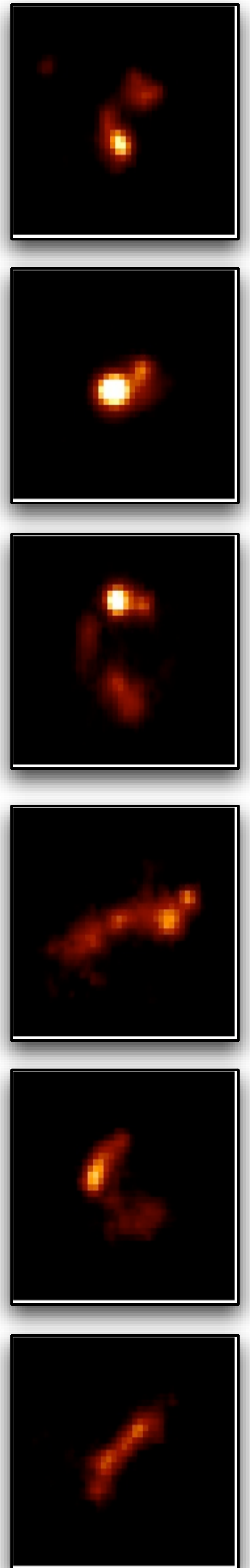


Gas Masses and Gas Fractions: Applications of the Kennicutt-Schmidt Law at High Redshift

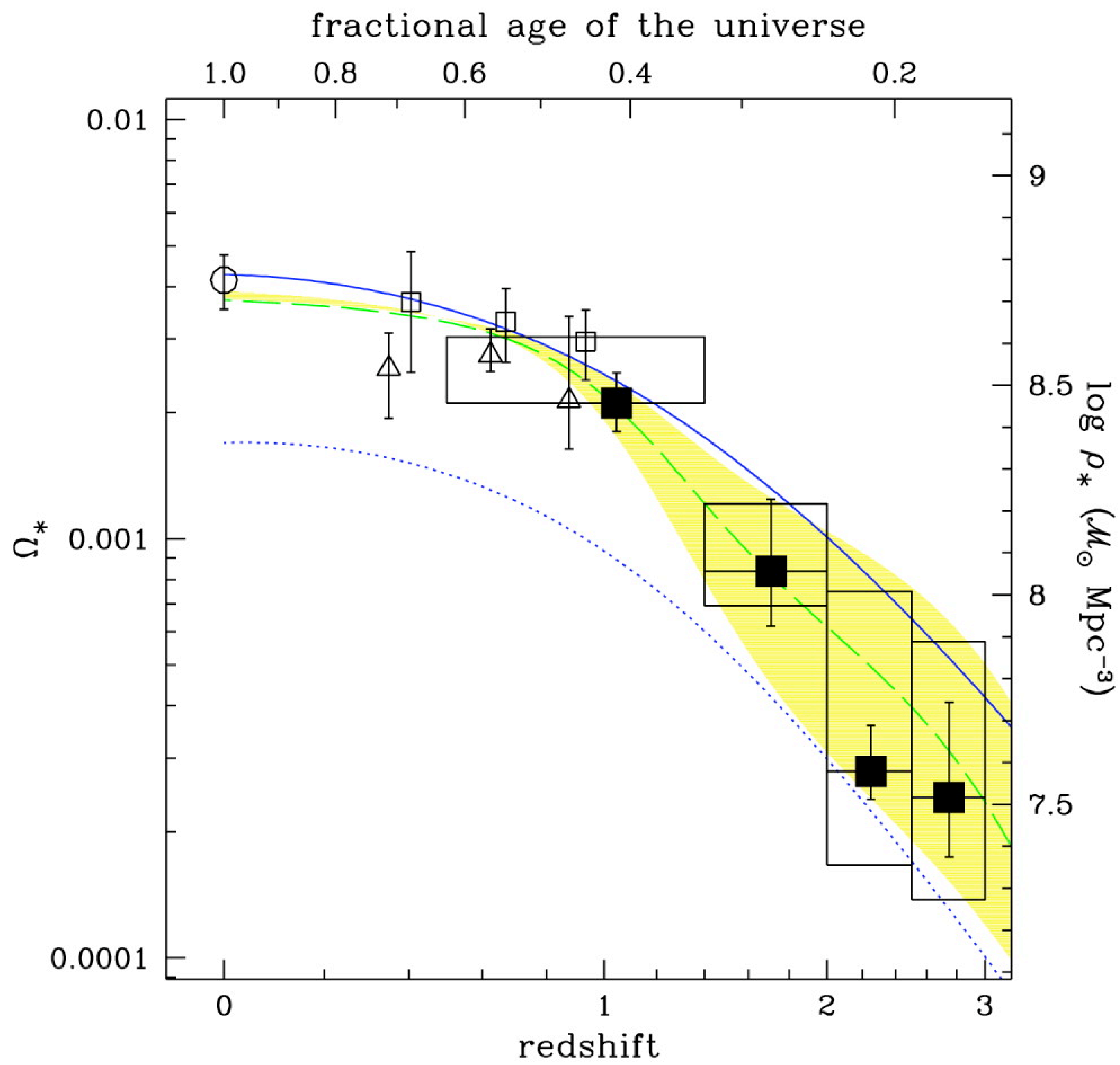
Dawn Erb (CfA)
Kennicutt-Schmidt Workshop, UCSD
December 19, 2006

Overview

- Properties of star-forming galaxies at z~2:
  - Star formation rates and surface densities
  - Stellar and dynamical masses
  - Metallicities
- All these better understood with knowledge of gas masses and gas fractions
  - Not yet directly measurable at high redshift
  - Use Kennicutt-Schmidt law to infer gas properties

The Epoch of Peak Star Formation

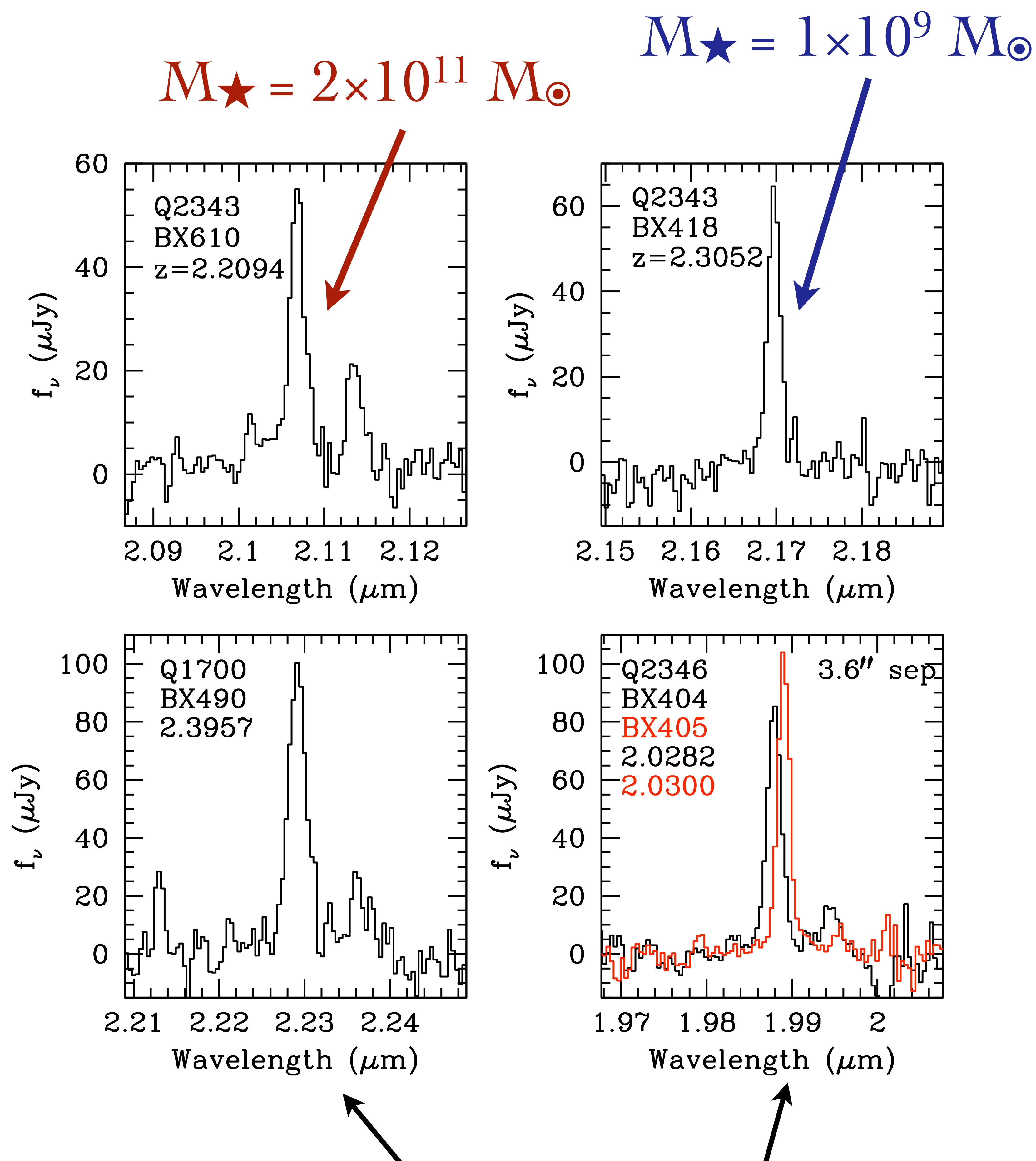
- Understanding star formation at z~2 critical to understanding the formation of today's galaxies
- 50-75% of today's stellar mass density formed by z~1, but only 3-14% by z~3 (Dickinson et al 2003, Rudnick et al 2003)
- Also peak AGN activity, transition from morphologically irregular galaxies to Hubble sequence



Dickinson et al 2003

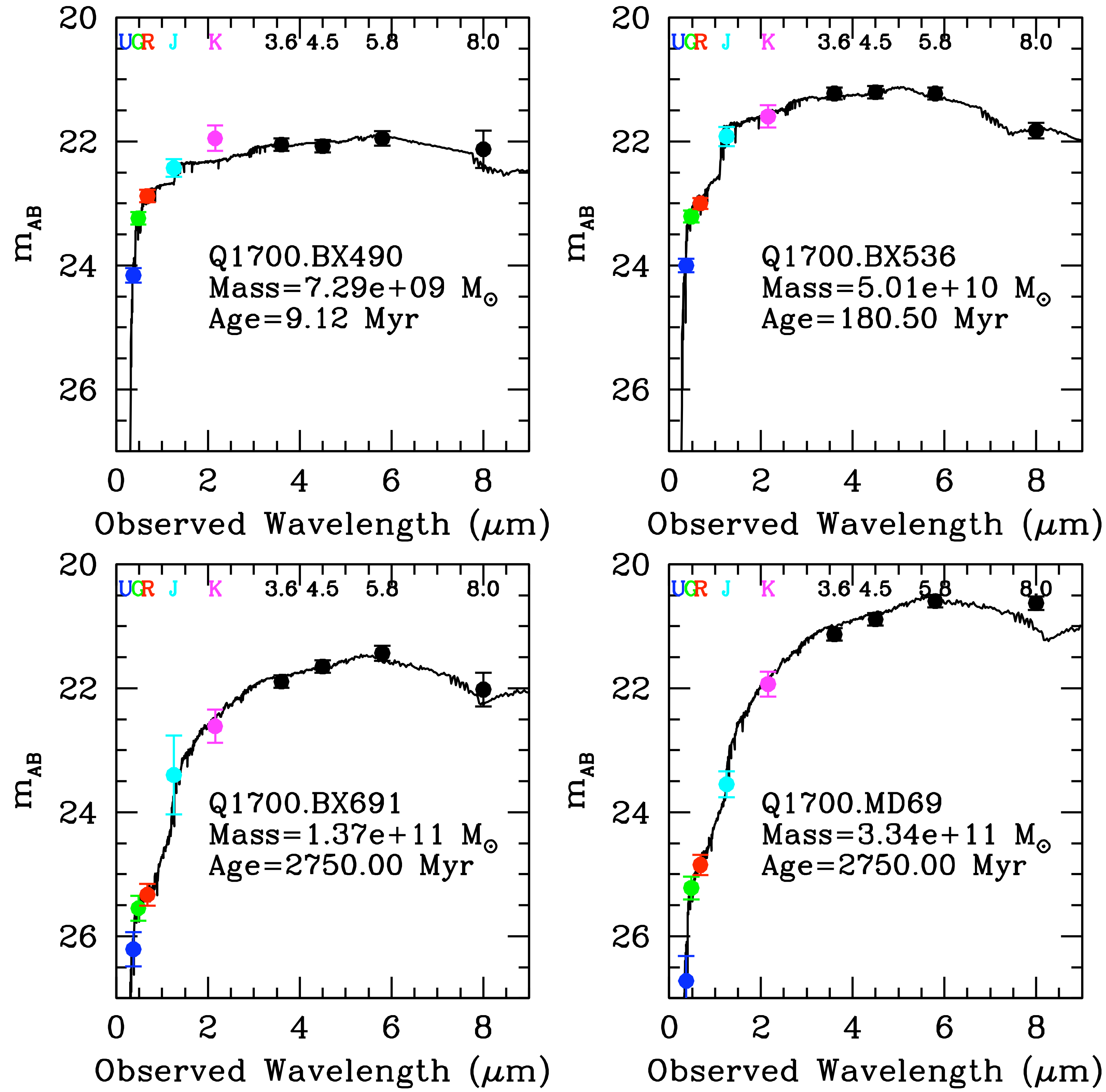
Observational Background I

- z~2 galaxies selected by rest-frame UV colors, redshifts confirmed with rest-frame UV spectra
- Hα spectroscopy of 114 galaxies — sample large enough for statistics
  - Star formation rates
  - Kinematics and dynamical masses
  - Approximate sizes from spatial extent
  - Metallicities from [NII]/Hα ratio



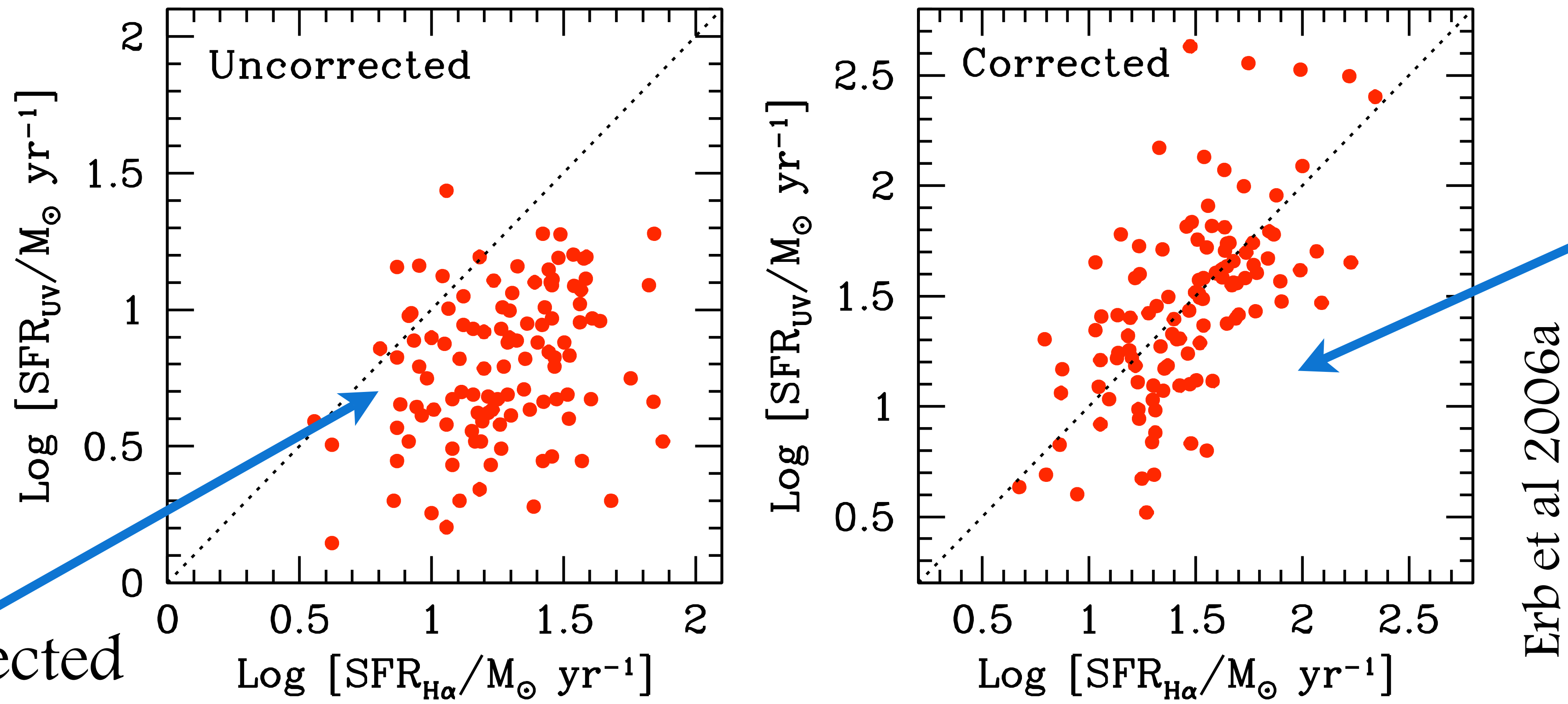
Observed in K-band
1-2 spectra at a time,
integrations ~1 hour

Observational Background II



- Fit model stellar populations to 0.3~8 μm photometry, using simple constant and exponentially declining star formation histories
- Determine stellar mass, age, reddening and star formation rate
- Stellar mass most robust parameter
- Similar results, smaller uncertainties when including Spitzer IRAC data

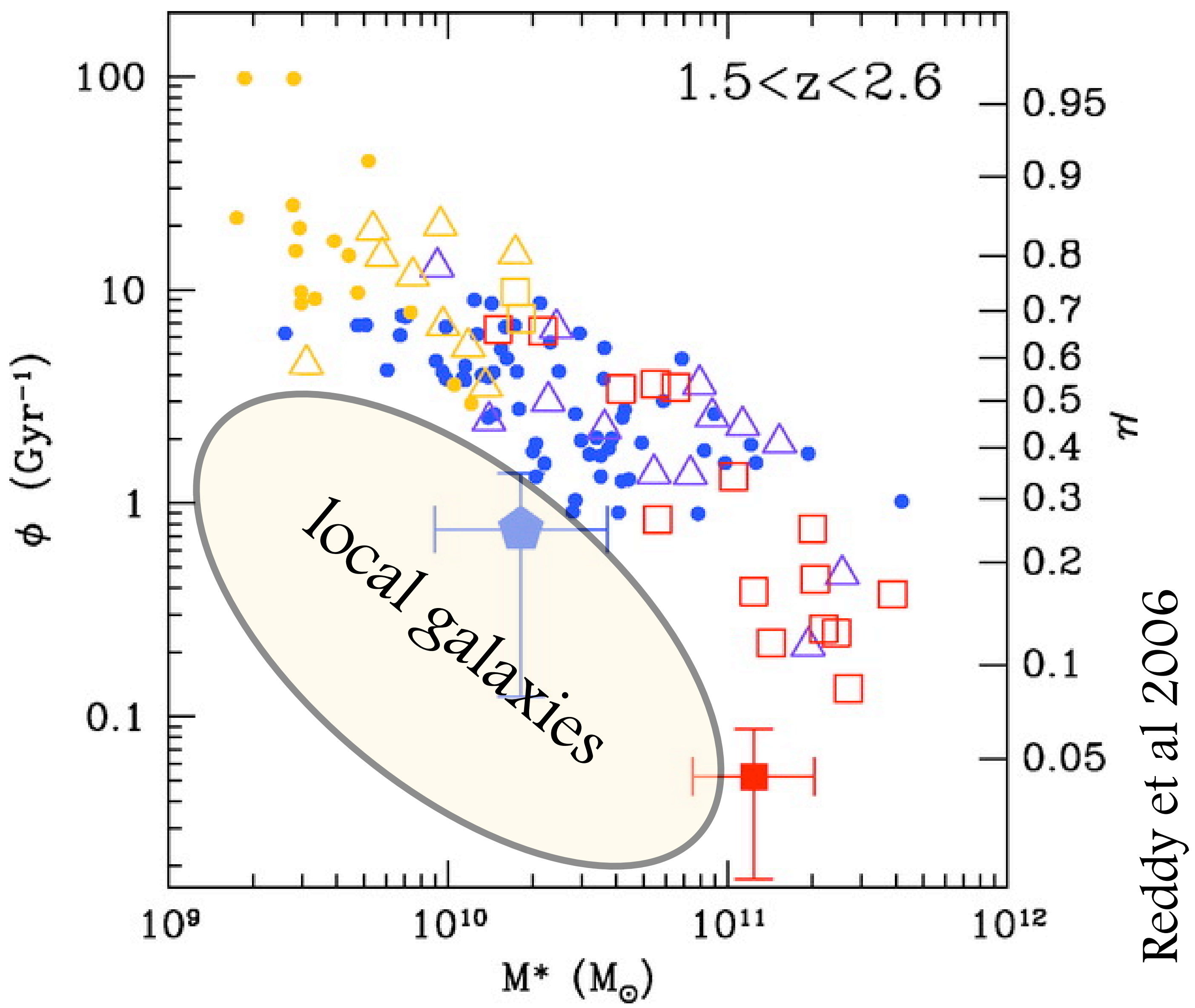
Star Formation at z~2



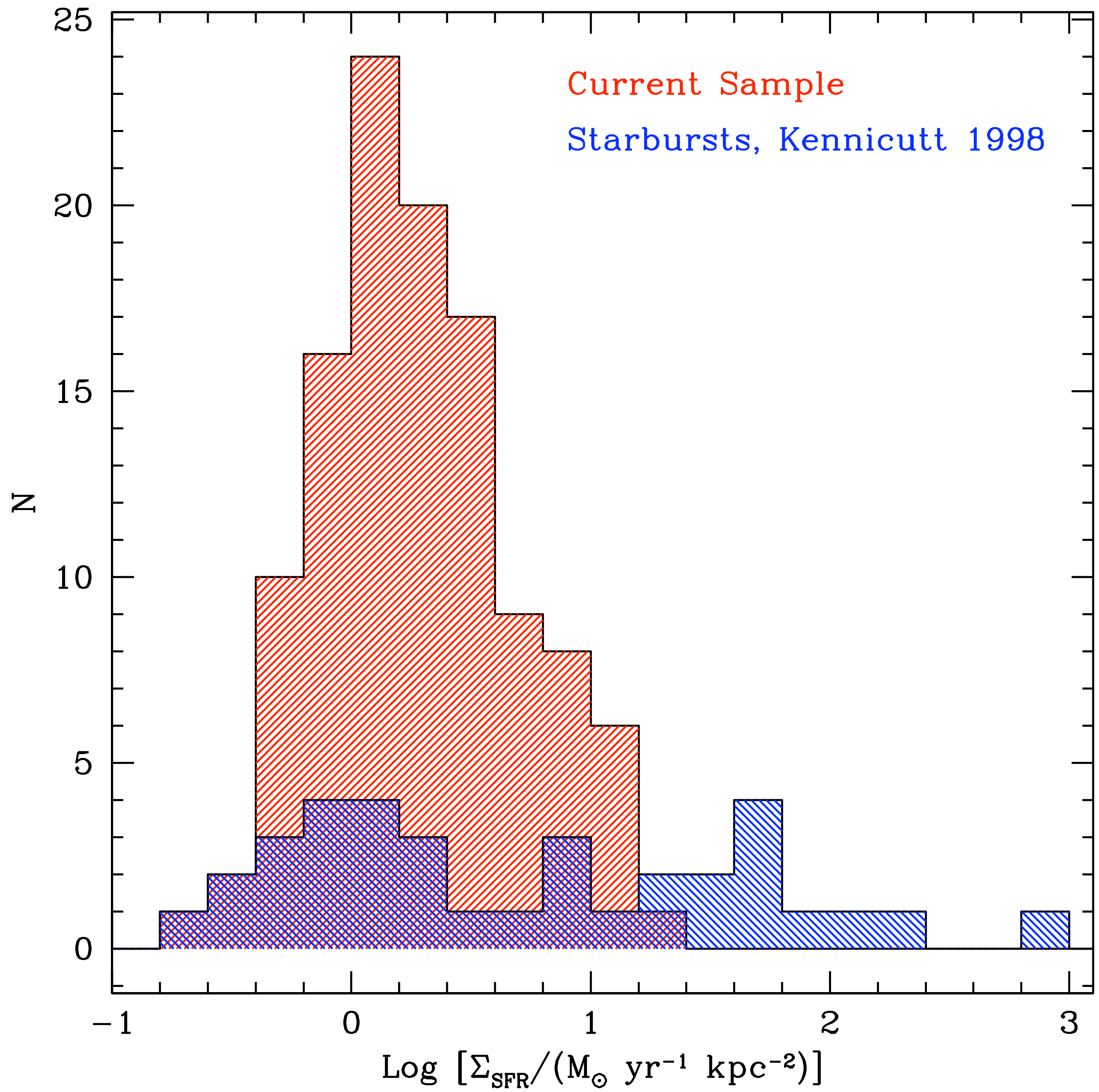
Extinction-corrected Hα vs. UV

Uncorrected Hα vs. UV

- Star formation rates from Hα, UV, mid-IR, X-ray and radio agree to factor of ~2
- Mean SFR ~30 $M_\odot\ yr^{-1}$, up to ~200 $M_\odot\ yr^{-1}$ (for Chabrier IMF)
- High specific star formation rates indicate active buildup of stellar mass, especially in lower mass galaxies



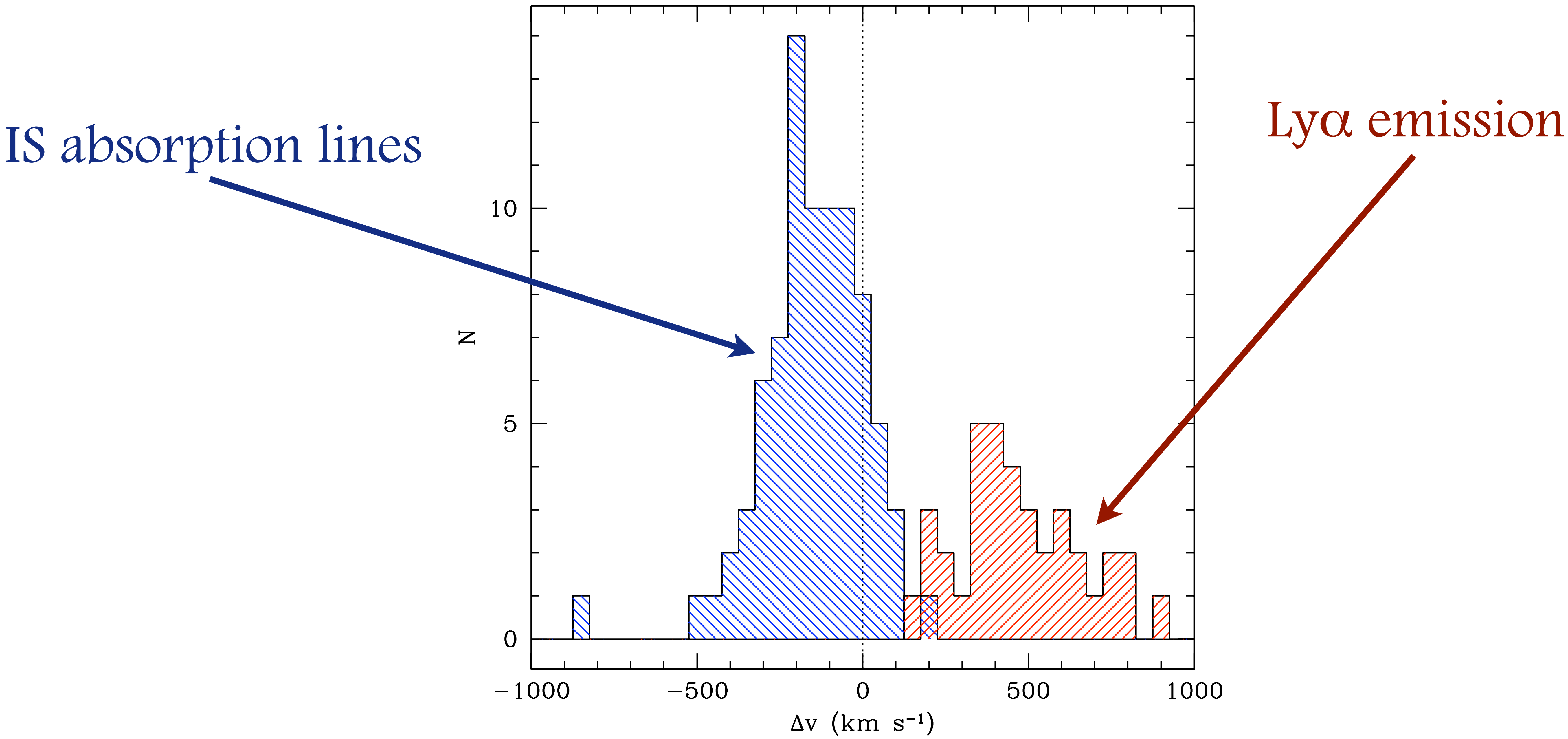
Star Formation Rate Surface Density



Erb et al 2006a

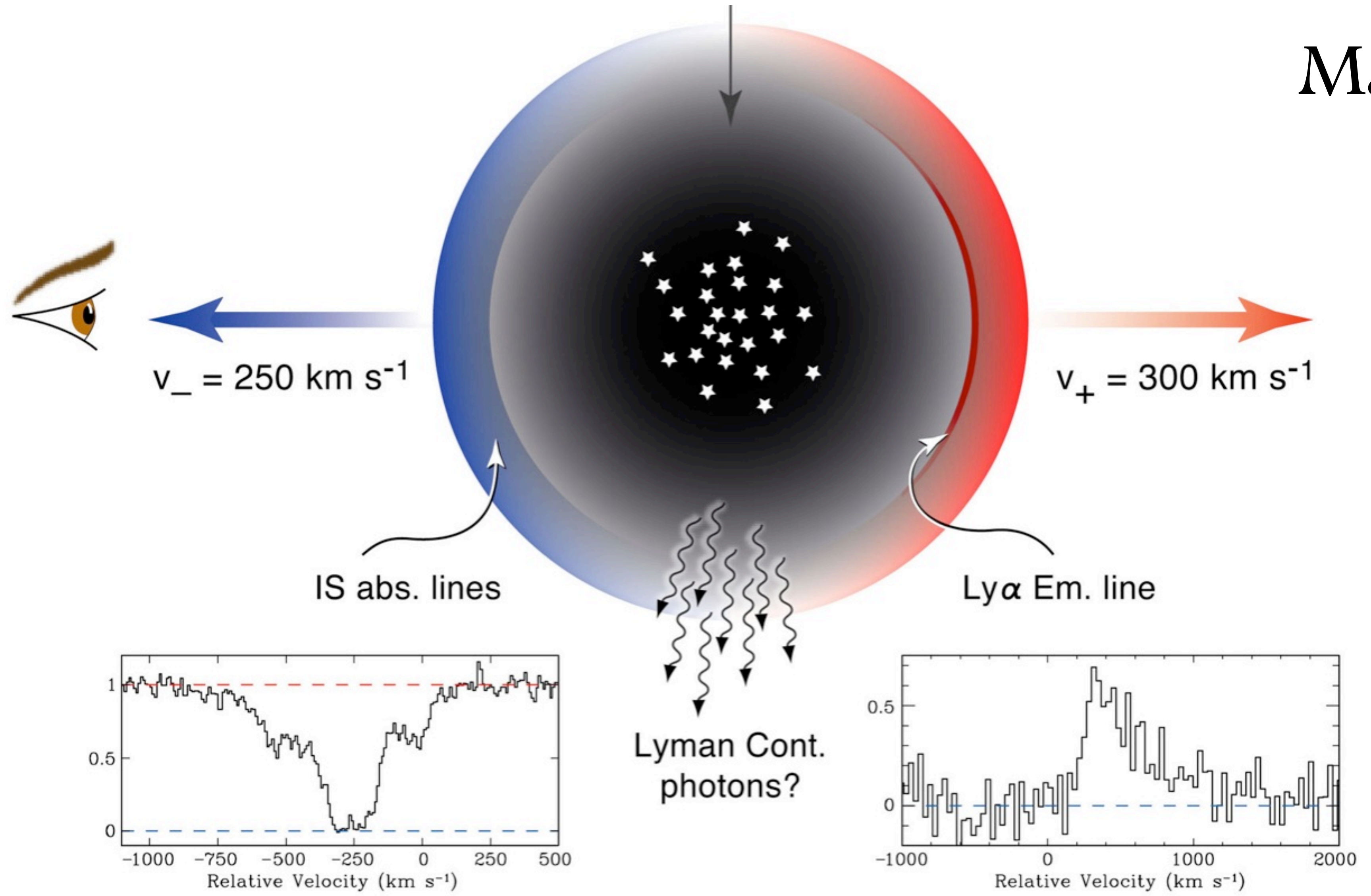
- Comparable to local starburst galaxies
- None at high end in z~2 sample because of inability to resolve star formation on small spatial scales
- All above threshold for outflows, $\Sigma_{SFR} > 0.1\ M_\odot\ yr^{-1}\ kpc^{-2}$

Star Formation Powered Galactic Outflows



- Offsets of several hundred km s^{-1} observed between nebular emission lines, interstellar absorption lines, and Lyα
- Explained by galactic-scale outflows
  - regulate star formation through feedback
  - deposit metals in IGM
    - correlation of galaxies, metal systems seen in absorption
    - local mass-metallicity relation
  - ubiquitous in galaxies with $\Sigma_{SFR} > 0.1\ M_{\odot}\ yr^{-1}\ kpc^{-2}$

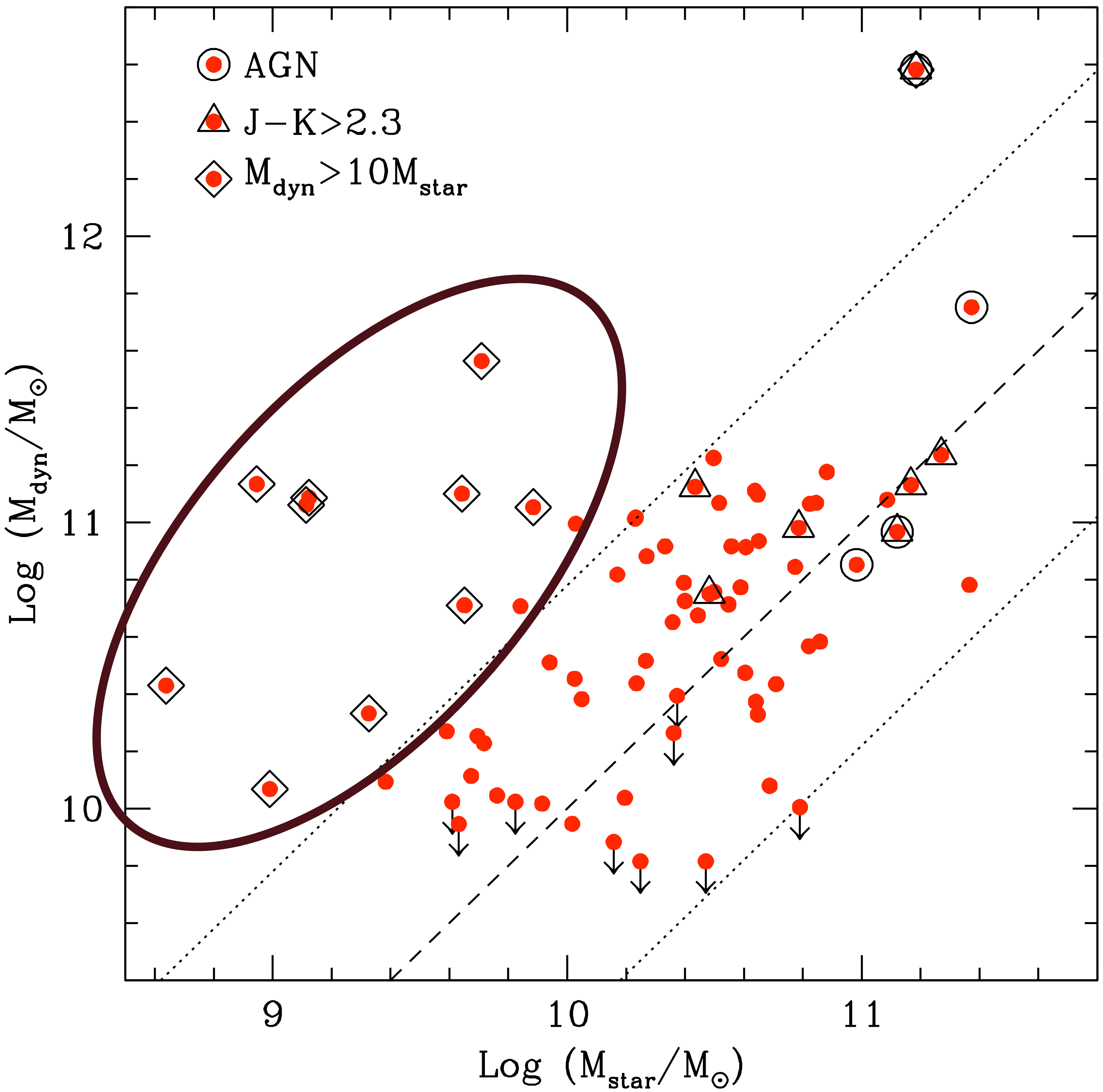
Star Formation Powered Galactic Outflows



Mass outflow rate ~ SFR or higher

- Offsets of several hundred km s^{-1} observed between nebular emission lines, interstellar absorption lines, and Lyα
- Explained by galactic-scale outflows
  - regulate star formation through feedback
  - deposit metals in IGM
    - correlation of galaxies, metal systems seen in absorption
    - local mass-metallicity relation
  - ubiquitous in galaxies with $\Sigma_{SFR} > 0.1\ M_\odot\ yr^{-1}\ kpc^{-2}$

Stellar and Dynamical Masses

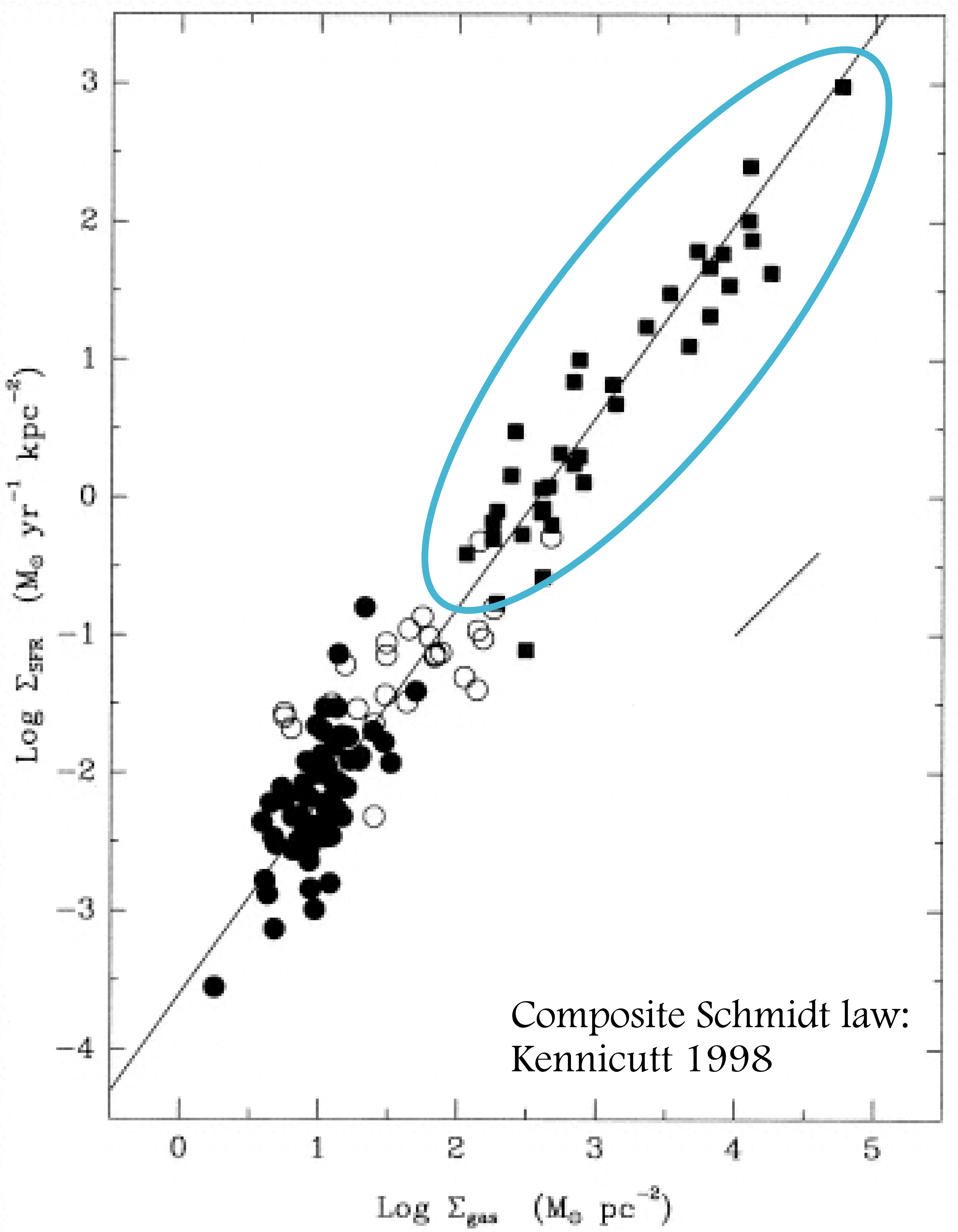


Erb et al 2006b

- Comparison of stellar masses from SED modeling with dynamical masses from width of Hα emission line
- Mean $M_{dyn} \sim 7\times10^{10}\ M_\odot$ (excluding AGN), ~2 times larger than mean stellar mass
- Most objects agree within uncertainties... but 10% of sample has $M_{dyn} \gg M_\star$
- These tend to have young ages, high Hα equivalent widths and high SFRs: Young galaxies with high gas fractions?

Need gas masses!

Applying the K~S Law at High Redshift



- Since gas masses can't yet be measured for most galaxies, estimate using K~S law

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}$$

- Use to estimate mass of cold gas associated with star formation

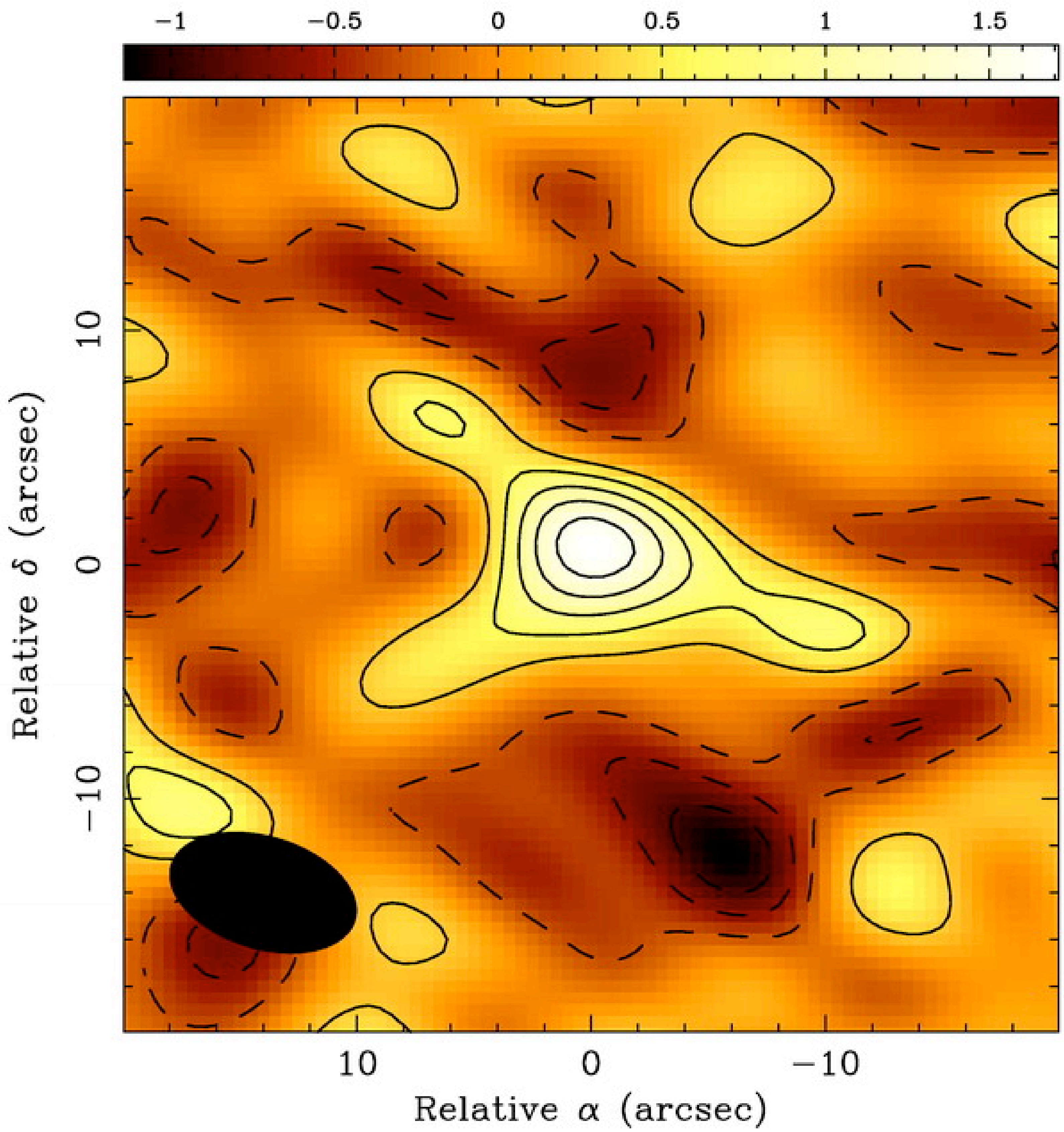
$$M_{\rm gas} \sim \Sigma_{\rm gas} r_{\rm H\alpha}^2$$

- And gas fraction

$$\mu = \frac{M_{\rm gas}}{(M_{\rm gas} + M_\star)}$$

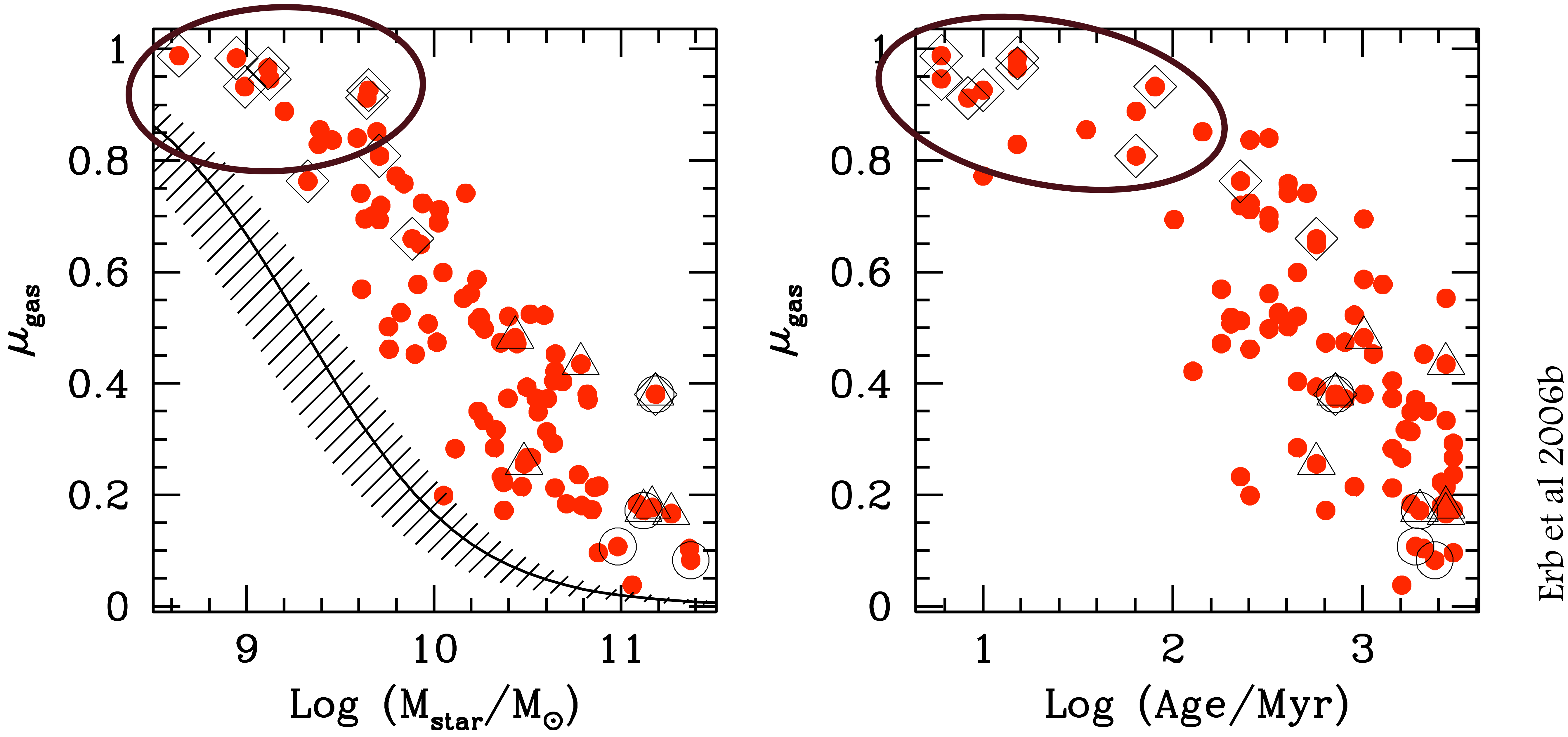
Testing the K-S Law at High Redshift

- Only one detection of molecular gas in a typical star-forming galaxy at high redshift
- MS1512-cB58, lensed LBG at z=2.7, consistent with local K-S law
- $\Sigma_{SFR} = 1.9 \pm 0.1\ M_\odot\ yr^{-1}\ kpc^{-2}$, in starburst regime
  - K-S law predicts $\Sigma_{SFR} = 1.6^{+2.3}_{-1.2}\ M_\odot\ yr^{-1}\ kpc^{-2}$ from measured gas surface density
- CO also detected in luminous submm galaxies



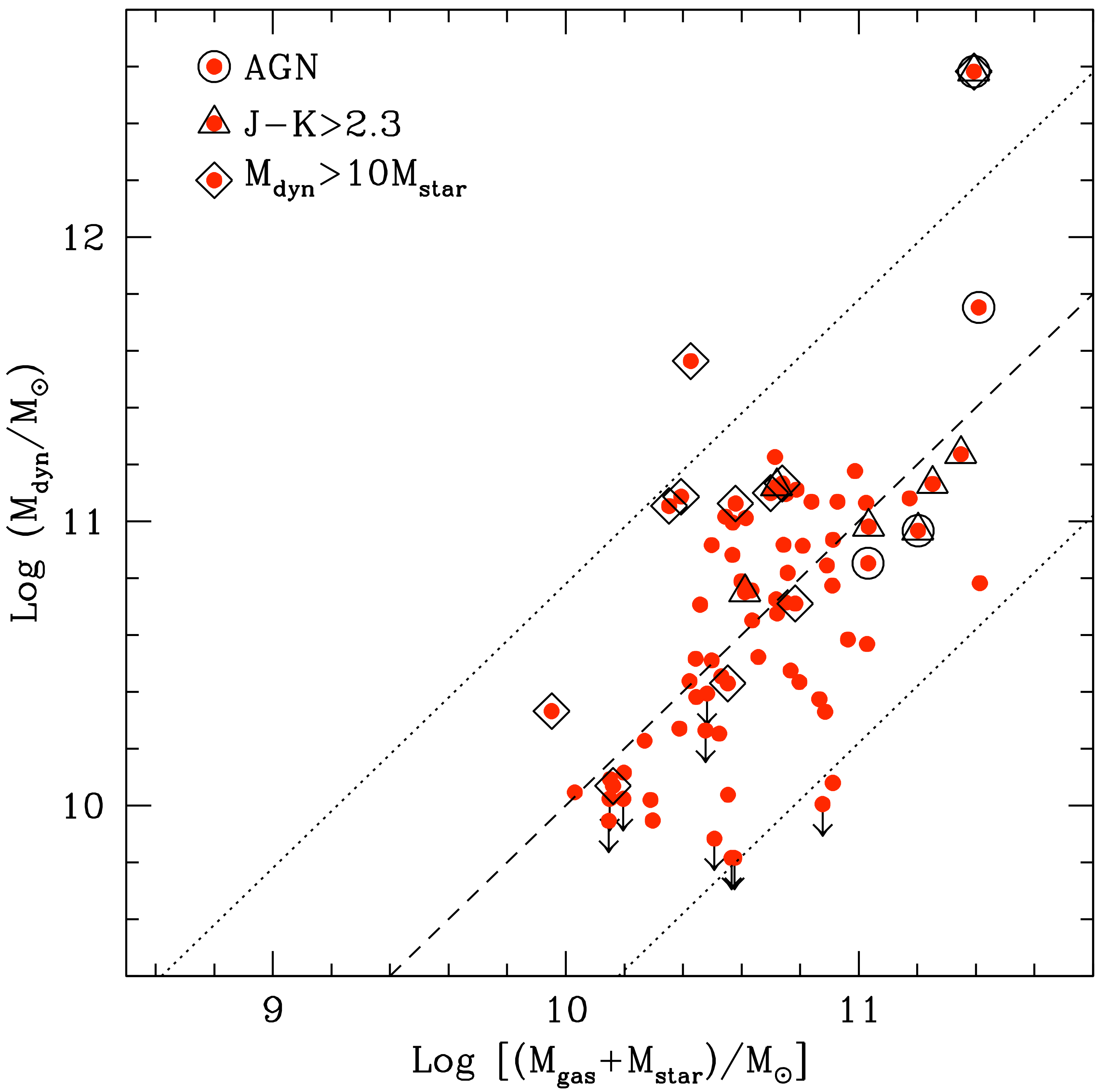
CO (3-2) emission in cB58, from Baker et al 2004

Estimated Gas Fractions



- Mean gas fraction ~50%
- Decreasing gas fraction with increasing stellar mass and age
- Objects with $M_{dyn} \gg M_{\star}$ have high gas fractions

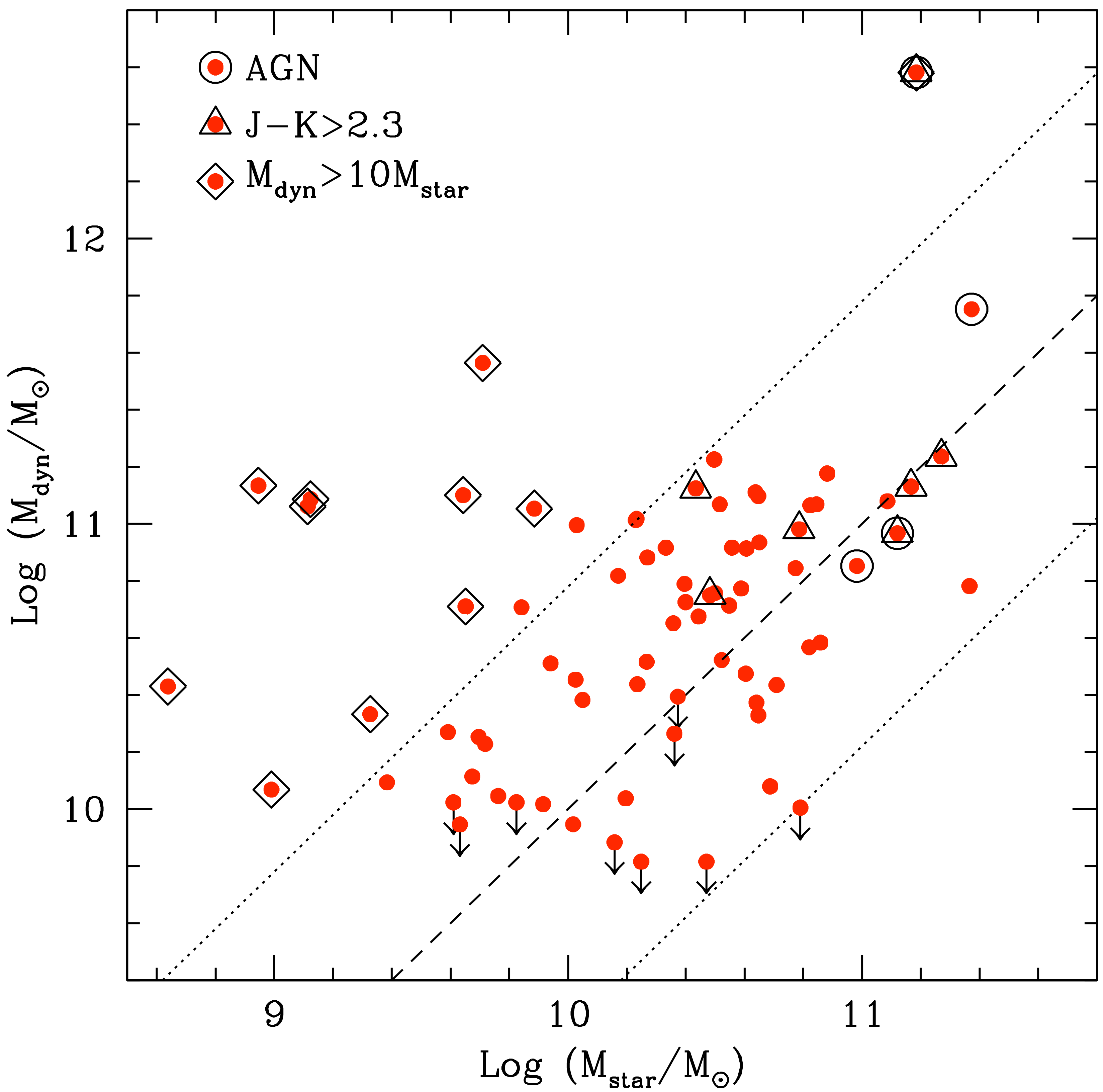
Gas, Stellar and Dynamical Masses



Erb et al 2006b

- Combined $M_{gas}+M_\star$ strongly correlated with M_{dyn}
- $M_{gas}+M_\star$ and M_{dyn} agree within a factor of 3 for 85% of sample

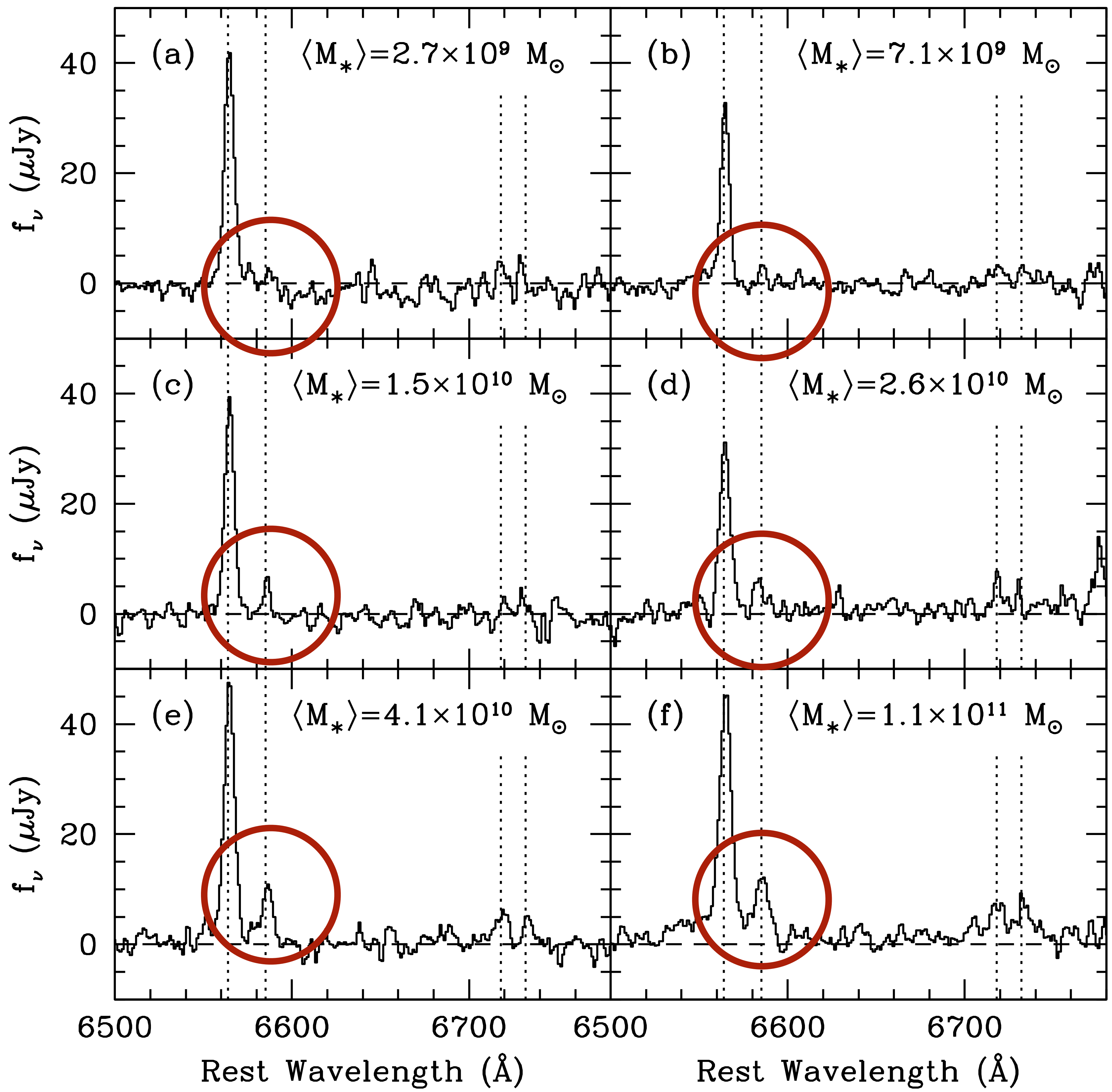
Gas, Stellar and Dynamical Masses



Erb et al 2006b

- Combined $M_{gas}+M_{\star}$ strongly correlated with M_{dyn}
- $M_{gas}+M_{\star}$ and M_{dyn} agree within a factor of 3 for 85% of sample

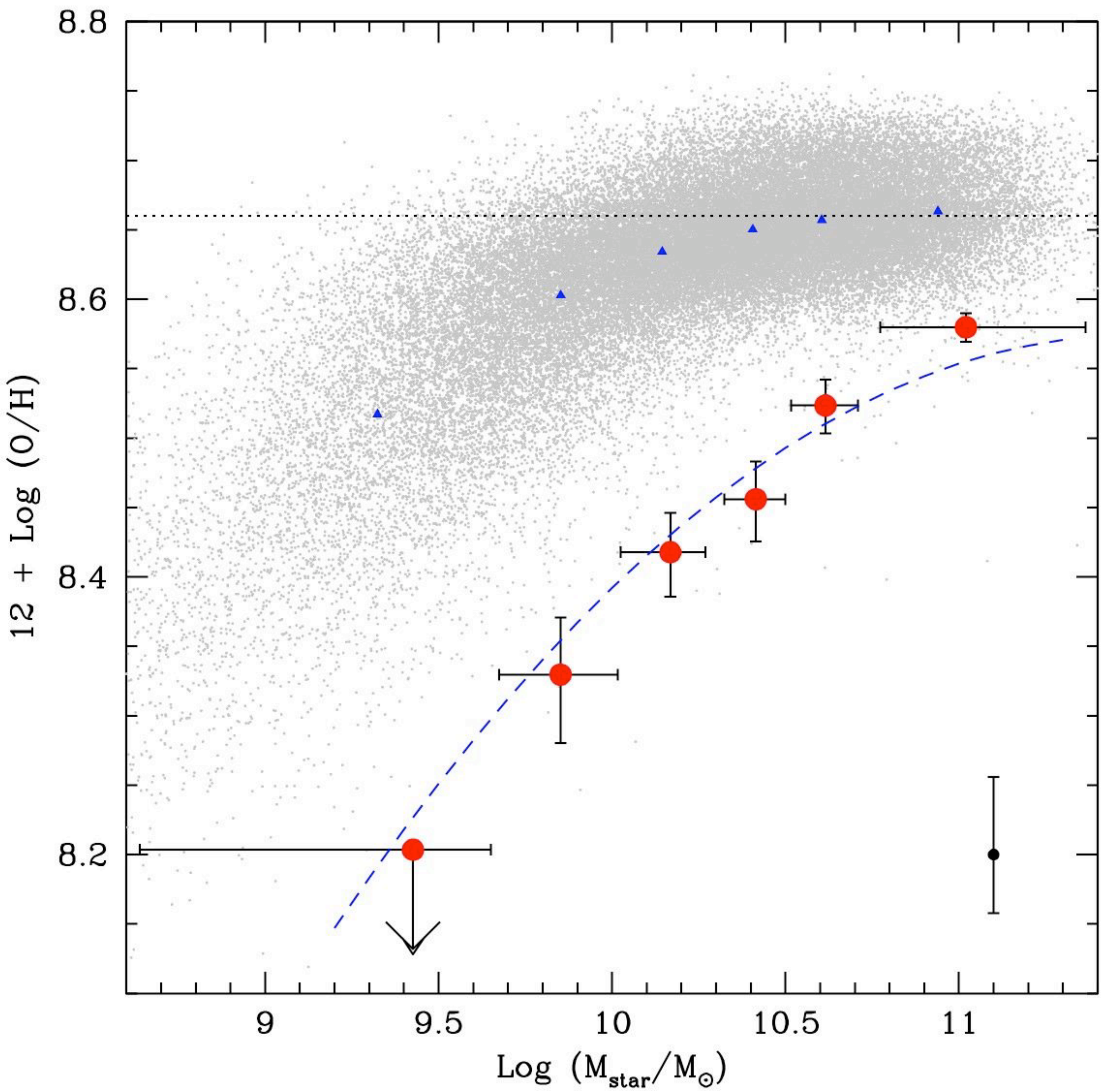
Metallicities from Hα, [NII] Spectra



Erb et al 2006c

- Measuring metallicities with [NII]/Hα ratio
- [NII] line is weak, detected in individual objects only at high metallicity
- Divide sample by stellar mass, construct composite spectra — 14 or 15 galaxies in each bin
- Measure [NII]/Hα ratio of each composite

The Mass-Metallicity Relation at z~2



Erb et al 2006c

- Monotonic increase in metallicity with stellar mass
- Very similar shape to local relation, but offset
- Metallicity ~0.3 dex lower at a given mass compared to local galaxies
- Different evolutionary samples

Origin of the Mass-Metallicity Relation

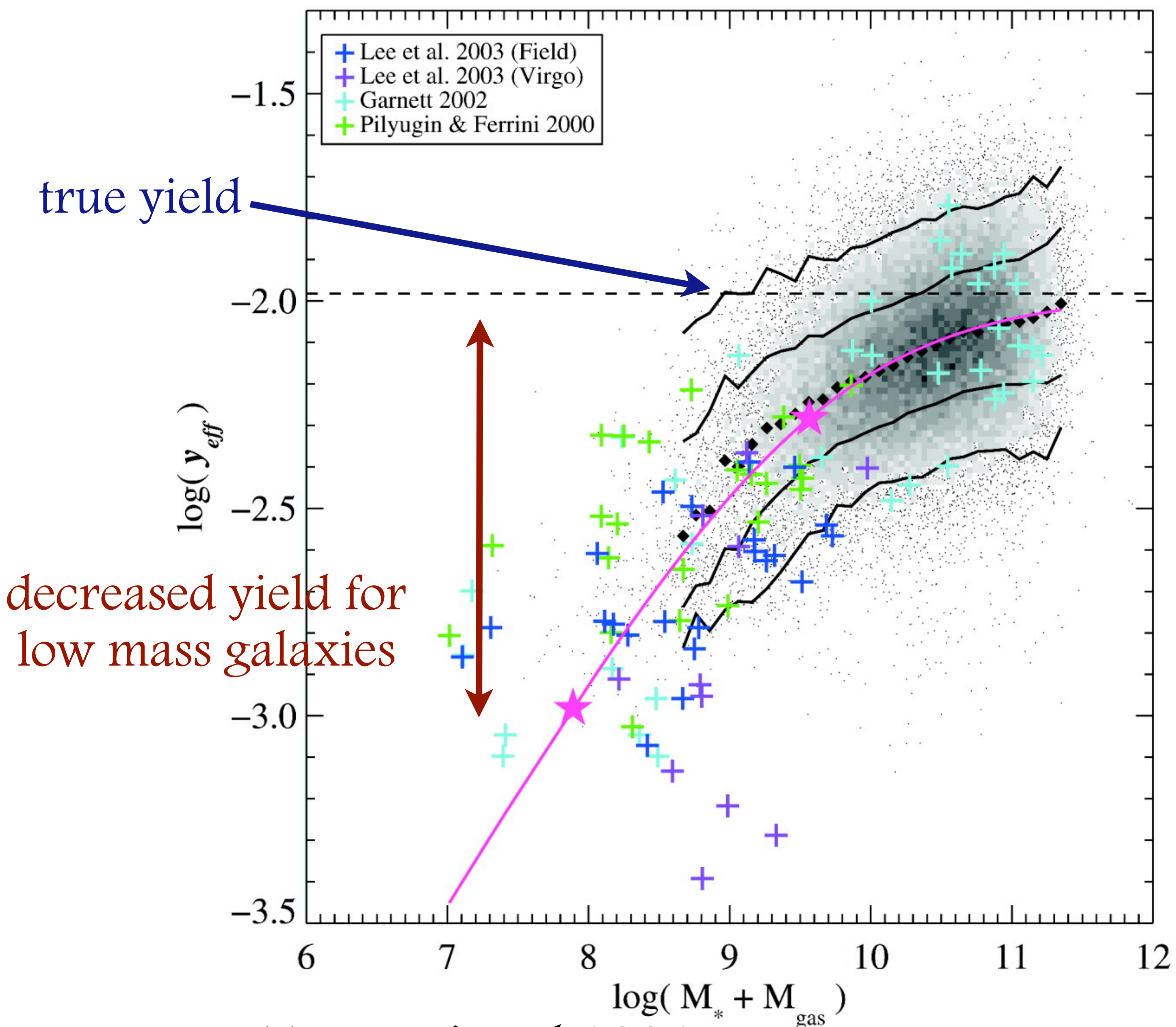
- Higher gas fractions in low stellar mass galaxies?
- Loss of metals from outflows in low mass systems?

Metallicity evolution in a closed box system:

Z = metallicity,
μ = gas fraction

$$Z = y \ln(1/\mu)$$

y = yield, ratio of mass of metals produced and ejected by stars to mass locked in long-lived stars and remnants



Tremonti et al 2004

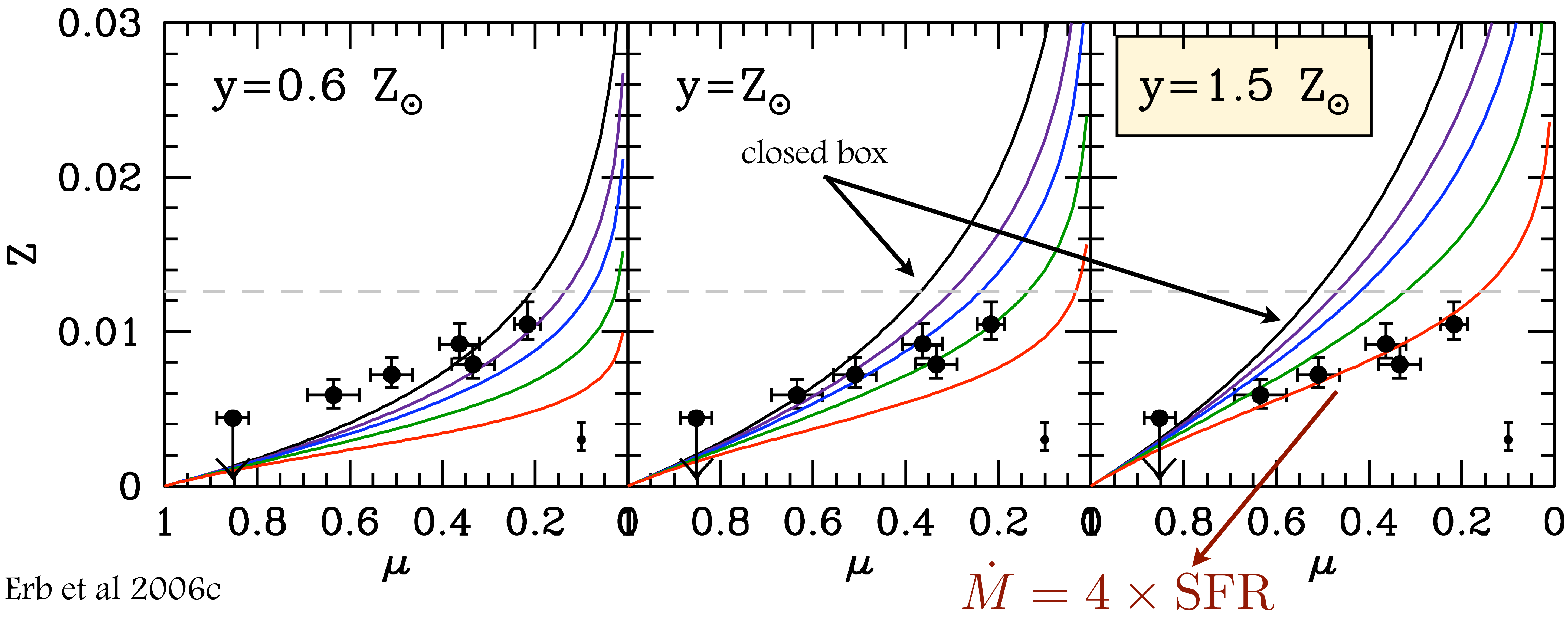
If metallicity and gas fraction observed:

$$y_{\rm eff} = Z/\ln(1/\mu)$$

Effective yield $y_{\rm eff}$ constant and equal to true yield y if closed box model applies

Decrease in $y_{\rm eff}$ indicates metal loss from outflows, or gas dilution via infall

Origin of the Mass-Metallicity Relation



Erb et al 2006c

- Modify closed box model for outflow rates $\dot{M} = f \times \mathrm{SFR}$
- Data best described by model with supersolar yield, outflow rate ~4 times SFR
- No evidence for differential mass loss across sample
- Mass-metallicity relation driven by decrease in gas fraction as gas converted to stars, modulated by strong outflows in galaxies of all masses

Summary

- Knowledge of gas masses and gas fractions significantly improves our understanding of z~2 galaxies
- Direct detection of molecular gas not yet possible for typical star-forming galaxies at high redshift, so use K-S law to infer gas masses
- Results:
  - Young galaxies with low stellar masses probably have high gas fractions
    - Stellar mass + gas mass ≈ dynamical mass
  - Gas fraction enables discrimination between models for origin of mass-metallicity relation
    - Best explained by decrease in gas fraction with star formation and strong outflows in galaxies of all masses
- Need direct measurements to test all this!
  - ALMA, Hα with adaptive optics