The stellar mass-metallicity relation at 2.5 < z < 5.0

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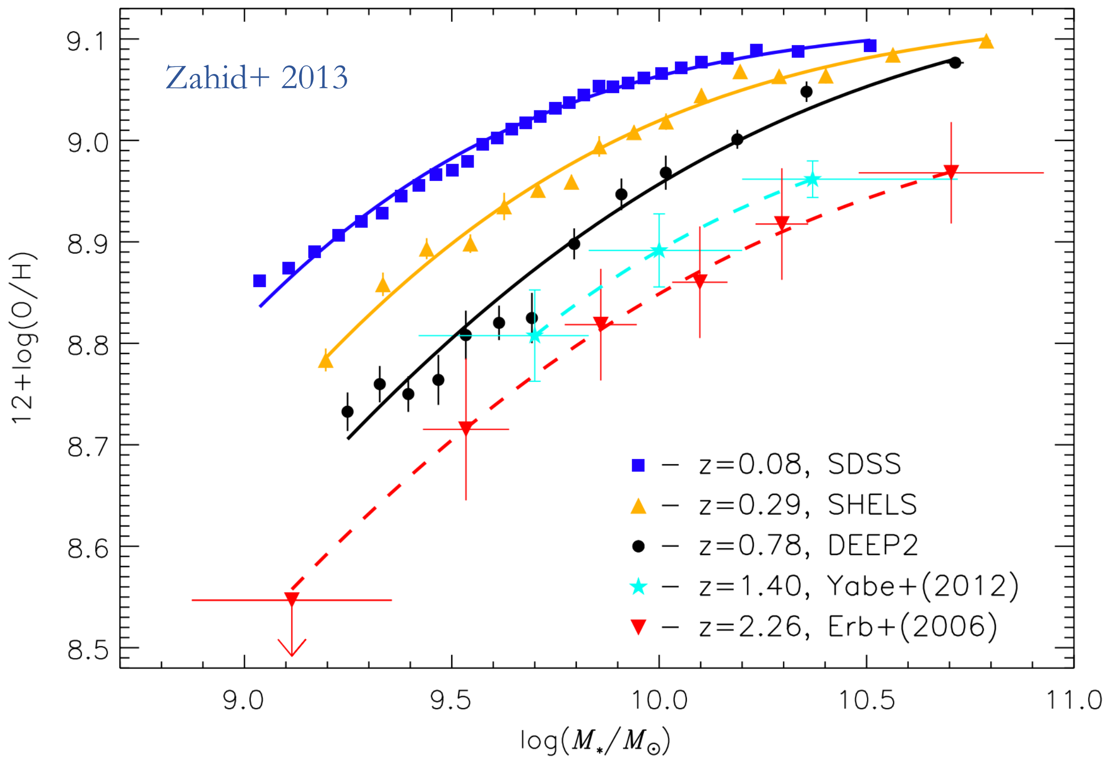
A deep VIMOS survey of the CANDELS UDS and CDFS fields

Gas-phase metallicity: observed out to z ~ 3



- The gas-phase mass-metallicity relation extensively studied to z ~ 3 (e.g. Maiolino & Mannucci 2019)
- Effected by a large number of systematic uncertainties (e.g. 0.8 dex between difference calibrations at z = 0, evolution of HII region parameters at high redshift etc..)

(Tremonti+04, Erb+06, Maiolino+08, Cullen+14, Steidel+14, Troncoso+14, Wuyts+14, Sanders+15, Onodera+16 …)

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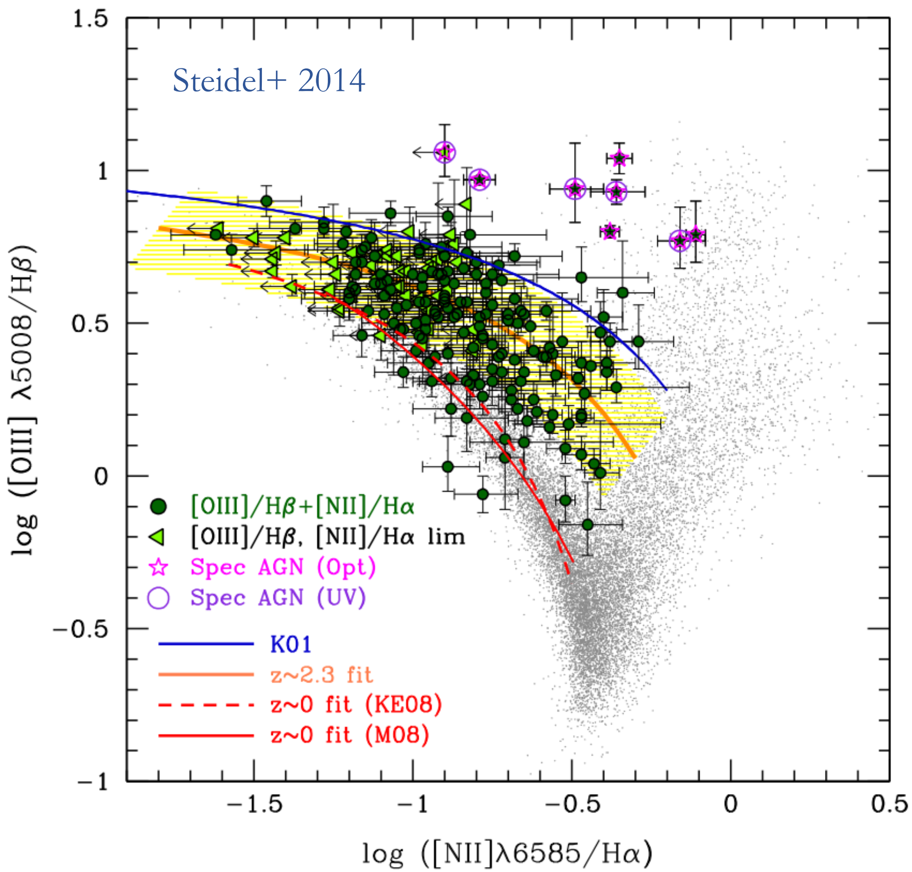
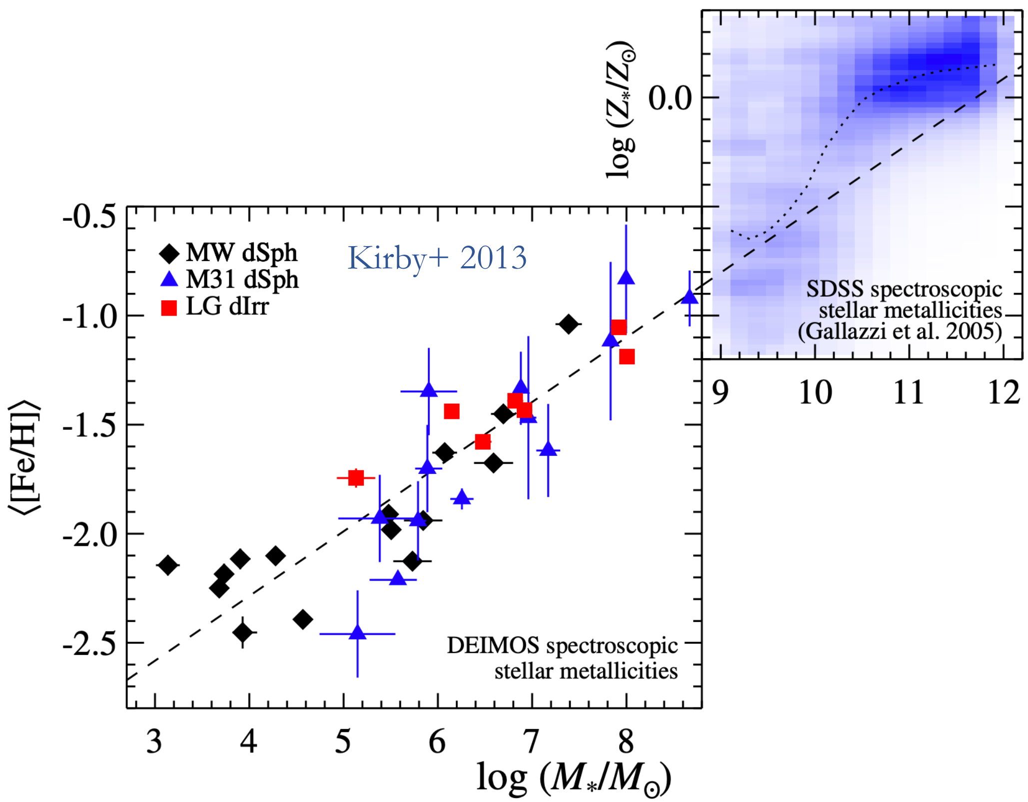


- The nebular line ratios at z > 2 are systematically offset from typical values at z=0 for reasons not related to metallicity evolution (e.g. hardness of the ionizing radiation field, ionization parameter, electron density, DIG, N/O variations …)

(Shapley+15, Cullen+16, Sanders+16, Kashino+17 …)

Alternative: stellar metallicities



- Stellar metallicities provide an alternative to gas-phase metallicities
- Immune issue relating to the evolution in ISM conditions, potentially fewer systematics?
- Much harder to observe however – need S/N of 15-20 in the continuum

(Gallazzi+05, Panter+08, Zahid+17, Lian+18 …)

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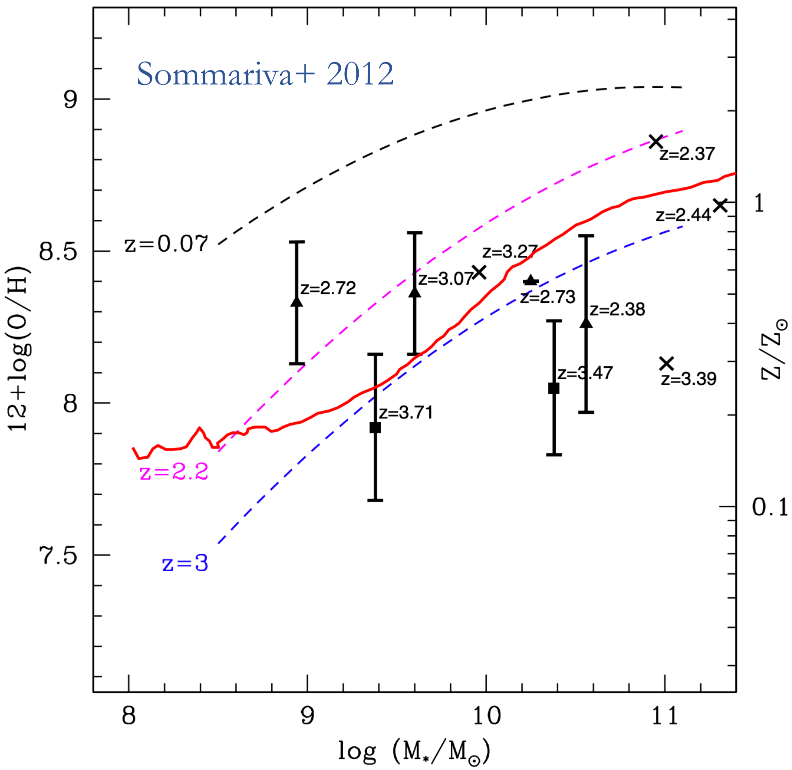

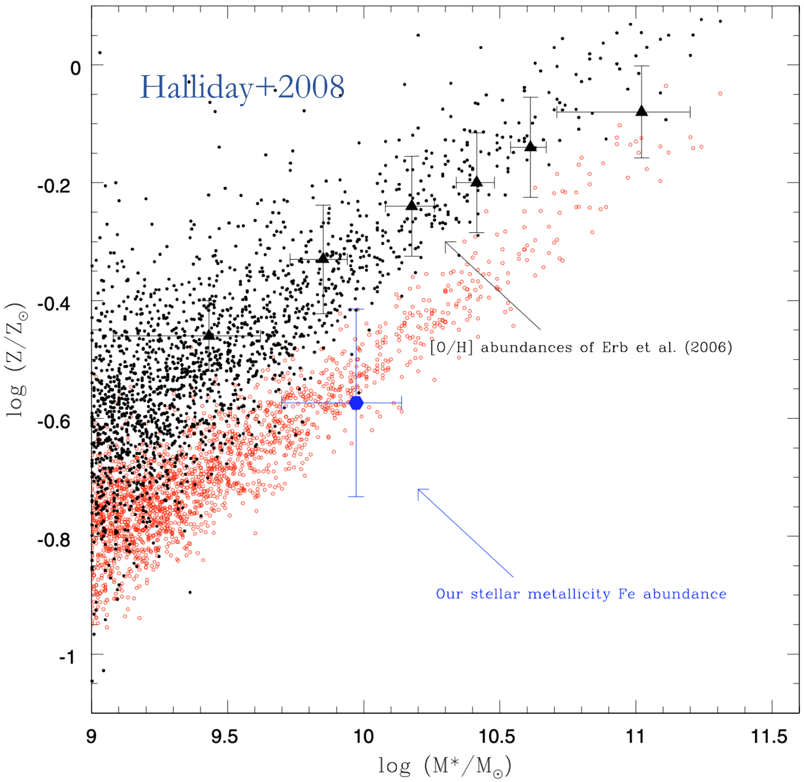

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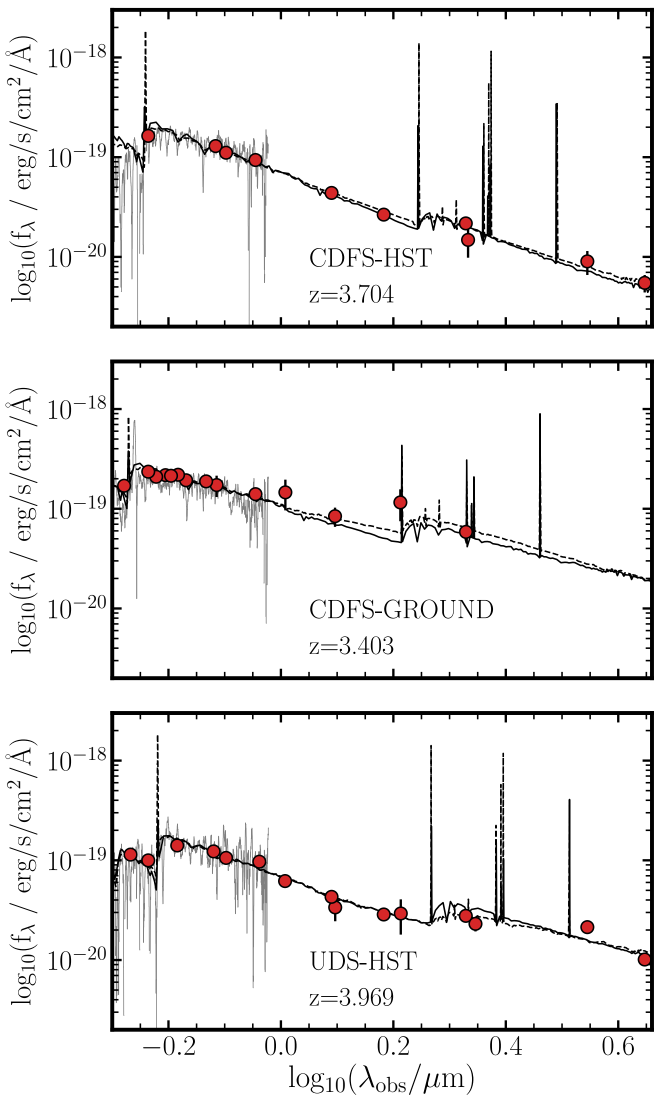
Measuring the stellar mass-metallicity relation at high-redshift with VANDELS

Cullen et al. 2019, MNRAS, 487, 2038 (arXiv:1903.11081)

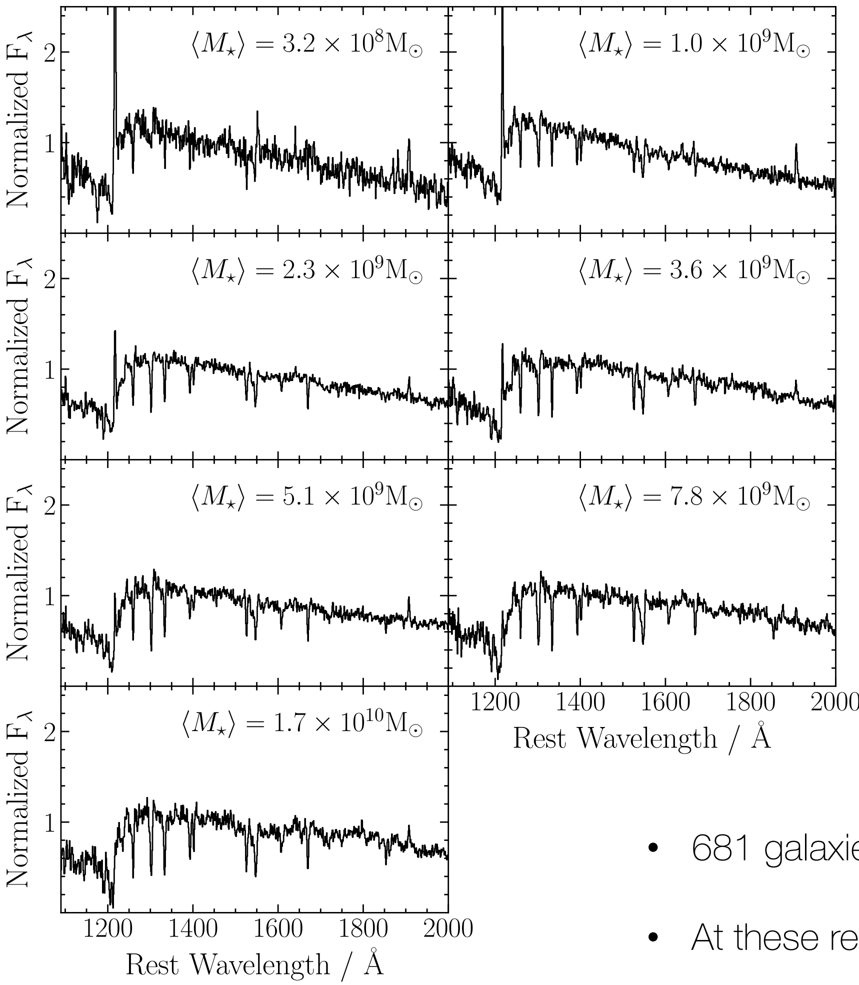
The VANDELS survey

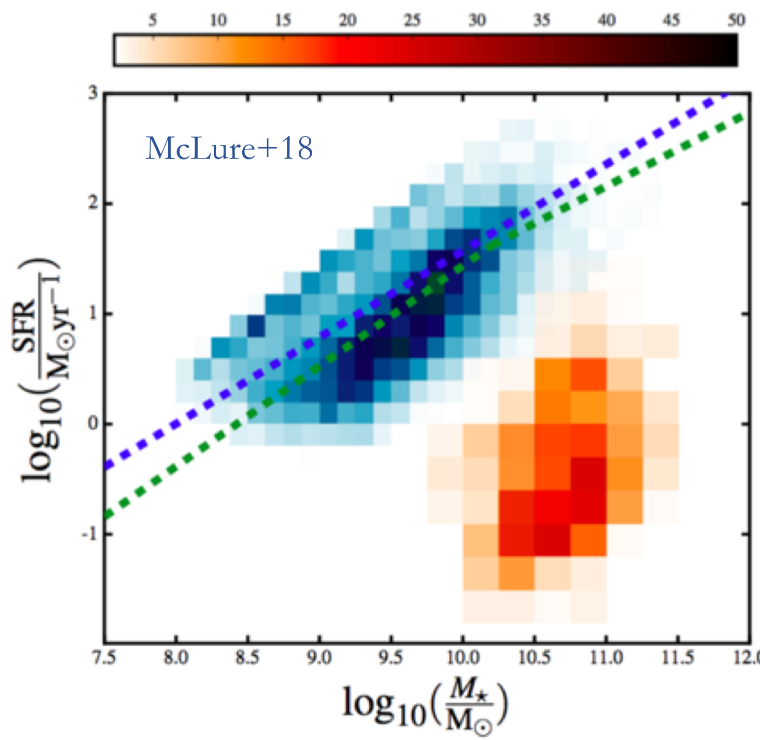
McLure+18, Pentericci+18



- ESO large spectroscopic survey targeting ~ 2000 galaxies with VIMOS in CDFS and UDS
- Spectra cover observed 0.48 – 1.0 micron with R = 580
- Sample consists of star-forming galaxies at $z > 2.5$ and quiescent galaxies at $1.0 < z < 2.5$
- USP of VANDELS is the extremely large integration times (up to 80 hr on source)

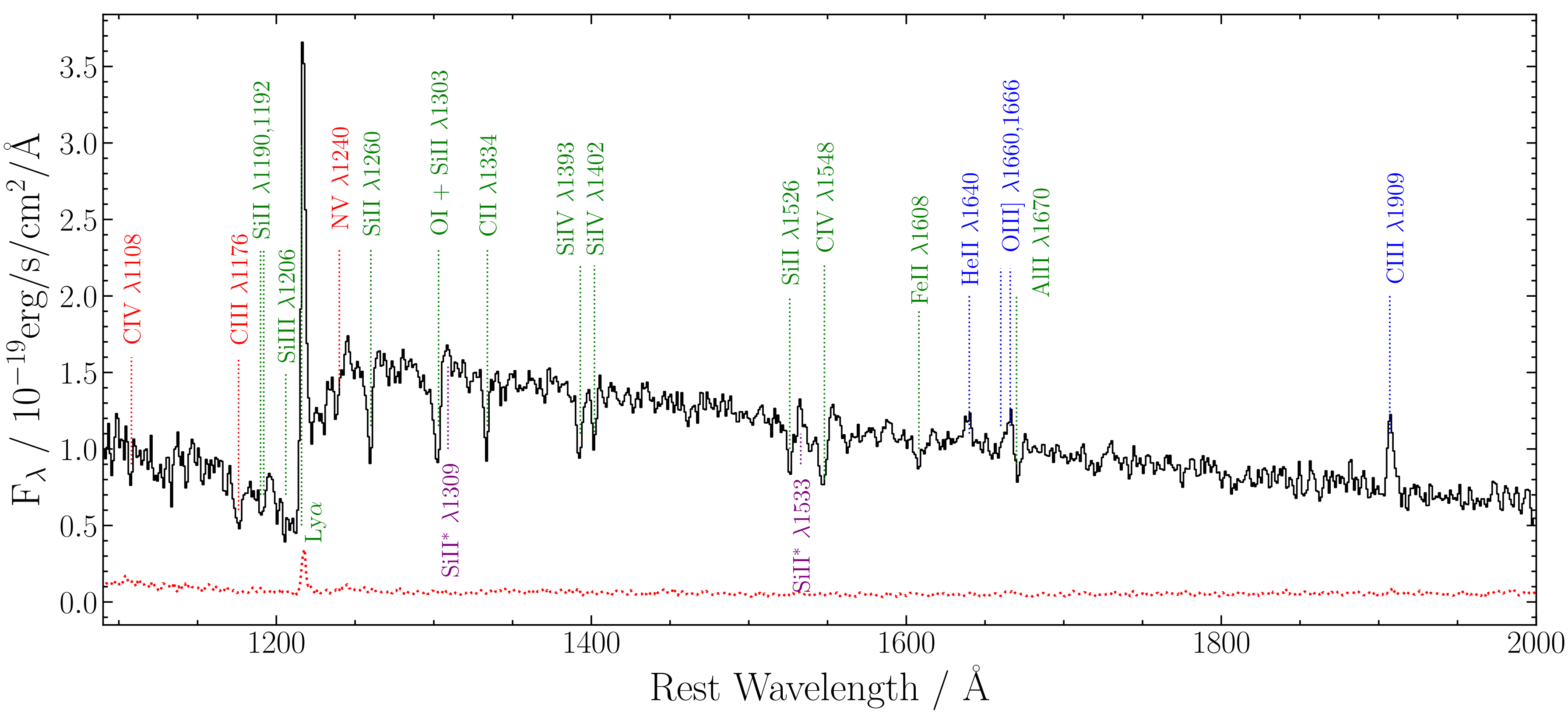
2.5 < z < 5.0 sample





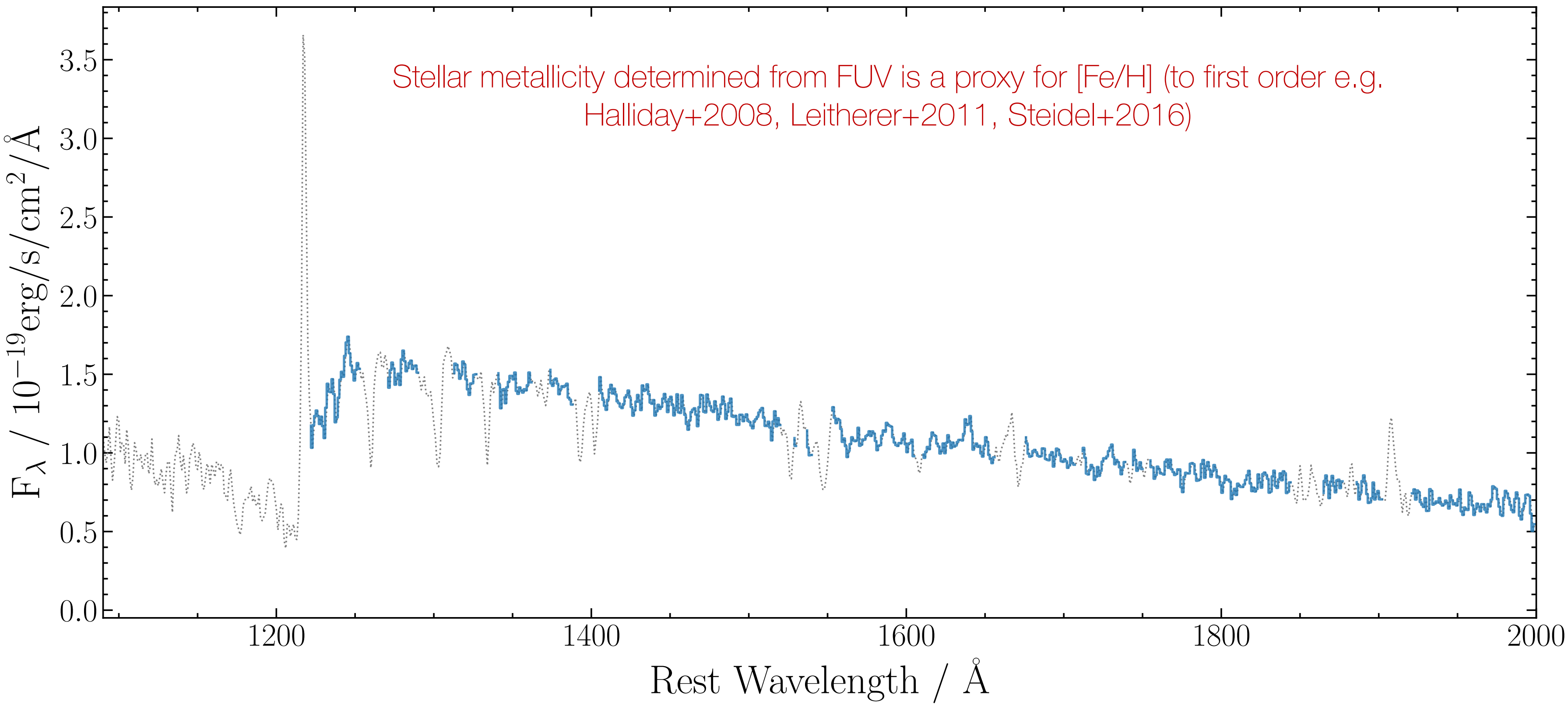
- 681 galaxies at 2.5 < z < 5.0 from VANDELS DR2 (< z > = 3.5)
- At these redshifts, VIMOS cover the rest frame FUV spectrum
- The sample spans 3 dex in stellar mass (10^8 – 10^{11} M_o) drawn from the main sequence of star formation

Rest-frame FUV spectra



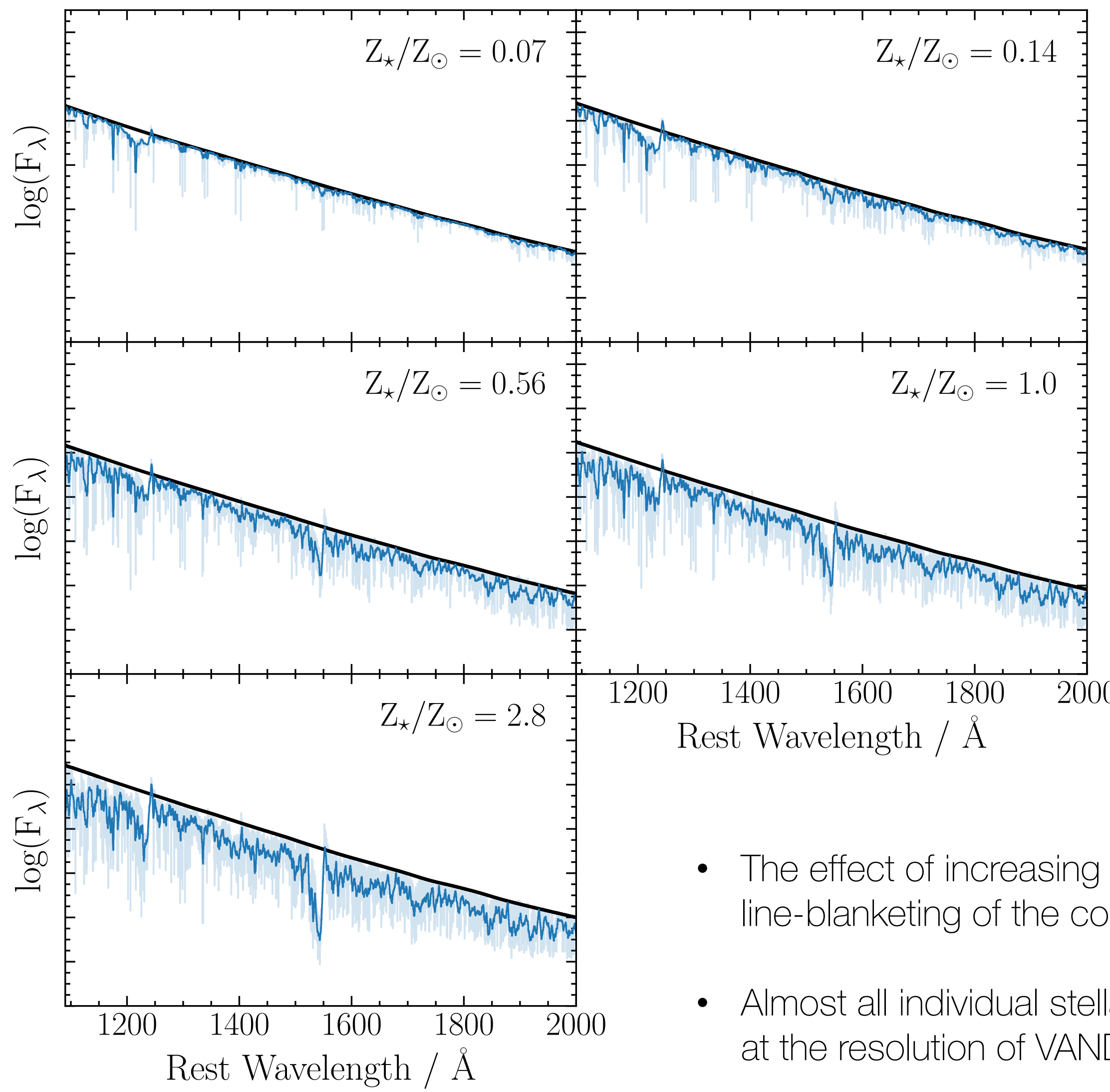
Stellar absorption *Low/High ionization ISM absorption* *Fine structure emission* *Nebular emission*

Rest-frame FUV spectra



Leitherer+2011: “Stellar photospheric features abound shortward of ~2000Å, where O- and B-star spectra exhibit heavy line blanketing, primarily by transitions of highly ionized iron and nickel”

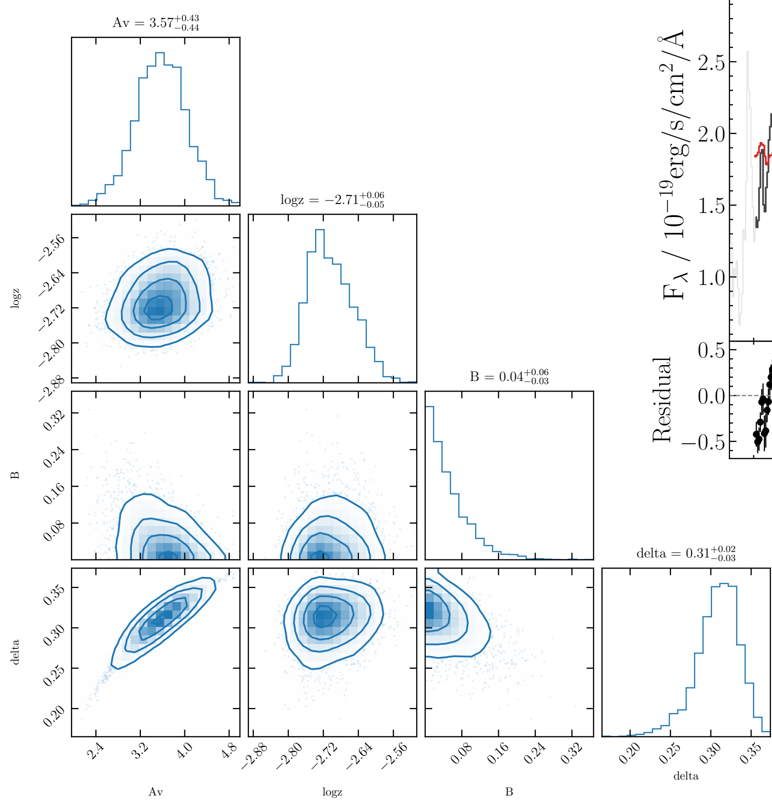
Effect of increasing metallicity

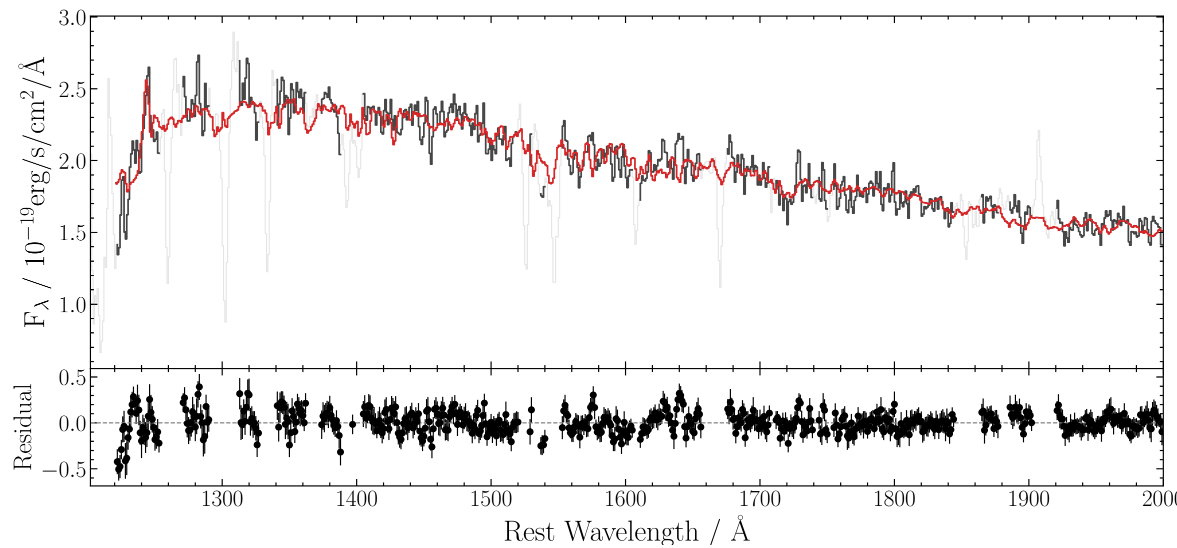


- The effect of increasing metallicity is an increasing line-blanketing of the continuum

- Almost all individual stellar absorption lines blended at the resolution of VANDELS spectra

Model fitting (Bayesian Nested Sampling)

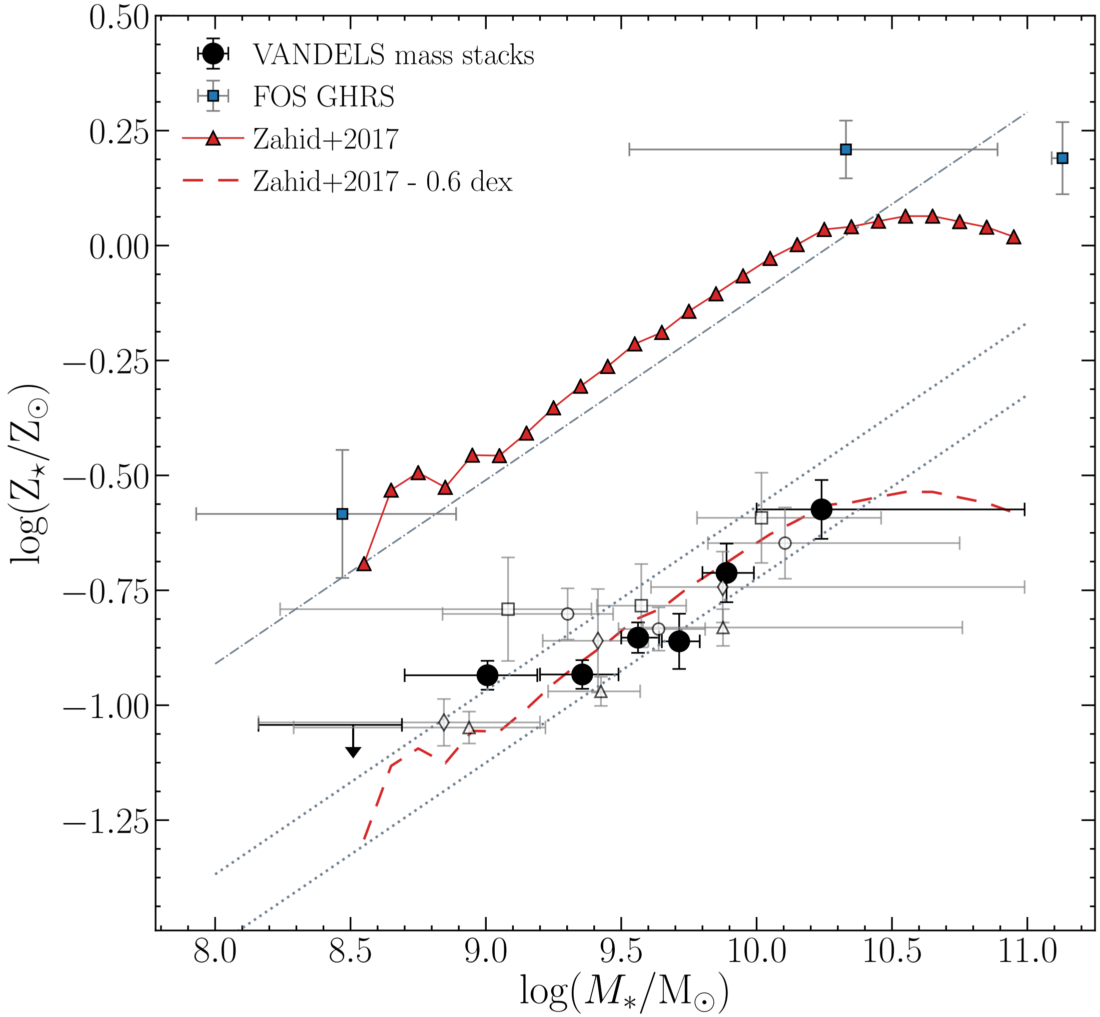




$$A_{\lambda,\mathrm{mod}} = \frac{A_V}{R_{V,\mathrm{mod}}}\left[k_{\lambda,\mathrm{Calz}}\frac{R_{V,\mathrm{mod}}}{R_{V,\mathrm{Calz}}}\left(\frac{\lambda}{5500\text{Å}}\right)^{\delta} + D_\lambda\right]$$

- Starburst99 WM-Basic models (constant SFH) + flexible dust prescription (4 free parameters)

Stellar MZR at 2.5 < z < 5.0



- MZR slope consistent with the slope of SDSS galaxies (Zahid+2017) with an offset of -0.6 dex
- log(Z) monotonically increases with stellar mass from < 7% to 25 % solar
- No evolution seen within the redshift range of our sample (2.5 < z < 5.0)

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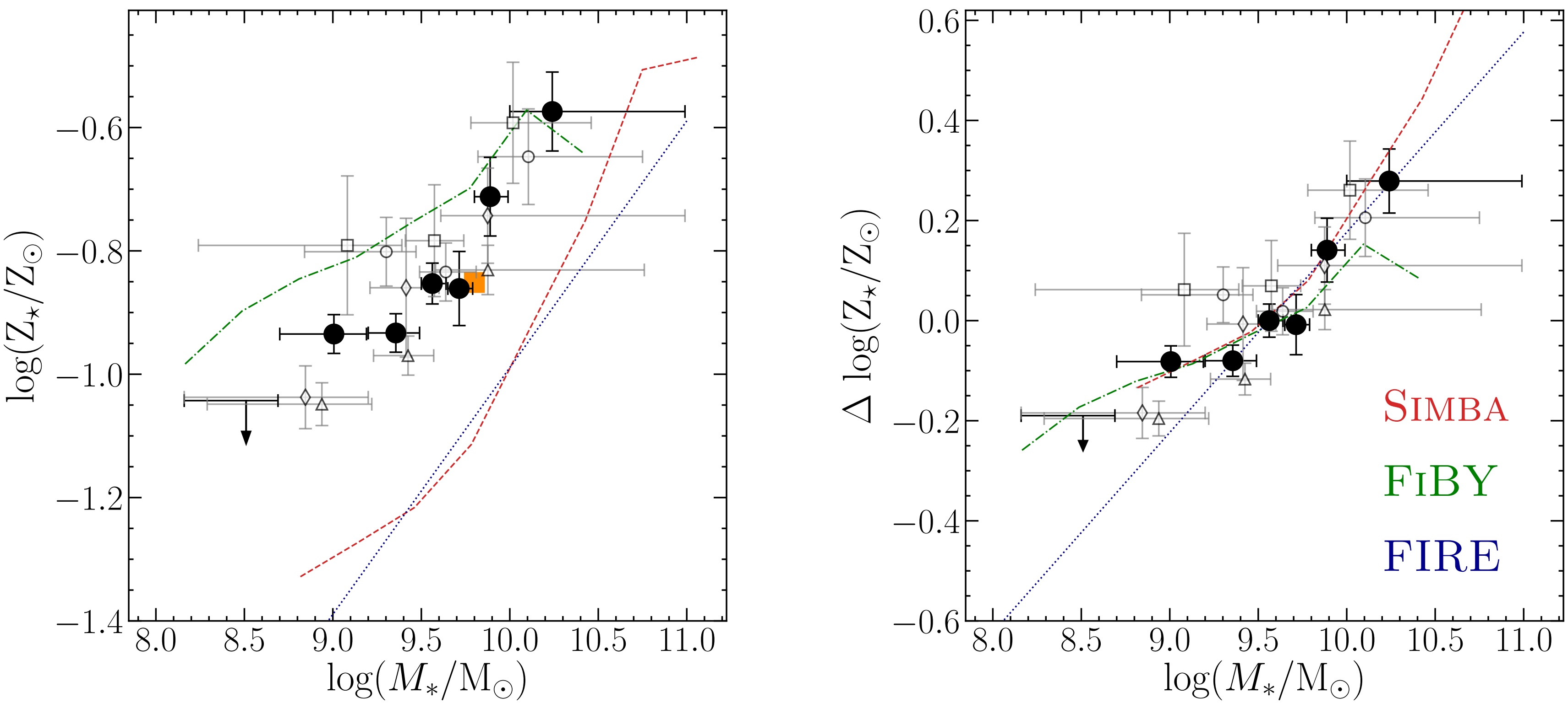
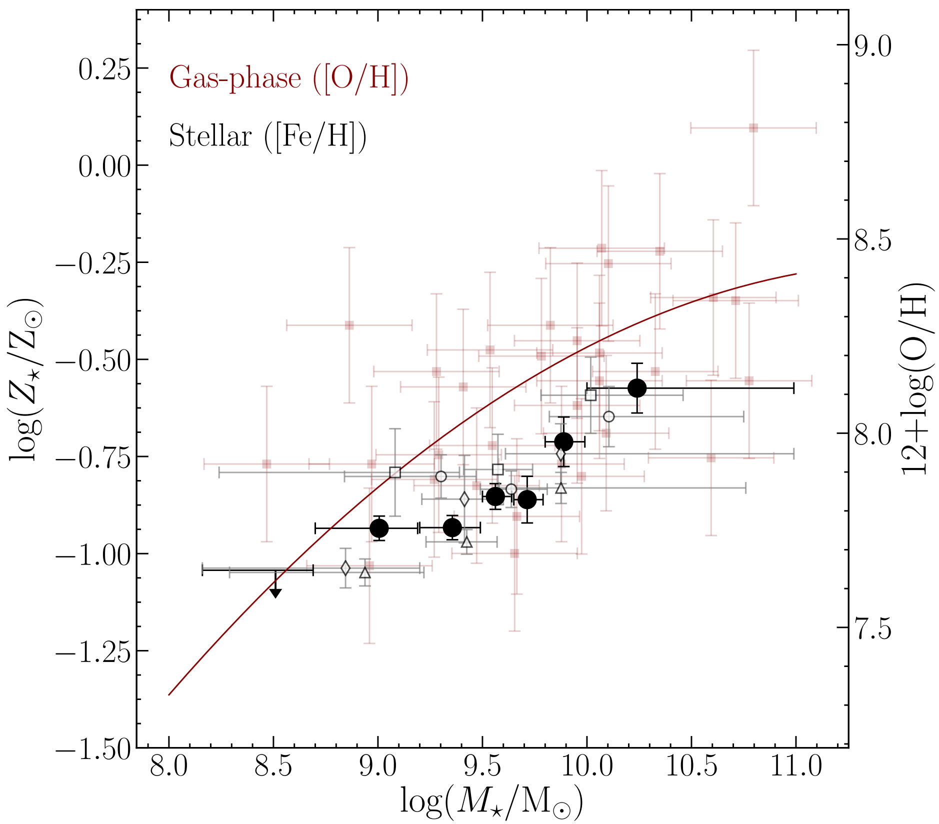


- Comparing to simulations, absolute abundances are not consistent, however the slope is generally well recovered

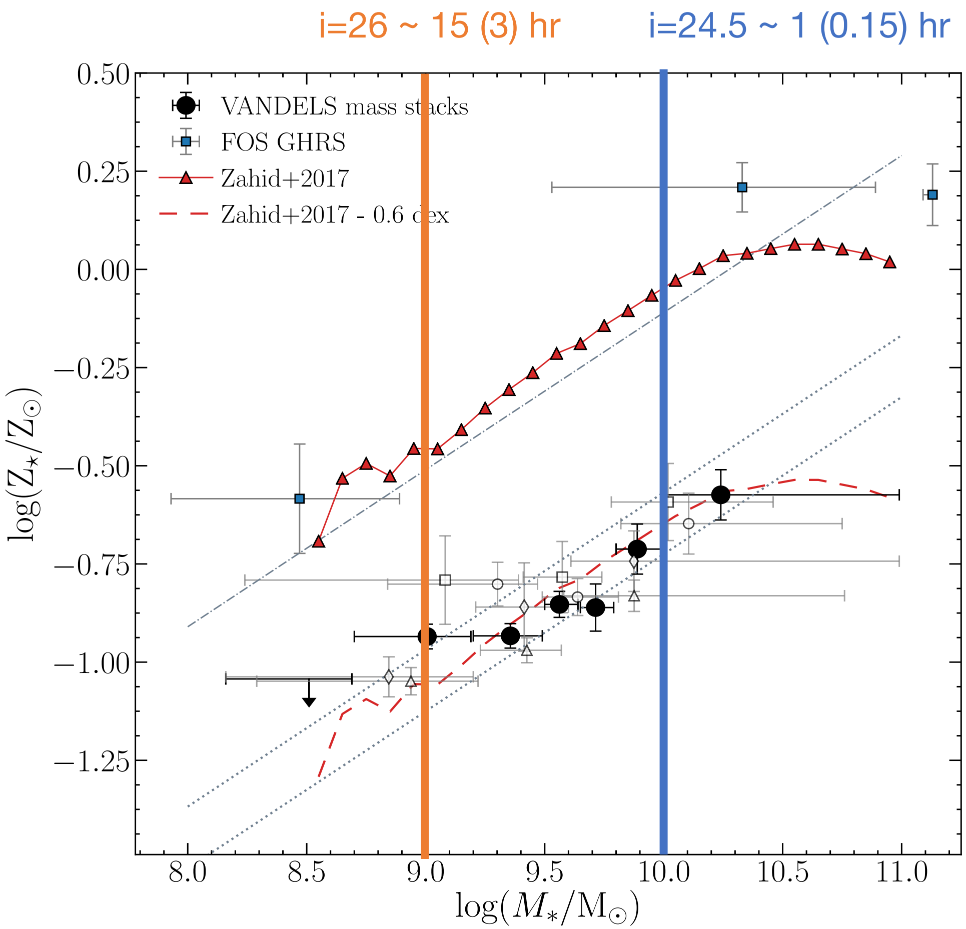
Alpha-enhancement?



Maiolino+08, Mannucci+09, Troncoso+14

- Comparing to published gas-phase metallicities (tracing O/H) at similar redshifts suggest alpha-enhancement of (O/Fe) ~ 2
- Need to be careful of sample biases etc
- Obvious next step in rest-frame optical follow-up of VANDELS galaxies

FUV metallicities in the ELT era



- Based on current sensitivity estimates, MOSAIC in the visible could achieve S/N = 15 in roughly 1 hour of integration for sources with i=24.5 (corresponds to ~ 10^{10} M_o at z=3.5)
- Galaxies with 10^9 M_o (i=26) could be observed in ~ 15 hours
- Degrading to VANDELS resolution would reduce the required times (to ~ 3, 0.15 hrs)
- ELT will allow estimates of individual metallicities at z=3-4 (and at higher redshifts by observing in near-IR)

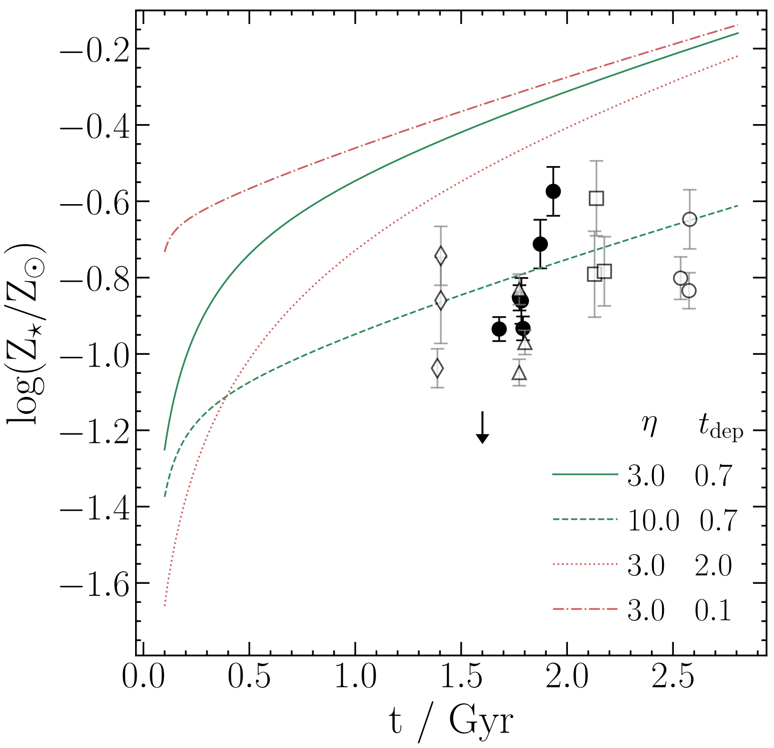
Summary

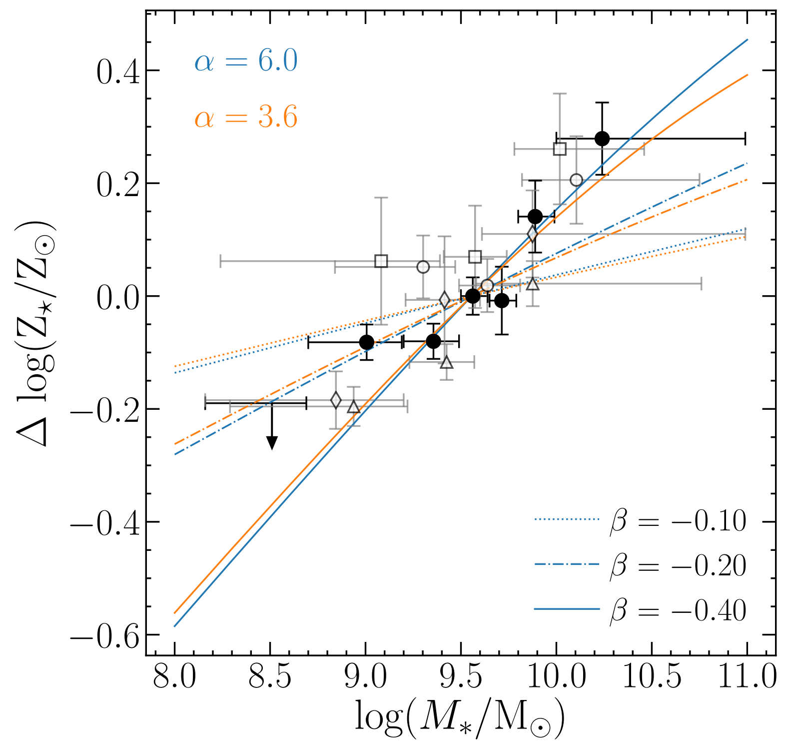
- Clear evidence for a stellar mass-metallicity relation at z = 3.5 with a similar slope to the local SDSS relation
- Stellar metallicity (Fe/H) increases from **< 0.07 Z_{o}** at 10^{8} M_{o} to **0.25 Z_{o}** at 10^{11} M_{o}
- Comparing to current estimates of O/H at z=3.5 implies an O/Fe ratio of >~ 2 x solar
- Current cosmological simulations reproduce the shape of the observed relation

Future work:

- With the full sample: secondary dependence on star formation rate (i.e. FMR)
- Follow-up near-IR spectroscopy for robust O/H measurements and alpha-enhancements (detailed modeling of the full FUV – optical spectrum)
- In the ELT-era: at similar redshifts obtain large samples of individual metallicity estimates + push similar studies to higher redshift (into the reionzation era)

Evidence for strong outflows?





Comparing to the *Weinberg, Andrews, Freudenburg 2017* analytical models: the low metallicities require large mass loading parameters (e.g. strong stellar winds). Consistent with FIRE predictions (e.g. Muratov+15)