UNDERSTANDING METALLICITY AT HIGH REDSHIFT UNIVERSE

KENTARO MOTOHARA

(IOA, UNIVSERSITY OF TOKYO)

GAS PHASE METALLICITY

GAS PHASE METALLICITY (OXYGEN ABUNDANCE) IS CRUCIAL TO UNDERSTAND GALAXY FORMATION/EVOLUTION, AS IT TRACES THE PREVIOUS STAR FORMATION HISTORY.

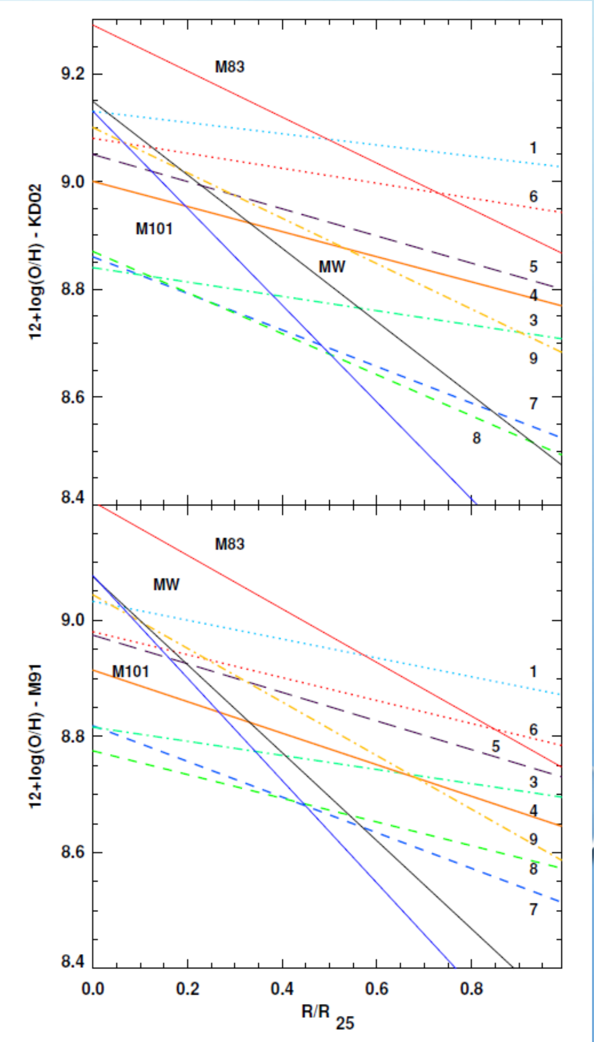
WHEN RESOLVED INTO SUB-GALACTIC SCALE, IT ALSO PROVIDES INFORMATION OF

- MASS ASSEMBLY/MERGER
- INFLOW/OUTFLOW

METALLICITY IN THE LOCAL GALAXIES

- METALLICITY IN CLOSE PAIRS ARE SYSTEMATICALLY LOWER THAN IN FIELD SPIRALS (KEWLEY+06)
- METALLICITY GRADIENT IN CLOSE PAIRS SHOWS SHALLOWER GRADIENTS THAN THOSE IN ISOLATED SPIRALS (KEWLEY+10)

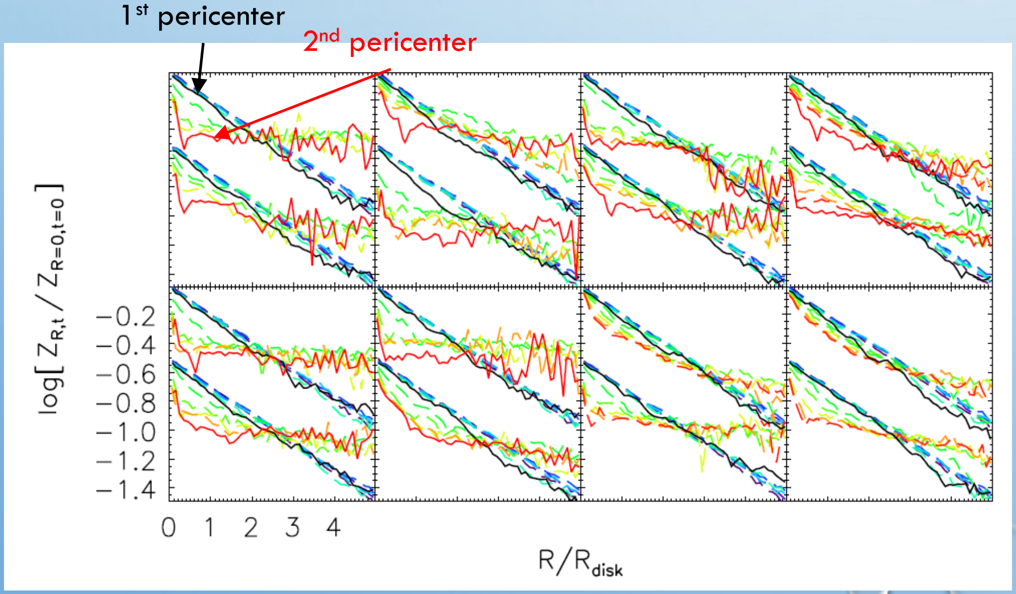
⇒ MERGER SUPPLIES LOW-METALLICITY GAS AT OUTER GALAXIES INTO THE CENTRAL REGION ?



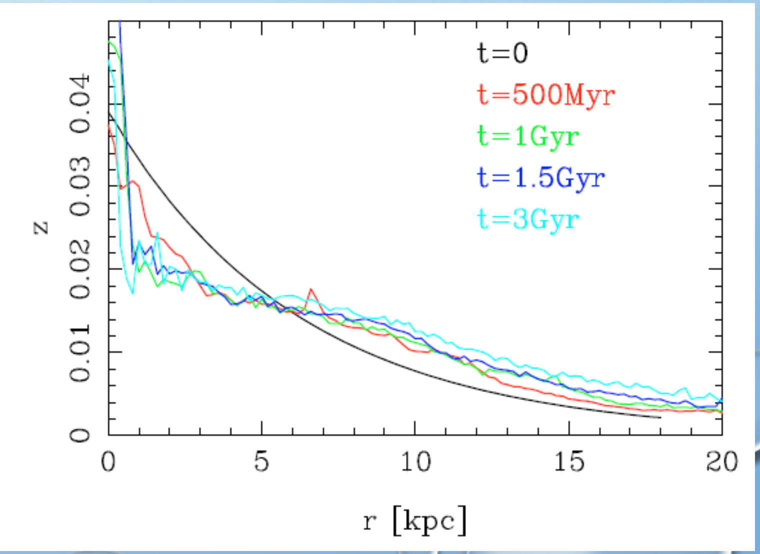
Kewley et al. ApJ 721, L48 (2010)

METALLICITY IN MERGER SIMULATION

- MERGER SIMULATIONS SHOW THAT METALLICITY AT A CENTER OF A GALAXY IS LOWERED DURING THE ENCOUNTER
- DUE TO GAS INFLOW



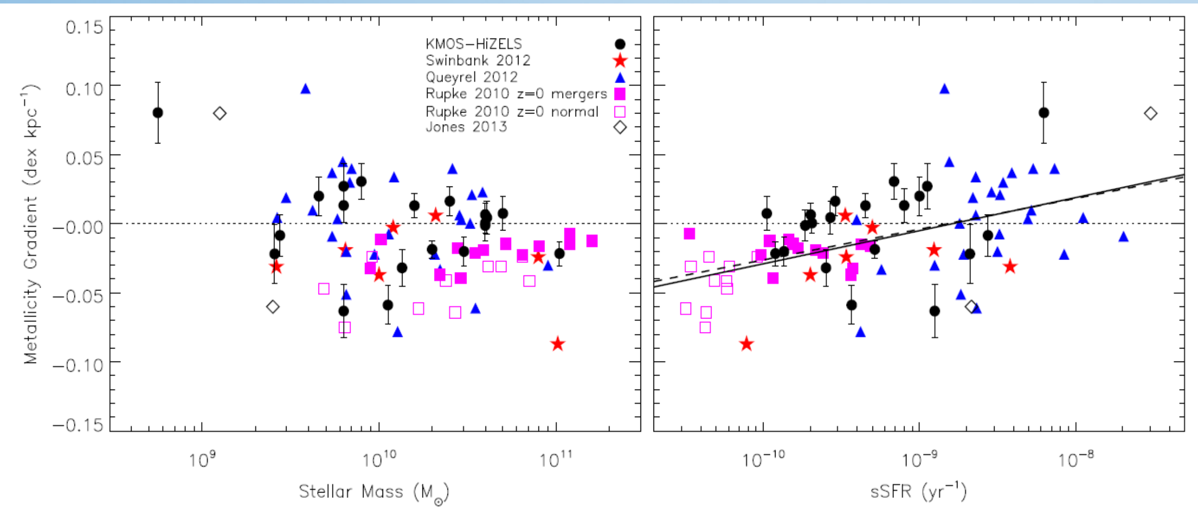
Rupke et al. ApJL 710, L156 (2010)



Montuori et al. A&A 518, A56 (2010)

INVERSE METALLICITY GRADIENT AT Z~1?

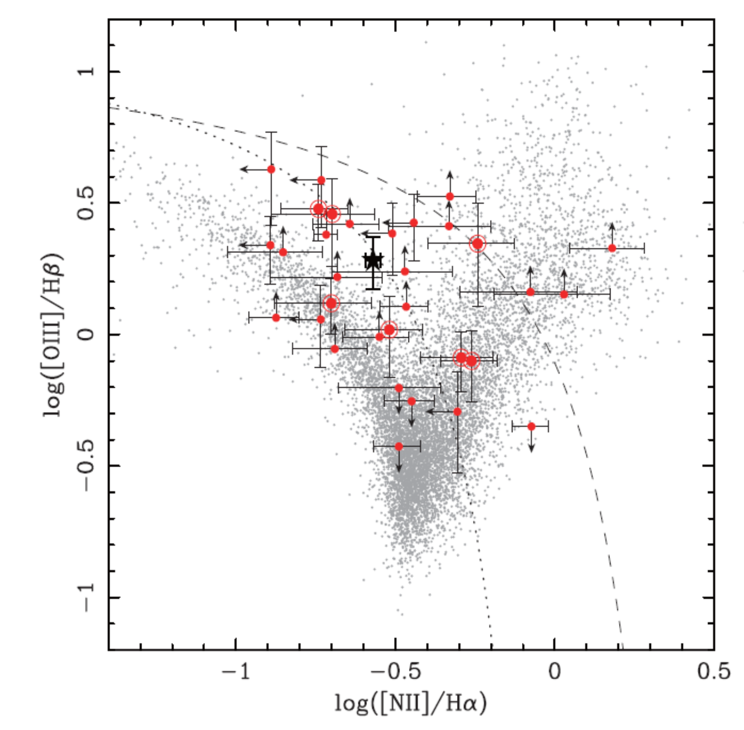
- SINFONI/KMOS OBSERVATIONS (QUEYREL+12, STOTT+14)
  - METALLICITY FROM N2 INDEX ([NII]6584/Hα6563)
- INNER PARTS OF GALAXIES SHOW LOWER METALLICITY
- EVIDENCE OF INTERACTION OR COLD STREAM



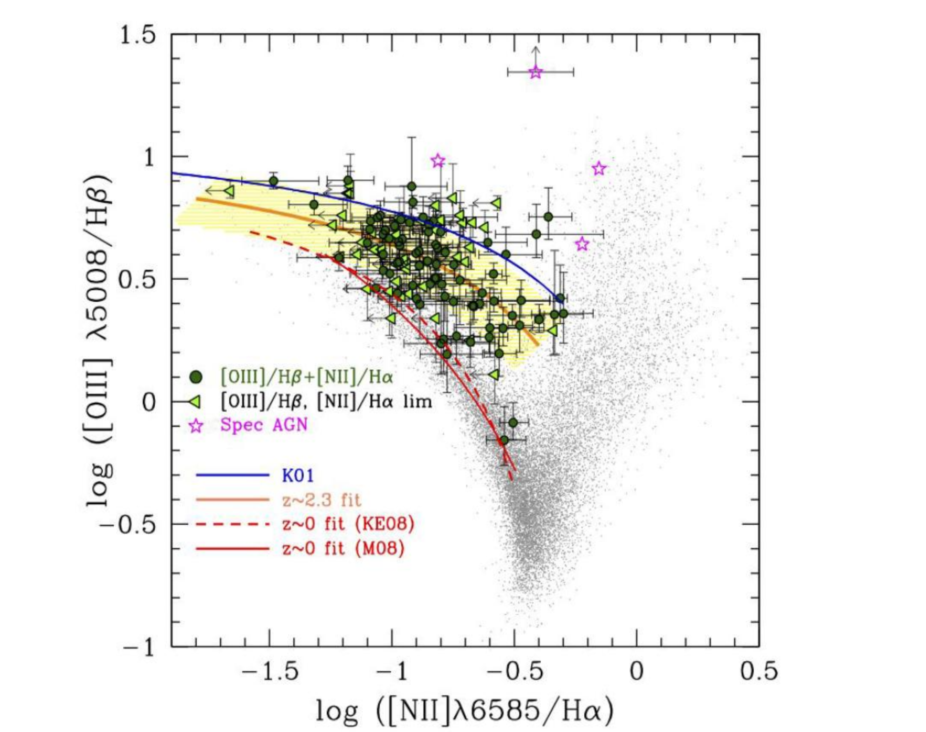
Stott et al., MNRAS in press (2014)

HOWEVER…
WE NEED TO UNDERSTAND PHYSICAL STATUS OF HII REGIONS

- HI-Z HII REGIONS OCCUPY DIFFERENT REGIONS ON BPT DIAGRAM



Yabe et al., PASJ 64, 60 (2012)



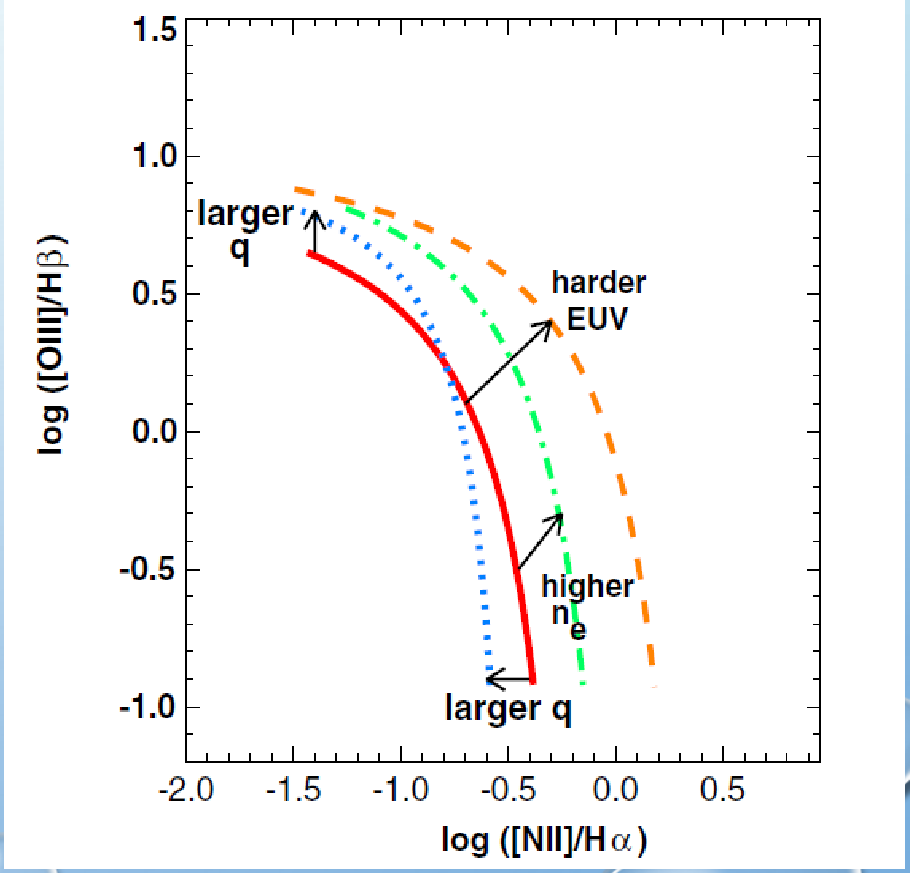
Steidel et al., arXiv:1405.5473

HIGHER NE? LARGER U? HARDER EUV?

N2 INDEX IS AFFECTED, THEN

- LARGER EUV OR NE
- SMALLER U

OVERESTIMATE METALLICITY.



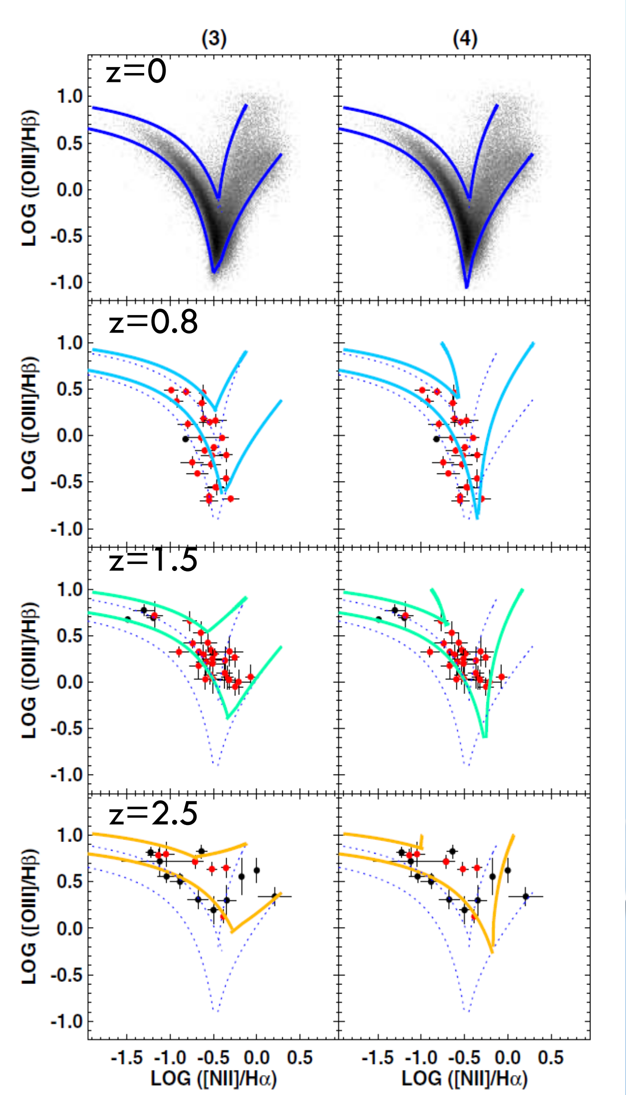
Kewley et al., ApJ 774, 100 (2013)

EVOLUTION OF BPT DIAGRAM

CAN BE EXPLAINED BY A EVOLUTION MODEL,

WHERE AT Z~2.5

- 10 TIMES DENSER ELECTRON DENSITY
- 2 TIMES HIGHER IONIZATION PARAMETER

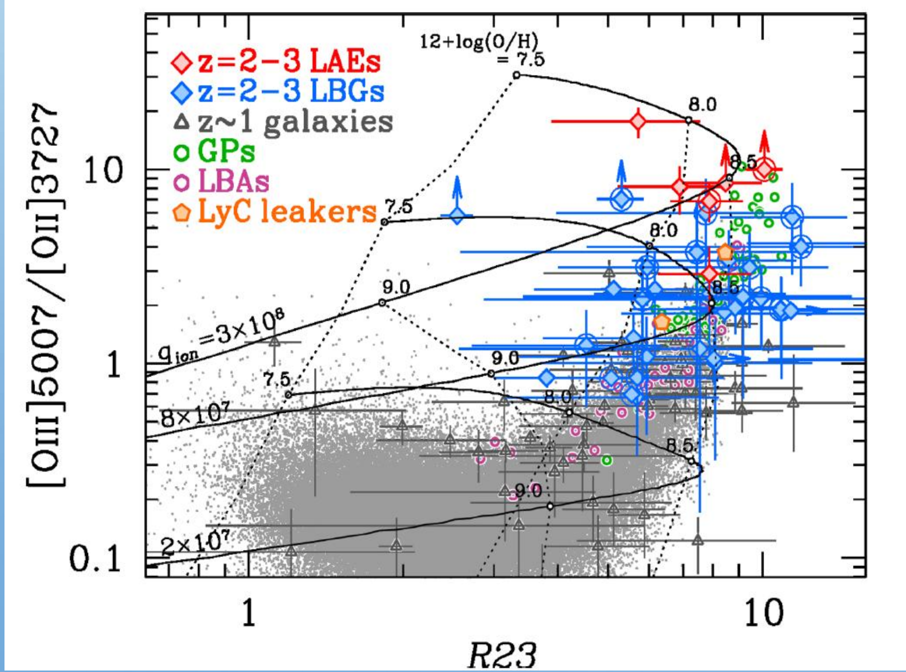


Kewley et al., ApJ 774, L10 (2013)

IONIZATION FIELD AT LAE/LBG

Z=2-3 LAE/LBG SHOWS 10 TIMES HIGER [OIII]/[OII]

CAN BE EXPLAINED BY 10 TIMES HIGHER IONIZATION PARAMETER



Nakajima & Ouchi, MNRAS 442, 900 (2014)

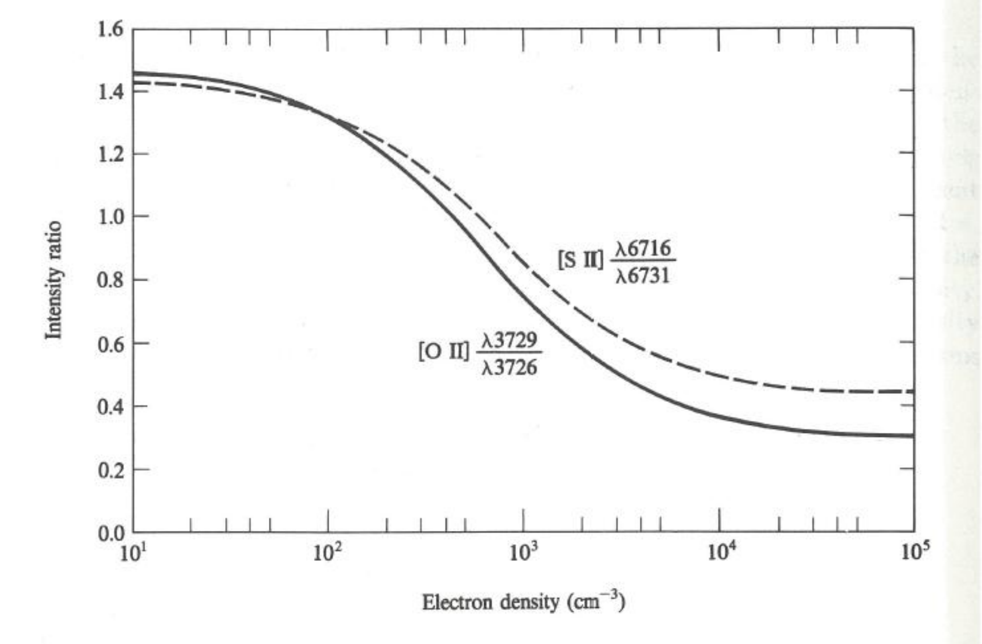
WHAT'S NEXT?

WE NEED TO UNDERSTAND PHYSICAL STATUS IN HII REGIONS AT HI-Z UNIVERSE

- DENSITY
- IONIZATION PARAMETER
- METALLICITY
- THEIR DISTRIBUTION WITHIN A GALAXY

ELECTRON DENSITY MEASUREMENT

- [OII]3729/3726
- [SII]6731/6716
- DEPENDS ON $\sqrt{T_e}$: HIGHER TEMPERATURE RESULTS IN LOWER DENSITY



METALLICITY MEASUREMENT (DIRECT METHOD)

- EMISSION LINE STRENGTH (FROM STATE j TO i) AGAINST A HYDROGEN LINE RELATES TO ABUNDANCE WITH THE FOLLOWING RELATION

$$\frac{I_{j\to i}}{I_{\mathrm{H}\beta}} = \frac{\nu_{j\to i} N_j q_{j\to i} b}{\nu_{\mathrm{H}\beta} N_p \alpha_{\mathrm{H}\beta}^{eff}}$$

THEREFORE, OXYGEN ABUNDANCE CAN BE OBTAINED BY

- $I_{[\mathrm{O\ I}]6300}/I_{\mathrm{H}\alpha} \Rightarrow N_{\mathrm{O}^0}/N_p$ (NEGLIGIBLE IN STROMGREN SPHERE)
- $I_{[\mathrm{O\ II}]3727}/I_{\mathrm{H}\beta} \Rightarrow N_{\mathrm{O}^+}/N_p$
- $I_{[\mathrm{O\ III}]4959+5007}/I_{\mathrm{H}\beta} \Rightarrow \frac{N_{\mathrm{O}^{++}}}{N_p}$

HOWEVER, COLLISIONAL TRANSITION RATE ($q_{j\to i}$) STRONGLY DEPENDS ON ELECTRON TEMPERATURE.

ELECTRON TEMPERATURE MEASUREMENT

- FOR DIRECT MEASUREMENT, [OIII]4363 OR [NII]5755 IS NECESSARY
- HOWEVER, THEY ARE EXTREMELY WEAK…
- STACKING MAY GIVES US SOME INSIGHT, ESPECIALLY WHEN METALLICITY IS LOW (AND TEMPERATURE IS HIGH)

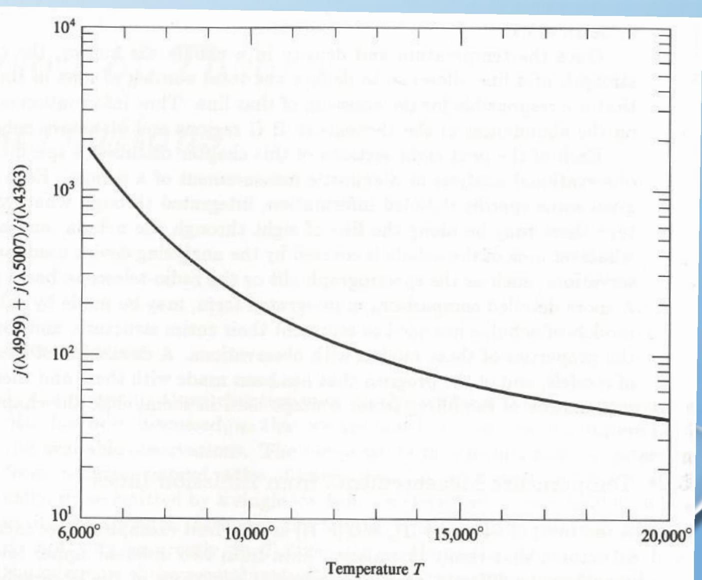


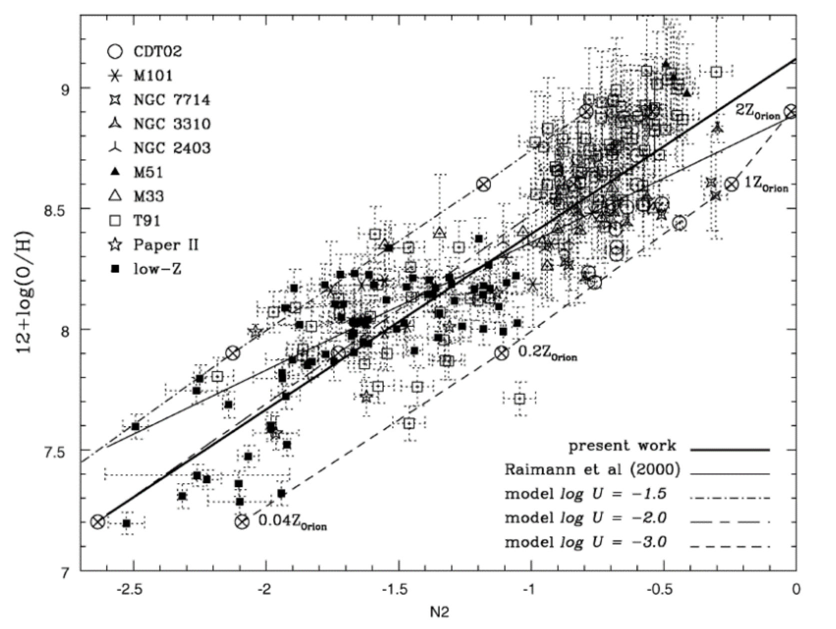
FIGURE 5.1
[O III] (λ4959 + λ5007)/λ4363 intensity ratio (in low-density limit $N_e \rightarrow 0$) as a function of temperature. Accurately calculated values shown here are indistinguishable from approximation of equation (5.4) using mean values of Ω.

METALLICITY MEASUREMENT (EMPIRICAL)

- N2 INDEX : [NII]6584/Hα6563
- O3N2 INDEX : ([OIII]5007/Hβ4861)/([NII]6584/Hα6563)
- R23 INDEX : ([OII]3727+[OIII]4959,5007)/Hβ4861

N2 INDEX

- [NII]6584/Hα6563 : MOST POPULAR
- HIGHER IONIZATION PARAMETER $\Rightarrow$ LOWER N2
- LARGER ELECTRON DENSITY $\Rightarrow$ HIGHER N2
- CAN BE USED AT $12 + \log(O/H) < 9$

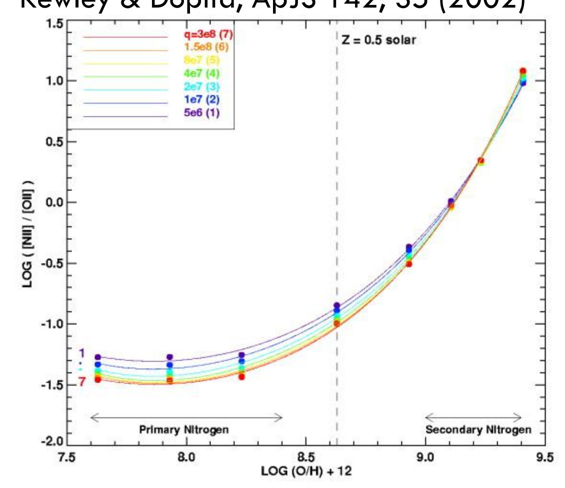


Denicolo, Terlevich, Terlevich, MNRAS 330, 69 (2002)

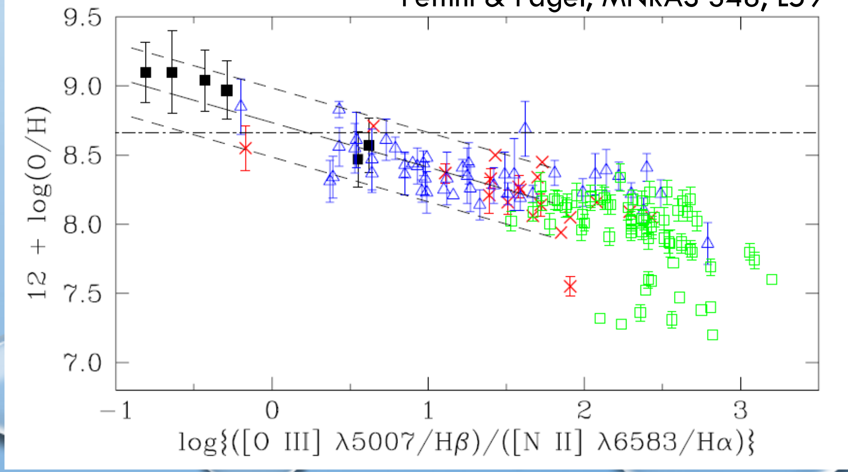
O3N2 METHOD

- ([OIII]5007/Hβ4861)/([NII]6584/Hα6563)
- MEASURE SECONDARY NITROGEN EXCESS (N/O)
- FOR SUPER-SOLAR METALLICITY : $12 + \mathrm{LOG}(O/H) > 8.5$
- AGAIN, AFFECTED BY ELECTRON TEMPERATURE (BUT LESS?)

Kewley & Dopita, ApJS 142, 35 (2002)

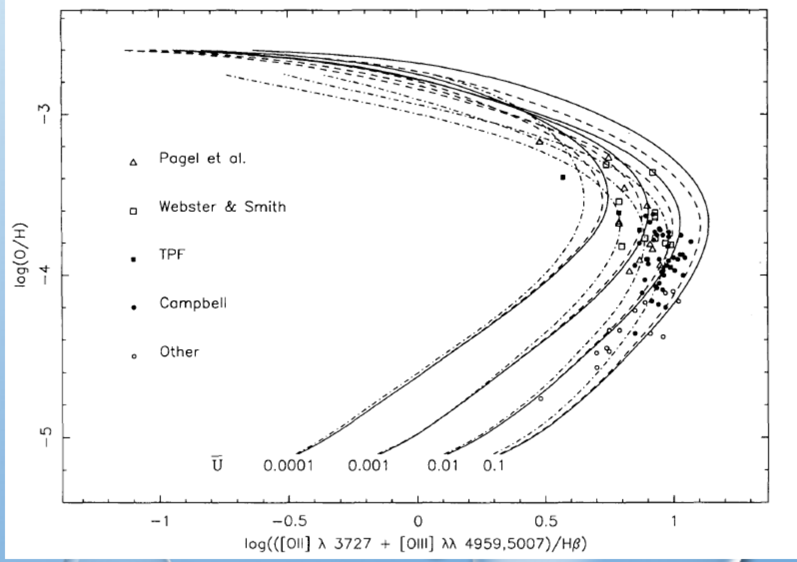


Pettini & Pagel, MNRAS 348, L59



R23 METHOD

- ([OII]3727+[OIII]4959,5007)/Hβ4861
- BIMODAL DISTRIBUTION
  - CAN BE SEPARATED IN COMBINATION WITH O3N2 INDEX
- AFFECTED BY IONIZATION PARAMETER
- NEED CORRECTION FOR DUST EXTINCTION

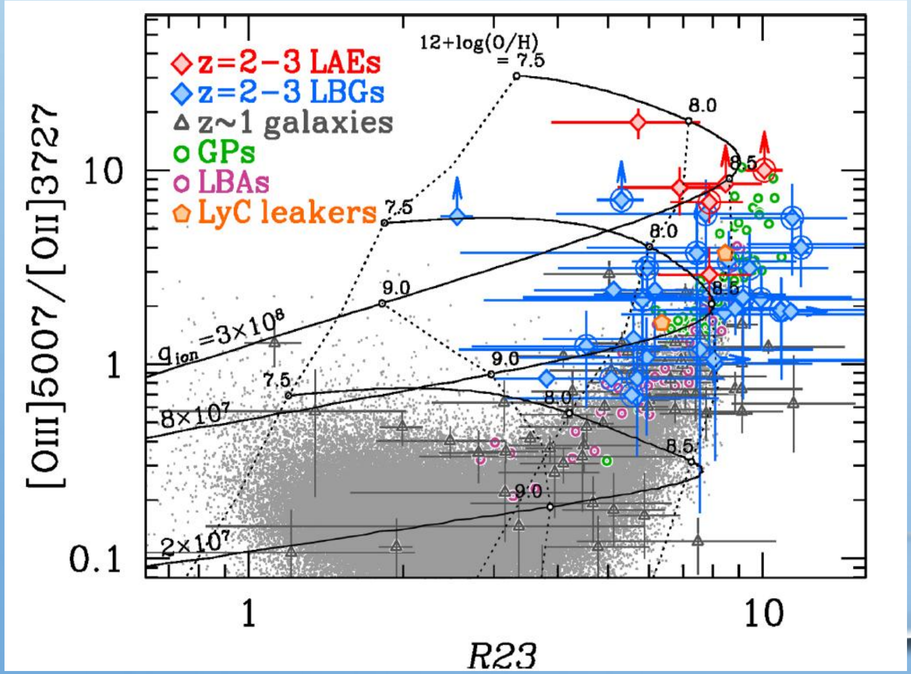


McGaugh, ApJ 380, 140 (1991)

IONIZATION PARAMETER

[OIII]5007/[OII]3727 WILL BE A GOOD INDICATOR

NEED CORRECTION FOR DUST EXTINCTION



Nakajima & Ouchi, MNRAS 442, 900 (2014)

METALLICITY MEASUREMENT (EMPIRICAL)

- N2 INDEX : [NII]6584/Hα6563
- O3N2 INDEX : ([OIII]5007/Hβ4861)/([NII]6584/Hα6563)
- R23 INDEX : ([OII]3727+[OIII]4959,5007)/Hβ4861

ALL THE INDICES MAY REQUIRE CORRECTION FOR DIFFERENT ENVIRONMENT

OBSERVATIONS OF ALL THE EMISSION LINES ARE NECESSARY TO SOLVE THE PROBLEM

IFU SURVEY OF Z=1-2 GALAXIES

- VARIOUS GALAXIES AT Z=1~2
  - SAMPLES MAYBE SUPPLIED BY EXISTING SURVEYS(SXDS, GOODS-N, SDF) AND NEWLY PLANNED SWIMS-18 SURVEY (ON TAO/SUBARU)
- COVER WHOLE MAJOR OPTICAL EMISSION LINES
  - [SII]6731/6716
  - Hα6563+[NII]6584
  - [OIII]5007
  - Hβ4861
  - ([OIII]4363) : POSSIBLY BY STACKING?
  - [OII]3729/3726
- SPECTRAL RESOLUTION SHOULD BE ENOUGH TO RESOVE [OII] : R>3000

SENSITIVITY OF ULTRA-SUBARU

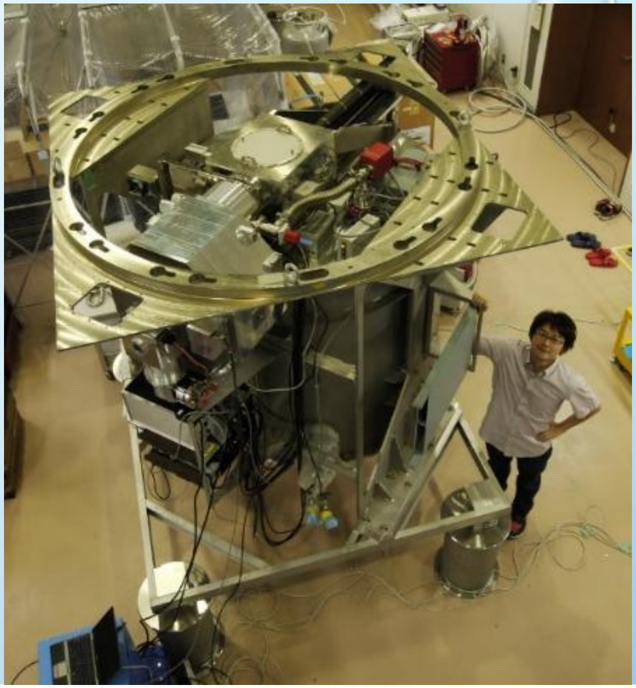
- MAX 1.8ARCSEC FOV/STARBUG ⇒ 12KPC DIAMETER
- 0.2ARCSEC SAMPLING ⇒ 1.4KPC
  7KPC DIAMETER SPLIT INTO 19 FIBERS
- REPLACEMENT OF DETECTORS AND GRISMS MAY PROVIDE BETTER SENSITIVITY BY ~1.5MAG
- STILL, SENSITIVITY IS A BIG PROBLEM : NEED TO BE BRIGHTER BY ~2MAG THAN NORMAL SPECTROSCOPIC TARGETS
  ⇒ POSSIBLE TARGETS WILL BE THOSE WITH $K_{AB}<21$

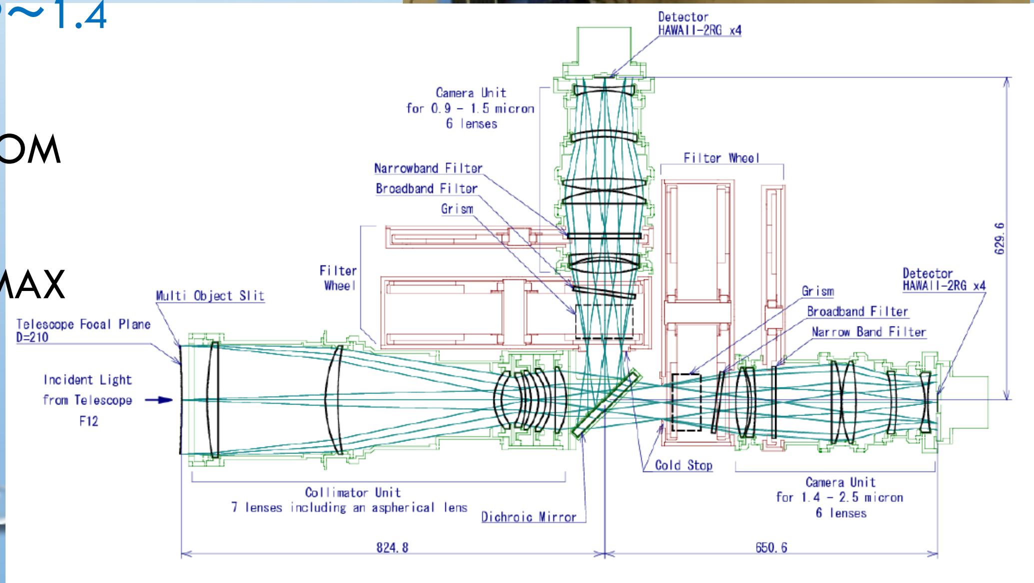
SWIMS

SWIMS

SIMULTANEOUS-COLOR **W**IDE-FIELD **I**NFRARED **M**ULTI-OBJECT **S**PECTROGRAPH

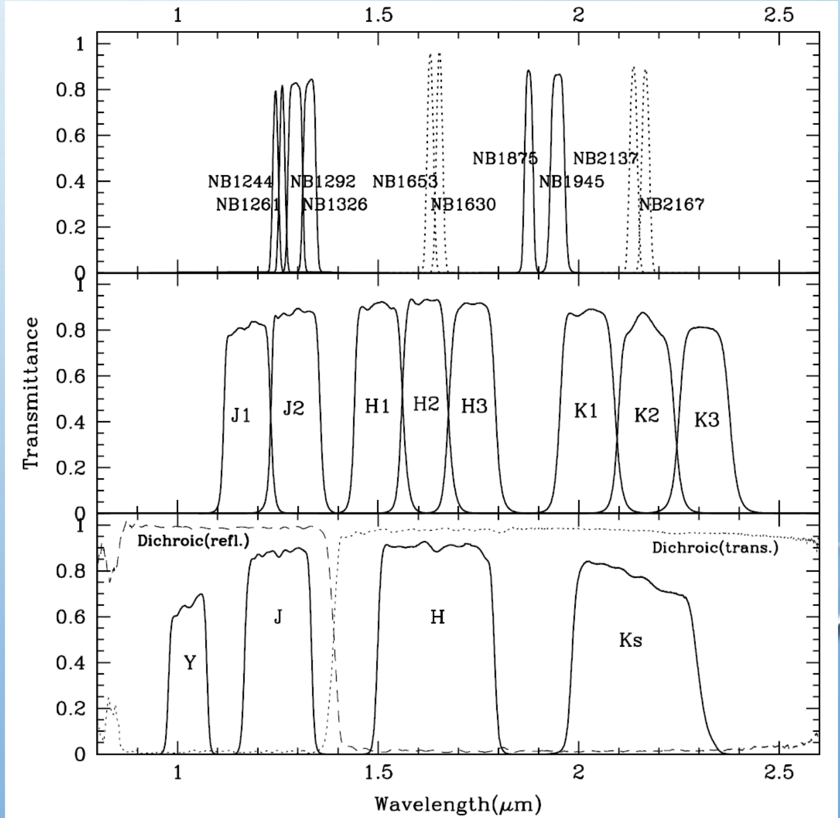
- 1^{ST} GENERATION INSTRUMENT FOR TAO 6.5M
- FOV OF 9.6'Φ ON TAO
- 2-BAND SIMULTANEOUS IMAGING AT 0.9～1.4 / 1.4～2.4MICRON
- CAPABLE OF R=1000 SPECTROSCOPY FROM 0.9 TO 2.5 MICRON IN A SINGLE SHOT
- CAPABLE OF MOS SPECTROSCOPY FOR MAX 40 OBJECTS
- WILL BE CARRIED INTO SUBARU AS A PI INSTRUMENT IN FY2015





SWIMS-18

- WIDE FIELD SURVEY USING 18 FILTERS
  - 9 MBFS, 6 NBFS, 3 BBFS
- 1SQ.DEGREE FOV
  - MBF SURVEY
    - ACCURATE PHOTO-Z AT Z=1-3
    - 1.2E7 MPC3 VOLUME
  - NBF SURVEY
    - DUAL LINE EMITTER SURVEY (HA/[OIII], ETC)
    - 7.5E5 MPC3 VOLUME



ANSWERS TO QUESTIONS

(Q1) WHAT IS THE OPTIMUM SPATIAL SAMPLING (OR DIAMETER IN ARCSEC OF EACH FIBER IN THE BUNDLE) AND FOV OF THE BUNDLE?

LARGER FOV PER BUNDLE IS PREFERABLE
0.2ARCSEC (~1.4KPC) IS ENOUGH

(Q2) WHAT IS THE OPTIMUM AND MINIMUM NUMBER OF THE FIBER BUNDLES (OR MULTIPLICITY) IN THE 13'.6 DIAMETER FOV?

NUMBER DENSITY OF K_{AB}<21 MAG Z=1-2 GALAXIES IS ~0.2/ARCMIN^2, THEREFORE, THE OPTIMUM NUMBERS IS ~30.

HOWEVER, THEY CAN BE COVERED WITH MULTIPLE SHOTS, SO THE MINIMUM NUMBER CAN BE THAT OF THE BASELINE SPECIFICATION (16 WITH 1.8ARCSEC FOV).

(Q3) WHAT IS THE CRITICAL WAVELENGTH RANGE IN NEAR-INFRARED COVERED BY THE STARBUG SYSTEM (0.9-2.0MICRON)?

FULL RANGE OF 0.9-2MICRON IS NECESSARY TO SAMPLE ALL THE IMPORTANT OPTICAL EMISSION LINES FROM [OII]3727 TO [SII]6731 AT REDSHIFT UPTO ~2.

(Q4) WHAT IS THE OPTIMUM SPECTRAL RESOLUTION?

R=3000 IS PREFERRED TO RESOLVE VELOCITY FIELD OF THE GALAXY AS WELL AS TO RESOLVE [OII]3726/3729.

HOWEVER, WIDE WAVELENGTH COVERAGE IS ANOTHER IMPORTANT FEATURE FOR EFFECTIVE OBSERVATION. IT WILL BE NICE IF ZJ OR HK SPECTRUM CAN BE TAKEN WITH A SINGLE SHOT.

(Q5) WHAT IS THE SENSITIVITY REQUIREMENT FOR THE PHASE-I INSTRUMENT?

K_{AB}~22.5 PER FIBER

(Q6) PLEASE DESCRIBE A BRIEF OBSERVATION PLAN FOR YOUR SCIENCE CASE WITH THE FIBER BUNDLE MULTI-OBJECT IFU.

- NUMBER OF OBJECTS / SURVEY AREA : TBD
- FIELDS : SWIMS-18 FIELD, SXDS, GOODS-N ….
- NUMBER OF NIGHTS TO COMPLETE YOUR SURVEY : TBD, 1 POINTING/NIGHT?
- UNIQUENESS

(Q7) HOW COULD THE PROPOSED SCIENCE CASES BE COMPETITIVE OR COMPLEMENTARY TO THE SCIENCE WITH 30M CLASS TELESCOPES (E.G. TMT) OR SPACE TELESCOPES (E.G. JWST) IN 2020S?

THE PROPOSED OBSERVATIONS CAN BE CARRIED OUT ONLY FOR THE BRIGHTEST OBJECTS BY 8M CLASS TELESCOPES, WITH COARSE (>1KPC) SAMPLING.
TMT WILL PROBE GALAXIES WITH L* OR FAINTER LUMINOSITY, WITH HIGHER SPATIAL RESOLUTION.

(Q8) PLEASE DESCRIBE THE REQUIREMENTS FOR PHASE-II INSTRUMENT (STARBUGS + DEDICATED SPECTROGRAPH) TO DEVELOP YOUR SCIENCE CASE.

- FIBER BUNDLE CONFIGURATIONS : 0.2"/FIBER, FOV OF EACH BUNDLE LARGER THAN 1.8ARCSEC, # OF BUNDLES ~30
- WAVELENGTH COVERAGE : 0.7 TO 2.0 MICRON
- SPECTRAL RESOLUTION : R=3000
- SENSITIVITY : K_{AB}=22.5MAG/FIBER (WHEN BINNED DOWN TO R~500)

(Q9) WHAT IS THE UNIQUE POINT OF THE FIBER BUNDLE MULTI-OBJECT IFU WITH STARBUGS COMPARED TO THE IMAGER OR MULTI-OBJECT SLIT SPECTROGRAPH?

HIGH EFFICIENCY SURVEY SPEED WITH MULTI-OBJECT IFU CAPABILITY.