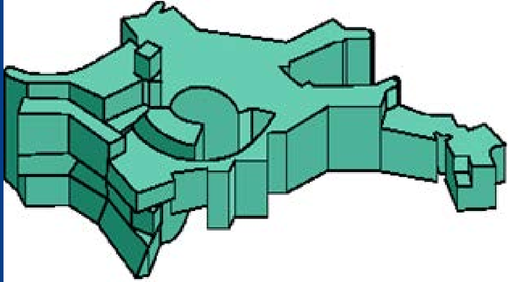
THE COSMIC HISTORY OF ELEMENT FORMATION



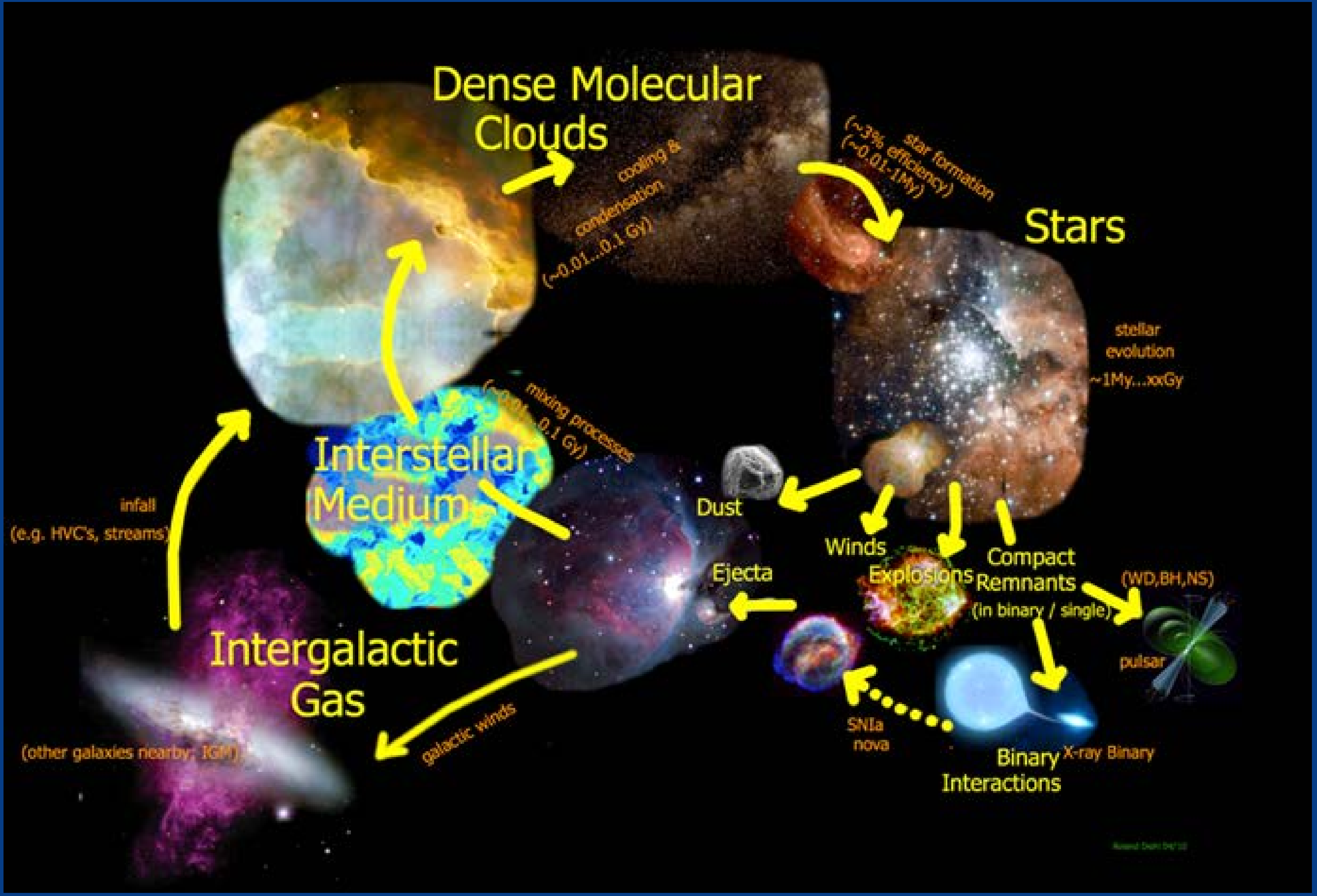
Wolfgang Hillebrandt, MPI für Astrophysik

Lecture, Graduiertenkolleg GRK1147,
January 23, 2014

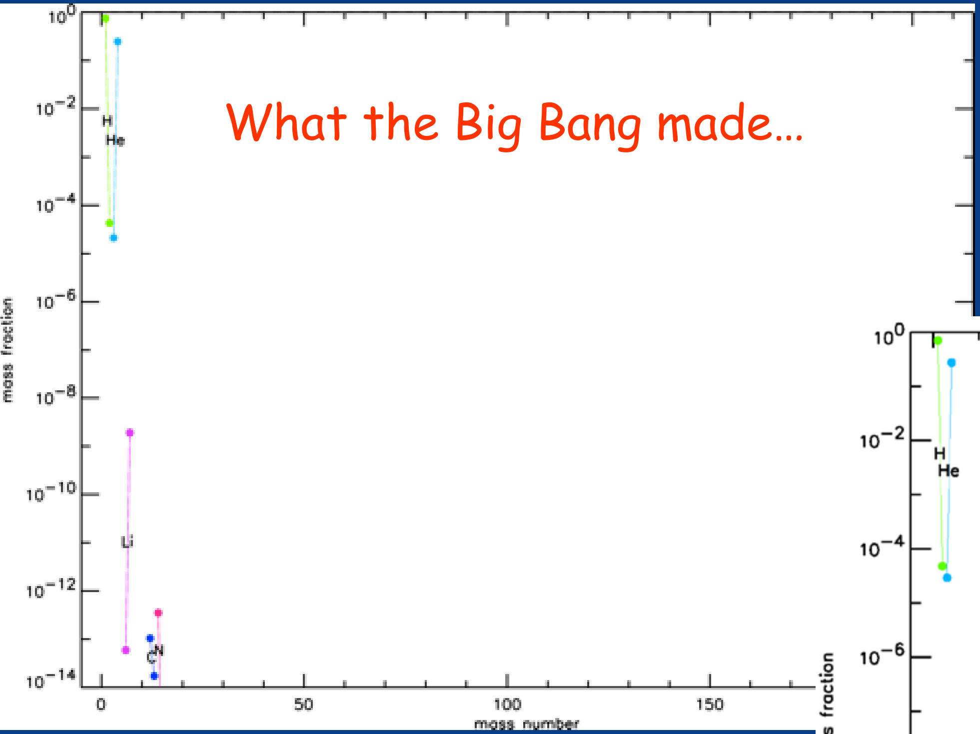
Outline:

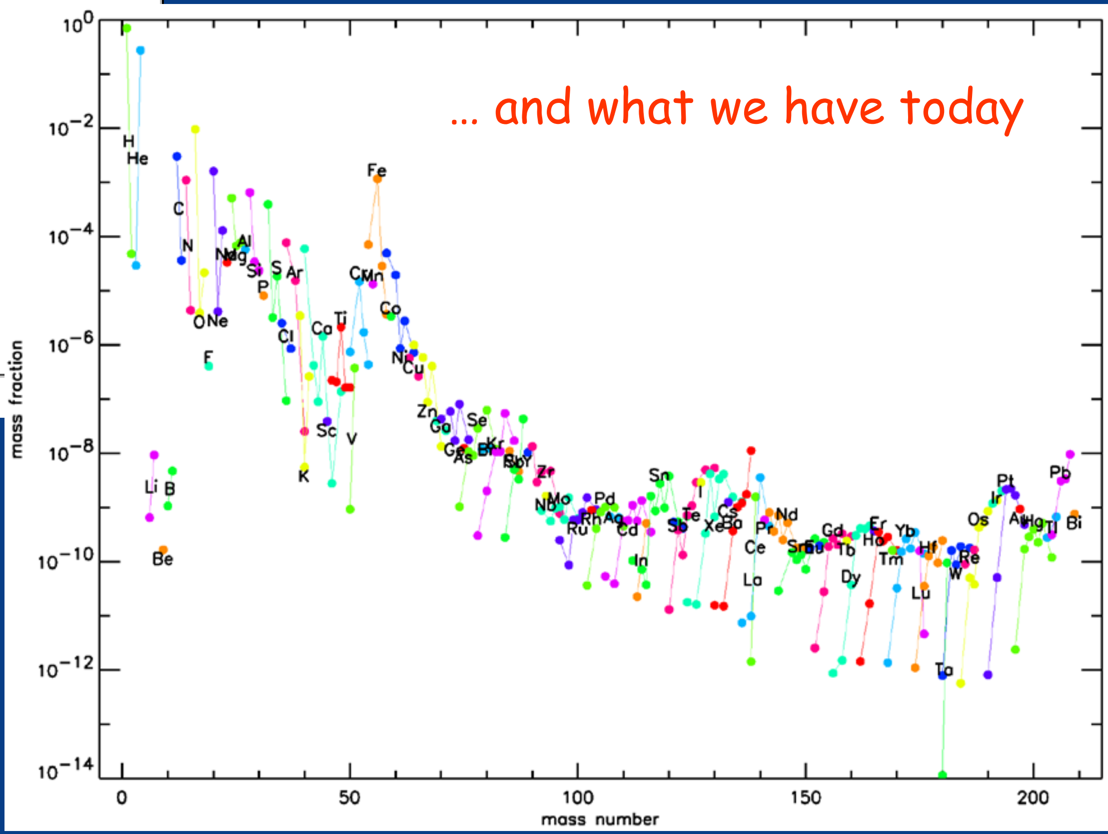
- Introduction
- *Abundance determinations*
- *Galactic chemical evolution*
- *Type Ia supernovae: an example*

0. INTRODUCTION



COMPOSITIONAL EVOLUTION OF THE UNIVERSE





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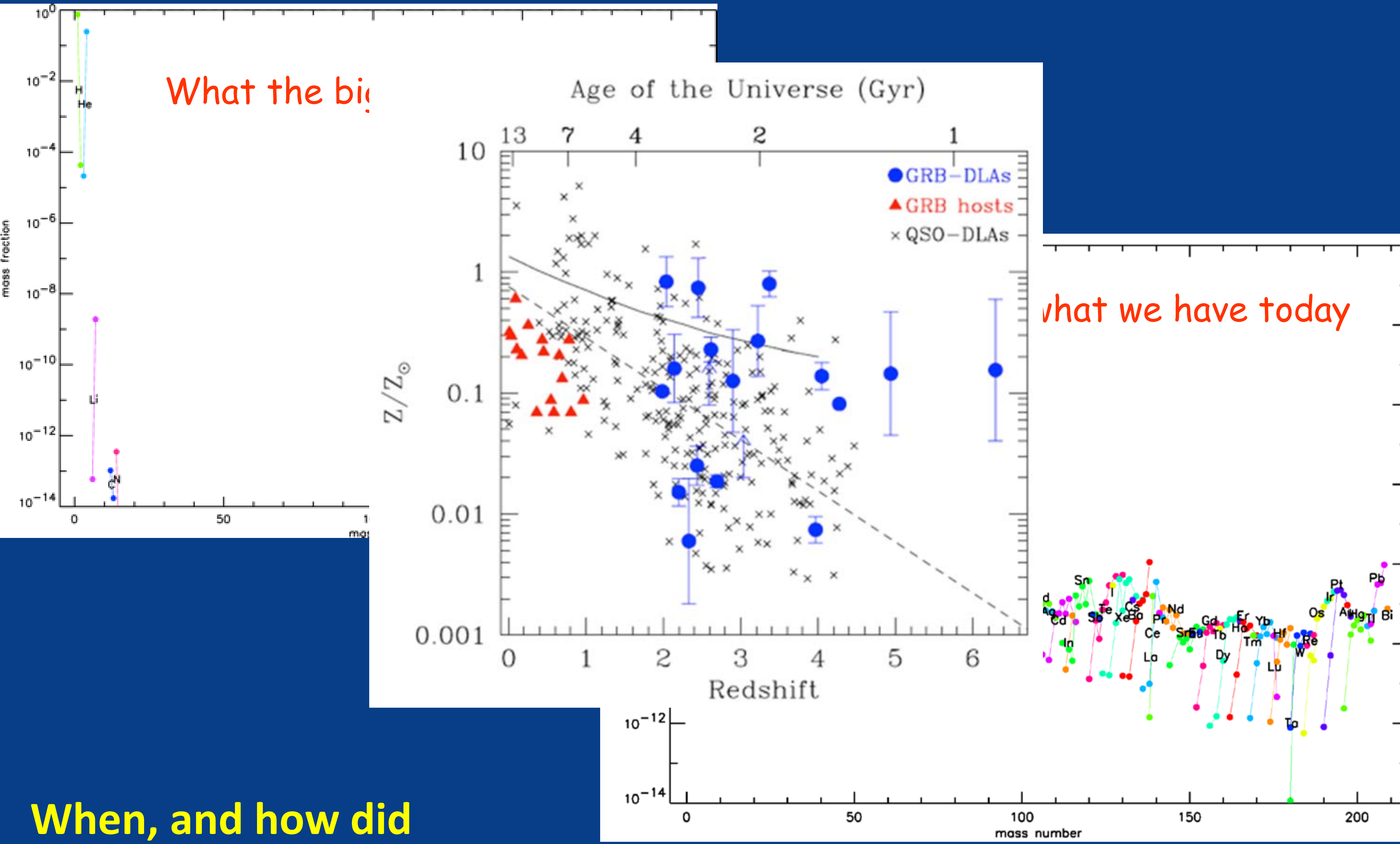
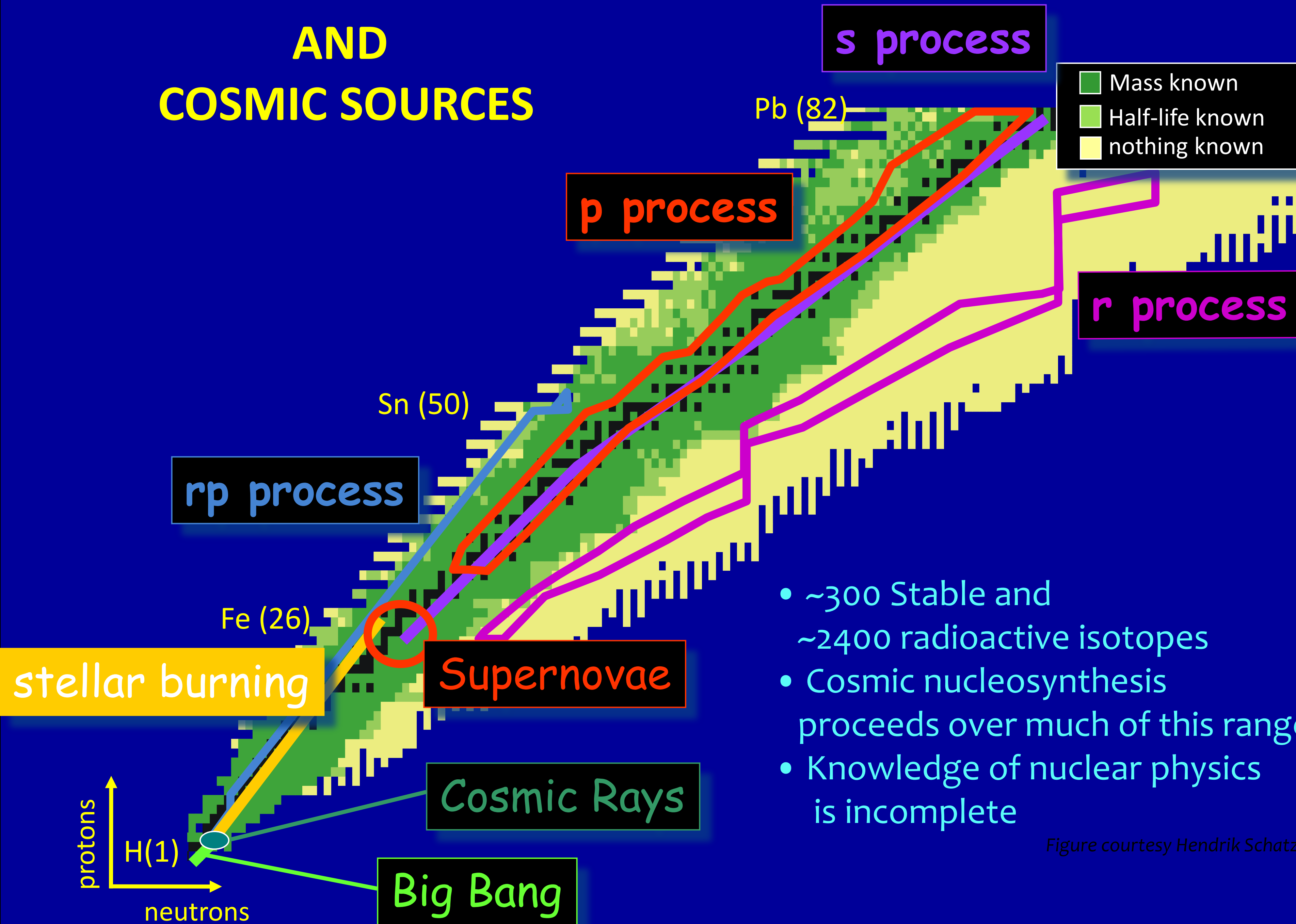


When, and how did metal enrichment happen??

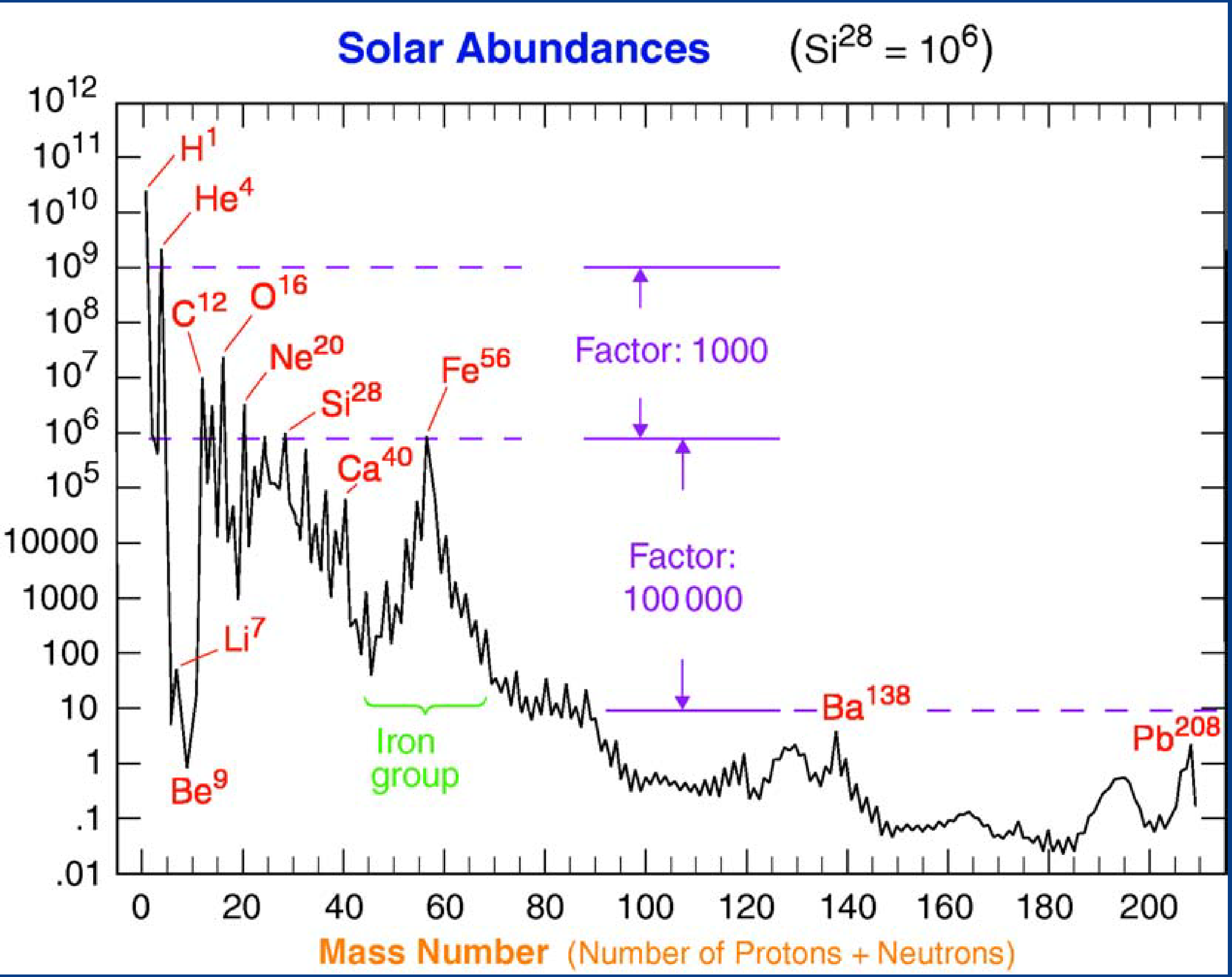
THE ISOTOPIC LANDSCAPE AND COSMIC SOURCES



- ~300 Stable and ~2400 radioactive isotopes
- Cosmic nucleosynthesis proceeds over much of this range
- Knowledge of nuclear physics is incomplete

Figure courtesy Hendrik Schatz

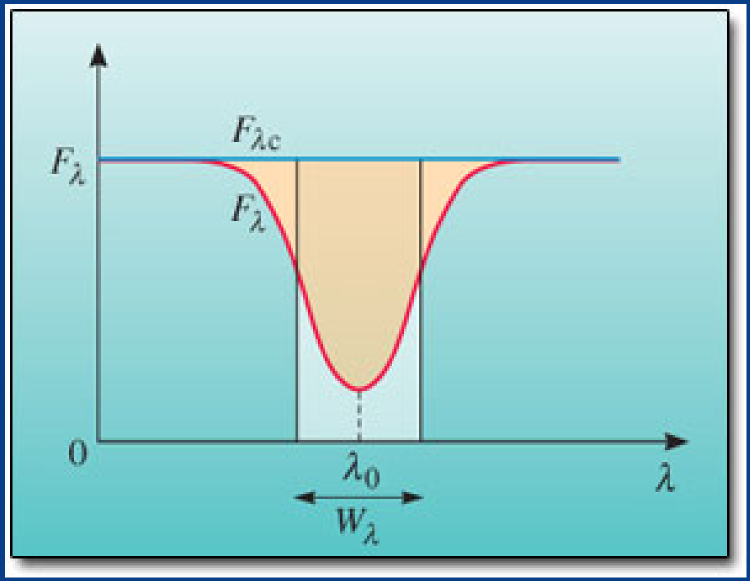
1. ABUNDANCE DETERMINATIONS



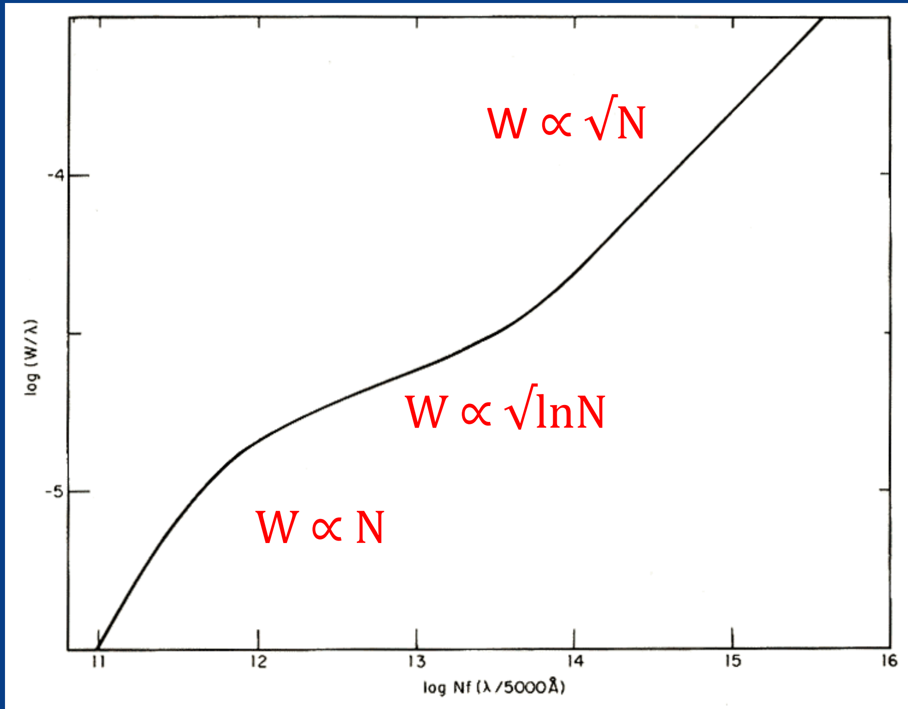
Anders & Grevesse (1989)

STELLAR SPECTRA - SPECTRAL SYNTHESIS

- *Oscillator modeling*
  - *oscillator strength*
  - *natural width*
  - *pressure broadening*
  - *Doppler broadening*
- *Line strength often described by equivalent width*



- *Simple approach: Abundance determination from "curve of growth": W: equivalent width f: oscillator strength (example: for the sun)*



STELLAR SPECTRA - SPECTRAL SYNTHESIS

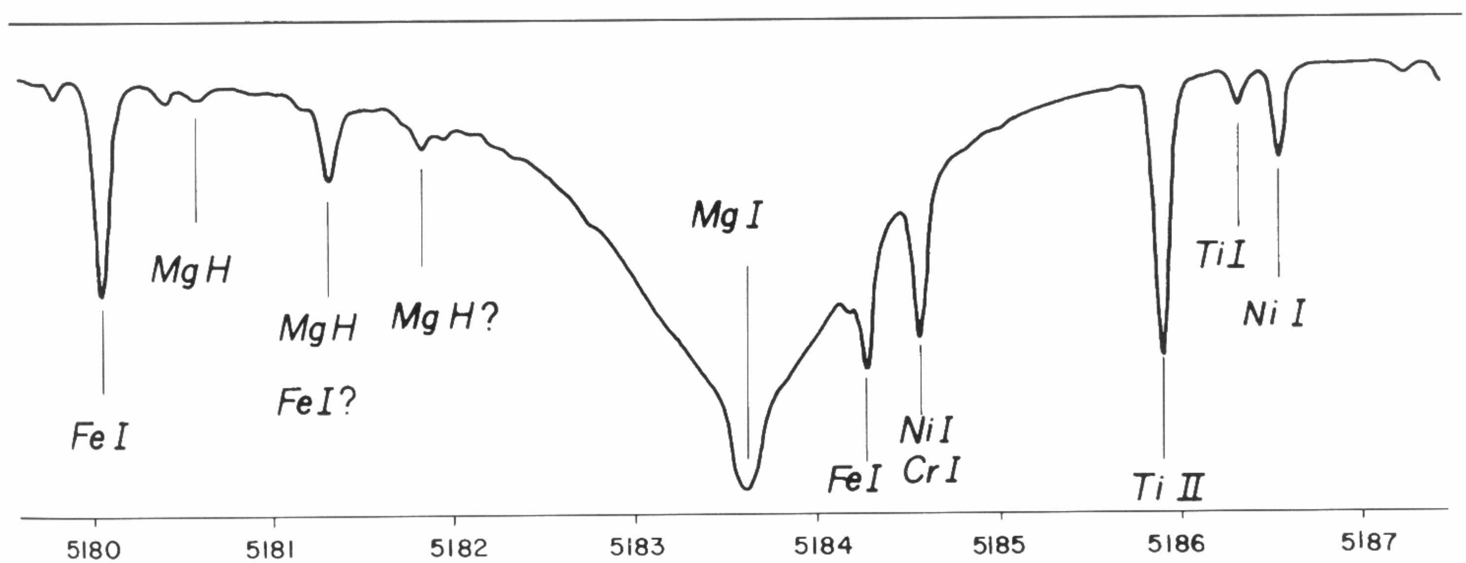
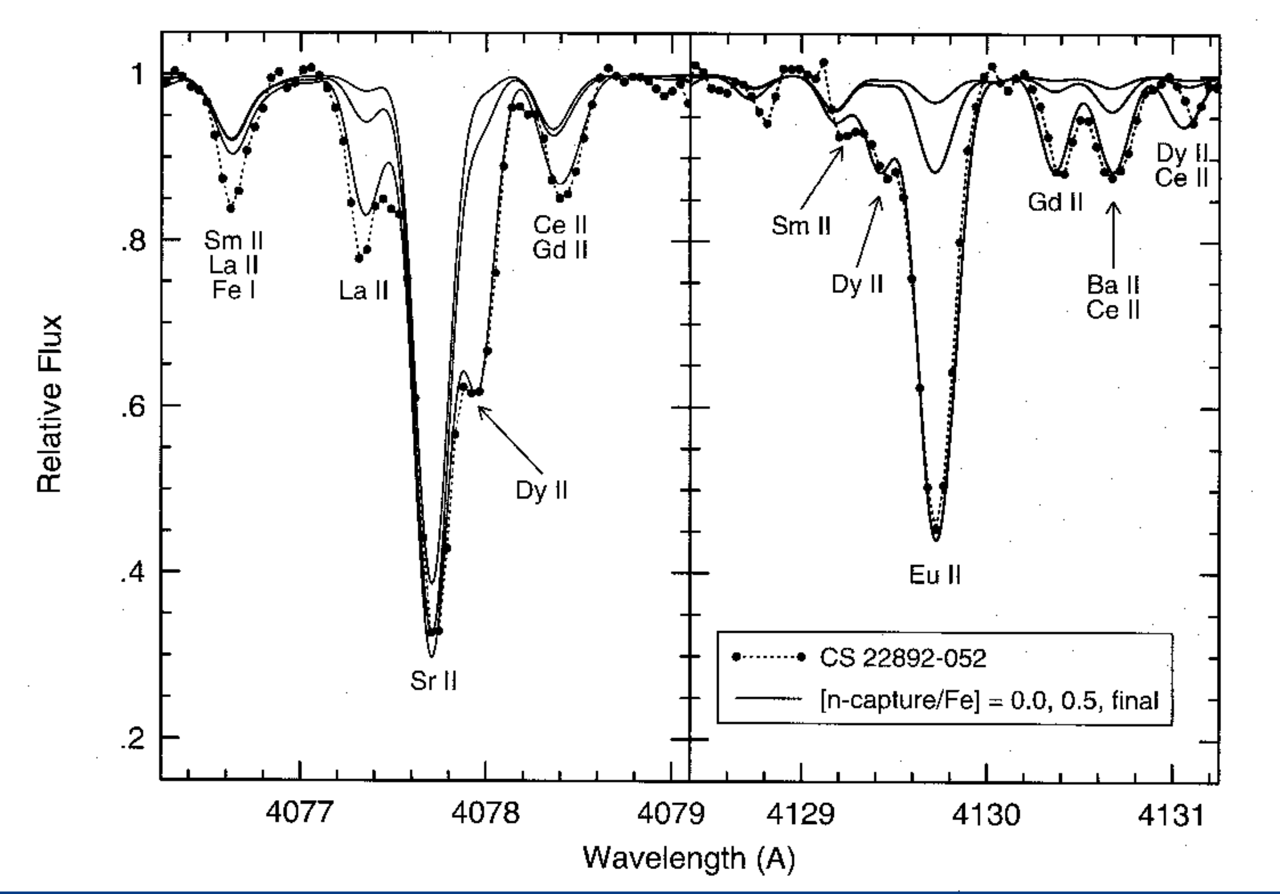


Fig. 3.9. A very strong absorption line of Mg I in the solar spectrum, dominated by damping wings. Adapted from the Liège Atlas (Delbouille *et al.* 1973).

- *It is not sufficient to consider only one line; one has to take more lines into account*
- *Detailed problem is complex; theoretical uncertainties and difficulties*

STELLAR SPECTRA - SPECTRAL SYNTHESIS

- *Whole spectrum is calculated from a model atmosphere*
- *Simultaneous determination of effective temperature, gravity, and abundances*



Resulting abundance ratio:
[Fe/H] ≈ -3.1
(Sneden et al., 1996)

“Bracket notation”:

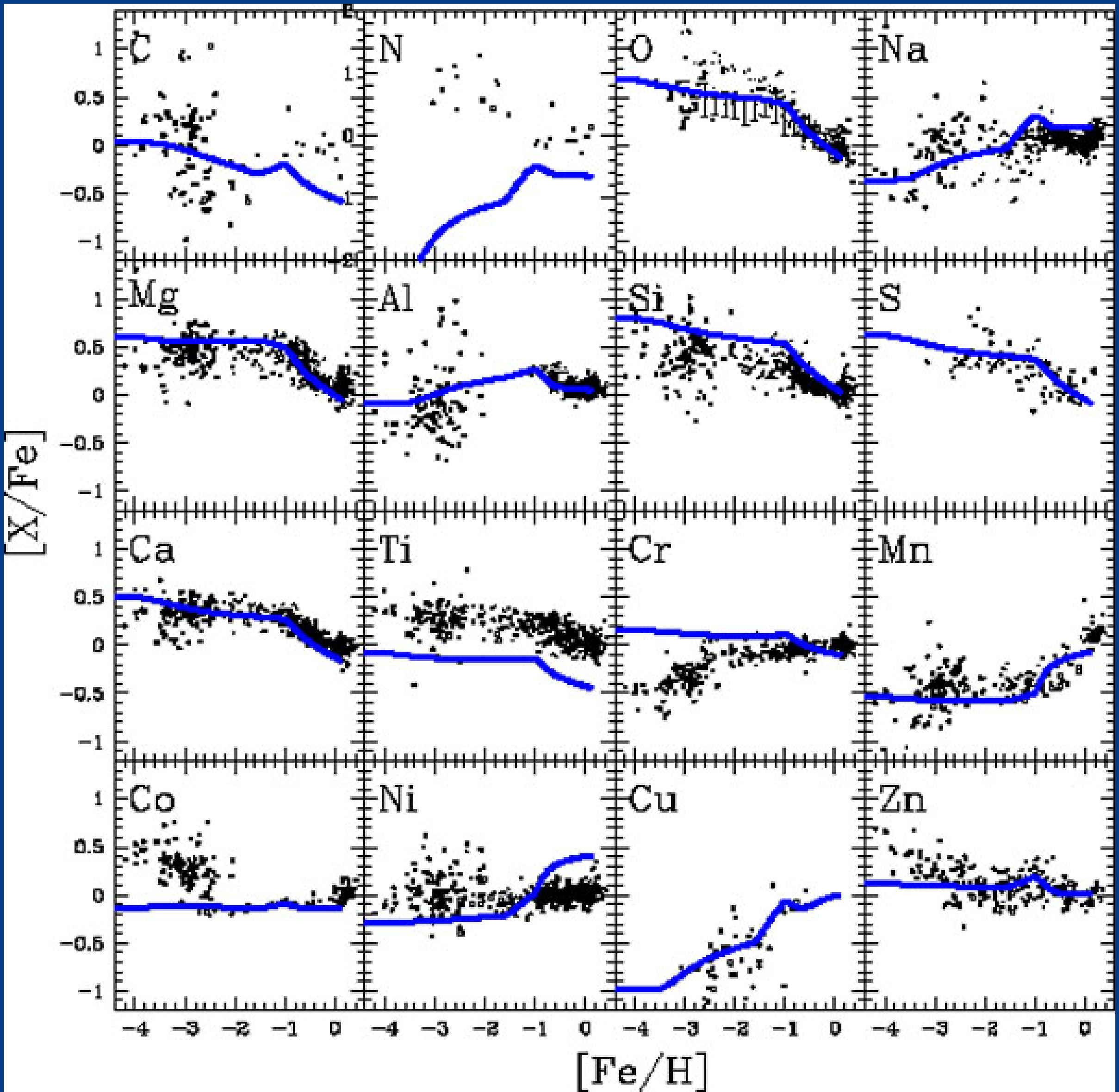
$$[i/j] := \log(X_i/X_j) - \log(X_i/X_j)_\odot$$

i.e.:

$$[Fe/H] = \log\{(X_{Fe}/X_H)/(X_{Fe}/X_H)_\odot\}$$

RESULTS - A FEW EXAMPLES

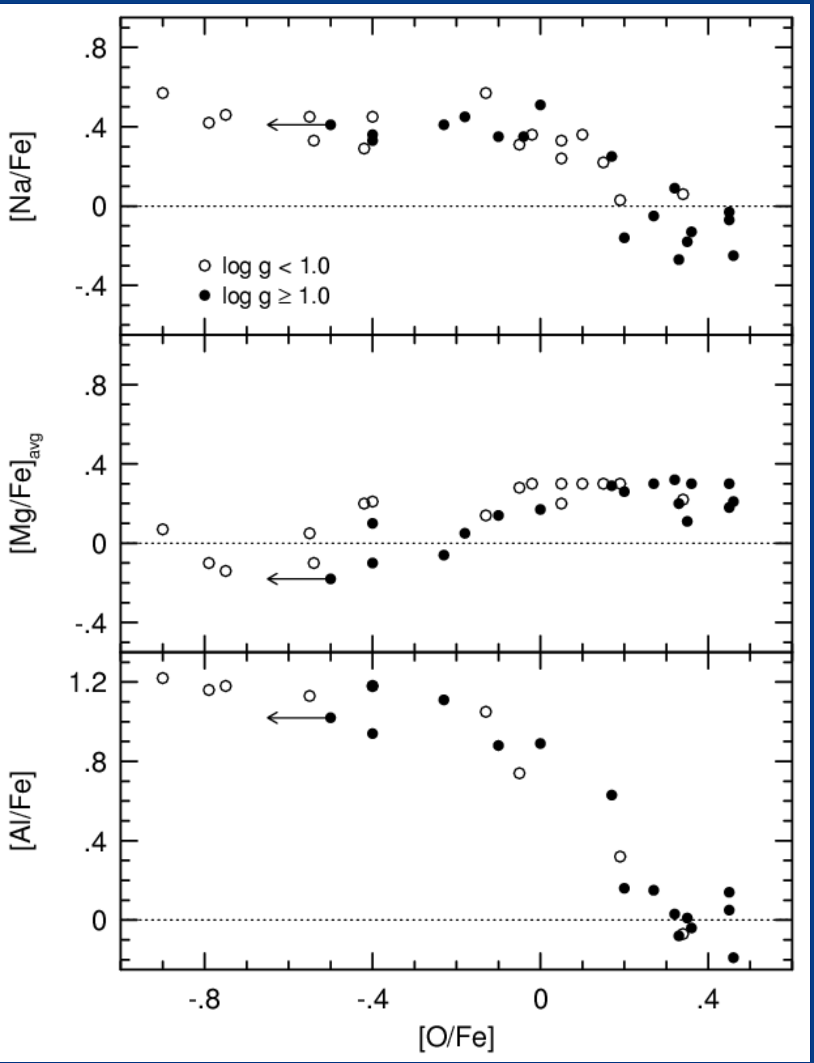
- *Stars in the solar neighbourhood*



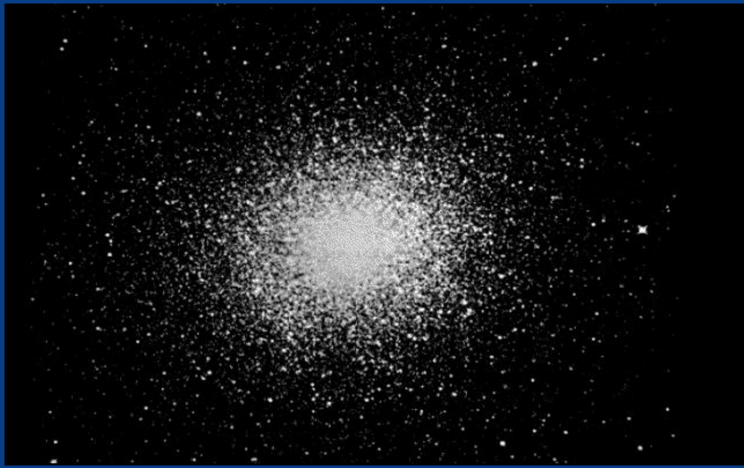
Nomoto et al. (2006) (blue lines: model "predictions")

RESULTS - A FEW EXAMPLES

- *Light element abundances in halo stars*



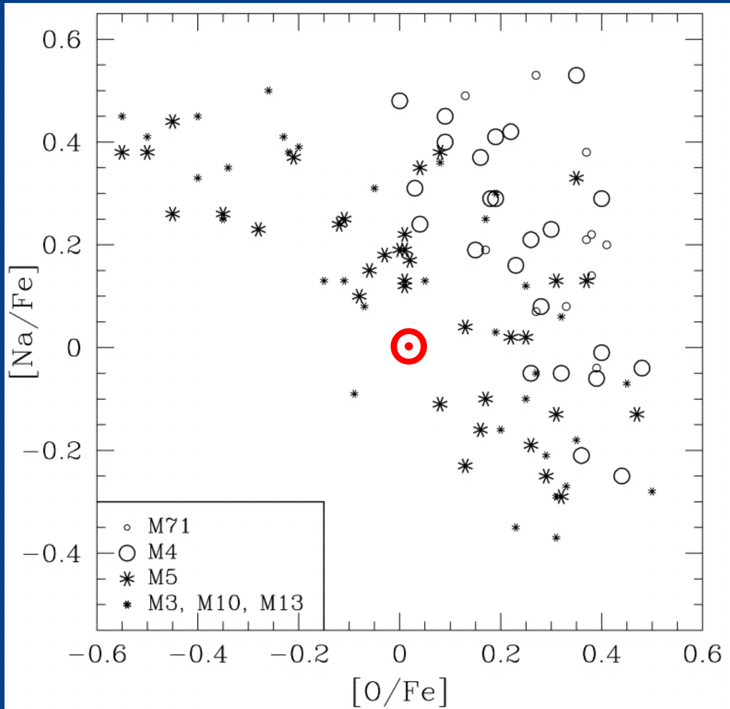
Kraft et al. (1997)



M 13

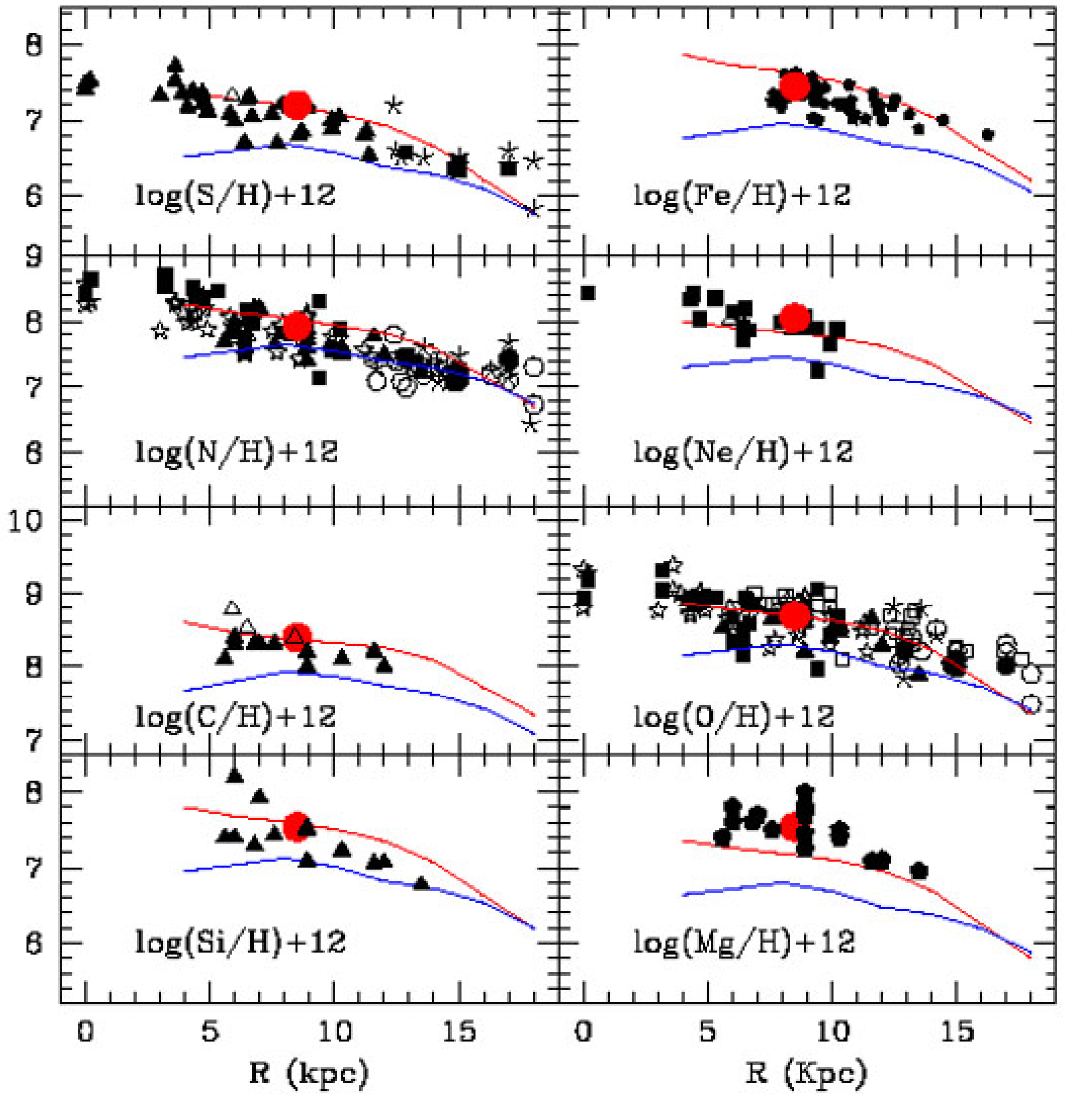
Very non-solar!

Caretta et al. (2009)



RESULTS - A FEW EXAMPLES

- *Galactic abundance gradients (stars and ISM)*



__Abundances vary with galactocentric radius!__

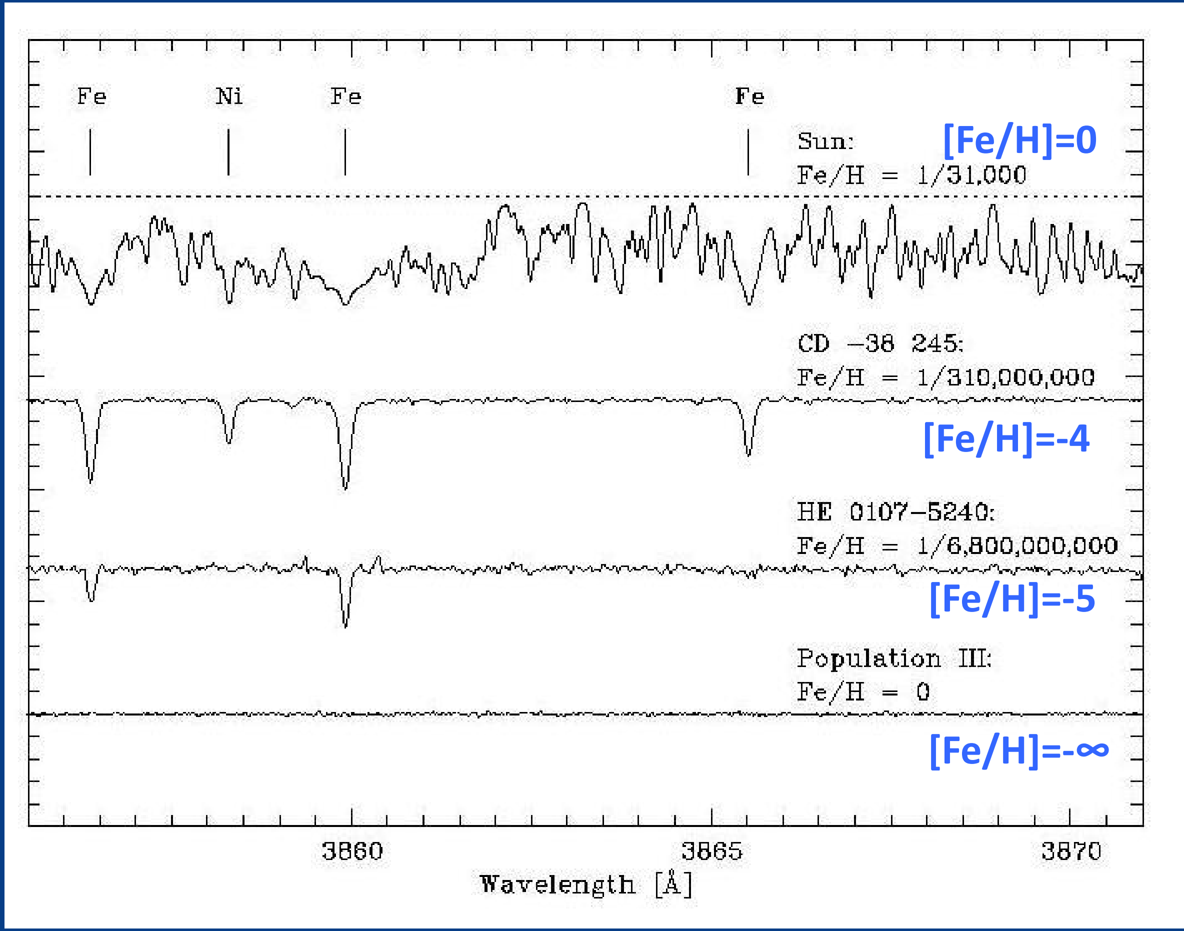
Chiappini et al. (2001)
(red dot: sun;
solid lines: models)

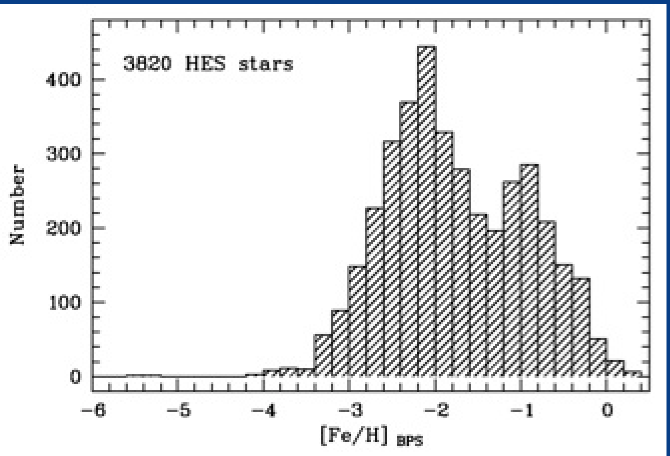
OBSERVATIONS OF EARLY-GENERATION STARS

– *memories of first stellar/SN nucleosynthesis*

Time since Big Bang

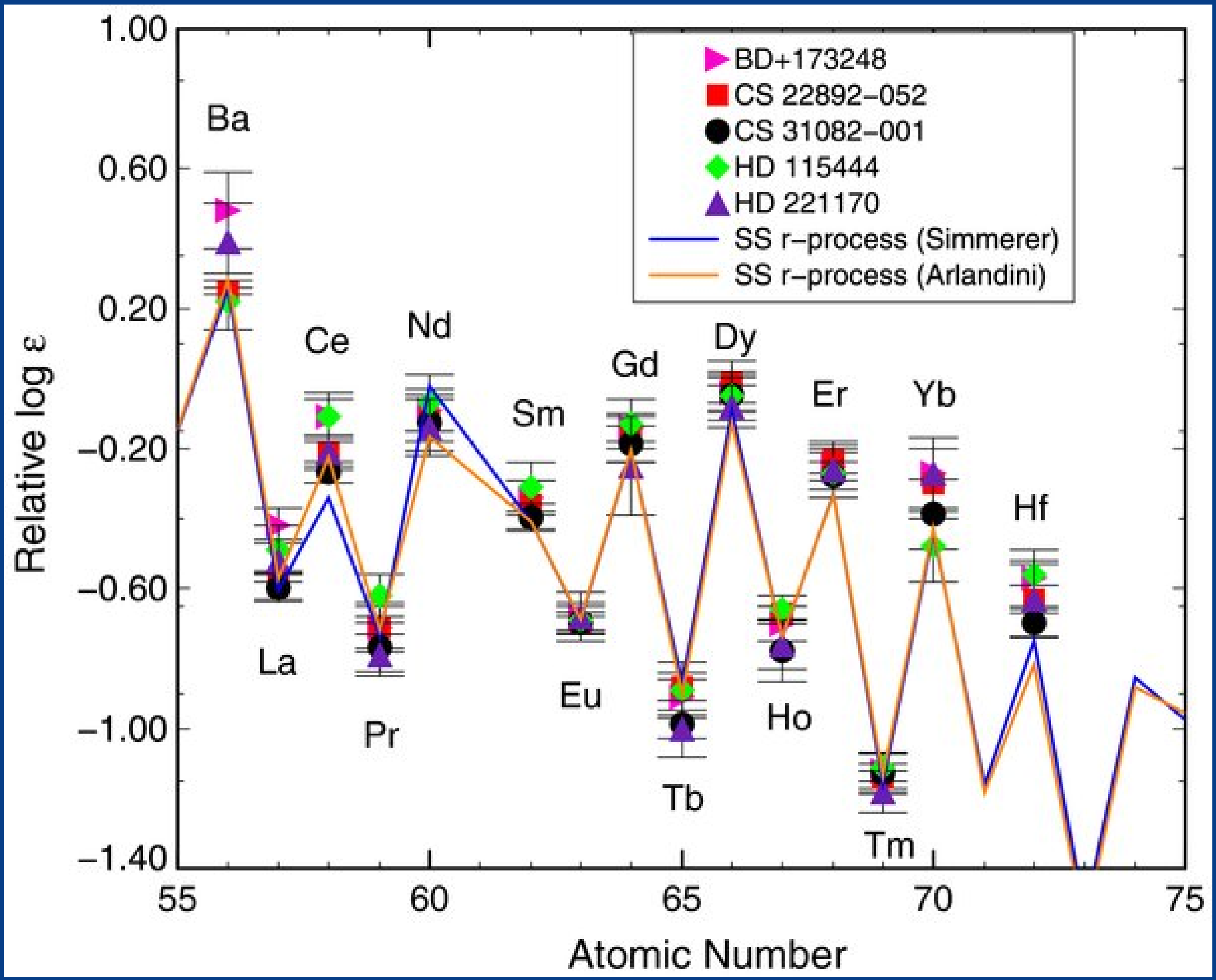
– *rare:*
  - *2 stars at [Fe/H]<-5*





need high-resolution and large surveys

OBSERVATIONS OF EARLY-GENERATION STARS

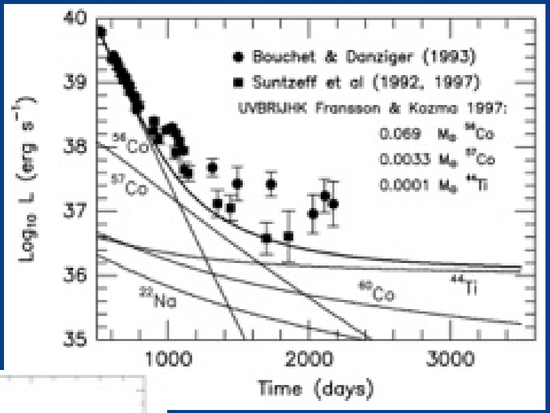


Rare earth abundances in r-rich halo stars and solar-system r- only abundances (Arlandini et al. (1999) and Simmerer et al. (2004)) (normalized at Eu).

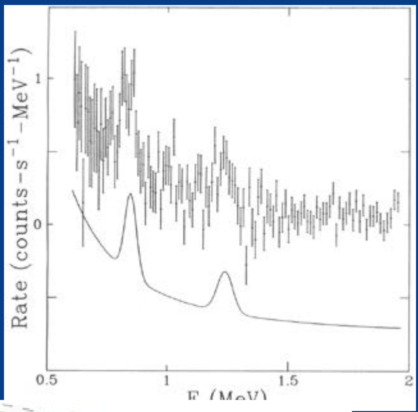
Sneden et al. (2009)

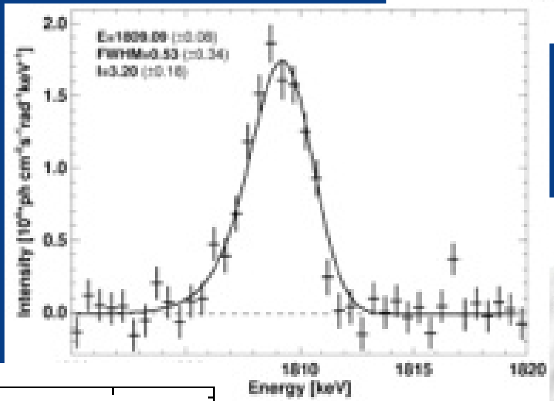
OBSERVATIONS OF EJECTA FROM NUCLEOSYNTHESIS SOURCES

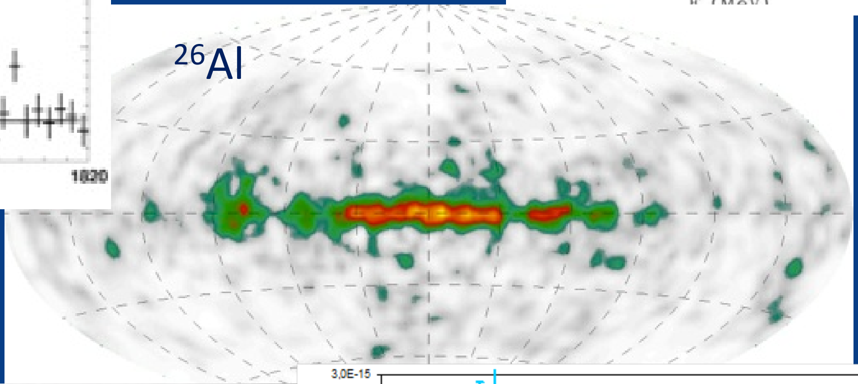
- *in-situ measurement of nucleosynthesis ejecta in (current-Universe) sources*
  - *more detail accessible*
  - *test the models*

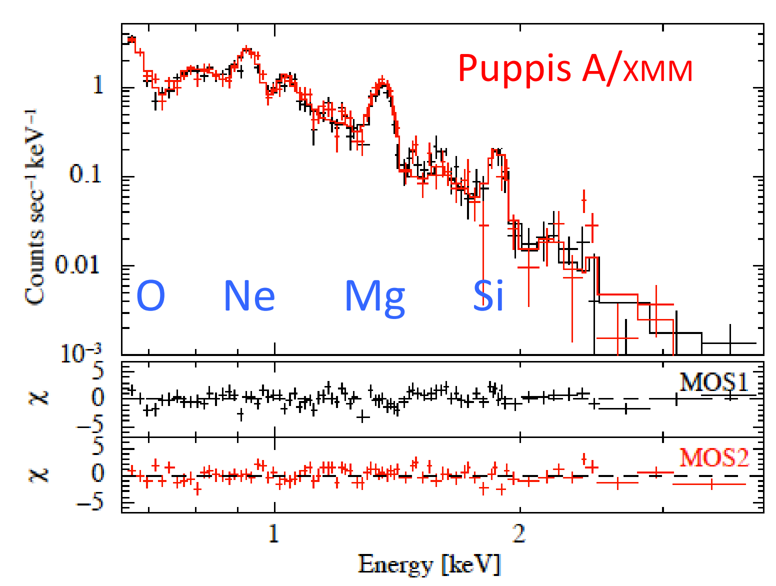


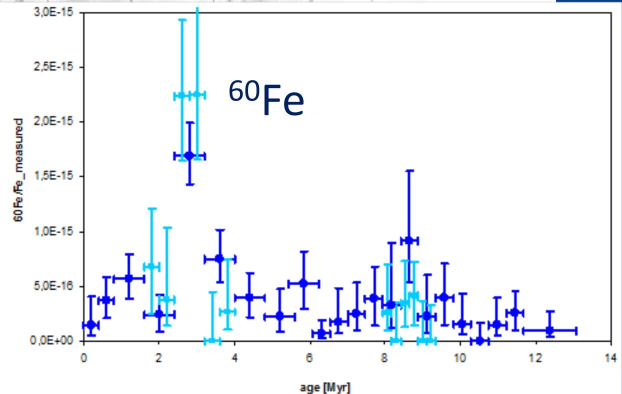
SMM/SN1987A
^{56}Ni decay



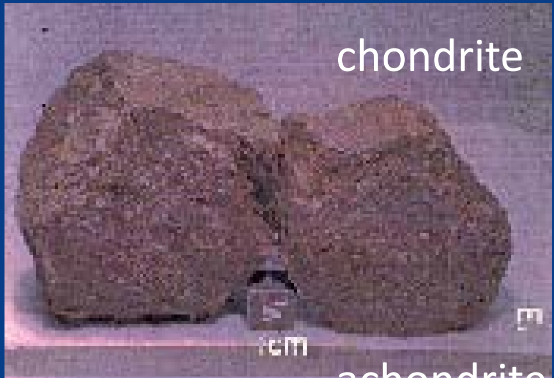








METEORITES – SOLAR-SYSTEM ISOTOPIC ABUNDANCES



- **Chondrites:** contain tiny rounded bodies (chondrules)
- **Achondrites:** quite different in composition and structure, resembling terrestrial material

- ***Carbonaceous chondrites:***
- Primitive chondrites
- Most representative abundances

- Chemical composition can be measured with extraordinary high accuracy (mass spectrometry)
- Seem to be representative of solar system matter
- *But: no information about other stars!*

SUMMARY – PART 1

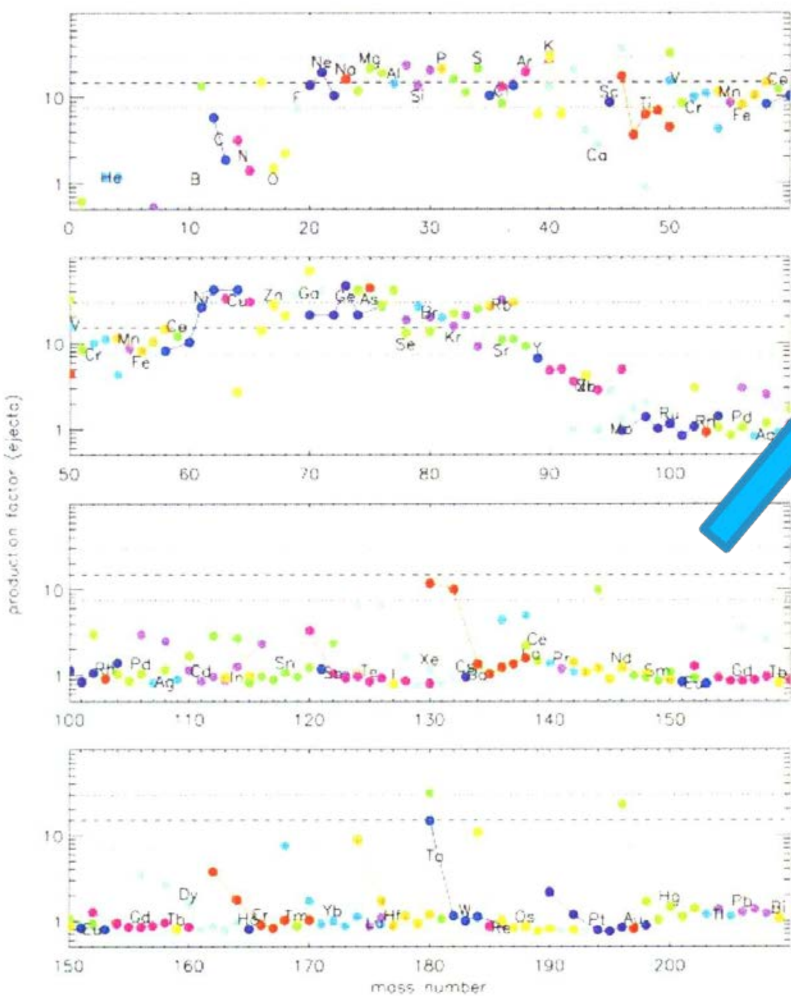
- **Solar system element/isotope abundances are well determined (solar spectrum, cc-chondrites):**
  How `typical‘ is the sun (CNO, iron)?
  Conflict with helioseismology (Asplund et al.)?

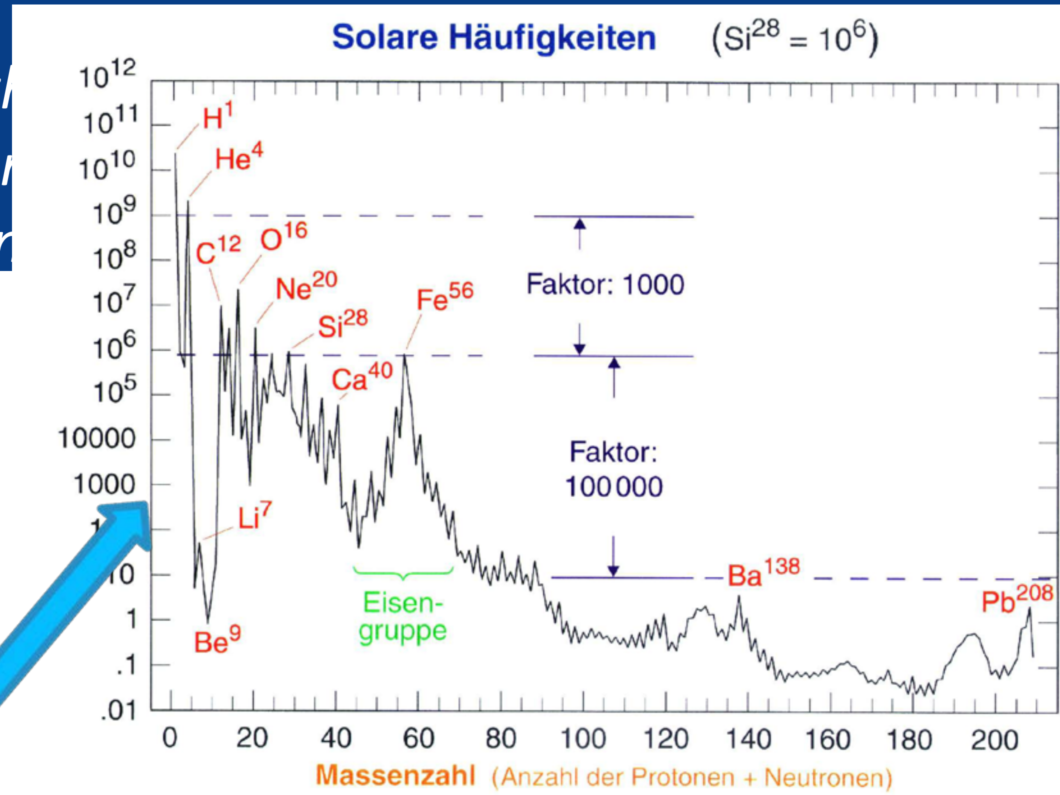
- **Isotopic abundances (other than solar) are known in a few rare cases only (requires high-quality high-resolution spectra)**

- **Abundances in stars (and the ISM) show a lot of scatter (metallicity, `abundance gradients‘, different populations, `anomalies‘):**
  Is this, in part, a problem of the abundance determinations (spectra quality and modeling)?
  Or is there a physical reason we can understand?

2. GALACTIC CHEMICAL EVOLUTION (GCE)

- *GCE tries to understand th… composition of the Univer… the contributions of the in…*





Woosley, Heger & Weaver (2002)

We need to know:

- Initial conditions
- Stellar birth-rate function (the rate at which stars are formed from the gas, and their mass spectrum):
  star-formation rate (SFR) $*$ *initial mass function (IMF)*
- Stellar yields (how elements are produced in stars and restored into the interstellar medium)
- Gas flows (infall, outflow, radial flow).

INITIAL CONDITIONS

1. Start from a gas cloud already present at t=0 ('monolithic model'). No flows allowed ('closed-box')

or, alternatively,

assume that the gas accumulates either fast or slowly and the system has outflows ('open model')

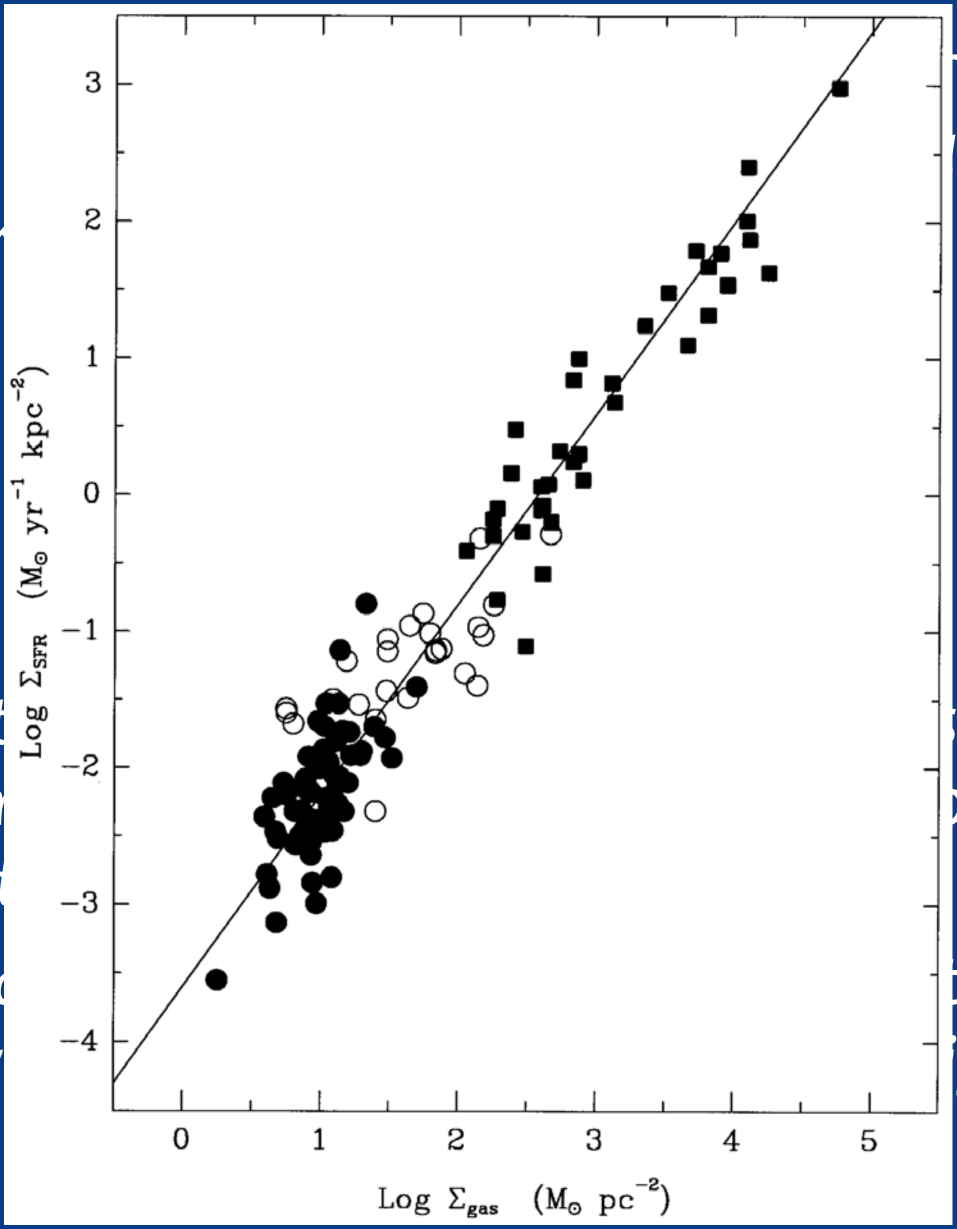
2. Assume that the gas at t=0 is primordial (no metals)

or, alternatively,

assume that the gas at t=0 is pre-enriched by Pop III stars

PARAMETRIZATION OF THE SFR

- *The mos*[...]*he Schmidt (1959) la*[...]*l to some power (k*



- *Kennicut*[...]*studying star form*[...]*ending of the rotat*
- *Other p*[...]*ture, viscosity*[...]*ignored*

OTHER PARAMETRIZATIONS OF THE SFR

- *SF induced by spiral density waves (Wyse & Silk, 1998; Prantzos, 2002)*

$$SFR = aV(R)R^{-1}\sigma_{gas}^{1.5}$$

- *SF accounting for feedback (Dopita & Ryder, 1974)*

$$SFR = \nu\sigma_{tot}^{k_1}\sigma_{gas}^{k_2}$$

INITIAL MASS FUNCTION

- Distribution of stellar masses at birth. Definitions:
  – number fraction of stars formed per interval $[m, m+dm] = \Phi(m)$
  – mass fraction of stars formed ... $m\Phi(m) = \xi(m)$
    normalisation:

$$\int_{min}^{max} m\Phi(m)dm = 1$$

  min, max are minimum and maximum stellar masses

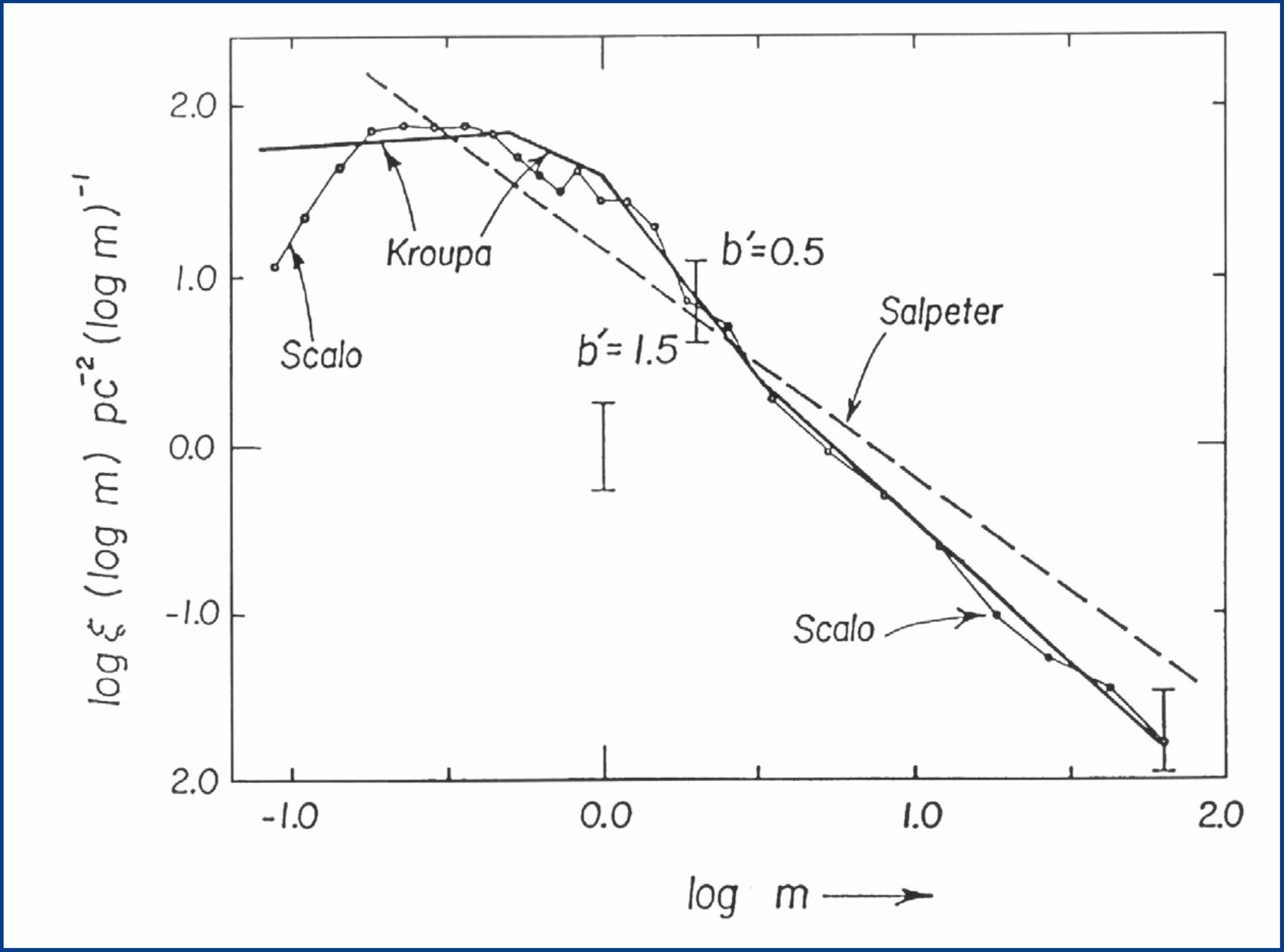
- Observations: star counts in the local region (take into account the life time of the stars), star counts in starforming regions.

- Analytic approximations: (piecewise) powerlaws. The simplest case is the Salpeter IMF:

$$\xi(m) \propto m^{-1.35}$$

- Uncertainties: no detailed understanding of SF process yet, IMF at low metallicity

INITIAL MASS FUNCTION



STELLAR YIELDS

During their evolution and at their death, stars release processed matter. The NS products (yields) depend on stellar mass and composition. CE requires detailed knowledge of stellar life times and NS yields.

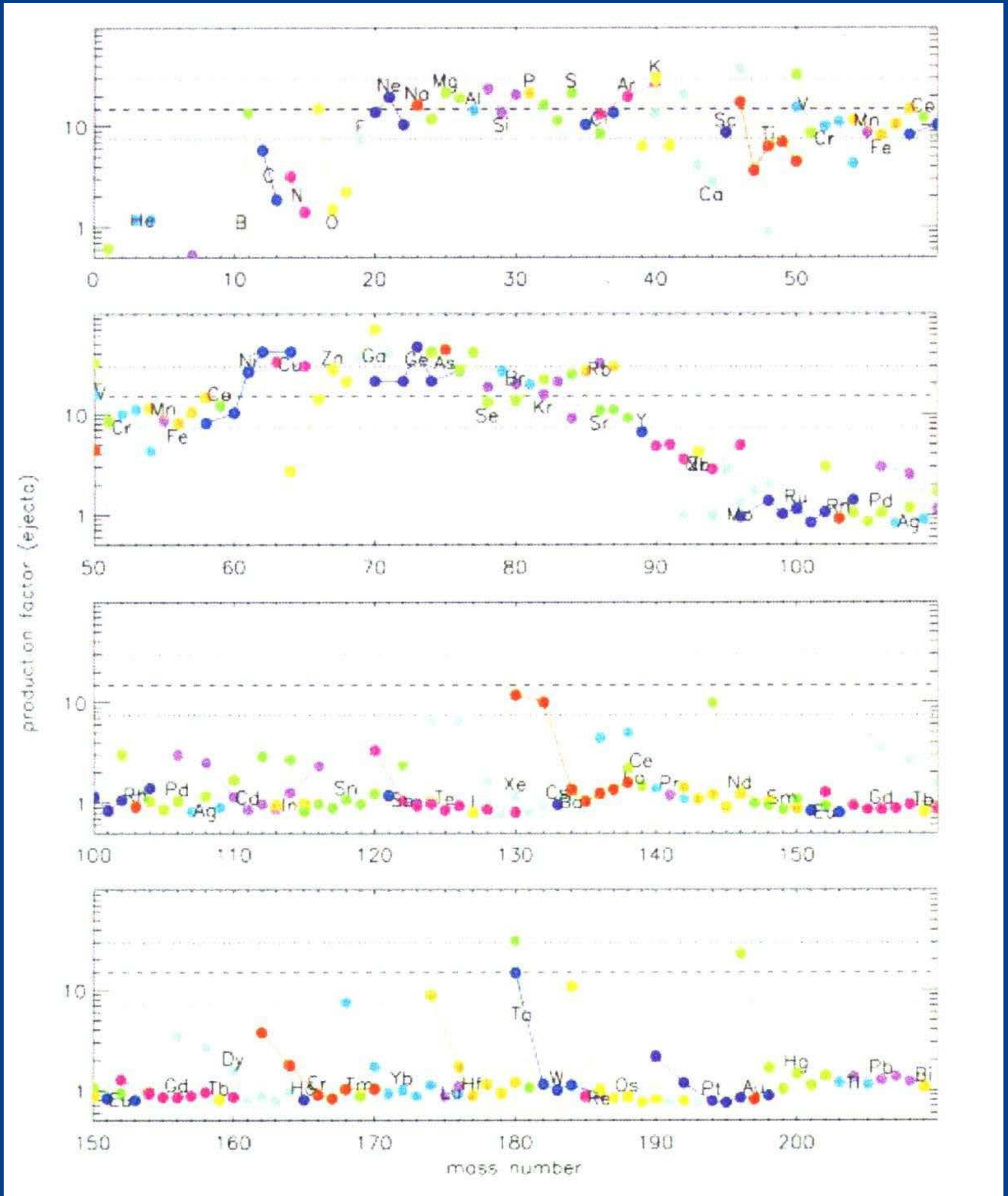
STELLAR YIELDS

TABLE III. The origin of the light and intermediate-mass elements.

Species	Origin	Species	Origin	Species	Origin
^{1}H	BB	^{30}Si	C,Ne	^{51}V	α,Ia-det,xSi,xO,ν
^{2}H	BB	^{31}P	C,Ne	^{50}Cr	xSi,xO,α,Ia-det
^{3}He	BB,L*	^{32}S	xO,O	^{52}Cr	xSi,α,Ia-det
^{4}He	BB,L*,H	^{33}S	xO,xNe	^{53}Cr	xO,xSi
^{6}Li	CR	^{34}S	xO,O	^{54}Cr	nse-IaMCh
^{7}Li	BB,ν,L*,CR	^{36}S	He(s),C,Ne	^{55}Mn	Ia,xSi,ν
^{9}Be	CR	^{35}Cl	xO,xNe,ν	^{54}Fe	Ia,xSi
^{10}B	CR	^{37}Cl	He(s),xO,xNe	^{56}Fe	xSi,Ia
^{11}B	ν	^{36}Ar	xO,O	^{57}Fe	xSi,Ia
^{12}C	L*,He	^{38}Ar	xO,O	^{58}Fe	He(s),nse-IaMCh
^{13}C	L*,H	^{40}Ar	He(s),C,Ne	^{59}Co	He(s),α,Ia,ν
^{14}N	L*,H	^{39}K	xO,O.ν	^{58}Ni	α
^{15}N	novae,ν	^{40}K	He(s),C,Ne	^{60}Ni	α, He(s)
^{16}O	He	^{41}K	xO	^{61}Ni	He(s),α,Ia-det
^{17}O	novae, L*	^{40}Ca	xO,O	^{62}Ni	He(s),α
^{18}O	He	^{42}Ca	xO	^{64}Ni	He(s)
^{19}F	ν,He,L*	^{43}Ca	C,Ne,α	^{63}Cu	He(s),C,Ne
^{20}Ne	C	^{44}Ca	α,Ia-det	^{65}Cu	He(s)
^{21}Ne	C	^{46}Ca	C,Ne	^{64}Zn	ν-wind,α,He(s)
^{22}Ne	He	^{48}Ca	nse-IaMCh	^{66}Zn	He(s),α,nse-IaMCh
^{23}Na	C,Ne,H	^{45}Sc	α,C,Ne,ν	^{67}Zn	He(s)
^{24}Mg	C,Ne	^{46}Ti	xO,Ia-det	^{68}Zn	He(s)
^{25}Mg	C,Ne	^{47}Ti	Ia-det,xO,xSi	r	ν-wind
^{26}Mg	C,Ne	^{48}Ti	xSi,Ia-det	p	xNe,O
^{27}Al	C,Ne	^{49}Ti	xSi	$s(A<90)$	He(s)
^{28}Si	xO,O	^{50}Ti	nse-IaMCh,He(s)	$s(A>90)$	L*
^{29}Si	C,Ne	^{50}V	C,Ne,xNe,xO		

Woosley, Heger & Weaver (2002)

STELLAR YIELDS



Woosley, Heger & Weaver (2002)

MASS EJECTION

Ejected matter is mixed into the gas.
One star of mass *m* (life time $\tau(m)$) contributes to the enrichment of a nuclear species *i* according to its return function $R^i(t,m)$

$$E^i(t,m) = \int_0^{\tau(m)} R^i(t,m)dt$$

Assumption: all matter is ejected in a single event (i.e. on a timescale negligible compared to the galactic evolution timescales) and mixed into the (local) gas ("instantaneous recycling"):

$$R^i(t,m) = \delta(t-\tau(m))R^i(m)$$

R^i is the mass of species *i* that is ejected by the star: the initial mass at formation, minus the remnant (w^i_m), plus the production (p^i_m)

$$R^i(m) = m\,X^i\,(t-\tau(m)) - w^i_m + m\,p^i_m$$

For an ensemble of stars with a birthrate $B(t,m)$

$$E^i(t) = \int_{min}^{max} B(m, t-\tau(m))R^i(m)dm$$

ENRICHMENT OF THE GAS COMPONENT

Total gas ejection from stars:

$$E(t) = \int_{min}^{max} (m - w_m) * SFR(t - \tau(m)) * IMF(m)dm$$

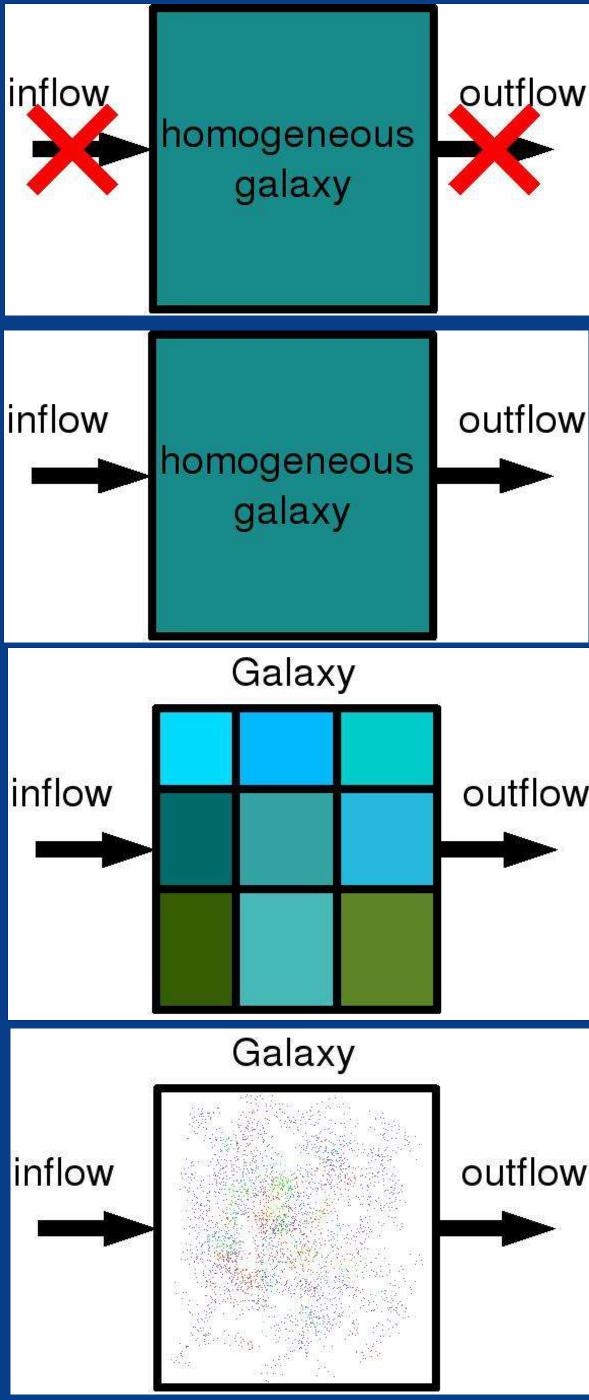
Abundance of a species *i* in the gas changes due to star formation, stellar ejection, inflows (with abundance X^i_f), and outflows:

$$\frac{d}{dt}(X^i M_g) = -X^i * SFR + E^i + X^i{}_f f - X^i e$$

(*f*: inflowing mass; *e*: outflowing mass)

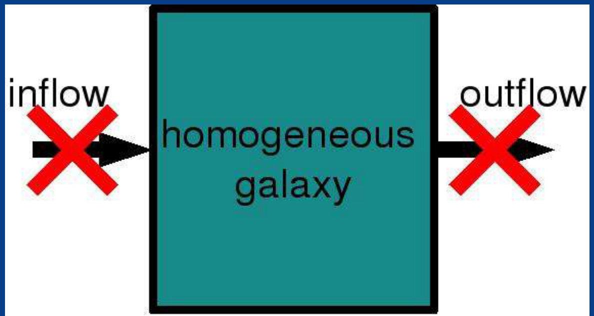
CHEMICAL EVOLUTION MODELS

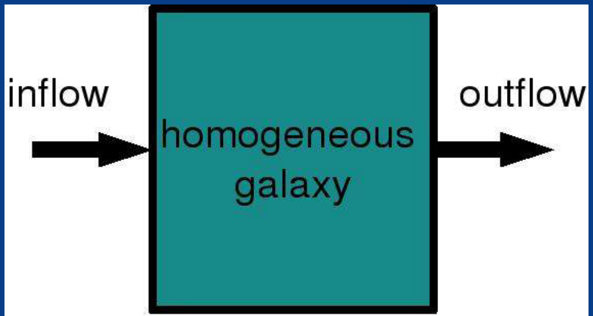
- *One-zone models:*
  perfect mixing in the homogeneous physical domain
  – closed box models
  – open box models: some prescription of infall and outflows
- *Multizone models:*
  coupled open box models with interzone mass transfer
- *Chemodynamical models:*
  (multidimensional) selfconsistent treatment of the entire galaxy with all/some of the components and interactions described above.



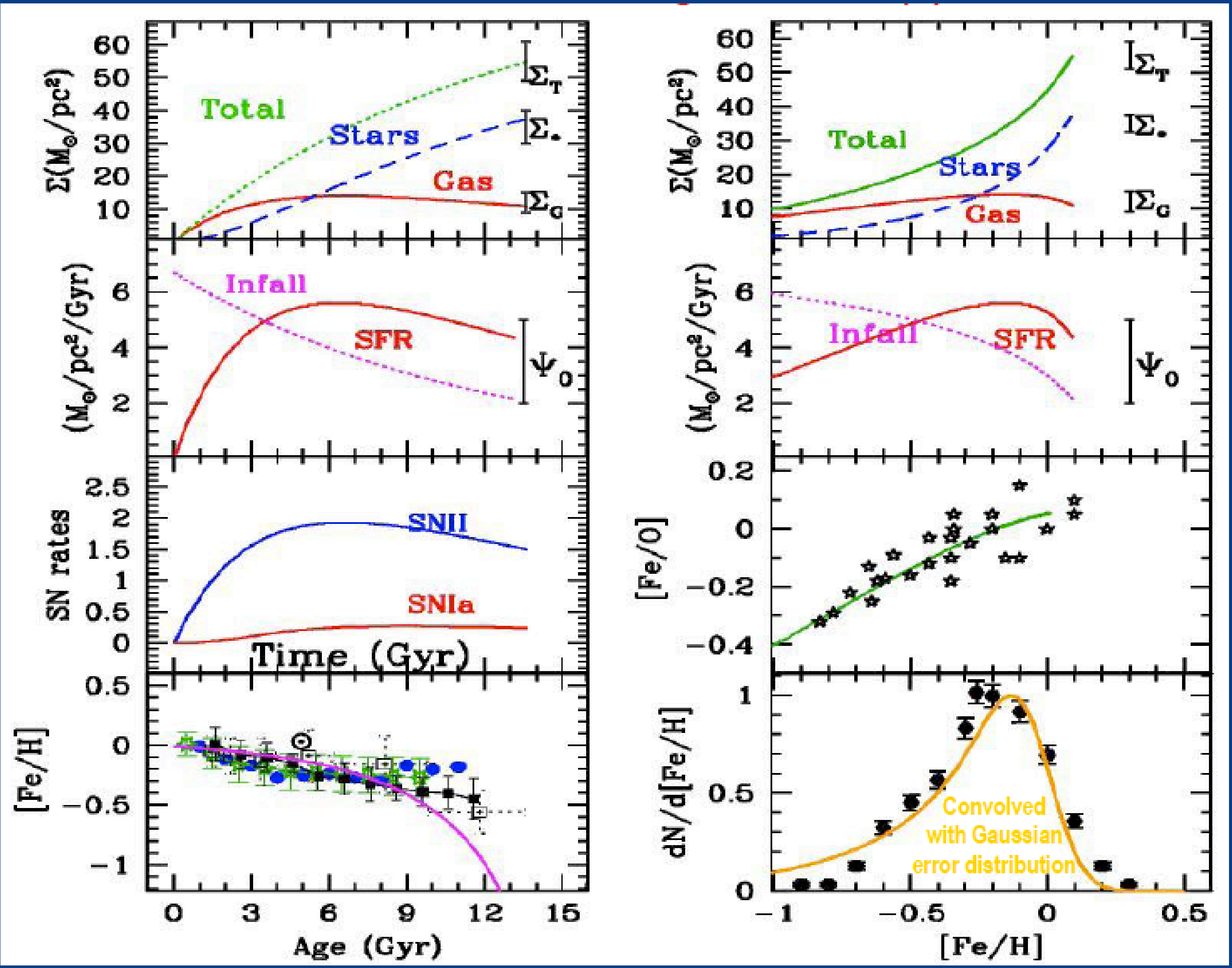
ONE-ZONE MODEL IN MORE DETAIL

- Assume homogeneity in the physical domain (galaxy,...) due to fast mixing, neglect spatial derivatives and therefore large-scale coupling ==> equations for the integral quantities gas mass and stellar mass, and for the (spatially constant) abundances, star formation rates, ...
- Boundaries closed (the “simple model”) or open (replenishment of the gas by infall of (primordial?) matter, outflow of processed gas).
- Initial conditions: no stars, only gas with primordial composition.
- Allows to understand basic effects like the age-metallicity relation and the distribution of stars with metallicity.





HOW DO THE MODELS PERFORM?

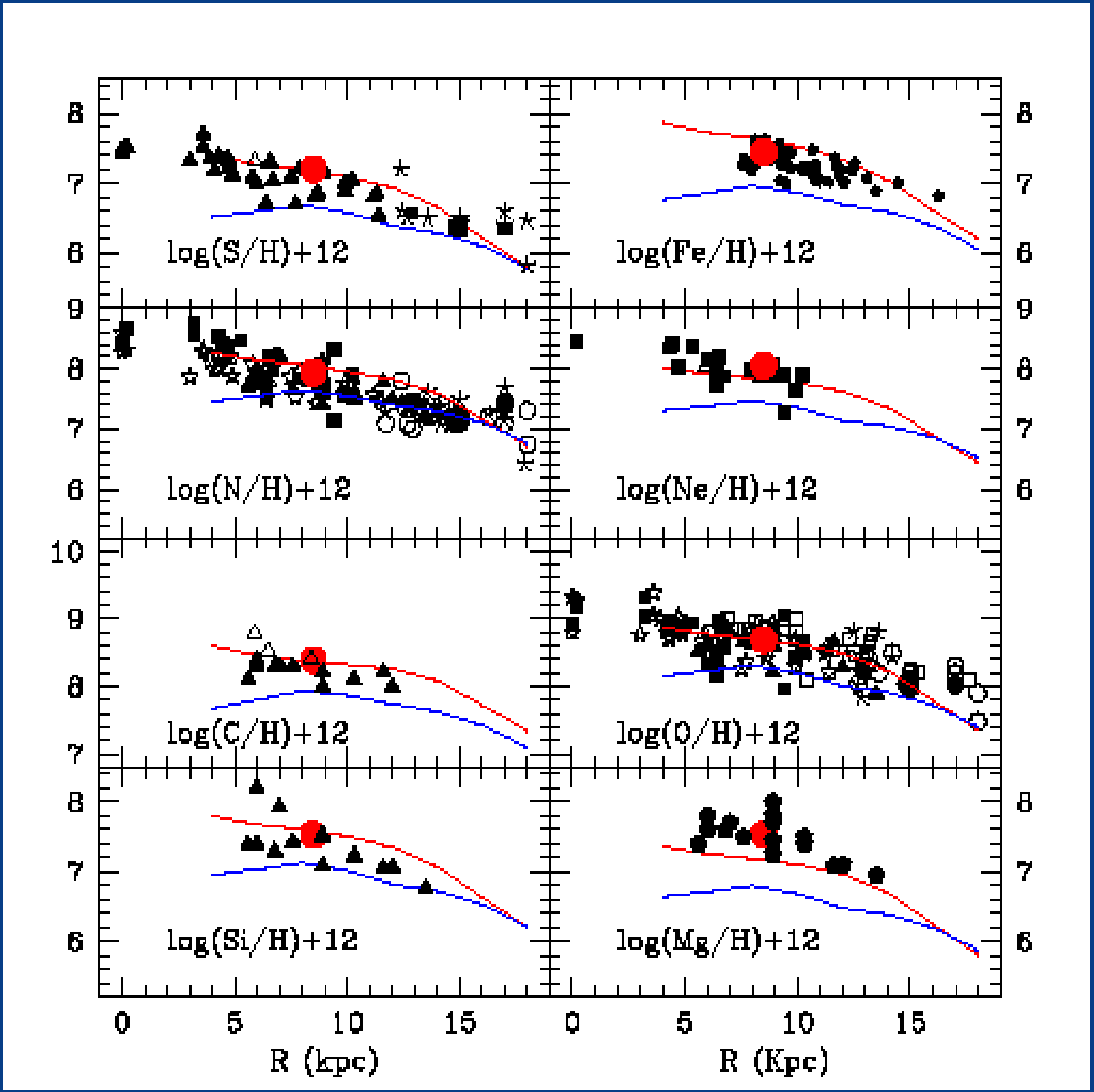


Solar neighbor-hood (Prantzos, 2011)

Metallicity distribution of G-type stars

- *Solar neighborhood looks OK*

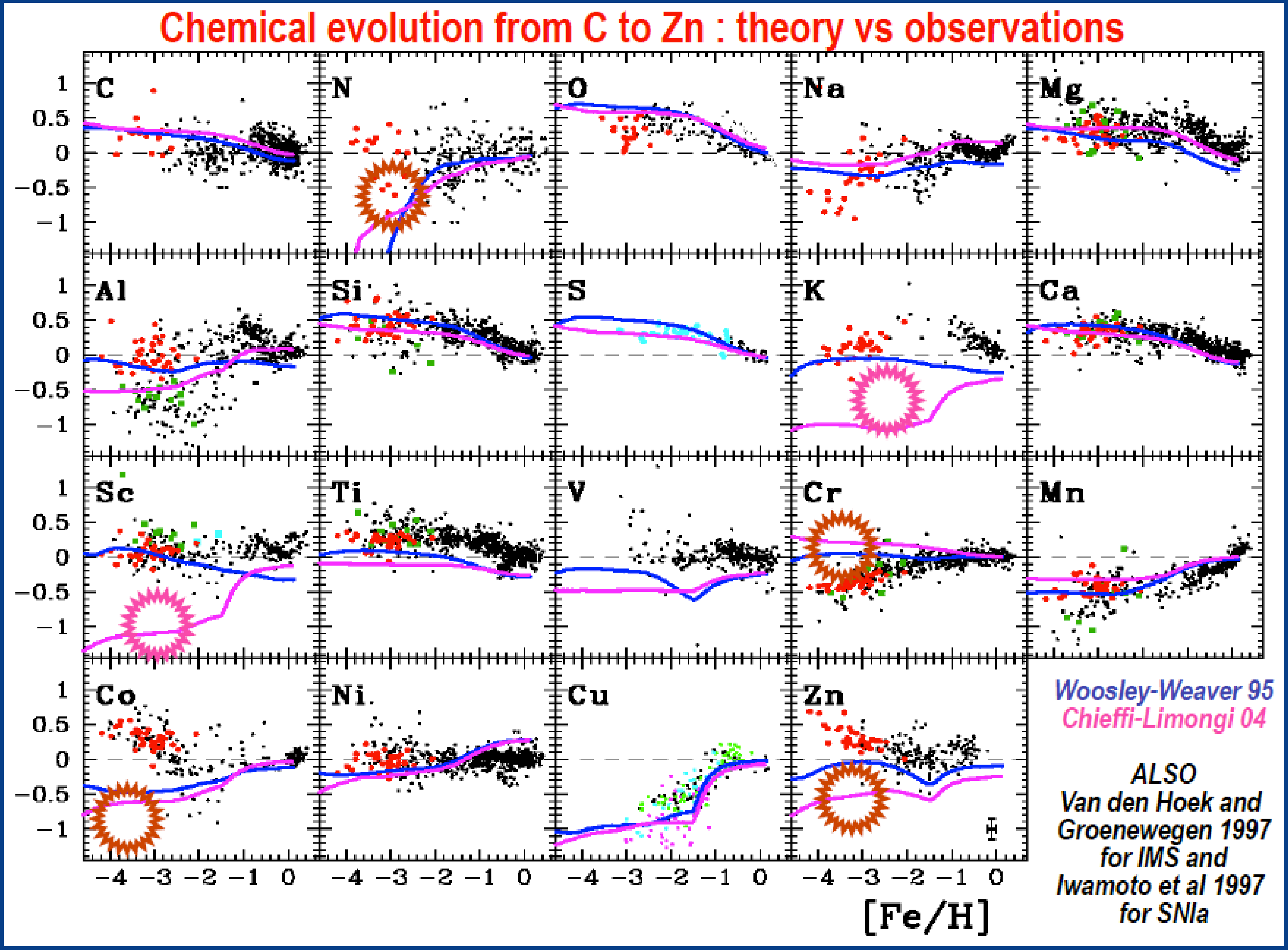
HOW THE MODELS PERFORM?



Time progesses from ‘blue’ to ‘red’.

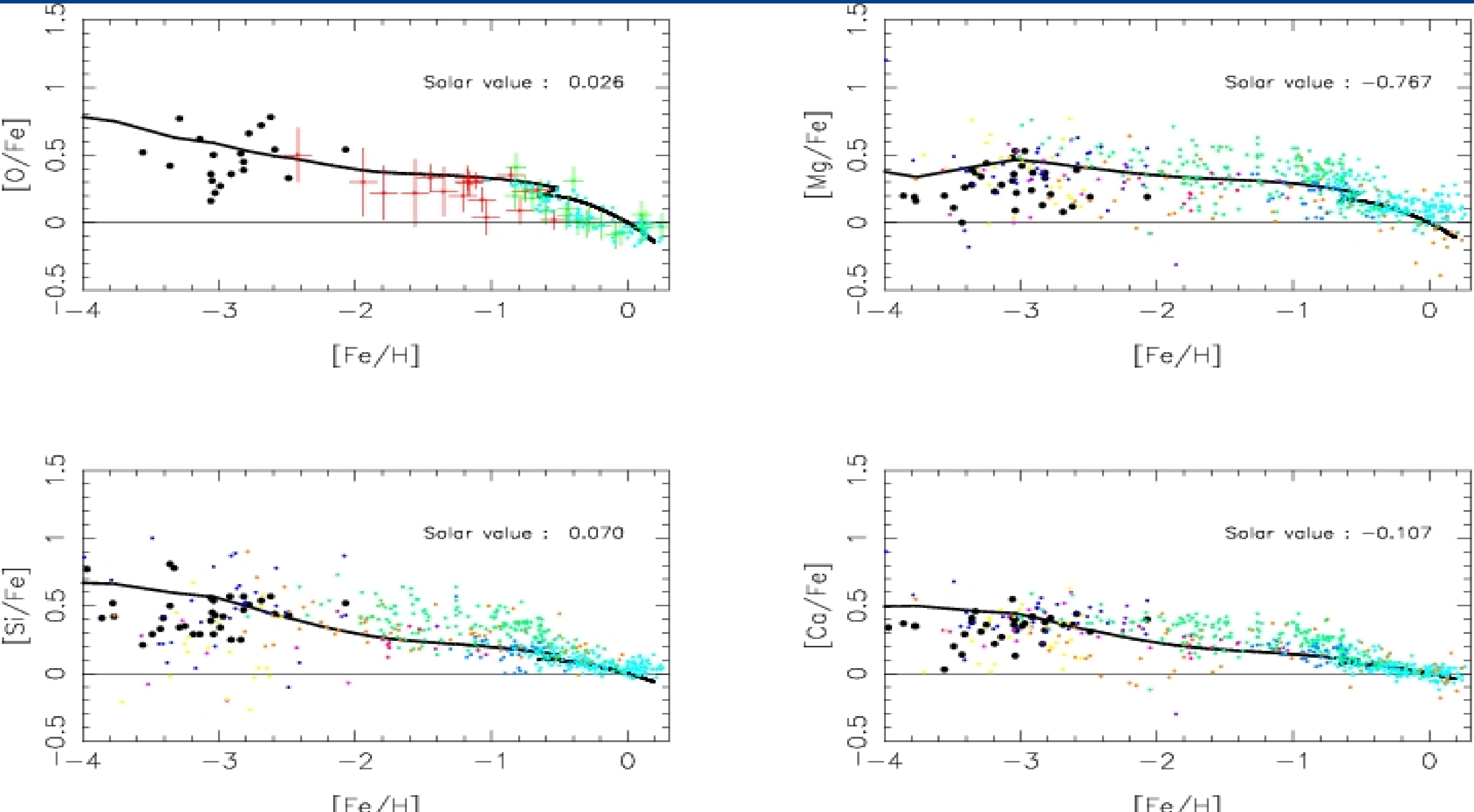
Chiappini et al. (2001)

➢ *Abundance gradients look OK (inhomogenous models)*



- *But: galactic elemental composition NOT consistently reproduced*

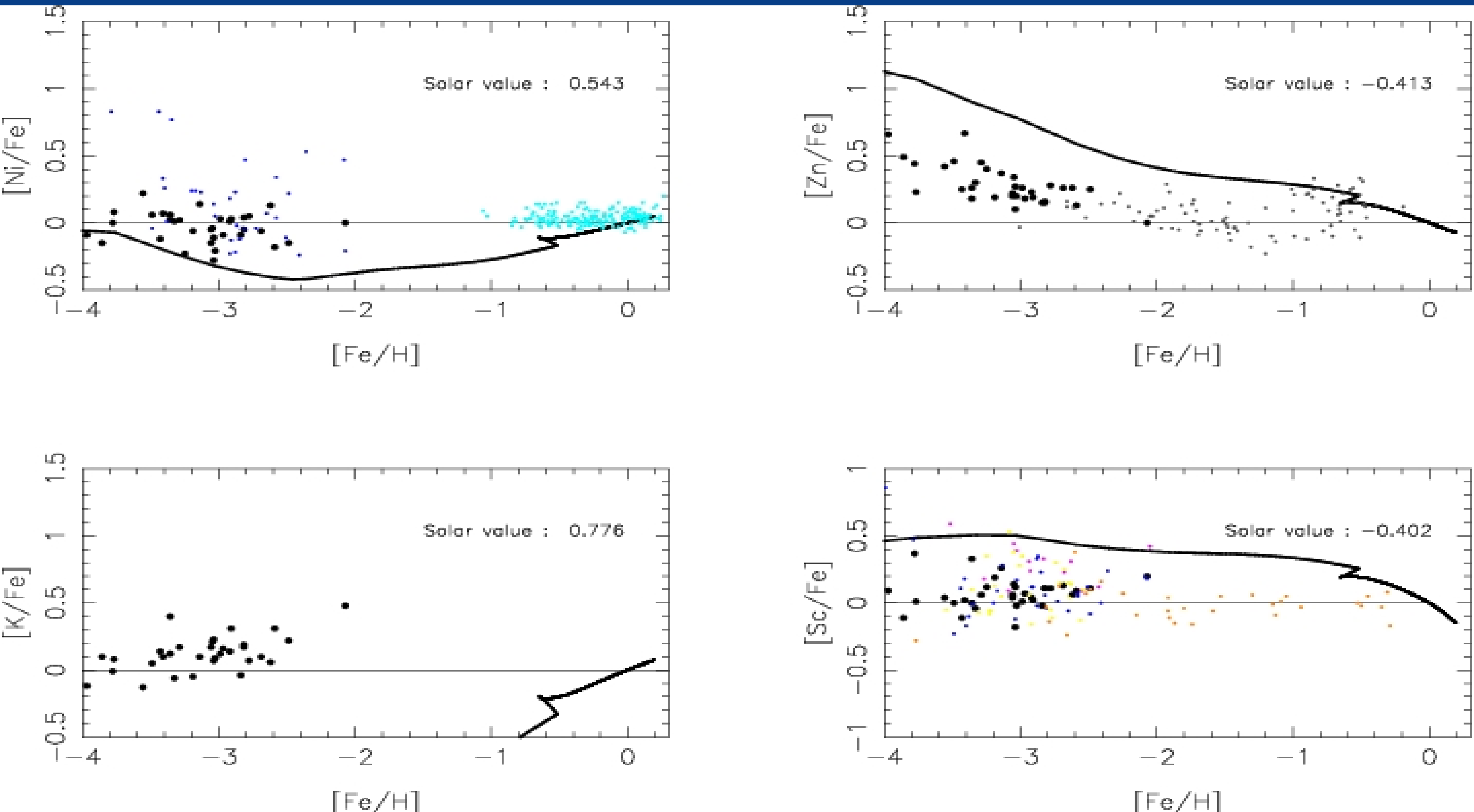
HOW THE MODEL PERFORM?



'Solar value': prediction at the time when the solar system formed

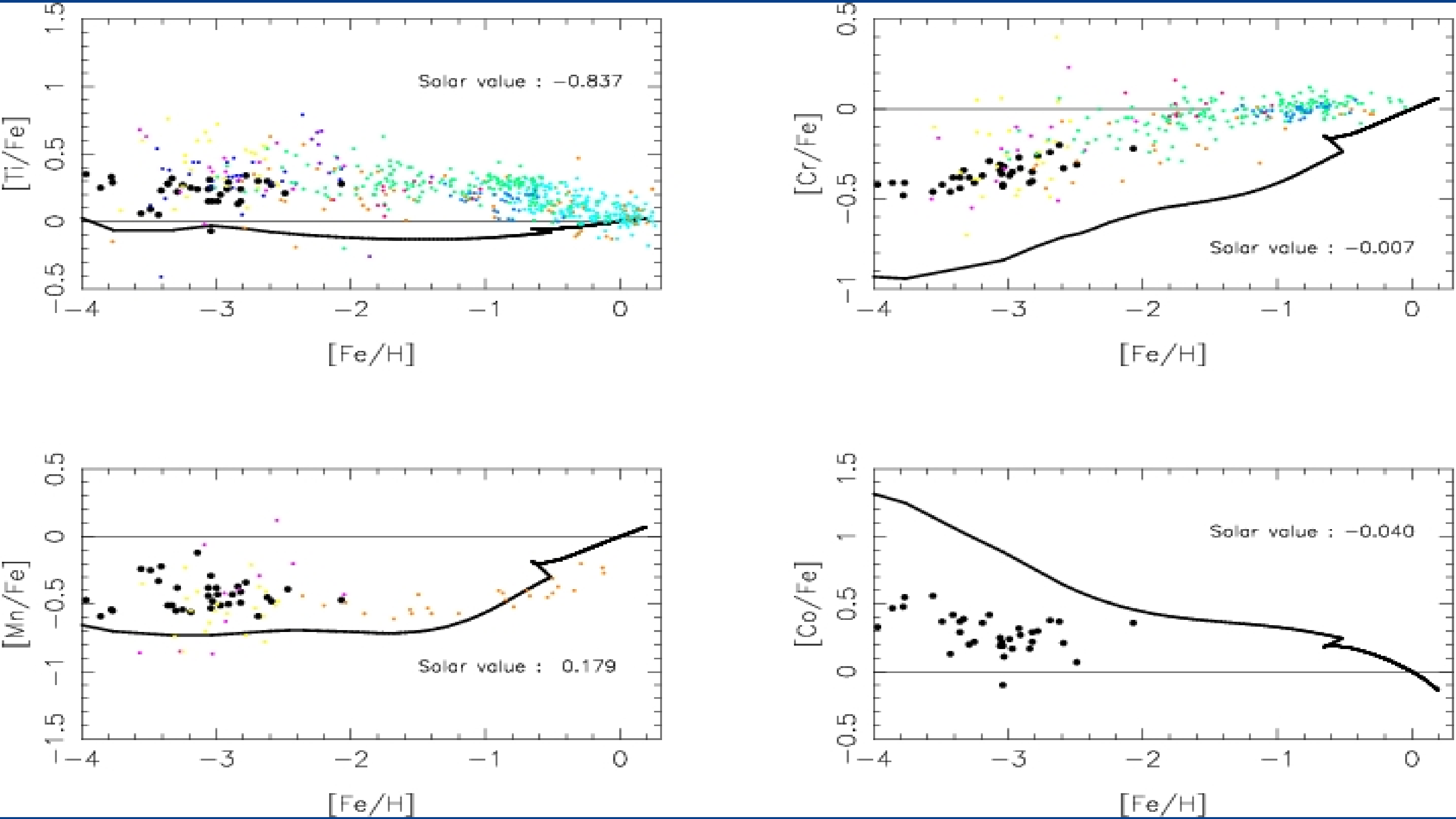
Francois et al. (2004)

HOW THE MODEL PERFORM?



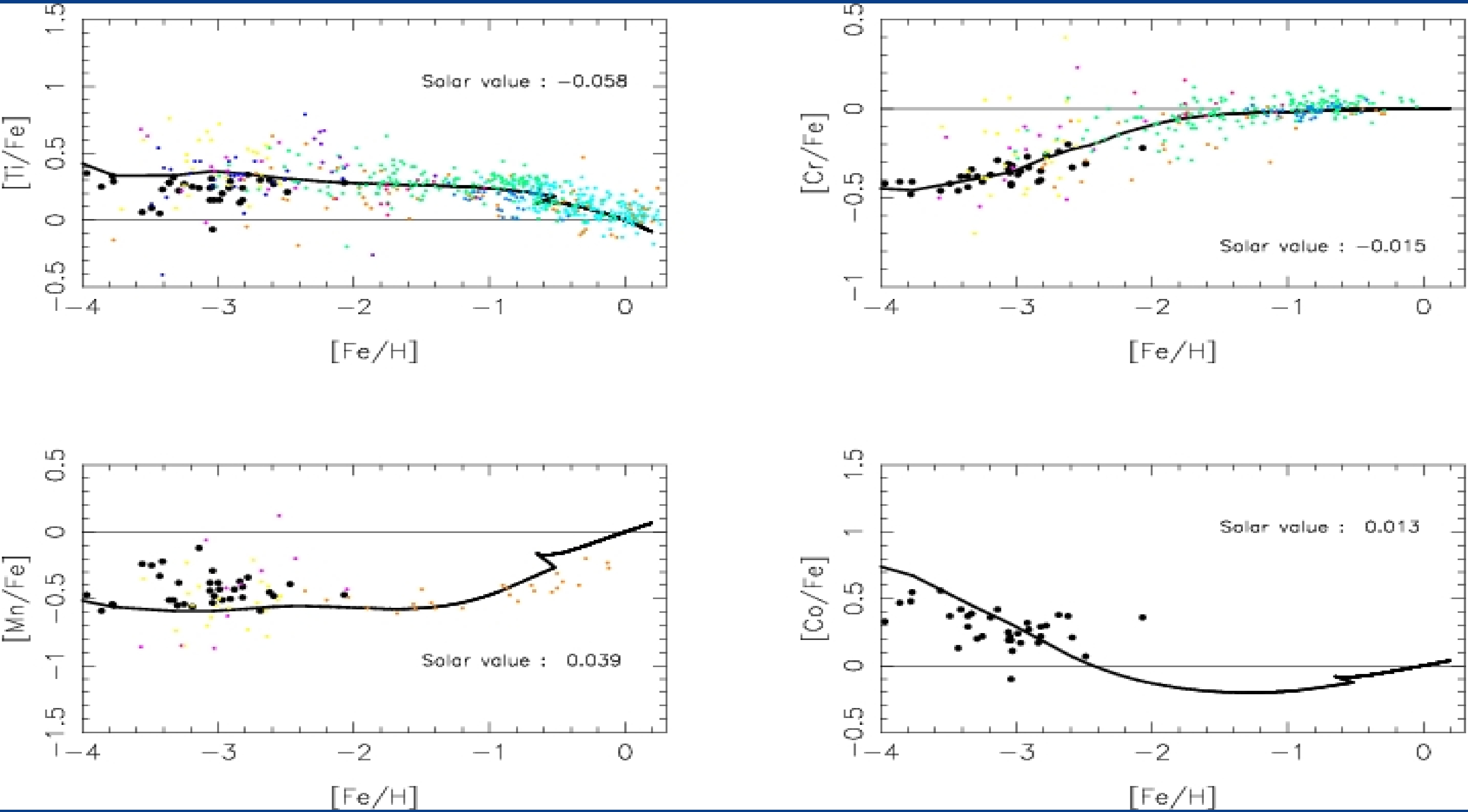
Francois et al. (2004)

HOW THE MODEL PERFORM?



Francois et al. (2004)

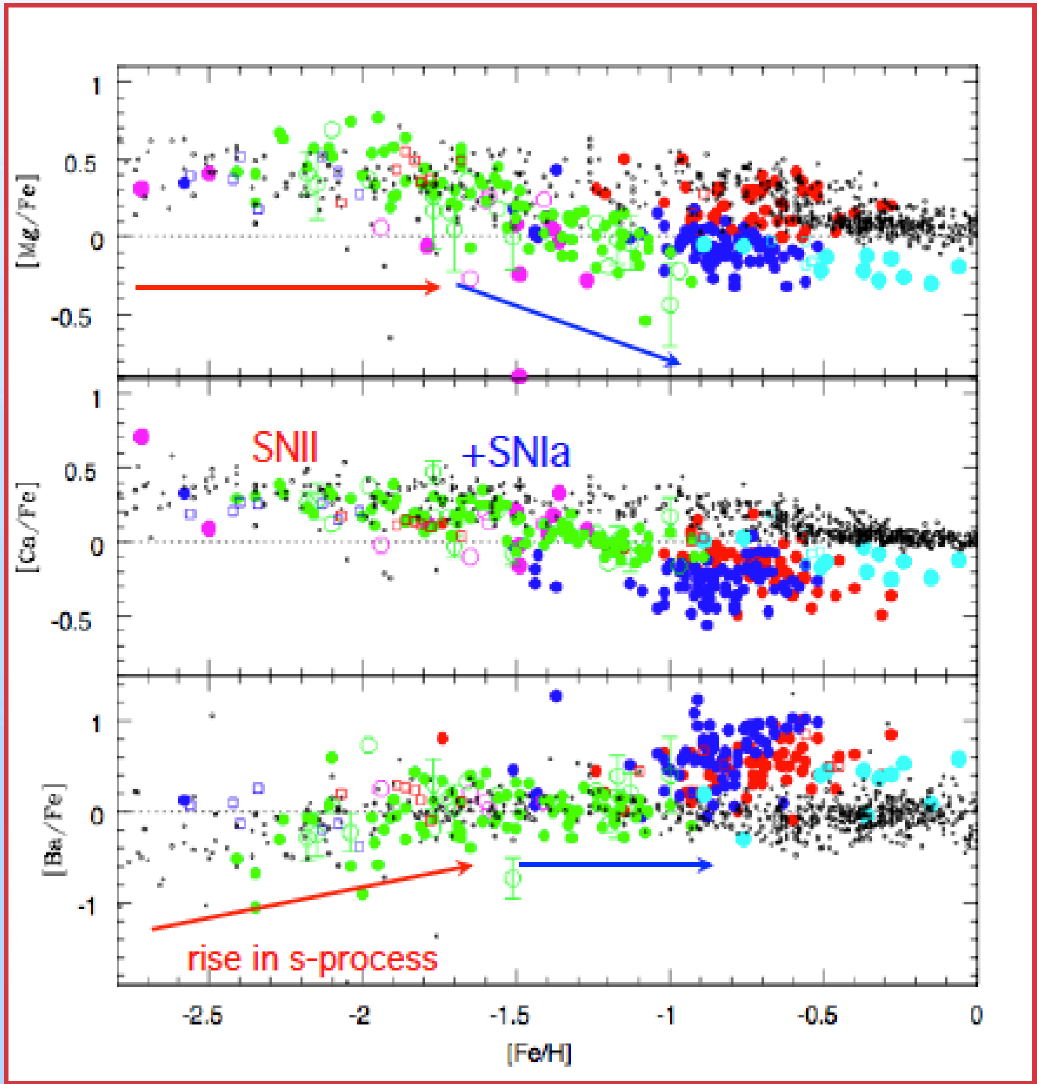
ARE THE STELLAR YIELDS WRONG (SN Ia)?



Francois et al. (2004)

OTHER GALAXIES: SN Ia VS. SN II

Large stellar samples in 5 different dSphs



Tolstoy, Hill, Tosi, 2009, ARAA

The position of the **knee** is present at lower metallicities >> slower evolution >> SNIa contribute at lower metallicities

s-process: very efficient in galaxies with strong SFR at younger ages (<5Gyrs): Fnx >> LMC >> Sgr >> Scl

LMC	Pompeia et al. 2008
Sgr	Sbordone et al. 2007
Fornax	Letarte et al 2007 (PhD)
Sculptor	Tolstoy et al. 2009 + Geisler et al. 2005
Carina	Koch et al. 2008 + Shetrone et al. 2003
MW	Venn et al. 2004

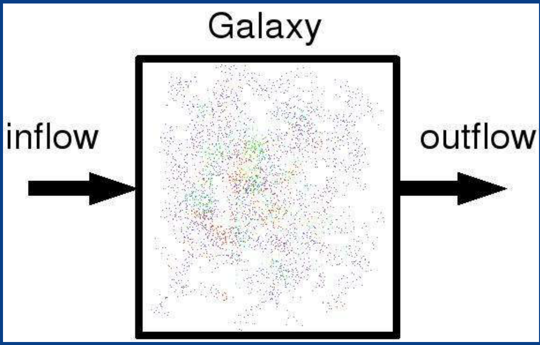
SUMMARY – PART 2

- **GCE models are able to reproduce the evolution of many GCE parameters in the Milky Way and other galaxies, such as abundance patterns (as well as starformation rates and stellar populations) reasonably well.**

- **But, despite of rather many (free) parameters, there are several problems still (N, Co, ...):**
  Limited data sets? Stellar astrophysics? Cosmological model (initial data, ...)?

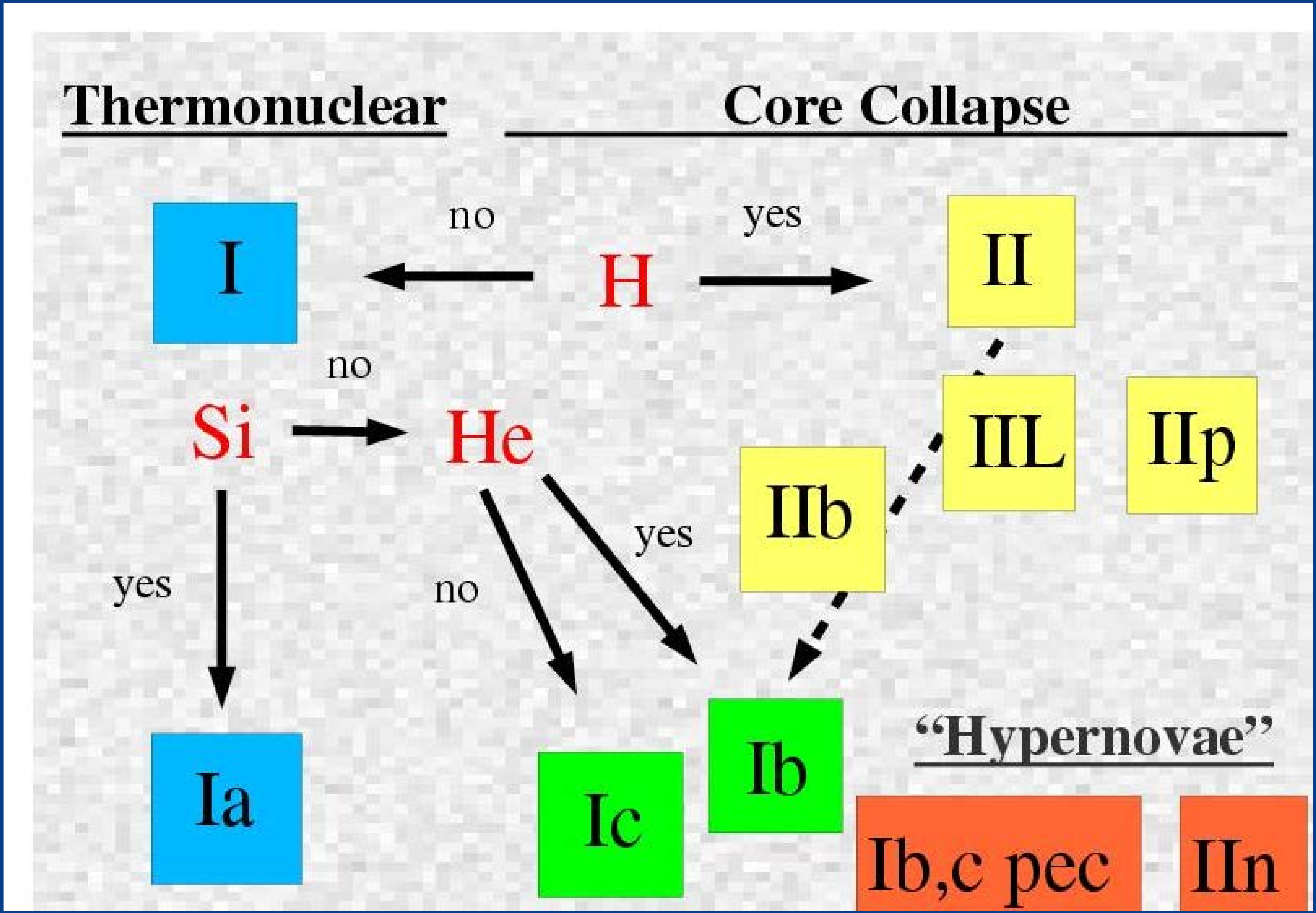
- **Goal: models with more \`predictive power':**
  Chemo-dynamical models.

CHEMO-DYNAMICAL MODELS

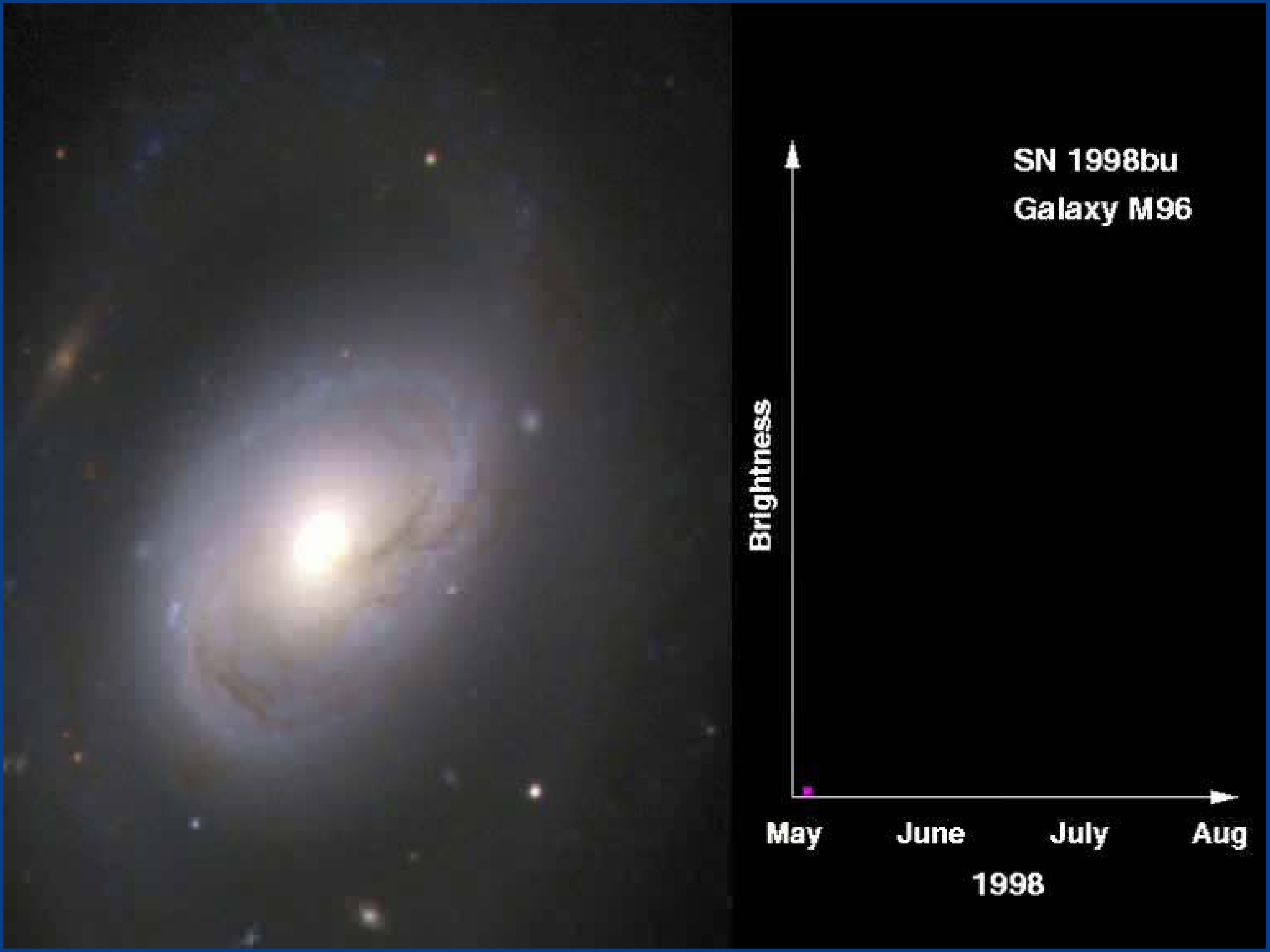


- Simulate the dynamical & chemical evolution of a galaxy selfconsistently, tracing a limited number of species.
- Initial conditions:
  – parametrisation of an early state of the galaxy (from a cosmological simulation of the evolution of largescale structure starting at high redshift).
- Comparison with observations by determination of
  – the morphological and kinematic structure
  – the starformation rate and the rates for PN, SN
  – the distribution of elements over the galaxy
  – the stellar populations (==> synthetic spectra)

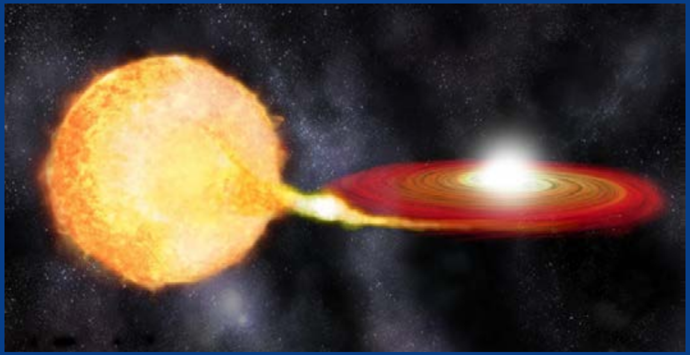
3. TYPE Ia SUPERNOVAE



3. TYPE Ia SUPERNOVAE



THE ‘ZOO’ OF (POSSIBLE) THERMONUCLEAR EXPLOSIONS

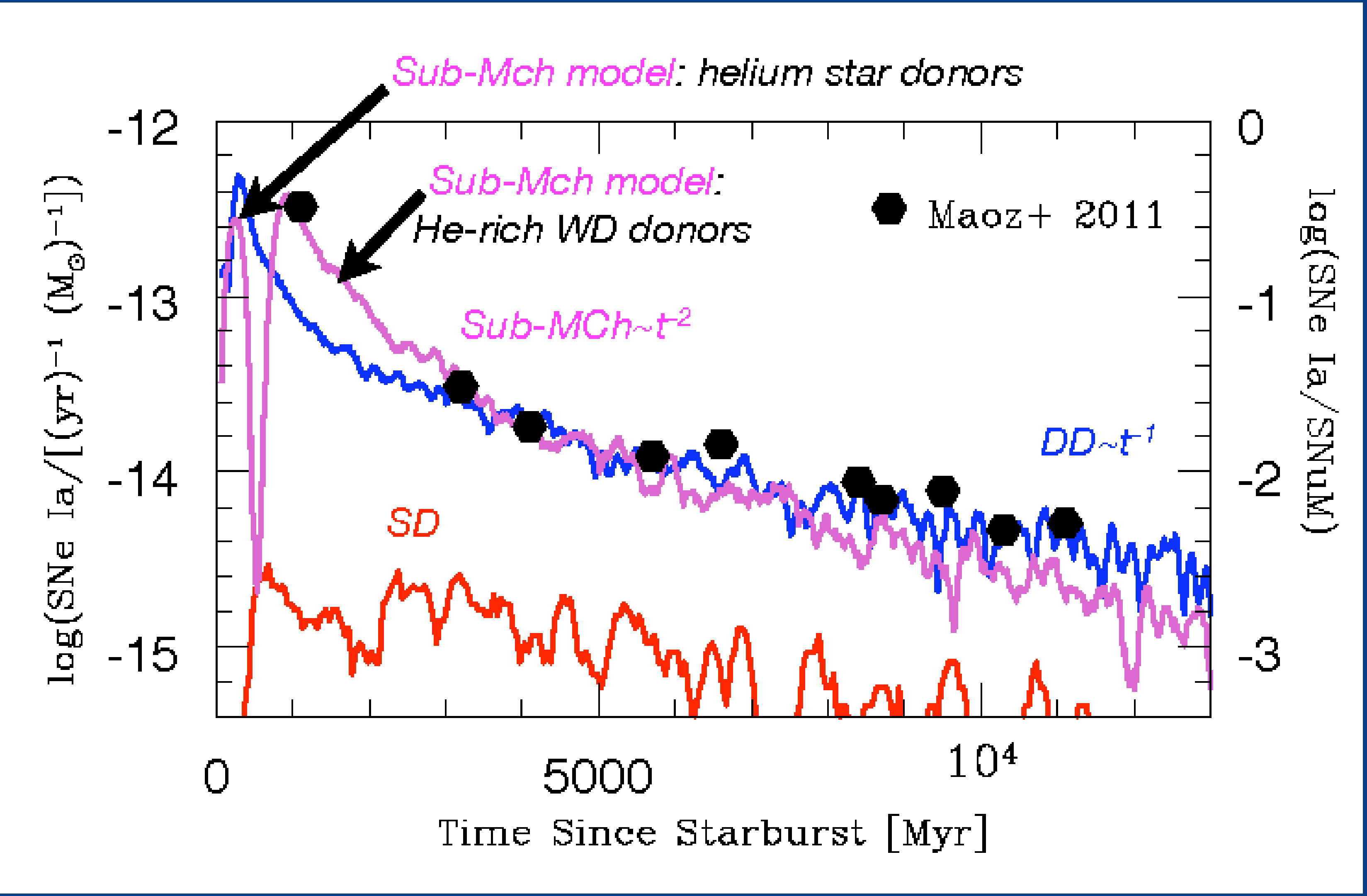


- *‘Single degenerates’*
  - Chandrasekhar mass
    - Pure deflagration
    - ‘delayed’ detonation
  - sub-Chandrasekhar mass

- *‘Double degenerates’*
  - C/O + C/O
  - C/O + He

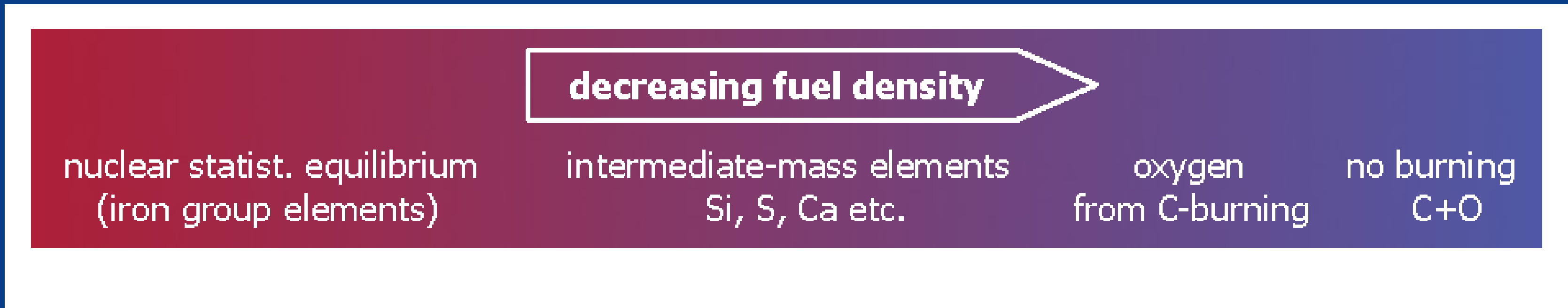
Which of them are realized in Nature? All of them?

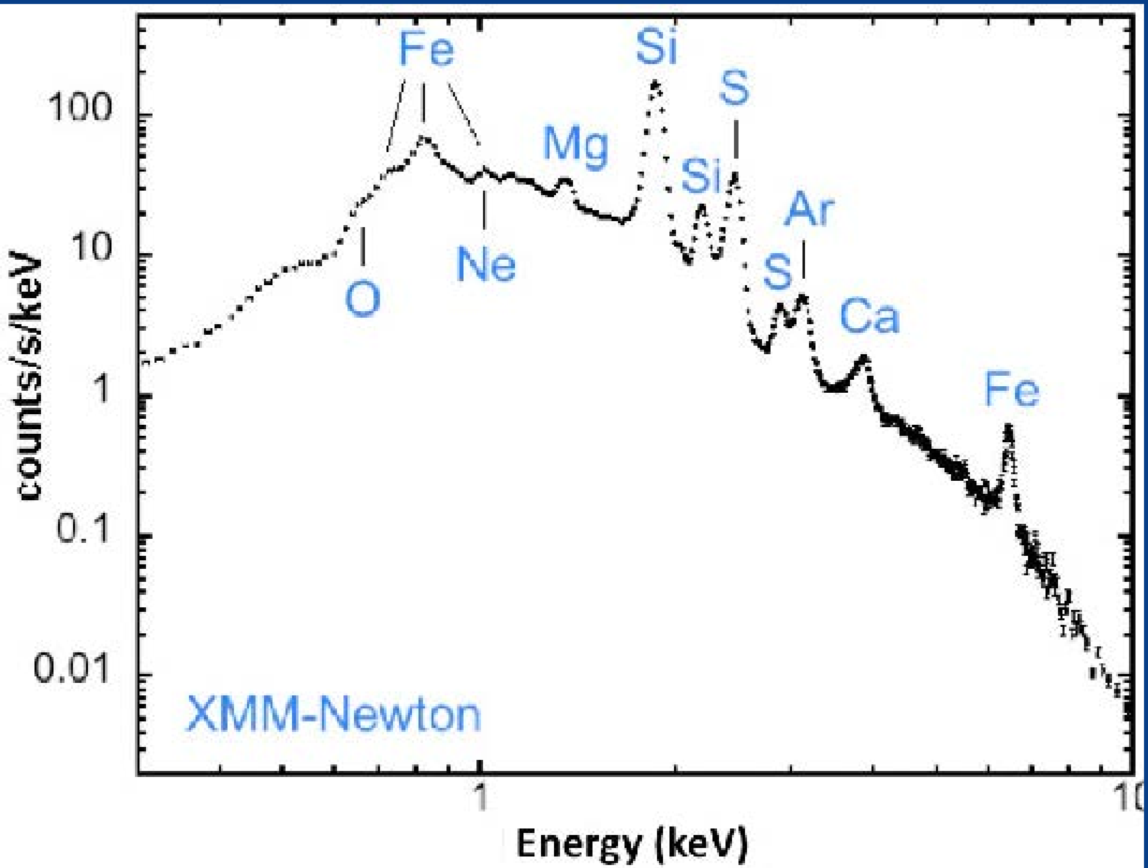
HOW MUCH DO DIFFERENT CHANNELS CONTRIBUTE TO THE RATE?



Ruiter et al. (2011)

NUCLEOSYNTHESIS IN SN Ia

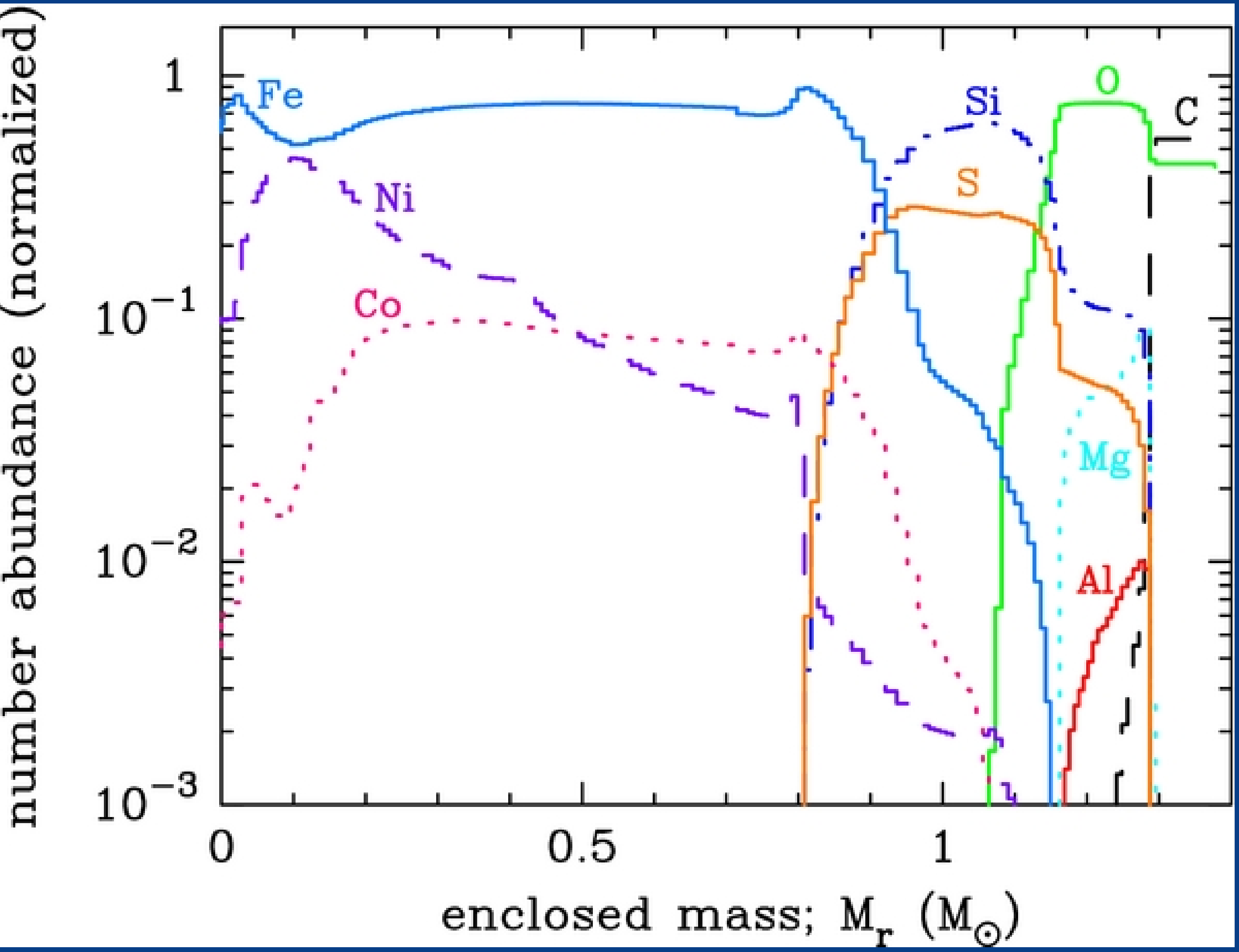




Tycho's supernova
(SN 1572)
X-ray spectrum
(Badenes et al. 2006):
M(Fe) ≈ 0.74M$_{\odot}$

"W7" - AN EXAMPLE ....

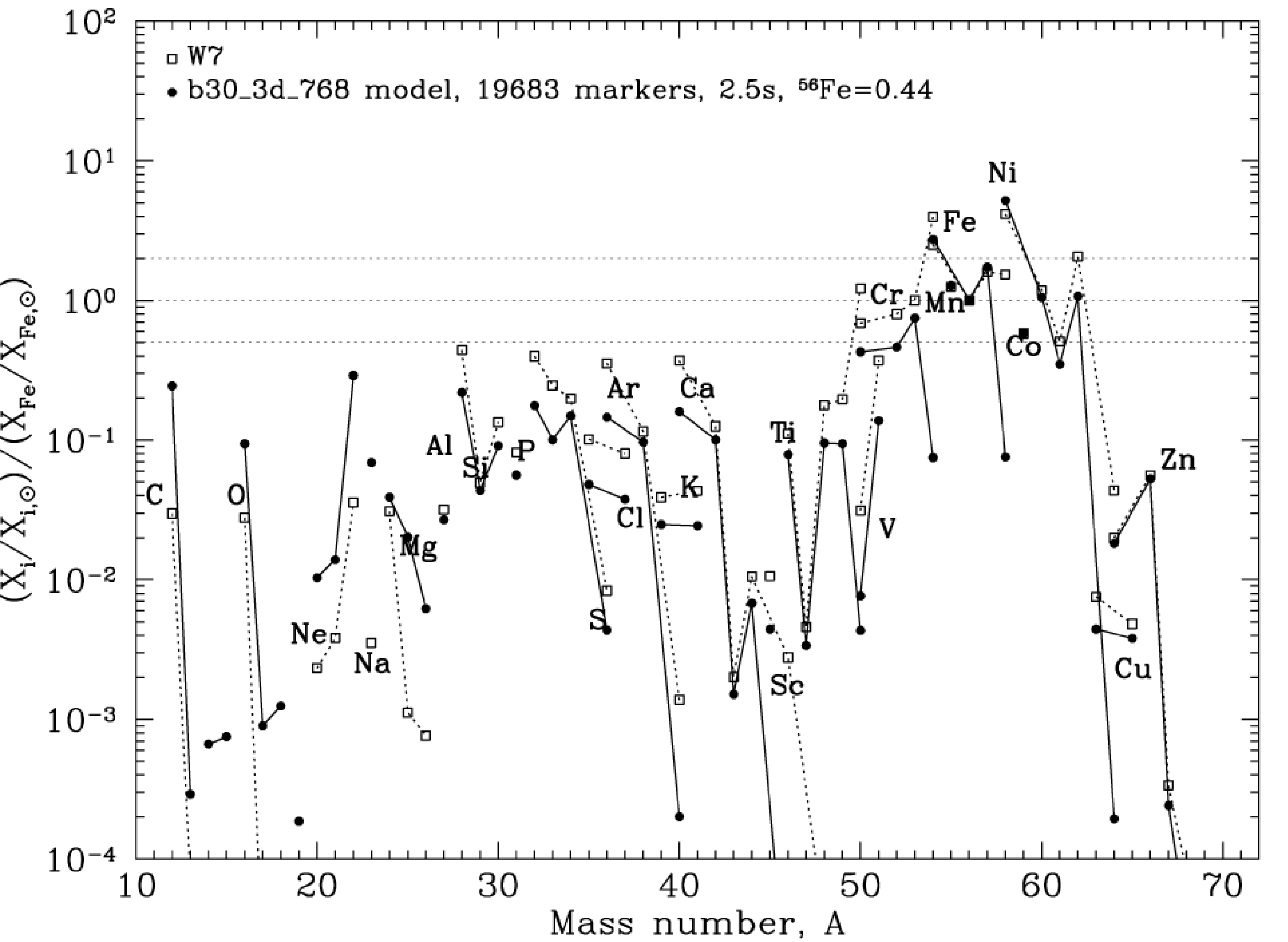
(Single-denerate M_{Chan} with parametrized burning speed)



Iwamoto et al. (1999)

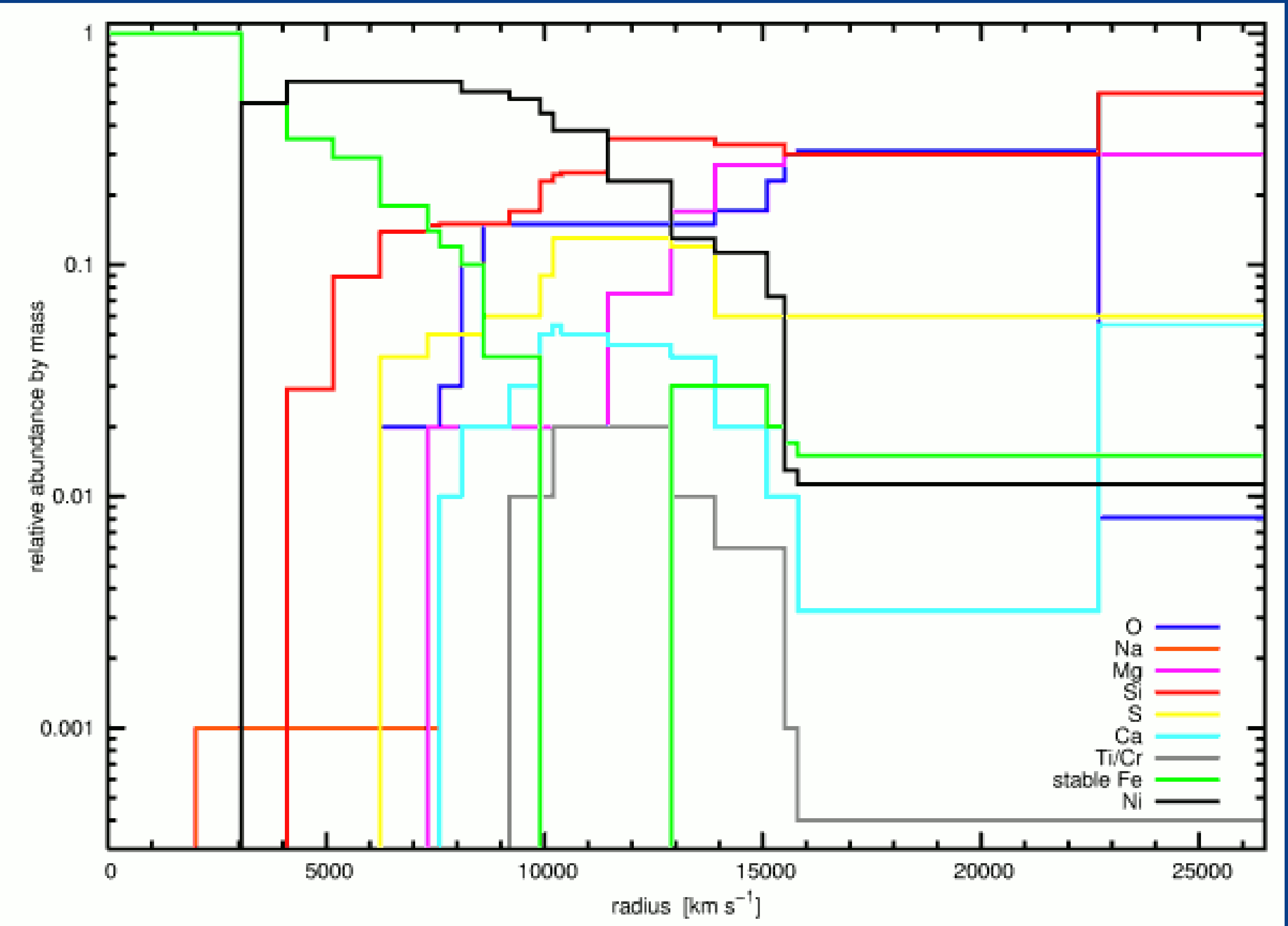
…. OR A "PURE-DEFLAGRATION" MODEL

$^{56}Ni_{b30} = 0.44 M_\odot$ $^{56}Ni_{W7} = 0.63 M_\odot$



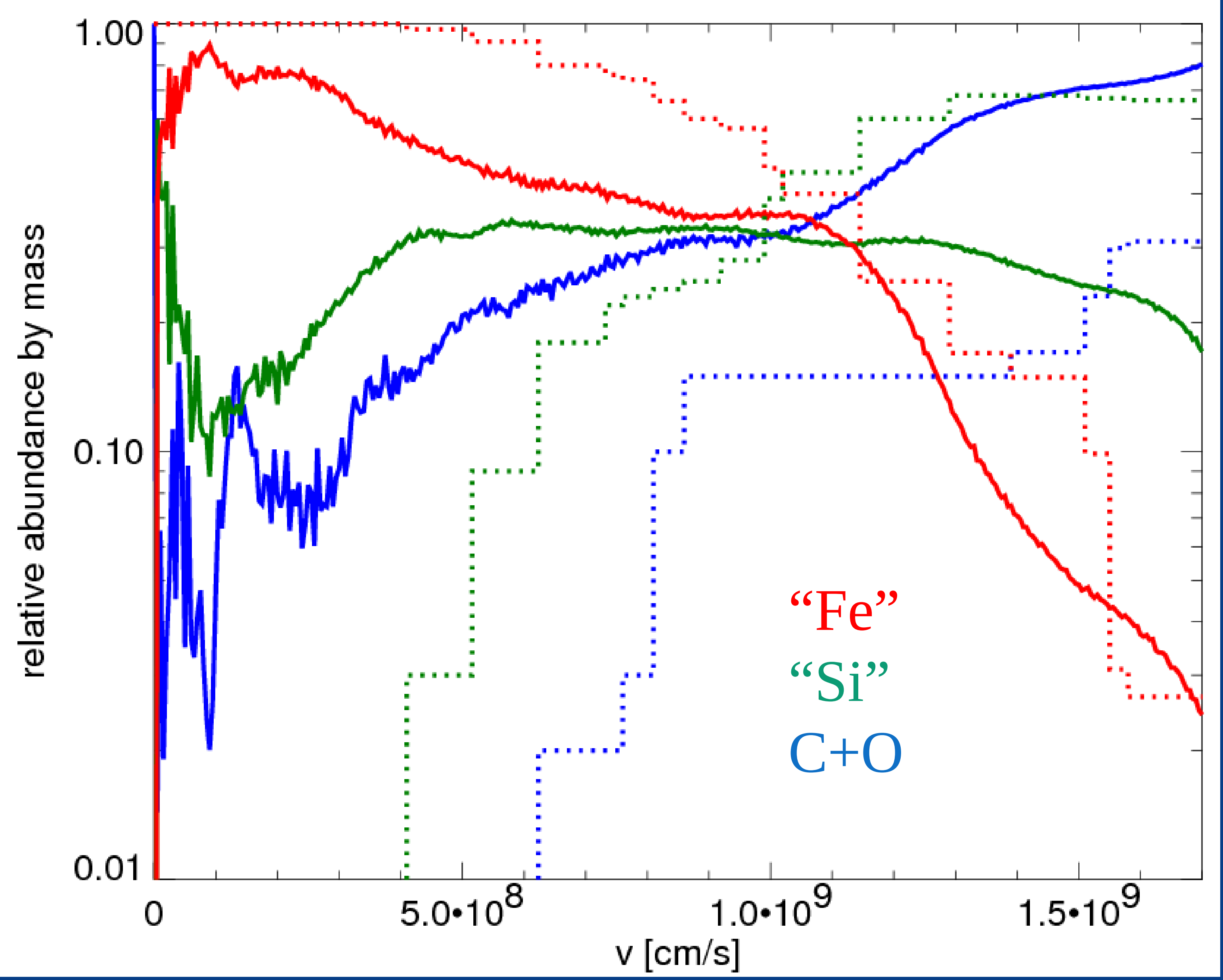
Travaglio et al. (2004)

"ABUNDANCE TOMOGRAPHY" – RECONSTRUCTED ABUNDANCES



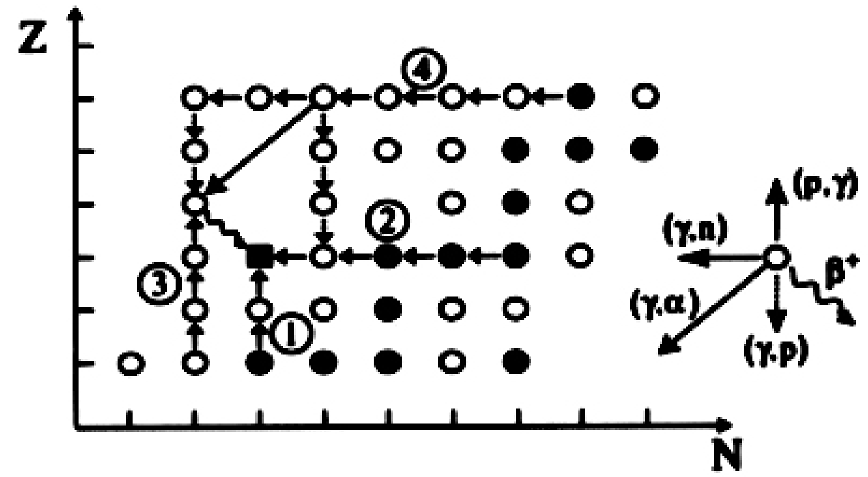
SN 2002bo (Stehle et al., 2005)

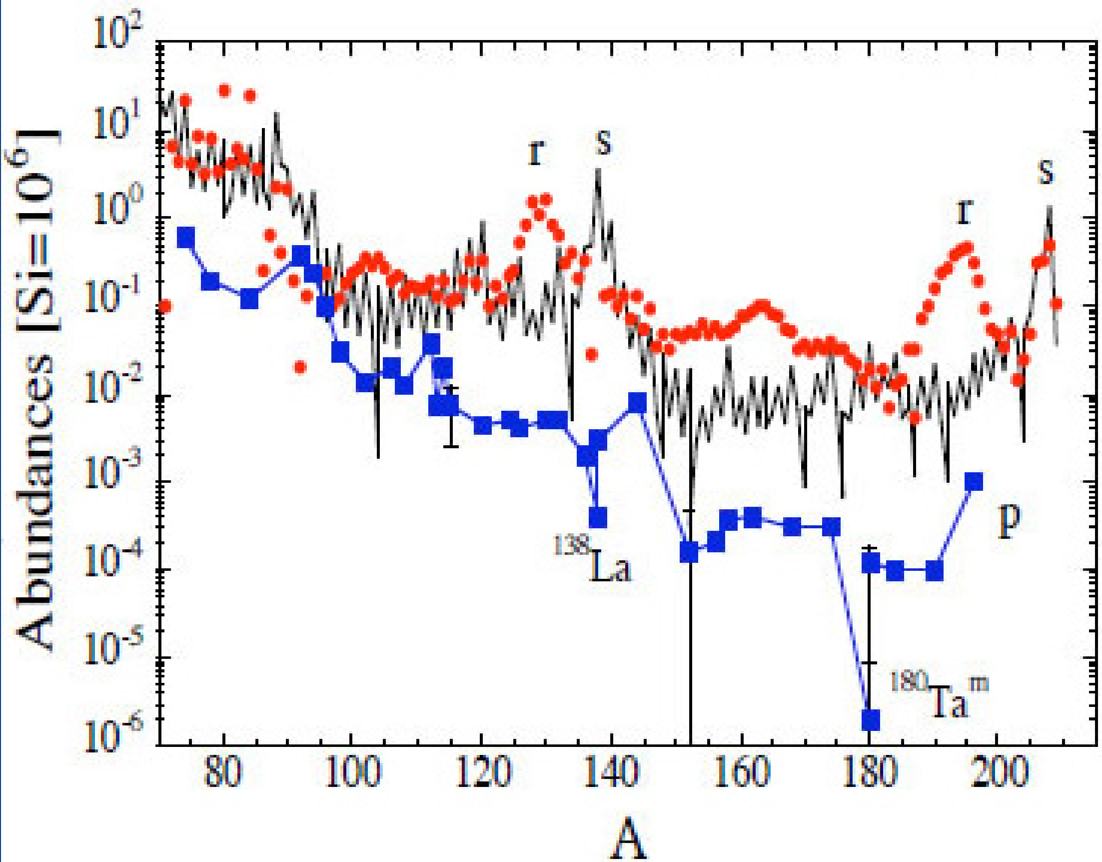
THEORY VS. OBSEVATIONS



SN 2002bo; model: Röpke et al. (2007)

P-PROCESS AND SNe Ia

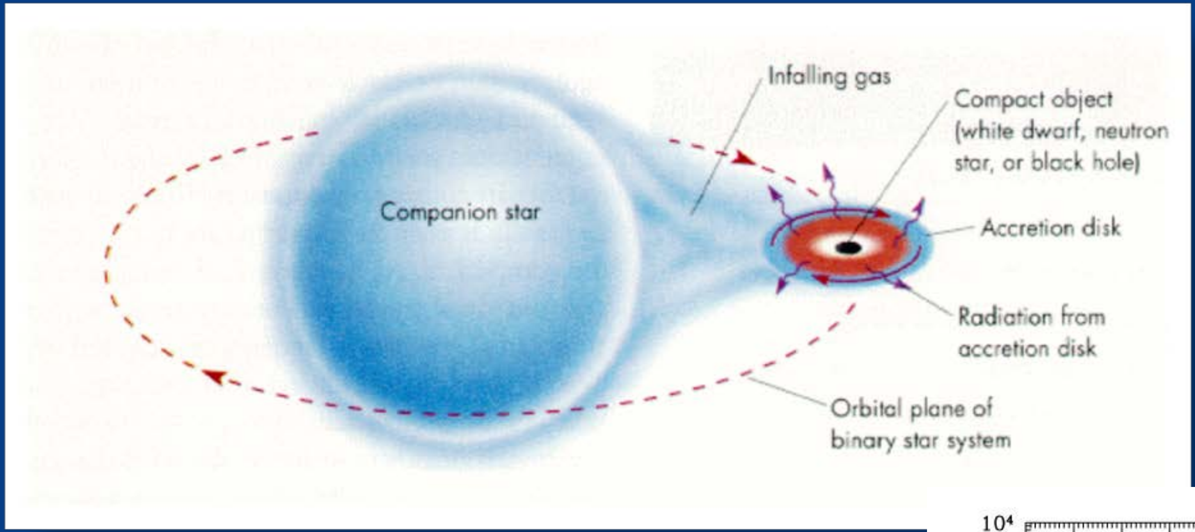




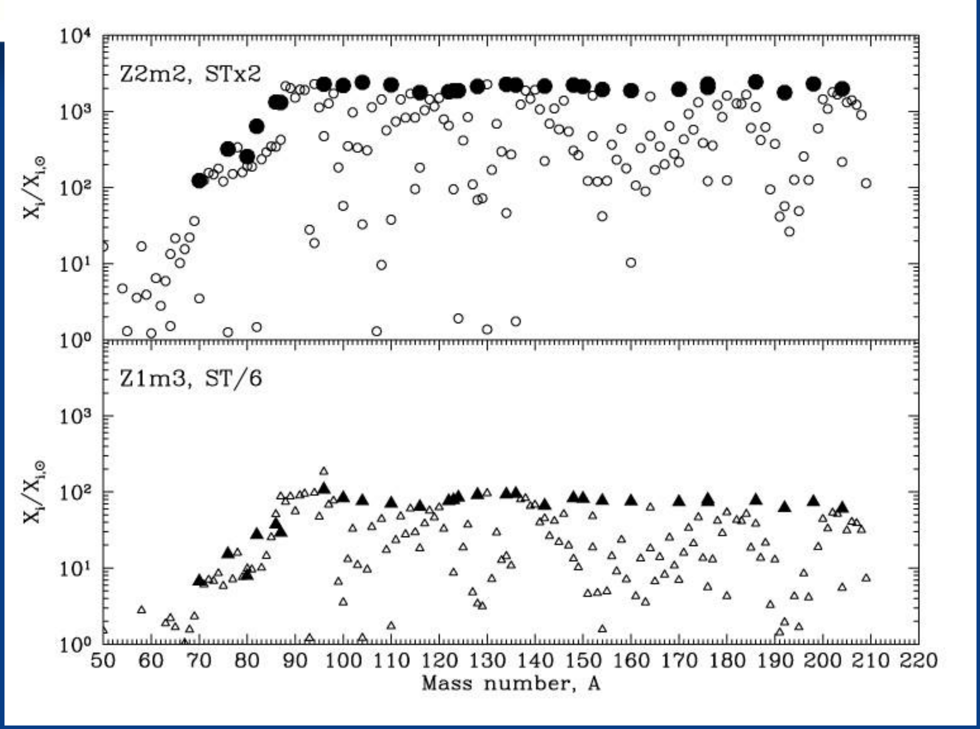
35 p-process isotopes in the solar system:

photo-dissociation of pre-existing s-process seed?

P-PROCESS AND SNe Ia

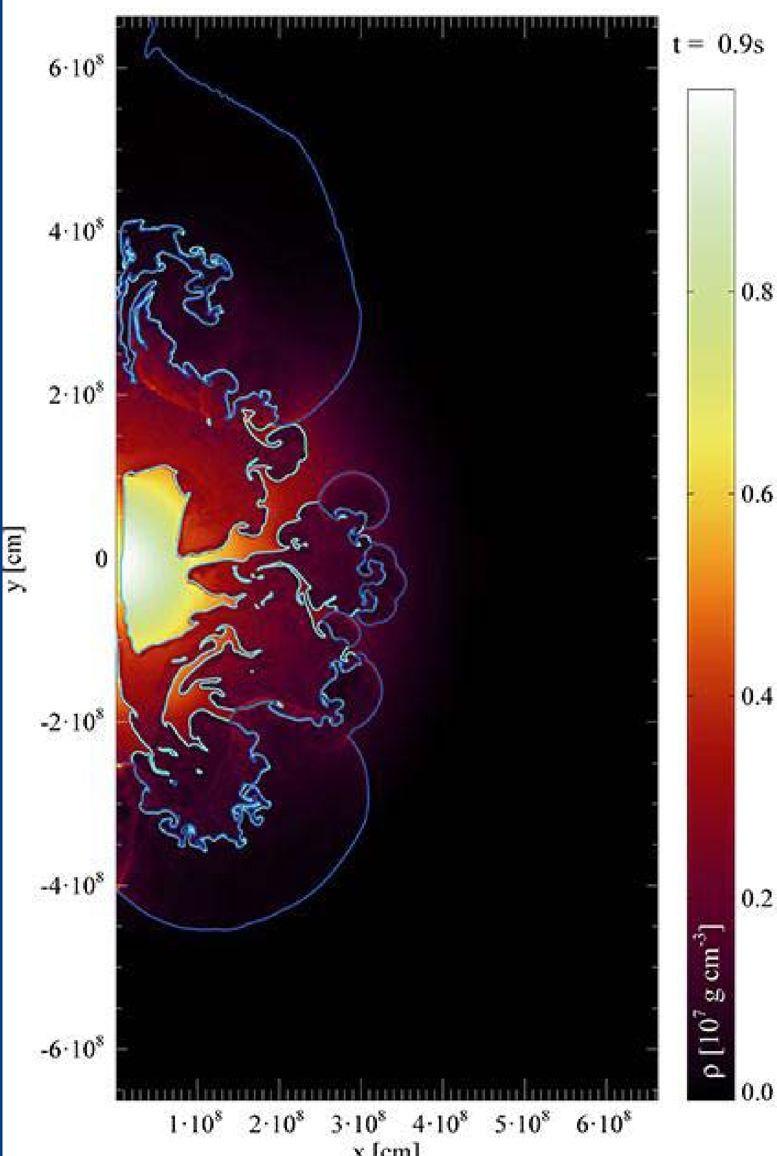


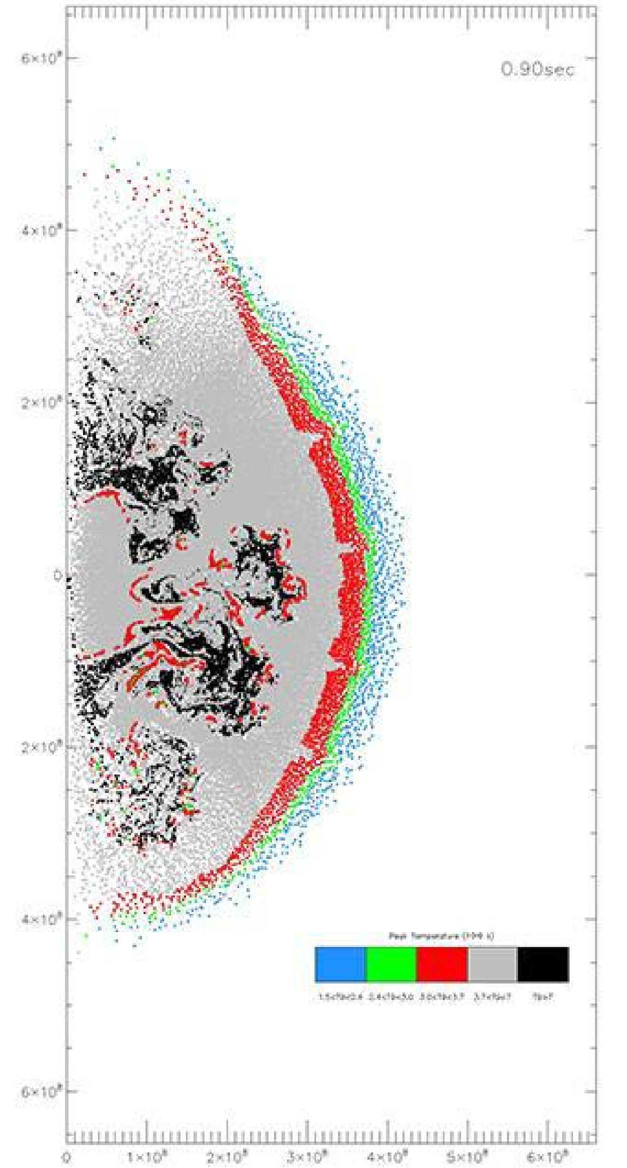
s-process seed



May work for the single-degenerate scenario
(Travaglio et al. 2011, 2013)

P-PROCESS AND SNe Ia





black: > 7.0 10^9 K

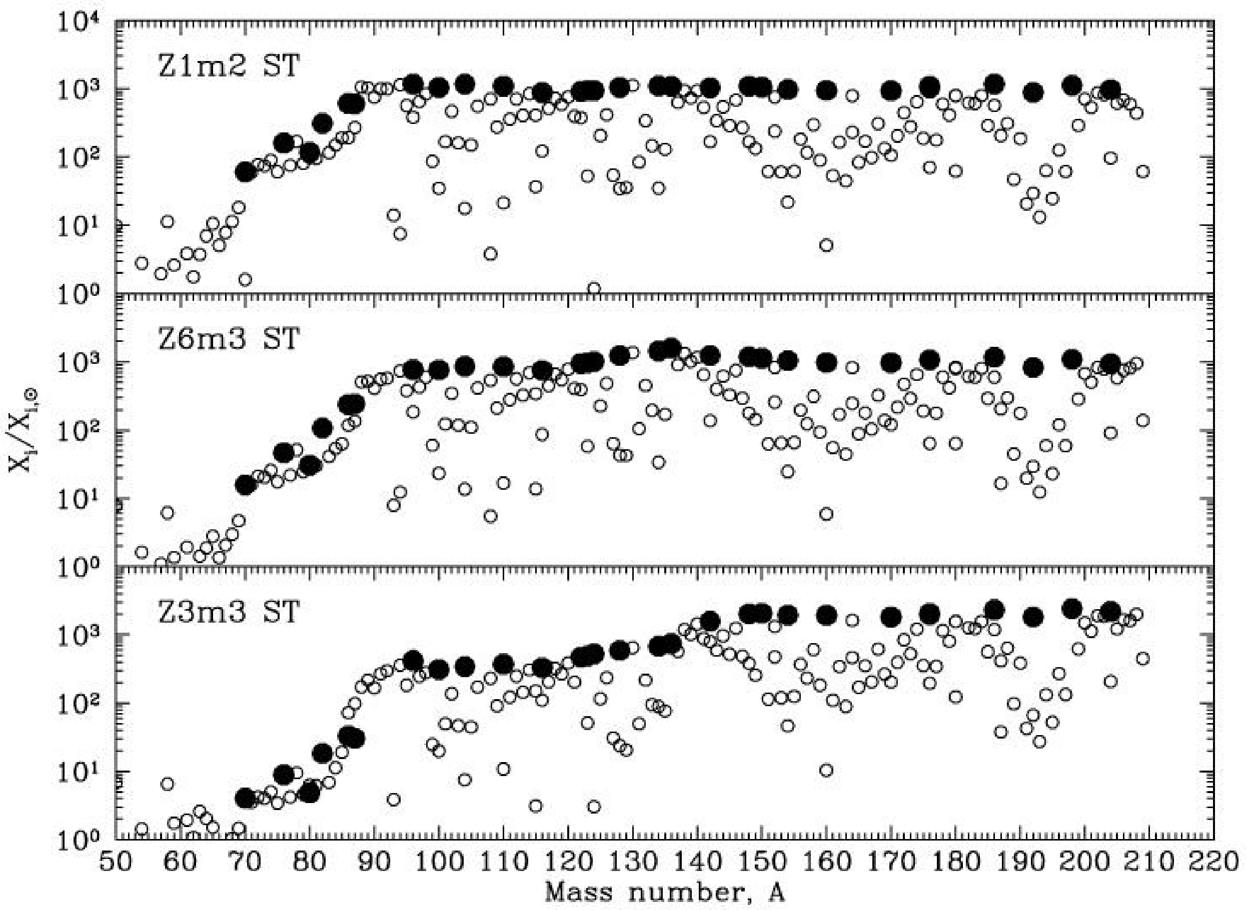
grey: $3.7<T_9<7.0$

red: $3.0<T_9<3.7$

green: $2.4<T_9<3.0$

blue: $1.5<T_9<2.4$

P-PROCESS IN SNe Ia and Chemical Evolution



<u>*s-process seed*</u>

(black dots: s-only isotopes)

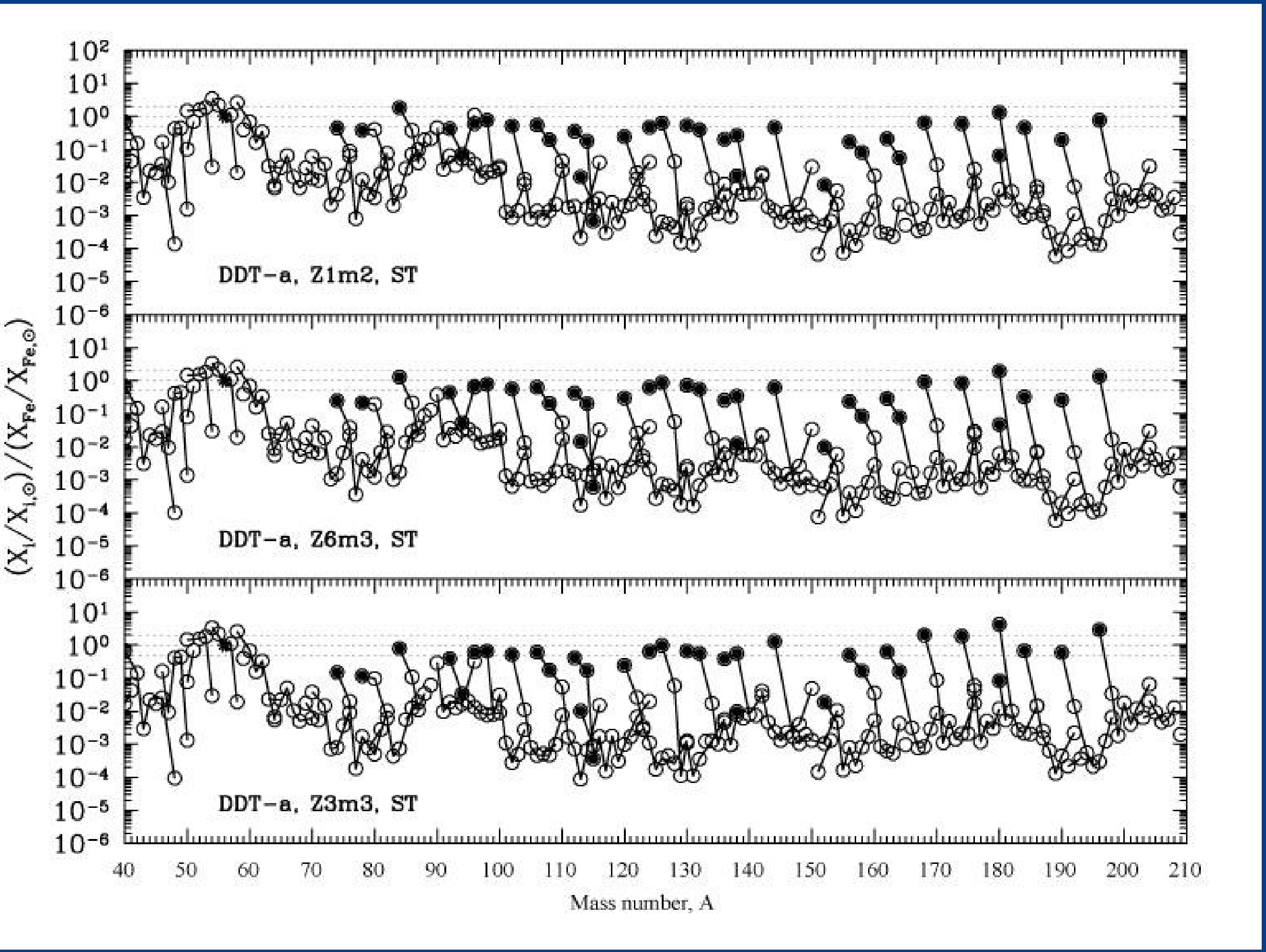
Z = 0.01

Z = 0.006

Z = 0.003

Travaglio et al. (2013)

P-PROCESS IN SNe Ia and Chemical Evolution



p-process abundances

(2D DDT model, black dots: p-only)

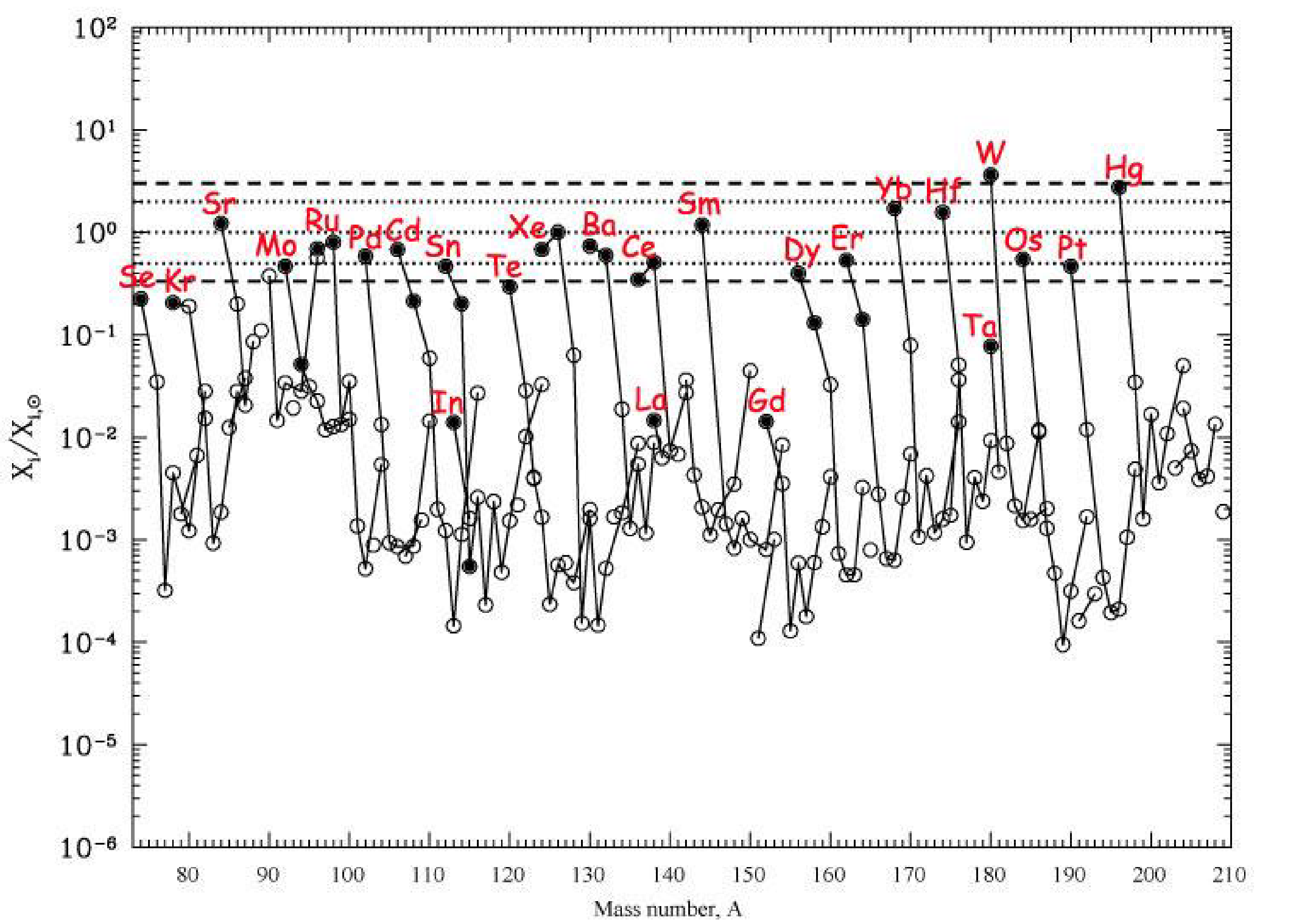
Z = 0.01

Z = 0.006

Z = 0.003

Travaglio et al. (2013)

P-PROCESS IN SNe Ia and Chemical Evolution



[Predicted solar system p-process abundances]

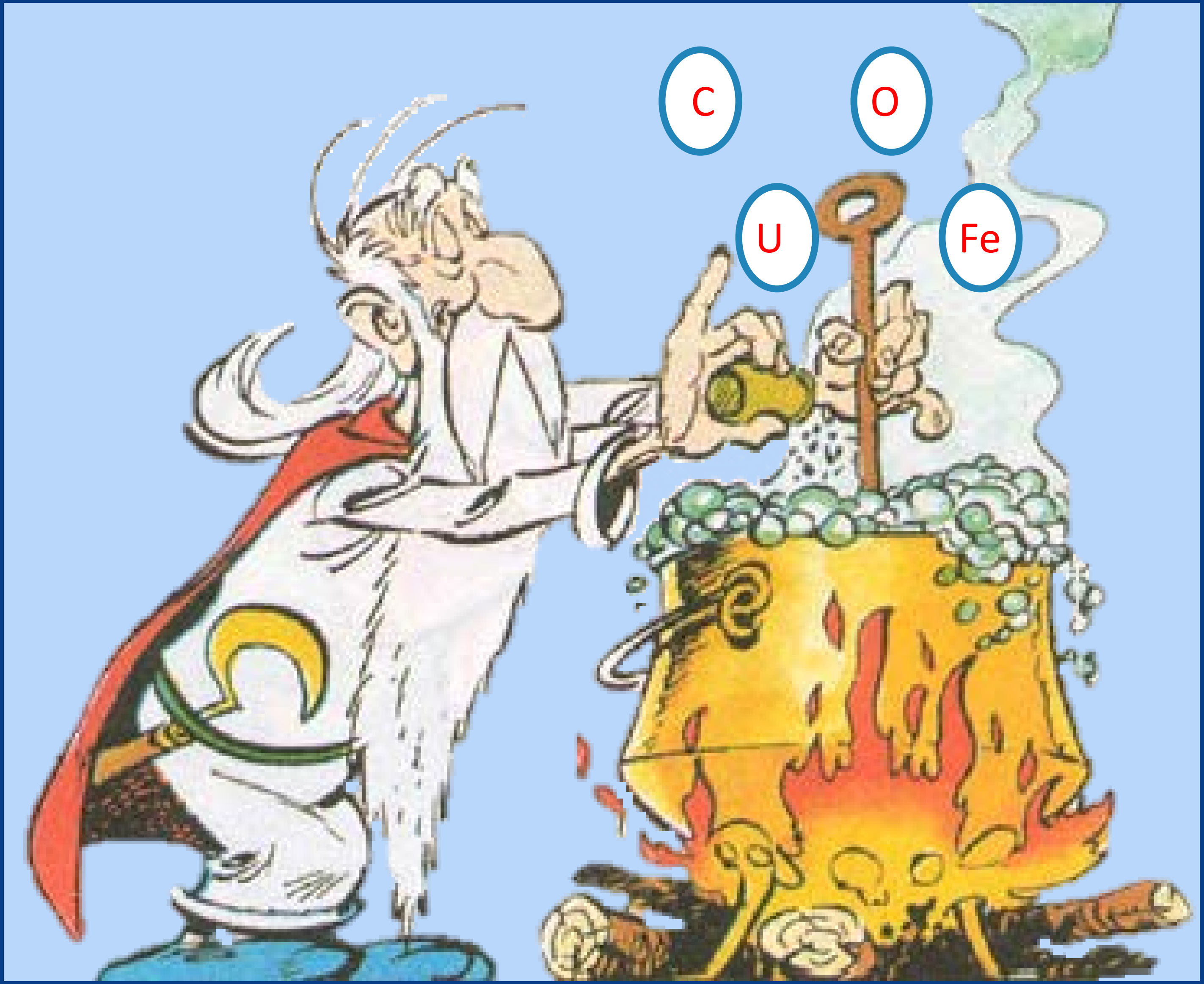
(simple model)

Travaglio et al. (2013)

SUMMARY – PART 3

- **SN Ia synthesize significant amounts of heavy elements (^{56}Fe, ^{48}Ca, p-process, ...):**
  Confirmed by, both, models and observations.
  Thus the yields of SNe Ia are fairly well known.

- **However, it is not yet clear which progenitor chanel contributes how much to chemical evolution but this is an important question not only because iron is often used as a proxy to measure time.**



Thank you for your attention !

LITERATURE

Narayan C. Rana, Chemical Evolution of the Galaxy, Annual Review of Astronomy and Astrophysics, **29** (1991) 129-162

Francesca Matteucci, The Chemical Evolution of the Galaxy, Kluwer, Astrophysics and Space Science Library (2003)

Francesca Matteucci, Chemical evolution of the Milky Way and its Satellites, 37th Saas-Fee Advanced Course, " The Origin of the Galaxy and the Local Group", eds. E. Grebel and B. Moore (2008)

Andrew McWilliam, Abundance Ratios and Galactic Chemical Evolution, Annual Review of Astronomy and Astrophysics, **35** (1997) 503-556

Nikos Prantzos, An Introduction to Galactic Chemical Evolution, "Stellar Nucleosynthesis: 50 years after B2FH", C. Charbonnel and J.P. Zahn (Eds.), EAS publications Series (2008)