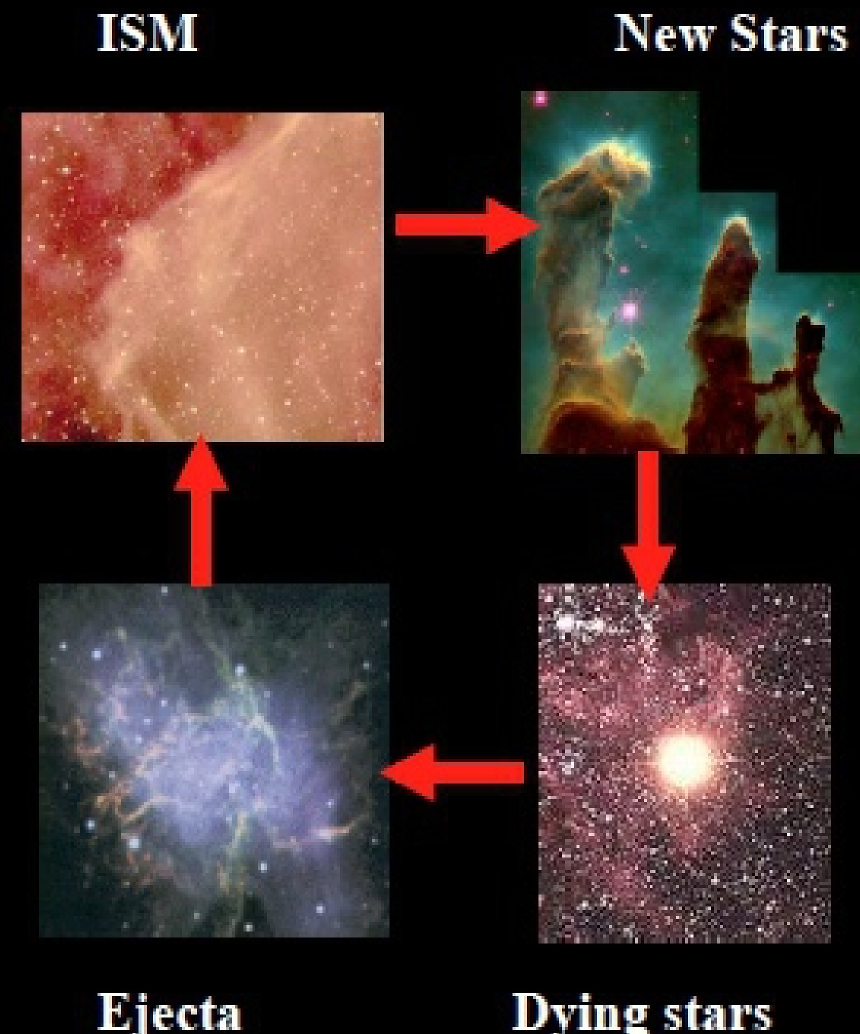
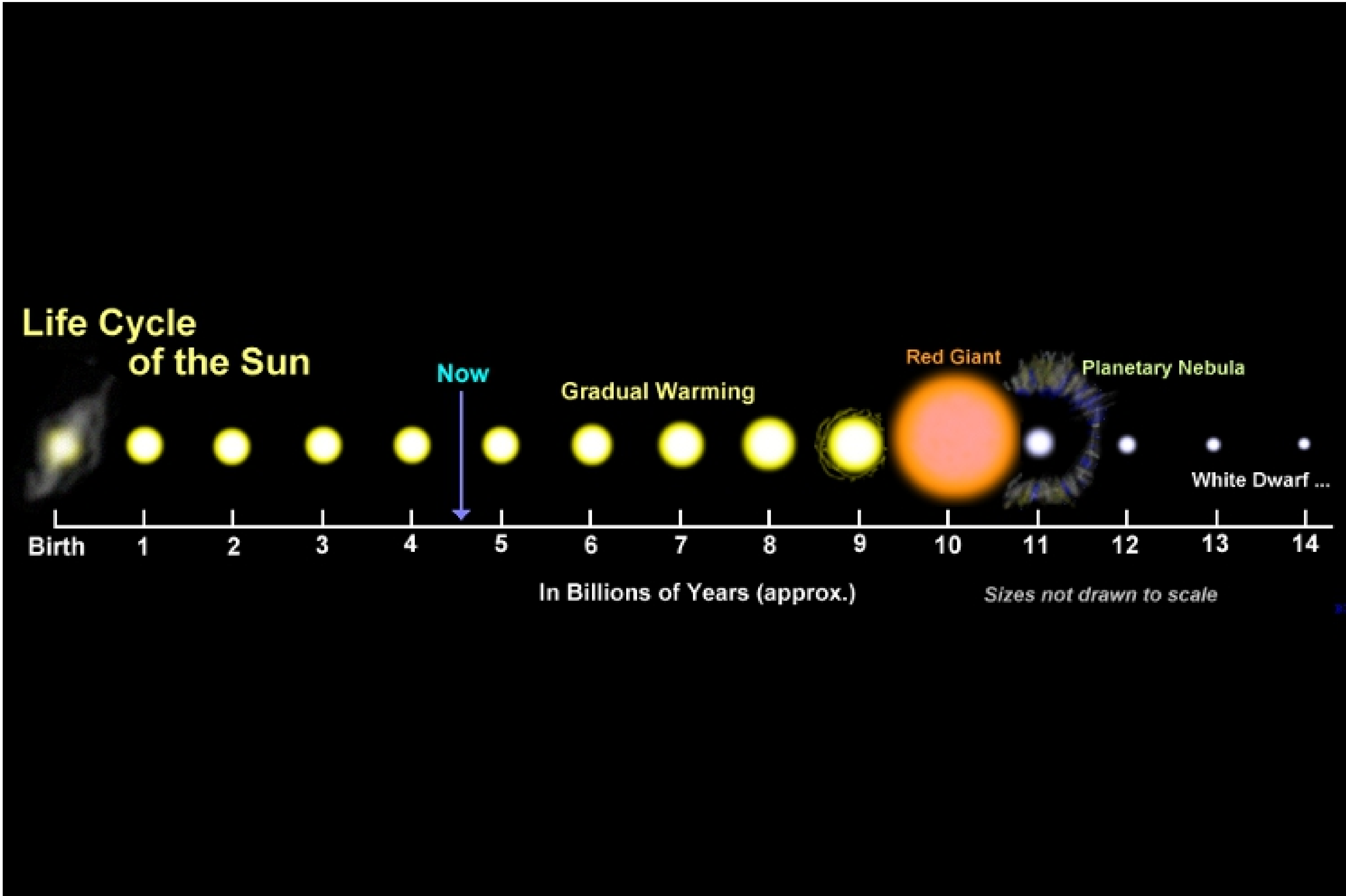
Cycle of GAS and STARS in Galaxies

- *Gas is transformed into stars*
- *Each star burns H and He in its nucleus and produces heavy elements*
- *These elements are partially returned into the interstellar gas at the end of the star's life*
  - *Through winds and supernovae explosions*
  - *Some fraction of the metals are locked into the remnant of the star*

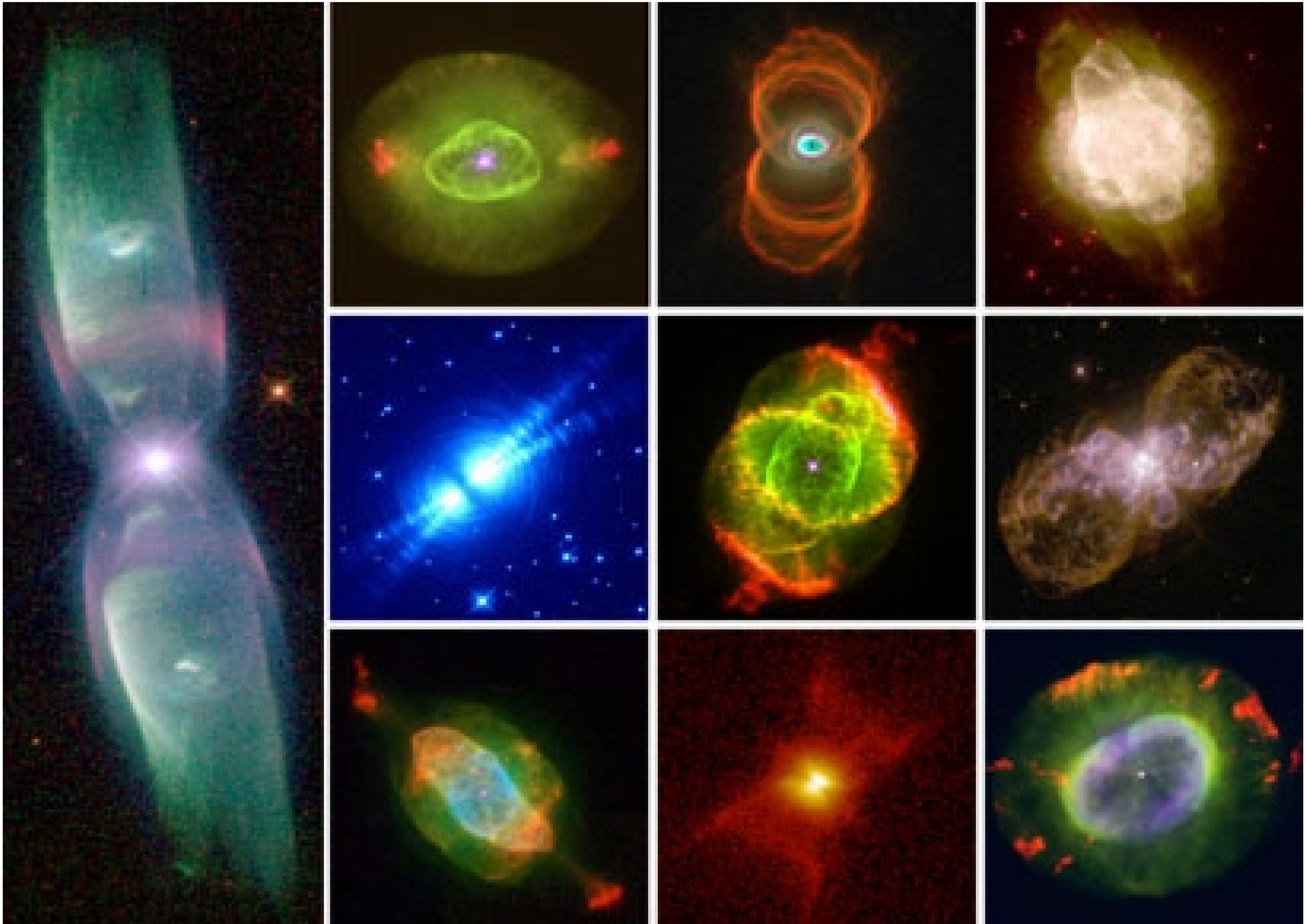


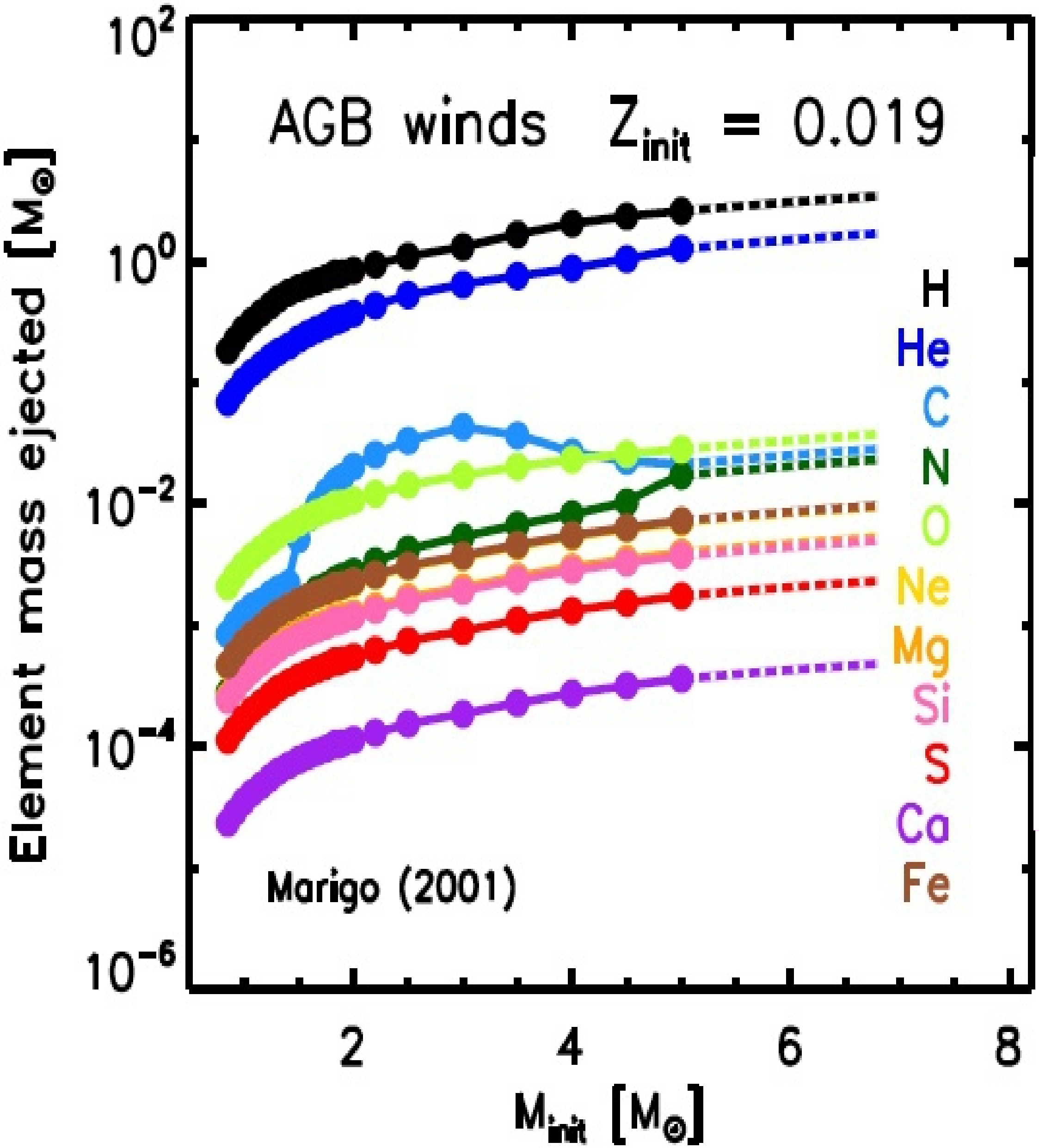
This implies that the chemical abundance of the gas in a star-forming galaxy should evolve with time

Life-cycle of low mass stars like the sun

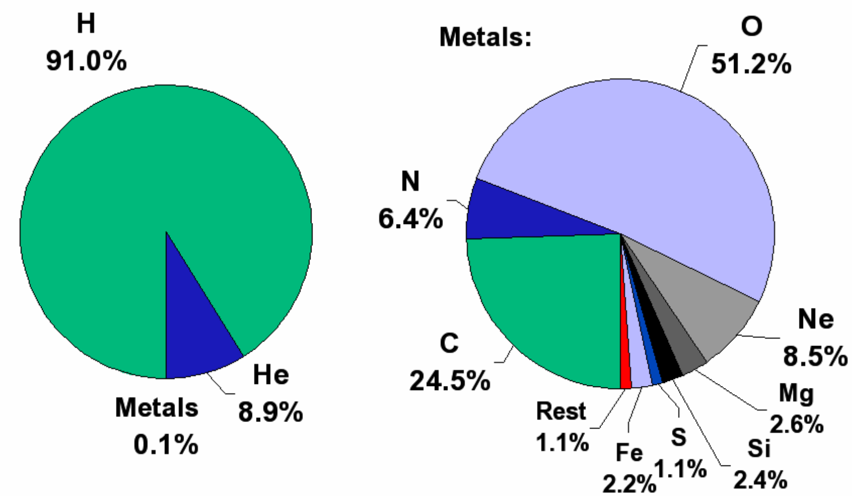


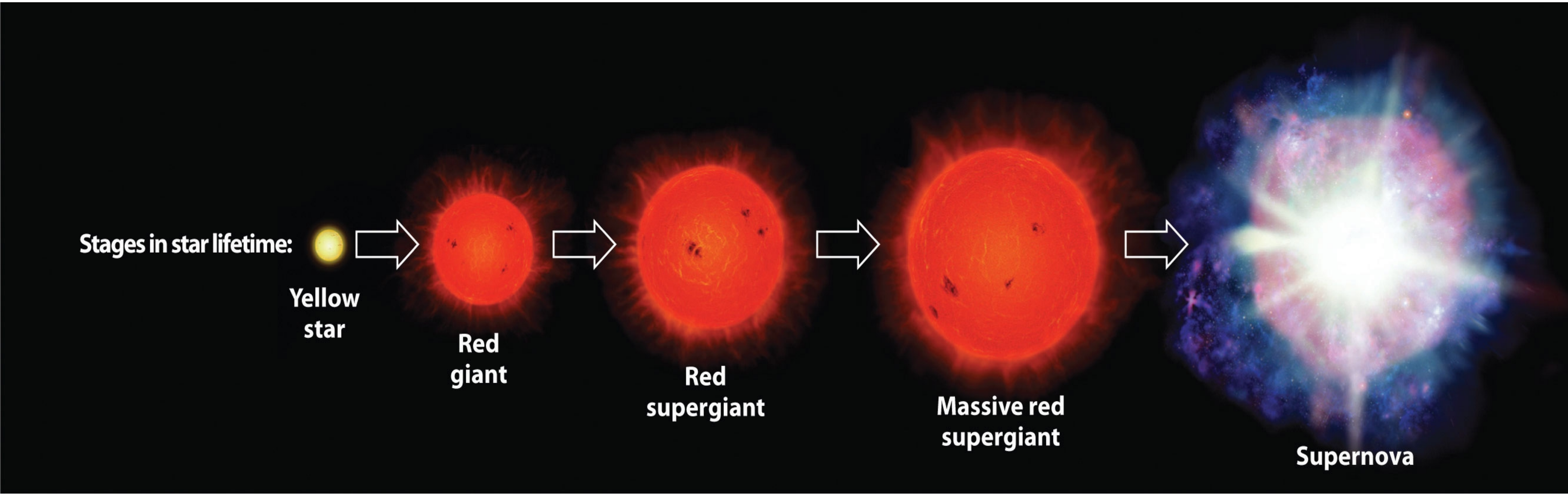
Mass ejection from stars like our sun (Planetary Nebulae)





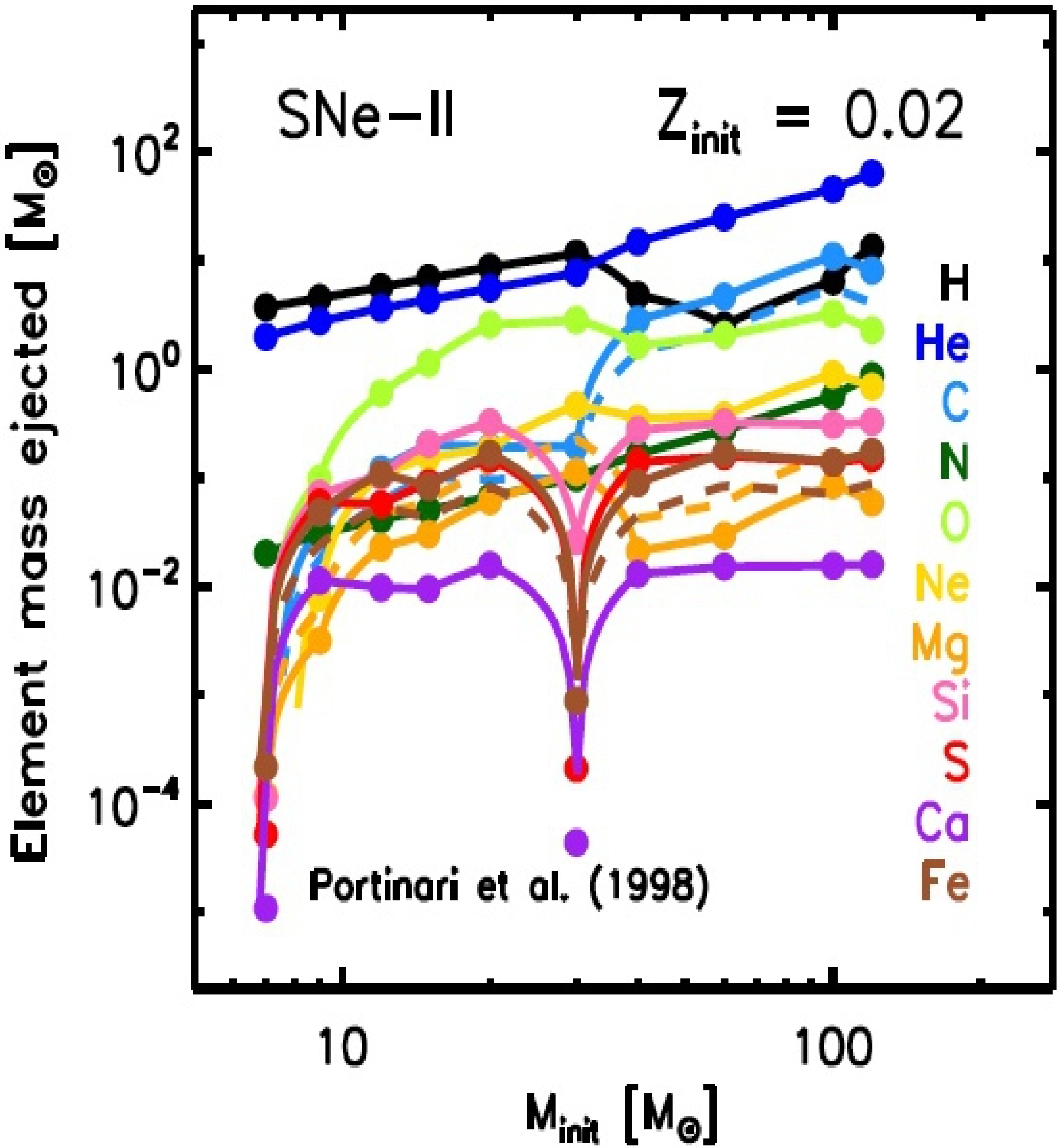
Chemical composition of the Sun

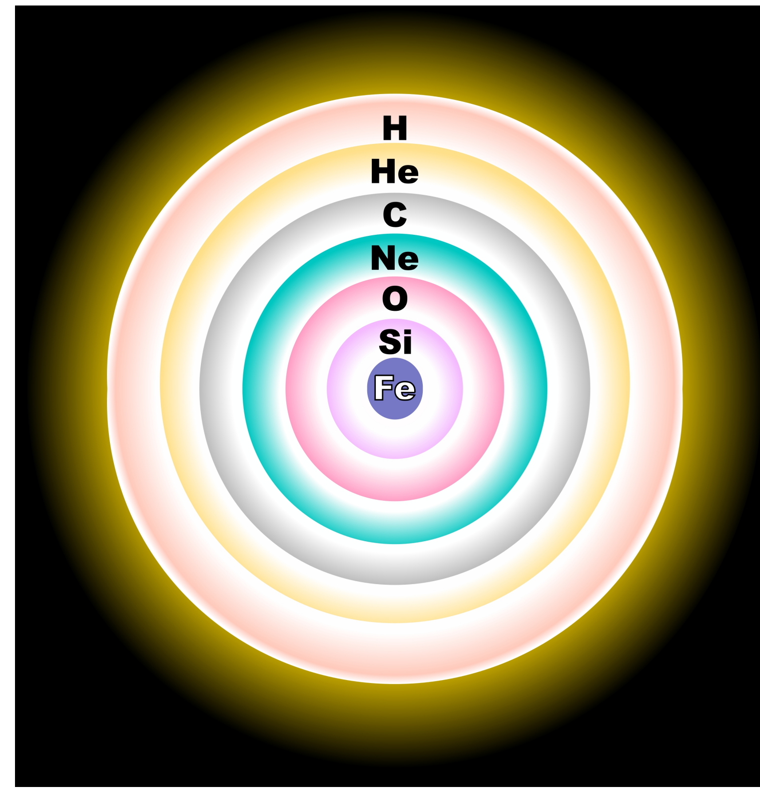


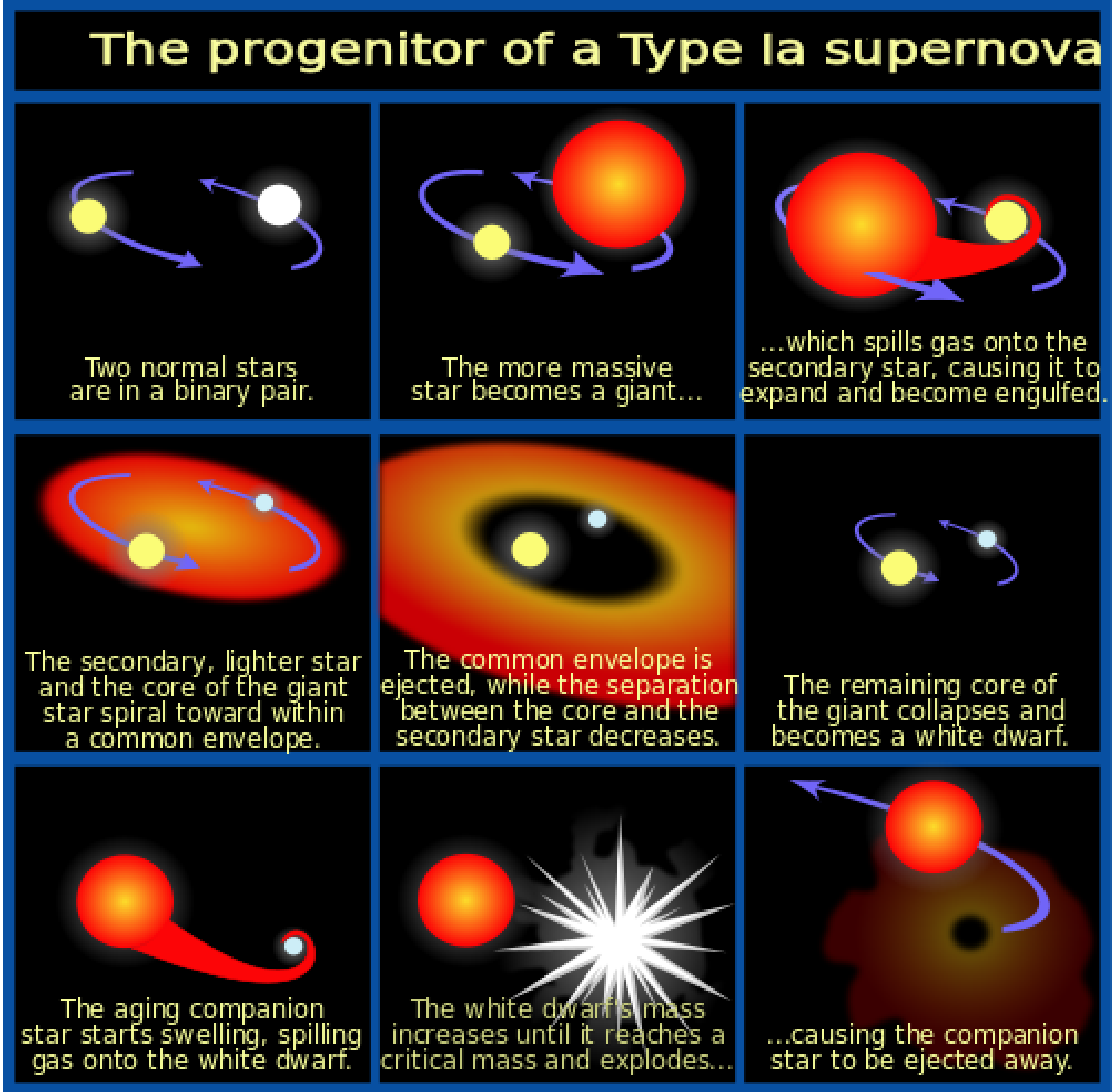


Core Temperature:	1.5×10^7 K	2×10^8 K	7×10^8 K	3×10^9 K	1×10^{11} K
Primary Nuclear Reaction:	^{1}H fusion	^{4}He fusion	$^4He + ^{12}C$ $^{12}C + ^{12}C$ $^{12}C + ^{16}O$	Proton–neutron exchange reactions	Multiple neutron captures
Elements Formed:	He	C, O, Ne, Mg	Na, Si, S, Ar, Ca	Fe, Ni	Elements with $Z > 28$

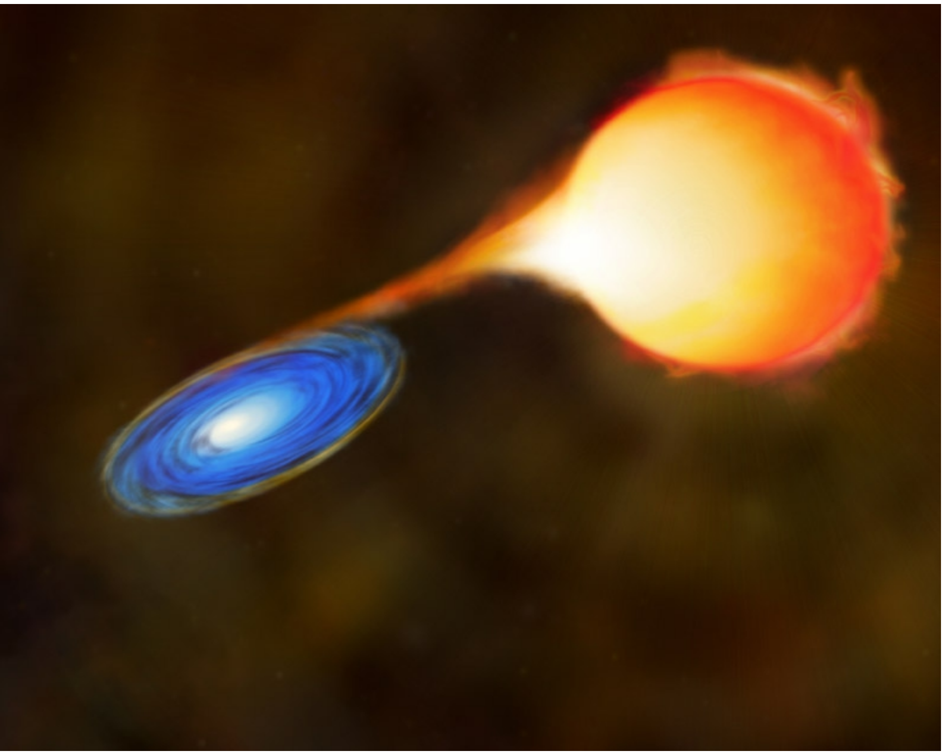
Stars more mass than 8 M (sun) end their lives in supernova explosions

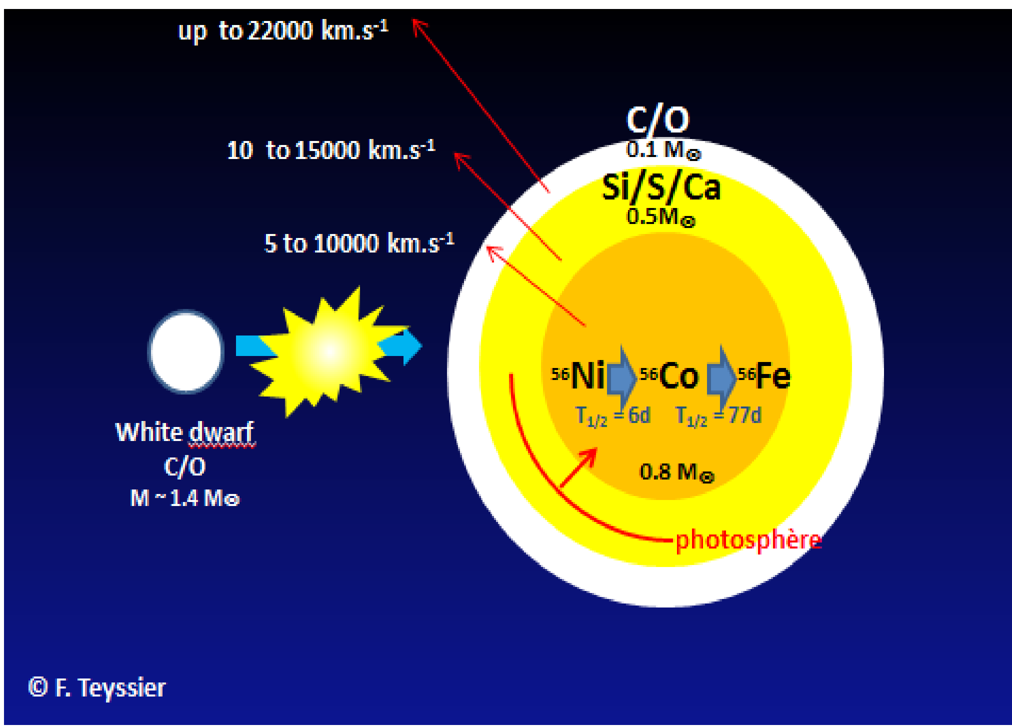

SNe−II
Z_{init} = 0.02
10^2
10^0
10^{-2}
10^{-4}
Element mass ejected [$M_\odot$]
H
He
C
N
O
Ne
Mg
Si
S
Ca
Fe
Portinari et al. (1998)
10
100
M_{init} [$M_\odot$]


H
He
C
Ne
O
Si
Fe

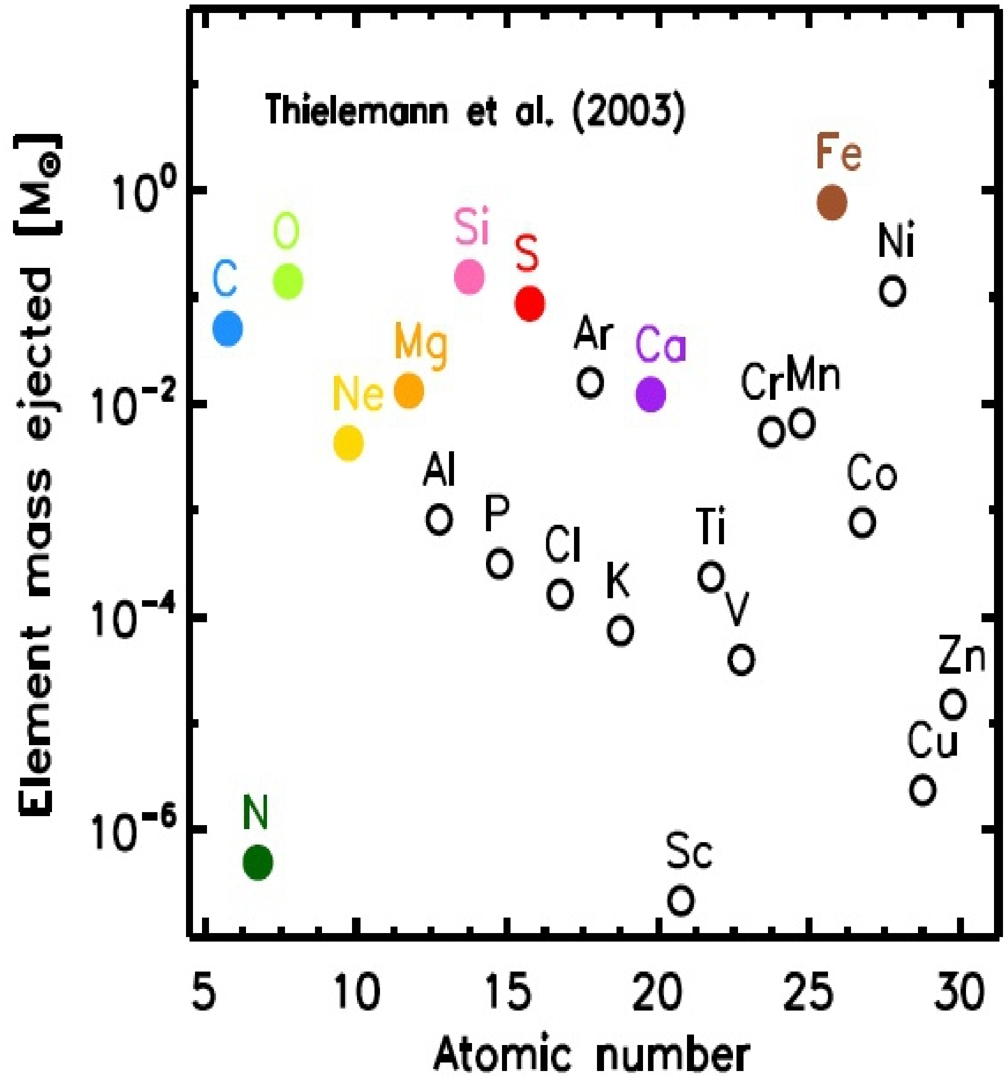


The progenitor of a Type Ia supernova
Two normal stars are in a binary pair.
The more massive star becomes a giant...
...which spills gas onto the secondary star, causing it to expand and become engulfed.
The secondary, lighter star and the core of the giant star spiral toward within a common envelope.
The common envelope is ejected, while the separation between the core and the secondary star decreases.
The remaining core of the giant collapses and becomes a white dwarf.
The aging companion star starts swelling, spilling gas onto the white dwarf.
The white dwarf's mass increases until it reaches a critical mass and explodes...
...causing the companion star to be ejected away.





up to 22000 km.s^{-1}
C/O
0.1 M$_\odot$
10 to 15000 km.s^{-1}
Si/S/Ca
0.5M$_\odot$
5 to 10000 km.s^{-1}
^{56}Ni ^{56}Co ^{56}Fe
$T_{1/2}$ = 6d $T_{1/2}$ = 77d
0.8 M$_\odot$
White dwarf
C/O
M ~ 1.4 M$_\odot$
photosphère
© F. Teyssier



Thielemann et al. (2003)
Element mass ejected [M$_\odot$]
10^0
10^{-2}
10^{-4}
10^{-6}
Atomic number
5
10
15
20
25
30
C
O
N
Ne
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn

Modeling Chemical Evolution

To start, let's consider the types of parameters and variables that are involved. First, there are the global variables, all of which are a function of time.

M_g: Total mass of interstellar gas
M_s: Total mass of stars
M_w: Total mass of stellar remnants (white dwarfs)
M_t: Total mass of the system
E: the rate of mass ejection from stars
E_Z: the rate of metal ejection from stars
W: the creation rate of stellar remnants.

Naturally, $M_t = M_g + M_s + M_w$.

Ψ: Rate of star formation
f: Rate of infall or outflow of material from the system
Z_f: Metal abundance of the infall (or outflow) material
$\phi(m)$: the Initial Mass Function

w: the mass of a stellar remnant

τ_m: the main-sequence lifetime of a star

m_{tn}: the turnoff mass of a population with $t = \tau$

p_z: the stellar recyclable mass fraction that is converted to metal z and then ejected into space.

Given the above variables and parameters, the goal is to derive $Z(t)$, the fraction of metals (individually, or as a group) in the interstellar medium as a function of time.

Equations of Chemical Evolution

$$\frac{dM_t}{dt} = f$$

Total mass conservation

$$\frac{dM_s}{dt} = \Psi - E - W$$

Change in stellar mass

$$\frac{dM_g}{dt} = -\Psi + E + f$$

Change in gas mass

$$\frac{dM_w}{dt} = W$$

Change in remnant mass

$$\frac{d(ZM_g)}{dt} = -Z\Psi + E_Z + Z_f f$$

Change in metals:

1) metals locked up in stars
2) metals released by stars
3) metals added from/lost to the external medium

Relate mass return , stellar remnant formation, and metal input rates to stellar parameters

$$E = \int_{m_{tn}}^{m_u} (m - w)\Psi(t - \tau_m)\phi(m, t - \tau_m)dm$$

where m_u is the upper mass limit of the stellar IMF, and m_{tn}, the turnoff mass at time t. Similarly, the equation for the total mass of remnants formed is

$$W = \int_{m_{tn}}^{m_u} w\Psi(t - \tau_m)\,\phi(m, t - \tau_m)dm$$

The equation for E_Z is a bit more complicated since it has two terms: one to represent the amount of *new* metals created by a star and released during mass loss, and a second to represent the amount of metals that were lost from the ISM when the star formed, but are now being re-released. Mathematically, this is

$$E_Z = \int_{m_{tn}}^{m_u} mp_z\Psi(t - \tau_m)\,\phi(m, t - \tau_m)dm +$$

$$\int_{m_{tn}}^{m_u} (m - w - mp_z)Z(t - \tau_m)\Psi(t - \tau_m)\,\phi(m, t - \tau_m)dm$$

Finally, there is an equation of metal conservation. If $\bar{Z}_s$ is the average metal content in stars, then the total amount of metals produced in a galaxy over a Hubble time is

$$\bar{Z}_s M_s + Z M_g = \int_0^t \int_{m_{tn}}^{m_u} m p_z \Psi(t' - \tau_m) \phi(m, t' - \tau_m) dt' dm$$

SIMPLIFICATIONS

1) The initial mass function of stars is independent of time. That is, φ(m,t) = φ(m).

2) Instantaneous recycling approximation. The approximation says that there are two types of stars in a galaxy: those that live forever, and those that evolve and die instantaneously.

Main Sequence Lifetimes

Spectral Type	Mass ($\mathcal{M}/\mathcal{M}_\odot$)	Luminosity ($\mathcal{L}/\mathcal{L}_\odot$)	Lifetime (years)
O5 V	60	7.9×10^5	5.5×10^5
B0 V	18	5.2×10^4	2.4×10^6
B5 V	6	820	5.2×10^7
A0 V	3	54	3.9×10^8
F0 V	1.5	6.5	1.8×10^9
G0 V	1.1	1.5	5.1×10^9
K0 V	0.8	0.42	1.4×10^{10}
M0 V	0.5	0.077	4.8×10^{10}
M5 V	0.2	0.011	1.4×10^{11}

Note the values. Stars with $\mathcal{M} > 5\mathcal{M}_\odot$ evolve in less than 10^8 years, which, in cosmological terms, is almost instantaneously. On the other hand, stars with mass less than about $1\mathcal{M}_\odot$ live forever. So the approximation only breaks down for a limited mass range.

Let's choose m_1 to be the dividing line between stars that live forever, and stars that evolve instantaneously. Let's also define three new quantities, the **Return fraction** of gas

$$R = \int_{m_1}^{\infty} (m - w)\phi(m)dm$$

the **Baryonic Dark Matter fraction**

$$D = \int_{m_1}^{\infty} w\phi(m)dm$$

and the **Net Yield** (of element i)

$$y_i = \frac{1}{1-R}\int_{m_1}^{\infty} mp_z\phi(m)dm$$

It can then be shown that $E = R\,{}^{9}\Psi$, $W = D\,\Psi$, and

$$E_Z = \Psi\left\{ZR + y_z(1-R)\right\}$$

With our two assumptions, the equations of chemical evolution become

$$\frac{d\mathcal{M}_t}{dt} = f$$

$$\frac{d\mathcal{M}_s}{dt} = (1 - R - D)\Psi$$

$$\frac{d\mathcal{M}_g}{dt} = -(1 - R)\Psi + f$$

$$\frac{d\mathcal{M}_w}{dt} = D\Psi$$

$$\frac{d(Z\mathcal{M}_g)}{dt} = -Z\Psi(1 - R) + y_z\Psi(1 - R) + Z_f f$$

Noting that:

$$\frac{d(Z\mathcal{M}_g)}{dt} = Z\frac{d\mathcal{M}_g}{dt} + \mathcal{M}_g\frac{dZ}{dt}$$

Substituting for dM_g/dt then yields

$$\mathcal{M}_g\frac{dZ}{dt} = y_z\Psi(1 - R) + (Z_f - Z)f$$

The Closed Box Model of Chemical Evolution

As an example of what a chemical evolution model can do, consider a closed system, where all the material for current star formation comes from mass lost by a previous generation of stars. In this case, there is no infall, and, from (9.23),

$$\mathcal{M}_g \frac{dZ}{dt} = y_z \Psi(1 - R) + (Z_f - Z) f = y_z \Psi(1 - R)$$

In addition,

$$\frac{d\mathcal{M}_g}{dt} = -(1 - R)\Psi + f = -(1 - R)\Psi$$

By dividing these two equations, we get

$$\mathcal{M}_g \frac{dZ}{dt} \Bigg/ \frac{d\mathcal{M}_g}{dt} = \mathcal{M}_g \frac{dZ}{d\mathcal{M}_g} = -y_z$$

Since y_z is a constant of stellar evolution

$$\int_{Z_0}^{Z_1} dZ = -y_z \int_{\mathcal{M}_{g0}}^{\mathcal{M}_{g1}} \frac{d\mathcal{M}_g}{\mathcal{M}_g} \Longrightarrow \boxed{Z_1 - Z_0 = -y_z \ln\left(\frac{\mathcal{M}_{g0}}{\mathcal{M}_{g1}}\right)}$$

where Z_0 and $\mathcal{M}_{g_0}$ represent the initial metallicity and gas mass of the galaxy, and Z_1 and $\mathcal{M}_{g_1}$ represent those quantities today.

Note that if we measure gas-phase metallicities and gas masses for galaxies, we can deduce the net yield y_Z. If the closed box model is correct, y_Z should be constant, i.e. A TEST

Prediction 2: Metallicity distribution of stars

Define $\mu = M_g/M_t$, $\sigma = M_s/M_t$ The closed-box solution gives:

$$\mu_1 = \mu_0 \exp\left\{-\frac{Z_1 - Z_0}{y_z}\right\}$$

In other words, as the system evolves, the gas fraction will decrease exponentially with Z.

Take the derivative with respect to Z:

$$\frac{d\mu}{dZ} = -\frac{\mu_1}{y_z} \exp\left\{-\frac{Z_1 - Z_0}{y_z}\right\}$$

$$\frac{d\mathcal{M}_s}{dt} \Big/ \frac{d\mathcal{M}_g}{dt} = \frac{d\sigma}{d\mu} = -\frac{(1-R-D)}{(1-R)}$$

so

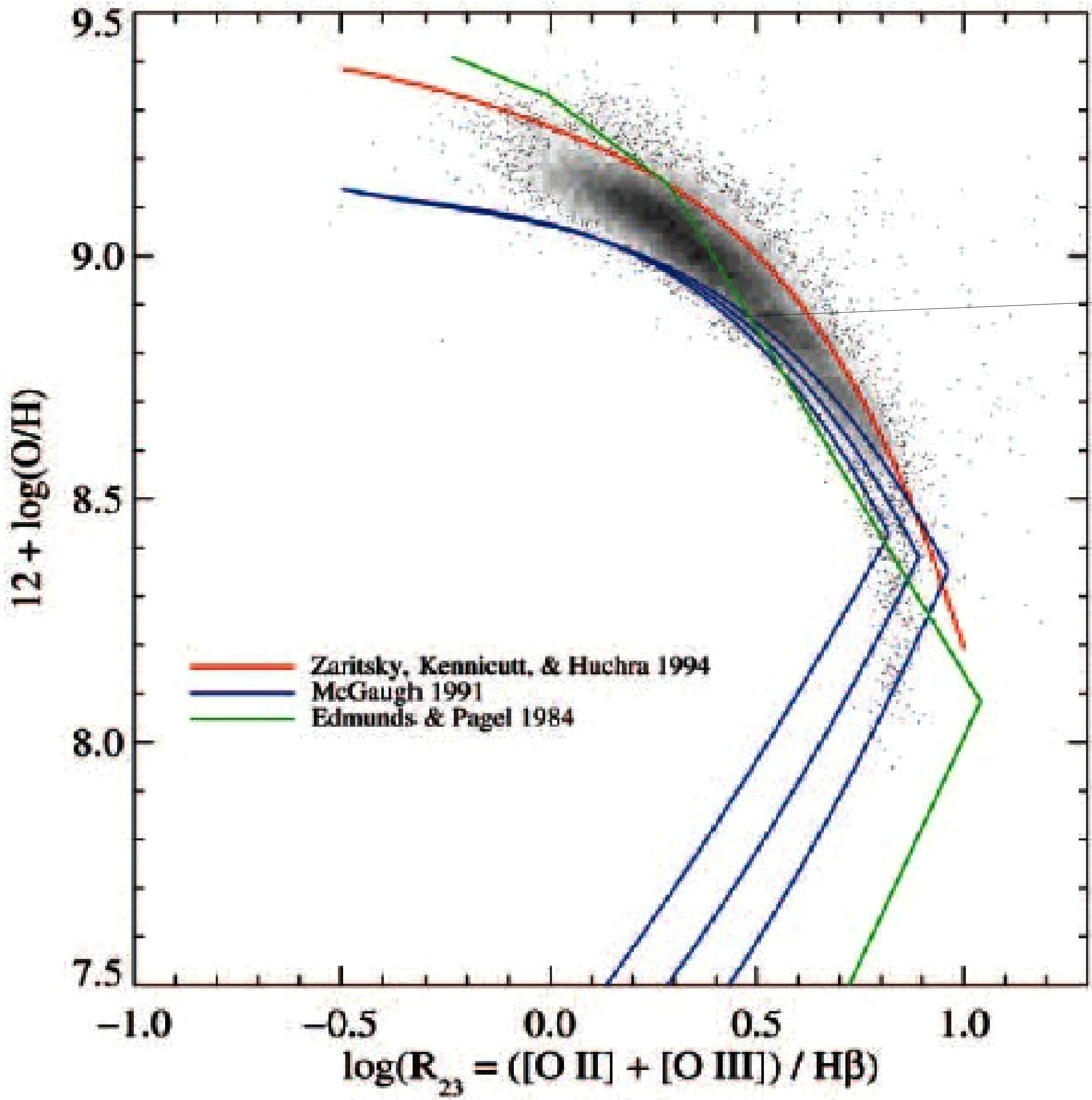
$$\frac{d\sigma}{dZ} = \left(\frac{d\mu}{dZ}\right)\left(\frac{d\sigma}{d\mu}\right) = \left(\frac{\mu}{y_z}\right)\left(\frac{1-R-D}{1-R}\right)\exp\left\{-\frac{Z_1-Z_0}{y_z}\right\}$$

Finally, if we put this equation in terms of $\log Z$, instead of Z, then

$$\boxed{\frac{d\sigma/\sigma_1}{d\log Z} = (\ln 10)\left(\frac{Z_0}{y_z}\right)\left(\frac{1-R-D}{1-R}\right)\left(\frac{\mu_1}{\sigma_1}\right)\exp\left\{-\frac{Z_1-Z_0}{y_z}\right\}}$$

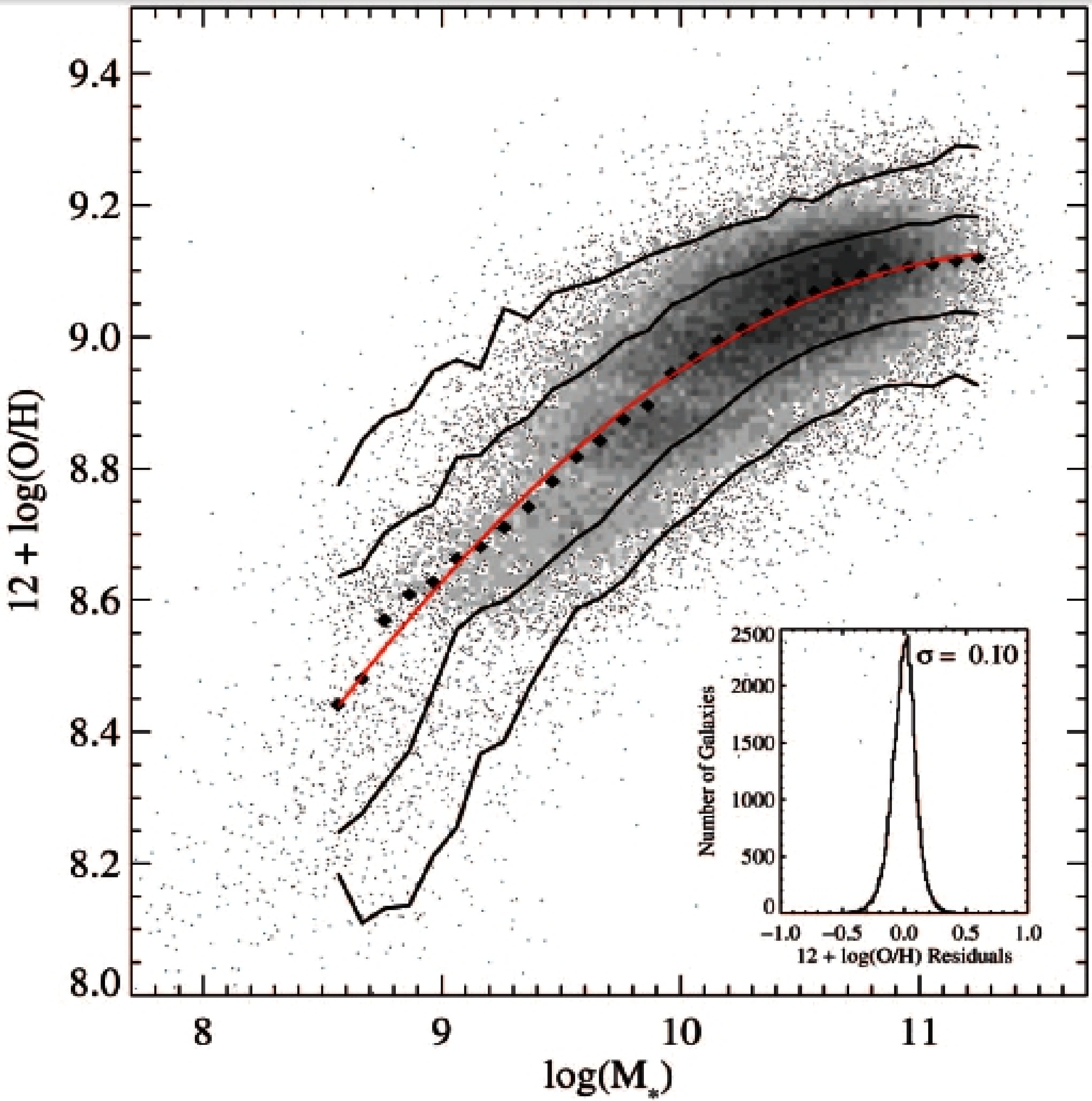
Predicted metallicity distribution of stars

Measurement of gas-phase metallicities through nebular emission lines



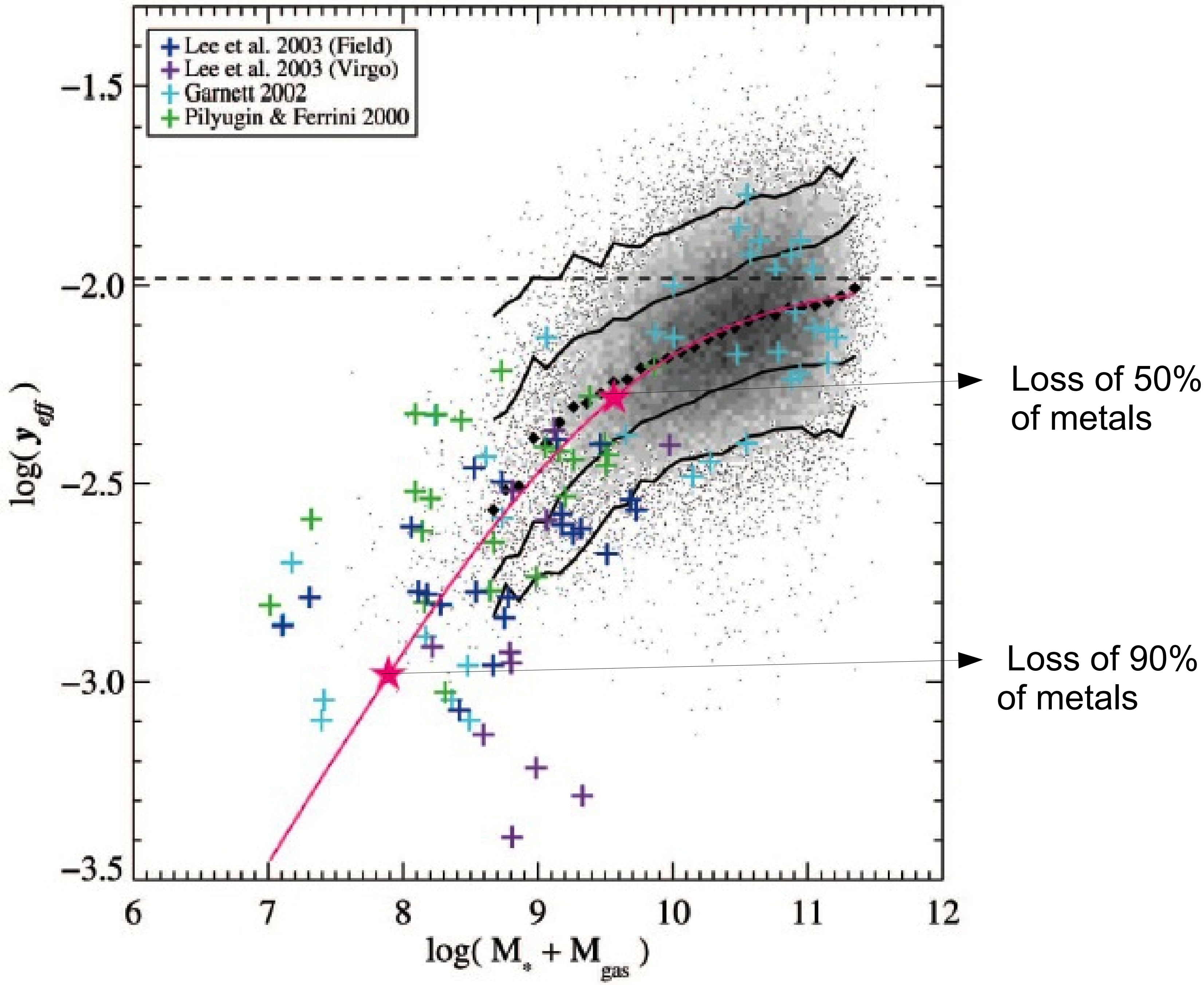
Calibration of metallicity using photo-ionization models

RELATION BETWEEN GAS-PHASE METALLICITY AND STELLAR MASS

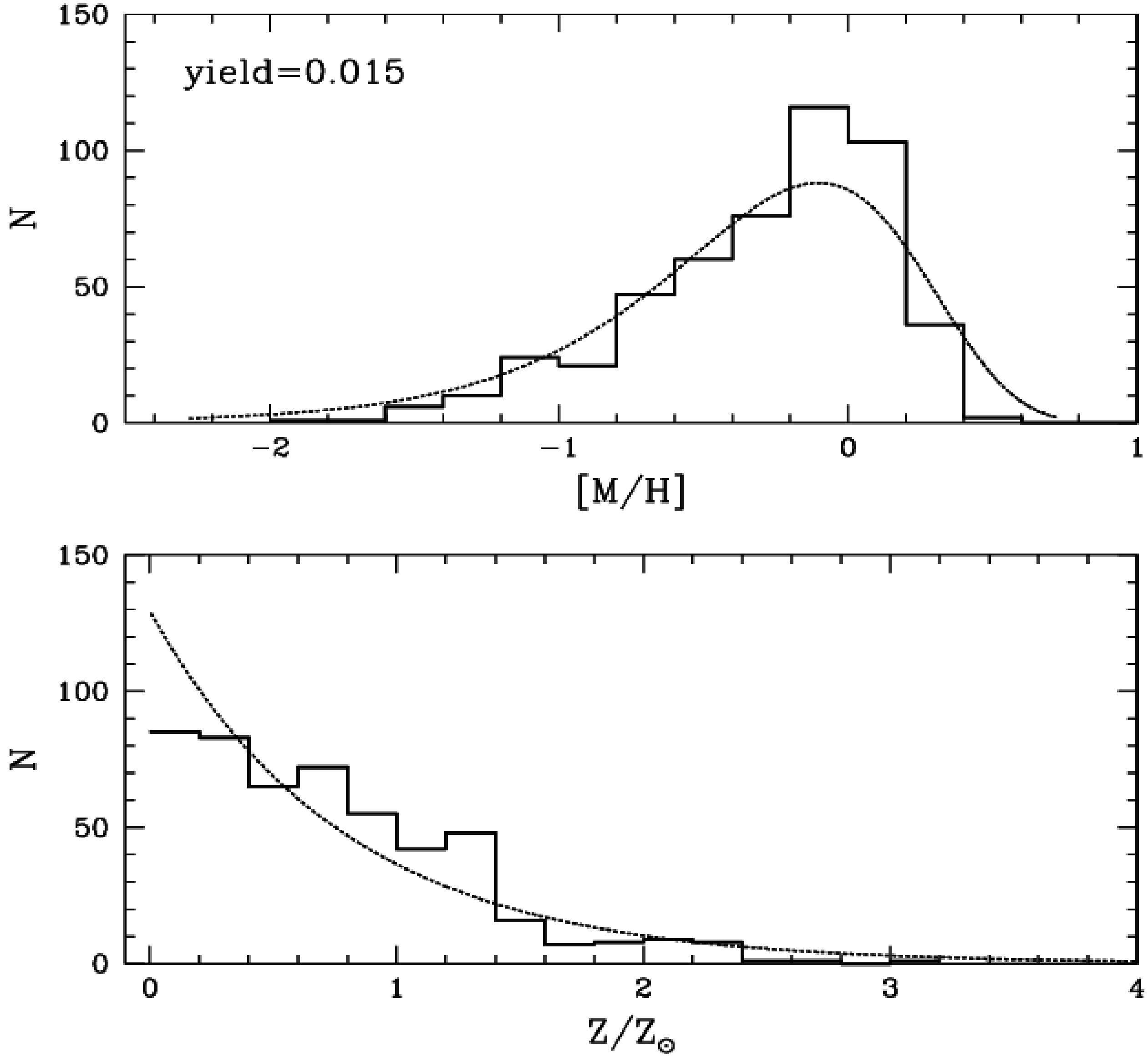


The net yield decreases in low mass galaxies, indicating

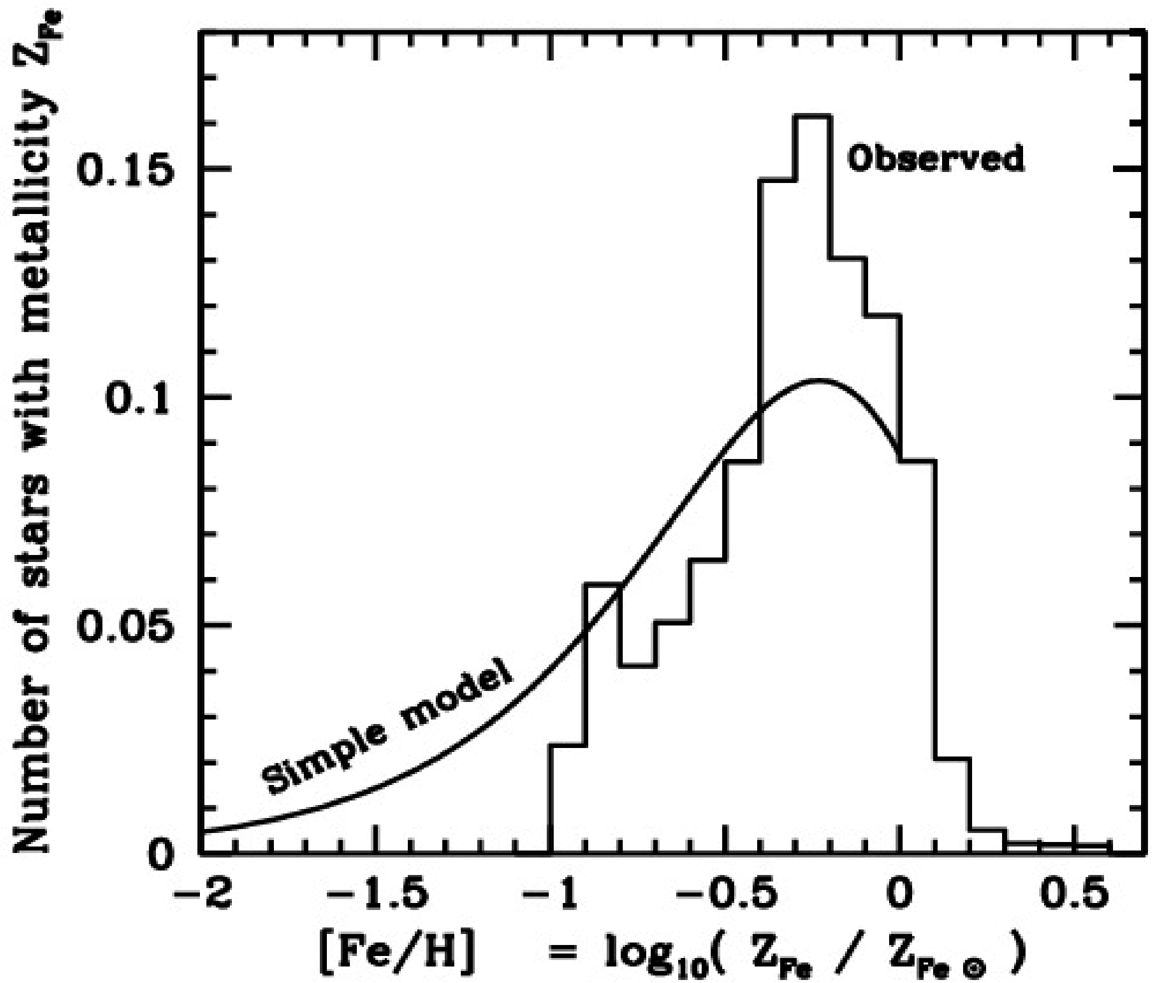
LOSS OF METALS



Metallicity distribution of bulge stars follows prediction of closed-box model

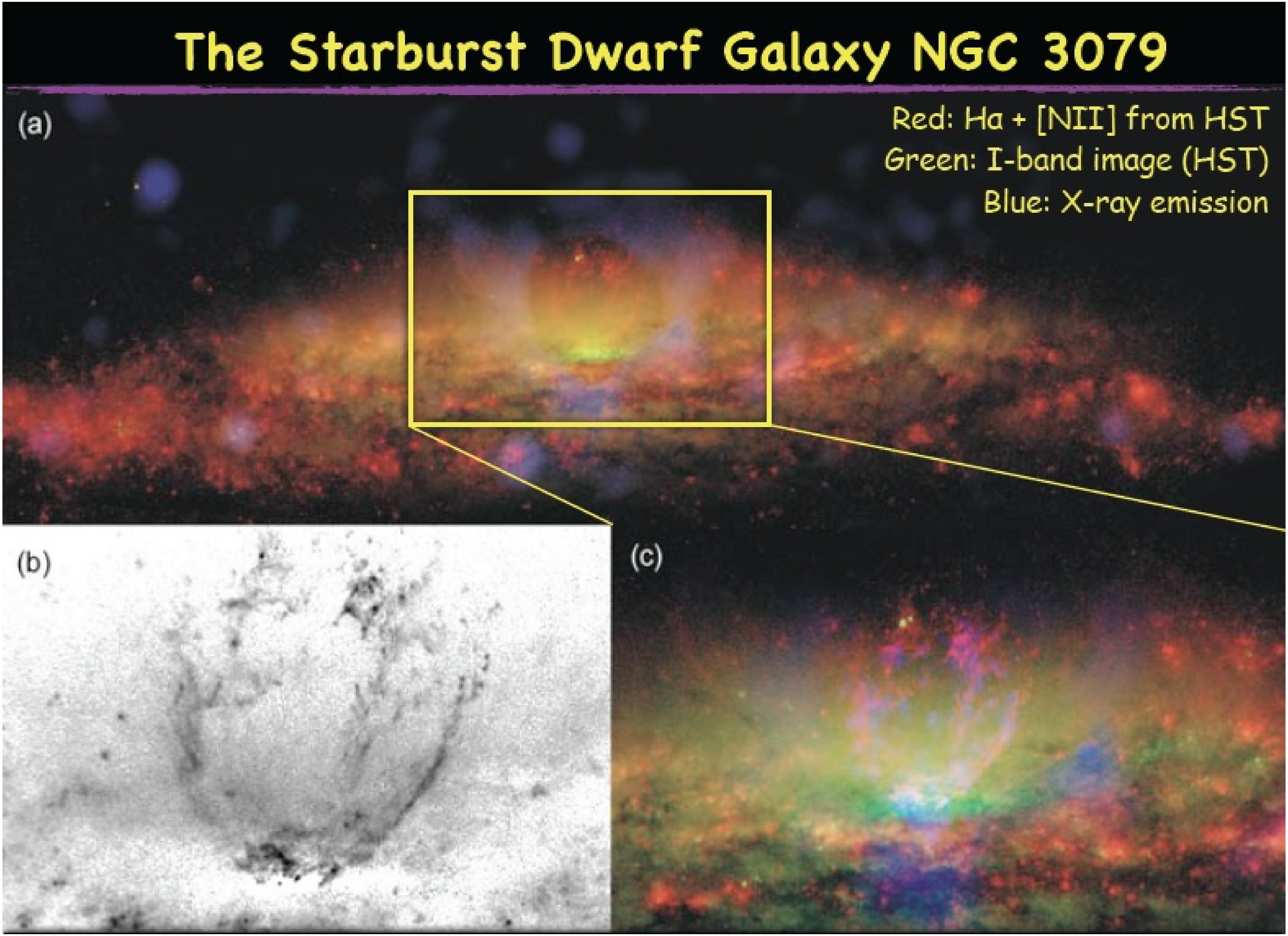


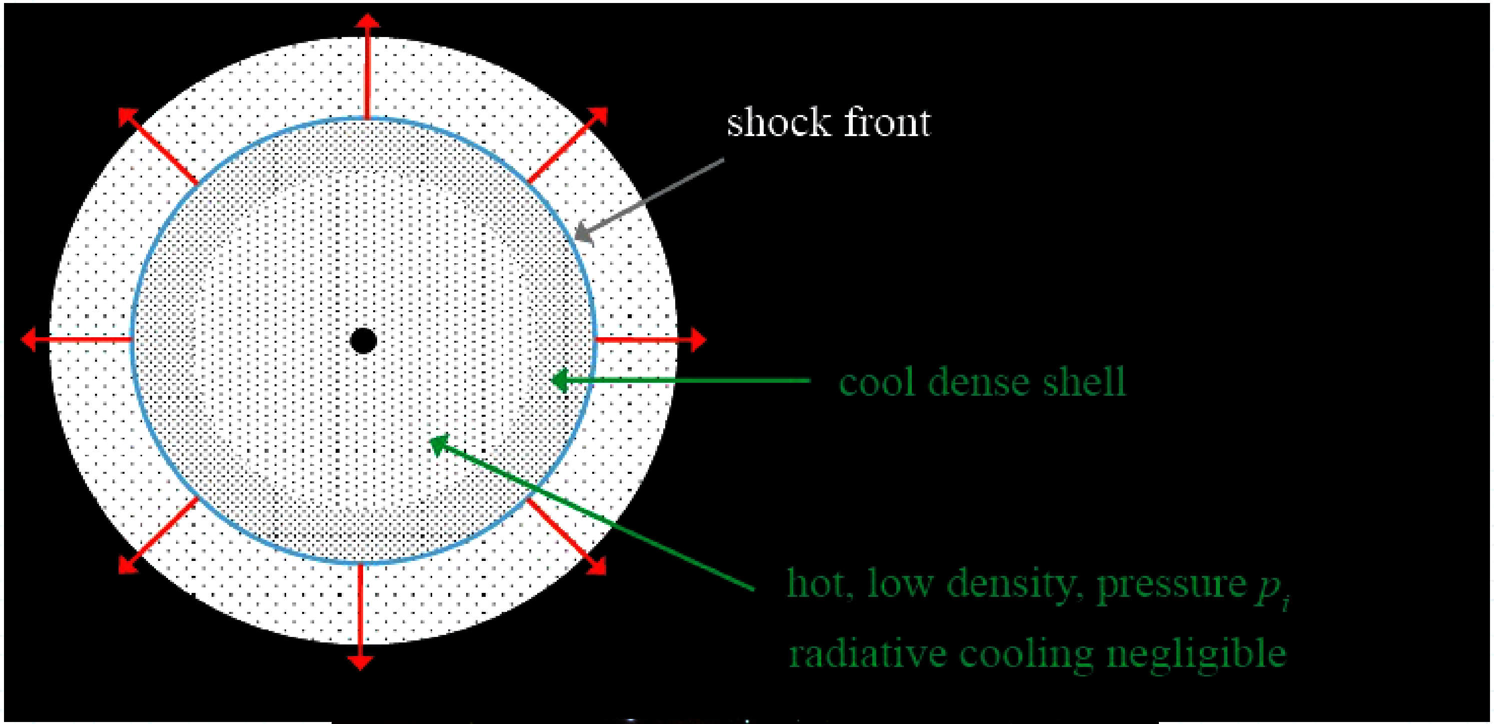
The metallicity distribution of disk stars does not....



The observed differential metallicity distribution for stars in the solar neighbourhood, compared with the Simple Model prediction for $p = 0.010$ and $Z_1 = Z_\odot = 0.017$. [The observed distribution uses data from Kotoneva et al., M.N.R.A.S., 336, 879, 2002, for stars in the Hipparcos Catalogue.]

Expulsion of gas and metals from galaxies occurs as a result of a **galactic wind** powered by many supernovae explosions


The Starburst Dwarf Galaxy NGC 3079
(a)
Red: Ha + [NII] from HST
Green: I-band image (HST)
Blue: X-ray emission
(b)
(c)


shock front
cool dense shell
hot, low density, pressure p_i
radiative cooling negligible

Summary phases of supernova shell expansion

1. Early phase ($m_{swept} < m_{ejecta}$):

   Free expansion, $R_s = v_s\, t$

2. Sedov phase ($m_{swept} > m_{ejecta}$ and $t < t_{rad}$):

   Energy conservation, $R \propto t^{2/5}$

3. Radiative "snowplow" phase ($t > t_{rad}$):

   Momentum conservation, $R \propto t^{1/4}$ or $R \propto t^{2/7}$

4. Merging phase:

The kinetic energy of the shell is now transferred to the ISM. Detailed calculations show that the kinetic energy at fading is ~0.01 of the initial explosion energy

In this scenario $\varepsilon_{SN} \sim 0.01$; almost all SN energy is radiated away...

Towards Higher Efficiency: Overlapping SNRs

In order to make SN feedback more efficient, one needs to ensure that another SN goes off inside the SNR before it has radiated away most of its energy.

This requires a SN rate $\boxed{\zeta\,\dot{\rho}_* \geq \dfrac{3}{4\pi R_{\rm SN}^3\, t_{\rm SN}}}$

If we set R_{SN} and t_{SN} to be the shock radius and time at the onset of the radiative phase, i.e., $t_{SN} = t_{rad}$ and $R_{SN} = r_{sh}(t_{rad})$, and we write $\dot{\Sigma}_* = \dot{\rho}_*/2H$ with H the scale-height of the disk, then we obtain

$$\boxed{\dot{\Sigma}_* > 18.3\, M_\odot {\rm kpc}^{-2} {\rm yr}^{-1} \left(\frac{H}{0.2\,{\rm kpc}}\right) \left(\frac{\zeta}{10^{-2} M_\odot^{-1}}\right)^{-1} \left(\frac{n_{\rm H}}{{\rm cm}^{-3}}\right)^{1.82}}$$

SuperNova Feedback (ejection)

To get a feel for whether the energy input from SN can be relevant for galaxy formation, imagine ejecting a mass $M_{\rm ej}$ from the center of a NFW dark matter halo.

This requires an energy injection of $E_{\rm ej} = \frac{1}{2} M_{\rm ej} V_{\rm esc}^2$. Using that, to a good approximation, the escape velocity from the center of a NFW halo is $V_{\rm esc} \simeq \sqrt{6\,c}\,V_{\rm vir}$ where c is the halo concentration parameter, we have that $E_{\rm ej} \simeq 3\,c\,M_{\rm ej}\,V_{\rm vir}^2$

The energy available from SN is $\boxed{E_{\rm fb} = \varepsilon_{\rm SN}\,\zeta\,M_*\,E_{\rm SN}}$

$\varepsilon_{\rm SN} \leq 1$ = fraction of SN energy available for feedback (not just radiated away)

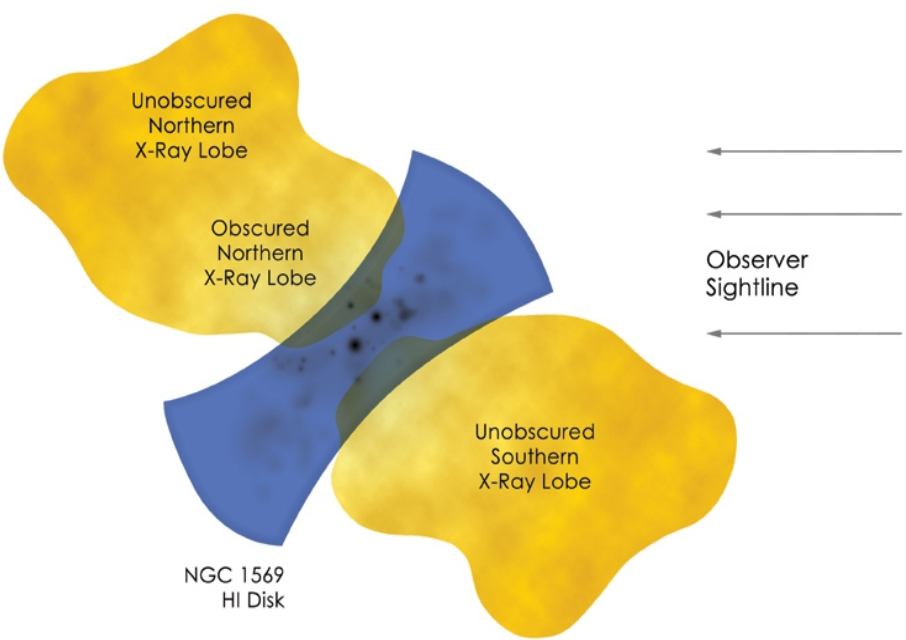
$\zeta \simeq 0.01\,M_\odot^{-1}$ = number of SN produced per Solar mass of stars formed (IMF dependent)

$E_{\rm SN} \simeq 10^{51}\,{\rm erg}$ = energy supplied per SN

Equating $E_{\rm fb}$ to $E_{\rm ej}$ we obtain that $\boxed{\frac{M_{\rm ej}}{M_*} \simeq 0.4\,\varepsilon_{\rm SN} \left(\frac{c}{10}\right)^{-1} \left(\frac{V_{\rm vir}}{200\,{\rm km/s}}\right)^{-2}}$

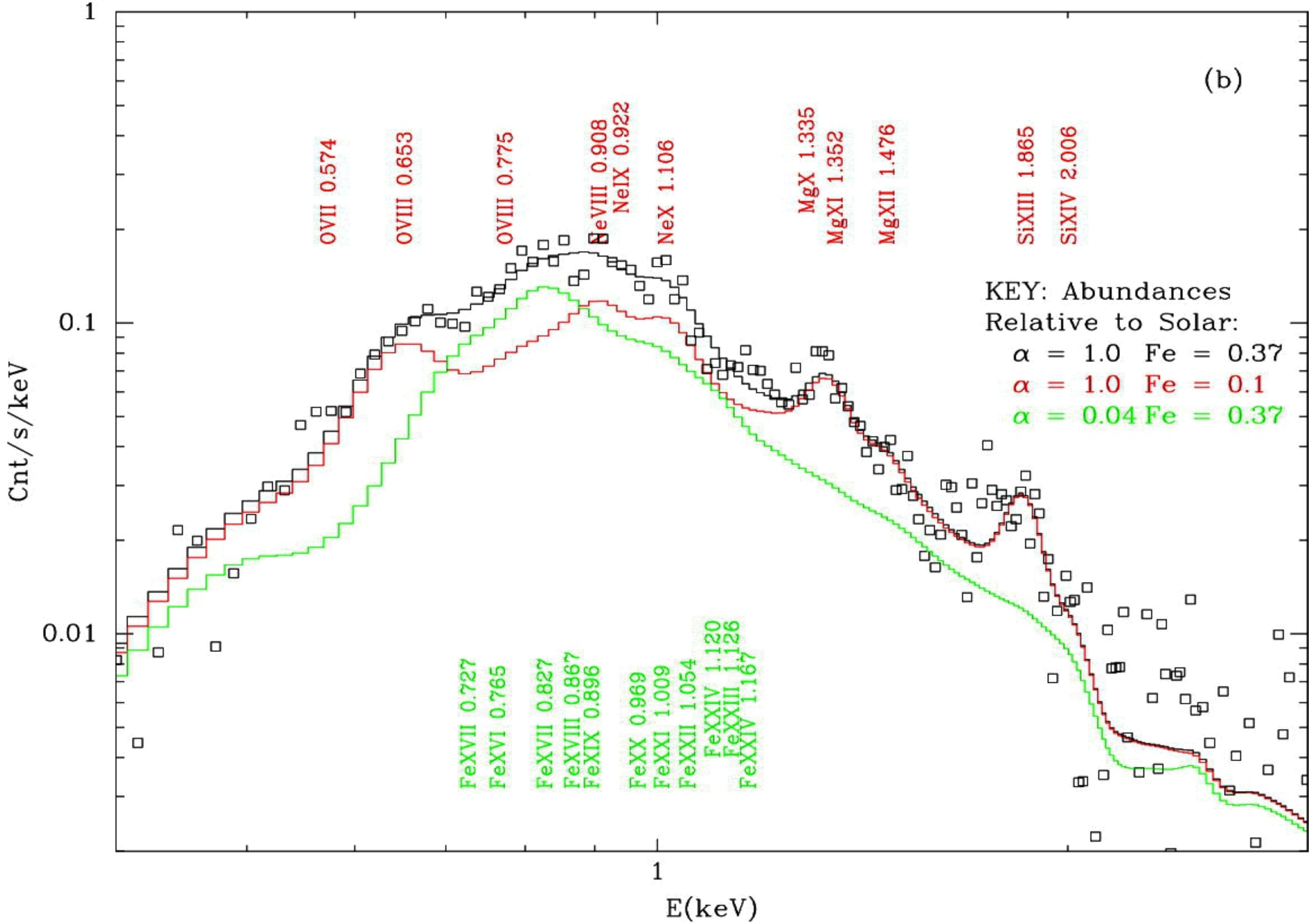
Hence, even if 100% of the SN energy can be converted into kinetic energy of a galactic wind, SN can only eject about 40% of the stellar mass from a MW-sized halo.

This efficiency increases with decreasing halo mass; for $V_{\rm vir} = 50\,{\rm km/s}$ we have that $M_{\rm ej} \leq 6.4\,M_*$.



Direct observational evidence that these galactic winds drive metals out of the galaxy.

Through X-ray Spectroscopy: tight contraints on relative abundances of elements produced in Type II supernova explosions.



Temperature of hot gas around starburst galaxies constant as a function of the mass/rotation speed of the galaxy: this means gas is too hot to be in virial equilibrium with the dark matter halo of the smaller systems ==> escape