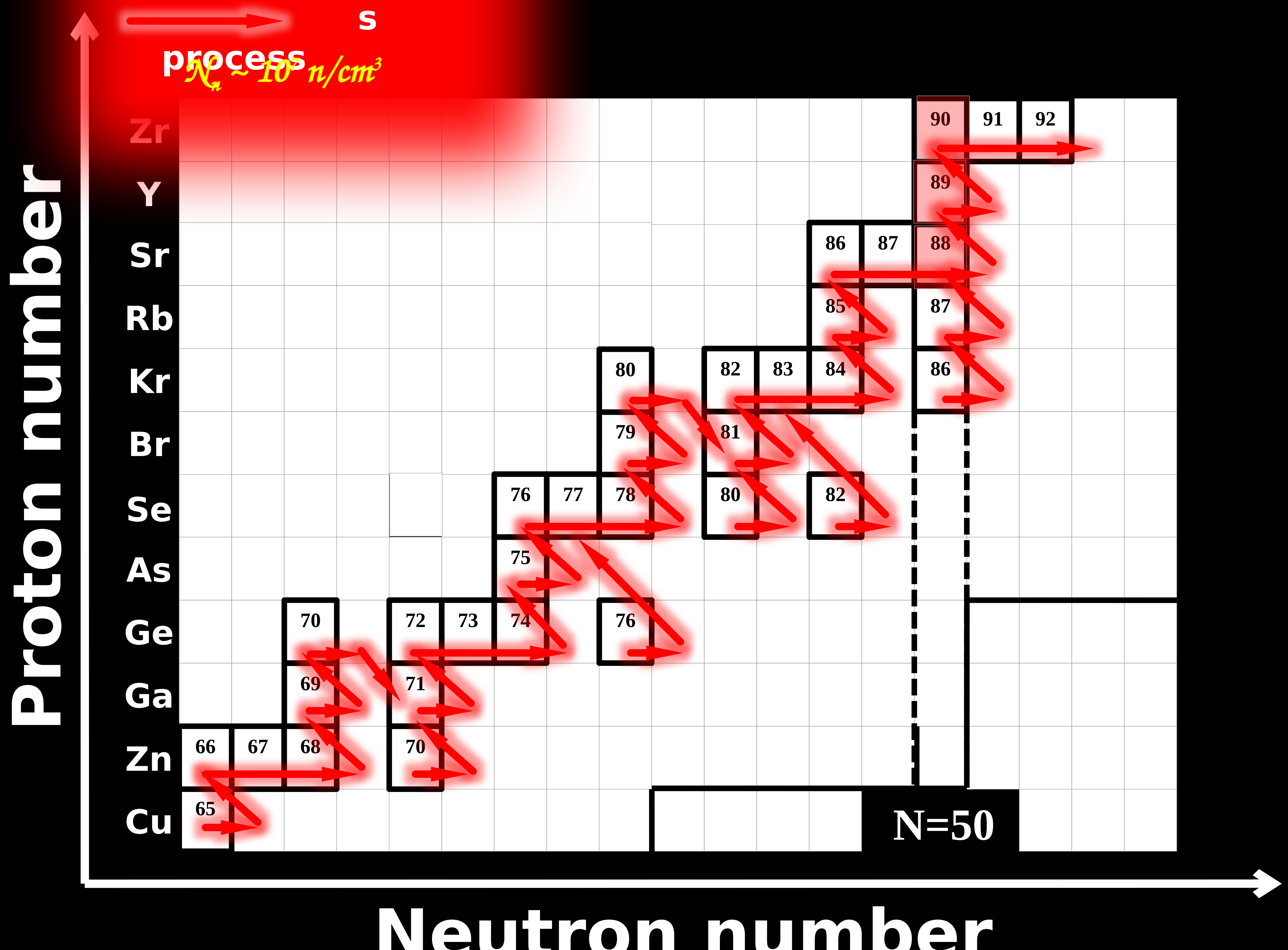
News from theoretical AGB models: are we going in the right direction?

S. Cristallo & D. Vescovi

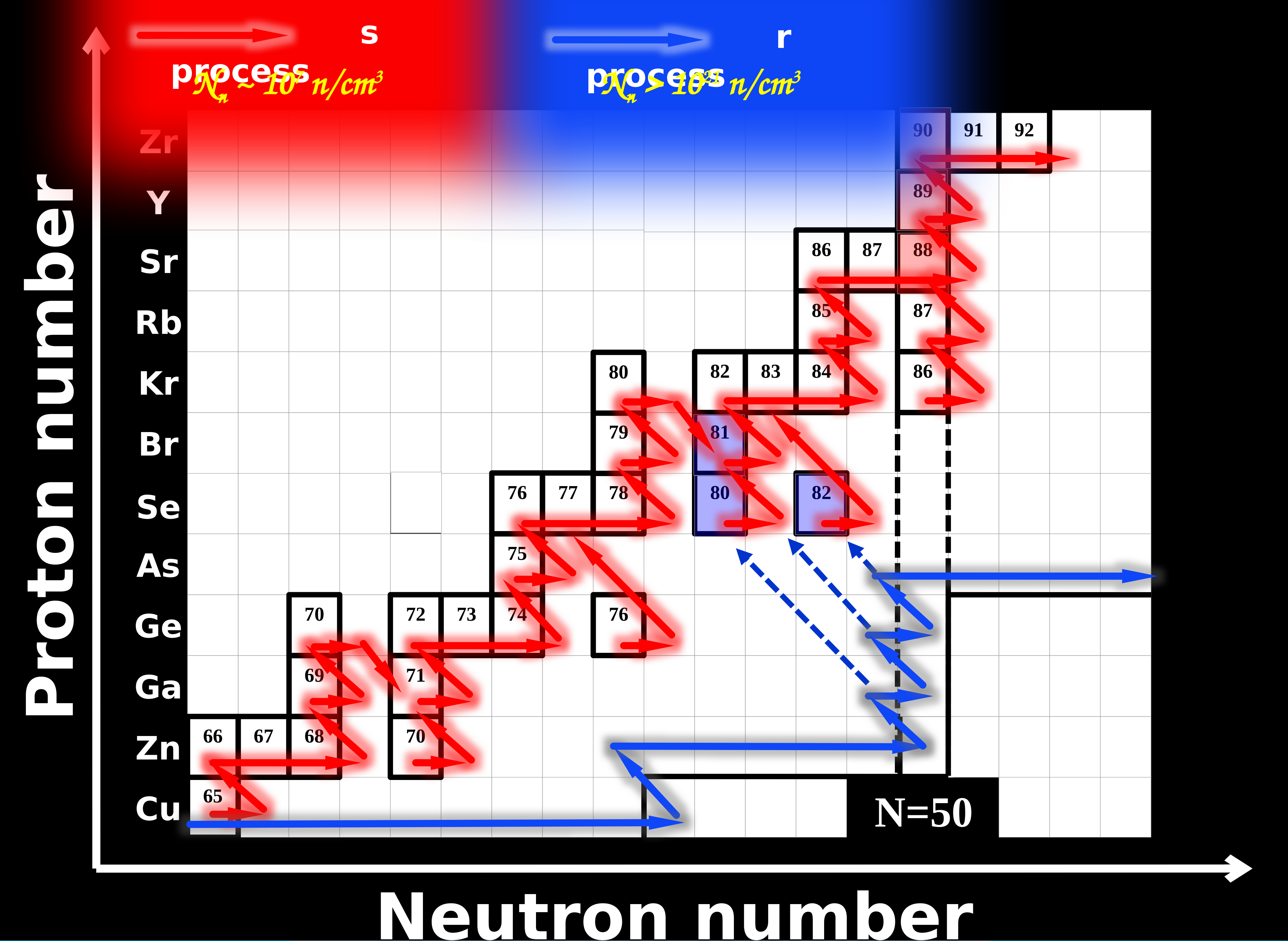
INAF - Osservatorio Astronomico d'Abruzzo

OUTLINE

- **Brief introduction to AGB stars and the s-process**
- **<u>PAST & PRESENT</u>: the FRUITY database**
- **<u>FUTURE</u>: magnetic models**
- **Comparison to observations**



s
process
$N_n \sim 10^7$ n/cm^3
Proton number
Zr
Y
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90
91
92
89
86
87
88
85
87
80
82
83
84
86
79
81
76
77
78
80
82
75
70
72
73
74
76
69
71
66
67
68
70
65
N=50
Neutron number


s
process
r
process
Proton number
Neutron number
Zr
Y
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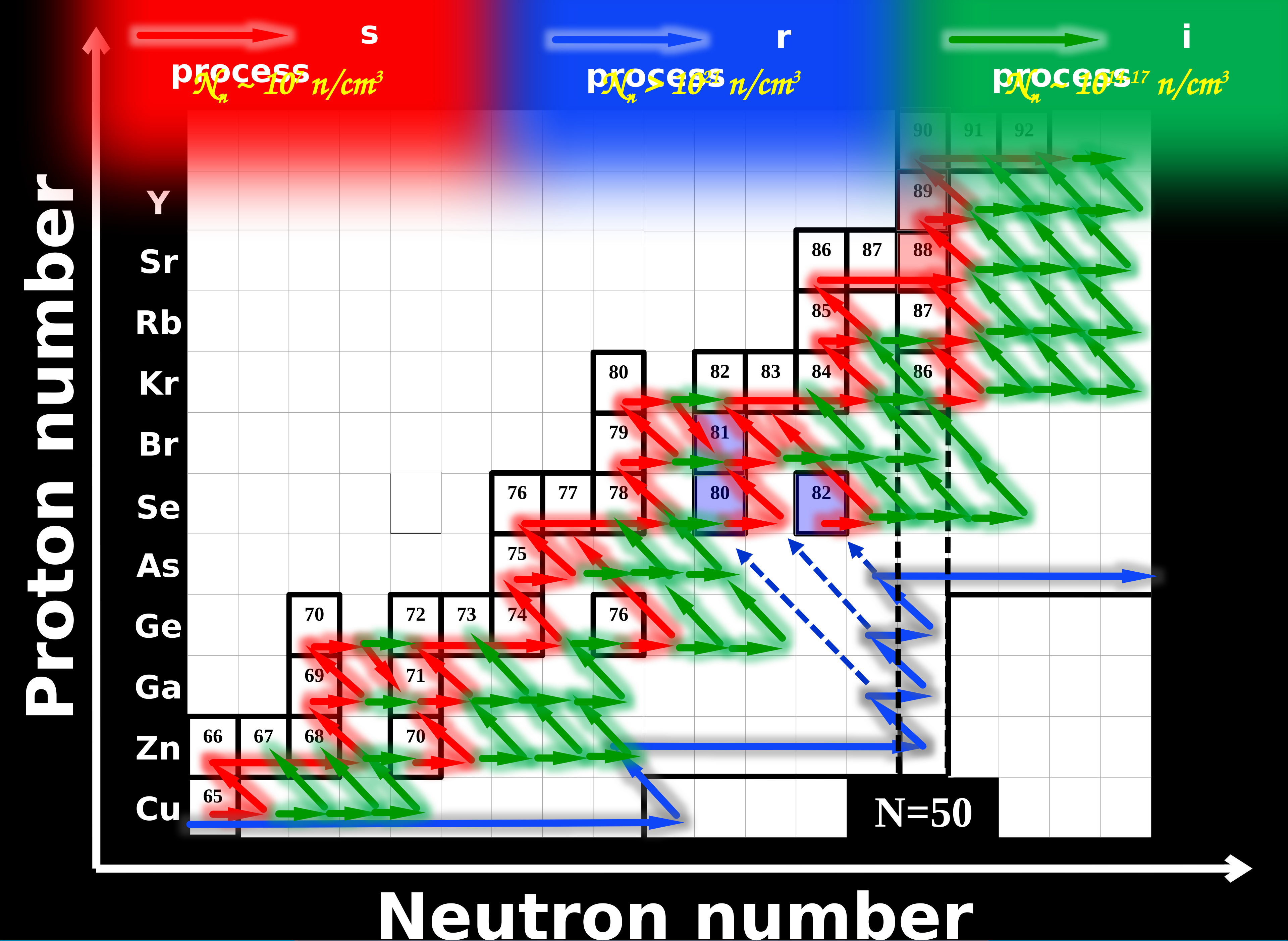
N=50


s process
r process
i process
Proton number
Neutron number
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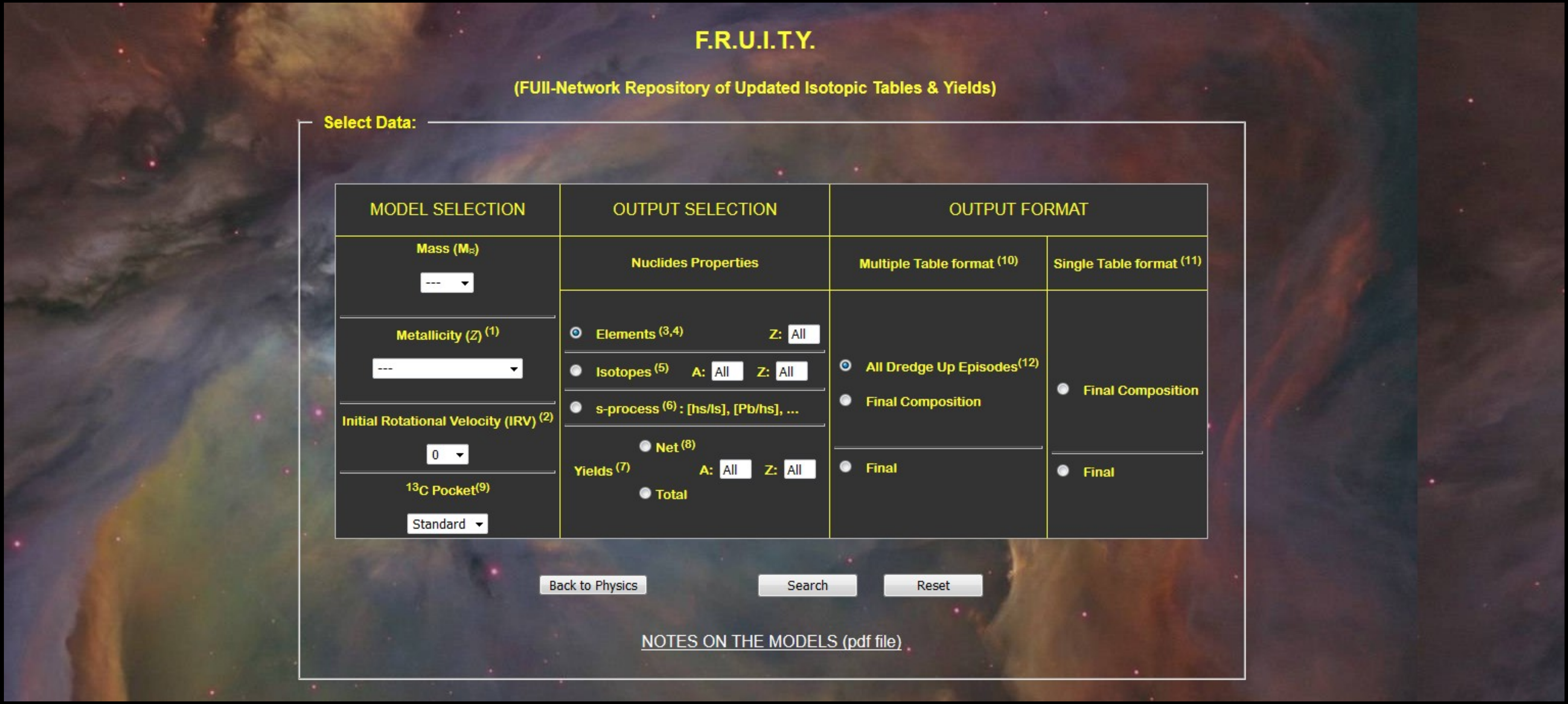
Sr
Rb
Kr
Br
Se
As
Ge
Ga
Zn
Cu
90 91 92
89
86 87 88
85 87
80 82 83 84 86
79 81
76 77 78 80 82
75
70 72 73 74 76
69 71
66 67 68 70
65
N=50

F.R.U.I.T.Y.

FUll-Network Repository of Updated Isotopic Tables & Yields



SC+ 2011,2015

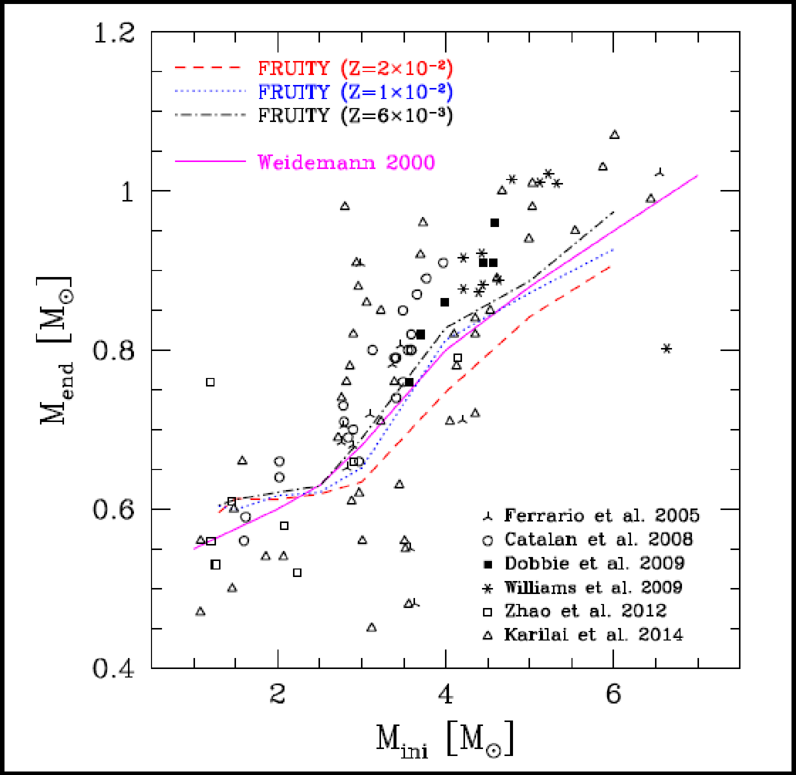
fruity.oa-abruzzo.inaf.it

$-2.85 \leq [Fe/H] \leq +0.3$

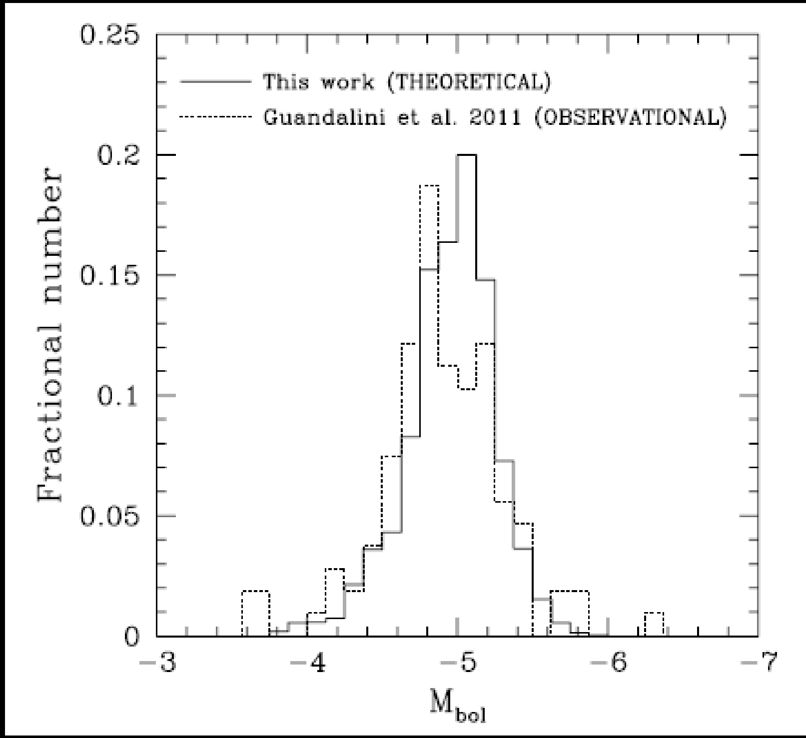
$1.3 \leq M/M_{sun} \leq 6.0$

OBSERVATIONS (physics)

Initial-to-final mass relations



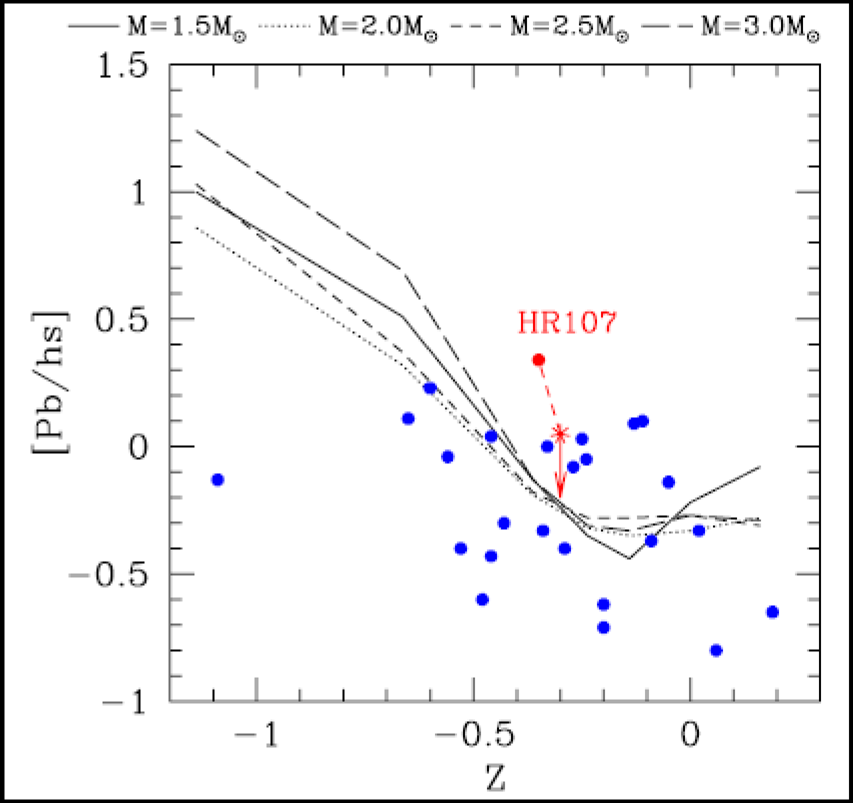
Luminosity Function of C-stars



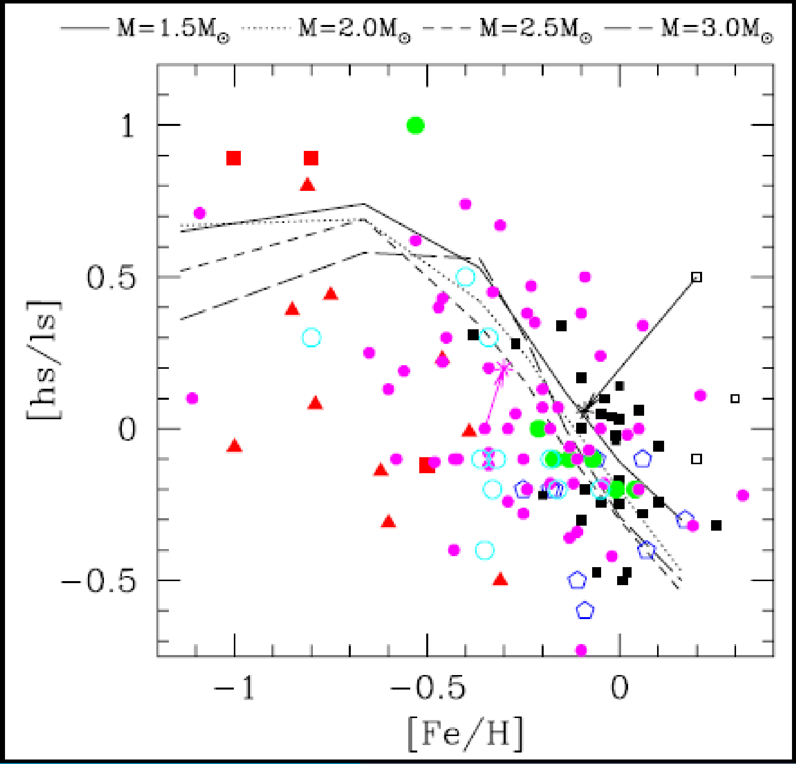
SC+ 2011

OBSERVATIONS (spectroscopy)

Third to second s-process peak



Second to first s-process peak



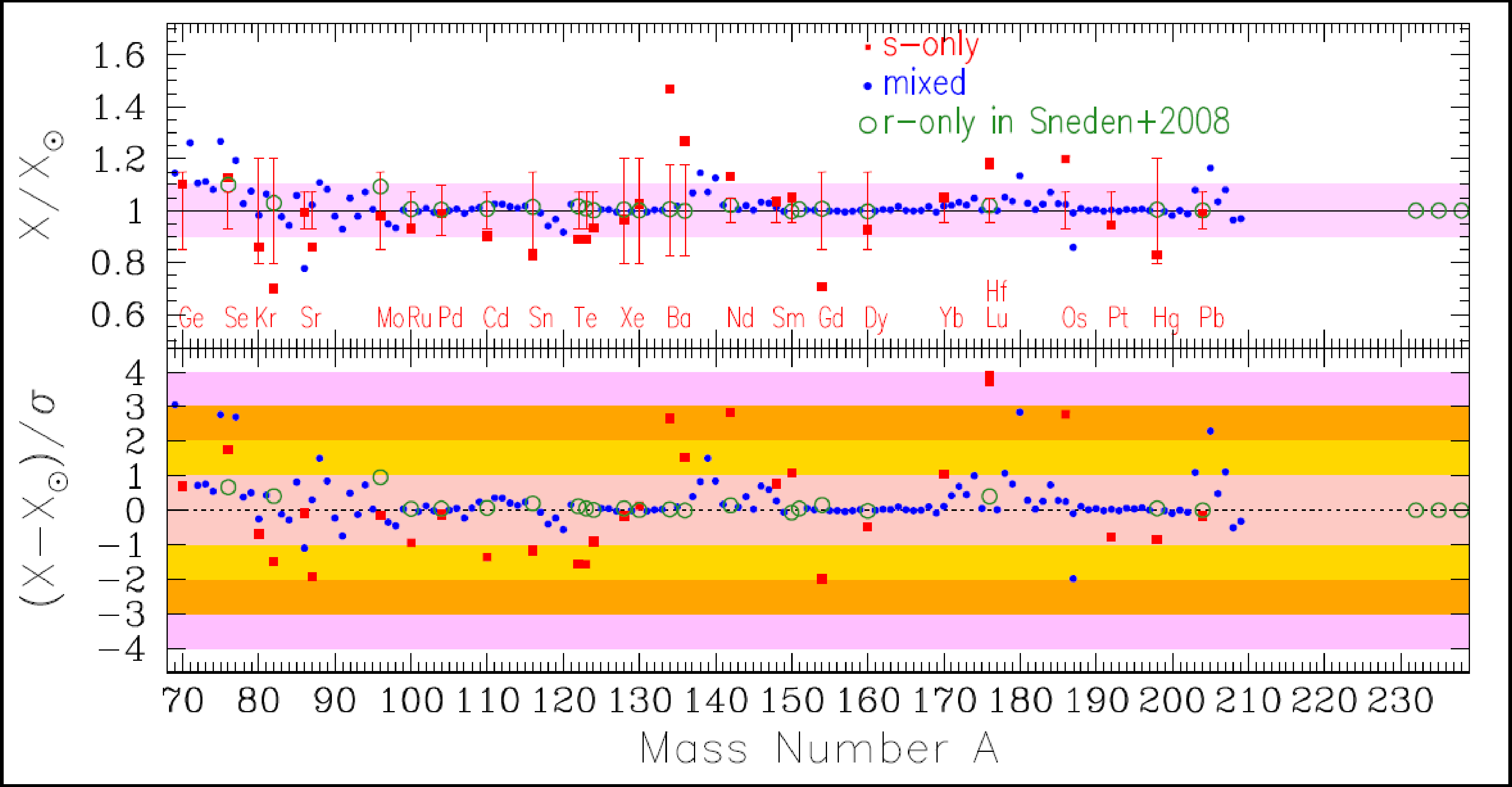
SC+ 2011

[ls/Fe]= [Sr,Y,Zr/Fe]

[hs/Fe]= [Ba,La,Ce,Nd/Fe]

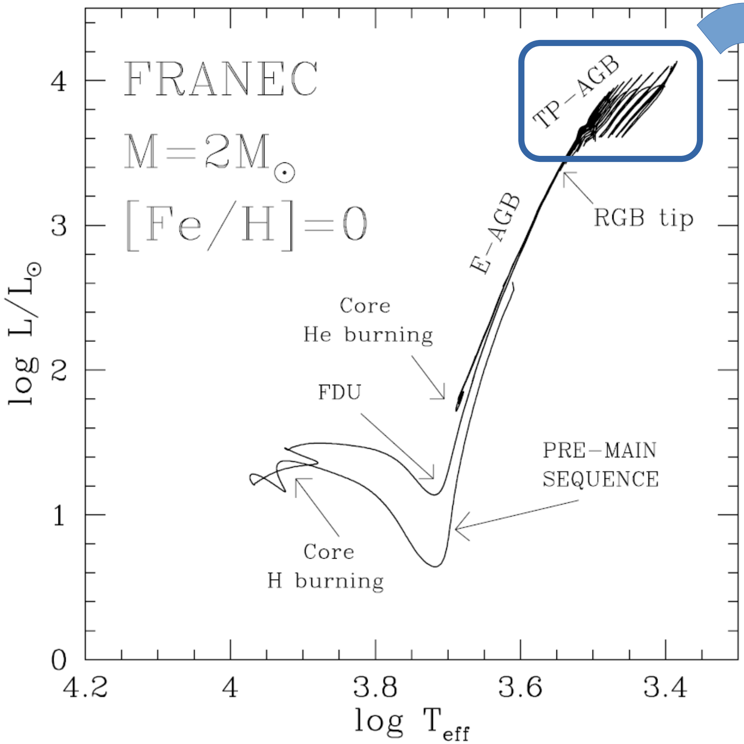
[hs/ls]=[hs/Fe]-[ls/Fe]

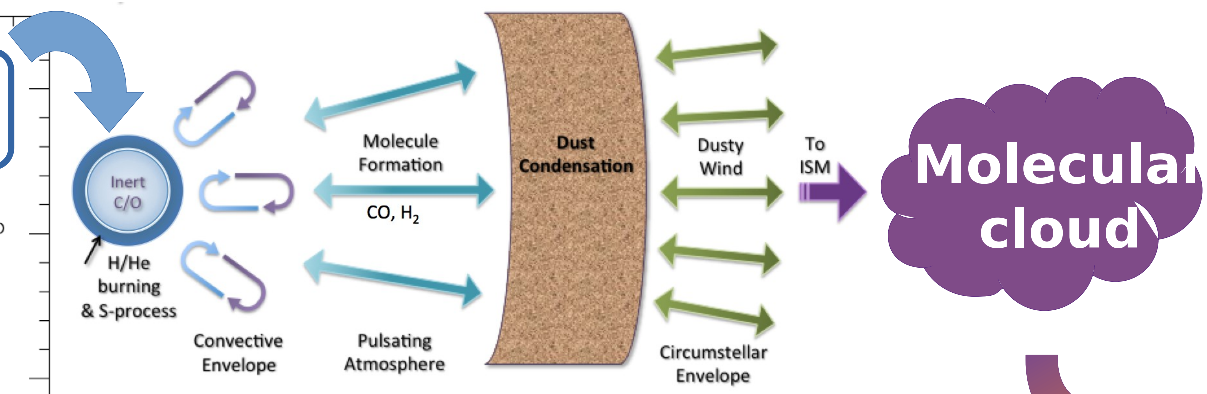
Comparison to solar distribution

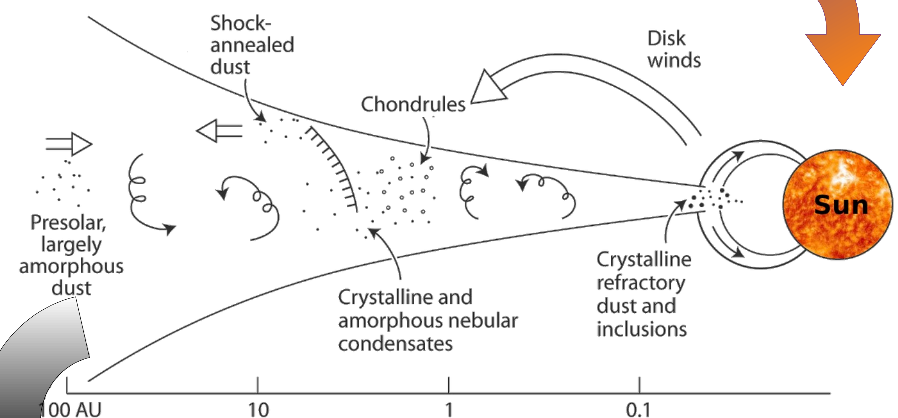


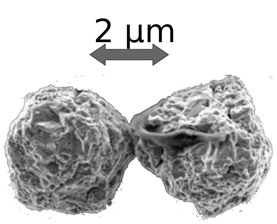
Prantzos+ 2020

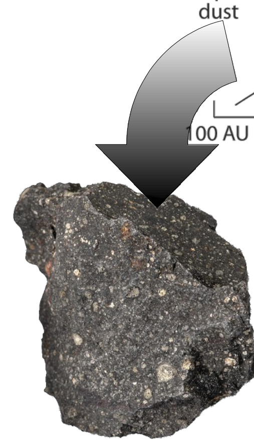
AGB stars and presolar SiC grains











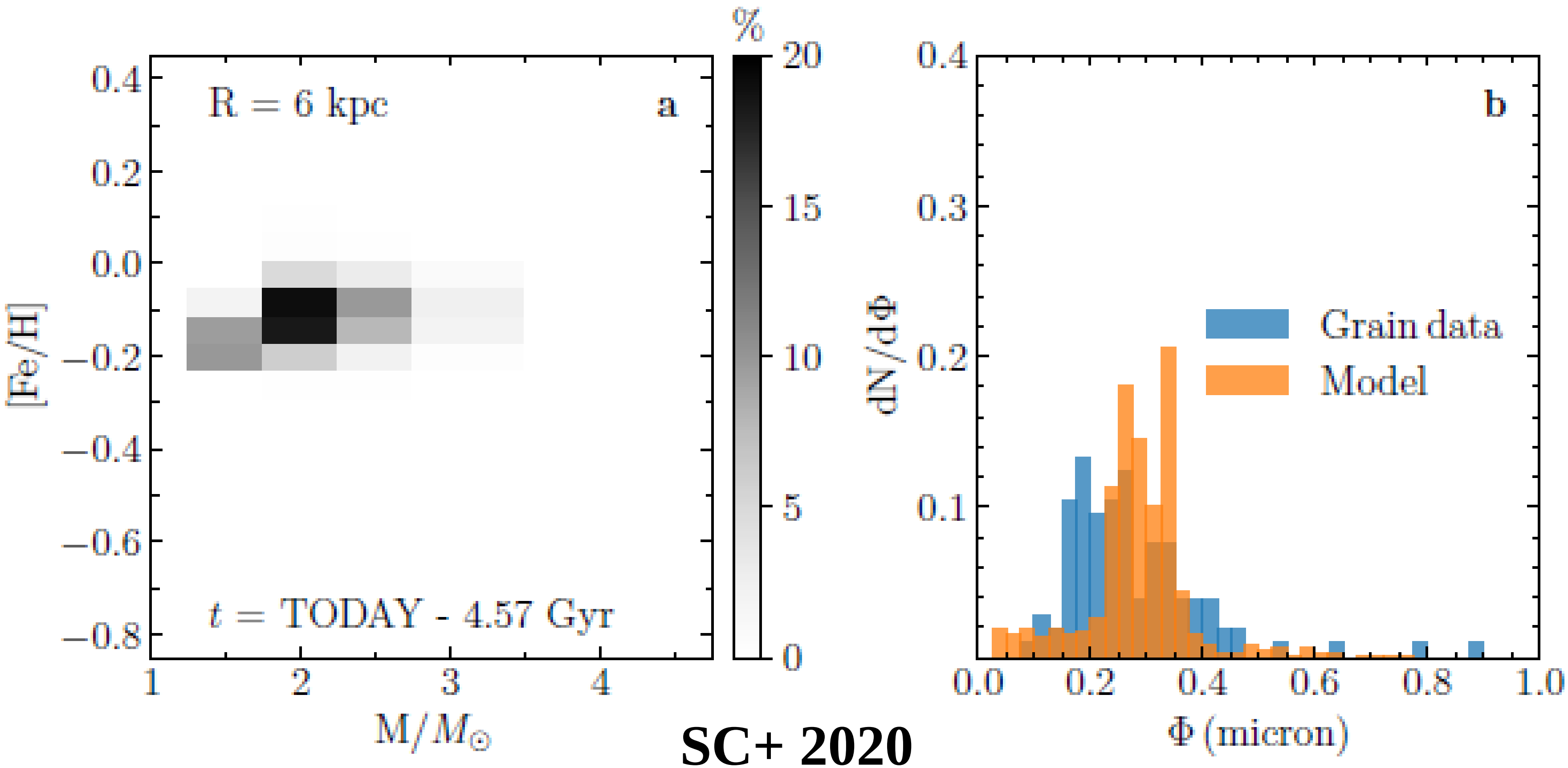
Meteorites
and asteroids

Presolar
grains

CONSTRAINTS TO STELLAR MODELS

Telescopes	Laboratories
Large uncertainties (≈2)	Small uncertainties (≈10%)
No infos on isotopic composition	Isotopic abundances
Elemental abundances	No infos on elementa abundances
We know the origin: able to define at least the metallicity	We guess which was the parent star

First important question is: which stars are progenitor of pre-solar SiC grains?



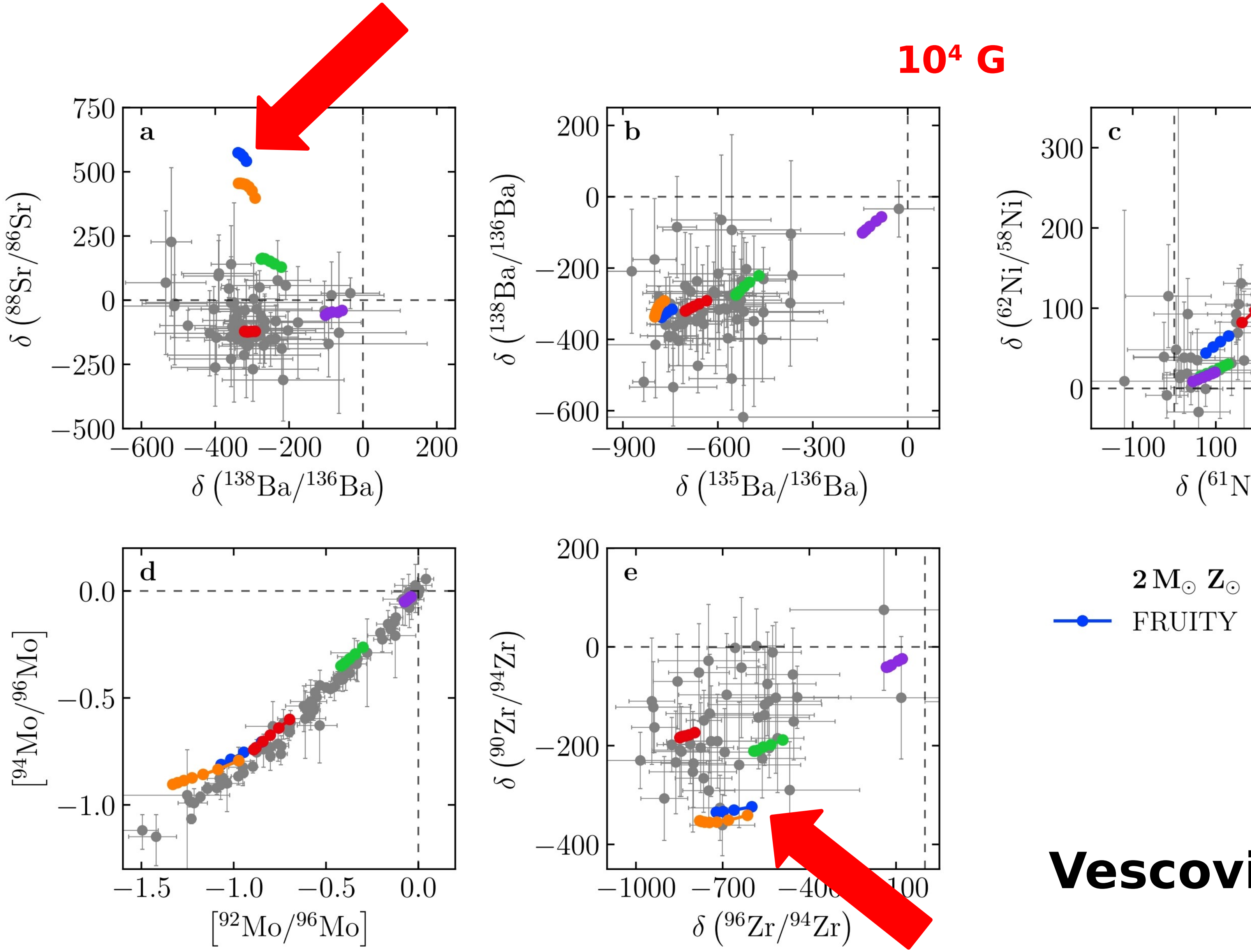
SC+ 2020

Our models predict that the SiC production at the epoch of the Solar System formation is dominated by contributions from AGB stars with $M \approx 2M_{SUN}$ and $Z \approx Z_{SUN}$, which are thus likely <u>the parent stars of presolar SiC grains identified in extraterrestrial materials</u>.

SiC Grains

$$\delta(^{88}Sr/^{86}Sr)=[(^{88}Sr/^{86}Sr)_{grain}-(^{88}Sr/^{86}Sr)_{SS}-1]x1000$$

10^4 G

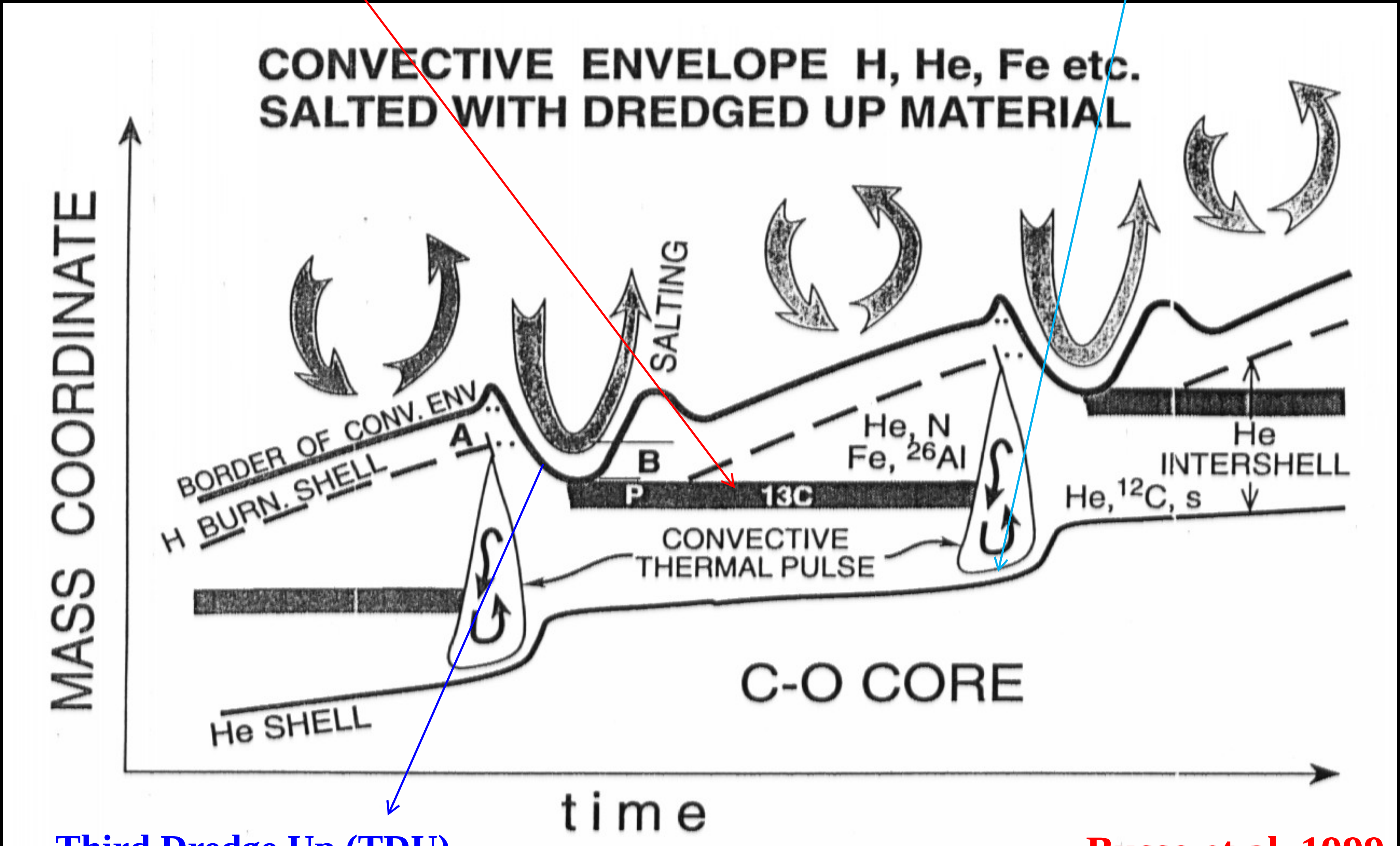


Vescovi+ 2020

The s-process in AGB stars

$^{13}C(\alpha,n)^{16}O$ reaction

$^{22}Ne(\alpha,n)^{25}Mg$ reaction



Third Dredge Up (TDU)

Busso et al. 1999

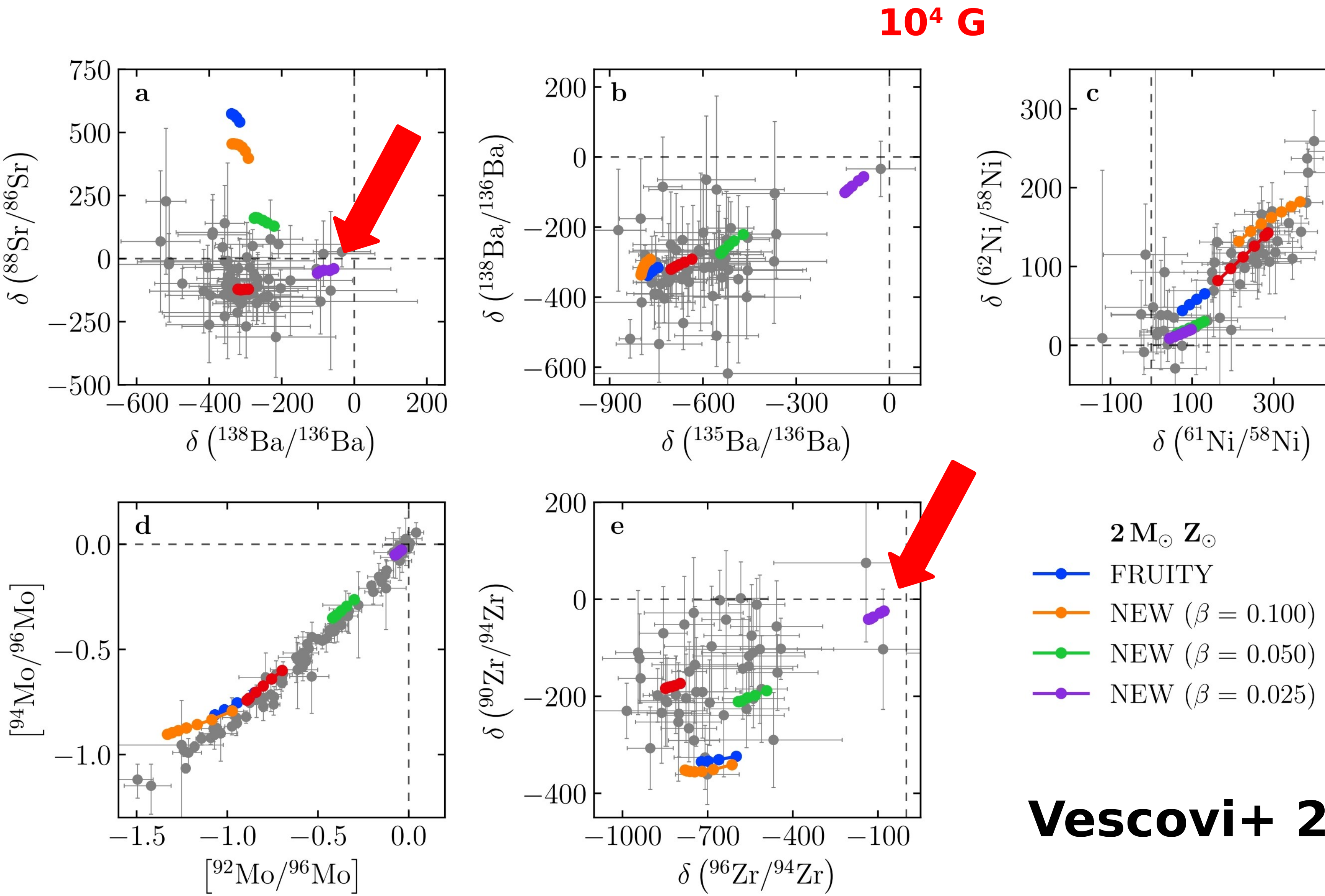
The ^{13}C pocket in stellar evolutionary models

- ✓ **Opacity induced overshoot** (SC+2009)
- ✓ **Convective Boundary Mixing + Gravity Waves** (Battino+ 2017)
- ✓ **Magnetic-induced mixing** (Vescovi+2020)

How does the ^{13}C pocket change?

- ✓ **Rotation-induced mixing** (Herwig+ 2003; Siess+ 2004; Piersanti+ 2013)

SiC Grains



Vescovi+ 2020

A new working hypothesis: magnetic induced mixing

Nucci & Busso 2014

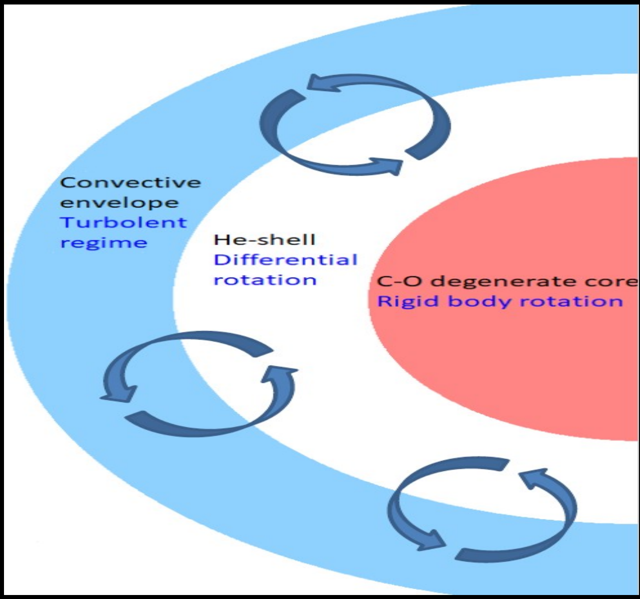
$$v_r = \frac{dw(t)}{dt} r^{-(k+1)}$$

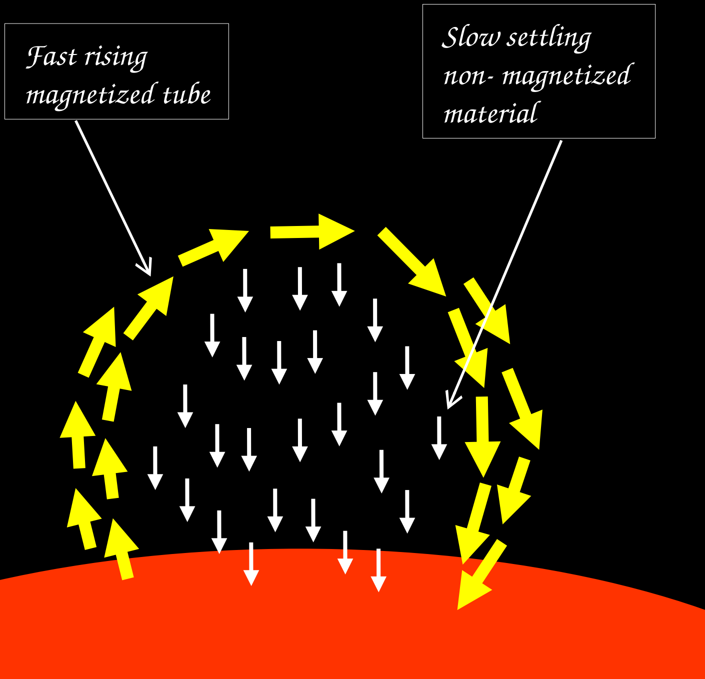
$$B_\varphi = \Phi(\xi) r^{k+1}, \quad [\xi = -(k+2)w(t) + r^{k+2}].$$

A magnetized stellar plasma in the quasi-ideal MHD regime, with a density distribution closely following a power law as a function of the radius (r ∞ r^k, with $k < -1$), reaches a dynamic equilibrium and is in radial expansion.
The result above is analytically exact.

$$v_{down}(r) = v(r_p) \frac{\rho(r_p)}{\rho(r_{h+1})} \left(\frac{r_h}{r_p}\right)^{k+2} \left(\frac{r_h}{r}\right)^{k+1}$$

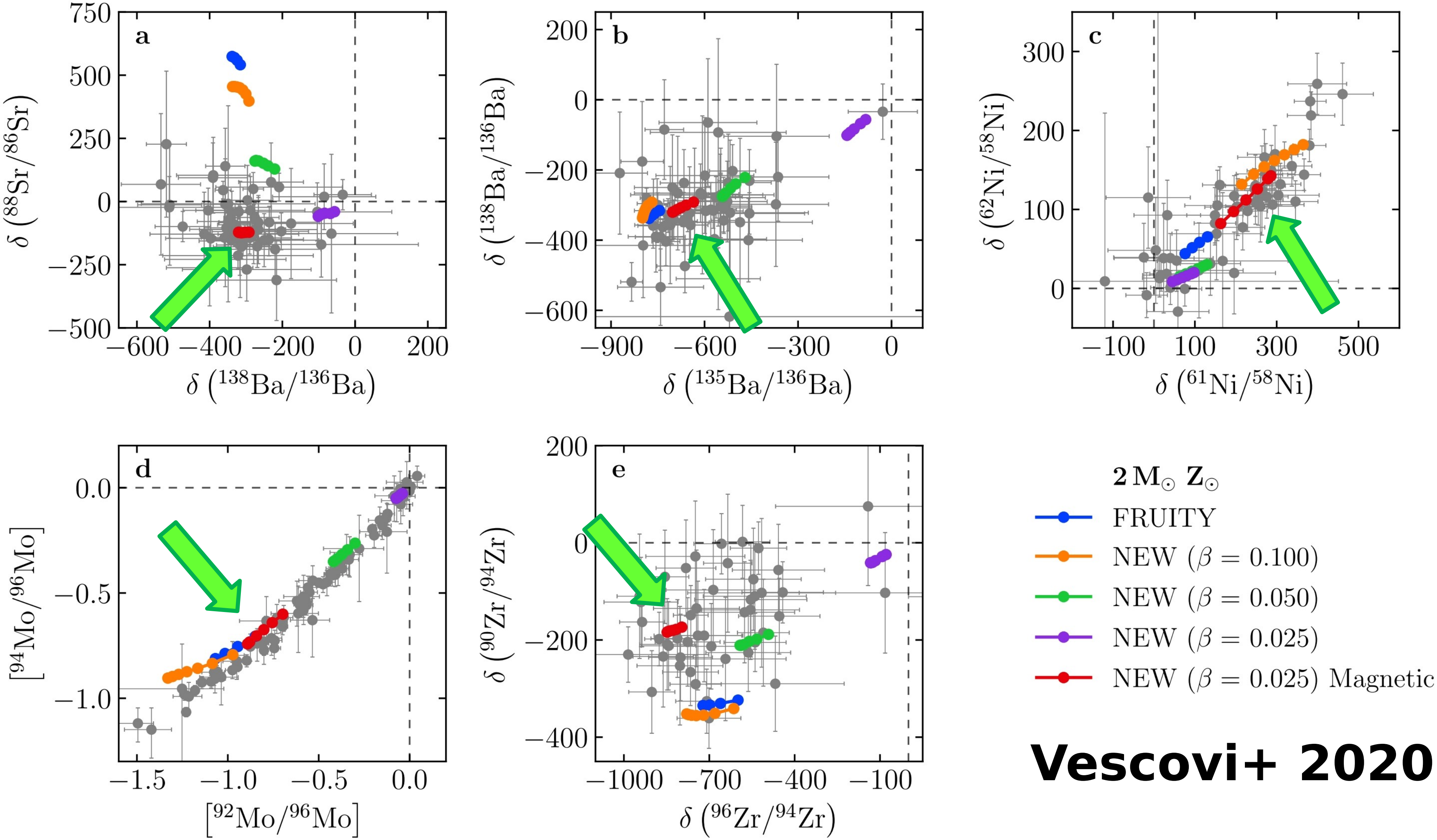
In strong field regimes, the magnetic field tends to concentrate in flux tubes. As a consequence of the magnetic extra-pressure, these tubes are buoyant (see, e.g., Parker 1955). Due to the effect of the magnetic buoyancy, a matter flow is pushed from the He-intershell toward the envelope. This, in turn, induces a downflow flux, in order to guarantee mass conservation.





SiC Grains

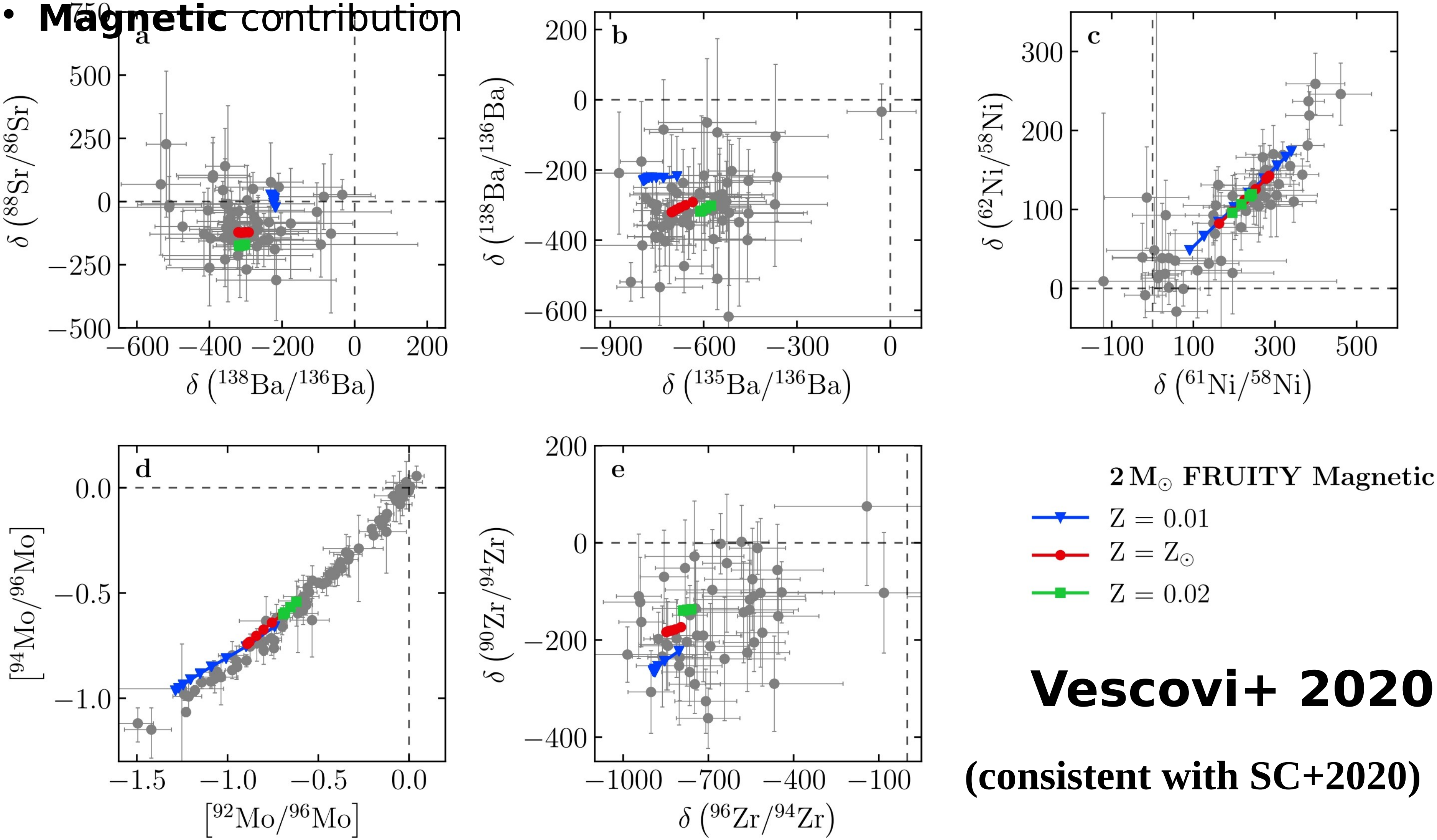
- **Magnetic** contribution account for SiC data!!
- Best fit for $u_p = 5 \times 10^{-5}$ cm/s and $B_\varphi = 5 \times 10^4$ G



Vescovi+ 2020

SiC Grains I

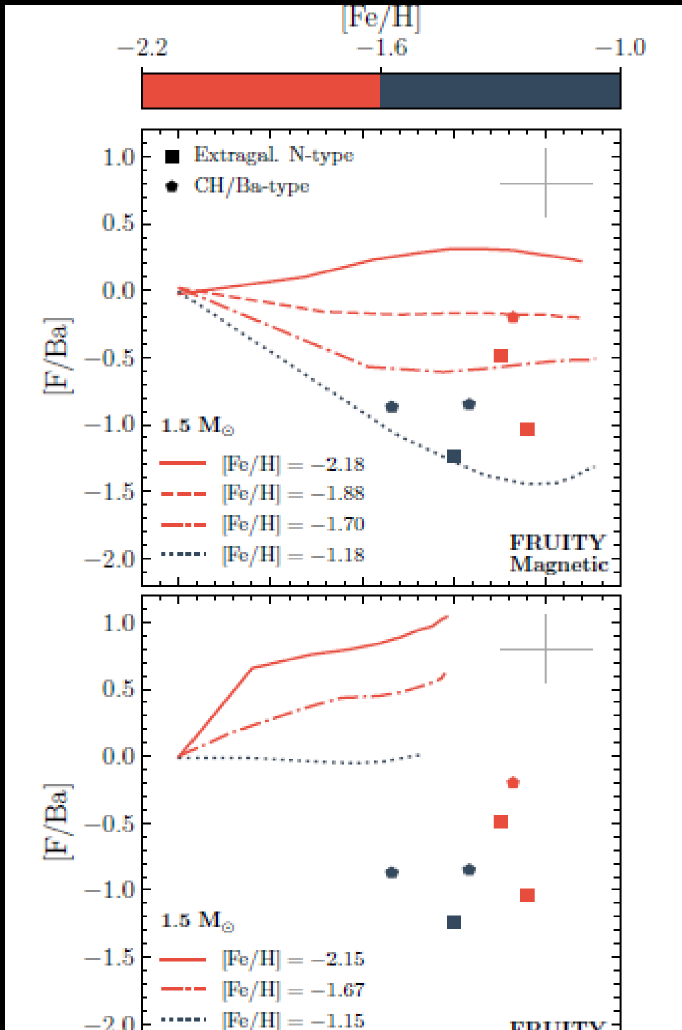
- Stellar models with **same initial mass** (2 $M_\odot$) and **close-to-solar metallicity**
- **Magnetic** contribution



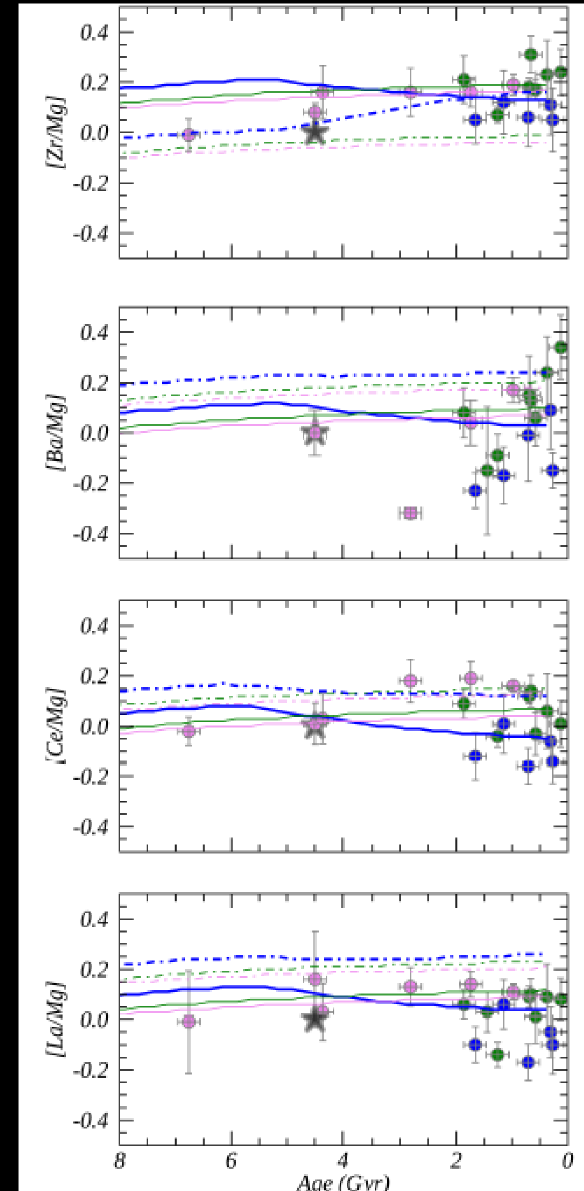
Vescovi+ 2020

(consistent with SC+2020)

Magnetic induced mixing



[Ba/Fe]



Better agreement

1. *Young Open Clusters;*
2. *Fluorine @ low Z.*

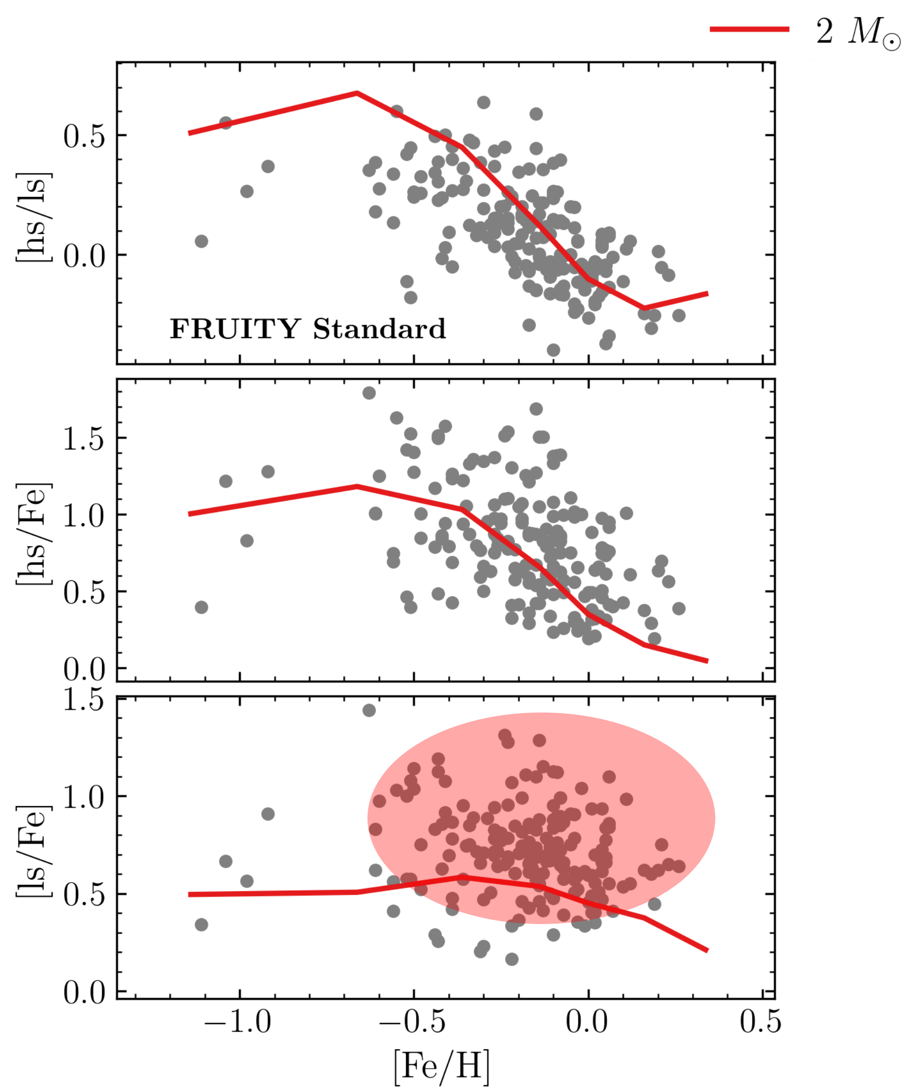
Vescovi+ 2021

Magrini+ 2021

WHAT'S NEXT?

- Ba stars
- C-stars
- S-stars
- Post-AGB stars

Ba-stars



2 $M_\odot$
FRUITY Standard
[hs/ls]
[hs/Fe]
[ls/Fe]
[Fe/H]
0.5
0.0
1.5
1.0
0.5
0.0
1.5
1.0
0.5
0.0
−1.0
−0.5
0.0
0.5

The origine of magnetic fields in stars

Still largely debated topic:

1. **fossil relics in stably stratified radiative regions (inherited from previous evolutionary phases);**
2. **dynamo-generated in turbulent convective layers.**

Since the time-scale for ohmic decay of a large-scale field is typically longer than stellar lifetime, the radiative regions may be regarded as perfectly conducting and the magnetic field is then "frozen" into the plasma.

During a Thermal Pulse, turbulence leads to rapid reconnection that dissipates any large-scale coherent field.
HOWEVER, convection, rotation, and shear within the convective region will regenerate the field through dynamo action: numerical simulations suggest that convective layers are site of very efficient small-scale dynamos.

BUT: we are interested in a axisymmetric toroidal magnetic field.

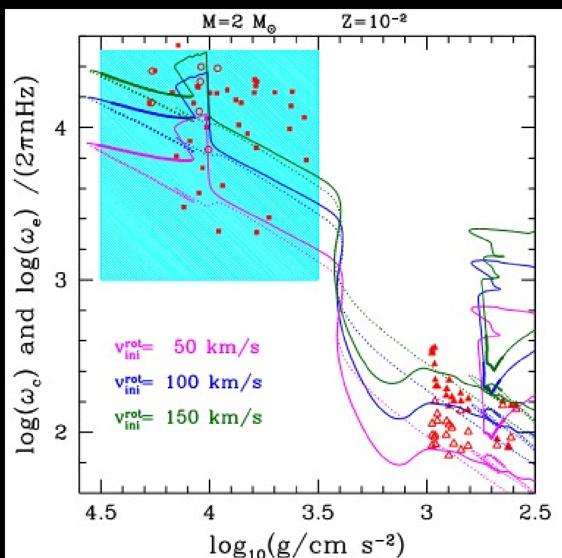
The origine of magnetic fields in stars

Such a field could be achieved through the stretching of a preexisting low-magnitude poloidal field in the radiative zone below the convective envelope after the quenching of a thermal pulse, via the action of differential rotation around the rotation axis.

$$\frac{\partial B_\varphi}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\Omega r^2 B_\mathrm{p}\right) = \Omega q B_\mathrm{p}$$

$$\frac{1}{2}(r\Omega(t))^2 + \frac{B_\varphi^2}{8\pi\rho} = \frac{1}{2}(r\Omega_{ini})^2$$

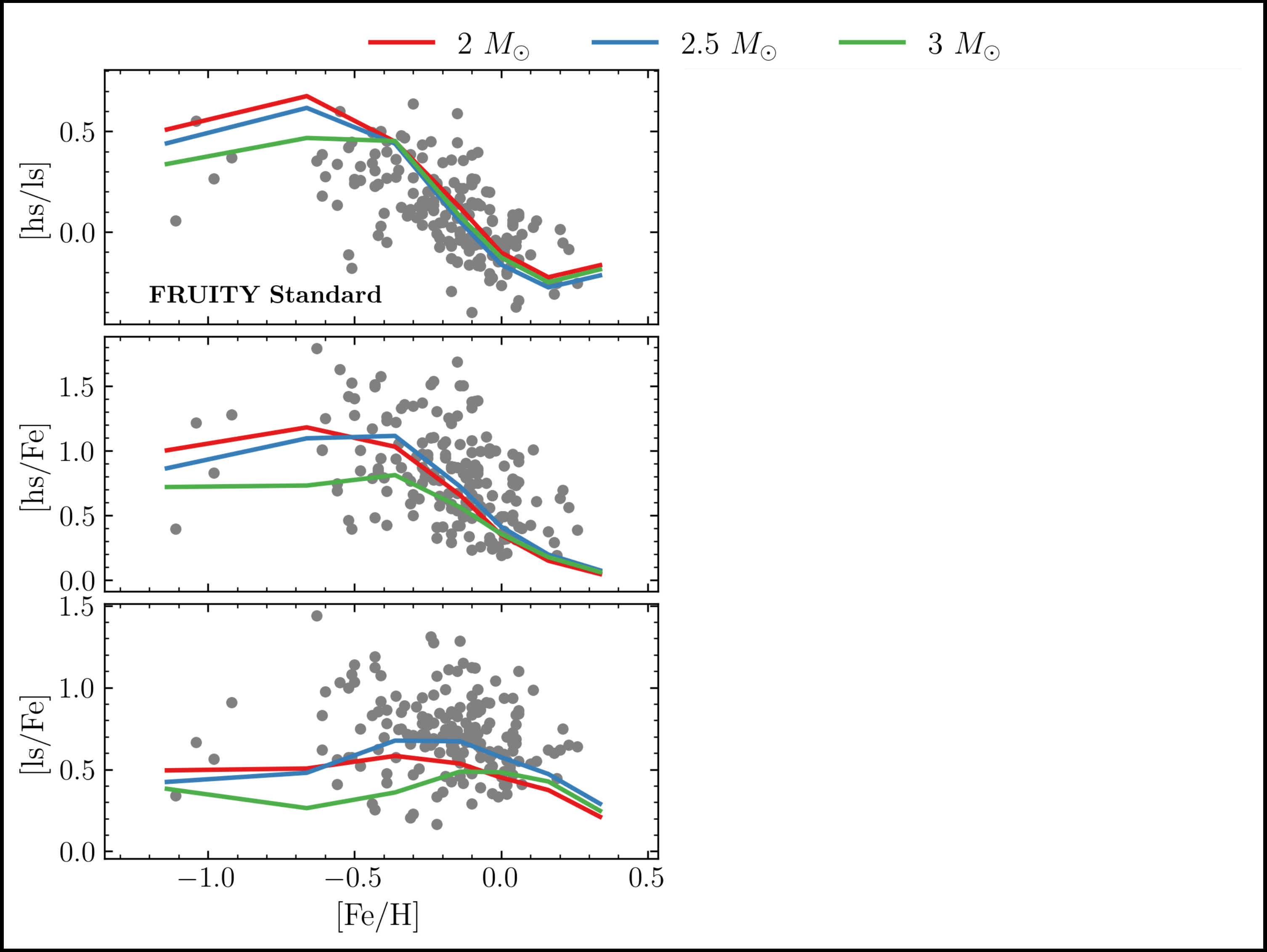
$B_P \approx 10$ G□ $B_\varphi \approx 10^5$ G



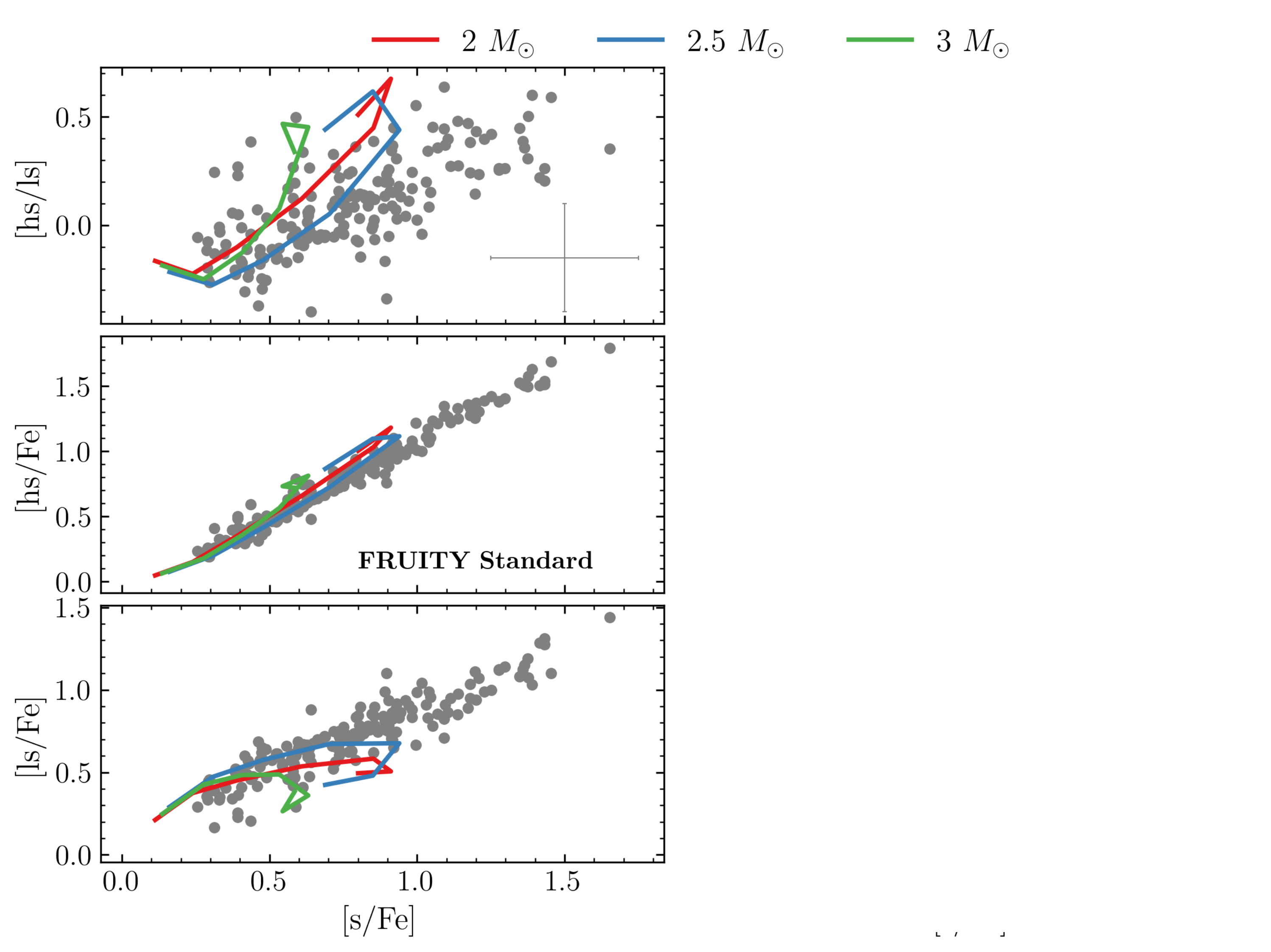
Artificial viscosity added to match asteroseismic data.

1. *Different initial rotation velocities;*
2. *Different TDU efficiencies.*

Ba-stars

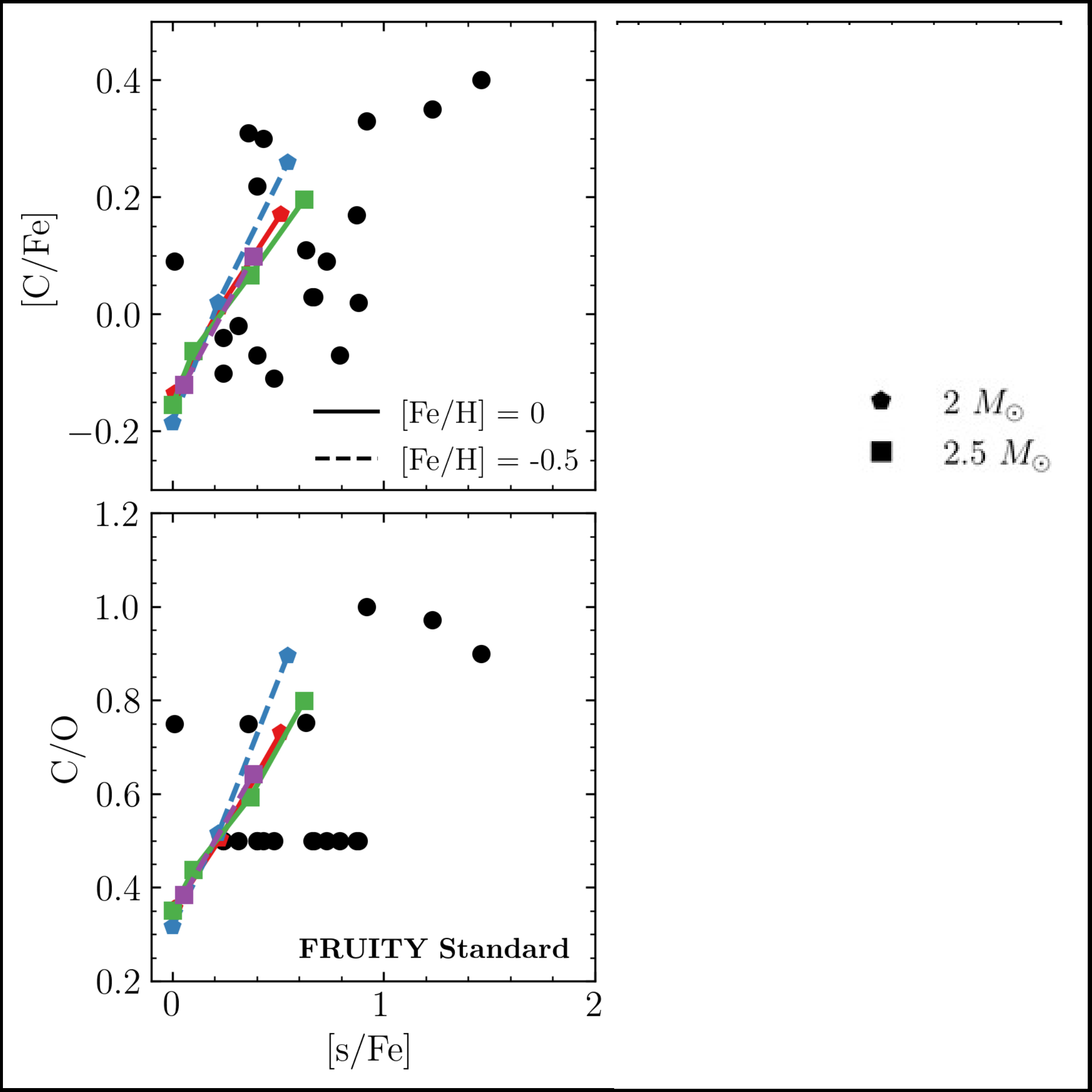


Ba-stars

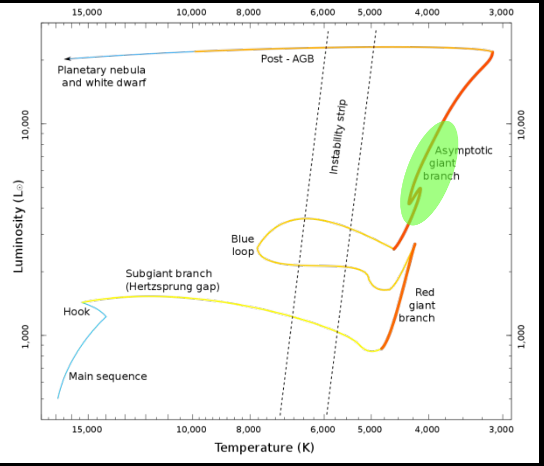


2 $M_\odot$
2.5 $M_\odot$
3 $M_\odot$
[hs/ls]
[hs/Fe]
FRUITY Standard
[ls/Fe]
[s/Fe]
0.0
0.5
1.0
1.5

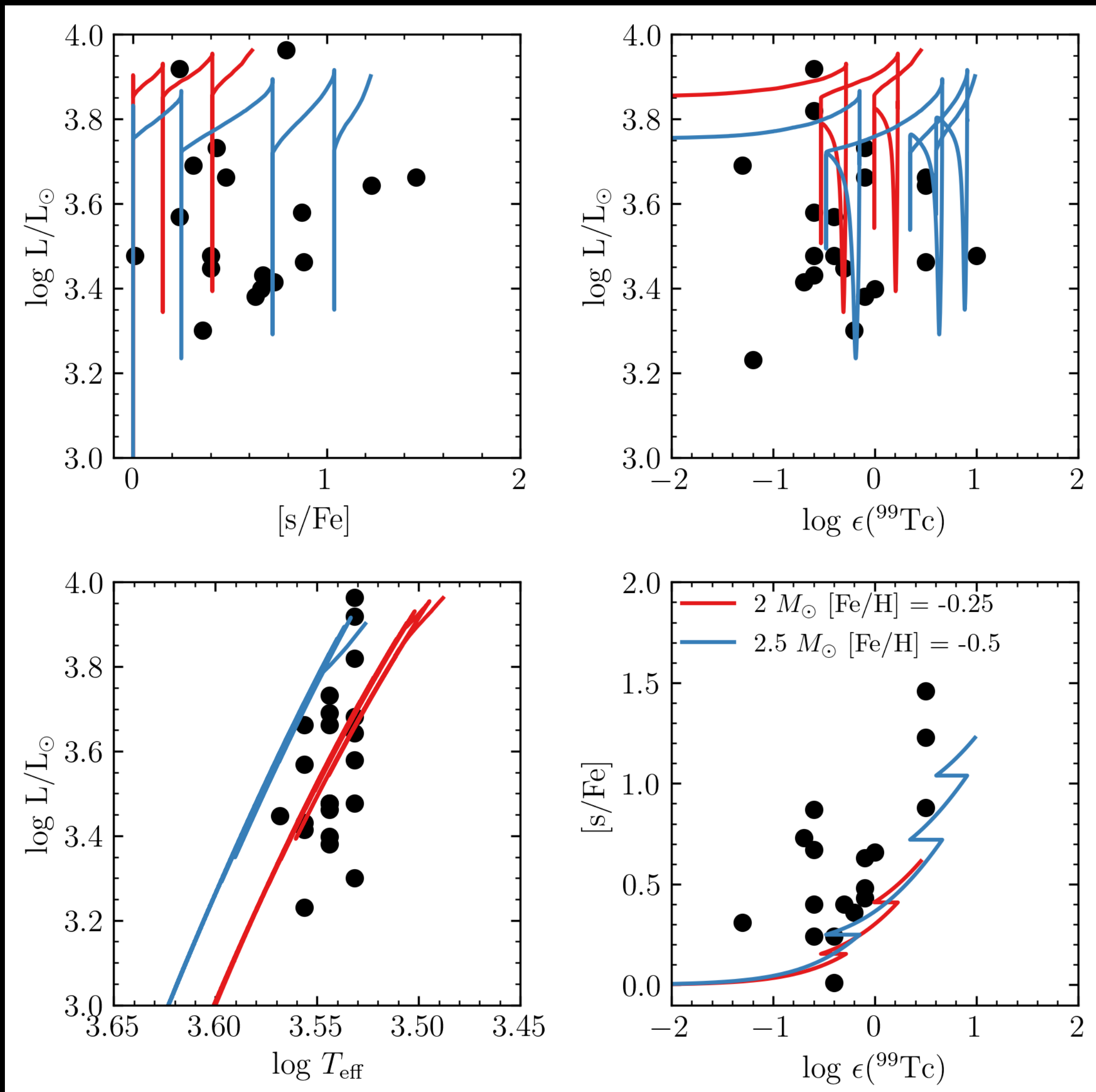
S-stars



0.3 < C/O < 1.0

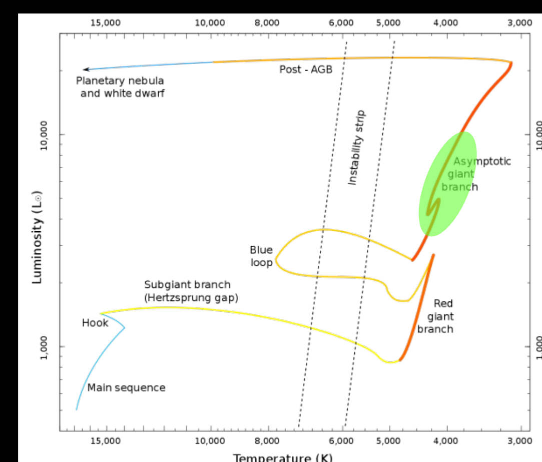


S-stars

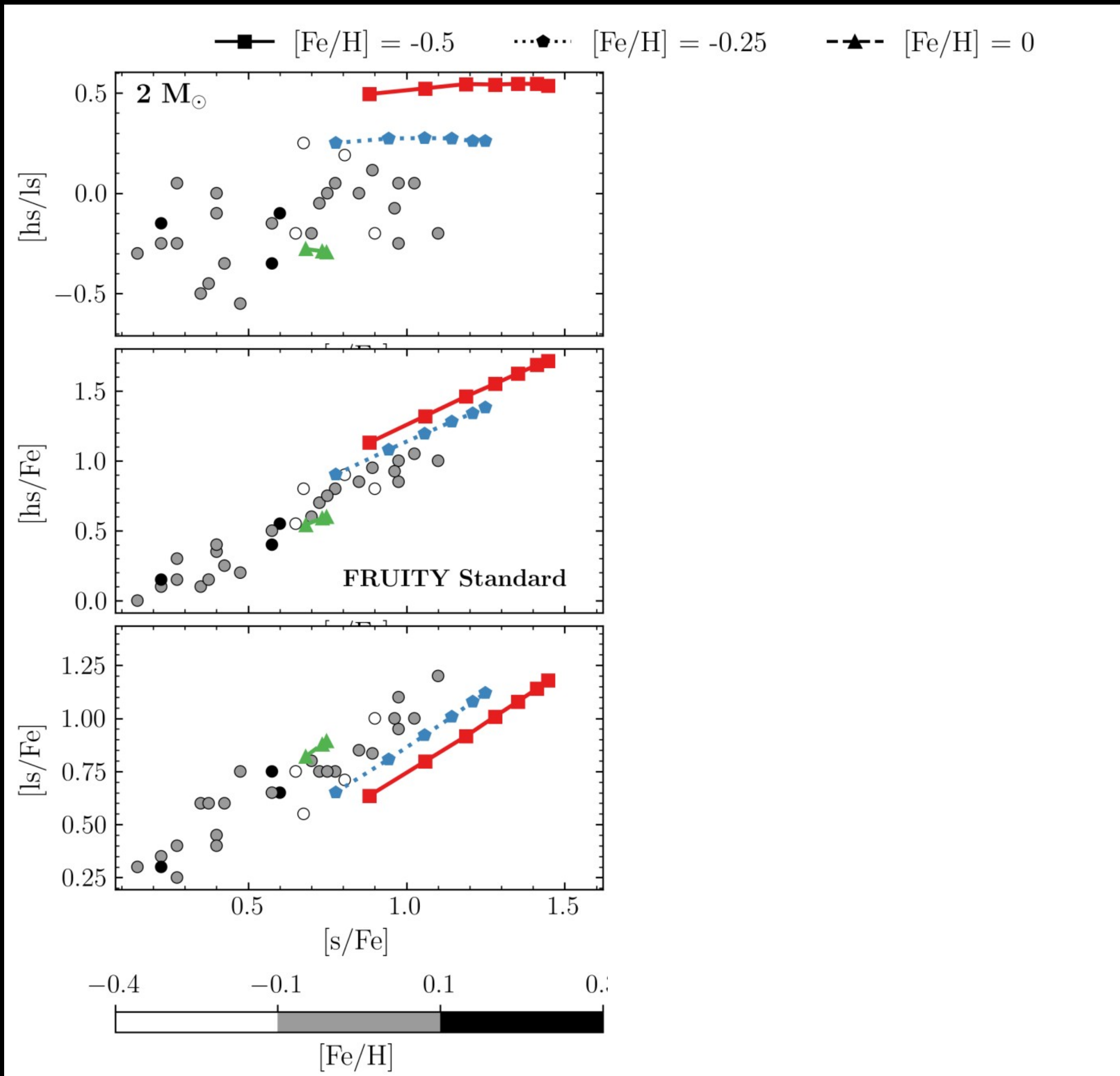


0.3 < C/O < 1.0

Tc is freshly produced by TDU
[Merrill 1952]

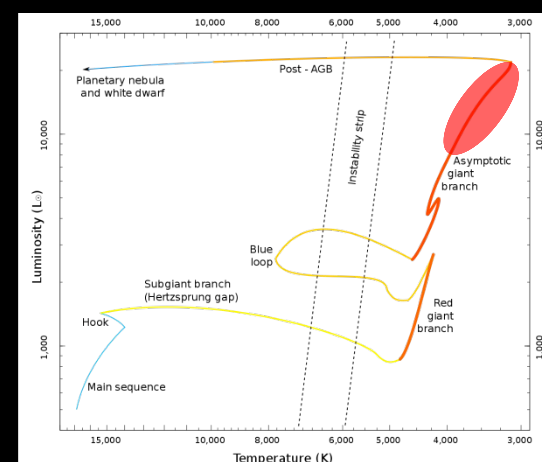


C-stars



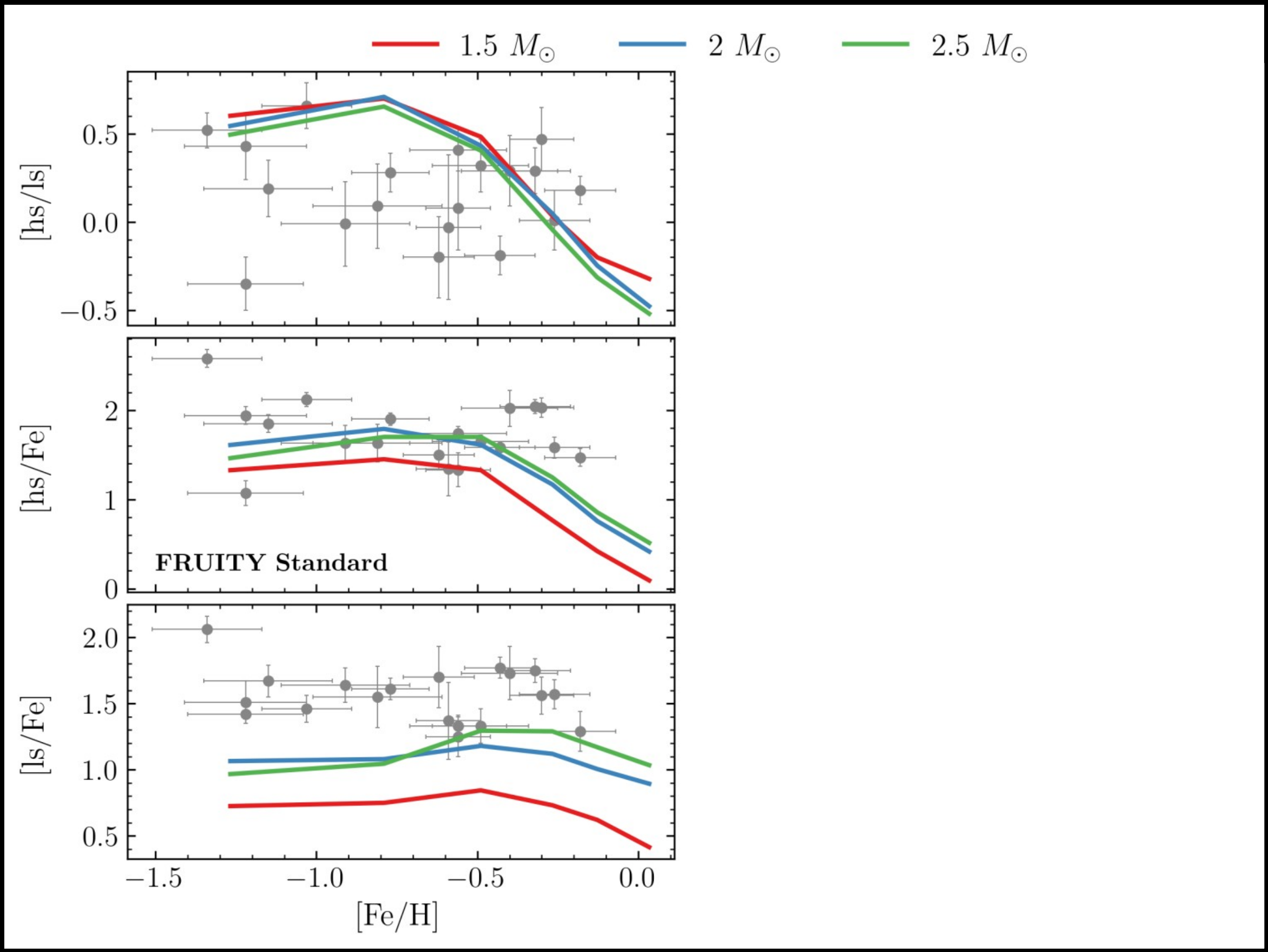
[Fe/H] = -0.5
[Fe/H] = -0.25
[Fe/H] = 0
2 M⊙
FRUITY Standard
[hs/ls]
[hs/Fe]
[ls/Fe]
[s/Fe]
[Fe/H]

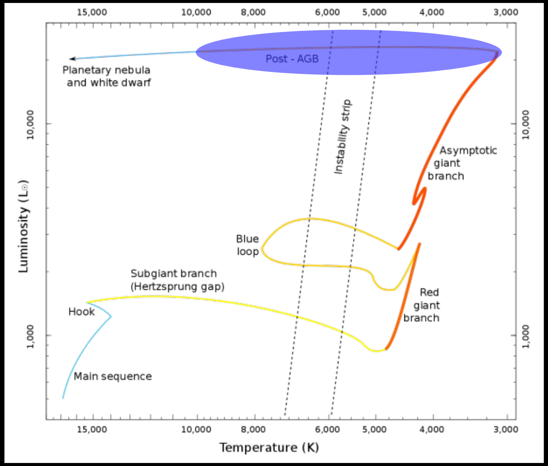
C/O > 1.0



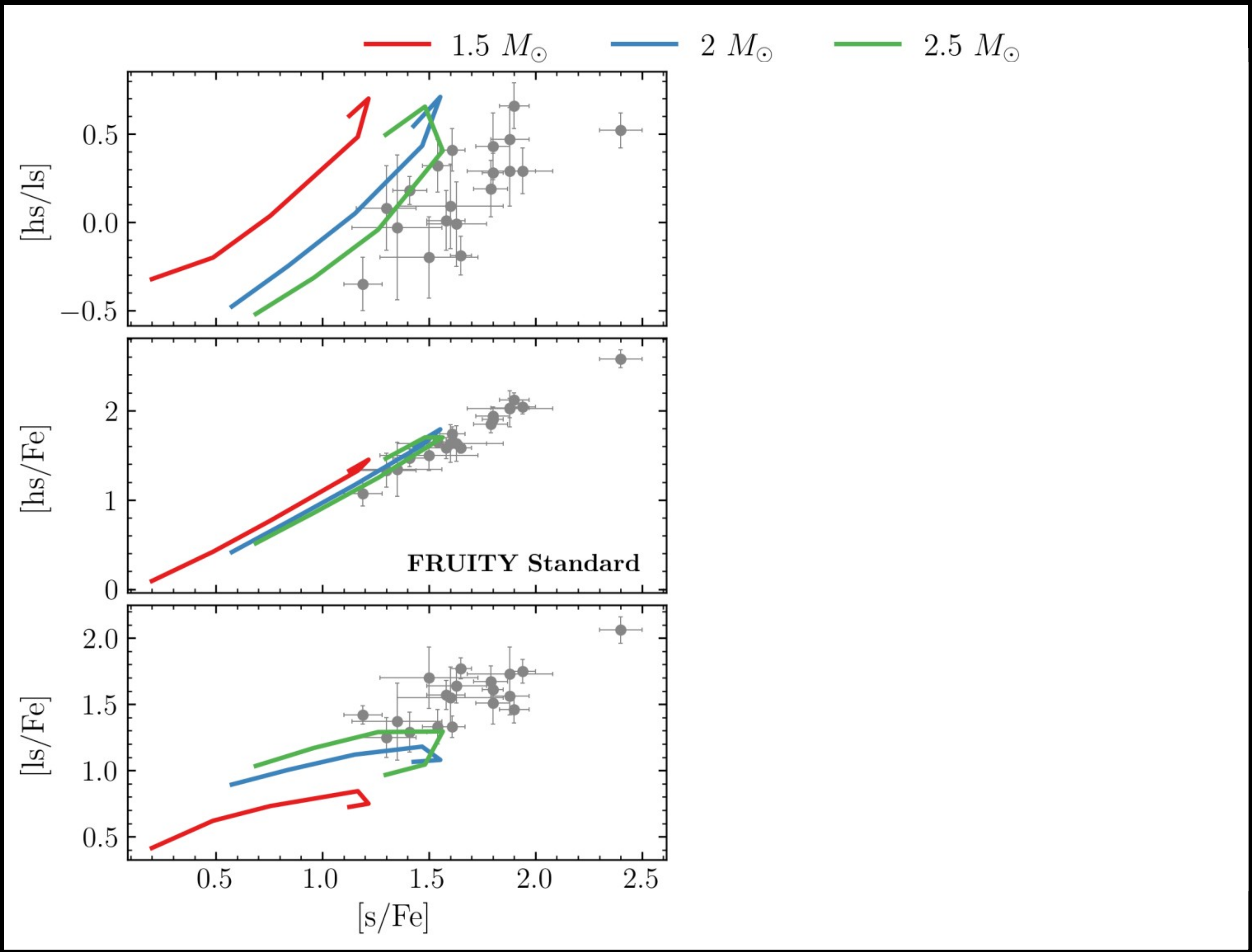
Post - AGB
Planetary nebula and white dwarf
Instability strip
Asymptotic giant branch
Blue loop
Subgiant branch (Hertzsprung gap)
Red giant branch
Hook
Main sequence
Luminosity (L☉)
Temperature (K)

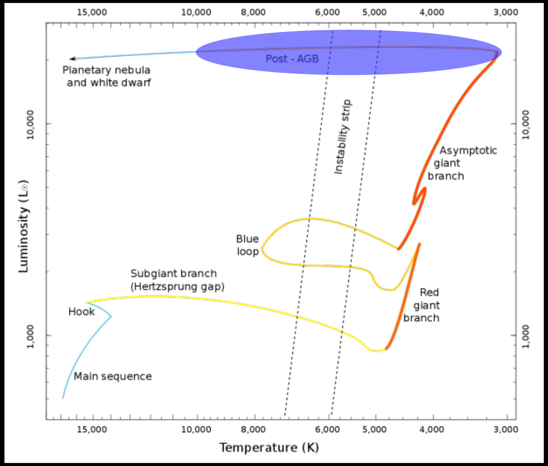
Post-AGB stars



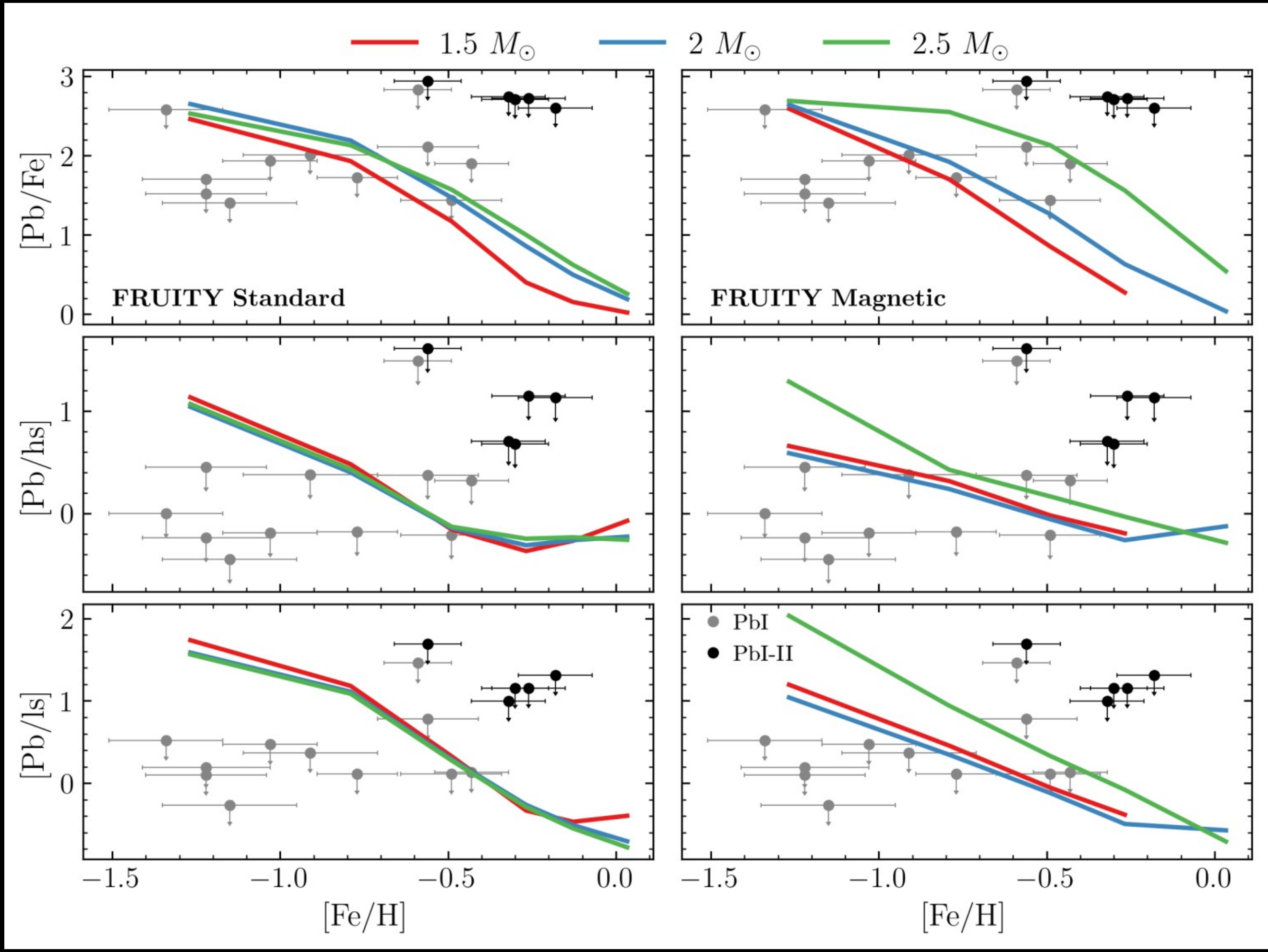


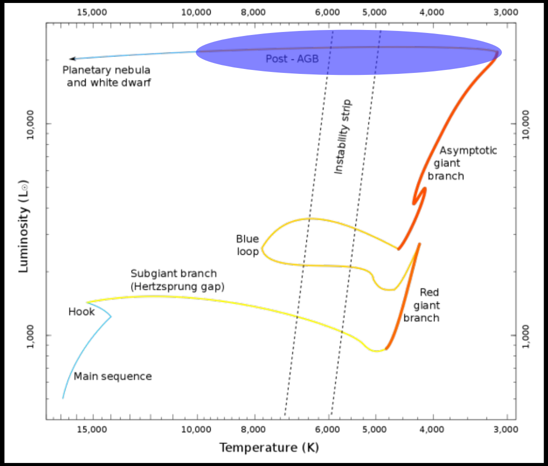
Post-AGB stars



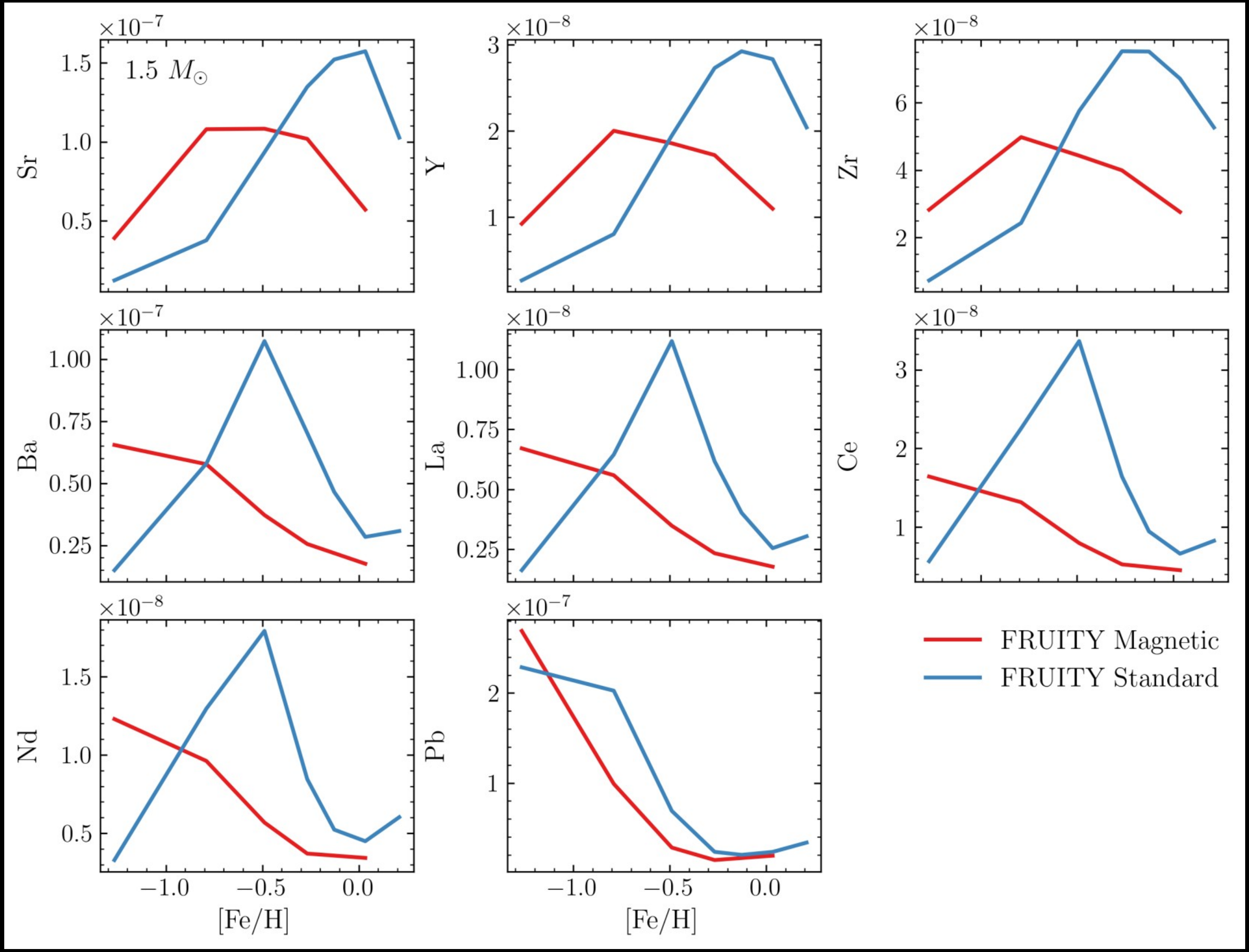


Post-AGB stars





…and finally YIELDS!



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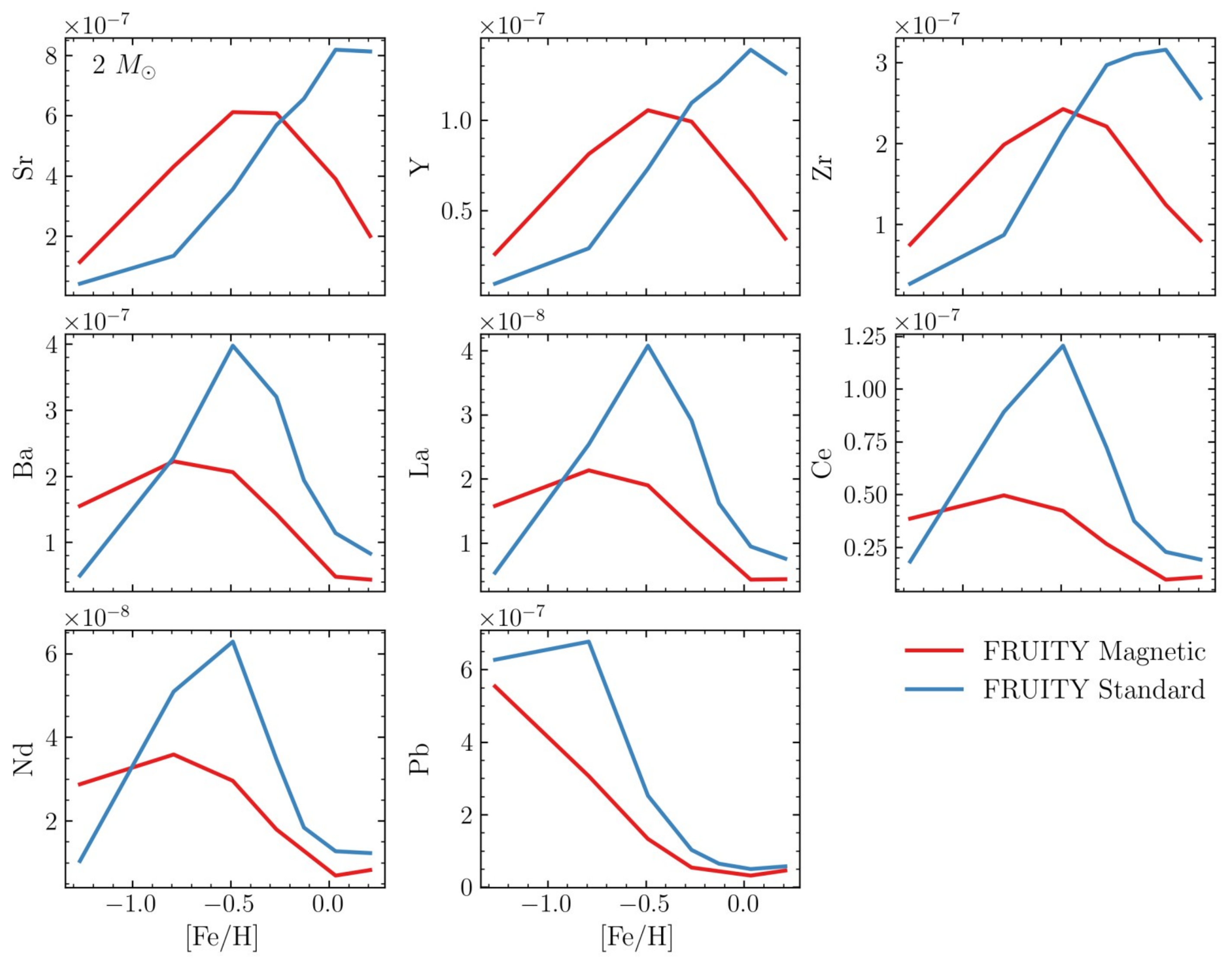

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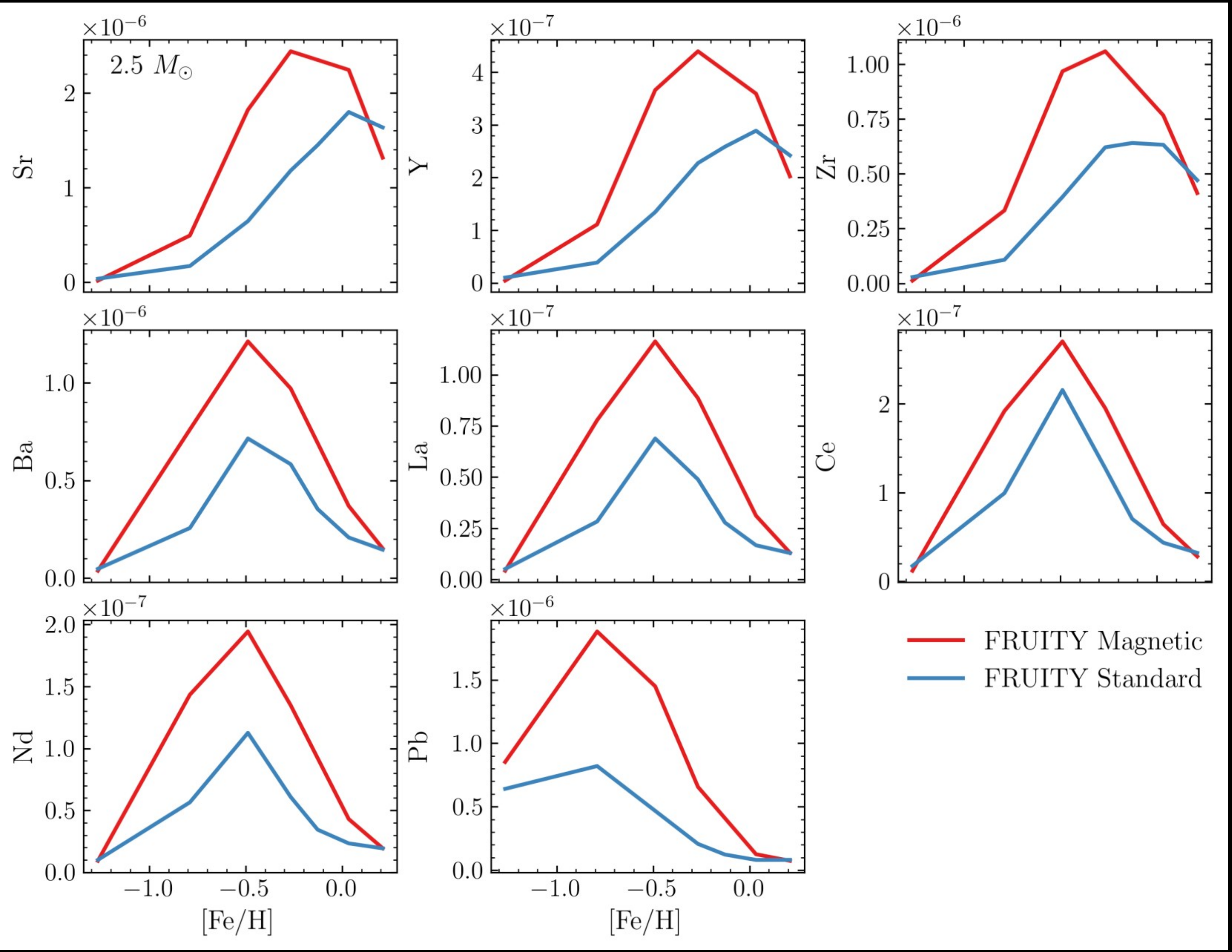

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