Modeling the evolution of galaxies through semi-analytic spectral fitting

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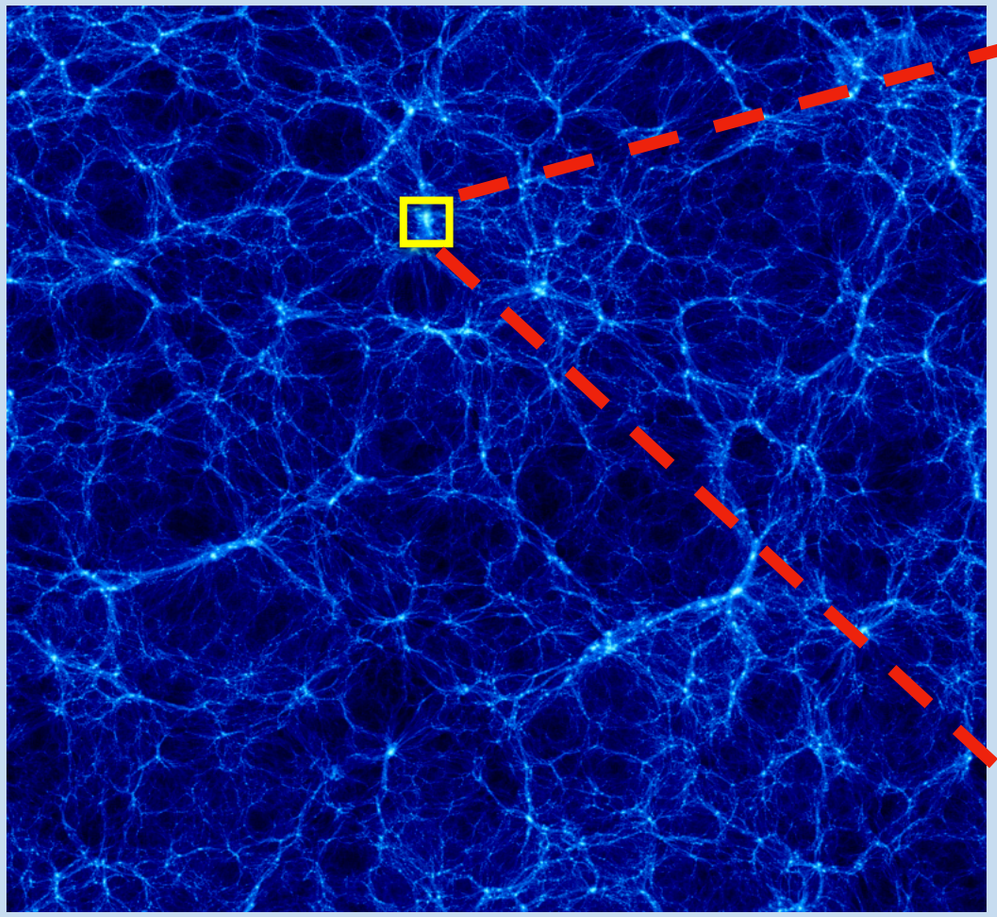
Galaxy evolution in a nutshell

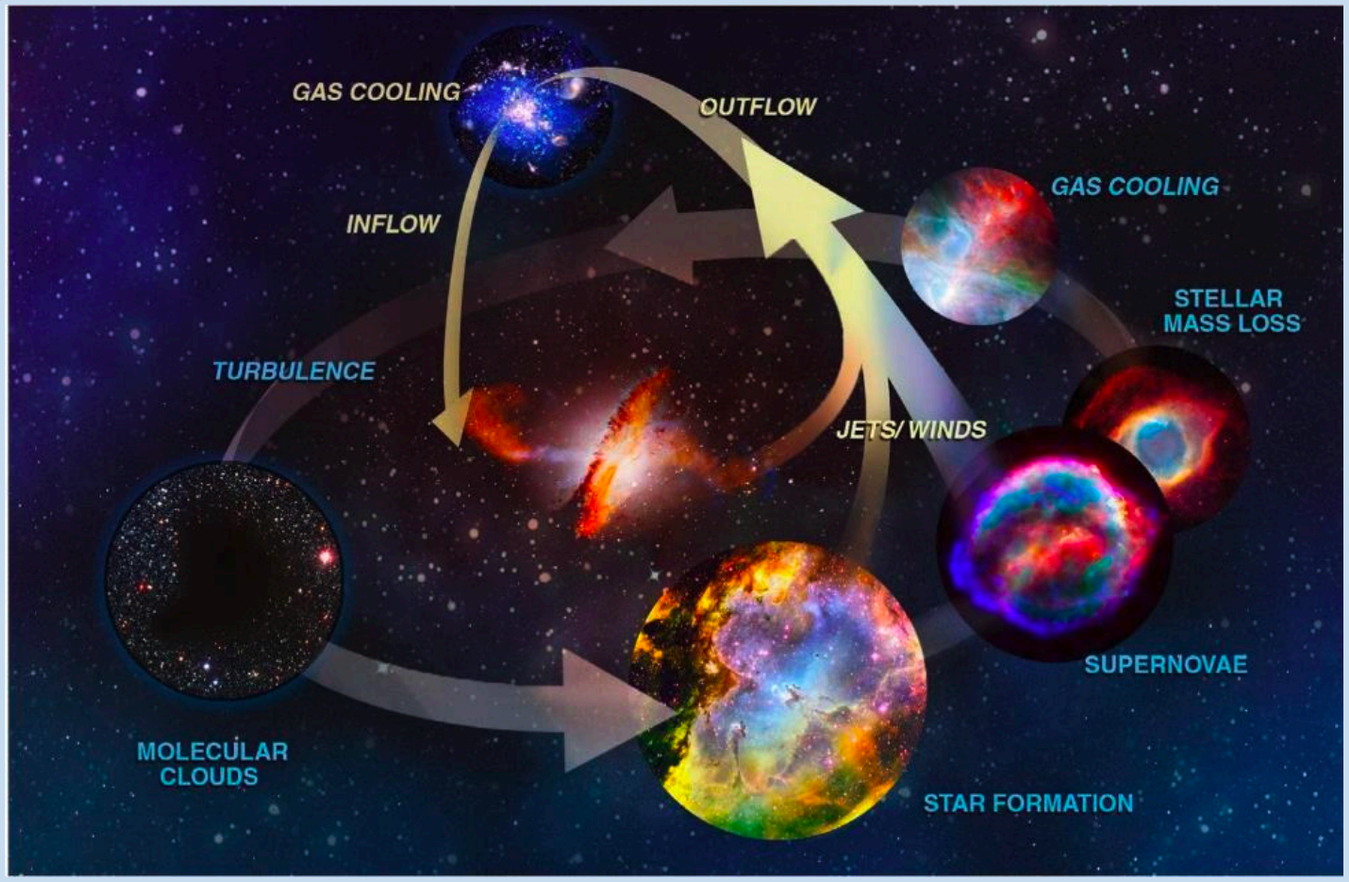
Formation of dark matter halos

Structure formation and growth through gravitational instability and dark matter halo mergers

Galaxy formation in the centers of dark matter halos

Gas flows in and out of the galaxy
Star-gas-star cycling within the galaxy



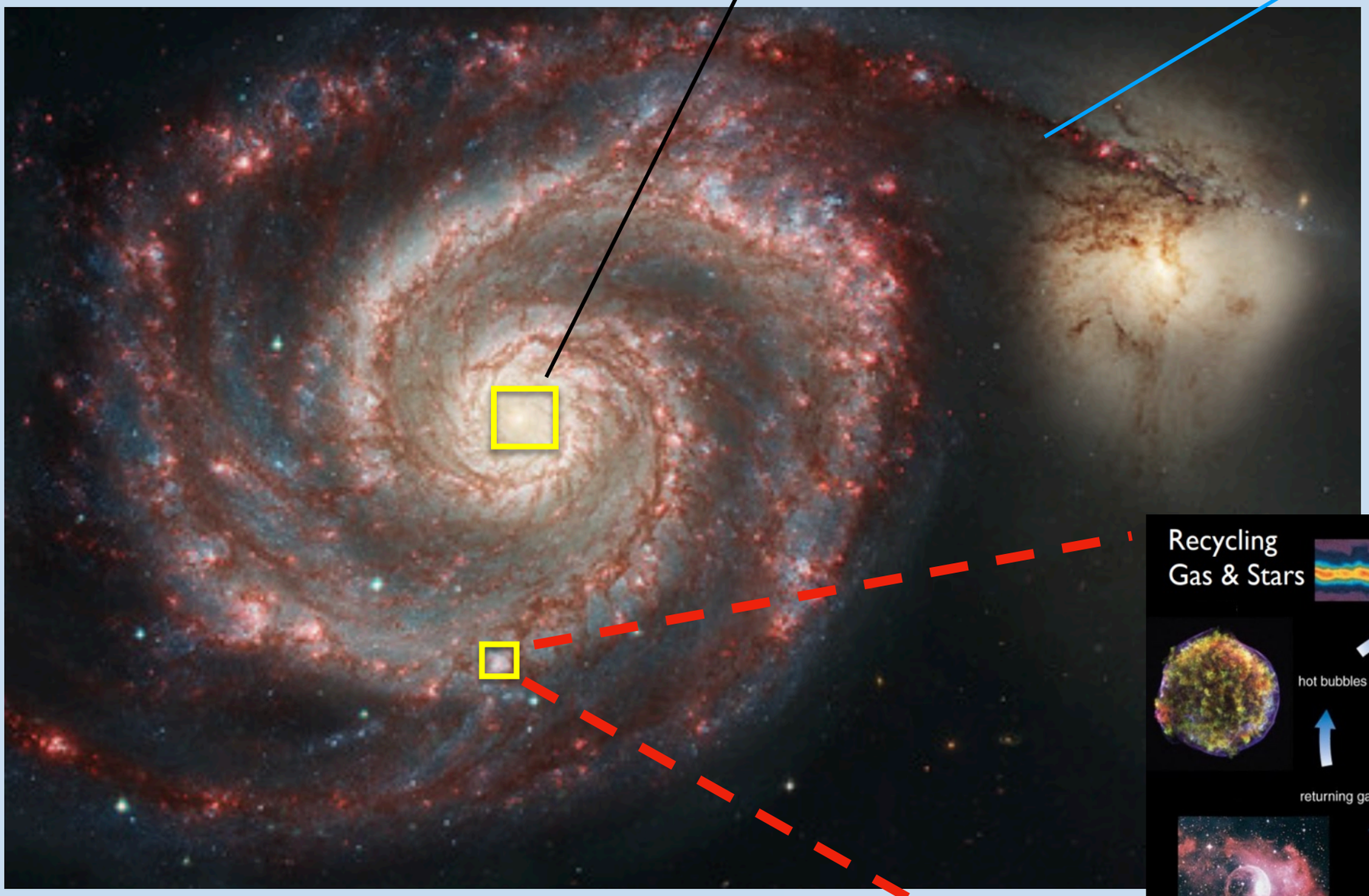


Galaxy evolution in a nutshell

Complex Byronic physics at different scales

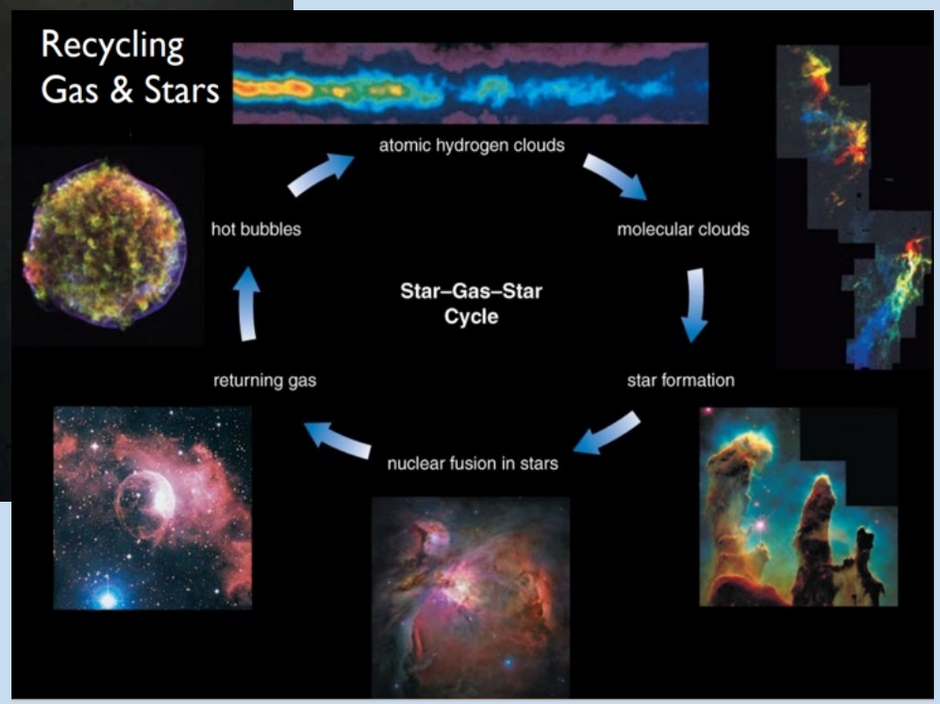
AGN feedback/
coevolution of SMBH
and the galaxy

Merger/interaction



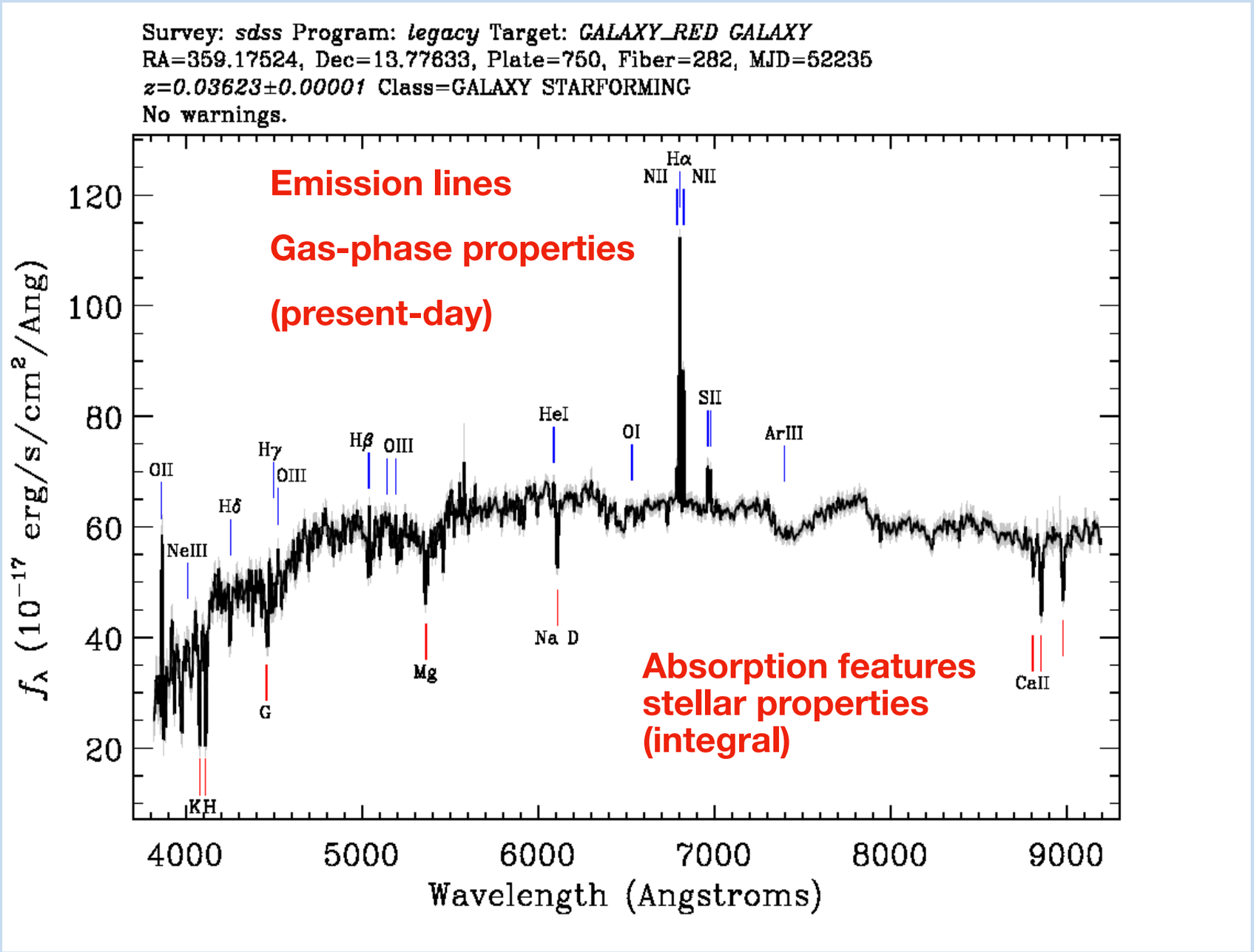
Credit: vdHoeven/NASA/JPL-Caltech/R. Kennicutt (Univ. of Arizona)/DSS

Star-gas-star cycling

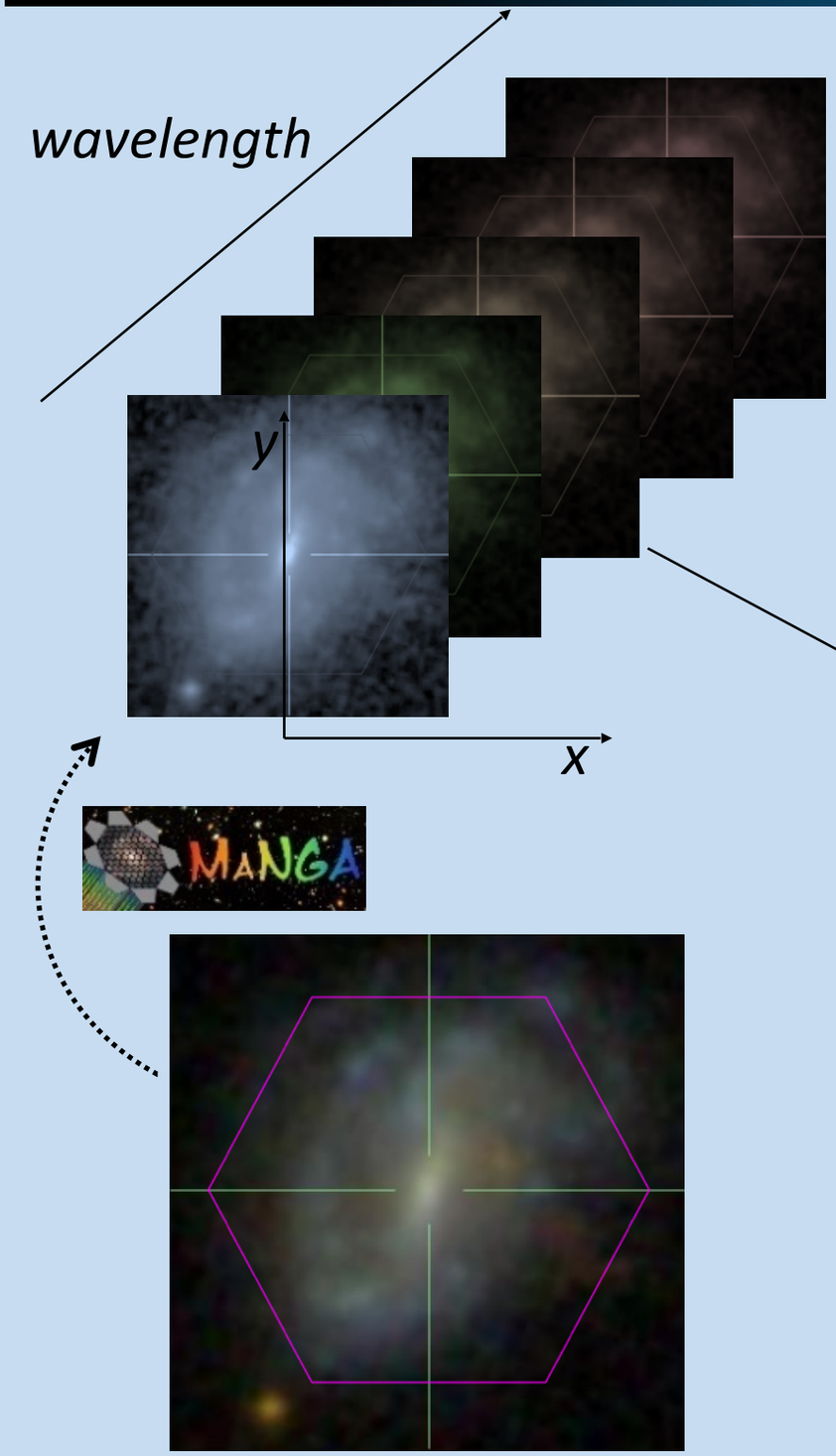


Spectra as the key in understanding galaxy evolution

- The spectra of galaxies encode a wealth of information regarding their formation and evolution

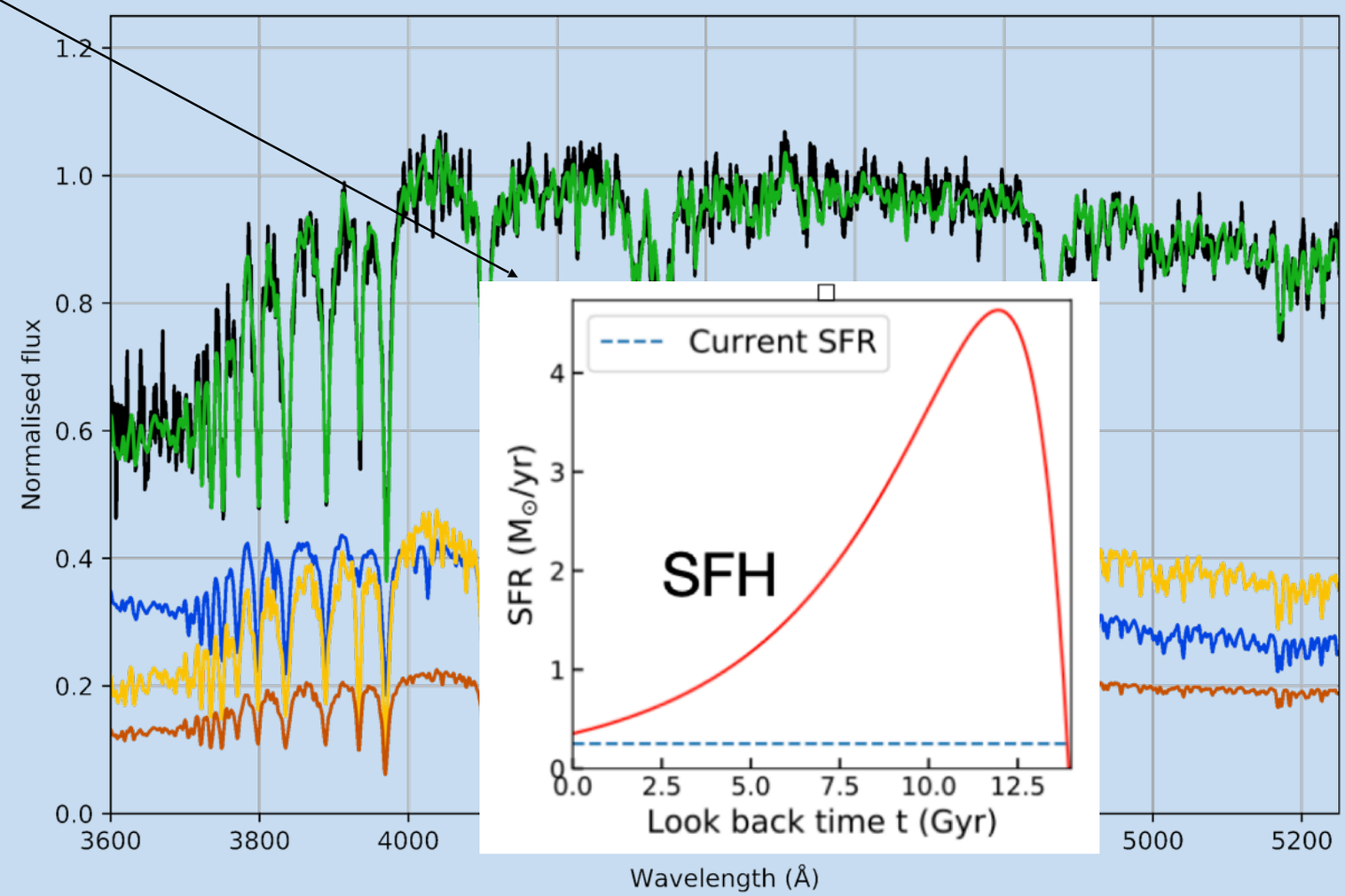


Reconstructing the lives of galaxies with MaNGA data



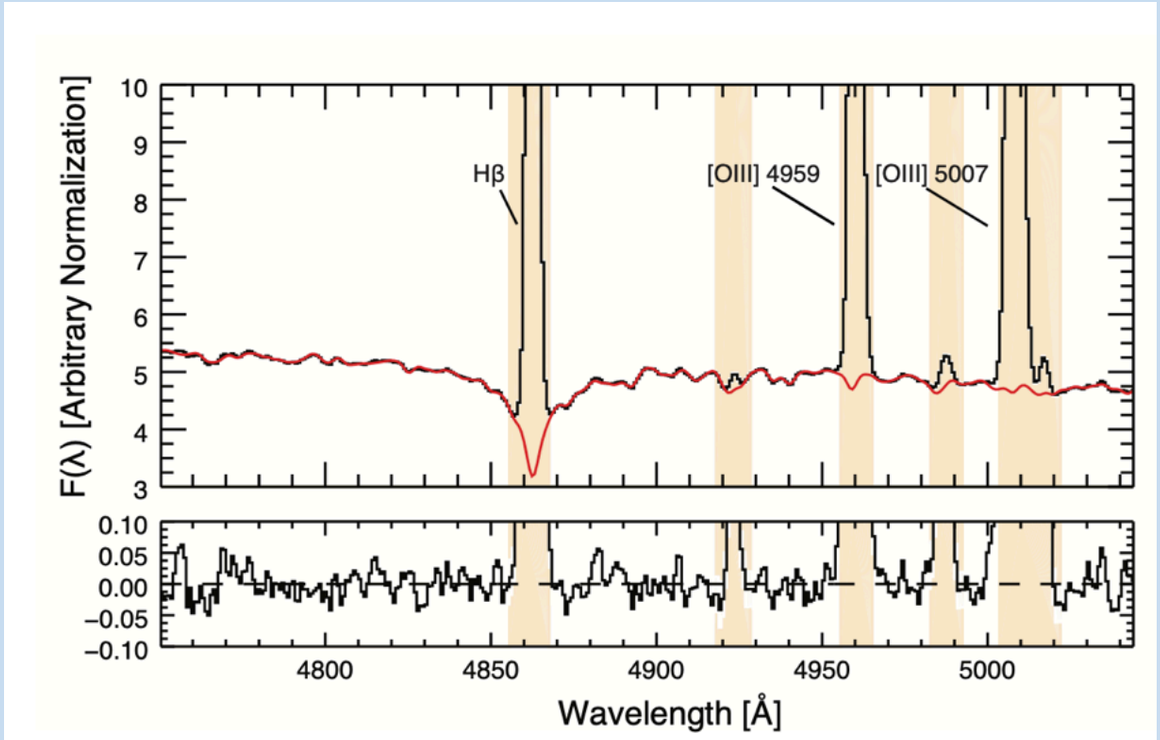
- The spectra of galaxies encode a wealth of information regarding the formation and evolution of galaxies
- Spectral fitting techniques are fast improving to extract useful physics from the spectra

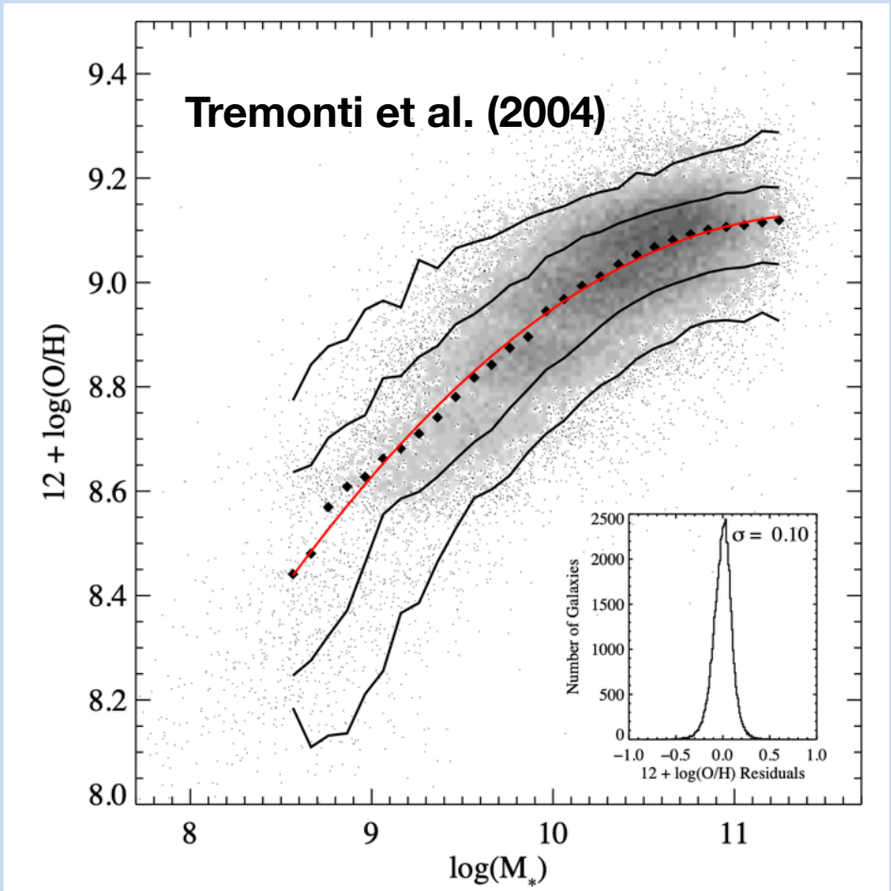
Spectral fitting code
(Starlight, pPXF)

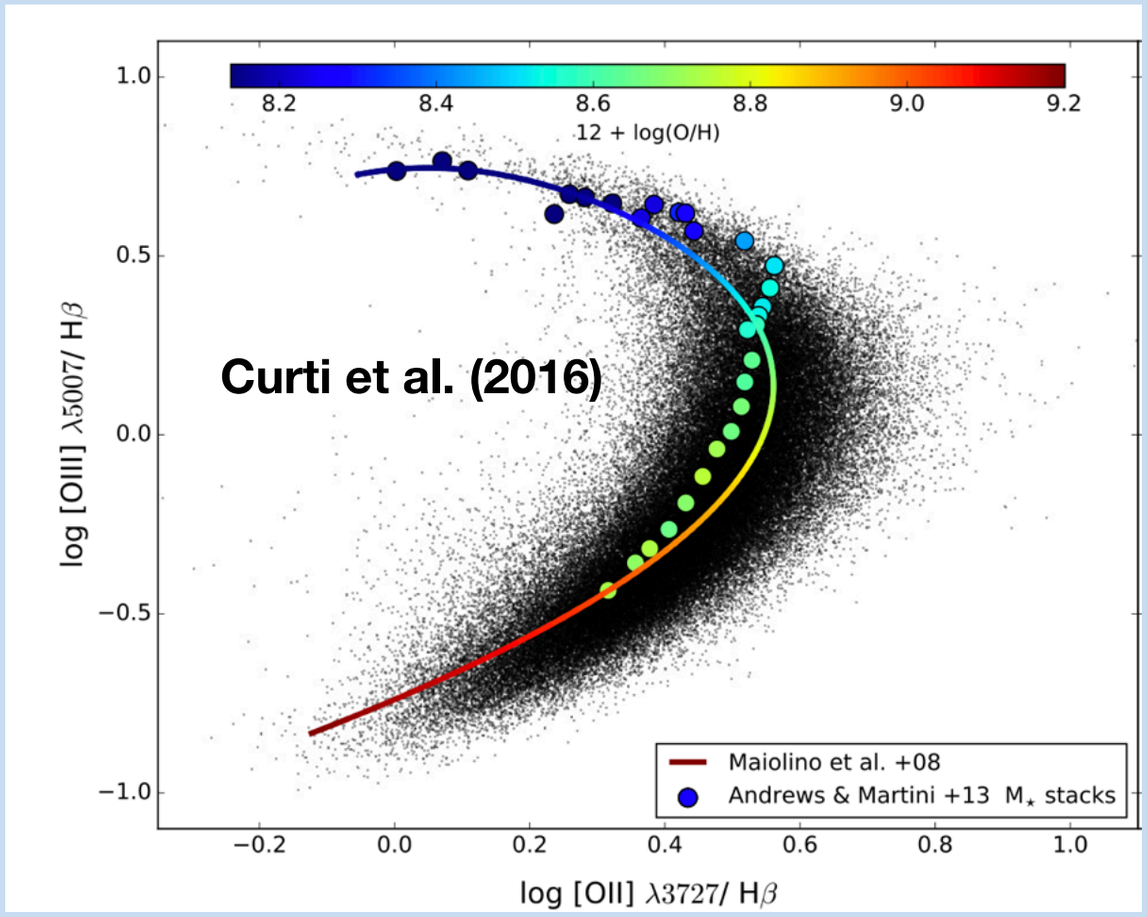


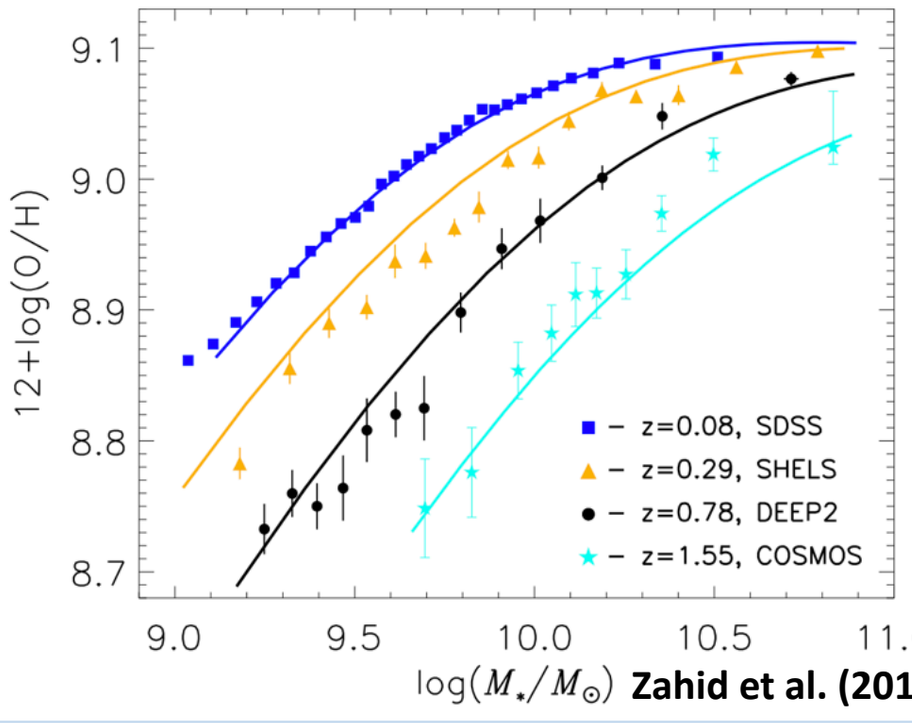
Mapping Nearby Galaxies at Apache Point Observatory (MaNGA): spatially resolved observation of more than 10,000 galaxies in the local universe

Chemical evolution of galaxies: emission line diagnostics



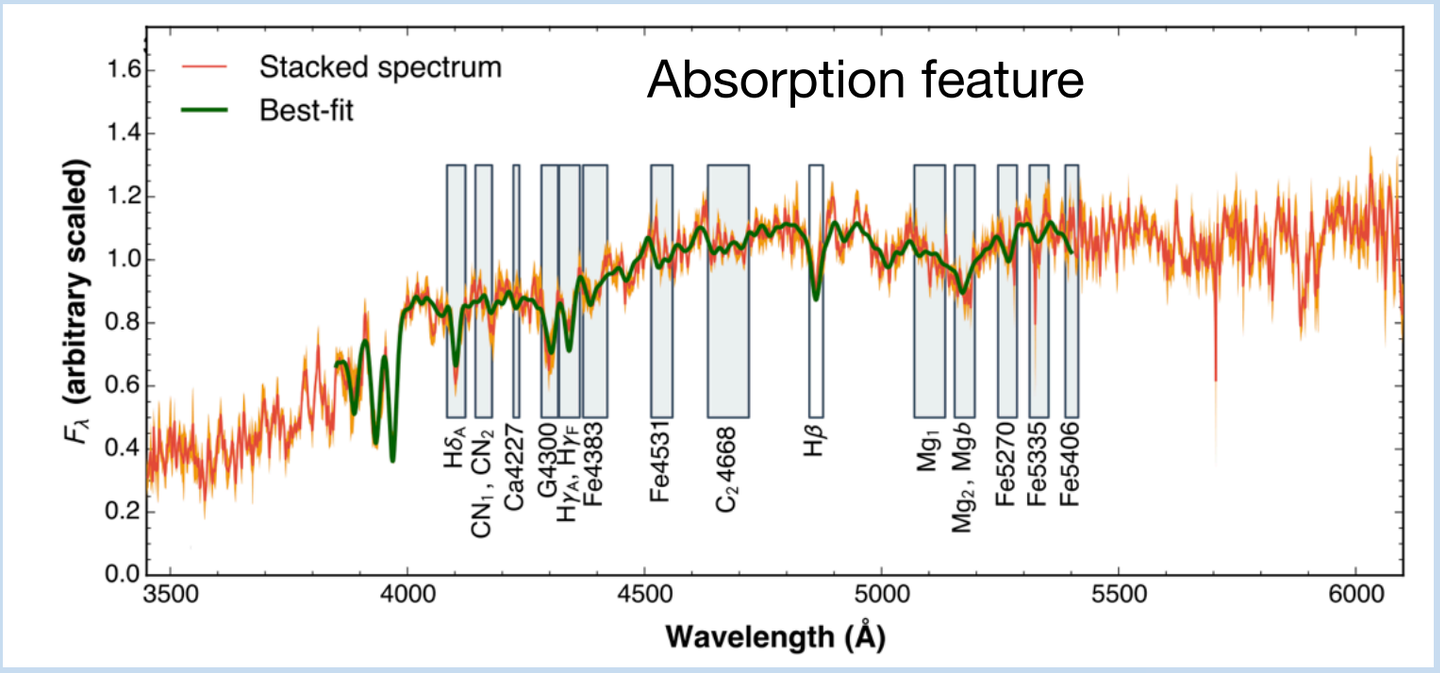


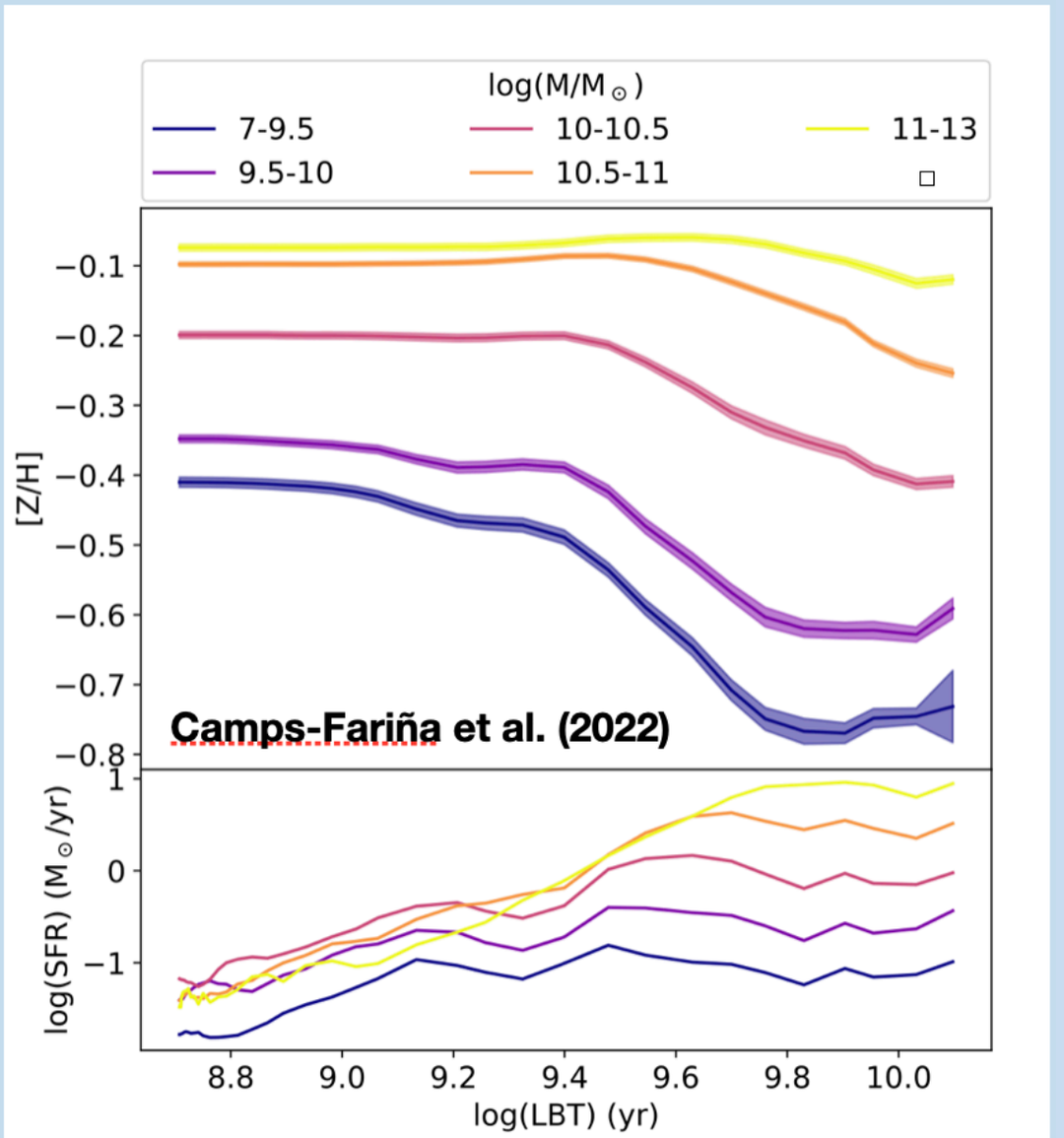


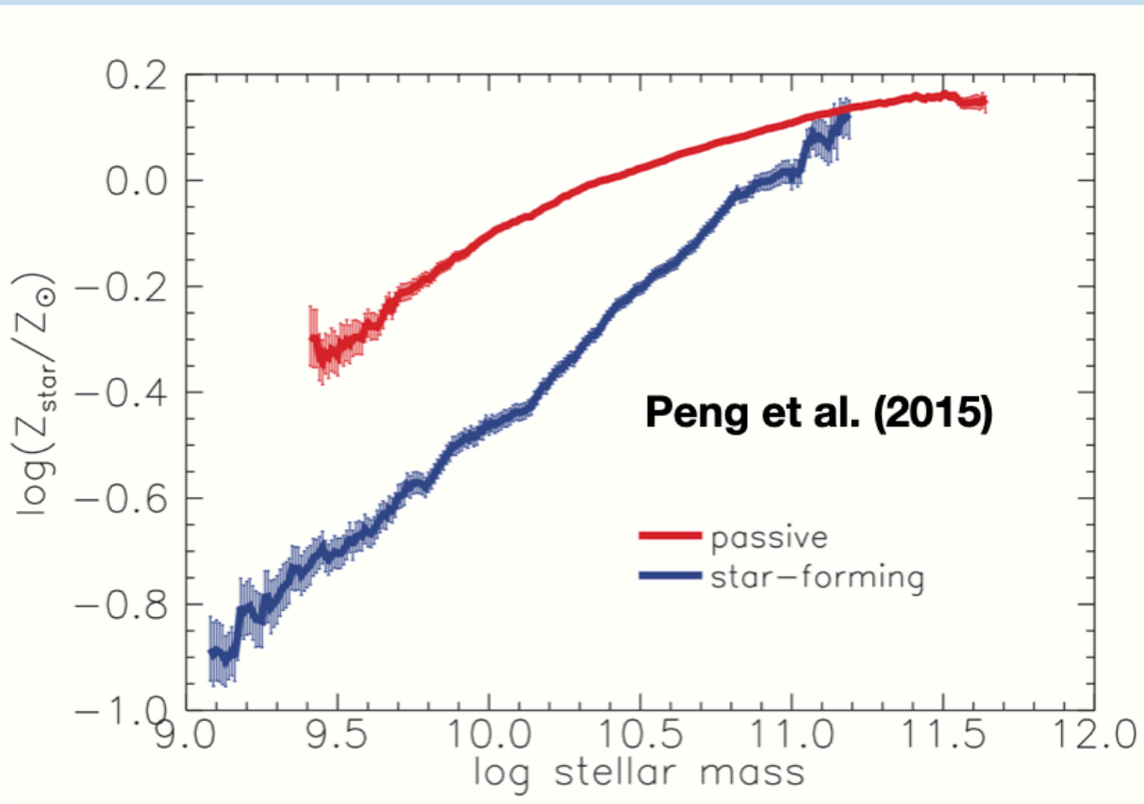


Zahid et al. (2014b)

Chemical evolution of galaxies from stellar populations

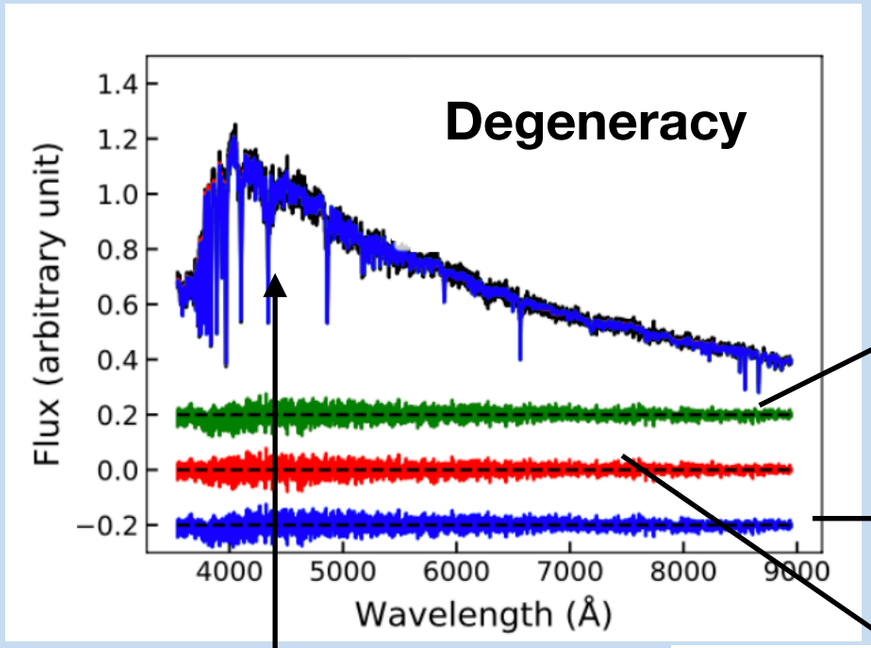


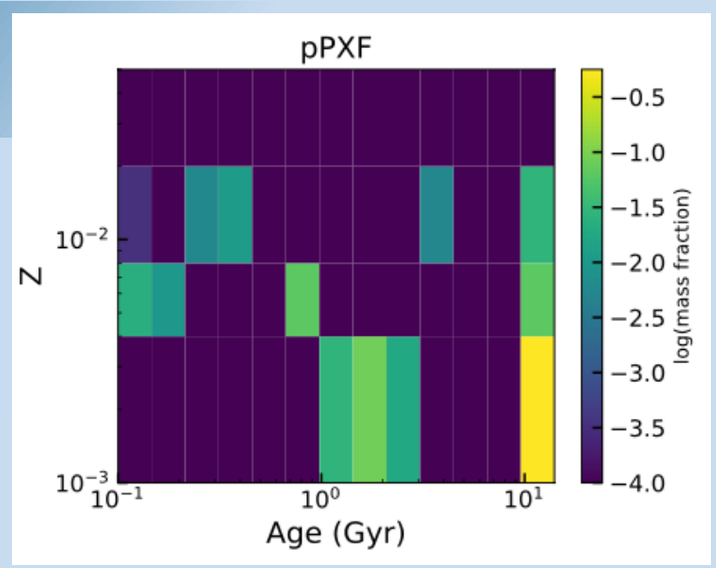


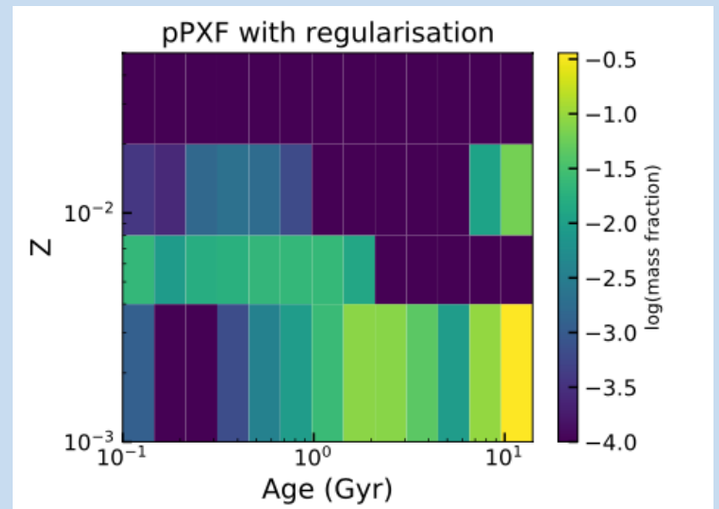


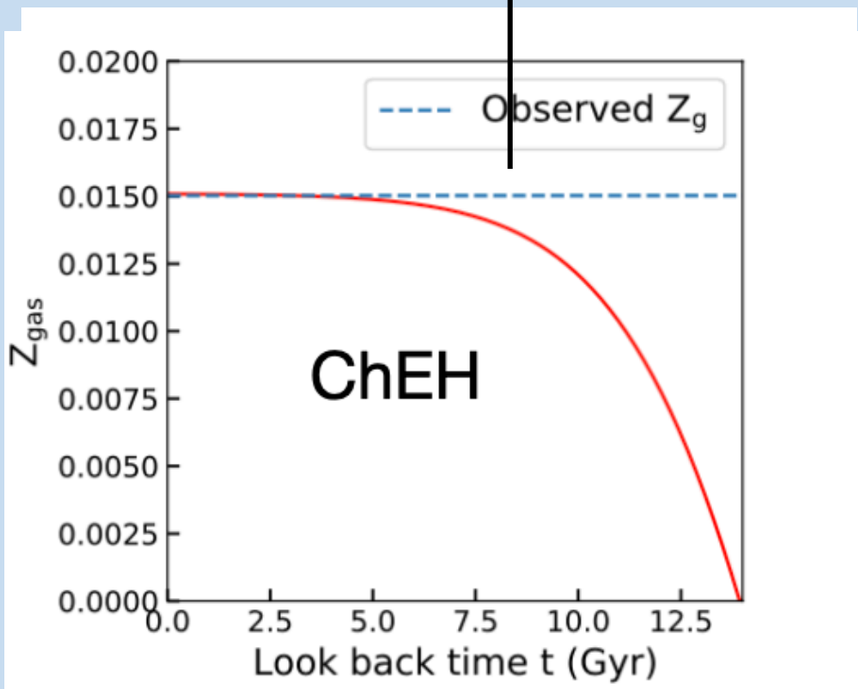
Limitations of traditional spectral fitting methods

- **Linear combinations can be arbitrary!**

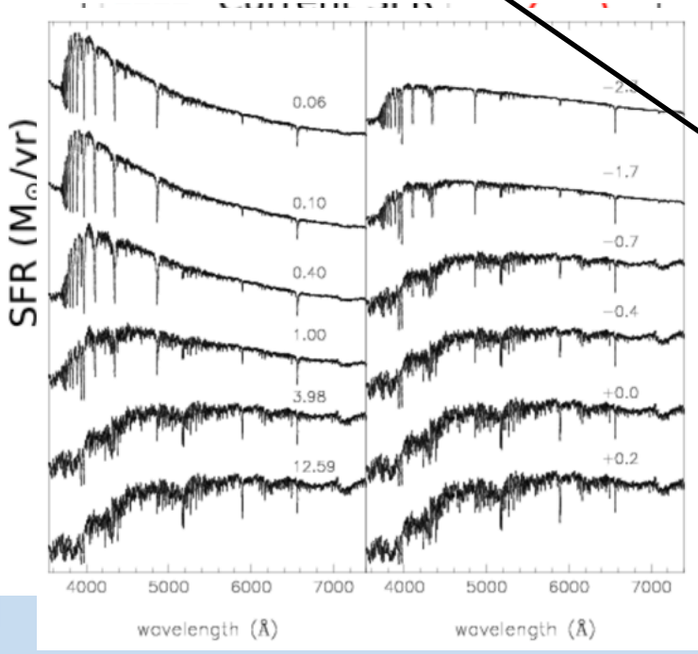


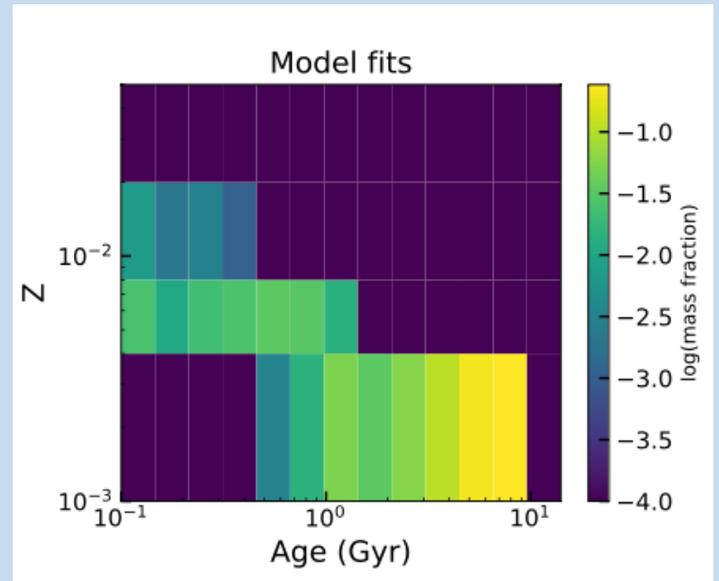






$$M_\lambda = M_{\lambda_0}\left(\sum_{j=1}^{N_\star} x_j b_{j,\lambda} r_\lambda\right) \otimes G(v_\star, \sigma_\star),$$





- **Lack of physical insights: what is behind the averaged age & metallicity?**

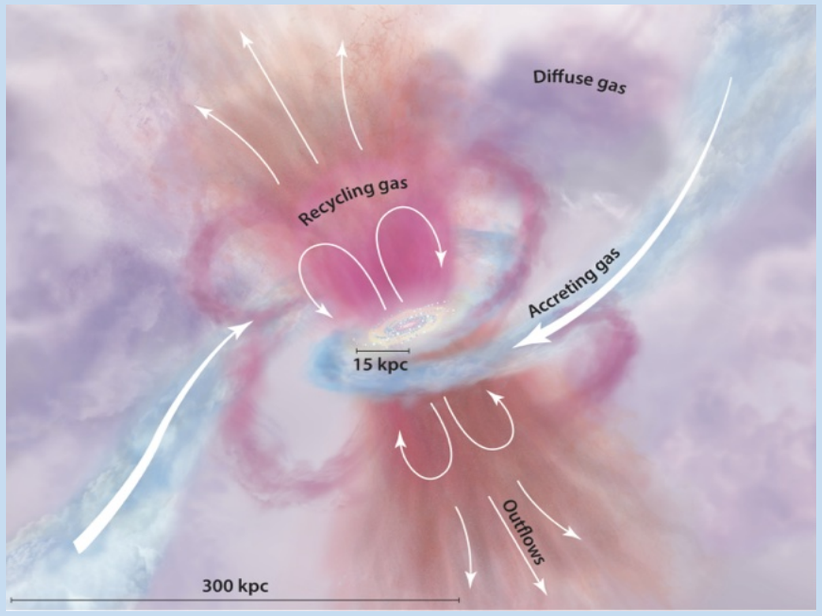
Semi-Analytic Spectral Fitting : basic idea

- **Basic ingredients & assumptions :**

1. Inflows bring pristine gas into the galaxy. The star form rate is proportional to the amount of gas through a star formation law

2. A fraction of stars die after their formation, and return a fraction of metal-enriched gas into the interstellar medium (ISM), we assume the gas to be well-mixed at all times

3. Outflows take away metal-enriched gas and suppress the metallicity enrichment process



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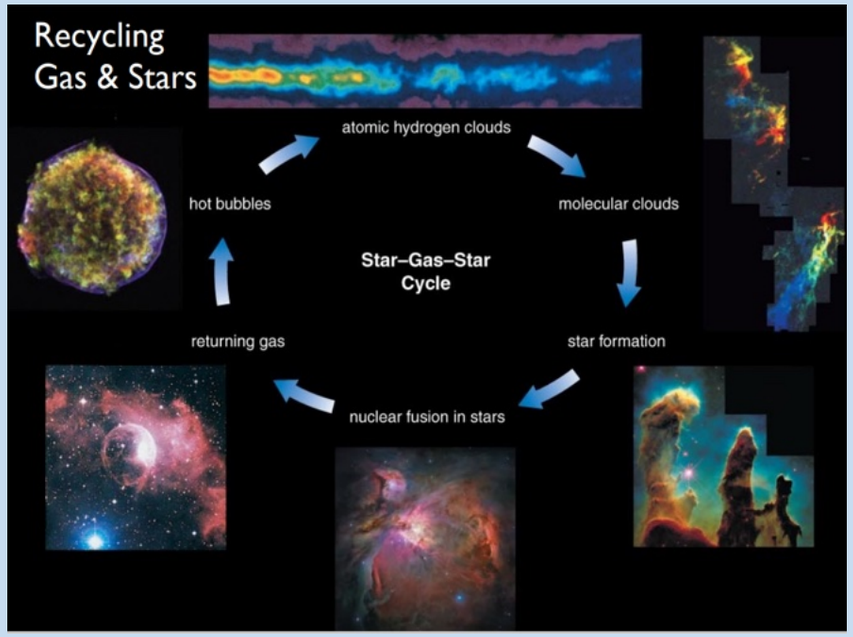

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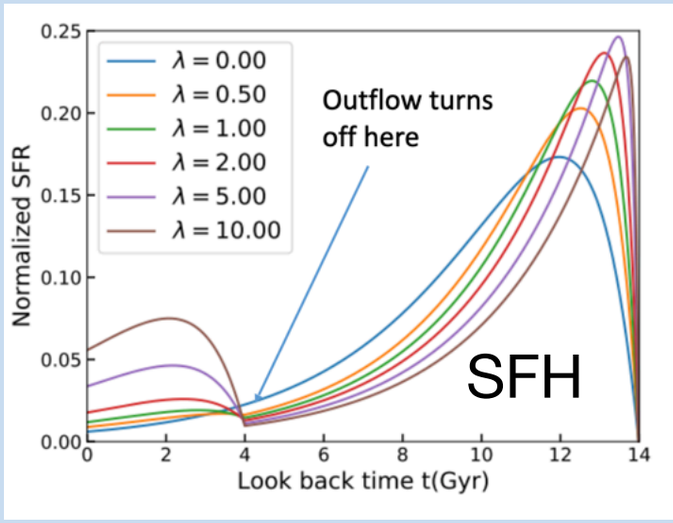
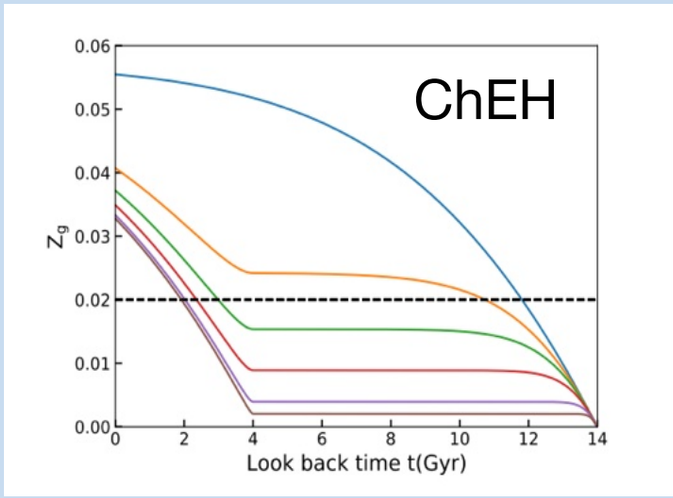
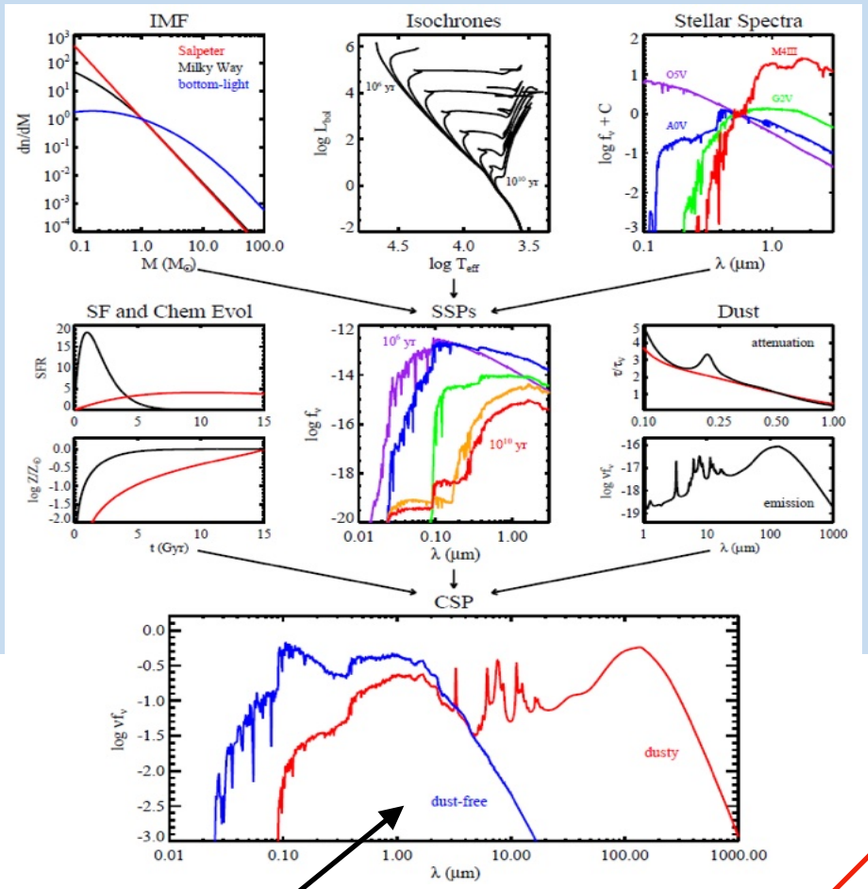




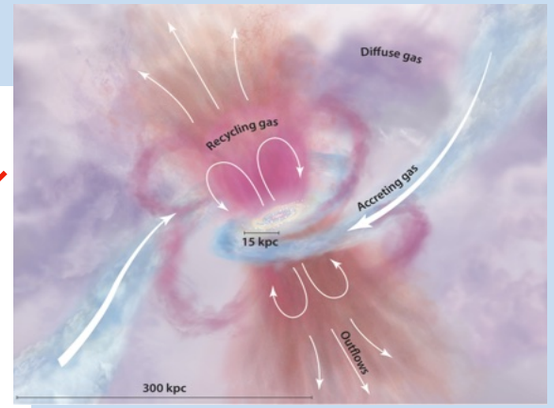
- **Self-consistent, physically motivated, helping to understand the physics**

Semi-analytic spectral fitting : the workflow

- Corresponding spectrum is calculated with stellar population synthesis models
- Spectrum, current gas phase metallicity and SFR are used to compare with the observation in a Bayesian context



- Parameters are used to derived the SFH and ChEH using the chemical evolution model



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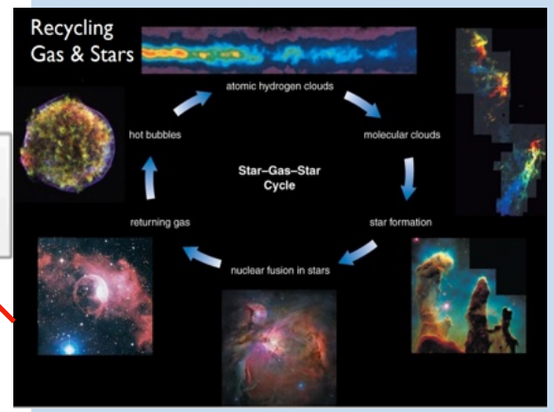
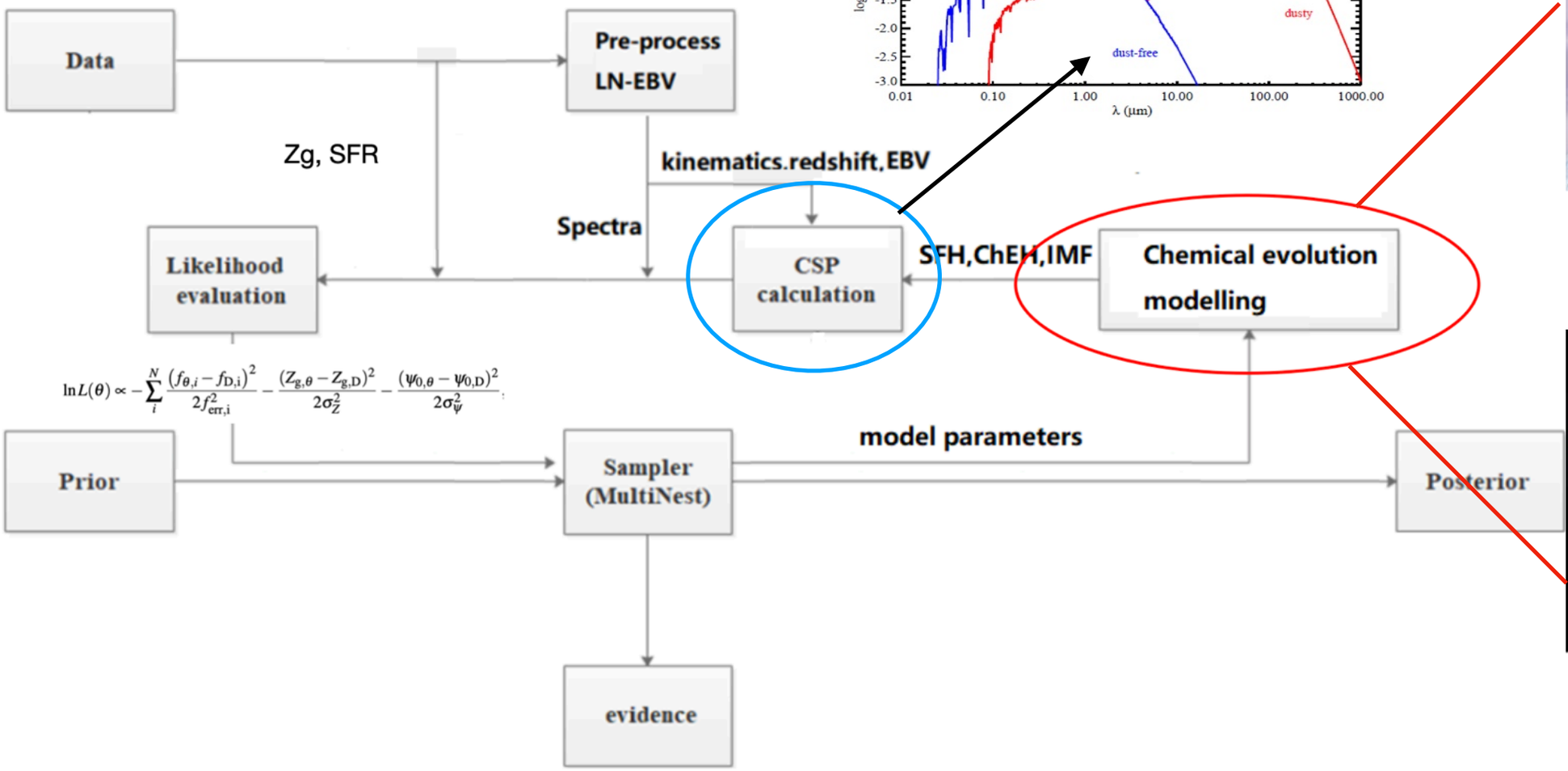




Semi-analytic spectral fitting : example application on MaNGA galaxies

Traditional

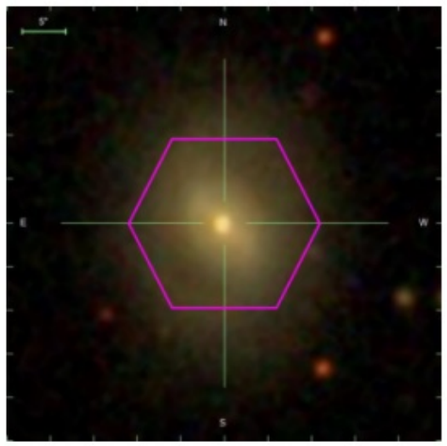
Parameter	description	Prior range
Γ_u; Γ_b	IMF slopes	$[0.3, 3.5]$
$\log(Z/Z_\odot)$	metallicity	$[-2.3, 0.2]$
τ	SFH parameter	$[0.0, 10.0]$
α	SFH parameter	$[0.0, 20.0]$
τ_v	dust optical depth at 5500 Å	$[0.0, 2.0]$

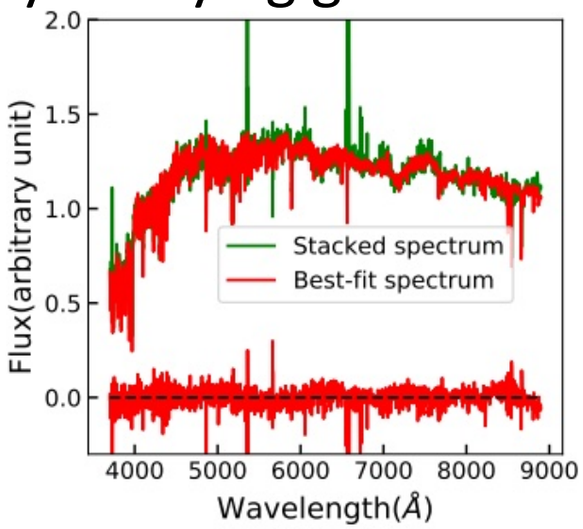
Semi-analytical

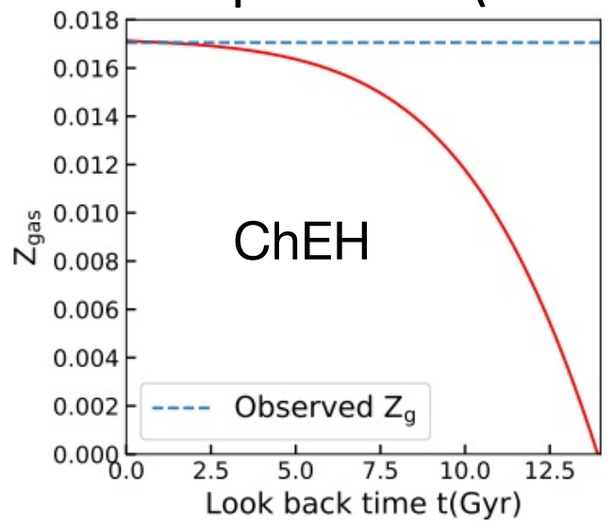
Table 1. Priors of model parameters used to fit galaxy spectra

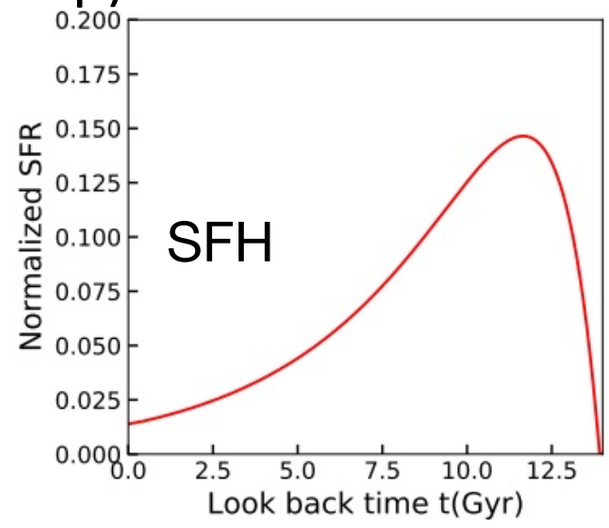
Parameter	Description	Prior range
y_Z	Effective yield	$[0.0, 0.08]$
τ	Gas infall timescale	$[0.0, 14.0]$Gyr
t_0	Start time of gas infall	$[0.0, 14.0]$Gyr
λ	The wind parameter	$[0.0, 10.0]$
$t_{\rm cut}$	The time that outflow turns off	$[0.0, 14.0]$Gyr
$E(B-V)$	Dust attenuation parameter	$[0.0, 0.5]$

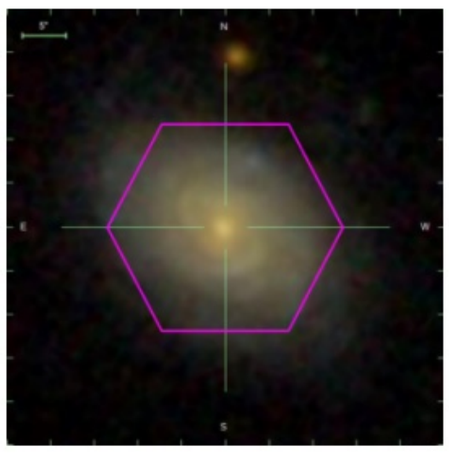
- Exponentially decaying gas infall + time-dependent (two-step) outflow

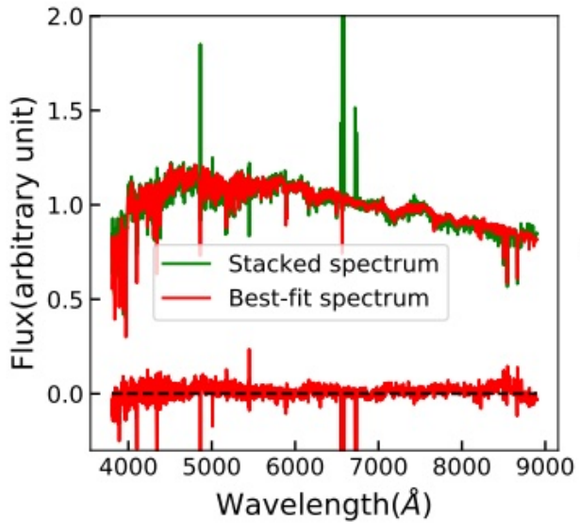


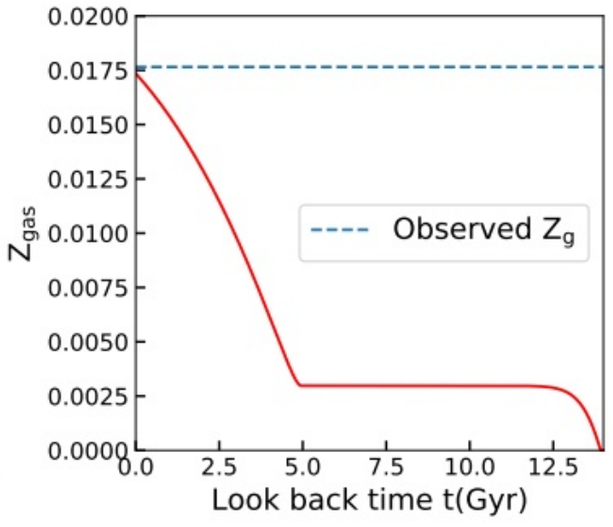


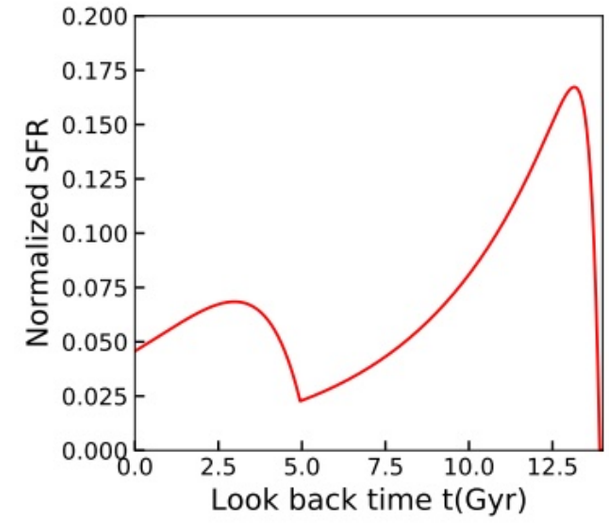








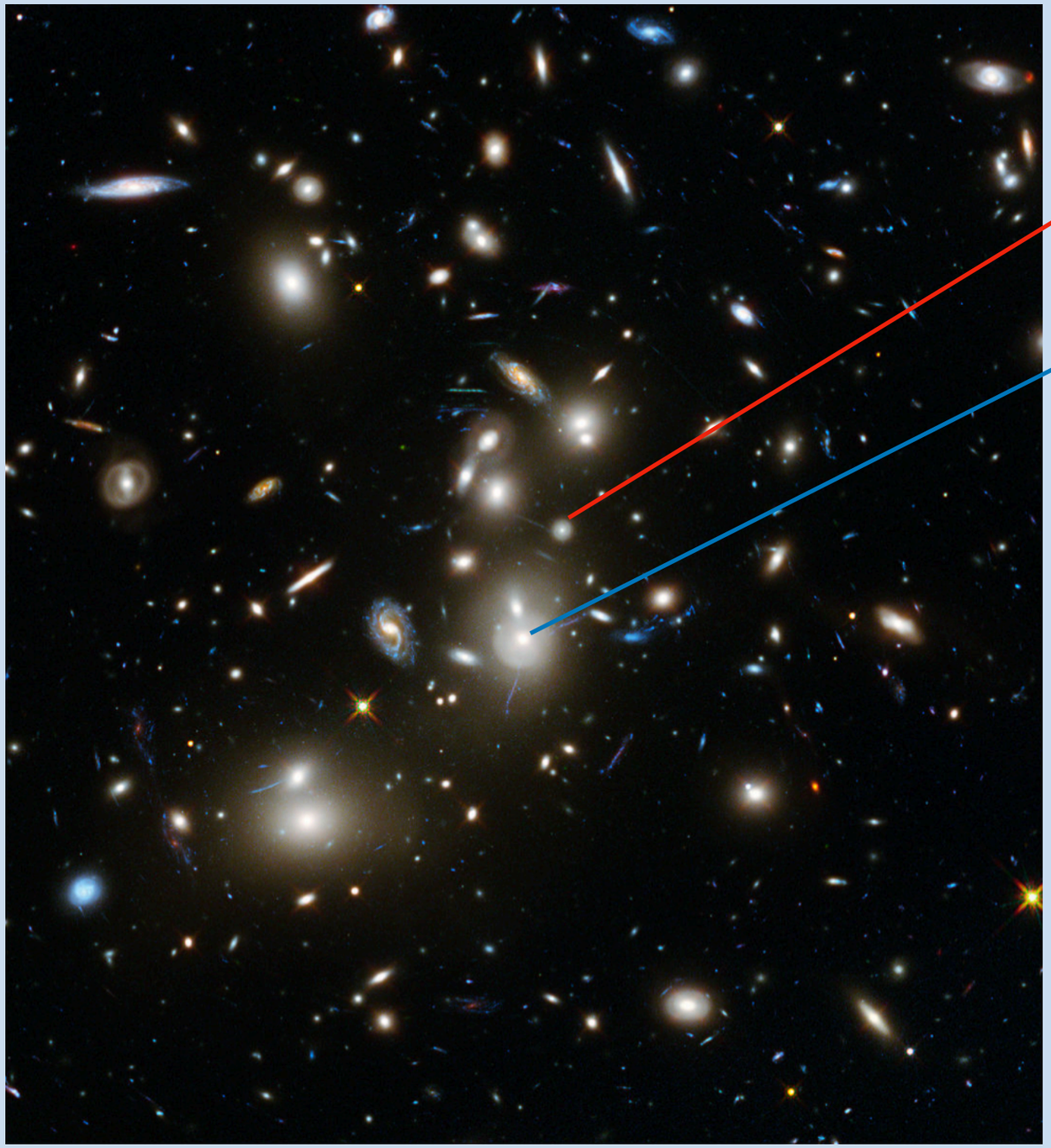


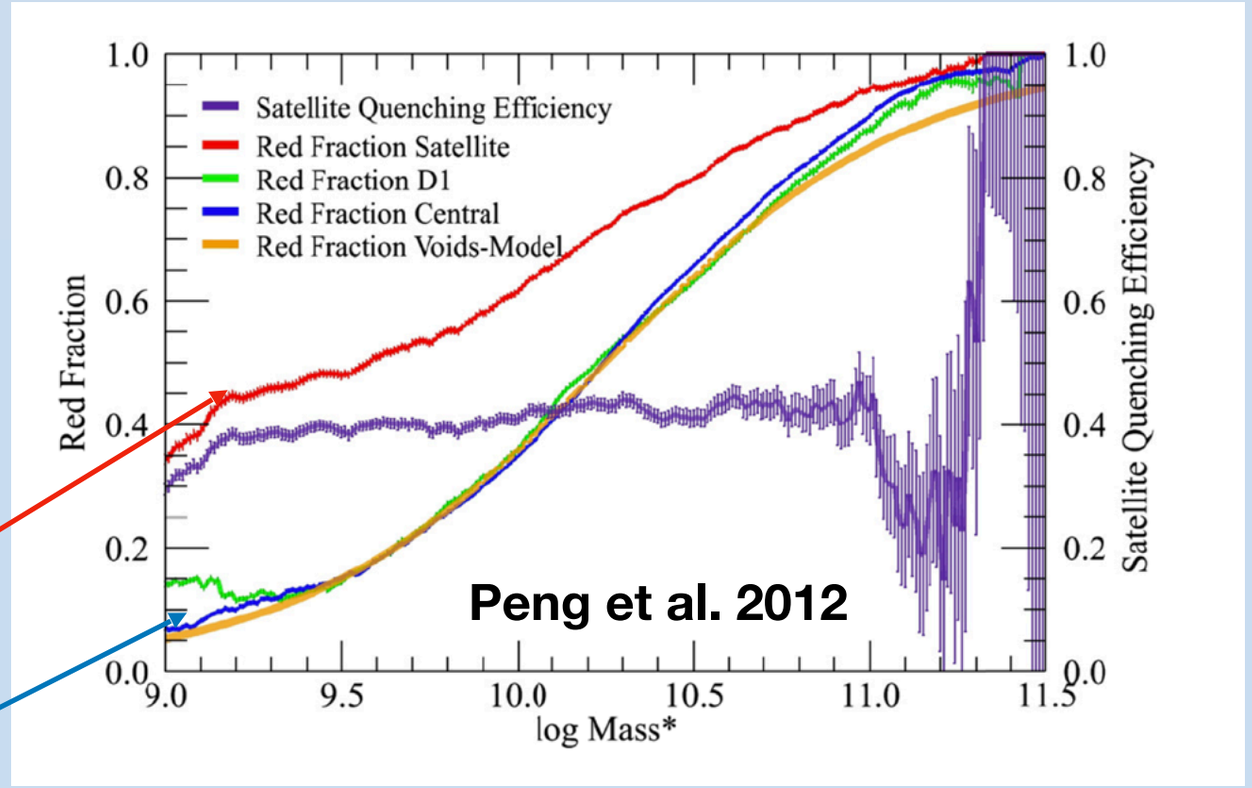


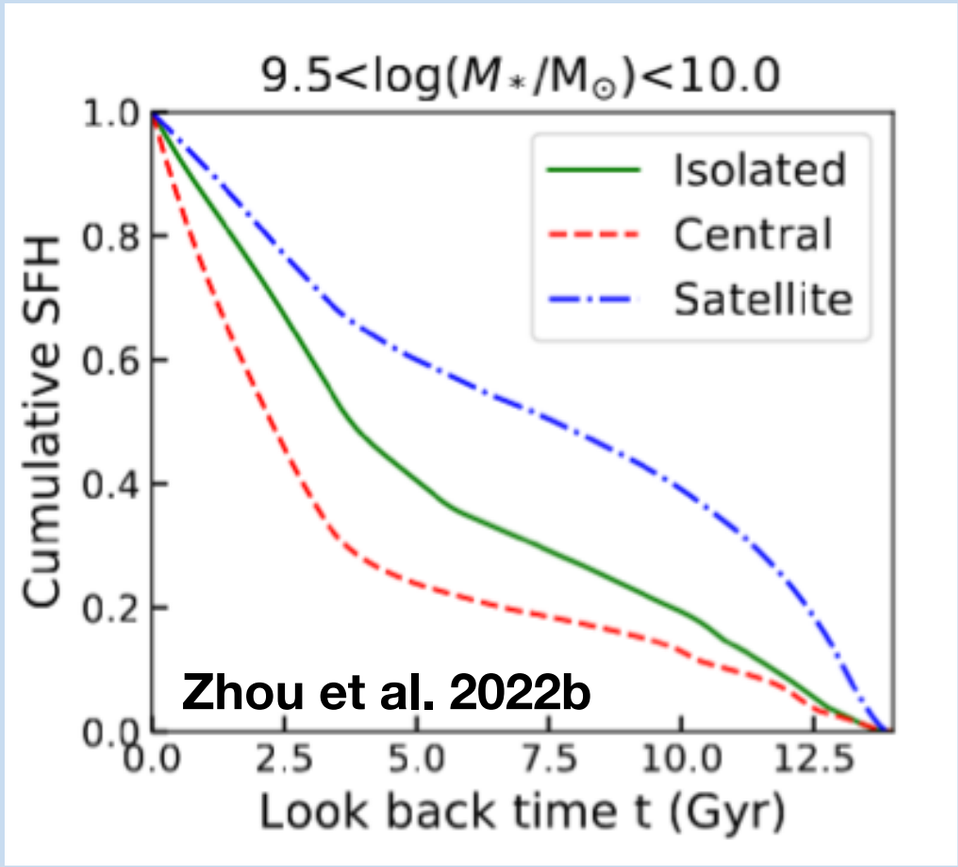
Zhou et al. 2022a

Environment quenching in MANGA

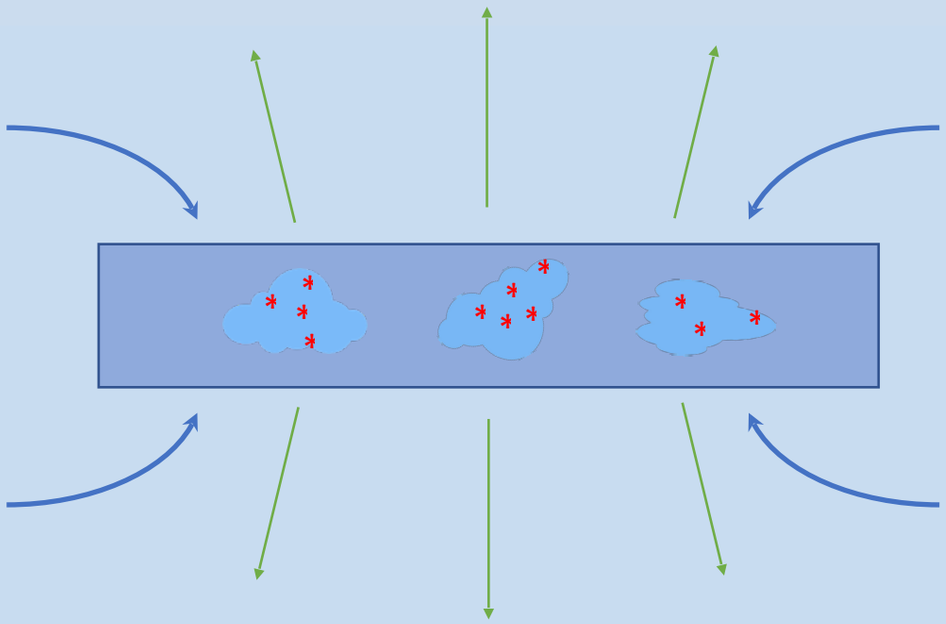
Satellites are more likely to be red and dead!





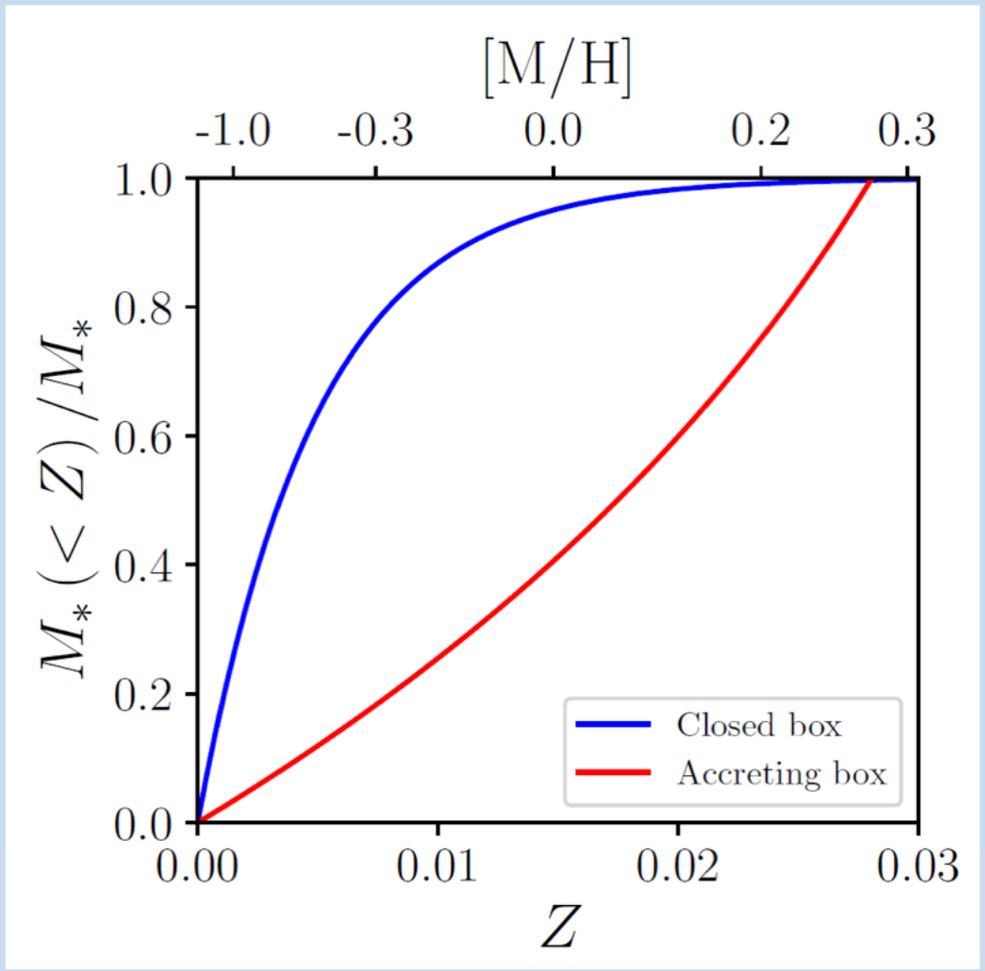


Evidence for gas removal & strangulation in low-mass satellites

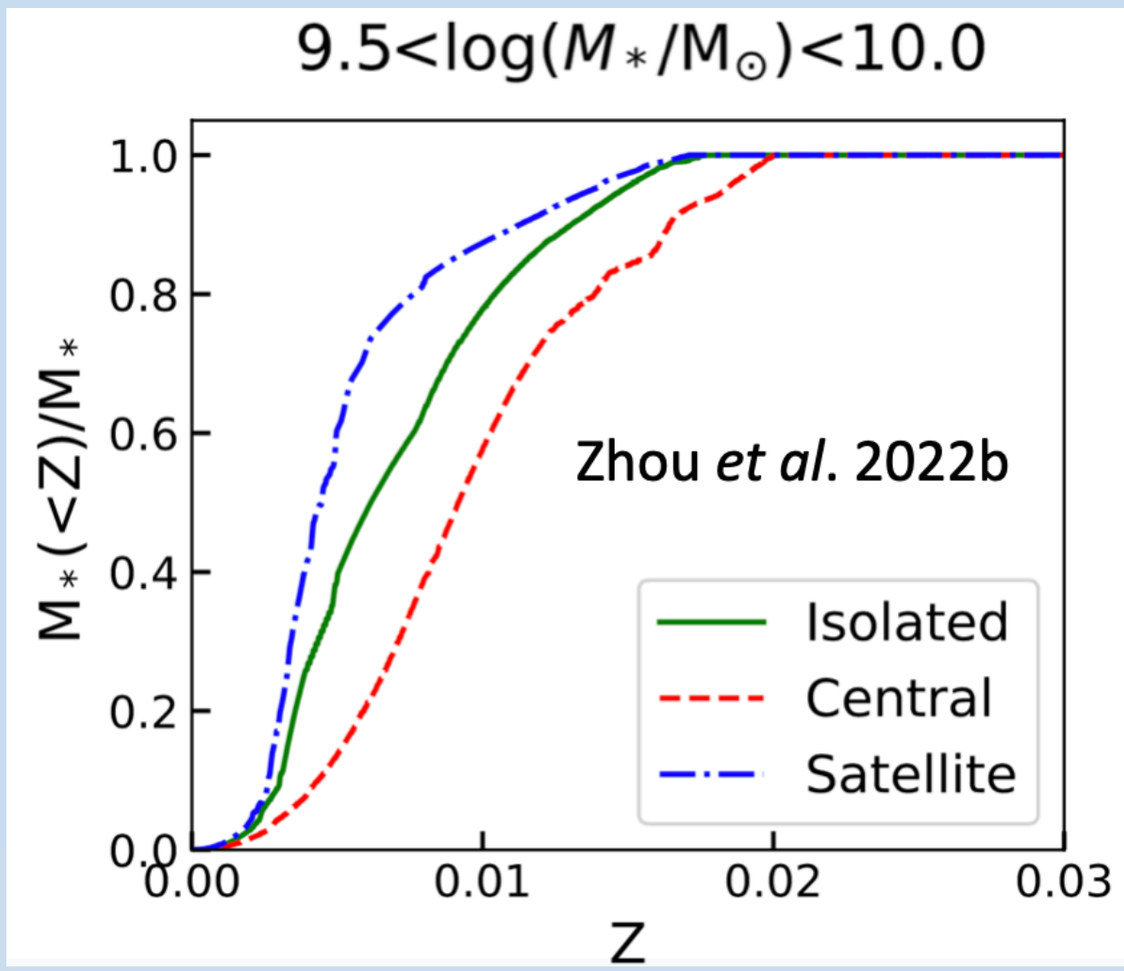


Low-mass satellite galaxies evolve like a ‘closed box’ or ‘leaky box’, indicating strangulation & gas being stripped out

Central galaxies evolve like an ‘accreting box’, i.e. continuously fed by the group halo

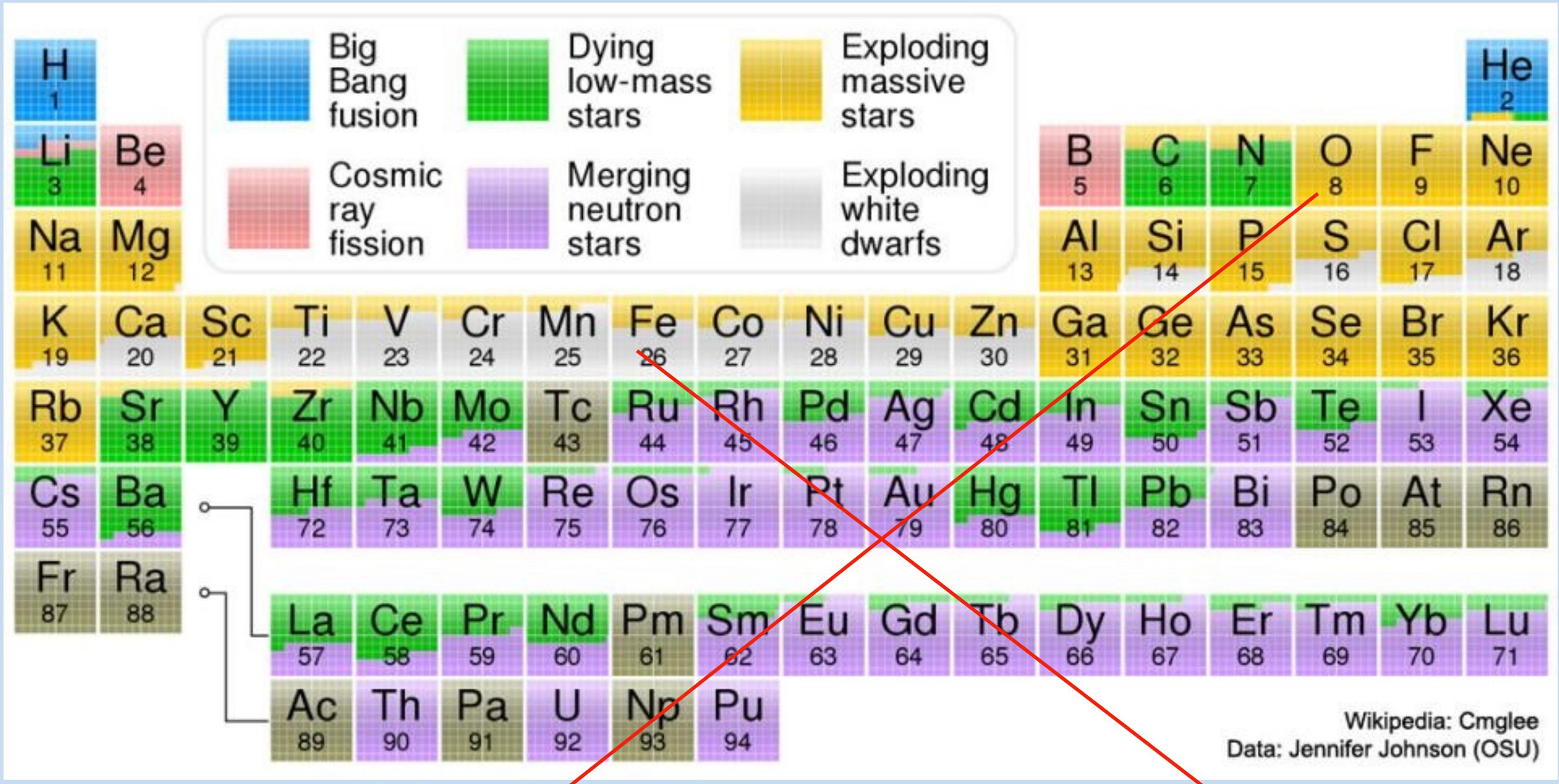


Greener *et al*. 2021



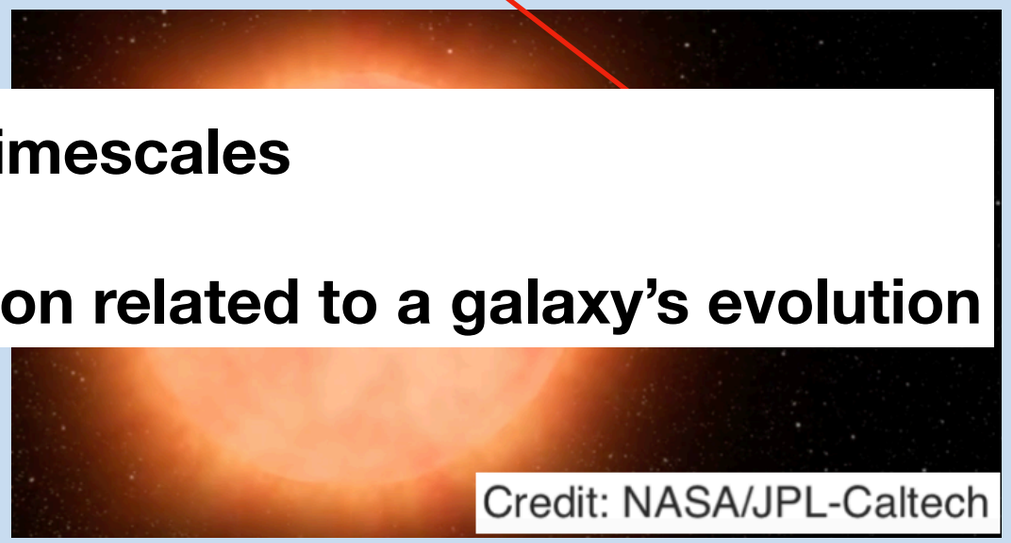
Zhou *et al*. 2022b

Origin of different elements in the universe



[α/Fe] correlates with star formation timescales

Abundance patterns contain information related to a galaxy's evolution

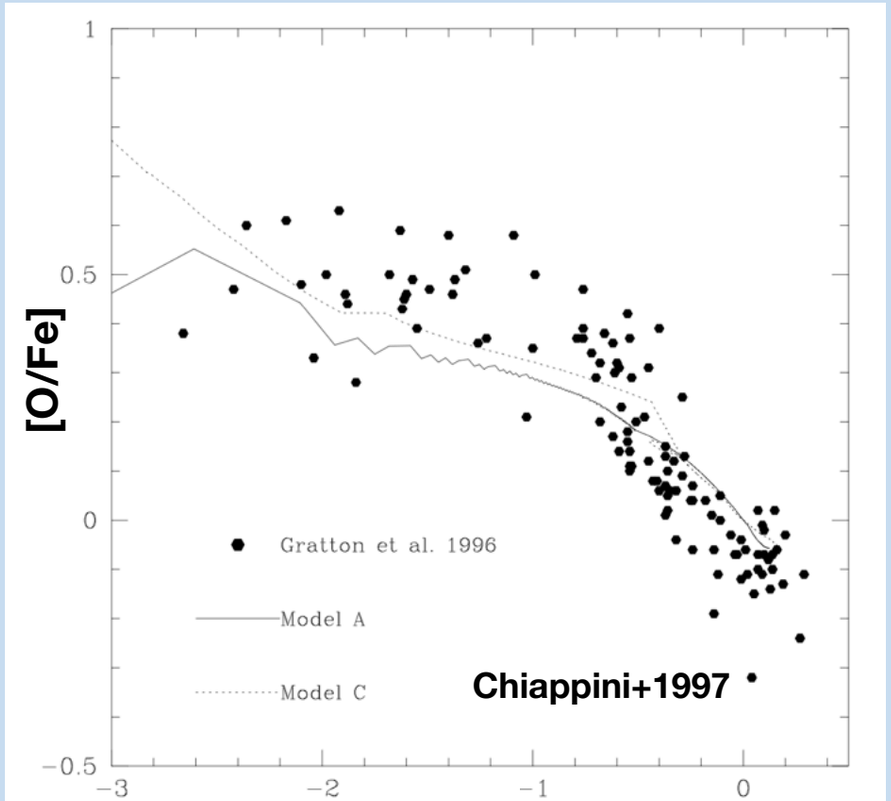


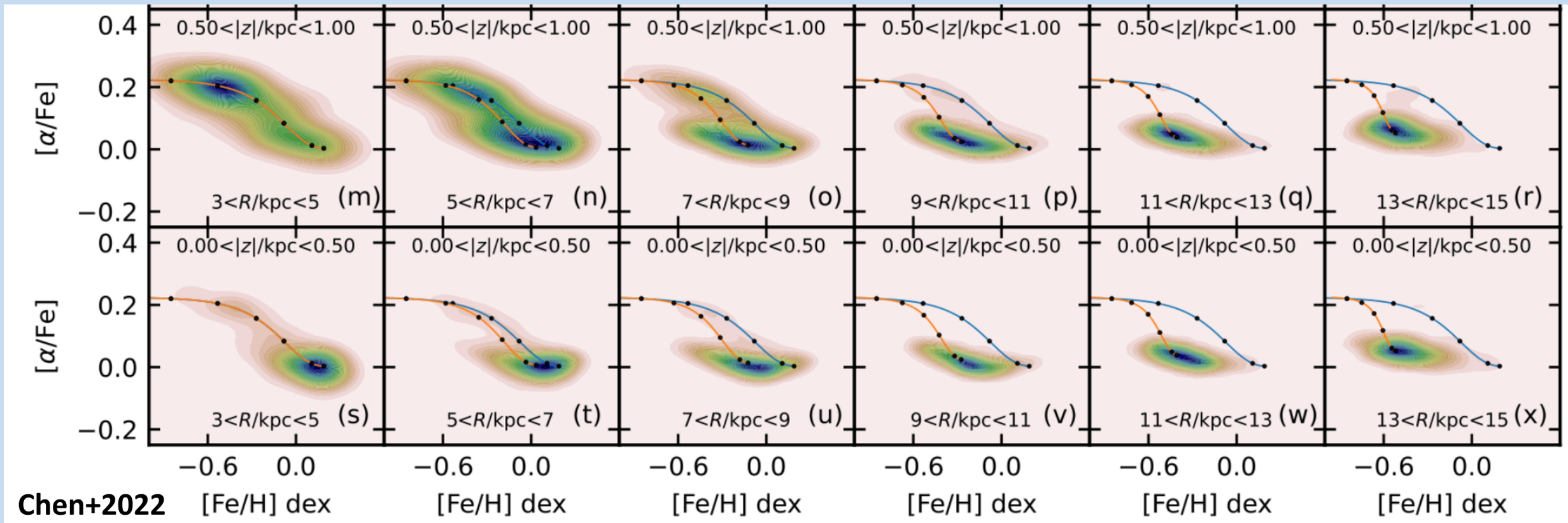
Delayed with a timescale of~1Gyr

Bimodal distribution on [α/Fe] vs [Fe/H] in the Milky Way

Such chemical patterns can be reproduced with chemical evolution models

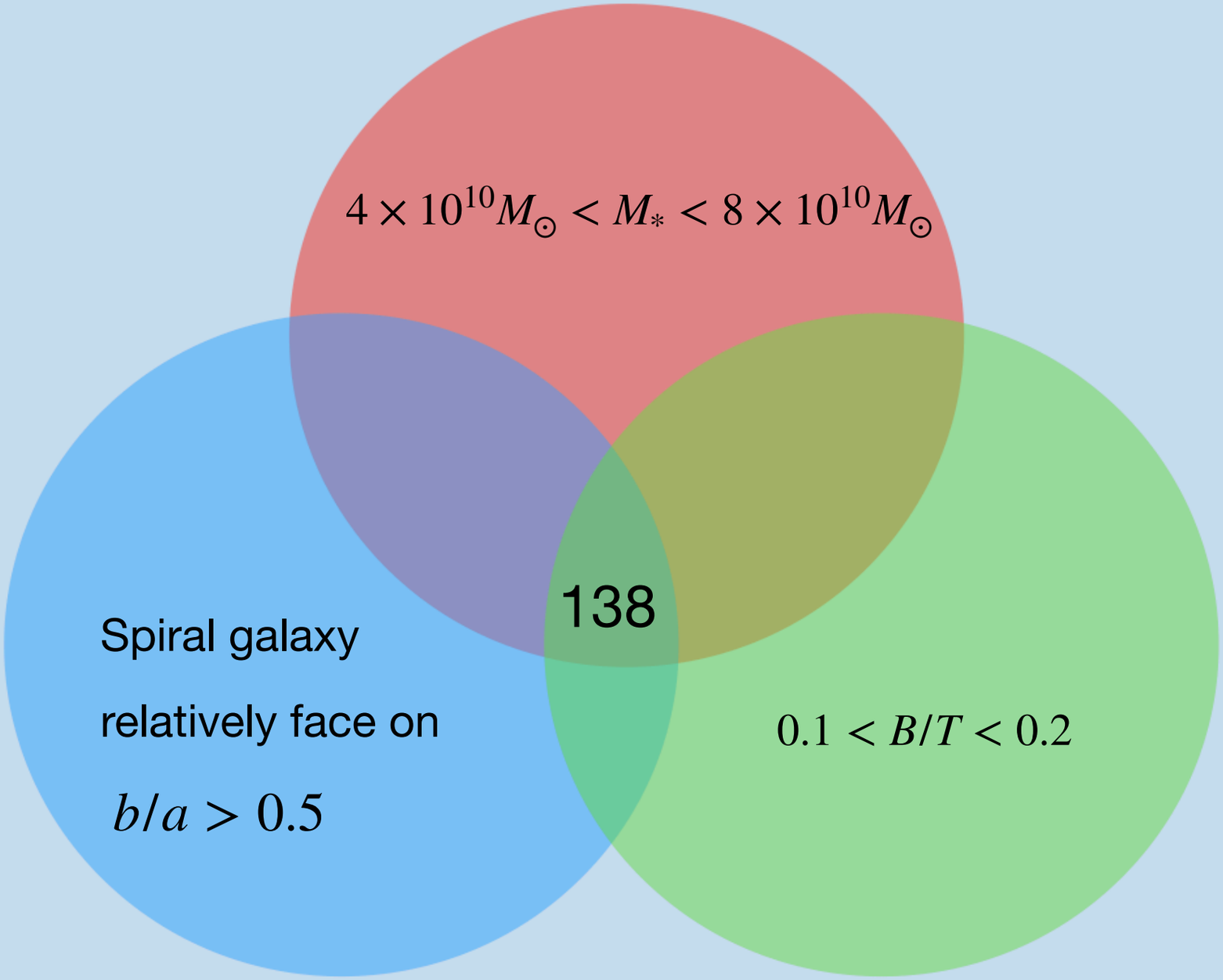
The APOGEE survey has revealed detailed structures & radial dependence of such chemical patterns in the Milky Way



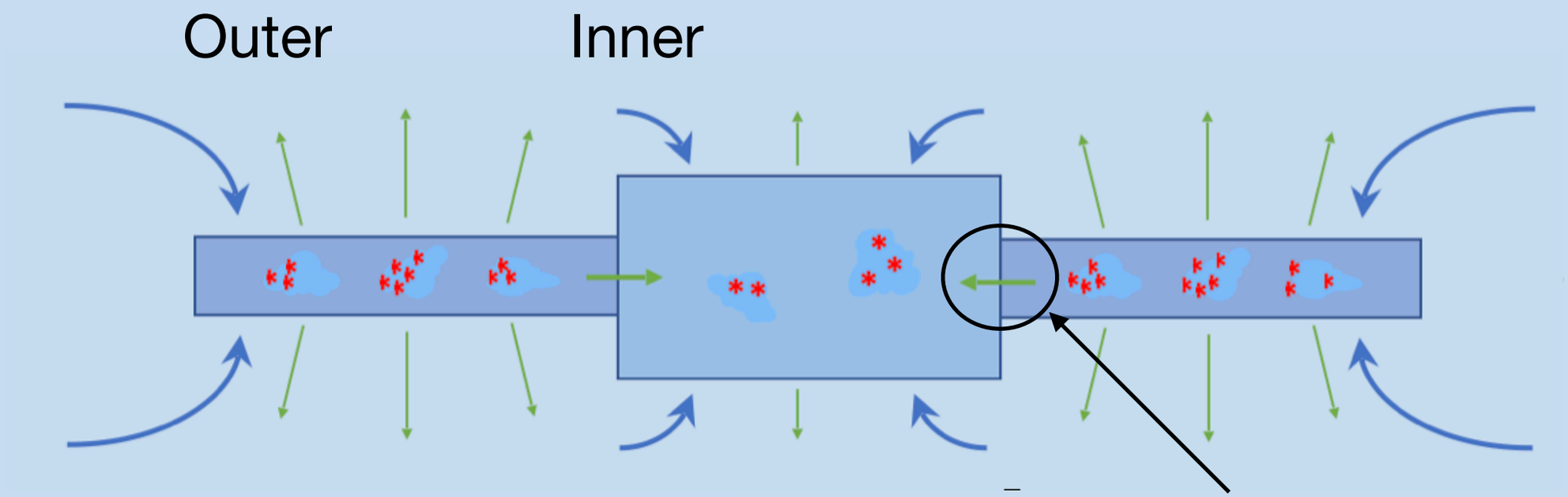


Milky Way analogues (MWAs) in MaNGA

- **MaNGA allows investigating chemical evolution in Multiple regions**
- **Comparing the evolution of MWAs and the Milky Way would help to understand both**



Modeling the chemical evolution of MWAs



Chemical evolution model including radial flow

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Delayed released of Fe by SNIa

$$\frac{\mathrm{d}M_{\mathrm{WD}}}{\mathrm{d}t} = \begin{cases} 0 & \text{for } 0 < t \leq 0.15\,\mathrm{Gyr} \\ -M_{\mathrm{WD}}/1.5\,\mathrm{Gyr} & \text{for } T > 0.15\,\mathrm{Gyr}. \end{cases} \quad (5)$$

Schönrich & Binney (2009)

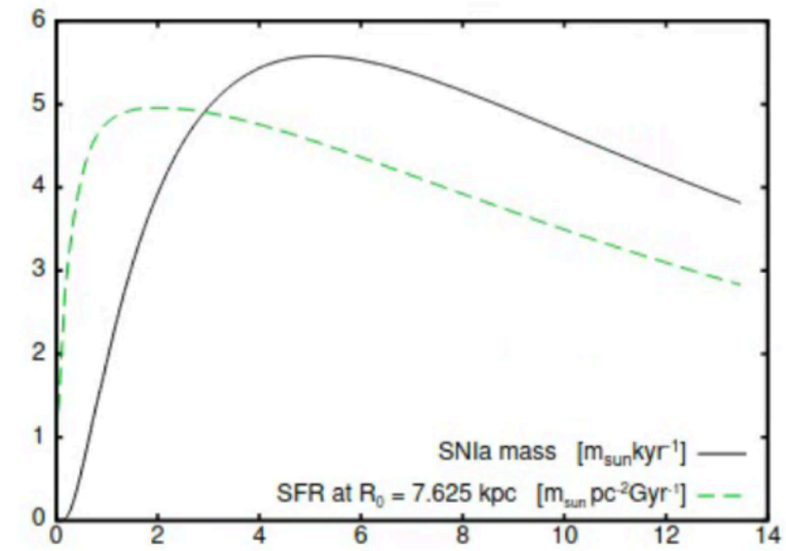
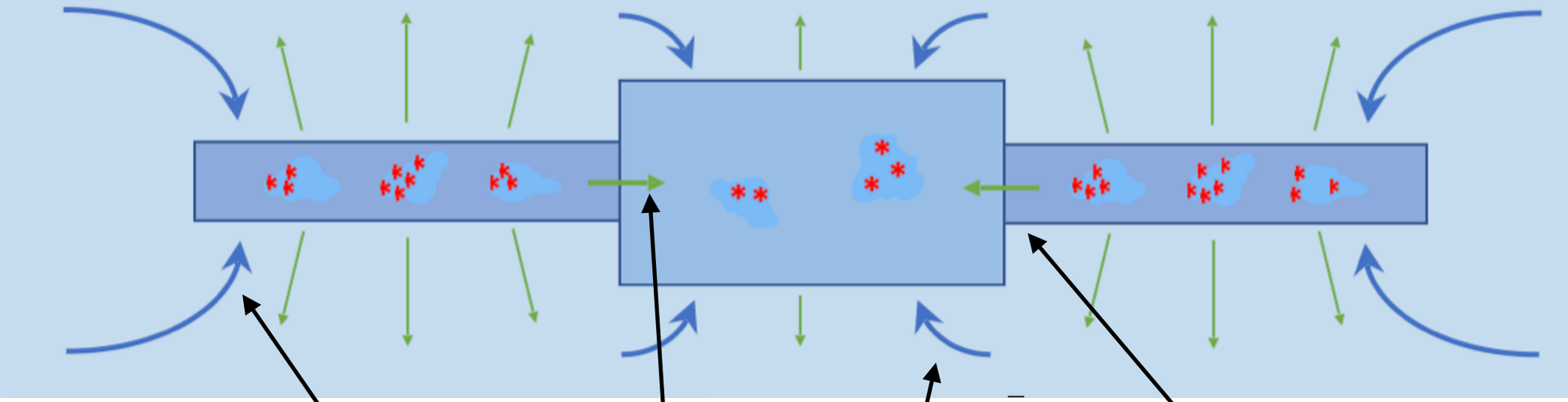


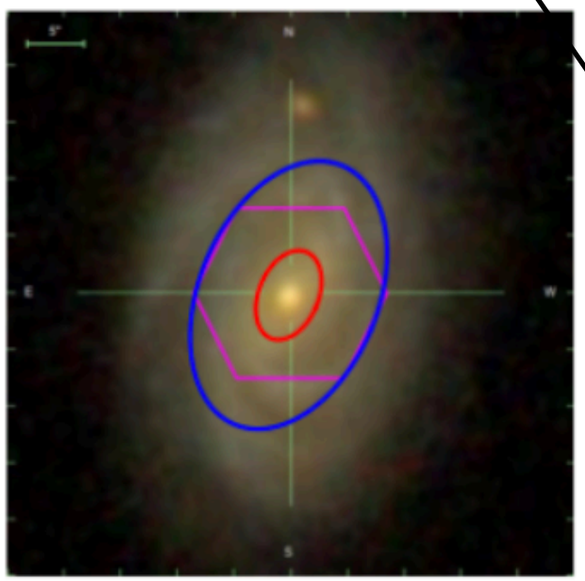
Figure 1. The rate of mass injection by SNIa in the standard model (solid black line) versus time. The broken green line gives the star formation rate in the solar annulus.

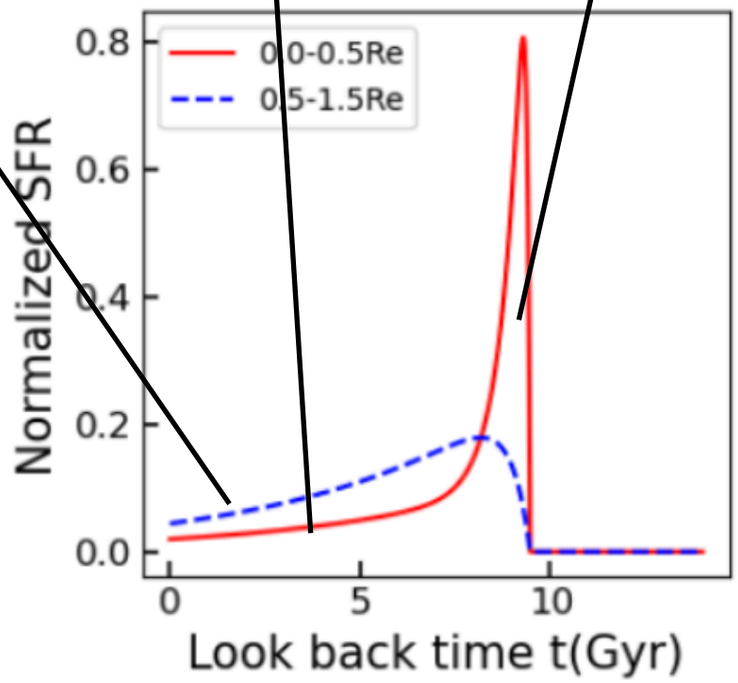
Spatially-Resolved Semi-Analytic Spectral Fitting

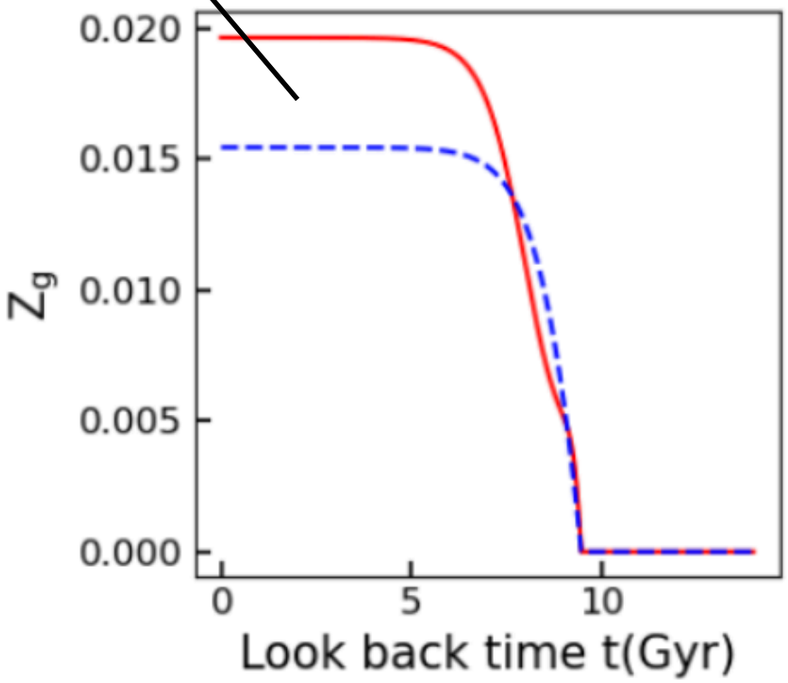
- **Centers of some Milky-Way-Like galaxies are found to have two major star formation epochs**
- **Inner and outer regions of the galaxies can talk with each other though radial gas flow**



MCG+05-32-062







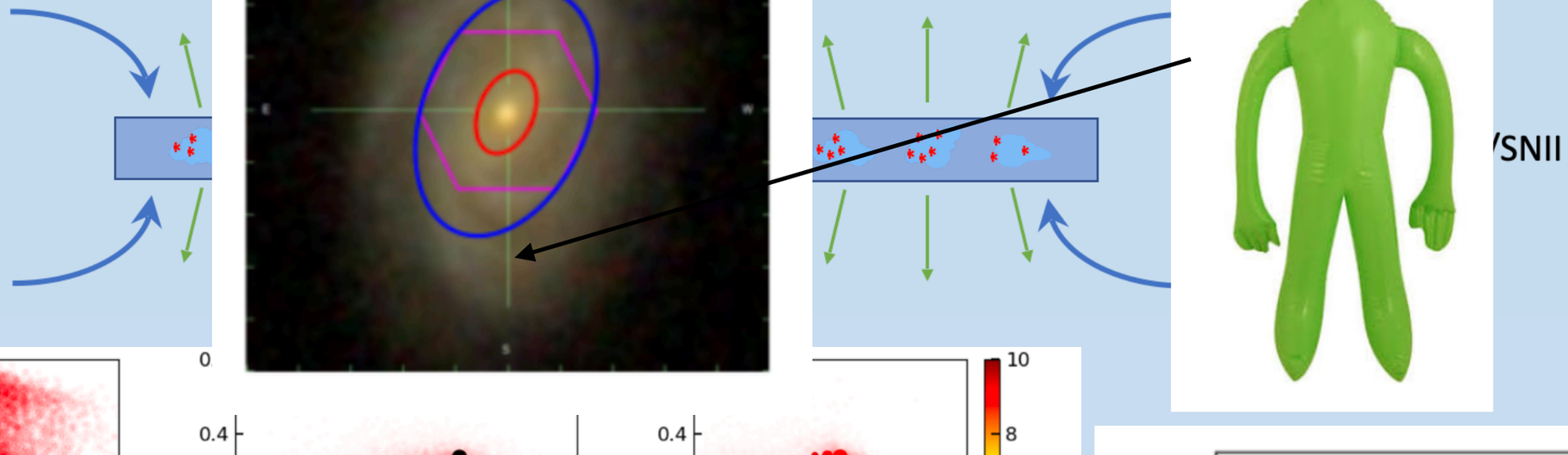
Zhou *et al*. 2023a

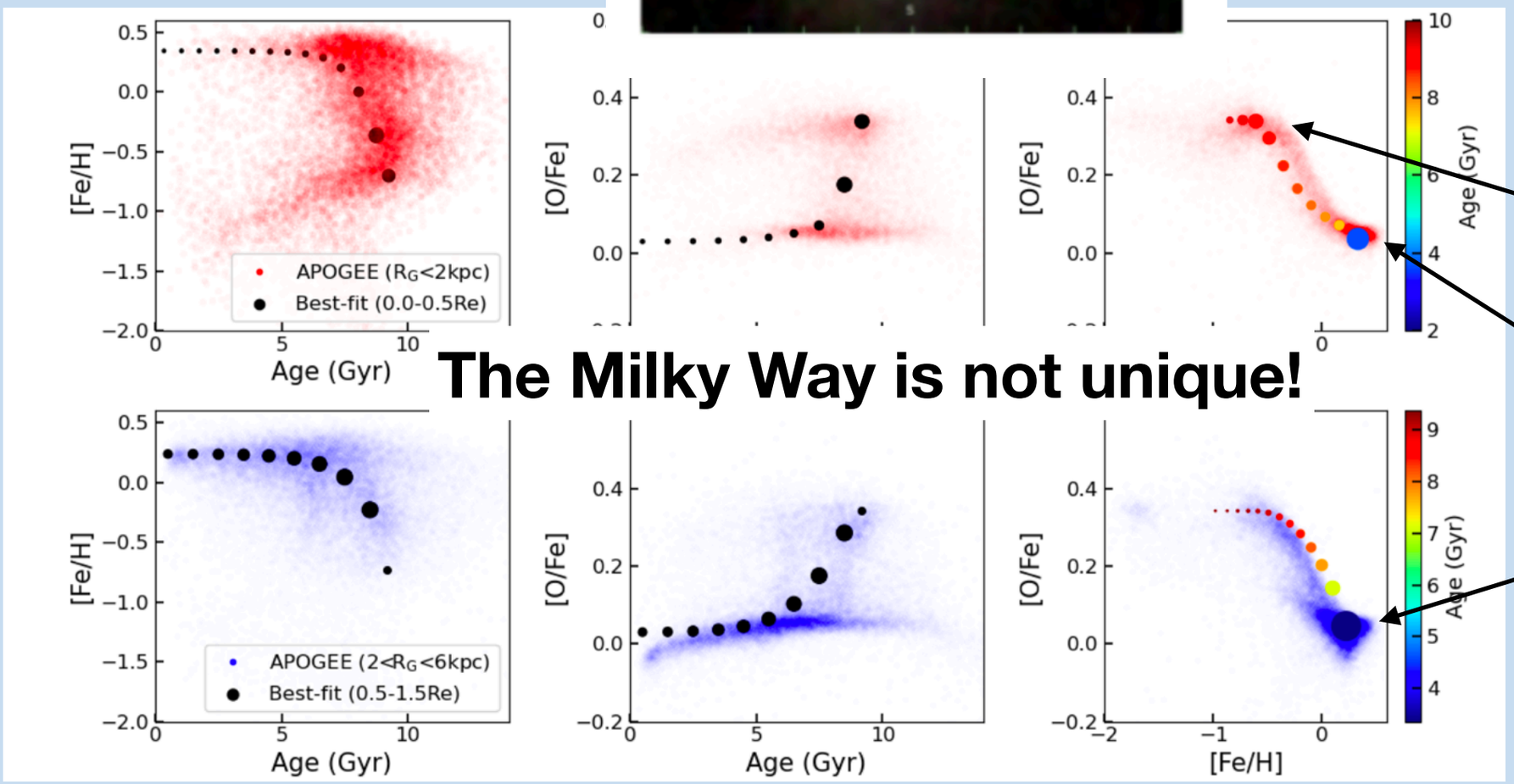
The Milky-Way twin in MaNGA

Comparison with the ... ments from the M...

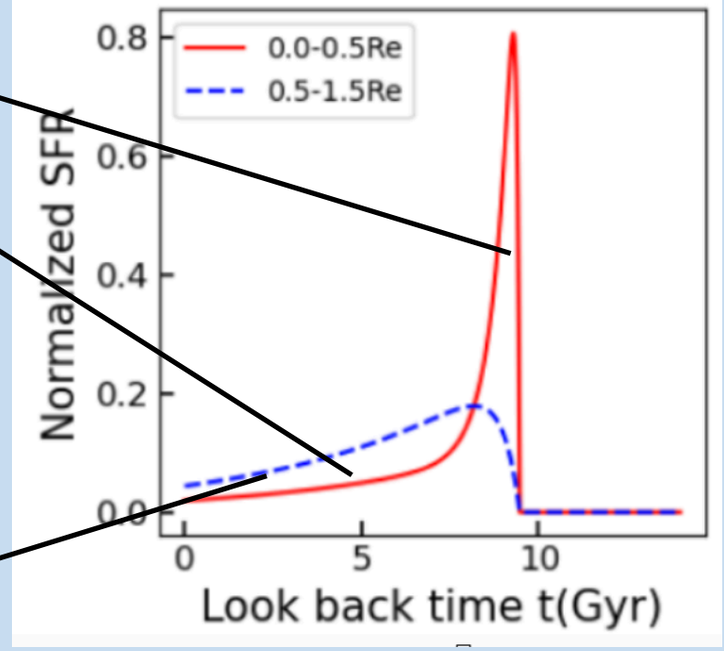
Fe: CCSN + Delayed r... ith timescale~1Gy...

O: CCSN





The Milky Way is not unique!

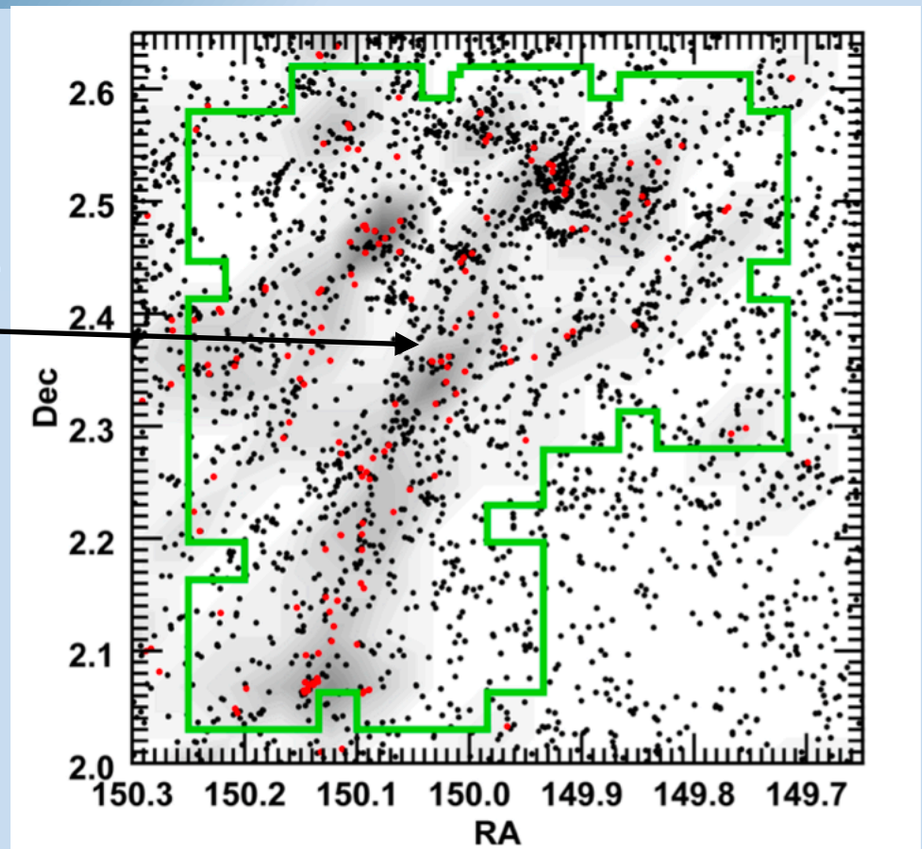


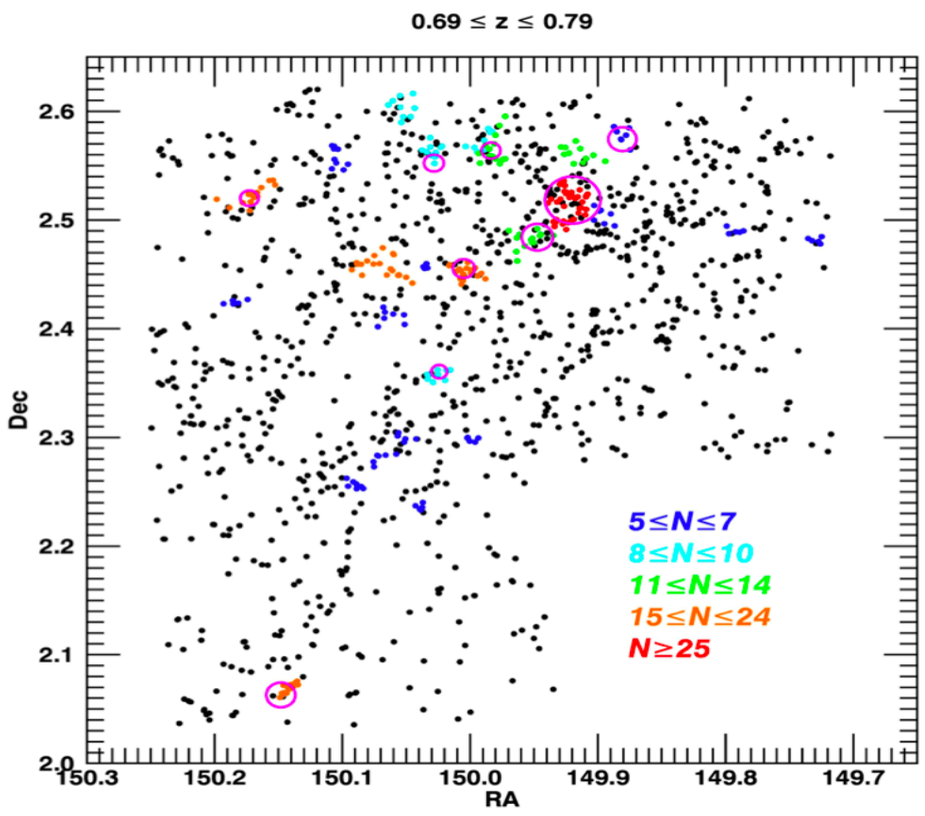
Zhou *et al*. 2023a

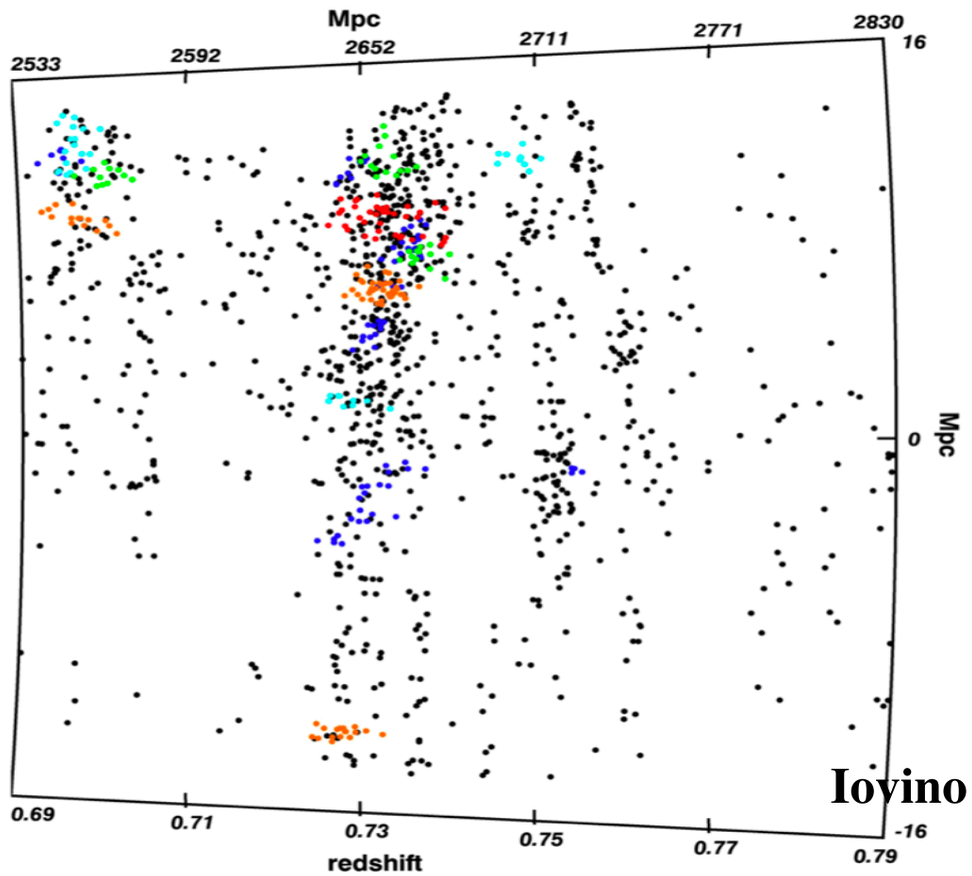
Evolution of SFG at z~0.7: view from the COSMOS-WALL

The COSMOS-Wall structure at redshift ~0.7

Containing galaxies from a wide range of environments — a perfect region for investigating environmental effects!







Iovino et al. 2016

Evolution of SFG at z~0.7: the environment dependence

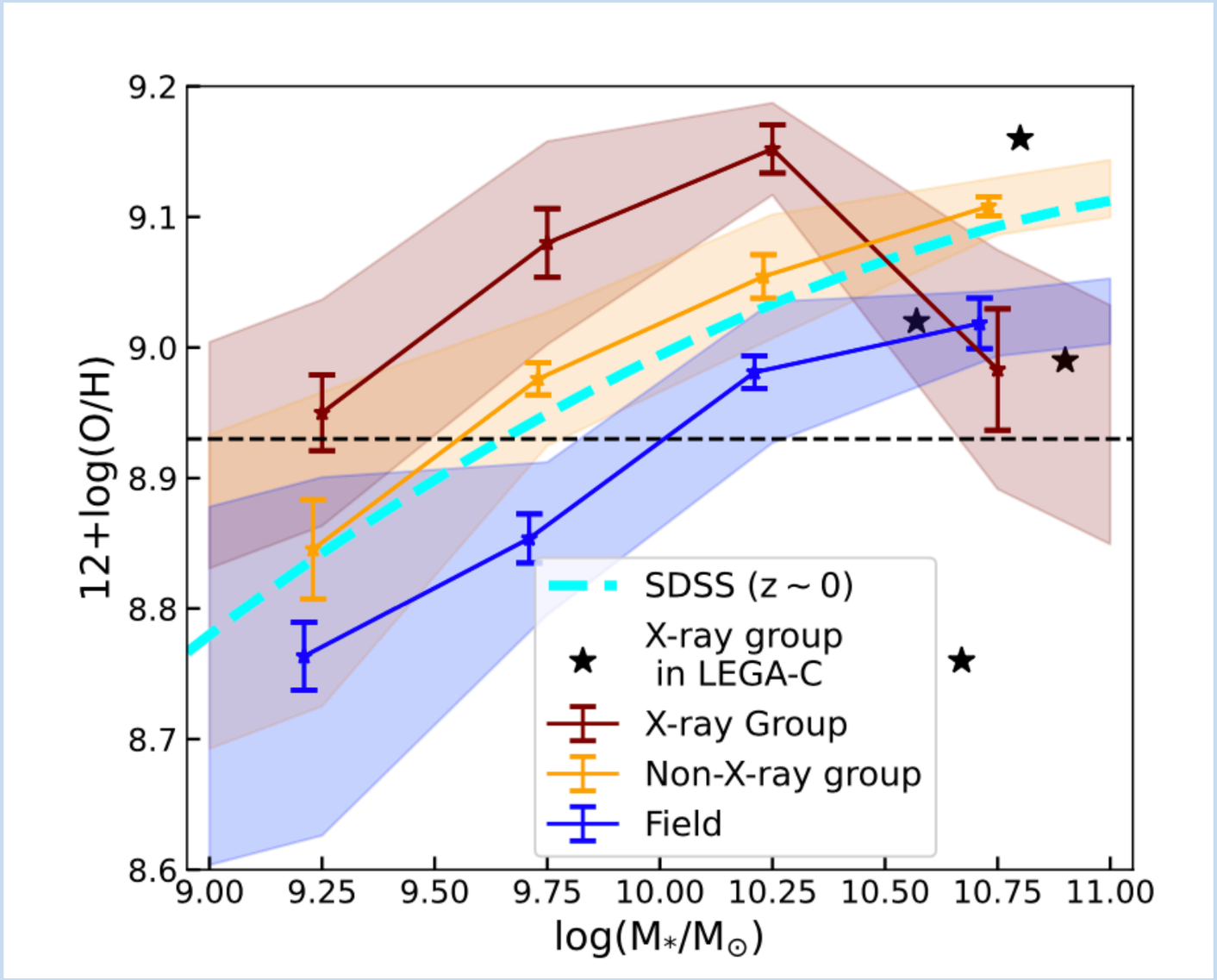
Gas phase metallicities are measured for galaxies within the COSMOS-Wall region —>The environment has an impact on the chemical composition of galaxies

X-ray groups: galaxies from massive groups with an X-ray counter part

Non-X-ray groups: galaxies from smaller groups without an X-ray counter part

Field: galaxies that are relatively isolated

Galaxies resided in more massive groups are found to be more chemically-enriched

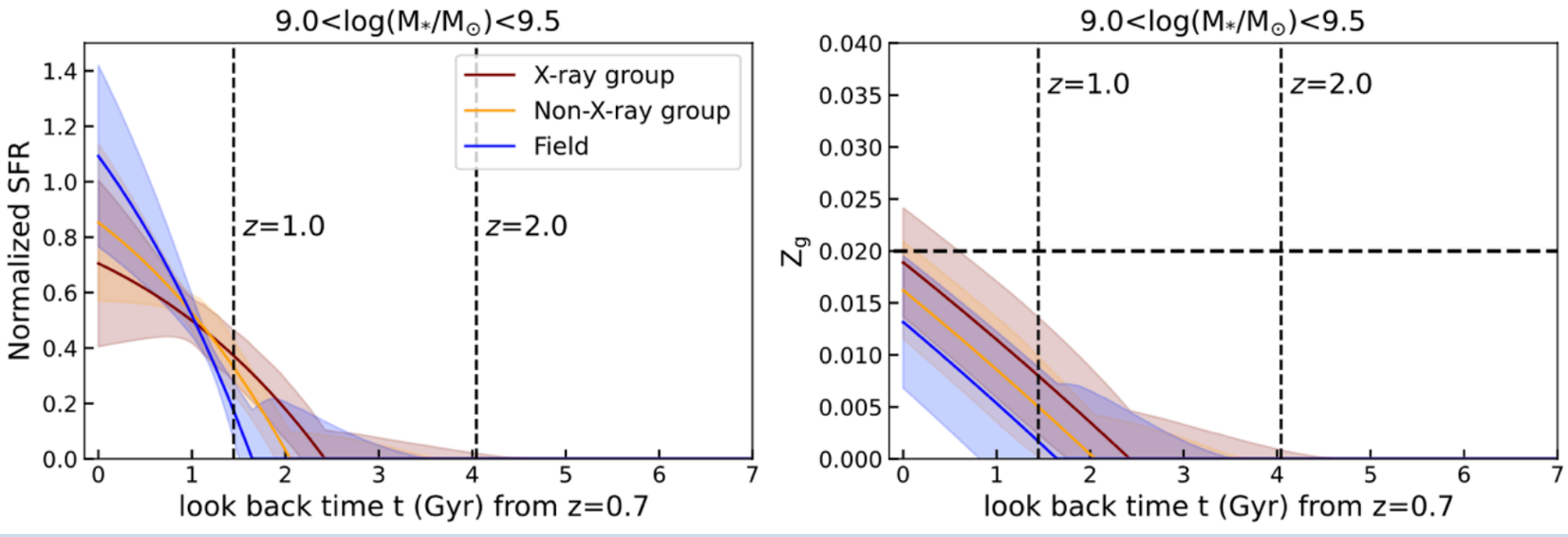


Zhou *et al*. 2024, to be submitted

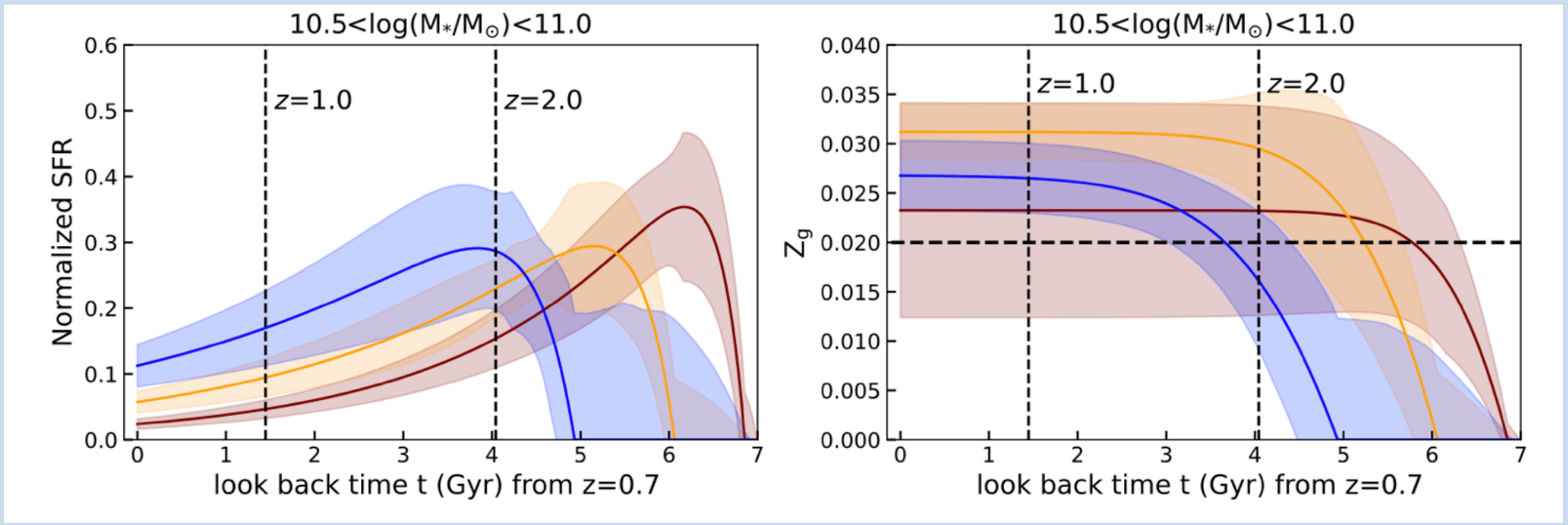
Evolution of SFG at z~0.7: the environment dependence

galaxies resided in more massive groups form systematically earlier

Low mass end: the earlier formation lead to higher gas-phase metallicities



High mass end: some X-ray group galaxies may have experienced stronger outflow that leads to low gas gas-phase metallicities

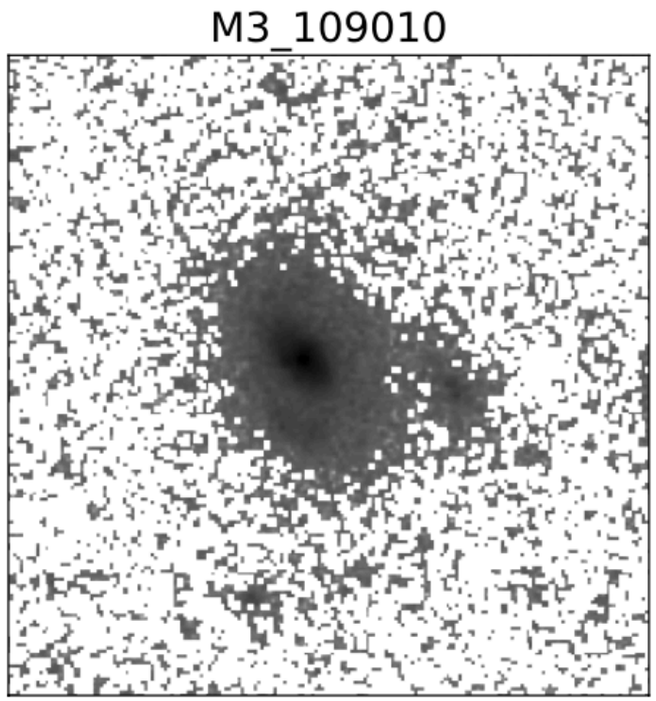


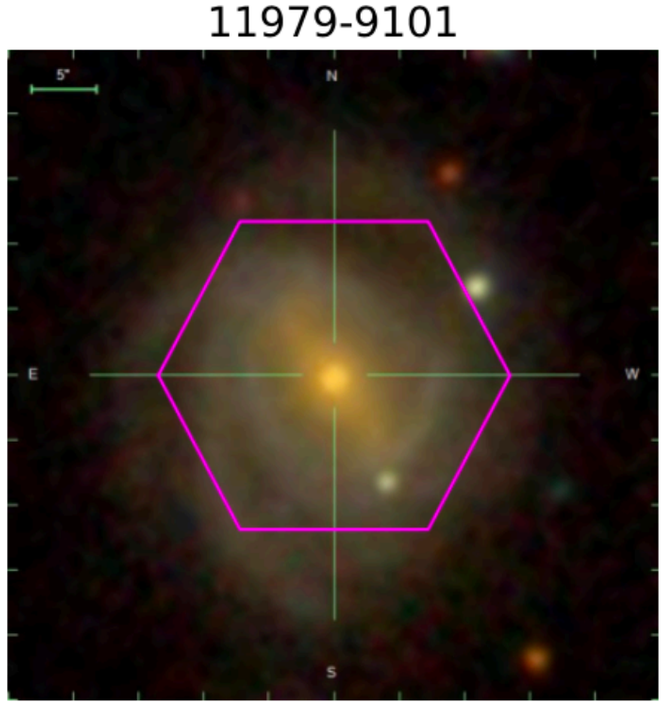
Zhou *et al*. 2024, to be submitted

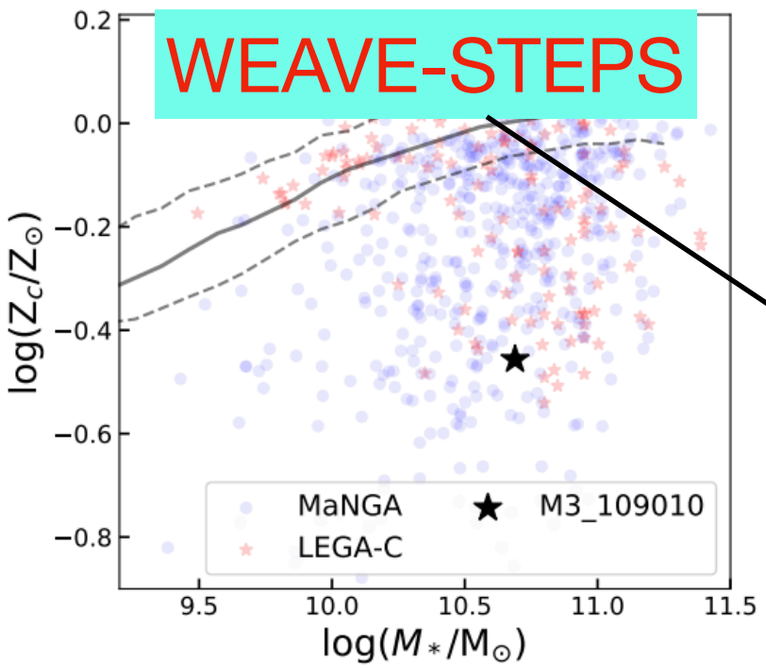
Linking galaxies from low to high redshifts: what we have

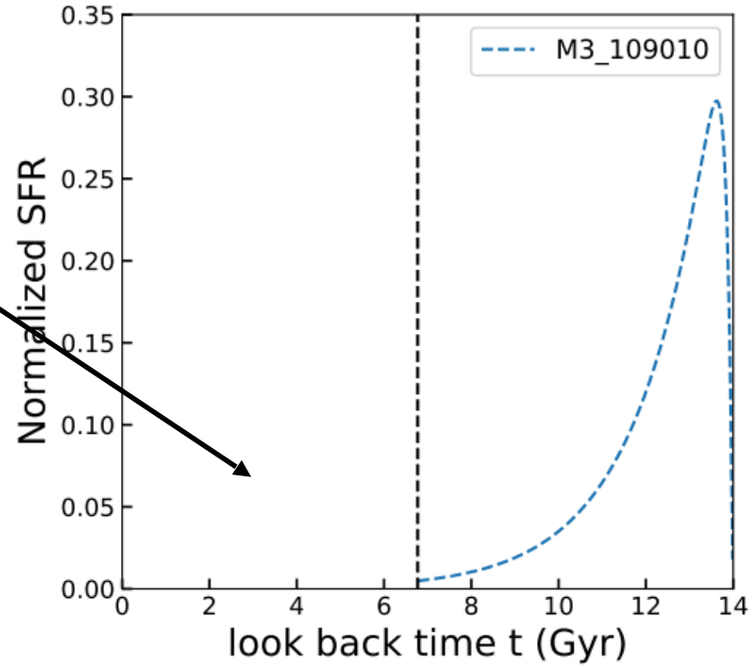
A galaxy at z~0.7 from the Large Early Galaxy Astrophysics Census (LEGA- C)

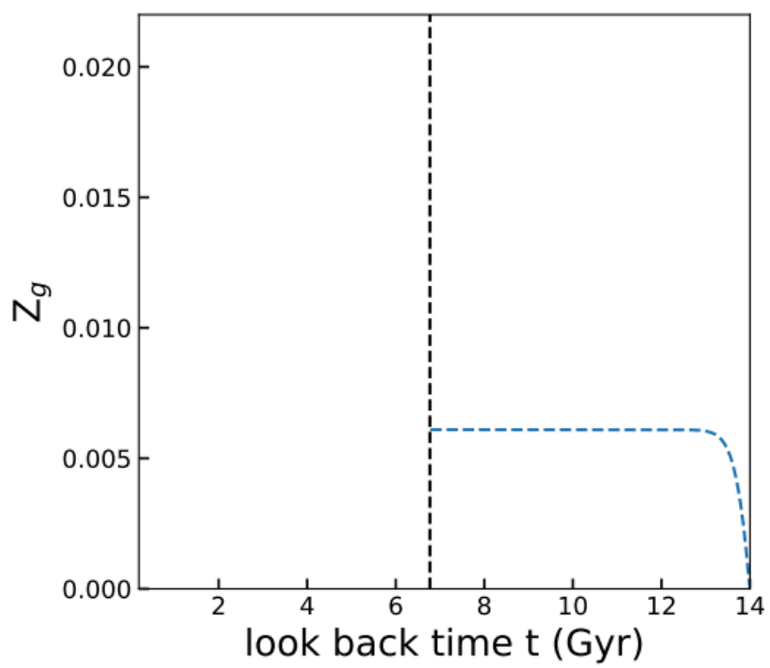
By matching the LEGA-C galaxy with MaNGA galaxies on the mass-metallicity plane, we expect this galaxy to experience a secondary star formation and chemical enrichment between z~0.7 and z~0.0







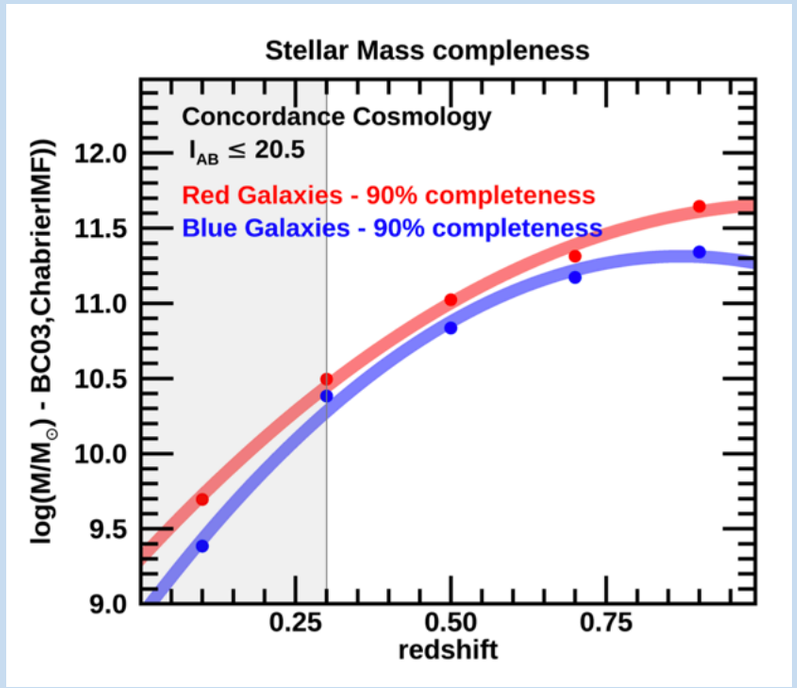


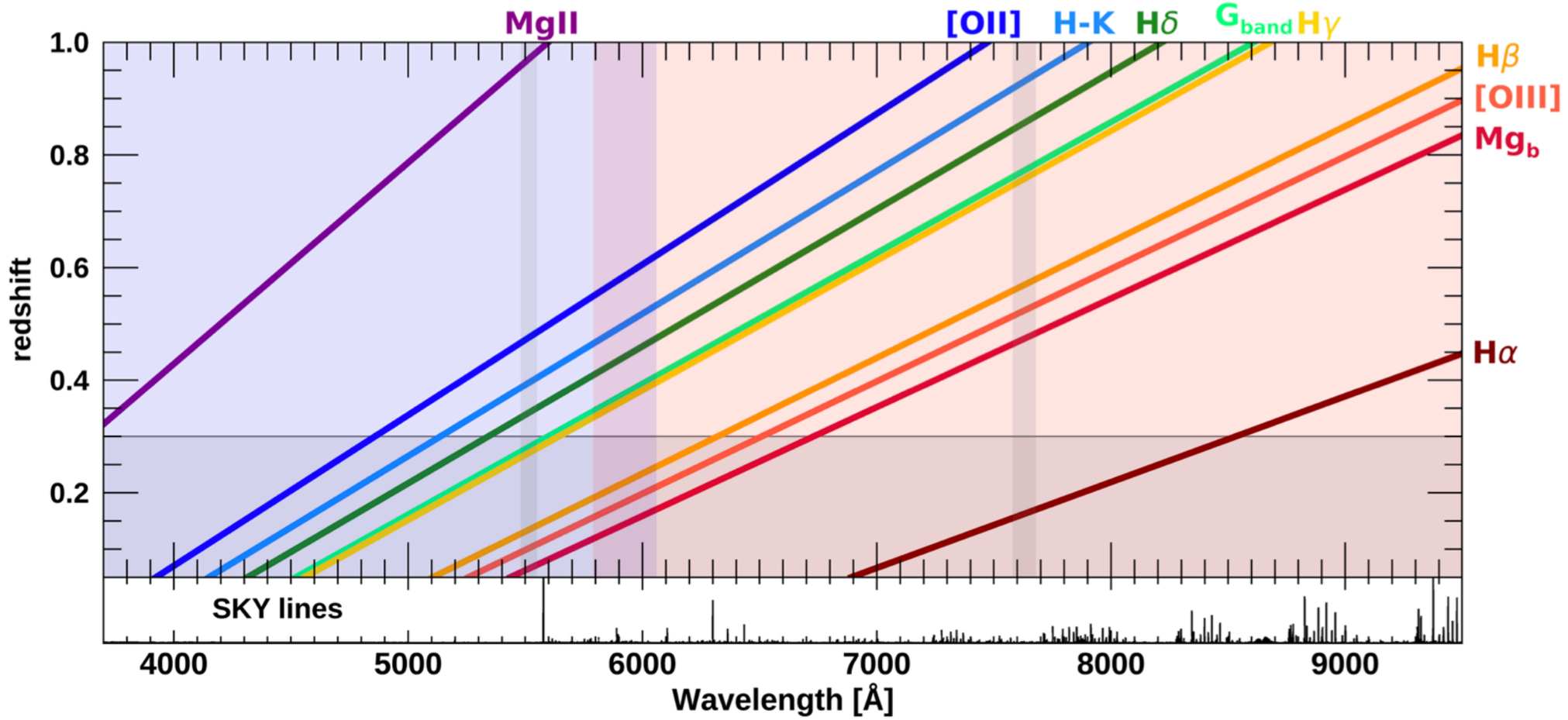


Zhou *et al*. 2023, arXiv: 2310.19107

Linking galaxies from low to high redshifts: what we need

The WEAVE-Stellar Population Survey is one of the eight surveys that will use a total of approximately 1150 nights over five years of WHT time to obtain high-quality (S/N~10 at R~5000) spectra of ~**25, 000 galaxies in 0.3<z<0.7**





Summary

We develop a novel semi-analytic spectral fitting approach to analyze the evolution of galaxies in a series of works:

1. We analyze a complete sample of disk galaxies and reconstruct the down-sizing evolution in mass, metallicity, as well as predict the evolution of MZR at different redshifts (Zhou *et al*. 2022a, arXiv:2205.03069);

2. We investigate the environment effects on galaxy evolution, and identify the environment effects on gas flows in low-mass central/ satellite galaxies (Zhou *et al*. 2022b, arXiv:2212.01918);

3. We use a chemical evolution model with radial flow to fit MW-like galaxies in MaNGA, finding MWAs that have similar evolution as the Milky Way in terms of the evolution of Z, [O/Fe], and radial variations (Zhou *et al*. 2023a, arXiv: 2212.09127)

4. By investigating galaxies within the COSMOS-WALL structure, we discuss how the environment has shaped a galaxy's evolution (Zhou *et al*. 2024, to be submitted)