Investigating environmental effects on galaxy evolution in the high-redshift Universe

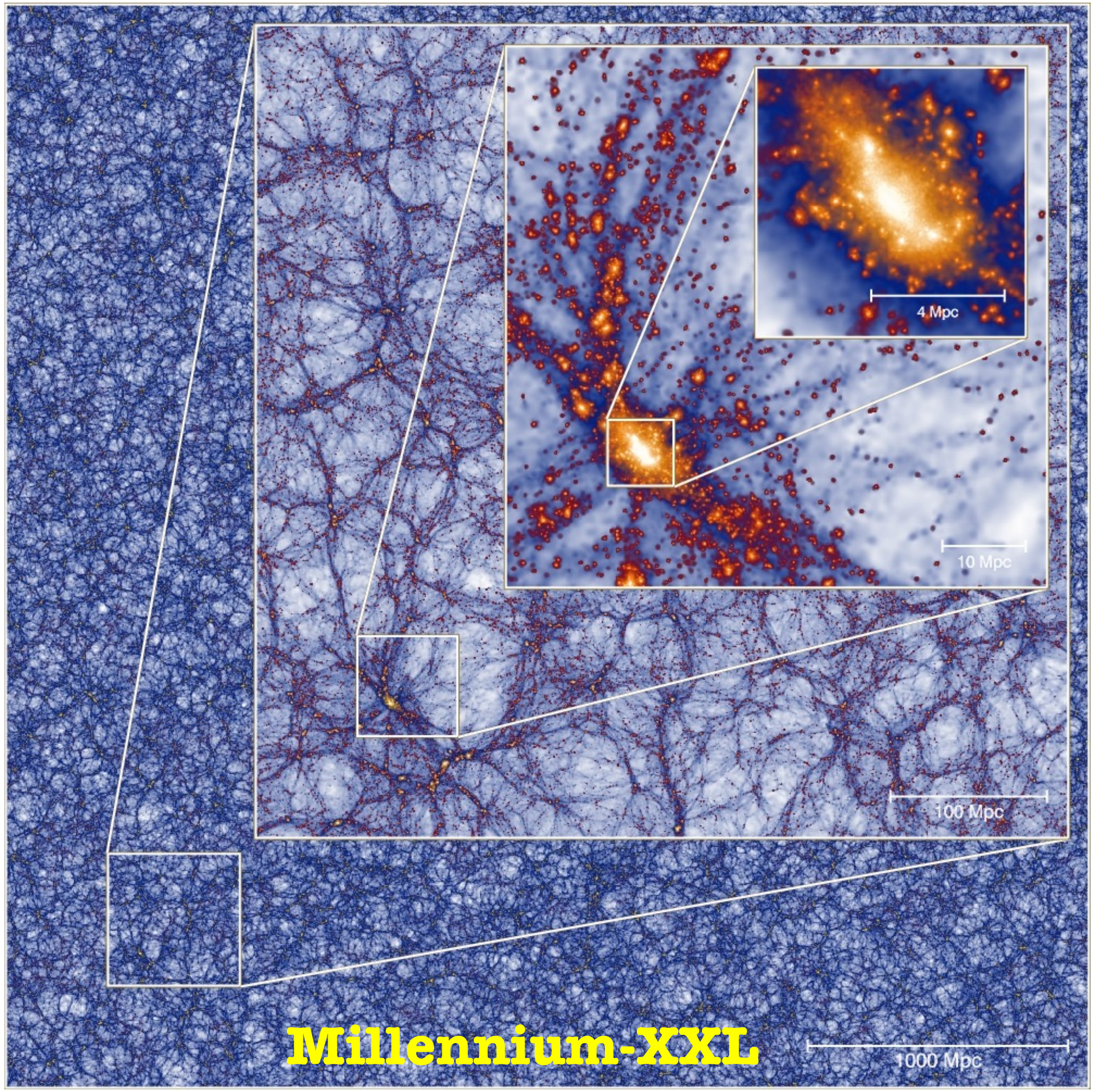
Antonello Calabrò

OAR INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

In collaboration with L. Pentericci, B. Garilli + team VANDELS and GAEA

INAF-IASF 15 December 2021

The Universe seen at different scales

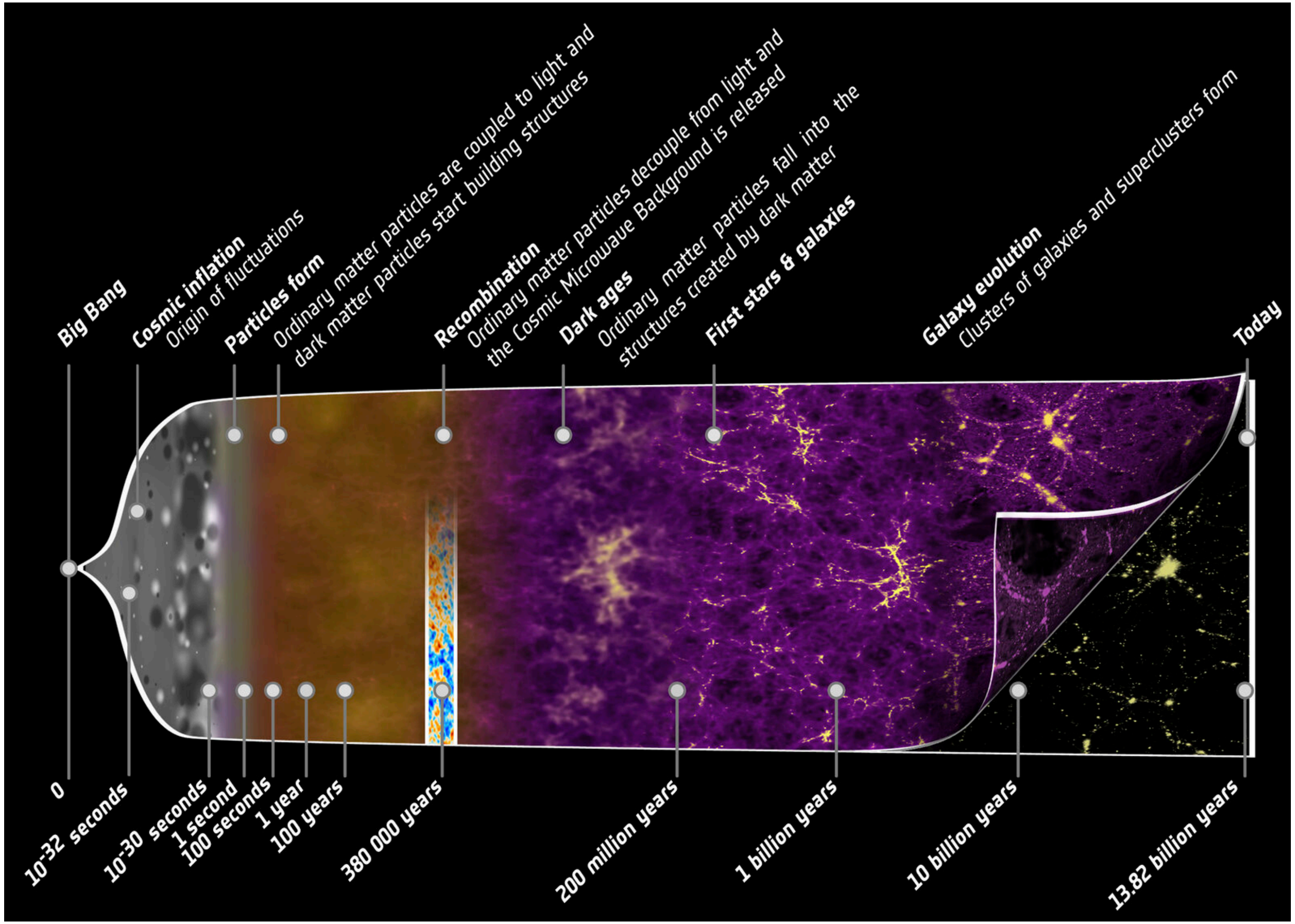


COSMOLOGICAL PRINCIPLE :
The Universe is isotropic and homogeneous on very large ~ 1Gpc scales (assumption of the general relativity, Einstein 1917)

COSMIC WEB :
Intricate, multi-scale, inter-connected network of galaxies, intergalactic gas, and dark matter

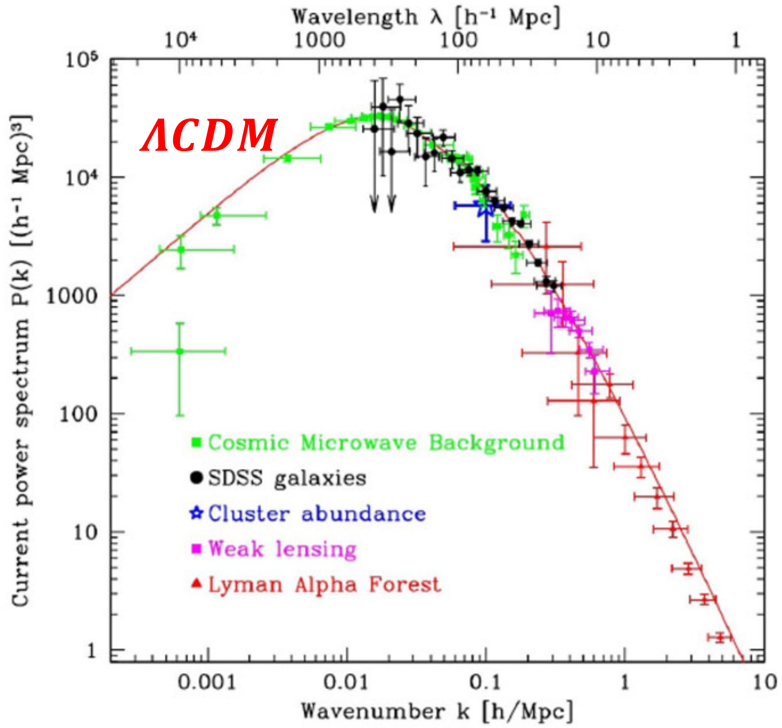
- It is the fundamental spatial organization of matter on scales of 1—100 Mpc
- formed of dense compact clusters, long elongated filaments, sheetlike walls surrounding near-empty voids (Bond et al. 1996)

The history of structure formation



Planck-collaboration

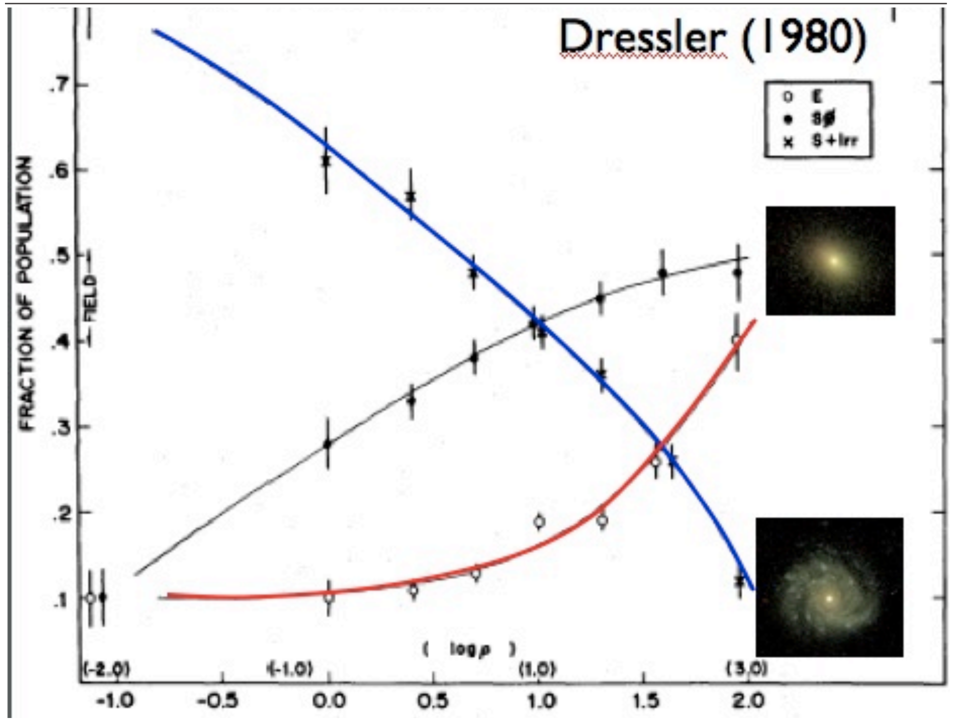
The large-scale distribution of galaxies results from the gravitational evolution and hierarchical clustering of the density fluctuations imprinted on dark matter during inflation.



Tegmark +2004

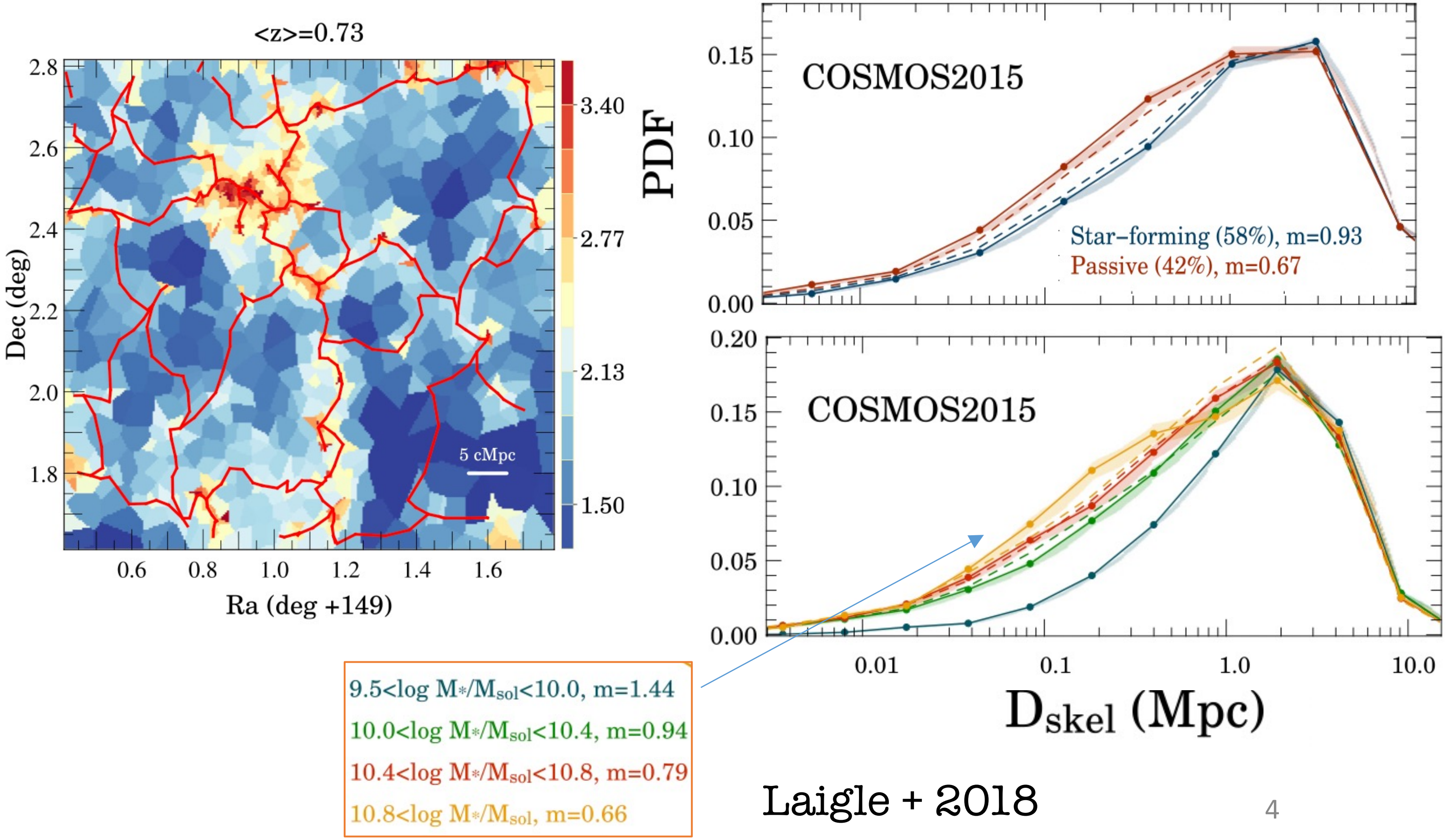
Does the cosmic web influence galaxy evolution ?

- Morphology - density relation (Dressler +1980)
- SFR - density relation (Kauffmann +2004)
- galaxies in clusters (i.e., overdense regions) evolve faster than in voids (Thomas +2005)



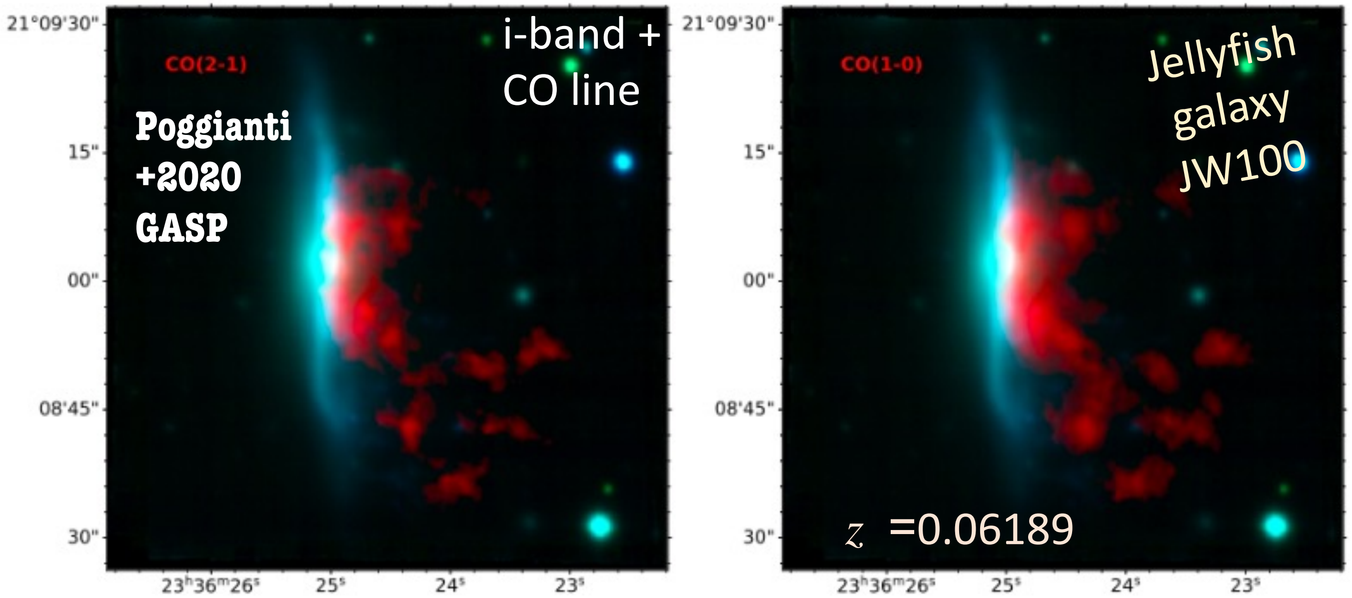
log ρ_{proj}

- also the cosmic web impacts on galaxy properties:
- most massive galaxies are statistically closer to their neighbouring filaments.
- at fixed stellar mass, passive galaxies are found closer to their filament, while star-forming galaxies lie further away

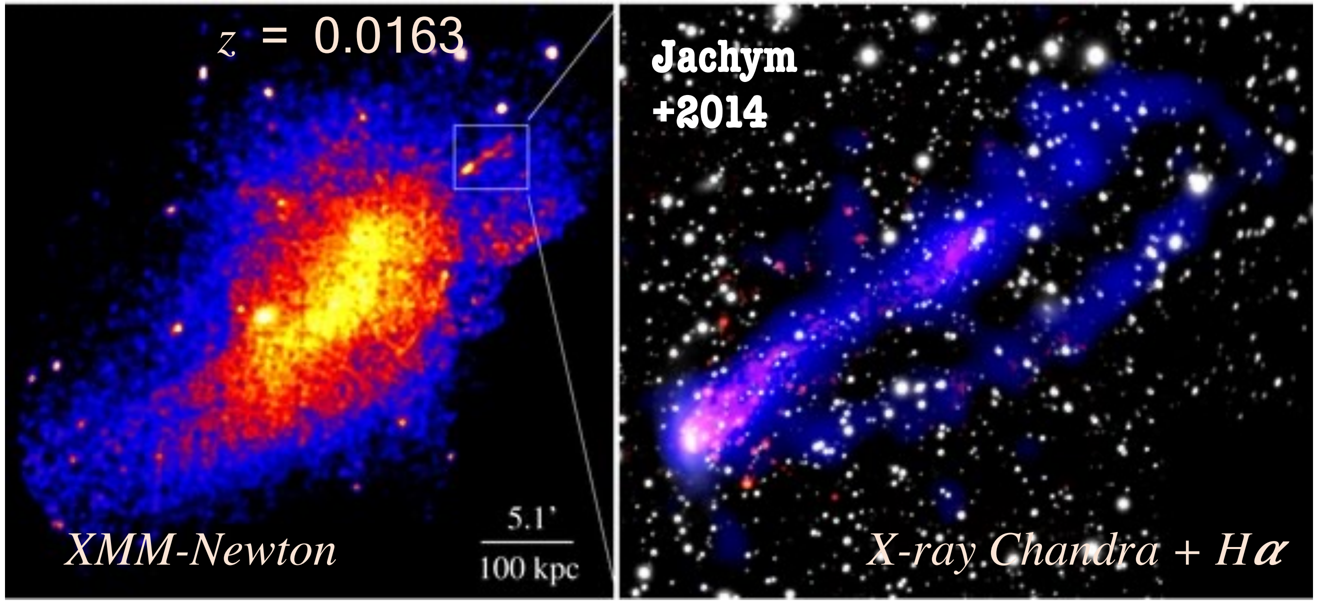


Laigle + 2018

Showcase examples of environmental effects in the local Universe



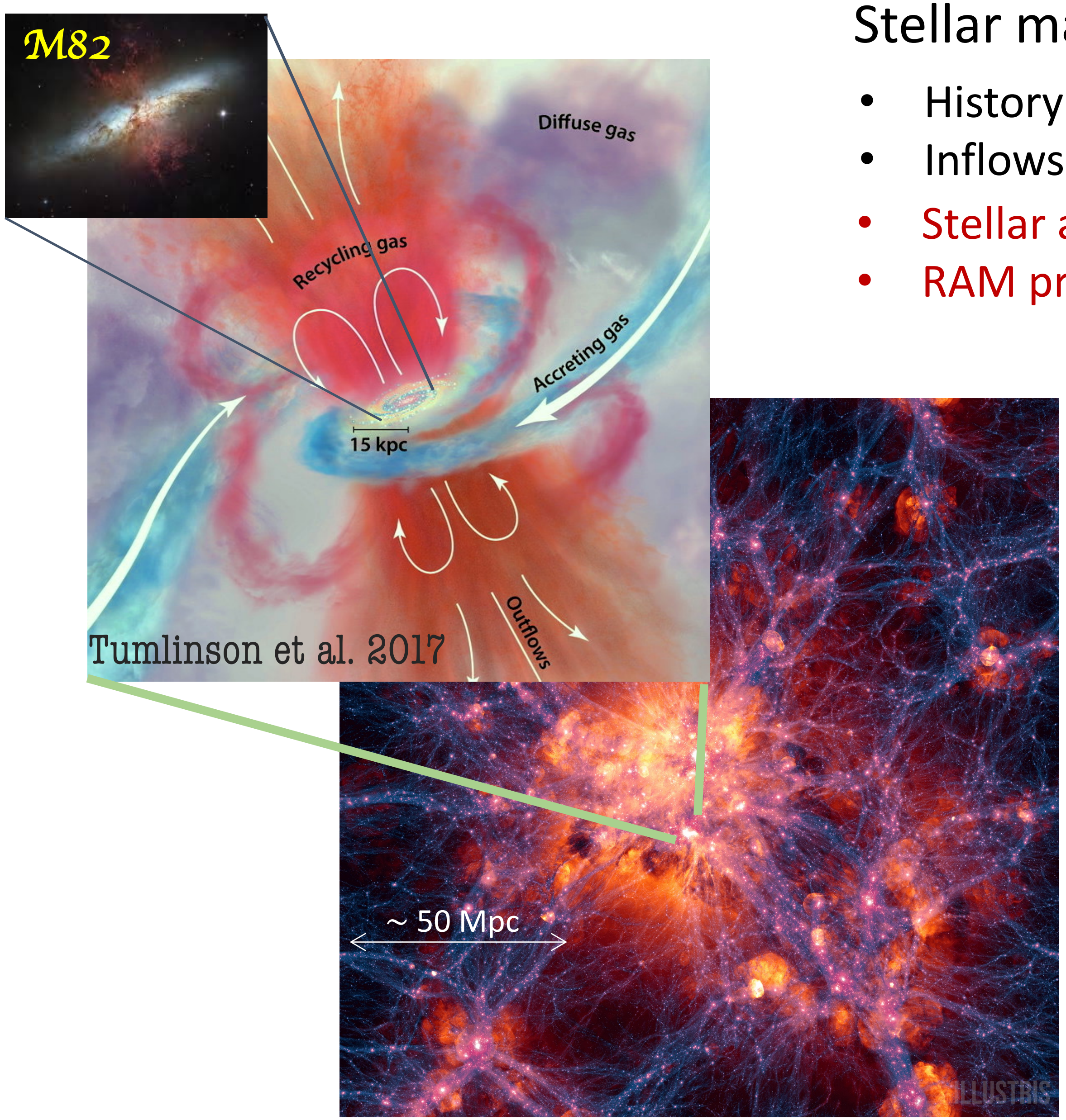
Examples of RAM-pressure stripping in the local Universe



Environmental processes on large (~ Mpc) scales :

- ram pressure stripping (e.g., Abadi+99, Kapferer+09, Sun+10, Ebeling+13)
- harassment (e.g., Moore+96, Bialas+15)
- starvation/strangulation (e.g., Peng+15)
- cosmological starvation (e.g., Dekel +09, Aragon-Calvo +19)

The metallicity is a key parameter to test the galaxy-environment interaction

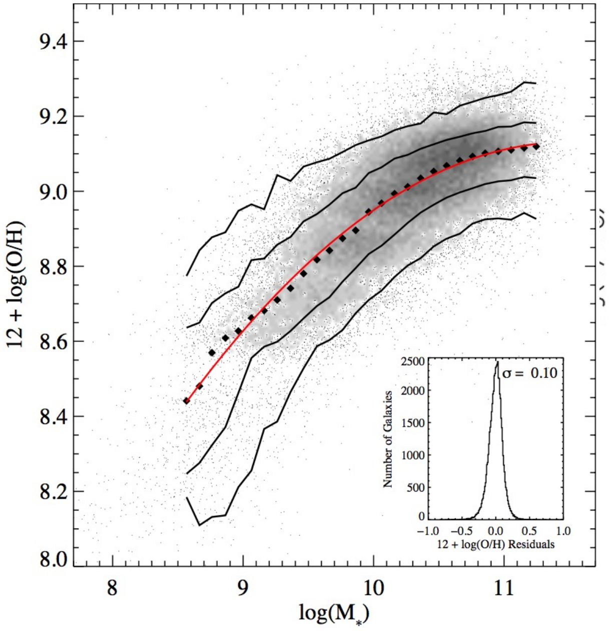


Stellar mass – metallicity relation (MZR) sensitive to :

- History of star-formation
- Inflows from the cosmic web
- Stellar and AGN driven outflows
- RAM pressure stripping, harassment, starvation

(ionized) gas-phase metallicity

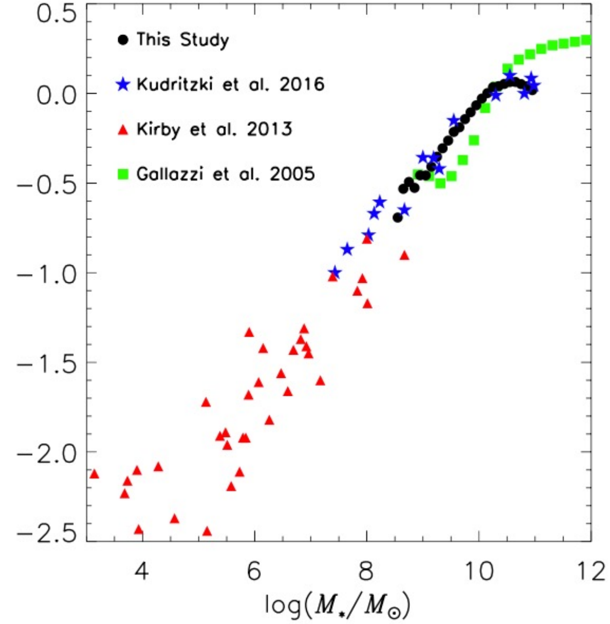
- $Z_{gas} = 12 + \log(O/H)$



Tremonti +2004

Stellar metallicity

- $Z_{*} \sim \log(Fe/H)$

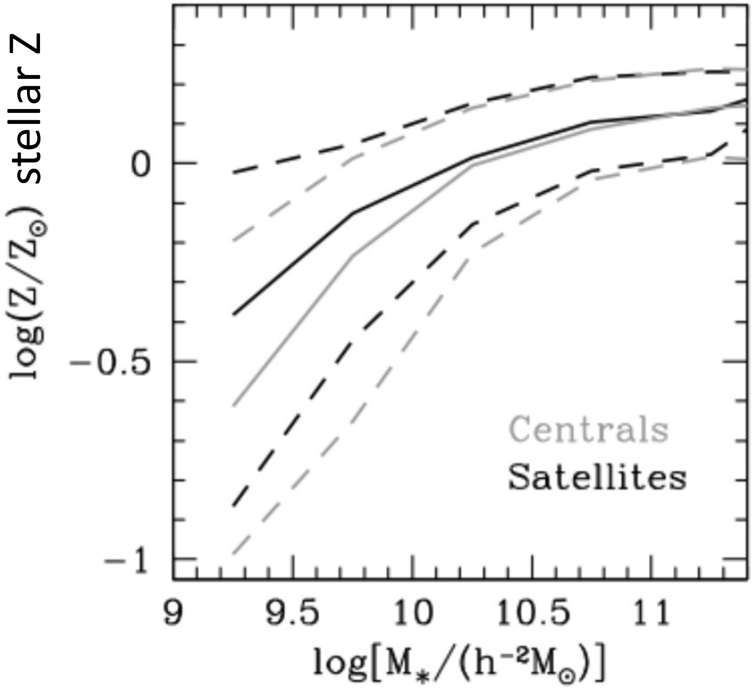


Zahid +2017

Statistical characterization of environmental effects in the local Universe

SATELLITE – CENTRAL galaxies

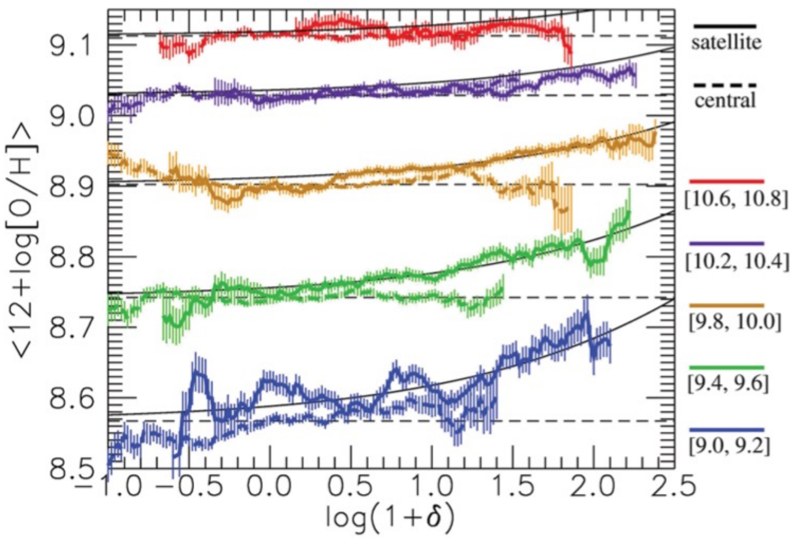
both the ionized gas and the stars of satellites are more metal-rich than of equally massive centrals (e.g., Pasquali +10, Shimakawa +15, Bahe +16, Trussler +21)



Pasquali +2010

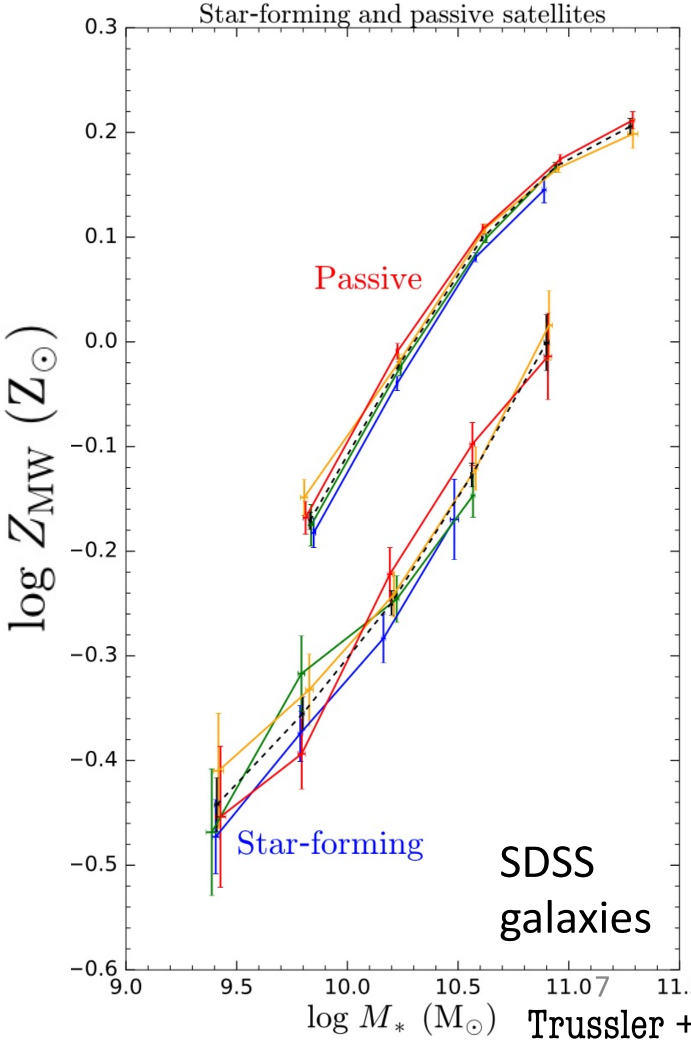
LOWER – HIGHER DENSITY FIELD

star-forming satellites at different stellar masses form a tight sequence in the average overdensity – gas metallicity plane (e.g., Peng & Maiolino +14, Maier +19)



Peng & Maiolino +2014

Star-forming galaxies show no environmental effects on **stellar** metallicity, while passive and green valley satellites do



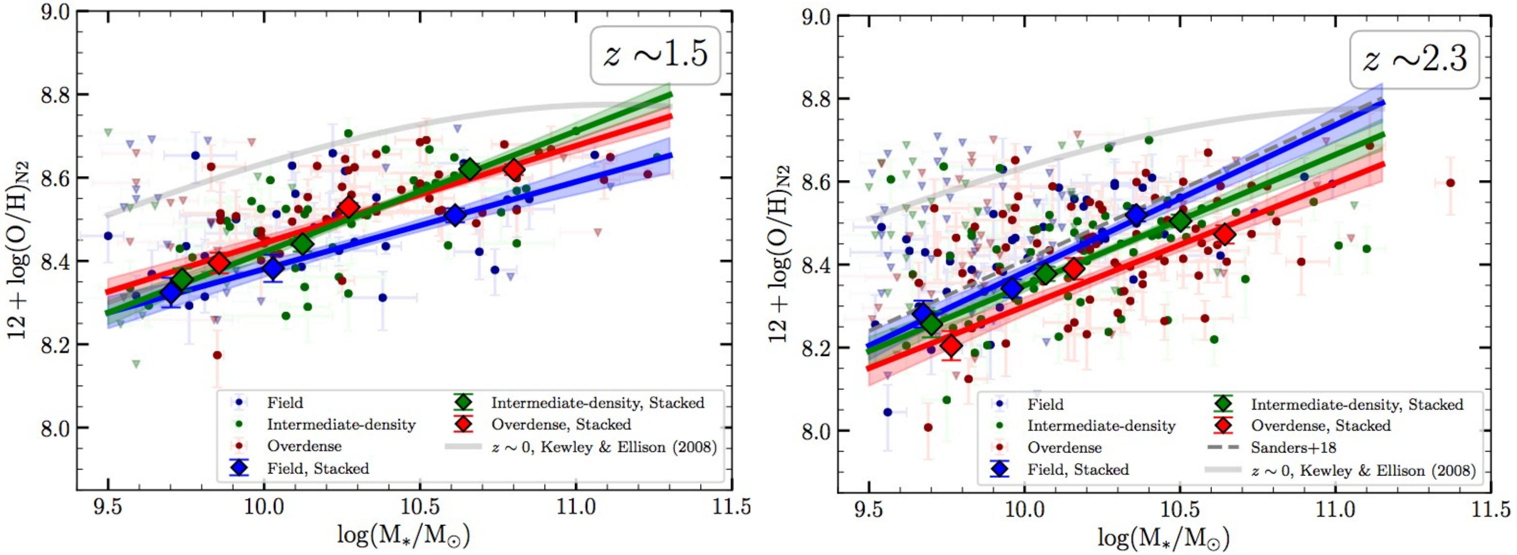
Trussler +2021

High-redshift studies of environmental effects

- Galaxy clusters are the earliest fingerprint of galaxy formation and evolution (Kravtsov & Borgani 12)
- High-density regions are crucial to investigate the physical processes responsible for the triggering and suppression of star formation and black hole activity

RECENT RESULT from the MOSDEF survey :

Reversal of the MZR - environmental density dependence at z ~ 2



Chartab et al. 2021

Gas-phase metallicity

Different observational results :

1) Z_{gas} low-mass cluster galaxies > Z_{gas} field galaxies (e.g., Kulas +13, Maier +19)
The offset of the mass–metallicity relation in dense environment becomes larger at higher redshifts (Shimakawa +15)

2) no significant environmental dependence at z ~ 2 (e.g., Tran +15, Kacprzak +15, Namiki +19)

3) Z_{gas} cluster galaxies < Z_{gas} field (e.g., Valentino +15)

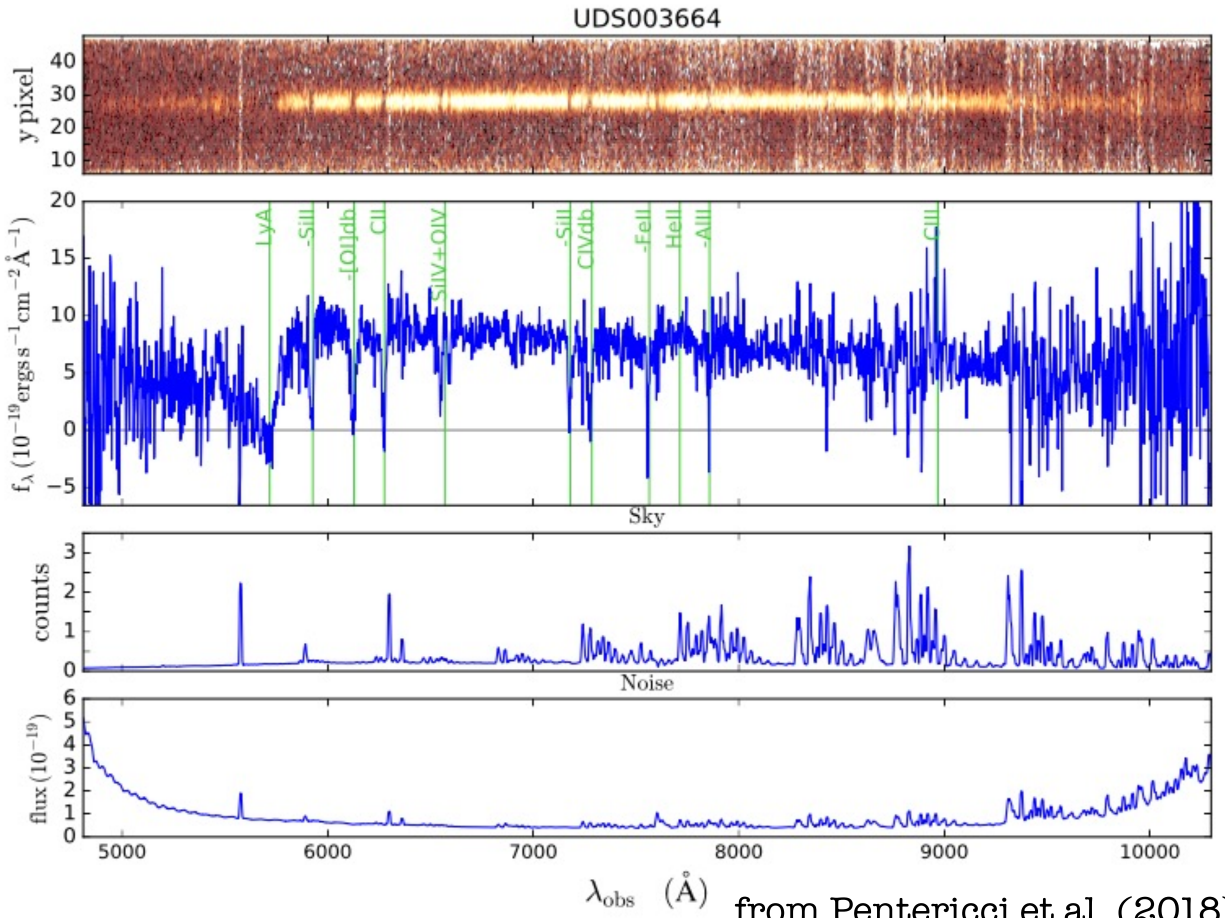
The effects on the stellar metallicity at high-z are still unknown

VANDELS : the deepest spectroscopic large survey at $z > 2$

- ultradeep **optical spectroscopic survey** of ~ 2000 galaxies with the VIMOS spectrograph at the ESO-VLT
- P.I. : L.Pentericci and R.Mc Lure

- covering an area of 0.2 deg^2 , centered on the CANDELS- CDFS and UDS fields
- the main targets are **star-forming galaxies at redshift $2 < z < 5$** ($i_{mag} < 27.5$ or 26 in wide fields)
- 20-80 hours of integration per source → high S/N spectra (above 7 for 80% of the sources)

- spectral coverage: 4900 Å < λ < 9800 Å, with resolving power R = 580 ($\Delta\lambda_{res} \simeq 2.8$ Å in rest-frame)
- z_{spec} accuracy $\simeq$ 150 km/s



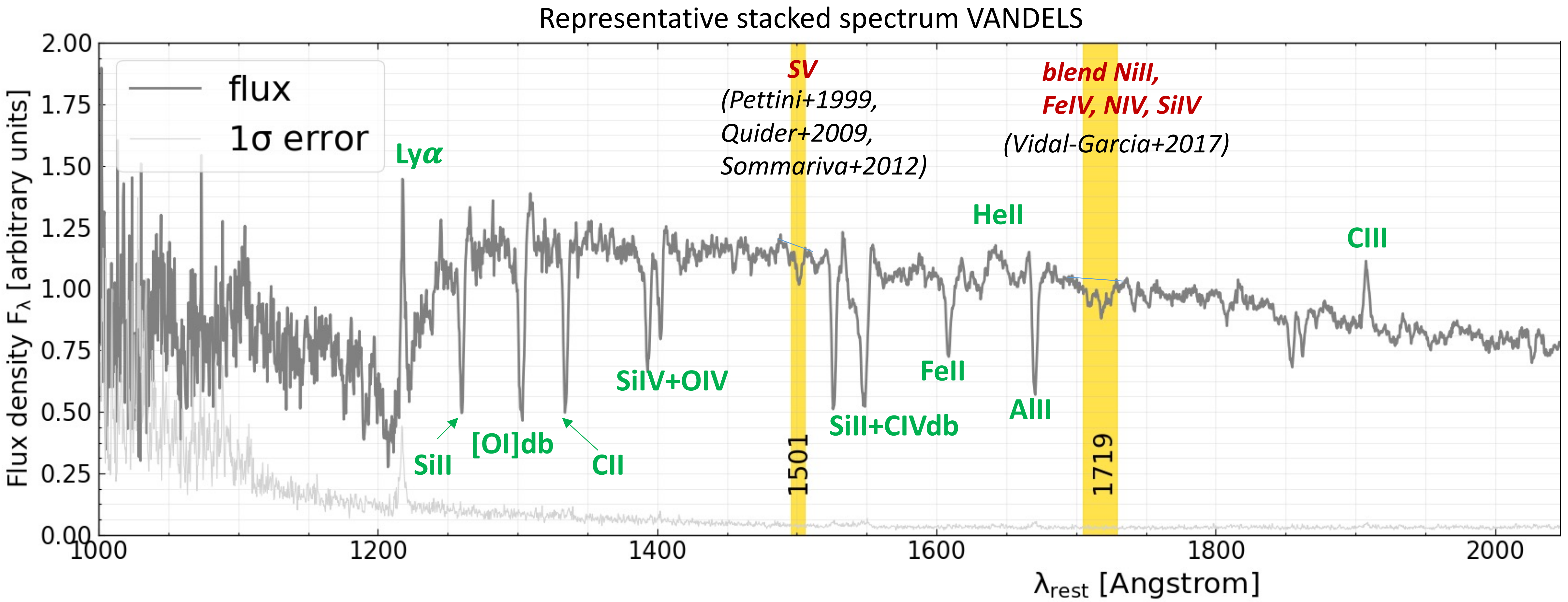
from Pentericci et al. (2018)

The VANDELS ESO public spectroscopic survey:

final Data Release of 2087 spectra and spectroscopic measurements

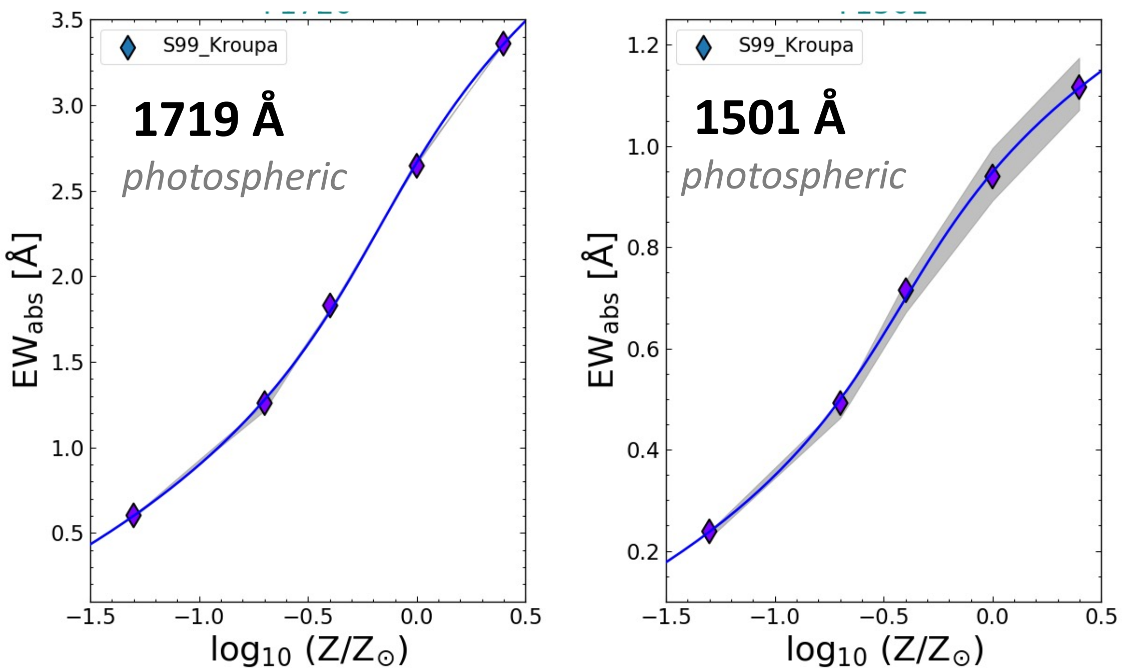
B. Garilli and VANDELS team , 2021

Metallicity calibration with FUV stellar photospheric absorption lines

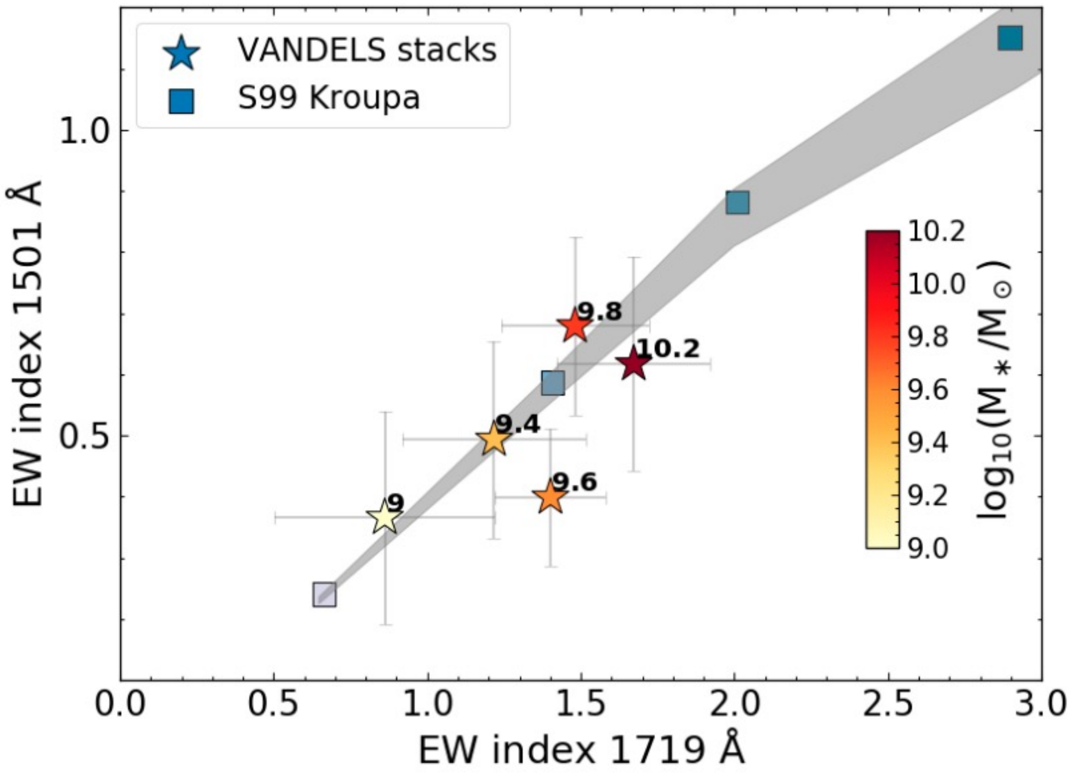


- probing galaxy properties with UV absorption lines (e.g., Fanelli+92, Rix+04, Leitherer+11)
- **1501** and **1719** Å absorption features depend on metallicity only ; they are not affected by variations of age, dust, IMF, nebular continuum, and ISM absorption contamination (Vidal-Garcia et al. 2017)

Metallicity calibration with FUV stellar photospheric absorption lines



Calabrò et al. 2020

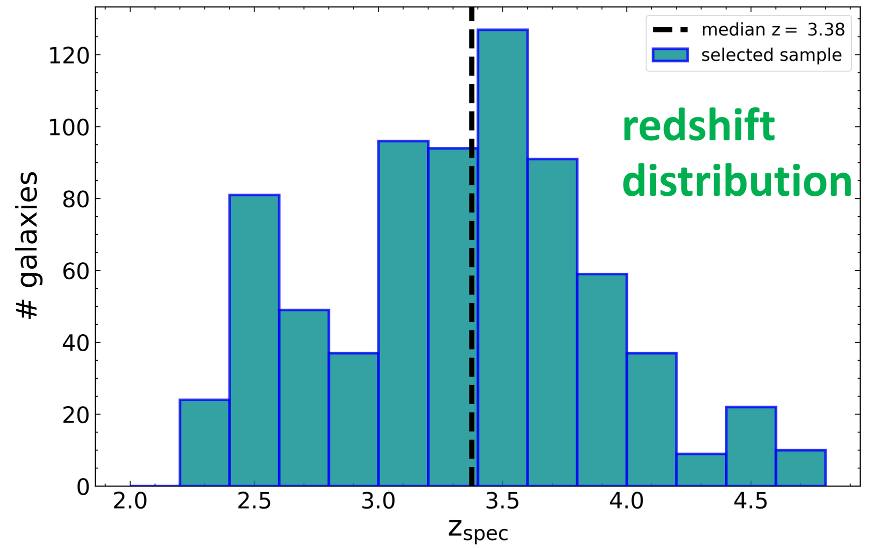


- **calibration based on Starburst 99** (S99) spectra (Leitherer+2010), converted to VANDELS resolution, at $Z_* = 0.05, 0.2, 0.4, 1$ and $2.5 \times Z_\odot$

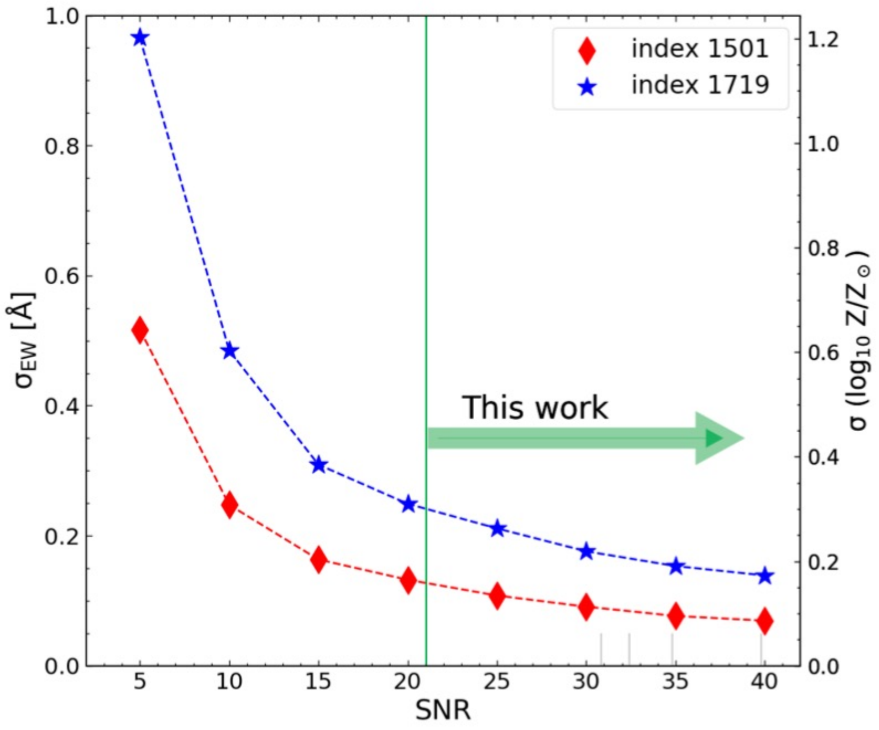
- the final metallicity is the median from the two indices
- metallicity tracing the iron abundance in young (O-B) stars

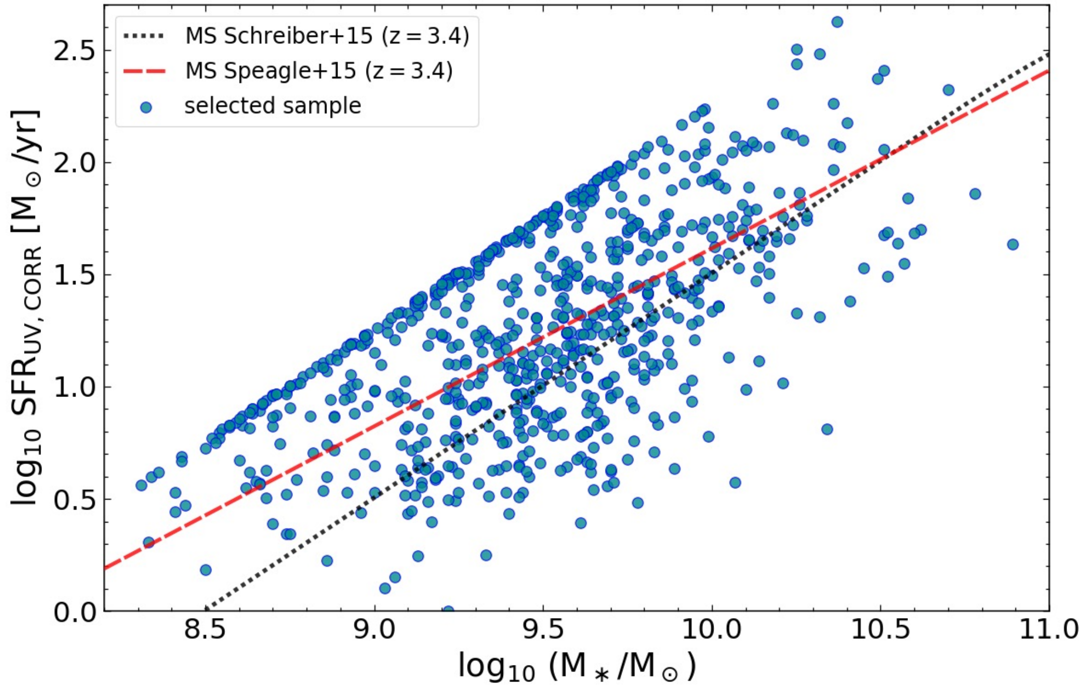
Sample selection and spectral stacks

- spectroscopic redshift $2 < z_{spec} < 5$, with quality flag 3 or 4 (> 95 % probability to be correct)
- final sample : 732 galaxies in total (CDFS + UDS), 580 with β slope
- representative of the star-forming Main Sequence at $z \sim 3$

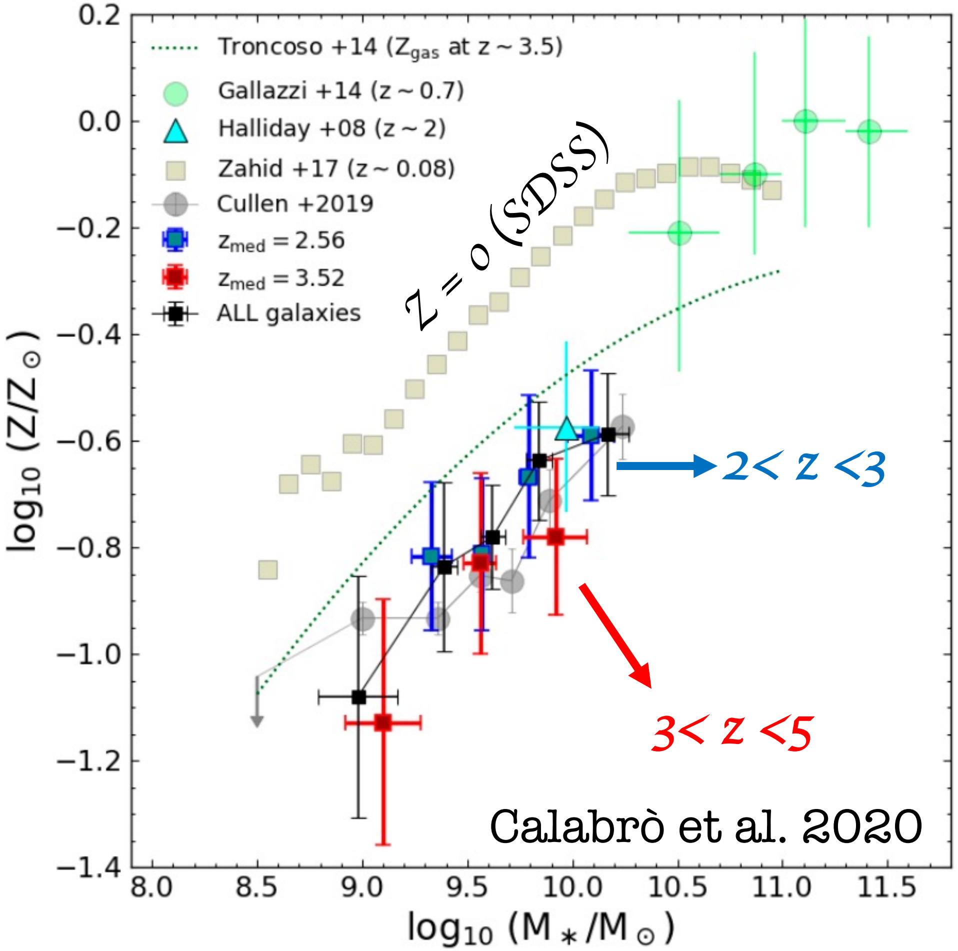


the need for spectral stacking



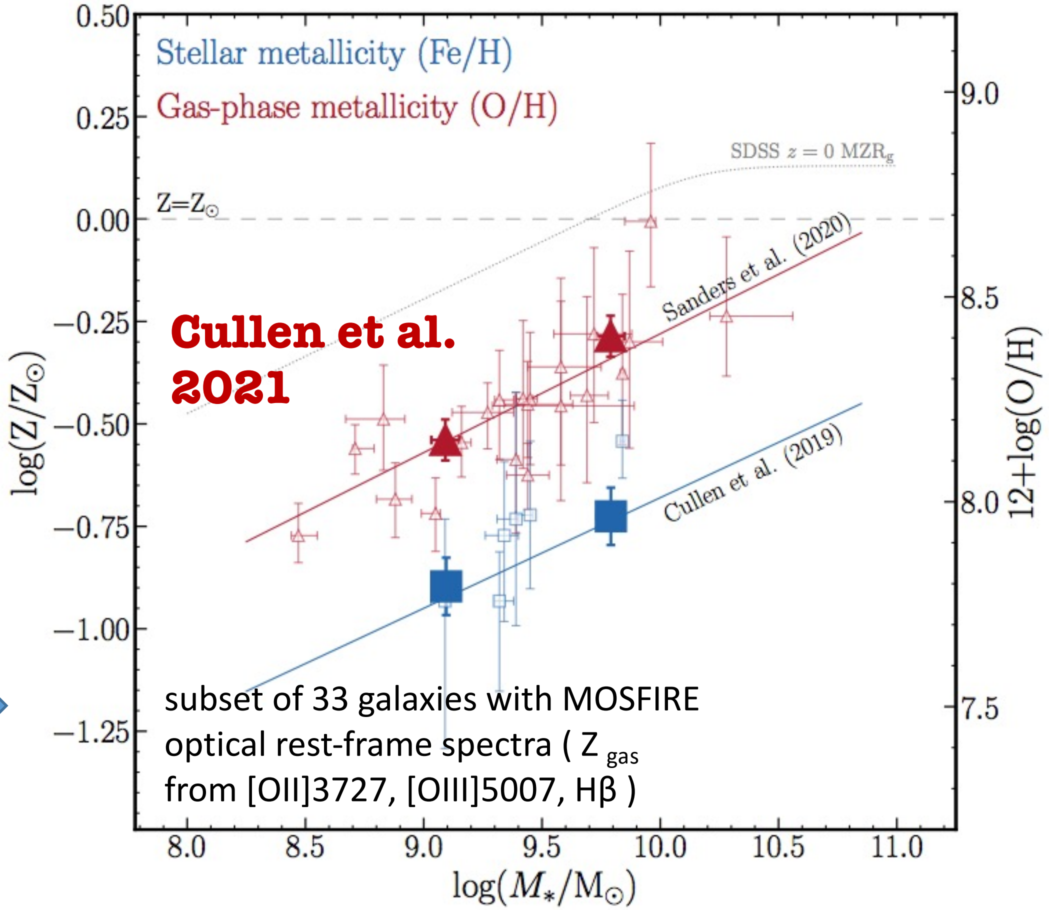


The stellar and gas-phase MZR of VANDELS star-forming galaxies



Z_* (~ Fe/H)

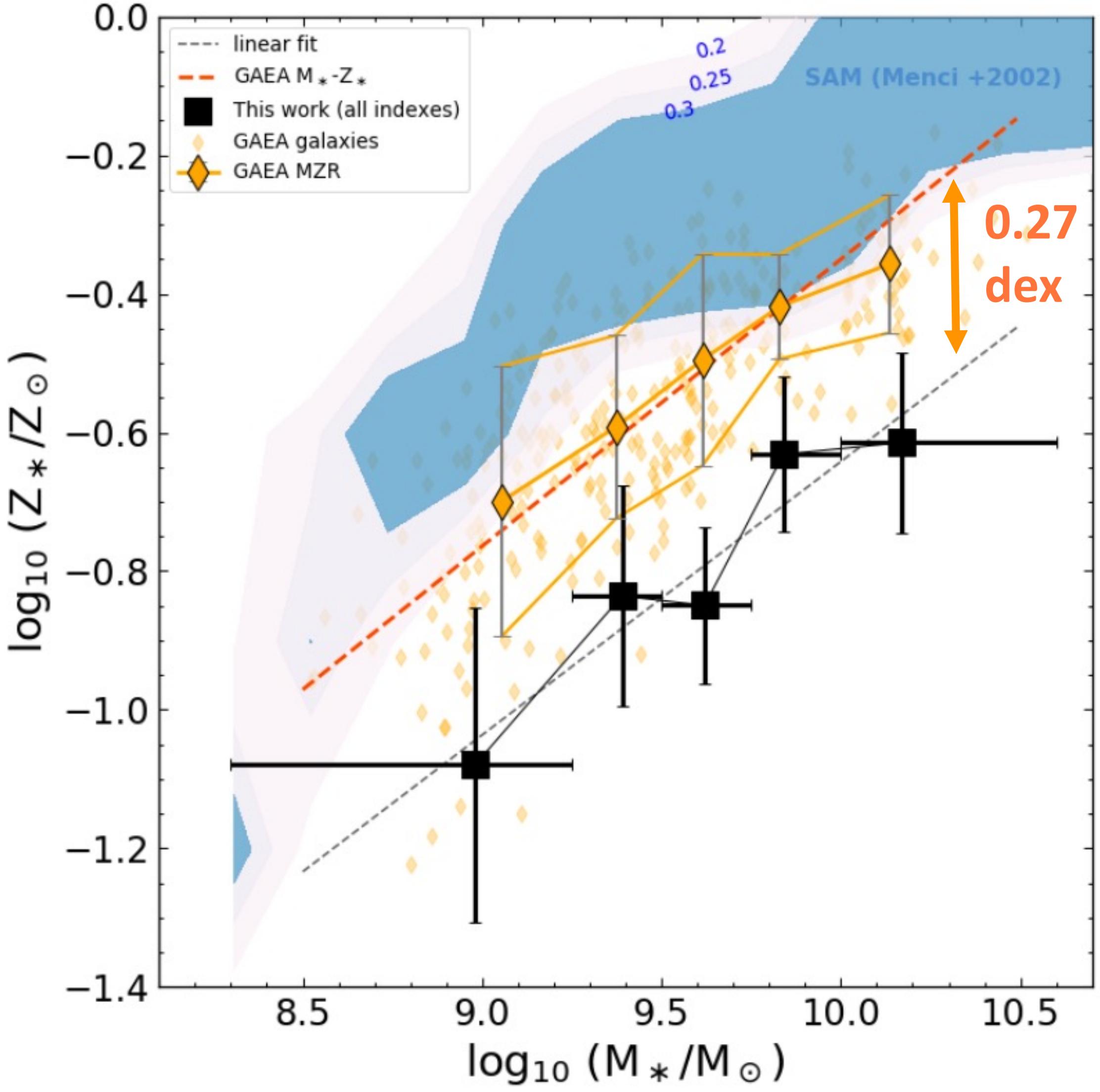
Z_{gas} (~ O/H)



- MZR at z ~ 3 is ~ 0.5 dex lower than the local relation (N.B. they trace slightly different stellar populations)
- no significant evolution between z = 2 and 5

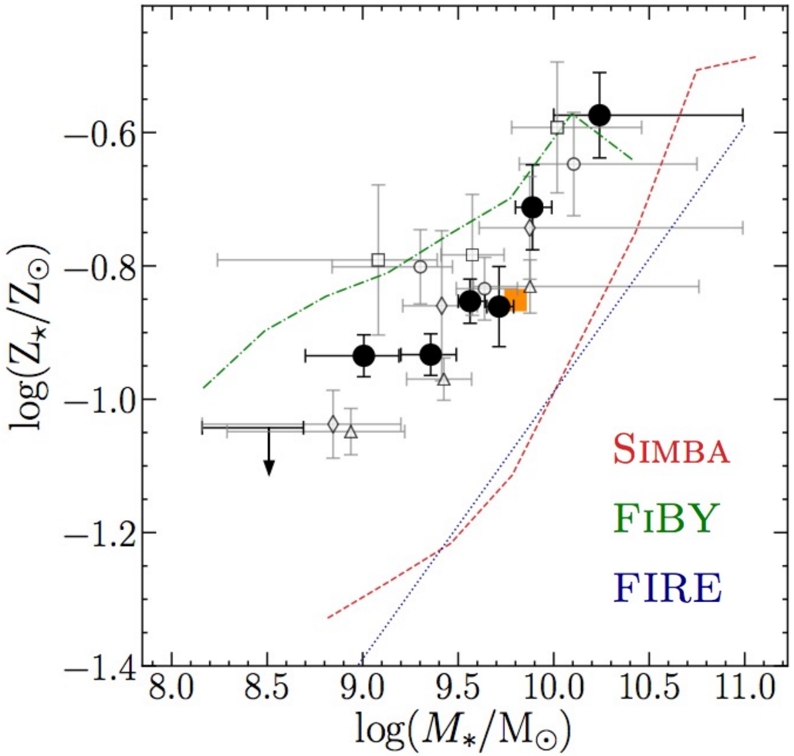
- α enhancement O/Fe ≃ (2.54 ± 0.38) × $(O/Fe)_\odot$ independent on M_*

Comparison to model predictions :



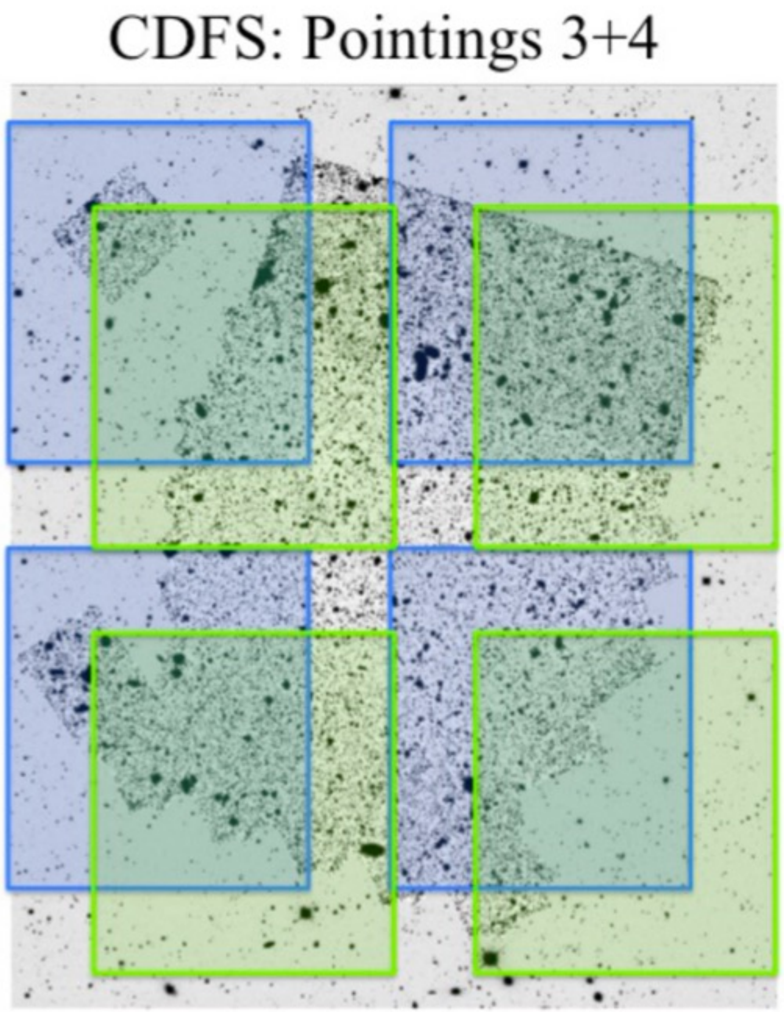
Calabrò et al. (2021)

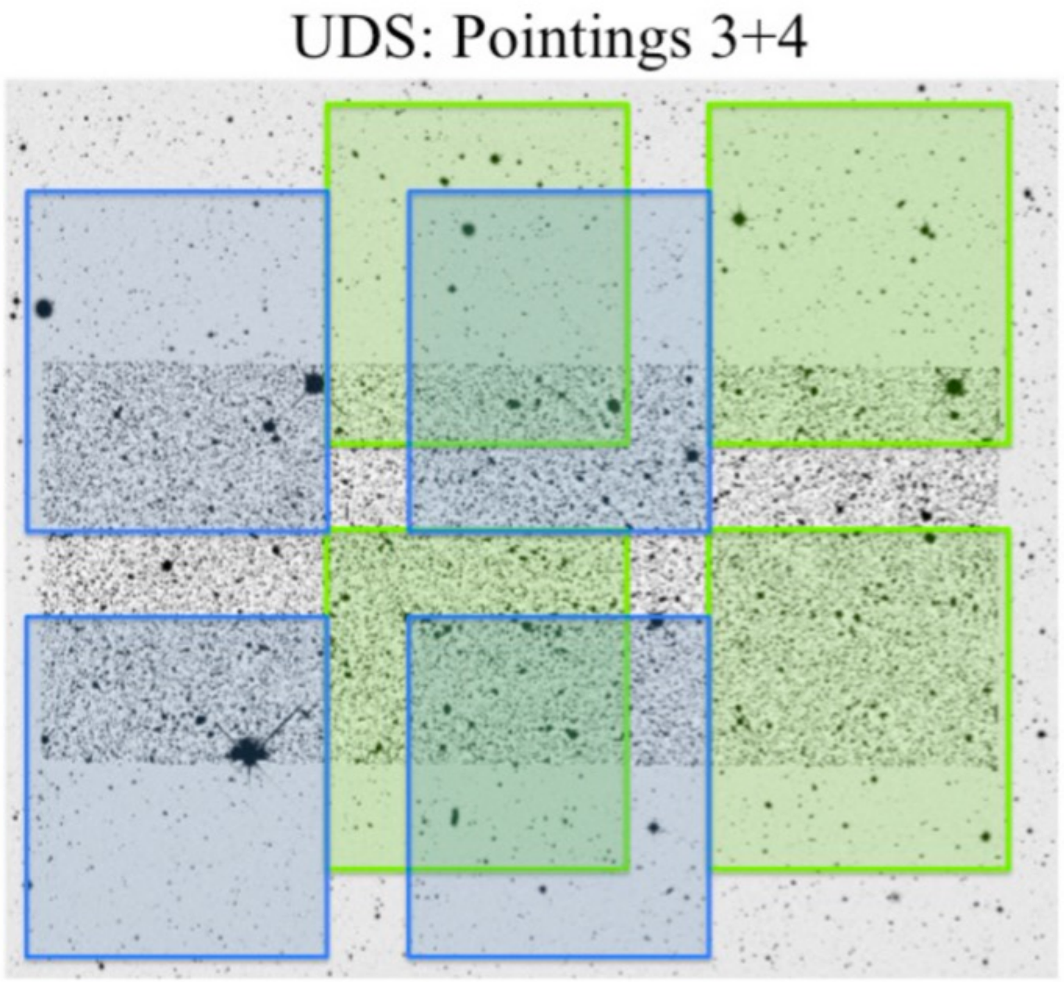
- hydrodynamical simulations and semi-analytic models (SAM) predict correctly the observed slope of the MZR
- … but there is still a normalization offset



Cullen et al. (2019) – VANDELS

VANDELS: a larger view in the UDS and CDFS fields



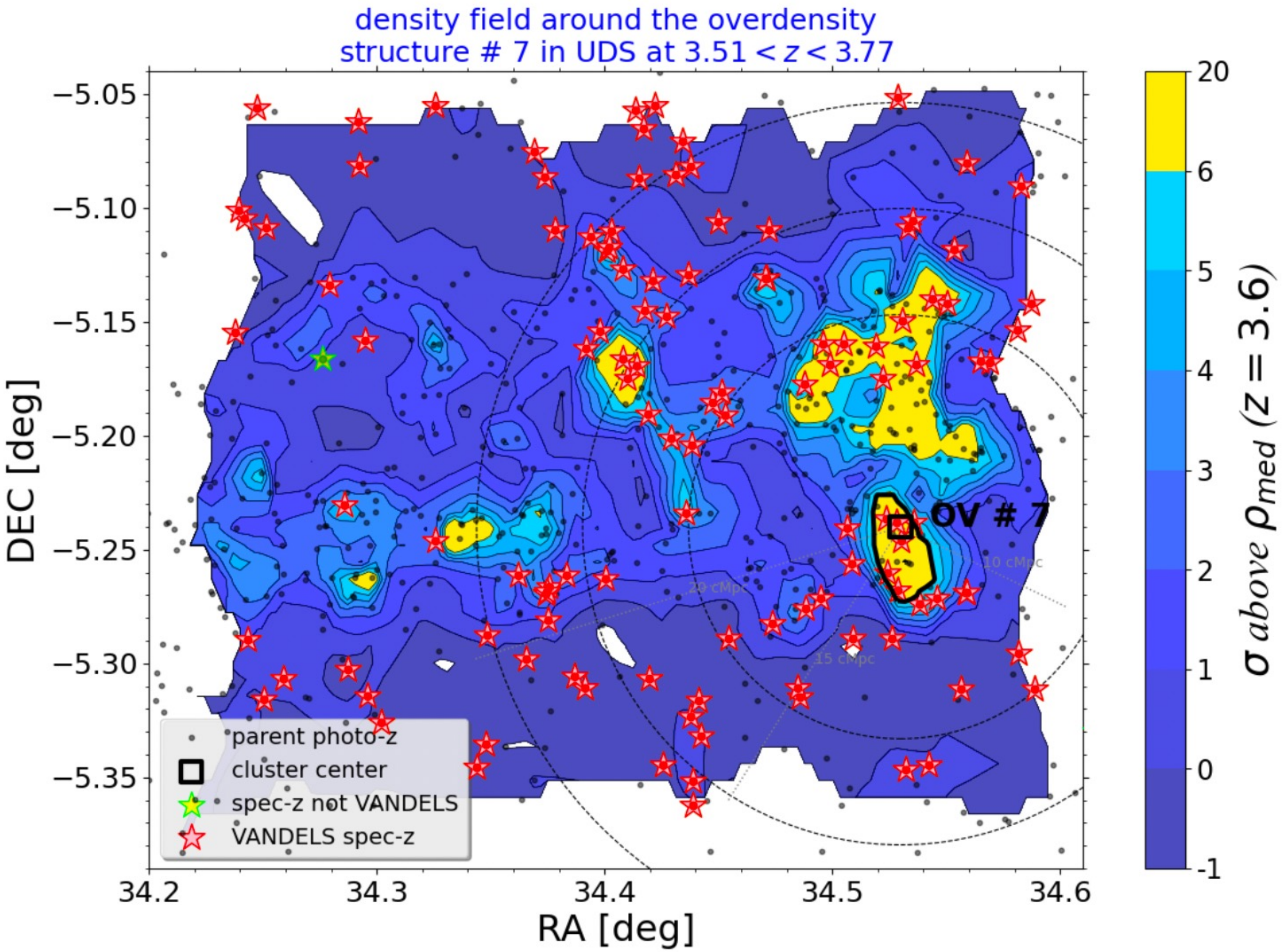


20k sources in CDFS+UDS at 2<z<4

(~10 % have spectroscopic redshift, of which ~40 % from VANDELS with q_{flag}>2)

B. Garilli and VANDELS team , 2021

Protocluster and overdensity structure definition 1



20k sources in CDFS+UDS
(~10 % have spectroscopic redshift, of which ~40 % from VANDELS with q_{flag}>2)

⇩

local density field (ρ= gal/[Mpc^3])
by using a 3D algorithm (Trevese +07, Castellano +07, Pentericci +13)

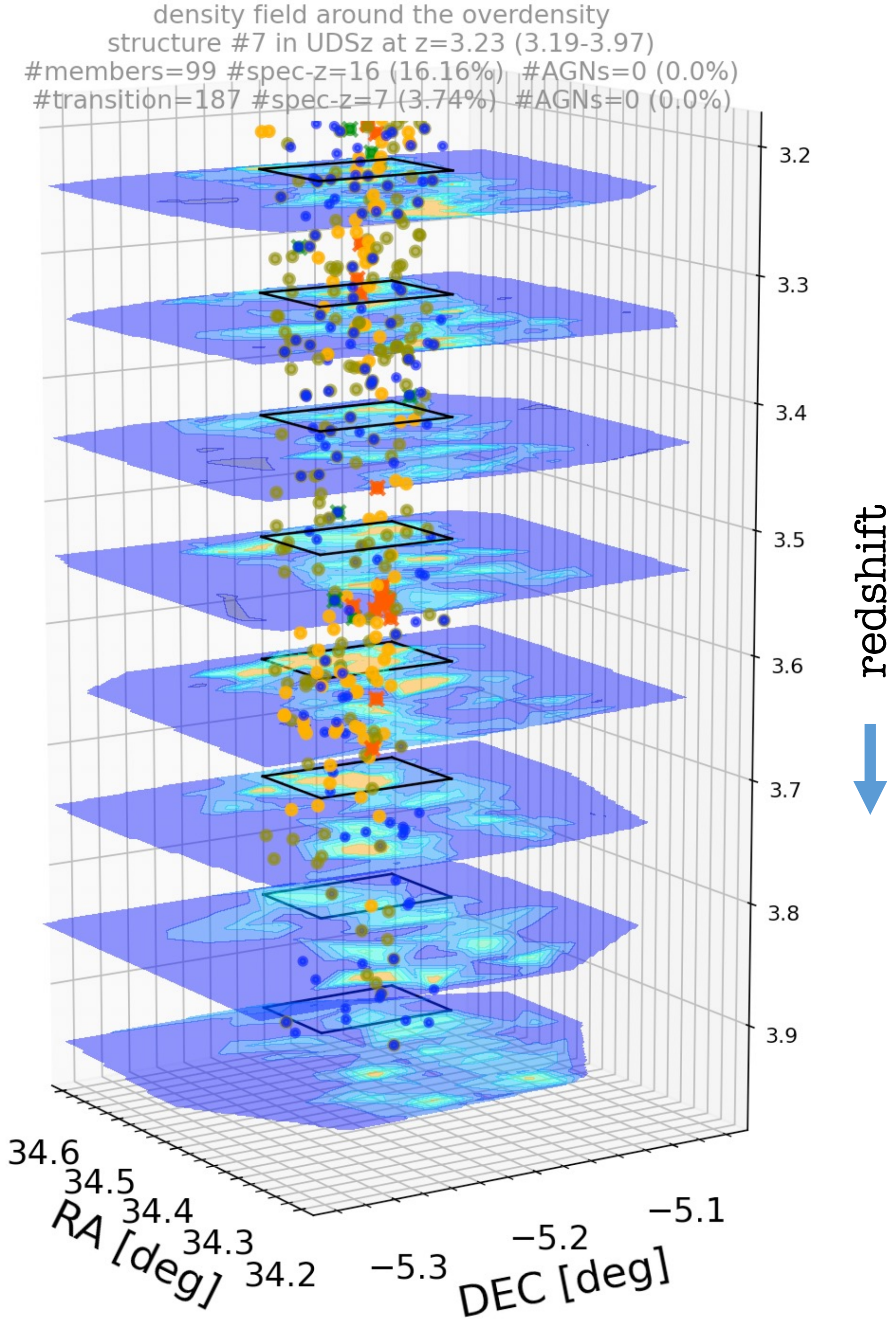
⇩

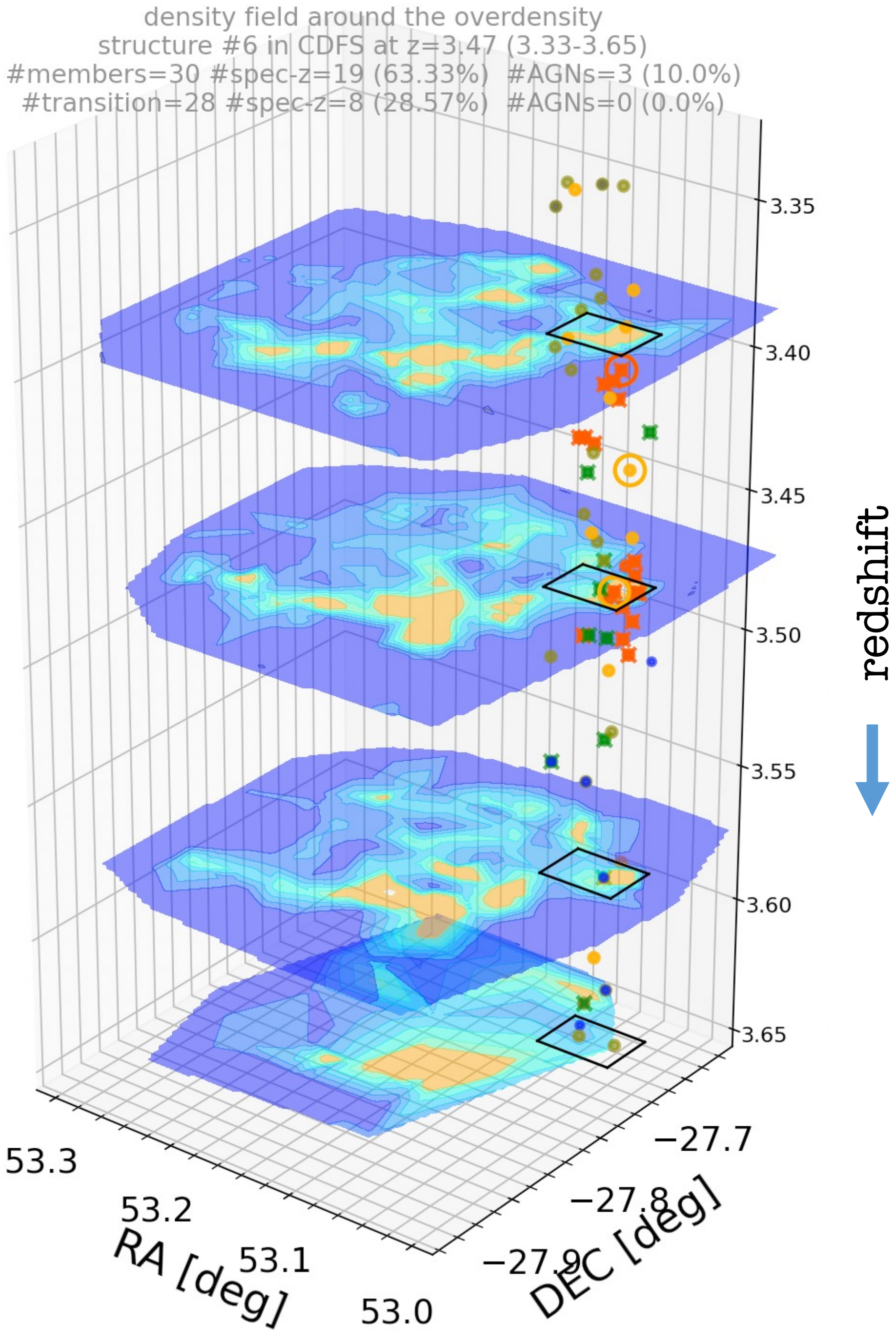
overdensity finder :
At least 3 galaxies with
$\rho > \rho_{med} + 2 \times \sigma\ (\rho_{med})$
within 4.5-8 cMpc at redshift 3.

⇩

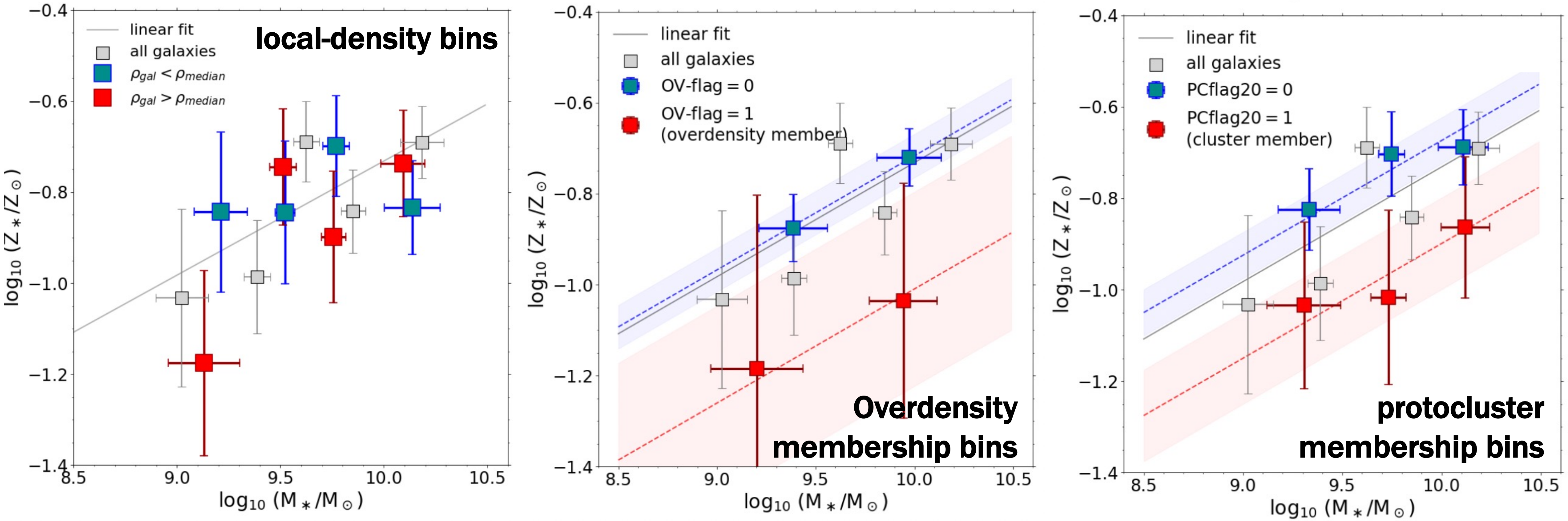
13 overdensity structures identified in CDFS and 9 in UDS (2 < z < 4)

Guaita et al. 2020


density field around the overdensity
structure #7 in UDSz at z=3.23 (3.19-3.97)
#members=99 #spec-z=16 (16.16%) #AGNs=0 (0.0%)
#transition=187 #spec-z=7 (3.74%) #AGNs=0 (0.0%)
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
redshift
34.6
34.5
34.4
34.3
34.2
RA [deg]
−5.3
−5.2
−5.1
DEC [deg]


density field around the overdensity
structure #6 in CDFS at z=3.47 (3.33-3.65)
#members=30 #spec-z=19 (63.33%) #AGNs=3 (10.0%)
#transition=28 #spec-z=8 (28.57%) #AGNs=0 (0.0%)
3.35
3.40
3.45
3.50
3.55
3.60
3.65
redshift
53.3
53.2
53.1
53.0
RA [deg]
−27.7
−27.8
−27.9
DEC [deg]

A weak environmental effect on the stellar phase MZR



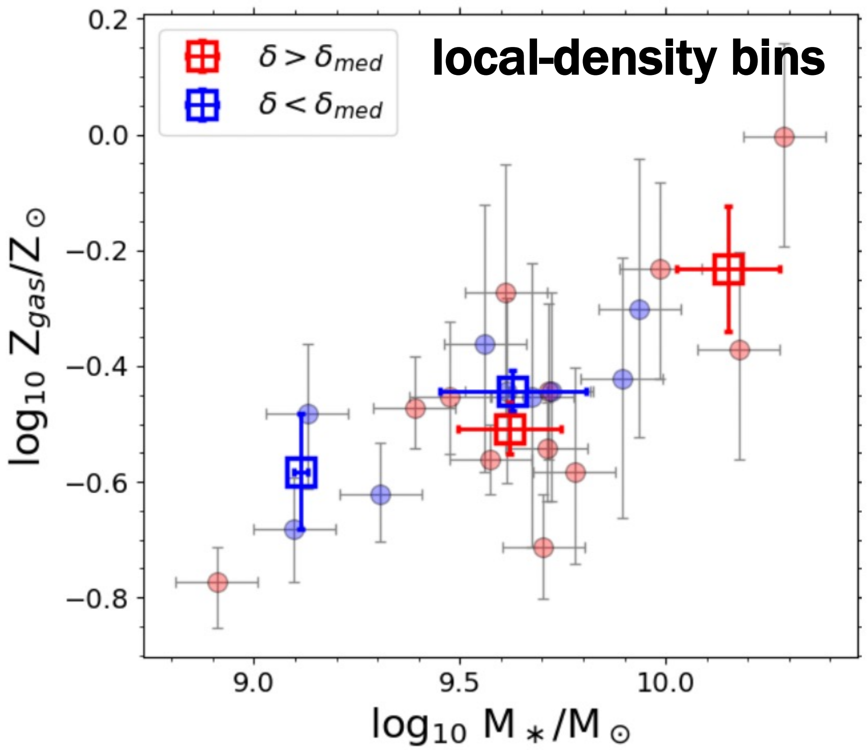
Calabro et al. 2022 (submitted to A&A)

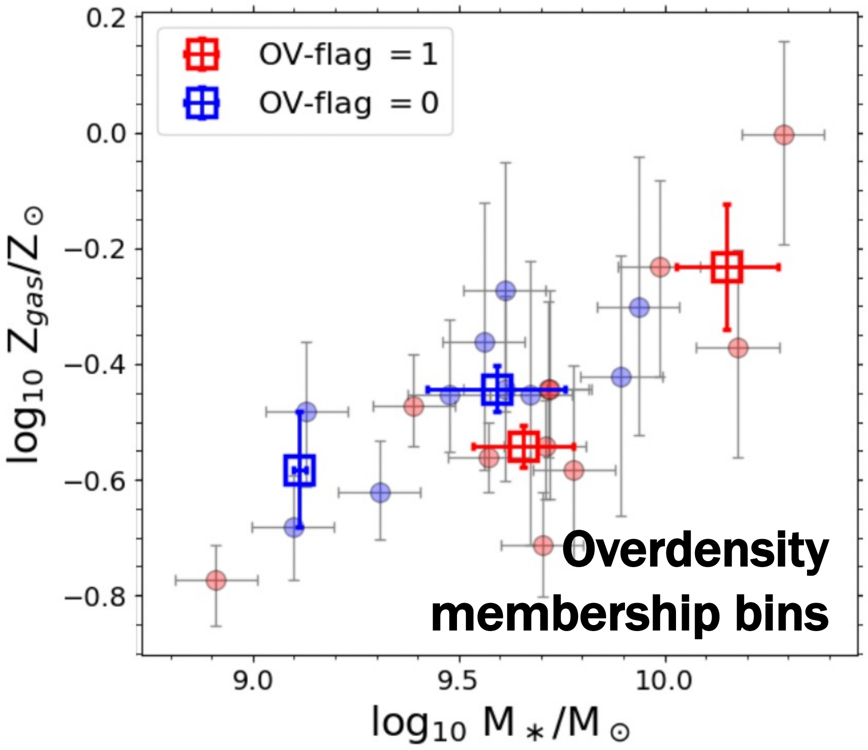
- low mass galaxies ($M_* < 10^{9.5}$ M_{sun}) in high-density regions are more metal poor than isolated systems

- galaxies inside the densest structures and protocluster cores are more metal poor compared to galaxies in the field with the same M_* , by ~ 0.2 dex (the significance is at 1 σ level)

Environmental effects are likely present, but only in the vicinity of the densest overdensity cores

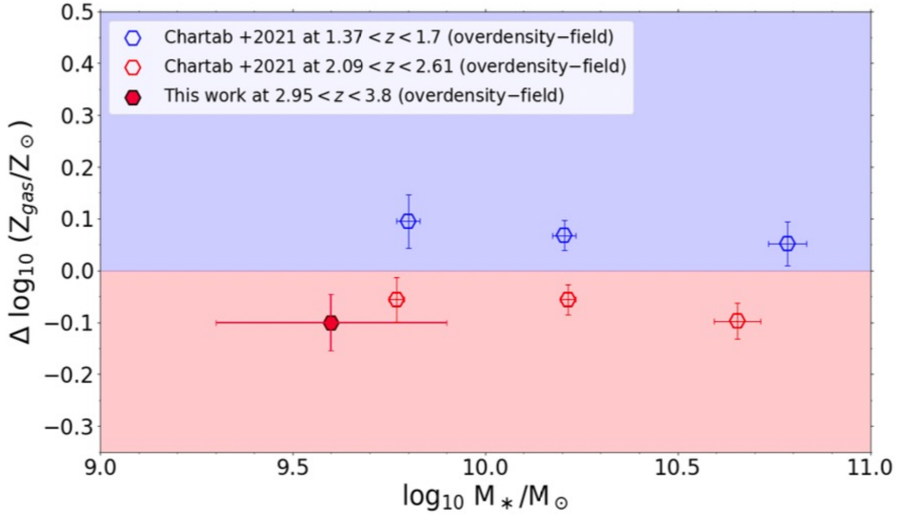
Environmental dependence of the gas - phase MZR





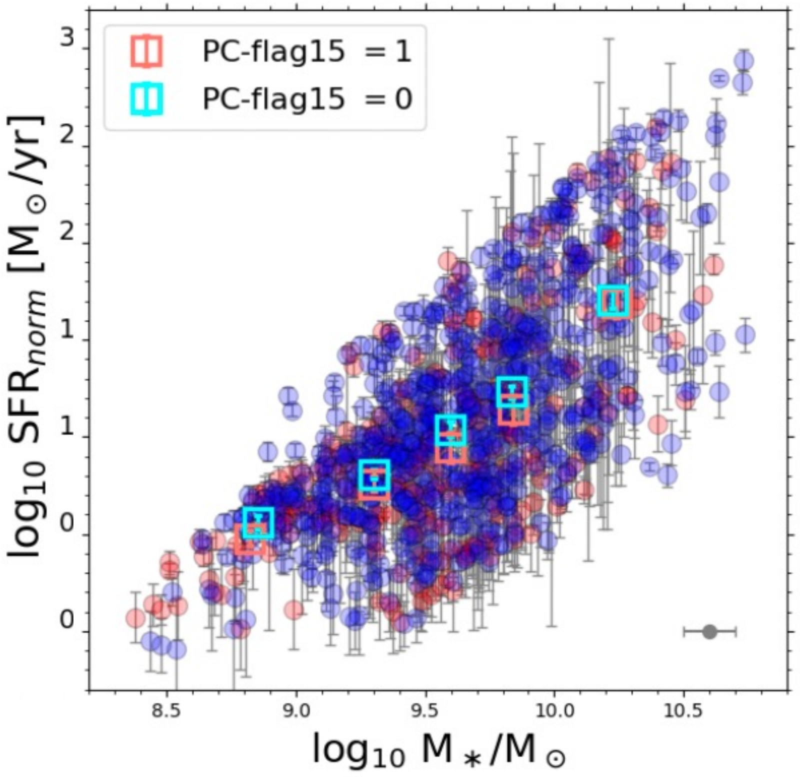
Calabro et al. 2022 (submitted)

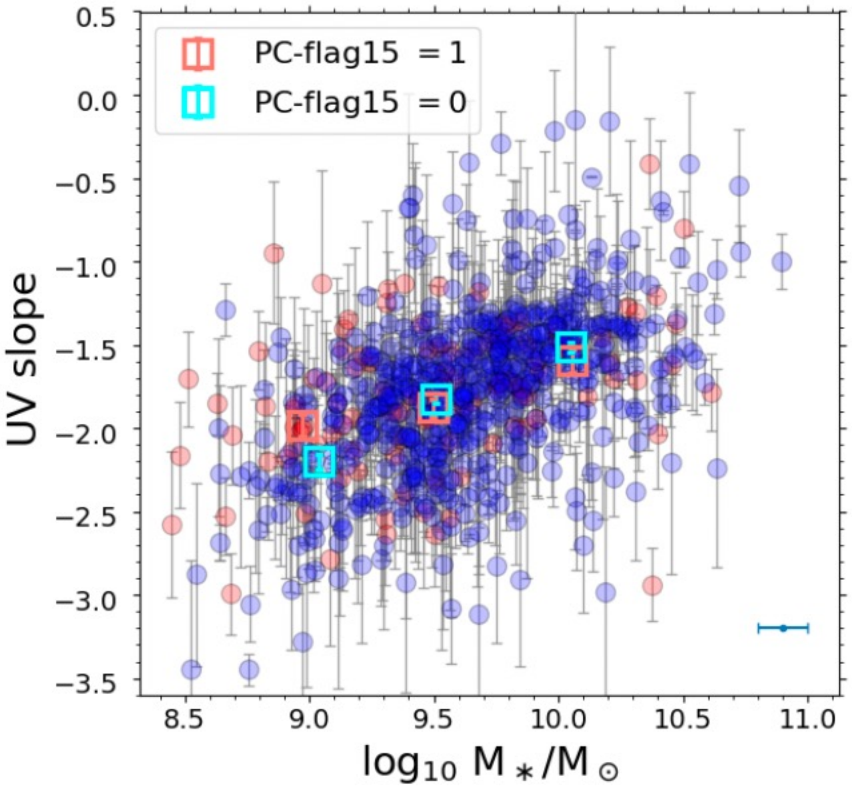
- galaxies inside the overdensity structures also have a lower gas-phase metallicity compared to the field, at $M_* \sim 10^{9.6} M_{sun}$
- $\Delta\, log_{10} Z_{gas} = 0.1$ dex, with a significance of 2 σ



consistent with the results from the MOSDEF survey, suggesting a reversal of the MZR - density relation at z > 2

Possible physical explanations of the environmental dependence





The environmental dependence is not driven by selection effects: galaxies in overdensities and in the field have similar SFR and UV-slope

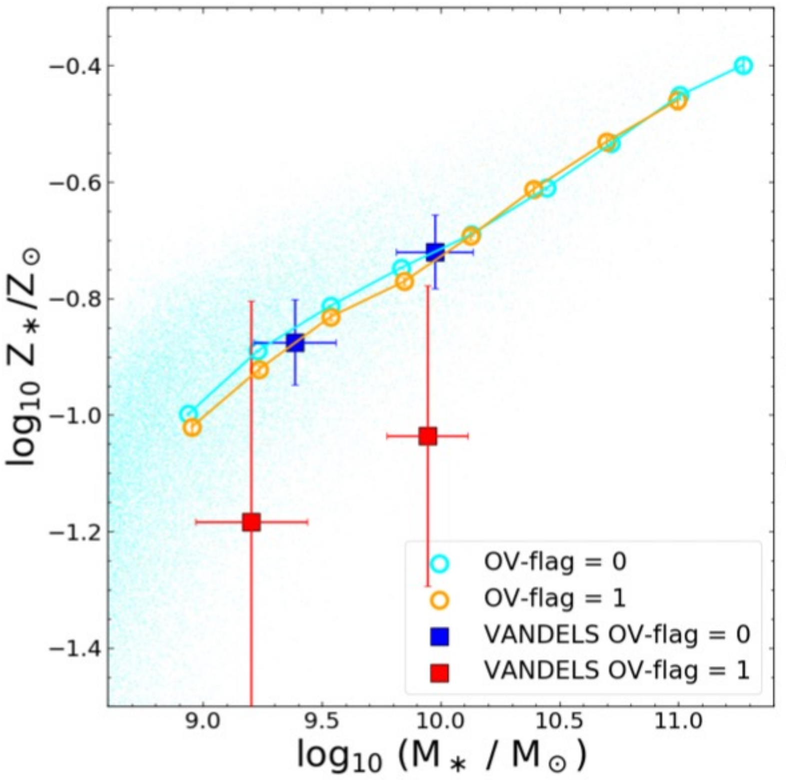
Other possible explanations :

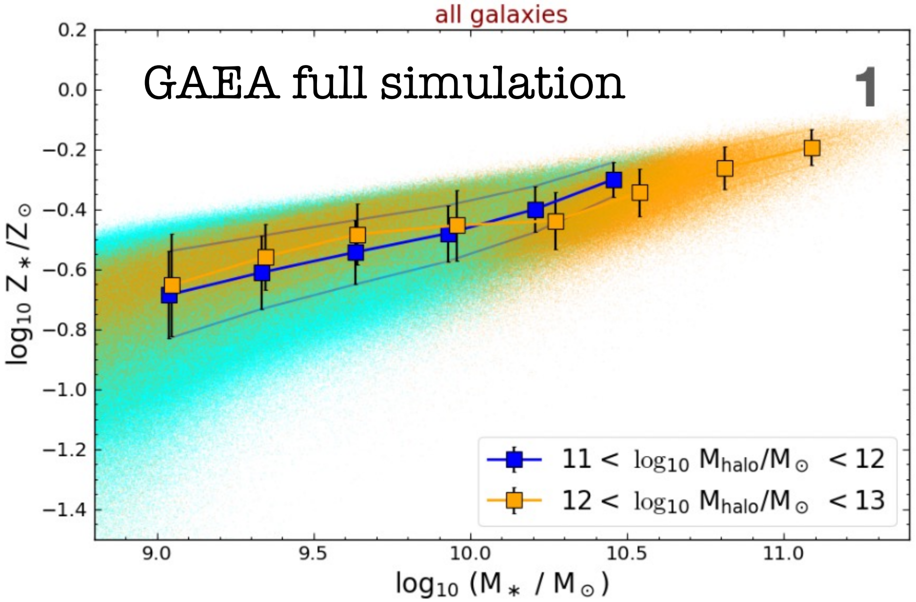
- more efficient inflows of metal-poor gas inside overdensities (see also Chartab +2021)
- more powerful stellar and AGN feedback depriving galaxies from their metals
- harassment, RAM pressure stripping, mergers

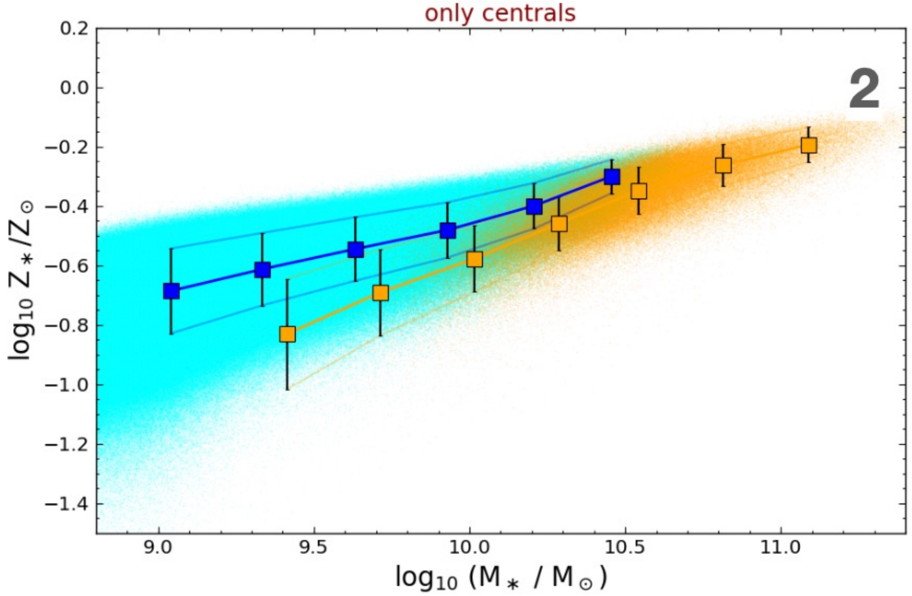
Comparison with SAMs and hydrodynamical simulations 1

The Galaxy Evolution and Assembly semi-analytic model (GAEA) (De Lucia +2014, Hirschmann +2016, Fontanot +2017, Fontanot +2021)

mock catalog (sSFR > 0.1 Gyr^{-1})







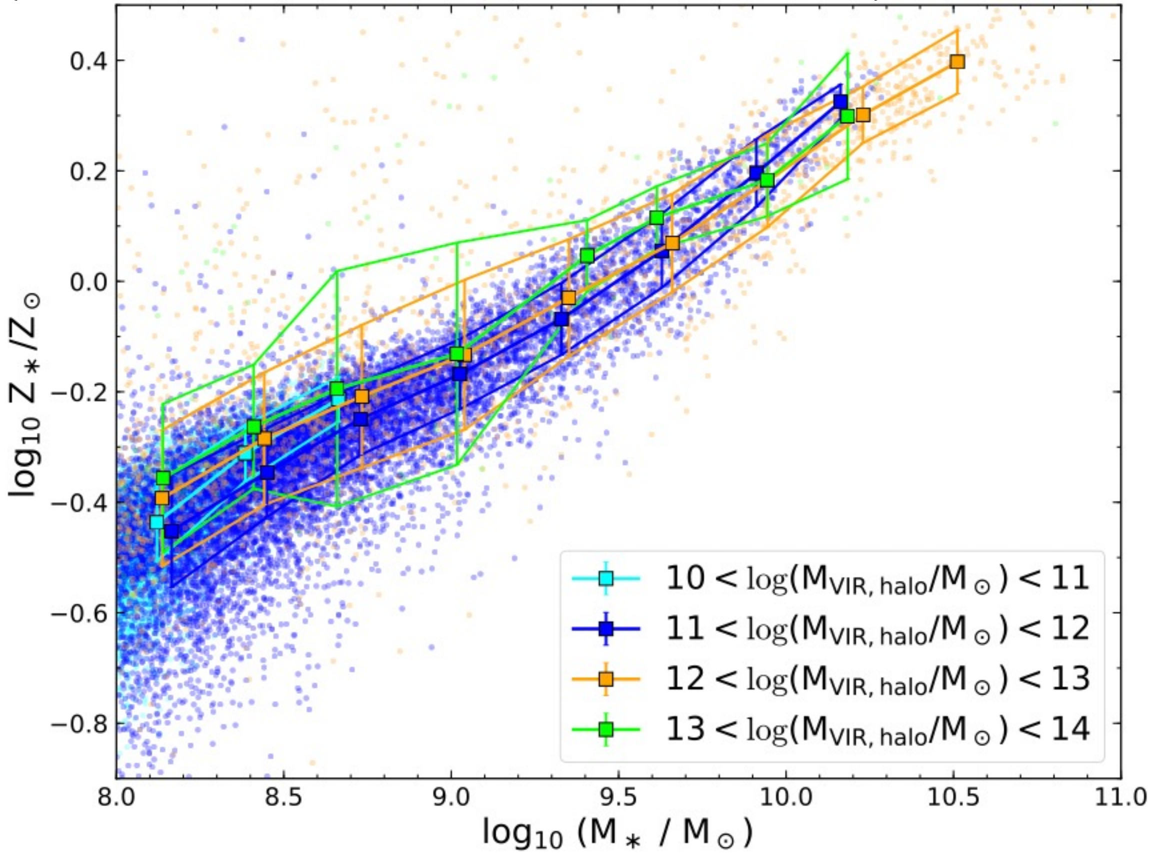
- No environmental effect for the global star-forming galaxy sample
- Central galaxies in more massive haloes are more metal-poor

- The physics of satellites inside clusters might be reconsidered to take into account environmental processes

Comparison with SAMs and hydrodynamical simulations 2

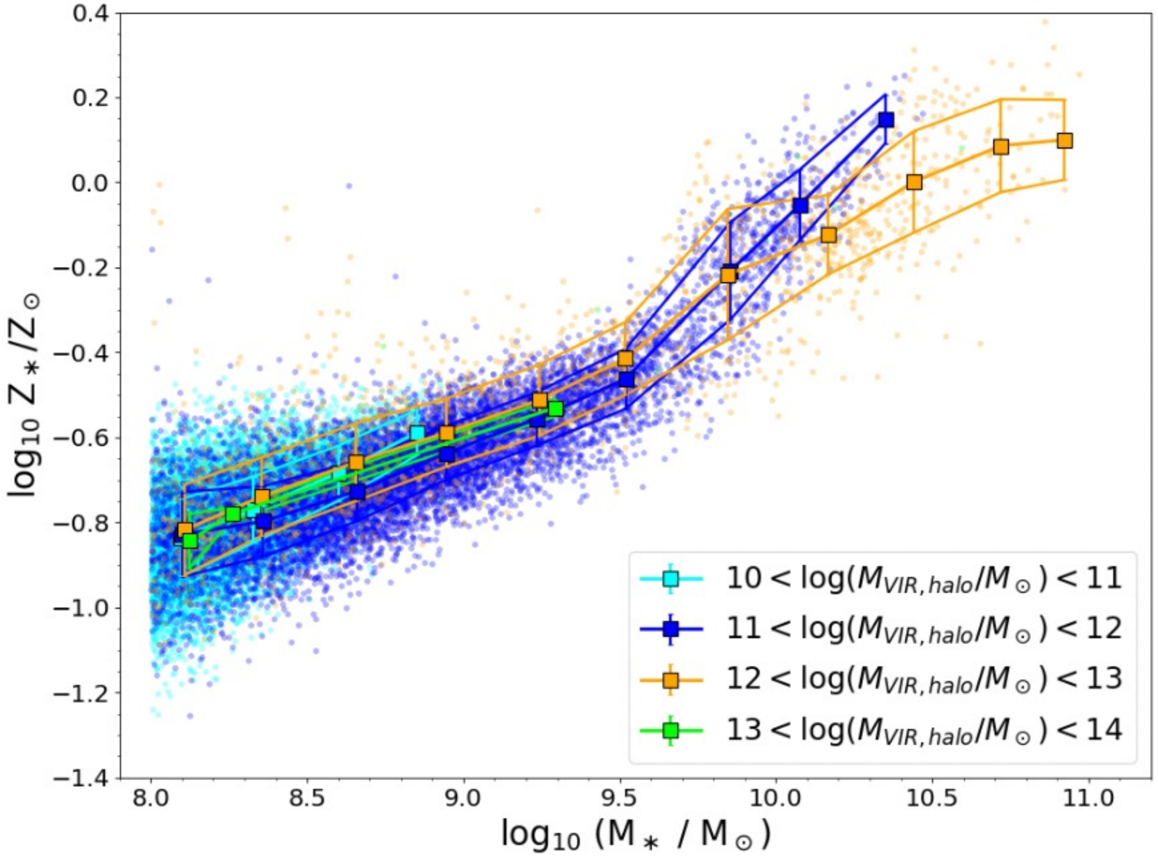
EAGLE simulations

- The largest EAGLE simulation (Ref-L100N1504) has a comoving cubic volume with size 100 Mpc.
- Mass resolution of 9.7×10^6 M_{sun} for dark matter (inclusion of stellar and AGN feedback).



Illustris – TNG 300 cMpc

- mass resolution elements 5.9×10^7, 1.1×10^7 M_{sun} for DM and gas, respectively (Springel +18, Nelson +18, Pillepich +18)



no significant environmental effects

Summary and conclusions

- a stellar mass - stellar metallicity relation (MZR) is in place already from $z \sim 4$
- it is $\sim$ 0.5 dex lower than the local MZR
- galaxies at $z \sim 3$ are alpha-enhanced ($O/Fe \simeq (2.54 \pm 0.38) \times (O/Fe)_{\odot}$)
- Semi-analytic models and hydrodynamical simulations predict the observed slope of the MZR, but they fail to reproduce the correct normalization

- no environmental dependence of the MZR as a function of galaxy density
- we find a weak environmental effect only closer to the overdensity cores: galaxies in protoclusters are on average more metal poor compared to the field, by 0.2 dex (1 $\boldsymbol{\sigma}$ significance) for the stellar-phase, and by 0.1 dex (2 $\boldsymbol{\sigma}$ significance) for the gas-phase
- SAMs and hydrodynamical simulations are in tension with observations, as they do not predict significant environmental effects

Thanks for the attention !!