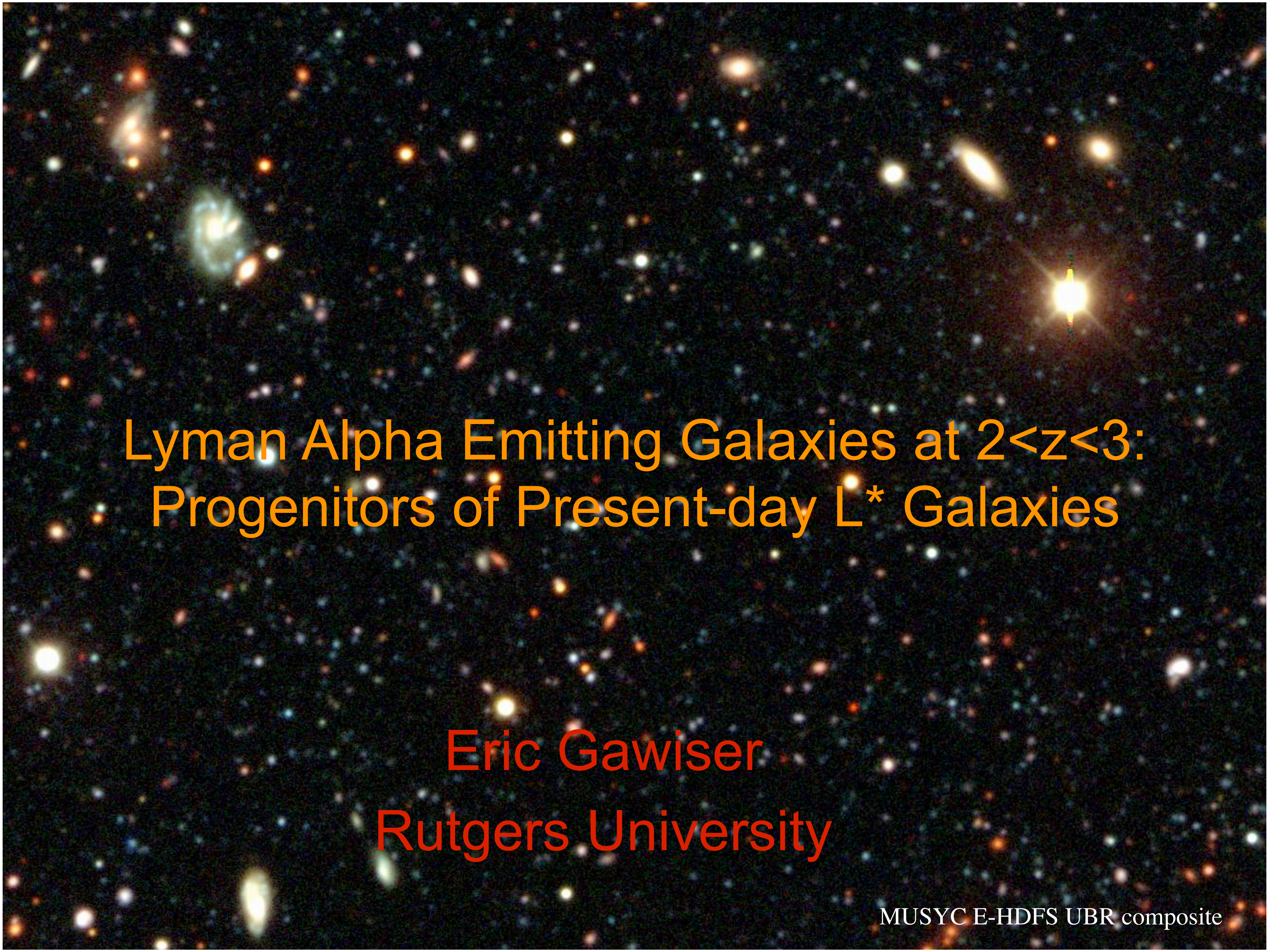


MUSYC E-HDFS UBR composite

What We Know About Galaxy Formation

What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology

CMB + galaxy P(k) + Type Ia SNe $\rightarrow$

Ω_Λ=0.7, Ω_m=0.3, Ω_b=0.04, H_0=70 km/s/Mpc

What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxies

Well-studied in Milky Way and nearby galaxies

What We Know About Galaxy Formation

- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxies
- Integral Constraints: Cosmological quantities

Baryon budget:

Star Formation Rate Density (SFRD) is average over space at a given time ($M_\odot$/yr/Mpc^3)

Stellar Mass Density ($\rho_*(t)=\int_0^t d\rho_*/dt$),

Metal Density ($\rho_*(t)=1/42 \int_0^t d\rho_*/dt$)

are integral constraints on SFRD over time

CIB + FIRB constrain integrated SFRD to z=0

What We Know About Galaxy Formation

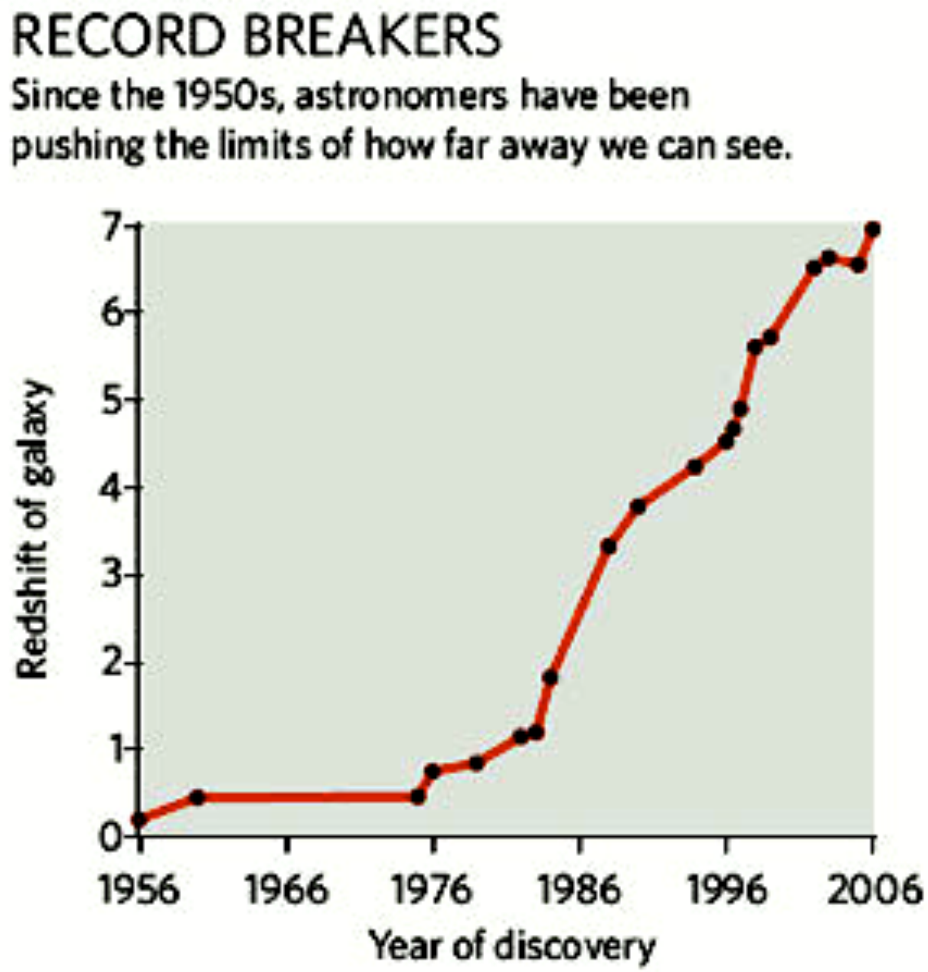
- Initial Conditions: WMAP cosmology
- Final Conditions: Low-z galaxies
- Integral Constraints: Cosmological quantities
- Identified Galaxy Zoo at z~3

Lyman break galaxies, Lyman alpha emitters, Distant red galaxies, Active Galactic Nuclei, Damped Lyman alpha systems, Submillimeter galaxies

However: Evolutionary sequence unclear, which (if any) are progenitors of typical galaxies like the Milky Way?

Why high redshift? Galaxy formation hard to study in local universe

High-z = Jurassic Park of young galaxies



Nature Sep. 14, 2006

Why high redshift?

Galaxy formation hard to study in local universe

High-z = Jurassic Park of galaxies

Why z=2-3?

Galaxy formation epoch

Median galaxy young

Statistical samples obtainable

MUSYC

(Multiwavelength Survey by Yale-Chile)

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Paulina Lira (U. Chile)
Meg Urry (Yale)
Nicholas Bond (Rutgers)
Gabriel Brammer (Yale)
Carie Cardamone (Yale)
Marijn Franx (Leiden)
Harold Francke (U. Chile/Yale)
Lucia Guaita (P.U. Catolica)
Leopoldo Infante (P.U. Catolica)
Sheila Kannappan (UNC)
Sugata Kaviraj (Oxford)
Mariska Kriek (Princeton)
Ivo Labbe (OCIW)
Kyoung-Soo Lee (Yale)
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Nelson Padilla (P.U. Catolica)
Ryan Quadri (Leiden)
Kevin Schawinski (Oxford)
Ned Taylor (Leiden)
Ezequiel Treister (Hawaii-IfA)
Shanil Virani (Yale)

www.physics.rutgers.edu/~gawiser/MUSYC

Gawiser et al 2006a, ApJS 162, 1

MUSYC: A Square-degree Survey of the Formation and Evolution of Galaxies and their Central Black Holes

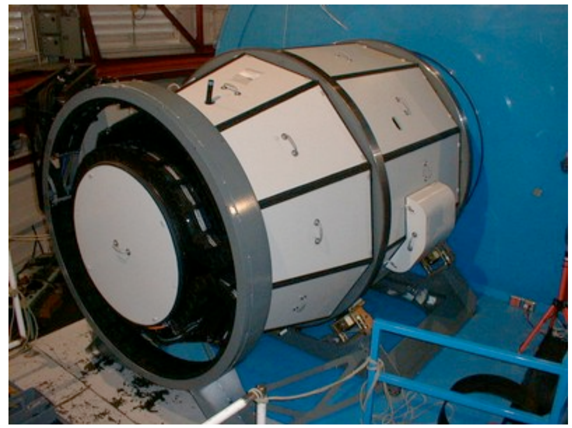
Science Projects:

1. **Census of galaxies at z=3 (Gawiser)**
2. Evolved galaxies at 2<z<3 (van Dokkum)
3. Properties of K-selected galaxies at z<2 (Lira)
4. AGN demographics at 0<z<6 (Urry)
5. Proper motion + color survey for white and brown dwarfs (Méndez)
6. Groups and clusters at z<1 (Christlein)
7. Recent star formation in ellipticals (Yi)

Etc.

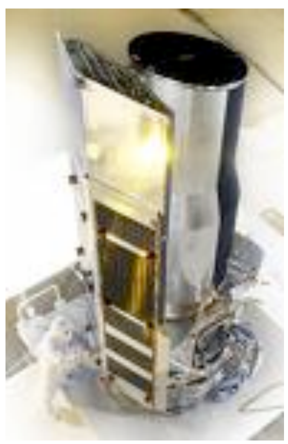
Where did we obtain the data?

CTIO4m
+MOSAIC
Found LAE galaxies in narrow-band images



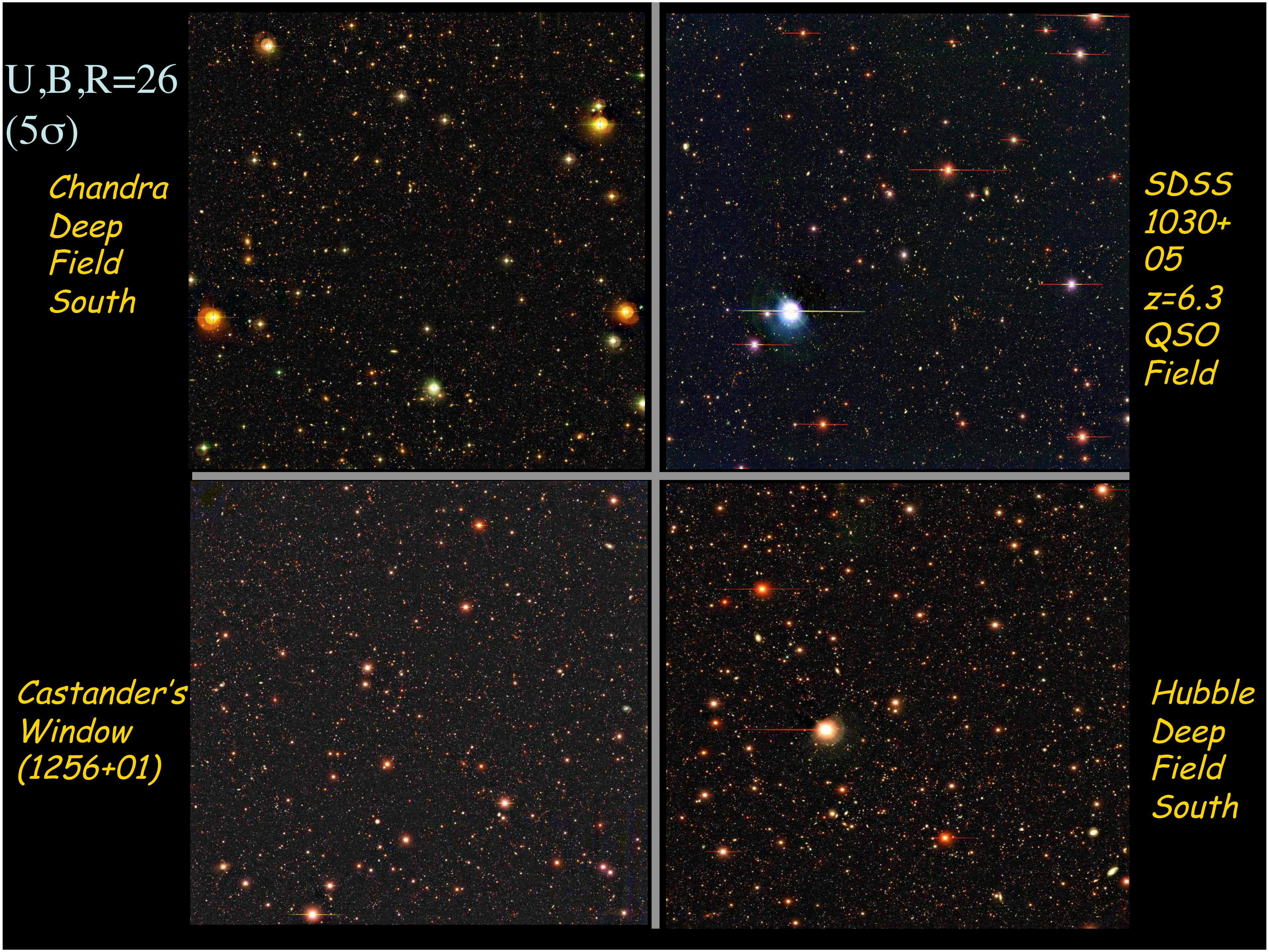
Magellan
+IMACS
Confirmed LAE redshifts, purity of sample

Spitzer
+IRAC
Measured stellar mass, number of stars in LAE galaxies



HST
+ACS
Determined sizes of LAE galaxies from archival GOODS images

(LAE = Lyman Alpha Emitting)


U,B,R=26
(5σ)
Chandra Deep Field South
SDSS 1030+05 z=6.3 QSO Field
Castander's Window (1256+01)
Hubble Deep Field South

277,341 objects in square-degree optical catalog

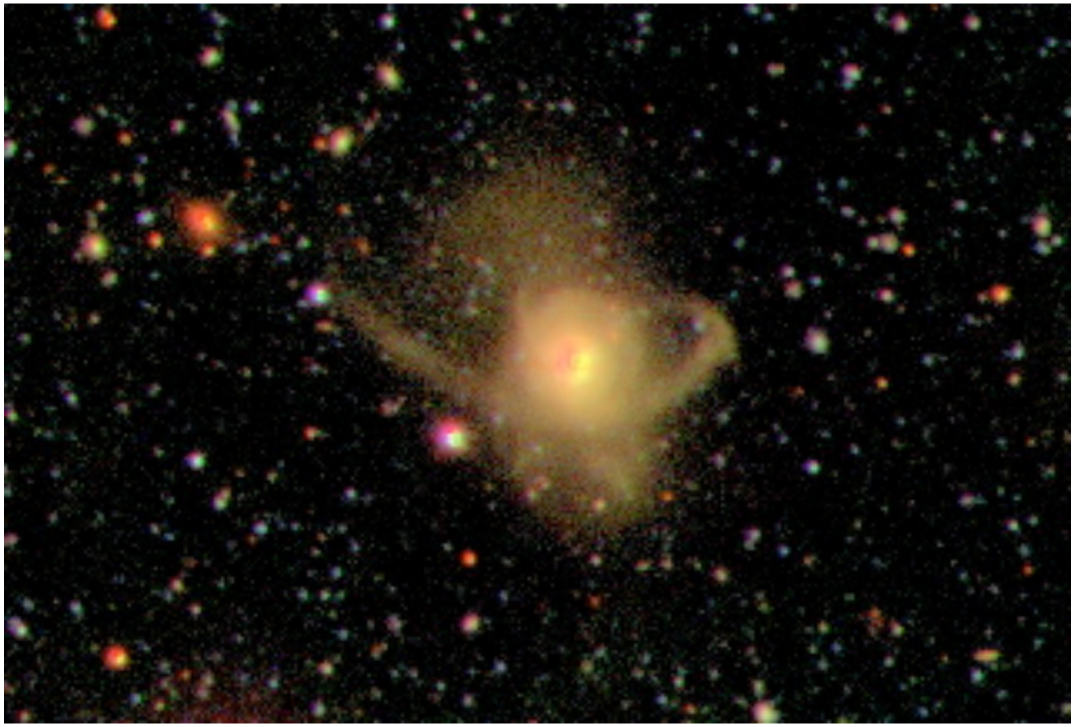
5σ Point Source Limits (AB mags):

Field	# Obj.	BVR	U	B	V	R	I	z	**NB5000**
E-CDFS	84410	27.1 0.85”	26.0	26.9	26.4	26.4	24.6	23.6	**25.5**
E-HDFS	62968	26.3 0.95”	26.0	26.1	26.0	25.8	24.7	23.6	24.0
SDSS 1030	69619	26.5 0.85”	25.8	26.0	26.2	26.0	25.4	23.7	24.8
CW 1255	60344	26.5 1.15”	26.0	26.2	26.1	26.0	25.0	24.1	24.4

BVR-selected catalogs complete to R=25 (total mag.)

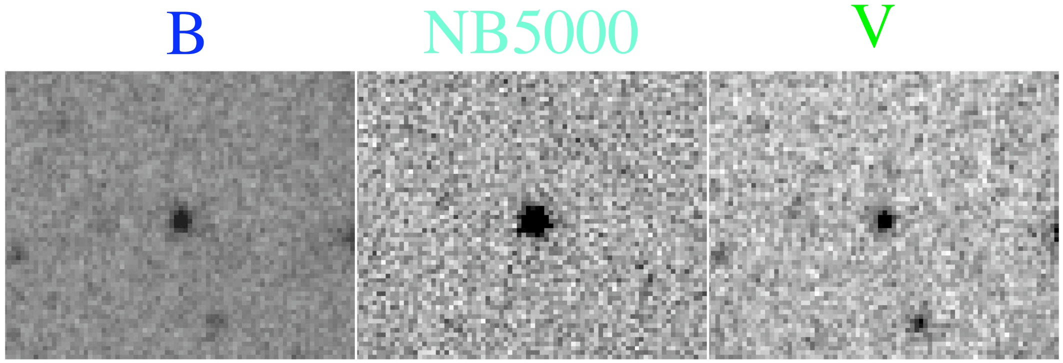
A square degree imaged to the spectroscopic limit!

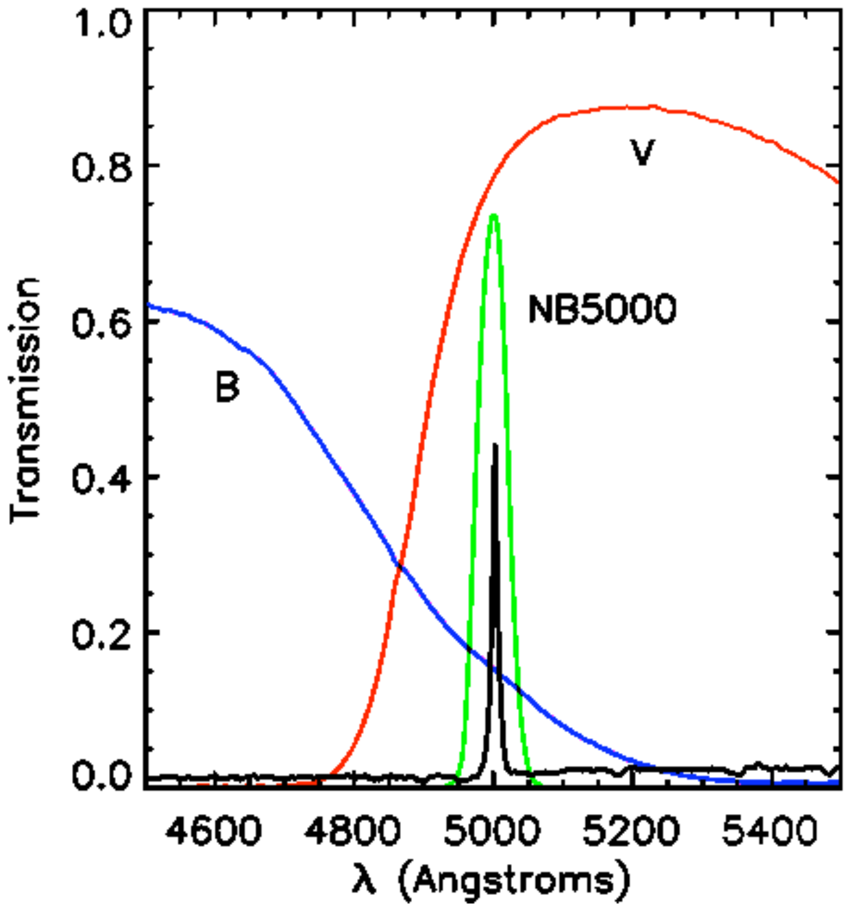
MUSYC



SDSS

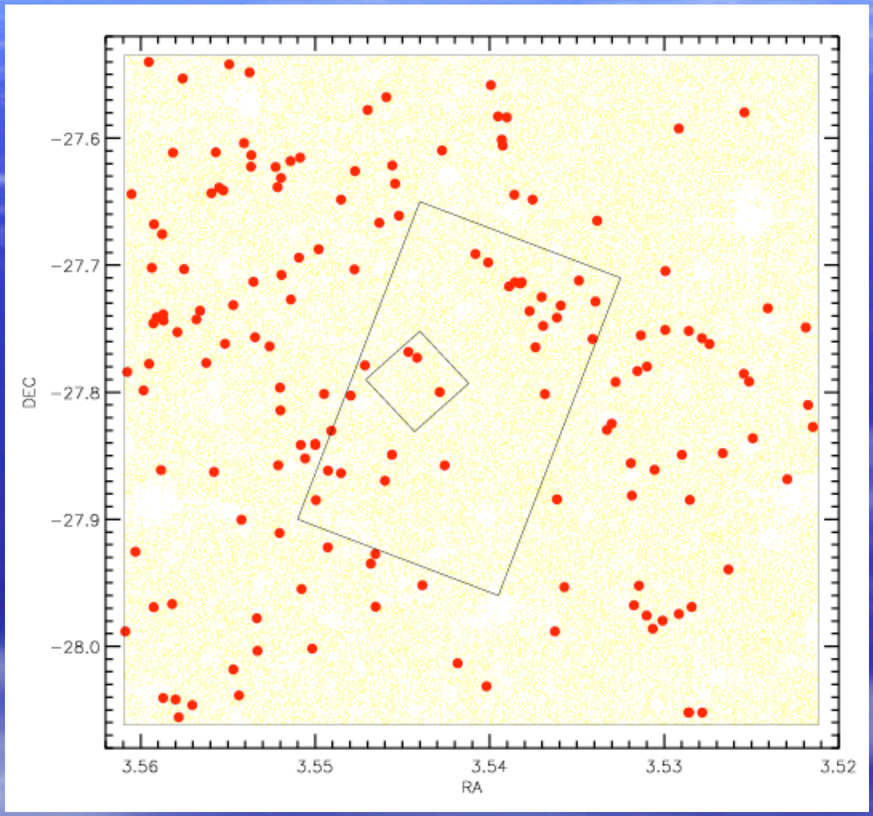
Lyman α Emitter (LAE)





MUSYC plus Caryl Gronwall,
Robin Ciardullo, John Feldmeier

z=3.1 LAE angular clustering in MUSYC-ECDFS



162 narrow-band selected LAE candidates

Spatial and angular auto-correlation functions:

$$dP(r) = \rho_g^2[1 + \xi_{gg}(r)]\, dV^2$$

$$dP(\theta) = \eta_g^2[1 + w_{gg}(\theta)]\, d\Omega^2$$

Projection of $\xi_{gg}(r) = b_g^2\, \xi_{DM}(r)$ into
$w_{gg}(\theta) = \int dz_1 \int dz_2\; p(z_1)p(z_2)\, \xi_{gg}(r(z_1,z_2,\theta))$

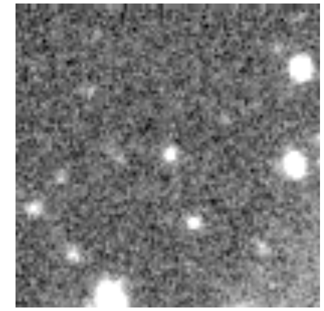
Need to measure redshift distribution p(z) for inversion of $w_{gg}(\theta)$ to determine b_g

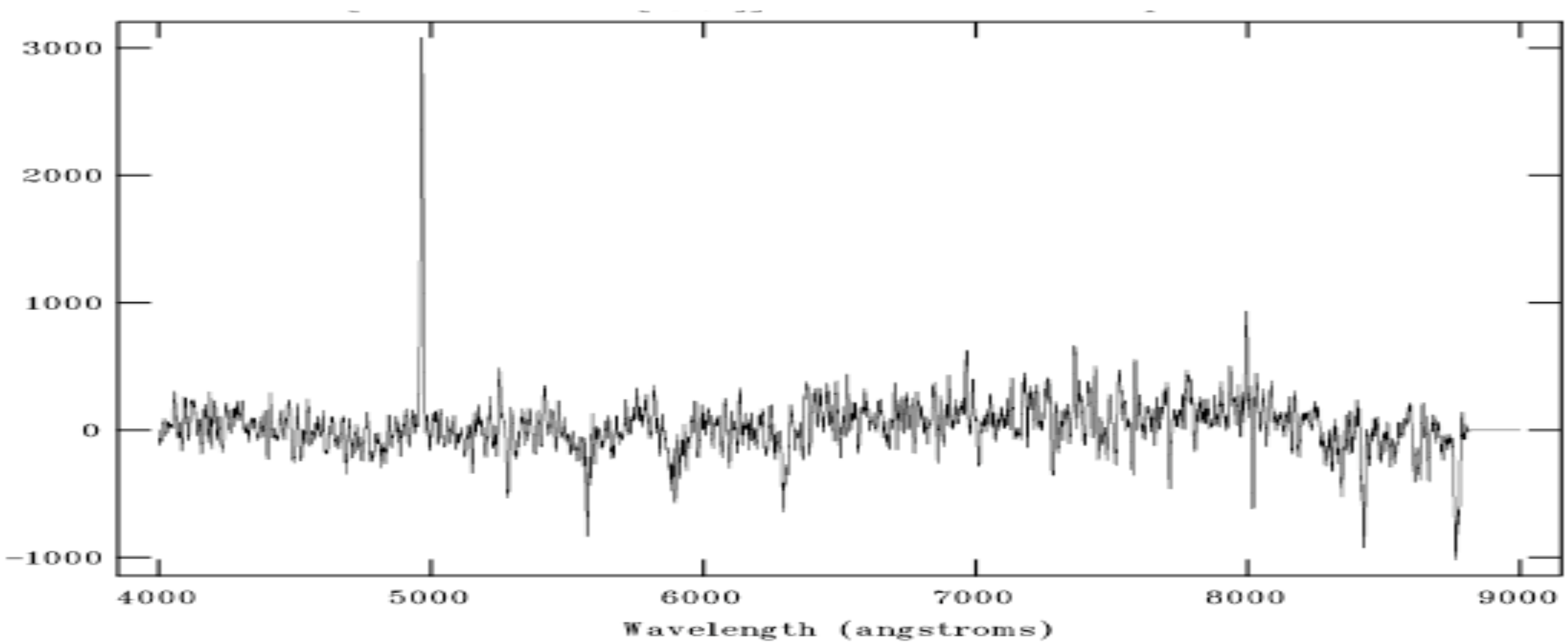
b_g determines typical dark matter halo mass (Mo & White 1996, MNRAS 282, 347)

LAE in E-CDFS, R=25.7, z=3.085

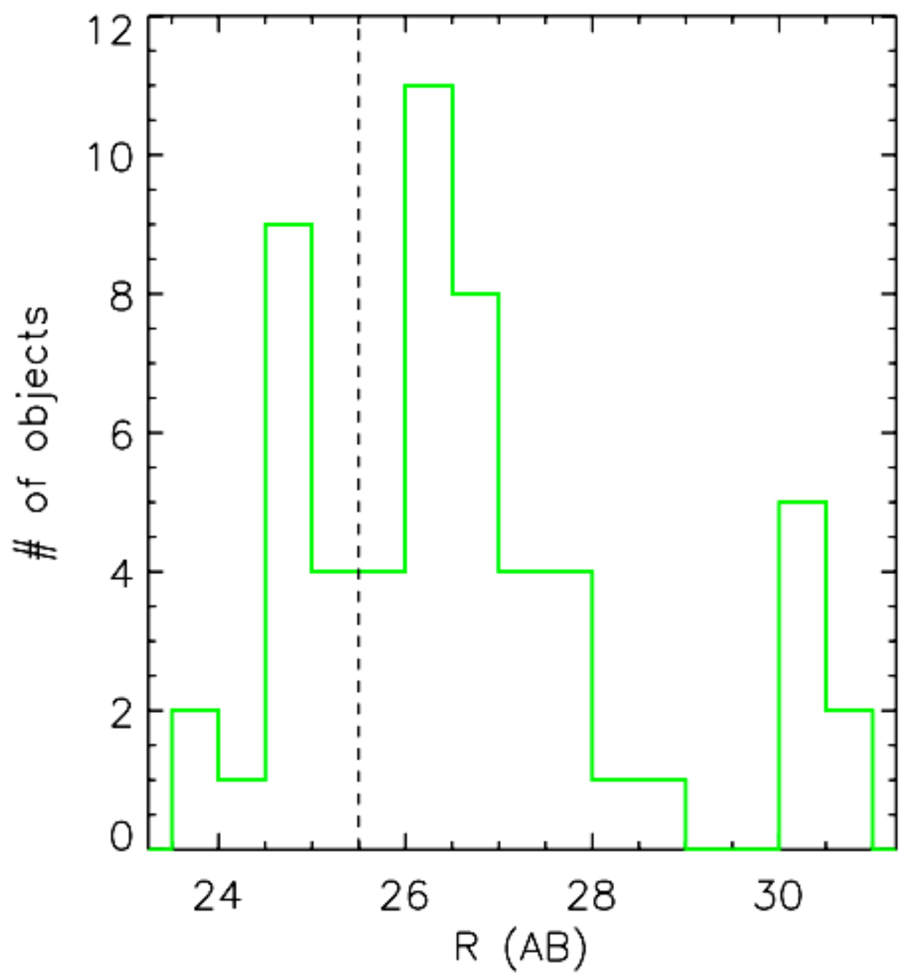
Lyα EW_{obs}=200Å, SFR≥30 $M_{\odot}$/yr

(6 hr exposure with Magellan+IMACS)



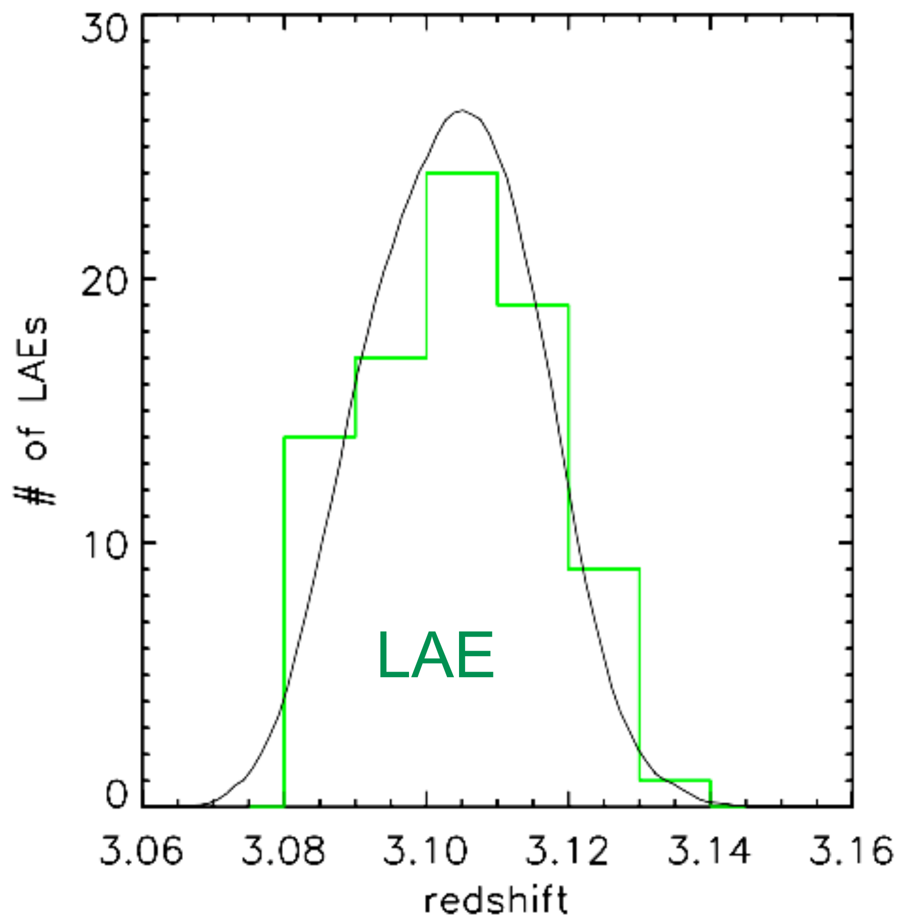


Lyman Alpha Emitters probe the z=3 luminosity function much deeper than Lyman break galaxies (R<25.5)



60 spectroscopically confirmed LAEs in MUSYC-ECDFS

Redshift distribution
(84 spectroscopically confirmed LAEs in 3 MUSYC fields)



Dark curve shows selection function:
narrow-band filter response
convolved with EW distribution

Further analyses led by:

Harold Francke (U. Catolica) -

Clustering analysis of LAE, LBG, AGN at 2<z<3

Lucia Guaita (U. Catolica/Rutgers) –

Selection and analysis of z=2.1 LAEs

Jean Walker-Soler (Rutgers) - Millenium halo catalogs

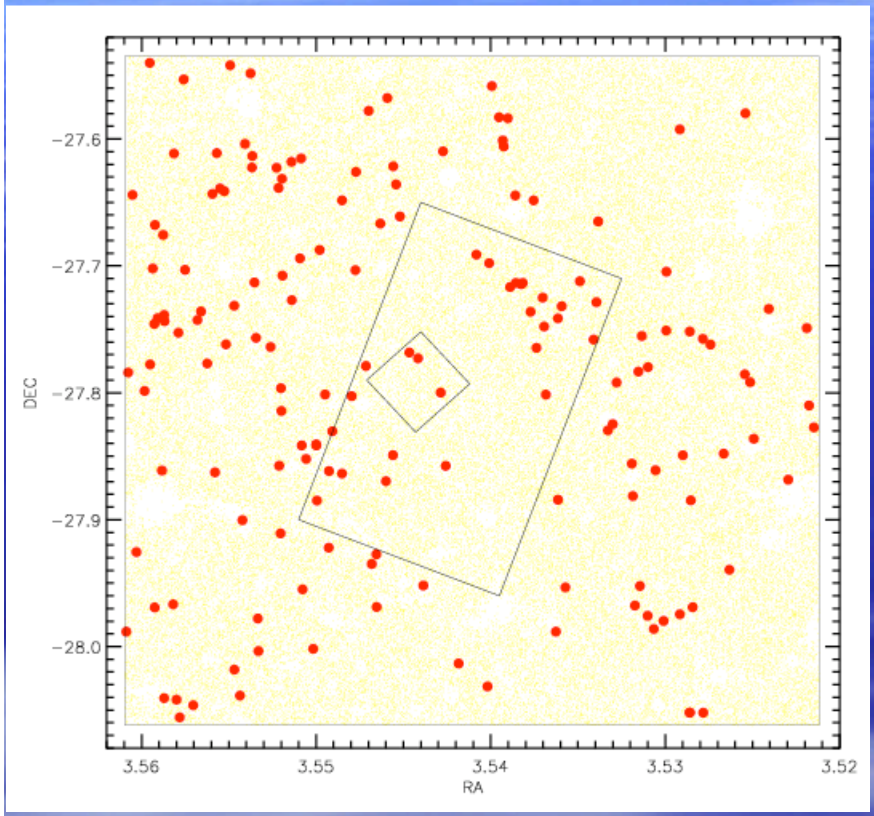
Nick Bond (Rutgers) – HST-ACS morphologies

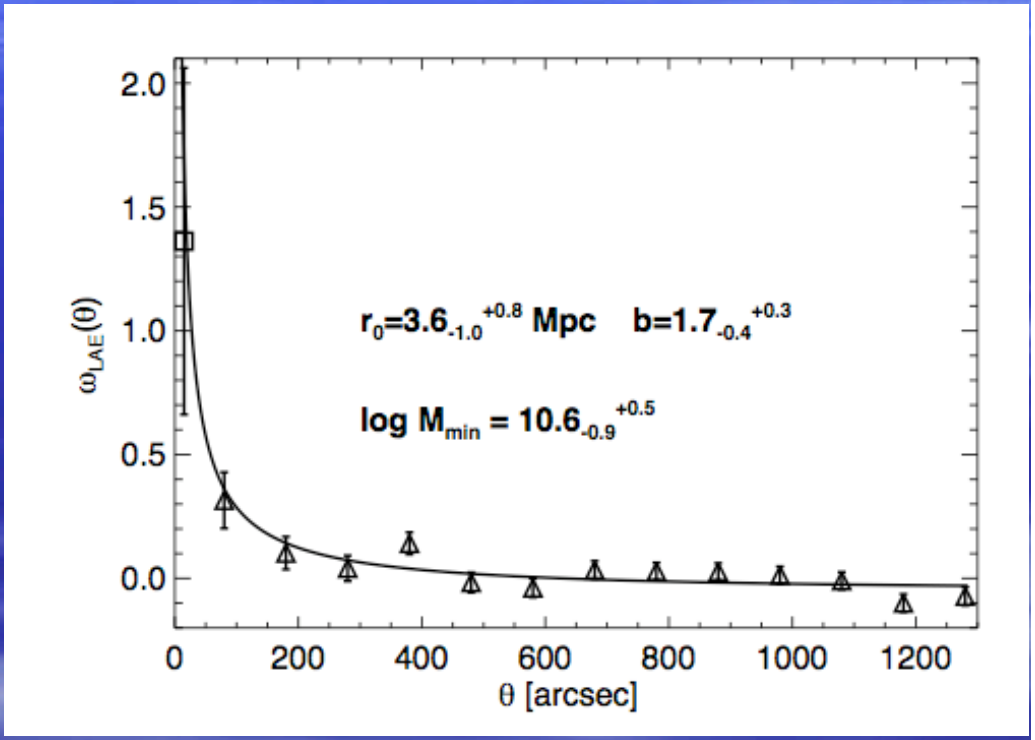
Kamson Lai (UCSC) - Careful IRAC photometry

Kevin Schawinski (Yale) - Dual-population SED fitting

LAE clustering in MUSYC-ECDFS

(Gawiser et al 2007, ApJ 671, 278)



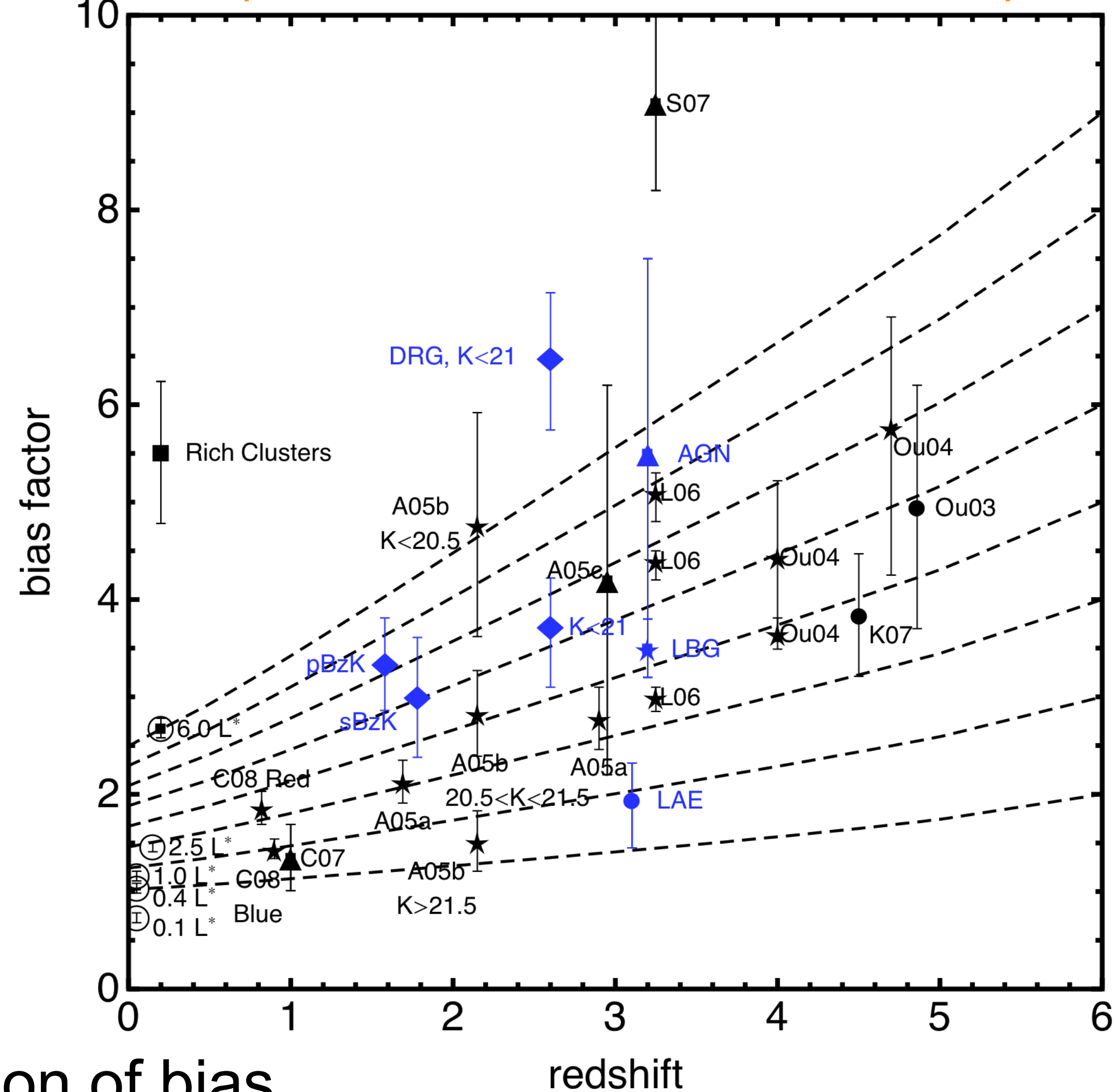


162 LAE candidates

Clustering analysis by Harold Francke

LAEs at z=3.1 evolve into ~L* galaxies at z=0

(Gawiser et al. 2007, ApJ 671, 278,   Francke et al. 2008, ApJL 673, L13)

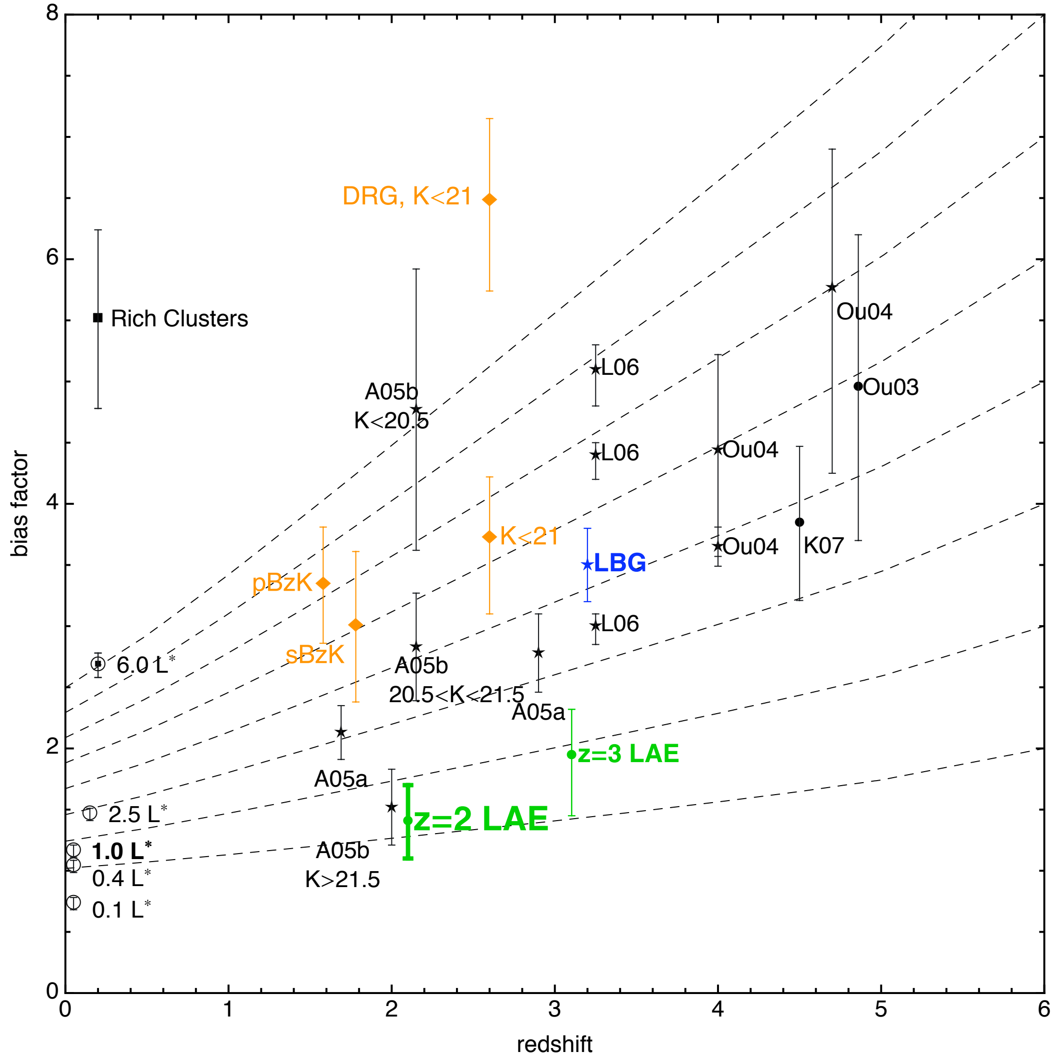


Evolution of bias

(dashed tracks are median of conditional mass function)

LAEs at ***z*=2.1** evolve into ~L* galaxies at *z*=0

(Guaita et al. 2009, in preparation)



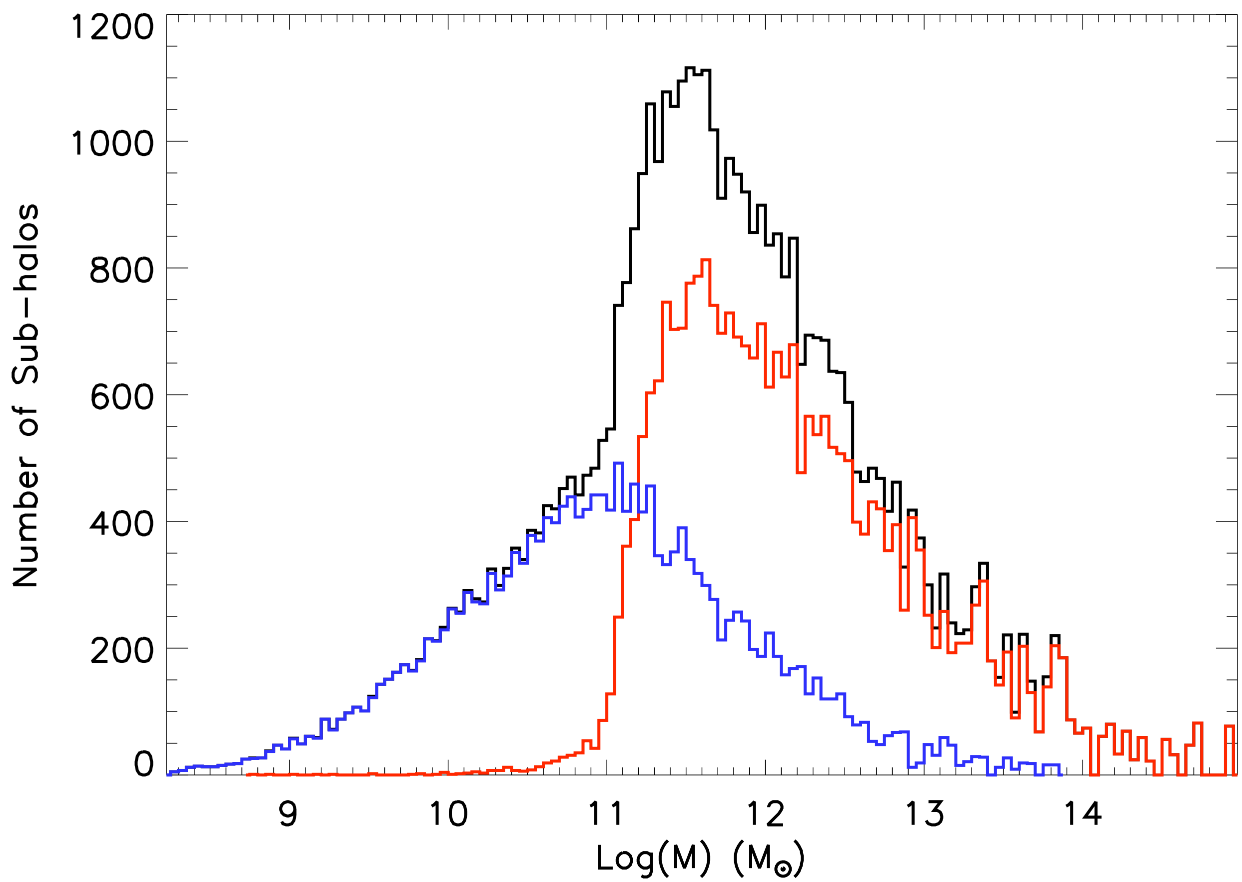
Evolution of bias

(dashed tracks are median of conditional mass function)

z=0 mass function of descendants of z=3.1 LAEs from Millenium-2 halo catalogs

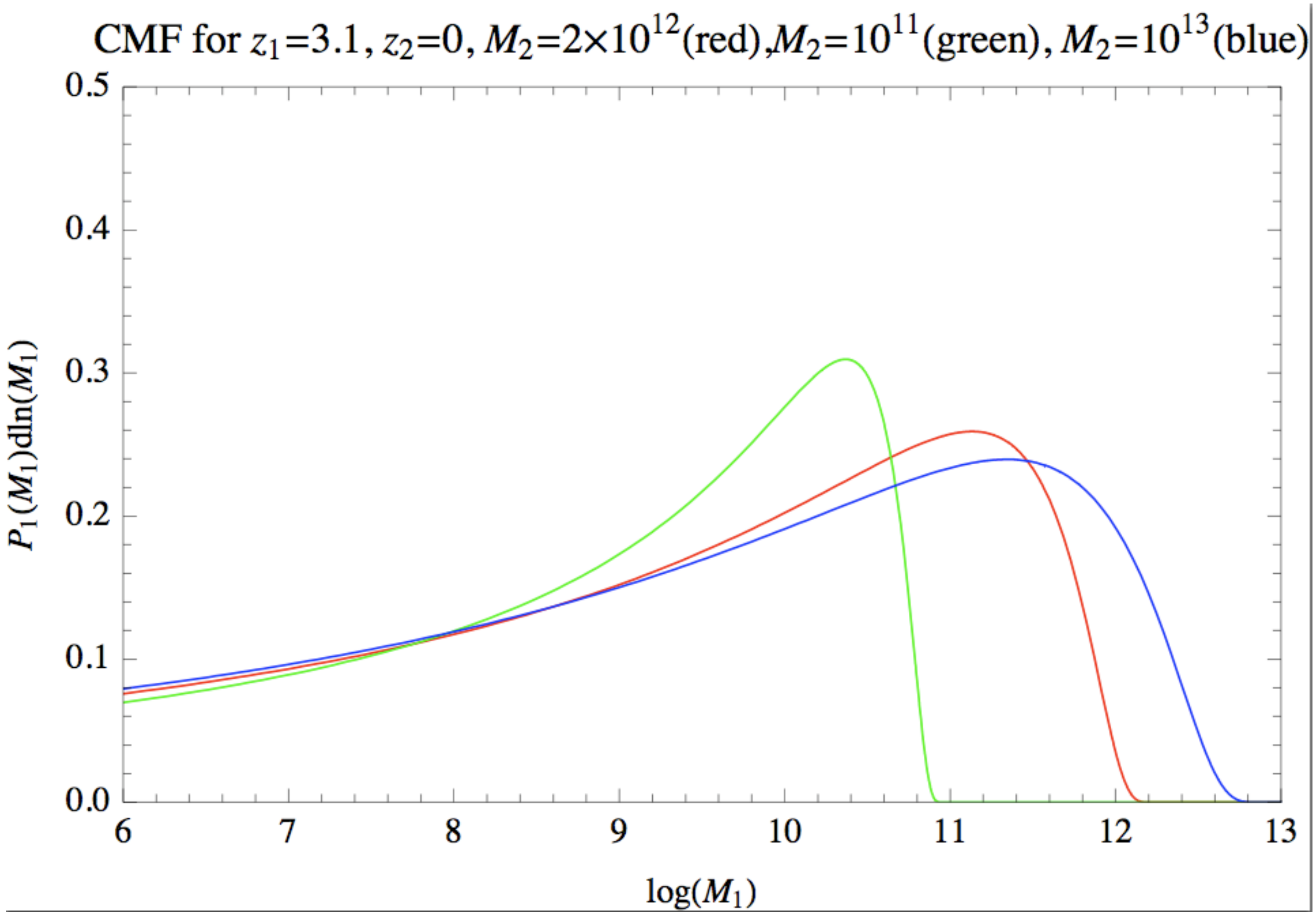
(Walker-Soler et al. 2009, in prep)

Number of (Sub-)Halos

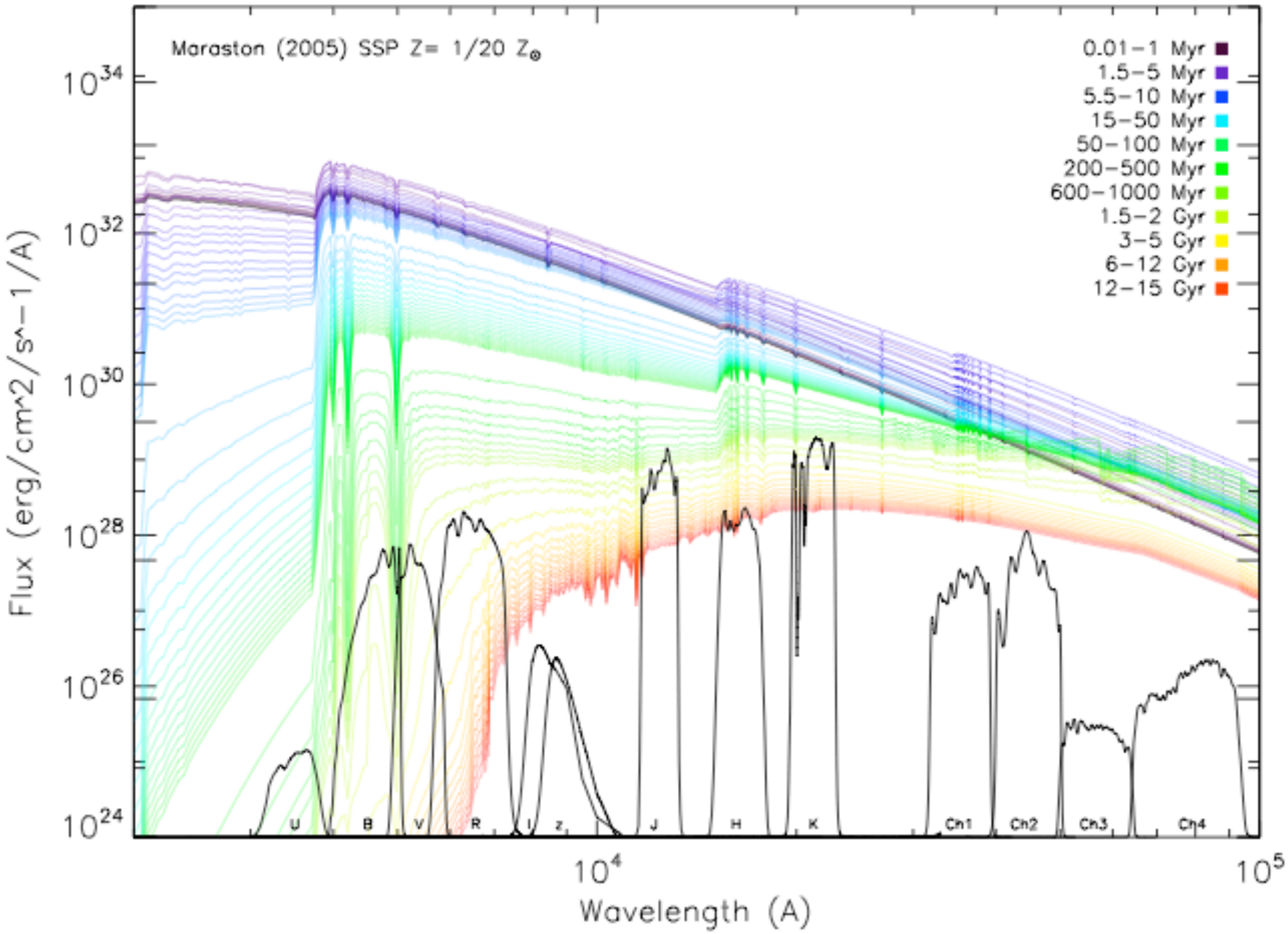


Log(Mass [M⊙])

Inverse Conditional Mass Function:
What was halo mass distribution of L* progenitors at z=3.1?
(red curve)

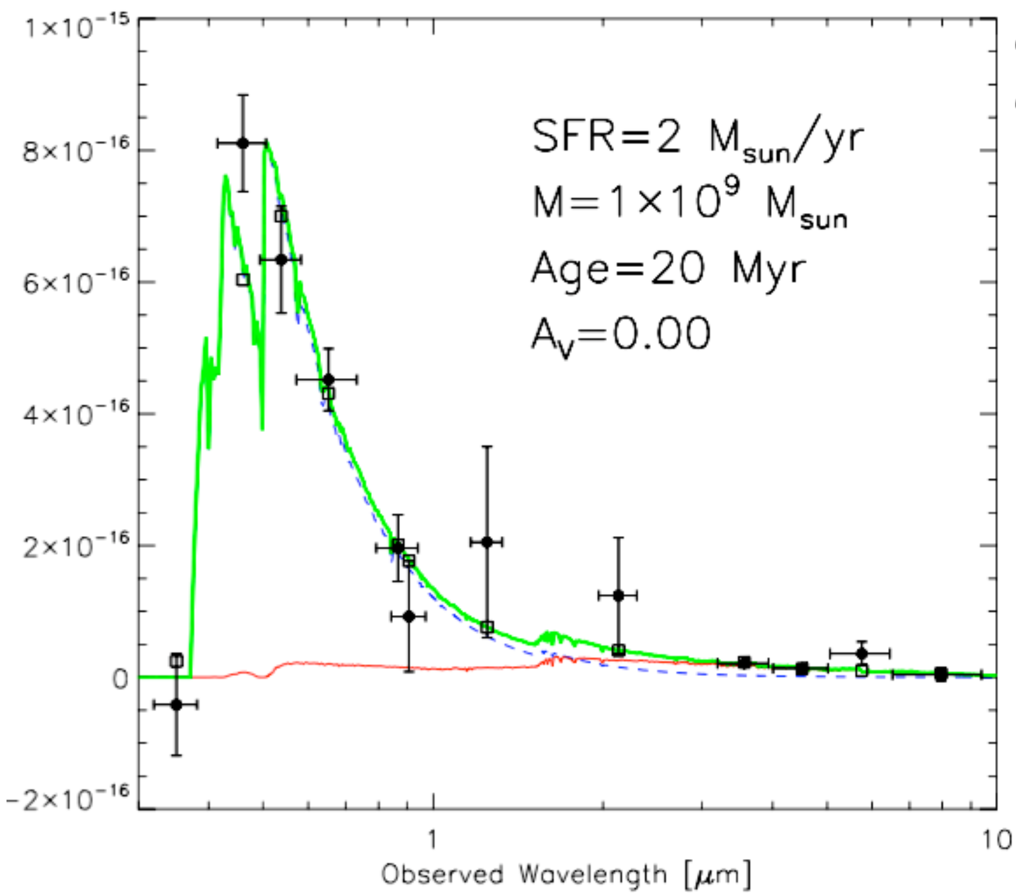


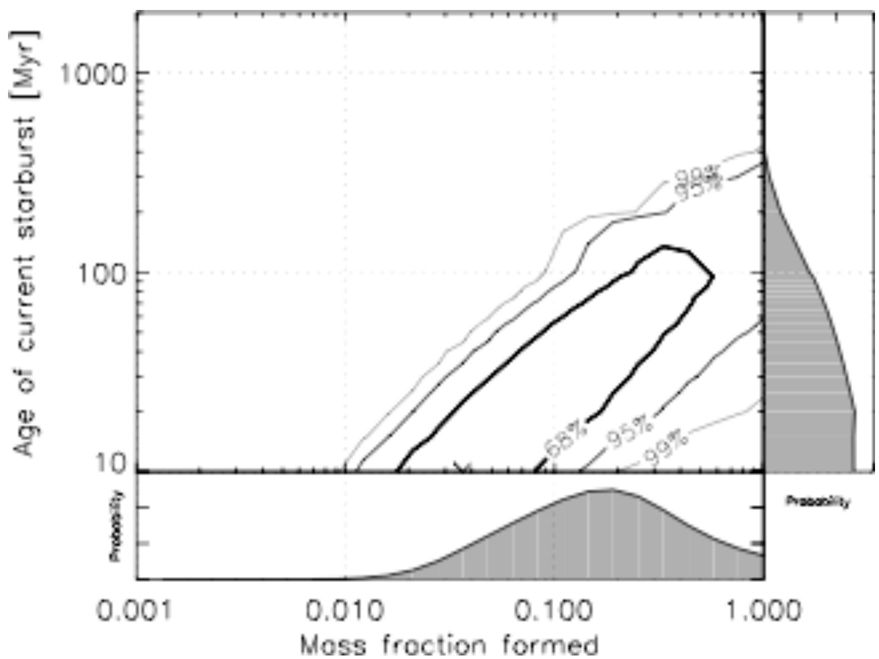
Measuring the age of a galaxy (z=3)

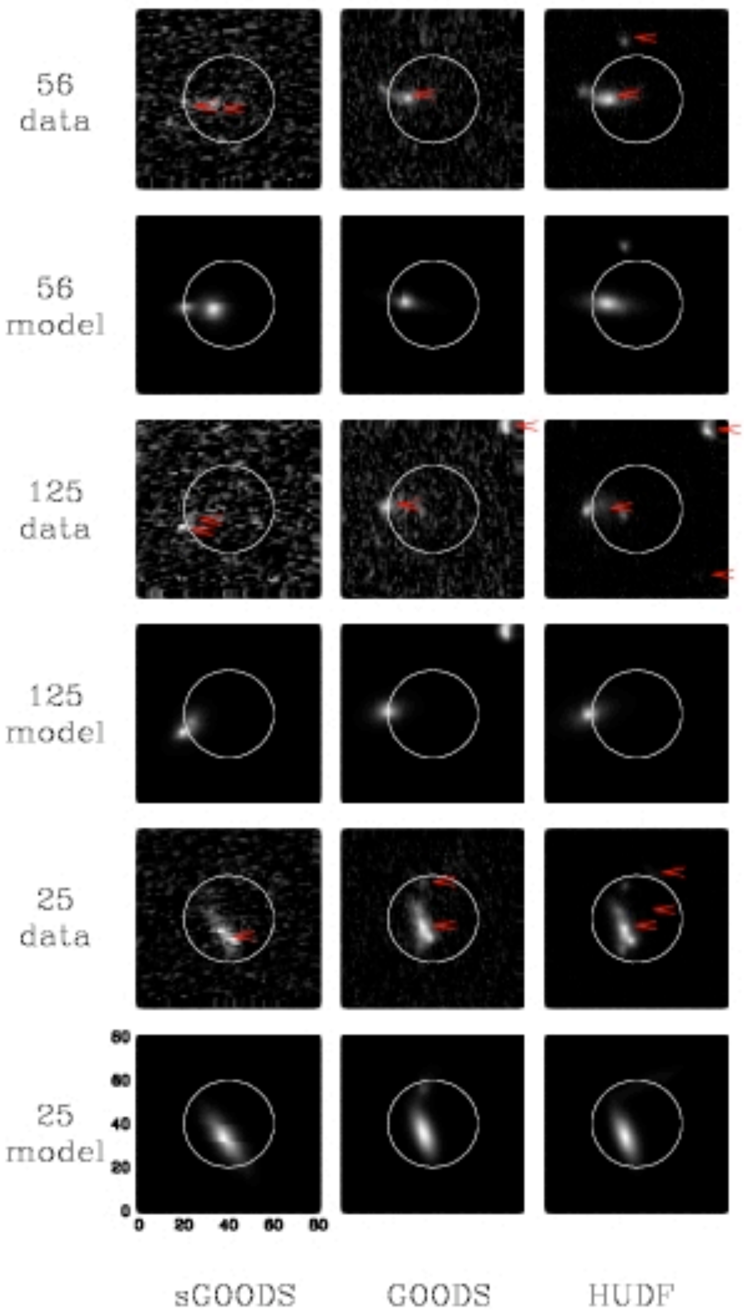


Two-population fit to stacked SED of IRAC-undetected LAEs

(Gawiser et al 2007, ApJ 671, 278)





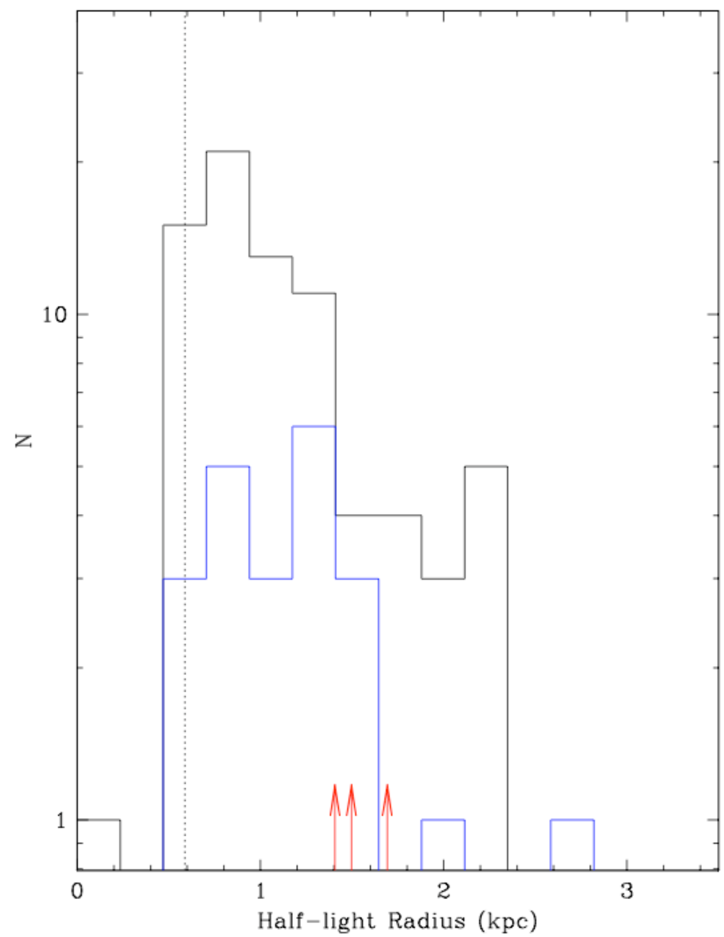


Lyman Alpha Emitters are small,
with 0.5-2 kpc half-light radii,
mix of disk-like and bulge-like Sersic indices

(Bond et al 2009 ApJ submitted ArXiv:0907:2235, Gronwall et al 2009 in prep.)

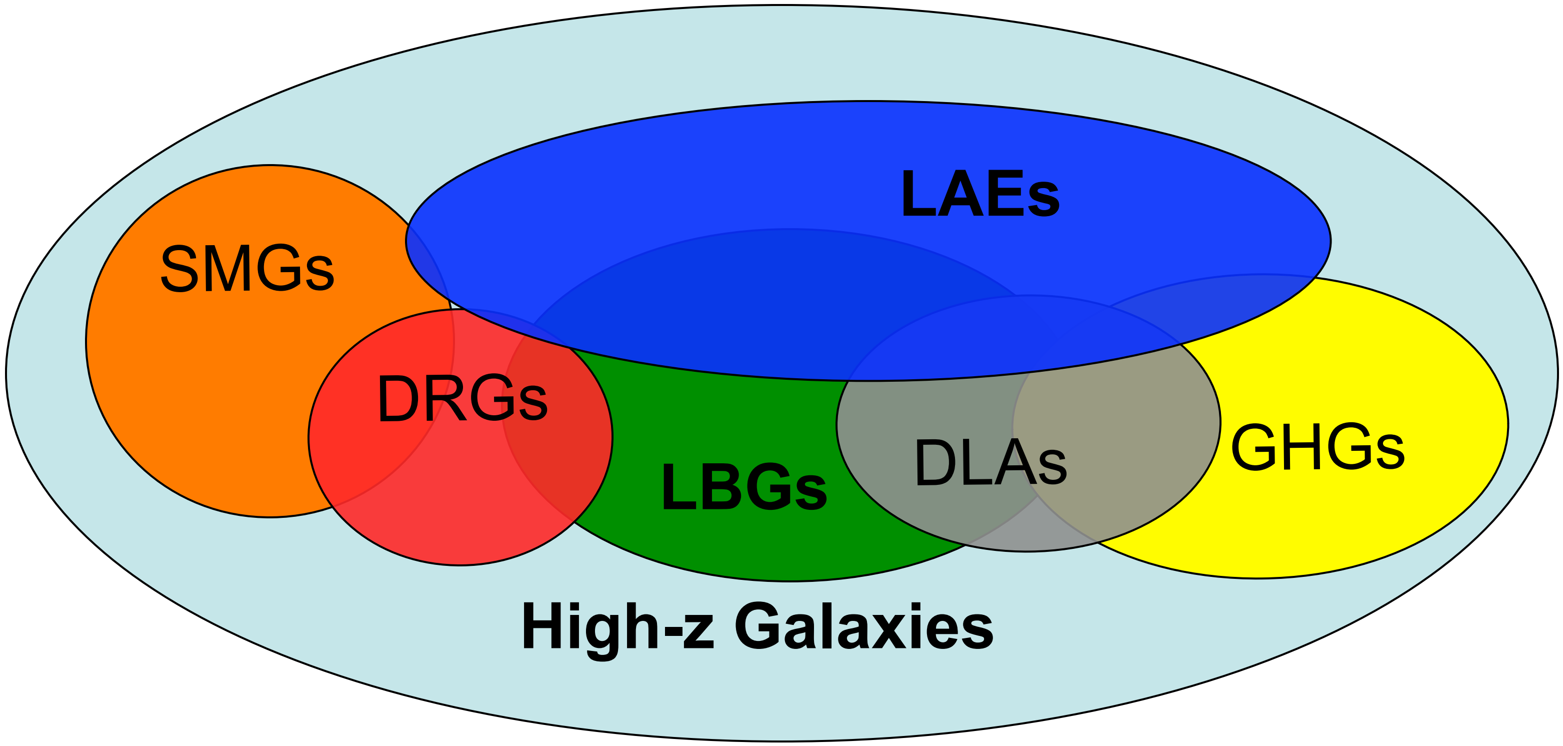
Initial Results: PHOT Half-Light Radius Distribution

- Half-light radius distribution (not accounting for PSF) Black: GEMS, Blue: GOODS, Red: UDF
- Dotted line indicates approximate resolution limit
- Most objects have $R_e < 2$ kpc, many unresolved
- At higher S/N, separate clumps merge into single resolved objects



Galaxies at z=3: TLAs

- LAE=Lyman Alpha Emitter
  selected via strong emission line (early stage of star formation)
- LBG=Lyman Break Galaxy
  selected via Lyman break, blue continuum (starburst)
- DRG=Distant Red Galaxy
  selected via Balmer break in observed NIR
- SMG=Sub-Millimeter detected Galaxy
  hyperluminous in sub-mm, implying huge SFR, heavy dust
- DLA=Damped Lyman α Absorption system
  selected in absorption, N(HI)>10^{20} cm^{-2}
- GHG=GRB (Gamma-Ray Burst) Host Galaxy
  Burst rate is some function of SFR, host redshifts are easiest via Lyα
- AGN=Active Galactic Nucleus
  selected in X-rays, mid-infrared or via LBG-like colors



← Higher M_*, M_{DM}, $L_{bolometric}$, SFR, dust, AGN fraction

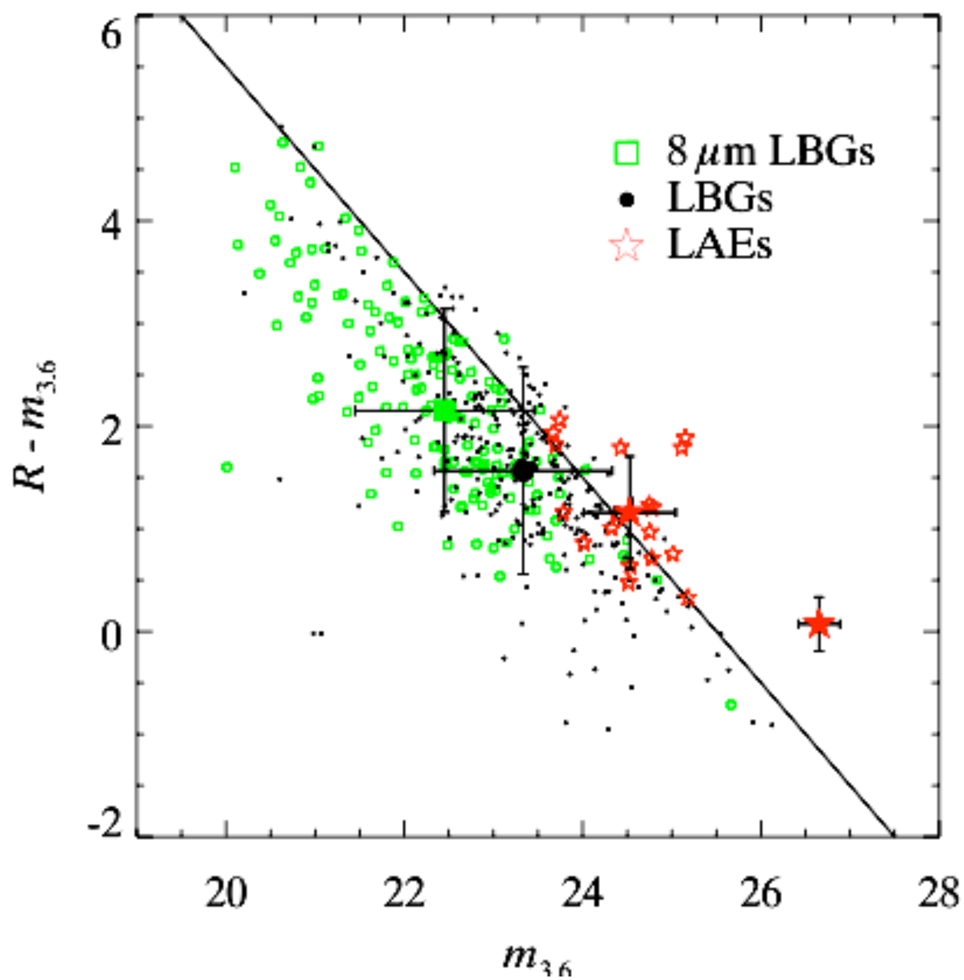
An evolutionary sequence?

z=3 universe	LAE	LBG	DRG	SMG	DLA
Space density (n_i / h_{70}^{-3})	1.5×10^{-3} Mpc^{-3} MUSYC	2×10^{-3} Mpc^{-3} Adelberger+05	3×10^{-4} Mpc^{-3} MUSYC	2×10^{-6} Mpc^{-3} Chapman+03	ALMA
SFR per object (SFR_i)	3 $M_\odot$ yr^{-1} MUSYC	30 $M_\odot$ yr^{-1} Shapley+01	130 $M_\odot$ yr^{-1} MUSYC	1000 $M_\odot yr^{-1}$ Chapman+05	1-30 $M_\odot yr^{-1}$ (~2 objects) Moller+02, Bunker+04
Stellar mass per object ($M_{*,i}$)	10^9 $M_\odot$ MUSYC	2×10^{10} $M_\odot$ Shapley+05	$2\times10^{11} M_\odot$ van Dokkum +04	LESS	JWST
Clustering length ($r_{0,i} / h_{70}^{-1}$)	4±1 Mpc MUSYC	7±1 Mpc MUSYC	10±2 Mpc MUSYC	16±7 Mpc Webb+03	4±2 Mpc Cooke+05

Cosmological quantities:	LAE	LBG	DRG	SMG	DLA
SFR density ($\rho_{SFR,i} = n_i \times SFR_i$)	0.01 $M_\odot yr^{-1} Mpc^{-3}$ MUSYC	0.1 $M_\odot yr^{-1} Mpc^{-3}$ Steidel+99	0.04 $M_\odot yr^{-1} Mpc^{-3}$ MUSYC	0.02 $M_\odot yr^{-1} Mpc^{-3}$ Chapman +05	0.03 $M_\odot yr^{-1} Mpc^{-3}$ Wolfe, EG & Prochaska 03
Stellar mass density ($\rho_{*,i} = n_i M_{*,i}$)	$10^6 M_\odot Mpc^{-3}$ MUSYC	$10^7 M_\odot Mpc^{-3}$ Shapley+01	$6 \times 10^7 M_\odot Mpc^{-3}$ MUSYC	LESS	JWST
DM halo mass	$10^{11} M_\odot$ MUSYC	$10^{12} M_\odot$ MUSYC	$3 \times 10^{12} M_\odot$ MUSYC	$10^{13} M_\odot$ MUSYC	$10^{9-12} M_\odot$ Cooke+05

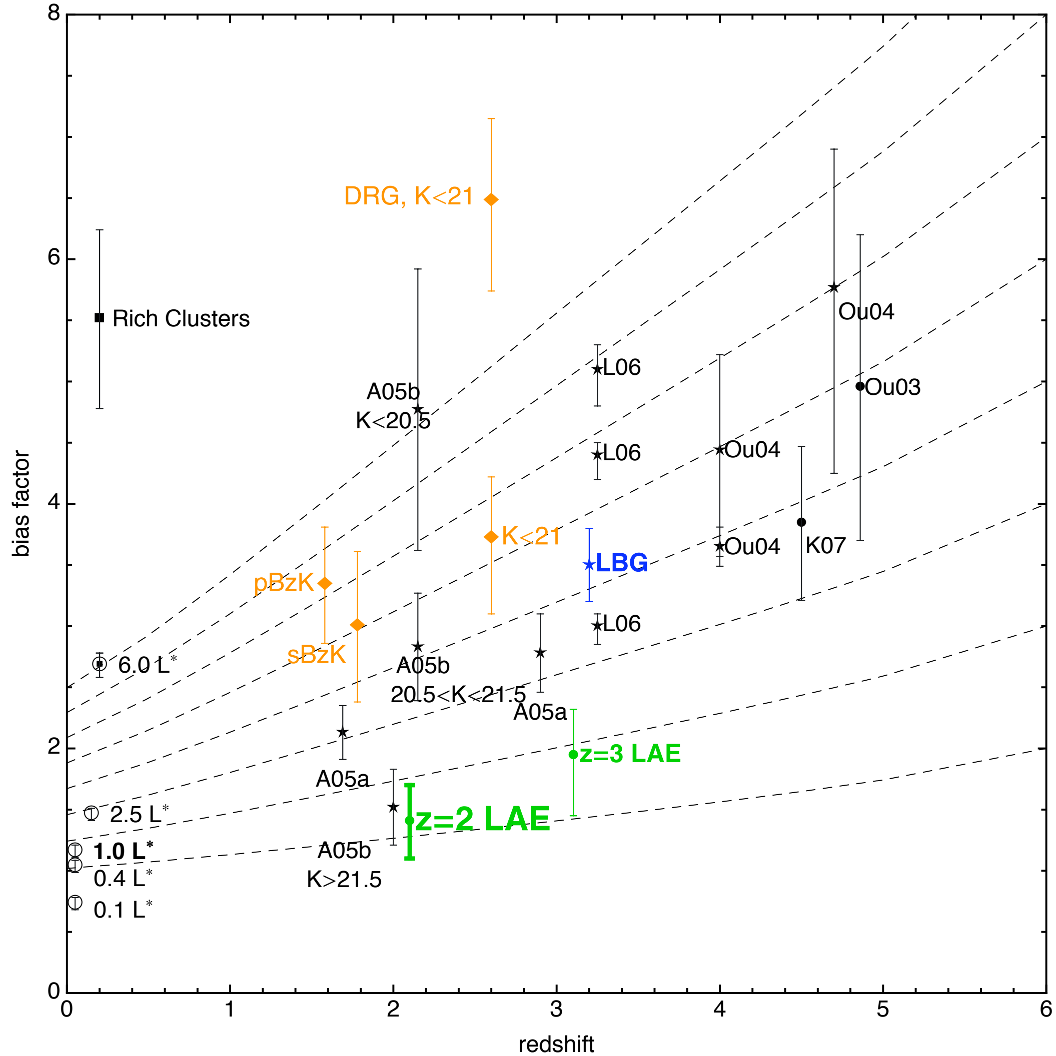
Color-(IRAC)magnitude diagram

(Lai et al 2008, ApJ 674, 70)



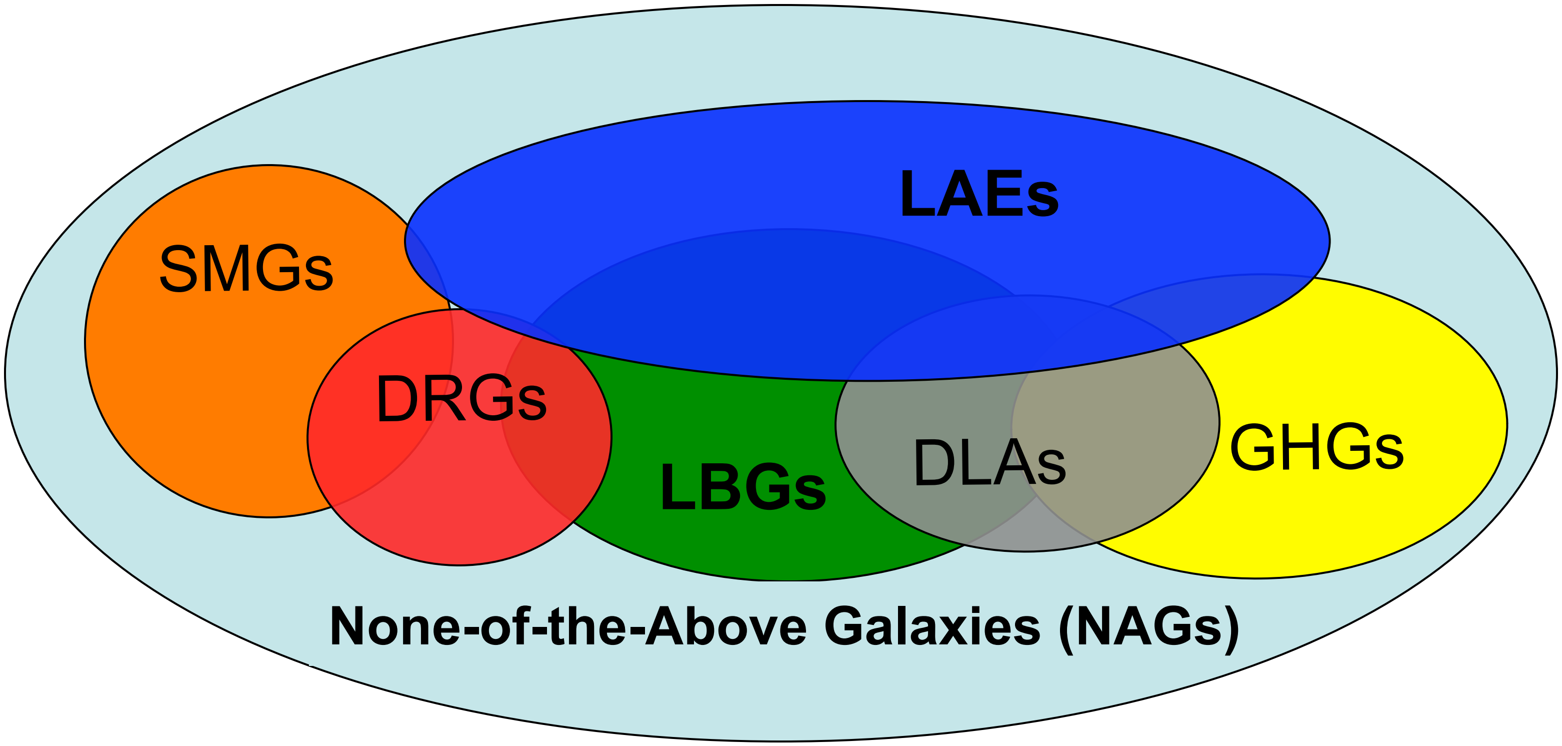
LAEs at 2<z<3 evolve into ~L* galaxies at z=0

(Gawiser et al. 2007, ApJ 671, 278, Guaita et al. 2009, in prep.)



Evolution of bias

(dashed tracks are median of conditional mass function)



← Higher M_*, M_{DM}, $L_{bolometric}$, SFR, dust, AGN fraction

Are we missing anything?

Conclusions

- The Lyα emission line allows LAEs to be selected and confirmed spectroscopically to the lowest bolometric luminosity of any high-redshift technique.
- With low stellar masses ($M<10^9$ $M_\odot$), LAEs have the highest *specific* SFR of any galaxy population. This is consistent with the young starburst age of 20 Myr inferred for the dominant population not detected by IRAC.
- Only 2-3% of LAEs at $2<z<3$ host AGN revealed through X-rays, high ionization emission lines, or IRAC colors.
- LAEs at $2<z<3$ have dark matter halo masses of $\sim10^{11} M_\odot$. They will evolve into ~L* galaxies today. Most LBGs, DRGs, SMGs and AGN will evolve into more massive, highly-biased galaxies today (ellipticals and cluster members).
- An evolutionary sequence LAE➔LBG➔DRG➔SMG may occur. Most LAEs at $2<z<3$ never make it past the "LBG" (star-forming galaxy) stage. Higher-redshift LAEs appear to complete the sequence and become part of massive elliptical galaxies today.