# The Fate of the Local Group (Forbes+00)

The elliptical galaxy formerly known as the Local Group

MW and M31 will probably merge in ~ 4 Gyr

by that time they will have swallowed all their smaller comp.

➜ normal field elliptical

When young stellar pops will have faded: $M_V \leq -21$.

The Globular Clusters will survive.

[Gas-rich mergers make starbursts & produce new GCs]

Collect all 700 Local Group GCs with their luminosities

& metallicities [Fe/H] + account for their fading

➜ ~ universal GC Luminosity Function

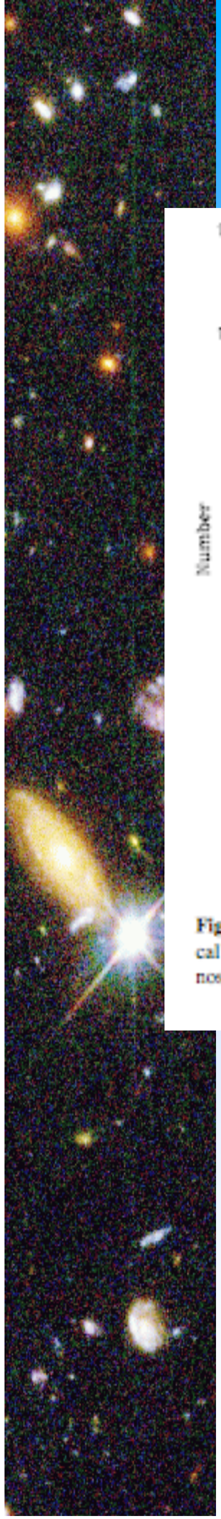
➜ ~ normal bimodal GC [Fe/H] distribution with peaks at

[Fe/H] = -1.55 & -0.64

MP / MR = 2.5 / 1 MP metal-poor, MR metal-rich

➜ ~ normal GC specific frequency $S_N = N_{GC} \cdot 10^{0.4(MV+15)} \sim 3$

# The Fate of the Local Group (Forbes+00)



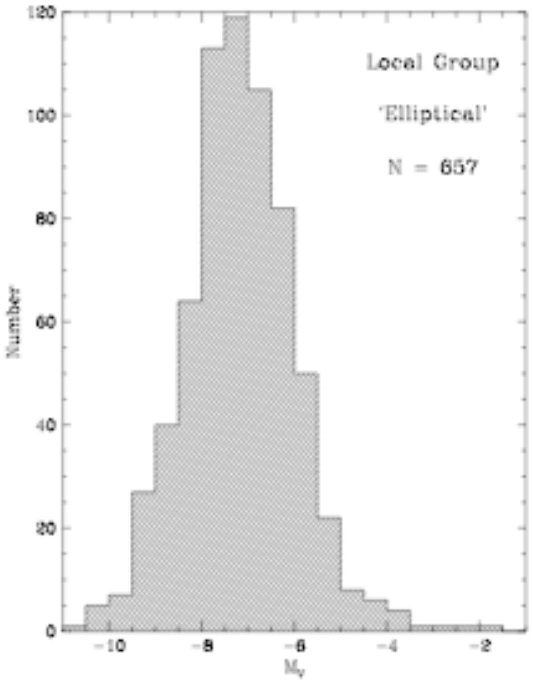


**Fig. 1.** Absolute magnitude distribution for the Local Group 'Elliptical'. The distribution resembles the 'universal' globular cluster luminosity function.

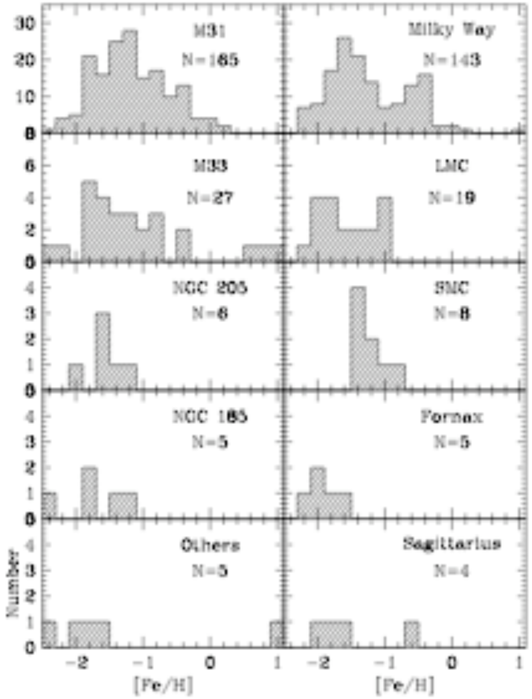


**Fig. 2.** Metallicities of Local Group globular clusters. The number of available globular clusters with individual measurements is indicated in each panel.

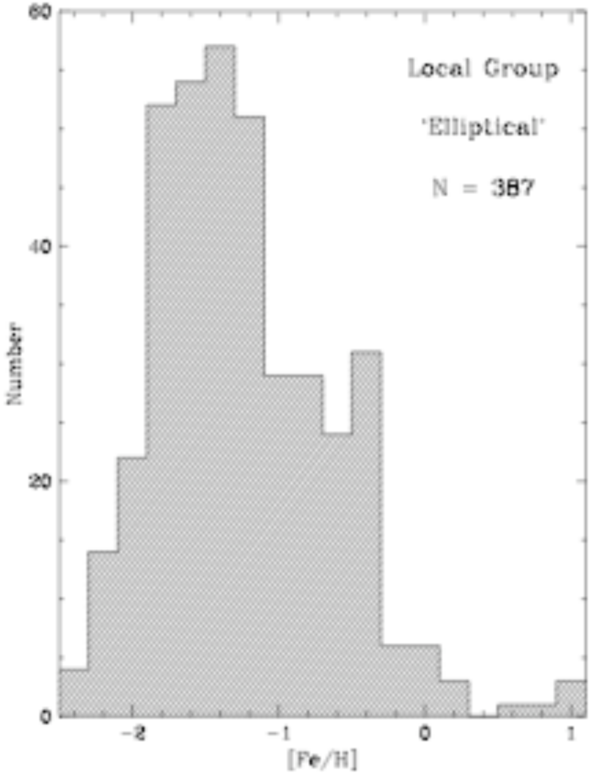


**Fig. 3.** Metallicity distribution for the Local Group 'elliptical'. The distribution reveals two peaks at [Fe/H] = –1.55 and –0.64.

## Final mergers of the Local Group
## ➜ normal field elliptical

# Chemical Evolution of Galaxies

**Modelling the chemical evolution of galaxies:**

- Basic principles
- MW and Local Group galaxies
- Galaxies at high redshifts

# Chemical Evolution : Gas & Stars

Big Bang : H, He, (...., Li)

all heavy elements ( > H, He := astrophys. „metals“)

- ☞ fusioned within stars,
- ☞ get back into gas phase by stellar winds, PN, SNe
- ☞ built into later stellar generations

Chemical abundances in the gas determined by

→ Stellar Initial Mass Function
→ Star Formation History of the galaxy
→ Stellar lifetimes & yields (mass, composition)
→ In- & outflow of gas

→ $Z^{Gas}(t)$, $X_i^{Gas}(t)$ from modified Tinsley (68ff) equations
+ SNIa contributions

# Chemical Evolution of Galaxies

## Basic principles

☆ Initial conditions (gas cloud with all or part of present mass)

☆ Initial abundances (Big Bang or Pop3 pre-enrichment)

☆ IMF w. normalisation $\int_{ml}^{mup} \Phi(m)\, m\, dm = 1$

or = FVM (=0.5) (Bahcall+03)

Salpeter 1955 $\Phi(m) \sim m^{\alpha}$, $\alpha = -2.35$

Kroupa+03 : flatter below 1 $M_{\odot}$

☆ SFR(t) : spirals: $SFR(t) := \Psi(t) \sim (G(t) / M_{tot})$, G : gas mass

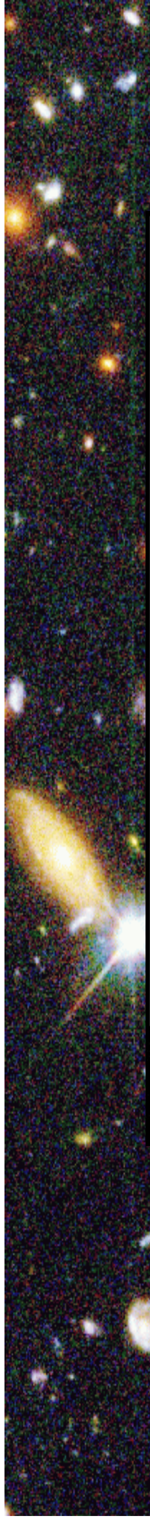
☆ Infall/outflow rates & abundances or closed box

☆ Stellar yields & lifetimes

☆ Assumption how to mix recycled and remaining gas

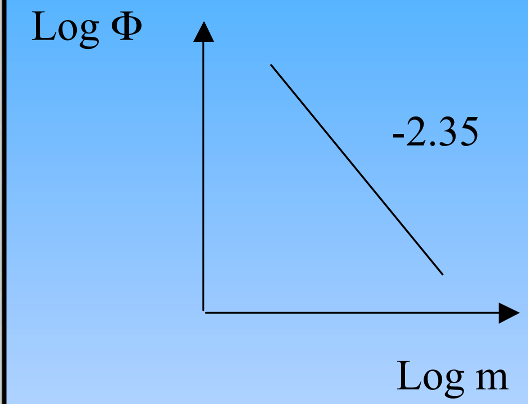
☆ Equations combining all this (B. Tinsley 1968ff)

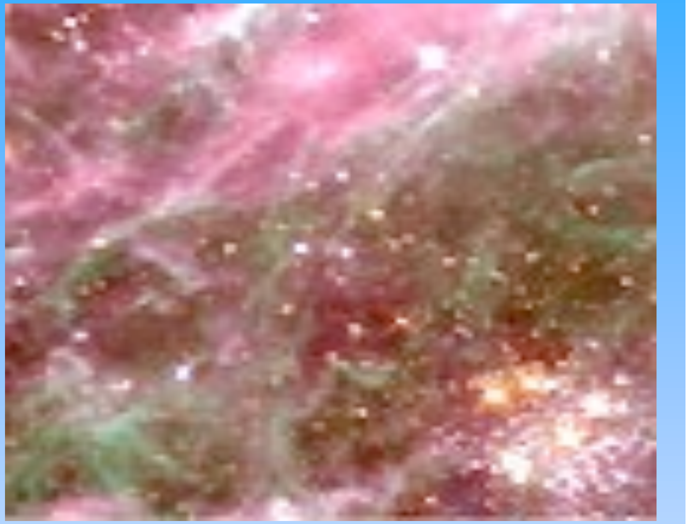
# Chemical & Spectral Evolution of a Galaxy
# GALEV



**Star-Birth Clouds · M16** HST · WFPC2

PRC95-44b · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA





Normalisation :

$$\int_{ml}^{mup} m\,\Phi(m)\,dm = 1$$

$m_l$ : hydrogen burning limit
$m_{up}$ : ~120 - 140 $M_\odot$

## Stellar population :

- → Stellar Initial Mass Function (Salpeter 1955, Kroupa+ 1993ff)
- → Stellar evolutionary tracks, lifetimes, yields
- → Star Formation History of the galaxy

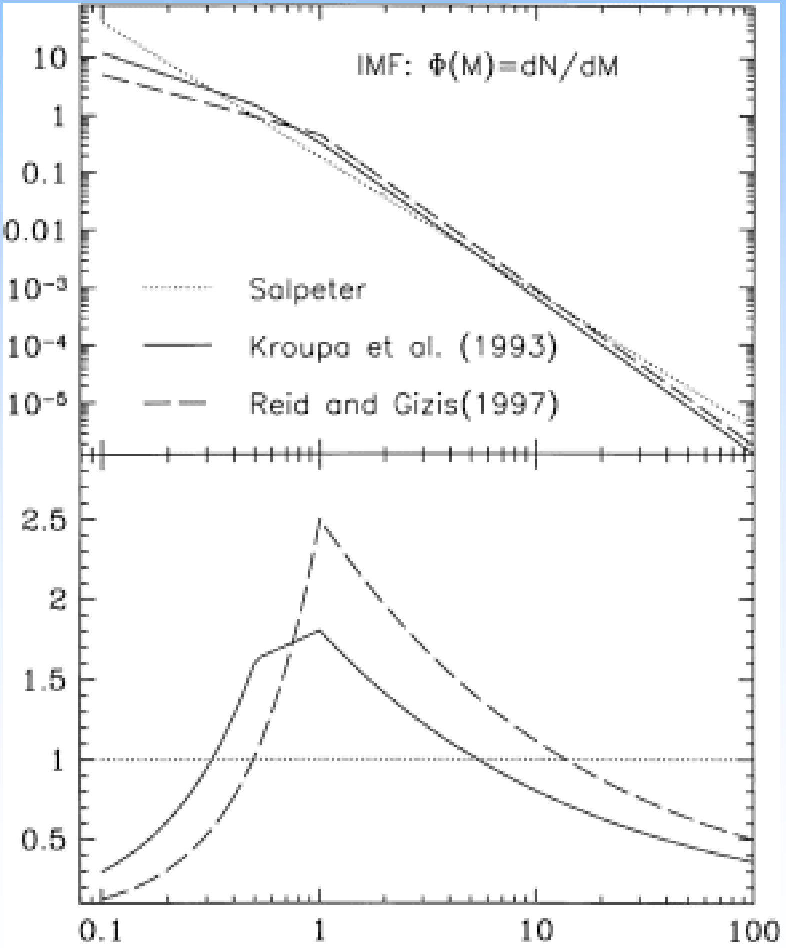
# Chemical Evolution of Galaxies

IMF normalisation ➜ IMFs with flatter slopes have

☛ more low-mass stars : lock up chem. elements

☛ fewer high-mass stars : important for enrichment

IMF : little impact on optical colours,
more on UV & emission lines,
much on chem. evolution !

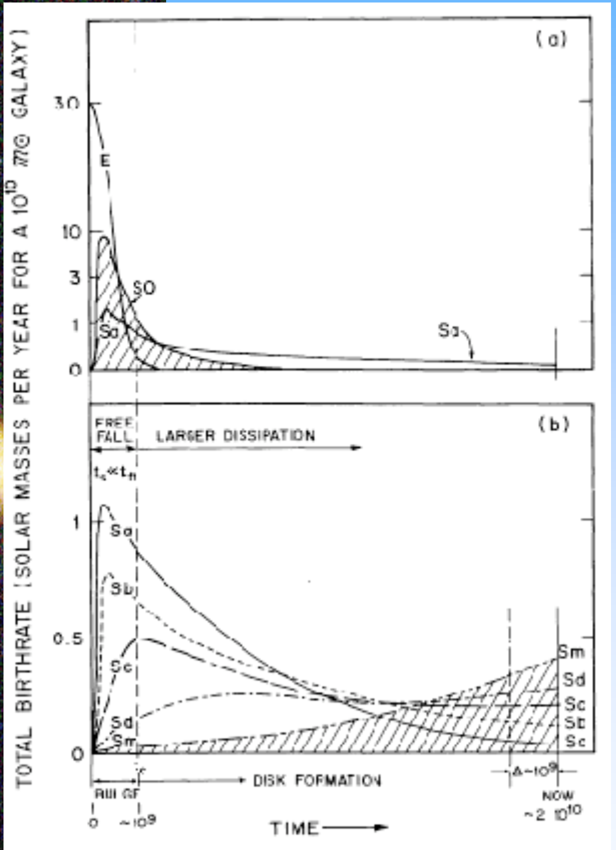


# Chemical & Spectral Evolution of a Galaxy GALEV

Simplified parameterisations : SFR(t) = $\Psi$(t)

SFR (E) ~ exp (-t / 1 Gyr)

SFR (Sp) ~ a · G(t) / M (t)



with efficiency parameter a chosen as to yield characteristic timescales for SF t* increasing from 2 Gyr for S0 through
13 Gyr (SFR ~ const.) for Sd

(SFR(t*) = 1/e SFR(t=0))

(Sandage 1986)

**Stellar population :**

→ Stellar Initial Mass Function (Salpeter 1955, Kroupa+ 1993ff)

→ Stellar evolutionary tracks, lifetimes, yields

→ Star Formation History of the galaxy

# Chemical Evolution of Galaxies

Stellar yield : newly produced and ejected mass of a given chemical element by a star of mass m, depends on mass & chem. composition of star

Primary element : element directly produced from H or He (e.g. O from 3$\alpha$ process)

Secondary element : element produced starting from heavy elements already present in the star at birth (e.g. N produced in the CNO cycle)

chemical evolution for a secondary element $X_s$ formed from a seed element Z : $X_s \sim Z^2$

abundance ratio $X_s/Z \sim Z$

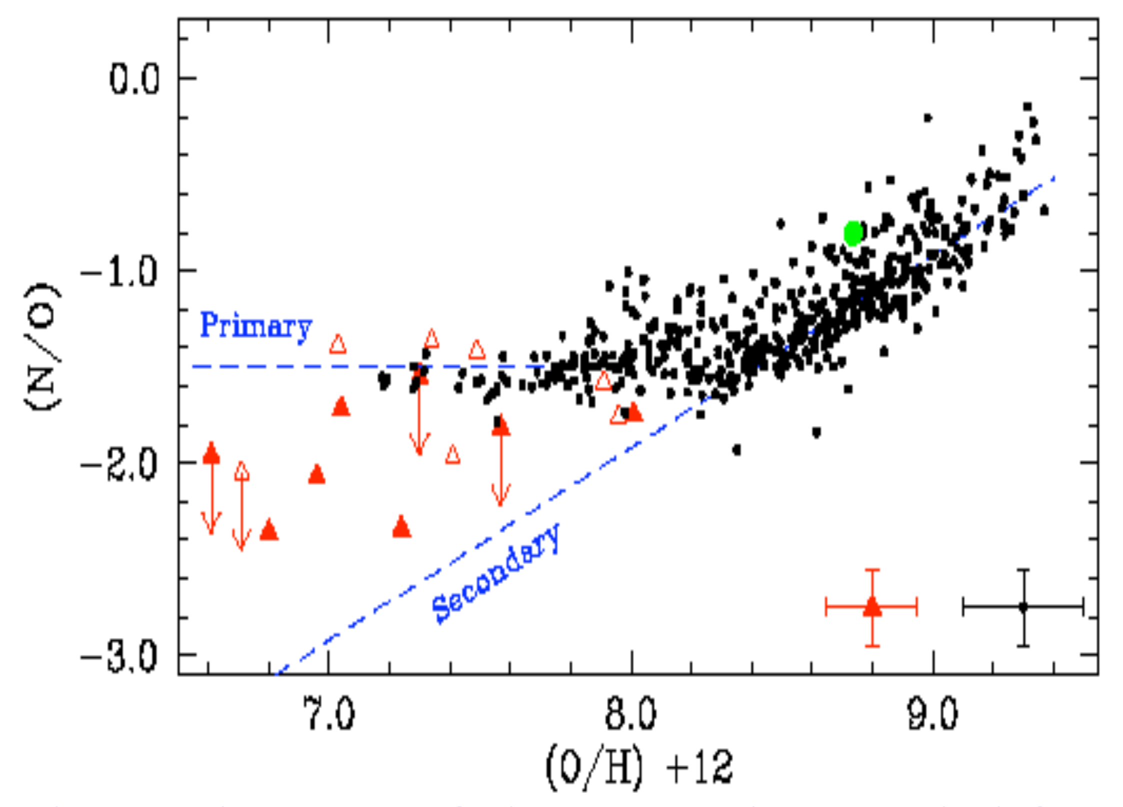
# Chemical Evolution of Galaxies

**Primary element & secondary elements**

**Pettini et al. (2002)**

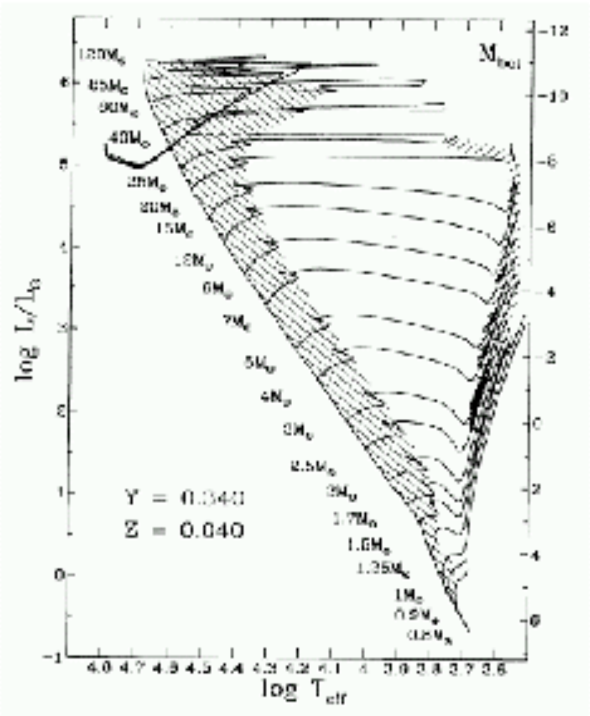
**Small dots : extragalactic HII regions**

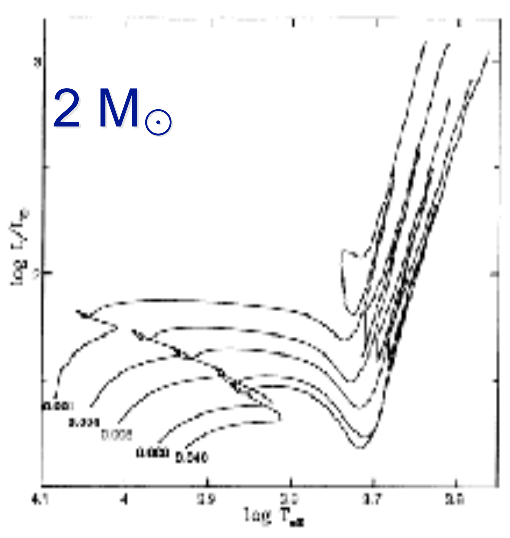
**Red triangles : Damped Lyman-alpha systems (DLA)**

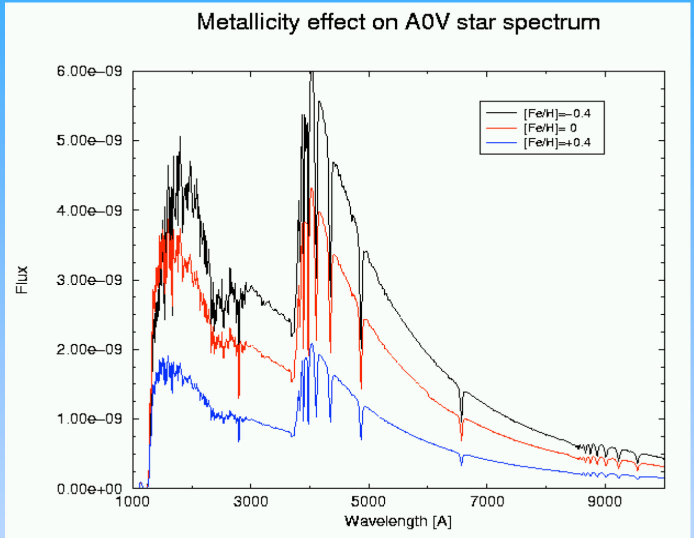


**Dashed lines mark the solution of the simple model for a primary and a secondary element**

# Chemical & Spectral Evolution of Galaxies







Z=0.020  $\tau(1\ M_\odot) \sim 10*10^9$ yr,  $\tau(100\ M_\odot) \sim 2*10^6$ yr

Z=0.004  $\tau(1\ M_\odot) \sim 7*10^9$ yr,  $\tau(100\ M_\odot) \sim 3*10^6$ yr

**Stellar population :**

- → **Stellar Initial Mass Function**
- → **Stellar evolutionary tracks, lifetimes (m, Z) & yields (m, Z)**
- → **Star Formation History of the galaxy**

# Stellar Yields

Stars fusion heavy elements in their nuclei & set free part of them to the ISM/gas at (shortly before) the end of their lives (onion shell scheme)

$m_\star < 8\,M_\odot$ : PN : H, He, C, N, O
$m_\star > 8\,M_\odot$ : winds : H, He, C, N, O
SNII : -- " -- + Ne, Mg, Si, Ar, Ca, . . . , Fe, Ni

binary stars (appropriate mass ratio & orbit) :
SNIa : $0.6\,M_\odot$ Fe

timescales : PN, SNIa : $\sim 10^9$ yr
winds, SNII : $\sim 10^5 \ldots \sim 10^7$ yr

yields (winds, SNII) : metallicity dependent

$$\dot{M}_{\mathrm{wind}} \sim Z^4$$

# Chemical Evolution of Galaxies

**Stellar yields :**

Low and intermediate mass stars (0.8 - 8 $M_\odot$) produce
He, N, C and heavy s-process elements.

They die as C-O white dwarfs, when single, and
can die as Type Ia SNe when binaries.

Stellar yields : winds and PNe (Maeder+96ff,
van den Hoek & Groenewegen 97, both for diff. Z

SNIa yields : Nomoto+84, Thielemann+xx, no Z-depend.

Massive stars (m > 8 - 10 $M_\odot$) produce mainly
$\alpha$-elements (O, Ne, Mg, Si, S, Ar, Ca, Ti), some Fe,
light s-process elements and r-process elements

Stellar yields : Woosley & Weaver 95, Thielemann+96,
Limongi & Chieffi 03, Nomoto+07, for diff. Z

They explode as core-collapse SNe : SNII

# Chemical Evolution of Galaxies

Type Ia SNe :

Single-degenerate scenario (Whelan & Iben 1974):

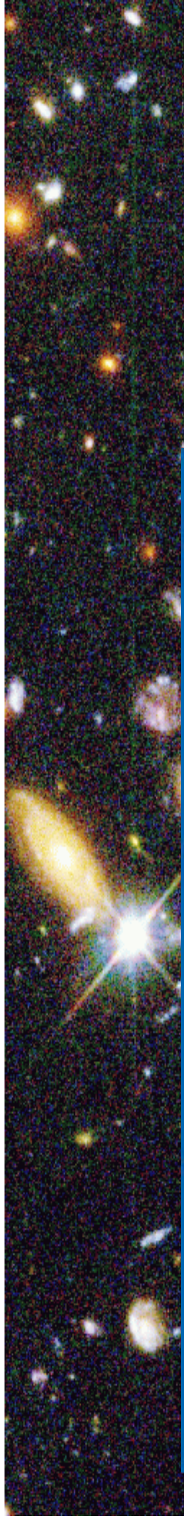
Binary system : 2 stars with m < 8 $M_\odot$

primary becomes C-O white dwarf

secondary becomes RG : fills its Roche lobe, mass flows onto the WD, drives it towards the Chandrasekhar limit: primary explodes by C-deflagration & produces 0.6 $M_\odot$Fe

+ traces of other elements from C to Si

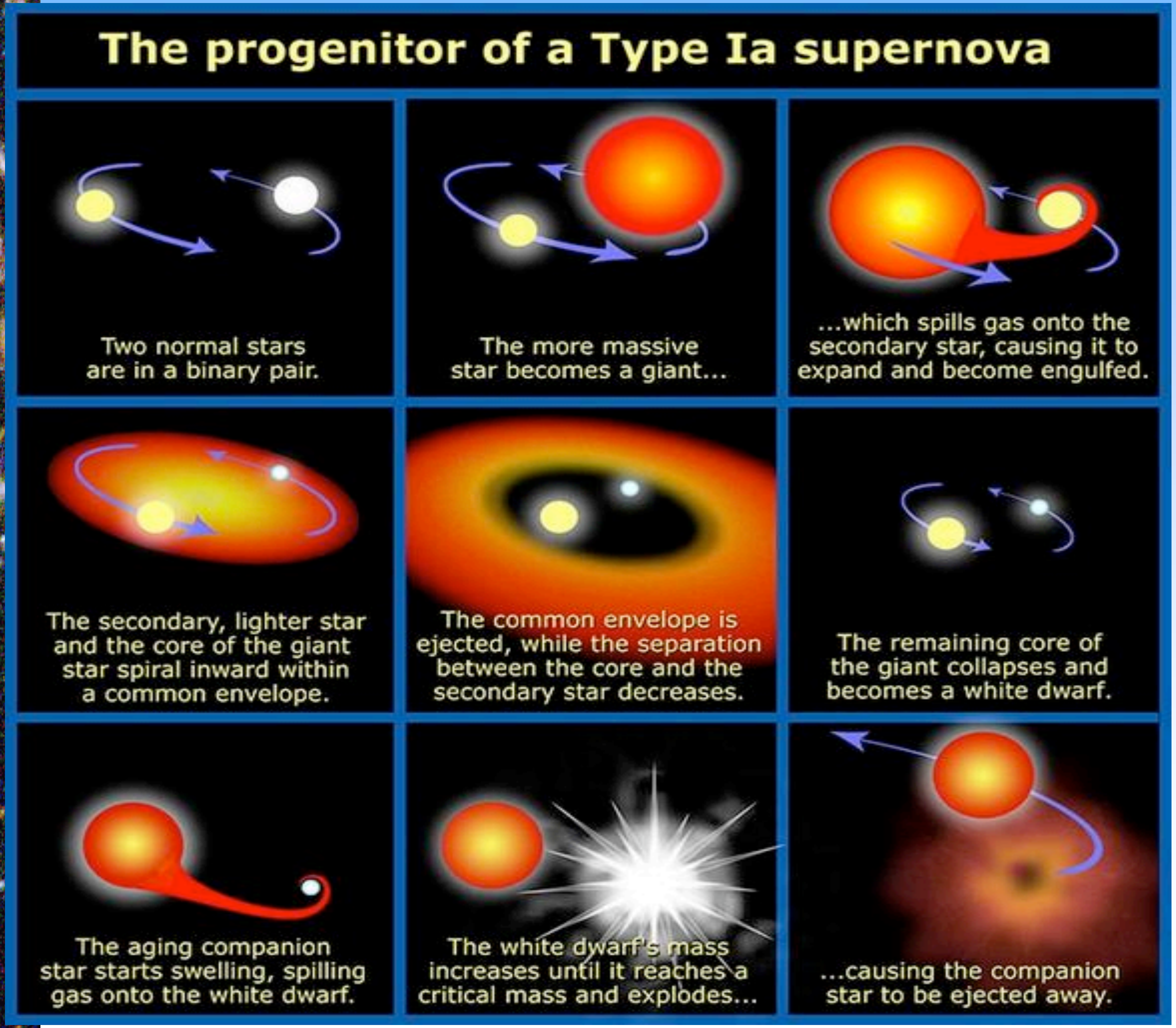
Clock for SNIa: lifetime of secondary : ≥ 1 Gyr !



# Chemical Evolution of Galaxies

## Type Ia SNe :

## Single-degenerate scenario (Whelan & Iben 1974):



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 inward within a common envelope.

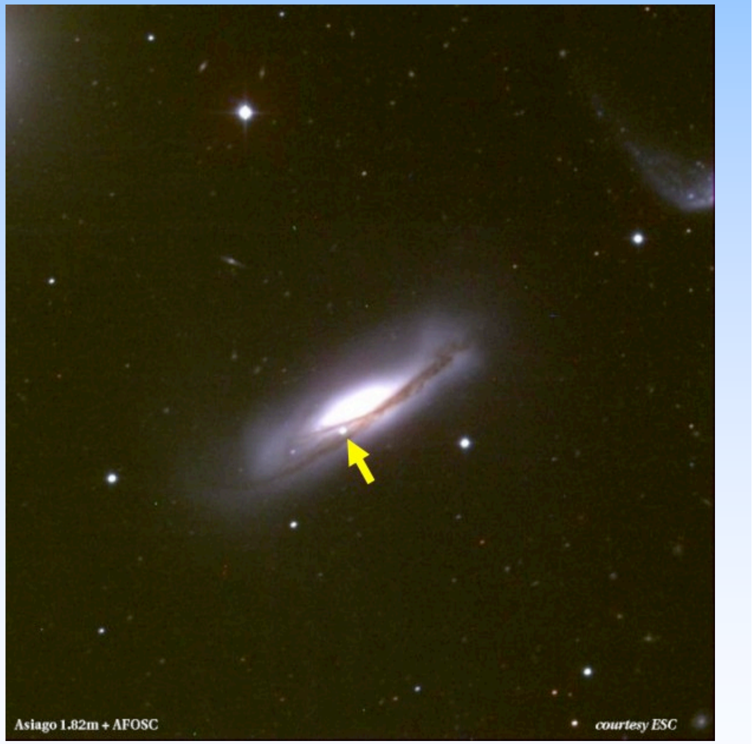
The common envelope is ejected, while the separation between the core and the secondary star decreases.

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.

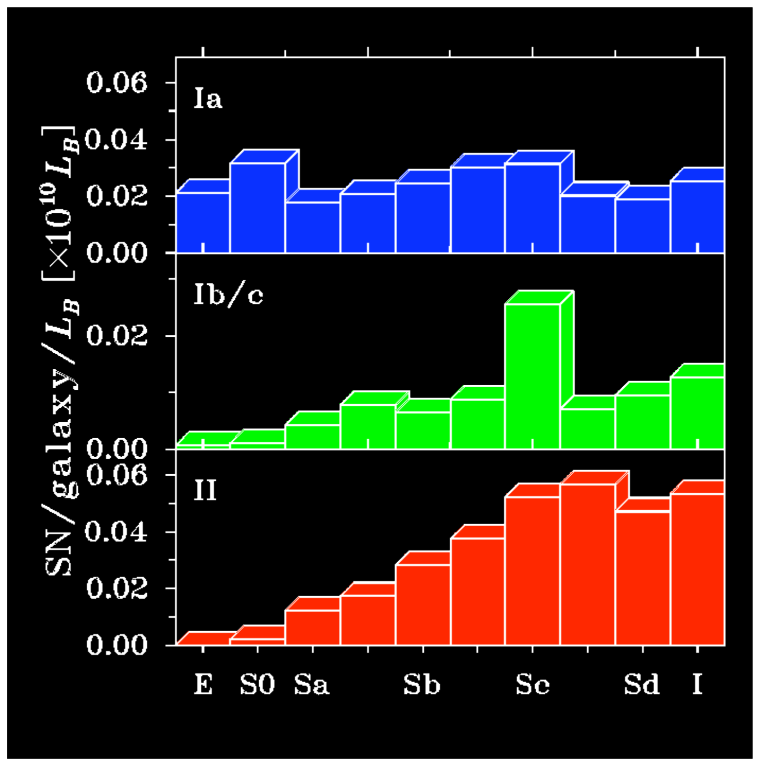


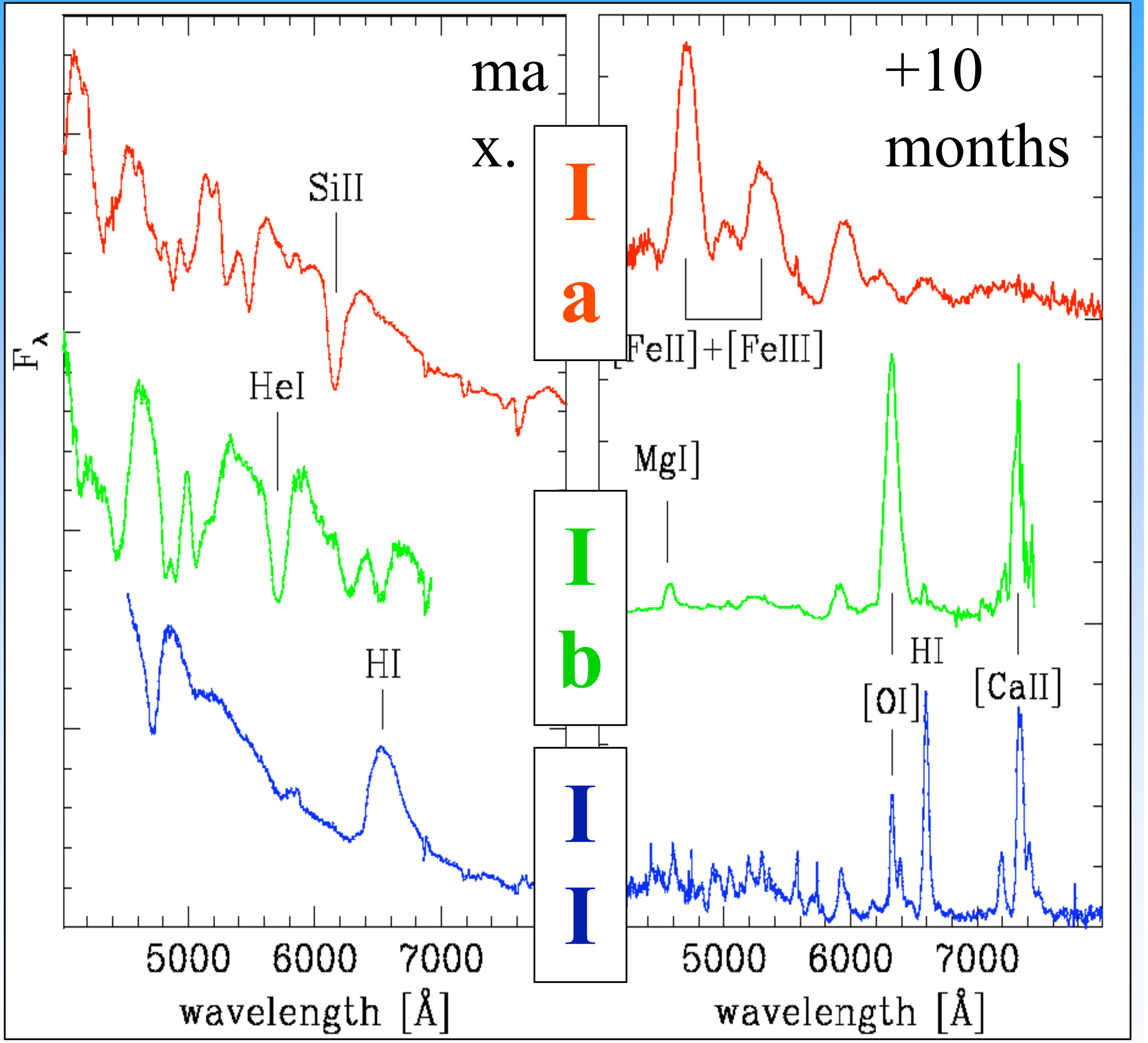
# Chemical Evolution of Galaxies

Type II SNe arise from the core collapse of massive stars
($m = 8 - 40\ M_\odot$) and produce mainly alpha-elements
(O, Mg, Si, Ca...) and some Fe,
leave neutron star remnant

Stars more massive ($m > 40\ M_\odot$) can end up as
Type Ib/c SNe,
leave neutron star, or black hole ?

# Basic SN types and rates





(adopted from Matteucci 07)

# Nucleosynthesis : summary

During the Big Bang light elements are formed :

H, D, $^{3}$He, $^{4}$He, $^{7}$Li

Spallation process in the ISM produces 6Li, Be and B

Type II SNe produce α-elements (O, Ne, Mg, S, S, Ca), some Fe, light s- and r-process elements

Type Ia SNe produce mainly Fe and Fe-peak elements + some traces of elements from C to Si

Low and intermediate mass stars produce

$^{4}$He, C, N, s-process (A>90)

Deuterium is only destroyed to produce 3He (which then also gets destroyed

# Chemical Abundances

**Definitions :**

mass fraction (all elements >H, He) =: metallicity Z

solar metallicity (photospheric abundances) $Z_\odot \sim 0.02$

gas metallicities/abundances:

HII regions : O – abundance : R23 method,
from emission lines

HI neutral gas : from HI absorption lines
(physical & chem. parameters !)

given in terms of 12 + log (O/H) number ratios rel. to H

$Z_\odot \sim 0.02 \quad \leftrightarrow \quad 12+\log(O/H) = 8.9$

solar abundances not easy to determine &
≠ meteoritic abund.

Anders & Grevesse 89, Grevesse+96, Asplund+05, . . .

# Solar Abundances

(Asplund+05)

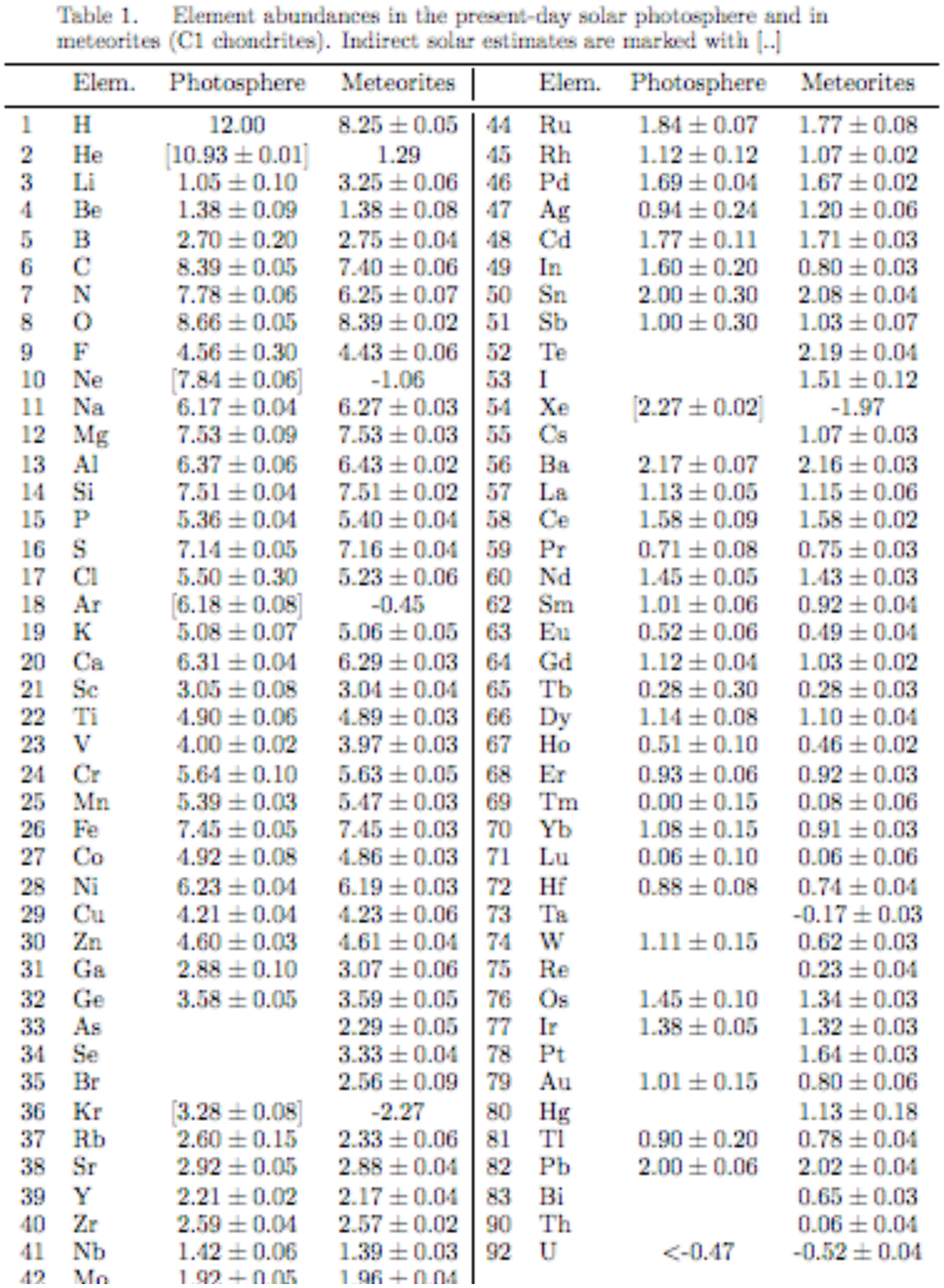


Table 1. Element abundances in the present-day solar photosphere and in meteorites (C1 chondrites). Indirect solar estimates are marked with [..]

| | Elem. | Photosphere | Meteorites | | Elem. | Photosphere | Meteorites |
|---|---|---|---|---|---|---|---|
| 1 | H | 12.00 | 8.25 ± 0.05 | 44 | Ru | 1.84 ± 0.07 | 1.77 ± 0.08 |
| 2 | He | [10.93 ± 0.01] | 1.29 | 45 | Rh | 1.12 ± 0.12 | 1.07 ± 0.02 |
| 3 | Li | 1.05 ± 0.10 | 3.25 ± 0.06 | 46 | Pd | 1.69 ± 0.04 | 1.67 ± 0.02 |
| 4 | Be | 1.38 ± 0.09 | 1.38 ± 0.08 | 47 | Ag | 0.94 ± 0.24 | 1.20 ± 0.06 |
| 5 | B | 2.70 ± 0.20 | 2.75 ± 0.04 | 48 | Cd | 1.77 ± 0.11 | 1.71 ± 0.03 |
| 6 | C | 8.39 ± 0.05 | 7.40 ± 0.06 | 49 | In | 1.60 ± 0.20 | 0.80 ± 0.03 |
| 7 | N | 7.78 ± 0.06 | 6.25 ± 0.07 | 50 | Sn | 2.00 ± 0.30 | 2.08 ± 0.04 |
| 8 | O | 8.66 ± 0.05 | 8.39 ± 0.02 | 51 | Sb | 1.00 ± 0.30 | 1.03 ± 0.07 |
| 9 | F | 4.56 ± 0.30 | 4.43 ± 0.06 | 52 | Te | | 2.19 ± 0.04 |
| 10 | Ne | [7.84 ± 0.06] | -1.06 | 53 | I | | 1.51 ± 0.12 |
| 11 | Na | 6.17 ± 0.04 | 6.27 ± 0.03 | 54 | Xe | [2.27 ± 0.02] | -1.97 |
| 12 | Mg | 7.53 ± 0.09 | 7.53 ± 0.03 | 55 | Cs | | 1.07 ± 0.03 |
| 13 | Al | 6.37 ± 0.06 | 6.43 ± 0.02 | 56 | Ba | 2.17 ± 0.07 | 2.16 ± 0.03 |
| 14 | Si | 7.51 ± 0.04 | 7.51 ± 0.02 | 57 | La | 1.13 ± 0.05 | 1.15 ± 0.06 |
| 15 | P | 5.36 ± 0.04 | 5.40 ± 0.04 | 58 | Ce | 1.58 ± 0.09 | 1.58 ± 0.02 |
| 16 | S | 7.14 ± 0.05 | 7.16 ± 0.04 | 59 | Pr | 0.71 ± 0.08 | 0.75 ± 0.03 |
| 17 | Cl | 5.50 ± 0.30 | 5.23 ± 0.06 | 60 | Nd | 1.45 ± 0.05 | 1.43 ± 0.03 |
| 18 | Ar | [6.18 ± 0.08] | -0.45 | 62 | Sm | 1.01 ± 0.06 | 0.92 ± 0.04 |
| 19 | K | 5.08 ± 0.07 | 5.06 ± 0.05 | 63 | Eu | 0.52 ± 0.06 | 0.49 ± 0.04 |
| 20 | Ca | 6.31 ± 0.04 | 6.29 ± 0.03 | 64 | Gd | 1.12 ± 0.04 | 1.03 ± 0.02 |
| 21 | Sc | 3.05 ± 0.08 | 3.04 ± 0.04 | 65 | Tb | 0.28 ± 0.30 | 0.28 ± 0.03 |
| 22 | Ti | 4.90 ± 0.06 | 4.89 ± 0.03 | 66 | Dy | 1.14 ± 0.08 | 1.10 ± 0.04 |
| 23 | V | 4.00 ± 0.02 | 3.97 ± 0.03 | 67 | Ho | 0.51 ± 0.10 | 0.46 ± 0.02 |
| 24 | Cr | 5.64 ± 0.10 | 5.63 ± 0.05 | 68 | Er | 0.93 ± 0.06 | 0.92 ± 0.03 |
| 25 | Mn | 5.39 ± 0.03 | 5.47 ± 0.03 | 69 | Tm | 0.00 ± 0.15 | 0.08 ± 0.06 |
| 26 | Fe | 7.45 ± 0.05 | 7.45 ± 0.03 | 70 | Yb | 1.08 ± 0.15 | 0.91 ± 0.03 |
| 27 | Co | 4.92 ± 0.08 | 4.86 ± 0.03 | 71 | Lu | 0.06 ± 0.10 | 0.06 ± 0.06 |
| 28 | Ni | 6.23 ± 0.04 | 6.19 ± 0.03 | 72 | Hf | 0.88 ± 0.08 | 0.74 ± 0.04 |
| 29 | Cu | 4.21 ± 0.04 | 4.23 ± 0.06 | 73 | Ta | | -0.17 ± 0.03 |
| 30 | Zn | 4.60 ± 0.03 | 4.61 ± 0.04 | 74 | W | 1.11 ± 0.15 | 0.62 ± 0.03 |
| 31 | Ga | 2.88 ± 0.10 | 3.07 ± 0.06 | 75 | Re | | 0.23 ± 0.04 |
| 32 | Ge | 3.58 ± 0.05 | 3.59 ± 0.05 | 76 | Os | 1.45 ± 0.10 | 1.34 ± 0.03 |
| 33 | As | | 2.29 ± 0.05 | 77 | Ir | 1.38 ± 0.05 | 1.32 ± 0.03 |
| 34 | Se | | 3.33 ± 0.04 | 78 | Pt | | 1.64 ± 0.03 |
| 35 | Br | | 2.56 ± 0.09 | 79 | Au | 1.01 ± 0.15 | 0.80 ± 0.06 |
| 36 | Kr | [3.28 ± 0.08] | -2.27 | 80 | Hg | | 1.13 ± 0.18 |
| 37 | Rb | 2.60 ± 0.15 | 2.33 ± 0.06 | 81 | Tl | 0.90 ± 0.20 | 0.78 ± 0.04 |
| 38 | Sr | 2.92 ± 0.05 | 2.88 ± 0.04 | 82 | Pb | 2.00 ± 0.06 | 2.02 ± 0.04 |
| 39 | Y | 2.21 ± 0.02 | 2.17 ± 0.04 | 83 | Bi | | 0.65 ± 0.03 |
| 40 | Zr | 2.59 ± 0.04 | 2.57 ± 0.02 | 90 | Th | | 0.06 ± 0.04 |
| 41 | Nb | 1.42 ± 0.06 | 1.39 ± 0.03 | 92 | U | <-0.47 | -0.52 ± 0.04 |
| 42 | Mo | 1.92 ± 0.05 | 1.96 ± 0.04 | | | | |

# Chemical Abundances

**Definitions :**

stellar metallicities/abundances:

from stellar absorption lines

(e.g. Lick indices)

problems : spectral resol., S/N, crowding of lines, no clean features

(e.g. Fe line contains 40% contribution from Ca)

(Tripicco & Bell 95)

given in terms of $[X/H] := \log (X/H) - \log (X/H)_{\odot}$

mass fractions !

often : [Fe/H], but also : [Mg/H], [Mg/Fe], $[\alpha/\mathrm{Fe}]$

[Fe/H] = 0 solar
= -1 1/10 solar
= -2 1/100 solar

# Chemical Evolution of Galaxies

Assumption how to mix freshly enriched (hot) gas set free in stellar winds and SNe with rest :

Instantaneaous Recycling Approximation (IRA)

stars > 1 $M_\odot$ die instantaneously (wrong)

stars < 1 $M_\odot$ live forever (~ true)

➜ allows for analytical solution

Account for individual stellar lifetimes $\tau(m, Z)$

➜ numerical models

Returned mass fraction : $m_t$ = turn-off mass = mass of star for which $\tau(m)=t$

$$R := \int_{mt}^{mup} (m - m_{rem}) \Phi(m)\, dm$$

# Chemical Properties of the Milky Way

## Structure & abundances :

molecular disk : scale height ~65 pc

young thin stellar disk : scale height ~100 pc : $Z_\odot$ =: PopI

old(er) stellar disk : scale height ~325 pc : $<Z_\odot$ =: PopII

thick disk : scale h. ~1.5 kpc : $<Z_\odot$ =: PopII

(2% disk density)

halo stars : radius > 60 kpc: -1.5 > [Fe/H] > -5.4

halo GCs : radius ~120 kpc: -0.8 > [Fe/H] > -2.5

## Gradients :

☆ O – abundances in HII regions : 9.2 (inner regions)
. . . 8.0 (outer regions)
with large scatter ±0.5 at every radius

☆ [Fe/H] (intermed. age open clusters) :
+0.2 (inner regions) . . . -1 (outer regions)
with scatter ±0.3 at every radius

# Chemical Properties of the Milky Way

**Gradients :**

☆ O – abundances in HII regions : 9.2 (inner regions)
. . . 8.0 (outer regions)
with large scatter ±0.5 at every radius
(Vilchez & Esteban 96)

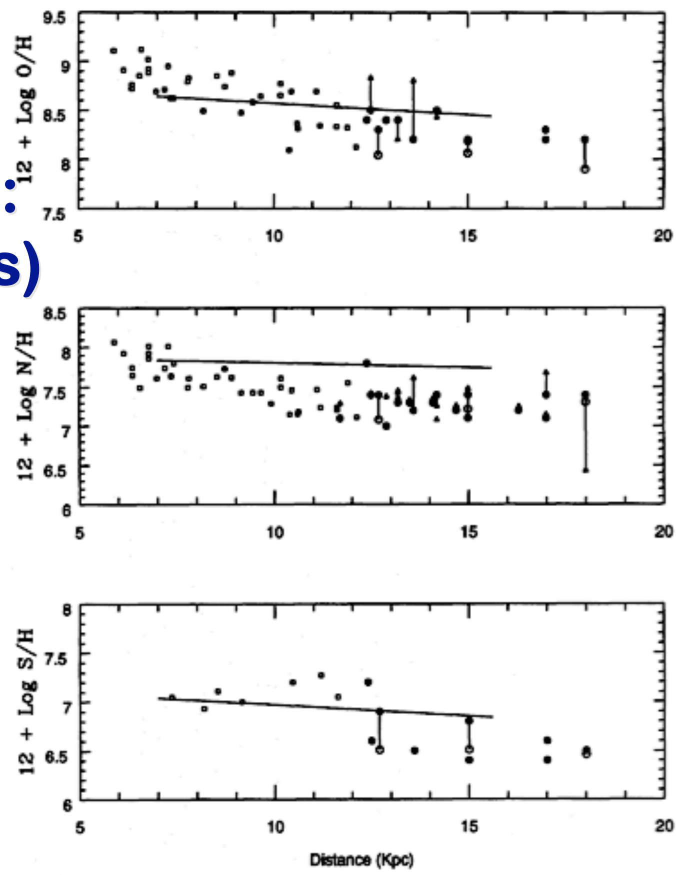


Figure 6. The global gradients of O/H, N/H and S/H in the Milky Way from 5 kpc onwards. Data from Shaver et al. (1983): empty squares; FS91: empty triangles; and for this work, filled and empty circles have been assembled. Abundance points corresponding to the same object are connected. The abundance gradients derived from B stars are illustrated by straight solid lines. The Shaver et al.

☆ [Fe/H] (intermed. age open clusters) :
+0.2 (inner regions) . . . -1 (outer regions)
with scatter ±0.3 at every radius
(Friel & Janes 93)

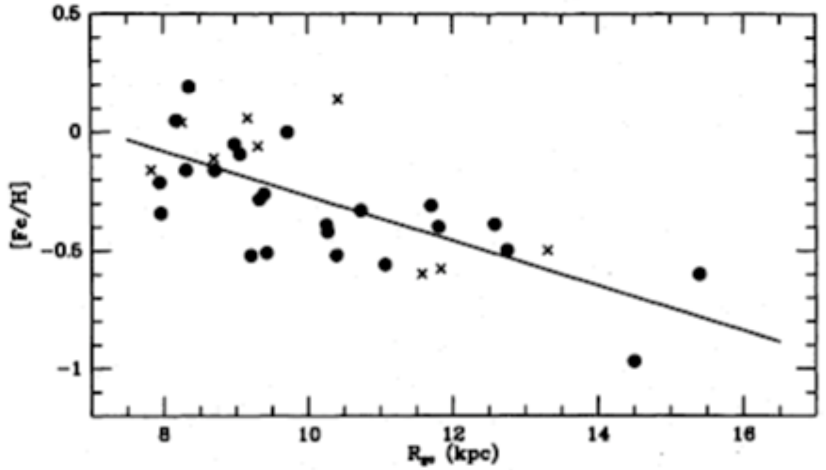


Fig. 2. The abundance gradient in the Galactic disk for open clusters older than about 1 Gyr. Filled circles denote clusters with our spectroscopic abundance determinations. Crosses denote values for 9 more clusters with abundances

# Chemical Evolution of Galaxies

Infall/outflow rates:

closed box : no infall/outflow

open systems : infall rate F(t)

const. in time or

$\sim \exp(-t/\tau)$ or even $\sim \exp(-t/\tau(r))$

outflow rate E(t)

$\sim$ SFR(t)

Infall abundances $Z_F$, $X_{iF}$: primordial (Big Bang or Pop3)

Outflow abundances $Z_E$, $X_{iE}$: ????

outflow triggered by stellar winds & SNe: hot & freshly enriched

outflows observed to entrain neutral material, how much ????

Closed box : simplest model, allows for analytical solution

# Modelling the Chemical Evolution of Galaxies

## Tinsley's equations :

(Beatrice Tinsley 1980, Fund. Cosmic Phys. 5, 287)

☆ $M_{tot} = M_{baryon} = G+S$ gas + stars

☆ $dG/dt = -\Psi + e\ (+F - E)$ $\Psi$ :SFR, F : inflow, E : outflow rate

☆ $dS/dt = +\Psi - e$ e : ejection rate from stars

all quatities =f(time)!

$$e(t) = \int_{mt}^{mup} (m - m_{rem})\, \Psi(t - \tau_m)\, \Phi(m)\, dm$$ $\Phi$ :IMF,

$m_t$ : turn-off mass, $m_{up}$ : upper mass limit (IMF)

☆ $d(GZ)/dt = + e_Z - Z \cdot \Psi + Z_F \cdot F - Z_E \cdot E$

$$e_Z(t) = \int_{mt}^{mup} [(m - m_{rem}) Z(t - \tau_m) + m\, p_Z(m)]\, \Psi(t - \tau_m)\, \Phi(m)\, dm$$

$p_Z(m)$ : newly produced yield of star with mass m (mass fraction)

# Modelling the Chemical Evolution of Galaxies

## Abundance evolution of individual elements :

In analogy to global metallicity : $Z \rightarrow X_i$

i : H, He, C, N, O, Mg, Mn, Al, Si, S, Cr, Fe, Ni, Zn

$$d(GX_i)/dt = + e_{Xi} - X_i \cdot \Psi + X_{iF} \cdot F - X_{iE} \cdot E$$

$$e_{Xi}(t) = \int_{mt}^{mup} [(m - m_{rem})X_i(t - \tau_m) + m p_{Xi}(m)]\ \Psi(t - \tau_m)\ \Phi(m) dm$$

but split IMF in mass range 3 – 8 $M_\odot$ into fraction A of binaries giving rise to SNIa and fraction (1-A) of single stars or binaries that do not end as SNIa.

Use for SNIa binaries yields for SNIa (e.g. Nomoto+97ff, Thielemann+98)

$p_{Xi}(m)$ : newly produced yield in element $X_i$ of star with mass m (mass fraction)

# Chemical Evolution of Galaxies

**Equations :**

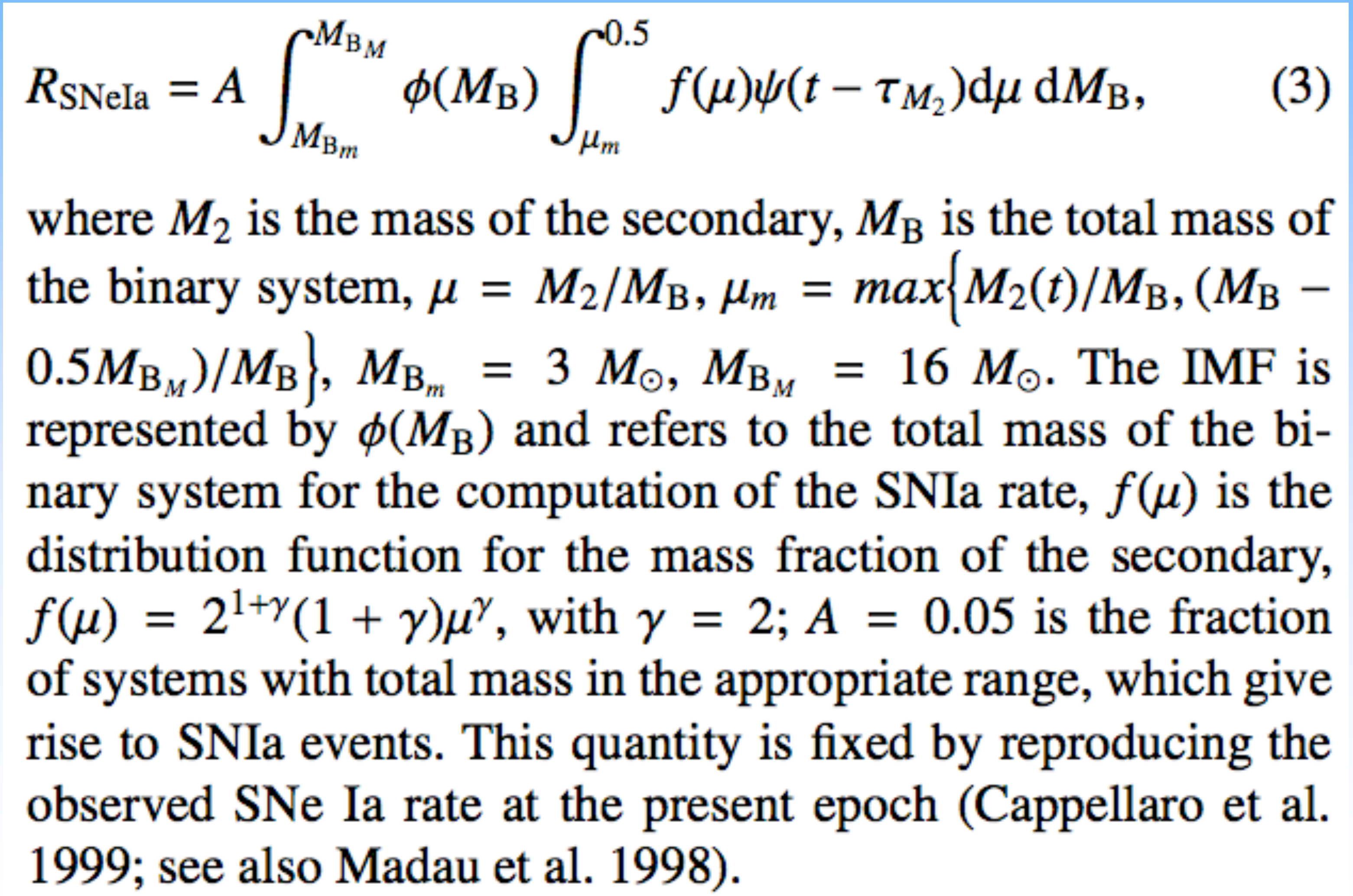
$G_i$ := mass fraction of gas in the form of element i

$$
\begin{aligned}
\dot{G}_i(t) = {} & -\psi(r,t)X_i(r,t) + \int_{M_{\mathrm{L}}}^{M_{\mathrm{B}m}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)\mathrm{d}m \\
& + A\int_{M_{\mathrm{B}m}}^{M_{\mathrm{B}M}} \phi(M_{\mathrm{B}})\left[\int_{\mu_{\mathrm{min}}}^{0.5} f(\mu)\psi(t-\tau_{m2})Q_{mi}(t-\tau_{m2})\mathrm{d}\mu\right]\mathrm{d}M_{\mathrm{B}} \\
& + (1-A)\int_{M_{\mathrm{B}m}}^{M_{\mathrm{B}M}} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)\mathrm{d}m \\
& + \int_{M_{\mathrm{B}M}}^{M_U} \psi(t-\tau_m)Q_{mi}(t-\tau_m)\phi(m)\mathrm{d}m + X_{A_i}A(r,t). \qquad (1)
\end{aligned}
$$

# Chemical Evolution of Galaxies

## Equations :

### SNIa rate : (Matteucci & Greggio 83)



$$R_{\mathrm{SNeIa}} = A \int_{M_{\mathrm{B}_m}}^{M_{\mathrm{B}_M}} \phi(M_{\mathrm{B}}) \int_{\mu_m}^{0.5} f(\mu)\psi(t-\tau_{M_2})\,\mathrm{d}\mu\,\mathrm{d}M_{\mathrm{B}}, \tag{3}$$

where $M_2$ is the mass of the secondary, $M_{\mathrm{B}}$ is the total mass of the binary system, $\mu = M_2/M_{\mathrm{B}}$, $\mu_m = max\left\{M_2(t)/M_{\mathrm{B}}, (M_{\mathrm{B}} - 0.5M_{\mathrm{B}_M})/M_{\mathrm{B}}\right\}$, $M_{\mathrm{B}_m} = 3\ M_{\odot}$, $M_{\mathrm{B}_M} = 16\ M_{\odot}$. The IMF is represented by $\phi(M_{\mathrm{B}})$ and refers to the total mass of the binary system for the computation of the SNIa rate, $f(\mu)$ is the distribution function for the mass fraction of the secondary, $f(\mu) = 2^{1+\gamma}(1+\gamma)\mu^{\gamma}$, with $\gamma = 2$; $A = 0.05$ is the fraction of systems with total mass in the appropriate range, which give rise to SNIa events. This quantity is fixed by reproducing the observed SNe Ia rate at the present epoch (Cappellaro et al. 1999; see also Madau et al. 1998).

# Analytical Solution

Assumptions : ideal and instantaneous mixing
1 gas phase only

with closed box
Instantaneous Recycling Approximation
$Z(0)=0, G(0)=M_{tot}$

analytical solution :

$Z(t) = - y \ln (G/M_{tot})$

y: total yield := mass ratio of newly produced heavy elements restored to ISM vs. locked up in stars

metallicity increases as gas content decreases

# Modelling the Chemical Evolution of Galaxies

## Observations :

☆ Age – metallicity relation of Milky Way stars

☆ G – dwarf problem in solar neighbourhood (& E gals)
(i.e. low number of very metal – poor stars)

☆ [α/Fe] vs [Fe/H] trend in Milky Way disk & halo stars

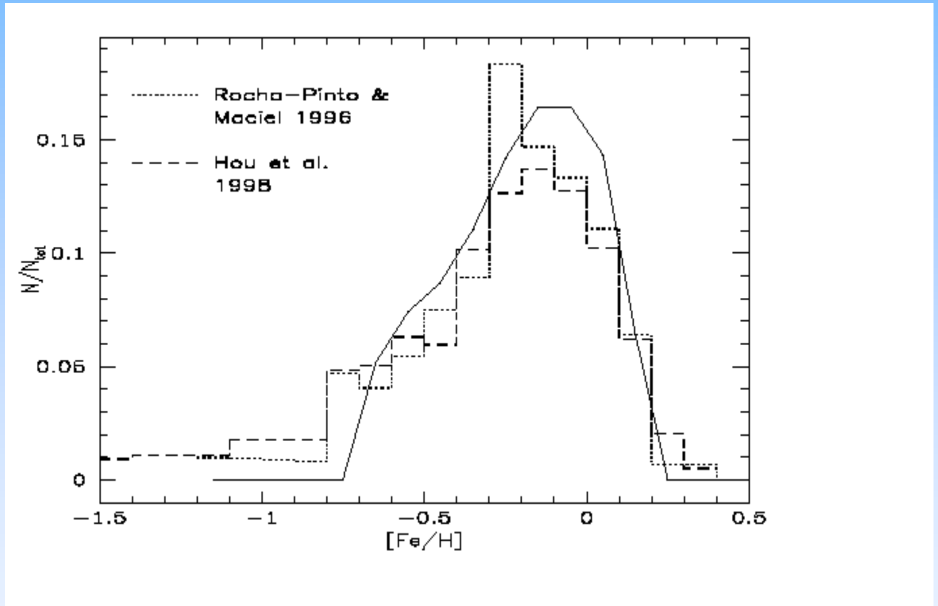
not reproduced by closed – box simple models

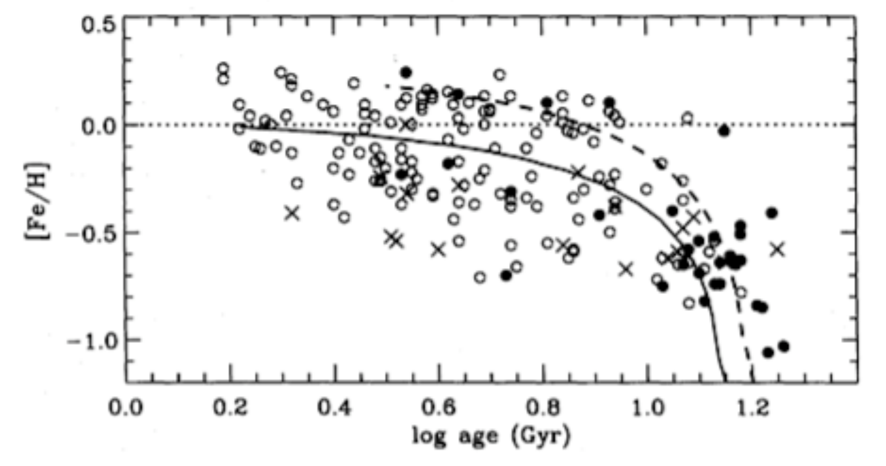
require
* infall or
* Pop3 or
* chemo – dynamical evolution or
* metallicity – dependent stellar yields
(chemically consistent chem. evol.)

# Modelling the Chemical Evolution of Galaxies

## Observations :

☆ Age – metallicity relation of Milky Way stars





☆ G – dwarf problem in solar neighbourhood (& E gals)
(i.e. low number of very metal – poor stars)

☆ [α/Fe] vs [Fe/H] trend in Milky Way disk & halo stars

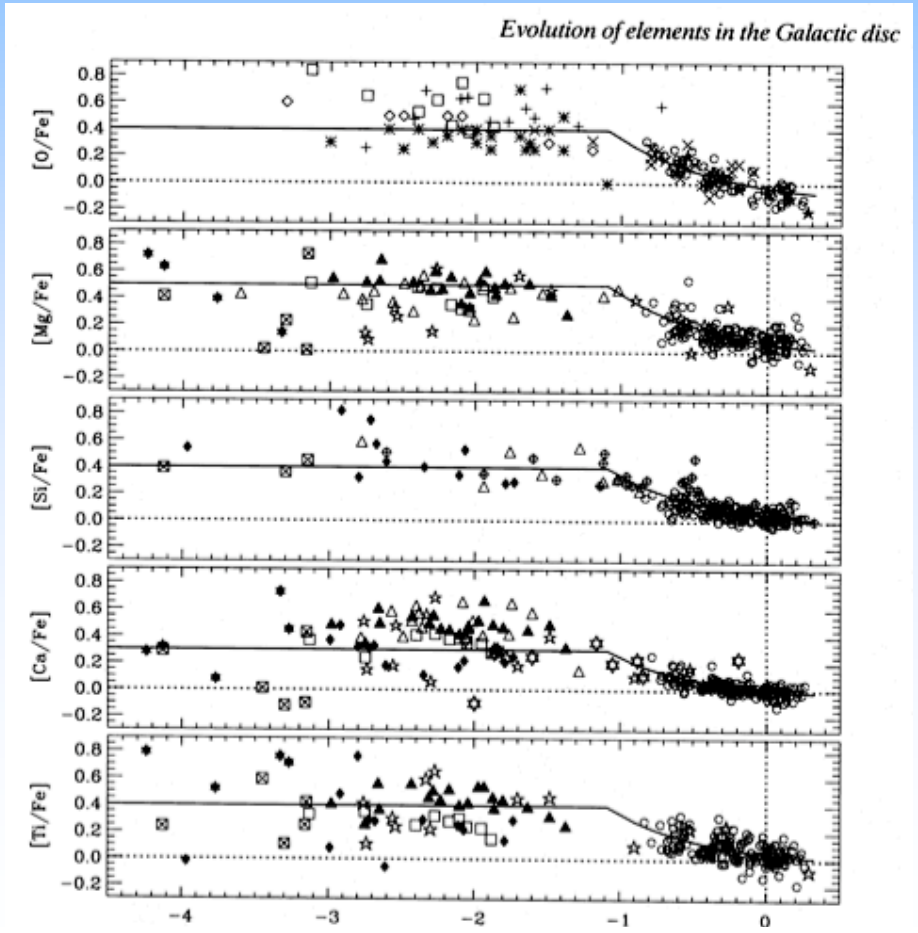
not reproduced by closed – box simple models

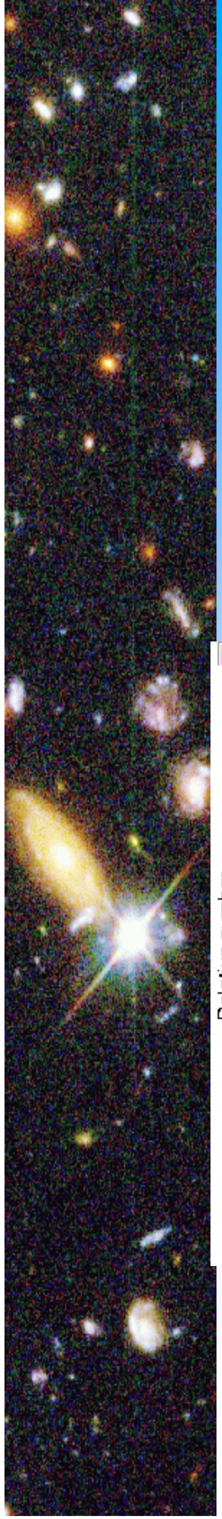
# Modelling the Chemical Evolution of Galaxies

## Observations :

☆ [α/Fe] vs [Fe/H] trend in Milky Way disk & halo stars
(Pagel & Tautvaisiene 95)

not reproduced by closed – box simple models



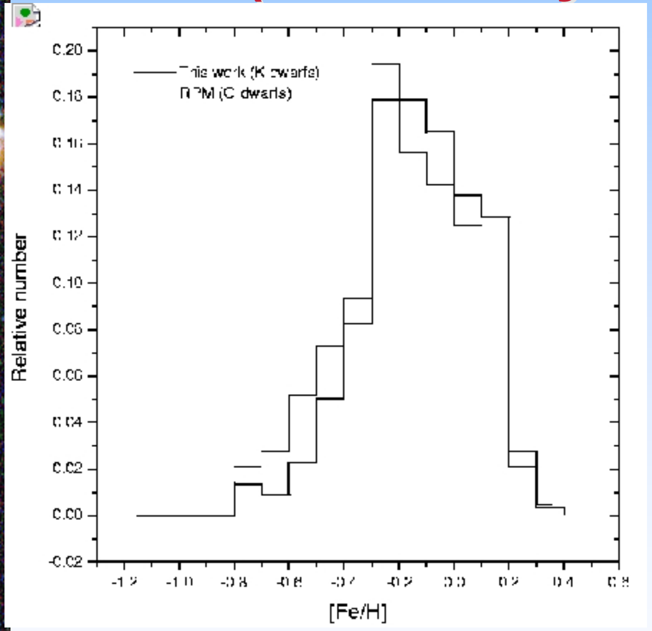


# Modelling the Chemical Evolution of Galaxies

- ⁎ broad metallicity distribution of stars in solar neighb.
- ⁎ broad metall. distrib. of stars & GCs in Elliptical gals

requires accounting for composite metallicity distribution of stars within galaxies

(chemically consistent evolutionary synthesis)



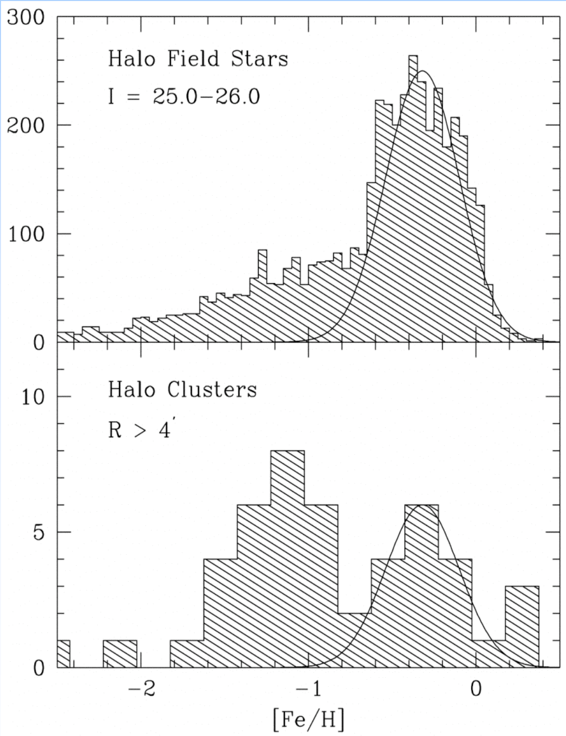
Metall. distribution of solar neighborhood stars

(Rocha-Pinto & Maciel 1998)

Δ[Fe/H] > 2 dex

Metall. distribution of halo stars and GCs in NGC 5128

(Harris et al. 1999)



# Chemically Consistent Chemical Evolution

Stellar yields at low Z differ significantly from $Z_\odot$ yields

--> stellar yield ratios [N/O], [C/O], [Mg/Fe], . . .

change with metallicity !

For elements with different nucleosynthetic origin,

ISM abundance ratios depend on SFH

**SNII elements** (O, Mg, Ca, ..., = $\alpha$) vs.

**intermediate stellar mass elements** (C, N) vs.

**SNIa elements** (Fe, Ni, Zn,...)

→ via the SFH, stellar evolution and galaxy evolution get intimately coupled !

In principle,

stellar evol. tracks/isochrones, yields, model atmospheres are required for the full range of element ratios !!

(not available yet)

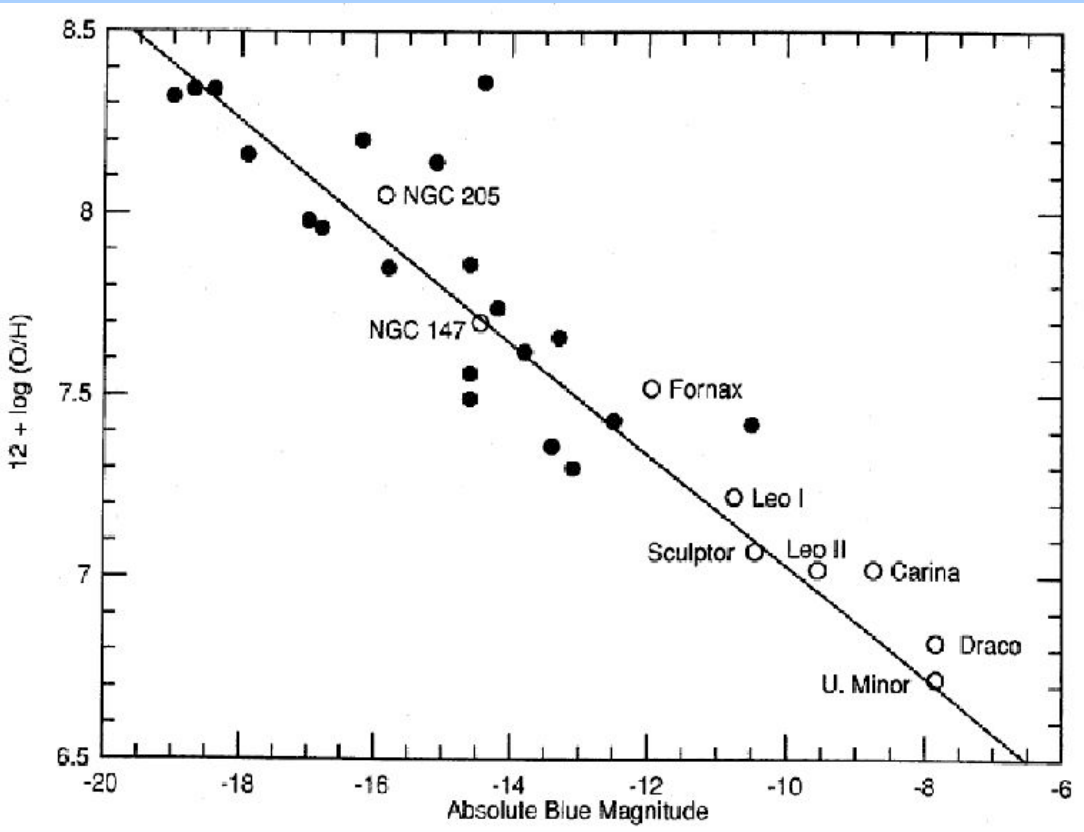
# Chemical Evolution of Dwarf Galaxies

## Observations :

* **Luminosity – metallicity relation for dwarf galaxies (dEs & dIrrs on same scale !?)**

(Skillman+89)

**SFR(t) explains the light along with the metals**



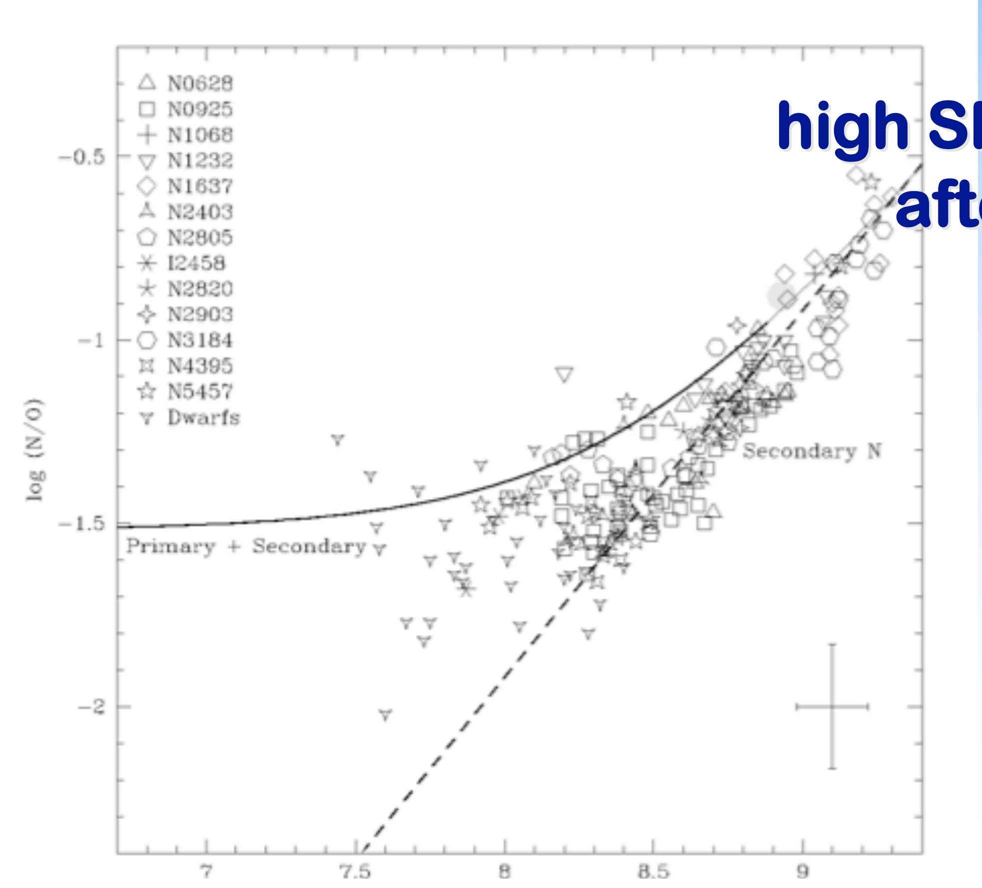
# Chemical Evolution of Dwarf Galaxies

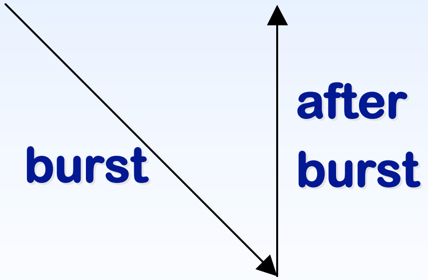
Observations :

* N/O vs O/H in SFing dwarf galaxies : big scatter in N/O at fixed O/H (van Zee+98)

explained by fluctuating SFRs / intermittend bursts

high SFR/burst : O/H increases (SNII)
after burst : O/H decreases , N/O increases (intermed. mass stars)





# Chemically Consistent Chemical Evolution

Cosmological model ($H_o$, $\Omega_m$, $\Omega_\Lambda$, $z_f$) : time <-> redshift

$X_i(t)$ <-> $X_i(z)$

i : H, He, C, N, O, Mg, Mn, Al, Si, S, Cr, Fe, Ni, Zn

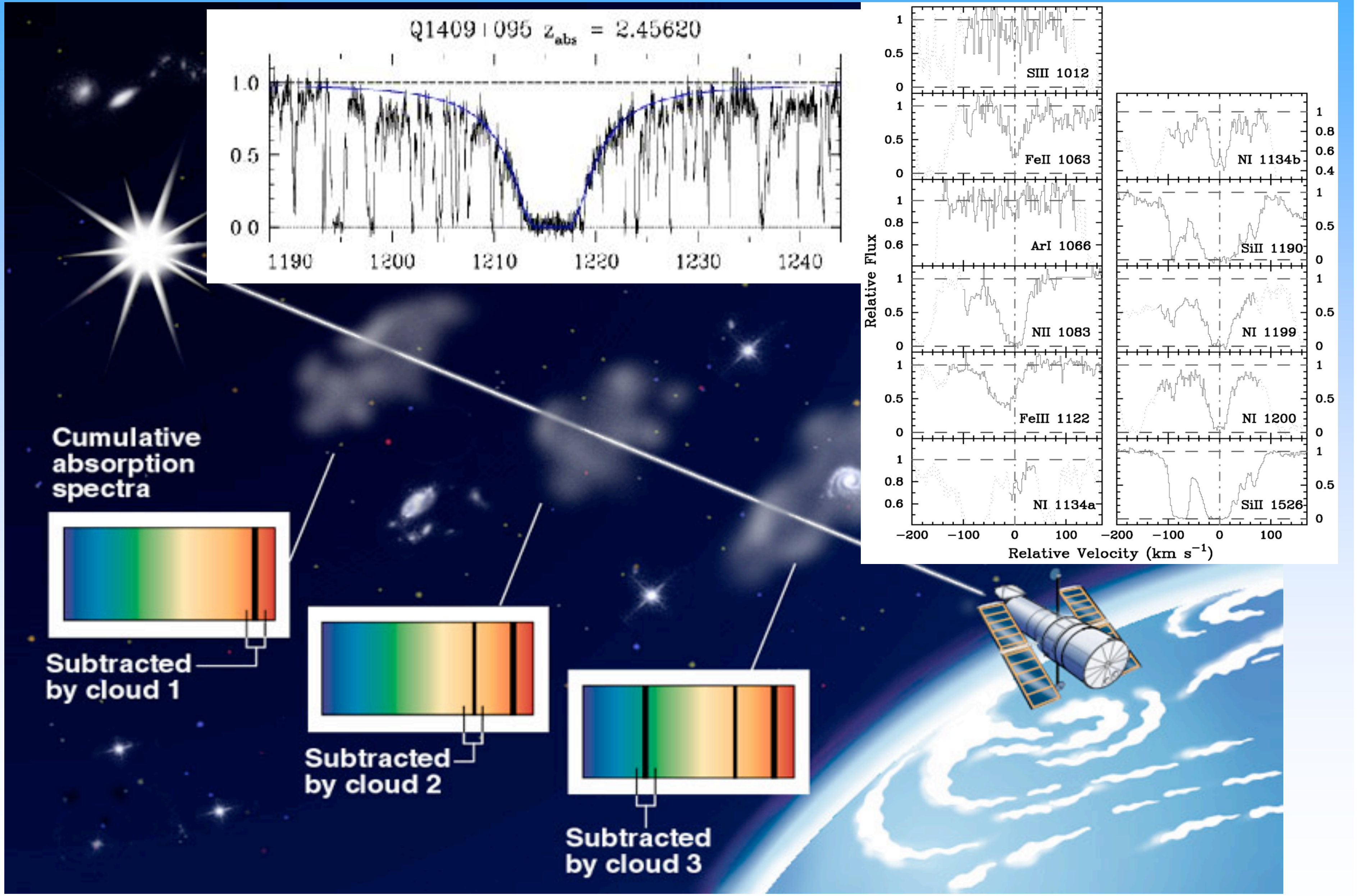
Redshift evolution of ISM abundances in spirals <--> Damped Lya Absorber abundances (Keck HIRES spectra)

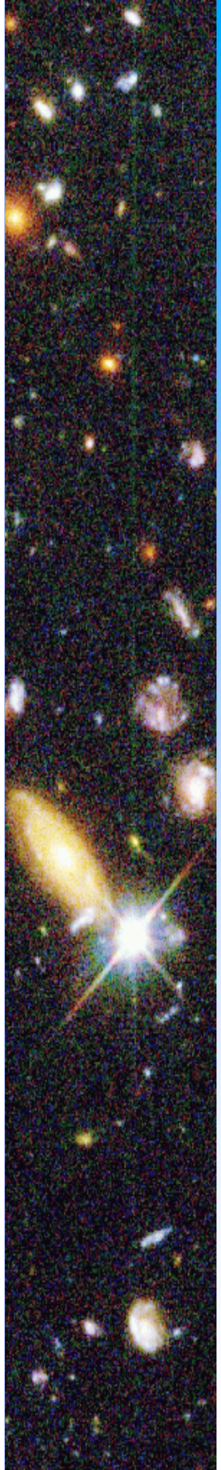
DLAs contain bulk of baryonic matter at z ~ 2 . . . 3

⟨mass of gas in DLA⟩ ~ ⟨mass of stars + gas in local spiral⟩

DLAs = (proto-) galactic disks ?

# Chemically Consistent Chemical Evolution – Damped Lyman Alpha Absorbers





# Chemically Consistent Chemical Evolution – Damped Lyman Alpha Absorbers

★ **CC spiral models explain redshift evolution of DLAs ✔**

z~4 . . . . . . z~0 (over > 90 % age of the Universe)

★ **DLAs = spiral progenitors ✔**

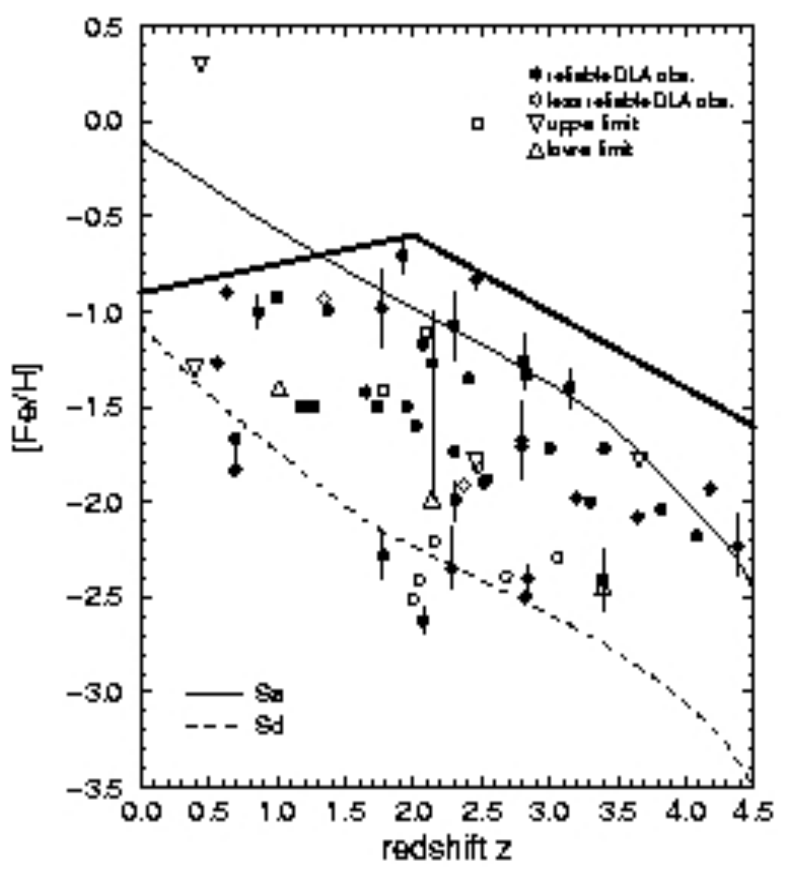
model abundances -> local
HII abundances for z -> 0

★ **change in the DLA galaxy population towards low z**

gas poor & metal rich galaxies
drop out of DLA sample

★ **low luminosities of DLA galaxies**

confirmed by many non-detections
and few VLT detections

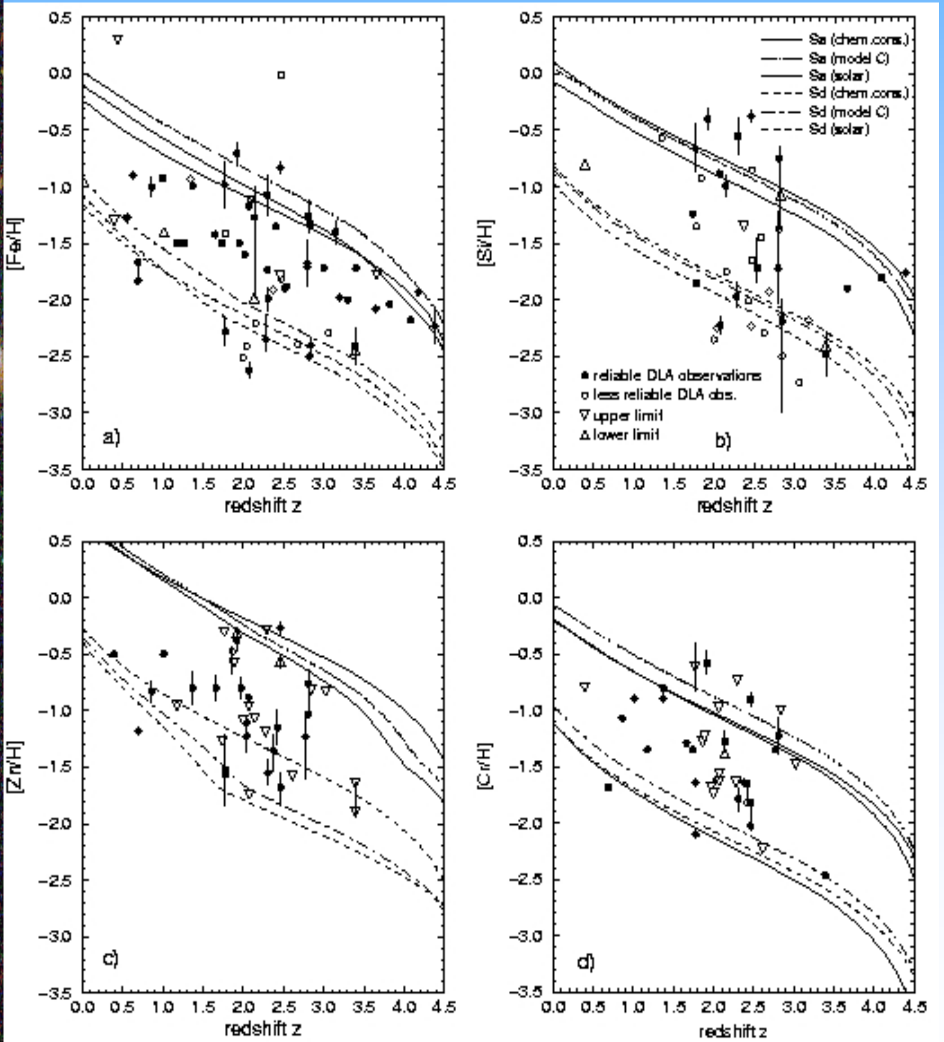


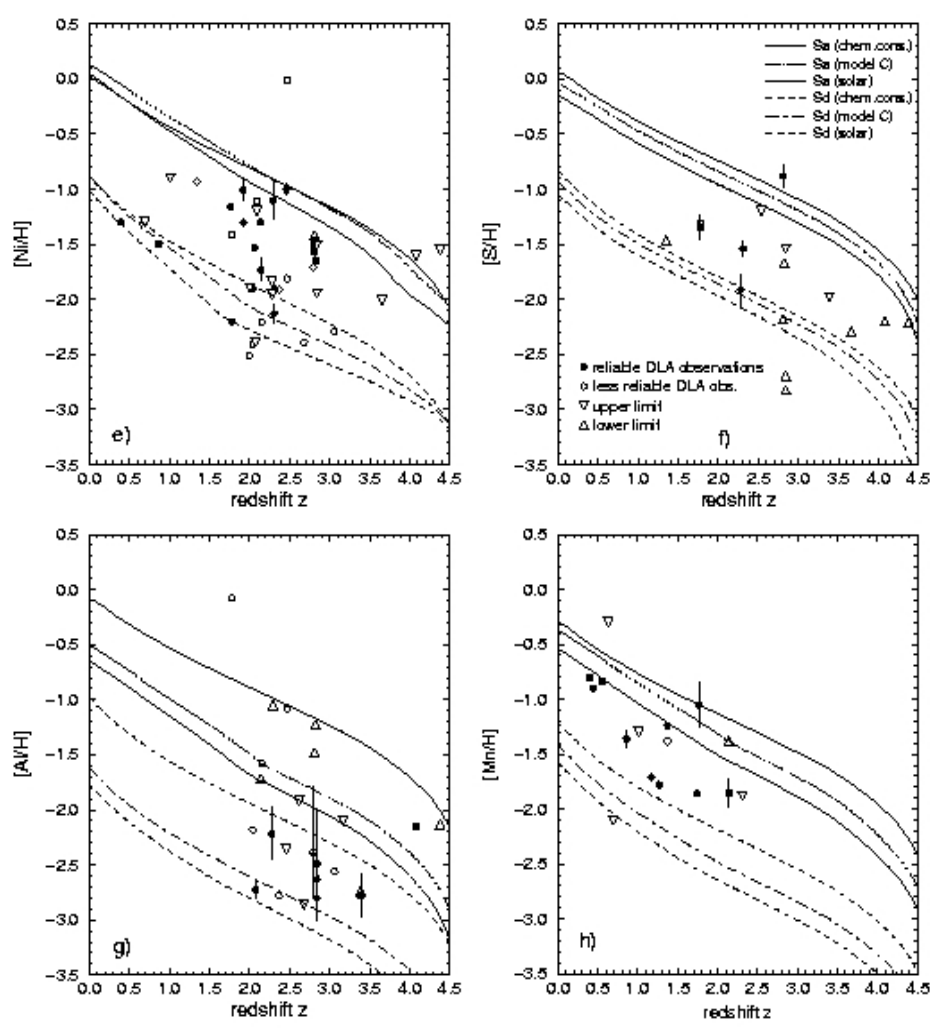
(Lindner, Fritze, Fricke 1999, Fritze, Lindner, Möller 1999)

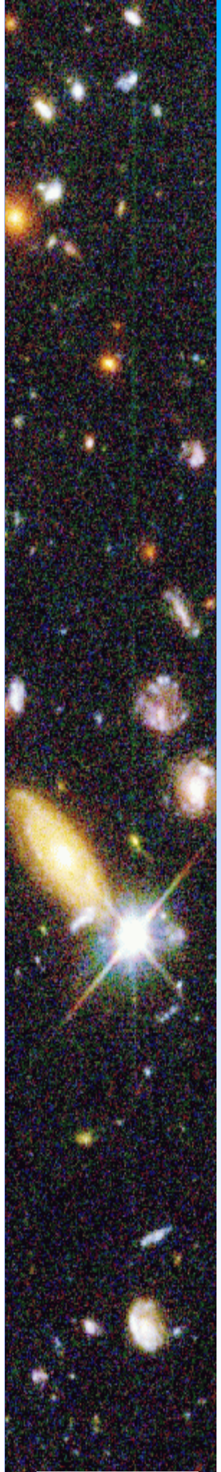
# **Chemically Consistent Chemical Evolution**

**(Lindner, FvA, Fricke 1999)**

**Spiral ISM abundances <--> DLA abundances**







# Chemically Consistent Chemical Evolution – Damped Lyman Alpha Absorbers

★ DLA = transition stage in the life
of ~ all (spiral) galaxies

not much room for infall :

★ high masses of spiral galaxies @ z ~ 2 - 4 :

~ 50% of present $M_{tot}$, mostly gas

(Lindner+99, Fritze+99)

confirmed by HIRES kinematics (Prochaska & Wolfe 00ff)