The Subaru FMOS Galaxy Redshift Survey (FastSound): The mass-metallicity relation and the fundamental metallicity relation at z~1.4

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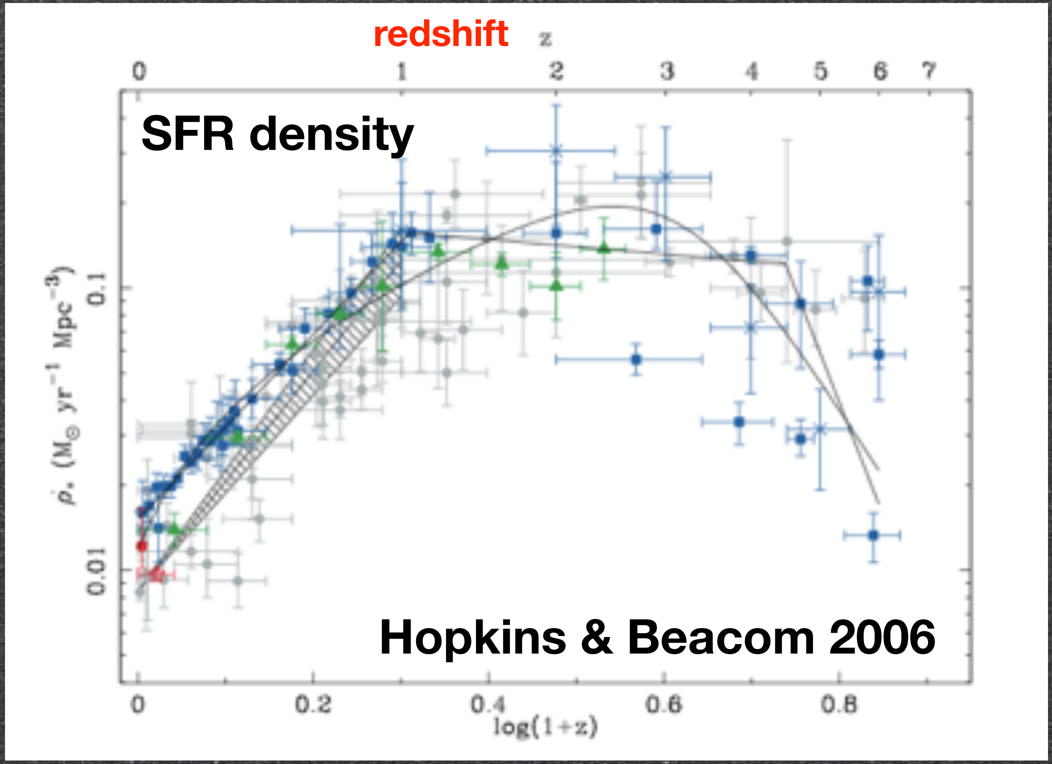
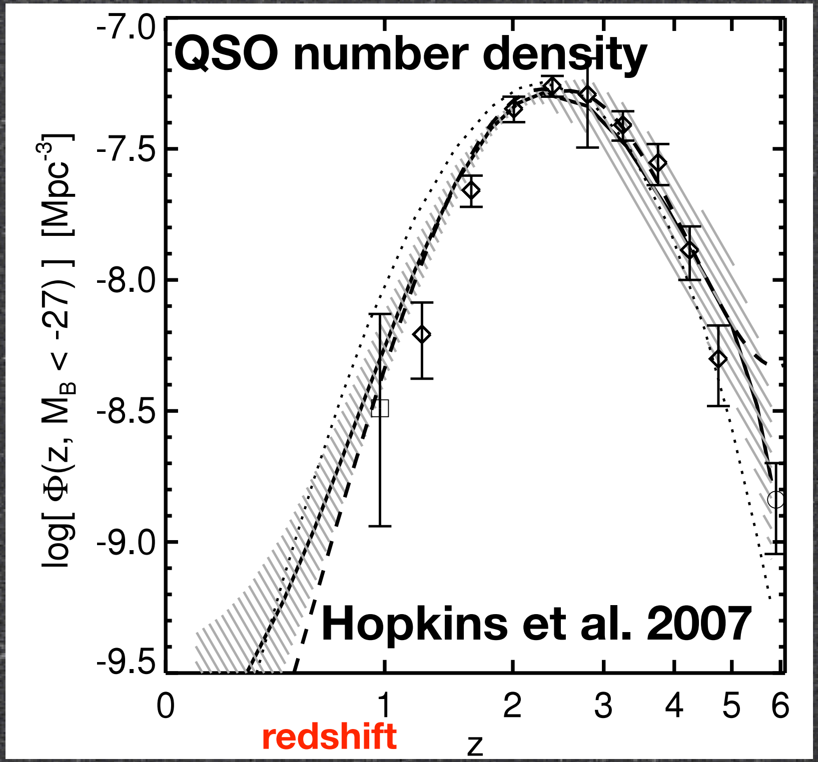
Background:

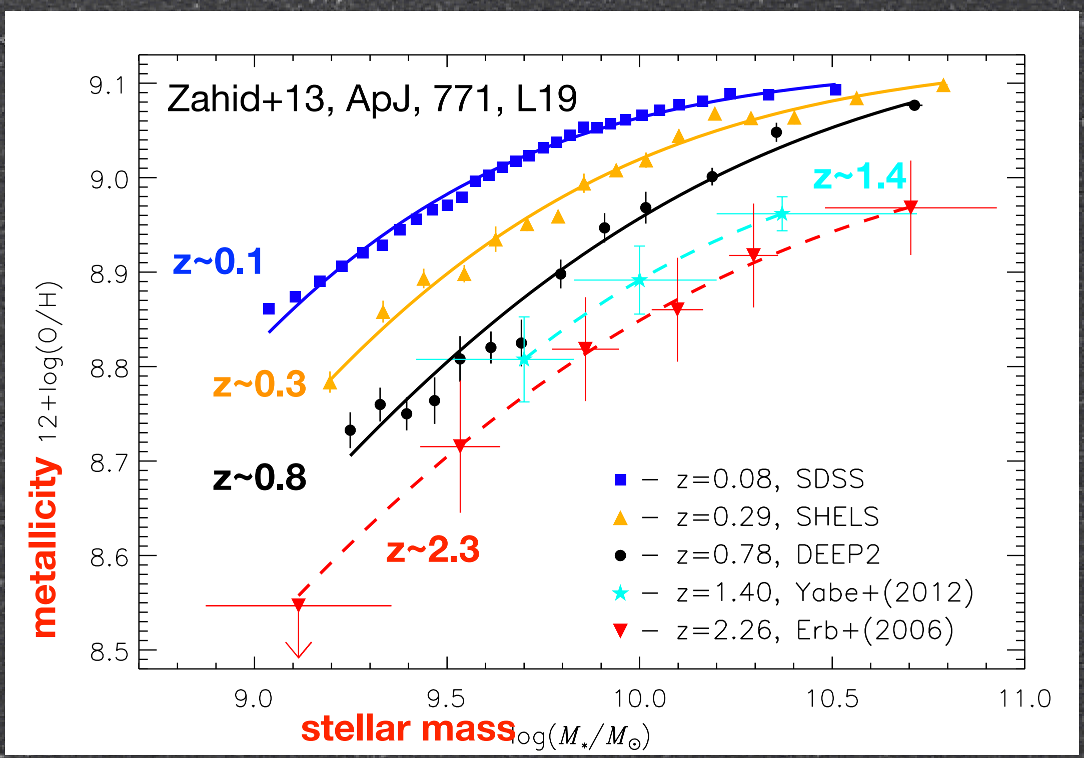
- "Cosmic high noon" in the cosmic history at z=1-2
  - ✓ "Peaks" and "drastic changes" in various properties of galaxies
    - Peak of star-formation activity
    - Peak of AGN activity
    - Emergence of galaxy morphology (such as Hubble sequence)
- Spectroscopic properties remain unclear because primary emission lines (such as Hα, Hβ, [OIII], [NII]) enter in NIR wavelength region at z~1-2
- Large systematic survey in NIR is desirable

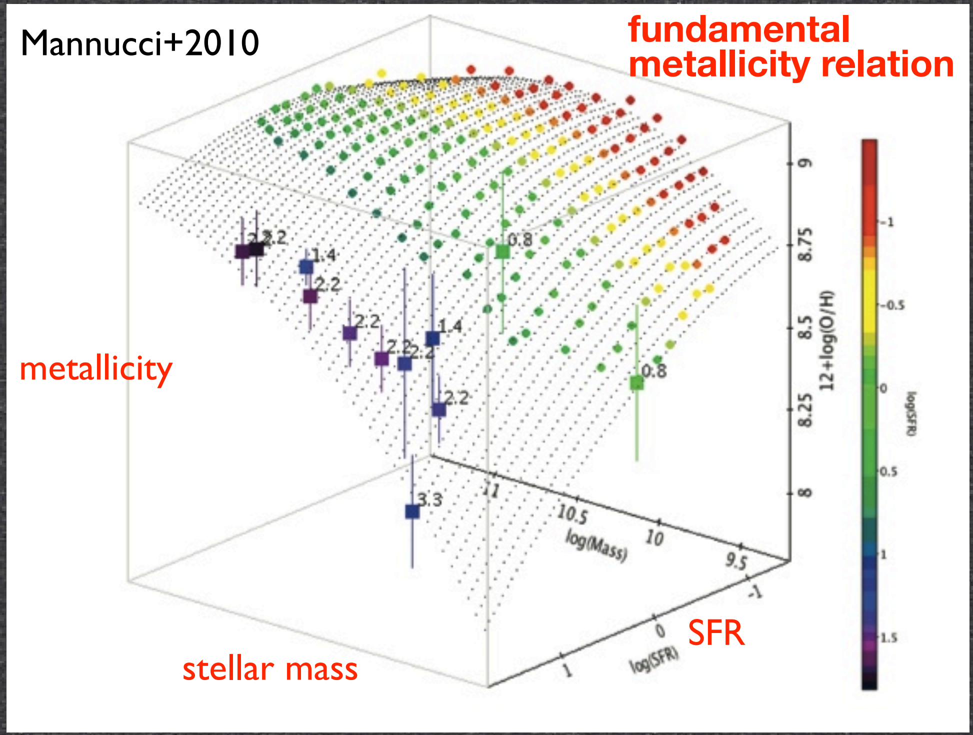




Background:

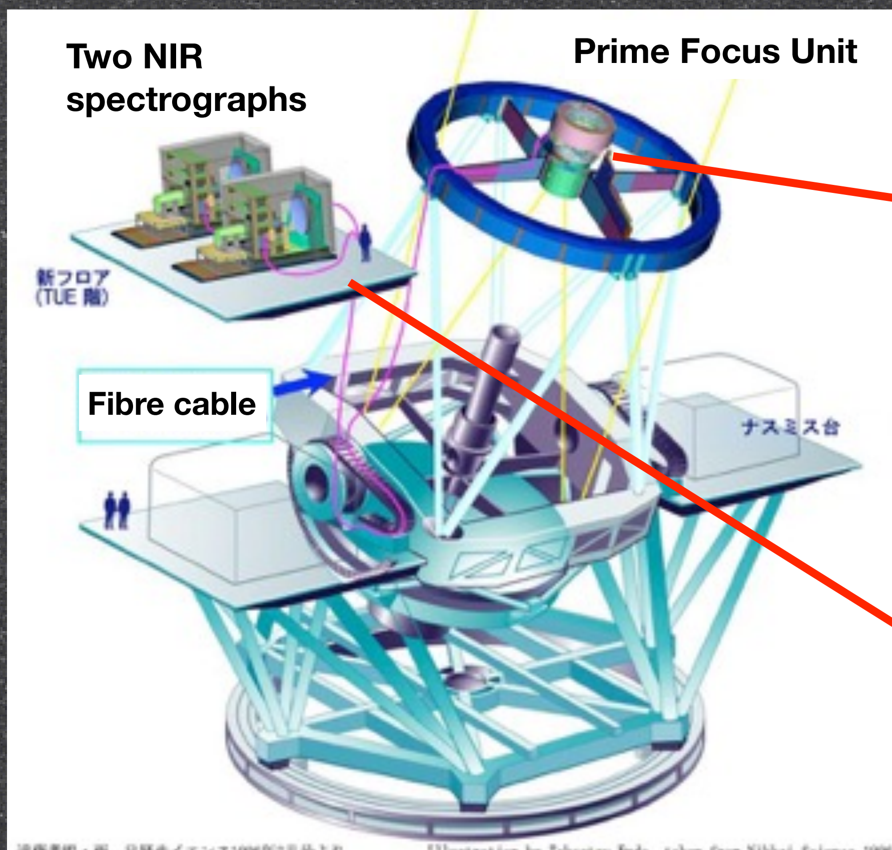
- Star-formation history traced by gas metallicity
  - ✓ Metallicity is a quantity that contains the past star-formation activity and gas inflow and outflow history as well.
  - ✓ Correlation between stellar mass and metallicity (MZR)
  - ✓ SFR dependence of the MZR (Fundamental Metallicity Relation=FMR)
  - ✓ Redshift evolution of the MZR and FMR
- MZR and FMR at z>1 still remain unclear because samples are small
- Subaru/FMOS is a powerful instrument for studies in this redshift range



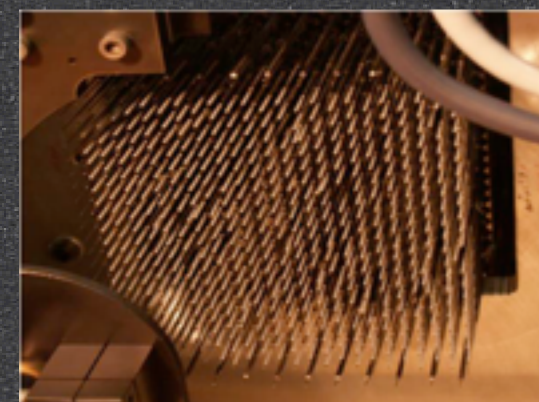


FMOS (Fibre Multi Object Spectrograph):

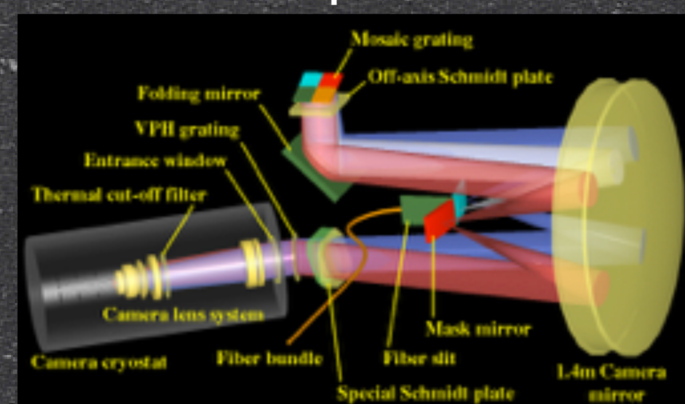
- What is FMOS?
  - ✓ Fibre-fed NIR multi-object spectrograph on the Subaru Telescope (8.2m)
  - ✓ Prime Focus Unit with fibre positioner “Echidna” (400 fibres, 30 arcmin Φ)
  - ✓ Two NIR (0.9 - 1.8μm) spectrographs (IRS1 & 2)
  - ✓ Low Resolution (LR; R~650) and High Resolution (HR; R~3000) mode
  - ✓ Details are presented by Kimura et al. 2010, PASJ, 62, 1135



FMOS on the Subaru Telescope



Fiber positioner “Echidna”

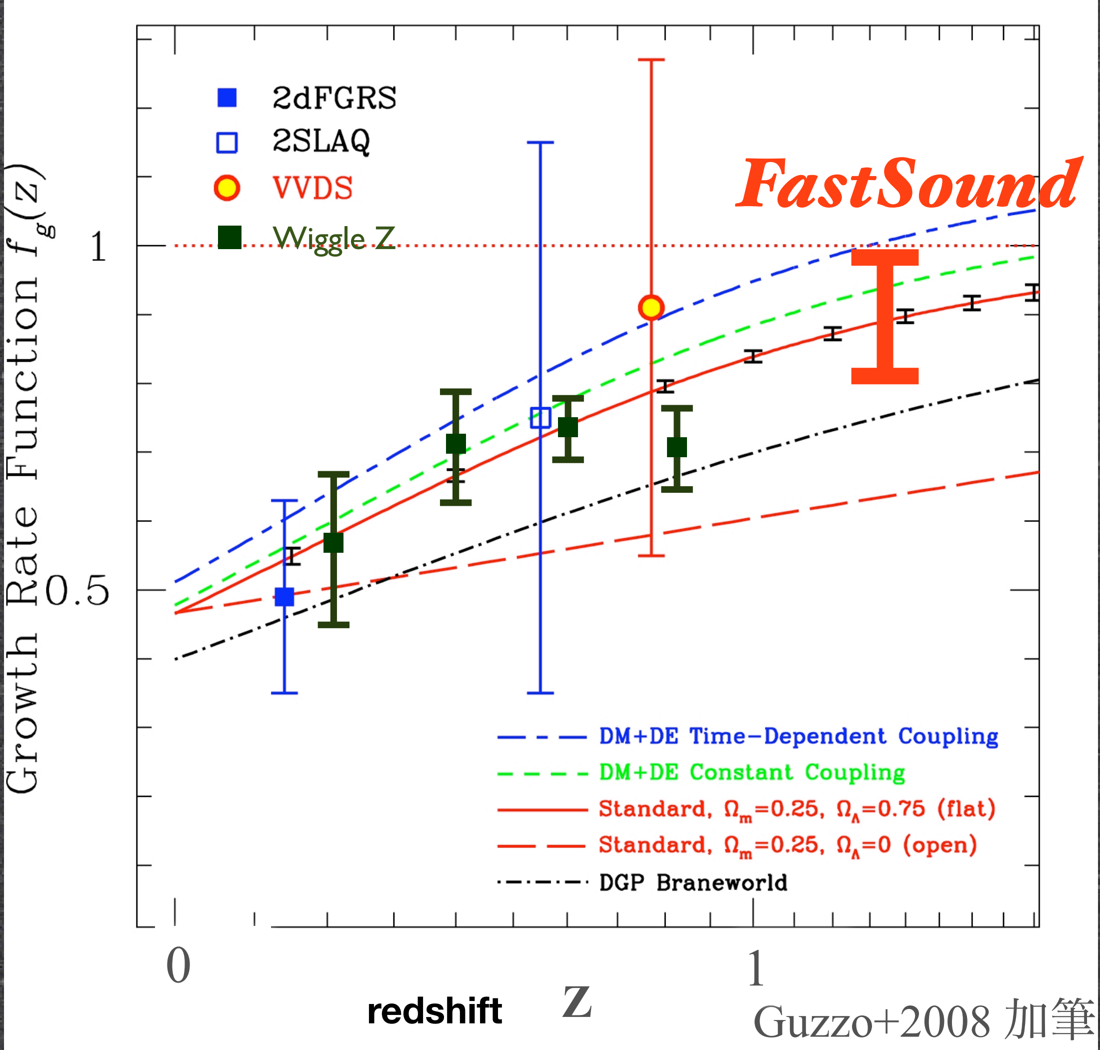


Optical design of FMOS including OH-mask mirror

FMOS Galaxy Redshift Survey (FastSound):

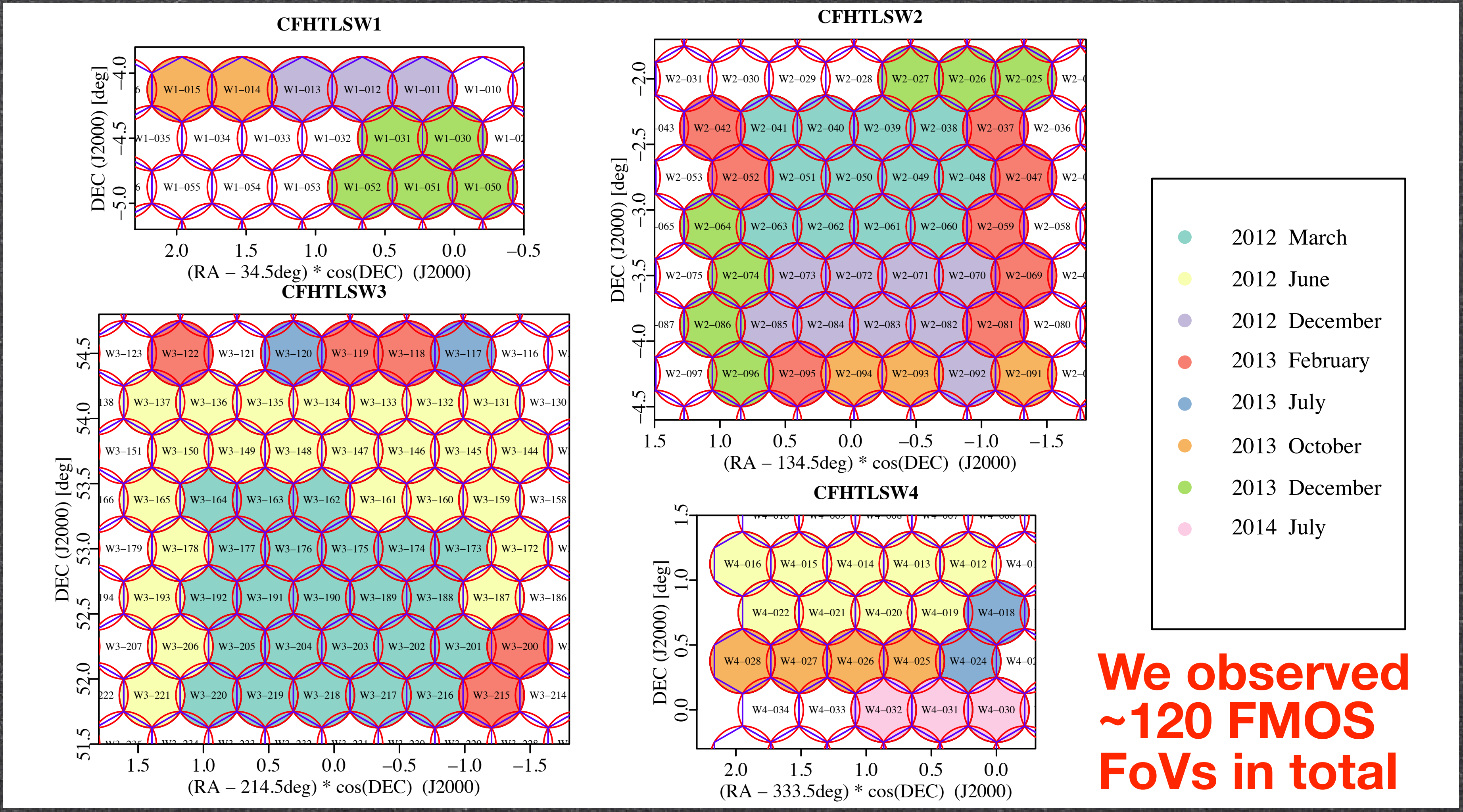
- Cosmological redshift Survey at z=1.2-1.5 with Subaru/FMOS
- Goal: The first detection of RSD at z>1
- Constraints to the gravitational theory

- Fields: CFHTLS-Wide regions (W1, W2, W3, W4; 20 deg^2, ~0.1 Gpc^3)
- Targets: Photometric redshift (z_{ph}) selection (z_{ph}=1.1-1.6) + additional colour cut
- Survey was carried out during the Subaru Strategic Program (SSP) from Mar. 2012 to Jul. 2014
- See details by Tonegawa et al. 2015 PASJ submitted (arXiv: 1502.07900)

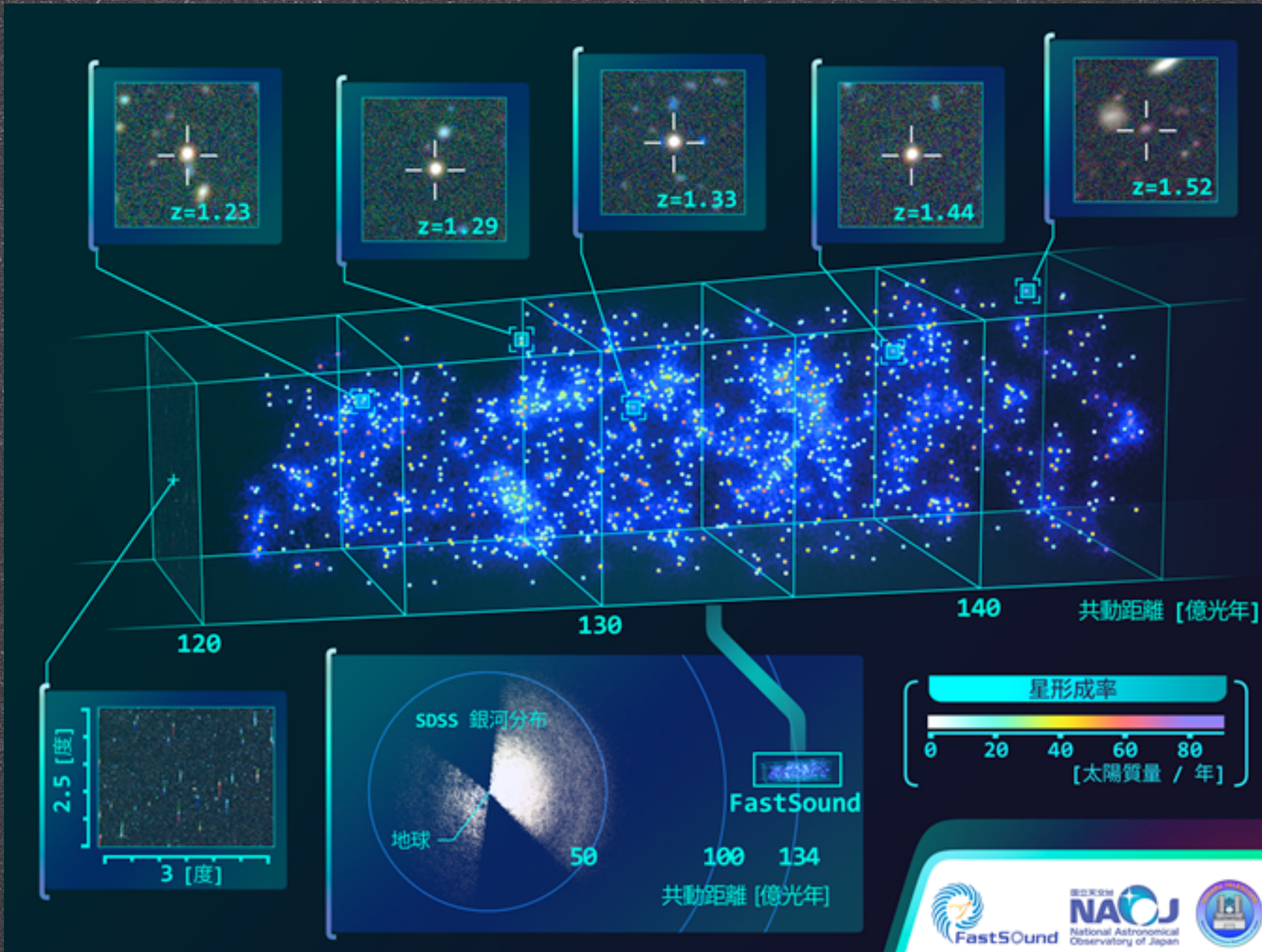


FMOS Galaxy Redshift Survey (FastSound):

- Observation: FMOS high resolution (Hs prime) mode (1.43-1.67μm)
- On source exposure time is 30 min. in each FoV (~0.2 deg^2)
- Hα line detection (S/N>4) from ~4,000 star-forming galaxies
- Spectroscopic redshift ranges from 1.18 to 1.54 (z_{med}~1.36)

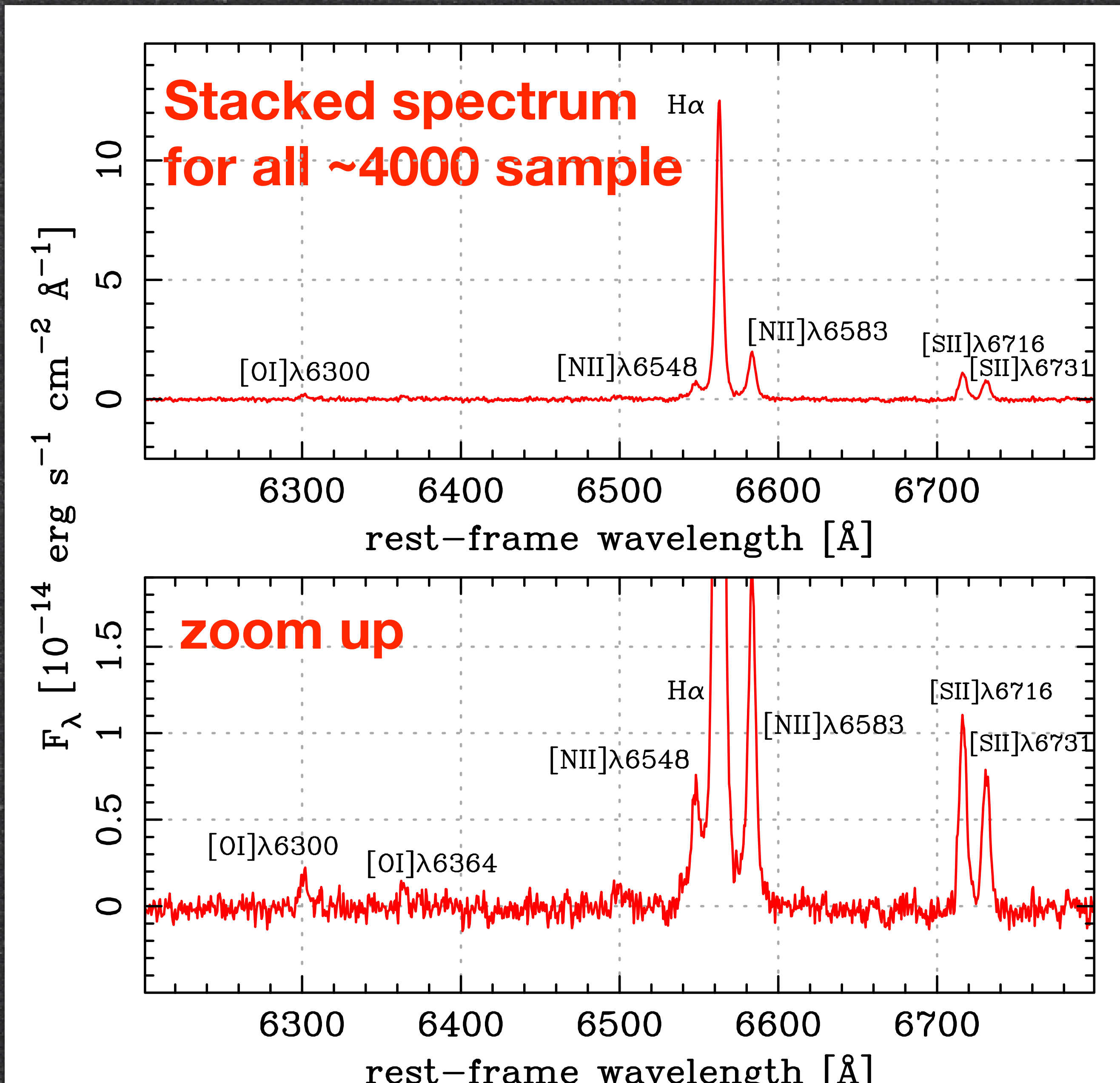


We observed ~120 FMOS FoVs in total



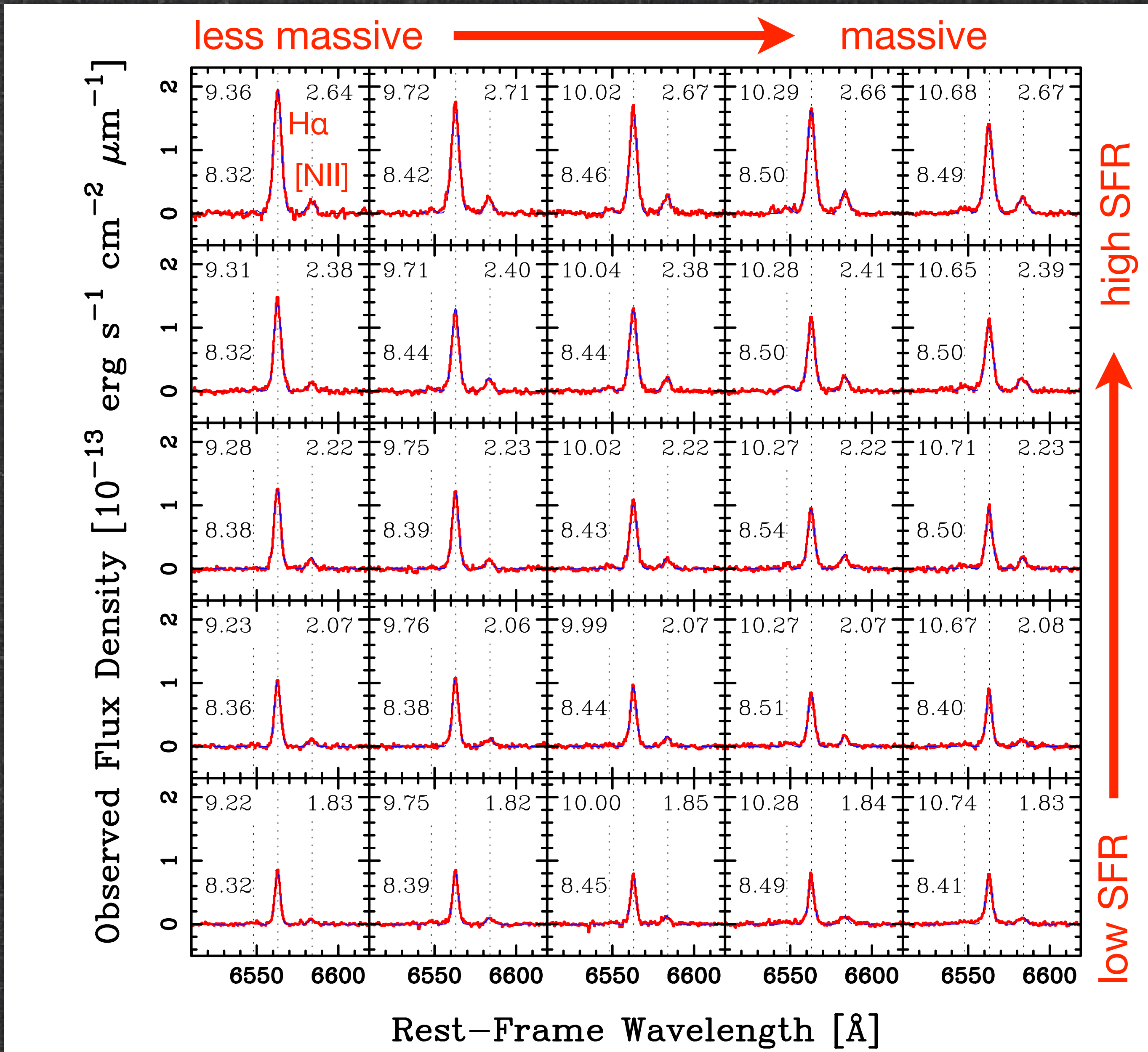
Subaru Telescope Press Release Aug. 2013 http://www.subarutelescope.org/Topics/2013/08/07/index.html

Spectral stacking analysis:



- Quality of individual spectrum is not so good, and thus, a spectral stacking analysis is applied in this study

Spectral stacking analysis:



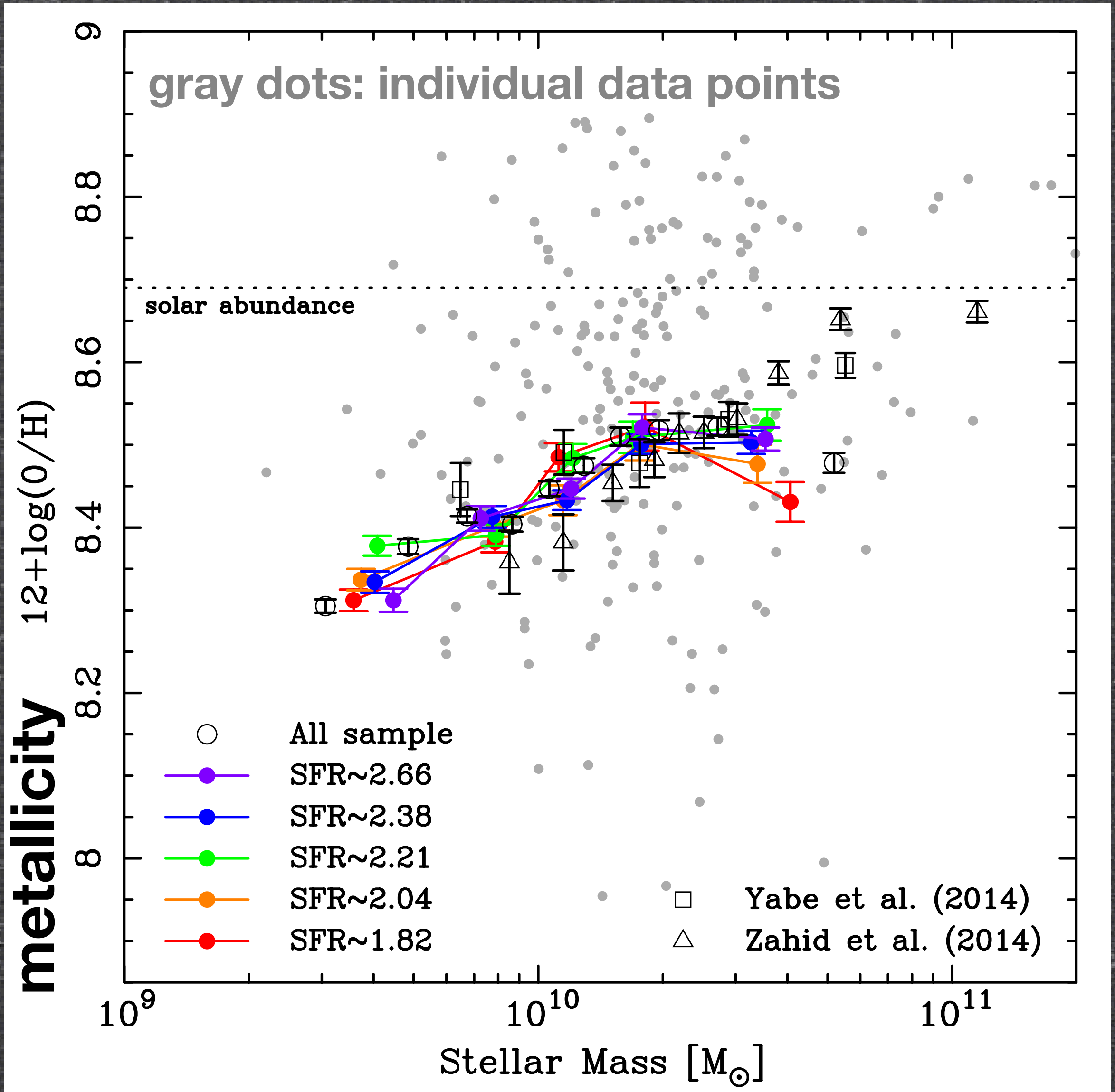
Stacked spectra around Hα line (6563Å)

- **Stacking analysis dividing sample into stellar mass and SFR bin (5 masses x 5 SFRs)**

The number of galaxies in each bin is ~160

Mass-metallicity relation at z~1.4:

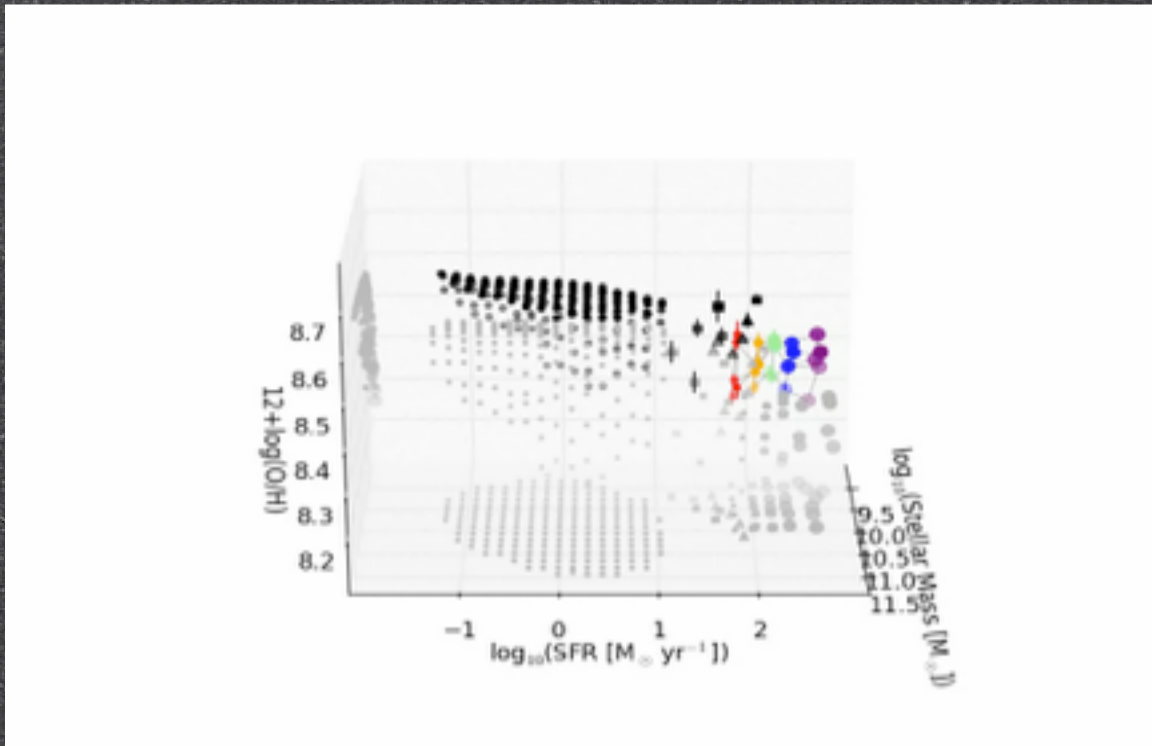
- Metallicity from [NII]λ6584/Hα (N2 method; Pettini & Pagel 04)
- The MZR at z~1.4 is established by using ~4,000 sample (the largest sample in this redshift range ever)

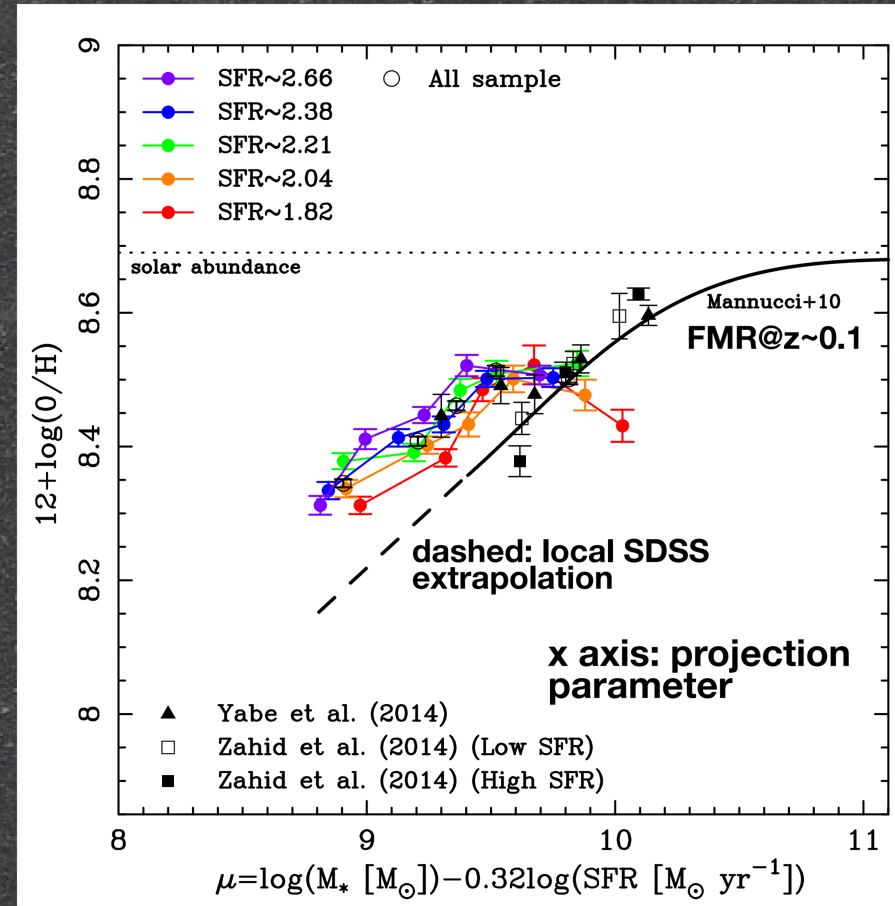


Roughly consistent with previous observational results in the similar redshift range (Yabe+14: GTO/SXDS, Zahid+14: COSMOS)

No clear SFR dependence of the MZR can be seen

Fundamental metallicity relation at z~1.4:

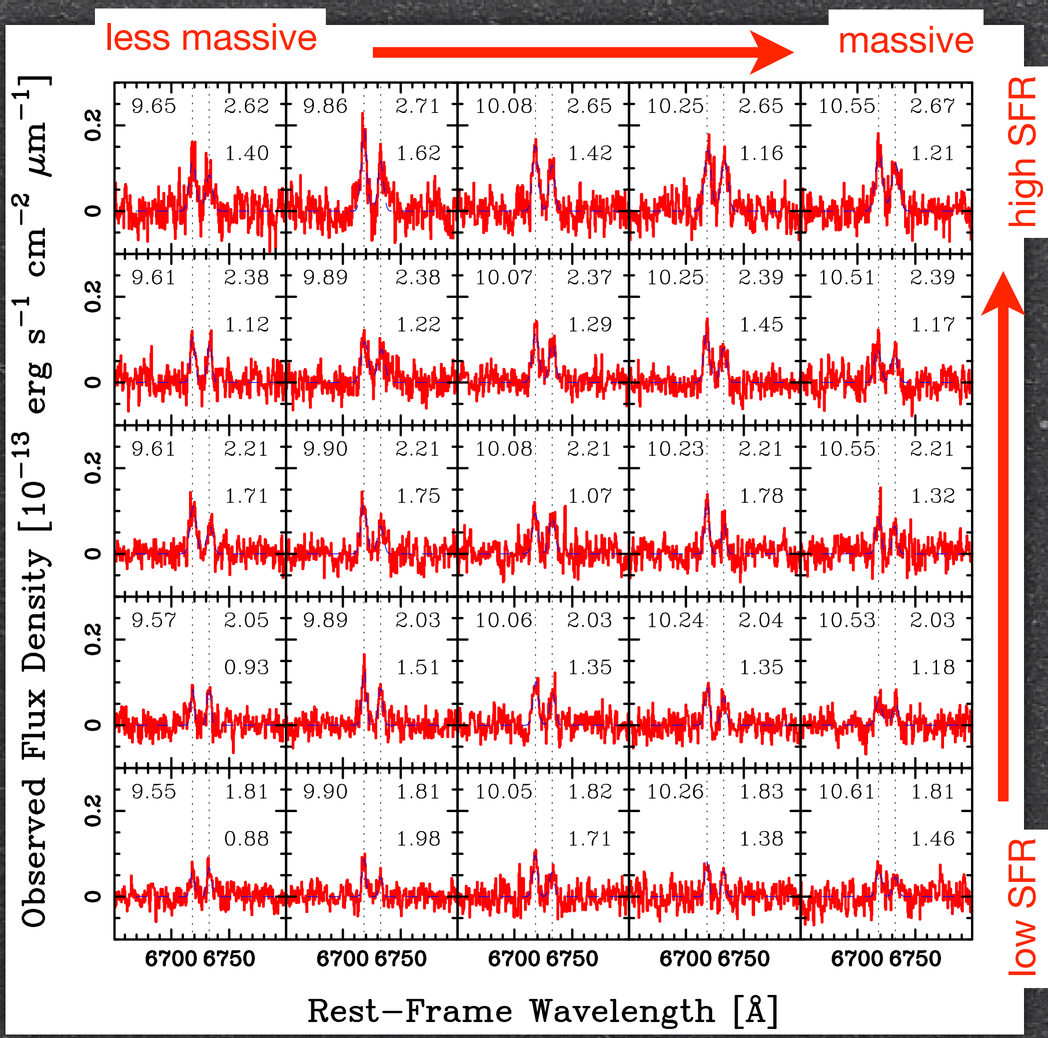


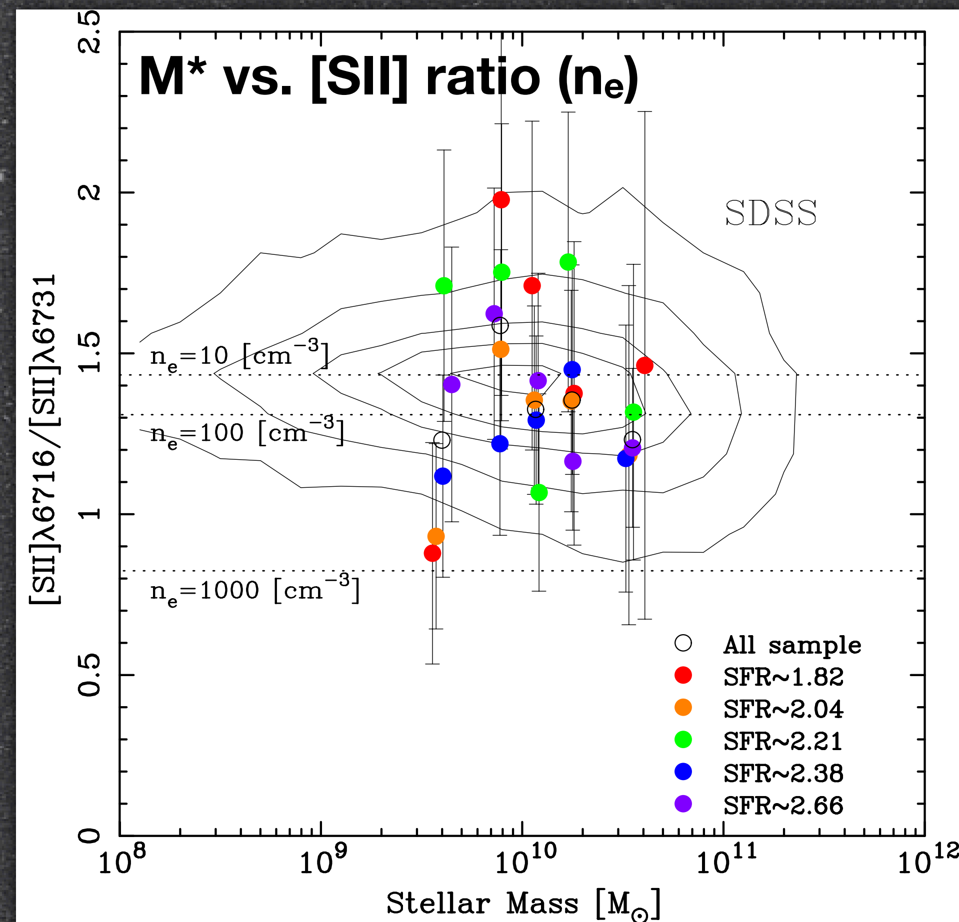


- Flat in metallicity with increasing SFR
- Higher metallicity than the extrapolation of the FMR at z~0.1
  - Redshift evolution of FMR?
  - Deviation of FMR in high SFR?
  - Problem in metallicity indicator (N2 method)?

[SII]λλ6717,6731 emission lines:

- [SII]λλ6717, 6731 detected significantly
- [SII]λ6717/[SII]λ6731 line ratio as a good tracer of electron density
- n_e ~ 10 - 500 cm^{-3} (comparable to SDSS galaxies at z~0.1)

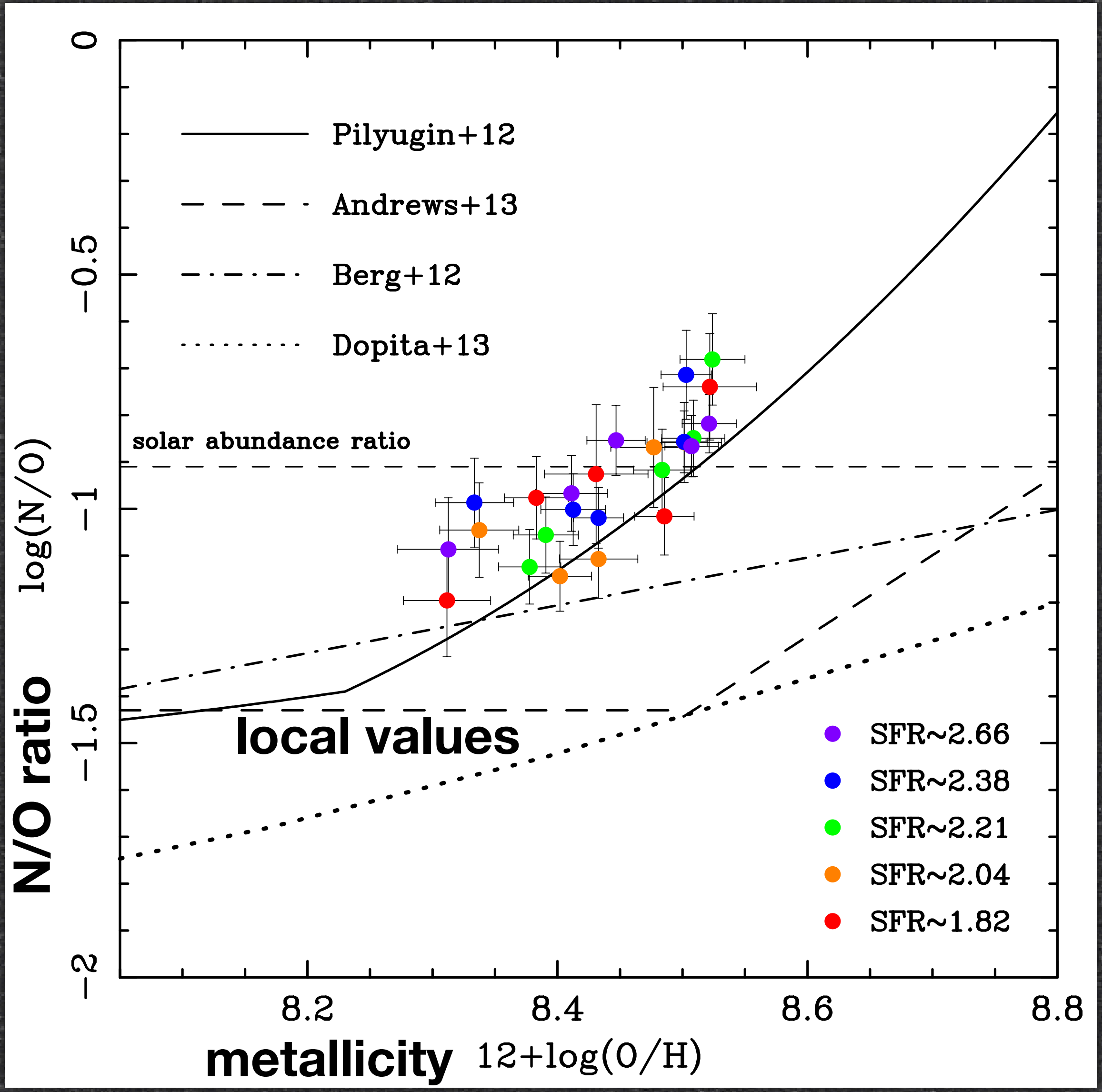




[SII]λλ6717,6731 lines from stacked spectra

Nitrogen-to-Oxygen ratio (N/O):

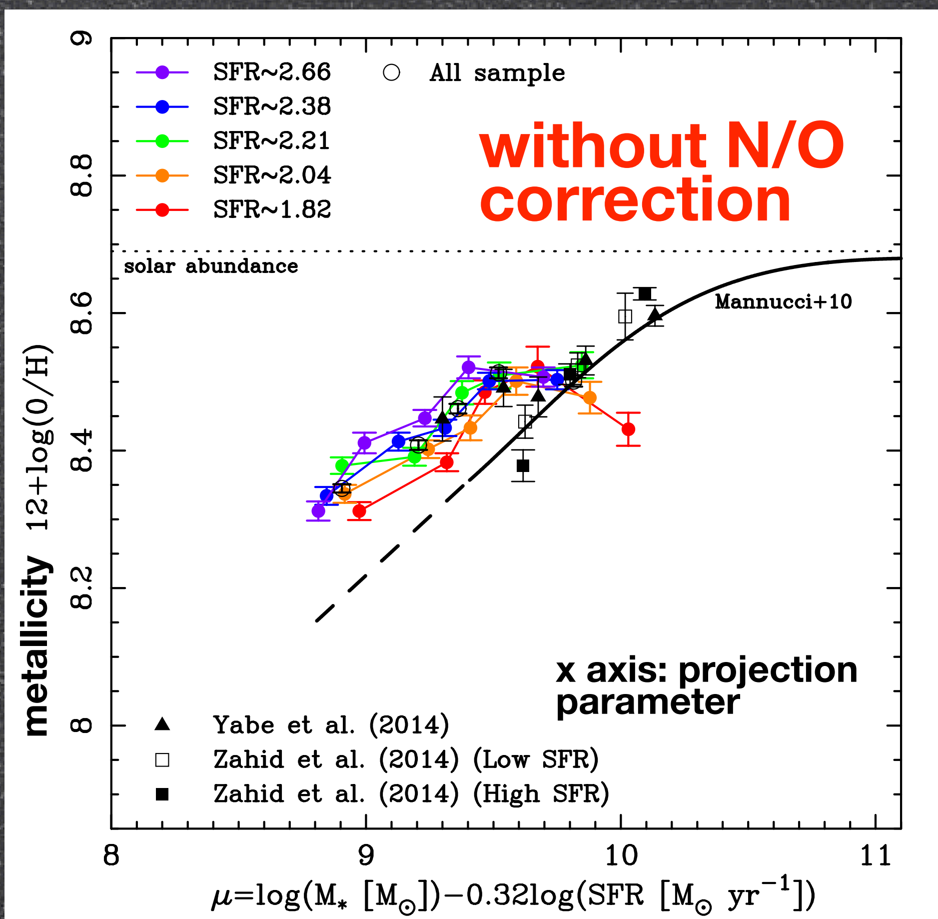
- N2S2([NII]λ6584/[SII]λλ6717,6731) : N/O indicator (Perez-Montero+09)
- Higher metallicity shows higher nitrogen-to-oxygen ratio (N/O)
- At a fixed metallicity, higher N/O than local galaxies (~solar value)

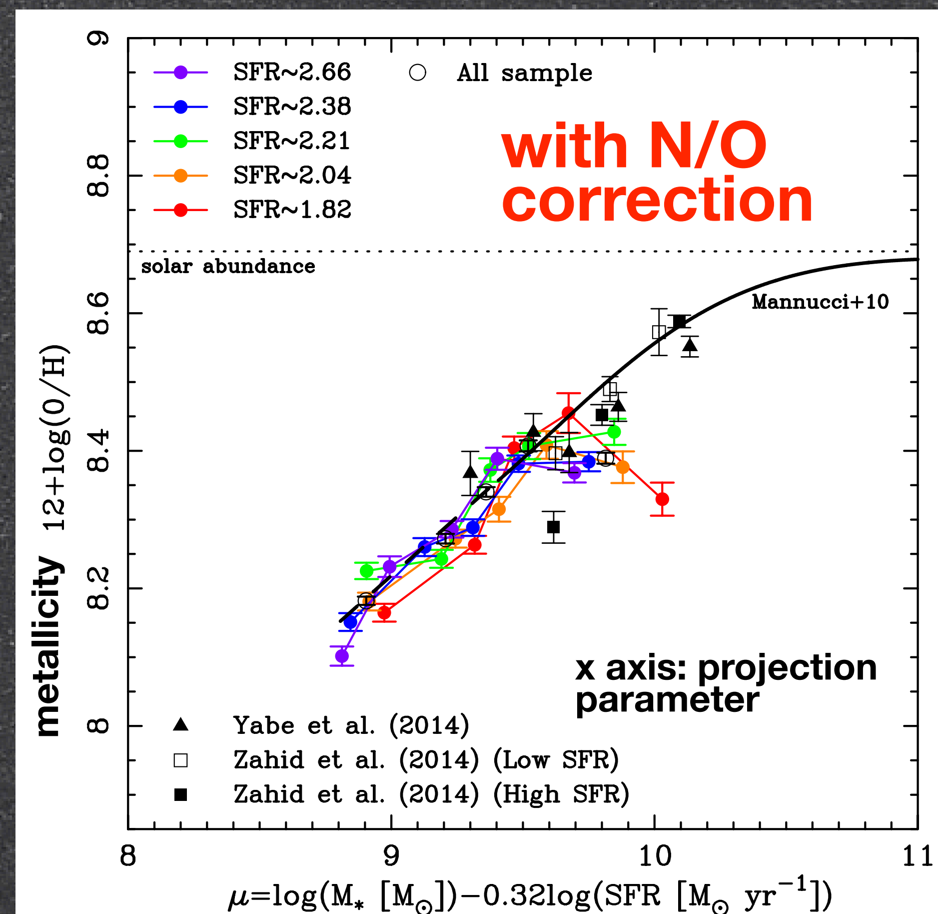


- "Green Pea" galaxies show similar higher N/O (e.g., Amorin+10, Hawley12)
- Similarly higher N/O at high-z has been reported (e.g., Masters+14, Steidel +14)
- Higher SFR shows higher N/O?

Fundamental metallicity relation revisited:

- Metallicity with N2 may be overestimated due to N/O enhancement
- N2 method with N/O effect included (Perez-Montero & Contini 09)
  - 12+log(O/H)=0.79 N2 - 0.56 log(N/O) + 8.41
  - The metallicity of our sample is re-calculated
- Metallicity taking into consideration the N/O effect is in good agreement with the extrapolation of the local FMR



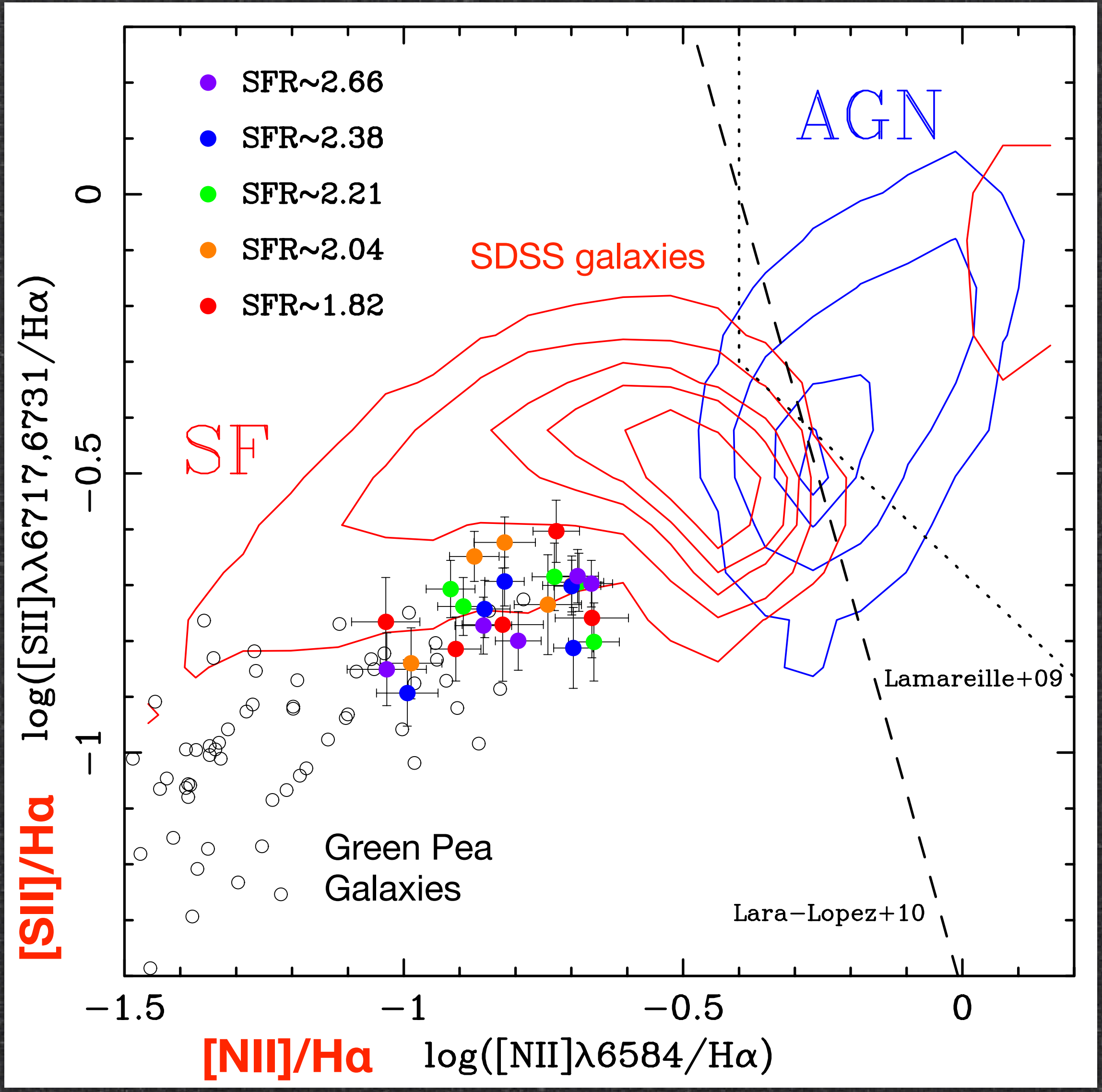


Summary:

- Cosmological redshift survey with Subaru FMOS (Fastsound)
- ~4000 Hα detection at z=1.18-1.54 (z_{med}~1.36)
- Spectral stacking analysis in each stellar mass and SFR bin
- The stellar mass-metallicity relation (MZR) at z~1.4
  - ✓ The largest NIR spectroscopic sample at z>1
  - ✓ Good agreement with previous observations
  - ✓ No clear dependence of SFR on the MZR
  - ✓ Flatter in high SFR regime comparing to the local FMR
- Significant detection of [SII]λλ6717,6731 emission lines
  - ✓ Electron density comparable to that at z~0.1
  - ✓ Nitrogen-oxygen (N/O) abundance ratio at z~1.4
  - ✓ Higher N/O than z~0.1 at fixed metallicity
  - ✓ Metallicity based on N2 method is overestimated
- After N/O correction for metallicity, our result is in good agreement with the extrapolation of the local FMR
- An excellent test case for the future Subaru MOS instrument, PFS

N2S2 diagram：

- N2S2 ([NII]λ6584/Hα vs. [SII]λλ6717,6731/Hα)
- Our sample is not largely contaminated by AGN
- [NII]λ6584/Hα and [SII]λλ6717,6731/Hα is lower than local galaxies



- The line ratio of our sample at z~1.4 is comparable to that of local "Green Pea" Galaxies
- At a fixed [NII]/Hα, [SII]/Hα decreases with increasing SFR

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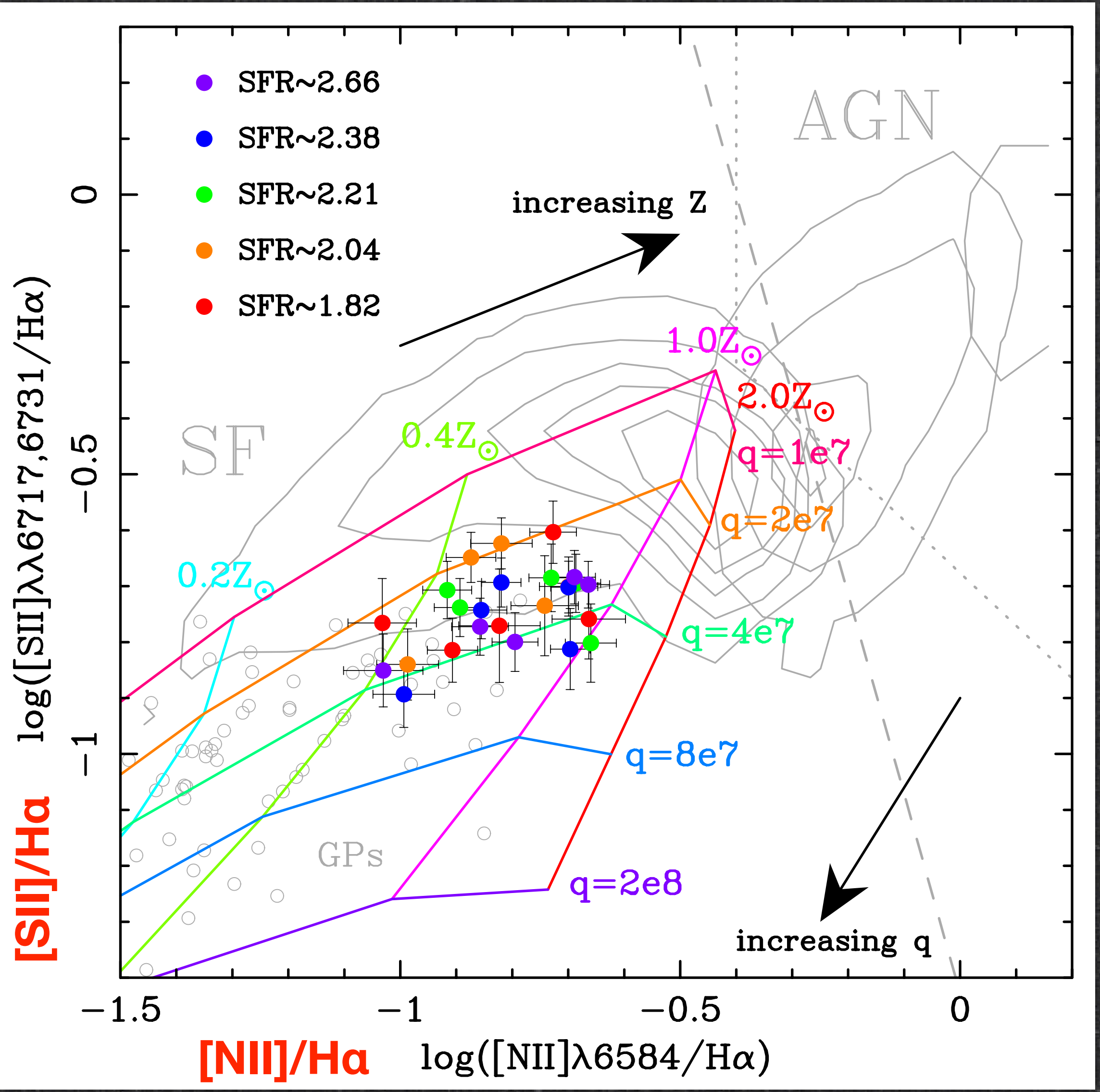

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- Comparison with photoionization model MAPPINGS III (Levesque+10): Higher ionization parameter (q) than local galaxies

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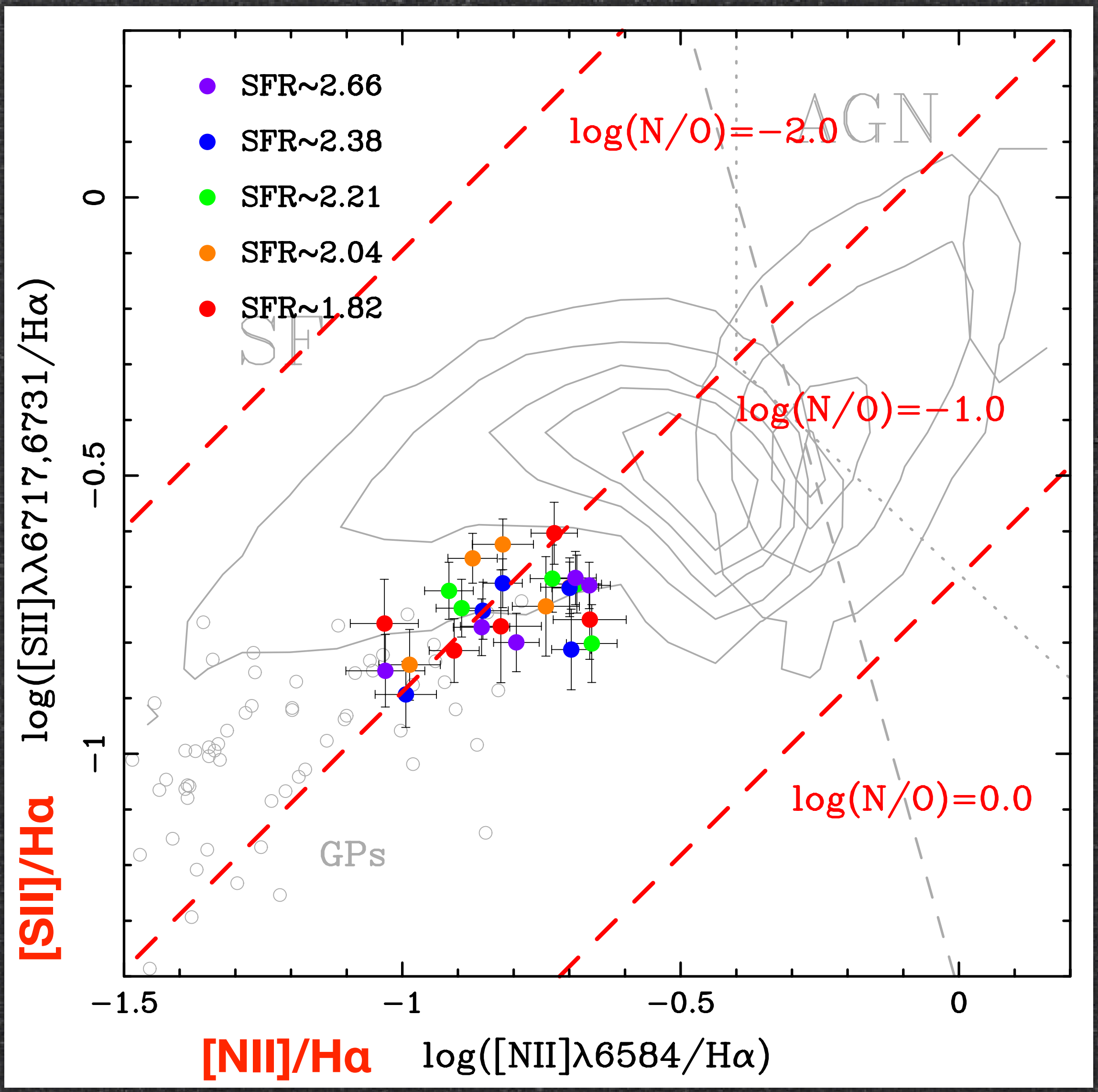

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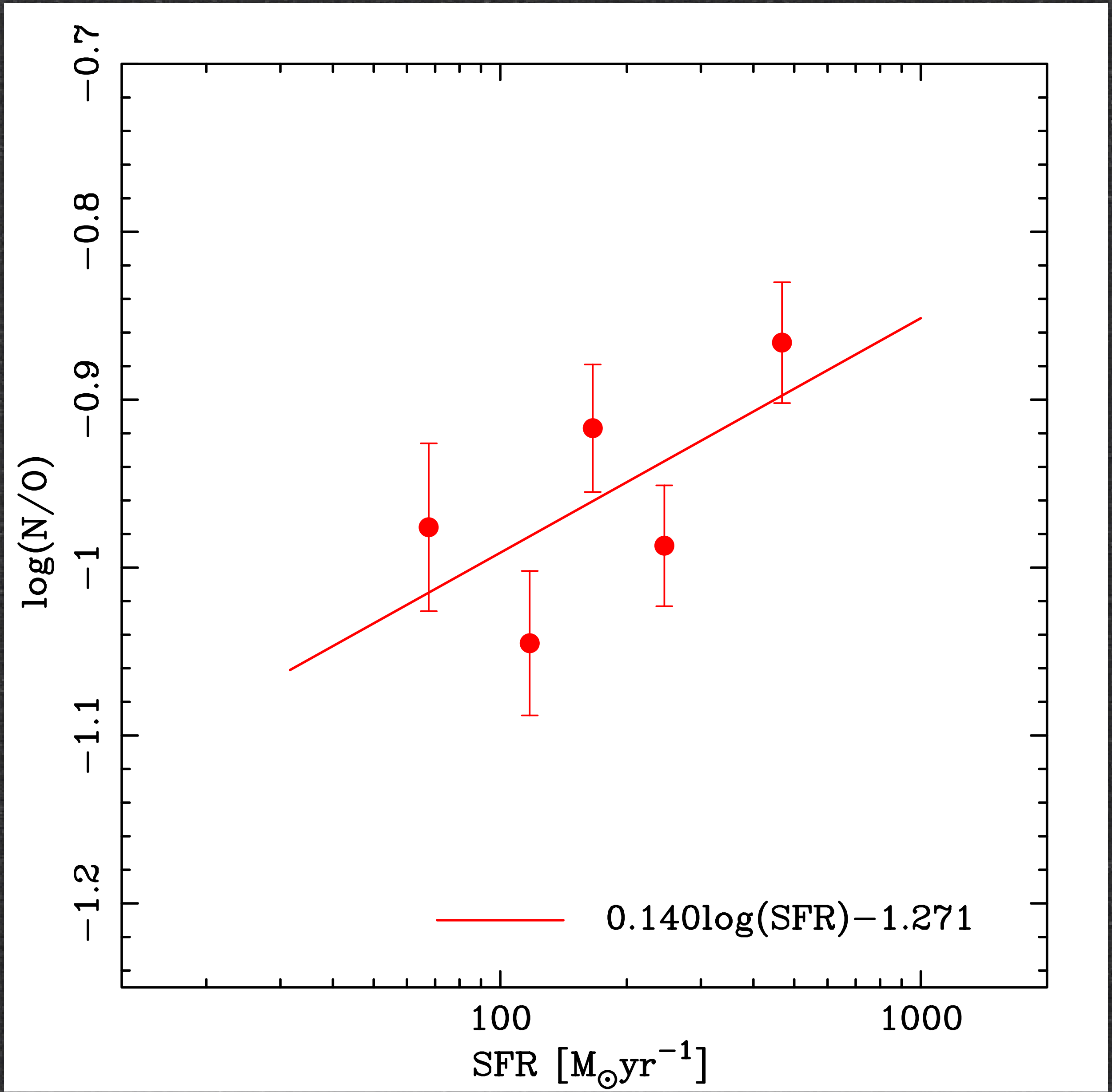
- At a fixed [NII]/Hα, [SII]/Hα decreases with increasing SFR
- Comparison with photoionization model MAPPINGS III (Levesque+10): Higher ionization parameter (q) than local galaxies
- Direction of increasing N/O is different from that of q

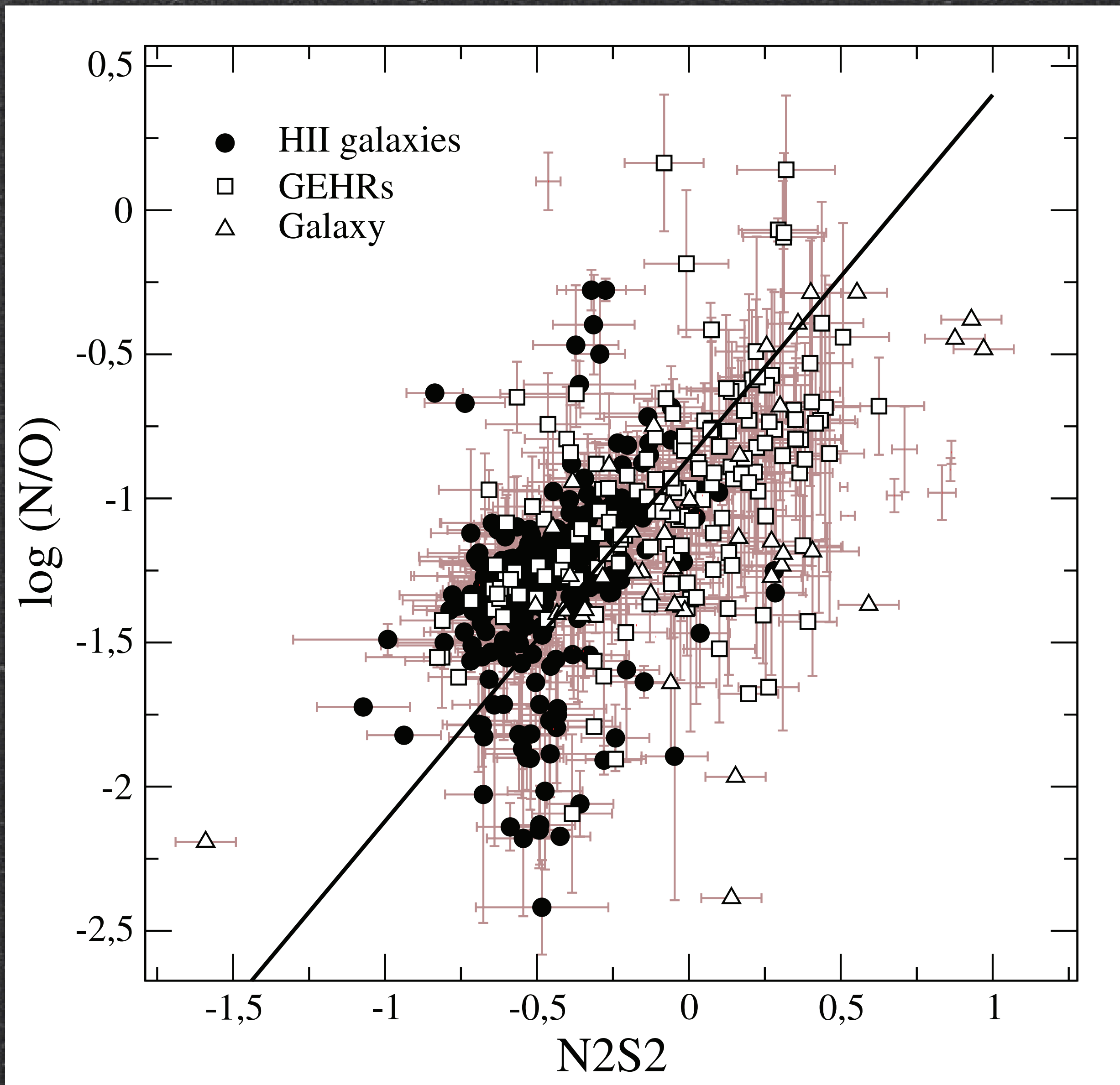
Dependence of SFR on N/O：

- Higher SFR shows higher N/O



N/O calibration (N2S2 index) :

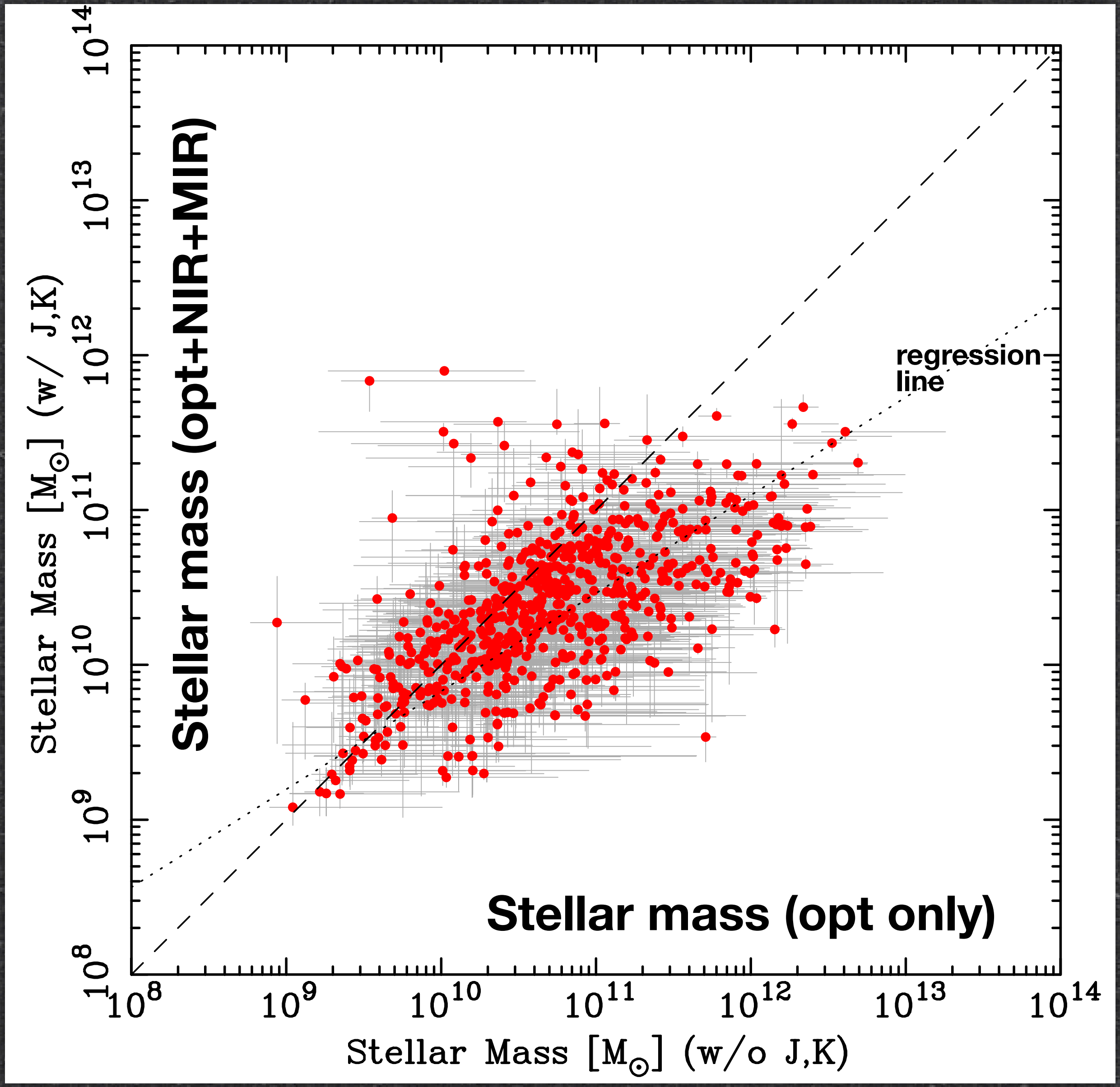
Perez-Montero & Contini 2009:



- $\log(N/O)=1.26\times N2S2-0.86$
- S.D. ~0.3 dex
- Less affected by dust extinction

Uncertainty of stellar mass estimation：

Comparison of stellar mass (w/ or w/o NIR/MIR data)



- ~20% of our sample have NIR and/or MIR data coverage
- Stellar masses derived with only optical data tend to be overestimated
- If the object has only optical data, the stellar mass is corrected for this trend

- **It is worth noting that the uncertainty of the stellar mass does not affect the conclusions in this work largely**

Nitrogen-to-Oxygen ratio (N/O) :

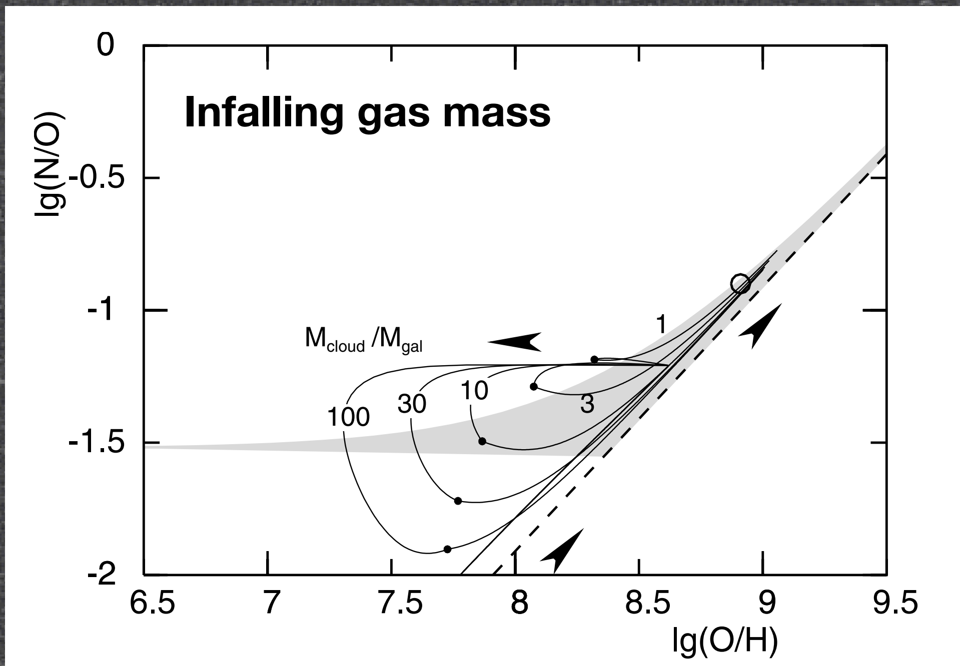
- The origin of the higher N/O(~solar) relative to local galaxies
- Time-delayed nitrogen enhancement (e.g., Edmunds & Pagel 78)
  - ✓ Nitrogen from low-/intermediate-mass stars
  - ✓ Contradicted to the trend that higher SFR shows higher N/O?

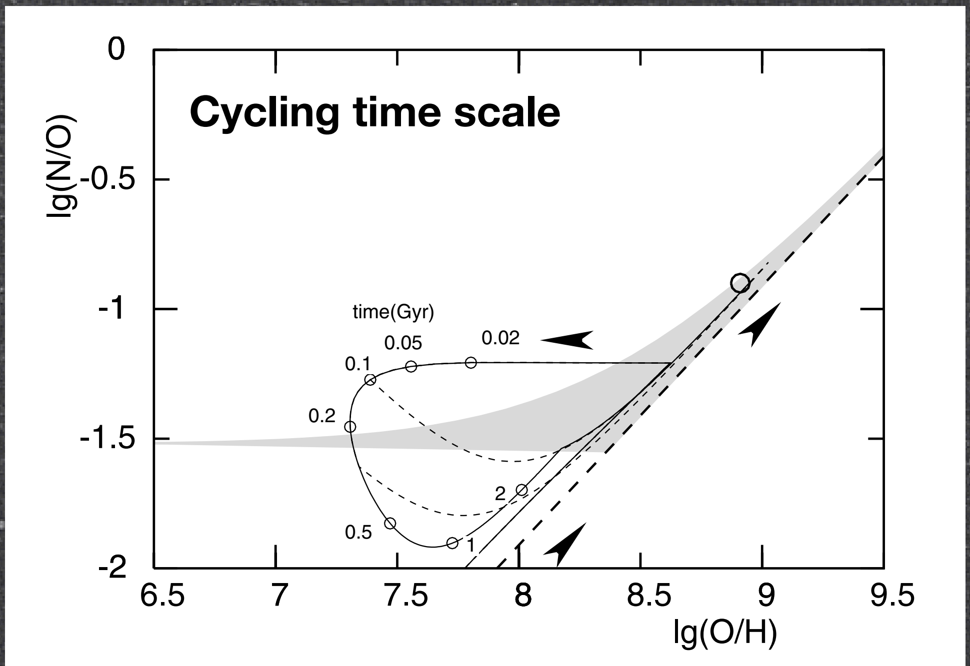
- Effect of Wolf-Rayet stars?
  - ✓ Nitrogen rich Wolf-Rayet (WN) (e.g., Brinchmann+08)
  - ✓ Actual effects is not clear yet (e.g., Perez-Montero+13, James+13)

- Inflow of metal poor gas?
  - ✓ Metallicity decreases keeping high N/O by the dilution effect
  - ✓ High-z galaxies are really secondary dominated? (Masters+14)

- Selective gas outflow by the SN driven winds?
  - ✓ If outflow is SN driven, oxygen rich gas is expelled
  - ✓ N/O abundance ratio decreases (e.g., van Zee+06)
  - ✓ This explains the fact that higher SFR shows higher N/O

Infalling metal poor gas:





Köppen & Hensler 2005, A&A, 434, 531