Studying Gas Phase Metallicity of z < 1 Star Forming Galaxies with Subaru/PFS

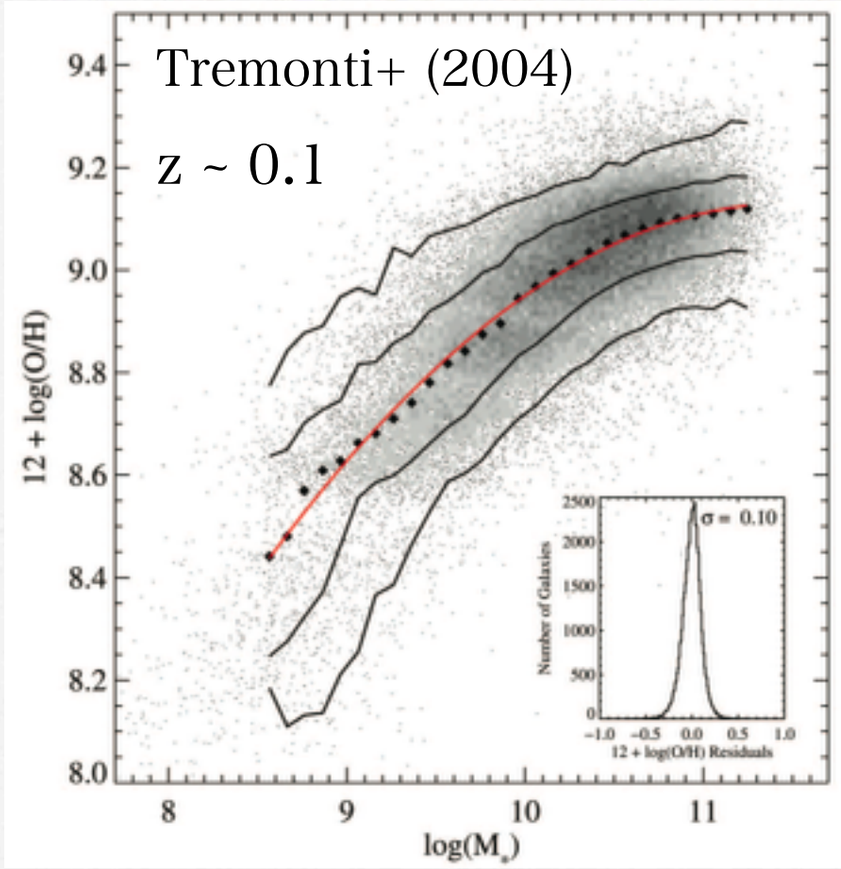
Yuu NIINO (NAOJ)

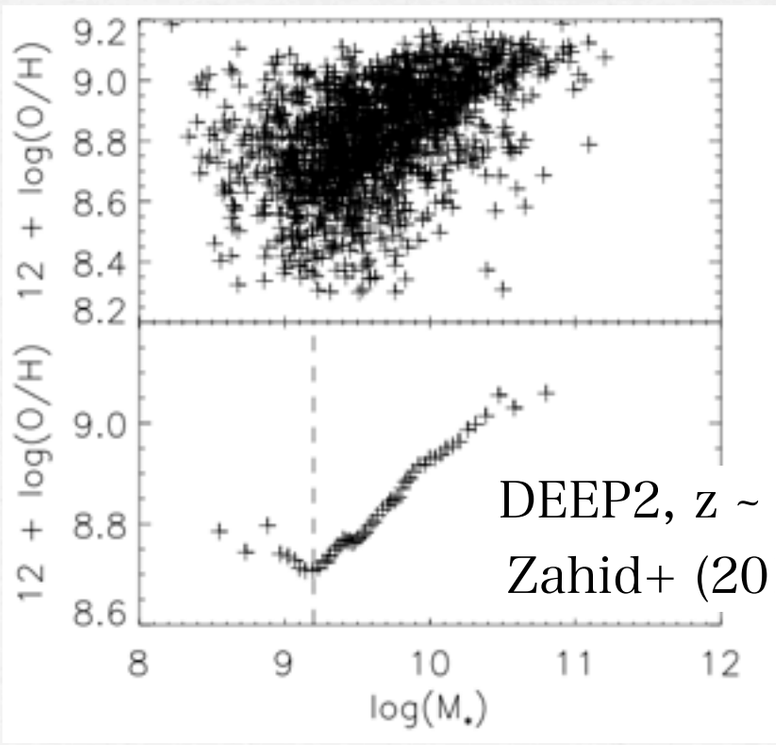
13 Nov. 2015

PFS-SSP Galaxy Survey Workshop

M★-Z relation

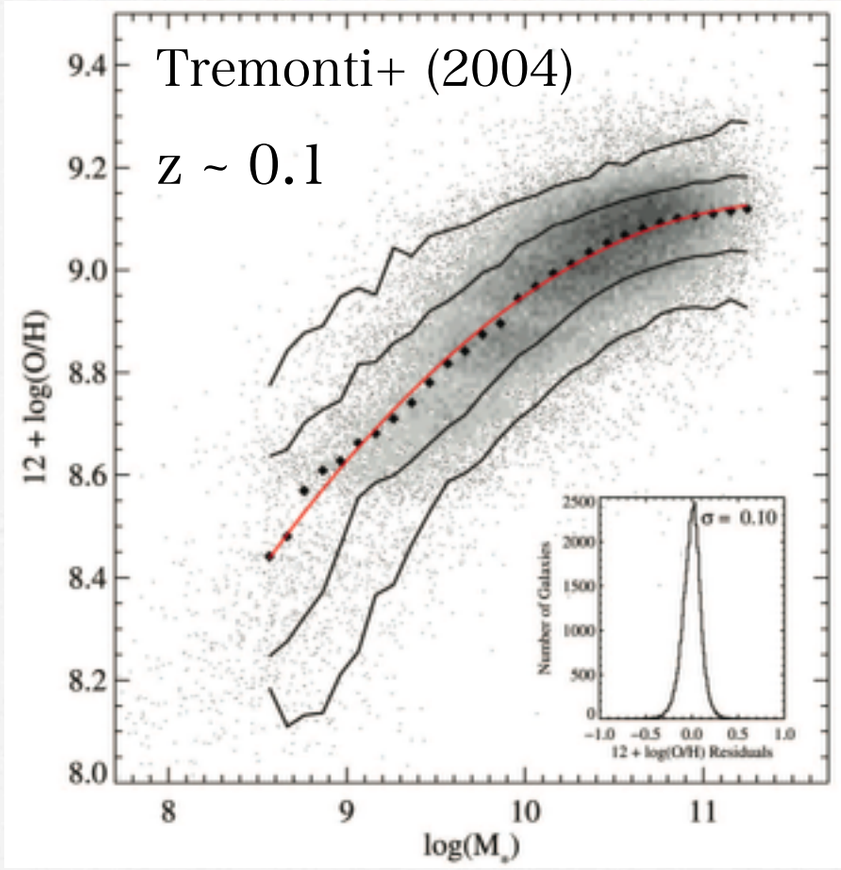
- The M★-Z relation at z ~ 0.1 is determined by the spectroscopy of ~ 53,000 galaxies (SDSS).
- Recent spectroscopic galaxy surveys (zCOSMOS, DEEP2) determined the M★-Z relation at z > 0.5.
  - ~ 10^3 galaxies per $\Delta z \sim 0.1$
  - Smaller than SDSS but statistically sufficient.

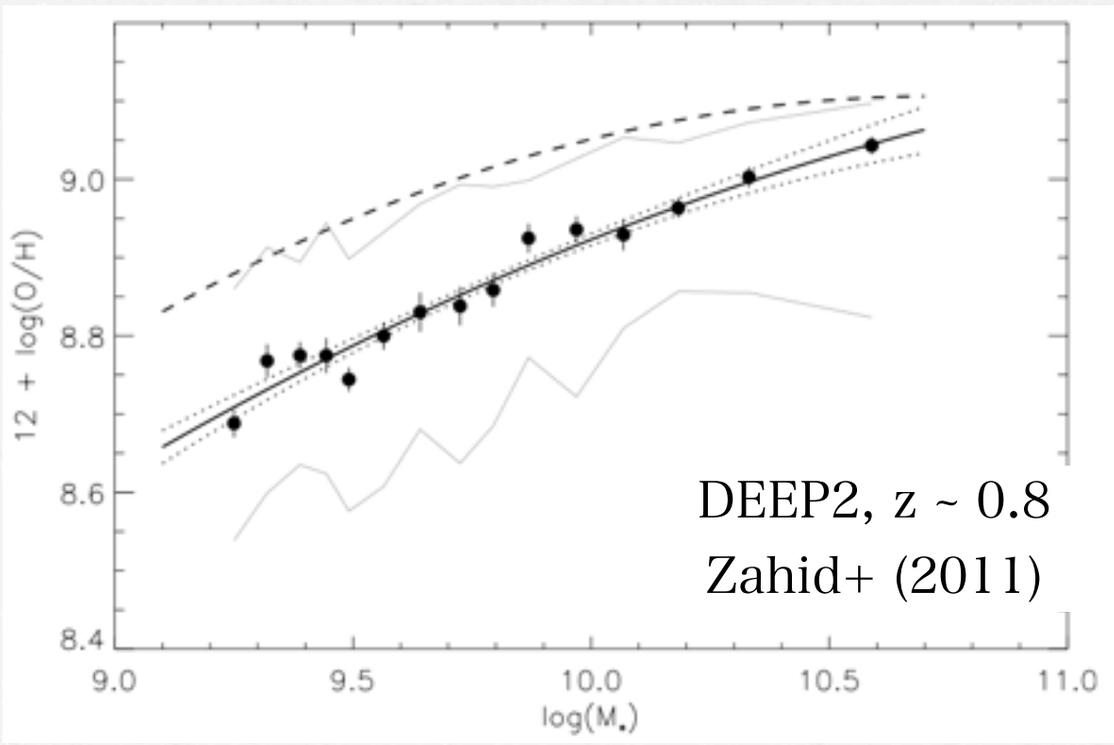




M★-Z relation

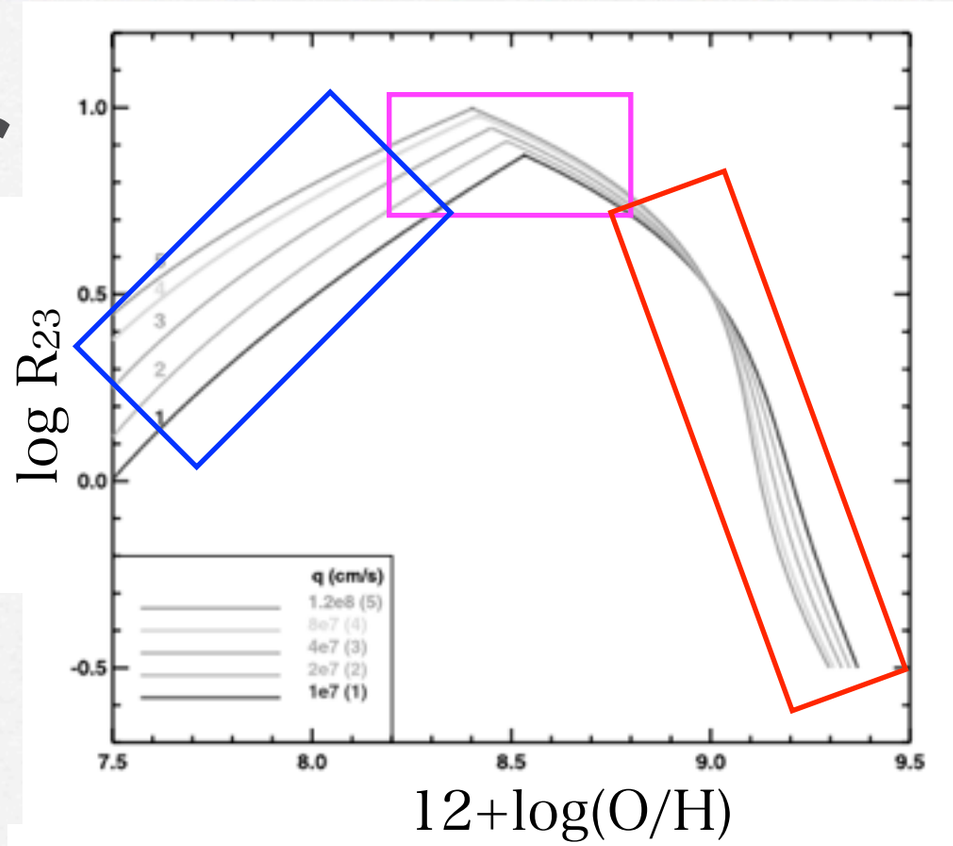
- The M★-Z relation at z ~ 0.1 is determined by the spectroscopy of ~ 53,000 galaxies (SDSS).
- Recent spectroscopic galaxy surveys (zCOSMOS, DEEP2) determined the M★-Z relation at z > 0.5.
  - ~ 10^3 galaxies per $\Delta z \sim 0.1$
  - Smaller than SDSS but statistically sufficient.

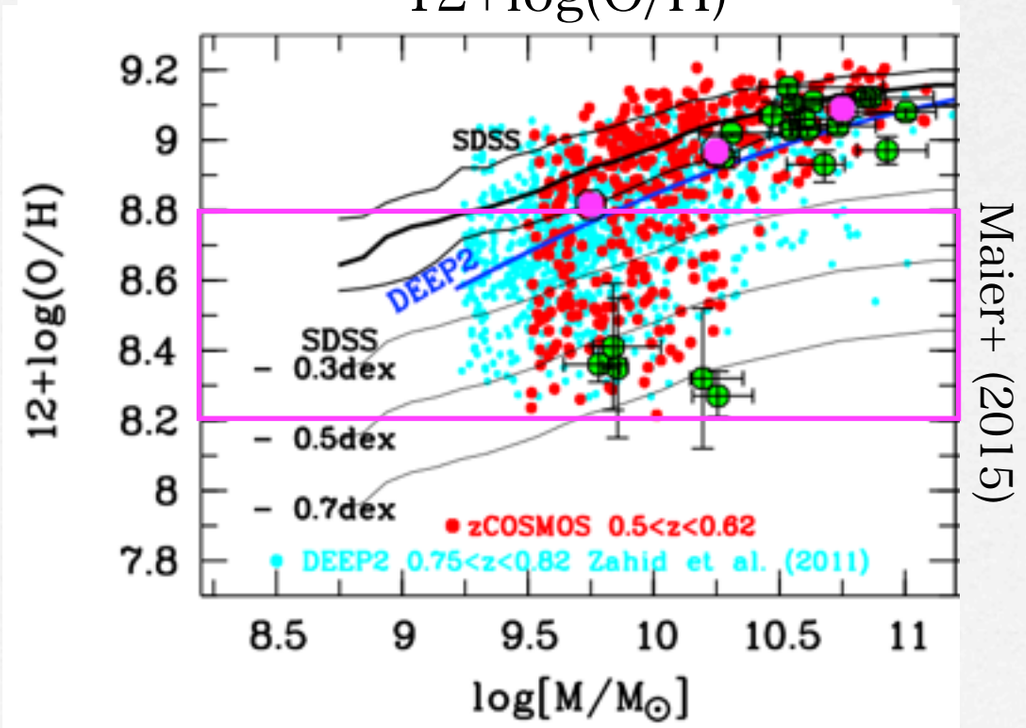




Metallicity Indicator

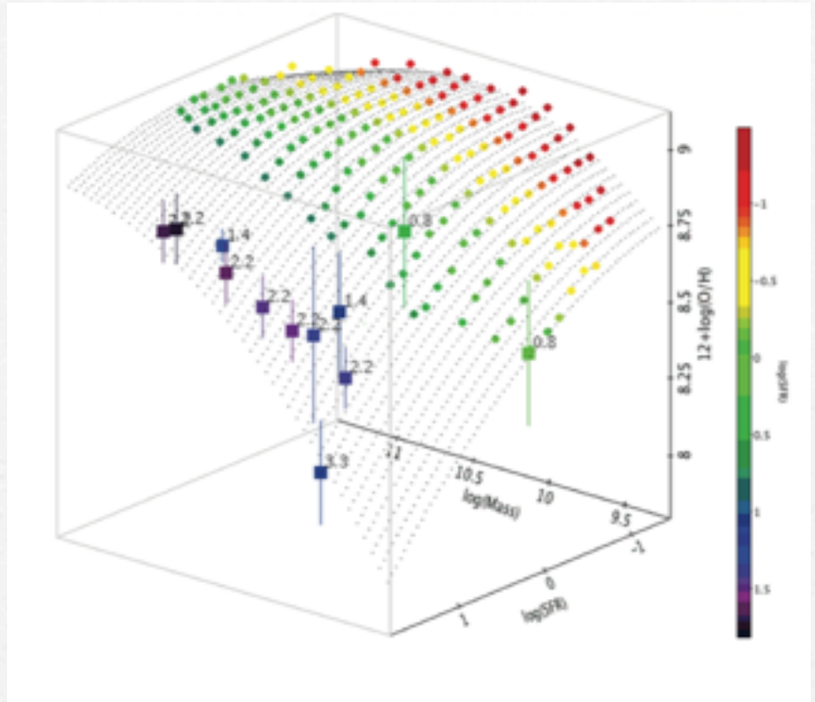
- Optical spectrographs do not cover Hα, [NII]6584 @ z > 0.5
  - R23 = ([OII]+[OIII])/Hβ
    - bivalued
    - not metallicity sensitive at 12+log(O/H) ~ 8.5
    - Extinction correction is important.
- Shimakawa-kun's talk



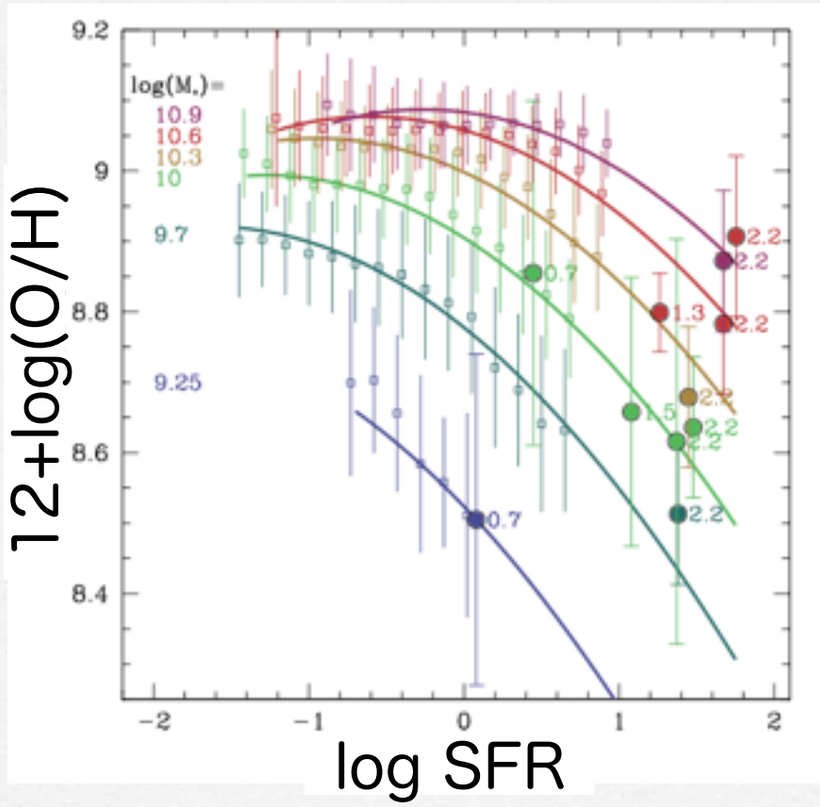


$M_\star$-SFR-Z relation

- Metallicity (Z) of star forming galaxies correlates with $M_\star$ and also SFR (Ellison+ 2008)
- Galaxies at wide variety of redshifts agree with one relation (Mannucci+ 2010; Lara-López+ 2010).
  - Fundamental Metallicity Relation (FMR)?

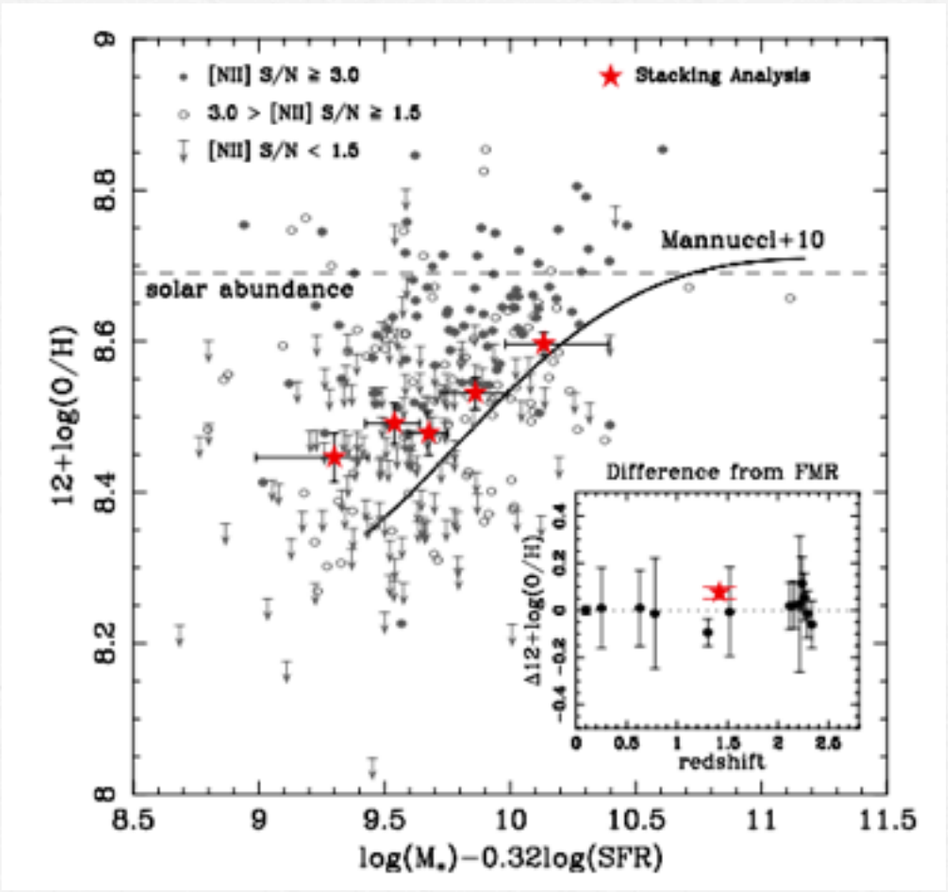


Mannucci+ (2010)



No evolution?

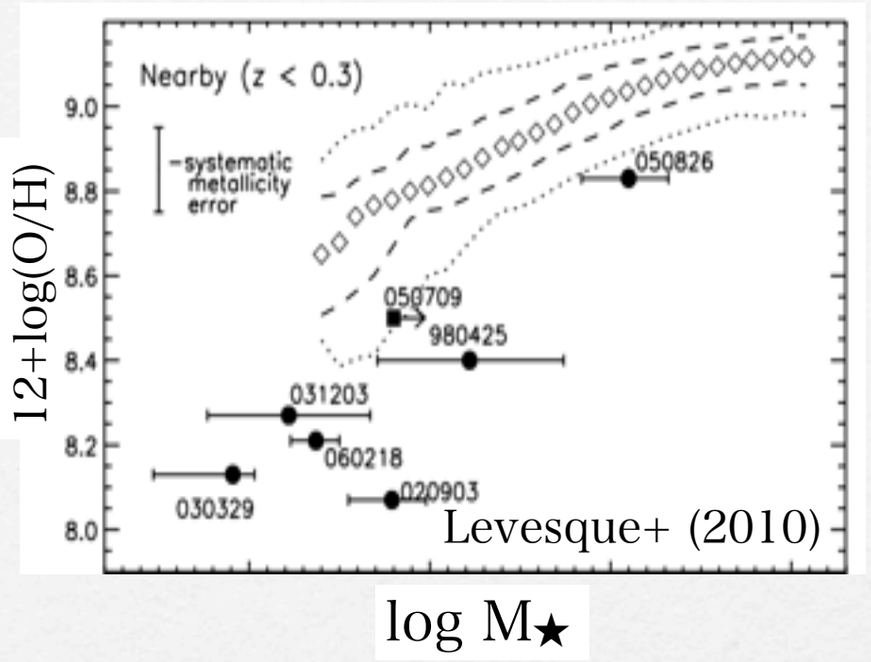
- If the M★-SFR-Z relation really does not evolve, it constrains the mechanism of galaxy evolution (e.g. Lilly+ 2013, Forbes+ 2014).
- Many spectroscopic galaxy surveys double check the M10 relation.
  - Some agree with M10,
  - some disagree with M10,
  - others agree in log(O/H) value but not in the gradient.

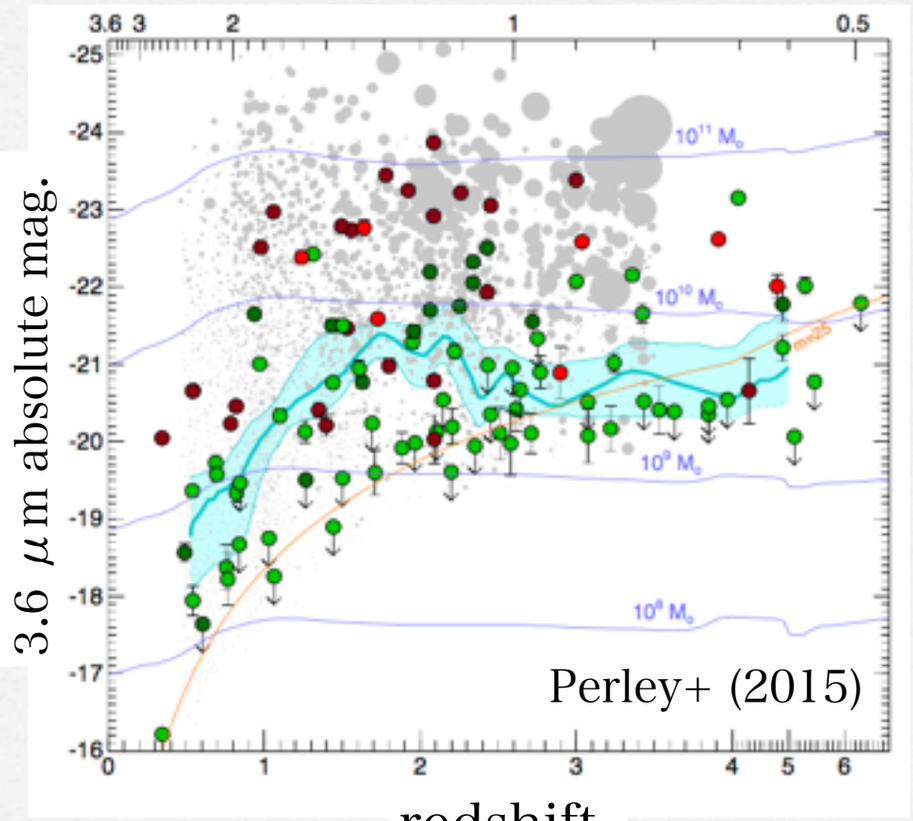


Yabe+ (2014)

Impacts on Other Fields

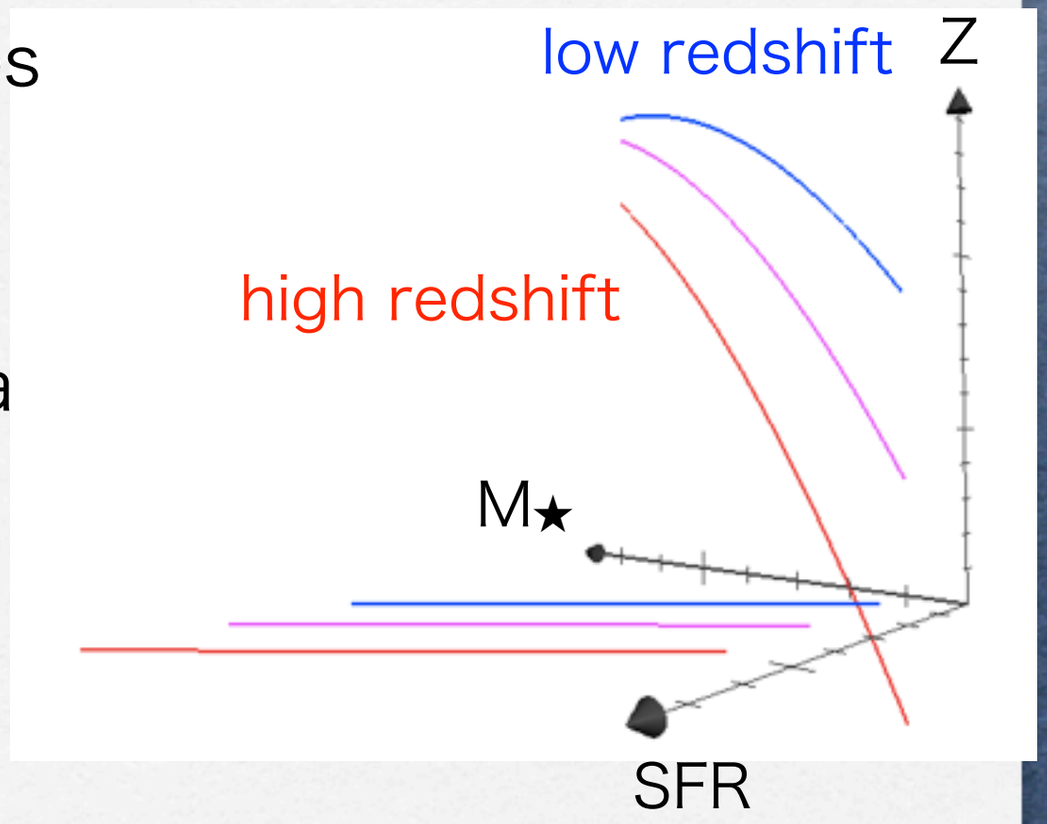
- stellar explosion studies
  - SFR and metallicity are essential parameters to understand the production of GRB and SN Ibc.
  - $z \lesssim 0.3$ GRB host galaxies are low-mass & low-metallicity.
    - small sample number
  - At z ~ 1, number of GRBs increases.
  - Host galaxy properties also changes.
  - Understanding of SFR and metallicity at is necessary to understand what is happening.





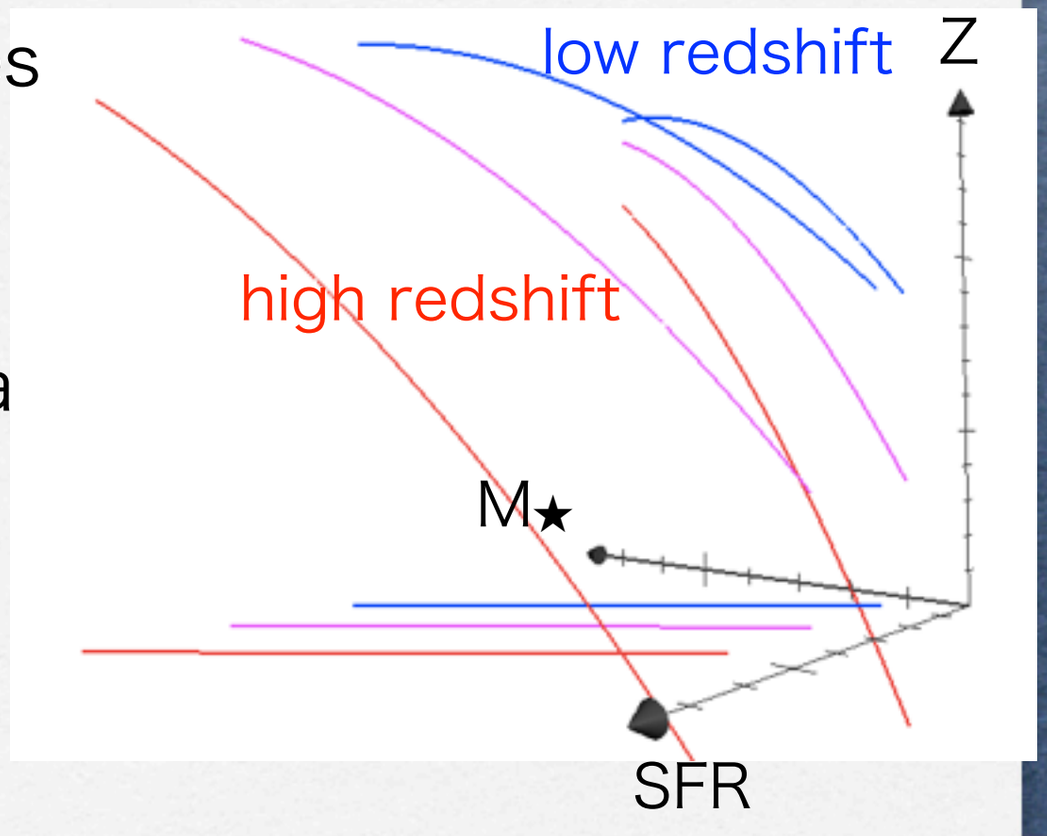
Evolution Track of Galaxies in 3D ($M_\star$, SFR, Z) Space

- There are M★-Z relation, and main sequence (M★-SFR) relation of galaxies at each redshift.
  - The relations evolve with redshift.
- Galaxies from various redshifts form a surface in the M★-SFR-Z space.
  - This surface can be reproduced without any SFR-Z correlation.
- Testing the agreement of galaxies at various redshifts to a surface in the 3D space does not test SFR-Z correlation.



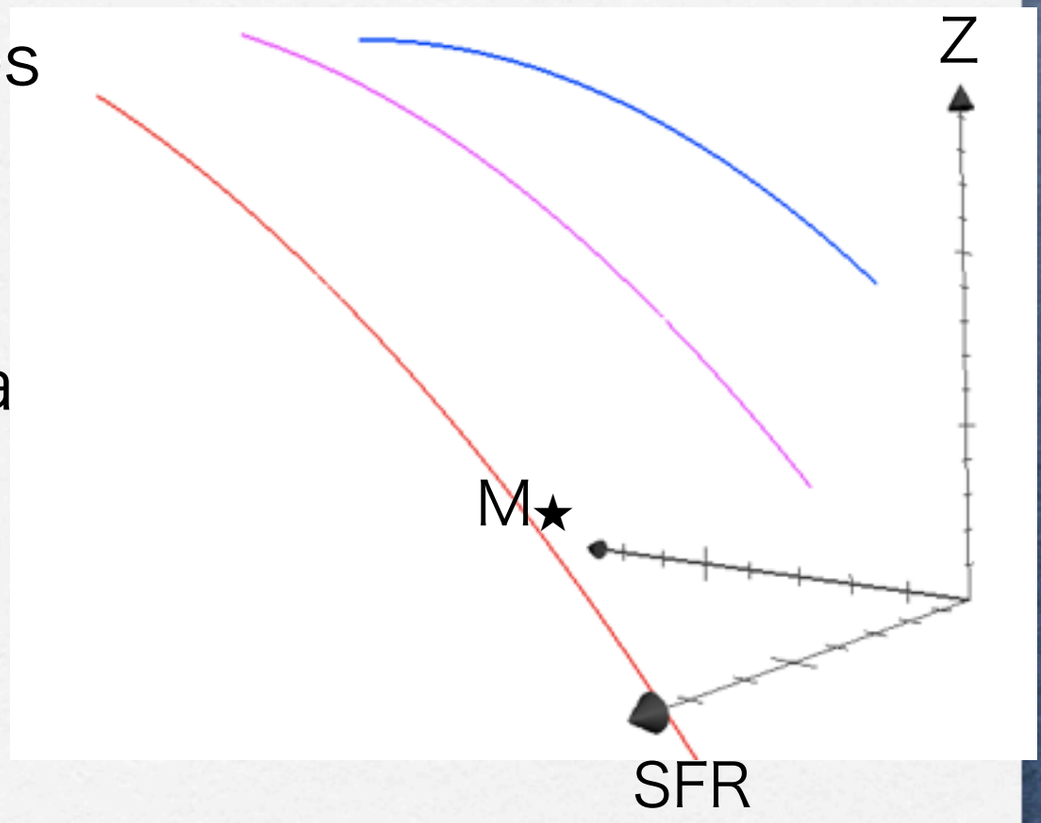
Evolution Track of Galaxies in 3D ($M_\star$, SFR, Z) Space

- There are M★-Z relation, and main sequence (M★-SFR) relation of galaxies at each redshift.
  - The relations evolve with redshift.
- Galaxies from various redshifts form a surface in the M★-SFR-Z space.
  - This surface can be reproduced without any SFR-Z correlation.
- Testing the agreement of galaxies at various redshifts to a surface in the 3D space does not test SFR-Z correlation.



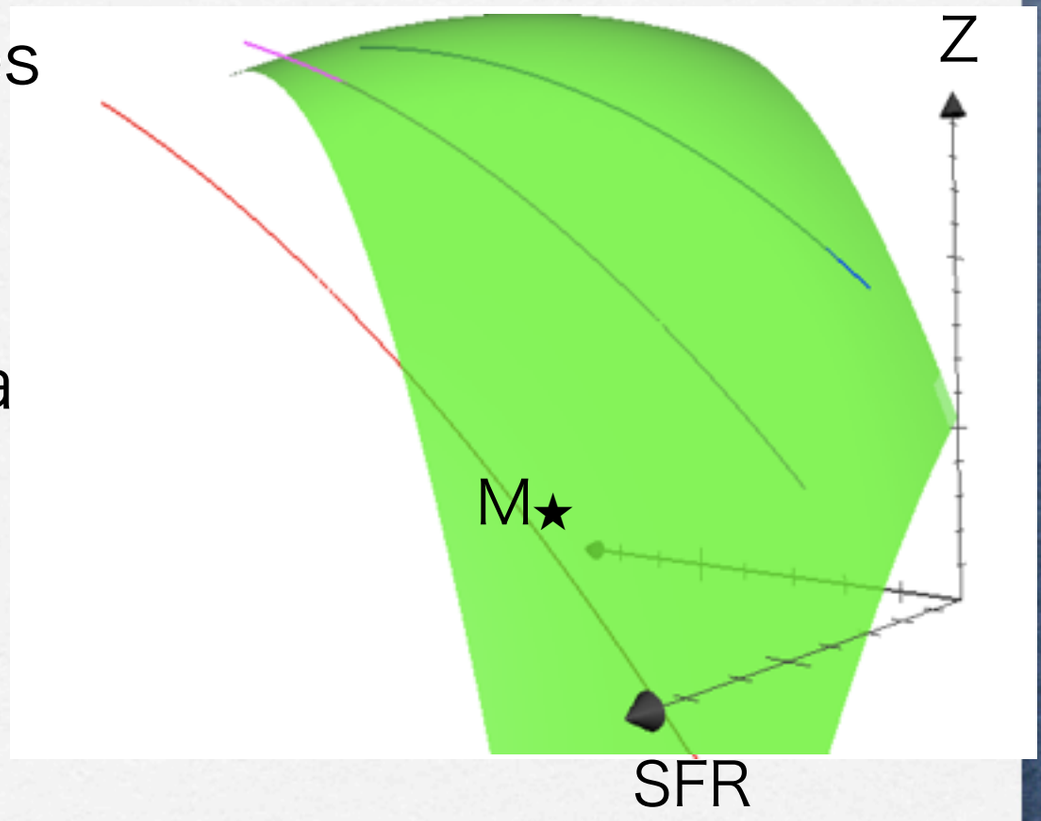
Evolution Track of Galaxies in 3D ($M_\star$, SFR, Z) Space

- There are $M_\star$-Z relation, and main sequence ($M_\star$-SFR) relation of galaxies at each redshift.
  - The relations evolve with redshift.
- Galaxies from various redshifts form a surface in the $M_\star$-SFR-Z space.
  - This surface can be reproduced without any SFR-Z correlation.
- Testing the agreement of galaxies at various redshifts to a surface in the 3D space does not test SFR-Z correlation.



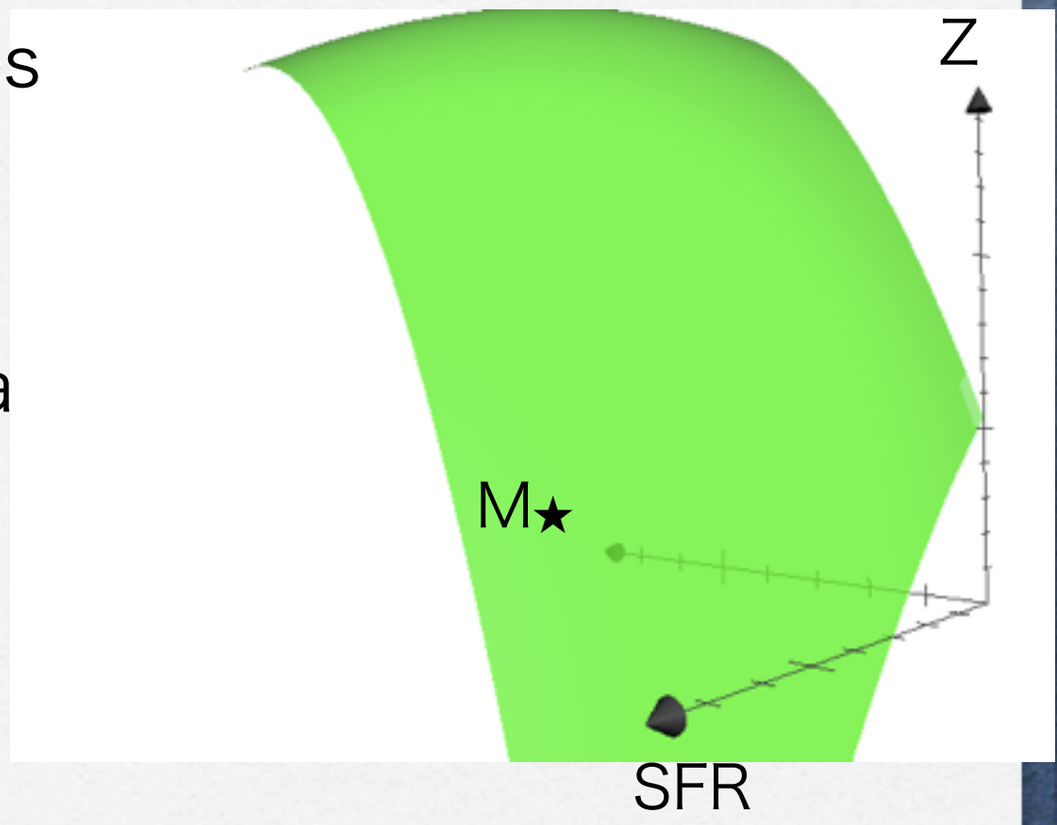
Evolution Track of Galaxies in 3D ($M_\star$, SFR, Z) Space

- There are $M_\star$-Z relation, and main sequence ($M_\star$-SFR) relation of galaxies at each redshift.
  - The relations evolve with redshift.
- Galaxies from various redshifts form a surface in the $M_\star$-SFR-Z space.
  - This surface can be reproduced without any SFR-Z correlation.
- Testing the agreement of galaxies at various redshifts to a surface in the 3D space does not test SFR-Z correlation.



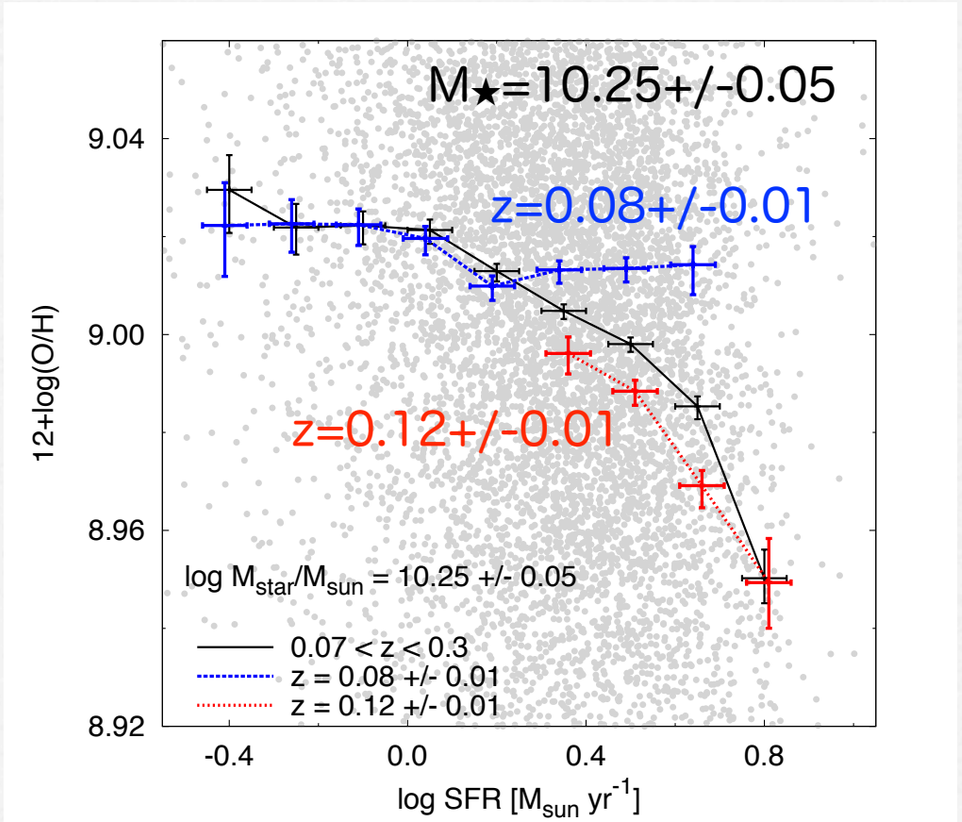
Evolution Track of Galaxies in 3D ($M_\star$, SFR, Z) Space

- There are $M_\star$-Z relation, and main sequence ($M_\star$-SFR) relation of galaxies at each redshift.
  - The relations evolve with redshift.
- Galaxies from various redshifts form a surface in the $M_\star$-SFR-Z space.
  - This surface can be reproduced without any SFR-Z correlation.
- Testing the agreement of galaxies at various redshifts to a surface in the 3D space does not test SFR-Z correlation.



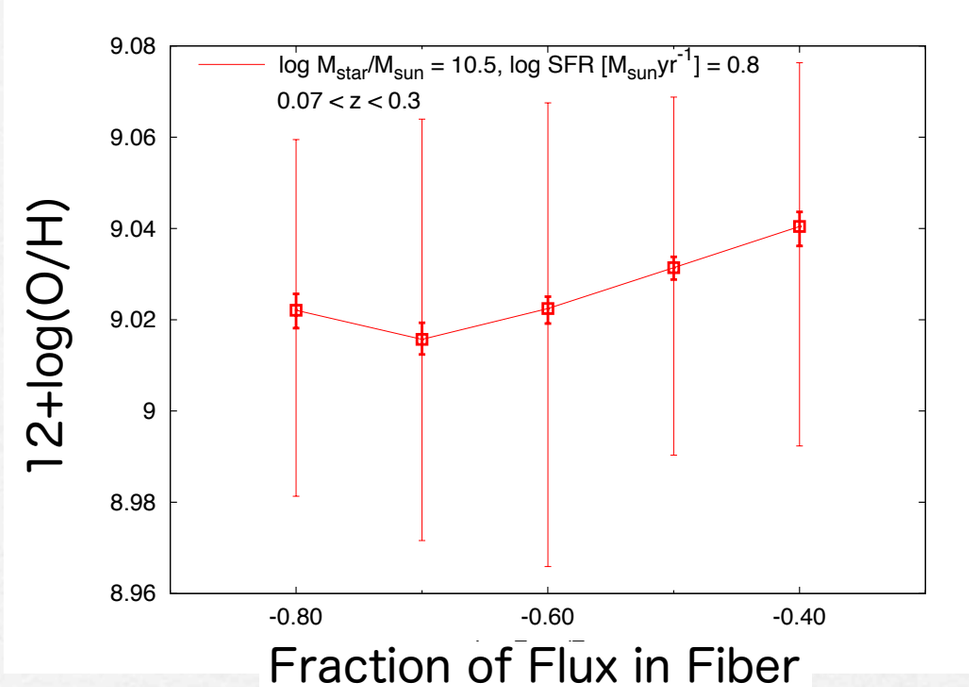
Evolution of M★-SFR-Z relation

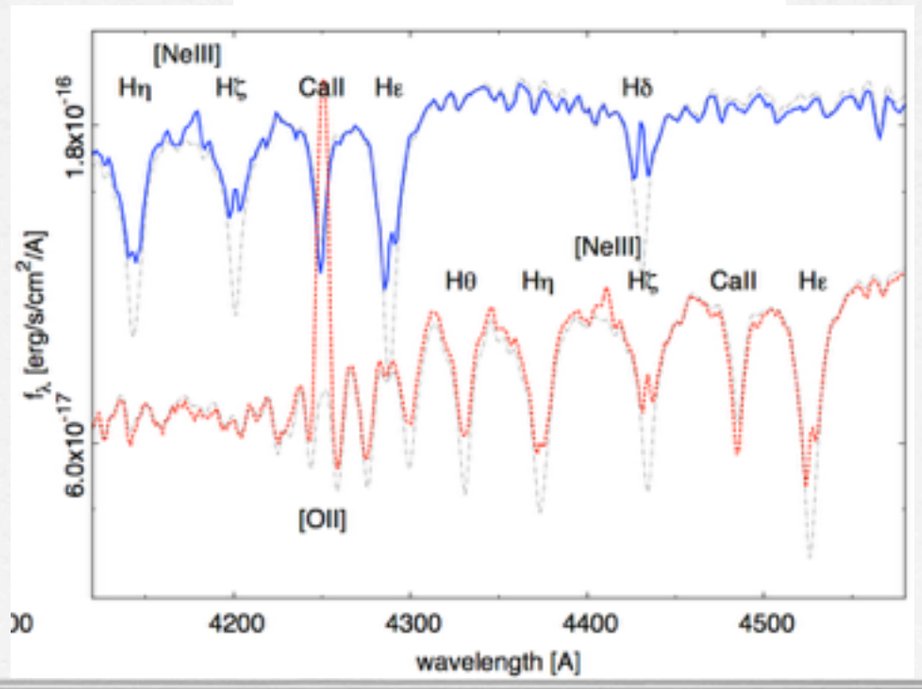
- The M★-SFR-Z relation of SDSS galaxies in very narrow redshift bins $\delta z = 0.02$ (Niino 2012).
- Galaxies at $z < 0.1$ have higher metallicity than galaxies at $z > 0.1$ with the same M★ & SFR.
- The SFR-Z correlation exists even in the $\Delta z = 0.02$ bins.
  - The relation in each bin is different from the relation of all galaxies.



Evolution of $M_\star$-SFR-Z relation

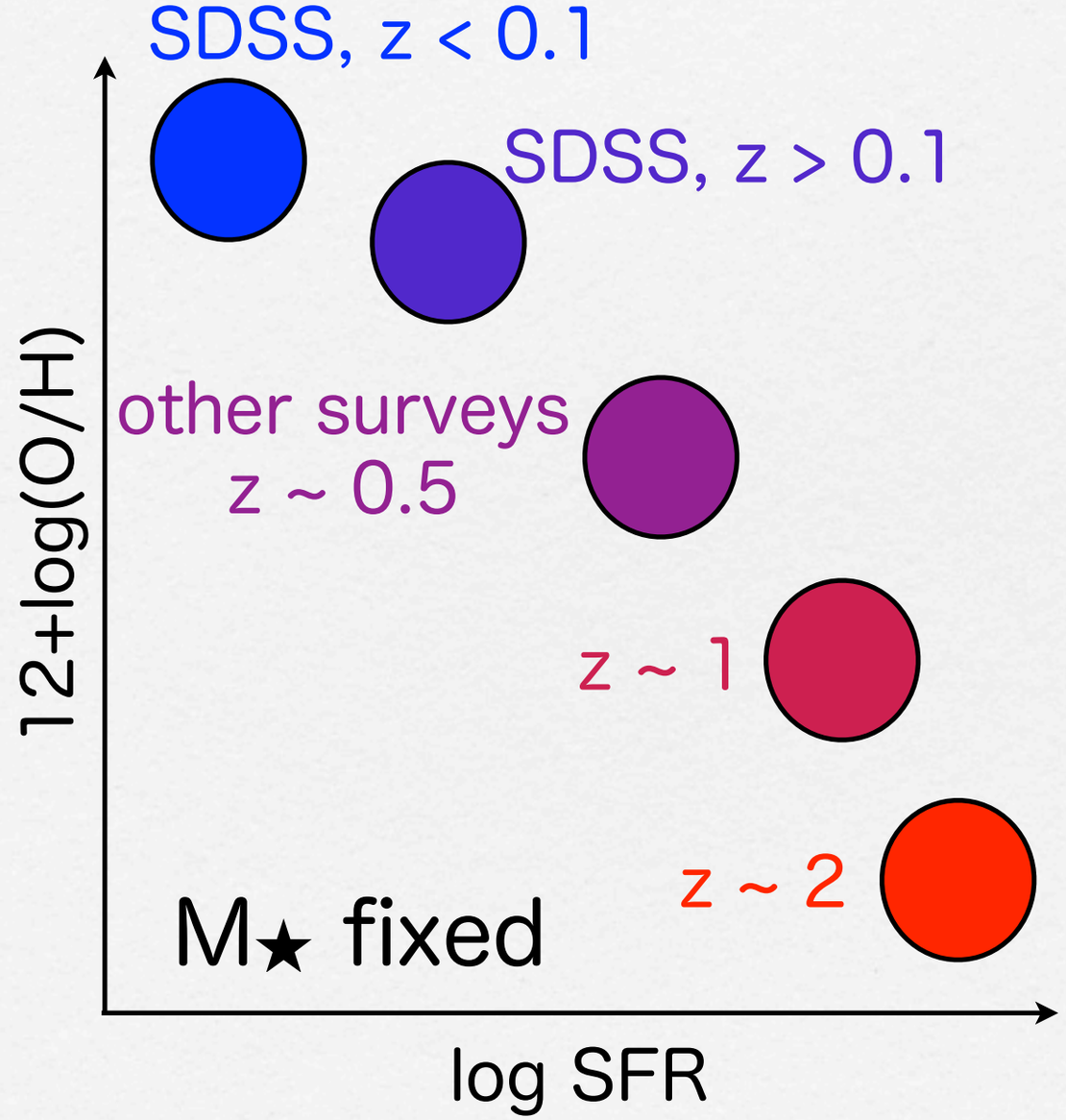
- Only a small range of redshift around z ~ 0.1 can be tested with the SDSS galaxies.
- Systematic error may play a role:
  - fiber aperture (unlikely)
  - Malmquist bias (unlikely)
  - continuum S/N (unlikely)
- More tests are necessary.





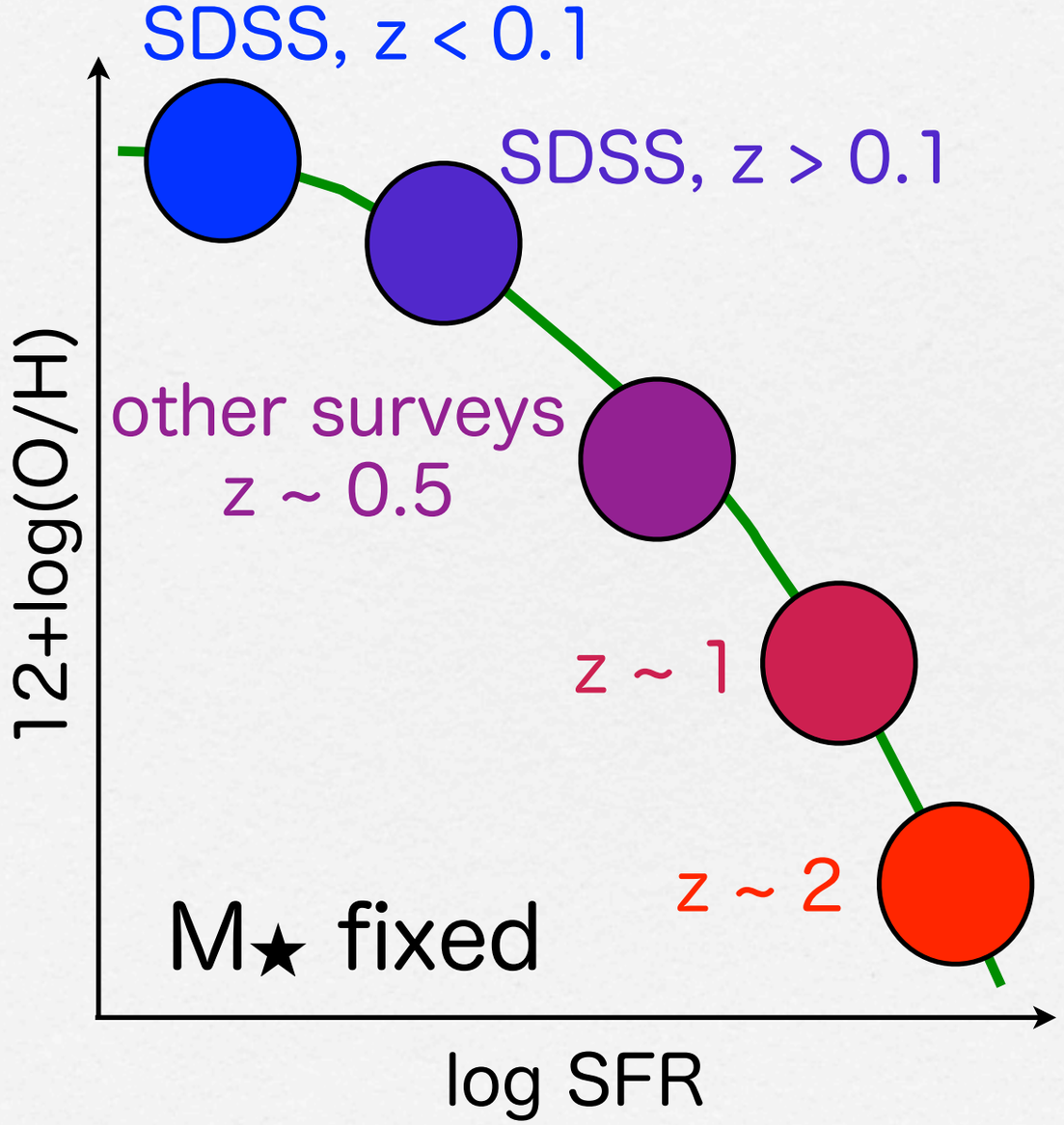
Discussion

- With fixed M★, higher-z galaxies have higher-SFR & lower-Z (green).
- The SFR-Z correlation at each redshift can be different from the green curve.
  - It can also evolve with redshift.
  - The SFR-Z correlation is not well constrained beyond z ~ 0.1.
- Metallicity may depend on both SFR and redshift.
  - In current studies, the two effects are degenerated.



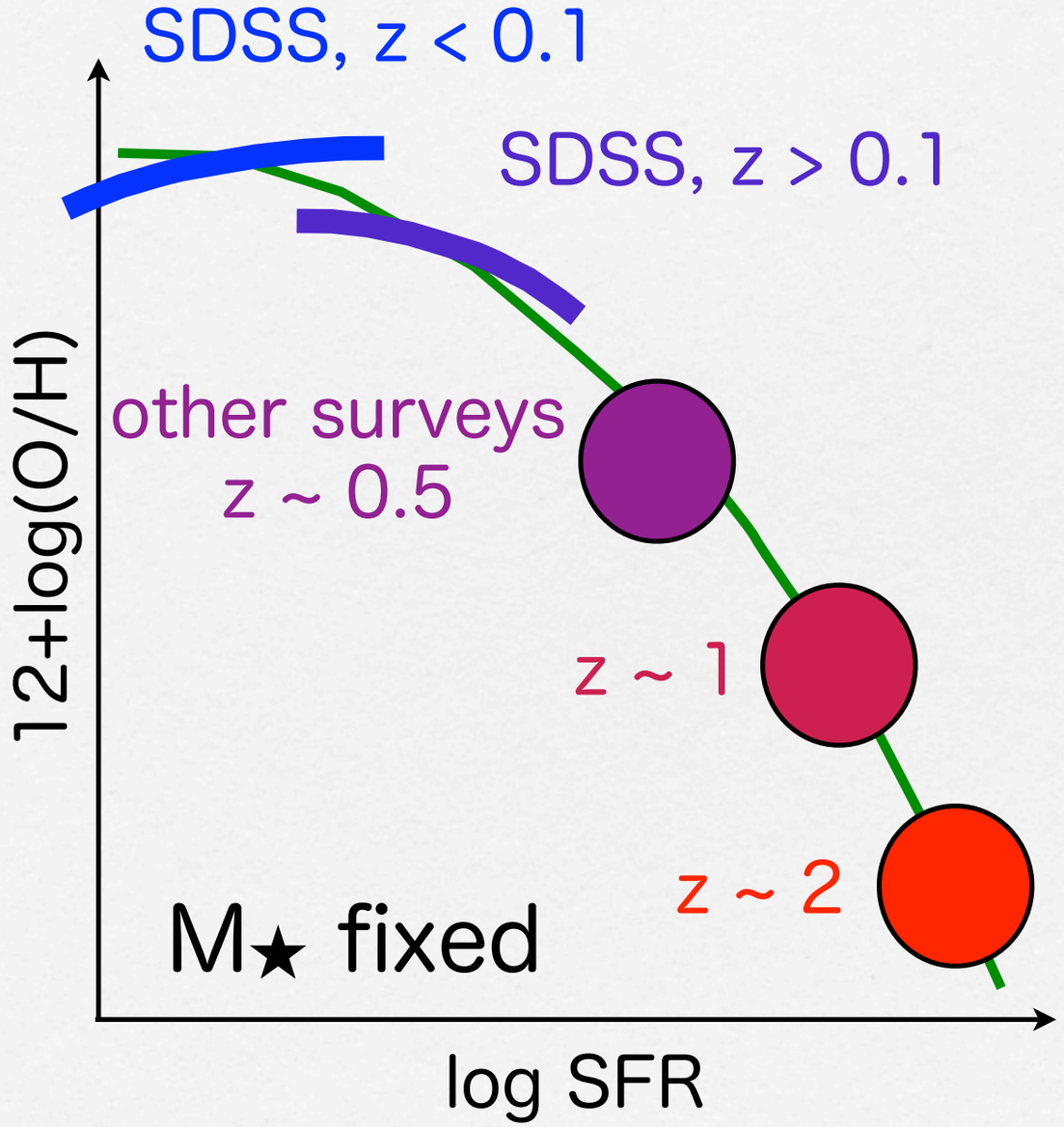
Discussion

- With fixed M★, higher-z galaxies have higher-SFR & lower-Z (green).
- The SFR-Z correlation at each redshift can be different from the green curve.
  - It can also evolve with redshift.
  - The SFR-Z correlation is not well constrained beyond z ~ 0.1.
- Metallicity may depend on both SFR and redshift.
  - In current studies, the two effects are degenerated.



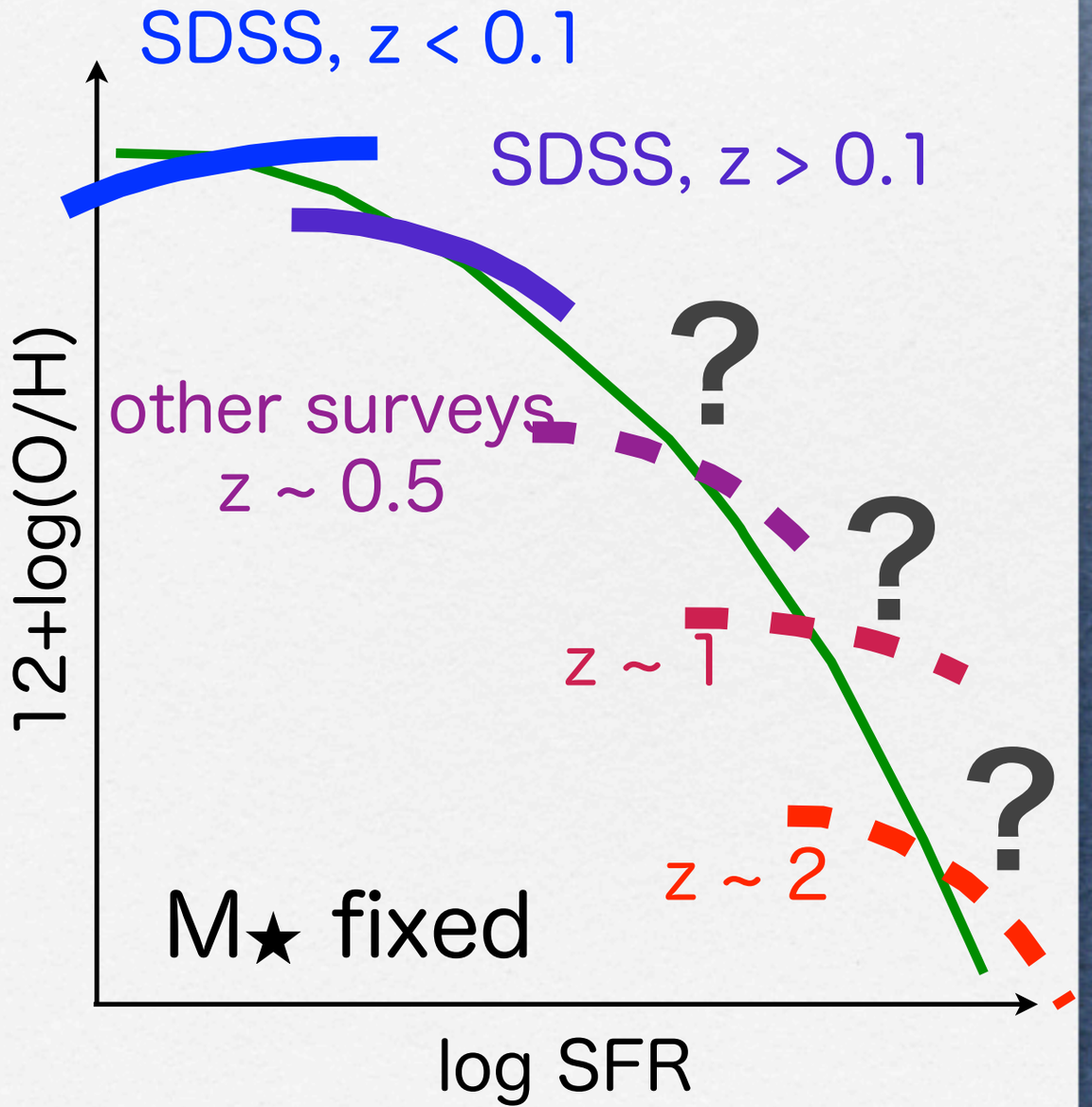
Discussion

- With fixed M★, higher-z galaxies have higher-SFR & lower-Z (green).
- The SFR-Z correlation at each redshift can be different from the green curve.
  - It can also evolve with redshift.
  - The SFR-Z correlation is not well constrained beyond z ~ 0.1.
- Metallicity may depend on both SFR and redshift.
  - In current studies, the two effects are degenerated.



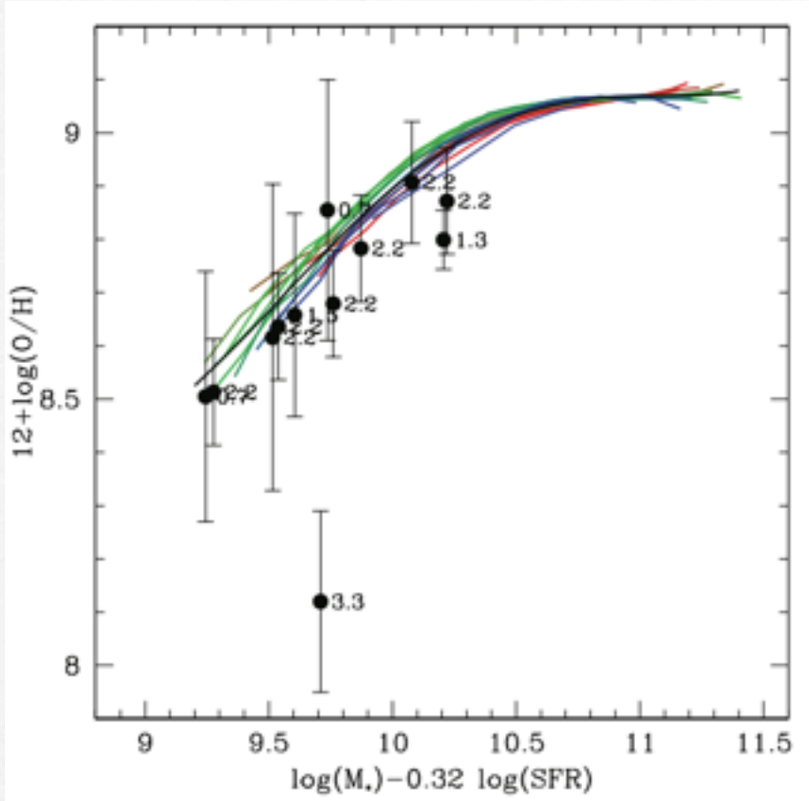
Discussion

- With fixed M★, higher-z galaxies have higher-SFR & lower-Z (green).
- The SFR-Z correlation at each redshift can be different from the green curve.
  - It can also evolve with redshift.
  - The SFR-Z correlation is not well constrained beyond z ~ 0.1.
- Metallicity may depend on both SFR and redshift.
  - In current studies, the two effects are degenerated.

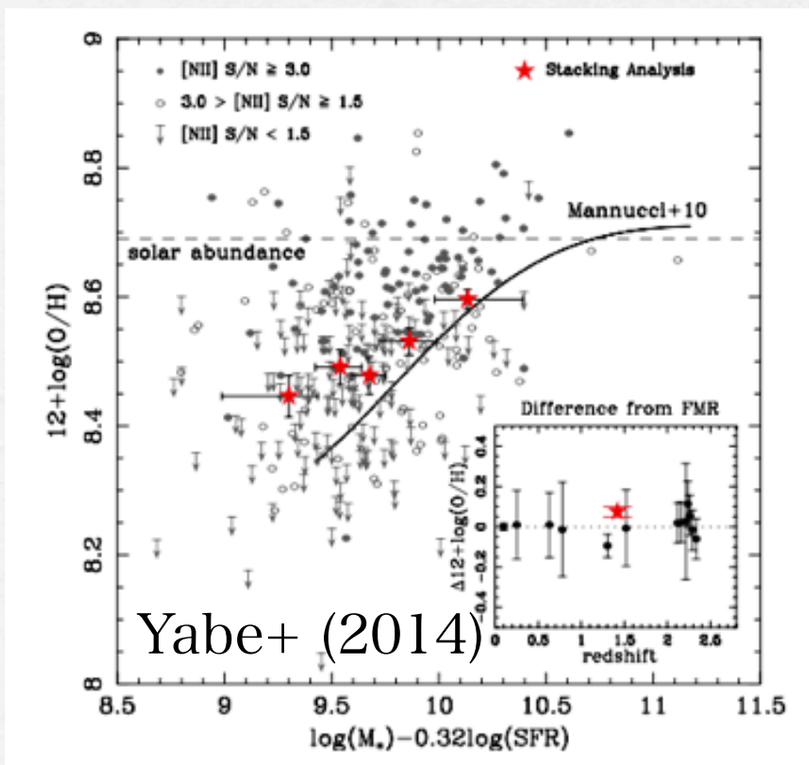


Degeneracy Between Parameters

- Gas-phase metallicity of a galaxy depends on M★, SFR, and redshift.
  - M★, SFR, and redshift also correlate each other.
- We need to solve complicated degeneracy between parameters to understand metallicity evolution of galaxies.
- 2D projection is not preferable.



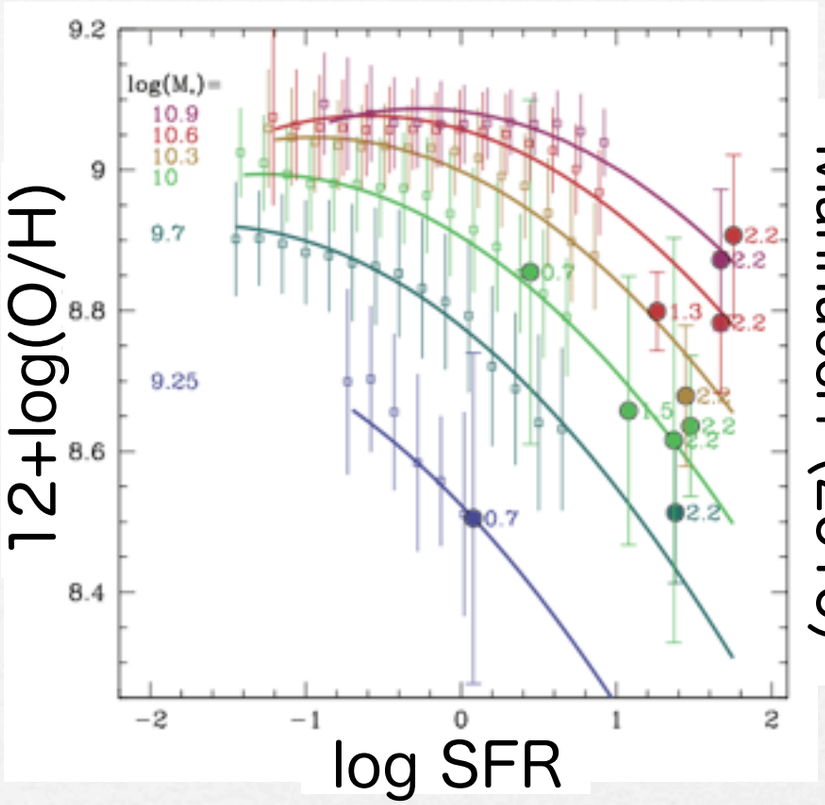
Mannucci+ (2010)



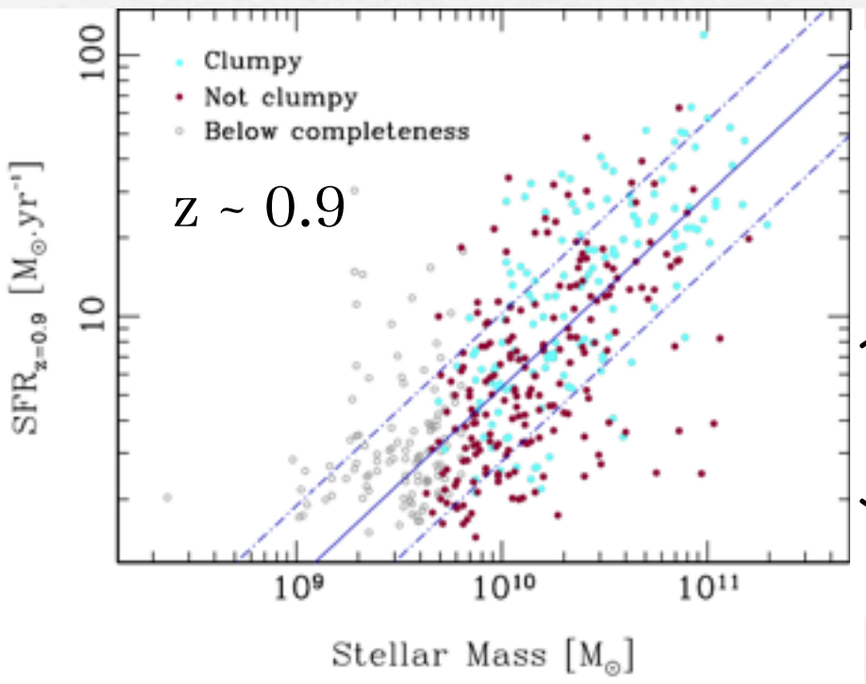
Yabe+ (2014)

Requirements

- Determine log(O/H) of galaxies at each M★, SFR, and redshift.
  - independently from SDSS
  - without 2D projection
- What survey do we need?
- Need to cover wide ΔlogSFR.
  - dlog(O/H)/dlogSFR ~ 0.1
  - galaxy number drops outside of the main-sequence.
  - ΔlogSFR ~ 0.5 (±1 σ of MS) → Δlog(O/H) ~ 0.05



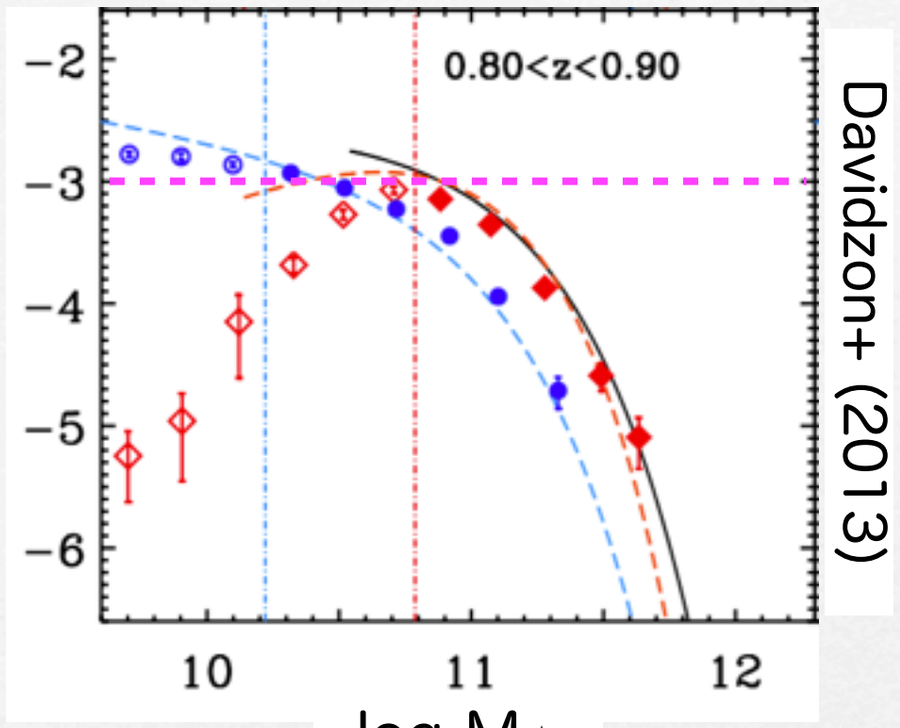
Mannucci+ (2010)



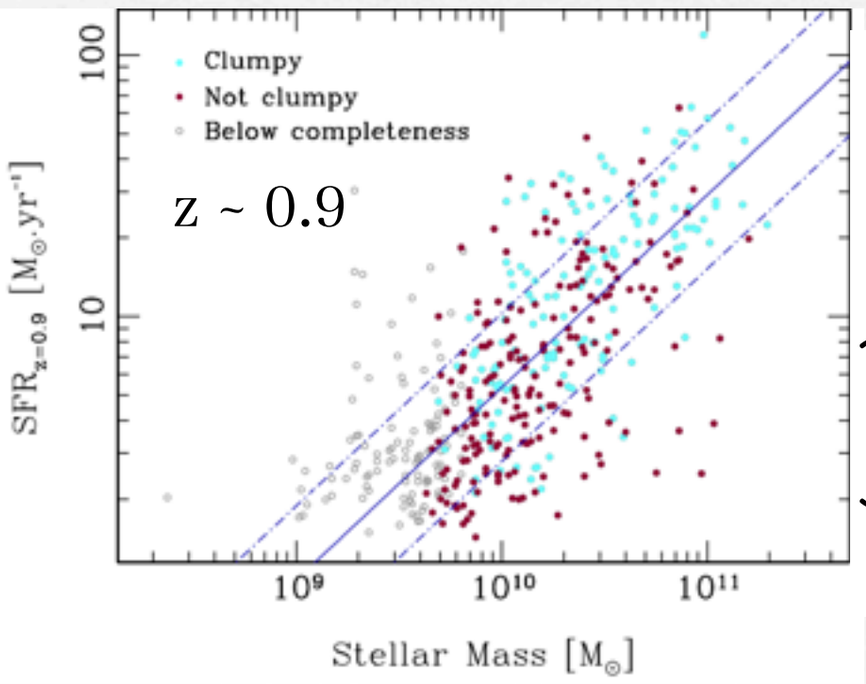
Salmi+ (2012)

Requirements

- Assuming:
  - ϕ ~ $10^{-3}\,\delta$ logM★ [Mpc^{-3}] below M*
  - V ~ $10^{7}\,\delta$ z [Mpc^{3}deg^{-2}]
  - σ_{MS} ~ 0.3 dex
  - $\sigma_{log(O/H)}$ ~ 0.1 dex
  - δ logM★= δ logSFR= δ z=0.1
- Error of mean = $\sigma_{log(O/H)}/N_{gal}^{1/2}$ < 0.01 requires N_{gal} > 100.
  - (at ±1 σ_{MS}) $\Omega_{survey}\times f_{sample} \gtrsim 10$ deg^2
- [NII] ~ 10^{-17} [erg s^{-1}cm^{-2}]
  - SFR = 10 [M$_\odot$yr^{-1}], z = 0.9, f_{ext} = 0.5



Davidzon+ (2013)



Salmi+ (2012)

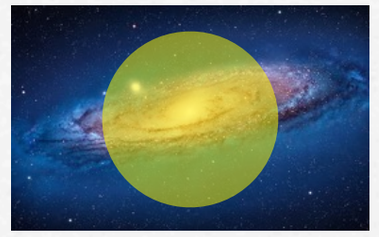
Summary

- To understand the M★-SFR-Z relation at z > 0.5, we will need:
  - wavelength range from [OII]3727 to [NII]6584
    - up to z ~ 0.9 with PFS
  - large survey area $\Omega_{survey} \times f_{sample} > 10$ deg^2
    - good enough statistics with in small enough parameter bins
- expected [NII] flux ~ 10^{-17} [erg s^{-1} cm^{-2}]
  - not very challenging (?)

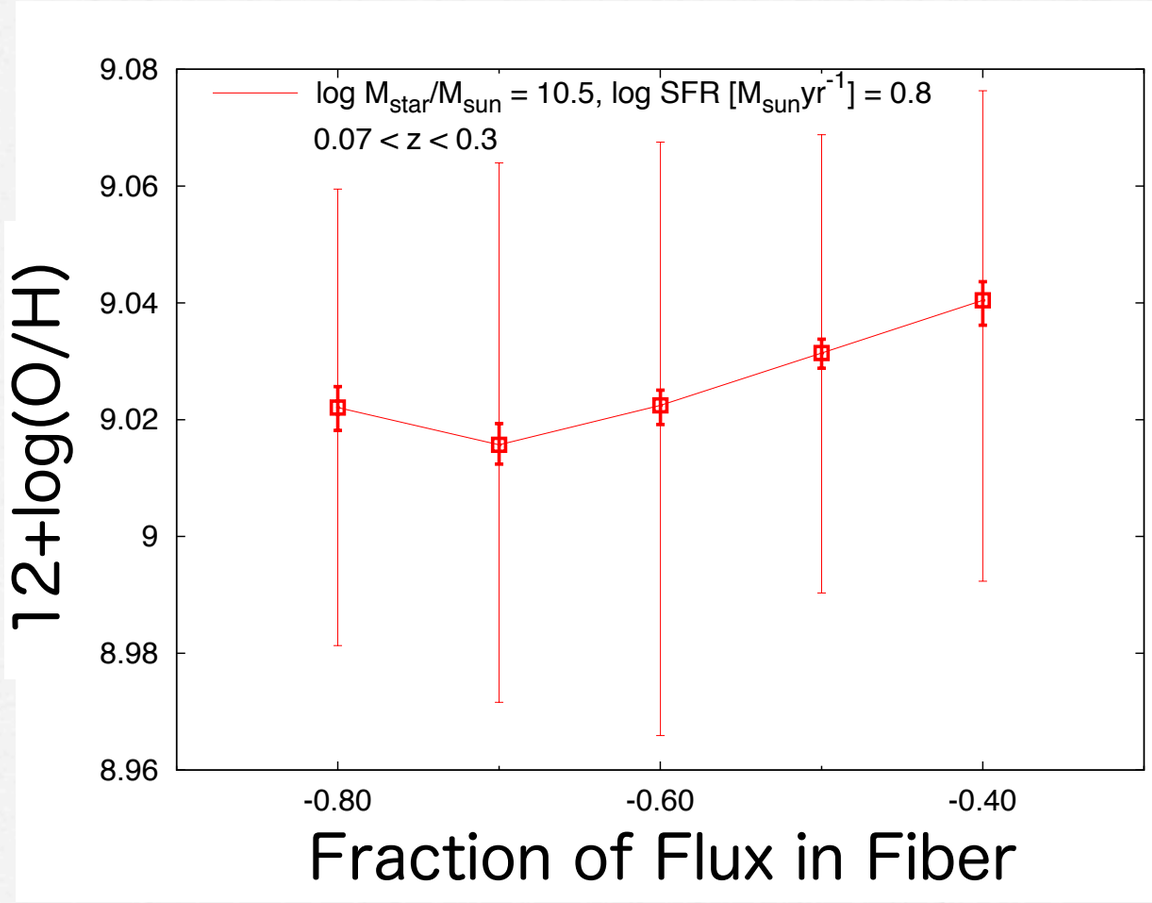
End of the Talk

Fiber Aperture Effect

- Spectroscopic fiber may cover larger area at higher redshift.
- Outskirt of a galaxy is metal poor than its center.
  - Larger covering fraction may result in low-Z.
- In reality, galaxies with larger covering fraction show higher-Z.
  - possibly due to the r_{eff}-Z relation (Ellison+ 2008)
  - The gradient effect looks weaker than the r_{eff} effect (~ the redshift effect).

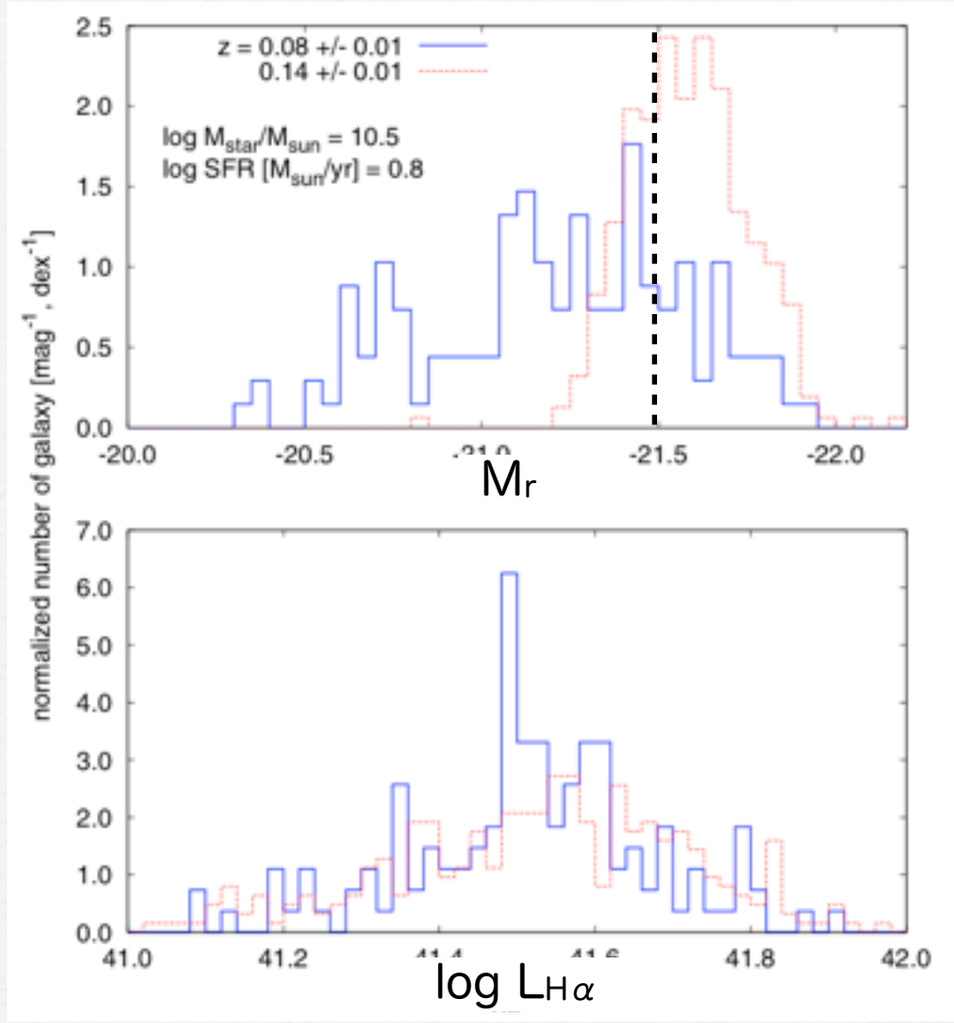


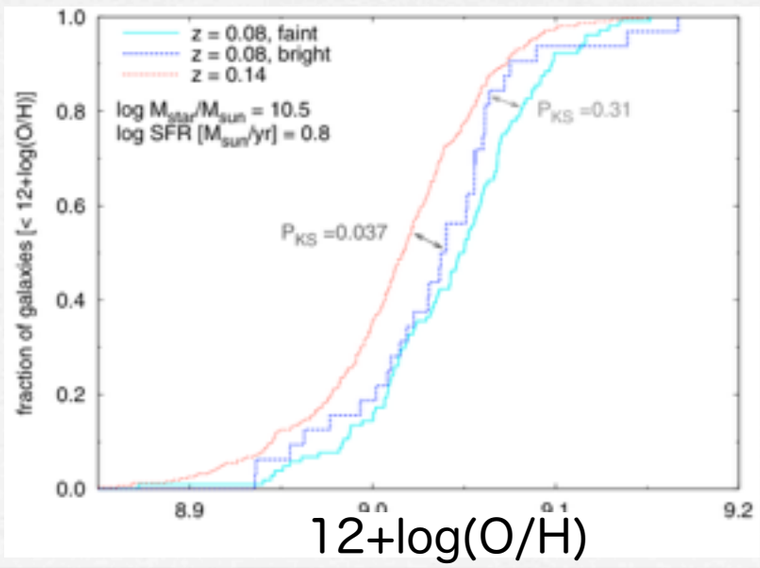
far



Mag Limit Effect

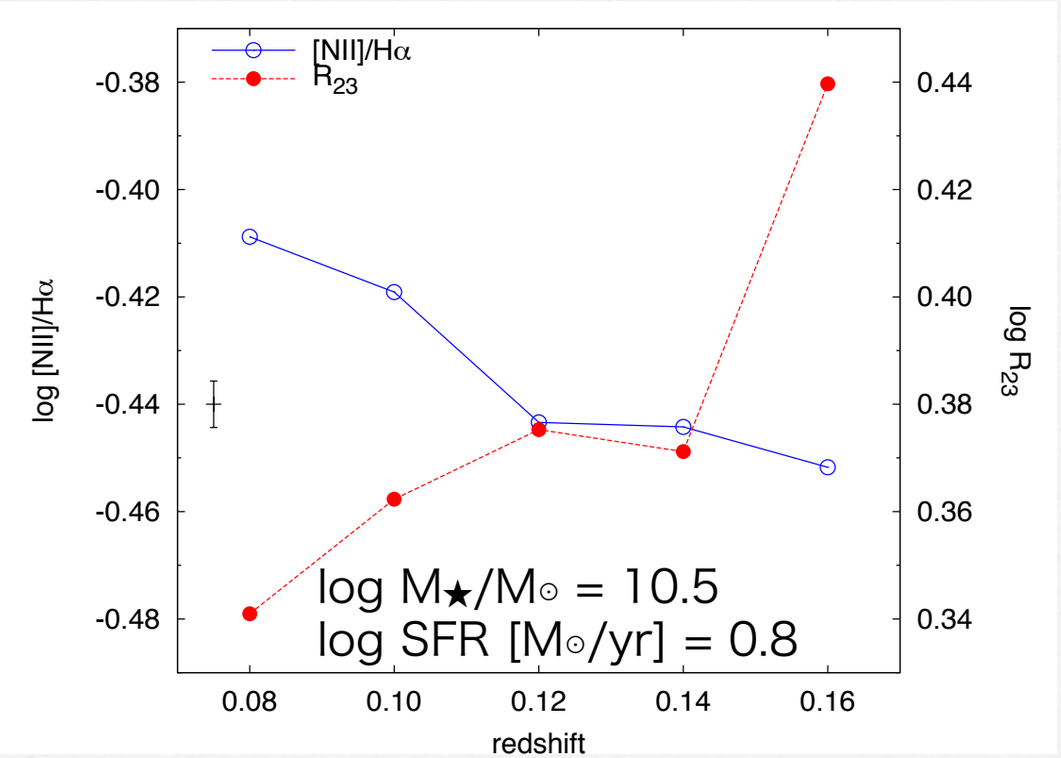
- The limiting magnitude of the SDSS spectroscopic sample (r < 17.77) may play a role.
  - The Hα S/N requirement doesn't affect the high SFR population.
- Separate z=0.08 sample into bright/faint subsamples at M_r = -21.5.
  - The bright and faint samples at z=0.08 are consistent to each other (P_{KS}=0.31).
  - The bright sample @ z=0.08 is inconsistent to z=0.14 sample (P_{KS}=0.037).

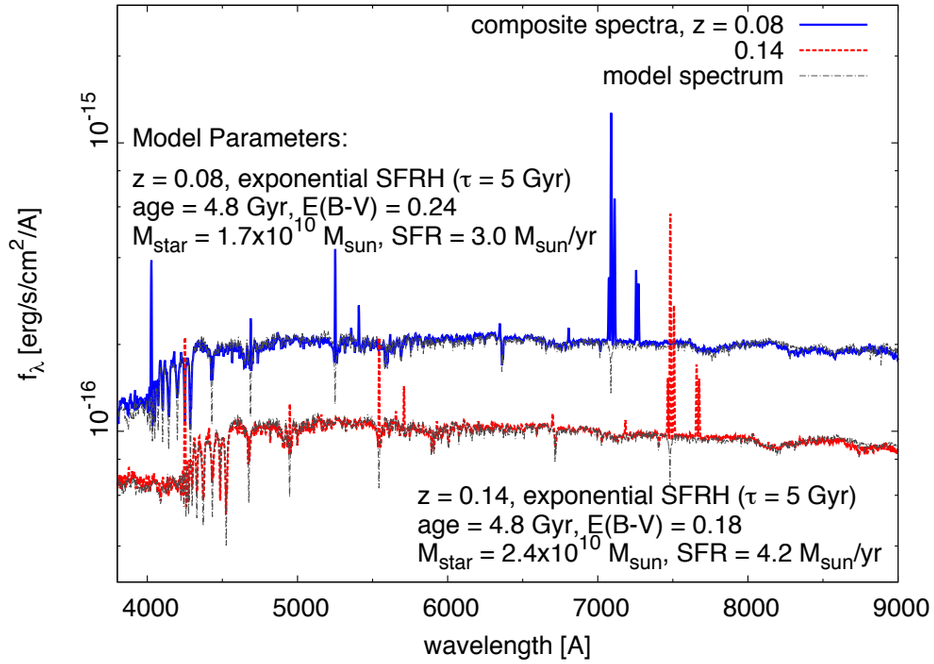


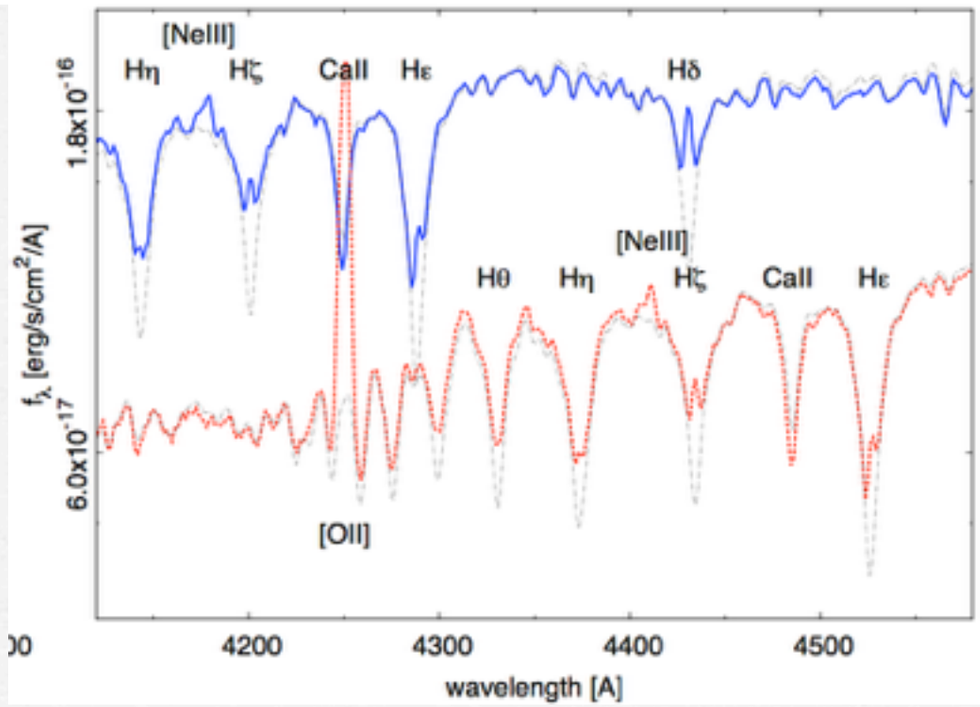


Noise and Continuum Subtraction

- Galaxies with similar M★ and SFR would have lower S/N at higher redshifts.
  - Compose average spectra to obtain very high S/N.
    - continuum S/N ≳ 100
- R_{23} and [NII]/Hα of the average spectra evolves in a consistent manner.

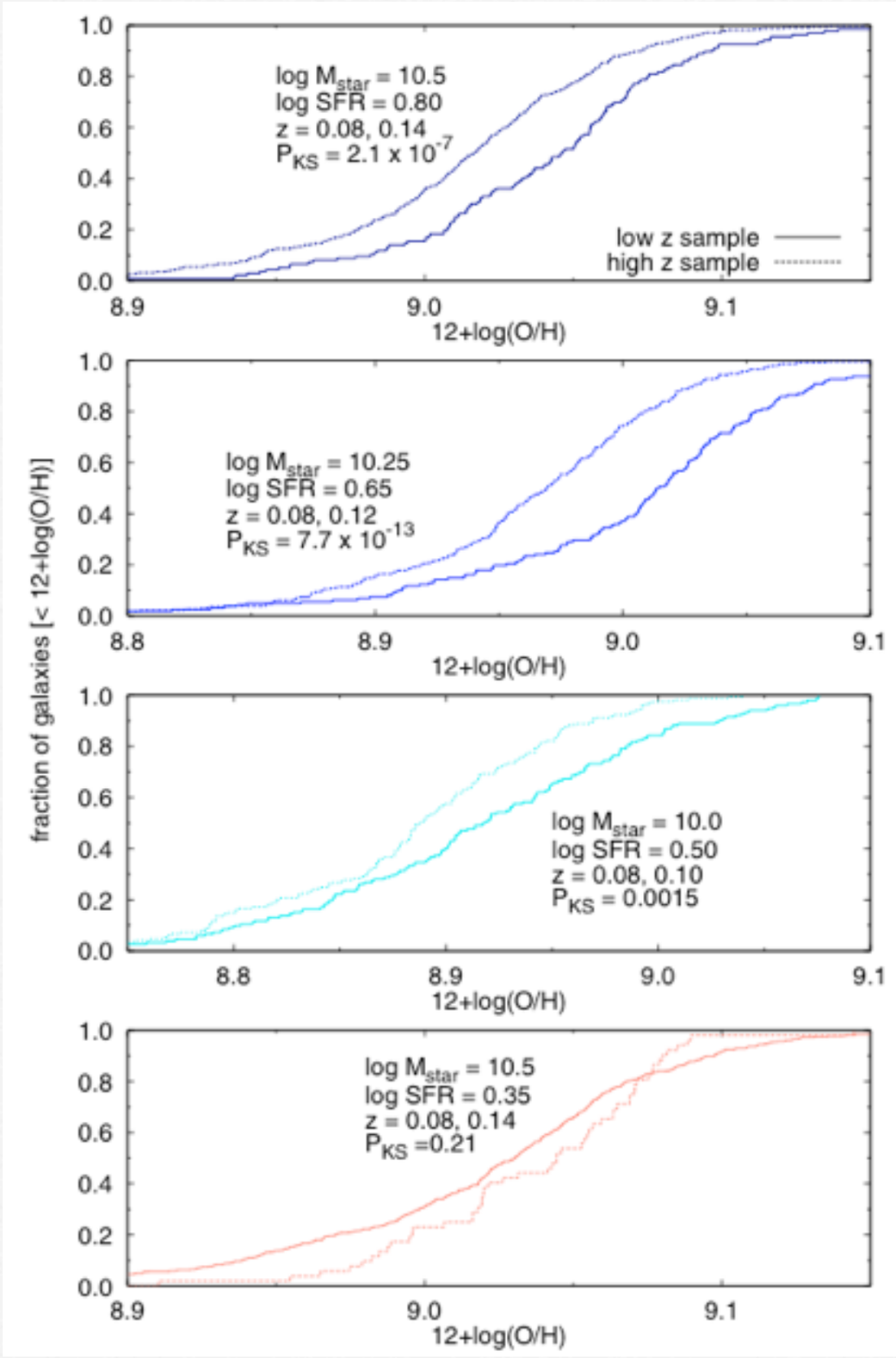


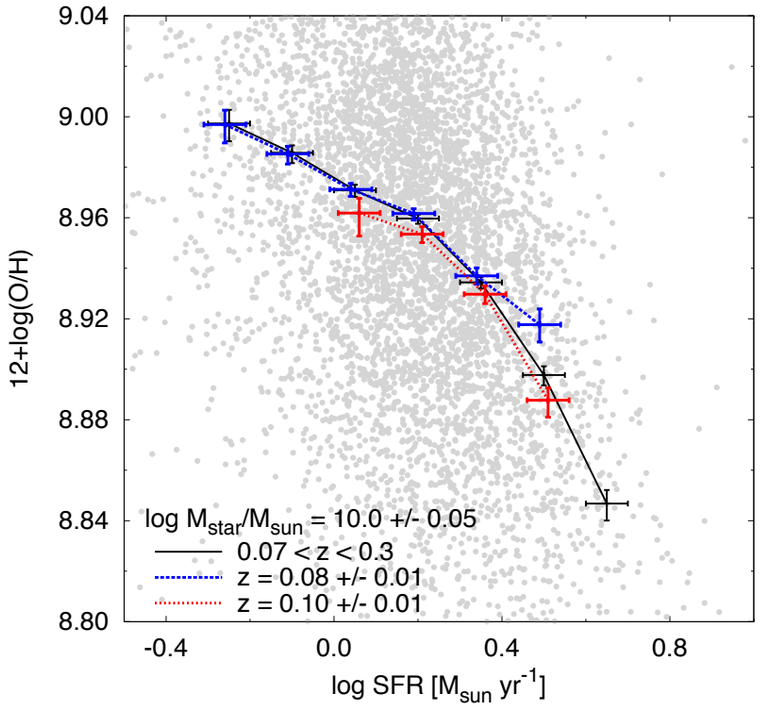


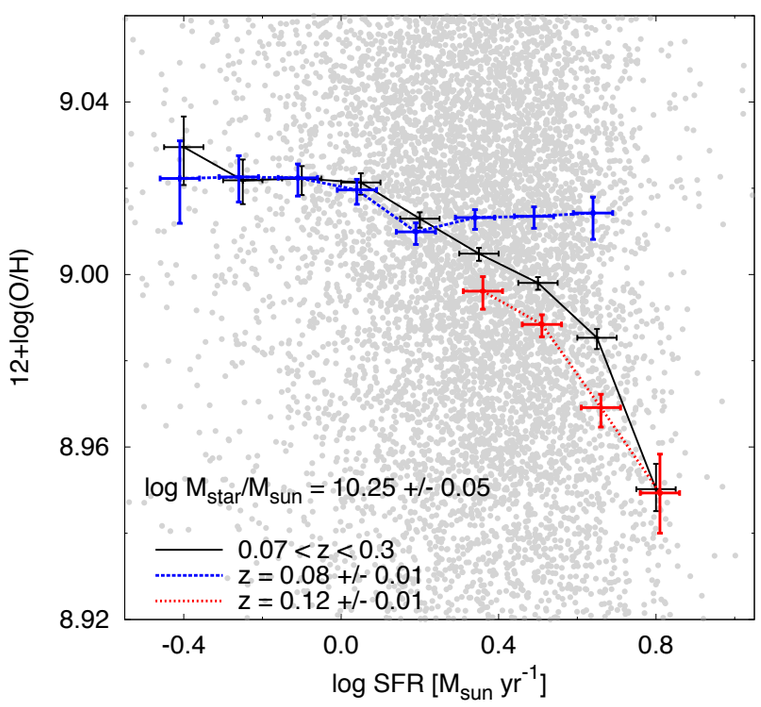


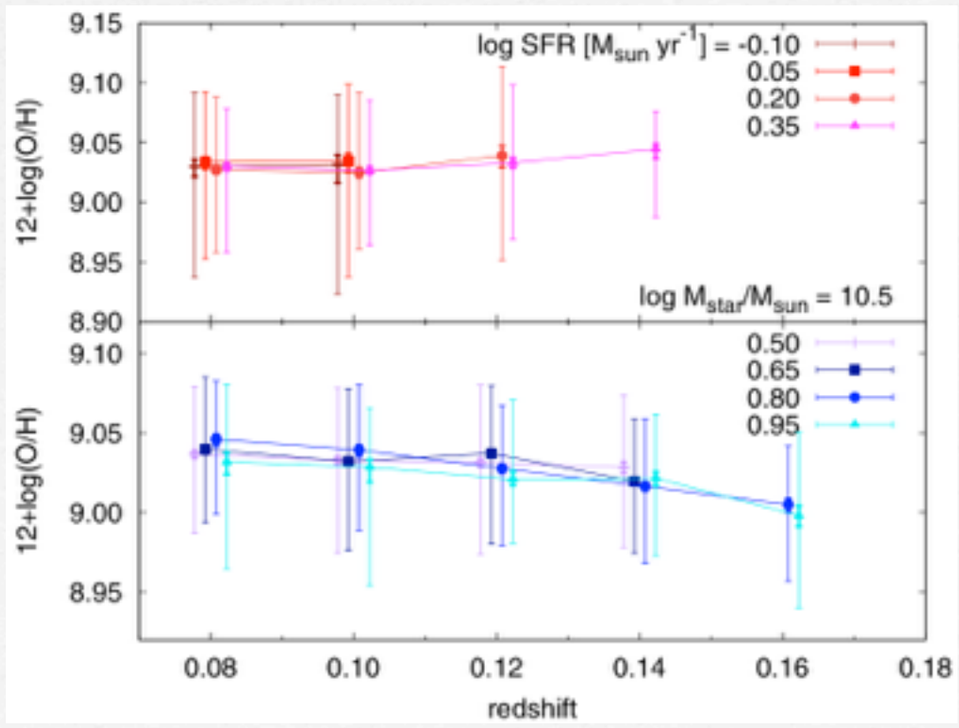
Is it significant?

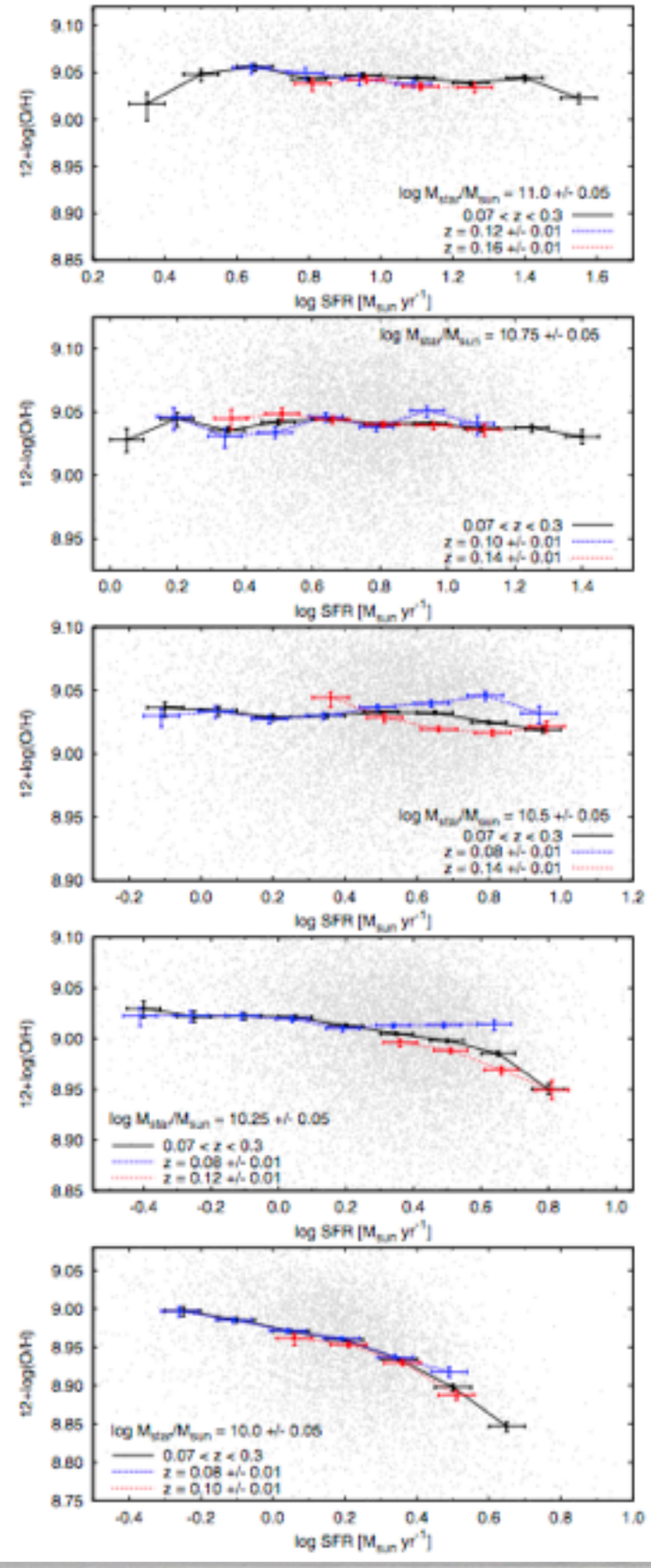
- The systematic difference of Z in different redshift bins is tiny.
  - ~ 0.05 dex
- Thanks to large sample of SDSS galaxies we can detect the evolution with high significance.
  - $P_{KS} < 0.002$




12+log(O/H)
log SFR [M_sun yr^-1]
log M_star/M_sun = 10.0 +/- 0.05
0.07 < z < 0.3
z = 0.08 +/- 0.01
z = 0.10 +/- 0.01


12+log(O/H)
log SFR [M_sun yr^-1]
log M_star/M_sun = 10.25 +/- 0.05
0.07 < z < 0.3
z = 0.08 +/- 0.01
z = 0.12 +/- 0.01


12+log(O/H)
redshift
log SFR [M_sun yr^-1] = -0.10
0.05
0.20
0.35
log M_star/M_sun = 10.5
0.50
0.65
0.80
0.95


12+log(O/H)
log SFR [M_sun yr^-1]
log M_star/M_sun = 11.0 +/- 0.05
0.07 < z < 0.3
z = 0.12 +/- 0.01
z = 0.16 +/- 0.01
log M_star/M_sun = 10.75 +/- 0.05
0.07 < z < 0.3
z = 0.10 +/- 0.01
z = 0.14 +/- 0.01
log M_star/M_sun = 10.5 +/- 0.05
0.07 < z < 0.3
z = 0.08 +/- 0.01
z = 0.14 +/- 0.01
log M_star/M_sun = 10.25 +/- 0.05
0.07 < z < 0.3
z = 0.08 +/- 0.01
z = 0.12 +/- 0.01
log M_star/M_sun = 10.0 +/- 0.05
0.07 < z < 0.3
z = 0.08 +/- 0.01
z = 0.10 +/- 0.01