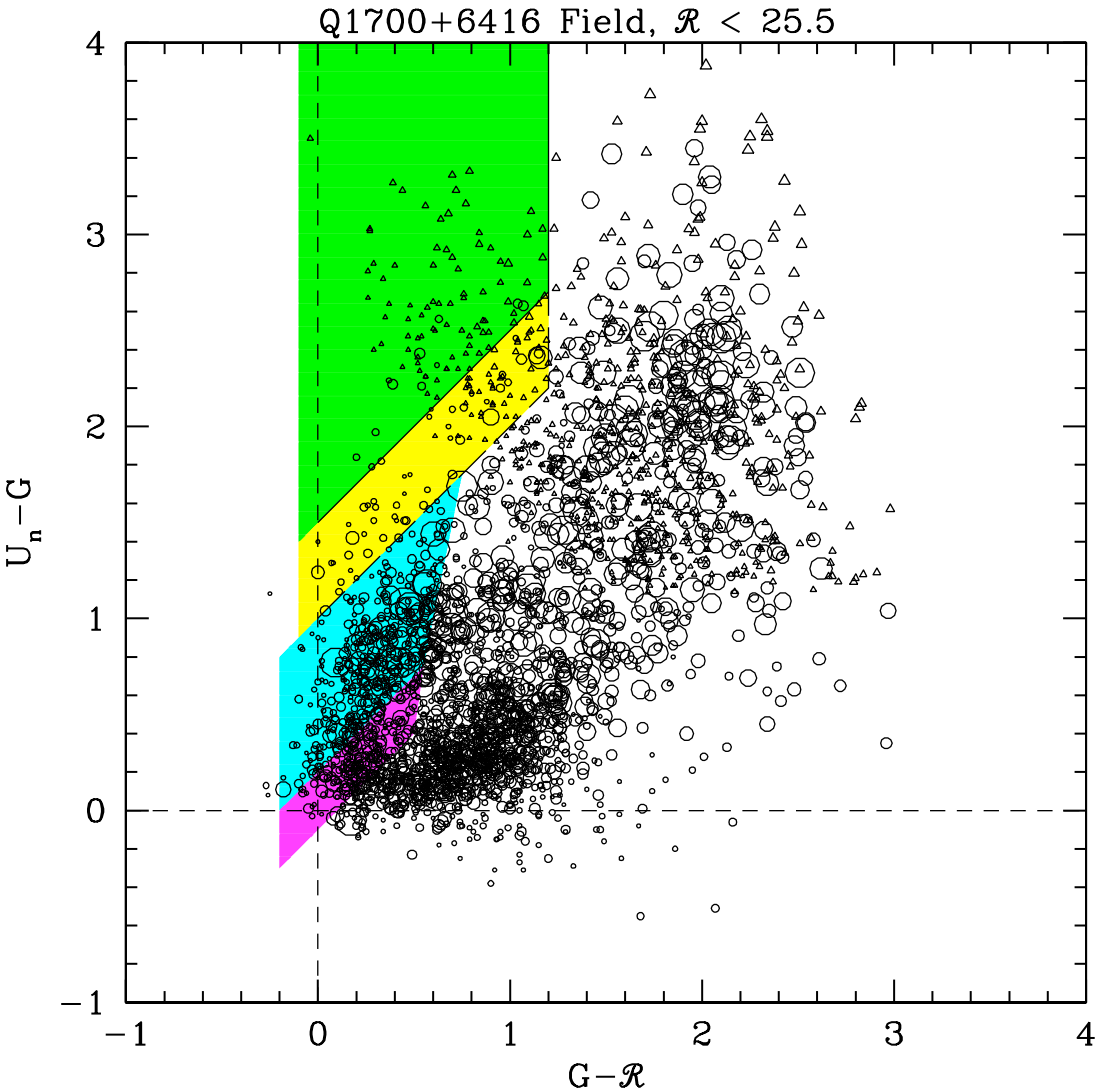
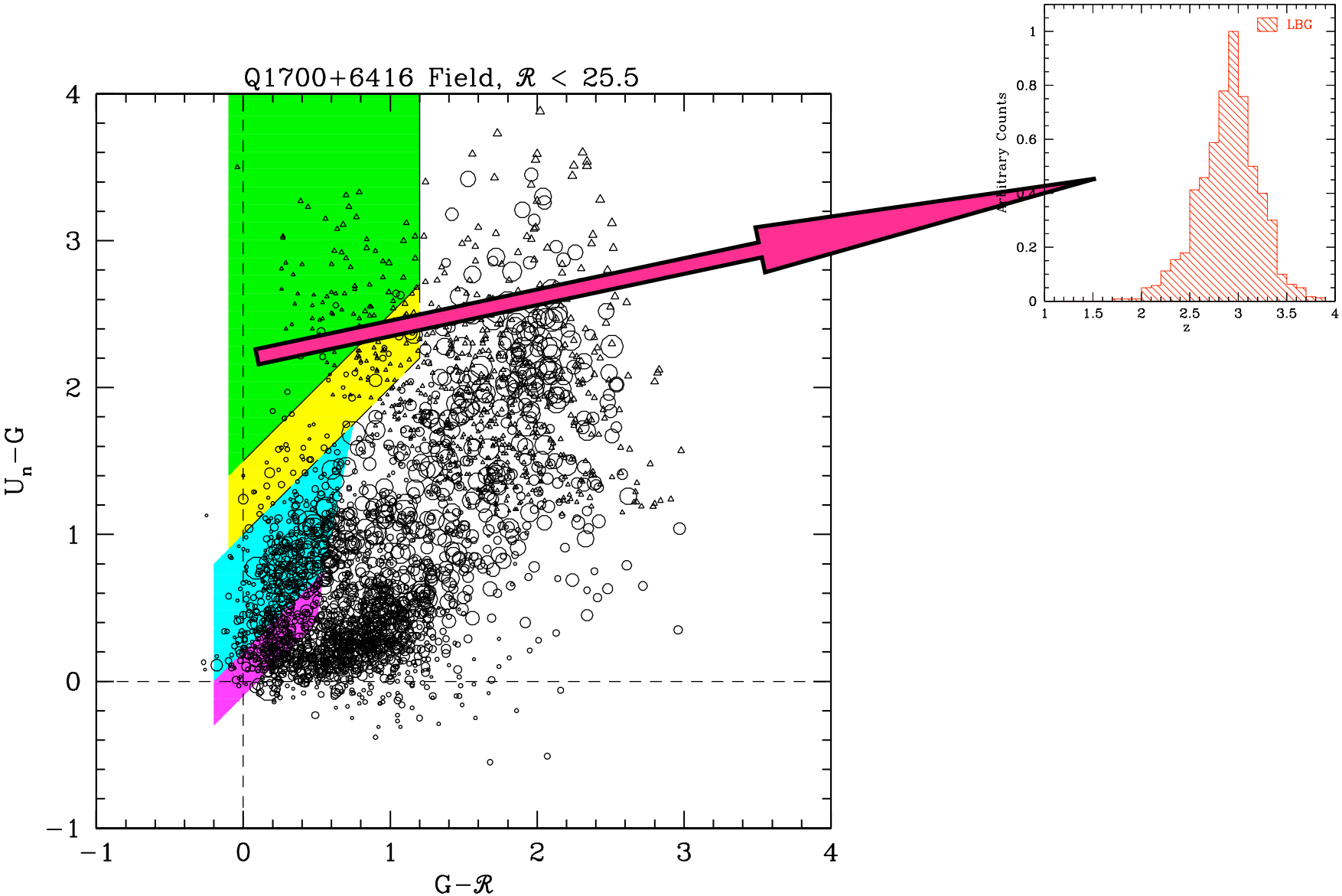
Lyman Break Galaxies: a Ten Year Perspective

Max Pettini
Institute of Astronomy

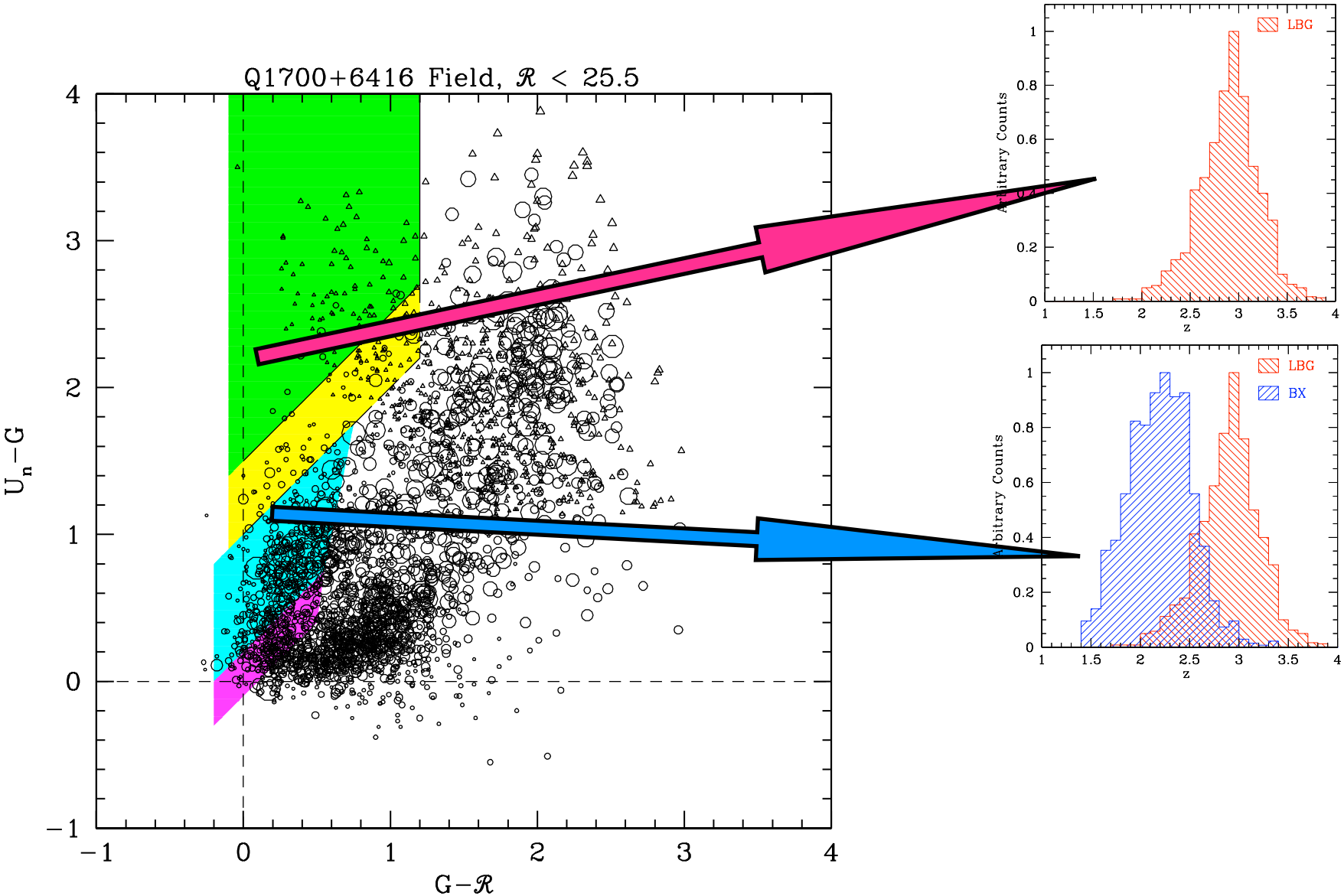
Efficient Photometric Preselection



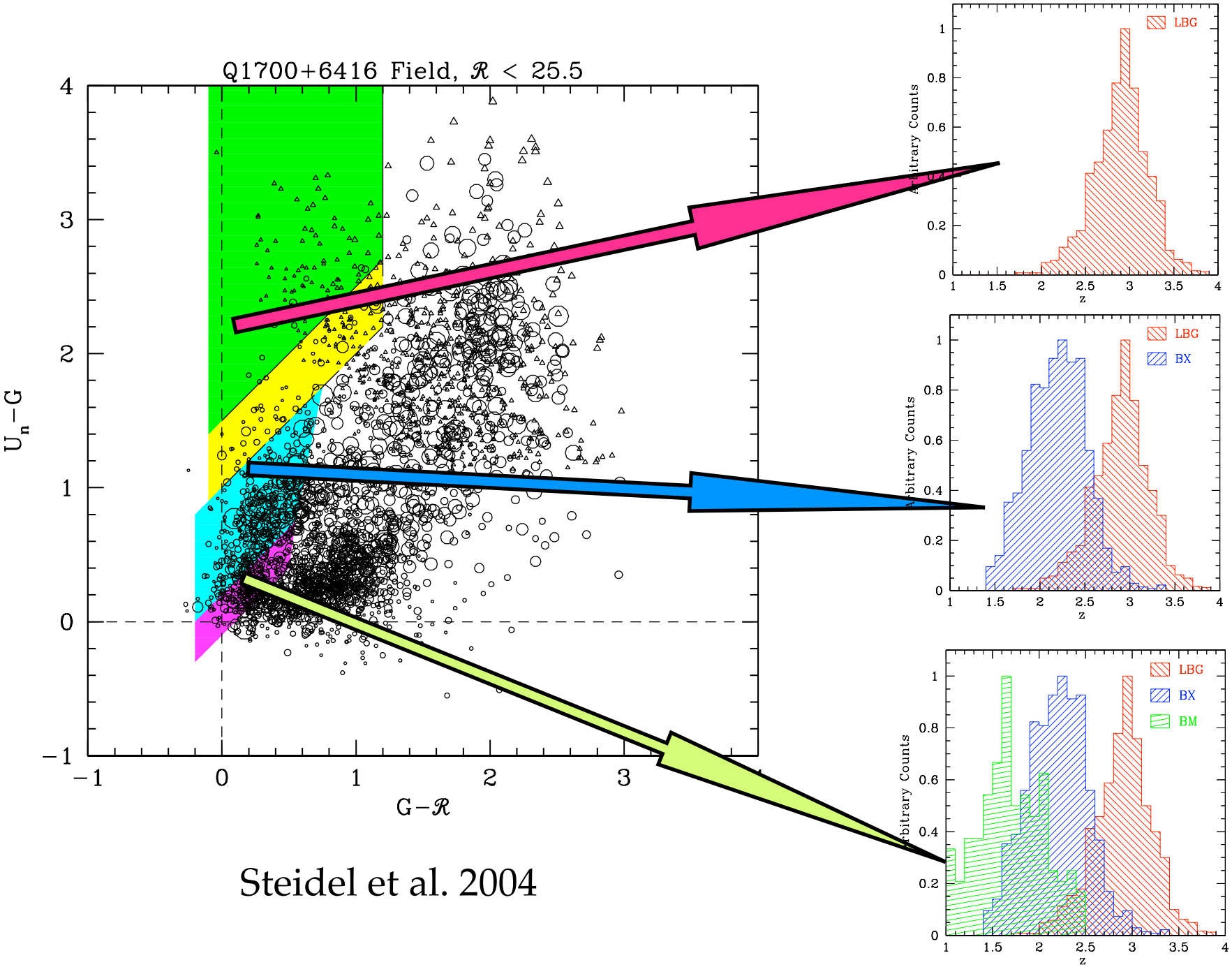
Efficient Photometric Preselection



Efficient Photometric Preselection

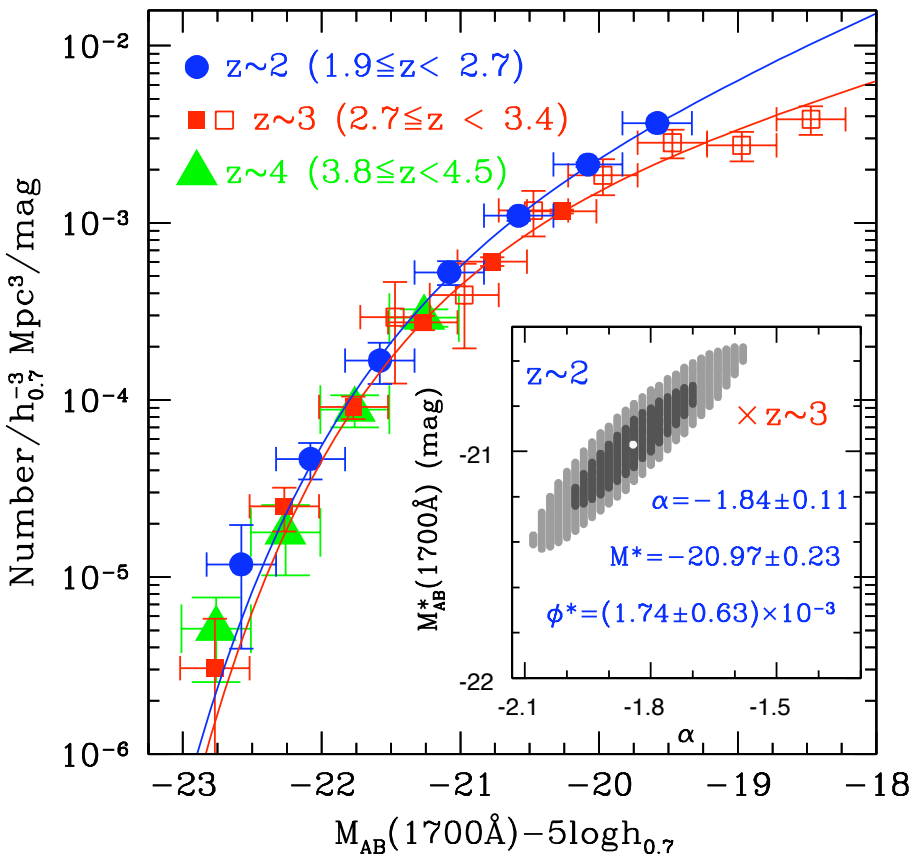


Efficient Photometric Preselection



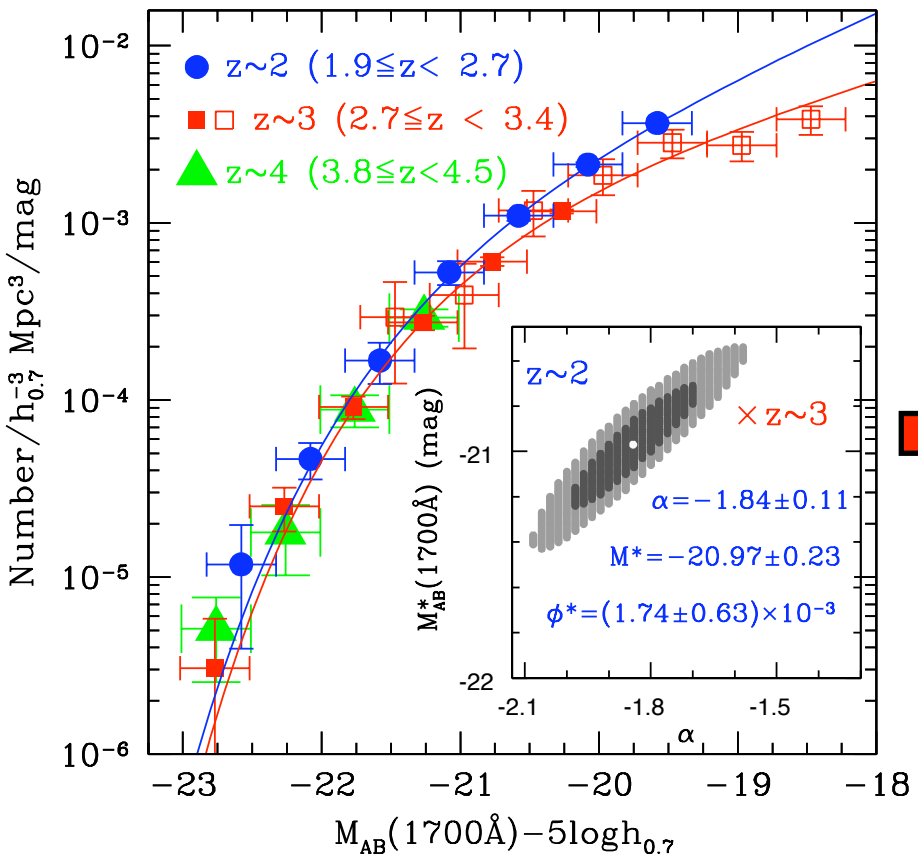
Steidel et al. 2004

Luminosity Function

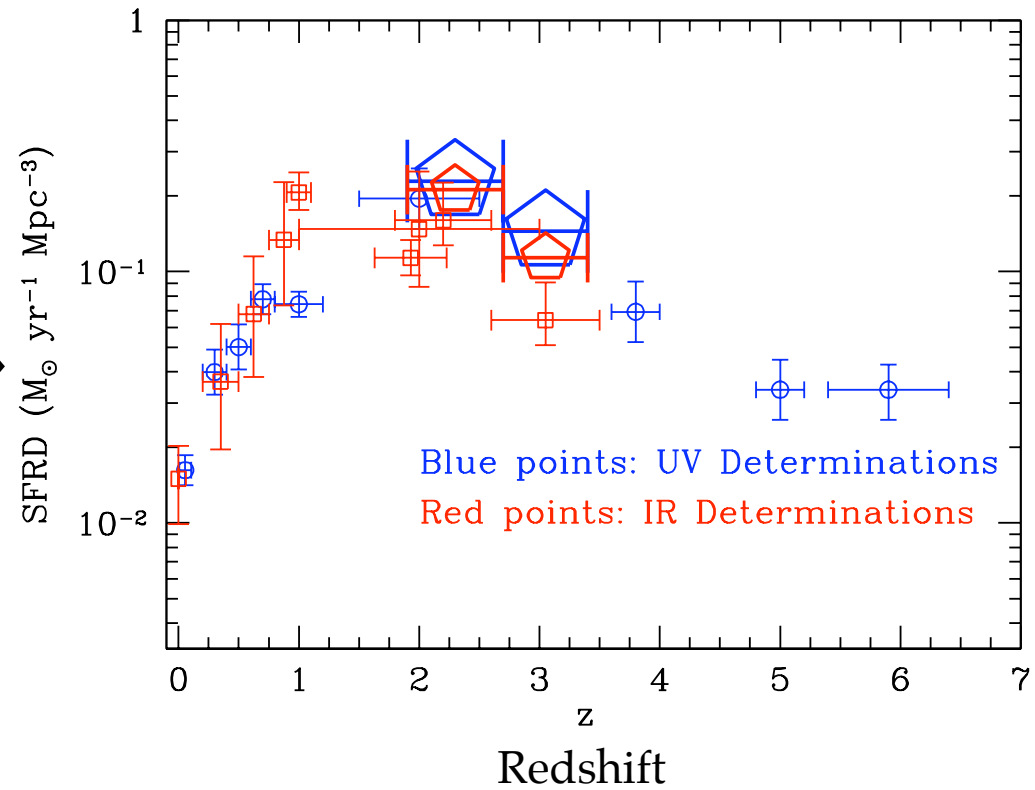


Reddy et al. 2007

Luminosity Function



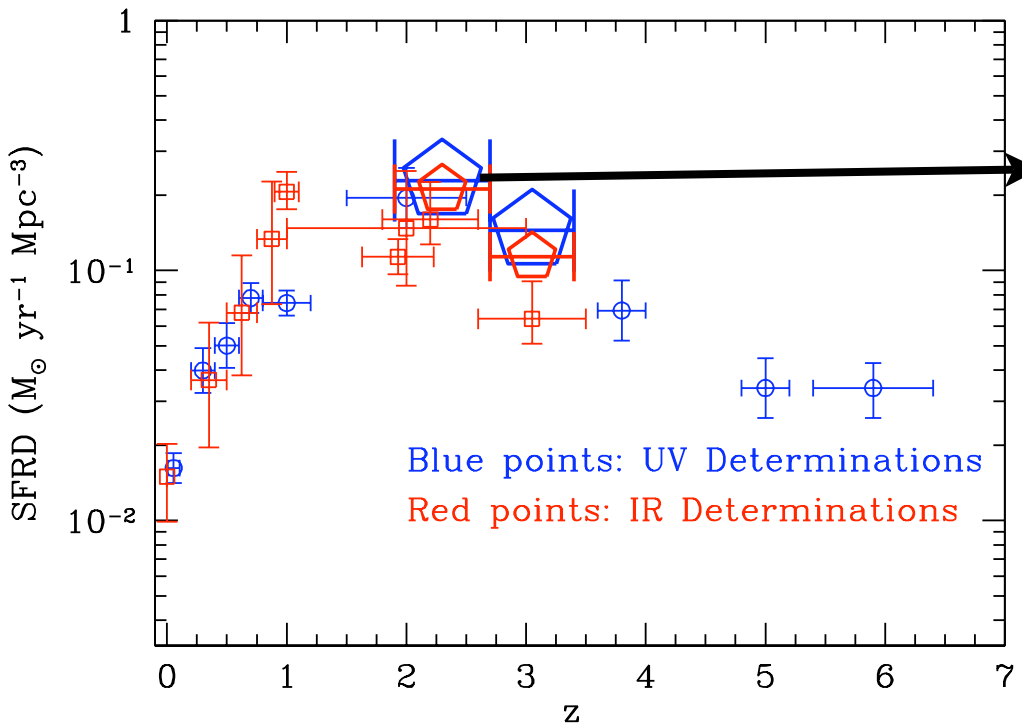
Star Formation History



Reddy et al. 2007

Dust Extinction

Star Formation History

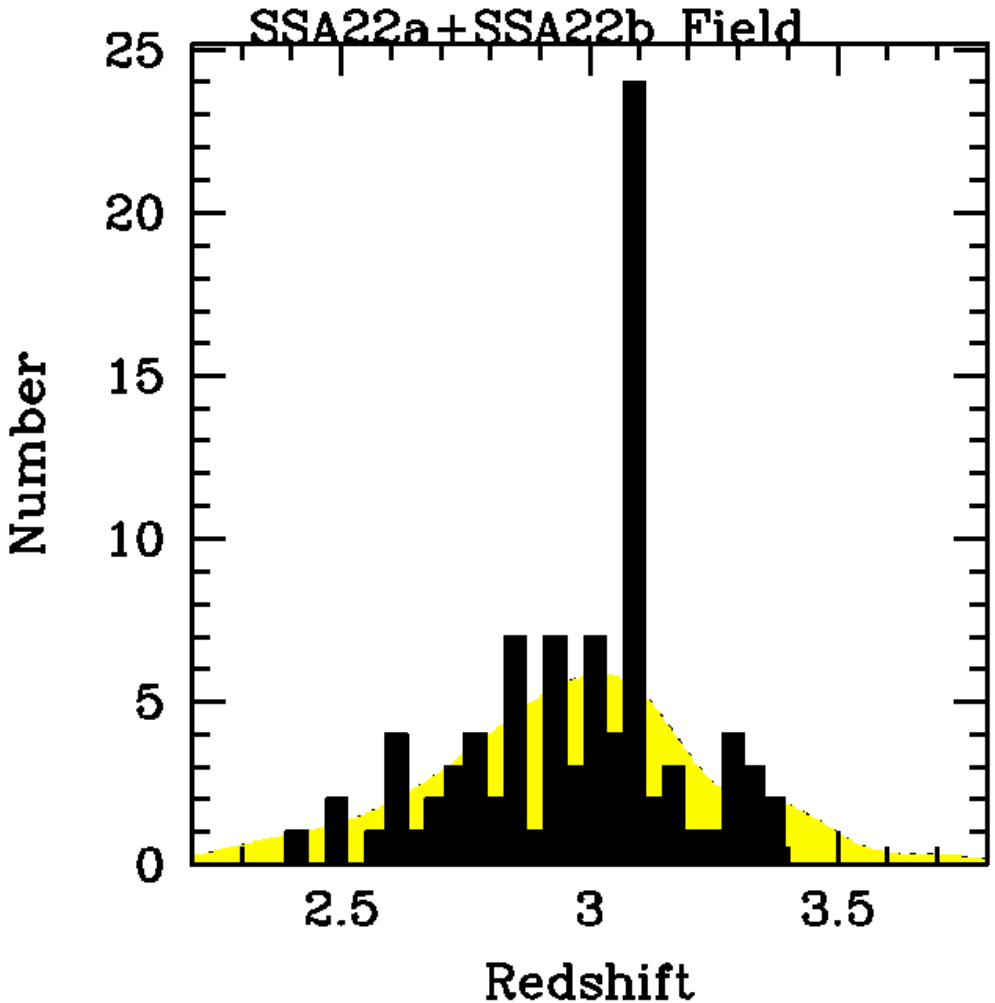


(i) UV extinction at 1500 Å: × 4–5 (from comparison with X-ray, radio, Hα, and 24 μm emission)

(ii) Consistent with UV cont. slope

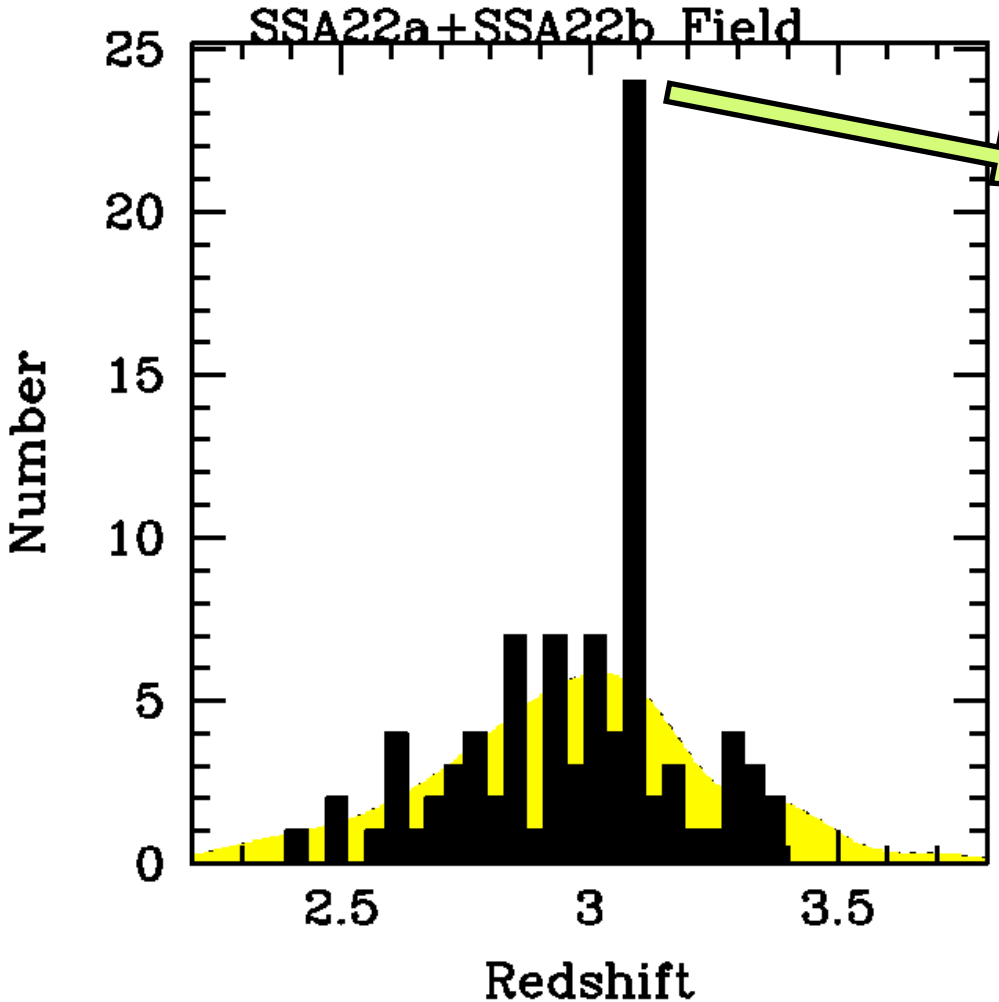
Reddy et al. 2007

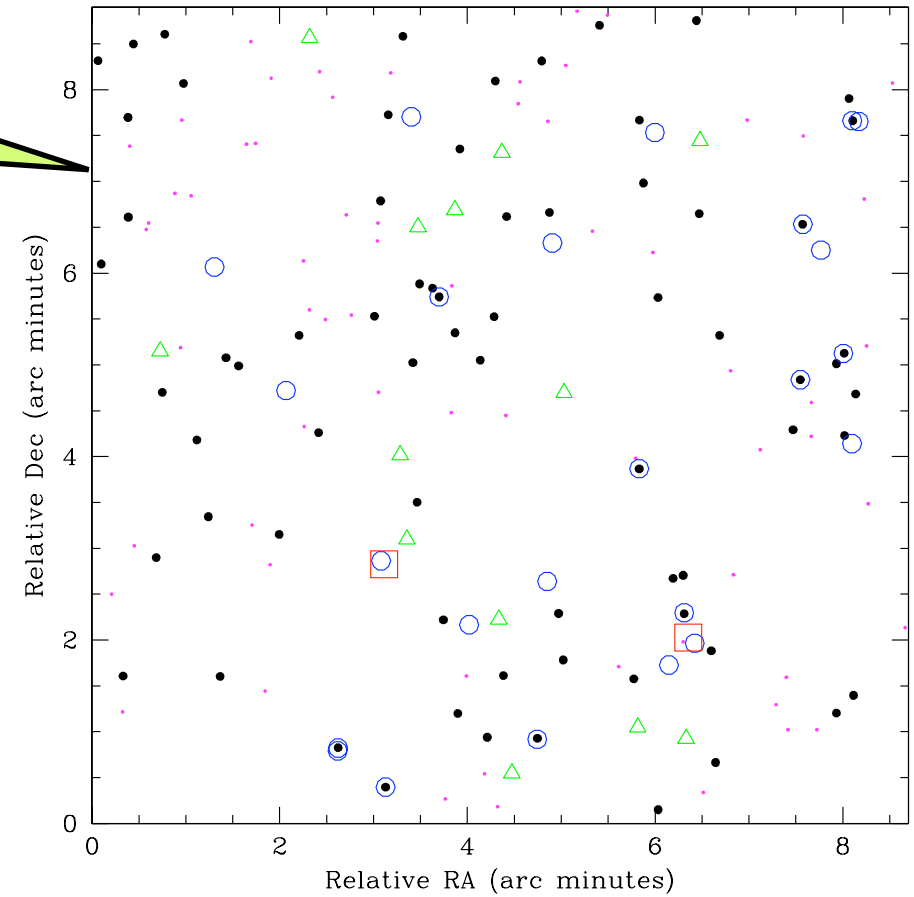
LBGs are Highly Clustered



Steidel et al. 1998

LBGs are Highly Clustered

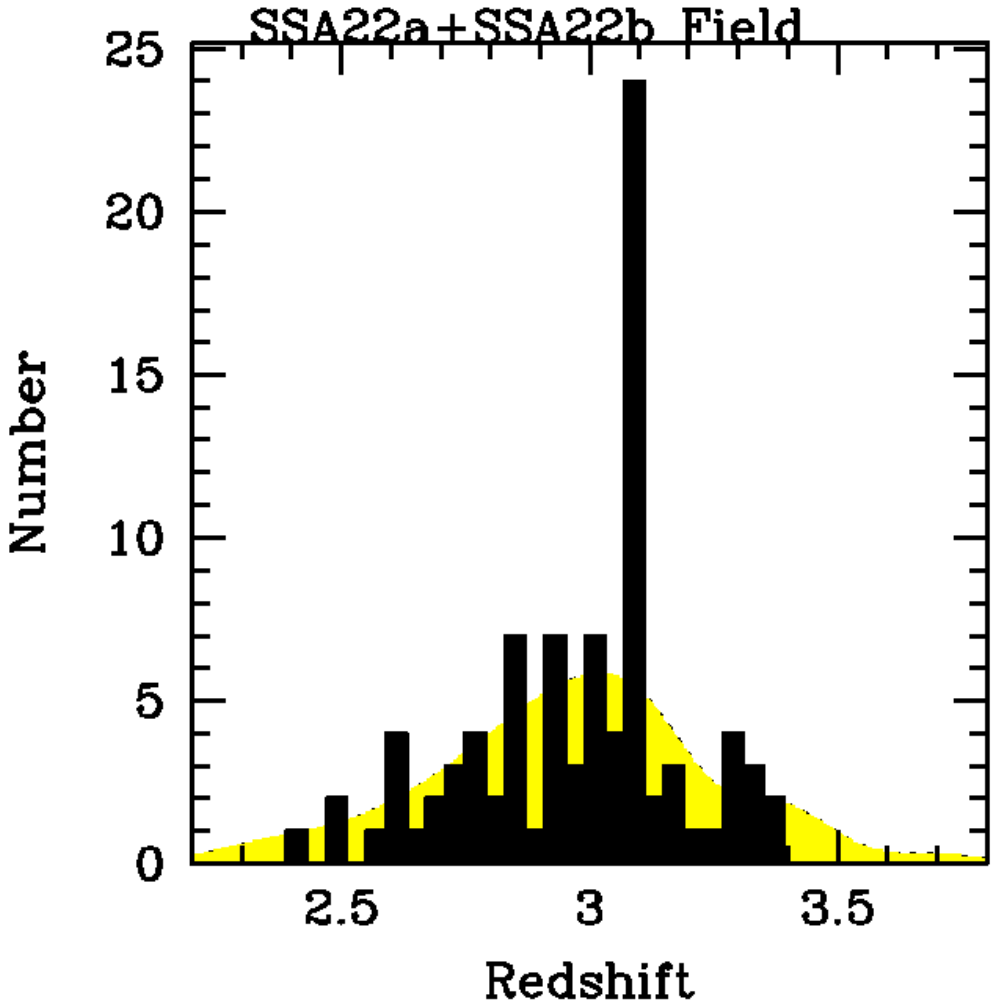


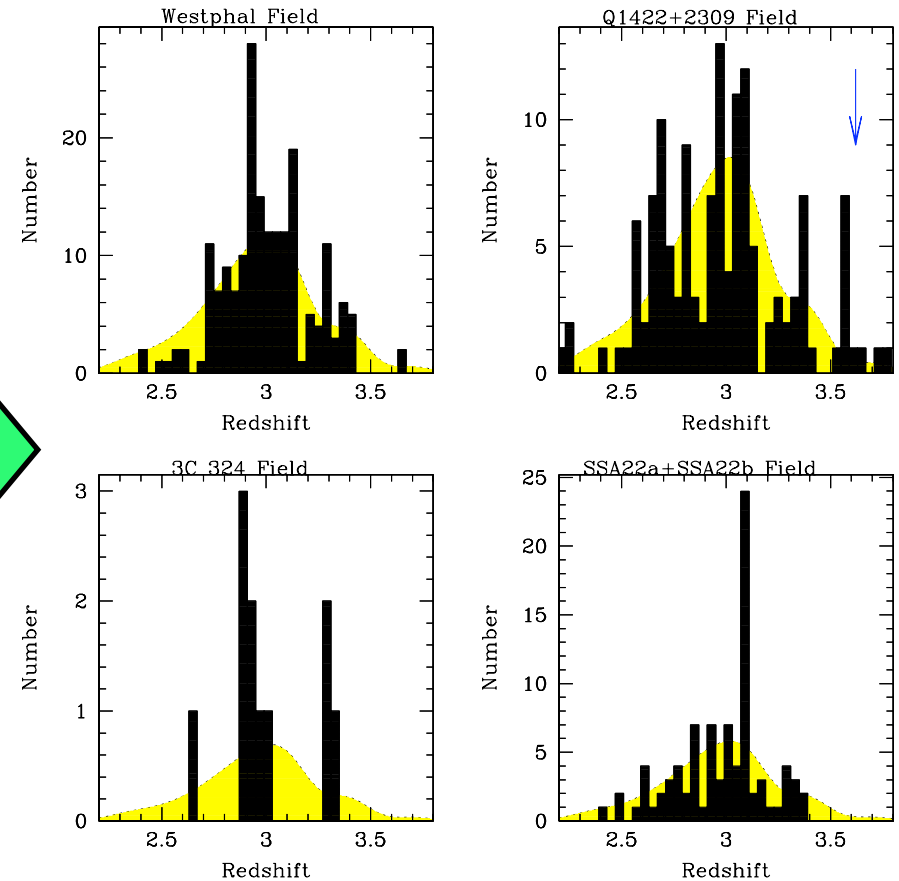


Steidel et al. 1998

Steidel et al. 2000

LBGs are Highly Clustered

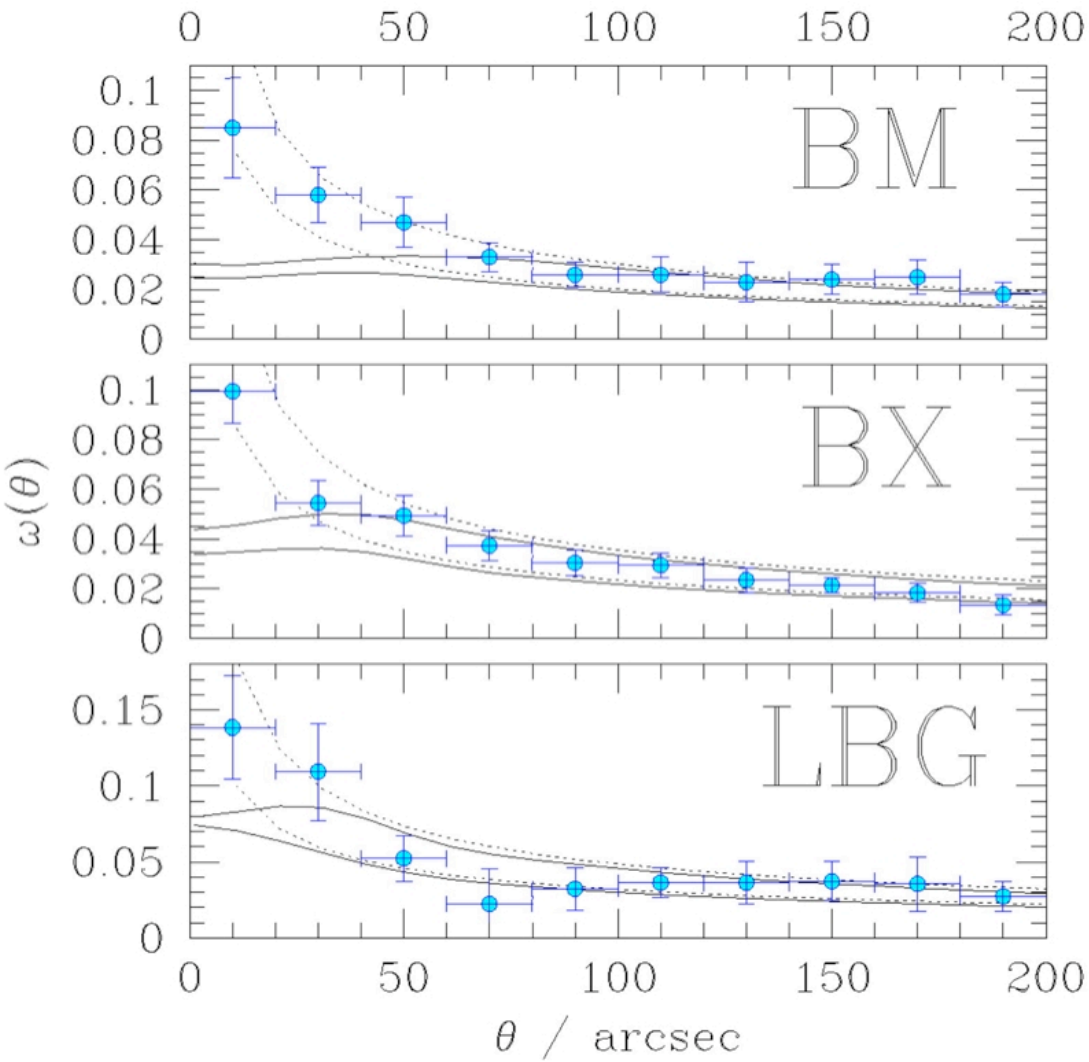




Steidel et al. 1998

Steidel et al. 2003

Observed galaxy angular correlation function matches that of simulated (GIF -LCDM) halos with masses:

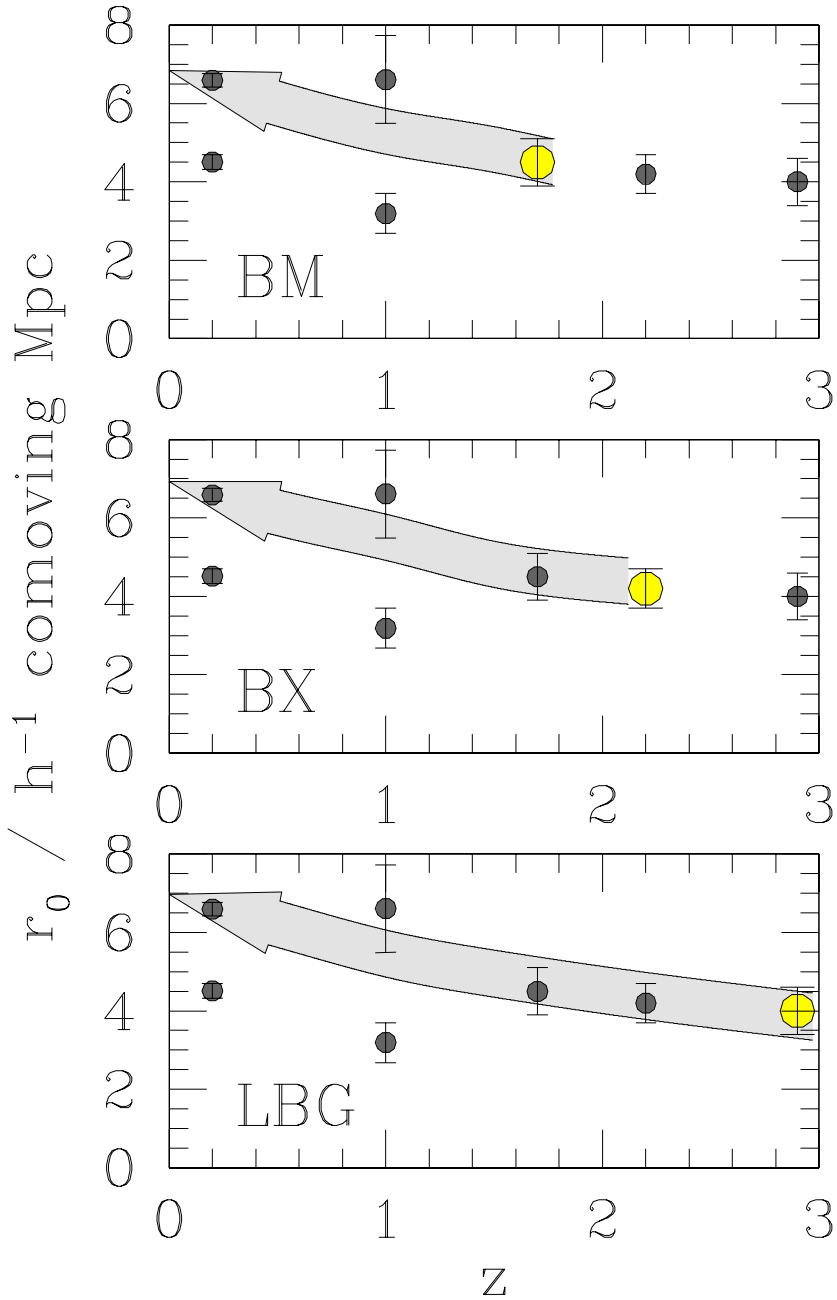


$$M_{\rm DM} = 10^{11.9} - 10^{12.3} M_\odot$$

$$M_{\rm DM} = 10^{11.8} - 10^{12.2} M_\odot$$

$$M_{\rm DM} = 10^{11.2} - 10^{11.8} M_\odot$$

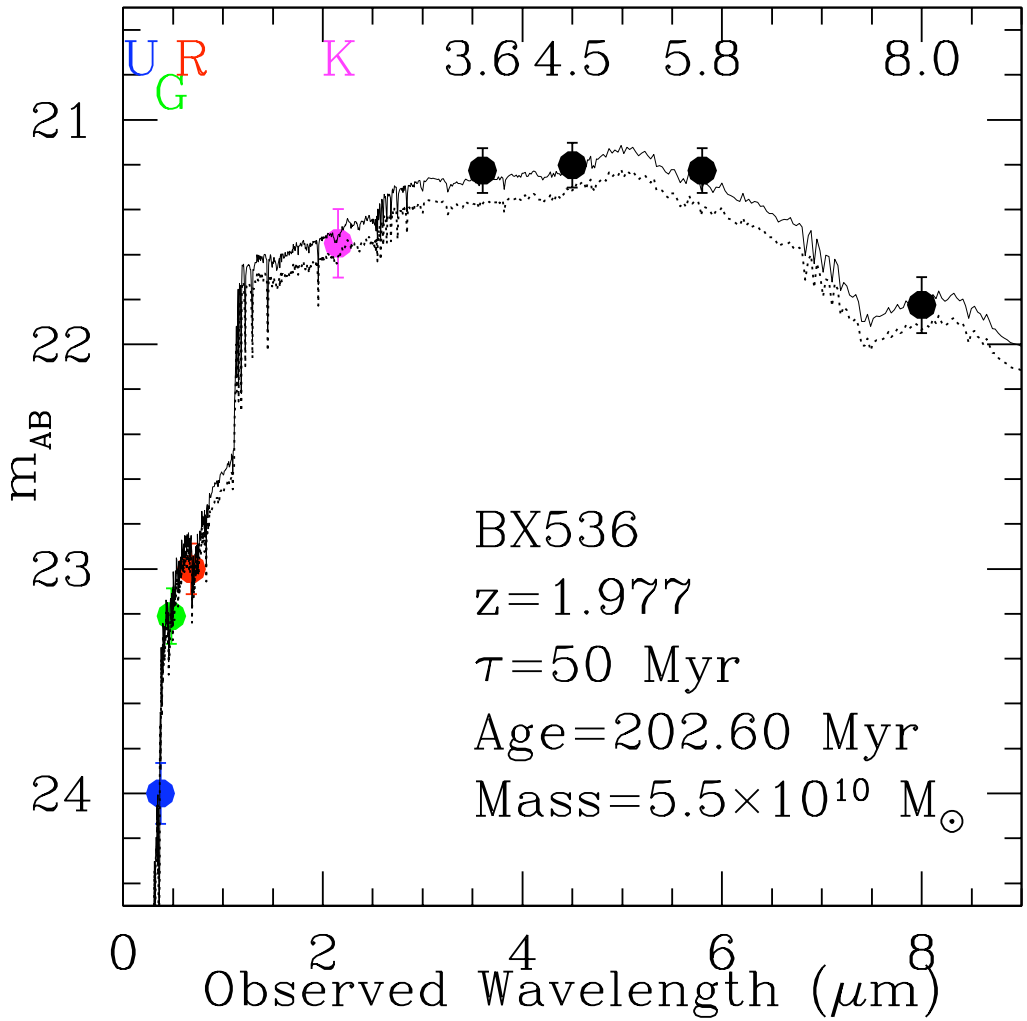
Adelberger et al. 2005



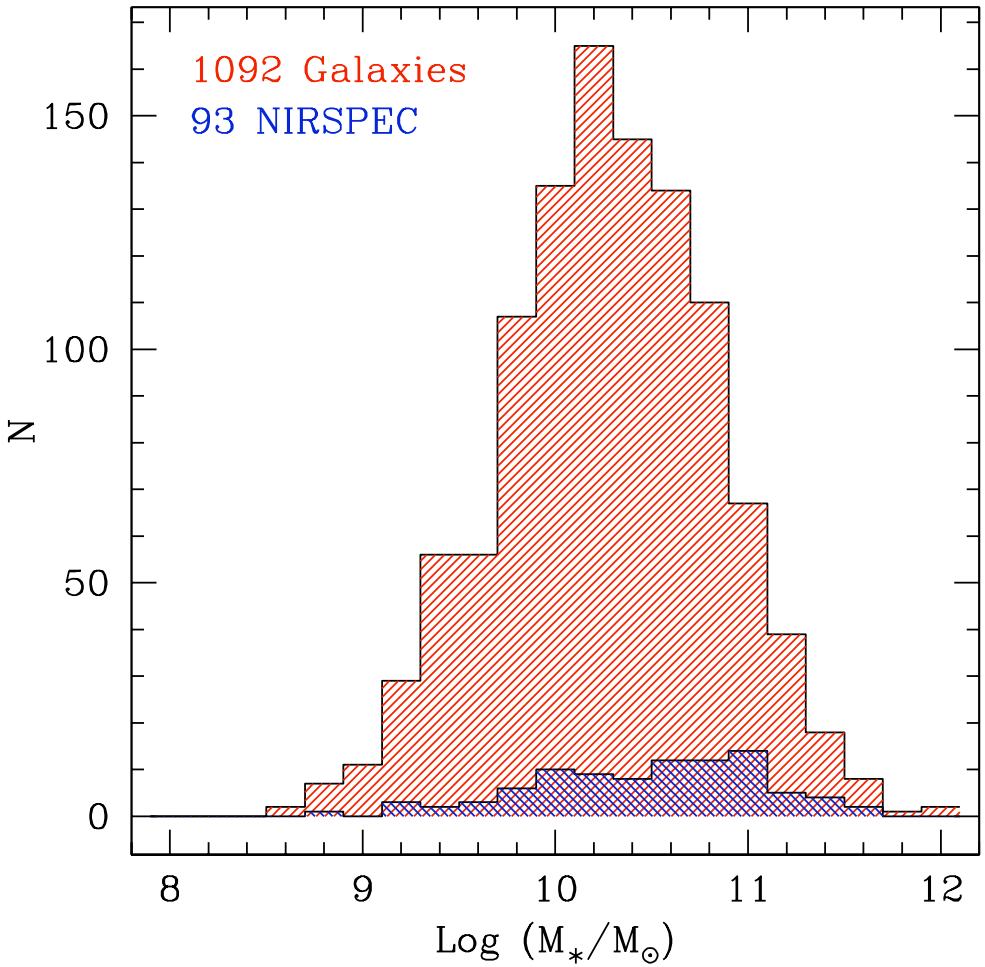
Combining $\omega(\theta)$ with spectroscopic redshift distributions, leads to:

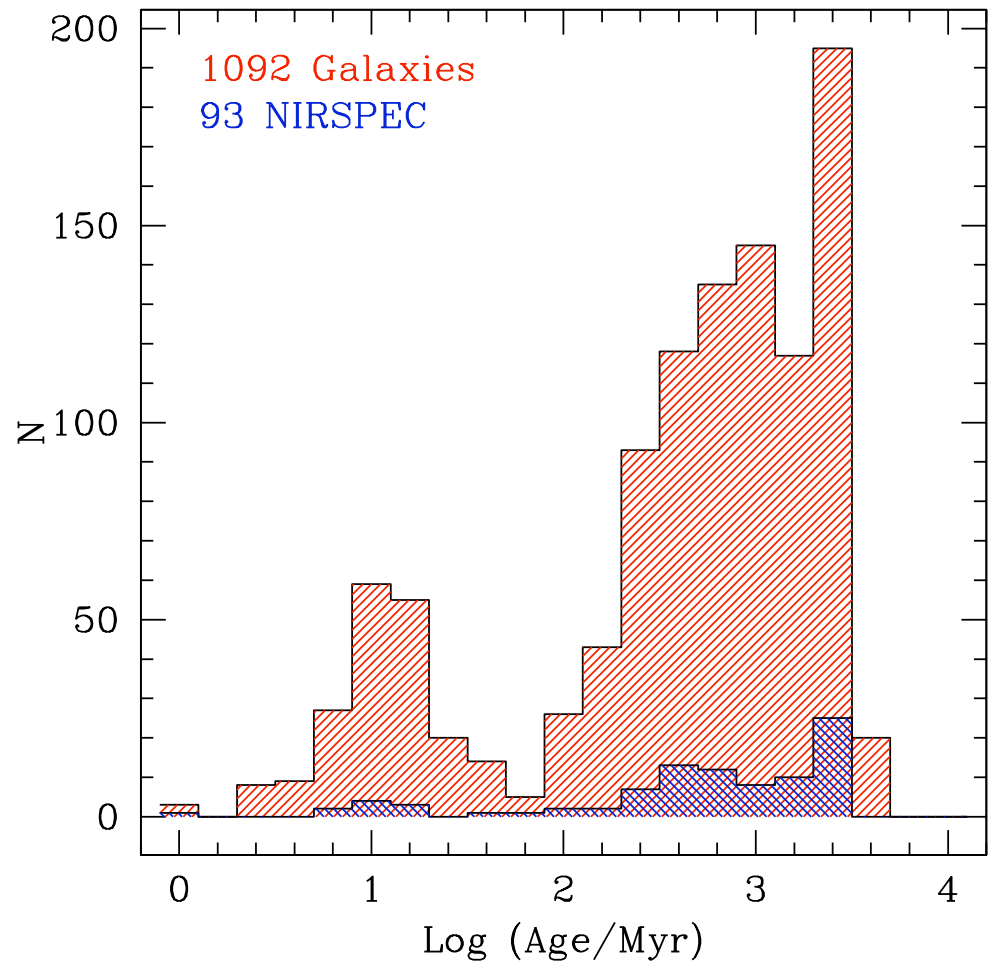
- $r_0 = 4.0 - 4.5\, h^{-1}\,\mathrm{Mpc} \quad (\gamma = 1.6)$
- Clustering length evolves from LBGs to BXs to BMs
- At $z = 1$ they would cluster like early-type DEEP galaxies
- At $z = 0.2$ they would cluster like elliptical SDSS galaxies

SED fitting with Bruzual & Charlot models



Shapley et al. 2005, Erb et al. 2006





Masses: $\sim 10^9 - 10^{11.5} M_\odot$

$\langle M_{\rm star} \rangle \simeq 2 \times 10^{10} M_\odot$

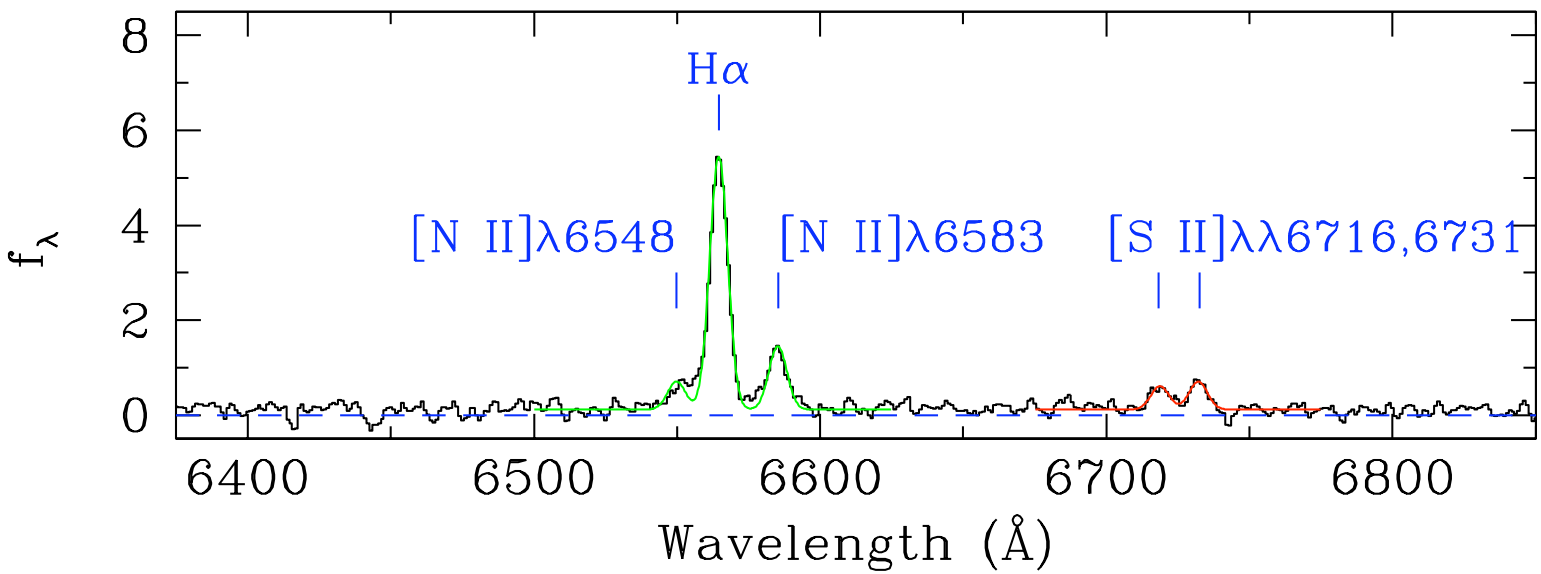
Ages: 10 Myr – 2 Gyr

15% with ages ≈ *t*(*z*)

Erb et al. 2007

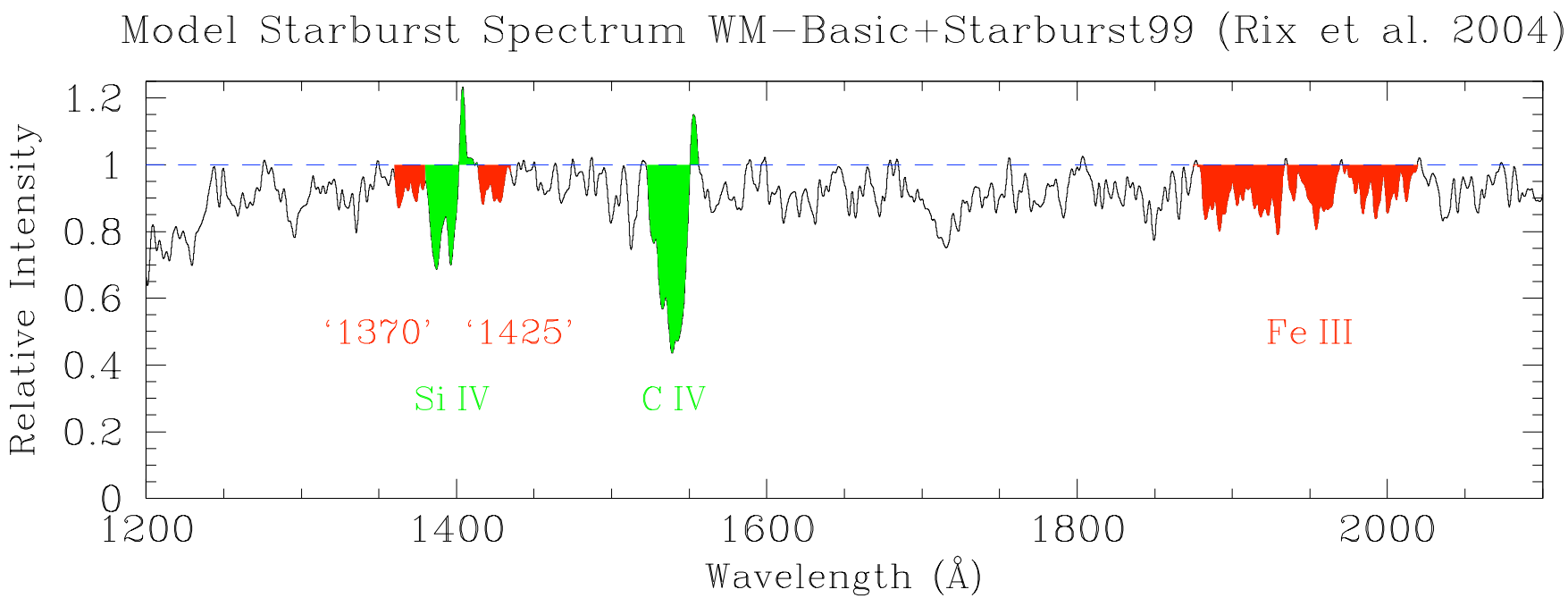
Metallicities deduced from:

- Nebular emission lines



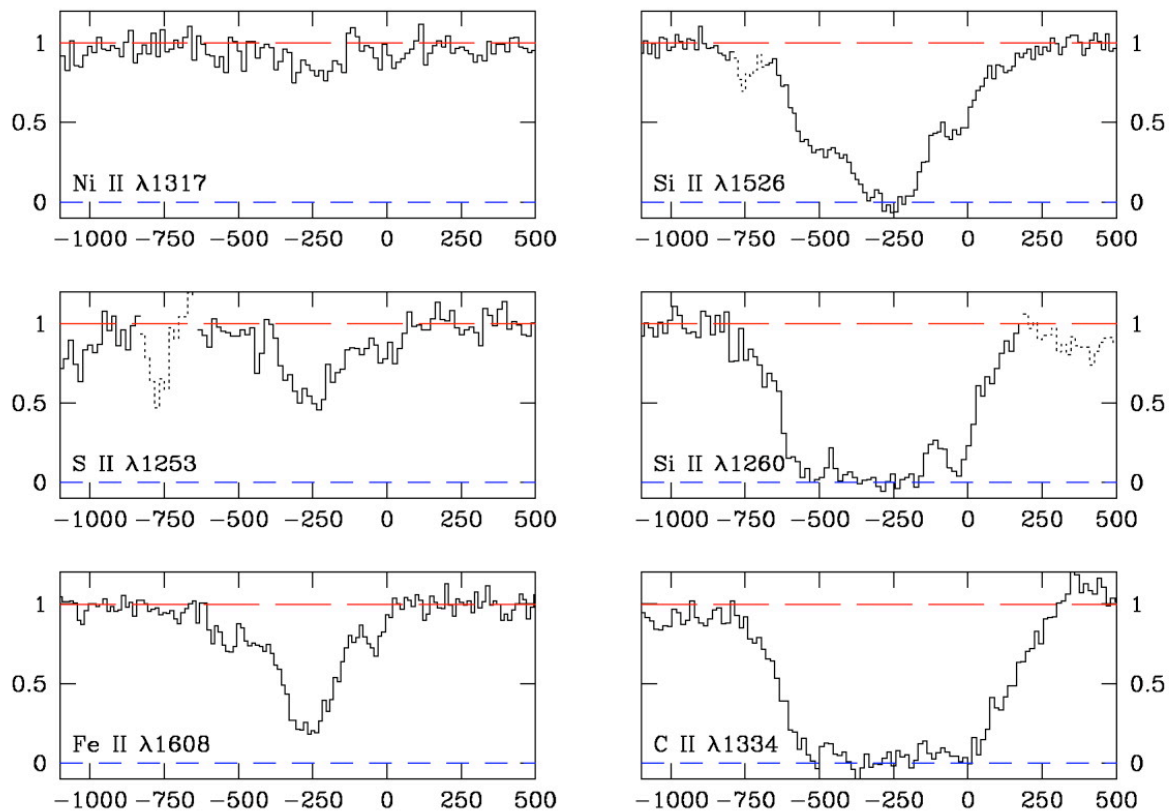
Metallicities deduced from:

- Nebular emission lines
- Stellar (OB) photospheric (red) and wind (green) lines



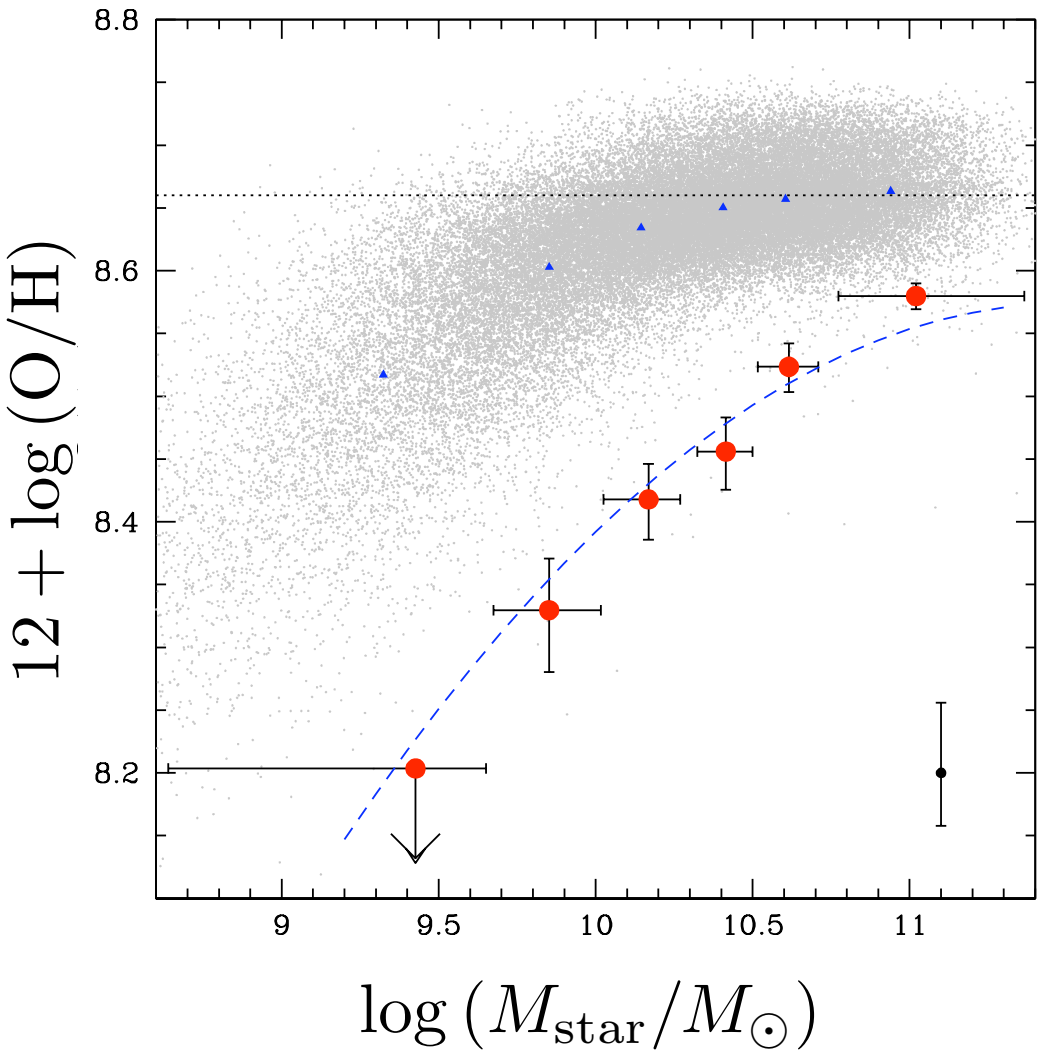
Metallicities deduced from:

- Nebular emission lines
- Stellar (OB) photospheric (red) and wind (green) lines
- Interstellar absorption lines



Relative velocity (km/s)

Stellar Mass-Metallicity Relation at $z = 2$

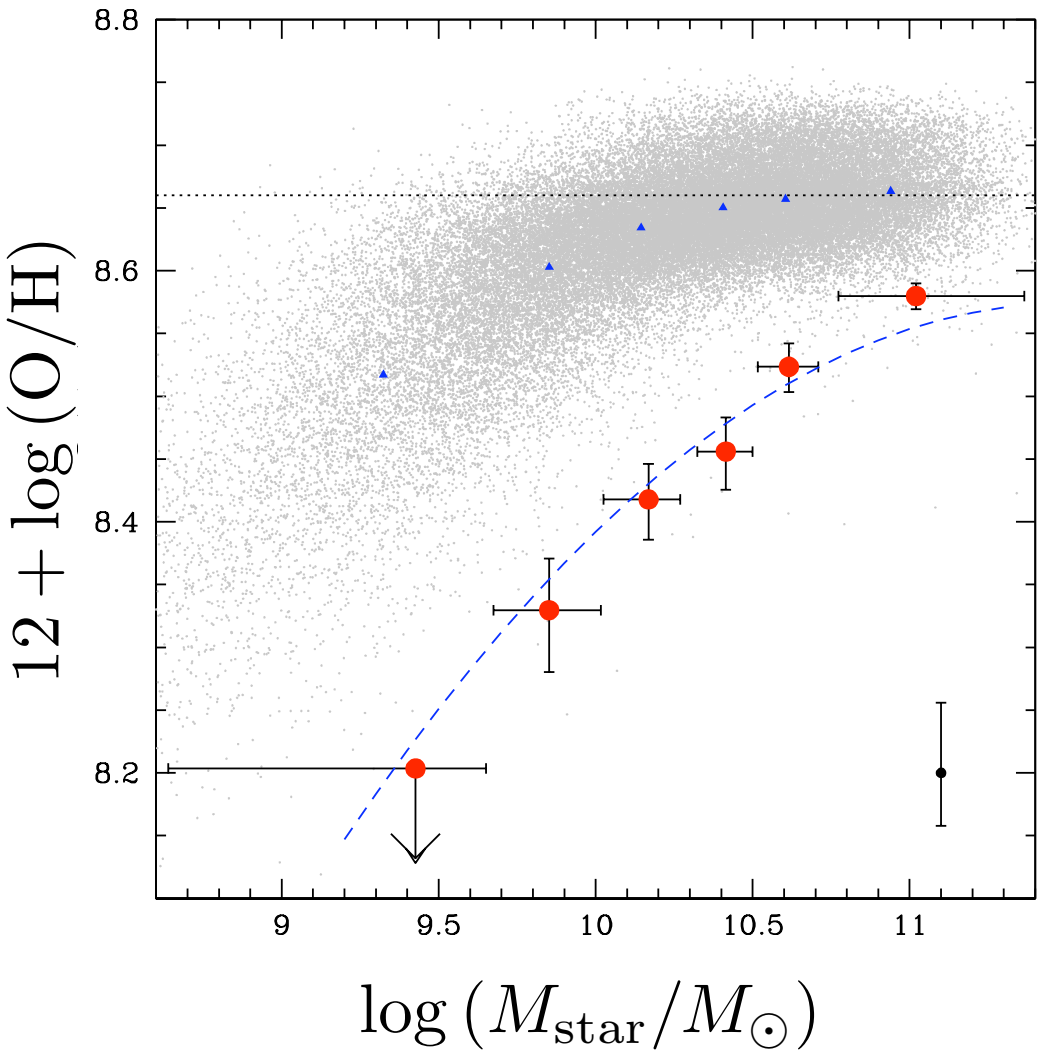


Note:

- Most galaxies have (O/H) $\gtrsim 1/3\,(\mathrm{O/H})_{\odot}$

Erb et al. 2006

Stellar Mass-Metallicity Relation at $z = 2$

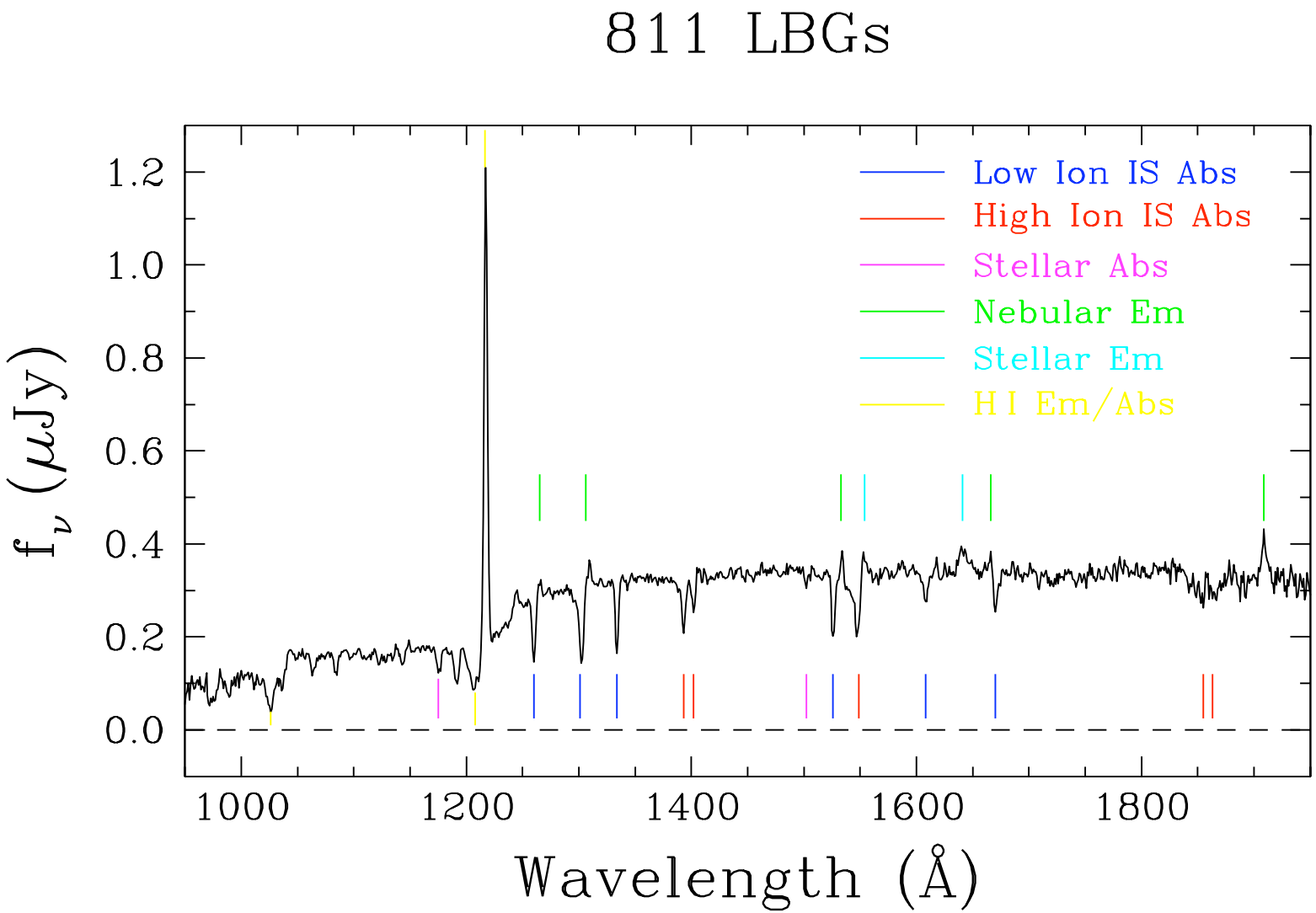


Note:

- Most galaxies have (O/H) $\gtrsim 1/3$ (O/H)$_{\odot}$
- Offset from present-day (SDSS) $M - Z$ relation

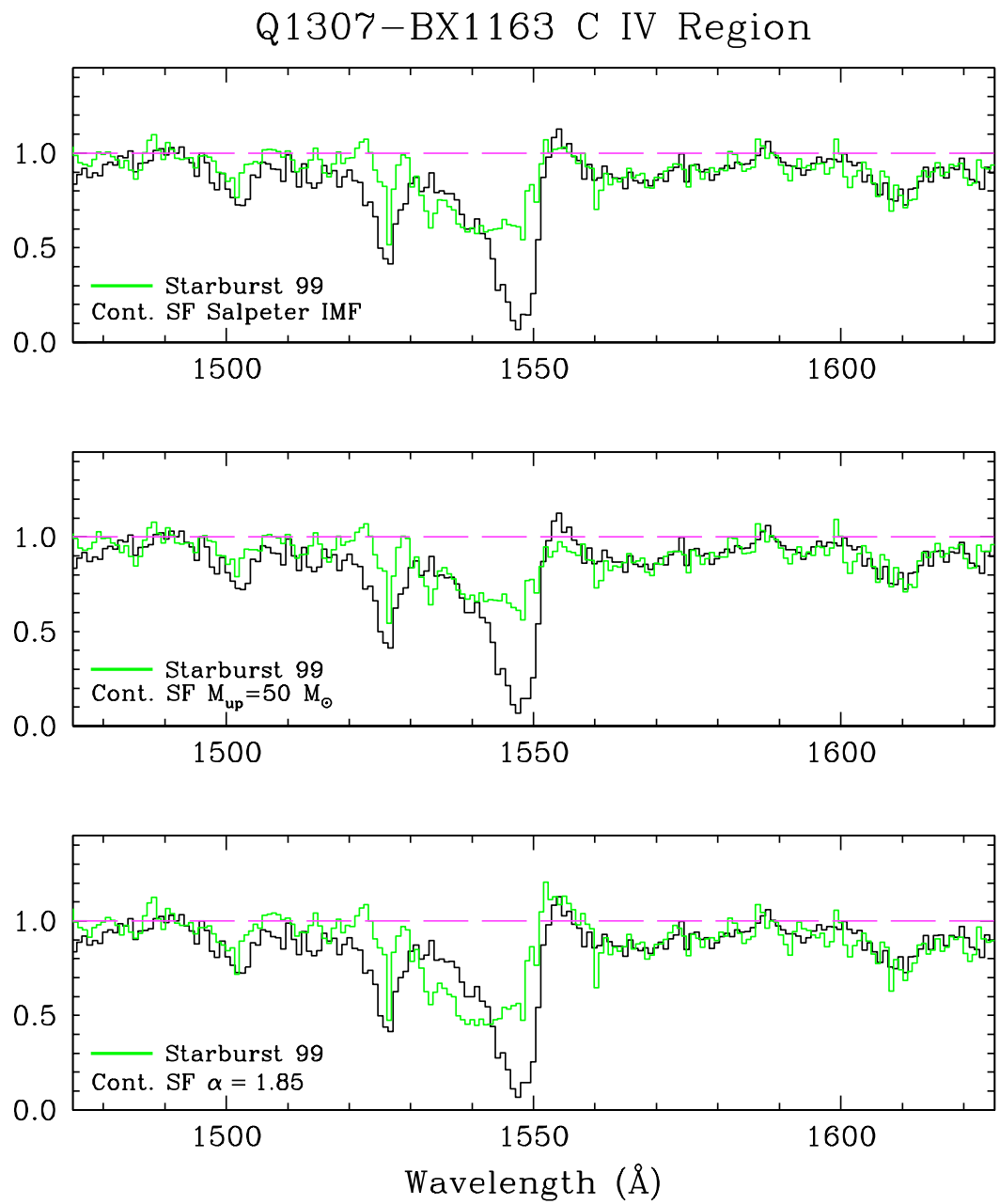
Erb et al. 2006

The rest-frame UV spectra are rich in diagnostic features from: stellar photospheres, winds, H II regions and the ambient ISM

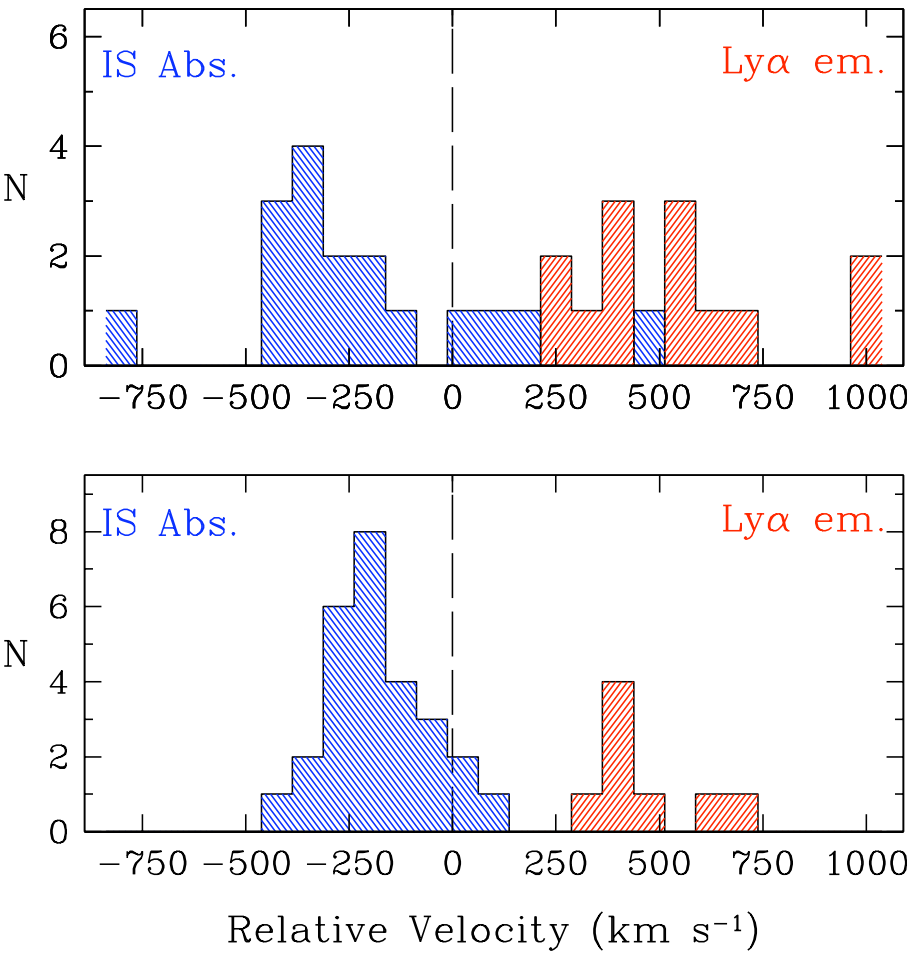


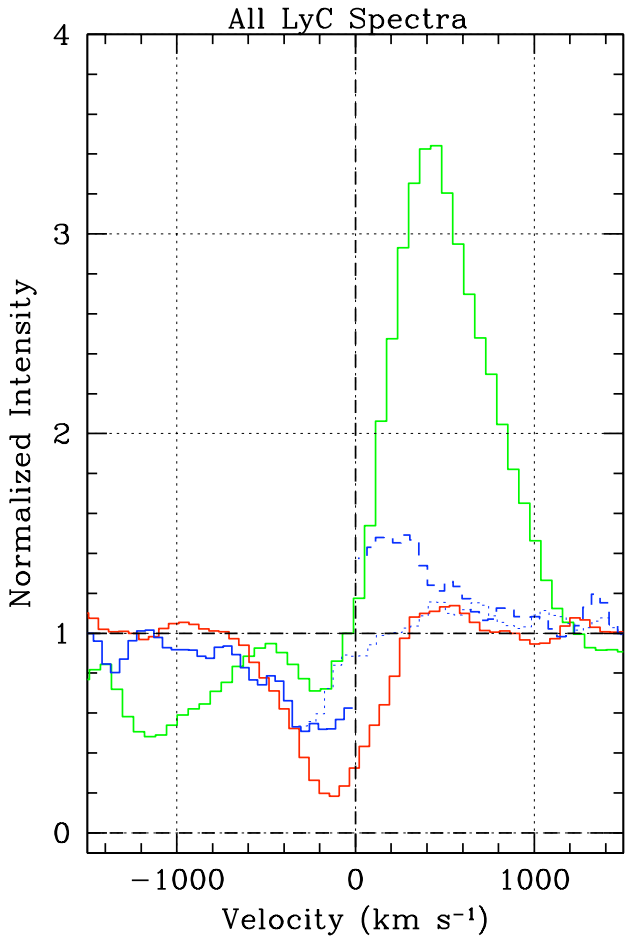
Shapley et al. 2003

A Salpeter IMF is favoured for stars with $M > 10M_\odot$



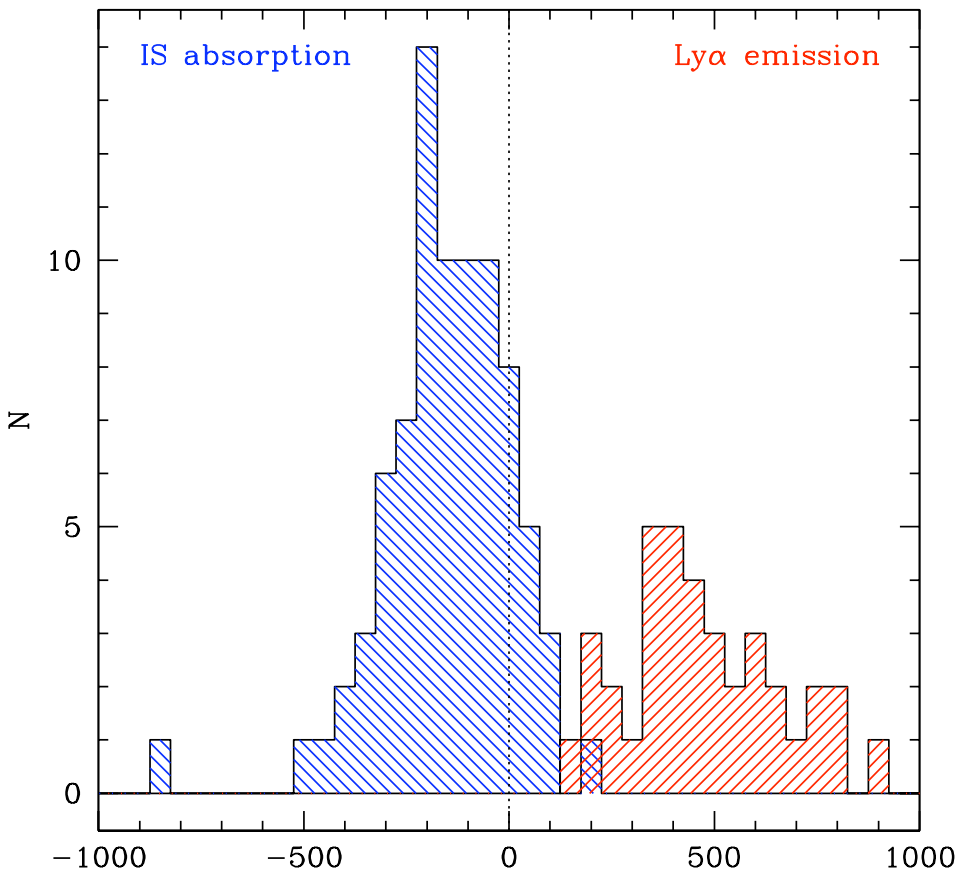
Large-scale motions *within* LBGs



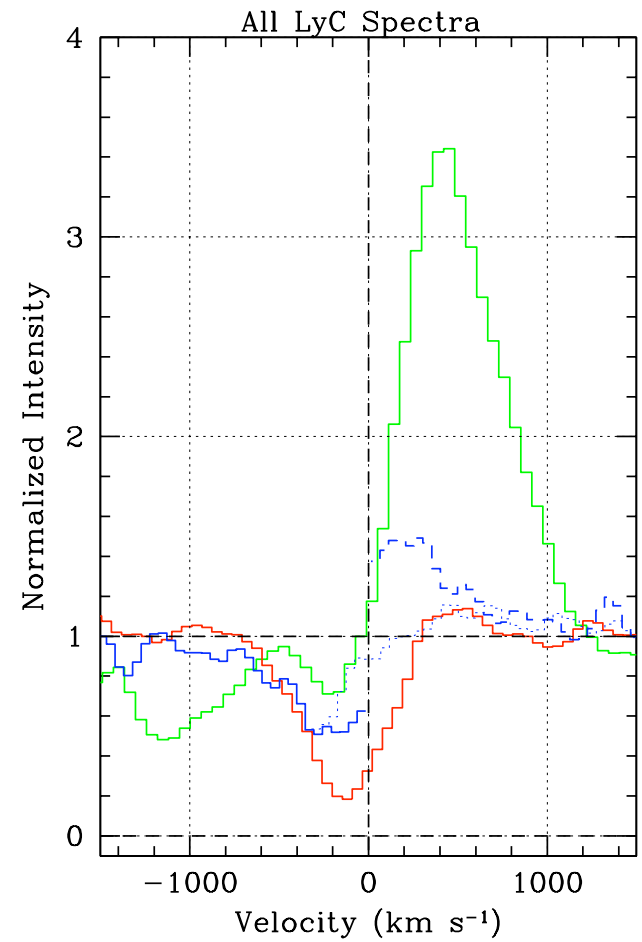


Steidel et al. 2004, 2007

Large-scale motions *within* LBGs



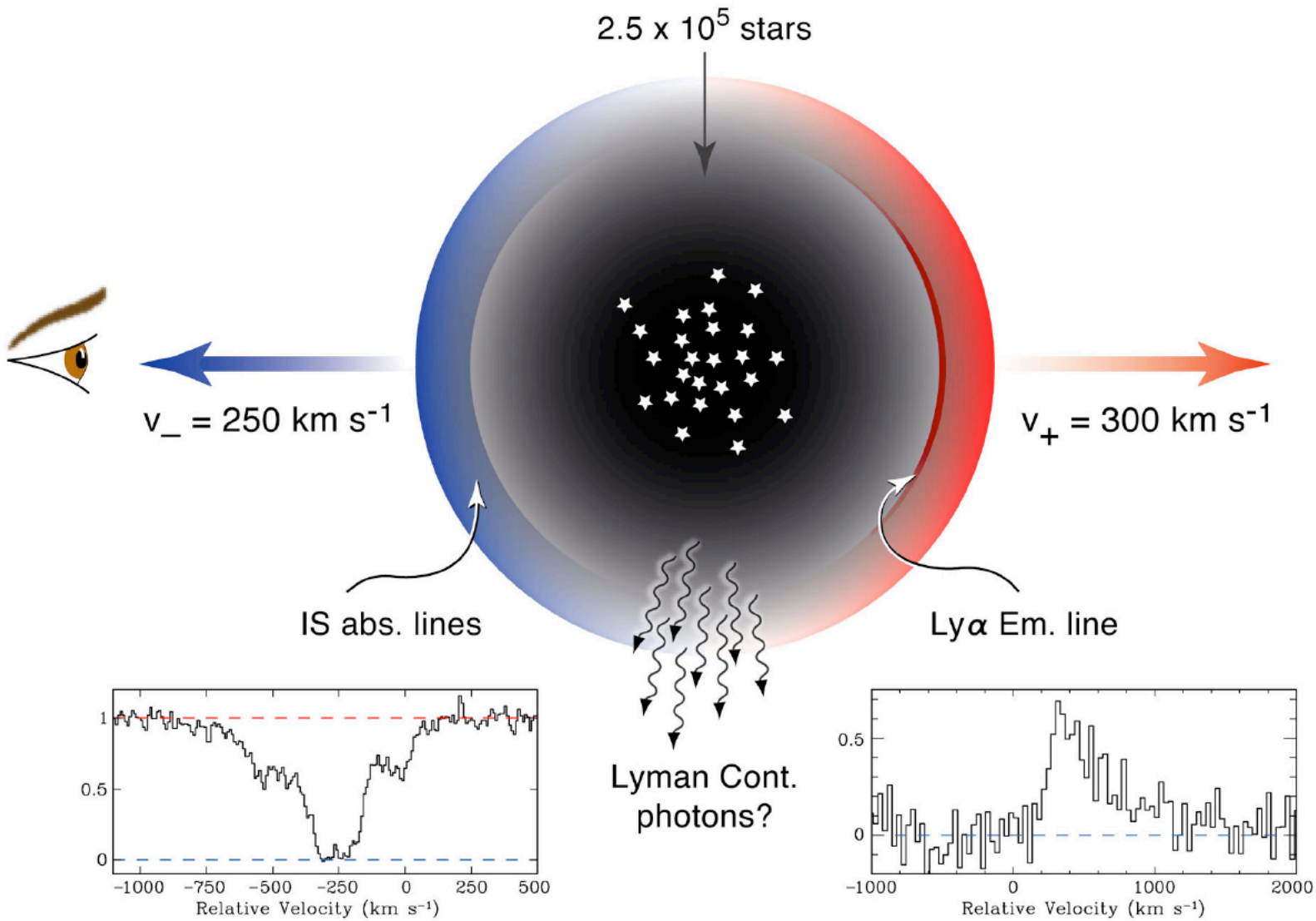
Offset Velocity from Systemic (km/s)



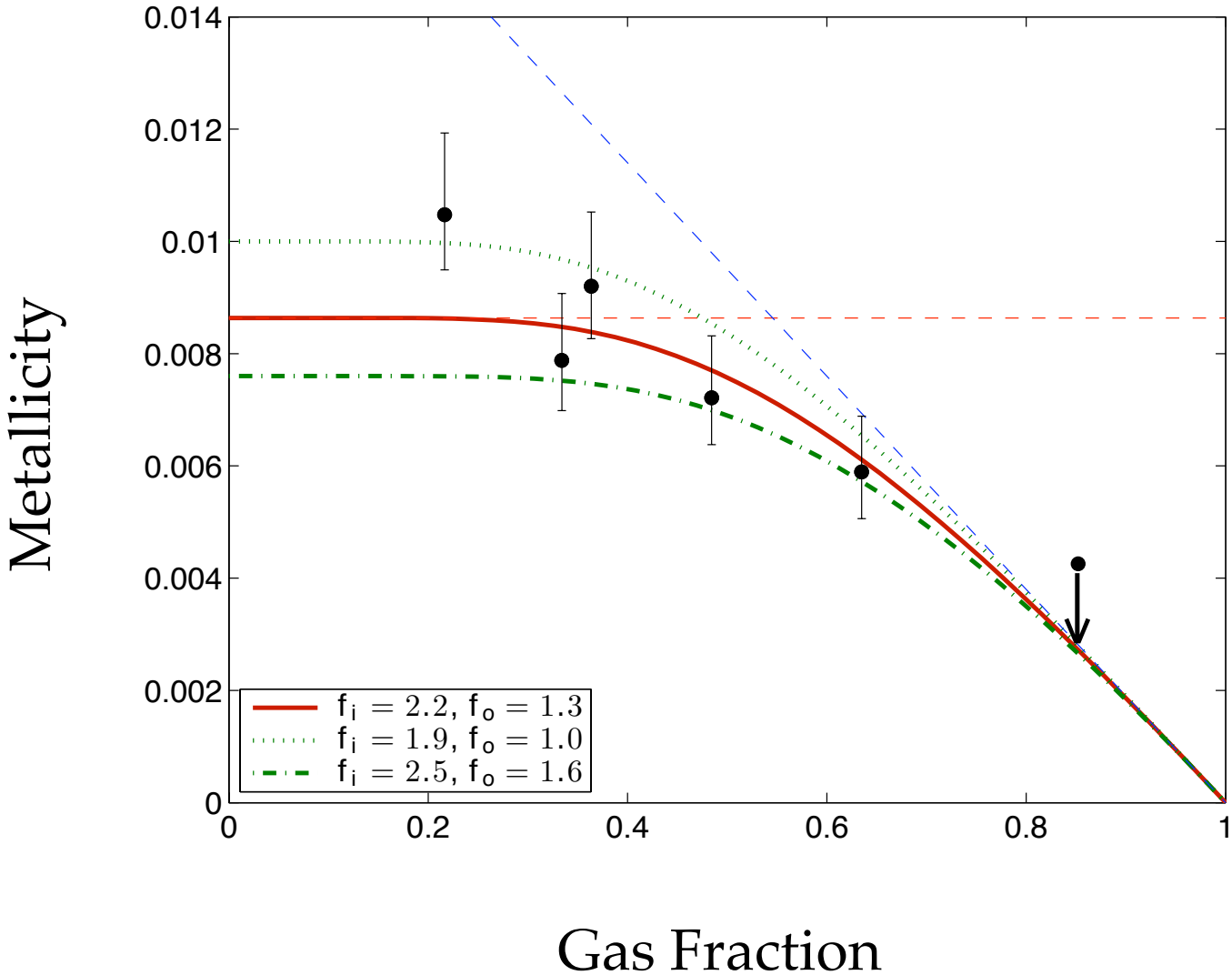
Steidel et al. 2004, 2007

GALACTIC SCALE OUTFLOW

$M_{out} \geq 80 M_{\odot} yr^{-1} \gtrsim M_{in} \approx 40 M_{\odot} yr^{-1}$



Outflow (and inflow) required to match M-Z and Z-y relations



$$\dot{M}_{\rm out} \simeq \dot{M}_*$$

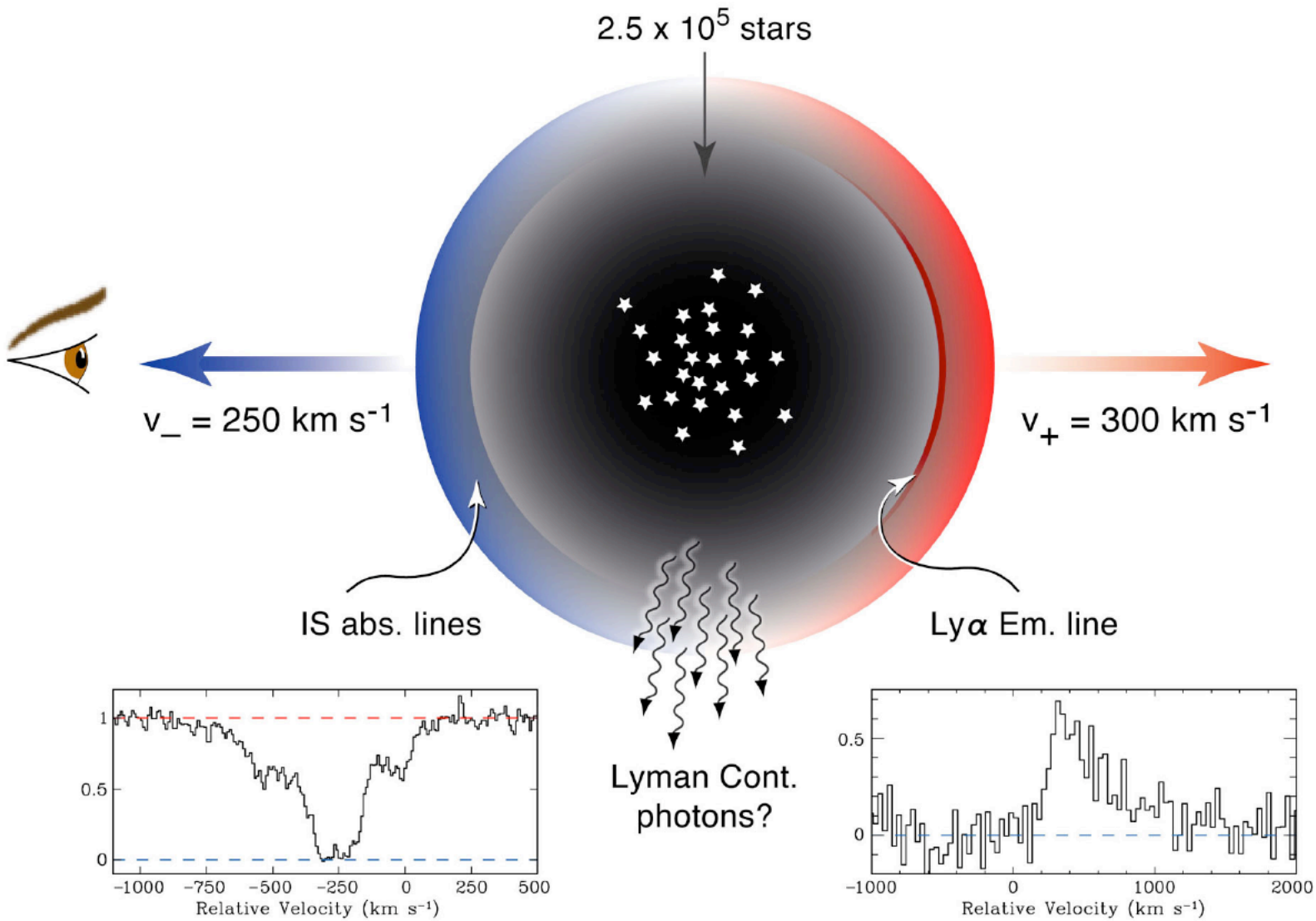
$$\dot{M}_{\rm in} \simeq \dot{M}_{\rm out} + \dot{M}_*$$

$$y = 0.019 = 1.5 Z_\odot$$

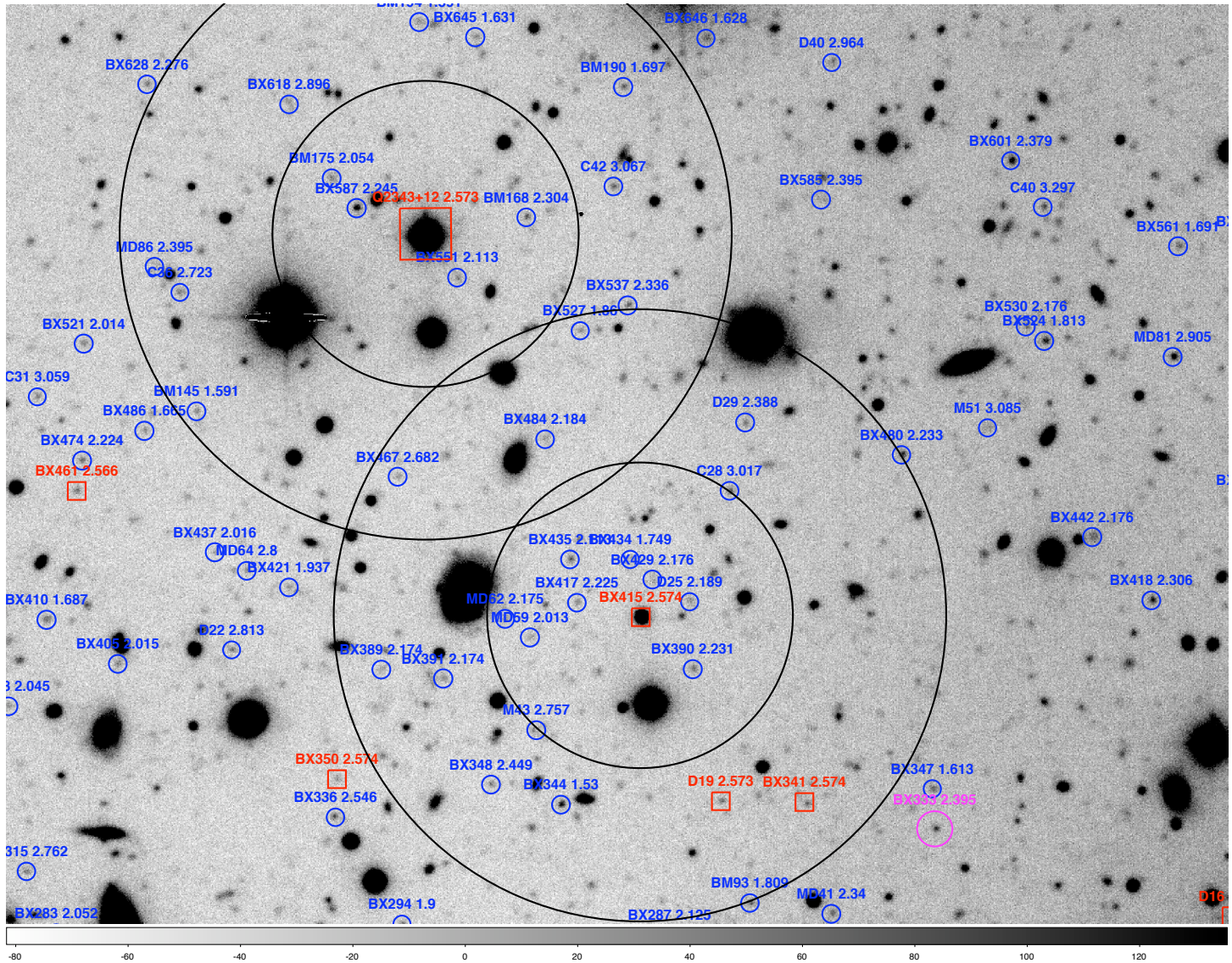
Erb 2008

GALACTIC SCALE OUTFLOW

$M_{out} \geq 80 M_{\odot} yr^{-1} \gtrsim M_{in} \approx 40 M_{\odot} yr^{-1}$



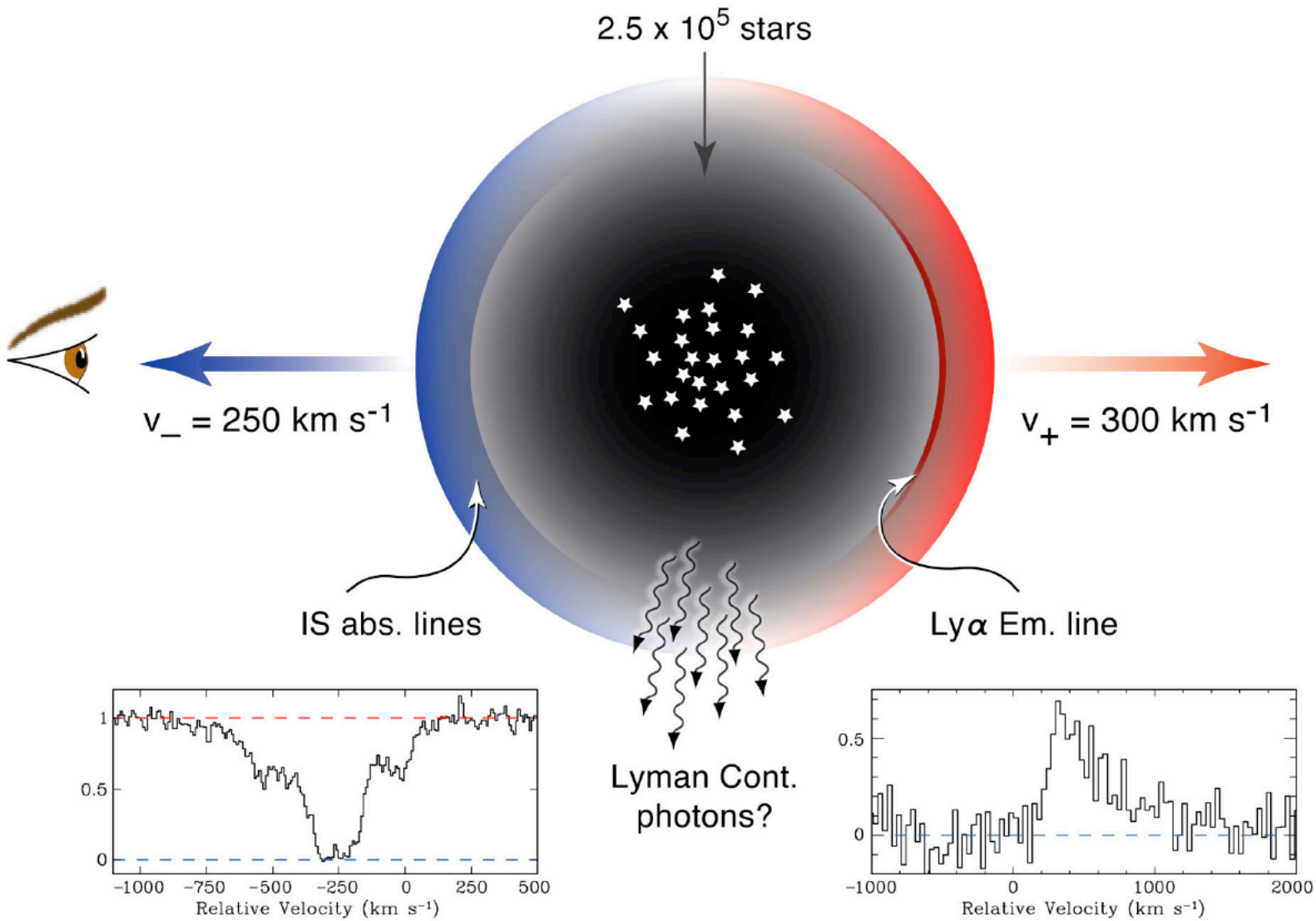
Q2343+125 Field



Rix et al. 2007

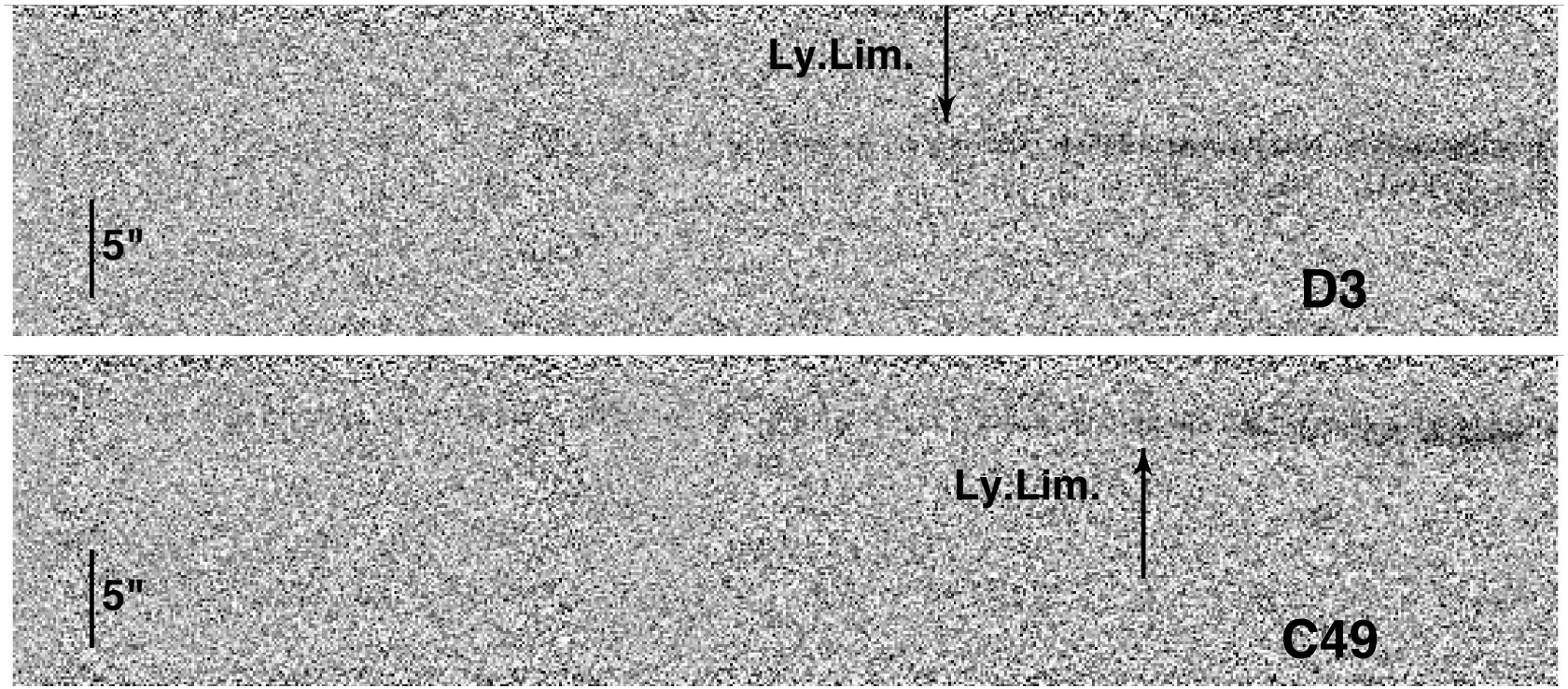
GALACTIC SCALE OUTFLOW

$M_{out} \geq 80 M_{\odot} yr^{-1} \gtrsim M_{in} \approx 40 M_{\odot} yr^{-1}$



Lyman Continuum Radiation from LBGs

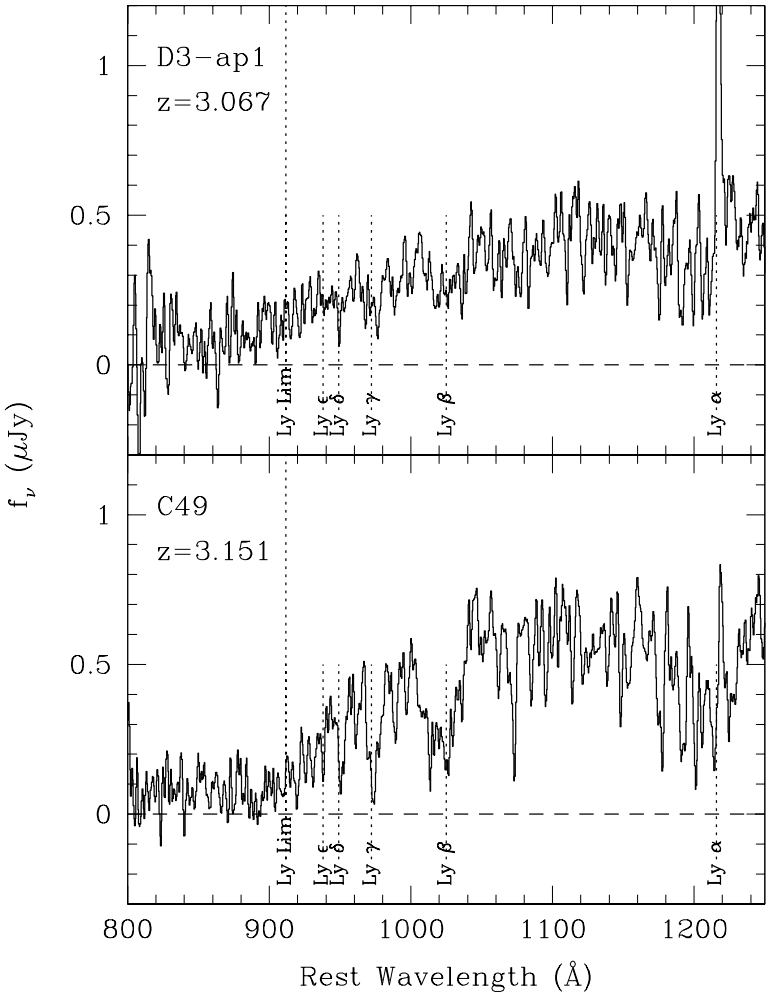
Shapley et al. 2006



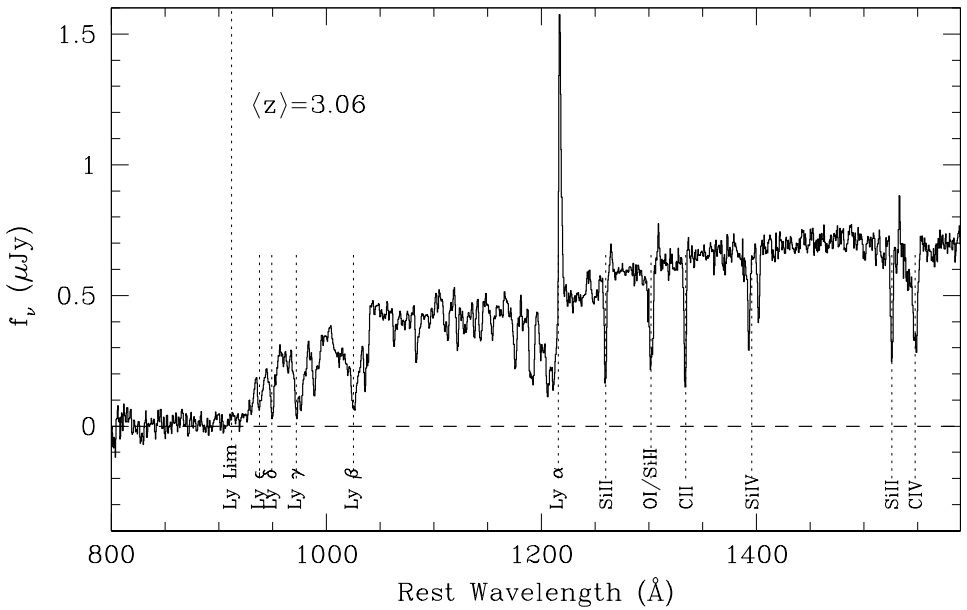
Deep (30 000 – 80 000 s) spectroscopy of 14 galaxies

With LRISB can now reach to $\lambda_{\rm obs} \simeq 3200$ Å, $\lambda_0 \simeq 800$ Å

Lyman Continuum Radiation from LBGs

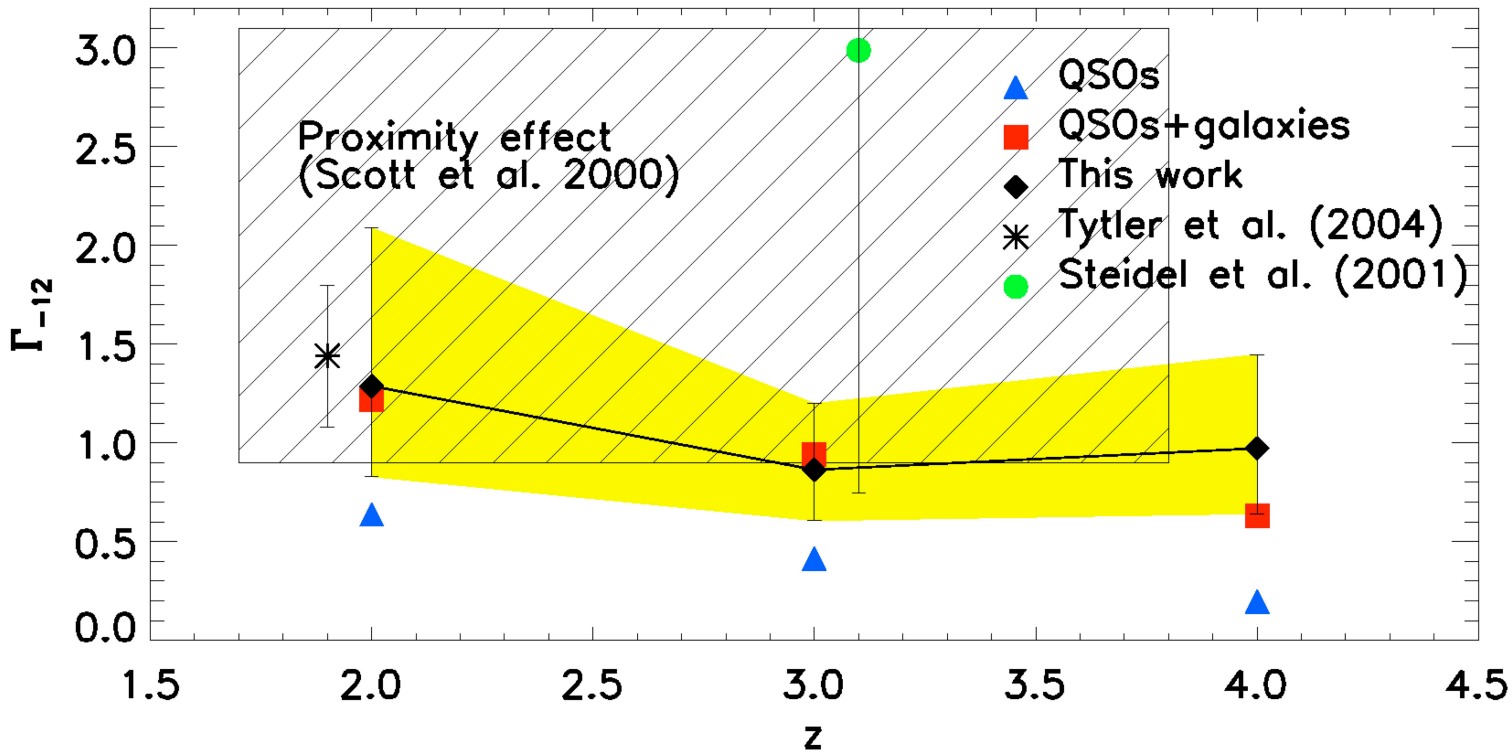


Composite of 14 spectra



Two out of 14 show signal below the Lyman edge

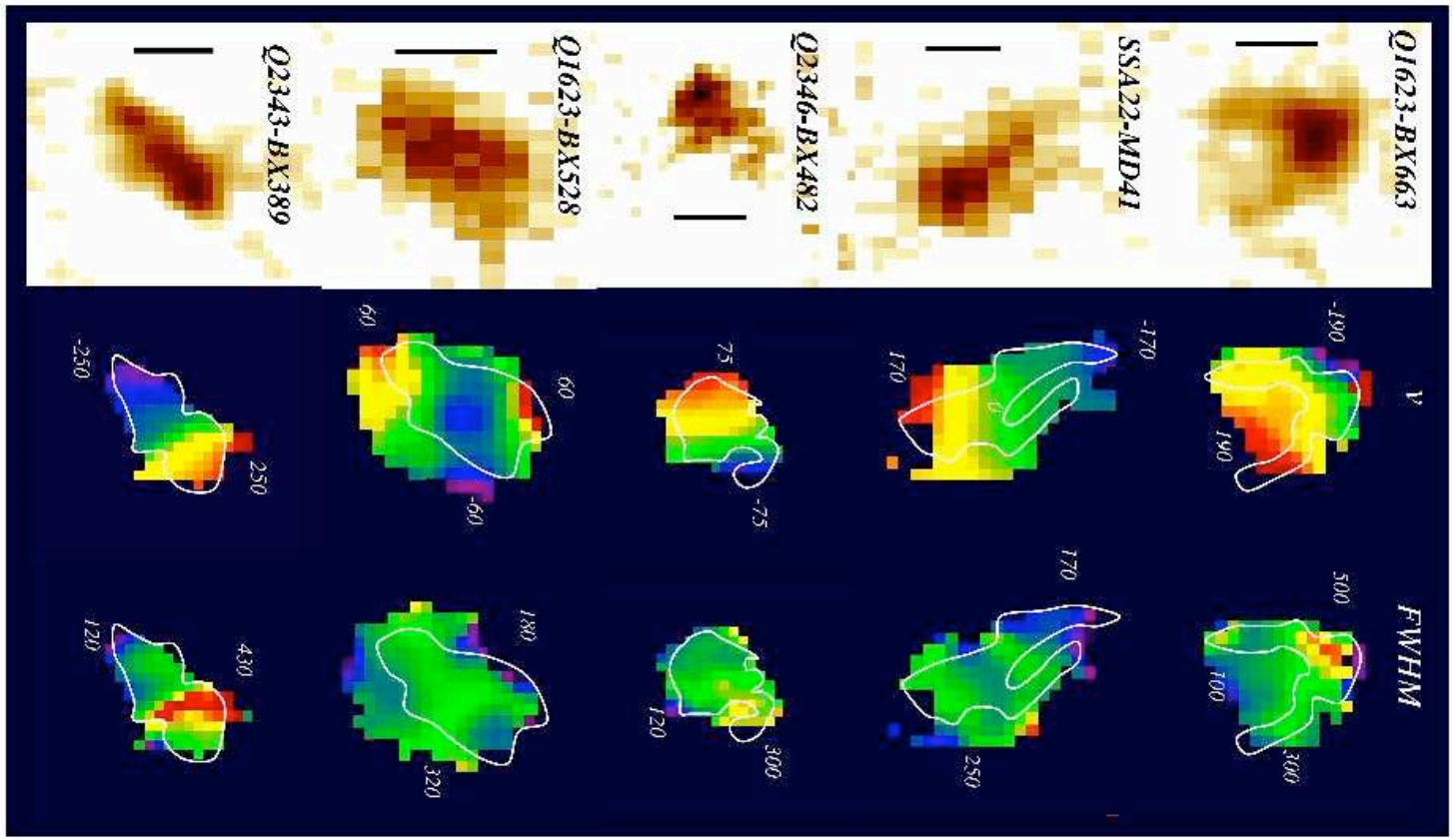
Metagalactic Ionising Background



$\log J_\nu^{\rm gals} \simeq 2.6 \times 10^{-22}$; $\log J_\nu^{\rm QSOs} \simeq 2.4 \times 10^{-22}$ (Hunt et al. 2004)

Together $\Longrightarrow$ $\Gamma_{-12} \simeq 1.3$, in good agreement with Bolton et al. (2005).

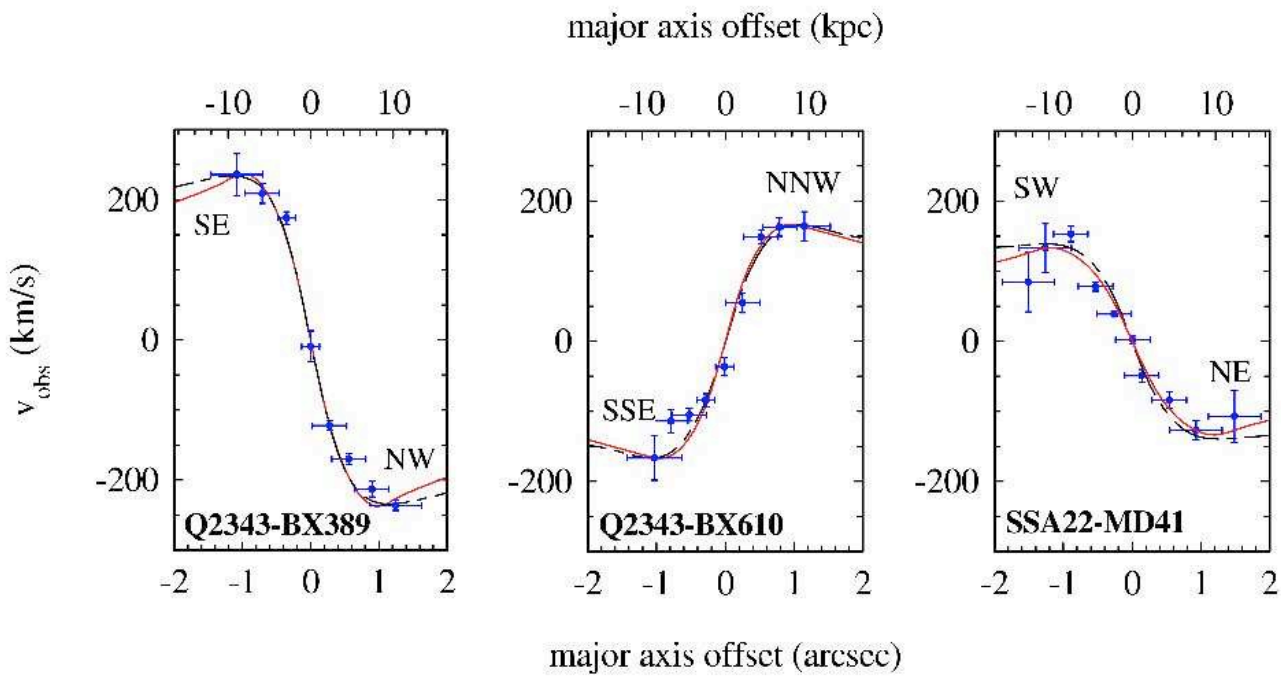
Integral Field NIR Spectroscopy with SINFONI favours rotation in some of the cases studied so far:



Hα maps with a spatial resolution of $\sim 0.5'' \simeq 4$ kpc

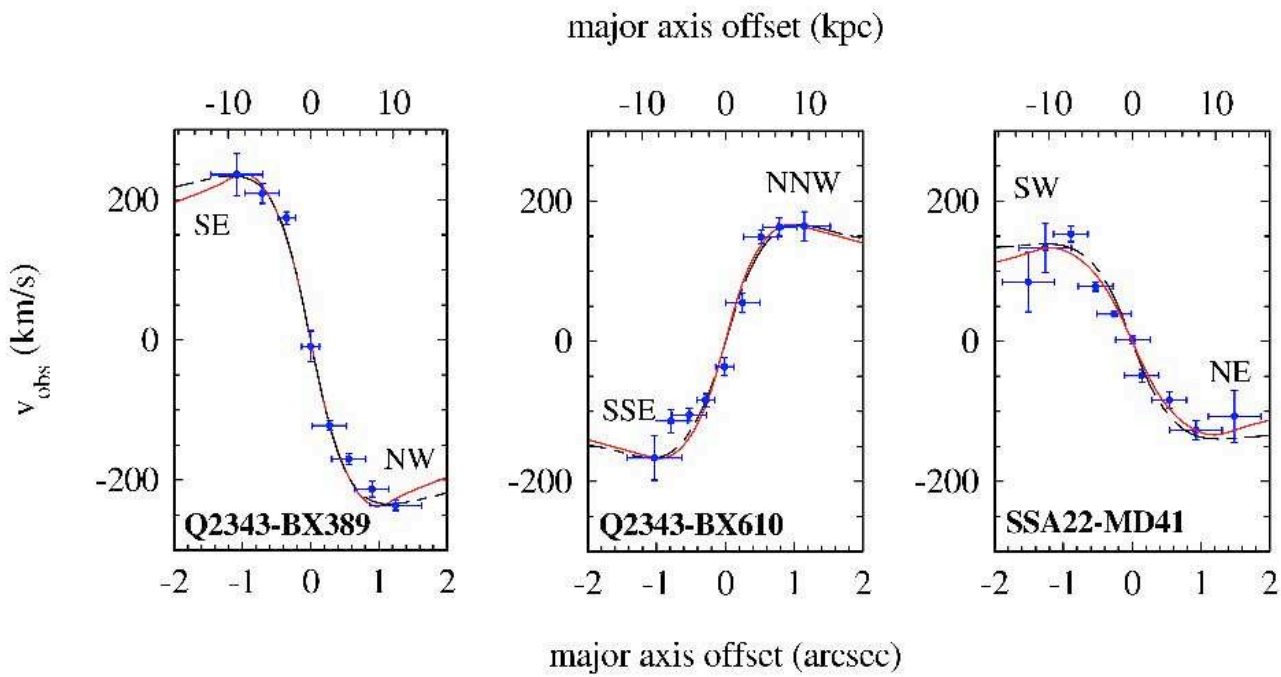
Förster Schreiber et al. 2006

Rotating disk models fit well the kinematics of some gals:



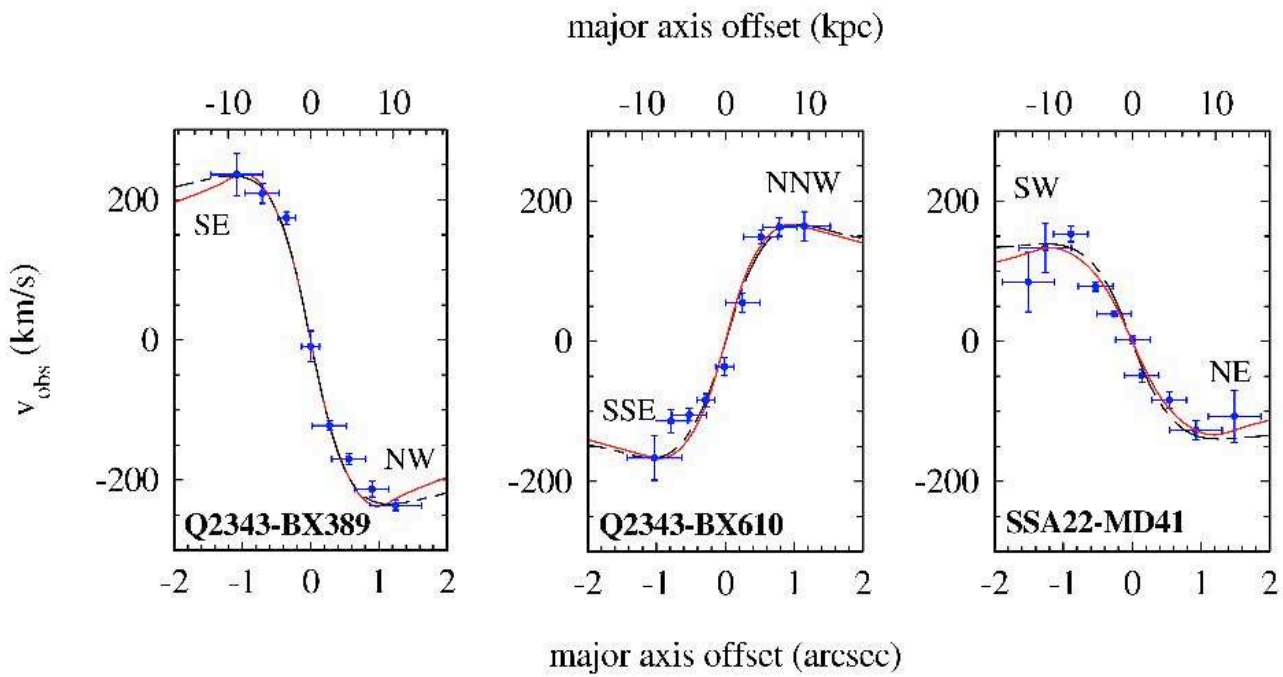
- Rotation curves followed to $\gtrsim 10$ kpc

Rotating disk models fit well the kinematics of some gals:



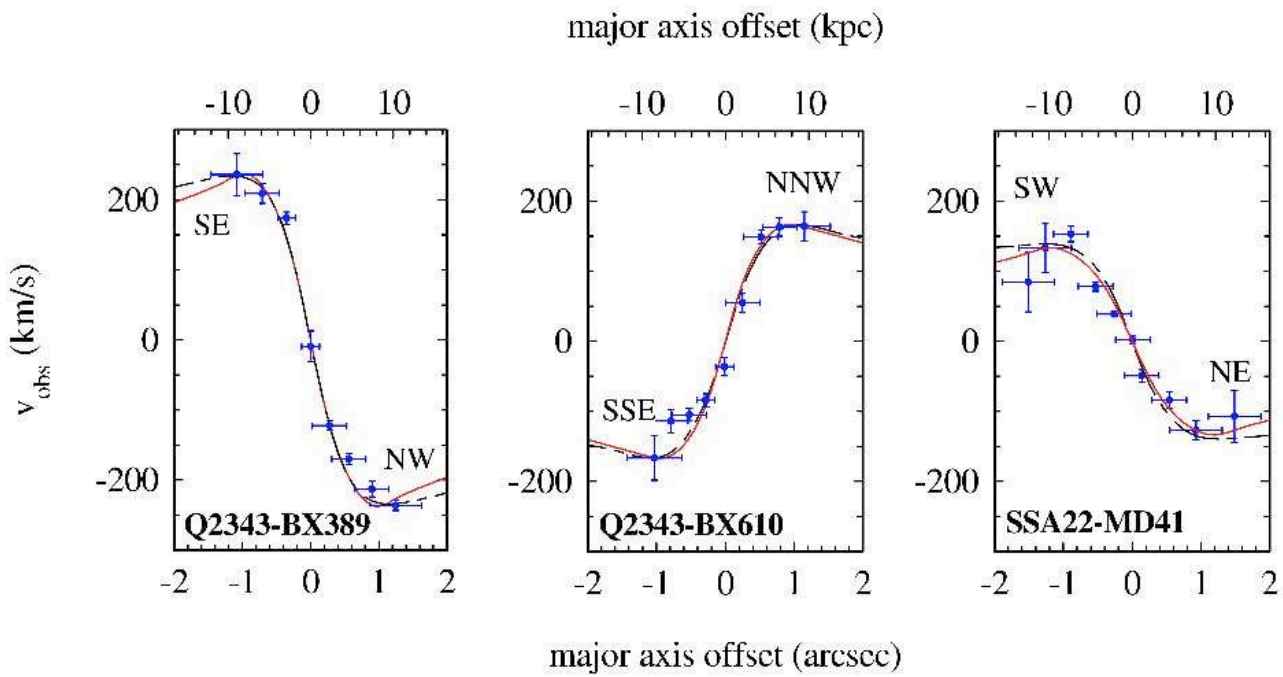
- Rotation curves followed to $\gtrsim 10$ kpc
- Maximum circular velocities $V_{\rm c} \simeq 180 \pm 90$ km s^{-1}

Rotating disk models fit well the kinematics of some gals:

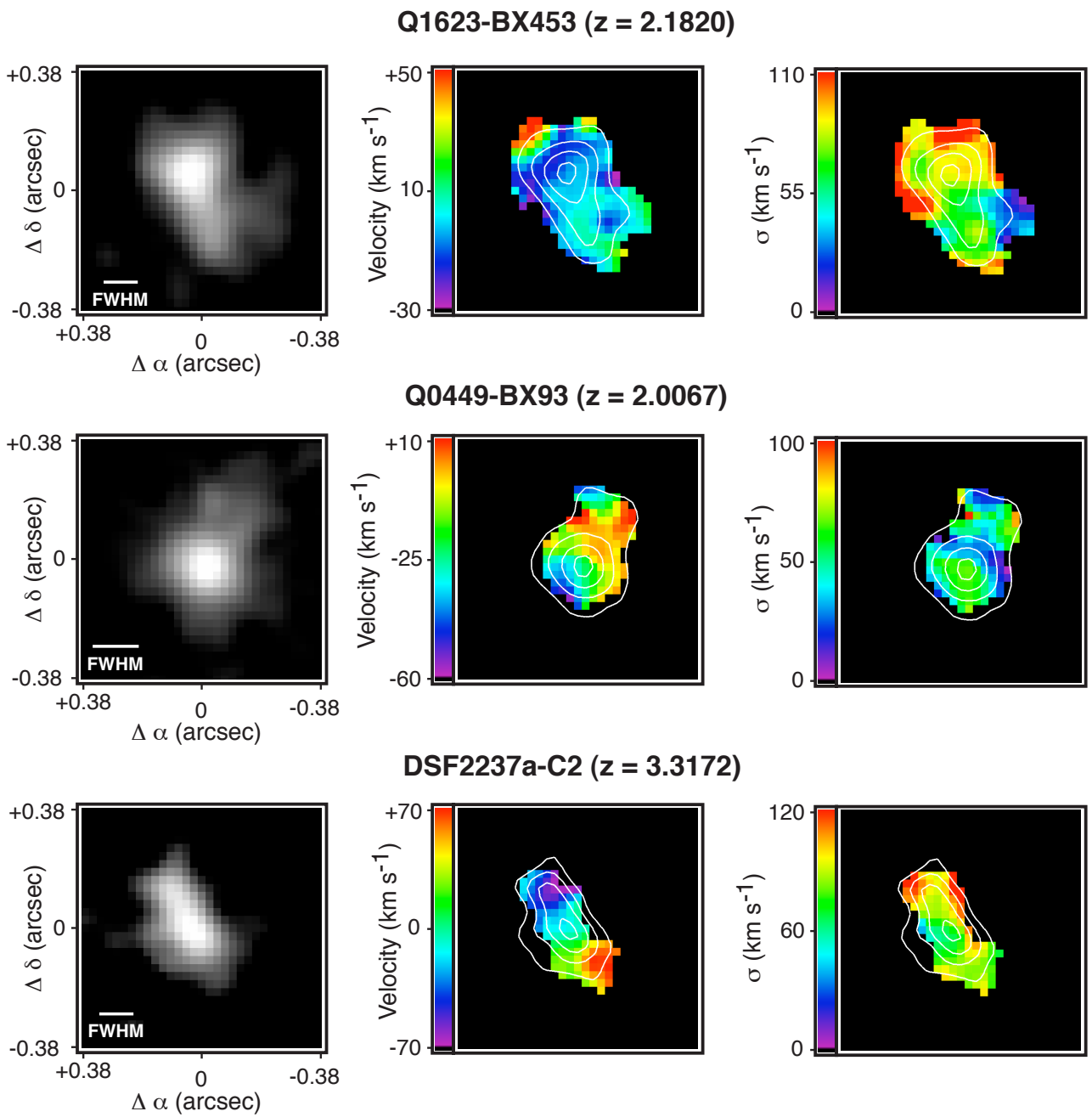


- Rotation curves followed to $\gtrsim 10$ kpc
- Maximum circular velocities $V_{\rm c} \simeq 180 \pm 90$ km s^{-1}
- Implied $M_{\rm dyn} \simeq (0.5 - 25) \times 10^{10} M_\odot$, $\frac{\langle M_{\rm dyn} \rangle}{\langle M_\star \rangle} \simeq 10^{0.1 \pm 0.3}$

Rotating disk models fit well the kinematics of some gals:



- Rotation curves followed to $\gtrsim 10$ kpc
- Maximum circular velocities $V_{\rm c} \simeq 180 \pm 90$ km s^{-1}
- Implied $M_{\rm dyn} \simeq (0.5 - 25) \times 10^{10} M_\odot$, $\frac{\langle M_{\rm dyn} \rangle}{\langle M_\star \rangle} \simeq 10^{0.1 \pm 0.3}$
- These are *thick* disks, z scale height $h_{\rm z} \simeq 1 - 1.5$ kpc



$\sim$ 6 kpc

OSIRIS - Keck II

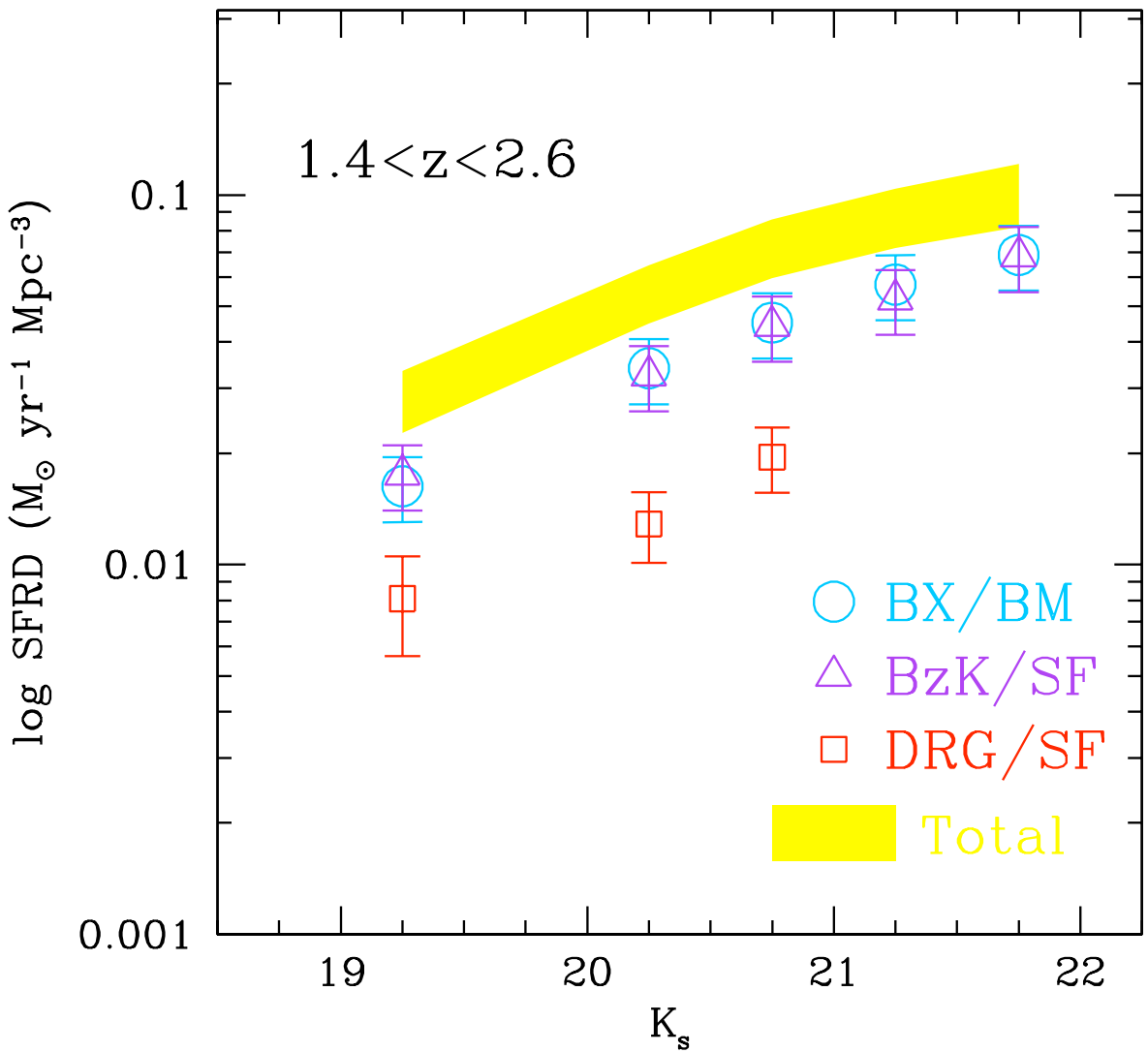
0.1 - 0.15 " FWHM
(0.025 " pixels)

Law et al. 2007

Concluding Thoughts

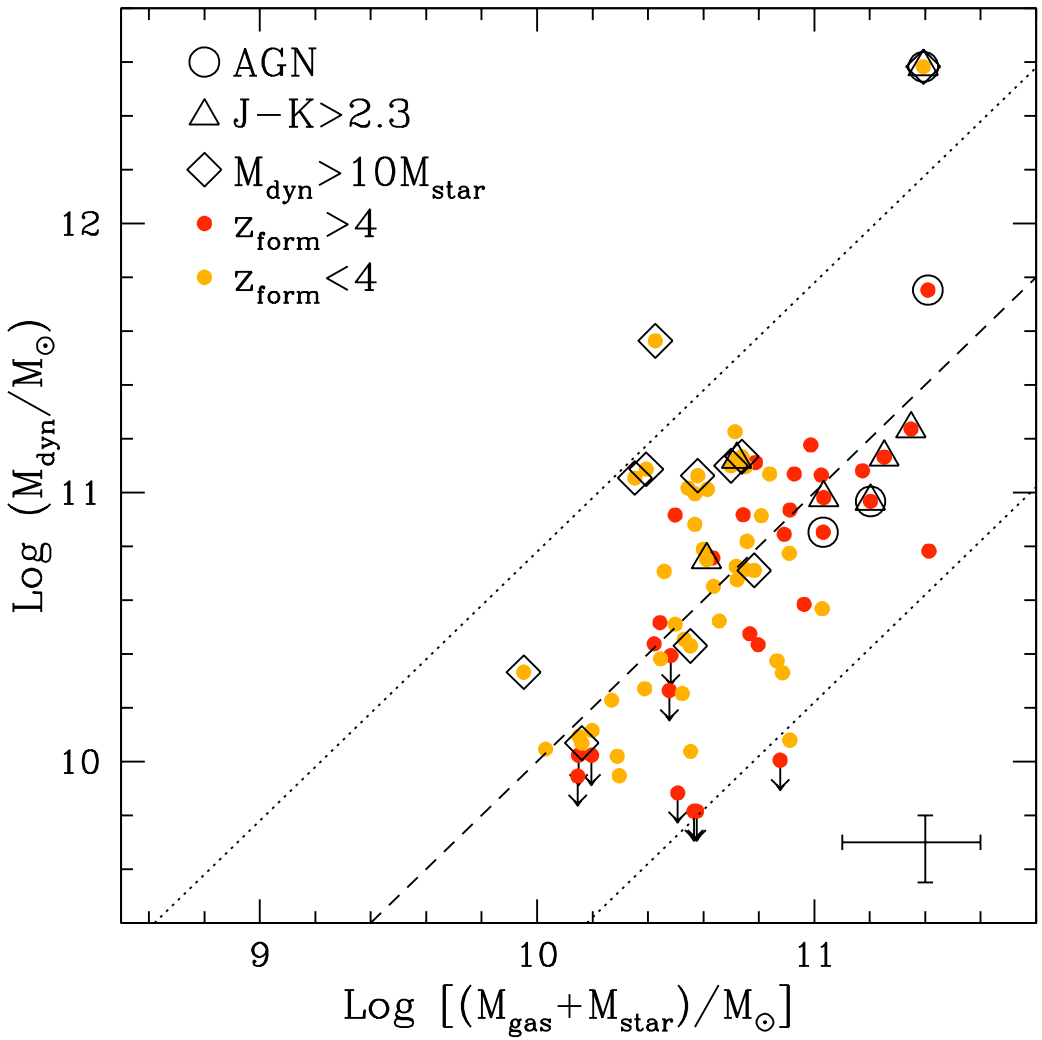
- Over the last ten years we have established many of the physical properties of the dominant population of galaxies at $z = 2 - 3$. Looking ahead:
- Clarify the incidence of rotation vs. disp. dominated kinematics
- What factors determine the escape fraction of LyC photons?
- Develop a coherent physical picture of the inflow and outflow. Why do we not see the infalling gas which fuels star formation? What volumes of the IGM are affected by the outflows?
- What are the properties of galaxies at the faint end of the LF?

The End

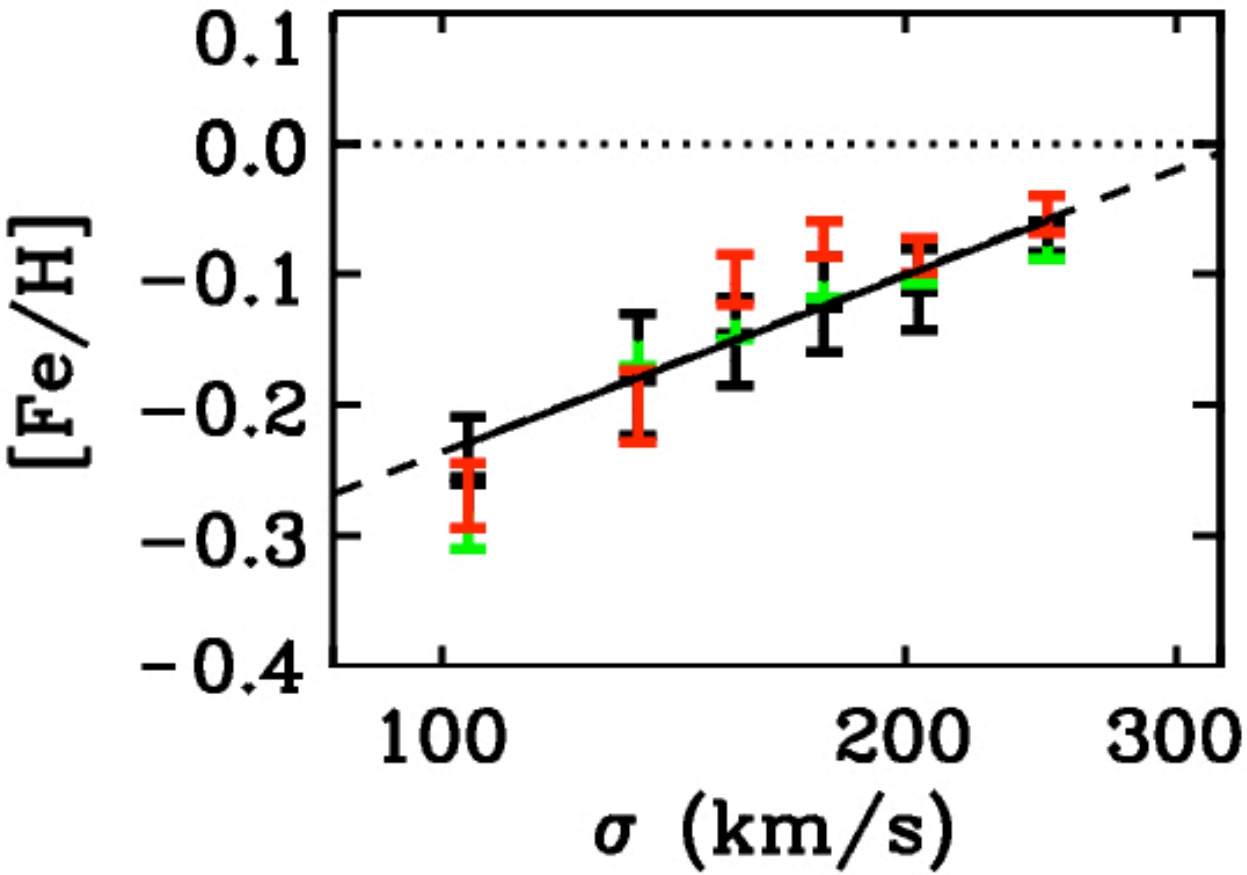


Reddy et al. 2005

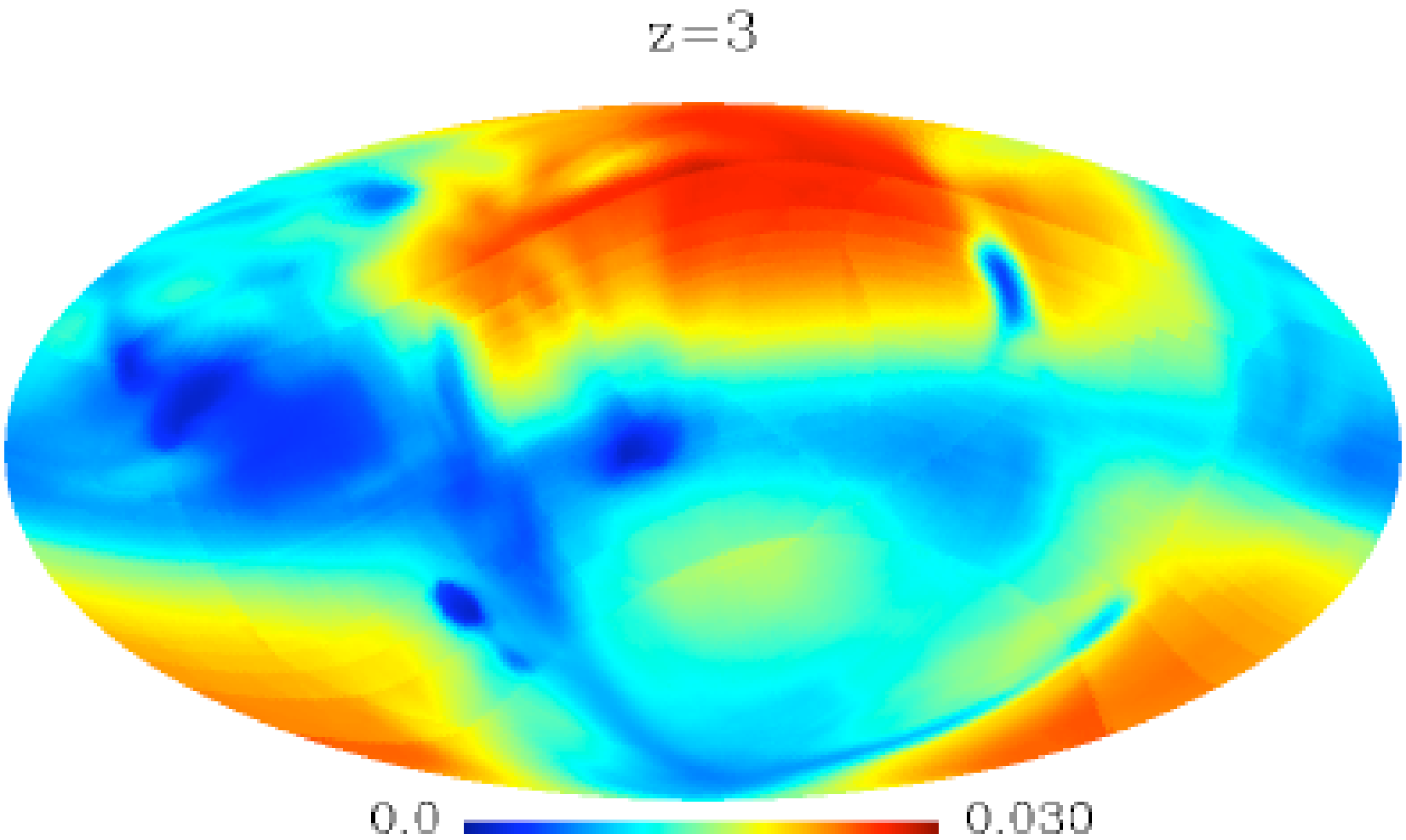
When gas masses are included, approx. agreement between total baryonic mass and dynamical mass



SDSS Ellipticals



Graves et al. 2007



Gnedin et al. 2007