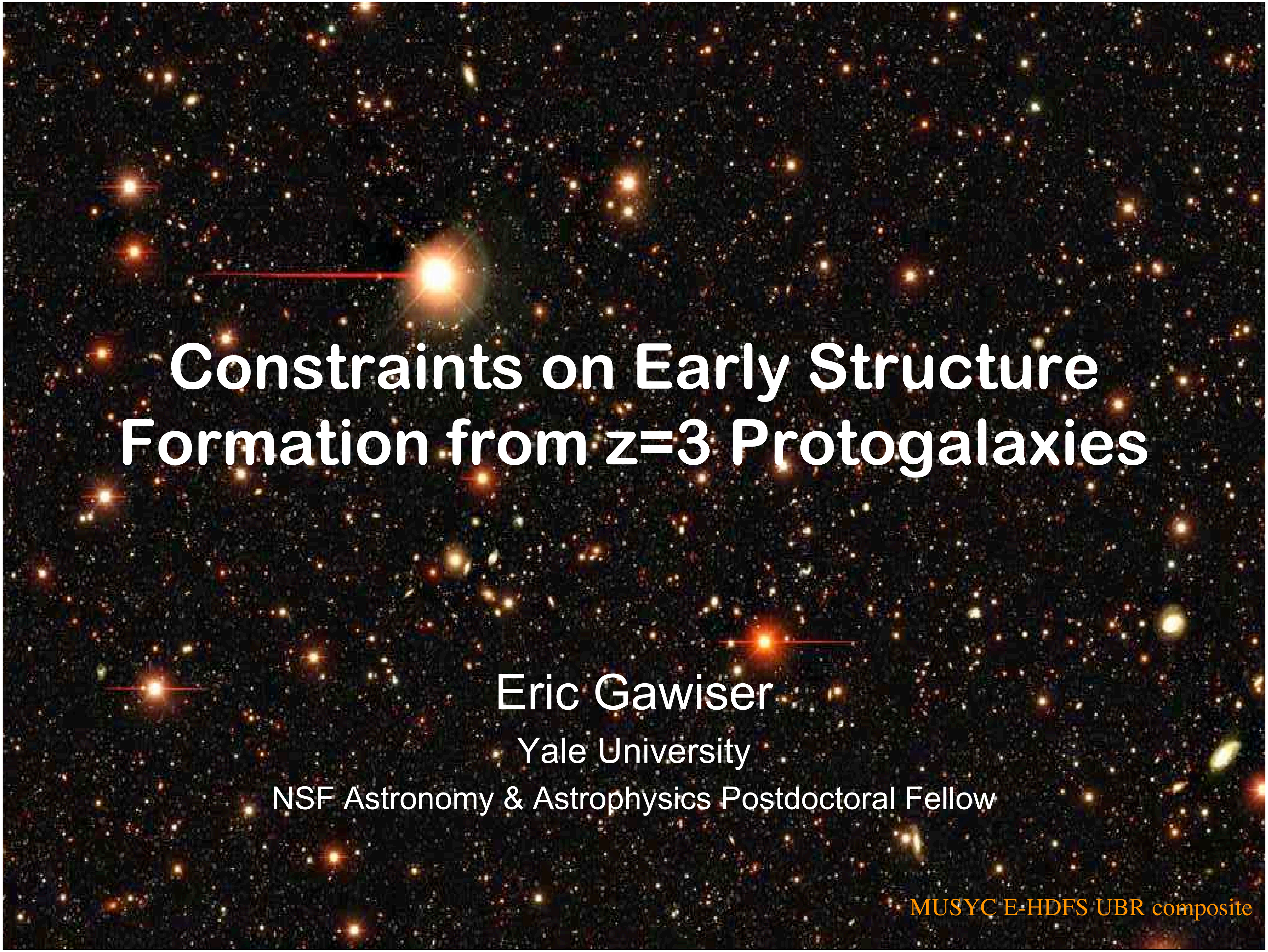
Constraints on Early Structure Formation from z=3 Protogalaxies

Eric Gawiser

Yale University

NSF Astronomy & Astrophysics Postdoctoral Fellow



MUSYC E-HDFS UBR composite

Outline

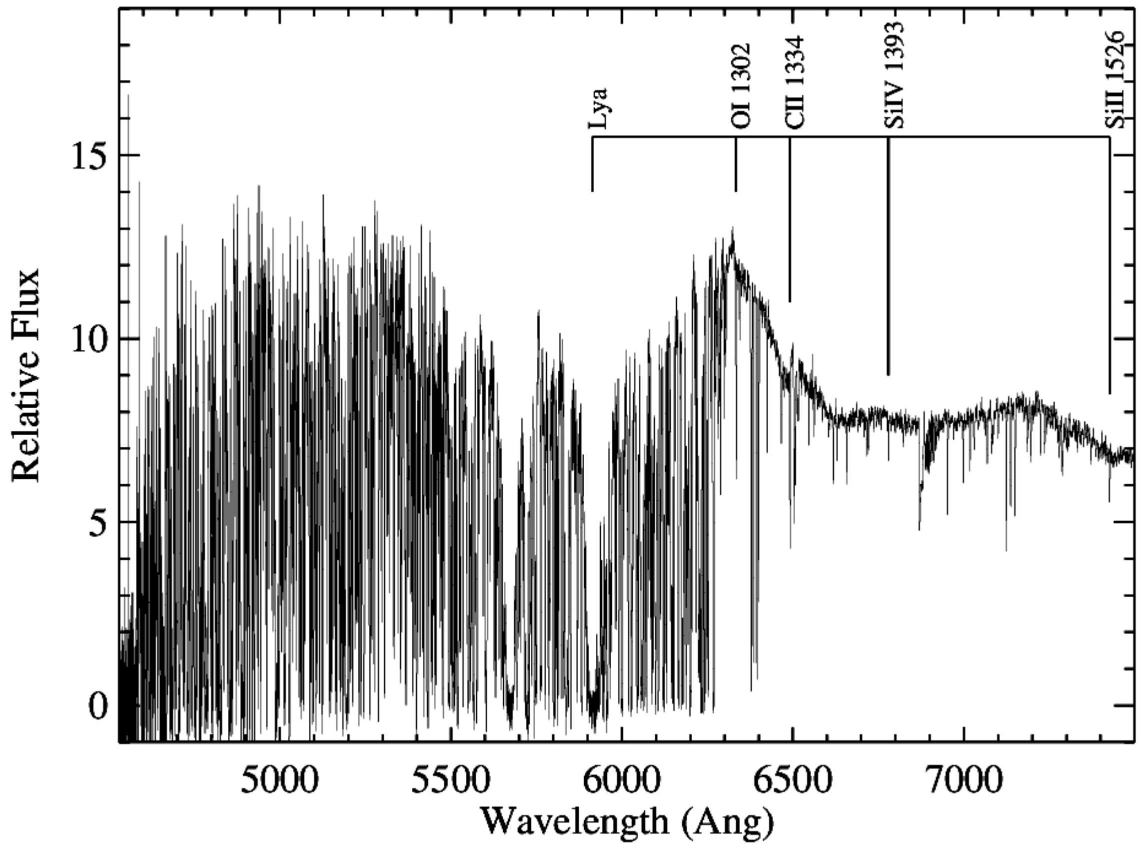
Constraints from Damped Lyman alpha Absorbers (DLAs)

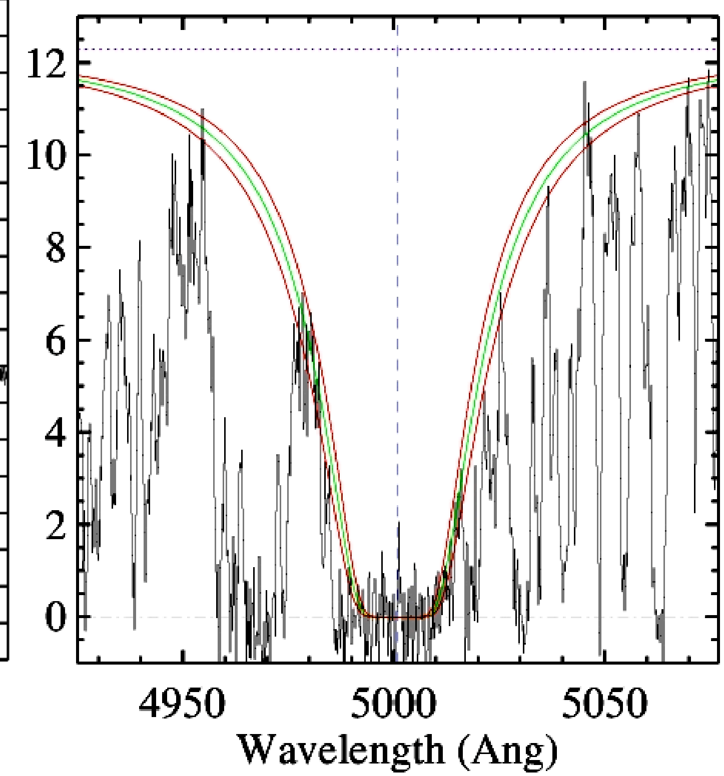
(see Wolfe, Gawiser & Prochaska 2005, ARAA 43, 861, astro-ph/0509481 and references therein)

The MUSYC Census of Protogalaxies at z=3

(see Gawiser et al. 2005, ApJS in press, astro-ph/0509202 and www.astro.yale.edu/MUSYC)

AGN with Damped Lyman α Absorber (DLA)

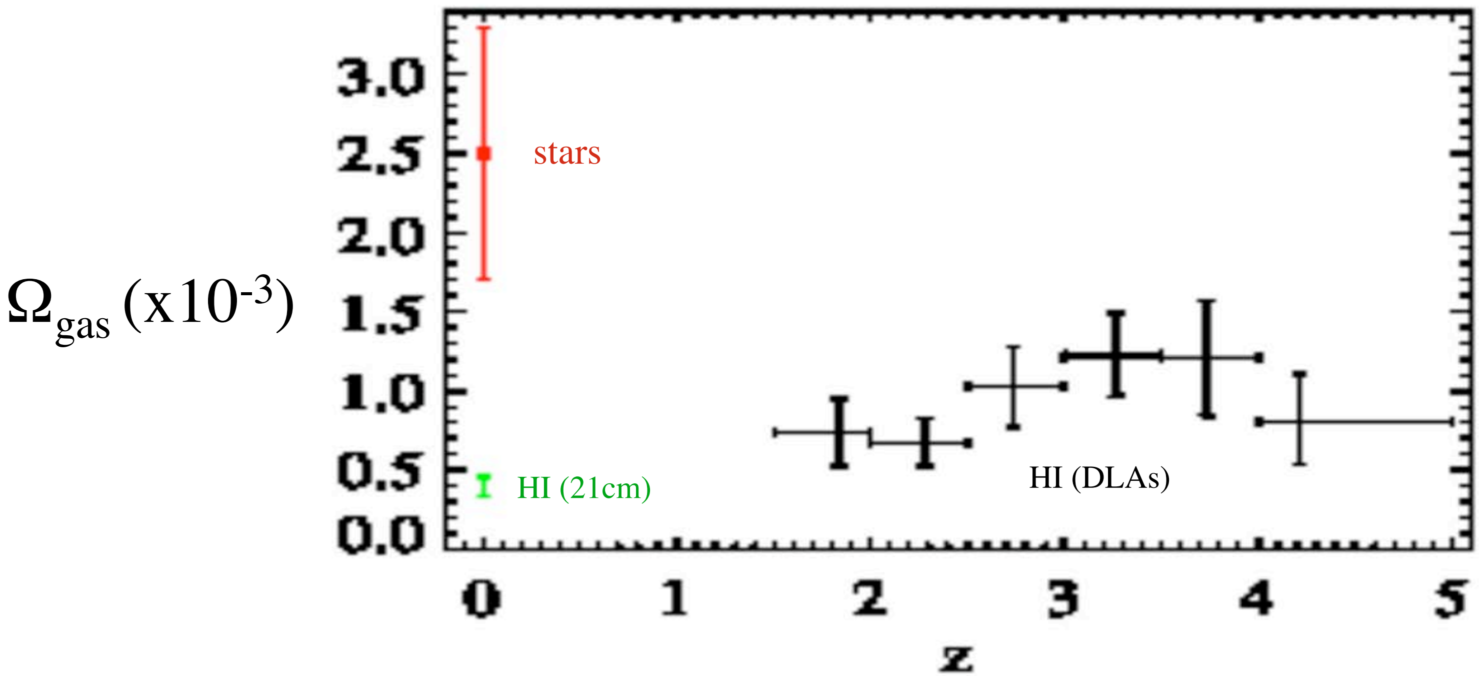




DLAs have $N(HI) > 2 \times 10^{20} cm^{-2}$, sufficient to self-shield against (re)ionization

Most systems with $10^{19} < N(HI) < 2 \times 10^{20}$ ("sub-DLAs") are predominantly ionized
➔ "Super-Lyman Limit Systems"

Cosmic density of neutral gas



DLAs contain majority of HI, vast majority of neutral gas

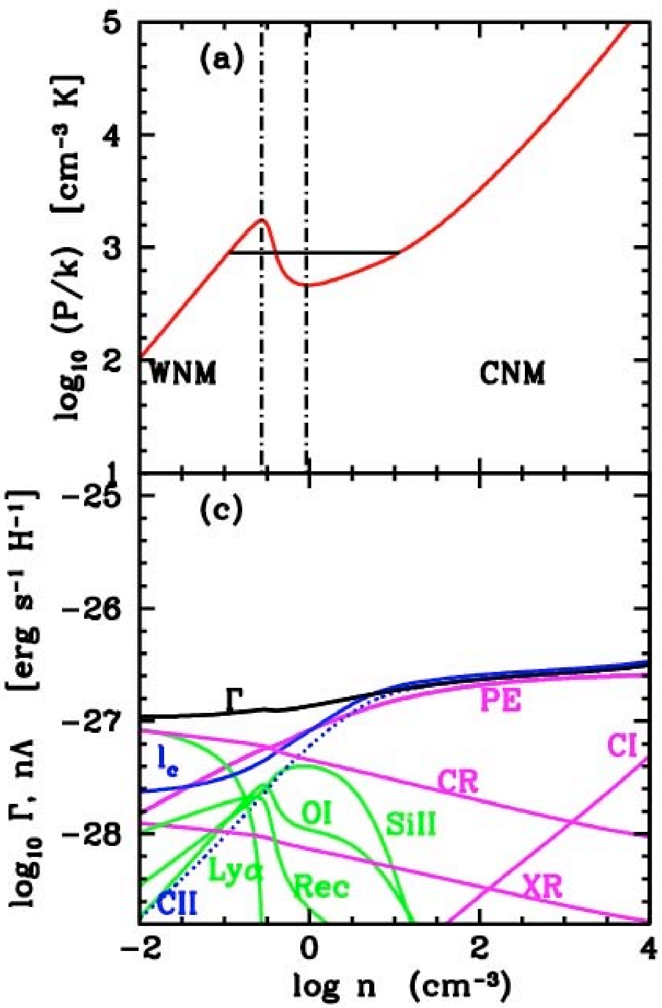
Neutral gas reservoir traced by DLAs is depleted by z=0, forming >~ half of the stars seen today

History of neutral gas

Closed box: $d\rho_{gas}/dt = -d\rho_*/dt$

Open box: $d\rho_{gas}/dt = -d\rho_*/dt$ + infall + merging - winds

Interstellar Medium at z=3



CNM/WNM

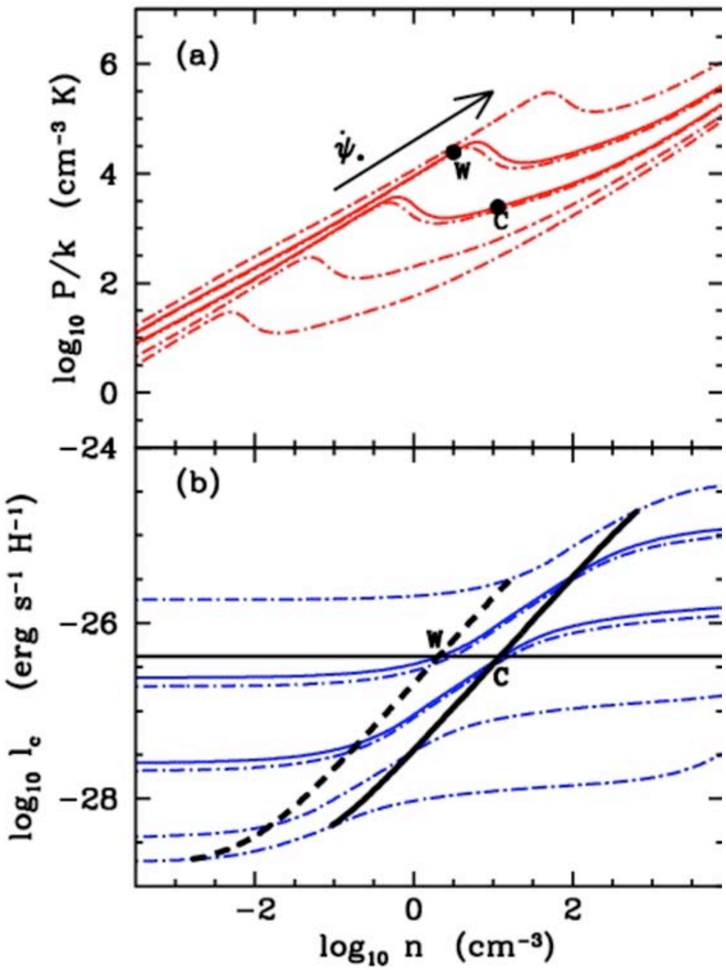
CII* absorption → cooling rate l_c

In CNM, CII* cooling measures the total heating rate, but in WNM it only sees a fraction of it.

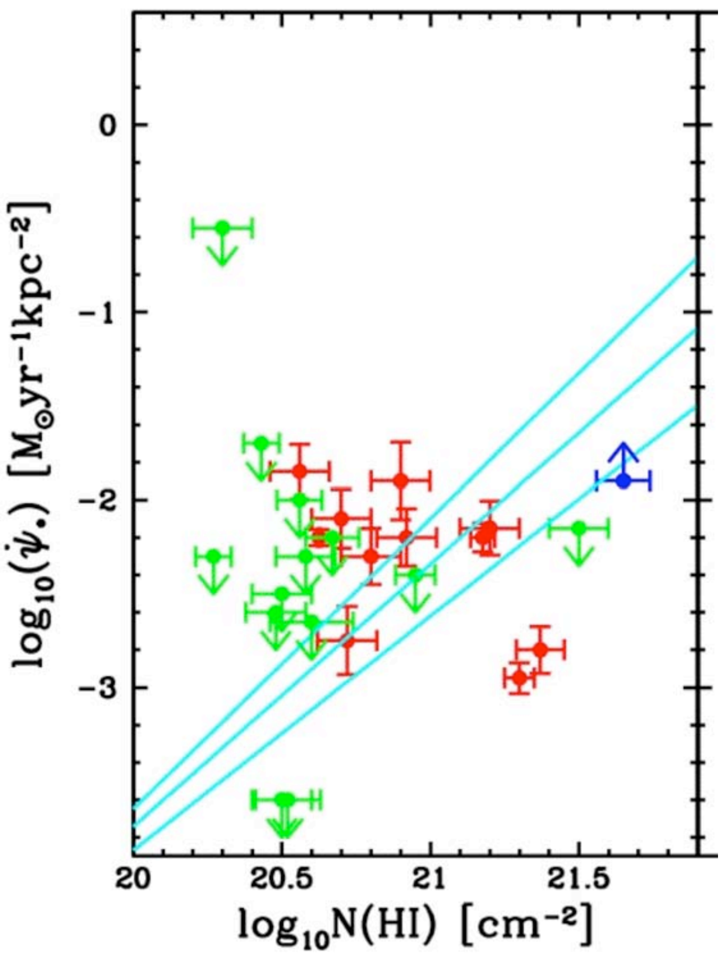
About half of DLA lines of sight appear to represent pure WNM.

WIM also seen in CIV, SIV absorption lines

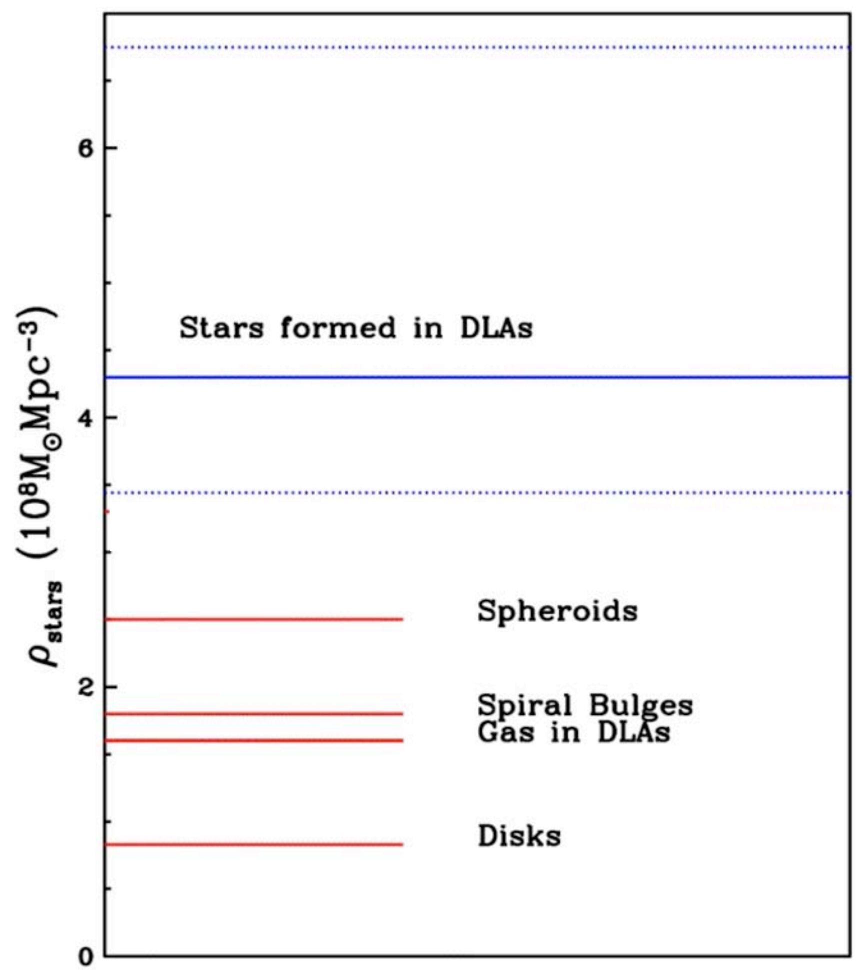
Determining SFR/area



Does the Schmidt-Kennicutt relation hold at z=3?

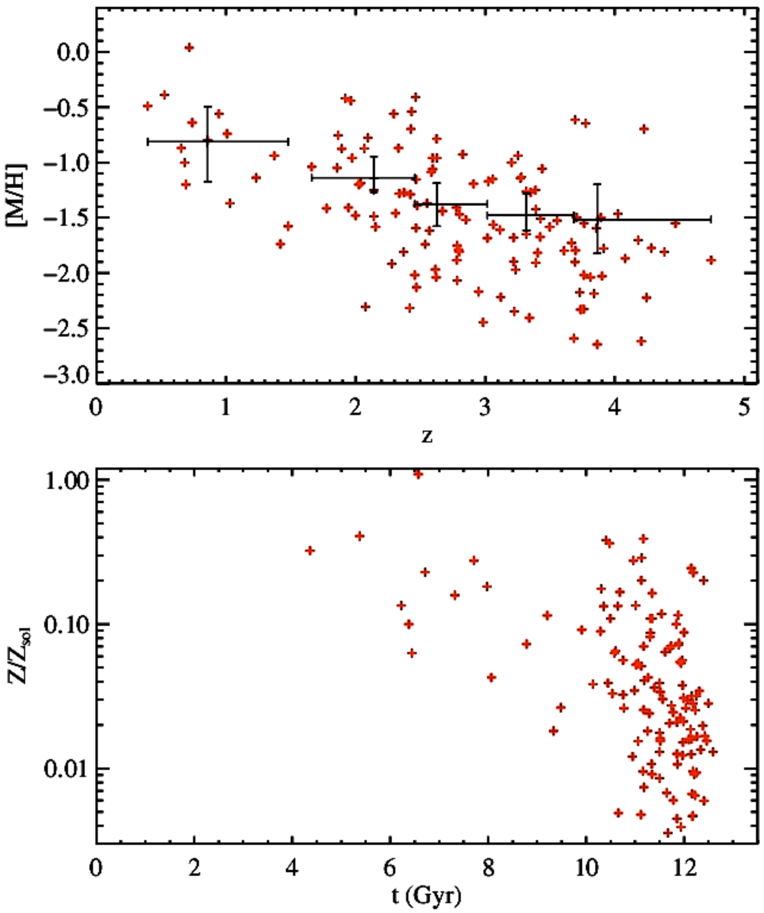


DLA SFR consistent with forming all present-day stars



Wolfe, Gawiser & Prochaska 2003, ApJ 593, 235

Cosmic metal enrichment history

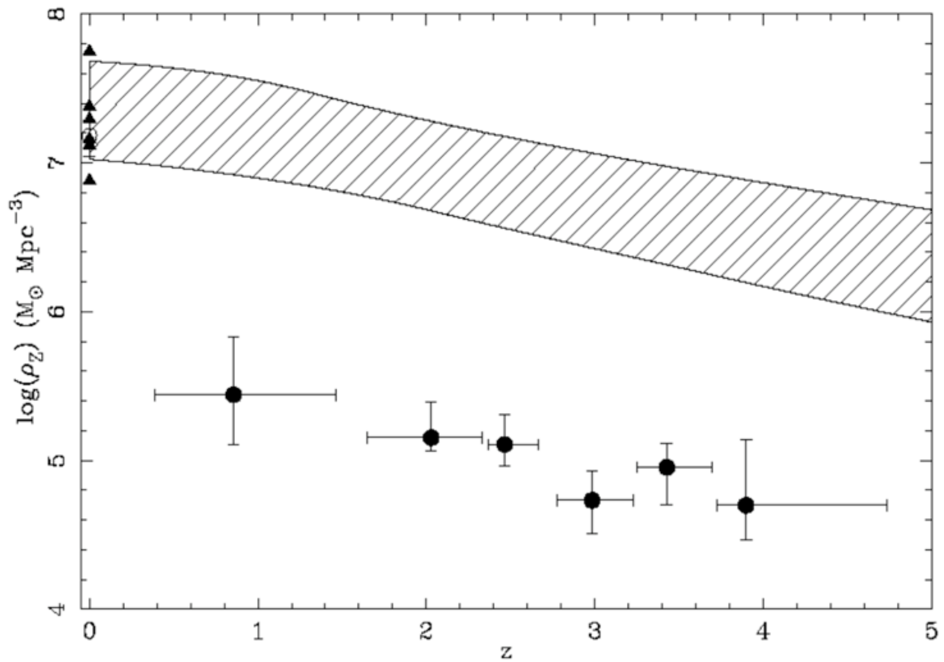


Cosmic metallicity traced by DLAs rises gradually

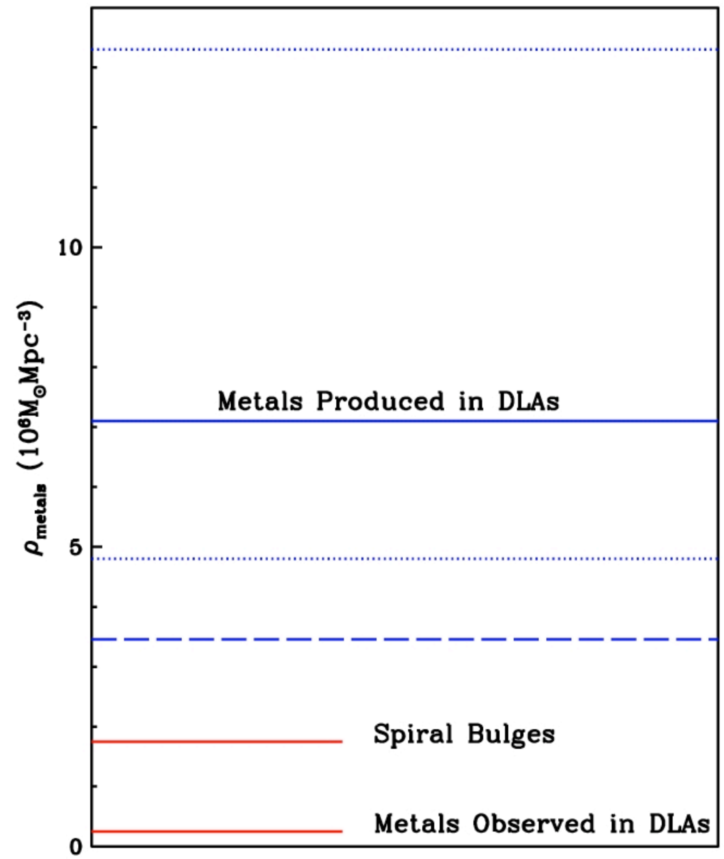
Floor at -2.6

(Qian & Wasserburg 2003, ApJ 596, L9 explain with rapid rise in metallicity caused by first burst of star formation)

The Missing Metals Problem

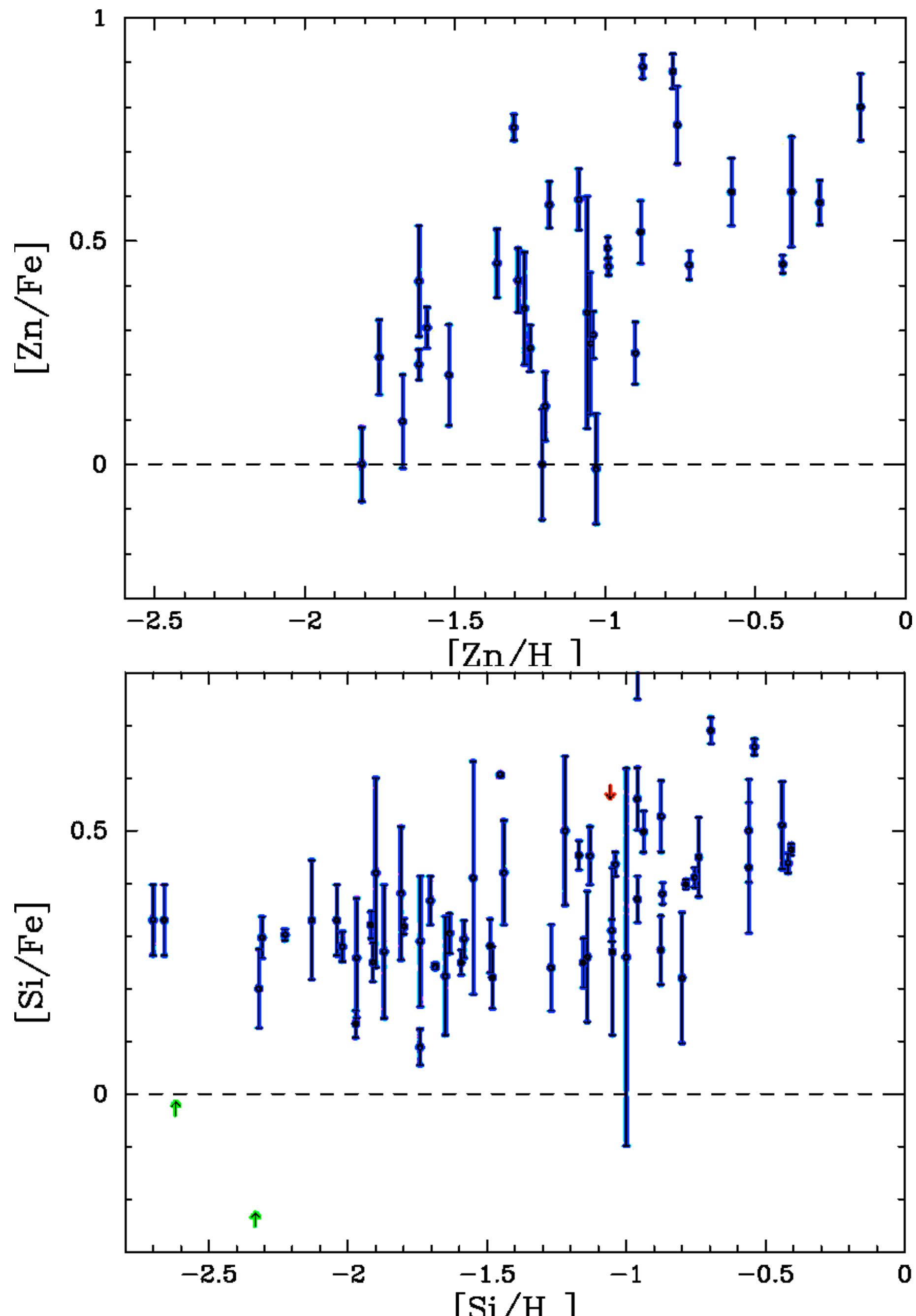


Hopkins, Rao & Turnshek 2005, ApJ 630, 108

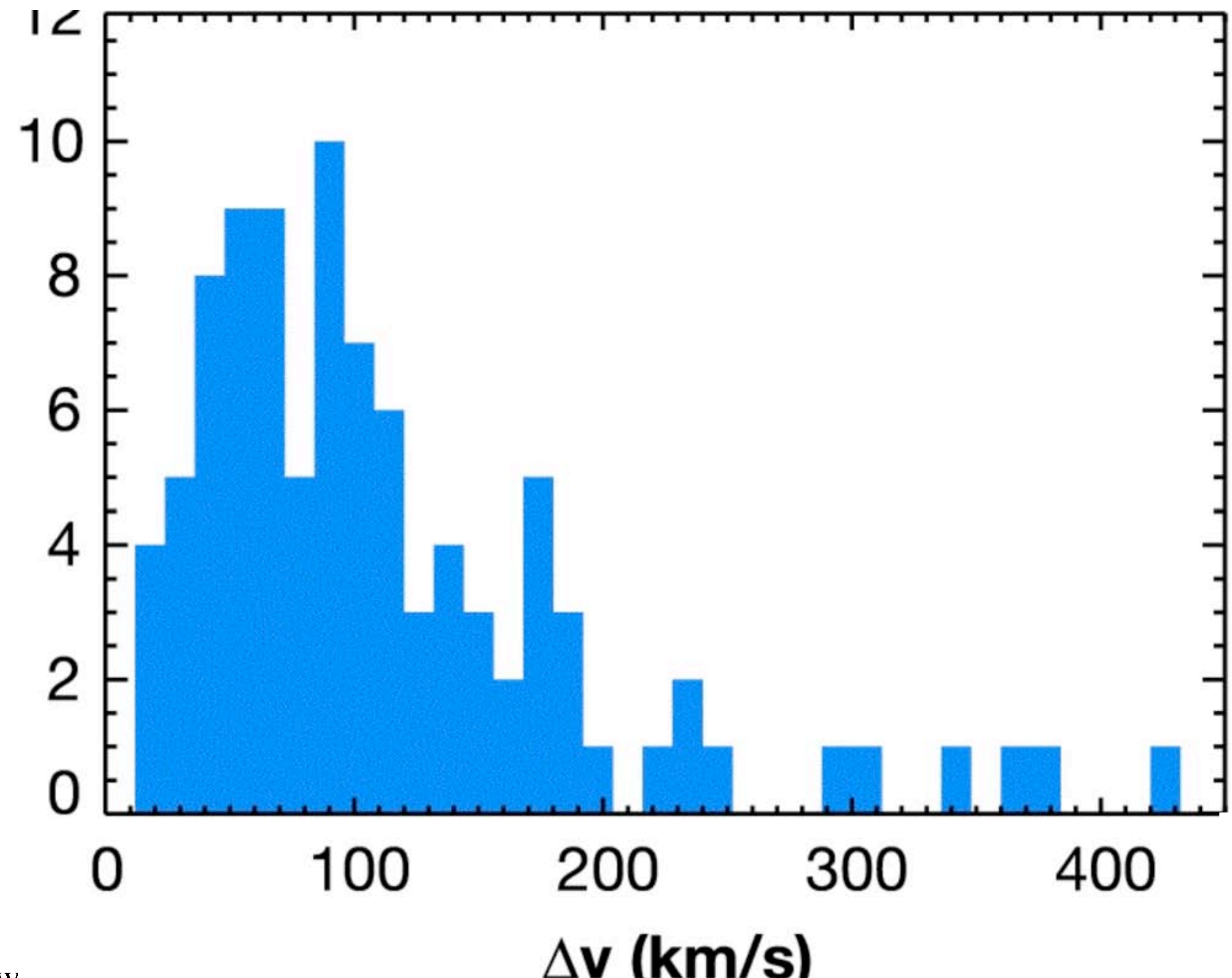


Solved by sequestering metals in "bulges" or superwinds?

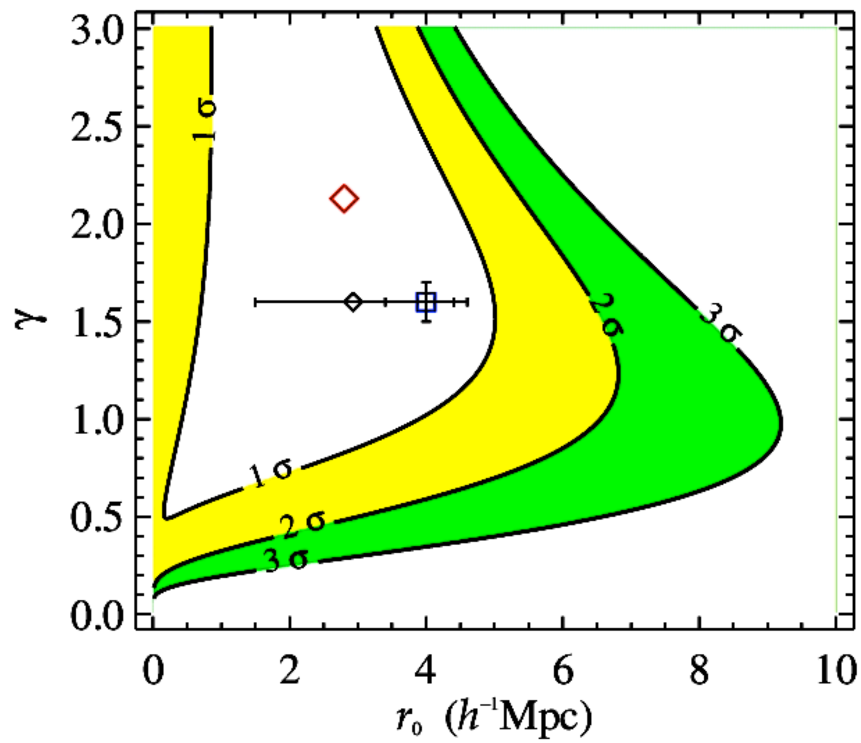
Evidence for dust depletion and alpha enhancement in DLAs



DLA Kinematics: Disks or Clumps?



First Determination of the DLA dark matter halo bias



Cooke, EG, et al 2005

Using DLA-LBG cross-correlation method of Gawiser et al 2001, ApJ 562, 628

Census of Protogalaxies at z=3: Motivation

- Searching for the progenitors of typical galaxies like the Milky Way - are they found amongst the zoo of objects at z=3?

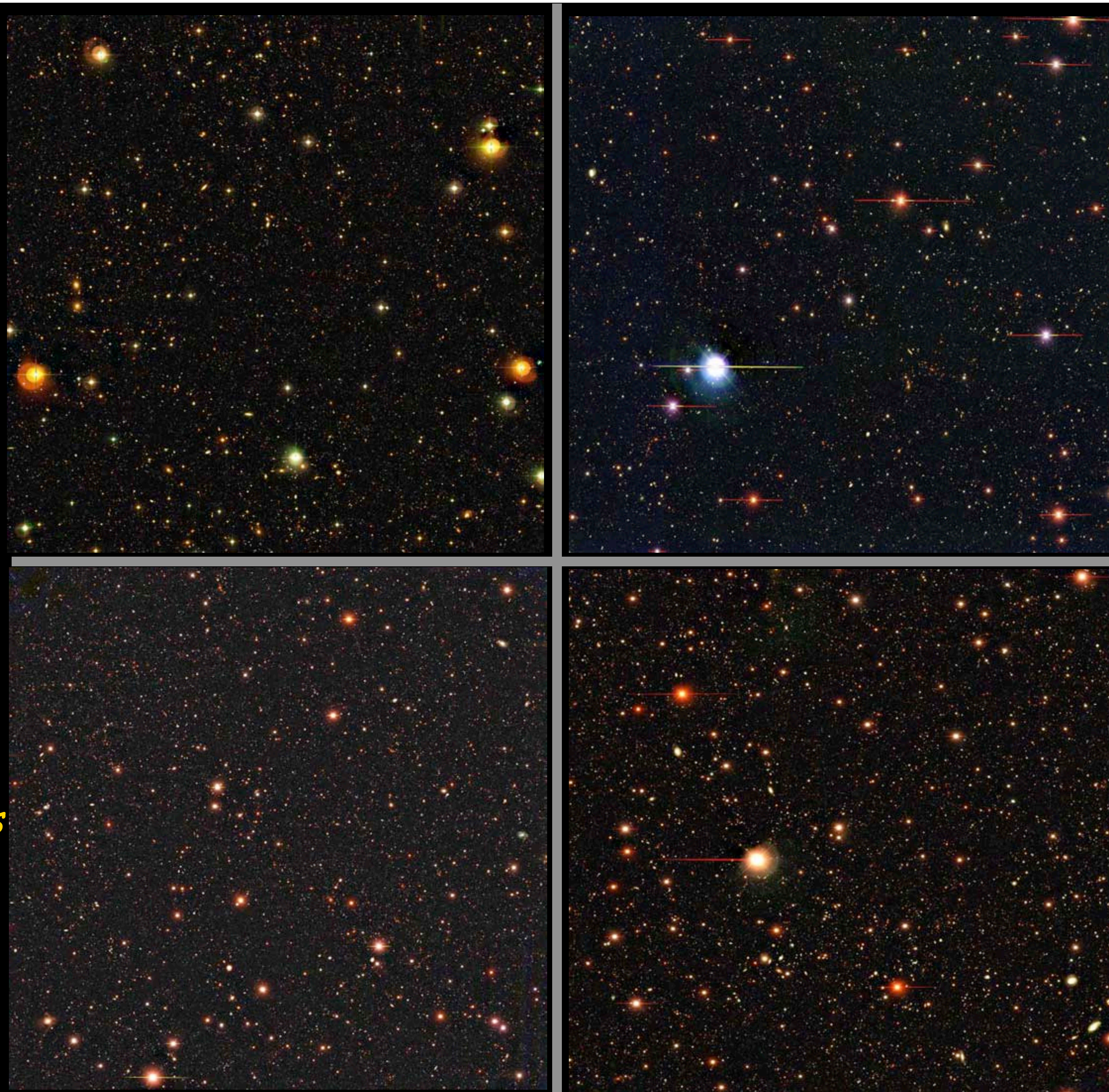
- Cosmological quantities (SFR, stellar mass buildup) should be summed over all high-redshift objects, not just DLAs, which trace the low-dust neutral gas, or LBGs, which trace the bright end of the luminosity function

MUSYC
(Multiwavelength Survey by Yale-Chile)

Eric Gawiser (Yale, P.I.)
Pieter van Dokkum (Yale, P.I.)
Paulina Lira (U. Chile)
José Maza (U. Chile)
Meg Urry (Yale)
Martin Altmann (U. Chile)
F.J. Castander (IEEC-Barcelona)
Daniel Christlein (U. Chile/Yale)
Paolo Coppi (Yale)
Harold Francke (U. Chile Ph.D. student)
Marijn Franx (Leiden)
David Herrera (Yale)
Leopoldo Infante (P.U. Catolica)
Sheila Kannappan (U. Texas)
Charles Liu (CUNY/AMNH)
Danilo Marchesini (Yale)
Rene Méndez (U. Chile)
Ryan Quadri (Yale Ph.D. student)
Ned Taylor (Leiden Ph.D. student)
Ezequiel Treister (U. Chile Ph.D. student)
Shanil Virani (Yale Ph.D. student)
Sukyeung Yi (Oxford)

www.astro.yale.edu/MUSYC

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!

Gawiser et al. 2005, ApJS in press, astro-ph/0509202.

Summary of TLAs

- LBG=Lyman Break Galaxy

  selected via Lyman break, blue continuum (starburst)
- LAE=Lyman Alpha Emitter

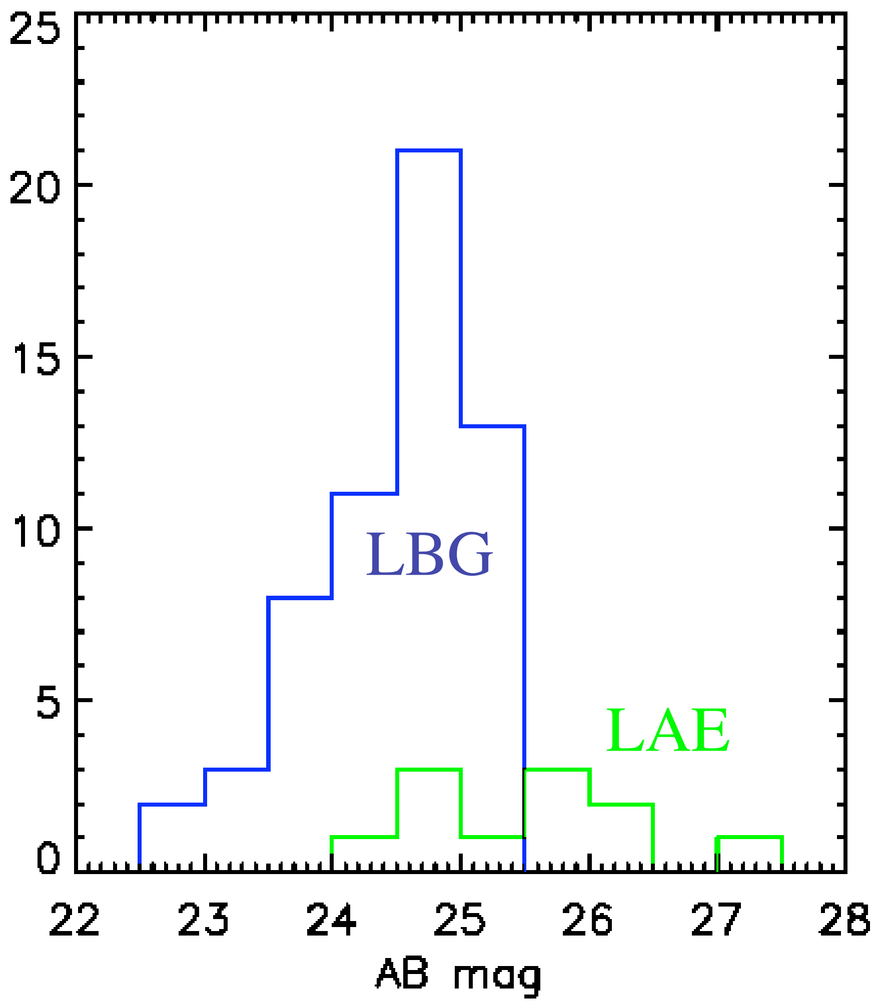
  selected via strong emission line (early stage of star formation)
- DRG=Distant Red Galaxy

  selected via Balmer break in observed NIR
- AGN=Active Galactic Nucleus

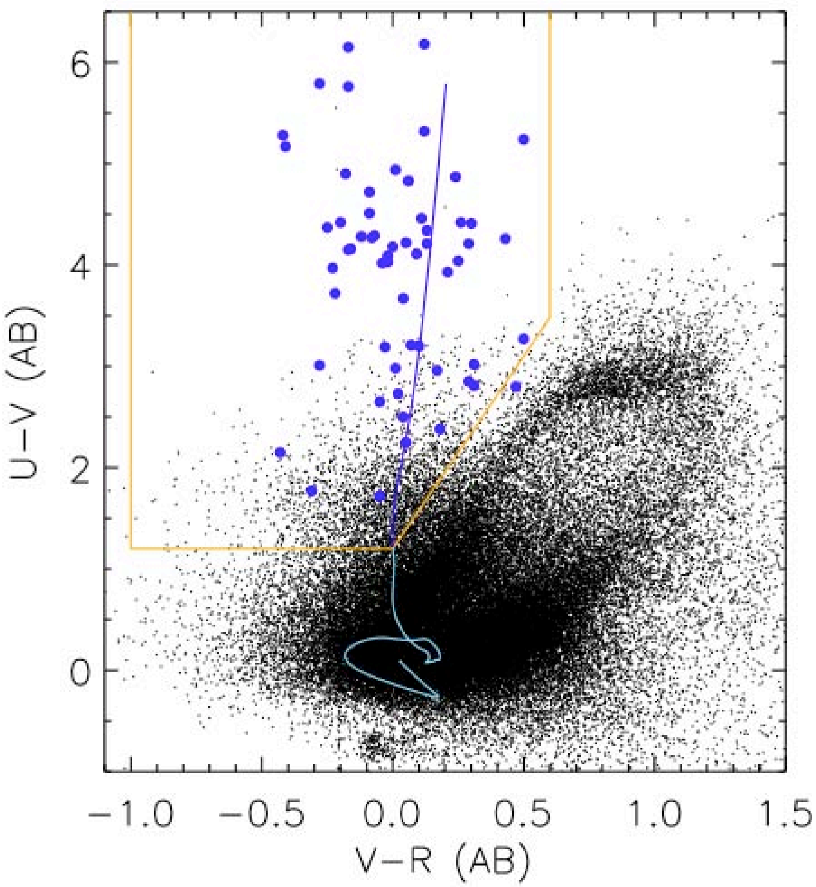
  selected in X-rays and/or via LBG-like colors
- DLA=Damped Lyman α Absorption system

  selected in absorption, $N(HI)>10^{20}$ cm^{-2}

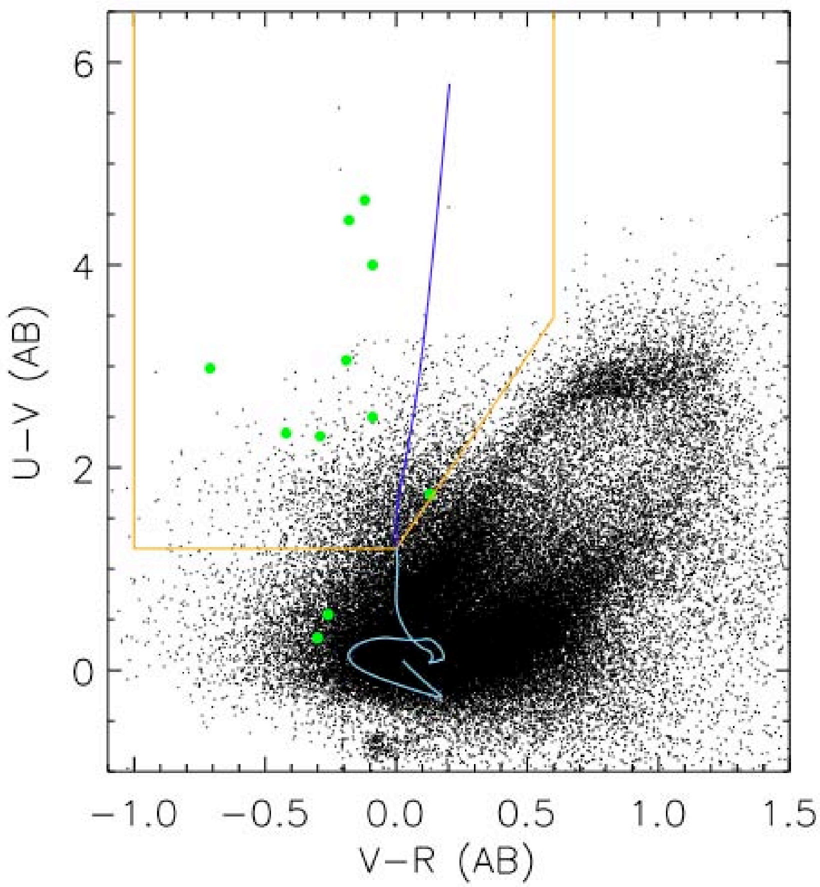
Rest-frame UV continuum flux



UVR colors of confirmed objects

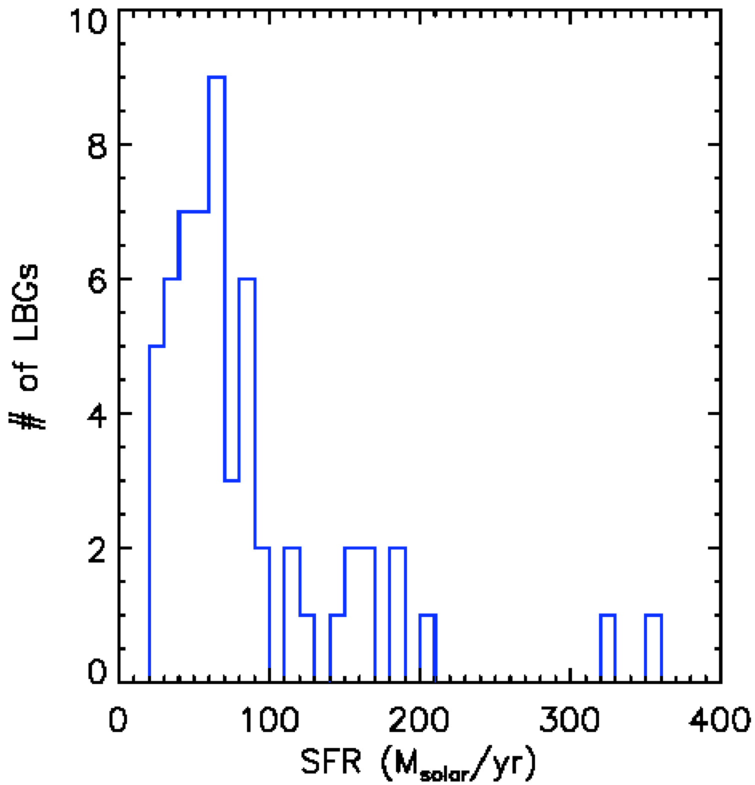


Confirmed LBG

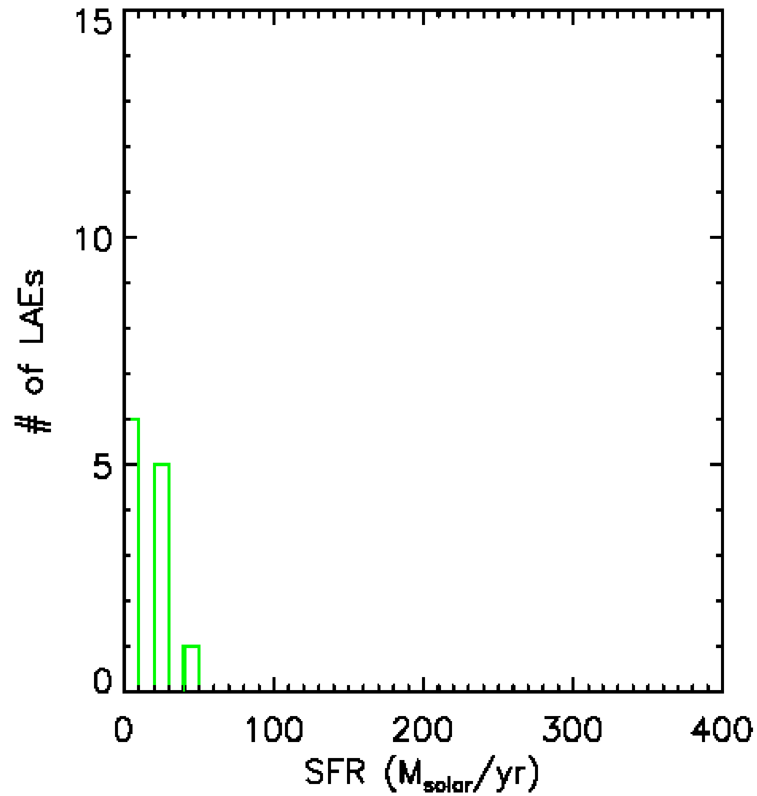


Confirmed LAE

Distributions of Star Formation Rate

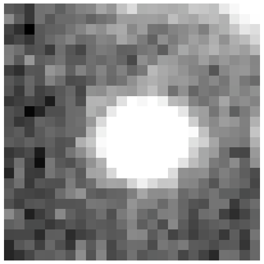


Confirmed LBG

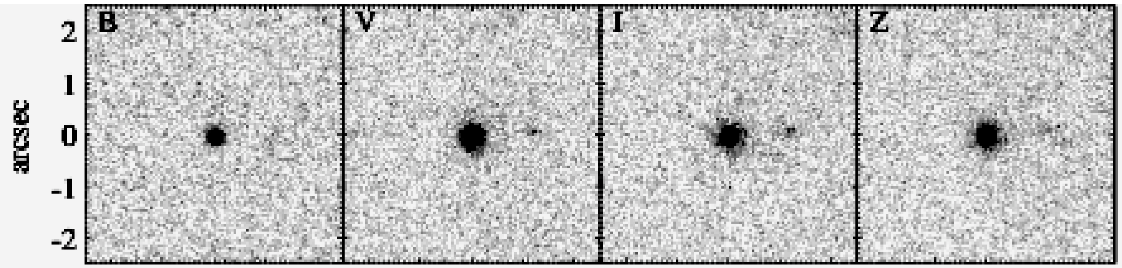


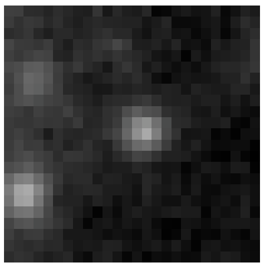
Confirmed LAE

HST-ACS Images: irregular morphology at z=3

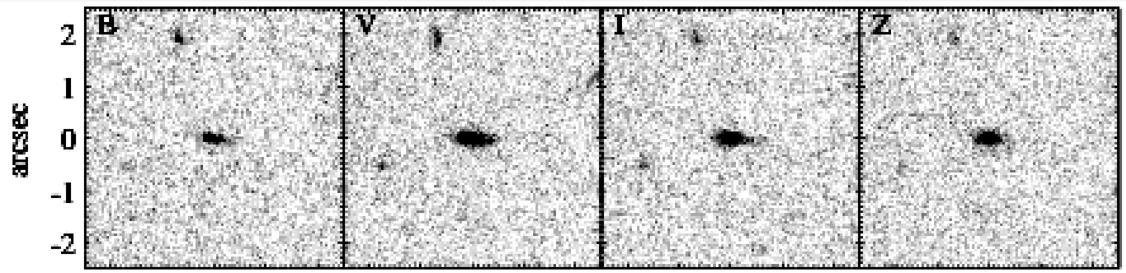


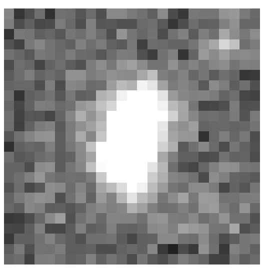
AGN
z=3.60
R=22.4



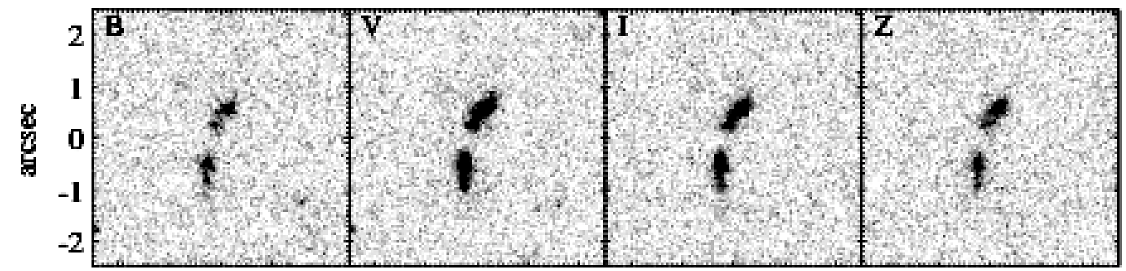


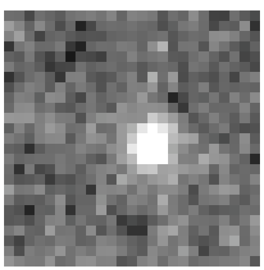
LBG
z=3.37
R=24.3



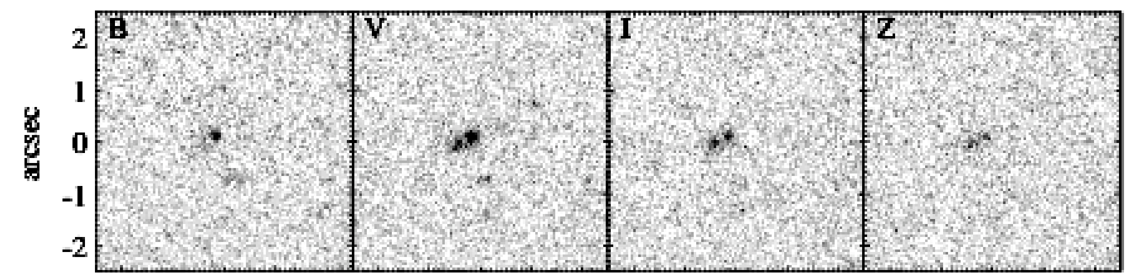


LBG
z=3.24
R=23.8



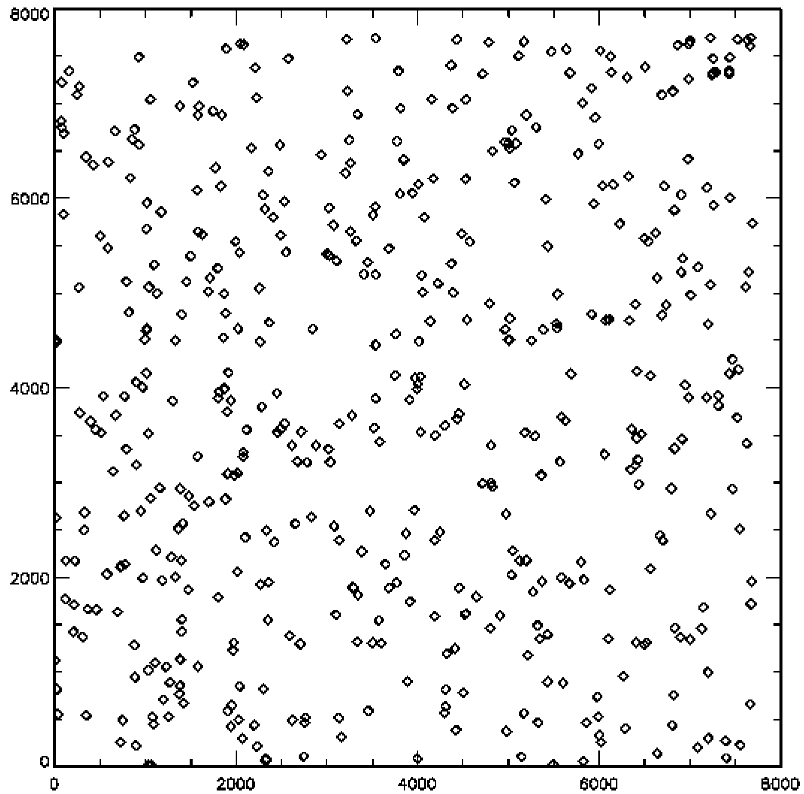


LAE
z=3.10
R=26.1

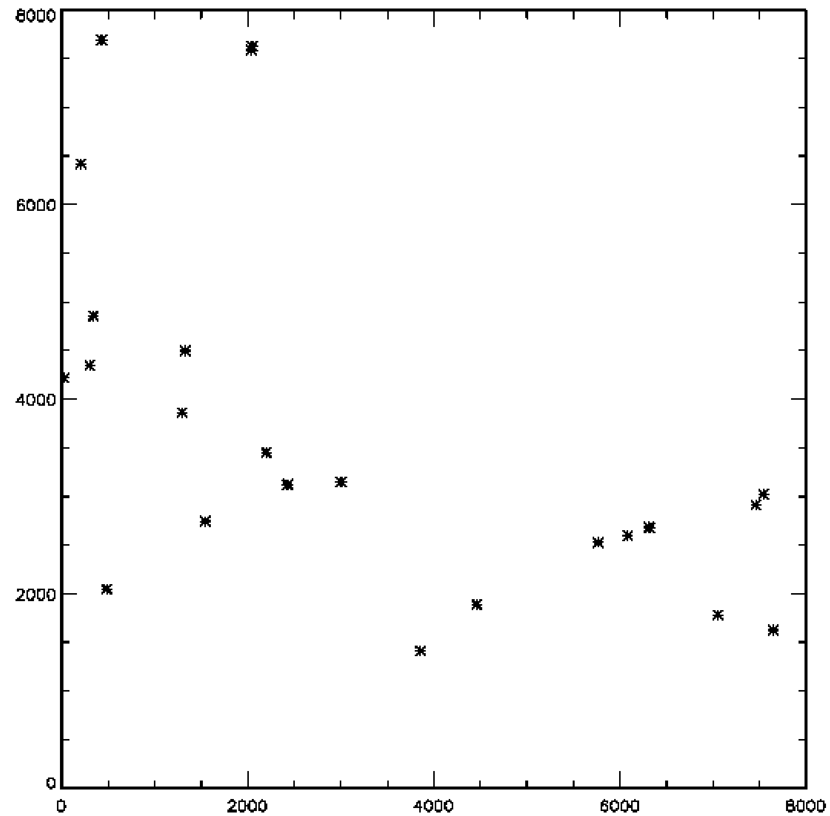


Angular distributions, CW1255

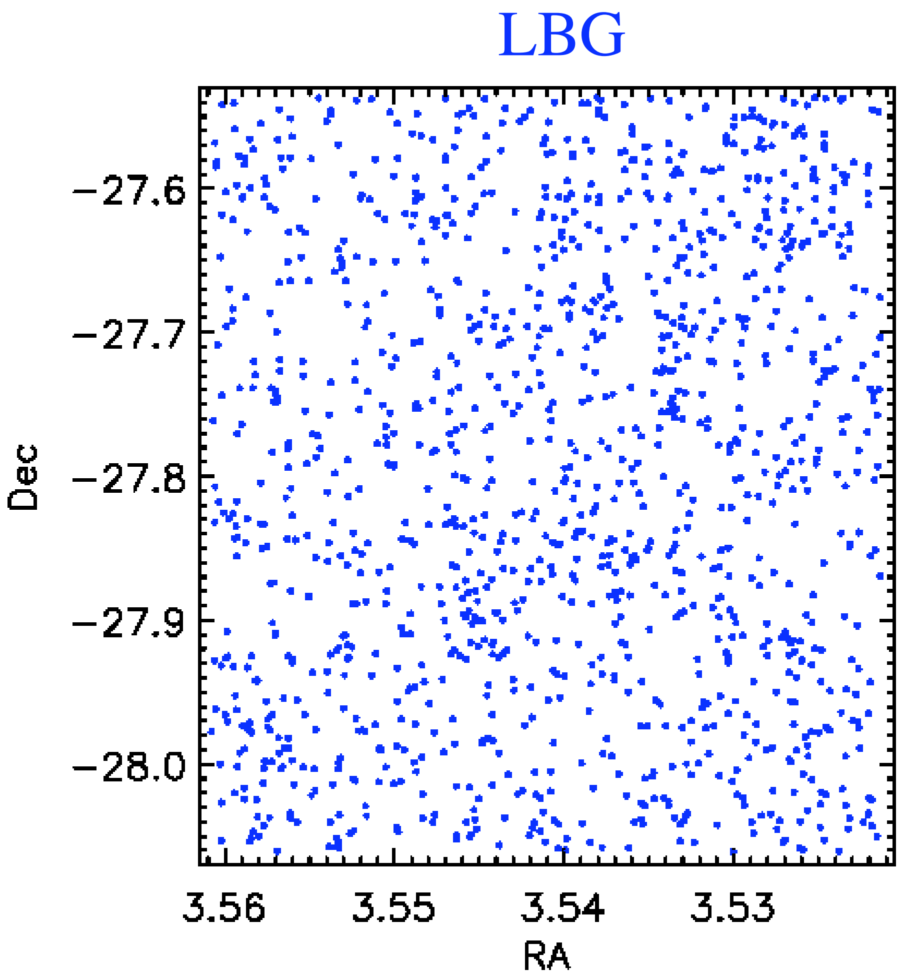
LBG

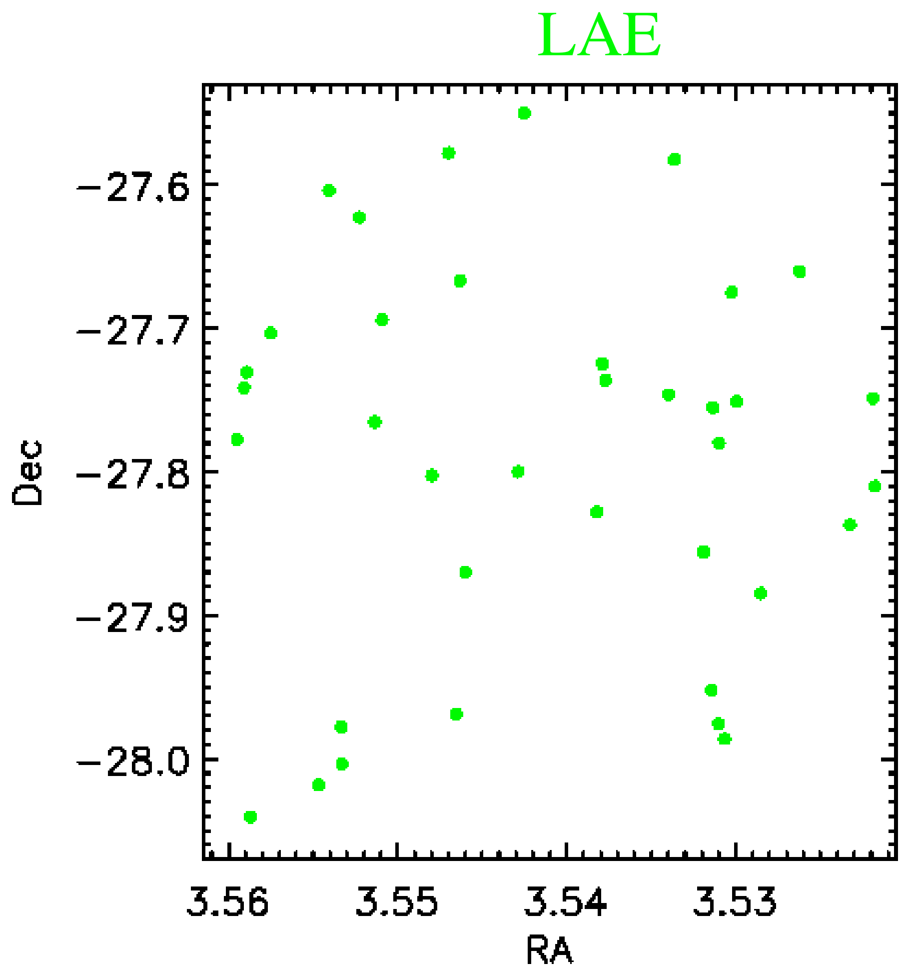


LAE



Angular distributions, E-CDFS





z=3 universe	LBG	LAE	DRG	AGN (host galaxies)	DLA
Space density (n_i / h_{70}^{-3})	2×10^{-3} Mpc^{-3} Adelberger et al 05	4×10^{-4} Mpc^{-3} MUSYC	3×10^{-4} Mpc^{-3} MUSYC	3×10^{-5} Mpc^{-3} Hunt et al 04	ALMA
SFR per object (SFR_i)	30 $M_\odot$ yr^{-1} Shapley et al 01 60 $M_\odot$ yr^{-1} MUSYC	10 $M_\odot$ yr^{-1} Hu et al 98 20 $M_\odot$ yr^{-1} MUSYC	200 $M_\odot$yr^{-1} van Dokkum et al 04	M	1-50 $M_\odot$ yr^{-1} (2 objects) Moller et al 02, Bunker et al 04
Stellar mass per object ($M_{*,i}$)	10^{10} $M_\odot$ Shapley et al 01	M	$2 \times 10^{11} M_\odot$ van Dokkum et al 04	M	JWST
Clustering length ($r_{0,i} / h_{70}^{-1}$)	6±1 Mpc Adelberger et al 05 5±1 Mpc MUSYC	4±1 Mpc MUSYC	7±2 Mpc MUSYC Quadri et al 05	7±2 Mpc Adelberger & Steidel 05	4±2 Mpc Cooke, EG et al 05

M = MUSYC, in progress

Cosmological quantities:	LBG	LAE	DRG	AGN (host galaxies)	DLA
SFR density ($\rho_{SFR,i} = n_i \times SFR_i$)	0.1 $M_\odot$ yr $^{-1}$ Mpc^{-3} Steidel et al 99	0.01 $M_\odot$yr $^{-1}$ Mpc^{-3} MUSYC	0.06 $M_\odot$ yr $^{-1}$ Mpc^{-3} MUSYC	M	0.03 $M_\odot$ yr $^{-1}$ Mpc^{-3} Wolfe, EG & Prochaska 03
Stellar mass density ($\rho_{*,i} = n_i M_{*,i}$)	10^7 $M_\odot$ Mpc^{-3} Shapley et al 01	M	6x10^7 $M_\odot$ Mpc^{-3} MUSYC	M	JWST
DM halo mass	3x10^{11} $M_\odot$ Adelberger et al 05	10^{11} $M_\odot$ MUSYC	3x10^{12} $M_\odot$ MUSYC	3x10^{12} $M_\odot$ Adelberger & Steidel 05	10^{11} $M_\odot$ Cooke, EG et al 05

M = MUSYC, in progress

Conclusions

- MASS: Neutral gas reservoir needed to form all present-day stars is in place at z=3 in the DLAs.
  LBGs do not dominate the stellar mass budget at z=3, but DRGs probably do.
  All spectroscopically-confirmed samples have dark matter halo masses of at least $10^{11}M_{\odot}$ even though typical z=3 dark matter halos have $10^{9}M_{\odot}$.
- LIGHT: LAEs probe the z=3 luminosity function deeper than LBG samples but have similar colors revealing rapid SF.
  Sum of SFR density of LBG, LAE, DRG, DLA gives total of $0.2\ M_{\odot}\ yr^{-1}\ Mpc^{-3}$ at z=3.
- CHEMISTRY: Star formation is occurring in or near the DLA neutral gas reservoir but >90% of metals produced are sequestered in compact SF regions or released into IGM via superwinds.