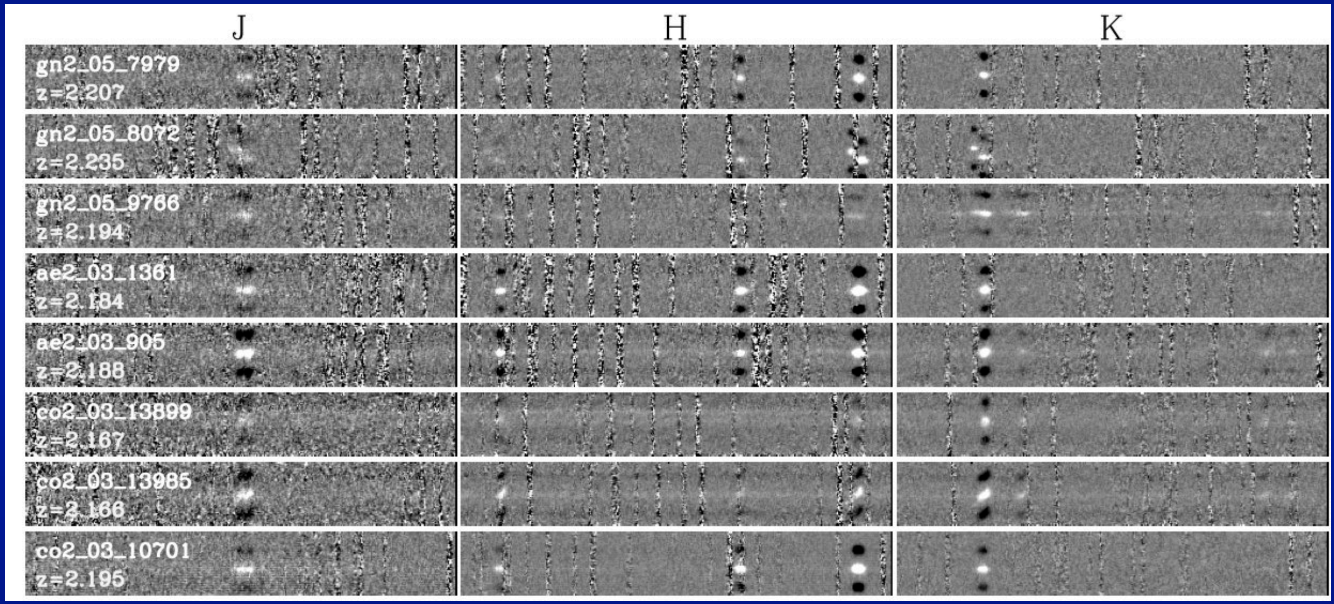
MOSFIRE Deep Evolution Field (MOSDEF) Survey: Study of the Rest-Frame Optical Properties of Galaxies at $1.5 < z < 3.5$



The MOSDEF Team

Alison Coil, Mariska Kriek, Bahram Mobasher, Naveen Reddy, Alice Shapley, Brian Siana, Bill Freeman, Ryan Sanders, Sedona Price, Laura DeGroot, Irene Shivaei

Layout

1. Introduction
2. The MOSDEF Survey
3. Preliminary Science
4. On-going and Future Plans
5. Conclusions

Introduction

• What are the physical processes driving star formation in individual galaxies?

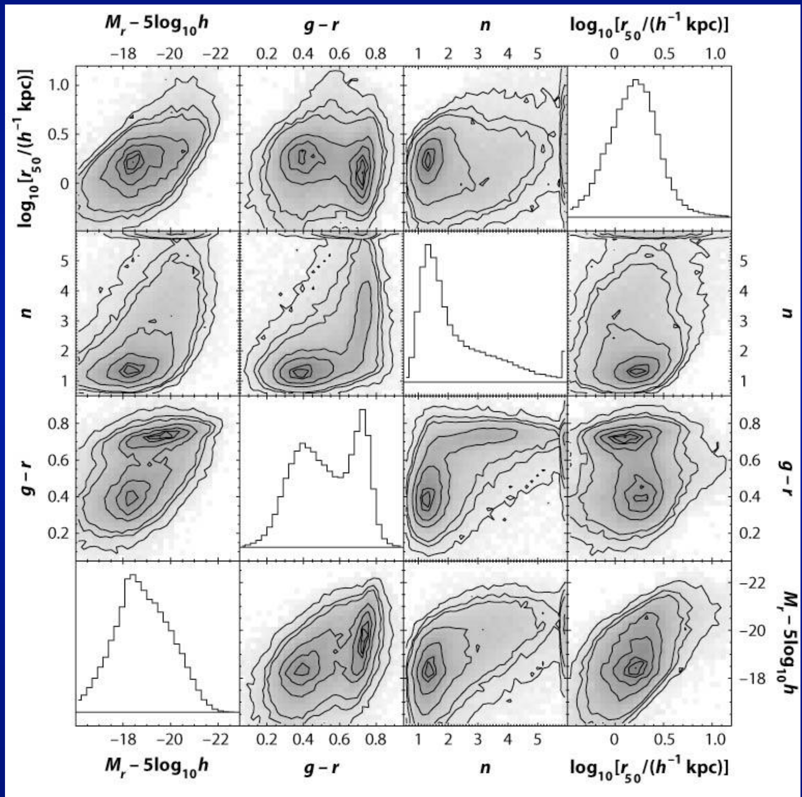
• How are stellar mass and structure assembled in galaxies (in situ star formation vs. mergers)?

• 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



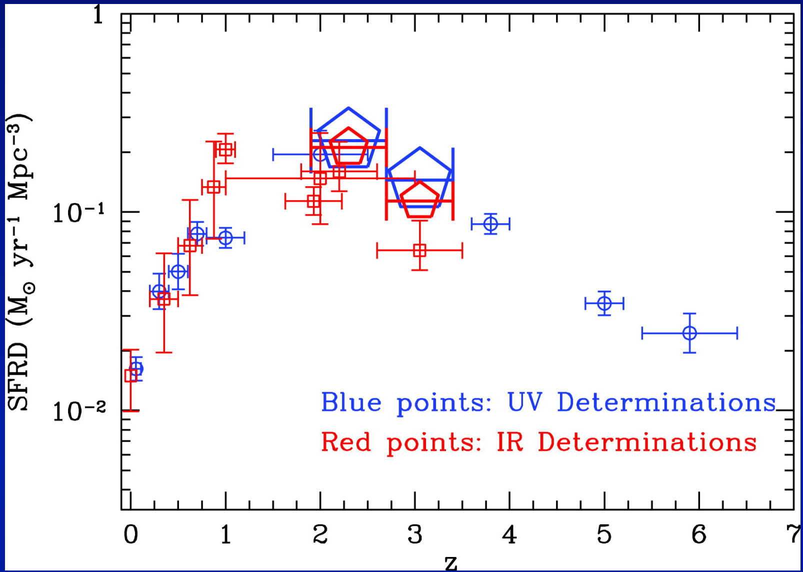
Blanton MR, Moustakas J. 2009.
Annu. Rev. Astron. Astrophys. 47:159–210

(Blanton & Moustakas 2009)

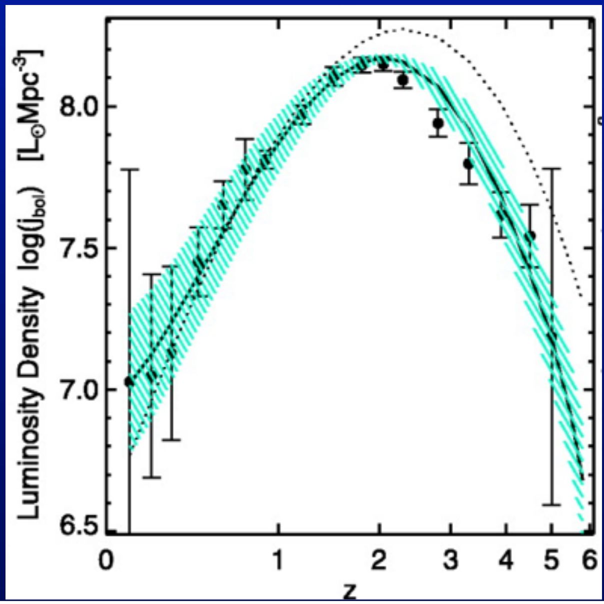
- Massive surveys like the Sloan Digital Sky Survey SDSS) and 2dF Galaxy Redshift survey give detailed description of local galaxy population: the endpoint.
- Spectra of >10^6 galaxies, imaging for orders of magnitude more.
- Distributions in luminosity, color, mass (stellar, dynamical, BH), structure,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

The Next Frontier: z~1.5-3.5

(Reddy et al. 2008)

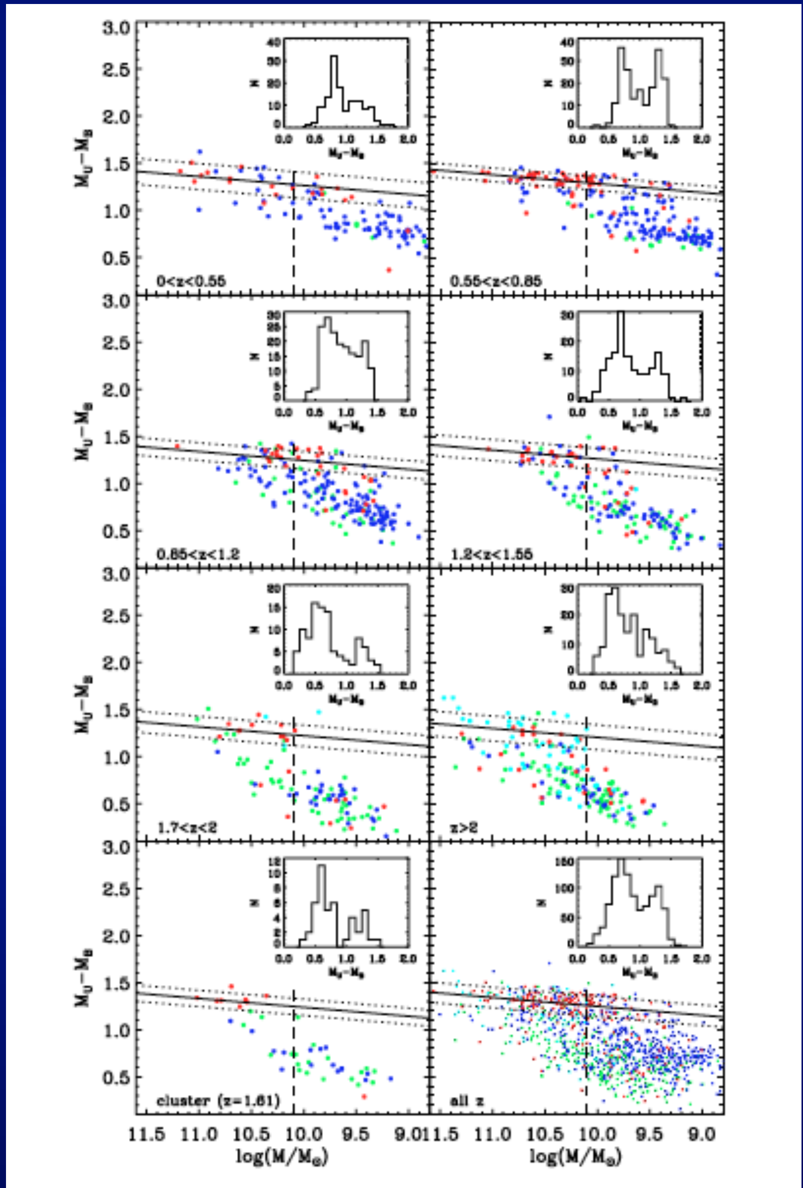


(Hopkins et al. 2007)



- 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.

The Next Frontier: z~1.5-3.5



(Cassata et al. 2008)

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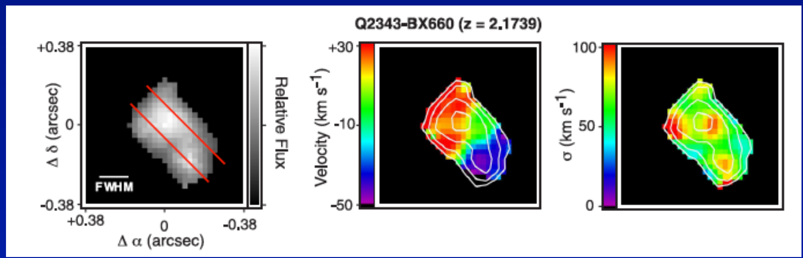
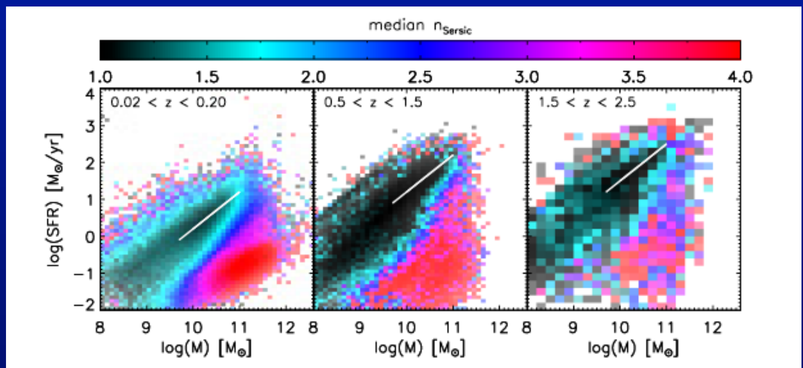
The Next Frontier: z~1.5-3.5

(Law et al. 2009)



(Wuyts et al. 2011)



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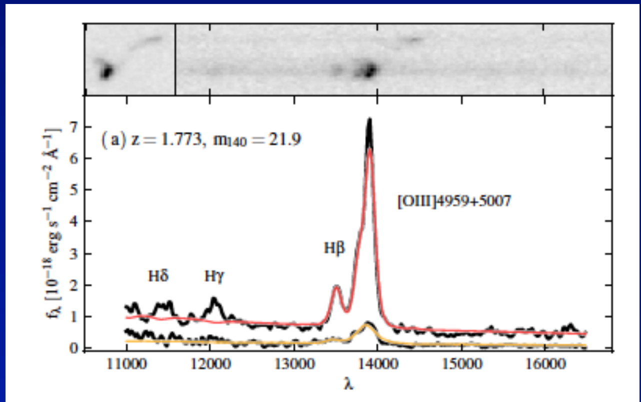
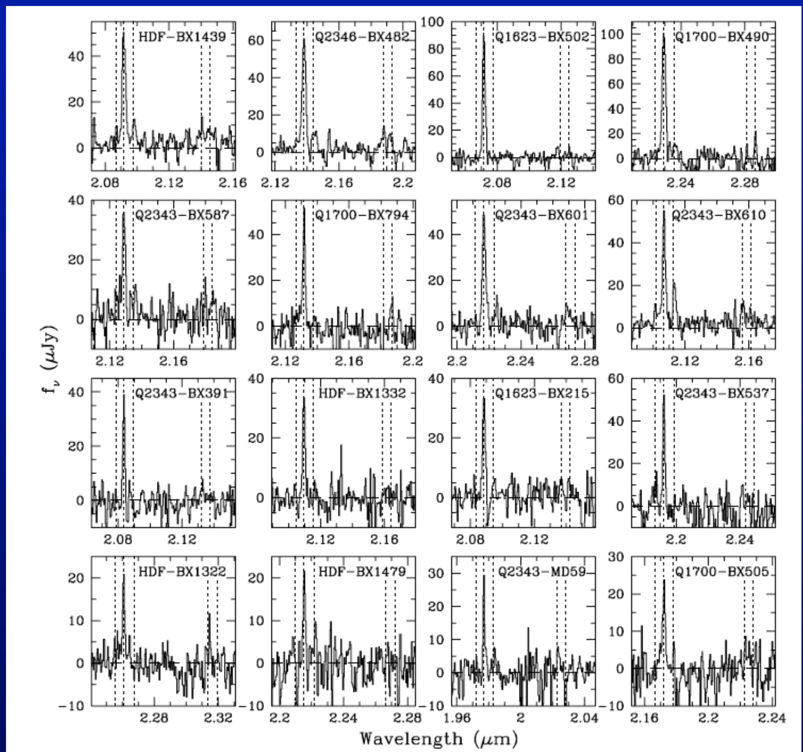
Spectroscopy at z>1.5



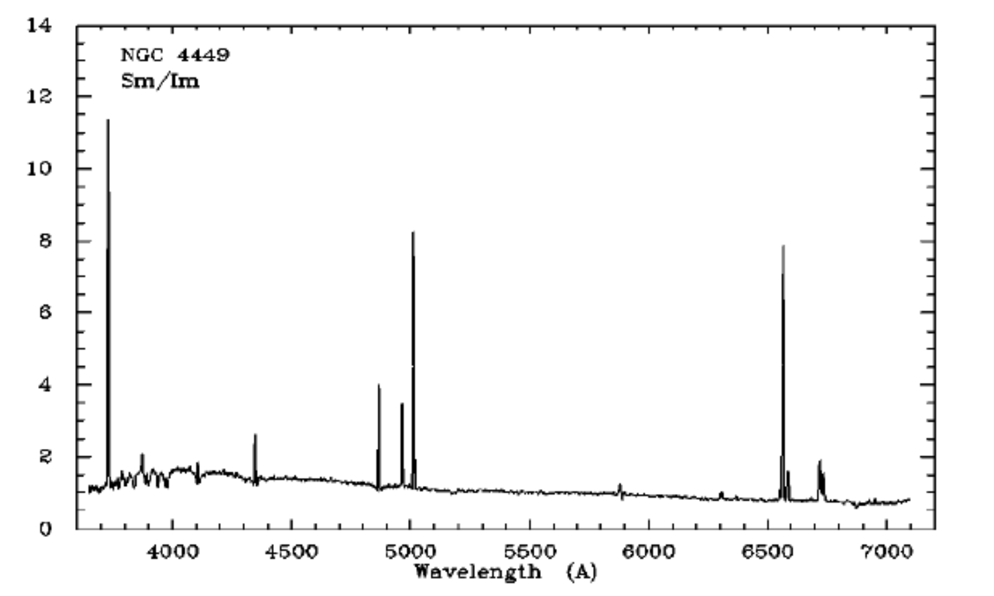
(Brammer et al. 2012)



(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

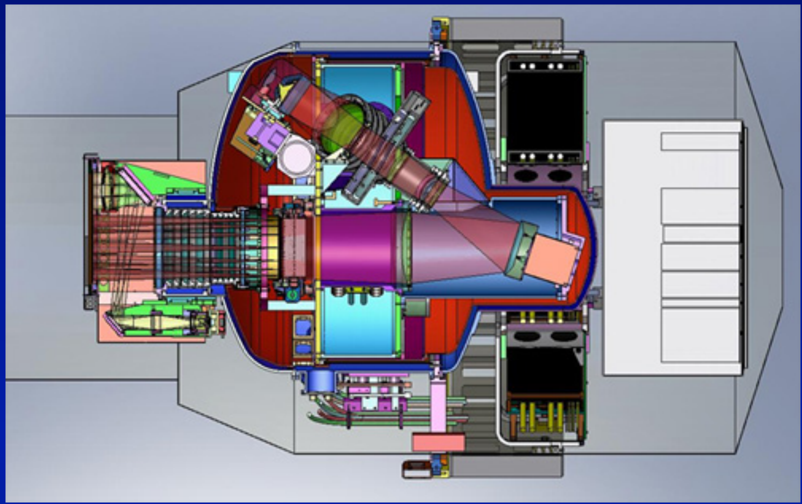


(Kennicutt 1998)

- 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
    {[OII] and [SII] doublet ratios}
  - Ionization parameter
    {[OIII]/[OII]}
  - Electron temperature
    {[OIII] ratios}
  - Dust extinction
    {Balmer line ratios}

MOSFIRE Deep Evolution Field (MOSDEF)

Keck/MOSFIRE

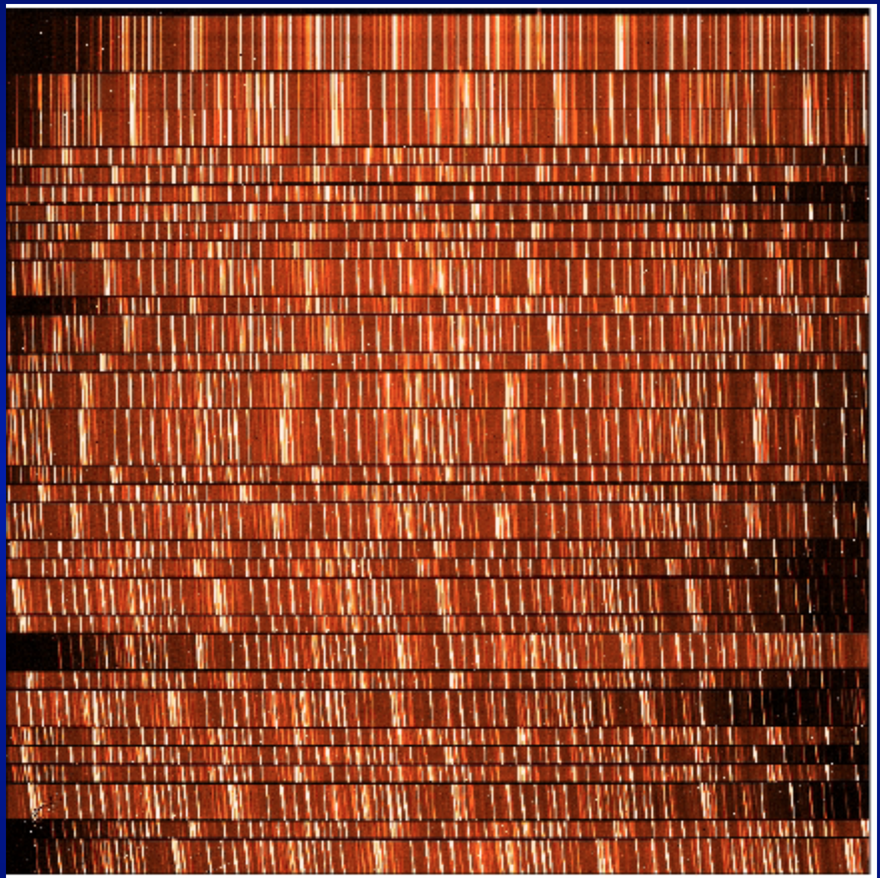


- Keck/MOSFIRE: Multi-Object Spectrometer for Infra-Red Exploration; co-Pis: McLean (UCLA) and Steidel (Caltech)
- Near-IR (0.9-2.5 μm) spectroscopy over $6.1' \times 3.0'$ FOV, one band (YJHK) at a time, multiplex advantage up to 46 slits using robotic, cryogenic configurable slit unit. R=2300-3300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

Also Irene Shivaei's Talk this morning

The MOSDEF Survey

The MOSFIRE Deep Evolution Field Survey

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Alice Shapley (UC Los Angeles)
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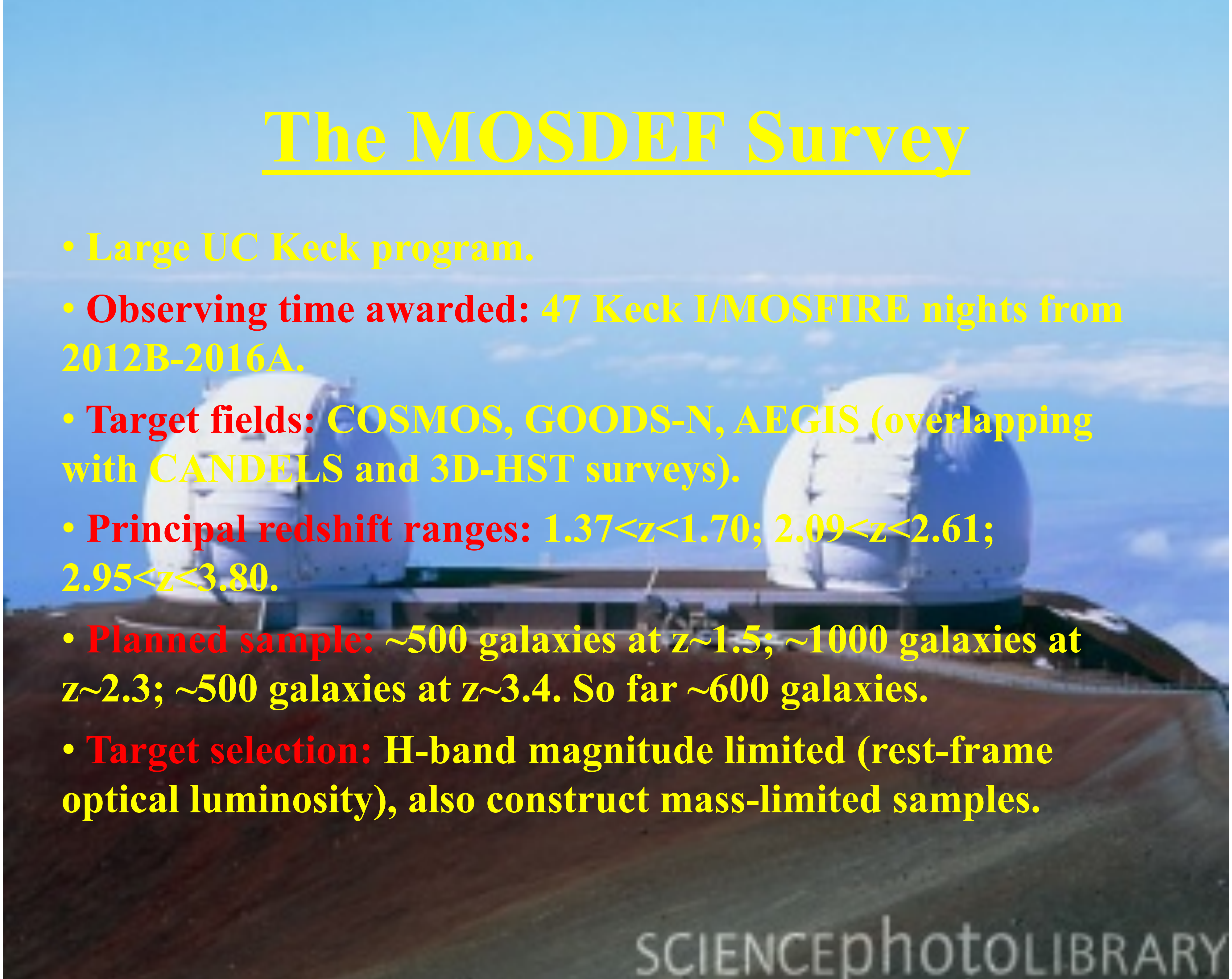
Marc Krumholz (UC Santa Cruz)

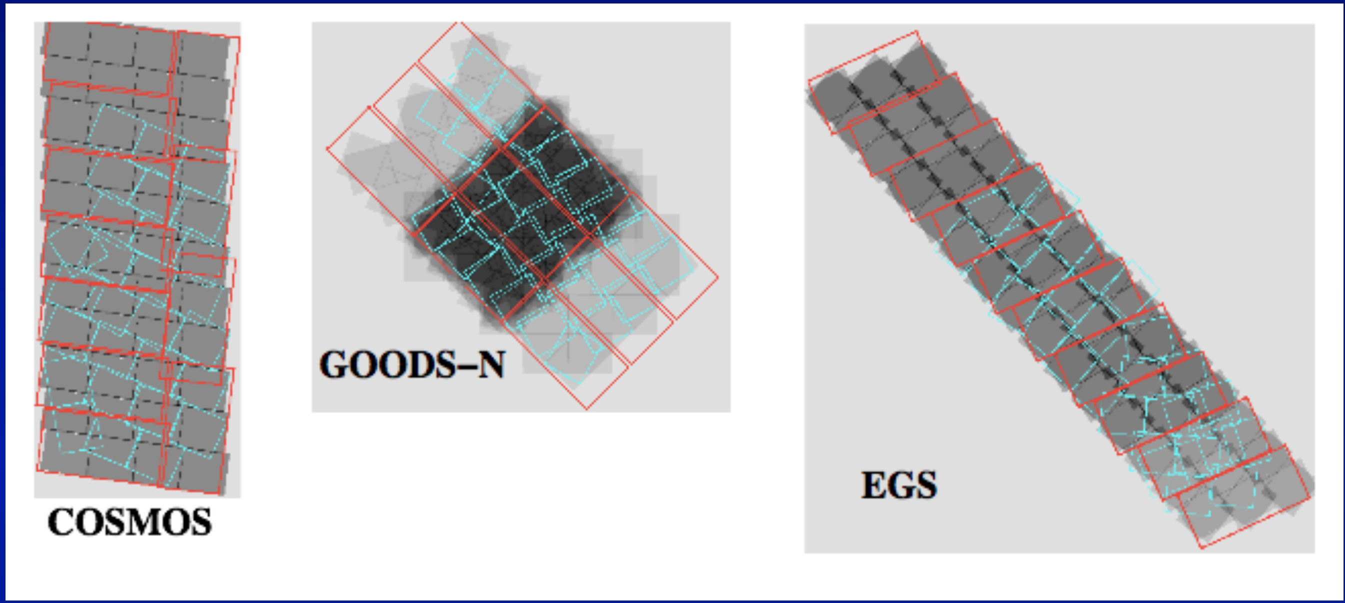
Collaborators
James Aird (Durham University)

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 $z\sim3.4$. So far ~600 galaxies.
- **Target selection:** H-band magnitude limited (rest-frame optical luminosity), also construct mass-limited samples.



The MOSDEF Survey: Target Fields



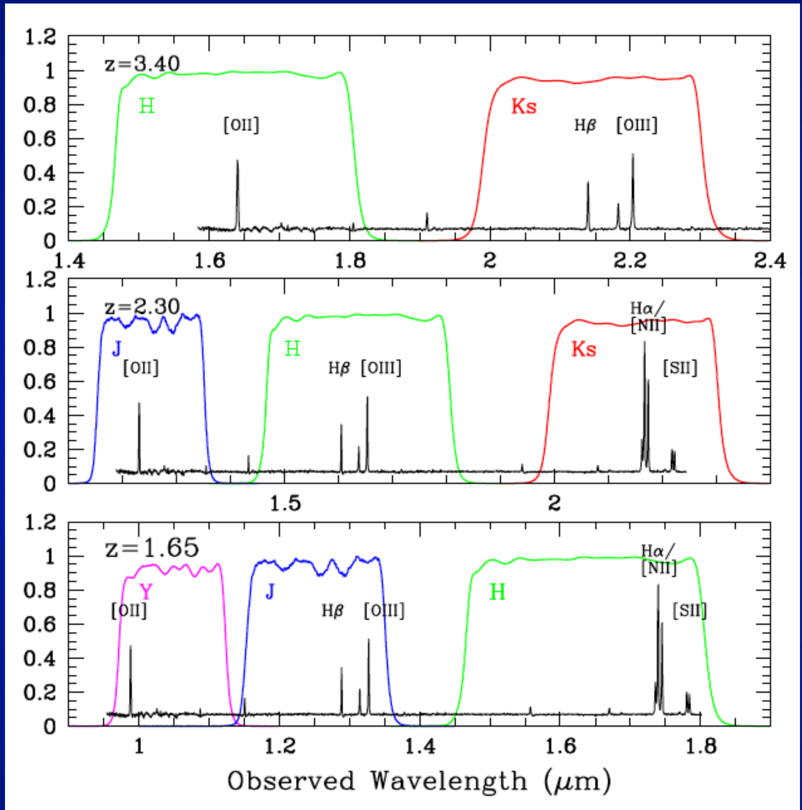
• Target fields: COSMOS, GOODS-N, AEGIS (overlapping with CANDELS and 3D-HST surveys)

• 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.

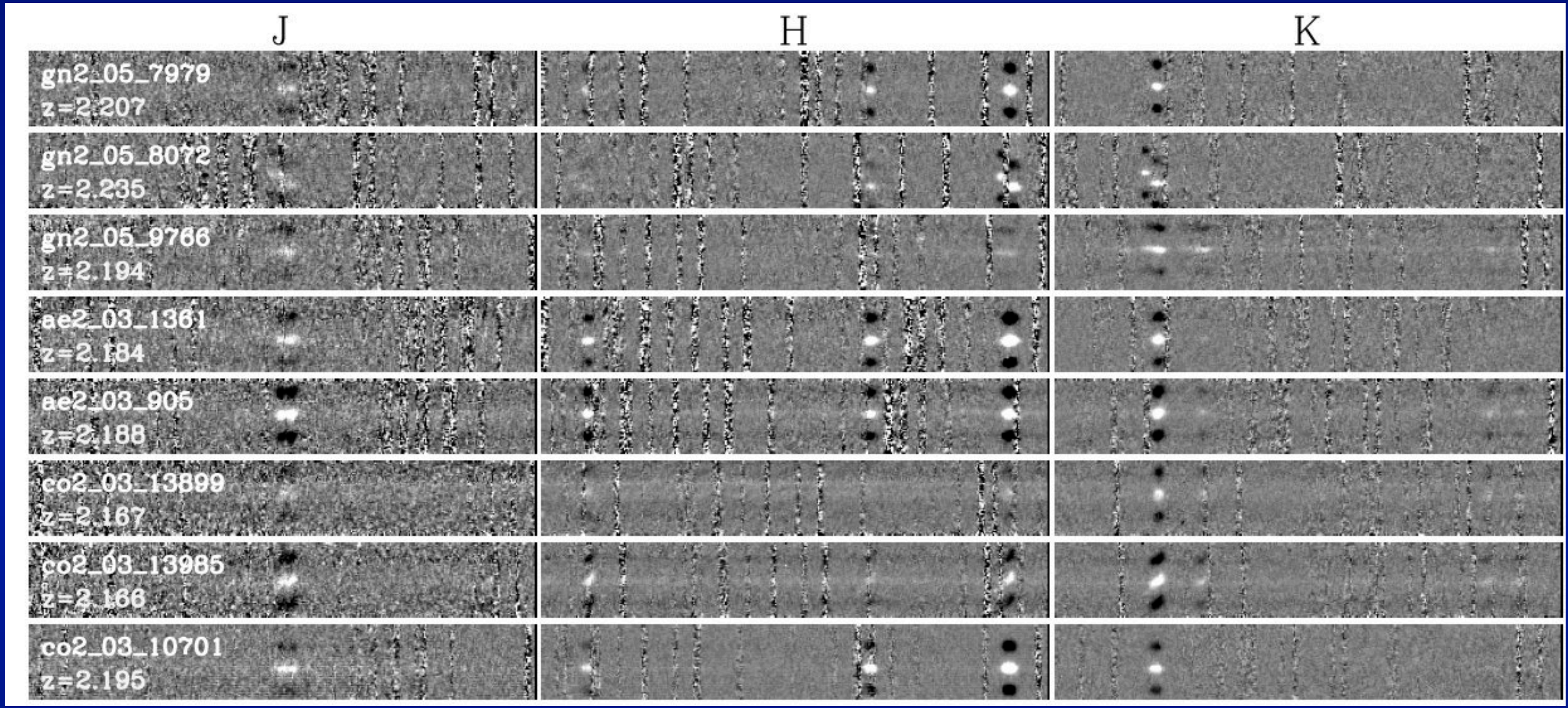
• Catalogs: 3D-HST photometric compilation, photometric redshifts, stellar population modeling

The MOSDEF Survey: z Ranges



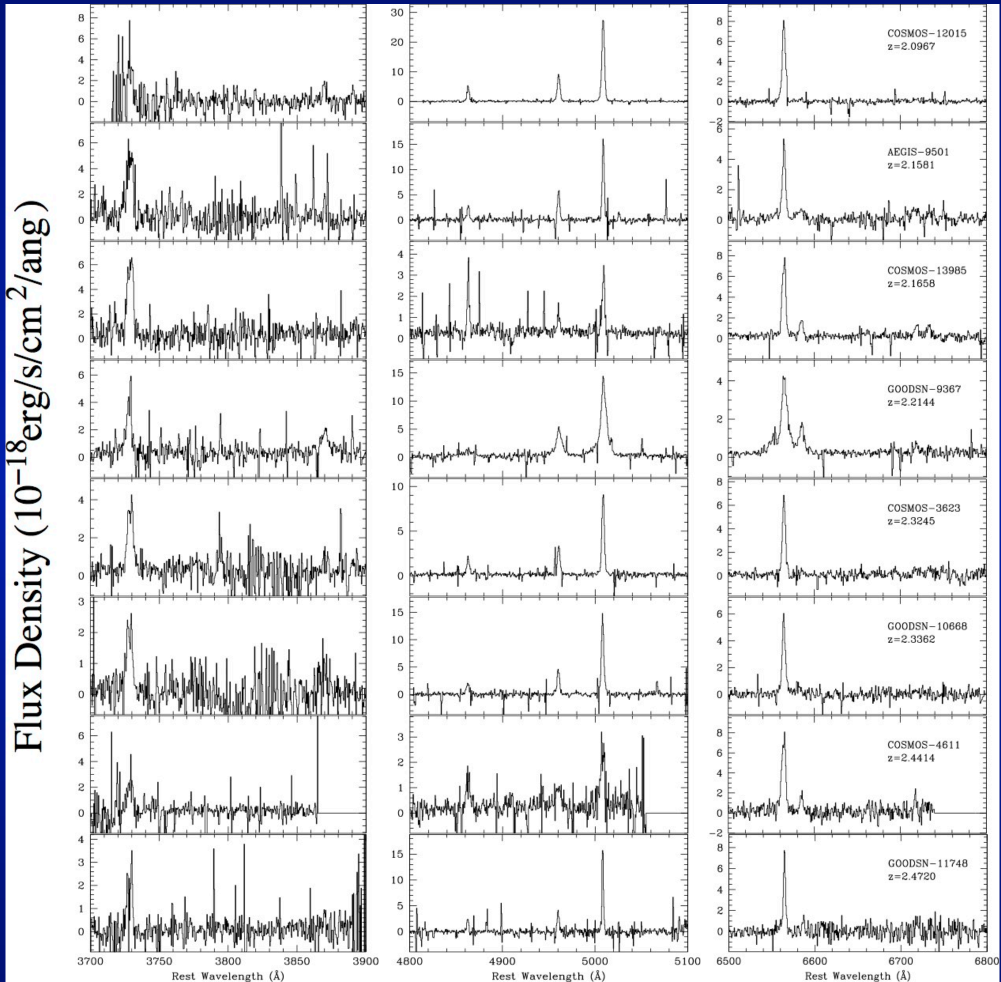
- Principal redshift ranges:
  - ✧ 1.37<z<1.70
  - ✧ 2.09<z<2.61
  - ✧ 2.95<z<3.80
- Ranges selected to optimize detection of rest-frame optical emission lines within windows of atmospheric transmission.

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

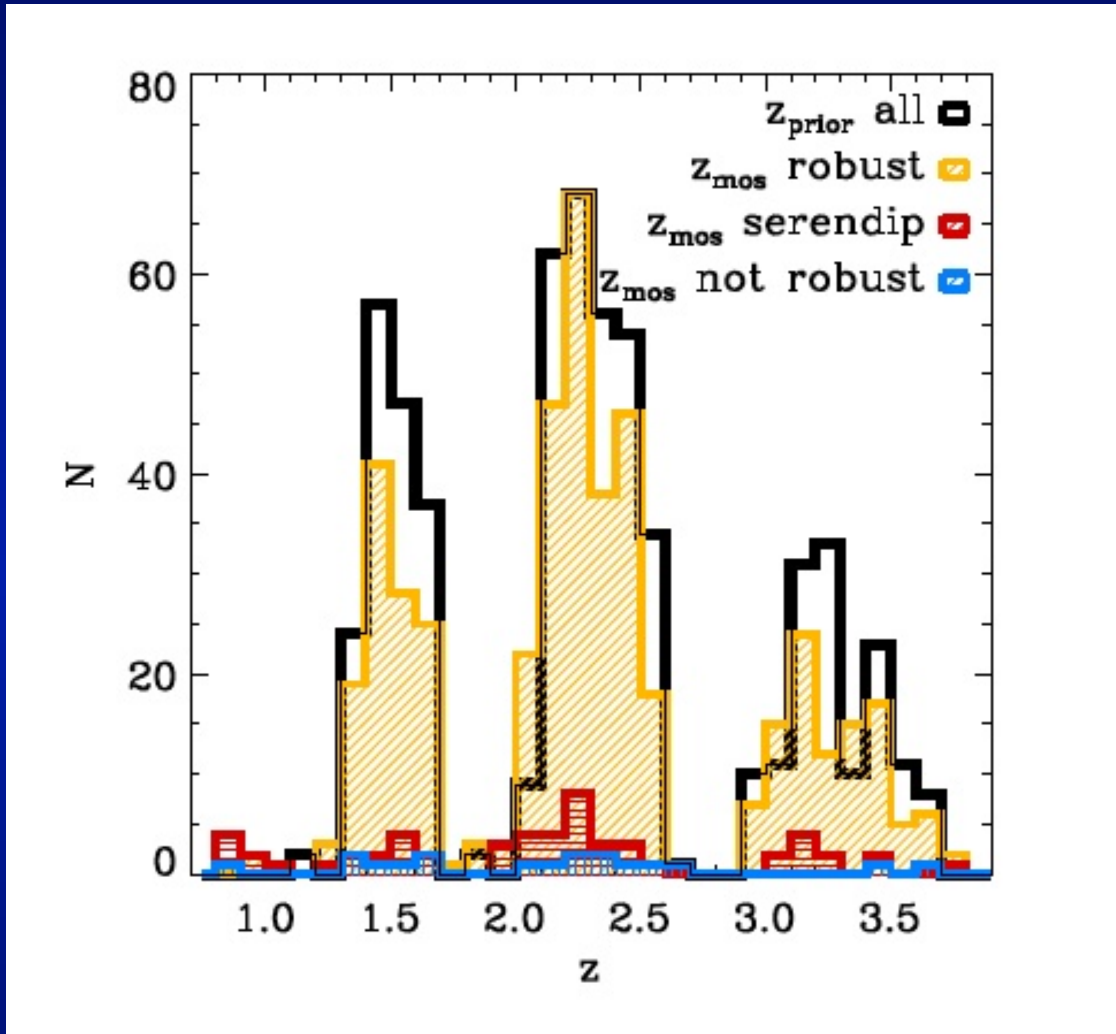


- Example extracted, flux-calibrated 1D spectra.
- [OII] in J, [OIII]+Hb in H, Ha +[NII]+[SII] in K

Redshift Dist

Better than 85% success rate even for the faint bins

In 2 hours of exposure, a S/N~3 achieved for Ha flux of ~10-18 erg/s/cm^2 in K-band at z~2.



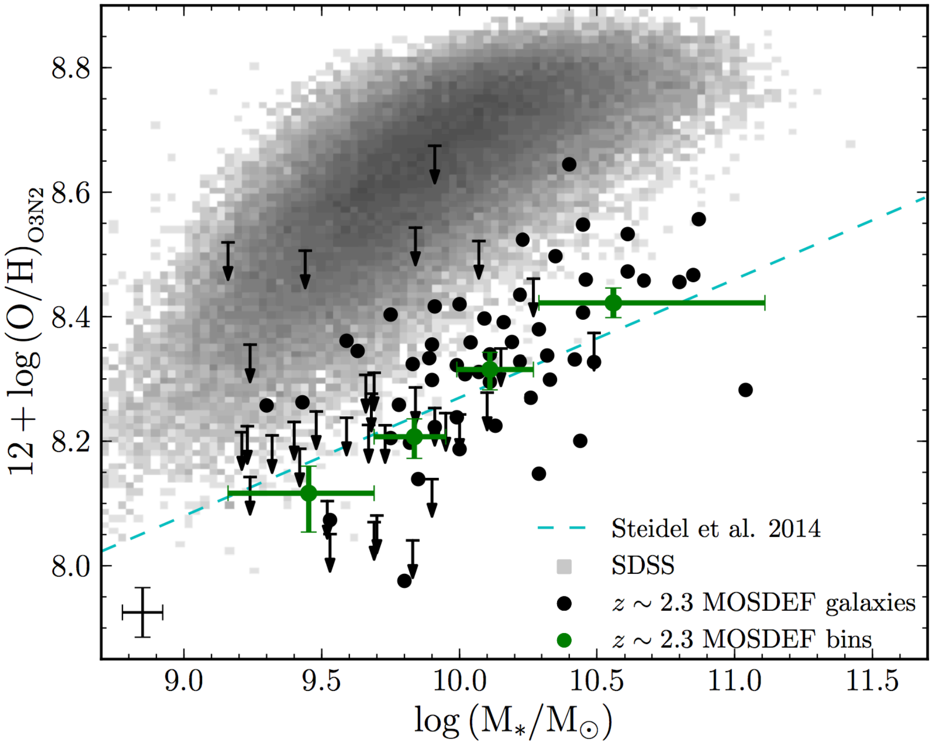
Preliminary Science

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

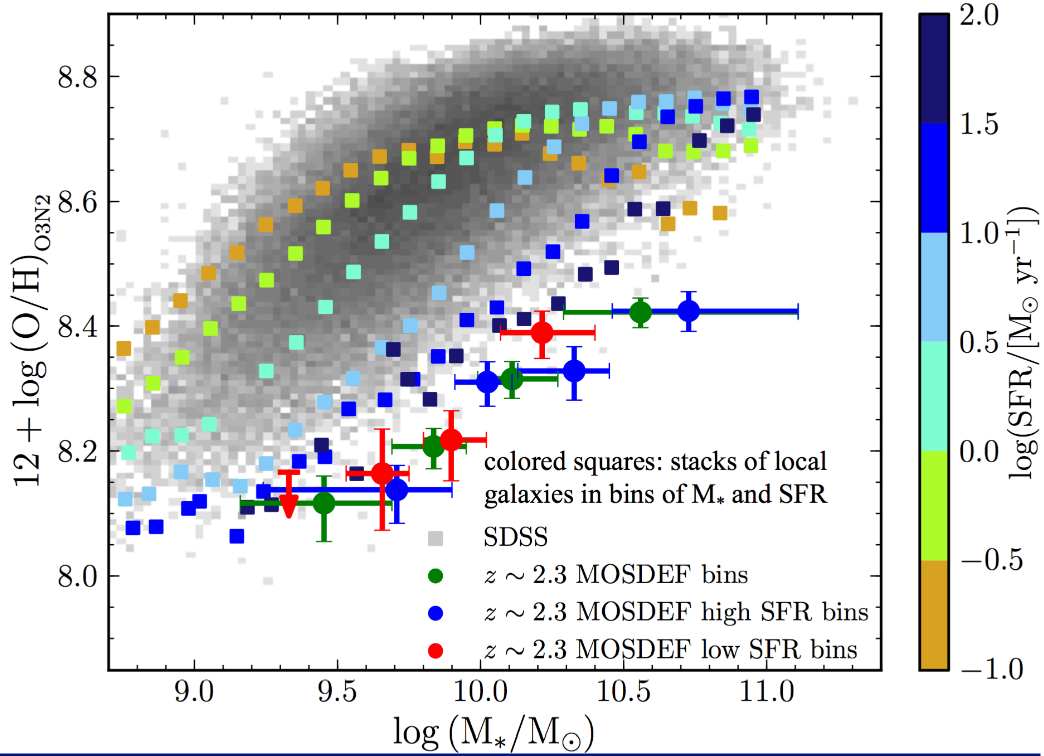
Mass, Metallicity, and SFR at z ~ 2.3 (Sanders et al. 2015)

The mass-metallicity relation at z ~ 2.3:



z ~ 2.3 star-forming galaxies are offset ~ 0.3 dex lower in metallicity compared to local galaxies

Does the FMR extend to z ~ 2.3?



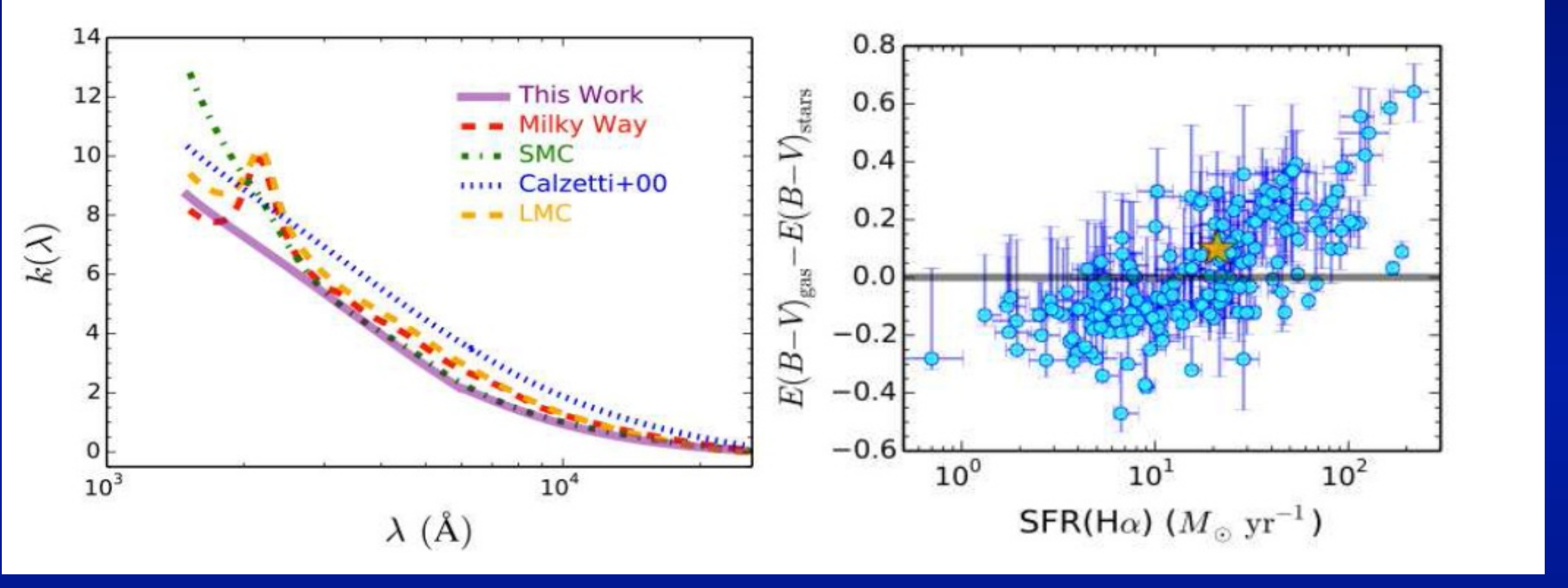
no significant SFR dependence observed among individual or stacked z ~ 2.3 galaxies. z ~ 2.3 galaxies do not fall on the local M-Z Relation but instead are offset ~0.1 dex lower in metallicity

Metallicities determined from O3N2

Star formations measured from Ha lines corrected for extinction. Galaxies are divided into bins of high and low SFRs. Small squares indicate bins of SFRs in SDSS.

We see an evolution of the M-Z relation with redshift in the range $0 < z < 2.3$. The evolution does not depend on SF activity.

SFR-Extinction Law at z~2
Reddy et al (ApJ 2015- submitted)

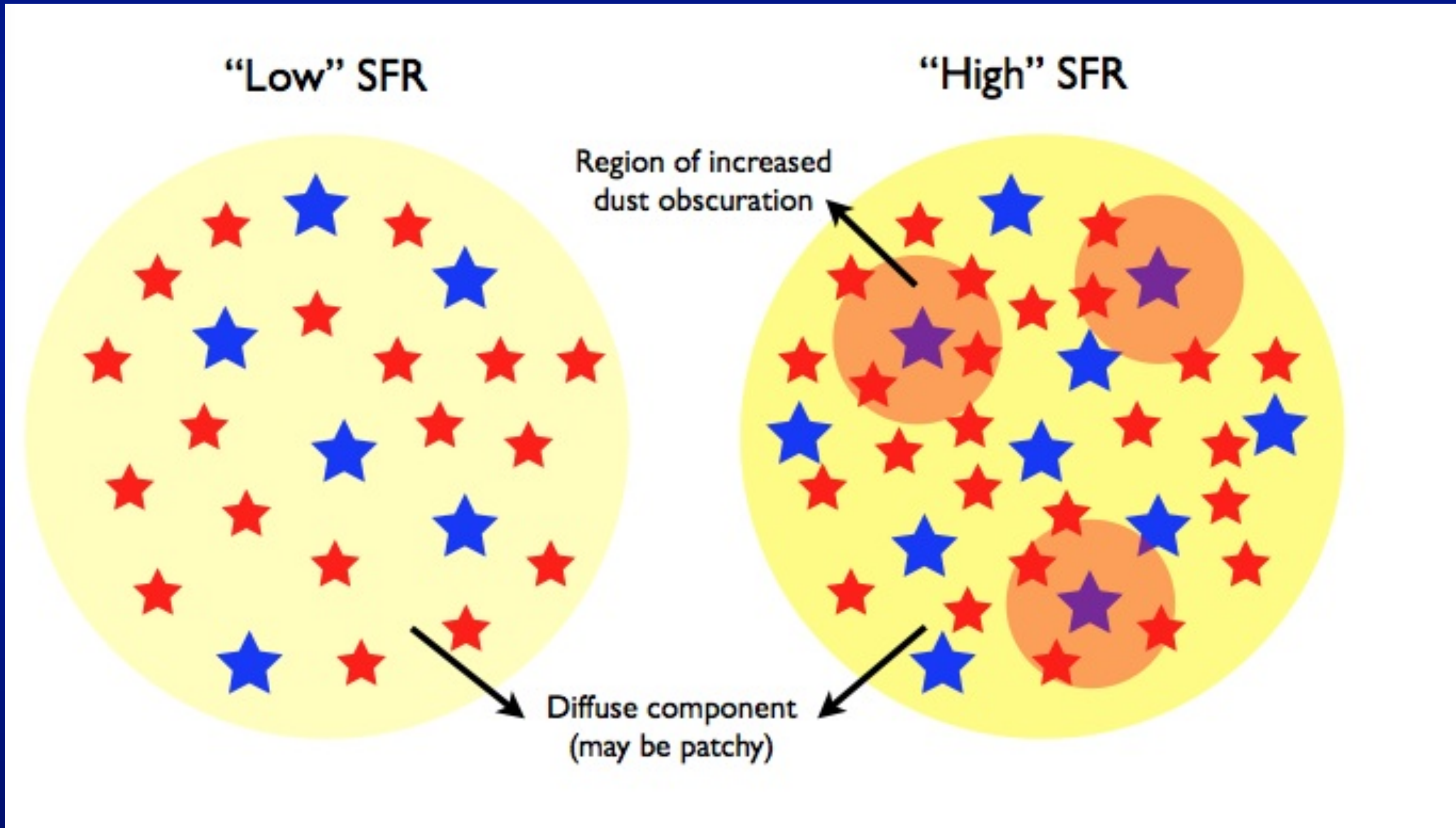


Comparison between extinction curves from this study (at z~2) with Calzetti, based on local starburst galaxies. At shorter wavelengths, the slope is parallel to Calzetti's law with lower normalization

Differences between the gas and continuum extinctions as a function of SFRs. Galaxies with higher SFRs exhibit larger obscuration of nebular lines relative to the continuum.

Nebular vs. Continuum Extinction

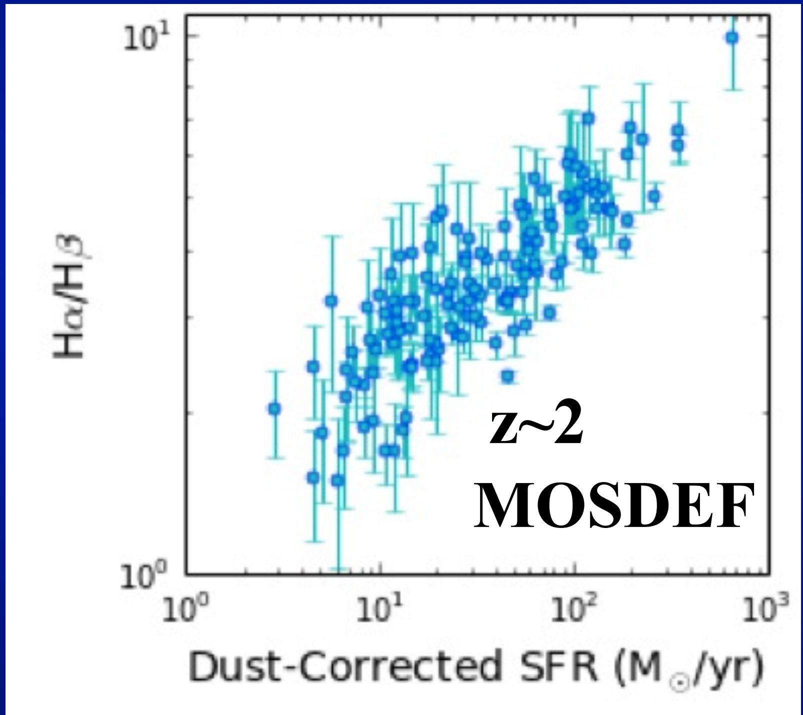
Credit: Naveen Reddy



Interpretation of the Extinction vs. SFR Relation

The geometry of dust and gas that can account for the trends seen in the E(B-V) vs. SFR figure. At lower SFRs, stars of all masses are uniformly obscured. At higher SFRs (>20 Msun/yr, Chabrier), the diffuse region becomes more dust-enriched (darker shade of yellow), while regions of more highly obscured SFR (red regions) become prominent. As the SFR increases, these more obscured regions begin to dominate the nebular line and bolometric luminosities. The diffuse component dominates the UV through optical SED at both low and high SFRs.

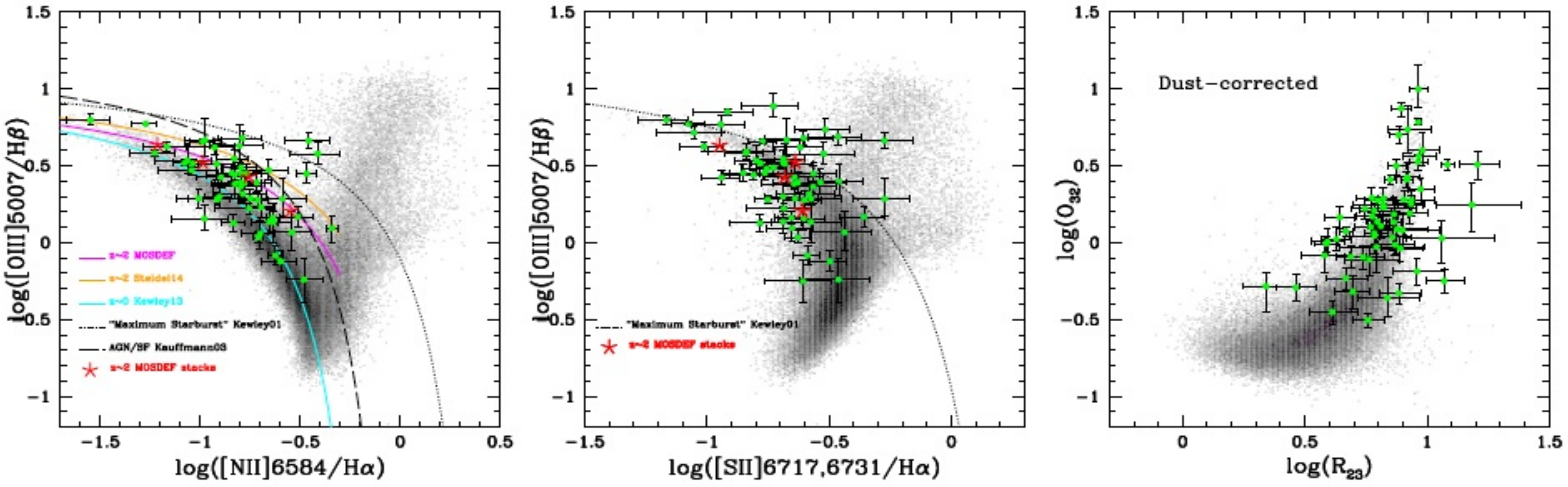
The MOSDEF Survey: Science



(Reddy et al. 2015)

- 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, lots of scatter, difference correlated with SFR.
- Nebular extinction correlated with dust-corrected SFR.

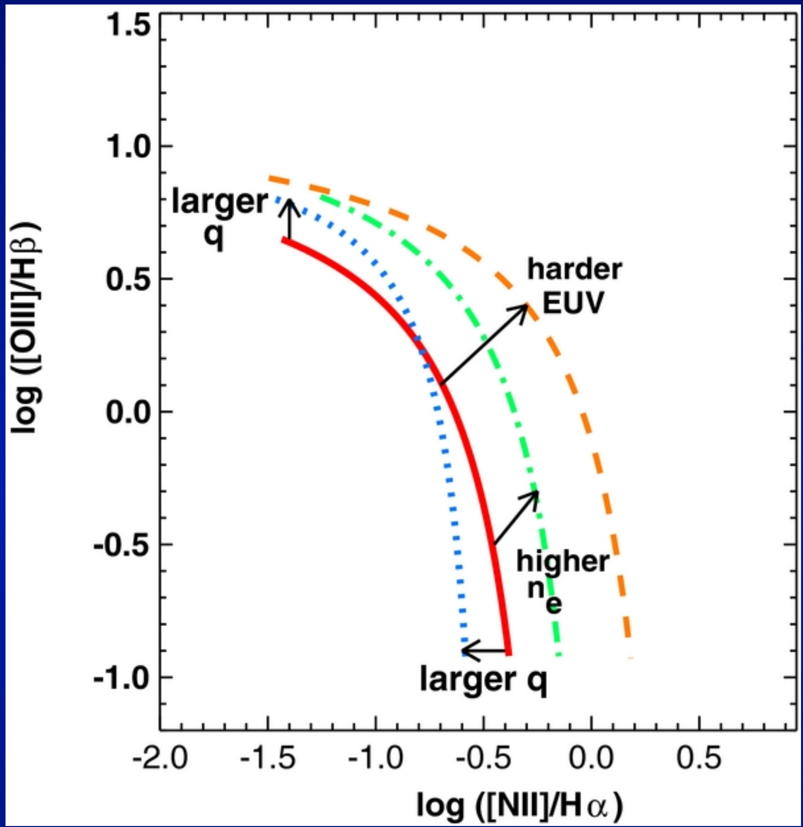
Evolution of BPT Diagram to z ~ 2
Shapley et al ApJ 2015



The BPT Diagrams

- 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

The MOSDEF Survey: Science



(Kewley et al. 2013)

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!**

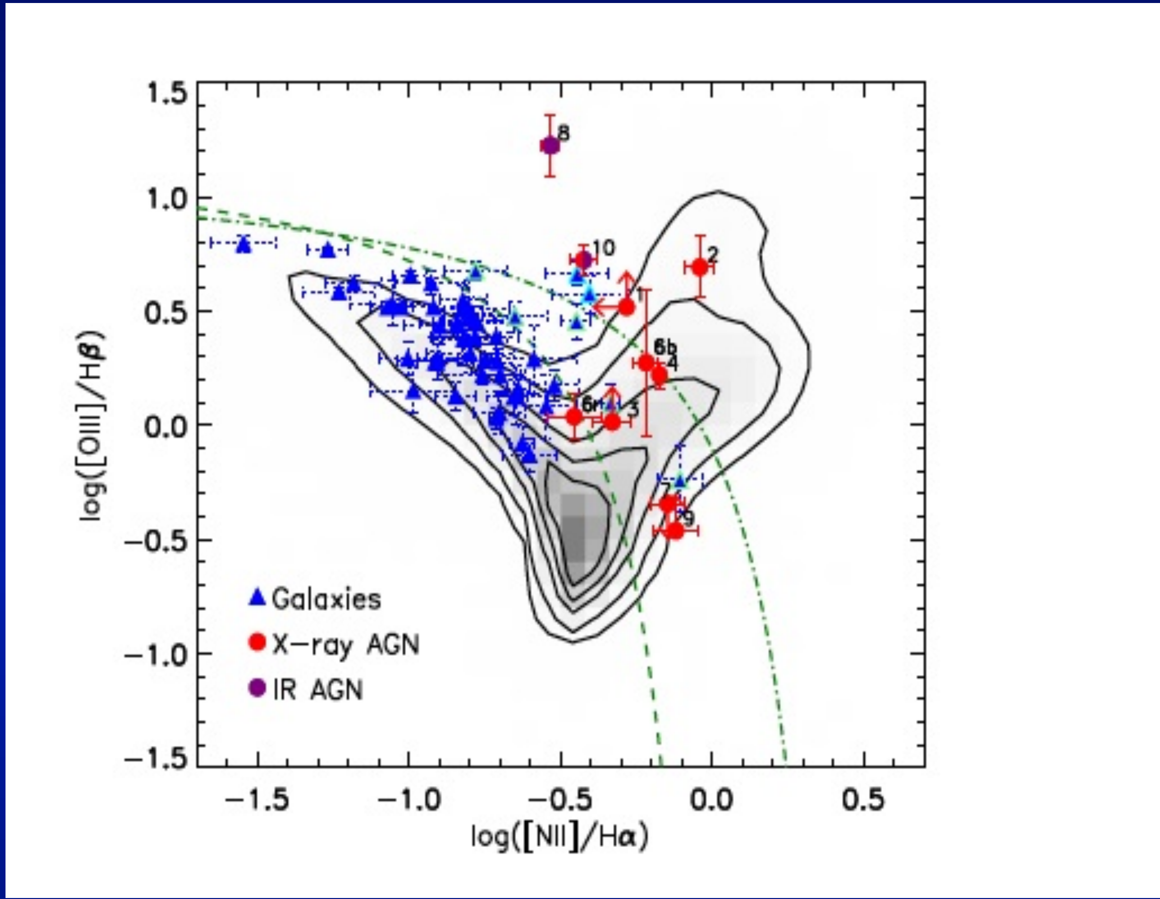
BPT diagram for MOSDEF galaxies at z~2.3, compared to similar relation from SDSS at z ~0. MOSDEF galaxies are offset from the local SF galaxies but not as significantly as in a UV-selected sample (Steidel et al 2015).

The z~2.3 SF galaxies scatters symmetrically around the z~0 SDSS sample

The MOSDEF z~2.3 sample closely follows the higher-end of the [OIII]/[OII] vs. R23 diagram at z~0 with no systematic offset

BPT Diagram for AGN at z ~ 2.3

Coil et al ApJ 2015



BPT diagram for AGN at z~2.3. The contours show the position of the SDSS galaxies at z~0. Blue and red symbols show locations of galaxies and AGN respectively. The lines separate SF galaxies and AGN

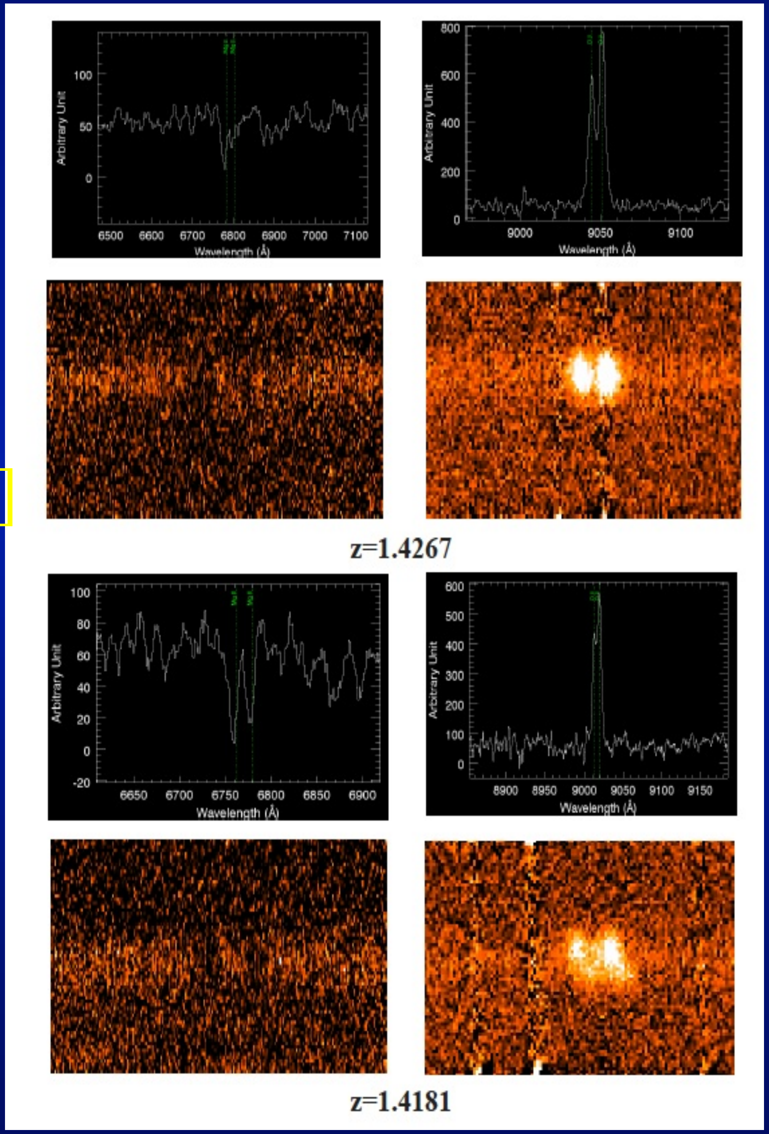
Keck DEIMOS Spectroscopy

Optical (Keck/DEIMOS) spectroscopy of MOSDEF galaxies is currently in progress.

The aim here is to acquire UV MgII and FeII lines to estimate the outflow from galaxies. These data will be used to study the evolution of galaxy outflow with look-back time as well as its relation with SFR, metallicity and mass of MOSDEF galaxies

Keck/DEIMOS Spectra

DEIMOS 1D and 2D spectra show detection of MgII lines and resolution of [OII] doublets. Measuring [OII] also gives another Diagnostic for measuring SFRs in 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!