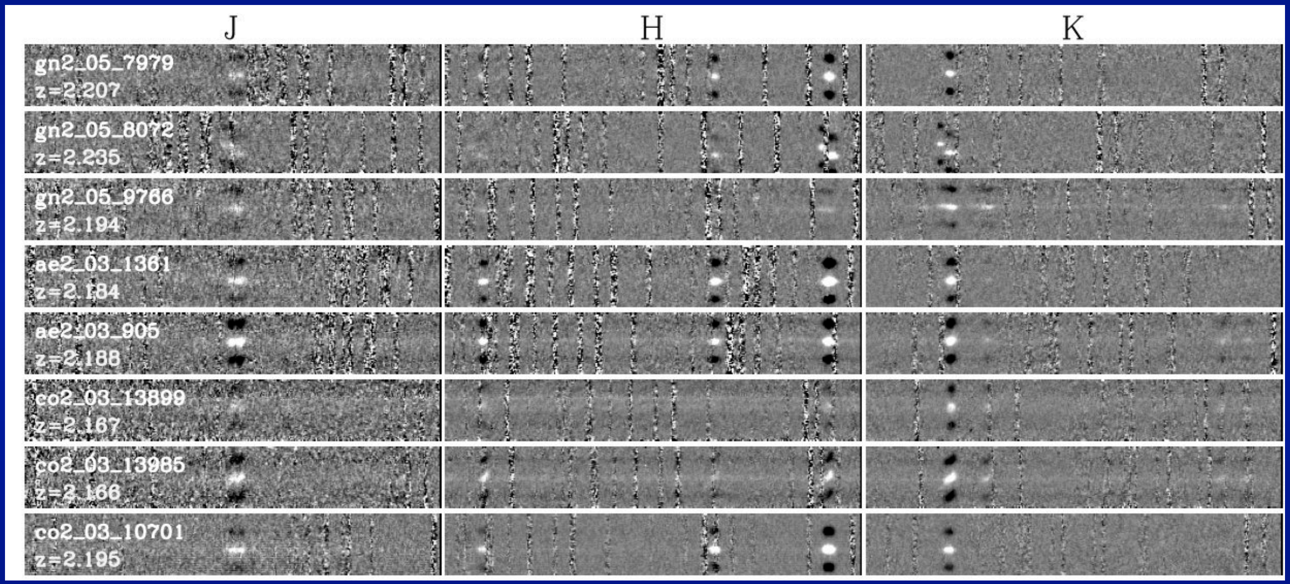
Rest-frame Optical Spectra: A Window into Galaxy Formation at z~2



Alice Shapley (UCLA)

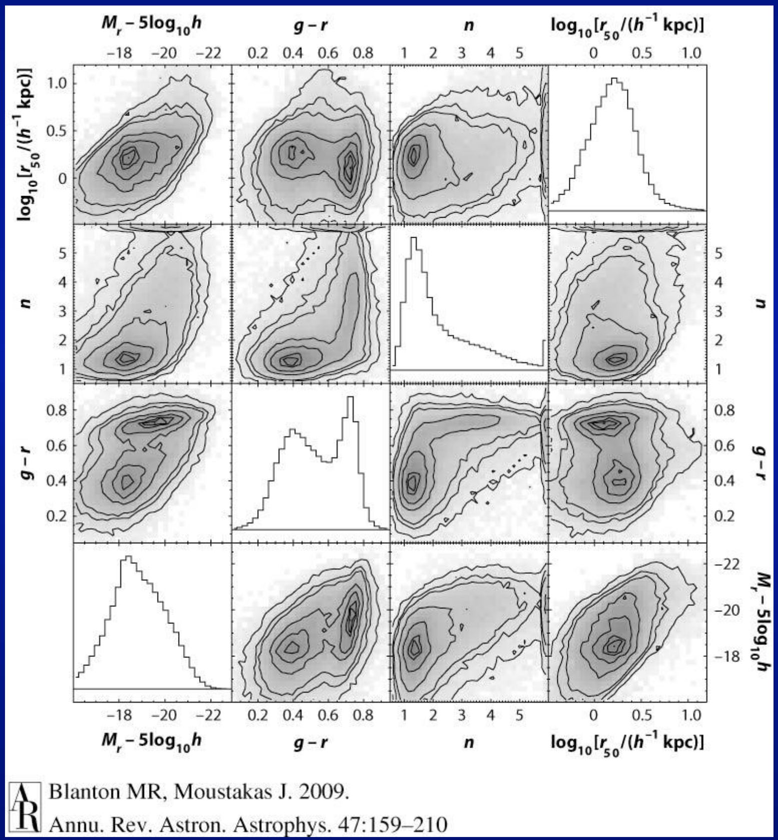
Collaborators: Mariska Kriek, Naveen Reddy, Brian Siana, Alison Coil, Bahram Mobasher, Bill Freeman, Ryan Sanders, Sedona Price, Laura DeGroot

Introduction

- What are the physical processes driving star formation in individual galaxies?
- How are stellar mass and structure assembled in galaxies (in situ star formation vs. mergers)?
- How do galaxies exchange gas and heavy elements with the intergalactic medium?
- What is the nature of the co-evolution of black holes and stellar populations?

Rest-frame optical spectroscopic observations across cosmic time will address all of these questions.

The Local Universe



(Blanton & Moustakas 2009)

- Massive surveys like the Sloan Digital Sky Survey SDSS) and 2dF Galaxy Redshift survey give detailed description of local galaxy population: the endpoint.
- Imaging and spectra of $>10^6$ galaxies.
- Distributions in luminosity, color, mass (stellar, dynamical, BH), structure, gas content, metallicity, environment, clustering.
- Correlations among these properties.

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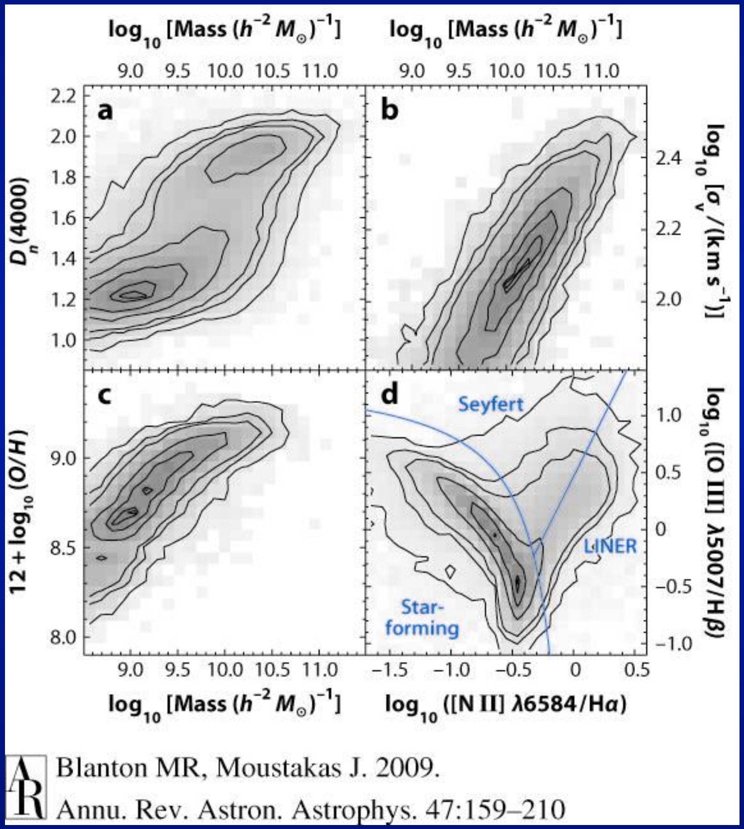

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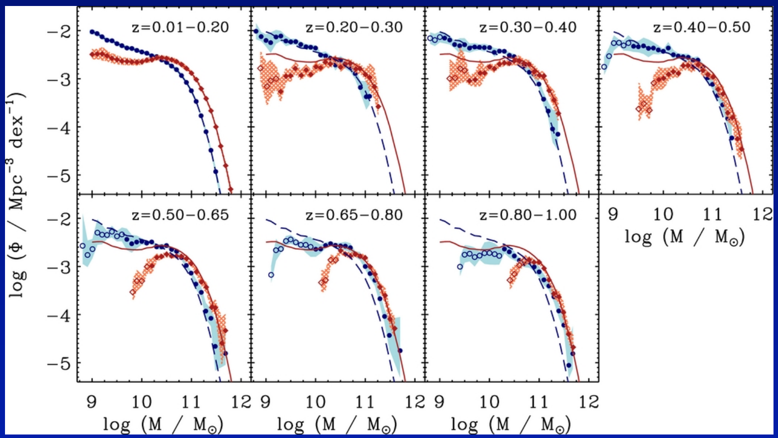
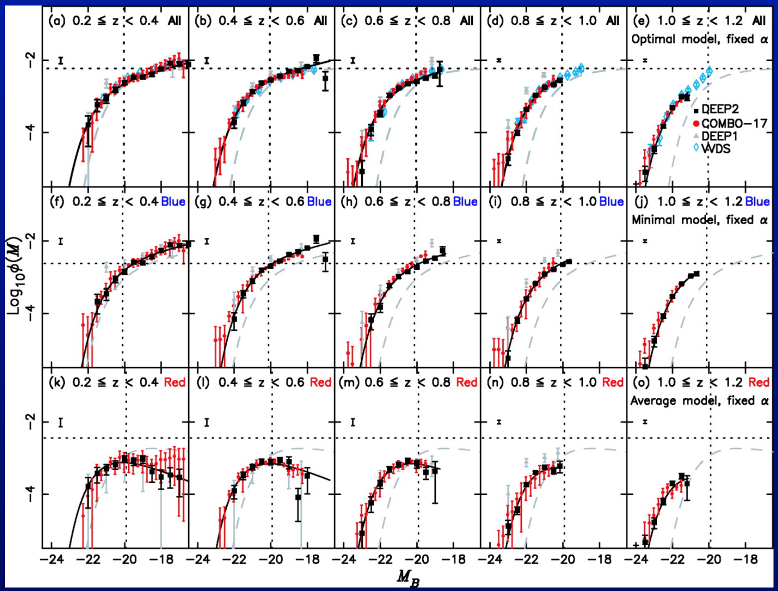
Earlier Epochs

(Moustakas et al. 2013)

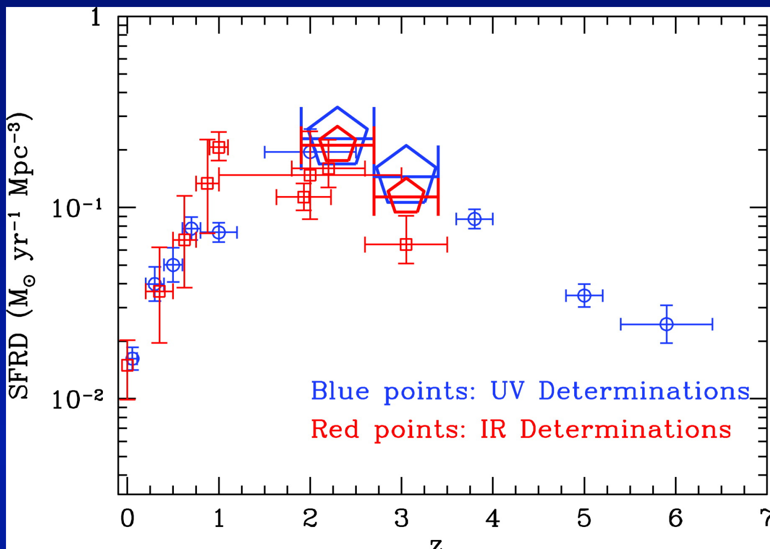


(Faber et al. 2007)

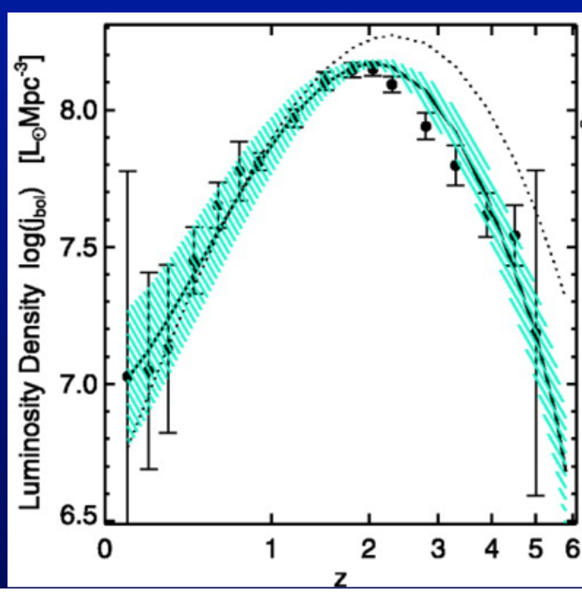


- For the full story, we need data from earlier epochs.
- Several spectroscopic surveys probe out to z~1 (DEEP2, VVDS, zCOSMOS, PRIMUS). Sample sizes of ~10^4-10^5 galaxies.
- Evolution in luminosities, masses, colors, sizes, and environments of star-forming and quiescent galaxies.

The Next Frontier: z~1.5-3.5



(Reddy et al. 2008)



(Hopkins et al. 2007)

- z~1.5-3.5 hosts the peak of both star formation and BH accretion activity.
- Qualitative imprints of local galaxy population (bimodal distribution of colors, strong clustering of red galaxies).
- Big differences as well: diversity among massive galaxies; absence of cold, quiescent disks; higher specific SFRs; ubiquitous galaxy outflows.

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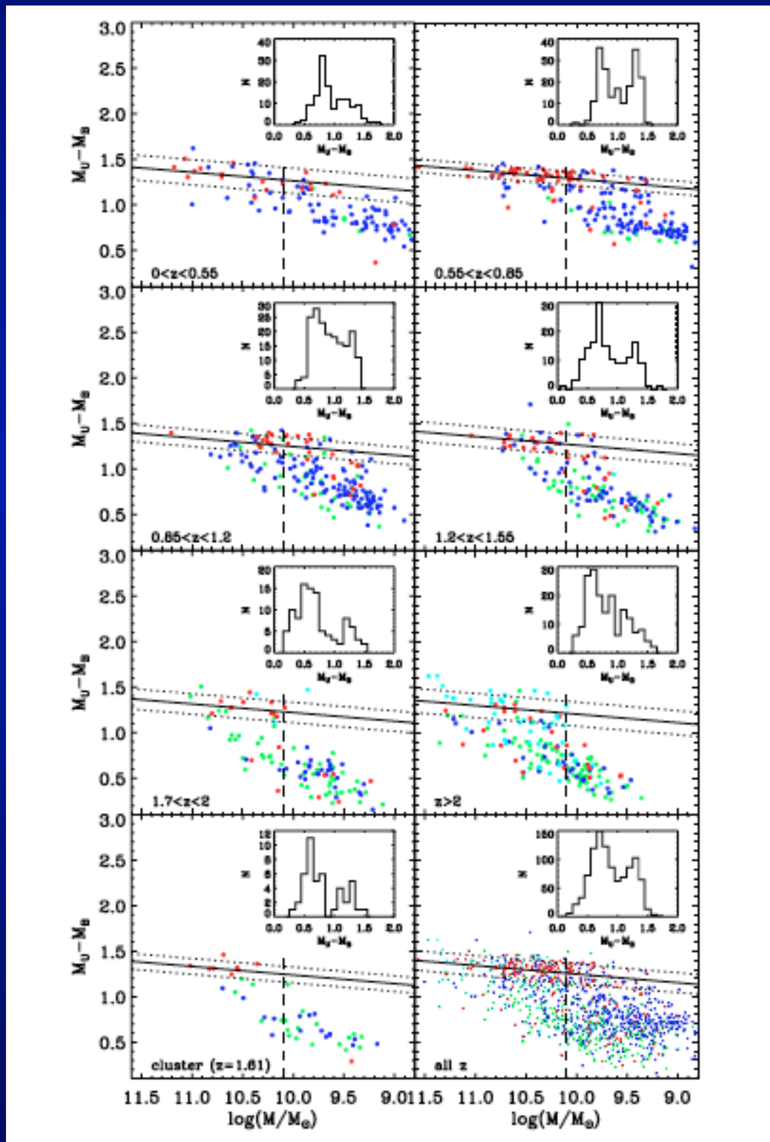

(Cassata et al. 2008)

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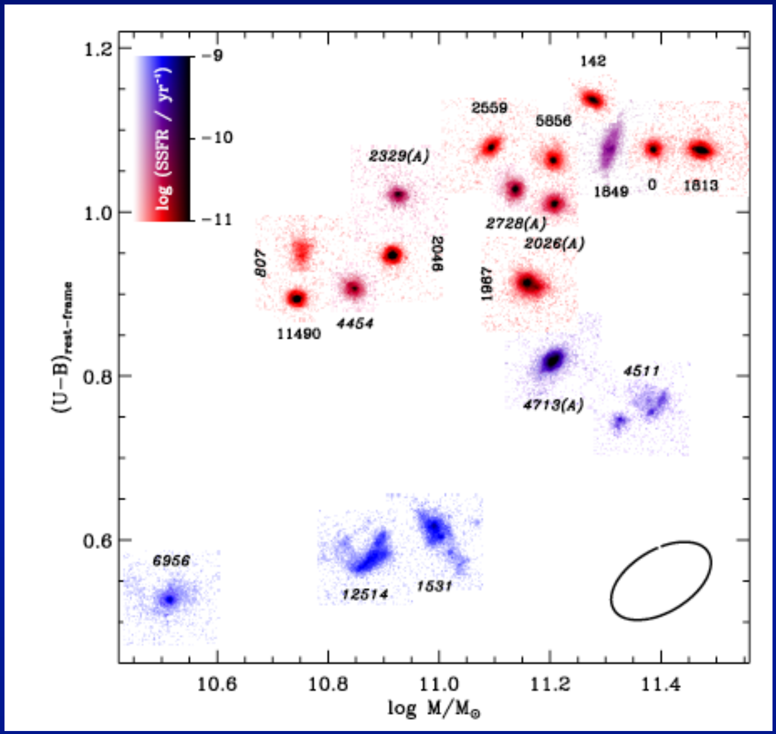
The Next Frontier: z~1.5-3.5

(Kriek et al. 2009)



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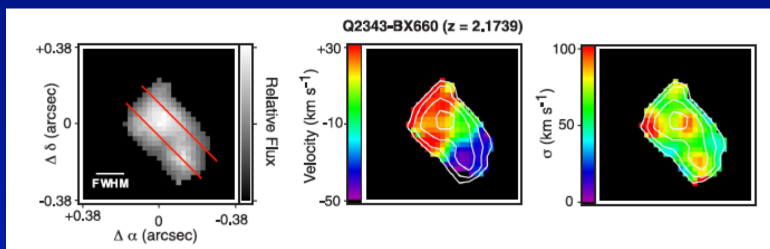
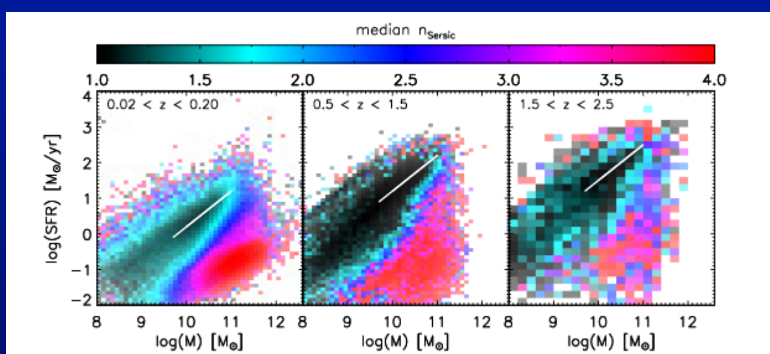
The Next Frontier: z~1.5-3.5

(Wuyts et al. 2011) (Law et al. 2009)





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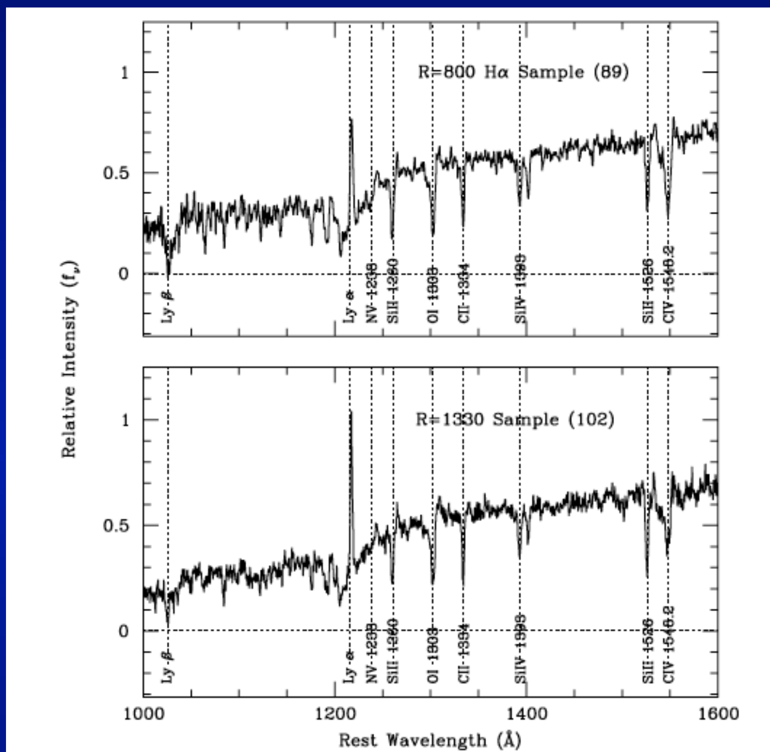
Spectroscopy at z>1.5

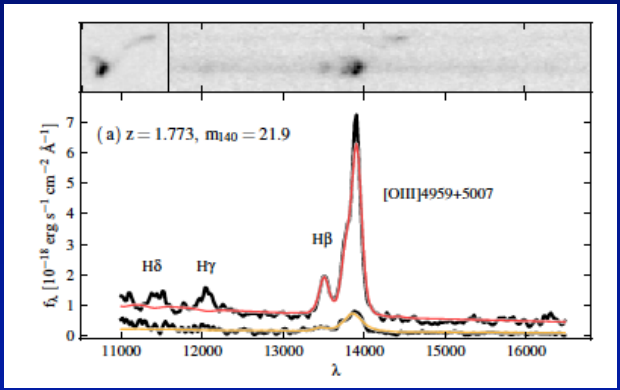
(Steidel et al. 2010)



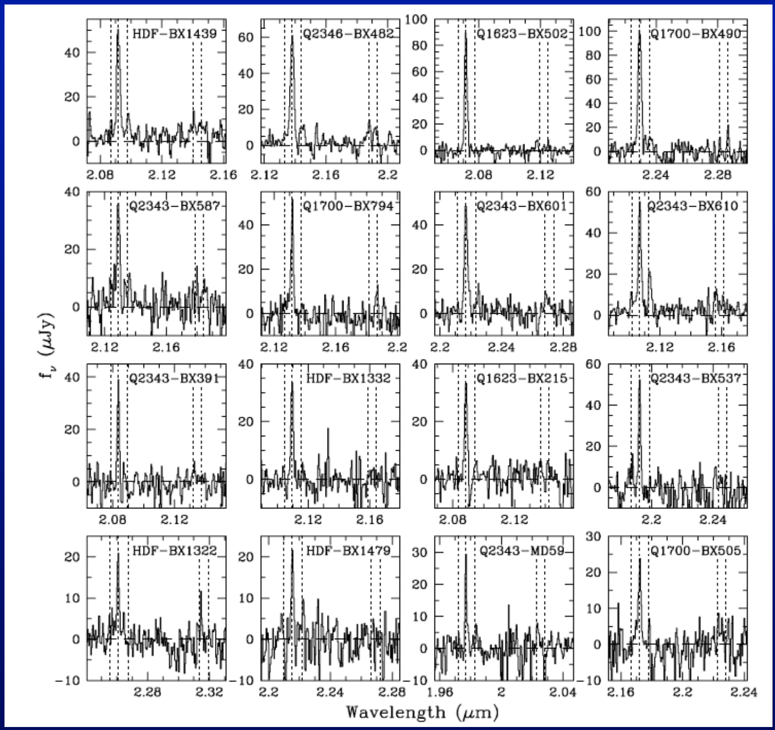
- Most studies of galaxies at z>1.5 based on multi-wavelength photometry photometric redshifts.
- Until recently, spectroscopy was dominated by rest-UV observations of UV-selected galaxies (e.g., Steidel et al. 2003, 2004).
- Such studies are weighted towards relatively blue, star-forming galaxies.
-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

Spectroscopy at z>1.5

(Brammer et al. 2012)

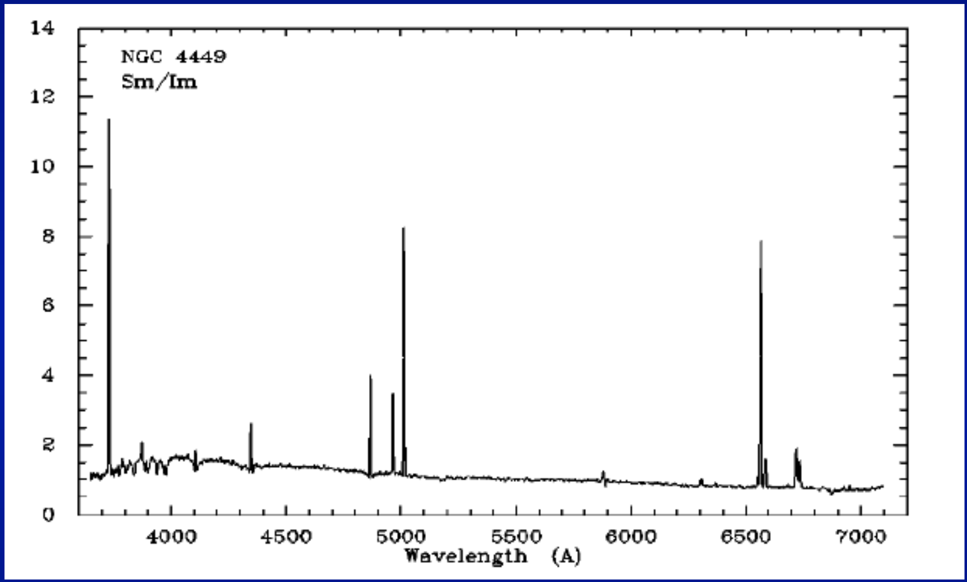


(Erb et al. 2006)



- 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).

Rest-frame Optical Spectra



(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
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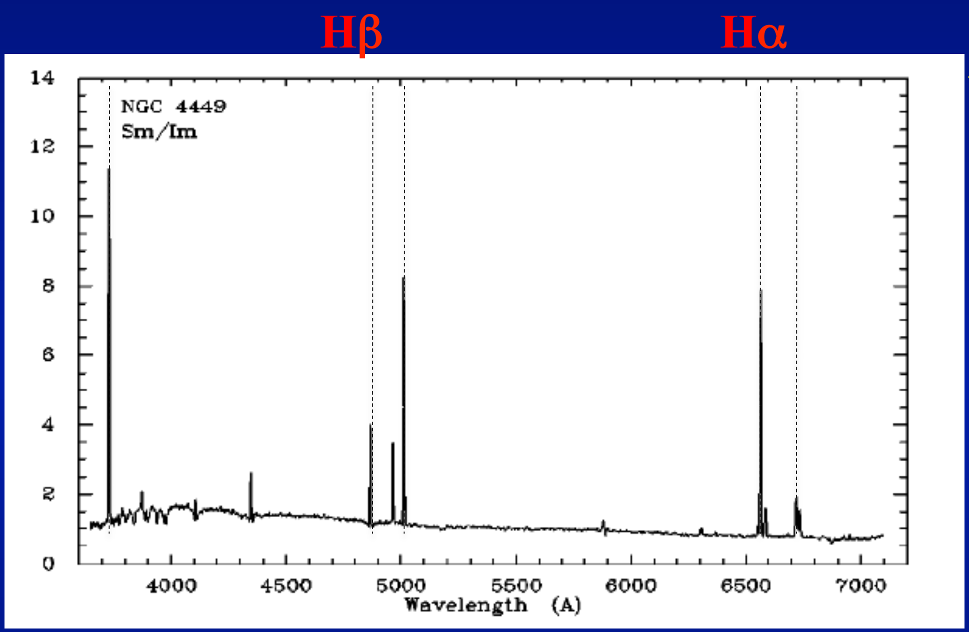

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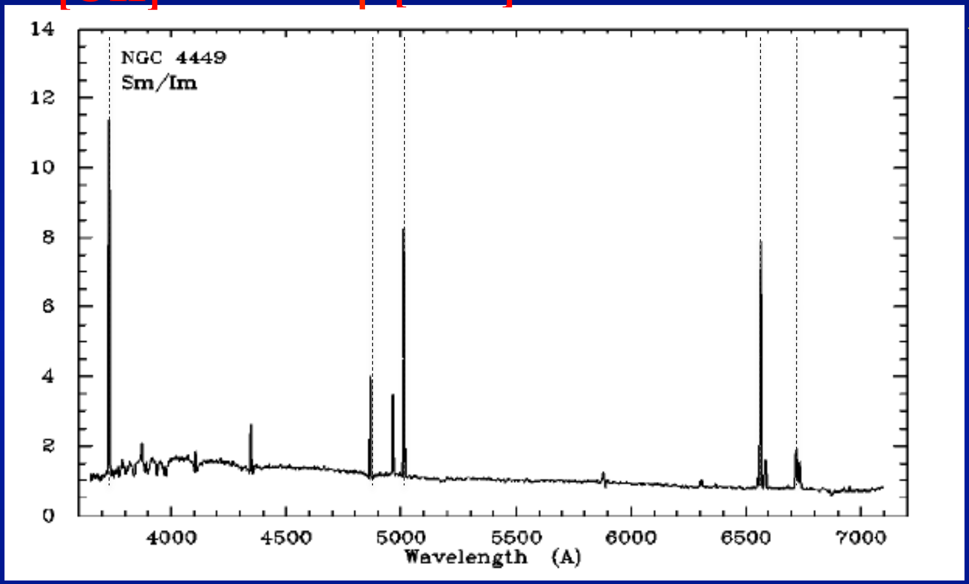
Rest-frame Optical Spectra

[OII] Hβ [OIII]



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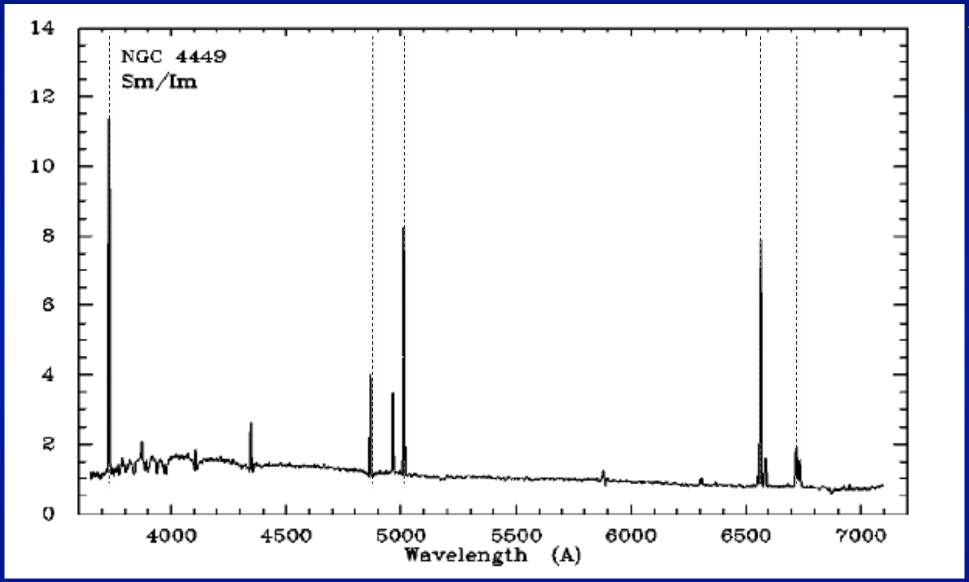
Rest-frame Optical Spectra

Hα+
[NII]



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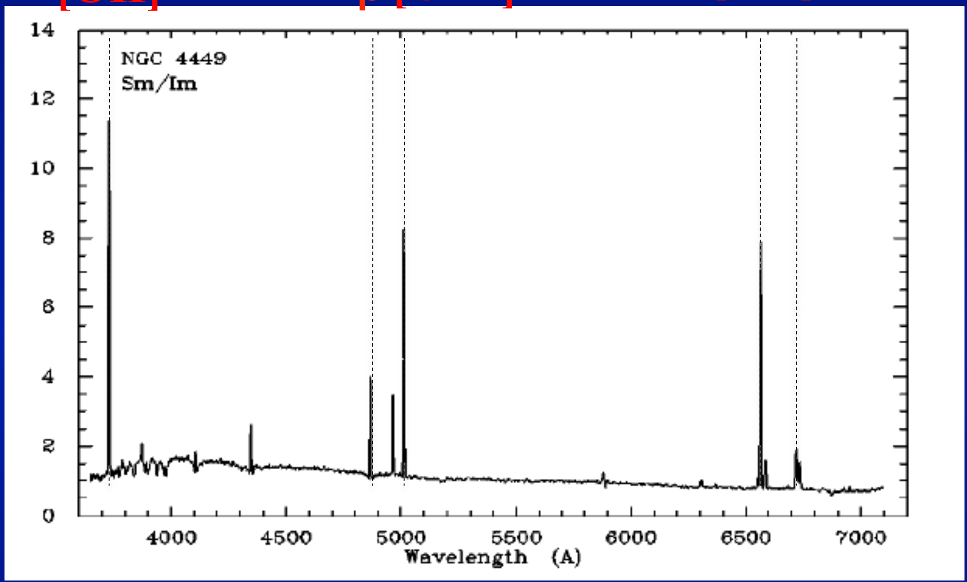

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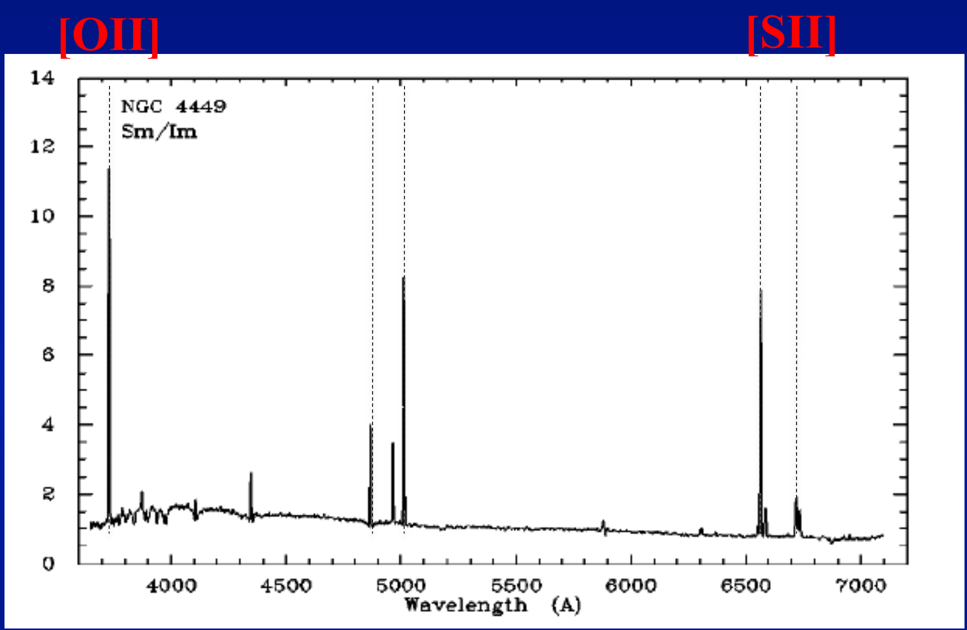

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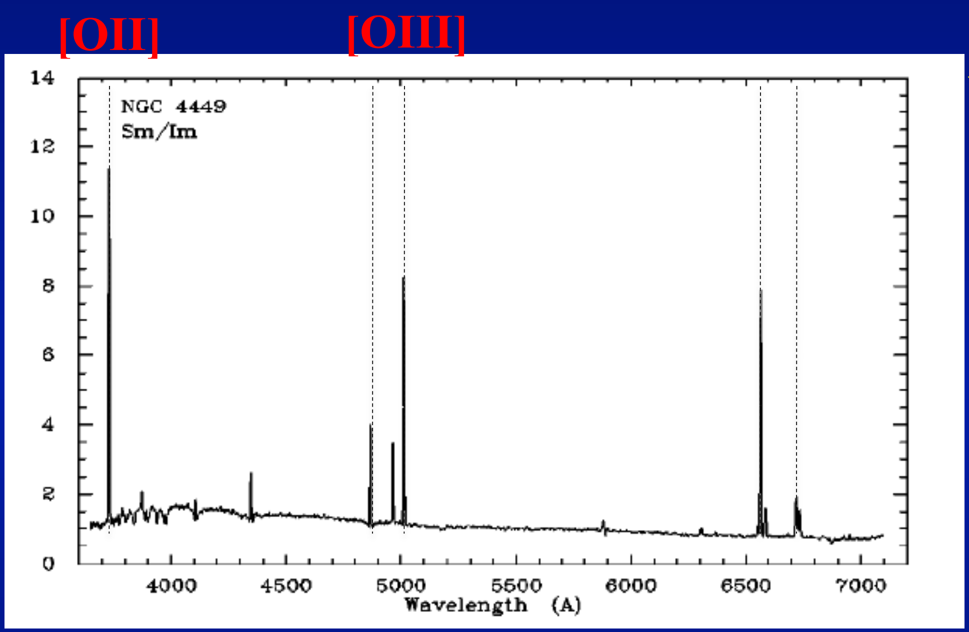

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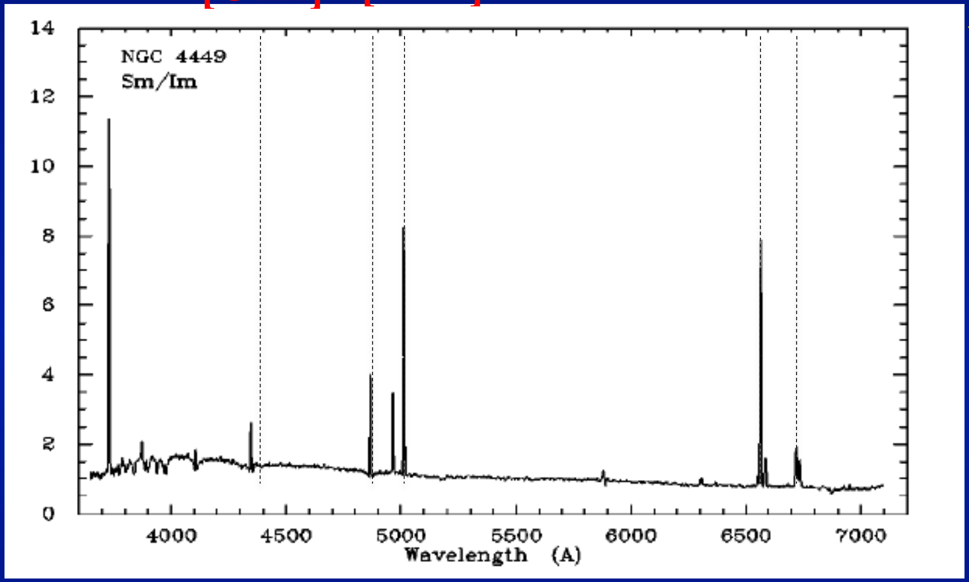
Rest-frame Optical Spectra

[OIII] [OIII]



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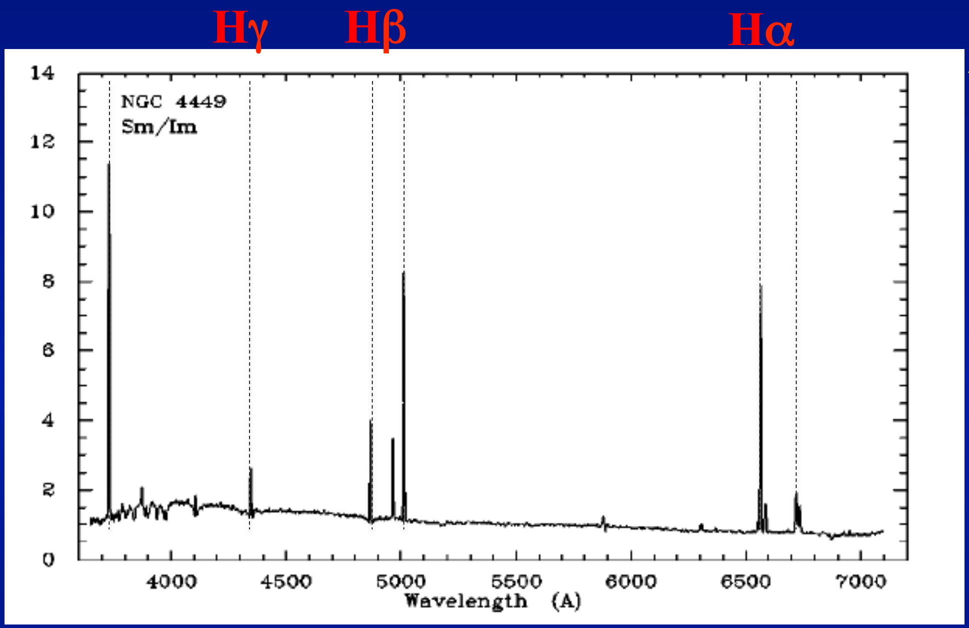

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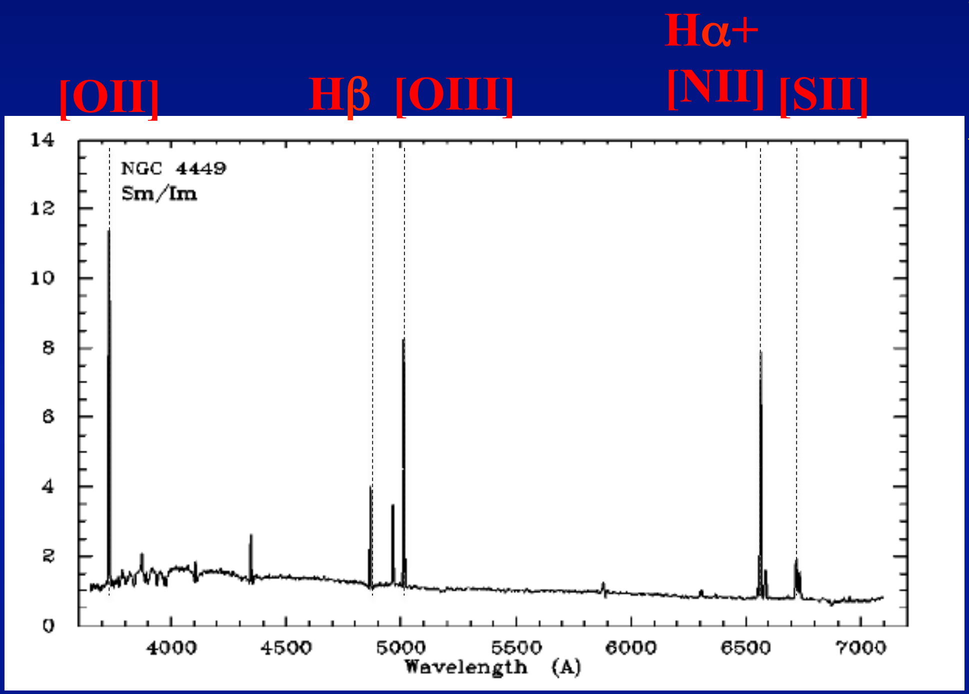

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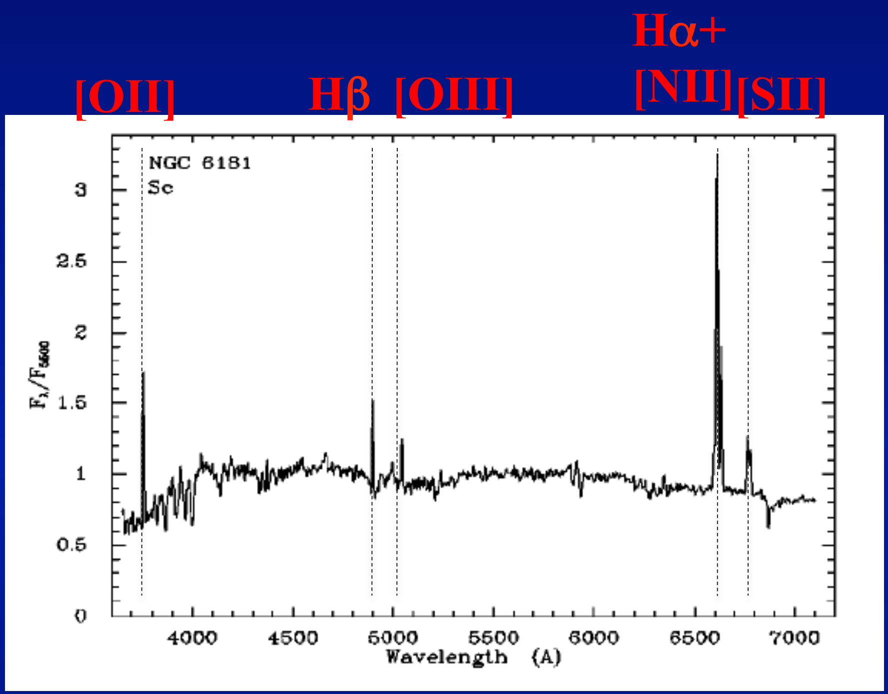

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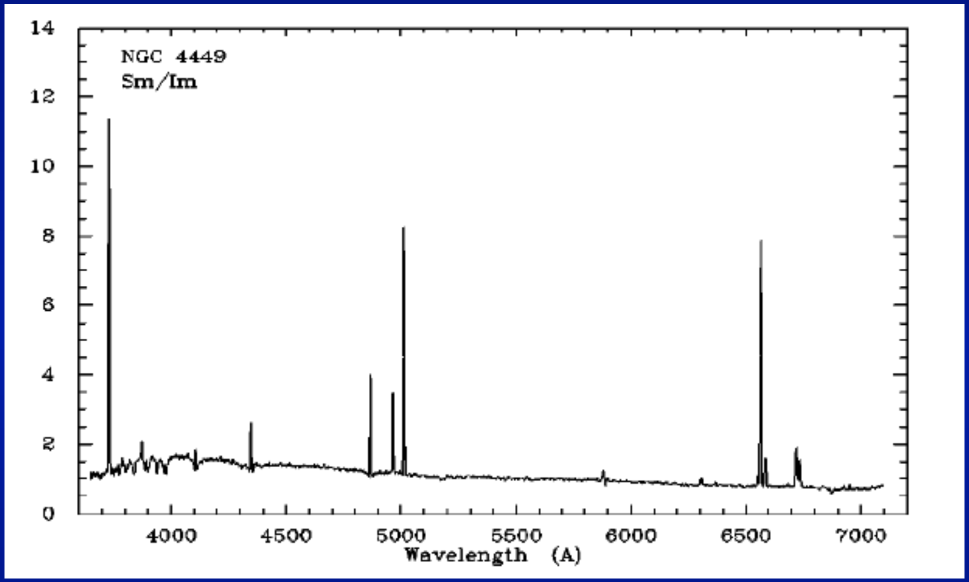
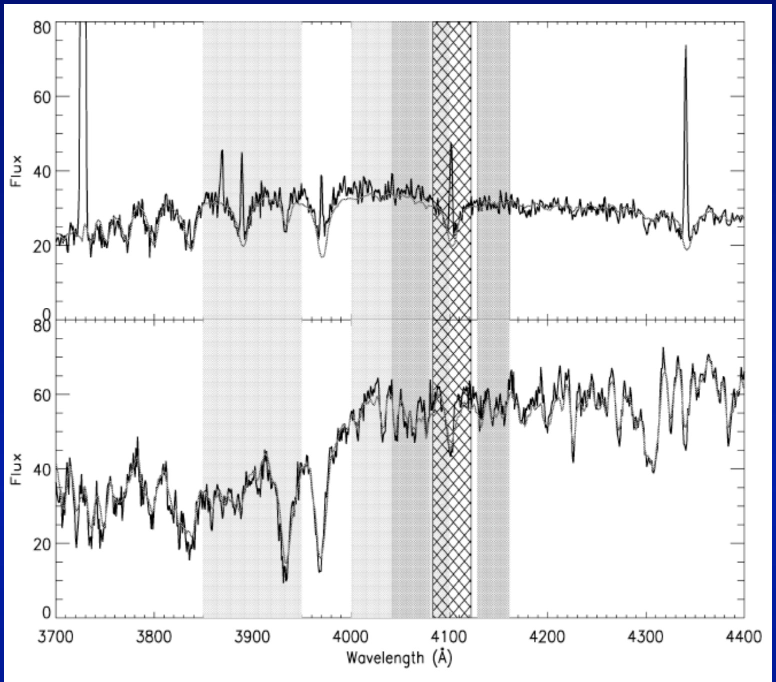


(Kennicutt 1998)

- In addition
  - dynamical masses
  - AGN/SF discrimination
  - outflow properties

Rest-frame Optical Spectra

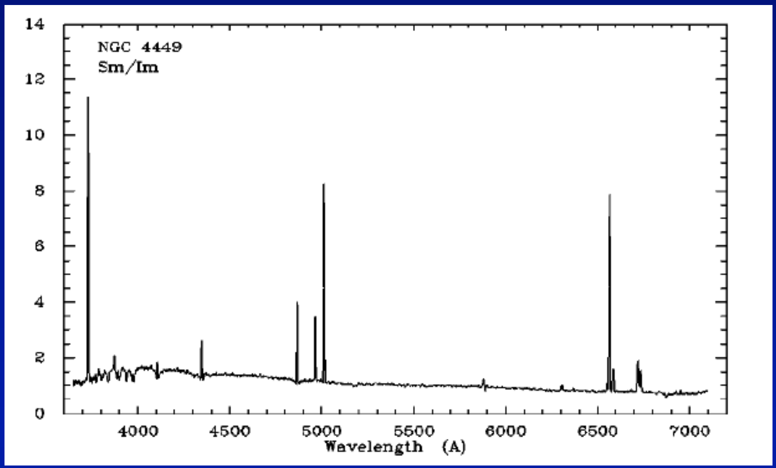


(Kauffmann et al. 2003)

- Absorption lines
- At low-z (e.g., SDSS), spectral diagnostics, $D_n(4000)$, $H\delta_A$, others, have been used to infer M/L, fraction of mass formed in burst, stellar velocity dispersion, metallicity.
- The samples for which such measurements have been assembled at z>1.4 are in the "handfuls."
- Continuum spectroscopy is HARD at these redshifts.

Rest-frame Optical Spectra

(Kennicutt 1998)



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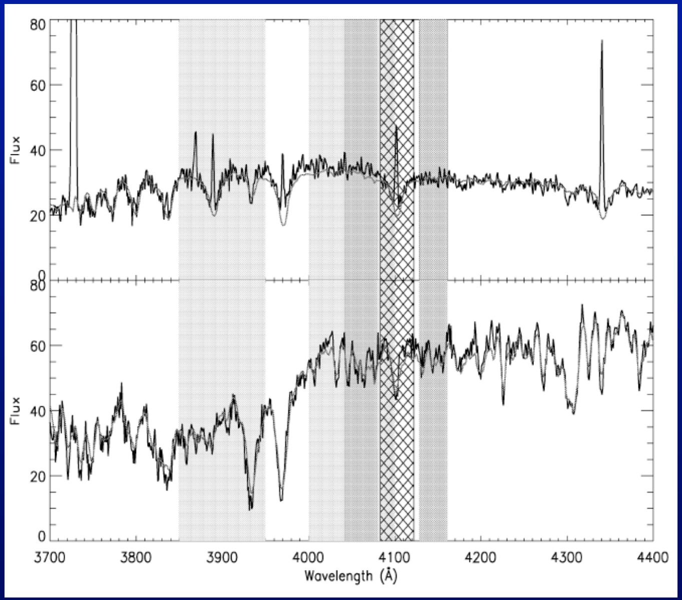
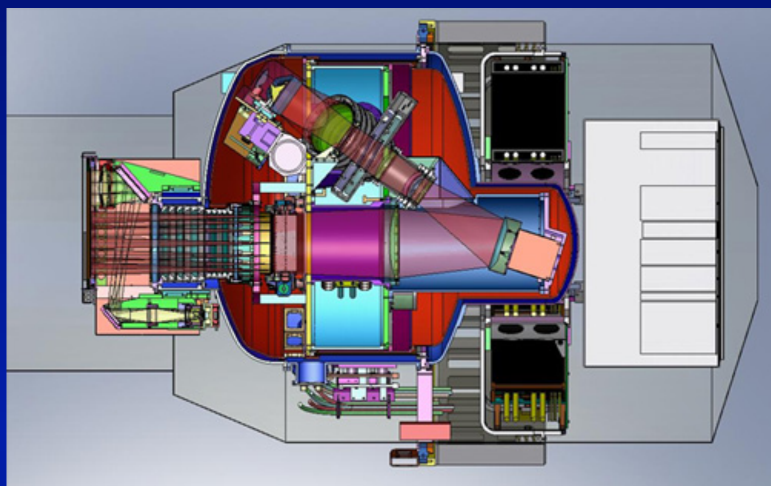


- Emission-line set: [OII], Hβ, [OIII], Hα, [NII], [SII]
- Absorption-line set: Balmer lines, Ca H&K, Mgb, 4000Å break
- These features form the basis of traditional optical spectroscopy, yield key insights into the stellar and gaseous content of galaxies.
- At $z > 1.4$, [OII] moves past 9000Å. Becomes a near-IR problem.
- To assemble statistical samples of rest-frame optical measurements, we need a transformative boost in S/N and survey efficiency for near-IR spectrographs.

Keck/MOSFIRE

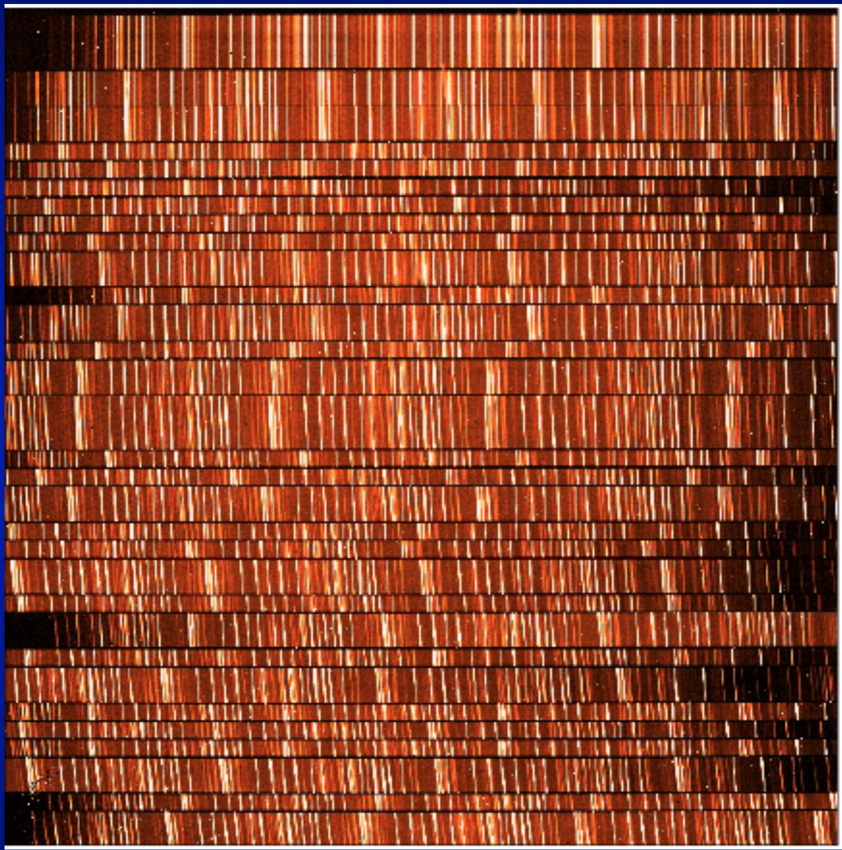


- Keck/MOSFIRE: Multi-Object Spectrometer for Infra-Red Exploration; co-Pis: McLean (UCLA) and Steidel (Caltech)
- Near-IR (0.9-2.5 μm) spectroscopy over $6.1' \times 3.0'$ FOV, one band (YJHK) at a time, multiplex advantage up to 46 slits using robotic, cryogenic configurable slit unit. R=2300-3300 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



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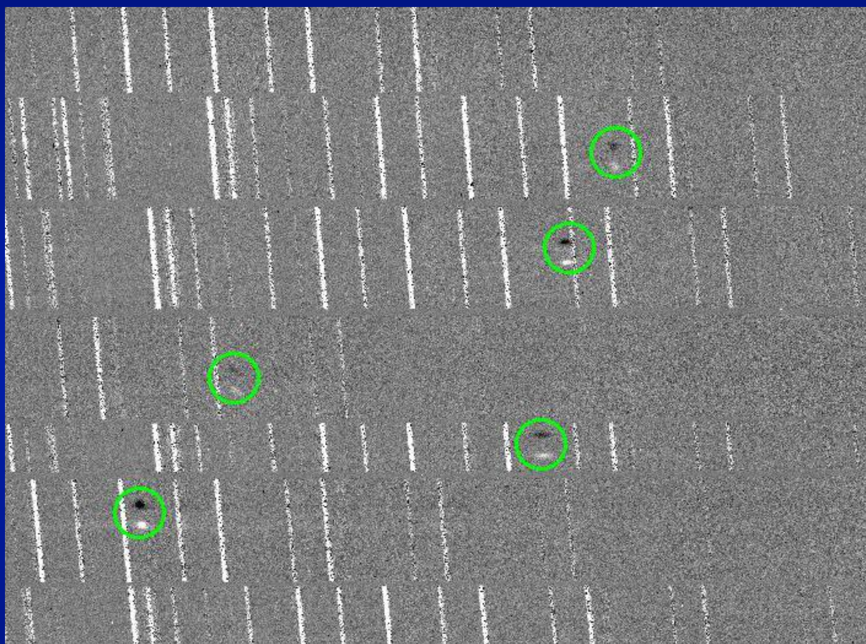
Keck/MOSFIRE



• 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 $z\sim1.5-3.5$:

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)

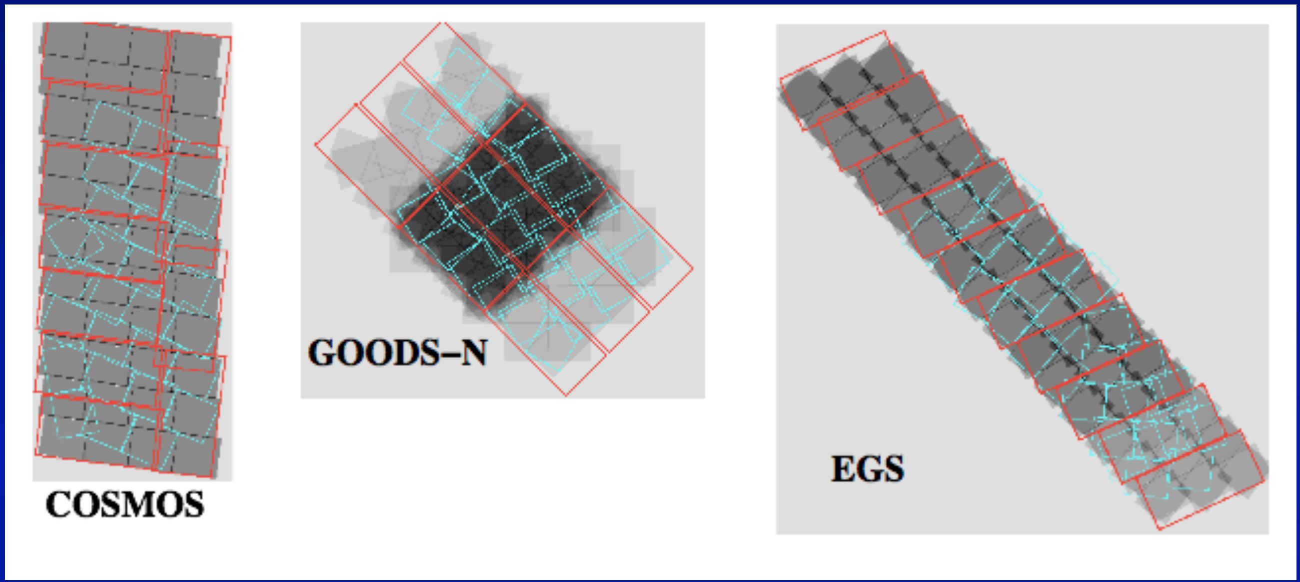
Theory Co-Is:
James Bullock (UC Irvine)
Charlie Conroy (UC Santa Cruz)
Romeel Dave (University of Western Cape)
Dusan Keres (UC San Diego)
Marc Krumholz (UC Santa Cruz)

Collaborators
James Aird (Durham University)

The MOSDEF Survey

- **Large UC Keck program.**
- **Observing time awarded: 47 Keck I/MOSFIRE nights from 2012B-2016A.**
- **Target fields: COSMOS, GOODS-N, AEGIS (overlapping with CANDELS and 3D-HST surveys).**
- **Principal redshift ranges:** $1.37<z<1.70$; $2.09<z<2.61$; $2.95<z<3.80$.
- **Planned sample:** ~500 galaxies at $z\sim1.5$; ~1000 galaxies at $z\sim2.3$; ~500 galaxies at $z\sim3.4$.
- **Target selection: H-band magnitude limited (rest-frame optical luminosity), also construct mass-limited samples.**

The MOSDEF Survey: Target Fields



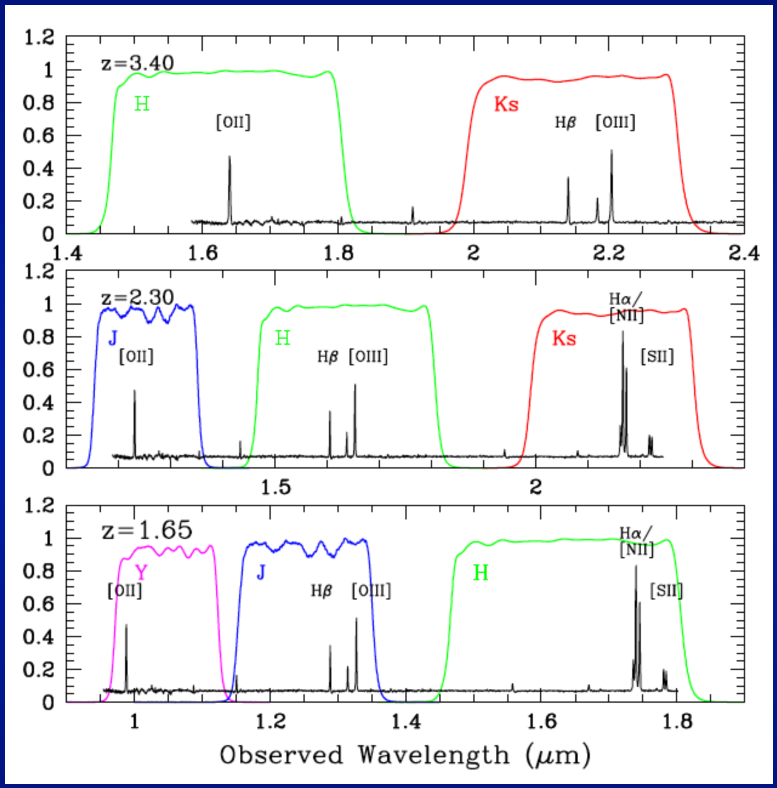
• Target fields: COSMOS, GOODS-N, AEGIS (overlapping with CANDELS and 3D-HST surveys)

• Extensive ancillary multi-wavelength photometric datasets: HST ACS+WFC3, Spitzer/IRAC+MIPS, Chandra, Herschel/PACS+SPIRE, VLA, ground-based imaging

• Existing spectroscopy: various ground-based sources, 3D-HST grism.

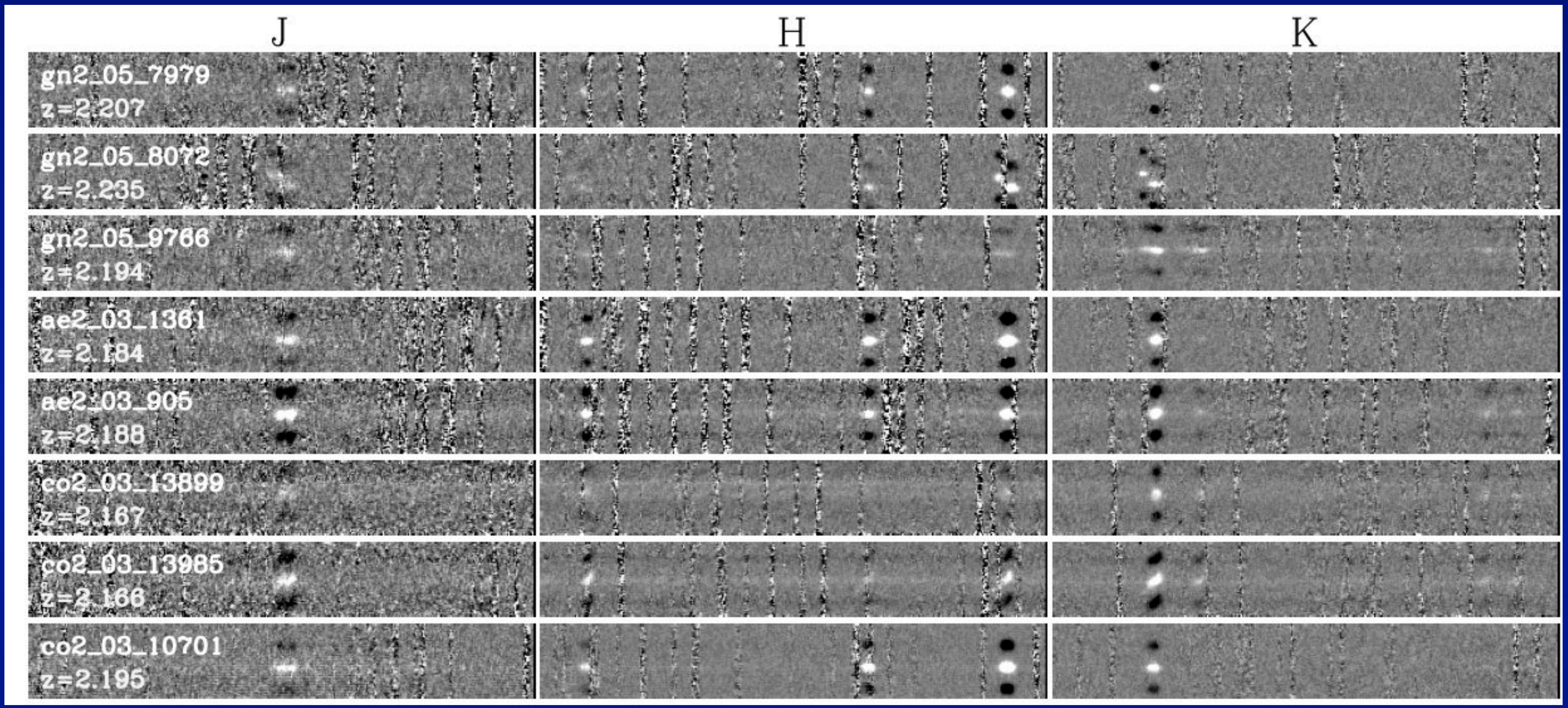
• Catalogs: 3D-HST photometric compilation, photometric redshifts, stellar population modeling

The MOSDEF Survey: z Ranges



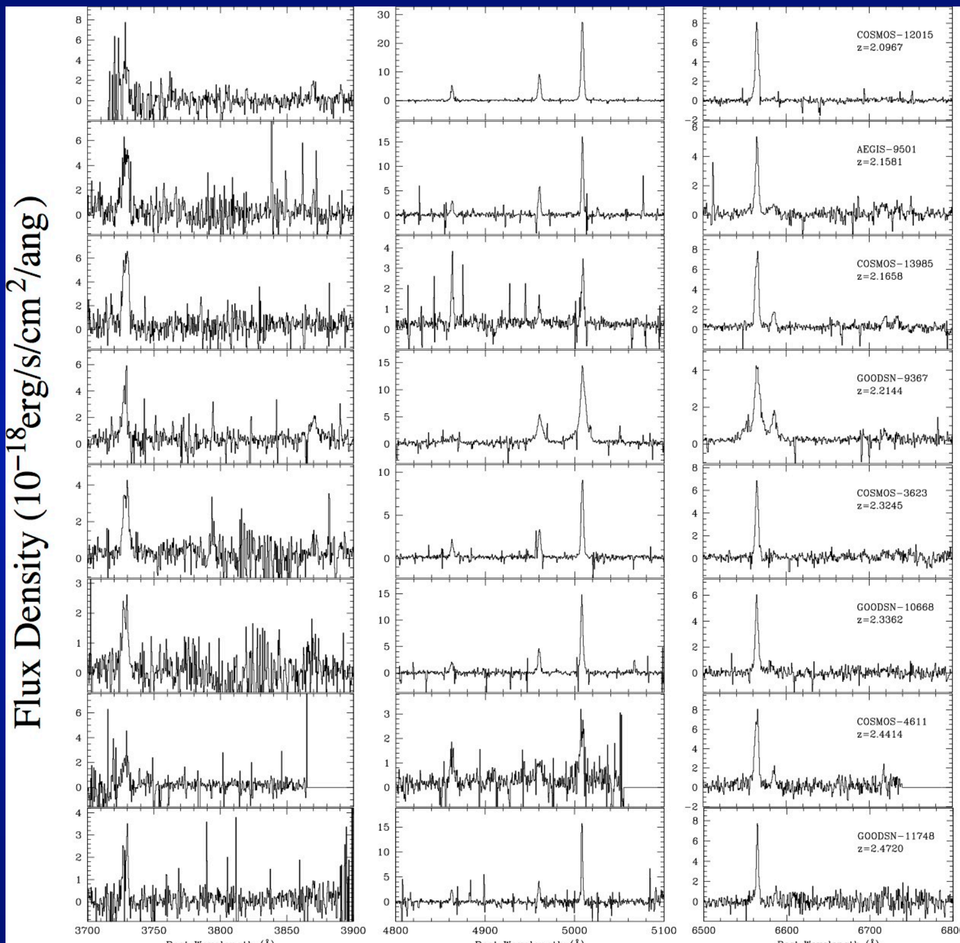
- **Principal redshift ranges:**
  - ✧ **1.37<z<1.70**
  - ✧ **2.09<z<2.61**
  - ✧ **2.95<z<3.80**
- **Ranges selected to optimize detection of rest-frame optical emission lines within windows of atmospheric transmission.**

The MOSDEF Survey: Spectra



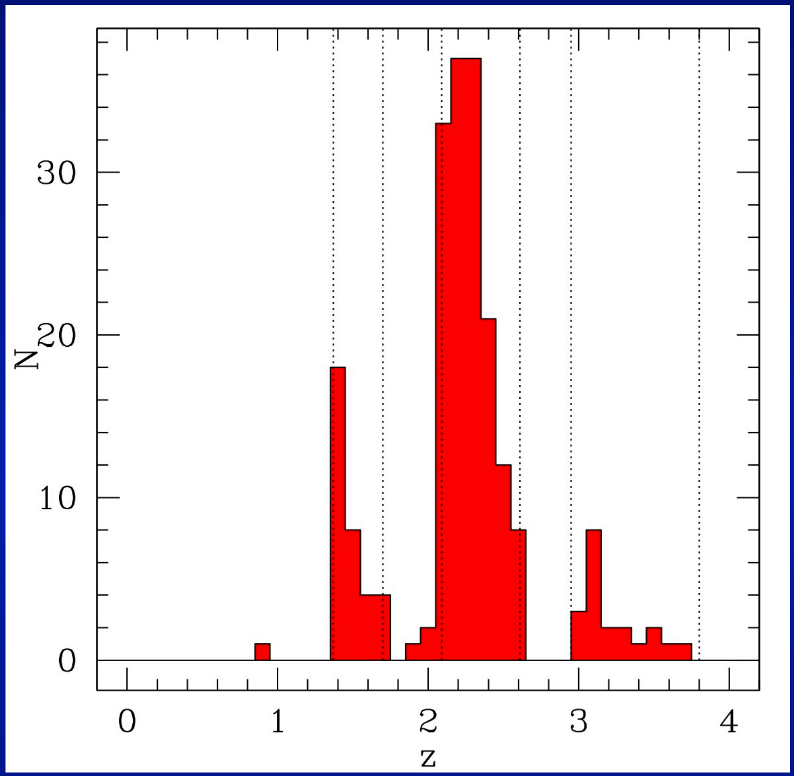
- **Example z~2 2D spectra**
- **[OII] in J, [OIII]+Hb in H, Ha+[NII]+[SII] in K**
- **Range of line ratios, velocity widths, spatial morphologies**

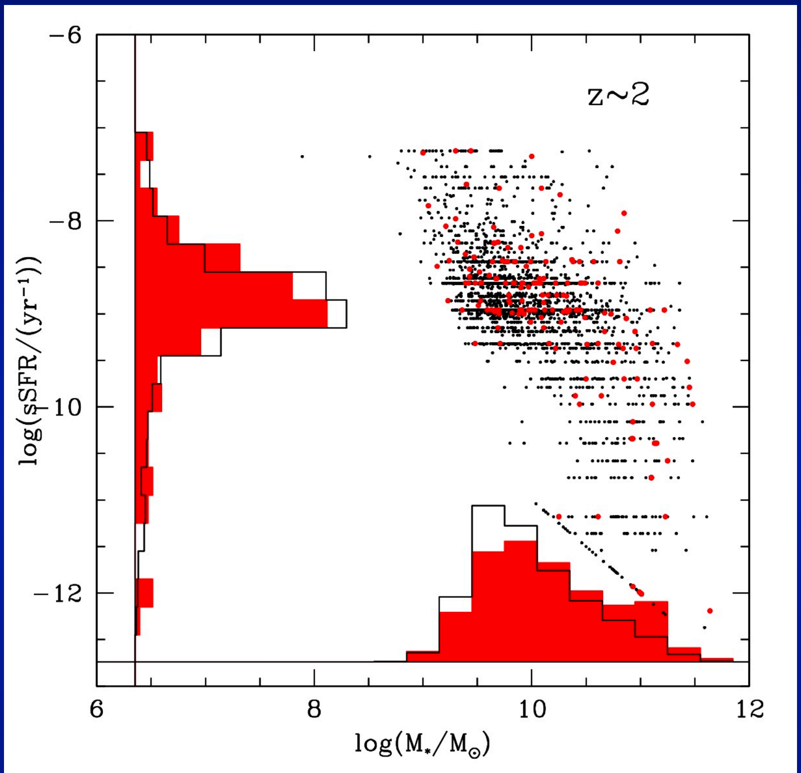
The MOSDEF Survey: Spectra



- Example extracted, flux-calibrated 1D spectra.
- [OII] in J, [OIII]+Hb in H, Ha +[NII]+[SII] in K

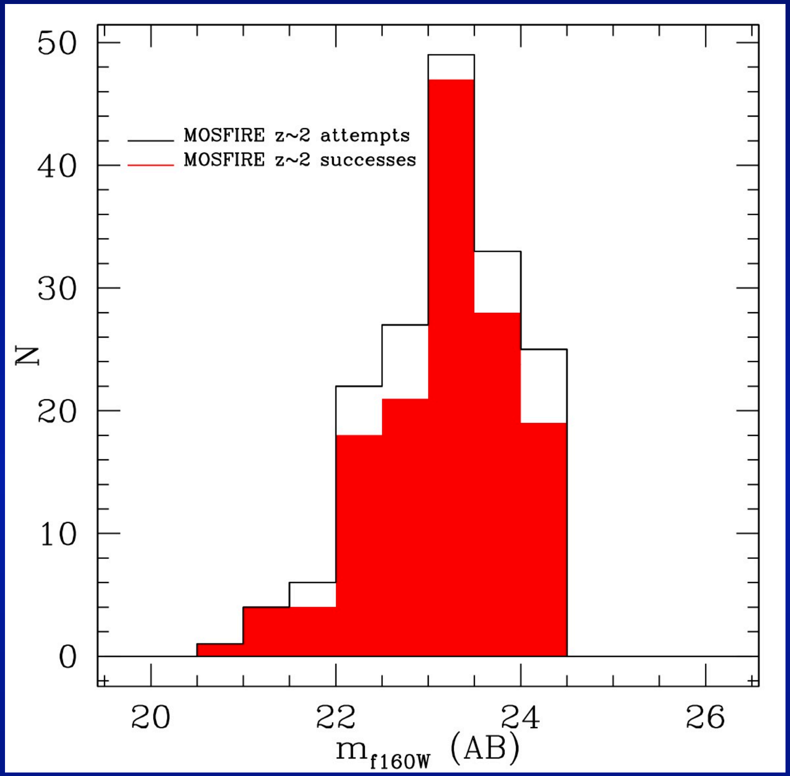
The MOSDEF Survey: Demographics

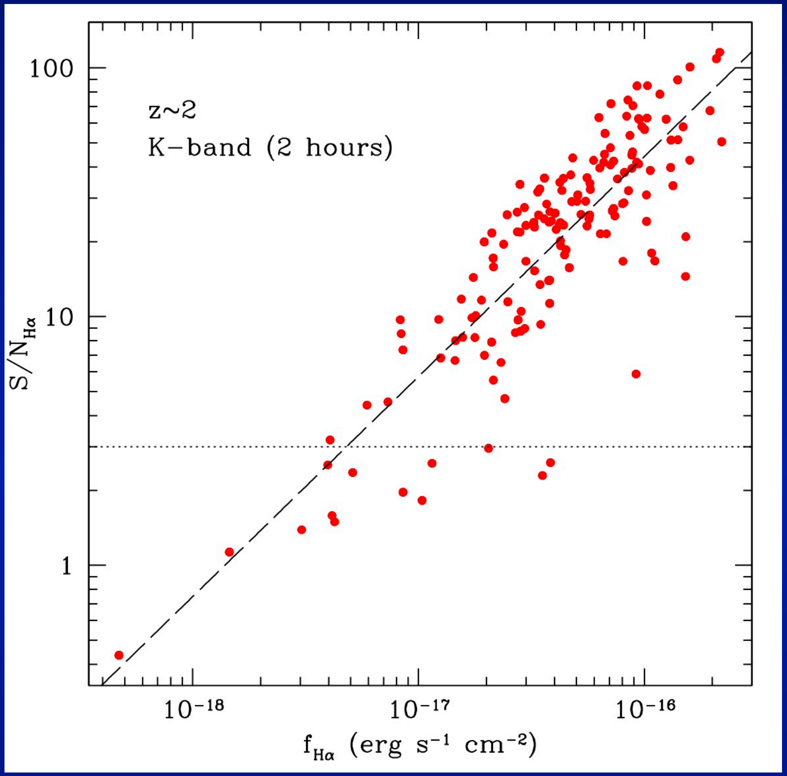




- 3 target redshift ranges clearly visible. Focus on z~2 range (~170 targets)
- Wide range of properties probed in M*, sSFR space in z~2 sample. Complete to 10^{10} $M_{\odot}$, measurements down to 10^{9} $M_{\odot}$.

The MOSDEF Survey: Success





• Overall 85% spectroscopic success rate. Success rate remains above 75% even in faintest bin.

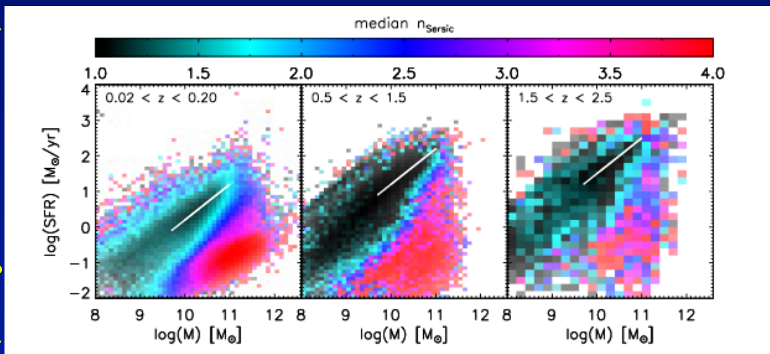
• Achieve S/N=3 for Hα fluxes of few times 10^{-18} erg/s/cm^2 in K-band with 2-hour exposure times, corresponds to SFR~1$M_\odot$/yr at z~2.

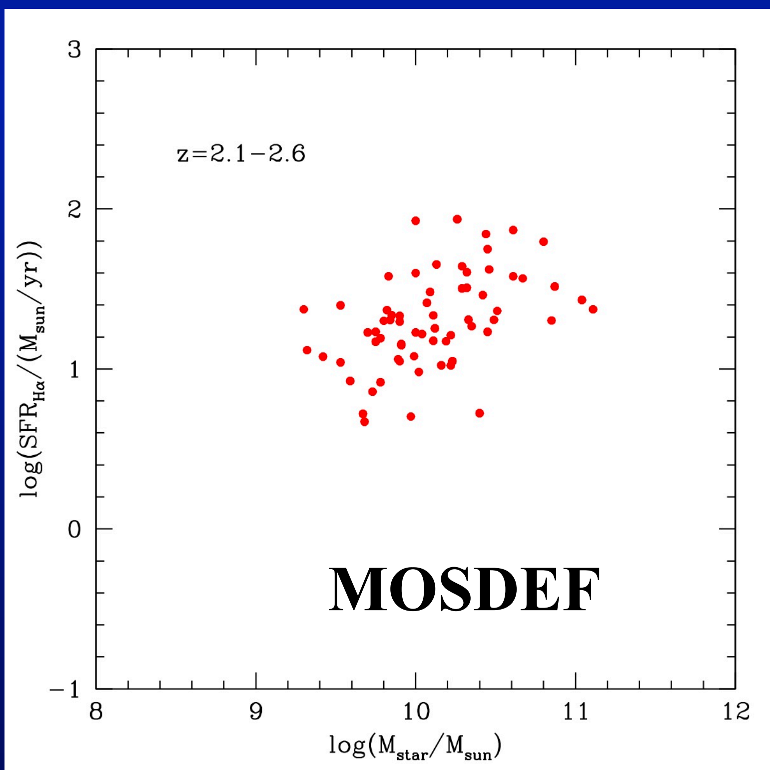
The MOSDEF Survey: Science

- 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: Science

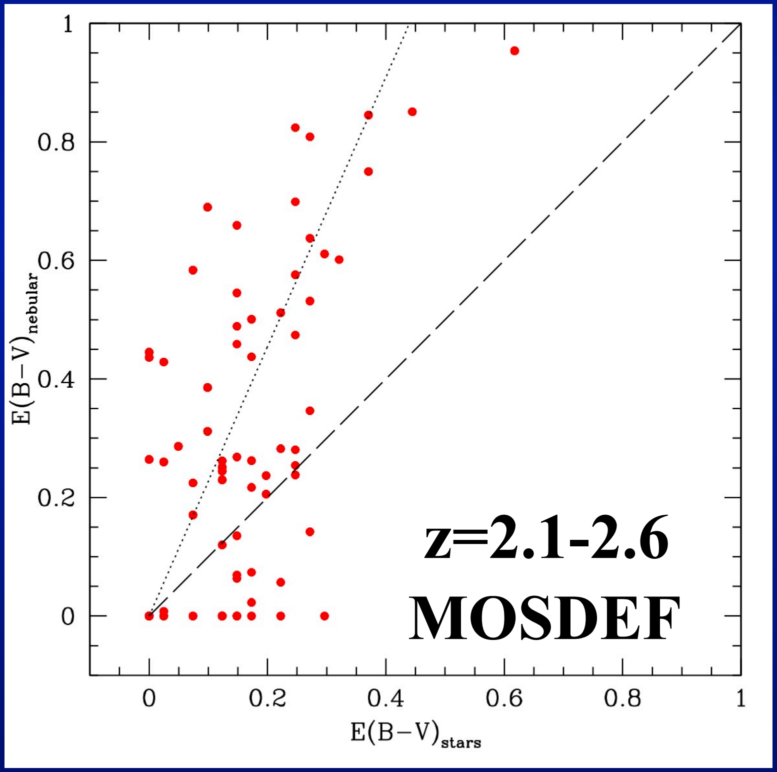
(Wuyts et al. 2011)





- Star formation and the growth of galaxies
- SFR vs. M* relation used to quantify the growth of galaxies. Evolution in normalization, slope, and scatter.
- Most previous samples are either photometric only, or very incomplete. Most use rest-UV or SED fitting for SFR estimates.
- Hα is *instantaneous* measure of SFR, true measure of stochastisity, deviations from the "main sequence" of star formation. Comparisons between UV and Hα SFRs will also be very useful (IMF, SF-history).
- Measurement of rest-frame optical emission lines will allow for cleaner SED fits.

The MOSDEF Survey: Science

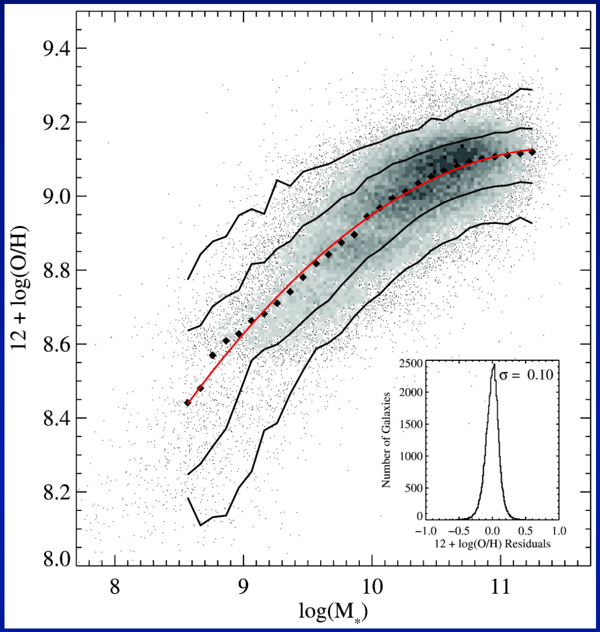


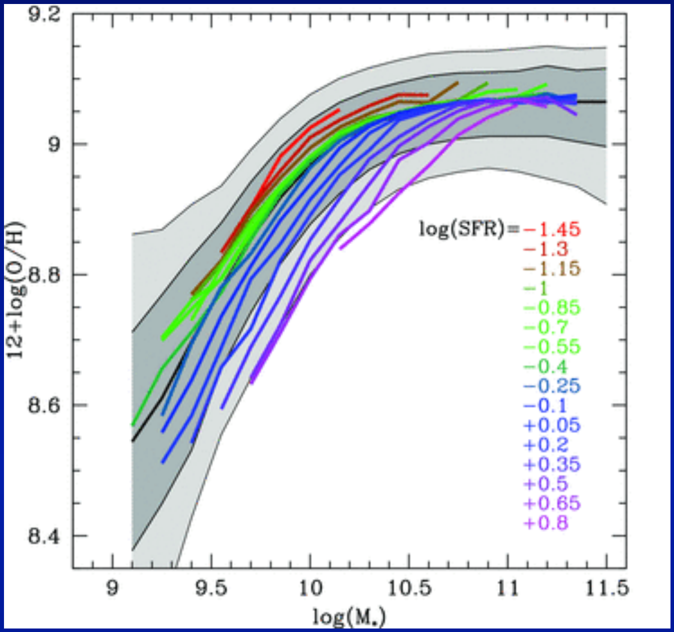
(Reddy et al. 2014)

- Dust attenuation
- Vast majority of dust extinction estimates at high z are based on rest-frame UV colors or SED fitting.
- In order to utilize Hα for SFR estimates, we need robust estimates of *nebular* extinction.
- Much debate about nebular vs. stellar extinction at high redshift.
- For the first time, we are obtaining a statistical sample of Balmer decrements for *individual objects* at z>1.
- Early results suggest nebular extinction systematically higher than stellar extinction.
- More consistent with relation $E(B-V)_{neb}=1/0.44E(B-V)_{stars}$ than $E(B-V)_{neb}=E(B-V)_{stars}$, like local starbursts.

The MOSDEF Survey: Science

(Tremonti et al. 2004)



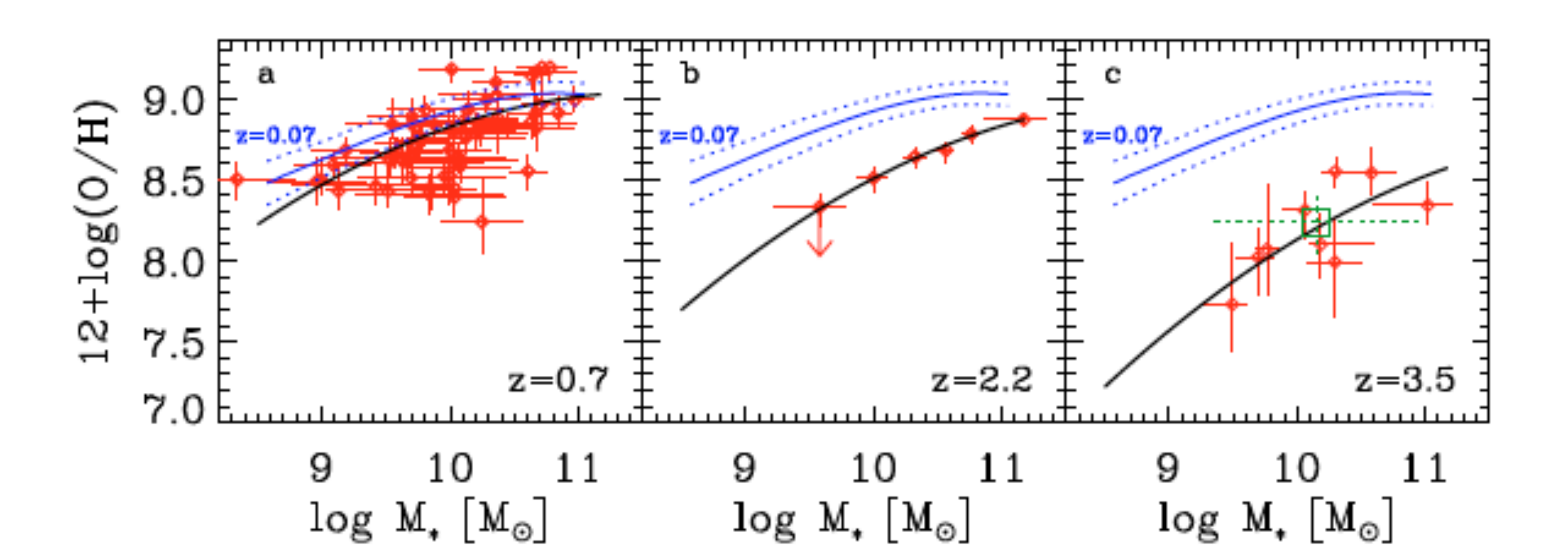


(Mannuci et al. 2010)

- **Metallicities**

- **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).**
- **Meaningful when considered together with stellar masses (M-Z relation), gas masses and SFRs → Gas flows!**
- **Samples of objects at z > 1 with individual M-Z measurements are tiny, while the stacked sample at z = 2. 2 masks the scatter in the relation.**

The MOSDEF Survey: Science



(Maiolino et al. 2008)

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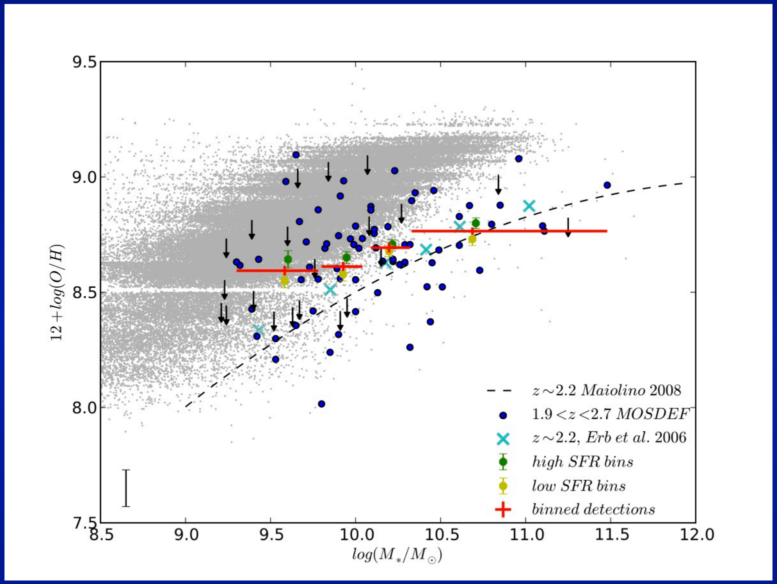
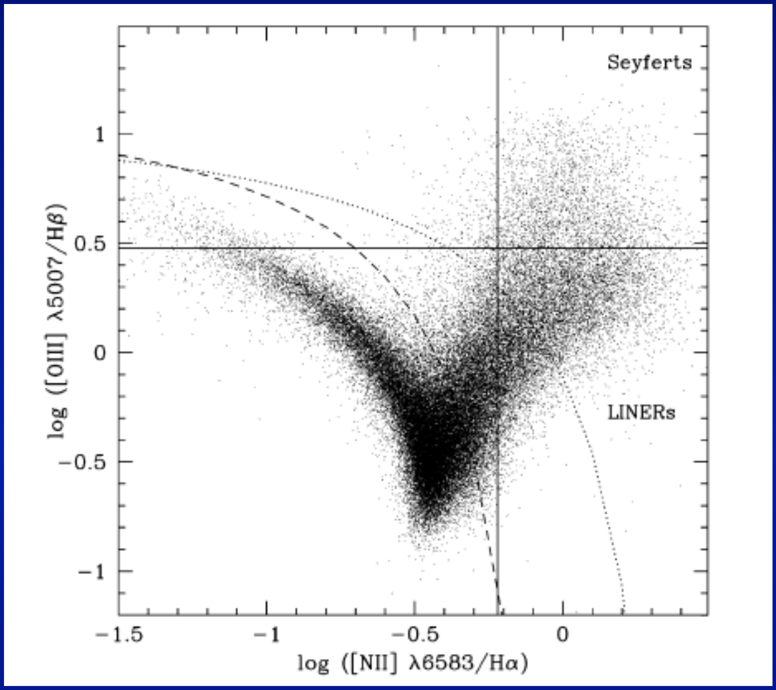
The MOSDEF Survey: Science



(Sanders, Shapley et al. 2014)

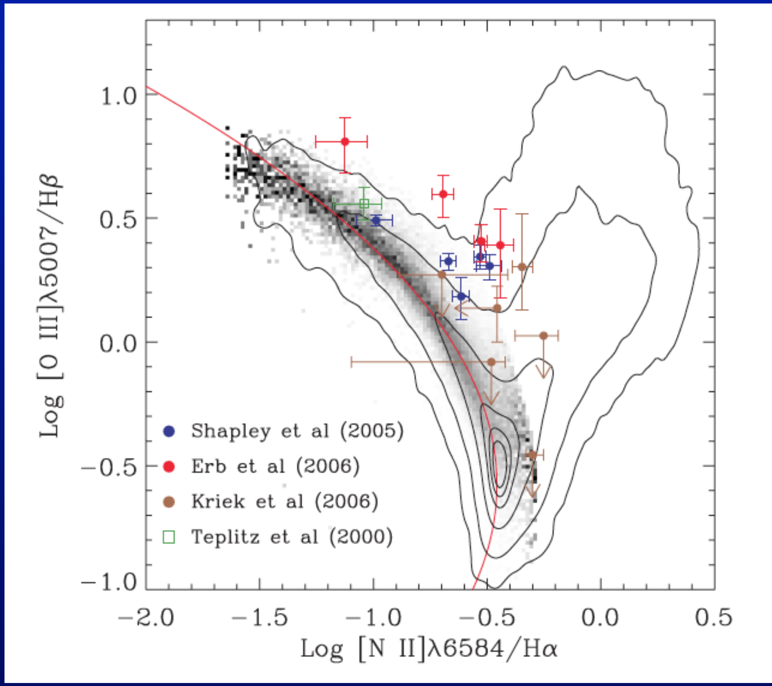
- **Metallicities**
- **We have assembled "N2" metallicities for our z~2 sample.**
- **Detect well-known offset towards lower metallicity at fixed mass.**
- **Scatter!**
- **Fair sample at z~2.**
- **We don't detect the "Fundamental Metallicity Relation" seen at low redshift, with higher-SFR galaxies offset towards lower metallicity at fixed mass.**
- **There may be issues with using locally-calibrated metallicity indicators….**

The MOSDEF Survey: Science



(Kauffmann et al. 2003)

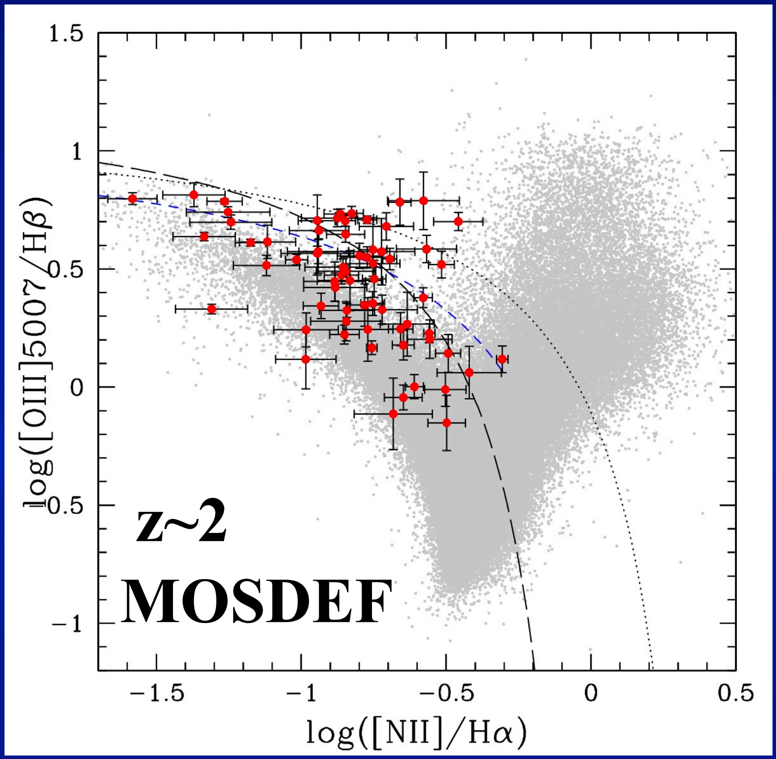
- Physical conditions
- As we showed several years ago with small samples of objects, z>1 star-forming galaxies are “offset” in the BPT excitation diagram used to separate star-forming galaxies from AGNs.



(Brinchmann et al. 2008)

What is the cause of this offset?

The MOSDEF Survey: Science

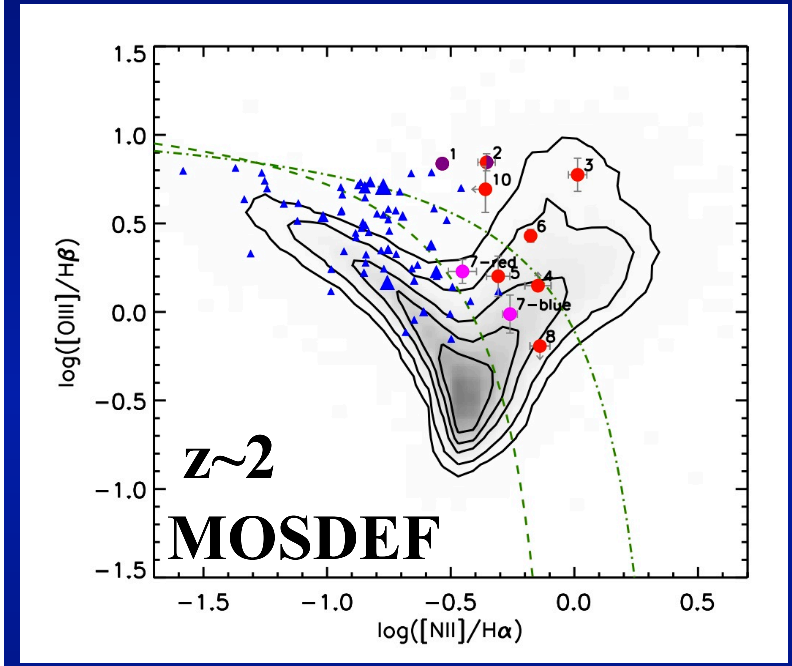


(Shapley et al. 2014)

What is the cause of this offset?

- **Physical conditions**
- **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!**

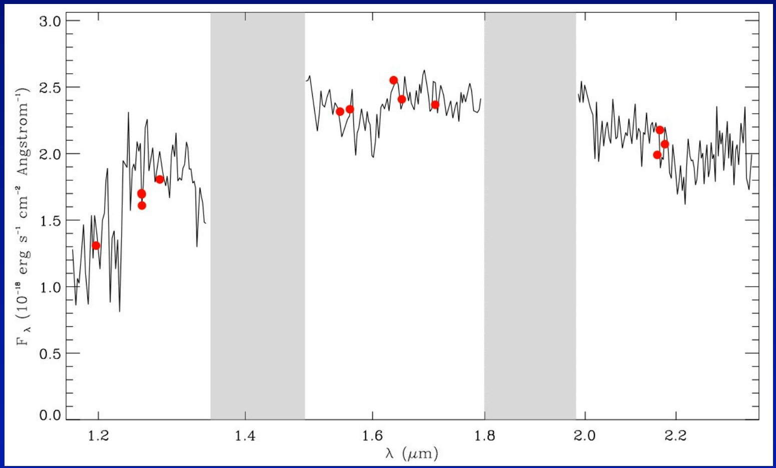
The MOSDEF Survey: Science

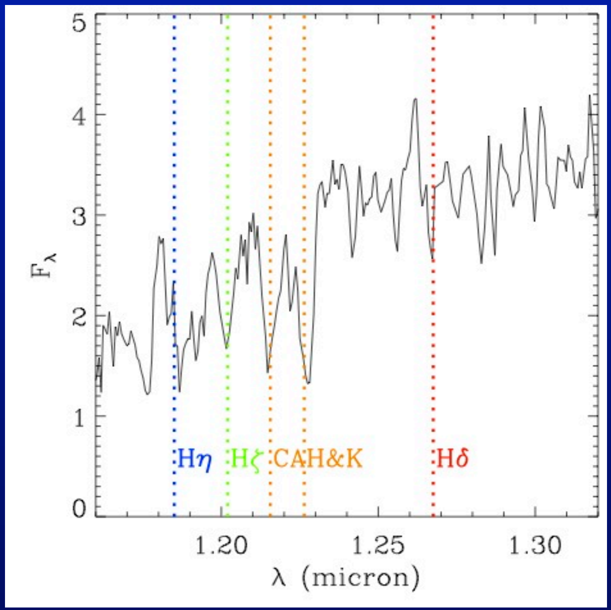


(Coil et al. 2014)

- **AGN activity**
- **We typically target a small number of X-ray and/or IR-selected AGNs on each mask.**
- **Use MOSFIRE spectra to identify additional AGNs.**
- **We will study AGN demographics, distributions of BH accretion rates, methods of AGN detection.**
- **With early sample of AGNs (red X-ray, burgunday IR), we are starting to understand the excitation properties of these systems, and how they relate to star-forming galaxies.**
- **Local discriminators (BPT, MeX) may not work as well at z~2.**

The MOSDEF Survey: Science





(Kriek et al. 2014)

- Stellar absorption lines
- The current sample of z>1.5 galaxies with continuum and stellar absorption detections is less than ten objects (van de Sande et al. 2013)!
- We detect continuum for our brightest targets, e.g., COSMOS-11982 (z=2.09).
- Even better, we detect stellar absorption lines!!!
- Detailed comparision with stellar population models → SF-history.
- Robust estimates of dynamical mass (combined with HST imaging).
- Estimate of *stellar* metallicity.
- Stacking to detect absorption lines in fainter galaxies.

Summary

- We have entered into a new regime for rest-frame optical spectroscopy of the distant universe.

- It is now possible to obtain robust, unbiased statistical samples of the gaseous and stellar contents of galaxies at z>1.

- We are conducting the MOSDEF survey with MOSFIRE on Keck. The survey leverages existing multi-wavelength datasets in the COSMOS, AEGIS, and GOODS-N fields, and will address many key questions in galaxy formation.

- With MOSDEF, we probe the star-formation and assembly histories of galaxies, their dynamical and structural properties, the evolution of their dust and metal content, the physical conditions under which stars are forming, the cycling of baryons, and the evolution of AGN activity.

- The survey has commenced, with early science underway. Stay tuned for much, much more!