The Fundamental Metallicity Relation up to $z \sim 0.7$

Investigating different methods of comparison of different samples

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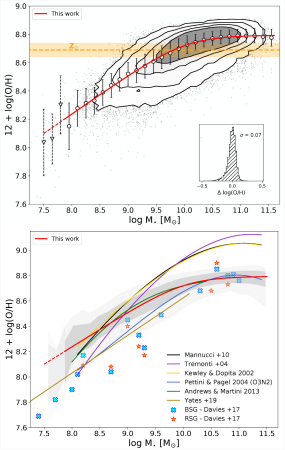
Introduction

What is the Mass Metallicity Relation (MZR)?

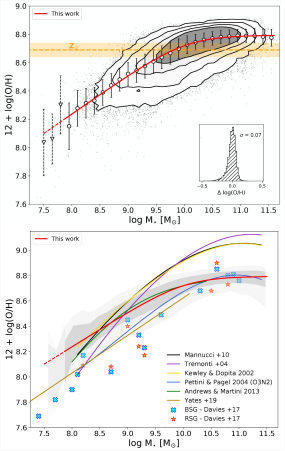
- Relation between stellar mass ($M_\star$) & metallicity (Z) of galaxies
- Reflects the fundamental role of galaxy mass in regulating galactic chemical evolution



Source: Curti et al. (2020)

What is the origin of the Mass Metallicity Relation (MZR)?

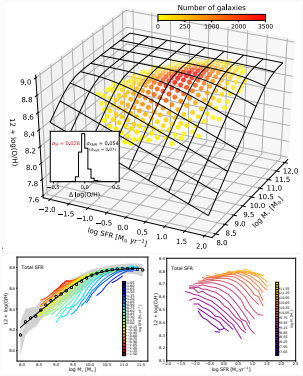
- Shaped by two mechanisms (Lian et al. 2018a,b)
  - The metal enrichment suppressed at early times in low-$M_\star$ galaxies
  - The metal enrichment must stop at $z \sim 1.5$ in high-$M_\star$ galaxies
- Need of a time-dependent mechanism to regulate metal enrichment
  - Time-dependent star formation efficiency (SFE, Lilly et al. 2013)
  - Time-dependent metal outflow or time-dependent initial mass function (IMF, Lian et al. 2018a,b)



Source: Curti et al. (2020)

What is the Fundamental Metallicity Relation (FMR)? The relation between MZR and SFR

- Relation between stellar mass ($M_\star$), SFR, & metallicity (Z) of galaxies (Mannucci et al. 2010; Curti et al. 2020; Kumari et al. 2021)
- No evolution observed up to $z \sim 2.5$ (Mannucci et al. 2010)
- Effects of gas flows
  - Inflow $\longrightarrow$ dilution + ignition of SFR
  - Outflow $\longrightarrow$ starvation + removal of metals

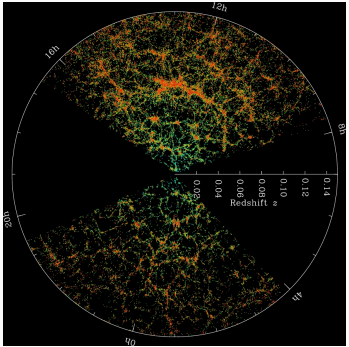


Source: Curti et al. (2020)

Surveys

Surveys

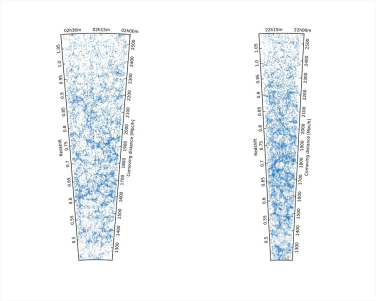
- Sloan Digital Sky Survey (SDSS)



Source: `https://www.sdss.org/science/`

Alam et al. (2015)

- VIMOS Public Extragalactic Redshift Survey (VIPERS)

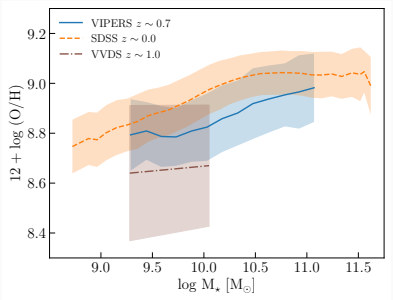


Source: `http://vipers.inaf.it/`

Guzzo & VIPERS Team (2013)

MZR: from $z \sim 0$ to $z \sim 1$

- SDSS ($0.027 < z < 0.3$): $\sim$ 150 000 star-forming galaxies
- VIPERS ($0.5 < z < 0.8$): $\sim$ 5000 star-forming galaxies, with a full set of emission lines
- VVDS ($0.89 < z < 1.24$): $\sim$ 40 star-forming galaxies (Pérez-Montero et al. 2009)



Source: Pistis et al. (2022a), in prep.

- In agreement within uncertainties
- General trend of metallicity with cosmic time rising at a given M$_\star$

Different approaches to the comparison of the FMR from different surveys

How to compare samples at different redshifts?

- MZR is known to change with z because galaxies increase metallicity with time at all stellar masses
- 3D FMR ($M_\star$-SFR-Z) is expected/measured to not evolve
- How to compare different samples at different z in a quantitative way?

Different approaches to the comparison of the FMR from different surveys

- Infer the FMR from its projections (direct cross-matching on physical properties — p-control sample — and their scatter around main sequence, MS — galaxy type, t-control sample)
- Non-parametric framework (specific SFR, sSFR, normalized to the median sSFR of SDSS sample, Salim et al. 2014, 2015): “indirect” cross-matching on physical properties
- Non-parametric framework (sSFR normalized to the MS sSFR, Pistis et al. 2022a, in prep.): “indirect” cross-matching according to the distance from the star-forming main sequence (MS) — galaxy type

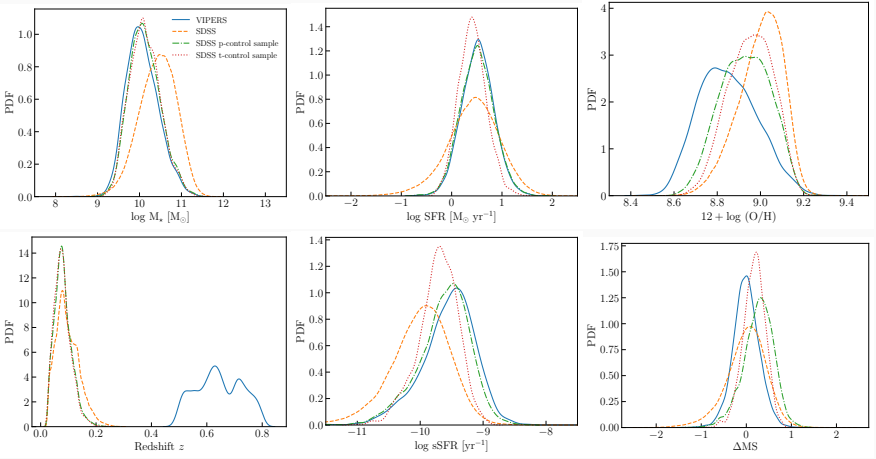
Direct cross-matching — physical properties: p-control sample

- For each VIPERS galaxy we select all SDSS galaxies in a radius of 0.1 dex in $\log \mathrm{M}_\star$ and $\log \mathrm{SFR}$
- We measure the distance in $\log \mathrm{M}_\star$ and $\log \mathrm{SFR}$
- We keep a maximum of three closest galaxies to each VIPERS galaxy

Direct cross-matching — galaxy type: t-control sample

- For each VIPERS galaxy, we found the correspondent SFR at low-z from the MS
- We simulate the scatter around the MS with adding $N(\mu, \sigma)$
- $\mu = 0$, σ is the SFR standard deviation of VIPERS in a 0.1 dex mass bin
- We proceed as for p-control sample

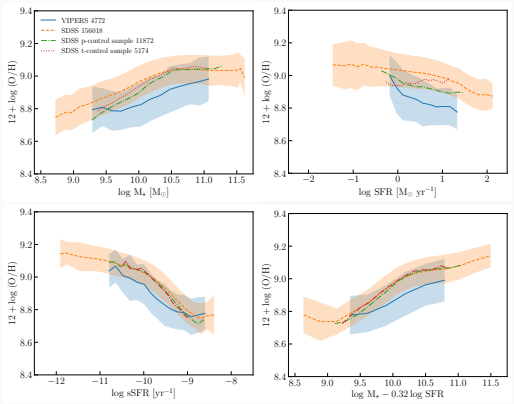
Direct cross-matching: properties' distributions



Source: Pistis et al. (2022a), in prep.

Direct cross-matching — FMR projections I

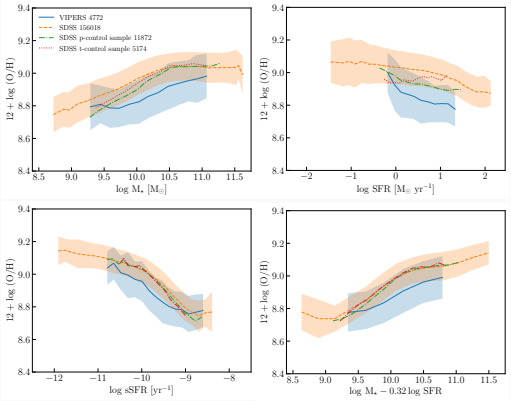
- SDSS control samples have a small shift at low stellar mass with respect to the SDSS full sample
- Metallicity versus SFR: p-control sample higher but parallel to the VIPERS sample; t-control sample shows a positive correlation
- Cross-matching does not result in any difference in metallicity versus the combination of$M_\star$ and SFR planes with respect to the full SDSS sample



Source: Pistis et al. (2022a), in prep.

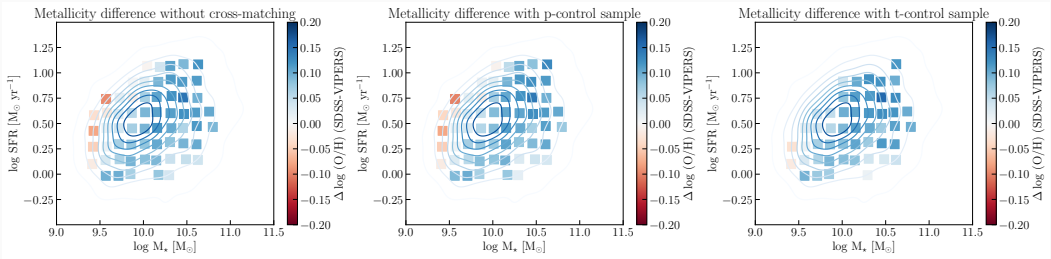
Direct cross-matching — FMR projections II

- P-control sample does not show the same projections than VIPERS data $\longrightarrow$ **Evolution of the FMR(?)**
- MZR and metallicity versus SFR are the most evolving projections
- The relations between metallicity and combination of $M_\star$ and SFR evolve the least



Source: Pistis et al. (2022a), in prep.

Direct cross-matching — FMR direct comparison

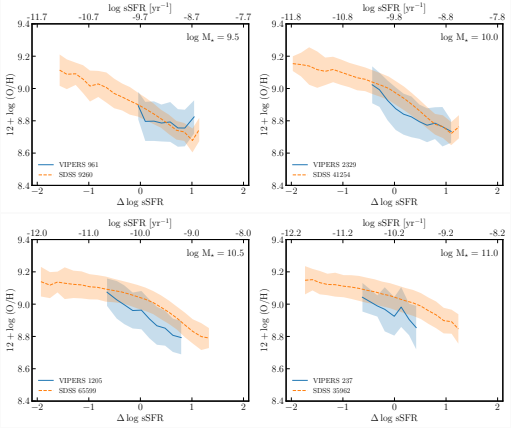


Source: Pistis et al. (2022a), in prep.

- Metallicity difference between SDSS-based samples and VIPERS increasing with $M_\star$
- No metallicity differences with/without cross-matching $\longrightarrow$ **No evolution of the FMR (?)**

Indirect cross-matching by physical properties

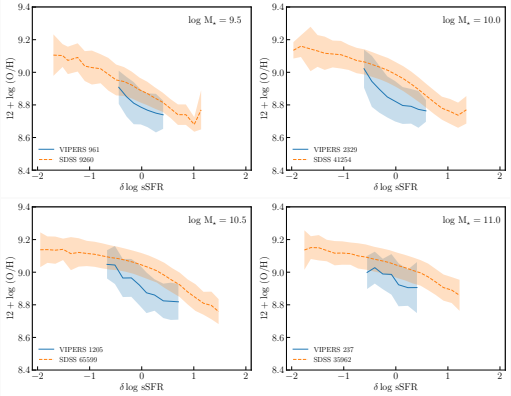
- Metallicity versus sSFR plane bias independent (introduced by data selection or observation, Pistis et al. 2022b, accepted)
- Normalization of the sSFR on the median low-z sSFR allows to compare galaxies with the same physical properties
- Difference between samples increasing with $M_\star$ in agreement with Salim et al. (2015) at $z \sim 2.3$



Source: Pistis et al. (2022a), in prep.

Indirect cross-matching by distance to star-forming main sequence (MS)

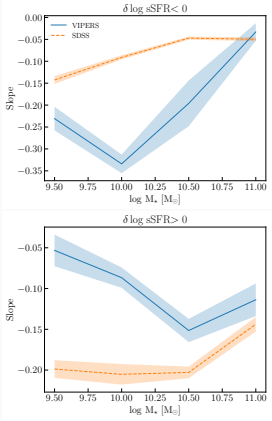
- Normalization of the sSFR on the sSFR predicted from the MS
- Bigger difference at small $M_\star$ than in indirect cross-matching on physical properties
- Allows us to study the metallicity dilution/enrichment below ($\delta \log \mathrm{sSFR} < 0$) and above ($\delta \log \mathrm{sSFR} > 0$) MS



Source: Pistis et al. (2022a), in prep.

Indirect cross-matching: dilution/starvation scenario I

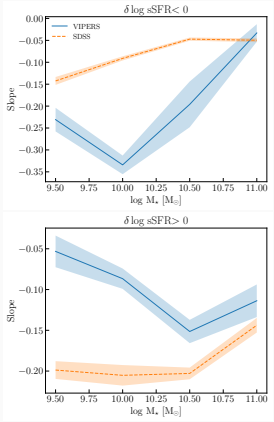
- Slope from the fit of the metallicity versus $\delta \log$ sSFR in each mass bin
- $\delta \log$ sSFR < 0: decreasing slope $\longrightarrow$ dry-mergers in VIPERS
- $\delta \log$ sSFR > 0: small slope for VIPERS $\longrightarrow$ metallicity of the infalling gas close to the ISM



Source: Pistis et al. (2022a), in prep.

Indirect cross-matching: dilution/starvation scenario II

- Hypothesis of pristine gas infalling is not always true
- Dark matter halo bias $\longrightarrow$ reduction of the differences in the slope at different redshift at high-$M_\star$



Source: Pistis et al. (2022a), in prep.

Conclusions

Conclusions

- FMR & its projections — comparison between $z \sim 0$ (SDSS) and $z \sim 0.7$ (VIPERS)
- FMR & its projections — evolution

Conclusions: parametric method

- Parametric method — direct cross-matching on physical properties and distance from main sequence
  - Difficult to infer information on FMR from its projections
  - Evolution of the MZR and metallicity versus SFR
  - No evolution of the metallicity versus combinations of $M_\star$ and SFR
  - **FMR does not evolve**
  - Metallicity difference between SDSS-based samples and VIPERS increasing with $M_\star$

Conclusions: non-parametric methods I

- Non-parametric method — indirect property cross-matching
  - Bias independent (introduced by data selection or observation, Pistis et al. 2022b, accepted)
  - sSFR normalized by median value at low redshift: compare galaxies with the same physical properties without the step of cross-matching
  - **FMR does not evolve**
  - Metallicity difference between SDSS and VIPERS samples increasing with $M_\star$

Conclusions: non-parametric methods II

- Non-parametric method — indirect galaxy type cross-matching
  - Bias independent (ntroduced by data selection or observation, Pistis et al. 2022b, accepted)
  - sSFR normalized by the MS value: compare galaxies with the same distance from the MS without the step of cross-matching
  - Higher metallicity difference at low-$M_\star$

Conclusions: analogies & dissimilarities between methods

1. Analogies
   - Direct and indirect cross-matching on physical properties $\longrightarrow$ metallicity difference increasing with $M_\star$
2. Dissimilarities
   - Flattening at low-$M_\star$ IN VIPERS (similar to VVDS, Pérez-Montero et al. 2009) not observed in the indirect method $\longrightarrow$ need to study directly MZR or FMR
   - Indirect cross-matching on galaxy type does not lead to the same conclusions than other methods

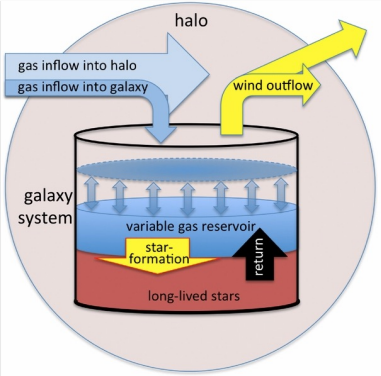
Conclusions: why indirect methods are better?

1. Pros of indirect methods of comparison
   - Simpler than studying the projections
   - Straightforwardly compare galaxies with the same properties or type
   - Independent on biases introduced by data selection or observations
2. Cons of direct methods of comparison
   - Direct method needs to take into account biases
   - FMR projections evolve $\longrightarrow$ difficult to infer information on the whole FMR

Thank you for your attention!

What is the origin of the Mass Metallicity Relation (MZR)?

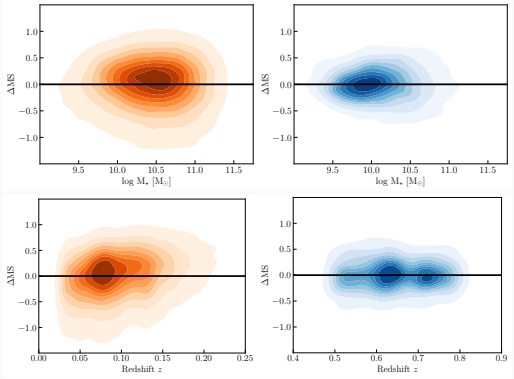
- Gas inflow $\longrightarrow$ the star formation
- Evolution of stellar population $\longrightarrow$ production of metals
- Evolution of stellar population $\longrightarrow$ energy injection to the ISM
- Energy injection to the ISM $\longrightarrow$ gas outflow



Source: Maiolino & Mannucci (2019)

Direct cross-matching — galaxy type: according to the distance from the galaxy main sequences

- MS: $\log \mathrm{SFR}\,(\mathrm{M}_\star, z)$
- $\log \mathrm{SFR}_{\mathrm{MS}}^{\mathrm{SDSS}}\,(\mathrm{M}_\star) = \alpha \log \mathrm{M}_\star + \beta$
- $\log \mathrm{SFR}_{\mathrm{MS}}^{\mathrm{VIPERS}}\,(z, \mathrm{M}_\star) = \alpha\,(z) \log \mathrm{M}_\star + \beta\,(z)$



Source: Pistis et al. (2022a), in prep.