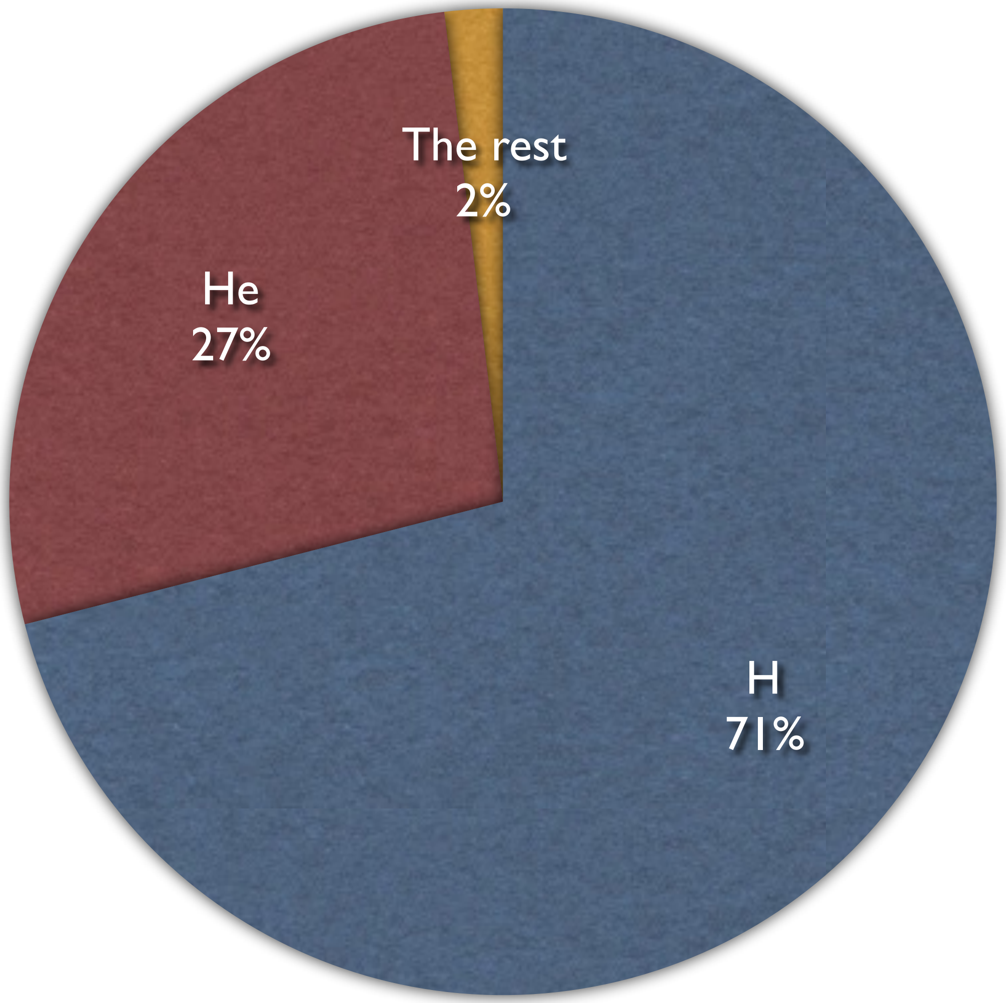
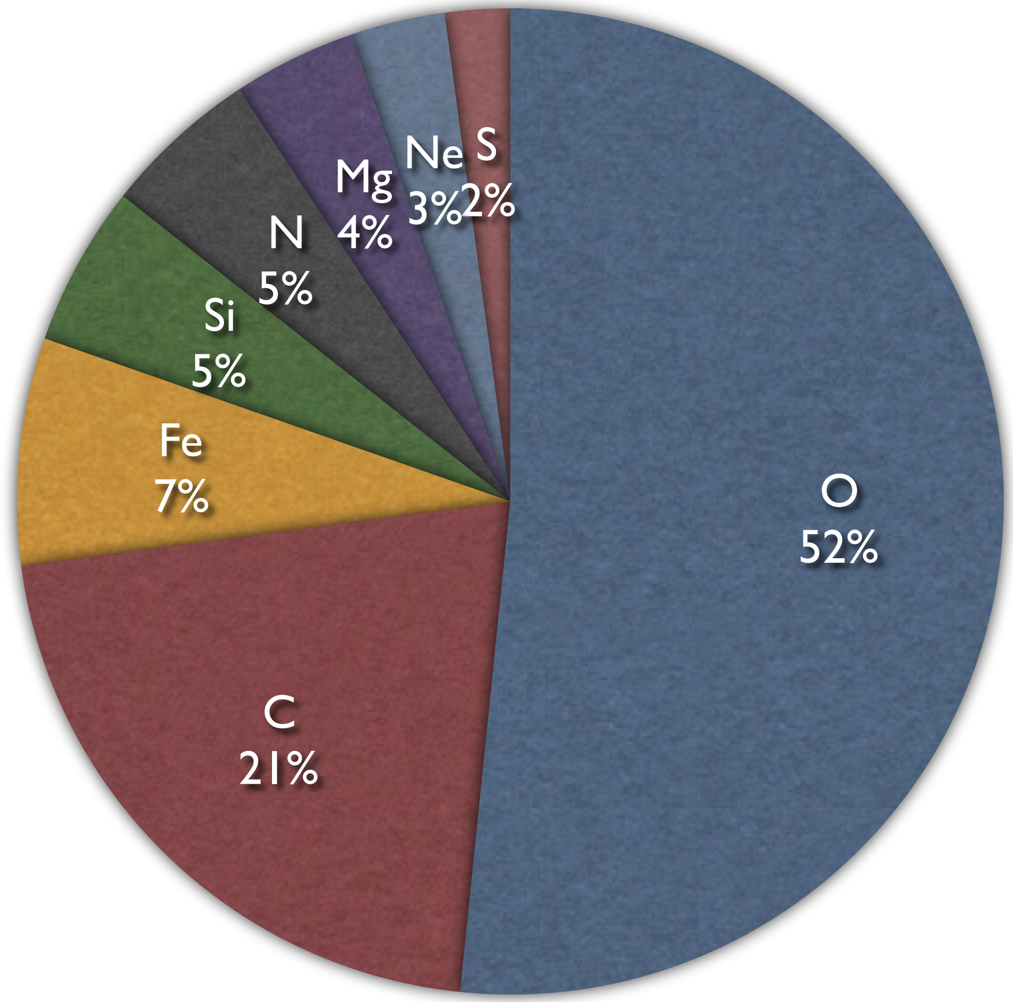
# Chemical Evolution

# Composition of the Sun

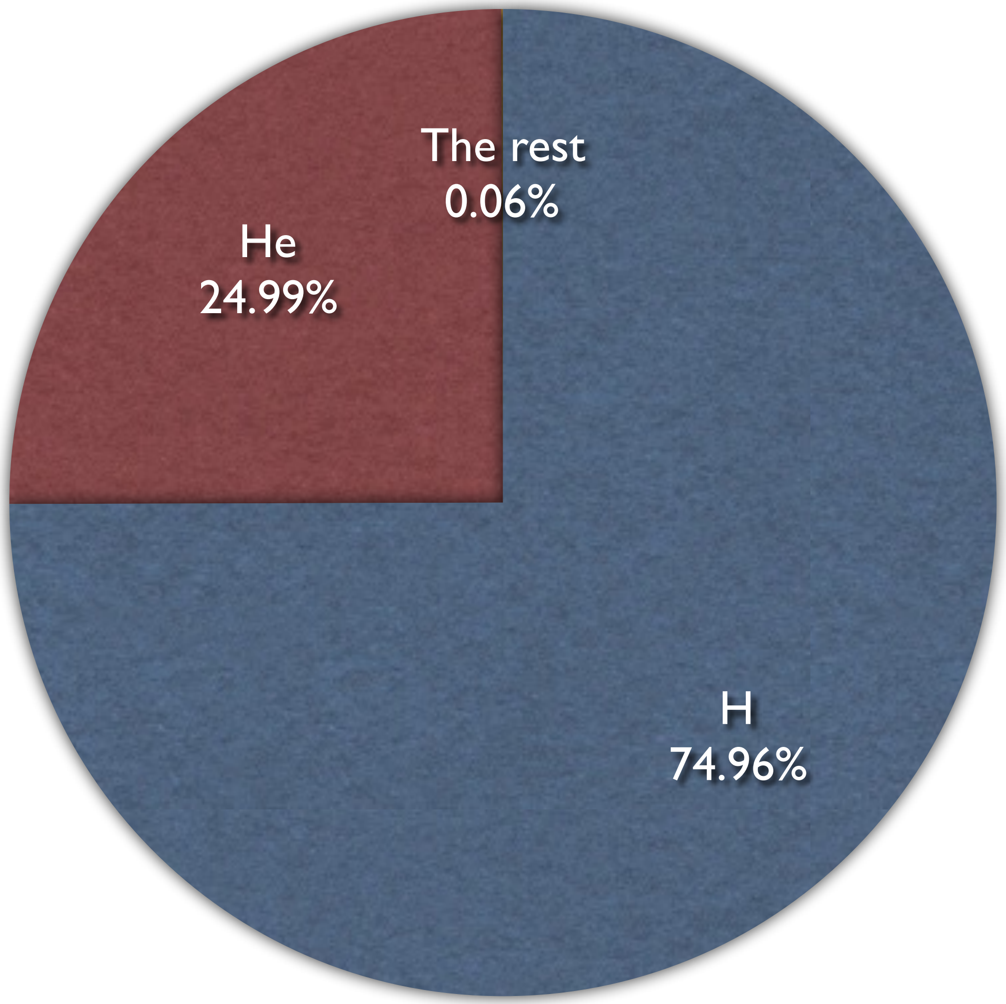


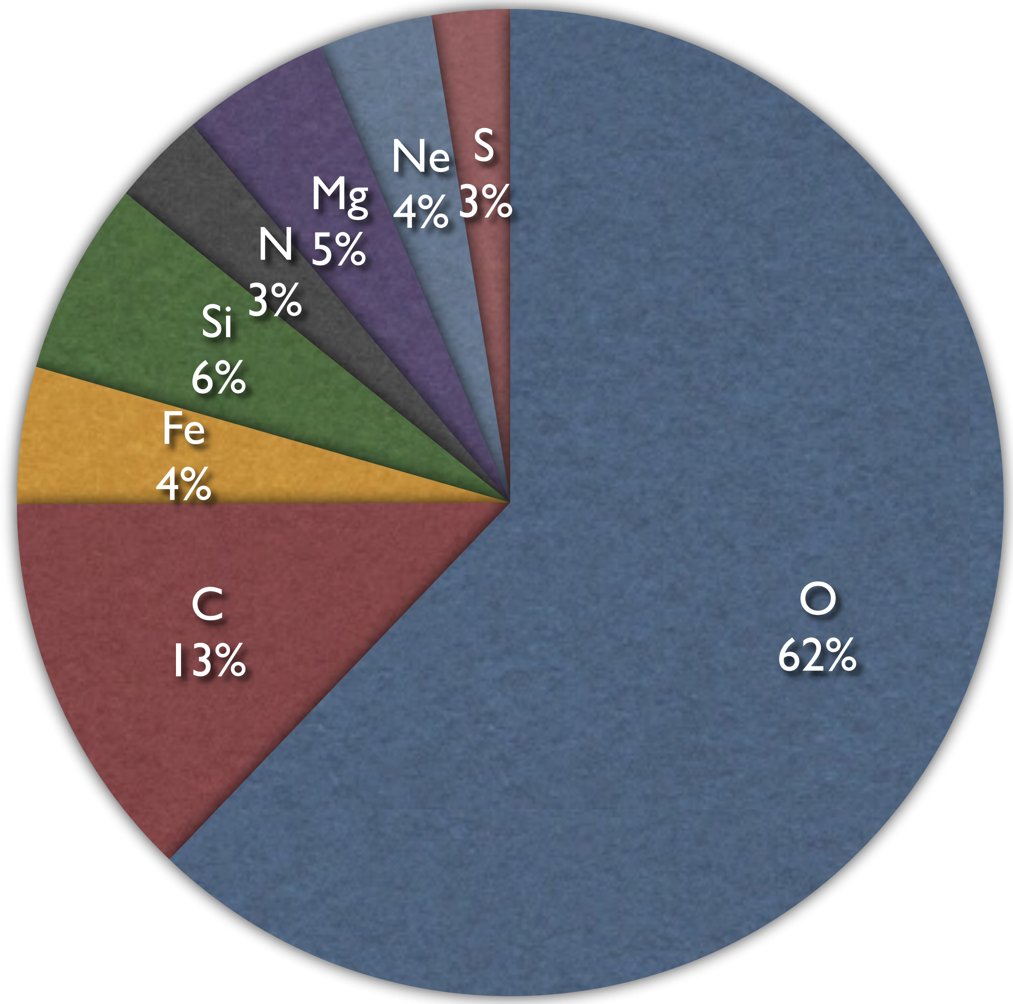

"The rest"




http://hyperphysics.phy-astr.gsu.edu/hbase/tables/suncomp.html

# Composition of halo star

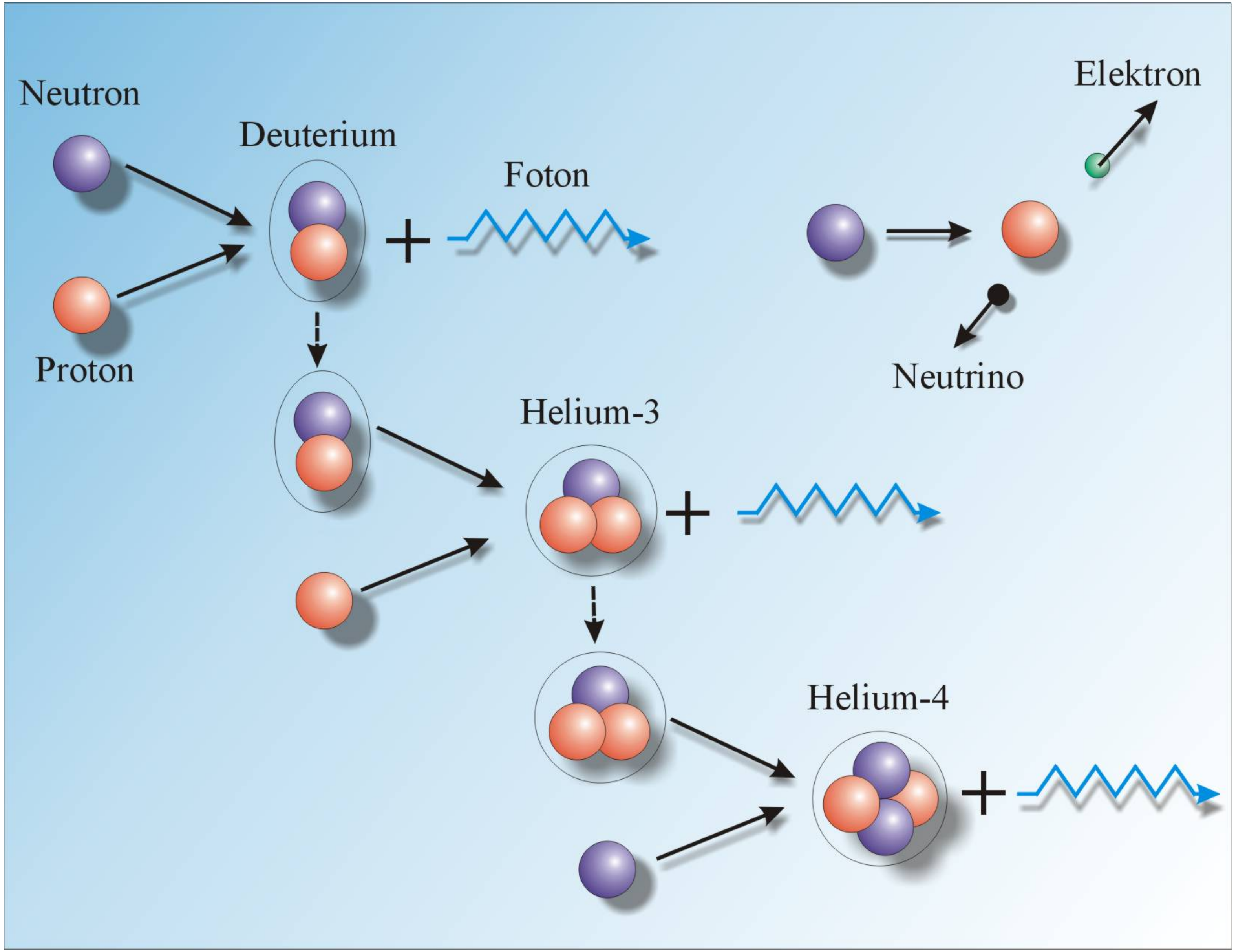


# Origin of the elements

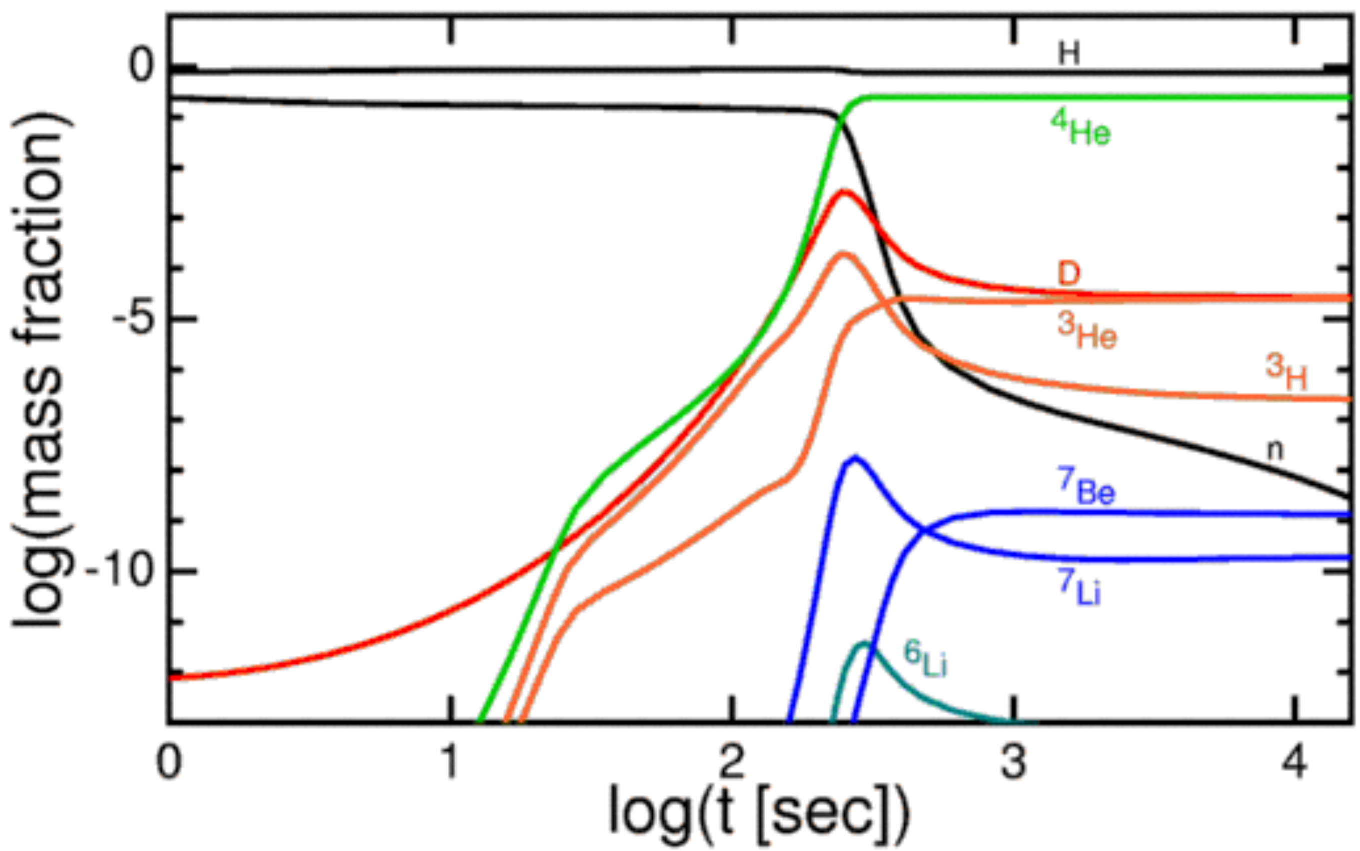
- H, He + small amount of Li:
  Mostly formed during the "Big Bang" when the Universe was very dense and very hot.

# Hydrogen burning during ~ 10 minutes in the Early Universe produces 25% Helium




**Neutron decay (12 minutes)**

# Abundances vs. time




http://www.astro.ucla.edu/~wright/BBNS.html

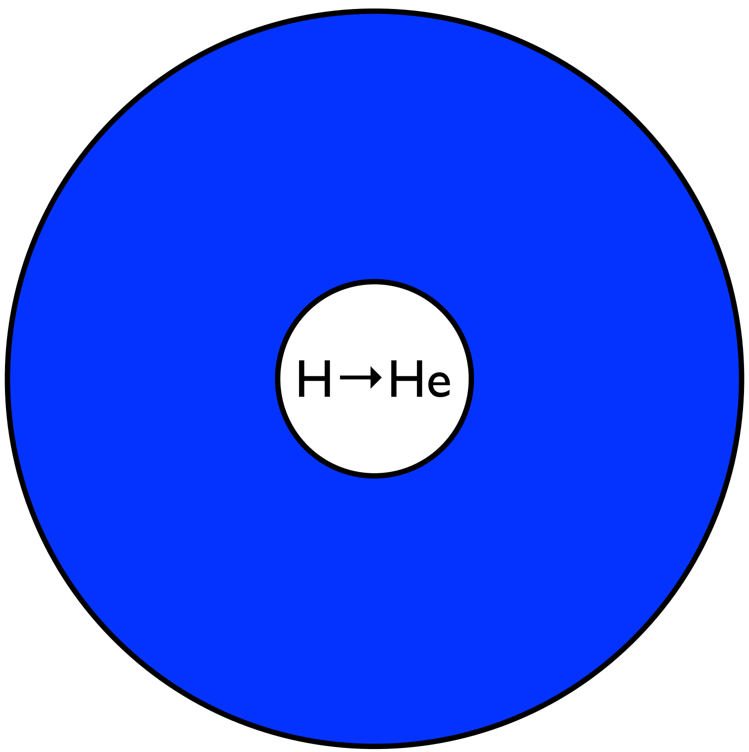
# Origin of the elements

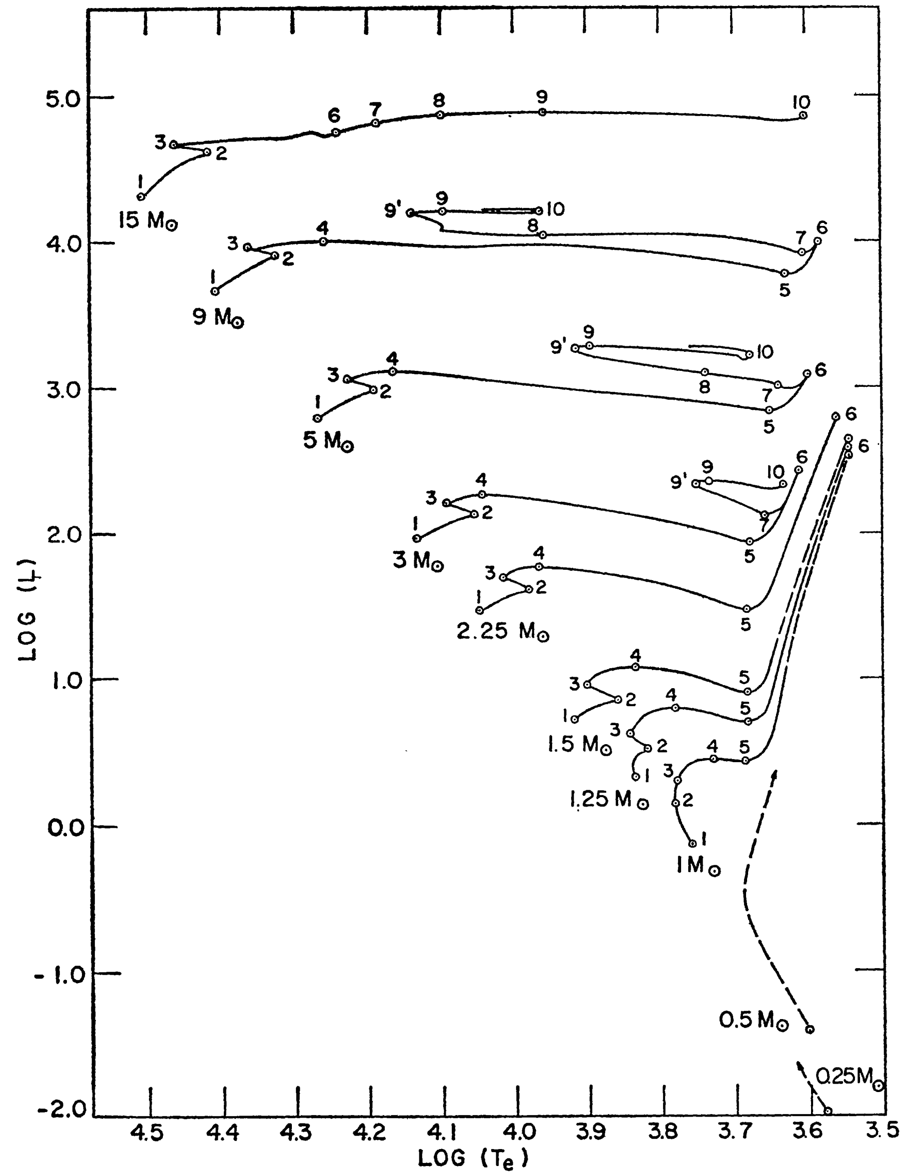
- H, He + small amount of Li:
  Mostly formed during the "Big Bang" when the Universe was very dense and very hot.
- Everything else:
  - Supernovas of Type II (stars with $M > 8\ M_\odot$; lifetimes $< 40\times10^6$ years)
  - Supernovas of Type Ia (exploding white dwarfs) - delay of $10^8$ - $10^9$ years
  - AGB stars, planetary nebulae, Novae, etc.
- H and He are mostly of *cosmological origin*, whereas other elements were formed via *nuclear reactions in stars*

# Nucleosynthesis in massive stars

## 1. Star on main sequence

Hydrogen burning in core
(pp and CNO cycles)



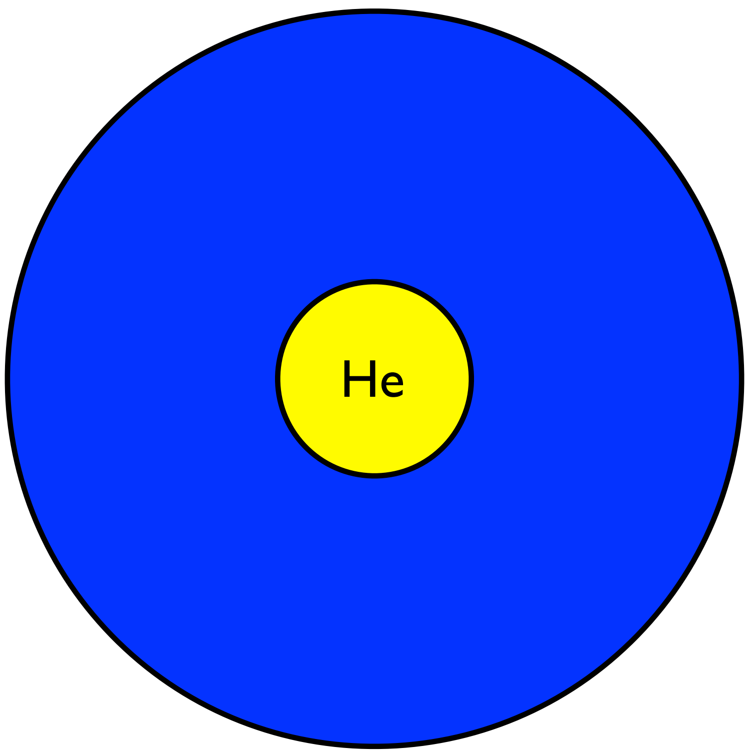



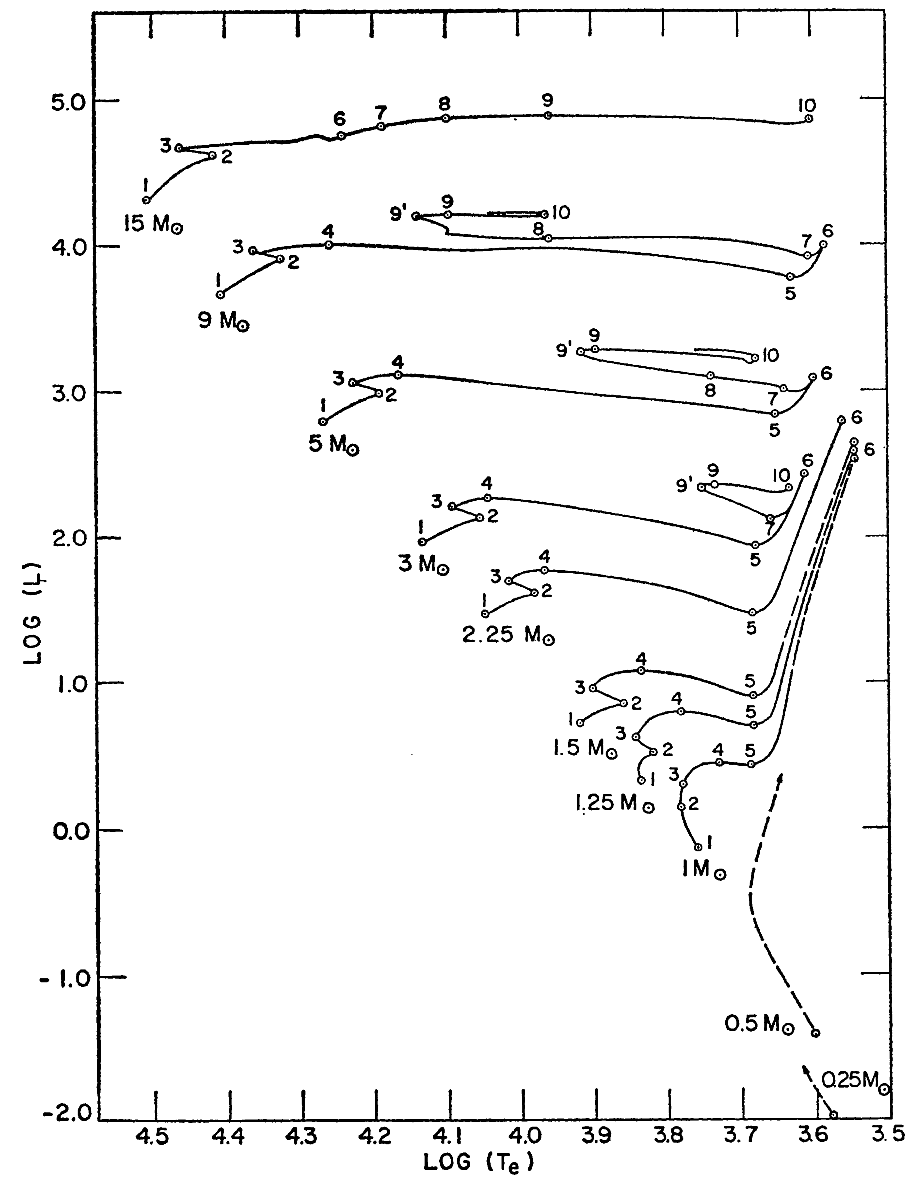

Iben (1967)

# Nucleosynthesis in massive stars

## 2. End of main sequence

Hydrogen exhausted in core.
No energy source, star contracts



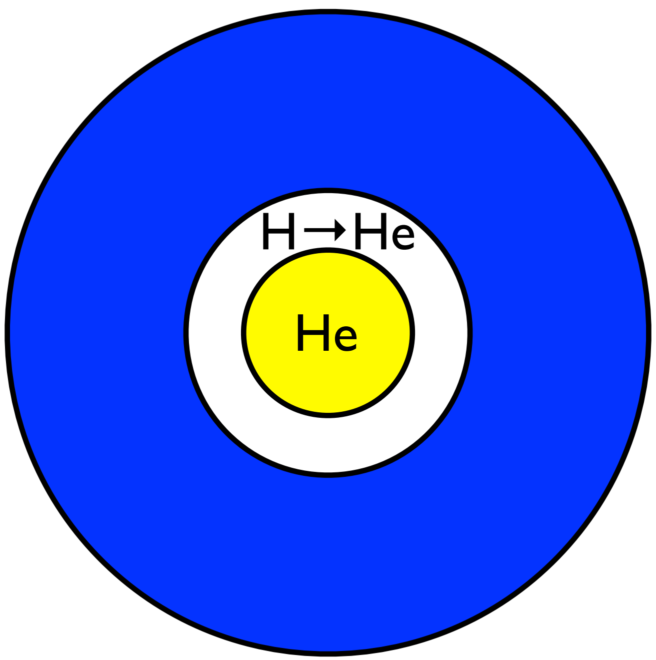



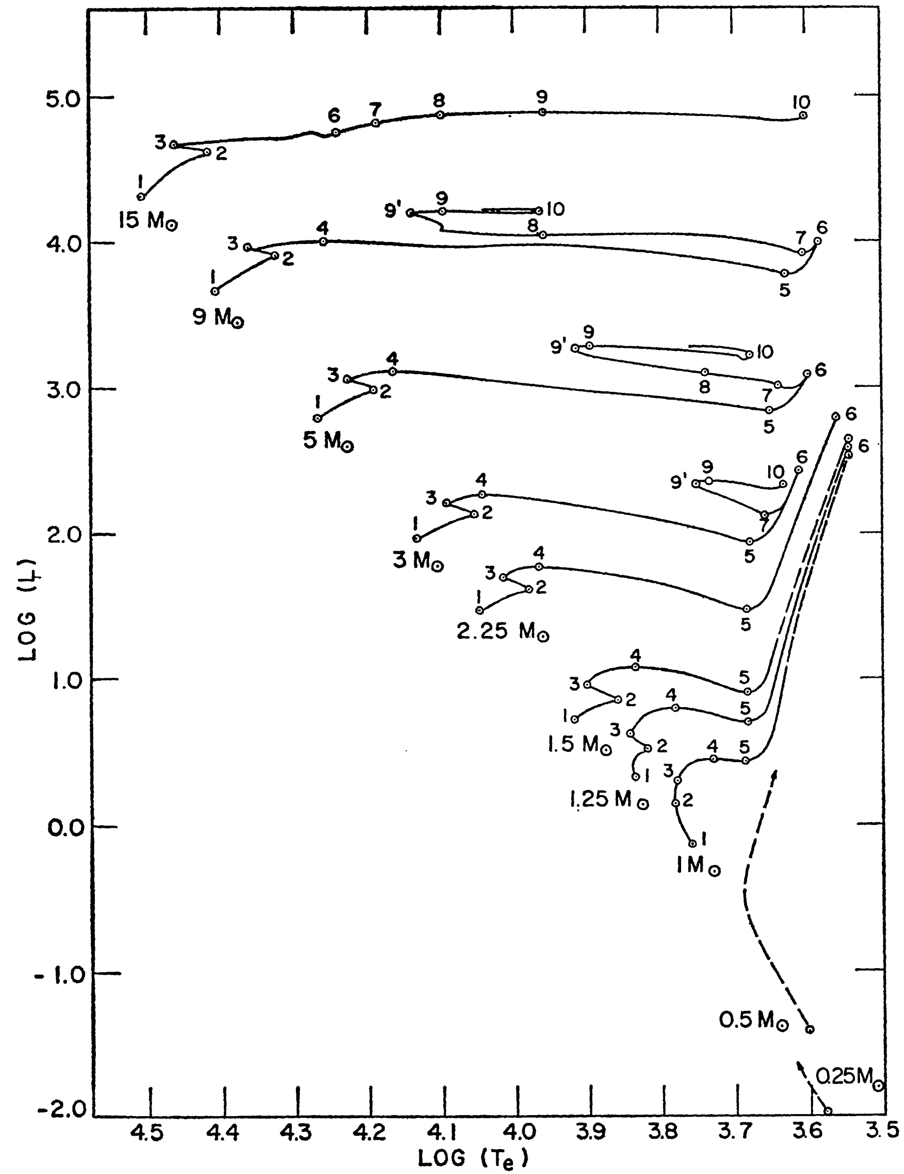

Iben (1967)

# Nucleosynthesis in massive stars

## 3-5. Shell H-burning

H is ignited in a shell around the He core, adding mass to it. The star expands and cools



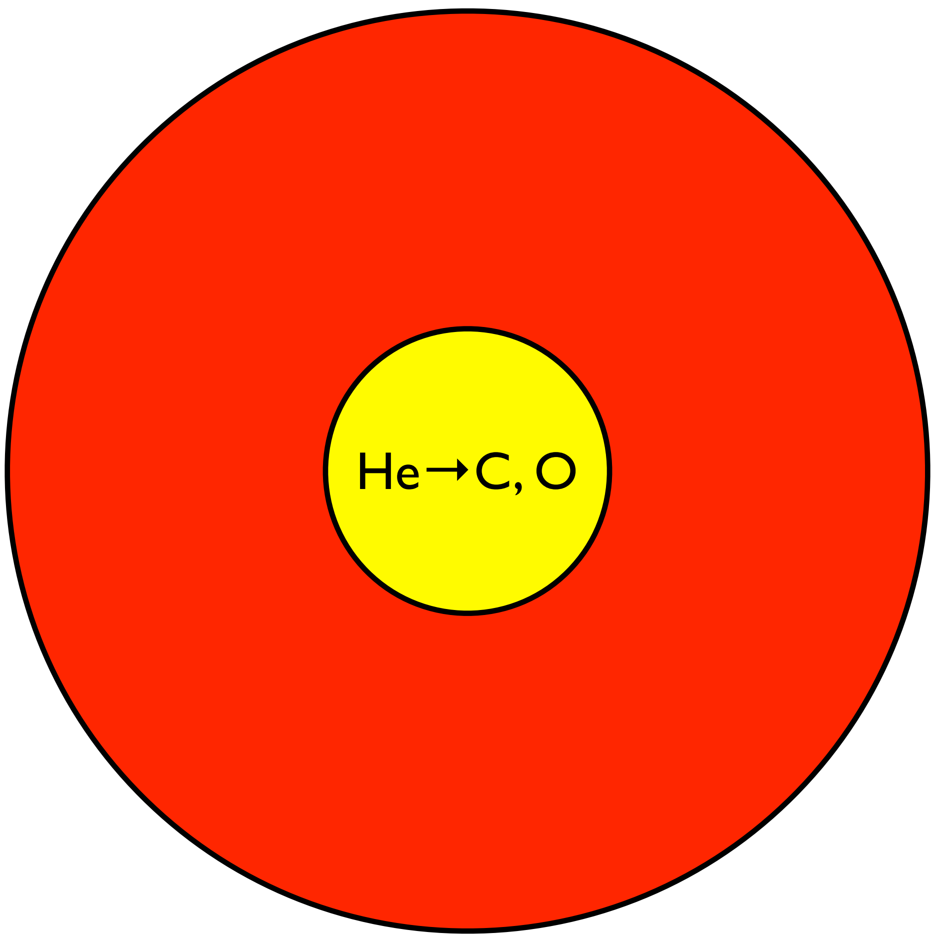



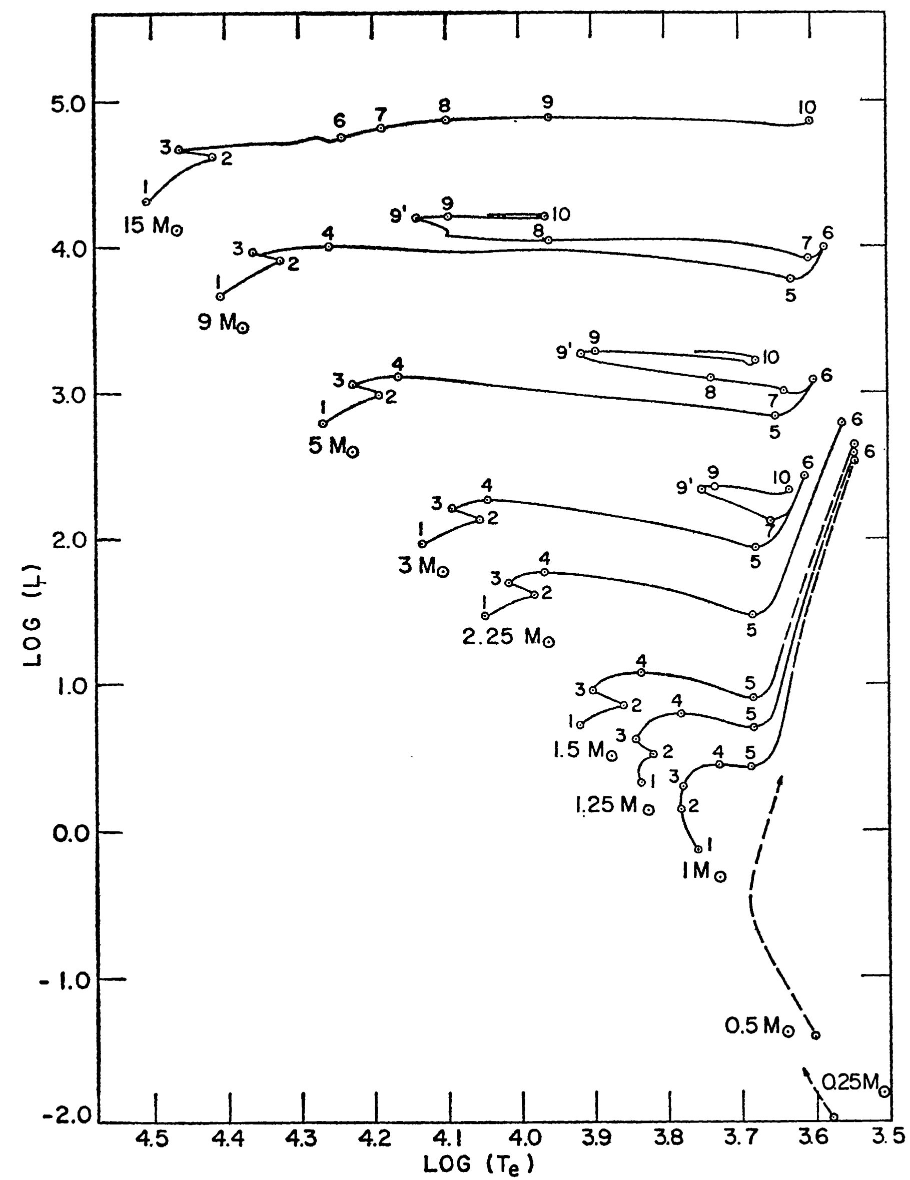

Iben (1967)

# Nucleosynthesis in massive stars

## 6-10. He-burning

He burning in core via "triple alpha process". "Blue loops" in H-R diagram



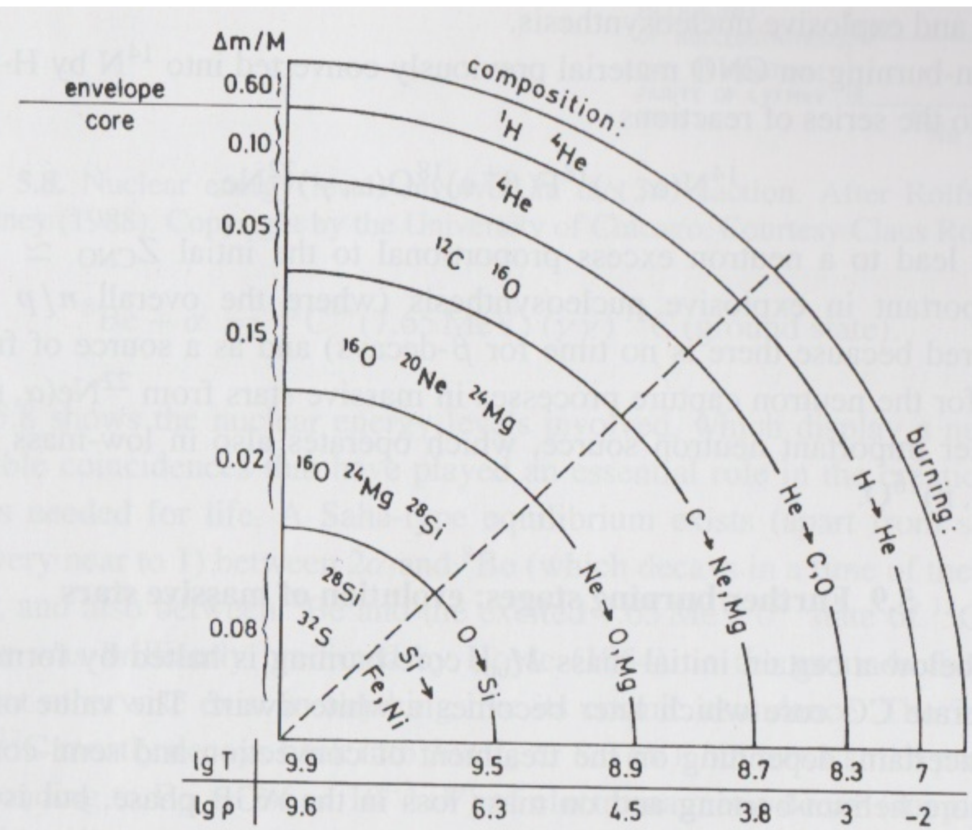




Iben (1967)

# Nucleosynthesis after He-burning

Eventually, the He is used up and the core consists (mainly) of C, O.

Subsequent evolution very fast; outer layers of star do not have time to react




25 $M_\odot$ star; Pagel (2009)

C-burning ($T_{core} \sim 10^9$ K, t ~ 1000 yr)

$$^{12}C+^{12}C \rightarrow {}^{24}Mg^* \rightarrow {}^{20}Ne+\alpha+\gamma$$
$$\rightarrow {}^{23}Ne+p+\gamma$$
$$\rightarrow {}^{23}Mg+n$$

Ne-burning ($T_{core} \sim 1.5\times10^9$ K, t ~ 1 yr)

$$^{20}Ne+\gamma \rightarrow {}^{16}O + \alpha$$
$$^{20}Ne+\alpha \rightarrow {}^{24}Mg + \gamma$$
$$^{24}Mg+\alpha \rightarrow {}^{28}Si + \gamma$$

Alpha-elements:

$^{16}O$, $^{20}Ne$, $^{24}Mg$, $^{28}Si$, etc.

# Type II Supernova

Fe,Ni core collapse → disintegration of Fe nuclei to p, n → neutron star + neutrinos

THE EVOLUTION AND EXPLOSION OF MASSIVE STARS. II. EXPLOSIVE HYDRODYNAMICS AND NUCLEOSYNTHESIS

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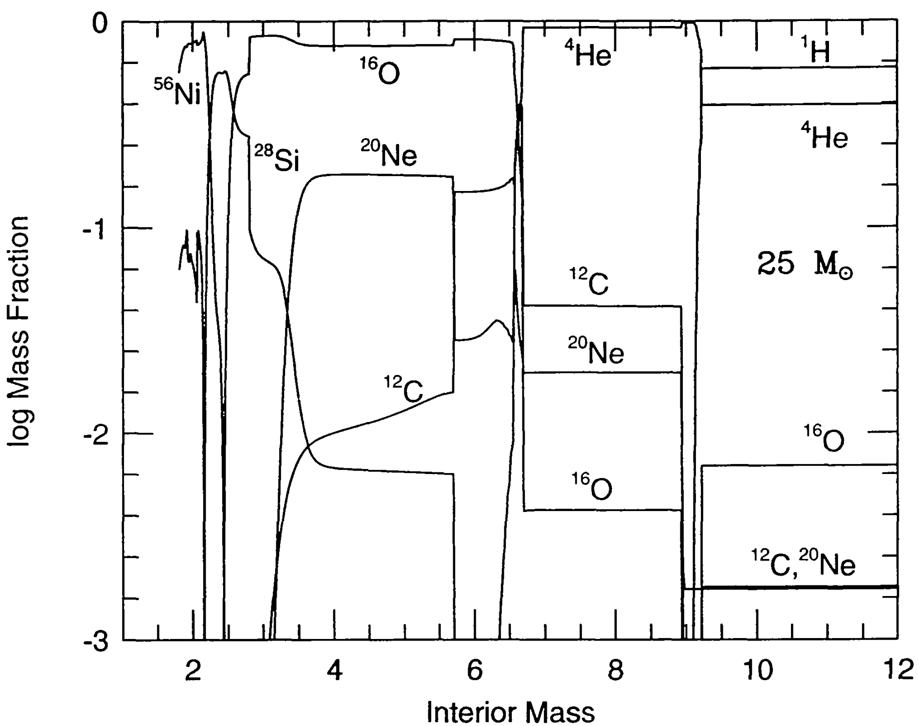
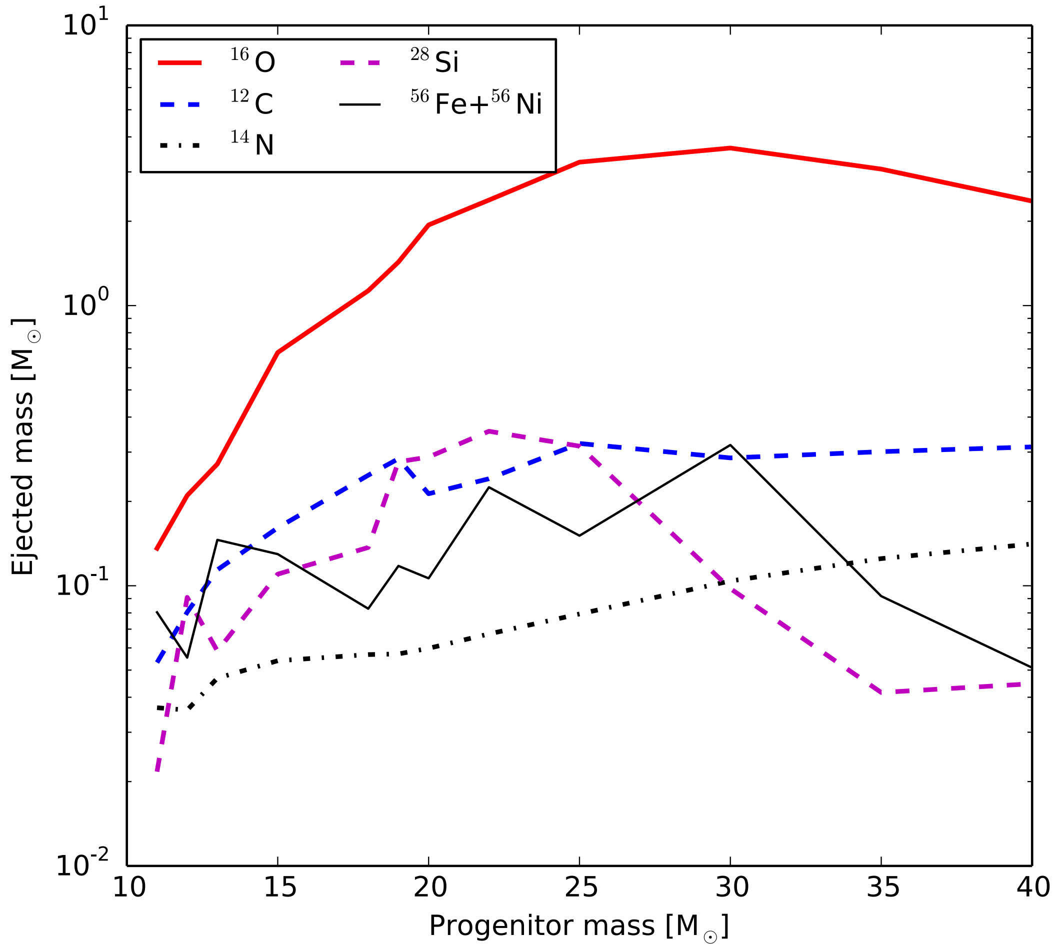
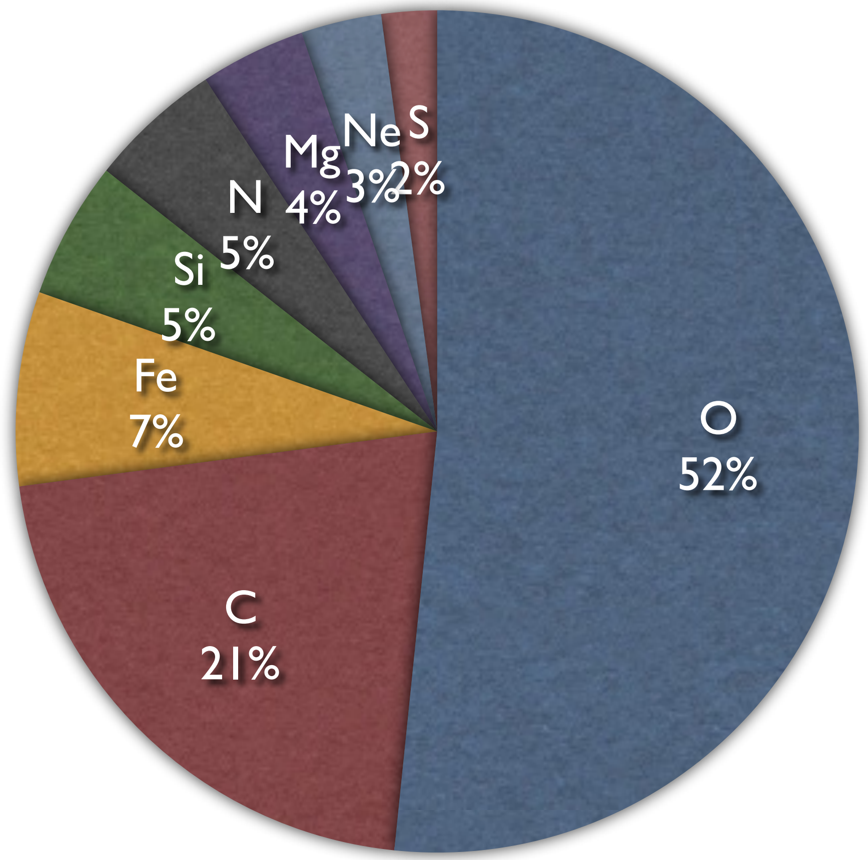
*Received 1995 January 24; accepted 1995 April 21*




"Onion skin" structure of a 25 $M_\odot$ star, prior to explosion as a Type II SNa

# Nucleosynthesis in Type II SNe

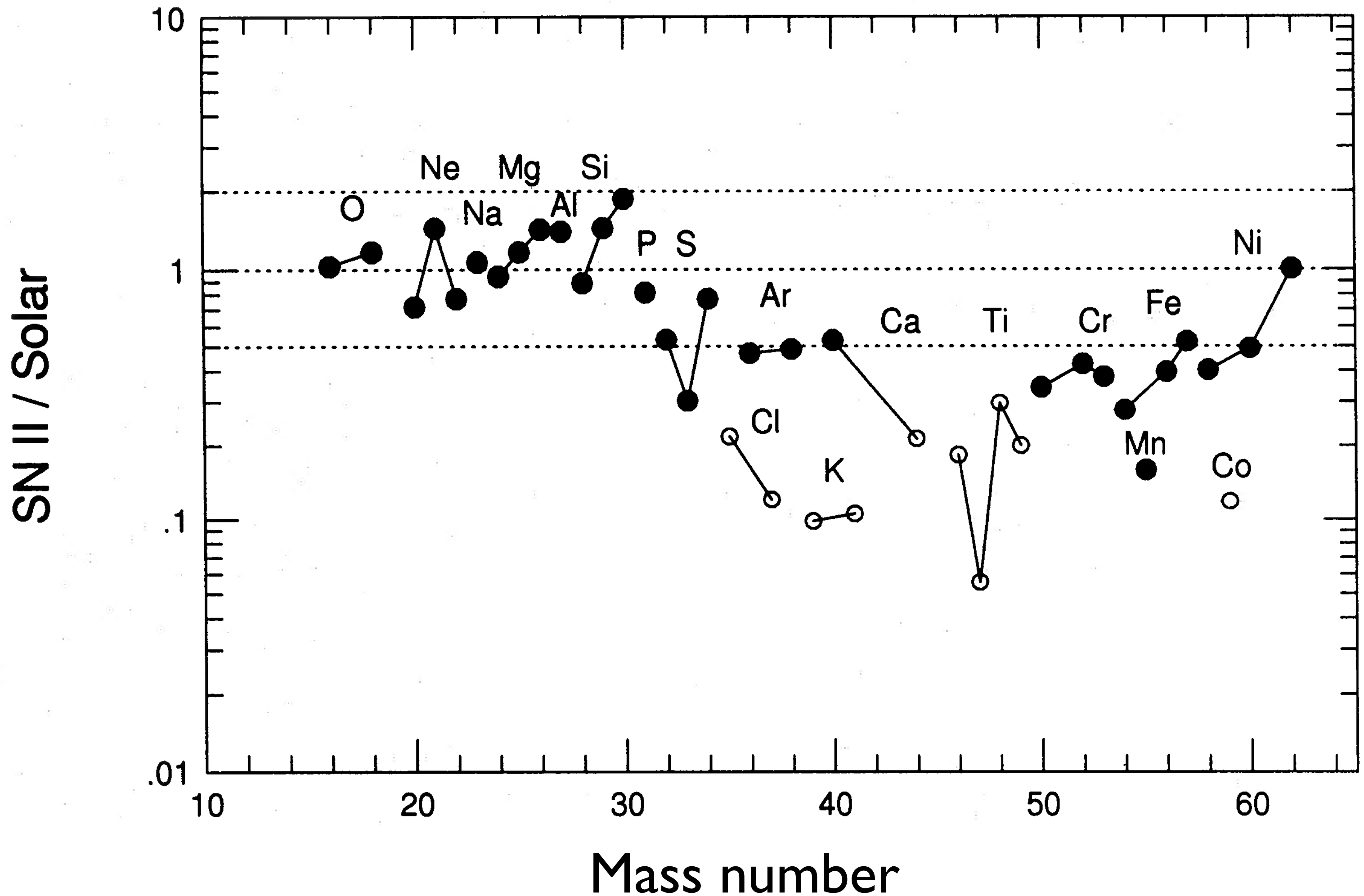



Data from Woosley & Weaver (1995)

# SN II yields relative to Solar composition

Type II SNe produce too few iron-peak elements (Cr, Mn, Fe, Ni)



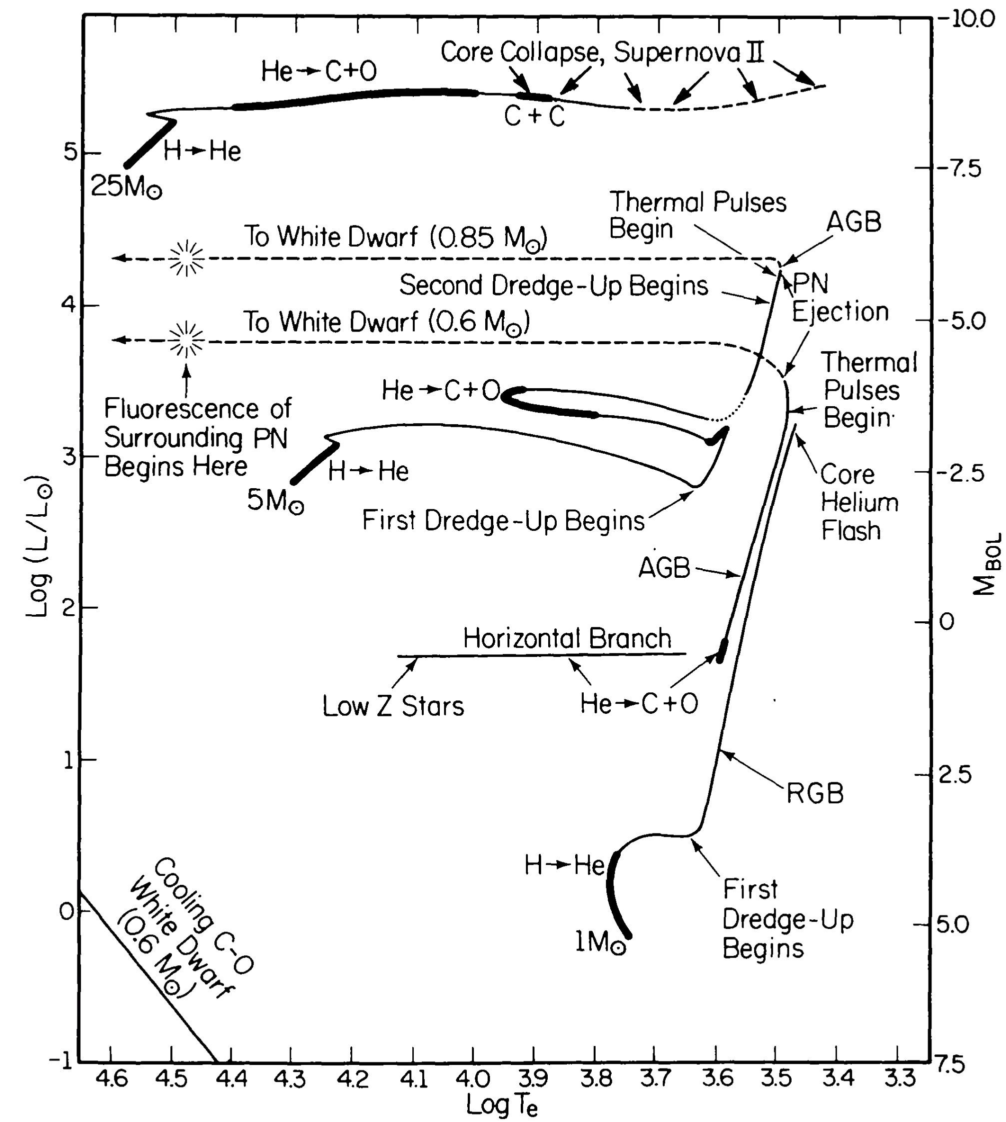

Tsujimoto et al. (1995)

# Nucleosynthesis in Type Ia SNe

Stars with initial mass less than (about) 8 $M_\odot$:

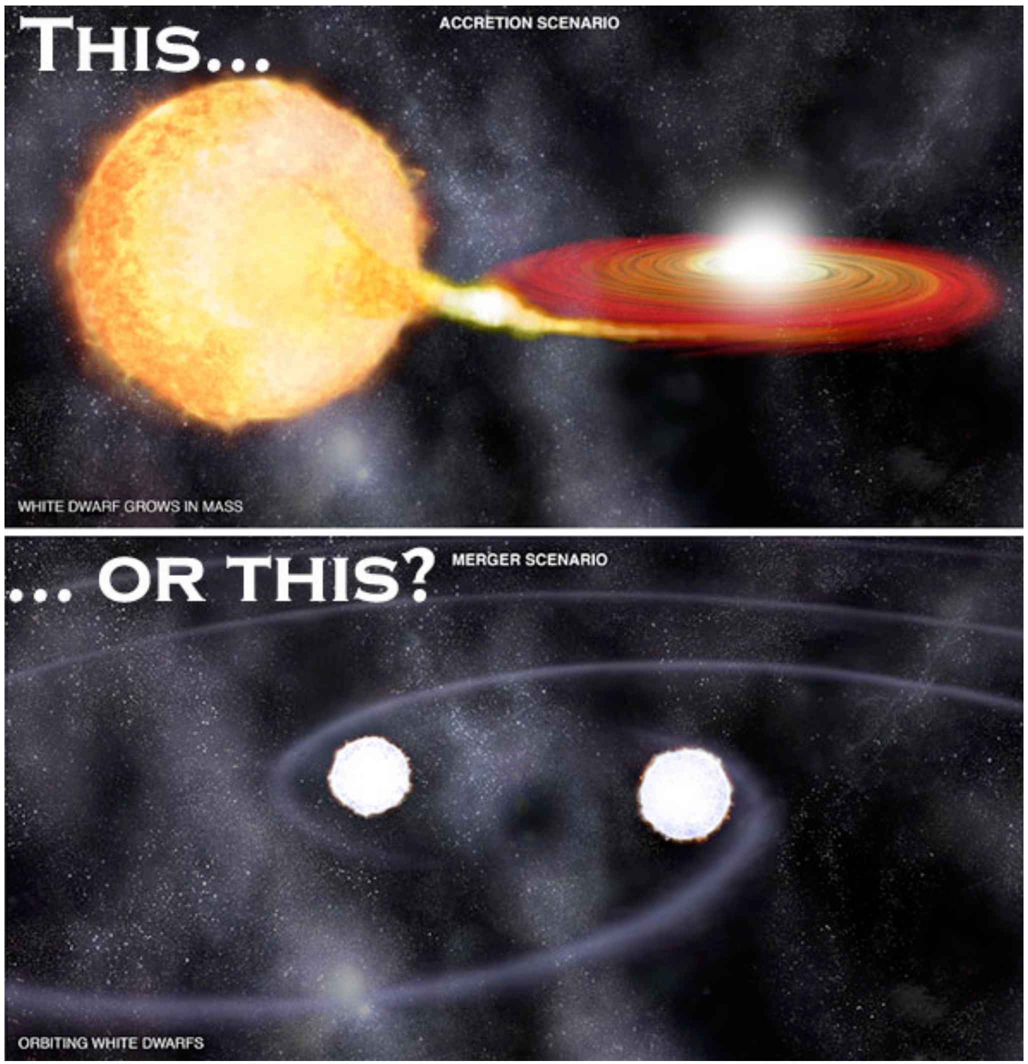
No C ignition; end product is a C-O white dwarf

Maximum mass of stable WD: 1.4 $M_\odot$ (*Chandrasekhar mass*)




Iben (1991)

# Nucleosynthesis in Type Ia SNe



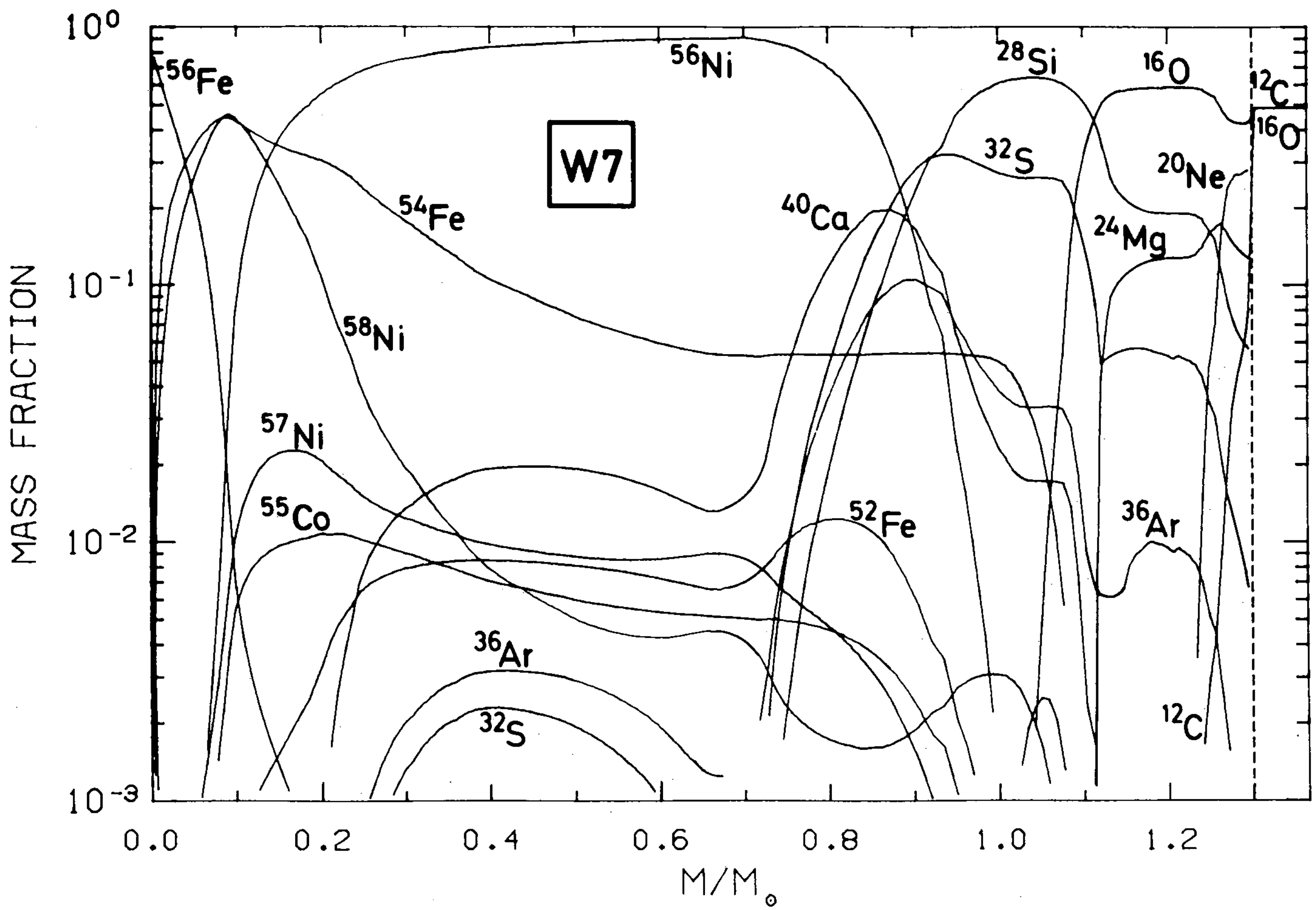

The mass of a WD may exceed the Chandrasekhar limit if it accretes matter from a companion, or mergers with another WD.

The result is then believed to be a SN explosion of Type Ia.

(Observationally, the Type I vs Type II refers to absence or presence of H lines)

# Nucleosynthesis in Type Ia SNe

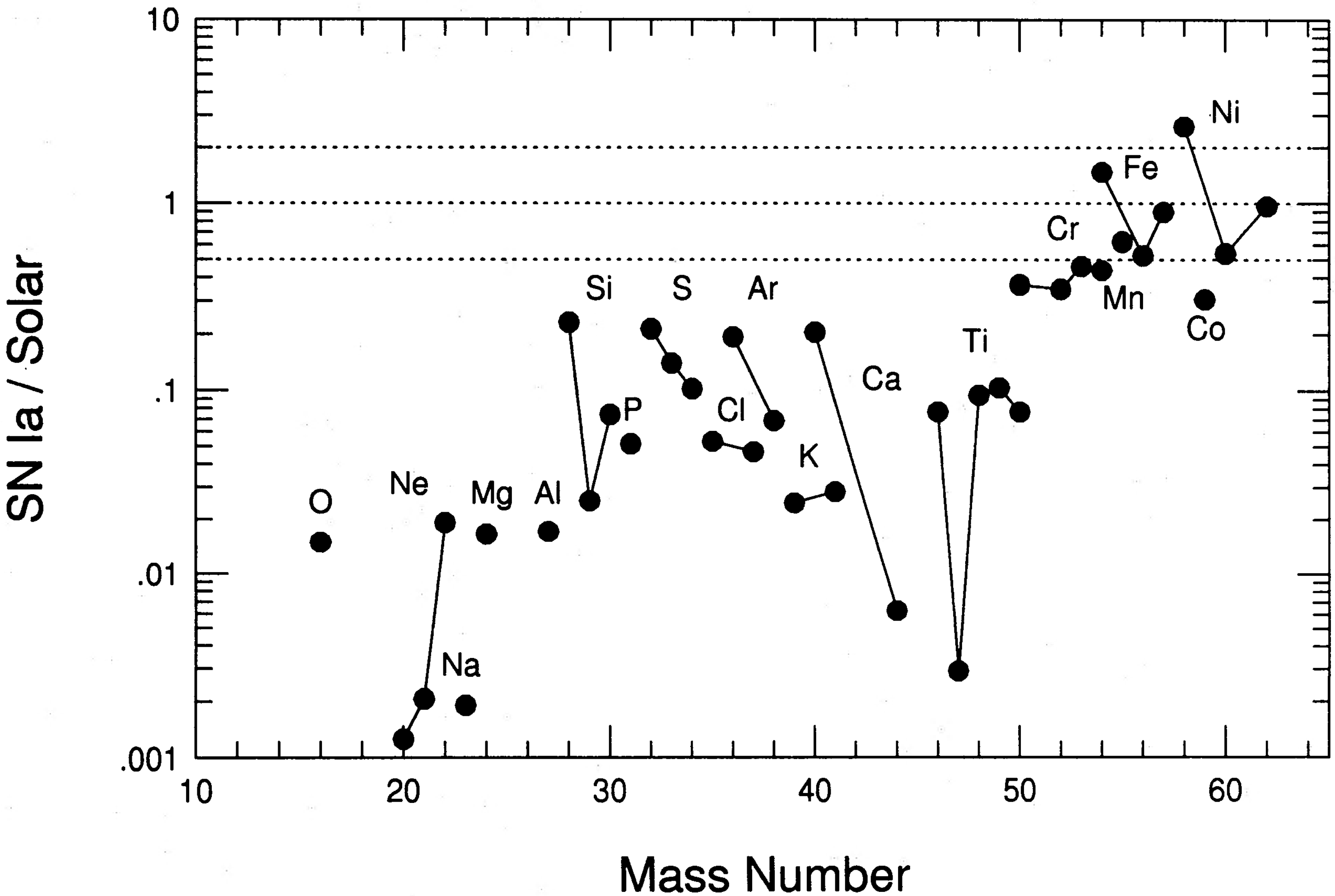
Type Ia SNe produce large amounts of $^{56}Ni$ (which then decays to $^{56}Fe$)




Nomoto et al. (1984)

# SN Ia yields relative to Solar composition

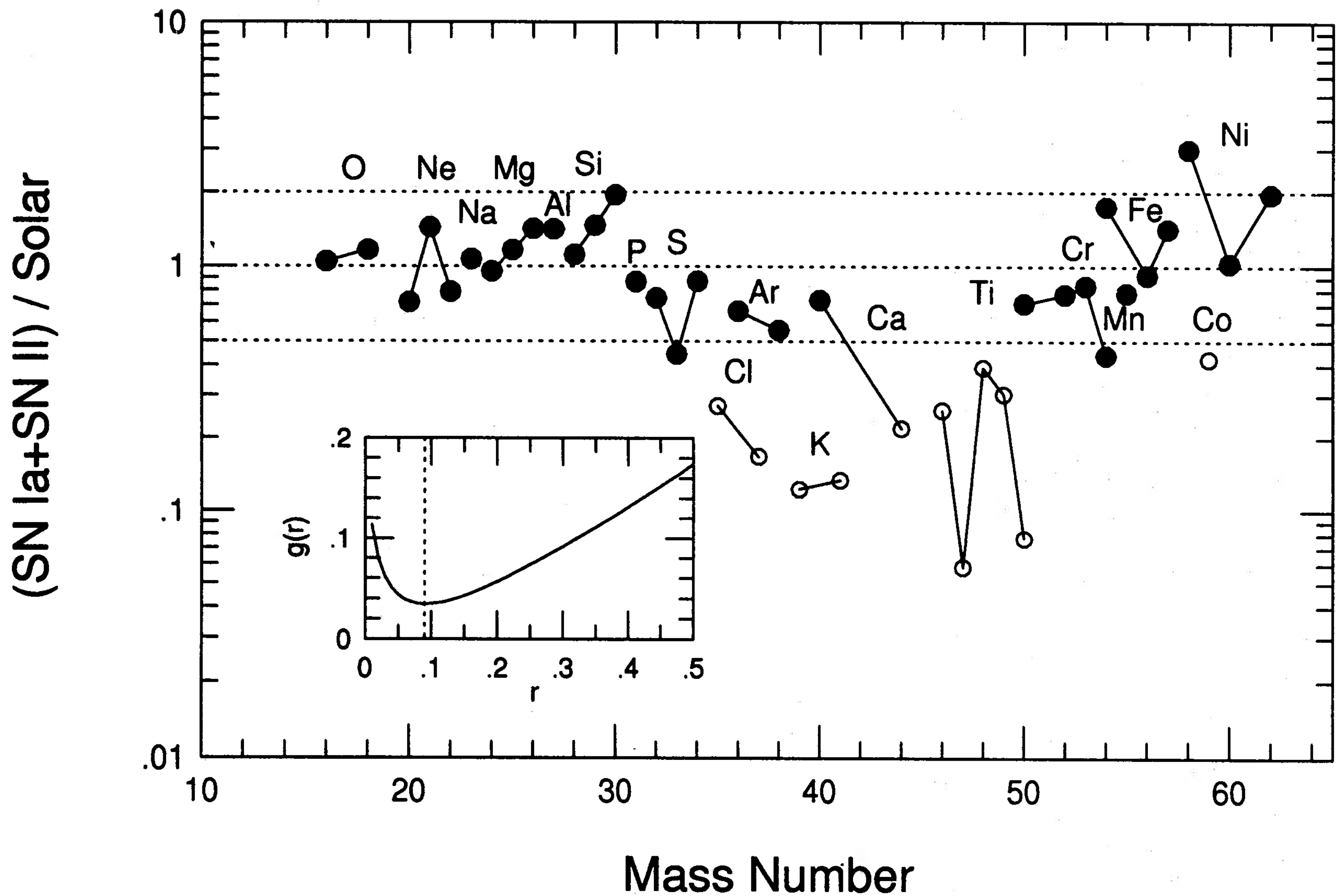
Type Ia SNe can account for Fe-peak elements




Tsujimoto et al. (1995)

# SNIa+II combined

Best fit: SN Ia contribute about 9% of the metals



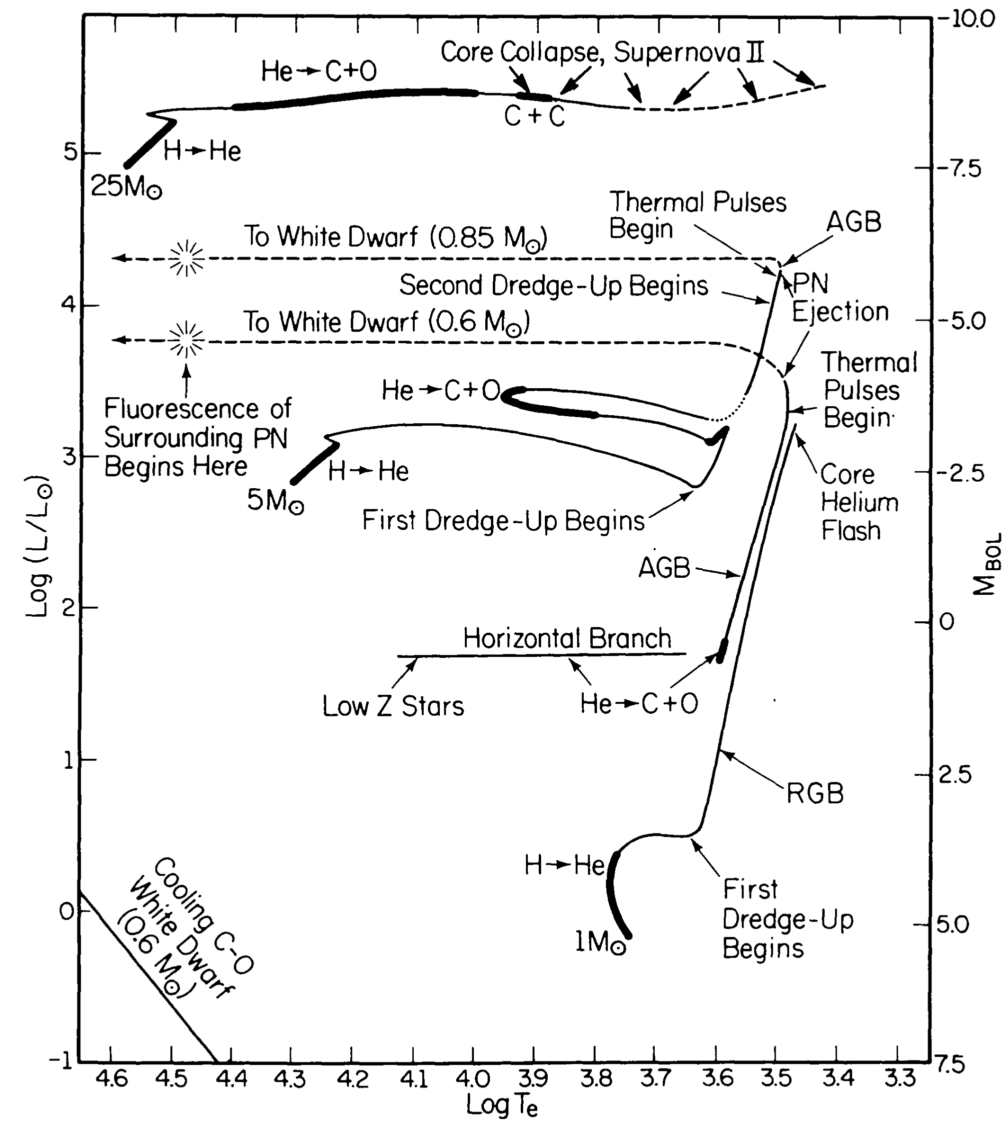

Tsujimoto et al. (1995)

# Nucleosynthesis in AGB stars

Stars on the *asymptotic giant branch* (AGB) undergo "dredge-ups" that bring products of H and He-burning (e.g. C) to the surface.

Also:
Neutrons are produced, e.g. via
$^{13}C + \alpha \rightarrow {}^{16}O + n$

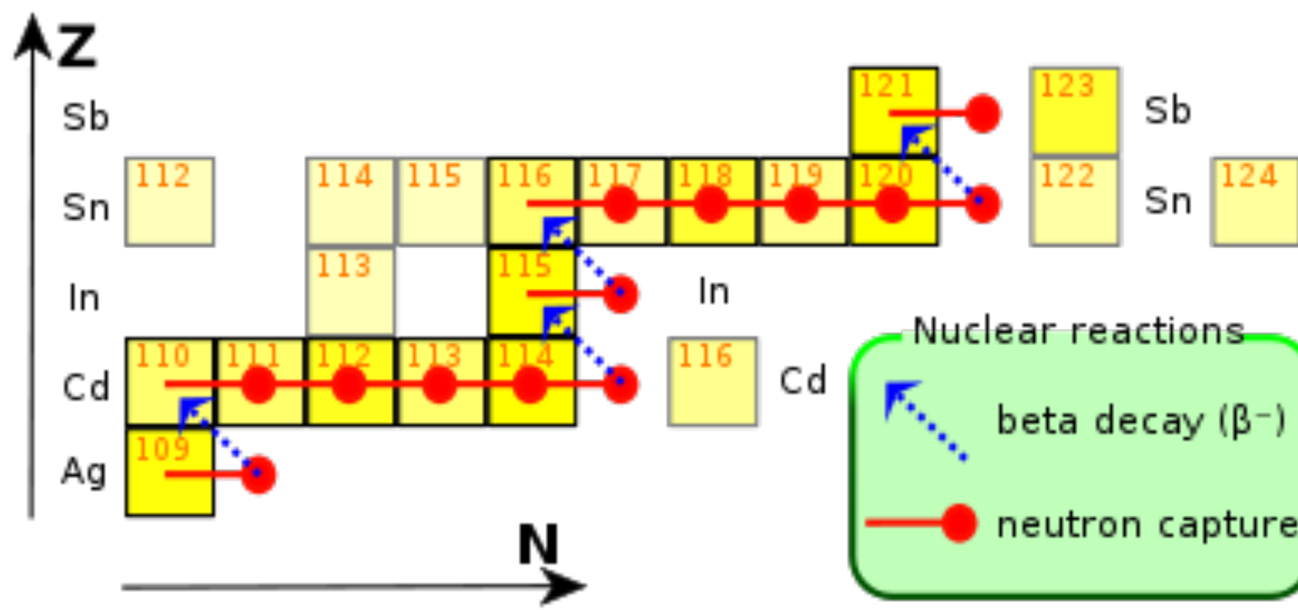
This enables the synthesis of *slow neutron capture* (*s*-process) elements.



# n-capture nucleosynthesis

Elements beyond the iron-peak can be synthesised by *n*-capture reactions.

*s*-process (AGB stars): capture "path" is interrupted by β-decay.
*r*-process (SNe): enough neutrons that even β-unstable nuclei can capture another neutron before decaying.




https://en.wikipedia.org/wiki/S-process

We can account for the Solar (system) composition by choosing a suitable combination of Type Ia and Type II SN nucleosynthesis.

But the overall scaling, and the relative contributions, have so far been treated as *free parameters*.

Next:
We need a real *Galactic Chemical Evolution* model.

# Important concepts

- *Metals*: All elements with atomic number > 2 (everything except H and He)
- ($X$, $Y$, $Z$) = fractions (by weight) of (H, He, metals). $Z \sim 0.019$ for the Sun
- $[Fe/H] = \log_{10} (N_{Fe}/N_H) - \log_{10} (N_{Fe}/N_H)_\odot$.
  Example:
  Solar iron abundance: $[Fe/H] = 0$
  100x less iron than the Sun: $[Fe/H] = -2$
- Bracket notation also used for other elements/ratios, e.g.:
  $[O/Fe] = \log_{10} (N_O/N_{Fe}) - \mathrm{Log}_{10} (N_O/N_{Fe})_\odot$.

# GCE: General expressions

Total (baryonic) mass: $M = M_g + M_s$ gas + stars

$$\frac{\mathrm{d}M}{\mathrm{d}t} = r_{\mathrm{acc}} - r_{\mathrm{ej}}$$

$r_{acc}$, $r_{ej}$ = rates of accretion, ejection

$$\frac{\mathrm{d}M_s}{\mathrm{d}t} = \psi - e$$

e = rate of matter ejection from stars

$\psi$ = star formation rate

$$\frac{\mathrm{d}M_g}{\mathrm{d}t} = r_{\mathrm{acc}} - r_{\mathrm{ej}} + e - \psi$$

$$\frac{\mathrm{d}(M_g Z)}{\mathrm{d}t} = e_Z - Z\psi + Z_{\mathrm{acc}} r_{\mathrm{acc}} - Z_{\mathrm{ej}} r_{\mathrm{ej}}$$

Pagel: "*Nucleosynthesis and Chemical Evolution of Galaxies*", Cambridge Univ. Press, 2007

# GCE equations

Matter ejection from stars:

Initial mass function

$$e(t) = \int_{m_{\tau=t}}^{m_U} (m - m_{\rm rem}) \psi \left[ t - \tau(m) \right] \phi(m) \, \mathrm{d}m$$

lifetime of star with mass *m*

Matter ejection from stars, in specific element $Z_i$:

$$e_{Z_i}(t) = \int_{m_{\tau=t}}^{m_U} \left[ (m - m_{\rm rem}) Z_i(t - \tau(m)) + m q_{Z_i}(m) \right] \psi \left[ t - \tau(m) \right] \phi(m) \, \mathrm{d}m$$

Unprocessed material, re-released to ISM

Freshly produced elements

Pagel: "*Nucleosynthesis and Chemical Evolution of Galaxies*", Cambridge Univ. Press, 2007

# Simple models for Galactic Chemical Evolution

- Closed box
- Leaky box
- Accreting box

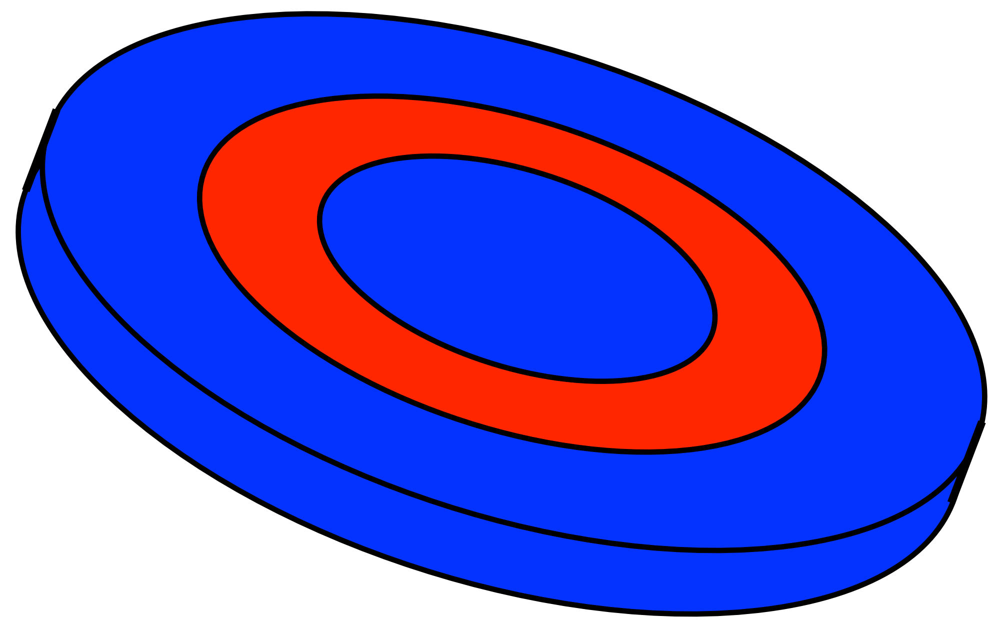
# The "Closed Box" model

- Closed system - no material can enter or leave the box.
- Initially, the box only contains gas (no stars)
- Evolution is followed in (small) time steps, during which:
  - Part of the gas is converted into stars
  - Some of these stars have very long lifetimes and act as passive "remnants"
  - The rest explode as SNe immediately (within one time step) and return their nucleosynthetic products ("metals") to the gas
  - The metals are immediately mixed with the gas

Closed box model:
A galaxy may be imagined as consisting of concentric zones that evolve independently of each other.

In each zone:

- Gas mass = $M_g$
- Mass in metals = $M_h$
- Mass locked up in remnants = $M_s$
- Metallicity = $Z = M_h/M_g$.



# The "Closed Box" model in words:

- In one time step:
  - Metals are produced. These are immediately mixed with the gas in the box (*instantaneous recycling* approximation)
  - $M_s$ *increases* by an amount $\delta M_s$
  - $M_g$ *decreases* by the same amount, $\delta M_g = -\delta Ms$
  - New metals produced = $p\ \delta Ms$, where $p$ is the *yield*.
    Yield depends on
    *a)* Stellar nucleosynthesis
    *b)* The relative numbers of high- and low-mass stars
    (i.e., the *Initial Mass Function*, IMF).
  - $M_h$:
    *Increases* by $p\ \delta Ms$ (just produced),
    *Decreases* by $Z\ \delta M_s$ (locked up in remnants)

# The Closed Box model:

Change in metallicity during a time step δt:

$$\delta Z = \delta\left(\frac{M_h}{M_g}\right) \qquad = \frac{\delta M_h}{M_g} - \frac{M_h}{M_g^2}\delta M_g$$

$$= \frac{1}{M_g}\left(\delta M_h - \frac{M_h}{M_g}\delta M_g\right) \qquad = \frac{1}{M_g}\left(p\delta M_s - Z\delta M_s - Z\delta M_g\right)$$

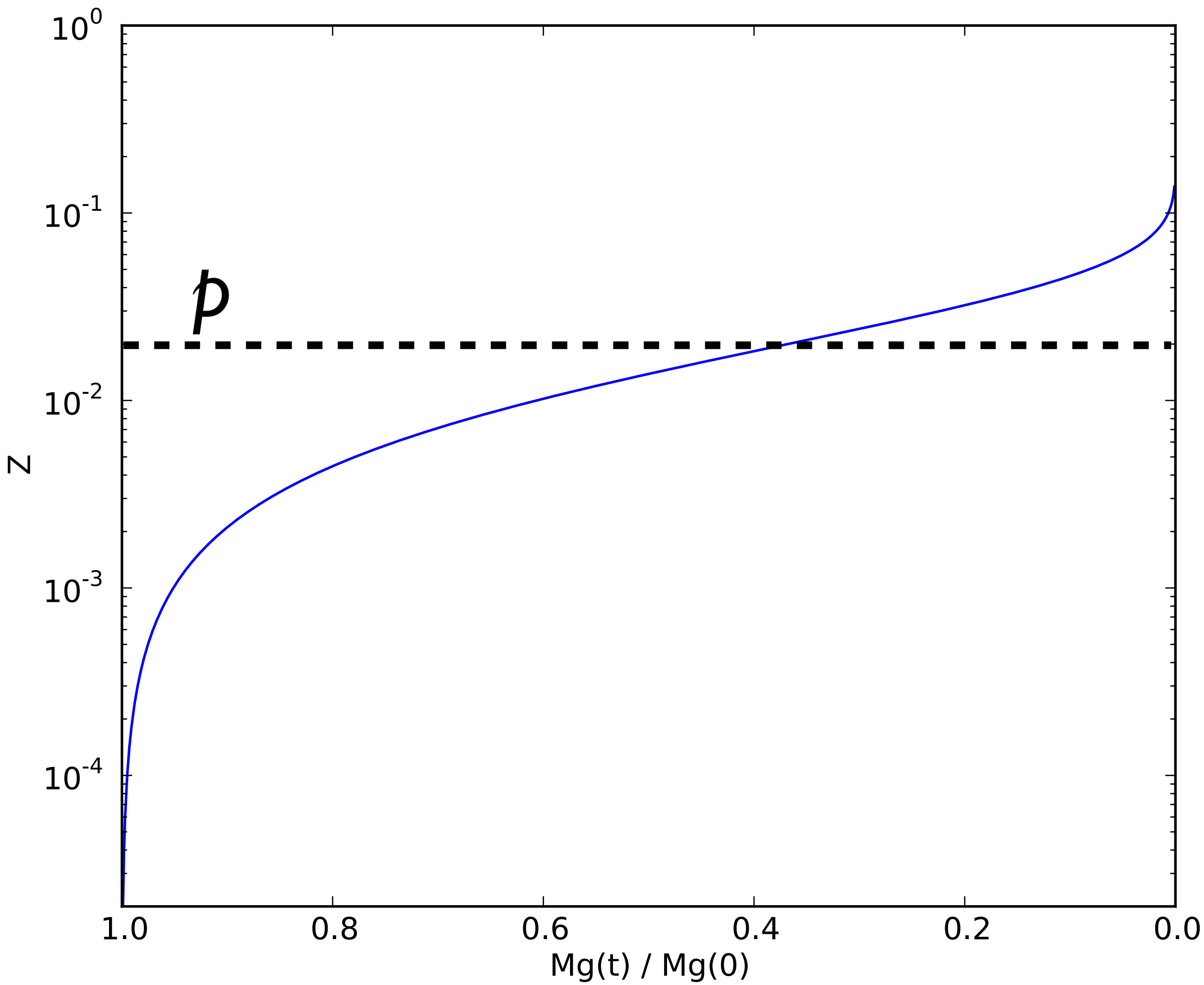
$$= \frac{1}{M_g}(-p\delta M_g + Z\delta M_g - Z\delta M_g) \qquad\qquad \delta M_g = -\delta M_s$$

$$\boxed{\delta Z = -p\delta M_g/M_g}$$

If *p* is constant and *Z=0* initially, then

$$\boxed{Z(t) =} -p\int_{M_g(0)}^{M_g(t)} M_g^{-1} dM_g \quad = -p\left[\ln M_g(t) - \ln M_g(0)\right] = \boxed{-p\ln\frac{M_g(t)}{M_g(0)}}$$

# Metallicity versus *f(gas)* (*p=0.02)*




The metallicity only depends on the *gas fraction* and *p* (under the assumptions made so far)

*Gas-poor* systems are *metal-rich* and vice versa.

$$f_{\rm gas} \equiv \frac{M_g}{M_g + M_s} = \frac{M_g(t)}{M_g(0)}$$

$$\boxed{\begin{aligned} Z(t) &= -p \ln \frac{M_g(t)}{M_g(0)} \\ &= -p \ln f_{\rm gas} \end{aligned}}$$

# What is the metallicity distribution of *stars*?

Stars formed until time *t* have *Z* < *Z(t)*, so

$$\begin{aligned} M_s(Z < Z(t)) = M_s(t) = M_g(0) - M_g(t) &= M_g(0) \left( 1 - \frac{M_g(t)}{M_g(0)} \right) \\ &= M_g(0)(1 - f_{\rm gas}(t)) \end{aligned}$$

$Z(t) = -p \ln f_{\rm gas}$ so $f_{\rm gas}(t) = e^{-Z(t)/p}$

The *cumulative* metallicity distribution is then

$$M_s(Z < Z(t)) = M_0(1 - e^{-Z(t)/p})$$

The *differential* metallicity distribution is:

$$\boxed{\frac{dM_s}{dZ} = \frac{M_0}{p} e^{-Z/p}}$$

# Average metallicity

Differential metallicity distribution:

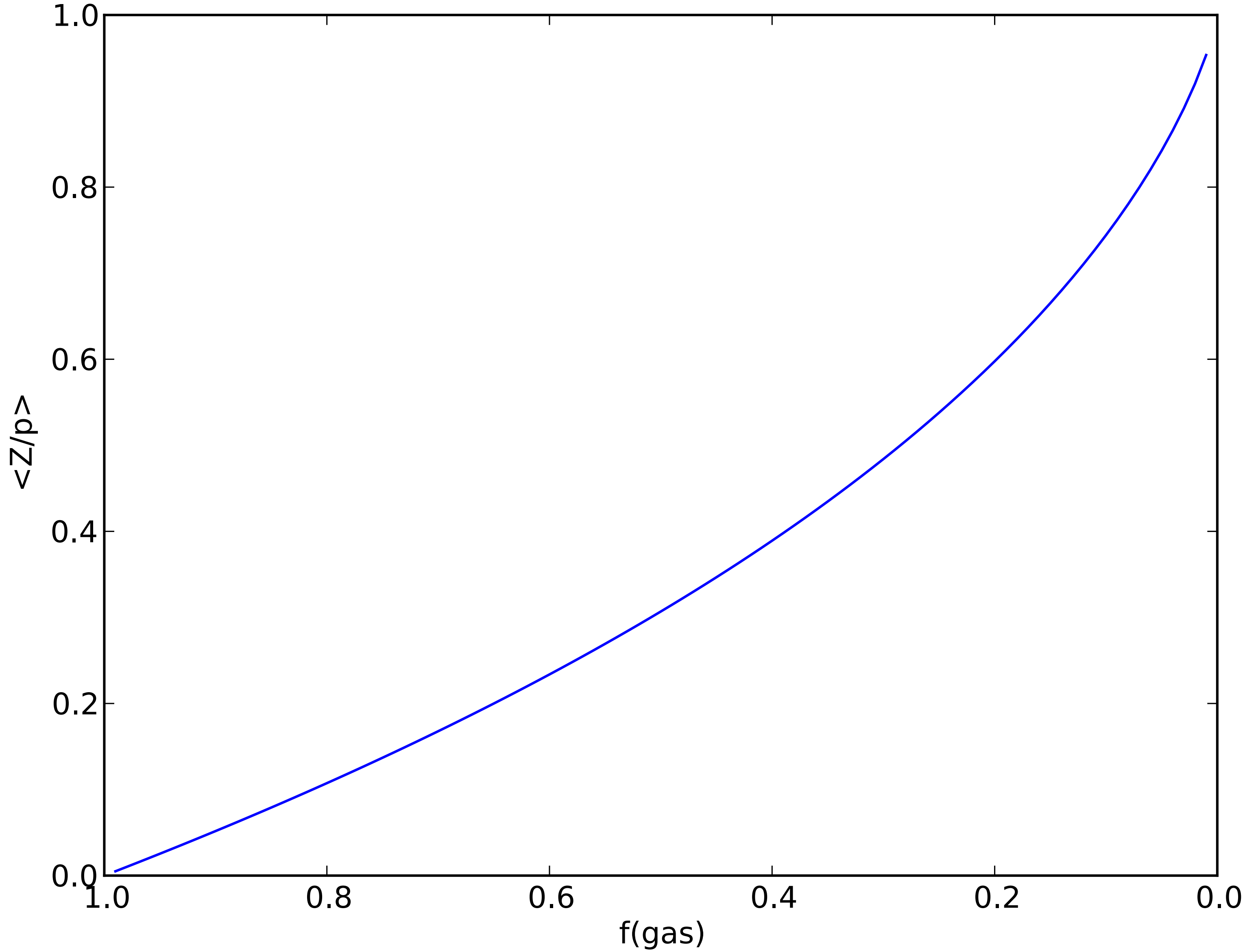
$$\frac{\mathrm{d}M}{\mathrm{d}Z} \equiv n(Z) = \frac{M_0}{p} e^{-Z/p}$$

The average metallicity is then

$$\langle Z \rangle = \frac{\int_0^{Z_{\max}} Z n(Z) \mathrm{d}Z}{\int_0^{Z_{\max}} n(Z) \mathrm{d}Z}$$

$$= \frac{\int_0^{-p \ln f_{\mathrm{gas}}} Z n(Z) \mathrm{d}Z}{\int_0^{-p \ln f_{\mathrm{gas}}} n(Z) \mathrm{d}Z} \qquad = p \left( 1 + \frac{f_{\mathrm{gas}} \ln f_{\mathrm{gas}}}{1 - f_{\mathrm{gas}}} \right)$$

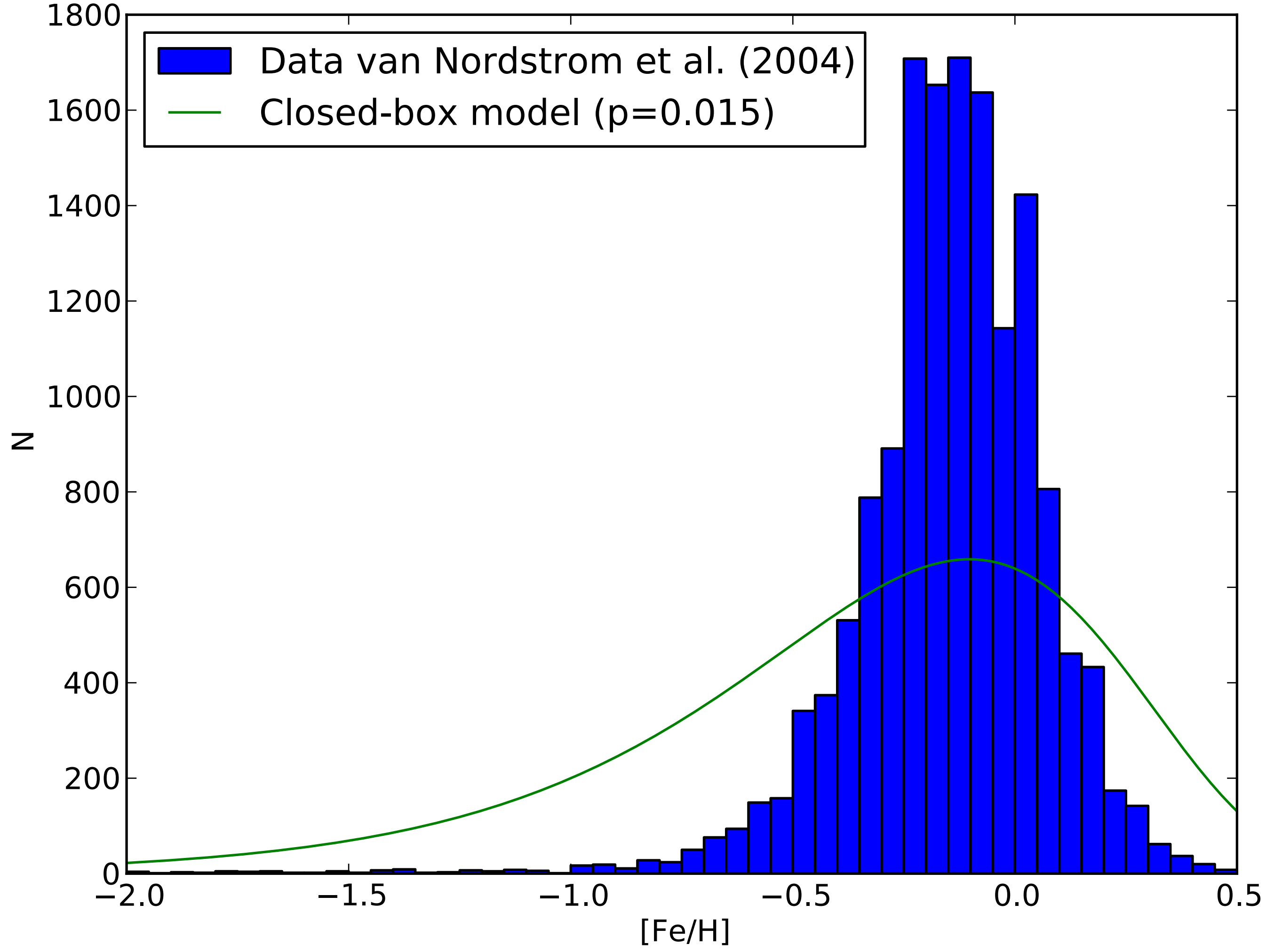
# Average metallicity: <Z> → *p* as $f_{gas}$ → 0



# Chemical evolution

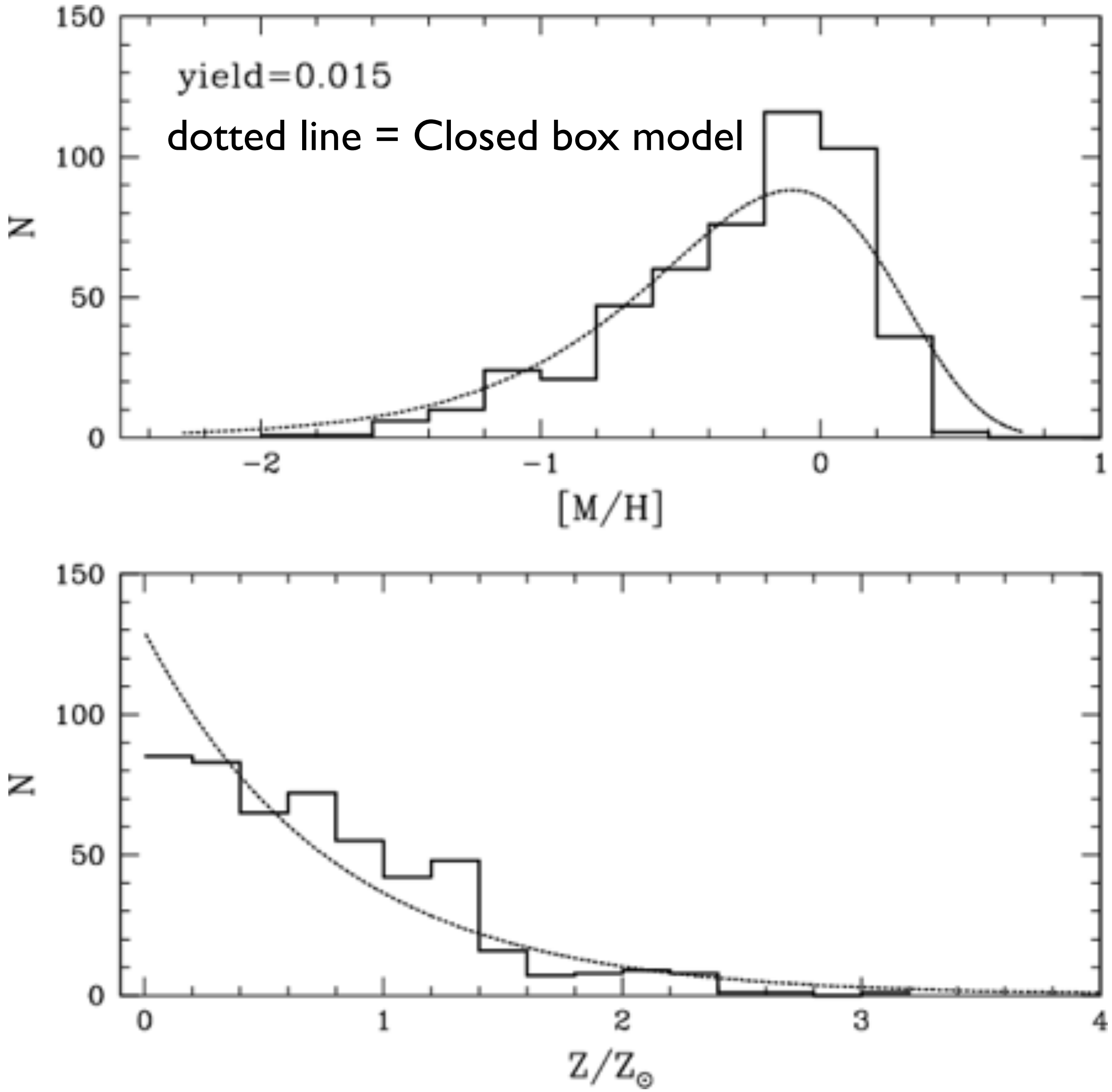
- The *time scale* for chemical enrichment is note important in the closed-box model with instantaneous recycling
- A brief, intense burst of star formation gives the same metallicity distribution as more continuous star formation.

# Metallicities of stars near the Sun




The closed-box model predicts too many metal-poor stars. This is known as the *G-dwarf problem*.

# Metallicities of stars in the Bulge

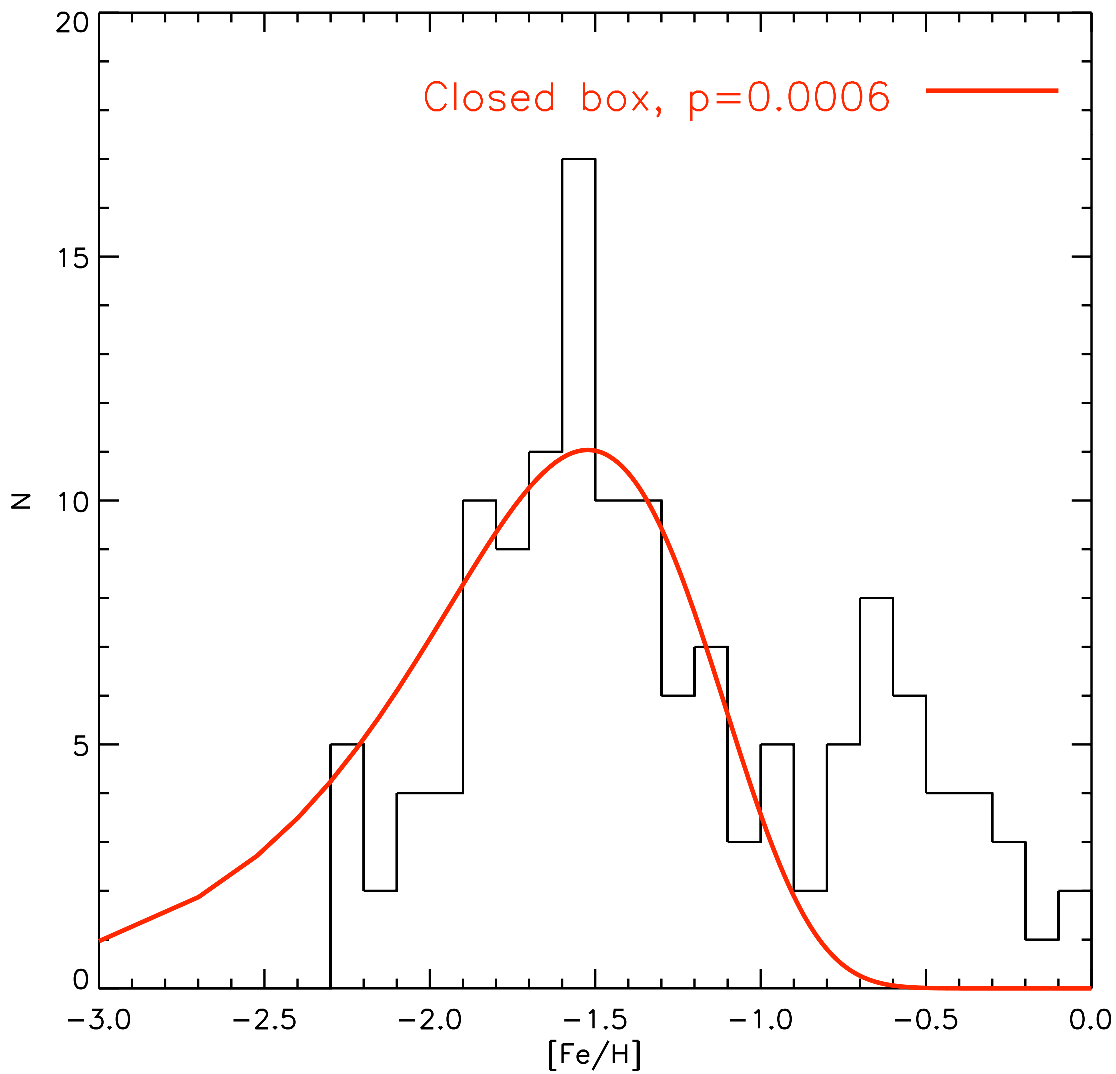



Metallicity distribution of stars in the bulge agrees well with the closed-box model.

*No G-dwarf problem in the bulge!*

Zoccali et al. 2003, A&A 399, 931

# Metallicities of globular clusters




Data from Harris 1996, AJ 112, 1487

The closed-box model is consistent with the metallicity distribution of metal-poor ('halo') globular clusters.

But maybe a hint at a "G-dwarf problem" for GCs?

However, the required yield is much smaller than for the bulge/disc!

# Metallicities of halo stars

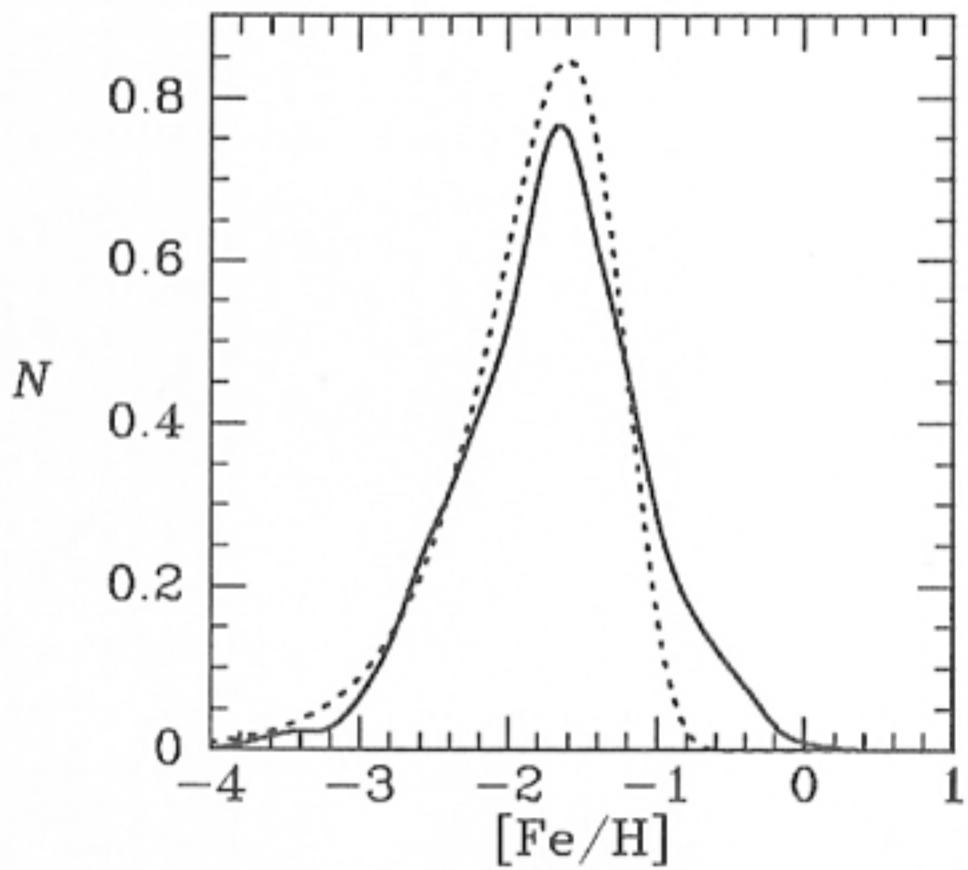



**Figure 10.37** Full curve: a normalized, generalized histogram of the metallicity distribution of 372 kinematically-selected halo MS stars. Dashed curve: the distribution predicted by the leaky-box model with $y_{\rm eff} = 0.025$. [After Ryan & Norris (1991) from data kindly supplied by S. Ryan]

# Modifications to the closed box model

- “Leaky box”: Gas *outflows* (for example, due to feedback from stellar winds and SN explosions)
- “Accreting box”: Gas *inflows* (e.g. intergalactic gas)

# Galactic wind in starburst galaxy M82

APOD 14.04.2006

# High-velocity gas clouds around the Milky Way

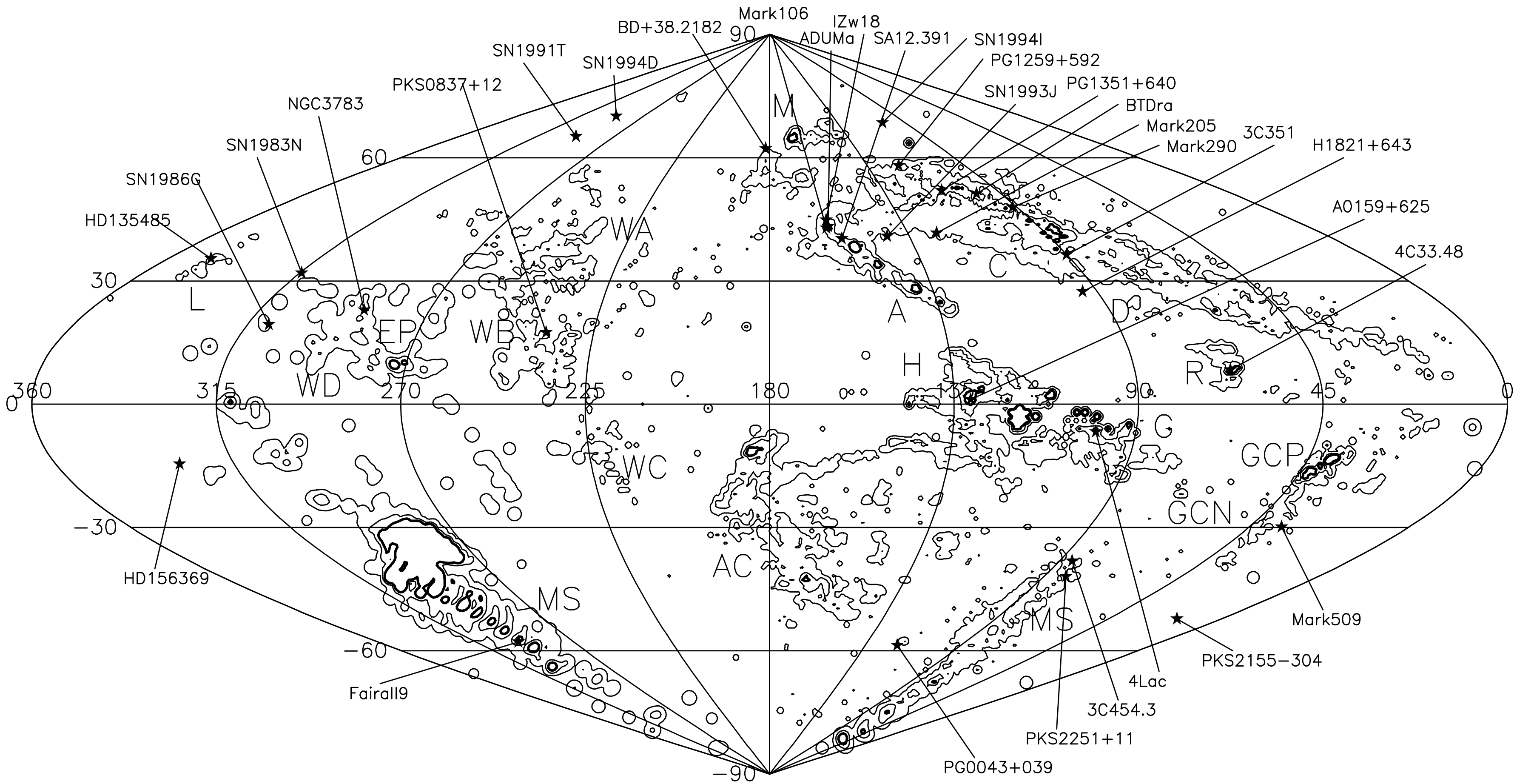



*Figure 1* Brightness temperature map of HVCs (HI with $|v_{LSR}| > 90$ km/s). Contours at 0.04, 0.5, and 1.5K. Common names of some complexes are indicated. Background sources in which high-velocity absorption has been detected or claimed are indicated (see Table 3, Table 4, and Section 4).

# Leaky box

The gas mass decreases due to star formation and *outflows*:

$$\delta M_g = -\delta M_s - \boxed{c\delta M_s}$$

1) star formation 2) outflows

$$M_g(t) = M_g(0) - M_s - \boxed{cM_s}$$

$$= M_g(0) - (1 + \boxed{c})M_s$$

Initially, there is only gas

$$\delta M_h = p\delta M_s - Z\delta M_s - \boxed{Zc\delta M_s}$$

Extra term due to outflows

$$\delta Z = \delta\left(\frac{M_h}{M_g}\right) = \frac{1}{M_g}\left(\delta M_h - \frac{M_h}{M_g}\delta M_g\right)$$

Same as closed box

$$\delta Z = \frac{1}{M_g}(p\delta M_s - Z\delta M_s - \boxed{Zc\delta M_s} - Z(-\delta M_s \boxed{- c\delta M_s})) = \frac{1}{M_g}(p\delta M_s)$$

$$\delta Z = \frac{p\delta M_s}{M_g(0) - (1 + \boxed{c})M_s}$$

## Closed box:

$$M_s(Z < Z(t)) = M_0(1 - e^{-Z(t)/p})$$

## Leaky box:

$$M_s(Z < Z(t)) = \frac{M_0}{(1+c)}\left[1 - \exp\left(-\frac{Z(1+c)}{p}\right)\right]$$

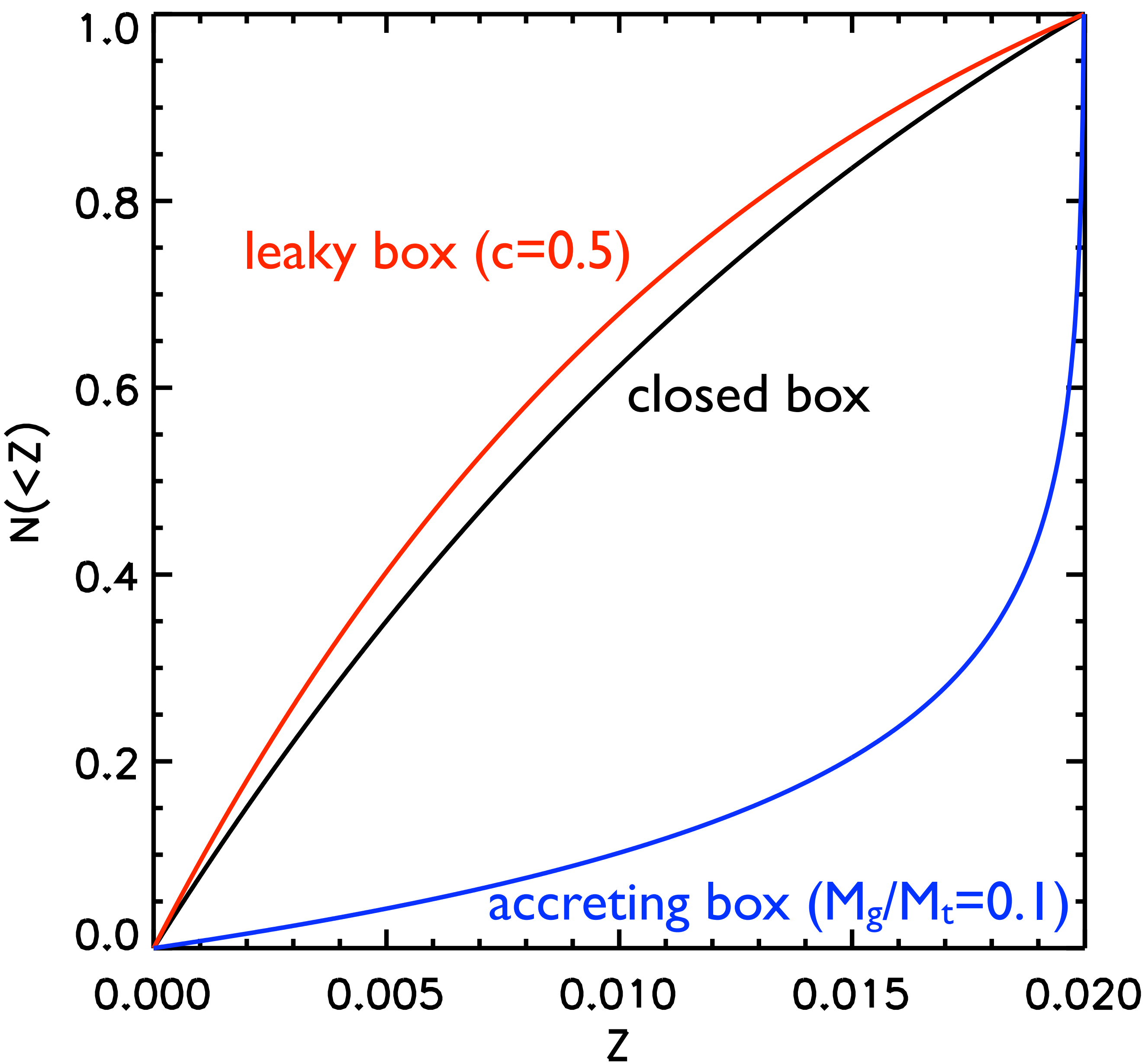
[Effective yield reduced by factor (1+c)]

# Accreting box

Assume "steady state" situation: $M_g$ = const (gas inflow equal to star formation rate).
If the inflowing gas is metal-free, then in each time step:

- $\delta M_g$ of gas added to ISM, $M_h$ unchanged
- $\delta M_s$ stars formed: $M_h$ *decreases* by $Z\,\delta M_g$
- $\delta M_h = p\,\delta M_s = p\,\delta M_g$ metals *returned* to ISM
- Net effect: An amount $Z\,\delta M_g$ of metals is replaced by $p\,\delta M_g$
- The metallicity of the gas converges to the yield $p$

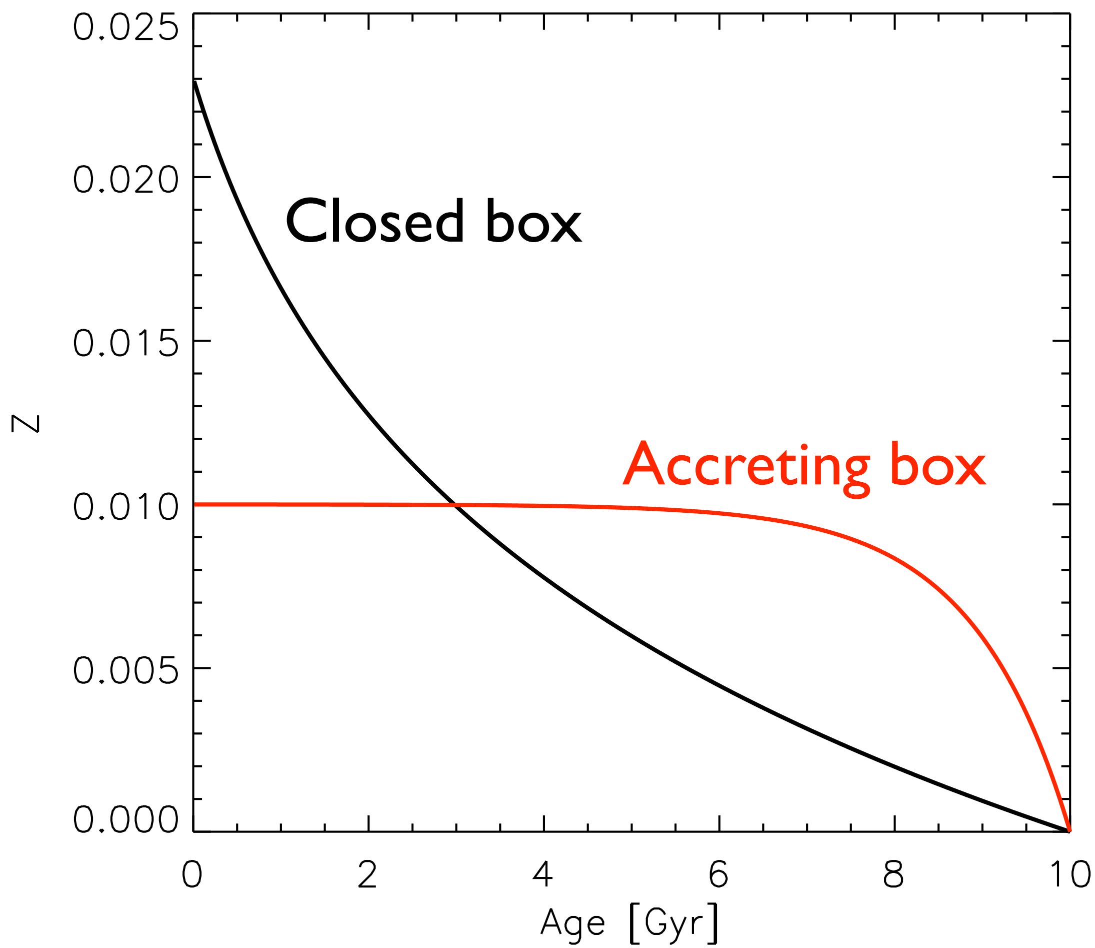
# All models: $p$=0.02




Lower fraction of metal-poor stars in the accreting box models

Solution to the G-dwarf problem?

# Age metallicity relation




If ISM is well mixed at all times, then there exists a unique relation between Z and Age.

This relation depends on the star formation history and details of the chemical evolution model (closed/accreting/leaky box, etc.)

Can we constrain the *age-metallicity* relation observationally?

Assuming $p=0.01$

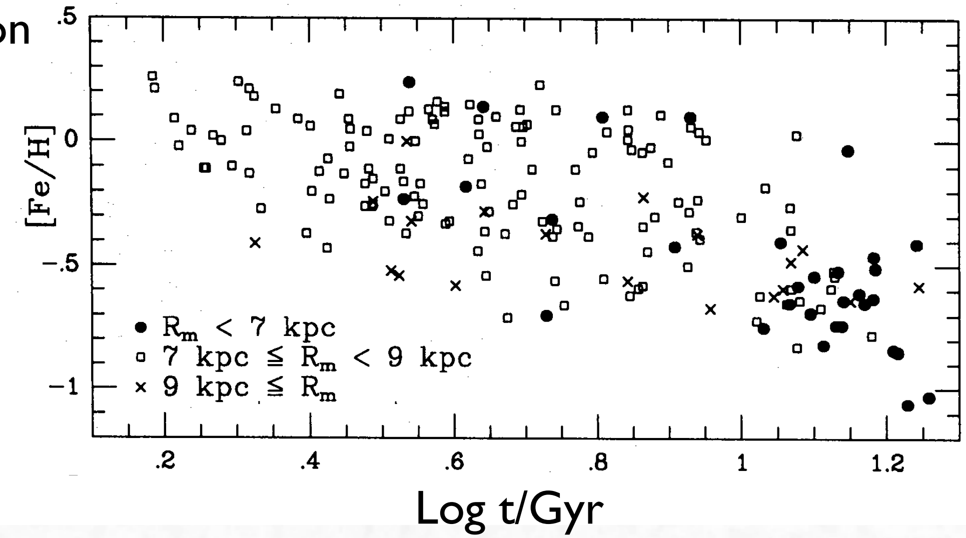
Closed box: $M_g(\text{now}) = 0.1\ M_g(0) \sim 0.11\ M_s(\text{now})$

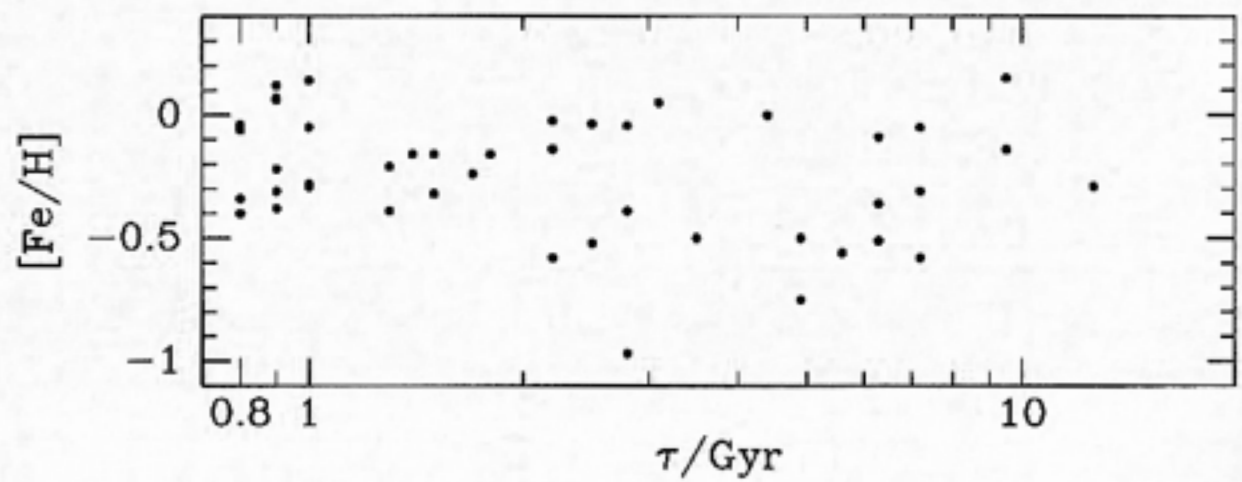
Accreting box: $M_g = 0.1\ M_s(\text{now})$

# Age-metallicity relation in Milky Way

Large scatter in metallicity at all ages - no clear age-metallicity relation in Galactic disk!

Stars (Edvardsson et al. 1993)

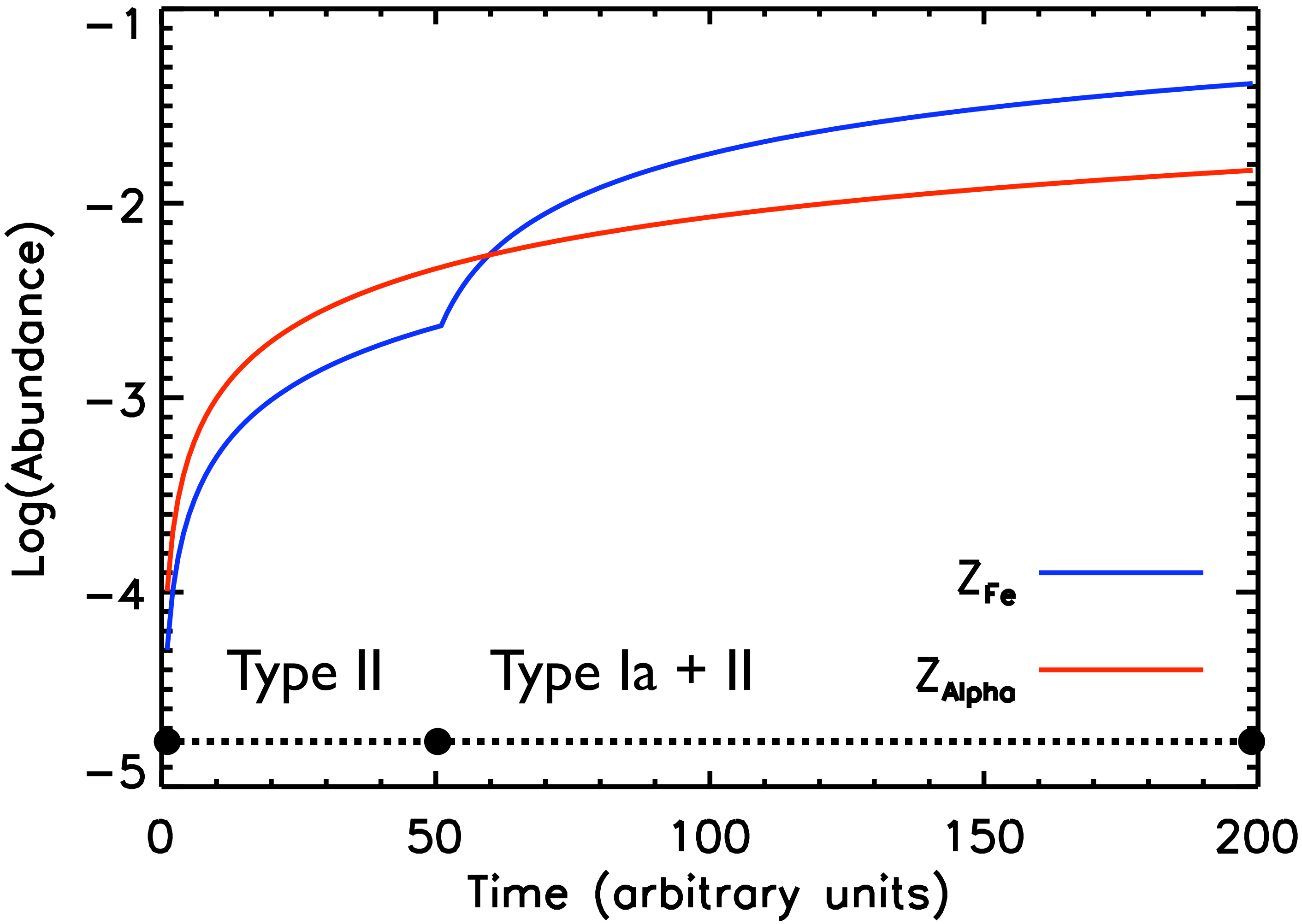



Open clusters (Friel et al. 1995)

# The α/Fe ratio

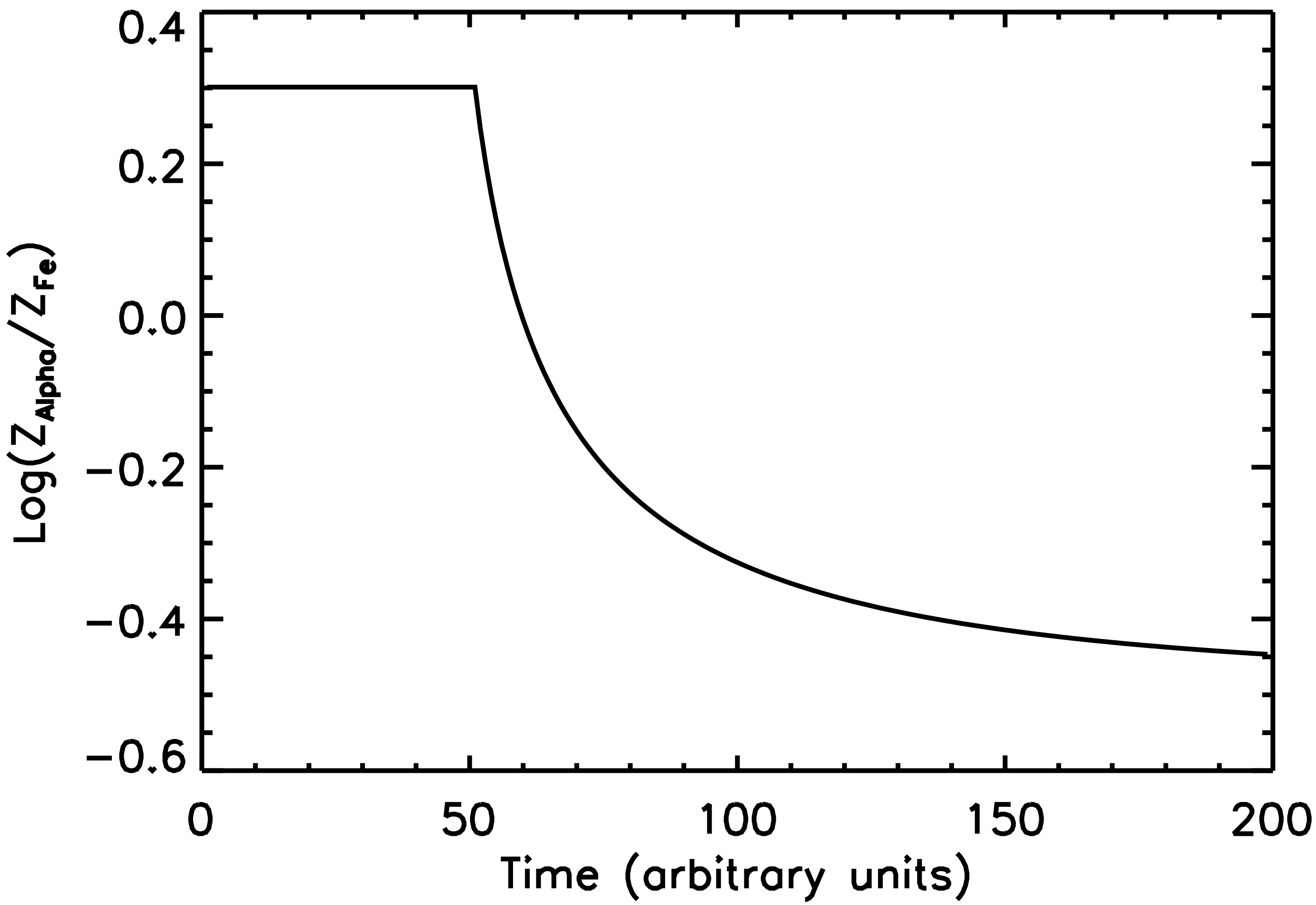
- "Alpha"-elements ($^{16}$O, $^{20}$Ne, $^{24}$Mg, $^{28}$Si, $^{32}$S, $^{36}$A, $^{40}$Ca) are preferentially produced in massive stars and returned to the ISM by Type II SNe.
- Type Ia SNe preferentially produce Fe
- Type II SNe explode almost immediately, while Type Ia SNe can have a long delay ($\sim 10^8$-$10^9$ yr).
- Stars that formed early are thus rich in alpha-elements, compared to stars that formed later



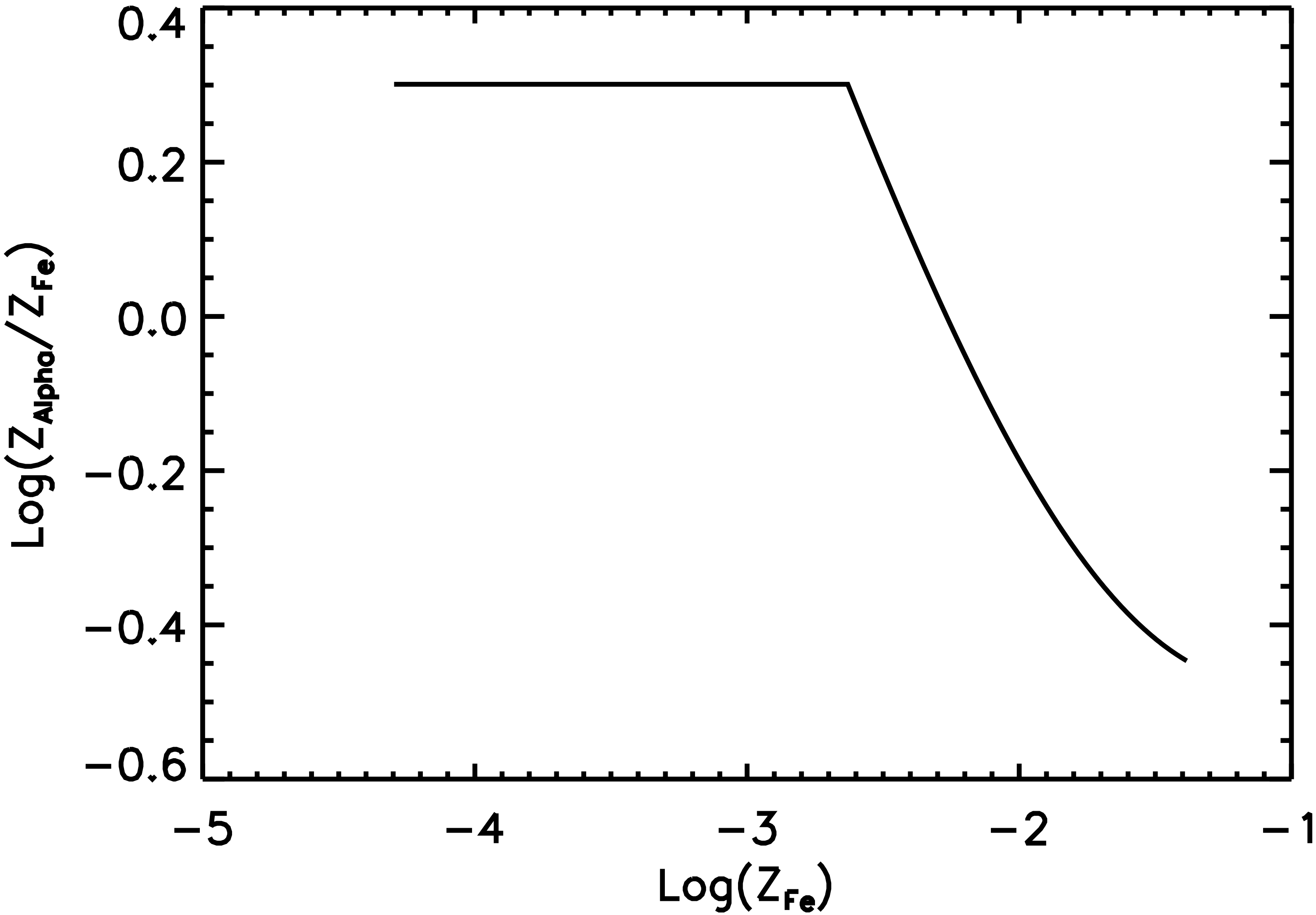

Delay = 50 steps

Initially, Type II SNe produce Alpha-elements (and some iron). After 50 time steps Type Ia SNe kick in and produce extra iron. [α/Fe] thus decreases.

# Log (Alpha/Fe) versus time




The α/Fe ratio is initially given by the relative yields in Type II SNe.
The α/Fe ratio later decreases as Type Ia SNe add more iron.




The “knee” in this plot corresponds to the level of iron enrichment that had been reached when Type Ia SNe started to contribute.

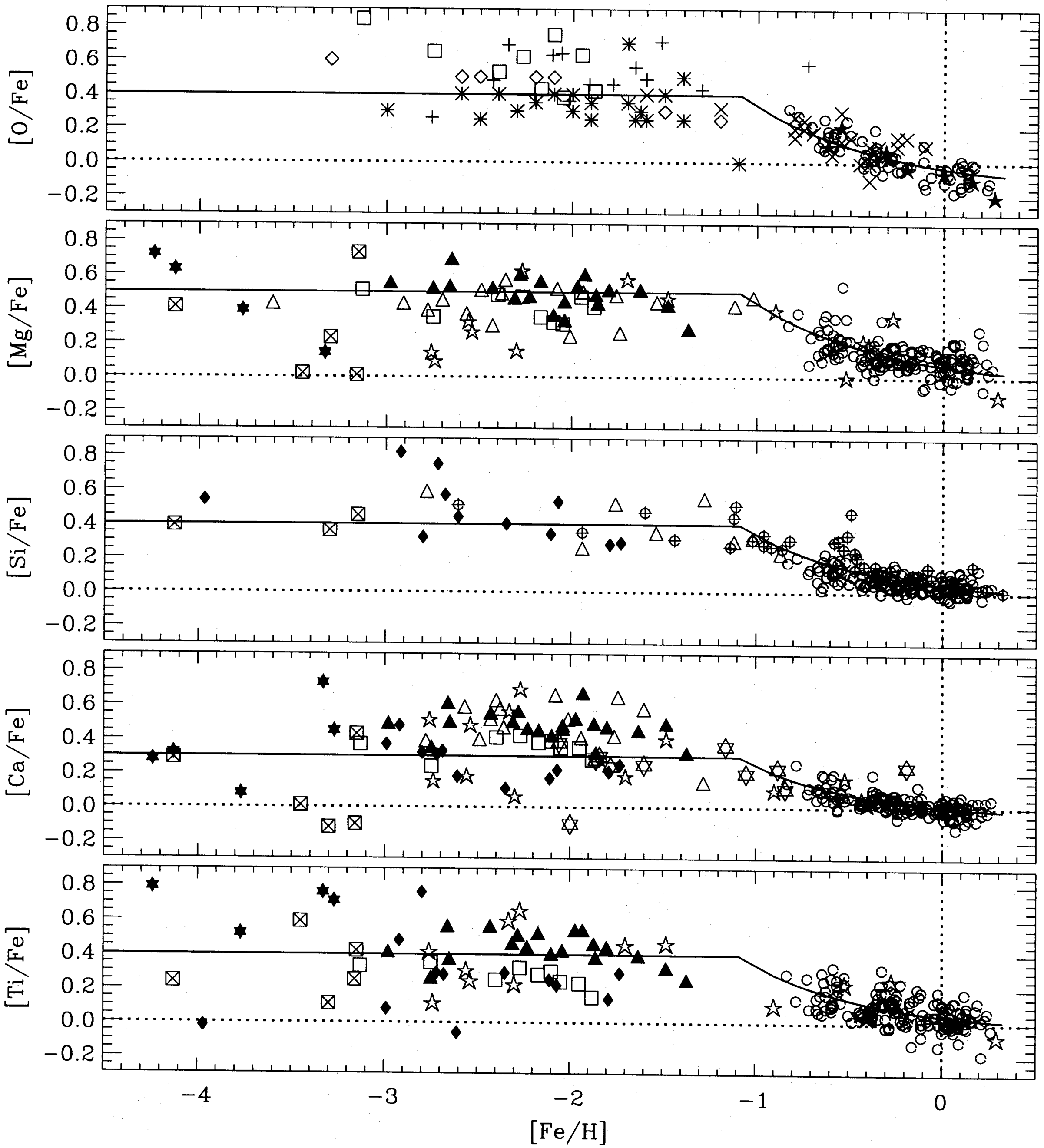
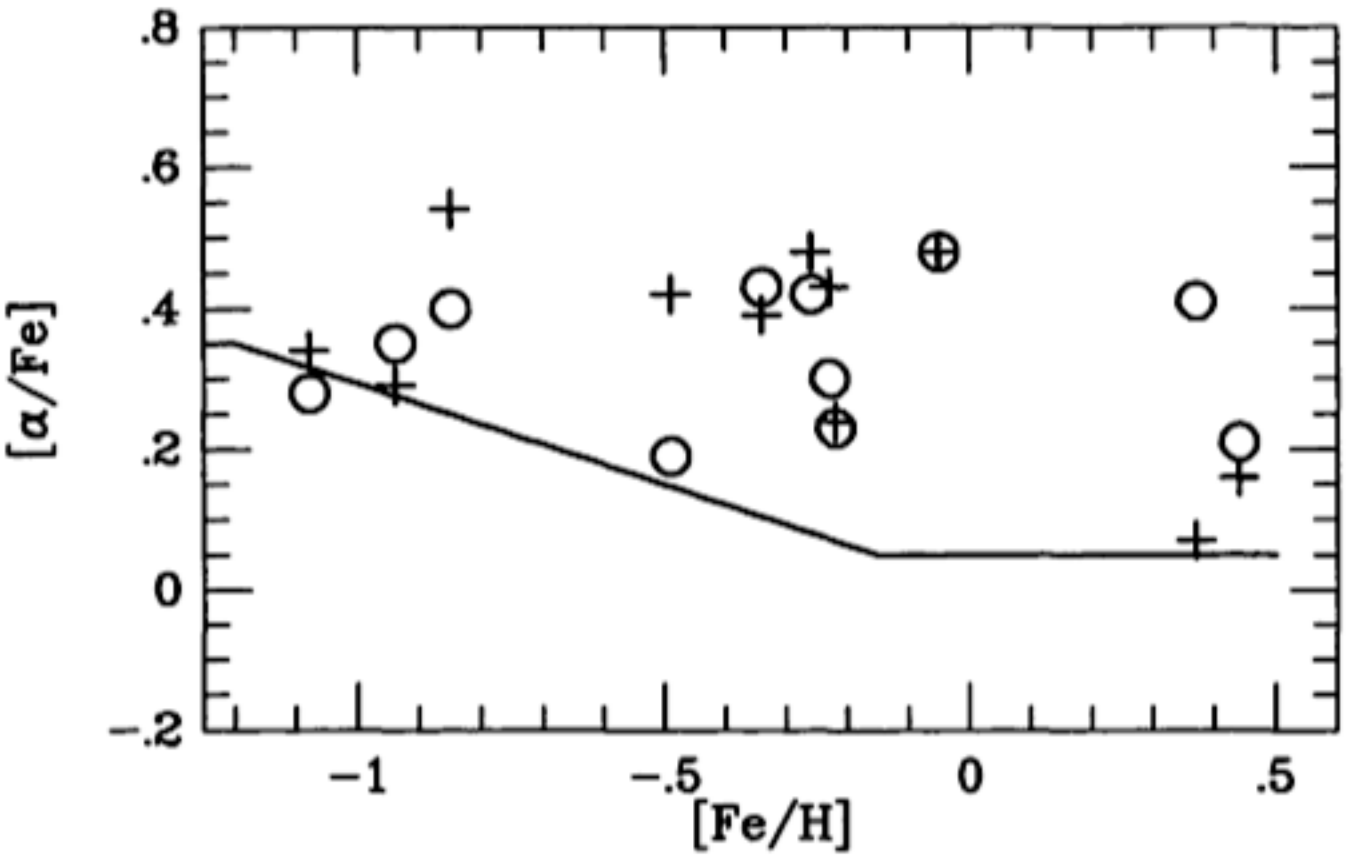



**Figure 3.** Oxygen, magnesium, silicon, calcium and titanium: iron abundance ratios plotted against metallicity [Fe/H] for nearby disc stars and extension to [Fe/H] = −4.5 (halo and metal-weak thick disc). Symbols indicate various data sources. Open squares: Nissen et al. (1994); squares with crosses: Primas, Molaro & Castelli (1994); open circles: Edvardsson et al. (1993) for $R_m \geq 7$ kpc; 'plus' signs: King (1993); filled six-cornered 'stars': Norris et al. (1993); open rhombs: Bessell, Sutherland & Ruan (1991); field triangles: Magain (1989); open triangles: Magain (1987); open five-cornered 'stars': Tautvaišienė & Straižys (1989); crosses: Barbuy & Erdelyi-Mendez (1989); asterisks: Barbuy (1988); filled rhombs: Gratton & Sneden (1988); open six-cornered 'stars': Hartmann & Gehren (1988); circles with 'plus' signs: François (1986); filled five-cornered 'stars': Kyröläinen et al. (1986).

Pagel & Tautvaisiene (1995)

# Alpha-elements in the Bulge

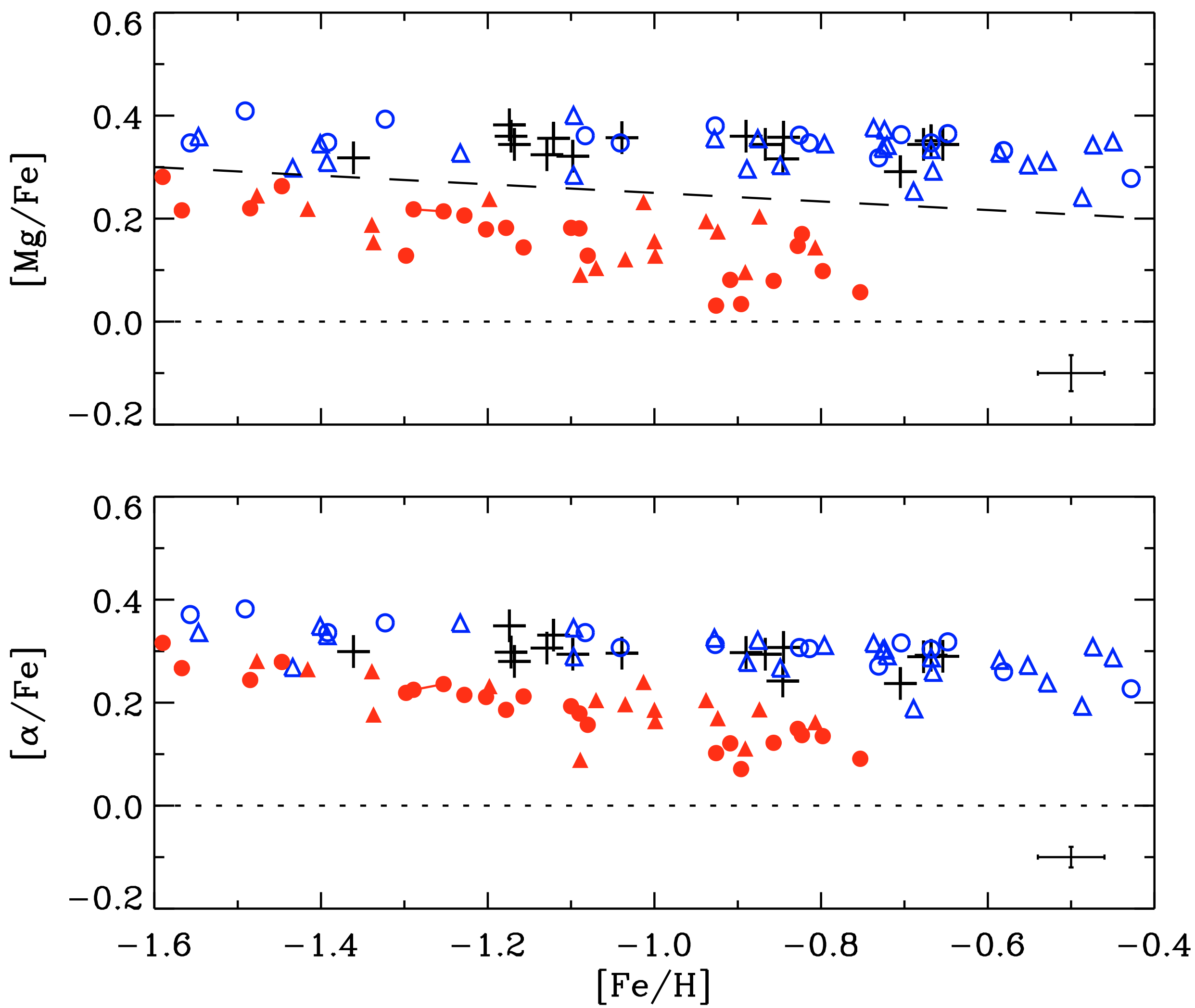



Circles: [Ti/Fe]
Plus: [Mg/Fe]
Line: Disc

In the bulge, also metal-rich stars have a high α/Fe-ratio

McWilliam & Rich 1994, ApJS 91, 749

# Two halo populations!

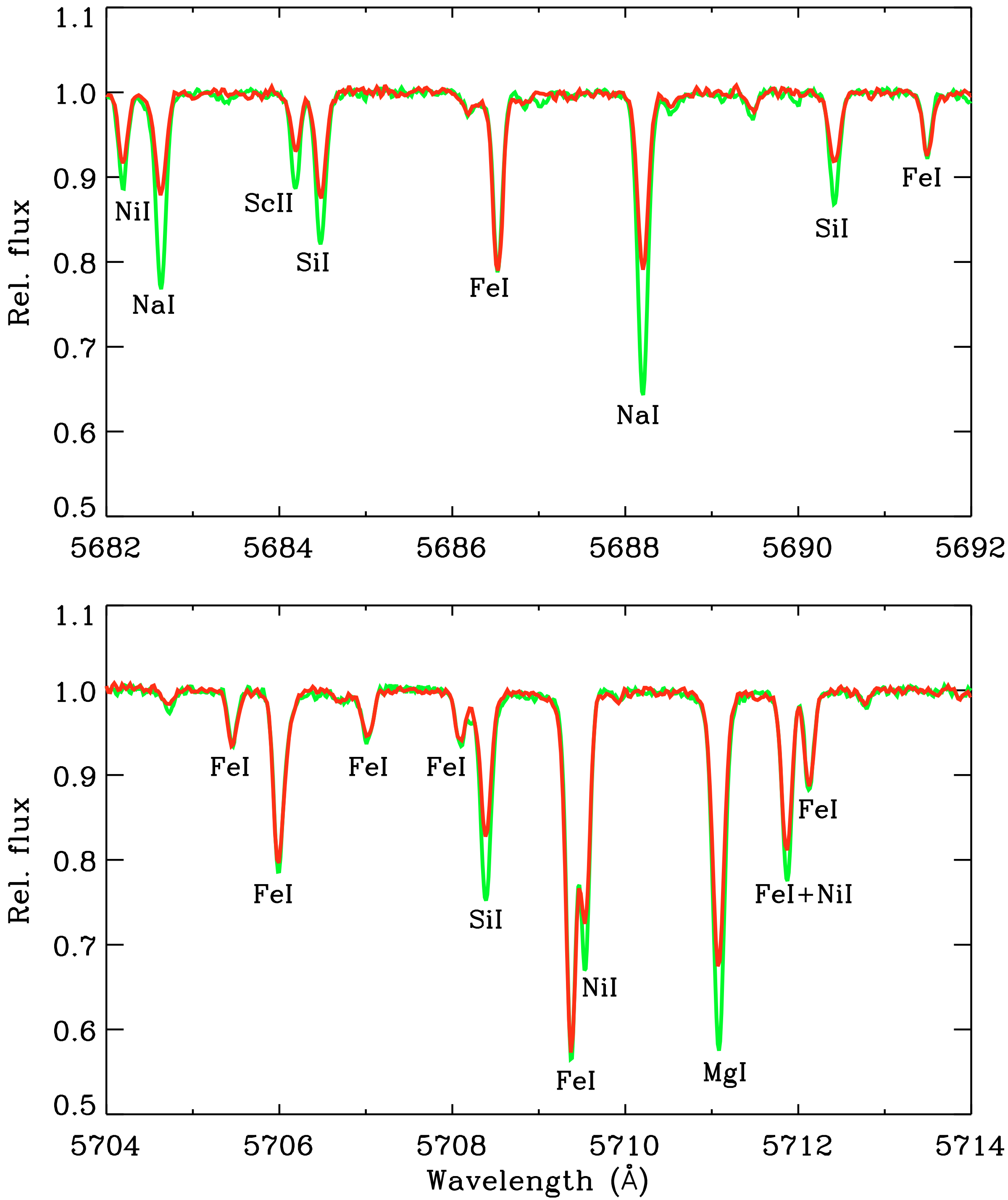



'+': Thick disc
o, △ : halo stars
(two diff. instr.)

Two sequences of halo stars, "low" and "high" alpha.

Both are "old" (10-13 Gyr)

Nissen & Schuster 2010

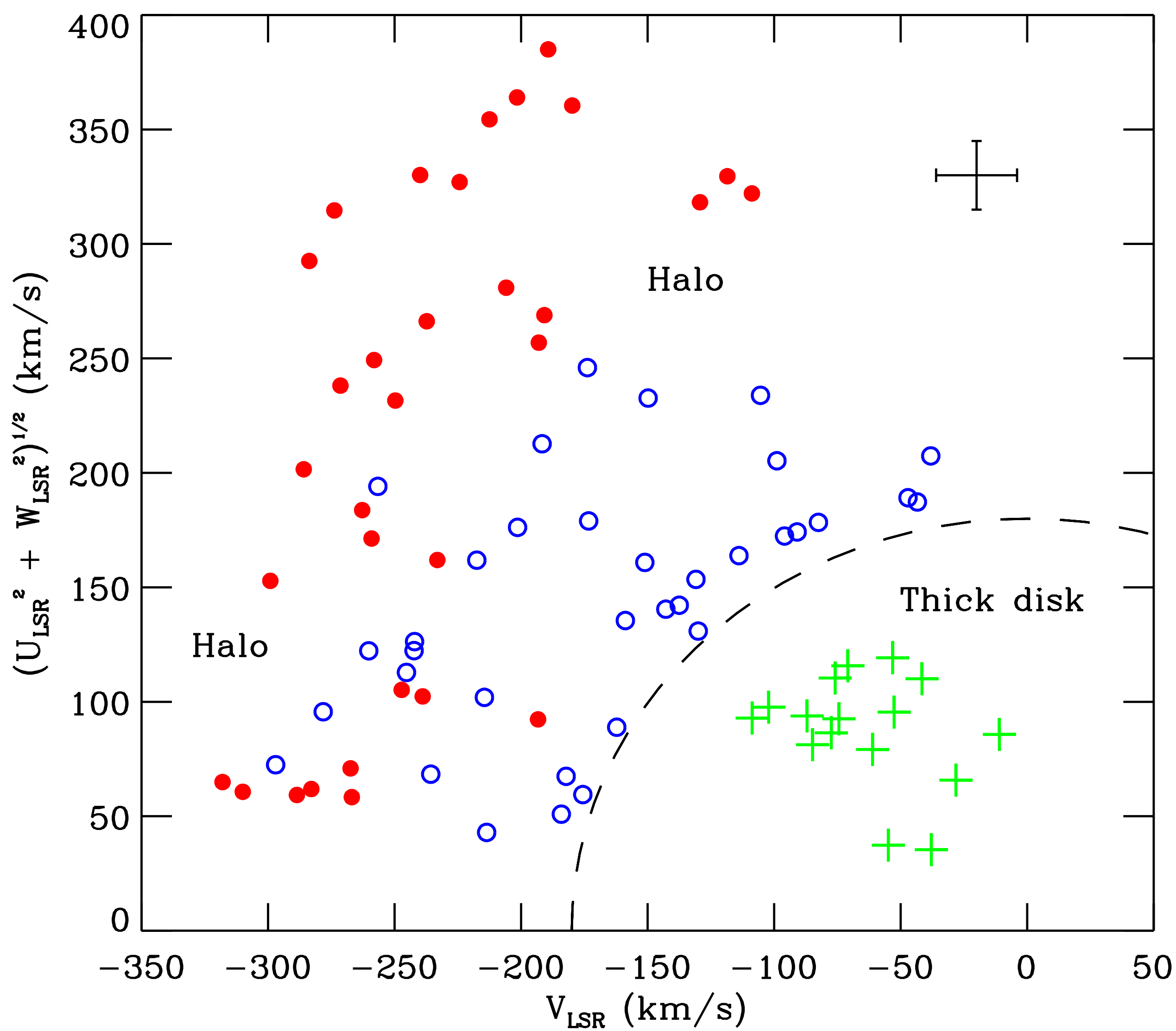



Spectra of low-alpha and high-alpha stars.

Similar [Fe/H], temperature, log g

Nissen & Schuster 2010

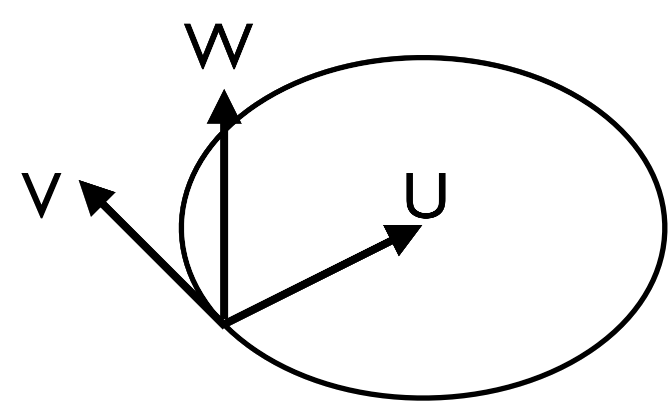
# Kinematics




o Low alpha

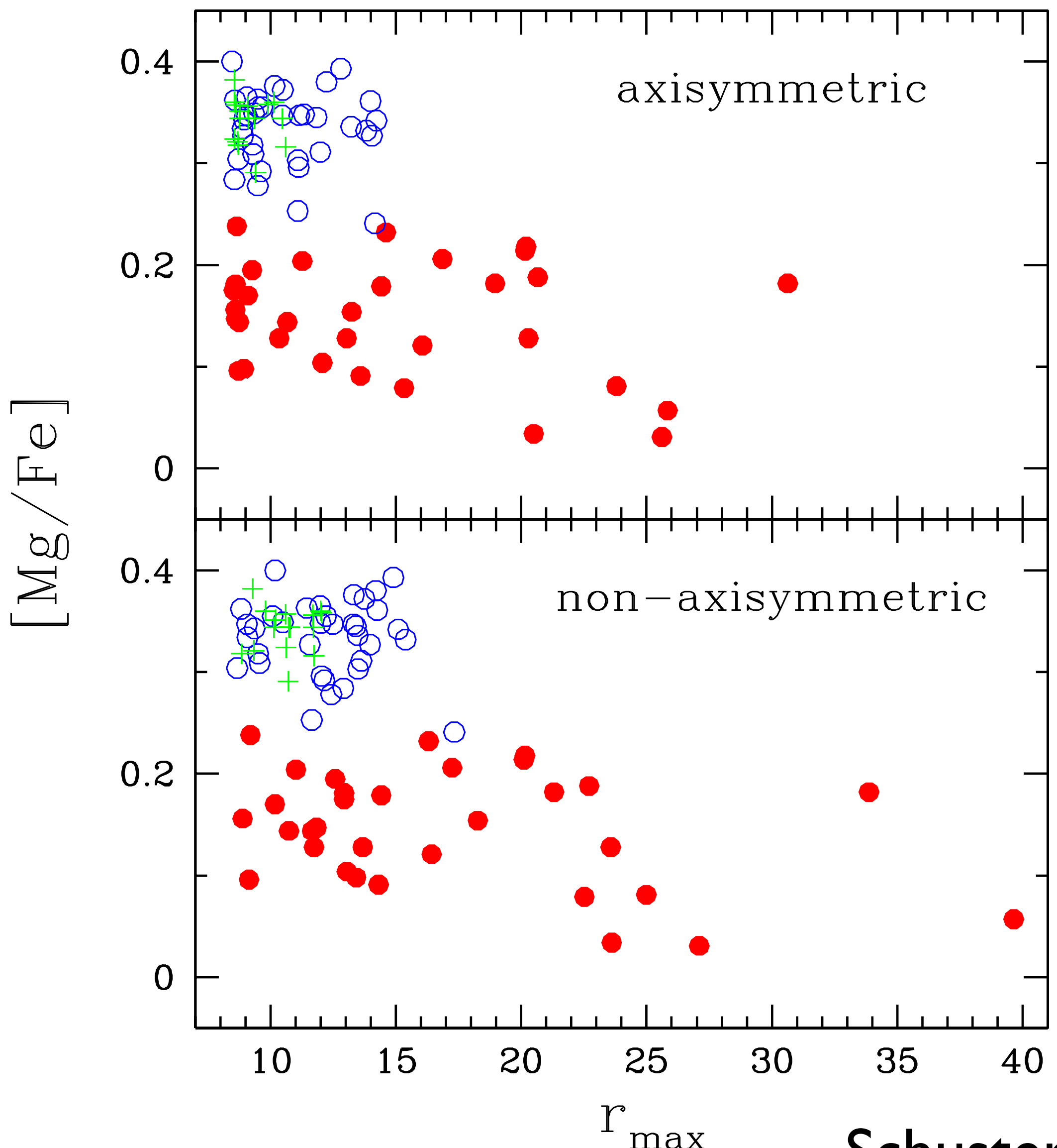
o High alpha

The "low alpha" stars have the *highest velocities* with respect to the Sun




Schuster & Nissen 2012

# Modelling of orbits

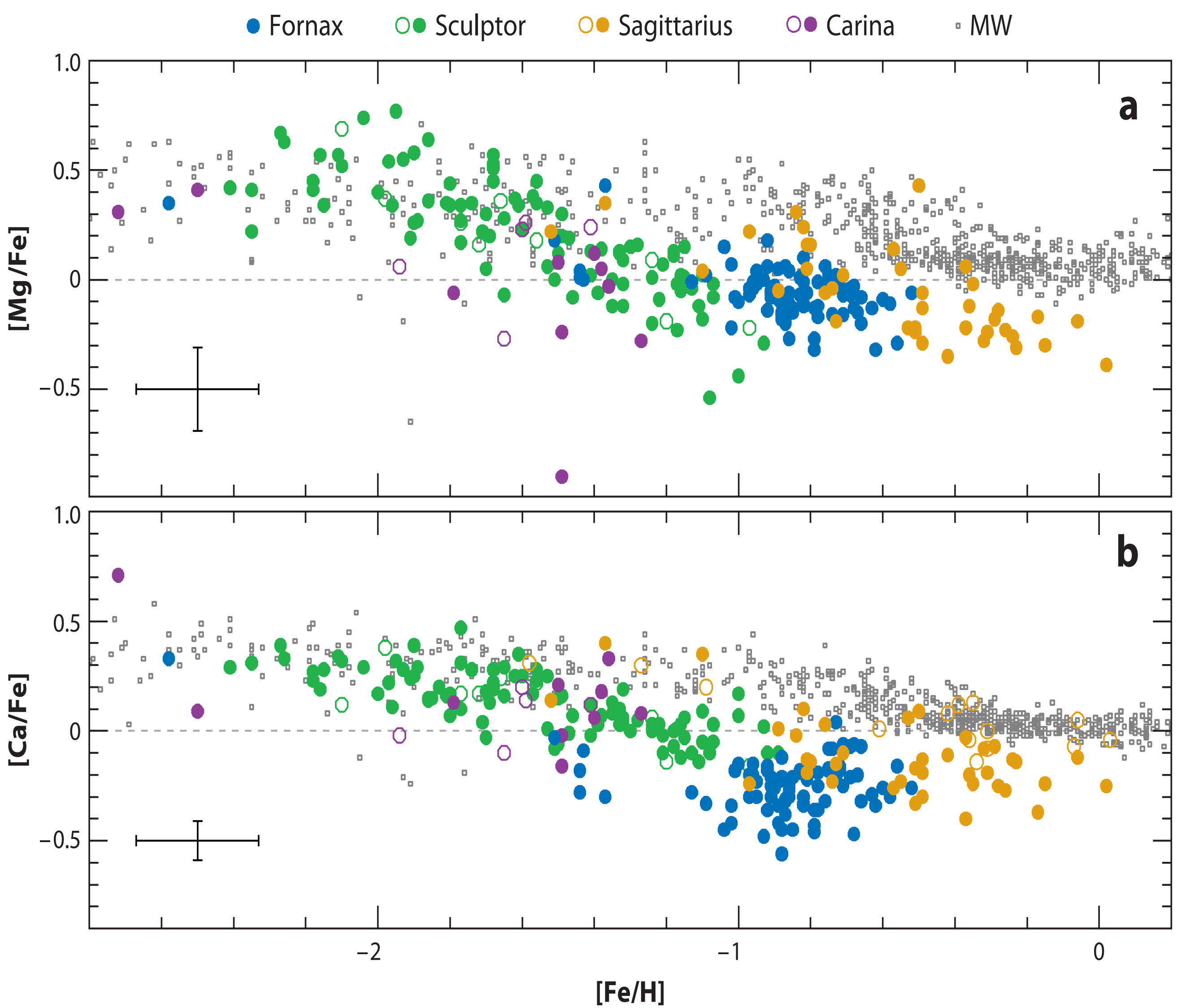



o Low alpha
o High alpha

The "low alpha" stars reach the *greatest distances* from the Galactic centre

Schuster & Nissen 2012

# Comparison with dwarf galaxies




Stars in dwarf galaxies have low [alpha/Fe], like the "low alpha" stars in the MW.

Evidence for accretion?

Tolstoy et al. 2009