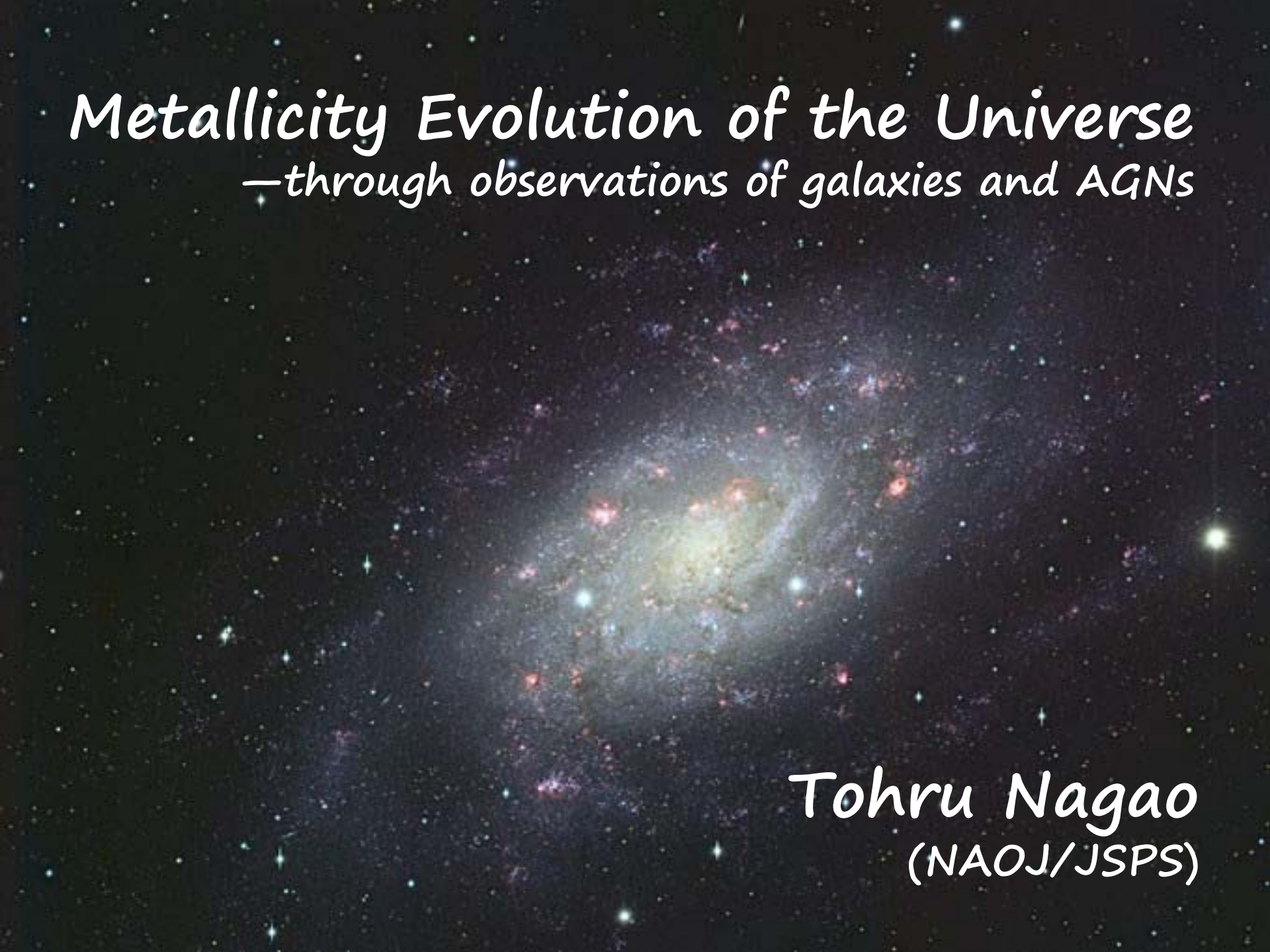


Metallicity Evolution of the Universe

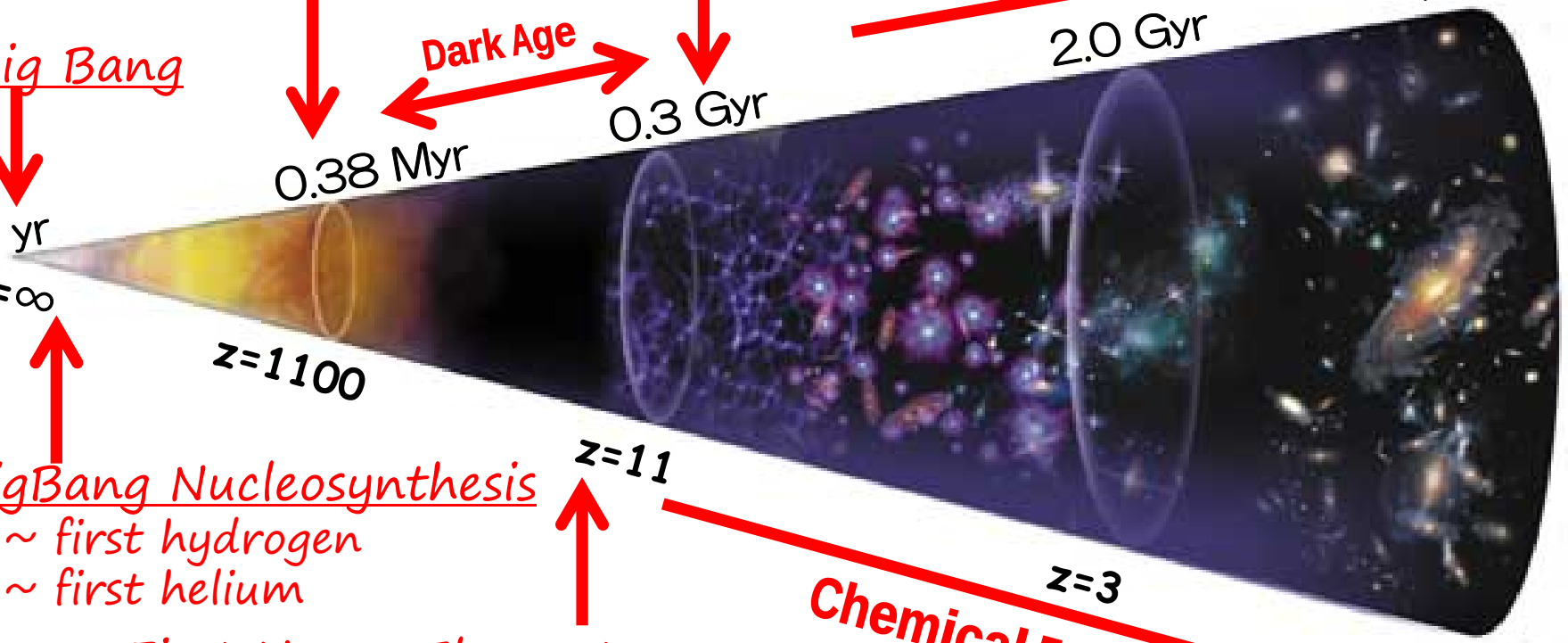
—through observations of galaxies and AGNs

Tohru Nagao
(NAOJ/JSPS)

Why Metallicity?

NGC 2403
(©Subaru, 2005)

Cosmic Chemical Evolution



Current Universe

Population III & Reionization

Recombination

Galaxy Evolution

Big Bang

Dark Age

13.7 Gyr

2.0 Gyr

0.3 Gyr

0.38 Myr

0 yr

z=∞

z=1100

z=11

z=3

z=0

Chemical Evolution

BigBang Nucleosynthesis
- ~ first hydrogen
- ~ first helium

First Heavy Elements
- ~ first stars, first suparnovae
- ~ second generations
- ~ third, fourth, ...

WHEN? WHERE? HOW MUCH?

- ~ earth-like planets
- ~ life, human, & you

Contents of This Presentation

(1) Metallicity Measurements of Galaxies

~ How to measure metallicity
~ Luminosity-metallicity & mass-metallicity relations
~ Toward high-z universe

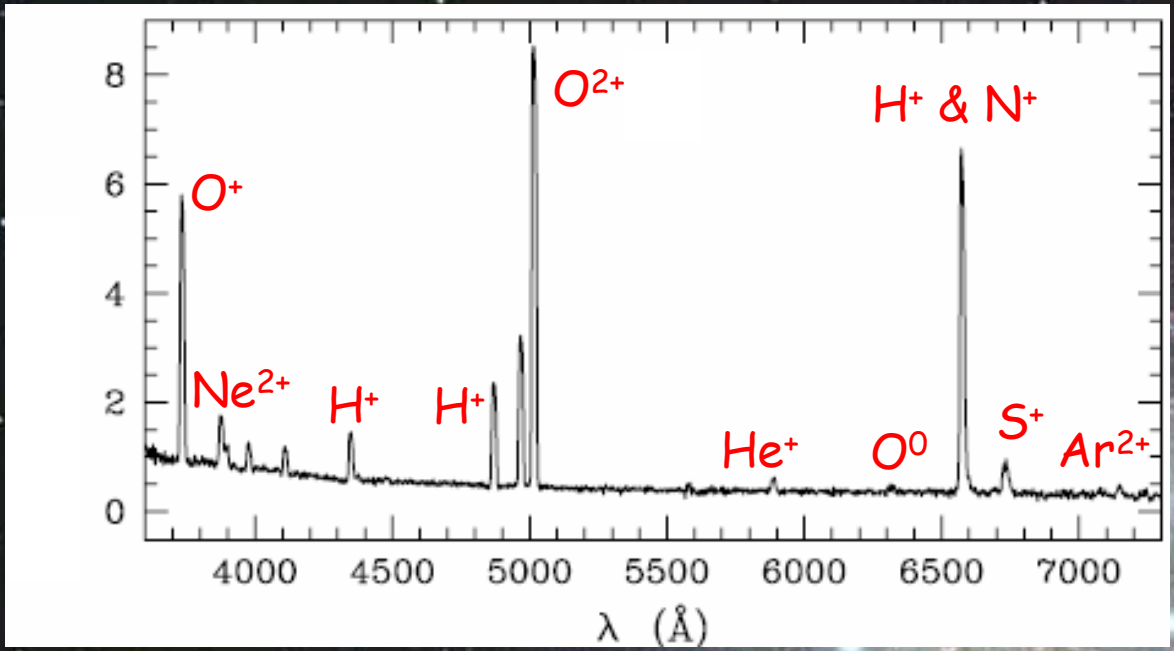
(2) Metallicity Measurements of AGNs

~ Far brighter than galaxies: possible excellent targets
~ How to measure metallicity: photoionization modeling
~ Broad-line regions vs. narrow-line regions
~ Luminosity-metallicity relation and its evolution

(3) Open Issues

~ Galaxies vs. AGNs
~ Searching zero-metallicity systems at high redshift

Metallicity Measurements of Galaxies



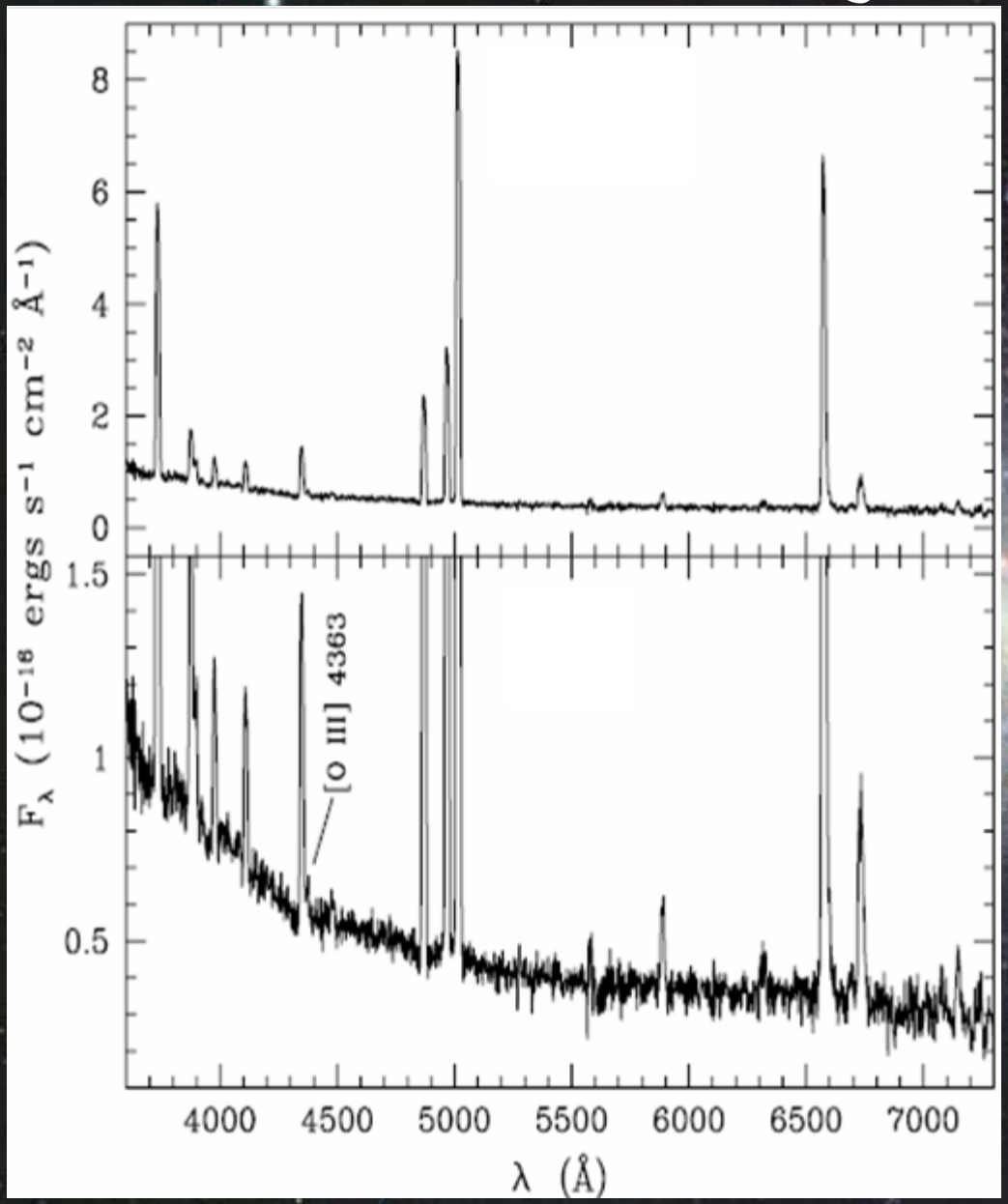
focusing on "O/H"

O/H
= $(O^0+O^+++O^{2+}+...)/H^+$
= $(O^0+O^++O^{2+})/H^+$

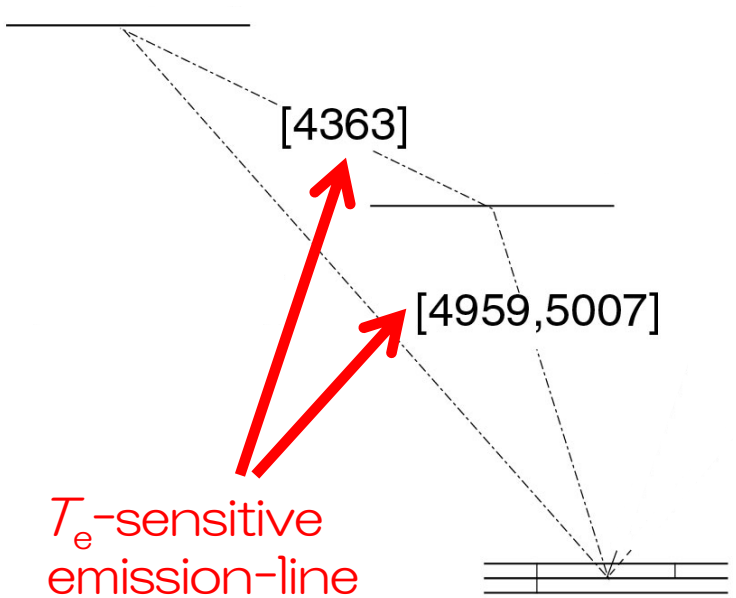
$$F(H^+) = \int N_p N_e h\nu\, \alpha(T)\, dV$$
$$F(O^0) = \int N_{O^0} N_e h\nu\, q_{O^0}(T)\, dV$$
$$F(O^+) = \int N_{O^+} N_e h\nu\, q_{O^+}(T)\, dV$$
$$F(O^{2+}) = \int N_{O^{2+}} N_e h\nu\, q_{O^{2+}}(T)\, dV$$

We need to know emission-line fluxes and gas temperature

Accurate Metallicity Measurements



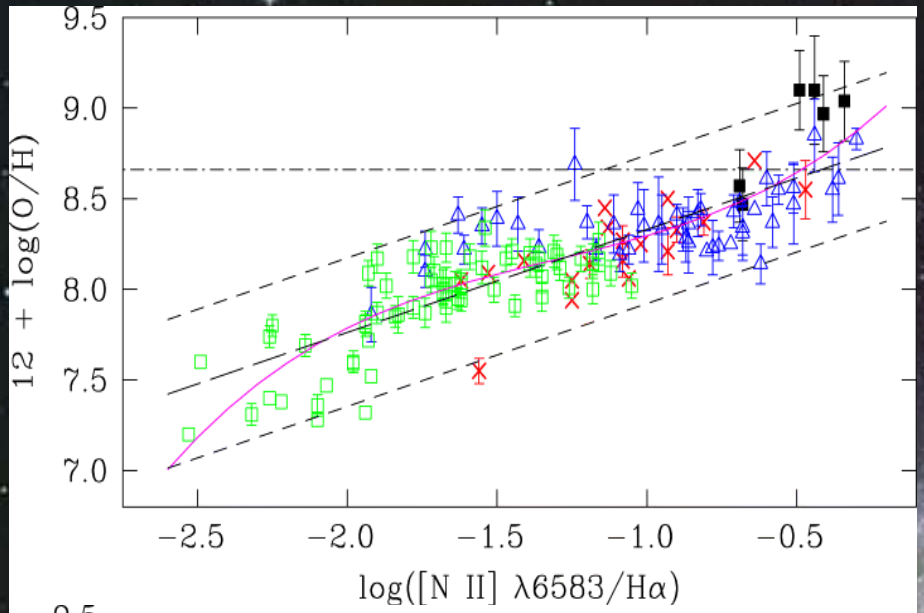
O^{2+} Grotrian diagram

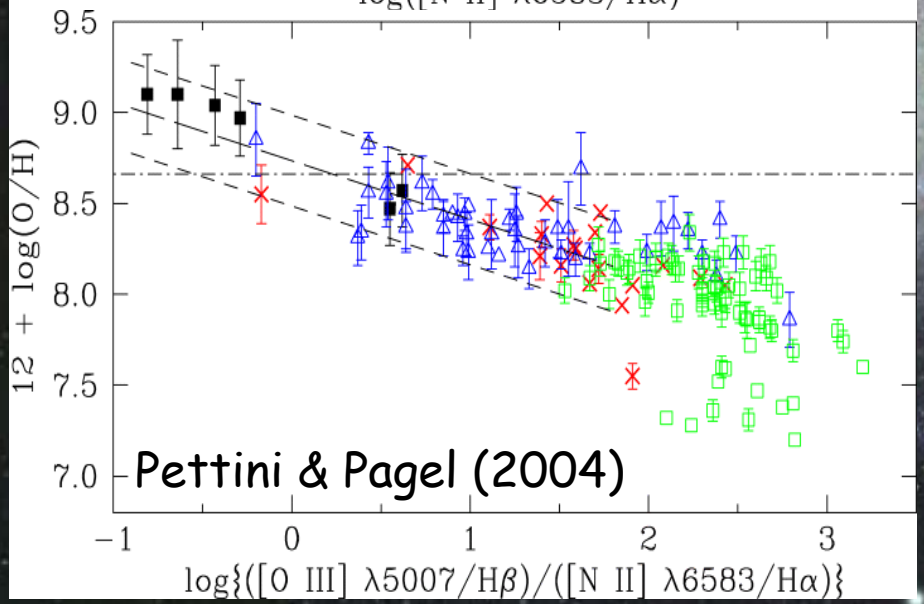


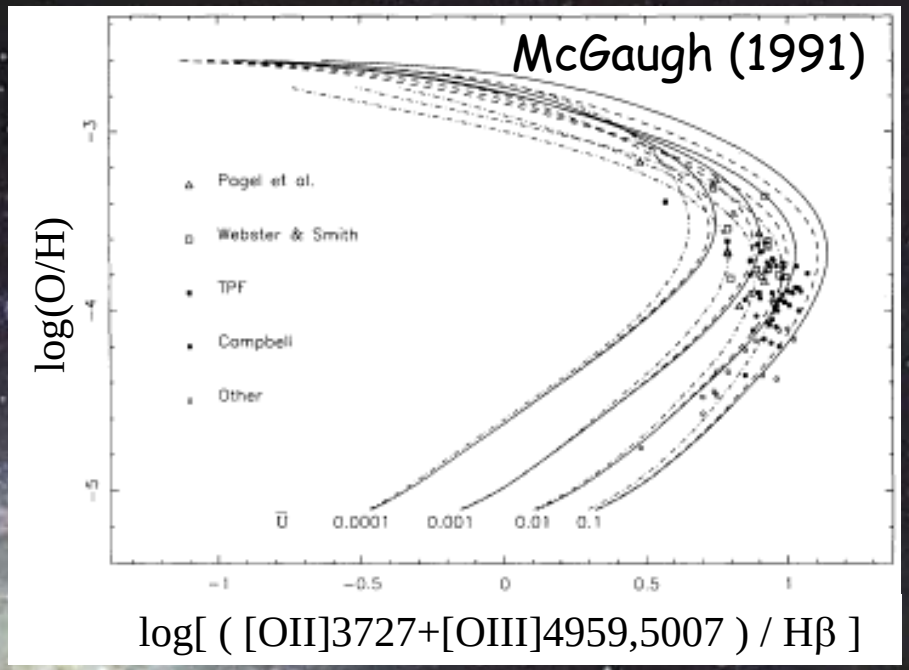
T_e-sensitive emission-line flux ratio

[OIII]4363 is available only in nearby galaxies...

Convenient Metallicity Measurements

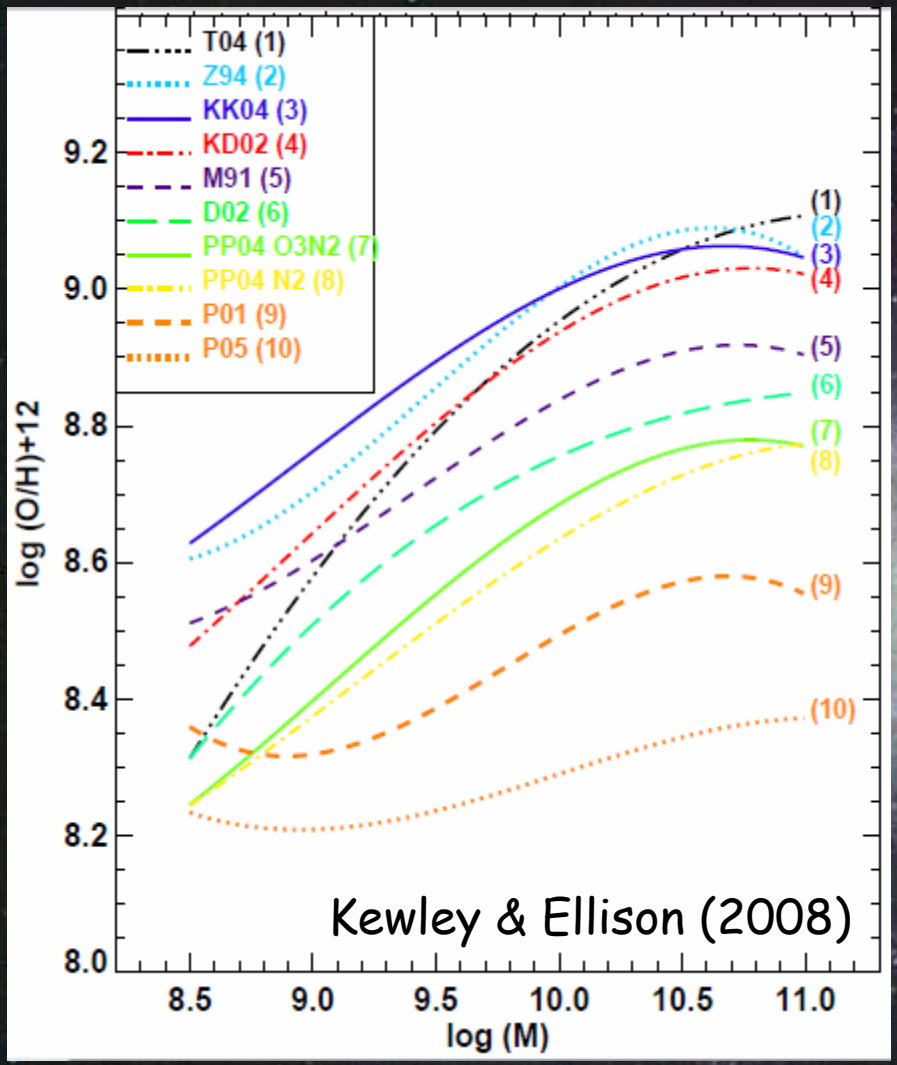


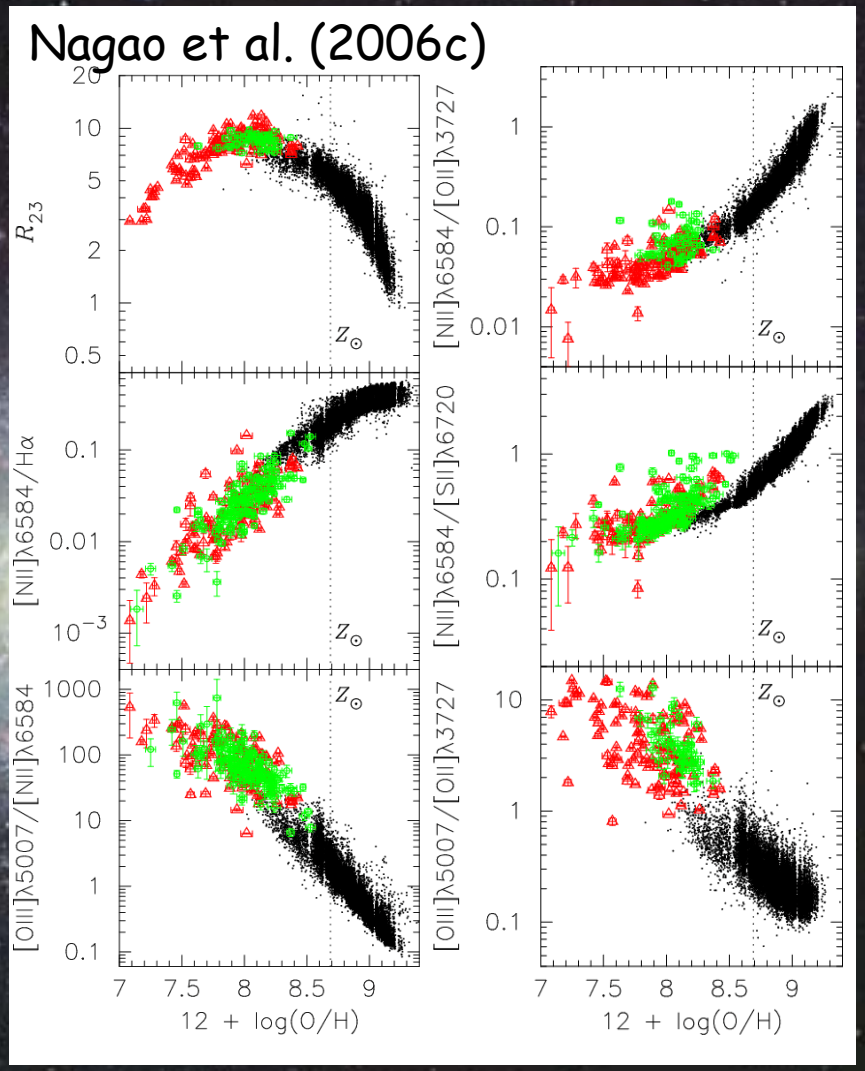




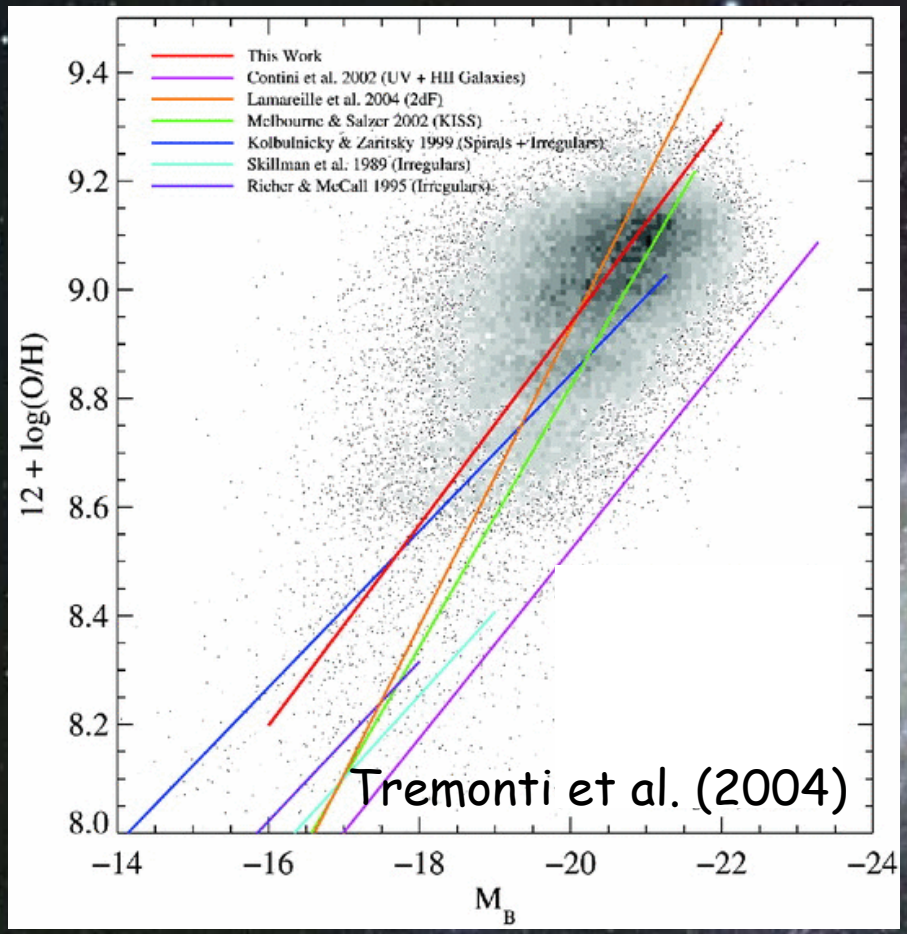
Using only strong lines
("strong-line methods")
→applicable to faint targets

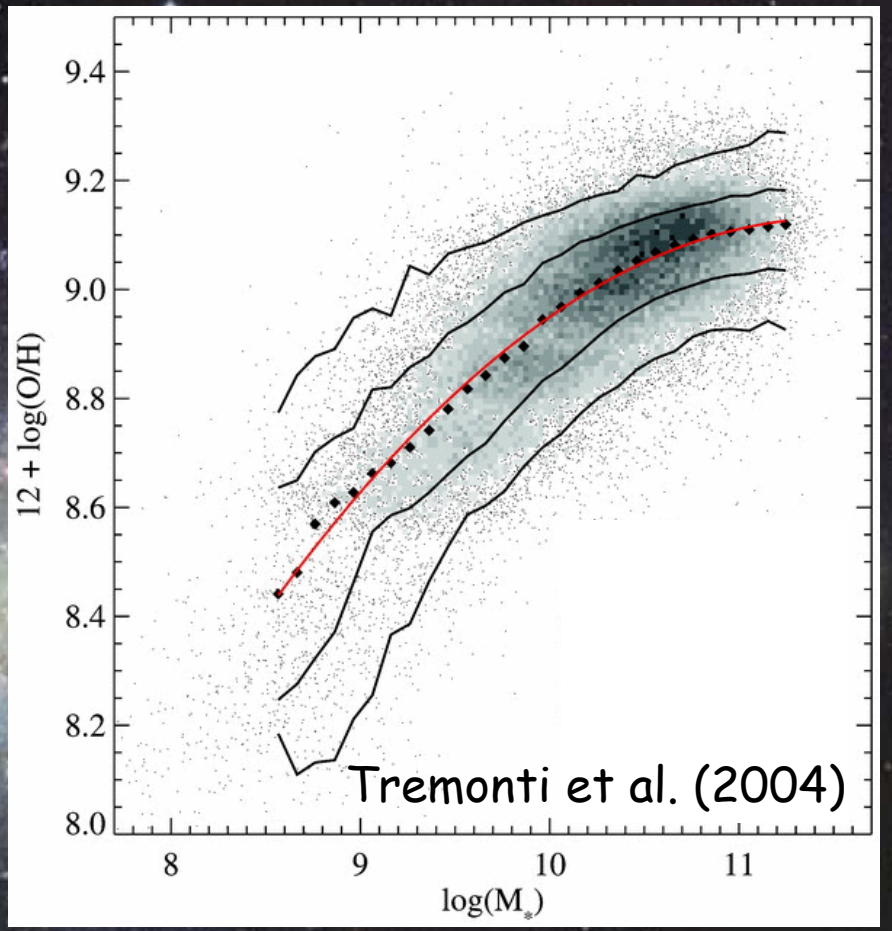
Calibrating Strong-Line Methods





Metallicity of Galaxies at z=0.1

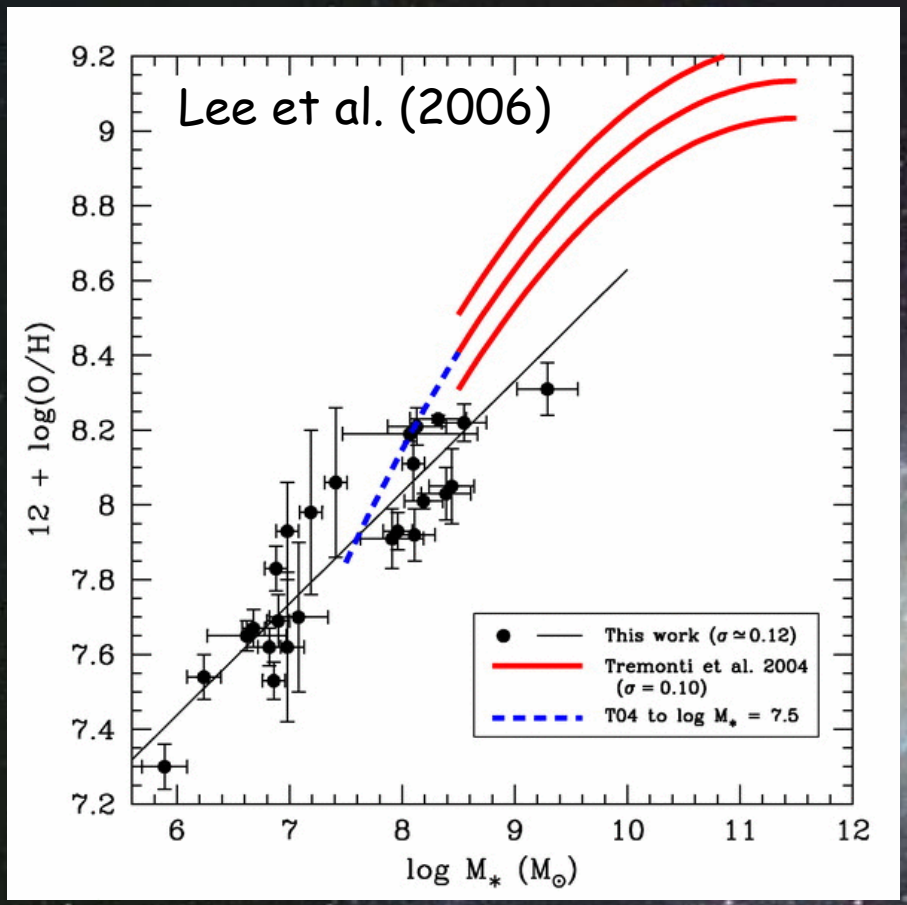




"Luminosity-Metallicity Relation"

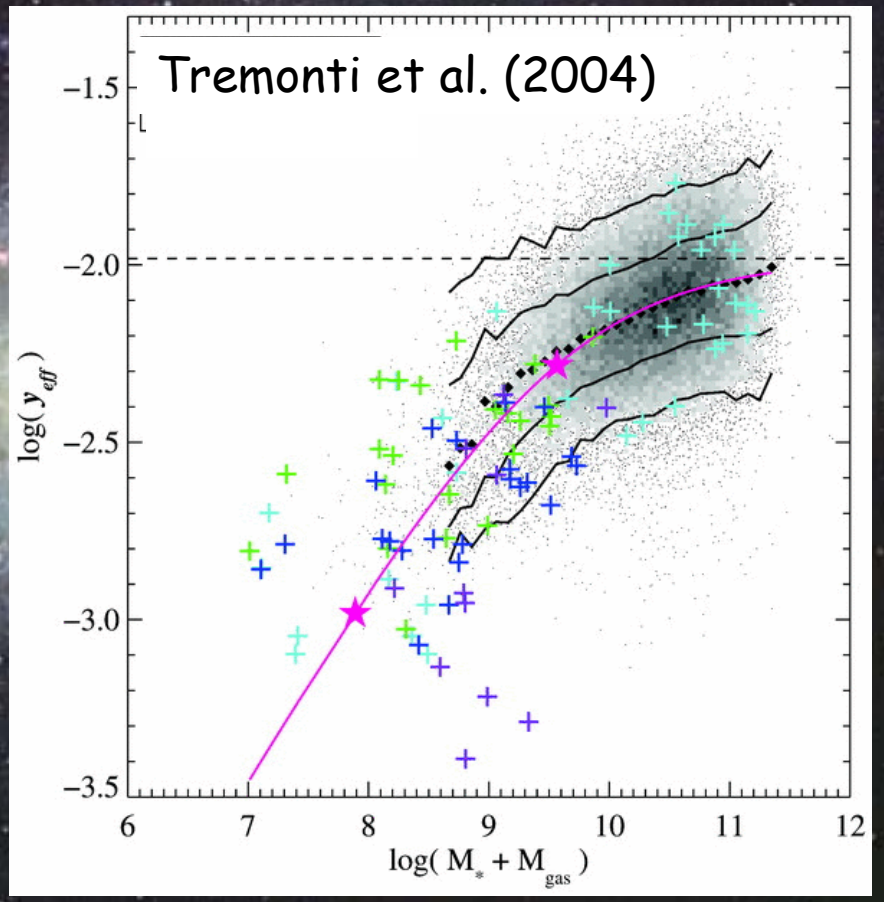
"Mass-Metallicity Relation"

Metallicity of Galaxies at z=0.1 (cont.)

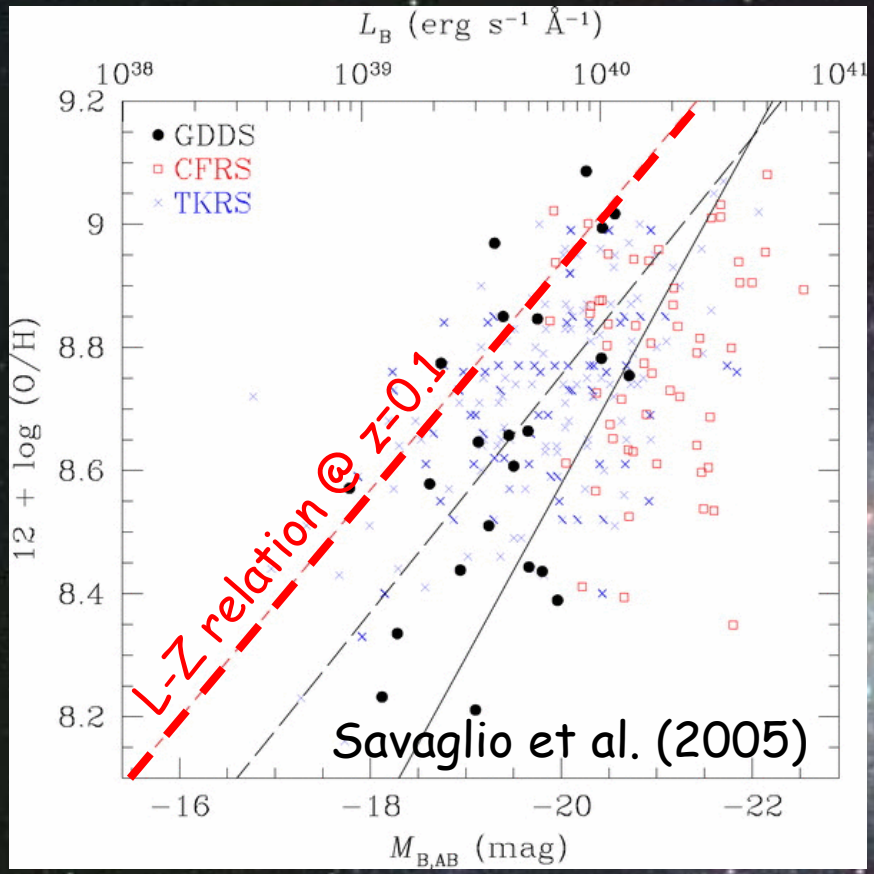


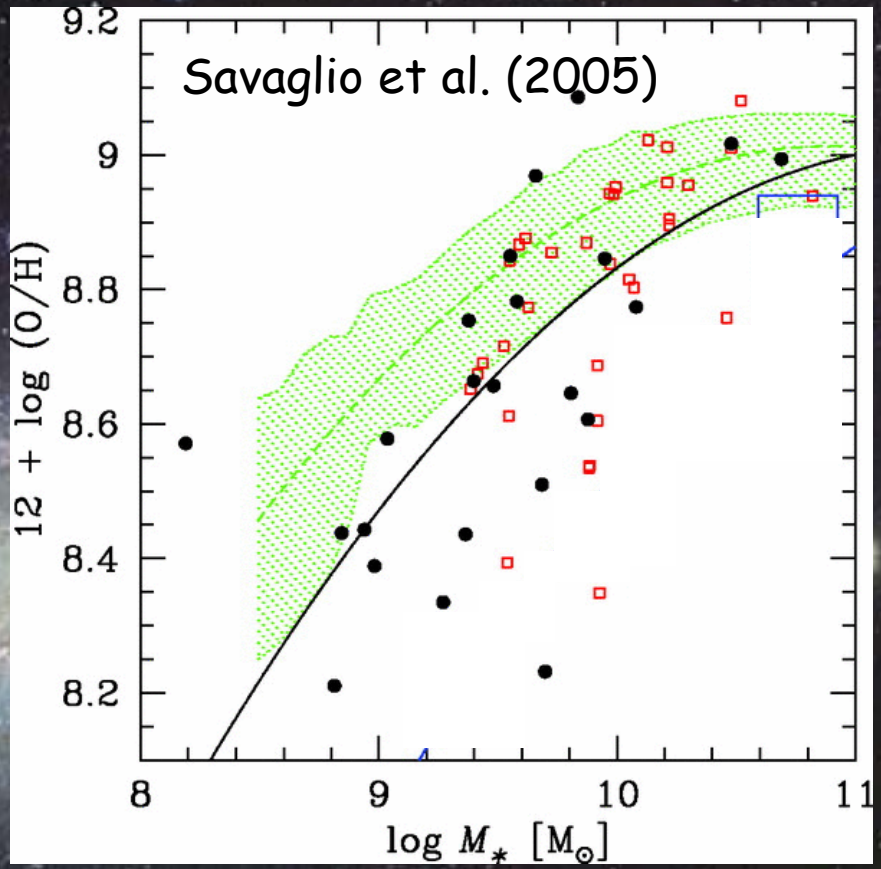
M-Z relation for
5 decades in stellar mass

Assuming "closed box":
$Z = y \ln(\mu_{gas}^{-1})$ ➔ "y_{eff}"



Metallicity of Galaxies at z=0.7

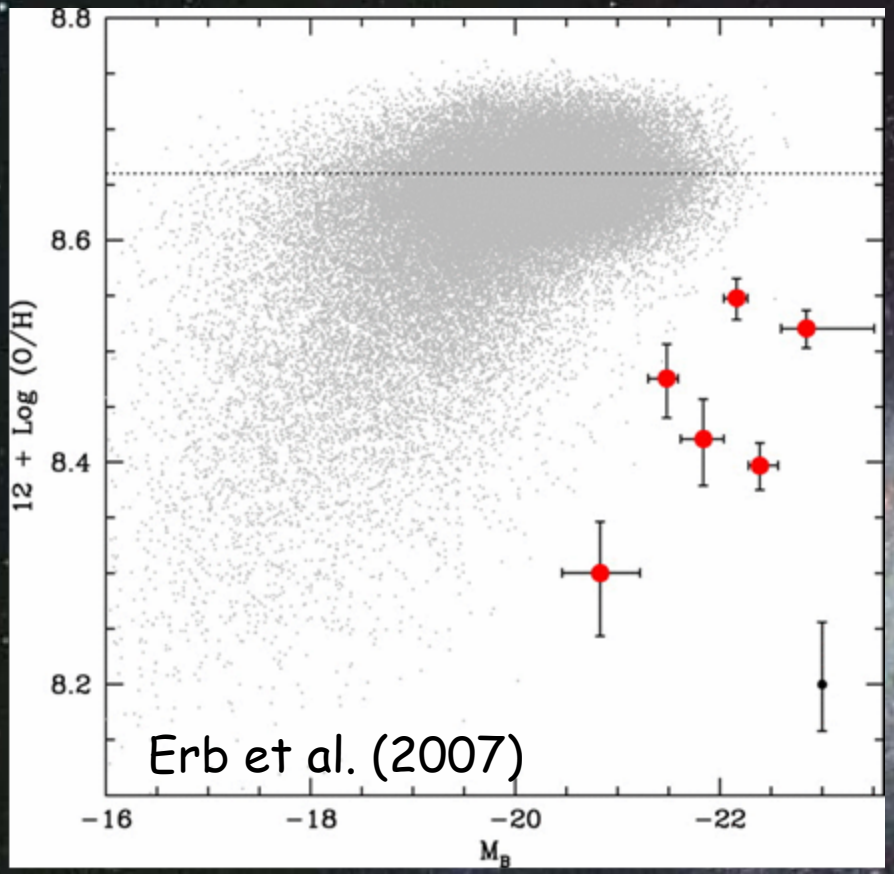


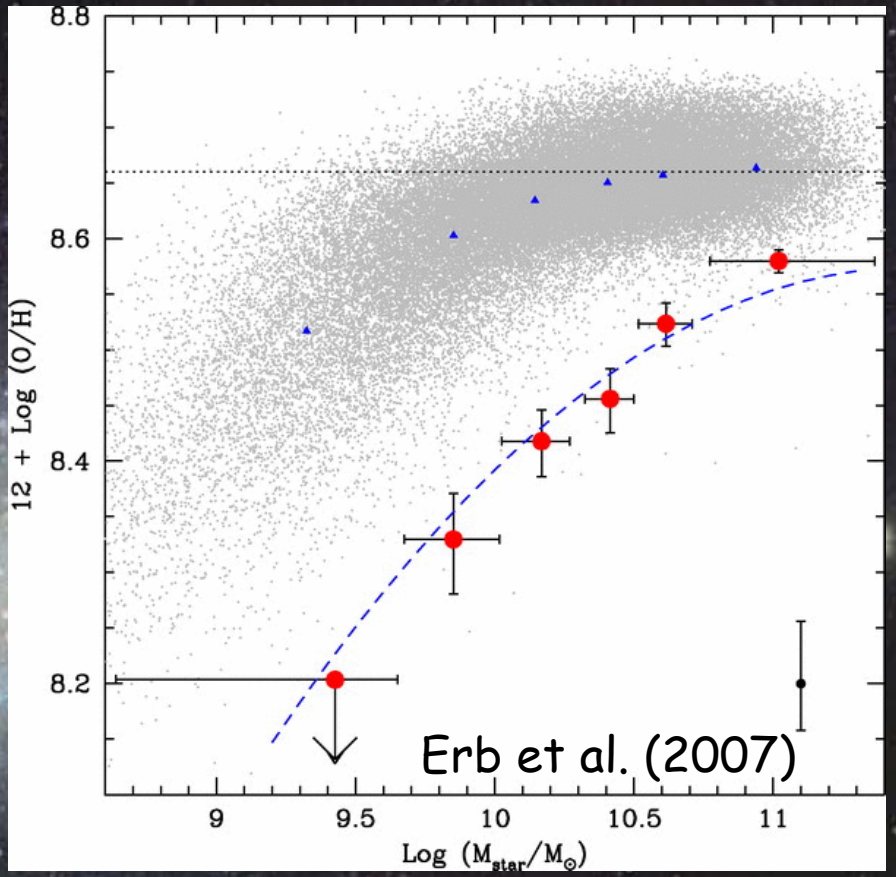


Evolving L-Z relation !!

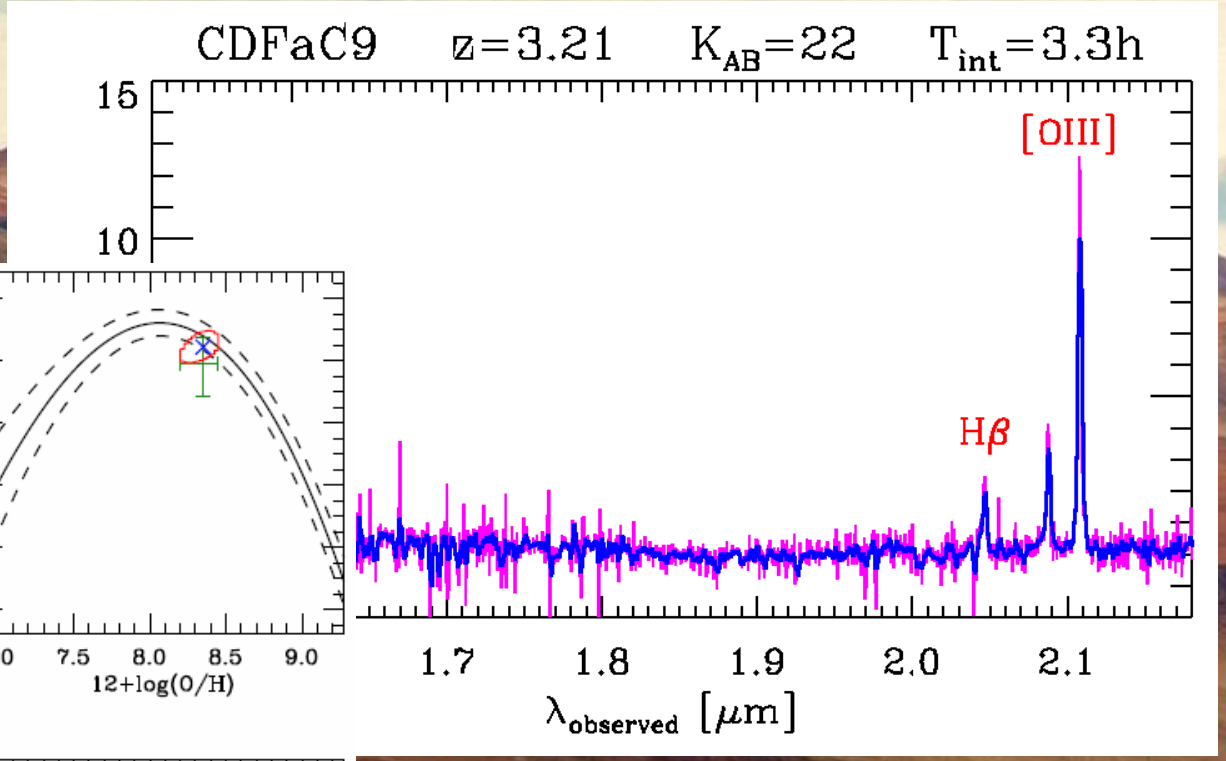
M-dependent M-Z evolution !!

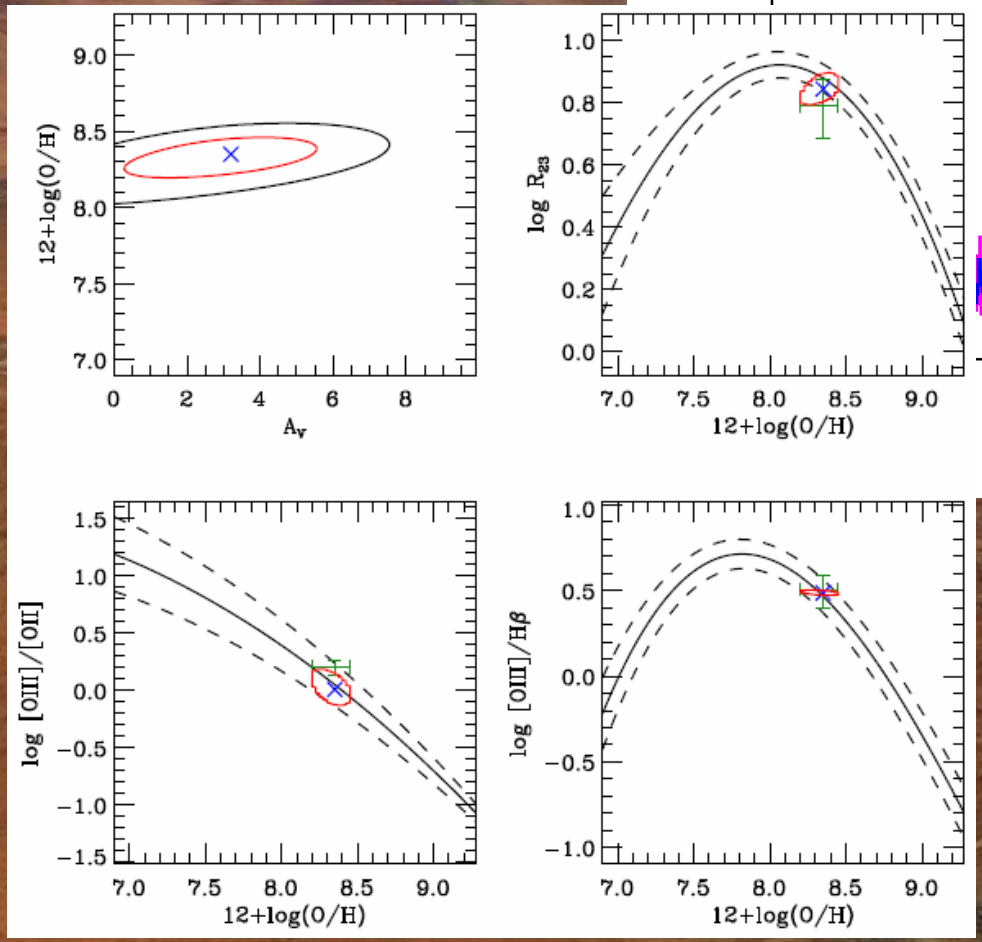
Metallicity of Galaxies at z=2





Metallicity of Galaxies at z=3

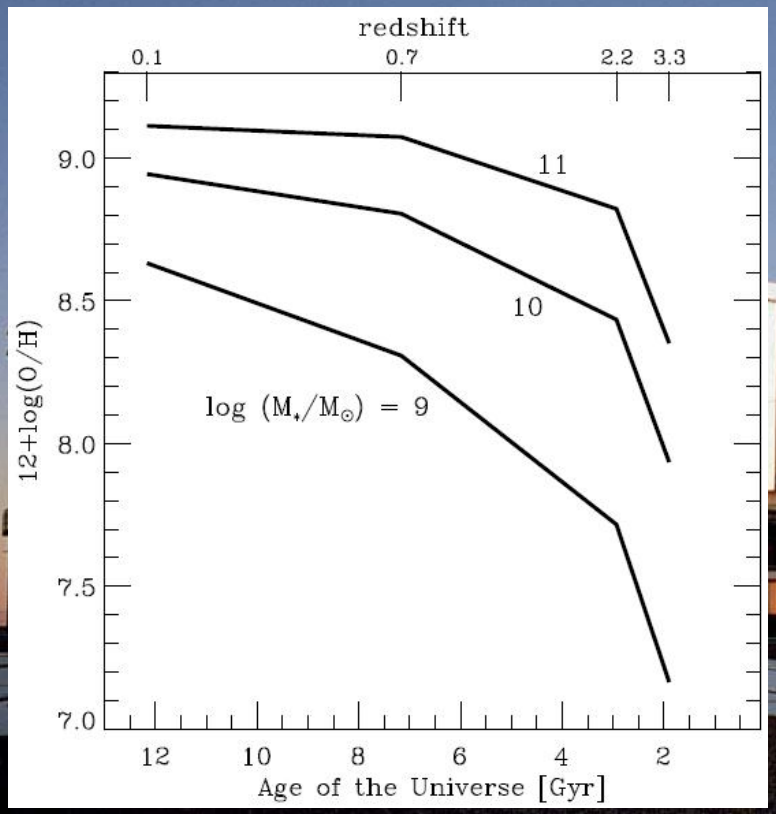


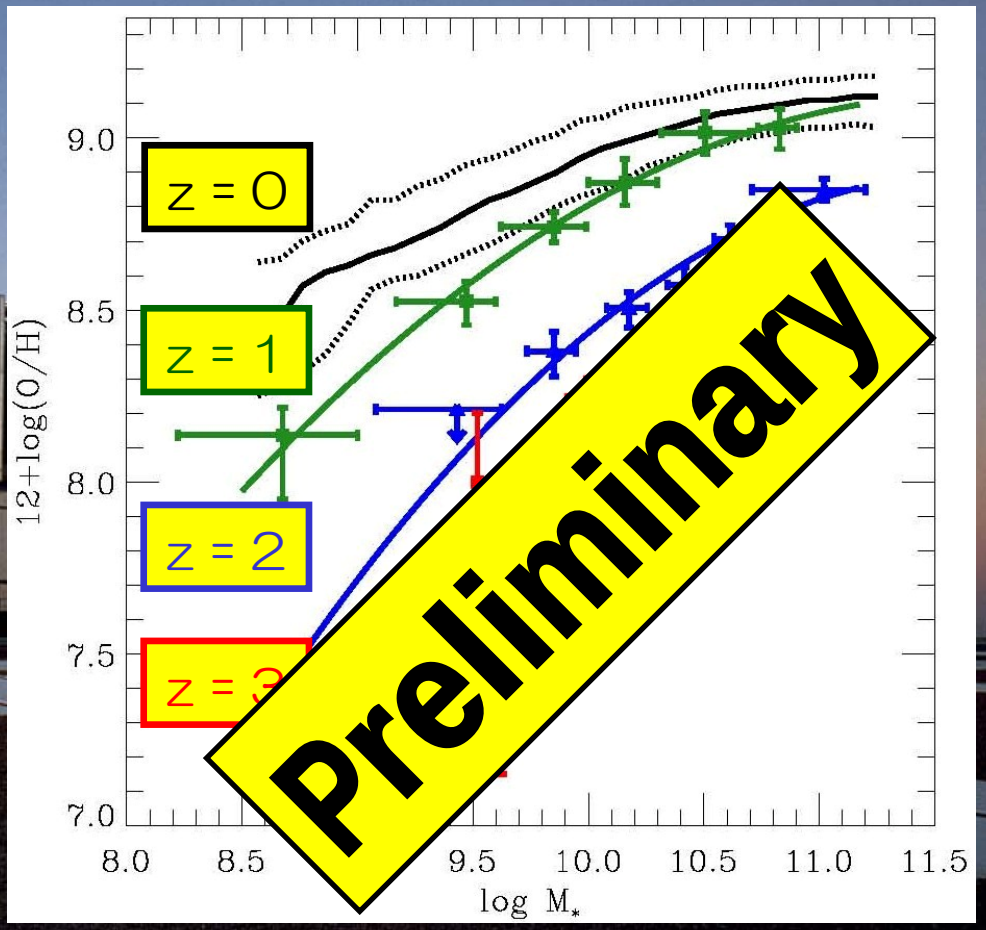


Maiolino, Nagao, et al. arXiv:0712.2880

Calibration: Nagao et al. (2006c)

M-Z Relation: Observational Result

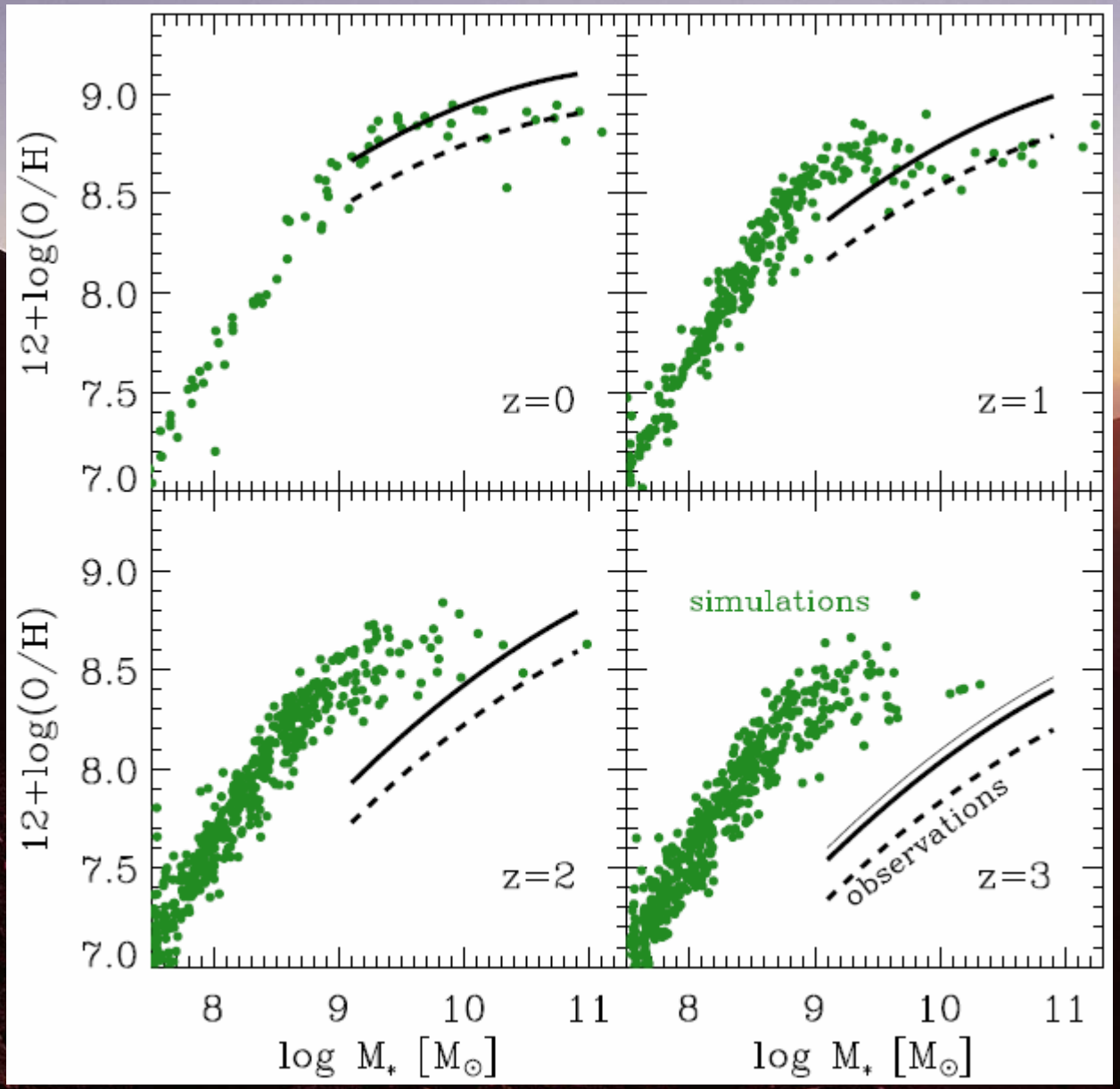




Maiolino, Nagao, et al., (2008)

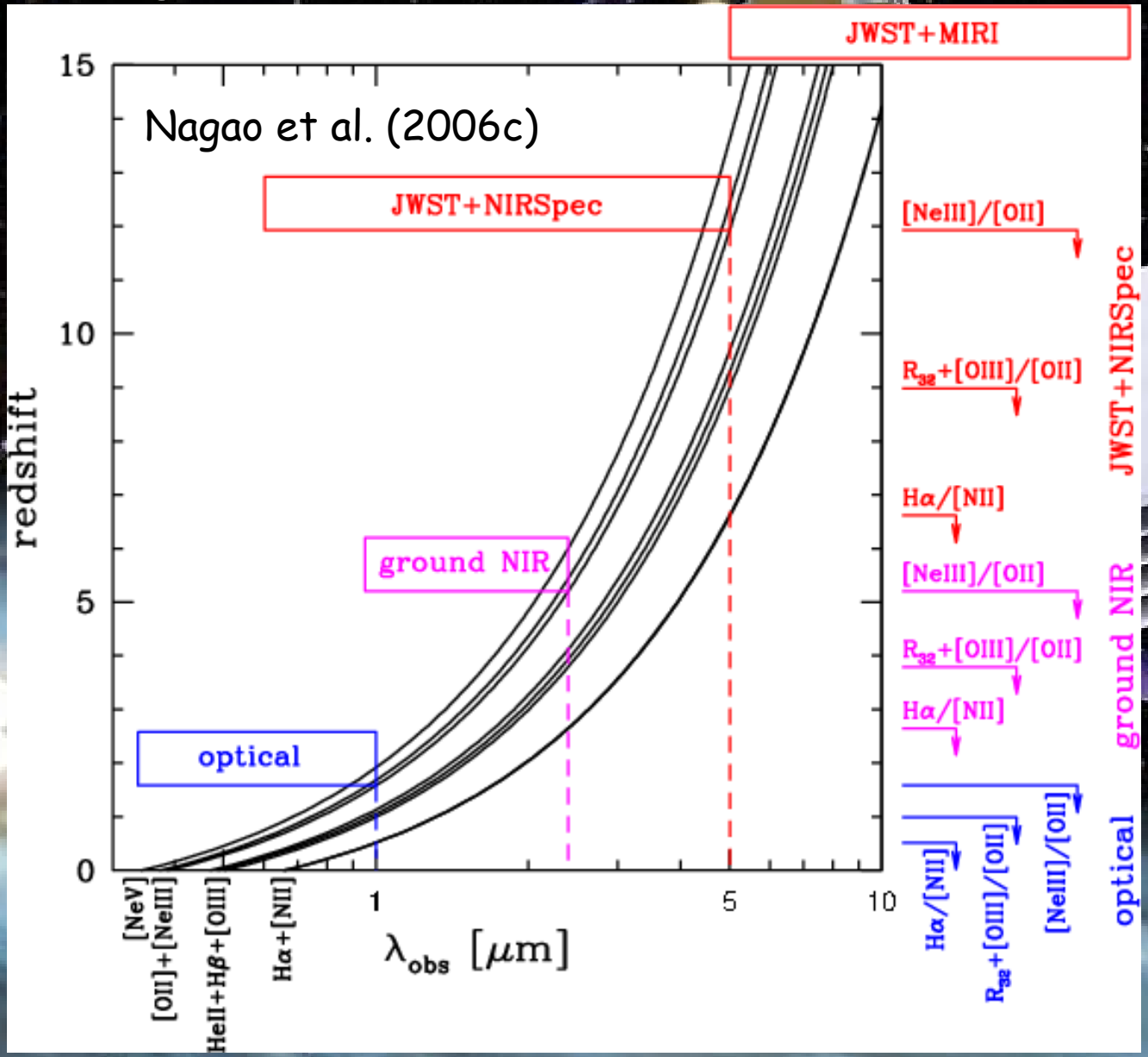
"Down-sizing chemical evolution"

M-Z Relation: Observations vs. Models

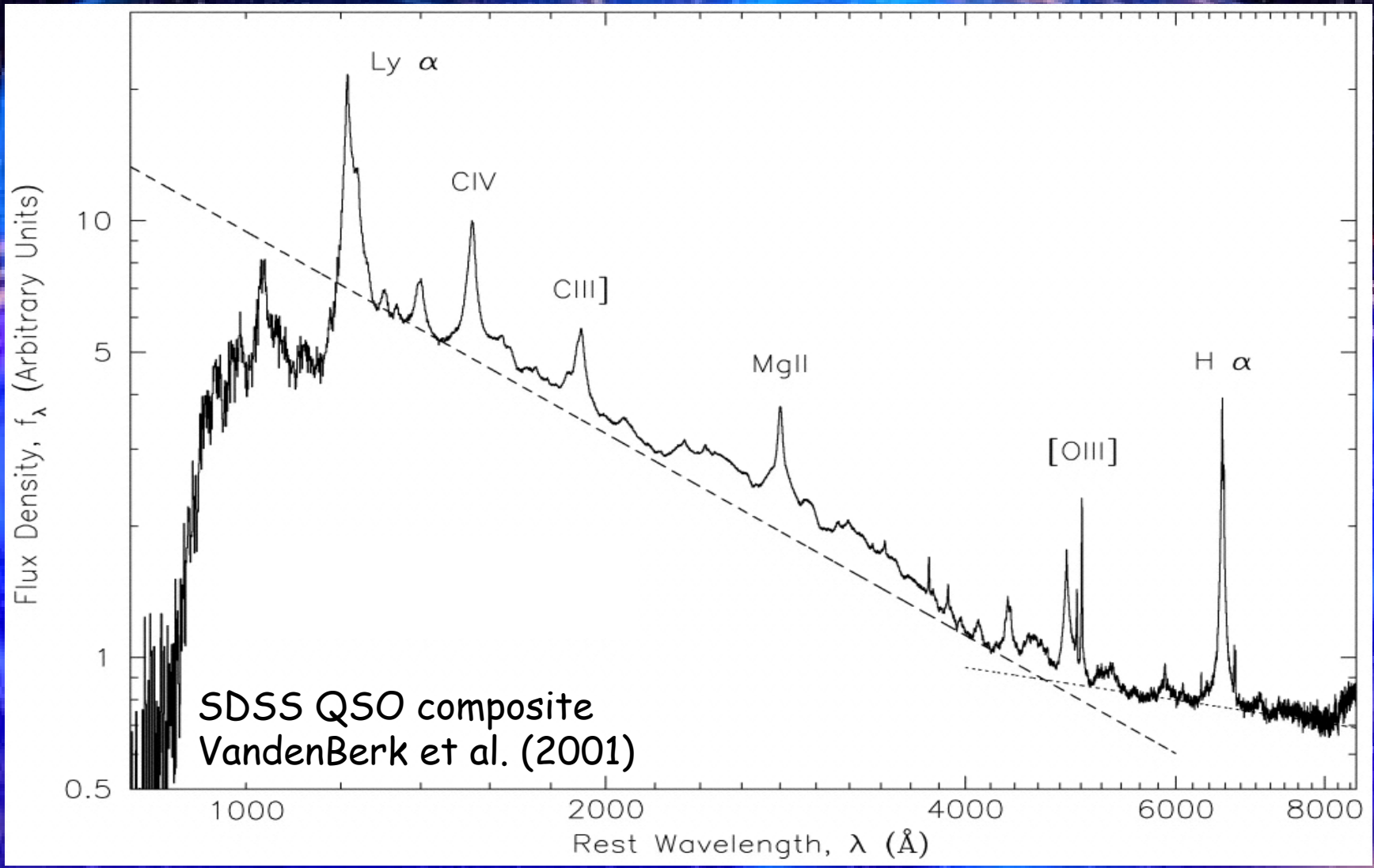


Simulation:
Kobayashi et al. 2007
Observations:
Maiolino, Nagao, et al.
arXiv:0712.2880

Metallicity of Galaxies at $z > 3$

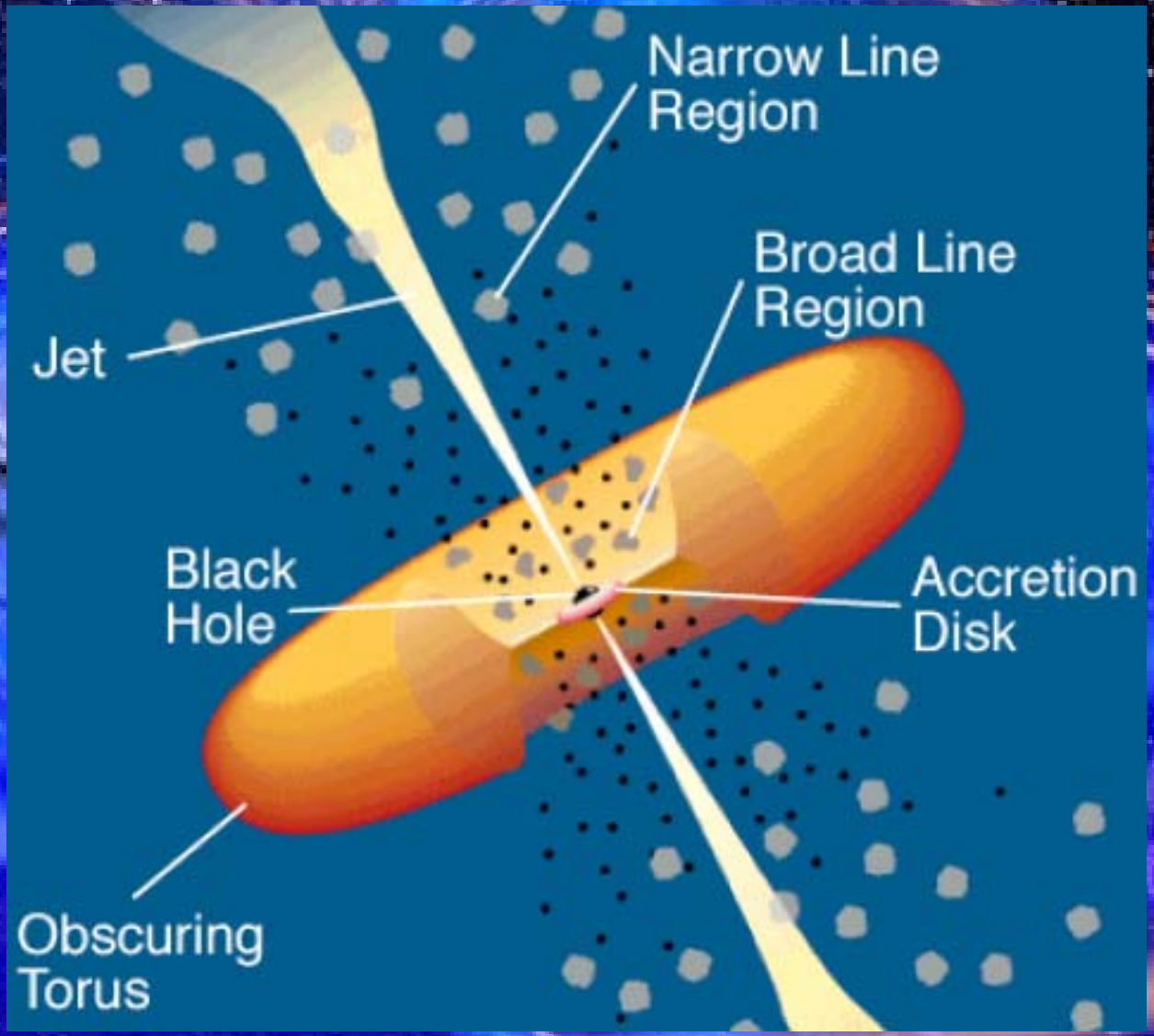


AGNs, instead of Galaxies



Very Luminous, Abundant UV Emission Lines

Ionized Regions in AGNs



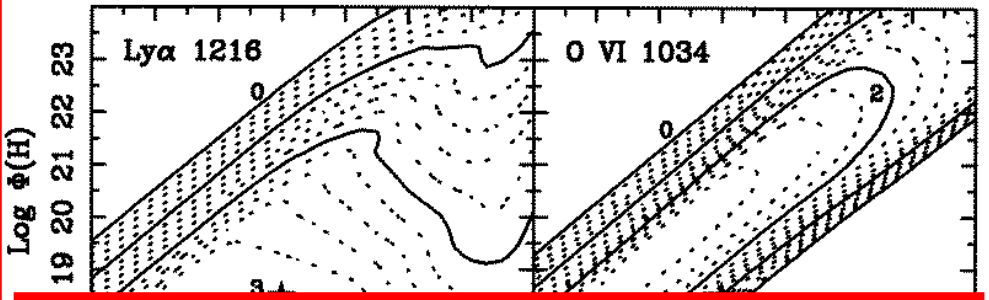
Urry & Padovani

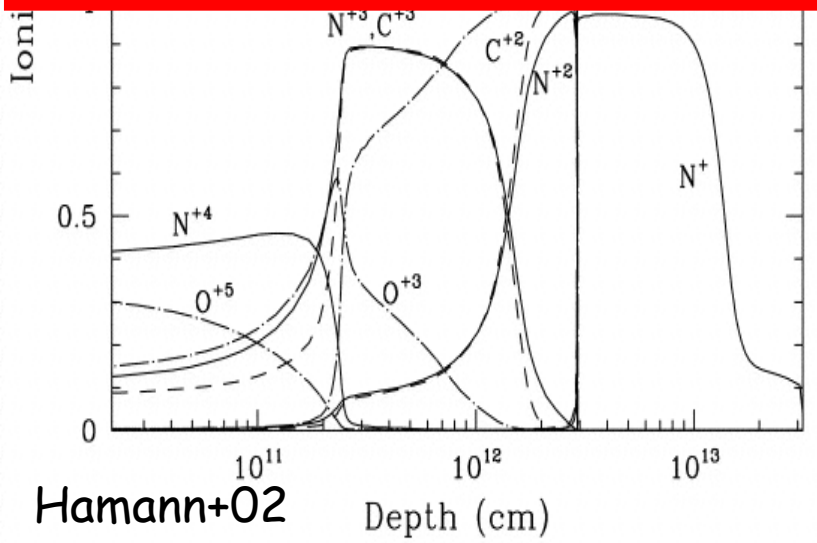
BLR Metallicity: Photoionization Model

TABLE 3

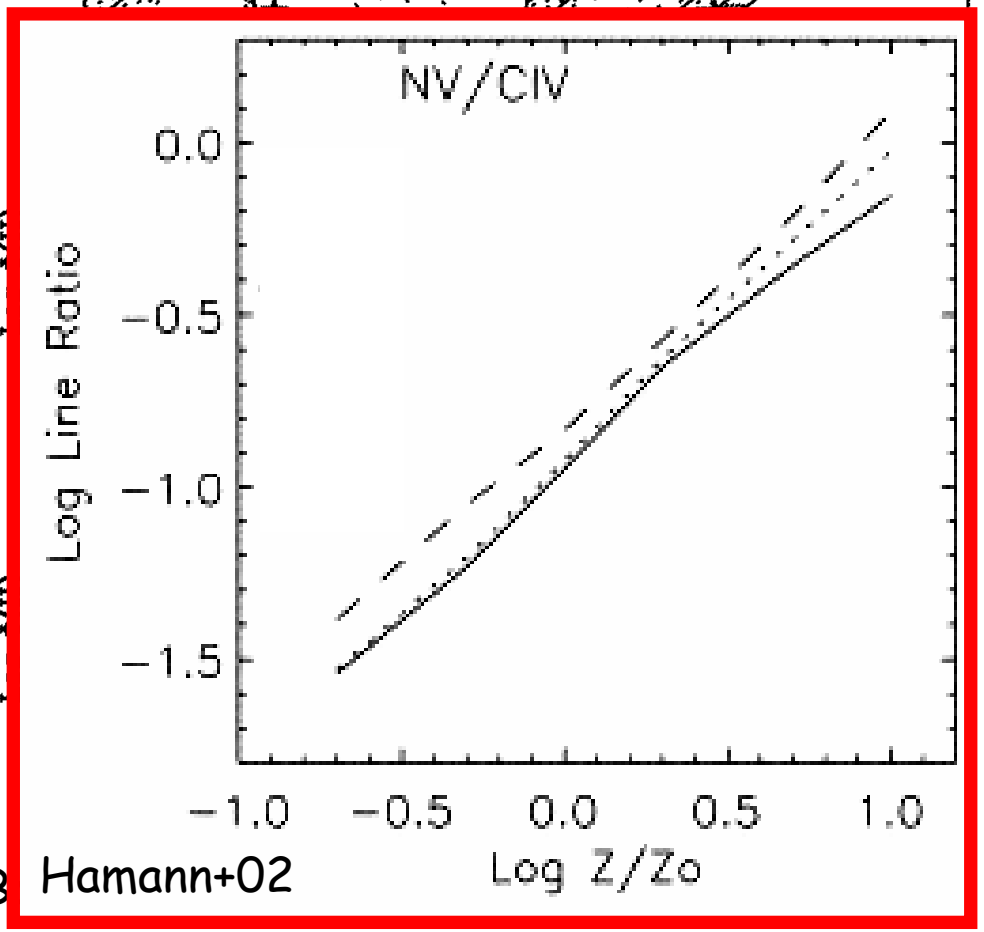
MODEL ABUNDANCES[a]

Z[b]	N/O	N	He
0.2	0.2	0.04	0.94
0.5	0.5	0.25	0.96
1.0	1.0	1.0	1.00
2.0	2.0	4.0	1.07
5.0	5.0	25.0	1.29
10.0.....	10.0	100.0	1.66



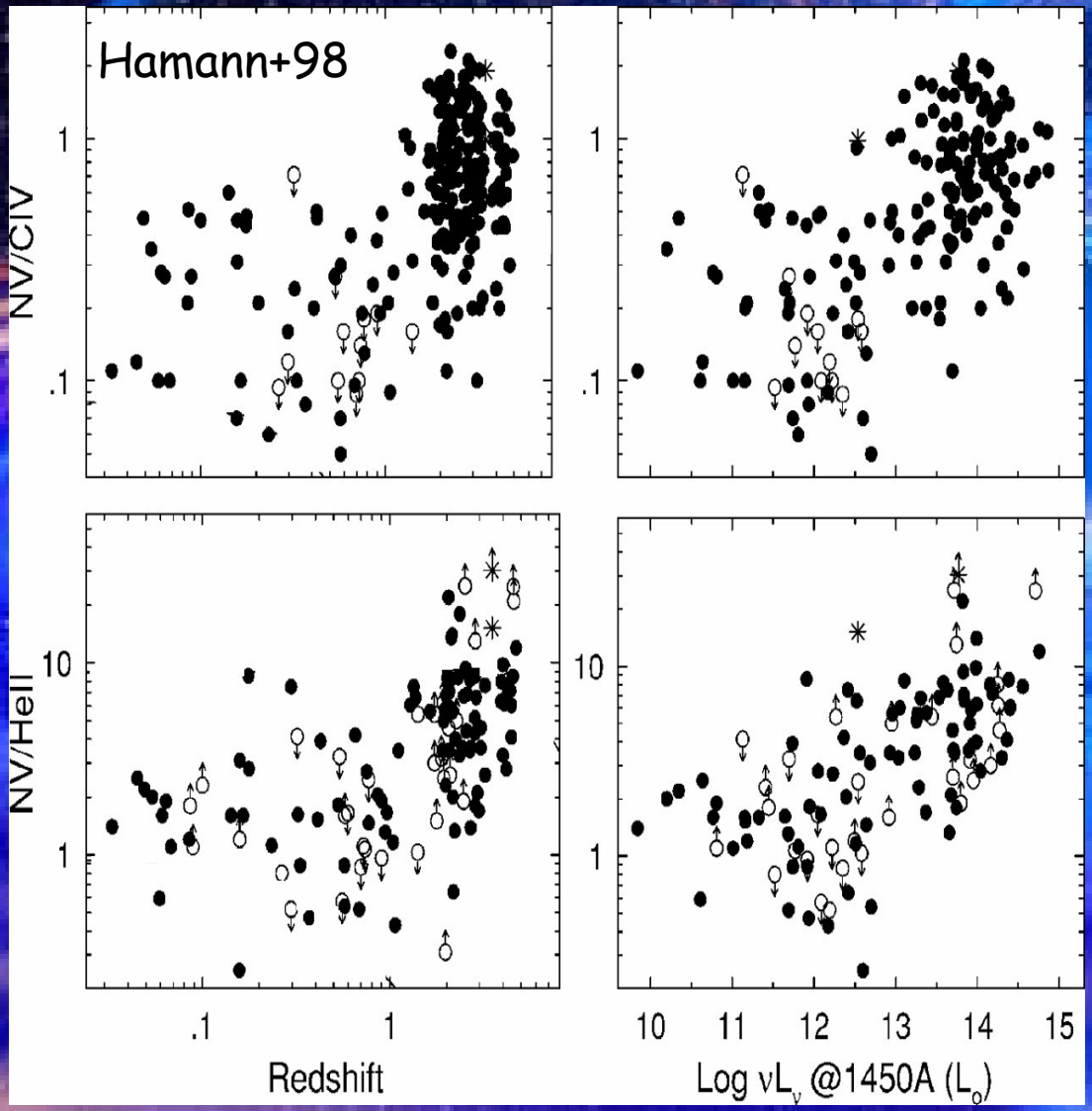


Hamann+02



Hamann+02

BLR Metallicity: Luminosity vs. Redshift

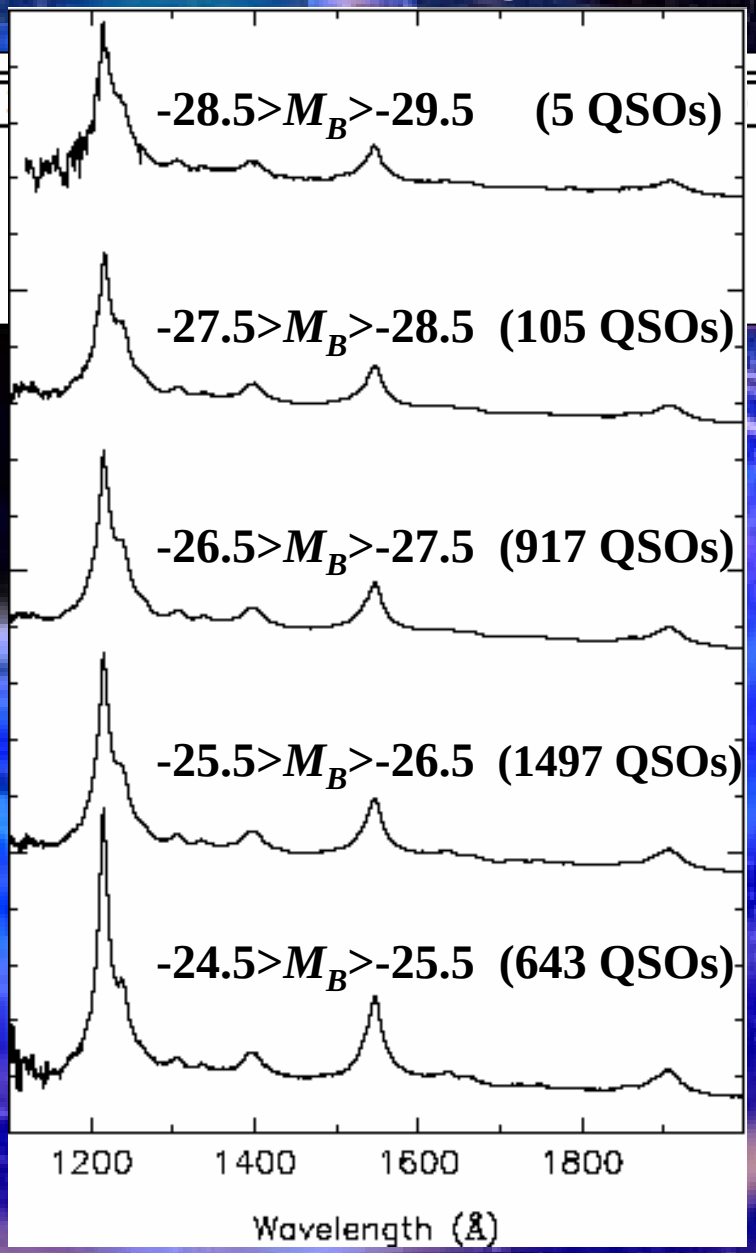


L vs. z:
which is fundamental?
"degenerated"?

BLR Metallicity: SDSS View

Nagao et al. (2006a)

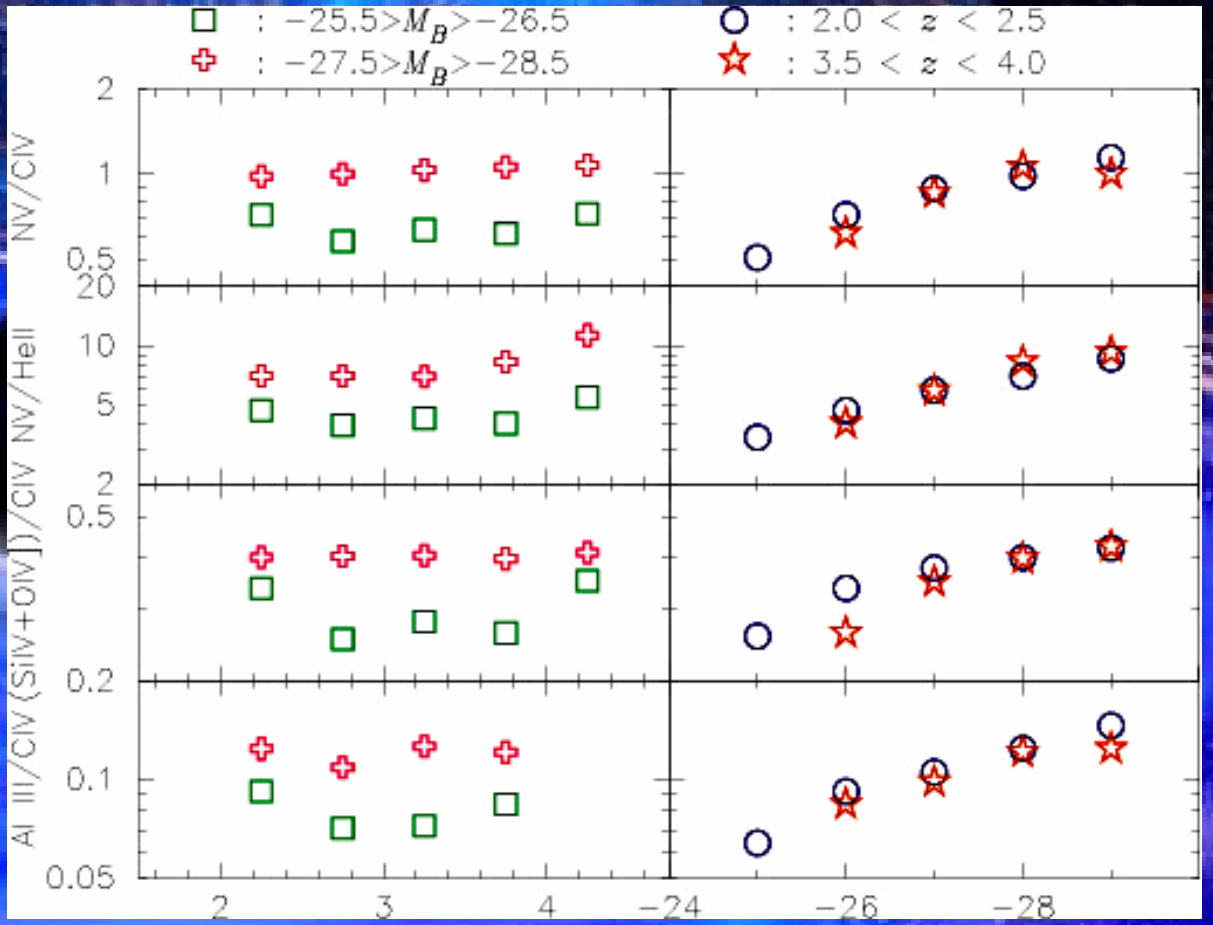
	$2.0 \leq z < 2.5$	$2.5 \leq z < 3.0$	Total
$-24.5 > M_B \geq -25.5$	643	50	694
$-25.5 > M_B \geq -26.5$	1497	284	2291
$-26.5 > M_B \geq -27.5$	917	385	1967
$-27.5 > M_B \geq -28.5$	105	71	350
$-28.5 > M_B \geq -29.5$	5	11	40



"Stacking Analysis"

BLR Metallicity: 2 < z < 4

Nagao et al. (2006a)



Redshift

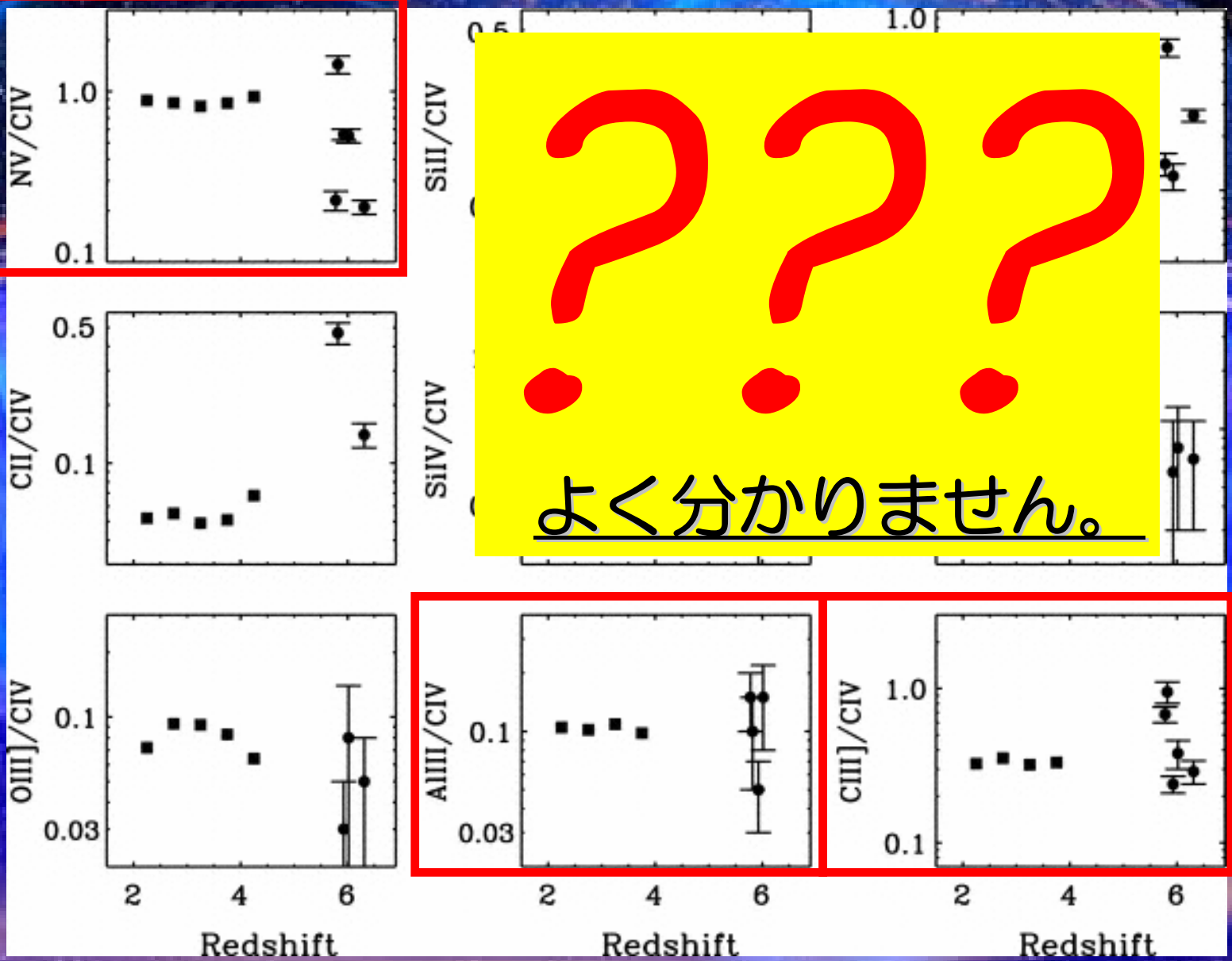
Luminosity

Tight M-Z_{BLR} rel.

No evolution up to z~4.5

BLR Metallicity: 4 < z < 6

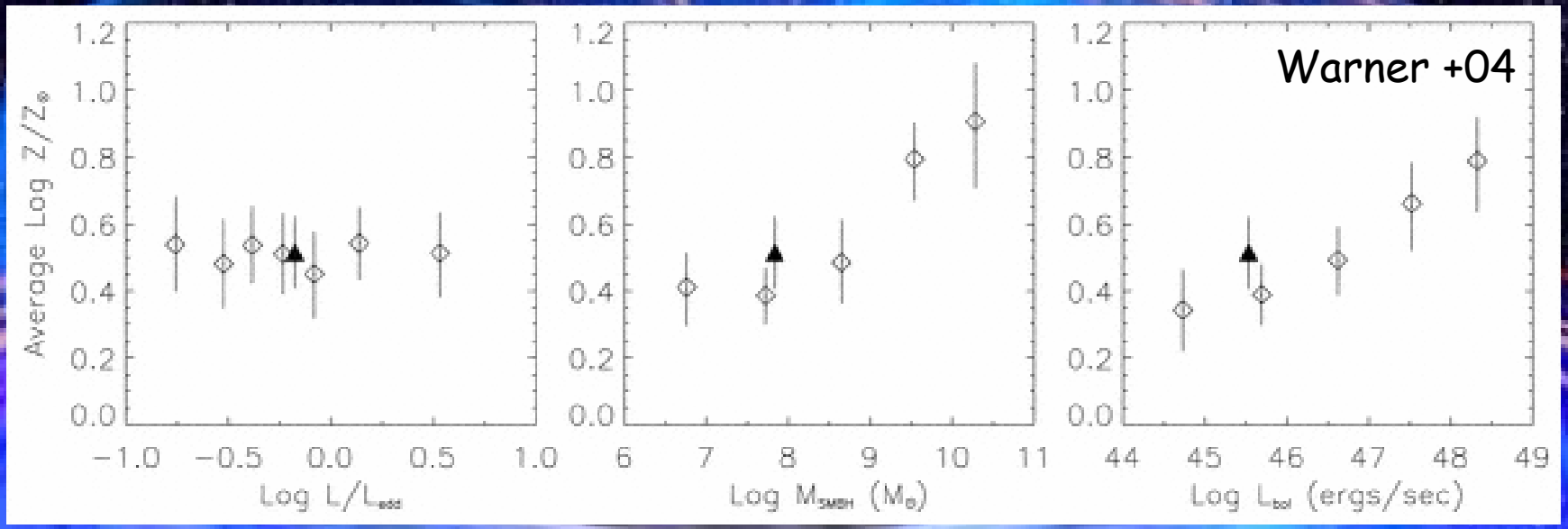
Jiang et al. (2007)

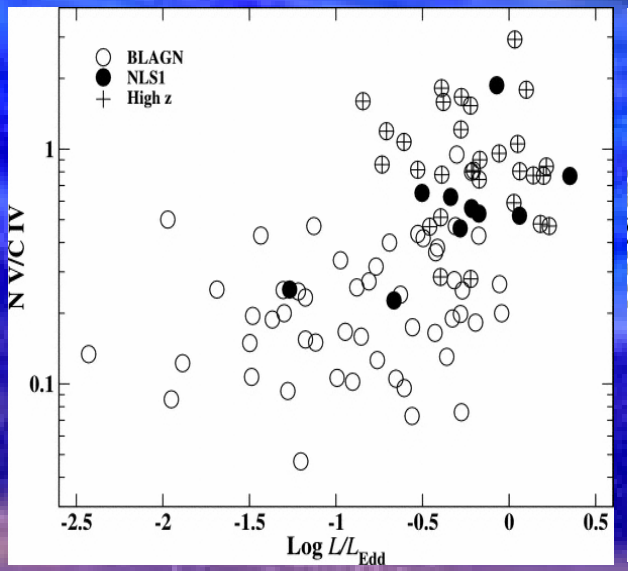


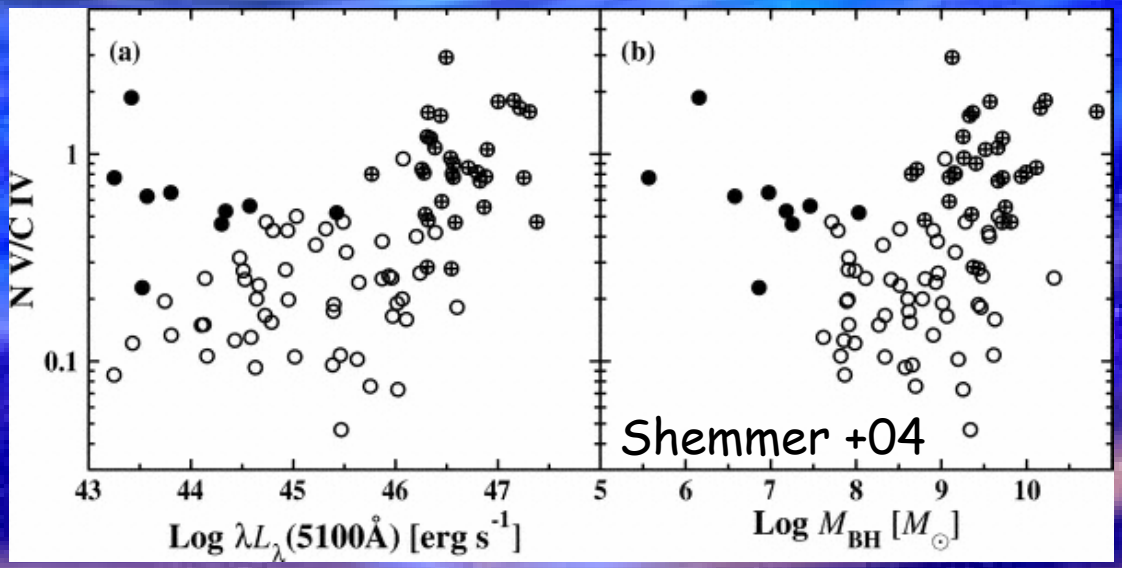
???

よく分かりません。

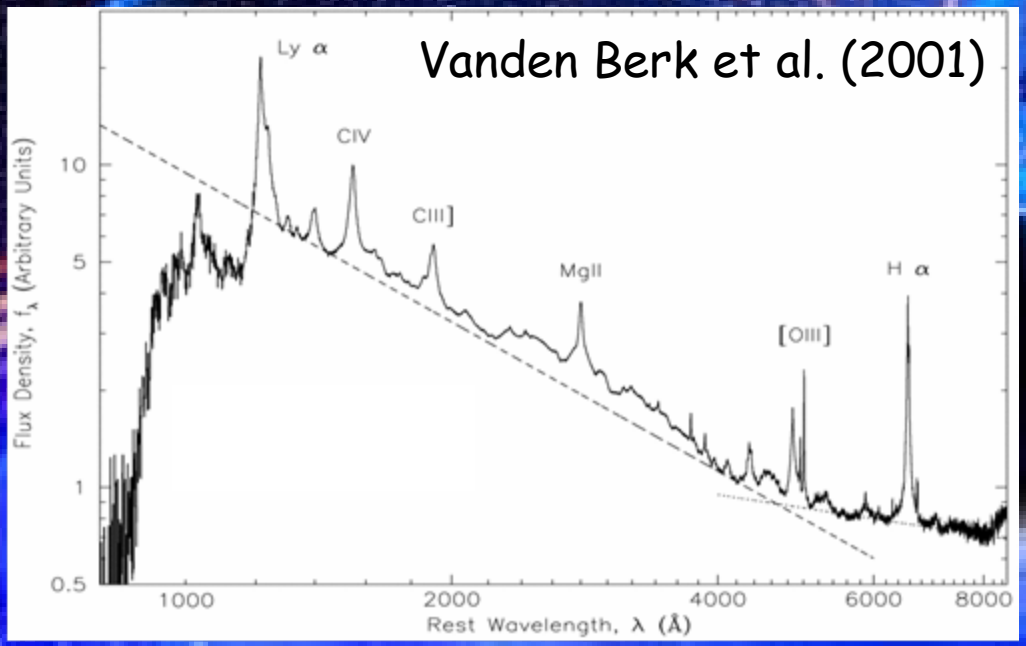
BLR Metallicity: Luminosity vs. M_{BH}

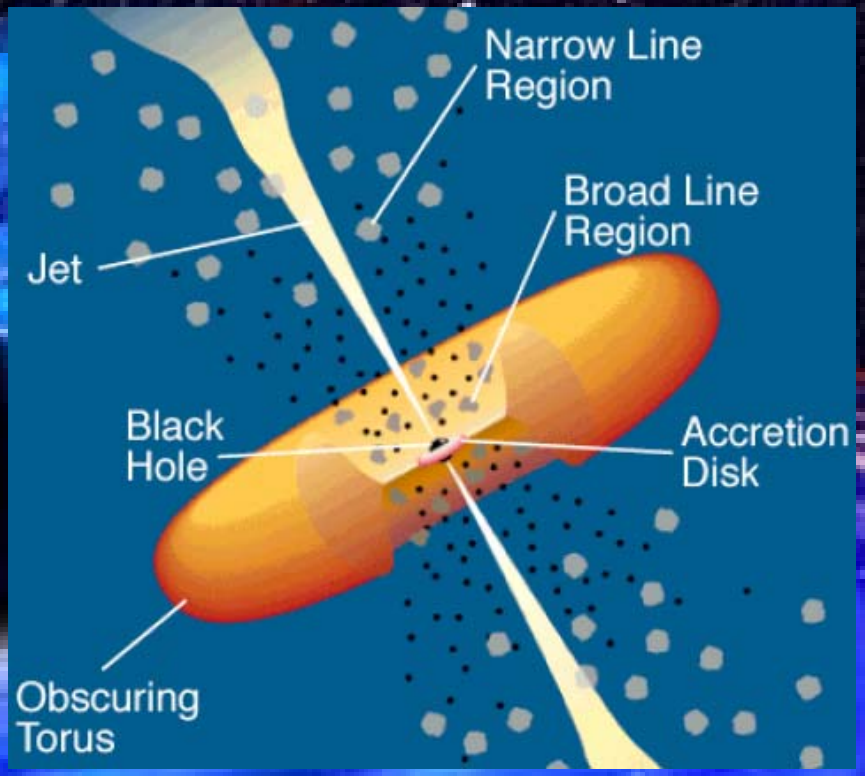






NLRs, instead of BLRs





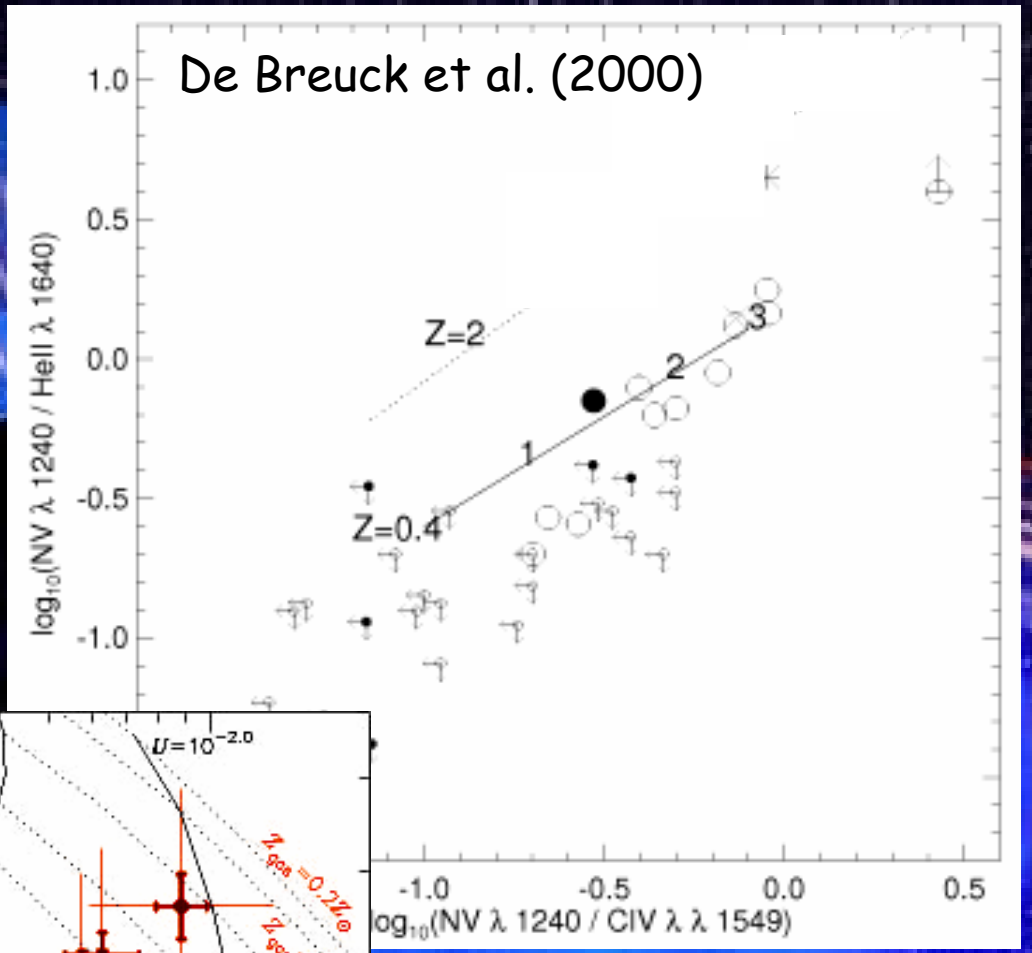
Focusing on type-2 AGNs

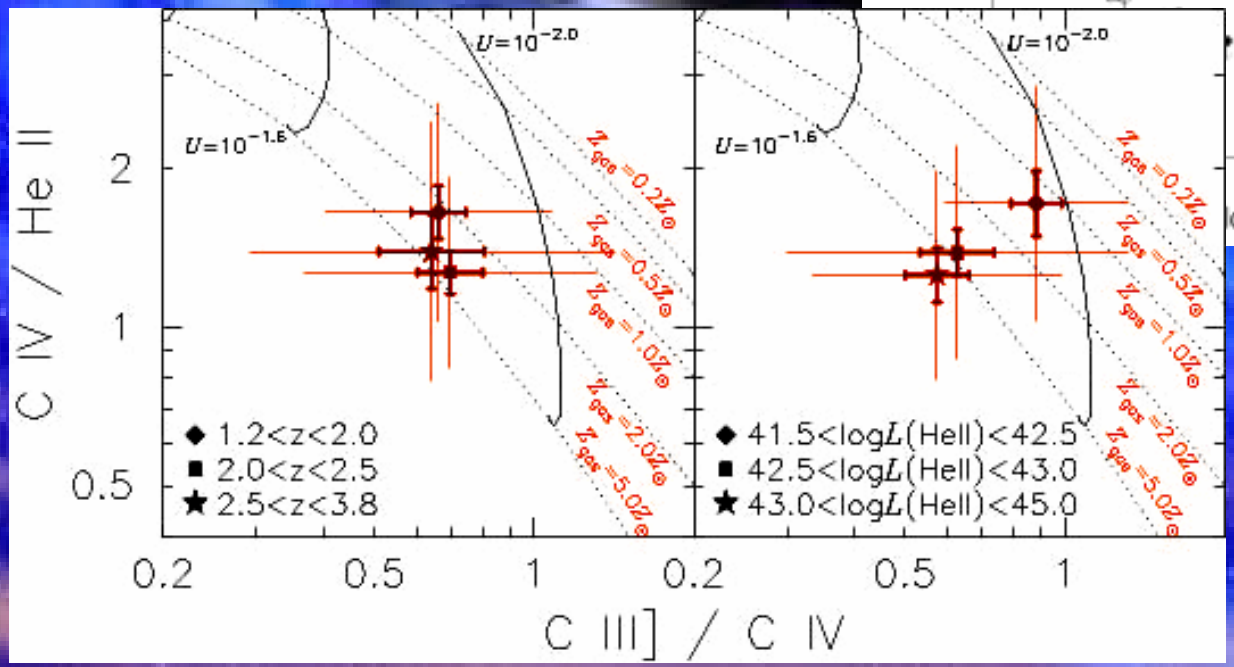
~ only very few type-2 quasars in high-z universe…

➔ Metallicity studies on "Narrow-Line Radio Galaxies"

NLR Metallicity

No redshift evolution
Luminosity dependence
Consistent to Z_{BLR}



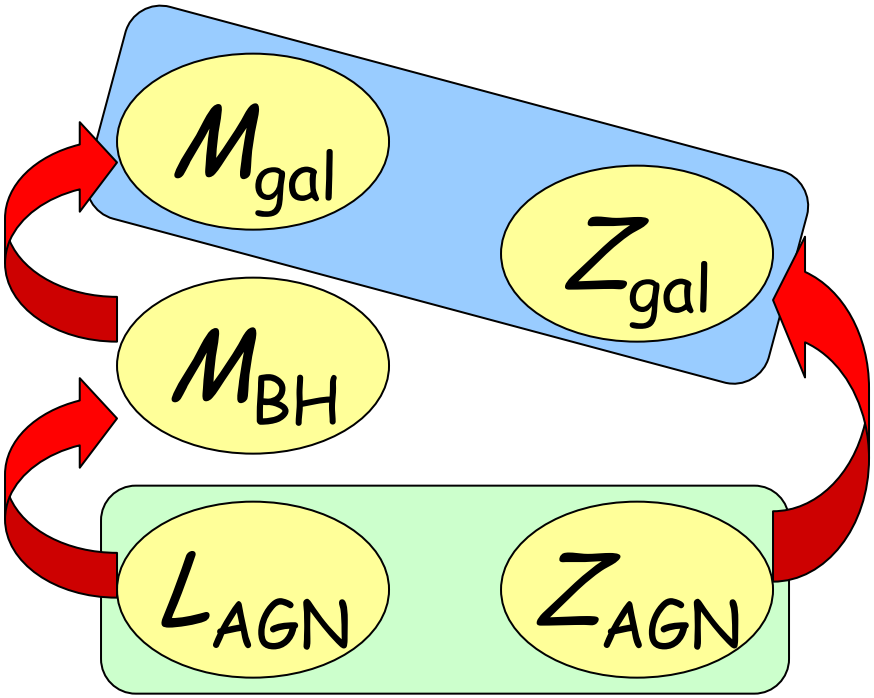


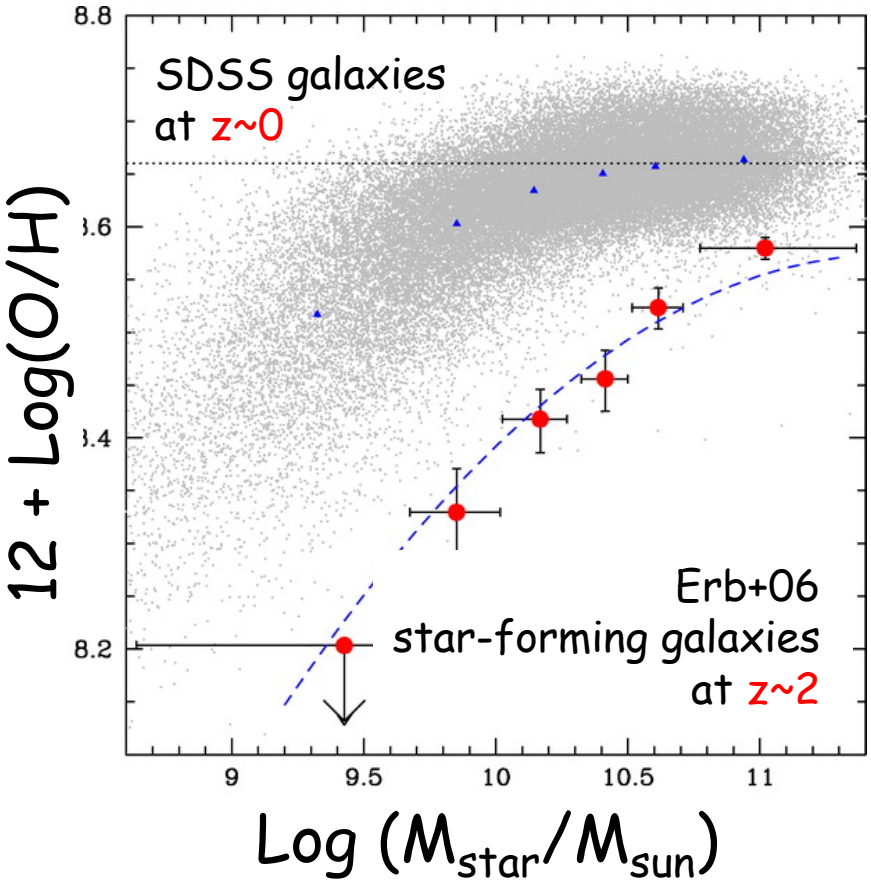
Nagao et al. (2006b)

Galaxies vs. AGNs

- L-Z Relation in AGNs
- Seen in both BLRs and NLRs
- No Redshift Evolution

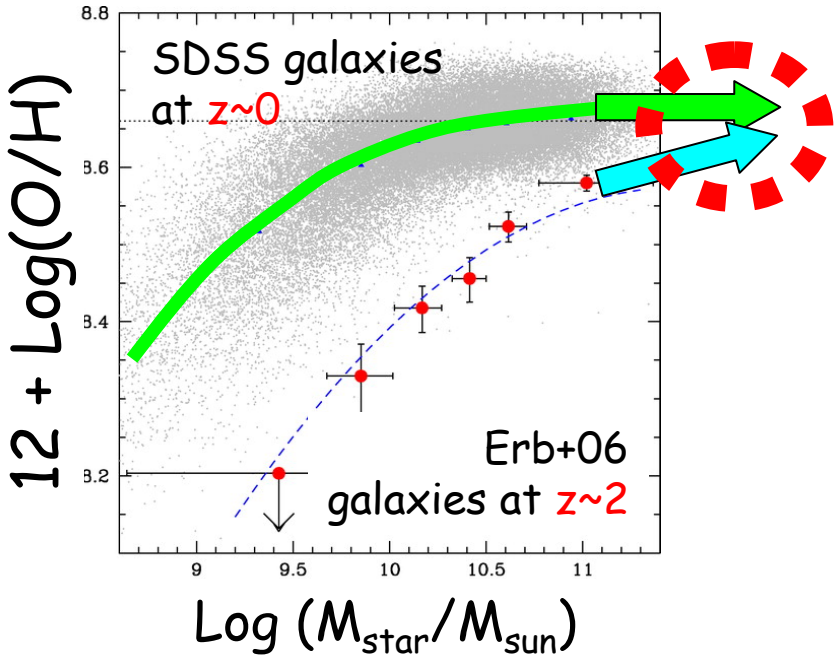
But, in (non-AGN) galaxies…
Clear Evol. in M-Z relation.

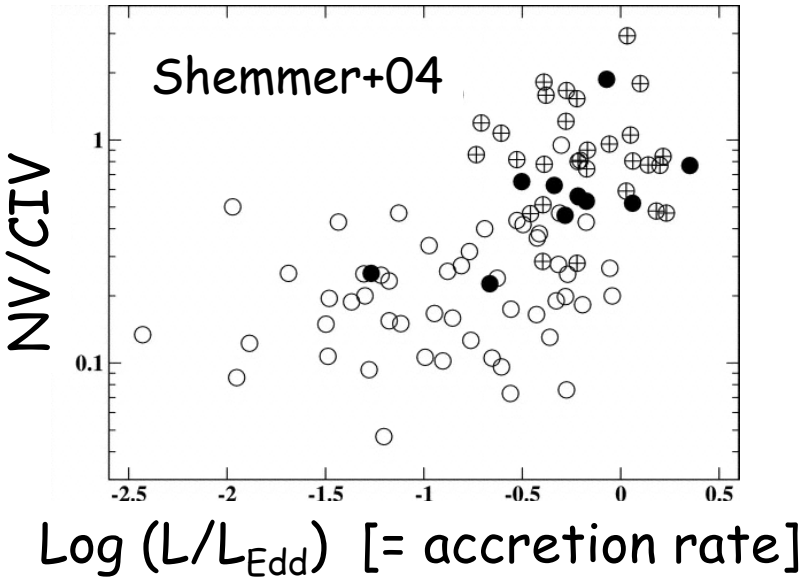




…inconsistent situation?

Galaxies vs. AGNs (cont.)





Interpretation (1)

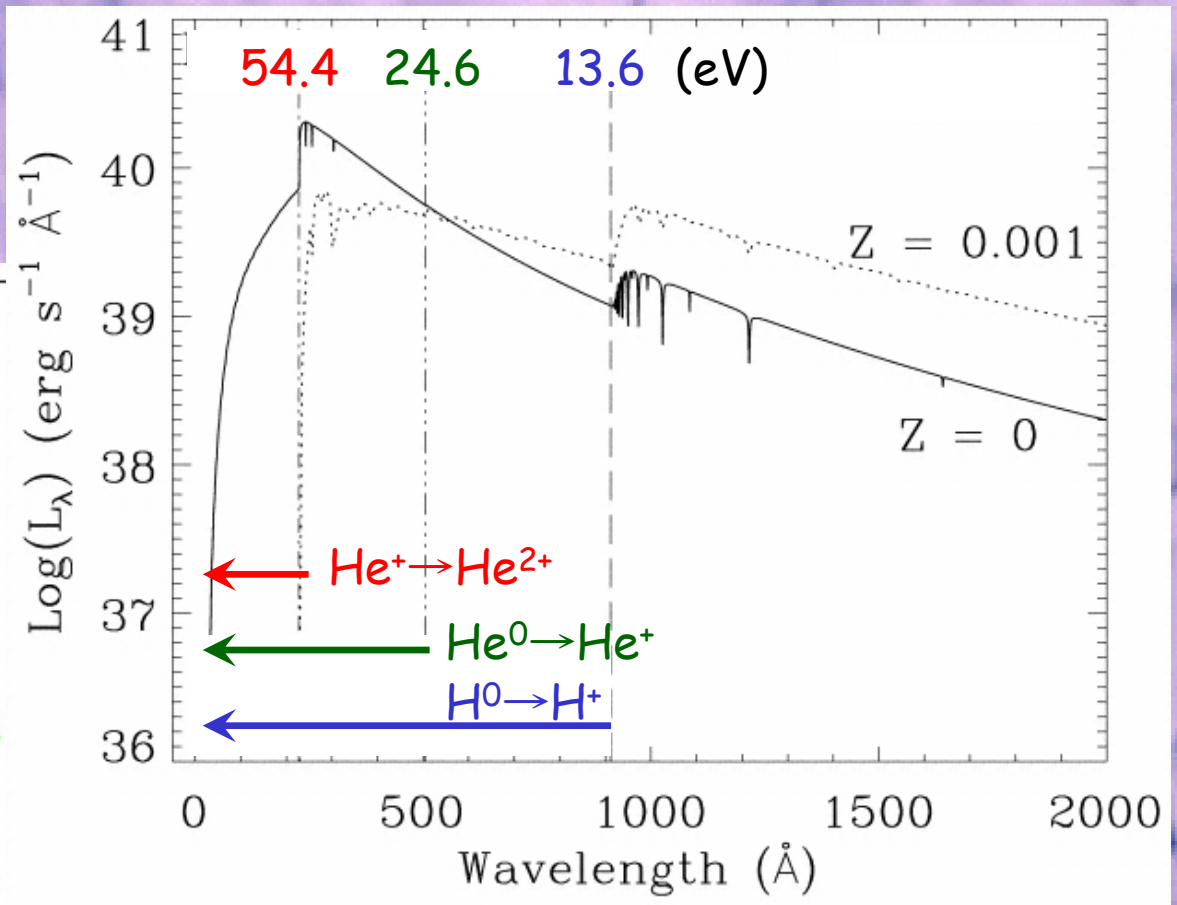
- Downsizing chemical evolution.
- Massive galaxies completed their evolution in higher redshift.
- High-z AGNs are associated in most massive galaxies.
- AGNs completed their evolution at z>4 (no evolution at z<4)…
- [cf. K-z relation of radio galaxies]

Interpretation (2)

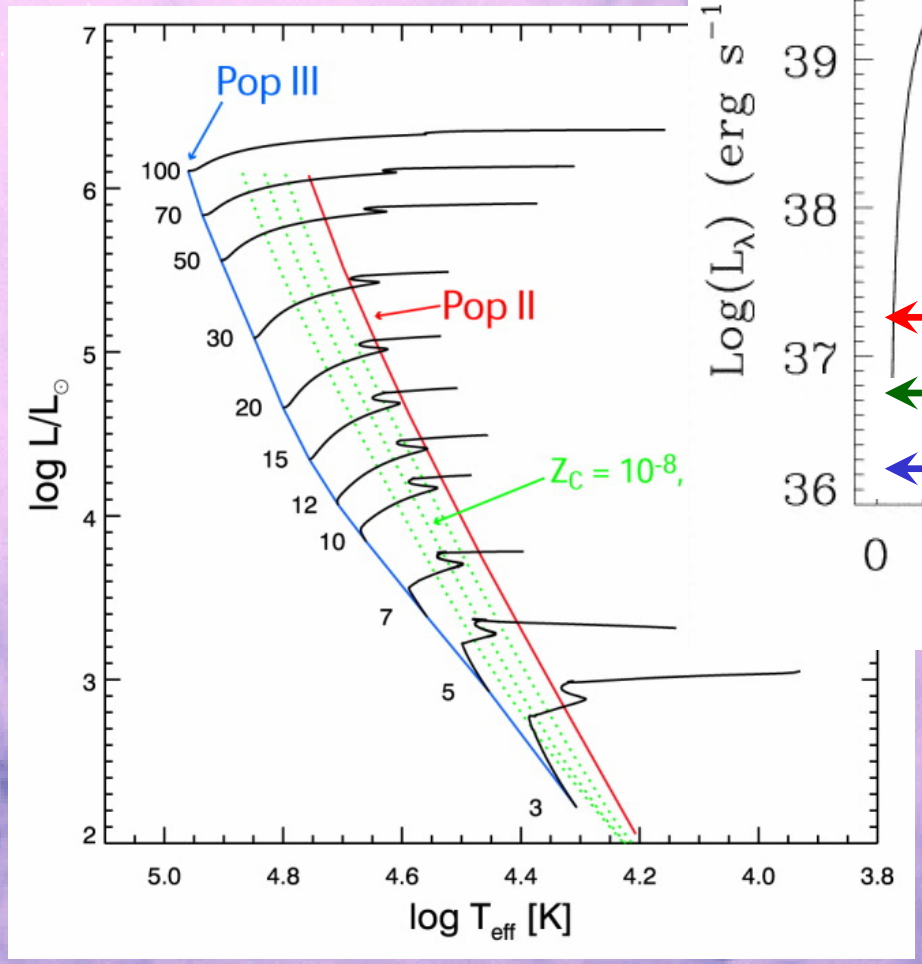
- AGN luminosity is determined by M_{BH} and accretion rate (L/L_{Edd}).
- L/L_{Edd} may be essential for Z.
- M_{BH} may be not important for Z.
- AGN L-Z relation and galaxy M-Z relation may be independent…

Toward Zero-Metallicity: PopIII

Tumlinson & Shull (2001)



Tumlinson et al. (2003)

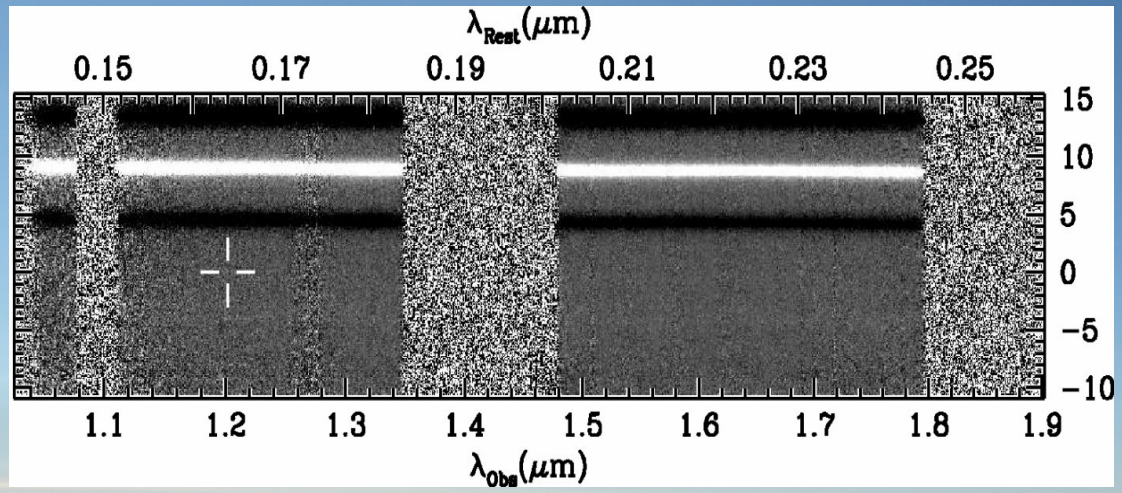


Pop III:
extremely strong Ly α
& moderate He II line

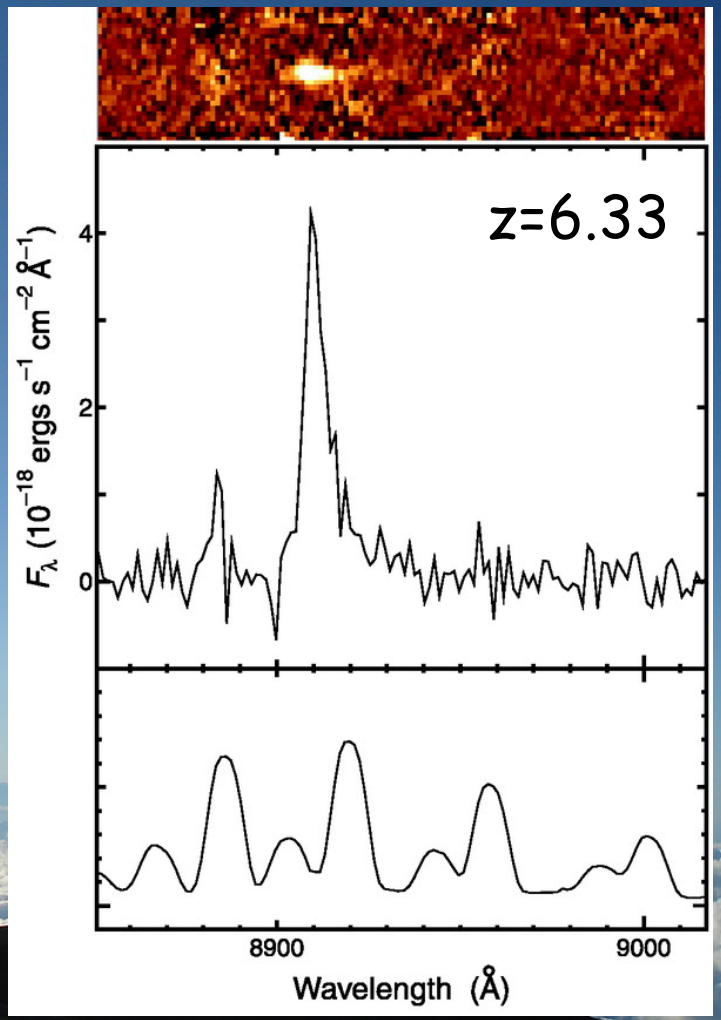
Yoshida et al. (2003)

Searching PopIII Galaxies

Nagao et al. (2005b)



Nagao et al. (2004)

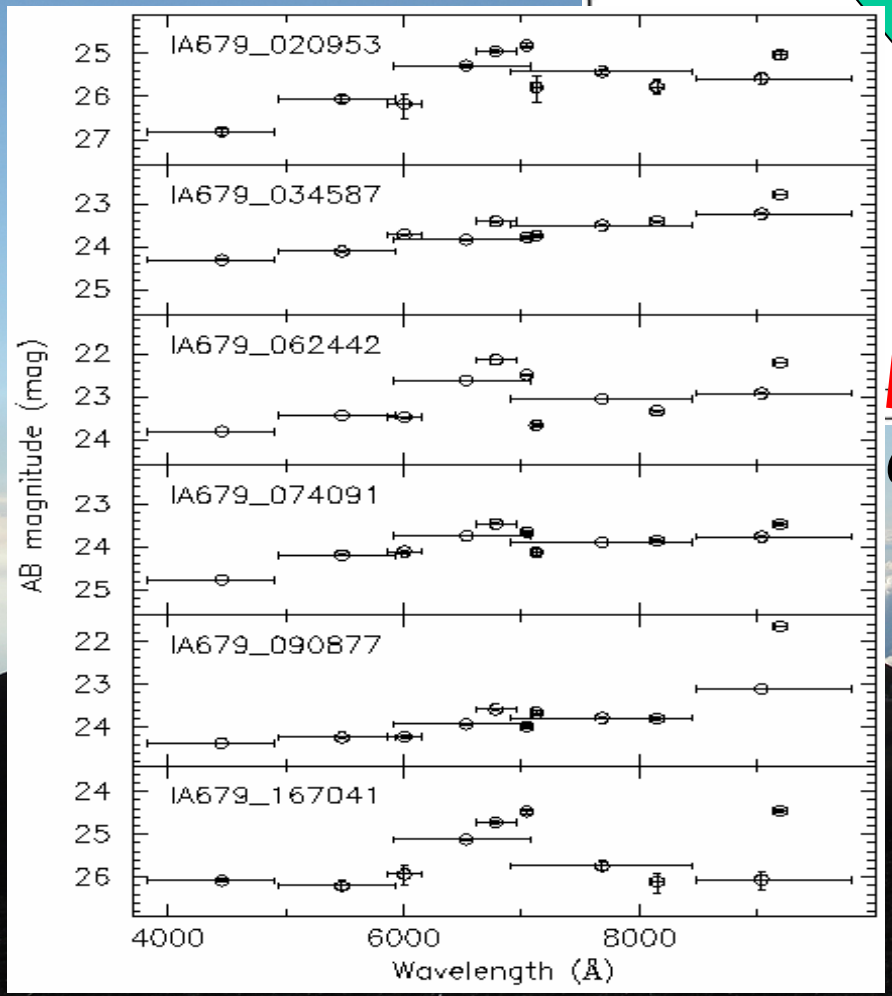


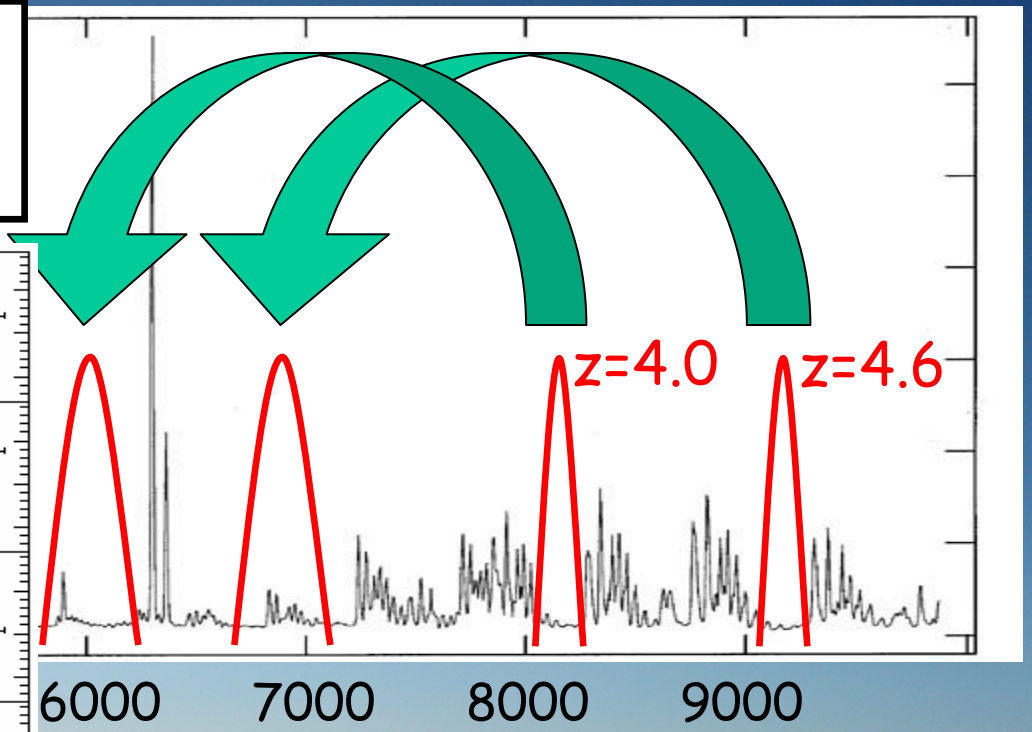
(°Д°;;

SDF i-drop with huge EW Lyα:
see also Nagao et al. (2005a, 2007)

Searching PopIII Galaxies (cont.)

Deep NB816/921 data in SDF
~ HeII emitters @z=4.0/z=4.6?
~ They should show Lyα also…

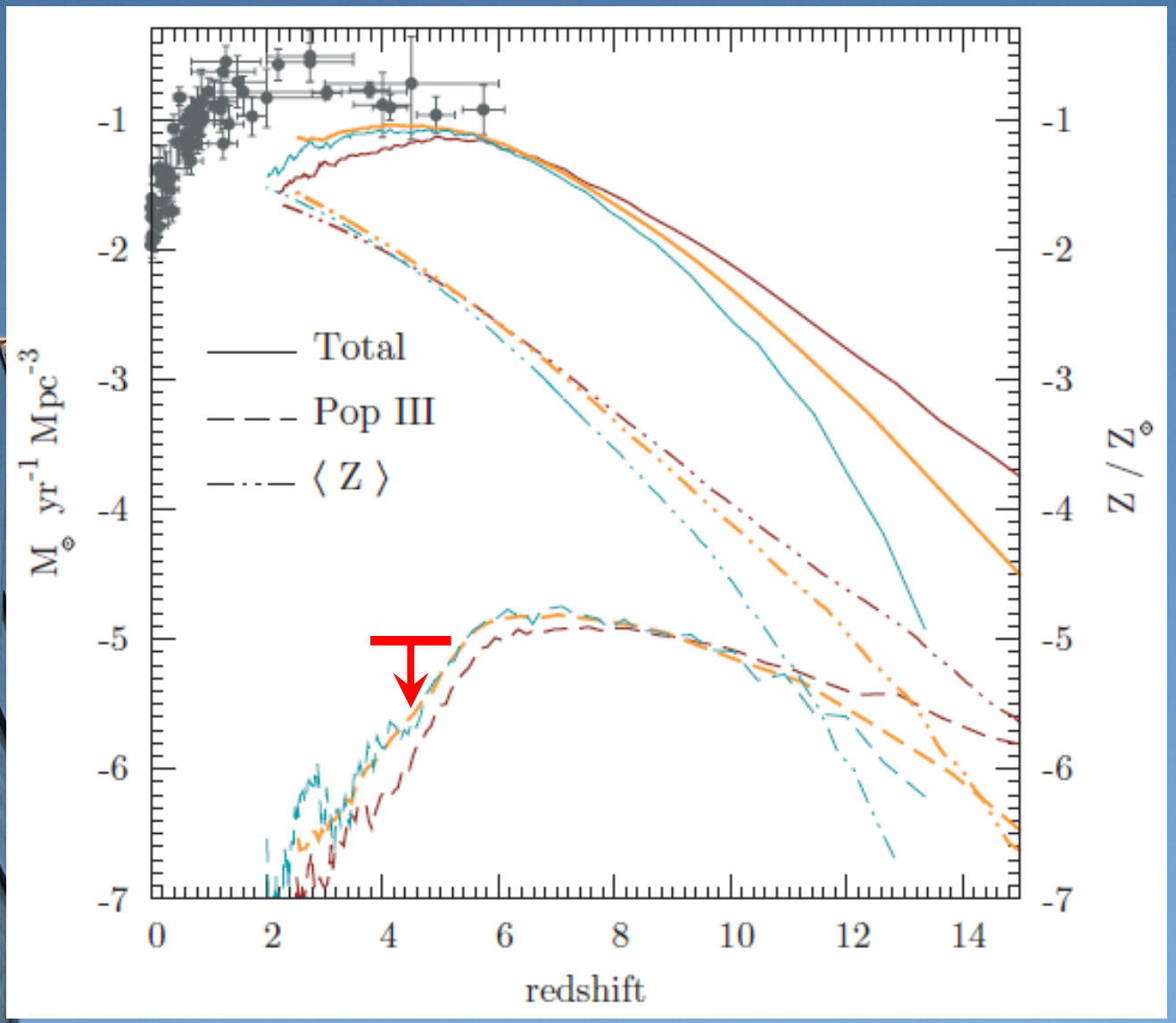




No candidates found…

Nagao et al. submitted

PopIII Galaxies: Observations vs. Models



SFRD model:
Tornatore +2007

Observational limit:
Nagao +2008

Summary

(1) Metallicity Measurements of Galaxies

~ Attention to calibrations of metallicity diagnostics
~ Downsizing evolution of the M-Z relation / Models ??
~ JWST is necessary to go beyond z=3
~ At z<3: stellar Z, Z gradient, abundance ratios, …

(2) Metallicity Measurements of AGNs

~ No evolution of the L-Z relation: both Z_{BLR} and Z_{NLR}
~ z>5: NIR spec needed (more targets crucial !!)
~ Narrow-line radio galaxies as interesting targets

(3) Open Issues

~ Galaxies vs. AGNs: lower-L / higher-z quasars needed
~ PopIII galaxies: challenging and feasible (??) science