すばる/GLAOで見る激動期の星形成銀河

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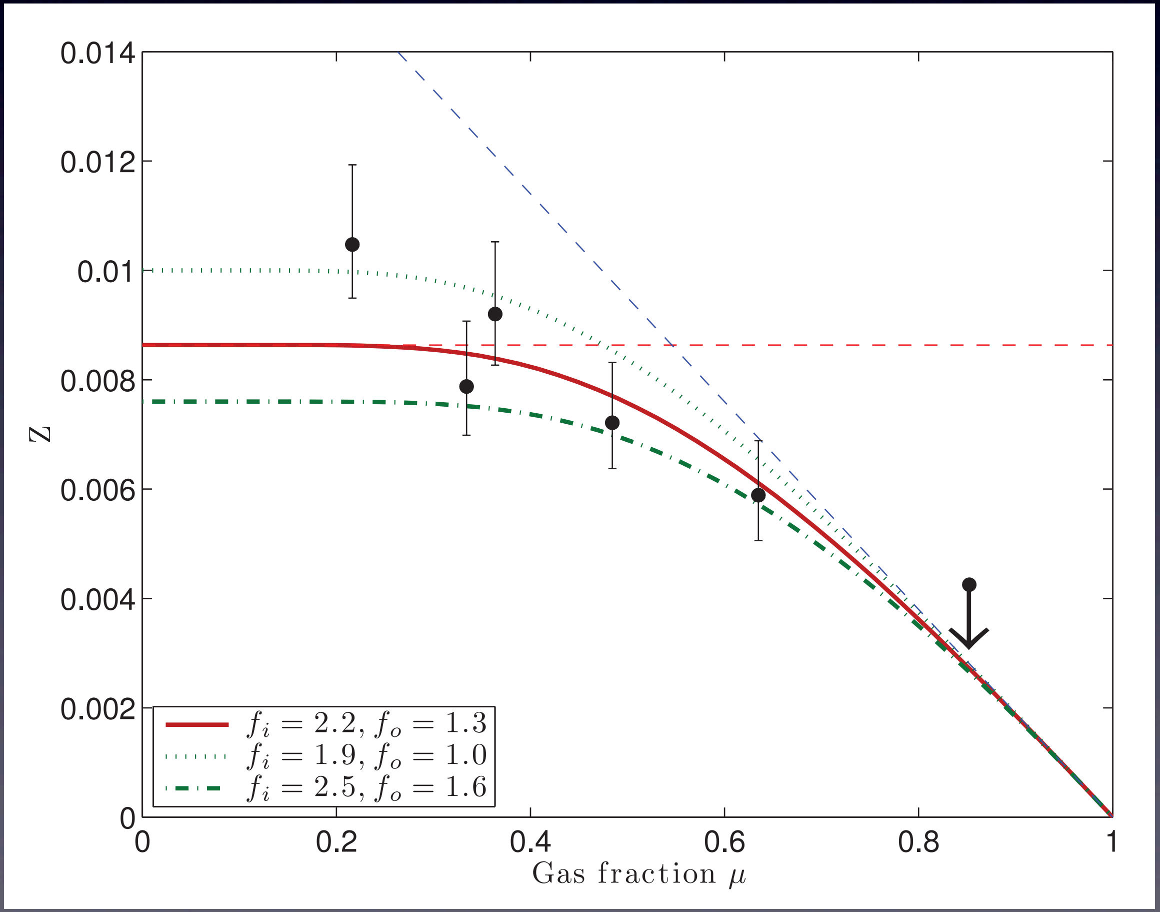
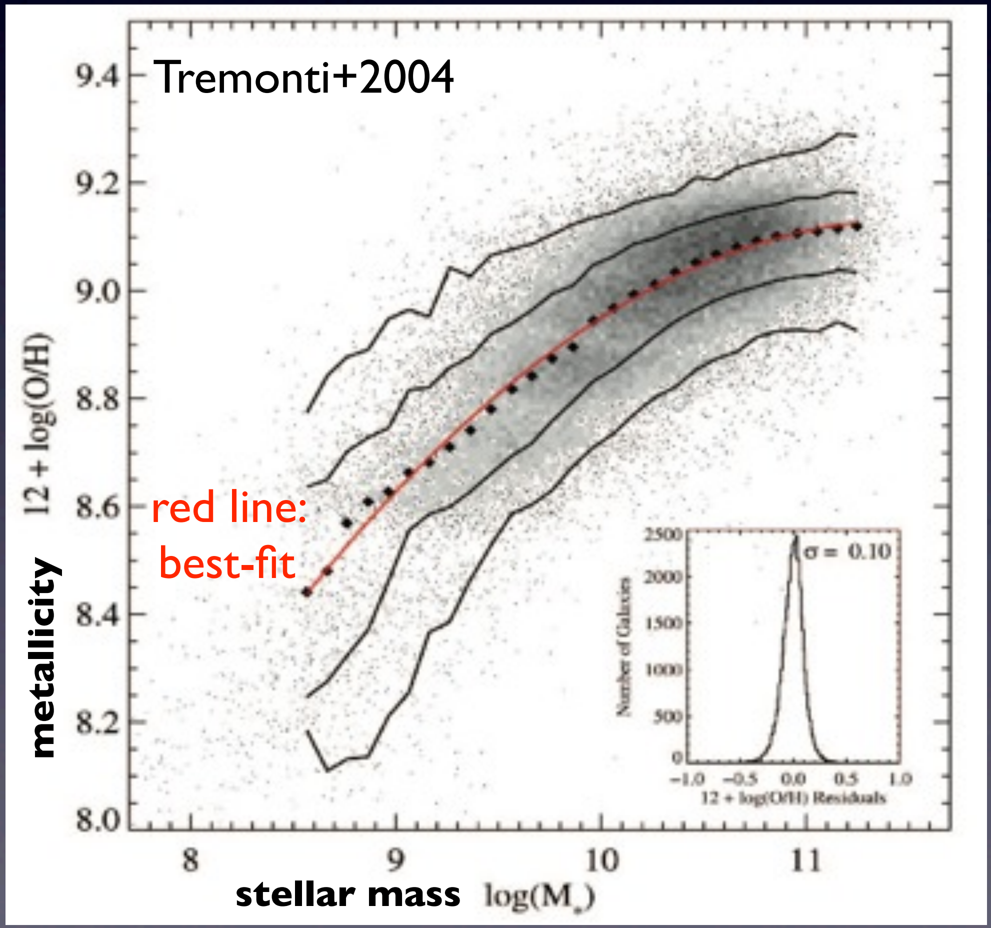
Introduction: Metallicity as a tracer of the past SF

- Gas-phase metallicity (hereafter, metallicity)
  - ✓ Metallicity traces the past star-formation activity
  - ✓ It also changes via gas infall/outflow of galaxies
  - ✓ Metallicity is a key to understand the galaxy evolution



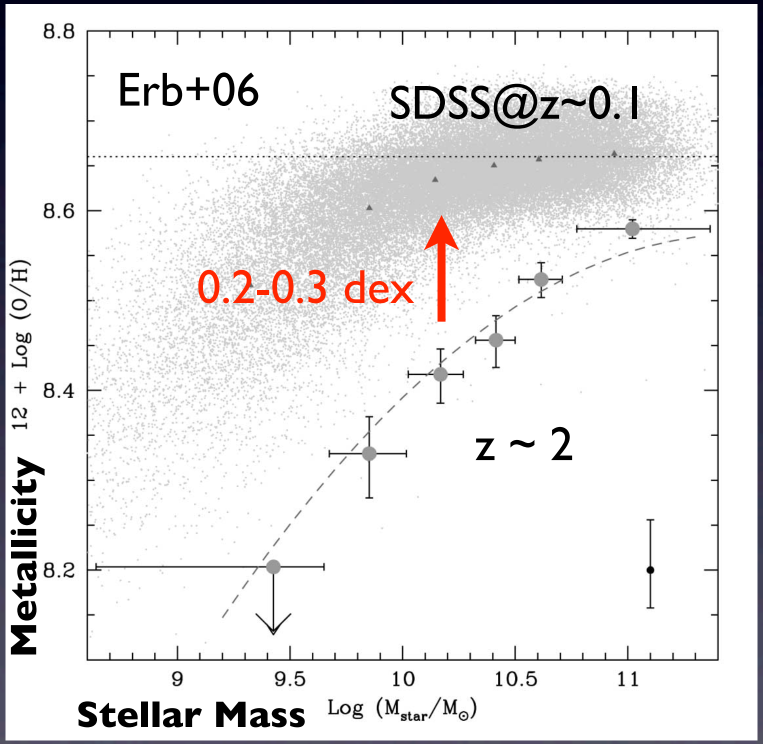
Introduction: Mass-Metallicity Relation at z~0

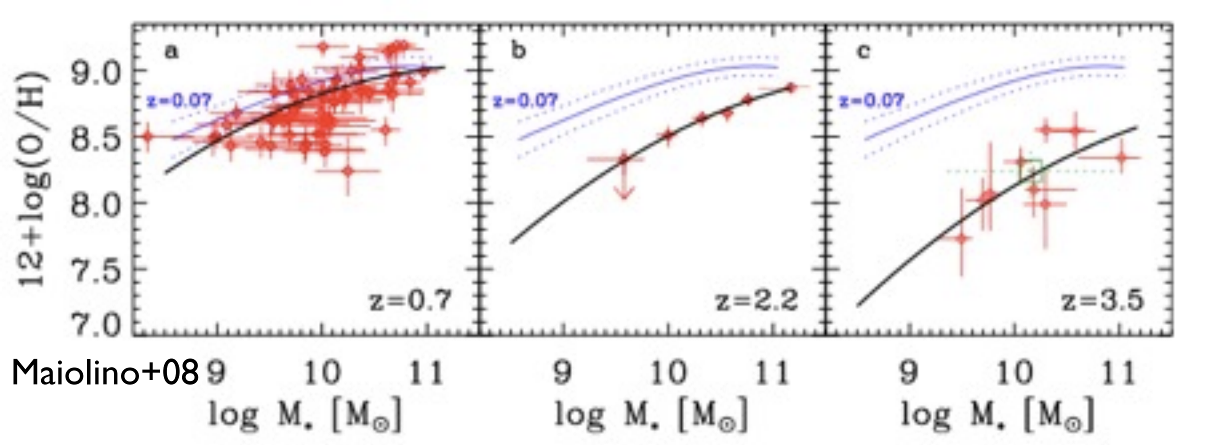
- Correlation between stellar mass (luminosity) and metallicity
- Now mass(luminosity)-metallicity (MZ) relation is well established at local universe with ~53000 SDSS galaxies at z~0.1 (Tremonti+04)
- Evolutionary stage of individual galaxies? Massive galaxies are (chemically) well evolved?

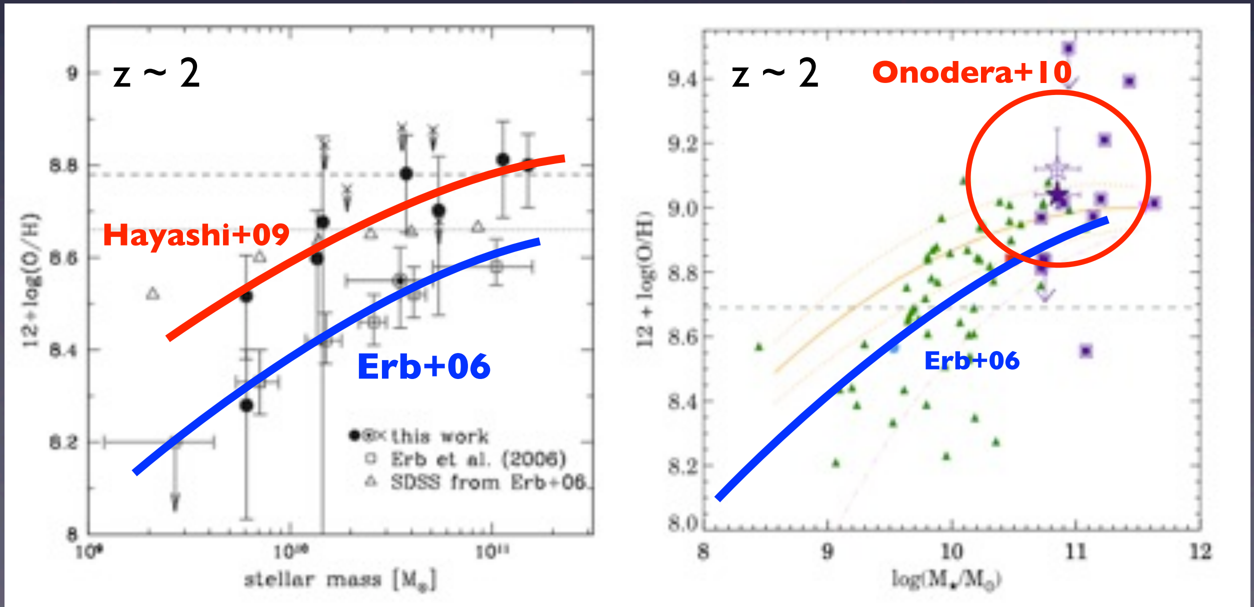


Introduction: Mass-Metallicity Relation at high redshift

- MZ relation at z~2 (e.g., Erb+06) and z~3(e.g.,Maiolino+08)
  - ✓ Evolution of the MZ relation from z~3 to z~0?
  - ✓ Still controversy as to the MZ relation at z~2
  - ✓ We need larger sample at z=1-2, when the universe is in the most active/violent phase

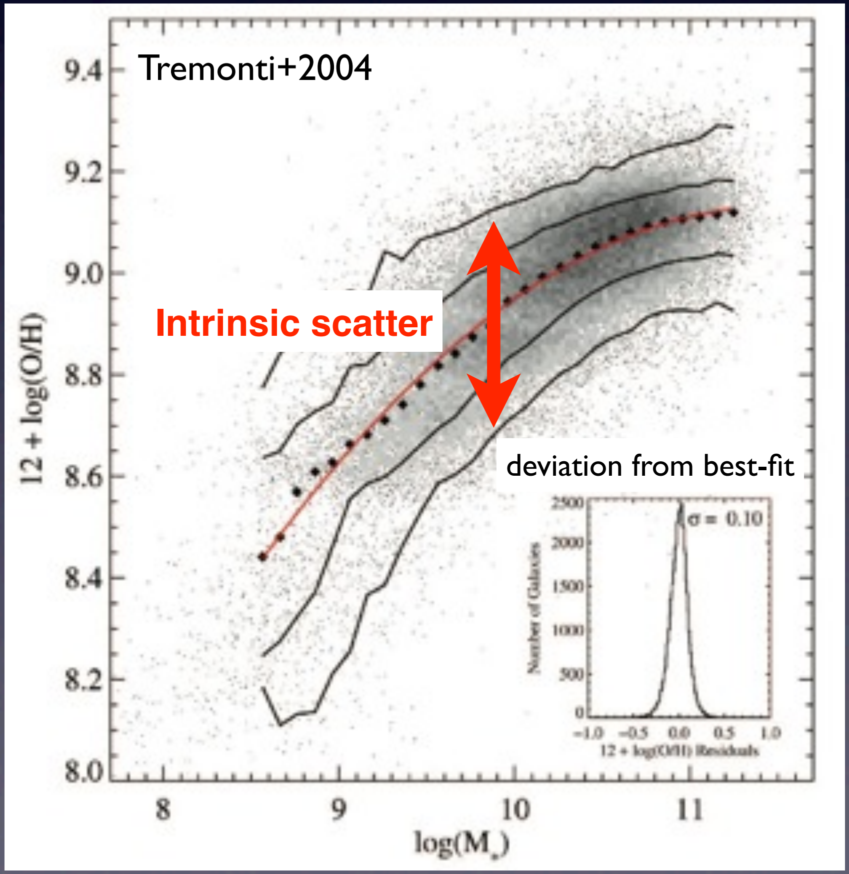


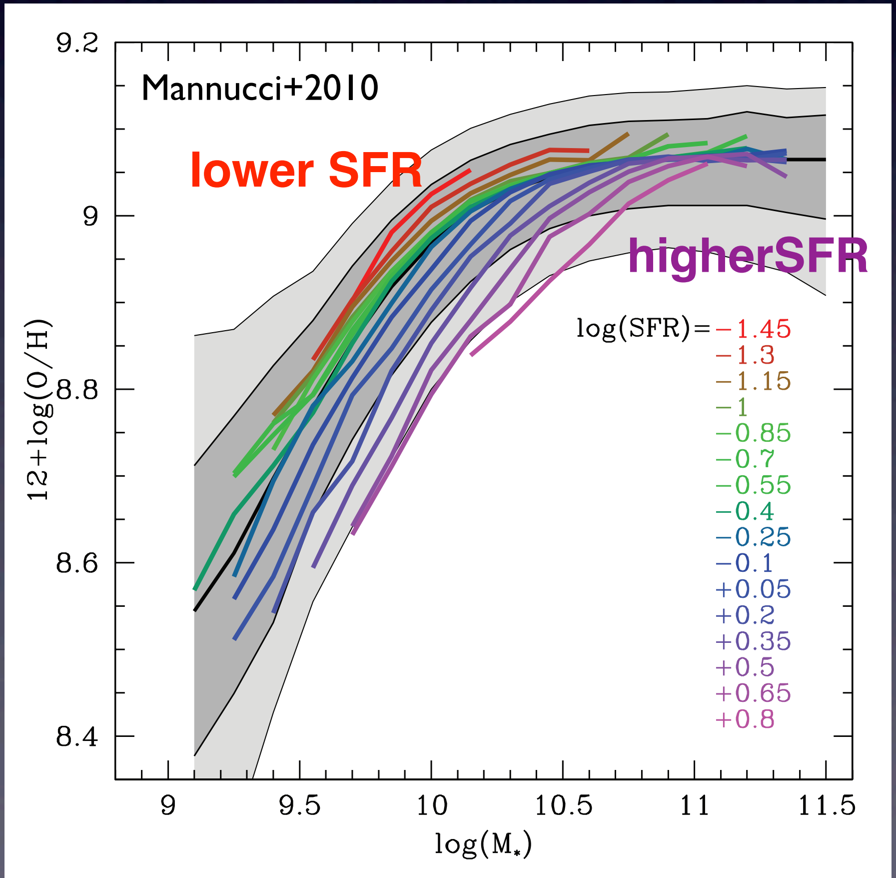




Introduction: Scatter of the Mass-Metallicity Relation

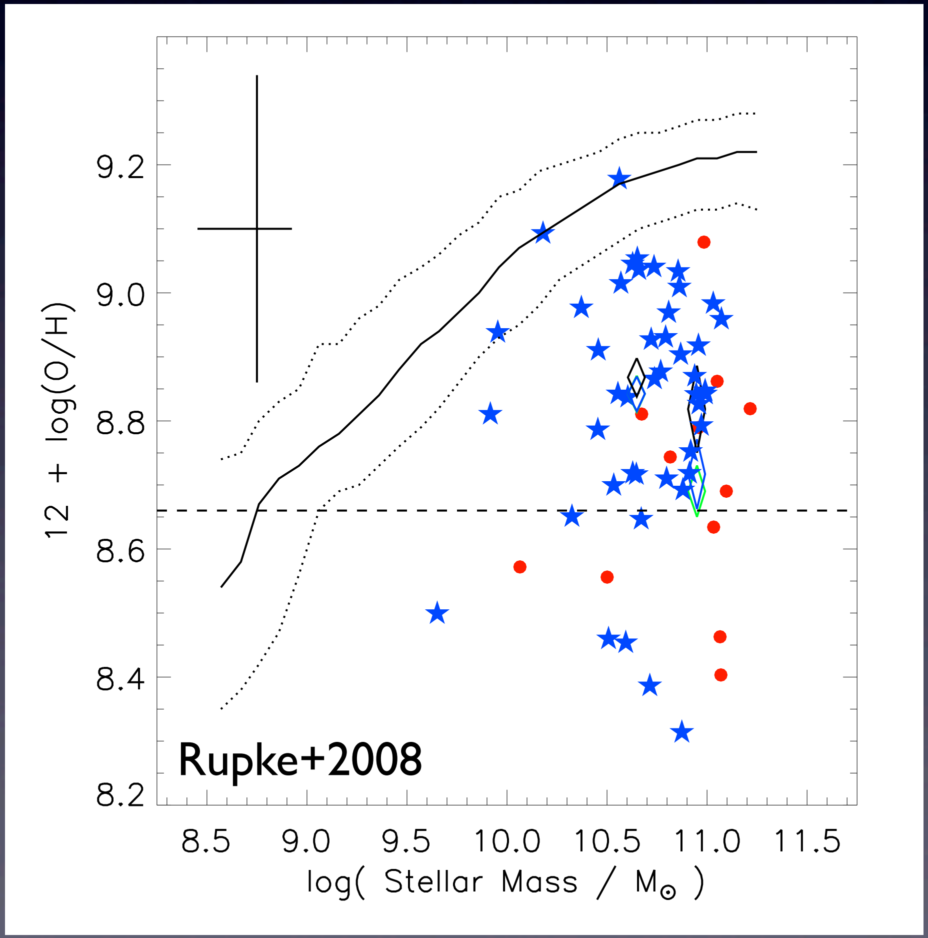
- The MZ relation at z~0.1 has intrinsic scatters (Tremonti+04)
- What physical parameters can explain this scatter?
  - ✓ SFR (Mannucci+2010), specific SFR (Ellison+2008), half light radius (Ellison+2008), galaxy interaction (Rupke+2008)
- The intrinsic scatter of the MZ relation at high-z is still unknown
- We need large sample at high-z

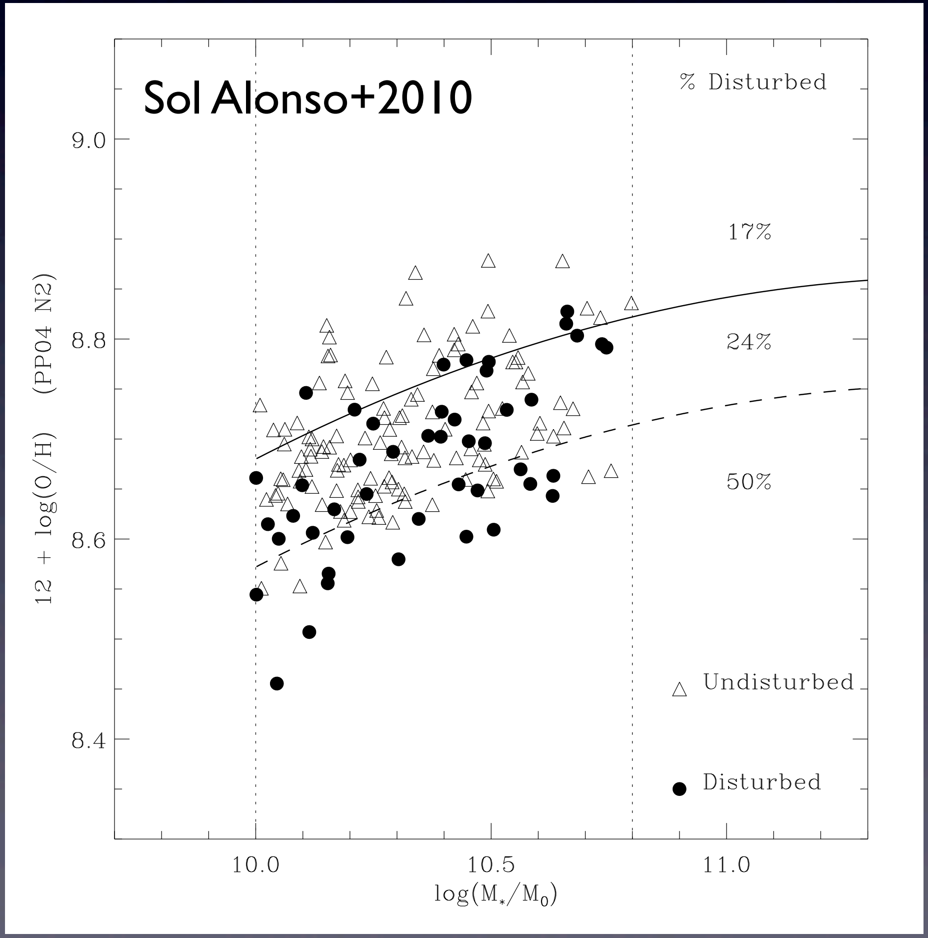




Introduction: Morphology Dependence?

- Morphology dependence on the mass-metallicity relation at z~0
  - ✓ ULIRG w/ merger feature show lower metallicity (Rupke+2008)
  - ✓ Disturbed galaxies show lower metallicity (Sol Alonso+2010)
- The morphology dependence still remains unclear at high redshift
- We need large sample at high-z

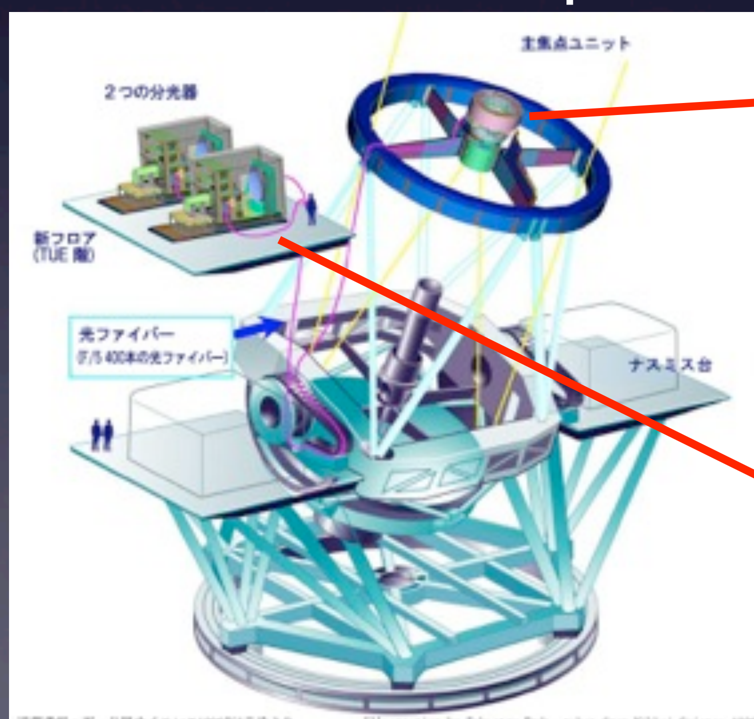




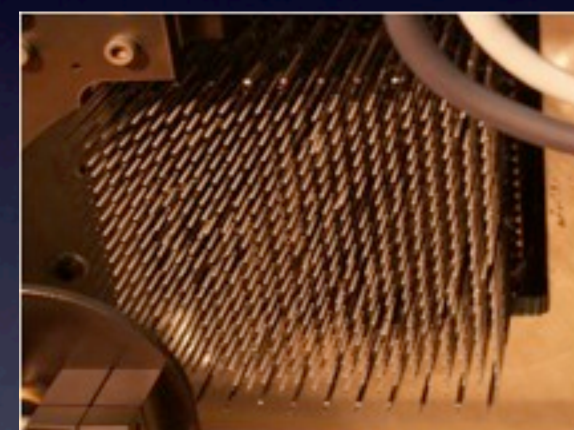
Introduction: FMOS on Subaru Telescope

- What's FMOS (Fibre Multi-Object Spectrograph)?
  - ✓ Second generation instrument for Subaru Telescope
  - ✓ Collaboration among Japan, UK, and Australia
  - ✓ Multi-object spectrograph in NIR (0.9-1.8μm) w/ 400 fibers and FoV of 30'Φ
  - ✓ Low Resolution (LR; R~650) and High Resolution (HR; R~3000) mode
  - ✓ Details are in Kimura et al. 2010, PASJ, **62**, 1135
  - ✓ We conduct large NIR spectroscopic surveys with FMOS

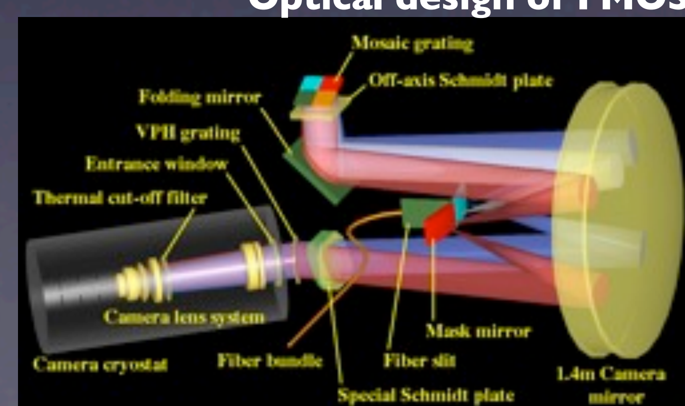
FMOS on the Subaru Telescope



Fiber positioner on prime focus

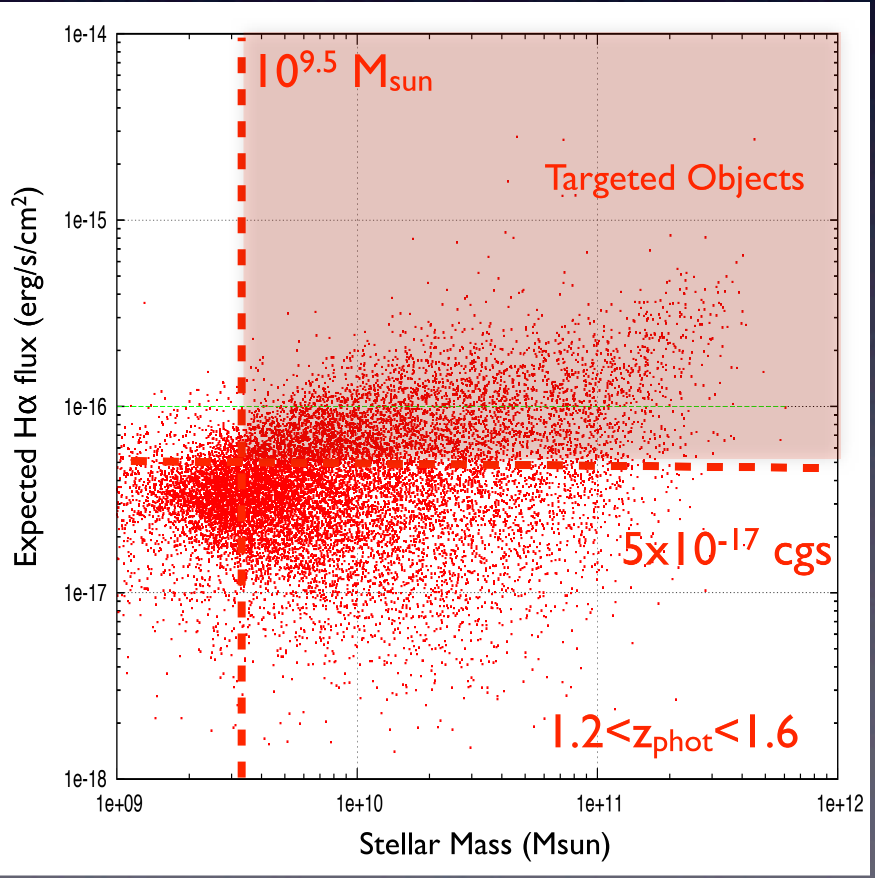


Optical design of FMOS



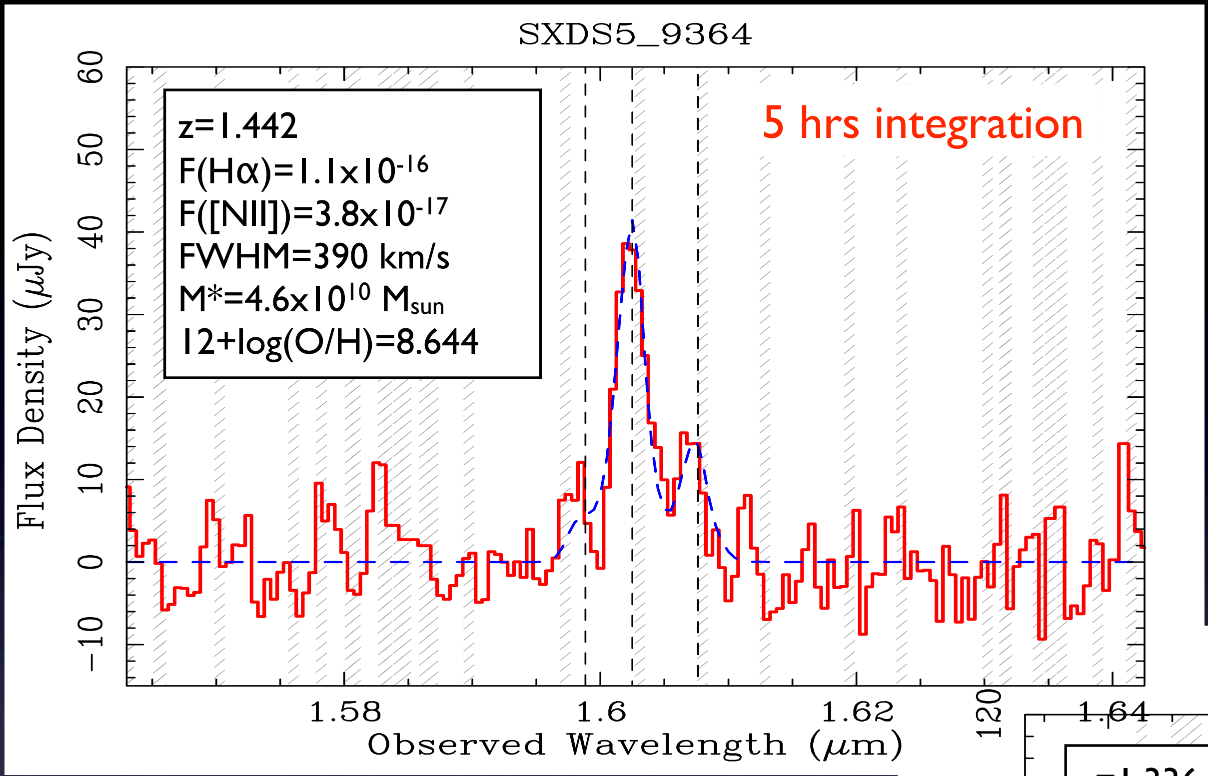
Sample Selection and Observations:

- Target Sample
  - ✓ Field : SXDS/UDS (effective area~0.7 deg^2)
  - ✓ We constructed a K-selected catalogue
    - ✳ z_{phot}, M* are derived from SED fitting
    - ✳ SFR from the rest-frame UV luminosity, E(B-V) from the rest-frame UV color
    - ✳ Expected F(Hα) is from the SFR and E(B-V)
    - ✳ E(B-V) for emission line is derived by using prescription by Cid Fernandes+05
  - ✓ $1.2<z_{phot}<1.6$, K<23.9 AB mag, $M_*>10^{9.5}$ M_{sun}, $F(H\alpha)^{exp}>5.0\times10^{-17}$ cgs
  - ✓ Excluding X-ray sources ($L_x>10^{43}$ erg/s)
  - ✓ 2500 objects in whole area of the SXDS



- Observations
  - ✓ Mainly FMOS/GTOs in 2010-2011
  - ✓ LR mode / Cross Beam Switch mode
  - ✓ Typical exposure time is 3-4 hrs per FoV
  - ✓ About 1200 objects are observed in total
- Data Reduction
  - ✓ FMOS reduction pipeline FIBRE-pac
  - ✓ Details are shown in Iwamuro+12
  - ✓ Fitting methods taking the OH mask effects into consideration

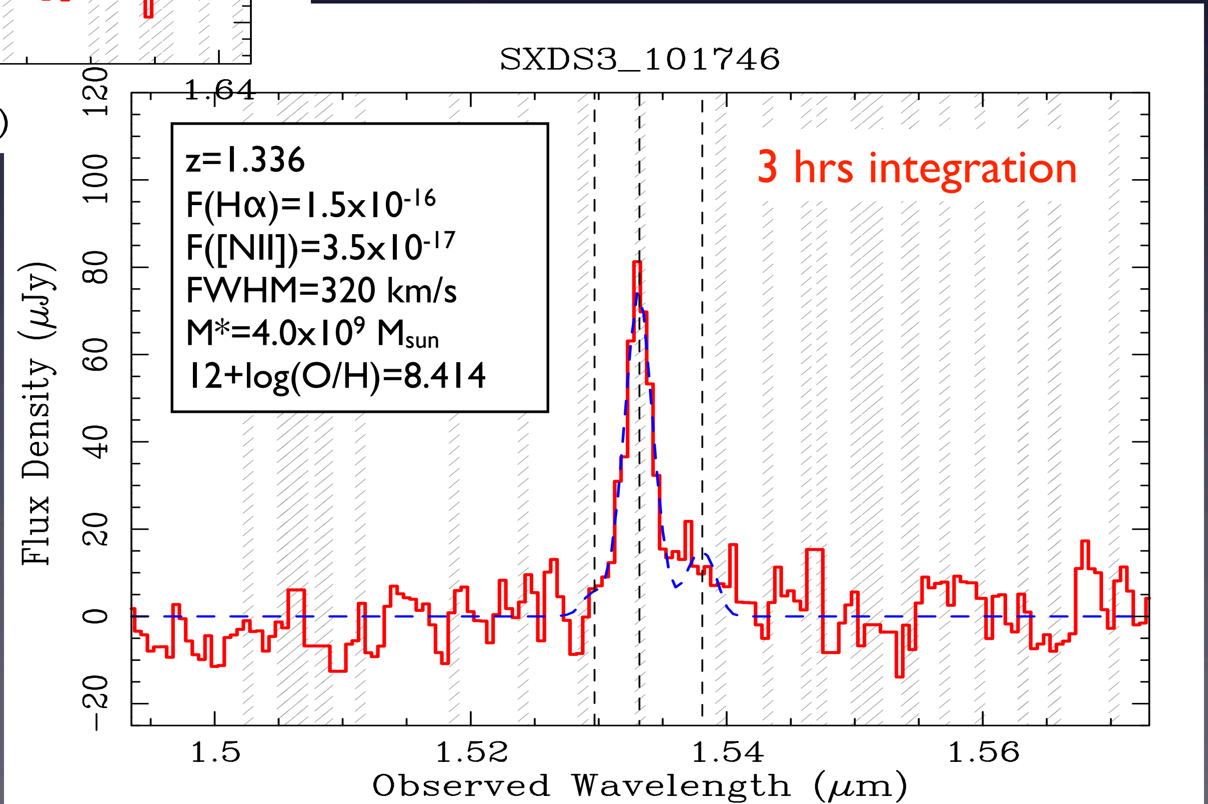
Observed Spectra:



We observed ~1200 targets in total. Among them, 343 objects show significant Hα emission (S/N>3) at z=1.2-1.6 (median=1.41). This is the largest NIR spectroscopic sample at z>1 ever.

Shaded area: OH airglow mask

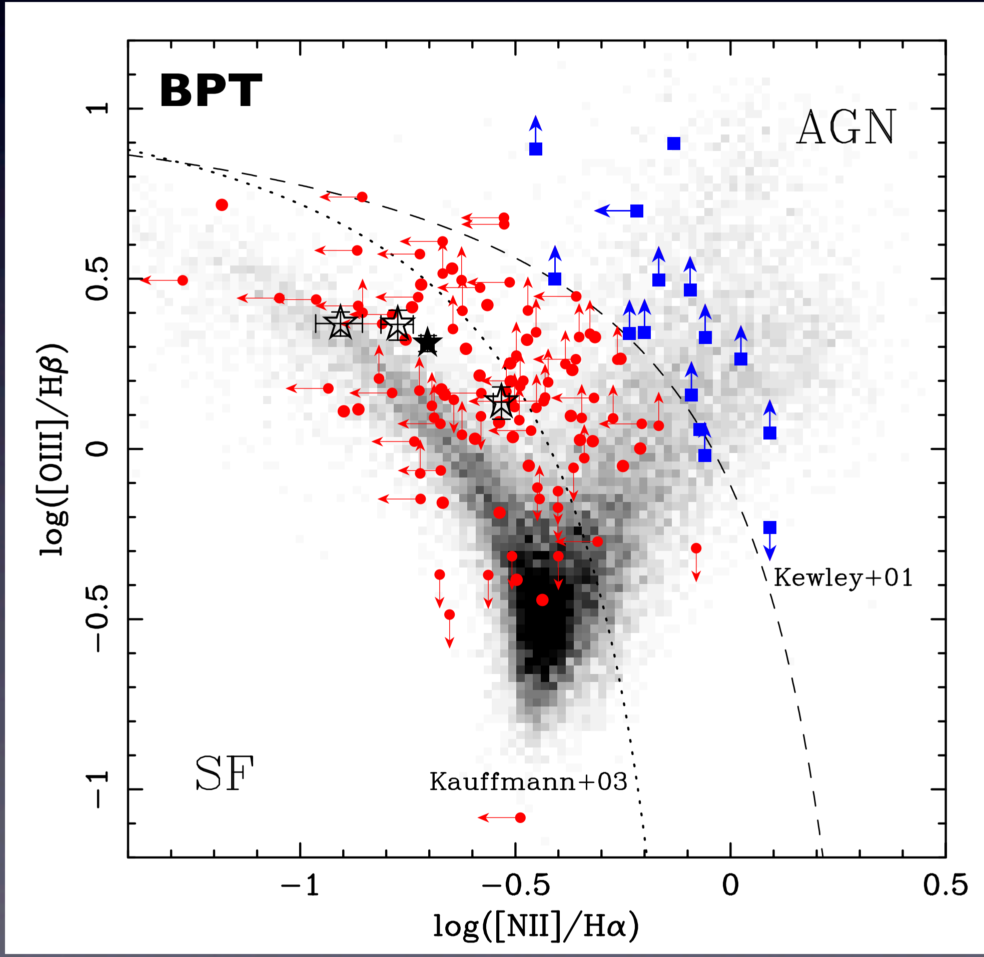
Solid : Observed Spectra
Dashed : Best-fit Model Spectra

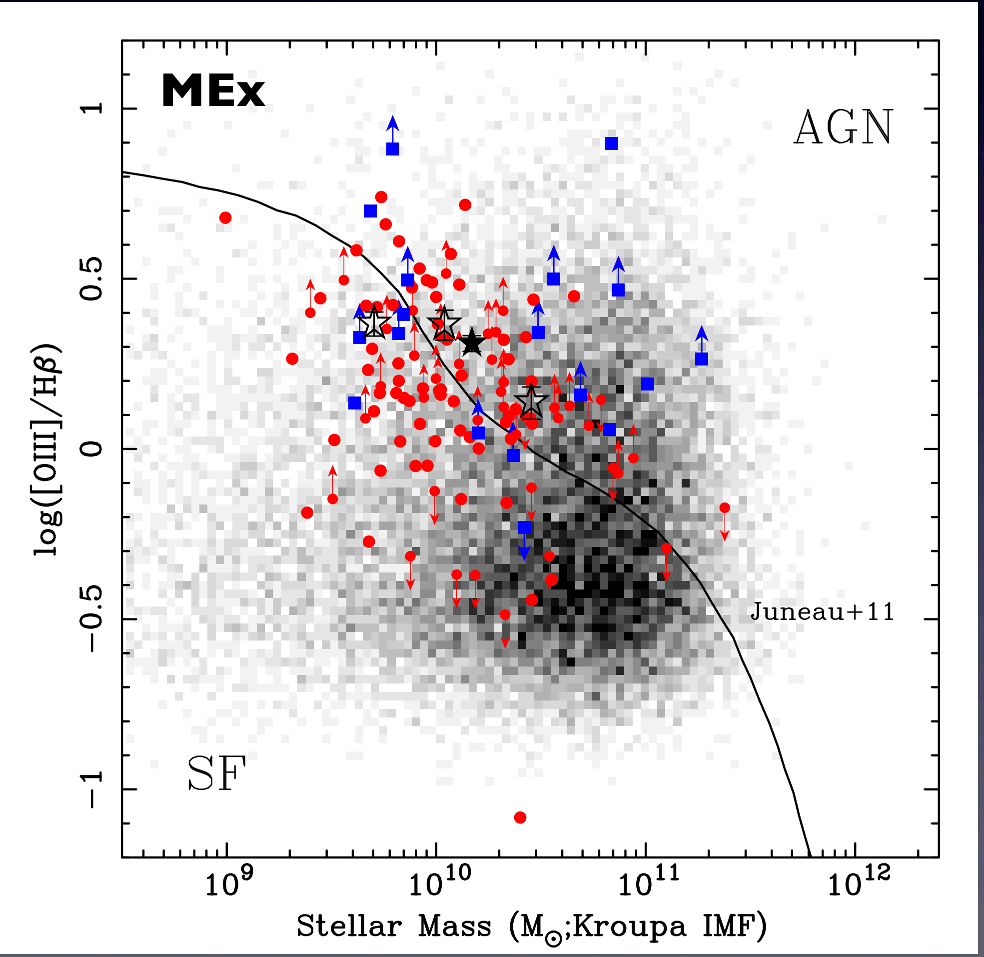


Initial results (GTO in 2010; 71 Hα detections) are already presented by Yabe+12 (PASJ, 64, 60). In this talk, we also present results from all GTO runs.

AGN contamination:

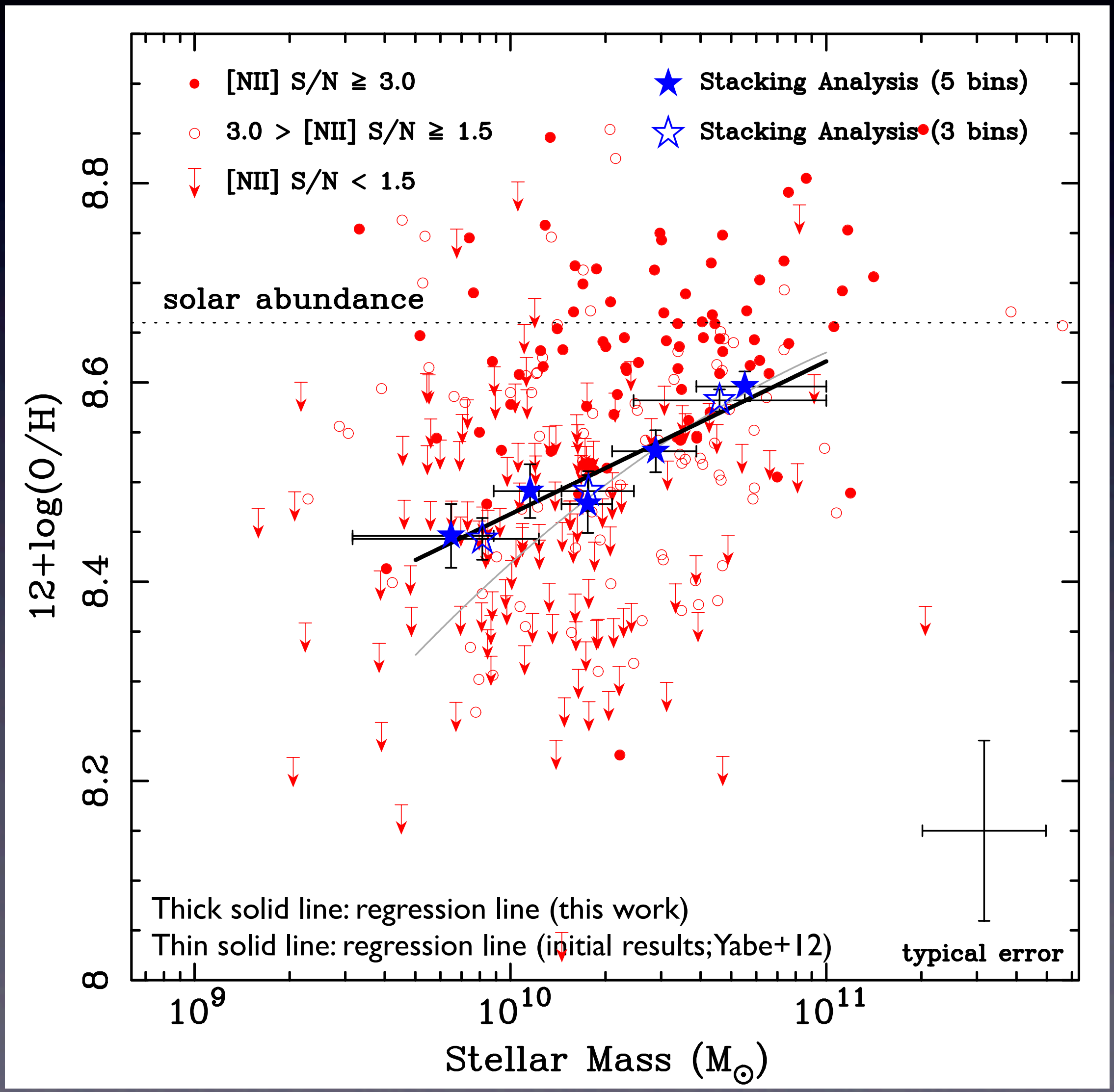
- AGN diagnostics from the BPT diagram ([NII]/Hα vs. [OIII]/Hβ)
- Most objects are placed in the SF region in the BPT diagram
- 21 objects are AGN candidates (BPT, extremely large [NII]/Hα ratio and line width)
- Stacking analysis shows that our sample is on the SF region on average
- AGN selection from the BPT generally consistent with the MEx selection (Juneau+11)





Mass-Metallicity Relation at z~1.4:

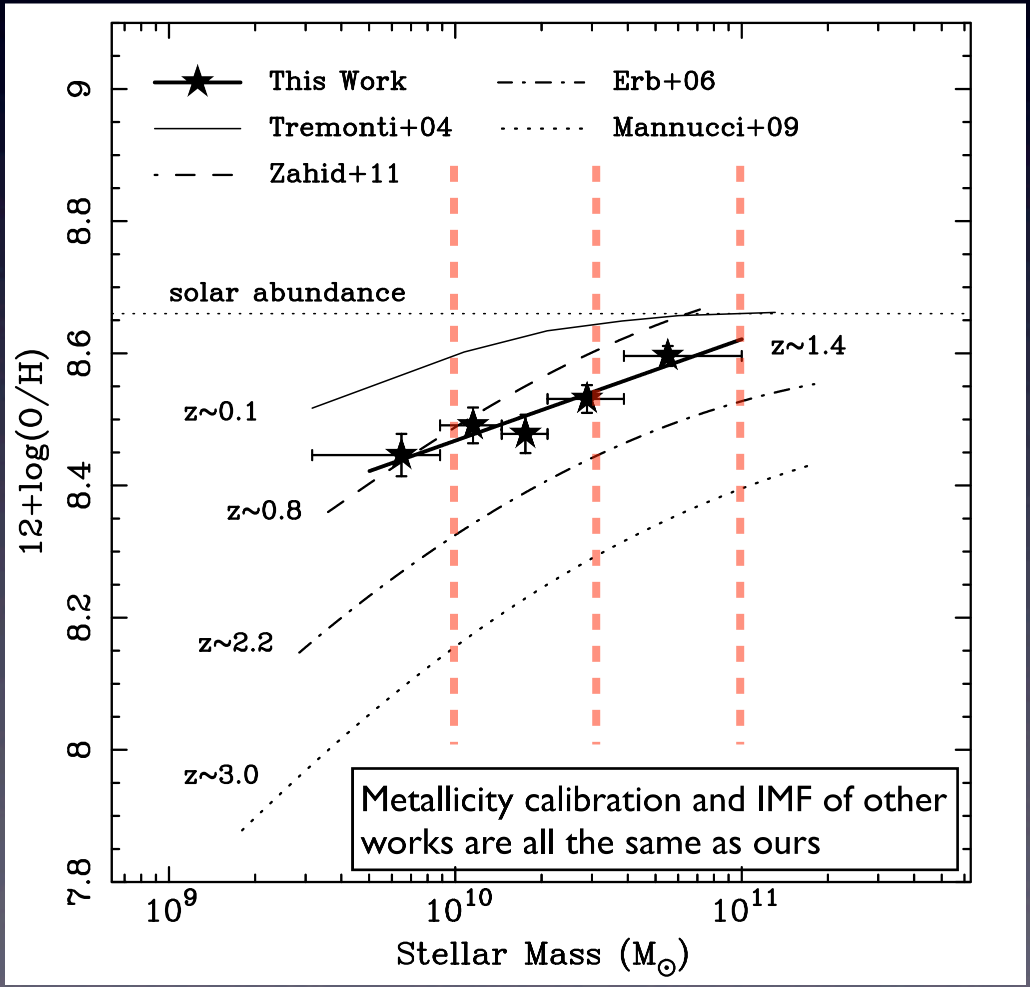
- Possible AGN candidates are excluded by using BPT diagram
- 12+log(O/H) from [NII]/Hα line ratio (N2 method; Pettini & Pagel 2004)
- No significant [NII] emission (S/N<3.0) from ~70% → Stacking analysis

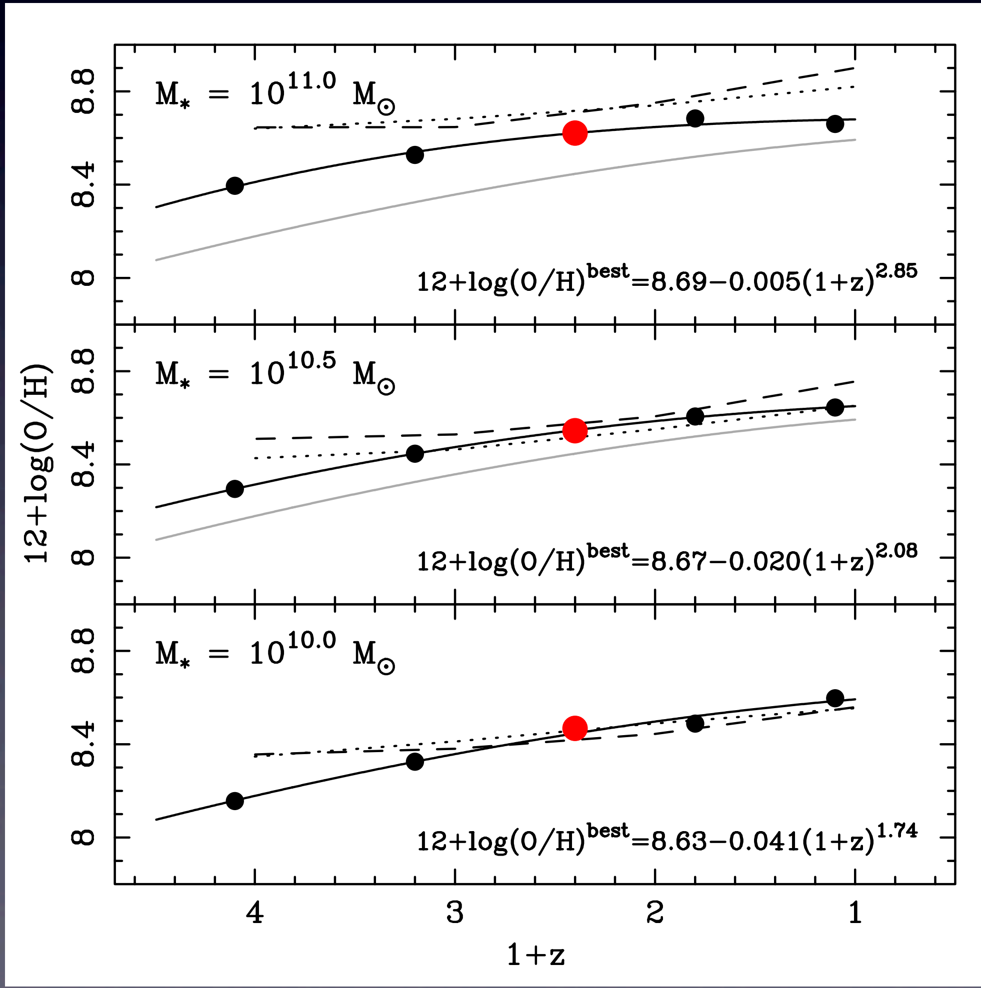


The largest sample ever at z>1

Cosmic Evolution of Mass-Metallicity Relation:

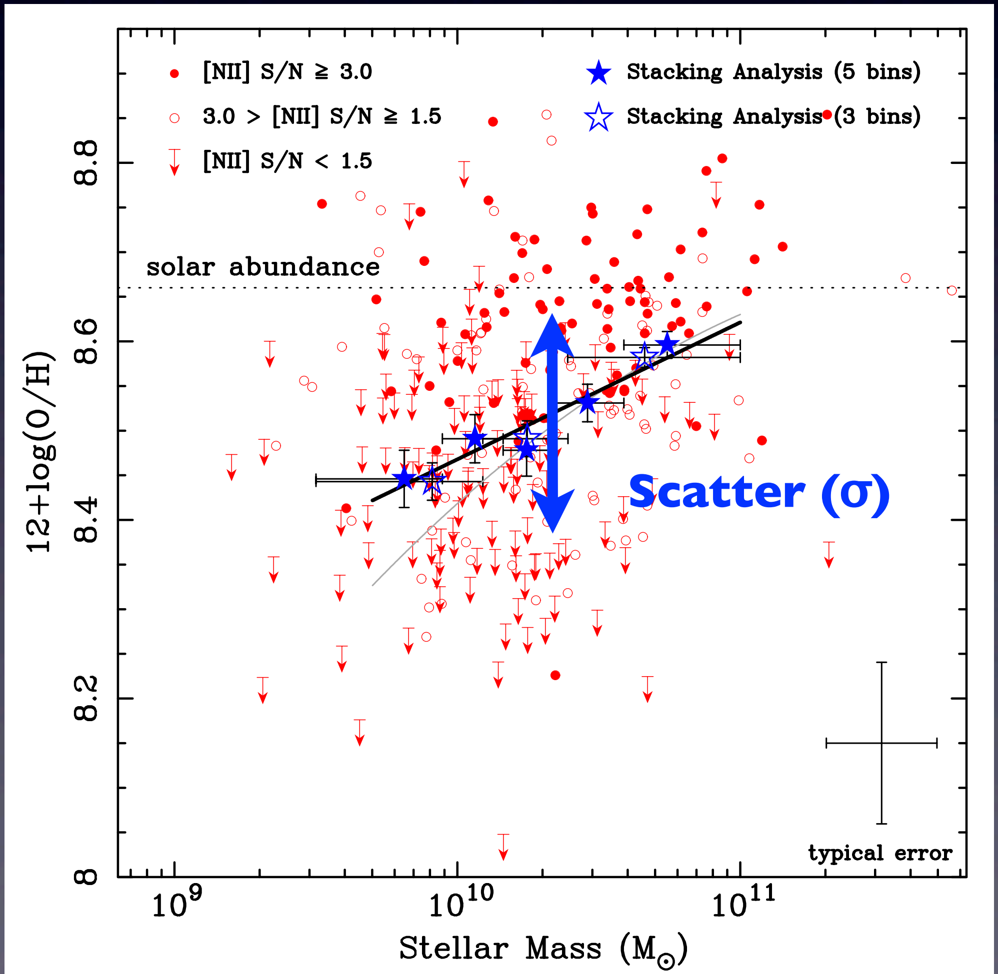
- Comparison to the previous works up to z~3
  - ✓ Our results at z~1.4 are between those at z~0.8 and z~2.2
  - ✓ Anti-downsizing-like evolution from z~1.4 to z~0.8?
- Evolution of the MZ relation from z~3 to z~0
  - ✓ Smoothly evolves from z~3 to z~0
  - ✓ MZ relation evolution from z~3 to z~0 at fixed stellar masses

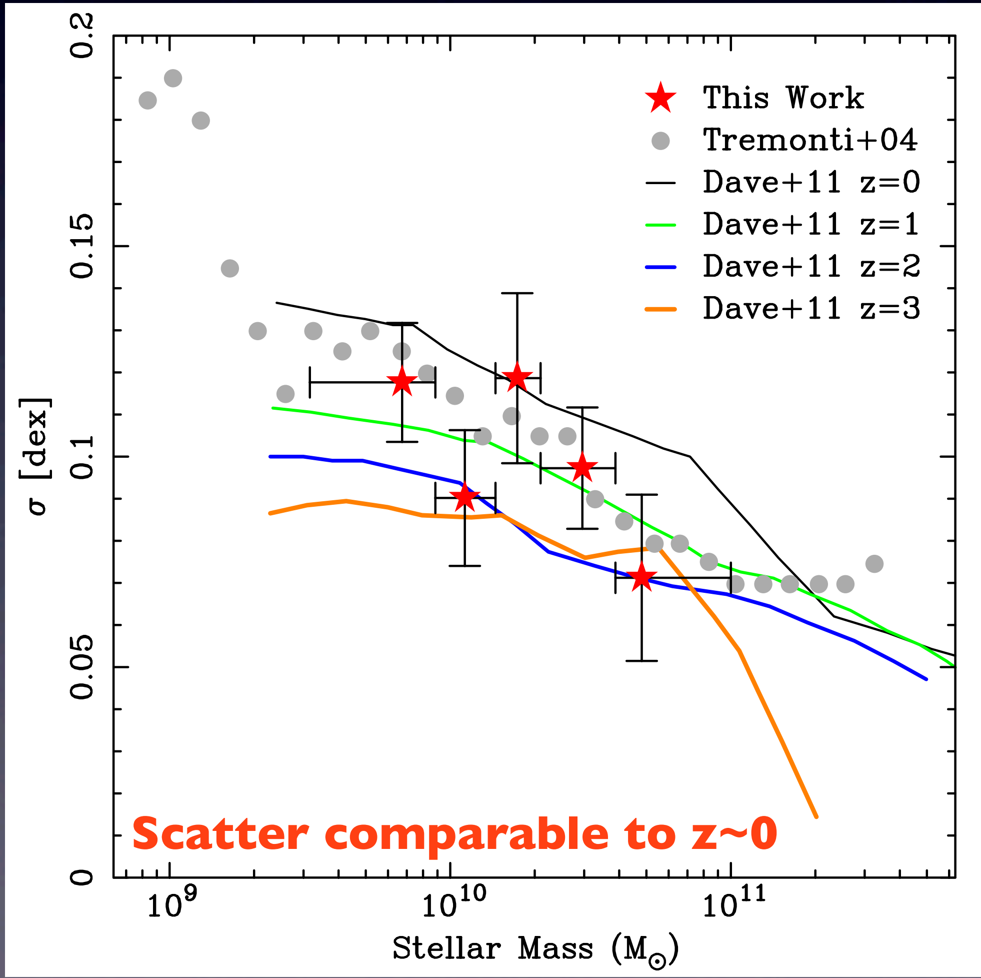




Intrinsic Scatter of Mass-Metallicity Relation:

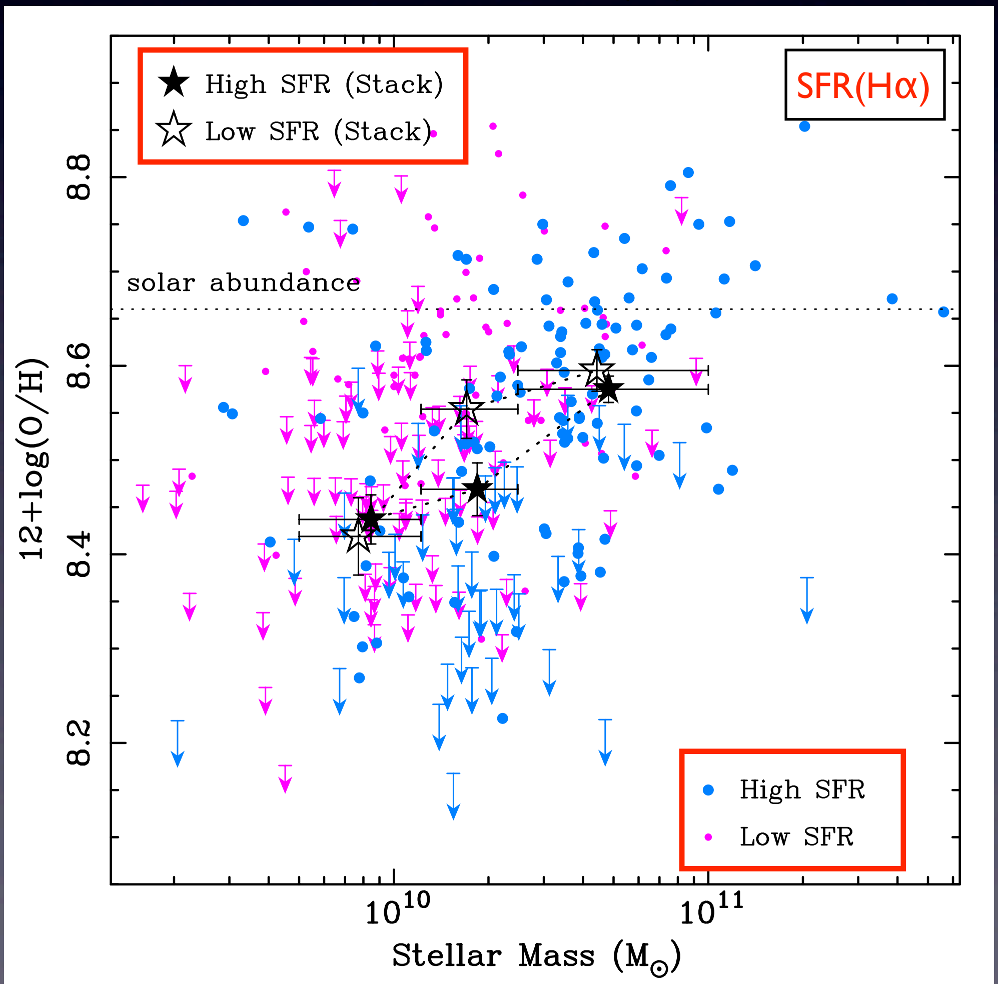
- We found that the MZ relation at z~1.4 has intrinsic scatters of ~0.1 dex
  - ✓ Observational errors are subtracted from the observed scatters
  - ✓ Well agrees with SDSS results at z~0.1 within the error bars
  - ✓ However, note that the values should be lower limit because some metallicities are upper limit, i.e., larger scatters at higher redshift
- What is the origin of this scatter?

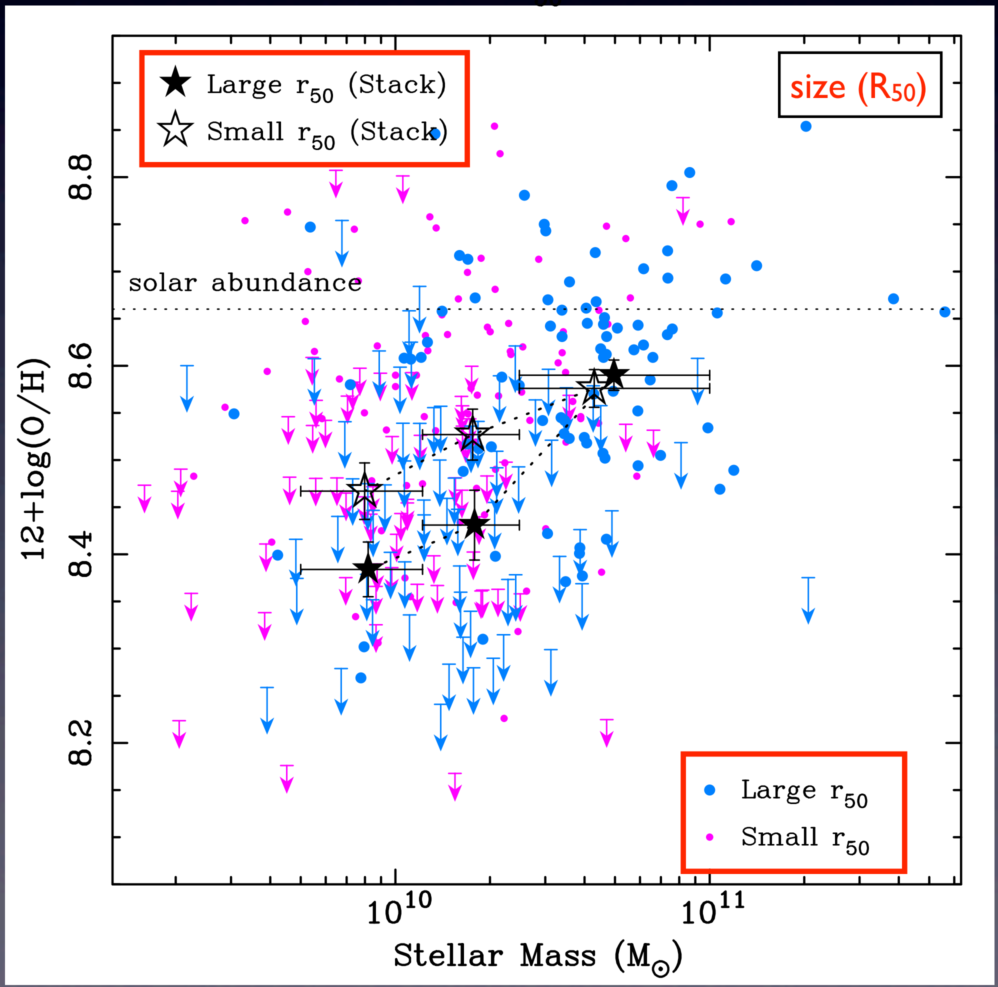




Second Parameter Dependency:

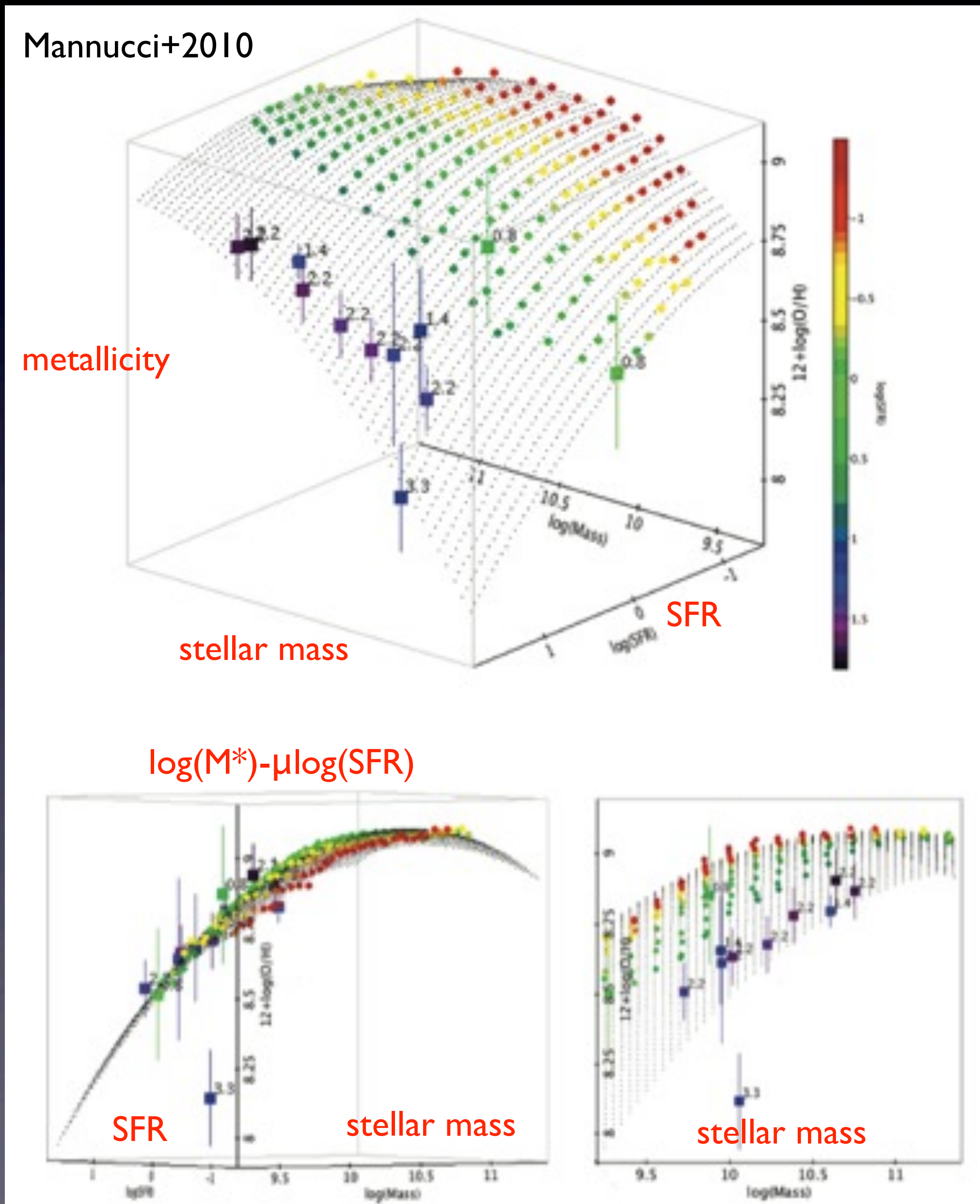
- Dependency of SFR and size on the MZ relation
  - √ SFR : derived from Hα luminosity corrected for the dust extinction
  - √ We take half light radius (R_{50}) as galaxy size (from K-band image)
  - √ Dividing the sample into two groups by the parameter
  - √ The dependency of SFR on the MZ relation is not clear
  - √ Galaxies with smaller R_{50} tend to show higher metallicities



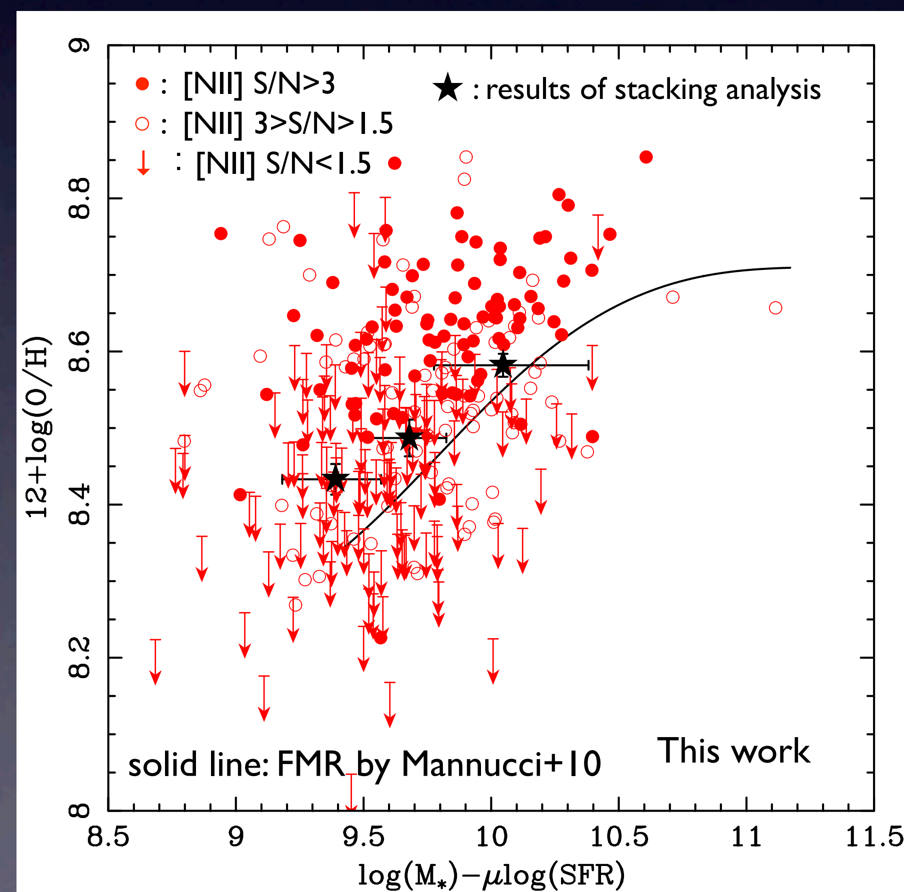


Fundamental Metallicity Relation:

- Mannucci+10 suggested that the scatter of the MZ relation at z~0.1 is reduced by SFR
  - ✓ They proposed the Fundamental Metallicity Relation (log(M*)-μlog(SFR) vs. 12+log(O/H)
  - ✓ They claimed that this FMR are unchanged from z~2 to z~0.1

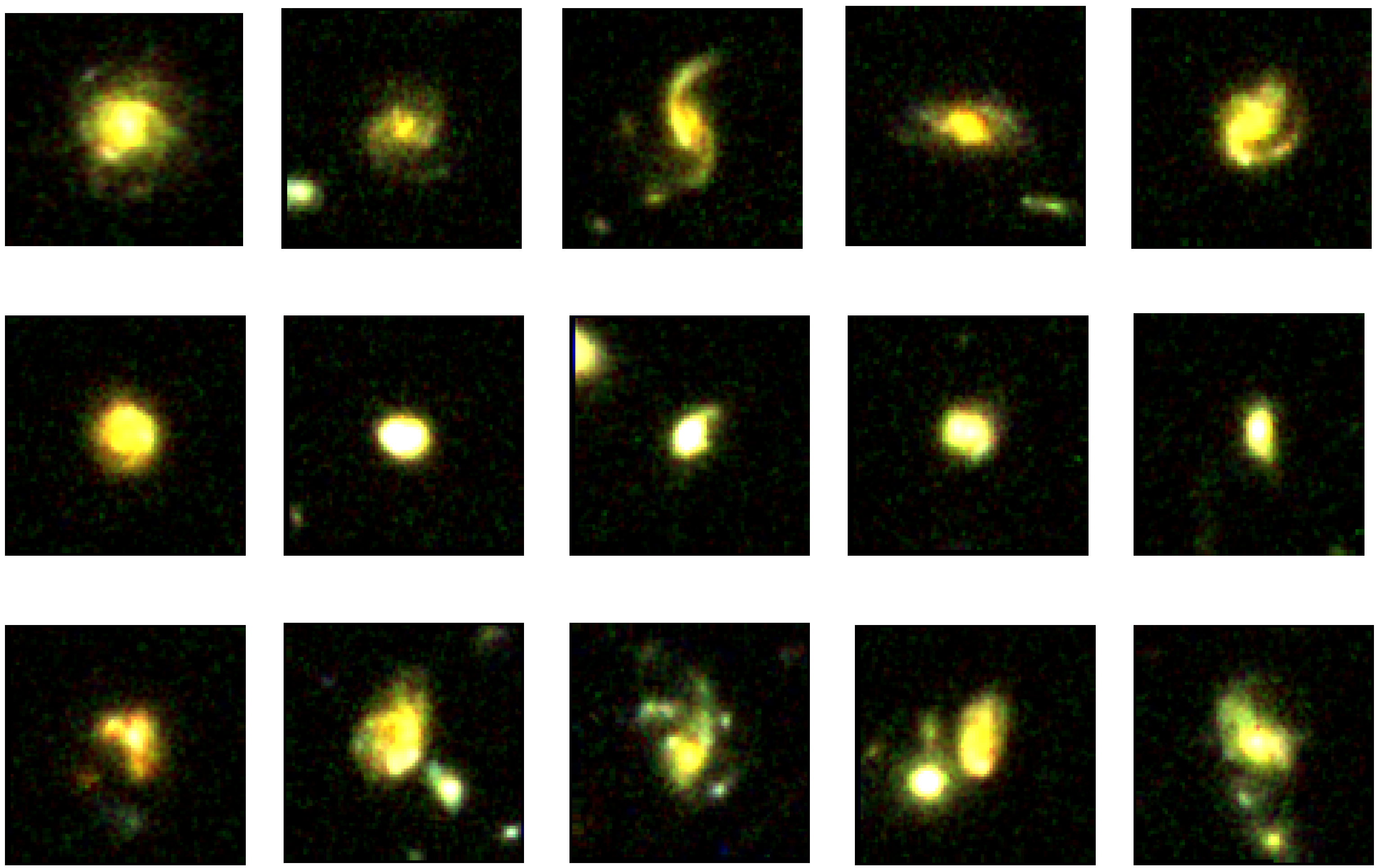


- Our result show that the scatter appear not to be reduced by the FMR
- Averaged metallicity against the log(M*)-μlog(SFR) is different from that by Mannucci+10



Morphology Dependency:

- Morphology can resolve internal structure of galaxies
- About 50 objects in the CANDELS/UDS field are observed with FMOS
- Various morphologies can be seen in the HST/ACS+WFC3 images



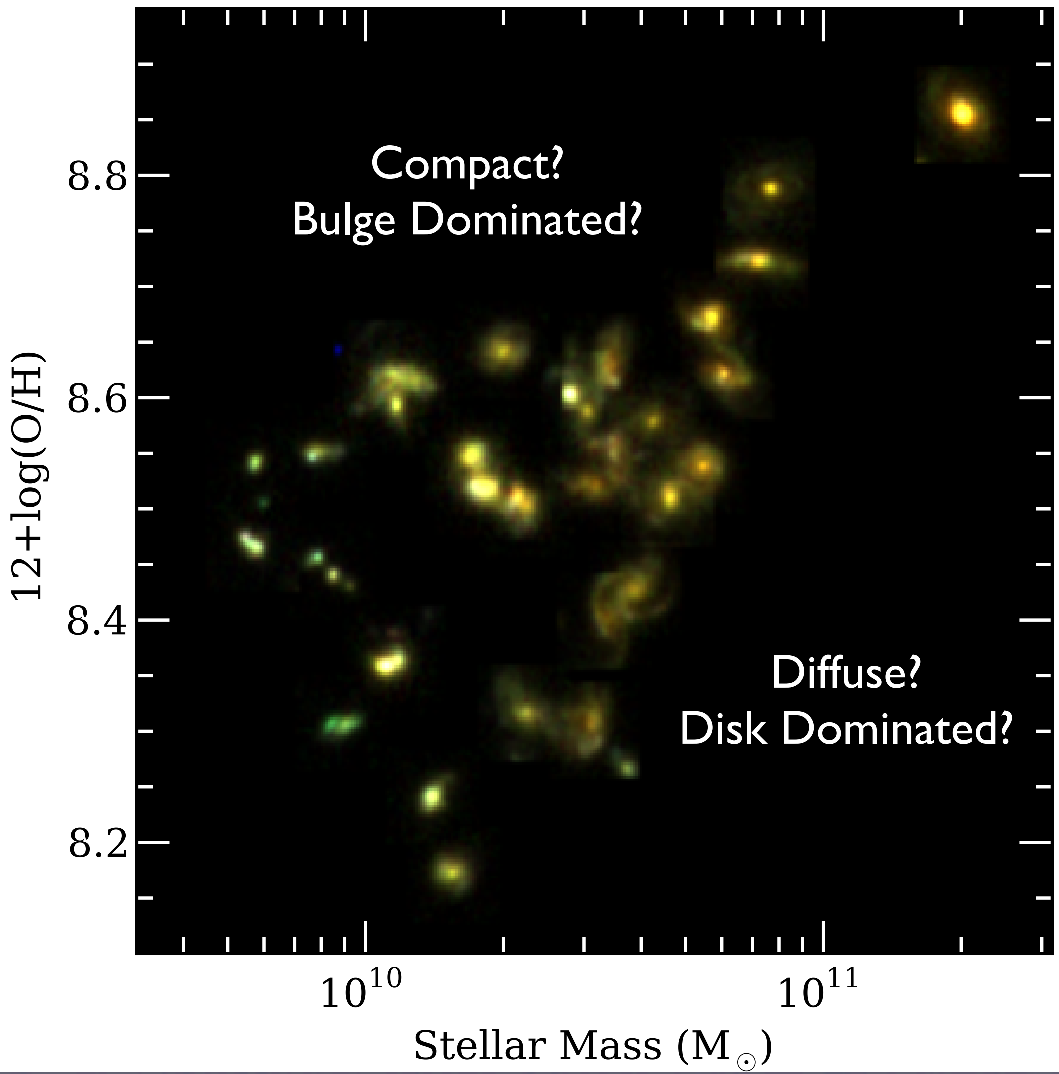
Color composites with HST/ACS+WFC3 images

Morphology Dependency:

- Morphology can resolve internal structure of galaxies
- About 50 objects in the CANDELS/UDS field are observed with FMOS
- For these objects, the morphology can be examined as well as metallicity

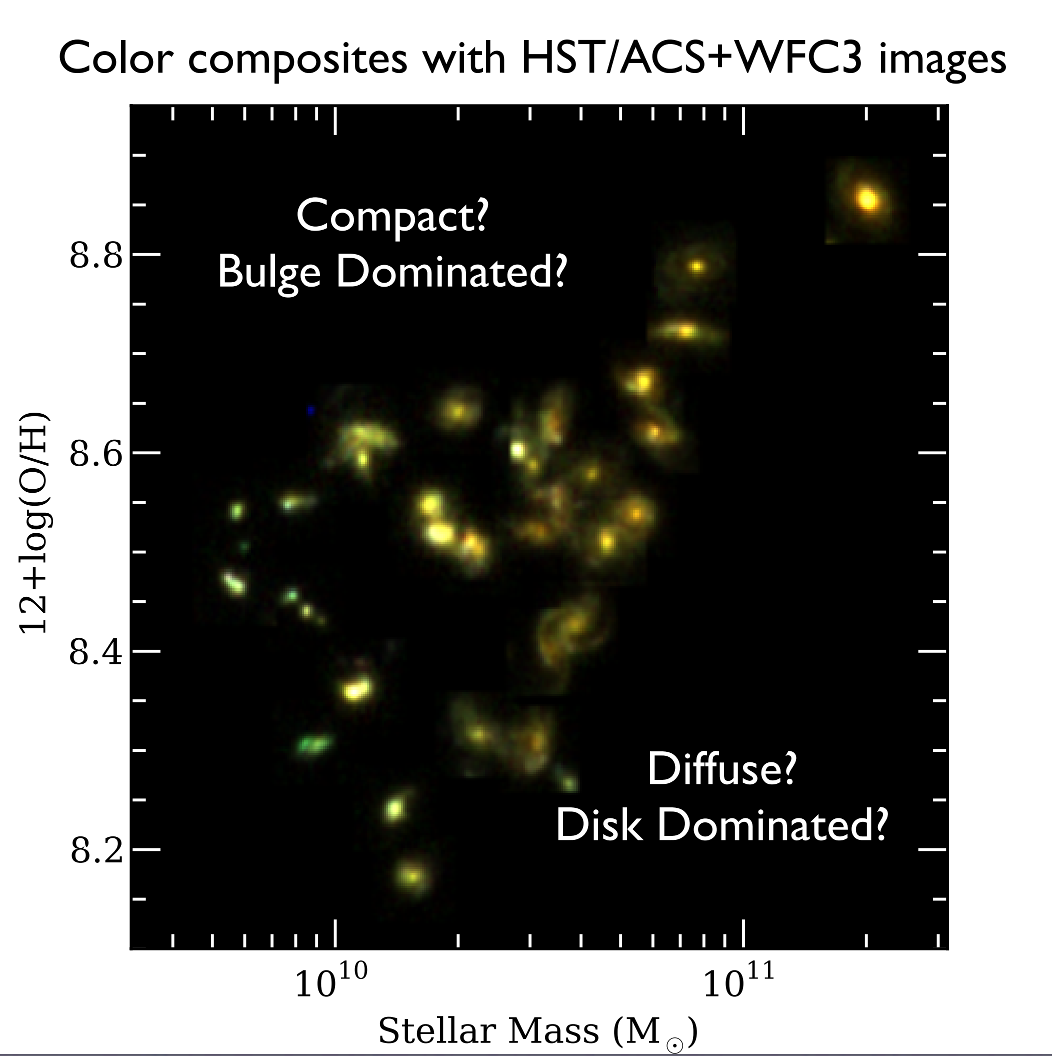
- Diffuse and disk dominated galaxies tend to show lower metallicity than compact and bulge dominated galaxies?
- If the gas mass fraction is the same, smaller and compact galaxies have higher gas surface density, higher SFR surface density, and thus the galaxies are chemically enriched?

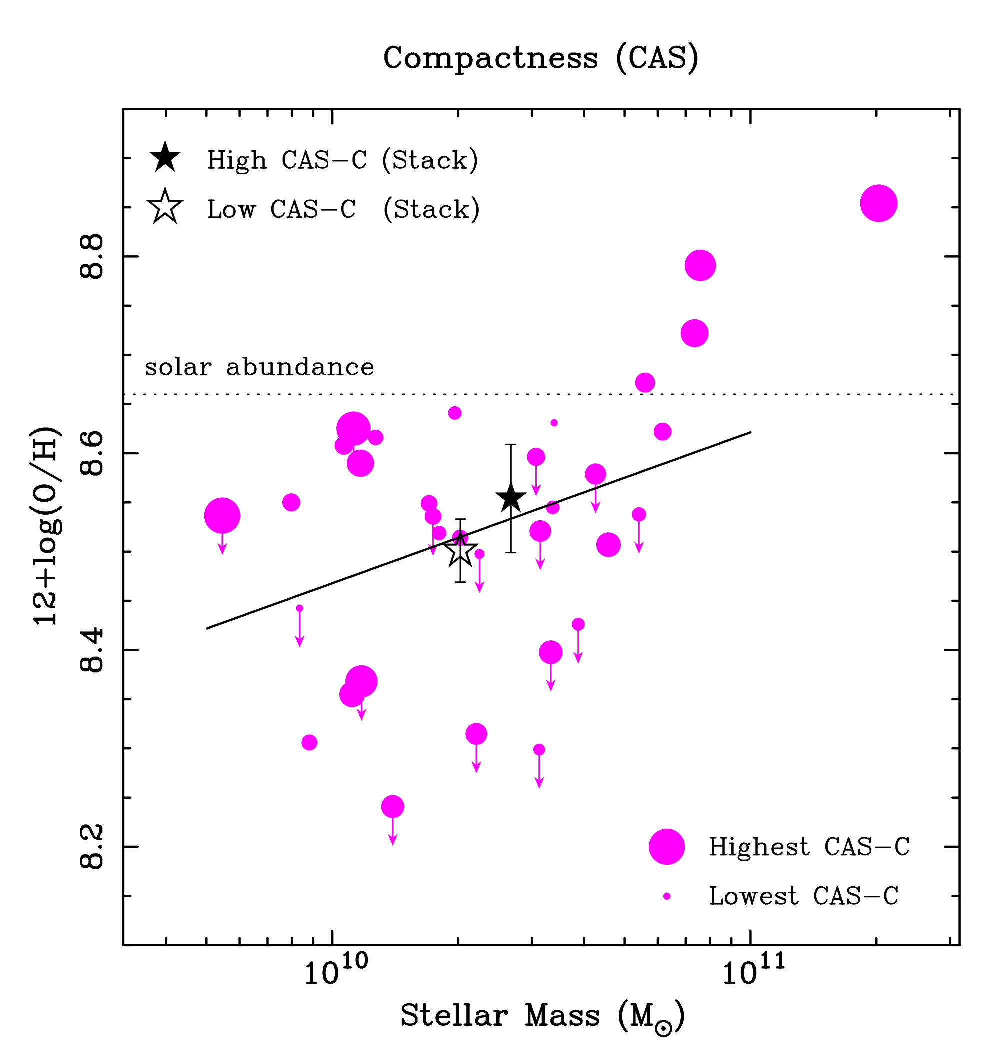
Color composites with HST/ACS+WFC3 images



Morphology Dependency: CAS parameters

- CAS parameterization (Conselice+03)
- Compactness (CAS-C) = 5log (r_{80}/r_{20})
- Galaxies with higher CAS-C (compact) shows higher metallicity at fixed mass?
- Well consistent with eye inspection?

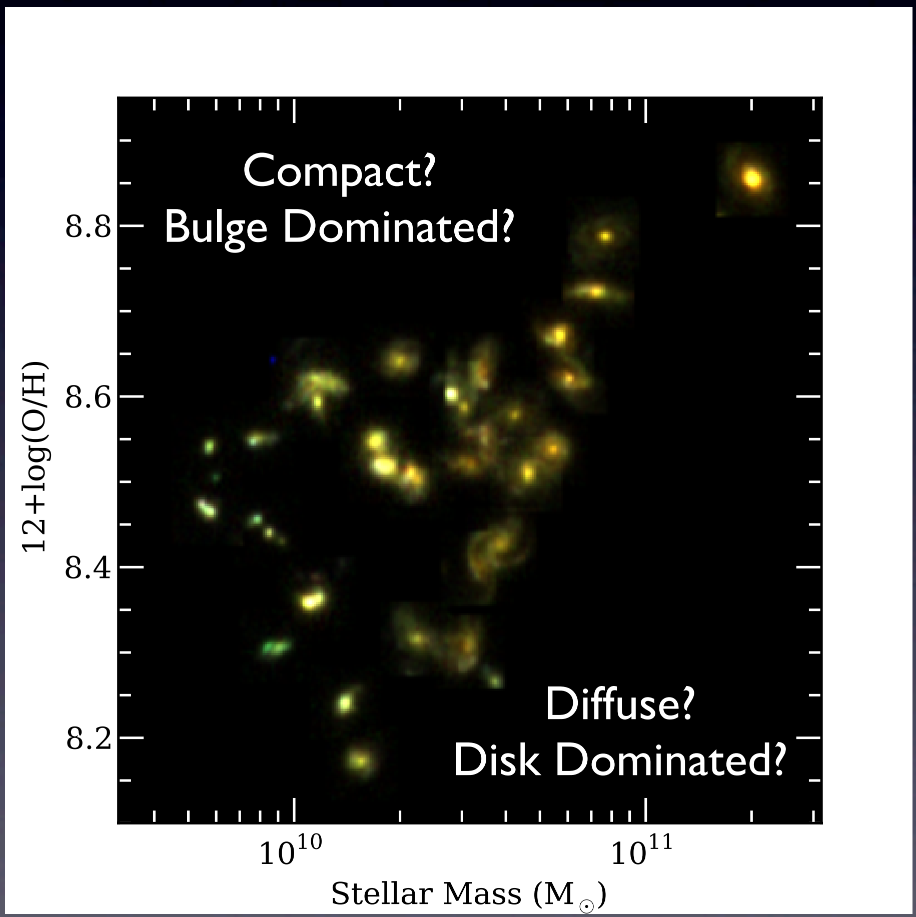




Summary 1:

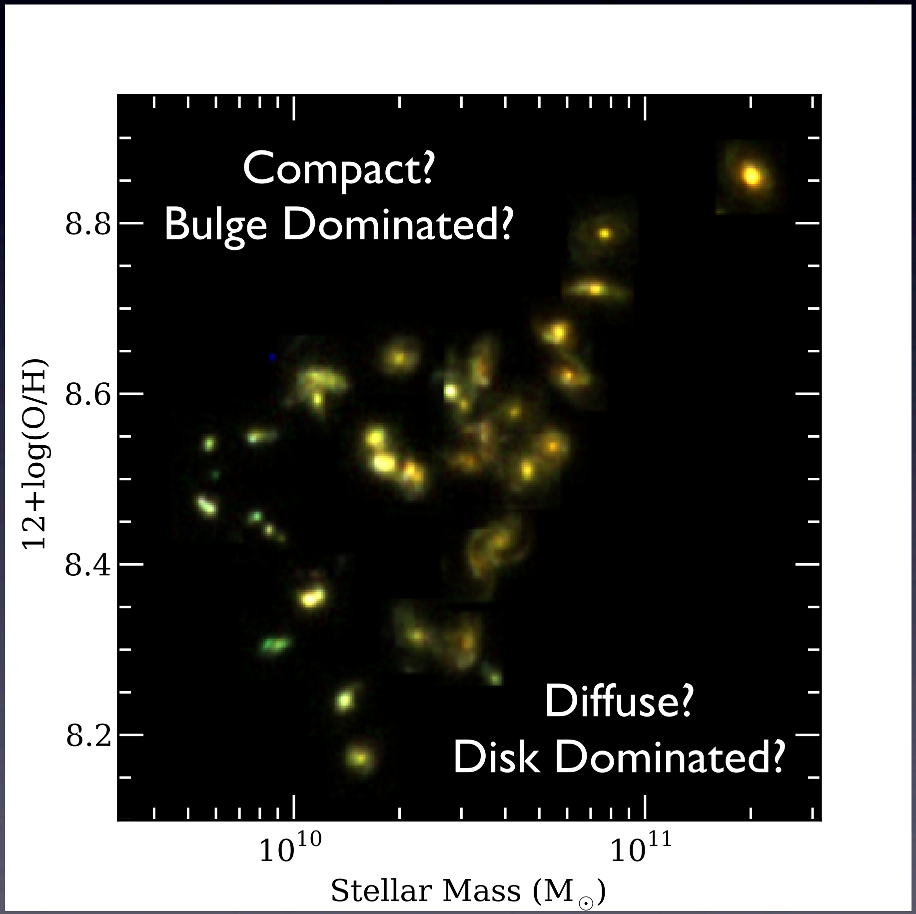
- We observed star-forming galaxies at z~1.4 are measured with Subaru/FMOS
- We detected Hα line from ~300 objects with significance of S/N>3
- Gas-phase metallicity is derived from [NII]/Hα line ratio
- We construct the mass-metallicity (MZ) relation at z~1.4 with the largest sample ever
- By comparing previous results:
    - ✓ The MZ relation evolves smoothly from z~3 to z~0
    - ✓ They agree with theoretical models with galactic winds
- The MZ relation at z~1.4 has an intrinsic scatter of ~0.1 dex
- We examined the dependency of physical parameters on the MZ relation for the scatter
    - ✓ Clear trend for size: Galaxies with larger R_{50} tend to show lower metallicity
    - ✓ No clear trend for SFR: Disagrees with that at z~0.1 by Mannucci+10
- Our results may show the morphology dependence
    - ✓ Bulge-dominated galaxies are located in the upper region on the MZ relation
    - ✓ Disk-dominated galaxies are located in the lower region on the MZ relation

What should we do next?



- Expanding the sample w/ morphology information available (from space or from ground)
- Internal (chemical) structure of galaxies (IFU?)
- Direct measurement the gas content (e.g., ALMA)

What should we do next?



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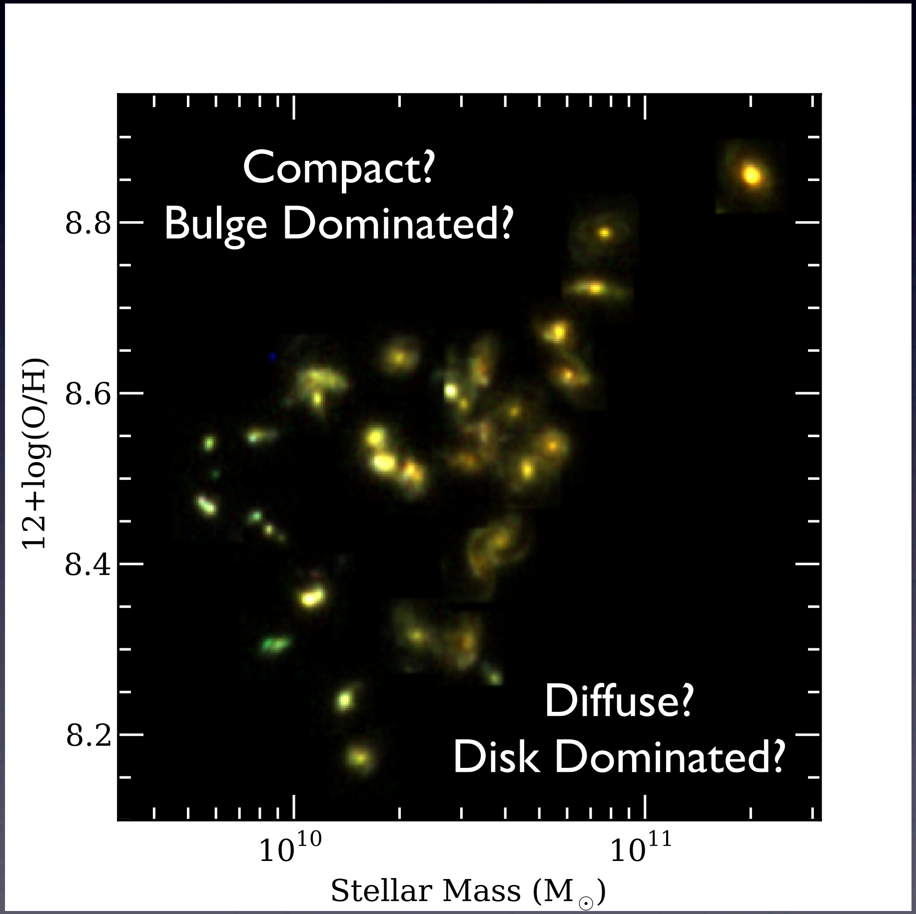


Expanding the sample w/ morphology information available (from space or from ground)

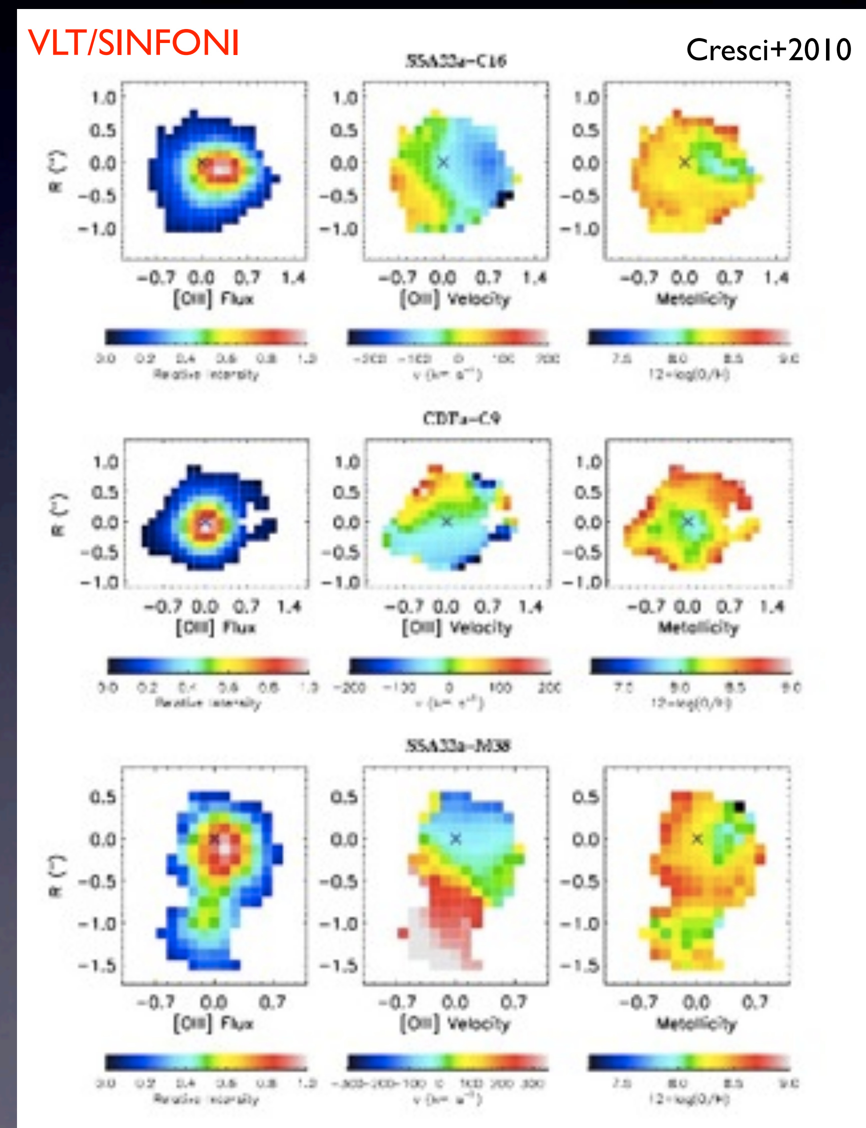
Internal (chemical) structure of galaxies (IFU?)

Direct measurement the gas content (e.g., ALMA)

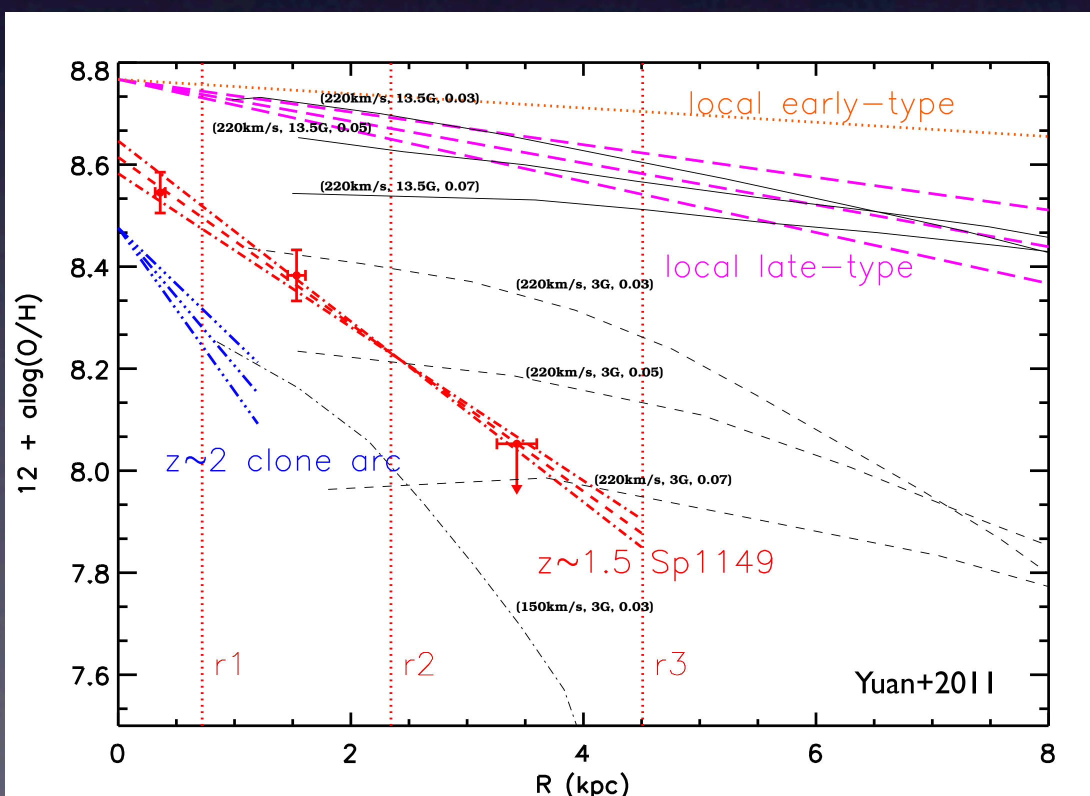
Spatially Resolved Metallicity Measurements:

- Metallicity gradient of galaxies at high redshift
  - ✓ Negative steeper metallicity gradient (Jones+10, Yuan+11)
  - ✓ Positive metallicity gradient (Cresci+10)
- Requirement for studies of metallicity gradients at z~1.4
  - ✓ Spatial resolution : ~0.2 arcsec w/ LGS-AO
  - ✓ Typical line flux ~ 2×10^{-16} cgs
  - ✓ Feasible in 1-2 hrs observations?

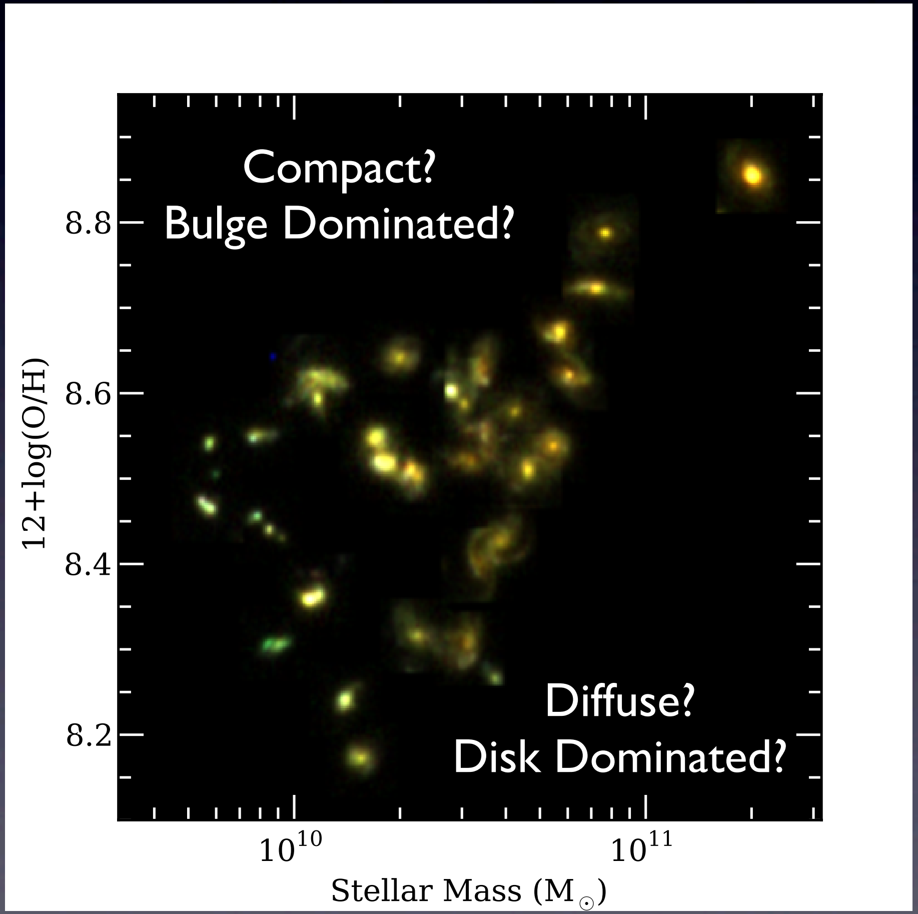
Positive Metallicity Gradient



Negative Steep Metallicity Gradient



What should we do next?



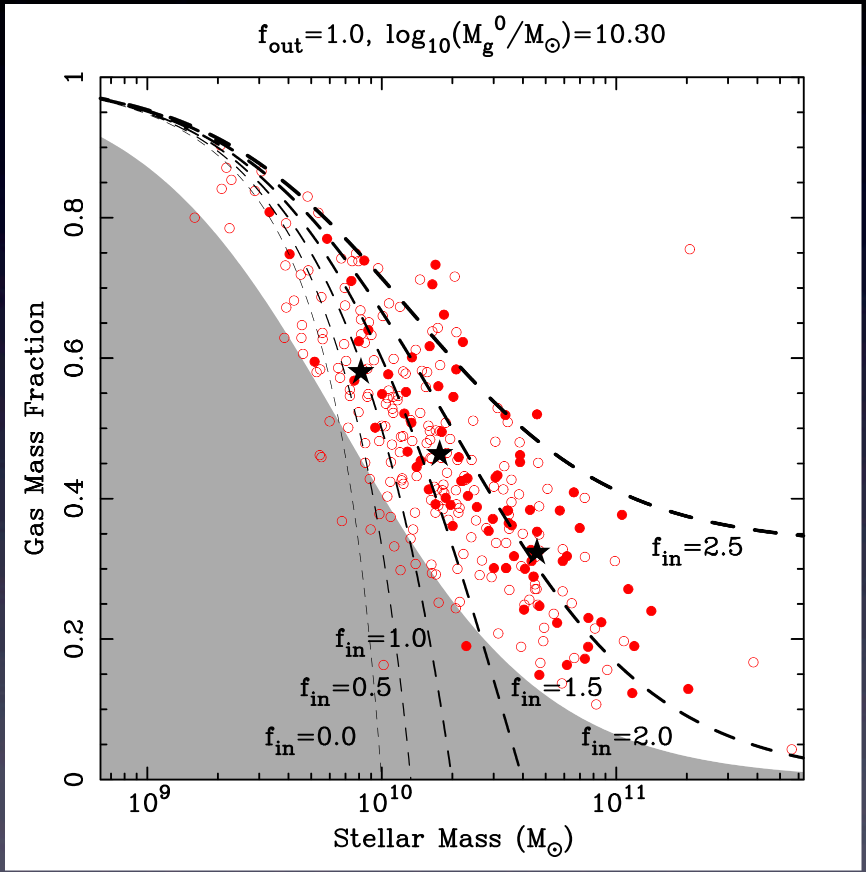
Expanding the sample w/ morphology information available (from space or from ground)

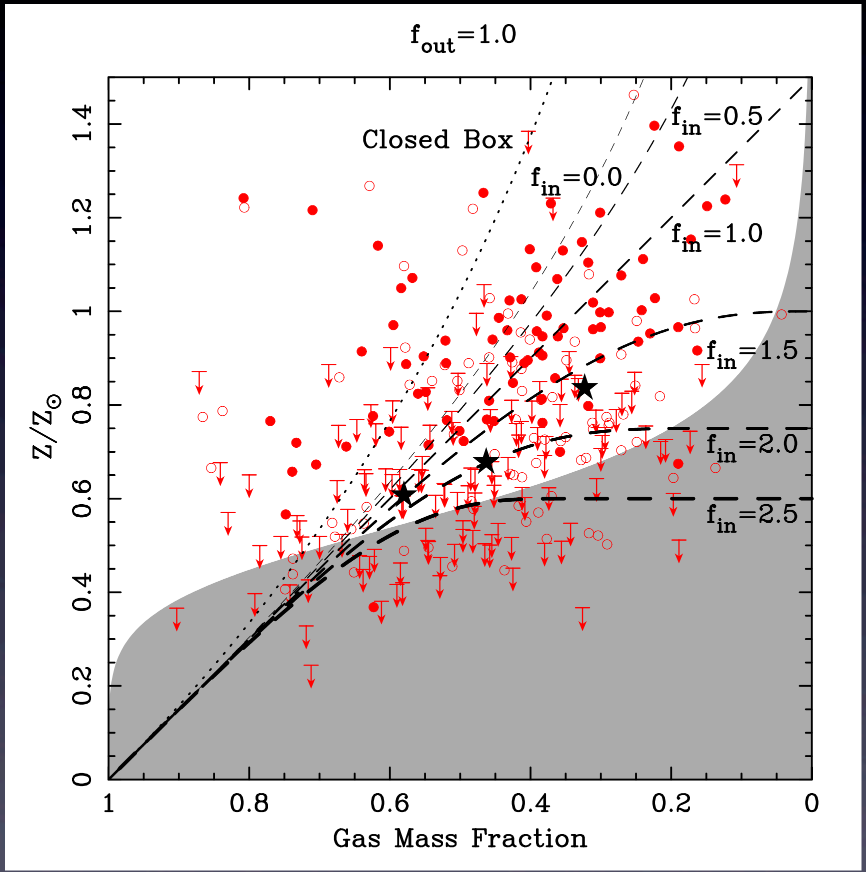
Internal (chemical) structure of galaxies (IFU?)

Direct measurement the gas content (e.g., ALMA)

Gas Mass Fraction: Analytic Model with Infall/Outflow

- Simple analytic model with inflow/outflow (e.g., Matteucci 2001, Erb 2008)
  - ✓ inflow rate and outflow rate are proportional to SFR
  - ✓ We assume that f_{out}=1.0 (e.g., Weiner+09, Steidel+10)
  - ✓ Ms vs. f_{gas} and f_{gas} vs. Z can be explained by f_{in}=1.5-2.0 models





Requires the direct measurements of the gas mass
→(Spatially resolved?) CO observations with ALMA

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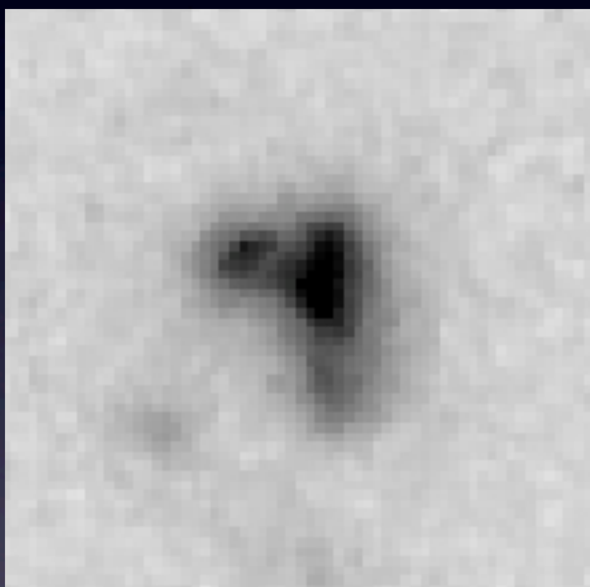
Requirement for the spatial resolution w/ AO

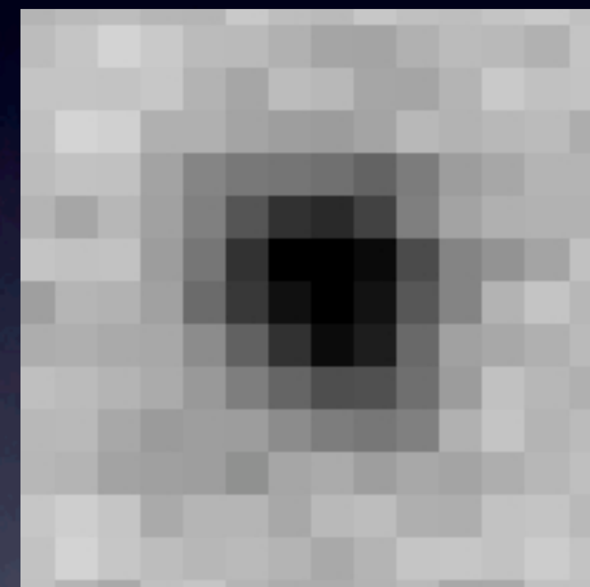
HST/WFC3



PSF FWHM~0.18”

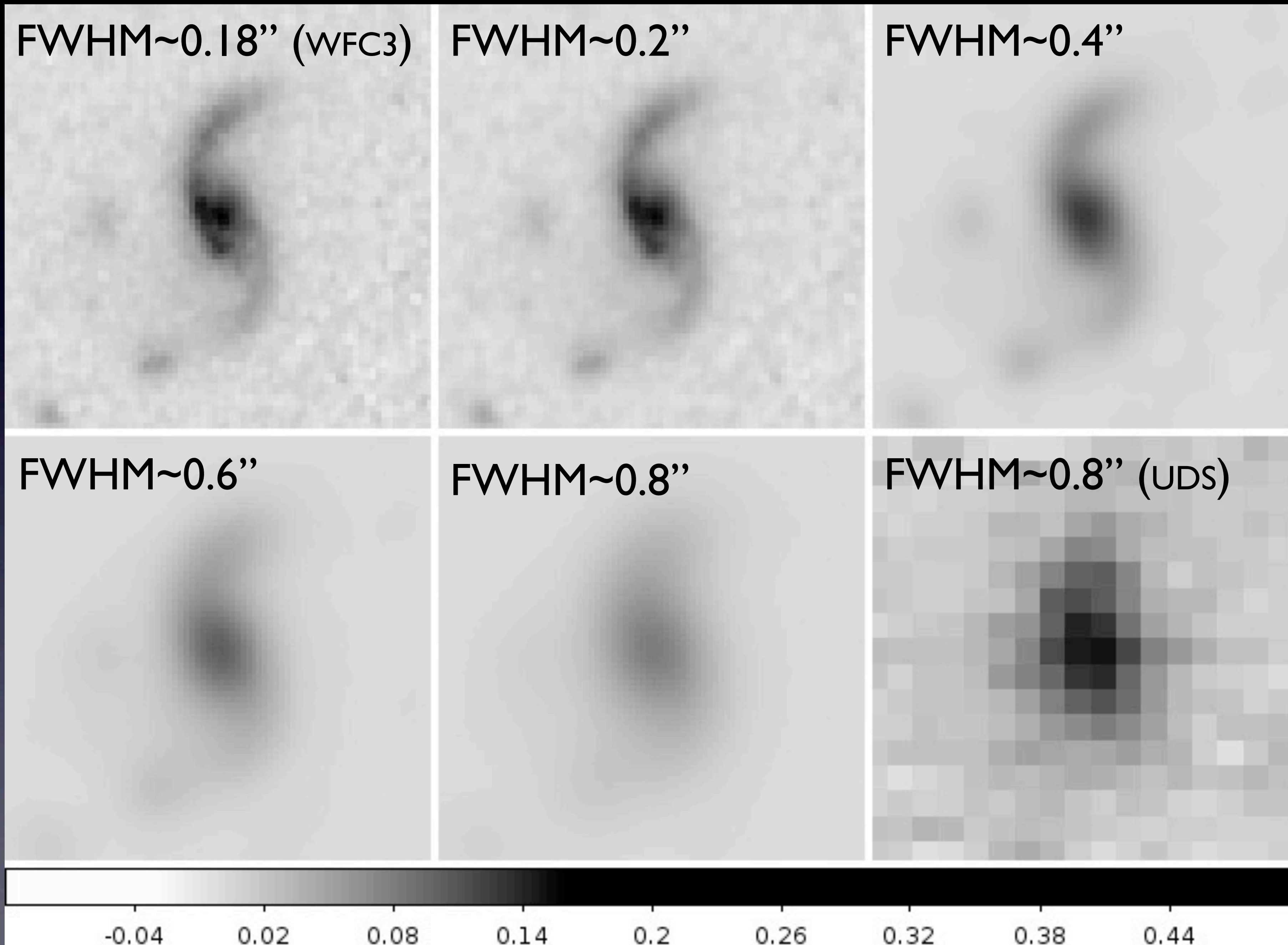
Subaru/GLAO?

UKIRT/WFCAM



PSF FWHM~0.8”

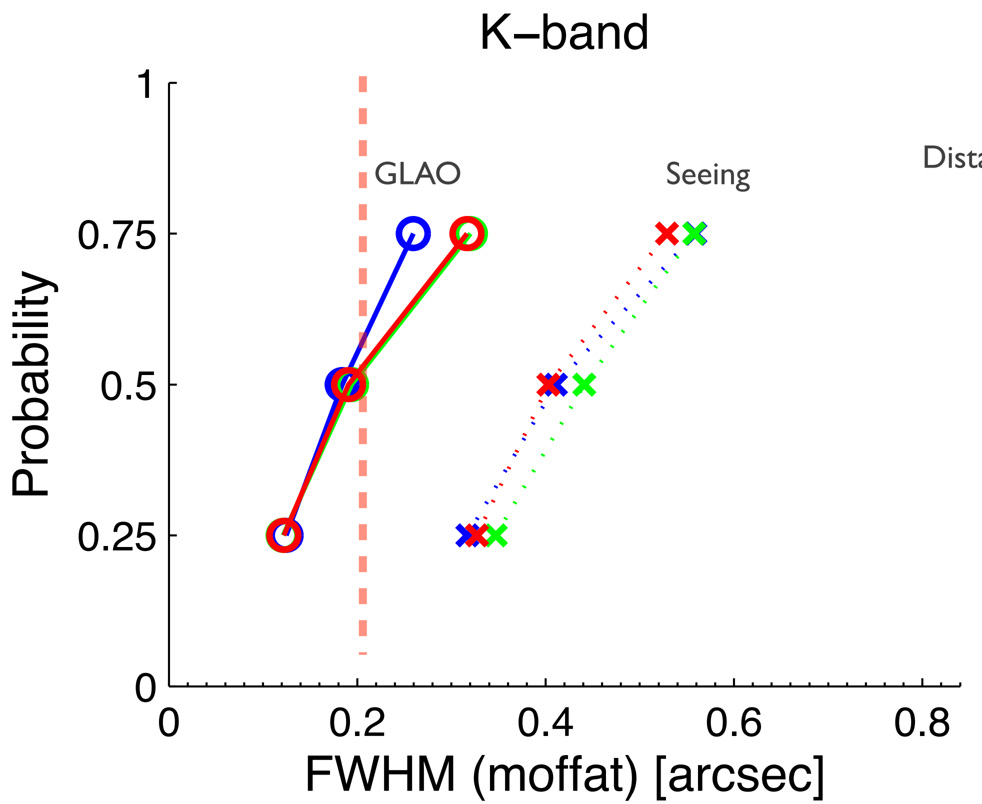
Requirement for the spatial resolution w/ AO



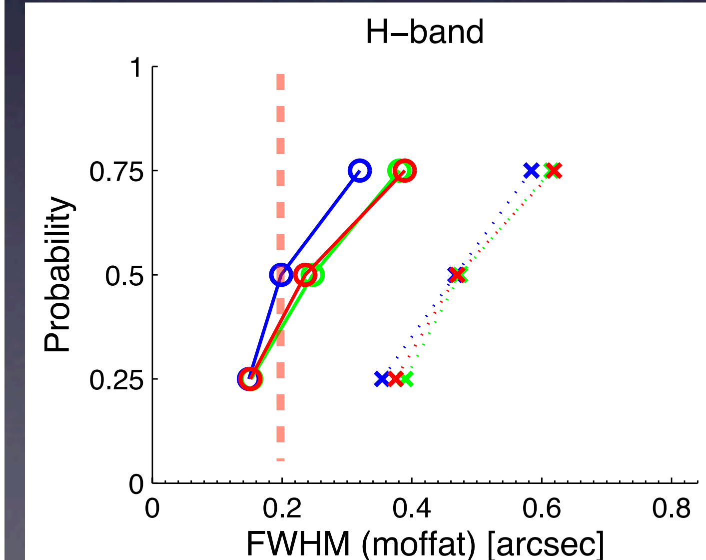
Feasibility: Morphology Measurements

- Expected FWHM of the Subaru GLAO system
  - ✓ FWHM~0.2” is expected in FoV of 20’ Φ in K-band
  - ✓ FWHM~0.2” is also expected in H-band
  - ✓ Longer wavelength is reasonable for the morphology studies?

Expected Performance of Subaru GLAO: FWHM Improvement

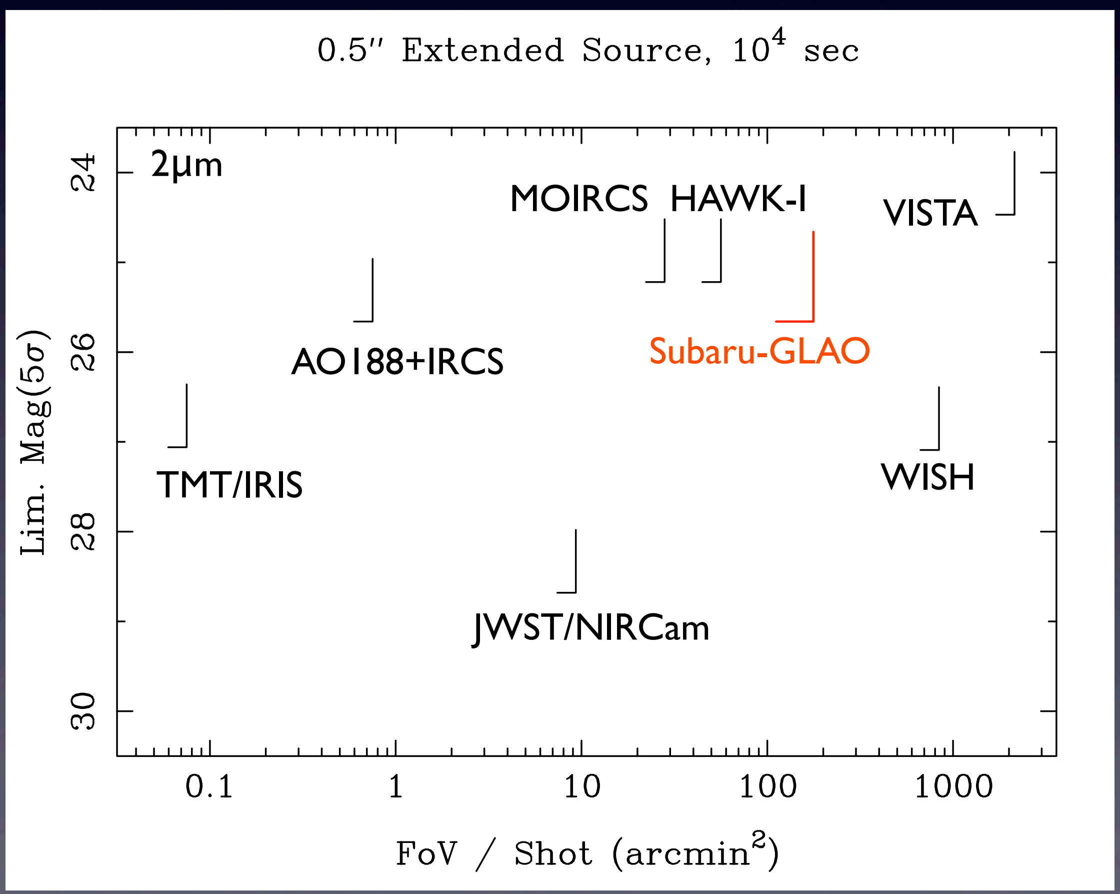


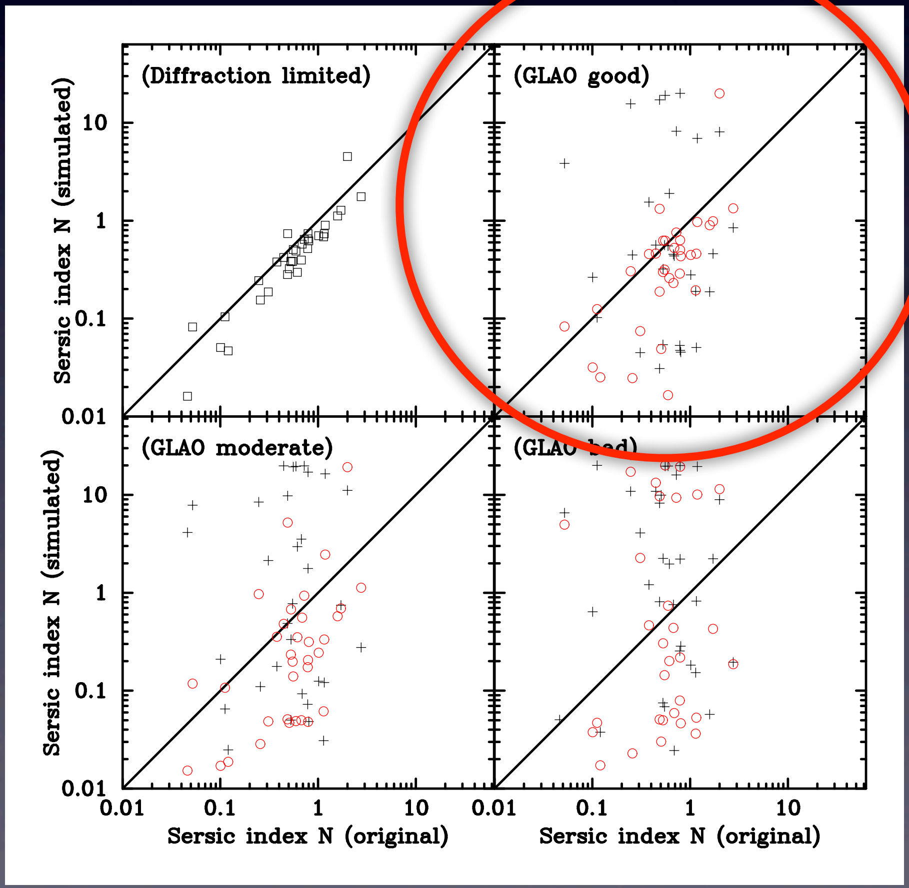
by S. Oya



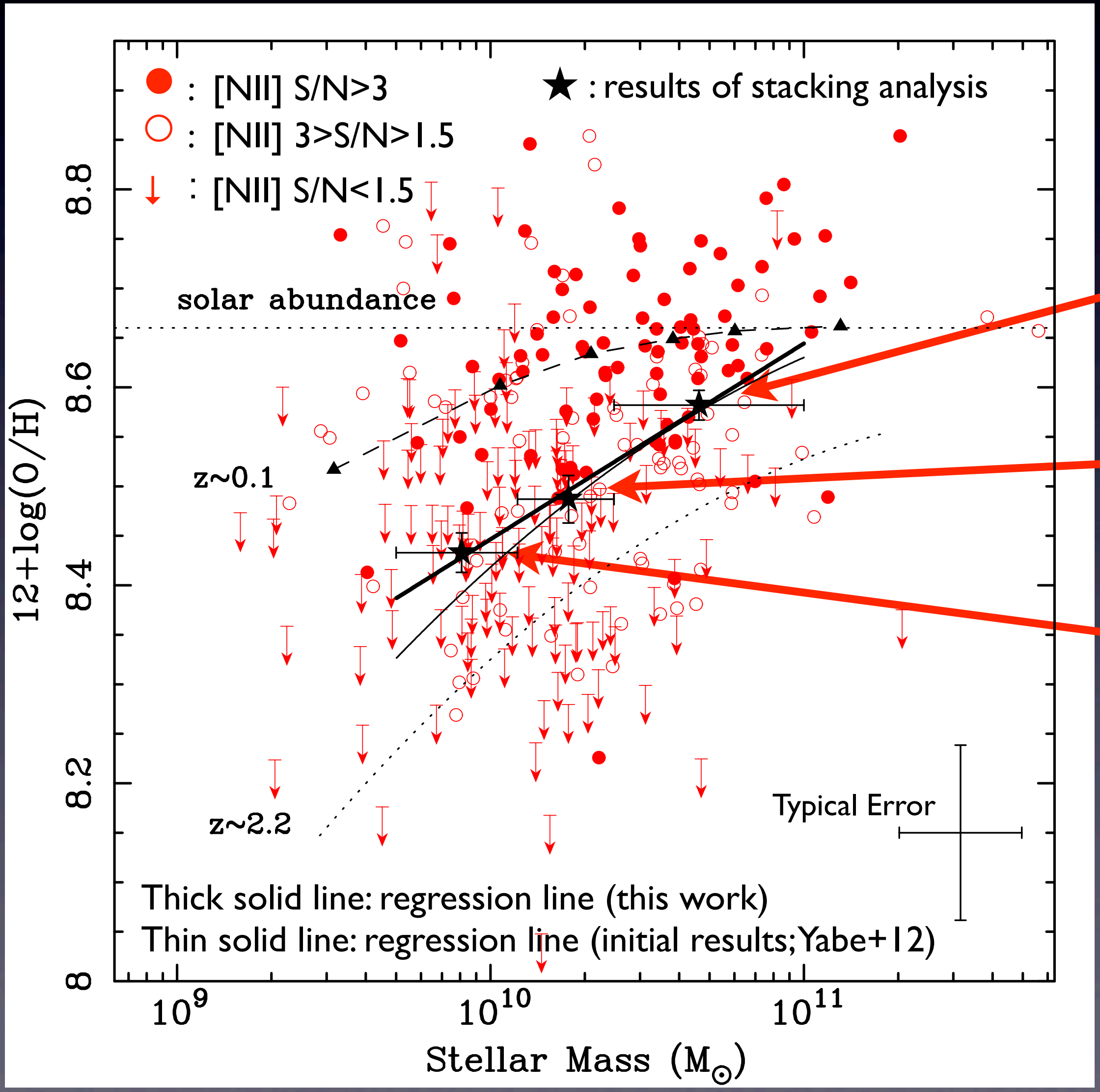
Feasibility: Morphology Measurements

- Expected Sensitivity of the Subaru GLAO system
  - ✓ K magnitudes of our sample range from 20-23 mag (typically K~22 mag)
  - ✓ 25-26 mag is sufficient for morphology studies of our sample
  - ✓ a few fours of integration is needed for one FoV?
  - ✓ Feasibility for measurement of morphology is good enough?





Feasibility: Expected Line Fluxes



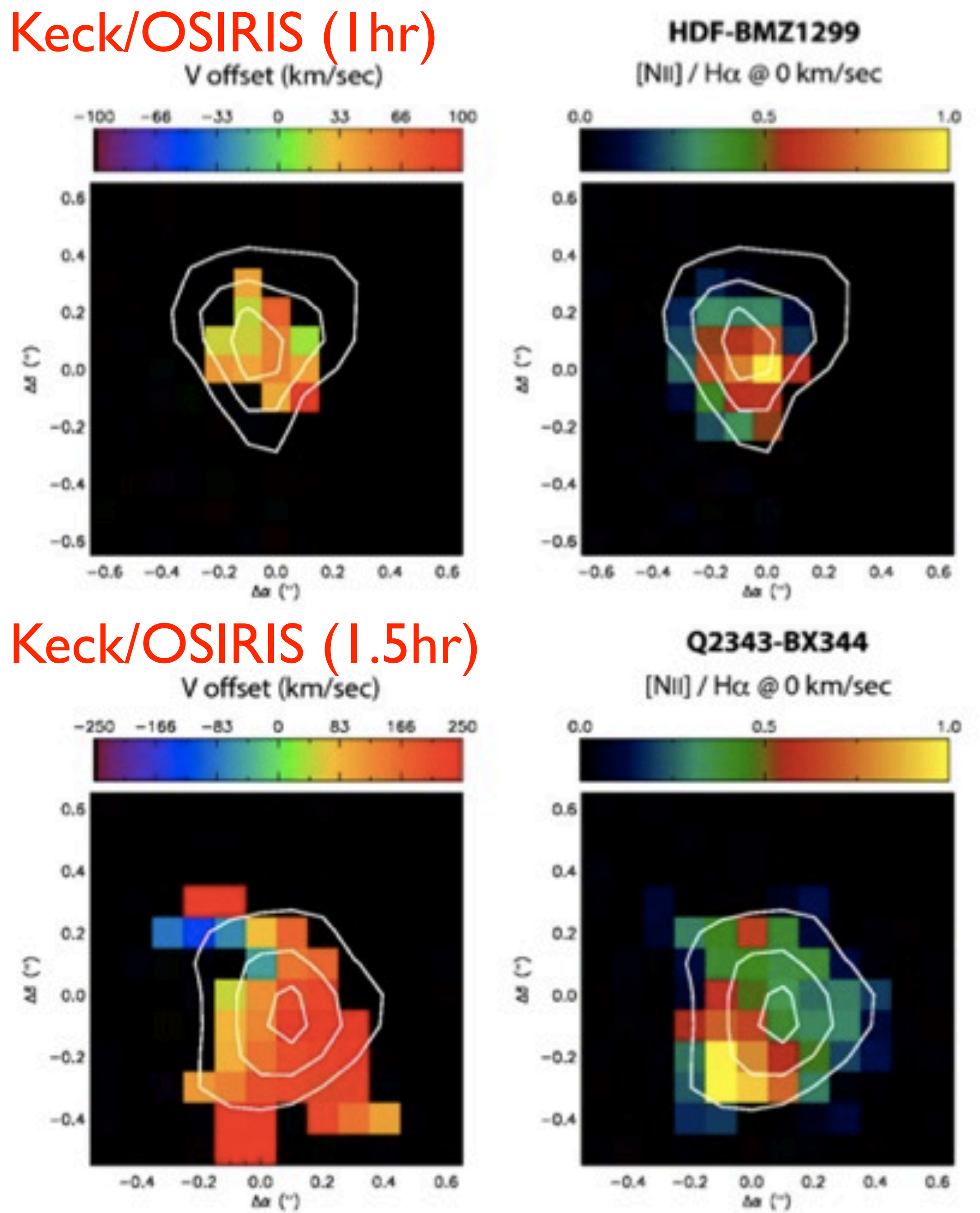
$F(H\alpha) = 1.8\times10^{-16}$ cgs
$F([NII]) = 5.2\times10^{-17}$ cgs

$F(H\alpha) = 2.0\times10^{-16}$ cgs
$F([NII]) = 3.4\times10^{-17}$ cgs

$F(H\alpha) = 1.7\times10^{-16}$ cgs
$F([NII]) = 2.1\times10^{-17}$ cgs

Feasibility: Existing Instruments

Wright+2009



w/ LGS-AO

Typical redshift: z~1.6

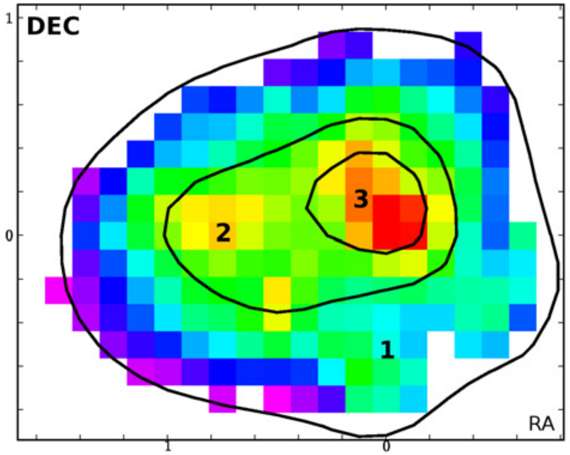
Typical integrated flux:
- $F(H\alpha) \sim 2\times10^{-16}$ cgs
- $F([NII]) \sim 7\times10^{-17}$ cgs

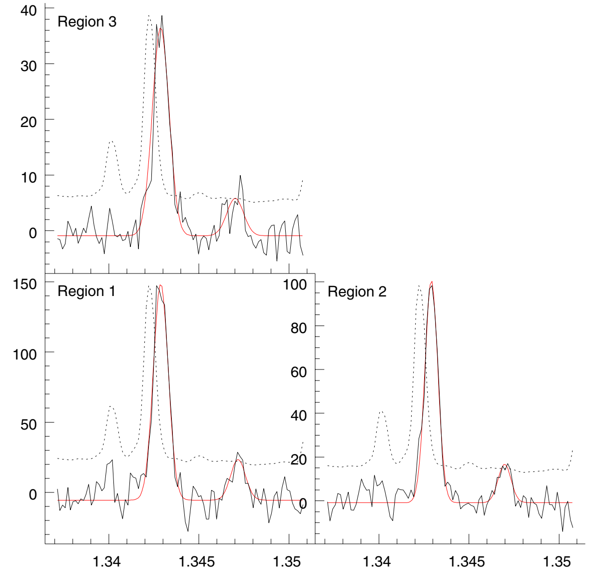
Typical integration time:
- 1-2 hrs

Feasibility: Existing Instruments

Queyrel+2012

VLT/SINFONI (2hrs)



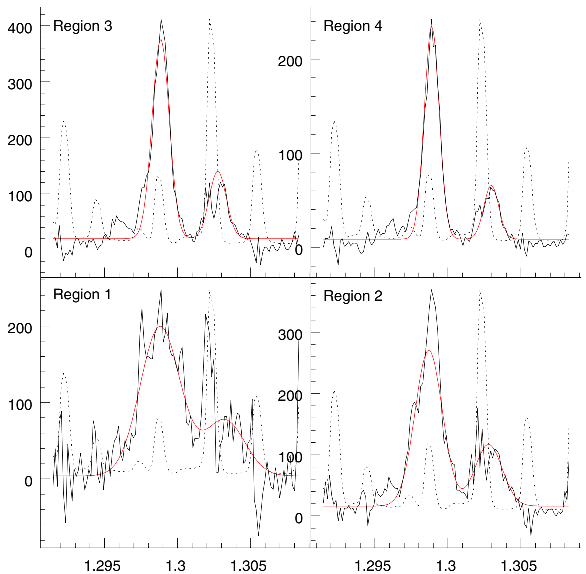


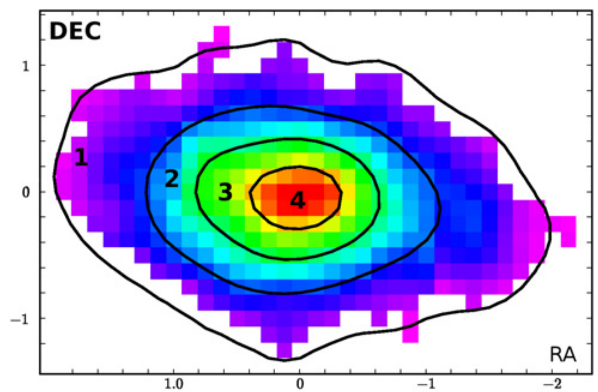
Typical redshift: z~1.2

Typical integrated flux:

$F(H\alpha) \sim 2 \times 10^{-16}$ cgs

$F([NII]) \sim 3 \times 10^{-17}$ cgs



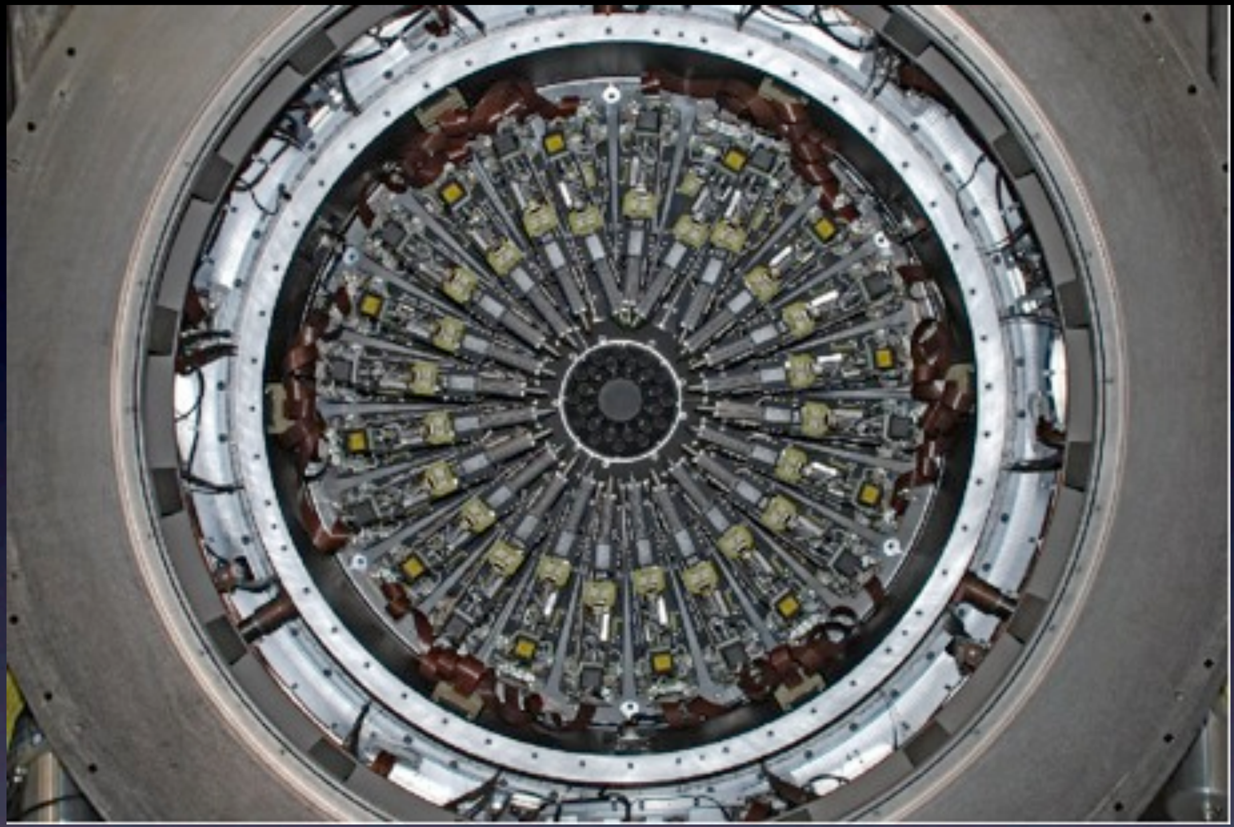


VLT/SINFONI (1.7 hrs)

Typical integration time:

1-2 hrs

Feasibility: Future Instruments



KMOS/VLT

KMOS-like multi-IFUs w/ AO are desirable

Strong request for the multi-IFU w/ GLAO

Survey Plan:

"Intensive search for the galaxy structure and the relation to the metallicity with wide-field instruments of the Subaru Telescope"

FMOS (Spectroscopy)

FoV~700 $arcmin^2$

+

nuMOIRCS (Imaging+IFUs) w/ GLAO

FoV~200 $arcmin^2$

Survey Plan:

"Intensive search for the galaxy structure and the relation to the metallicity with wide-field instruments of the Subaru Telescope"

- Target sample
  - ✓ We have ~2500 sample in the SXDS/UDS field (~0.7 deg^2)
  - ✓ The expected survey area: SXDS, COSMOS, EGS, GOODSs (~3 deg^2)
  - ✓ ~10000 objects at z=1-2 are sampled in these fields
- Observations with FMOS
  - ✓ We observe ~4000 objects with FMOS
  - ✓ Observing time: 4000 / 200 * 4.0 hrs = 80 hrs = 10 nights
  - ✓ 1500-2000 objects are probably detected
- Observations with new instruments w/ GLAO
  - ✓ Imaging survey is made for (a part of?) these targets in 3 deg^2
  - ✓ Observing time: 3 * 3600 / 200 * 5.0 hrs = 270 hrs ~ 30 nights
  - ✓ Multi-IFU survey is made for a part of these targets (1000 objects?)
  - ✓ Observing time: 1000 / 25 * 4 hrs = 160 hrs = 20 nights

Survey Plan:

"Intensive search for the galaxy structure and the relation to the metallicity with wide-field instruments of the Subaru Telescope"

FMOS (Spectroscopy)

10 nights

+

nuMOIRCS (Imaging+IFUs) w/ GLAO

~30 nights (Imaging) + ~20 nights (IFUs)

Survey Plan:

"Intensive search for the galaxy structure and the relation to the metallicity with wide-field instruments of the Subaru Telescope"

FMOS (Spectroscopy)

~2000 w/ metallicity

+

nuMOIRCS (Imaging+IFUs) w/ GLAO

1000-2000 w/ spatially resolved metallicity

Summary 2:

- Intensive survey for the galaxy structure and the relation to the metallicity with wide-field instruments of the Subaru Telescope
- Very unique survey with wide-field instruments on the Subaru
- ~10 nights observations with FMOS
- 1500-2000 objects with the (integrated) metallicity measurement
- ~30 nights observations with Imaging instruments with GLAO
- 1500-2000 objects with the morphology measurement
- ~20 nights observations with multi-IFUs with GLAO
- 1000 objects with the spatially resolved metallicity measurement
- ~50 nights observations with Subaru GLAO reveal the galaxy evolution

Morphology Dependency: For Kodama-san