Chemical evolution in L-GALAXIES:

implementation & comparison to obs

Rob Yates (MPE/MPA)

SAM workshop – Munich – 11th to 12th July 2017

GCE analytics

GCE implementation

To model GCE, we need to know…

1) How many stars of mass M die at time t

   IMF • SFR(t-τ_M) = death rate at time t

2) How much metal they eject at time t

   M_Z = Metal mass ejected by star of mass M

Therefore:

IMF • SFR(t-τ_M) • M_Z = Metal mass ejected by star of mass M at time t

The GCE equation

$$e_Z(t) = \int_{M_L}^{M_U} M_Z(M, Z_0)\ \psi(t - \tau_M)\ \phi(M)\ \mathrm{dM}$$

Metals — SFR — IMF

$e_Z(t)$ = The rate of ejection of metals from a simple stellar population (SSP)

$$M_Z = y_Z(M, Z_0) + Z_0 \cdot (M - M_r)$$

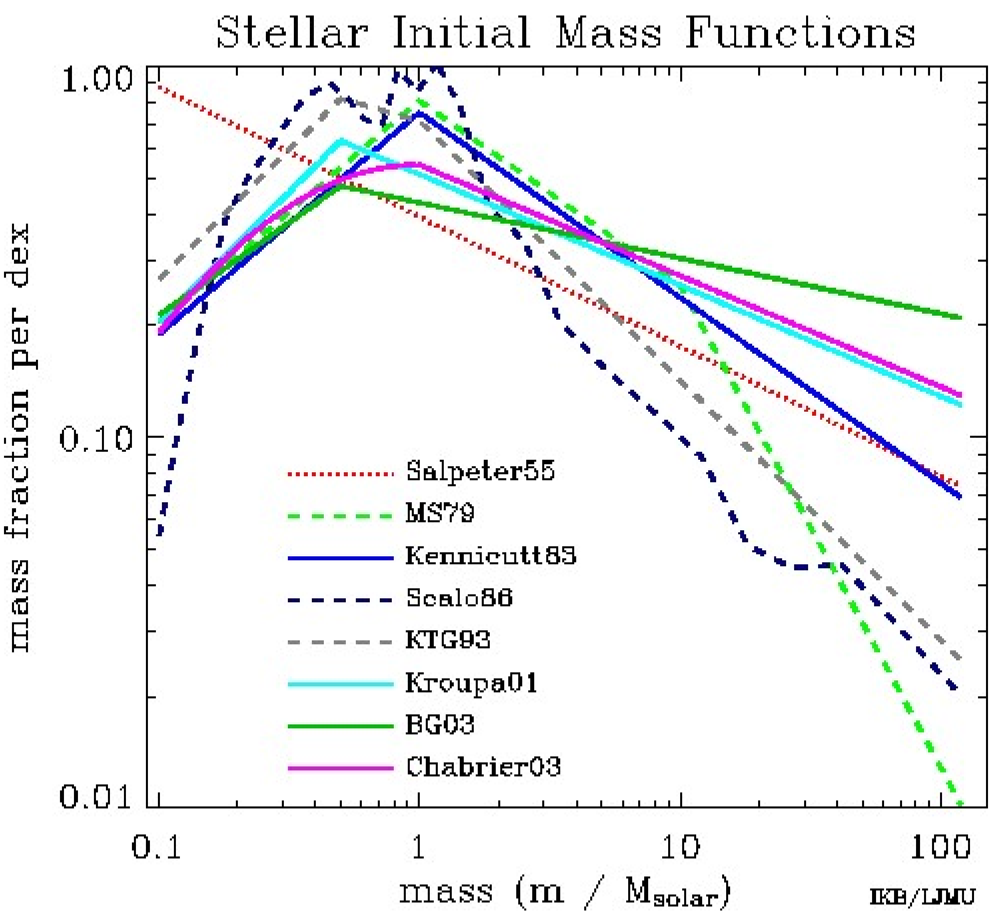
= The mass of metals ejected by one star of initial mass *M*, initial metallicity Z_o, and remnant mass M_r

$\psi(t - \tau_M)$ = The star-formation rate (SFR) at a time τ_M in the past

$\phi(M)$ = The stellar initial mass function (IMF)

The IMF

$$e_Z(t) = \int_{M_L}^{M_U} M_Z(M, Z_0)\, \psi(t - \tau_M)\, \phi(M)\, dM$$



Baldry 06

The IMF tells us how many stars of mass *M* there are.

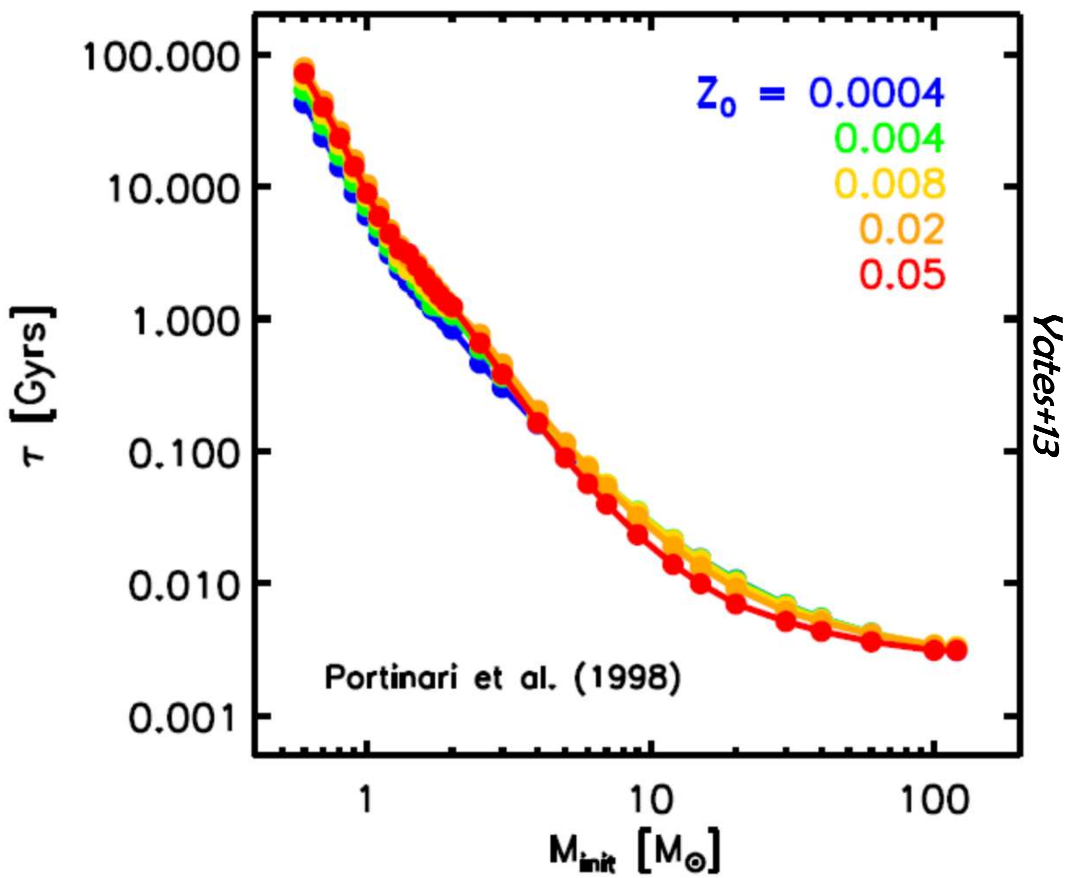
Different IMFs give different GCE results. e.g. more high-mass stars means more alpha elements...

Currently in L-GALAXIES, we assume a Chabrier 03 IMF (fixed in time and space), with $M_L = 0.1\ M_{sun}$ and $M_U = 120\ M_{sun}$:

$$\phi(M) = \begin{cases} A_\phi M^{-1} e^{-(\log M - \log M_c)^2/2\sigma^2} & \text{if } M \leqslant 1\mathrm{M}_\odot \\ B_\phi M^{-2.3} & \text{if } M > 1\mathrm{M}_\odot \end{cases}$$

Stellar lifetimes

$$e_Z(t) = \int_{M_L}^{M_U} M_Z(M, Z_0)\, \psi(t - \tau_M)\, \phi(M)\, dM$$



Simple, monotonic link between τ_M and *M*.

(t-τ_M) is therefore the birth time of a star of mass *M* exploding at time *t*.

Currently in L-Galaxies, we assume the weakly Z-dependent lifetimes of *Portinari+98*.

AGB winds

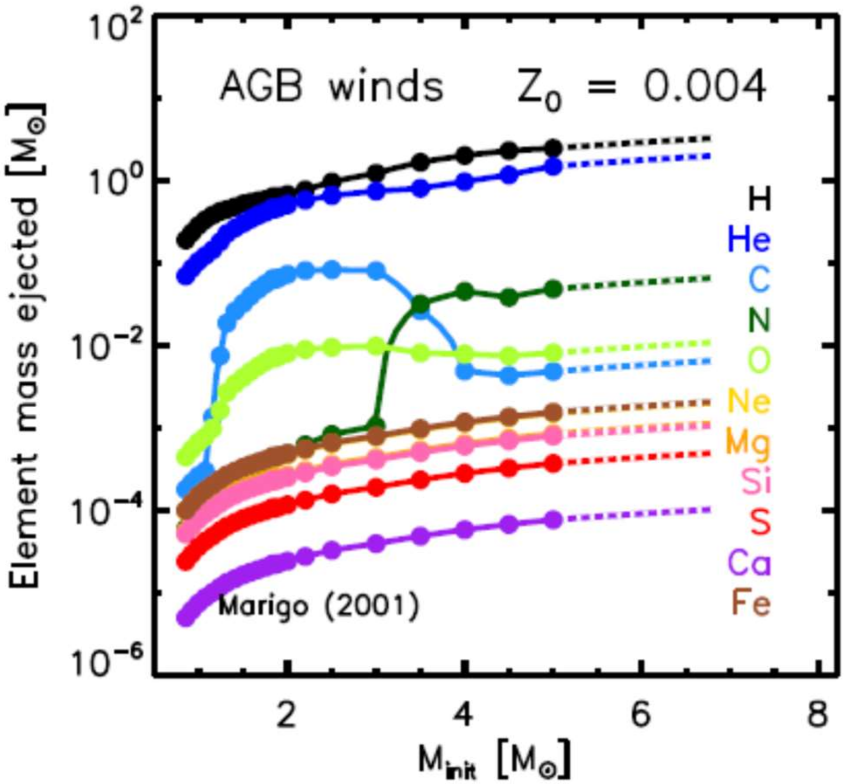
$$e_Z(t) = \int_{M_L}^{M_U} M_Z(M, Z_0)\ \psi(t - \tau_M)\ \phi(M)\ \mathrm{d}M$$

Intermediate-mass stars (0.85 – 7 M_{sun}) eject their outer layers during the thermally-pulsating asymptotic giant branch (AGB) phase.

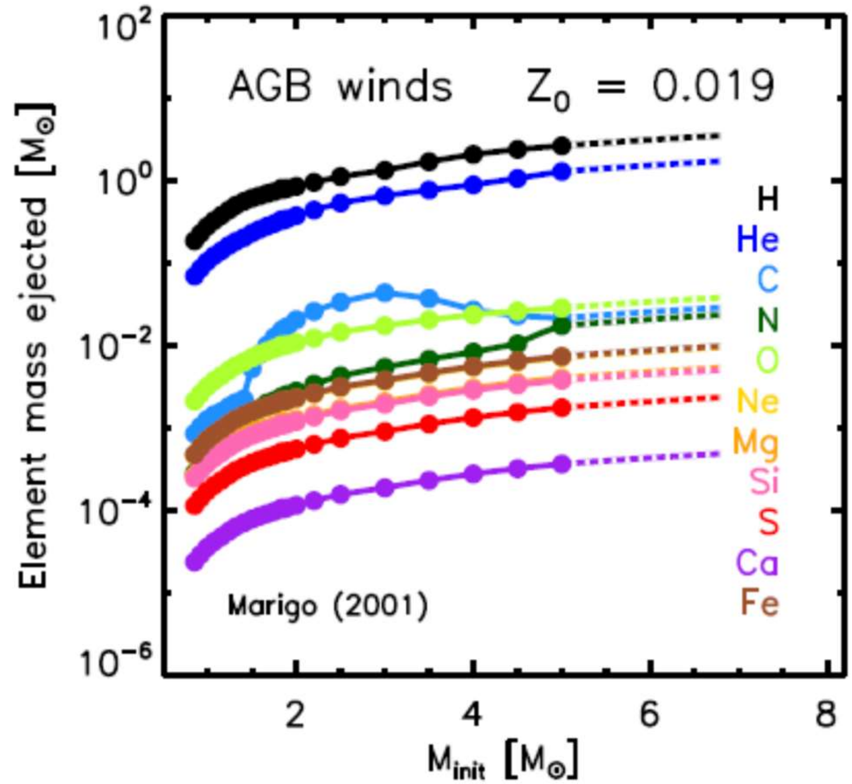
Currently in L-GALAXIES, we use the AGB wind yields of *Marigo 01.*

(We approximate that the winds eject at the end of the stars' lives)

Yates+13



Yates+13



SNe-II

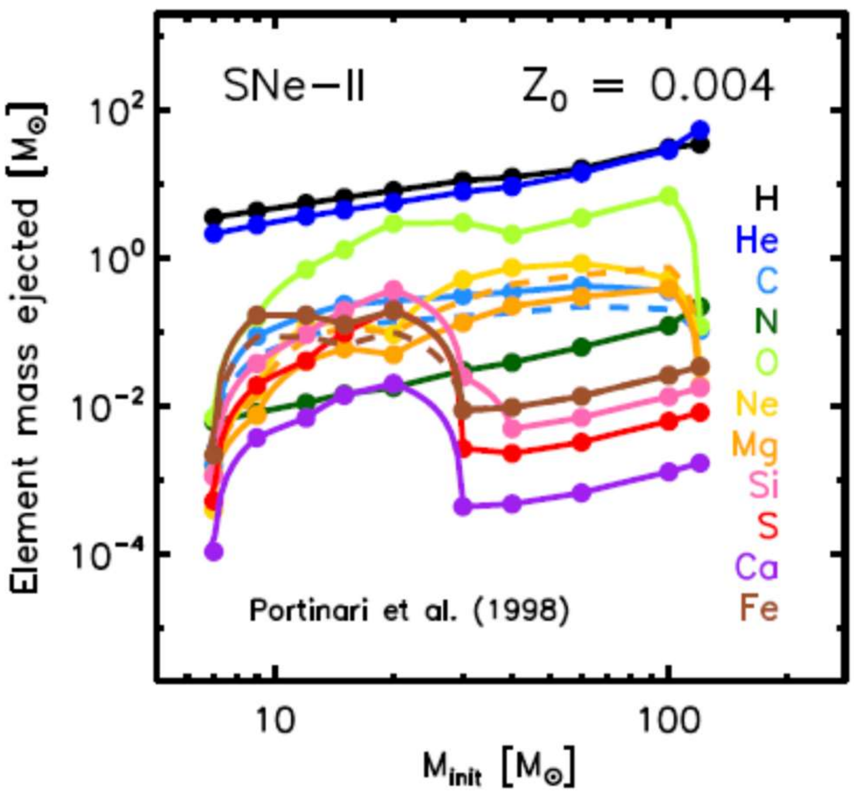
$$e_Z(t) = \int_{M_L}^{M_U} M_Z(M, Z_0)\ \psi(t - \tau_M)\ \phi(M)\ \mathrm{dM}$$

Massive stars (>7 M_{sun}) are assumed to explode mainly as type II core-collapse supernovæ (SN-II). These eject predominantly alpha elements (and H & He).

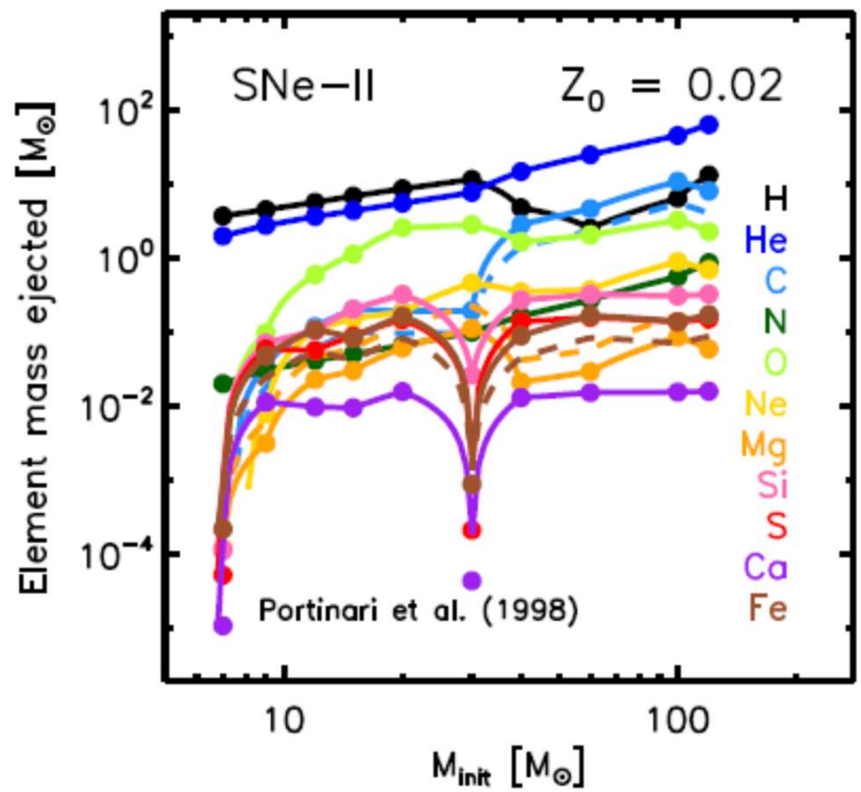
Currently in L-GALAXIES, we consider the SN-II yields of *Portinari+98*.

(Note the strong mass-dependence for the *Portinari+98* yields)

Yates+13

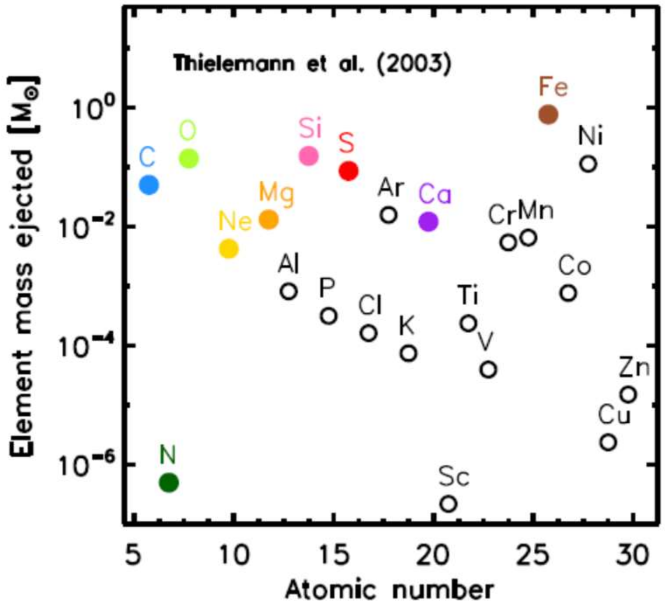


Yates+13



SNe-Ia

$$e_Z(t) = \int_{M_L}^{M_U} M_Z(M, Z_0)\ \psi(t - \tau_M)\ \phi(M)\ dM$$



Yates+13

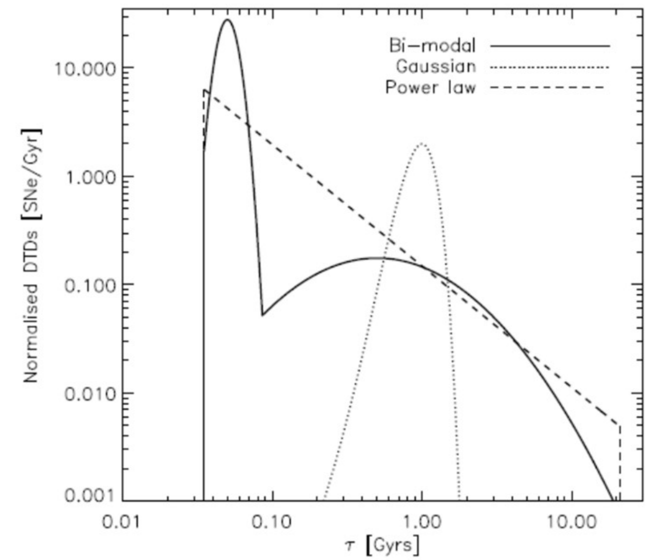
Some binary systems (2.8%) with total mass 3 – 16 M_{sun} (companion star mass 0.85 – 8 M_{sun}) can explode as type Ia supernovæ. These eject mainly Fe.

Currently in L-GALAXIES, we use the SN-Ia yields of Thielemann+03.

We allow some binary systems to blow AGB winds *and* explode as SNe-Ia.

The lifetimes of these binary systems are determined empirically, via a SN-Ia delay-time distribution (DTD).

Currently in L-GALAXIES, we include four different DTDs, with $\tau_{min} = \tau_{8Msun}$ = 35 Myr and $\tau_{max} = \tau_{0.85Msun}$ = 21 Gyr.



Yates+13

The detailed GCE equation

$$
\begin{aligned}
e_Z(t) \;=\; & \int_{0.85M_\odot}^{7M_\odot} M_Z^{\mathrm{AGB}}(M, Z_0)\, \psi(t-\tau_{\mathrm{M}})\, \phi(M)\, \mathrm{dM} && \longleftarrow \text{AGB winds} \\
& + A'\, k \int_{\tau_{8M_\odot}}^{\tau_{0.85M_\odot}} M_Z^{\mathrm{Ia}}\, \psi(t-\tau)\, \mathrm{DTD}(\tau)\, \mathrm{d}\tau && \longleftarrow \text{SNe-Ia} \\
& + (1-A) \int_{7M_\odot}^{16M_\odot} M_Z^{\mathrm{II}}(M, Z_0)\, \psi(t-\tau_{\mathrm{M}})\, \phi(M)\, \mathrm{dM} && \longleftarrow \text{SNe-II} \\
& + \int_{16M_\odot}^{M_{\max}} M_Z^{\mathrm{II}}(M, Z_0)\, \psi(t-\tau_{\mathrm{M}})\, \phi(M)\, \mathrm{dM}\;. && \longleftarrow \text{SNe-II}
\end{aligned}
$$

A = 0.028 = Fraction of stellar systems in range 3 – 16 M_{sun} that are SN-Ia progenitor binaries.

f_{3-16} = 0.0385 = Fraction of *all* stellar systems that are in range 3 – 16 M_{sun}.

$A' = A \cdot f_{3-16}$ = 0.0011 = Fraction of *all* stellar systems that are SN-Ia progenitor binaries.

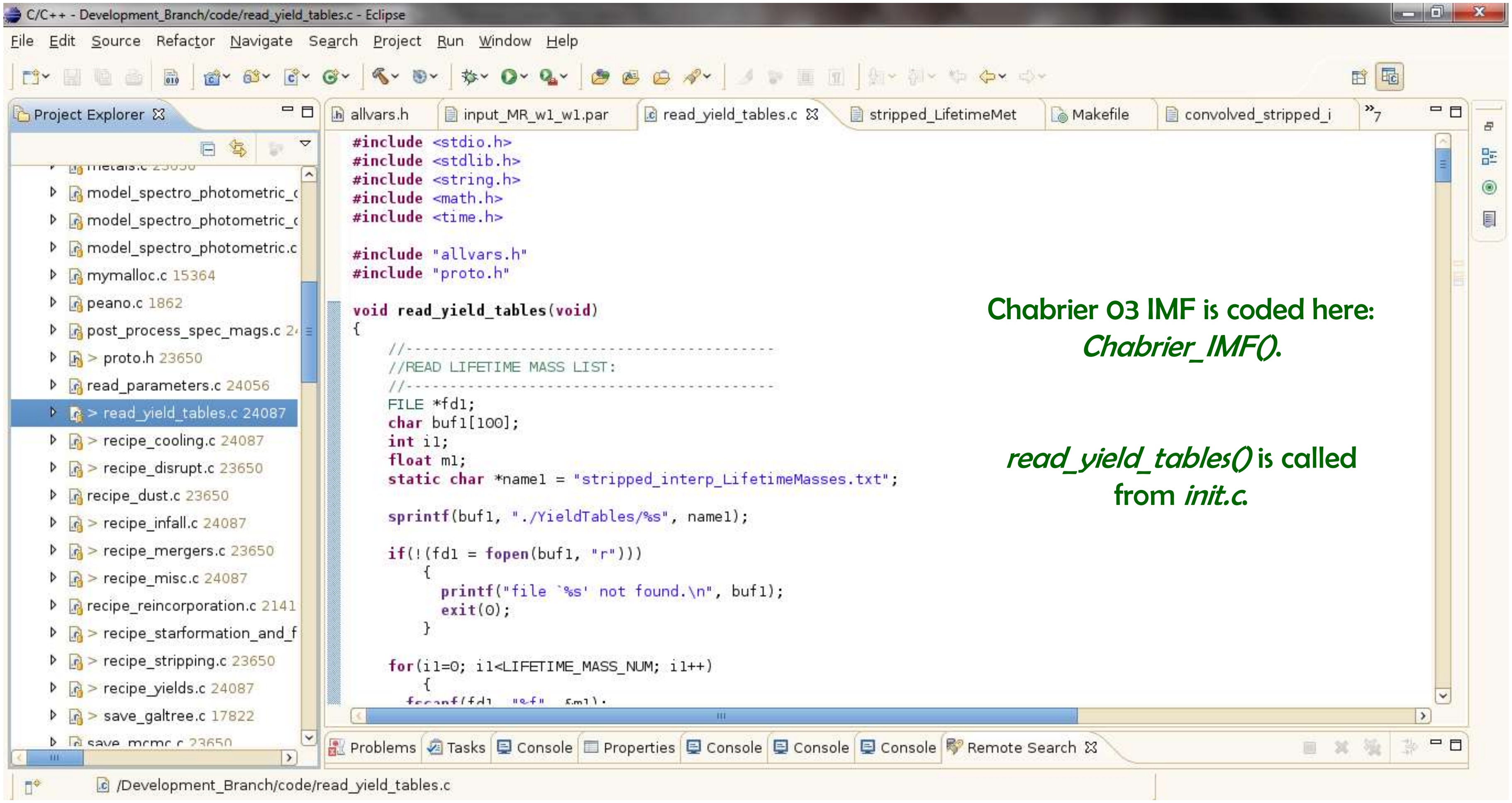
$k = \int_{M_{\min}}^{M_{\max}} \phi(M)\, \mathrm{d}M$ = 1.4772 = Number of stellar objects in a 1 M_{sun} SSP.

These parameters are all dependent on the IMF's shape & mass range.

In L-GALAXIES, A is tuned to the [Fe/H] distribution in the Milky Way stellar disc (Yates+13).

GCE coding

yields_read_tables.c



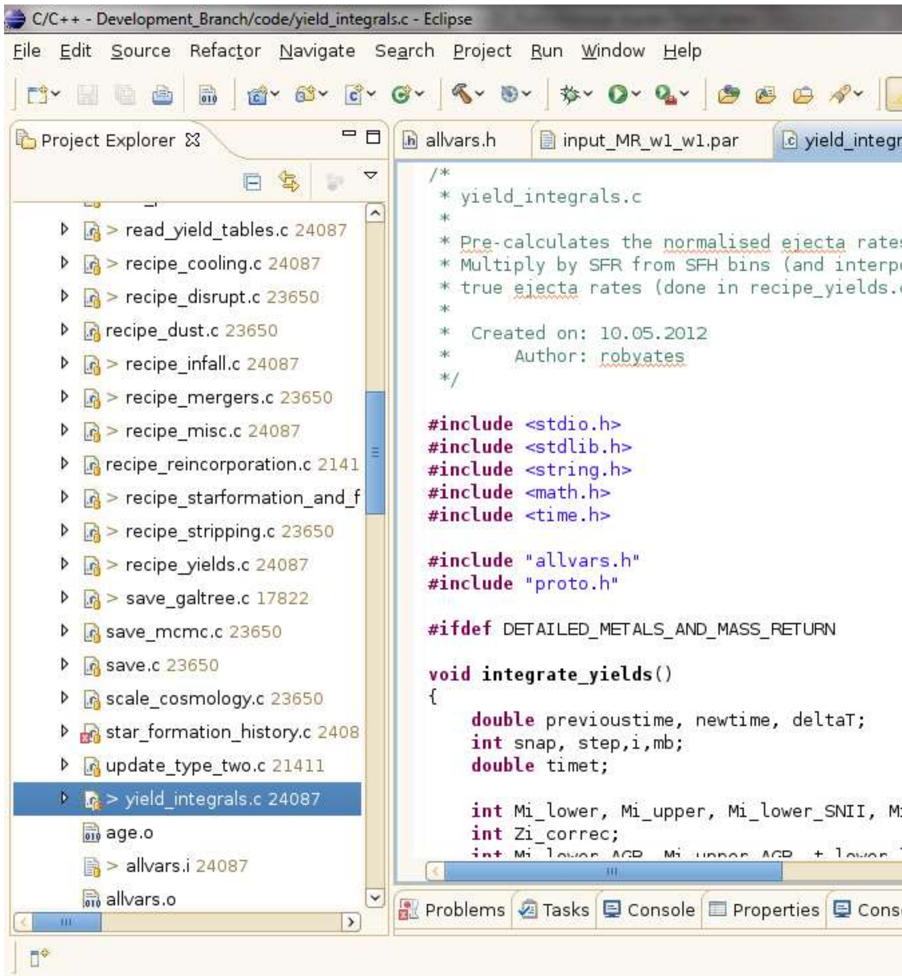
Chabrier 03 IMF is coded here: *Chabrier_IMF()*.

read_yield_tables() is called from *init.c*.

Reads yield tables and convolves them with the IMF.

Creates 2- or 3-dimensional arrays. e.g. *SNIITotalMetals[SNII_Z_NUM][SNII_MASS_NUM]*

yields_integrals.c



(Pre-)integrates the GCE equation, without model-dependent variables.

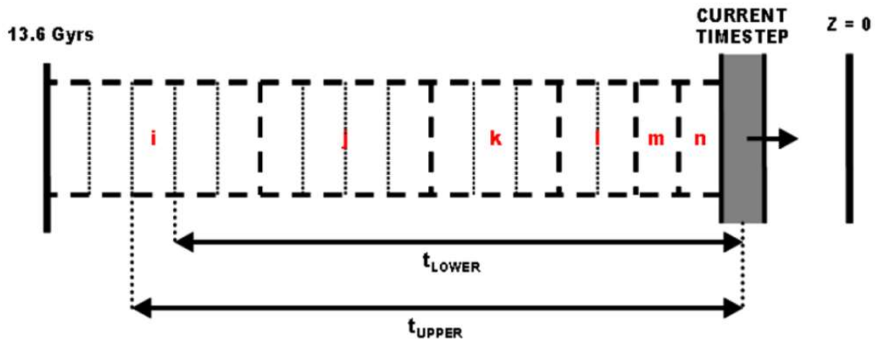
$$e_Z(t) = \psi(t-\tau)\left[\int_{M_L}^{M_U} M_Z(M, Z_0)\cdot\phi(M)\,\mathrm{d}M\right]$$

The 'normalised' ejecta rate is calculated for *N* 'mini bins' in every SFH bin of every timestep, for 6 metallicities, and stored in 3D arrays (look-up tables).

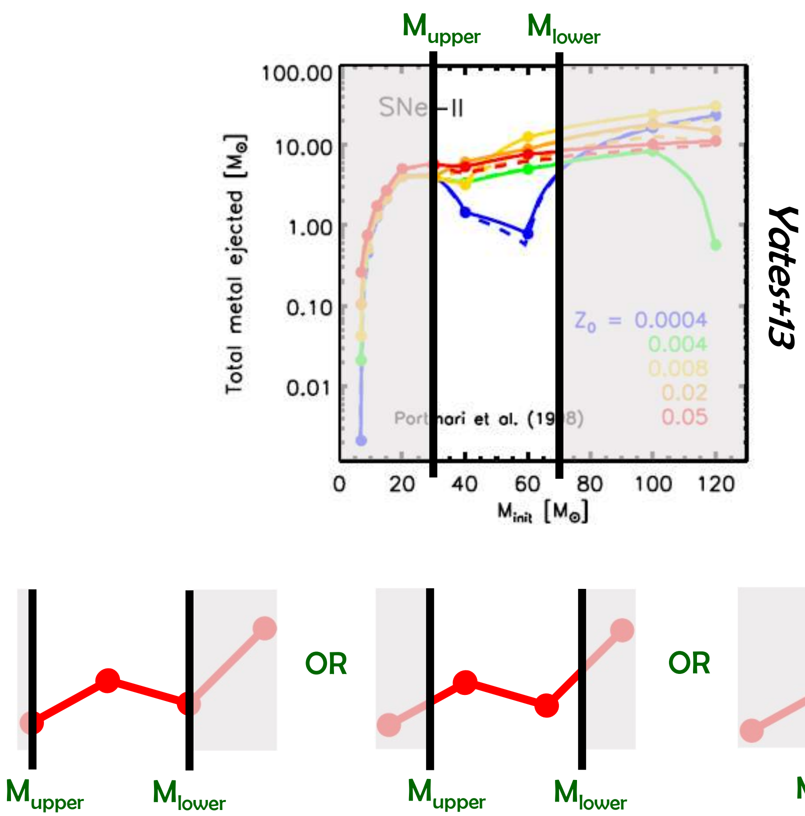
{ //Snapshots
{ //Timesteps
{ //SFH bins
{ //Mini bins (in-code sub-divisions of the SFH bins)
{ //Metallicities
e.g. NormSNIIMetalEjecRate[step][SFHbin][Z]
}
}
}
}
}

init_integrated_yields() is called from *init.c*.

yields_integrals.c



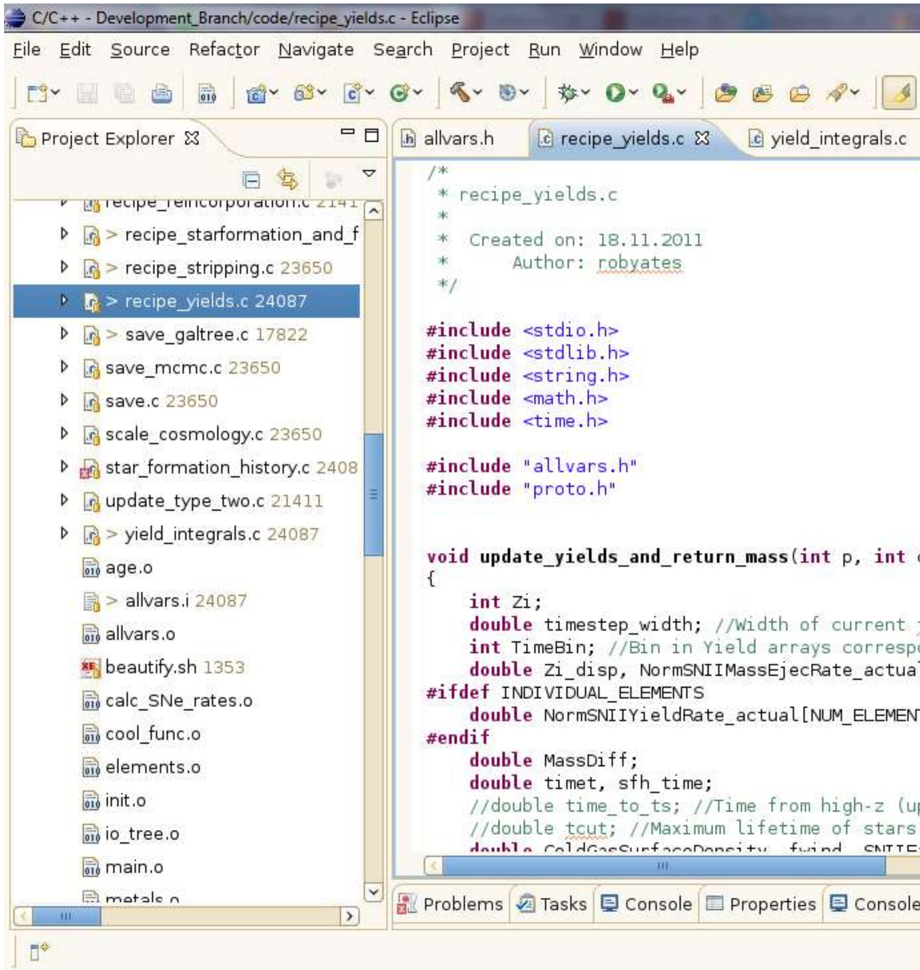
1) A maximum (M_{lower}) and minimum (M_{upper}) mass of stars to die in the current timestep from each mini bin is calculated.



2) The total/metal/element mass ejected is integrated over numerically between M_{upper} and M_{lower}.

3) The many *if* statements in *yields_integrals.c* account for different limits when integrating across the finite-resolution yield tables. e.g. M_{upper} and M_{lower} will likely be *between* two masses in the yield table grid – sometimes even both between the *same* two masses.

model_yields.c



Calculates actual total/metal/element mass ejected at every timestep for every galaxy.

Interpolates in-code between metallicities in the look-up tables using the true Z_0, and multiplies-in the true SFR.

$$M_Z = y_Z(M, Z_0) + Z_0 \cdot (M - M_r)$$

$$e_Z(t) = \psi(t - \tau) \left[\int_{M_L}^{M_U} M_Z(M, Z_0) \cdot \phi(M) \, \mathrm{d}M \right]$$

Material ejected into the *ColdGas* or *HotGas*, from the stellar disc, bulge, and halo stars, according to the chosen GCE set-up

update_yields_and_return_mass() is called from *main.c*, after star formation, merging, and black hole growth.

GCE *makefile* options

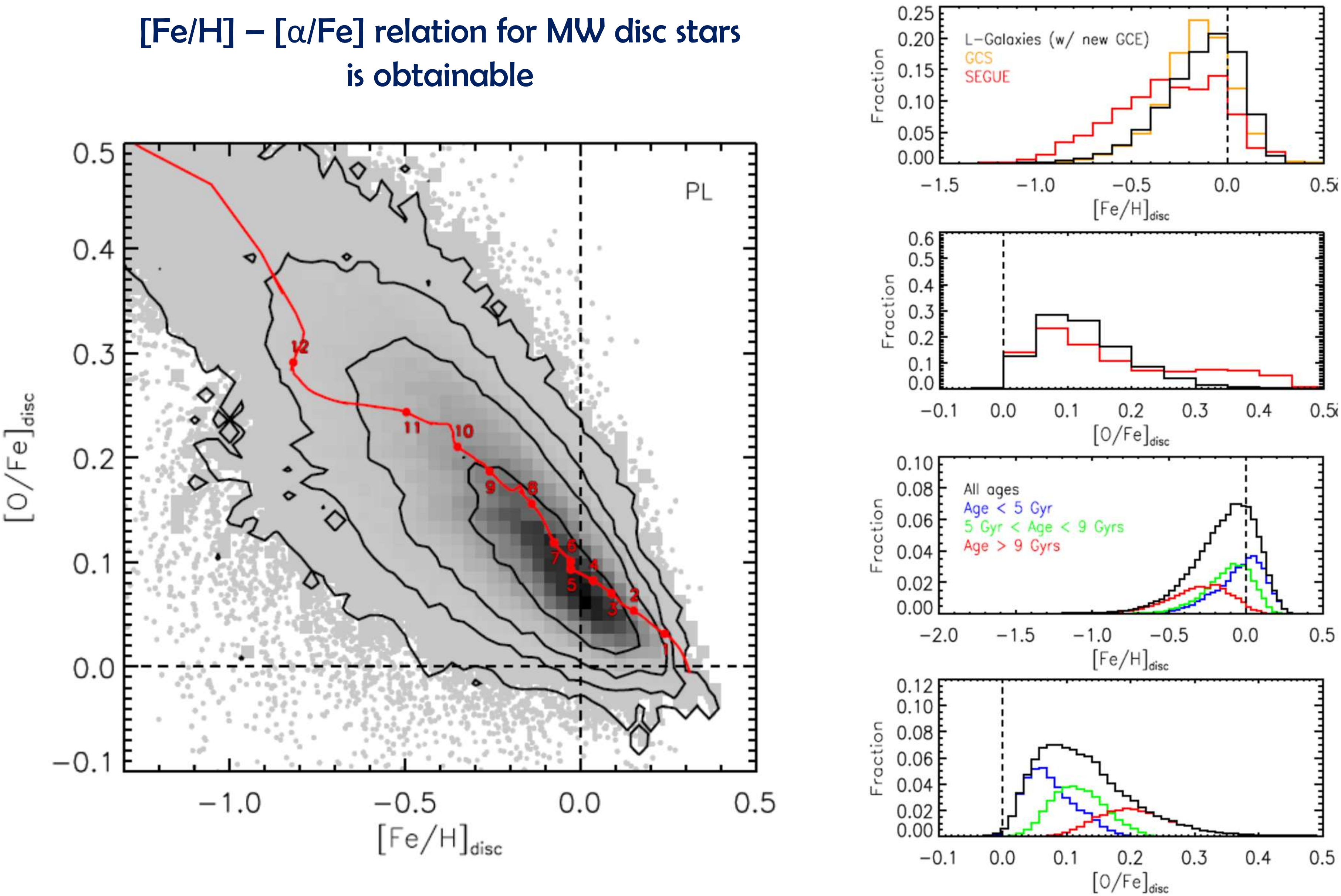
In *My_makefile_options* are the following GCE switches:

- OPT += -DFEEDBACK_COUPLED_WITH_MASS_RETURN: Switches on coupling between SN feedback and the chemical enrichment model.
- OPT += -DINDIVIDUAL_ELEMENTS: Switches on tracking of all 11 individual chemical elements.
- OPT += -DMAINELEMENTS: Switches on tracking of only 5 key chemical elements.
- OPT += -DMETALRICHWIND: Switches on galactic winds with a metallicity independent of that in the ISM.
- OPT += -DSNIATOHOT: Switches on direct enrichment of the CGM/ICM by SNe-Ia in the stellar disc.
- OPT += -DPORTINARI and -DCHIEFFI: Switch on the SN-II stellar yields of Portinari et al. (1998) or Chieffi & Limongi (2004).
- OPT += -DBIMODALDTD and –DGAUSSIANDTD and –DPOWERLAWDTD and –DRUITERDTD: Switch on one of the possible SN-Ia DTDs.
- OPT += -DINSTANTANEOUS_RECYCLE: Switches on instant return of metals at time of star formation, rather than at time stars die.

Past & future GCE projects

The Milky Way

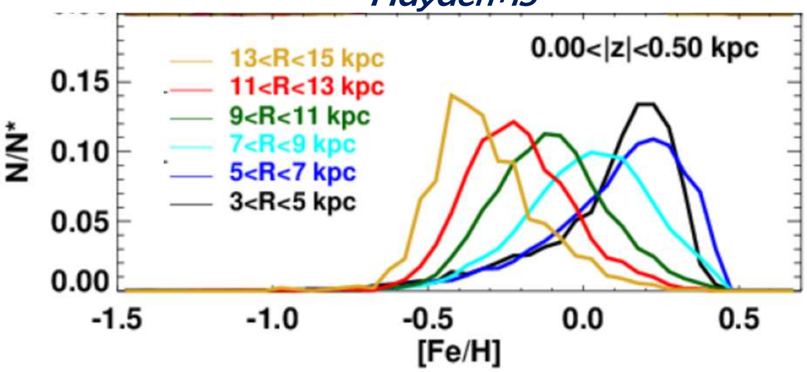
[Fe/H] – [α/Fe] relation for MW disc stars is obtainable



The Milky Way

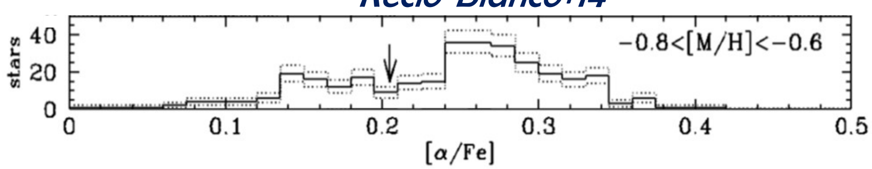
Chemical variations with radius and height

Hayden+15



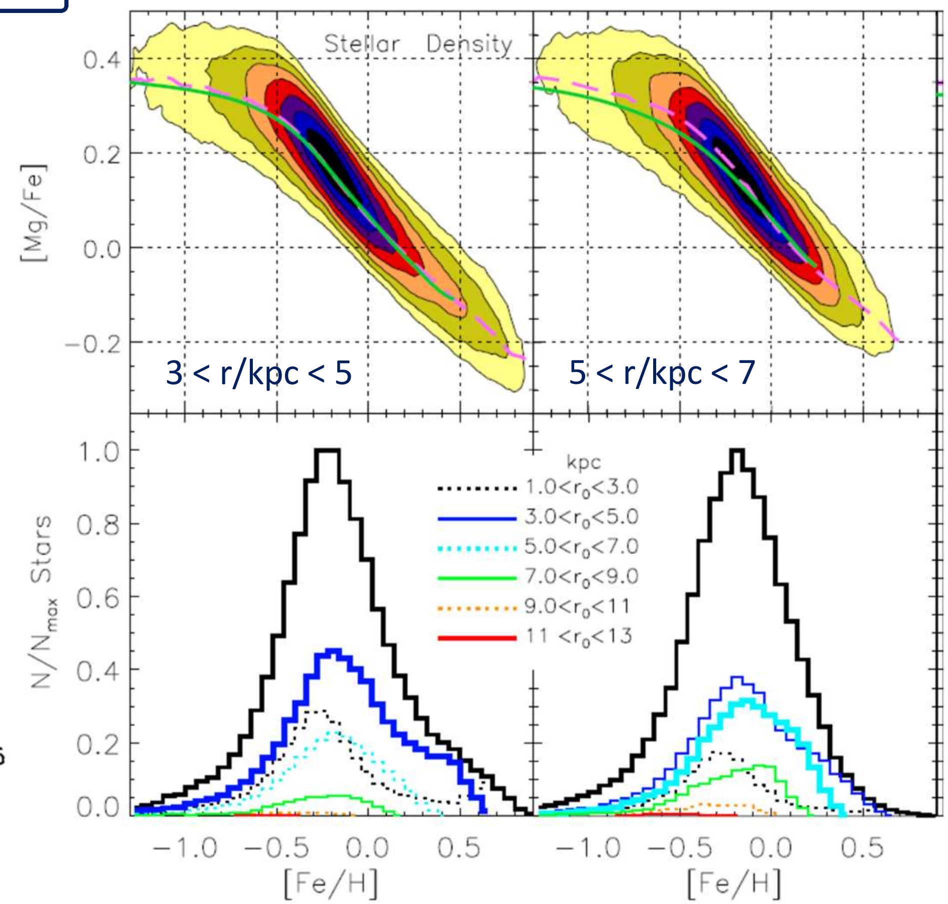
(Observations of ~70,000 red giants from the SDSS-APOGEE survey)

Recio-Blanco+14



(Observations of ~1,000 FGK-type stars from the *Gaia*-ESO survey)

Minchev+14

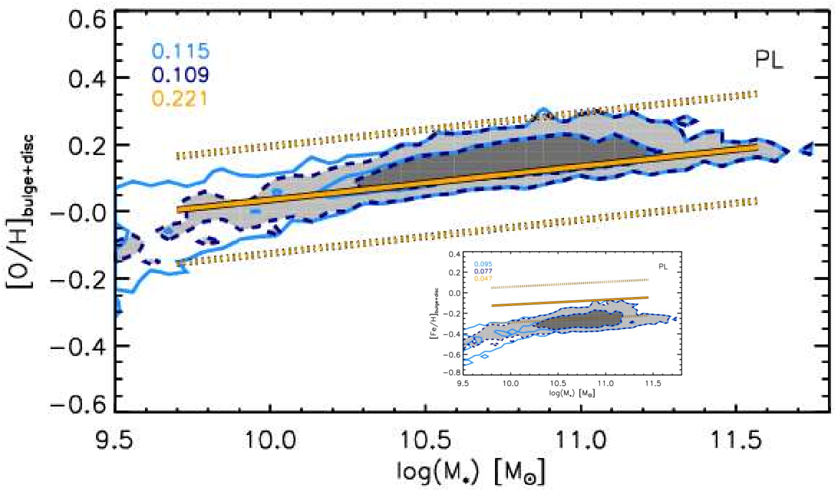


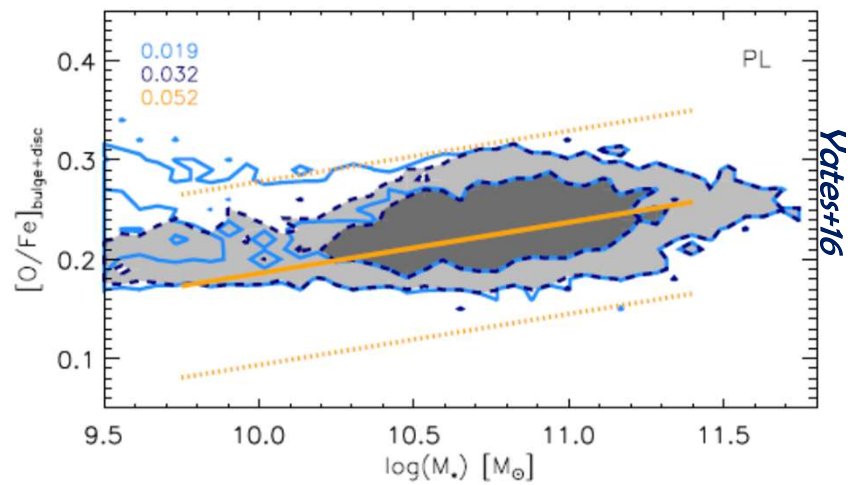
Is there a chemically-distinct thick disc? (e.g. Bovy+12b; Schönrich & Binney 09)

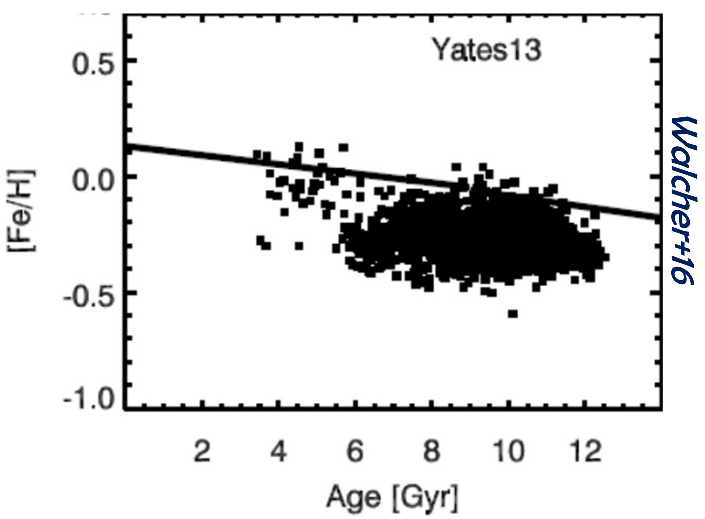
The roles of metal mixing, radial migration, gas flows, mass-loaded outflows, etc, should be assessed

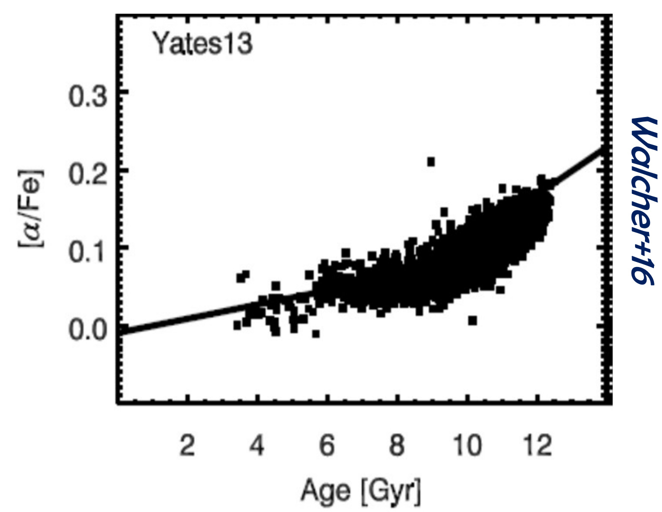
Early-type galaxies

Relations between key stellar population properties are simultaneously matched age, mass, [Fe/H] and [α/Fe]



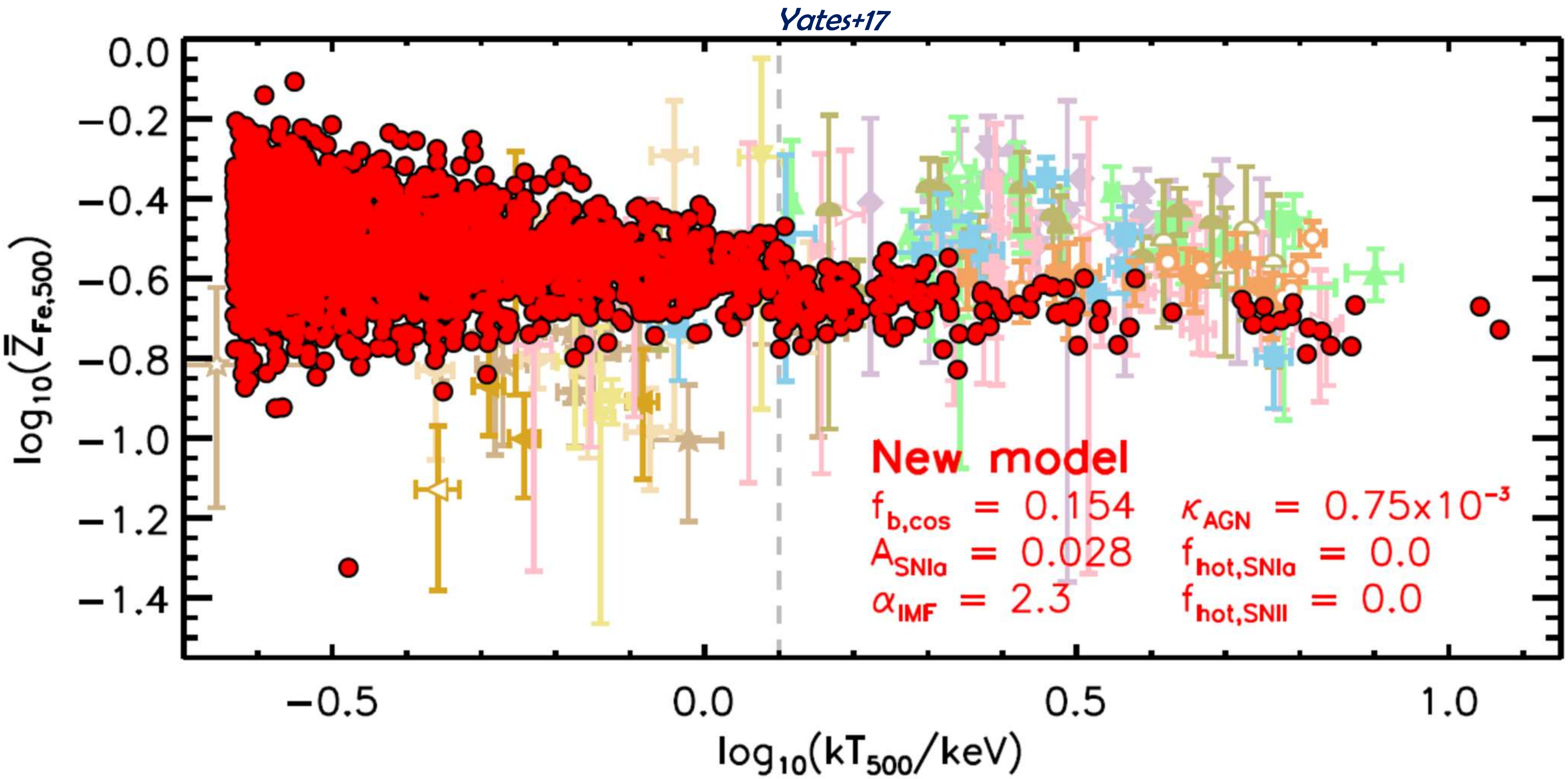






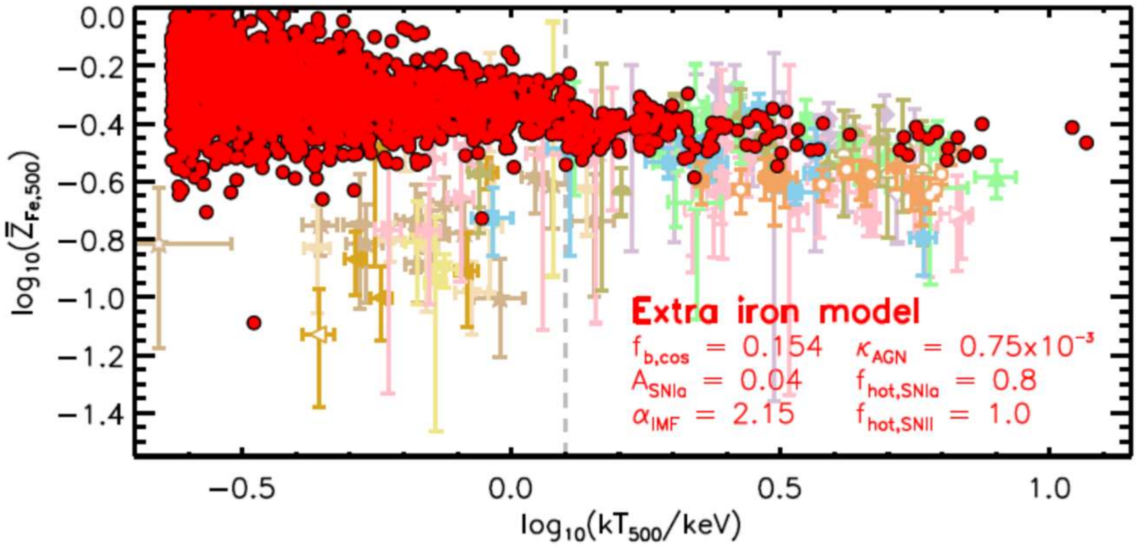
Intracluster medium

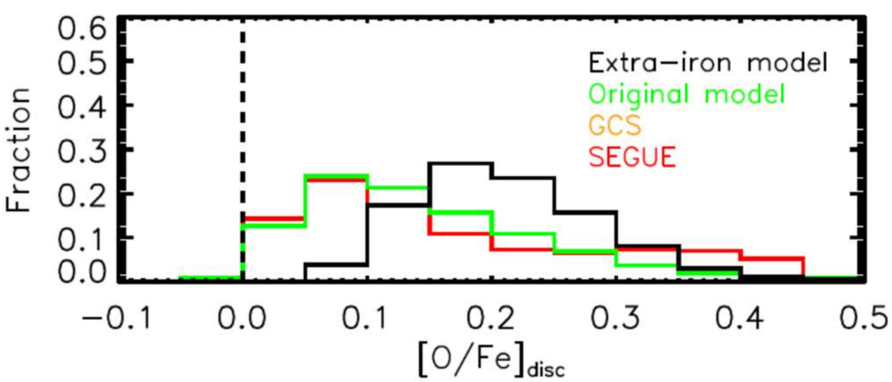
A highly-enriched ICM is now obtainable with improved infall/FB modelling and fairer comparisons to observations

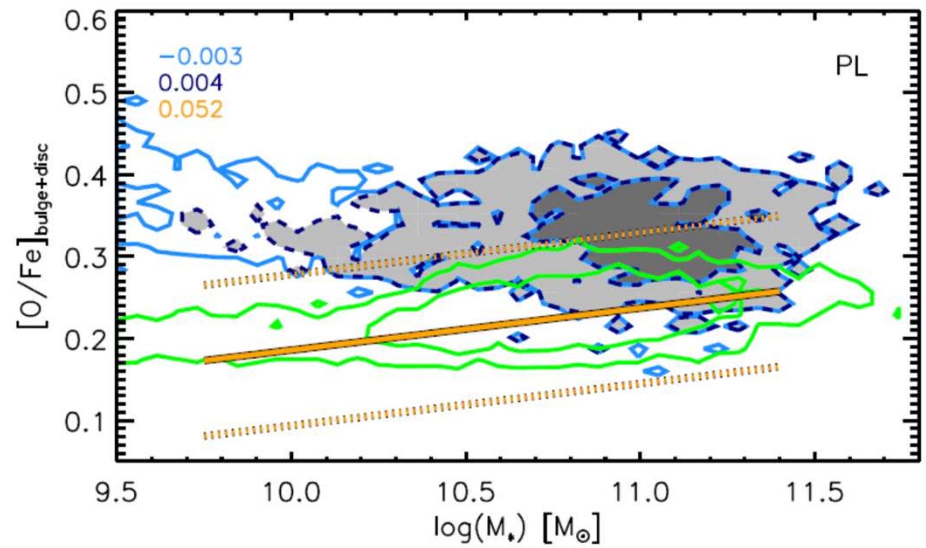


Intracluster medium

But we need to be careful not to destroy the consistency with other types of systems…





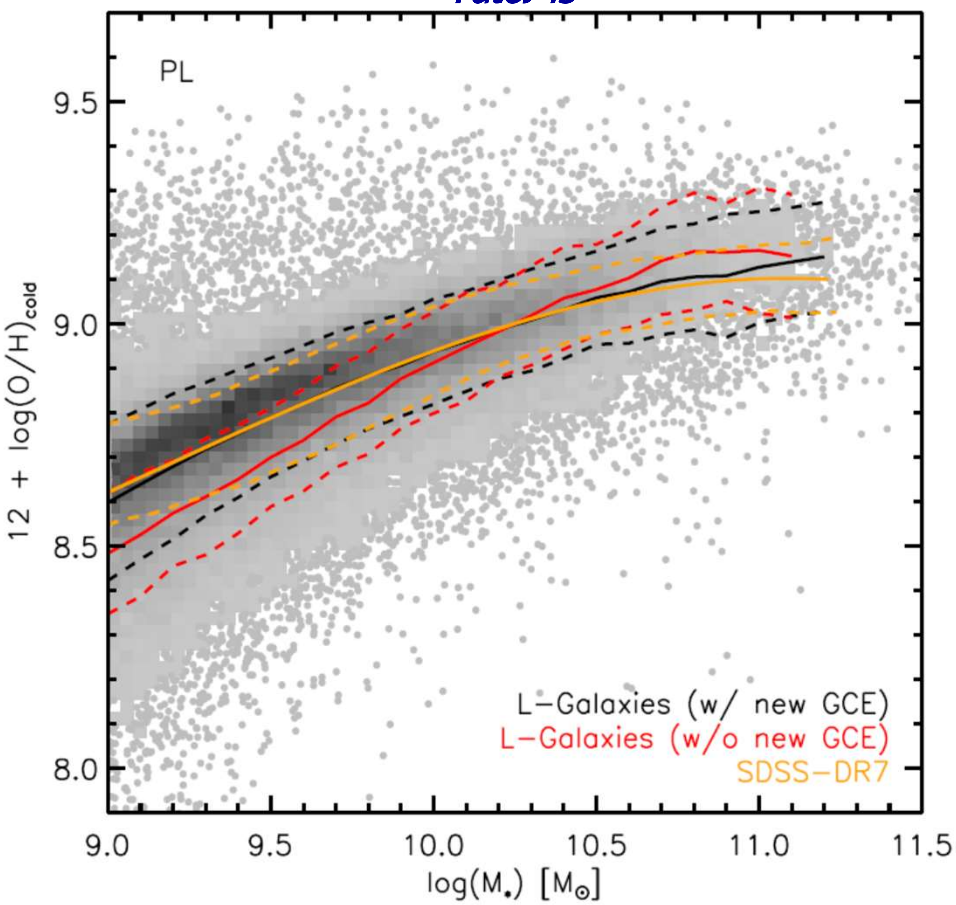


$M_\star$ - Z_g relation

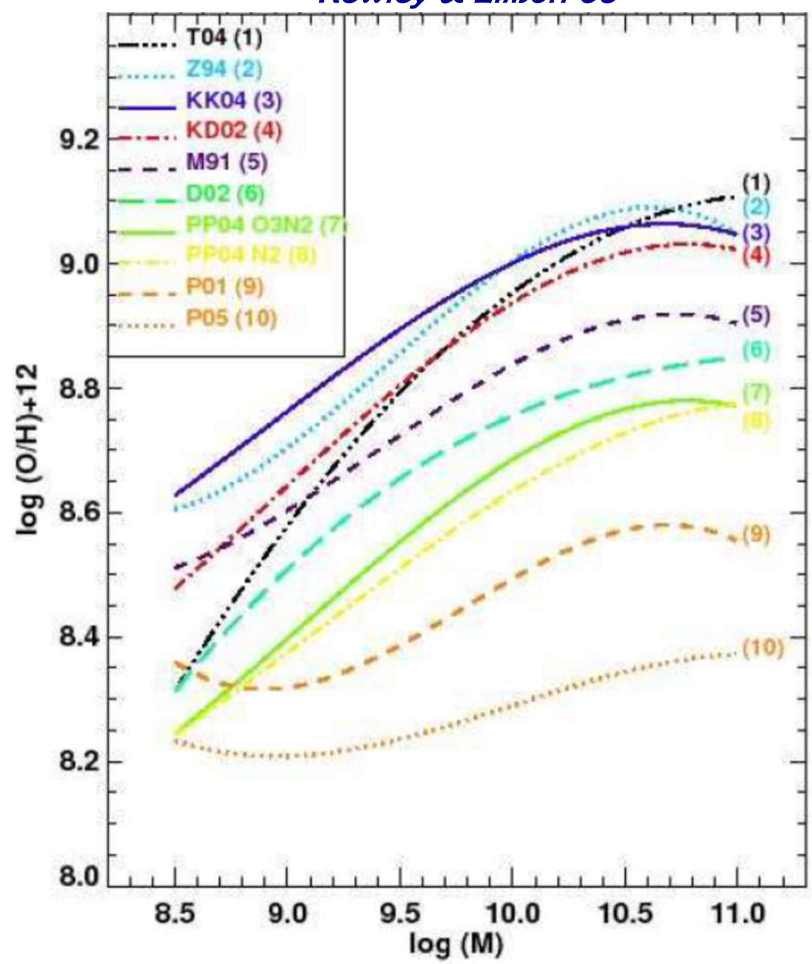
Previously a good match to the z=0 MZ_gR

But what is the true MZ_gR?...

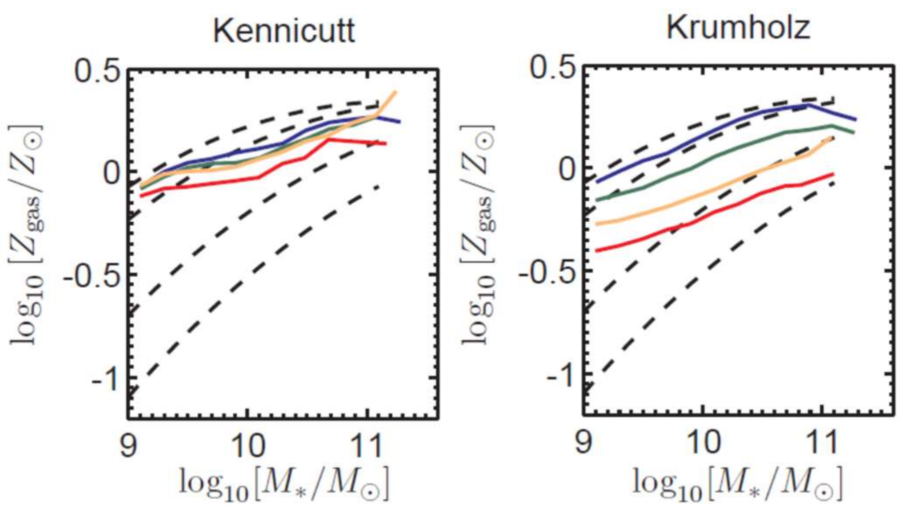
Yates+13



Kewley & Ellison 08

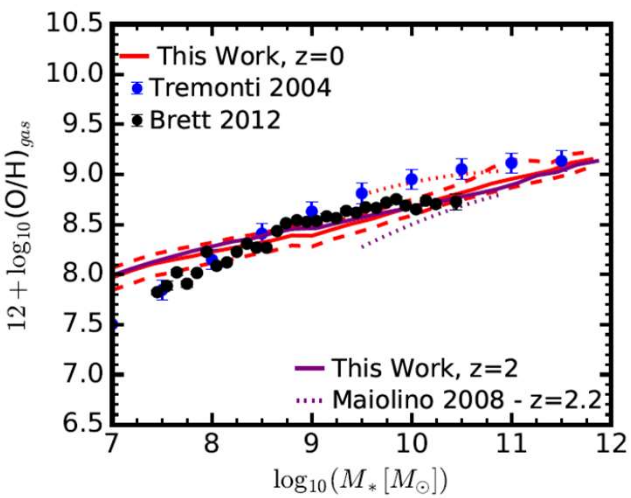


$M_\star$ - Z_g relation

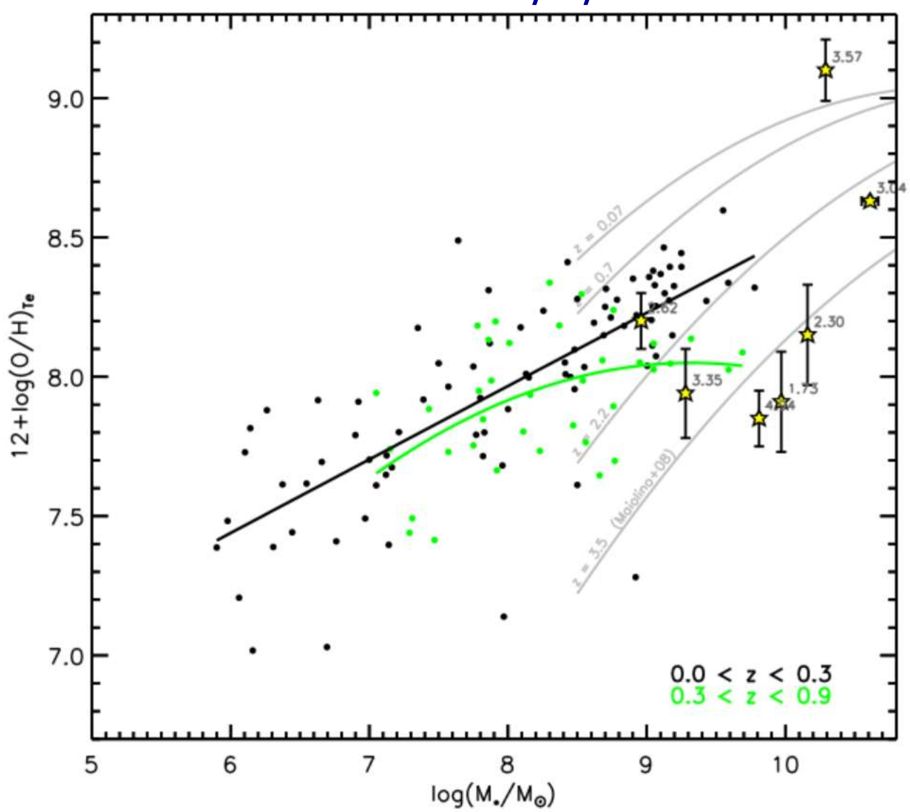


Fu+12

A large MZ_gR evolution is difficult for L-GALAXIES

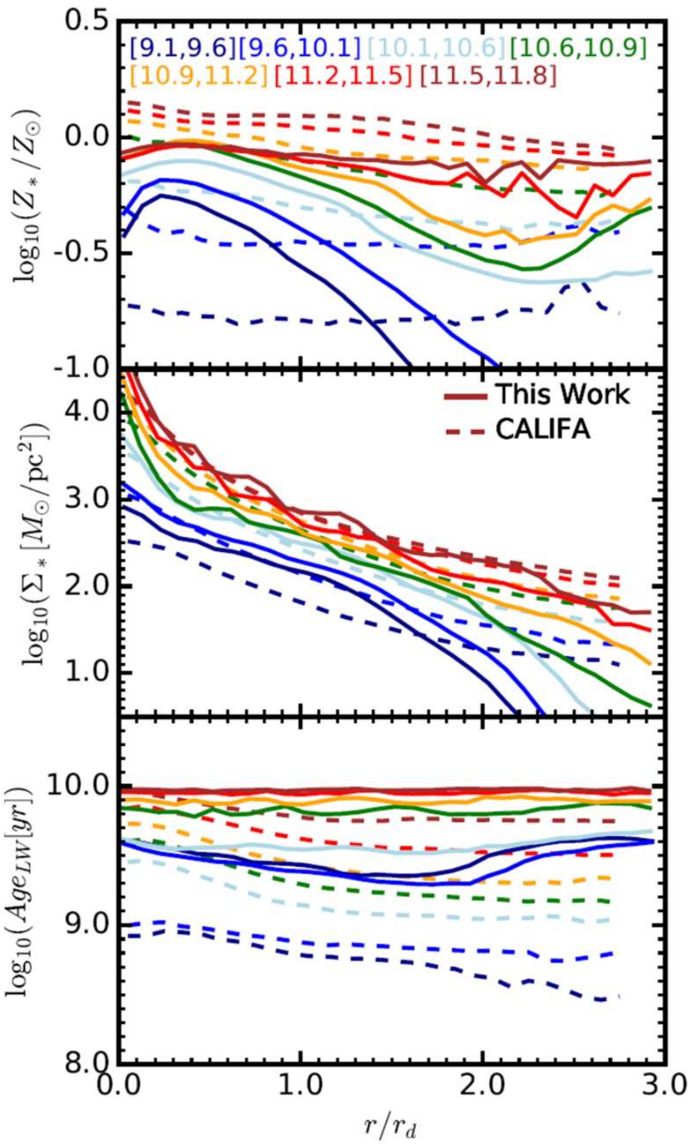


Yates in prep.

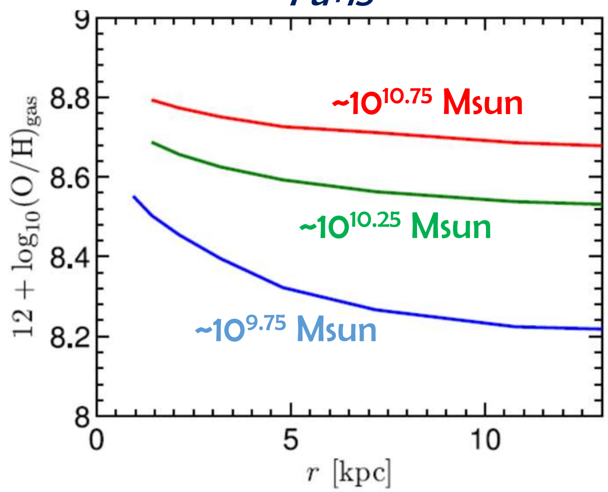


But how large is the true MZ_gR evolution anyway?...

Metallicity gradients



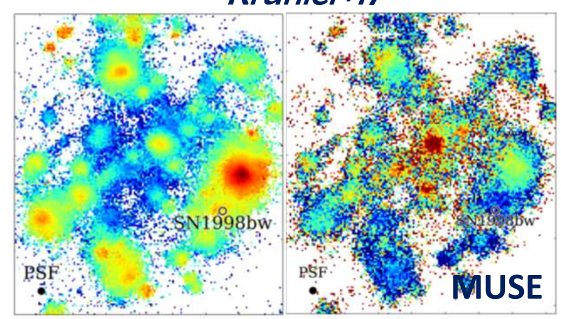
Fu+13



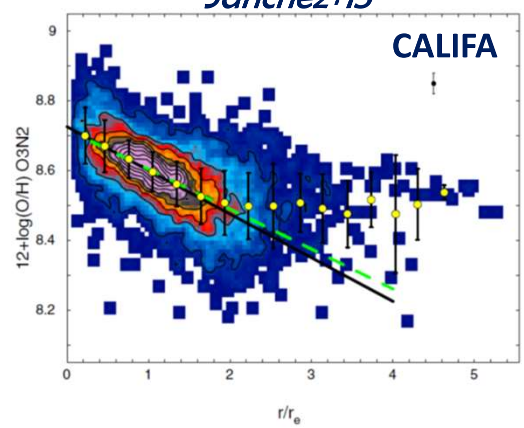
Metallicity gradients in the gas & stars are the next big step

But can we trust the latest observations?...

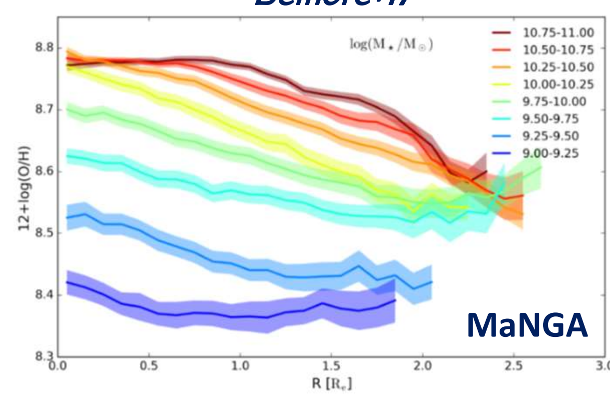
Krühler+17



Sánchez+15



Belfiore+17

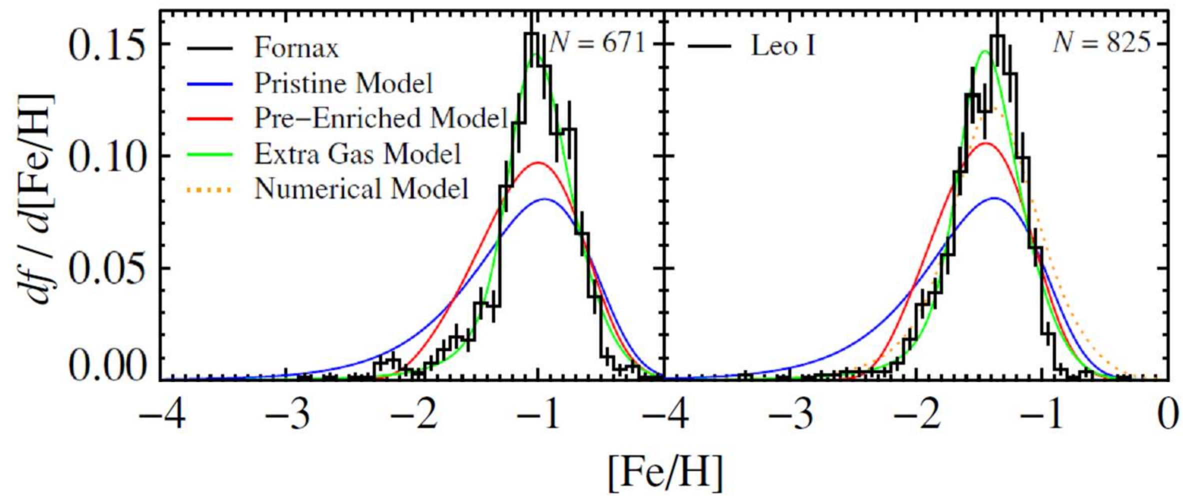


Dwarfs & bulges

Metallicity distributions in Local Group dwarfs:

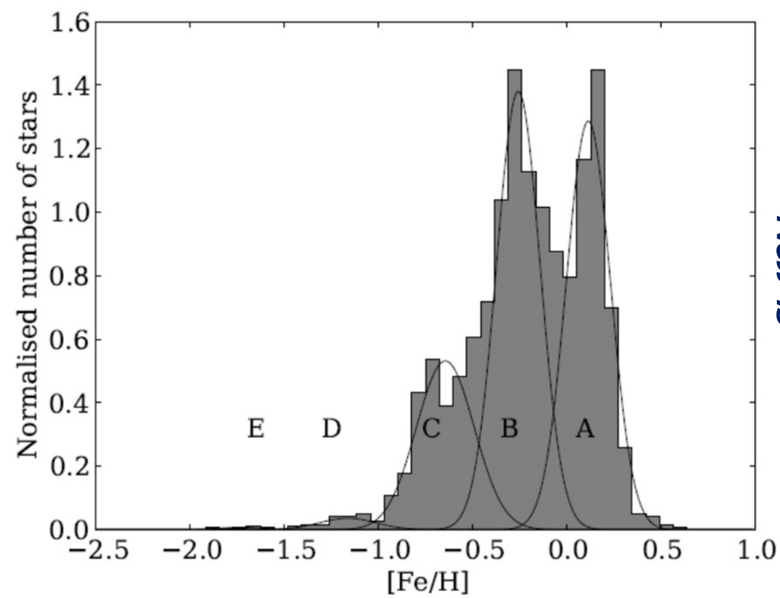
(use ELUCID or *Caterpiller* haloes?)

Kirby+11a



Metallicity distributions in the MW bulge:

(multiple formation epochs and/or mechanisms?)



Ness+13