Subaru seminar @ Subaru Telescope, NAOJ

10 March 2015

Physical conditions of the interstellar medium in star-forming galaxies at z~1.5

To be re-submitted soon to PASJ

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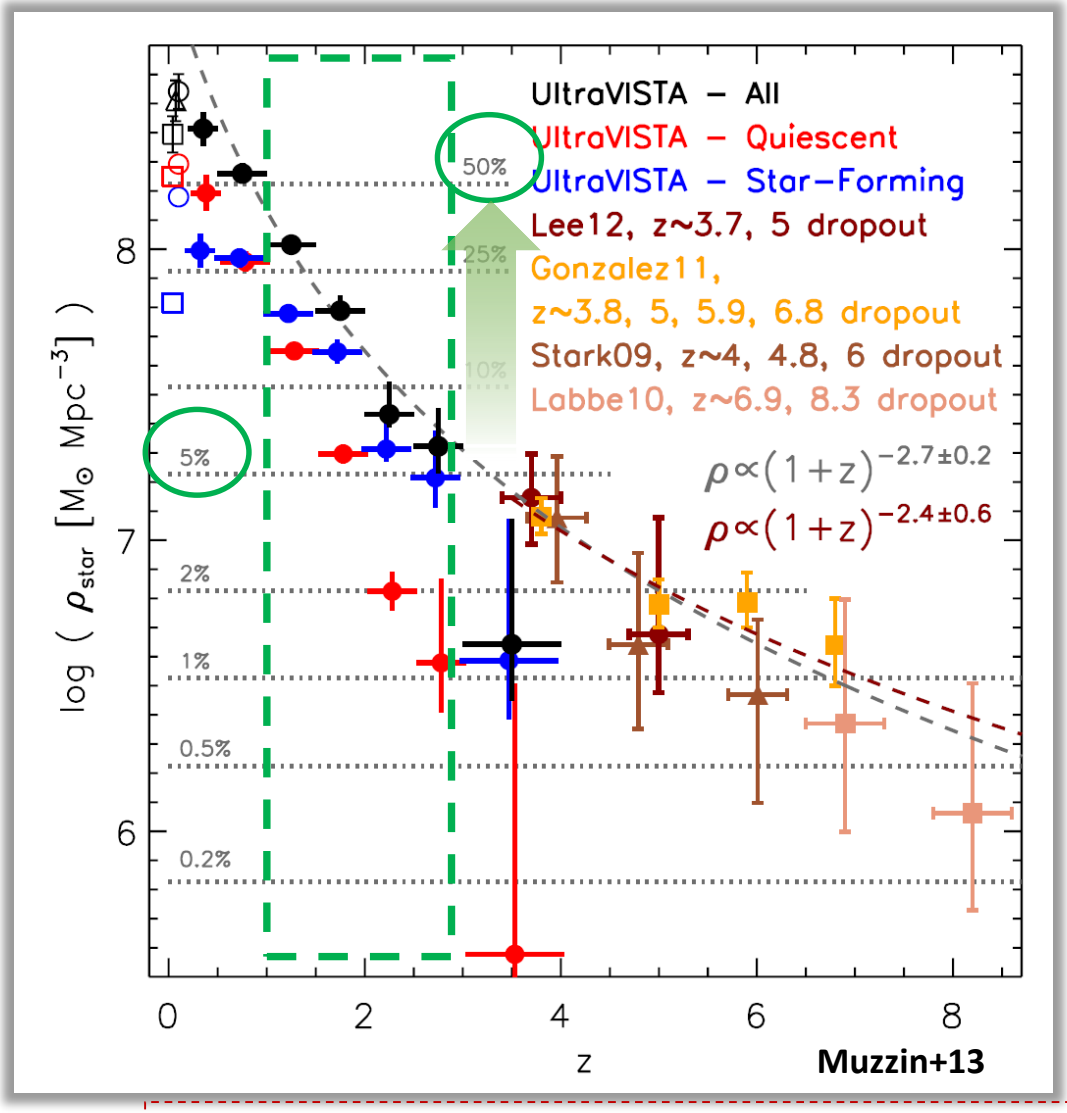
Abstract

- Subaru/FMOS near-IR spectroscopy for 118 [OII] emission line galaxies at z~1.5 in the Subaru Deep Field
- Six nebular emission lines in rest-optical: [OII], Hβ, [OIII], Hα, [NII], and [SII]
- Use the line ratios to investigate physical conditions of the ISM

A period called "Cosmic High Noon"



- **Stellar mass density**:
~10 times from ~5% to ~50%
(e.g., Muzzin+2013)

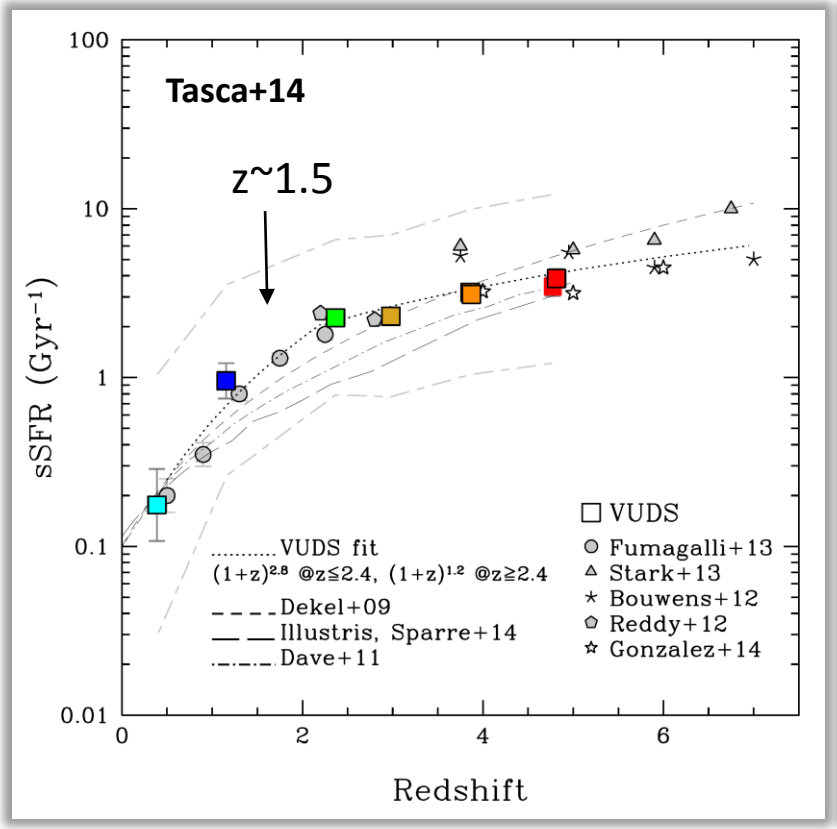
- **Star formation rate density**:
a peak at z=1-3 (e.g., Hopkins & Beacom 2006)

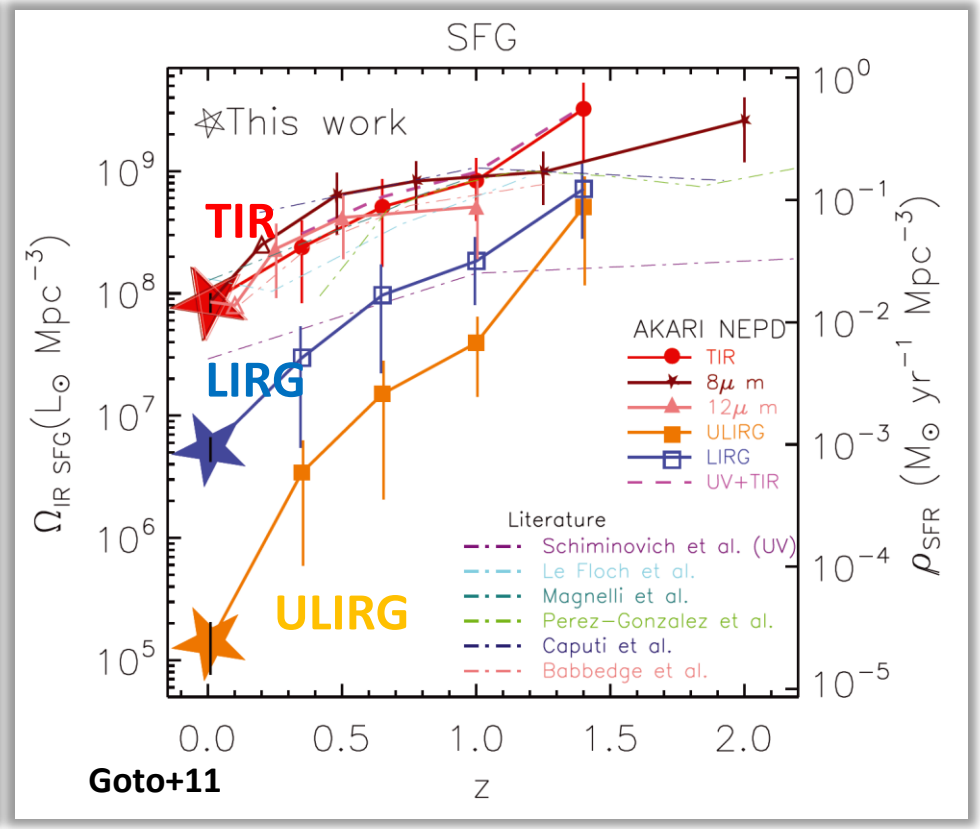
- **AGN activity**:
a peak at z=2-3 (e.g., Hopkins+2007)

- **Morphology**:
from irregular to one classifiable as a Hubble sequence
(e.g., Conselice+2005)

The redshift of z=1-3 is an era of ***rapid evolution*** of galaxy properties

Enhanced star formation activity at z>1.5





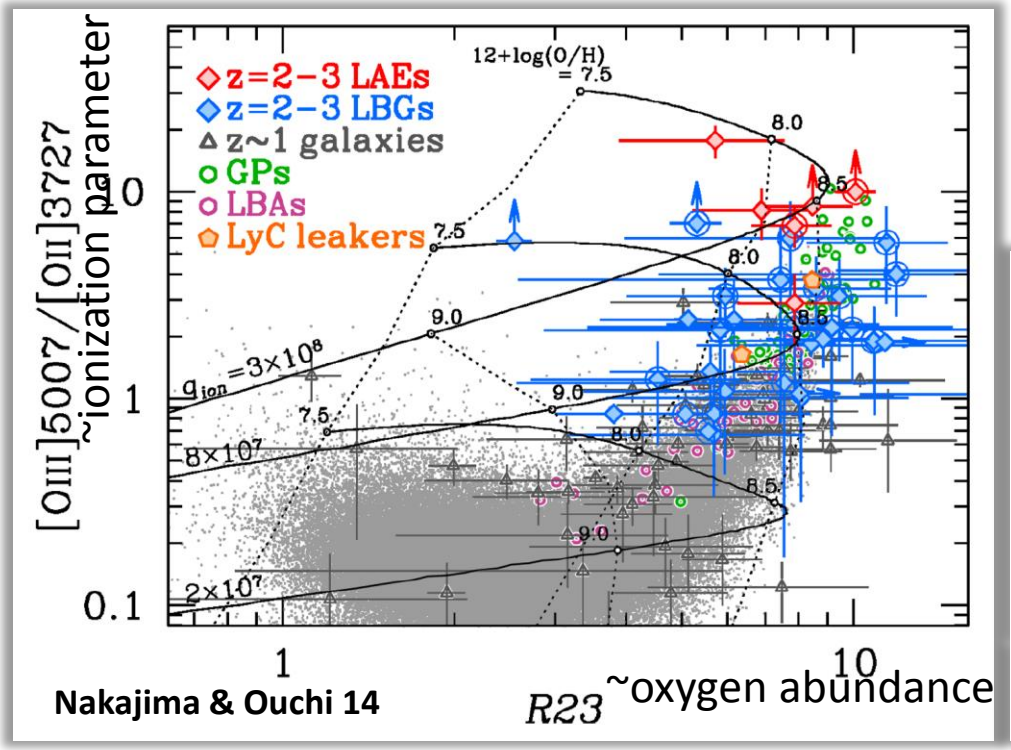
Specific SFR (SFR/M*) of galaxy is increasing with redshift higher

The contribution of LIRGs and ULIRGs to cosmic SFR density is increasing as redshift is higher

Larger contribution of young massive stars to radiation field can alter the condition of the ISM in high-z galaxies, compared to local galaxies.

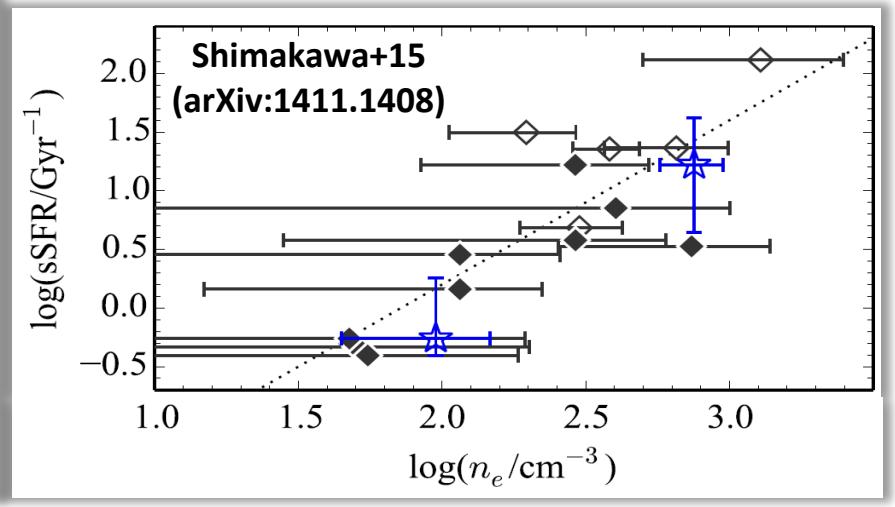
Physical condition of ISM for SF galaxies at z=2-3

Lyα emitters and Lyman break galaxies at z=2-3



Higher ionization parameter of LAEs and LBGs at a given metallicity

Hα emitters at z=2.2-2.5



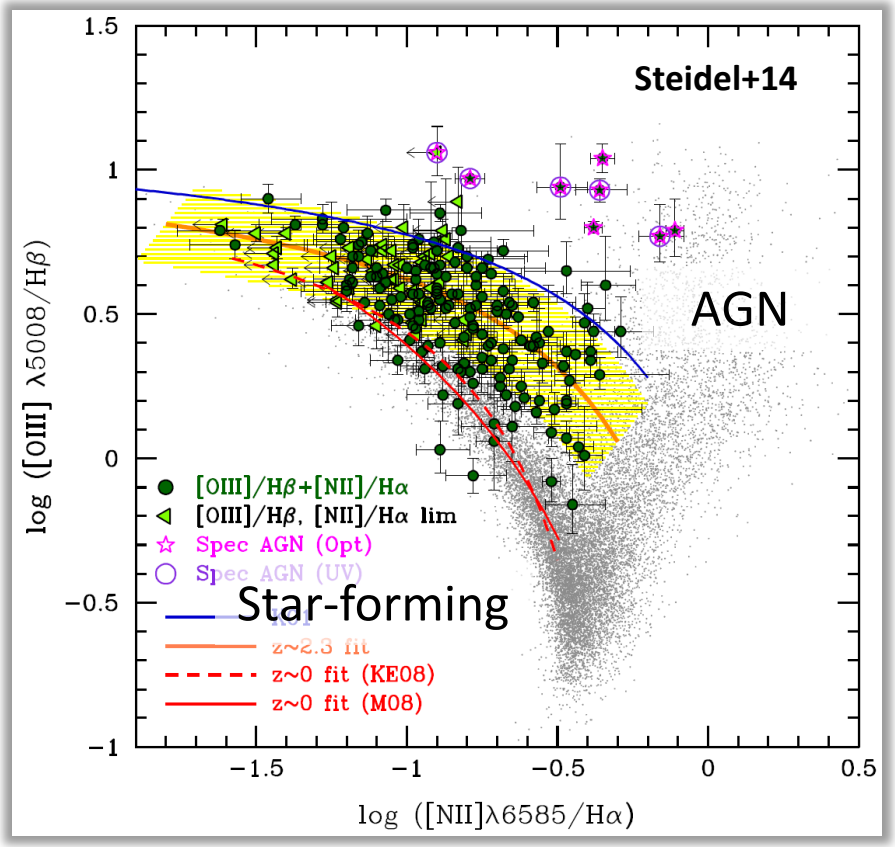
Positive correlation between electron density (n_e) and specific SFR

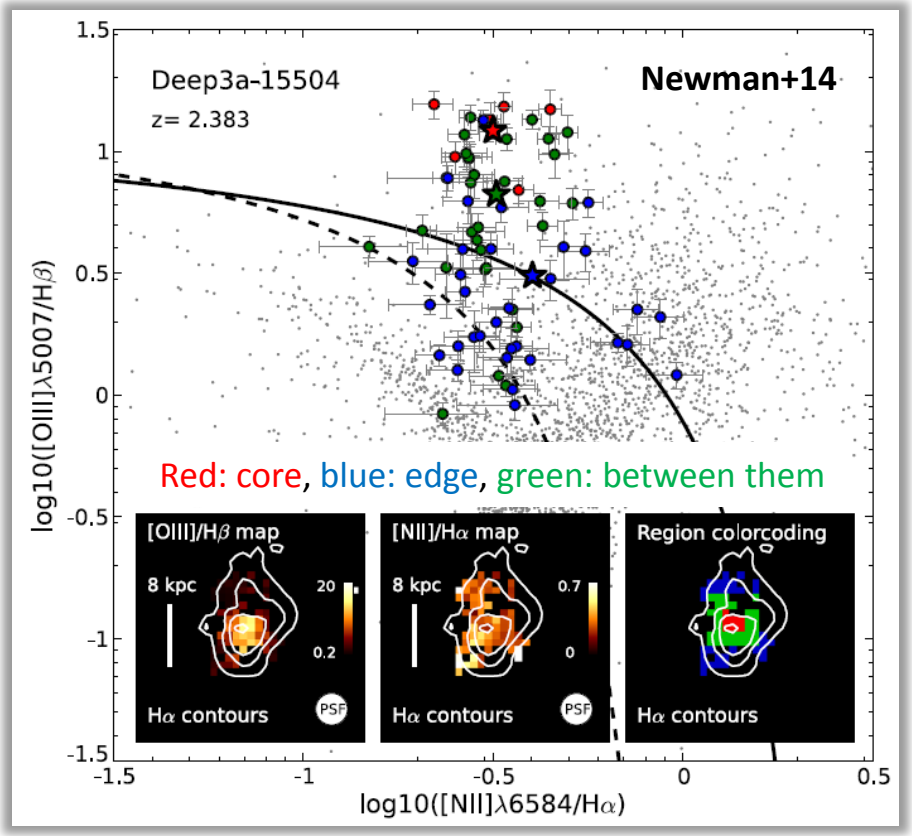
These results indicate that physical condition of ISM in z=1-2 galaxies can be different from that of the local galaxies

Offset of the intensity ratios of nebular emission lines

Well-known nebular emission lines in HII regions: Hα, Hβ, [OII], [OIII], [NII], [SII] and so on

BPT diagram: This diagram is frequently used to identify ionizing source



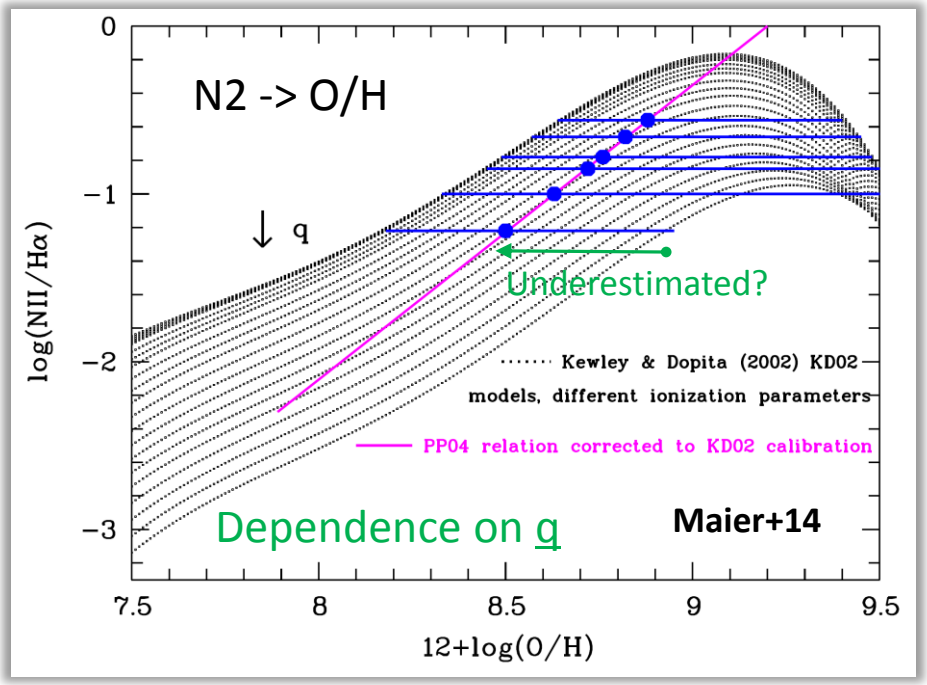


The offset is NOT necessarily due to AGN.

The line intensity ratios of z~2 galaxies show the offset from those of local galaxies.

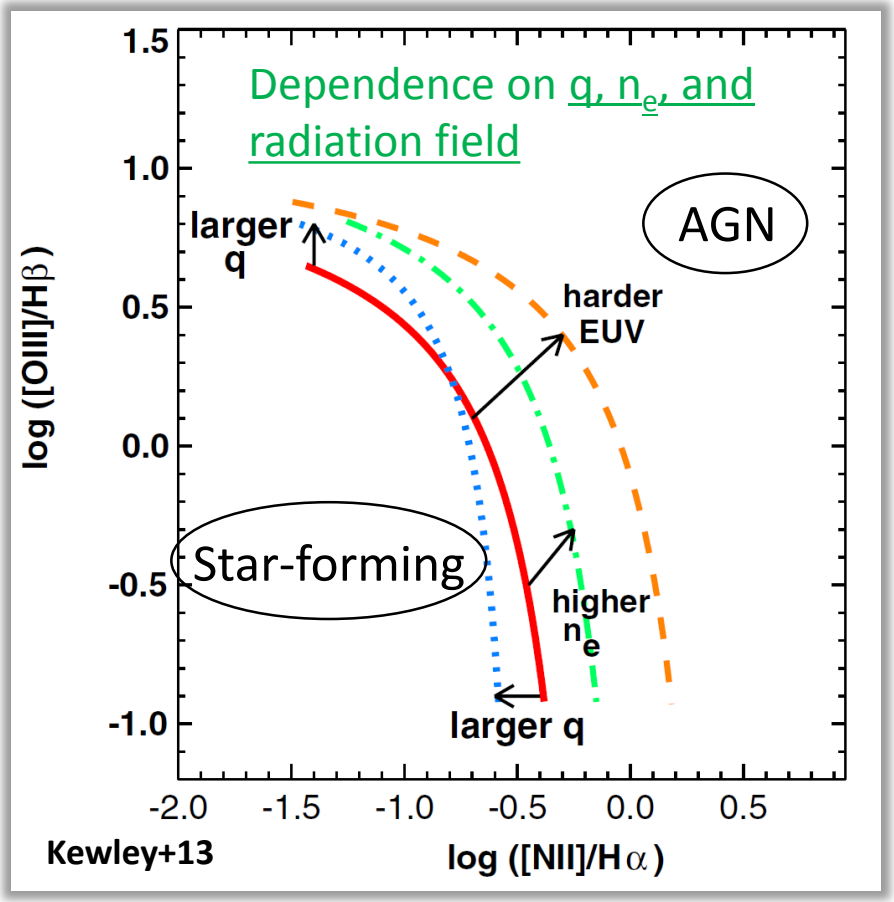
Impact on metallicity measurement and SF/AGN classification

The ratio of [NII]/Hα is frequently used to estimate oxygen abundance



If ionization parameter (q) of high-z galaxies is higher than local galaxies, oxygen abundance ***can be underestimated***.

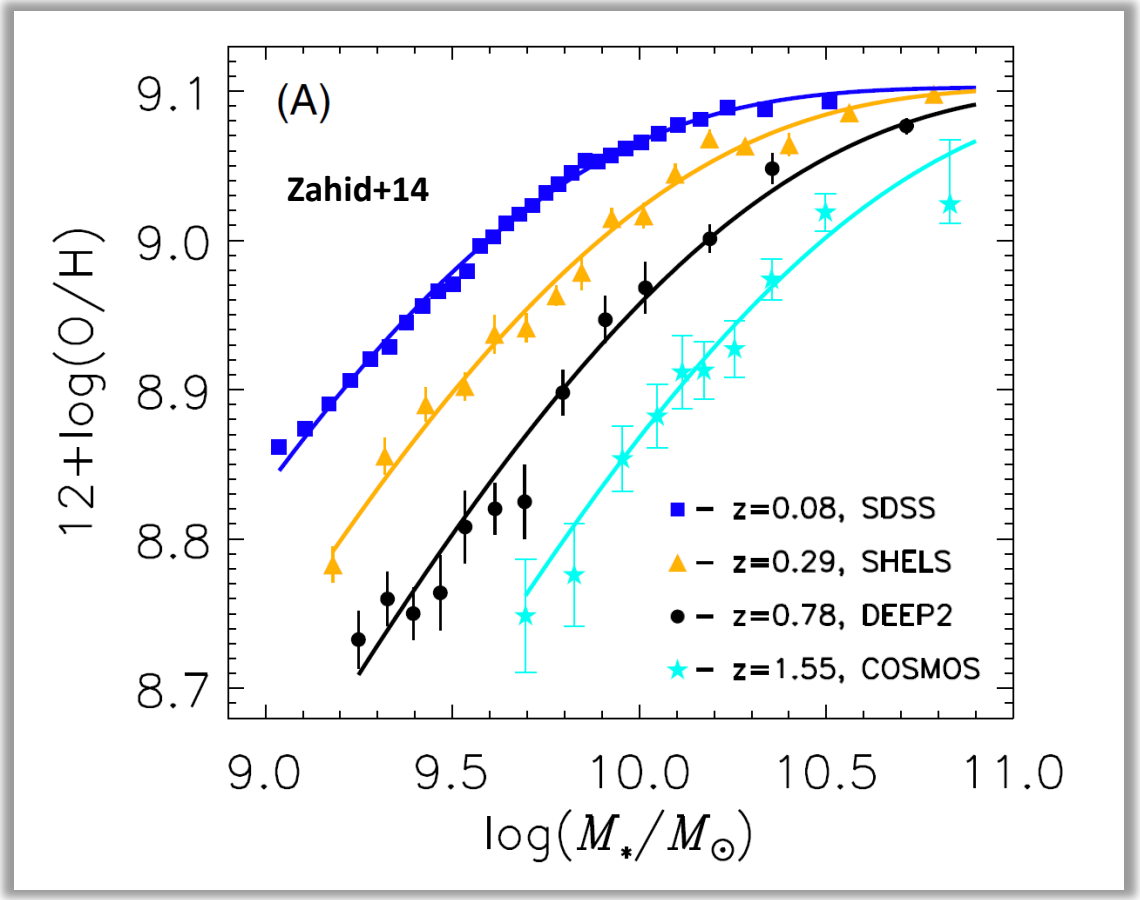
BPT diagram



The diagnositcs with nebular emissions may not be applicable to high-z galaxies

Is the redshift evolution of M-Z relation real?

Lower metallicity for galaxies with a given stellar mass at higher redshifts



With the evidences that the ISM condition may evolve with redshift, are the current measurements of metallcity reliable?

Our approach

First of all, we would like to better understand the HII regions of star-forming galaxies at z>1 where useful nebular emission lines to study galaxy properties are observed.

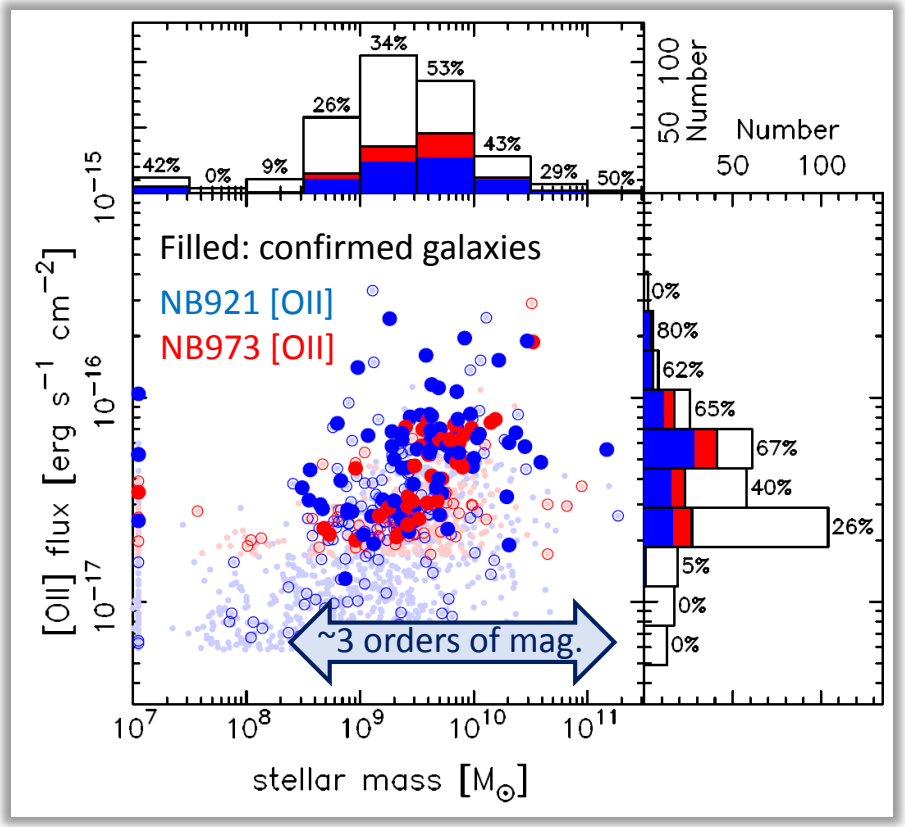
- Basic properties of the ISM in high-z galaxies:
  electron density, (electron temperature), ionizing source, ionization state, dust attenuation, and so on

- How different in the line intensity ratios, compared with local galaxies

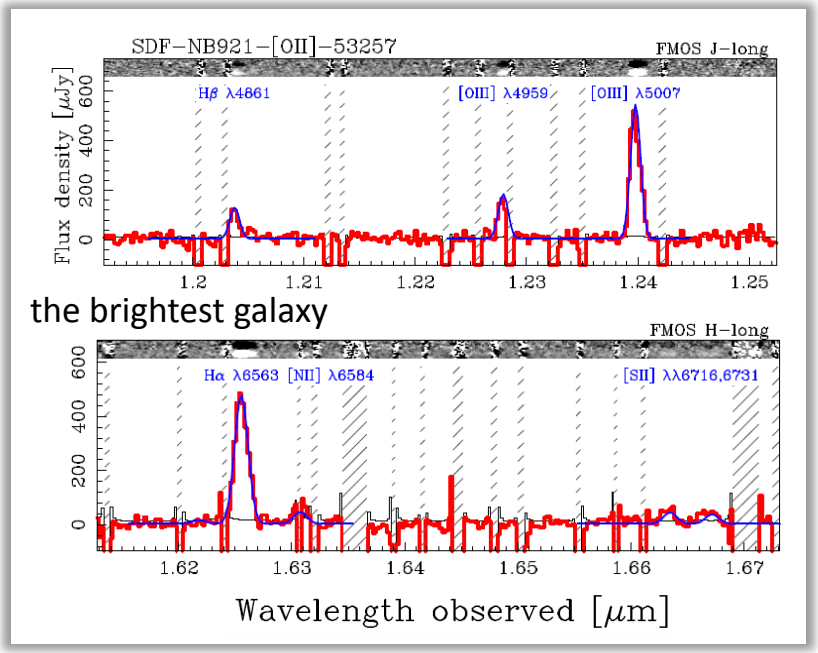
FMOS spectroscopy for [OII] emitters at z~1.5 in the SDF

Subaru/FMOS spectroscopy (S12A-028 and S14A-018)

- [OII] emitters at z=1.47 (NB921) and z=1.62 (NB973) selected by S-Cam (Ly+07,12)
- HR(R=2200) in **J**-long → Hβ and [OIII]λλ4959,5007
- HR in **H**-long → Hα, [NII]λ6584, and [SII]λλ6716,6731
- Stellar mass from the SED fitting to the NUV-to-NIR photometry (Ly+12)



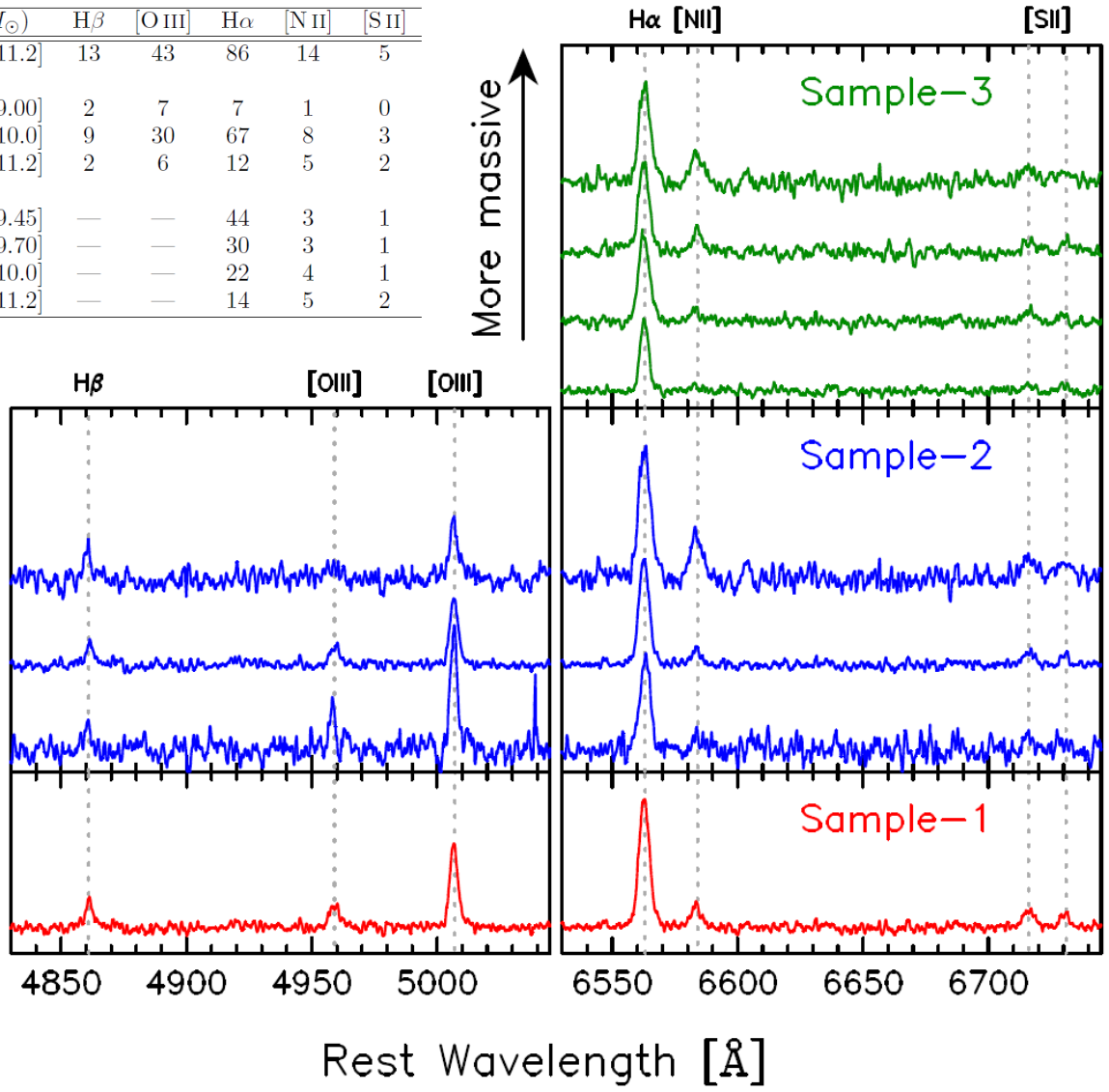
118 galaxies are spectroscopically confirmed
(115 Hα / 45 [OIII] / 13 Hβ / 14 [NII] / 5 [SII])
[OII] luminosity known for all of the galaxies



Composite spectra of [OII] emitters at z~1.5

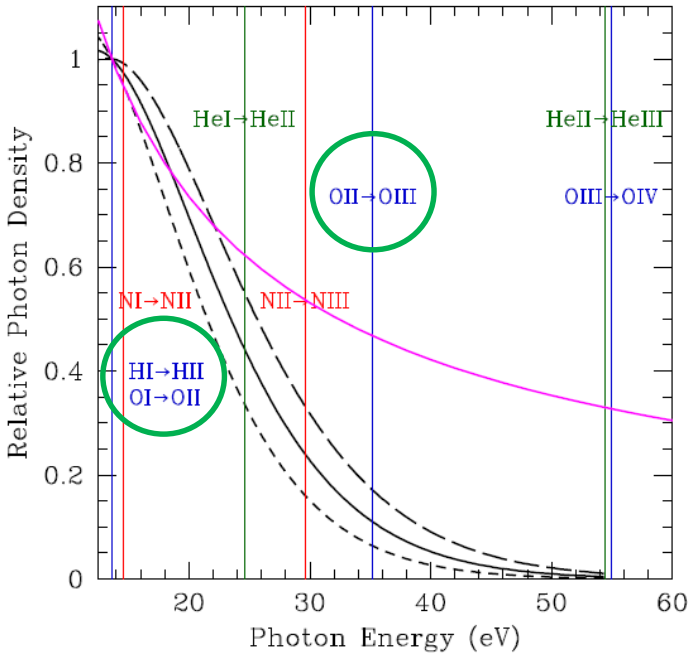
		Coverage	N_{total}	N	$\log(M_\star/M_\odot)$	Hβ	[O III]	Hα	[N II]	[S II]
sample-1		J and H	89	89	9.26 [8.49, 11.2]	13	43	86	14	5
sample-2		J and H	89							
	(1)			9	8.83 [8.49 ,9.00]	2	7	7	1	0
	(2)			68	9.62 [9.00, 10.0]	9	30	67	8	3
	(3)			12	10.3 [10.0, 11.2]	2	6	12	5	2
sample-3		H	113							
	(1)			47	9.25 [8.49, 9.45]	—	—	44	3	1
	(2)			30	9.46 [9.45, 9.70]	—	—	30	3	1
	(3)			22	9.85 [9.70, 10.0]	—	—	22	4	1
	(4)			14	10.3 [10.0, 11.2]	—	—	14	5	2

Luminosities of 6 lines ([OII], Hβ, [OIII], Hα, [NII], and [SII]) are available



What information do the nebular emission lines provide us with?

Steidel+14



Hα (λ6563) and Hβ (λ4861)

Recombination lines (Balmer series) from hydrogen:
directory reflect the number of ionizing photon

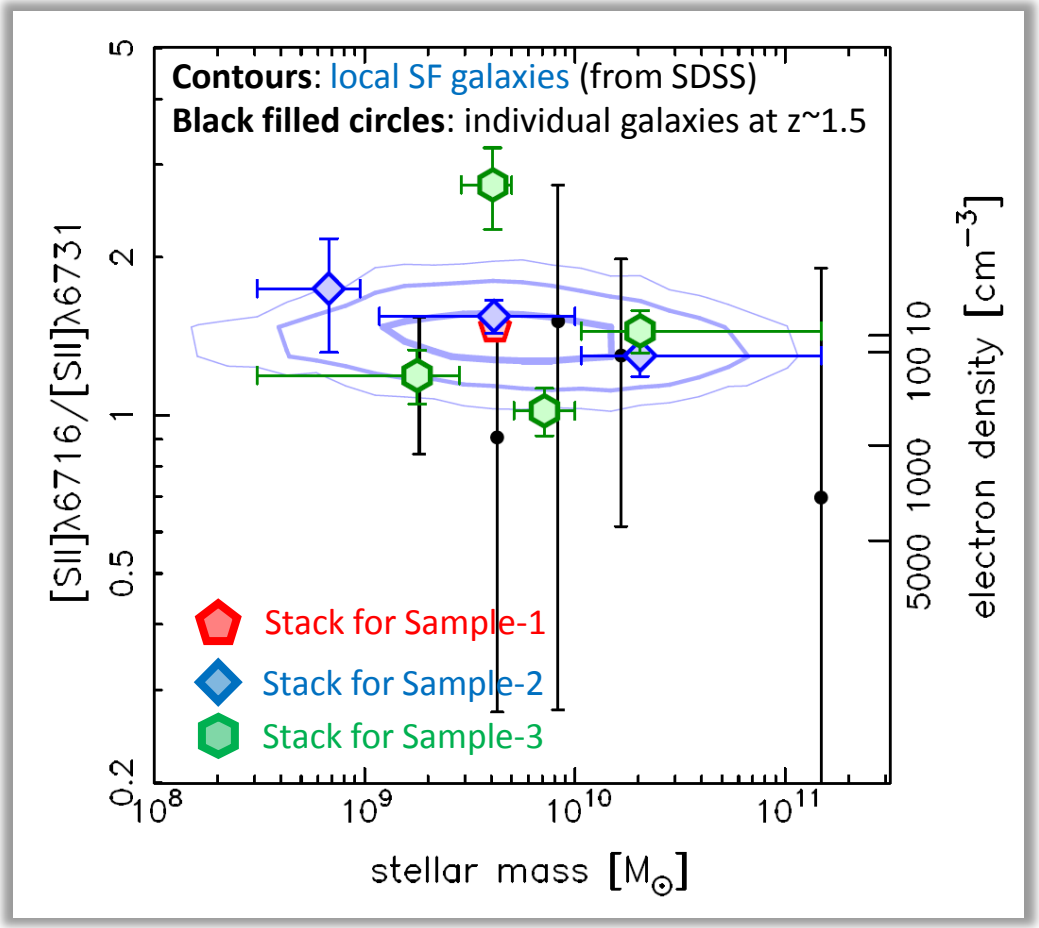
- **Luminosity: star formation activity**
- **Intensity ratio of Hα/Hβ: dust attenuation**

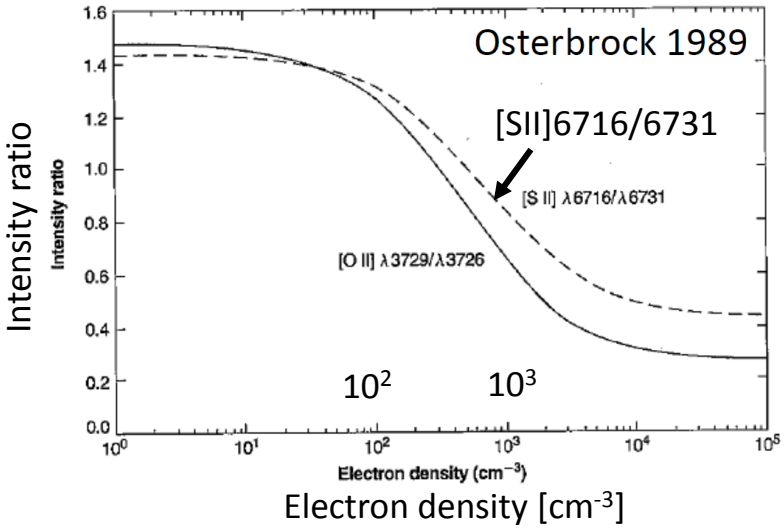
[OII](λ3727), [OIII] (λλ4959,5007),
[NII] (λ6584), and [SII] (λλ6716,6731)

Forbidden lines from ionized metal in HII regions:
excited by collision with electron and then de-excited by radiation
depends on electron temperature, electron density, and ionization state

- **[OII] luminosity: star formation activity (ionization potential ~ 13.6 eV)**
- **Intensity ratio of [OII] or [SII] doublet: electron density**
- **Intensity ratio of [OIII]/[OII]: ionization state**
- **Intensity ratio of R23, ([OII]+[OIII])/Hβ: oxygen abundance (O/H), ionization parameter**

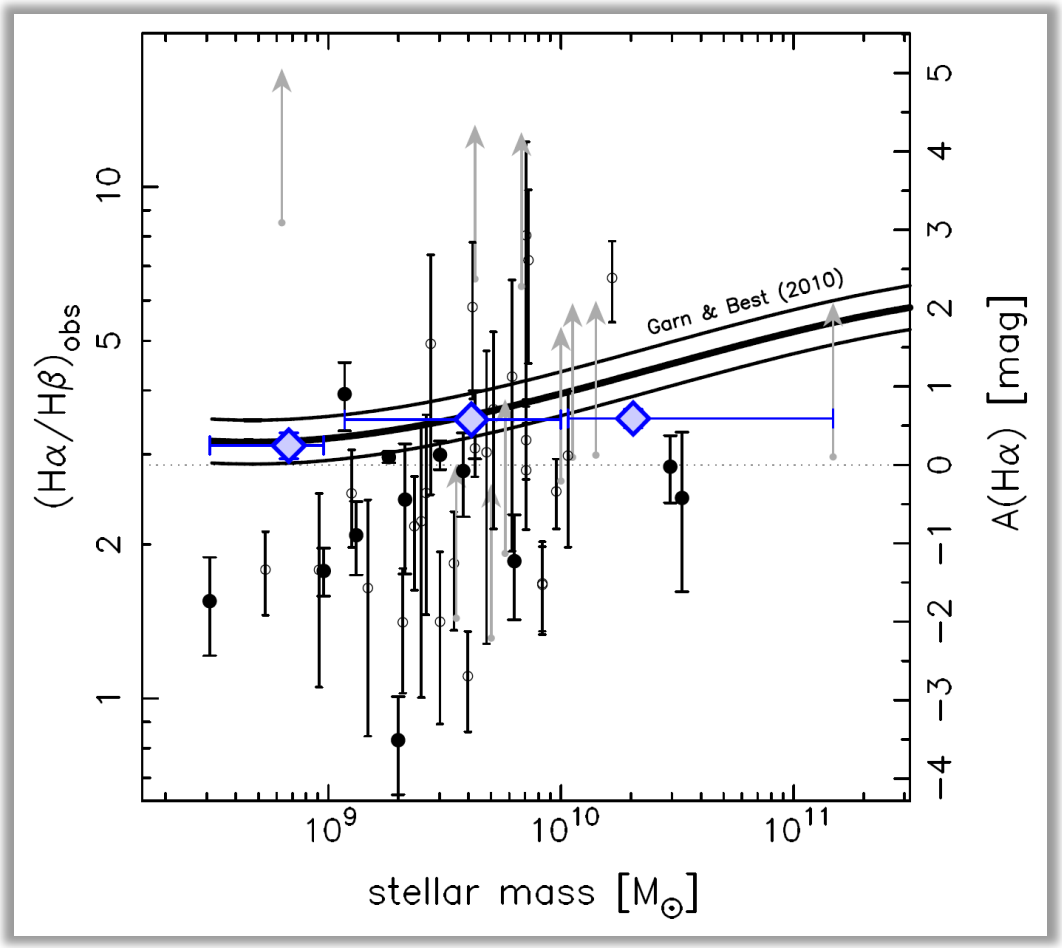
Electron density

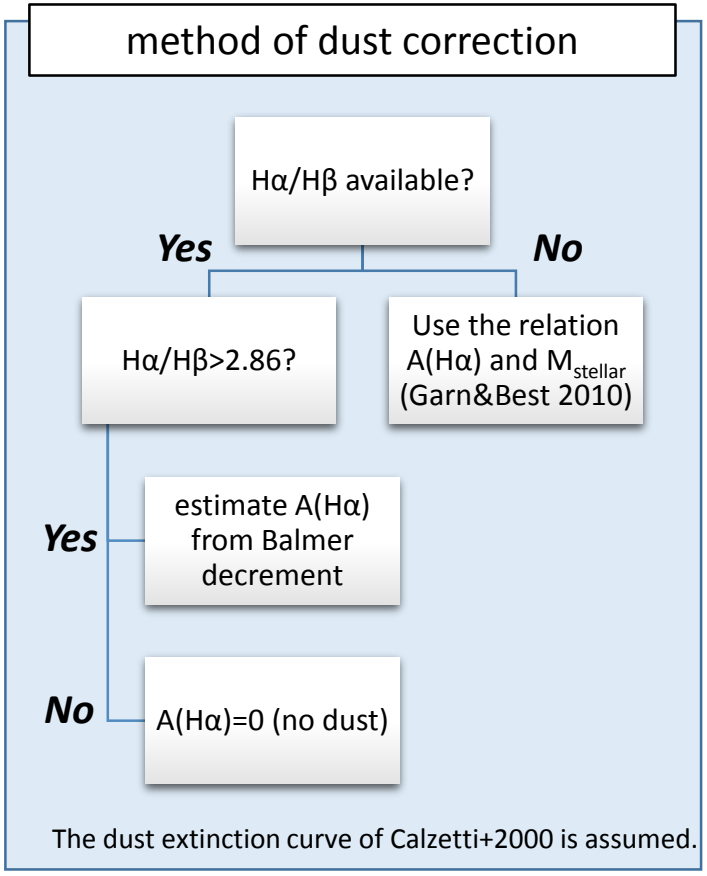




An electron density (n_e) of z~1.5 star-forming galaxies is consistent with typical electron densities for local galaxies, i.e., n_e~10-100 cm^{-3}.

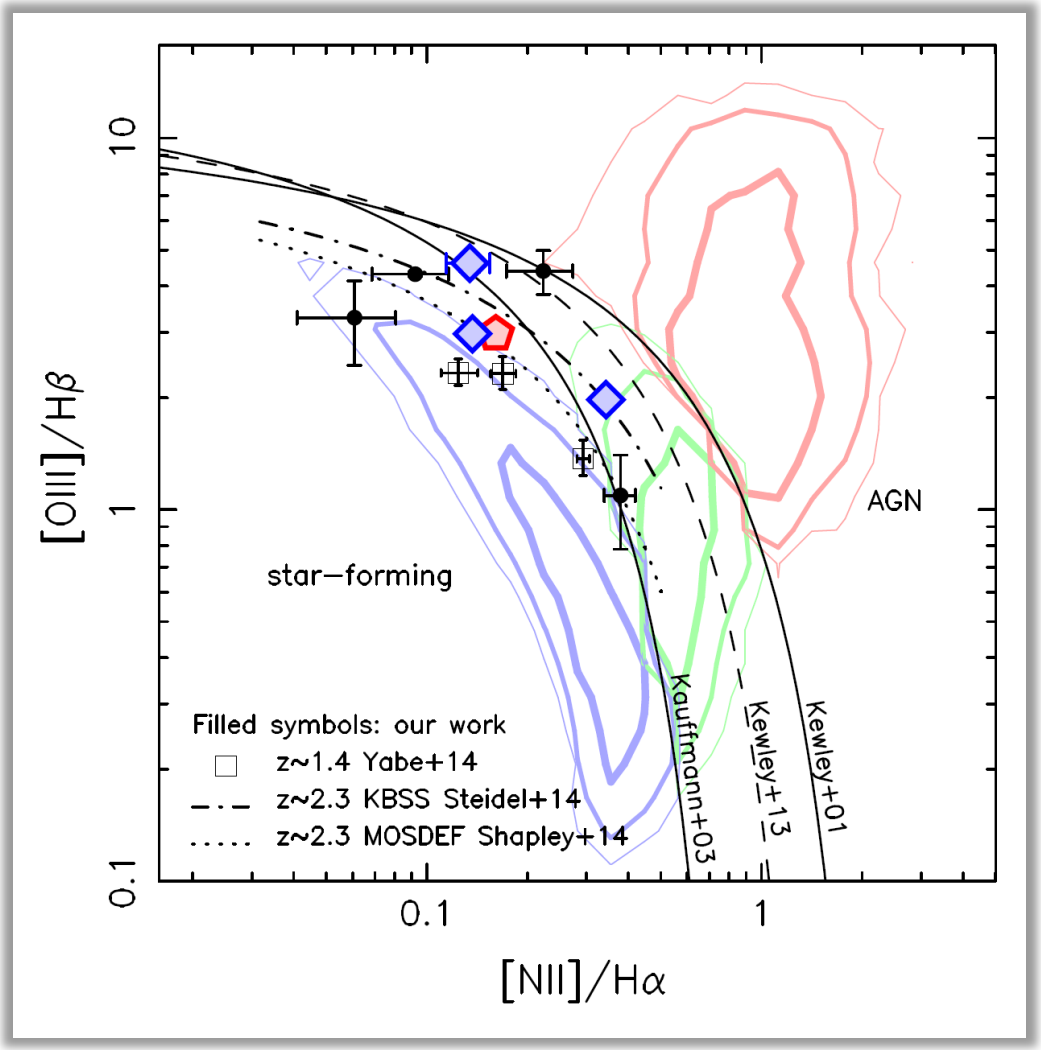
Balmer decrement (the ratio of Hα to Hβ)

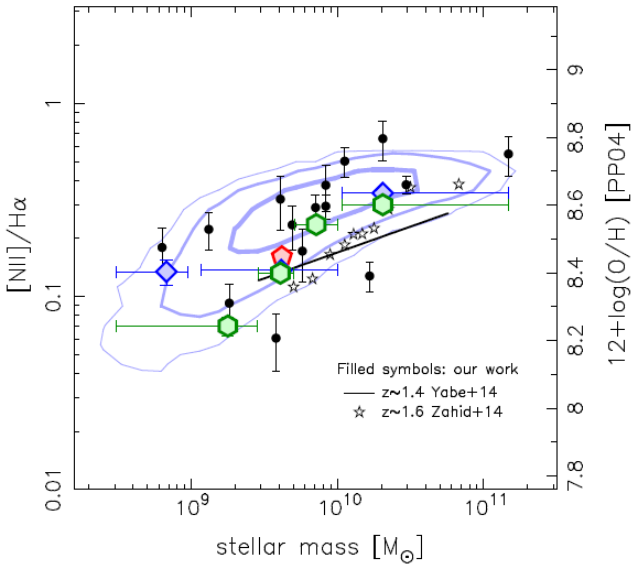




Under the assumption of Te=10^4K and n_e=100cm^{-3} for Case B recombination, the intrinsic Ha/Hb is 2.86 (Osterbrock 1989)

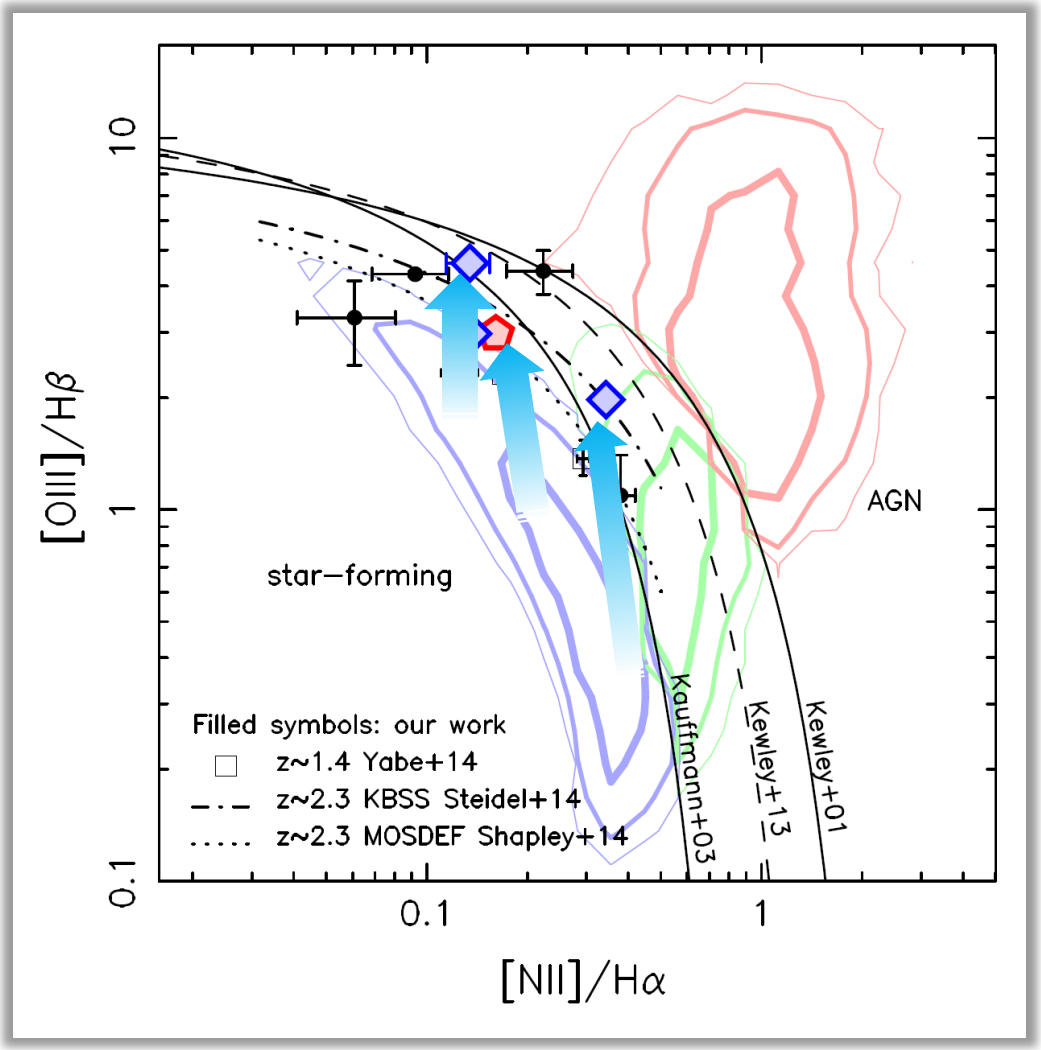
BPT diagram

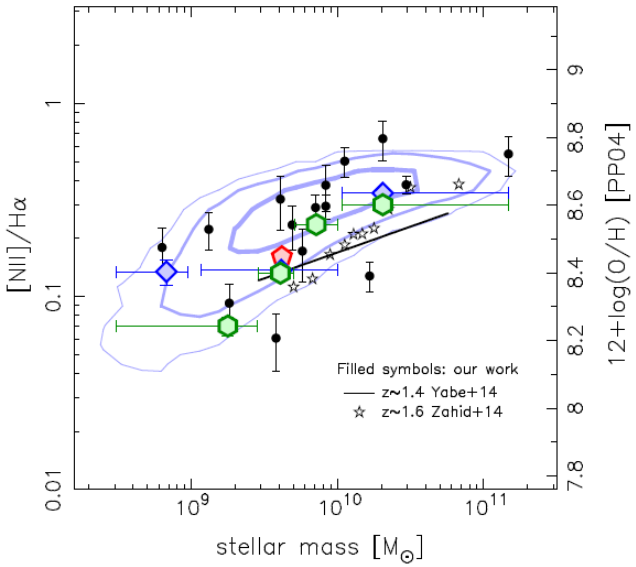




Offset of the line ratios, which is consistent with other studies

BPT diagram





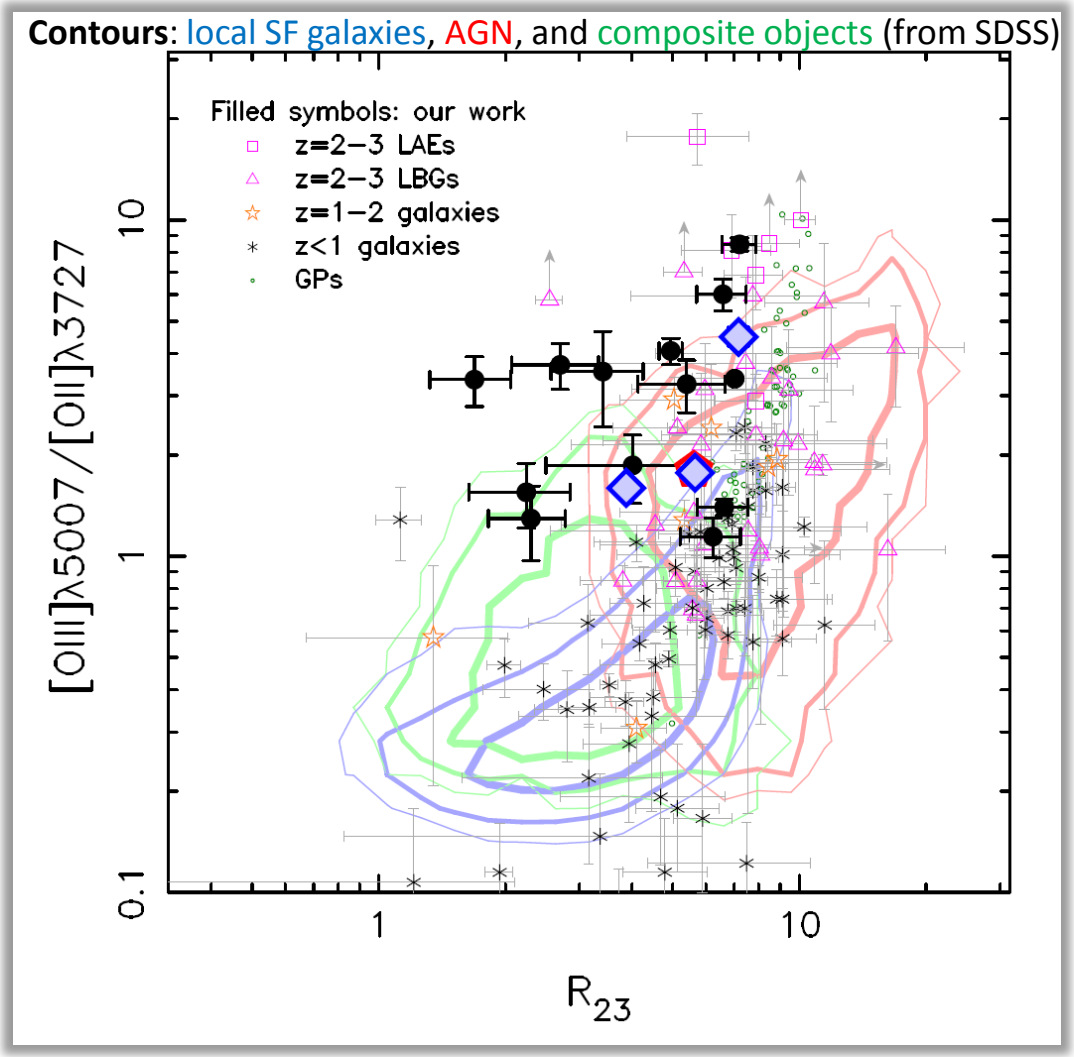
Shift toward large [OIII]/Hβ ratio for z~1.5 galaxies

Offset of the line ratios, which is consistent with other studies

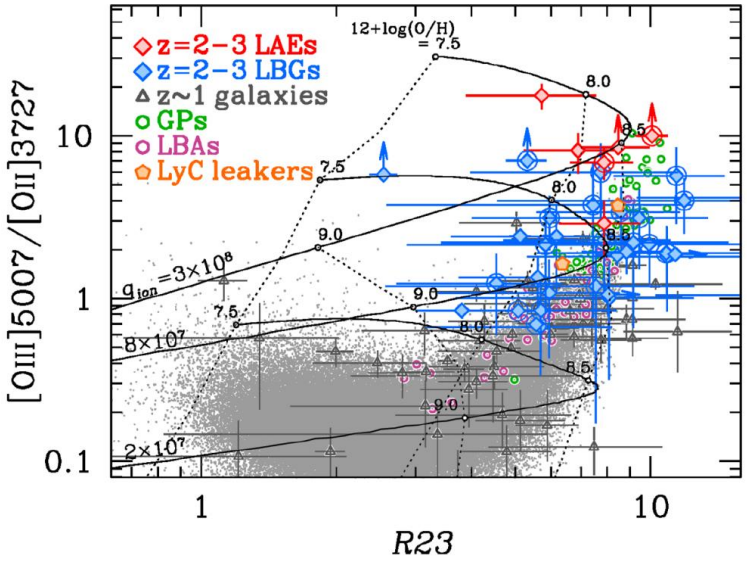
High ionization parameter of [OII] emitters at z~1.5

[OIII]/[OII]: indicator of ionization parameter
R23=([OII]+[OIII])/Hβ (i.e., oxygen abundance)

Contours: local SF galaxies, AGN, and composite objects (from SDSS)



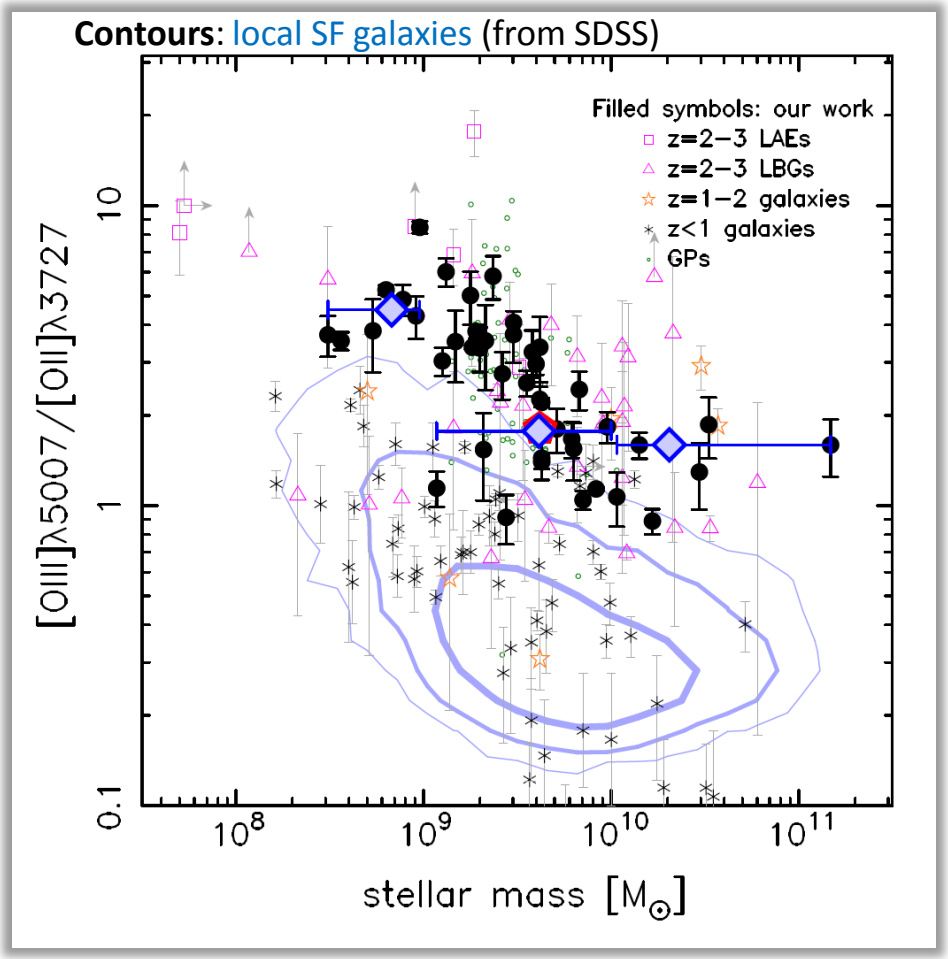
Nakajima & Ouchi 14



- Large [OIII]/[OII] ratios, compared to local SF galaxies
- Comparable to LAEs/LBGs at z=2-3

[OII] emitters at z~1.5 have large [OIII]/[OII] ratio of >~1, suggesting they have large q

Dependence of [OIII]/[OII] on stellar mass



- Less massive galaxies have larger [OIII]/[OII] ratios
- May be due to higher sSFR for less massive galaxies

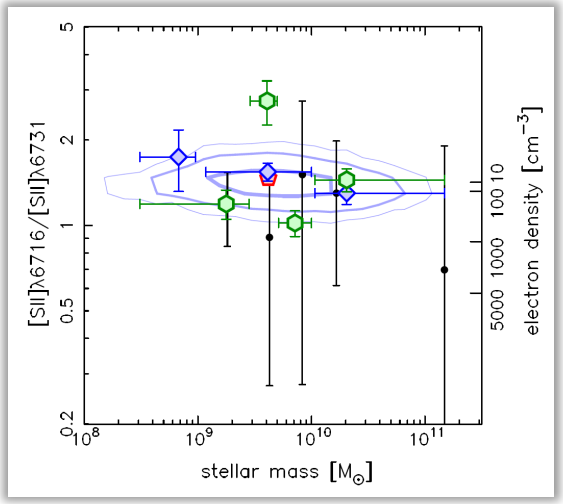
What causes the high ionization parameter?

$$q = \frac{Q_{H^0}}{4\pi R_s^2 n_H}$$

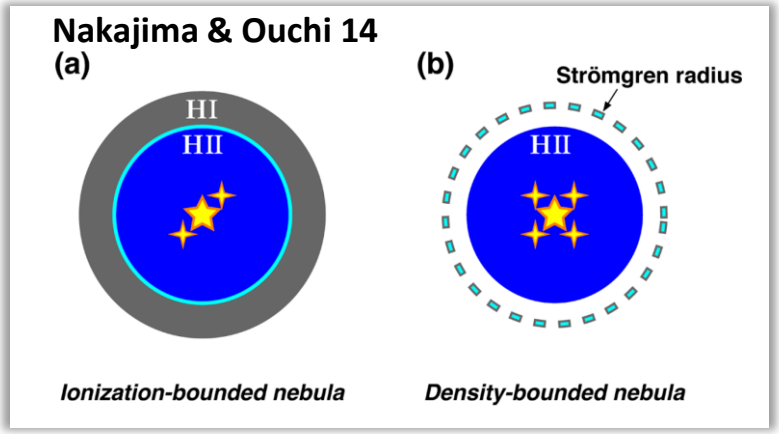
Q_{H^0} is the number of ionizing photons
R_s is the Strömgren radius
n_H is the hydrogen density

Three possible mechanisms

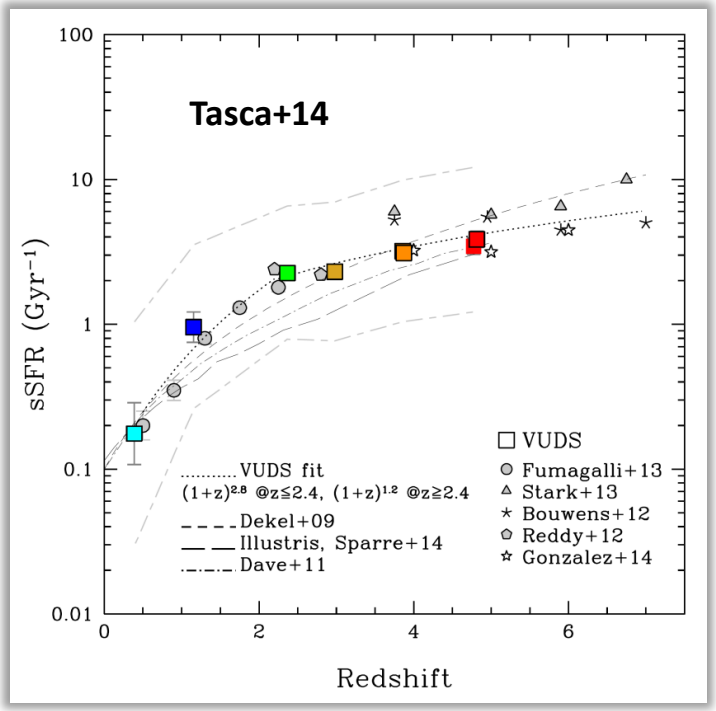
- Hydrogen density



- Geometry of nebular gas

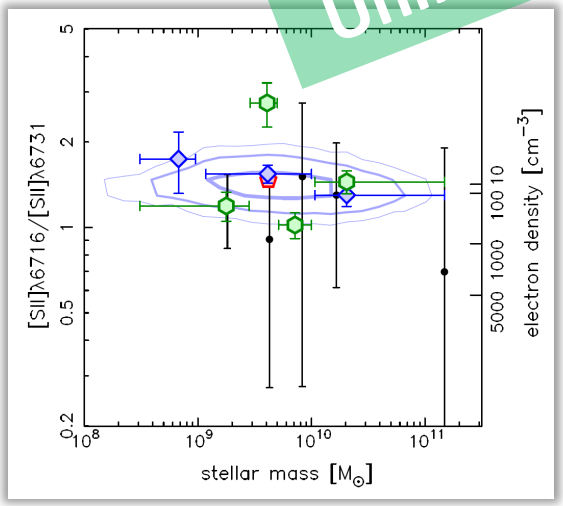


- Shape of ionizing radiation field



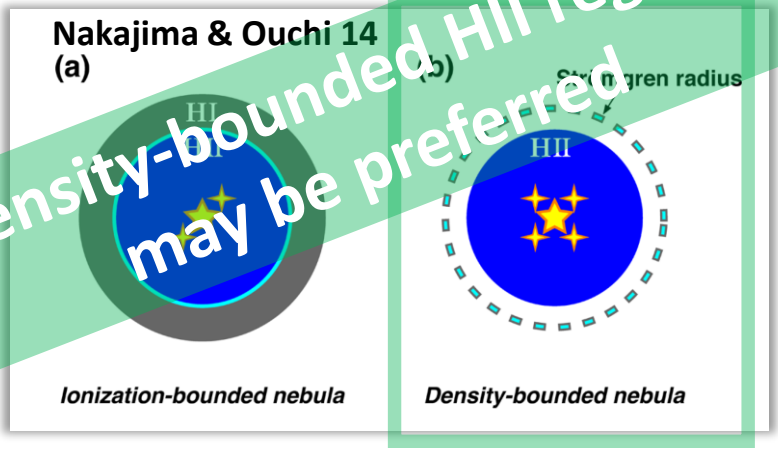
Three possible mechanisms

- Hydrogen density



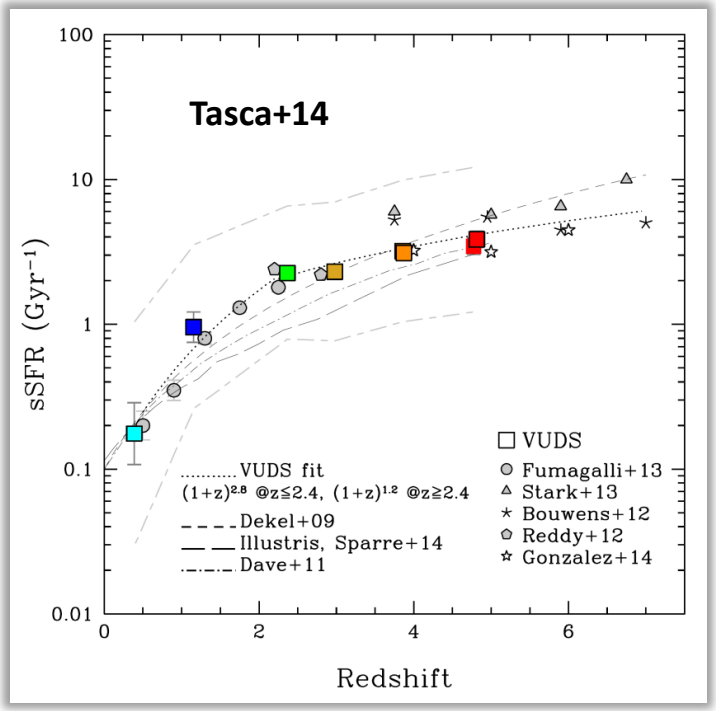
Unlikely

- Geometry of nebular gas



Density-bounded HII regions may be preferred

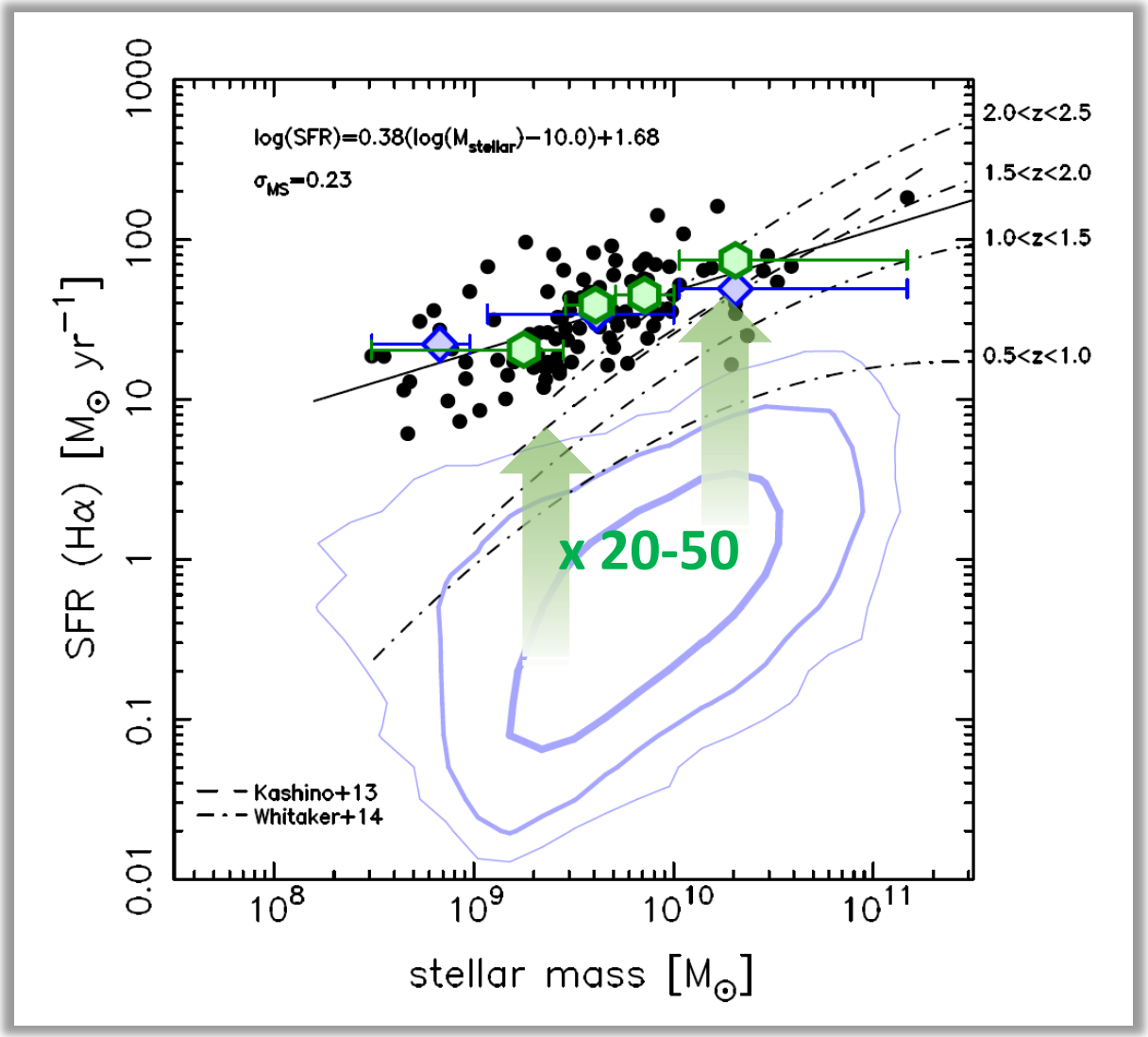
- Shape of ionizing radiation field



- Harder radiation field by young stellar populations
- The increasing number of ionizing photon from massive stars

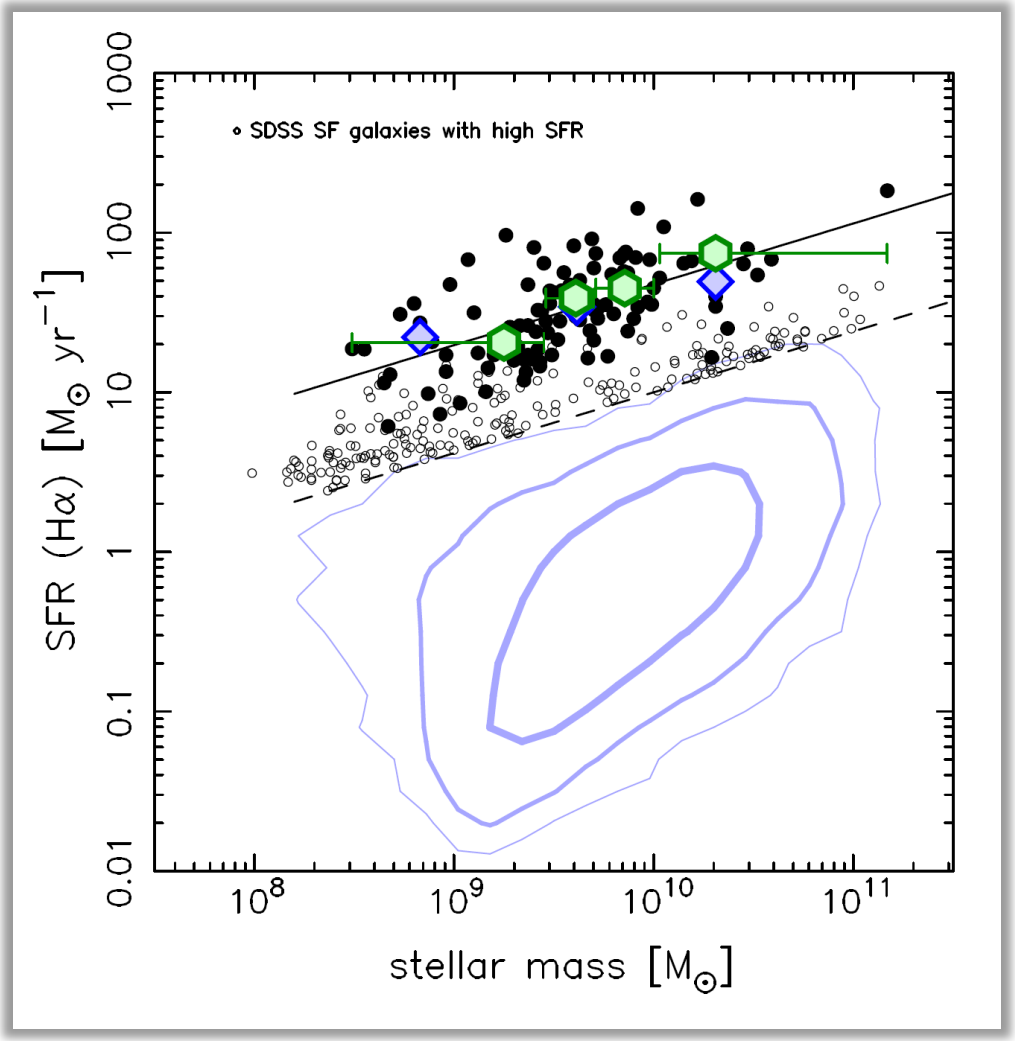
Main sequence of star-forming galaxies

[OII] emitters at z~1.5 follow the main sequence of star-forming galaxies

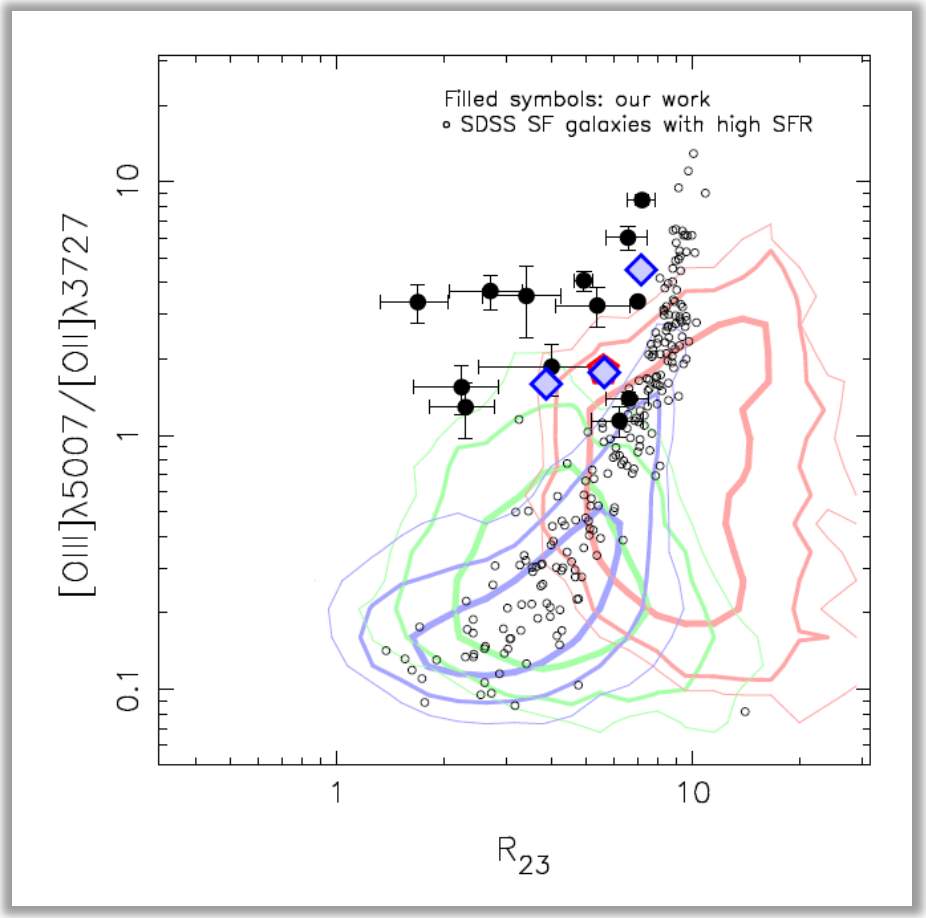


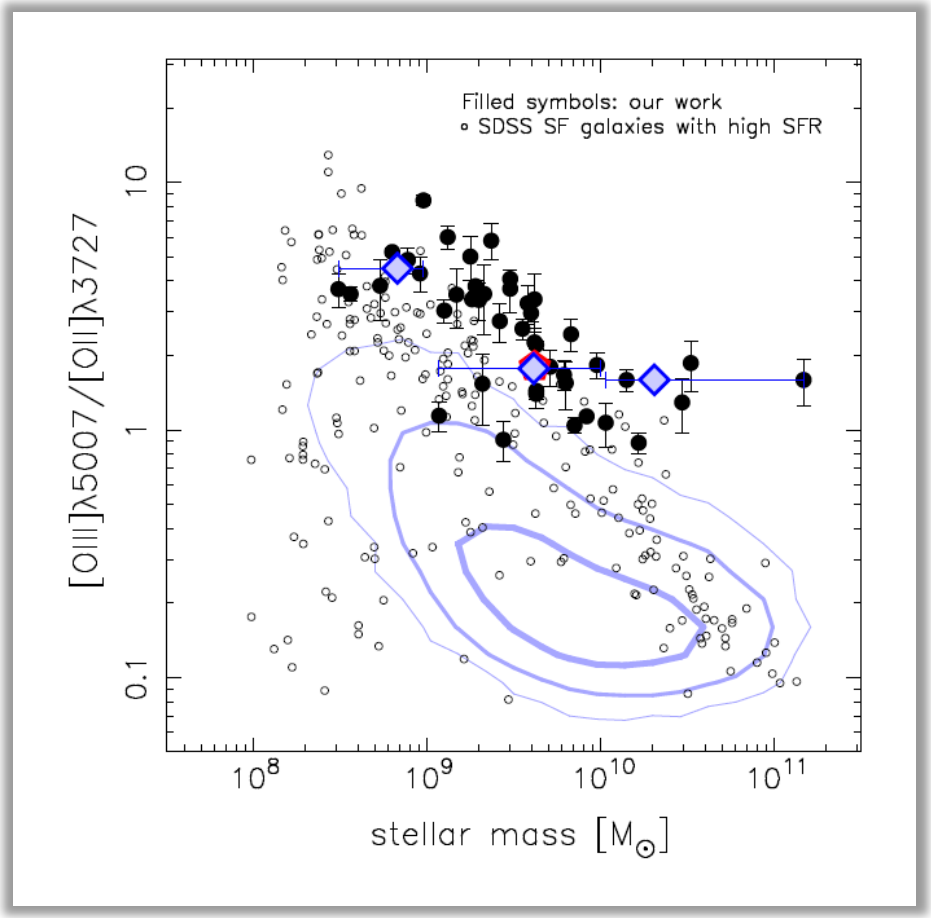
How are the local star-forming galaxies with high SFR?

Only quite a small number of local star-forming galaxies have SFRs comparable to [OII] emitters at z~1.5



SDSS galaxies with high SFR





- Difference in metallicity
- Not necessarily have large line ratios of [OIII]/[OII]

Harder radiation fields at high-z?

Summary

Hayashi et al., 2015, PASJ (Subaru Special Issue), submitted

- Subaru/FMOS Near-IR spectroscopy for 118 [OII] emission line galaxies at z~1.5 in the Subaru Deep Field
- Six nebular emission lines in rest-optical: [OII], Hβ, [OIII], Hα, [NII], and [SII]
- Use line ratios to investigate physical conditions of the ISM

This Talk

◆ **Strong [OIII] emission line**
- [OIII]/[OII] ratios larger than the local star-forming galaxies
- Less massive galaxies have larger [OIII]/[OII] ratios (mass dependence)

◆ **High ionization parameter**
- Harder radiation field by young stellar populations
- The increasing number of ionizing photon from massive stars

◆ **Maybe relatively higher N/O abundance ratio, compared to local galaxies**

◆ **A tight correlation between Hα and [OII]**
- [OII] can be a good indicator of star formation rate for galaxies at z~1.5

It is important to take account of ionization parameter and nitrogen abundance ratio, when metallicity is derived for high-z galaxies.