FIRST LIGHT
ADVANCED SCHOOL 2019

GALAXY FORMATION

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OUTLINE

Lecture.I

Galaxy formation: From the high-z to the Local Universe

Lecture.II

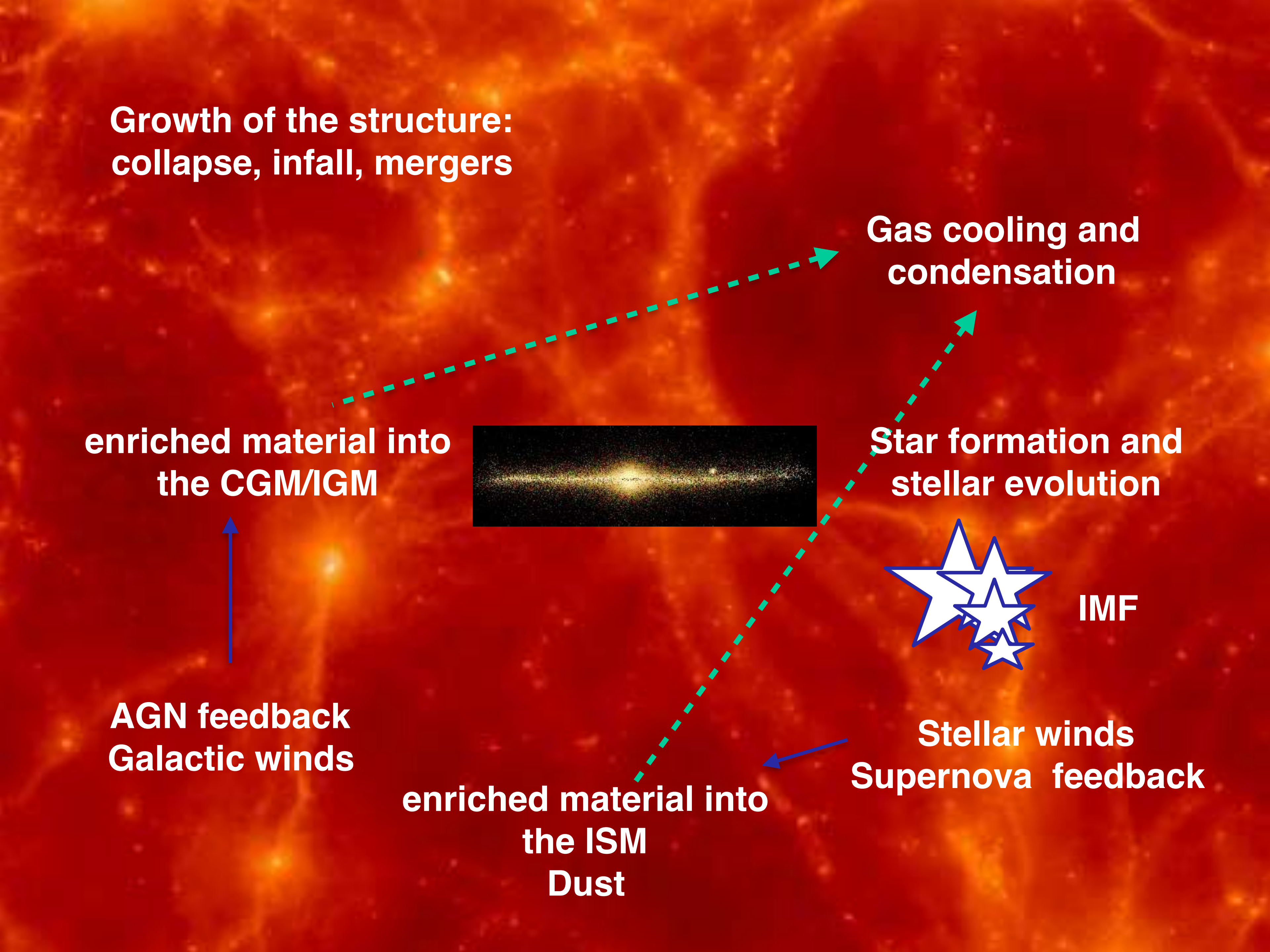
Galaxy formation: models and simulations

- Basic concepts
- Main ingredients
- Disc-dominated and Bulge-dominated galaxies

Lecture.III

Galaxy formation: chemical evolution

- The simple model
- Ingredients of Chemodynamical Models
- Sophisticated Chemo-dynamics Models


Growth of the structure:
collapse, infall, mergers
Gas cooling and
condensation
enriched material into
the CGM/IGM
Star formation and
stellar evolution
IMF
AGN feedback
Galactic winds
Stellar winds
Supernova feedback
enriched material into
the ISM
Dust

KEY INGREDIENTS

- Initial conditions: how galaxies are assembled
- Star formation model: how the gas is transformed into stars
- The initial mass function
- The stellar yields: AGB, Type II and Ia Supernova-different progenitors – different life-times
- Pristine or enriched gas accretion (Infall)
- Outflows (Supernovas and AGN feedbacks)

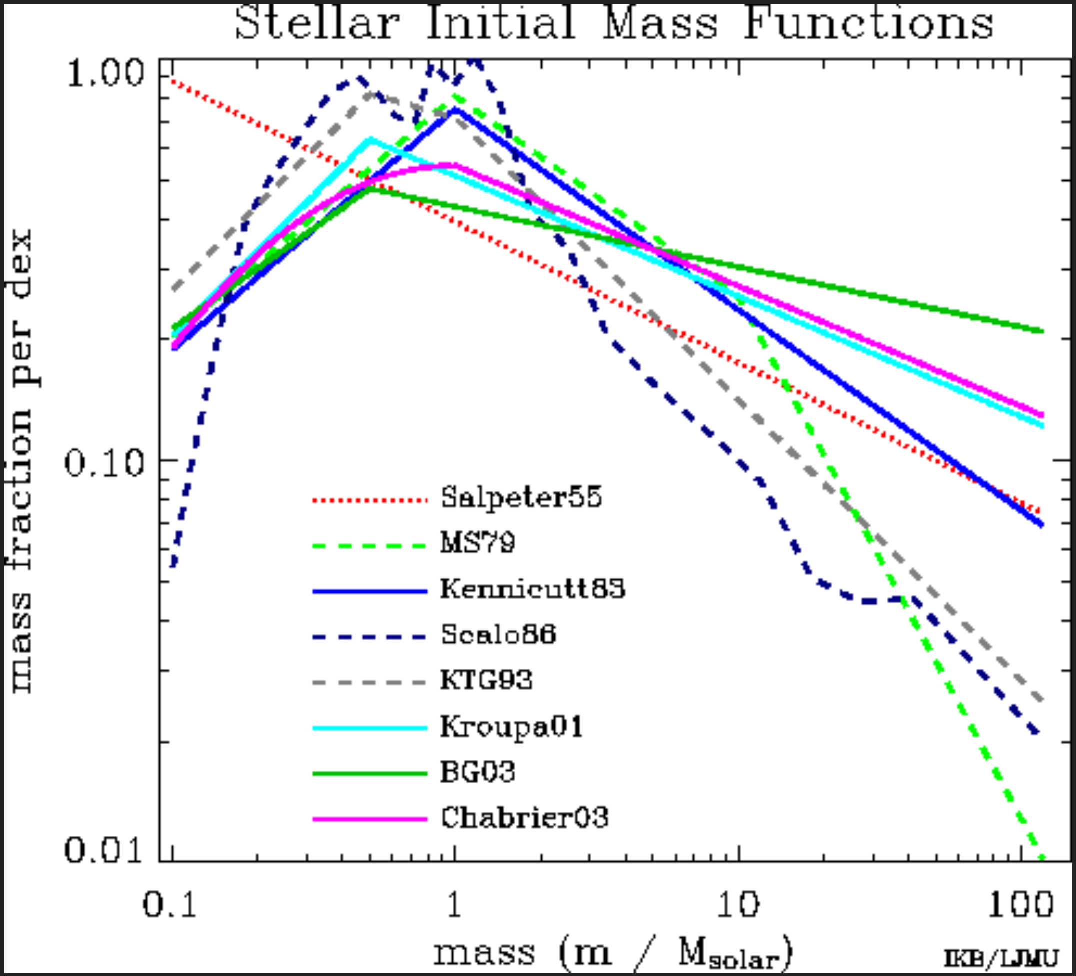
$$Z \equiv M_{\rm metals}/M_{\rm baryons}$$

$$[X/Y] \equiv \log(N_X/N_Y) - \log(N_X/N_Y)_\odot$$

$$12 + \log(X/H) \equiv 12 + \log(N_X/N_H)\,,$$

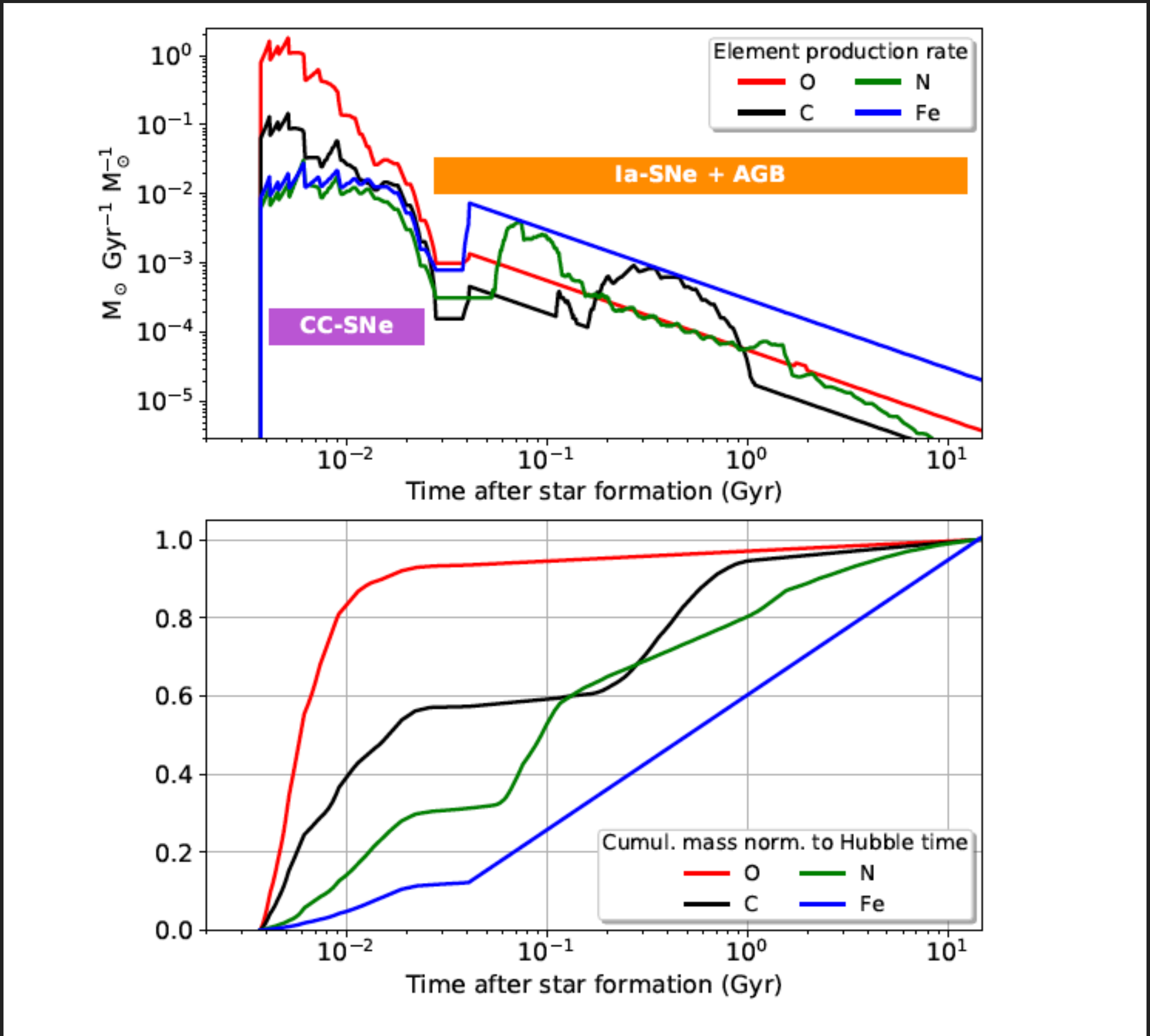
$$12 + \log(O/H) \equiv 12 + \log(N_O/N_H)$$

$12+\log(O/H)_\odot = 8.69$ Asplund+2009

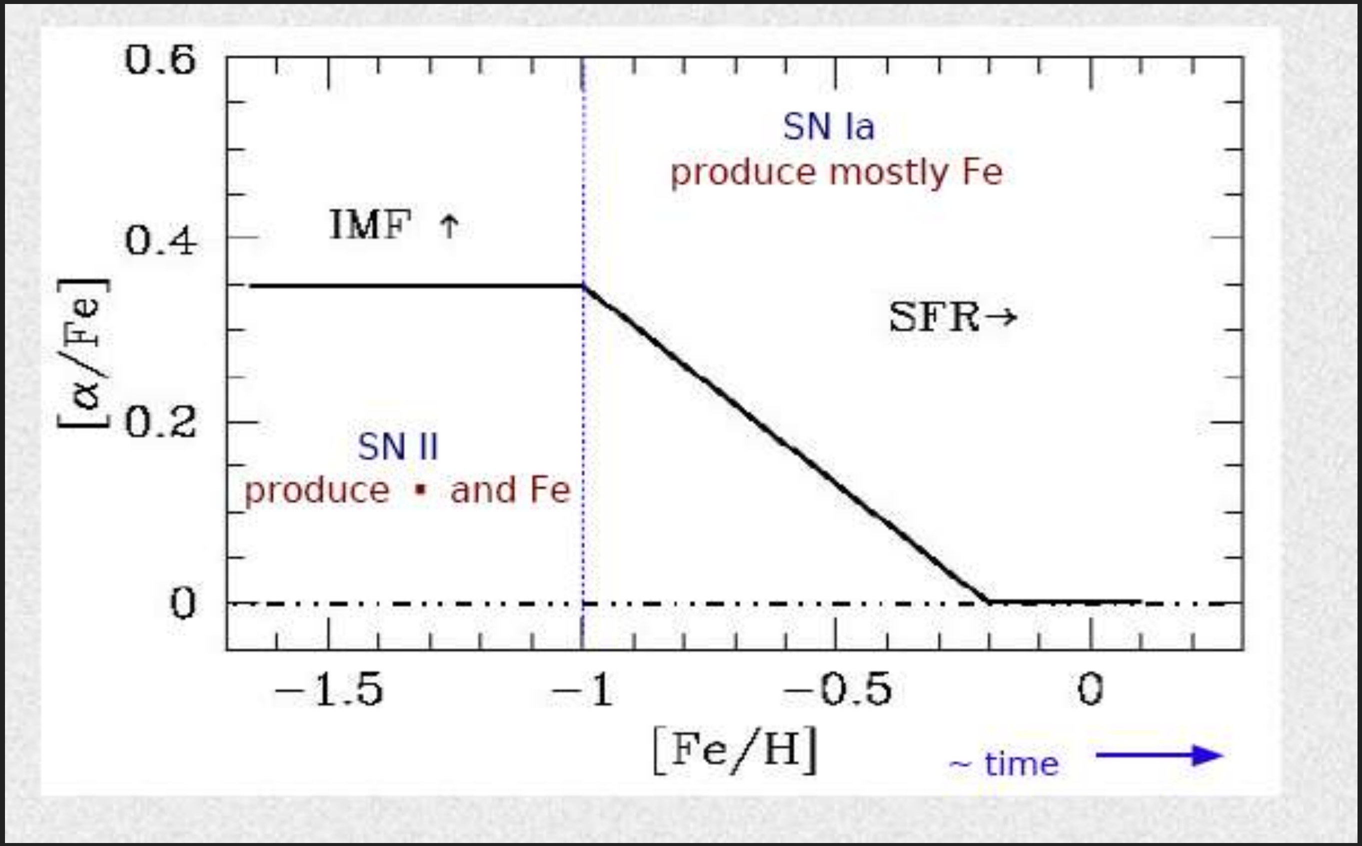

Stellar Initial Mass Functions
1.00
0.10
0.01
mass fraction per dex
0.1
1
10
100
mass (m / M$_{solar}$)
IKB/LJMU
Salpeter55
MS79
Kennicutt83
Scalo86
KTG93
Kroupa01
BG03
Chabrier03

ELEMENT PRODUCTION ACCORDING TO THE STELLAR SOURCE FOR A SSP

Maniolino & Mannuci 2019



SNIa:
after 40 Myr,
Power law t^{-1}



Relative abundances of [α/Fe]:

Relative abundances of SNII with respect to SNIa:
formation timescale of the systems

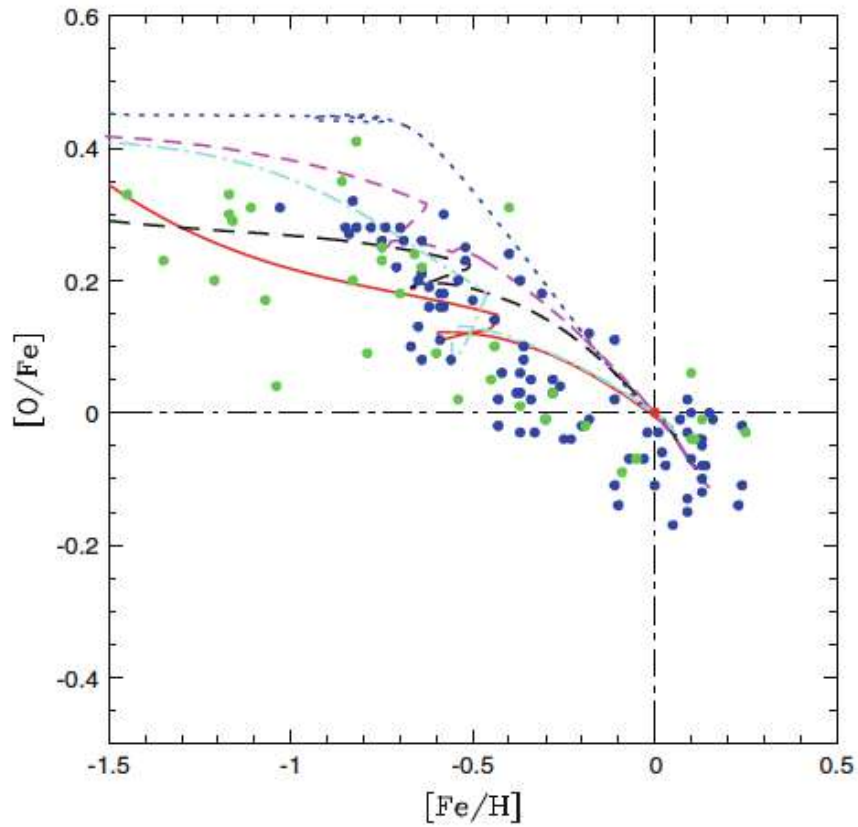


Fig. 5.7 Predicted and observed [O/Fe] vs. [Fe/H] in the solar neighborhood for different assumptions on the DTD of the explosion times of SNe Ia. The *short dashed curve* refers to the DTD of the SD scenario; the *continuous curve* refers to the bimodal DTD of Mannucci et al. (2006); the *dotted line* represents the Strolger et al. (2004) DTD; the *long dashed curve* refers to the DTD of Pritchett et al. (2008); the *dashed-dotted curve* refers to the DTD of the DD scenario (wide channel) of Greggio (2005). The model results are normalized to their own predicted solar abundances. See also Fig. 4.5. Models and figure from Matteucci et al. (2009) where the references to the data can be found

ONE-ZONE CLOSED BOX MODEL

Simple one-zone model as given by Tinsely (1980)

Four Main hypothesis:

- ❖The system is isolated: no inflows or outflows.
- ❖The systems is well mixed at all times
- ❖The systems starts from primordial abundances: Z(0)=0
- ❖IMF and nucleosynthesis yields are unchanged

- ❖Instantaneous recycling (all star with m<1Mo live for ever; all stars with m>1Mo die instantaneously.

ONE ZONE MODEL

$$\mu = \frac{M_{\rm gas}}{M_{\rm tot}}$$

$$M_{\rm tot} = M_* + M_{\rm gas},$$

$$Z = \frac{M_Z}{M_{\rm gas}},$$

Initial conditions

$$M_{\rm gas}(0) = M_{\rm tot}$$

$$Z(0) = 0.$$

Equation of evolution of the gas in the system

$$\frac{{\rm d}M_{\rm gas}}{{\rm d}t} = -\psi(t) + E(t),$$

Rate of returning material

$$E(t) = \int_{m(t)}^{\infty} (m - M_{\rm R})\psi(t - \tau_m)\varphi(m){\rm d}m,$$

Assuming instantaneous recycling condition:

Return fraction
R~0.20-0.50

$$R = \int_1^\infty (m - M_R)\varphi(m)\mathrm{d}m,$$

y_{zm}: yield for stellar generation

$$y_Z = \frac{1}{1-R}\int_1^\infty m p_{Zm}\varphi(m)\mathrm{d}m,$$

p_{zm} is the newly produced and ejected elements by a given stars m

$$\frac{\mathrm{d}Z}{\mathrm{d}M_{\mathrm{gas}}}M_{\mathrm{gas}} = -y_Z,$$

$$Z = y_Z \ln\left(\frac{1}{\mu}\right).$$

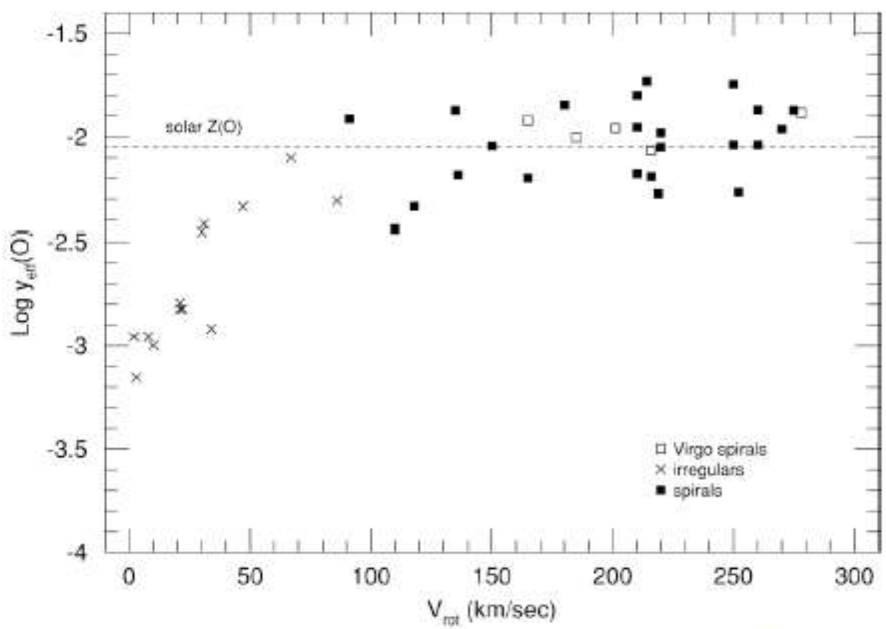
Effective Yield vs Galaxy Mass

Tully-Fisher : $(M / 10^{11} M_{\odot}) \sim (V_{rot} / 200 \text{ km/s})^4$

Lower yield in small galaxies because SN ejecta excape.

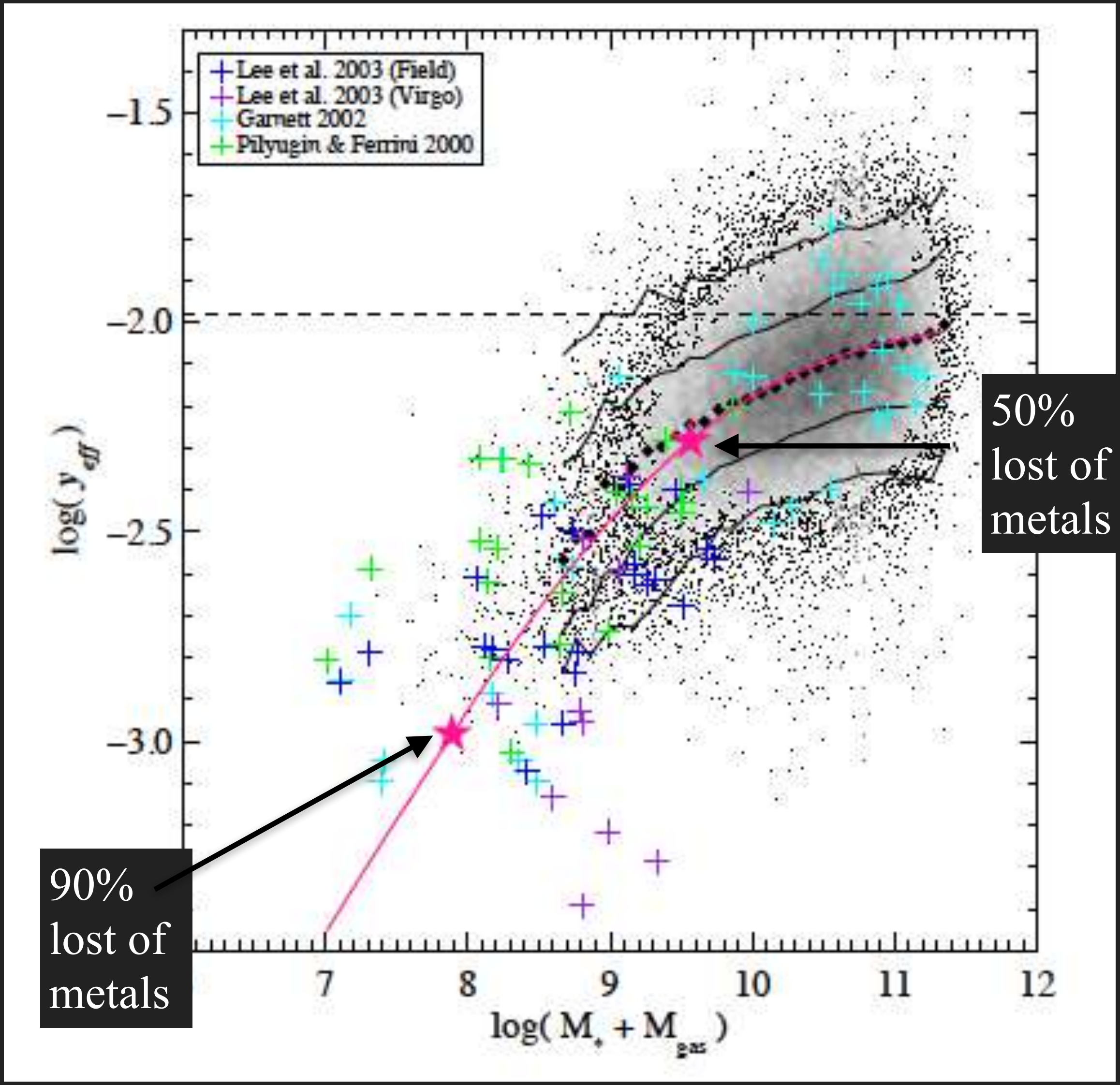
$$y_{eff} \equiv \frac{Z_{obs}}{\ln(1/\mu)}$$

$$\mu \approx \frac{M_G}{M_* + M_G}$$

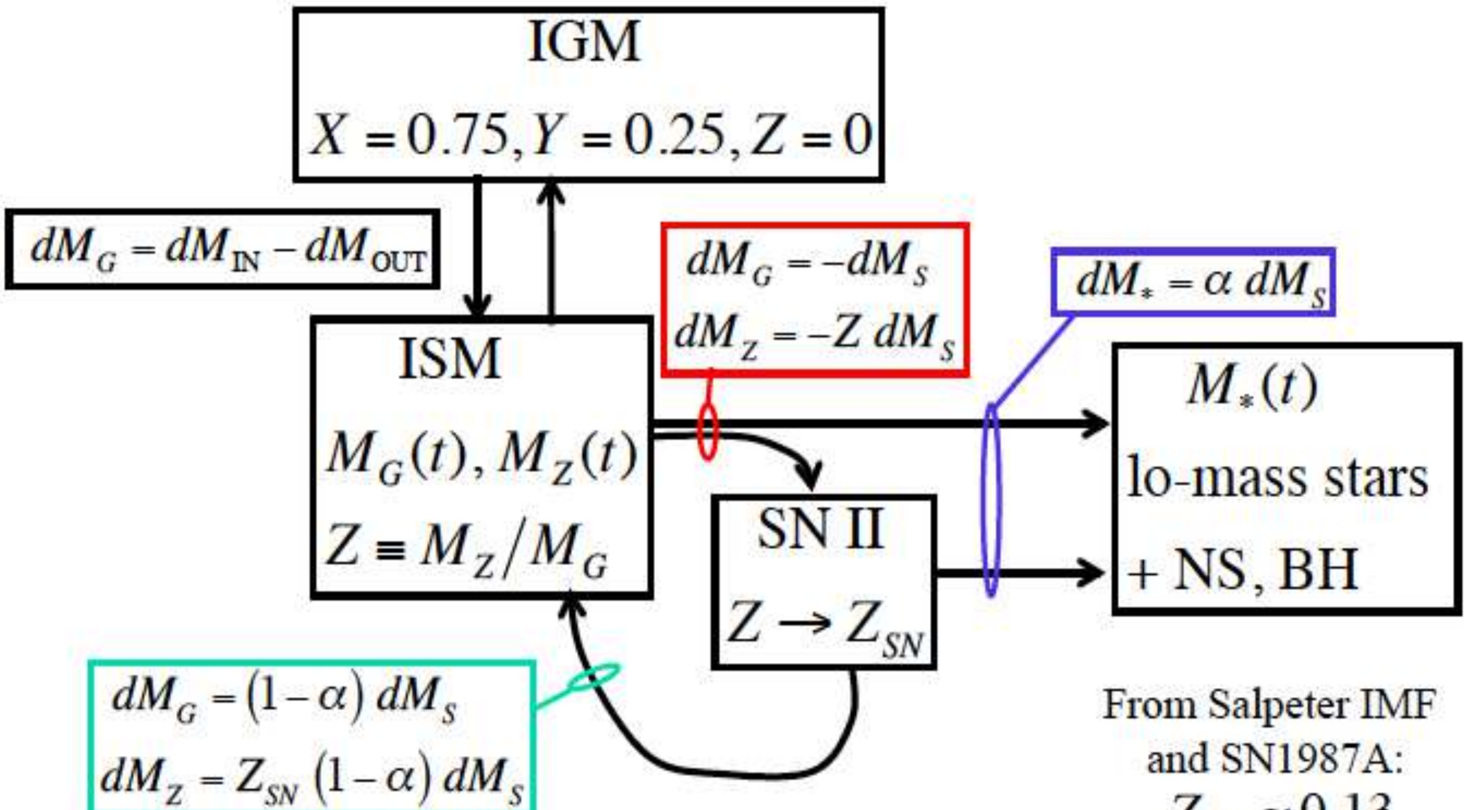


Garnett 2002

Tremonti+2014



ISM Recycling Model



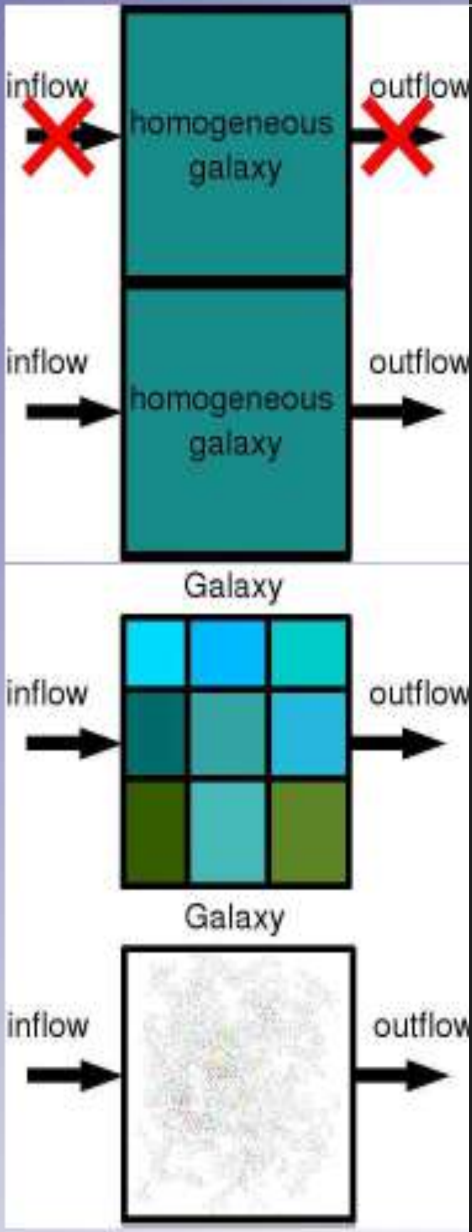
From Salpeter IMF and SN1987A:

$Z_{SN} \approx 0.13$

$\alpha \approx 0.93$

Chemical evolution models

- One-zone models:
  perfect mixing in the homogeneous physical domain
  - Closed-box models
  - Open box models: some prescription of infall and outflows
- Multi-zone models:
  coupled open-box models with inter-zone mass transfer
- Chemo-dynamical models:
  (multi-dimensional) self-consistent treatment of the entire galaxy with all/some of the components and interactions described above.



see Molla et al. 2018 for review on analytical chemical models

There are numerous chemodynamical models for galaxy formation which have sophisticated the Simple Model (e.g. Larson 1976; Tinsley & Laron 1979; Burkert & Hensler 1988; Ferrini et al. 1992; Chiappini, Matteucci & Gratton 1997;Molla et al. 2019):

- ❖sophisticated stellar evolution
- ❖simple initial conditions for galaxy formation

First attempts to introduce chemical feedback in SPH simulations of MilkyWay type galaxies:

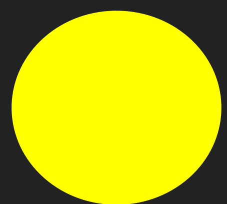
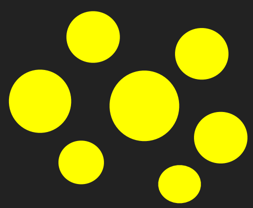
- ❖Steinmetz & Muller (1994)→ SNII; global metallicity Z
- ❖Raiteri et al. (1996; also Berczik 1999)→ SNII & SNIa; Fe & H

There are implementations that followed the metallicity Z (Springel & Hernquist 2003 and references therein)

Including chemical enrichment by **individual elements** provides a powerful tool to study galaxy formation in cosmological scenarios.
First implementations in a cosmological context:

- ❖Mosconi, Tissera, Lambas & Cora. (2001): SNII & SNIa, 13 ele.
- ❖ Lia, Portinari & Carraro (2002):detailed SE; difusion
- ❖ Kawata & Gibson (2003):SNII, SNIa,IS; Eth +Ekin
- ❖ Kobashashi (2004):detail SE; Eth +Ekin

Current cosmological models include a version of chemical evolution

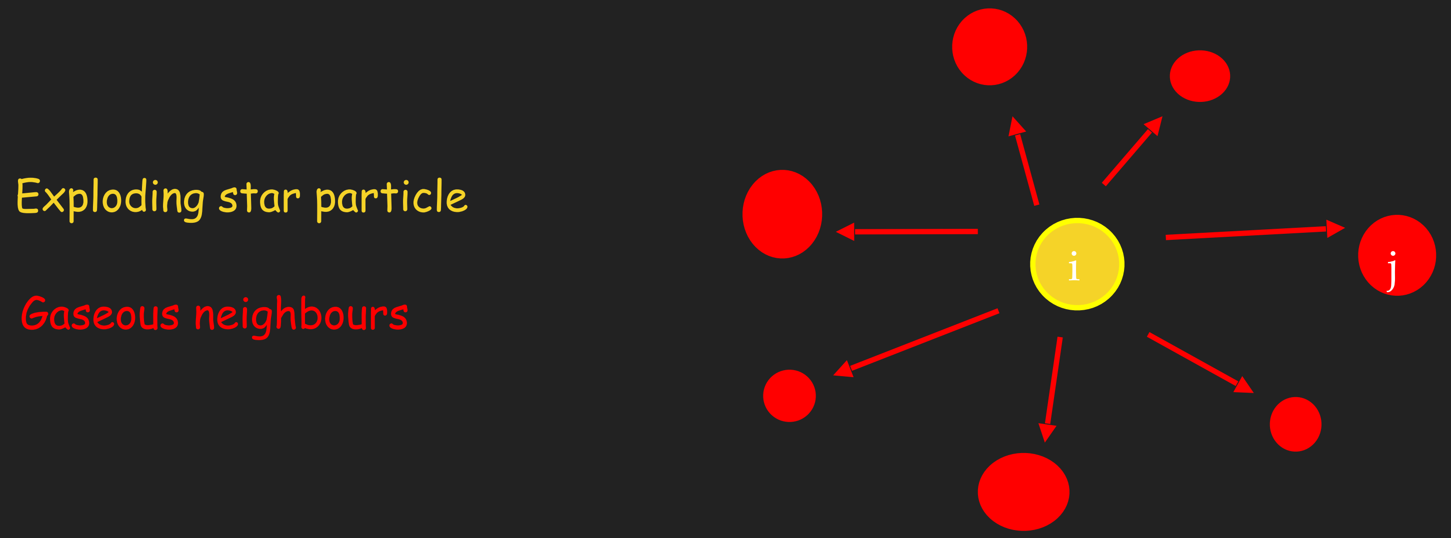
Numerical space		Physical space	Need
	↔		IMF: SNe / long-lived stars
Type II SNe		Mstar > 8 Msun, typical life-times ~106 yr Produce most O, Si, Ca, etc	
Type Ia SNe		Intermediate stars/binary systems typical life-times ~1 Gyr Produce most Fe	Nucleosynthesis yields
AGBs		Intermediate stars life-times ~1-2 Gyr C, N	

When SN explosions take place, metals are distributed according to the SPH technique (Mosconi+2001). For a given chemical element x at a particle i,

$$Mx_i = \sum_j m_{j/}\rho_j Mx_i \; W(r_{ij}, h_{ij})$$

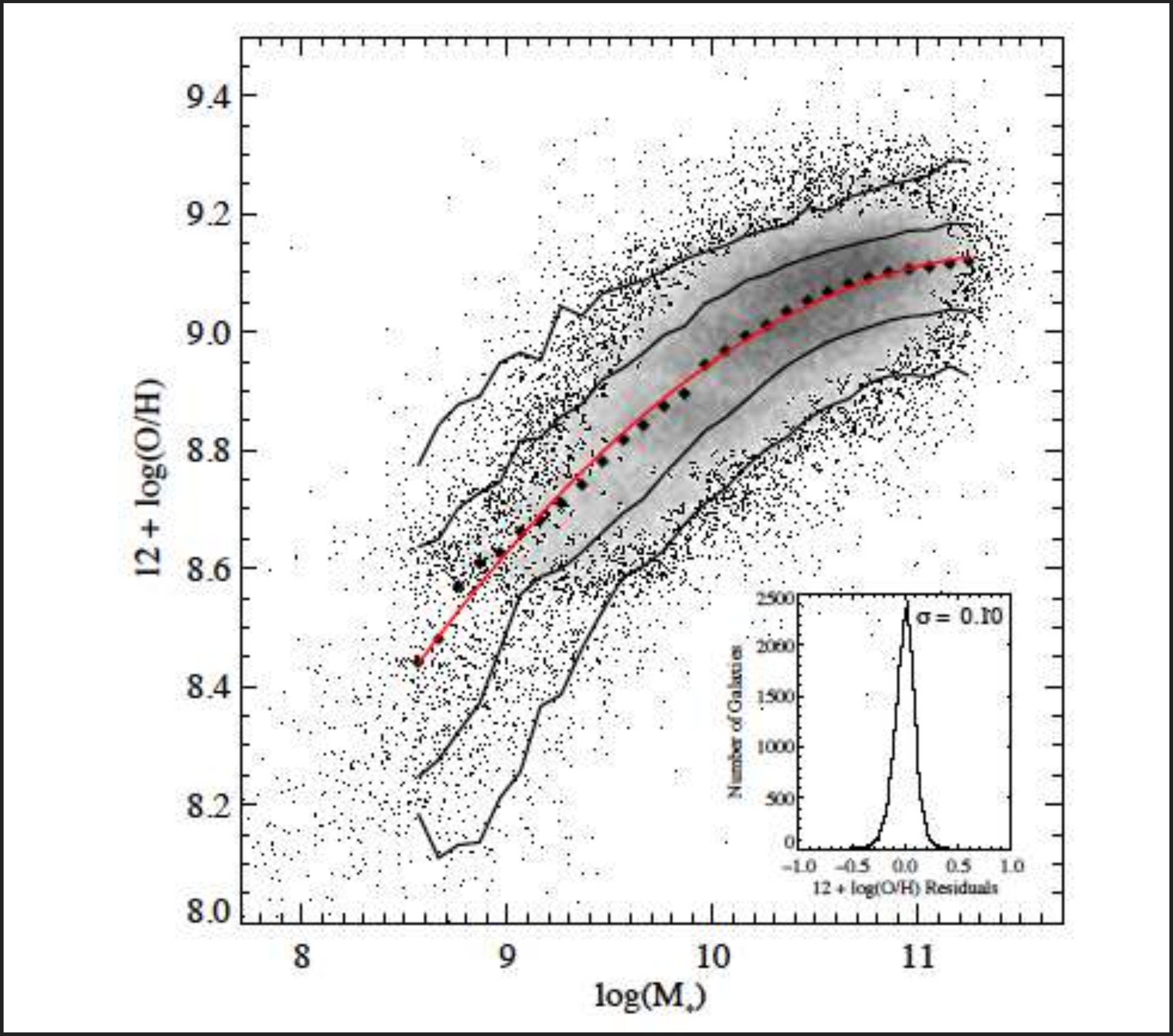
Neighbours will receive

$$Mx_j = m_{j/}\rho_j Mx_i \; W(r_{ij}, h_{ij})$$



GAS-PHASE MASS METALLICITY RELATION (MZR)

Tremonti+2014



CALIBRATION OF LINE EMISSION METALLICITY INDICATORS

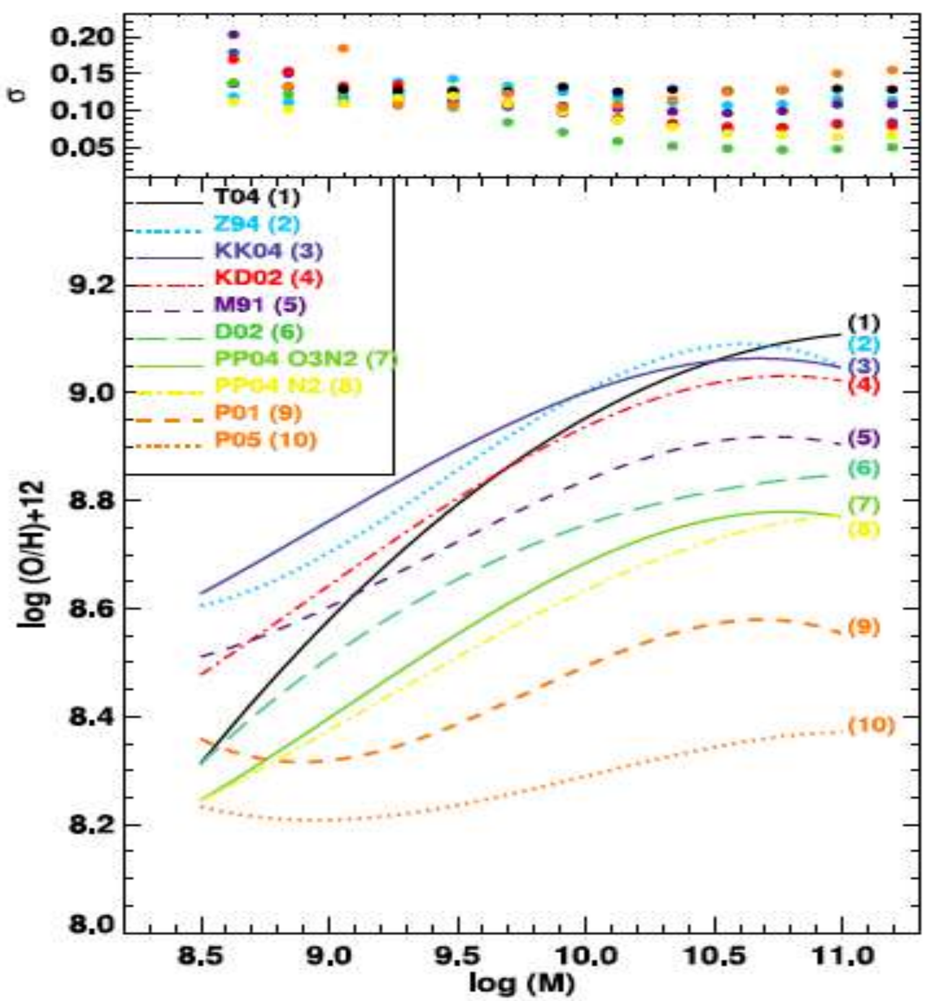


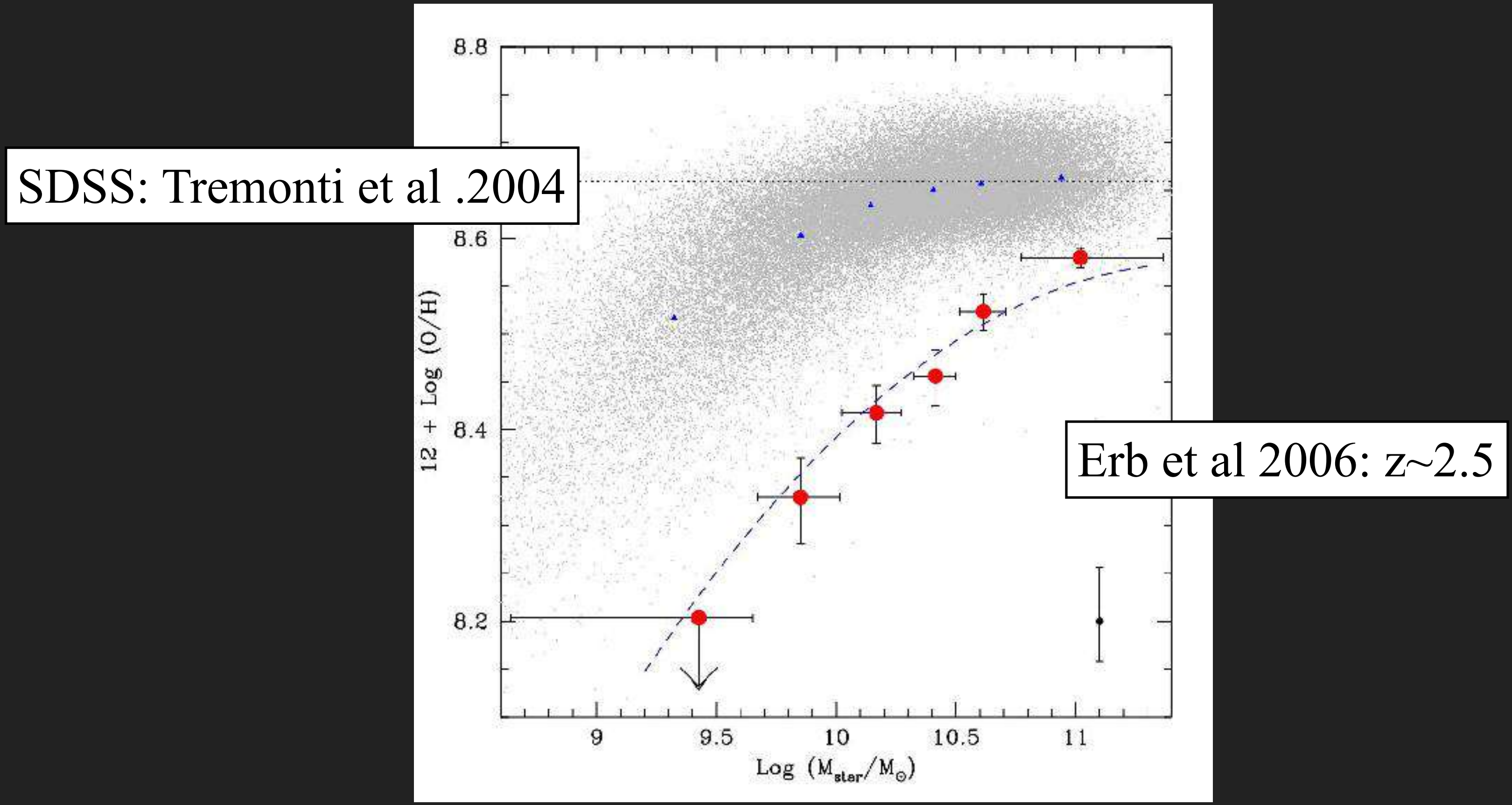
FIG. 2.—Robust best-fit *M-Z* relations calculated using the different metallicity calibrations listed in Table 1, except the T_e method. The top panel shows the rms scatter in metallicity about the best-fit relation for each calibration in 0.1 dex bins of stellar mass. The *y*-axis offset, shape, and scatter of the *M-Z* relation differ substantially, depending on which metallicity calibration is used.

Variation of the level of chemical enrichment with the adopted calibration.

Variation in the shape: relative level of enrichment between massive and small galaxies.

Ellison & Kewley (2008)

There are well-known LMR and MMR in the local Universe.
Observations suggest evolution in the zero point and slope of both relations.



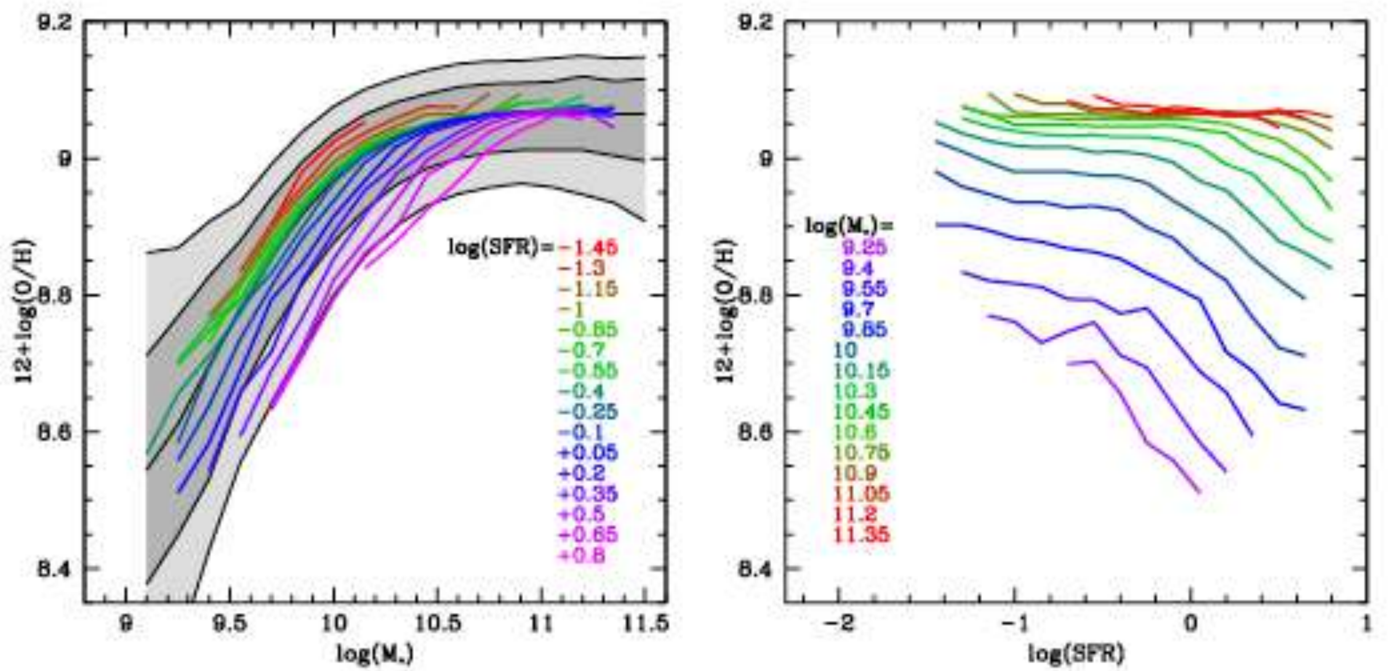
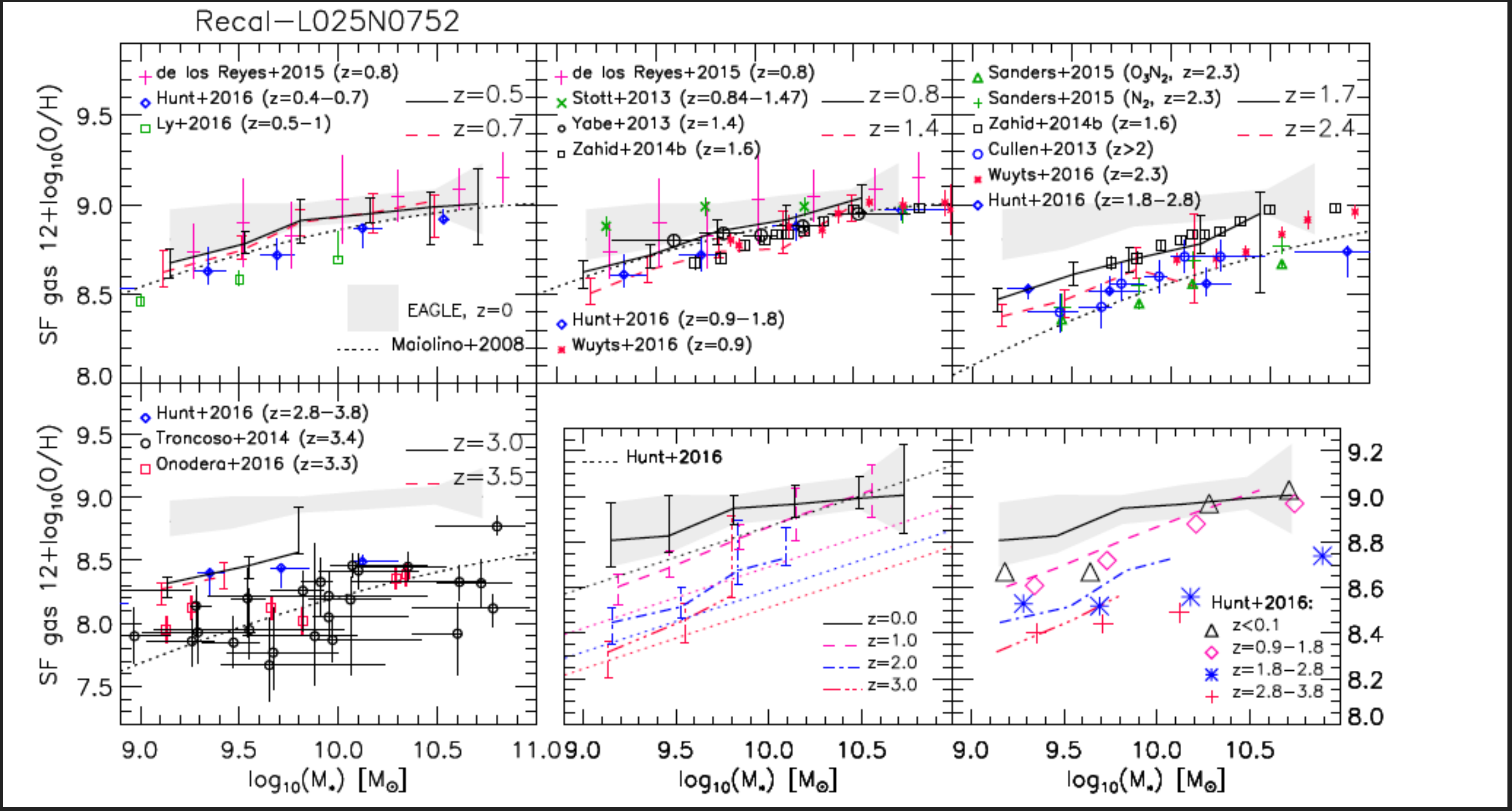
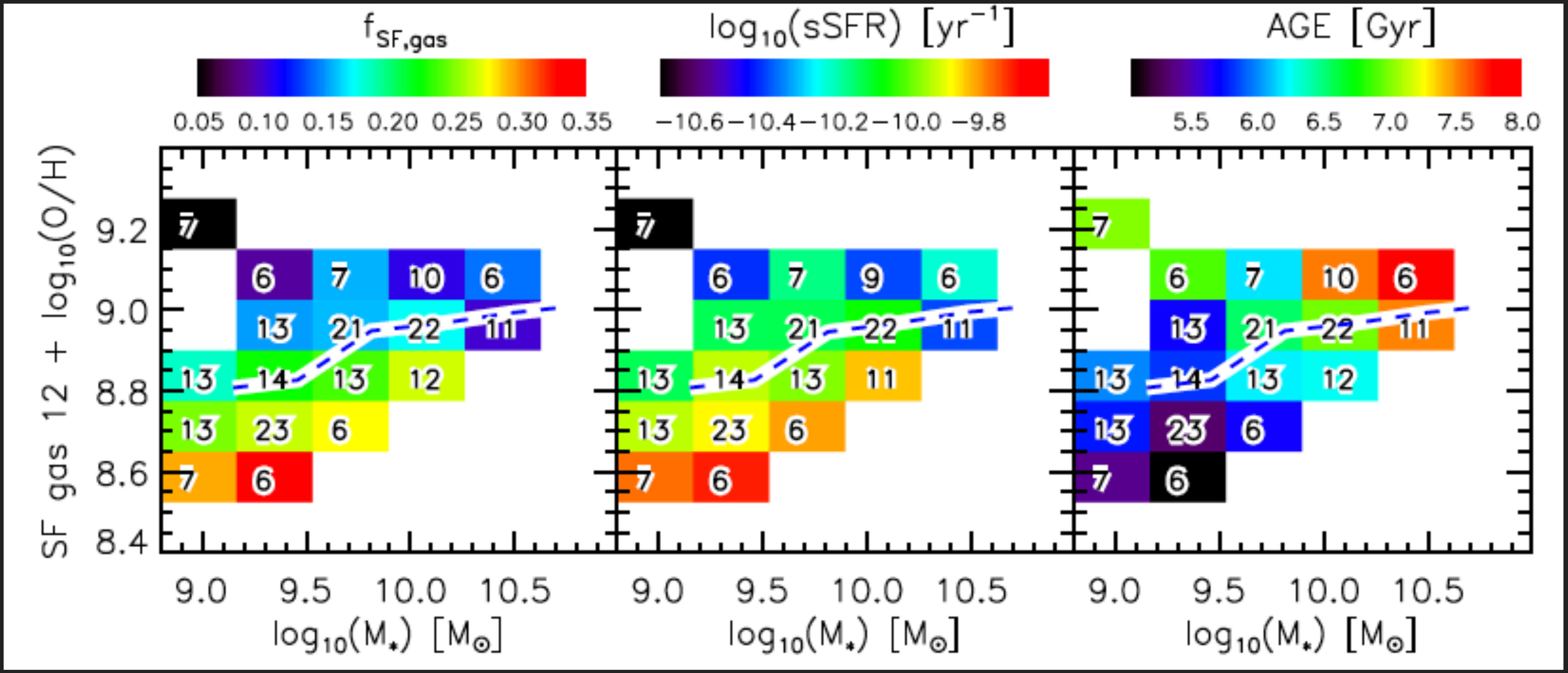


Fig. 21 The fundamental metallicity relation from Mannucci et al. (2010). Left: dependence of the gas metallicity on mass, in bins of SFR. The gray shaded areas contains 68% and 95% of the full, unbinned galaxy sample. Right: dependence of metallicity on SFR in bins of stellar mass.

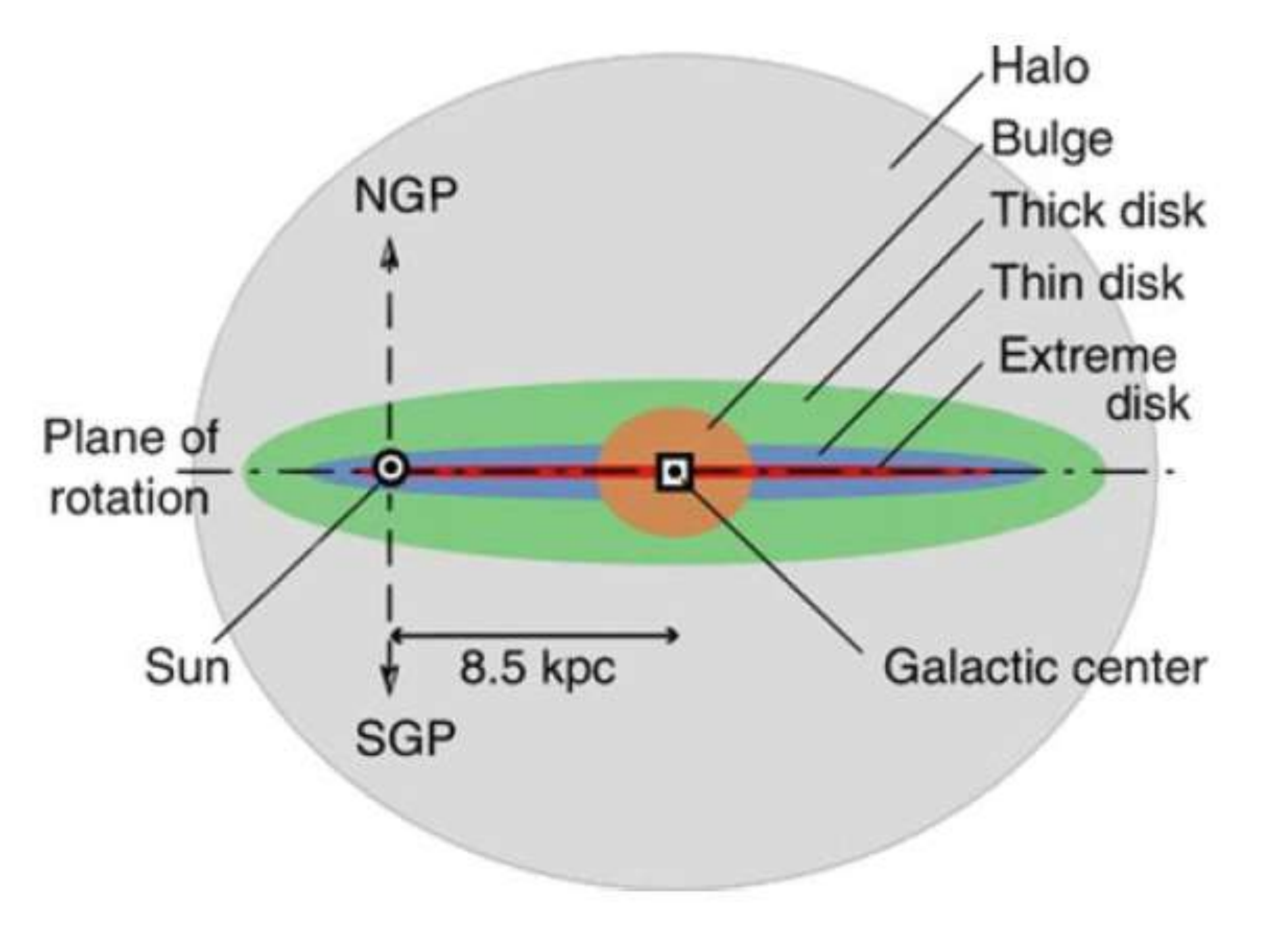
De Rossi+2018

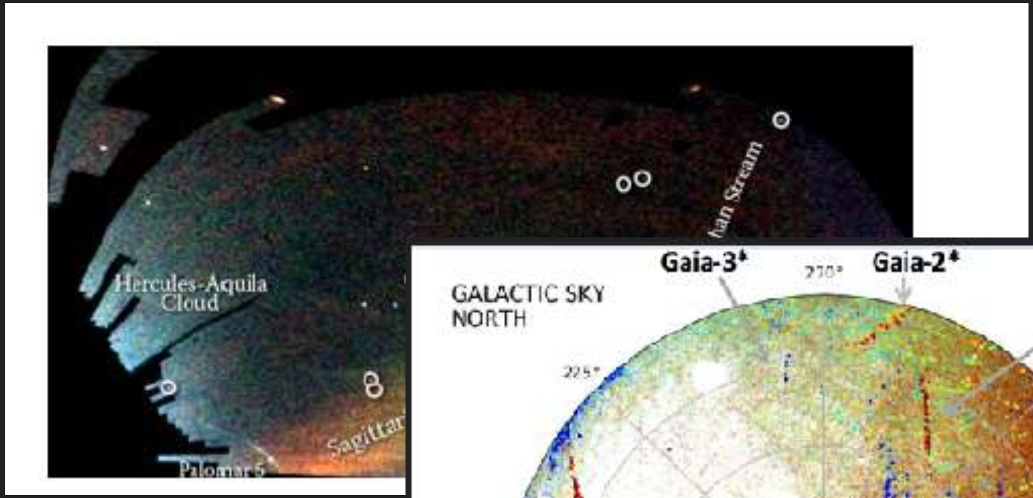


De Rossi+2018

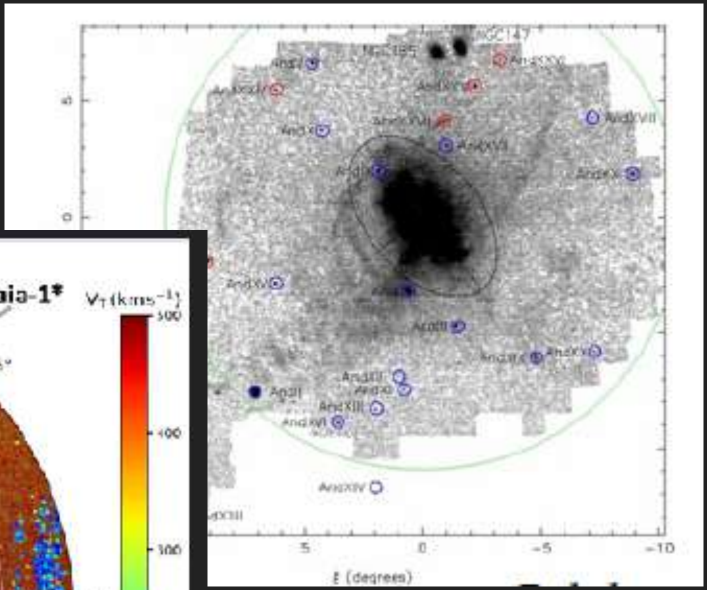


taken from Matteuci 2017

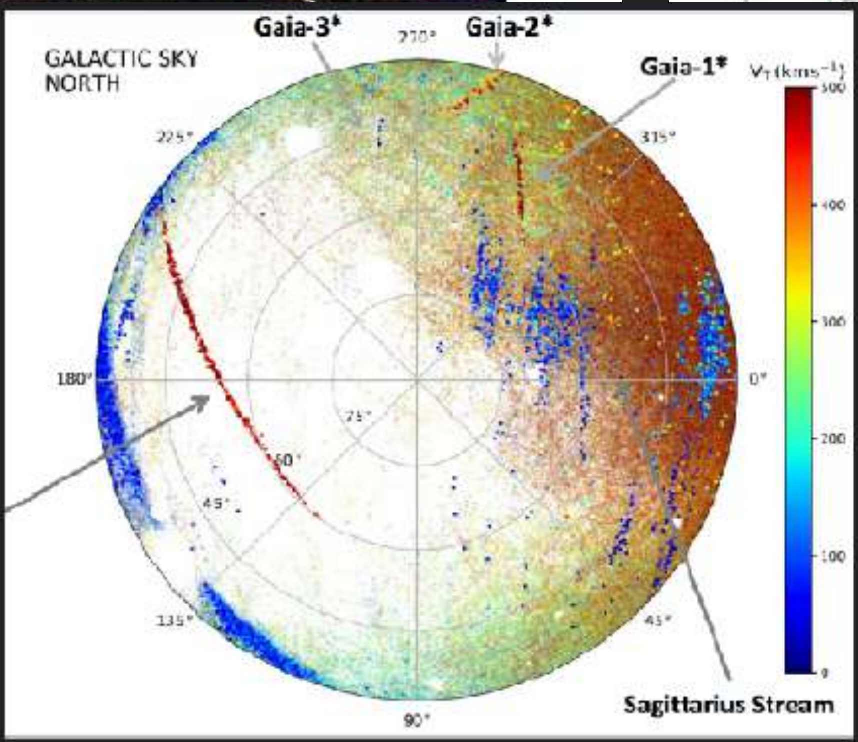




MW, Belokurov et al. 20

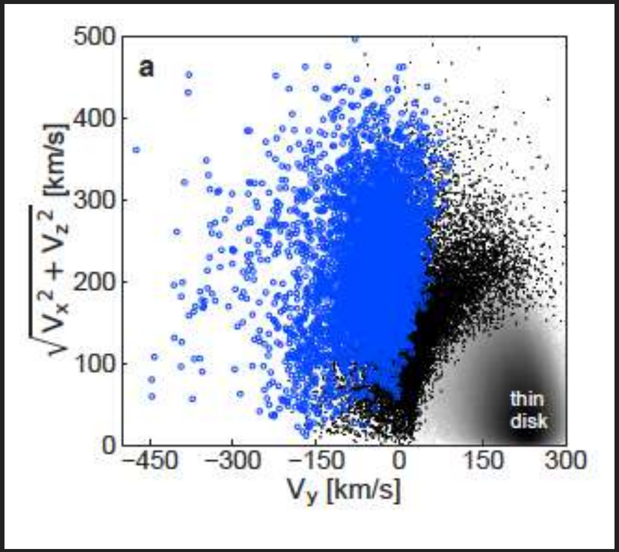


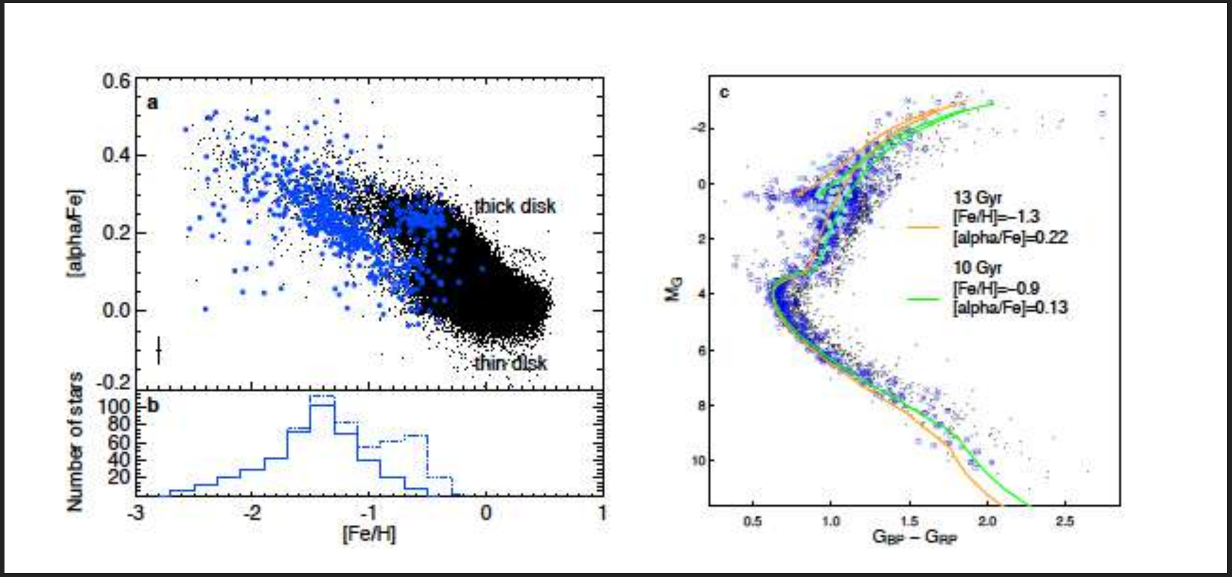
meda, Ibata et al. 2015



Malhan+ 2018

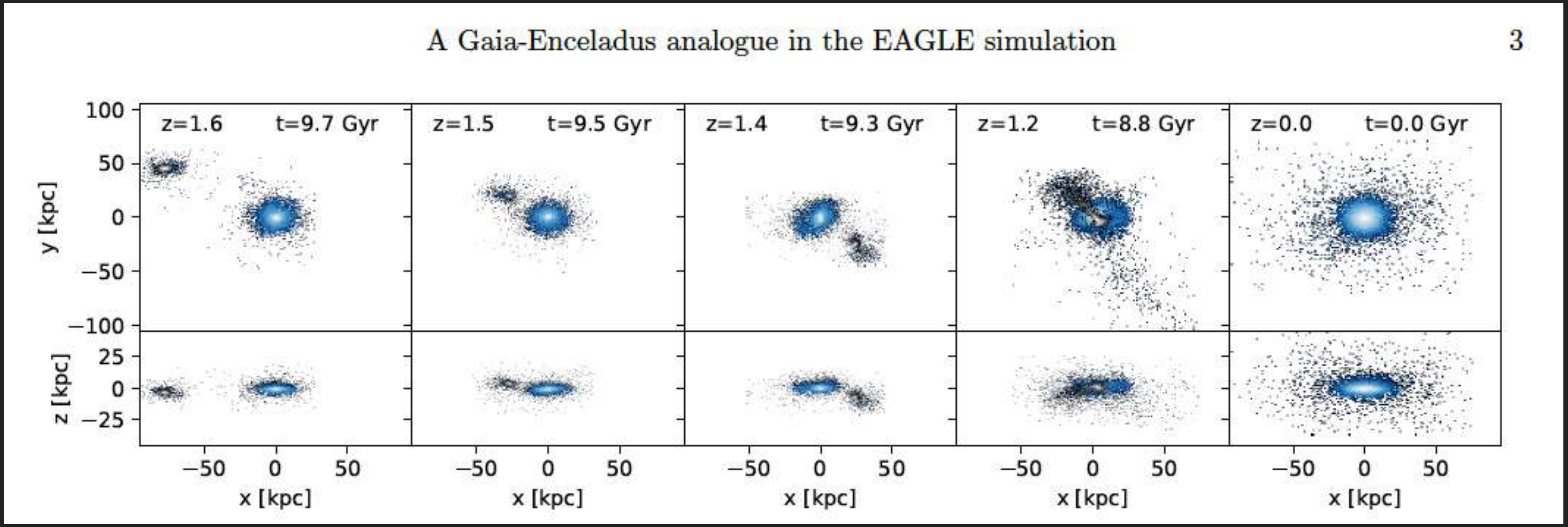
THE MILKY WAY STELLAR HALO



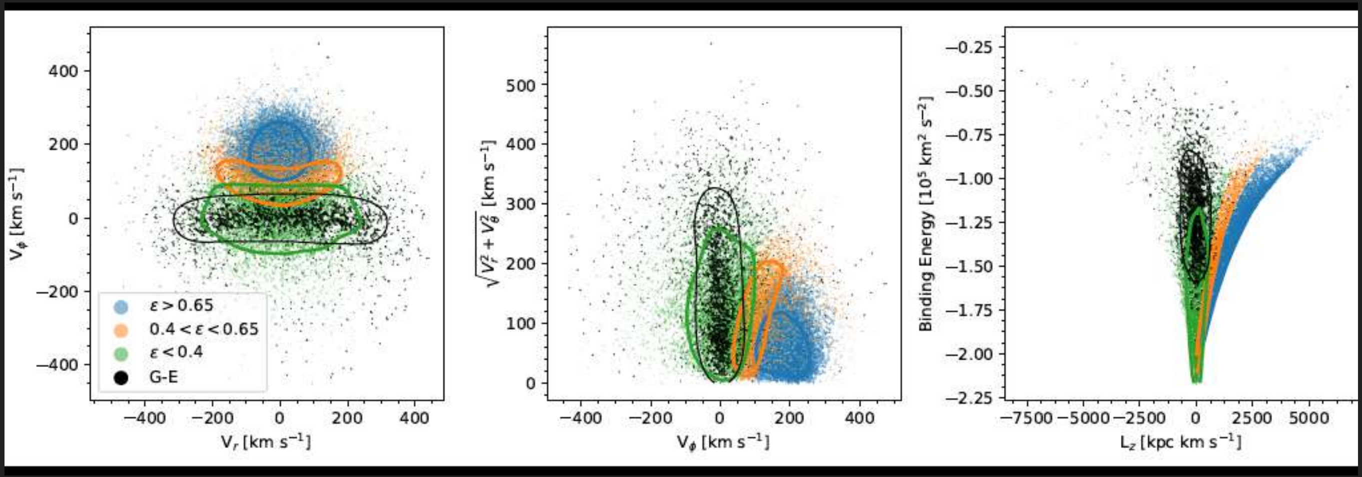


Helmi+2018

THE MILKY WAY STELLAR HALO



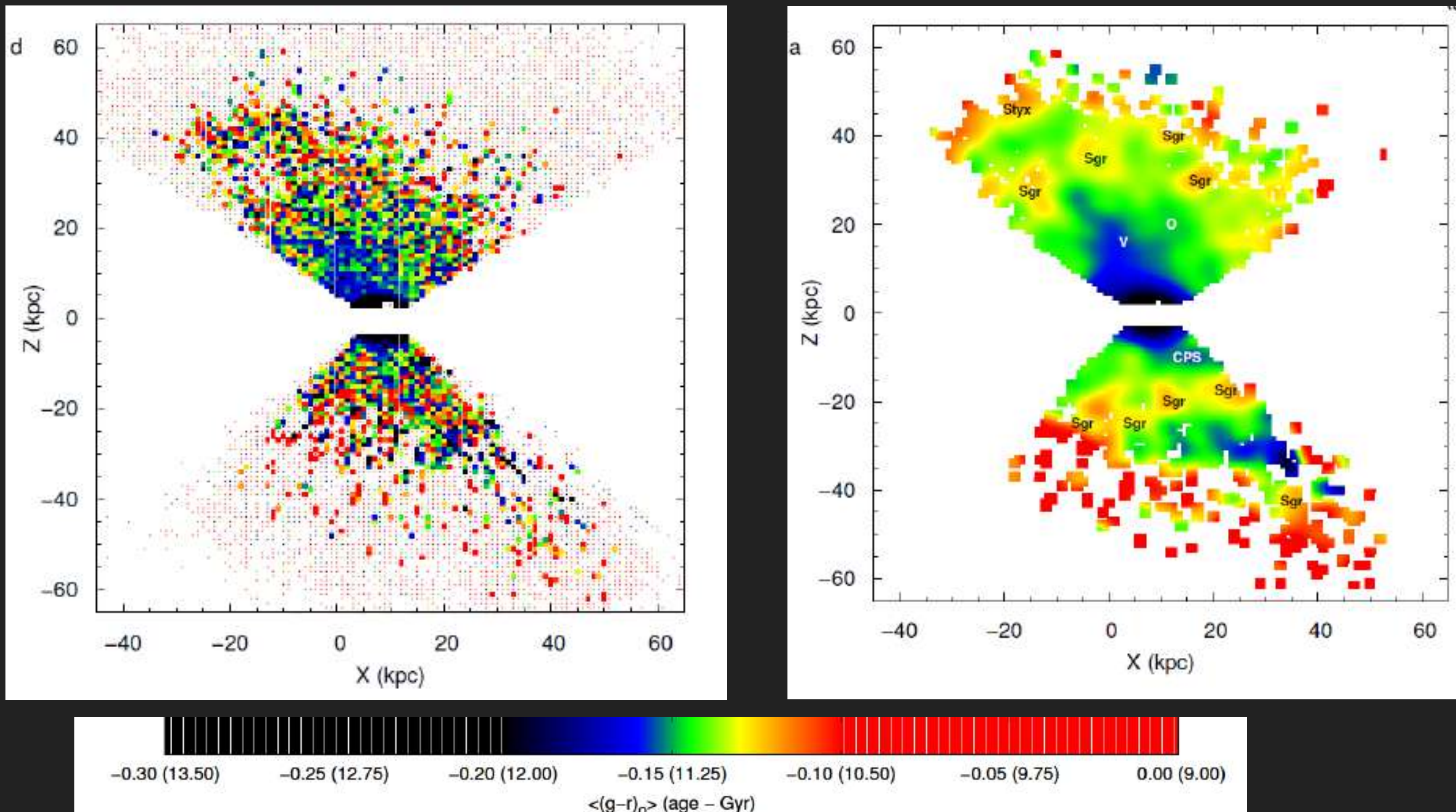
Bignone+2019



A Milky-Way analogue in EAGLE: the co-evolution of dynamical components

MILKY WAY STELLAR HALO

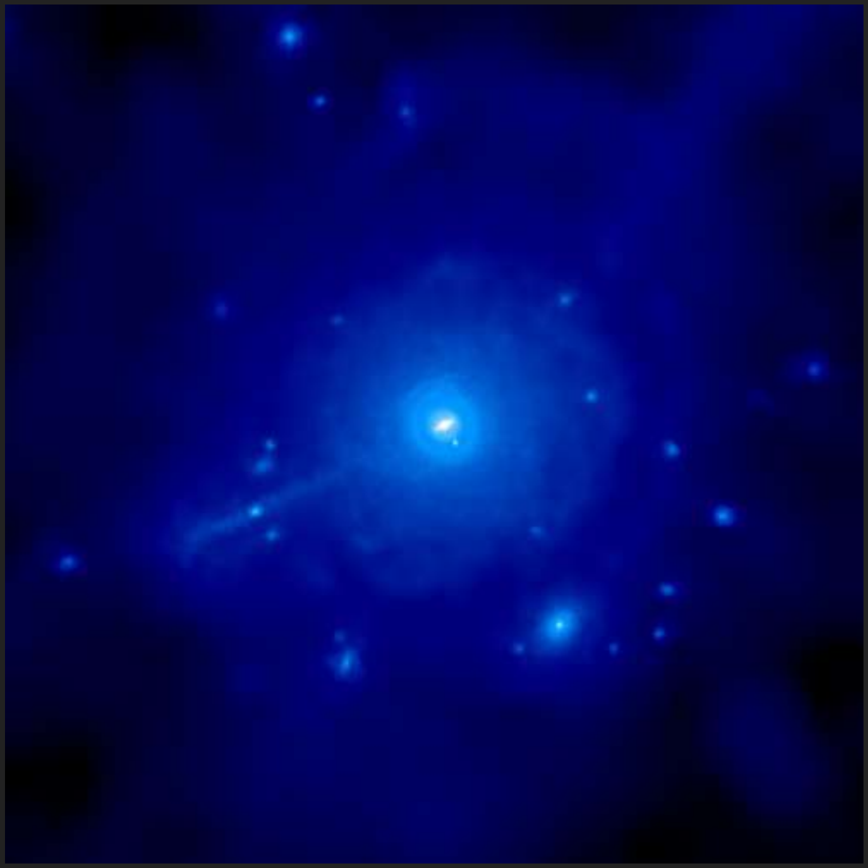
Carollo+2016



The MW stellar halo has an age of -25 Myr/kpc , with the oldest stars concentrated in the inner region.

MILKY WAY STELLAR HALO

Tissera+2014



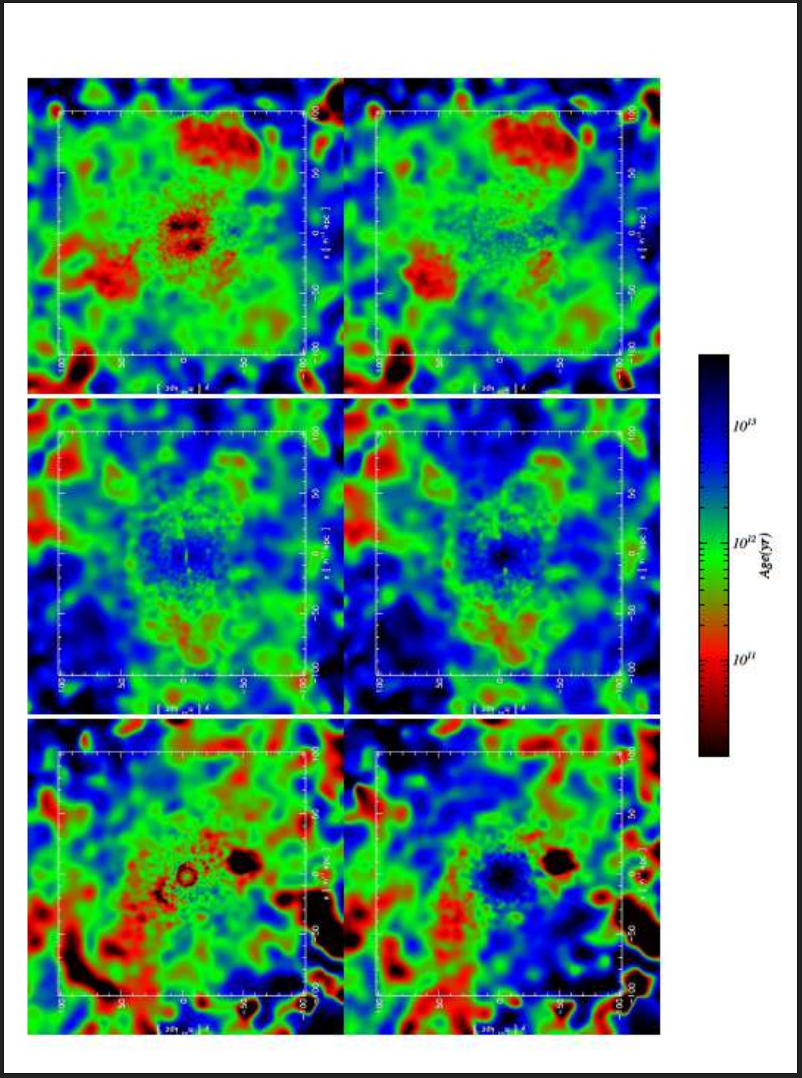
All stars (h>5 kpc)

Accreted (h>5 kpc)

Aq-A

Aq-C

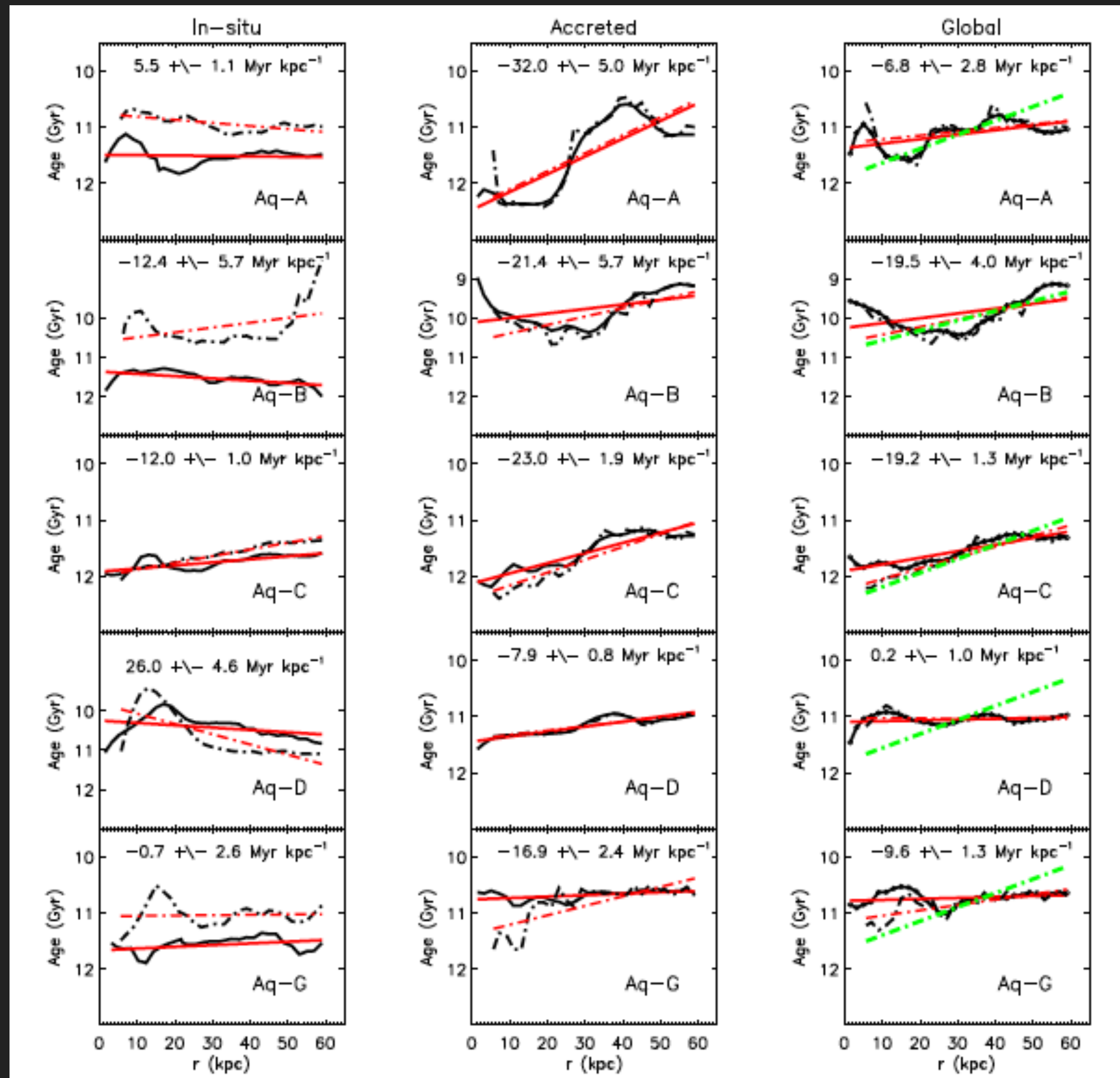
Aq-D



Carollo+2018

MILKY WAY STELLAR HALO

The MW halo is better reproduced if only accreted stars are considered.
In situ stars contribute with slightly younger SPs which seems not to be present in the central region of the MW in large amount



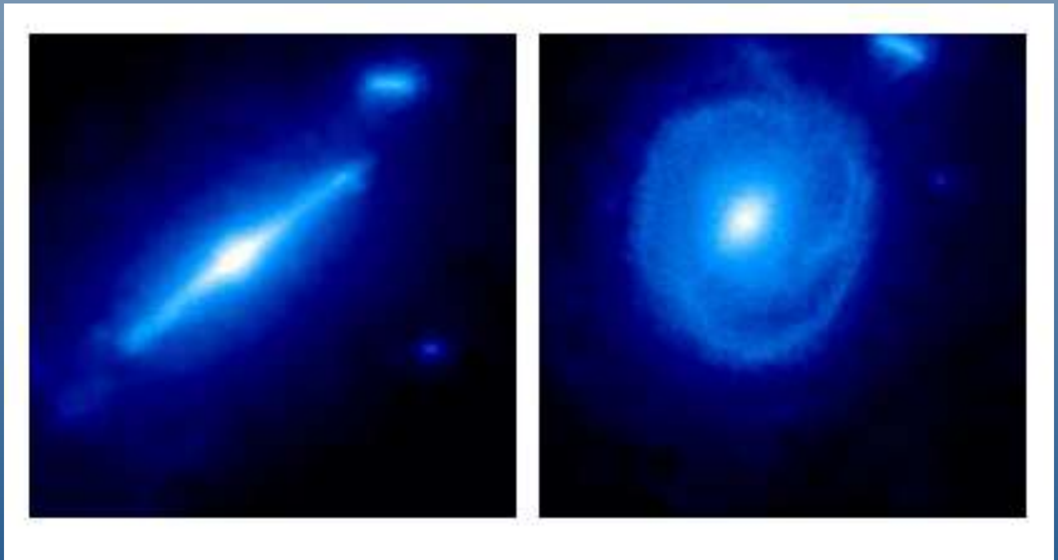
Carollo+2018

To compare models with observations:

The metallicity gradients in disc galaxies

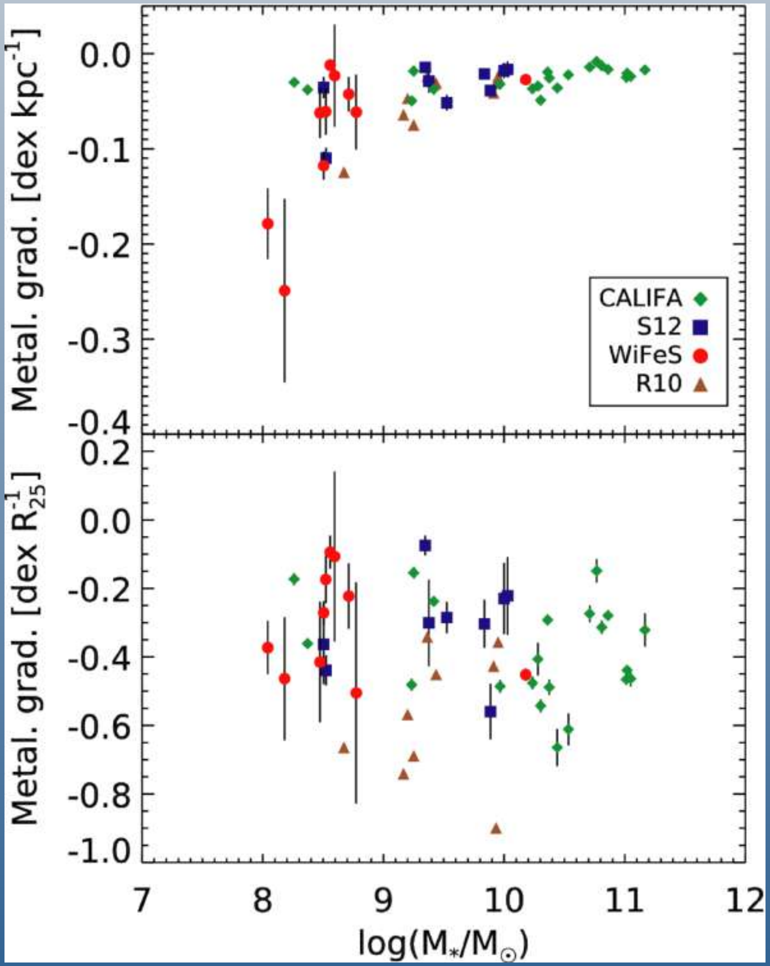
The standard model for disc formation based on angular momentum conservation

Negative metallicity gradients



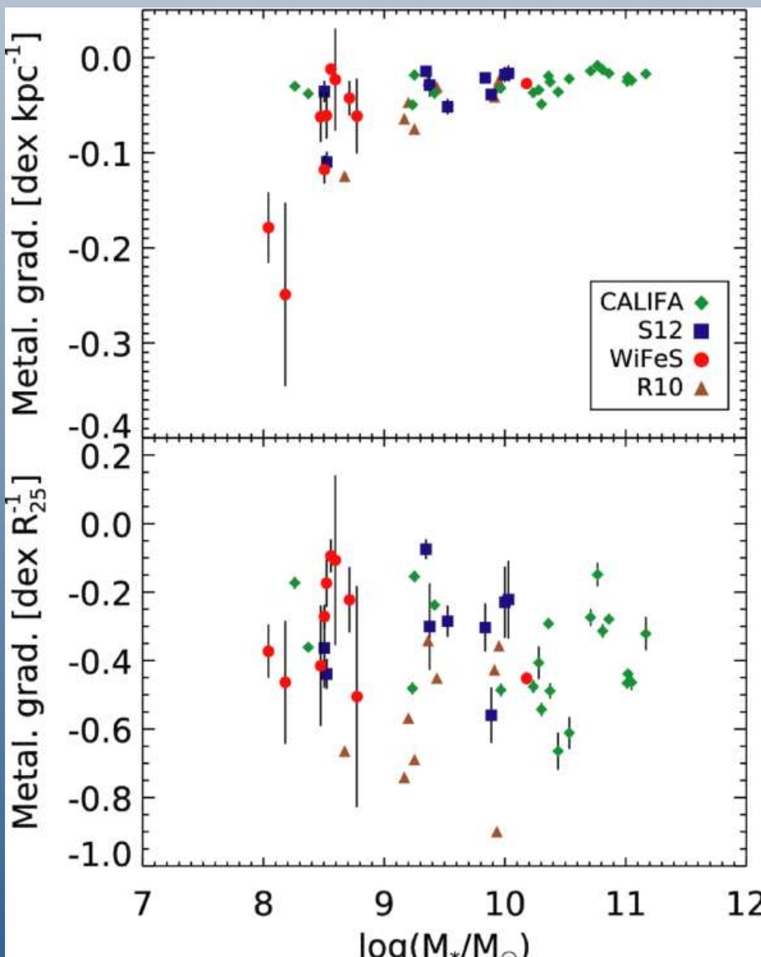
Mergers
Interactions
Migration
Secular evolution

Metallicity gradients in star-forming galaxies

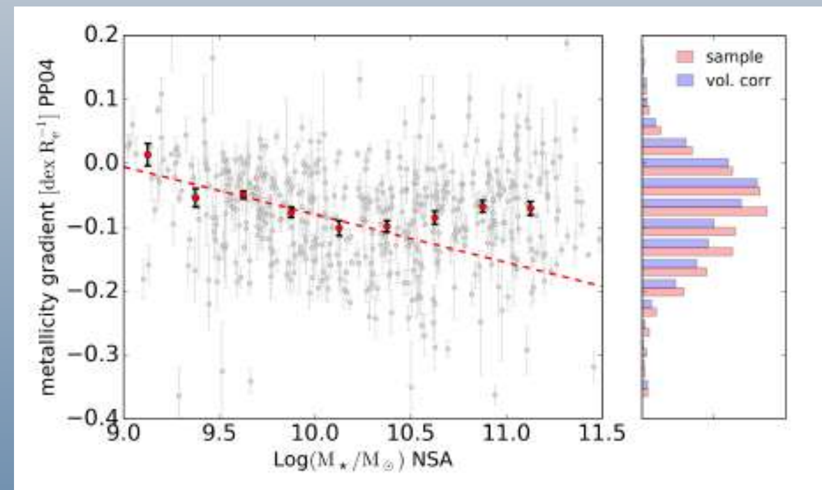


Ho+2015

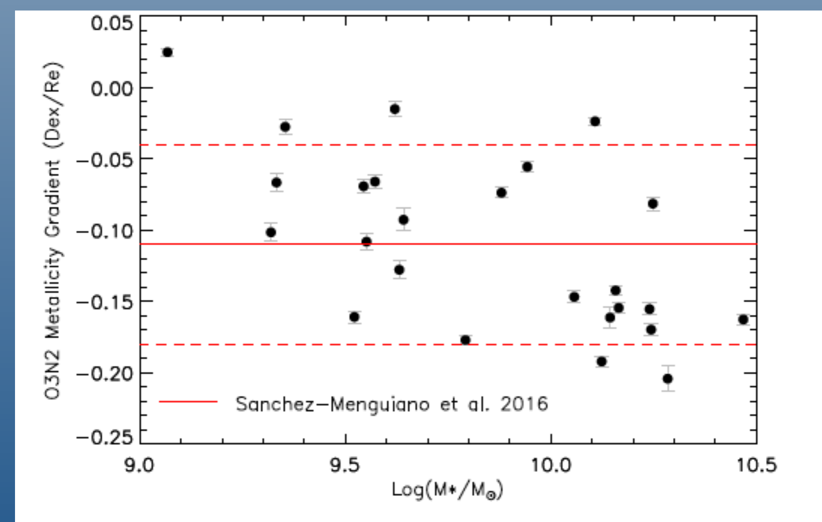
Metallicity gradients in star-forming galaxies



Ho+2015

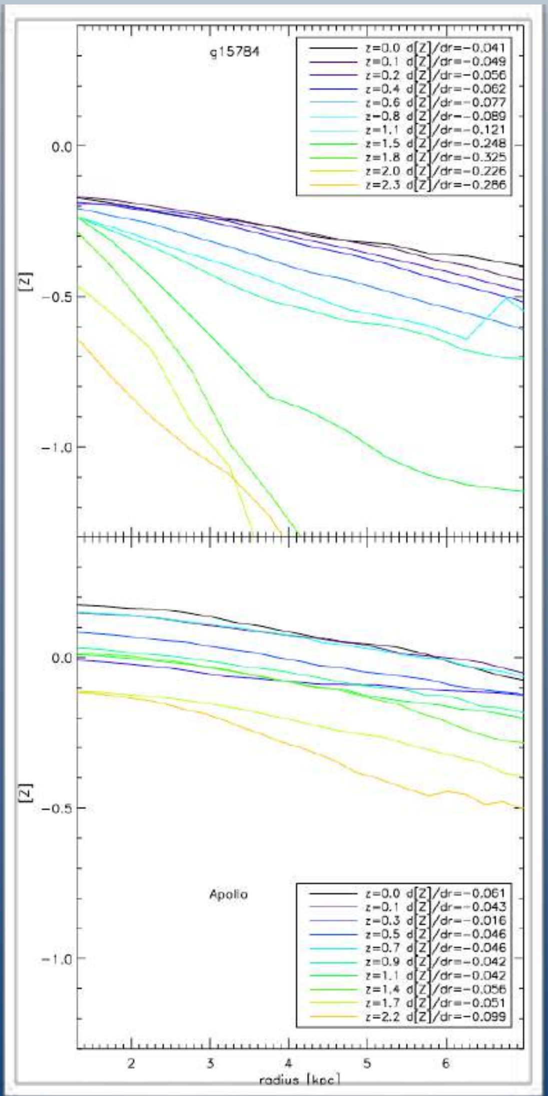


Belfiore et al 2017 (MaNGA)



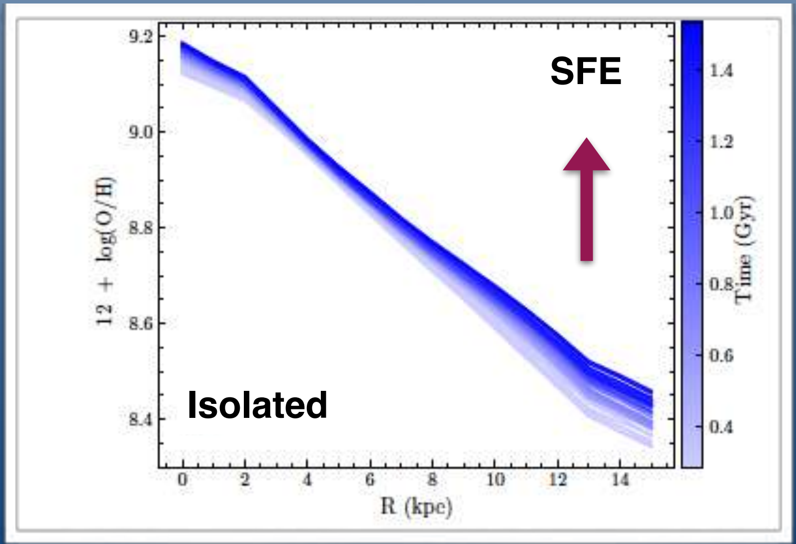
Poetrodjojo et al. 2018 (SAMI)

Star formation across the disc



Pilkington+2012

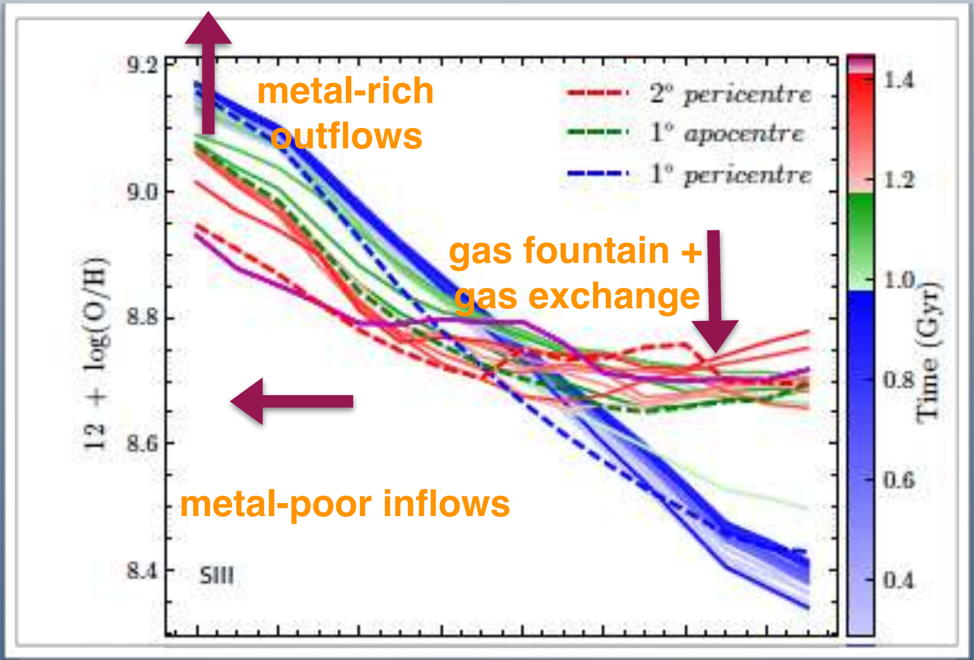
- Inside-out formation scenario gas discs have negative metallicity profiles: the slope is regulated by the star formation efficiency (e.g. Mollá+2017).
- Higher SFE —> weaker metallicity gradients.



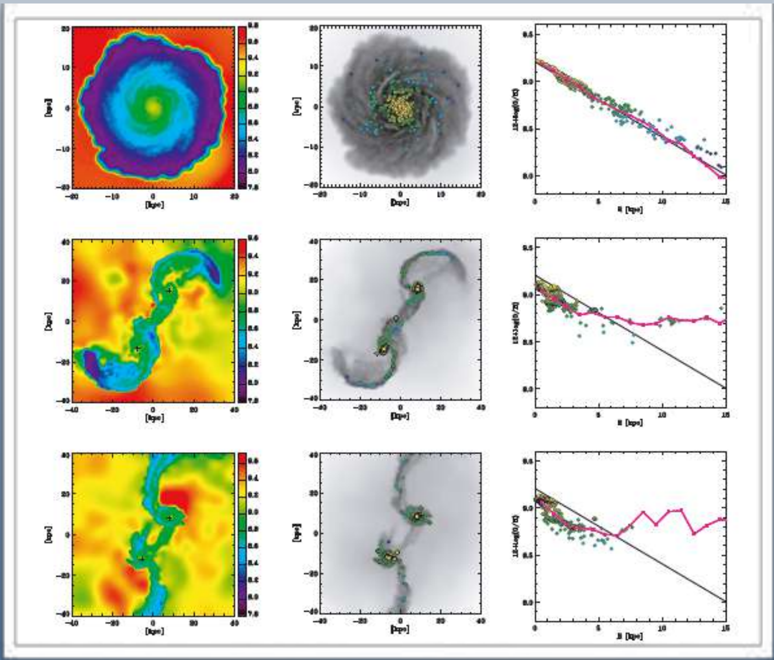
Sillero et al. 2017

Interactions and mergers

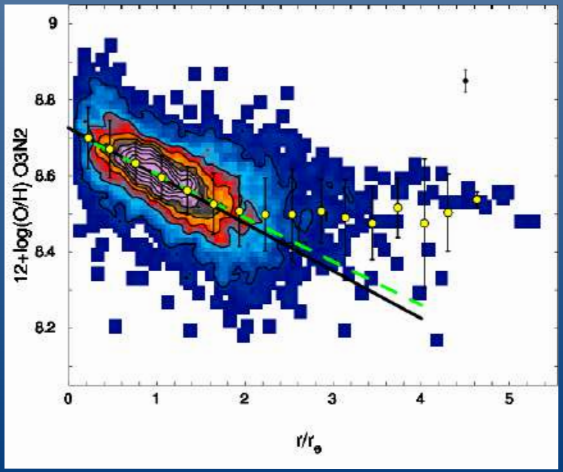
Sillero+2017



Perez+2011

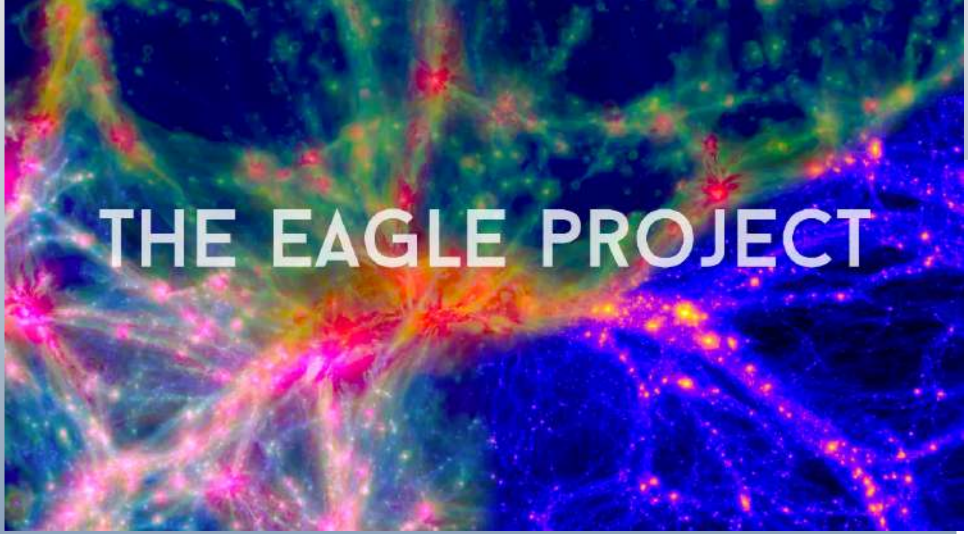


Sanchez et al. 2013



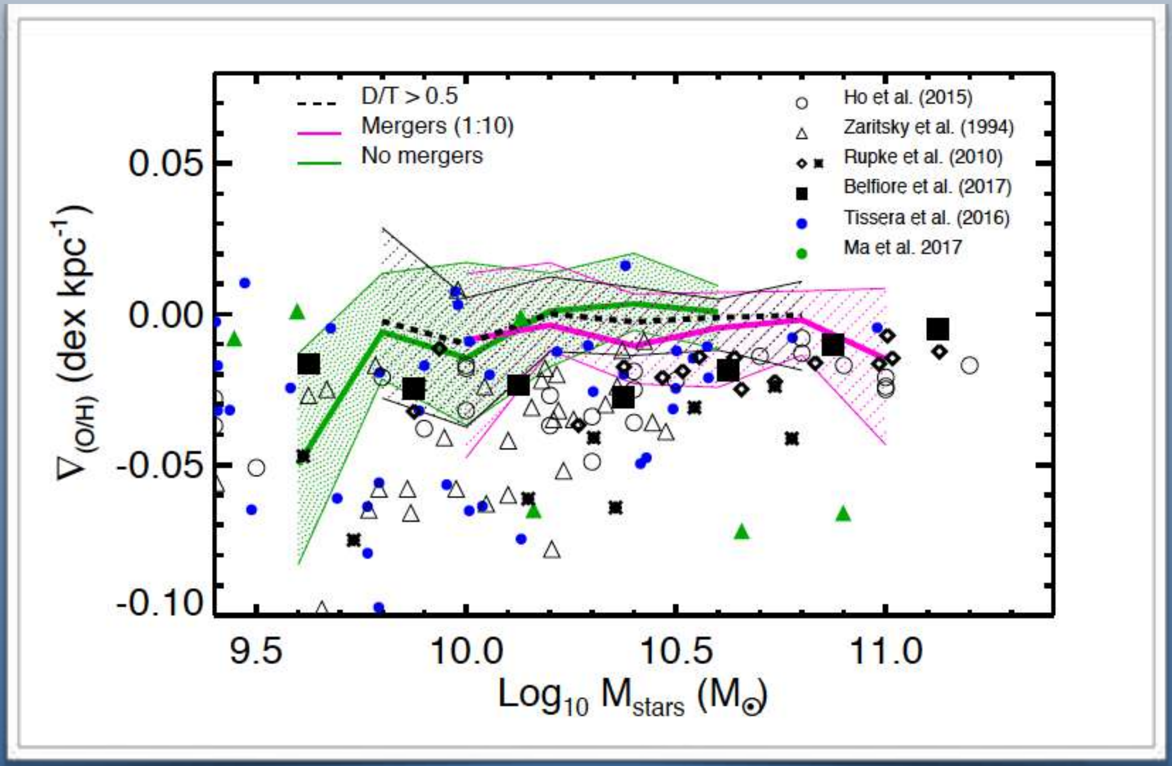
- Formation process: inside out.
- Feedback
- The assembly history: Interaction/mergers.
- Galactic fountain/material captured from the companion.

(e.g. Ruipke2010, Ho+2015,Tissera+2016:Ma+2017; Molla+2018)



We analysed the metallicity gradients in the (100 Mpc)^3 and (25 Mpc)^3 higher resolution simulations.

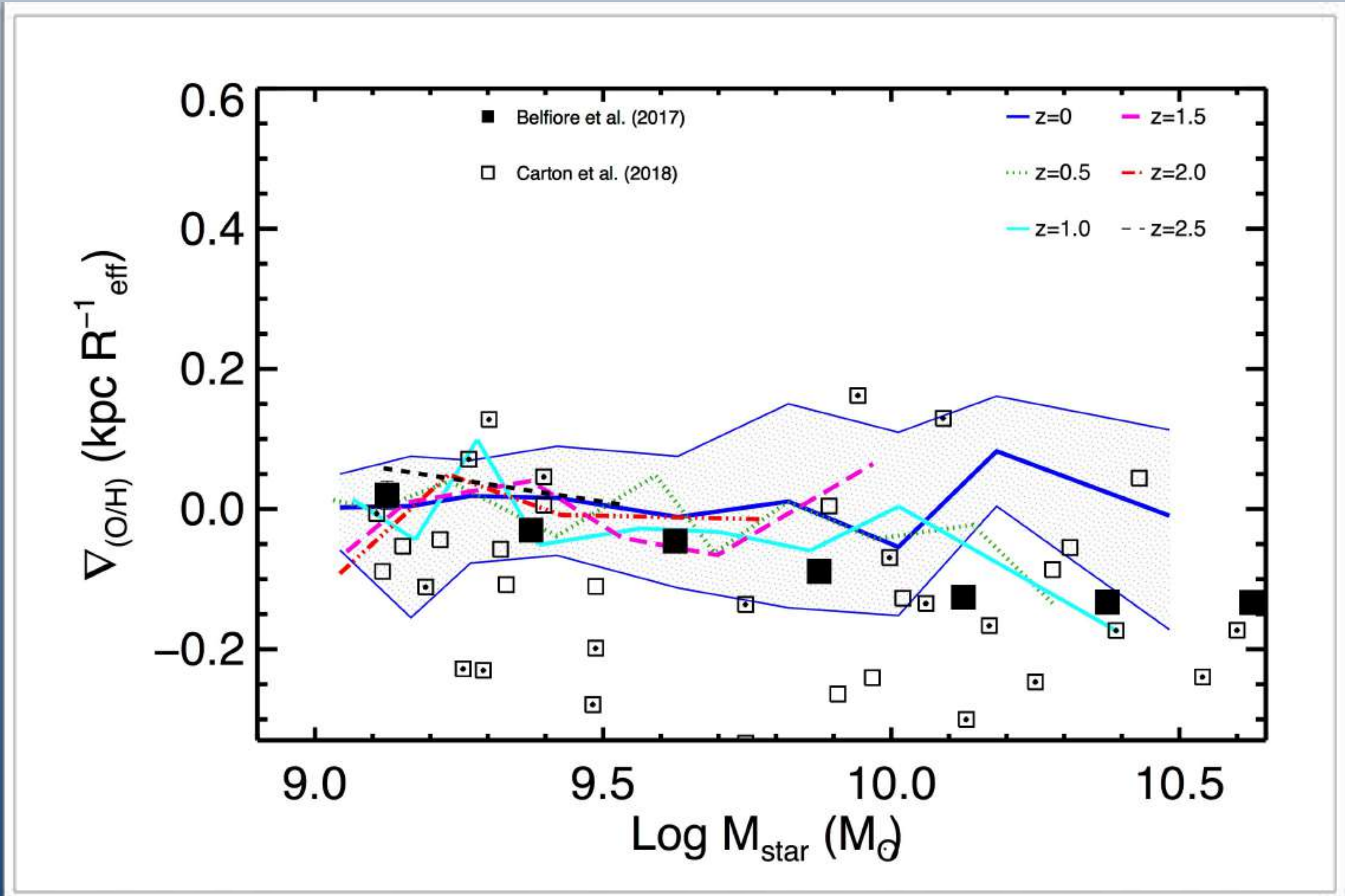
EAGLE simulations
Star forming gas disc abundances



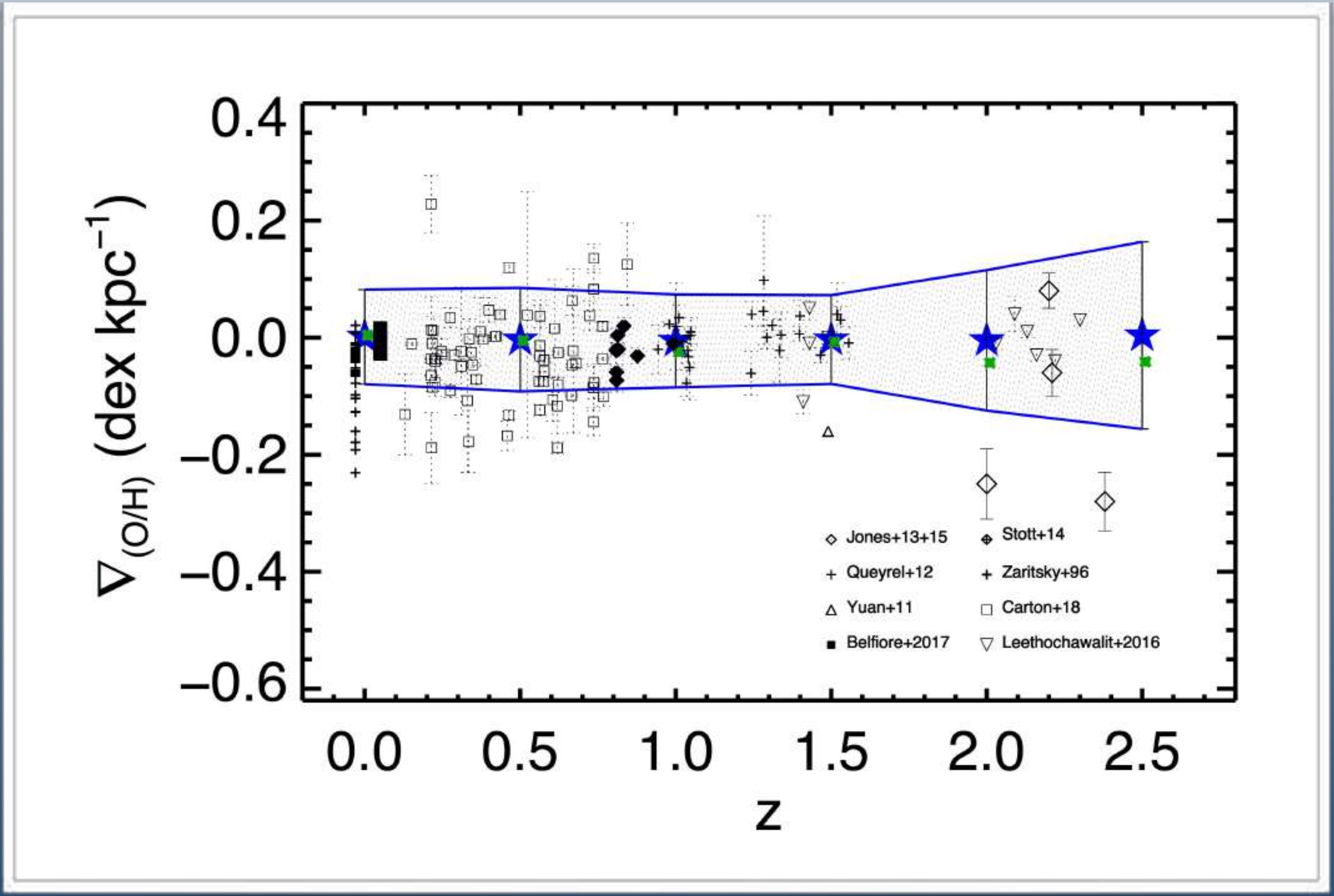
Tissera e+2019

- Disc metallicity gradients show a large variety.
- Galaxies that had no merger since z ~2 show a weak trend with stellar mass.
- Discs with negative gradients have slightly more recycled material.

Evolution of the oxygen abundance gradients



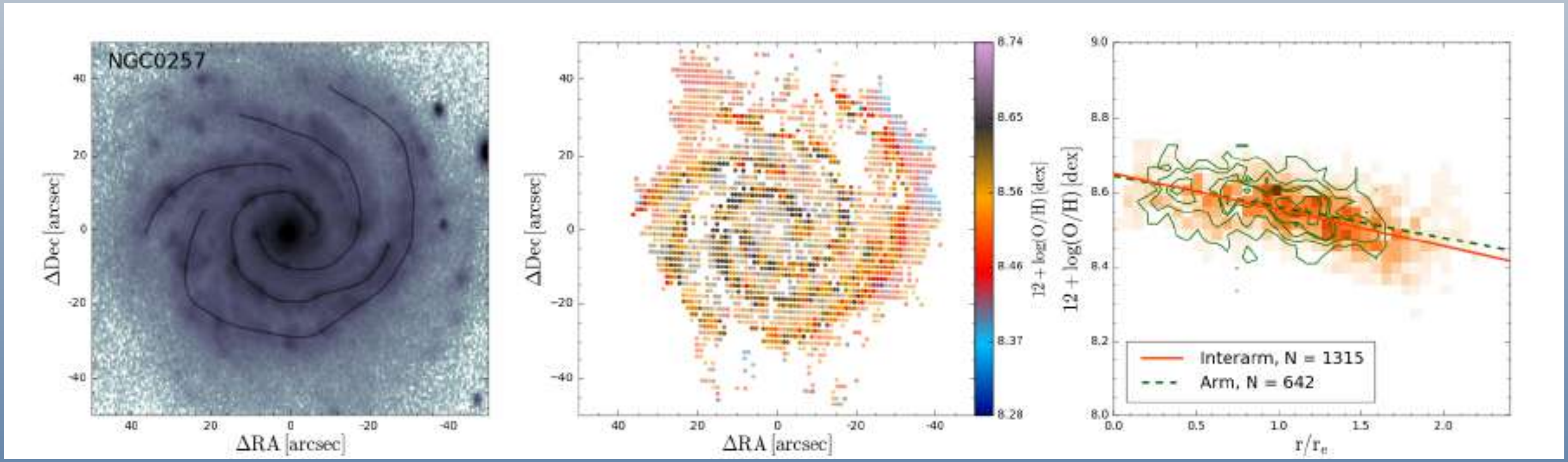
Evolution of the oxygen abundance gradients



EAGLE galaxies : No evolution with redshift is found for z <2.5.
Observations show a larger variety of metallicity gradients.

Azimuthal variation of the metallicity distributions

Azimuthal variation of the metallicity distributions

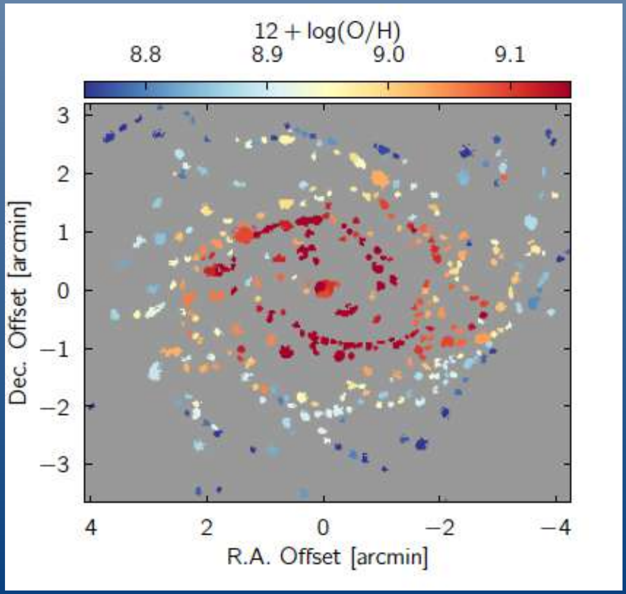


Sanchez-Menguiano+2017

Azimuthal variations in metallicity detected are about ~0.05-0.1 dex.

Metallicity gradients of SF regions in the arms tend to be slightly shallower.

CALIFA and MUSE obervations



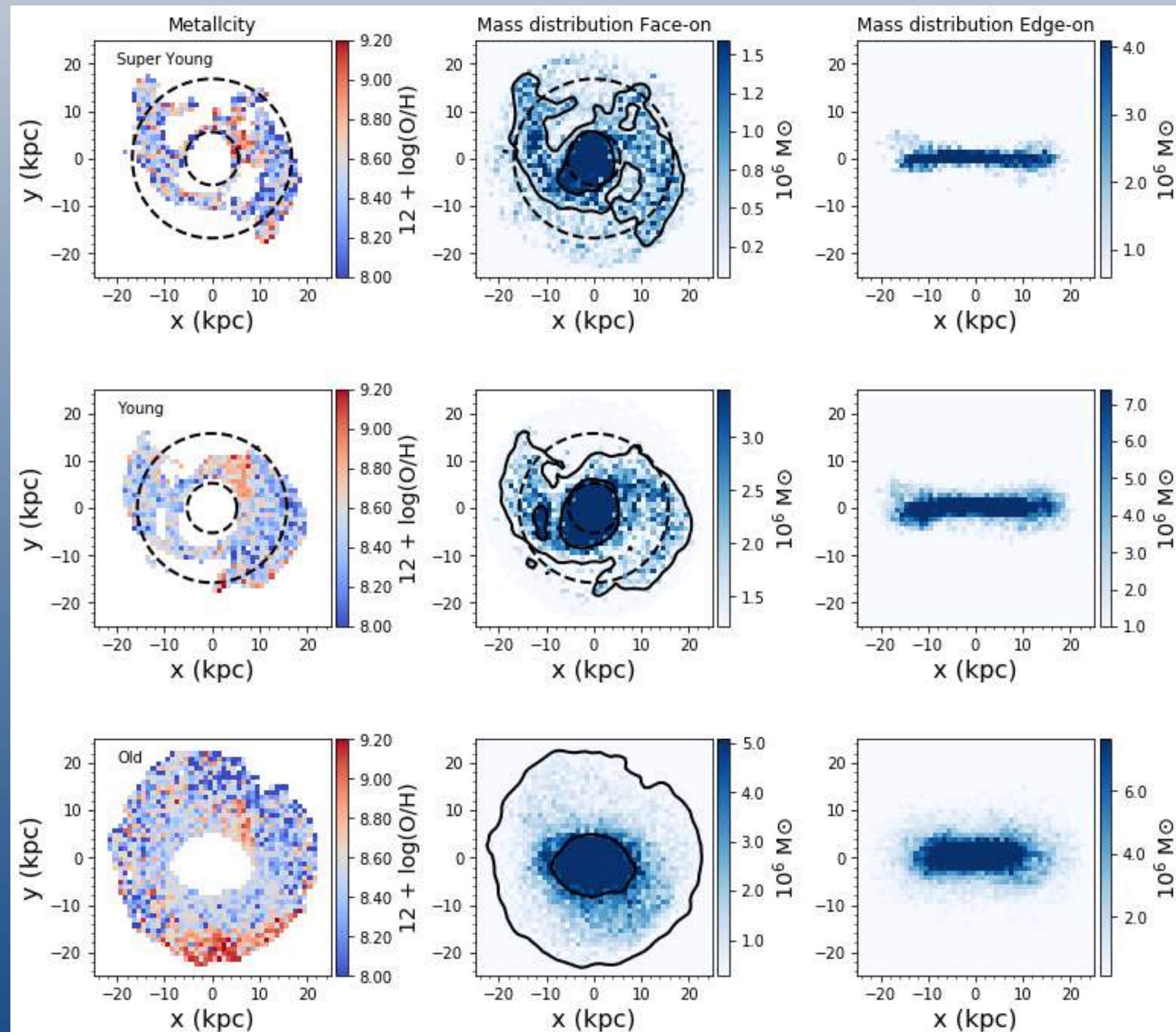
Ho+2018

Azimuthal variations in the EAGLE discs

age < 0.5 Gyr

0.5 Gyr <age < 2 Gyr

age > 2 Gyr



Solar+ in prep

EAGLE galaxies

GALAXY FORMATION