# Recent developments on the chemical evolution of the Milky Way disks

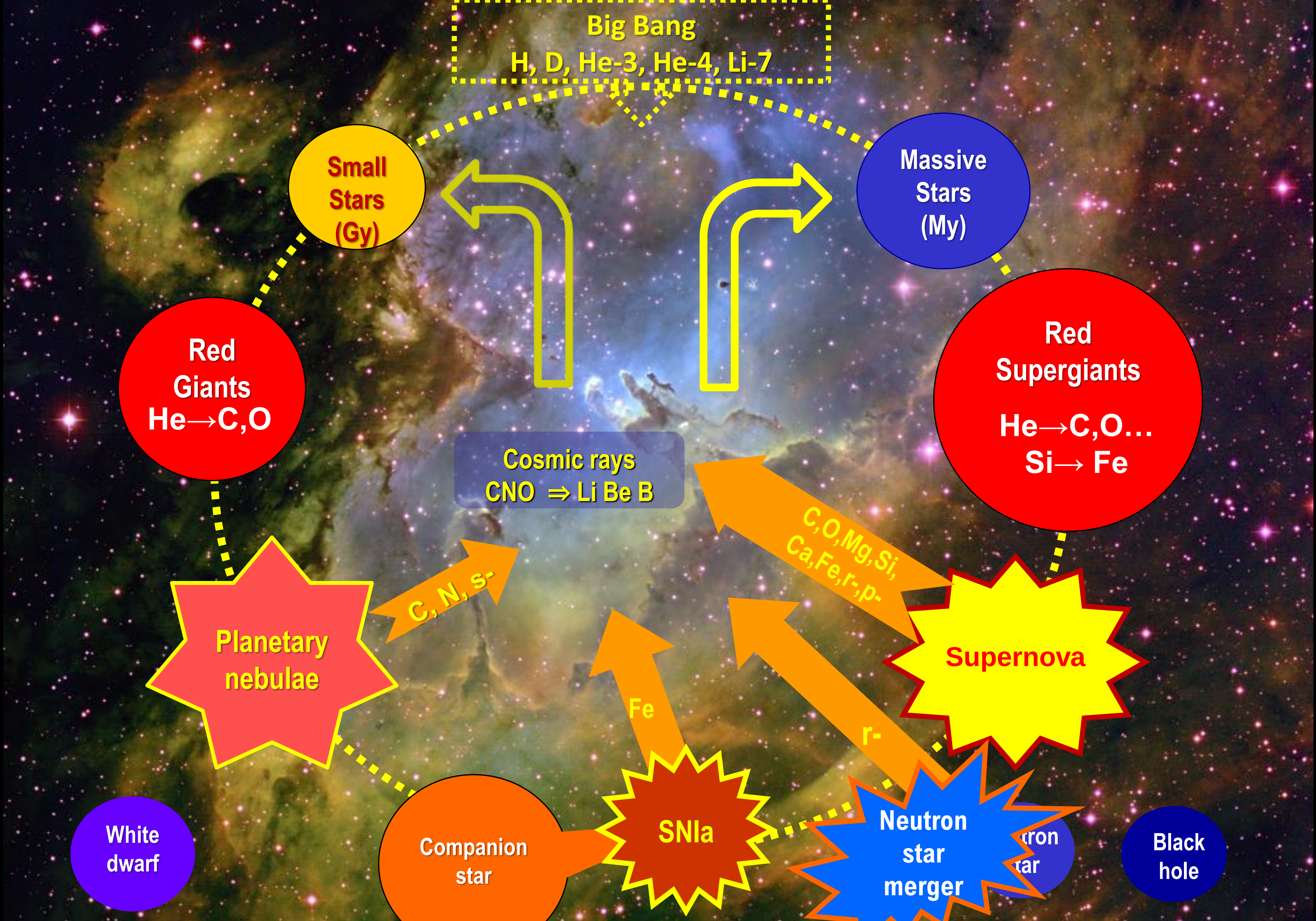
**Galactic chemical evolution with yields from rotating massive stars**
NP, C. Abia, M. Limongi, A. Chieffi, S. Cristallo 2018,2019

**Evolution of the Milky Way with radial motions of stars and gas**
M. Kubryk, NP, L. Athanassoula 2015a,b

# Stellar vs Galactic evolution

| | Star | Galaxy |
|---|---|---|
| Driver of evolution | Nuclear reaction rates<br>*f(T,ρ,X), Mostly measured, Well known* | Star Formation Rate<br>*SFR = f(Gas………)*<br>*Poorly known* |
| Main observational constraints | Hertszprung–Russel diagram<br>Well observed in detail<br>*Well understood* | Hubble diagram ,<br>Fundamental plane (?)<br>*Not yet understood* |
| Boundary conditions | Zero Age Main Sequence<br>*Formation / Environment unimportant (close binaries?)* | Cosmological fluctuation spectrum<br>*Formation / Environment important : gas/star accretion; galaxy interactions* |

**Galactic Chemical Evolution:**
**transformation of the chemical composition of gas and stars**
***Not (yet) a theory:***
**Rather a framework allowing us to interpret the vast amount of data of abundance patterns in stars, galaxies and the ISM**


Big Bang
H, D, He-3, He-4, Li-7
Small Stars (Gy)
Massive Stars (My)
Red Giants He→C,O
Red Supergiants
He→C,O…
Si→ Fe
Cosmic rays
CNO ⇒ Li Be B
C,O,Mg,Si,
Ca,Fe,r-,p-
C, N, s-
Planetary nebulae
Supernova
Fe
r-
SNIa
White dwarf
Companion star
Neutron star merger
Black hole

# Galactic Chemical Evolution (GCE)

## Main ingredients of Galactic Chemical Evolution models

***Stellar properties***

*(function of mass M and metallicity Z)*

- Lifetimes
- Yields (quantities of elements ejected)
- Masses of residues (WD, NS, BH)
- Rates of binary collisions

*From theory of Stellar evolution and nucleosynthesis*

*Scale: STARS ($10^6$ km)*

***Collective Stellar Properties***

- Star Formation Rate (SFR)
- Initial Mass Function (IMF)

*Observations Phenomenological recipes + Theoretical arguments*

*Scale: STAR FORMING REGIONS (10s-100s pc)*

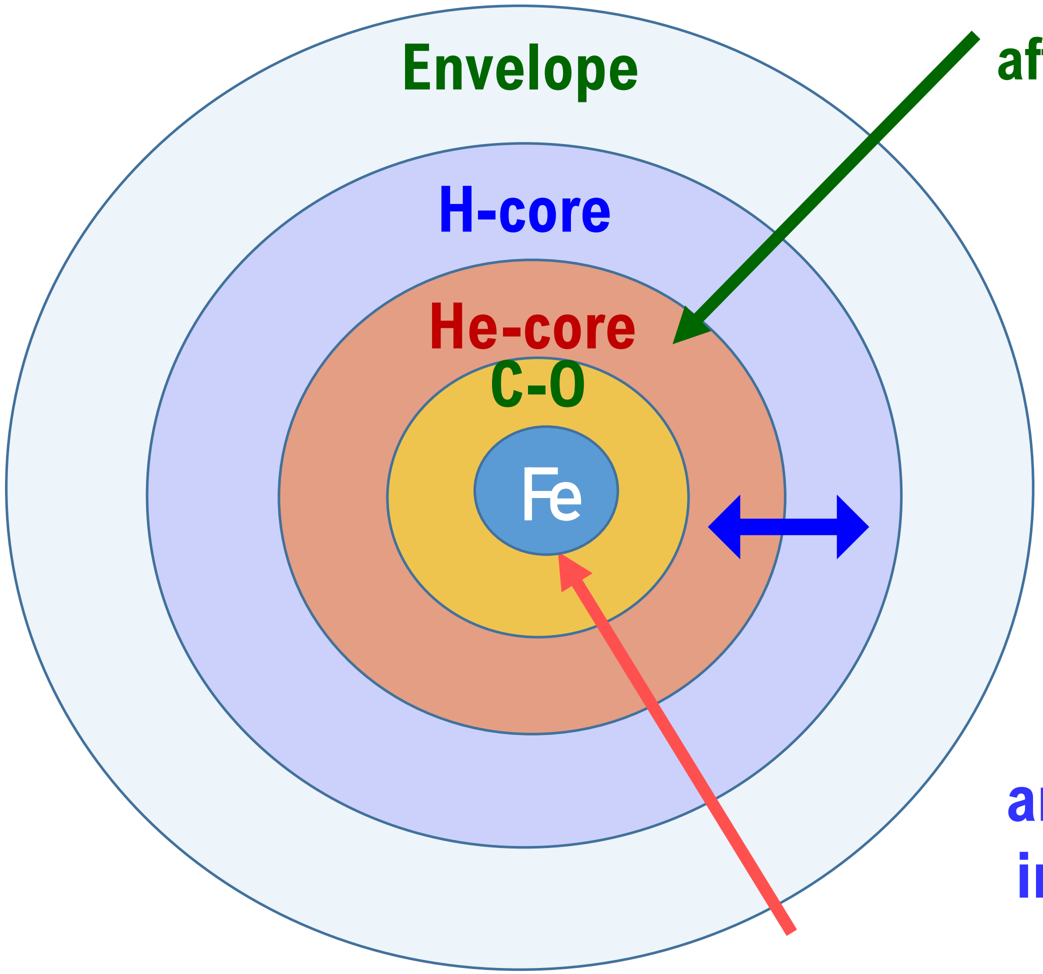
***Gas Flows***

- Infall
- Outflow
- Radial inflow (in disks)

*Observationally and Theoretically motivated*

*Scale: GALACTIC AND CIRCUMGALACTIC MEDIUM (several kpc)*

# YIELDS OF MASSIVE STARS IN A NUTSHELL



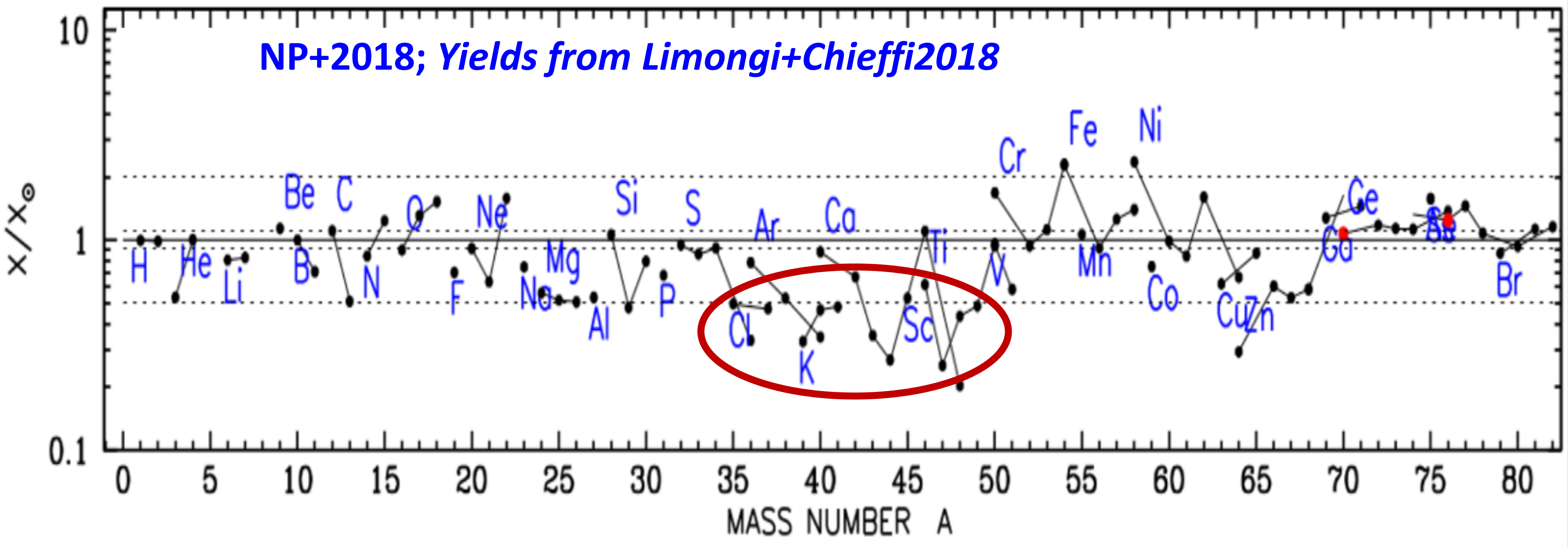

**Mass loss and Rotation**
affect the yields of « light » elements
CNO, F, Ne22, but also
Weak s-process (Sr peak)
produced in the H and He layers

**Rotation**
Mixes protons in He-burning regions
and products of H- and He-burning,
boosting production of
**CNO, F, Ne22, Weak s-process**
and turning « *secondary* » elements
into « *quasi-primary* » ones (N,F,s-)

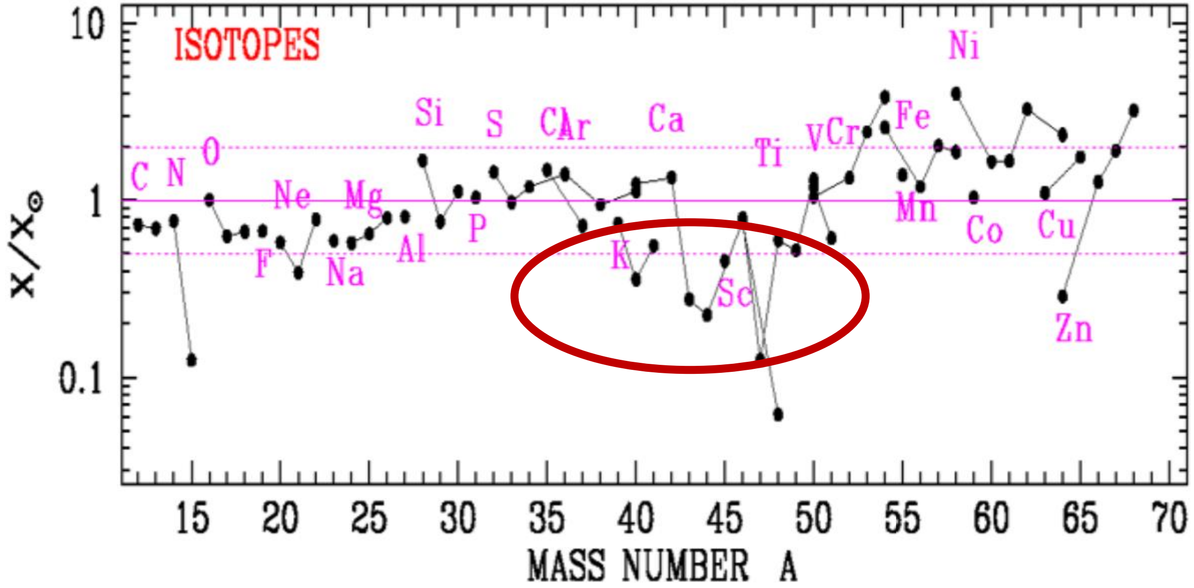
**The explosion mechanism « details »**
(energetics, mixing and fall-back, mass-cut)
affects the yields of elements produced near the core,
fom Cr to Zn (Fe-peak)

# Simple (1-zone) Evolution of Solar neighborhood: T – 4.5 Gy

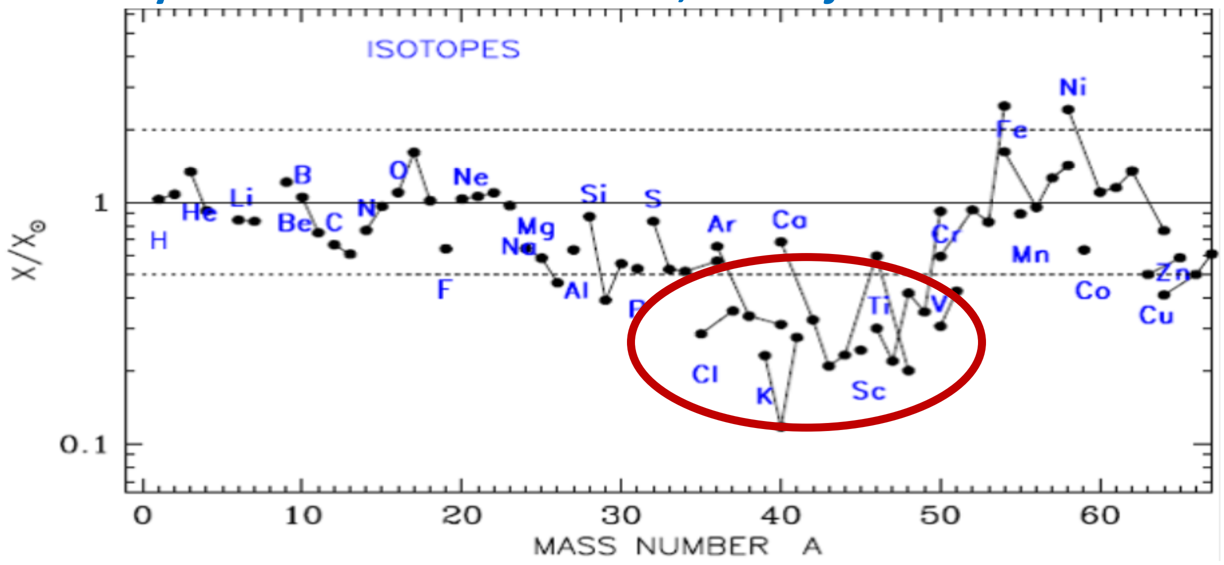
NP+2018; *Yields from Limongi+Chieffi2018*

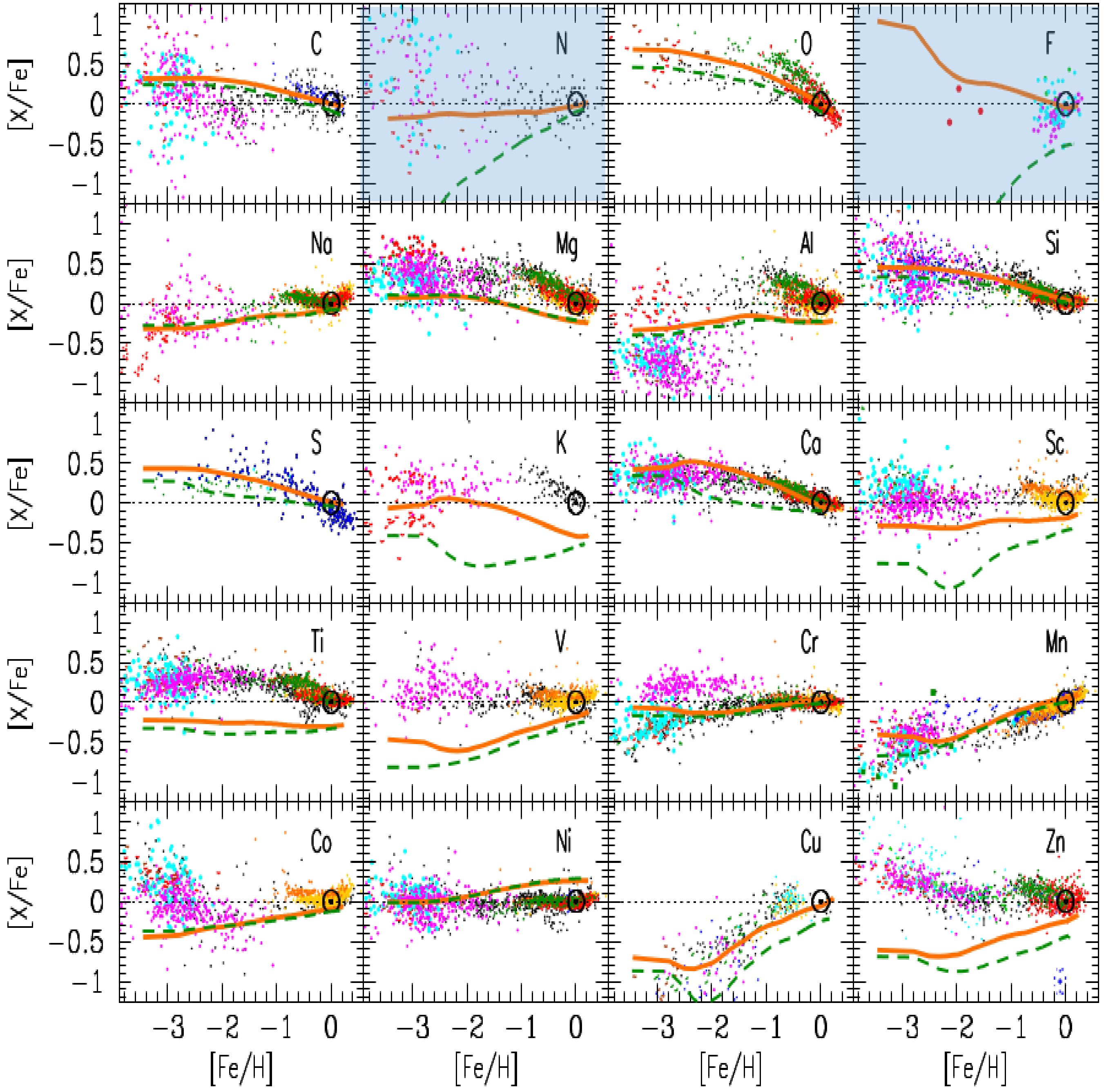



Goswami+NP 2000; *Yields from Woosley+Weaver1995*




Kubryk+NP+Athanassoula 2015; *Yields from Nomoto+2013*






***NP+2018***

**Chemical evolution with yields of rotating mas. stars**

**Rot vs Non Rot**

**Alpha/Fe evolution OK**

***Primary N ~OK***

***(Chiapinni et al. 2006)***

***Primary F***

**Mn, Cu: OK**

***Mg, Al: ~underproduced***

**Ti: *observ.* : like alpha**
***theory.* : like Fe**

**K, Sc, V, Zn: not OK**
**Zn: hypernovae?**

**Ni: problem with W7 model**

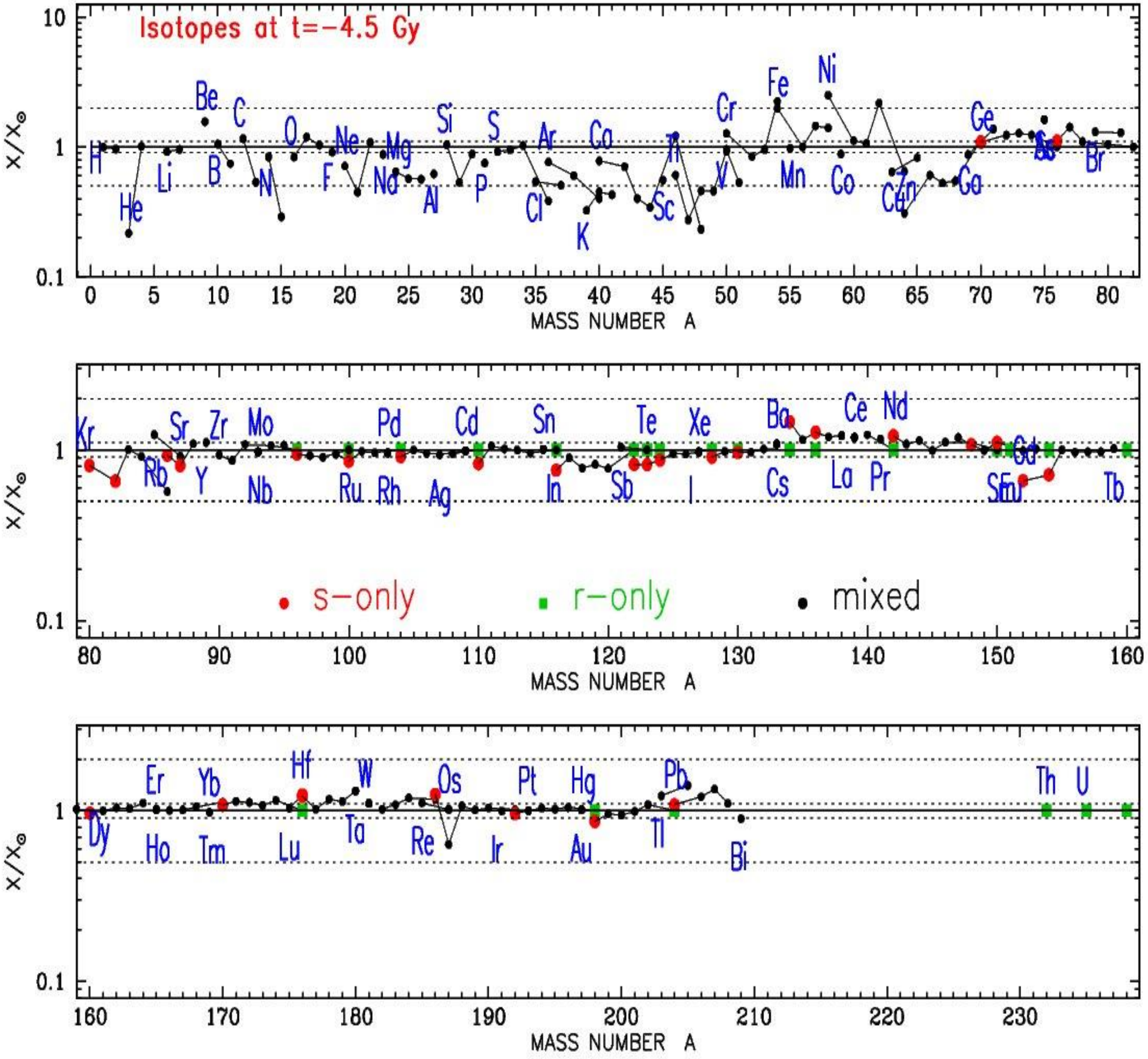
# Isotopic abundances

**Up to Zn:**
Better than a factor of 2

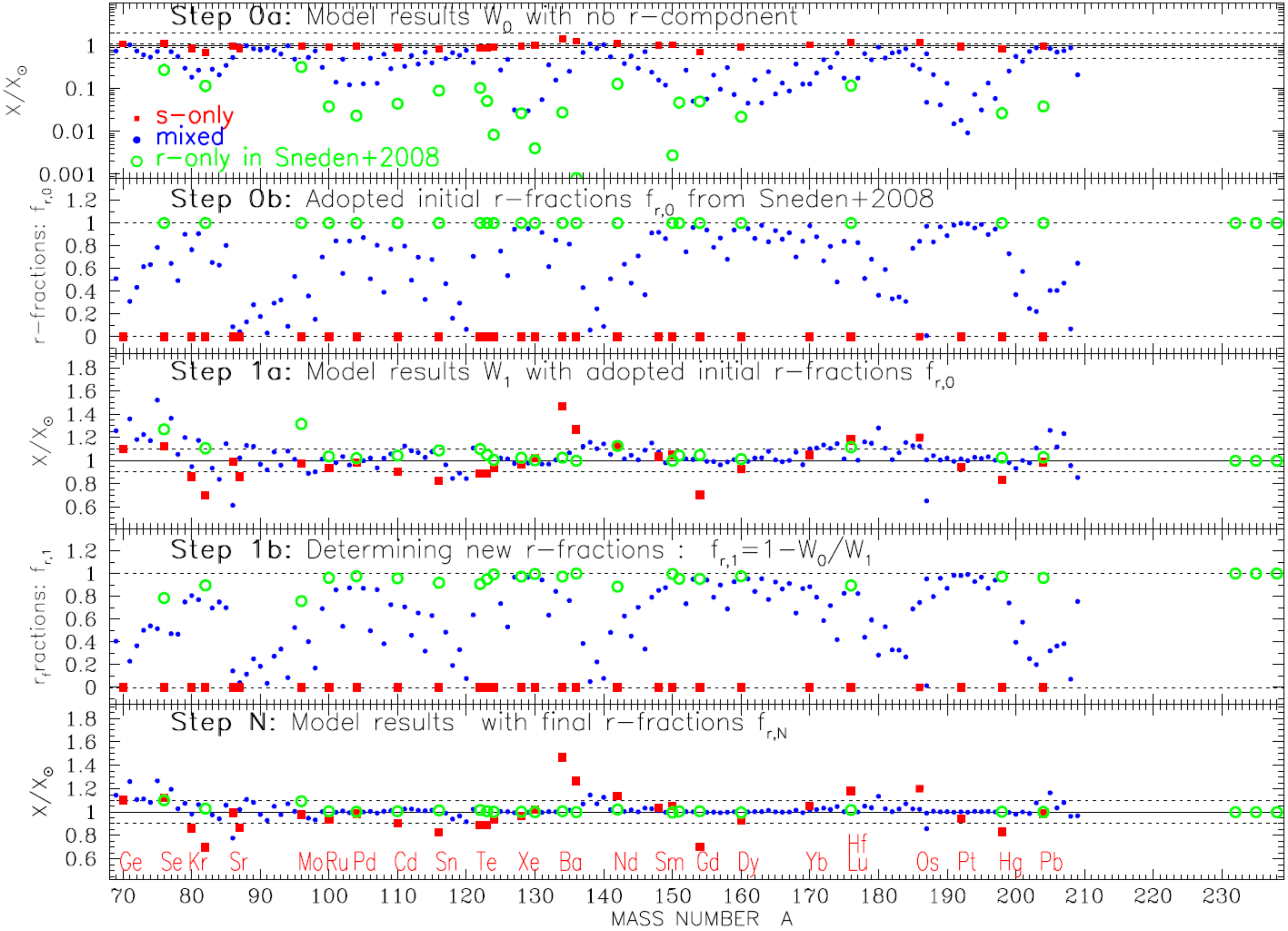
*Mg Al* Cl K Sc Ti V
*Poorly* reproduced

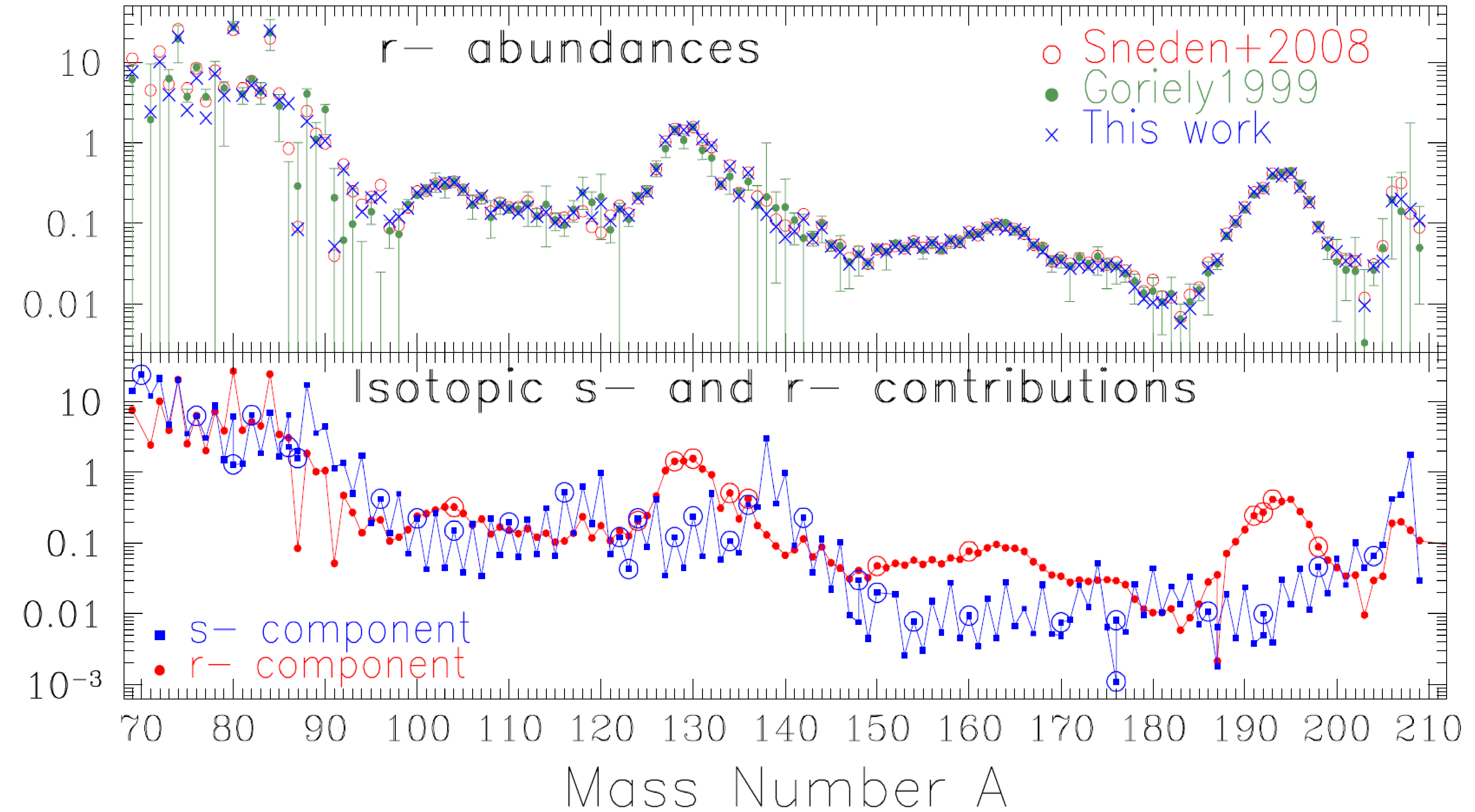
**Above Zn:**
Pure s- nuclei:
Better than ~40%

NP+2019
r- fraction:
Reevaluating
the r-residuals
by a bootstrap method

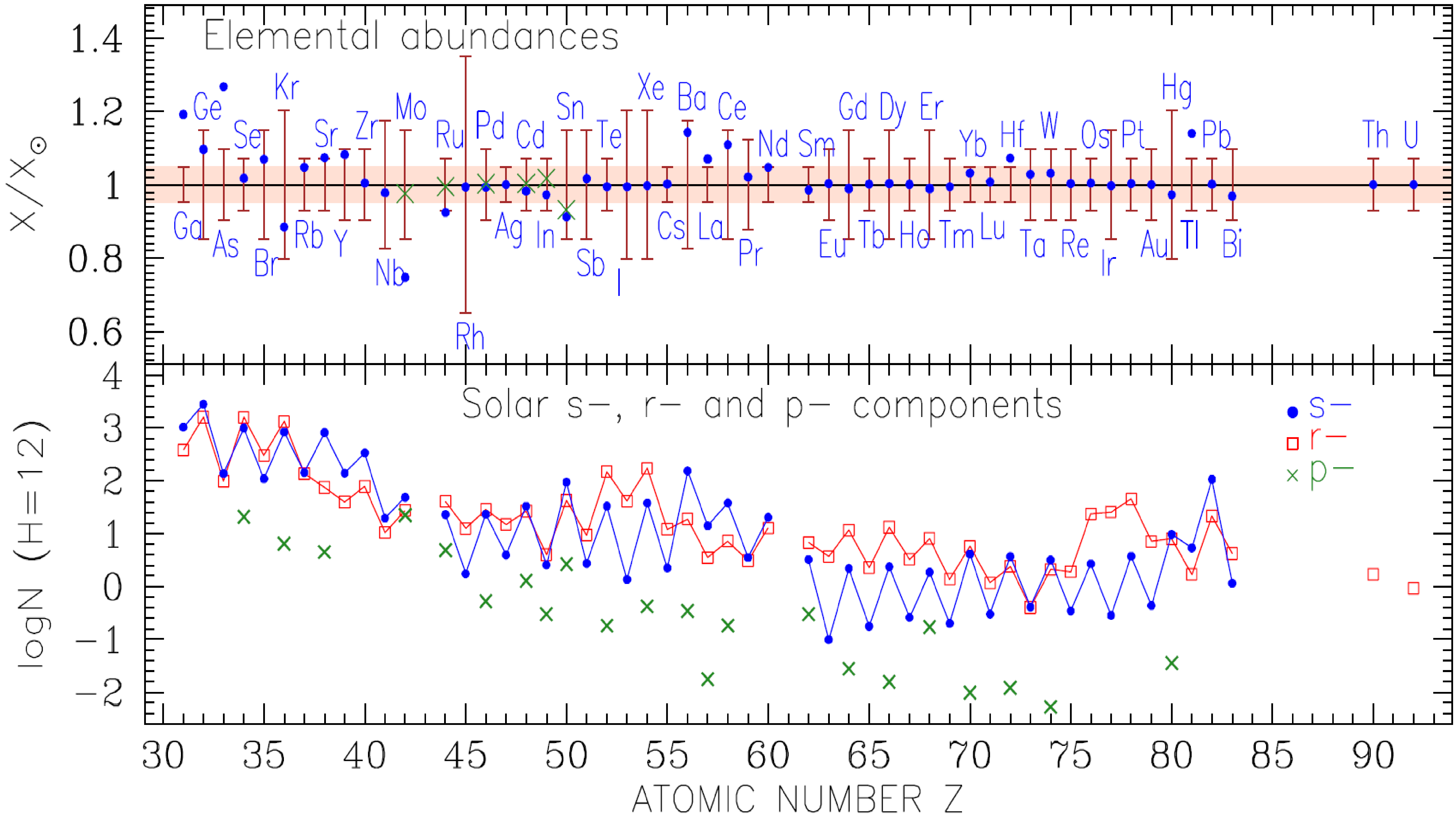


**NP+2019**
**r- fraction:**
**Reevaluating**
**the r-residuals**
**by a bootstrap**
**method**



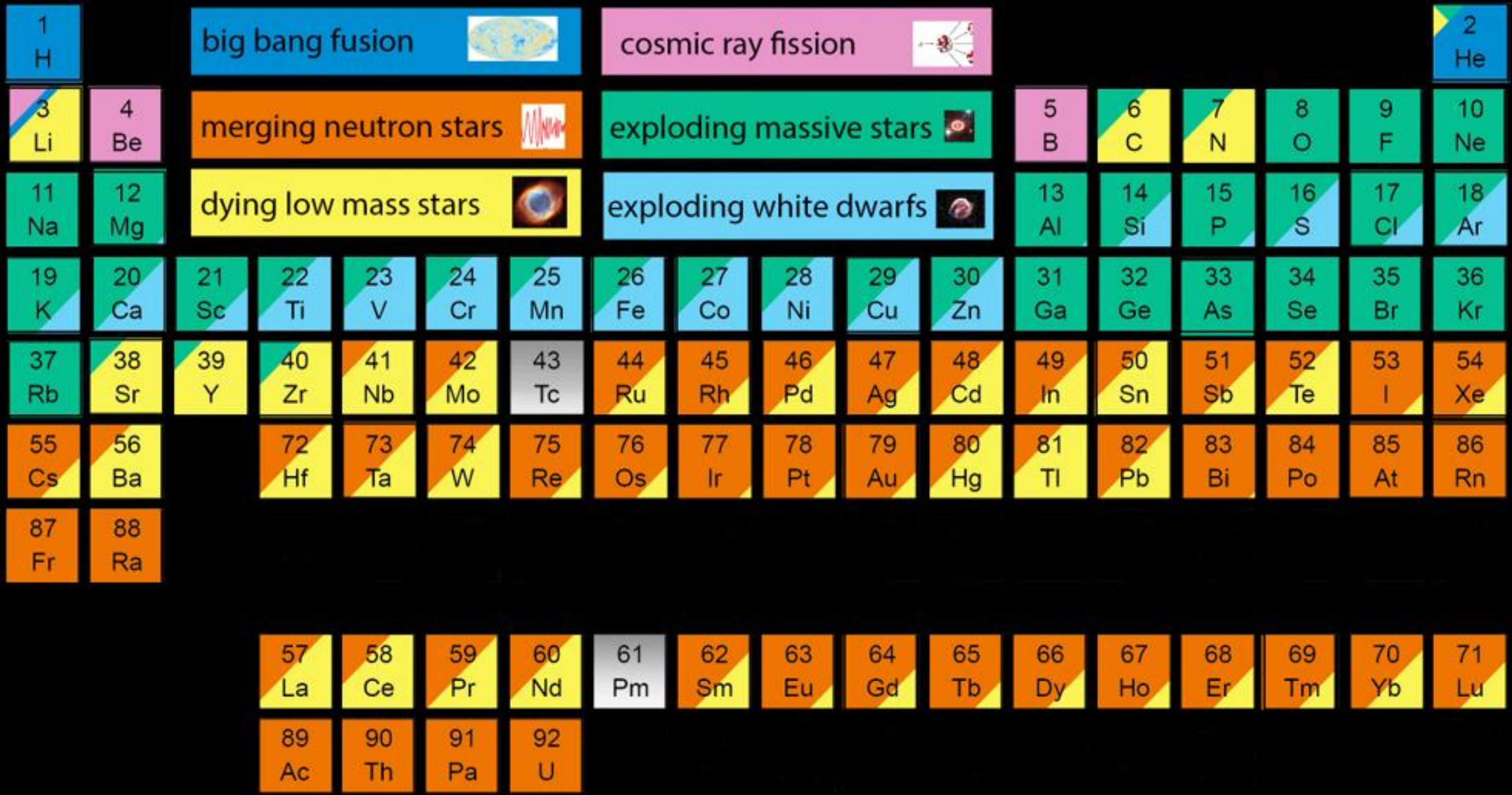


r− abundances
Sneden+2008
Goriely1999
This work
Isotopic s− and r− contributions
s− component
r− component
10
1
0.1
0.01
$10^{-3}$
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
Mass Number A



Elemental abundances
X/X⊙
1.4
1.2
1
0.8
0.6
Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Ru Rh Pd Ag Cd In Sn Sb Te I Xe Cs Ba La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Th U
Solar s−, r− and p− components
s−
r−
p−
logN (H=12)
4
3
2
1
0
−1
−2
30 35 40 45 50 55 60 65 70 75 80 85 90
ATOMIC NUMBER Z

# The Origin of the Solar System Elements

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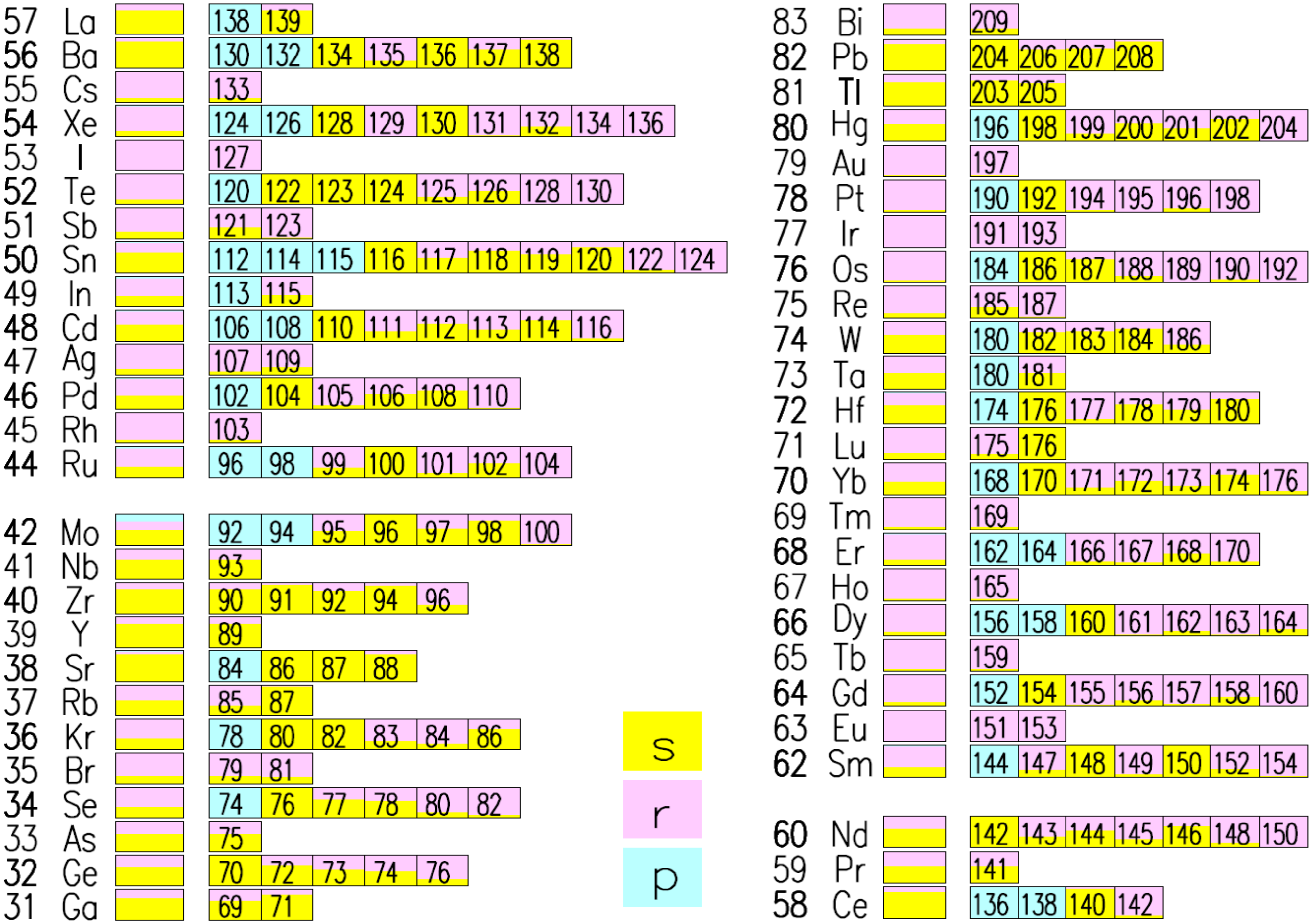
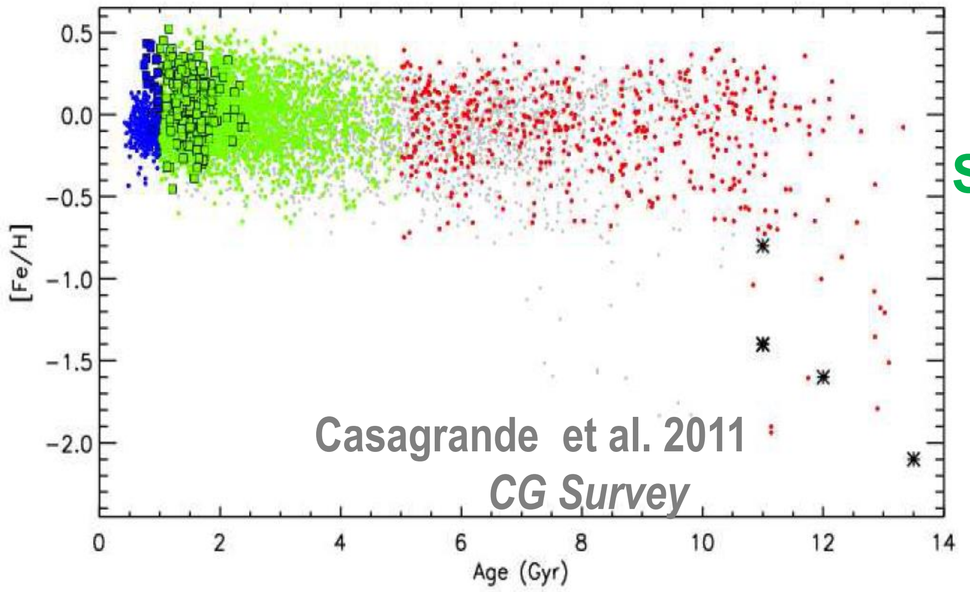
*NP*
*Abia*
*Cristallo*
*Limongi*
*Chieffi*
*2019*



# Inadequacy of the simple models for the solar neighborhood

## *1. Age-metallicity relation in the solar neighborhood*




**Little metallicity evolution in the past 10 Gyr**
**Sizeable dispersion ± 0.2 dex (~60% at 1 σ) at all ages**

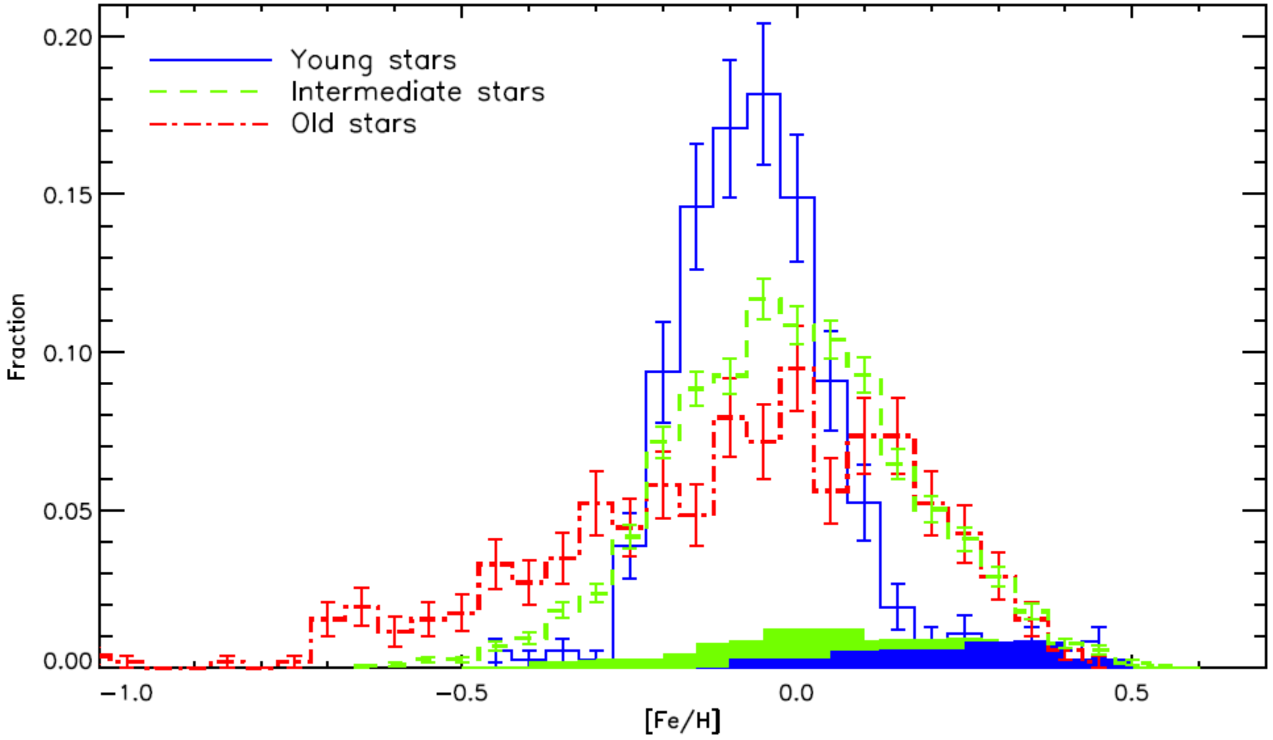
***Nieva+Przybilla (2012)*** **nearby B-stars: SOLAR composition**
**Fluctuations of less than 10% (0.04 dex) from the mean**

**Same for local gas: SOLAR to ~4% (Cartledge et al. 2006)**

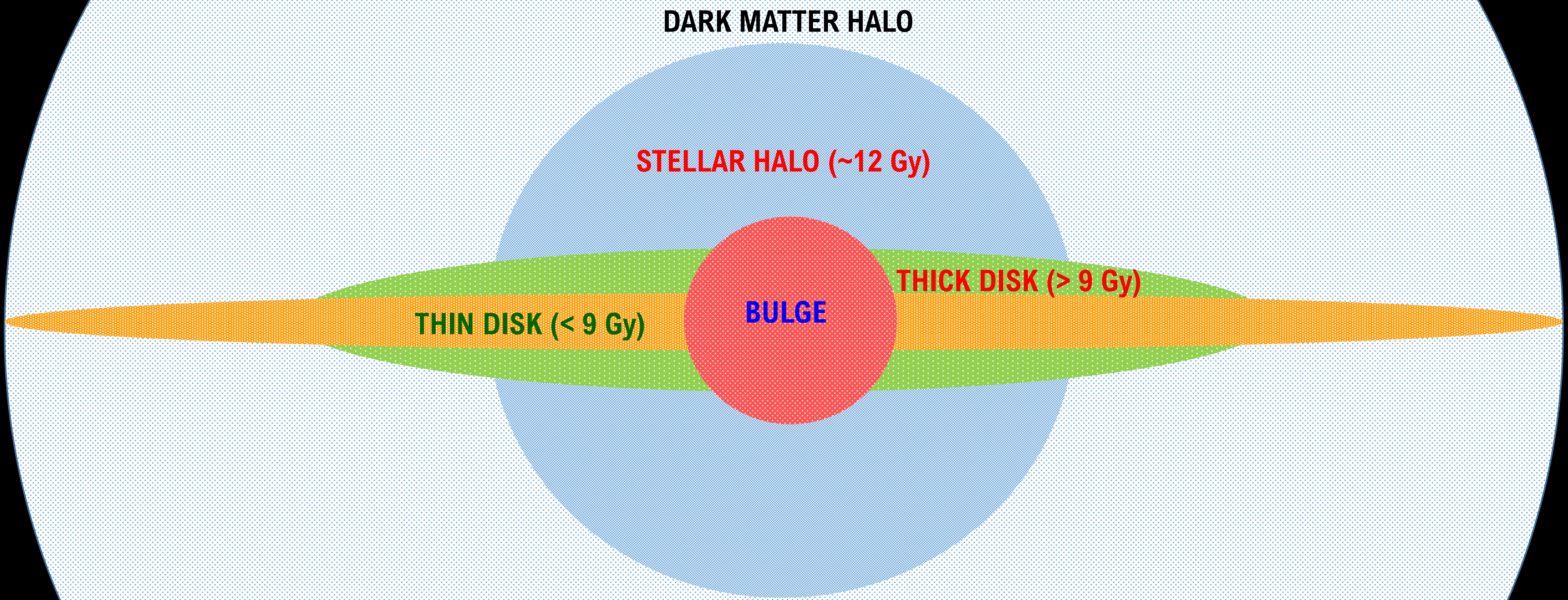
## *2. The metallicity distribution*

**Old *AND* young stars** of **both**
***high*** and ***low*** **metallicities**

**the most metallic stars (2-3 Z☉)**
- **cannot be LOCAL**
- **they are NOT the youngest**

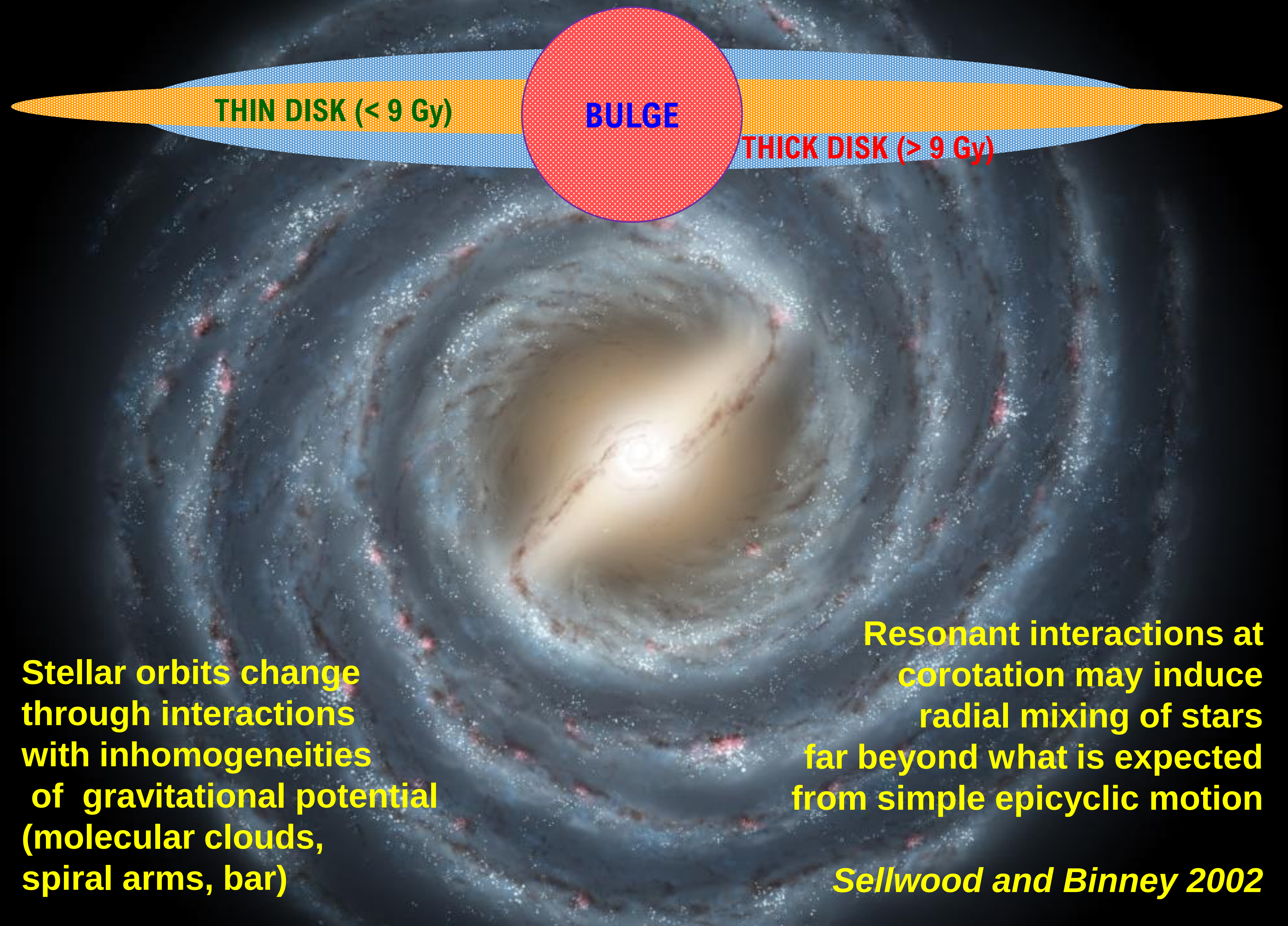


# THE MILKY WAY




**Thin vs Thick disks:** differences in age, morphology, kinematics and chemistry

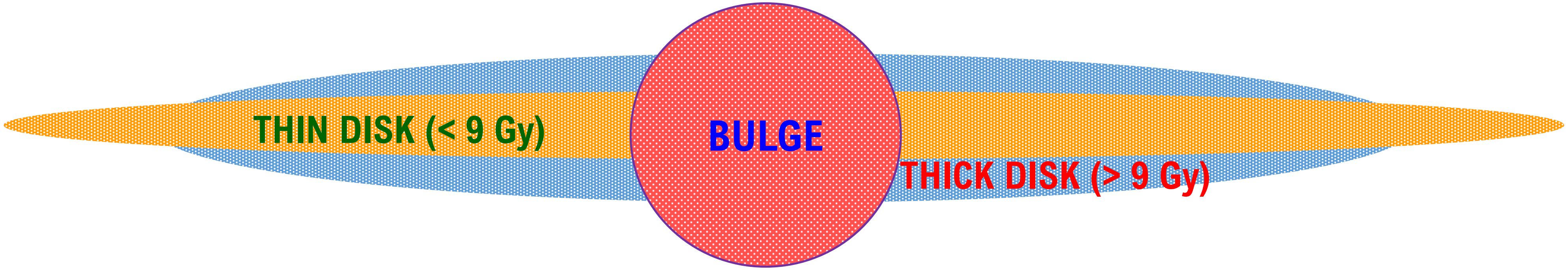
**Origin(s) of thick disk:** early merger(s), formation in highly turbulent medium, role of radial migration…




Stellar orbits change through interactions with inhomogeneities of gravitational potential (molecular clouds, spiral arms, bar)

Resonant interactions at corotation may induce radial mixing of stars far beyond what is expected from simple epicyclic motion

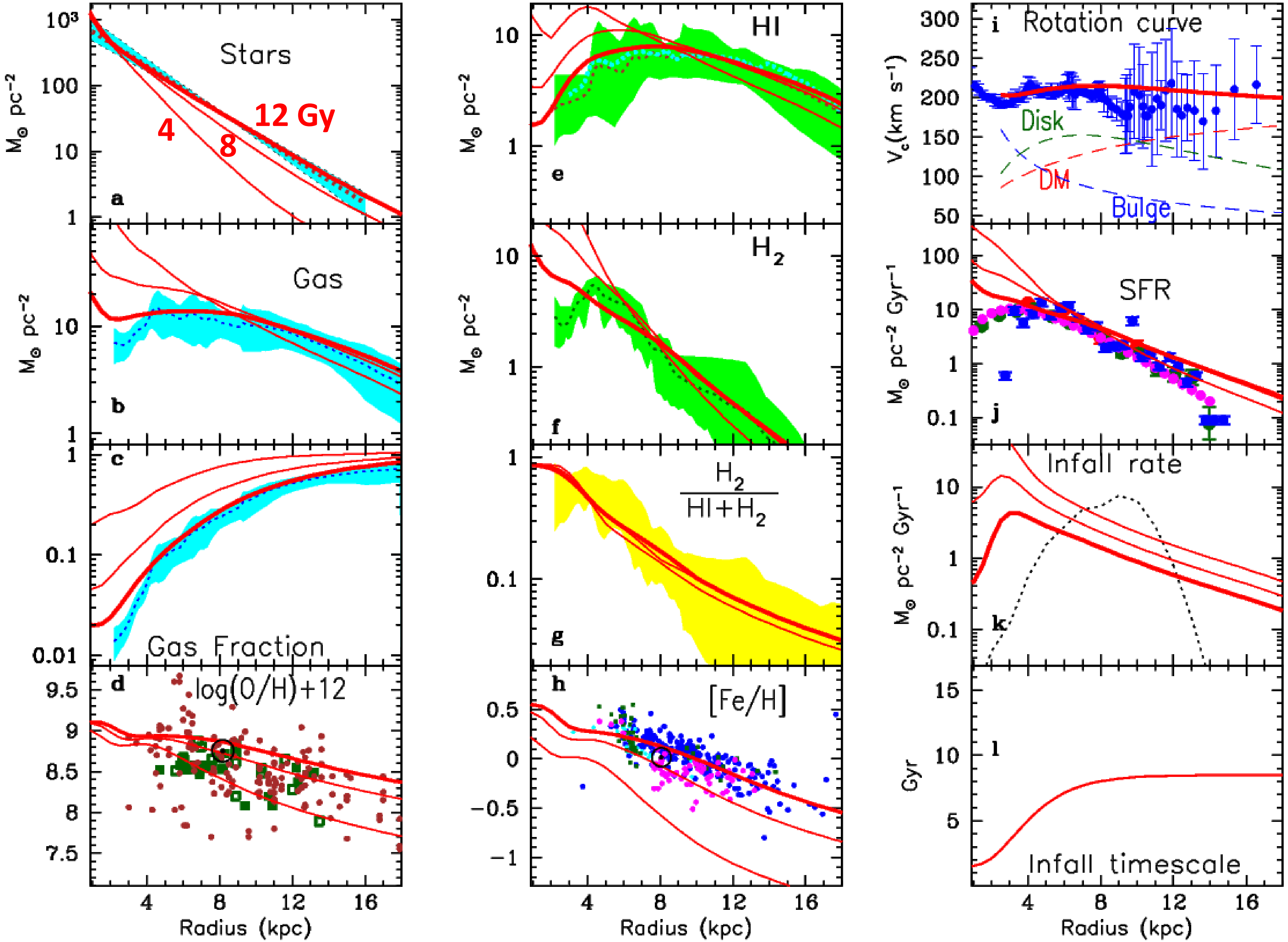
*Sellwood and Binney 2002*



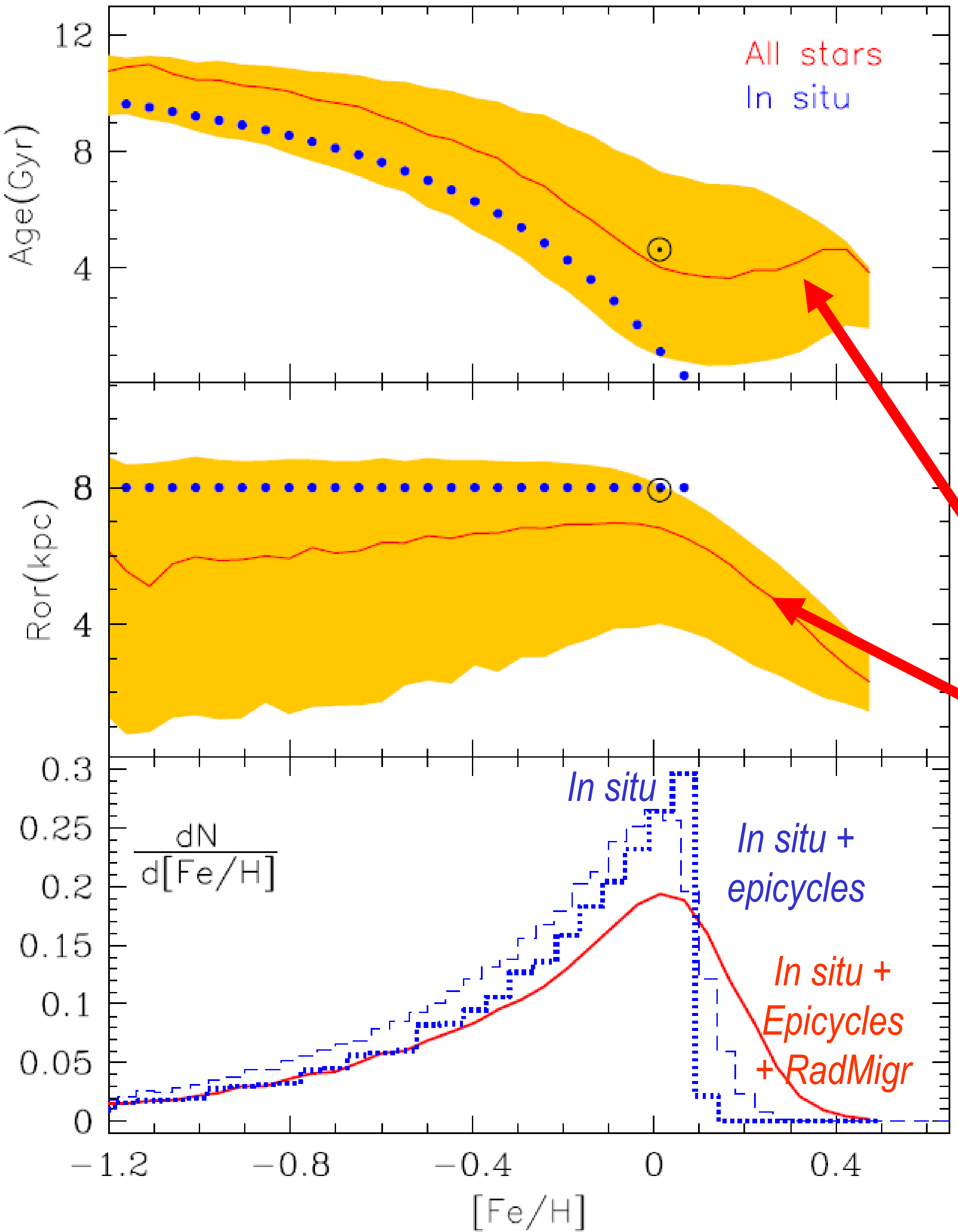

*Kubryk, NP, Athanassoula (AA 2015a,b):* 1D semi-analytical model

- Parametrized infall in a DM halo of 1.3 $10^{12}$ $M_\odot$
- inside-out disk formation , Star Formation Rate from H2,
- Stellar Initial Mass Function from Kroupa (2001),
- *radial motions of gas (radial inflow)*
- *radial migration of stars* (inspired from N-body disk simulations), *blurring+churning*
- detailed chemical evolution
- [H to Zn, with Z-dependent yields from massive – Nomoto+2006 and LIM (Karakas2010) stars
- observed Delayed Time Distribution for SNIa rate,

- [P+2019: H to Pb from Rotating massive stars (LC2018) and LIM (Cristallo+2015) stars]



Stars
12 Gy
4
8
a
Gas
b
c
Gas Fraction
d
log(O/H)+12
HI
e
$H_2$
f
$\frac{H_2}{HI+H_2}$
g
h
[Fe/H]
i
Rotation curve
Disk
DM
Bulge
SFR
j
Infall rate
k
l
Infall timescale
$M_\odot$ pc$^{-2}$
$V_c$(km s$^{-1}$)
$M_\odot$ pc$^{-2}$ Gyr$^{-1}$
Gyr
Radius (kpc)




## Solar Neighborhood

***Radial Migration***

**1. Increases the average stellar age by ~1 Gyr**

**2. … and brings locally stars from ~1.5 kpc inwards (on average)**

**3. The most metal-rich local stars come from several kpc inwards and are ~4 Gyr old**

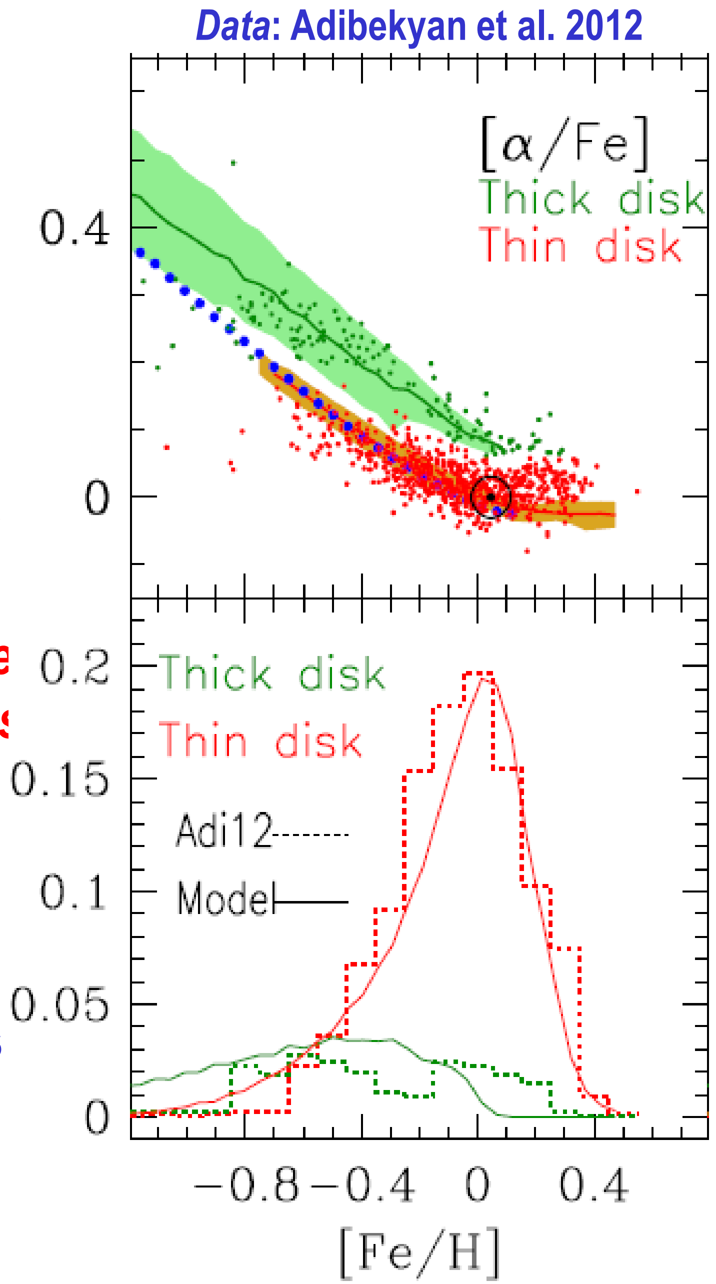
***Feuillet+2019***

*Assuming that*
the thick disk is
the old disk (>9 Gyr)

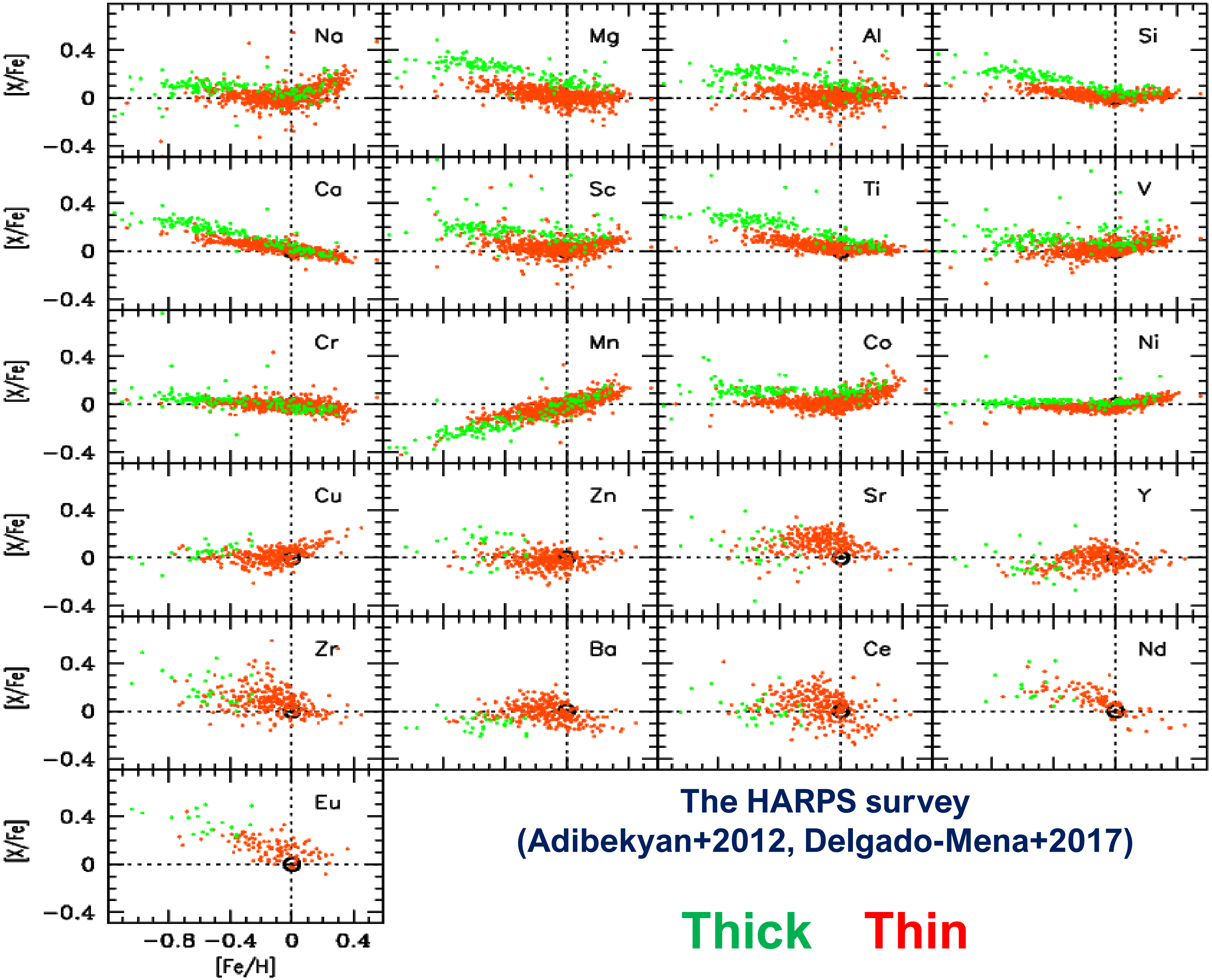
we recover the
Double branch
[a/Fe] vs Fe/H behavior

*because O and Fe source*
*have different timescales*

*and the*
metallicity distributions
*of both*
the thick and thin disks

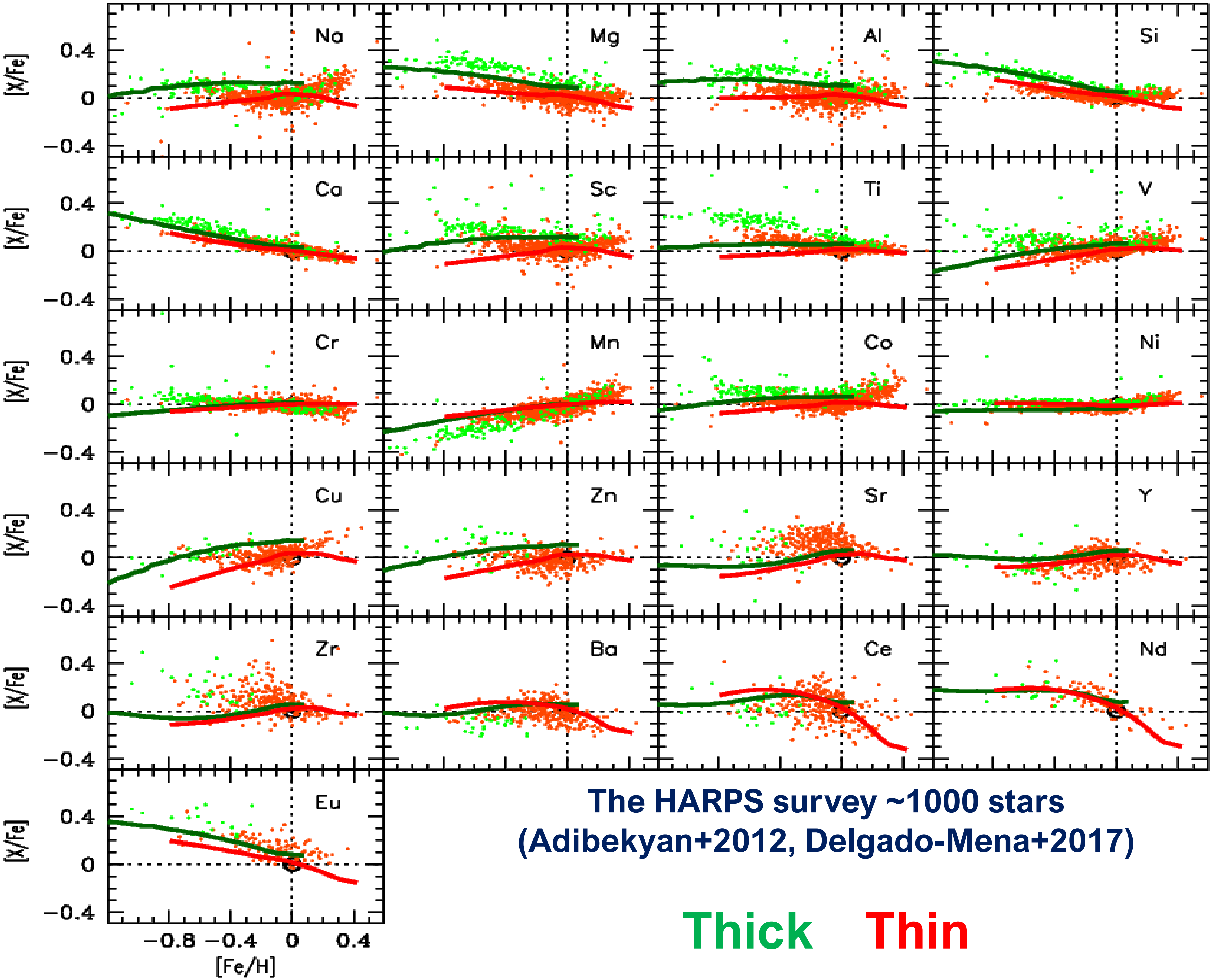



Stars in the local
thick disk
and in the metal-rich
thin disk
mostly from
the inner disk
(3-4 kpc)
with more rapid
star formation



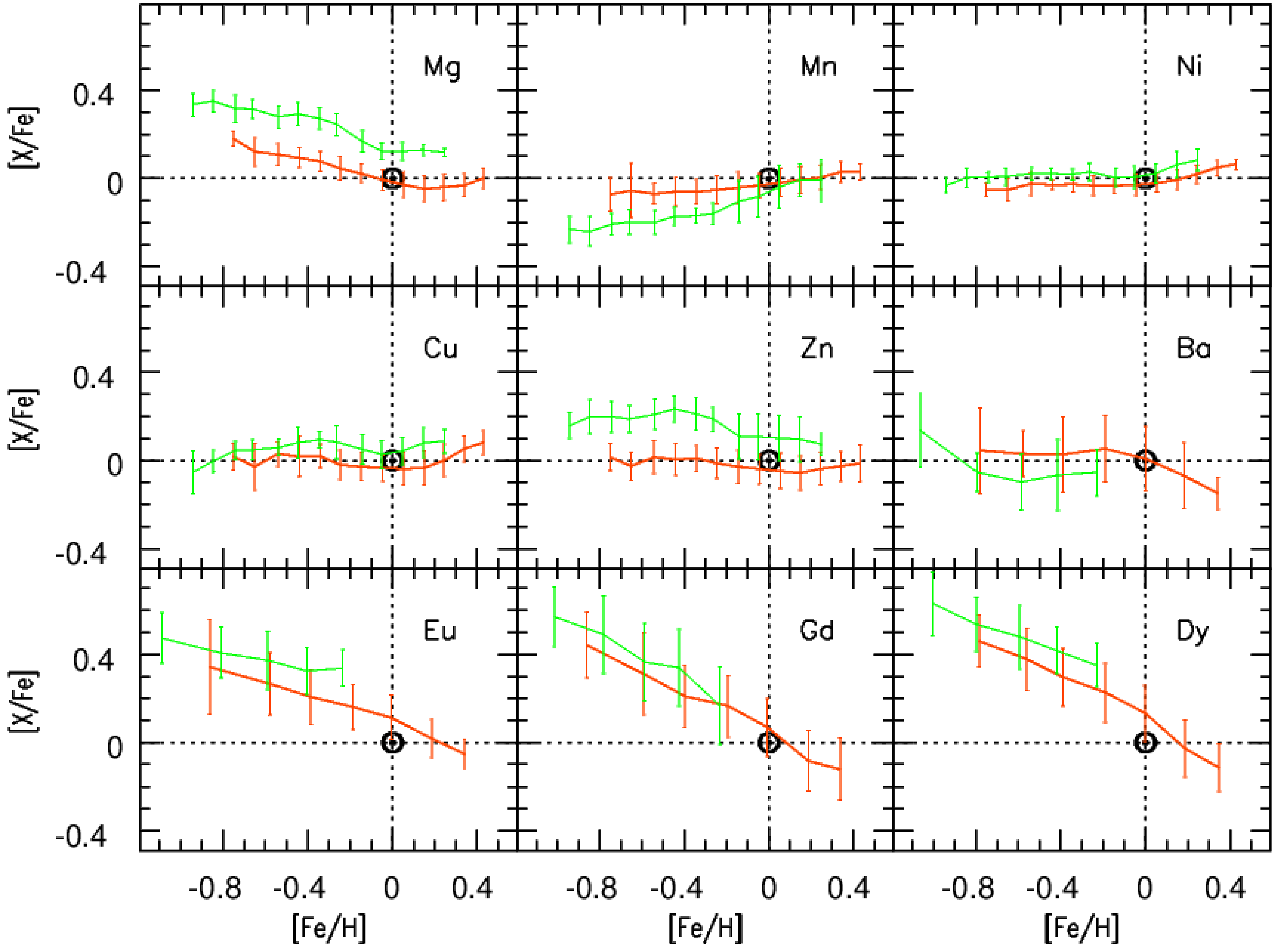

**The HARPS survey**
**(Adibekyan+2012, Delgado-Mena+2017)**

**Thick** **Thin**




**The HARPS survey ~1000 stars**
**(Adibekyan+2012, Delgado-Mena+2017)**

**Thick Thin**




**AMBRE project**
**~7000 stars**
**(Nice group,**
**Mikolaitis+2016**
**Guiglion+2018)**

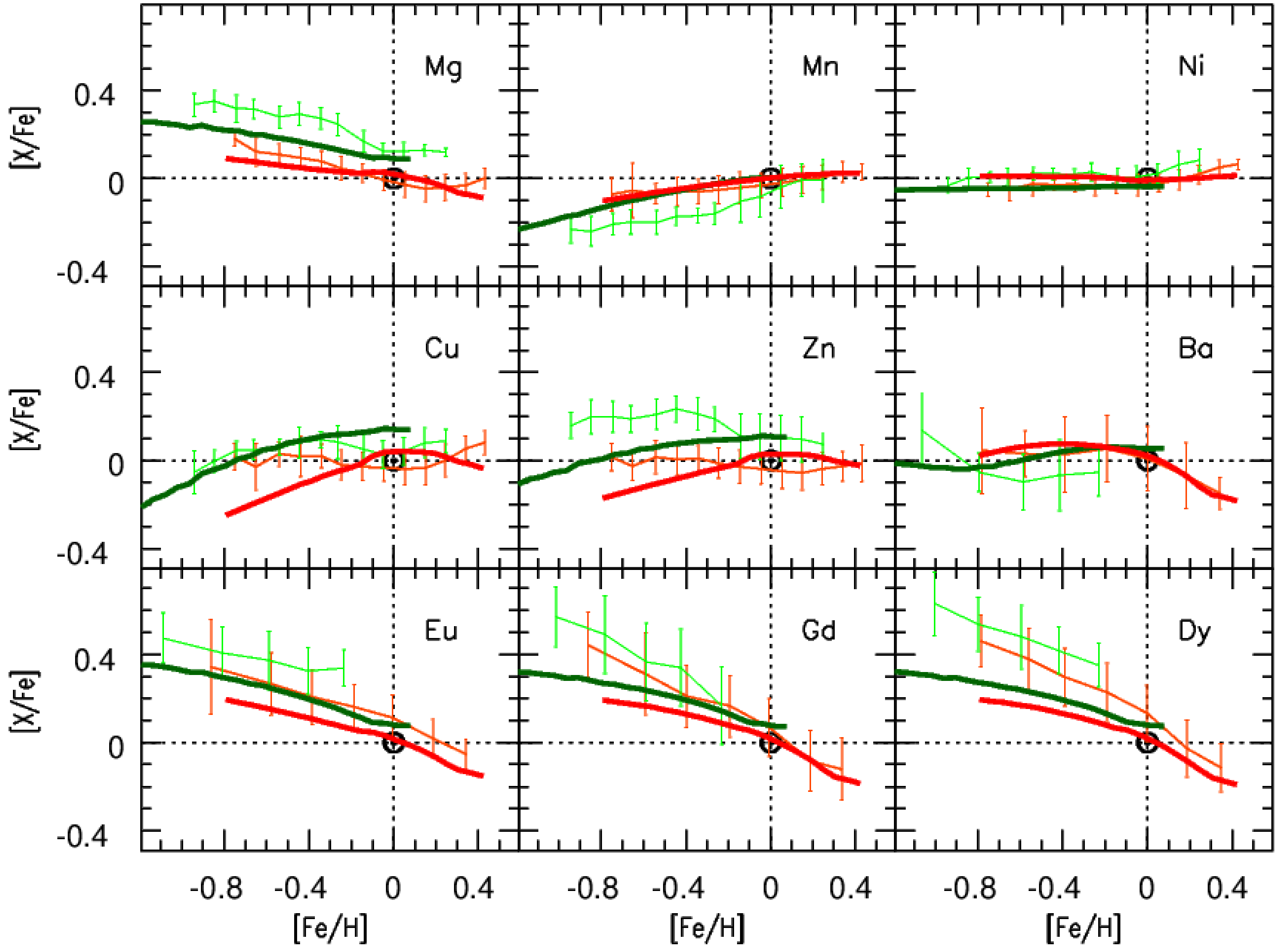
**Thick** **Thin**

**Other projects**

**GAIA/ESO survey**

**LAMOST**

**APOGEE**




**AMBRE project**
**~7000 stars**
**(Nice group,**
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**Guiglion+2018)**

**2-branch behaviour expected for ratios of elements with sources evolving on different timescales or having different metallicity dependences**

**Not expected for e.g. Ba/Fe (similar timescales)**

# The evolution of Li in the thin and thick *disks*

*(NP, de Laverny, Guiglion, Recio-Blanco, Worley 2017 )*

**At least three sources of Li:**

**Big Bang**

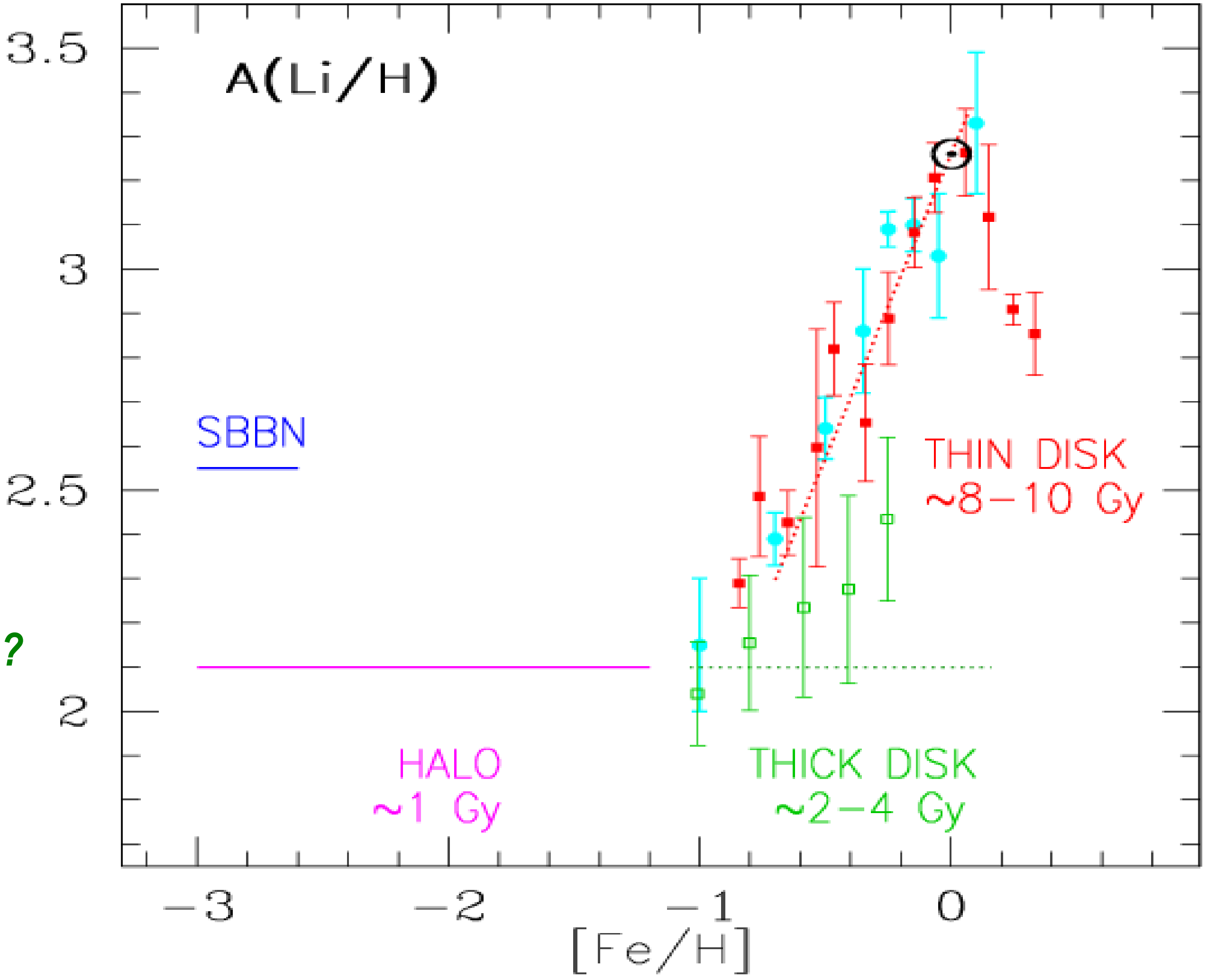
**Cosmic rays**

**Stellar (>60% of solar Li)**
***Delayed ([Fe/H]>-1) ⇒***
***Timescale > 1 Gy***

***2 important problems***

1. ***What is the primordial Li ($Li_P$)?***
***SBBN vs Spite plateau ?***

***2. Which stellar source ?***
***Novae , Red giants or AGBs ?***
***What timescale ?***




**AMBER data (*Guiglion et al. 2016*) suggest different sequences of evolution for the thick and thin disks**

Double sequence explained by radial migration, for

Thin disk <9 Gy
Thick disk >9 Gy

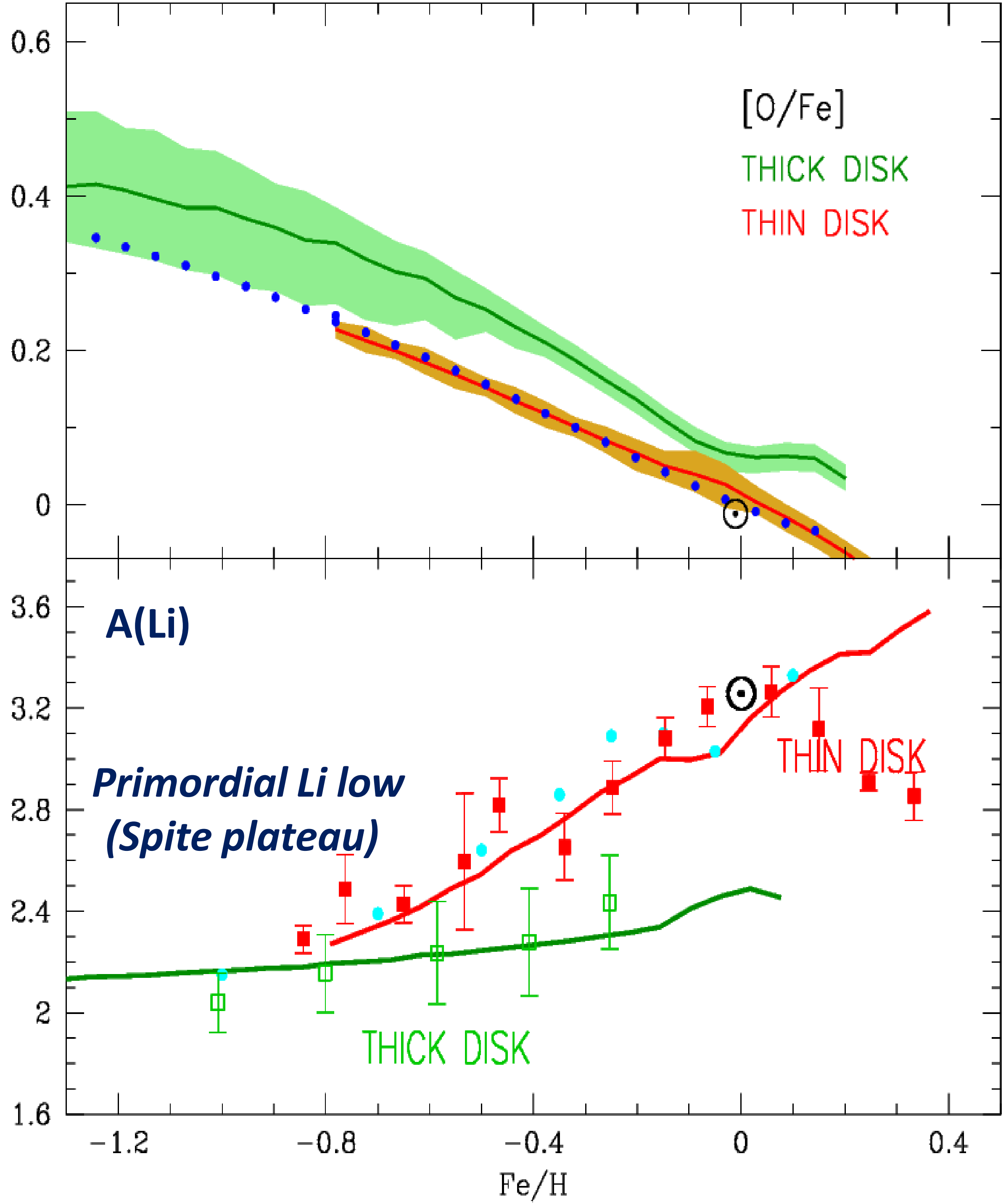
and long lived Li source
(M<1.6 M⊙, τ>2 Gy)

Starting with low primordial Li
*(Spite plateau)*

no Li depletion in stellar atmospheres is required

to explain the upper envelope of observations

*(NP, Guiglion, de Laverny, Rechio-Blanco 2017)*



# SUMMARY

**Stellar yields still uncertain, by factors of >2 (better for alpha elements)**
**they should be used with caution (*AND tested to Solar before use*)**

**New method for determining r-residuals from galactic chemical evolution**

**Wealth of forthcoming observations in MW will help, reducing statistical uncertainties**
***(but what about systematics?),*** **thus constraining the yields** ***(and stellar physics*****)**

**BIMODALITY (thin/thick) in abundance patterns: Only well established α/Fe vs Fe/H**

**No « absolute » (i.e. including timescales ) « template » exists for abundance patterns:**
**stellar ages will help with that**

**2-branch behaviour expected for ratios of elements with sources evolving**
**on different timescales or having different metallicity dependences;**
**for some elements, 2-branch behaviour not expected (e.g. Ba/Fe)**

**Li/H shows clearly a 2-branch behaviour;**
**it probably has a stellar source with timescale longer than Fe**