A Multi-Wavelength Study of Dust and Star Formation in Galaxies at z ~ 2

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MOSDEF Collaboration:

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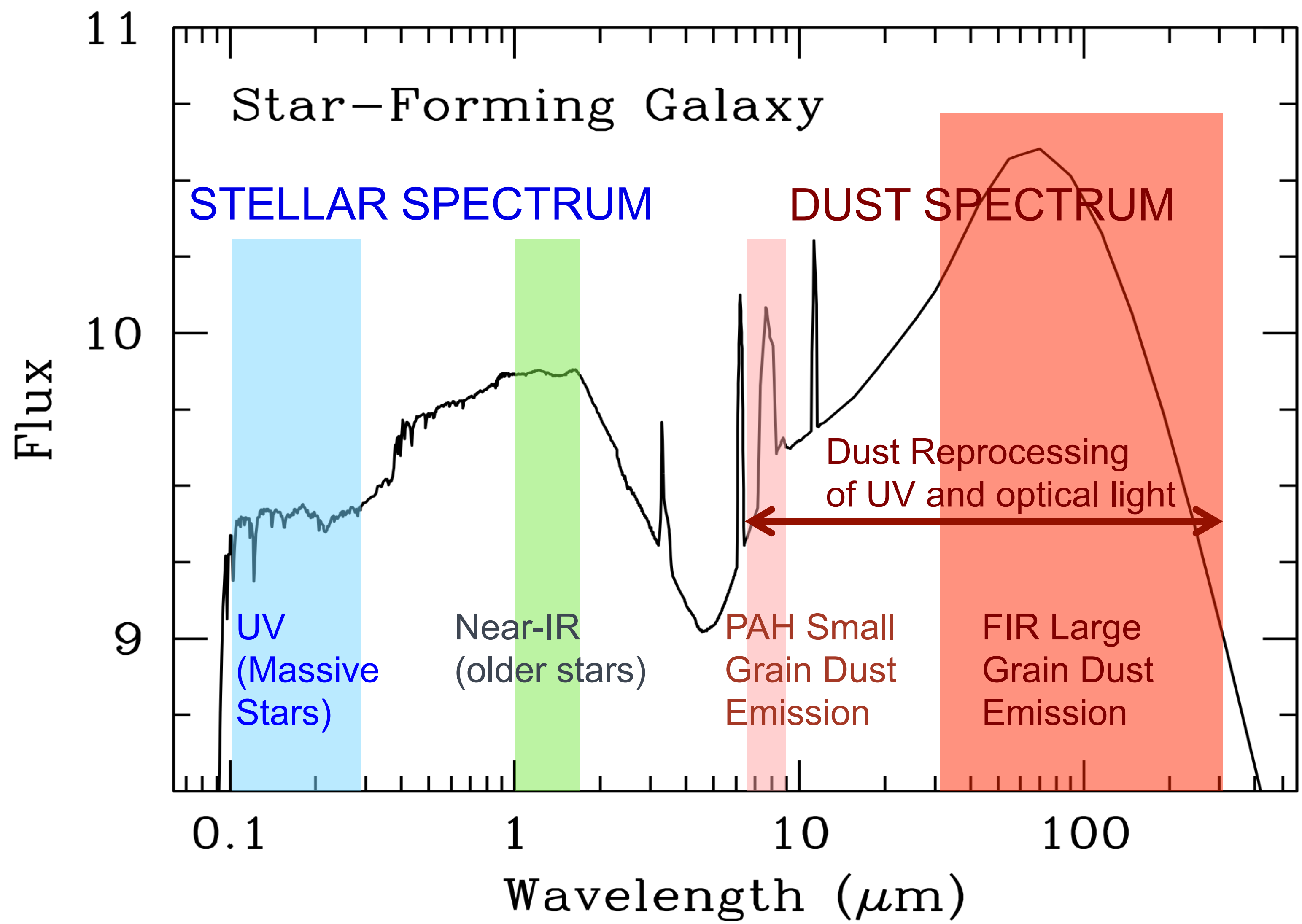
Outline

- Overview
  - A panchromatic view of galaxies
  - Why is redshift of z~2 interesting?
- The MOSDEF survey
- Star formation and mass assembly at z~2
  - The SFR-M_* relation
  - Comparison of SFR(Hα) with UV-to-far-IR SFR
- Interstellar dust and PAH grains at z~2
- Future projects
- Summary

Stars and Dust in Galaxies

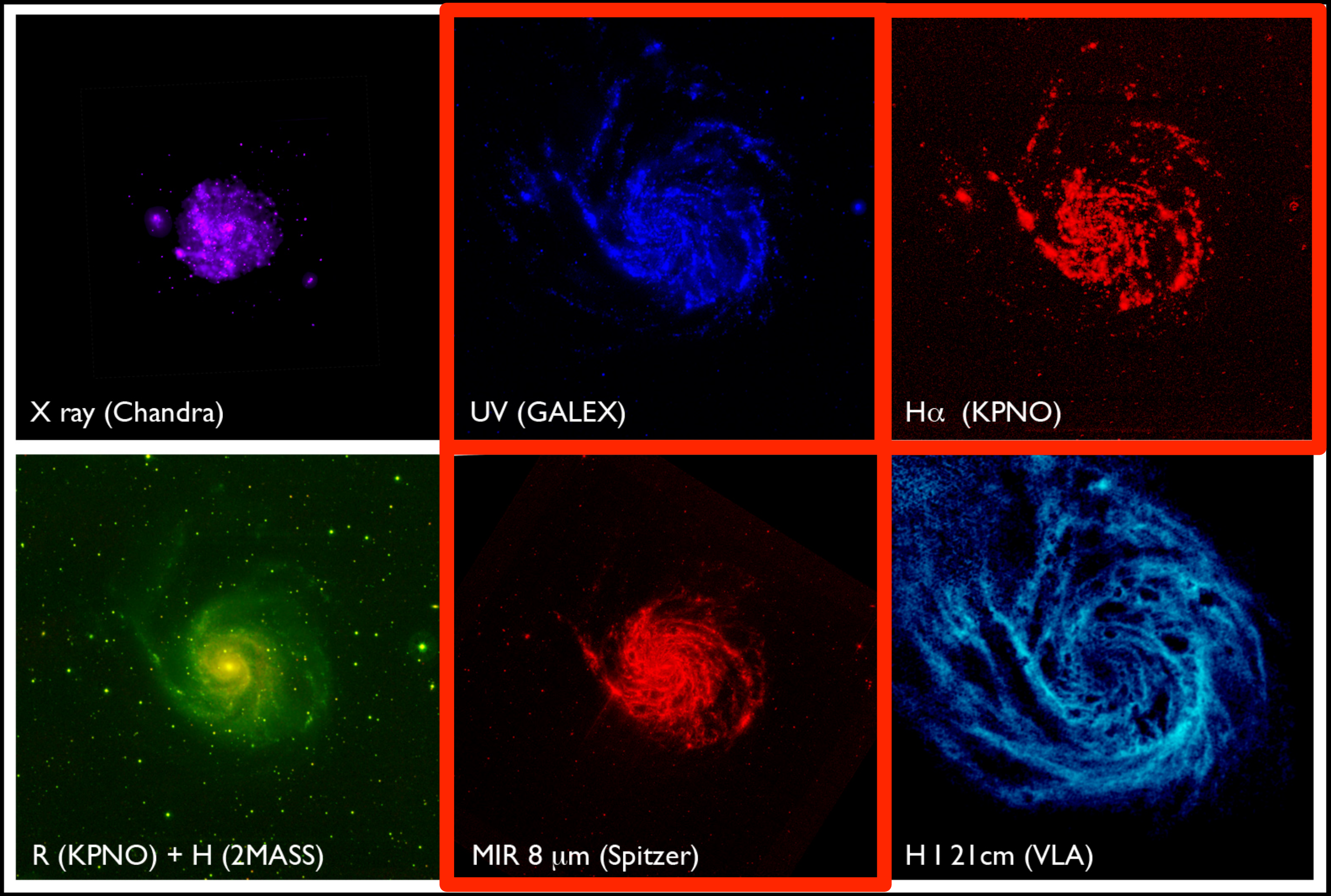
Milky Way, Credit & Copyright: Serge Brunier

Obtaining a Census of Star Formation in Galaxies



Credit: N. Reddy

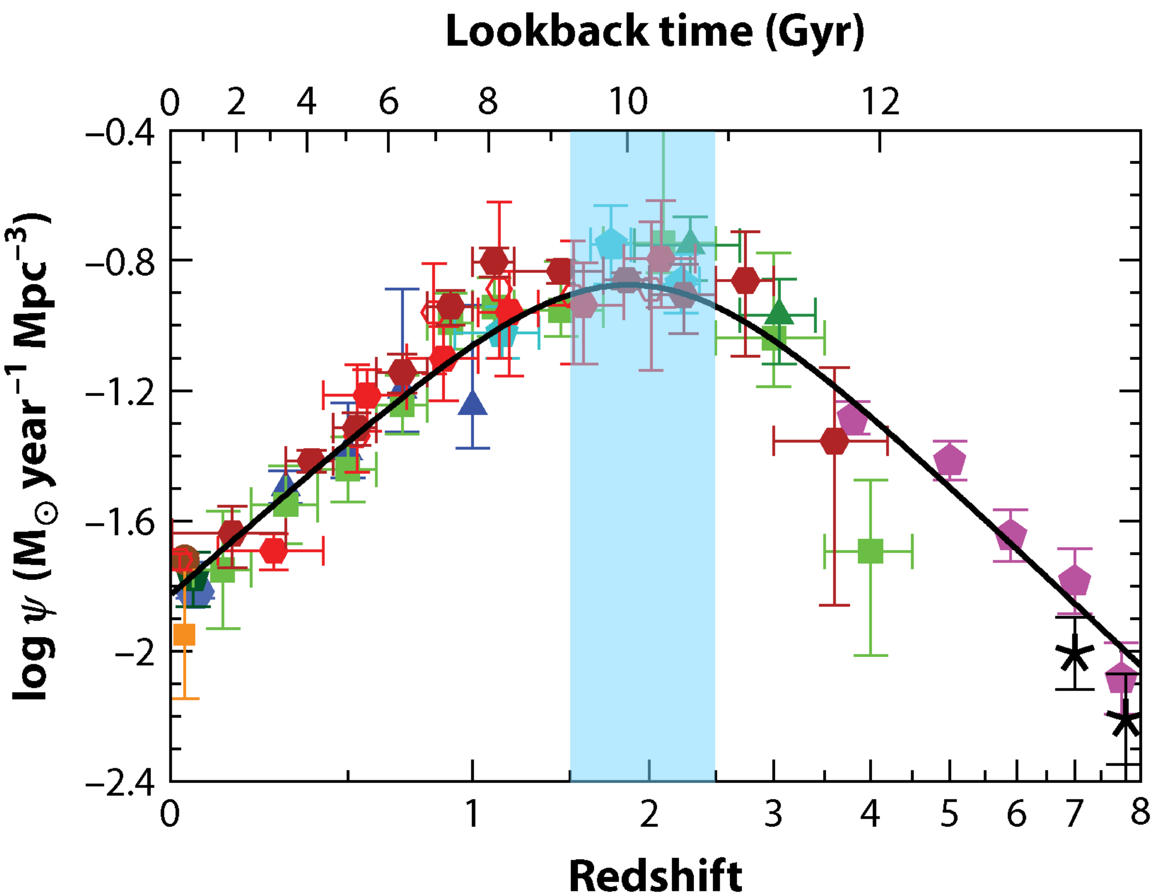
Multiwavelength data of the Spiral Galaxy M 101



Credit of the images: Chandra X ray data: NASA/CXC/JHU/K.Kuntz et al,; GALEX data: Gil de Paz et al. 2007, ApJS, 173, 185; R & Hα data: Hoopes et al. 2001, ApJ, 559, 878; 2MASS data: Jarrett et al. 2003, AJ, 125, 525; Spitzer 8 μm data: Dale et al. 2009, ApJ, 703, 517; VLA HI 21 cm : Walter et al. 2008, AJ, 136, 2563, *"The H I Nearby Galaxy Survey"*.

Credit of the composition: **Ángel R. López-Sánchez** (Australian Astronomical Observatory / Macquarie University).

Redshift of z ~ 2 : Peak of SFR Density



Madau P, Dickinson M. 2014.
Annu. Rev. Astron. Astrophys. 52:415–86

- Galaxies are assembling most of their stellar mass
- Can study interesting nebular emission lines (redshifted to near-IR) with 10-meter class telescopes
- Have access to a wealth of multi-wavelength indicators of star formation (X-ray, *UV, Hα, mid- and far-IR,* radio)

Star-Formation Rate Diagnostics
or How to Correct Dust Attenuation?

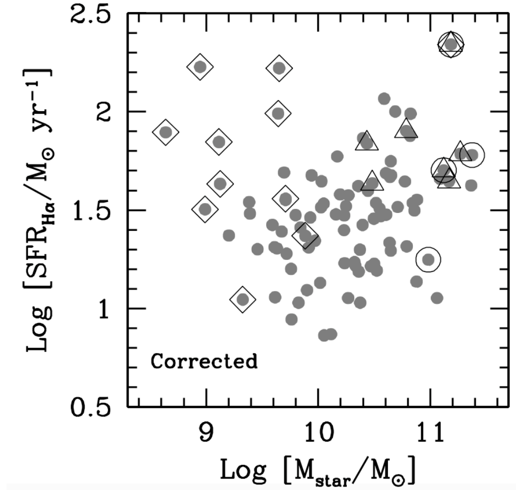
- Hα recombination line
  - Massive early-O type stars (indicator of *instantaneous* star-formation rate)
  - Obscured by dust
  - Possible to obtain individual measurements at z~2
- UV stellar emission
  - Massive O and B type stars
  - Heavily obscured by dust (A_{1600}~0.5-3.0)
- IR dust emission
  - Reprocessed light from absorbed UV photons
  - No large samples with individual detections at z~2

Hα;
Tracer of instantaneous star formation

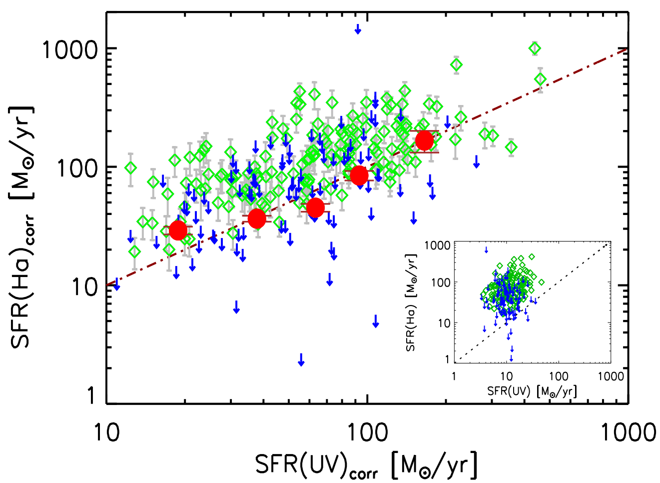
- Previous studies at z ~ 2
  - Small samples
  - UV-selected samples
  - No Hβ for dust correction

➢ We need *large unbiased* samples with *spectroscopic* Hα and Hβ measurements

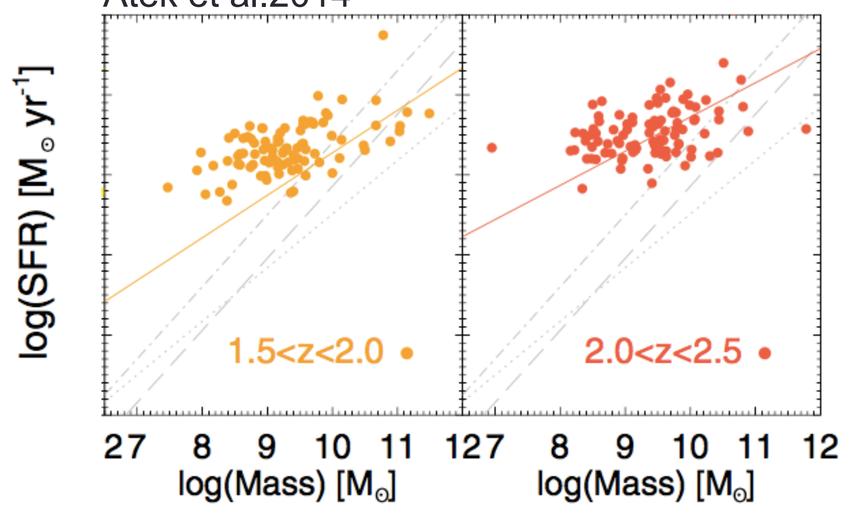
Erb et al. 2006



Shivaei et al. 2015a

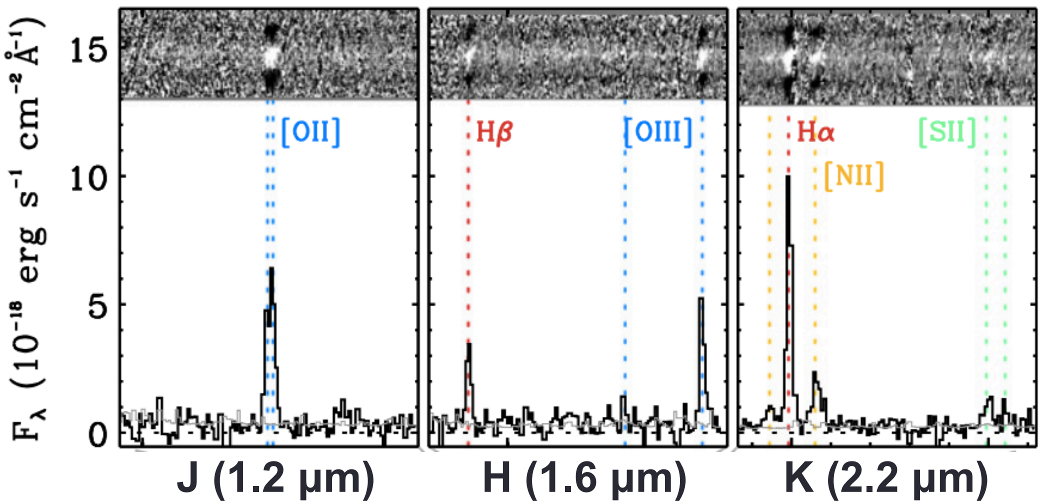


Atek et al.2014



The MOSDEF* Survey
*MOSFIRE Deep Evolution Field

Kriek+2015

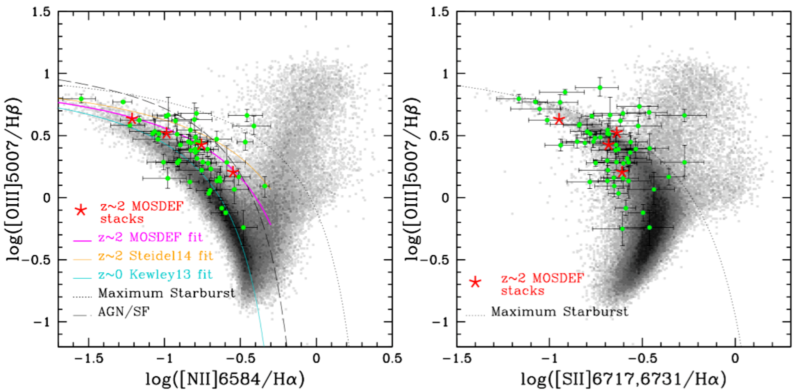


- Rest-frame optical spectra of ~ 1500 H-selected galaxies and AGNs
- $1.37 \leq z \leq 3.80$
- CANDELS fields
- 48.5 nights with MOSFIRE on Keck I (2012-2016)
- Collaboration between UC Berkeley, UCLA, UC San Diego, UC Riverside

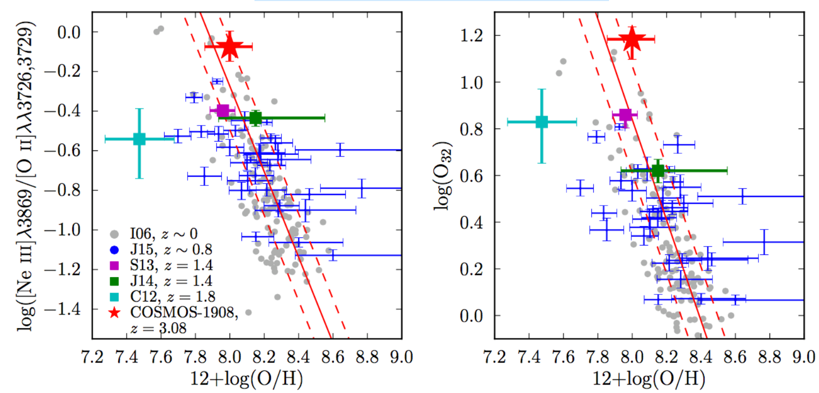
In MOSDEF we study:

- Excitation properties

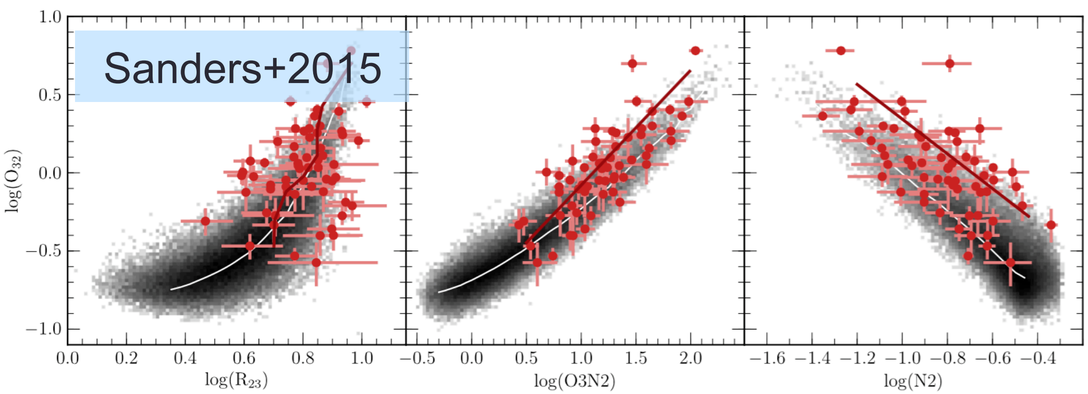
Shapley+2015



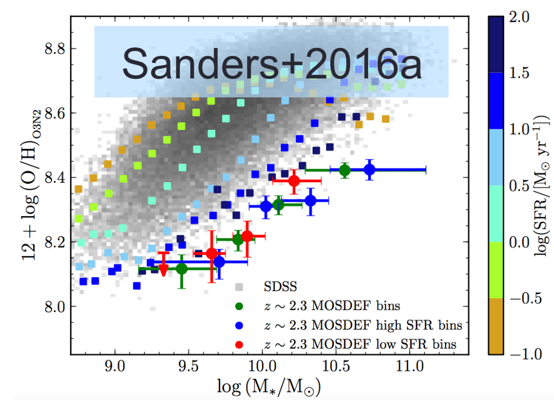
Sanders+2016b



Sanders+2015



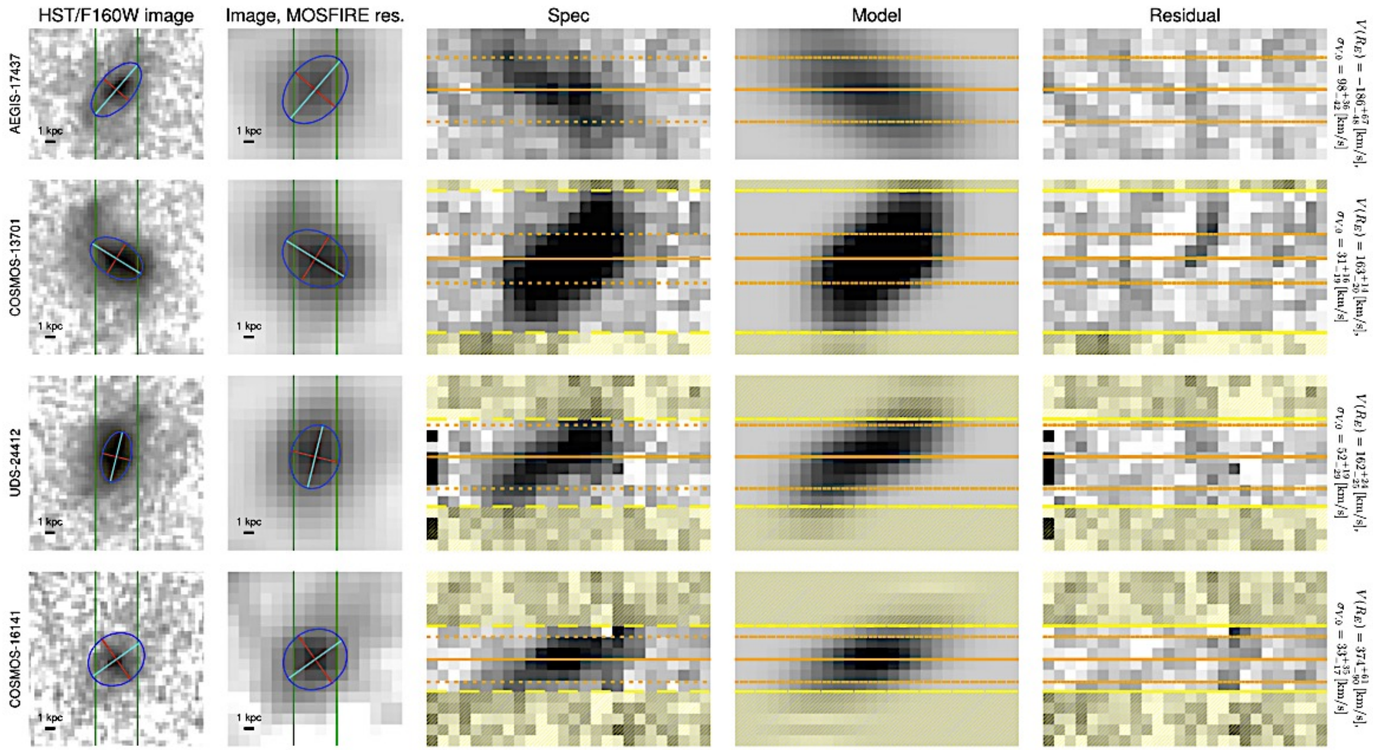
Sanders+2016a



In MOSDEF we study:

- Kinematics

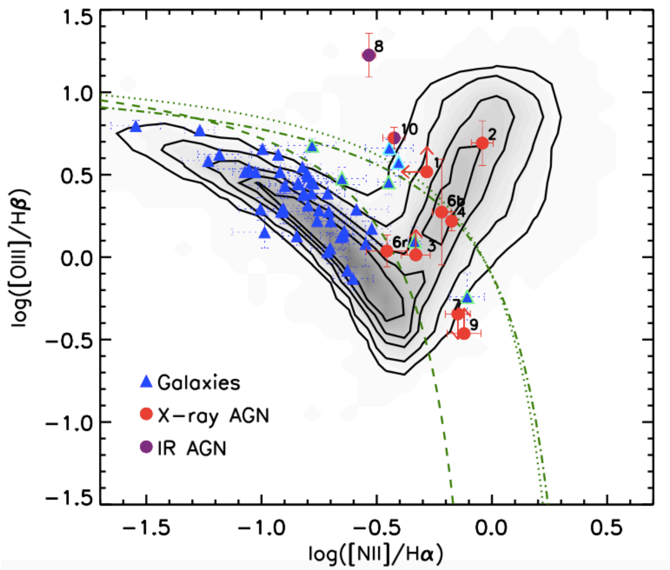
Price+2016



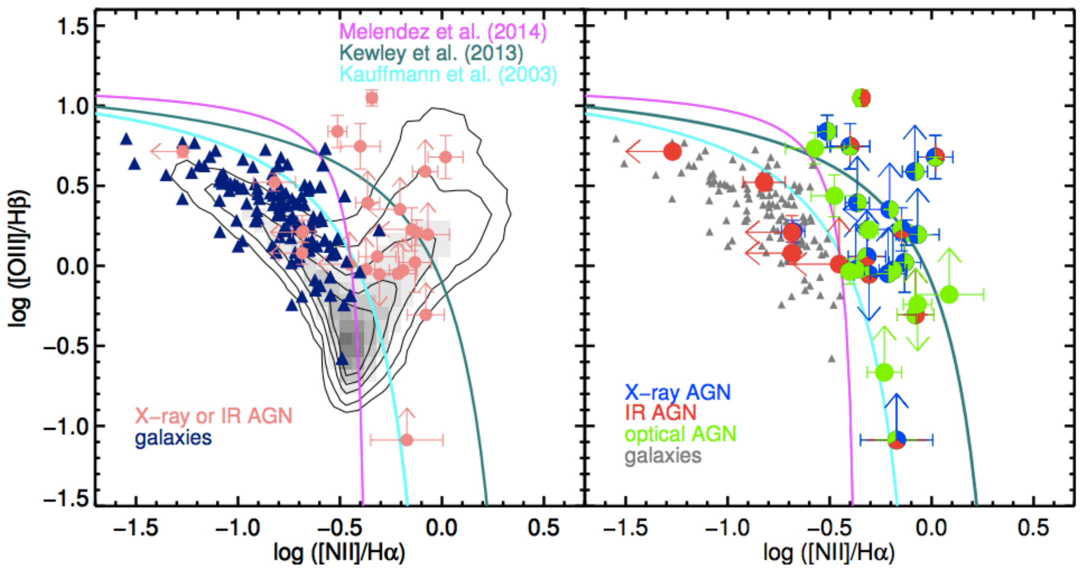
In MOSDEF we study:

- AGN and black hole activity

Coil+2015

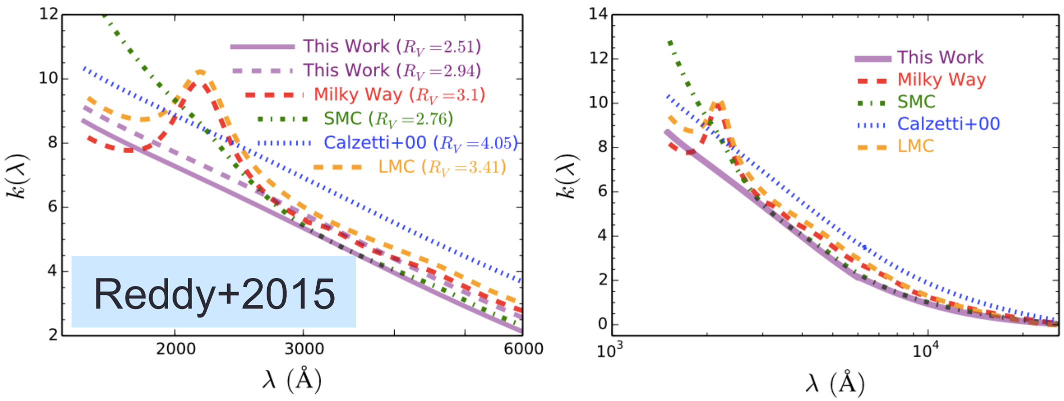


Azadi+2016

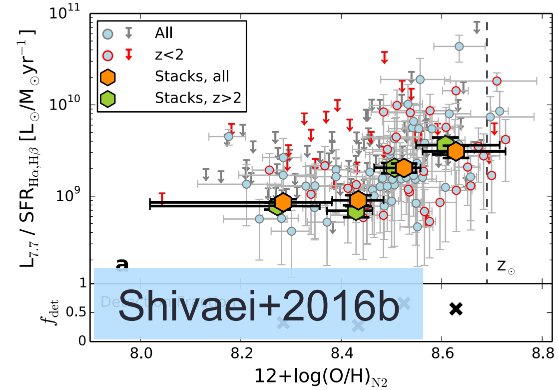


In MOSDEF we study:

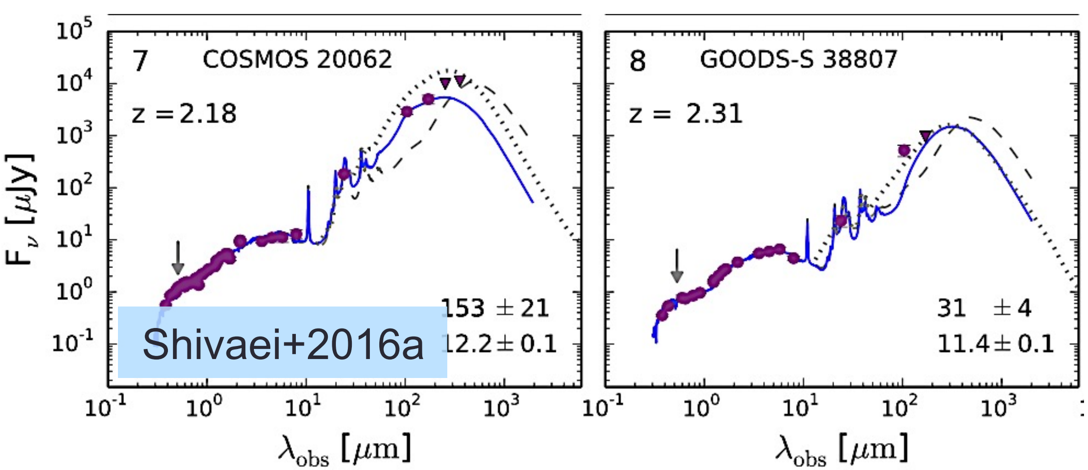
- Star formation and dust



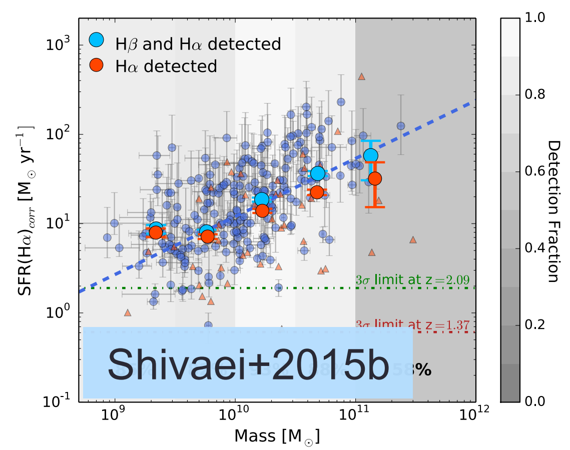
Reddy+2015



Shivaei+2016b



Shivaei+2016a

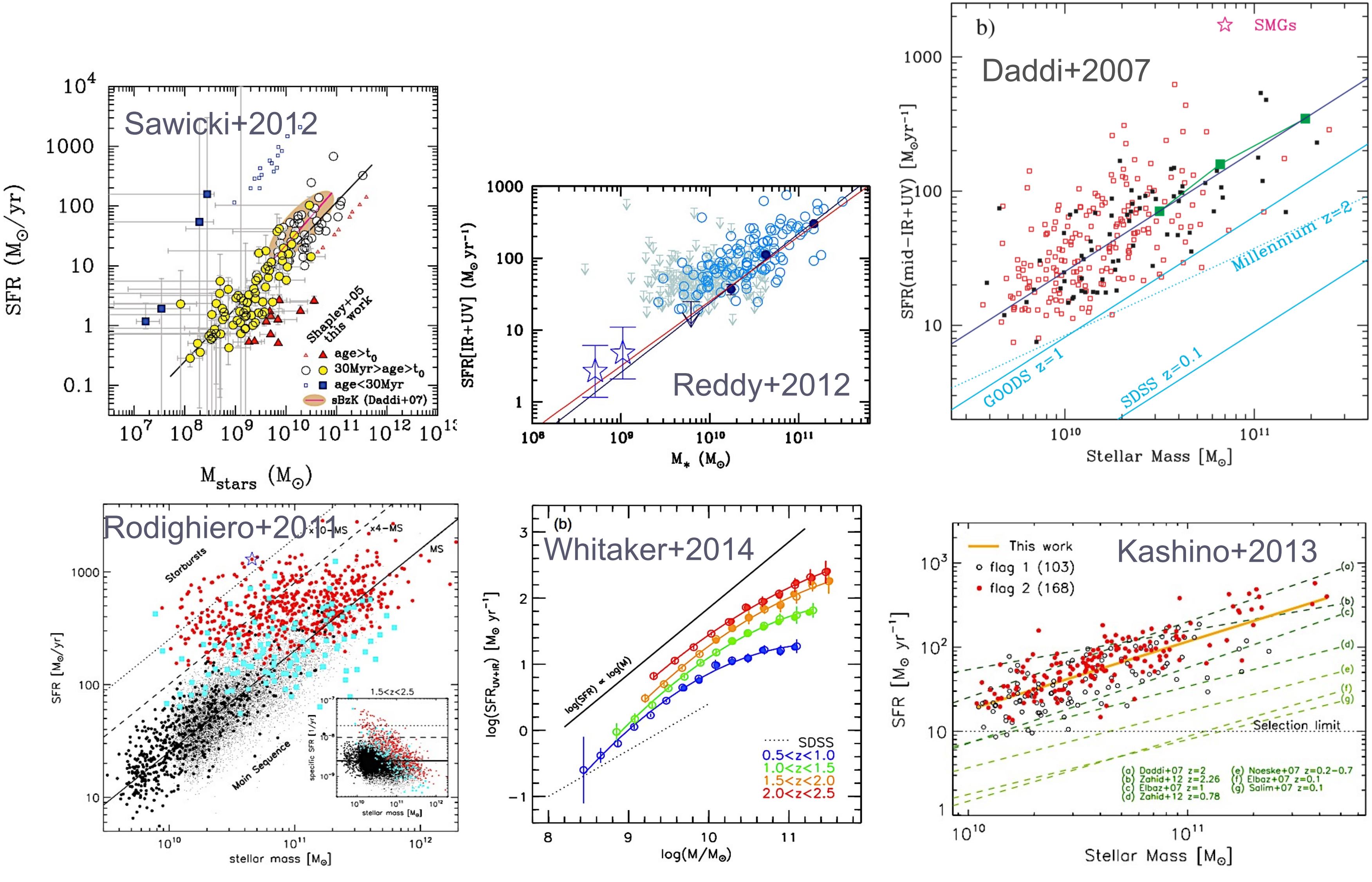


Shivaei+2015b

The MOSDEF Survey: mosdef.astro.berkeley.edu

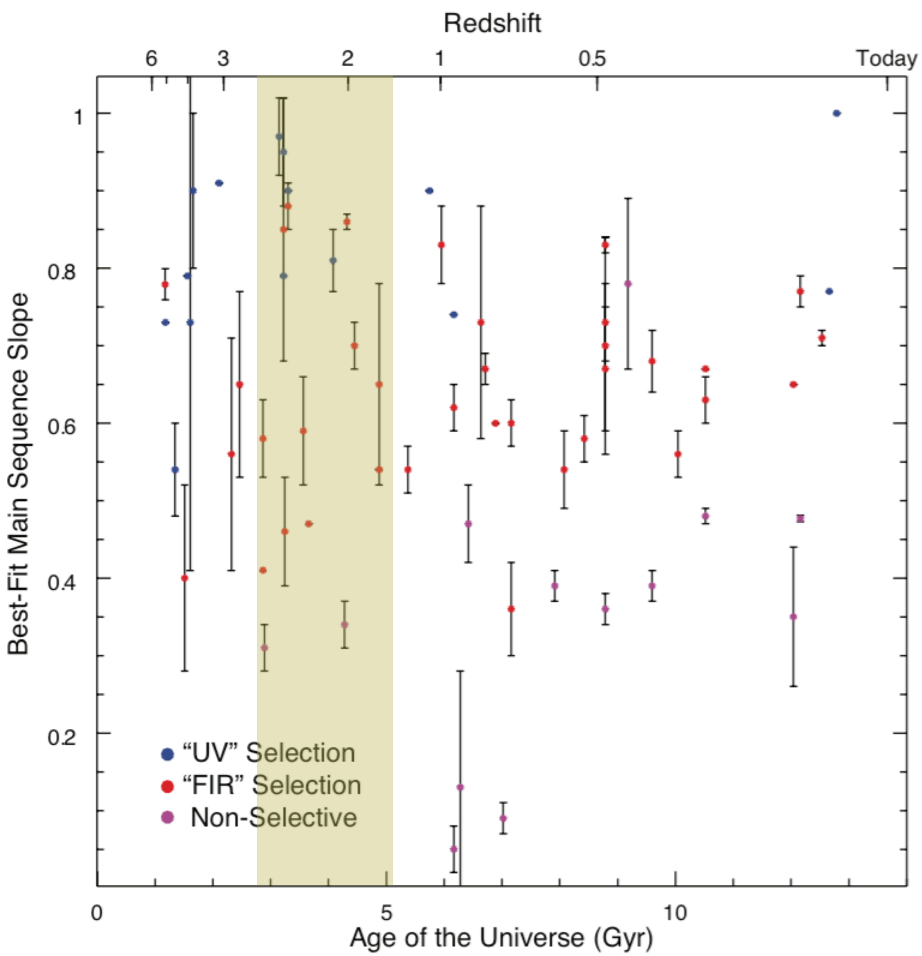
STAR FORMATION & MASS ASSEMBLY

The SFR-M* relation



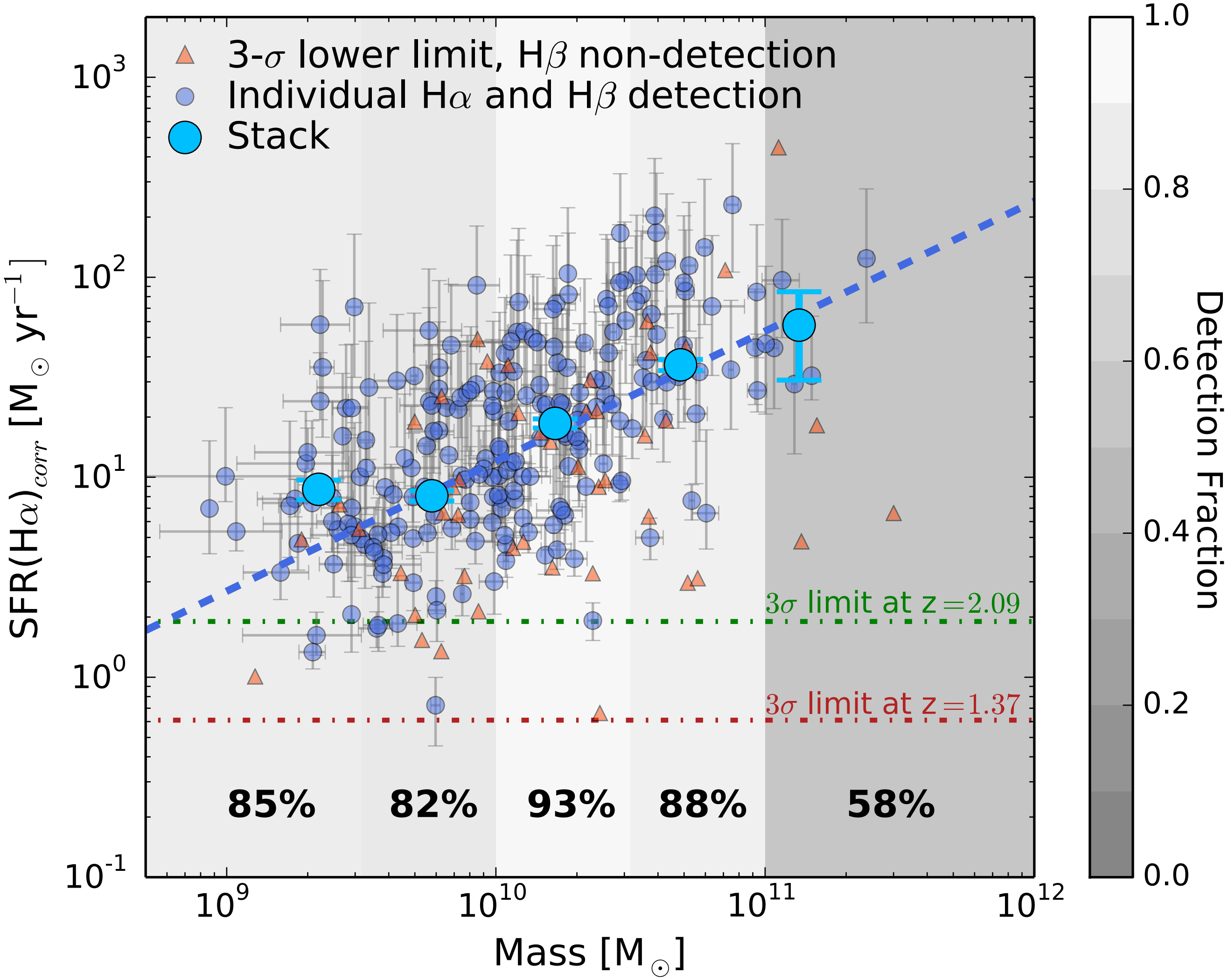
The SFR-M* relation

- Discrepancy in the literature:
  slope ~ 0.3 – 1.0



Speagle+2014

Slope = 0.58 ± 0.10 (z = 2.09 - 2.61)
0.65 ± 0.09 (z = 1.37 - 2.61)



Shivaei et al. 2015b

Slope = 0.58 ± 0.10 (z = 2.09 - 2.61)
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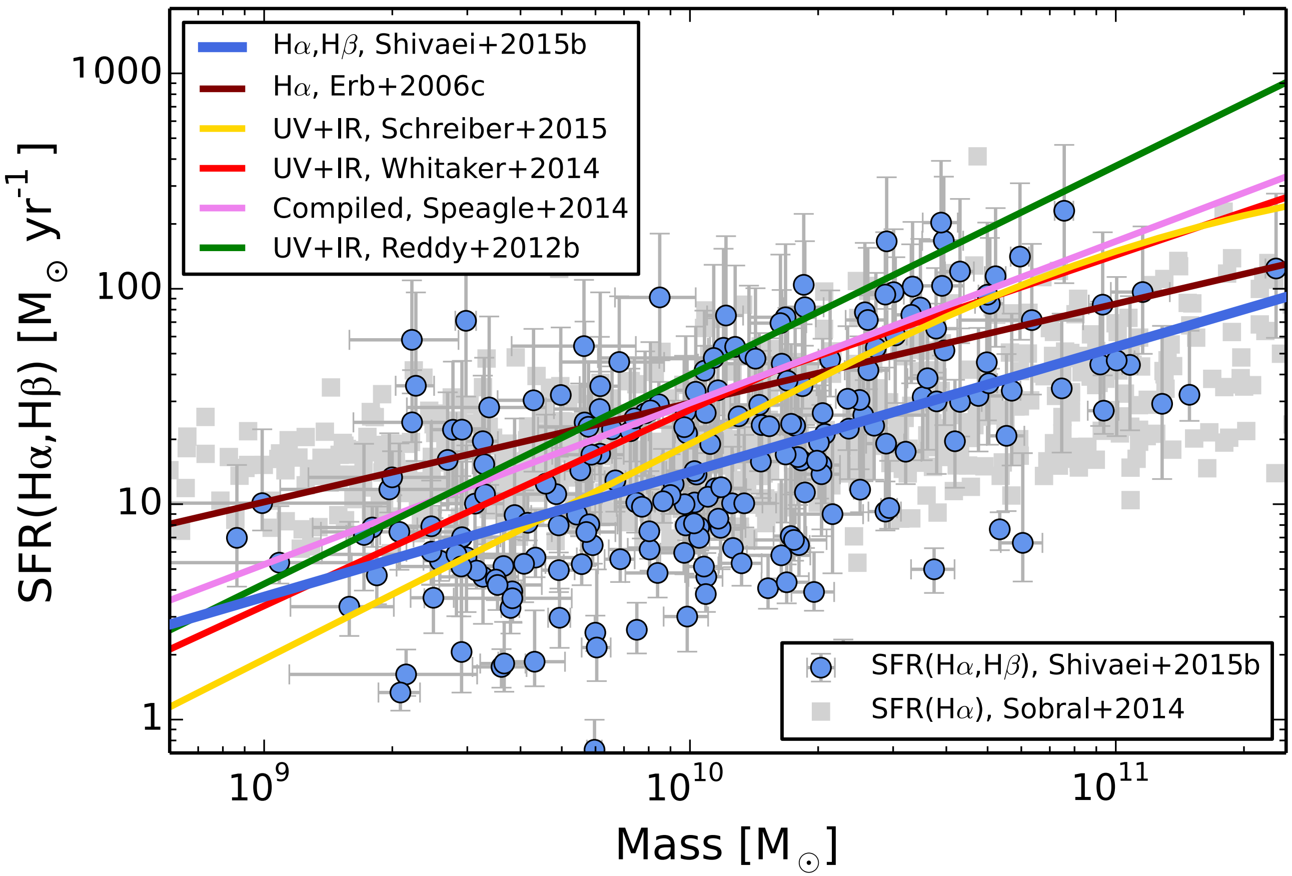
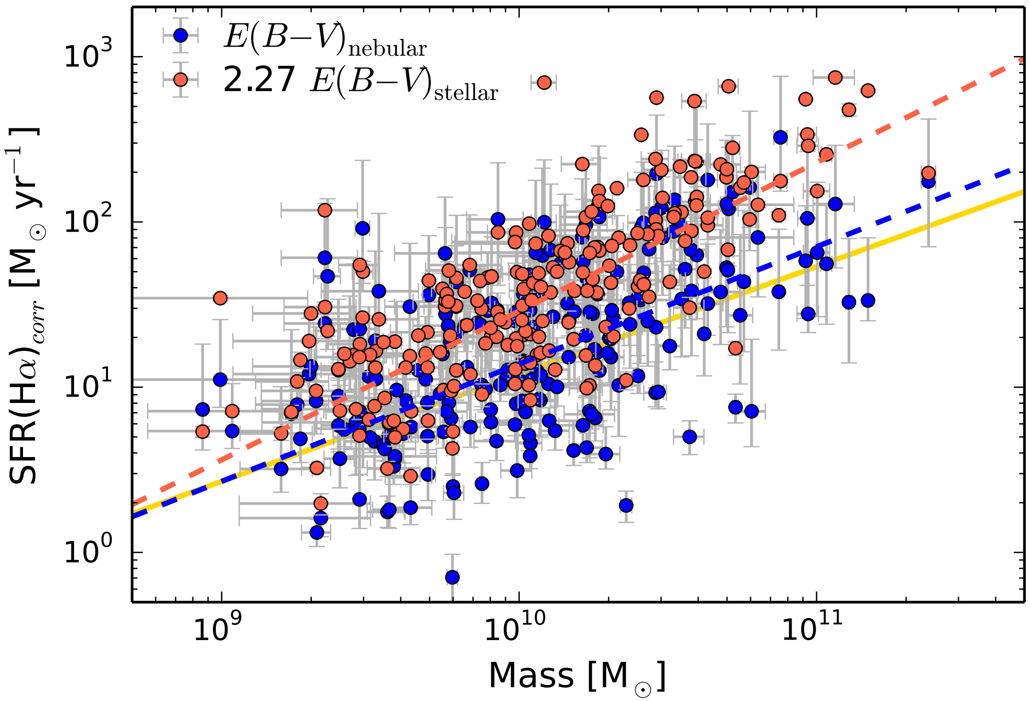


Shivaei et al. 2015b

 Irene Shivaei

- Discrepancy in the literature: slope ~ 0.3 – 1.0
- This study: 0.65 ± 0.09

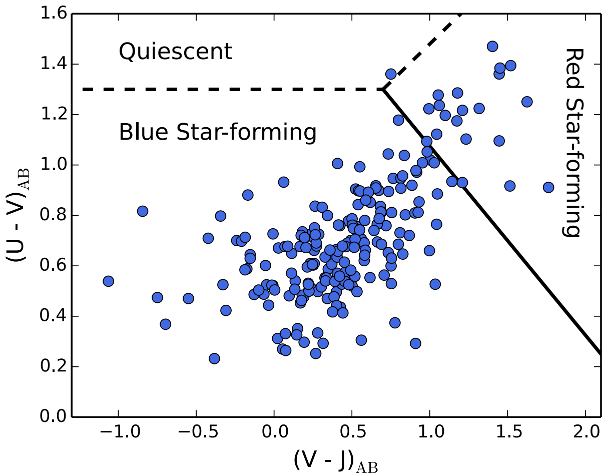
- Dust Correction

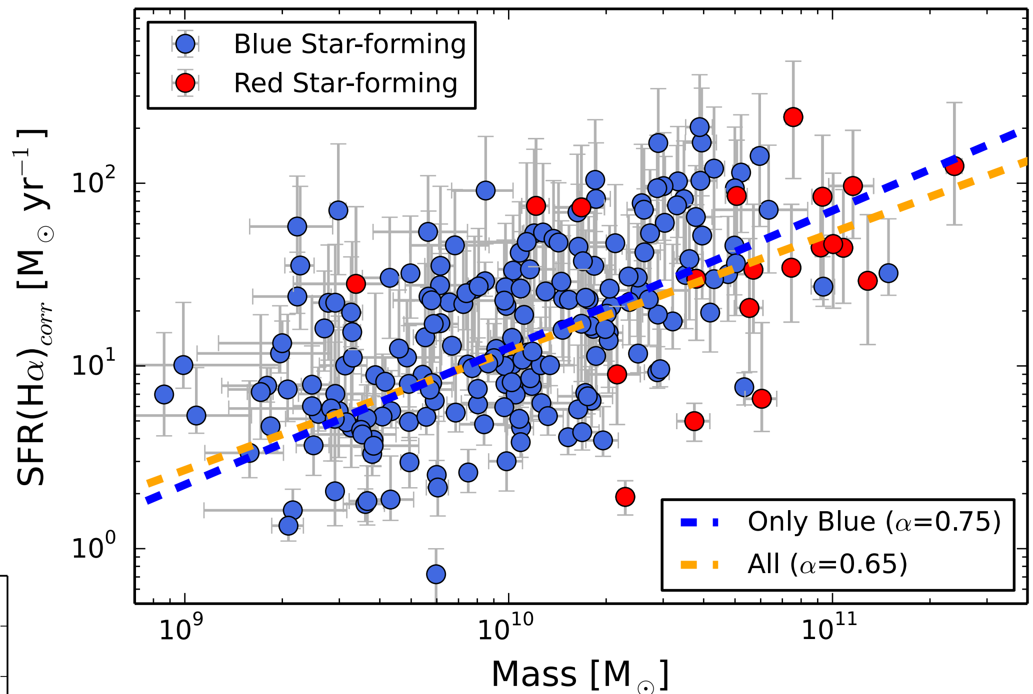


Shivaei et al. 2015b

- Discrepancy in the literature:
  slope ~ 0.3 – 1.0
- This study: 0.65 ± 0.09

- Dust Correction
- Sample biases

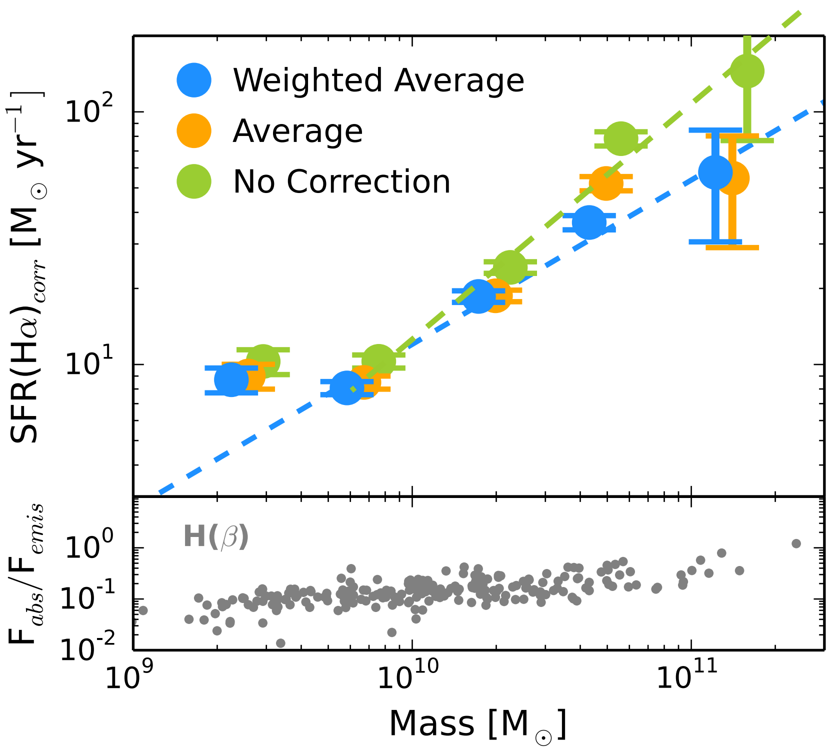




Shivaei et al. 2015b

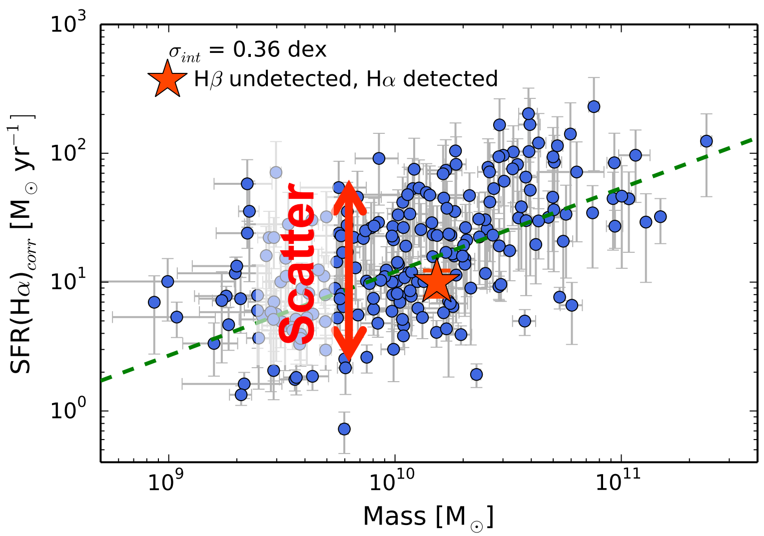
- Discrepancy in the literature:
  slope ~ 0.3 – 1.0
- This study: 0.65 ± 0.09

- Dust Correction
- Sample biases
- Absorption Correction



Shivaei et al. 2015b

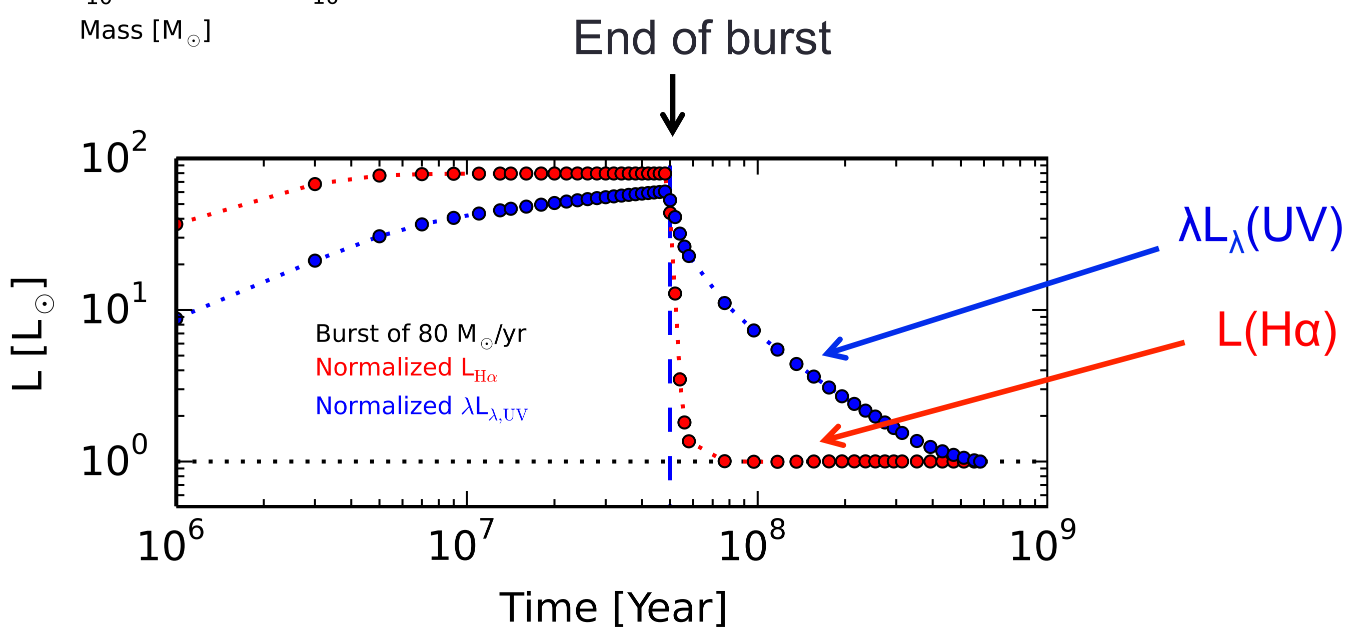
The SFR Scatter



Difference in the scatter of SFR(Hα)-M* and SFR(UV)-M*

SFR(UV): O and B type stars

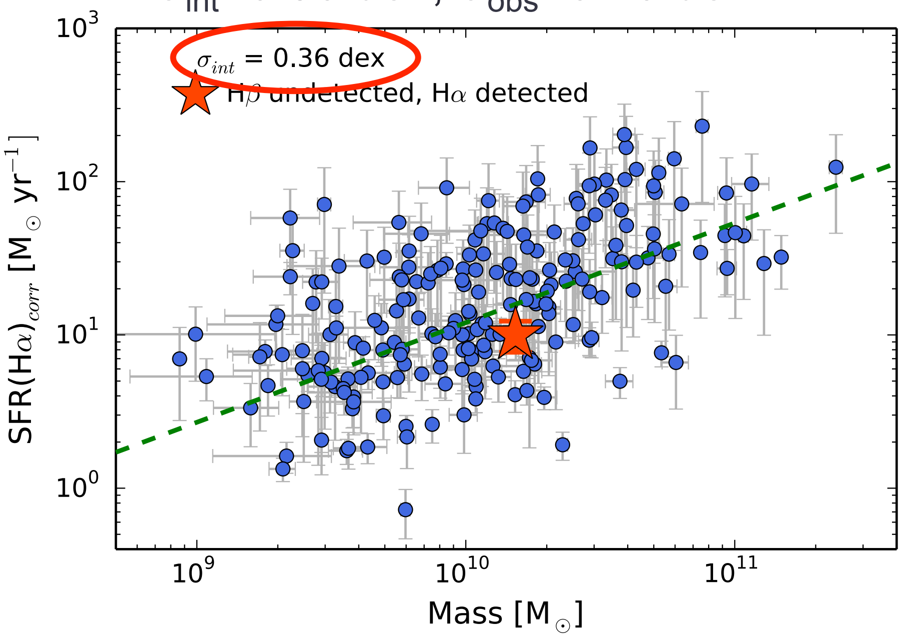
SFR(Hα,Hβ): O type stars



The SFR Scatter

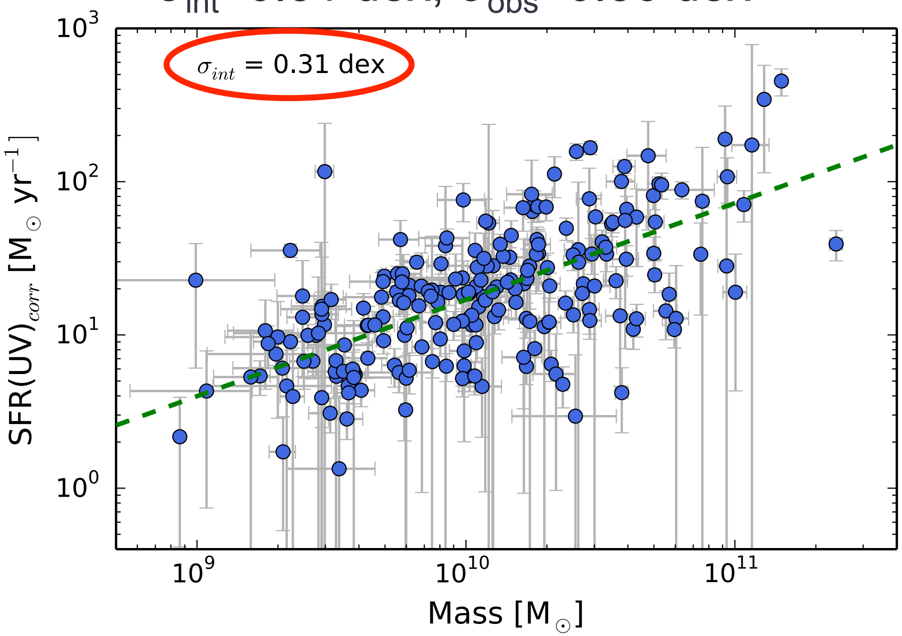
SFR(Hα,Hβ): O type stars

σ_{int}=0.36 dex, σ_{obs}=0.40 dex



SFR(UV): O and B type stars

σ_{int}=0.31 dex, σ_{obs}=0.36 dex



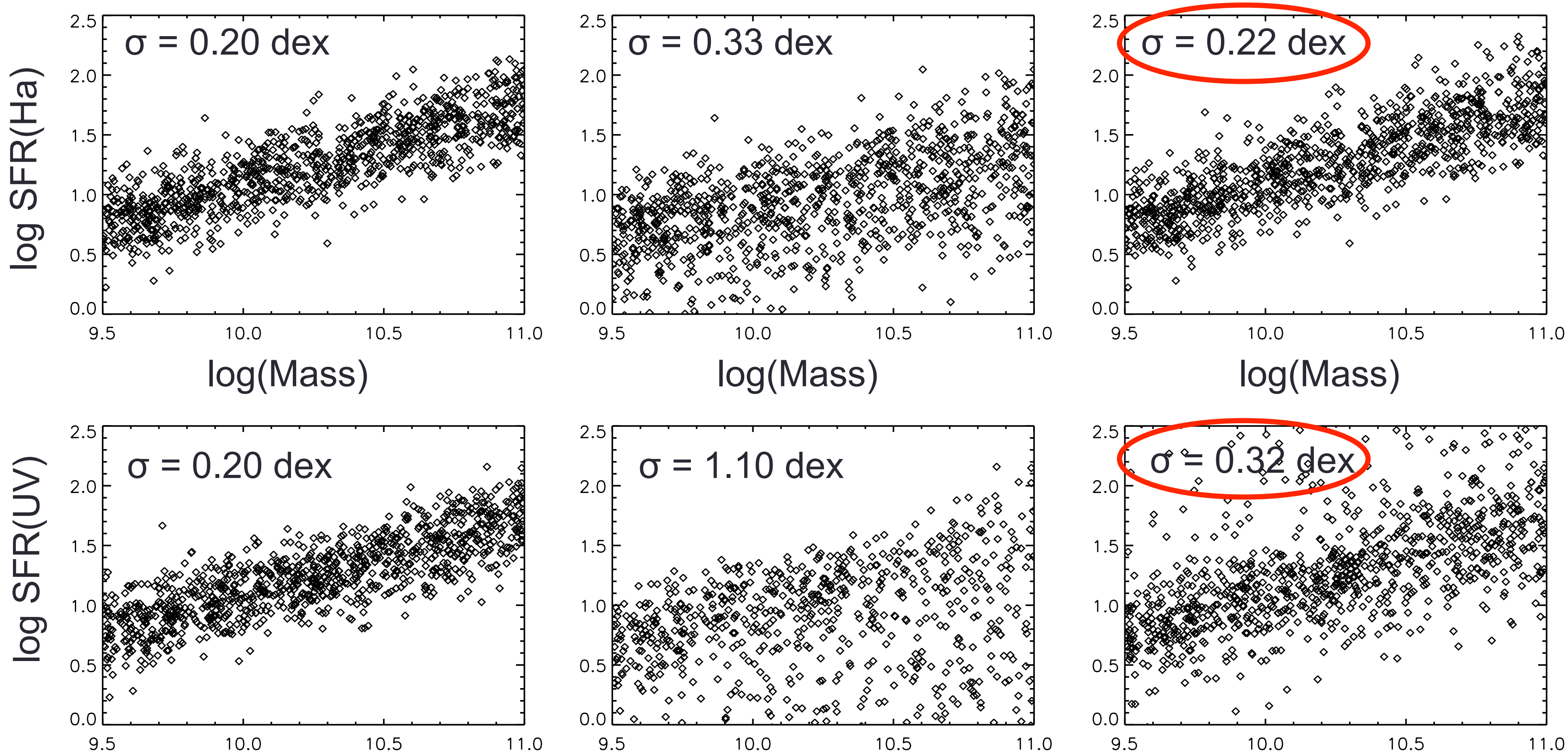
Galaxy-to-galaxy variations in:

- Dust attenuation curve
- IMF

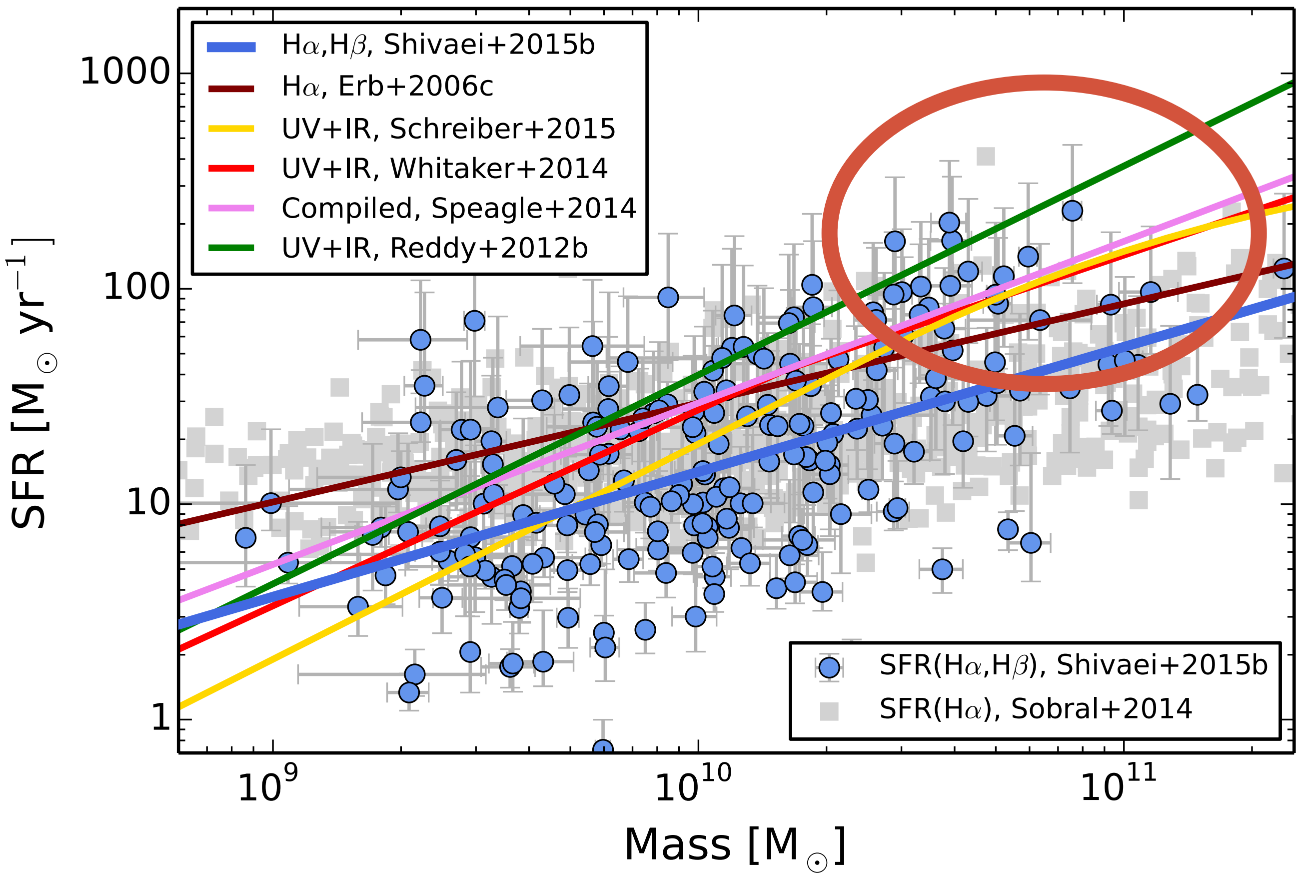
Shivaei et al. 2015b

Galaxy-to-galaxy variations in attenuation curve

Simulated → Attenuated, assuming different attenuation curves → Dust-corrected, assuming a single attenuation curve

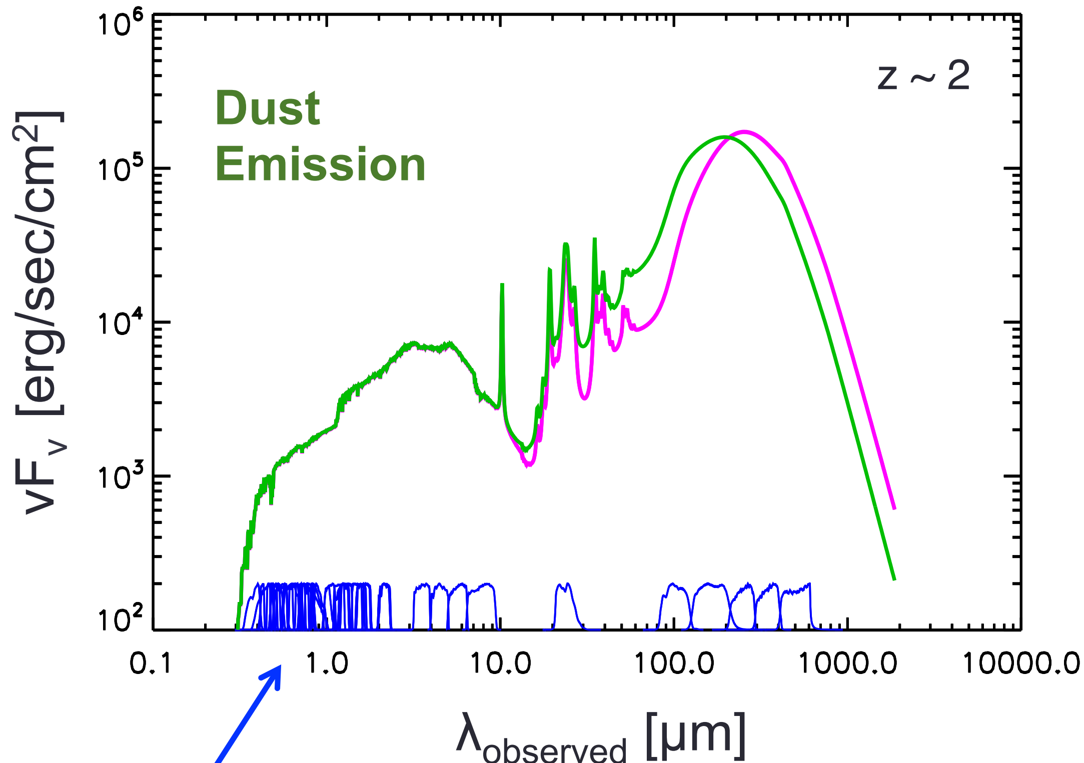


Are Hα and Hβ good tracers of SFR at z ~ 2?



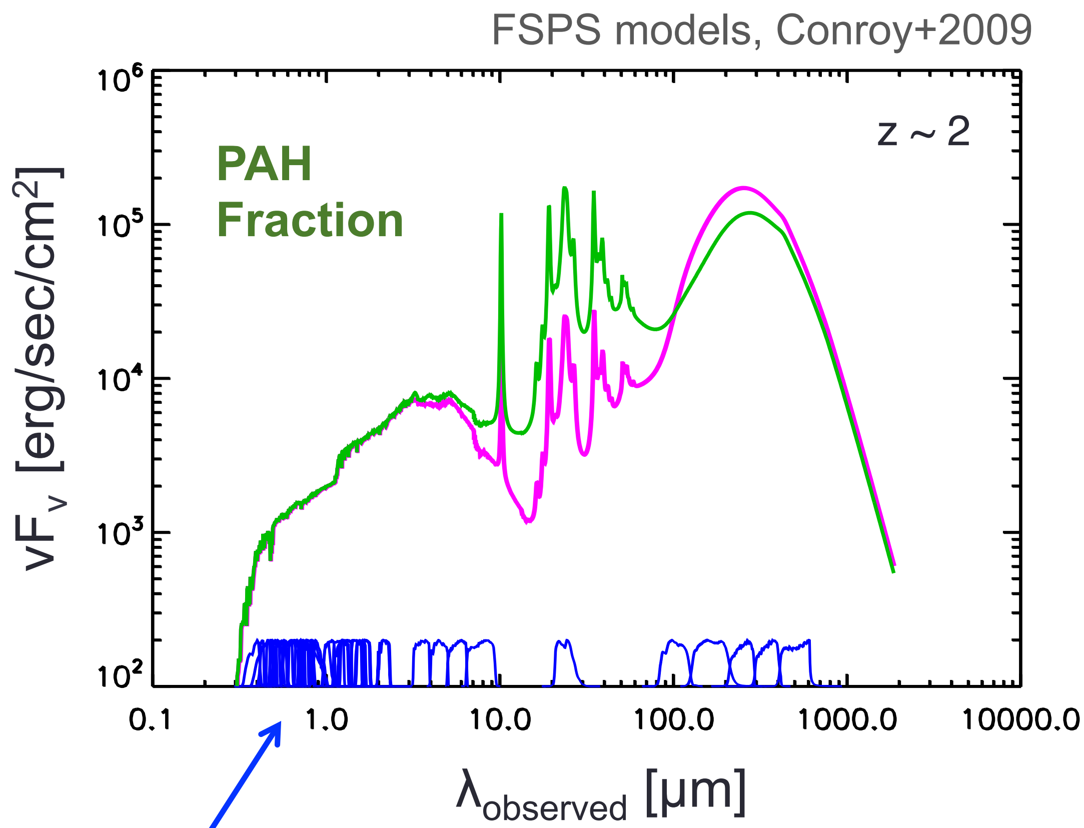
Panchromatic SED Modeling

FSPS models, Conroy+2009



Observed photometry from
0.3 to 500 μm

Panchromatic SED Modeling



Observed photometry from
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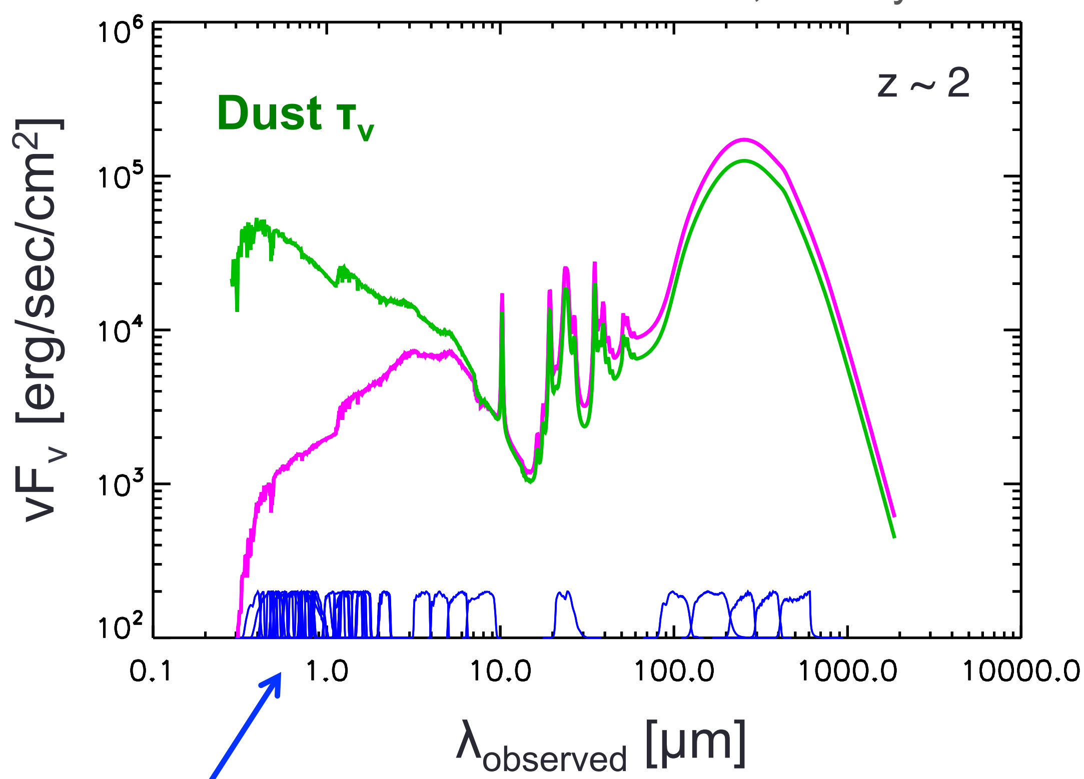
Panchromatic SED Modeling

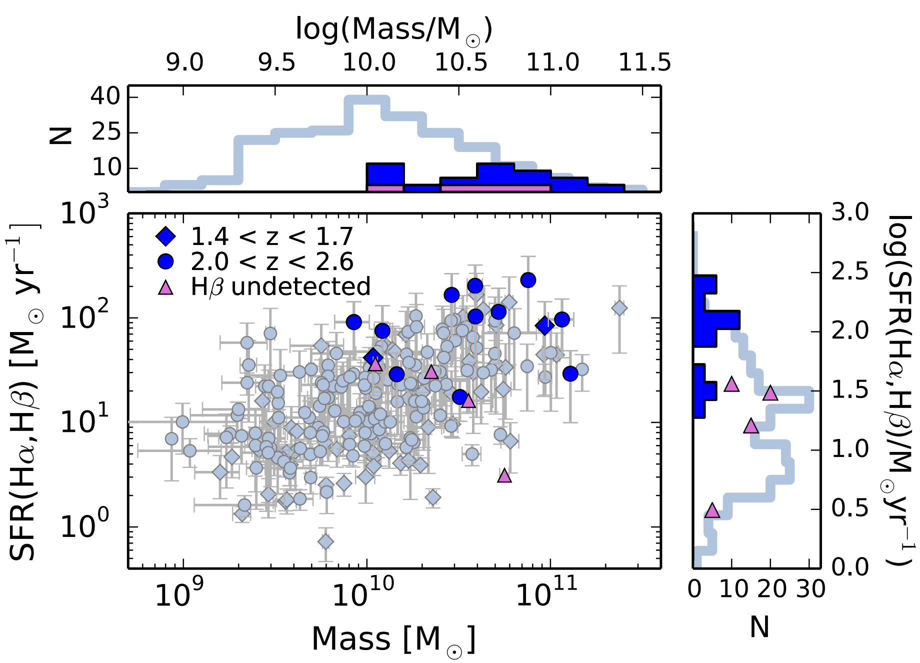
FSPS models, Conroy+2009

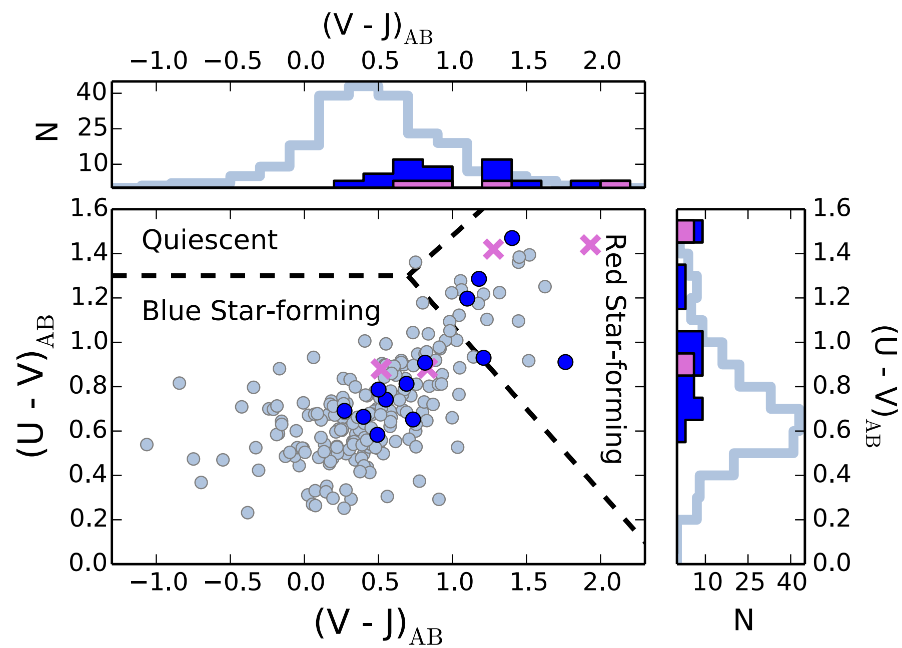


Observed photometry from
0.3 to 500 μm

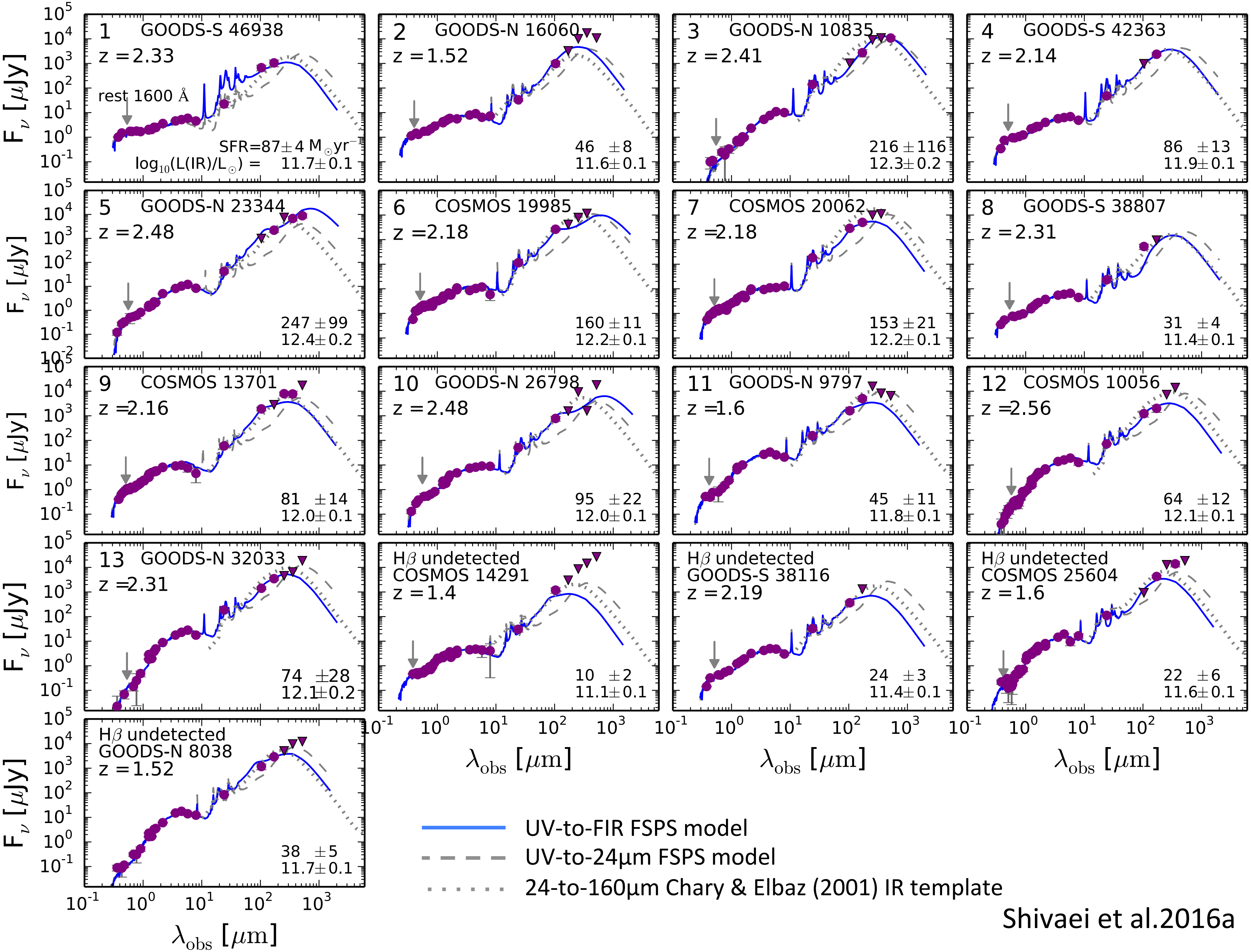
Selected 17 galaxies (out of ~100):

- Detection for Hα and at least two IR bands
  - 13 with both Hα and Hβ detected
- No AGN
- No nearby contamination in IR photometry

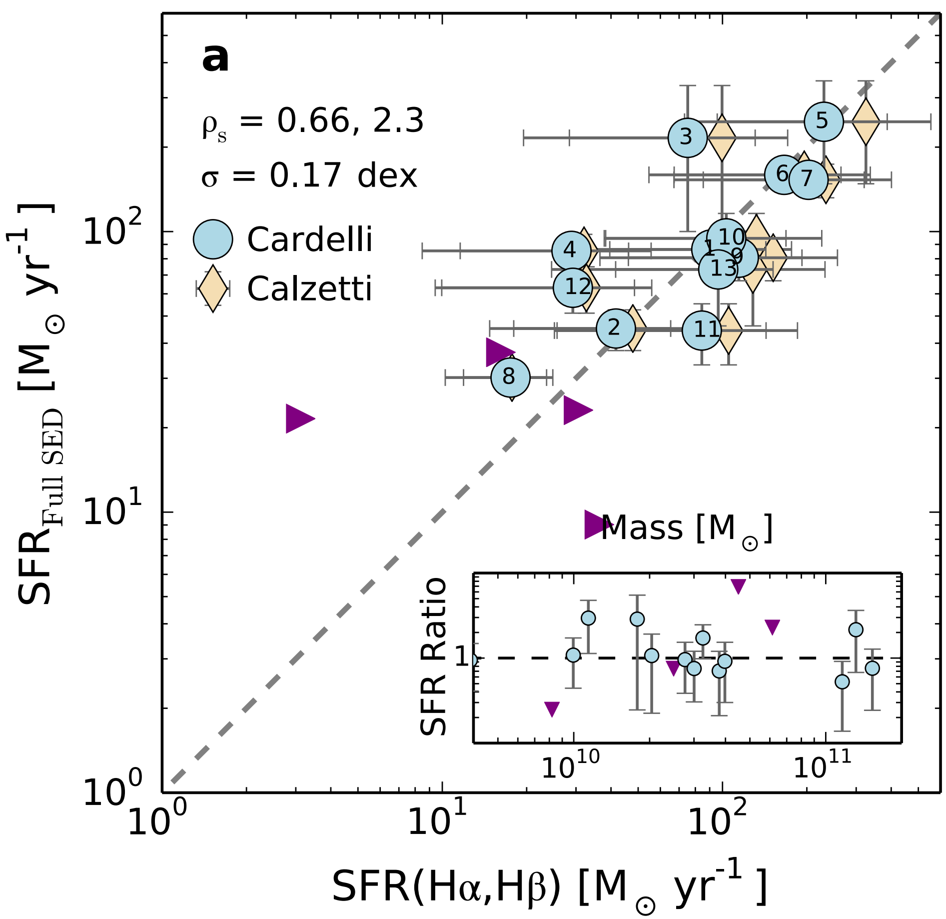




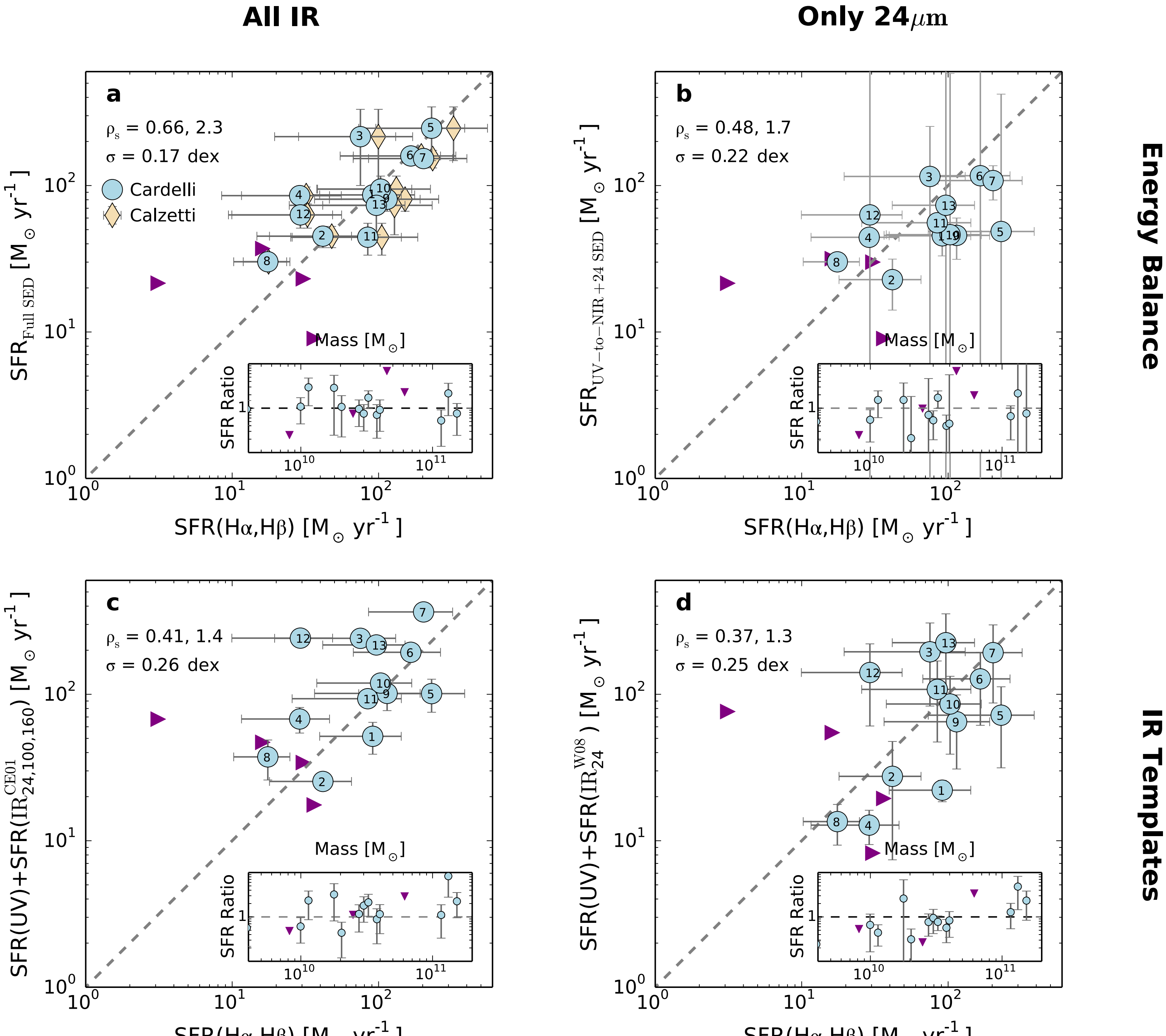
Shivaei+2016a



Shivaei et al.2016a



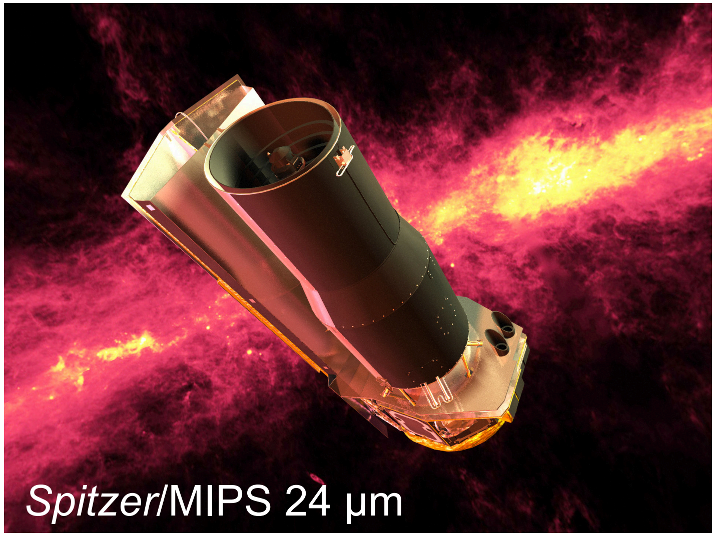
Shivaei et al. 2016a

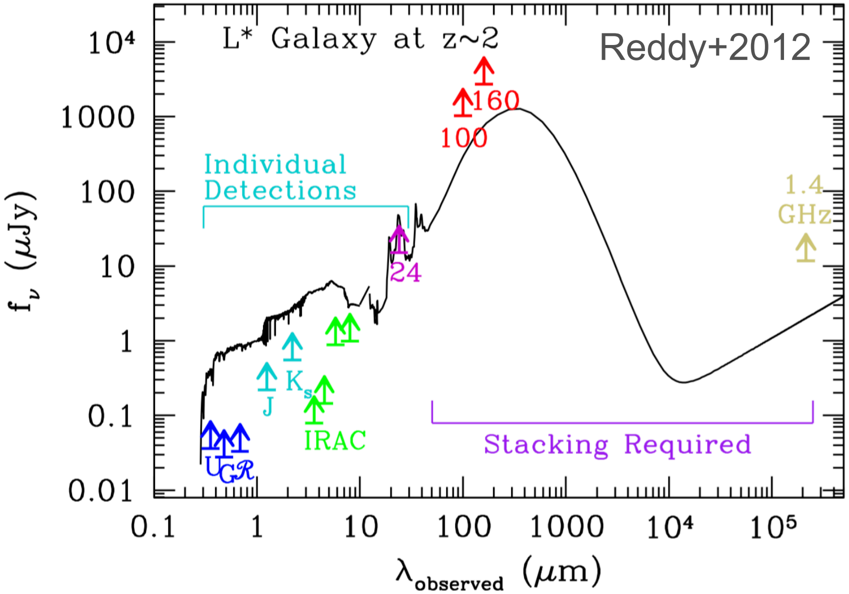


Shivaei et al. 2016a

AND PAH EMISSION

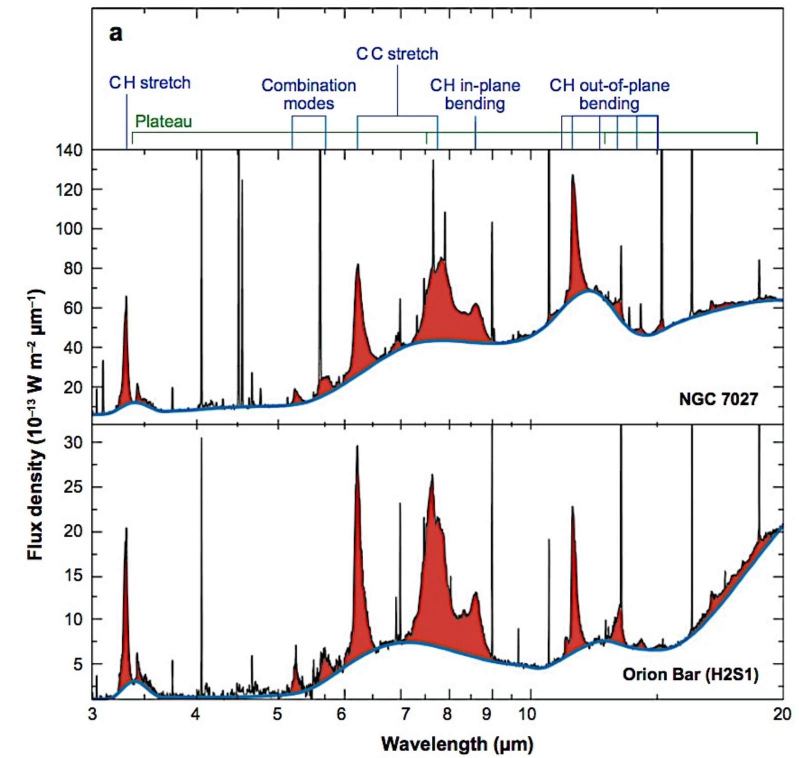
Is 8μm a good tracer of SFR?



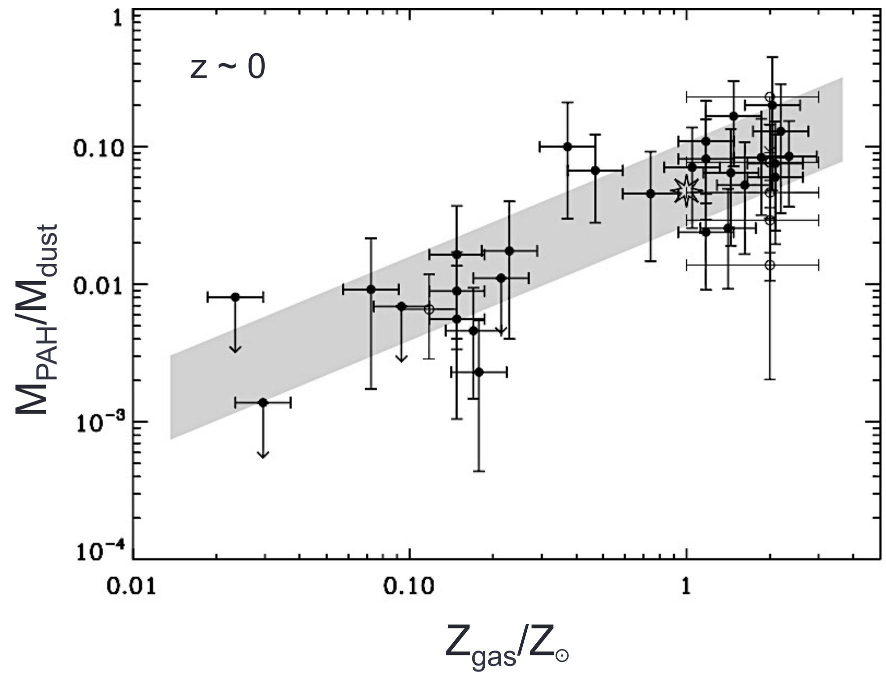


The PAH emission at 7.7μm

Tielens 2008



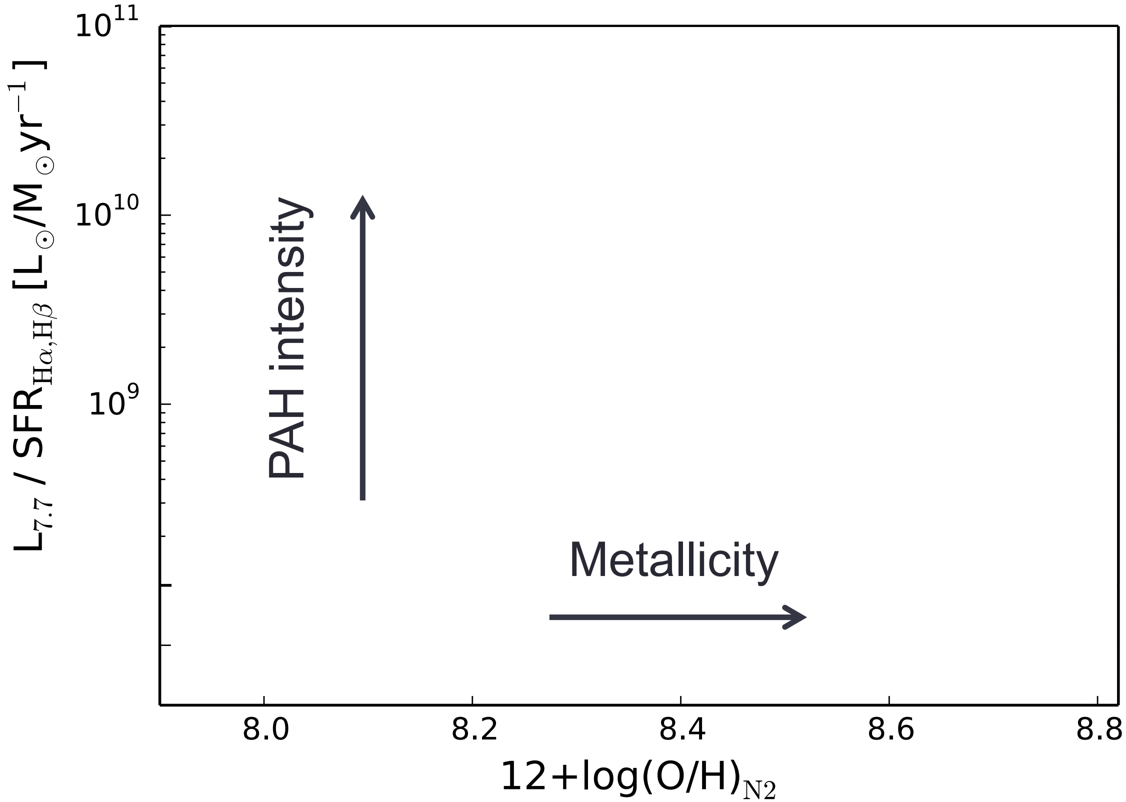
Galliano+2008



Mid-IR PAH bands

PAH correlation with metallicity

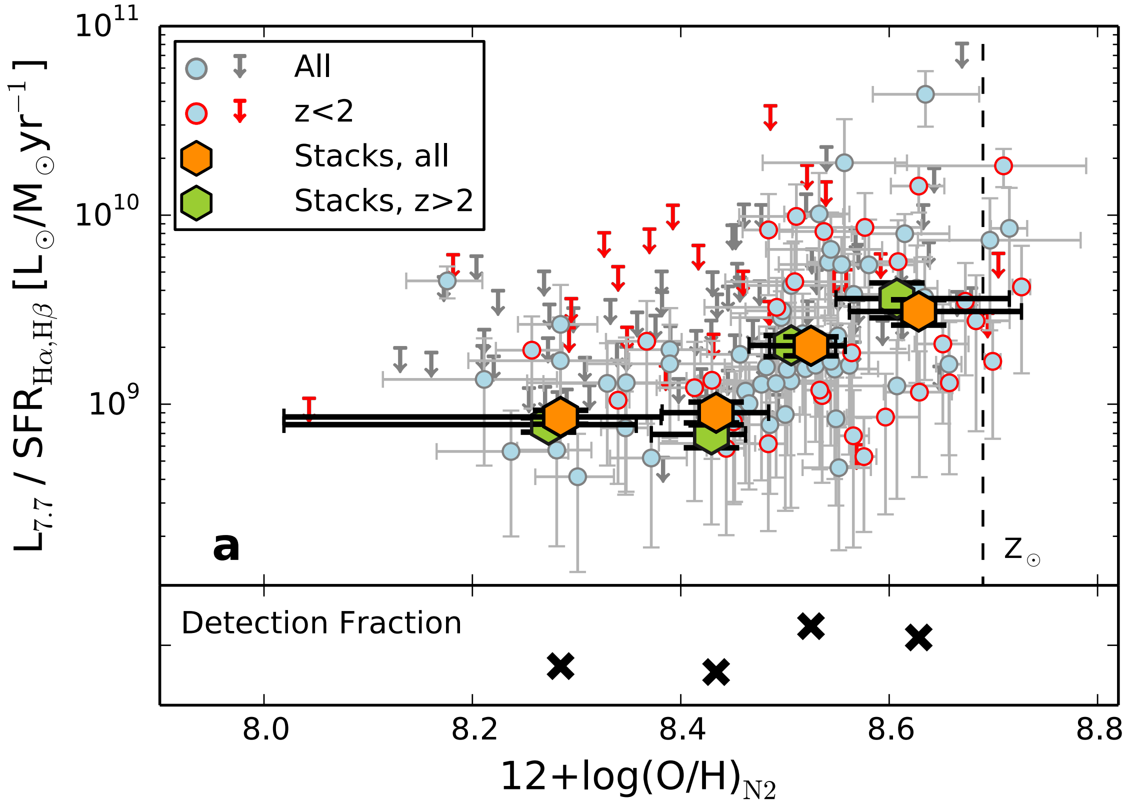
Is 7.7µm a good tracer of SFR?



Strength of 7.7µm luminosity for a given SFR is metallicity-dependent

Shivaei et al. 2016, submitted

Is 7.7μm a good tracer of SFR?



Strength of 7.7μm luminosity for a given SFR is metallicity-dependent

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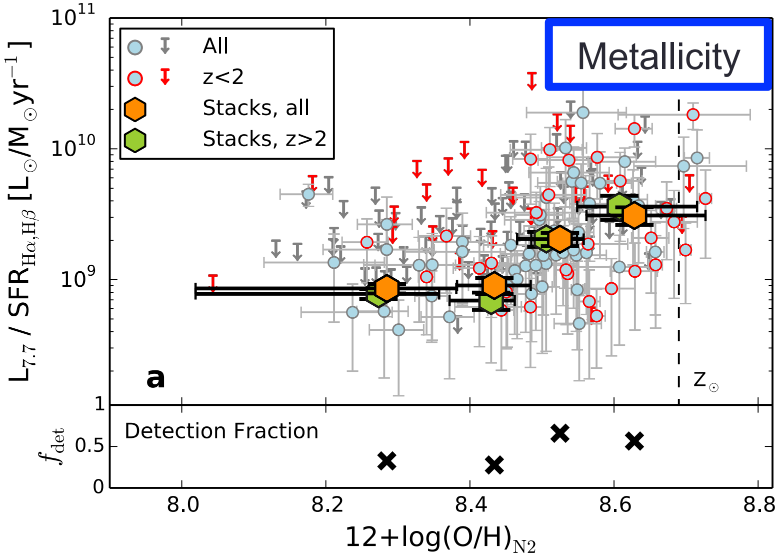
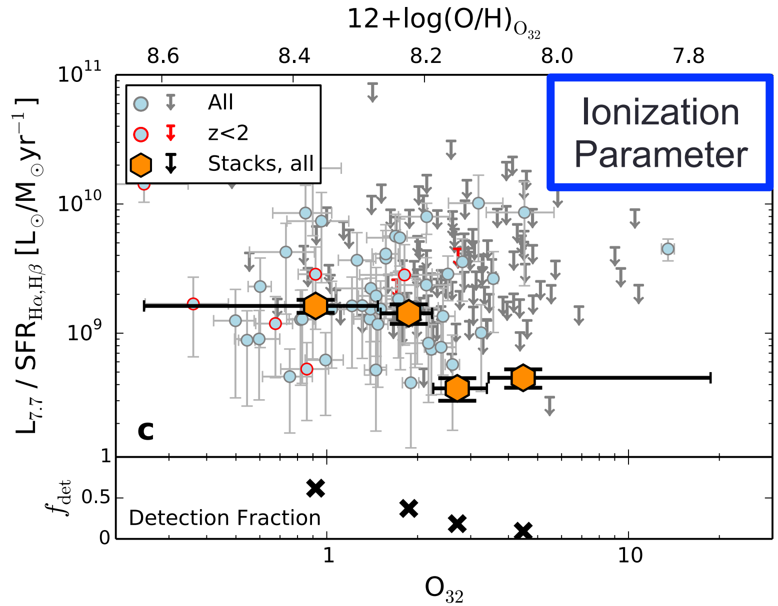
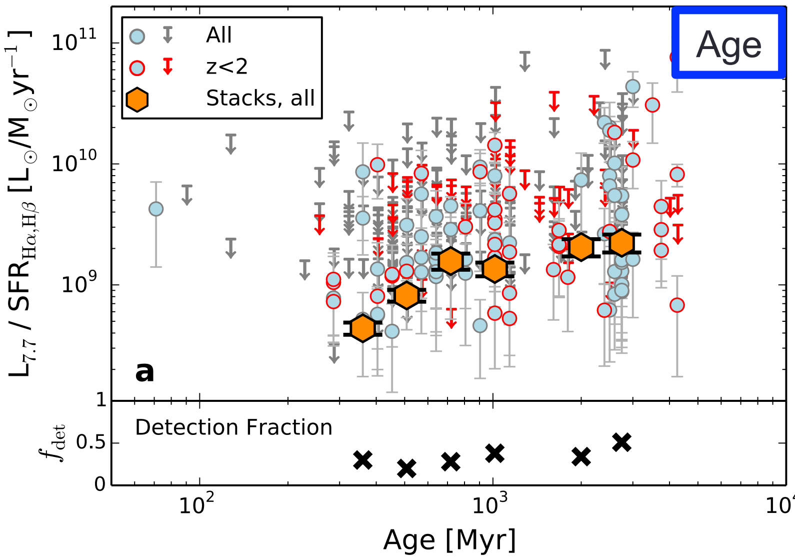
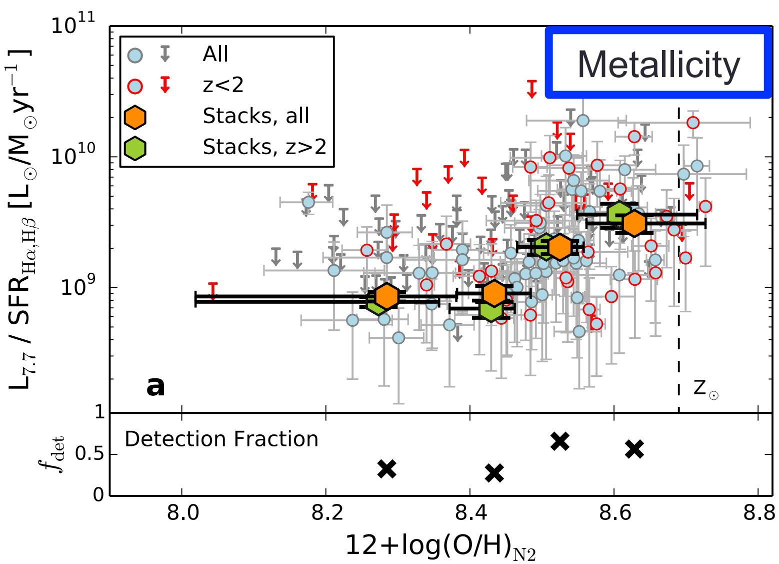


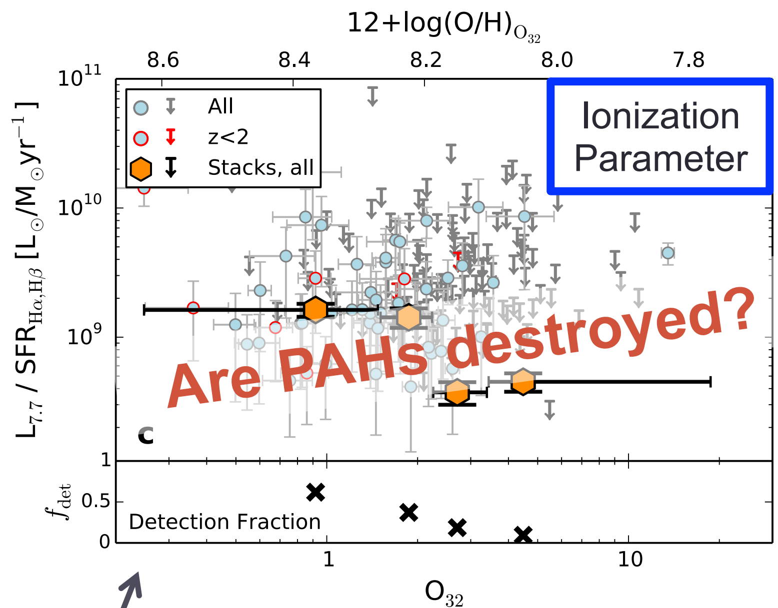


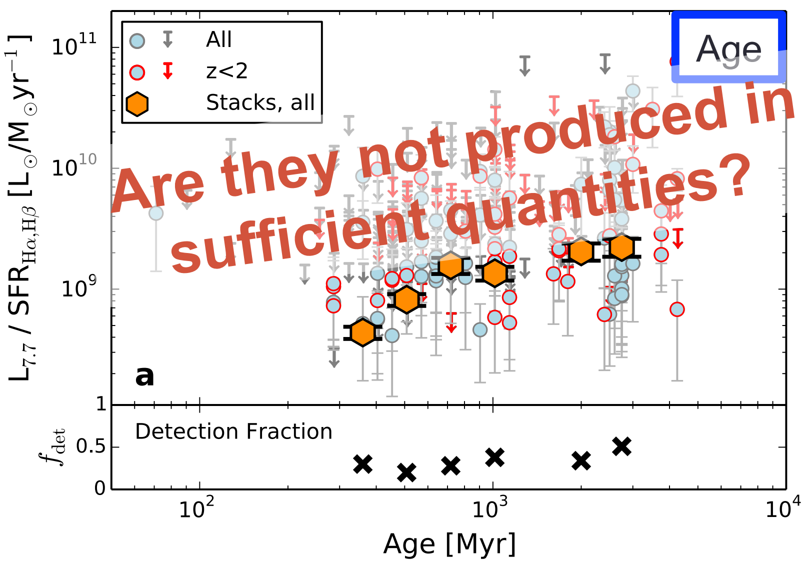


Why is the PAH intensity correlated with metallicity?

Shivaei et al. 2016, submitted



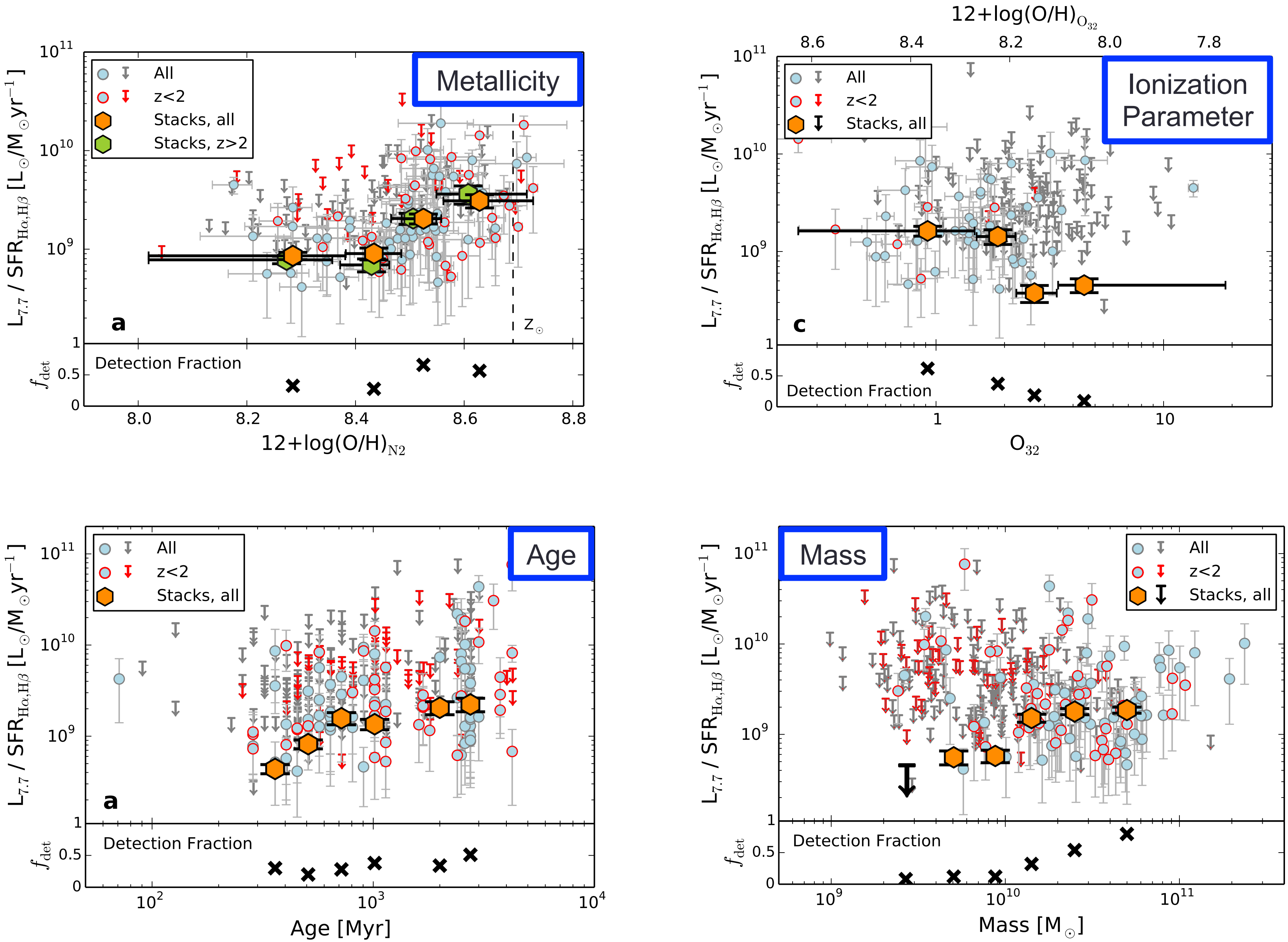




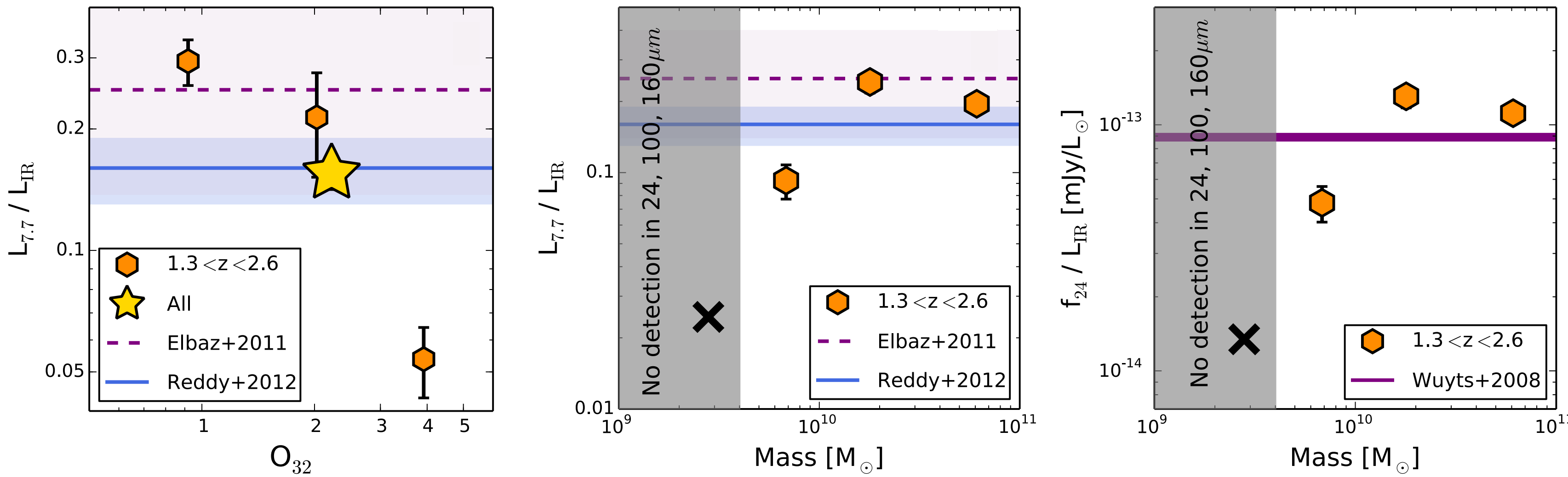
Why is the PAH intensity correlated with metallicity?

- The “nurture” scenario
- The “nature” scenario

Shivaei et al. 2016, submitted



Shivaei et al. 2016, submitted

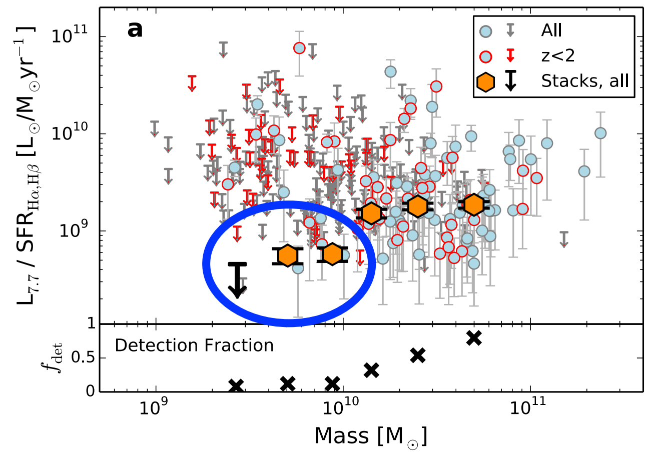


- Commonly-used conversions of L_8 (or f_{24}) to L_{IR} at z ~ 2 are only valid for massive and metal-rich galaxies.
- For galaxies with $M_* < 10^{10} M_\odot$, these conversions should be applied with caution as they underestimate the L_{IR} and SFR_{IR} by a factor of ~ 2.

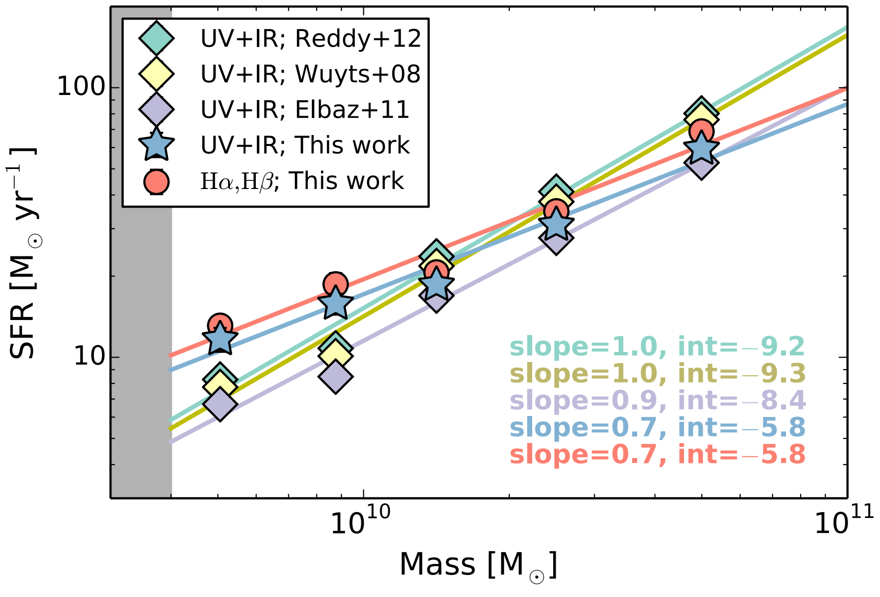
Shivaei et al. 2016, submitted

Implications for high-redshift studies

- The SFR-M* Relation and specific SFR



- Calibrations in the literature underestimate L_{IR} and SFR_{IR} for galaxies with masses below $M_*=10^{10}$ $M_\odot$
- Agreement between our mass-dependent SFR_{UV+IR} estimates and independently-derived $SFR_{H\alpha,H\beta}$
- sSFR at $M_*=10^{9.5}$ $M_\odot$ increases by x1.8

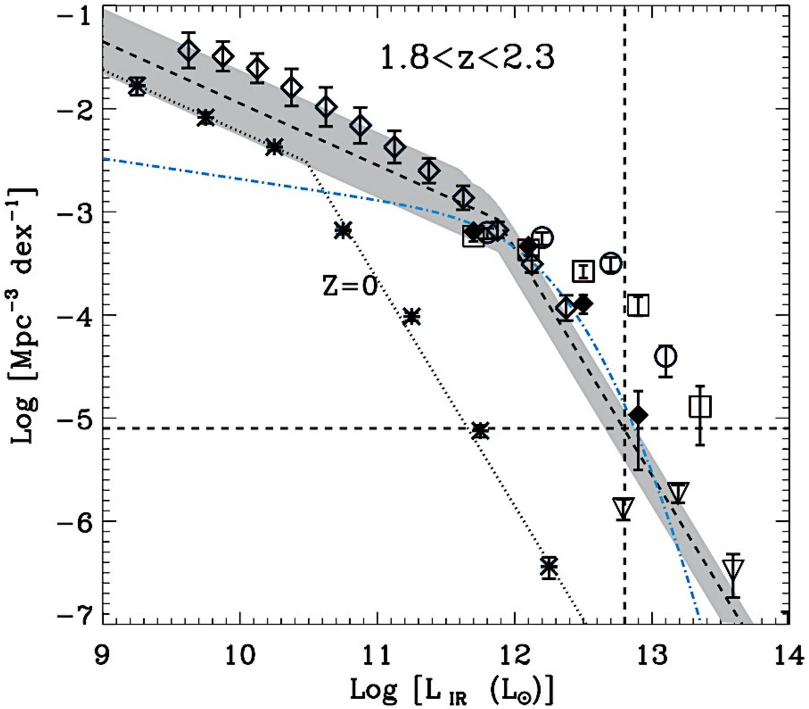


Shivaei et al. 2016, submitted

Implications for high-redshift studies

- The SFR-M_* Relation
- The IR luminosity density at z~2

Magnelli et al. 2011



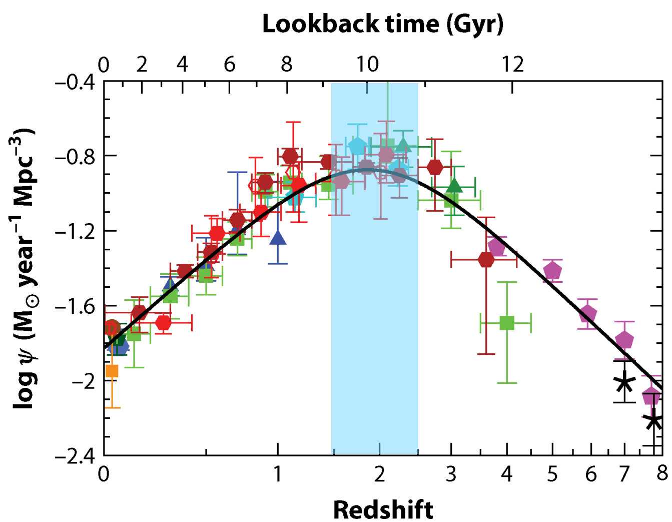
- Simulated 1000 galaxies
- Increased L_{IR} of galaxies below $L_{IR}=10^{11}\ L_\odot$
- Re-fit the luminosity function
- Results:
  - The number density of galaxies in IR bins below $10^{11}\ L_\odot$ increases by ≥ 0.3 dex
  - The faint-end slope steepens from −0.6 to ~ −0.7

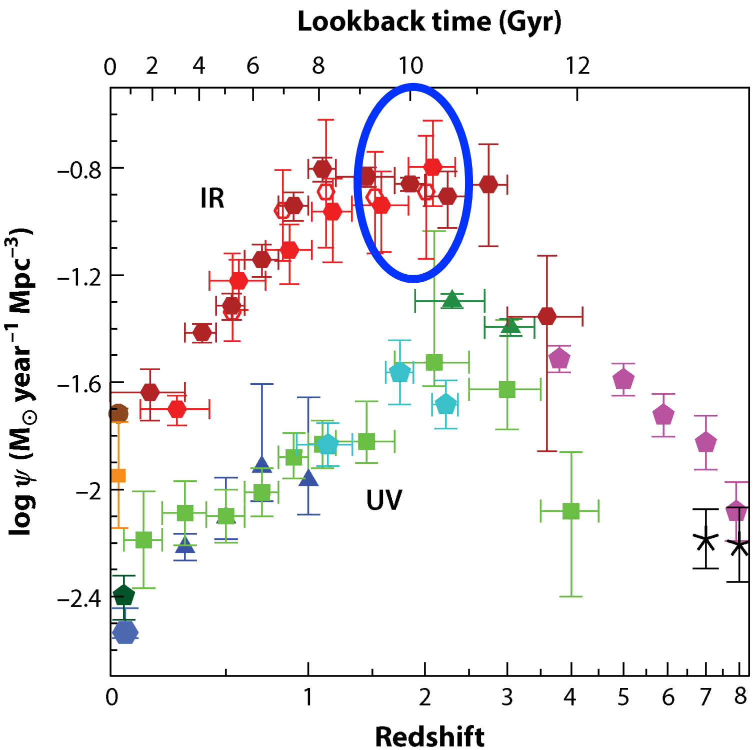
30% increase the IR luminosity density at z~2

Implications for high-redshift studies

- The SFR-M_* Relation
- The IR luminosity density at z~2
- The SFR density at z~2

30% increase in the SFR density at z~2



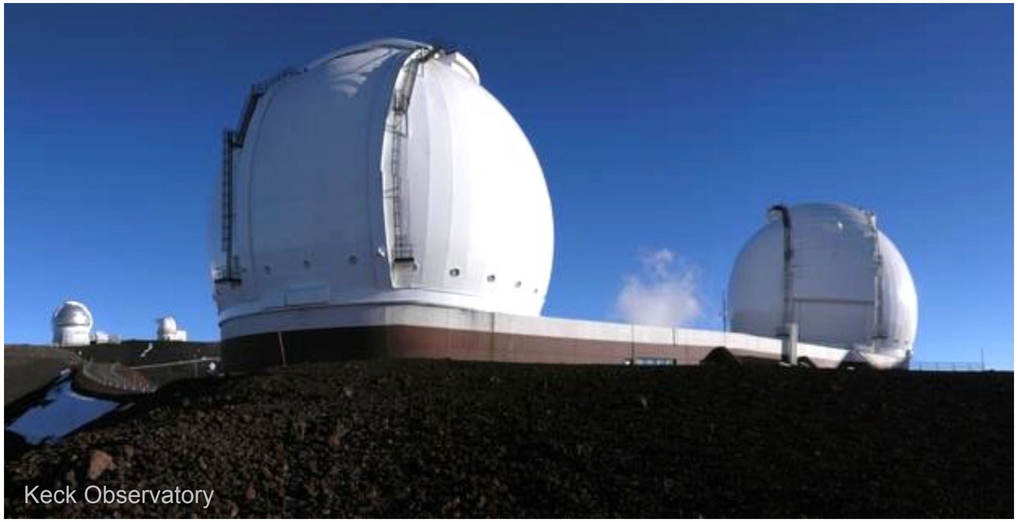


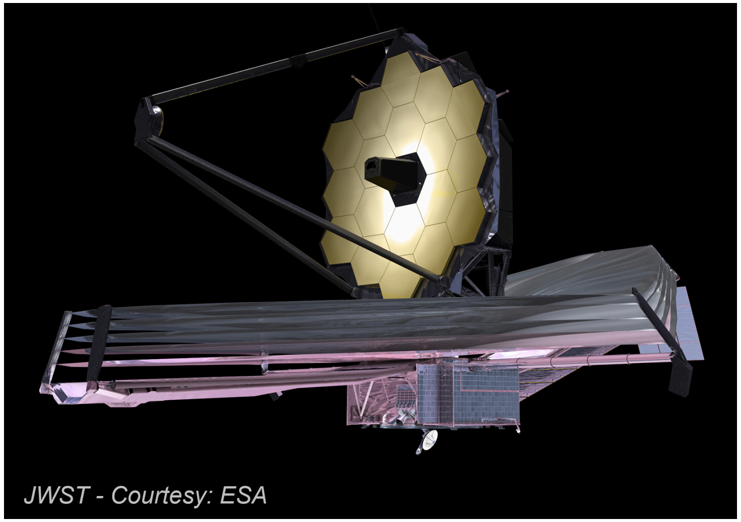
Madau P, Dickinson M. 2014.
Annu. Rev. Astron. Astrophys. 52:415–86

Current / Future Projects

- Other dust properties of galaxies at z~2
  - Investigating variations of the 2175Å extinction feature and its relation with the strength of the PAH 7.7μm feature
  - Determination of the dust attenuation curve of z~2 galaxies, using the full sample of MOSDEF with ~1000 galaxies
- Stochasticity of star formation in galaxies with low Hα/UV ratios using their rest-frame UV spectra (Keck/LRIS)

- Tracing PAH features in high-redshift galaxies (*JWST*/MIRI)
- Exploring dust grains destruction and production mechanisms (Keck, *JWST*, ALMA)


Keck Observatory


JWST - Courtesy: ESA

- Using the MOSDEF Hα and Hβ spectroscopic data, we **constrain the slope and scatter of the SFR-M_* relation** for star-forming galaxies at z ~ 2 *(Shivaei+2015b)*
- We show that by assessing the scatter in the SFR-M_* relation, unless we have direct measurements of galaxy-to-galaxy variations in the dust attenuation curve, we cannot constrain star formation stochasticity
- Even at high SFRs, **dust-corrected Hα luminosity,** using Balmer decrement, **is an accurate tracer of SFR** *(Shivaei+2016)*
- **Rest-frame 8μm luminosity is strongly dependent on metallicity** and should be treated with caution as a SFR and total IR luminosity estimator *(Shivaei+2016, submitted)*
    - The IR luminosity density and SFR density at z~2 are 30% higher than previously estimated
- With *JWST,* we will be able to observe PAH features and probe their physical conditions in even higher redshift galaxies