Advanced Coding Module I

Galactic Chemical Evolution (GCE)

Outline

The basics

- Metals' effect on galaxy evolution
- Simple GCE models

The analytics

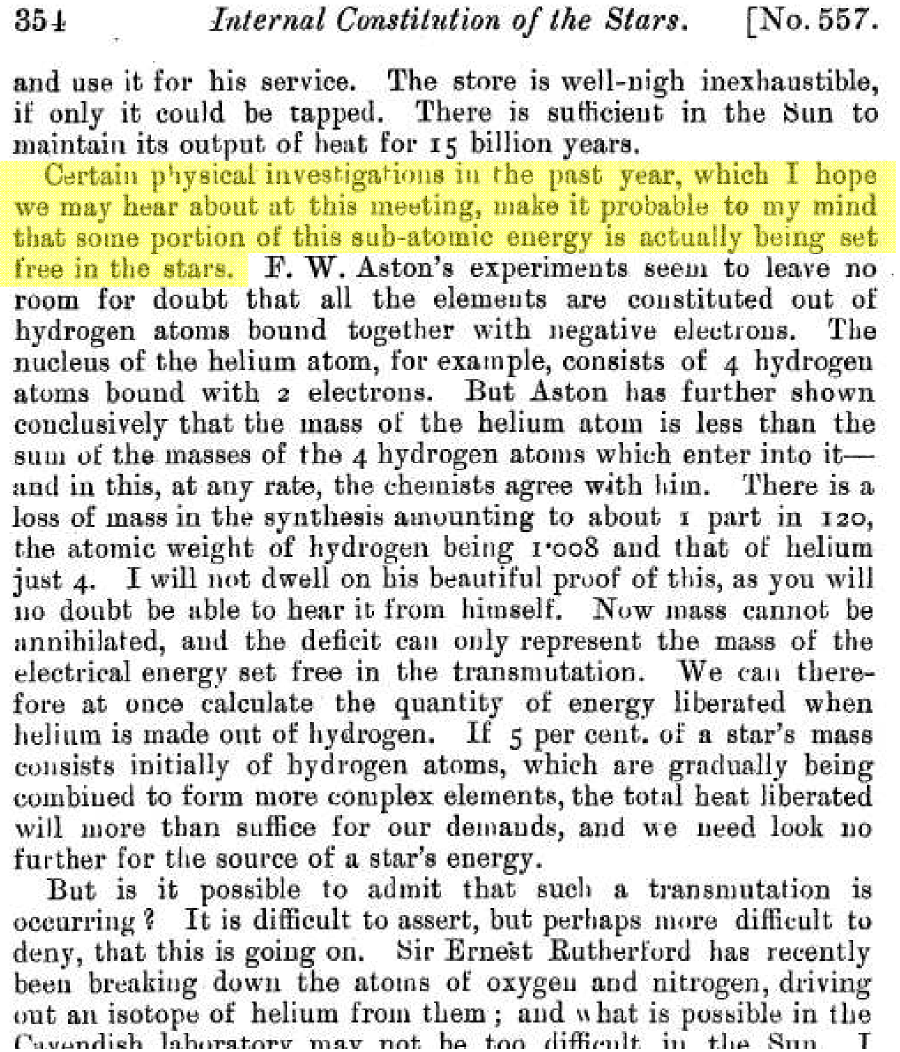
- The GCE equation
- IMFs, DTDs, and stellar yields

The coding

- Input and pre-processing
- In-code treatment of GCE
- How to get plottable output

The basics

Origins



354 *Internal Constitution of the Stars.* [No. 557.

and use it for his service. The store is well-nigh inexhaustible, if only it could be tapped. There is sufficient in the Sun to maintain its output of heat for 15 billion years.

Certain physical investigations in the past year, which I hope we may hear about at this meeting, make it probable to my mind that some portion of this sub-atomic energy is actually being set free in the stars. F. W. Aston's experiments seem to leave no room for doubt that all the elements are constituted out of hydrogen atoms bound together with negative electrons. The nucleus of the helium atom, for example, consists of 4 hydrogen atoms bound with 2 electrons. But Aston has further shown conclusively that the mass of the helium atom is less than the sum of the masses of the 4 hydrogen atoms which enter into it—and in this, at any rate, the chemists agree with him. There is a loss of mass in the synthesis amounting to about 1 part in 120, the atomic weight of hydrogen being 1·008 and that of helium just 4. I will not dwell on his beautiful proof of this, as you will no doubt be able to hear it from himself. Now mass cannot be annihilated, and the deficit can only represent the mass of the electrical energy set free in the transmutation. We can therefore at once calculate the quantity of energy liberated when helium is made out of hydrogen. If 5 per cent. of a star's mass consists initially of hydrogen atoms, which are gradually being combined to form more complex elements, the total heat liberated will more than suffice for our demands, and we need look no further for the source of a star's energy.

But is it possible to admit that such a transmutation is occurring? It is difficult to assert, but perhaps more difficult to deny, that this is going on. Sir Ernest Rutherford has recently been breaking down the atoms of oxygen and nitrogen, driving out an isotope of helium from them; and what is possible in the Cavendish laboratory may not be too difficult in the Sun. I

Eddington 1920

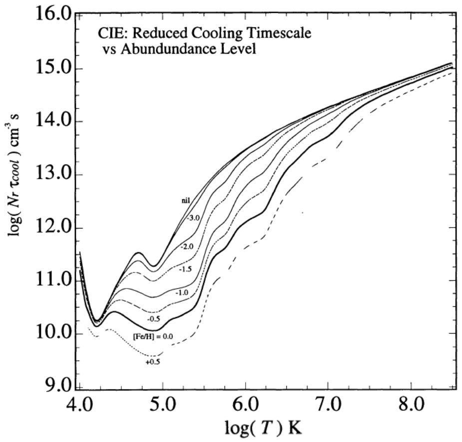
Heavy elements (metals) are, of course, synthesised in stars and ejected via supernovae and stellar winds.

Our job is to model the distribution of these elements throughout the Universe (i.e. among stars, ISM, CGM, ICM, IGM,...)

Metals & galaxy evolution

Metals affect many key processes…

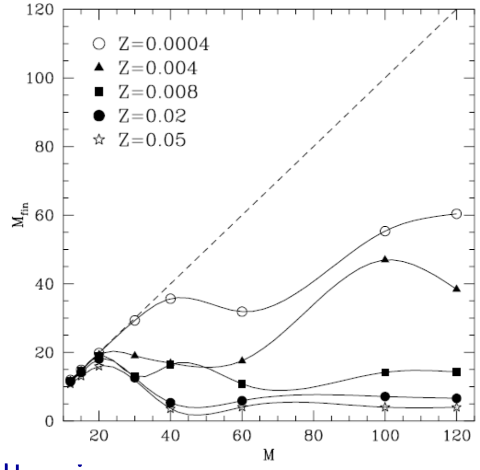
Gas cooling



Sutherland & Dopita 93

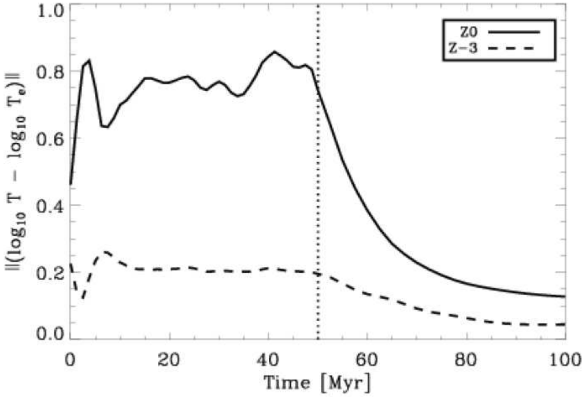
Stellar evolution

Portinari +98



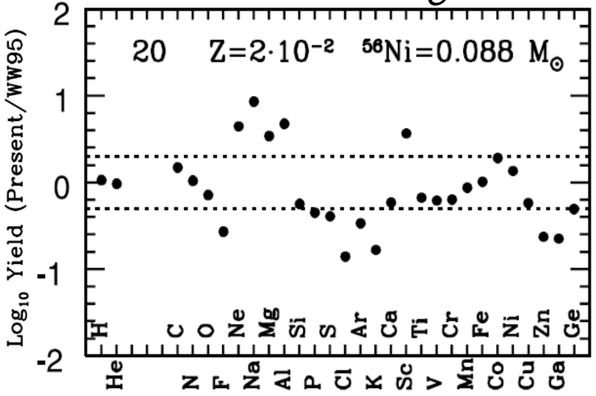
Star formation

Walch +11



Nucleosynthesis

Chieffi & Limongi 04

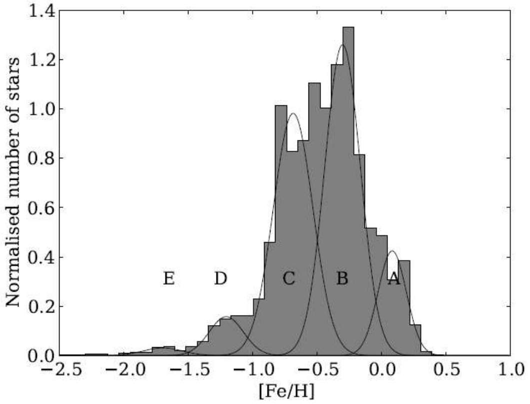


Metals & galaxy evolution

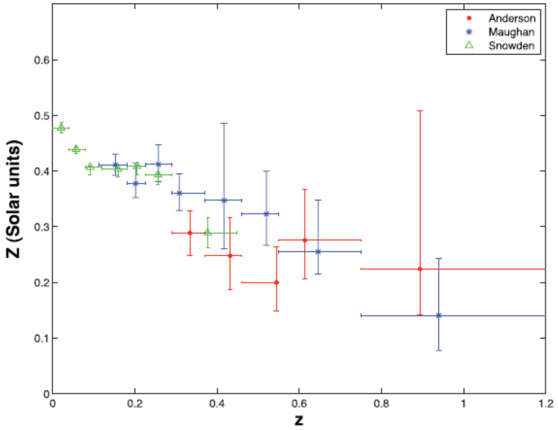
...and provide a record of how galaxies form.

Bulge growth

Ness +13

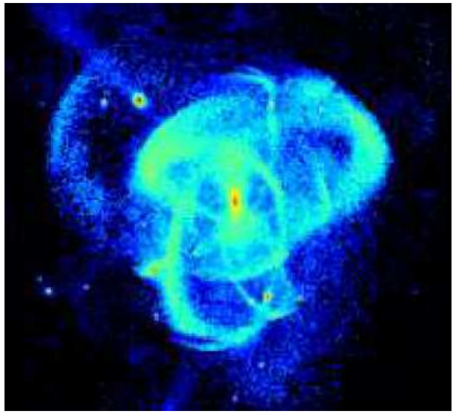


Cluster assembly



Anderson +09

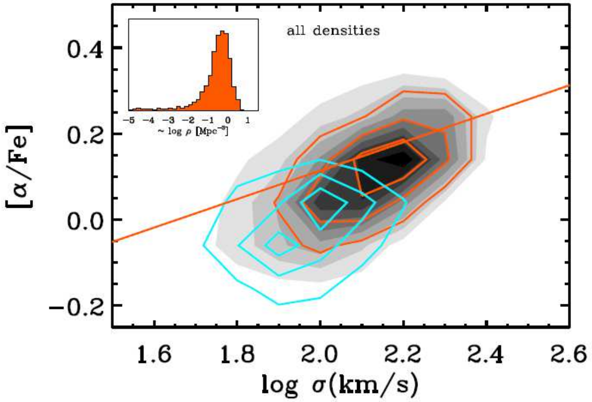
Stellar halo formation



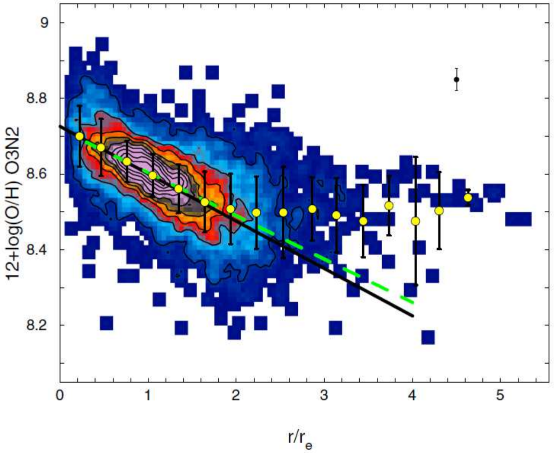
Cooper +10

Downsizing

Thomas +10



Inside-out discs

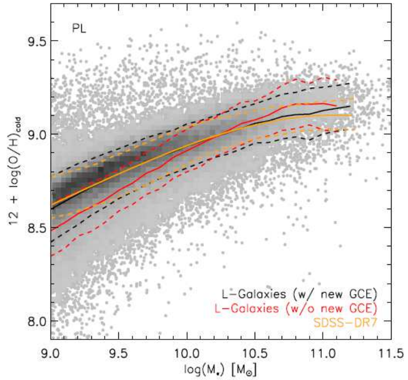


Sánchez +14

GCE in L-GALAXIES

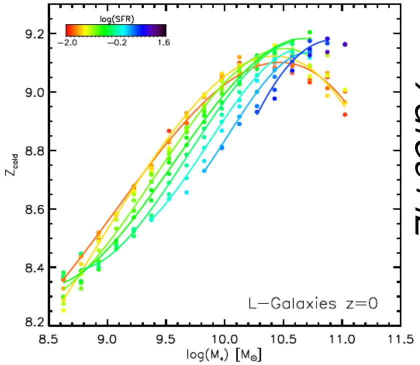
The sophisticated GCE model in L-GALAXIES can reproduce...

Low-redshift MZR



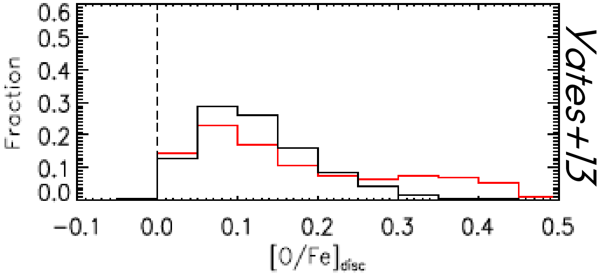
Yates+13

The FMR



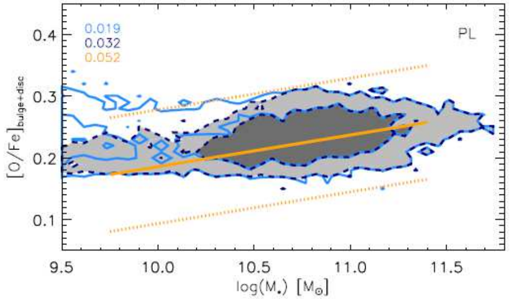
Yates+12

Milky Way [α/Fe] distribution



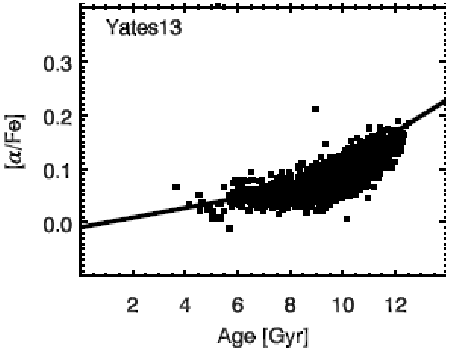
Yates+13

M*– [α/Fe] relation for ellipticals



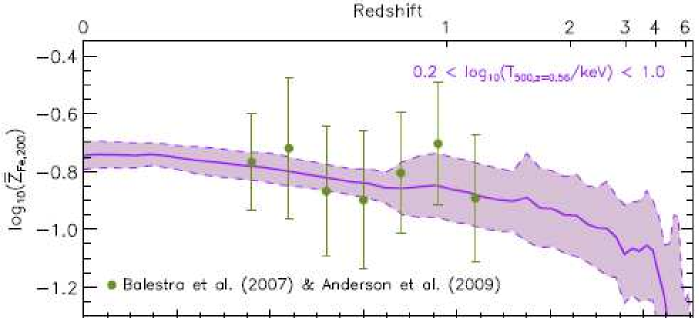
Yates+13

The 'universal' age- [α/Fe] relation



Walcher+(sub.)

Iron evolution in galaxy clusters



Yates+(in prep.)

Simple GCE models

The closed box

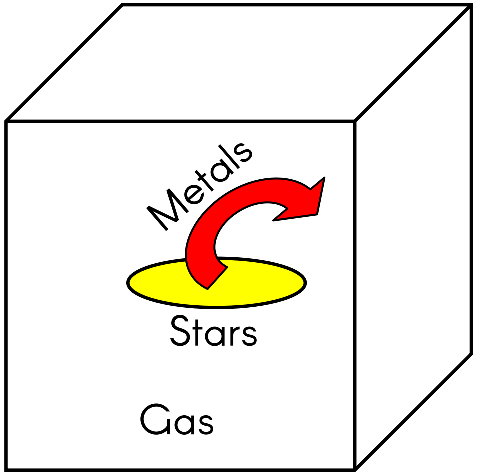
- Gas cannot enter or leave the system
- Stars form from initial gas and eject metals into the ISM

$$\frac{\mathrm{d}M_{\mathrm{Z,g}}}{\mathrm{d}t} = \underset{\uparrow}{-Z_{\mathrm{g}}\,\psi} + \underset{\uparrow}{Z_{\mathrm{g}}\,R\,\psi} + \underset{\uparrow}{y_{\mathrm{Z}}\,(1-R)\,\psi}$$

Metals locked into stars

Unprocessed metals returned to gas

Newly-processed metals returned to gas



Simple GCE models

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$$\frac{\mathrm{d}M_{\mathrm{Z,g}}}{\mathrm{d}t} = -Z_{\mathrm{g}}\,\psi + Z_{\mathrm{g}}\,R\,\psi + y_{\mathrm{Z}}\,(1-R)\,\psi$$

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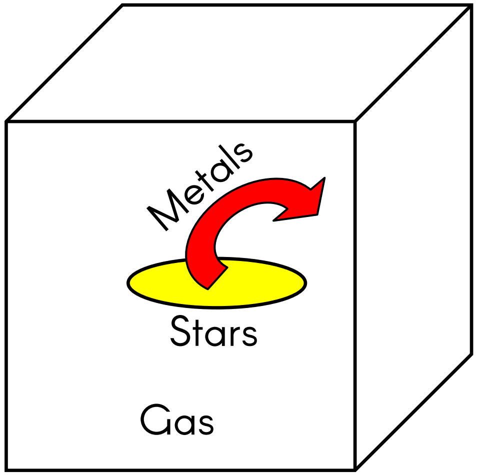
Newly-processed metals returned to gas

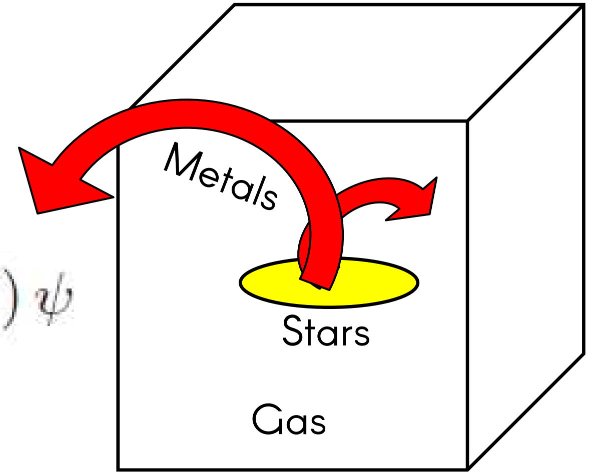


The leaky box

- Gas can leave but cannot enter the system
- Galactic winds can have a range of metallicities

$$\frac{\mathrm{d}M_{\mathrm{Z,g}}}{\mathrm{d}t} = -(1+\alpha)Z_{\mathrm{g}}\,\psi + Z_{\mathrm{g}}\,R\,\psi + y_{\mathrm{Z}}\,(1-R)\,\psi$$

Metals locked into stars or ejected



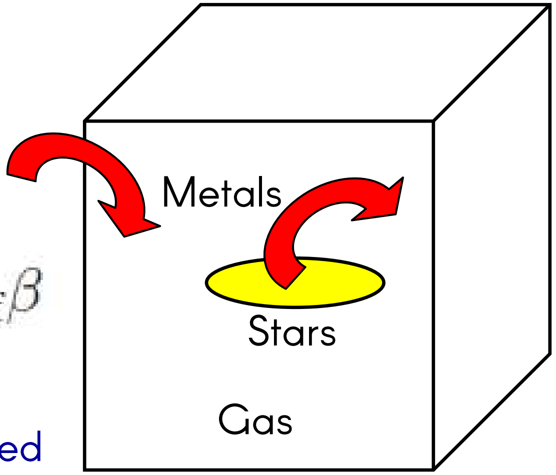
Simple GCE models

The accreting box

- Gas can enter but cannot leave the system
- Accreted gas expected to be (nearly) pristine

$$\frac{\mathrm{d}M_{\mathrm{Z,g}}}{\mathrm{d}t} = -Z_{\mathrm{g}}\,\psi + Z_{\mathrm{g}}\,R\,\psi + y_{\mathrm{Z}}\,(1-R)\,\psi + \underset{\uparrow}{Z_{\mathrm{inf}}\beta}$$

Metals accreted from IGM



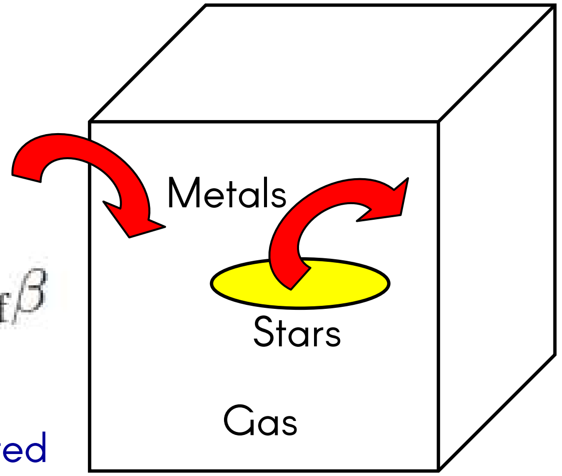
Simple GCE models

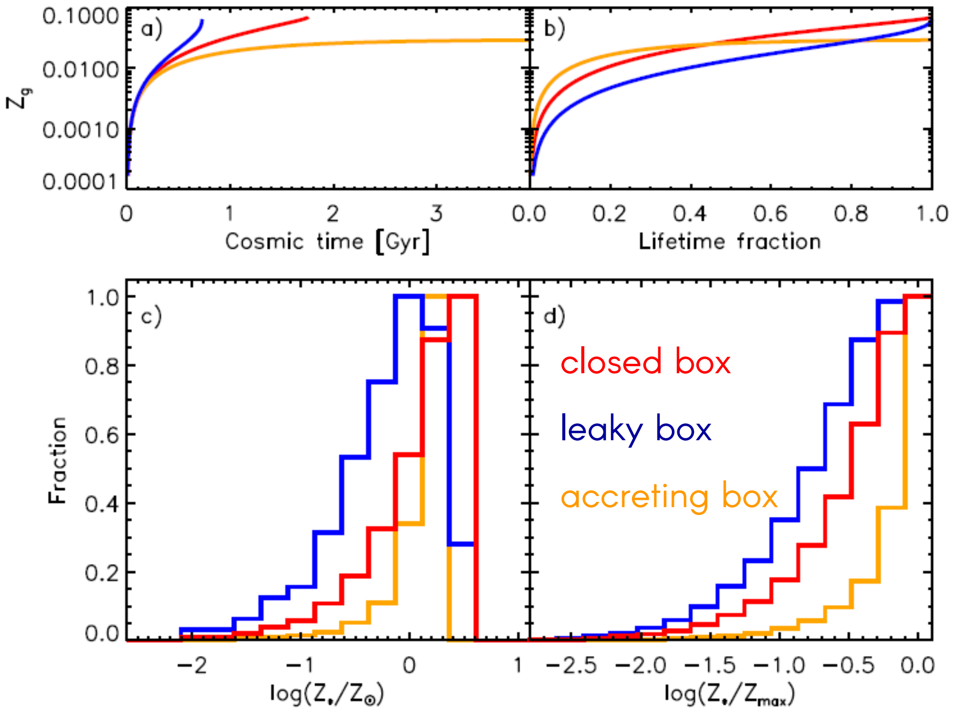
The accreting box

- Gas can enter but cannot leave the system
- Accreted gas expected to be (nearly) pristine

$$\frac{\mathrm{d}M_{\mathrm{Z,g}}}{\mathrm{d}t} = -Z_{\mathrm{g}}\,\psi + Z_{\mathrm{g}}\,R\,\psi + y_{\mathrm{Z}}\,(1-R)\,\psi + Z_{\mathrm{inf}}\beta$$

Metals accreted from IGM





Combinations of these simple models (i.e. a ‘breathing box’) can reproduce the MW G-dwarf metallicity distribution (see Tinsley 1980).

The analytics

The GCE equation

To model GCE, we need to know…

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

$$\mathrm{IMF} \bullet \mathrm{SFR}(t-\tau_M) = \text{death rate at time } t$$

2) How much metal they eject at time t

$$M_Z = \text{Metal mass ejected by star of mass } M$$

Therefore:

$$\boxed{\mathrm{IMF} \bullet \mathrm{SFR}(t-\tau_M) \bullet M_Z = \text{Metal mass ejected by star of mass } M \text{ at time } t}$$

The GCE equation

$$e_{\mathrm{Z}}(t) = \int_{M_L}^{M_U} \underset{\substack{\uparrow \\ \text{Metals}}}{M_{\mathrm{Z}}(M, Z_0)}\ \underset{\substack{\uparrow \\ \text{SFR}}}{\psi(t - \tau_{\mathrm{M}})}\ \underset{\substack{\uparrow \\ \text{IMF}}}{\phi(M)}\ \mathrm{dM}$$

$e_{\mathrm{Z}}(t)$ = The rate of ejection of metals from a simple stellar population (SSP)

$$M_{\mathrm{Z}} = y_{\mathrm{Z}}(M, Z_0) + Z_0 \cdot (M - M_{\mathrm{r}})$$

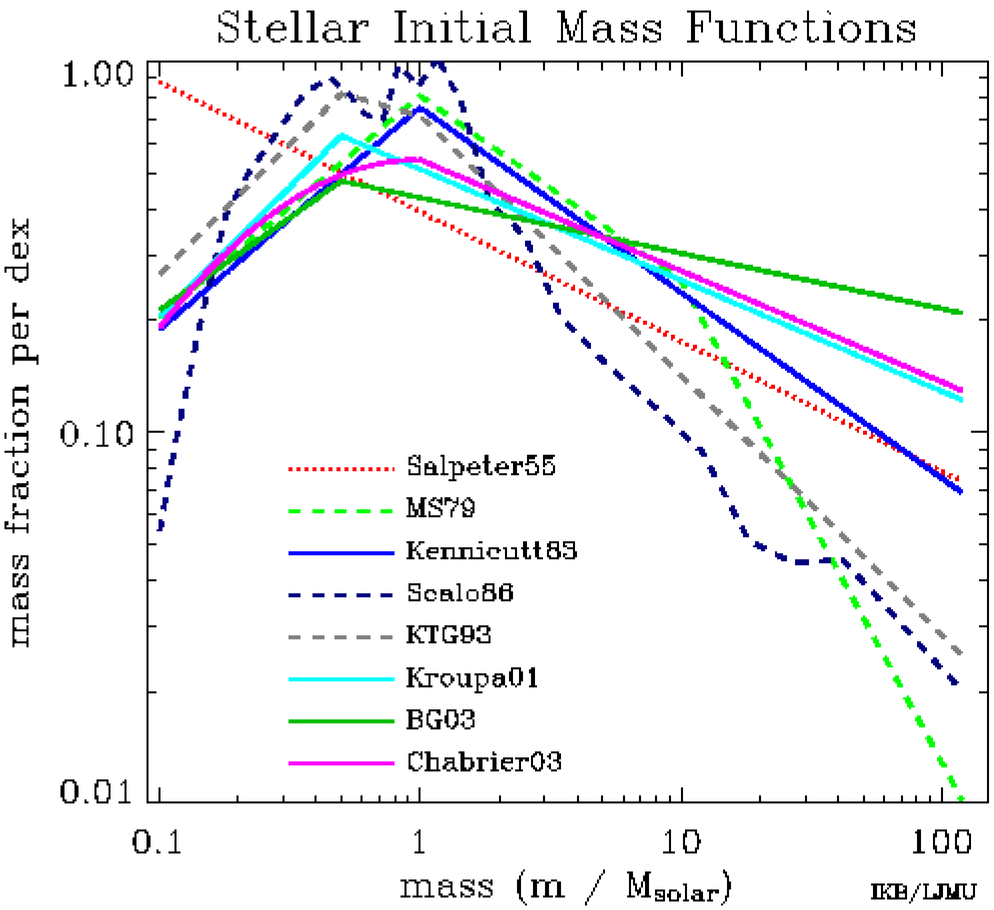
= The mass of metals ejected by one star of initial mass M, initial metallicity Z_O, and remnant mass M_r

$\psi(t - \tau_{\mathrm{M}})$ = 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.

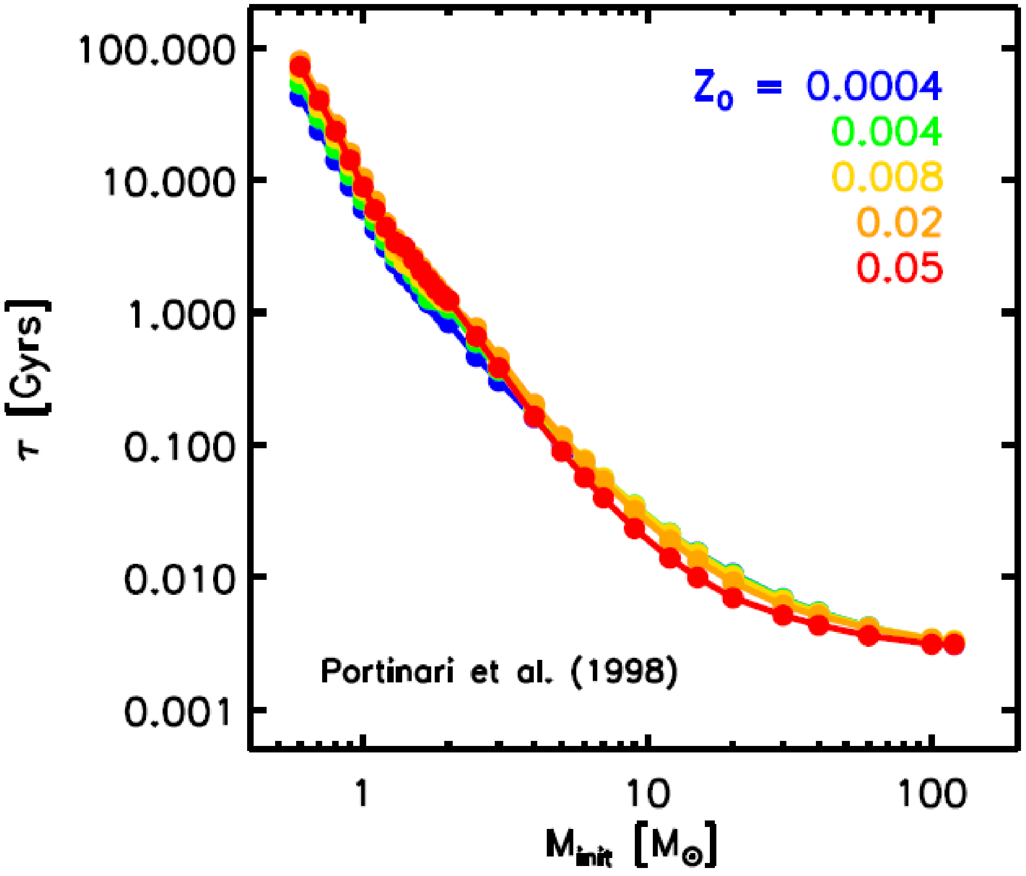
Different IMFs give different GCE results. e.g. more high-mass stars means more alpha elements...

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}:

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

Stellar lifetimes

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



Yates+13

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*.

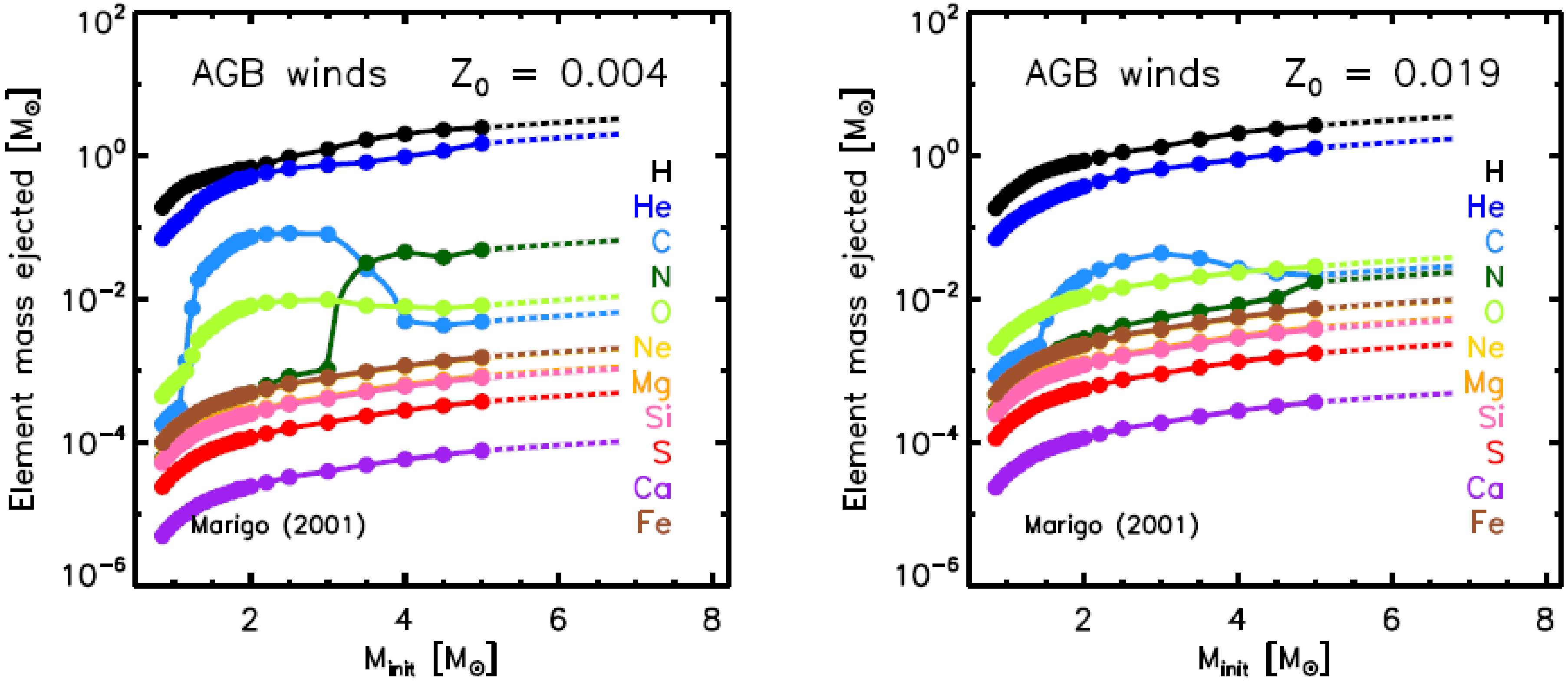
AGB winds

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

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

SNe-II

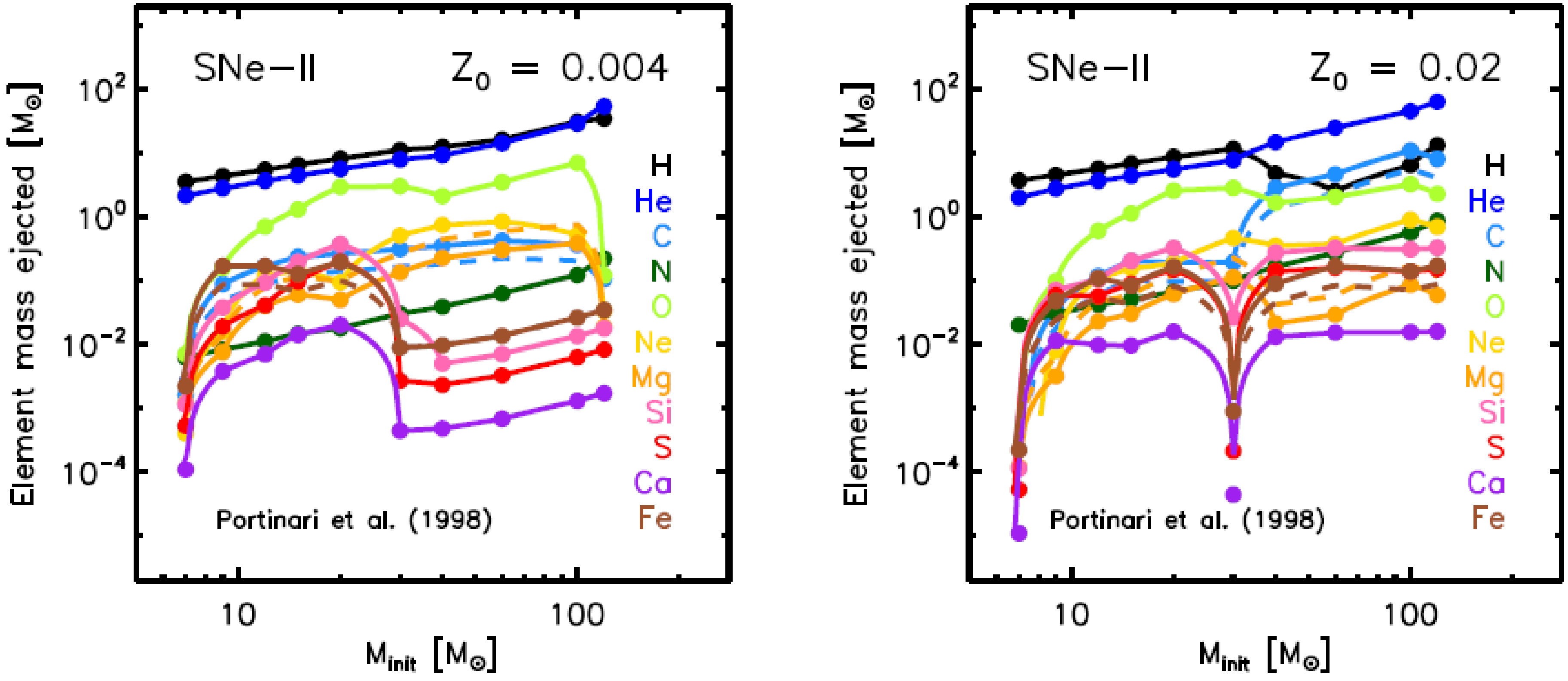
$$e_Z(t) = \int_{M_L}^{M_U} M_Z(M, Z_0)\, \psi(t - \tau_M)\, \phi(M)\, \mathrm{dM}$$

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 conisder the SN-II yields of *Portinari+98* and of *Chieffi & Limongi 04*.

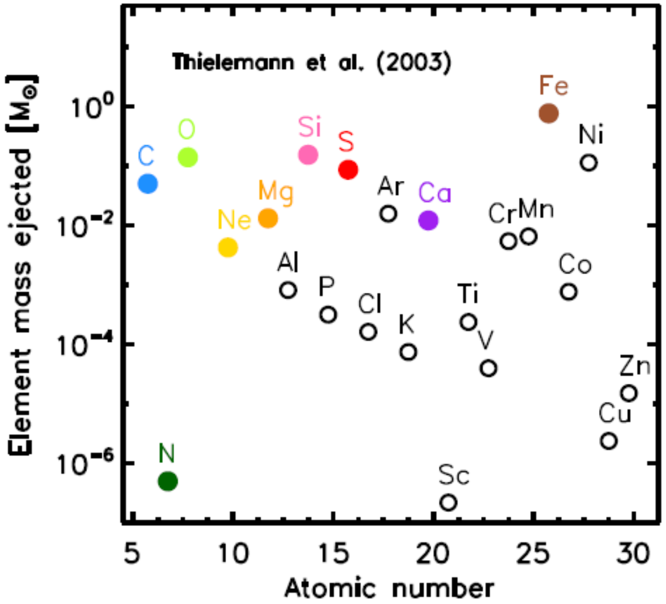
(Note the strong mass-dependence for the *Portinari+98* yields)

Yates+13



SNe-Ia

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



Yates+13

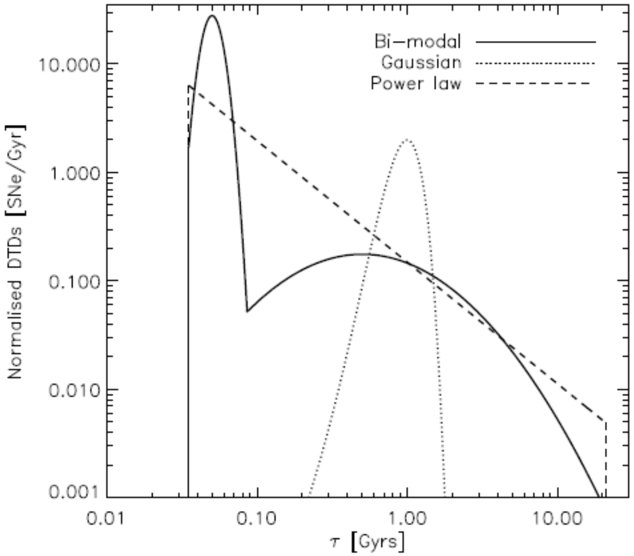
Some binary systems (2.8%) with total mass 3 – 16 M_{sun} (companion star mass 0.85 – 8 M_{sun}) can explode as type Ia supernovæ. These eject mainly Fe.

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 allow for 4 different DTDs, with $\tau_{min} = \tau_{8Msun}$ = 35 Myr and $\tau_{max} = \tau_{0.85Msun}$ = 21 Gyr.



Yates+13

SNe-Ia

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

- Power law: (*Maoz+12*)

$$\mathrm{DTD}_{\mathrm{PL}} = a(\tau/\mathrm{Gyr})^{-1.12} \qquad (\, a = 0.15242\ \mathrm{Gyr}^{-1})$$

- Gaussian: (*Strolger+04*)

$$\mathrm{DTD}_{\mathrm{NG}} = \frac{1}{\sqrt{2\pi\sigma_\tau^2}}\, e^{-(\tau-\tau_c)^2/2\sigma_\tau^2} \qquad (\, \sigma_\tau = 0.2\tau_c\ \mathrm{Gyr} \quad \tau_c = 1\ \mathrm{Gyr}\,)$$

- Bi-modal: (*Mannucci+06*)

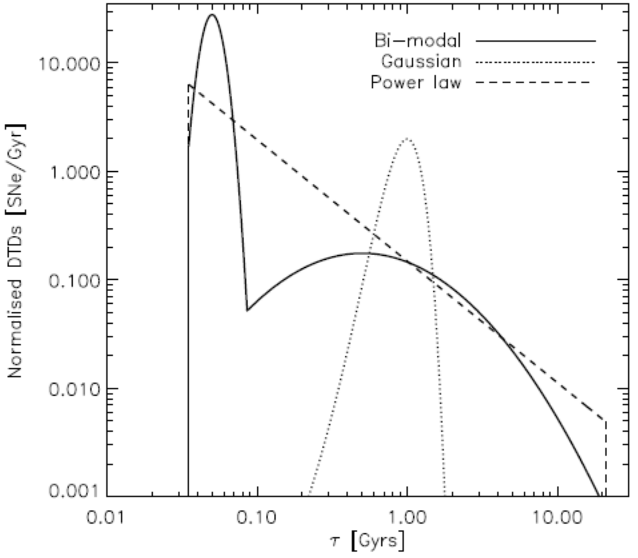
$$\log(\mathrm{DTD}_{\mathrm{BM}}) = \begin{cases} 1.4 - 50(\log(\tau/\mathrm{yr}) - 7.7)^2 & \text{if } \tau < \tau_0 \\ -0.8 - 0.9(\log(\tau/\mathrm{yr}) - 8.7)^2 & \text{if } \tau > \tau_0 \end{cases} \qquad (\ \tau_0 = 0.0851\ \mathrm{Gyr}\ )$$

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

Currently in L-GALAXIES, we allow for 4 different DTDs.

$\tau_{\mathrm{min}} = \tau_{8\mathrm{Msun}} = 35$ Myr

$\tau_{\mathrm{max}} = \tau_{0.85\mathrm{Msun}} = 21$ Gyr



Yates+13

The detailed GCE equation

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

The detailed GCE equation

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

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.

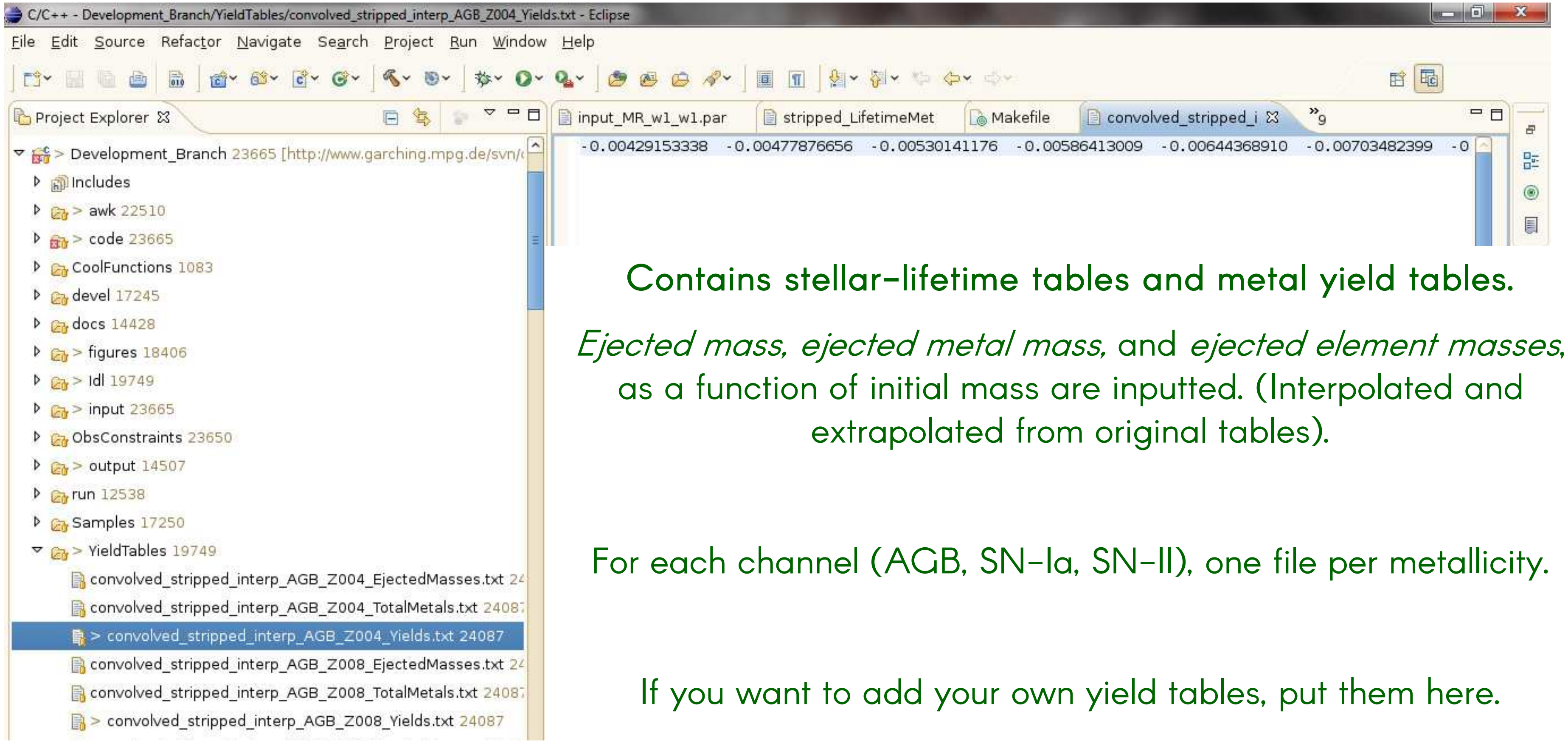
$k = \int_{M_{\min}}^{M_{\max}} \phi(M)\;\mathrm{d}M$ = 1.4772 = Number of stellar objects in a 1 M_{sun} SSP.

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).

The coding

./YieldTables



- > Development_Branch 23665 [http://www.garching.mpg.de/svn/
  - Includes
  - > awk 22510
  - > code 23665
  - CoolFunctions 1083
  - devel 17245
  - docs 14428
  - > figures 18406
  - > Idl 19749
  - > input 23665
  - ObsConstraints 23650
  - > output 14507
  - run 12538
  - Samples 17250
  - > YieldTables 19749
    - convolved_stripped_interp_AGB_Z004_EjectedMasses.txt 24
    - convolved_stripped_interp_AGB_Z004_TotalMetals.txt 2408
    - > convolved_stripped_interp_AGB_Z004_Yields.txt 24087
    - convolved_stripped_interp_AGB_Z008_EjectedMasses.txt 24
    - convolved_stripped_interp_AGB_Z008_TotalMetals.txt 2408
    - > convolved_stripped_interp_AGB_Z008_Yields.txt 24087

```
-0.00429153338  -0.00477876656  -0.00530141176  -0.00586413009  -0.00644368910  -0.00703482399  -0
```

Contains stellar-lifetime tables and metal yield tables.

Ejected mass, ejected metal mass, and *ejected element masses*, as a function of initial mass are inputted. (Interpolated and extrapolated from original tables).

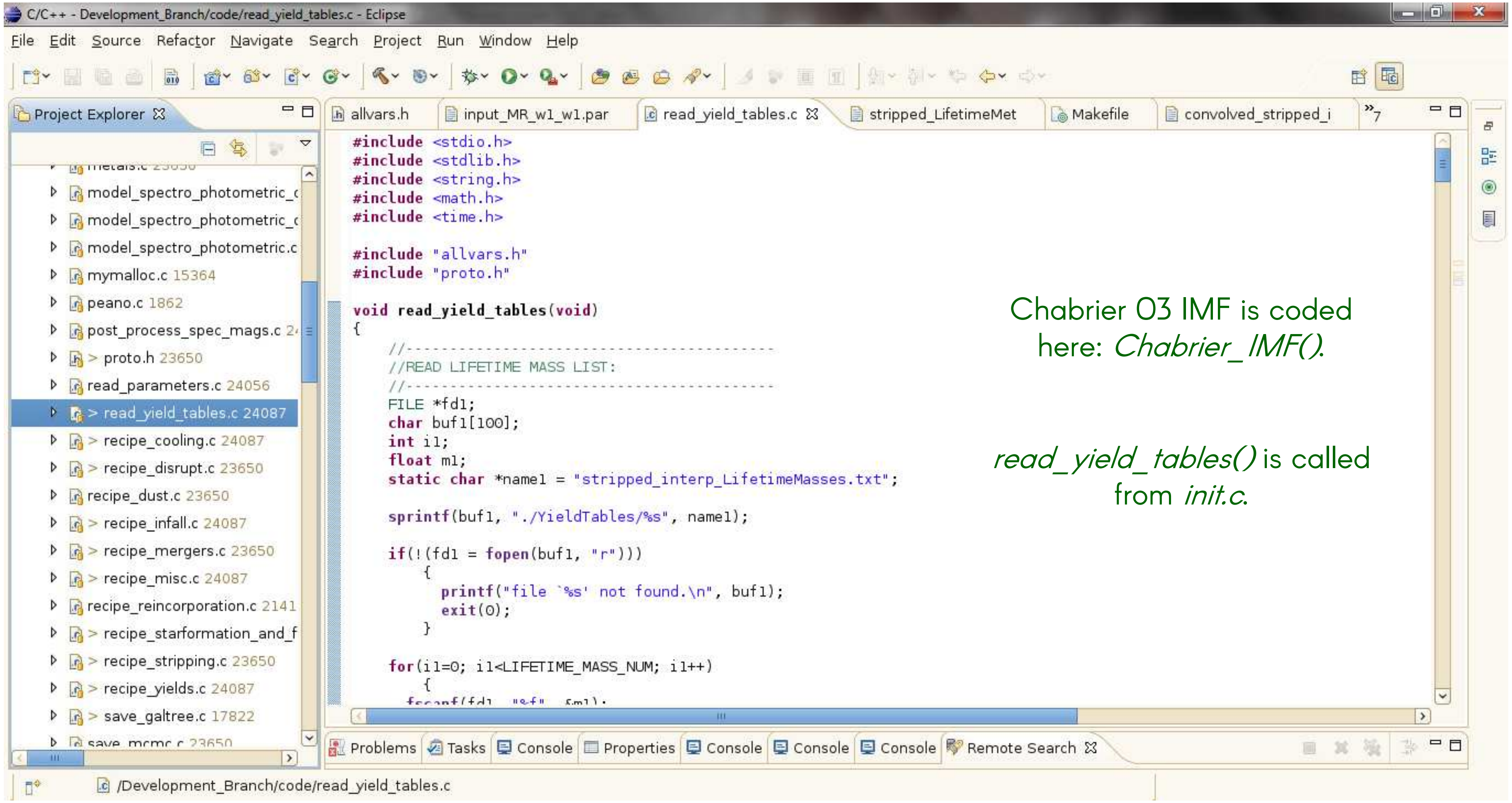
For each channel (AGB, SN-Ia, SN-II), one file per metallicity.

If you want to add your own yield tables, put them here.

Format: Y [M]   i.e. Y [M_0], Y [M_1], Y [M_2],...

Number of array elements given in *allvars.h*.
e.g. SNII_*MASS_NUM*

yields_read_tables.c



```c
#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>
#include <time.h>

#include "allvars.h"
#include "proto.h"

void read_yield_tables(void)
{
    //-------------------------------------------
    //READ LIFETIME MASS LIST:
    //-------------------------------------------
    FILE *fd1;
    char buf1[100];
    int i1;
    float m1;
    static char *name1 = "stripped_interp_LifetimeMasses.txt";

    sprintf(buf1, "./YieldTables/%s", name1);

    if(!(fd1 = fopen(buf1, "r")))
        {
          printf("file `%s' not found.\n", buf1);
          exit(0);
        }

    for(i1=0; i1<LIFETIME_MASS_NUM; i1++)
        {
      fscanf(fd1, "%f", &m1);
```

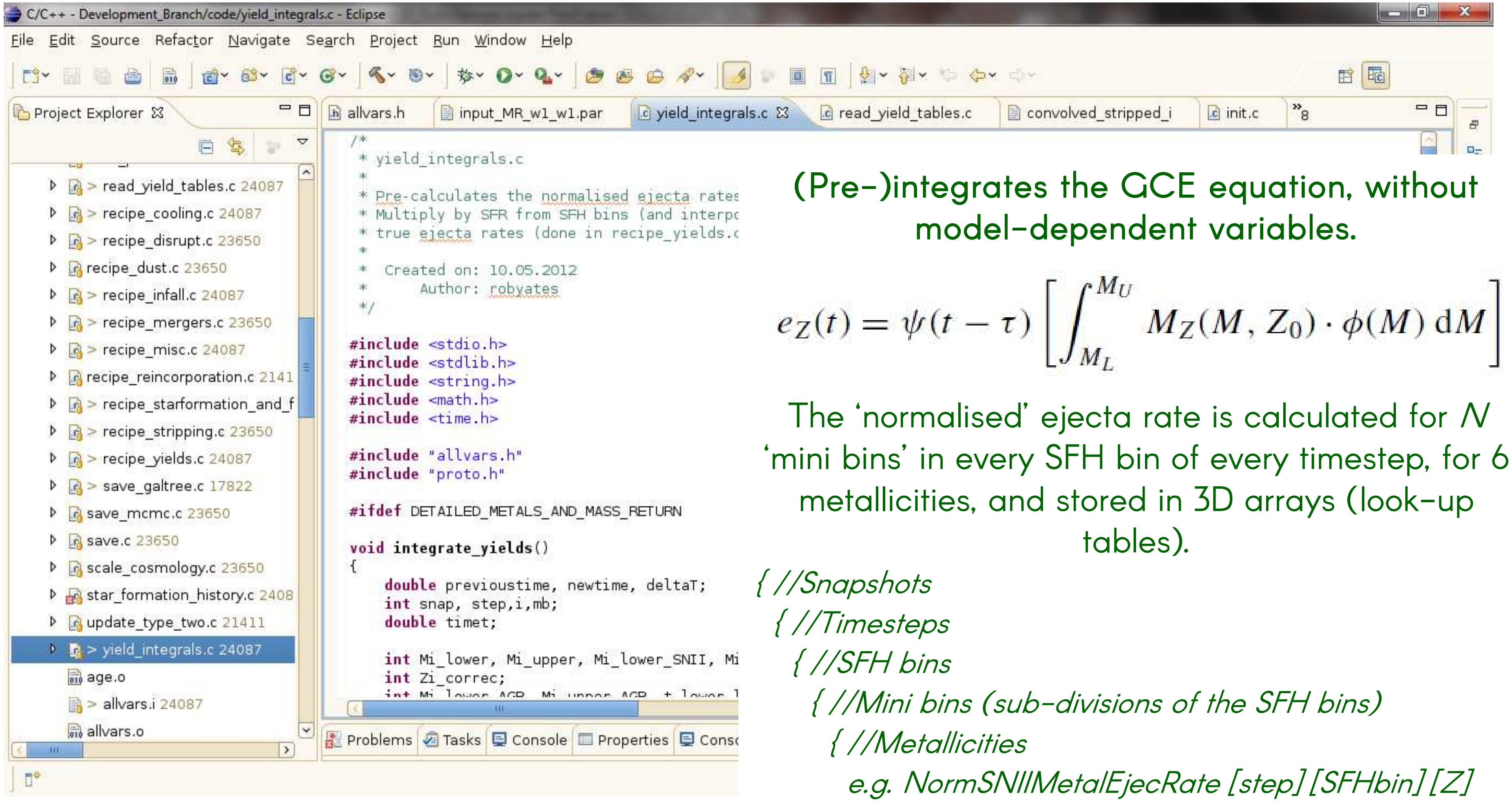
Chabrier 03 IMF is coded here: *Chabrier_IMF()*.

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



```c
/*
 * yield_integrals.c
 *
 * Pre-calculates the normalised ejecta rates
 * Multiply by SFR from SFH bins (and interpc
 * true ejecta rates (done in recipe_yields.c
 *
 *  Created on: 10.05.2012
 *      Author: robyates
 */

#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>
#include <time.h>

#include "allvars.h"
#include "proto.h"

#ifdef DETAILED_METALS_AND_MASS_RETURN

void integrate_yields()
{
    double previoustime, newtime, deltaT;
    int snap, step,i,mb;
    double timet;

    int Mi_lower, Mi_upper, Mi_lower_SNII, Mi
    int Zi_correc;
```

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

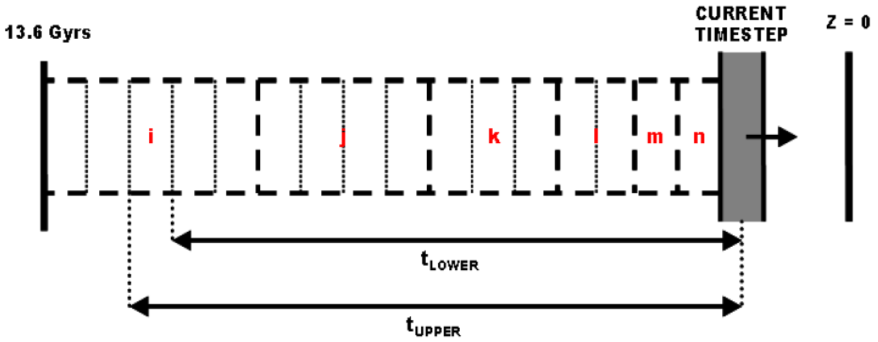
$$e_Z(t) = \psi(t-\tau)\left[\int_{M_L}^{M_U} M_Z(M, Z_0)\cdot\phi(M)\,\mathrm{d}M\right]$$

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).

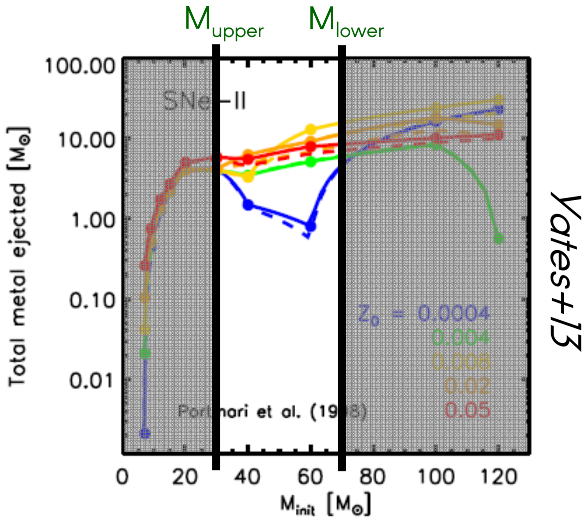
```
{ //Snapshots
 { //Timesteps
  { //SFH bins
   { //Mini bins (sub-divisions of the SFH bins)
    { //Metallicities
      e.g. NormSNIIMetalEjecRate [step] [SFHbin] [Z]
    }
   }
  }
 }
}
```

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

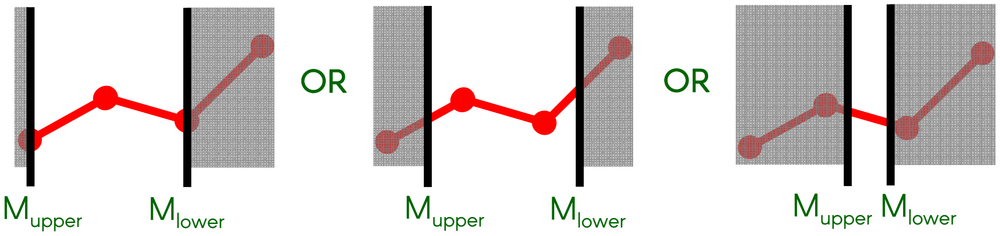
yields_integrals.c



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

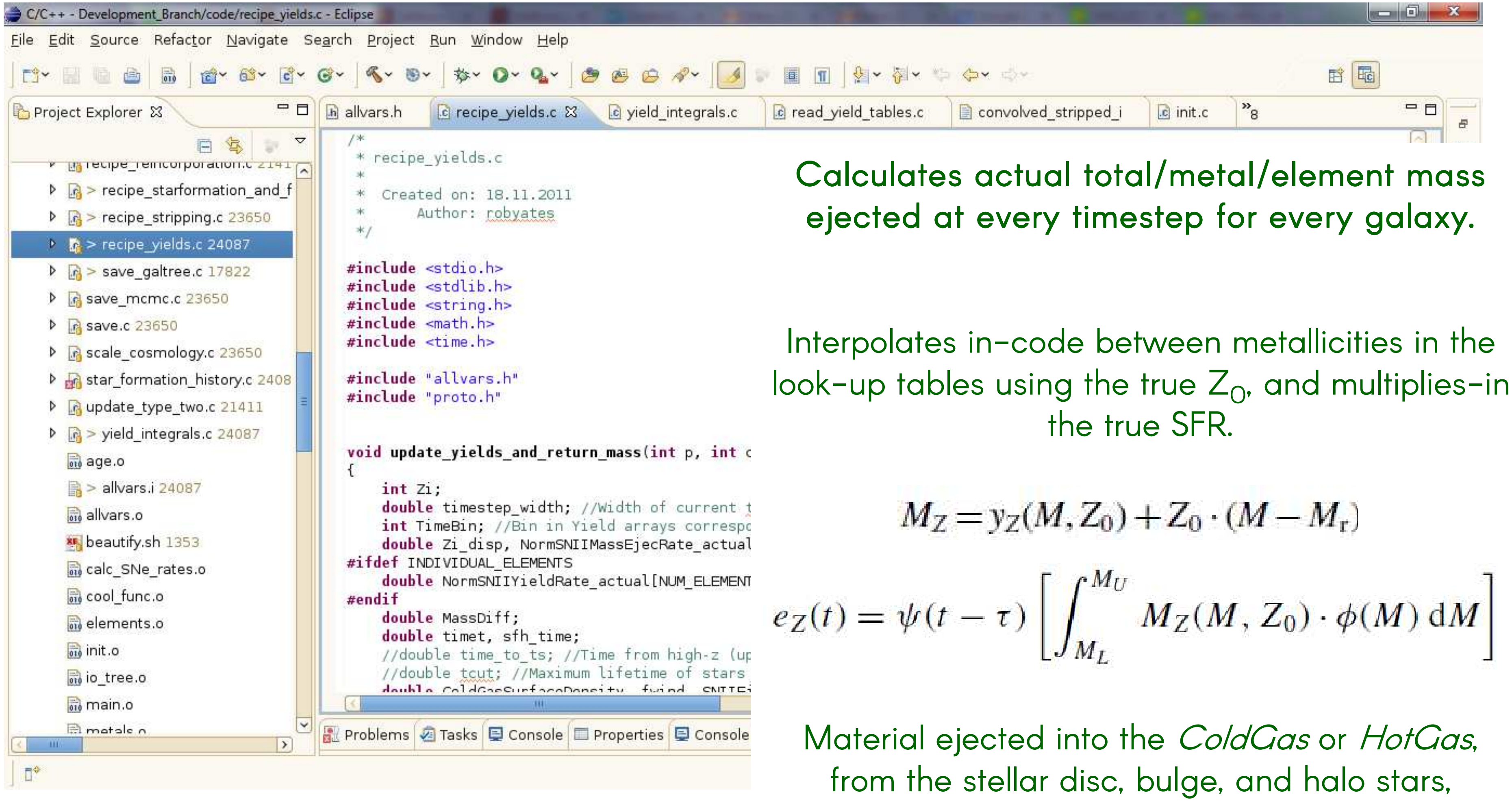


2) The total/metal/element mass ejected is integrated over numerically between M_{upper} and M_{lower}.



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



```c
/*
 * recipe_yields.c
 *
 *  Created on: 18.11.2011
 *      Author: robyates
 */

#include <stdio.h>
#include <stdlib.h>
#include <string.h>
#include <math.h>
#include <time.h>

#include "allvars.h"
#include "proto.h"


void update_yields_and_return_mass(int p, int c
{
    int Zi;
    double timestep_width; //Width of current t
    int TimeBin; //Bin in Yield arrays correspo
    double Zi_disp, NormSNIIMassEjecRate_actual
#ifdef INDIVIDUAL_ELEMENTS
    double NormSNIIYieldRate_actual[NUM_ELEMENT
#endif
    double MassDiff;
    double timet, sfh_time;
    //double time_to_ts; //Time from high-z (up
    //double tcut; //Maximum lifetime of stars
```

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.

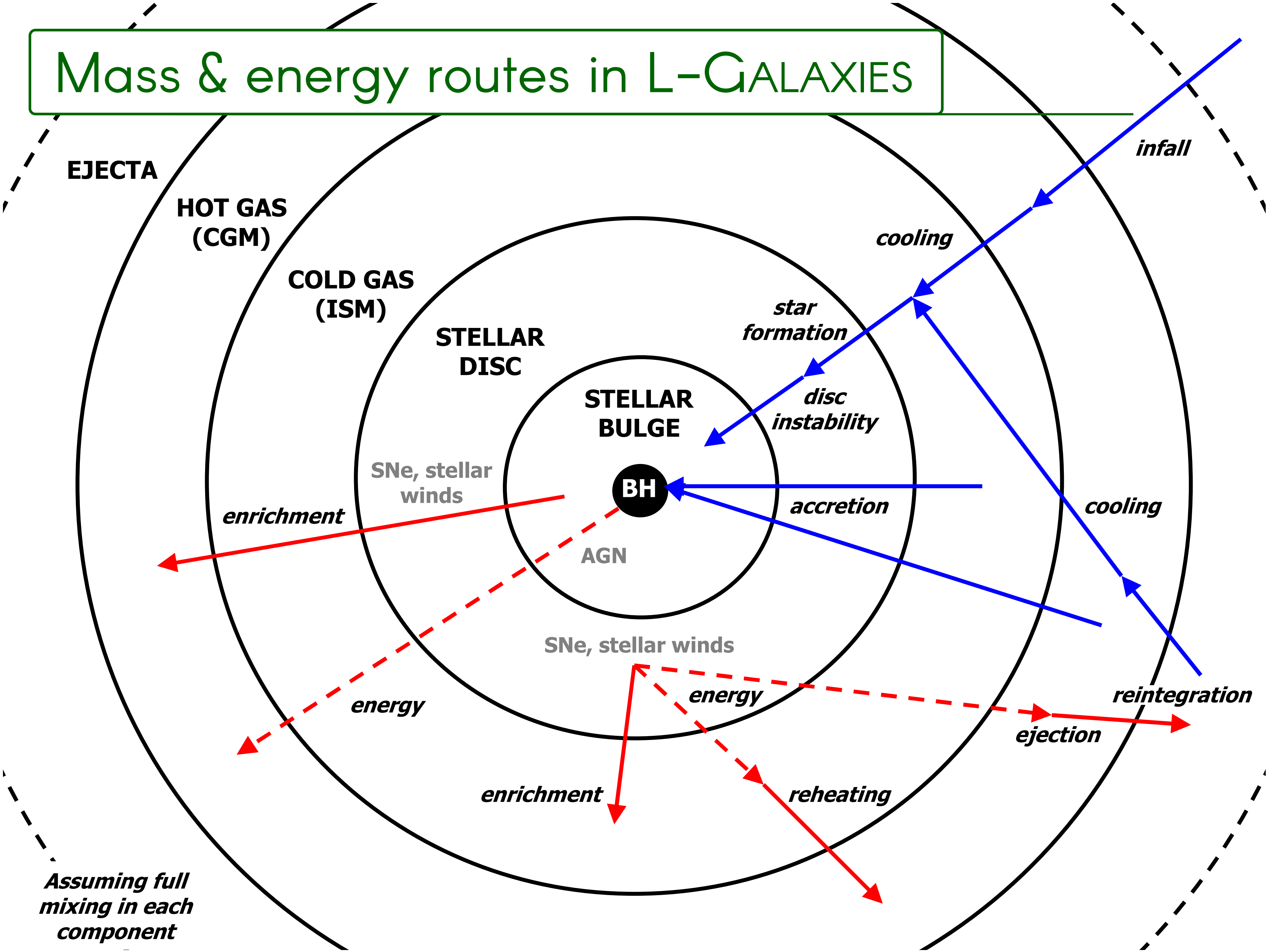
$$M_Z = y_Z(M, Z_0) + Z_0 \cdot (M - M_r)$$

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

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

Material ejected into the *ColdGas* or *HotGas*, from the stellar disc, bulge, and halo stars, according to the chosen GCE set-up (e.g. –DMETALRICHWIND, –DSNIATOHOT,...)

Mass & energy routes in L-GALAXIES



EJECTA

HOT GAS (CGM)

COLD GAS (ISM)

STELLAR DISC

STELLAR BULGE

BH

infall

cooling

star formation

disc instability

SNe, stellar winds

enrichment

accretion

cooling

AGN

SNe, stellar winds

energy

energy

reintegration

ejection

enrichment

reheating

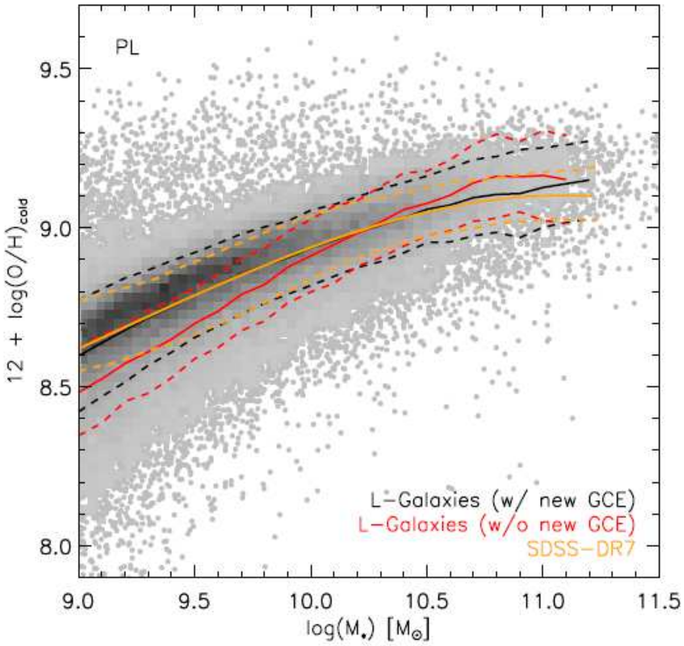
Assuming full mixing in each component

Syncing GCE with SN feedback

SN_feedback() is now called inside *model_yields.c*.

The amount of feedback now depends on the mass ejected by stars at that timestep (rather than the instantaneous SFR).

Therefore, there is less feedback *directly* after star formation. Feedback is distributed more over time.



Yates+13

This e.g. allows more (promptly-ejected) oxygen to remain in the ISM of lower-mass galaxies, making the MZR shallower.

Total SN feedback per SSP is still the same though. The SN feedback efficiency is increased, so that the stellar mass function is still ok.

Other adjustments

- *allvars.h:* All the GCE variables are stored in this header file.

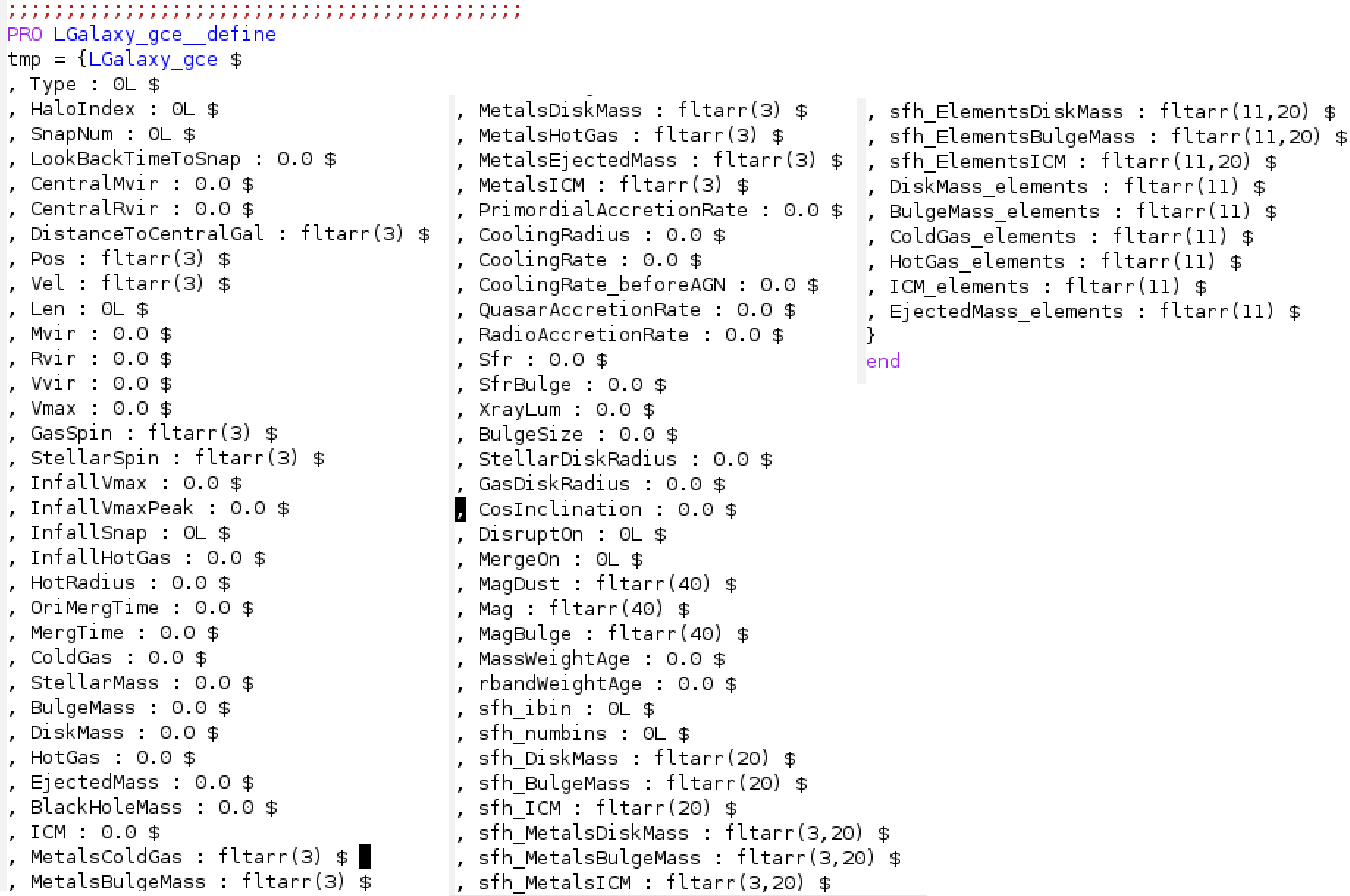
- *model_starformation_and_feedback.c*: Instantaneously recycled fraction no longer required. Stellar masses are updated in *model_yields.c* as stars die and eject material.

- *model_infall.c*: Pristine gas accreted onto DM haloes assumed to be 75% hydrogen and 25% helium.

- *yields_elements.c, metals.c,* and the transfer functions (*model_misc.c*): Metals and elements need to be transferred among the galaxy components in the same way as mass.

- *save.c*: The new GCE properties need to be outputted at the end...

Output structure with GCE (IDL)



```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
PRO LGalaxy_gce__define
tmp = {LGalaxy_gce $
, Type : 0L $
, HaloIndex : 0L $
, SnapNum : 0L $
, LookBackTimeToSnap : 0.0 $
, CentralMvir : 0.0 $
, CentralRvir : 0.0 $
, DistanceToCentralGal : fltarr(3) $
, Pos : fltarr(3) $
, Vel : fltarr(3) $
, Len : 0L $
, Mvir : 0.0 $
, Rvir : 0.0 $
, Vvir : 0.0 $
, Vmax : 0.0 $
, GasSpin : fltarr(3) $
, StellarSpin : fltarr(3) $
, InfallVmax : 0.0 $
, InfallVmaxPeak : 0.0 $
, InfallSnap : 0L $
, InfallHotGas : 0.0 $
, HotRadius : 0.0 $
, OriMergTime : 0.0 $
, MergTime : 0.0 $
, ColdGas : 0.0 $
, StellarMass : 0.0 $
, BulgeMass : 0.0 $
, DiskMass : 0.0 $
, HotGas : 0.0 $
, EjectedMass : 0.0 $
, BlackHoleMass : 0.0 $
, ICM : 0.0 $
, MetalsColdGas : fltarr(3) $
, MetalsBulgeMass : fltarr(3) $
, MetalsDiskMass : fltarr(3) $
, MetalsHotGas : fltarr(3) $
, MetalsEjectedMass : fltarr(3) $
, MetalsICM : fltarr(3) $
, PrimordialAccretionRate : 0.0 $
, CoolingRadius : 0.0 $
, CoolingRate : 0.0 $
, CoolingRate_beforeAGN : 0.0 $
, QuasarAccretionRate : 0.0 $
, RadioAccretionRate : 0.0 $
, Sfr : 0.0 $
, SfrBulge : 0.0 $
, XrayLum : 0.0 $
, BulgeSize : 0.0 $
, StellarDiskRadius : 0.0 $
, GasDiskRadius : 0.0 $
, CosInclination : 0.0 $
, DisruptOn : 0L $
, MergeOn : 0L $
, MagDust : fltarr(40) $
, Mag : fltarr(40) $
, MagBulge : fltarr(40) $
, MassWeightAge : 0.0 $
, rbandWeightAge : 0.0 $
, sfh_ibin : 0L $
, sfh_numbins : 0L $
, sfh_DiskMass : fltarr(20) $
, sfh_BulgeMass : fltarr(20) $
, sfh_ICM : fltarr(20) $
, sfh_MetalsDiskMass : fltarr(3,20) $
, sfh_MetalsBulgeMass : fltarr(3,20) $
, sfh_MetalsICM : fltarr(3,20) $
, sfh_ElementsDiskMass : fltarr(11,20) $
, sfh_ElementsBulgeMass : fltarr(11,20) $
, sfh_ElementsICM : fltarr(11,20) $
, DiskMass_elements : fltarr(11) $
, BulgeMass_elements : fltarr(11) $
, ColdGas_elements : fltarr(11) $
, HotGas_elements : fltarr(11) $
, ICM_elements : fltarr(11) $
, EjectedMass_elements : fltarr(11) $
}
end
```

Running the GCE

For L-Galaxies to compile & run with GCE on…

1) **Switch on GCE:**

   Uncomment –DDETAILED_METALS_AND_MASS_RETURN in *./My_Makefile_options*

2) **Create IDL structure for plotting:**

   a) In root directory, run:

      > make metadata

   b) Go to *~/AuxCode/awk/idl/*

      and save *LGalaxy.pro* as *LGalaxy_gce.pro*

   c) Edit this structure (see e.g. *LGalaxy_allElements.pro,* and copy/paste the correct metals and elements arrays)

   d) Copy *LGalaxy_gce.pro* to ~/AuxCode/Idl/

   e) Make *LGalaxy_gce.pro* the *Gstruct{}* in the *plots_public_release.pro* plotting code

GCE *makefile* options

In *My_makefile_options* are the following GCE switches:

(for more detail: http://galformod.mpa-garching.mpg.de/public/LGalaxies/makefile_input.php)

- **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.

Try it yourself!

- Try changing the SN-Ia DTD, to see how this alters iron abundances, and alpha enhancements.

- Try changing SN-II yield tables, to see how this changes oxygen abundances.

- How do metal-rich winds from SNe-II, or allowing SNe-Ia to directly enrich the *HotGas* change the chemistry of galaxies?

- What fraction of the total metal budget is contributed by AGB winds?

- There are two new plotting routines (IDL code snippets) to download and try with *plots_public_release.pro*. These will plot the MZR and the M_*– [a/Fe] relation.

Thanks for coming!