**Nikos Prantzos**
***Institut d'Astrophysique de Paris***

# Stellar Nucleosynthesis and Galactic Chemical Evolution

**Galactic chemical evolution with yields from rotating massive stars**

NP, C. Abia, M. Limongi, A. Chieffi, S. Cristallo 2018

**The impact of radial migration on the evolution of the Milky Way**

M. Kubryk, NP, L. Athanassoula, 2013, 2015a,b

**On the evolution of r-elements from neutron star mergers**

Y. Ishimaru, S. Wanajo, NP 2015

T. Ojima, Y. Ishimaru, S. Wanajo, NP, P. François 2018

1. Nucleosynthesis and Galactic chemical evolution (GCE) : Basics

2. Some new results with yields of rotating massive stars

3. Problems of simple GCE models in the Solar neighborhood

4. The role of radial migration in the evolution of the Milky Way disk

5. The role of hierachical galaxy formation in the evolution of r-elements

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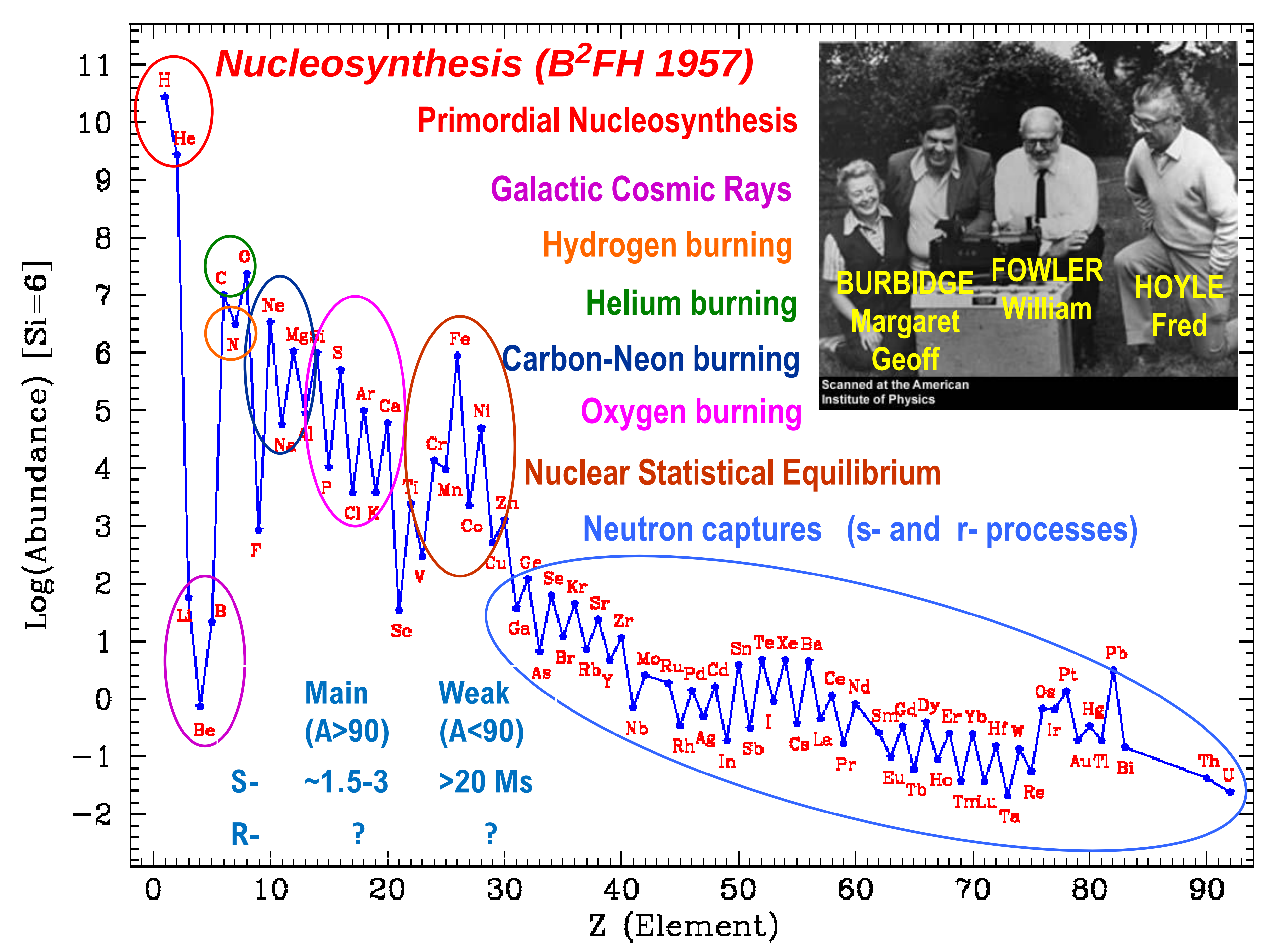
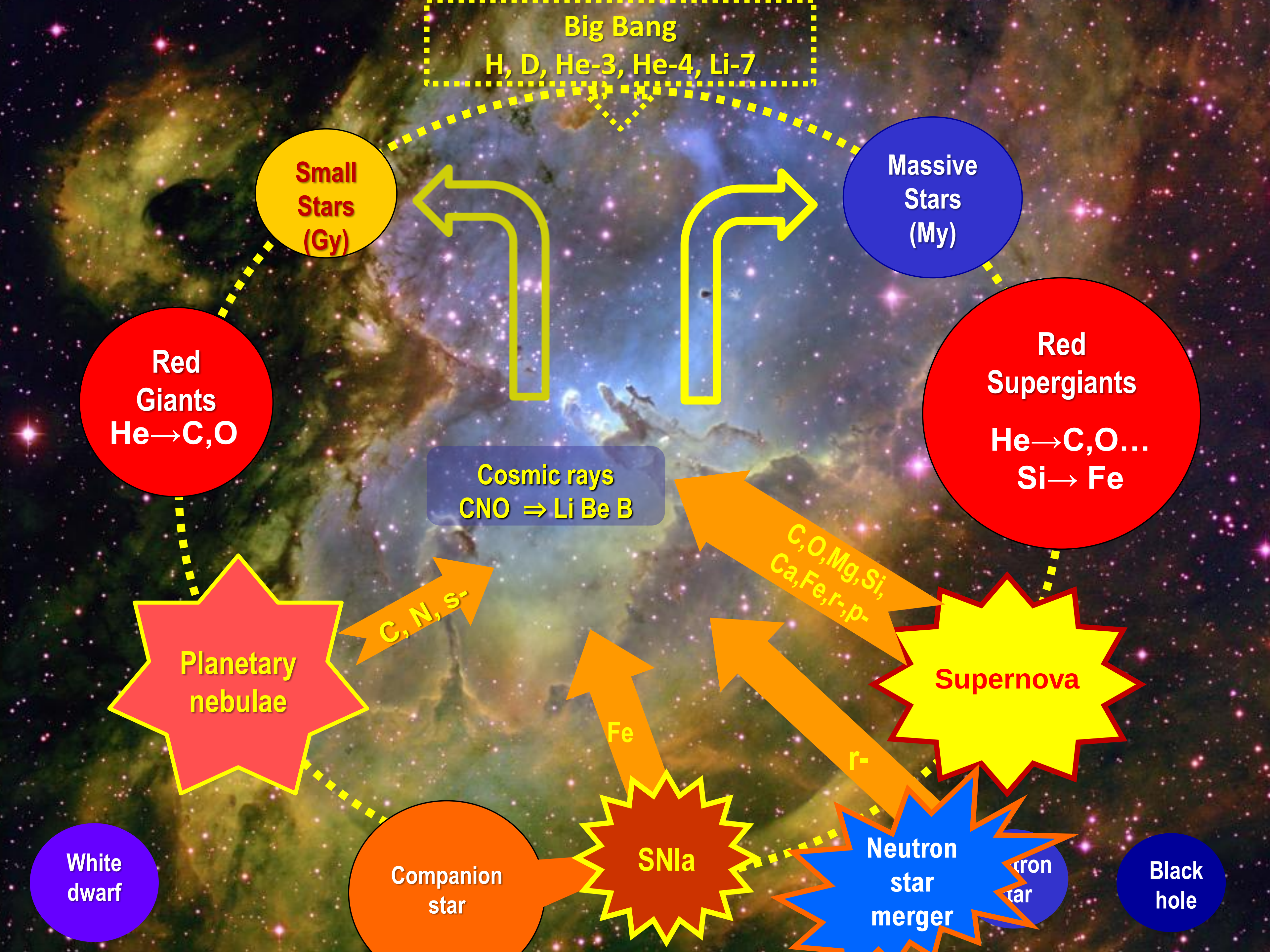


Nucleosynthesis (B2FH 1957)
Primordial Nucleosynthesis
Galactic Cosmic Rays
Hydrogen burning
Helium burning
Carbon-Neon burning
Oxygen burning
Nuclear Statistical Equilibrium
Neutron captures (s- and r- processes)
BURBIDGE Margaret Geoff
FOWLER William
HOYLE Fred
Scanned at the American Institute of Physics
Main (A>90)
Weak (A<90)
S- ~1.5-3 >20 Ms
R- ? ?
Log(Abundance) [Si=6]
Z (Element)
H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn 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


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, N, s-
C,O,Mg,Si,
Ca,Fe,r-,p-
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)*

# Aims of Galactic Chemical Evolution (GCE) studies

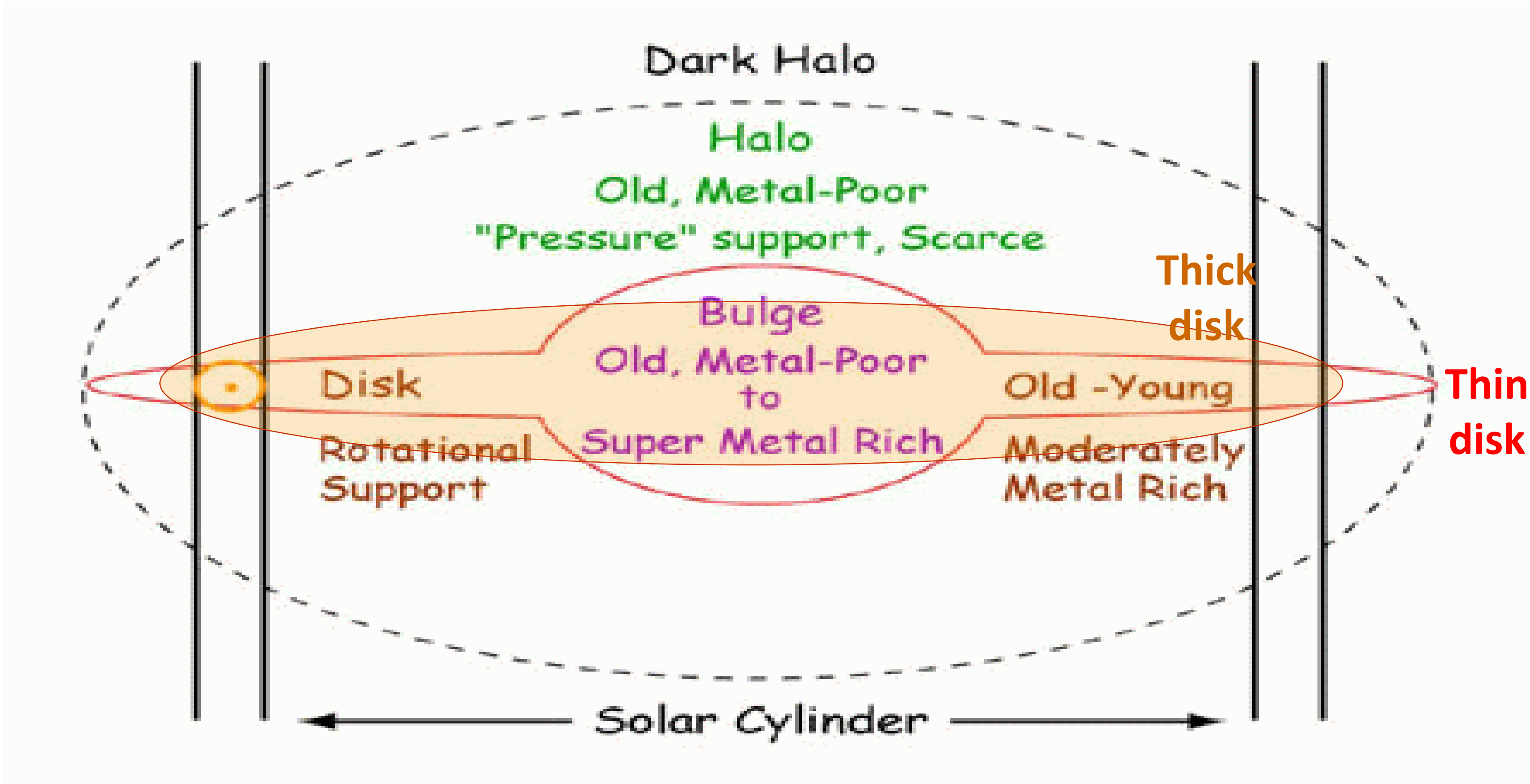
**To check / constrain our understanding of stellar nucleosynthesis**
(i.e. stellar yields and their dependence on stellar properties),
either ***statistically*** (mean, dispersion) or in ***individual objects***

**To establish a chronology of events in a given system**
e.g. ***when*** metallicity reached a given value, or ***when*** some stellar source (SNIa, AGB etc.) became important contributor to the abundance of a given isotope / element

**To infer how a system was formed**
(***Star Formation Rate, large scale gas mouvements***)
e.g. slow infall of gas in case of solar neighborhood

In principle: evolution = function of age
In practice : metallicity ([Fe/H]) of stars is observed (large age uncertainties)
**So: evolution = function of [Fe/H] assuming unique age-metallicity relation**

# The Milky Way : not a simple system




Local disk (8 kpc from GC): Composition of nearby young stars and gas is ~ solar
*(But: older stars are more metal poor, by a factor up to ten)*

Inner Galactic disk: metal rich young stars and gas (up to 3 times solar)

Outer Galactic disk: metal poor young stars and gas (down to 1/3 solar)

A younger (<9 Gyr), metal rich (<Z>~solar) and less extended vertically (h~0.3 kpc) THIN disk

An old (9-12 Gyr) metal poor (<Z>~0.2-0.3 solar) and more extended vertically (h~1kpc)THICK disk

# OLD Models of Solar Neighborhood

## Constraints:

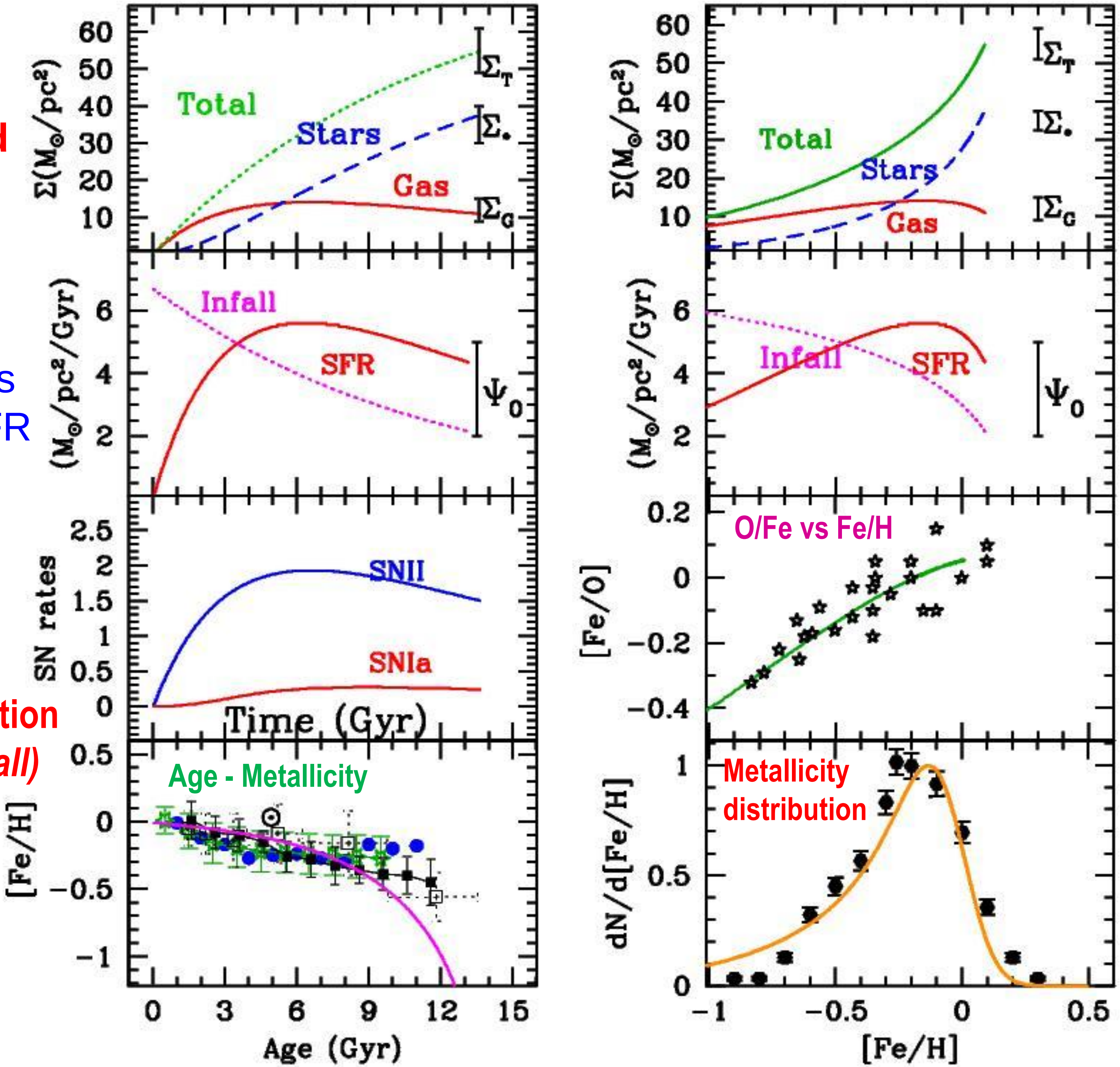
Local
column densities
of gas, stars, SFR

as well as

**Age – Metallicity**
**(*large dispersion*)**

**Metallicity distribution**
**(*requires slow infall*)**

**O/Fe vs Fe/H**
**(*requires SNIa for late Fe*)**



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## Grids of Stellar yields in GCE calculations

### Yields of massive stars

Woosley & Weaver 1995
12-40 M☉

Nomoto, Kobayashi, Tominaga 2013
13-40 M☉

Limongi and Chieffi 2018
13-120 M☉

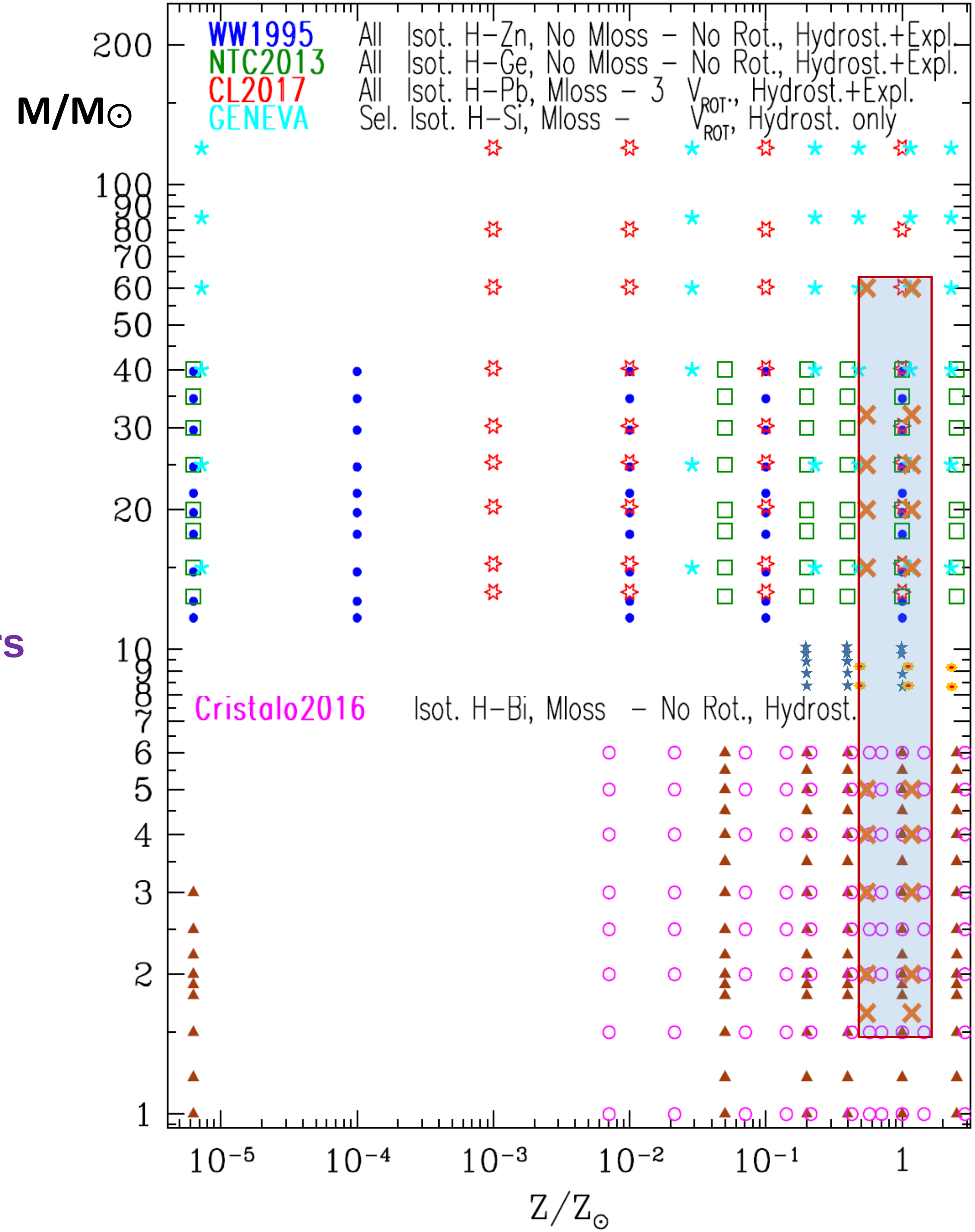
Maeder, Meynet, Hirschi 2006
15-120 M☉

### Yields of massive and LIM stars

Pignatari et al. 2016
1.5-60 M☉

### Yields of LIM stars

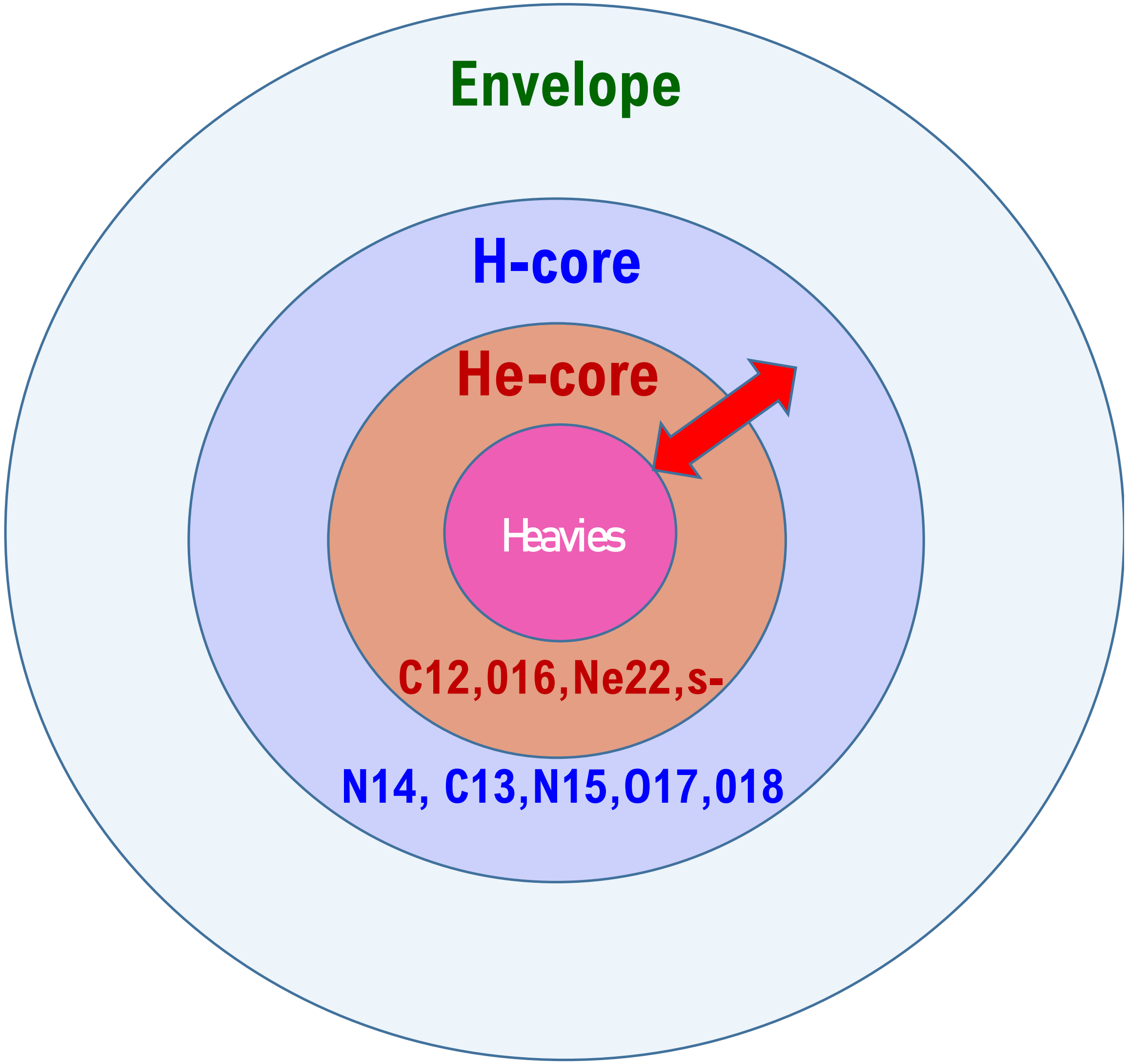
Karakas 2010 (1-6 M☉)
Karakas & Lugaro 2016 (1-8 M☉)
Cristalo et al. 2016 (1-6 M☉)
Doherty et al. 2014,2015 (7-9 M☉)



# Yields of massive stars for galactic chemical evolution studies

| | *Santa Cruz* Woosley-Weaver 1995 | *Tokyo* Nomoto et al. 2013 | *Geneva* Maeder, Meynet, Hirschi 2006 | *Roma* Limongi-Chieffi 2018 |
|---|---|---|---|---|
| Mass | 11 - 40 | 13 - 40 | 15 - 120 | 13 - 120 |
| Metallicity ($Z/Z_\odot$) | 0 - 1 | 0 - 2.5 | $10^{-8}$ – 2 | $10^{-3}$ - 1 |
| Mass loss | No | No | Yes | Yes |
| Hydrostatic | Up to Fe-core | Up to Fe-core | Up to Ne | Up to Fe-core |
| Explosive | Yes + $\nu$ - nucleosynthesis | Yes + high E at low Z | No | Yes |
| Rotation (km/s) | 0 | 0 | 0 – 800 *Not uniform in Z* | 0 - 150 - 300 at all Z |
| Isotopic composition | H to Zn | H to Ge | CNO and few selected elm. | H to Bi |

# ROTATIONAL YIELDS IN A NUTSHELL




## Rotation

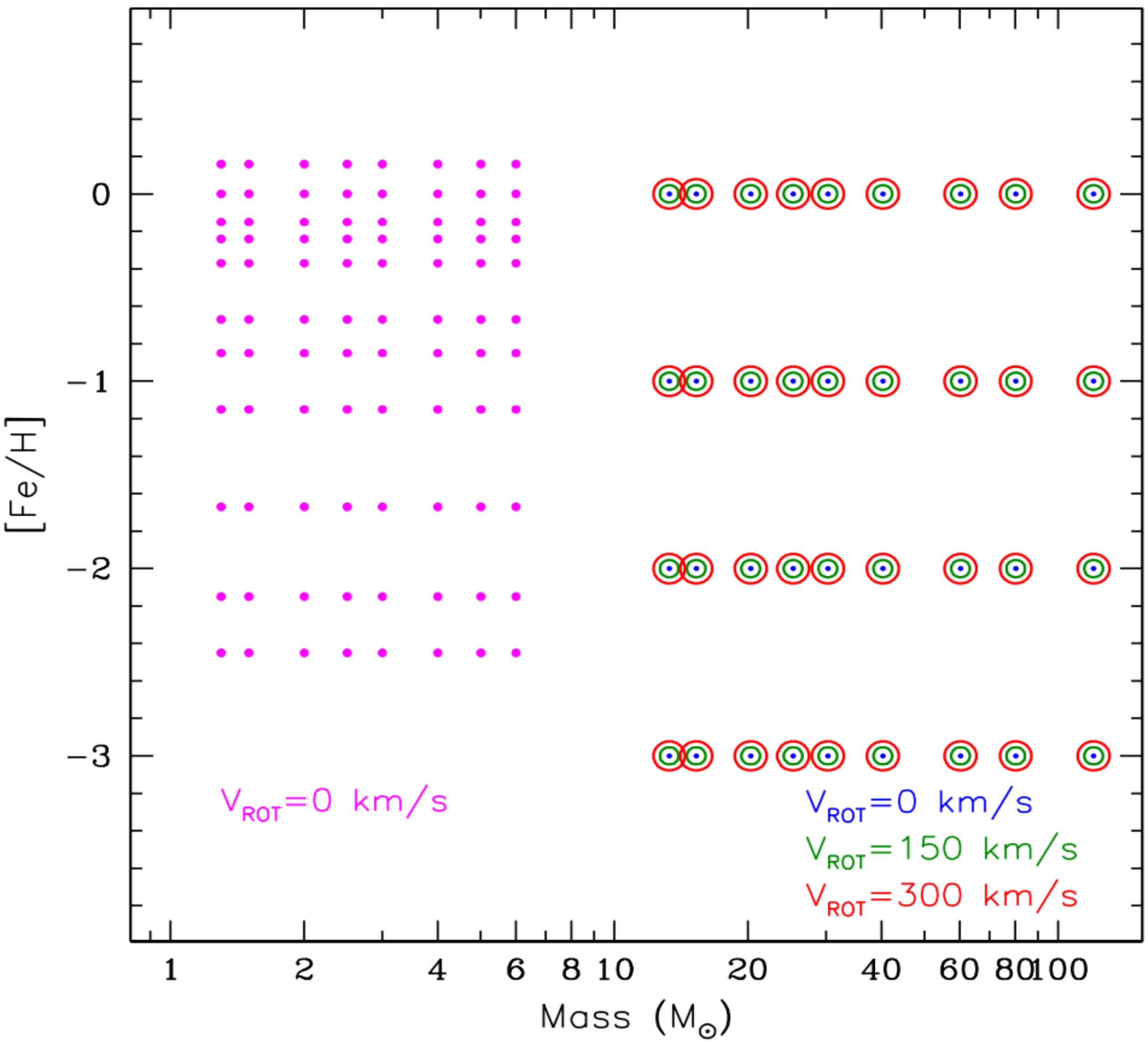
Increases sizes of convective cores and corresponding hydrostatic yields

Mixes protons in He-burning regions and products of H- and He-burning

boosting production of CNO,F,Ne22,S-process

and turns « *secondary* » elements into « *quasi-primary* » ones

## Adopted yields of Non Rotating LIMS *(Cristallo et al. 2015)* and Rotating massive stars *(Limongi and Chieffi 2018)*

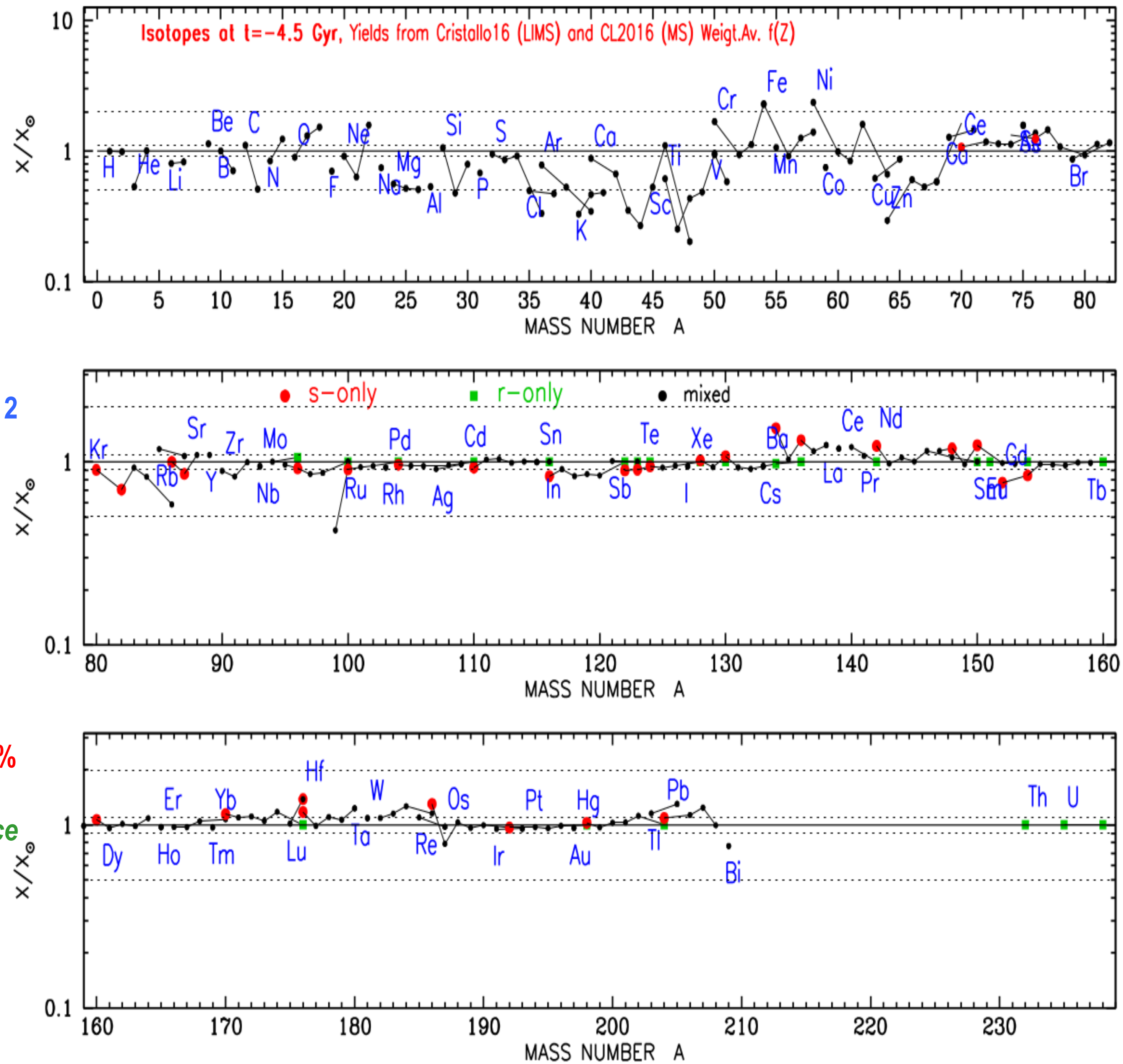



**How to chose which distribution of $V_{ROT}$ to adopt as a function of Z ?**

***A distribution function favouring more rotating stars at lowest metallicities***

**Producing primary N at [Z]~-3 and avoiding overproduction of s-nuclei at [Z]~-1**

# Isotopic abundances




**Up to Zn:**

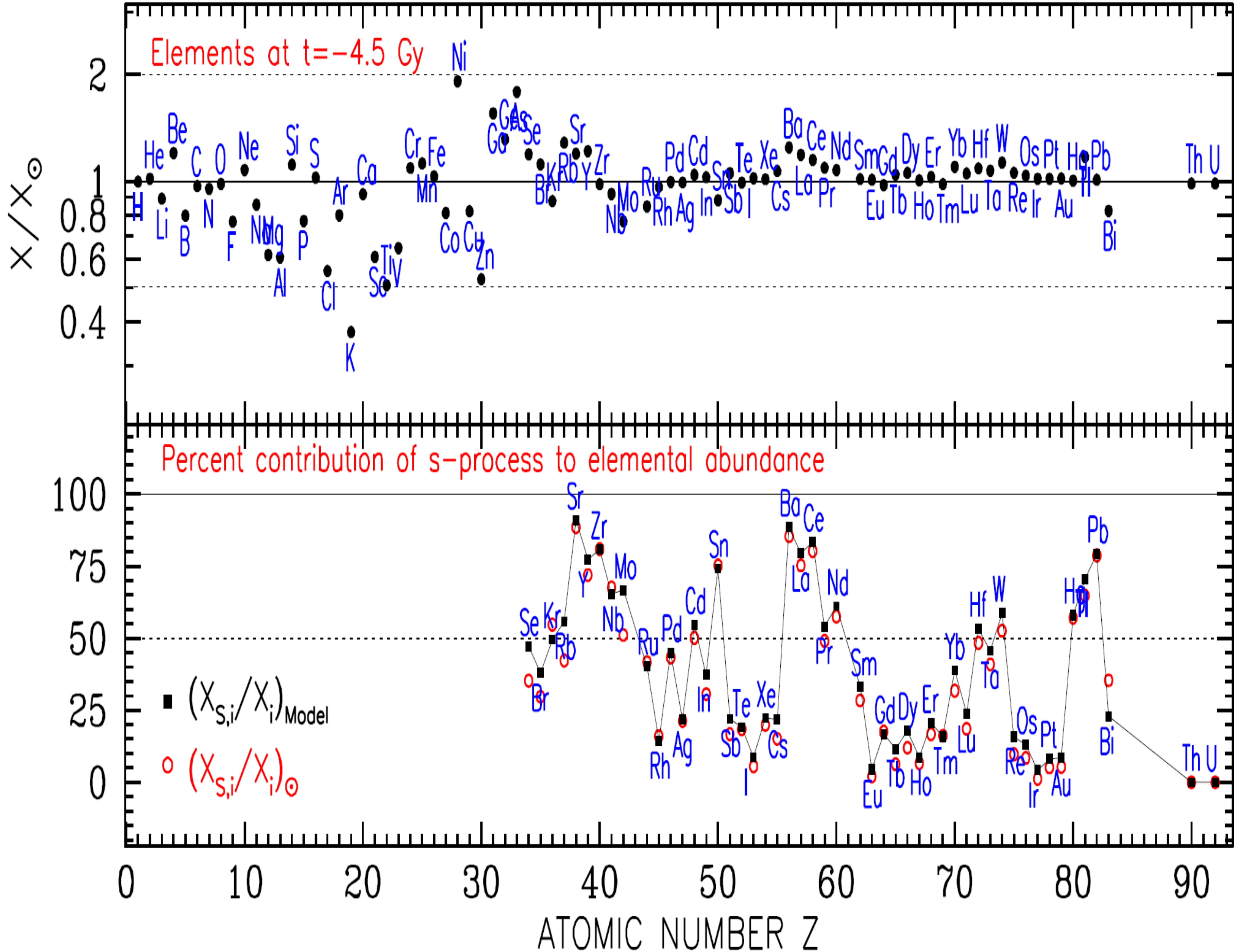
Better than a factor of 2

*Mg Al* Cl K Sc Ti V *Poorly* or underproduced

**Above Zn:**

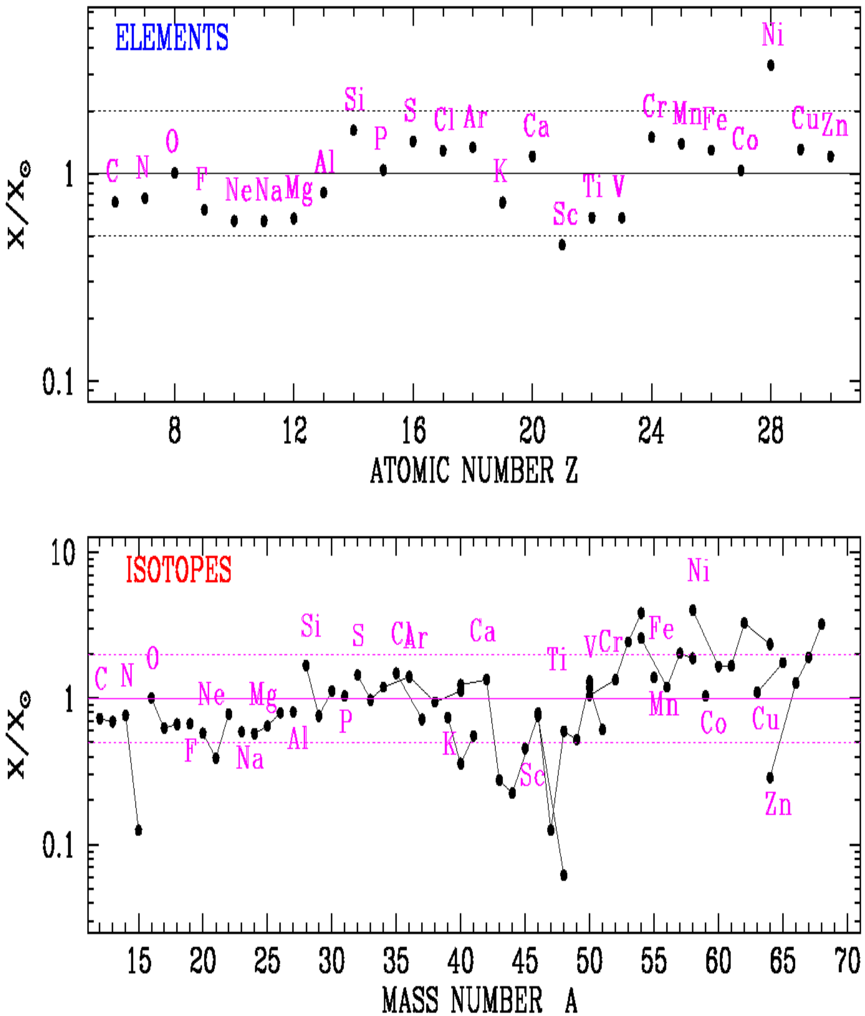
s- nuclei: Better than ~20%

*(r-yields fixed to reproduce solar r- component)*

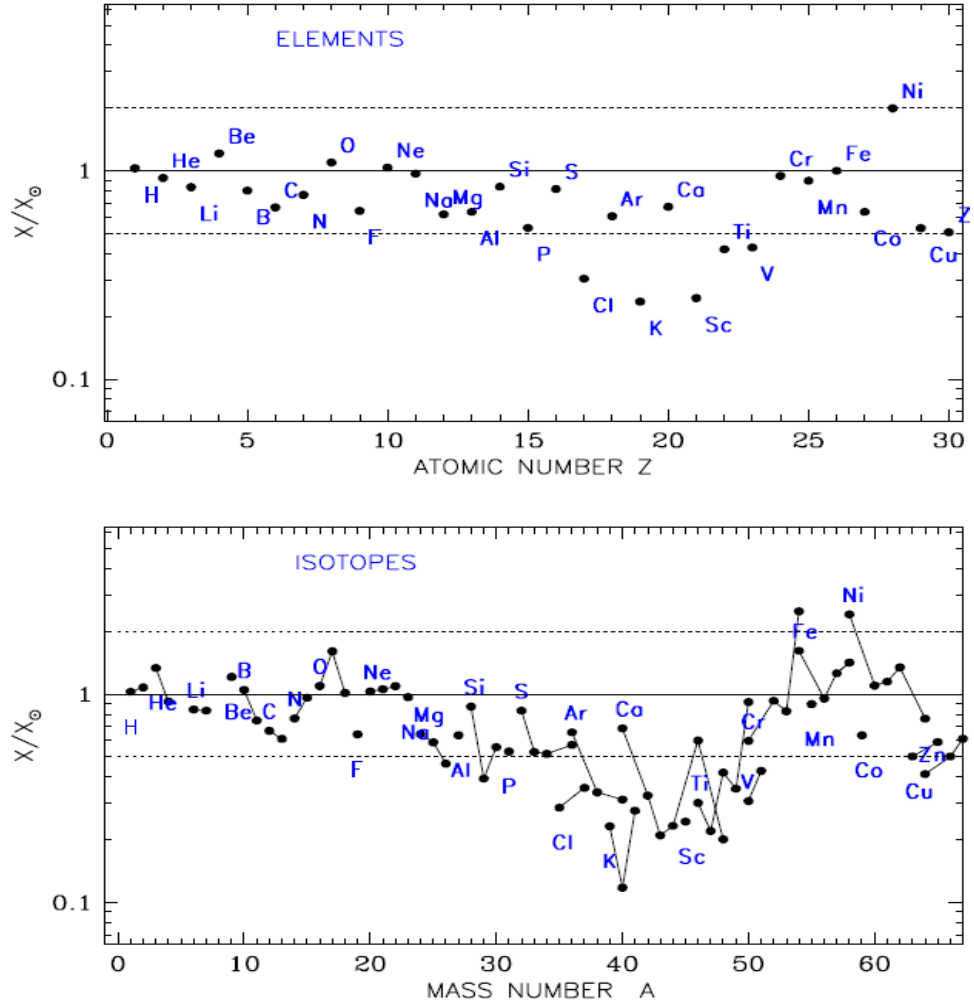


Elements at t=-4.5 Gy
Percent contribution of s-process to elemental abundance
$X/X_\odot$
$(X_{s,i}/X_i)_{Model}$
$(X_{s,i}/X_i)_\odot$
ATOMIC NUMBER Z

Yields from WW95



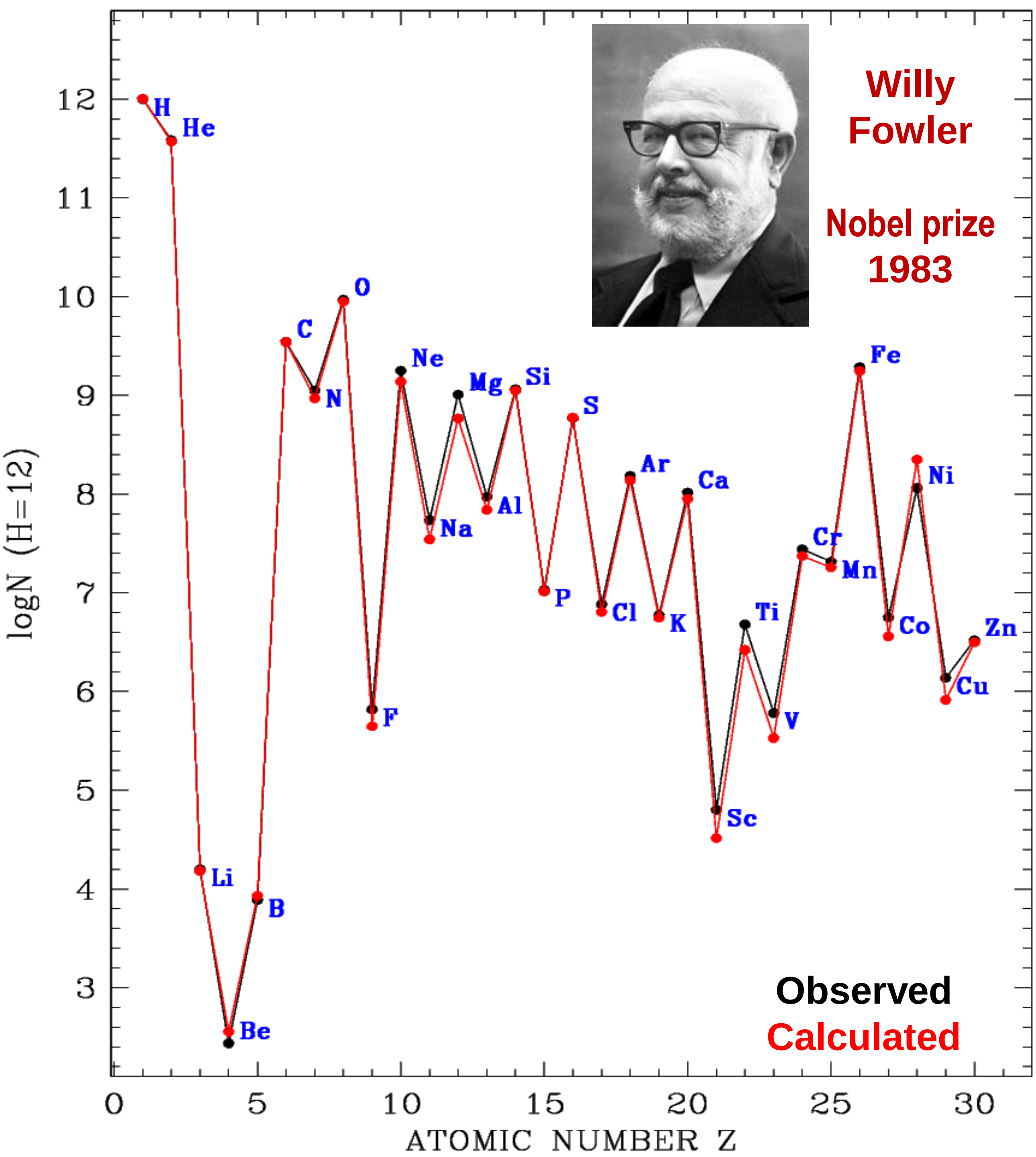

Yields from NKT2013

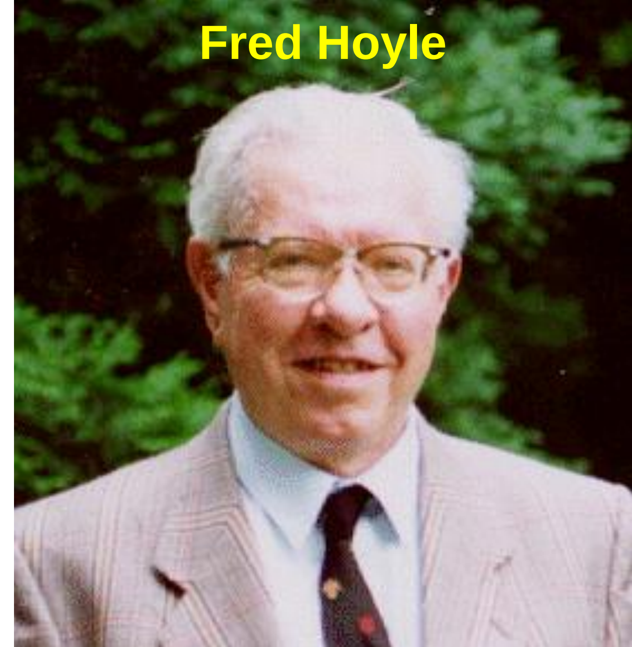


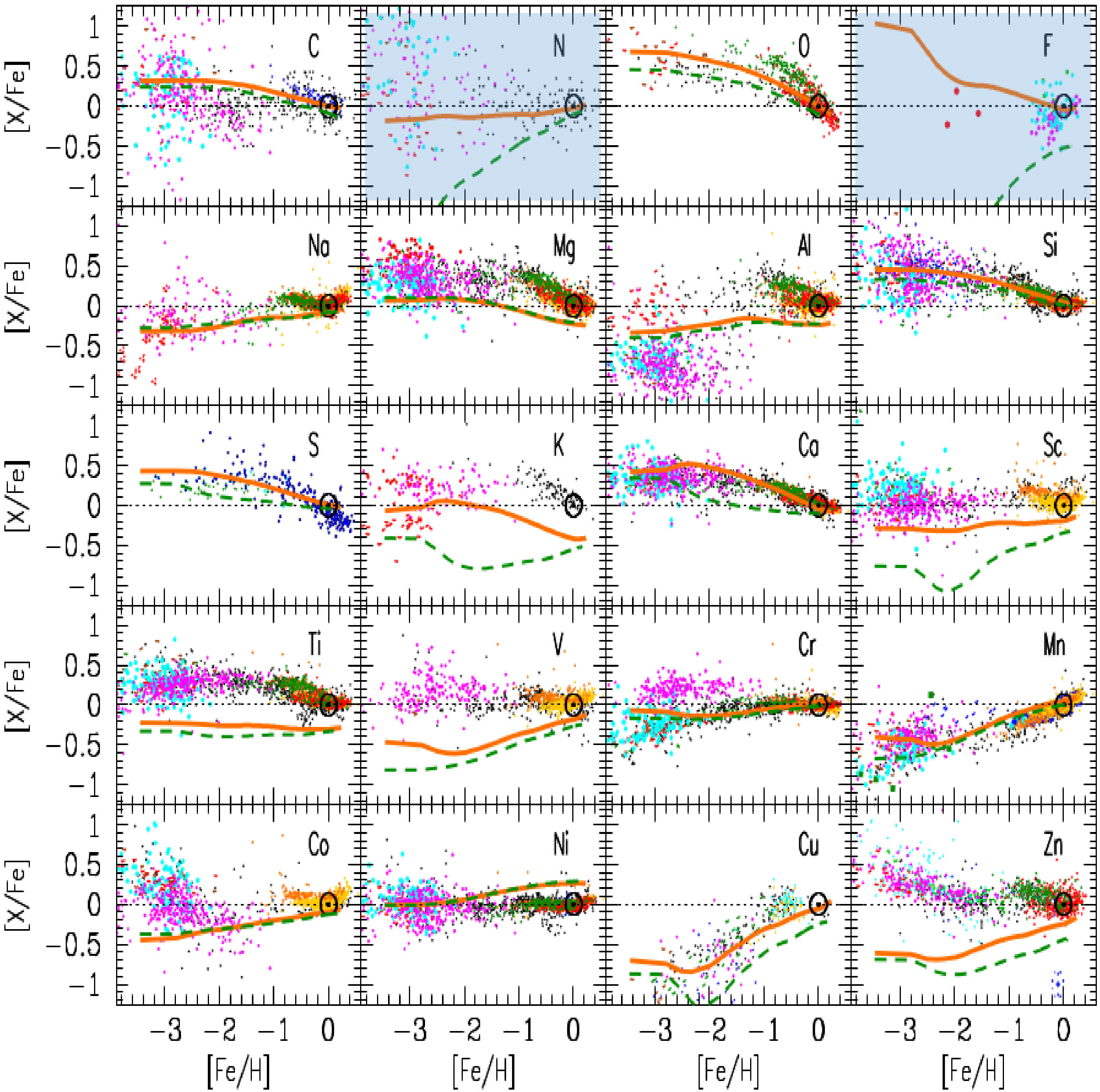

***Dispersion by a factor of 2:***

***Persistent problem for all sets of yields for (Cl), K, Sc, Ti V***

**Still, a triumph for stellar nucleosynthesis and chemical evolution !**


Willy
Fowler
Nobel prize
1983
logN (H=12)
ATOMIC NUMBER Z
0
5
10
15
20
25
30
3
4
5
6
7
8
9
10
11
12
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
Observed
Calculated


Fred Hoyle




**Chemical evolution with new yields of rotating stars**

**Rot vs Non Rot**

**Alpha/Fe evolution OK**

***Primary N ~OK***

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

***Primary F***

**Mn, Cu: OK**

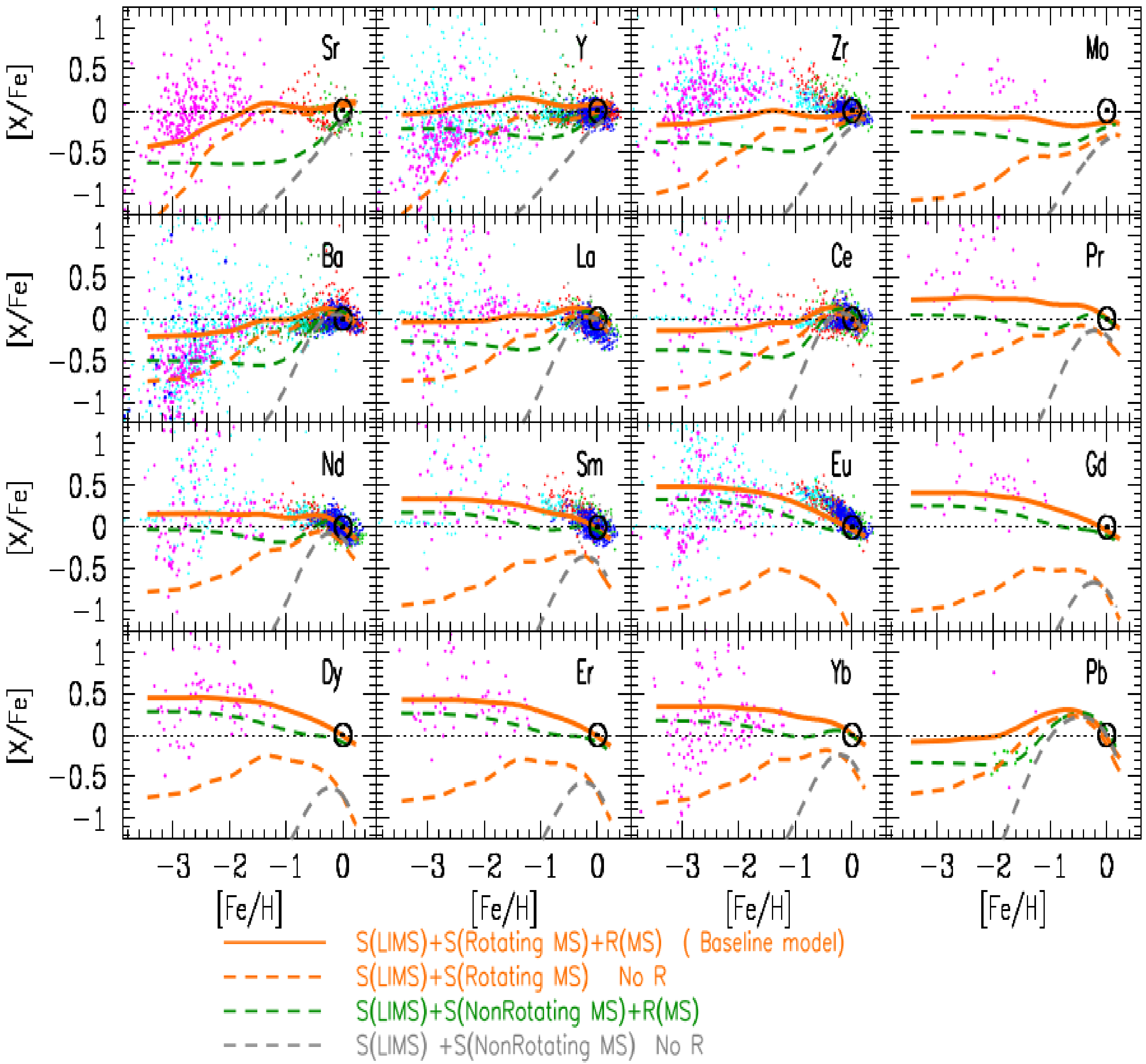
***Mg, Al: underproduced***

**Ti: *observ.* : like alpha**

***theory.* : like Fe**

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

**Ni: problem with W7 model of SNIa**




**Chemical evolution with new yields of rotating stars**

**Rot vs Non Rot**

**S-procces from LIMS is secondary and appears only at [Fe/H] > -1**

**S-process from rotating massive stars is quasi-primary, but at low metallicities it is overwhelmed by r-component (>90%)**

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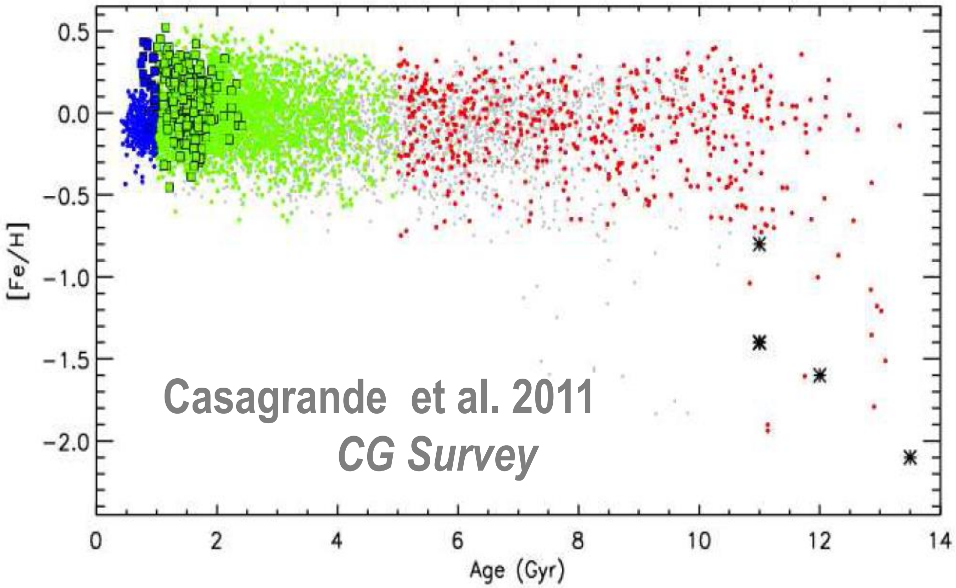
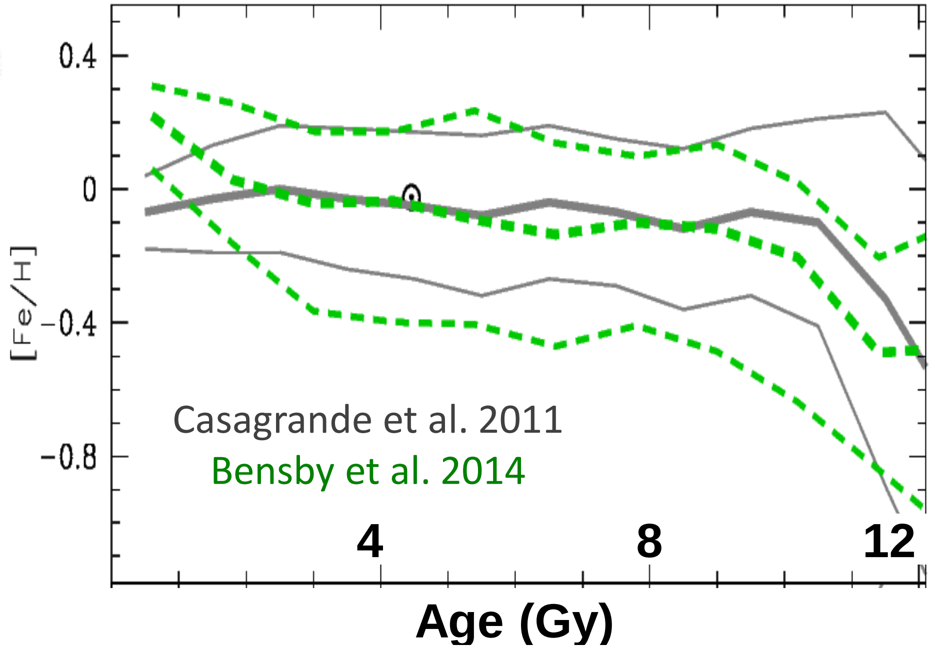
# Inadequacy of the simple models for the solar neighborhood
## *1. Age-metallicity relation in the solar neighborhood*




**Little metallicity evolution in the past 10 Gyr**

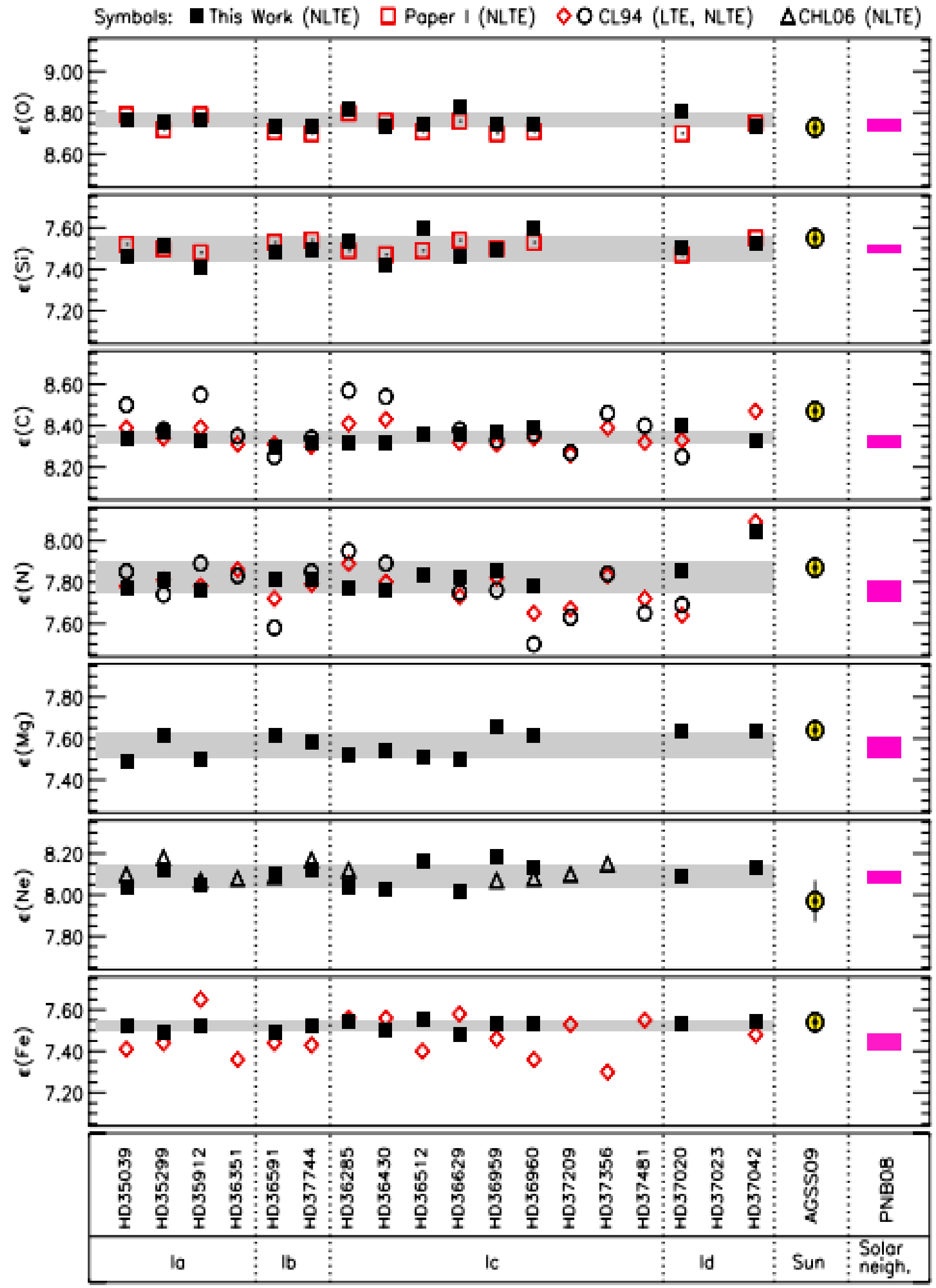
**Sizeable dispersion ± 0.2 dex (~60% at 1 σ) at all ages**



*Nieva and Simon-Diàz (2011):*
*11 OB-stars in Orion*

*Nieva and Przybilla (2012):*
nearby B-stars in the field
( within a few hundred pc from the Sun)
Fluctuations of less than 10% (0.04 dex) from the mean

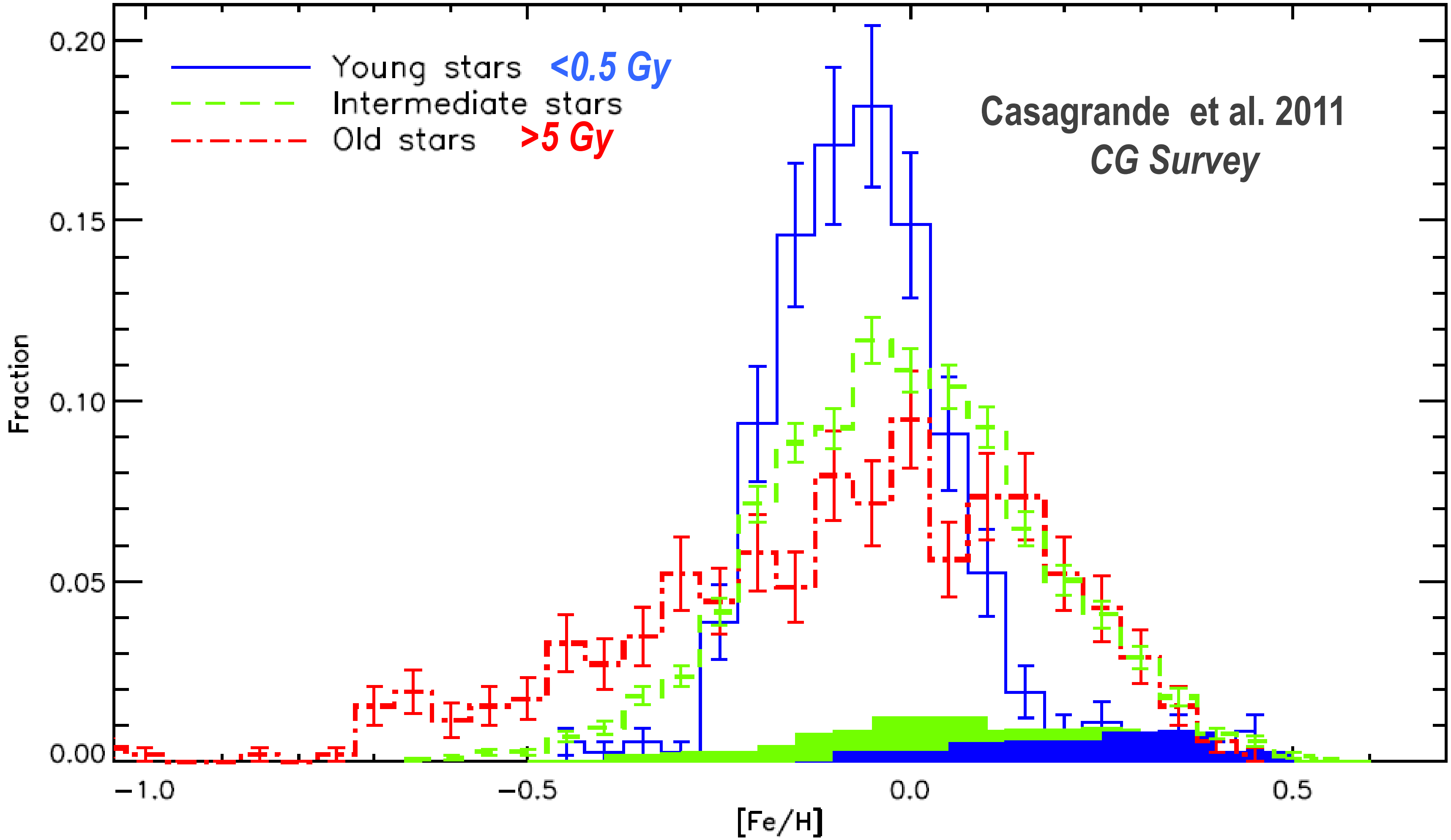
Same situation for local gas:
Solar to ~4% (Cartledge et al. 2006)




## The local metallicity is the same now and 4.5 Gy ago !

# Inadequacy of the simple models for the solar neighborhood

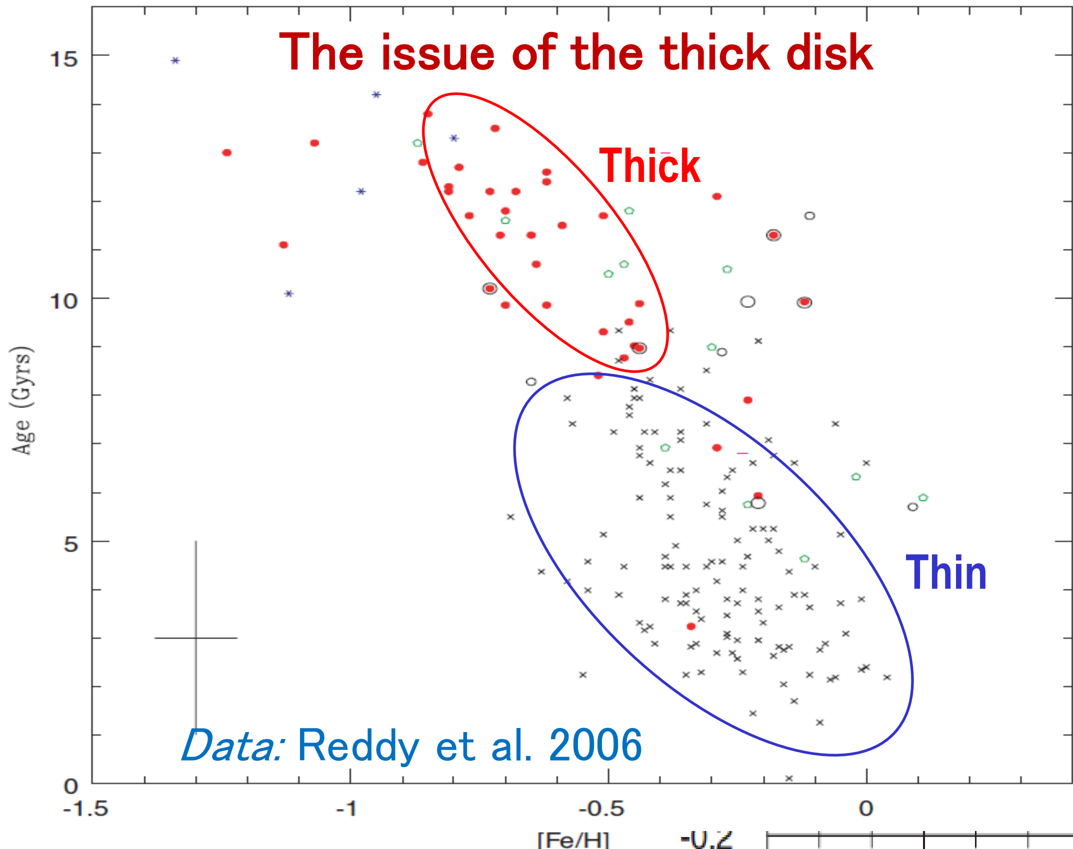
## *2. The metallicity distribution*

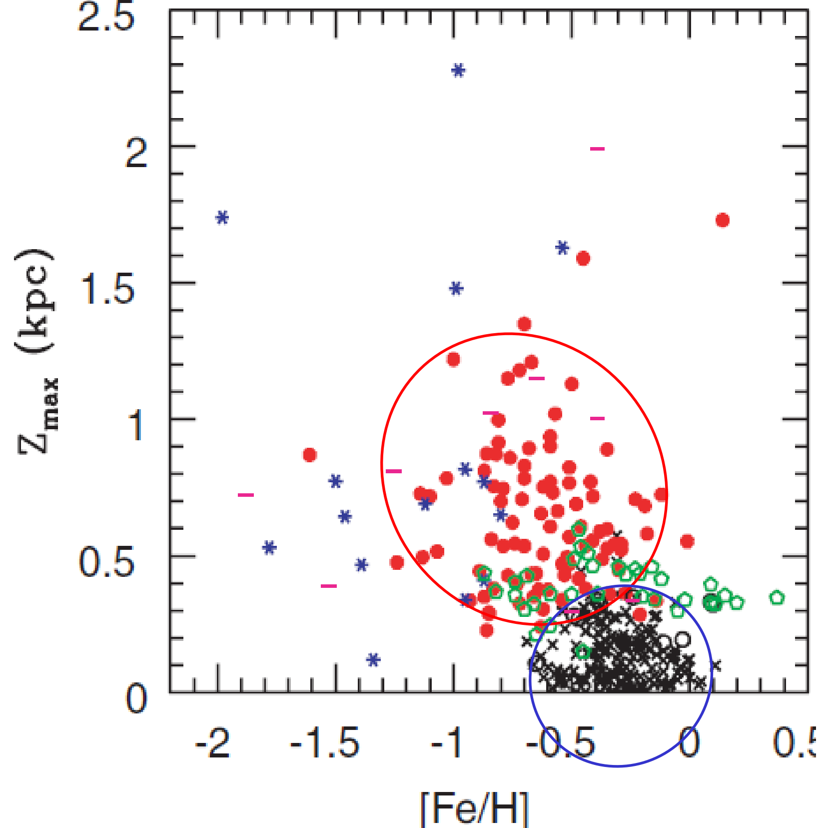


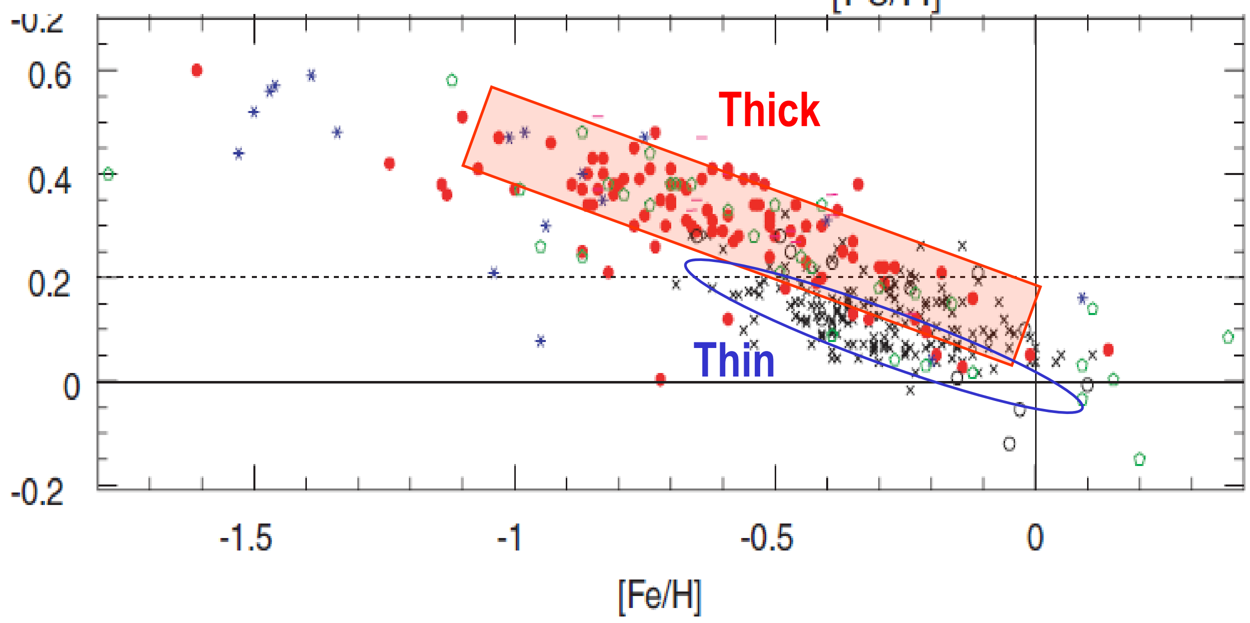

**Old *AND* young stars** of **both *high*** and ***low* metallicities**

- **the most metallic stars (2-3 Z☉) CANNOT be LOCAL**

**- they are NOT the youngest**




**Old** (>8-9 Gyr) stars,
have larger scaleheight,
velocity dispersion
and **higher O/Fe ratio**
than young (thin disk) stars
of the **same metallicity**

## Summary of features of the solar neighborhood impossible to reproduce with simple models of chemical evolution

- **Little metallicity evolution in the past 10 Gyr, on average**

- **Sizeable dispersion $\pm$ 0.2 dex (~60% at 1 $\sigma$) at all ages**

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

- **The most metallic stars (2-3 $Z_\odot$)are more metal rich than the local ISM and young stars ; they are NOT the youngest**

- **The two-branch behavior of O/Fe vs Fe/H in the local thick and thin disks**

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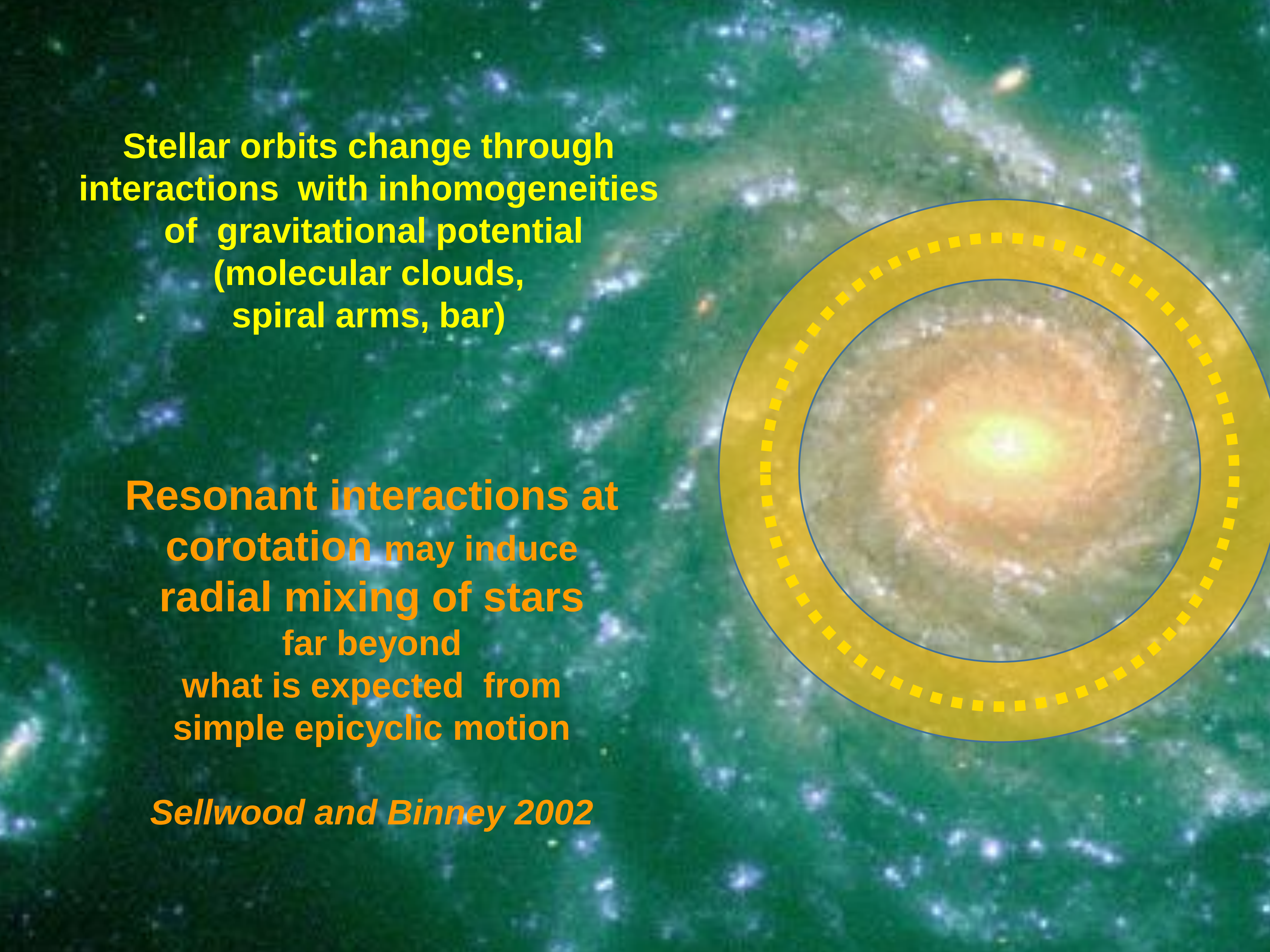

Stellar orbits change through
interactions with inhomogeneities
of gravitational potential
(molecular clouds,
spiral arms, bar)
Resonant interactions at
corotation may induce
radial mixing of stars
far beyond
what is expected from
simple epicyclic motion
Sellwood and Binney 2002

*DISK: NOT independently evolving rings*

***1-zone models INADEQUATE***

**Interaction between different rings**

***Radial inflow of gas***

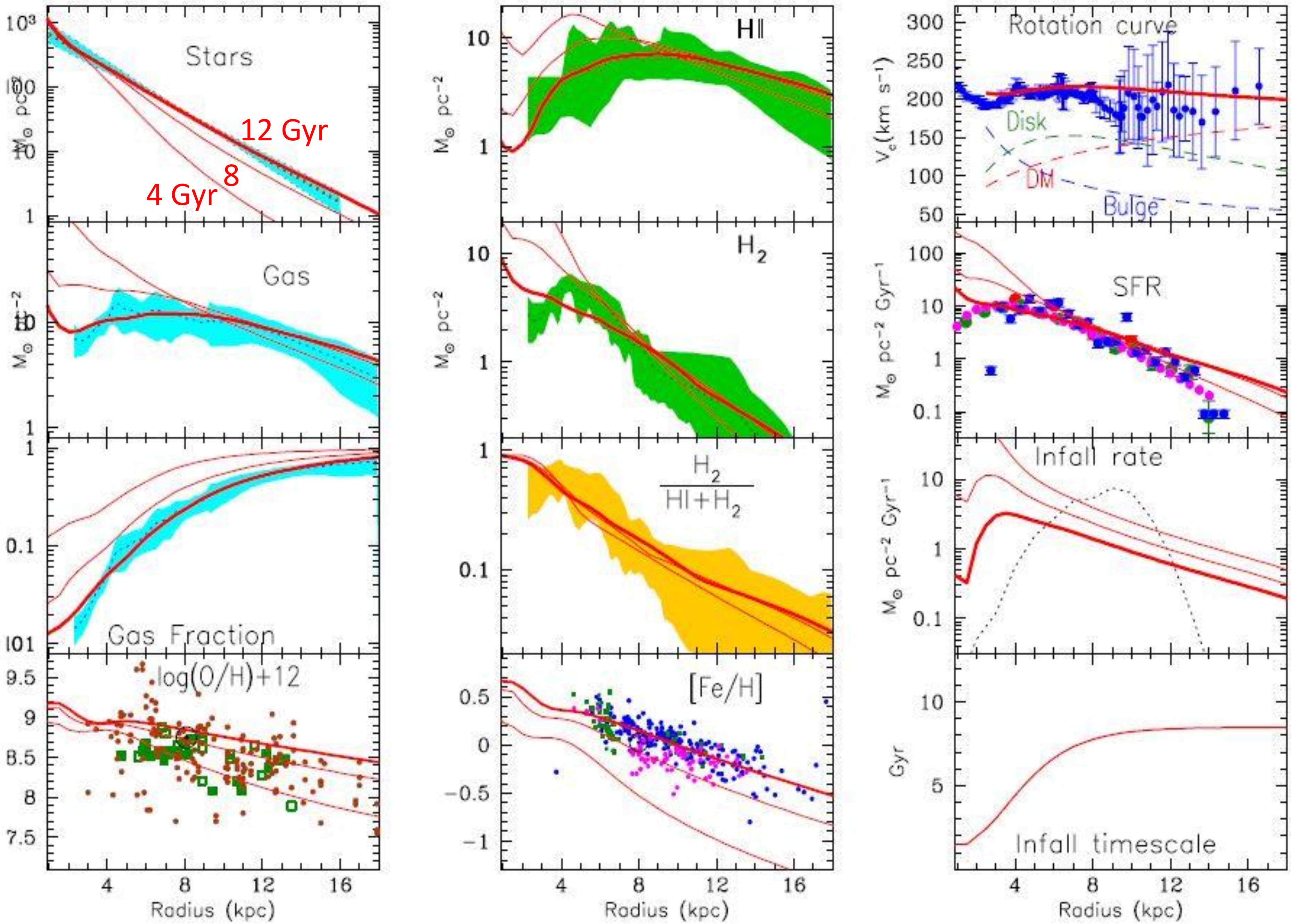
***Radial mixing of stars***

*Sellwood & Binney 2002*
*Schoenrich & Binney 2009*
*Minchev et al. 2013a,b*
*Loebman et al. 2010*
*Grant and Kawata 2013*

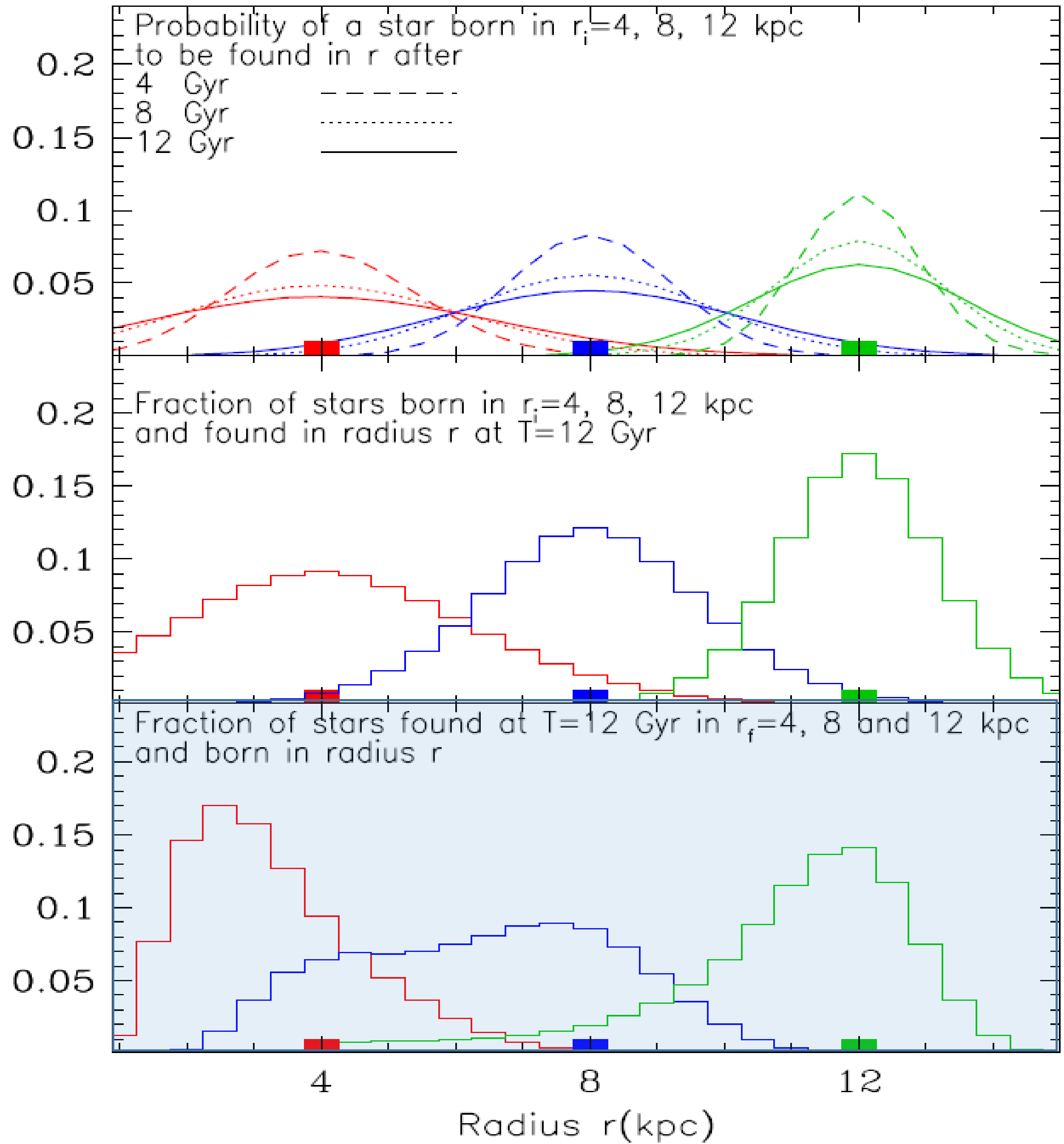
***Kubryk, NP, Athanassoula AA 2013, 2015a,b***

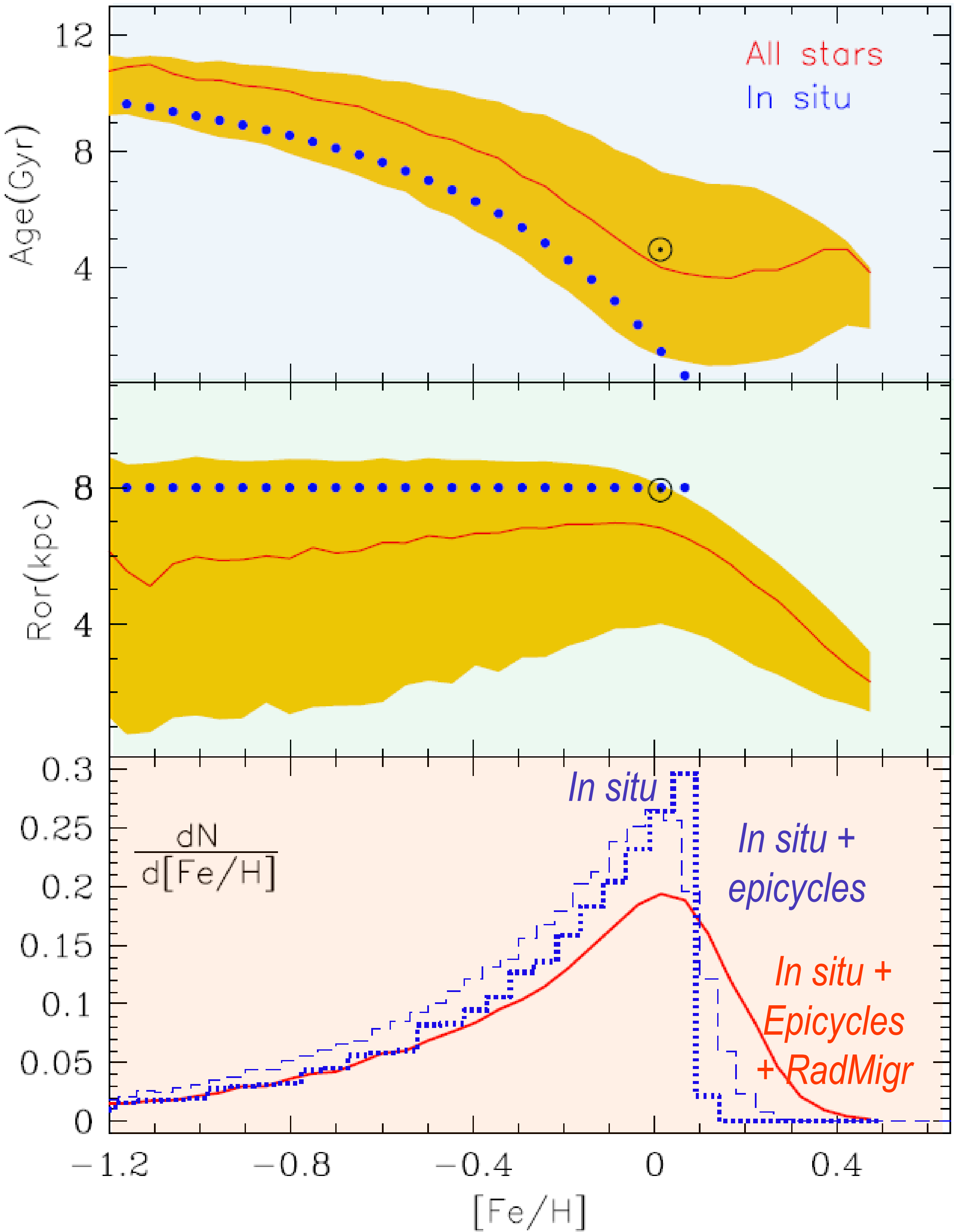
**1D semi-analytical model with parametrized infall in a DM halo,**
**SFR from H2, observed DTD for SNIa rate, detailed chemical evolution**
**(H to Zn, with Z-dependent yields from massive and LIM stars)**
***radial motions of gas (parameterised radial inflow)***
***radial migration of stars*** **(inspired from N-body simulations)**

# Comparison to present-day profiles of MW disk



# Probabilistic treatment of radial migration: transfert coefficients





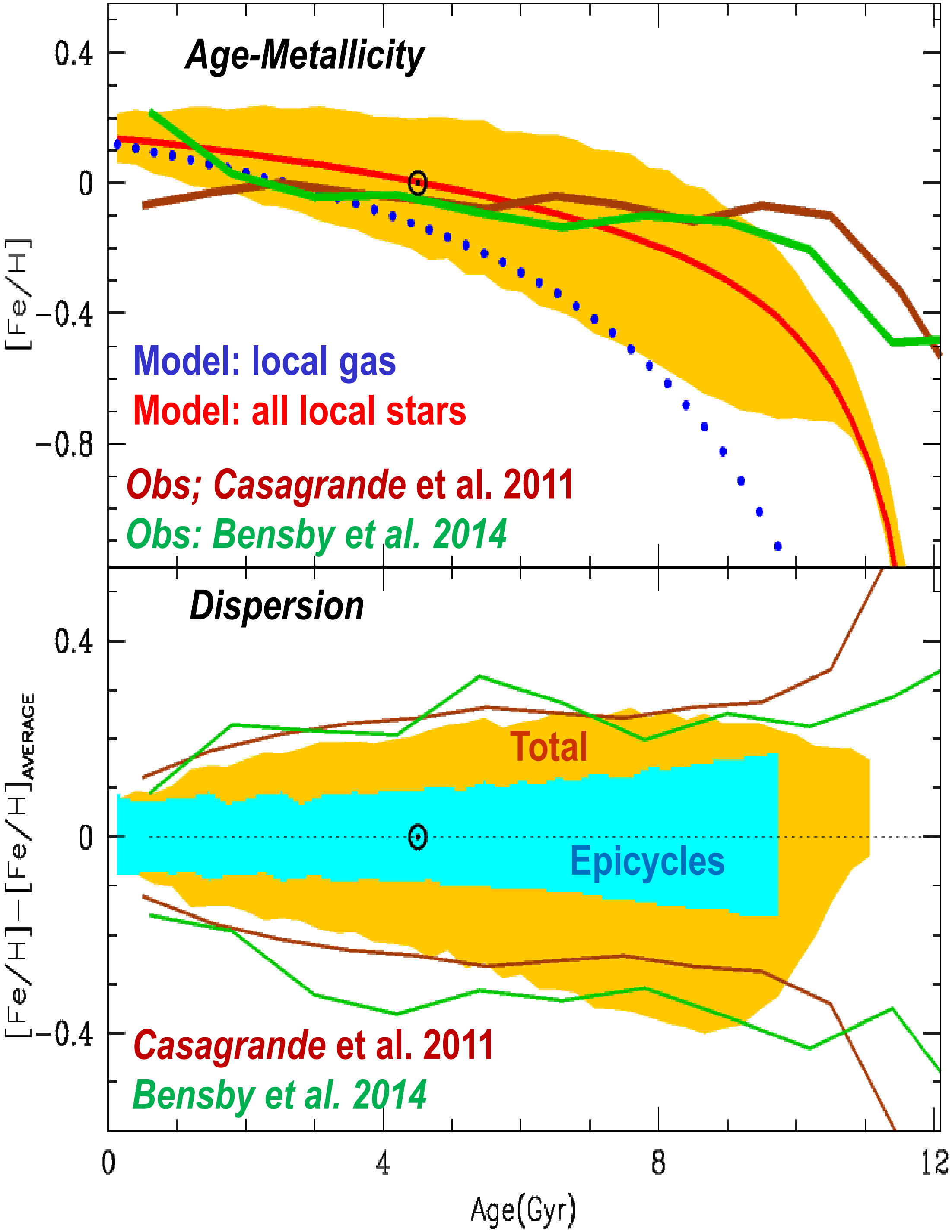

## Solar Neighborhood

***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**




# Solar Neighborhood
## Radial Migration

1. Modifies the apparent local SFR *(Röskar et al. 2008)*

2. Creates dispersion in the age-metallicity relation… *(Sellwood and Binney 2002)*

3. …more than the epicyclic motion (~0.08 dex)

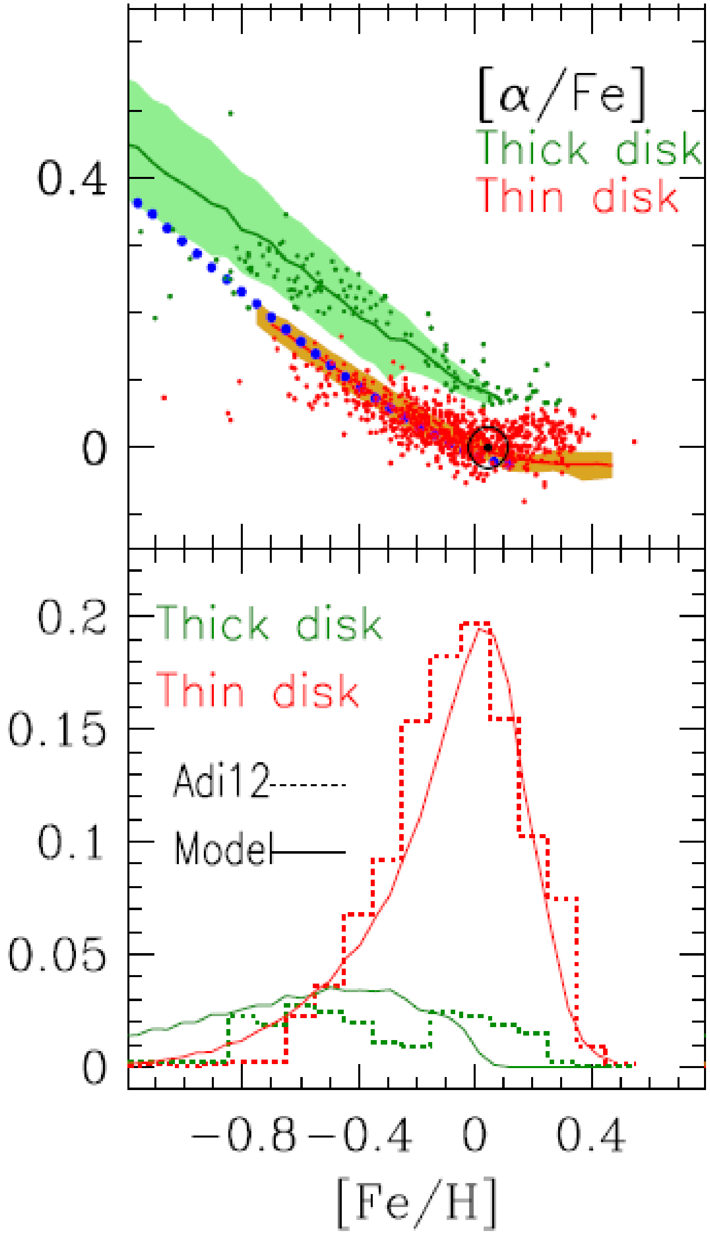
and comparable with observations (~0.2 dex)

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

**we recover the**
**Double branch**
**[a/Fe] vs Fe/H behavior**
***(Schoenrich and Binney 2009)***
***because O and Fe sources***
***have different timescales***

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

*Data*: Adibekyan et al. 2012

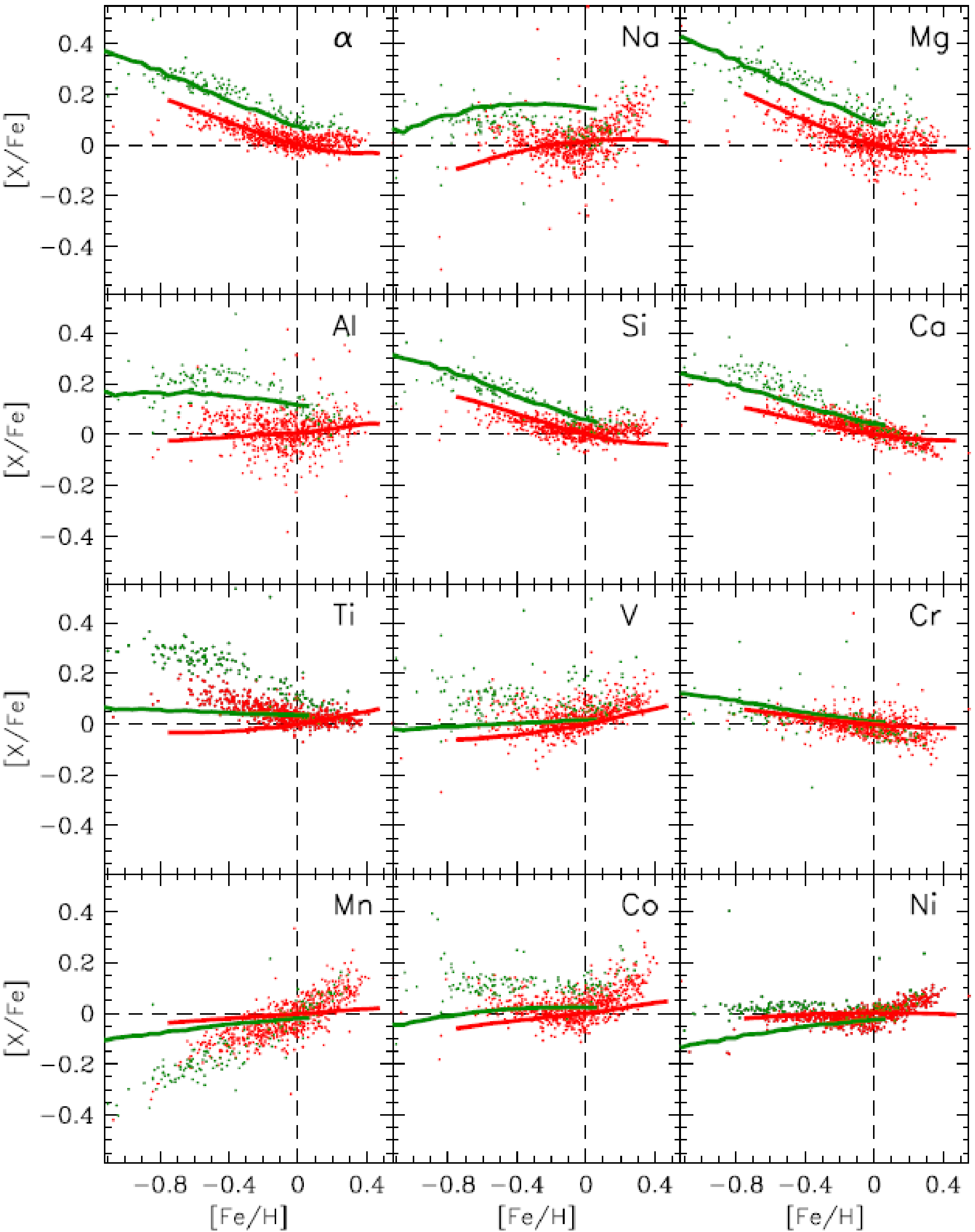



**Stars in the local**
**thick disk**
**and in the metal-rich**
**thin disk**
**mostly from**
**the inner disk**
**(3-4 kpc)**
**with more rapid**
**star formation**

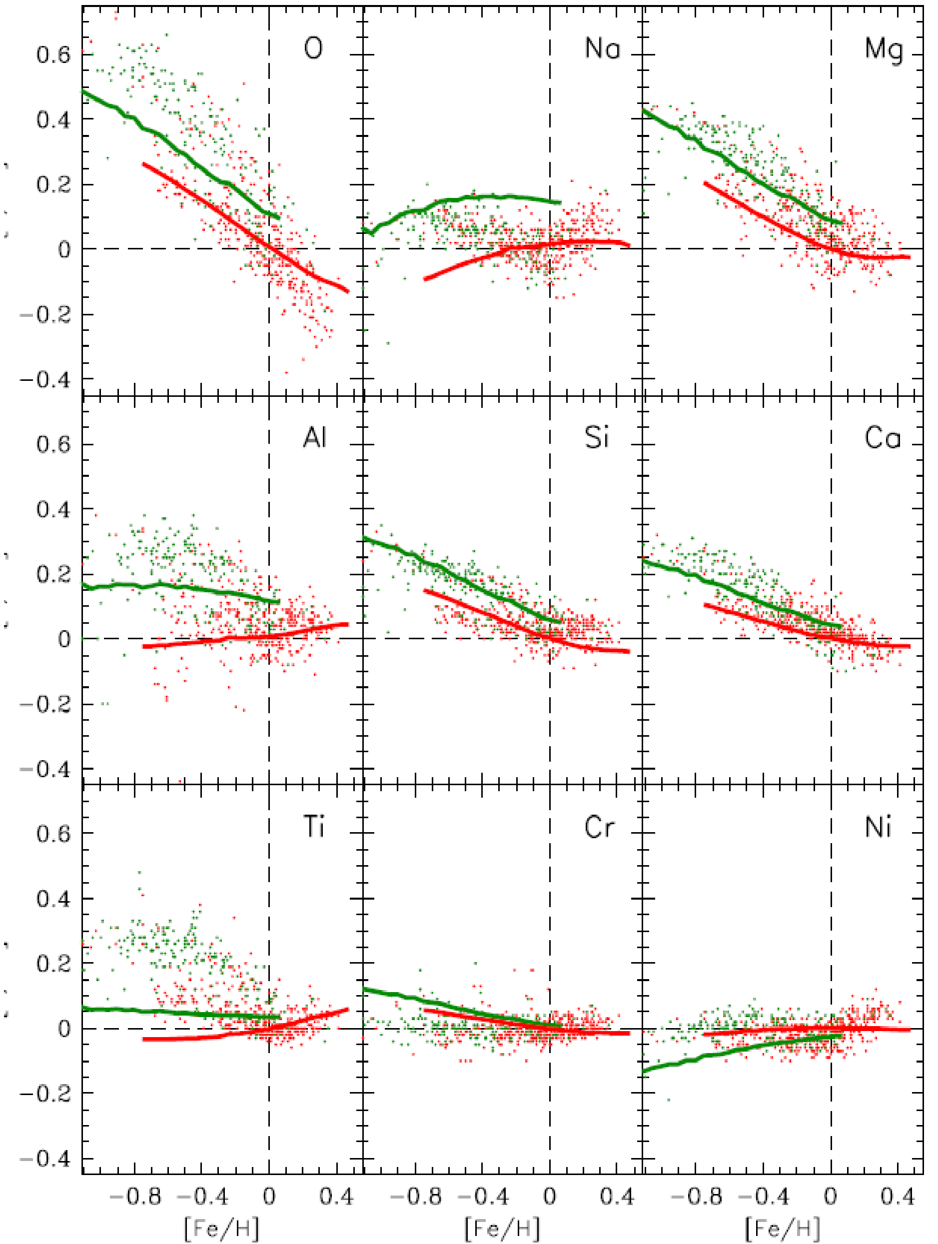
# Evolution of thin (<9 Gyr) and thick (>9 Gyr) disks

## Double [X/Fe] sequences obtained for elements with different formation timescales

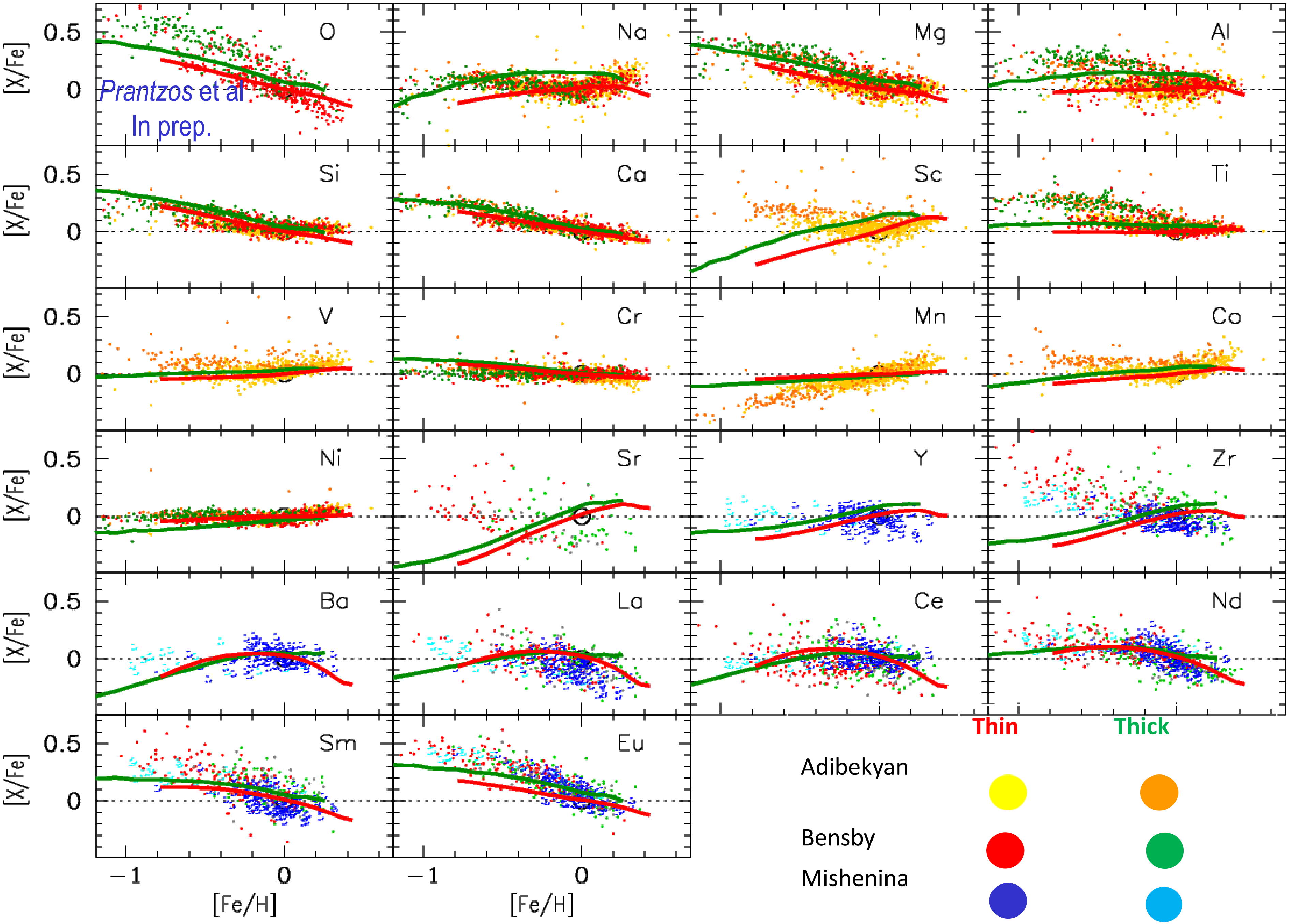
*Data*: Adibekyan et al. 2011

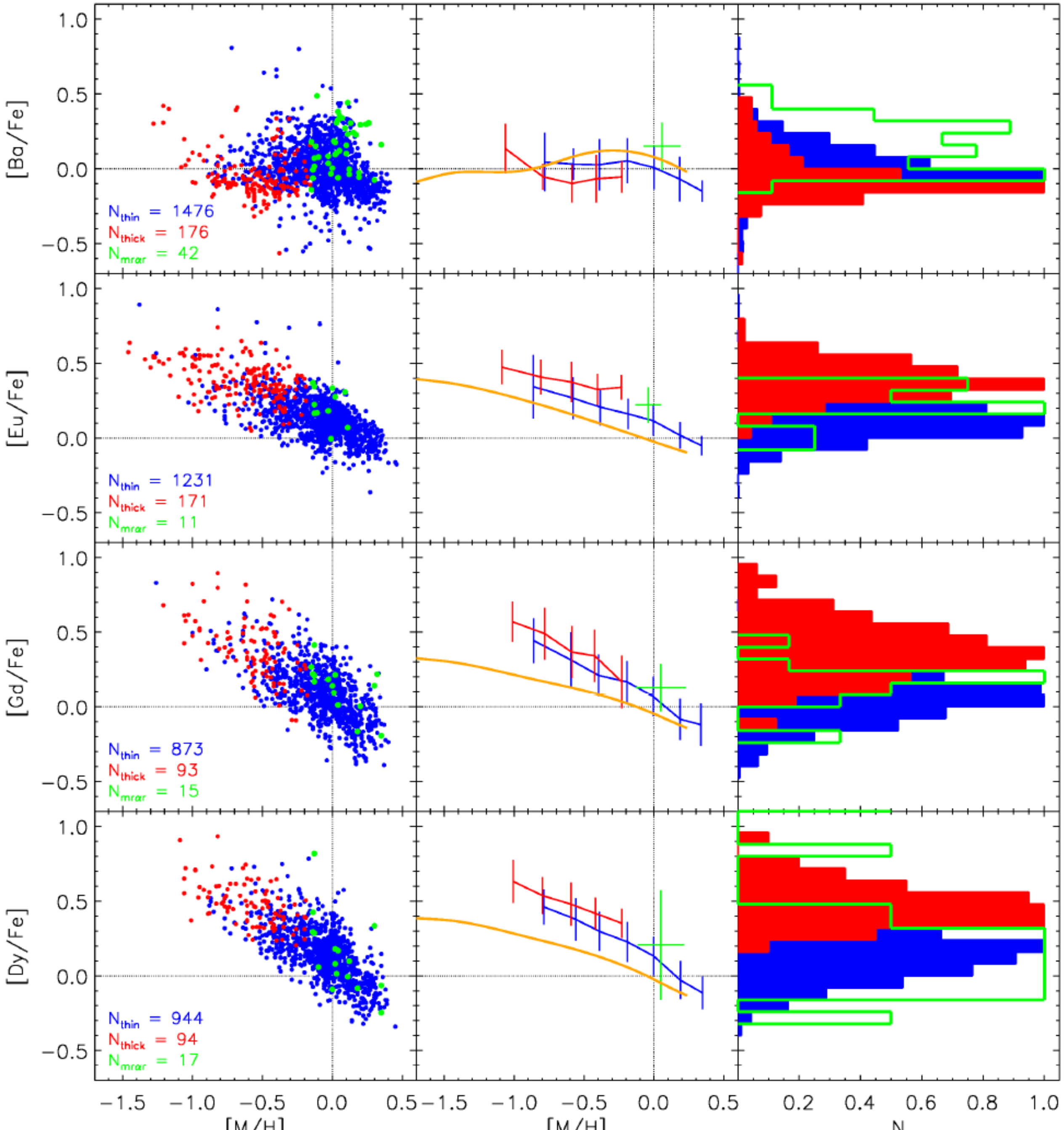



*Data*: Bensby et al. 2014



Calculations with new yields *(Rome)* for massive and LIM stars for all isotopes up to Pb (including s-nuclei)




[Ba/Fe]
[Eu/Fe]
[Gd/Fe]
[Dy/Fe]
N_thin = 1476
N_thick = 176
N_mrar = 42
N_thin = 1231
N_thick = 171
N_mrar = 11
N_thin = 873
N_thick = 93
N_mrar = 15
N_thin = 944
N_thick = 94
N_mrar = 17
[M/H]
[M/H]
N

## Radial migration in MW disk may explain

1. Dispersion in local age-metallicity

2. Presence of metal-rich stars locally

3. Presence of old metal-rich and young metal-poor stars locally

4. Double sequence of O/Fe in local thin and thick disks

5. Double sequence of Li/H in thin and thick disks *(NP, Guiglion, De Laverny, Recio-Blanco2017)*

**Different evolution of X/Fe in thin and thick disks will help constraining stellar nucleosynthesis for -1< [Fe/H] < 0.5**

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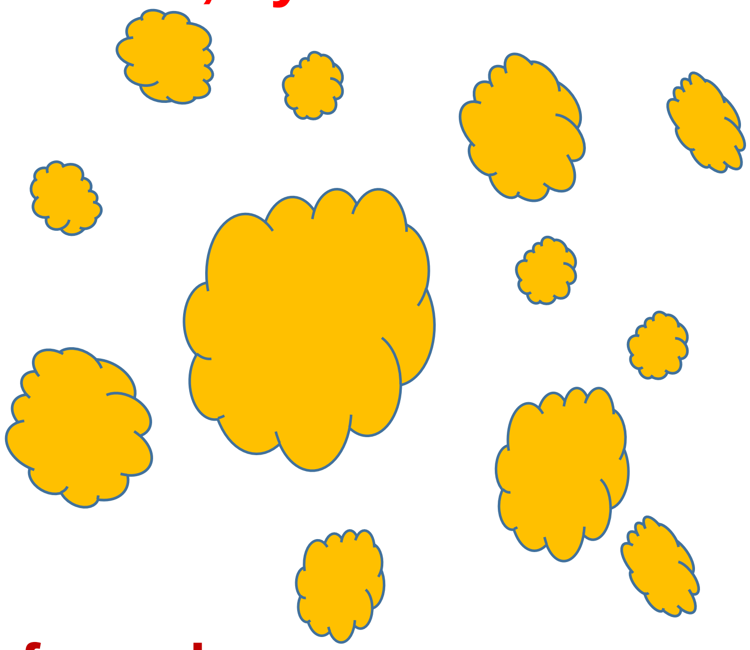
# The Galactic halo ( [Fe/H] <-1)
## not a single, uniform, system

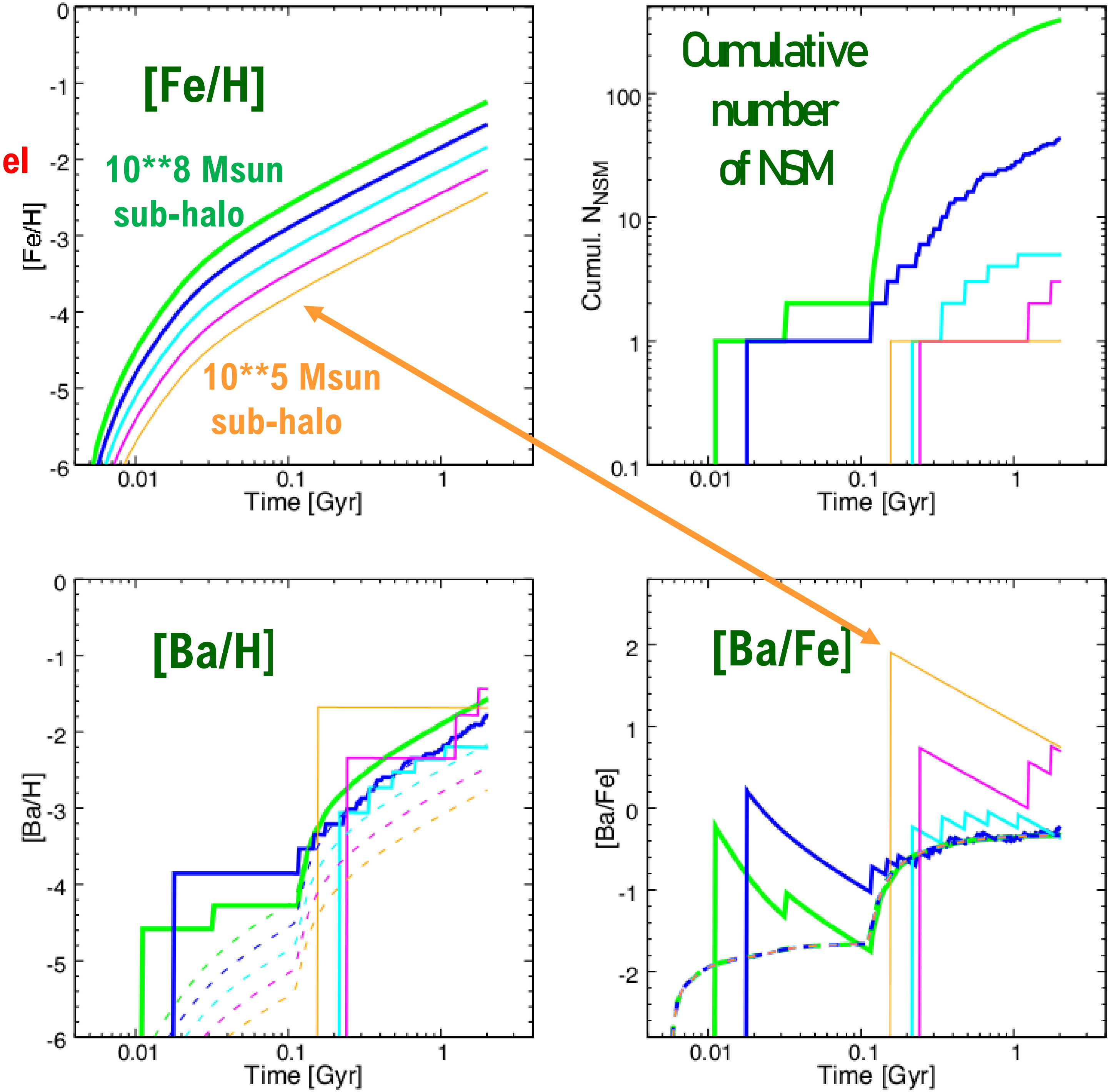


**Hierarchical merging of hundreds of smaller subhaloes evolving at different rates**

**Elements formed in sites evolving on different time scales will be affected in different ways** ***(NP in NIC 2006)***

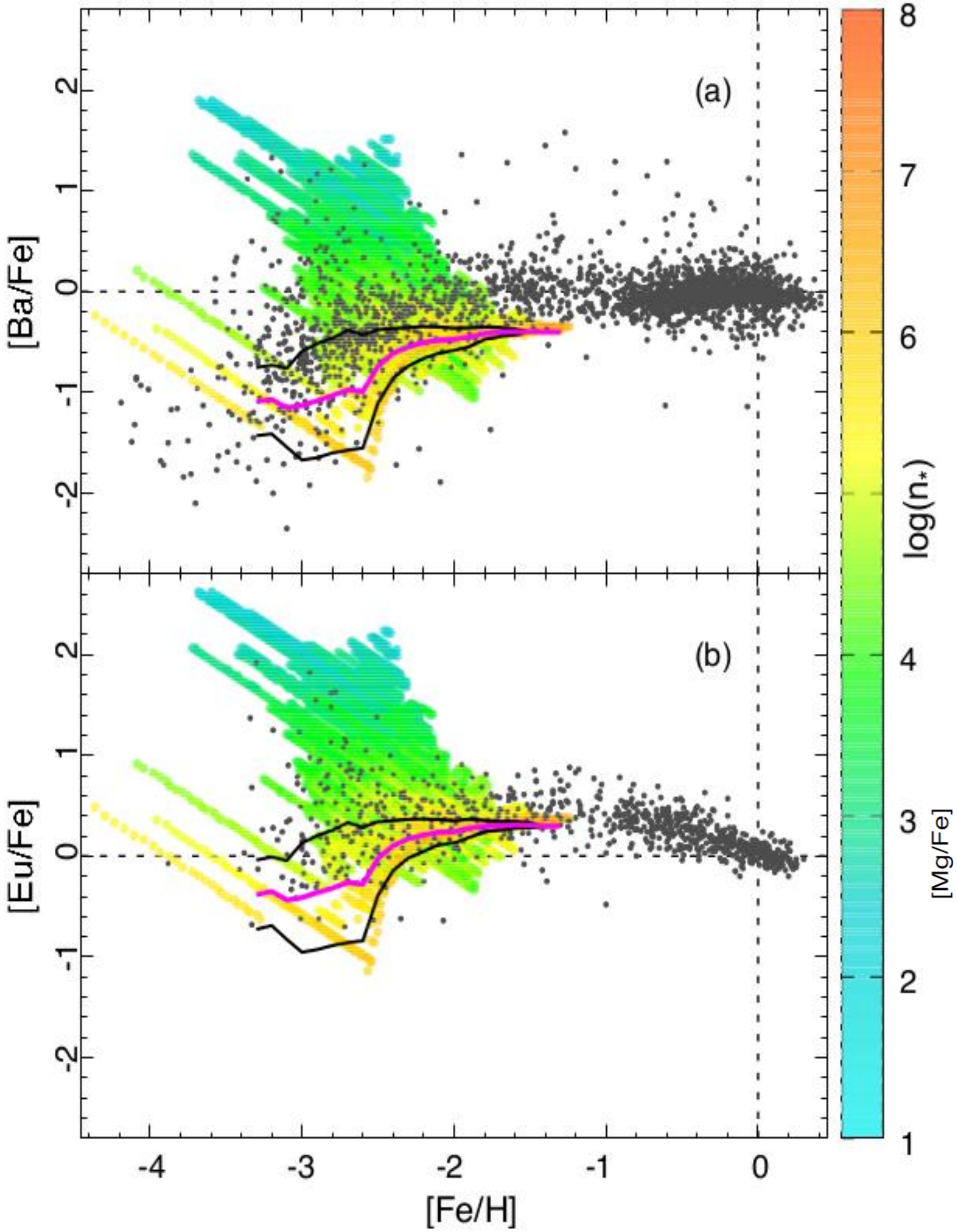
**e.g. Fe from CCSN (*short timescale, a few My)***
**and r- from NSM *(longer timescale, 10-100 My)***

**Stochastic evolution of r-elements from NSMs *(rare events)* in multi- subhalo model**




**Y. Ishimaru, S. Wanajo, NP 2015**

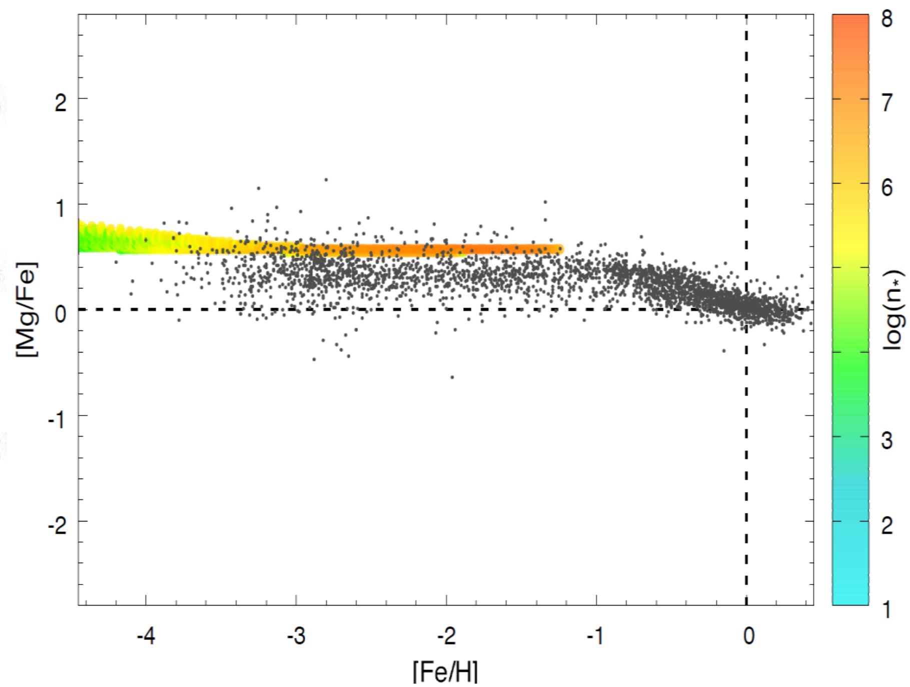
**T. Ojima, Y. Ishimaru, S. Wanajo, NP P. François 2018**




**The multi-sub-halo model can explain large dispersion of Heavy/Fe ratios at low Z if heavies produced in rare sites**

**AND**

**Low dispersion of alpha/Fe (produced in the same site)**



**Simple, one-zone models, inadequate to describe the evolution of either the Mily Way halo or disk**