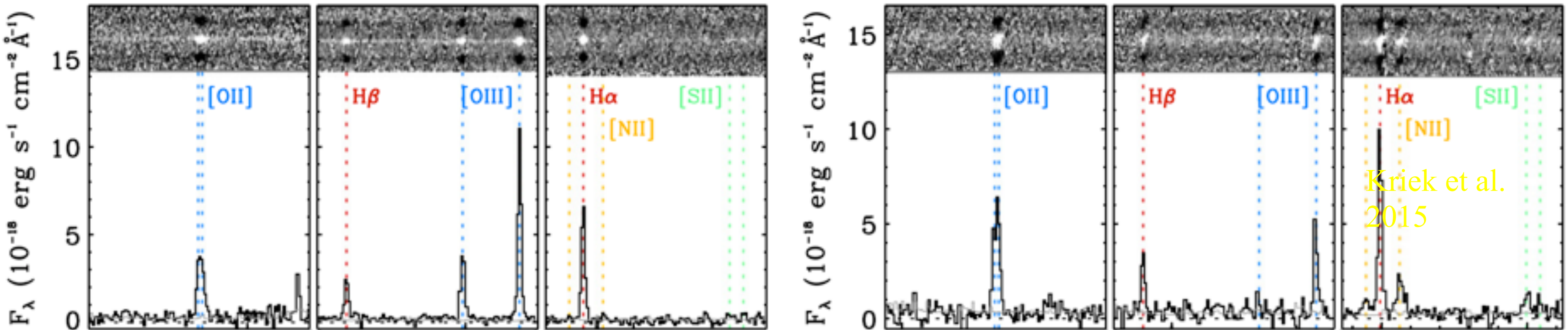
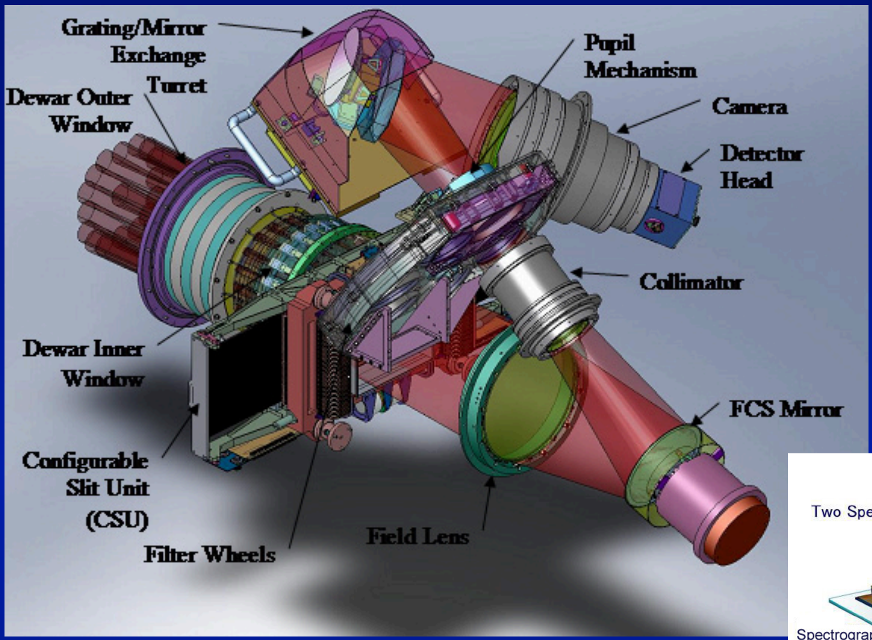
Untangling the New Landscape of z~2 Emission-line Measurements



Alice Shapley UCLA

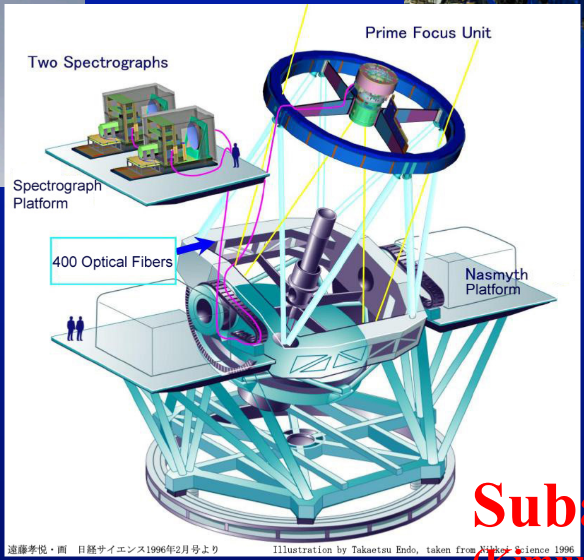
Collaborators: Mariska Kriek, Naveen Reddy, Brian Siana, Alison Coil, Bahram Mobasher, Bill Freeman, Ryan Sanders, Sedona Price, Laura DeGroot, Irene Shivaei, Mojegan Azadi, Gene Leung, Francesca Fornasini, Tara Fetherolf, Tom Zick

Ground-based Near-IR MOS



Keck/MOSFIRE
(McLean et al. 2012)

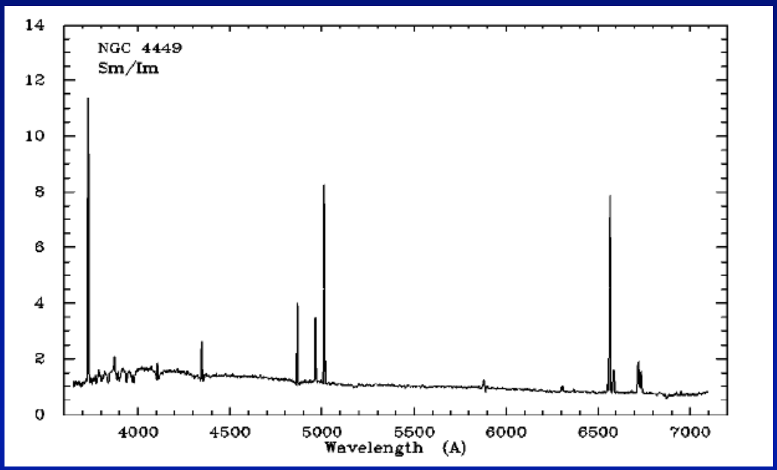
VLT/KMOS
(Sharples et la. 2013)



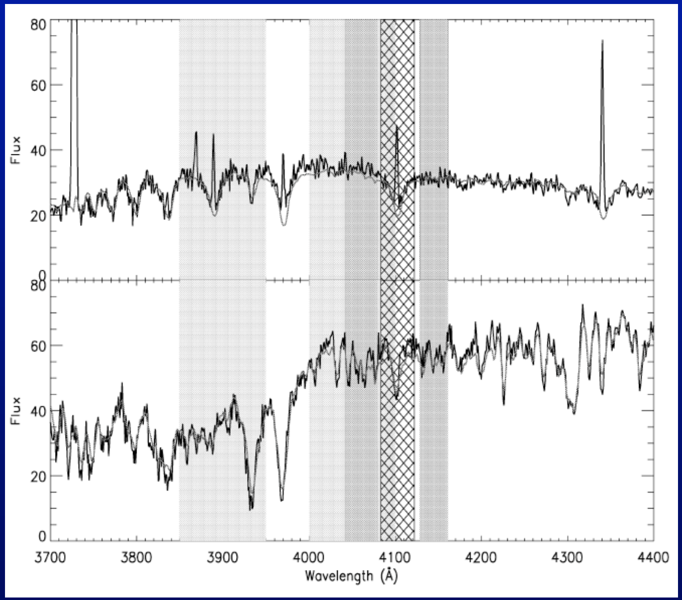
Subaru/FMOS
(Kimura et al. 2010)

Rest-frame Optical Spectra

(Kennicutt 1998)



(Kauffmann et al. 2003)

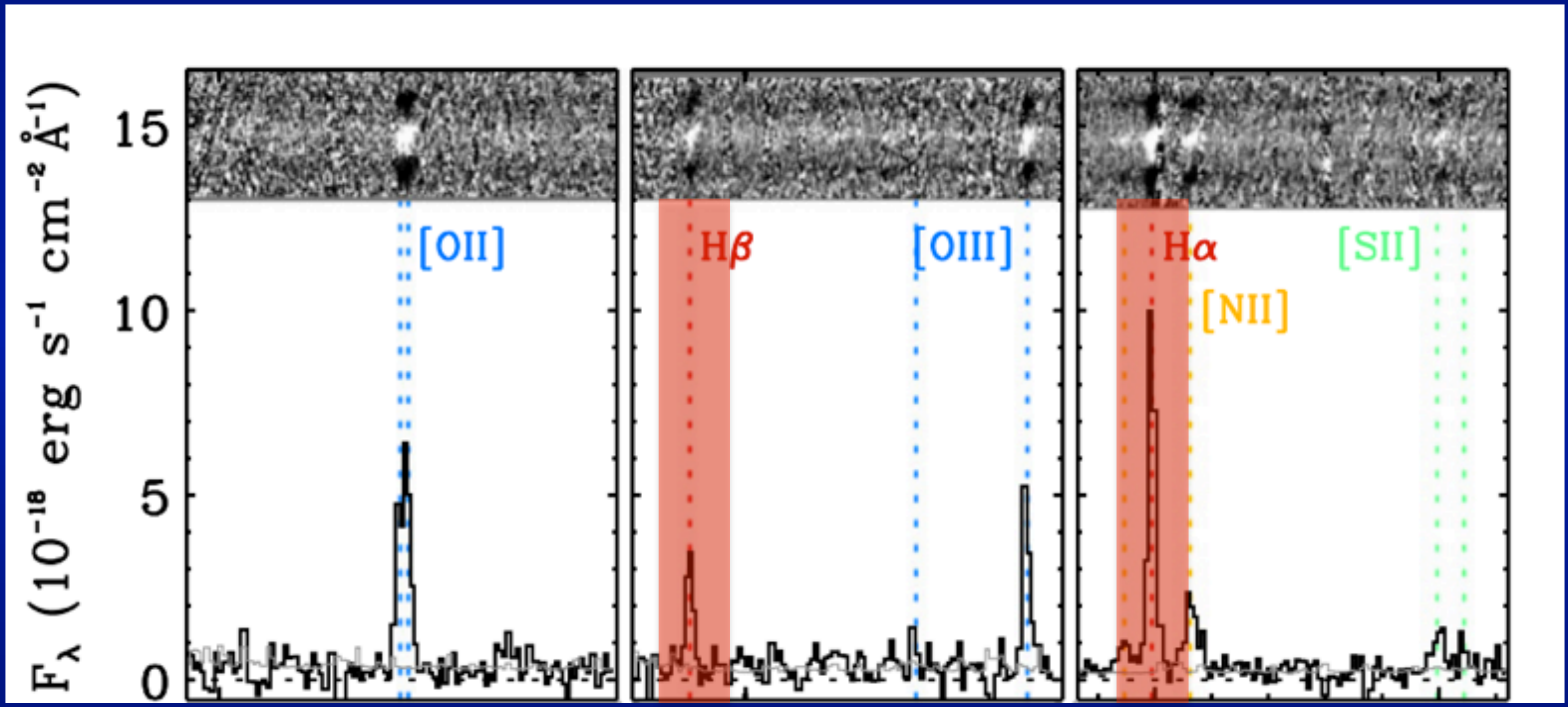


- Emission-lines: [OII], Hβ, [OIII], Hα, [NII], [SII]
- Absorption-lines: Balmer lines, Ca H&K, Mgb, 4000Å break
- Provide key insights into the stellar and gaseous contents of galaxies.

Rest-frame Optical Emission Spectra

Dust extinction

(Kriek et al. 2015)

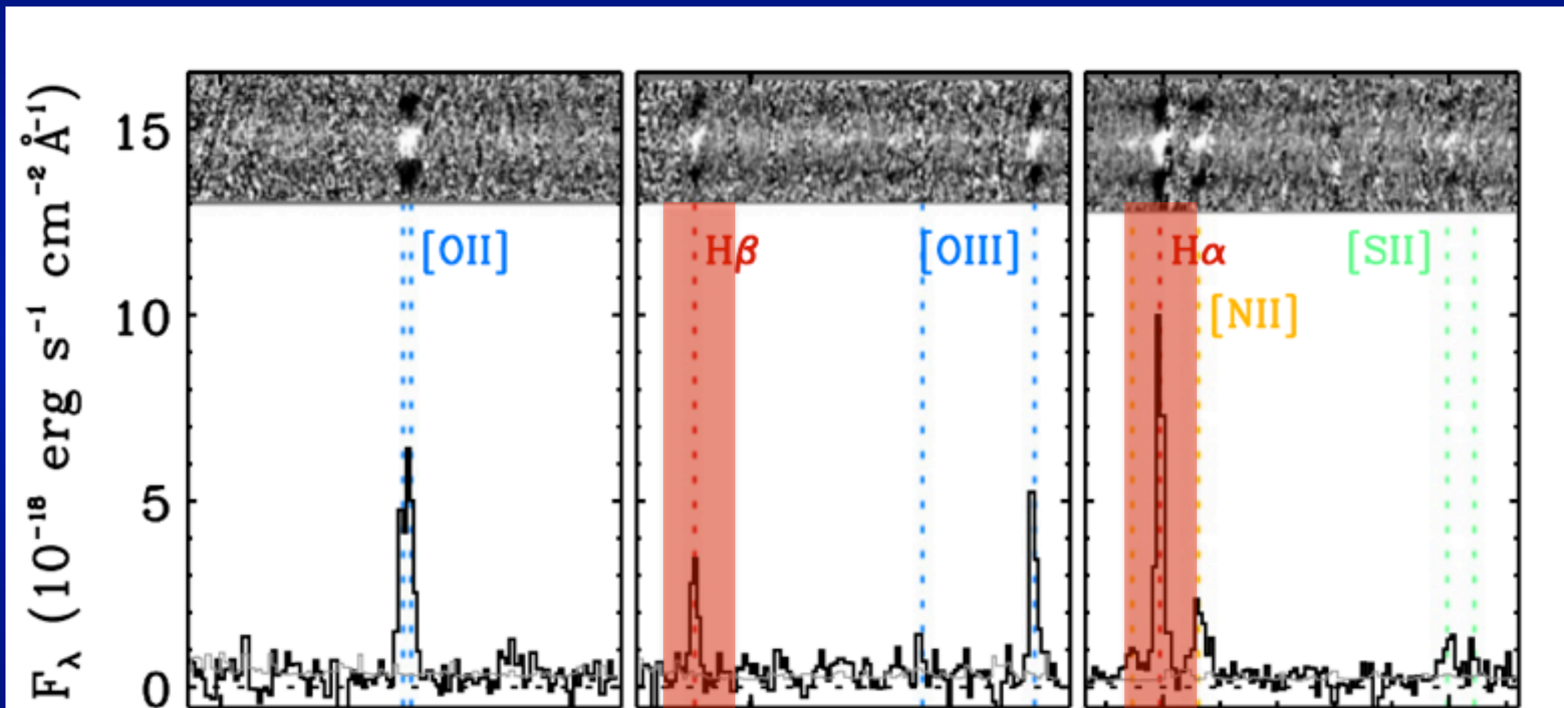


• Rest-frame optical emission lines can be used to constrain many basic galaxy properties!

Rest-frame Optical Emission Spectra

Star-formation Rate

(Kriek et al. 2015)

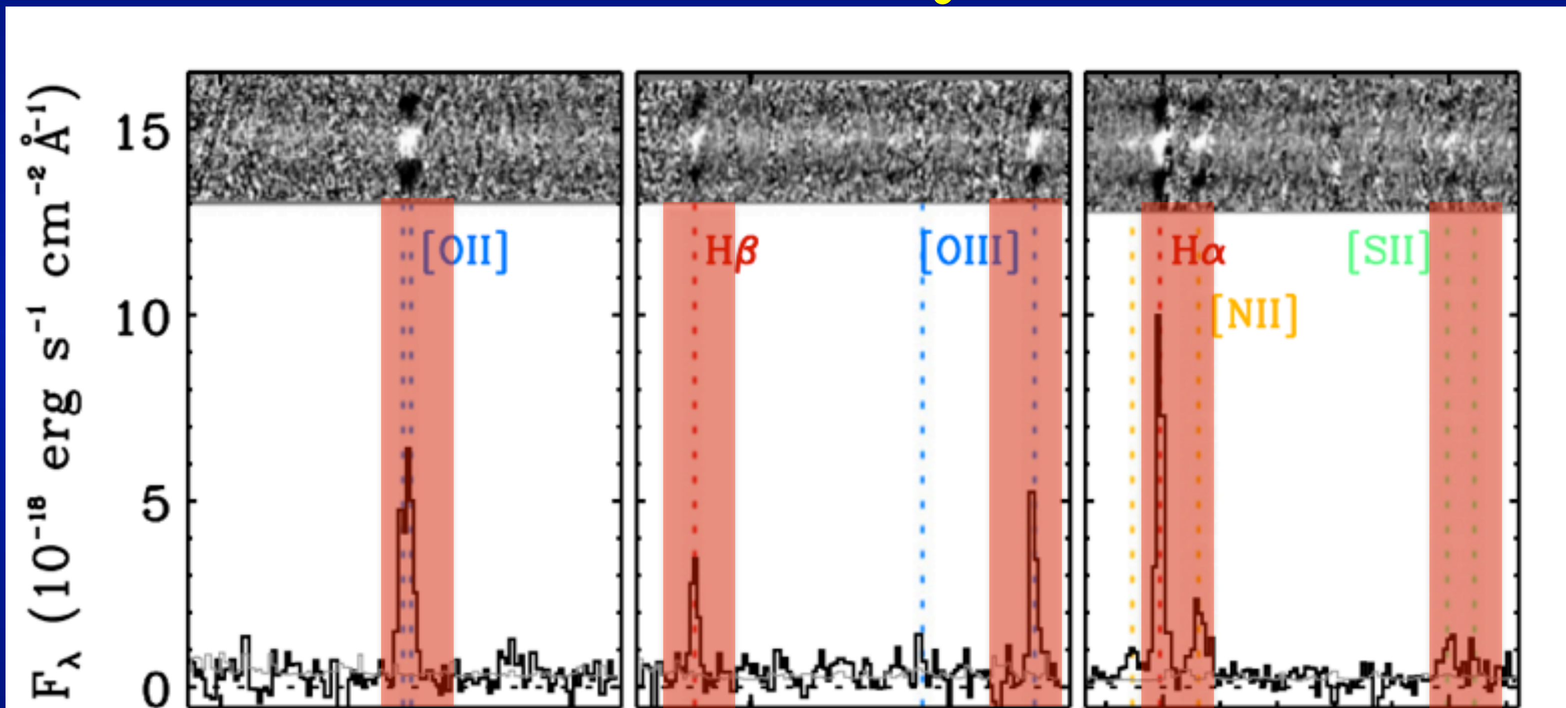


• Rest-frame optical emission lines can be used to constrain many basic galaxy properties!

Rest-frame Optical Emission Spectra

Metallicity

(Kriek et al. 2015)

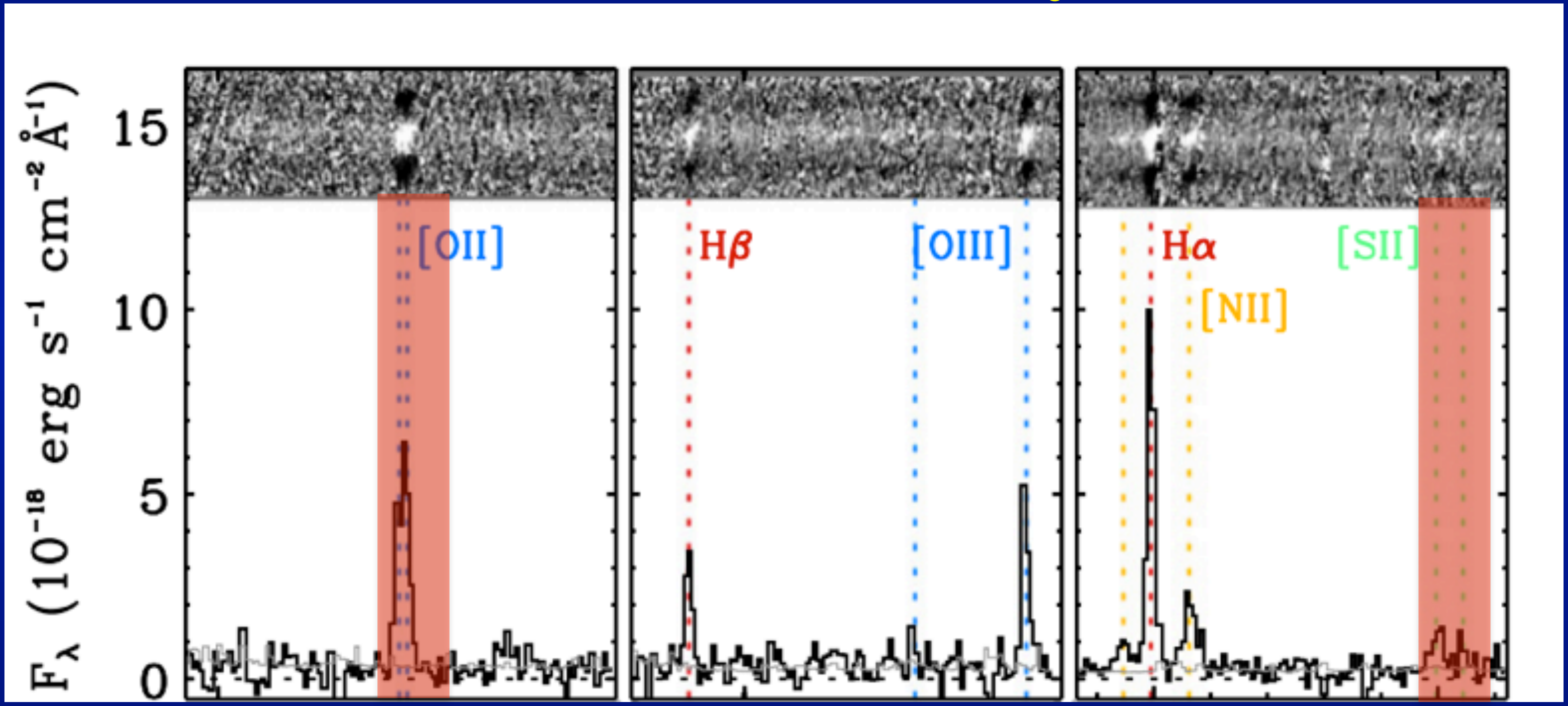


• Rest-frame optical emission lines can be used to constrain many basic galaxy properties!

Rest-frame Optical Emission Spectra

Electron Density

(Kriek et al. 2015)

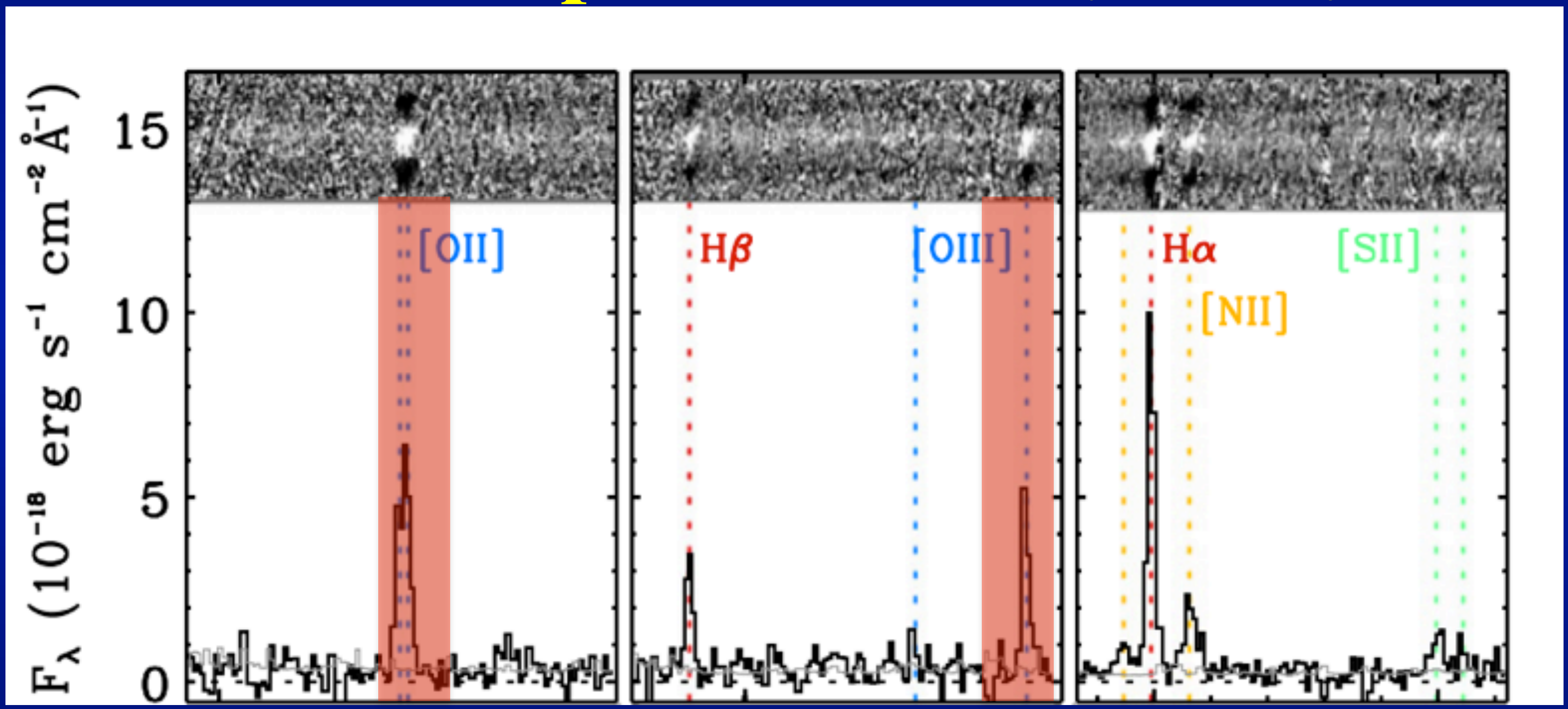


• Rest-frame optical emission lines can be used to constrain many basic galaxy properties!

Rest-frame Optical Emission Spectra

Ionization parameter $(Q_0/(4\pi r^2 c n_e))$

(Kriek et al. 2015)

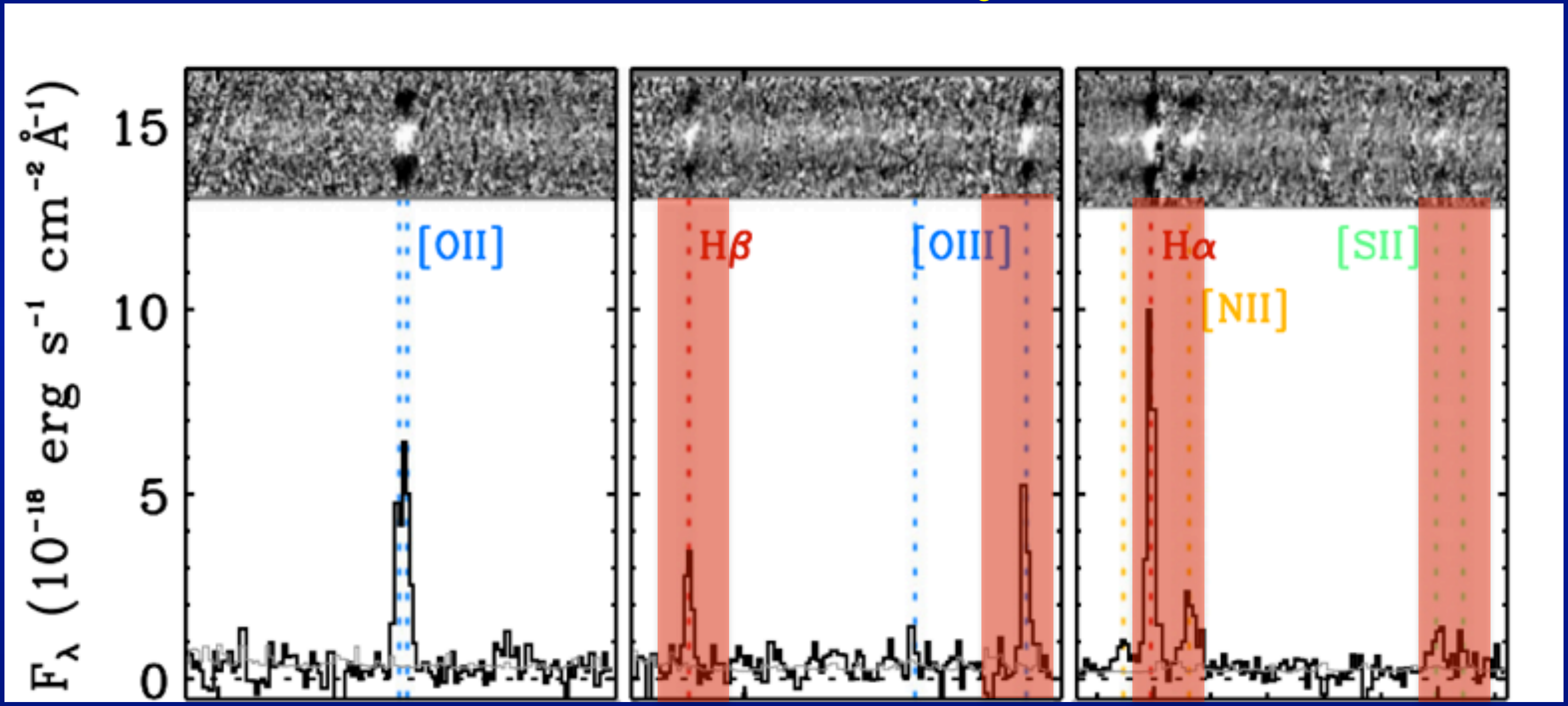


• Rest-frame optical emission lines can be used to constrain many basic galaxy properties!

Rest-frame Optical Emission Spectra

AGN activity

(Kriek et al. 2015)

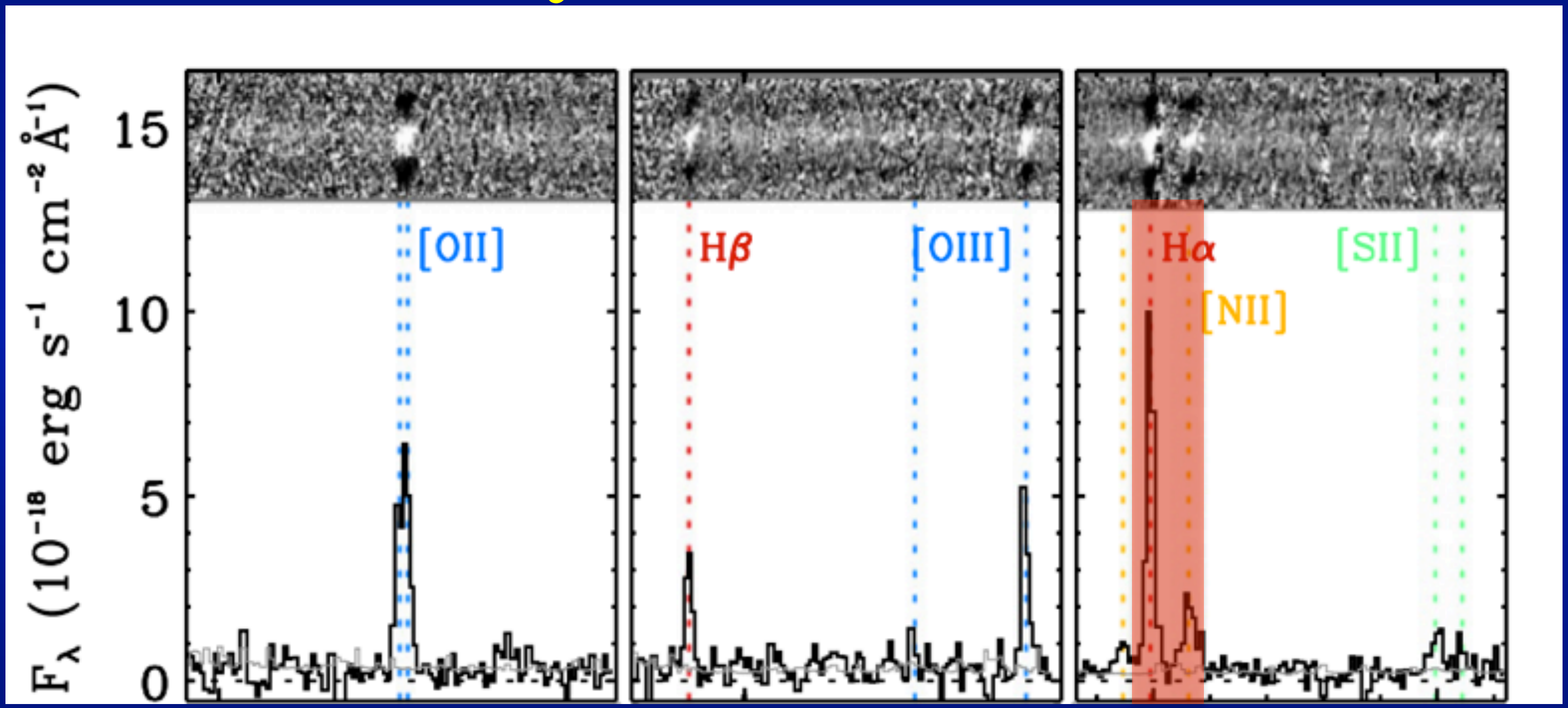


- Rest-frame optical emission lines can be used to constrain many basic galaxy properties!

Rest-frame Optical Emission Spectra

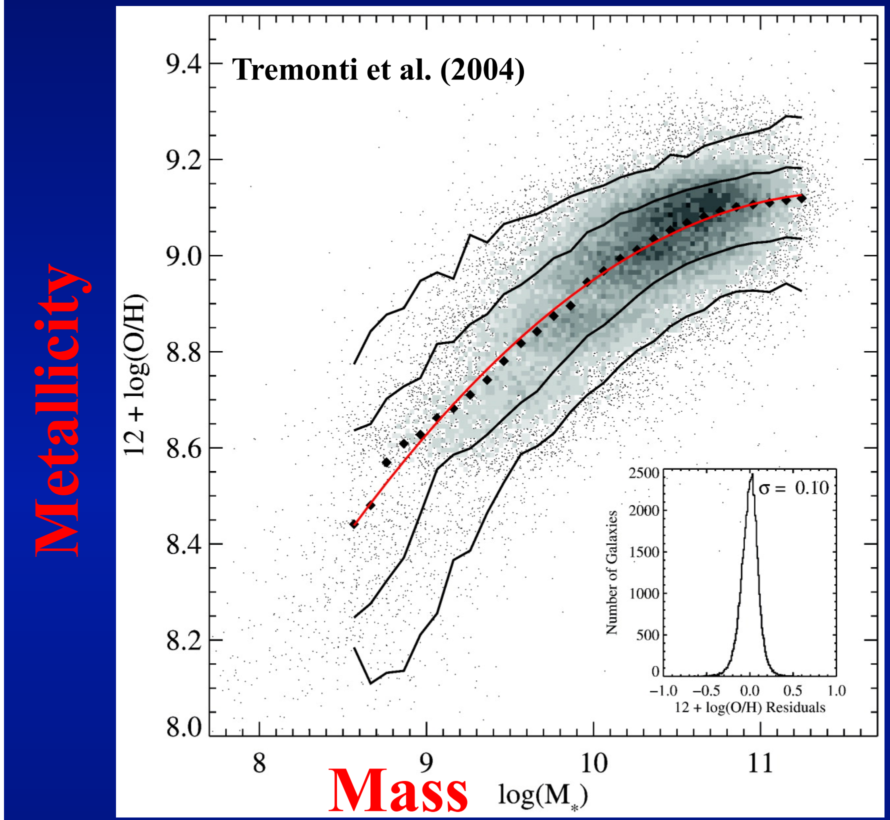
Virial dynamics, outflows

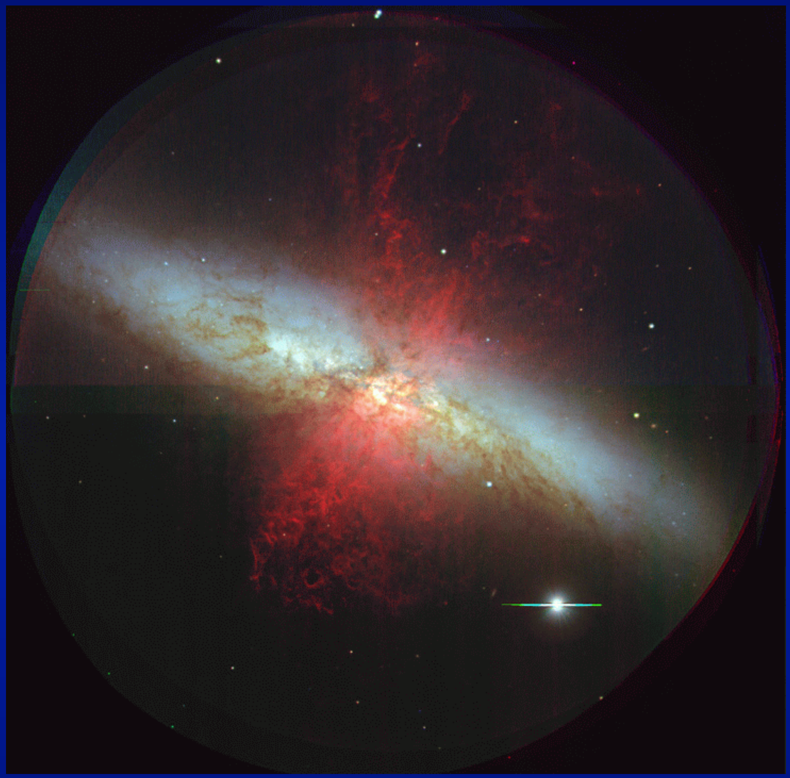
(Kriek et al. 2015)



• Rest-frame optical emission lines can be used to constrain many basic galaxy properties!

Big Questions: The MZR



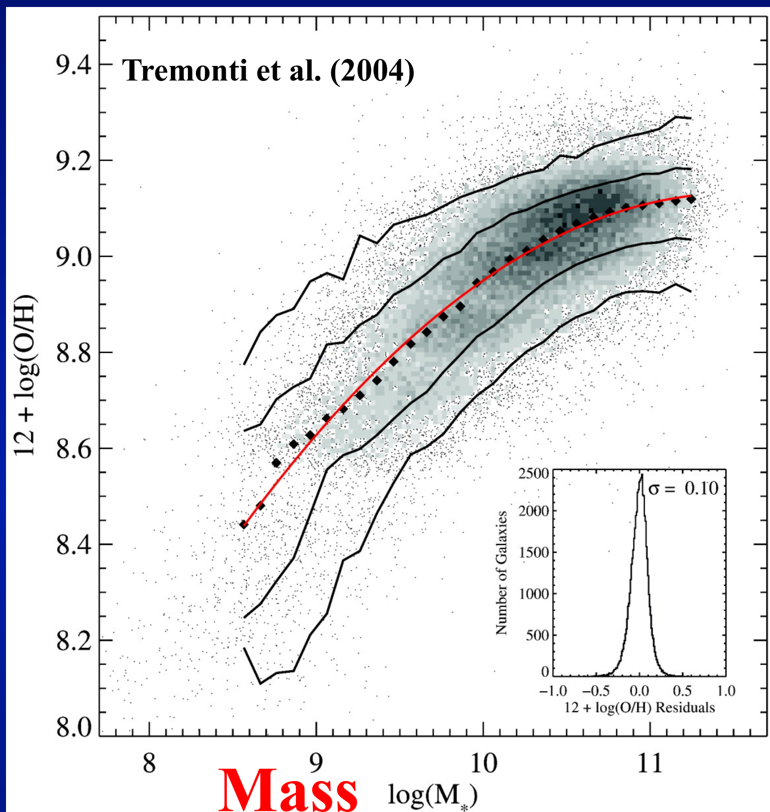


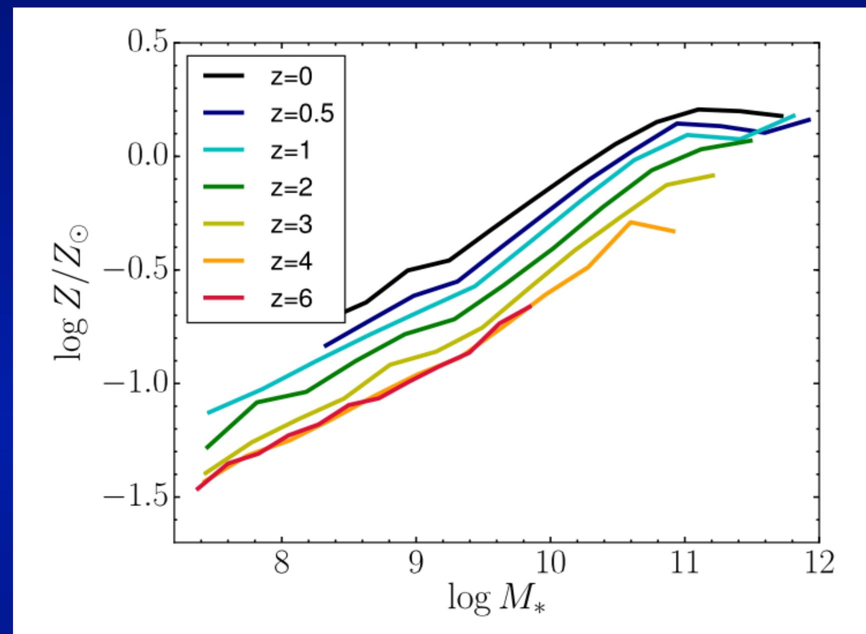
(Image credit: Subaru Observatory)

• Measuring how the metal content of galaxies varies as a function of galaxy mass and redshift may tell us something very fundamental about how gas cycles in and out of galaxies – i.e. how does outflow mass-loading factor vary with galaxy mass and redshift?

Big Questions: The MZR

Metallicity





(Dave et al. 2017)

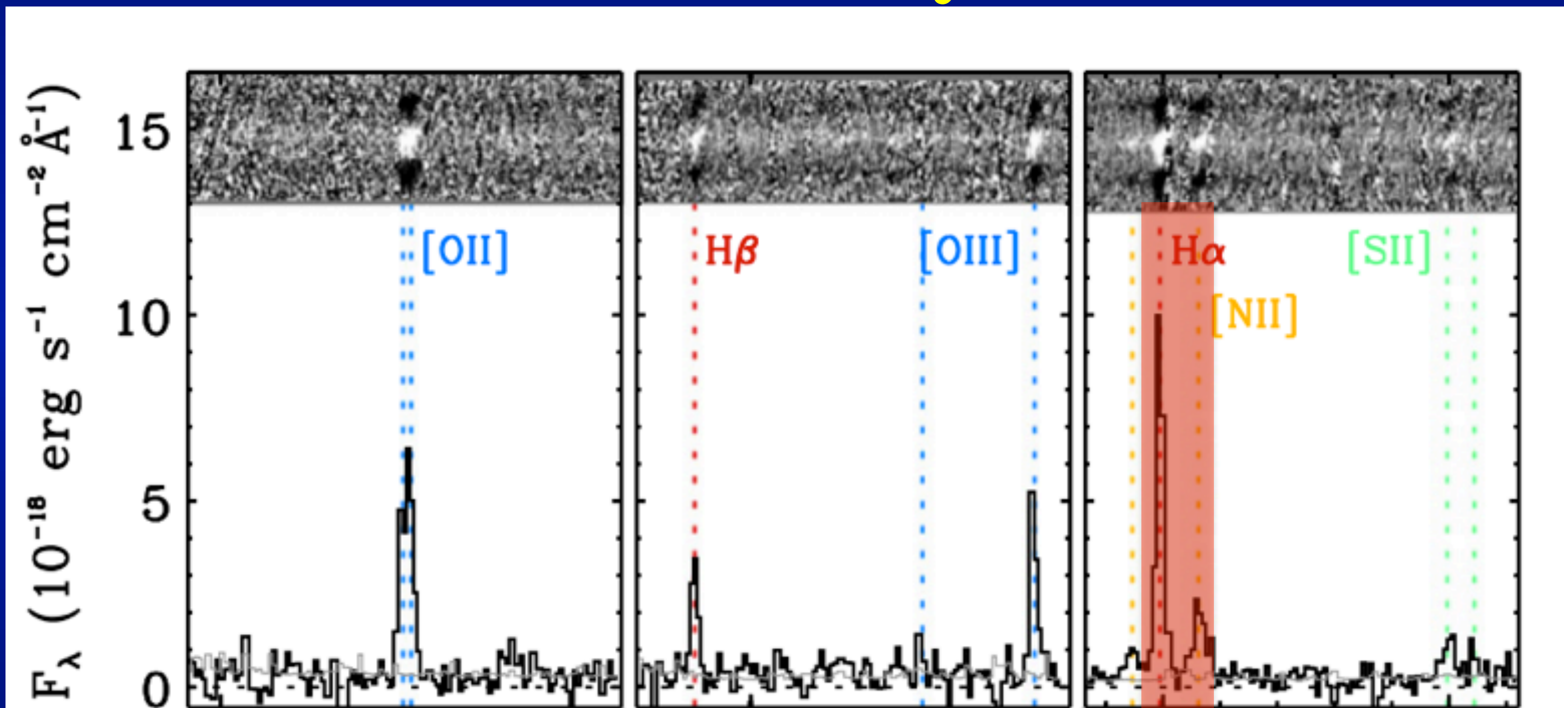
• Measuring how the metal content of galaxies varies as a function of galaxy mass and redshift may tell us something very fundamental about how gas cycles in and out of galaxies – i.e. how does outflow mass-loading factor vary with galaxy mass and redshift?

Recall…

Metallicity

N2

(Kriek et al. 2015)



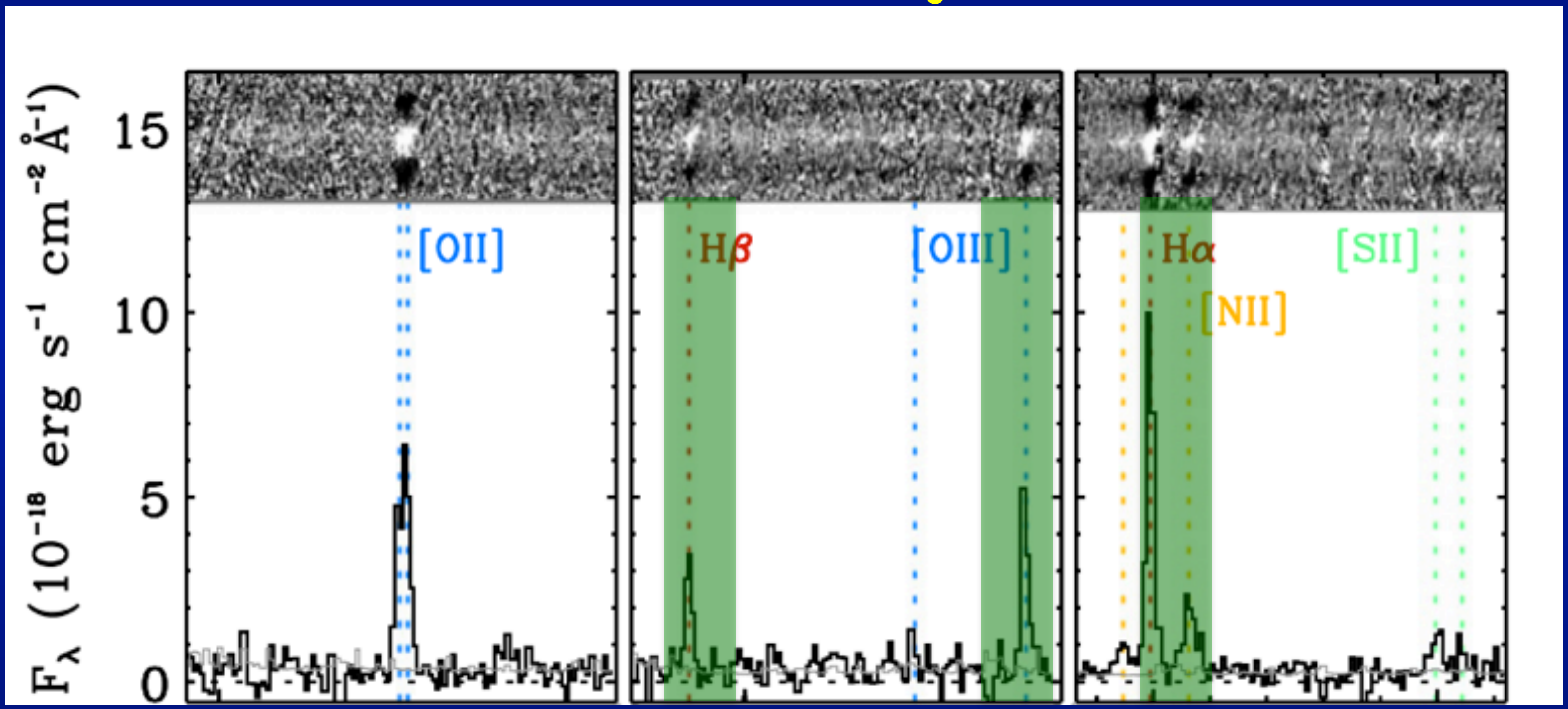
• **Strong rest-frame optical emission lines can be used to estimate gas-phase oxygen abundance.**

Recall…

Metallicity

O3N2

(Kriek et al. 2015)



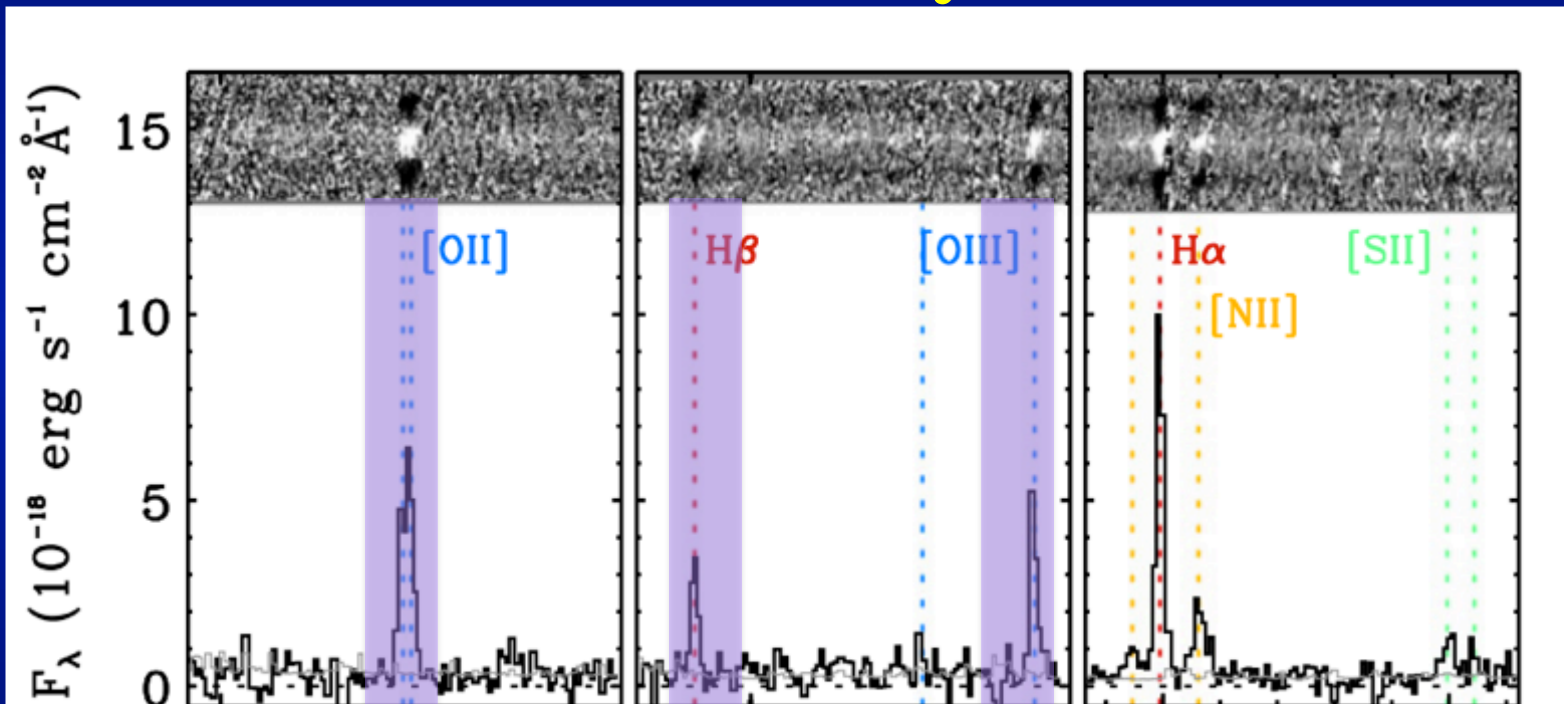
• Strong rest-frame optical emission lines can be used to estimate gas-phase oxygen abundance.

Recall…

Metallicity

R23

(Kriek et al. 2015)



• Strong rest-frame optical emission lines can be used to estimate gas-phase oxygen abundance.

Big Questions: Nature of ISM and Massive Stars at High z

(Image credit: NASA/ESA and The Hubble Heritage Team (AURA/STScI))

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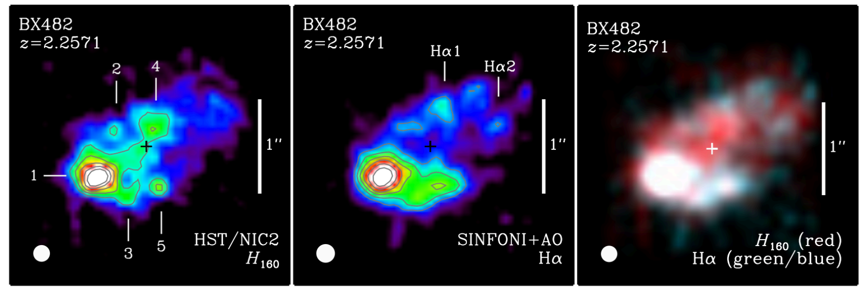
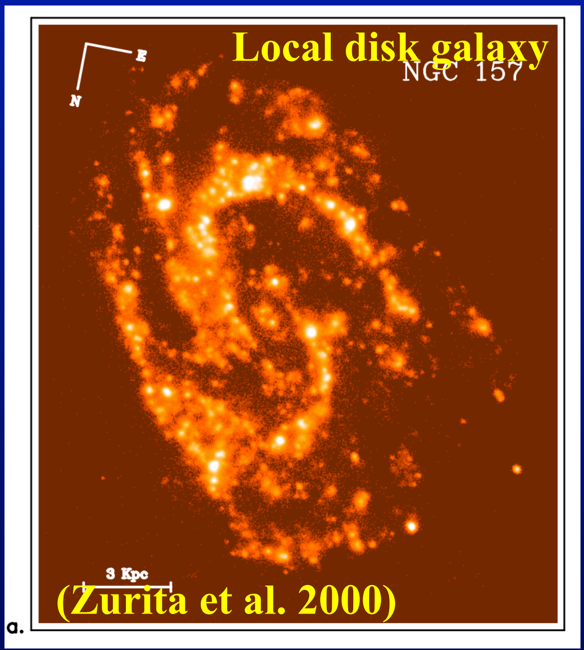
z~2 star-forming galaxy



(Forster Schreiber et al. 2011)

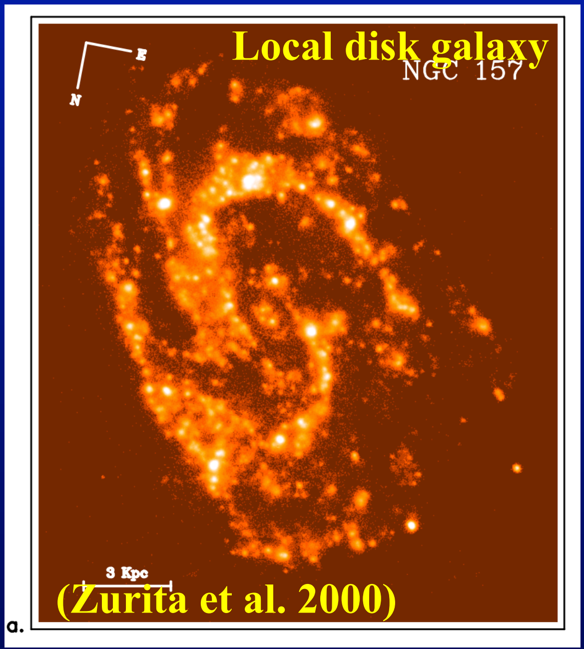


(Zurita et al. 2000)

What are the properties of the ionized ISM (e.g., pressure, density, turbulence, architecture, radiation field) and massive stars at high z?

Big Questions: Nature of ISM and Massive Stars at High z

(Image credit: NASA/ESA and The Hubble Heritage Team (AURA/STScI))



(Zurita et al. 2000)

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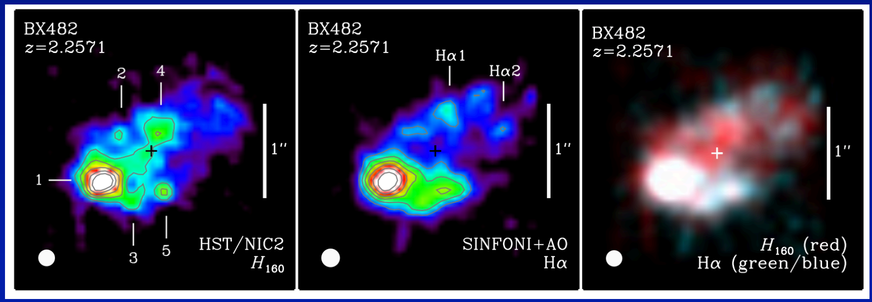
z~2 star-forming galaxy



(Forster Schreiber et al. 2011)

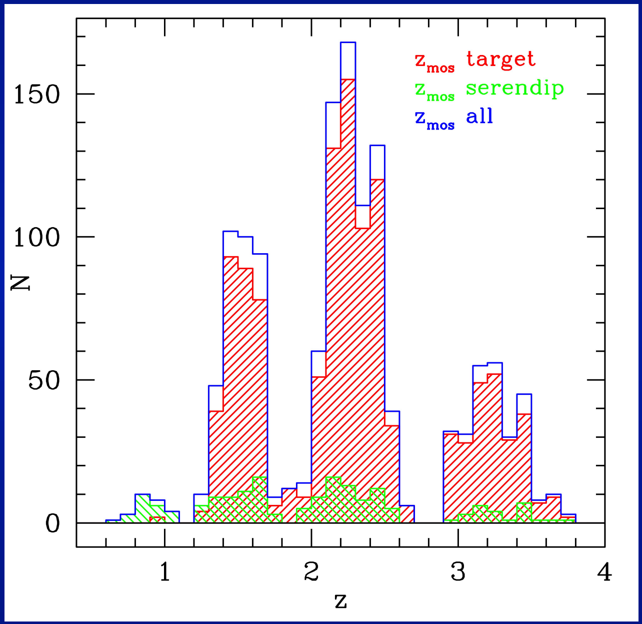
We should answer because (1) basic insight into high-z galaxies; (2) implications for how we measure metallicity at z~2.

Overview

- Current state of the art for near-IR MOS.
- Big questions for rest-optical emission-line studies.
- New, large surveys with Keck/MOSFIRE.
- What are we learning/fighting about/confused about?
- The path forward.

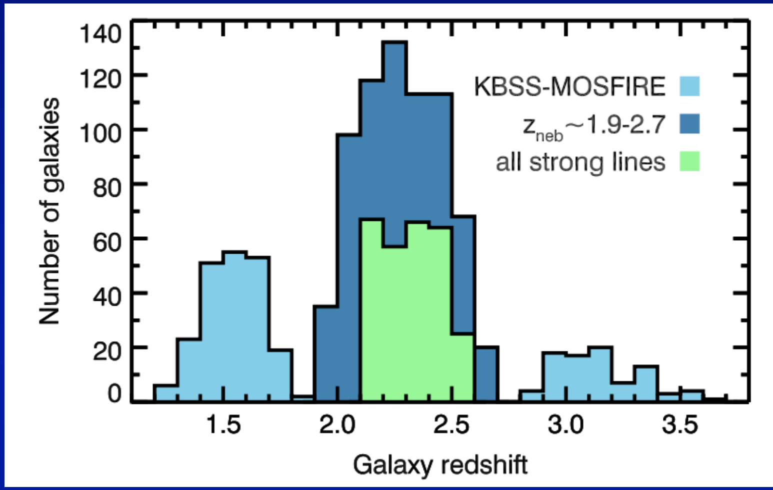
MOSDEF Survey

- **Co-PIs:** Alice Shapley, Mariska Kriek, Naveen Reddy, Brian Siana, Alison Coil, Bahram Mobasher
- **Observing time awarded by UC TAC:** 48.5 Keck I/MOSFIRE nights from 2012B-2016A.
- **Target fields:** HST Legacy Extragalactic Fields (exquisite multi-wavelength datasets).
- **Principal redshift ranges:** $1.37<z<1.70$; $2.09<z<2.61$; $2.95<z<3.80$ (9-12 billion years ago).
- **Sample:** ~1500 galaxies targeted (25% at z~1.5, 50% at z~2, 25% at z~3), ~1300 redshifts measured.
- **Target selection:** H-band magnitude limited (rest-frame optical luminosity).



KBSS Survey

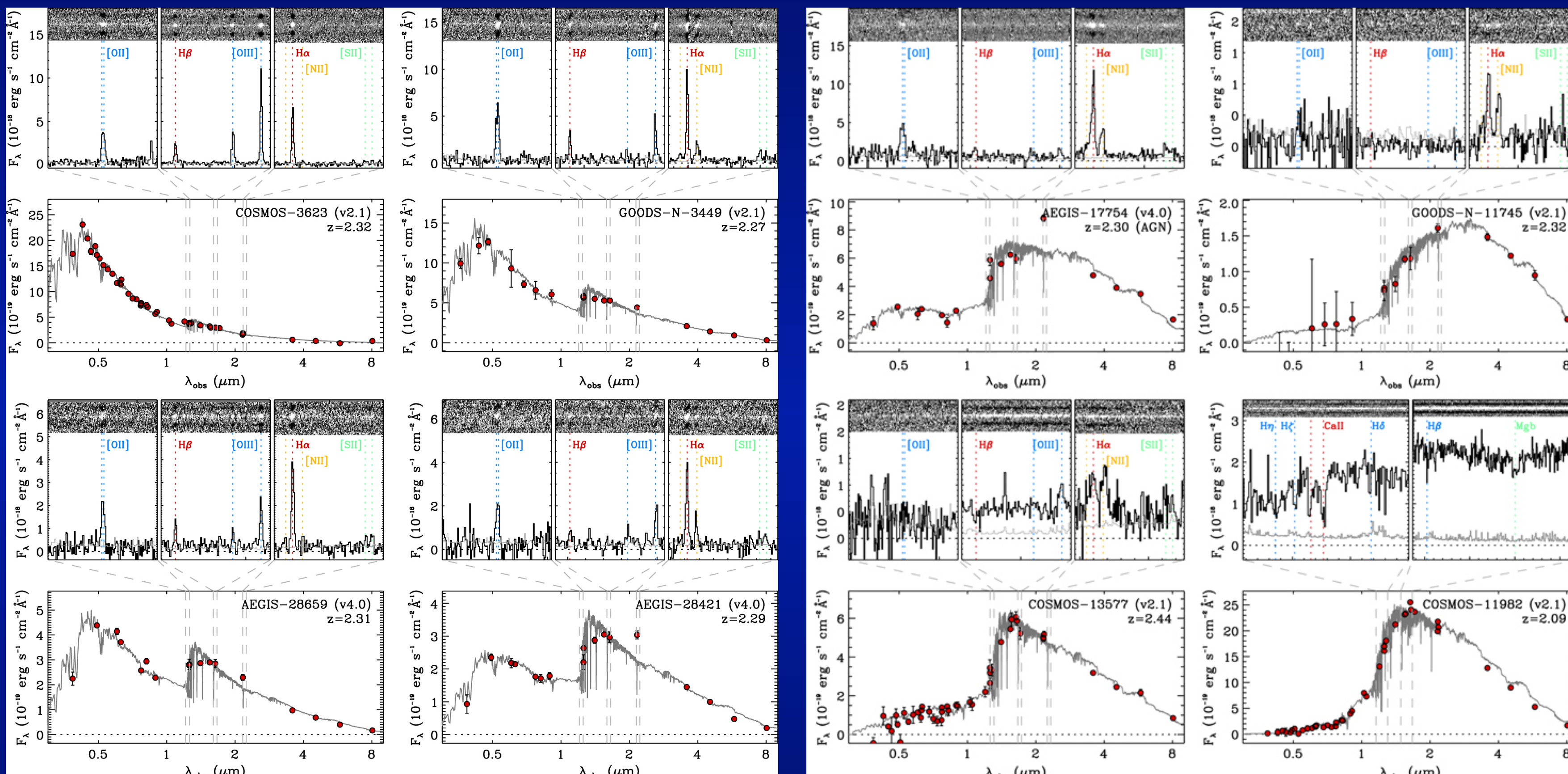
- **PI:** Chuck Steidel
- **Observing time awarded by Caltech TAC:** A LOT of Keck I/MOSFIRE nights.
- **Target fields:** QSO fields (IGM/Galaxy connection).
- **Principal redshift ranges:** Basically the same as MOSDEF.
- **Sample:** 1060 galaxies with redshifts (~70% at z=1.9-2.7).
- **Target selection:** UV (BX/MD/ BM/LBG) selection plus some additional redder galaxies.



(Strom et al. 2017)

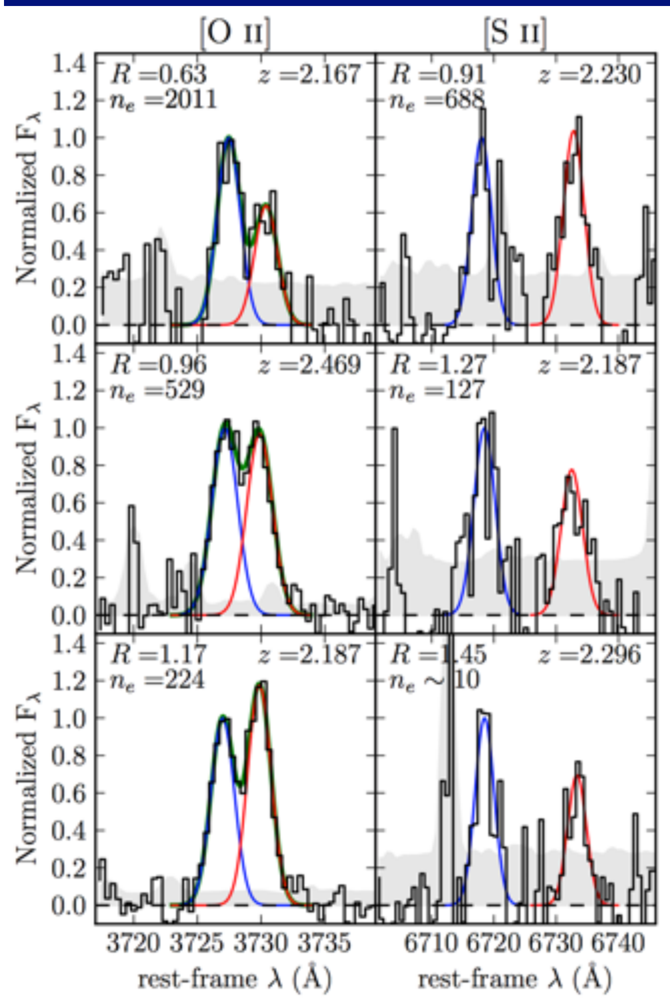
MOSDEF Spectra

(Kriek et al. 2015)



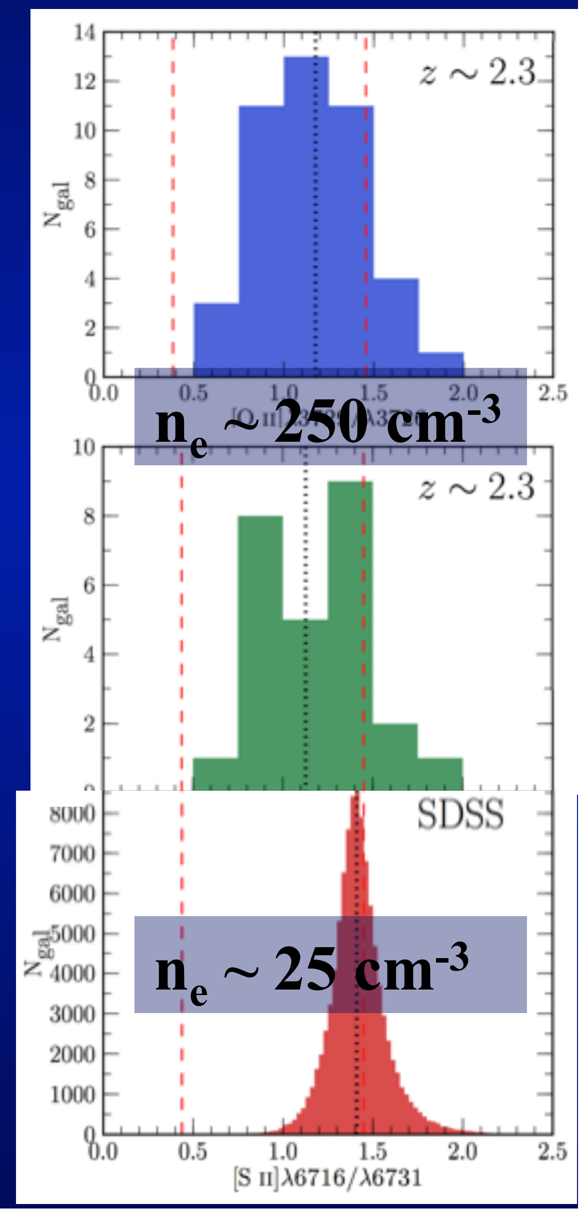
- MOSDEF z~2 spectra and SEDs
- Ordered by decreasing rest-frame UV/optical ratios

Consensus: HII Region Density is High



(Sanders et al. 2016a)

- **69 MOSDEF density measurements from 61 z~2.3 galaxies based on [OII] and [SII] doublet ratios**
- **All doublets are clean of skyline contamination**
- **Estimate densities using up-to-date atomic data**
- ***Electron density increases by a factor of 10 from z~0 to z~2.3***
- **KBSS+MOSDEF agree.**

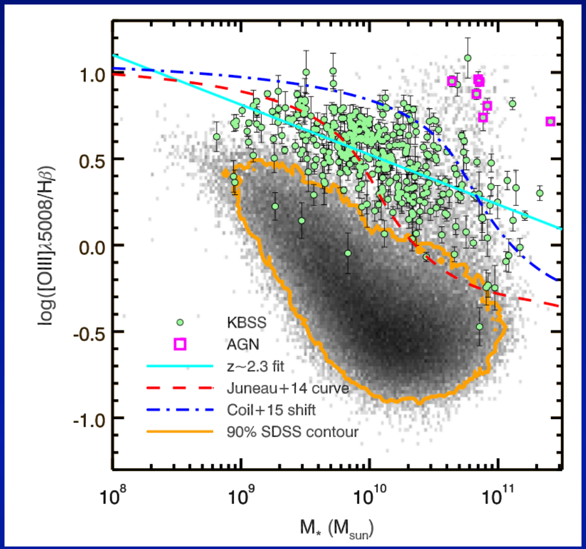


$n_e \sim 250\ cm^{-3}$

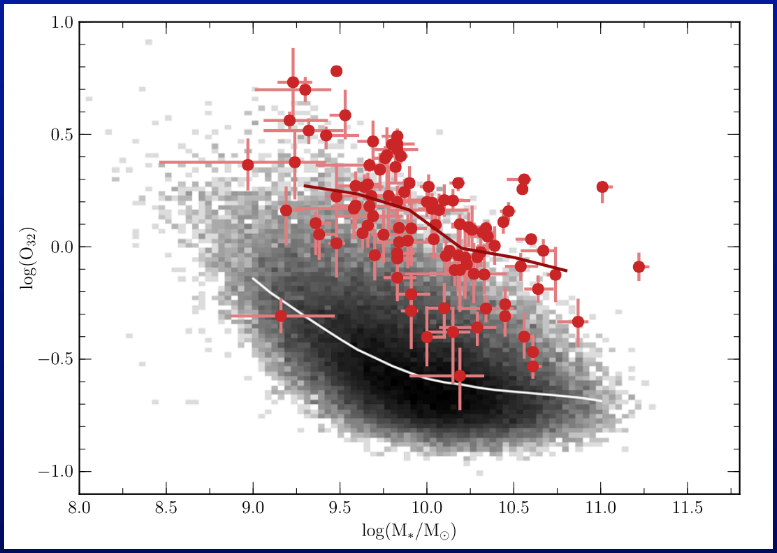
$n_e \sim 25\ cm^{-3}$

Consensus: Nebular Excitation is Higher at Fixed Mass

(Strom et al. 2017)



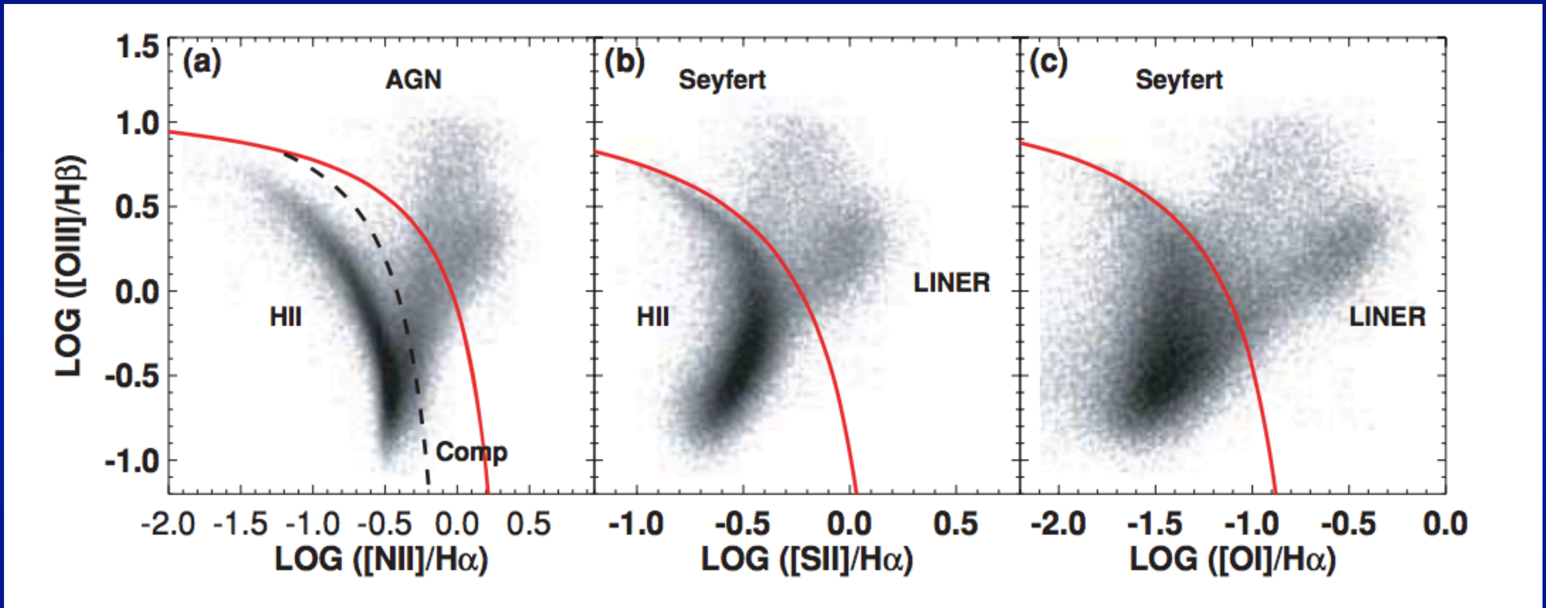
(Sanders et al. 2016a)



- At fixed stellar mass, both [OIII]/Hβ and [OIII]/[OII] are systematically higher at z~2-3 than at z~0.
- Simple explanation: galaxies have lower metallicity at fixed mass (recall Dave et al. 2017 MZR evolution) → evolution in the MZR.
- Note anti-correlation of, e.g., [OIII]/[OII] with mass at fixed redshift.
- Additional factors causing enhanced excitation at fixed mass?

- KBSS+MOSDEF agree.

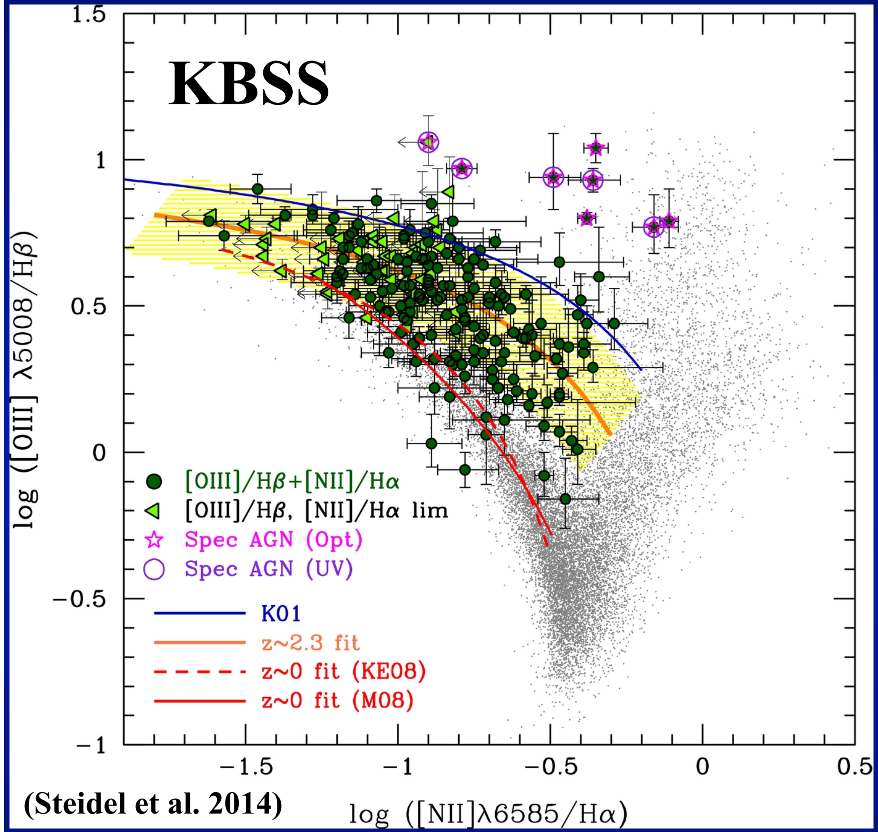
Tension: The O3N2 BPT Diagram

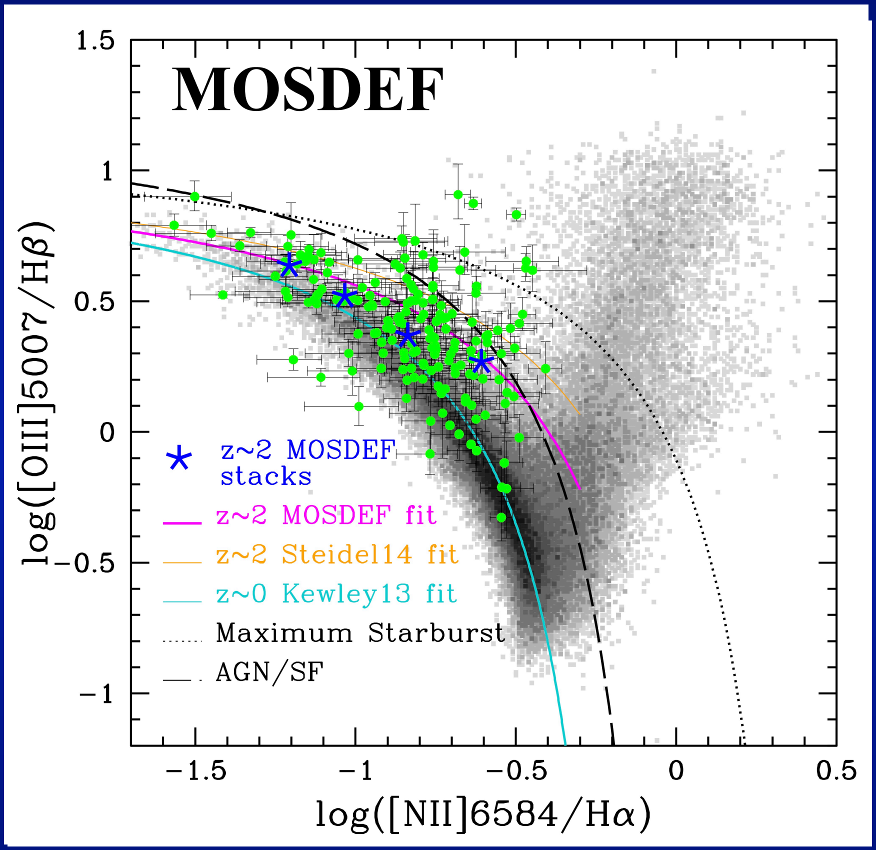


(Kewley et al. 2006)

- KBSS and MOSDEF find that z~2 galaxies occupy a different BPT locus from z~0 star-forming galaxies.
- The KBSS sample is more offset than the MOSDEF sample (by ΔO3~0.06 dex at fixed N2, or by ΔN2~0.15 dex at fixed O3).

Tension: The O3N2 BPT Diagram





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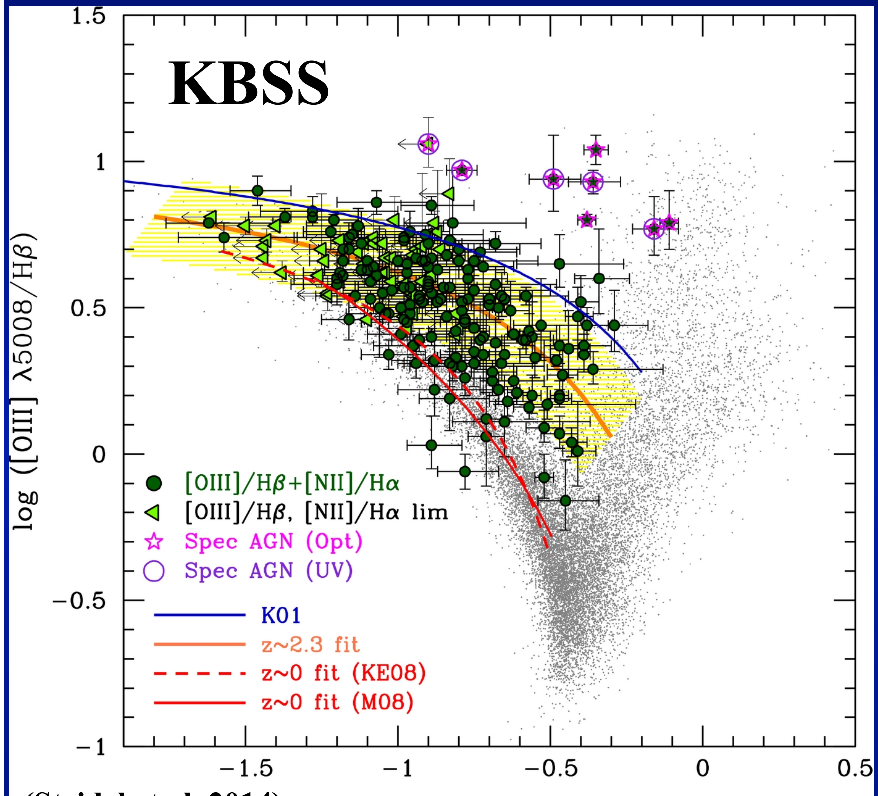
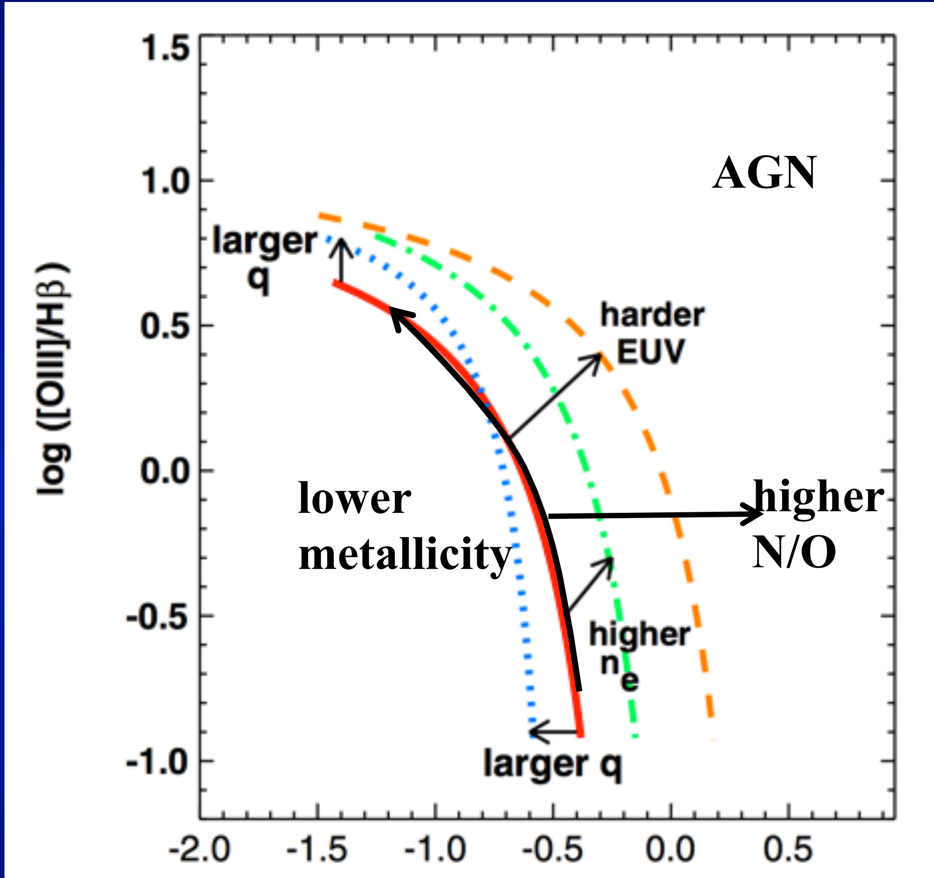


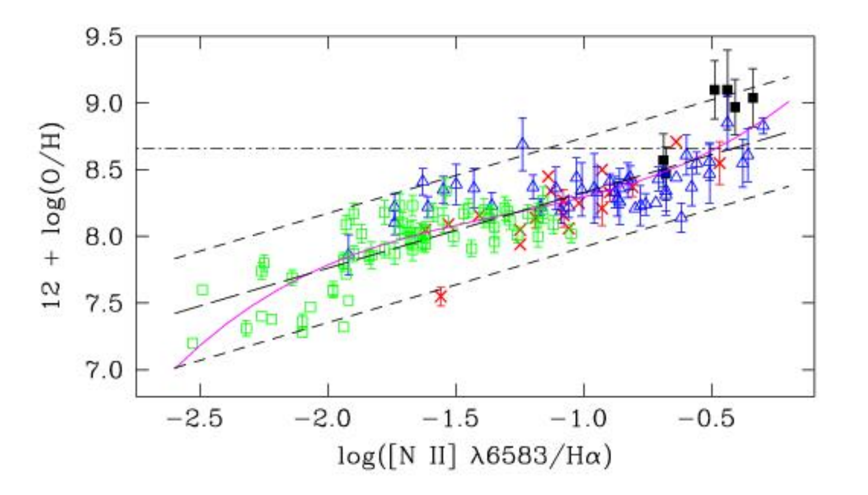
(Steidel et al. 2014)

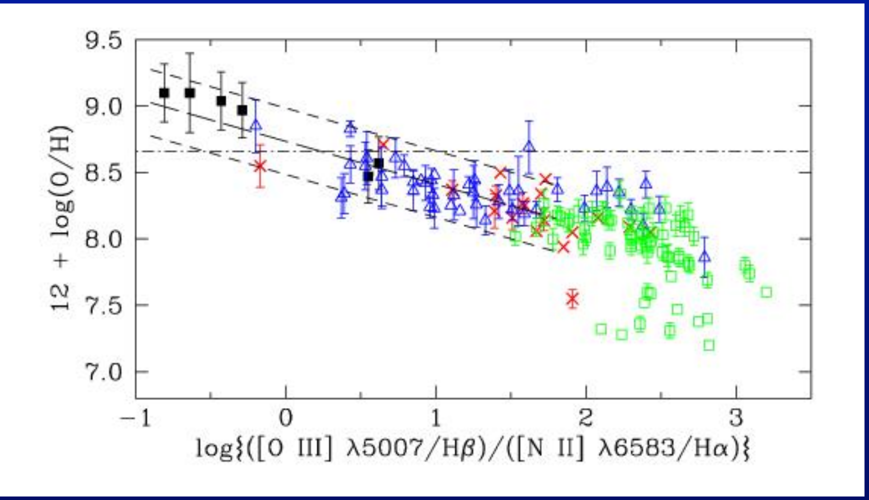


(Kewley et al. 2013)

- Different explanations for the driving force behind the BPT offset: AGN, harder ionizing spectrum at fixed metallicity (KBSS); enhanced N/O at fixed metallicity (MOSDEF); enhanced ionization parameter at fixed metallicity (others); contributions from shocked, outflowing gas (MOSDEF).

BPT Offset and Strong-line Metallicities



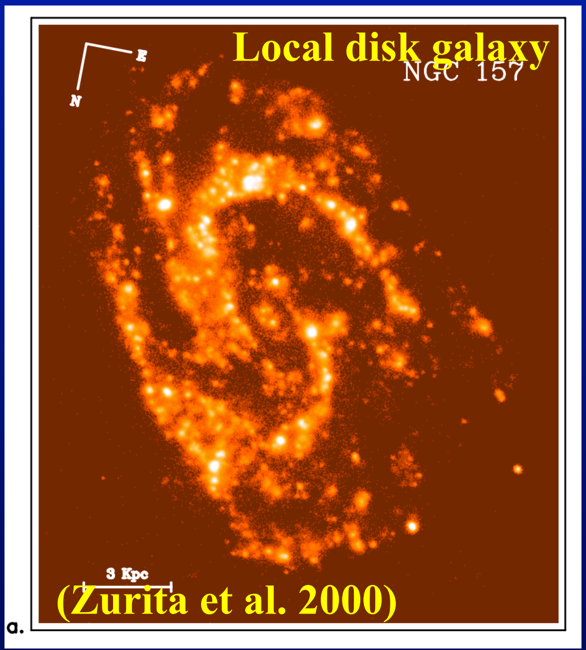


(Pettini & Pagel 2004)

- **BPT offset suggests different relation between metallicity and strong-line ratios.**
- **Common strong-line ratios for estimating metallicity:**
  - **N2: [NII]/Hα**
  - **O3N2: ([OIII]/Hβ)/([NII]/Hα)**
  - **R_{23}: ([OII]+[OIII])/Hβ**
  - **N2O2: [NII]/[OII]**

BPT Offset and the Nature of High-z Stars and Gas

(Image credit: NASA/ESA and The Hubble Heritage Team (AURA/STScI))



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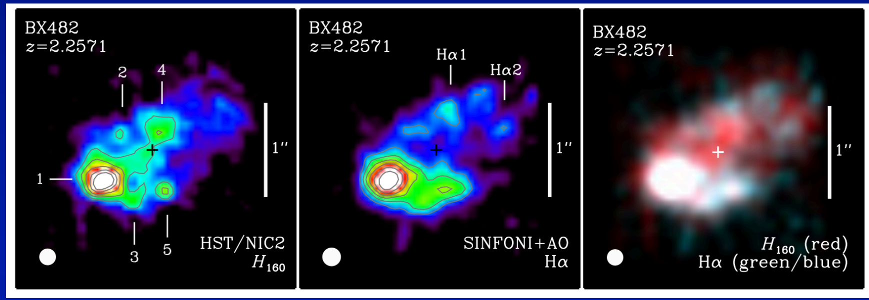
z~2 star-forming galaxy

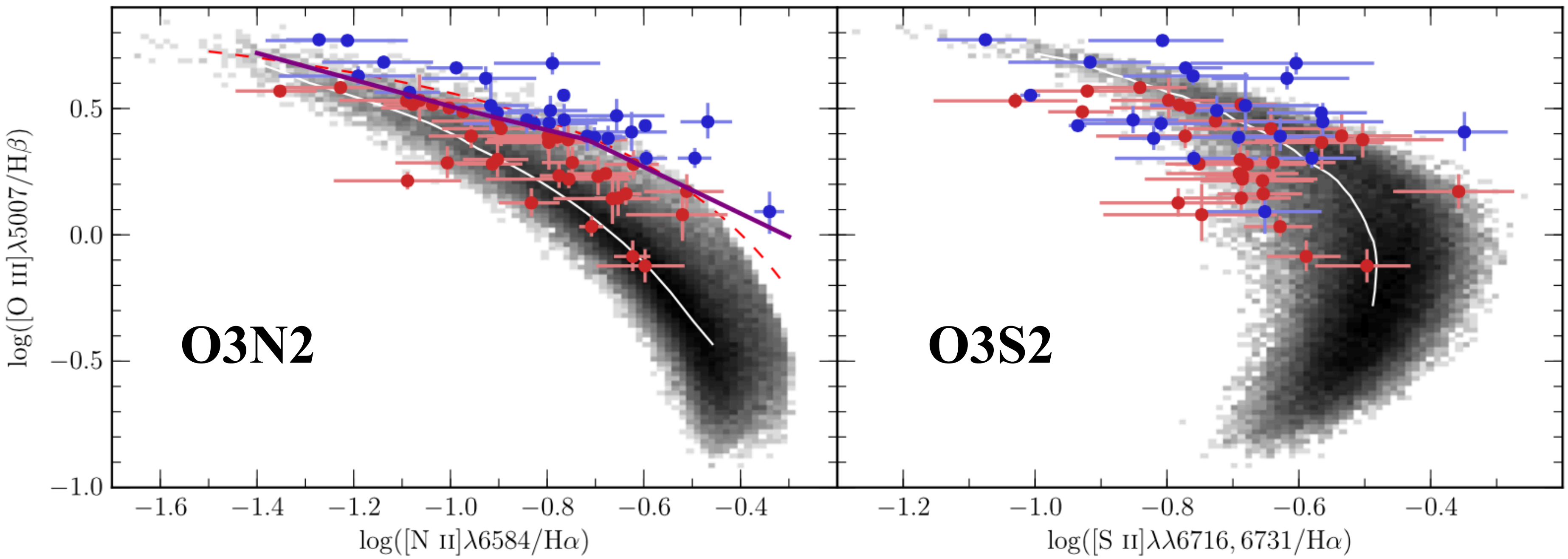


(Forster Schreiber et al. 2011)

- **BPT offset suggests systematically different conditions in star formation regions (density, ionization parameter, ionizing spectrum at fixed metallicity, abundance pattern).**

Tension: The O3S2 BPT Diagram

MOSDEF

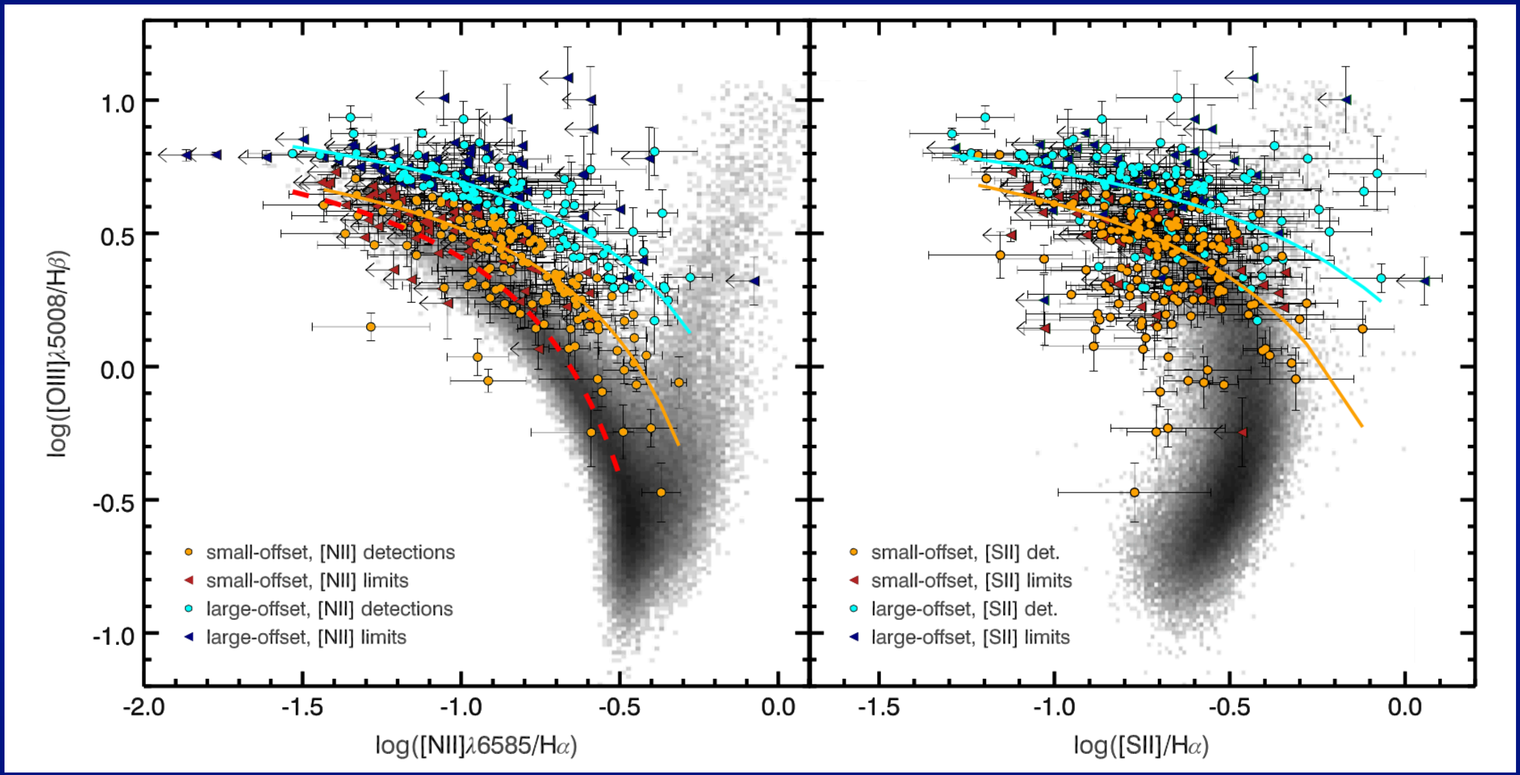


(Sanders et al. 2016a)

- z~2 galaxies scatter roughly symmetrically around z~0 O3S2 locus.
- z~2 galaxies more offset in O3N2 are evenly mixed in O3S2 (not segregated).
- Argues against harder ionizing spectrum at fixed metallicity, which would predict offsets in both O3N2 and O3S2.

Tension: The O3S2 BPT Diagram

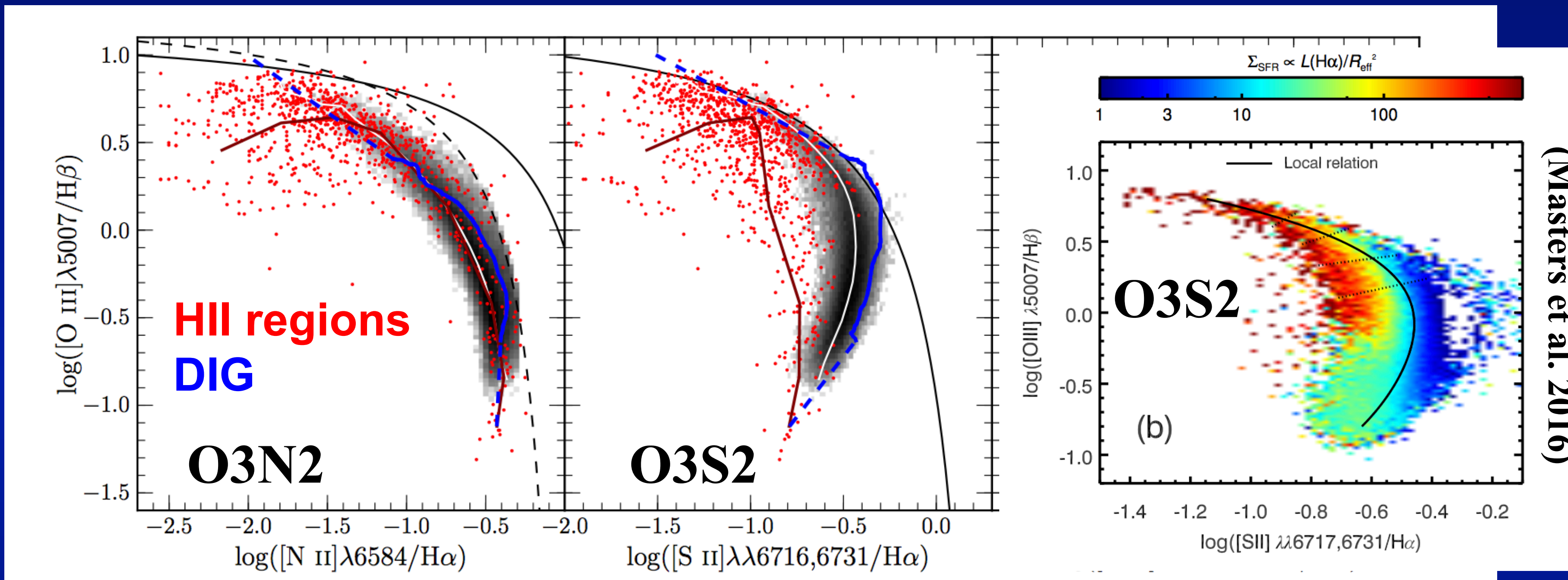
KBSS



(Strom et al. 2017)

- z~2 galaxies are also offset "upwards, to the right" from z~0 O3S2 locus.
- z~2 galaxies more offset in O3N2 are more offset in O3S2 (segregated).
- Consistent with predictions for harder ionizing spectrum at fixed metallicity (argued for on additional grounds, composite rest-UV spectrum).

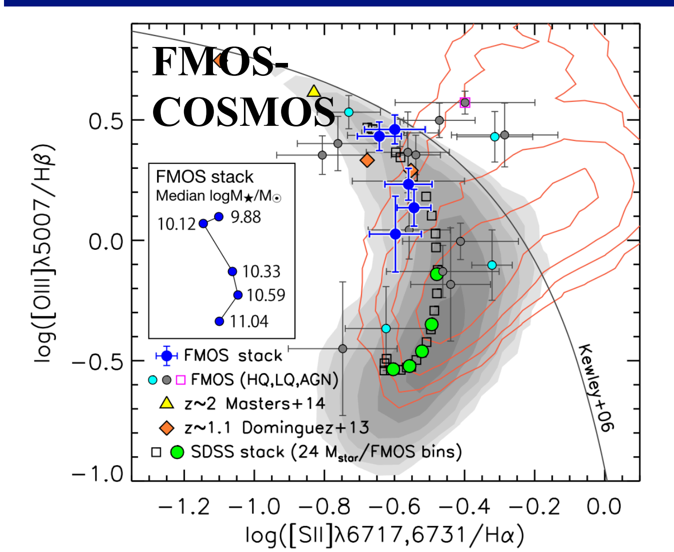
Tension: The O3S2 BPT Diagram



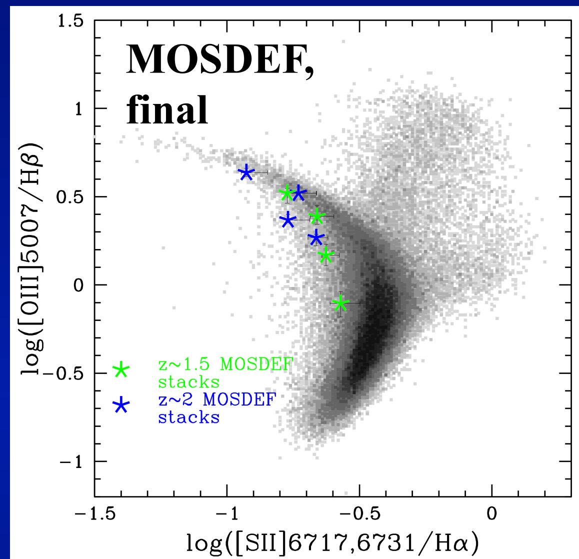
(Sanders et al. 2017)

- At z~0, HII regions and SDSS galaxies segregate in the O3S2 BPT diagram. Galaxies contain an ensemble of HII regions *and* DIG.
- z~2 galaxies should have lower fractional DIG contribution, just like high Σ_{SFR} galaxies at z~0, and, all else being equal, look more like HII regions (offset to the left; Masters et al. 2016).
- If they don't, suggests that other properties are different.

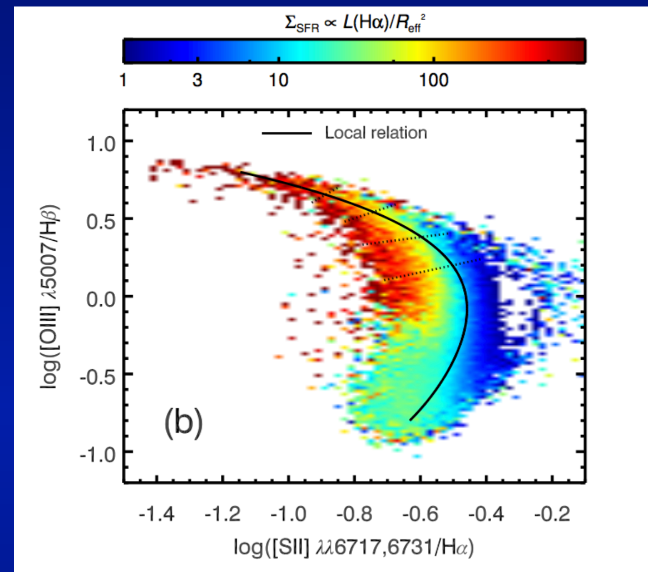
Tension: The O3S2 BPT Diagram



(Kashino et al. 2017)



(Shapley, in prep)

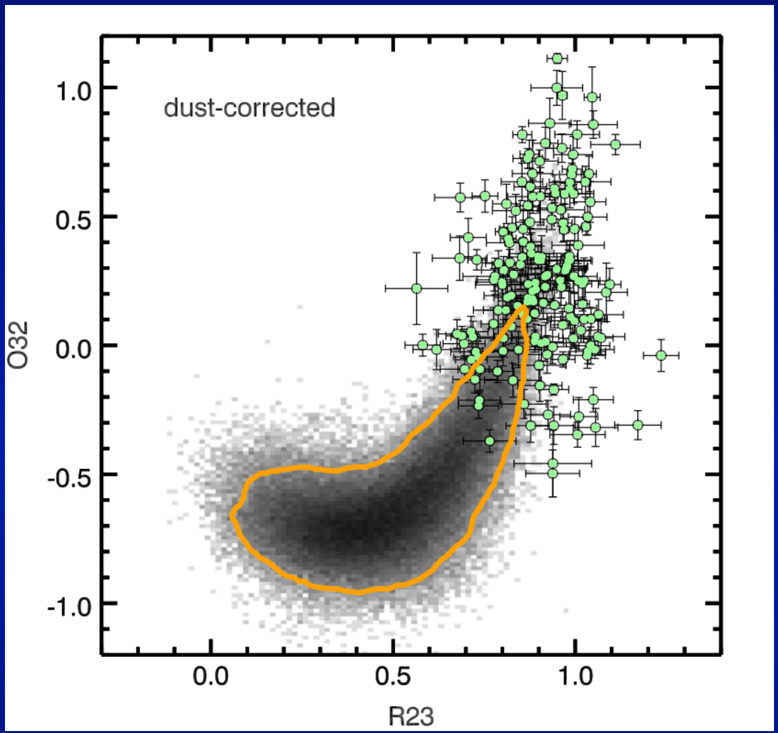


(Masters et al. 2016)

- O3S2 diagram from FMOS-COSMOS survey at z~1.6 offset to the left.
- MOSDEF z~1.5 and z~2 results (full sample) are consistent.
- High-z galaxies are intermediate between HII regions and SDSS sequence, suggestive of high Σ_{SFR} and low DIG fraction.

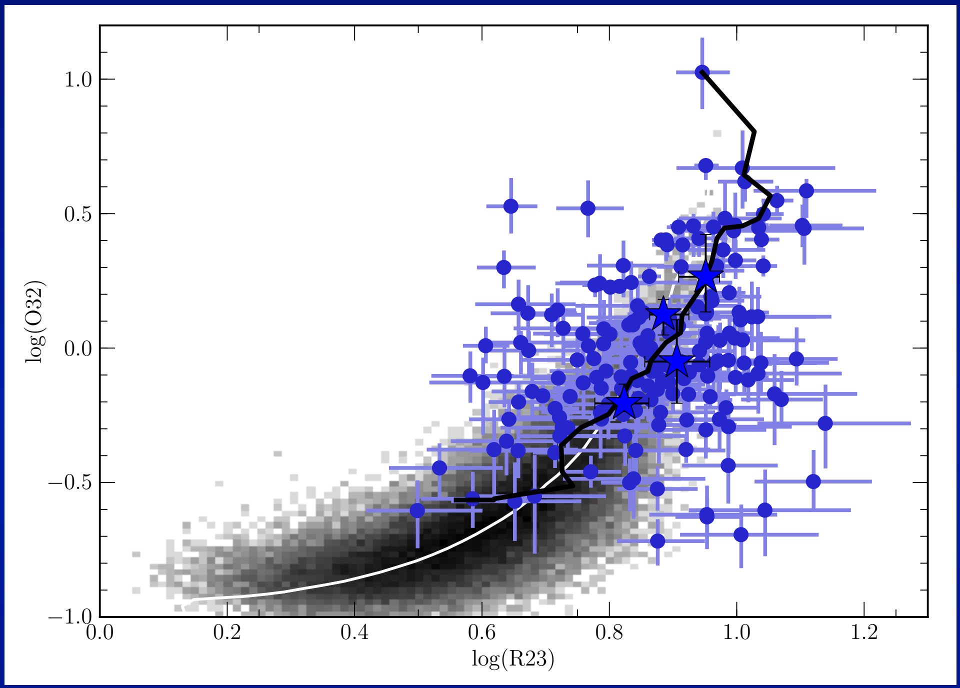
Tension: The O32 vs. R23 Diagram

KBSS



(Strom et al. 2017)

MOSDEF

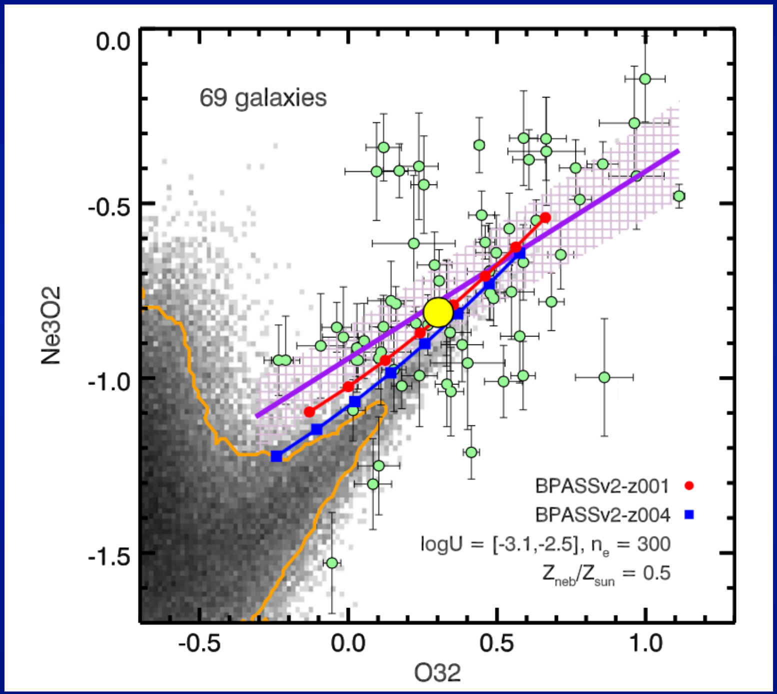


(Sanders et al., in prep)

- z~2 overlap the high-excitation, low-metallicity tail of SDSS galaxies.
- No systematic offset in the z~2 and z~0 sequences where they overlap.
- Different interpretations on the utility of O32/R23 as abundance indicators.
- Independent O/H measurements required. Is overlap a coincidence (given low DIG fractions at z~2)?

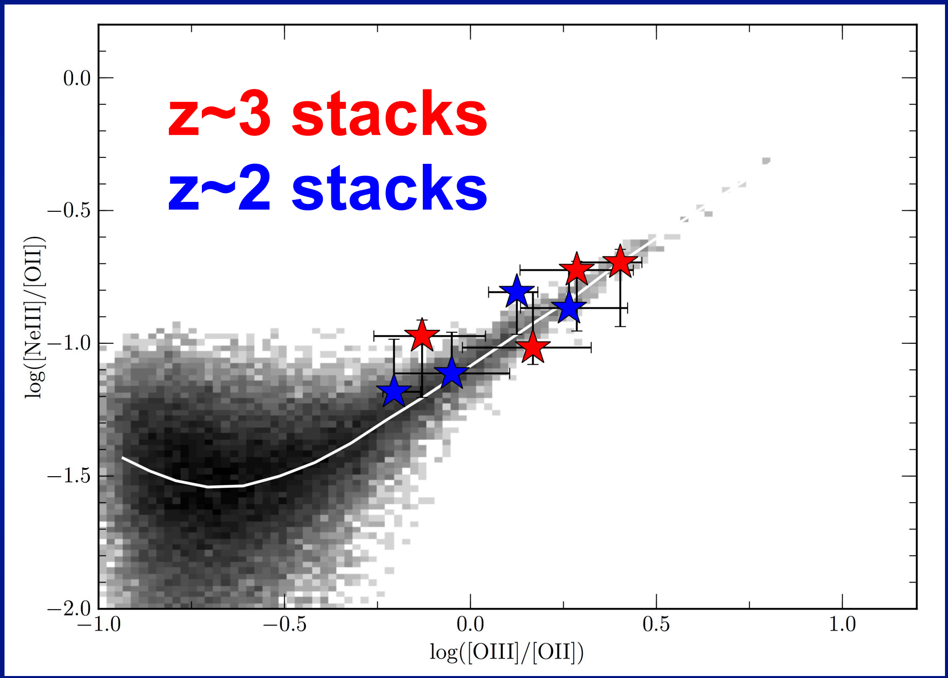
Tension: "Direct" Probe of Ionizing spectrum:Ne3O2/O32

KBSS



(Strom et al. 2017)

MOSDEF

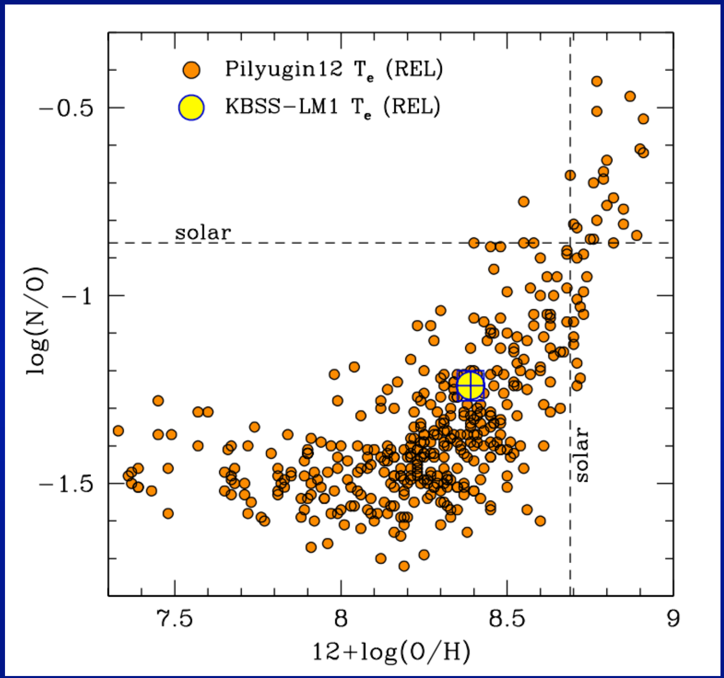


(Sanders et al., in prep)

- [NeIII]/[OII] vs. [OIII]/[OII] provides a probe of the ionizing spectrum (i.e., stellar metallicity).
- MOSDEF z~2-3 stacks entirely consistent with low-Z tail of SDSS. KBSS data suggests harder ionizing spectrum at fixed [OIII]/[OII]. Sample selection?

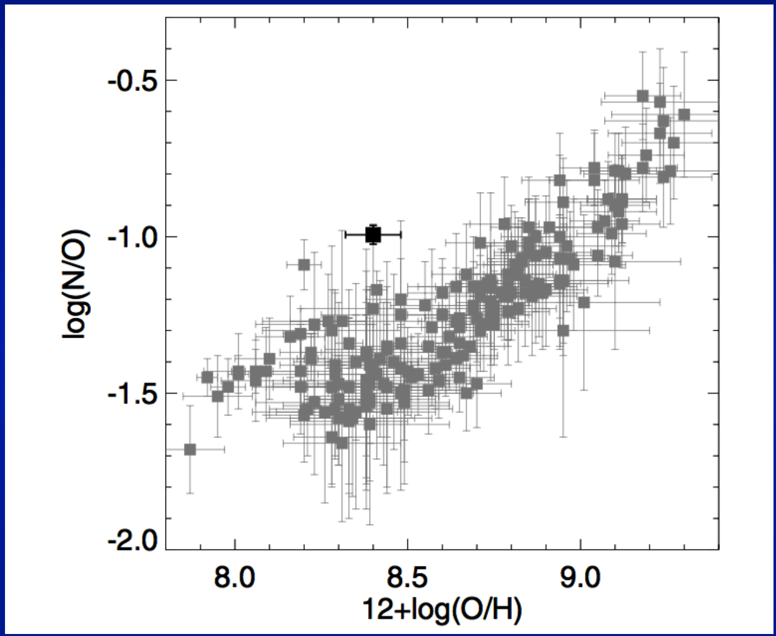
Tension: The N/O vs. O/H Relation

KBSS



(Steidel et al. 2016)

WISP

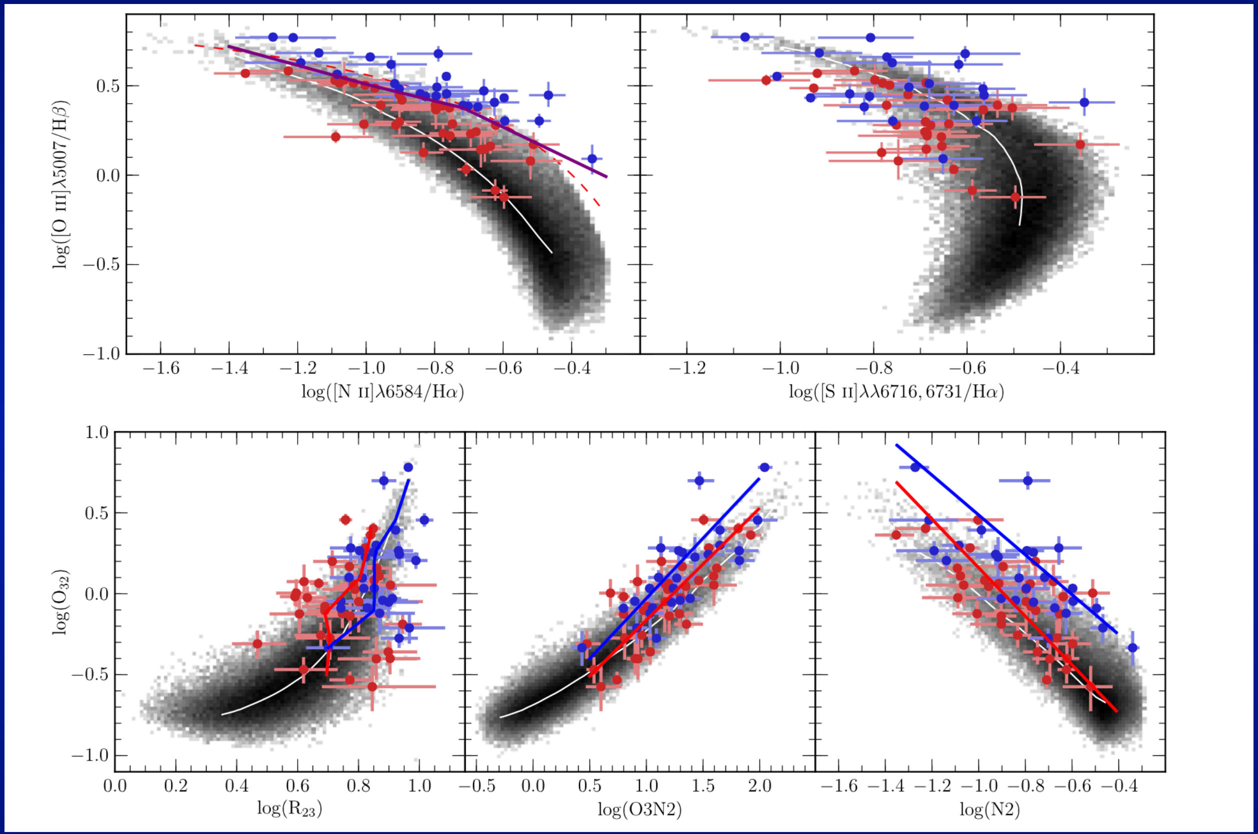


(Masters et al. 2014)

- KBSS z~2 composite spectrum has N2O2 (N/O) and 12+log(O/H) inferred from photoionization modeling that appear consistent with local relation.
- WISP composite (Masters et al. 2014) has N2S2 (N/O) and strong-line based 12+log(O/H) that appear discrepant from local relation.

Tension: The N/O vs. O/H Relation

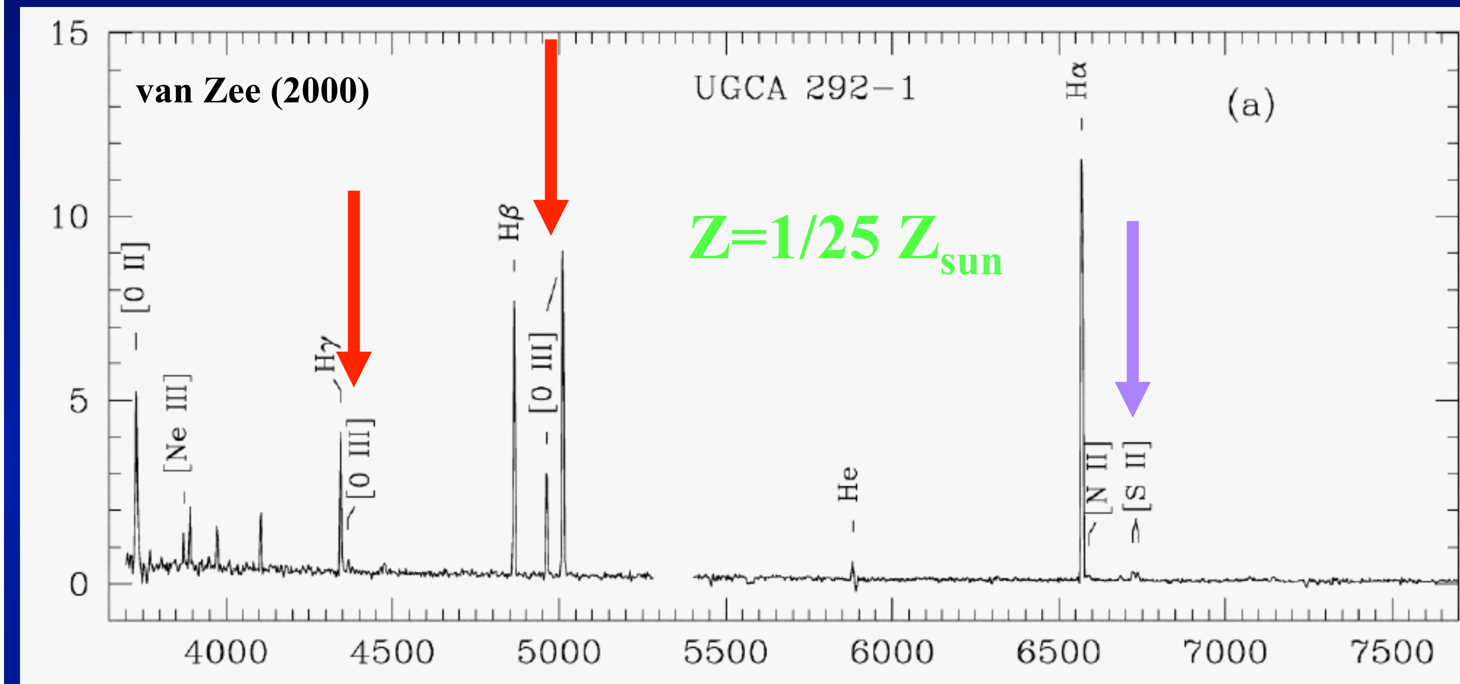
MOSDEF

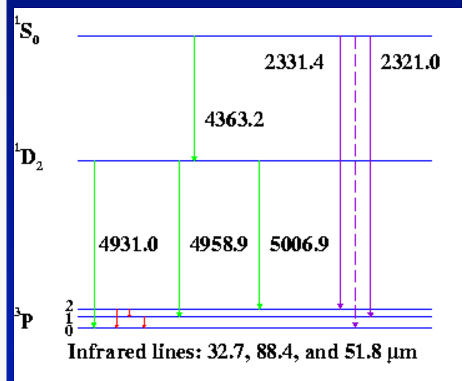


(Sanders et al. 2016a)

- MOSDEF statement about N/O enhancement is based on totality of strong-line diagrams (neglecting complexities of O3S2 and O32R23 BPT diagrams). Plausibly explained by enhanced N/O at fixed O/H.
- None of the above arguments is based on independent O/H or N/O estimates, as are typically obtained at z~0.

What now?: Direct Metallicities





$$12 + \log \mathrm{O}^{2+}/\mathrm{H}^{+} = \log \frac{\lambda 4959 + \lambda 5007}{\mathrm{H}\beta} + 6.200 + \frac{1.251}{t} - 0.55 \log t - 0.014 t,$$

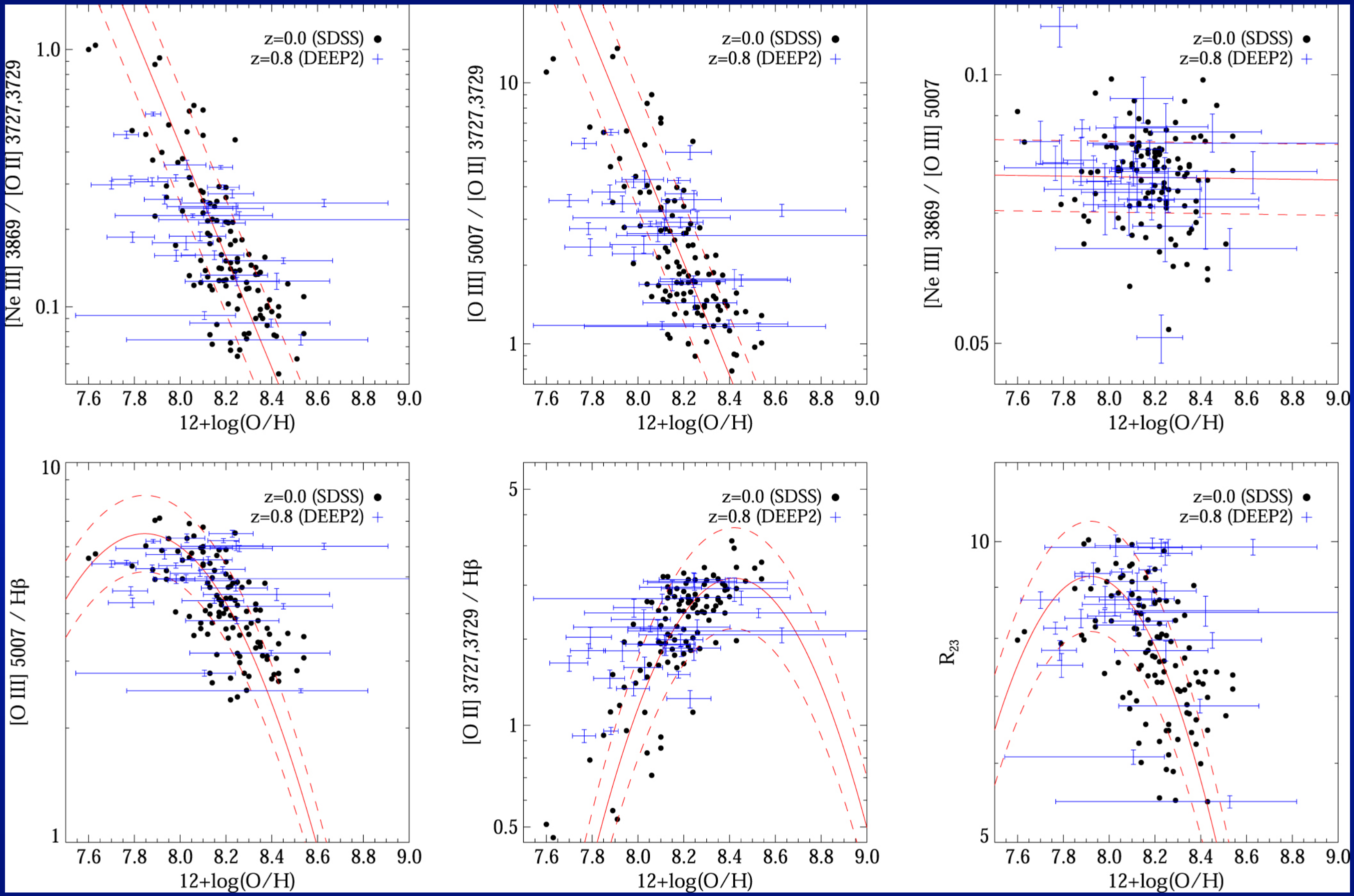
(From Izotov et al. 2006)

t=electron temp.=T$_e$

- **Use [OIII] 4363/(5007,4959) to get T$_e$, required for "direct" O/H estimate.**
- **Direct metallicities provide independent estimates of O/H – crucial for interpreting strong-line diagrams. No real progress w/o independent O/H.**

What now?: Direct Metallicities

(Jones et al. 2015)

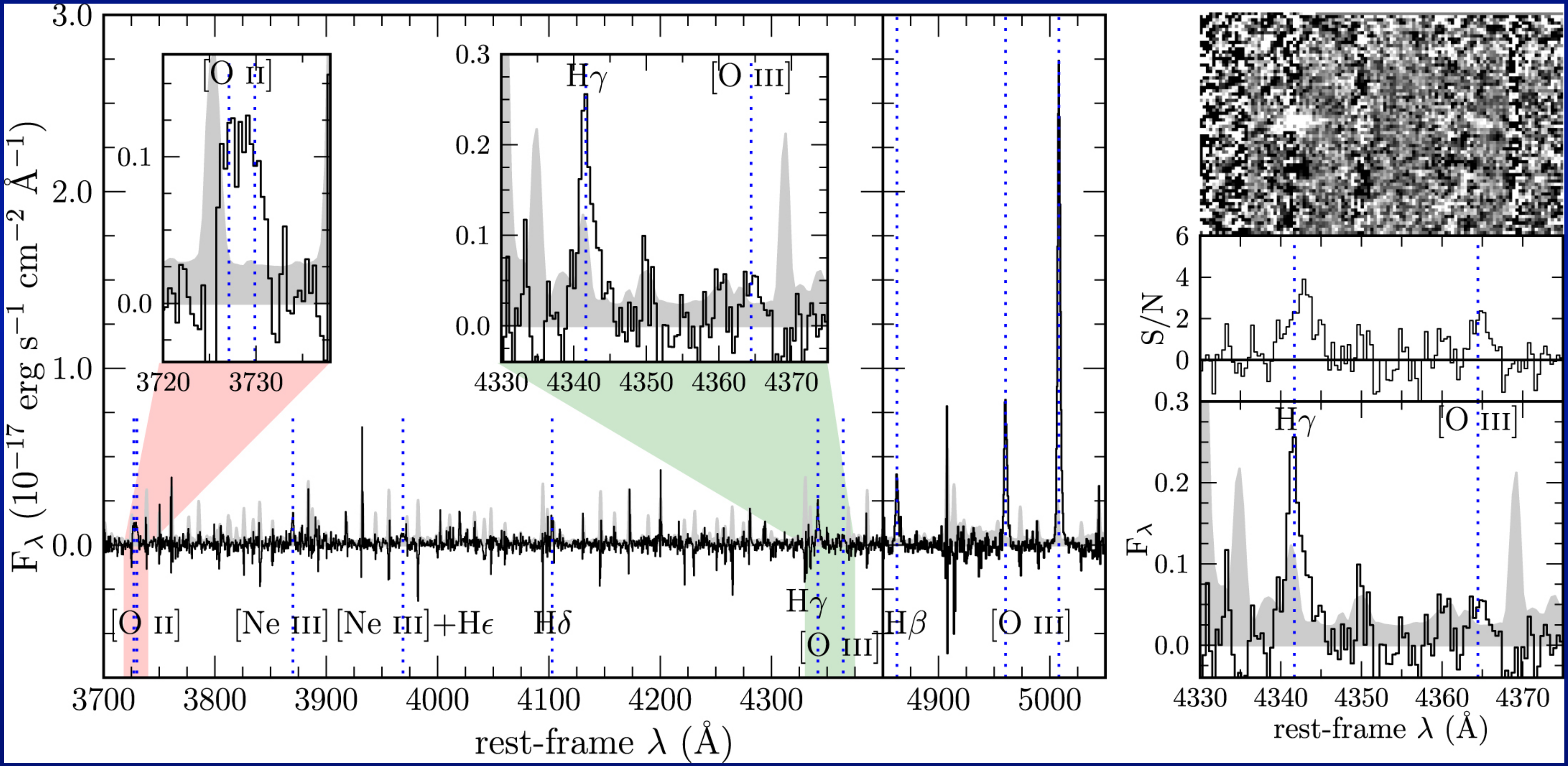


- N>=100 SDSS galaxies with such measurements (e.g., Izotov et al. 2006), 10s of galaxies out to z~1 (e.g., Jones et al. 2015).
- Exactly 1 direct measurement at z>2 (Sanders et al. 2016b).

What now?: Direct Metallicities

COSMOS-1908 (z=3.08)

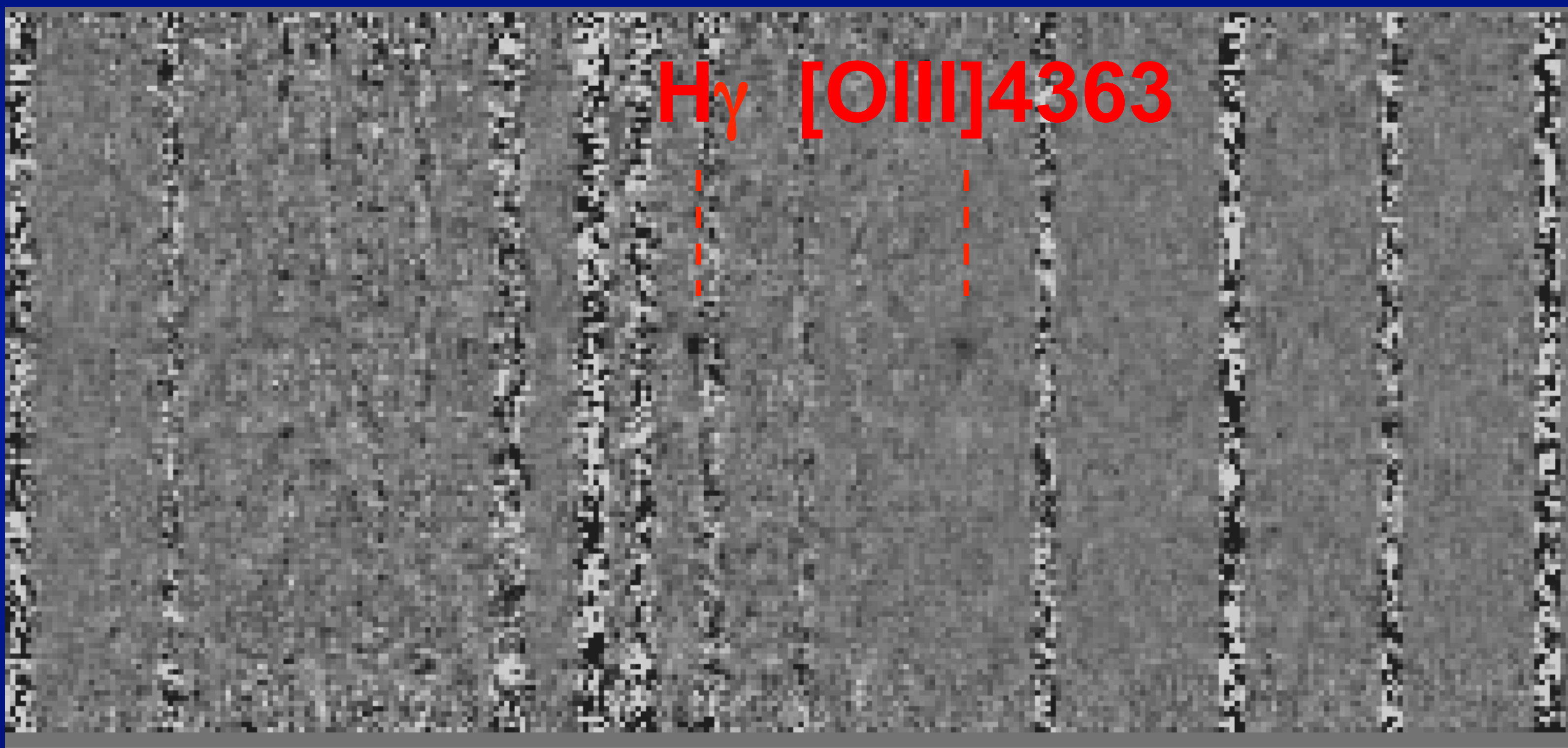
(Sanders et al. 2016b)



- MOSDEF *direct* O/H measurement at z=3.08, suggests z~3 galaxies follow roughly same relation between [OIII], Hb, [OII] and O/H as at z~0.

What now?: Direct Metallicities

GOODS-S-35910 (z=2.65)

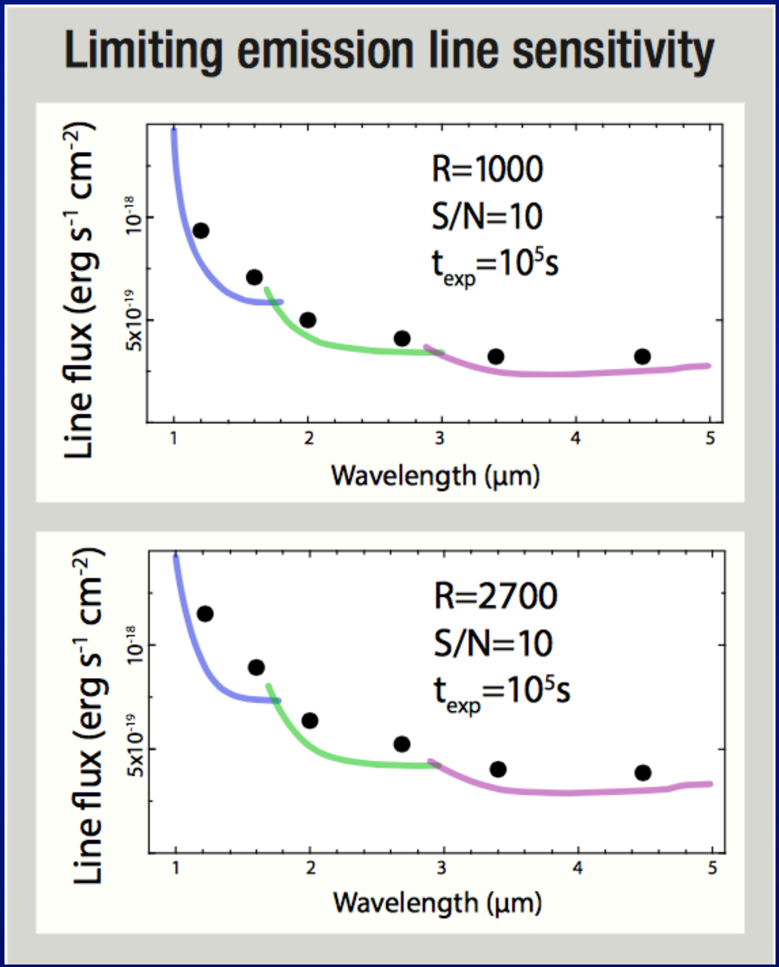


(Sanders et al., in prep)

- **MOSDEF contains additional [OIII]4363 detections, but some are missing key features in gaps in atmospheric transmission. Need to get past atmosphere.**

What now?: Direct Metallicities

JWST/NIRSpec



http://www.stsci.edu/jwst/instruments/nirspec/docarchive/NIRSpec-pocket-guide.pdf

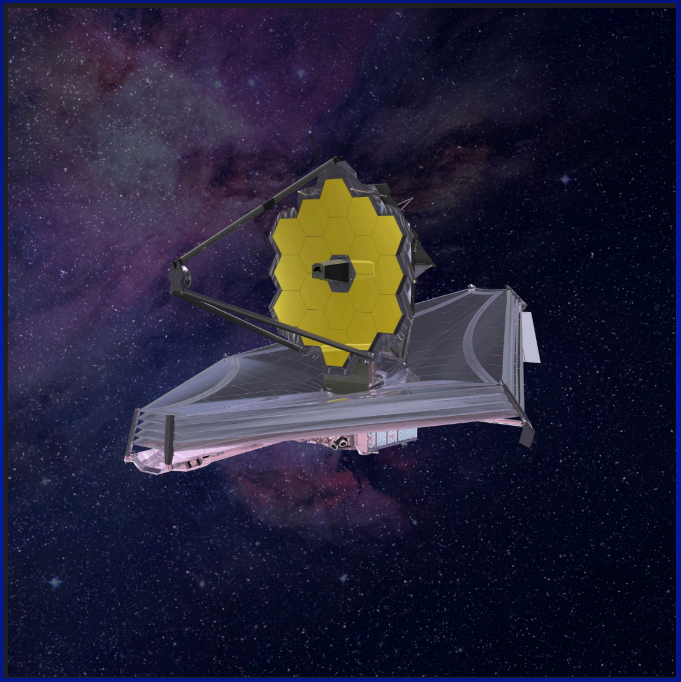
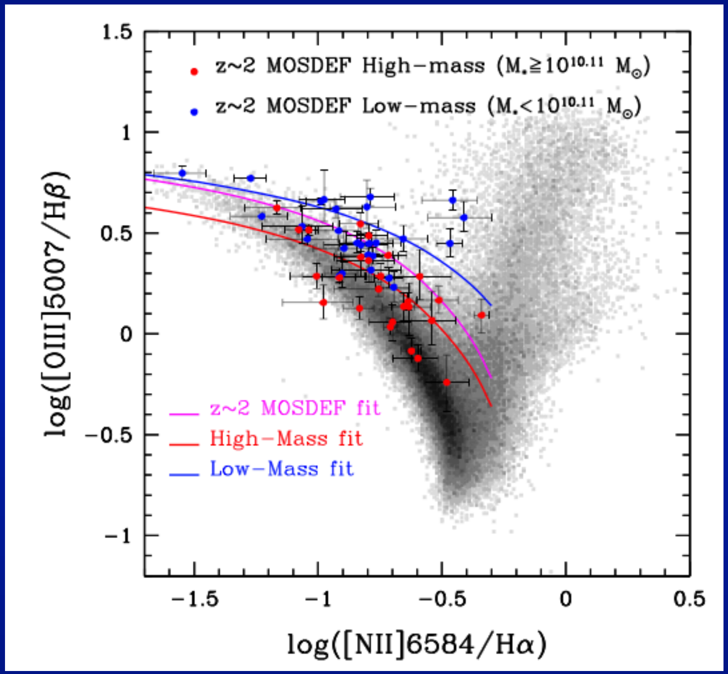


Image credit: NASA's JWST

- **The detection of [OIII]4363 and other weak auroral lines at z>2 will become possible with JWST/NIRSpec.**

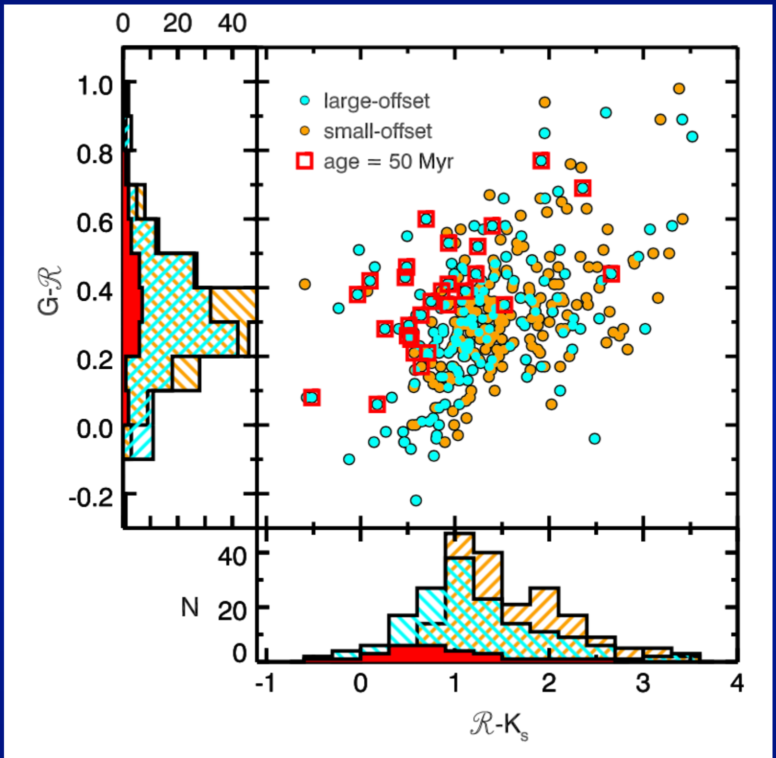
What now?: Sample Selection

BPT offset vs. mass



(Shapley et al. 2015)

BPT offset vs. SED shape

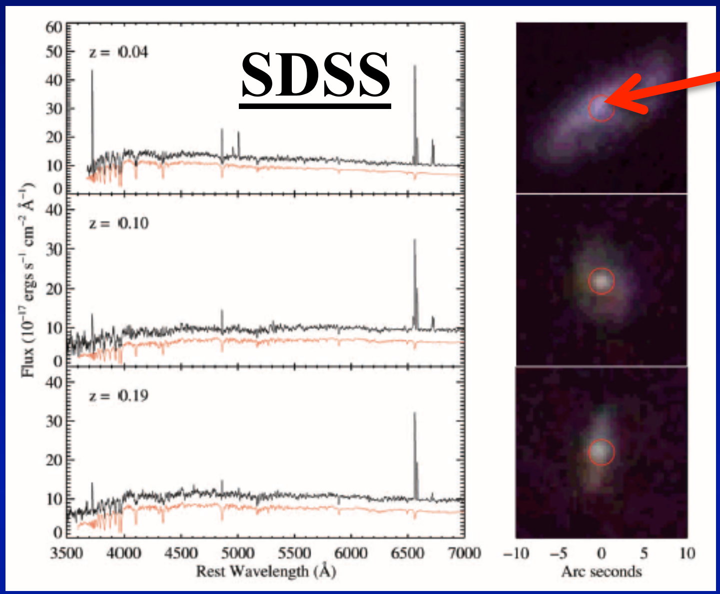


(Strom et al. 2017)

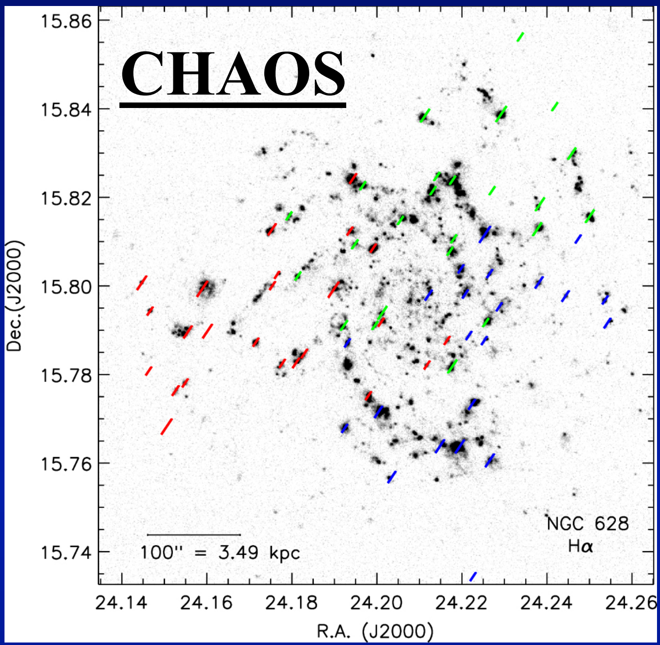
- **Since actual O3N2 and O3S2 BPT diagrams differ between KBSS and MOSDEF, and BPT offset depends on galaxy properties, need to understand different sample selection. (Joint KBSS+MOSDEF analysis).**

What now?: Spatial Resolution

(Tremonti et al. 2004)

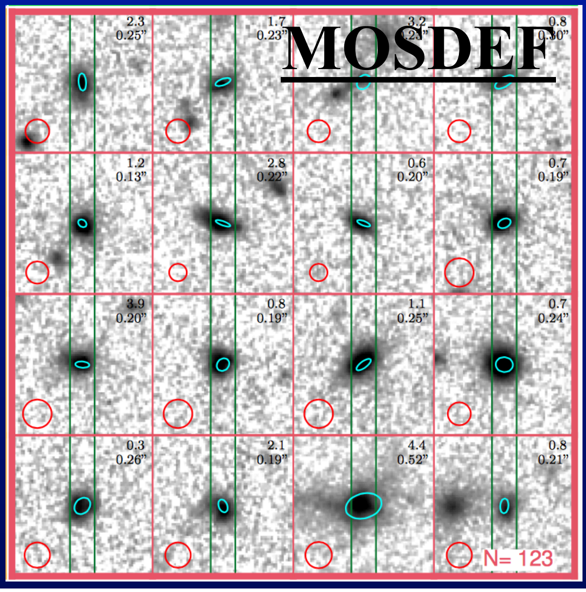


3" ~ 6 kpc at z=0.1



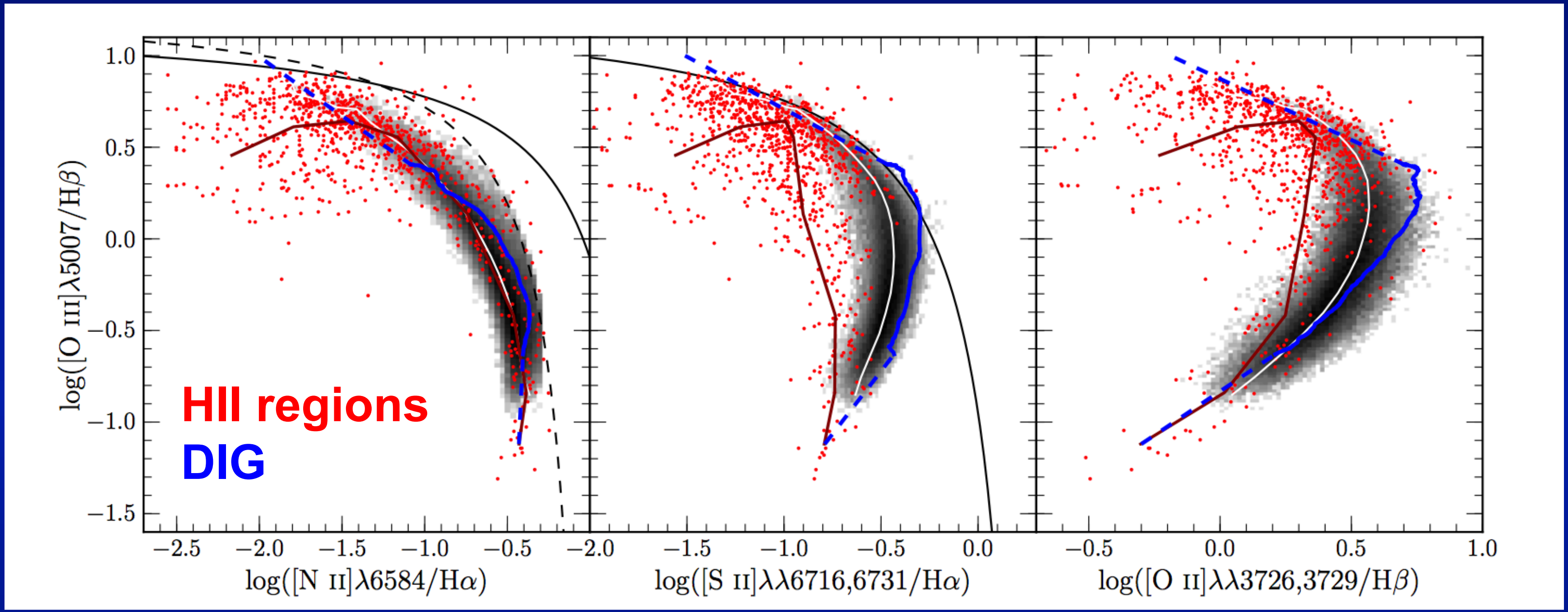
(Berg et al. 2015)

(Price et al. 2015)



- What do we miss by lacking spatial resolution?
  - Relative contributions of Diffuse Ionized Gas (DIG) and HII regions (excitation, density).
  - Contribution of AGN.
  - Gradients.
  - Clump properties.
- Keck/OSIRIS observations at ~1 kpc resolution. KLEVER survey (Curti talk).

What now?: Realistic Photoionization Models



(Sanders et al. 2017)

- Photoionization models used to infer metallicities from integrated galaxy spectra need to take into account distinct properties of HII regions and DIG, and flux-weighting effects of diverse HII regions (MAPPINGS, CLOUDY, Gutkin et al. 2016, Hirschmann et al. 2017, etc).
- At least at z~0, the properties inferred from an integrated galaxy spectrum will NOT represent the galaxy's median HII region properties.

Summary

• Large, statistical samples of emission lines measured during the peak epoch of star formation (z~1.5-3.5).

• At z~2, consensus that (1) ISM is typically higher density/pressure; (2) ionized gas excitation is significantly higher at fixed stellar mass.

• Much discussion of how z~2 galaxies populate the O3N2 BPT, O3S2 BPT, and the O32 vs. R23 emission-line diagrams, and the implications for inferring O/H and N/O, the nature of massive stars.

• In order to definitively understand the high-redshift emission-line properties, we must: (1) obtain independent “direct” O/H measures; (2) understand sample selection; (3) understand “archictecture” of high-z ISM (e.g., relative contributions of HII regions, DIG, other); (4) use realistic photoionization models taking into account (3).

• Much work to do, but next steps are clear, using JWST and other facilities.