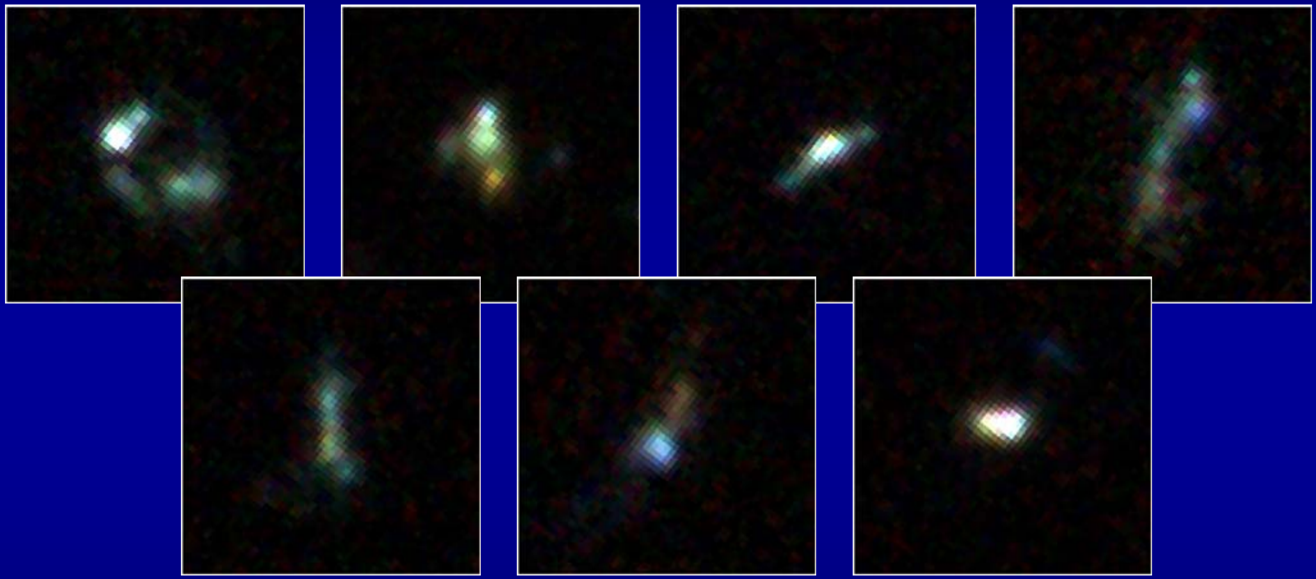
New Views of Galaxies at z~2-3



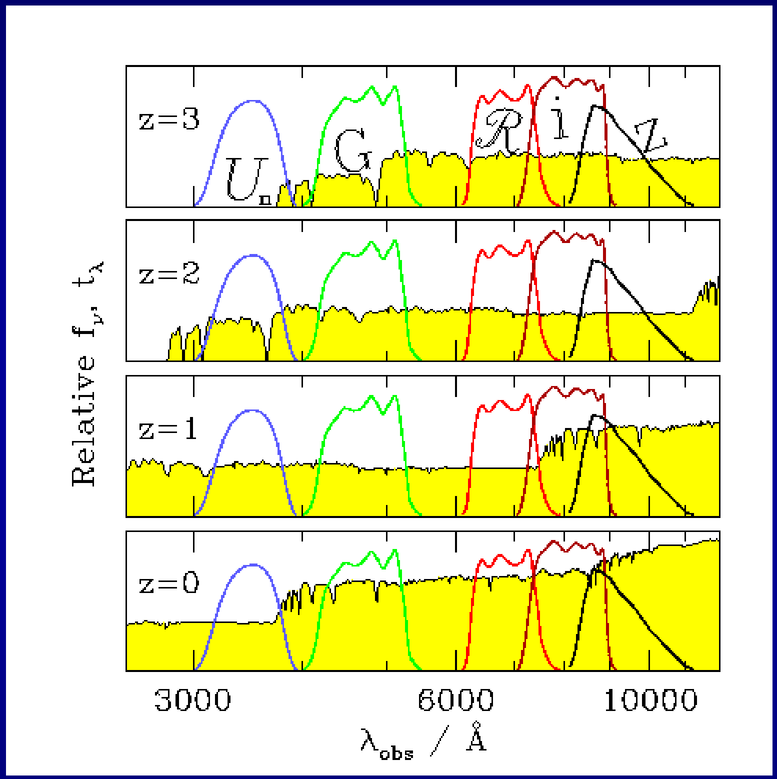
Alice Shapley (Princeton)

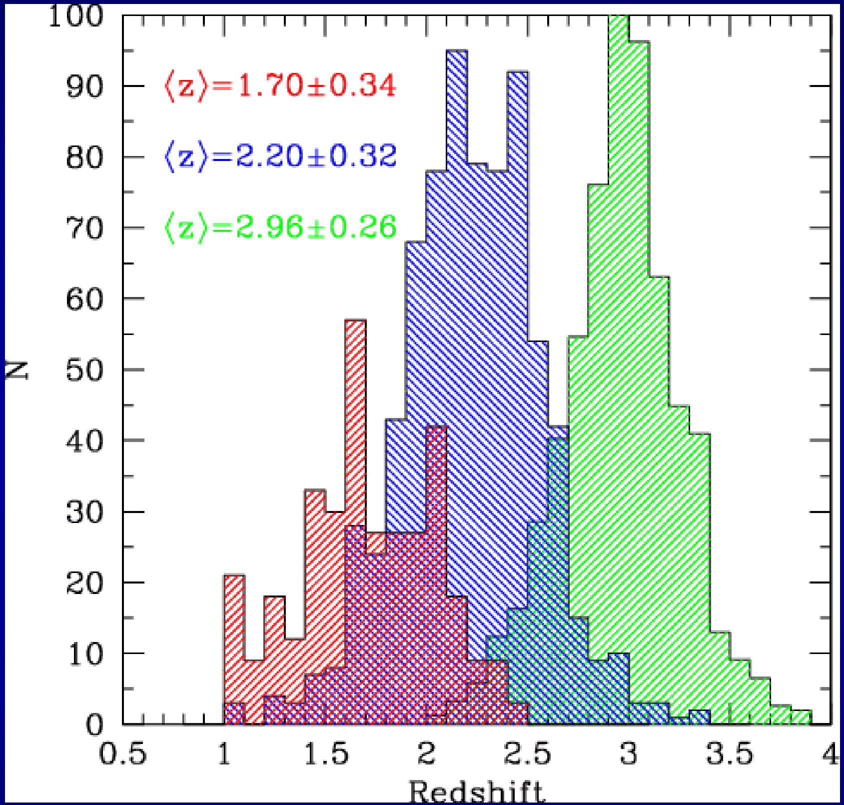
December 12th, 2005

Overview and Motivation

- Explosion of z~1.5-3.0 surveys (t_{lb}~9-11 Gyr)
- As opposed to traditional magnitude-limited surveys, down to specific flux limit, new results utilize several complementary selection techniques for finding high-z galaxies
- Review of different selection techniques
- Key questions addressed by current high-redshift samples
- New multi-wavelength observational results

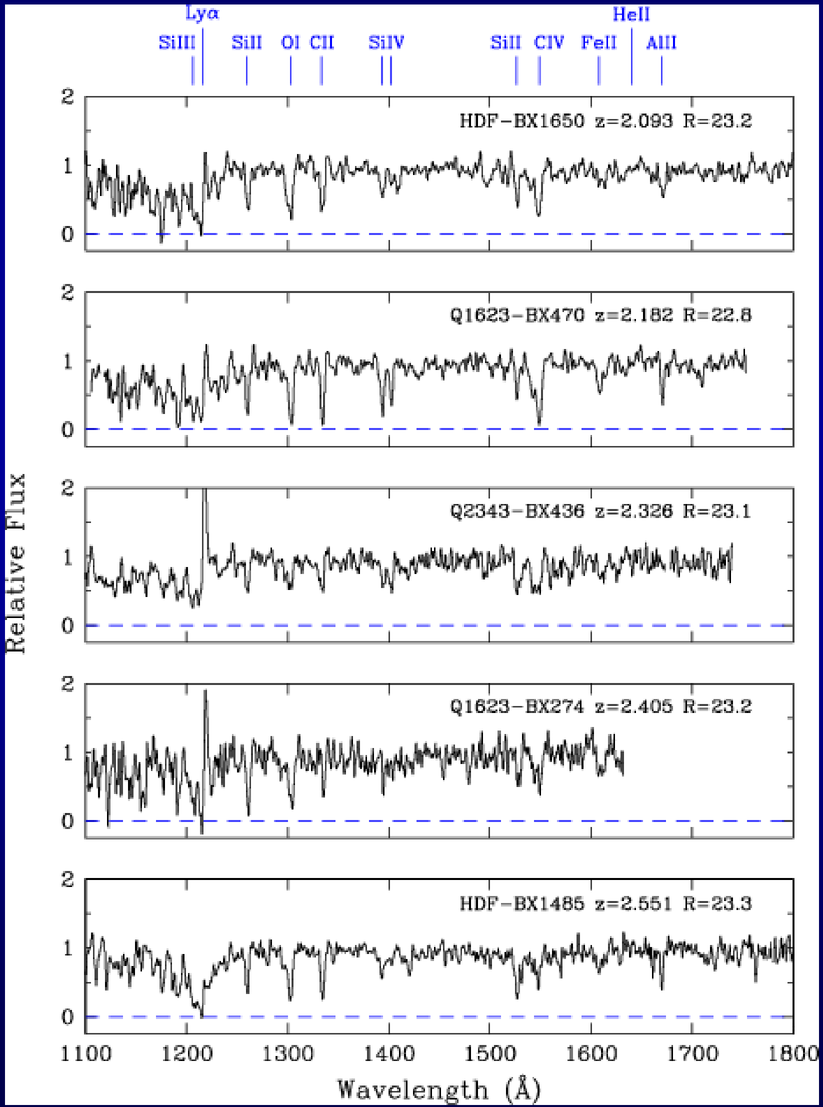
z>1.5 Rest-UV Color Selection





- z~3 UGR criteria (Lyman Break), adjusted for z~2 (Adelberger et al. 2004)
- Spectroscopic follow-up with optimized UV-sensitive setup (Keck I/LRIS-B)
- ~1000 galaxies at z~3, >750 galaxies with spectroscopic redshifts at z=1.4-2.5, in what was previously called the Redshift Desert

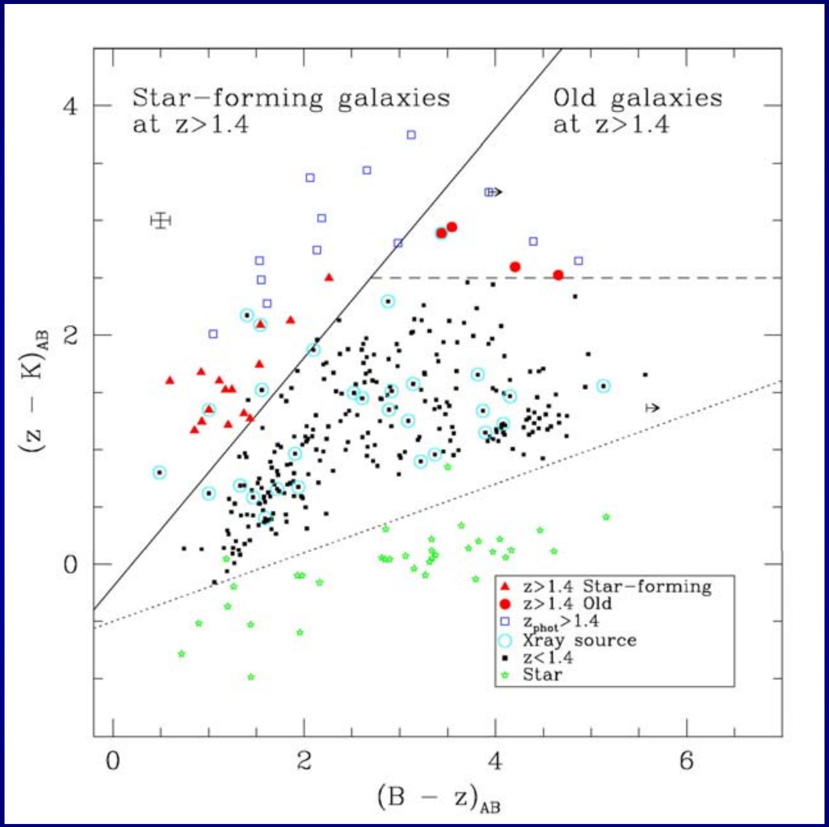
Measuring Redshifts: z~2



- Low- and high-ionization outflow lines
- He II emission, CIII] emission
- Fewer galaxies have Lyα emission (57% have no Lyα) than in z~3 sample (cf. SMG!)

(Steidel et al. 2004)

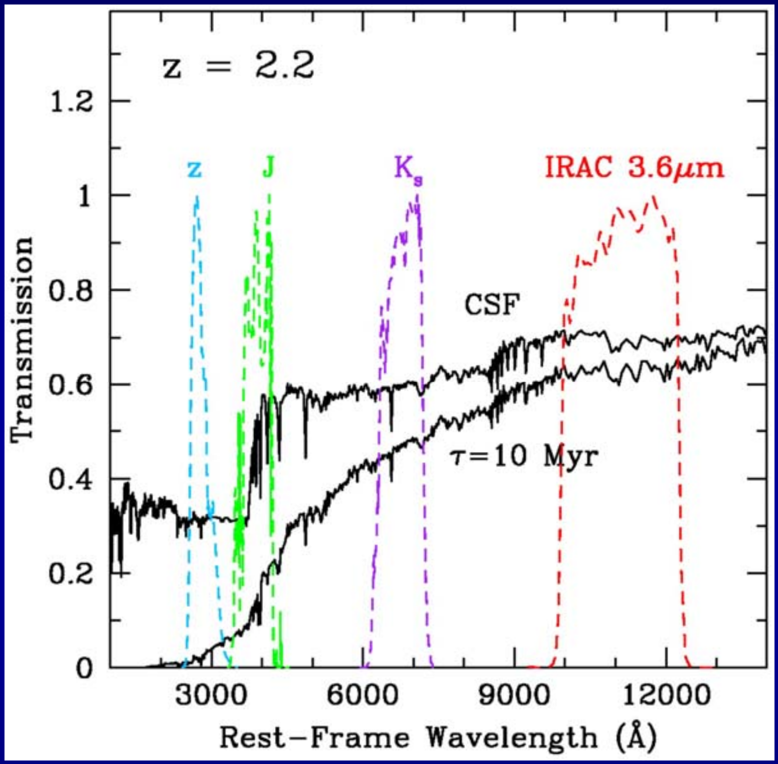
z>1.5 Near-IR selection (~40 zs)



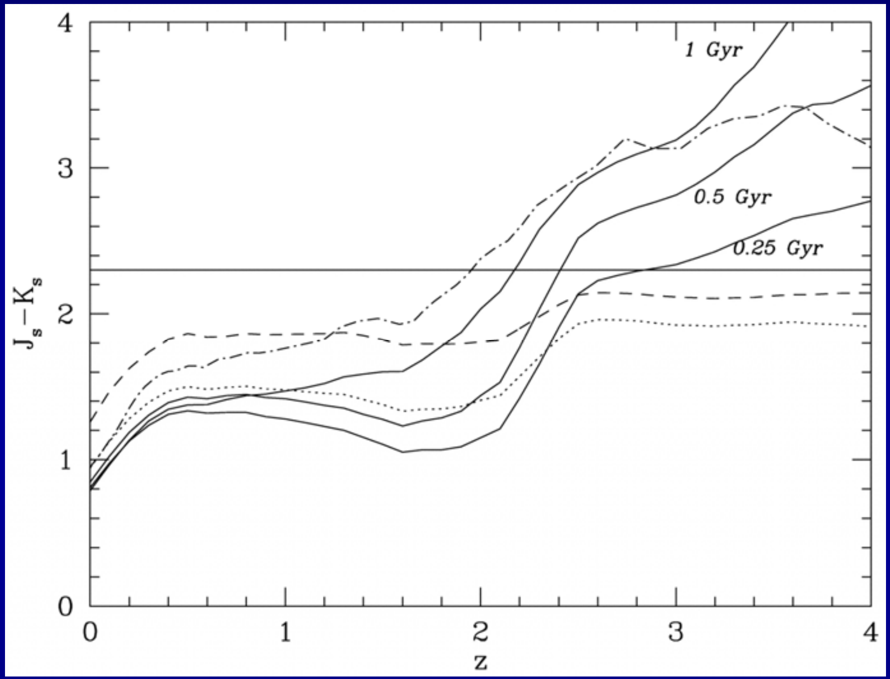
(Daddi et al. 2004)

- Extension of K20 survey group (i.e., get z's for everything with K<20), use B-z, z-K color criteria to select both star-forming galaxies and passive galaxies at z>1.4
- Incomplete for fainter objects with small Balmer Breaks, weighted more towards fairly massive objects
- Significant overlap of BzK/SF with UV-selected samples

z>1.5 FIRES/J-K selection (~20 zs)



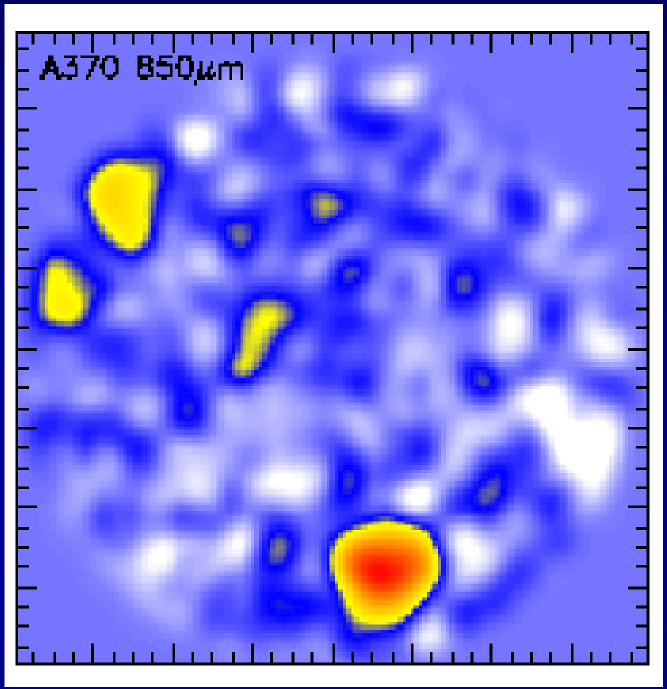
(Reddy et al. 2005)



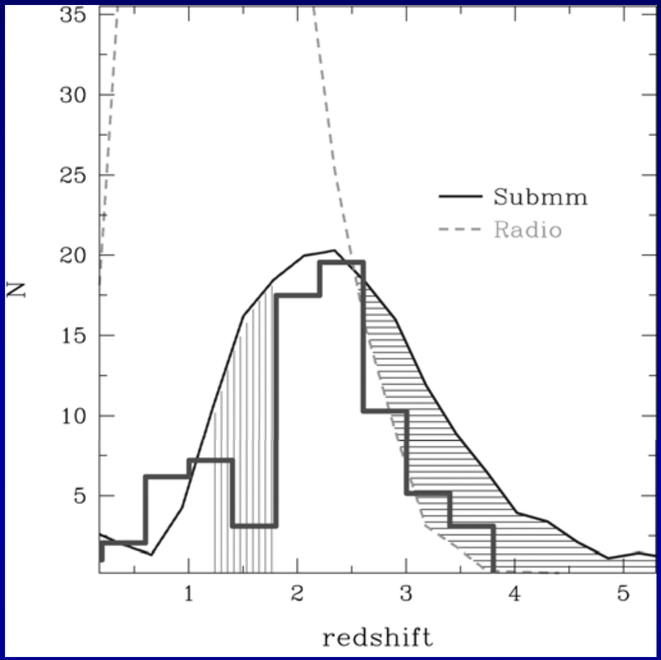
(Franx et al. 2003)

- **J-K>2.3 criteria meant to select evolved galaxies with significant Balmer/4000 Å breaks at z>2; turns out selection also yields dusty starbursts**
- **~25% appear to contain AGN (much higher than fraction of UV-selected population)**

z>1.5 Submm Selection (~75 zs)



(courtesy I. Smail)



(Chapman et al. 2005)

- Dusty galaxies with huge sfrs inferred from the submm flux (assuming T_d, and ~30% AGN contribution)
- Much rarer than other samples, but higher inferred sfr's, could contribute significantly to sfr density at high z
- Breakthrough: using radio positions for optical spectroscopy

z>1.5 Summary

• **In addition to UV-selected, BzK, J-K, submm, there are other techniques, such as the K-band/photo-z technique of the Gemini Deep Deep Survey (GDDS), and new *Spitzer* capabilities: IRAC (mass-selected), MIPS/24 micron (sfr-selected, analogous to SCUBA)**

• **Now that there are several groups using different selection techniques to find galaxies at z~2, we need to understand how the samples relate to each other (each sample has certain benefits but is incomplete; e.g., UV-selected sample has largest set of redshifts and spectra)**

• **Reddy et al. (2005) considered the overlap among different samples, and contribution of each to the sfr density at z~2-2.5**

Key Questions

- What is the evolution in global sfr and stellar mass density vs. z?
- What is the evolution in number density of galaxies as a function of (stellar) mass and star-formation rate?
- What are the star-formation histories of galaxies (burst/episodic, continuous), and how do they accumulate their stellar mass?
- What are the origins of different morphological types?
- What is the chemical enrichment in galaxies vs. z, and by how much do they enrich their surroundings (vs. mass)?
- What is the effect of supernovae/AGN feedback on gas in galaxies and the surrounding IGM?
- How do we make a continuous timeline of galaxies from high redshift to z~0 (map one sample to another)?

Key Techniques

- New multi-wavelength technologies are helping us address these questions, beyond ground-based optical imaging and spectroscopy
- Wide-field near-IR imaging (stellar masses) and near-IR spectroscopy (dynamical masses, sfr, chemical abundances)
- Chandra X-ray observations (sfr and AGN)
- Spitzer/IRAC (stellar masses) and MIPS (dust luminosity, sfr)
- HST ACS/NICMOS (morphologies)
- Full understanding of energetics and stellar and metal content is a multi-wavelength endeavor
- Detailed comparison with numerical simulations and semi-analytic models

Evolution of Galaxy Metallicities

Evolution of Galaxy Metallicities

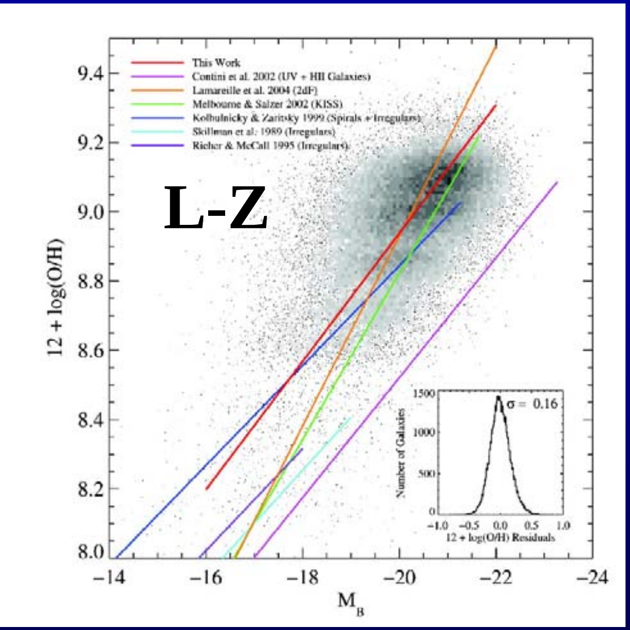
- Gas phase oxygen abundance in star-forming galaxies
- Fundamental metric of galaxy formation process, reflects gas reprocessed by stars, metals returned to the ISM by SNe explosions (HII regions in sf-galaxies, stars in early-type).
- Galaxies display universal correlations between Luminosity (L), Stellar mass (M), and metallicity (Z)
- Departures from closed-box expectations can reveal evidence for outflow/inflow
- Closed box:

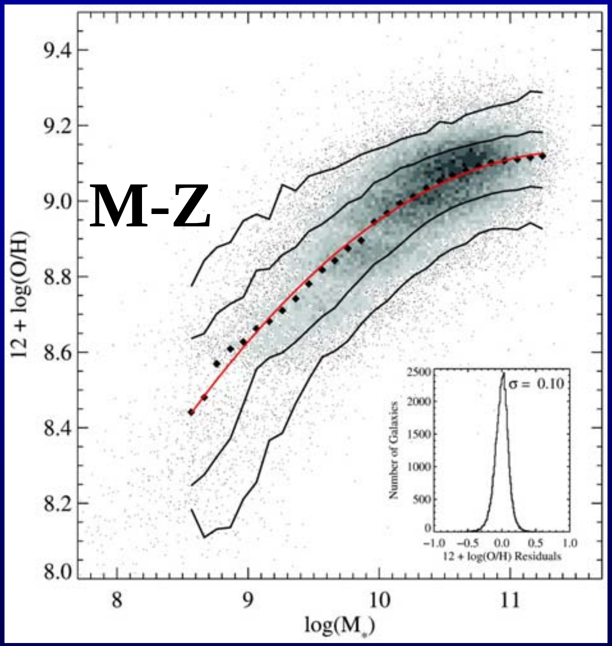
$$Z = y \times \ln(1/\mu)$$

(Z=metallicity, y=yield, μ=gas fraction=$M_{gas}/(M_{gas}+M_{*})$)

Evolution of Galaxy Metallicities

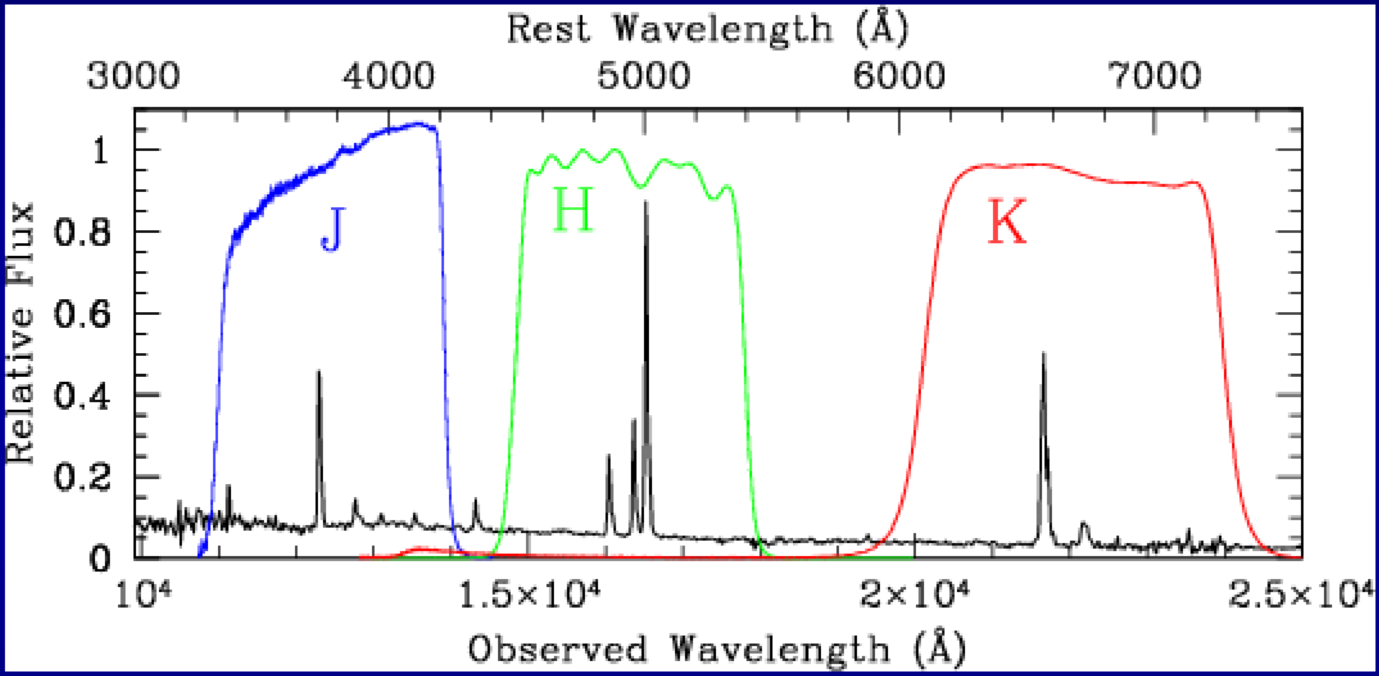
- 10,000s of galaxies in the local universe with O/H; SDSS is state of the art in L-Z and more fundamental M-Z, reveals evidence for increased importance of outflows in lower-mass galaxies
- Now the challenge is to obtain these measurements at high redshift (evolution will give clues, compare metal census with inferred metal density from integrating the global star-formation history)





(Tremonti et al. 2004)

Near-IR spectroscopy of z~2 gals

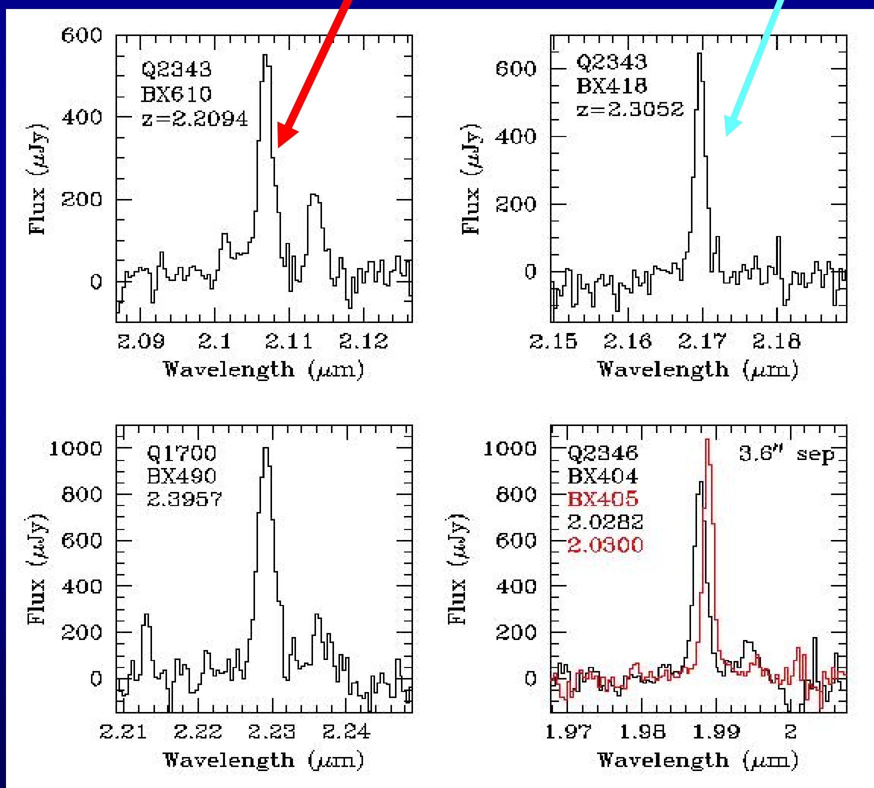


- z~2 ideal for measuring several neb lines in JHK
- evidence of M-Z relation at z~2, intriguing information about HII region physics

Near-IR spectroscopy of z~2 gals

$M^*=4\times10^{11}\ M_\odot$
K=19.3, J-K=2.3

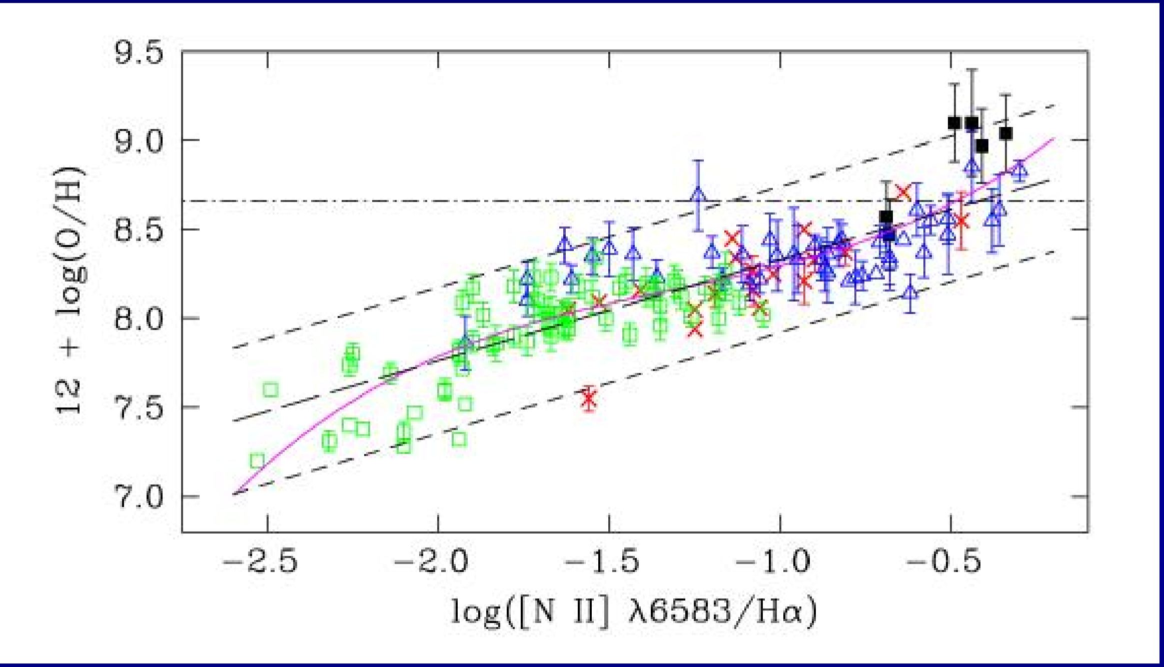
$M^*=5\times10^{9}\ M_\odot$



Hα spectra of 101 z~2 gals KeckII/NIRSPEC

- **Kinematics:** linewidths, M_{dyn}, some spatially-resolved, tilted lines, compare with stellar masses
- **Line ratios:** HII region metallicities, physical conditions
- **Hα fluxes:** SFRs, compare with UV, models
- **Offsets** between nebular, UV abs and Lyα em redshifts -> outflows

[NII]/Hα ratios: z~2 metallicities



N2=log([NII] 6584/Hα)

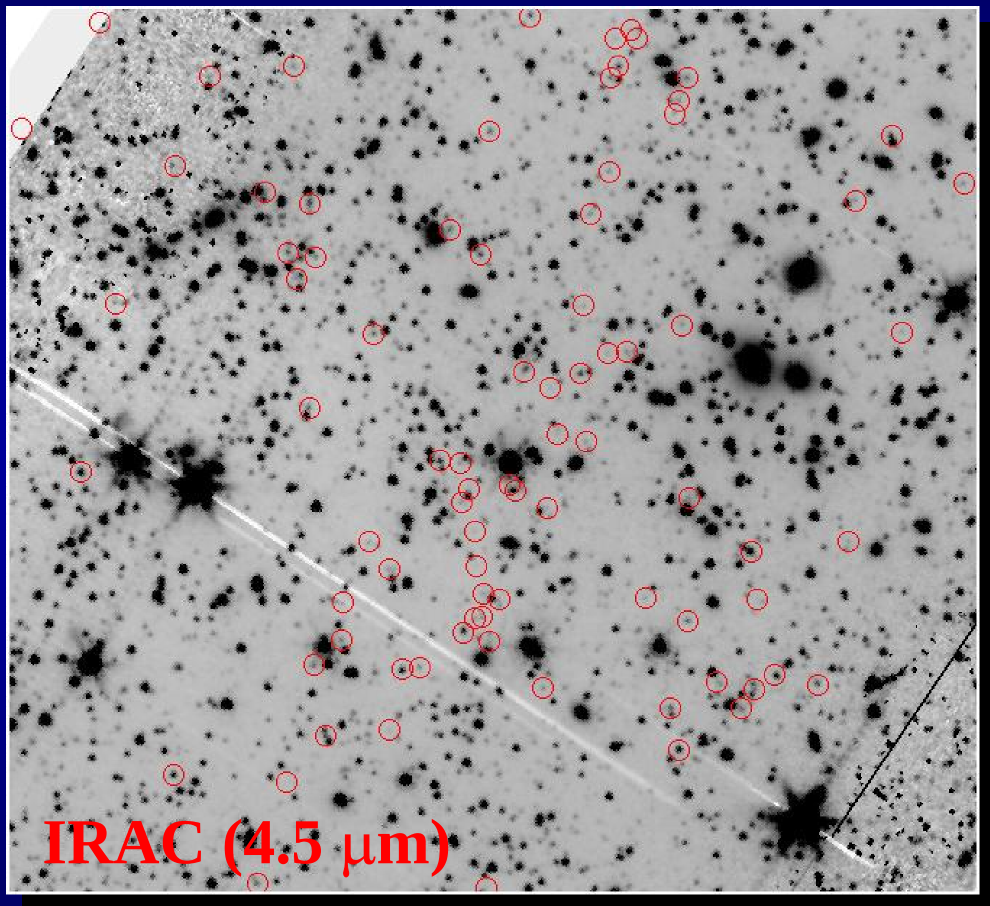
12+log(O/H)=8.9+0.57xN2

σ~0.18, factor of 2.5 in O/H

- **relationship between [NII]/Hα and O/H**
- **N is mixture of primary and secondary origin**
- **age, ionization, N/O effects, integ. spectra, DIG, AGN**

(Pettini & Pagel 2004)

Stellar Populations & Masses

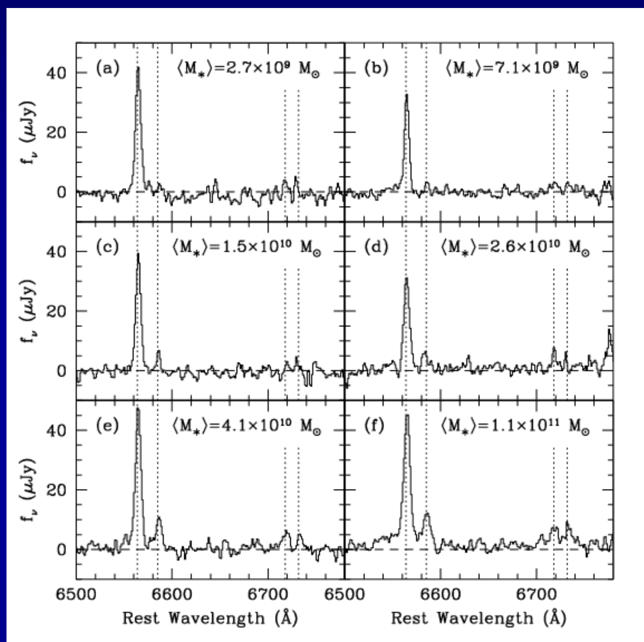


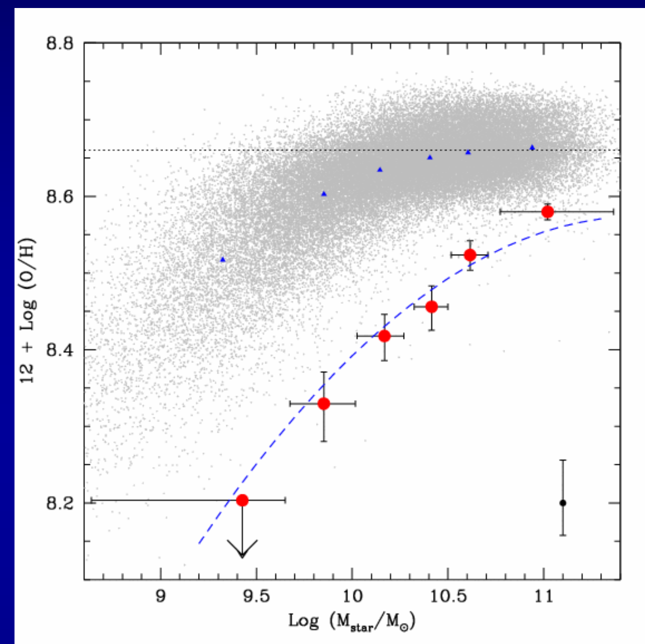
(Barmby et al. 2004, Shapley et al. 2005)

Near/Mid-IR Imaging

- Deep J, K imaging with WIRC, Palomar 5-m, to K_s~22.5, J~23.8
- 4 fields, ~420 galaxies with z_{sp}> 1.4
- Spitzer IRAC data in Q1700 field, 3.6, 4.5, 5.4, 8 μm
- Combine optical and IR SED to model stellar populations, masses

z~2 M-Z Relationship

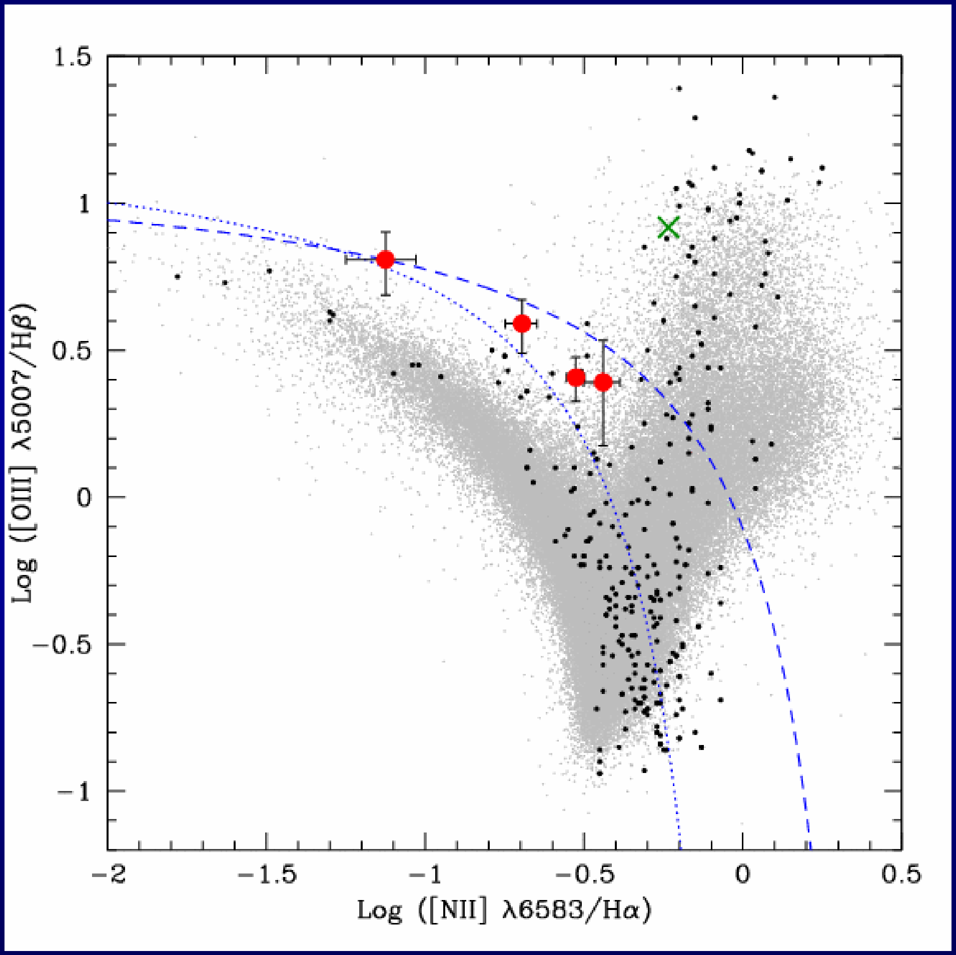




(Erb et al. 2005)

- New sample of 87 star-forming galaxies at z~2 with both M_* and [NII[/Hα (gas phase O/H) measurements; divide into 6 bins of M_*
- clear increase in [NII]/Hα with increasing M_* ➲M-Z at z~2!!
- Estimate gas fractions from Ha sfr, determine how Z changes with μ
- Shallow increase in Z with decrease of gas fraction, indicates outflow from galaxies over the whole range in stellar masses, not just less massive ones!

z~2 Physical Conditions



(Erb et al. 2005)

- Well-defined sequence in [OIII]/Hβ vs. [NII]/Hα in local galaxies (SDSS) (star-formation vs. AGN)
- small sample of z~2 star-forming galaxies with [OIII]/Hβ are offset from this locus (as is DRG)
- n_e, ionization parameter, ionizing spectrum (IMF, star-formation history)
- Implications for derived O/H

Summary

- Lots of new surveys targeting z~1.5-3.0, using complementary techniques
- The "redshift desert" doesn't exist anymore.
- Understanding the complementarity of different samples is crucial for constructing census of the star-formation, stellar mass, and heavy elements.
- Spectra and redshifts are also crucial for understanding spatial distribution and physical quantities, including spectra at IR wavelengths (area in which most IR surveys need work).
- One especially promising direction is comparison of stellar masses and metallicities -- probe of ISM, galaxy evolution, feedback, but also contribution of galaxies to enrichment of IGM
- Only a tiny fraction of discoveries being made in the z~2-3 Universe (just ask if you want to find out more…)