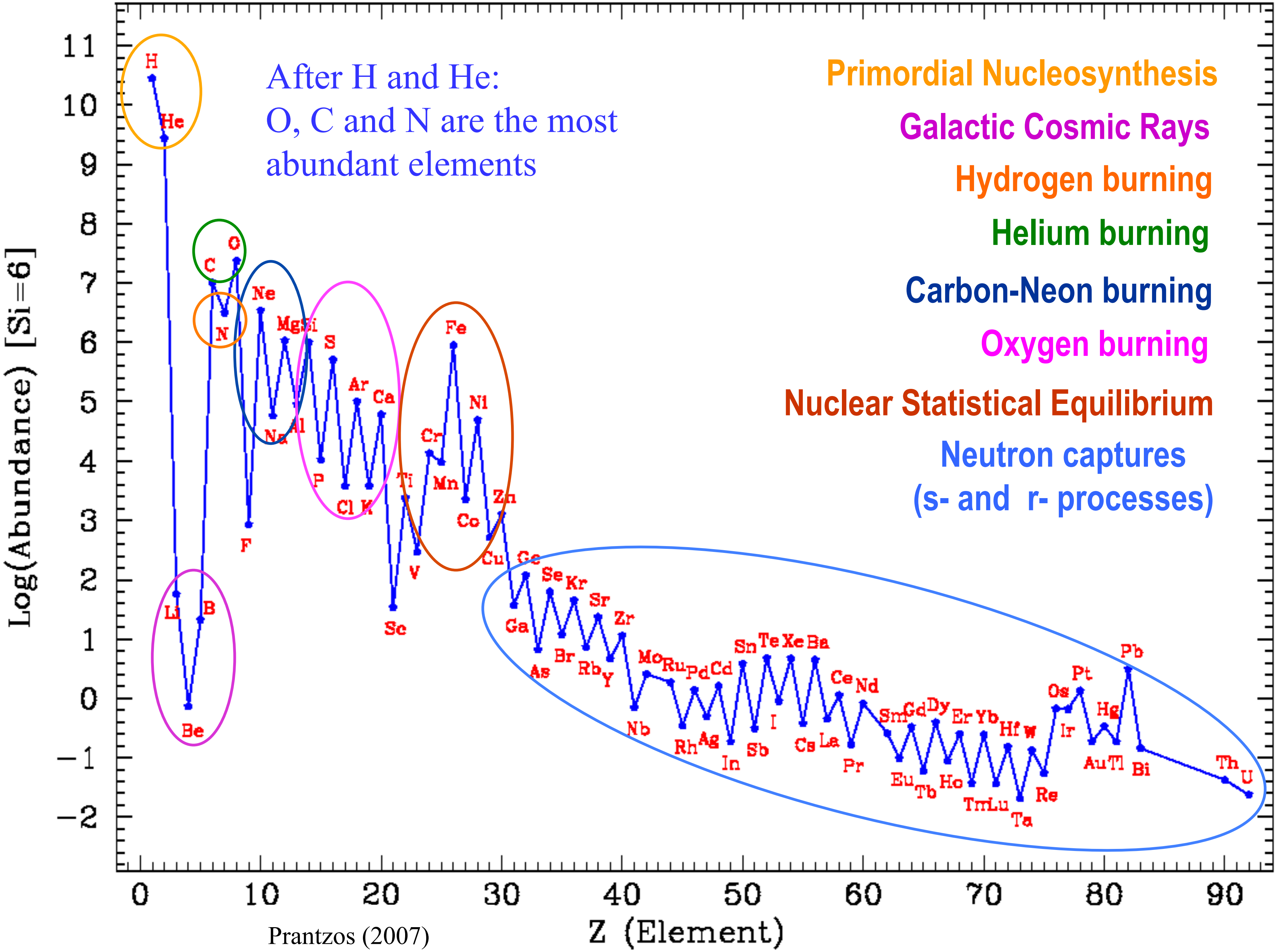
Lecture II

Different contributors to CE
Stellar yields



After H and He:
O, C and N are the most
abundant elements

Primordial Nucleosynthesis

Galactic Cosmic Rays

Hydrogen burning

Helium burning

Carbon-Neon burning

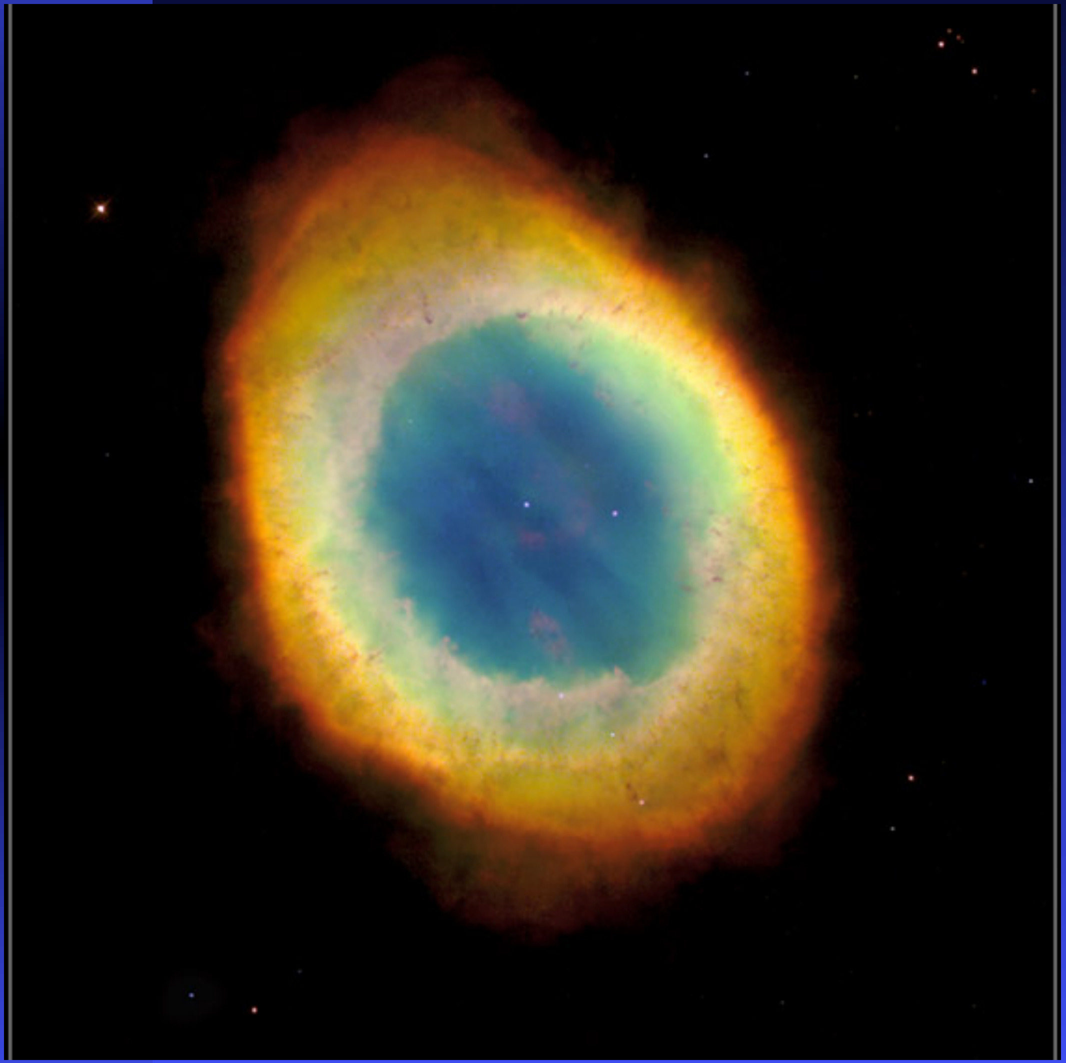
Oxygen burning

Nuclear Statistical Equilibrium

Neutron captures
(s- and r- processes)

Prantzos (2007)

Low and intermediate- mass stars: 0.8 - 8 M⊙



Long time-scales

30 Myr - several Gyr

^{3}He, ^{7}Li

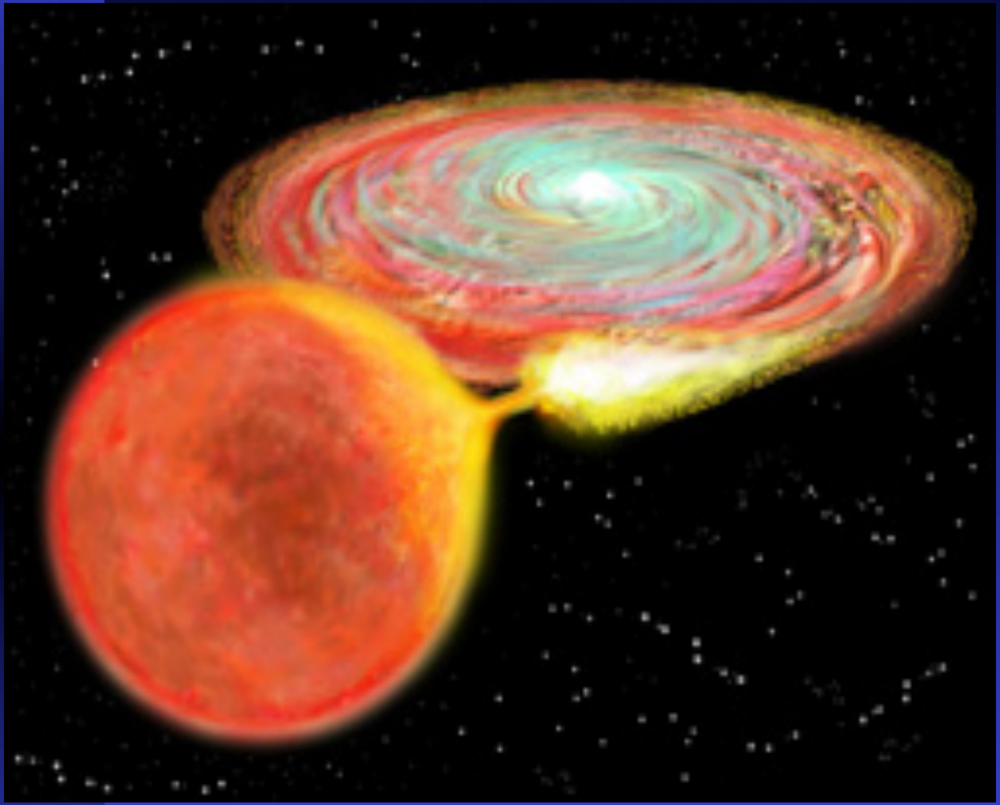
C, N, ^{4}He,

Heavy s-process elements

Death:

- C-O white dwarfs, when single
- Type Ia SNe when binaries (some)

SNIa



Long time-scales
30 Myr - several Gyr

Mainly Iron
(some S, Si, Ar, Ca)

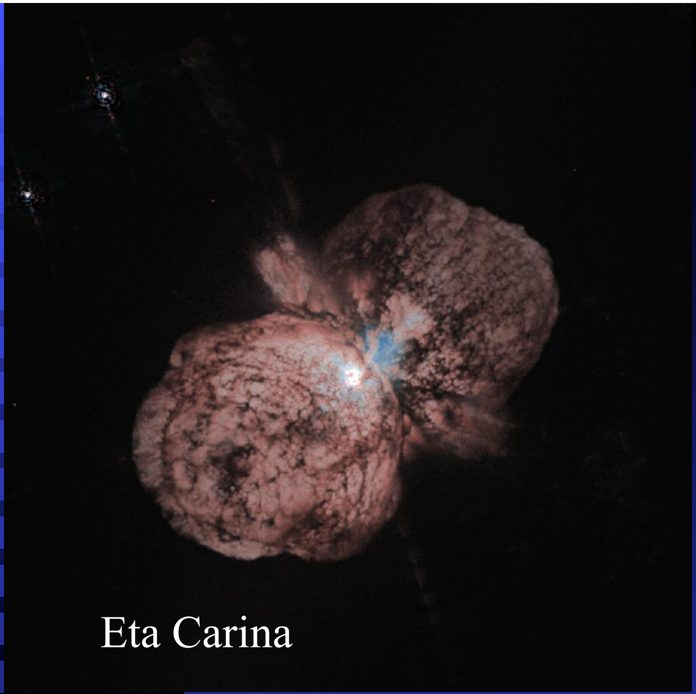
Double Degenerate scenario
Single Degenerate scenario

Type Ia SN progenitors

- ✓ Single-degenerate scenario (Whelan & Iben 1974; Han & Podsiadlowsky 2004) : a binary system with a C-O white dwarf plus a MS star. When the star becomes RG it starts accreting mass onto the WD. When the WD reaches the Chandrasekhar mass it explodes by C-deflagration as Type Ia supernova
- ✓ Double-Degenerate scenario (Iben & Tutukov, 1984) : two C-O WDs merge after loosing angular momentum due to gravitational wave radiation. When the two WDs of 0.7 M⊙ merge, the Chandrasekhar mass is reached and C-deflagration occurs.

The nucleosynthesis is similar in the two scenarios, but models uncertain!

Massive stars - M > 8-10 M⊙

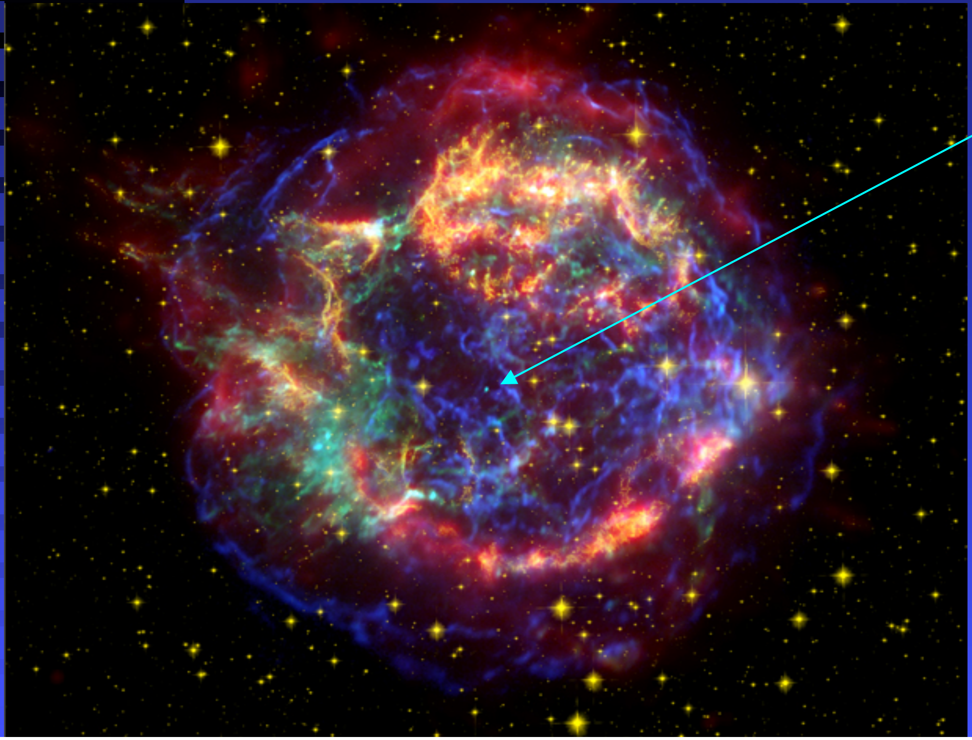


Eta Carina

Short time-scales

3-30 Myr

Mainly alphas (e.g. O), some Fe, light s-process elements, and r-process elements



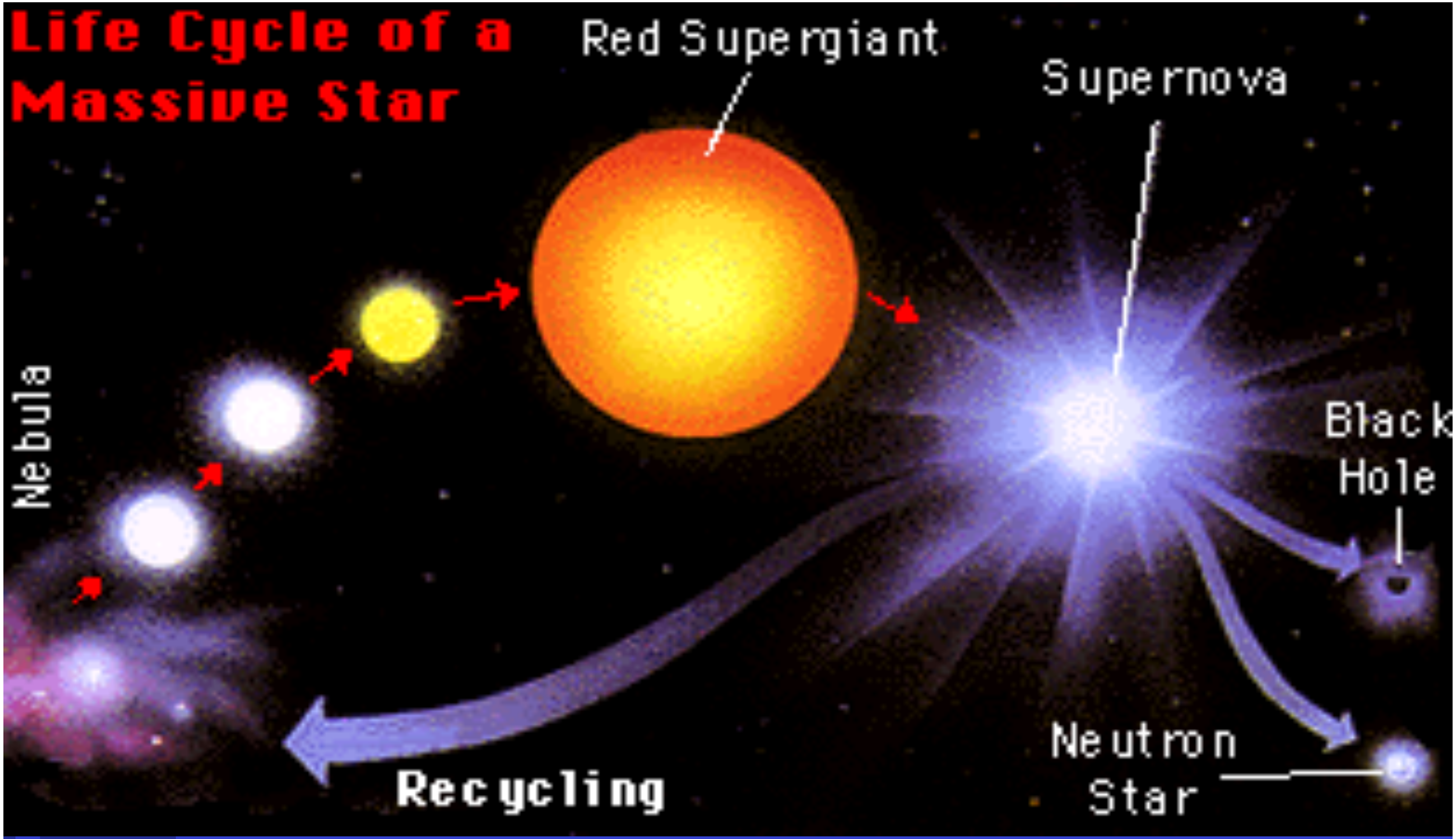
Neutron star

Death:

- Core collapse SNe
- Leave a Neutron stars or Black hole

Cassiopeia A - 300-year-old remnant of SN

IR Spitzer (red) + Optical Hubble (yellow) + X-ray Chandra (green and blue)



Type II SNe: Core collapse of massive stars (M=8-40 M⊙)

Type Ib/c SNe: Core collapse SNe from more massive progenitors (linked to gamma-ray bursts)

Comparison of the contribution of SNIa x SNII in M⊙ (weighted by Salpeter IMF - 10-50 M⊙)

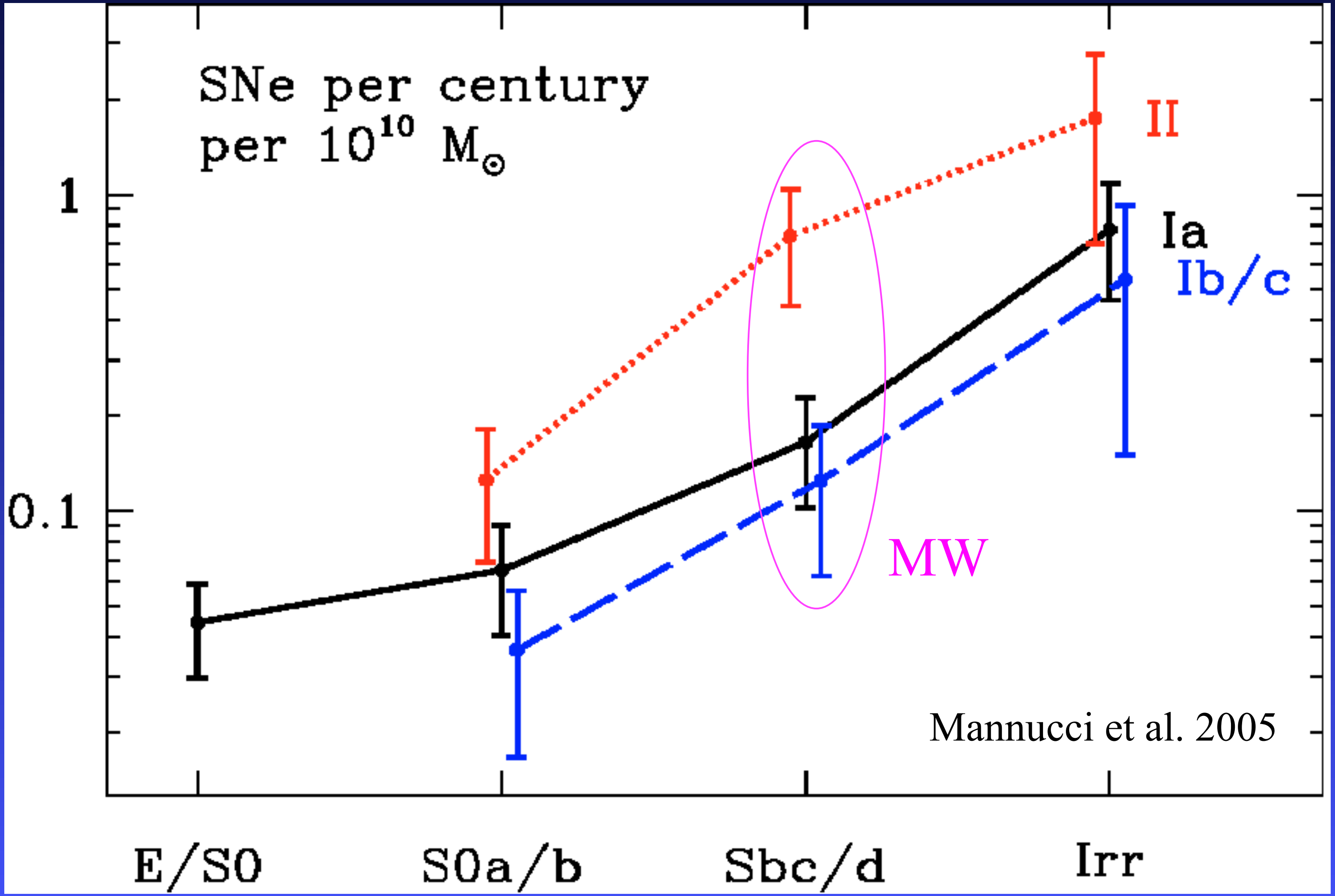
Element	SNIa (W7)	SNII (TNH95)
C	0.048	0.057
O	0.148	1.777
Ne	0.005	0.232
Mg	0.009	0.118
Si	0.153	0.133
S	0.086	0.040
Fe	0.744	0.121

+ Low and Intermediate Single mass stars

Table from Matteucci 2001

SNIa make 60% of the Fe in the Sun

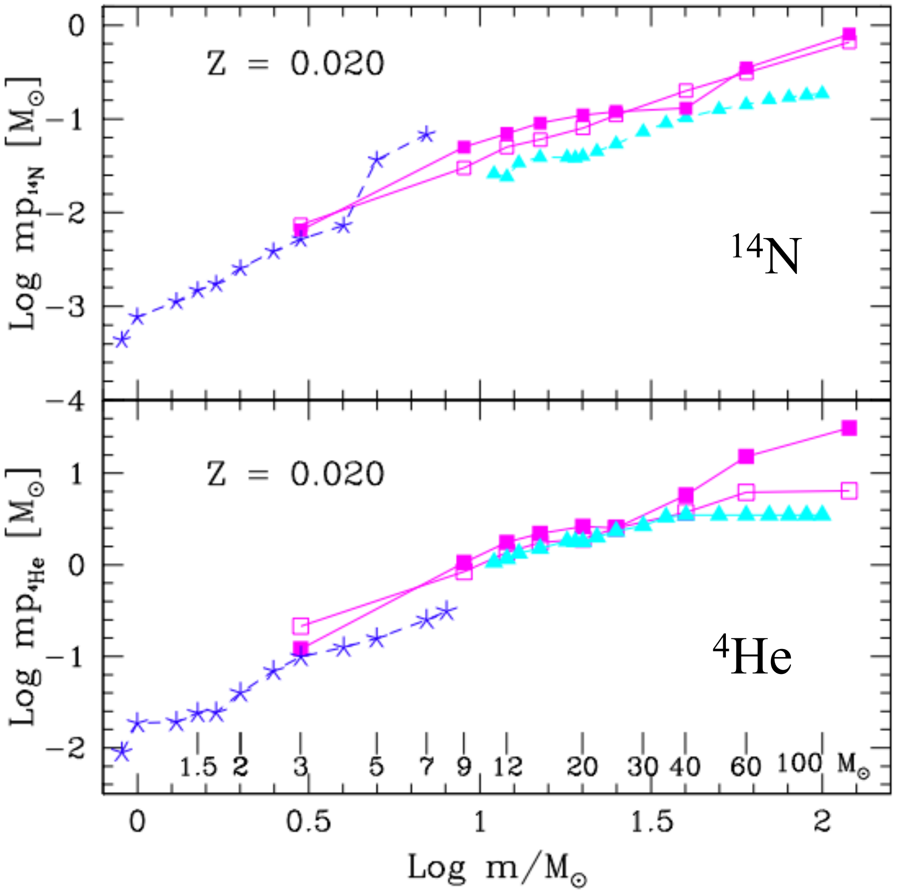
Core Collapse SNe (II+Ibc) = 5 x SNIa in Sbc Galaxy (MW).
But each SNIa produces ~7 times more Fe than a CCSN



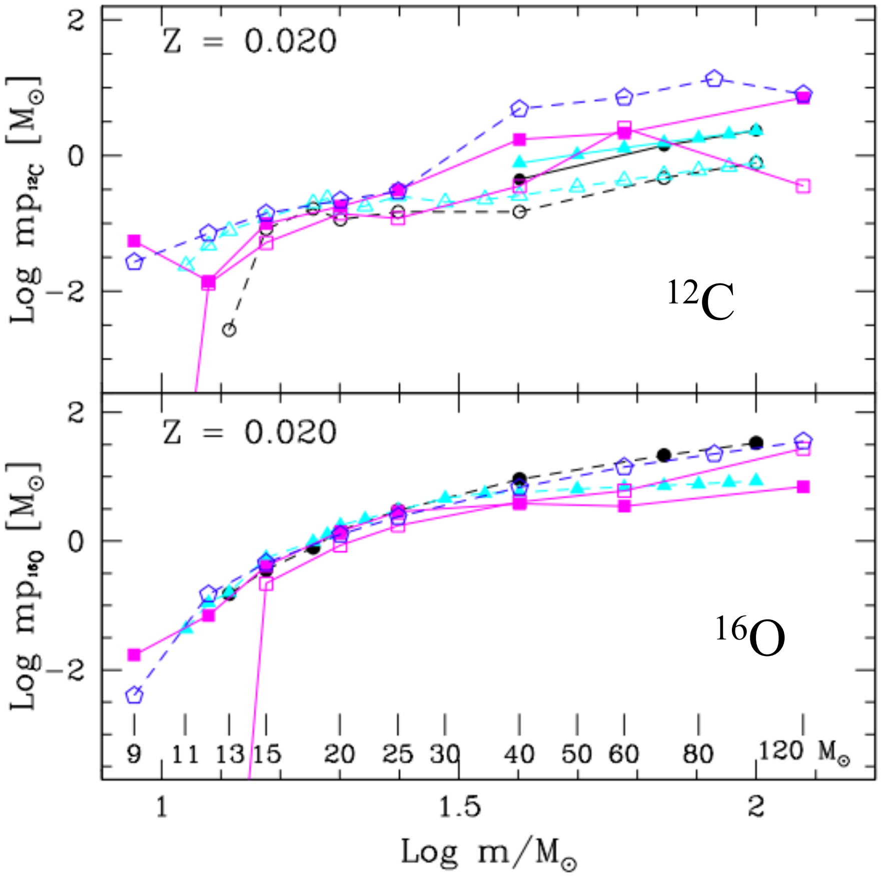
Mannucci et al. 2005

Building a CEM: Stellar Yields

All masses



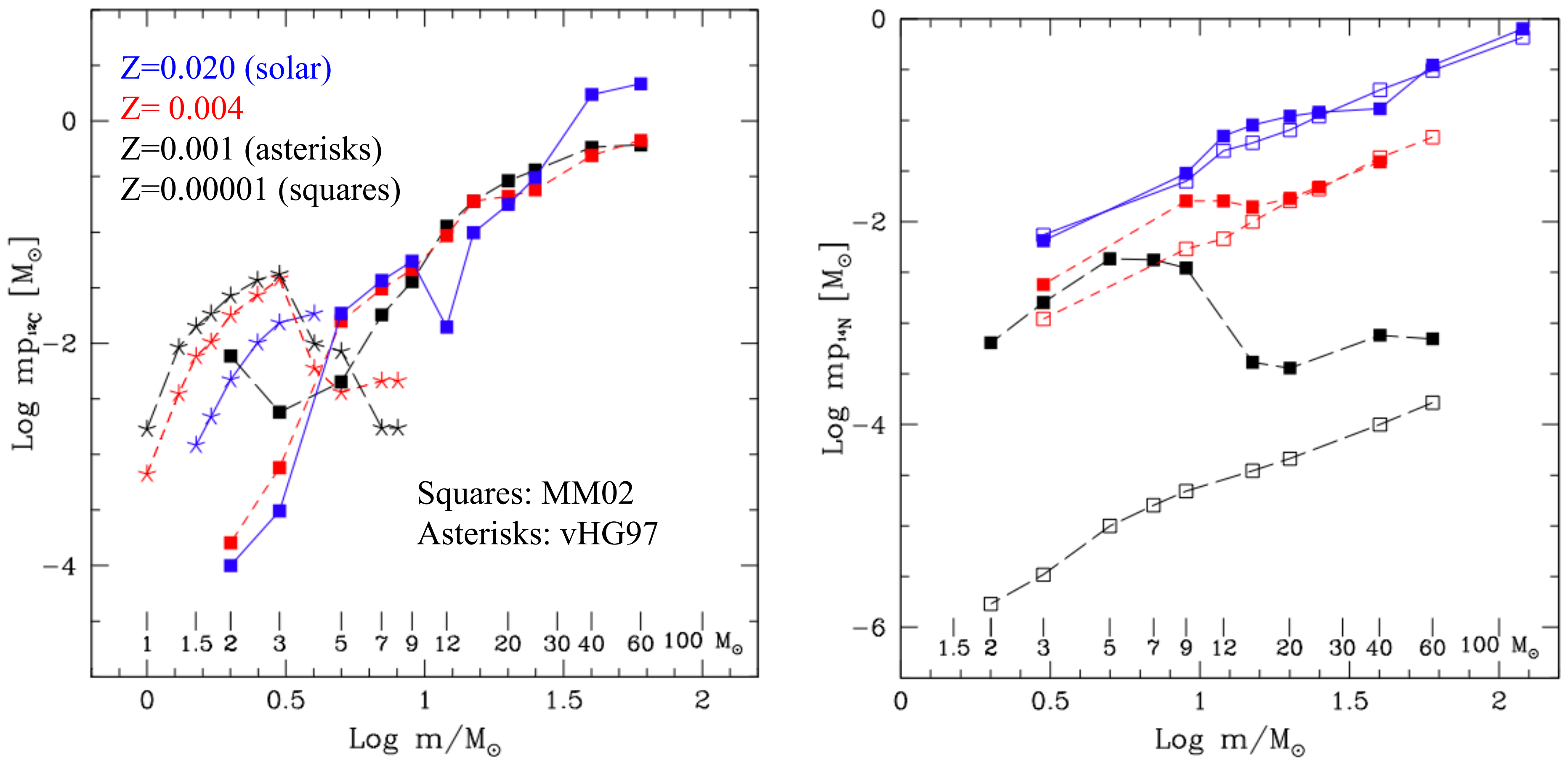
Massive Stars



- ✓ MM02, V_{rot}=0 (open squares)
- ✓ MM02, V_{rot}=300km/s (filled squares)
- ✓ Thielemann et al. 1996 (open circles)
- ✓ Woosley & Weaver 1995 (triangles)

- ✓ vHG97 (asterisks)
- ✓ Maeder (1992) (open pentagons)

Rotation: increases C & N production at low Z



Z=0.020 (solar)
Z= 0.004
Z=0.001 (asterisks)
Z=0.00001 (squares)

Squares: MM02
Asterisks: vHG97

Open squares: MM02 with V_{rot}=0km/s
Filled squares: MM02 with V_{rot}=300km/s

Chiappini, Matteucci, Meynet 2003 (MM02=Meynet&Maeder 2002; vHG97=van den Hoek & Groeneweegen 1997)

Lecture II

Simple Chemical Evolution Models

(analytical solutions)

Time evolution of the mass fraction of element *i* in the gas of a galaxy

$dM_{tot}/dt = A(t) - W(t)$

A = Accretion rate

W = outflow rate - Winds

$dM_g/dt = \boxed{-\psi(t)} + \boxed{E(t)} + A(t) - W(t)$

$M_{tot} = M_g + M_s$

Gas consumed to form stars

Gas restored by the stars back into the ISM

For *i*: $d(X_iM_g)/dt = -\psi(t)X_i(t) + \boxed{E_i(t)} + X_{iA}A_i(t) - X_iW_i(t)$

$\Sigma X_i(t) = 1$

Usually $W_i(t) = 0$ for MW disk, $W_i(t) \neq 0$ for dSph and Es

$W_i(t) = w_i\,\psi(t)$

w_i is a constant describing the efficiency of the galactic wind

Often infall is assumed to be exponential with a characteristic timescale

$A(t) = a\,e^{-t/\tau}$

And primordial composition

τ can be a function of R - galactocentric distance

The rate of mass ejection by dying stars

$$E(t) = \int_{M_t}^{M_U} (m - C_m)\ \psi(t-\tau_m)\ \phi(m)\ dm$$

Weighted by the IMF

Over all stars that have time to die before t: From Mu to the smallest mass with $\tau = t$, and $m=Mt$

Ejected mass by star of mass m

Born at time t - tm and dying at time t: tm < t

$Oi = Y_i(m) / [(m - Cm)\ X_i(t-tm)]$

Production factors that can be calculated for different metallicities Z (where Z is the summ of all *i*s heavier than helium).

The rate of ejection of element *i* by dying stars

$$E_i(t) = \int_{M_t}^{M_U} [(m - C_m)\ X_i(t-\tau_m) + Y_i]\ \psi(t-\tau_m)\ \phi(m)\ dm$$

Already present in the star

Newly produced by the star

Y_i = the mass ejected in the form of newly produced element *i* by a star of mass *m*

Analytical Solutions: The close box model + I.R.A.

$M_{gas}(0) = M_{tot}$; $A(t)=W(t)=0$

$\mu = M_{gas}/M_{tot}$

$$dX_iM_g/dt = -X_i\,\psi(t) + E_i(t)$$

$$E_i(t) = \int_{M_t}^{M_U} [(m - C_m)\,X_i(t-\tau_m) + Y_i]\,\psi(t-\tau_m)\,\phi(m)\,dm$$

+ Instantaneous Recycling Approximation

Stars with $m > 1M_\odot$ die instantaneously

Stars with $m < 1M_\odot$ live forever and do not contribute to CE

$(t-\tau_m) \to t$ I.R.A neglects the stellar lifetimes!

$$R = \int_{M_t = 1M_\odot}^{M_U} (m - C_m)\,\phi(m)\,dm$$

$$E_i(t) = \psi(t)\,R\,X_i(t) + y_i\,(1-R)\,\psi(t)$$

where

$$\boxed{y_i = [1/(1-R)] \int_{1M_\odot}^{M_U} Y_i(m)\,\phi(m)\,dm}$$

y_i = is the newly amount of an element *i* (for example, Z) created by a stellar generation, per unit mass locked into “eternal” objects = TRUE YIELD

The close box + IRA equation:

$dX_iM_g/dt = -X_i(t)\,\psi(t) + \psi(t)\,X_i\,R\,(t) + y_i\,(1\text{-}R)\,\psi(t)$

Has the analytical solution:

$X_i - X_i(0) = y_i \ln(1/\mu)$ where $\mu = M_{gas}/M_{tot}$ is the gas fraction

If for a given system we know X_i and μ we can use the equation above to estimate the yield. In this case:

$p_i = X_i/\ln(1/\mu)$ = EFFECTIVE YIELD

$p_i \longrightarrow y_i$ when close box + I. R. A is a good approximation

A simple case: $\psi(t) = \nu\, M_{gas}$ and $M_g(0)=M_{tot}$

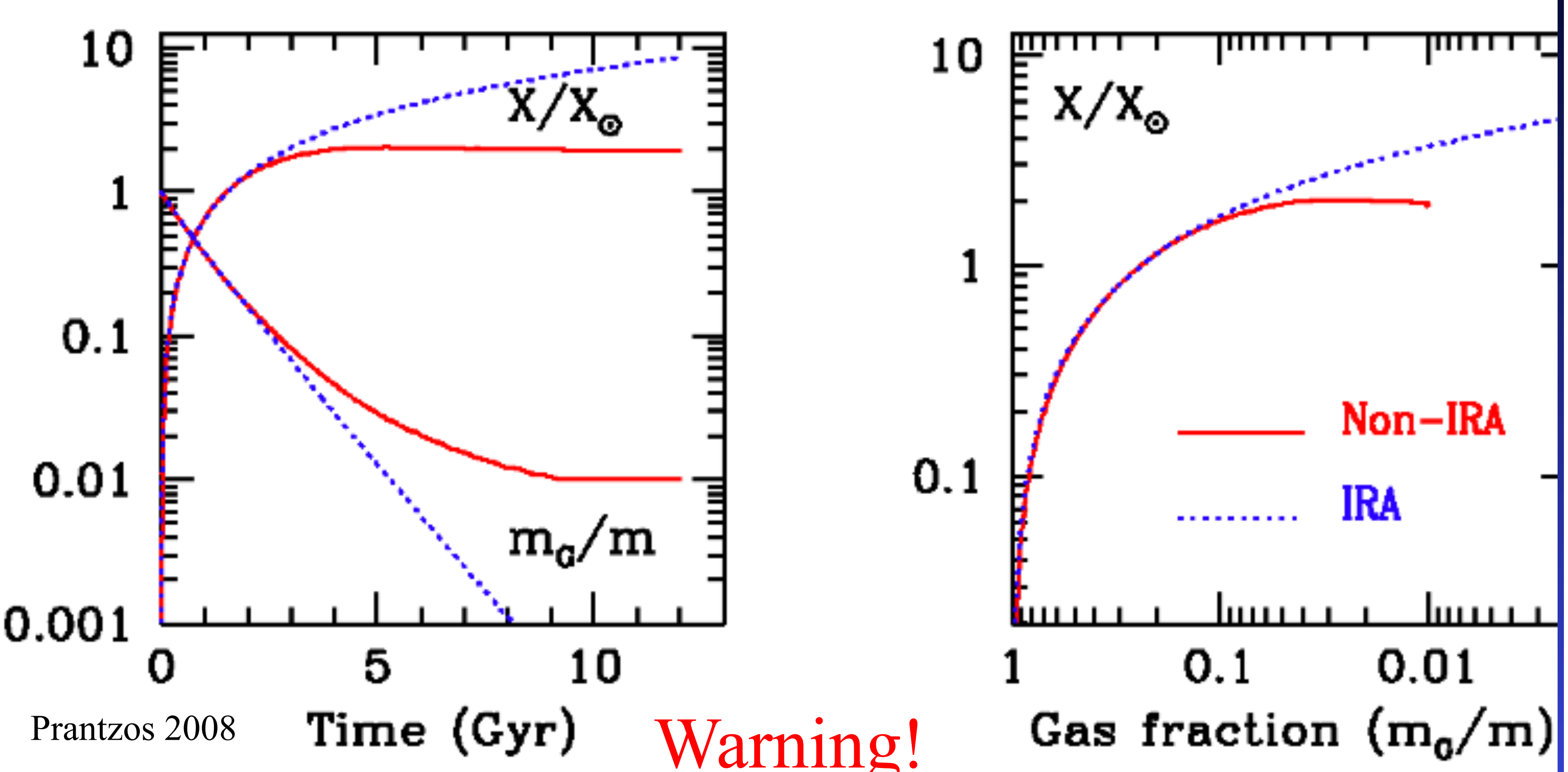
$dM_{gas}/dt = -\psi(t) + E(t)$, with $E(t) = \psi(t)\,R$

Solution: $M_{gas} = M_{tot}\, e^{-\nu(1\text{-}R)t}$ and $X_i\text{-}X_{i,0} = y_i\,\nu\,(1\text{-}R)\,t$

Metallicity roughly proportional to time

✓ I.R.A. OK for elements produced in massive stars (e.g. O)
✓ I.R.A. OK for systems where the gas fraction > 10%

Close box Model



Prantzos 2008

Warning!

“I.R.A. is not a good approximation in the case of elements such as iron, nitrogen, s-process and carbon which come partly or wholly from lower-mass stars with significant evolutionary time-scales of the order of a Gyr.” Pagel 1997

For the metallicity Z: Close box model with I.R.A:

$\boxed{Z = y_z \ln(1/\mu) \qquad \text{where } Z(0)=0}$

This is the metallicity Z in the gas and/or young stars

Other simple cases with Infall or Outflow (with I.R.A.):

Allowing for Infall:

$A_i(t) = (1\text{-}R)\,\psi(t)$ Extreme Infall case: constant gas mass

$$\boxed{X_i - X_{i,0} = y_i\,[1 - e^{(1-1/\mu)}]}$$

Allowing for outflow:

$W_i(t) = w\,\psi(t)$ Outflow proportional to the SFR

$$\boxed{X_i - X_{i,0} = [y_i/(1+w)]\,\ln(1/\mu)}$$

Primary vs. Secondary elements

Primary element: an element produced directly from H and He. Typical primary element: carbon or oxygen

Secondary element: an element produced from metals already present in the star at birth. Typical secondary: nitrogen

- ✓ For any two primary elements X_i and X_j we have:

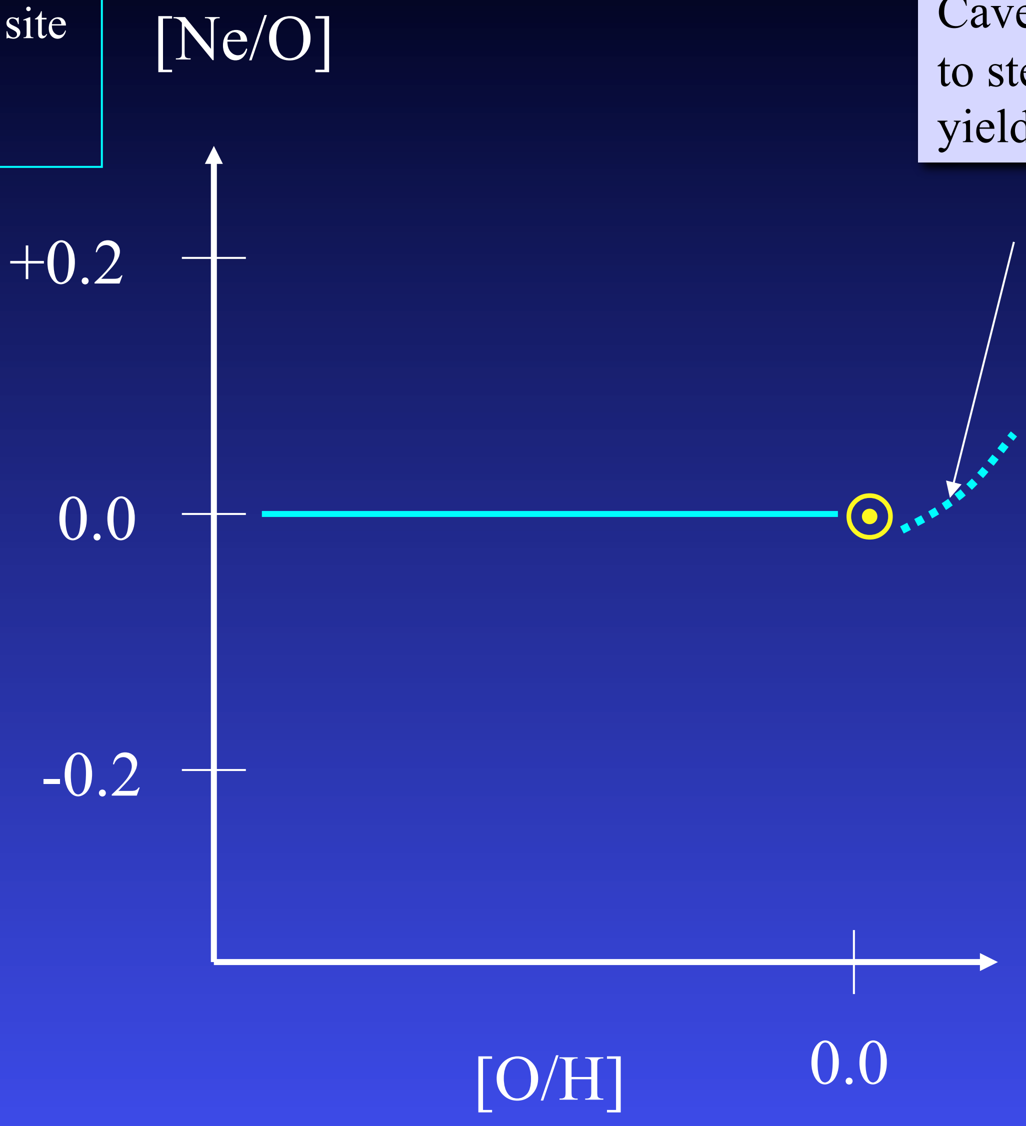
  $X_i/X_j = y_i/y_j = \text{constant}$

- ✓ For a secondary element X_s formed from a seed element X_p

  X_s/X_p is proportional to X_p → X_s is proportional to $(X_p)^2$

Two primary elements = Constant

Ne and O produced in the same site (massive stars)



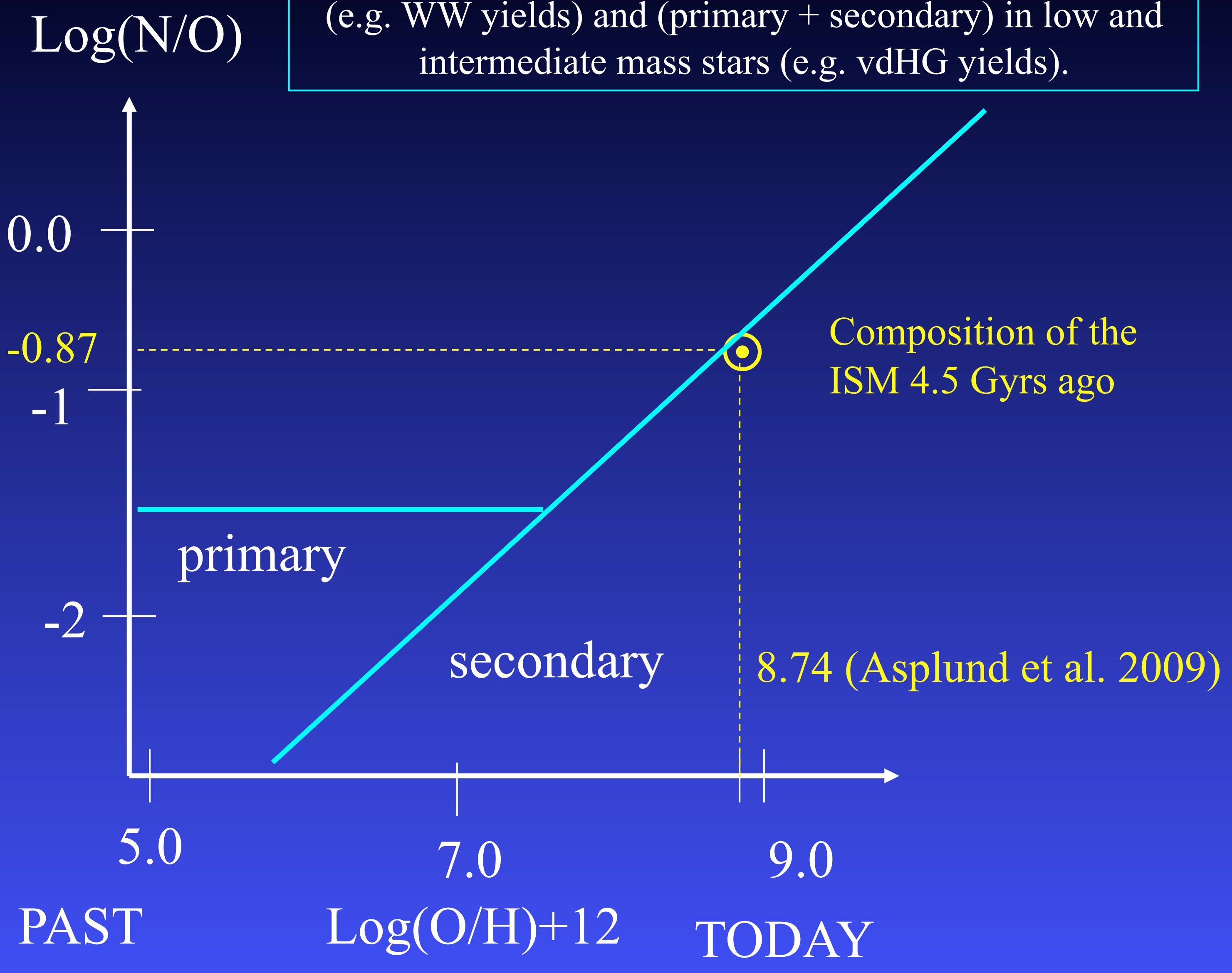
Caveat… it could be that due to stellar winds, the oxygen yield Y_O decreases at $Z > Z_\odot$!

O and Fe also two primary elements… But…

$[X/H] = \log(X/H) - \log(X/H)_\odot$

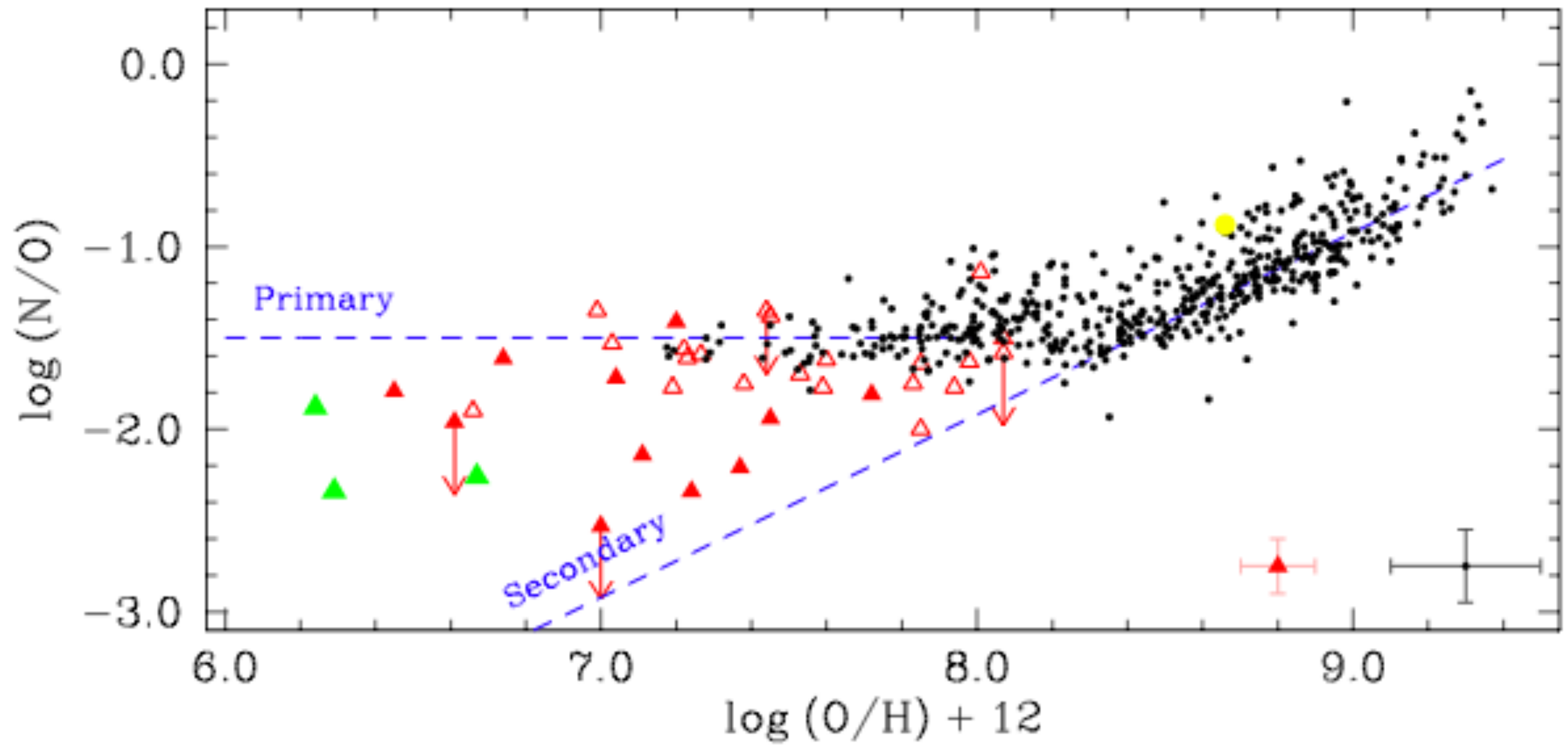
Secondary/primary vs. primary element

“Standard Stellar Models”: N secondary in massive stars (e.g. WW yields) and (primary + secondary) in low and intermediate mass stars (e.g. vdHG yields).



Composition of the ISM 4.5 Gyrs ago

8.74 (Asplund et al. 2009)

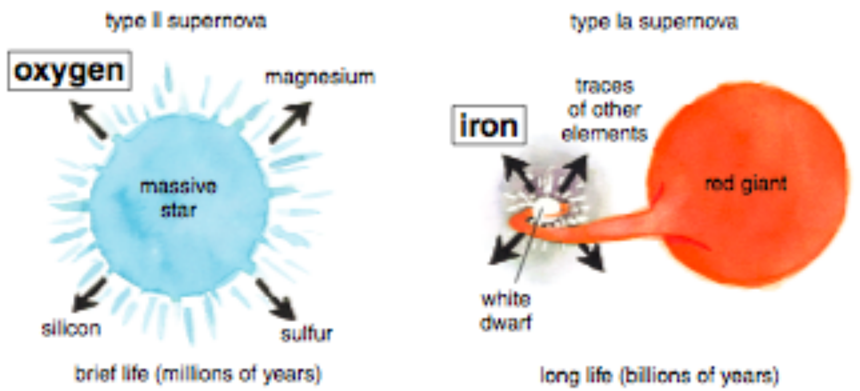


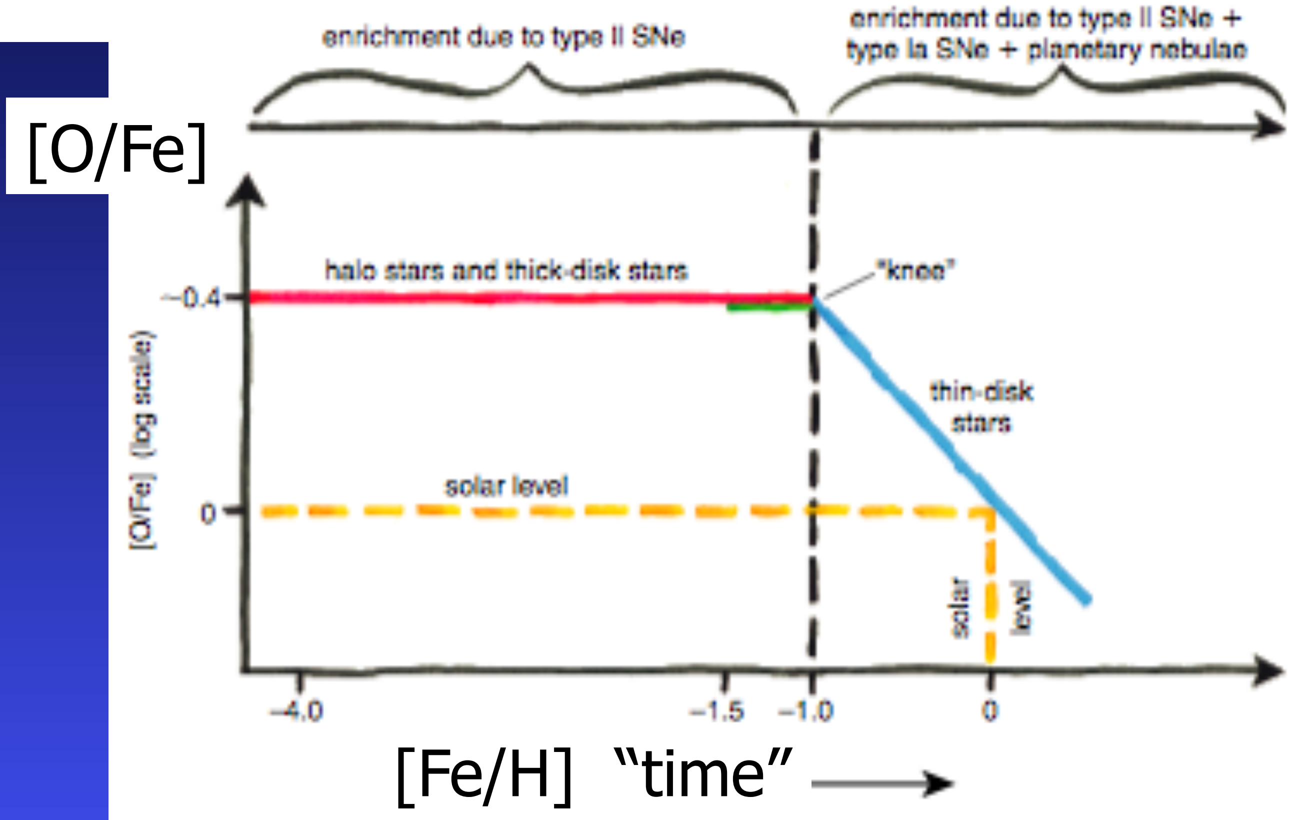
Pettini et al. 2008

The Time-Delay Idea
Abundance ratios as Cosmic Clocks

[O/Fe] x [Fe/H]

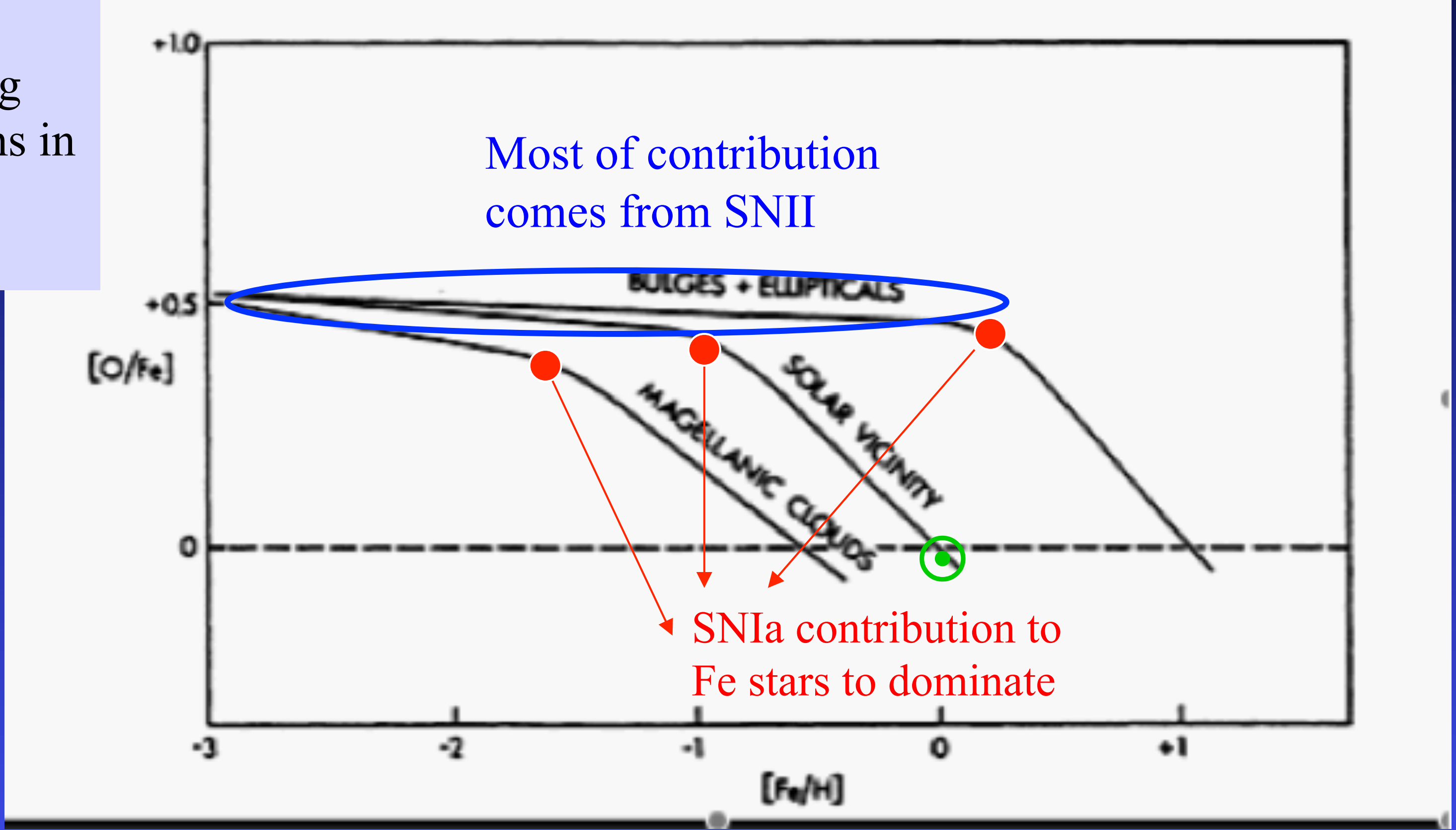
([X/H] = log(X/H) –log(X/H)_sun)





Fe comes both from SNII and SNIa, whereas O comes from SNII

Diagram representing observations in different galaxies



Most of contribution comes from SNII

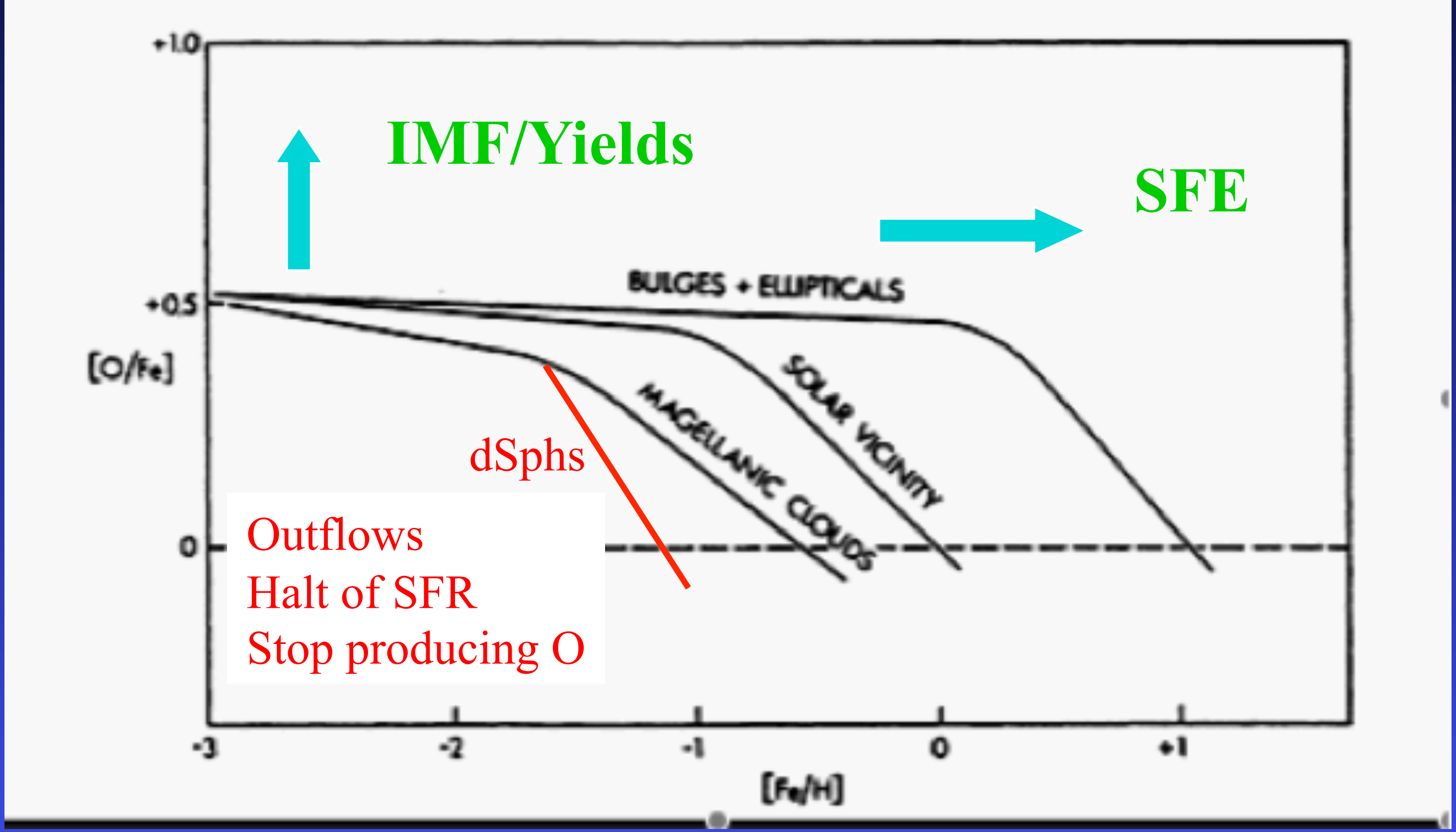
SNIa contribution to Fe stars to dominate

[O/Fe] vs. [Fe/H] in different galaxies

- SF EFFICIENCY: Determines which metallicity can be achieved before SNIa and LIMS have time to enrich the ISM

- INFALL: Replenishment of gas reservoir, allowing stars to continue to form. In this case massive stars keep contributing to the chemical enrichment (together with LIMS and SNIa)

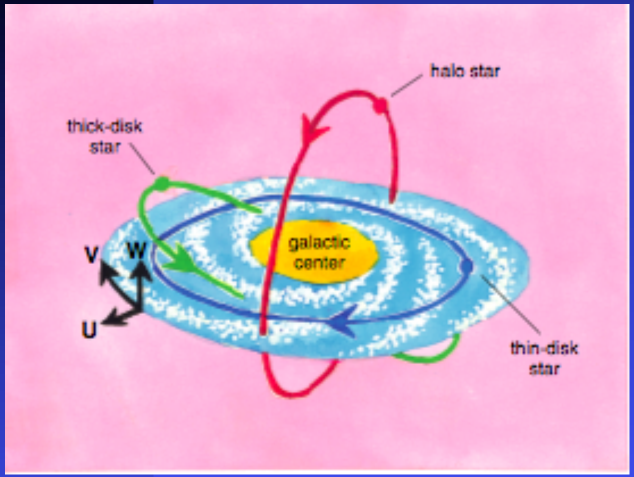
- OUFLOW: Expulsion of gas that can lead to a halt of the Star Formation -> no contribution from massive stars anymore, contribution only from SNIa and LIMS formed before the SFR stopped.

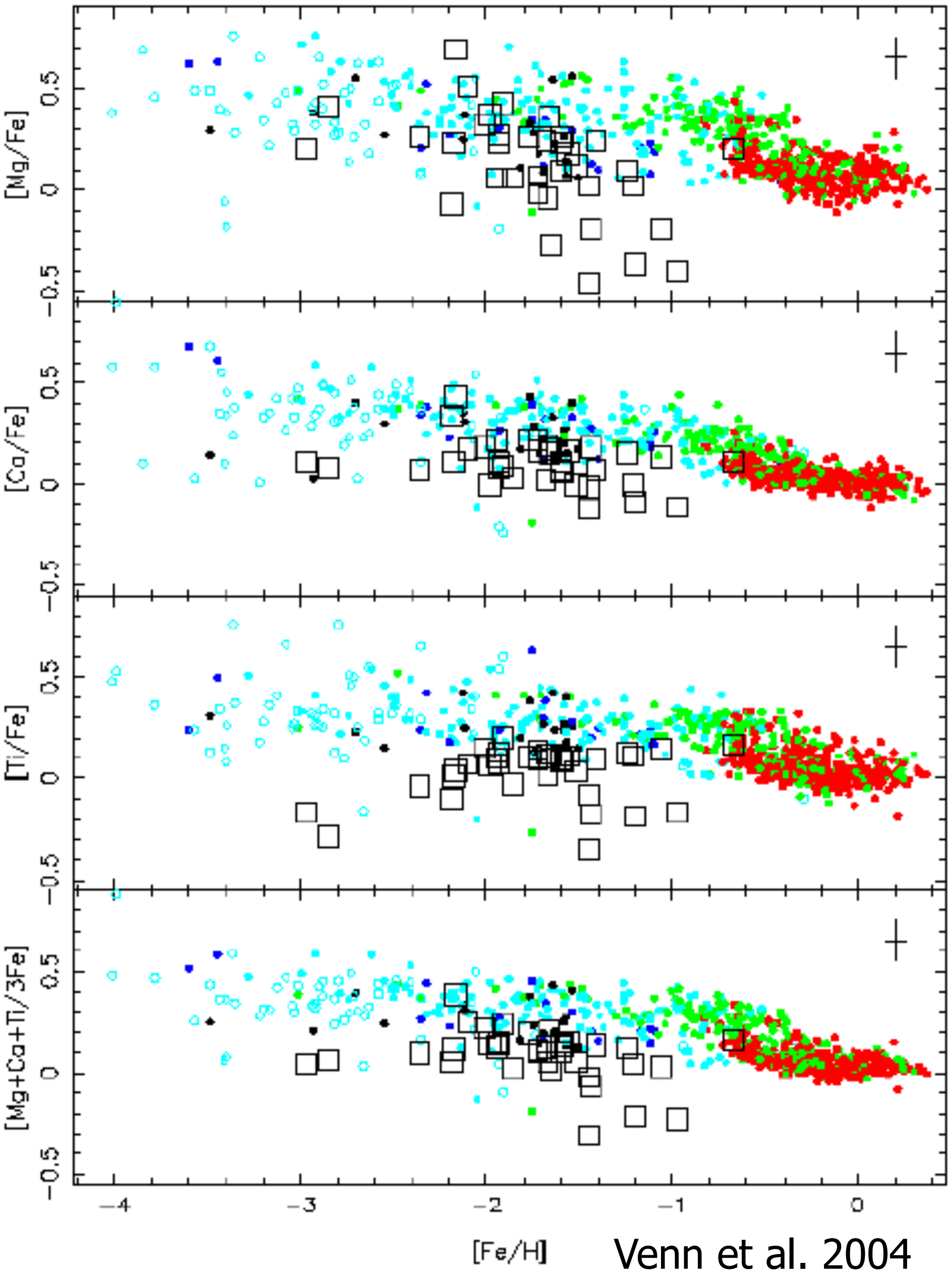


[O/Fe] vs. [Fe/H] in different galaxies

Squares: dSph stars

Dots: Identifications of different galactic components using kinematic probabilities from velocity ellipsoids:
thin disk + thick disk + halo + retrograde component





Venn et al. 2004