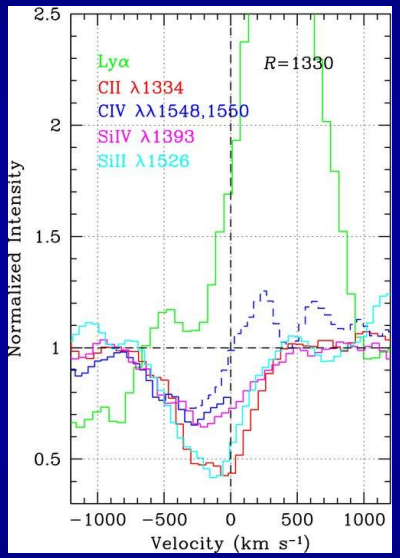
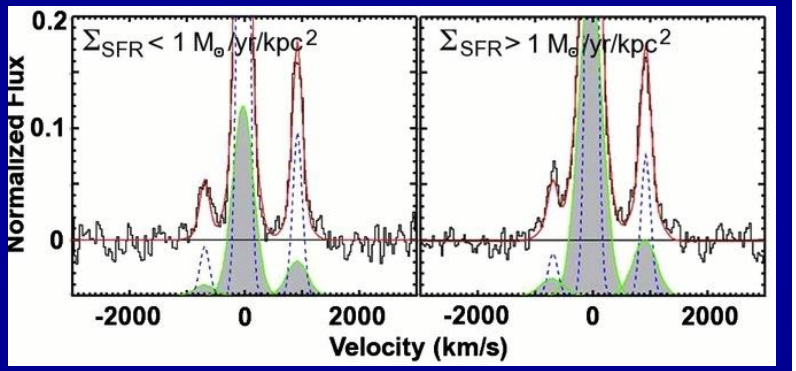
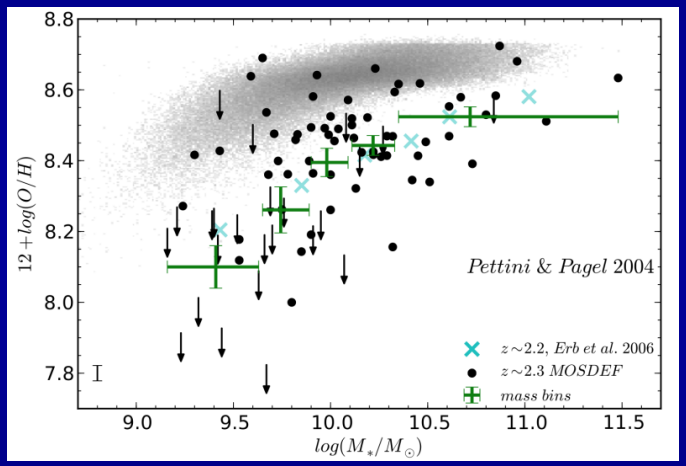
Outflows from High-Redshift Galaxies



Steidel et al. (2010)



Newman et al. (2012b)



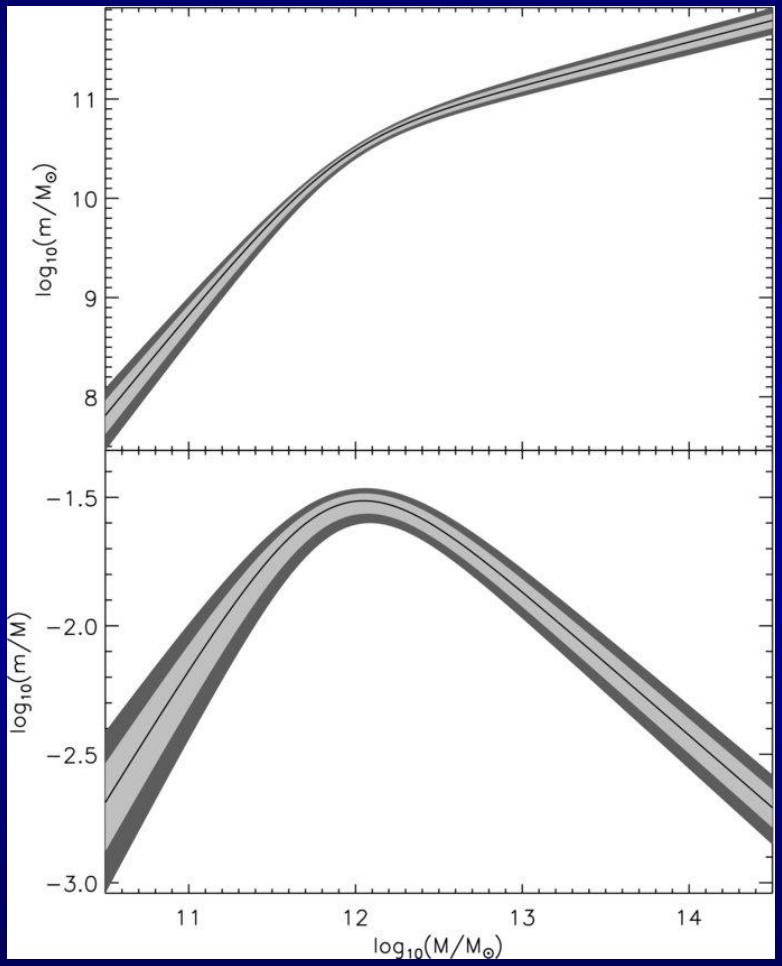
Sanders et al., in prep

Alice Shapley (UCLA)

Overview

- Importance of outflows
- Properties of outflows
- Direct Probes of Outflows at High Redshift (z~1-4)
  - Measurements
  - Mass outflow rates
  - Outflow scaling relations and “demographics”
  - Outflow geometry
  - Evolution
- M-Z relation and the MOSDEF project
- Concluding thoughts

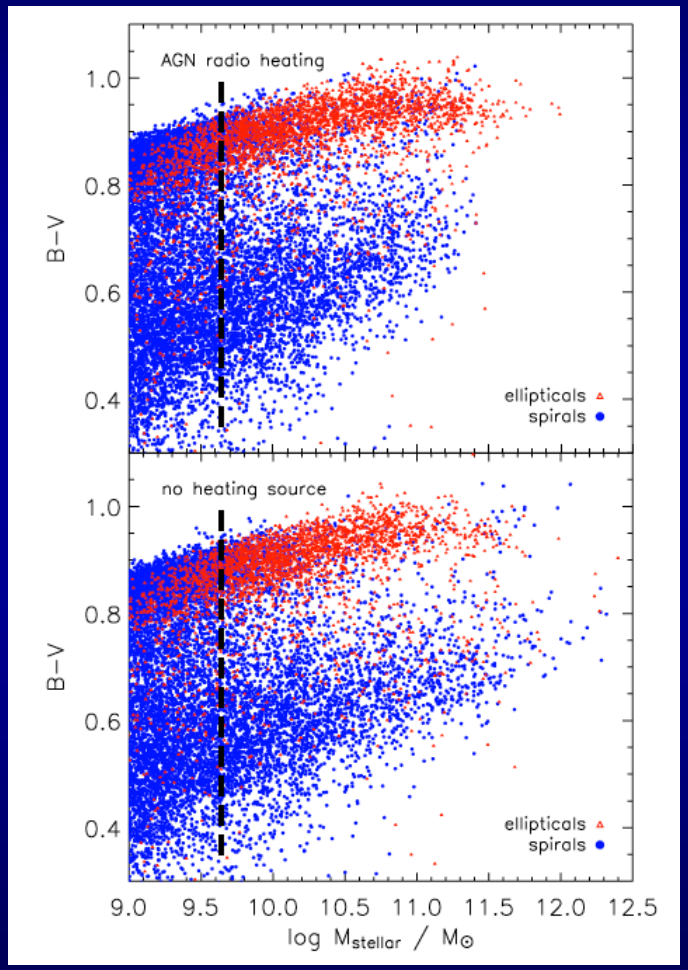
Importance of Outflows



(Moster et al. 2010)

- Feedback processes are key to successful models of galaxy formation and the IGM.
- Stellar vs. halo masses, especially at low and high-mass end.
- Red colors of massive galaxies at z~0.
- The enrichment of the IGM.
- Outflows are observed in local starbursts, and, commonly, at z>1.

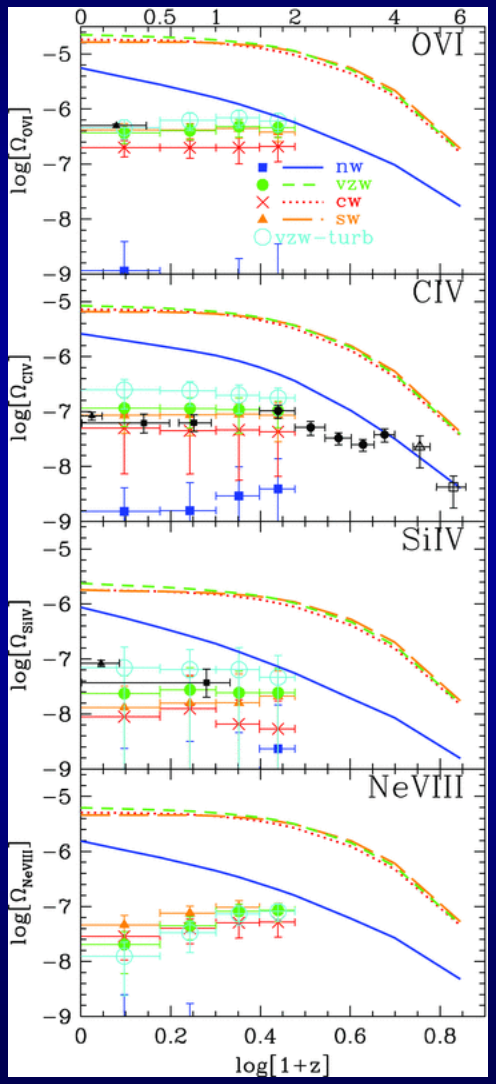
Importance of Outflows



(Croton et al. 2006)

- Feedback processes are key to successful models of galaxy formation and the IGM.
- Stellar vs. halo masses, especially at low and high-mass end.
- Red colors of massive galaxies at z~0.
- The enrichment of the IGM.
- Outflows are observed in local starbursts, and, commonly, at z>1.

Importance of Outflows



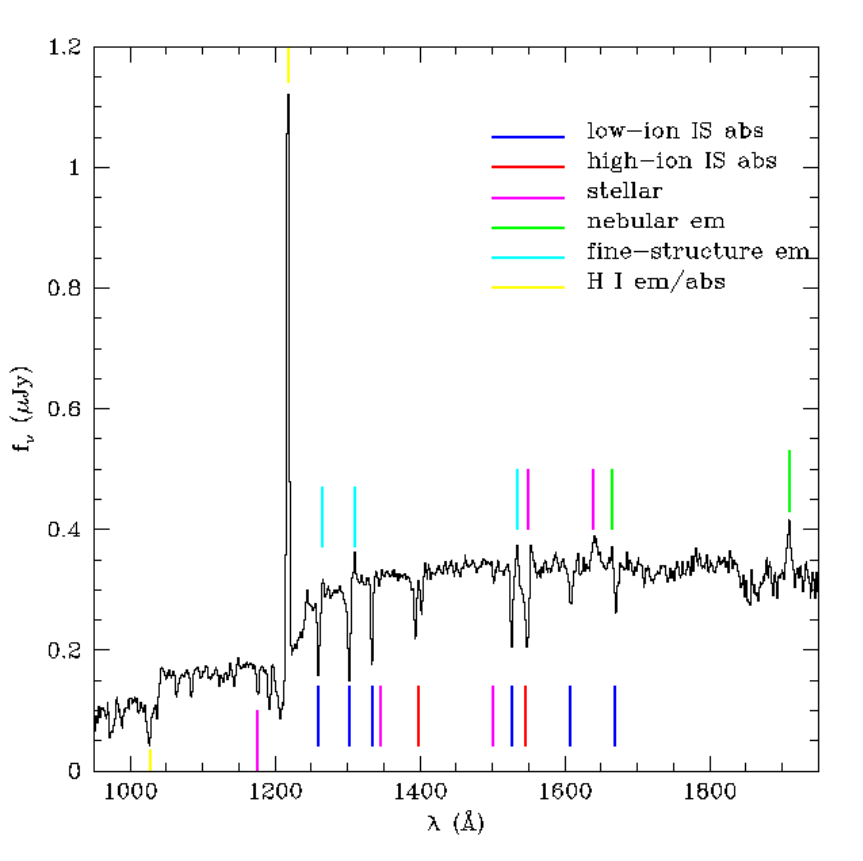
(Oppenheimer et al. 2012)

- Feedback processes are key to successful models of galaxy formation and the IGM.
- Stellar vs. halo masses, especially at low and high-mass end.
- Red colors of massive galaxies at z~0.
- The enrichment of the IGM.
- Outflows are observed in local starbursts, and, commonly, at z>1.

Properties of Outflows

- Mass outflow rates (e.g., $\dot{M}_{wind}=\Omega r^2 \rho v$)
- Mass loading factor: $\eta=\dot{M}_{wind}/SFR$
  - Scaling with galaxy mass or circular velocity
  - Discriminate between "momentum driven" ($\eta \sim 1/v_c$) and "energy driven" ($\eta \sim 1/v_c^2$) winds
  - Scaling with other galaxy properties (e.g., Σ_{SFR})
- Metal loading factor: $\zeta = Z_{wind}/Z_{ISM} \times \eta$ and scaling with mass
- Multi-phase structure and mass in each phase
- Geometry (e.g., bipolar or spherical, physical extent)
- Velocity structure (v_{wind} vs. r)
- Outflow kinematics vs. galaxy properties
- Fate of outflowing gas (v_{wind} vs. v_{esc})

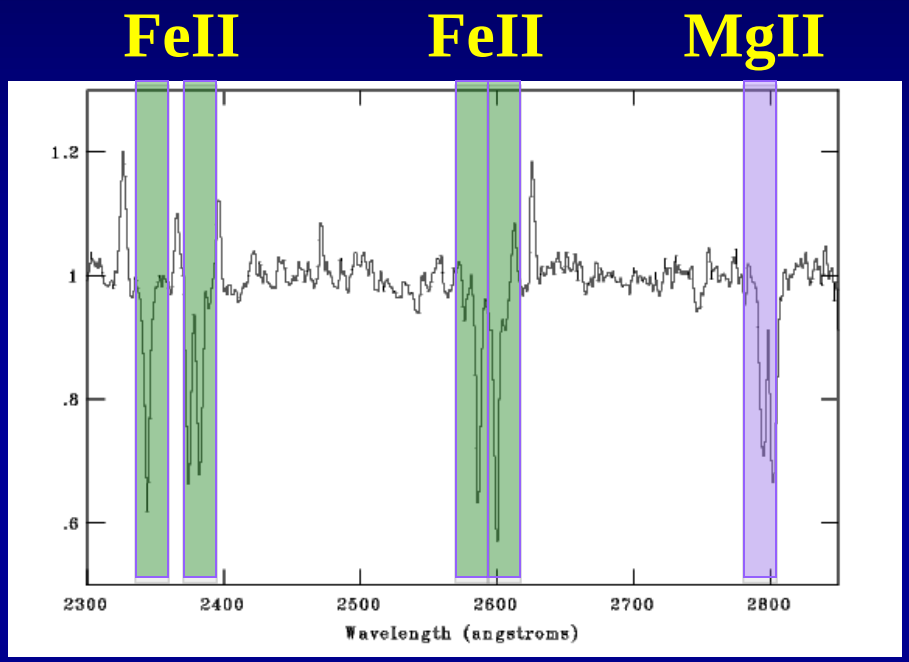
z>2 Outflow Features



- In star-forming galaxies at z>2, a host of rest-frame UV features within the range ~1200-2000 Å is used to trace outflows:
  - HI Lyα absorption and emission.
  - Low-ionization interstellar absorption lines (SiII, OI, CII, FeII, AlII) probing cool, neutral phase.
  - High-ionization interstellar absorption lines (SiIV, CIV) probing warmer, more highly ionized phase.
  - Potential to estimate HI column directly!

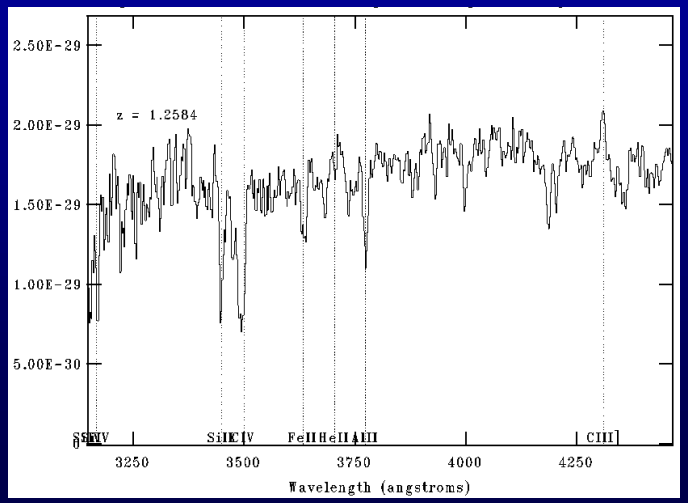
(Shapley et al. 2003)

z~1 Outflow Features

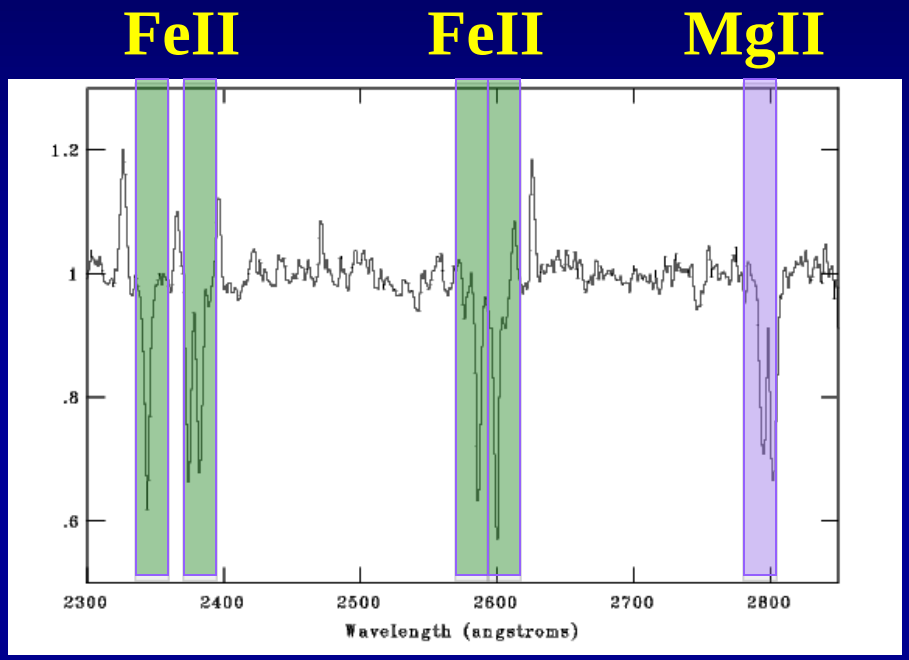


- In galaxies at z~0.5-1.5, use near-UV features:
  - FeII: FeII λ2250, λ2261, λ2344, λ2374, λ2382, λ2587, λ2600 Å.
  - MgII doublet λλ 2796, 2803.
  - MgI λ2852.
  - Probe cool gas.
  - Can use CIV, SiII, AlII as well, at z>1.1 with Keck/LRIS.

(Weiner et al. 2009; Rubin et al. 2010a,b; 2011, 2012, 2013; Martin, AS et al. 2012, 2013; Kornei, AS et al. 2012, 2013.)



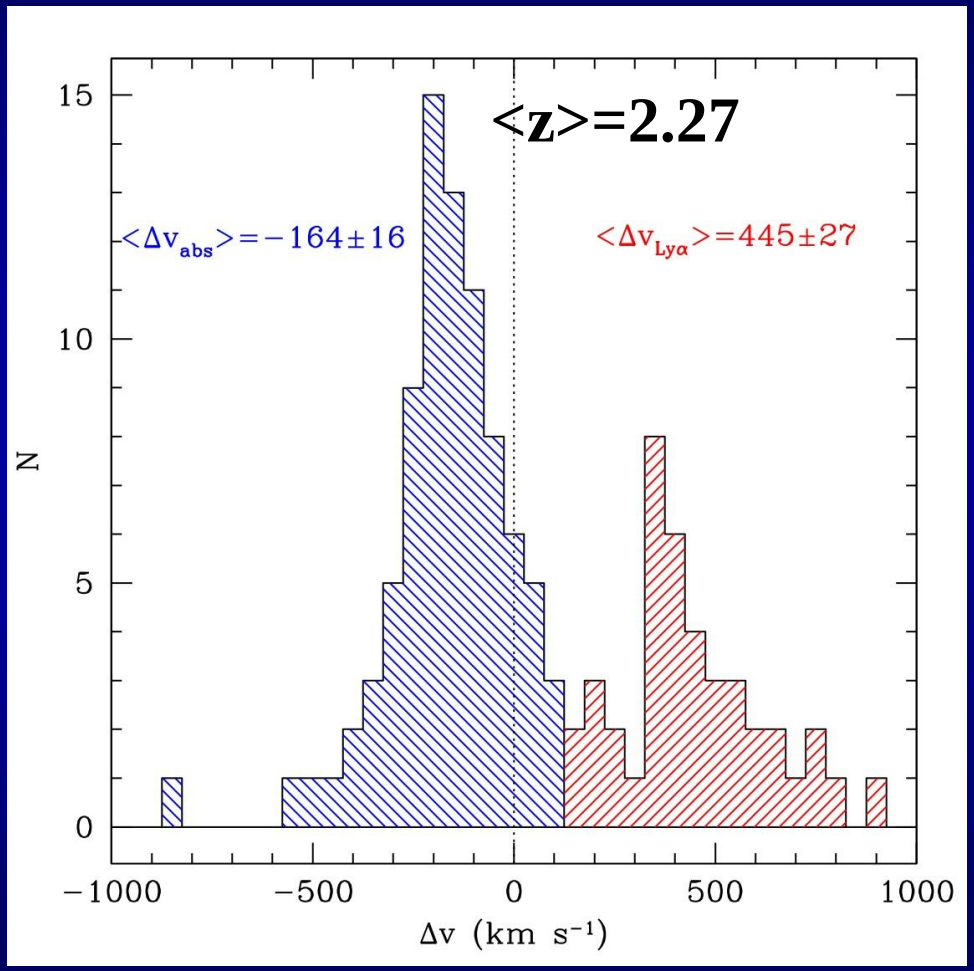
Quantifying an "Outflow"



(Weiner et al. 2009; Rubin et al. 2010a,b; 2011, 2012, 2013; Martin, AS et al. 2012, 2013; Kornei, AS et al. 2012, 2013.)

- Different methods for estimating outflow properties:
  - Velocity centroid of single-component fit
  - Decomposition into ISM+outflow components, velocity centroid of outflow component
  - EW of outflow component
  - Blue wing of single/outflow component
  - Full velocity profile
- Resolution of data is very important.

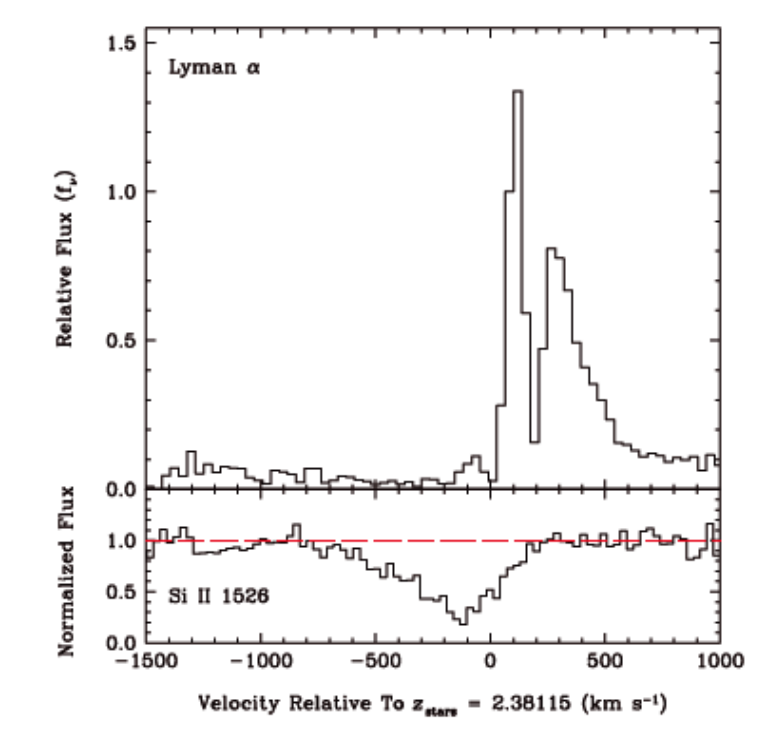
Systemic Redshifts



(Steidel et al. 2010)

- Kinematic signature: Redshifts measured for interstellar absorption, Lyα emission differ.
- At z~2-3, systemic redshifts indicate: Low-ionization absorption features typically blueshifted (Δv=-150 km/s), Lyα emission typically redshifted (Δv=+400-500 km/s).
- E.g., 89 galaxies at <z>=2.3 with Keck/NIRSPEC systemic redshifts, and rest-UV spectra (Steidel et al. 2010)
- Keck/MOSFIRE will dramatically increase sample with systemic redshifts (e.g., Erb et al. 2014).

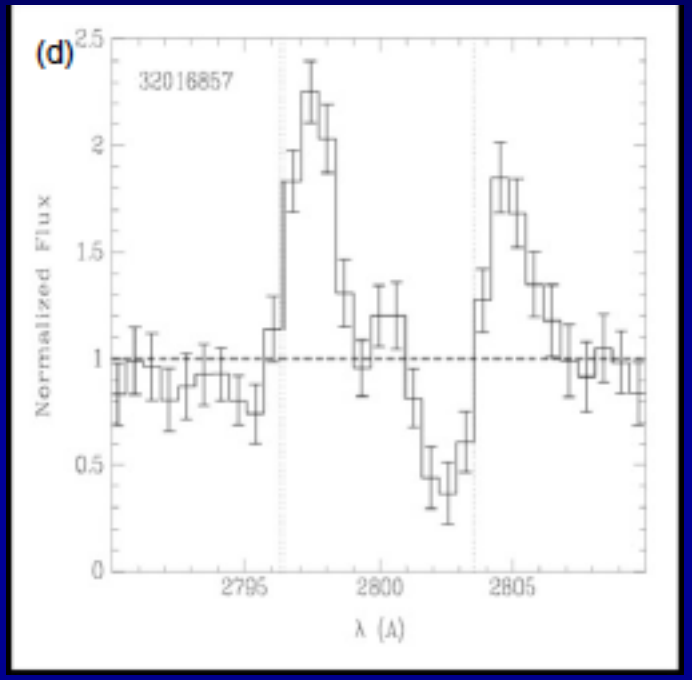
Resonant UV Emission Lines



"Cosmic Horseshoe", z=2.38 (Quider et al. 2009)

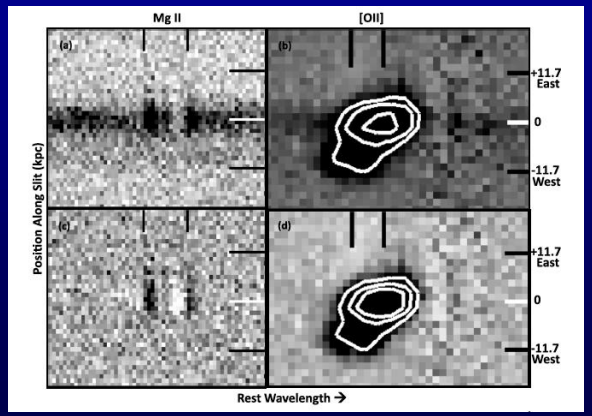
- Resonant Lyα emission, typically redshifted.
- Velocity structure of line should contain rich information about geometry, column density, and velocity structure of outflow (or inflow). See models by Verhamme, Schaerer et al.
- Angular extent also contains important clues (Steidel et al. 2011).
- Issue: most observations of unlensed high-z galaxies have velocity resolution coarser than ~200 km/s (typical is ~400-500 km/s), which limits ability to compare with model velocity profiles.

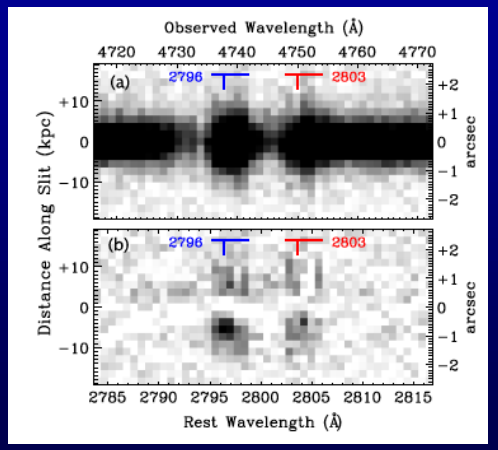
Resonant UV Emission Lines



(Martin et al. 2013)

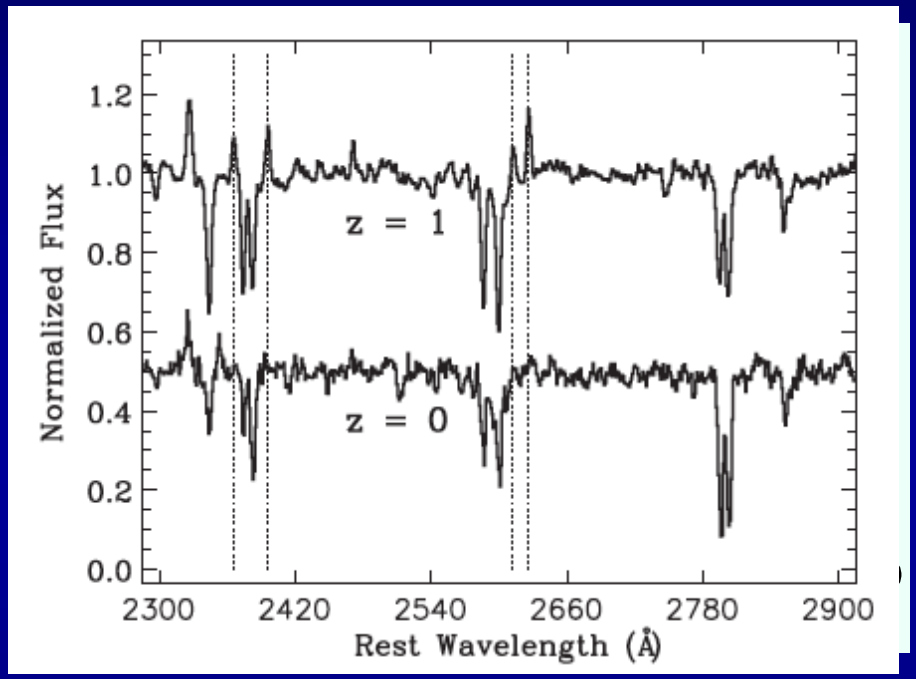
- Resonant MgII emission, typically redshifted.
- At least a couple of cases where MgII is spatially extended relative to the continuum, with different velocity structure from that of [OII] emission.
- Useful target for IFU measurements.





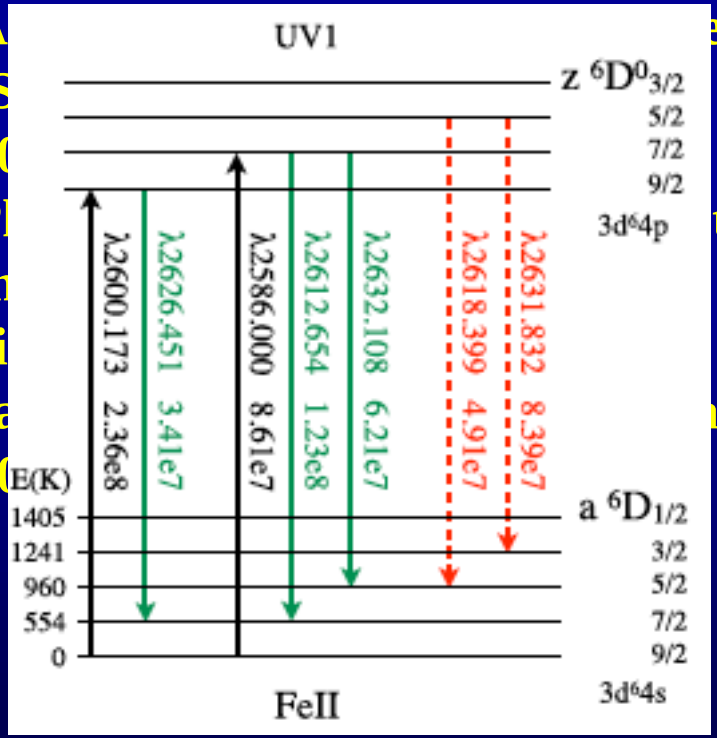
(Rubin et al. 2013)

Fine Structure UV Emission Lines

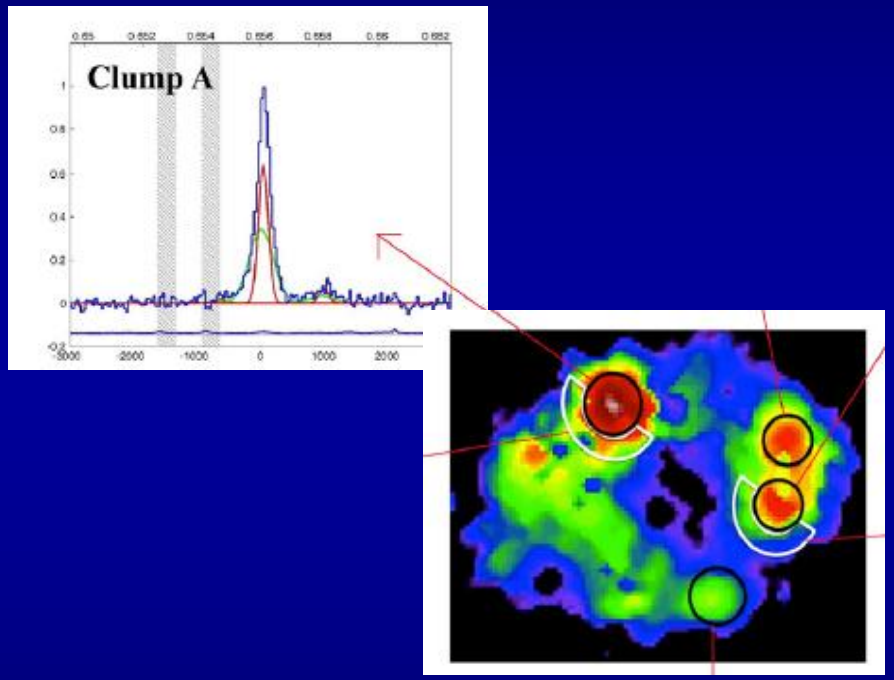


(Kornei, AS et al. 2013)

- FeII* emission not seen in composite UV spectrum of local starbursts (Leitherer et al. 2010). Commonly detected at z>1, generic prediction given FeII energy levels.
- A ed (S 20
- P ts th ci ra l. 20

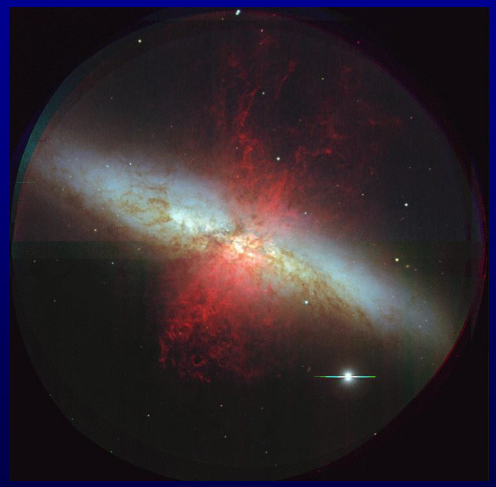


Broad Hα Emission



ZC406690 (z=2.19), Hα map

- VLT/SINFONI IFU maps of Hα from star-forming galaxies at z~2.
- Decompose Hα profiles into double-Gaussian fits.
- Broad Hα emission components (sometimes systematically blueshifted) associated with "clumps" and nuclei, interpreted as outflows.



(Image credit: Subaru Observatory)

(Newman et al. 2012a,b; Genzel et al. 2011, Forster Schreiber et al. 2014)

Mass Outflow Rates

- **Expression for outflow rate:**

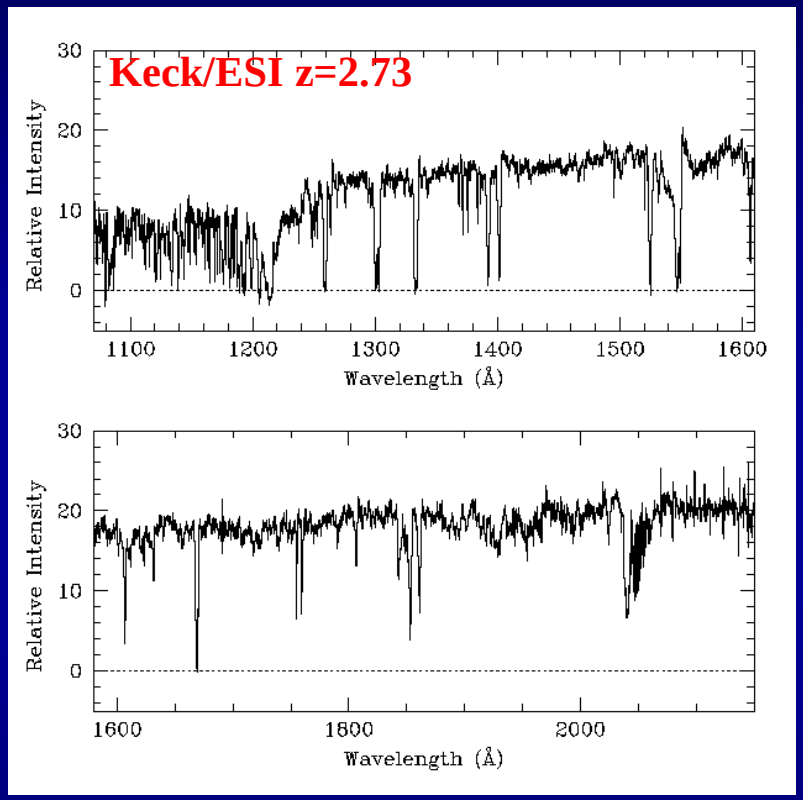
$$\dot{M}_w = \Omega r^2 \mu(r)\, n(r)\, v(r),$$

- **For absorption measurements, use column density N(HI), to rewrite as:**

$$\dot{M}_w \approx \Omega R_0 m_p N_{HI} v_\infty$$

- **Need to estimate Ω (covering factor), R_0 (radius at which wind is measured), N_{HI}, in addition to v_∞ (terminal velocity)**

Mass outflow rates at z>2: Absorption



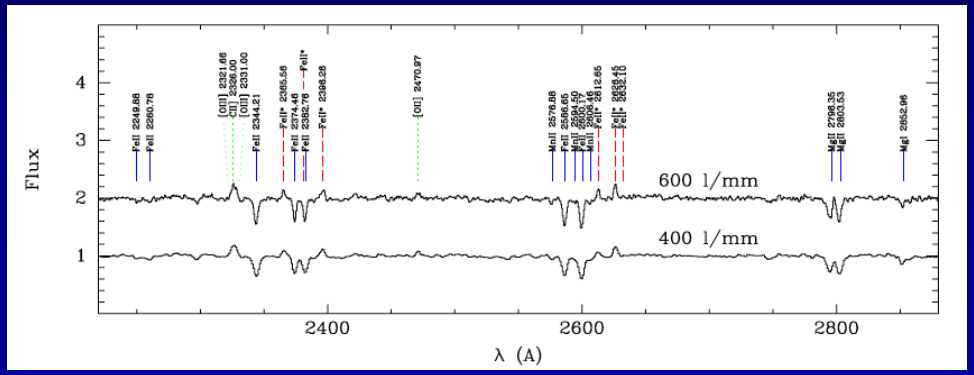
cB58 has non-average spectrum -- very strong Lyα and metal absorption lines

- MS1512-cB58, z=2.73, x30 magnification, R-mag~20.5 (Yee et al. 1996). Detailed studies of outflowing ISM, abundance pattern, multi-wavelength follow-up, very strong absorption lines (Pettini et al. 2000, 2002).

- For 10 years, this was the *only* LBG with a mass outflow estimate, where dM/dt~SFR, based on N_{HI}, v_{out}, $\Omega=4\pi$, assumption of R=1kpc

Mass outflow rates at z~1: Absorption

(Martin et al. 2012)



• Multiple FeII lines allow for N(Fe+) estimate in DEEP2/LRIS sample at z~1.

• In practice, estimate mass outflow rate as $\dot{M} = \Omega v R_0 N(\mathrm{H}) \bar{m}$.

• Martin, AS et al. (2012) use FeII column densities as follows

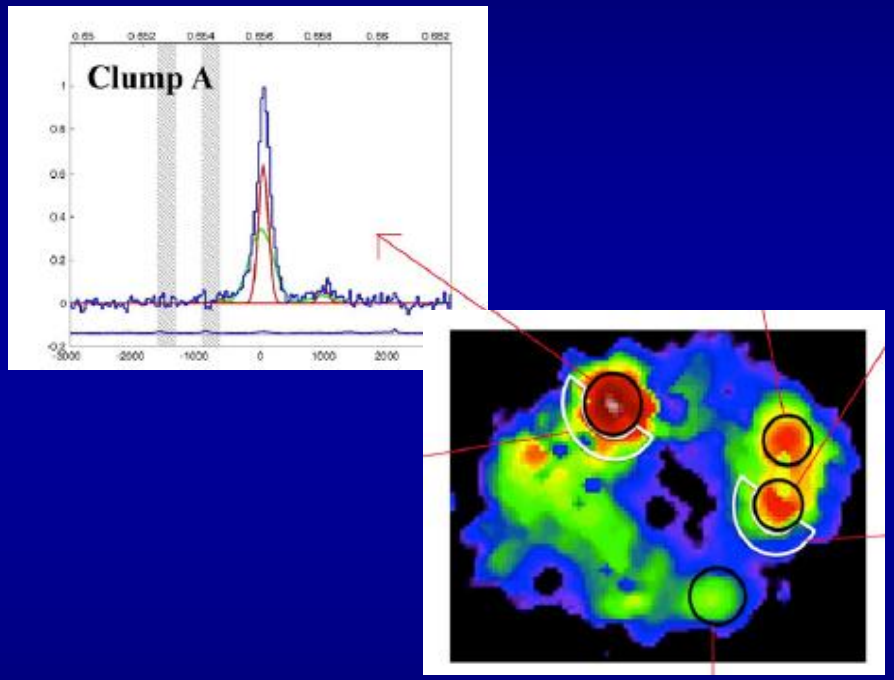
$$\dot{M} = 23\, M_\odot\, \mathrm{yr}^{-1} \left(\frac{\Omega}{\pi}\right) \left(\frac{v}{200\,\mathrm{km\,s^{-1}}}\right) \left(\frac{R_0}{1\,\mathrm{kpc}}\right) \times \left(\frac{N(\mathrm{Fe}^+)}{10^{16}\,\mathrm{cm}^{-2}}\right) \left(\frac{3.16\times10^{-5}}{n(\mathrm{Fe})/n(\mathrm{H})}\right) \left(\frac{0.5}{\chi(\mathrm{Fe}^+)}\right) \left(\frac{0.20}{d(\mathrm{Fe})}\right)$$

• For typical values in z~1 DEEP2 galaxies w/ significant blueshifts (35 galaxies out of 165 with absorption-line fits), suggests η~1.9.

• FeII column densities are uncertain. So is R_0, Fe/H, χ(Fe+), d(Fe).

• Lower η inferred when using only Doppler component.

Mass outflow rates at z>2: Emission



ZC406690 (z=2.19), Hα map

(Newman et al. 2012a; Genzel et al. 2011)

- **Broad component of clump Hα profiles used to estimate mass outflow rates and mass loading factor:**

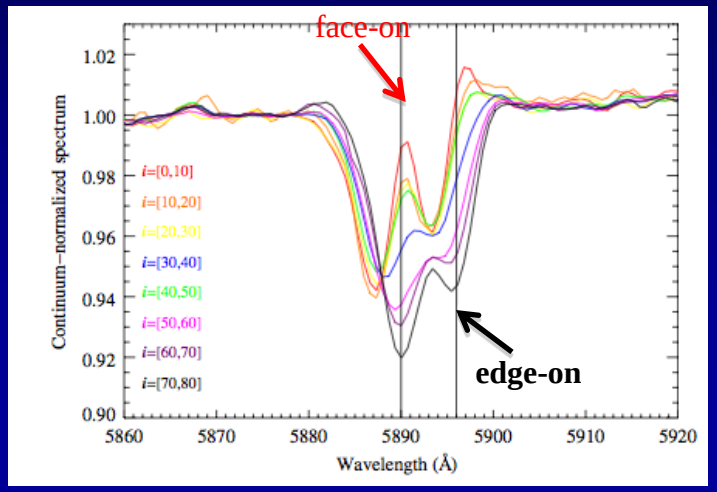
$$L_{\mathrm{H}\alpha} = \gamma_{\mathrm{H}\alpha} \int \Omega R^2 n_e(R) n_p(R)\, dR,$$

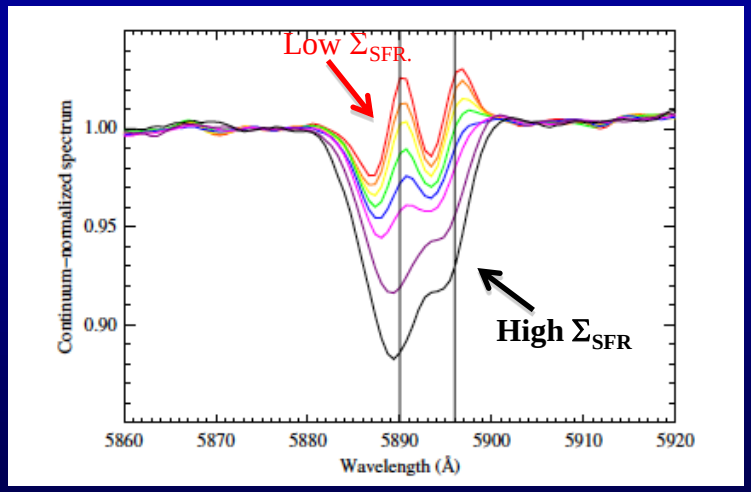
$$M_{\mathrm{H\,II,He}} = 1.36 \times m_p \int \Omega R^2 n_p\, dR = \frac{1.36 \times m_p L_{\mathrm{H}\alpha}}{\gamma_{\mathrm{H}\alpha} n_{\mathrm{eff}}},$$

$$\dot{M}_{\mathrm{out}} = \Omega R^2 1.36 \times m_p n(R) v_{\mathrm{out}} = M_{\mathrm{H\,II,He}} \times \frac{v_{\mathrm{out}}}{R_{\mathrm{out}}}$$

- $\dot{M}_{out} \sim L_{H\alpha}/n_{eff} \times v_{out}/R_{out}$
- **Major uncertainty is density distribution of wind, R_{out}. Conclude $\dot{M}_{out}$~SFR (i.e. η~1), but *extremely* uncertain (e.g., $\eta = 2.9\ ^{+27.6}_{-2.5}$).**

z~0 Outflow Kinematic Trends

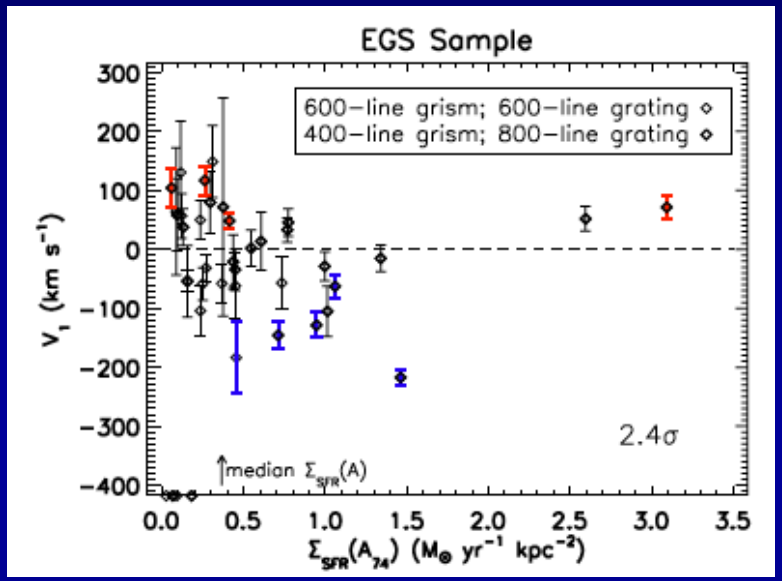




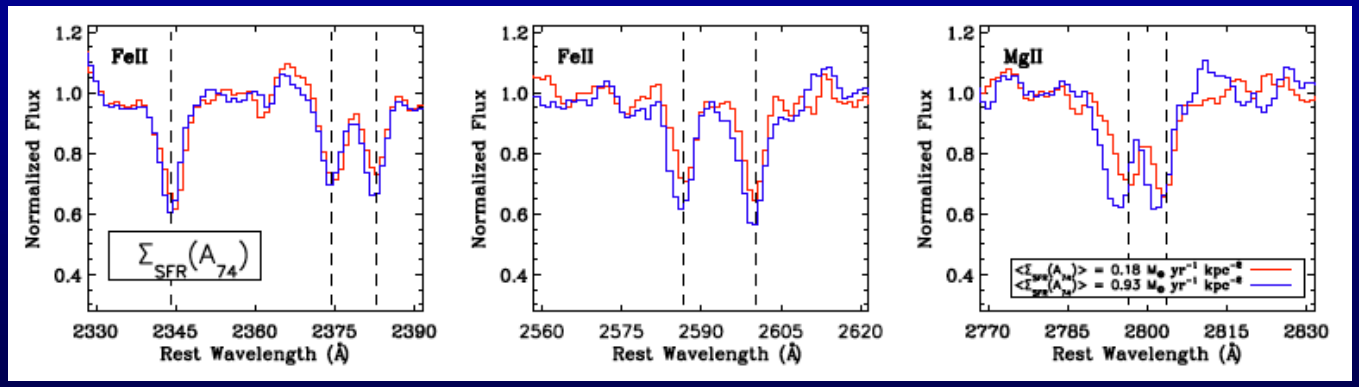
- ~140,000 galaxies drawn SDSS DR7, z_{med}~0.09, SFR~1 $M_\odot$/yr.
- Stack according to inclination, SFR, Σ_{SFR}, A_{UV}, M*. Correct Na I spectra for both stellar and systemic ISM component.
- Outflow component more prevalent in face-on galaxies.
- Outflow component EW correlates primarily with Σ_{SFR} and then A_{UV}. Amount of material propelled in outflow depends on Σ_{SFR}.
- Shallow trend of v_{out} with Σ_{SFR}, with $|v_{out}| \sim \Sigma_{SFR}^{0.1}$.

(Chen et al. 2010)

Outflow kinematics at z~1

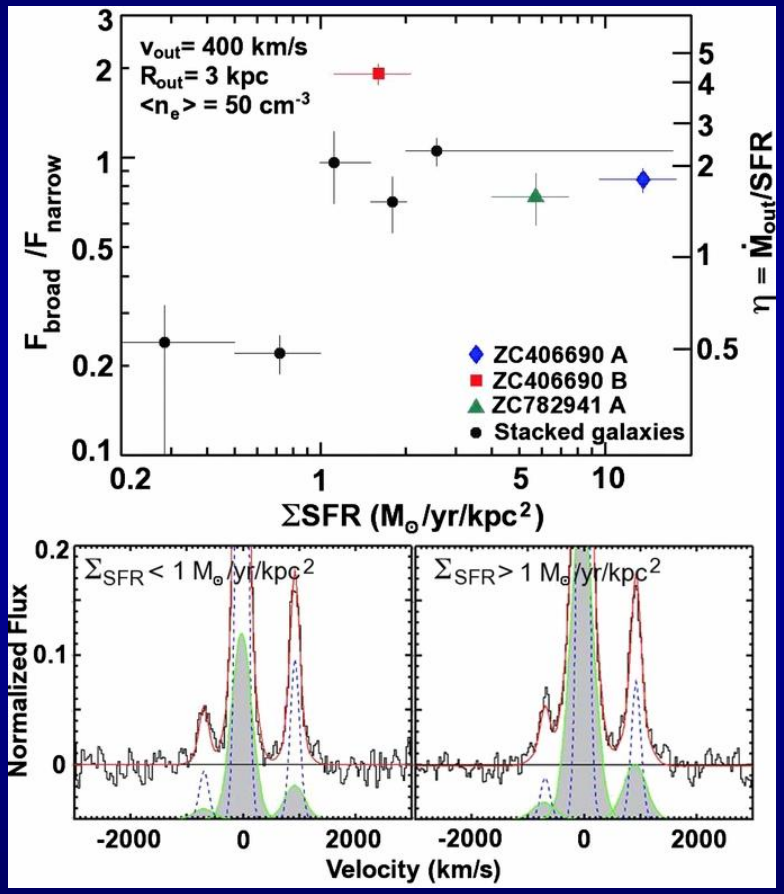


- 72 galaxies in the EGS field with Keck/LRIS spectra.
- Outflow speed and Σ_{SFR} are correlated at >3σ
- Composite spectra show the same effect (MgII)
- See also Bordoloi et al. (2013)



(Kornei, AS et al. 2012)

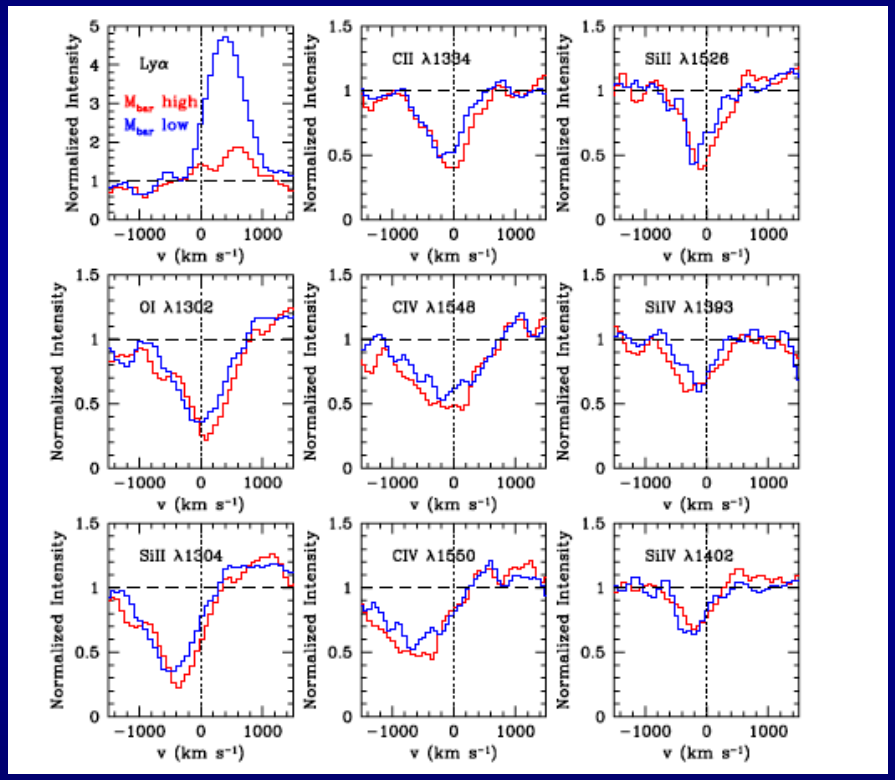
Outflow kinematics at z~2



- 27 galaxies with SINFONI IFU Hα spectra.
- Strongest correlation of broad flux fraction with Σ_{SFR}.
- Also find that more massive, smaller, higher-SFR, face-on galaxies have larger broad flux fraction. But Σ_{SFR} connection is the strongest.
- Suggest Σ_{SFR} threshold for wind breaking out, ~1 M_{sun}/yr/kpc

(Newman et al. 2012b)

Outflow kinematics at z~2-3

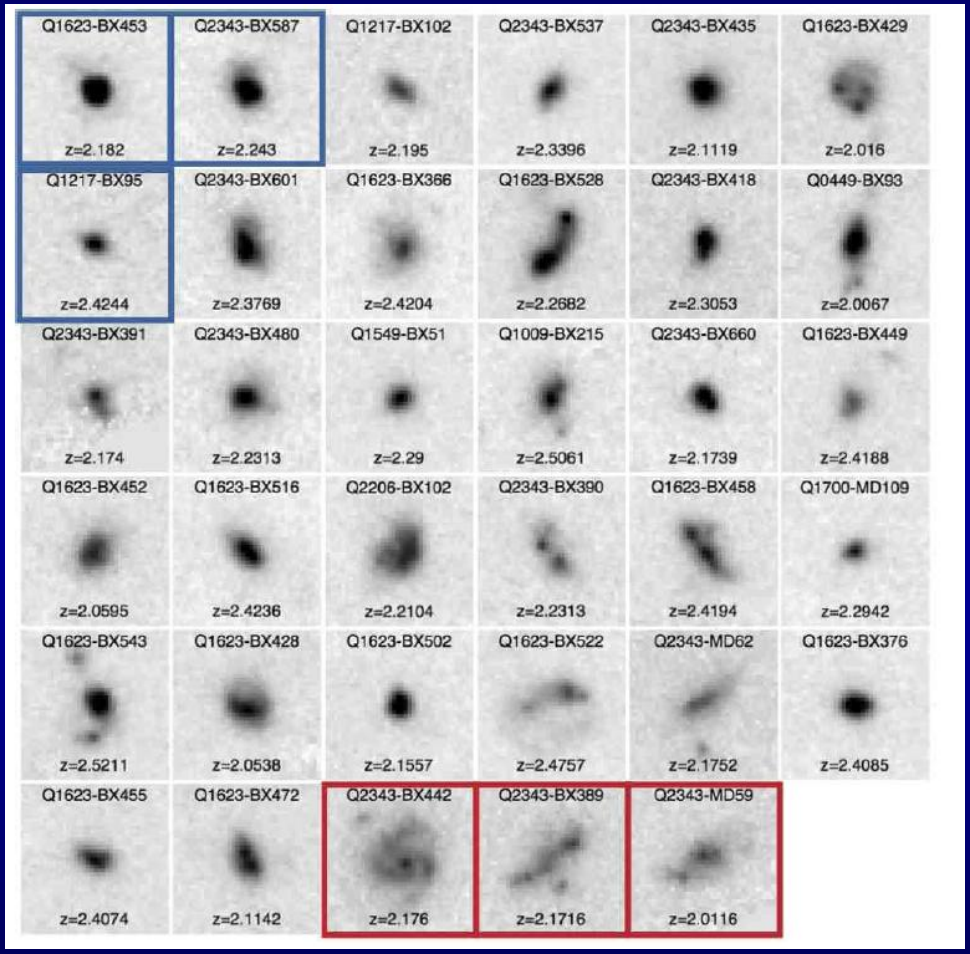


(Steidel et al. 2010)

- Sample of 89 galaxies with rest-frame optical spectra, stellar and gas (stellar+gas=total baryonic) mass estimates. Strongest trend is between $|v_{out}|$ and M_{bar}, with smaller $|v_{out}|$ for larger M_{bar}.

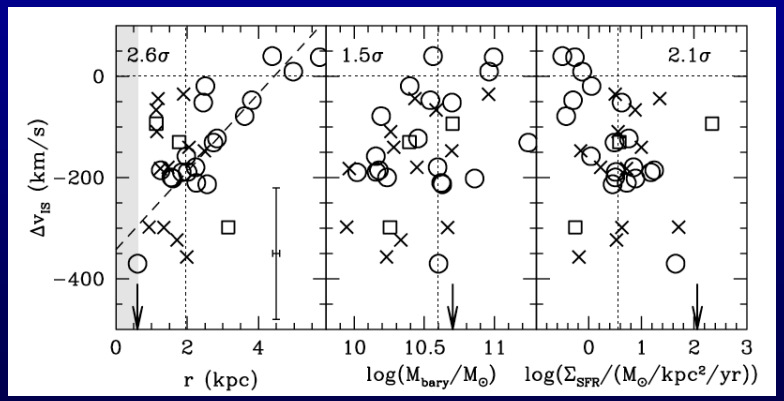
- Construct low and high M_{bar} samples. Find that blue wings of profiles are identical, with $|v_{max}|$~800 km/s. High M_{bar} sample is characterized by stronger absorption component at v_{out}>~0. Infalling material? Law et al. (2012c) find that galaxies with large radius have stronger v~0 component as well.

Outflow kinematics at z~2-3



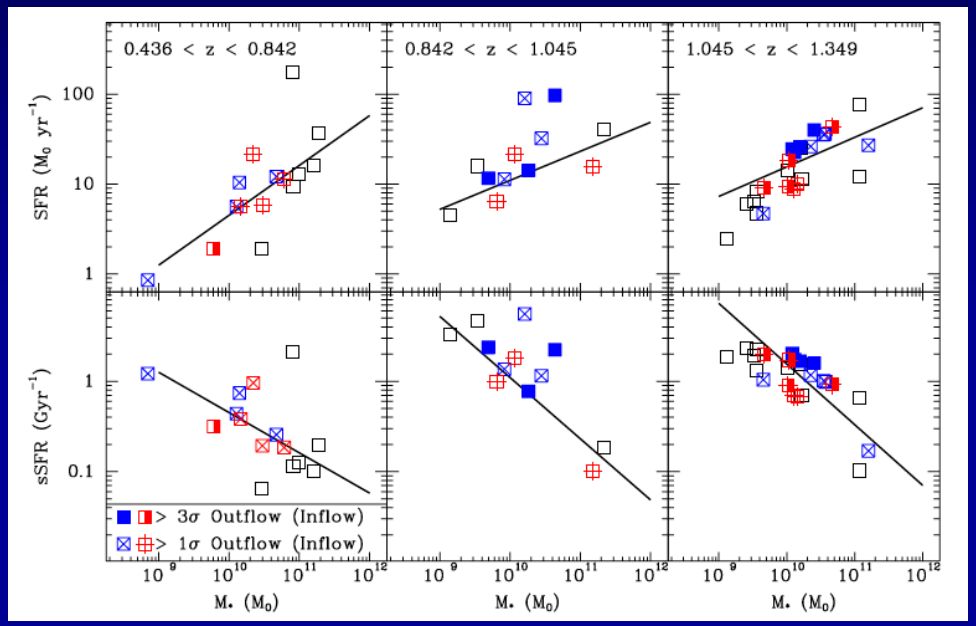
(Law et al. 2012c)

- Law et al. (2012c) use sample of 35 galaxies w/ HST/WFC3, rest-UV spectra, and systemic redshifts.
- Galaxies with large radius have stronger v~0 component as well (strongest correlation).
- 2.1σ correlation between absorption velocity centroid and Σ_{SFR}.
- No evidence for correlation between outflow speed and inclination.

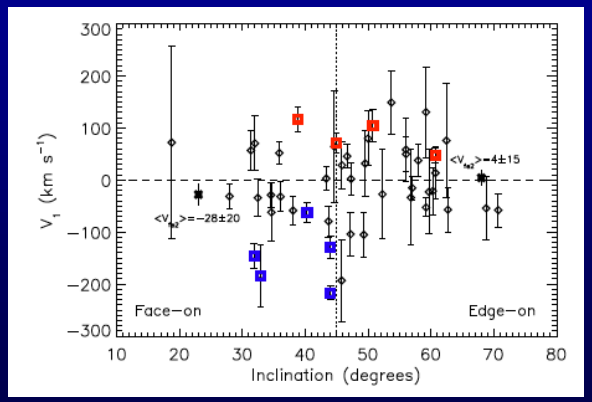


Outflow Geometry at z~1

(Martin, AS et al. 2012)



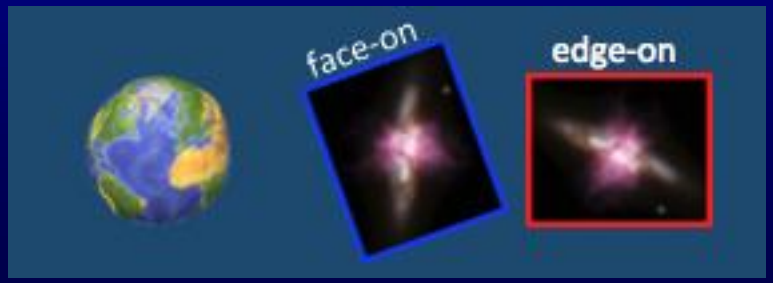
(Kornei, AS et al. 2012)



- Outflows detected in ~40% of DEEP2/LRIS sample at z~1.
- Outflow detection relatively independent of galaxy properties.
- Outflows more common in face-on systems (Kornei, AS et al. 2012; Bordoloi et al. 2013)
- z~1 outflows are collimated!!
- With detection fraction $\Omega/4\pi$:

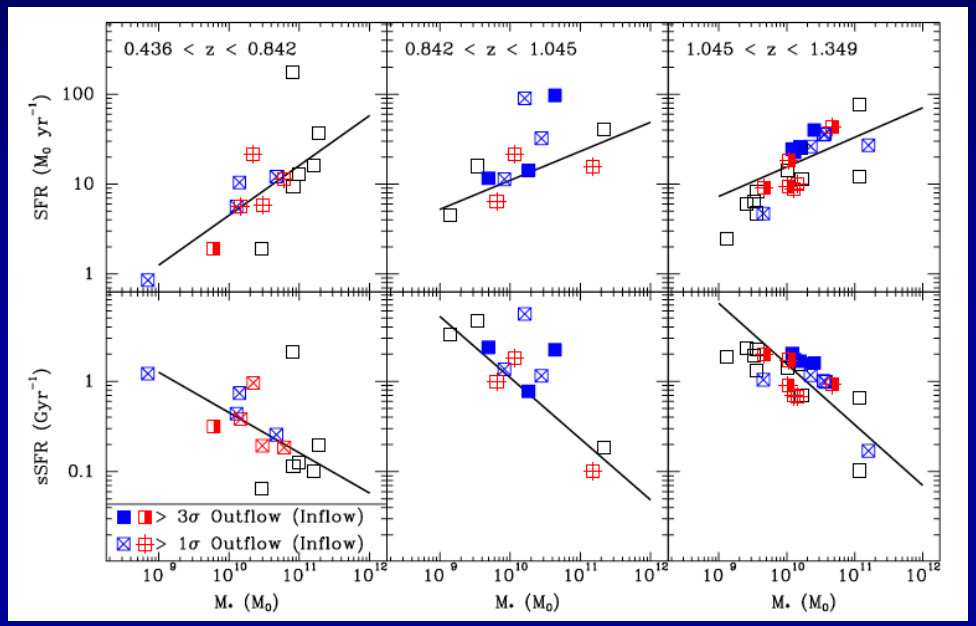
$$\Omega = 4\pi(1 - \cos\theta_B),$$

where θ_B=cone half angle

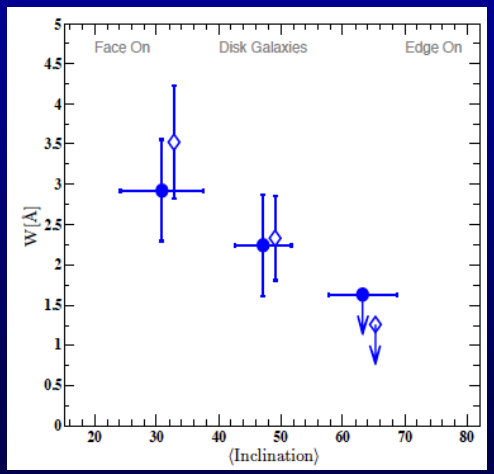


Outflow Geometry at z~1

(Martin, AS et al. 2012)



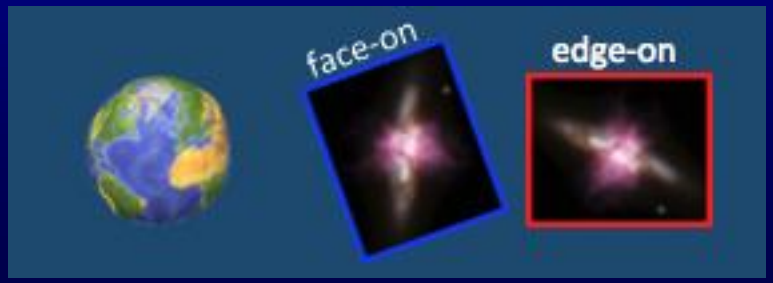
(Bordoloi et al. 2013)



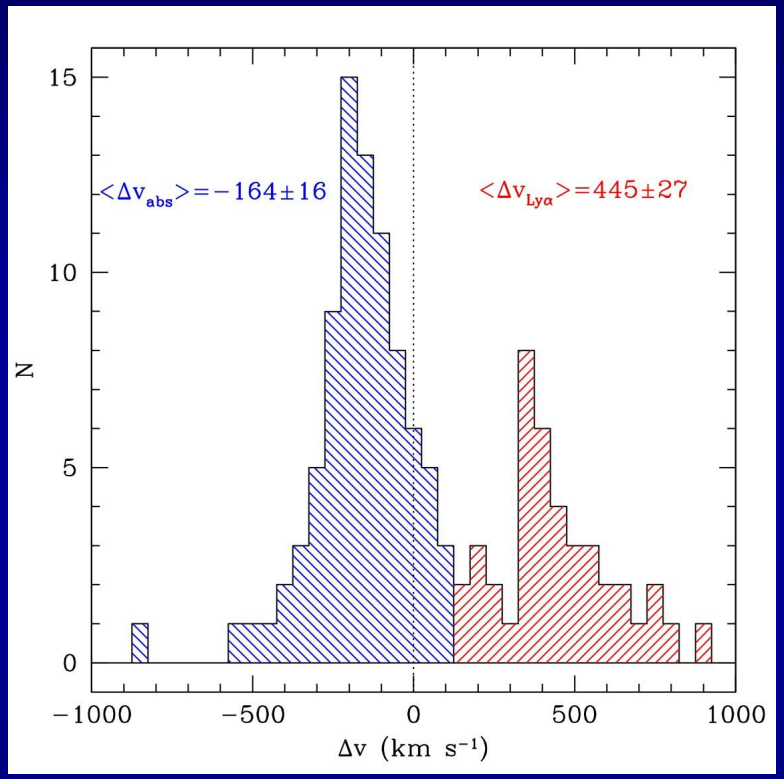
- Outflows detected in ~40% of DEEP2/LRIS sample at z~1.
- Outflow detection relatively independent of galaxy properties.
- Outflows more common in face-on systems (Kornei, AS et al. 2012; Bordoloi et al. 2013)
- z~1 outflows are collimated!!
- With detection fraction $\Omega/4\pi$:

$$\Omega = 4\pi(1 - \cos\theta_B),$$

where θ_B=cone half angle



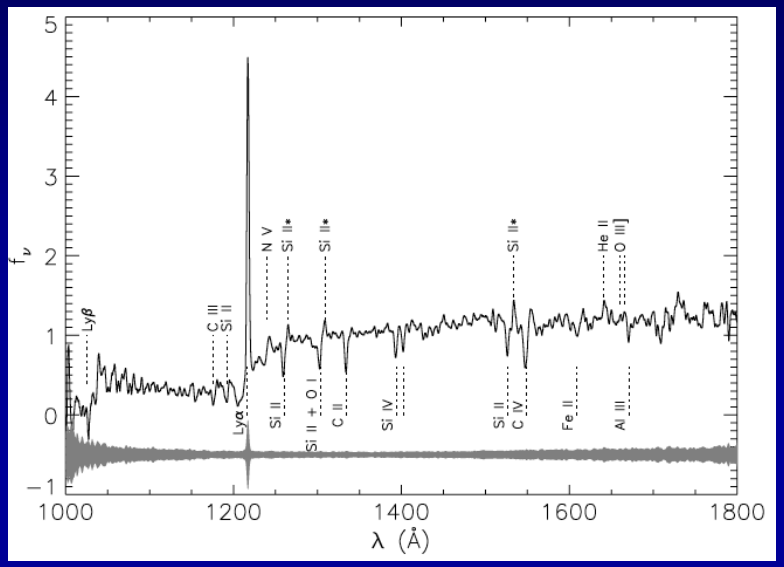
Evolution in Outflow Geometry

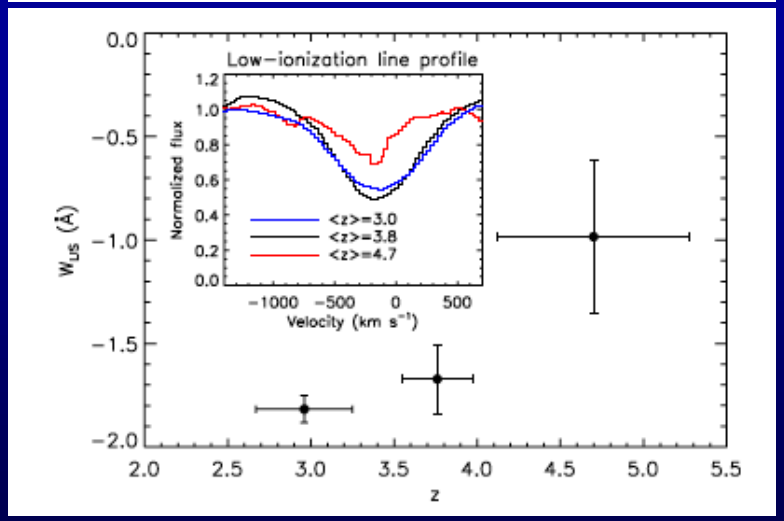


(Steidel et al. 2010)

- Outflow signature detected in almost all z>2 LBGs (in contrast to lower-z result).
- Law et al. (2012c) found no correlation between v_{out} and inclination.
- Suggests z>2 outflows are not collimated! More spherical in geometry?
- Related to emergence of disks at z~1.5?
- NB: Newman et al. (2012b) find difference in Hα broad flux fraction as a function of inclination.

Evolution from z~4 to z~3



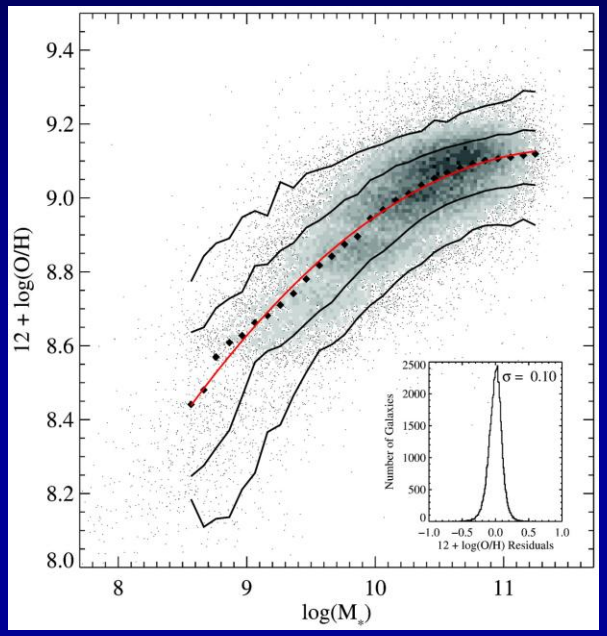


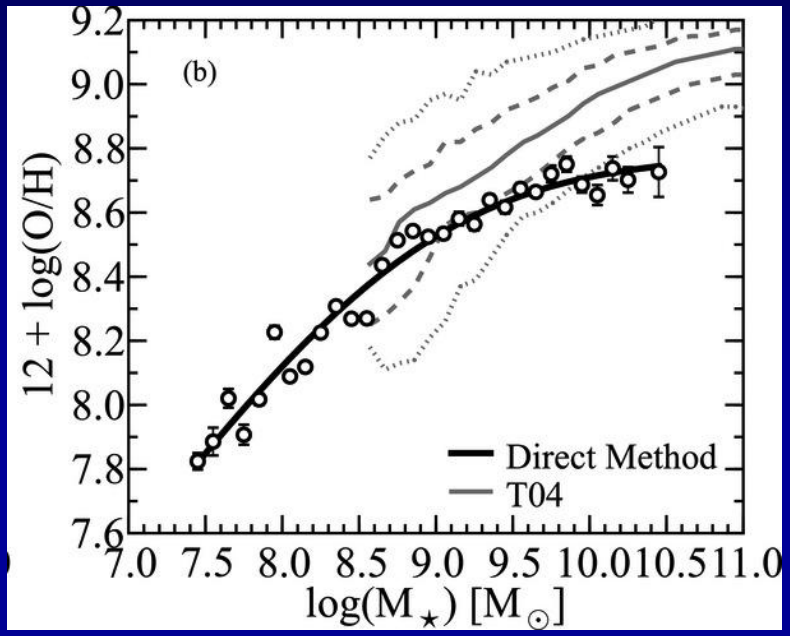
(Jones et al. 2012)

- Sample of 81 at 3.5<z<4.5 with Keck/DEIMOS or VLT/FORS spectra.
- Construct composite, which shows broad, blue-shifted IS absorption.
- For fixed Lyα EW and M_{UV}, galaxies at z~4 have lower IS absorption EW than at z~3.
- Evolution in spatial distribution, kinematics, covering fraction, optical depth?
- Other evidence that circumgalactic gas is less extended at z~ 4 than z~3: SiII* fine structure lines stronger at z~4 than at z~3.

Mass-Metallicity Relation

(Tremonti et al. 2004)



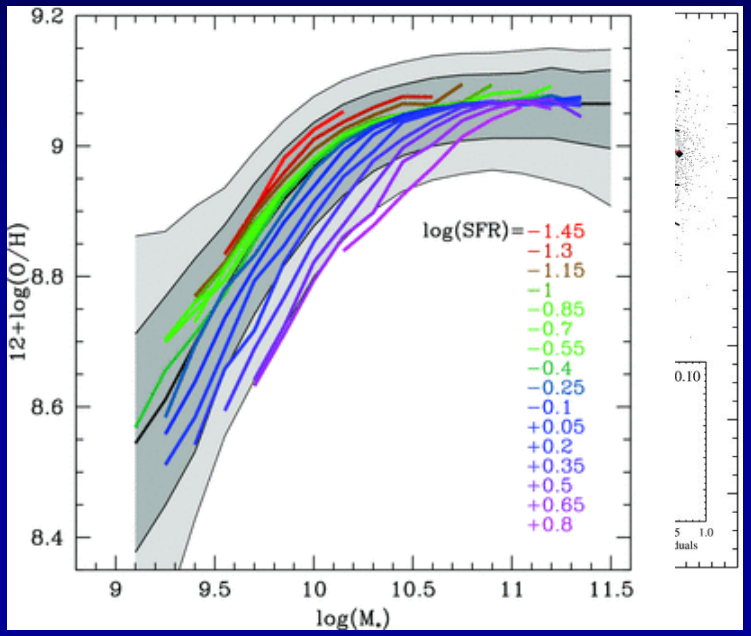


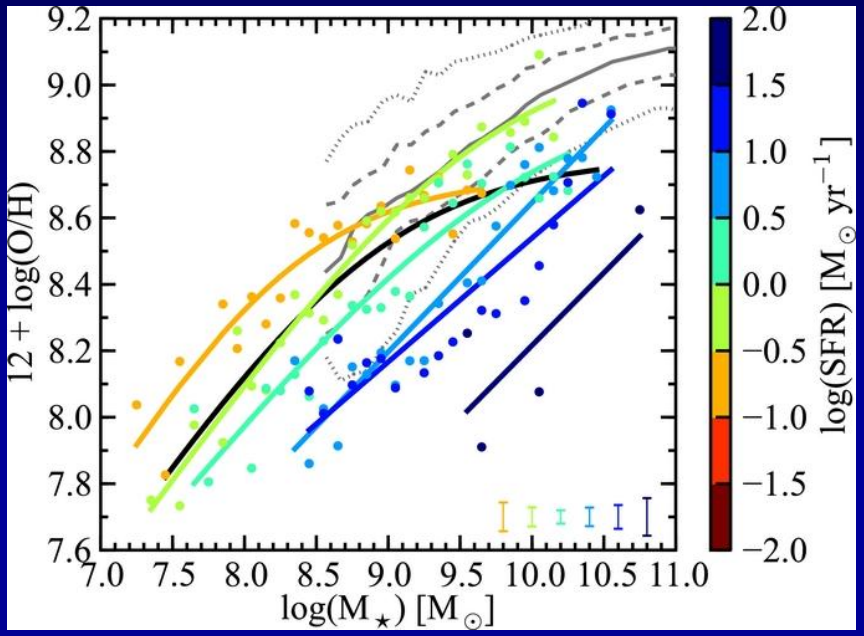
(Andrews & Martini 2013)

- **Metal content of galaxies reflects the past integral of star formation, modified by the effects of gas inflow (i.e., accretion) and outflow (i.e., feedback).**
- **"Metallicity" here means O/H gas-phase abundance.**
- **Consider together with stellar masses (M-Z relation), gas masses and SFRs (Fundamental Metallicity Relation.)**
- **Slope, normalization, and scatter in MZR, FMR, place constraints on models of gas outflow/inflow (e.g., Finlator & Dave 2008; Dave et al. 2012)!**

Mass-Metallicity Relation

(Mannucci et al. 2010)

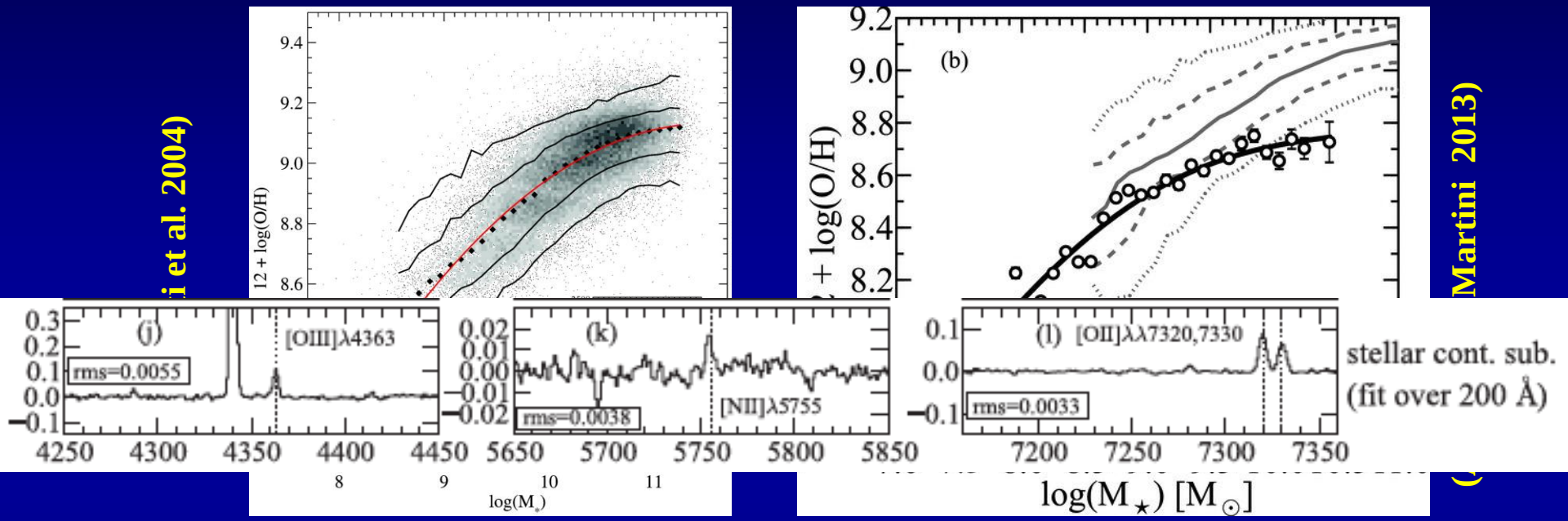




(Andrews & Martini 2013)

- **Metal content of galaxies reflects the past integral of star formation, modified by the effects of gas inflow (i.e., accretion) and outflow (i.e., feedback).**
- **"Metallicity" here means O/H gas-phase abundance.**
- **Consider together with stellar masses (M-Z relation), gas masses and SFRs (Fundamental Metallicity Relation.)**
- **Slope, normalization, and scatter in MZR, FMR, place constraints on models of gas outflow/inflow (e.g., Finlator & Dave 2008; Dave et al. 2012)!**

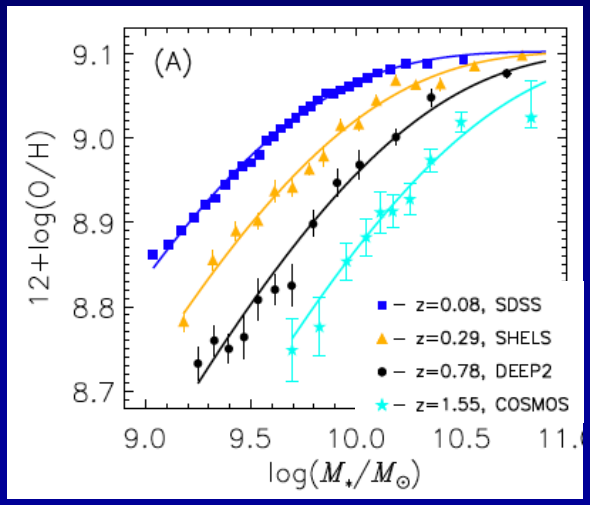
Mass-Metallicity Relation



- **New SDSS results from Andrews & Martini (2013) make use of "direct" oxygen abundances in stacked spectra – rather than empirical calibration.**
- **If $Z_{ISM} \approx y/(1+\eta)$, new SDSS MZR suggests η scales as $M_*^{-1/2}$ at low-mass end.**
- **Also obtain constraints on scaling of metal outflow rate (ζ) with M_* (much higher at lower stellar mass).**
- **Scatter in MZR may indicate time scale for equilibration following gas accretion event, merger, starburst.**

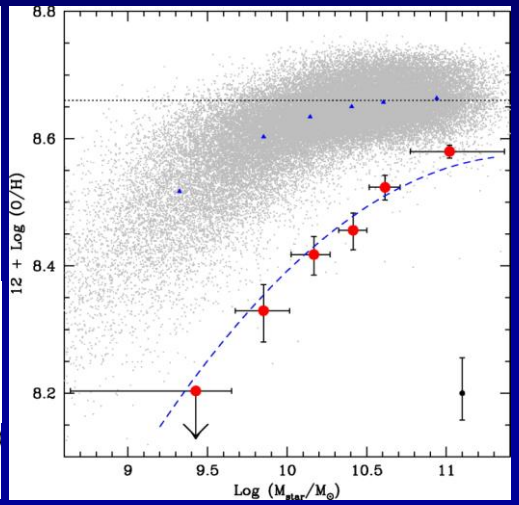
The MZR at High-z

z=0-1.6



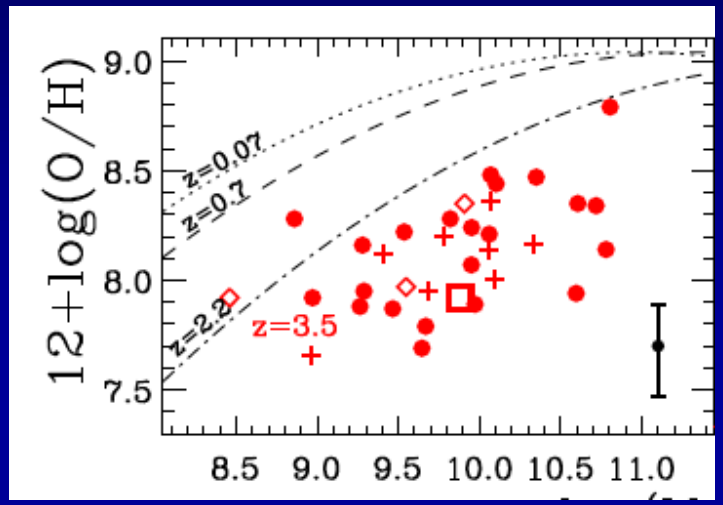
(Zahid et al. 2014)

z=2.2



(Erb et al. 2006a)

z=3.5

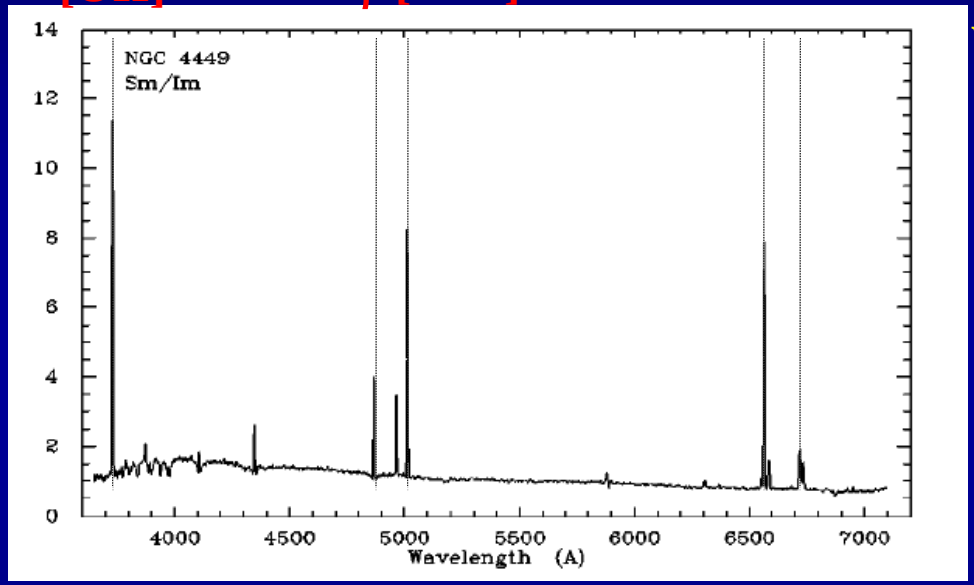


(Troncoso et al. 2014)

- Samples of objects at z > 1 with individual M-Z measurements are small, while the stacked samples at, e.g., z =2. 2 ,mask the scatter in the relation.
- Lots of new z>1 data coming in!
- So, how do we estimate O/H at high redshift, given that we can't make "direct" measurements like Andrews & Martini (2013)?

Rest-frame Optical Spectra

[OII] Hβ [OIII]

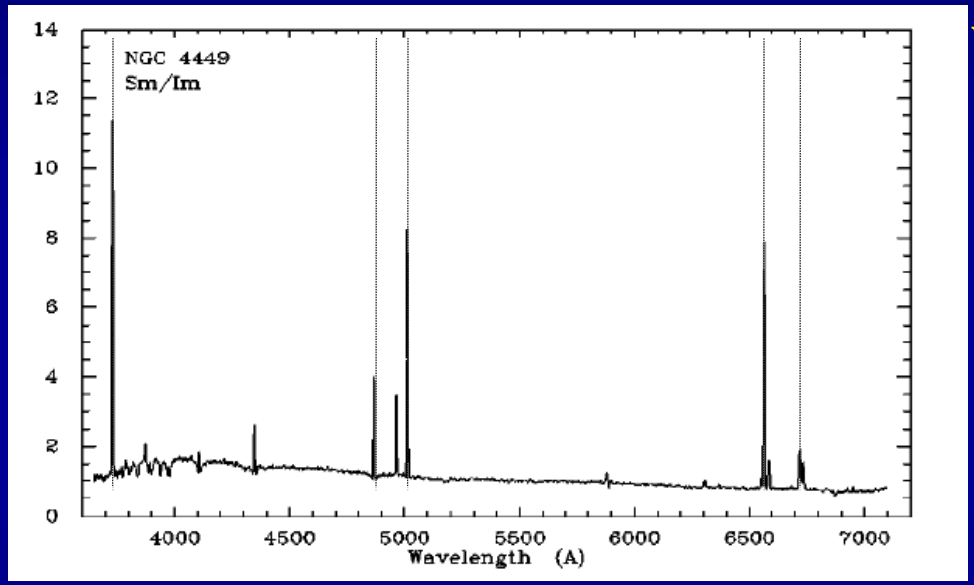


(Kennicutt 1998)

- Emission-line set: [OII], Hβ, [OIII], Hα, [NII], [SII]
- Ratios of emission lines used to infer a wide range of physical conditions:
  - SFR {Balmer lines}
  - Metallicity (oxygen) {R_{23}, N2, O3N2, others}
  - Electron density {[OII] and [SII] doublet ratios}
  - Ionization parameter {[OIII]/[OII]}
  - Electron temperature {[OIII] ratios}
  - Dust extinction {Balmer line ratios}

Rest-frame Optical Spectra

Hα+
[NII]



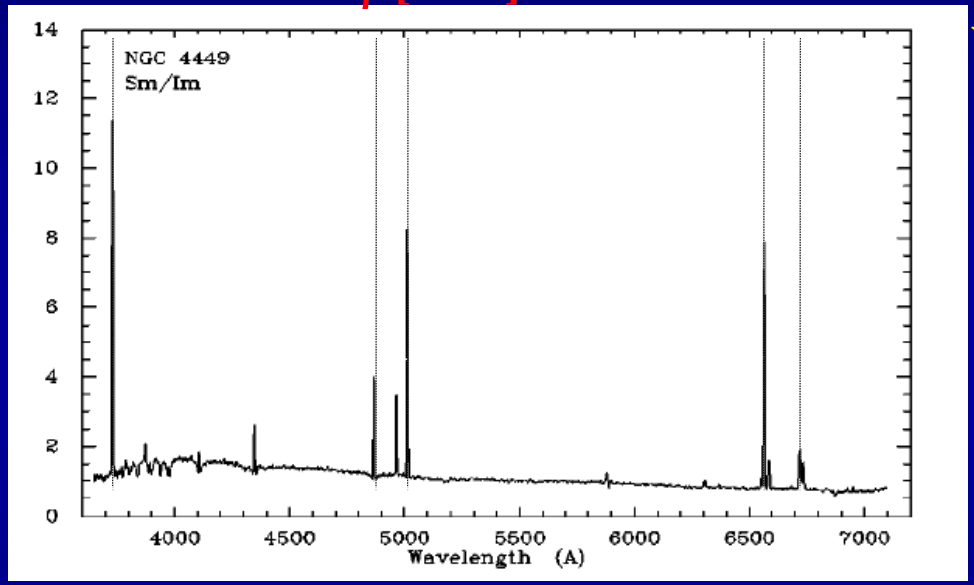
(Kennicutt 1998)

- Emission-line set: [OII], Hβ, [OIII], Hα, [NII], [SII]
- Ratios of emission lines used to infer a wide range of physical conditions:
  - SFR
    {Balmer lines}
  - Metallicity (oxygen)
    {R_{23}, N2, O3N2, others}
  - Electron density
    {[OII] and [SII] doublet ratios}
  - Ionization parameter
    {[OIII]/[OII]}
  - Electron temperature
    {[OIII] ratios}
  - Dust extinction
    {Balmer line ratios}

Rest-frame Optical Spectra

Hβ [OIII]

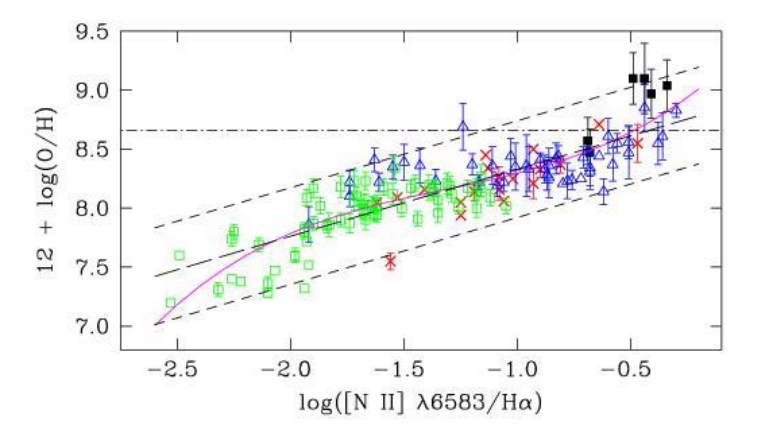
Hα+ [NII]

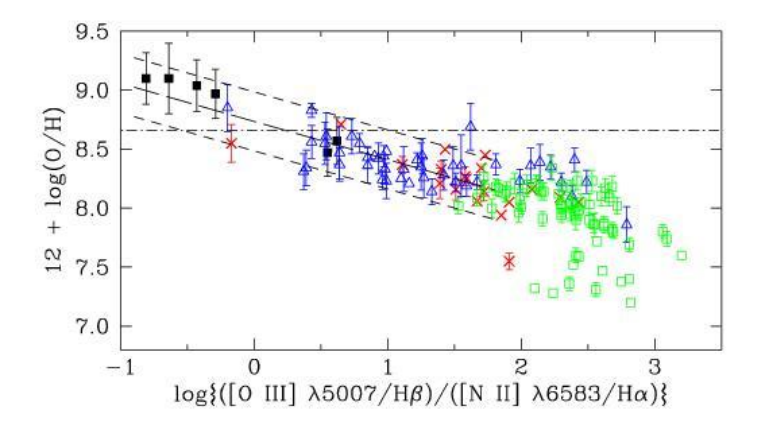


(Kennicutt 1998)

- **Emission-line set: [OII], Hβ, [OIII], Hα, [NII], [SII]**
- **Ratios of emission lines used to infer a wide range of physical conditions:**
  - **SFR**
    {Balmer lines}
  - **Metallicity (oxygen)**
    {R_{23}, N2, O3N2, others}
  - **Electron density**
    {[OII] and [SII] doublet ratios}
  - **Ionization parameter**
    {[OIII]/[OII]}
  - **Electron temperature**
    {[OIII] ratios}
  - **Dust extinction**
    {Balmer line ratios}

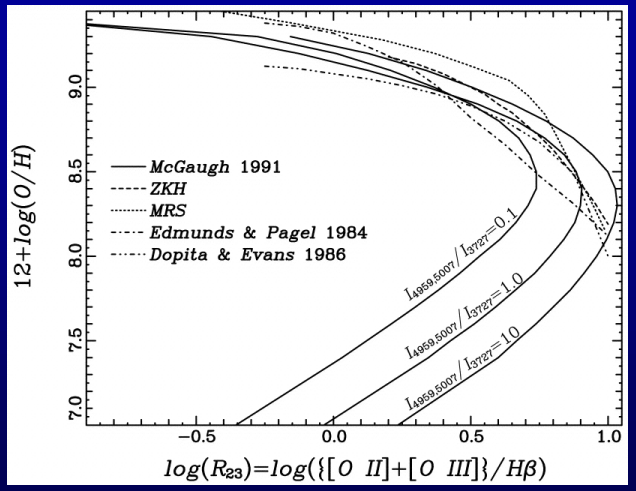
Common Metallicity Indicators



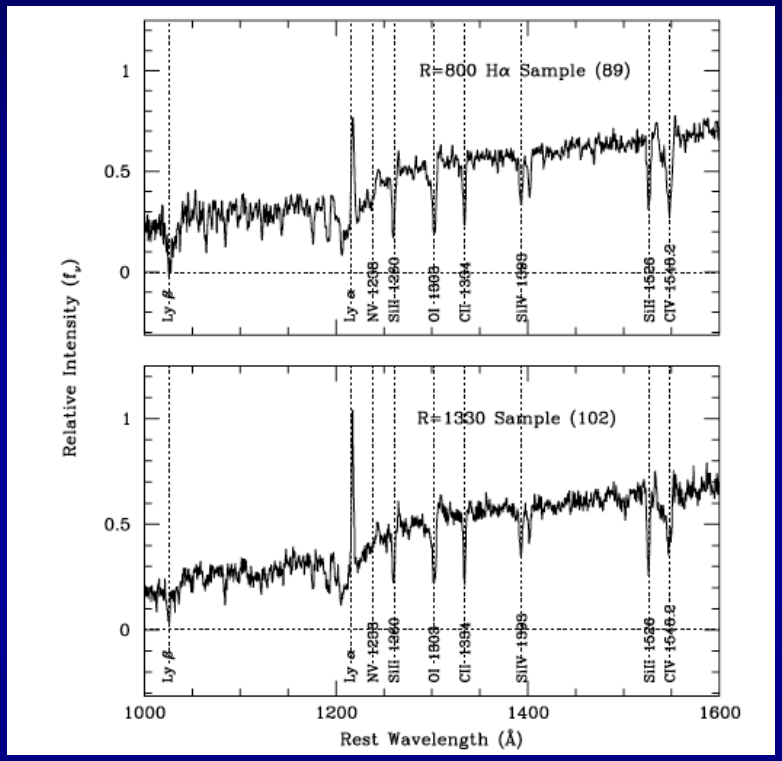


(Pettini & Pagel 2004)

- **Subsets of strong, rest-frame optical emission lines have been calibrated against "direct" methods, and photoionization models for local galaxies.**



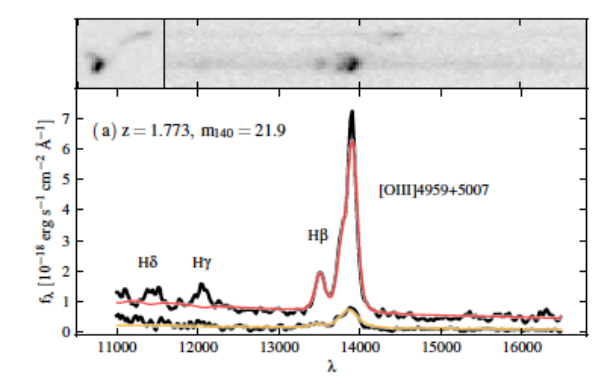
Spectroscopy at z>1.5



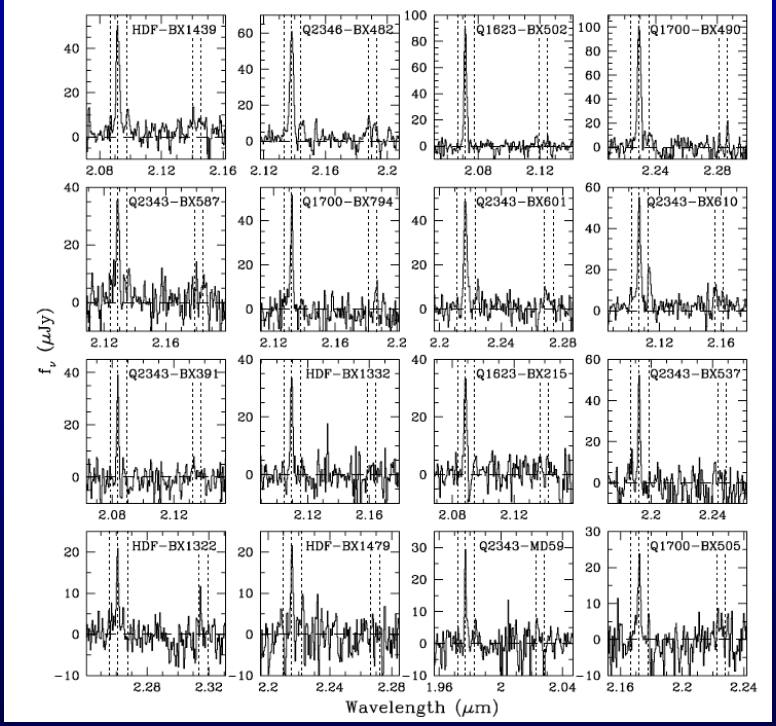
(Steidel et al. 2010)

- Most studies of galaxies at z>1.5 based on multi-wavelength photometry photometric redshifts.
- Until recently, spectroscopy was dominated by rest-UV observations of UV-selected galaxies (e.g., Steidel et al. 2003, 2004).
- Such studies are weighted towards relatively blue, star-forming galaxies.
- Rest-UV is a great probe of the ISM, outflows, and massive stars.

Spectroscopy at z>1.5



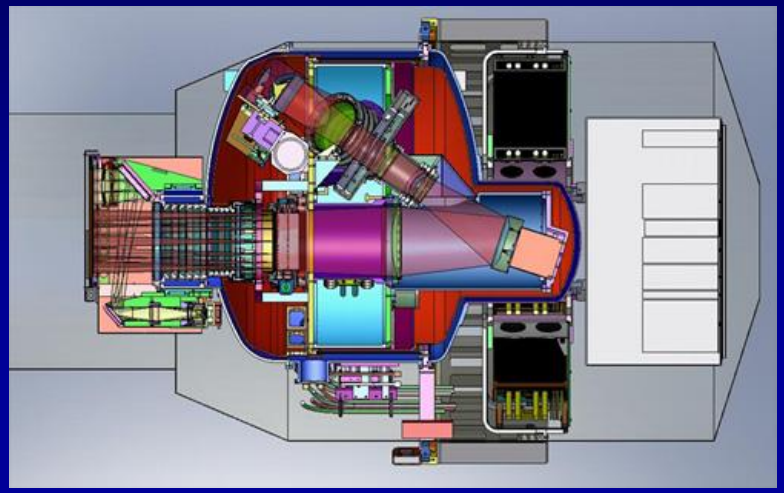
(Brammer et al. 2012)



(Erb et al. 2006)

- With the HST WFC3/IR grism, new surveys of ~10,000 galaxies with rest-frame optical spectroscopy for full range of galaxy types (3D-HST, WISP).
- Low resolution (R~130, i.e. >2,000 km/s), limited wavelength range (λ<1.6 μm).
- Samples of moderate (R>1000) resolution spectra at these redshifts are very small, and typically for one near-IR filter at a time (e.g., Erb et al. 2006).

Keck/MOSFIRE

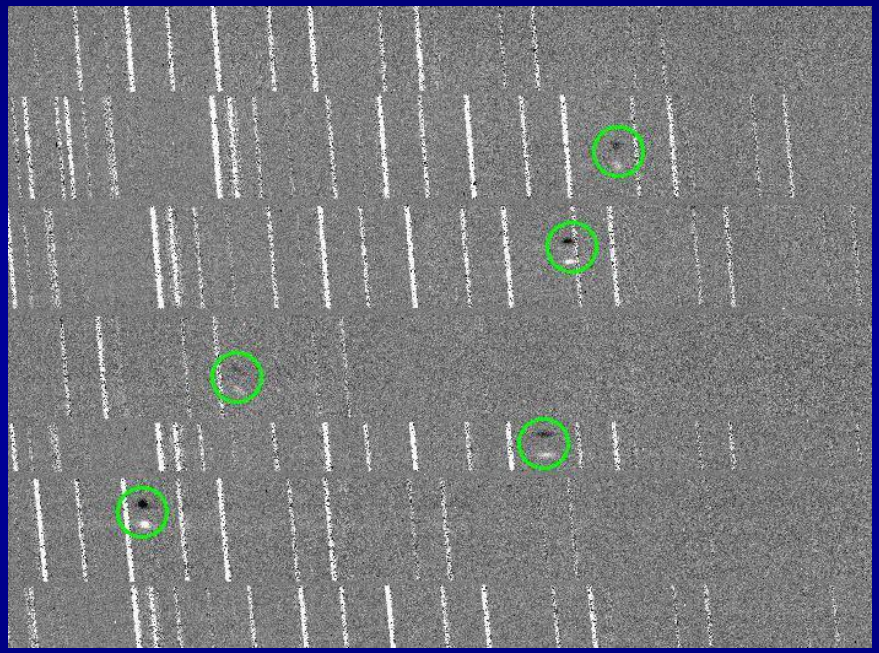


- Keck/MOSFIRE: Multi-Object Spectrometer for Infra-Red Exploration; co-Pis: McLean (UCLA) and Steidel (Caltech)
- Near-IR (0.9-2.5 μm) spectroscopy over 6.1’ × 3.0’ FOV, one band (YJHK) at a time, multiplex advantage up to 46 slits using robotic, cryogenic configurable slit unit. R=2300-3300 with 0.7” slit .
- Commissioned in spring 2012 on the Keck I telescope.
- Measurements of rest-frame optical spectra for z=0.5-5 galaxies.

MOSFIRE

http://www.astro.ucla.edu/~irlab/mosfire/

Keck/MOSFIRE



- **Sensitivity boost of at least a factor of ~5 relative to previous Keck instrumentation (NIRSPEC).**
- **Emission-line sensitivities of few x 10^{-18} erg/s/cm^2 in 2 hours.**
- **In practice, typical multiplexing of 30-35.**
- **Increase in survey efficiency of >2 orders of magnitude!!!!!**

MOSFIRE

http://www.astro.ucla.edu/~irlab/mosfire/

The MOSDEF Survey

• **Key requirements for an evolutionary census of the galaxy population at z~1.5-3.5:**

1. **Rest-frame optical spectroscopy covering all of the strongest rest-frame optical emission/absorption features (3700-7000 Å).**
2. **A large ($N>10^3$) sample of objects, spanning the full diversity of stellar populations.**
3. **Multiple redshift bins to enable evolutionary studies.**

The MOSFIRE Deep Evolution Field (MOSDEF) Survey achieves these goals.

The MOSDEF Survey

The MOSFIRE Deep Evolution Field Survey

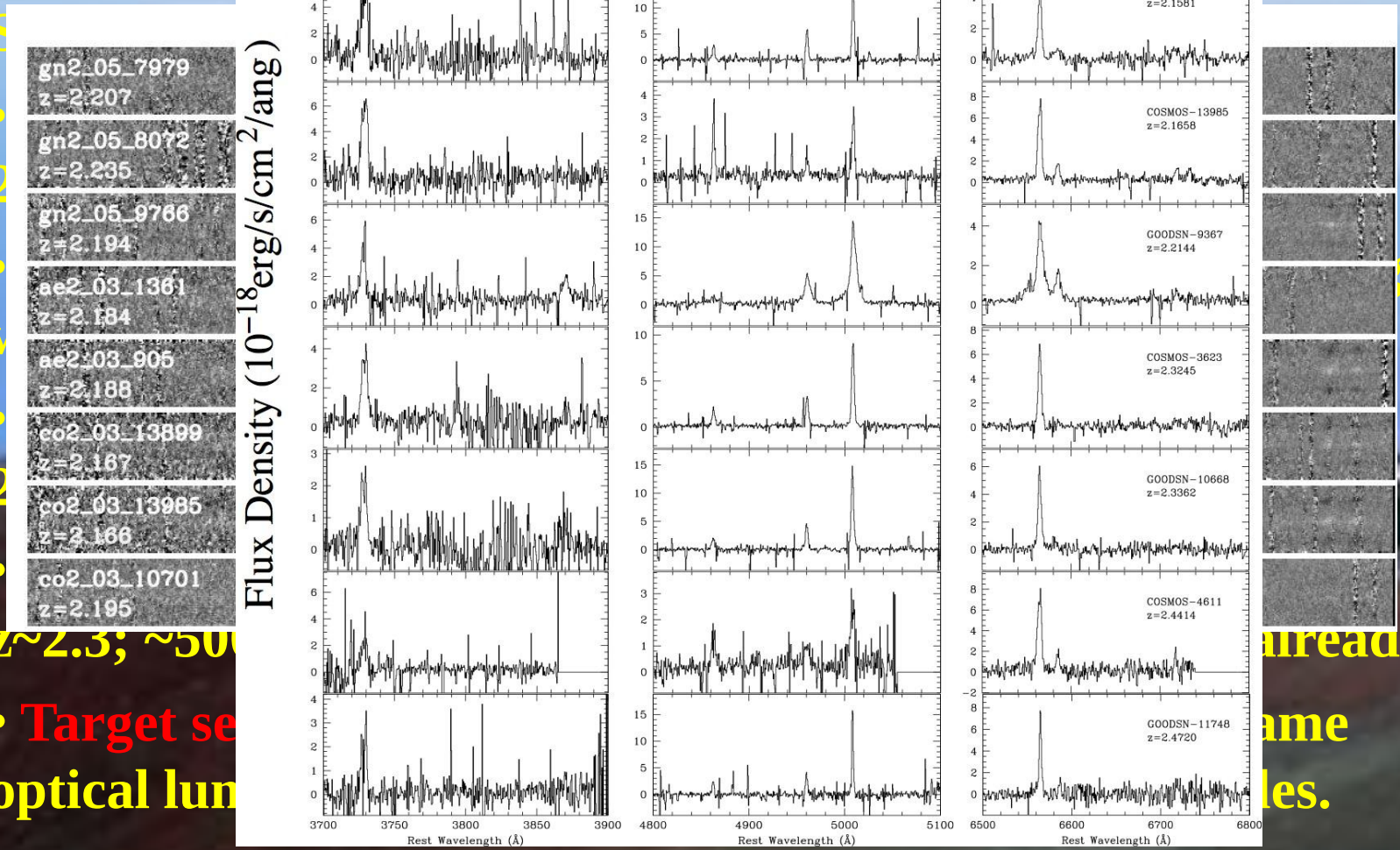
Co-PIs (in alphabetical order):
Alison Coil (UC San Diego)
Mariska Kriek (UC Berkeley)
Bahram Mobasher (UC Riverside)
Naveen Reddy (UC Riverside)
Alice Shapley (UC Los Angeles)
Brian Siana (UC Riverside)

Students:
William Freeman (UC Riverside)
Sedona Price (UC Berkeley)
Ryan Sanders (UC Los Angeles)
Irene Shivaei (UC Riverside)

Theory Co-Is:
James Bullock (UC Irvine)
Charlie Conroy (UC Santa Cruz)
Romeel Dave (University of Western Cape)
Dusan Keres (UC San Diego)
Marc Krumholz (UC Santa Cruz)

Collaborators
James Aird (Durham University)

The MOSDEF Survey

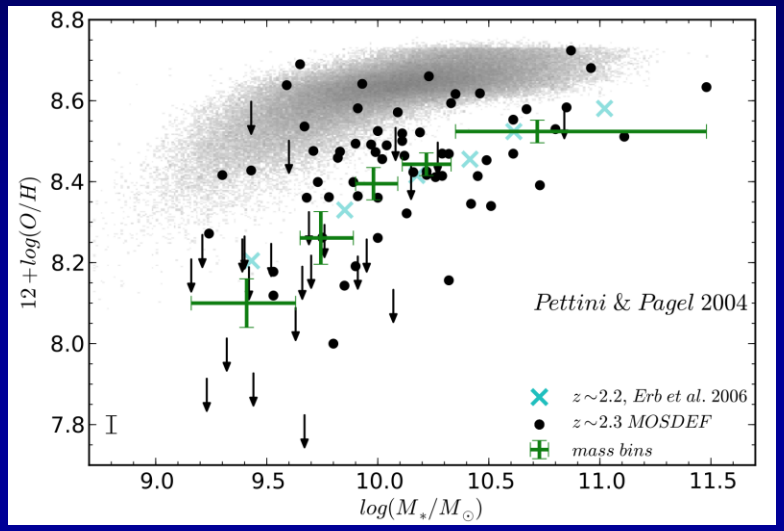


- Large UC… …eddy, Coil,
- …m
- …
- …already.
- Target se… …ame optical lum… …les.

The MOSDEF Survey: Science

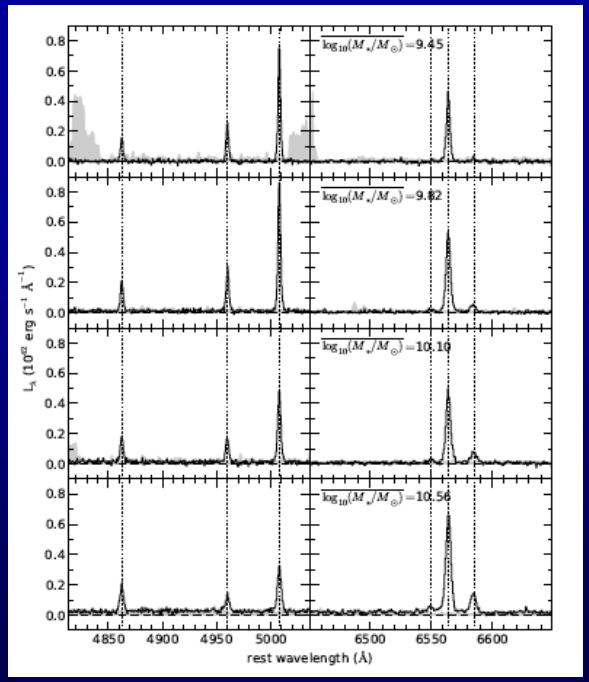
- Star formation and the growth of galaxies
- Dust attenuation
- Metallicities and physical conditions (density, excitation)
- The cycle of baryons (outflows, inflows)
- Dynamical masses and structural evolution
- AGN accretion and BH/Galaxy co-evolution

The MOSDEF Survey: MZR

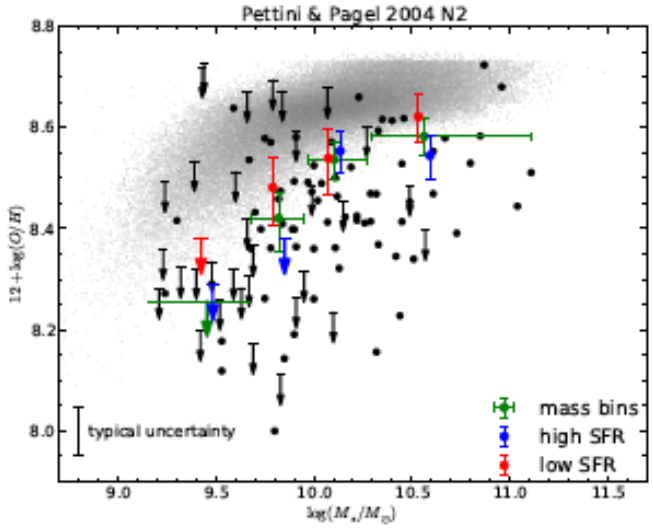


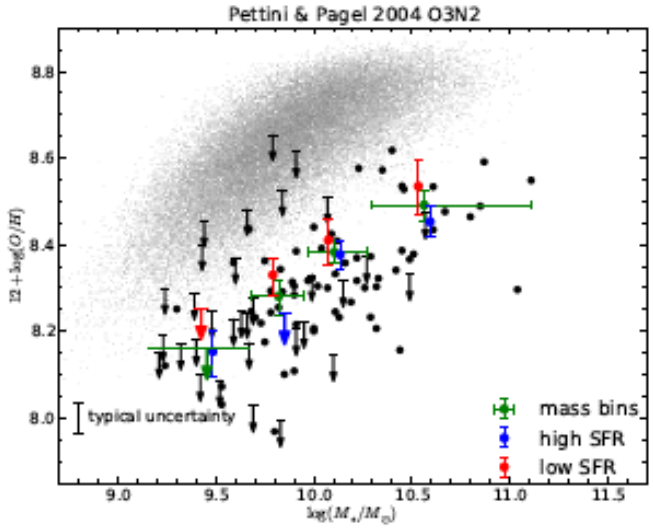
(Sanders, Shapley et al. 2014)

- We have assembled "N2" nad "O3N2" metallicities for our z~2 MOSDEF sample.
- Detect well-known offset towards lower metallicity at fixed mass.
- Scatter!
- Fair sample at z~2.



The MOSDEF Survey: MZR

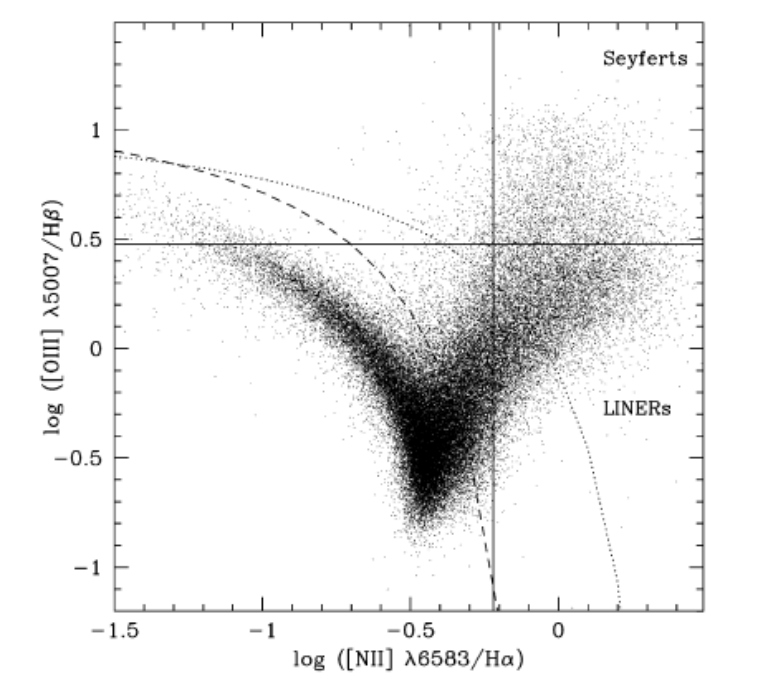




(Sanders, Shapley et al. 2014)

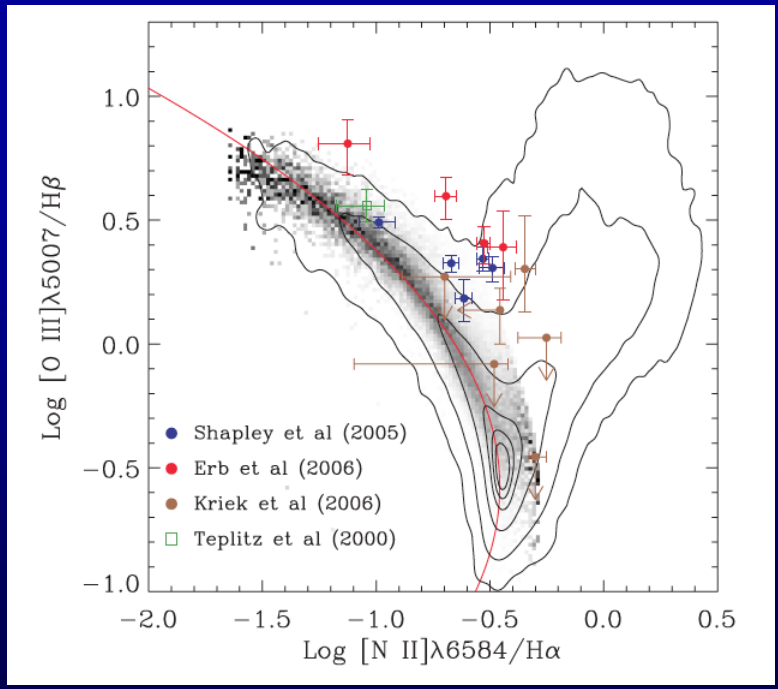
- We don't consistently detect the "FMR" seen at low redshift, with higher-SFR galaxies offset towards lower metallicity at fixed mass.
- Results depend on calibration, inclusion of limits.
- Also need to consider division of sample along SFR, bin in stellar mass.
- There may be issues with using locally-calibrated metallicity indicators….

The MOSDEF Survey: BPT



(Kauffmann et al. 2003)

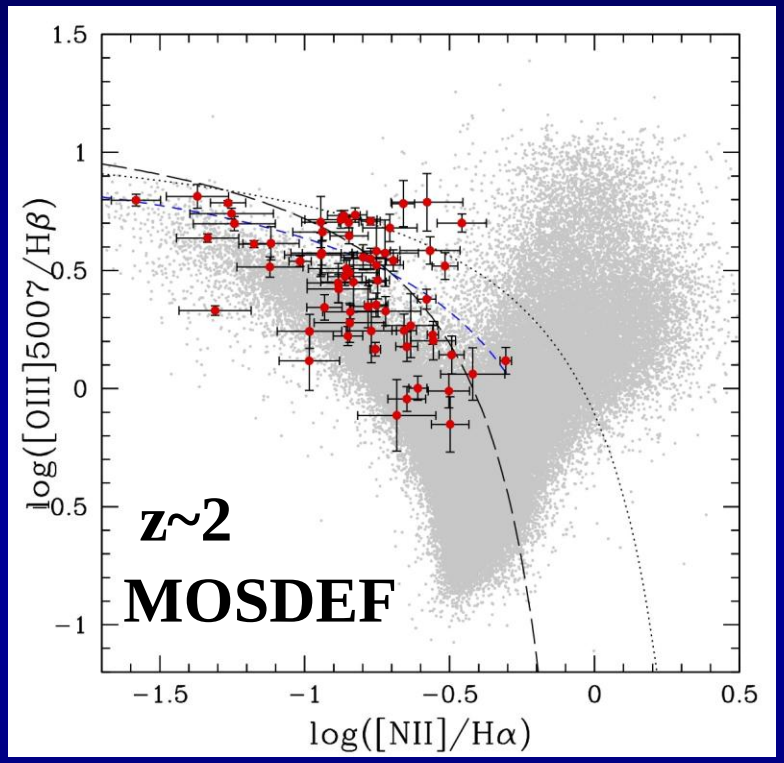
- As we showed several years ago with small samples of objects, z>1 star-forming galaxies are "offset" in the BPT excitation diagram used to separate star-forming galaxies from AGNs.



(Brinchmann et al. 2008)

What is the cause of this offset?

The MOSDEF Survey: BPT

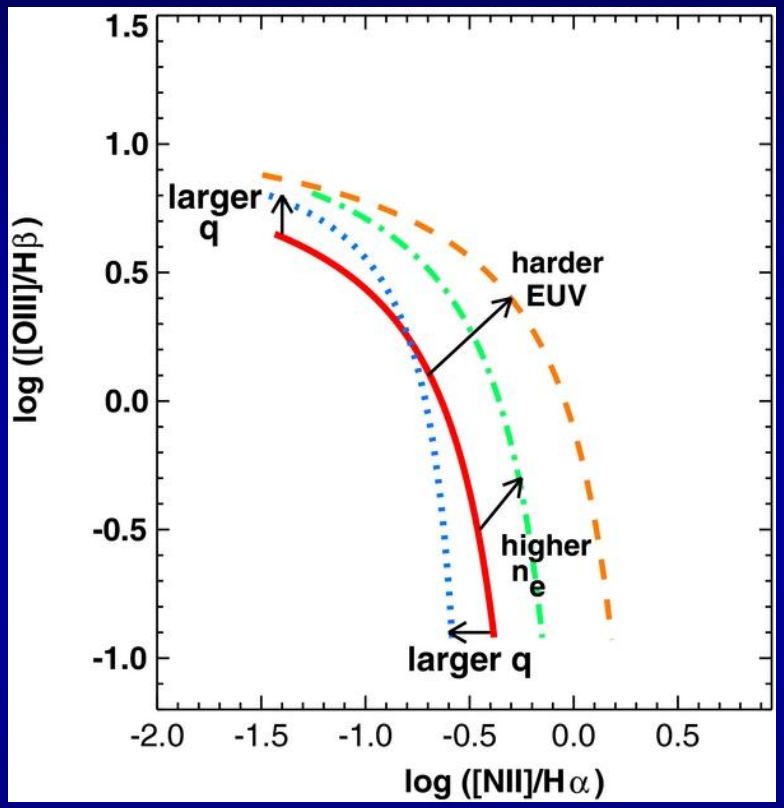


(Shapley et al. 2014)

What is the cause of this offset?

- **With a statistical sample already in early MOSDEF data, we can see that the offset is real!**
- **If line ratios are different in high redshift galaxies, suggests differences in physical conditions in HII regions.**
- **Higher ionization parameter (geometry of stars relative to gas); harder ionizing radiation field (e.g., Steidel et al. 2014; Kewley et al. 2013).**
- **With MOSDEF, we will isolate the factors leading to this offset (HII region density, ionization parameter, SFR surface density), and attempt to recalibrate metallicity indicators!**

The MOSDEF Survey: BPT

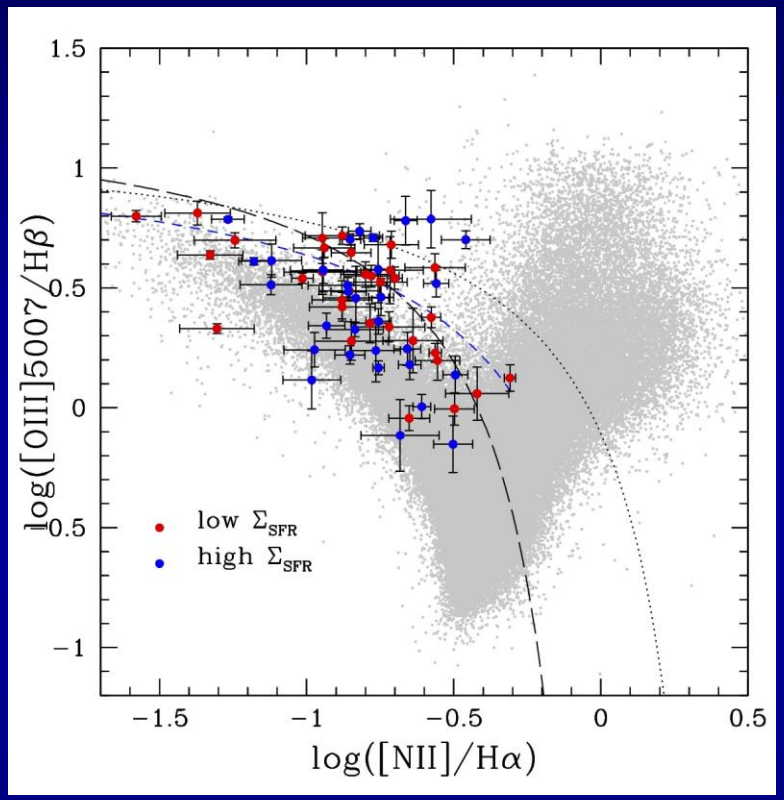


(Kewley et al. 2013)

What is the cause of this offset?

- **With a statistical sample already in early MOSDEF data, we can see that the offset is real!**
- **If line ratios are different in high redshift galaxies, suggests differences in physical conditions in HII regions.**
- **Higher ionization parameter (geometry of stars relative to gas); harder ionizing radiation field (e.g., Steidel et al. 2014; Kewley et al. 2013).**
- **With MOSDEF, we will isolate the factors leading to this offset (HII region density, ionization parameter, SFR surface density), and attempt to recalibrate metallicity indicators!**

The MOSDEF Survey: BPT

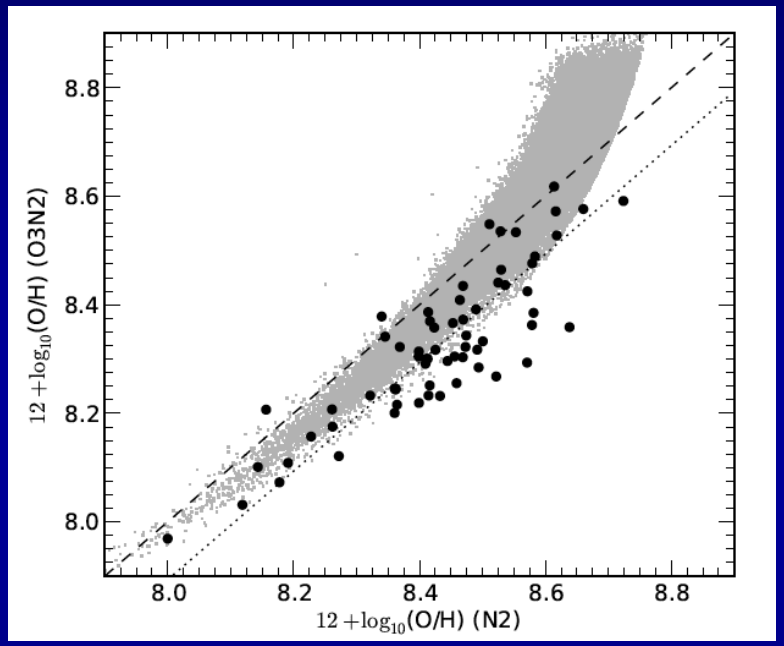


(Shapley et al. 2014)

What is the cause of this offset?

- **With a statistical sample already in early MOSDEF data, we can see that the offset is real!**
- **If line ratios are different in high redshift galaxies, suggests differences in physical conditions in HII regions.**
- **Higher ionization parameter (geometry of stars relative to gas); harder ionizing radiation field (e.g., Steidel et al. 2014; Kewley et al. 2013).**
- **With MOSDEF, we will isolate the factors leading to this offset (HII region density, ionization parameter, SFR surface density), and attempt to recalibrate metallicity indicators!**

The MOSDEF Survey: BPT



(Sanders et al. 2014)

What is the cause of this offset?

- With a statistical sample already in early MOSDEF data, we can see that the offset is real!
- If line ratios are different in high redshift galaxies, suggests differences in physical conditions in HII regions.
- Higher ionization parameter (geometry of stars relative to gas); harder ionizing radiation field (e.g., Steidel et al. 2014; Kewley et al. 2013).
- With MOSDEF, we will isolate the factors leading to this offset (HII region density, ionization parameter, SFR surface density), and attempt to recalibrate metallicity indicators!

Summary

- **Kinematic signatures of outflows at z~1-4 are straightforward to establish.**
- **We can further establish that the geometry of outflows appears to evolve: collimated at z≤1, not collimated at z>2, and that outflow kinematics are significantly correlated with Σ_{SFR}.**
- **Outflow physical properties most relevant for models of galaxy formation are very difficult to constrain observationally (e.g., mass/momentum/energy outflow rate, and η, mass loading factor).**
- **Absorption-line (and emission-line) data with higher spectral resolution will help (lensed galaxies, ; bigger telescopes), as current velocity data are crude and low-resolution.**
- **The M-Z relation holds promise for placing constraints on outflows, *if we can calibrate metallicity indicators.* The MOSDEF survey will be key for this.**
- **A different approach as well: perhaps better to "observe" simulations and reproduce absorption-line profiles in order to infer mass outflow rates.**