Surveying the star-forming galaxy population at z ~ 1.6 in COSMOS with Subaru/FMOS

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What are the drivers behind the formation and evolution of galaxies?

(in the context of star formation)

Internal

Dynamical instabilities

Supernova

AGN

stellar winds

gas exhaustion

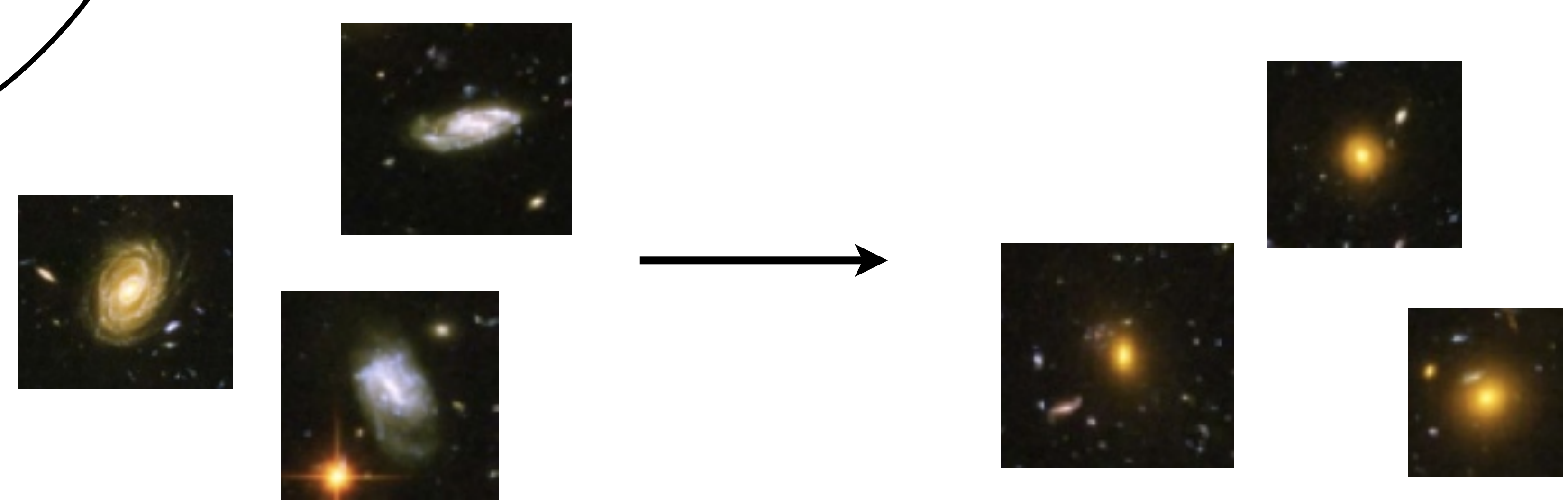
External

tidal interactions

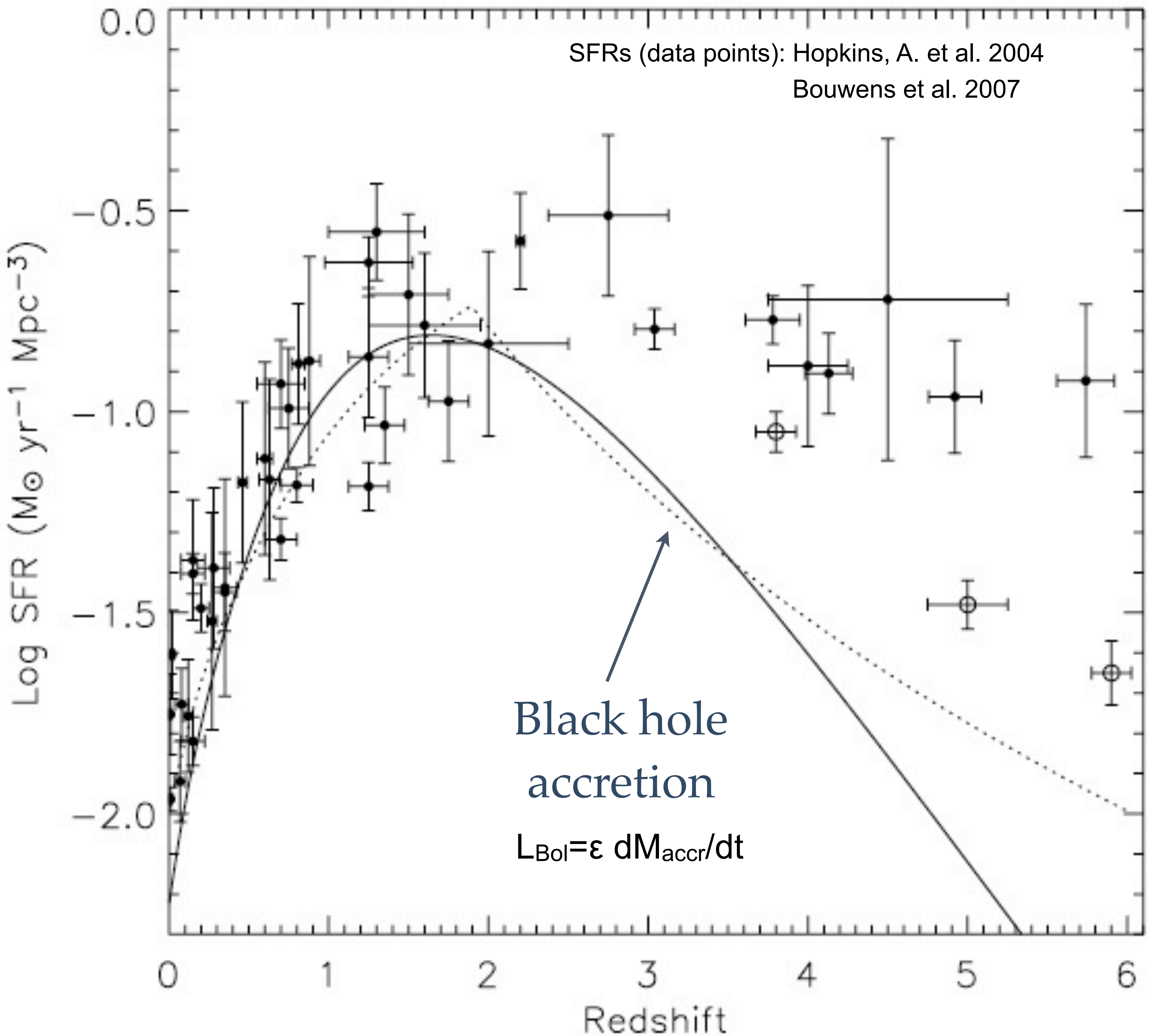
dark matter halo

galaxy mergers

large-scale gas accretion

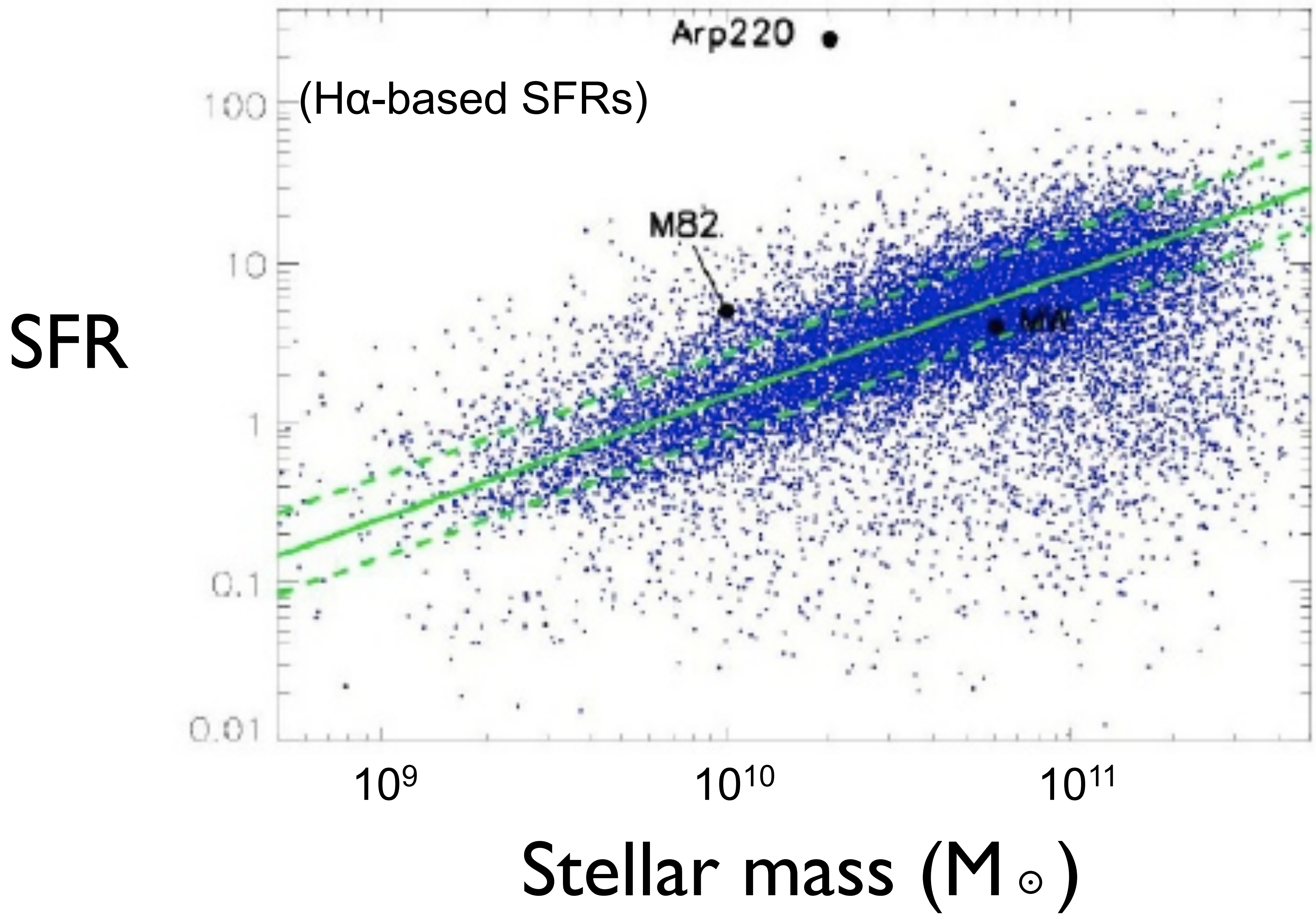


Star formation/BH accretion history of the Universe



JDS et al. 2008

Main sequence of star-forming galaxies

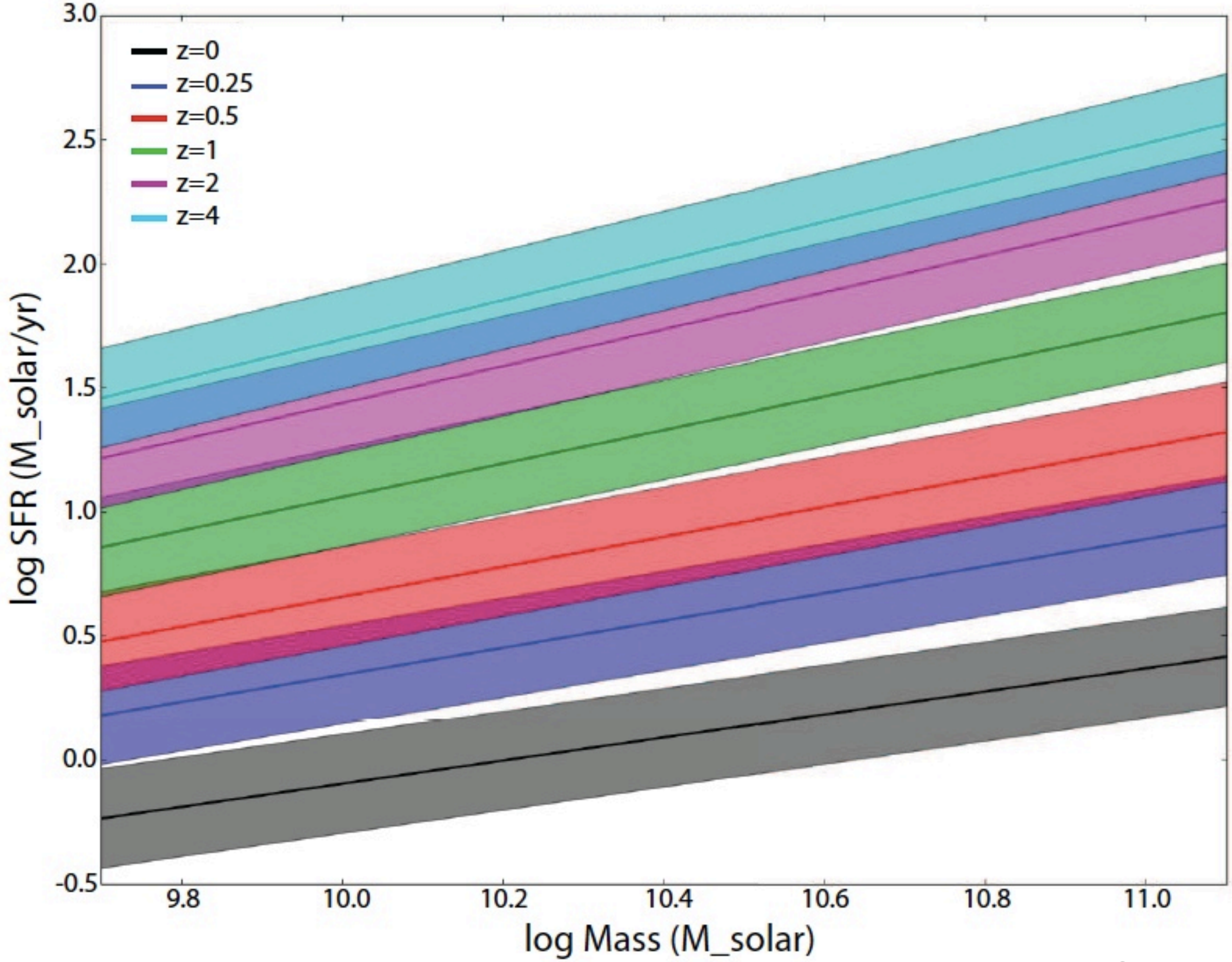


SDSS
(z < 0.3)

Elbaz et al. 2007

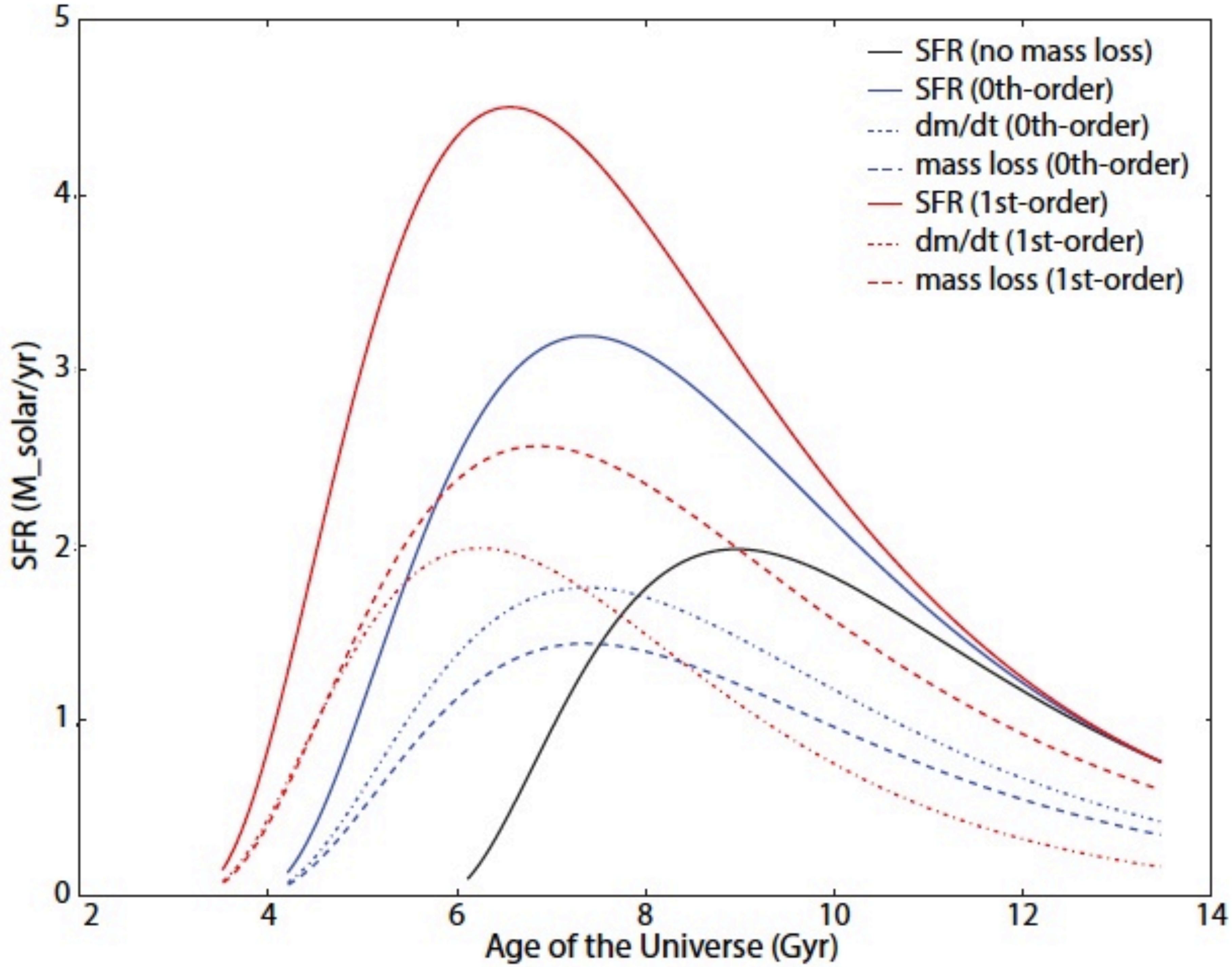
see Noeske et al. 2007; Pannella et al. 2009; Karim et al. 2011; Whitaker et al. 2012
+ many others

Main sequence of star-forming galaxies



Speagle, Steinhardt,
Capak and JDS 2014

Star-formation histories



Speagle, Steinhardt,
Capak and JDS 2014

What are the observables?

Internal

Dynamical instabilities

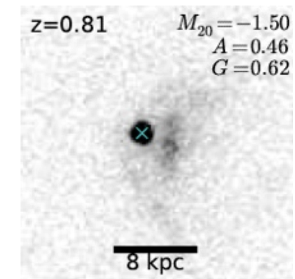
Supernova

AGN

stellar winds

gas exhaustion

space-based imaging



galaxy associations/ over-densities

dark matter halo

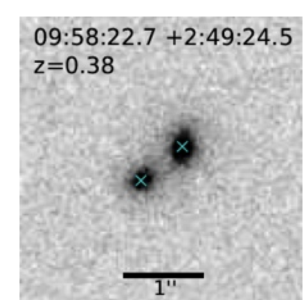
tidal interactions

External

galaxy mergers

large-scale gas accretion

close pairs from spec-z



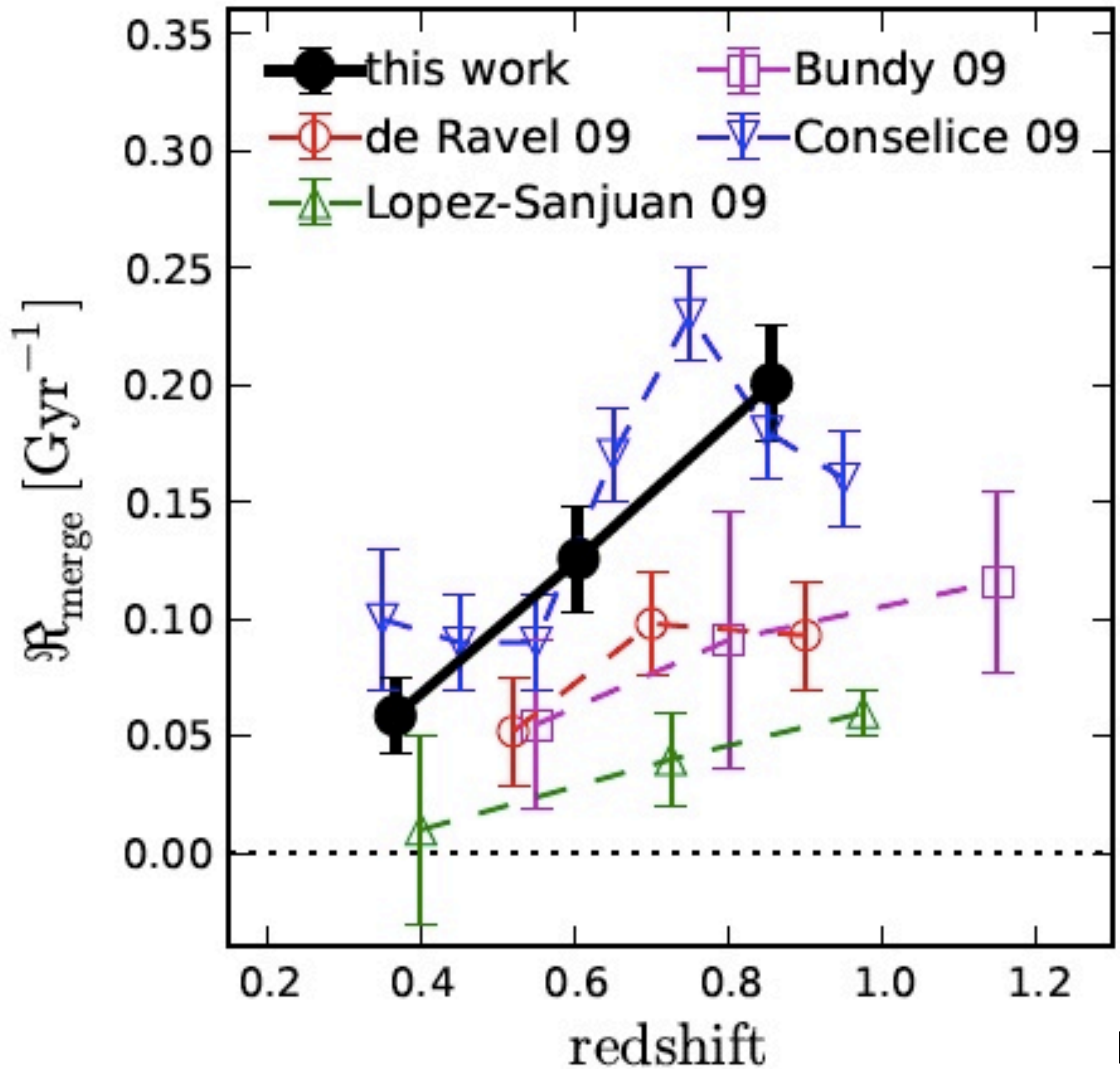
double nuclei

absorption systems

Distinguish various scenarios by accurately measuring galaxy properties:

Star formation rates, chemical abundances, ionization state, dust content

Galaxy mergers: not the dominant process



Lackner, JDS et al. 2014

Rodighiero et al. 2012; Sargent et al. 2013; Tasca et al. 2014

Spectroscopic redshift surveys

Rest-frame optical (emission-line) diagnostics:

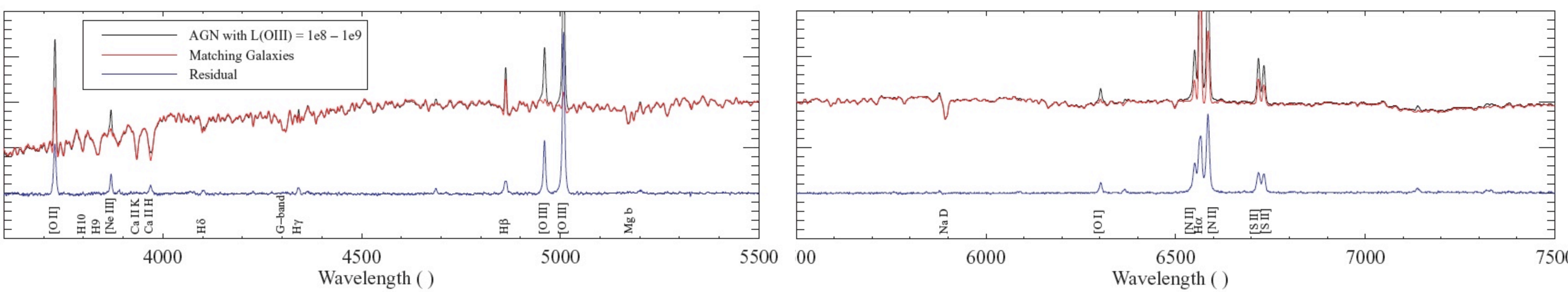
- Star formation rate (Hα) — Kennicutt 1998

- Metallicity: [NII]/Hα (N2), [OIII]/Hβ/[NII]/Hα (O3N2) — Tremonti et al. 2004

- Ionization state: [NII]/Hα vs. [OIII]/Hβ (BPT diagram) — Kewley et al. 2003

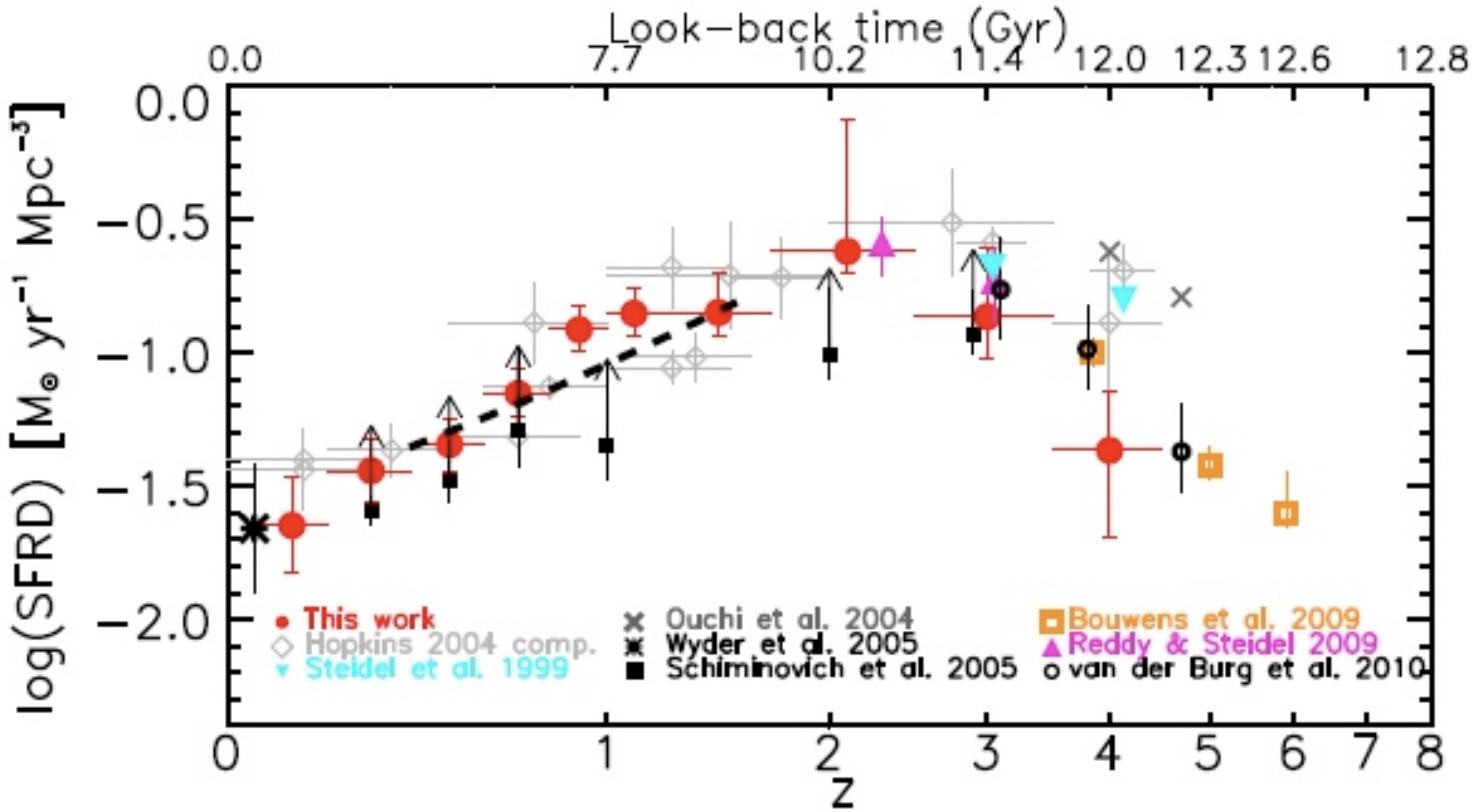
- Dust/extinction: Hβ/Hα (Balmer decrement)

- Presence of AGNs



Kauffmann et al. 2003

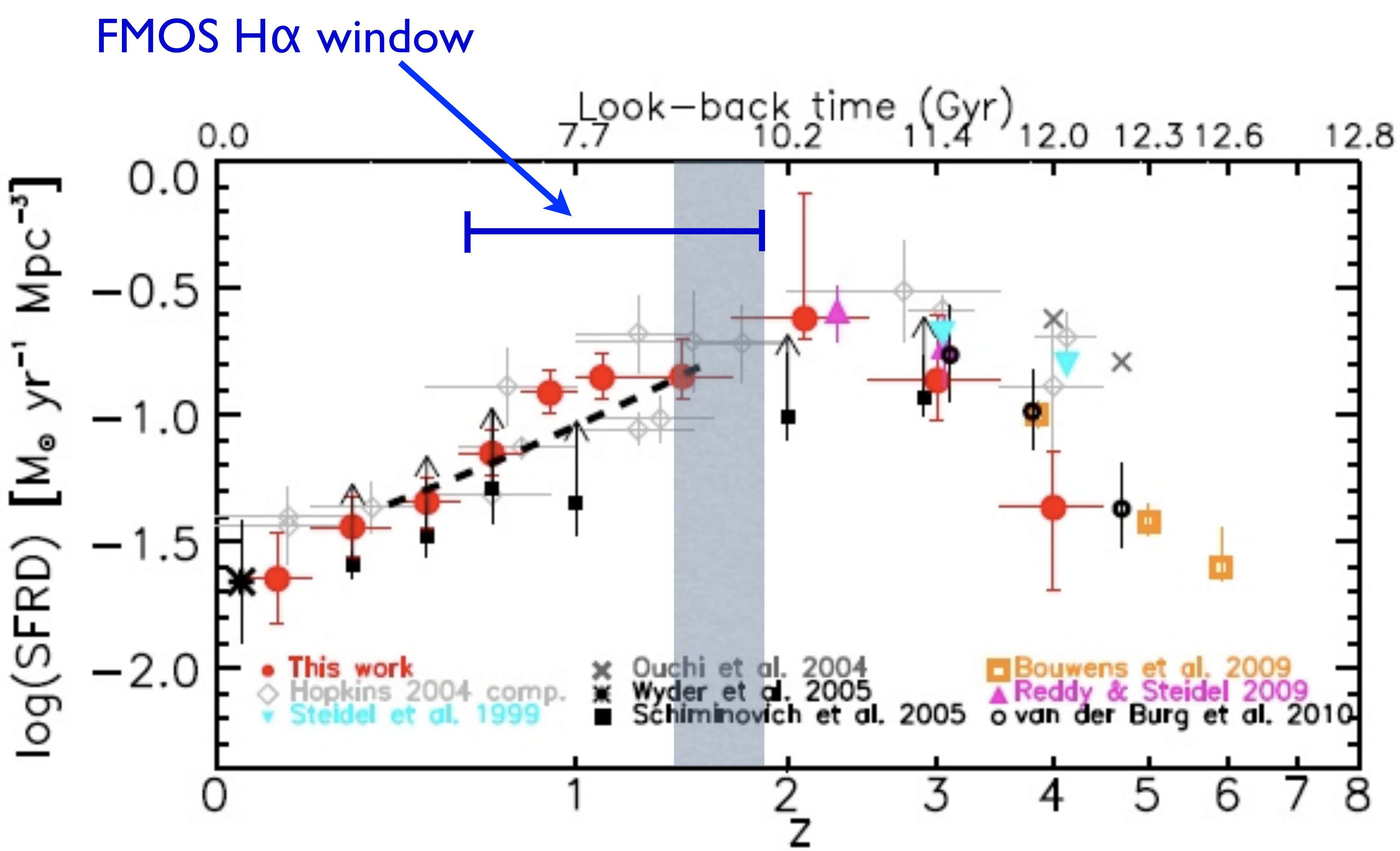
Global evolution of the galaxy population



Cucciati et al. 2011

Detailed studies of galaxies at peak (z ~ 2) is imperative

Global evolution of the galaxy population



Cucciati et al. 2011

Detailed studies of galaxies at peak (z ~ 2) is imperative

Fundamental questions in galaxy evolution at z ~ 1.6

✳ How does the sfr - mass relation evolve with redshift?

✳ Is pristine gas accreting onto galaxies at high-z?

Test whether a relation between
<u>metallicity-mass-(SFR)</u> exists (Mannucci et al. 2010)

✳ Does the ionization conditions evolve with redshift?

(Kewley et al. 2013a,b)

✳ Is the sfr - mass relation sensitive to local overdensity?

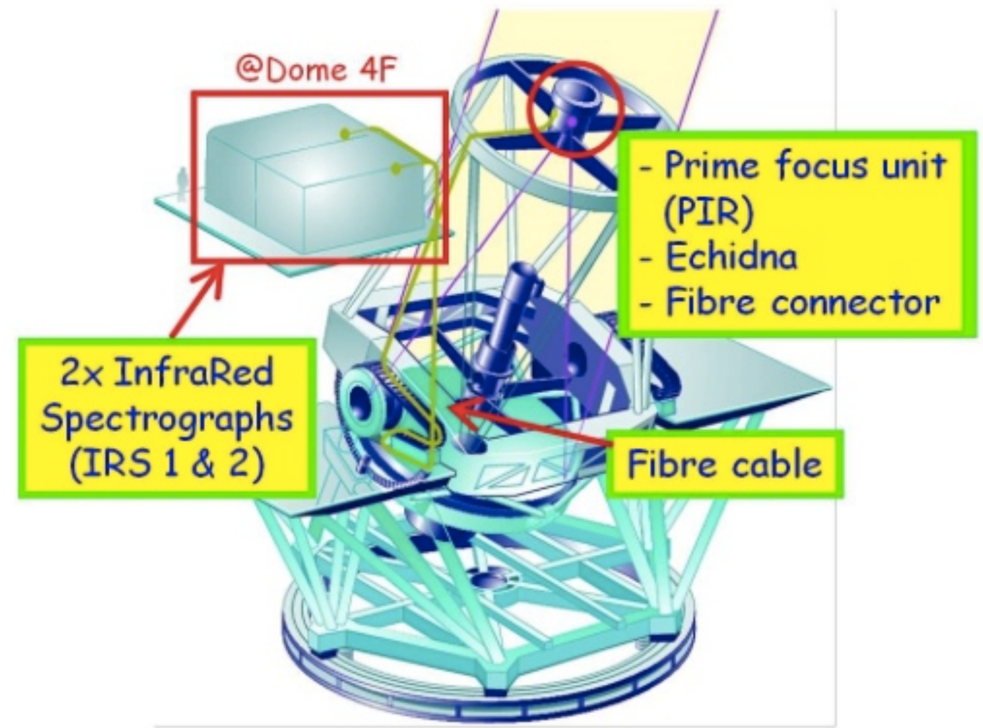
✳ What is the role of galaxy mergers and AGN?

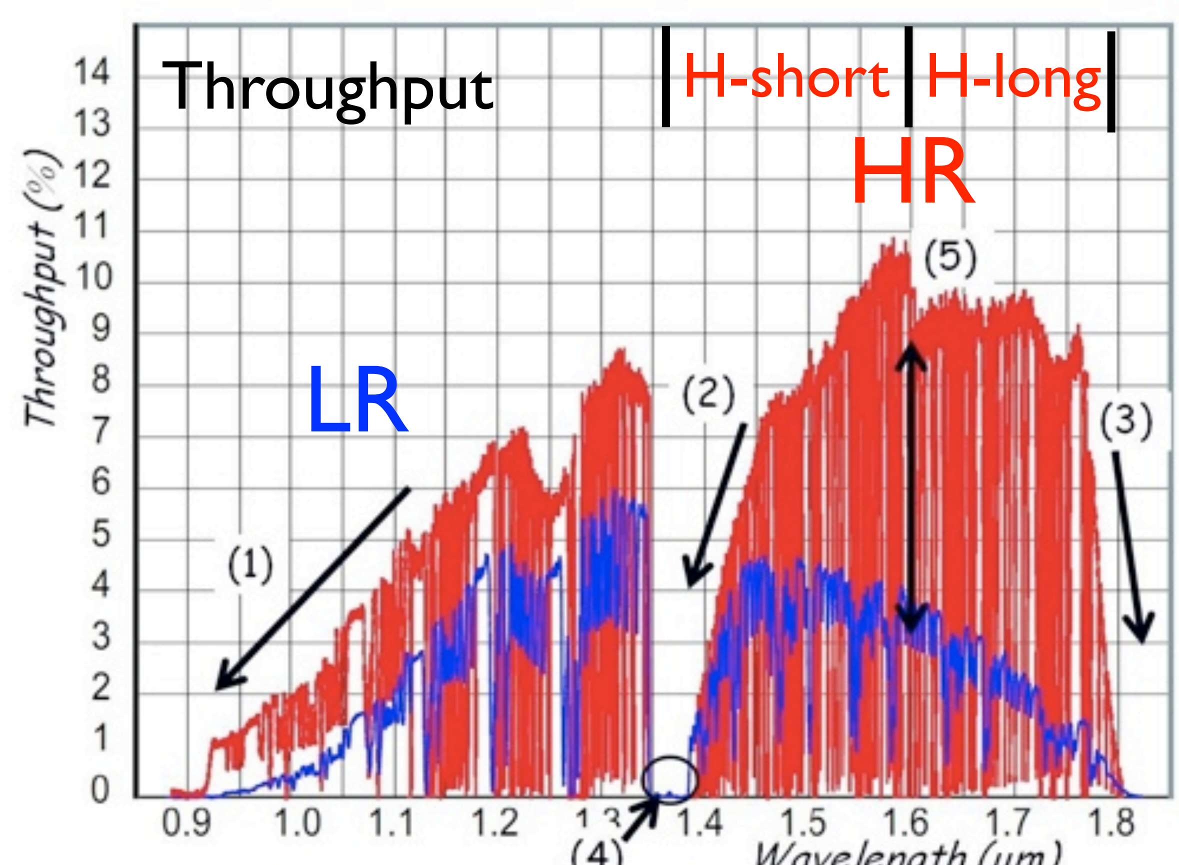
Subaru - Fiber Multi-object Spectrograph (FMOS)

- Built by Kyoto University, UK & NAOJ (PI: T. Maihara)
- commissioned in 2007

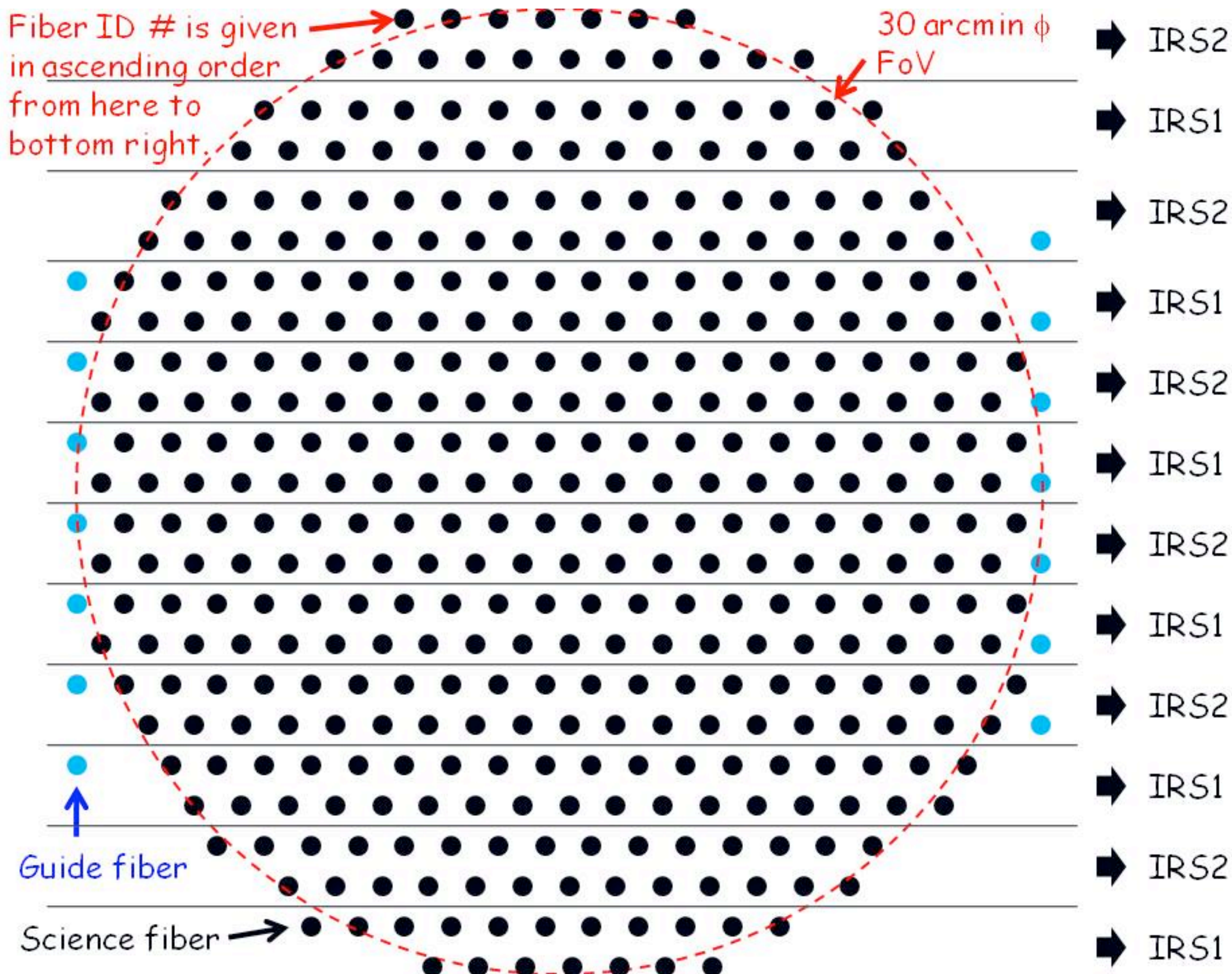
- 0.9 - 1.8 μm
- 400 fibers; 1.2″ diameter
- 30′ diameter FOV
- Echidna fiber system
- Airglow/OH suppression system (Iwamuro et al. 2006)
- Low (R=500) and high (R=2200) resolution
- 2048x2048 HgCdTe Hawaii-2 detectors
- Cross-beam switching (~200 fiber pairs can be assigned)
- two spectrographs (irs1 and irs2)

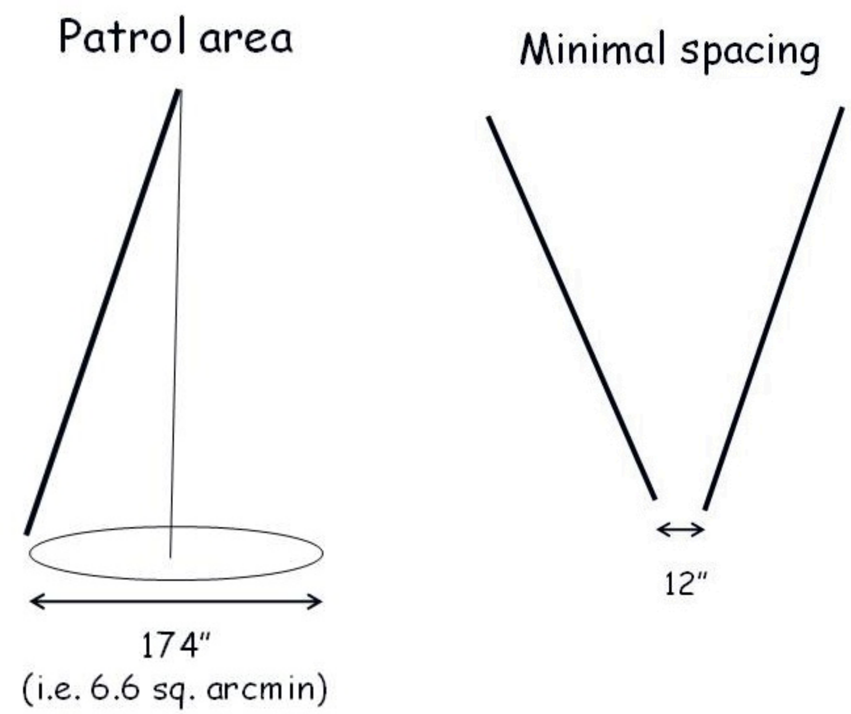
- Initial results (Yabe et al. 2012; Roseboom et al. 2012; Matsuoka, JDS et al. 2013)

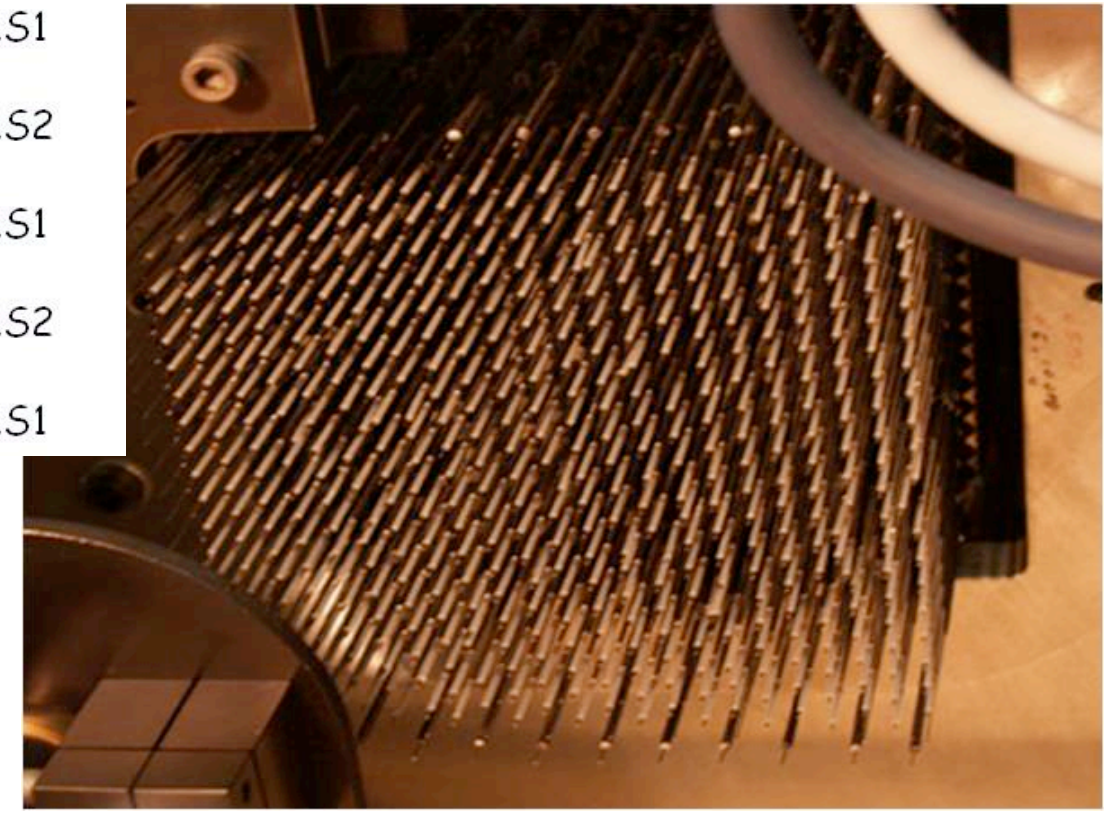




Subaru/FMOS







Kimura et al. 2012

A Subaru/FMOS NIR survey of SF galaxies at z ~ 1.6

- Emission-line survey
  - Intensive Subaru program (PI JDS)
  - 14 nights + 8 (IfA)
  - H-long grating: Hα, [NII] and [SII]

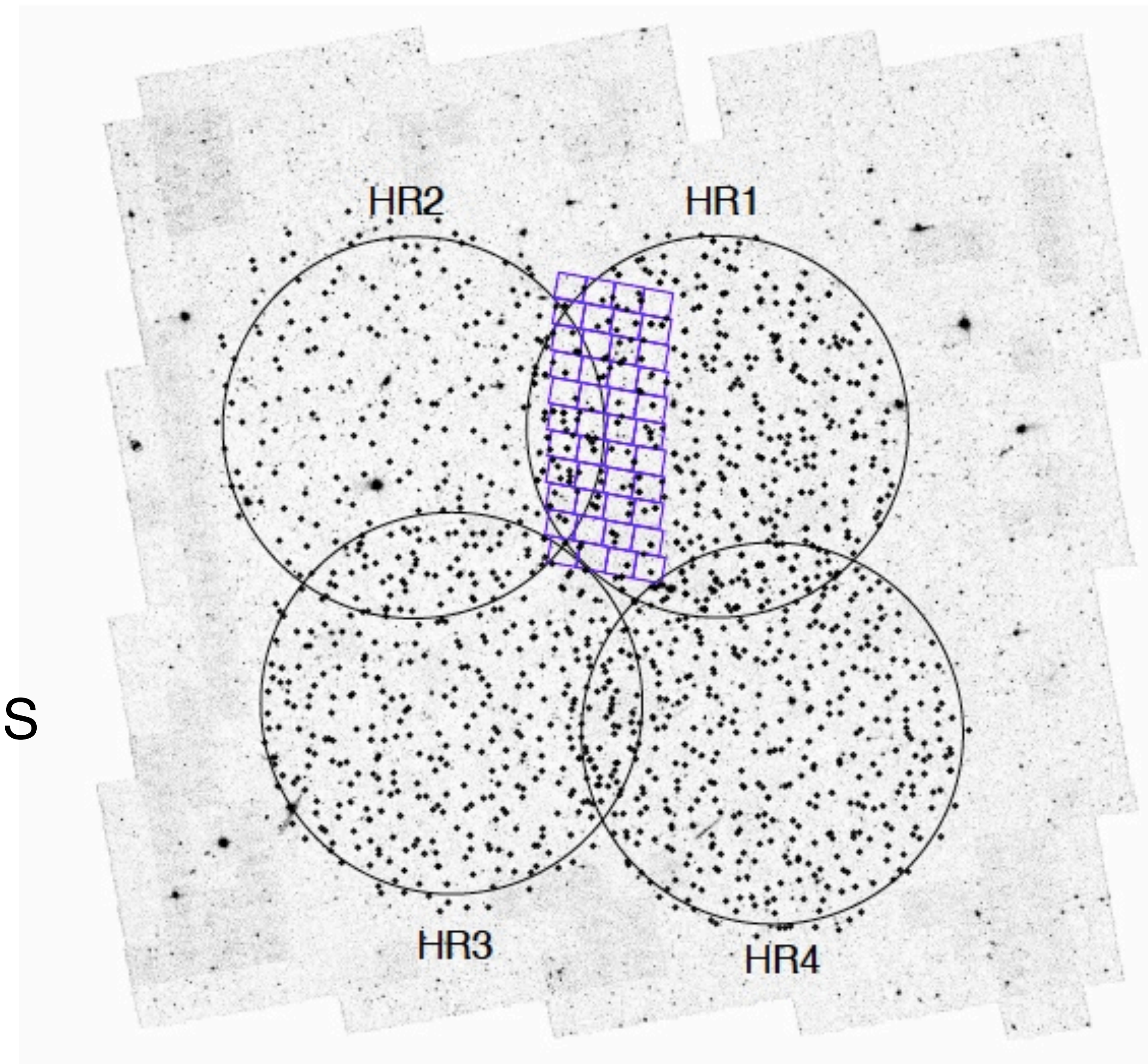
- Followup J-long observations
  - UH-IfA (PI Dave Sanders)
  - J-long grating (Hβ, [OIII]5007)

- SF galaxies in central sq. degree of COSMOS
  - $M_* > 10^{10}\ M_\odot$; $f_{H\alpha} > 4 \times 10^{-17}$ erg cm^{-2} s^{-1}

- Prioritize Herschel/PACS detections

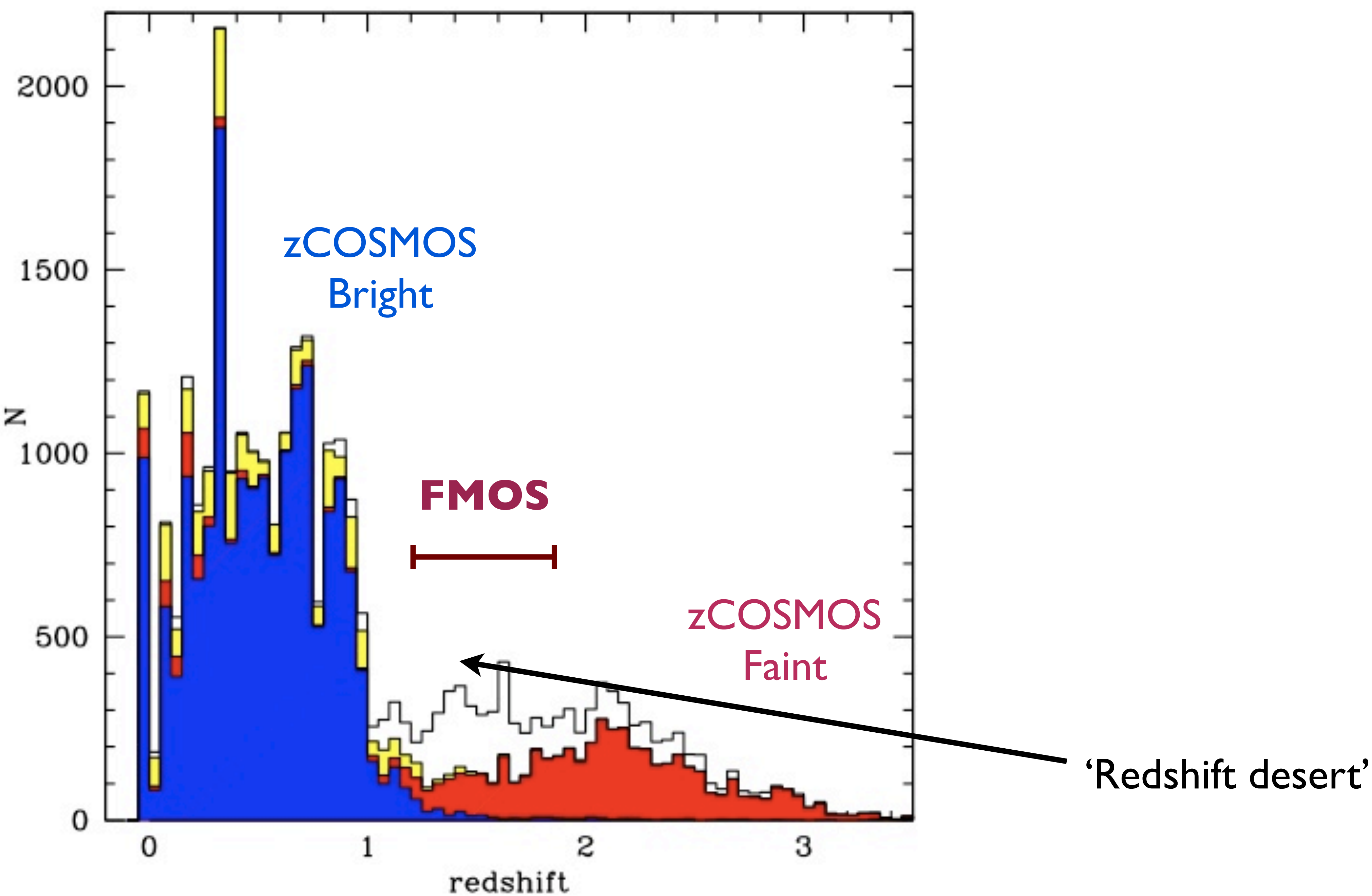
- ~850 redshifts from ~2200 spectra

COSMOS



JDS et al. 2014, arXiv:1409.0447

Spectroscopic surveys in COSMOS

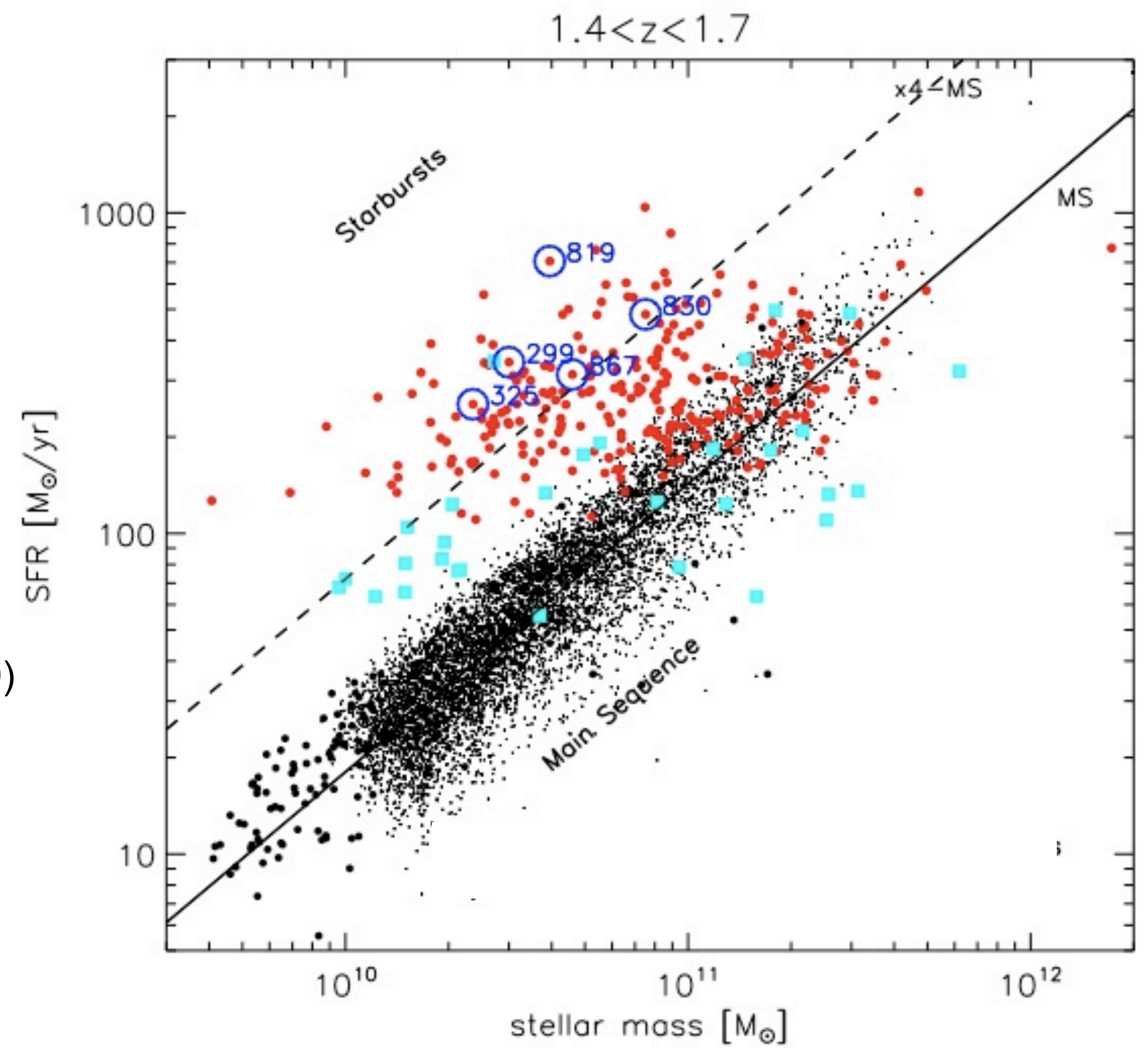


- Bright sample drops off drastically at z > 1
- Deep sample has a ~20% success rate at z~1.5

Target selection

- star-forming galaxies
  - K-selected (K < 23.5)
  - $M_{*} > 10^{10}\ M_{\odot}$
  - sBzK
  - along the star-forming main sequence
  - $f_{H\alpha} > 4 \times 10^{-17}$ erg cm^{-2} s^{-1}
    - SFR: B-band
    - E(B-V): B-z color
    - $E(B-V)^{neb} = E(B-V)^{stellar}/0.44$ (Calzetti et al. 2000)

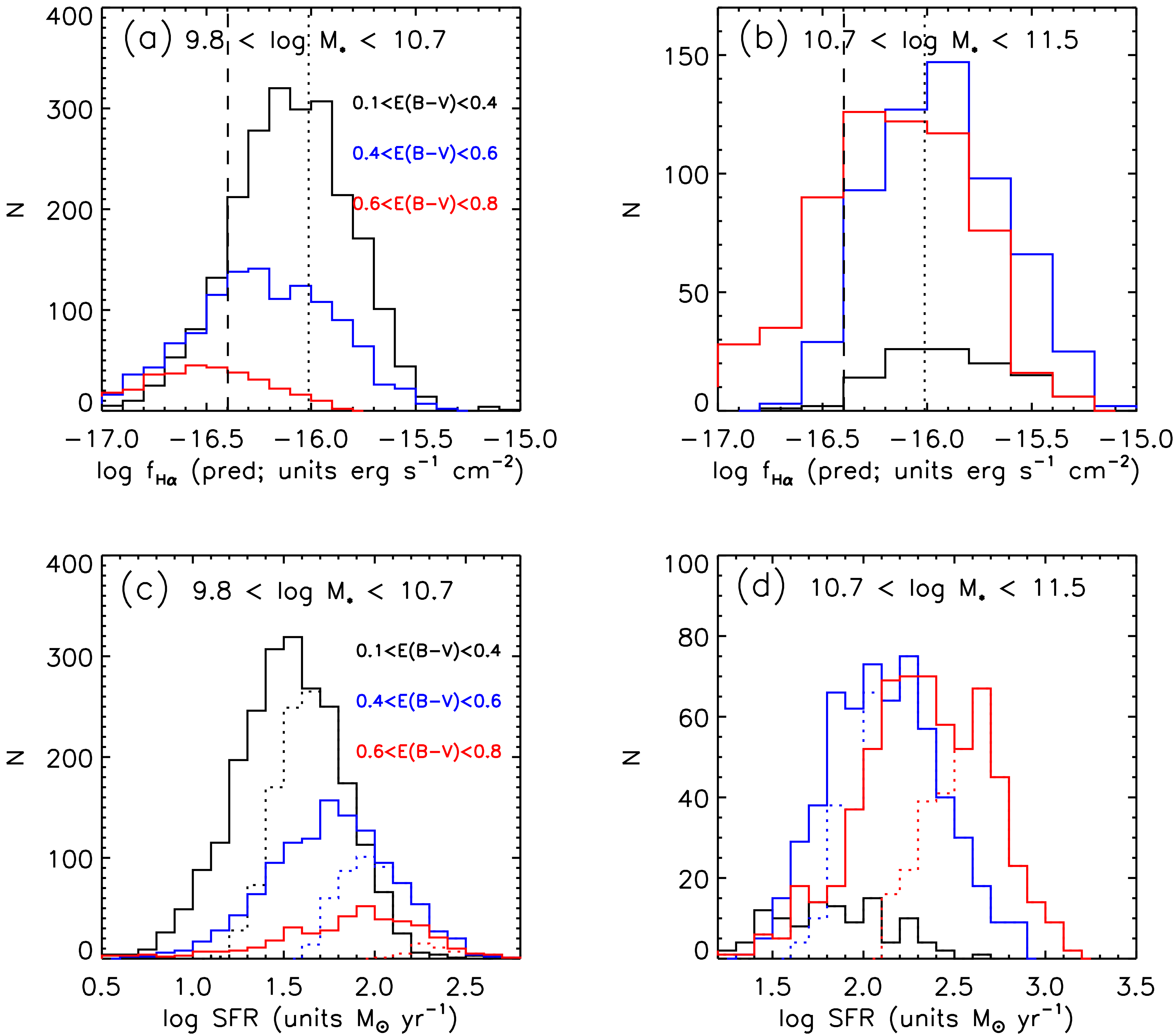
- Herschel/PACs sources
  - highly obscured SF galaxies
  - above or on M-S
  - near bright stars for future IFU/AO observations



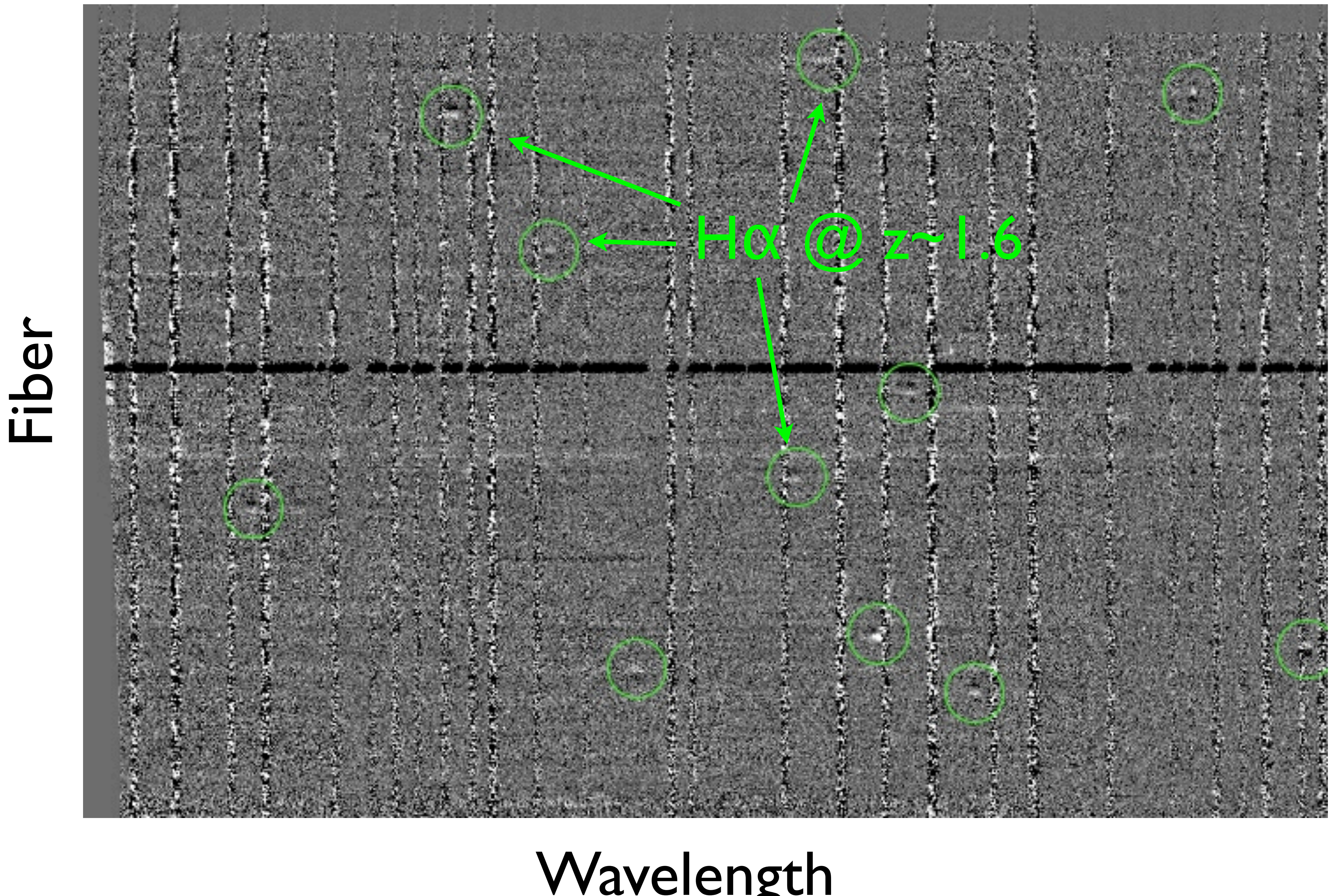
Rodighiero et al. 2010

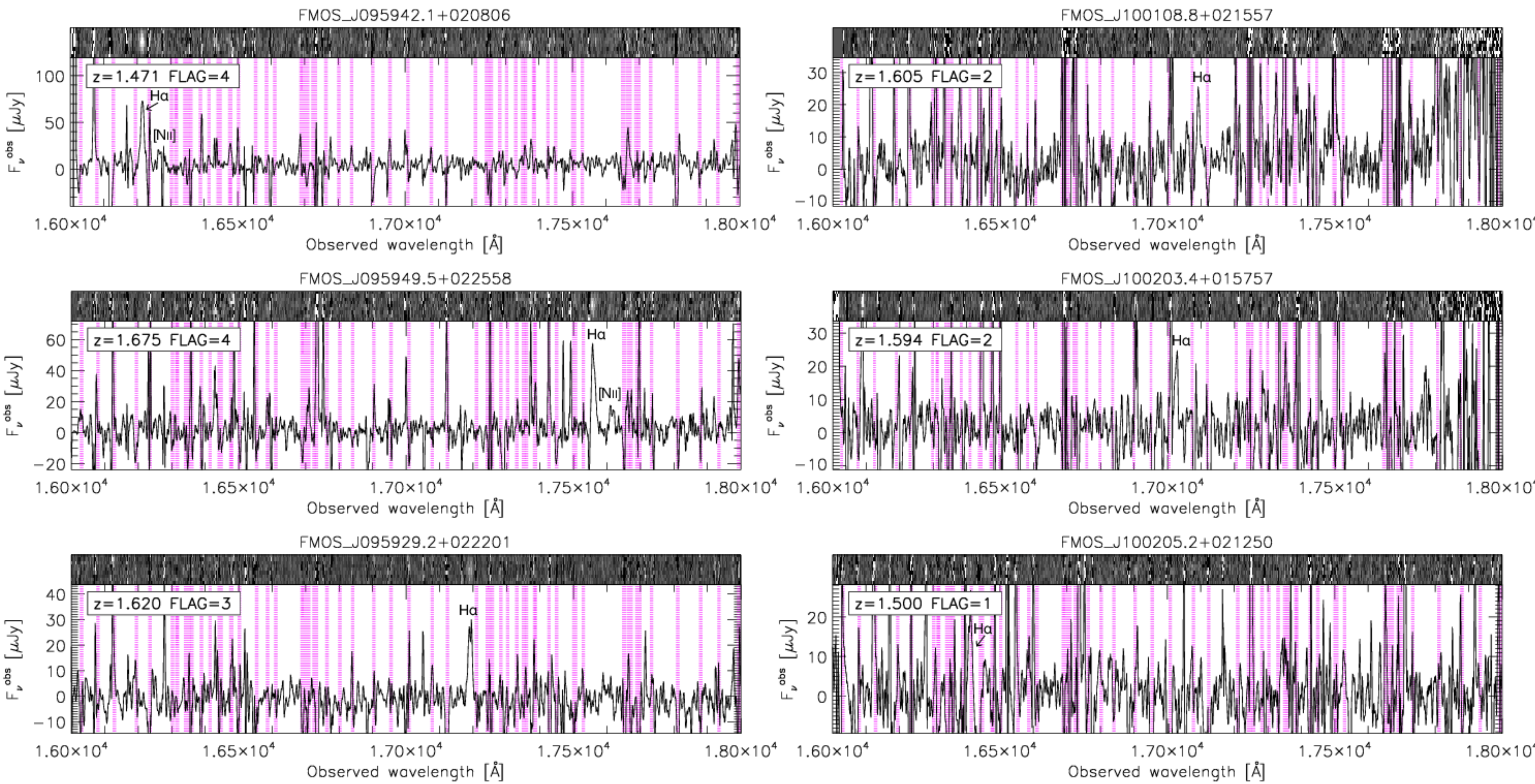
Filler targets: AGNs, low-mass galaxies

Sample biases

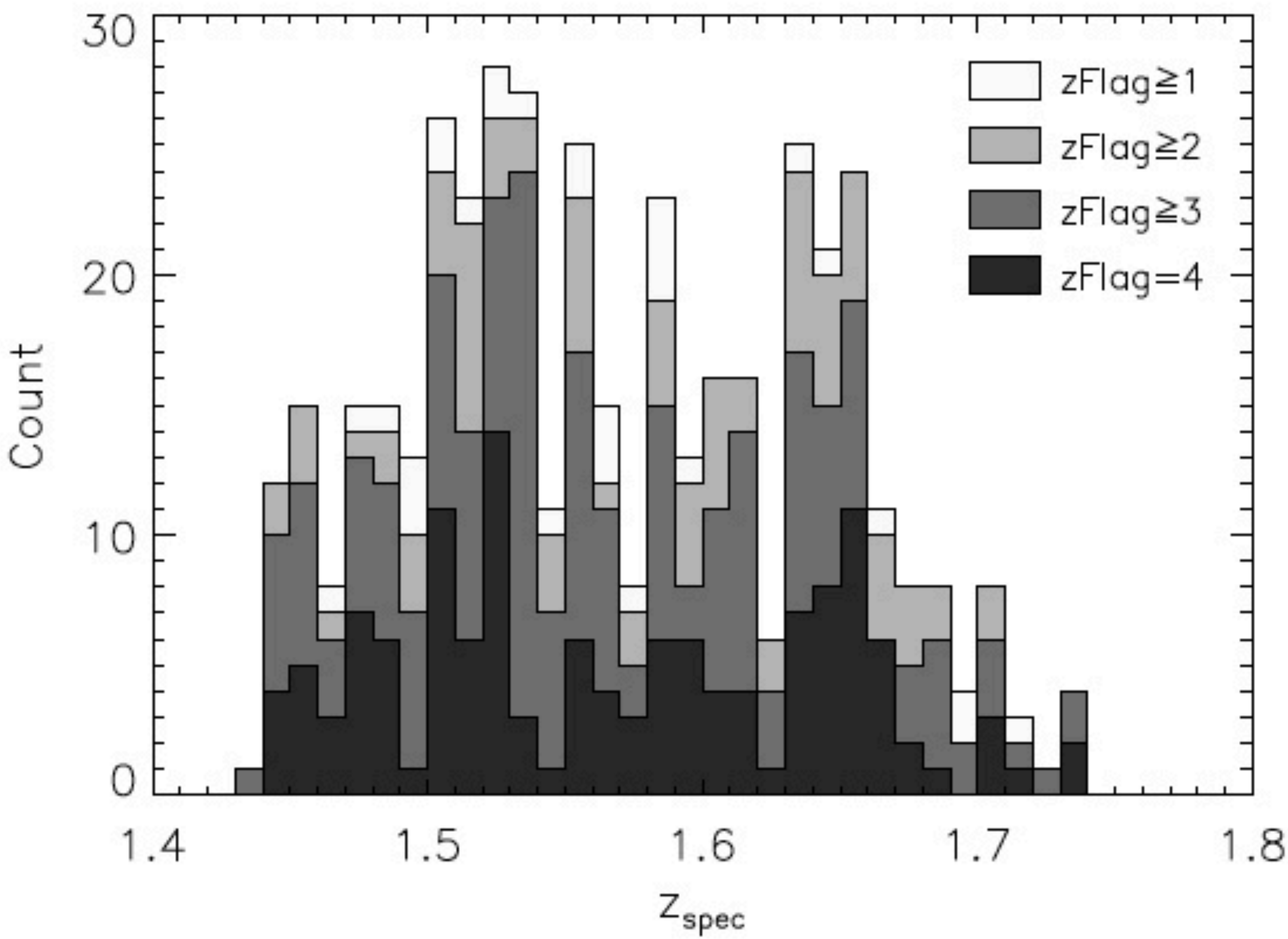


Pilot study: Results

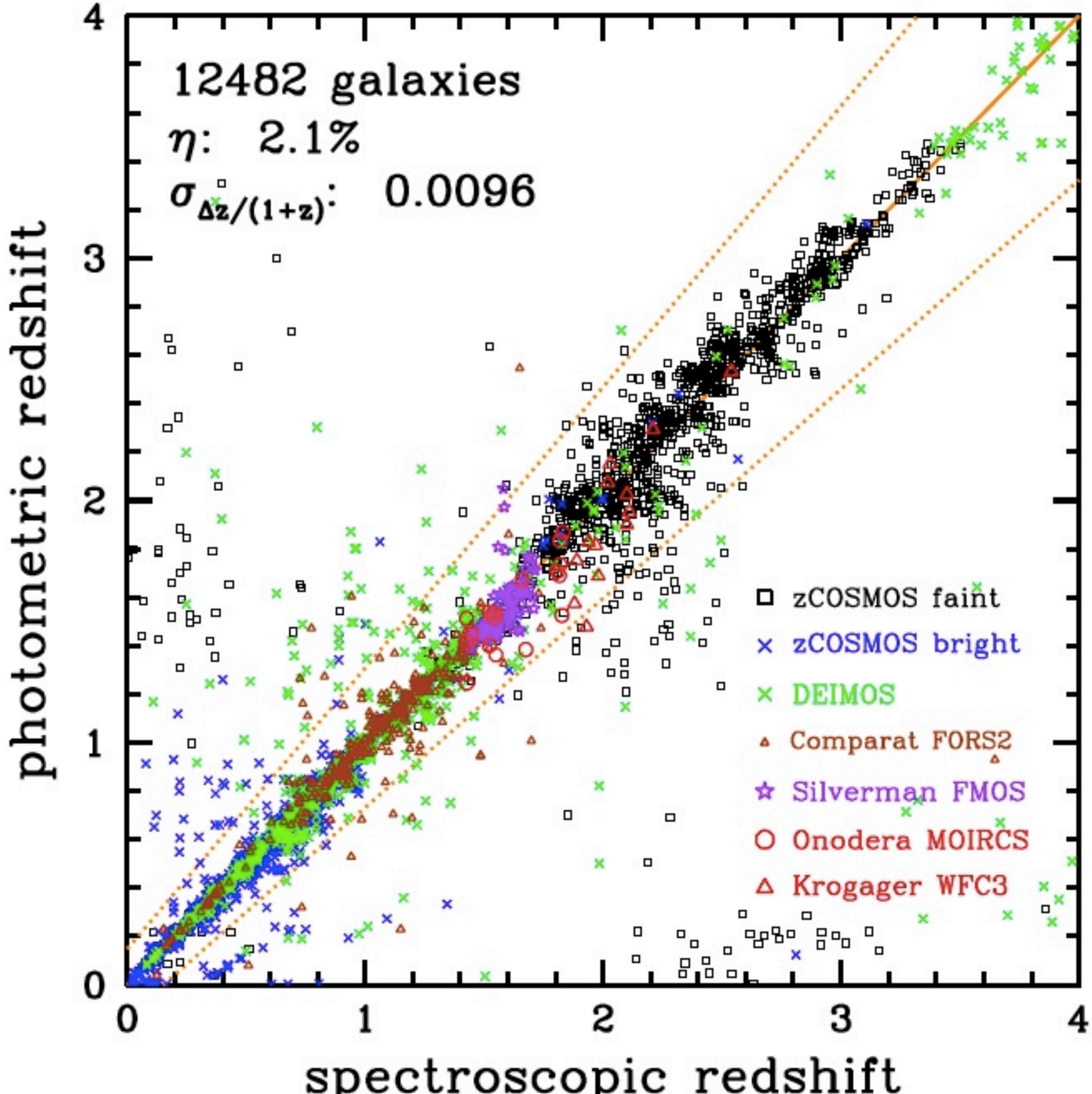




FMOS_J095942.1+020806
z=1.471 FLAG=4
Hα
[NII]
FMOS_J100108.8+021557
z=1.605 FLAG=2
Hα
FMOS_J095949.5+022558
z=1.675 FLAG=4
Hα
[NII]
FMOS_J100203.4+015757
z=1.594 FLAG=2
Hα
FMOS_J095929.2+022201
z=1.620 FLAG=3
Hα
FMOS_J100205.2+021250
z=1.500 FLAG=1
Hα
F_ν^obs [μJy]
Observed wavelength [Å]
1.60×10^4
1.65×10^4
1.70×10^4
1.75×10^4
1.80×10^4



zFlag≧1
zFlag≧2
zFlag≧3
zFlag=4
Count
30
20
10
0
1.4
1.5
1.6
1.7
1.8
z_{spec}



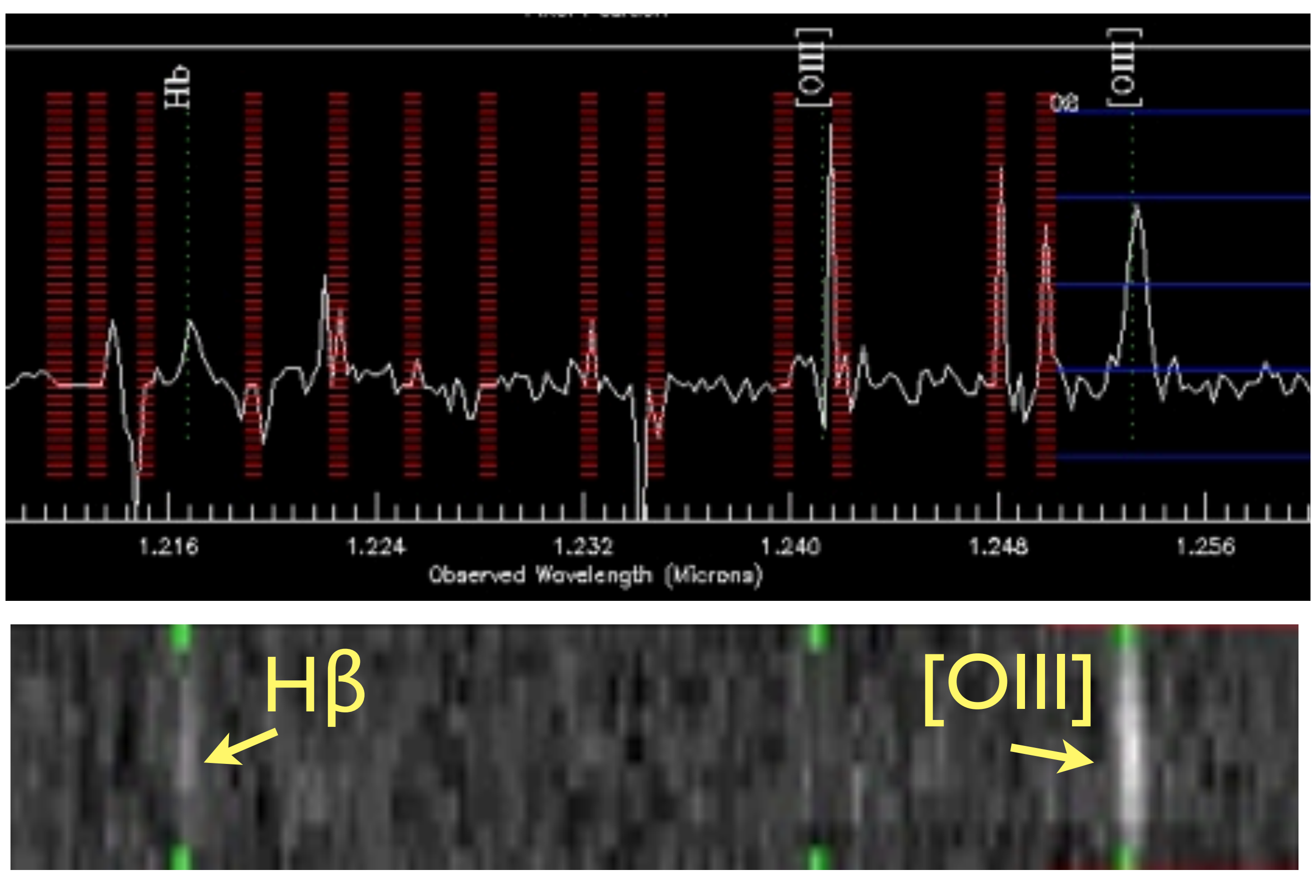
Ilbert et al. 2013

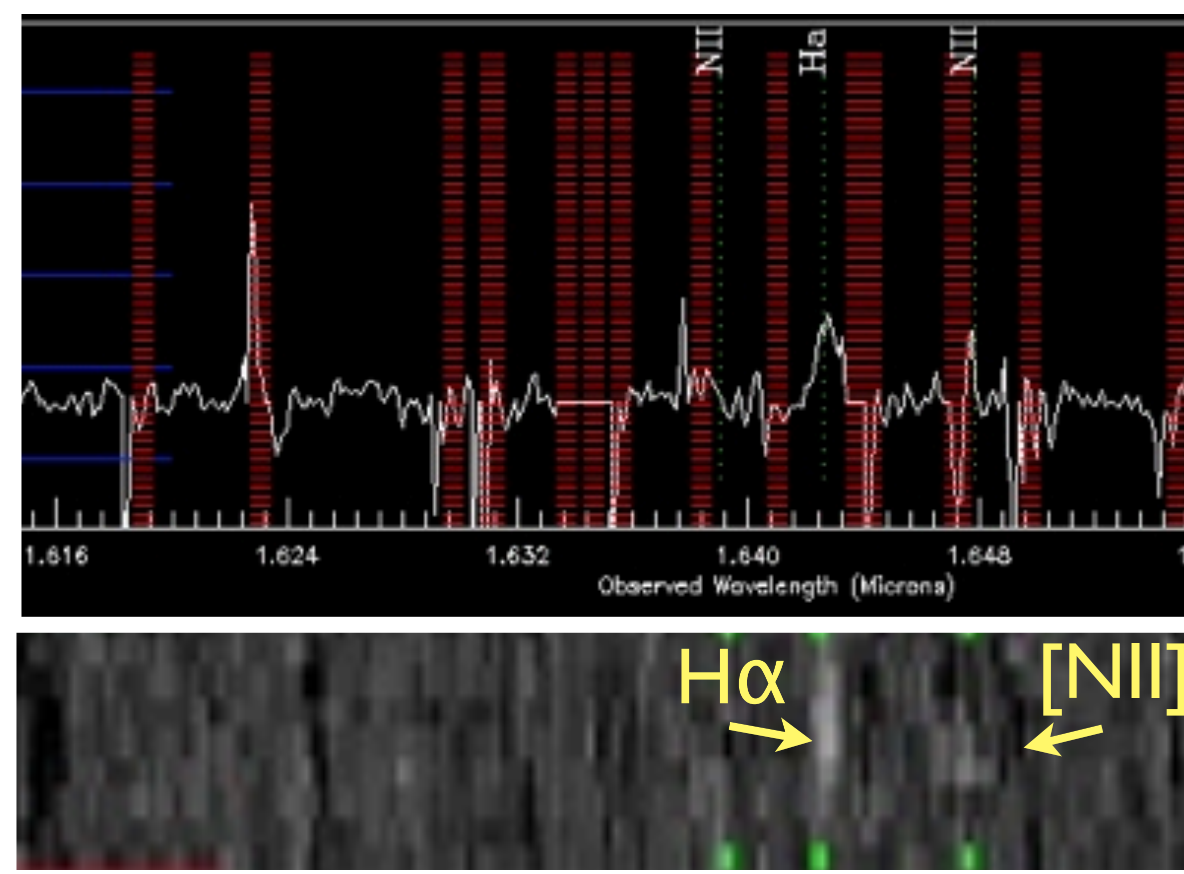
FMOS/J-long observations

University of Hawaii (PI Dave Sanders, Jeyhan Kartaltepe-NOAO)

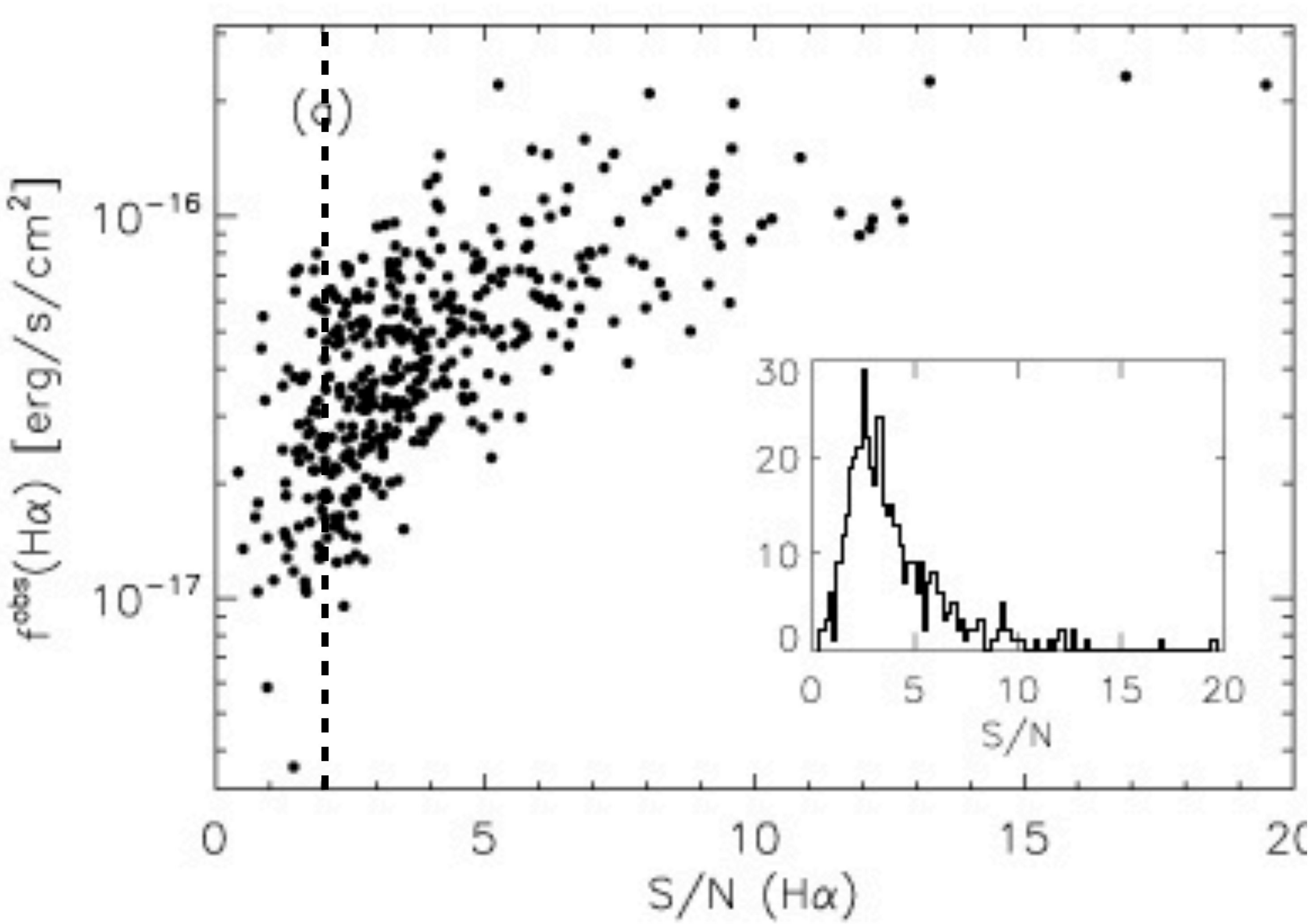
- Hα survey at 0.7 < z < 1.05 (Spitzer IR bright sources, New Chandra sources)
- Extinction corrections: Balmer decrement (single objects + stacked spectra)
- Check redshifts measured from H-long data (confirms wavelength solution)
- AGN identification (BPT diagram)
- Improvement of metallicity measurements

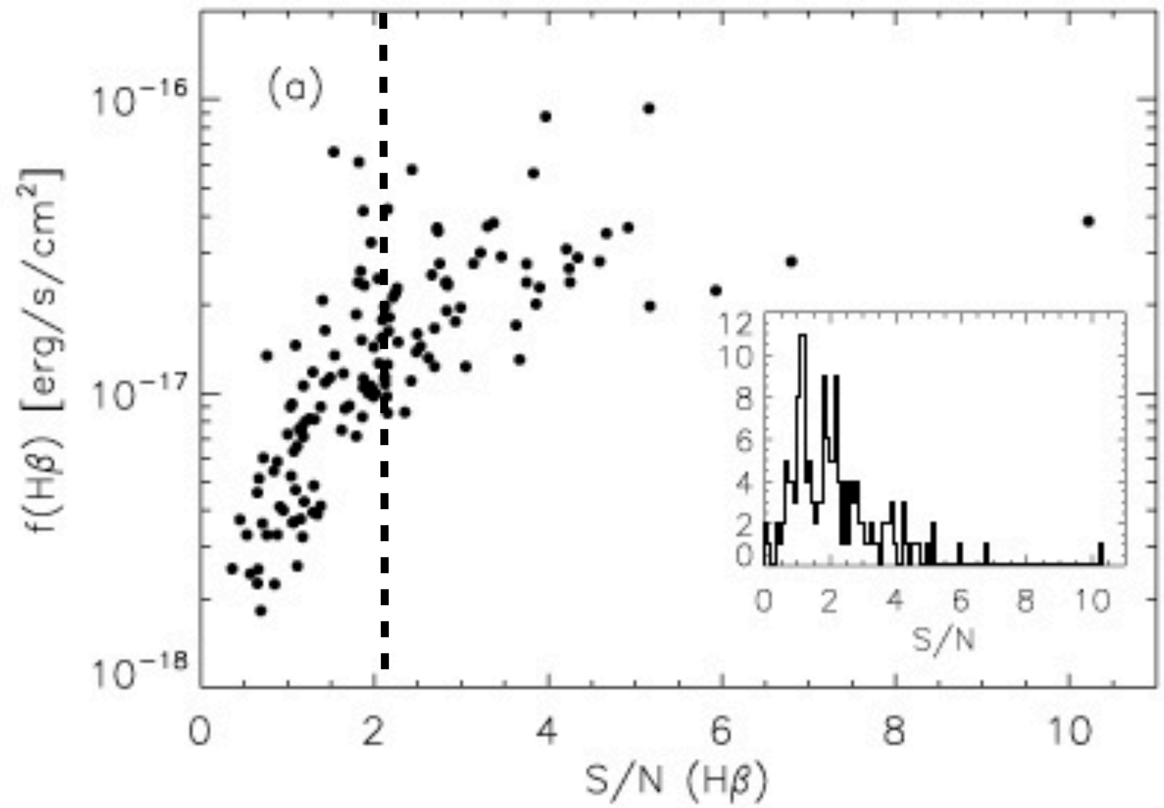
J-long sBzK @ zspec=1.5029 H-long

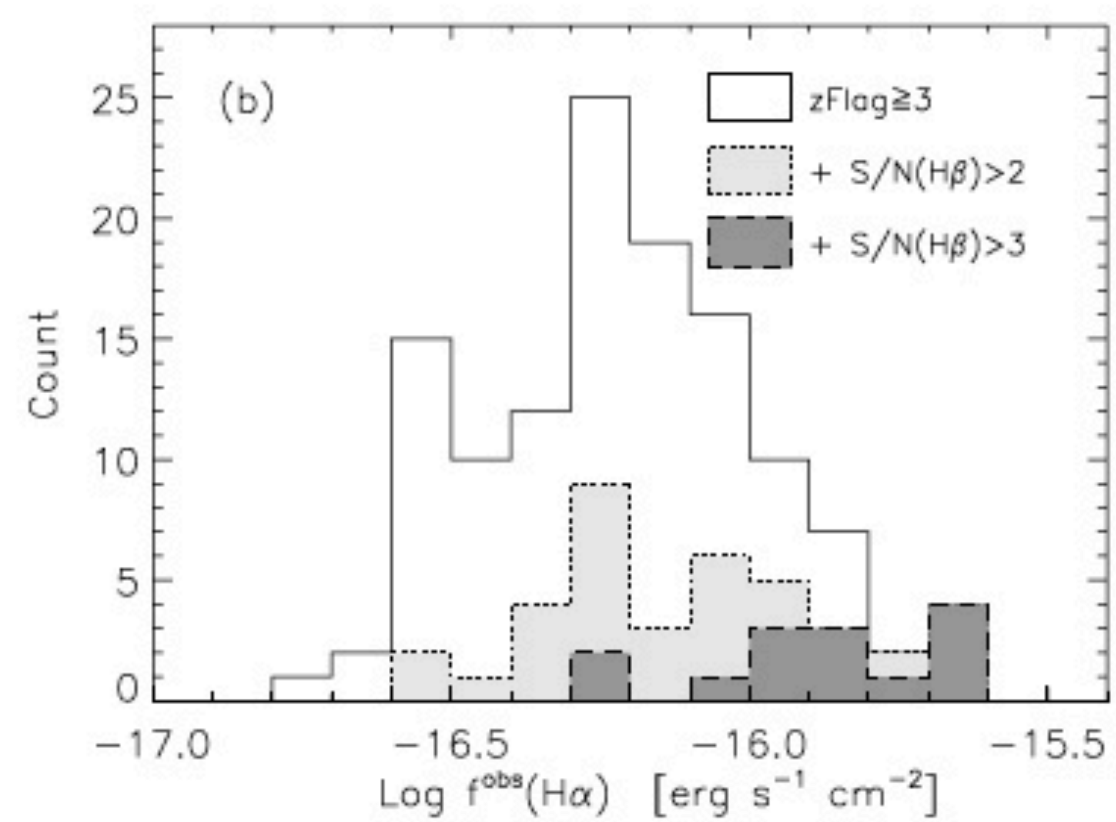




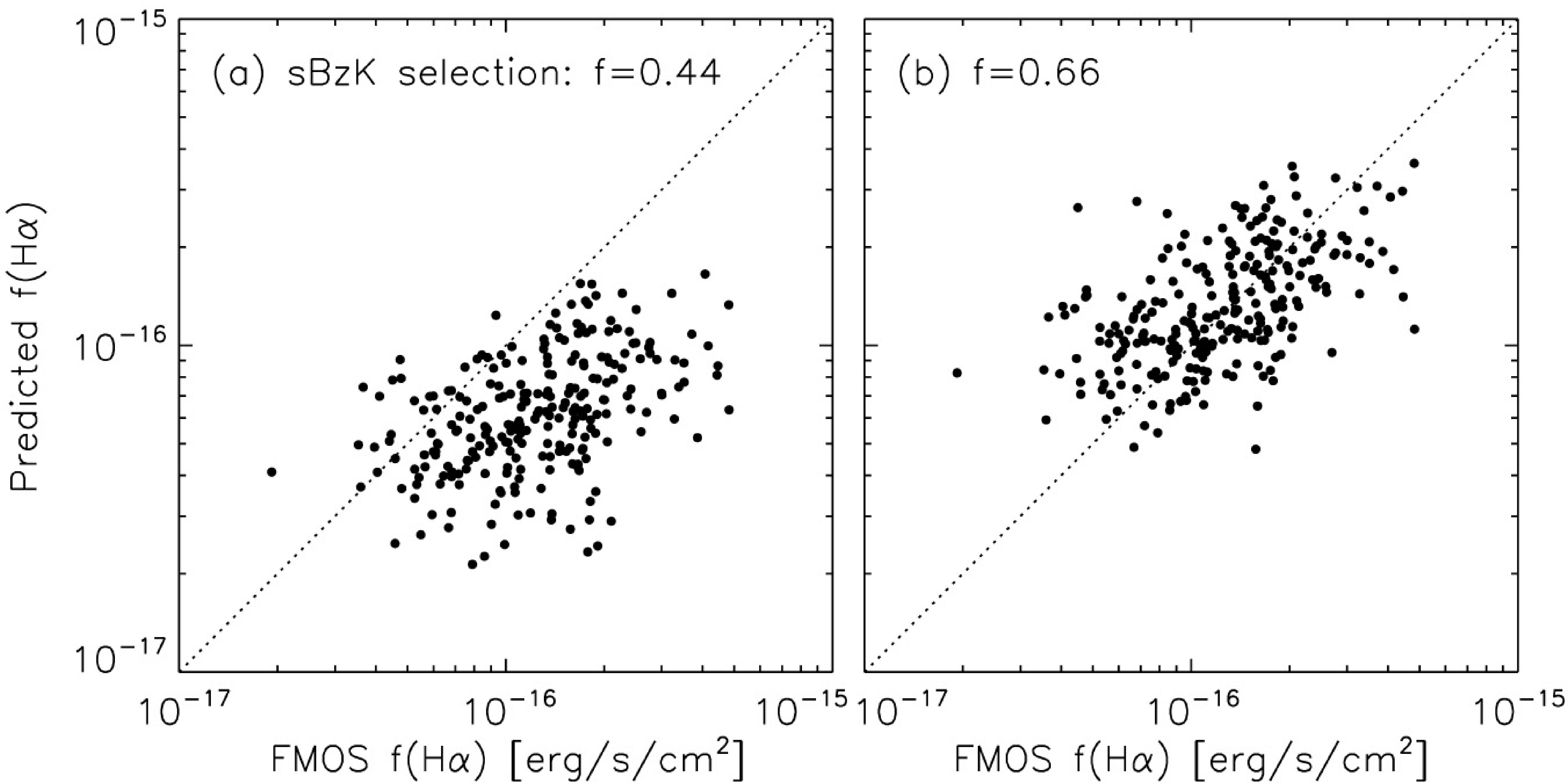
Emission-line fluxes



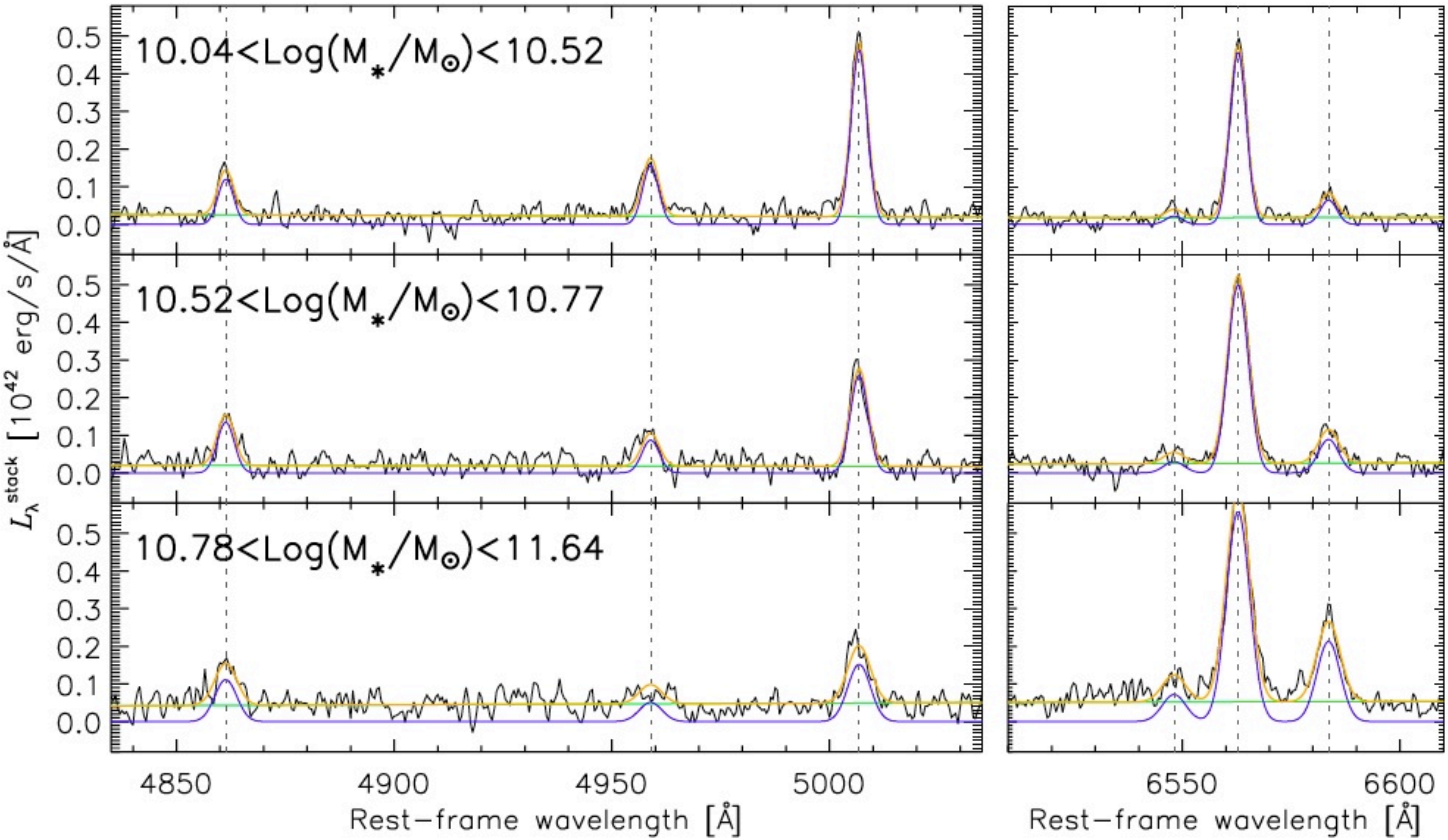




Predicted vs. Observed Hα flux

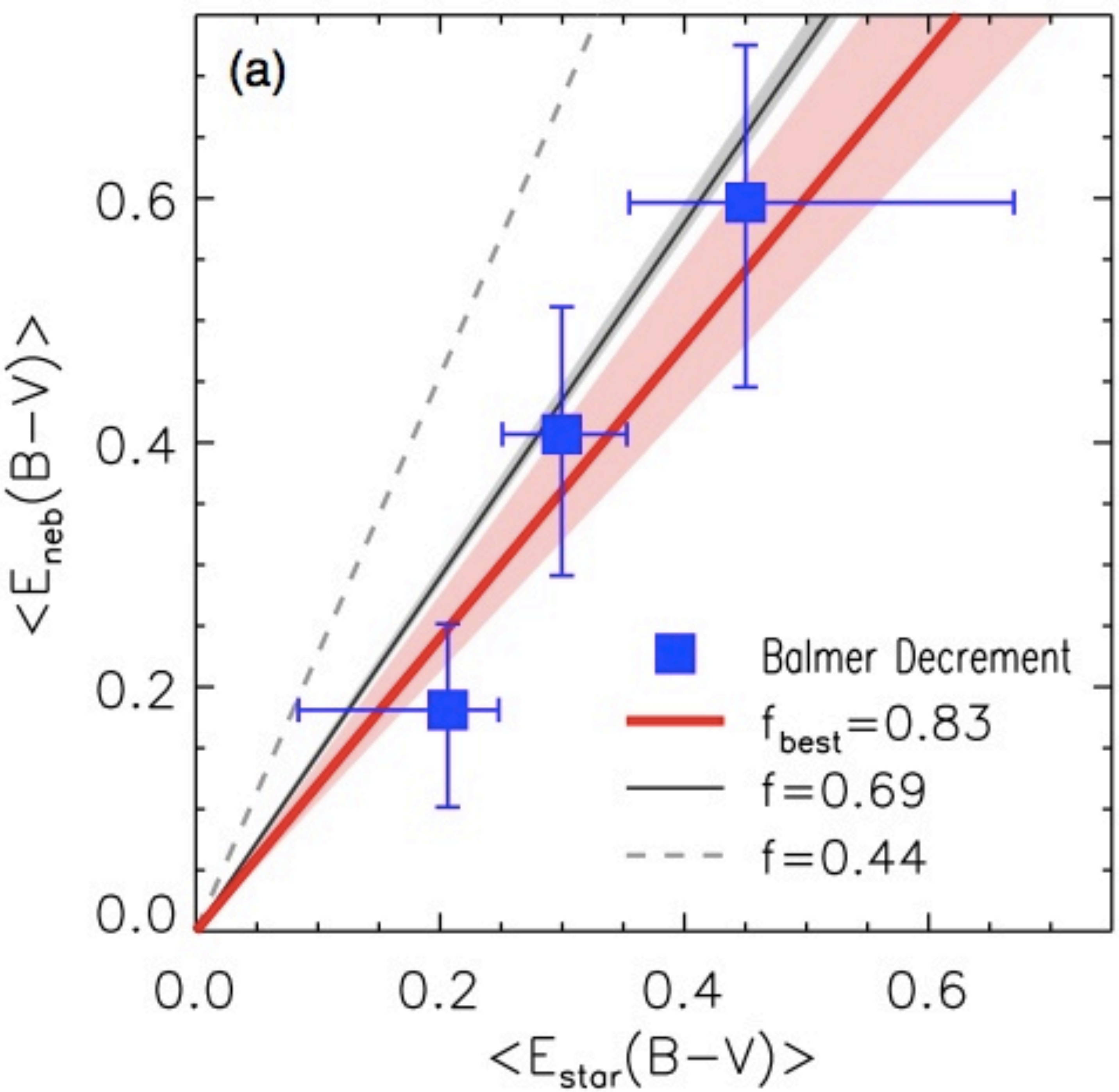


Stacking analysis



Dust extinction

based on Balmer decrement measured on stacked spectra

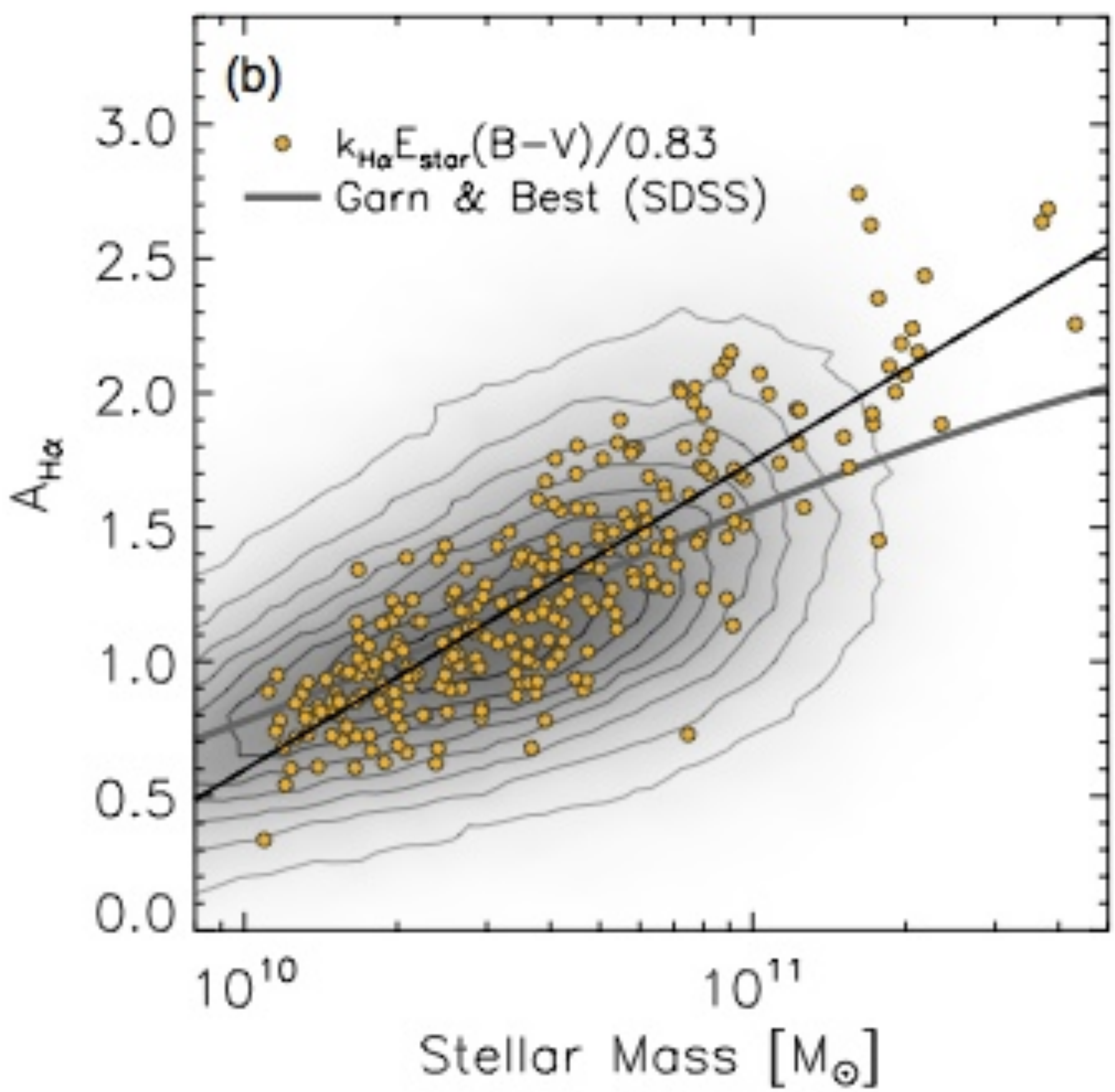


f-factor in disagreement with local starbursts (Calzetti et al. (2000))

Dust extinction
based on Balmer decrement measured on stacked spectra

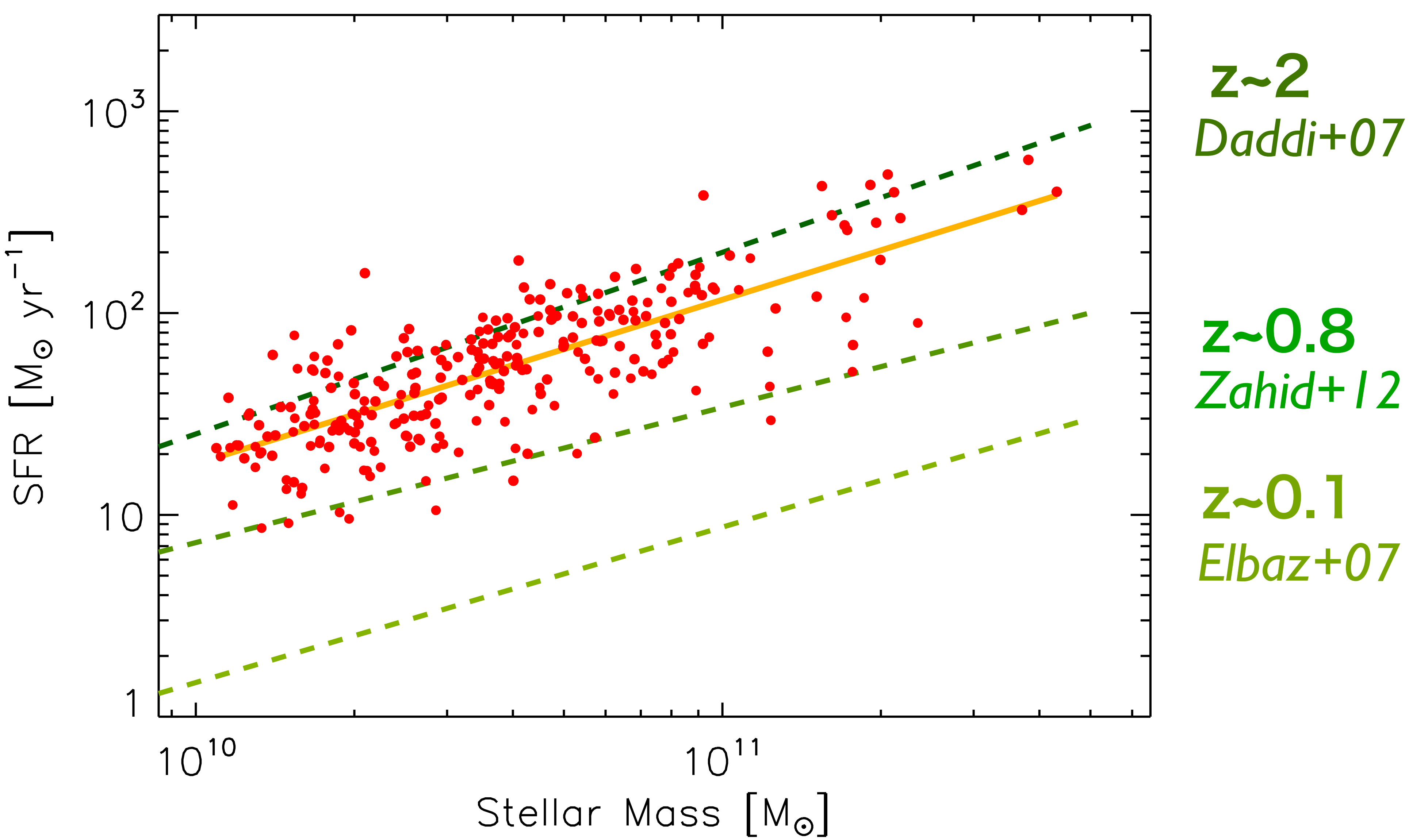
Fit relation:

$$A_{\mathrm{H}\alpha} = (0.654 \pm 045) + (1.010 \pm 0.67)(\log_{10} M_*/M_\odot - 10)$$



see Sobral et al. 2012

Star forming main sequence at z~1.6

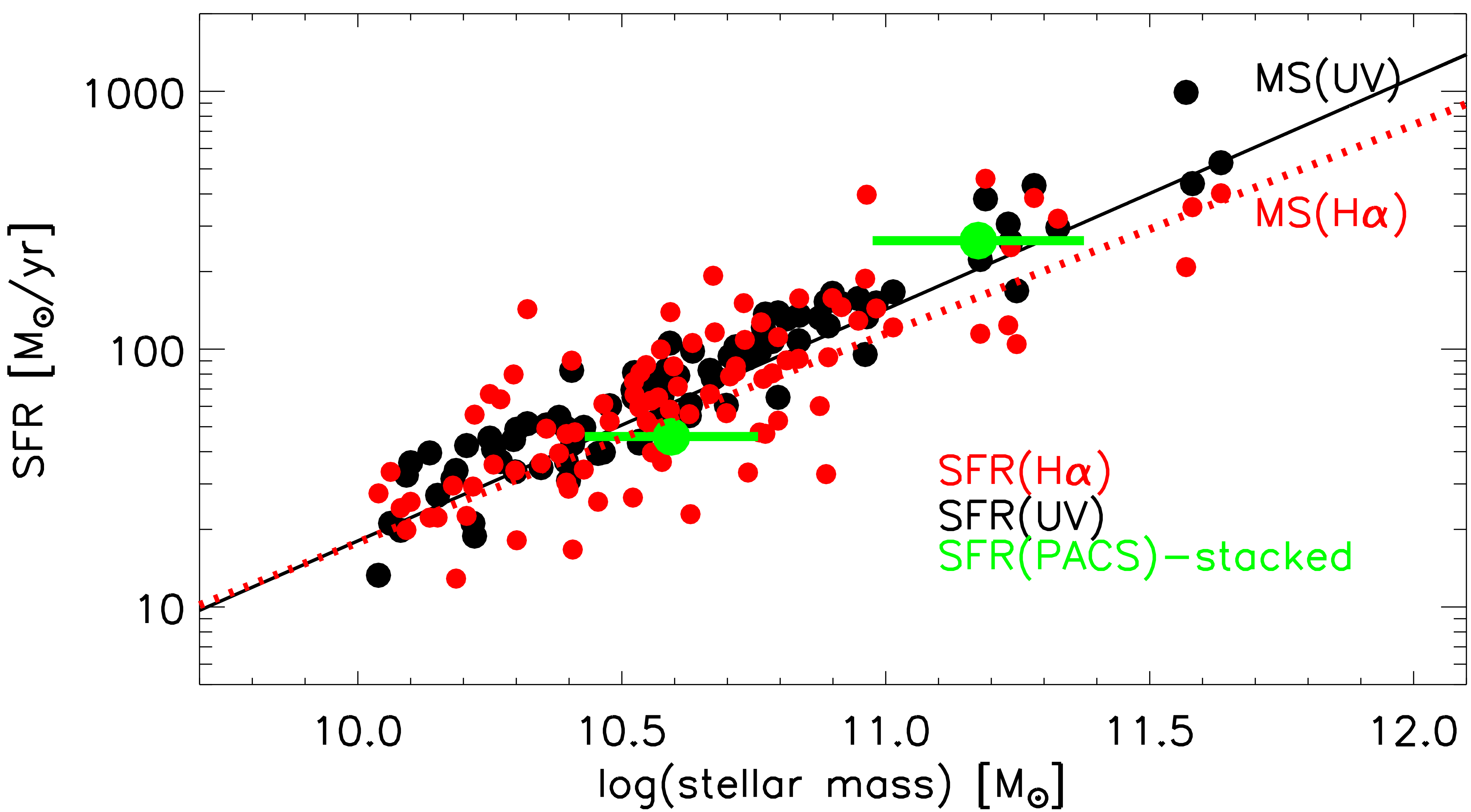


sigma~0.22 dex

$$\log \frac{SFR}{\mathrm{M_\odot yr^{-1}}} = 1.25_{\pm 0.03} + 0.81_{\pm 0.04} \log \left[\frac{M_*}{10^{10}\mathrm{M_\odot}} \right]$$

Kashino, JDS et al. 2013

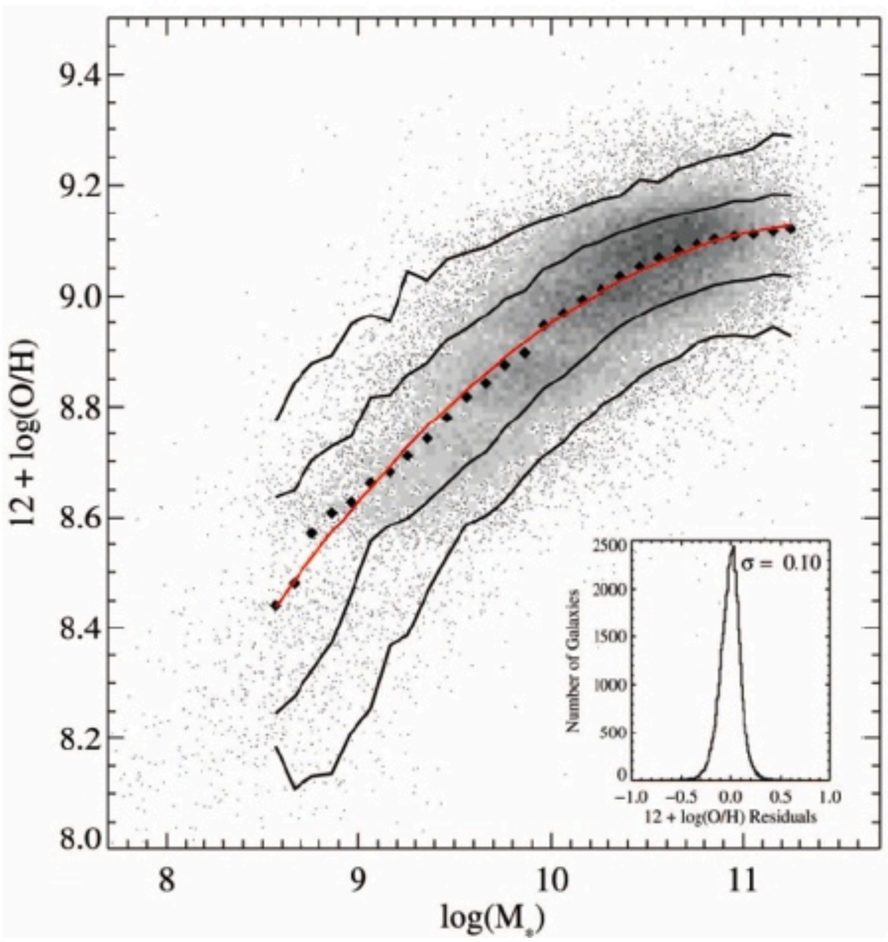
Are local calibrations of SF indicators (UV-Hα-FIR) applicable?



Rodighiero et al. 2014

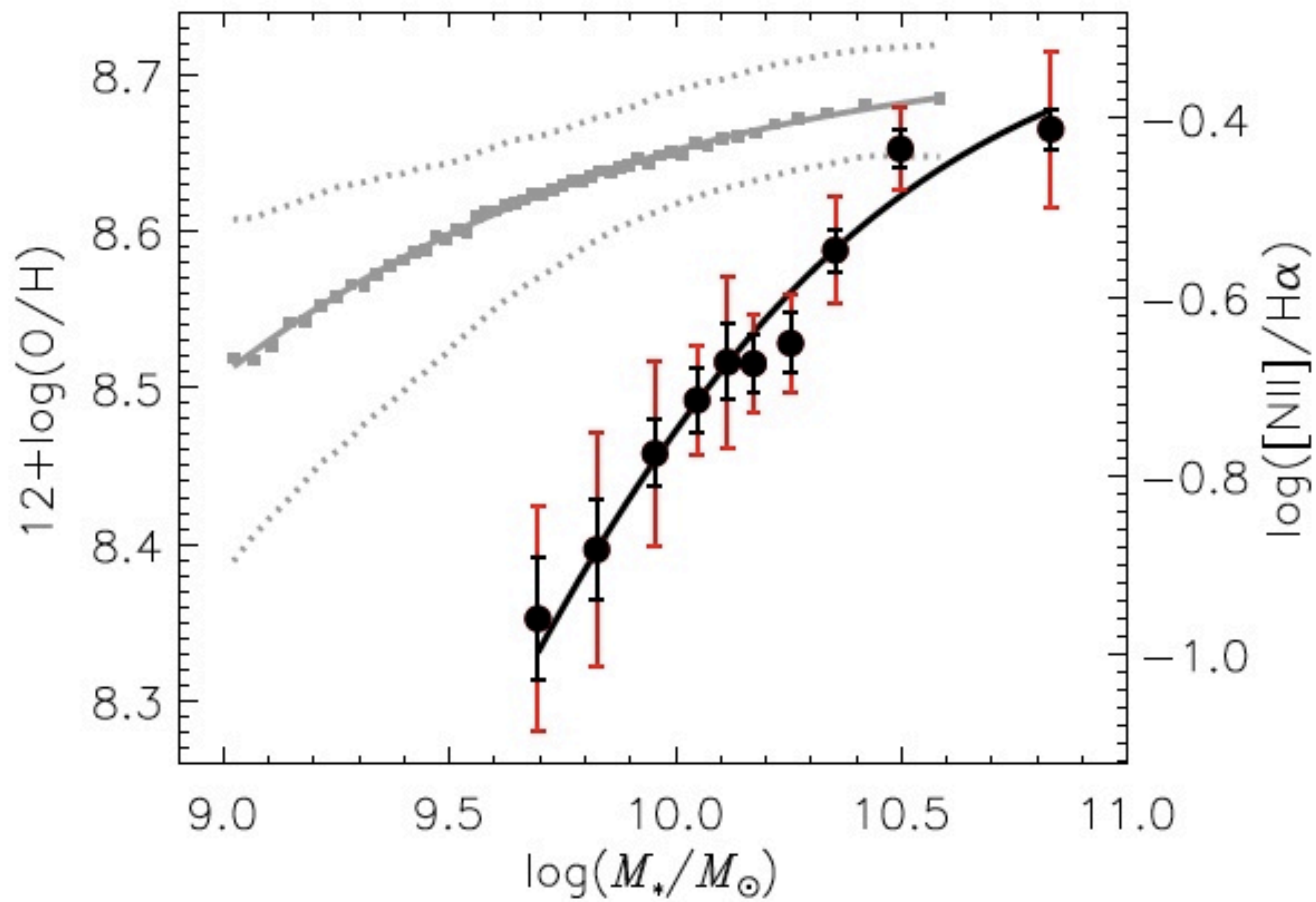
Mass-metallicity relation at high-z

SDSS (z ~ 0)

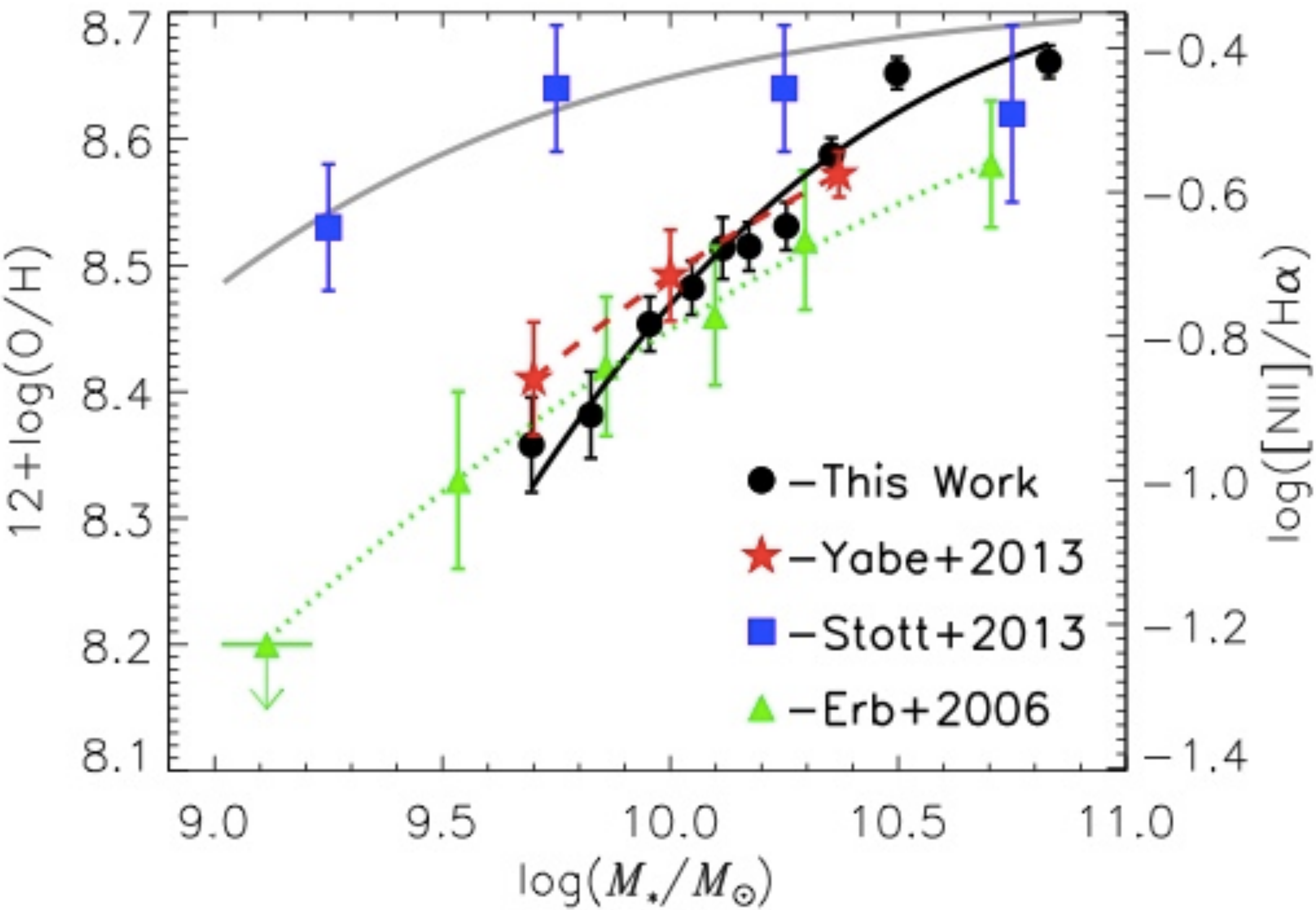


Tremonti et al. 2004

Subaru/FMOS

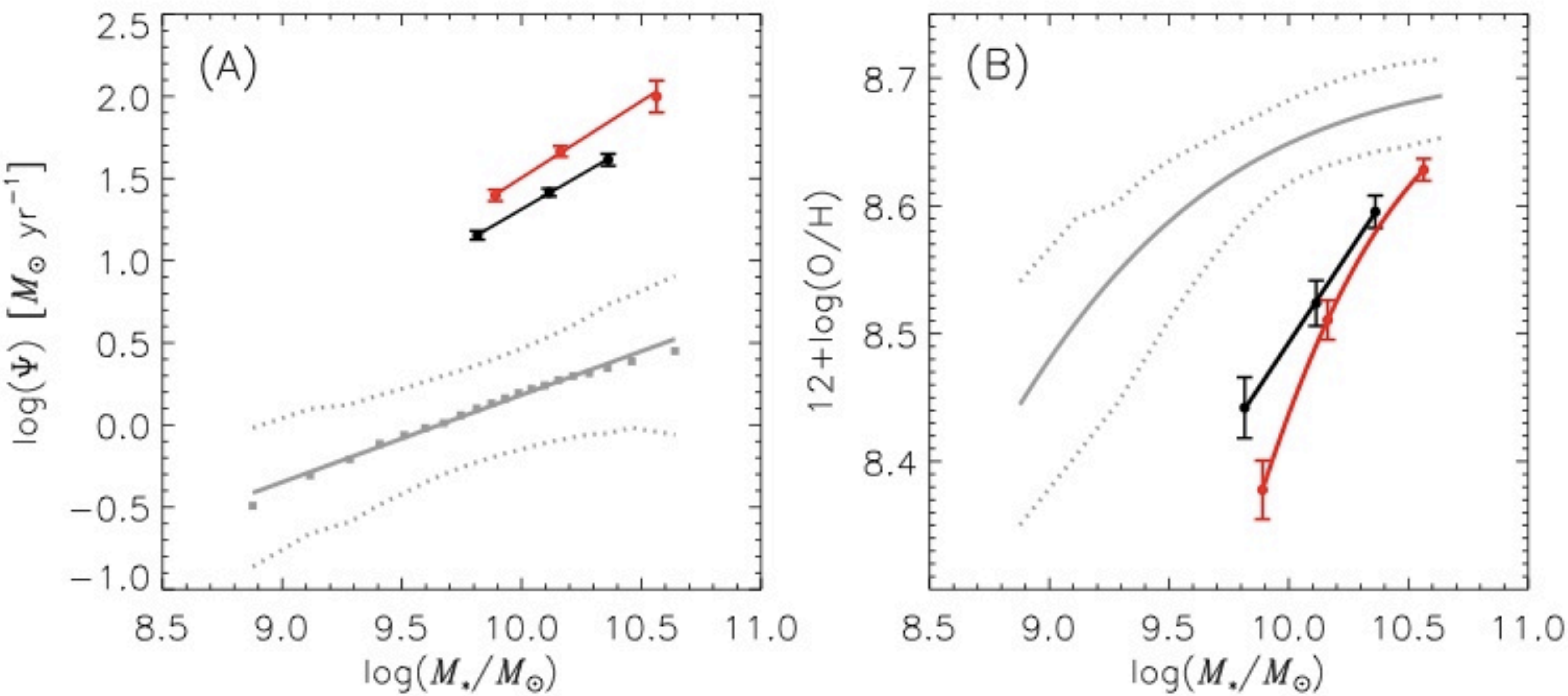


Zahid, Kashino, JDS et al. 2014



Zahid, Kashino, JDS et al. 2014

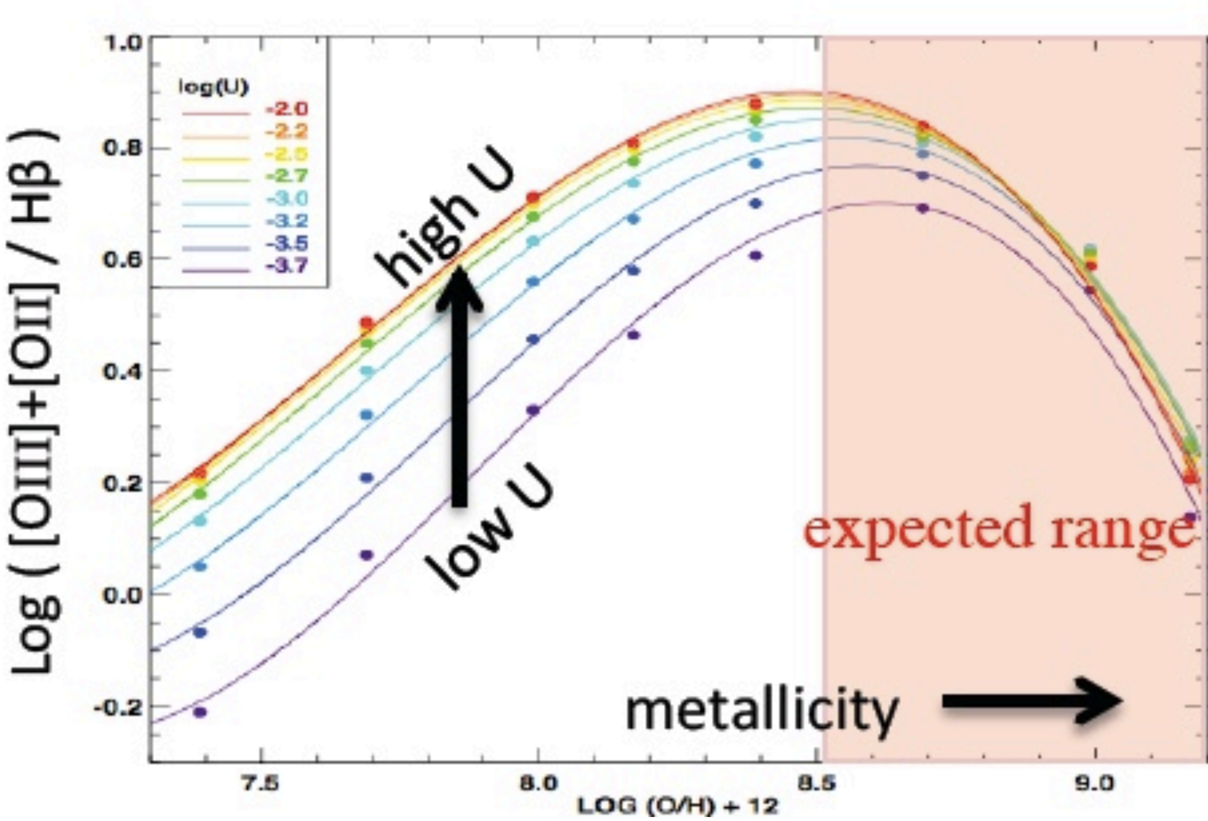
Mass-metallicity-SFR relation at high-z

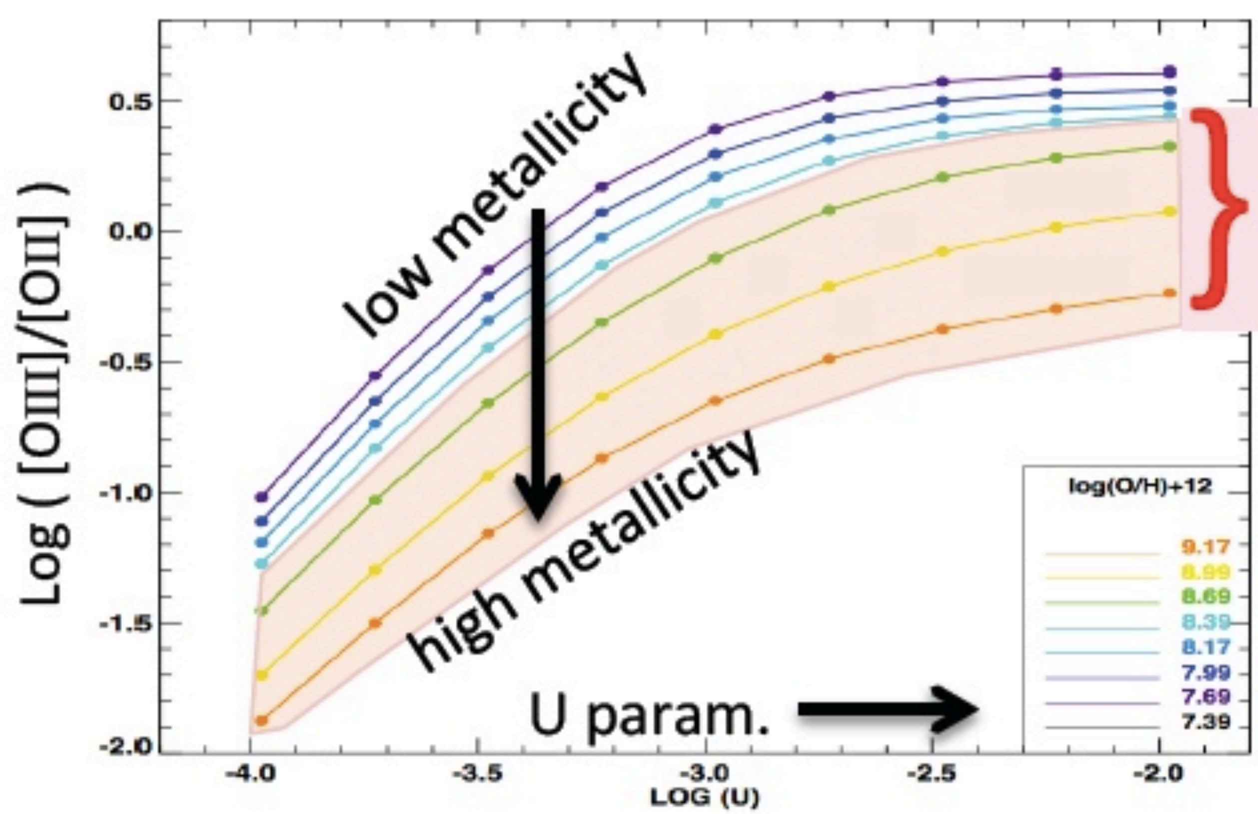


Zahid, Kashino, JDS et al. 2014

[OII] followup of FMOS galaxies

Keck/DEIMOS (PI Lisa Kewley)
VLT/VIMOS (PI Stephanie Juneau)





Break the degeneracy between metallicity and ionization parameter

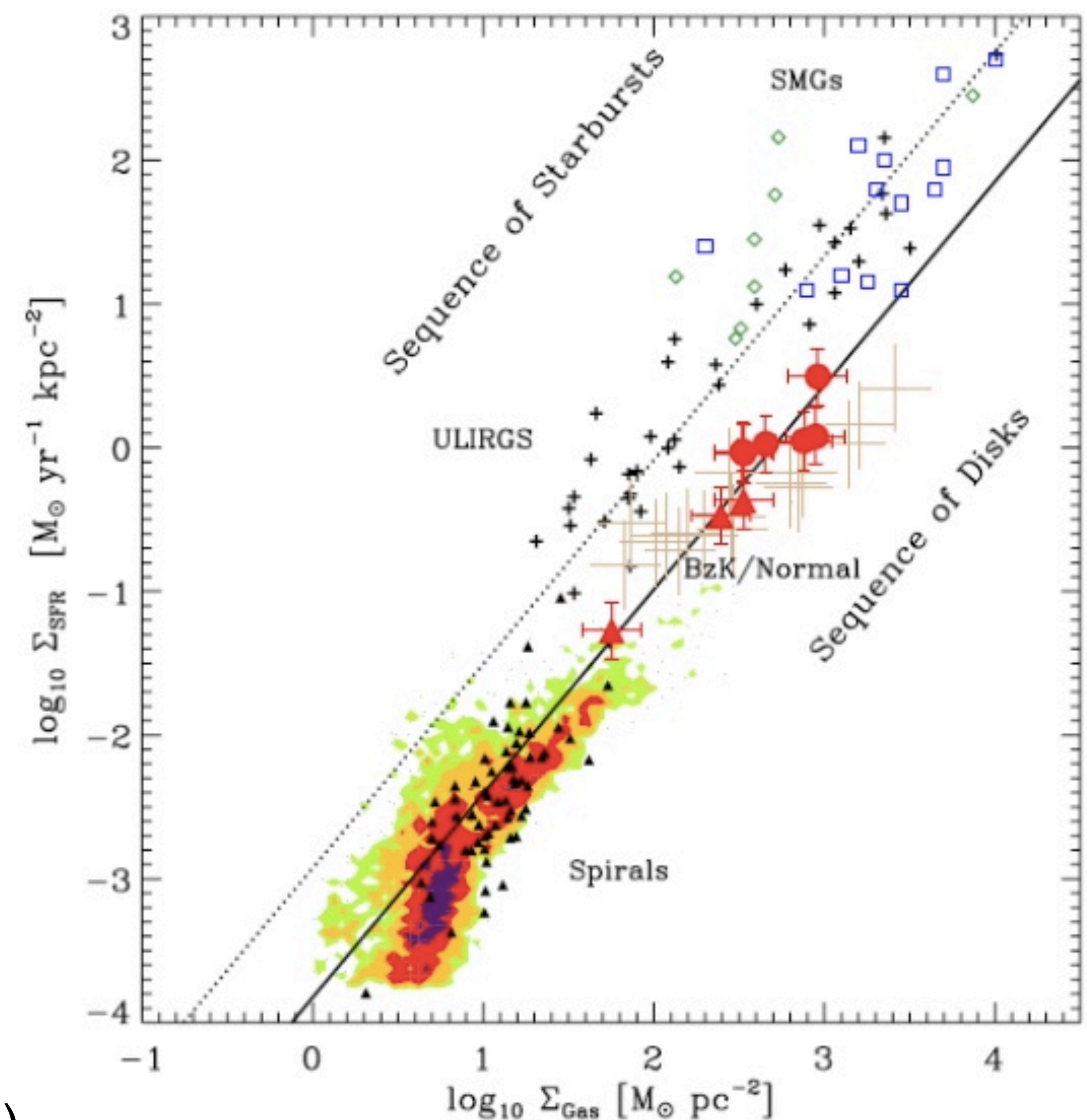
Recap

- Hα-based SFRs between ~10 - 400 $M_\odot yr^{-1}$ (should be gas rich)
- Ratio of nebular to stellar extinction (0.68) different that typically used (0.44)
- Dust extinction appears to be very similar to low-redshift galaxies
- Mass metallicity relation with a steeper slope than typically seen

High-z galaxies are dissimilar in their ISM properties to their low-z counterparts

Are extreme outliers from the SF MS similar to local ULIRGs?

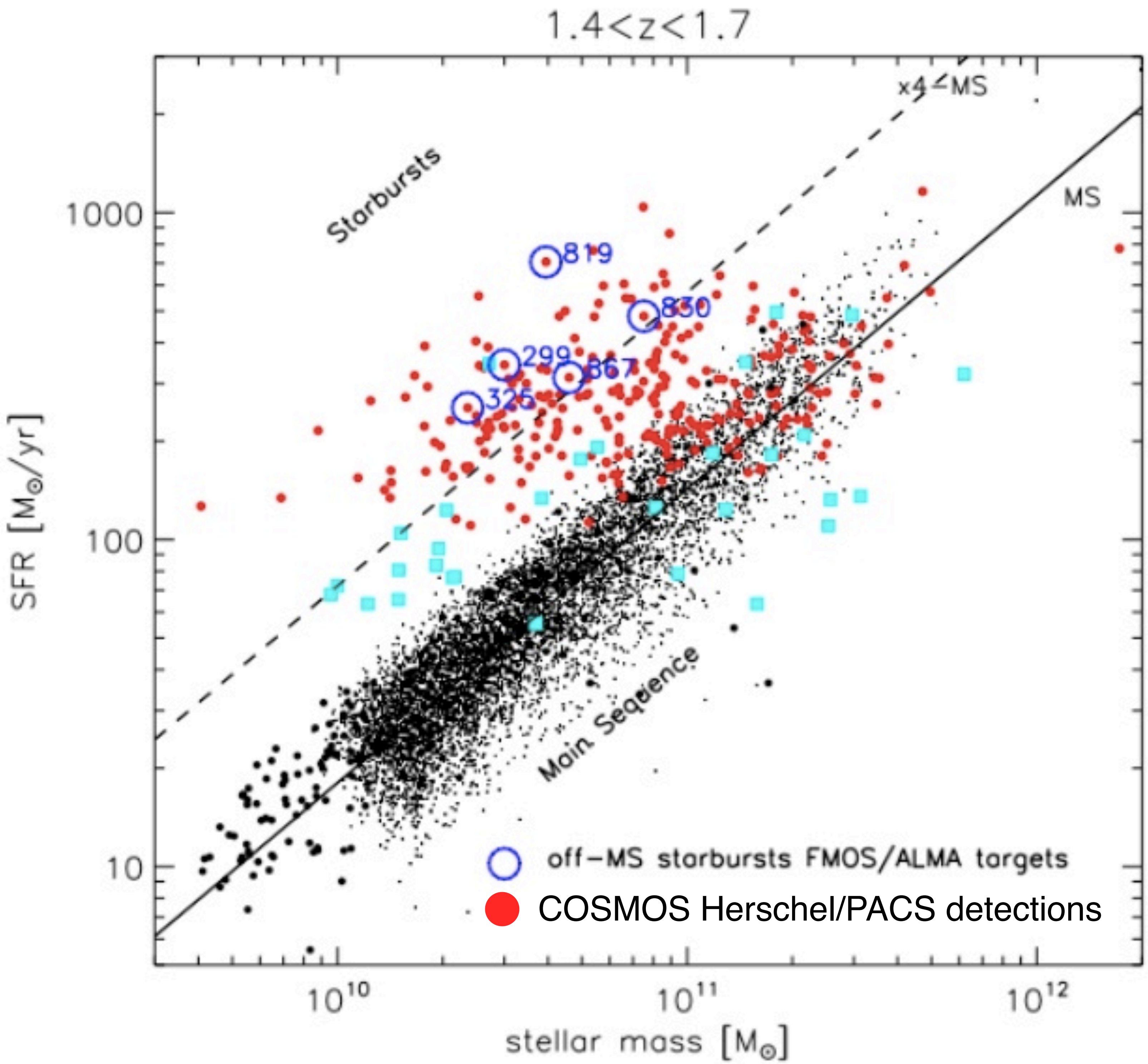
- Molecular gas
  - high gas fractions (e.g., Solomon et al. 1997)
  - centrally concentrated (Scoville et al. 1989)
- Elevated SF efficiency (Daddi et al. 2010; Genzel et al. 2010)
- Incidence of merging (Tacconi et al. 2008)
- Ionization conditions
  - evidence for shocks (Rich et al. 2011)



Daddi et al. 2010

ALMA followup of 5 OFF-MS galaxies at z ~ 1.5

CO line detection using the 2-1 transition (band 3)

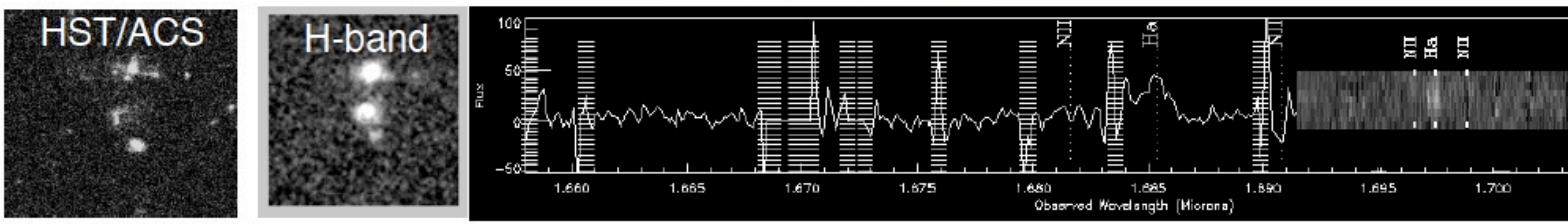


ALMA followup of 5 OFF-MS galaxies at z ~ 1.5

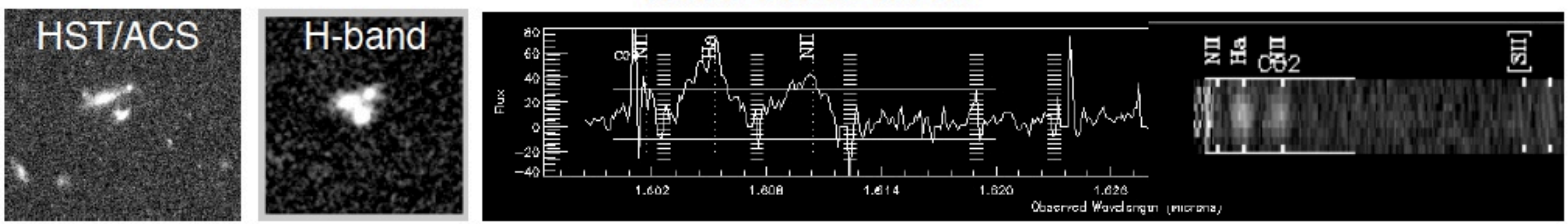
CO line detection using the 2-1 transition (band 3)

+ 2 from IRAM (G. Rodighiero)
PACS 282 (z=2.192; CO 3-2)
PACS 164 (z=1.647; CO 2-1)

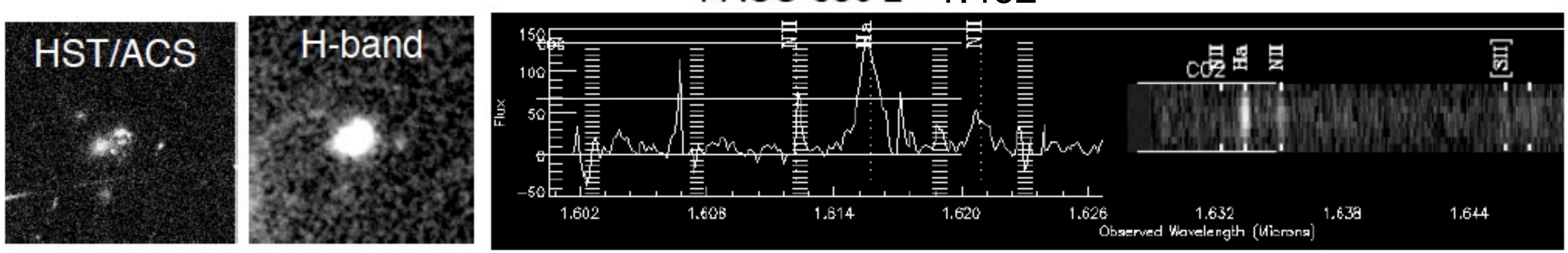
PACS-867 z=1.568



PACS-819 z=1.446



PACS-830 z= 1.462



Conclusions

Over 1000 NIR spectra to study the ISM of galaxies at z ~ 1.6

Properties differ substantially from the local Universe
(Dust, ionization, metallicity)

Understanding offsets in emission-line ratio diagnostics required new models (Kewley et al. 2013a,b; Steidel et al. 2014)

All while maintaing a tight SF main sequence and similar conversion efficiencies of gas to stars

ALMA (coupled with Herschel) opens a new dimension on ISM studies