Galaxy Chemical Abundances and ISM Conditions at High Redshifts: the Present State and Bright Future with ELTs

Ryan Sanders
University of California, Davis

The **MOS**FIRE **D**eep **E**volution **F**ield survey (MOSDEF) team:

UC-Los Angeles: **Alice Shapley**

UC-Berkeley: **Mariska Kriek**, Tom Zick

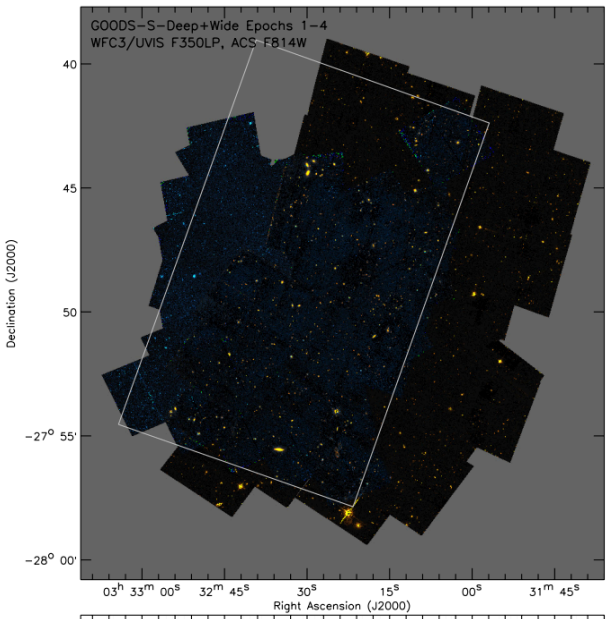
UC-Riverside: **Naveen Reddy, Brian Siana, Bahram Mobasher**, Bill Freeman, Tara Fetherolf

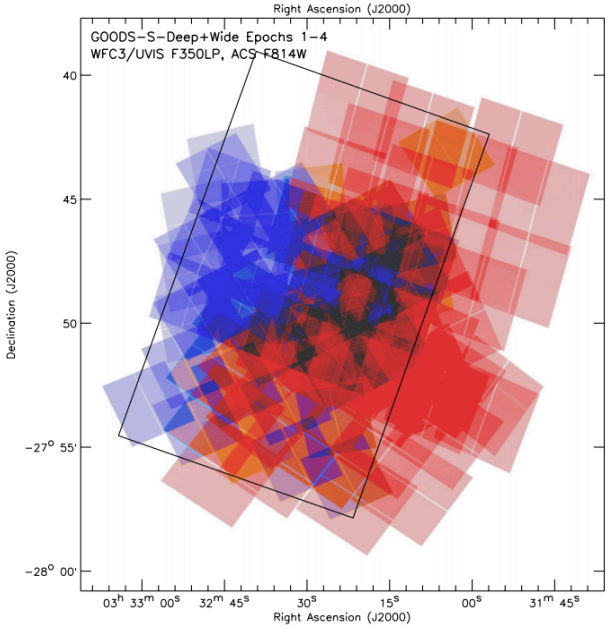
UC-San Diego: **Alison Coil**, Mojegan Azadi, Gene Leung

Irene Shivaei (Arizona), Sedona Price (MPE), Laura de Groot (Denison)

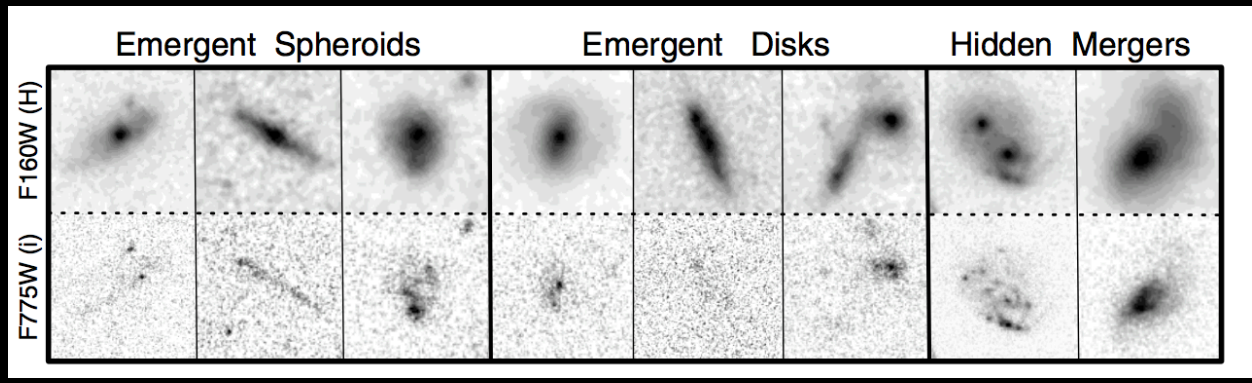
Guillermo Barro (U. of the Pacific), Francesca Fornasini (Harvard/CfA)

A golden age in galaxy evolution studies

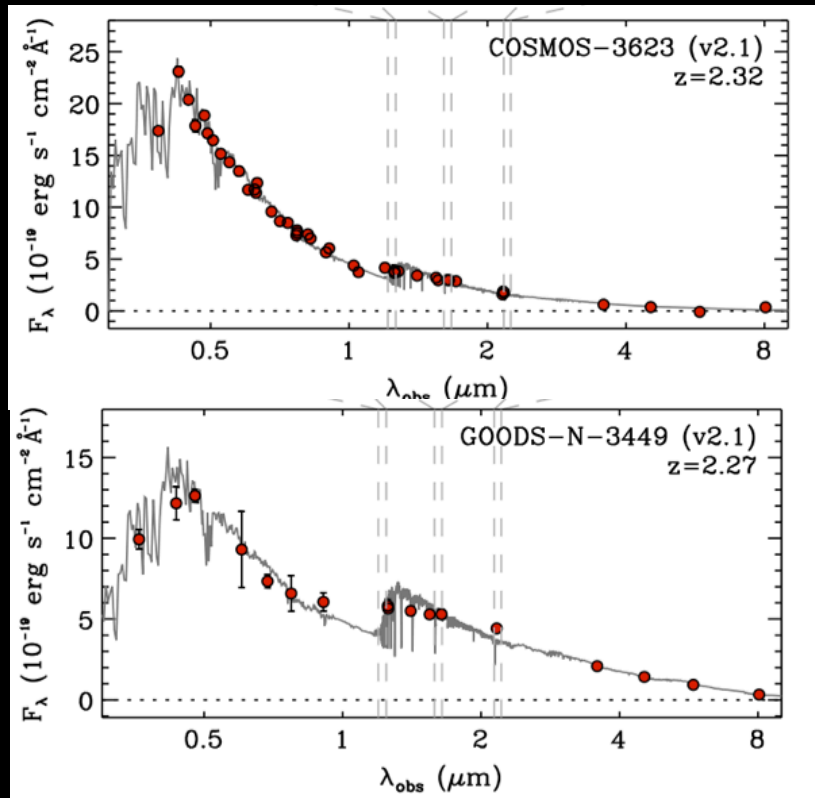




Koekemoer+2011



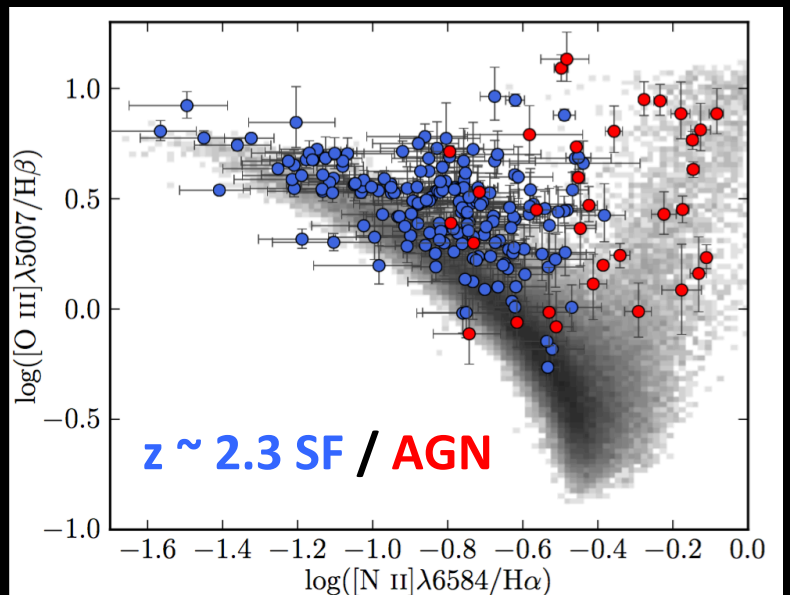
Grogin+2011

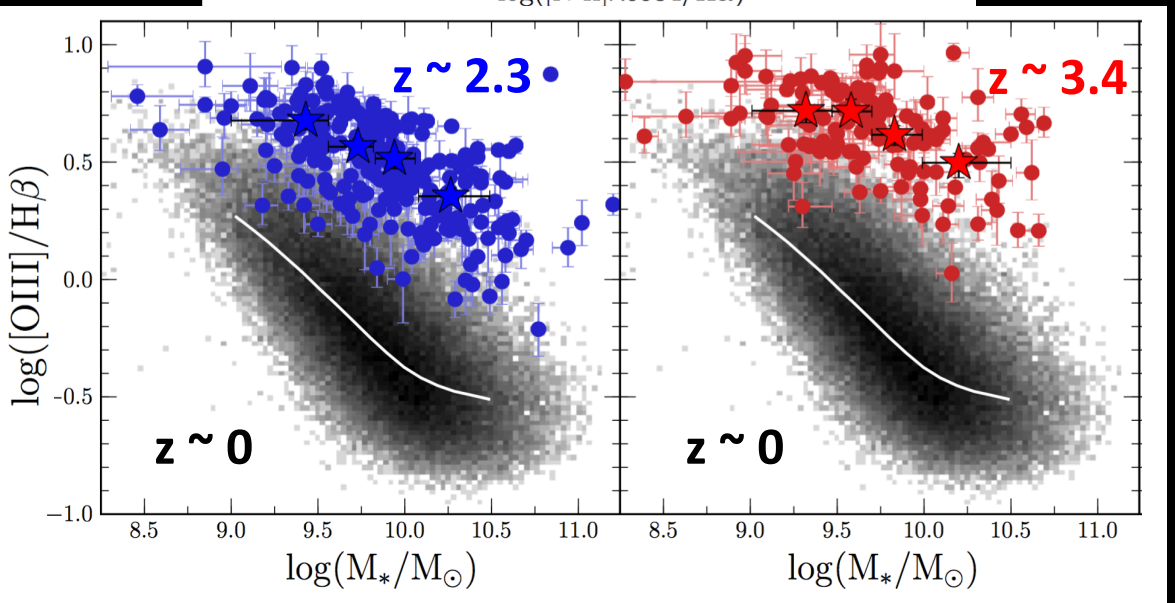


Kriek+2015

A golden age in galaxy evolution studies

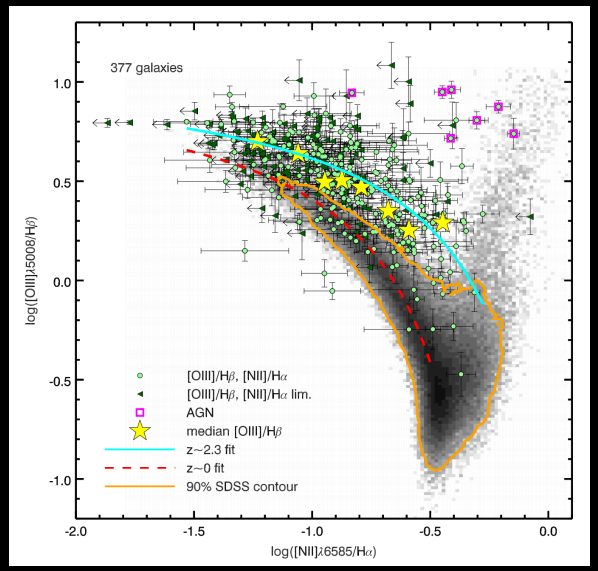
MOSDEF: 1.4 < z < 3.8





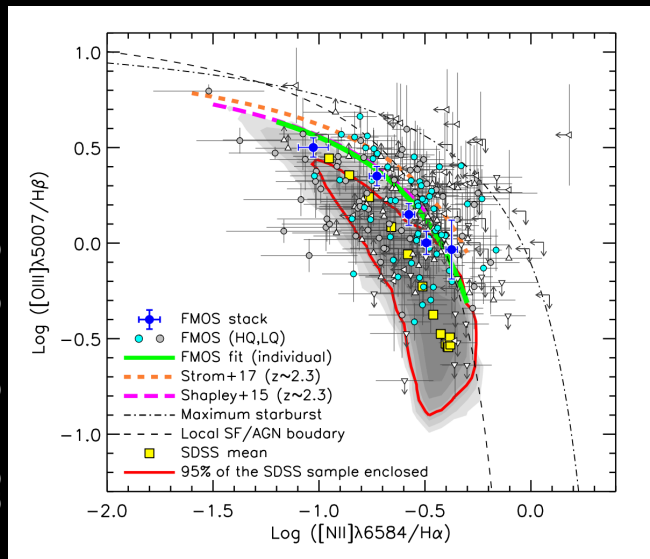
KBSS-MOSFIRE: z~2.3

Strom+2017



FMOS-COSMOS: z~1.5

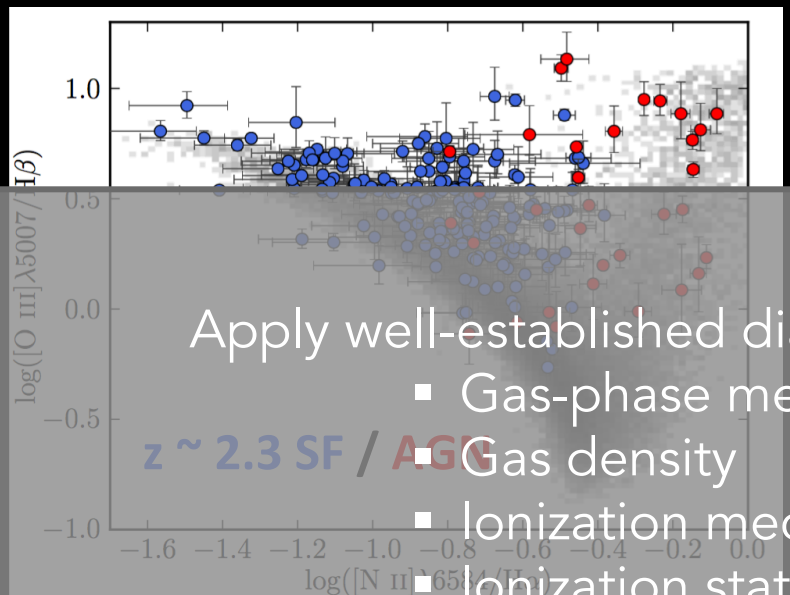
Kashino+2018

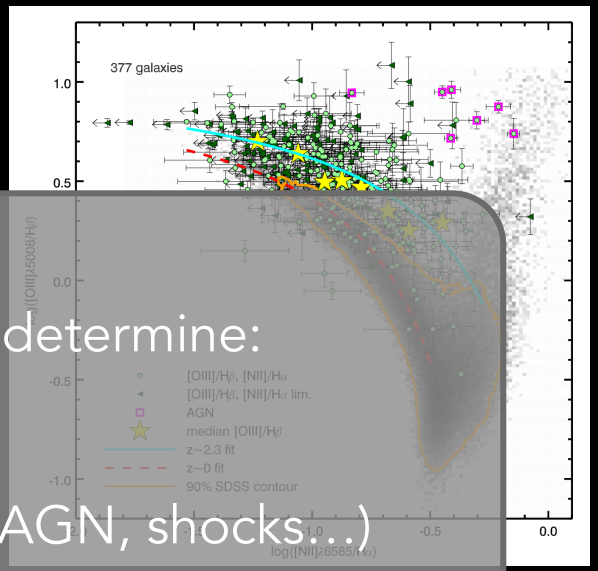


A golden age in galaxy evolution studies

MOSDEF: 1.4 < z < 3.8

KBSS-MOSFIRE: z~2.3

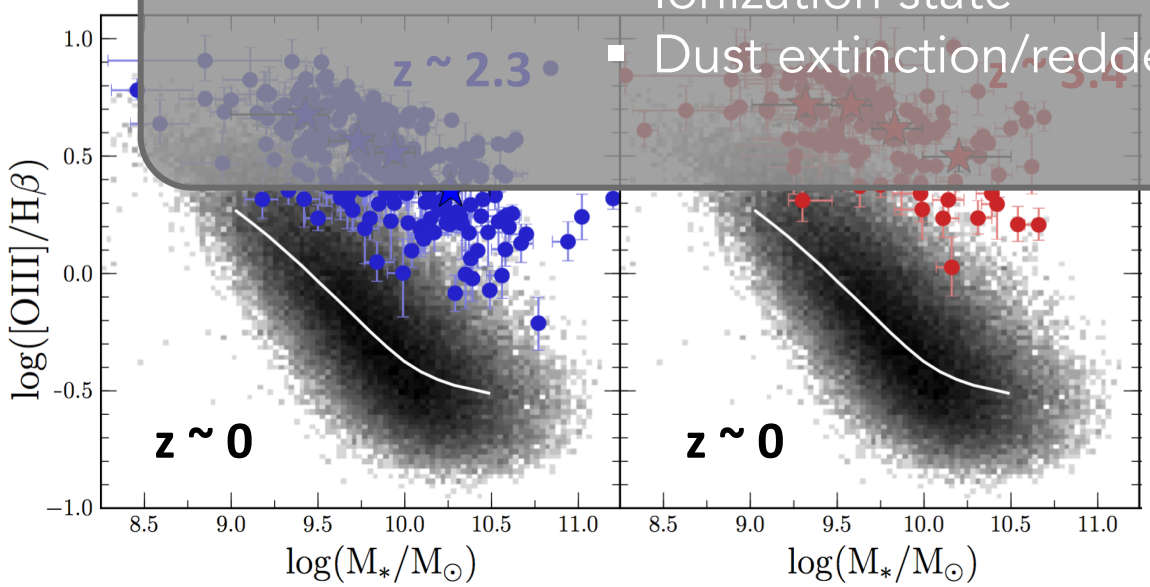


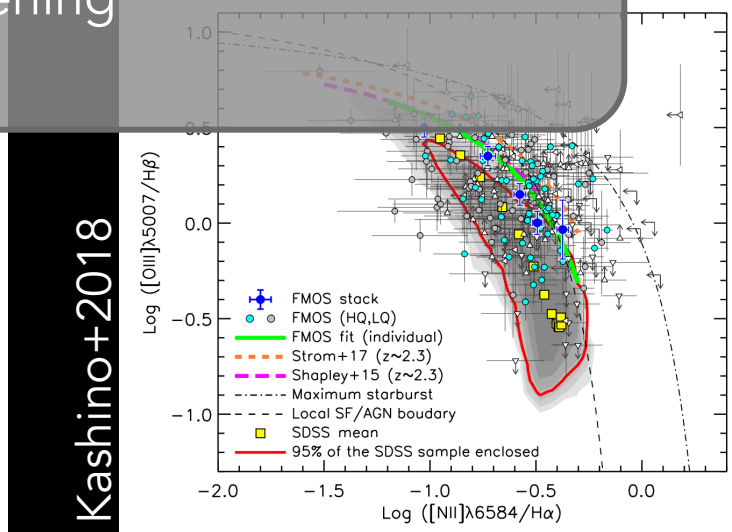


Apply well-established diagnostics to determine:

- Gas-phase metallicity
- Gas density
- Ionization mechanism (SF, AGN, shocks…)
- Ionization state
- Dust extinction/reddening

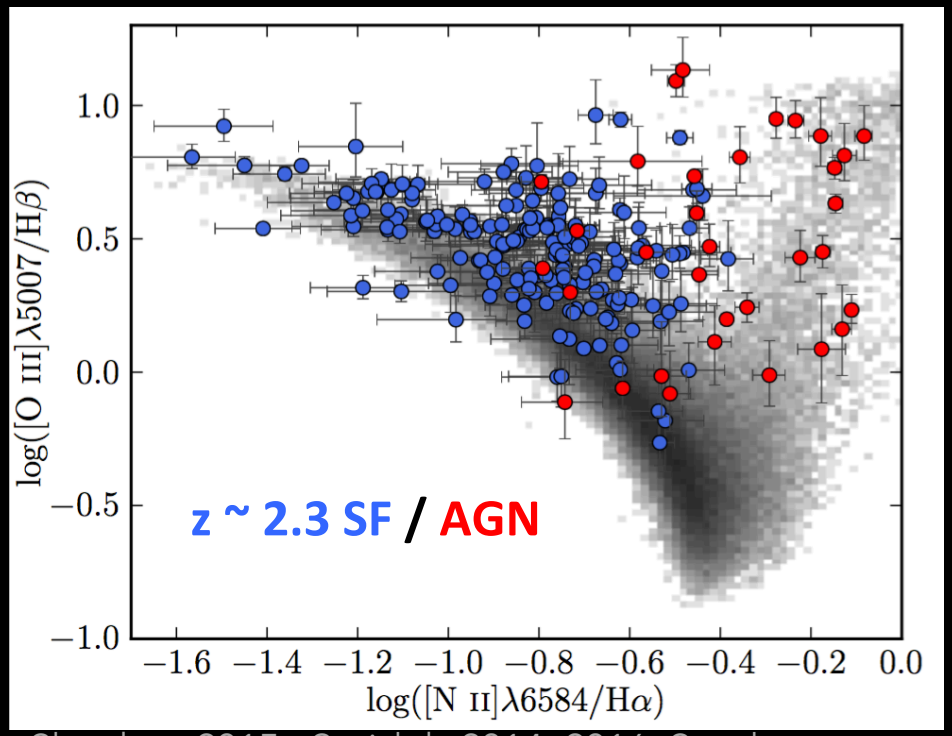
FMOS-COSMOS: z~1.5



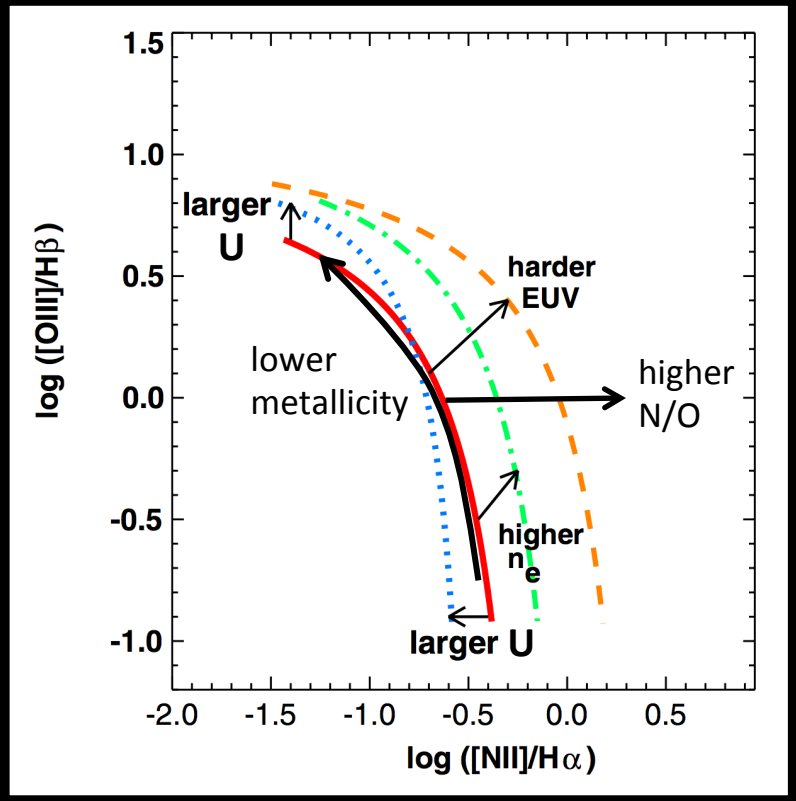


Evolving line-ratio sequences imply evolving ISM conditions

- Evolving ionized gas conditions call into question the applicability of local metallicity calibrations at high redshifts



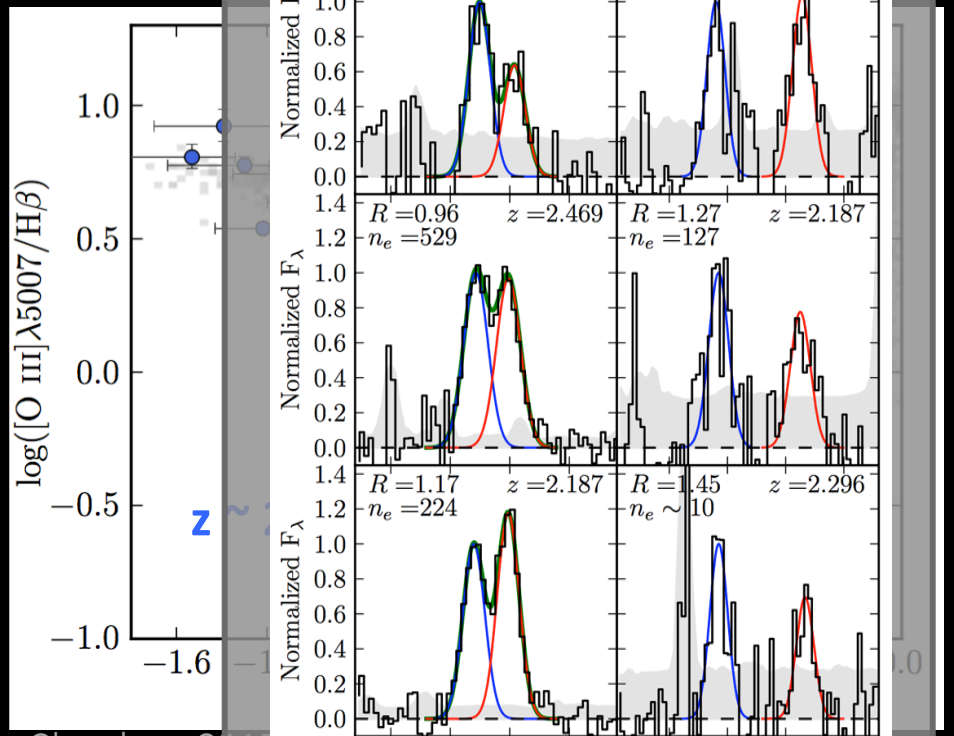
Shapley+2015, Steidel+2014, 2016, Sanders +2016, Strom+2017, 2018, Kashino+2017, …



Kewley+2013

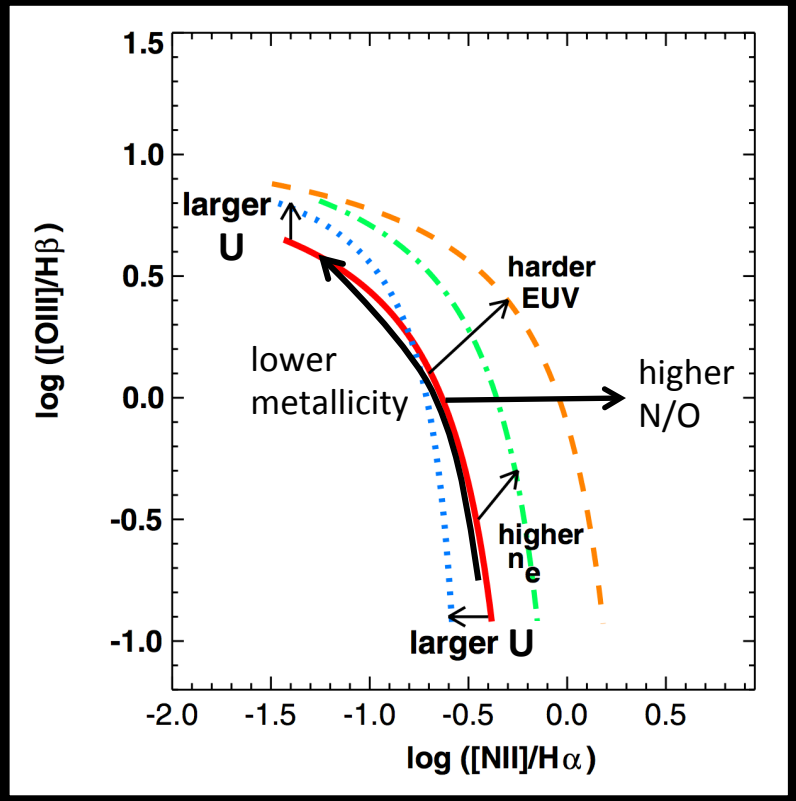
Evolving line-ratio sequences imply evolving ISM conditions

- Evolving ionized gas conditions call into question the applicability of local m[illegible] high redshifts



Shapley+2015
+2016, Strom[illegible]

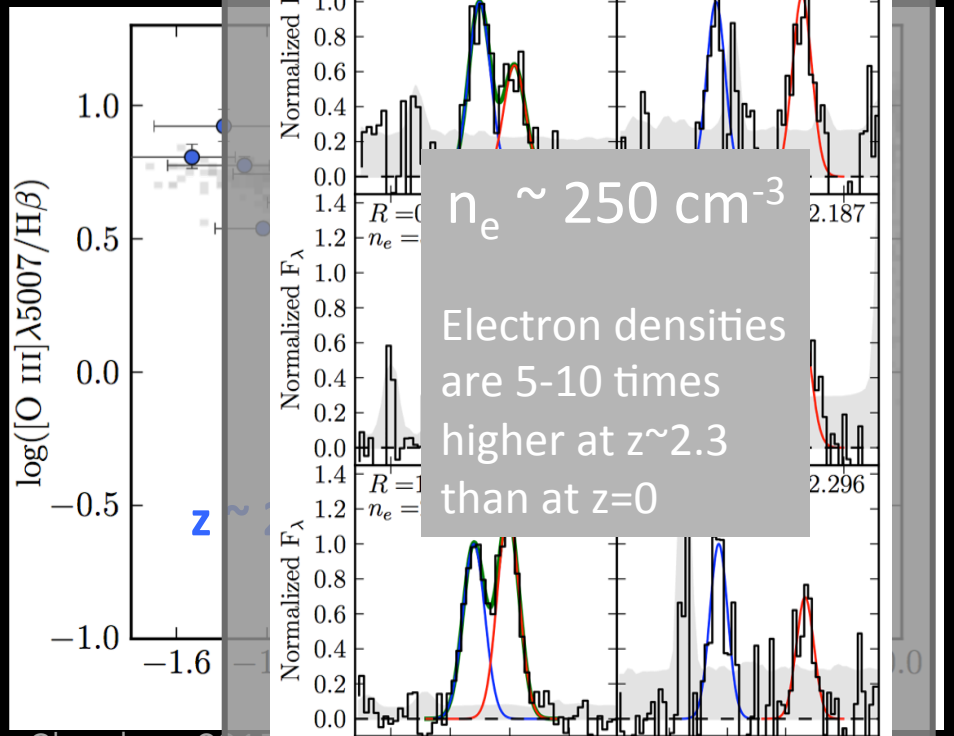
Sanders et al. 2016a



Kewley+2013

Evolving line-ratio sequences imply evolving ISM conditions

- Evolving ionized gas conditions call into question the applicability of local m[illegible] high redshifts

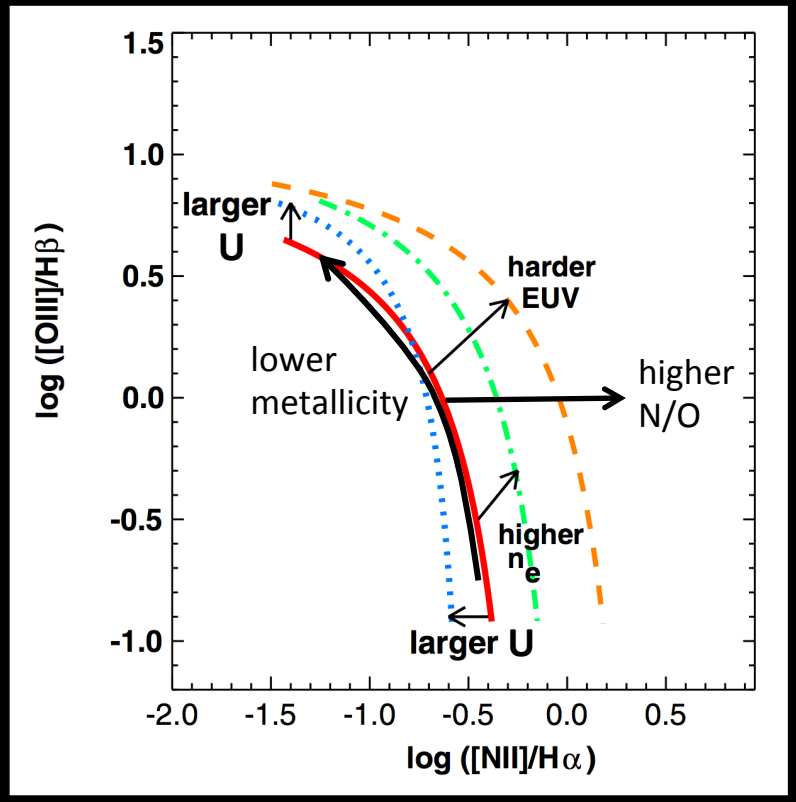


Shapley+2015 +2016, Strom[illegible]

n_e ~ 250 cm^{-3}

Electron densities are 5-10 times higher at z~2.3 than at z=0

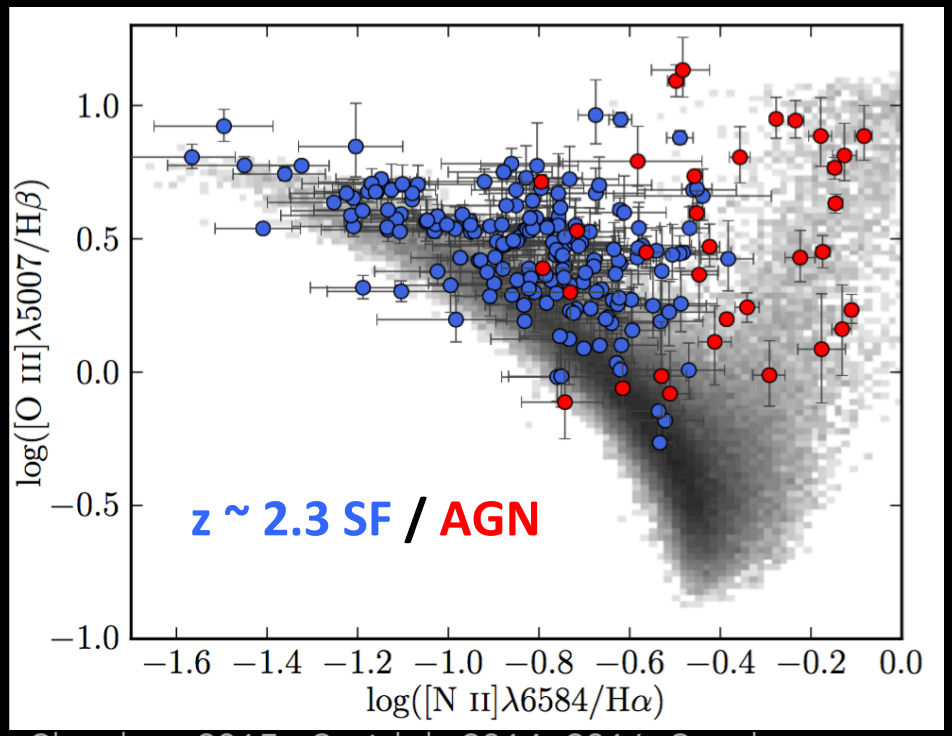
Sanders et al. 2016a



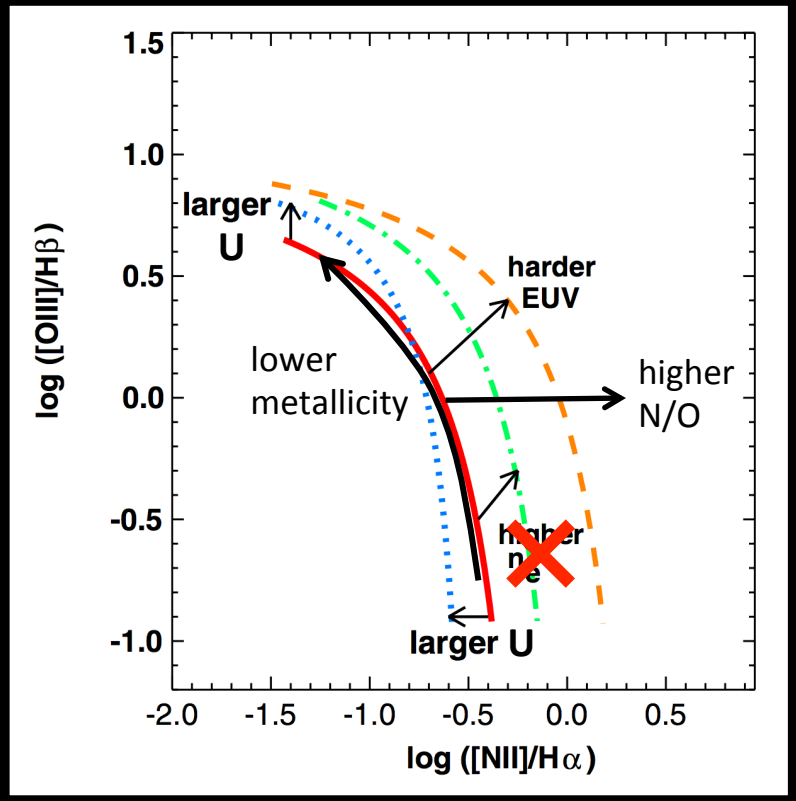
Kewley+2013

Evolving line-ratio sequences imply evolving ISM conditions

- Evolving ionized gas conditions call into question the applicability of local metallicity calibrations at high redshifts

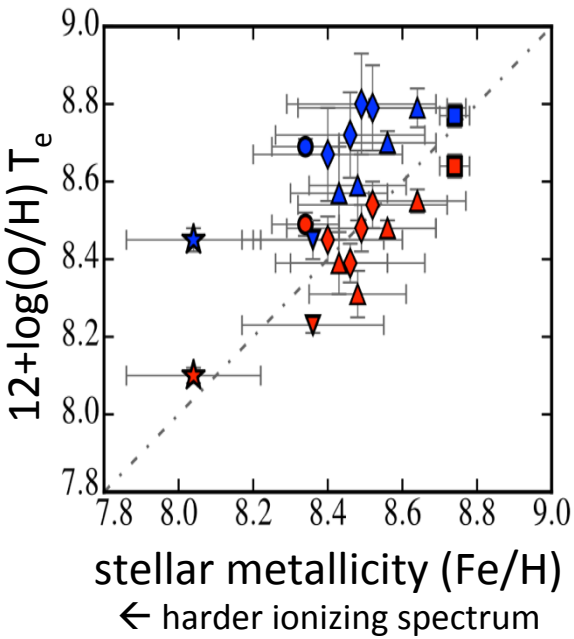


Shapley+2015, Steidel+2014, 2016, Sanders +2016, Strom+2017, 2018, Kashino+2017, …

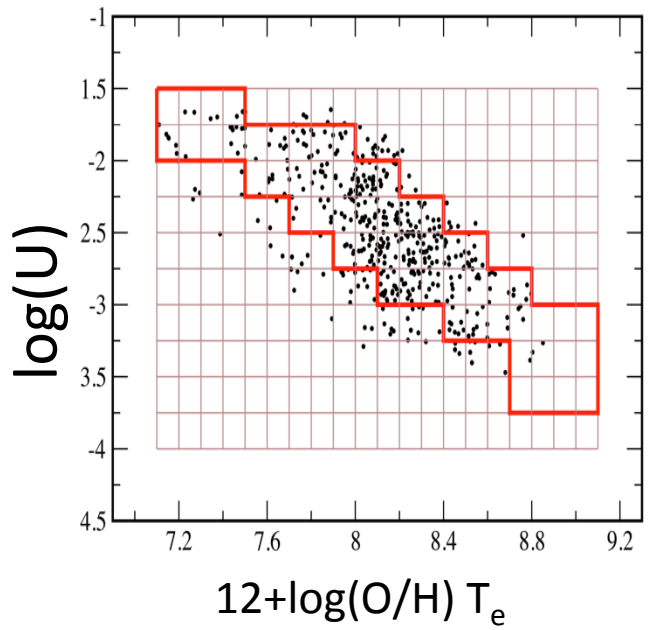


Kewley+2013

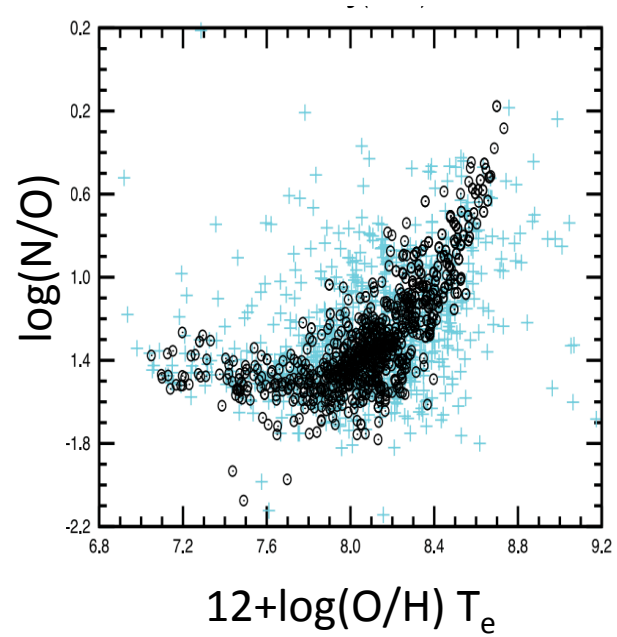
Physical properties (anti)correlate with nebular metallicity



Toribio San Cipriano+2017



Perez-Montero+2014

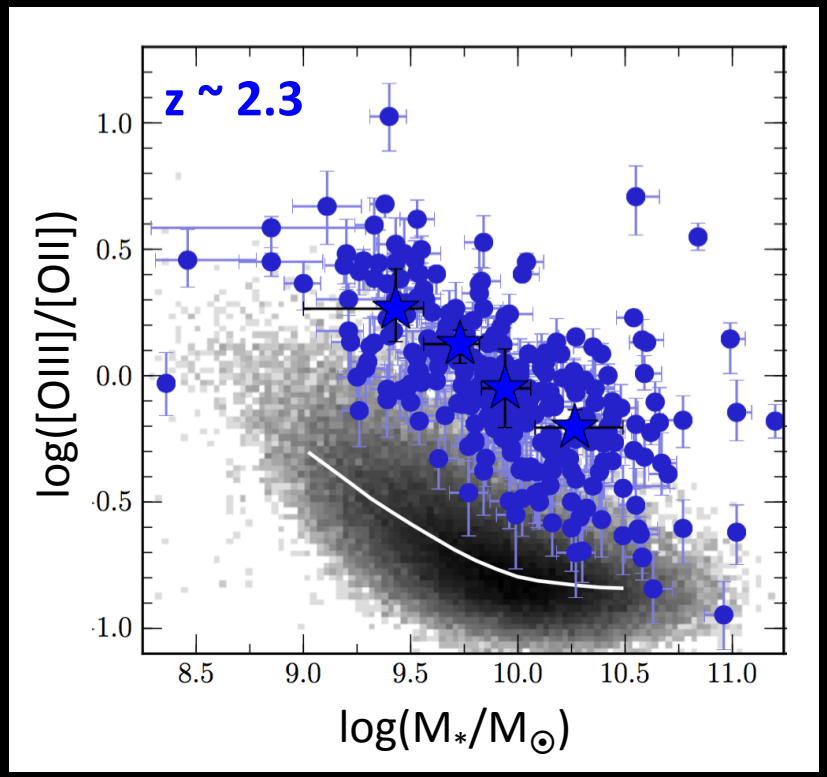


Pilyugin+2012

Tight relations between O/H and Z_*, U, N/O →narrow sequences in line ratio spaces
→ optical line ratios can be used to estimate nebular metallicity

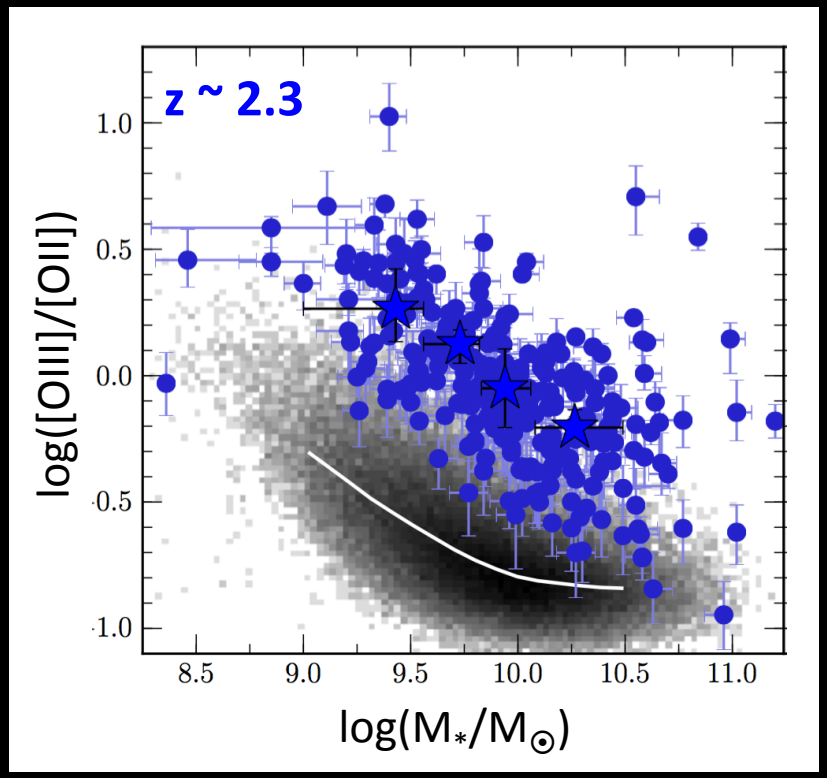
Not solvable by comparison at fixed stellar mass

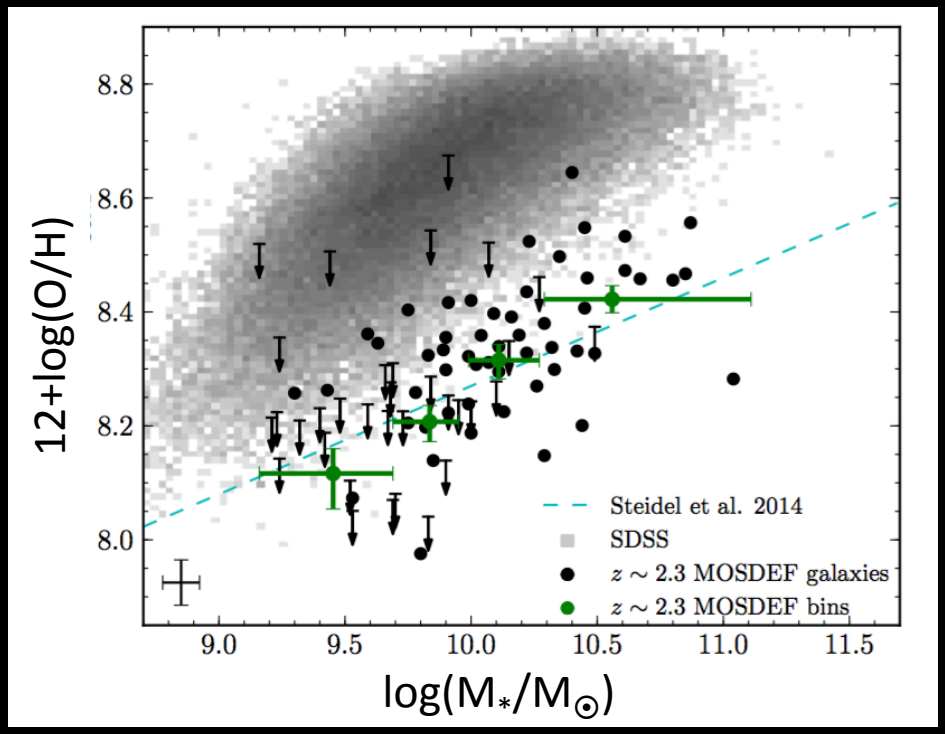
- Evolving ionized ISM conditions potentially bias metallicities at high-z



Not solvable by comparison at fixed stellar mass

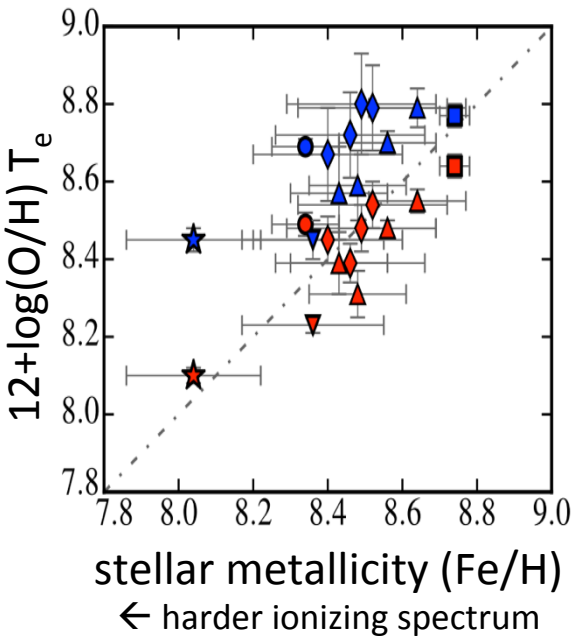
- Evolving ionized ISM conditions potentially bias metallicities at high-z



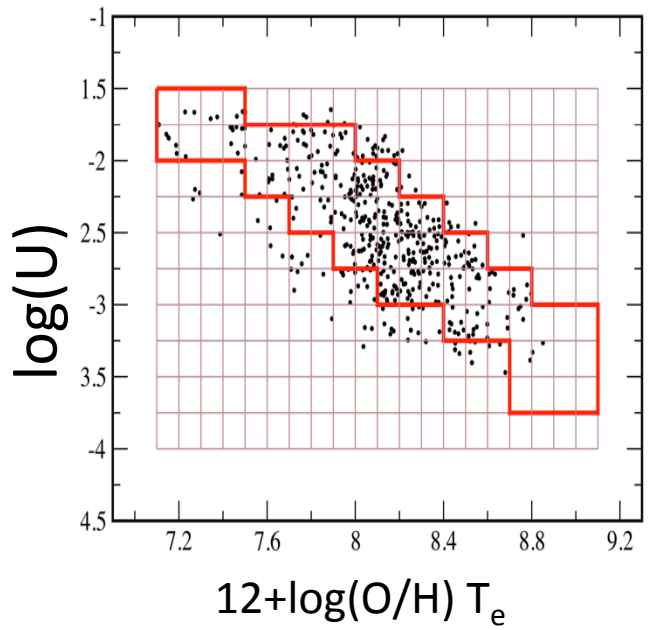


Sanders+2015

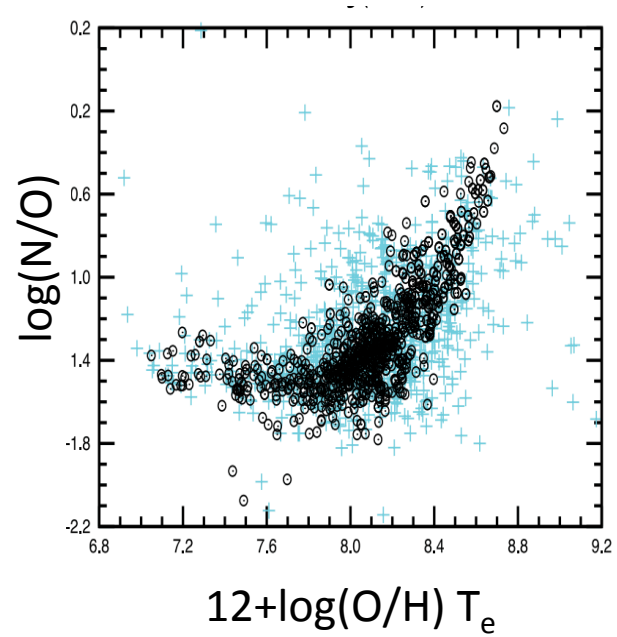
Physical properties (anti)correlate with nebular metallicity



Toribio San Cipriano+2017



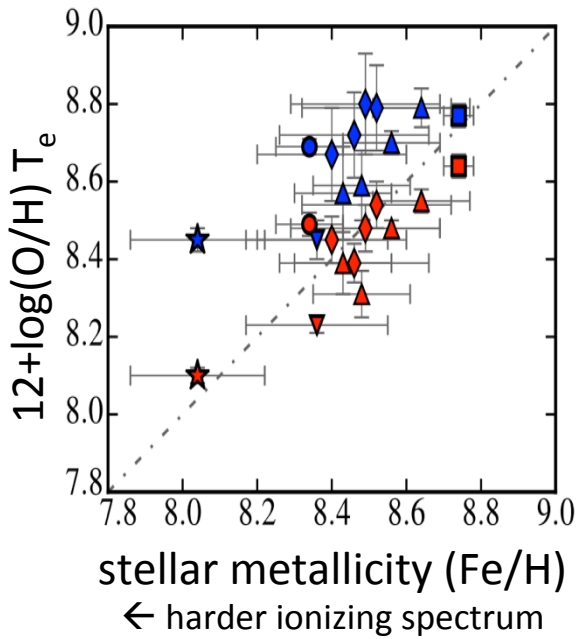
Perez-Montero+2014



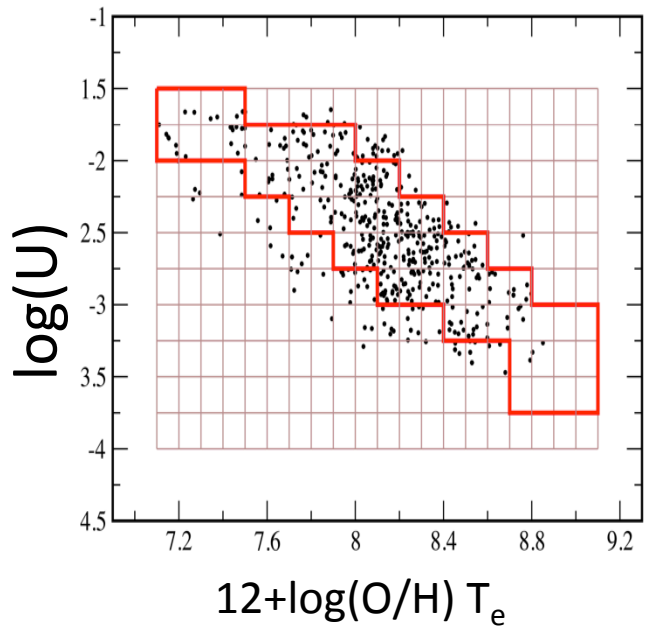
Pilyugin+2012

Tight relations between O/H and Z_*, U, N/O →narrow sequences in line ratio spaces
→ optical line ratios can be used to estimate nebular metallicity

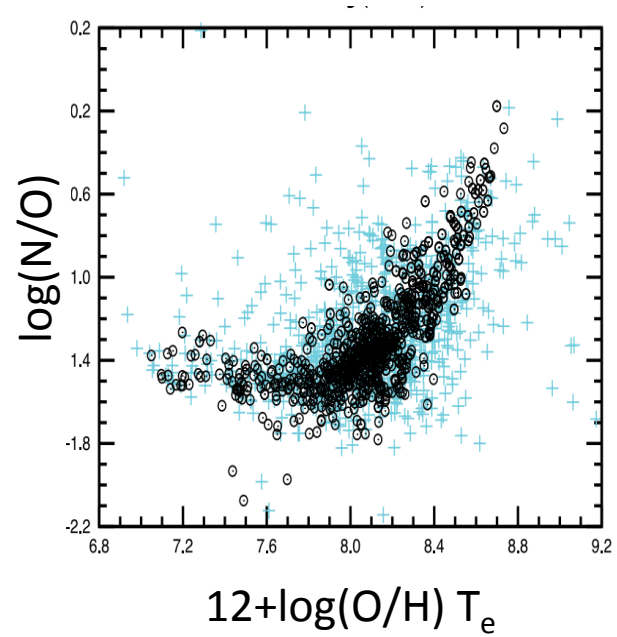
Physical properties (anti)correlate with nebular metallicity



Toribio San Cipriano+2017



Perez-Montero+2014



Pilyugin+2012

Tight relations between O/H and Z_*, U, N/O →narrow sequences in line ratio spaces
→ optical line ratios can be used to estimate nebular metallicity

Need an independent determination of nebular metallicity!

[OIII]λ4363

[OIII]λ4363 + [OIII]λ5007 + [OII]λ3727 + Hβ

+

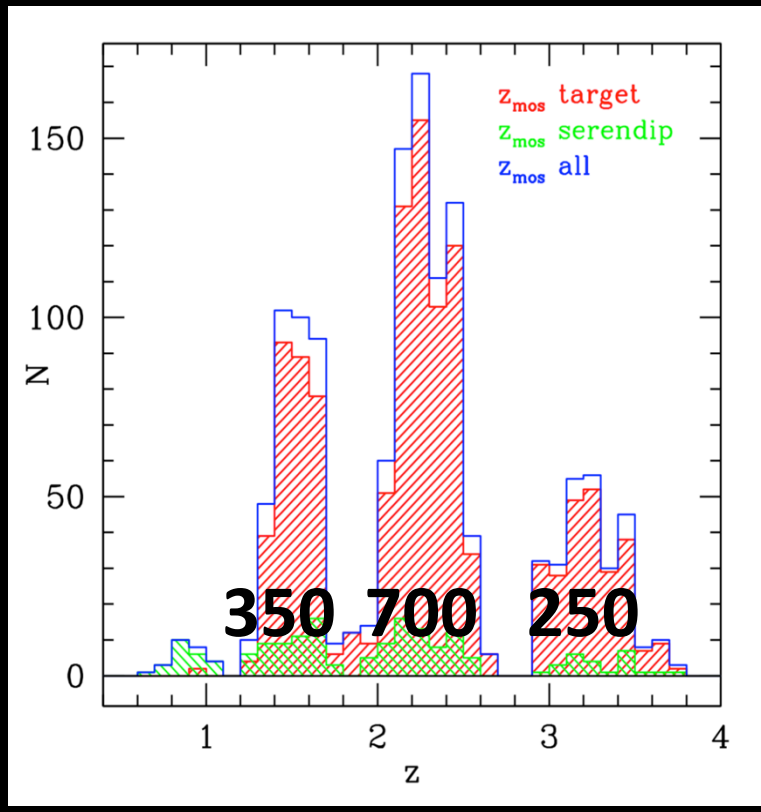
atomic physics

=

Nebular oxygen abundance

The MOSFIRE Deep Evolution Field survey

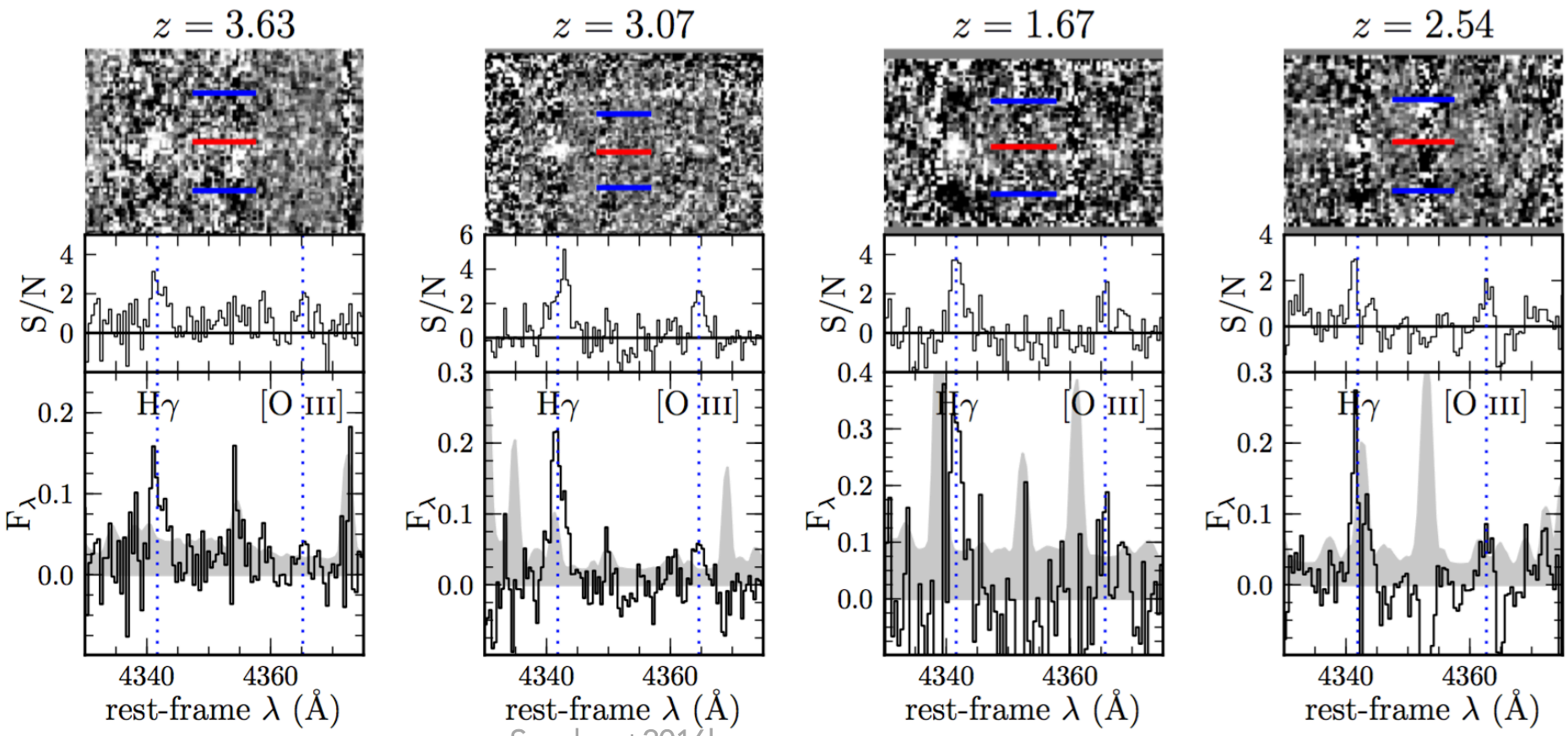
- Keck/MOSFIRE: high sensitivity, multiplexing, rest-frame optical spectra
- Rest-frame optical selected sample (observed H band)
- CANDELS fields with ancillary multi-wavelength data
- Large, representative sample of galaxies spanning a large dynamic range in stellar mass, SFR, and SED shape
- Multiple redshift ranges in order to study evolution



Observations completed in 2016: 1500 galaxies targeted, 1300 redshifts

T_e metallicities at z~2-3 from [OIII]λ4363

- 4 star-forming galaxies in the MOSDEF survey with T_e metallicities!



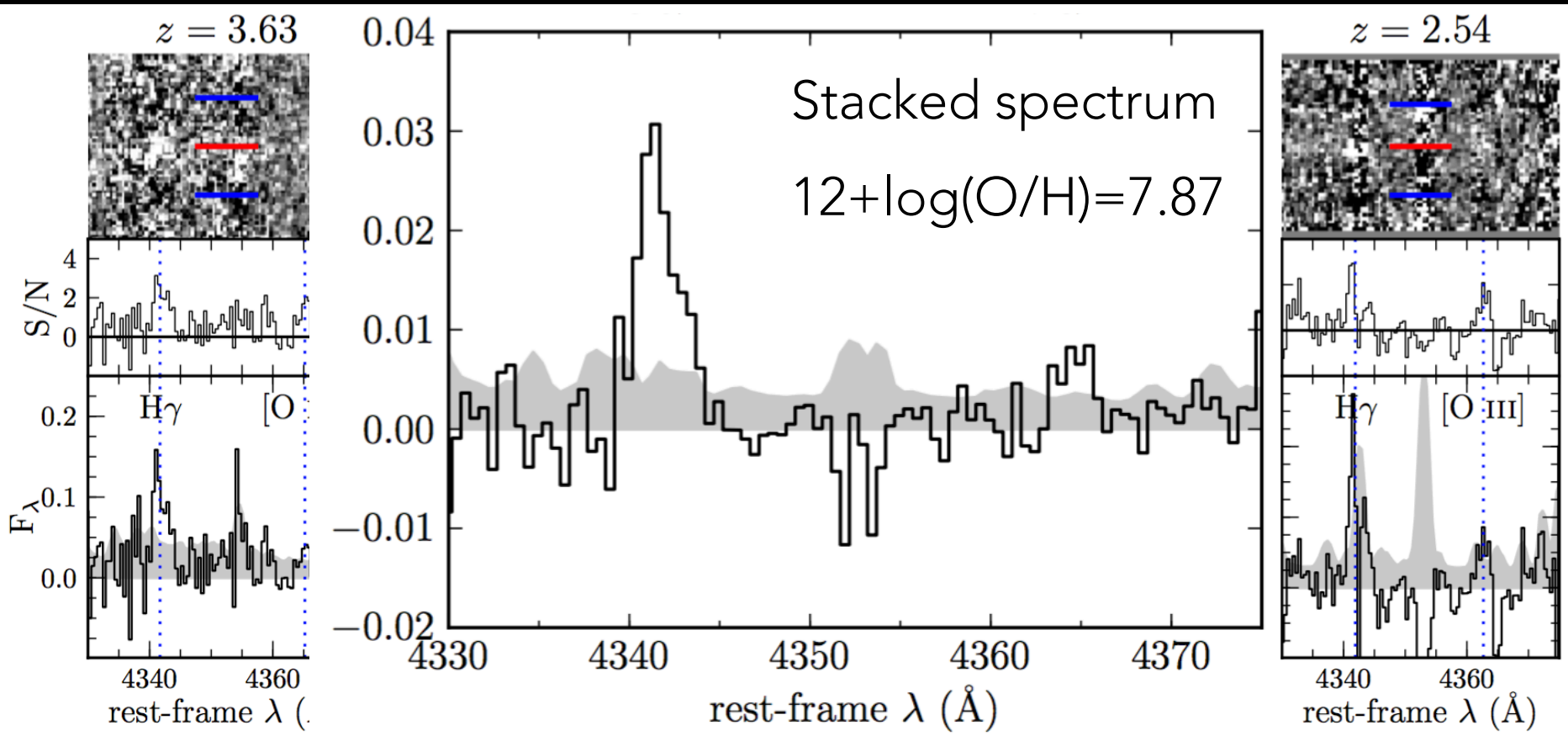
Sanders+2016b

Sanders+in prep

12+log(O/H) = 7.6 – 8.0 (0.1-0.2 $Z_\odot$)

T_e metallicities at z~2-3 from [OIII]λ4363

- 4 star-forming galaxies in the MOSDEF survey with T_e metallicities!



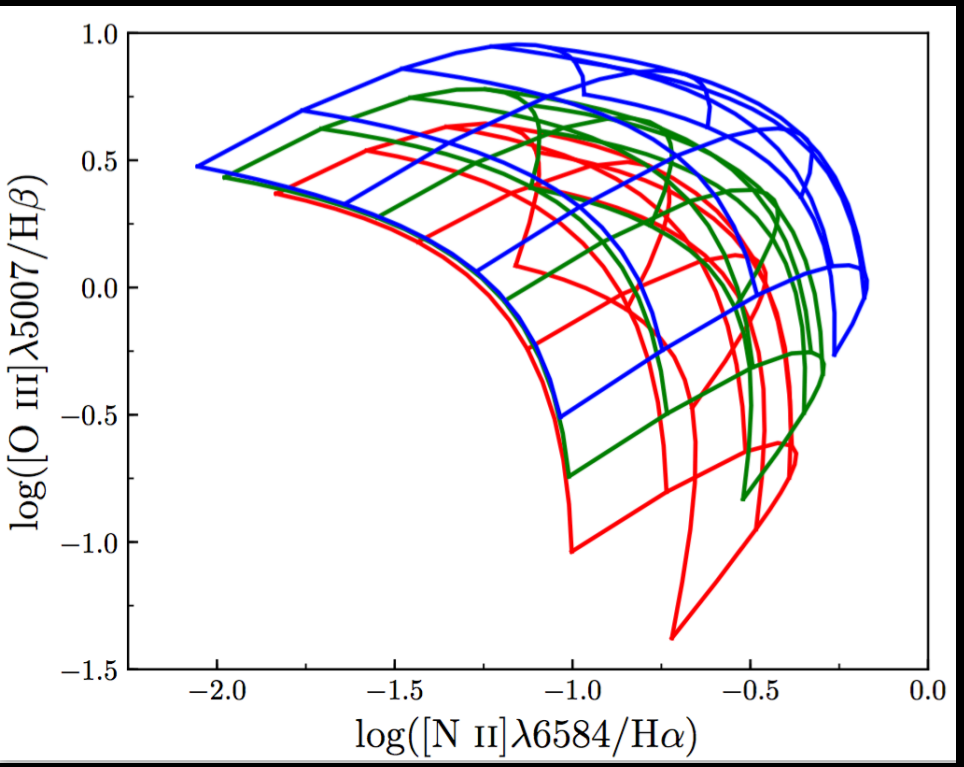
Sanders+in prep

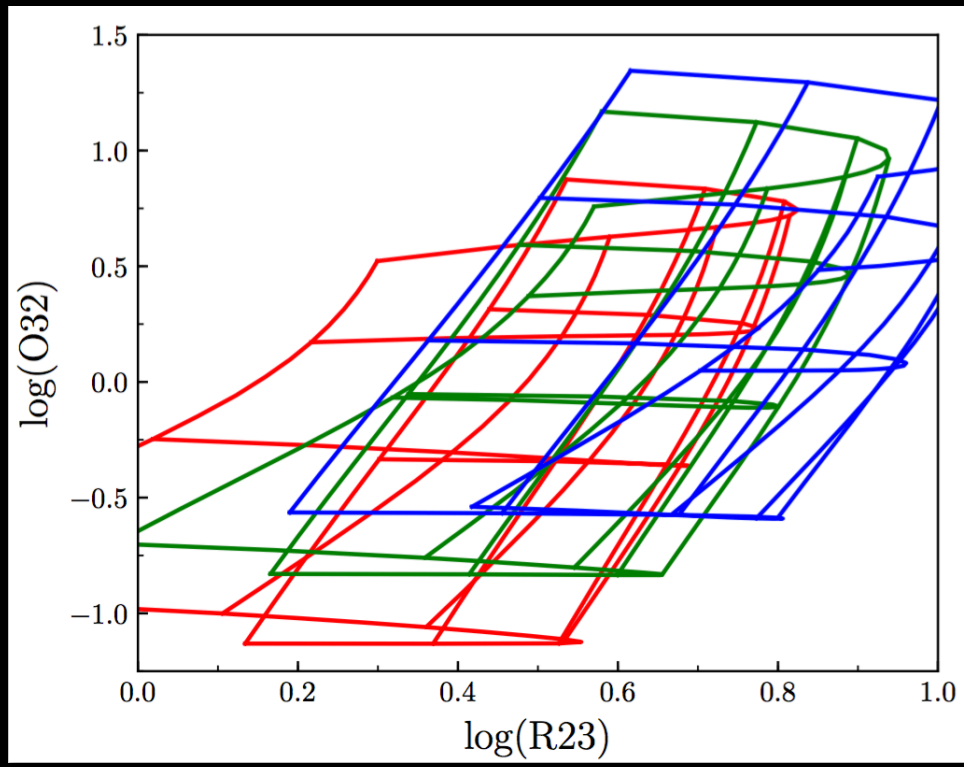
12+log(O/H) = 7.6 – 8.0 (0.1-0.2 $Z_\odot$)

Constraining ionization state with photoionization models

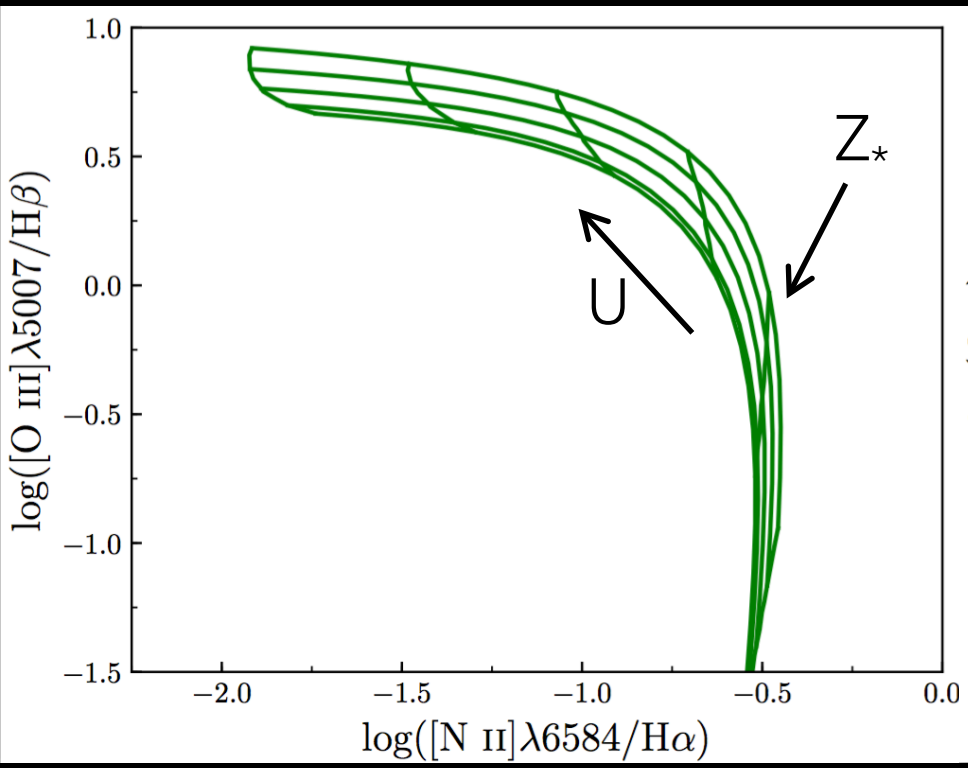
- Cloudy17 + BPASSv2.2.1 and Starburst99
  - Stellar metallicity → Fe/H:
    - BPASS: $Z_* = 0.0007 – 1.4\ Z_\odot$
    - SB99: $Z_* = 0.07 – 2.8\ Z_\odot$
  - High-mass IMF slope = –2.35
  - 10^8 years continuous star formation
  - Nebular metallicity → O/H: $Z_{neb} = 0.05 – 1.5\ Z_\odot$
  - Ionization parameter: log(U) = –1.0 to –4.0
  - Gas density: $n_H = 250\ cm^{-3}$
  - No dust grains
  - N/O freely varies

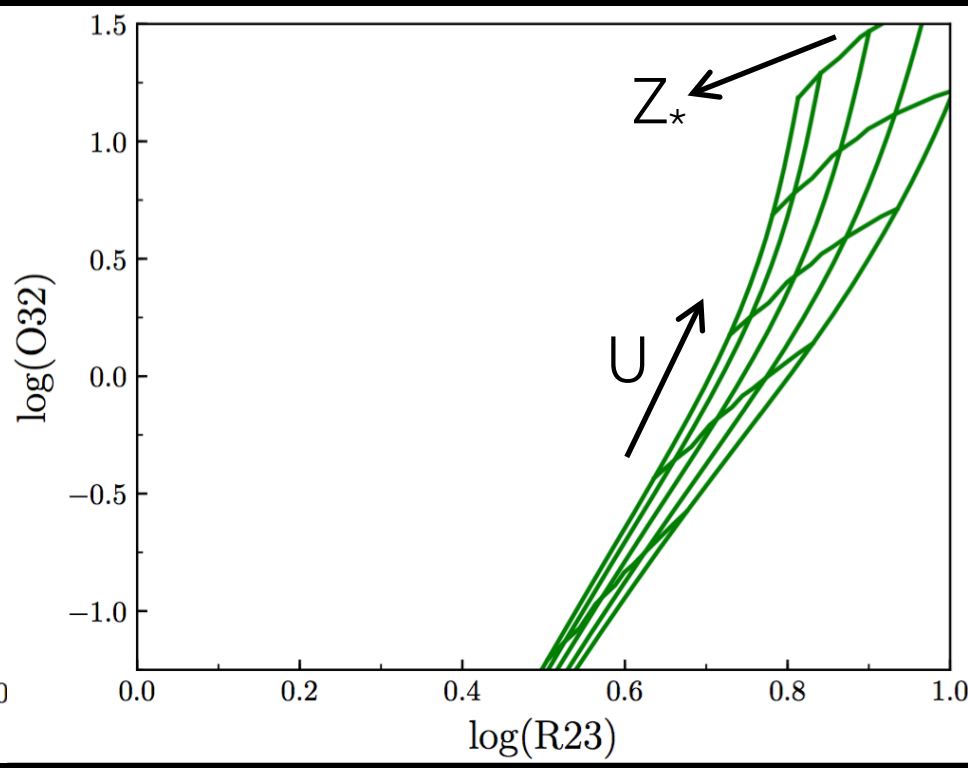
Full model grids = full of degeneracies



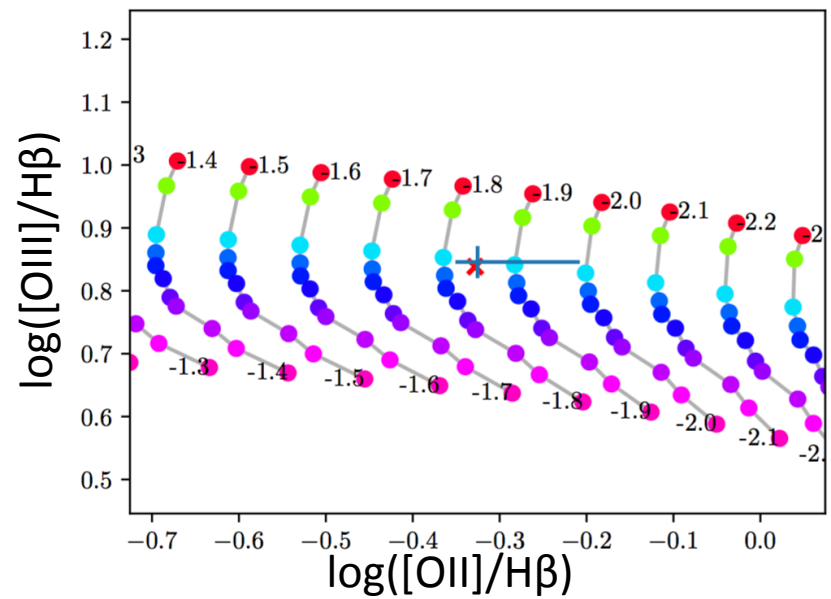


Grids at fixed Z_{neb} provide unambiguous U and Z_*



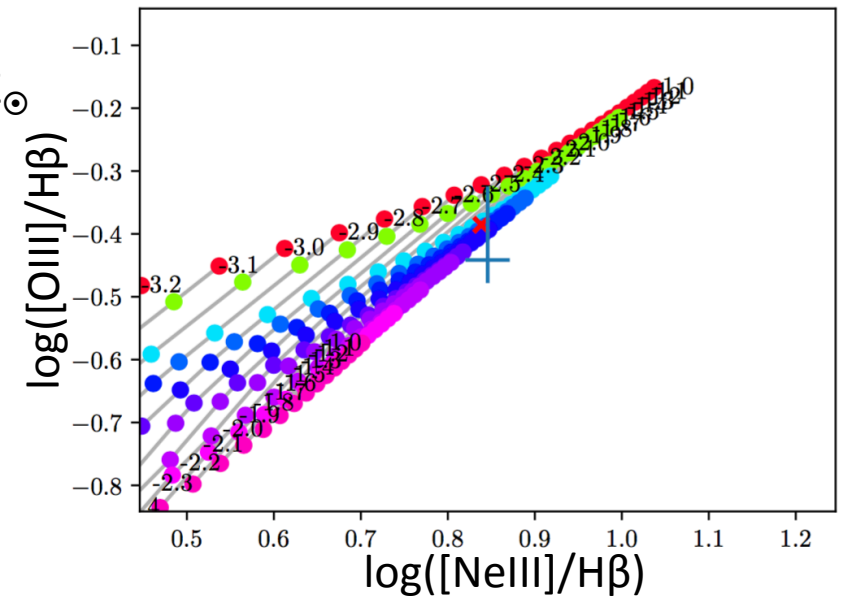


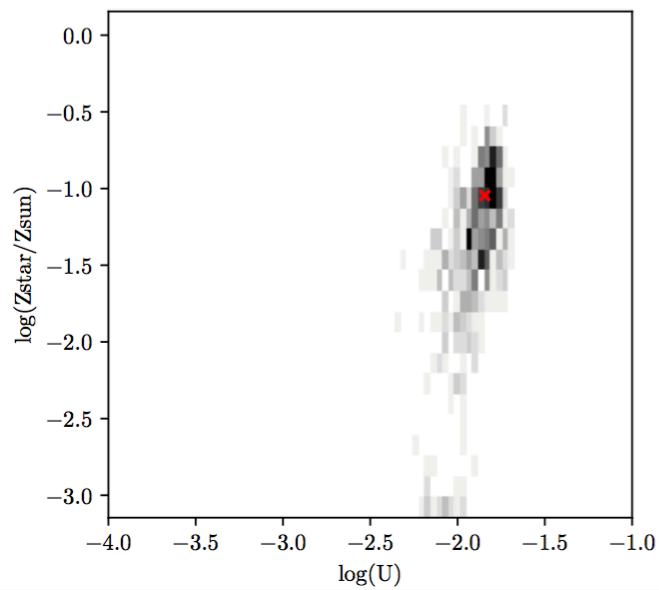
Constraints on U and Z_* with photoionization models

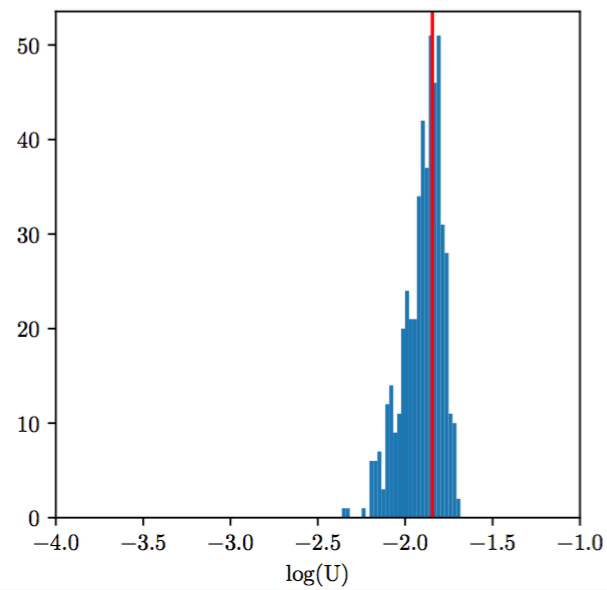


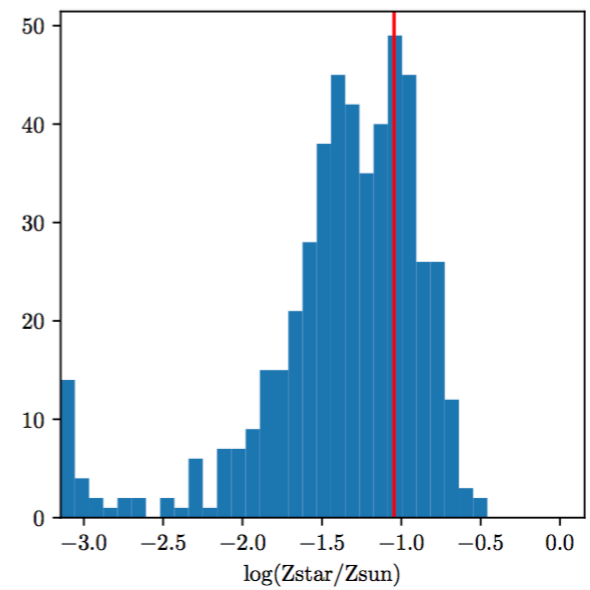
z=3.07

$Z_{neb}=0.2Z_{\odot}$

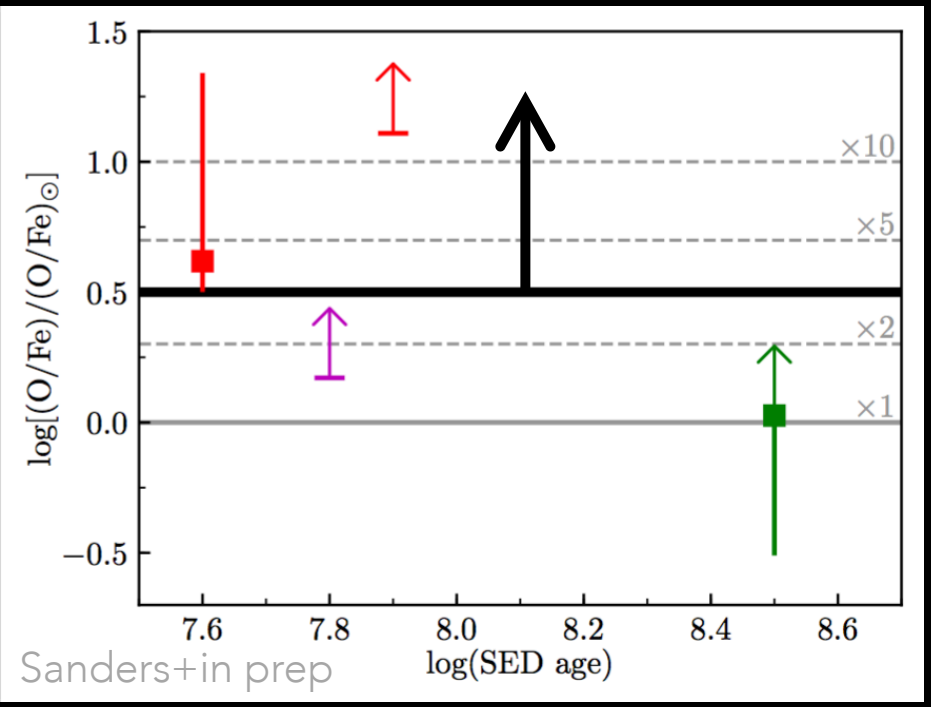








Hard ionizing spectra via α-enhancement



Sanders+in prep

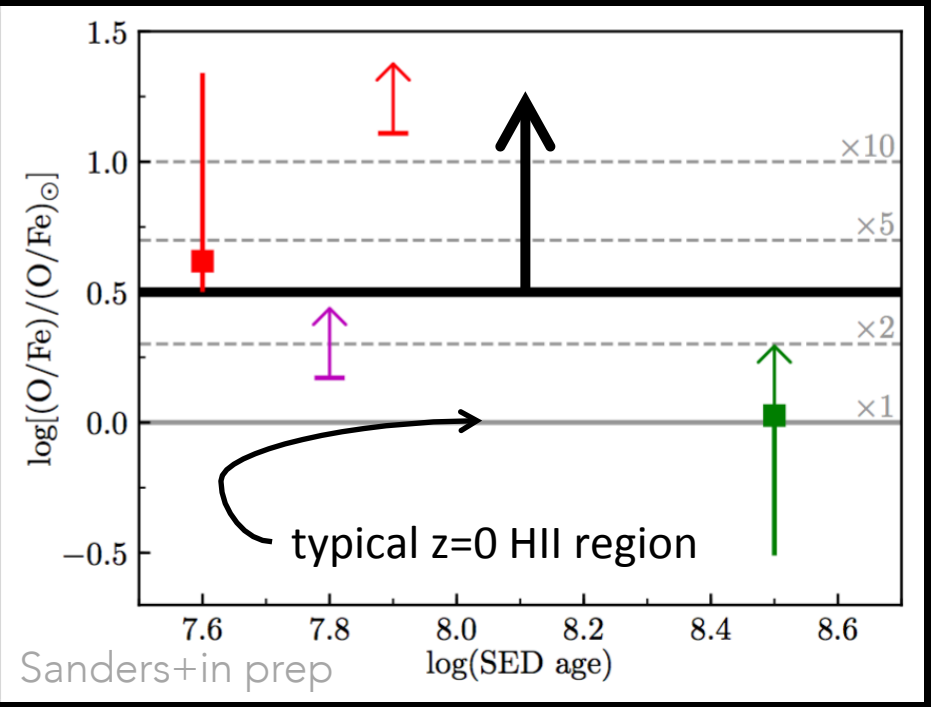
- 3 galaxies >3σ inconsistent with $(O/Fe)_{\odot}$
- Stack→α-enhanced by more than 3x
- z=3.07 galaxy: 5x solar O/Fe
- Young ages consistent with α-enhancement due to Type II Sne

Nomoto+2006, Steidel+2016

- Consistent with Steidel+2016 based on stacked UV+optical spectra of z~2 LBGs: 4-5x solar O/Fe

Harder ionizing spectra at fixed O/H are required to explain these spectra!

Hard ionizing spectra via α-enhancement



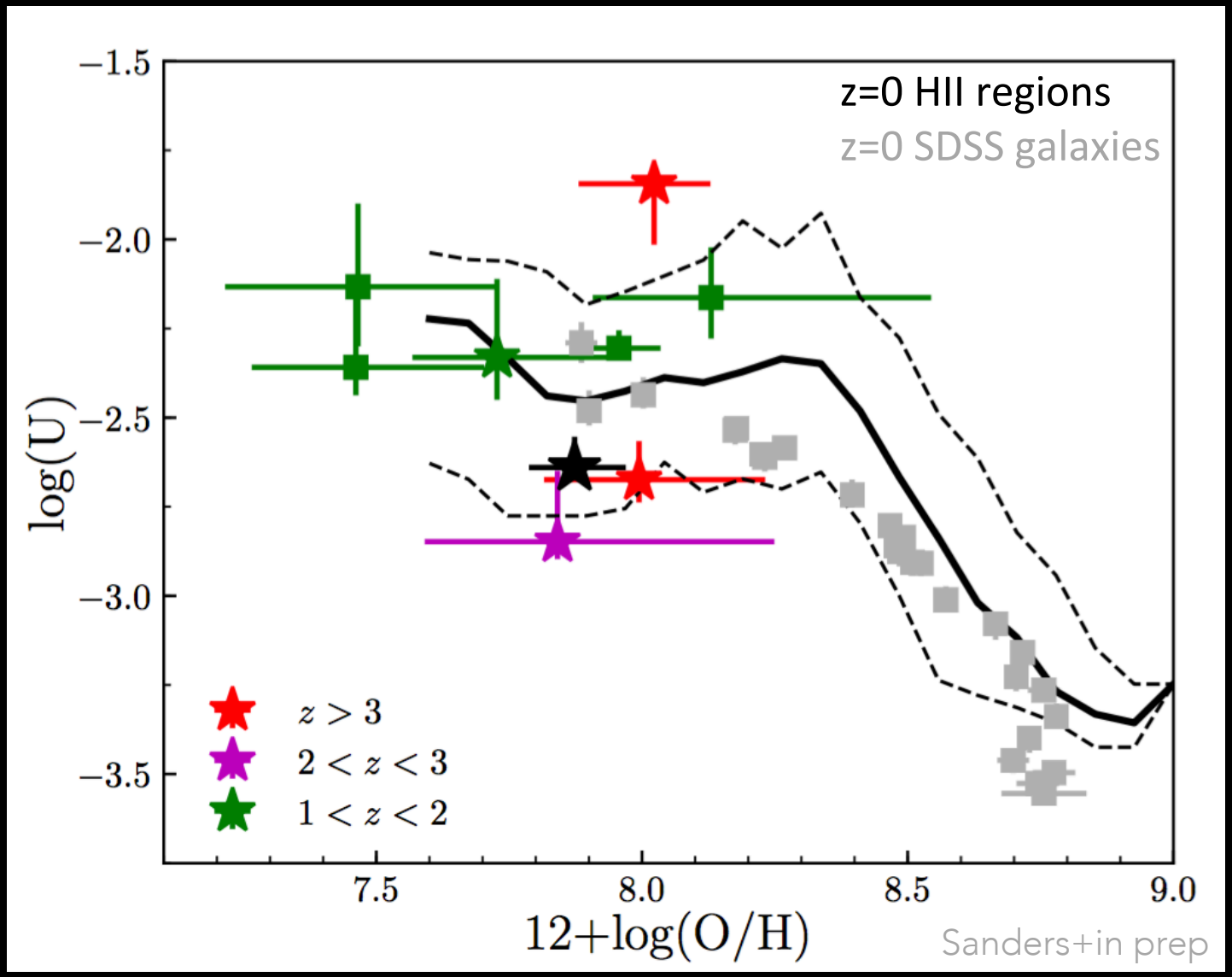
- 3 galaxies >3σ inconsistent with $(O/Fe)_{\odot}$
- Stack→α-enhanced by more than 3x
- z=3.07 galaxy: 5x solar O/Fe
- Young ages consistent with α-enhancement due to Type II Sne

Nomoto+2006, Steidel+2016

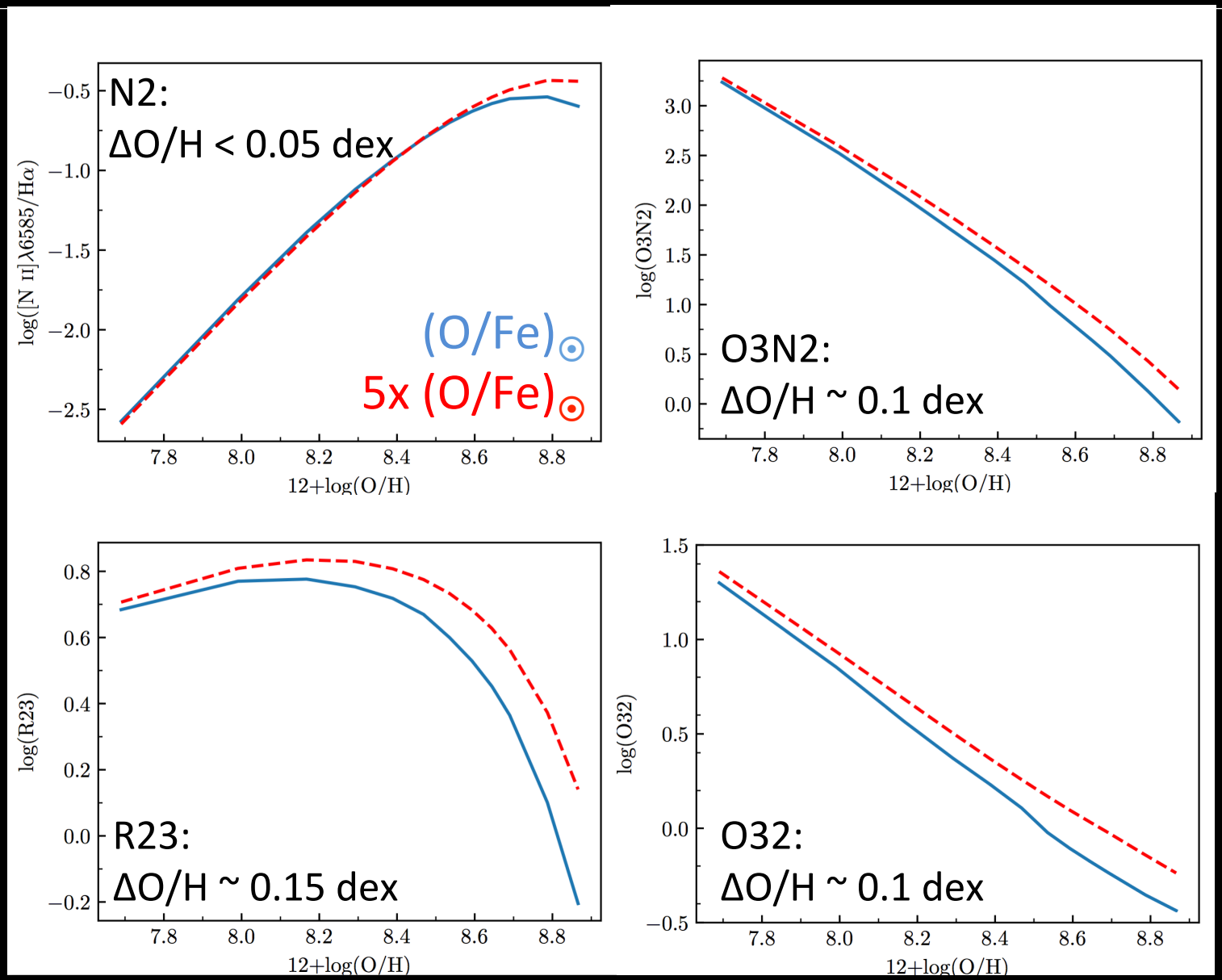
- Consistent with Steidel+2016 based on stacked UV+optical spectra of z~2 LBGs: 4-5x solar O/Fe

Harder ionizing spectra at fixed O/H are required to explain these spectra!

No evidence for elevated ionization parameters at z~1-3

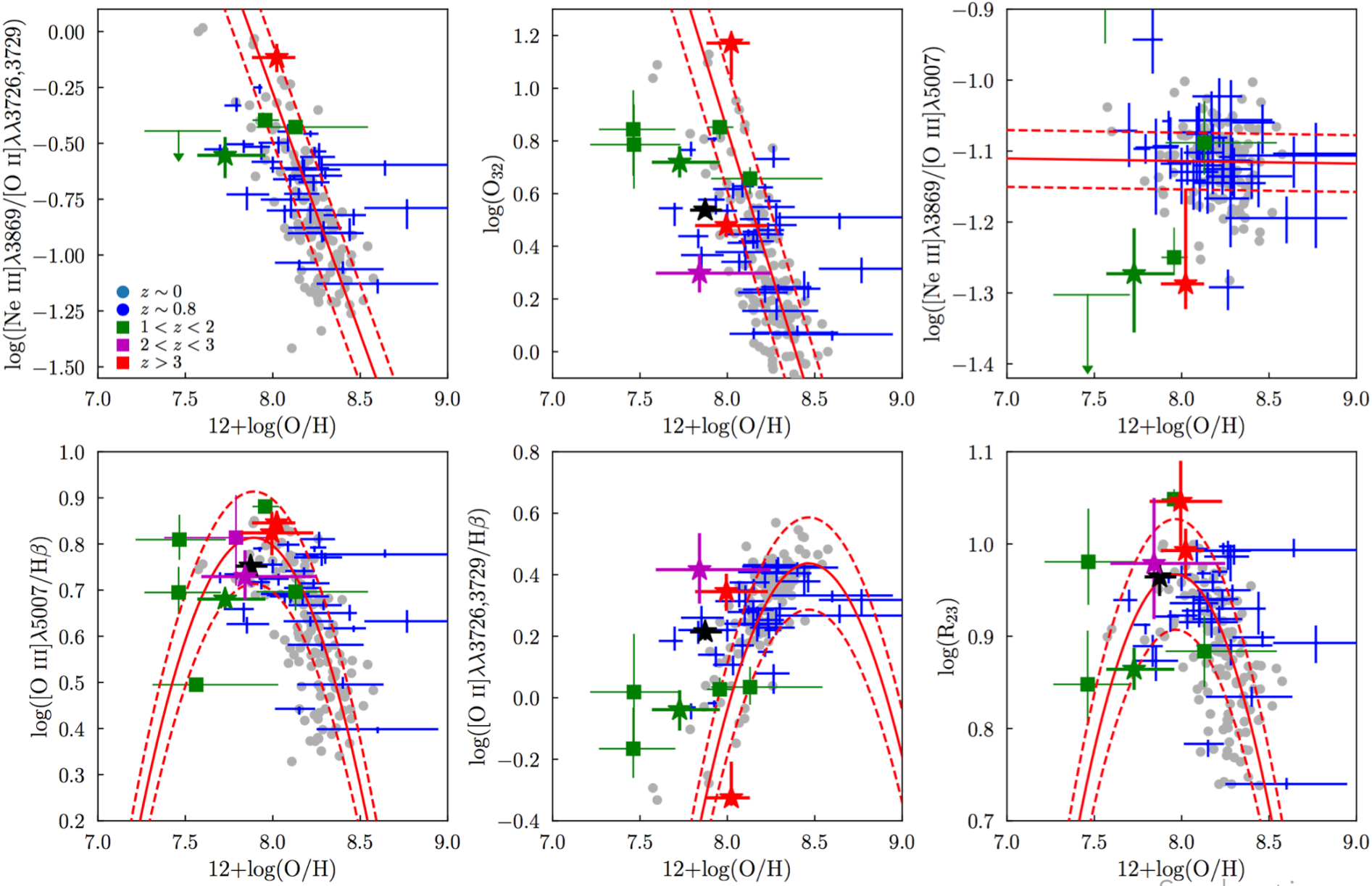


Potential impact on high-redshift metallicity determinations



Sanders+in prep

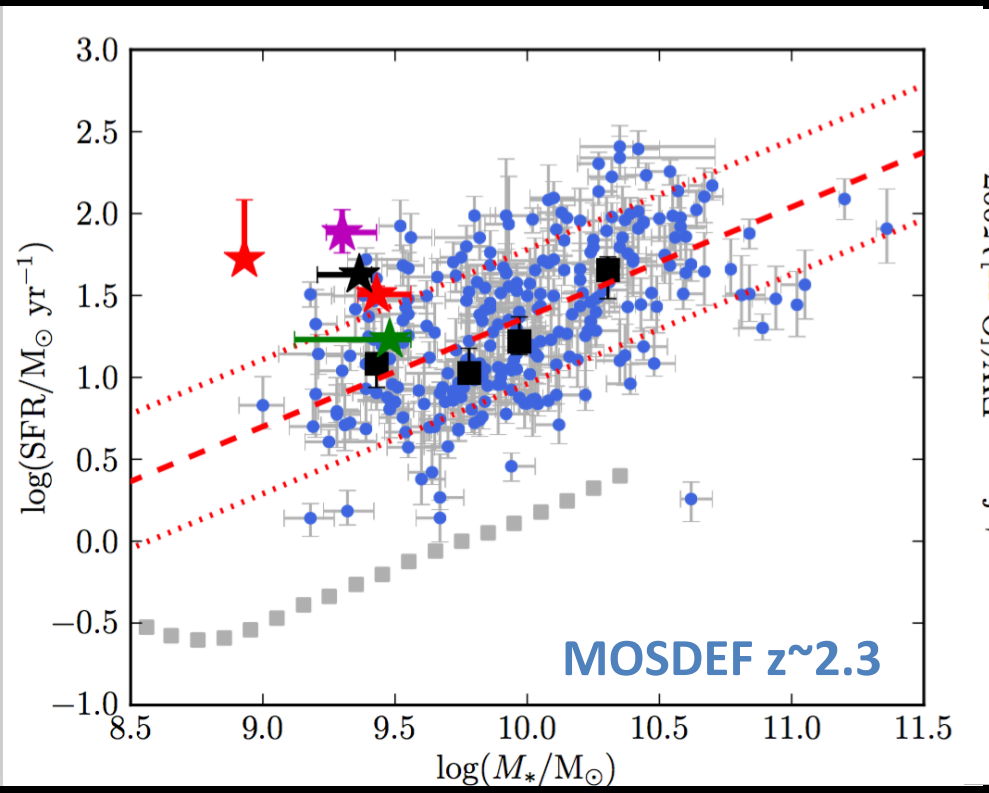
Testing z=0 metallicity calibrations at z>1

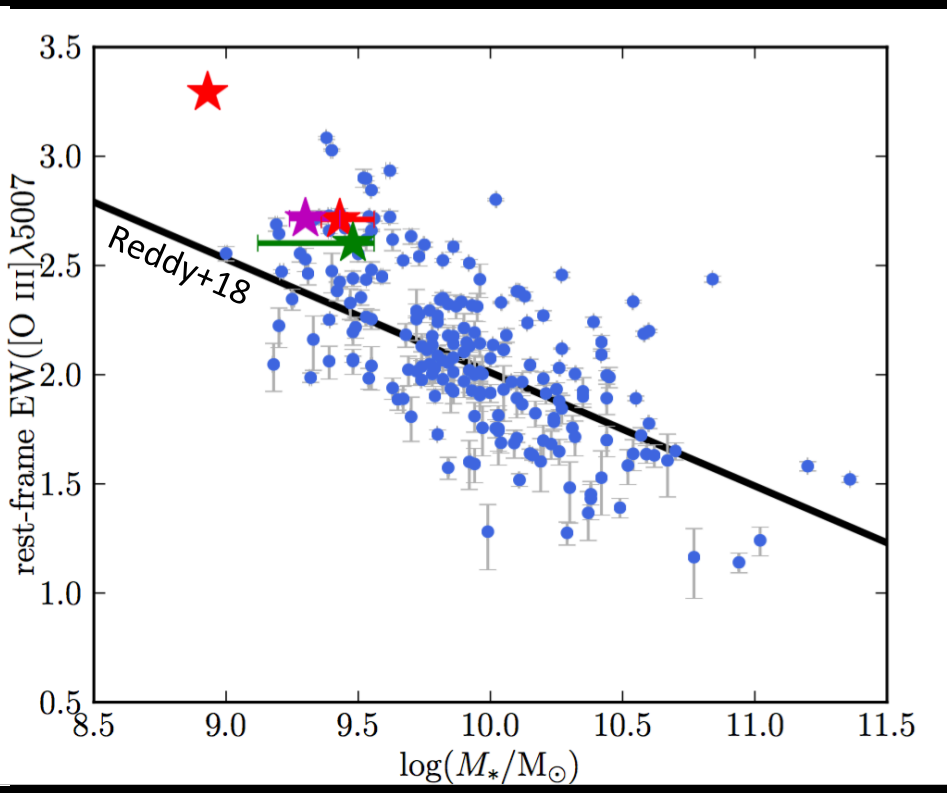


Sanders+in prep

Implications for typical z~2 galaxies are unclear

Detected [OIII]4363 emitters are extreme, highly unrepresentative!



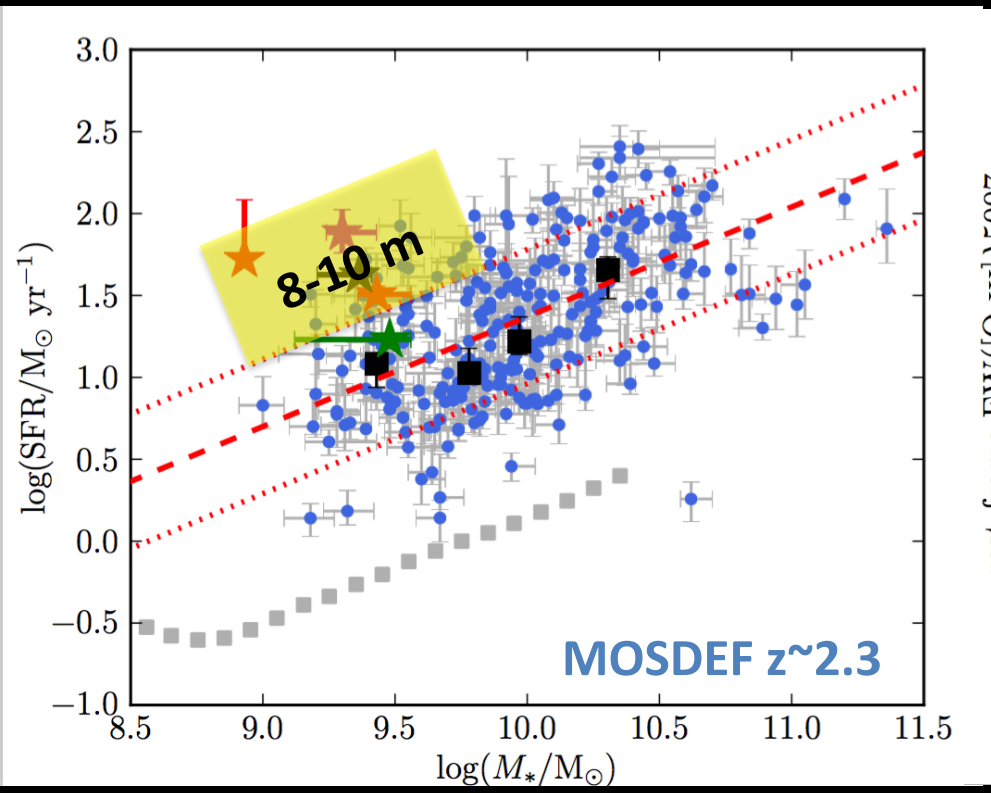


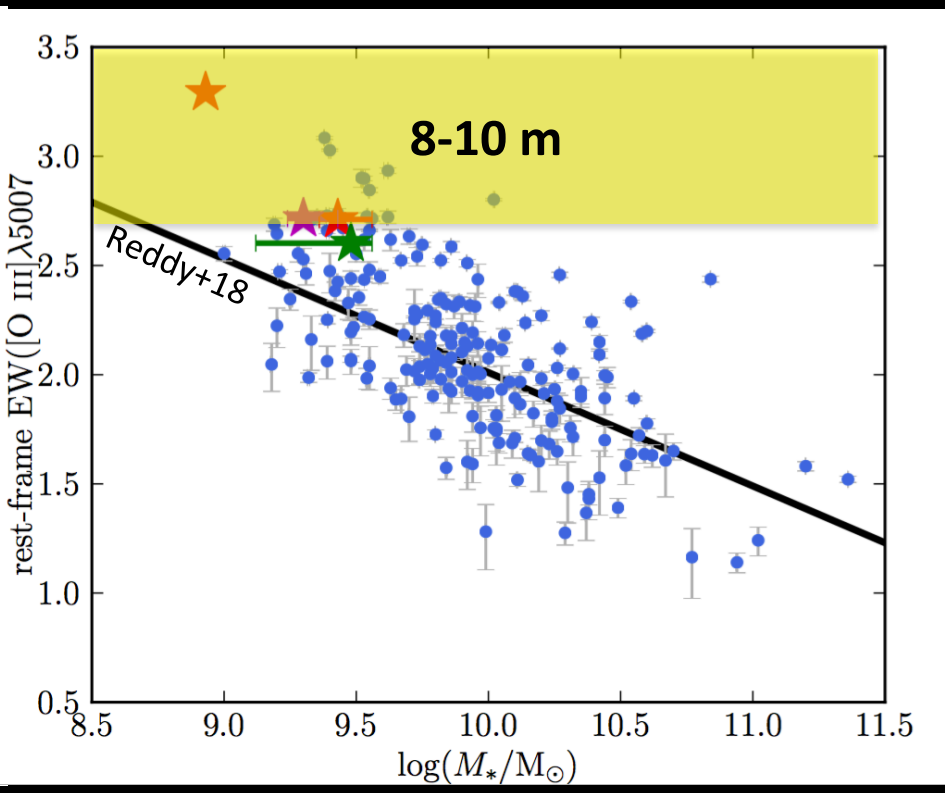
Sanders+in prep

- $\log(M_*/M_\odot) < 9.5$
- SFR elevated ~10x above the main sequence
- Rest-frame [OIII]5007 EW > 400 Å (up to 2000 Å)
- Very young stellar populations

Surveying [OIII] λ4363 at z~2 with Extremely Large Telescopes

ELTs→metallicity calibrations based on typical z~2-3 galaxies

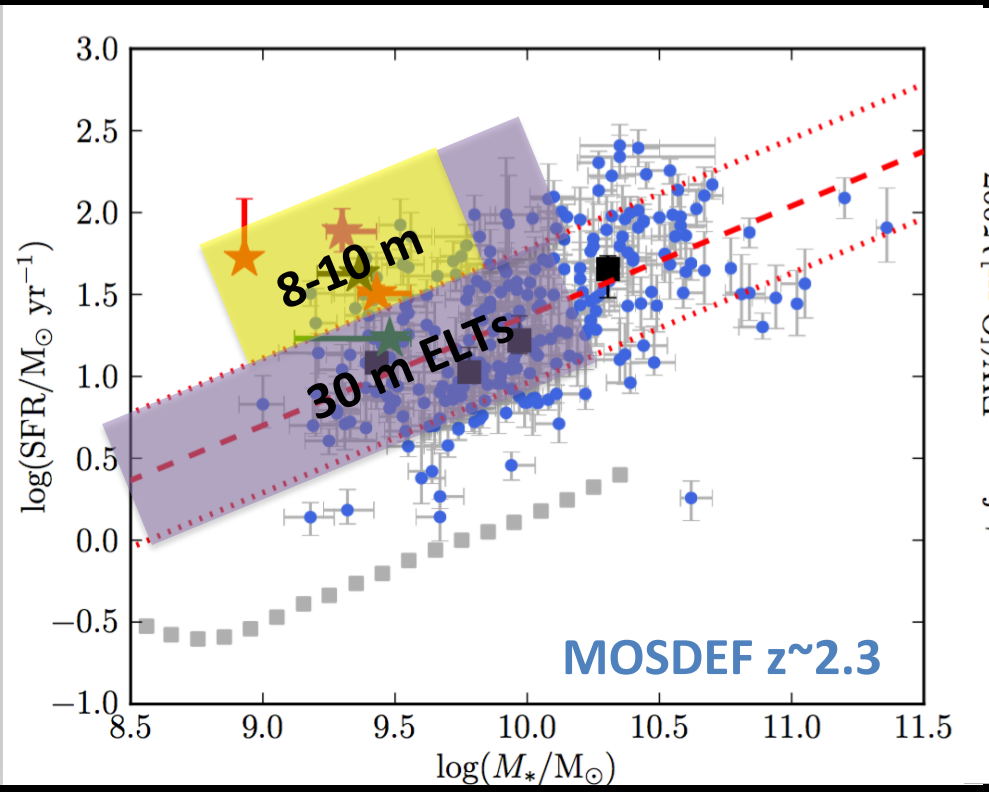


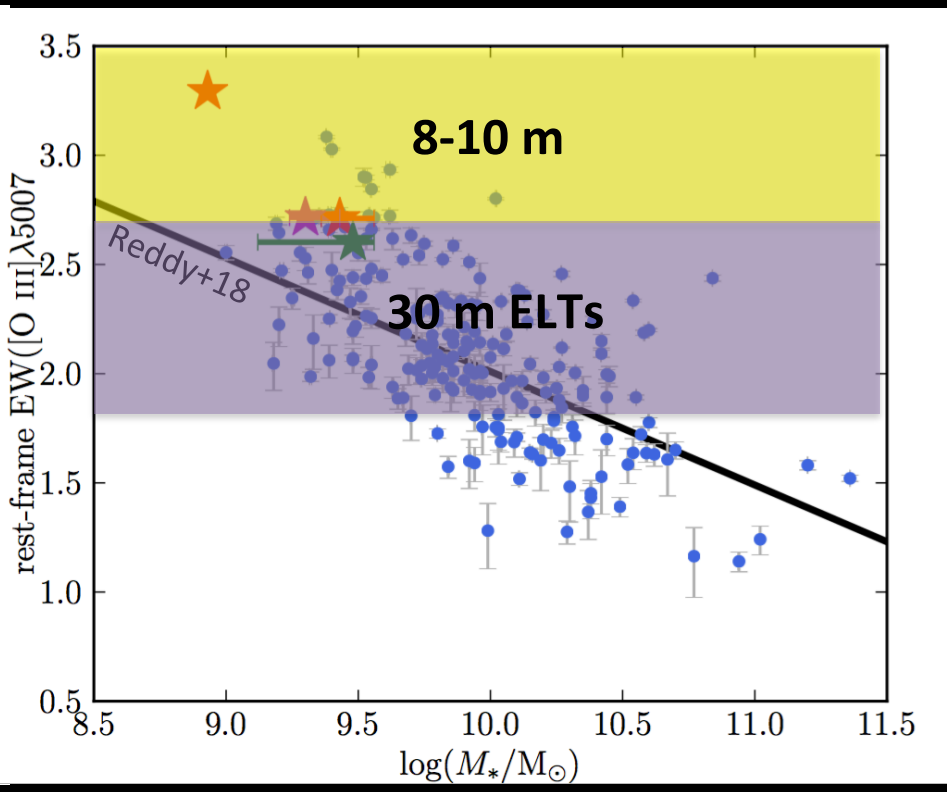


Sanders+in prep

Surveying [OIII] λ4363 at z~2 with Extremely Large Telescopes

ELTs→metallicity calibrations based on typical z~2-3 galaxies



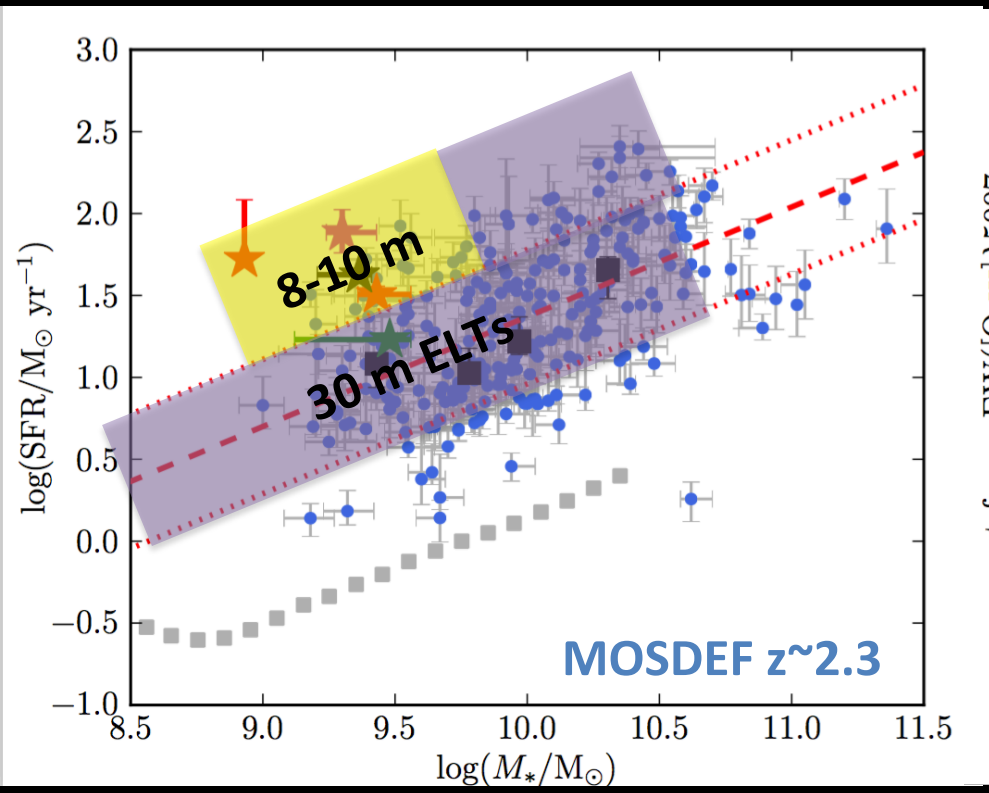


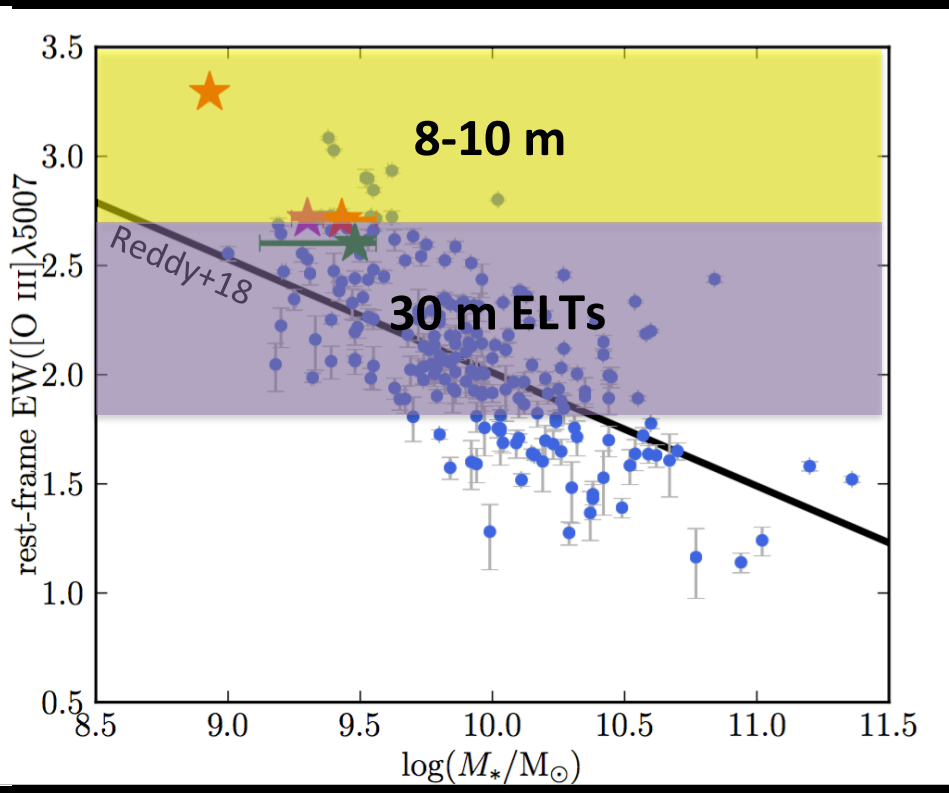
Sanders+in prep

- The raw sensitivity of NIRMOS on 30 m class telescopes is <u>required</u> to solve this problem
- JWST sensitivity is not high enough!

Surveying [OIII] λ4363 at z~2 with Extremely Large Telescopes

ELTs→metallicity calibrations based on typical z~2-3 galaxies



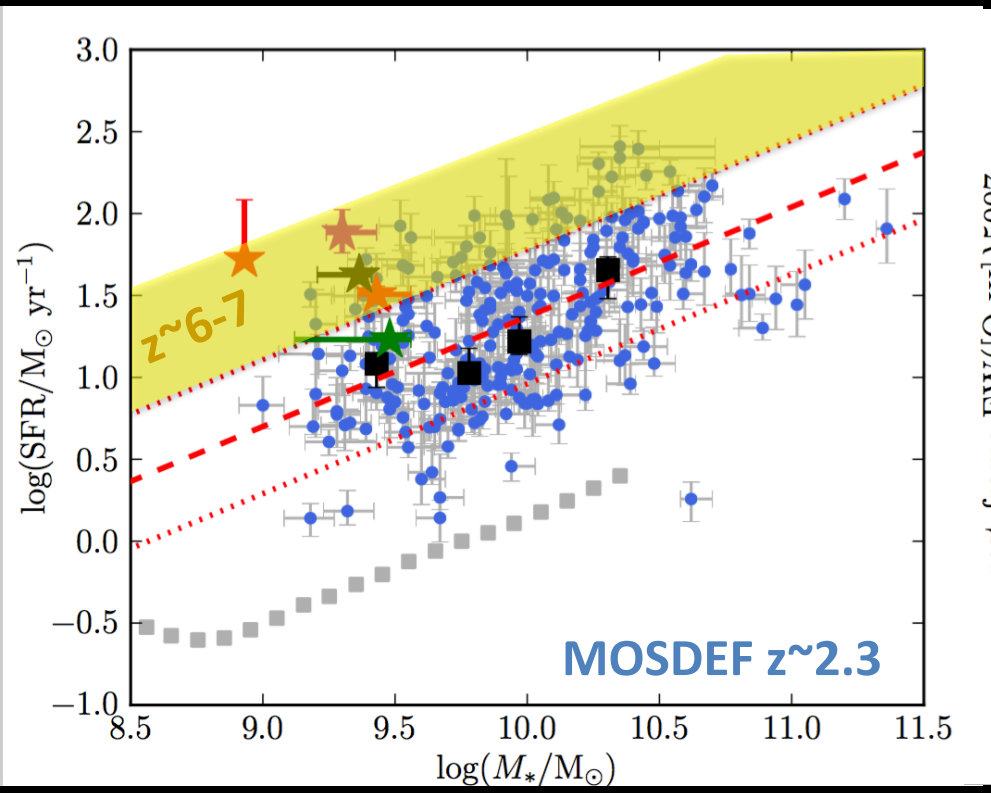


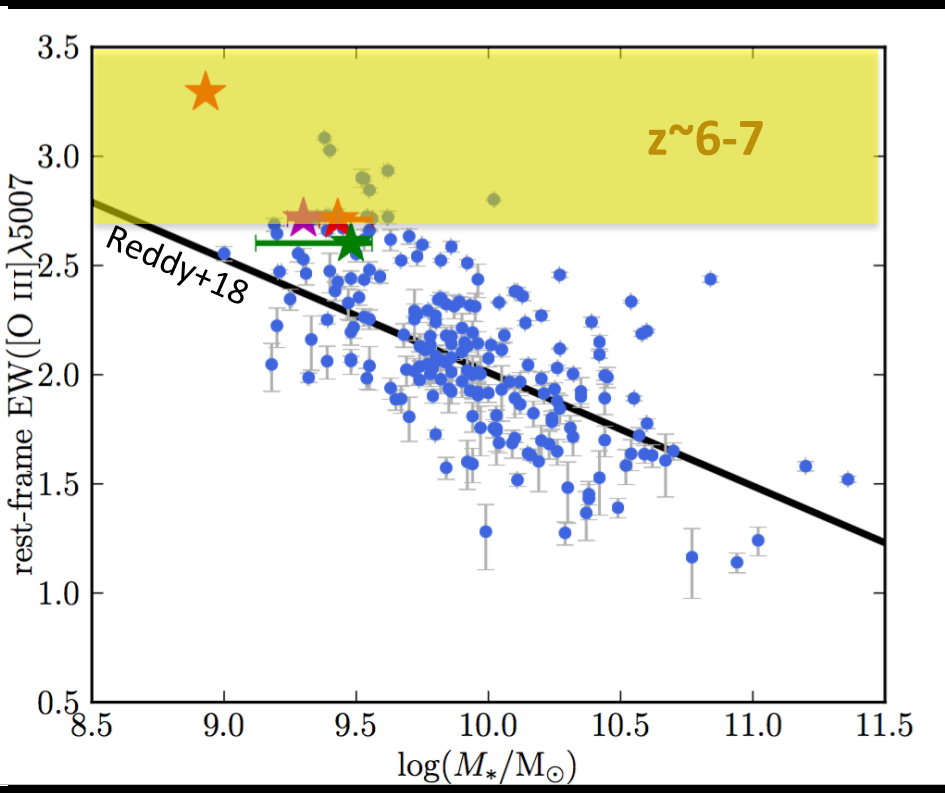
Sanders+in prep

- The raw sensitivity of NIRMOS on 30 m class telescopes is <u>required</u> to solve this problem
- Push to high-mass/metal-rich with [OII]λ7325, [NII]λ5755

Implications for EOR ionization state and metallicities

Detected [OIII]4363 emitters are z~6-7 analogs!





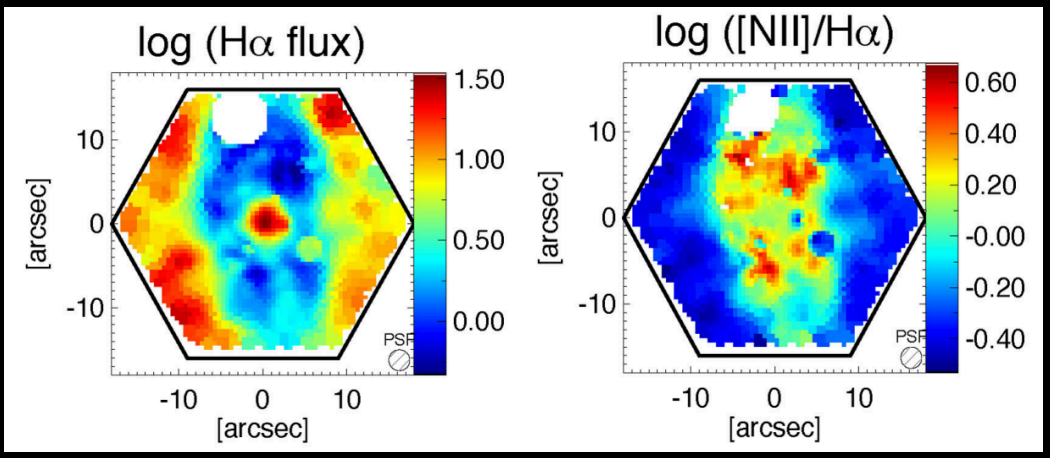
Sanders+in prep

- z>6: high SFR, high EW([OIII]) Smit+2014, Roberts-Borsani+2016
- Implies hard ionizing spectra in EOR due to young ages/α-enhancement

Spatially-resolved spectra: the architecture of the ionized ISM

Line emission in galaxies comes from more than HII regions!

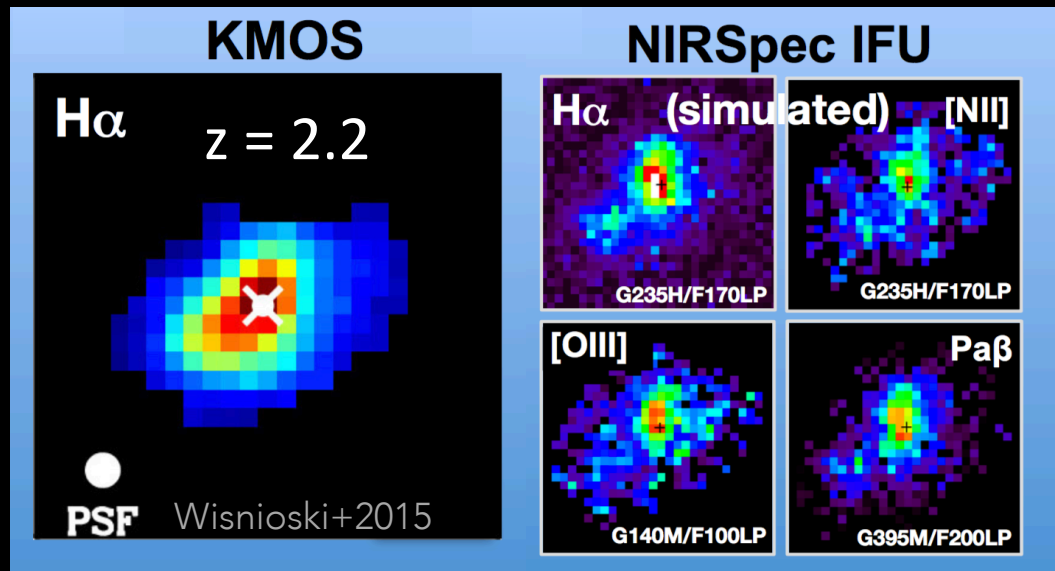
SDSS-IV MaNGA: z=0



- Diffuse Ionized Gas
  Zhang+2017, Sanders+2017
- Shocks Newman+2014
- Low-luminosity AGN Wright+2010

- Must have spectra on scales of discrete ISM structural components (i.e., HII regions) → ~100pc
  - Possible only with ELTs+AO!

- Many IFU line-map science cases: metallicity gradients, resolved scaling relations, kinematics, …

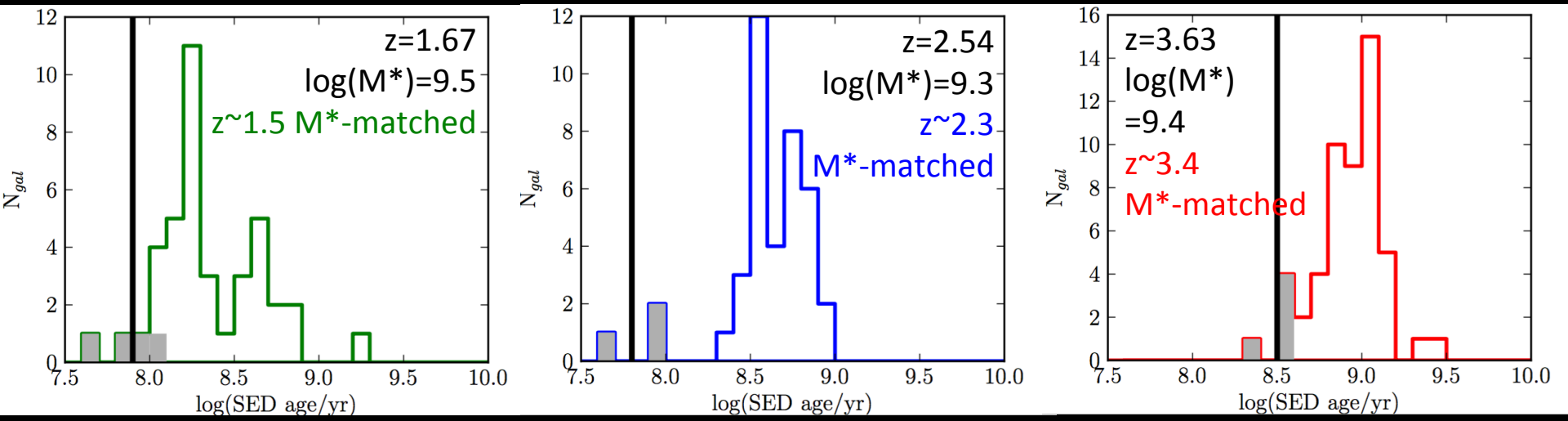


Summary

- MOSDEF survey: 4 detections of [OIII]4363 and temperature-based metallicities for galaxies at z~1.5-3.5, doubling the sample size at z>1
- z~2-3 extreme emission line galaxies require hard spectra produced by very young stellar populations that are ~5x α-enhanced compared to solar values
- Ionization parameters are not higher than z=0 galaxies at fixed nebular metallicity
- These galaxies have extreme properties: EW([OIII]) > 400Å, ~10x higher SFR than typical, very young stellar populations (z~6-7 analogs!)
- We must push to less-extreme galaxy properties to understand the gas-phase metallicities and ionization states of typical z~2 galaxies:
  - Sensitivity of ELTs is required to survey a representative sample
- High-resolution IFU emission-line maps must be leveraged to ensure proper interpretation and maximum science return from integrated spectroscopy

Implications for typical z~2 galaxies are unclear

Detected [OIII]4363 emitters are extreme, highly unrepresentative!



Sanders+in prep

How to select strong [OIII]4363 emitters:

- Very young stellar populations
- $\log(M_*/M_\odot) < 9.5$
- SFR elevated by ~10x
- Rest-frame [OIII]5007 EW > 400 Å (up to 2000 Å)