The effects of induced magnetic mixing in AGB stars

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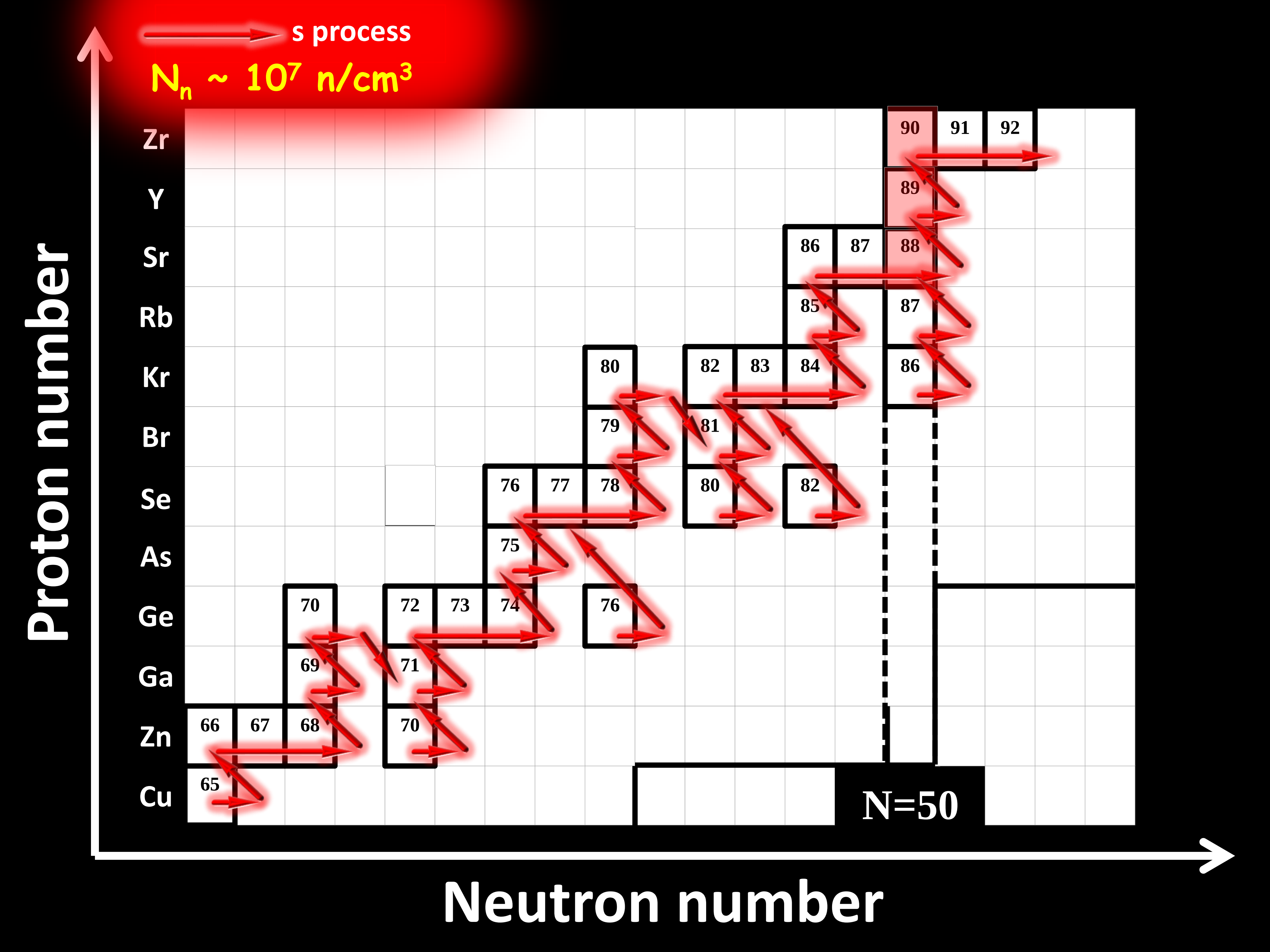
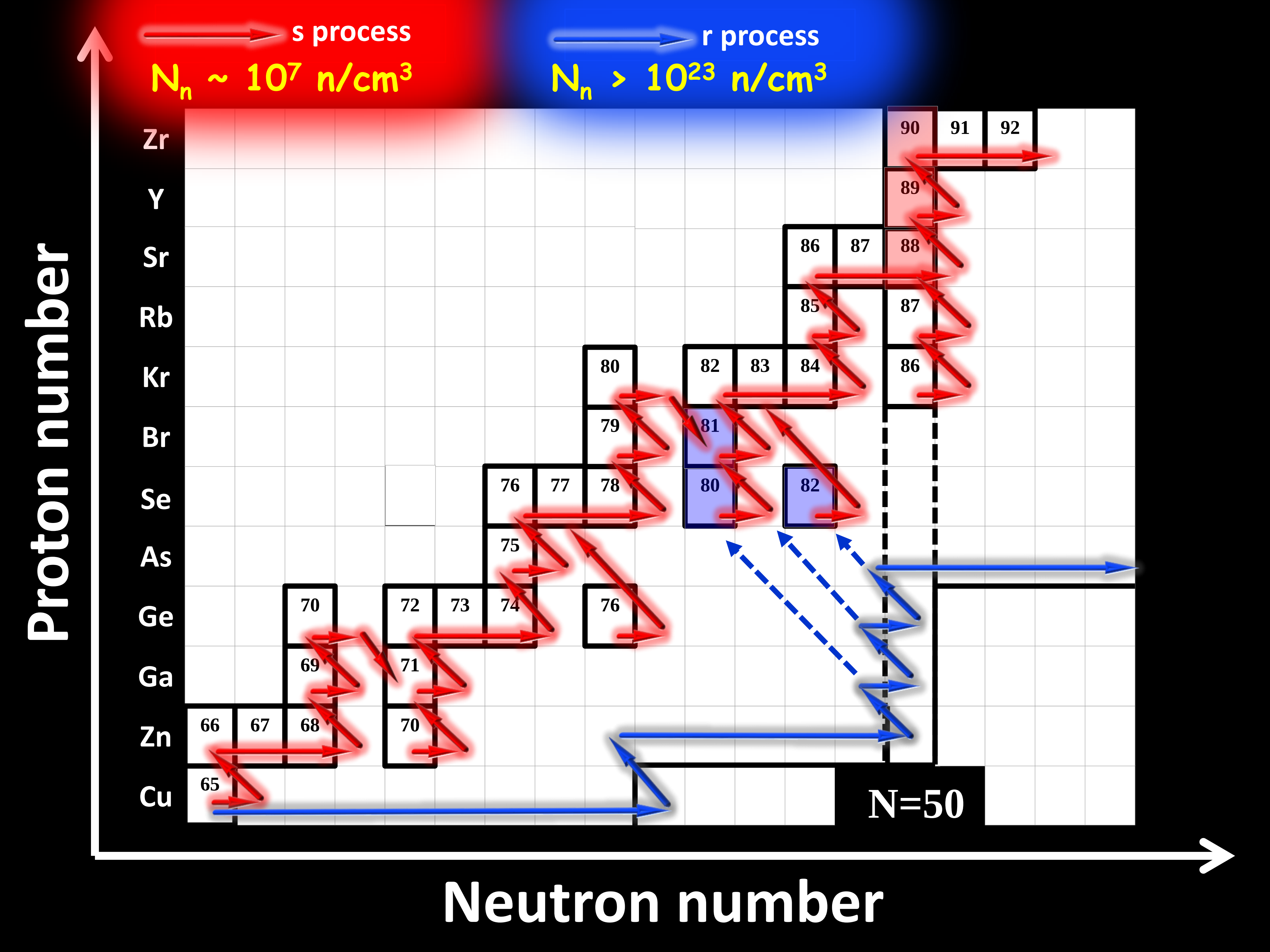
OUTLINE

- **PAST: FRUITY AGB models**
- **PRESENT & FUTURE: Magnetic AGB models**
- **Comparison to observations:**

  1. **Presolar Grains**
  2. **Ba-stars**
  3. **S-stars**
  4. **C-stars**
  5. **Post-AGB stars**


s process
$N_n \sim 10^7$ n/cm^3
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
Proton number
Neutron number



s process
$N_n \sim 10^7$ n/cm^3
r process
$N_n > 10^{23}$ n/cm^3
Proton number
Neutron 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
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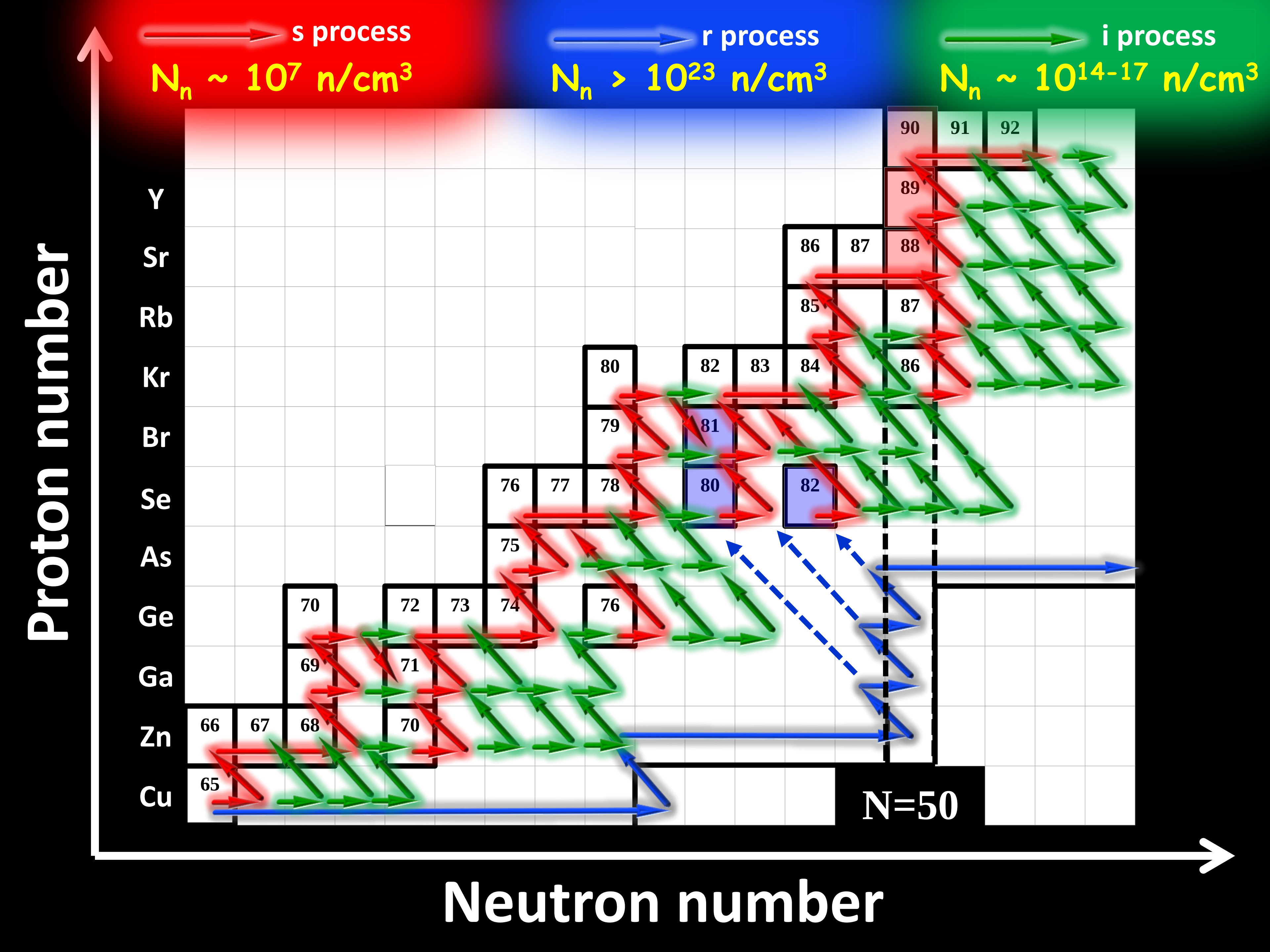
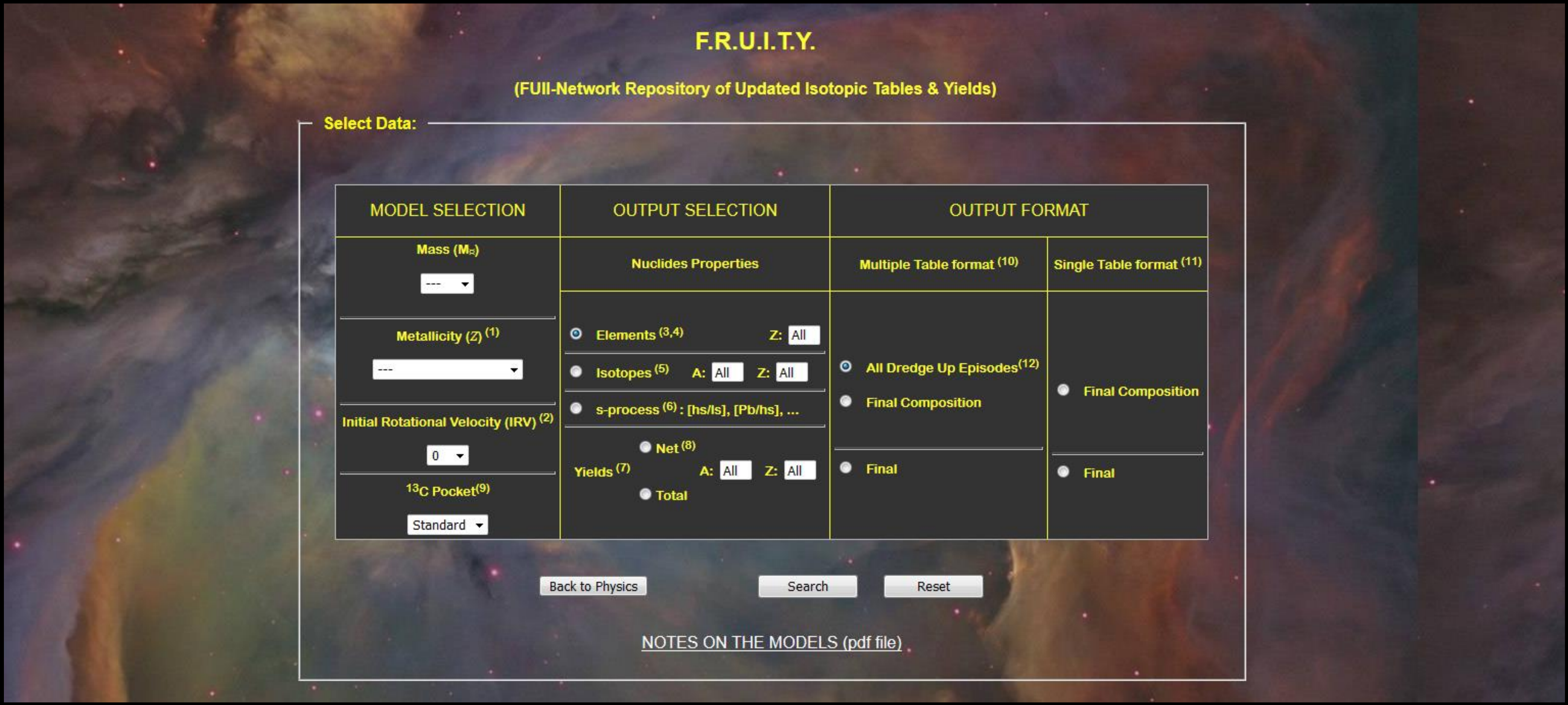
75
70
72
73
74
76
69
71
66
67
68
70
65
N=50


s process
$N_n \sim 10^7$ n/cm^3
r process
$N_n > 10^{23}$ n/cm^3
i process
$N_n \sim 10^{14-17}$ n/cm^3
Proton number
Neutron number
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

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

FUll-Network Repository of Updated Isotopic Tables & Yields



SC+ 2011,2015

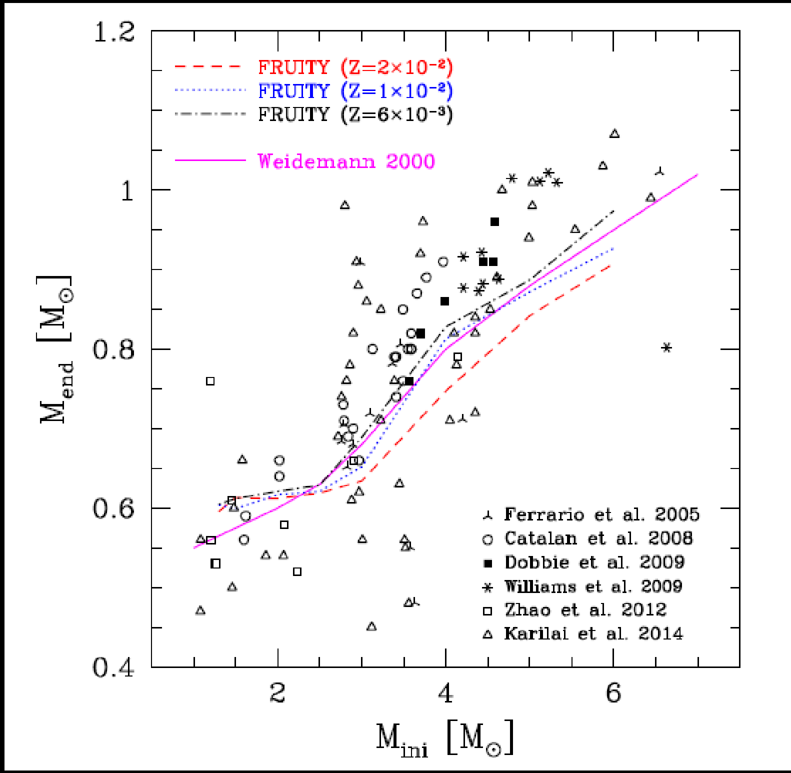
fruity.oa-abruzzo.inaf.it

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

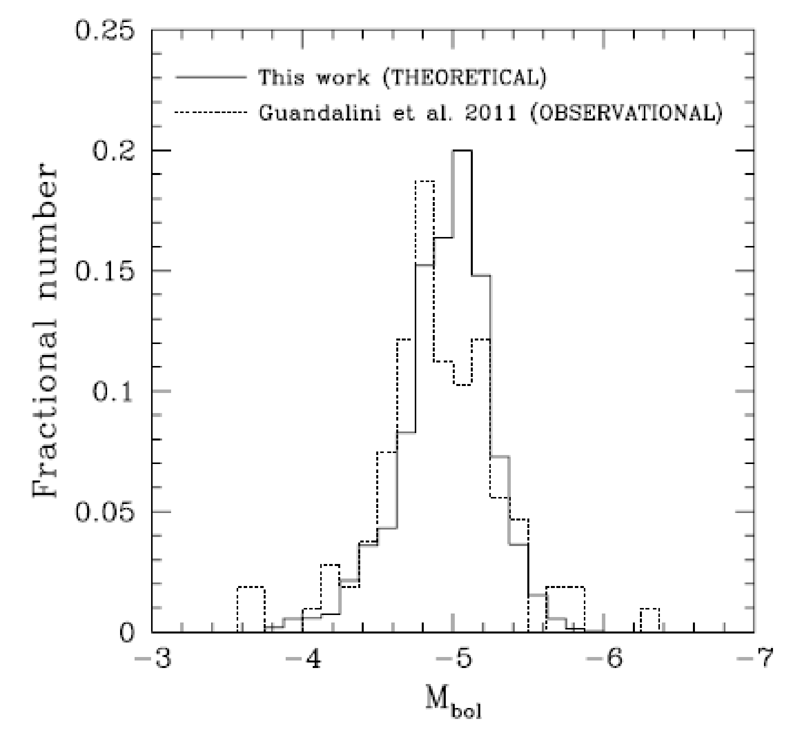
$1.3 \leq M/M_{sun} \leq 6.0$

OBSERVATIONS
(physics)

Initial-to-final mass relations



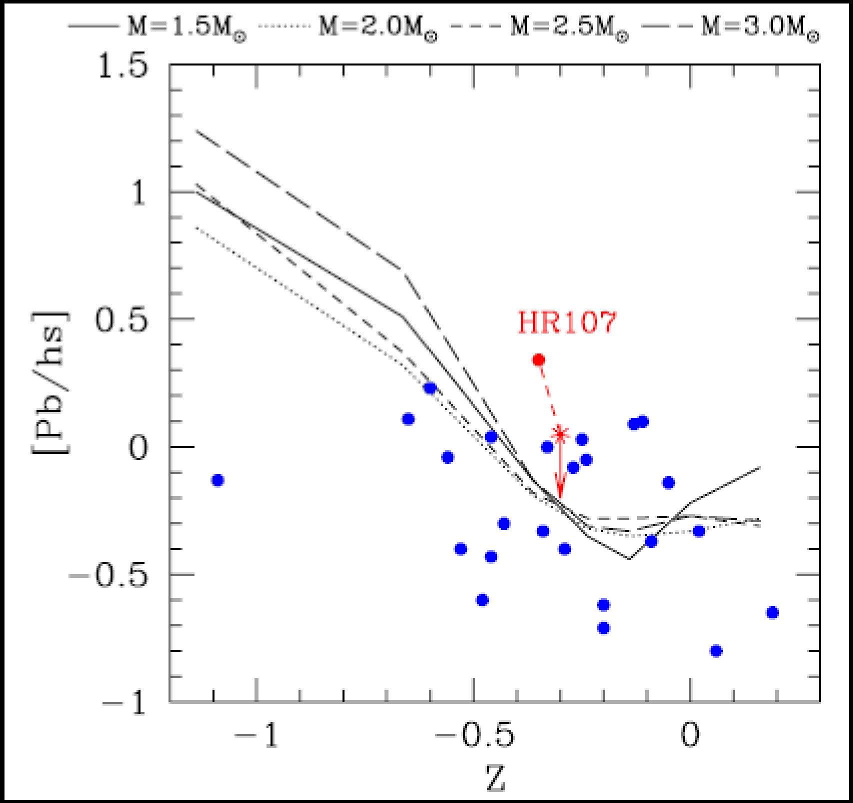
Luminosity Function of C-stars



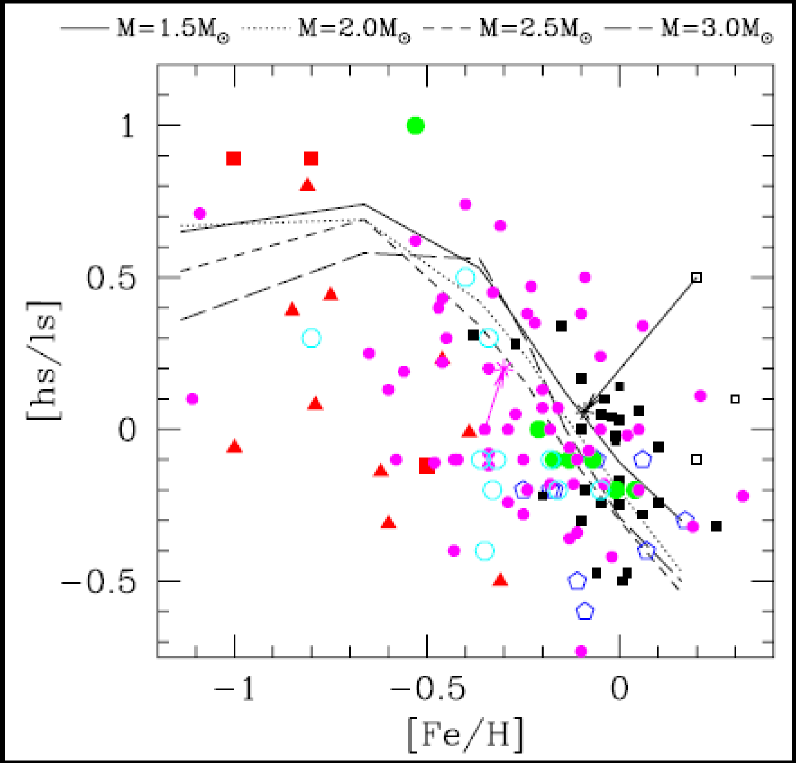
SC+ 2011

OBSERVATIONS (spectroscopy)

Third to second s-process peak



Second to first s-process peak



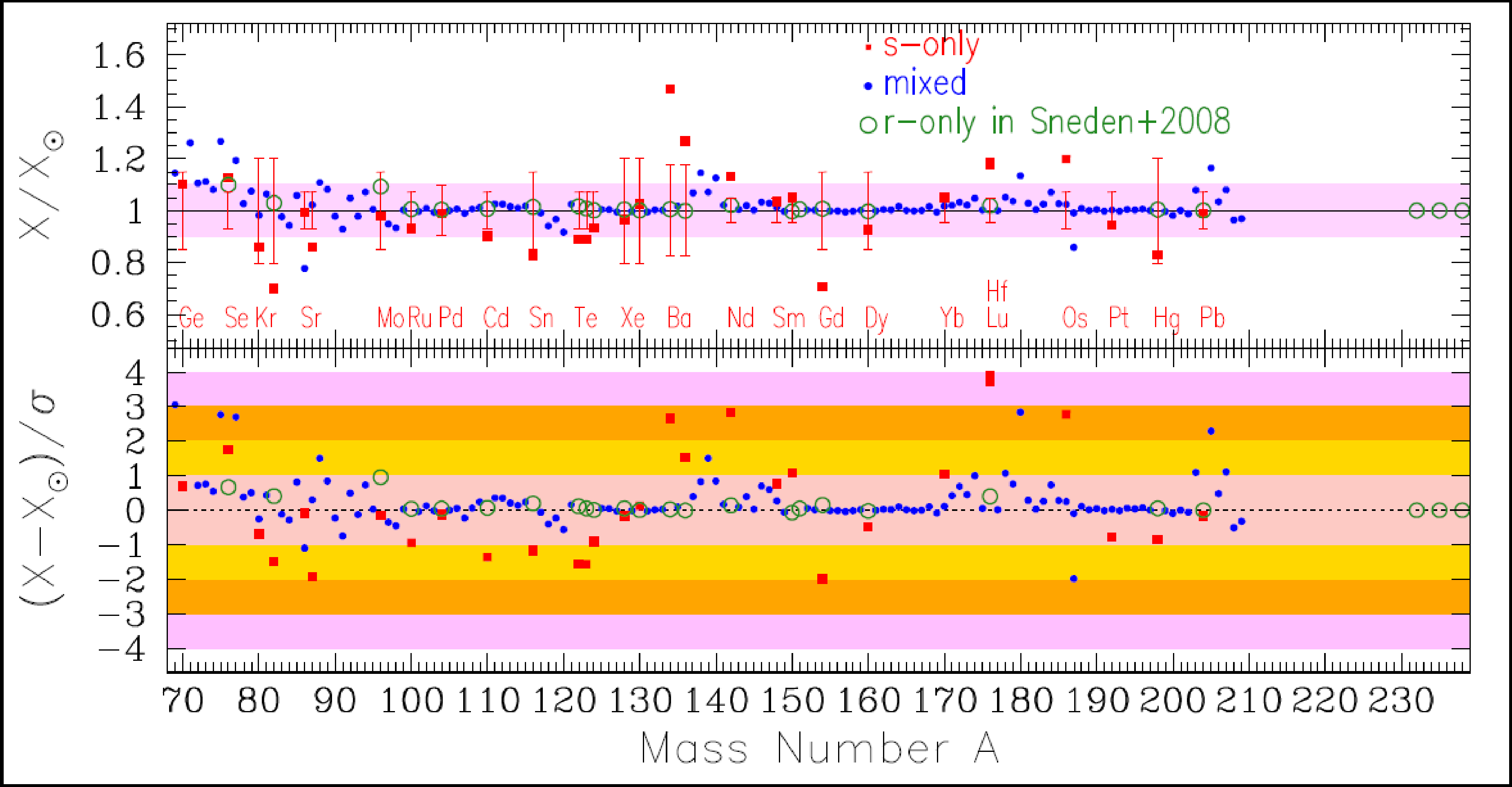
SC+ 2011

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

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

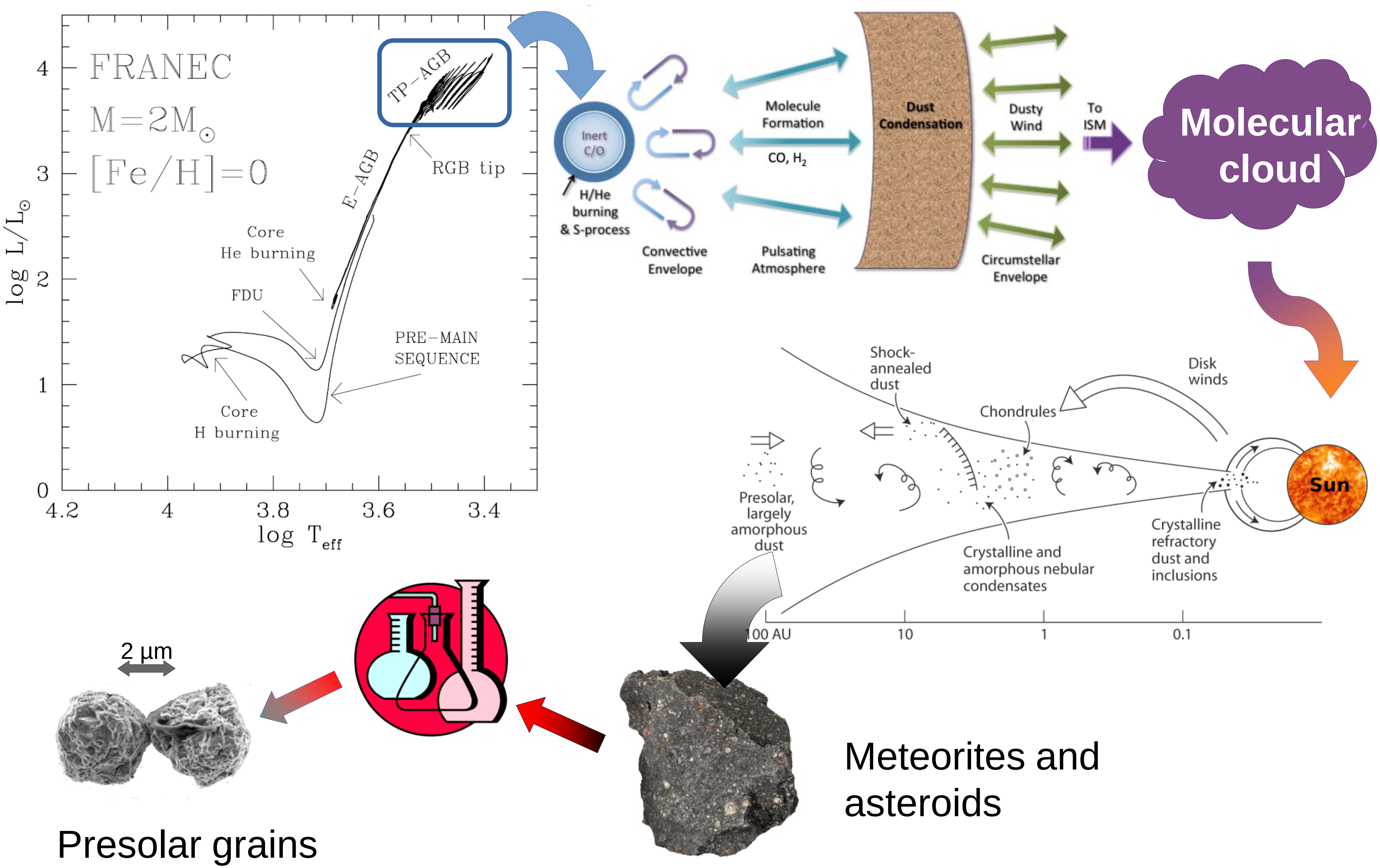
[hs/ls]=[hs/Fe]-[ls/Fe]

Comparison to solar distribution



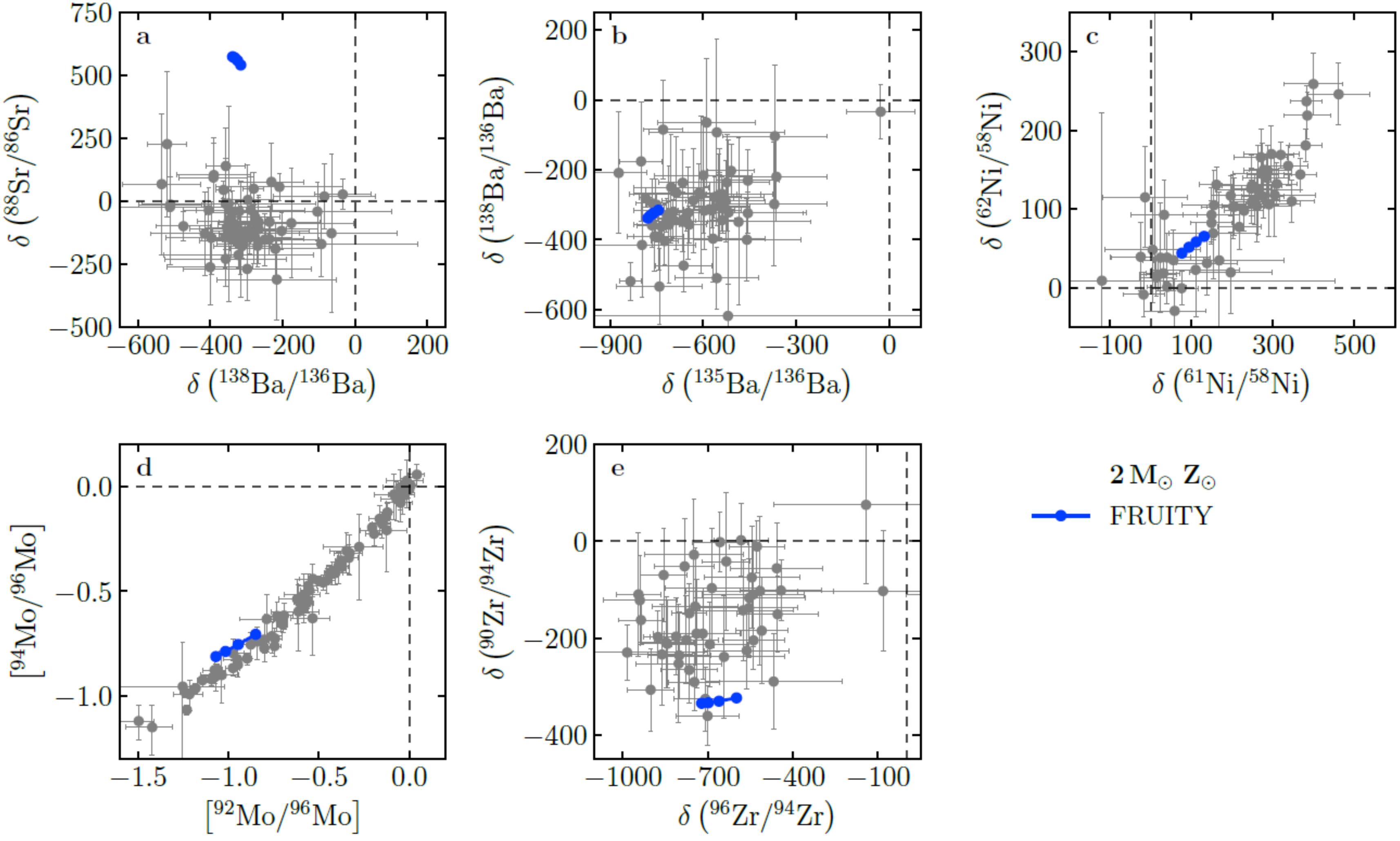
Prantzos+ 2020

AGB stars and presolar SiC grains



SiC Grains

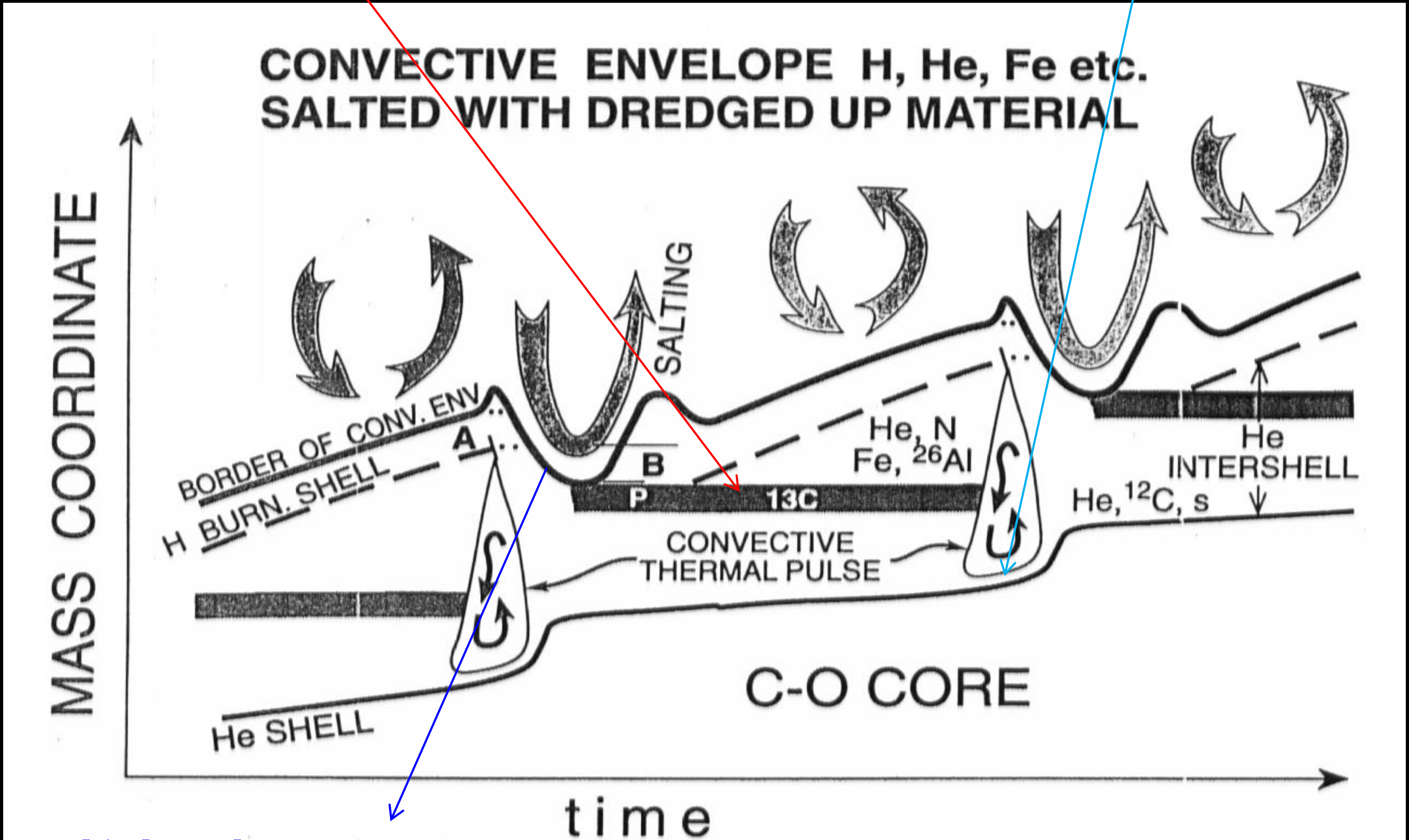
The disagreement between presolar SiC data and models is evident!



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)**

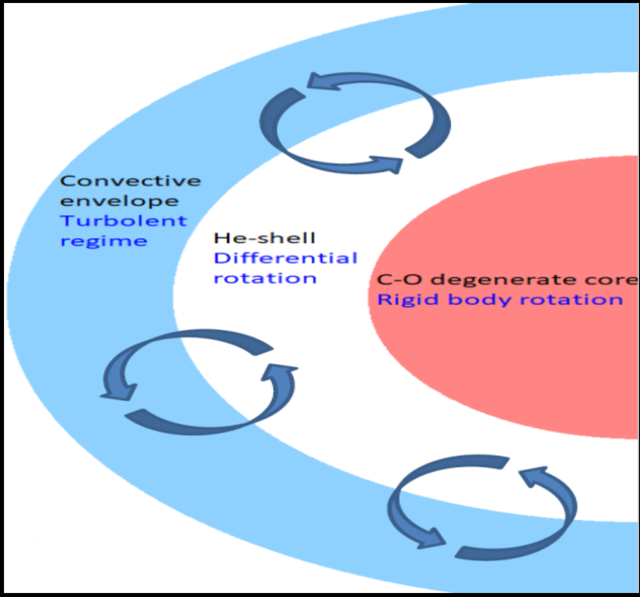
How does the ^{13}C pocket change?

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

Our working hypothesis: magnetic induced mixing

Nucci & Busso 2014

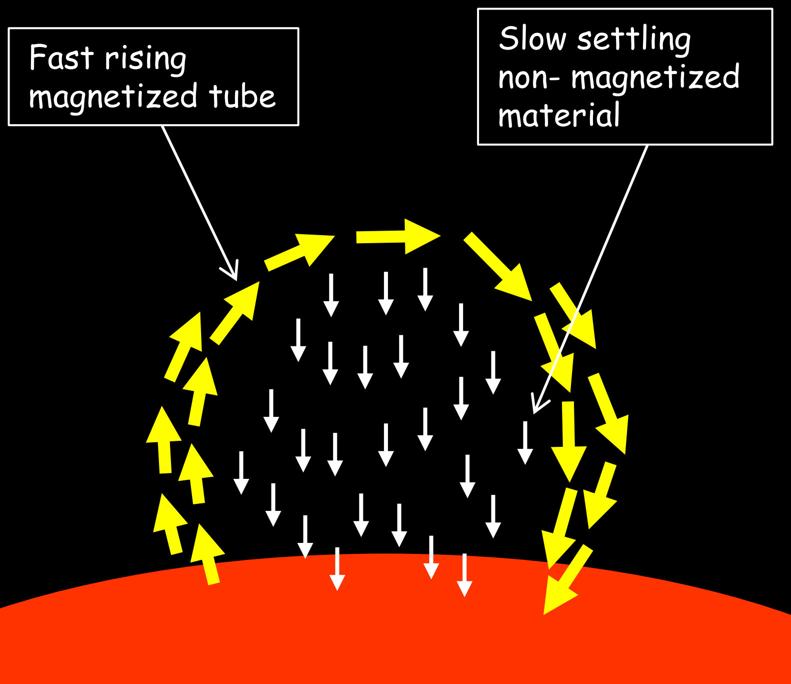
A magnetized stellar plasma in the quasi-ideal MHD regime, with a density distribution closely following a power law as a function of the radius ($r \infty r^k$, with $k<-1$), reaches a dynamic equilibrium and is in radial expansion.



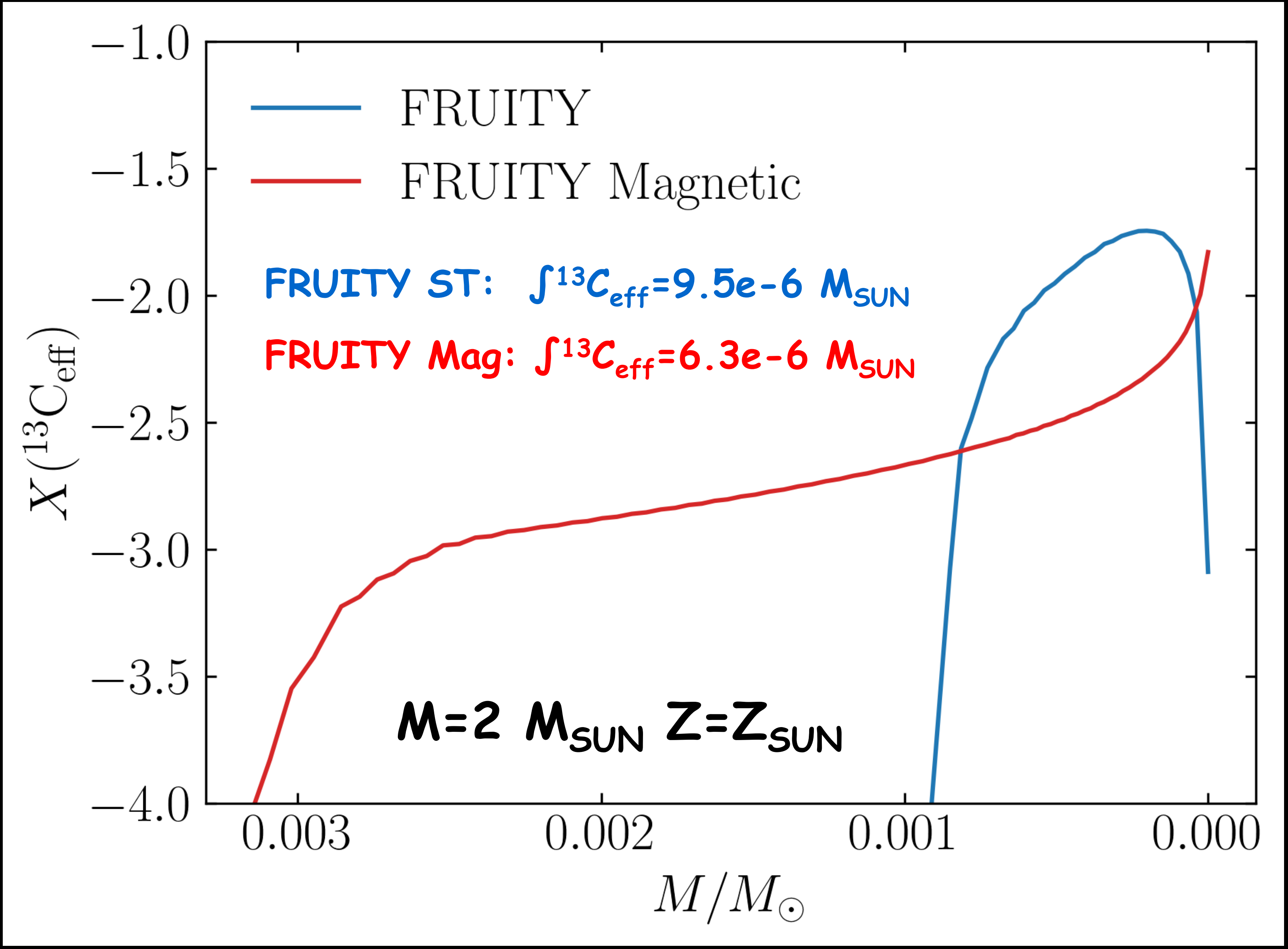
In strong field regimes, the magnetic field tends to concentrate in flux tubes. As a consequence of the magnetic extra-pressure, these tubes are buoyant (see, e.g., Parker 1955).

$$p(z) = p_i(z) + B^2/8\pi$$

Due to the effect of the magnetic buoyancy, a matter flow is pushed from the He-intershell to the envelope. This, in turn, induces a downflow flux, in order to guarantee mass conservation.

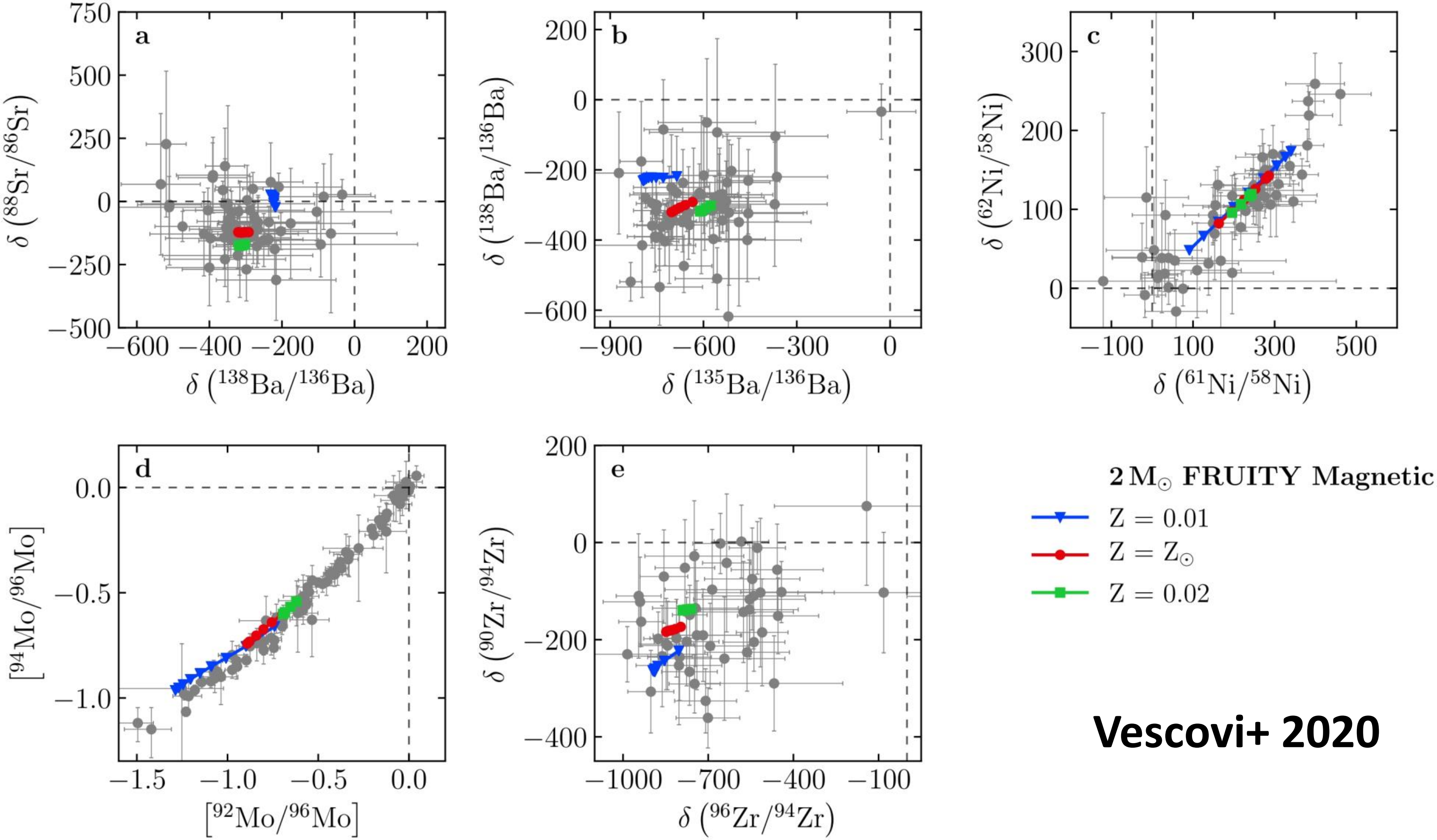


Magnetic ^{13}C-pocket vs FRUITY ^{13}C-pocket



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

WHAT'S NEXT?

- Ba stars (extrinsic AGBs)
- C-stars
- S-stars
- Post-AGB stars

The origin 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 the star's 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.

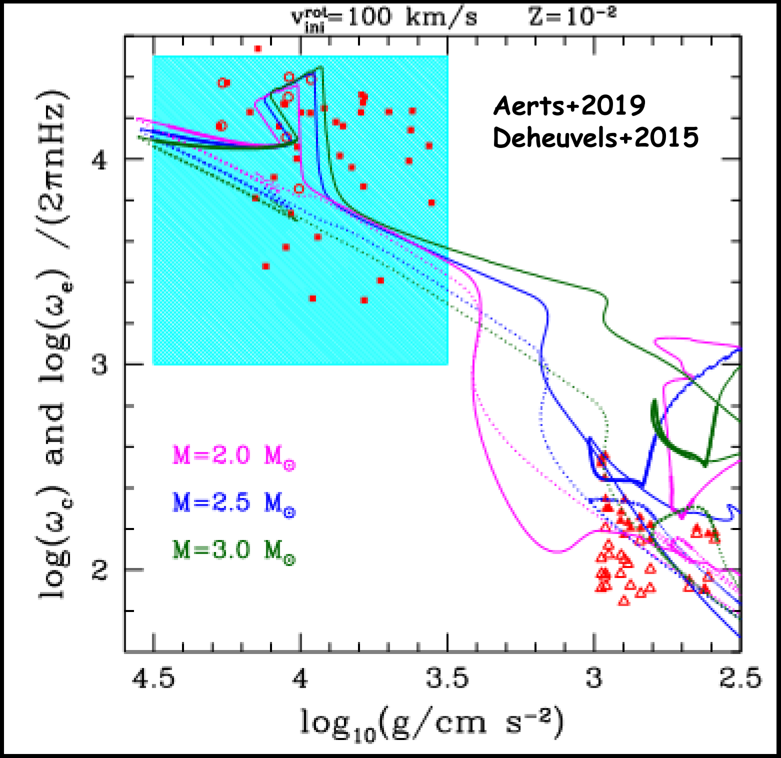
The origin of magnetic fields in stars

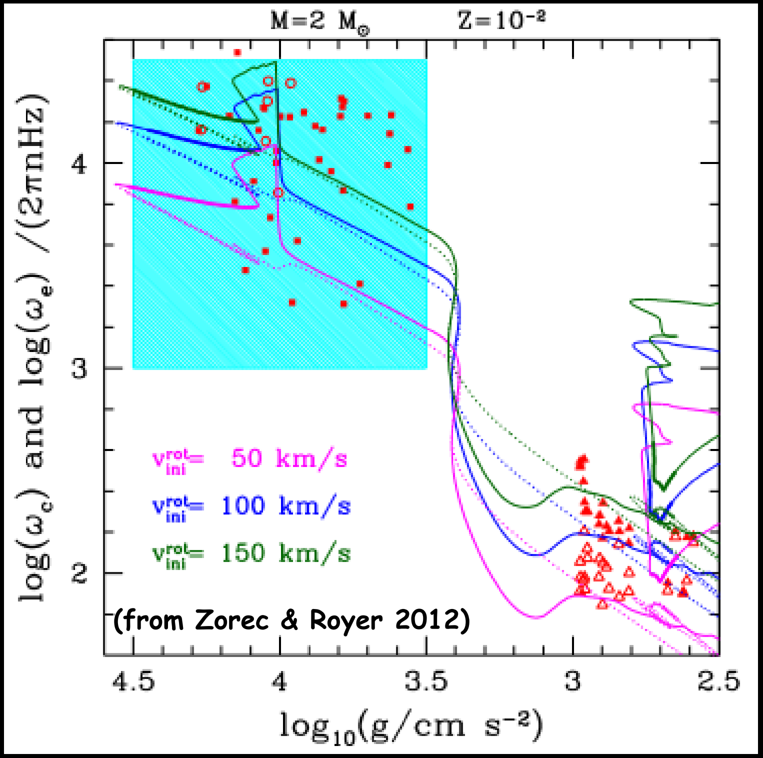
Such a field could be achieved through the stretching of a preexisting low-magnitude poloidal field in the radiative zone below the convective envelope after the quenching of a thermal pulse, via the action of differential rotation around the rotation axis.

$$B_\varphi \sim B_\mathrm{p}(\Omega q \Delta t)$$

$$q = \partial \ln \Omega / \partial \ln r$$

$B_P \approx 5$ G → $B_\varphi \approx 5 \times 10^4$ G





Artificial viscosity added to match asteroseismic data (e.g. Den Hartogh+2019).

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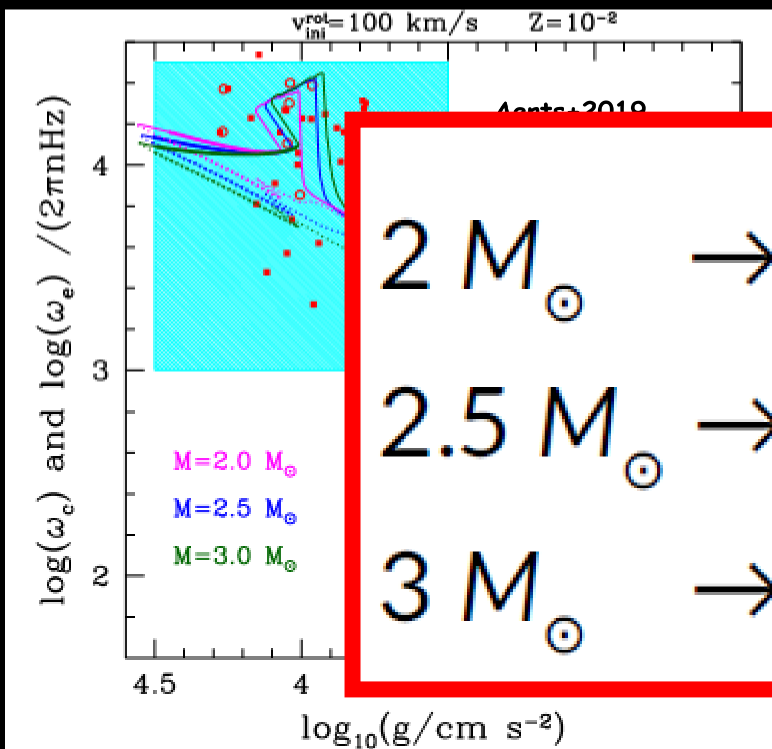
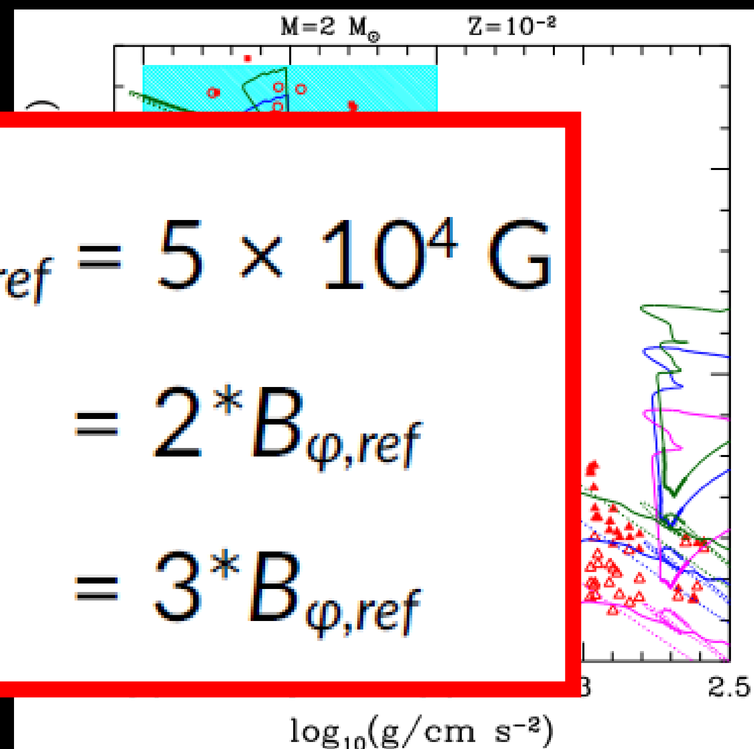


$$2\,M_\odot \rightarrow B_{\varphi,ref} = 5 \times 10^4\ \mathrm{G}$$

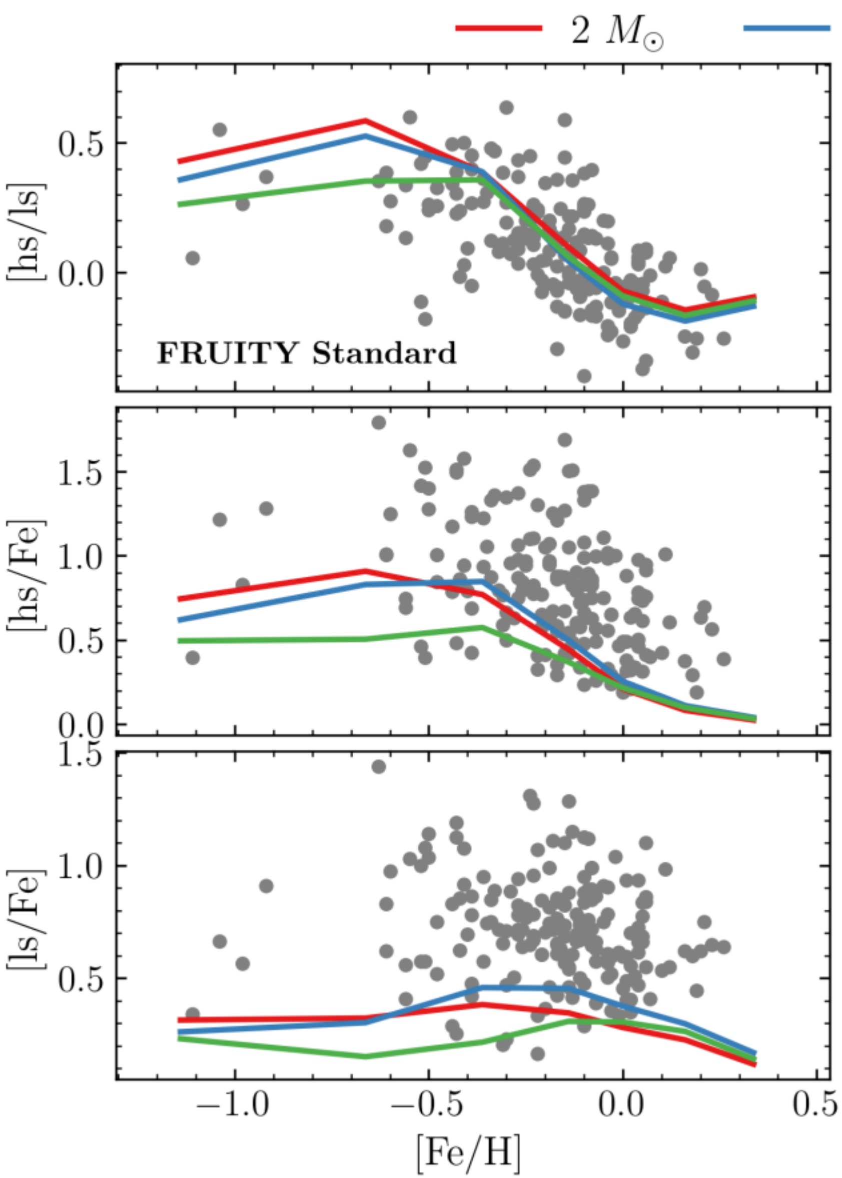
$$2.5\,M_\odot \rightarrow B_\varphi = 2^* B_{\varphi,ref}$$

$$3\,M_\odot \rightarrow B_\varphi = 3^* B_{\varphi,ref}$$



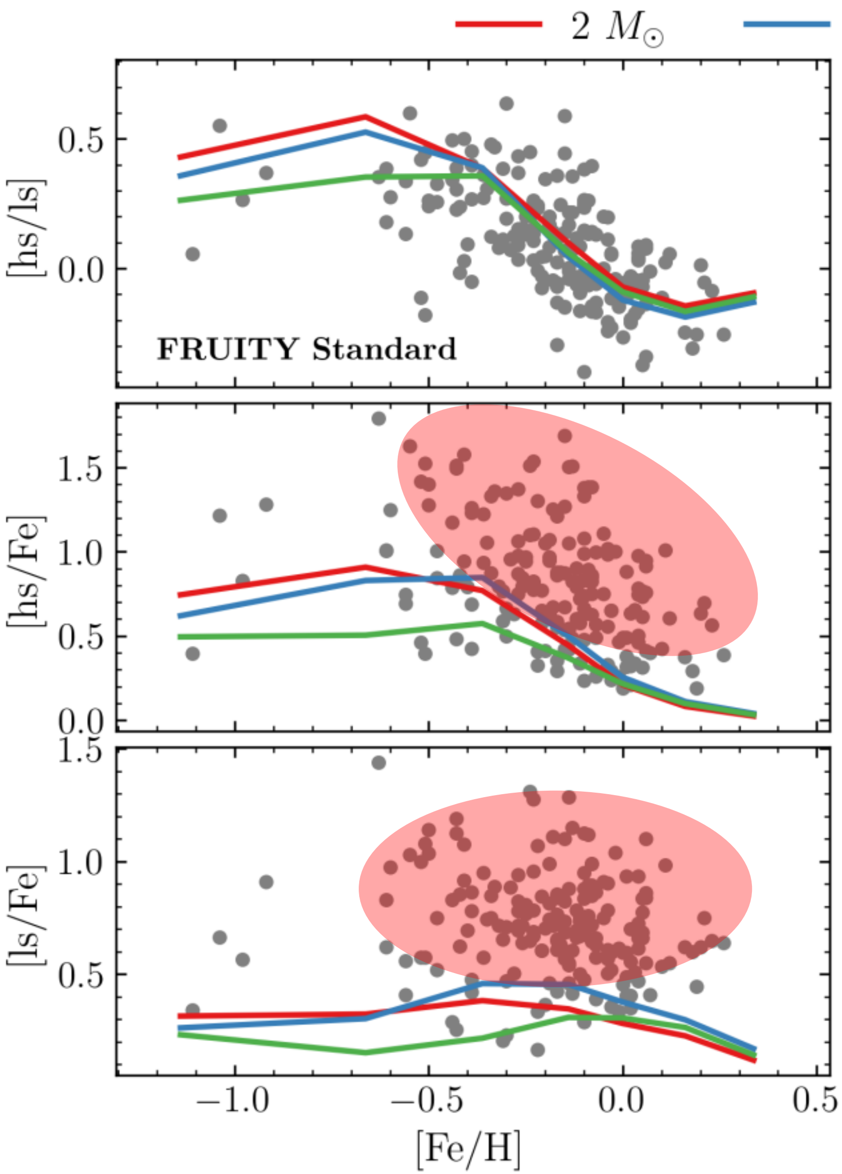
Artificial viscosity added to match asteroseismic data (e.g. Den Hartogh+2019).

Ba-stars



Cseh+18
De Castro+16
Pereira+11
Roriz+21a
Roriz+21b

Ba-stars



Cseh+18
De Castro+16
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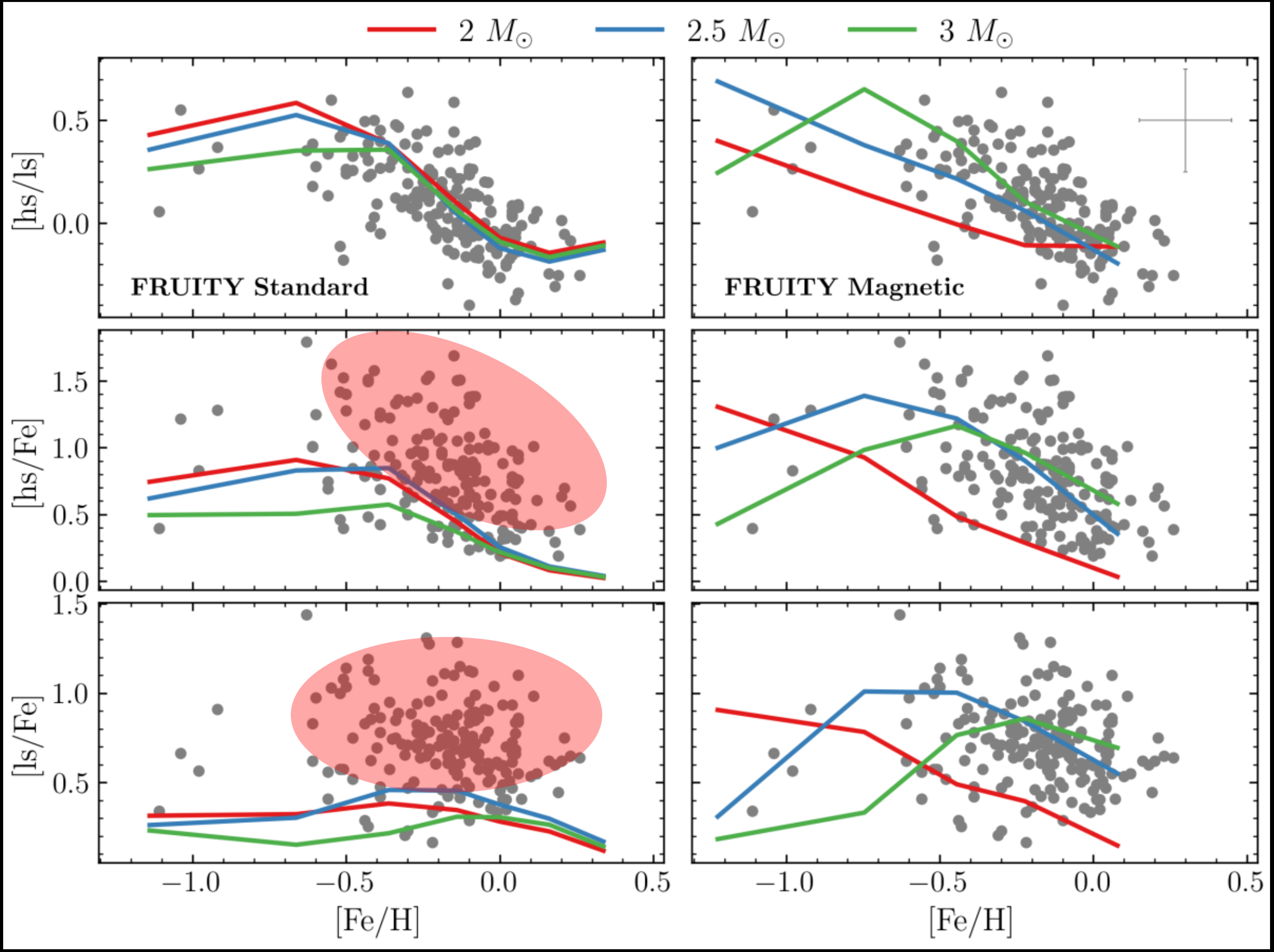
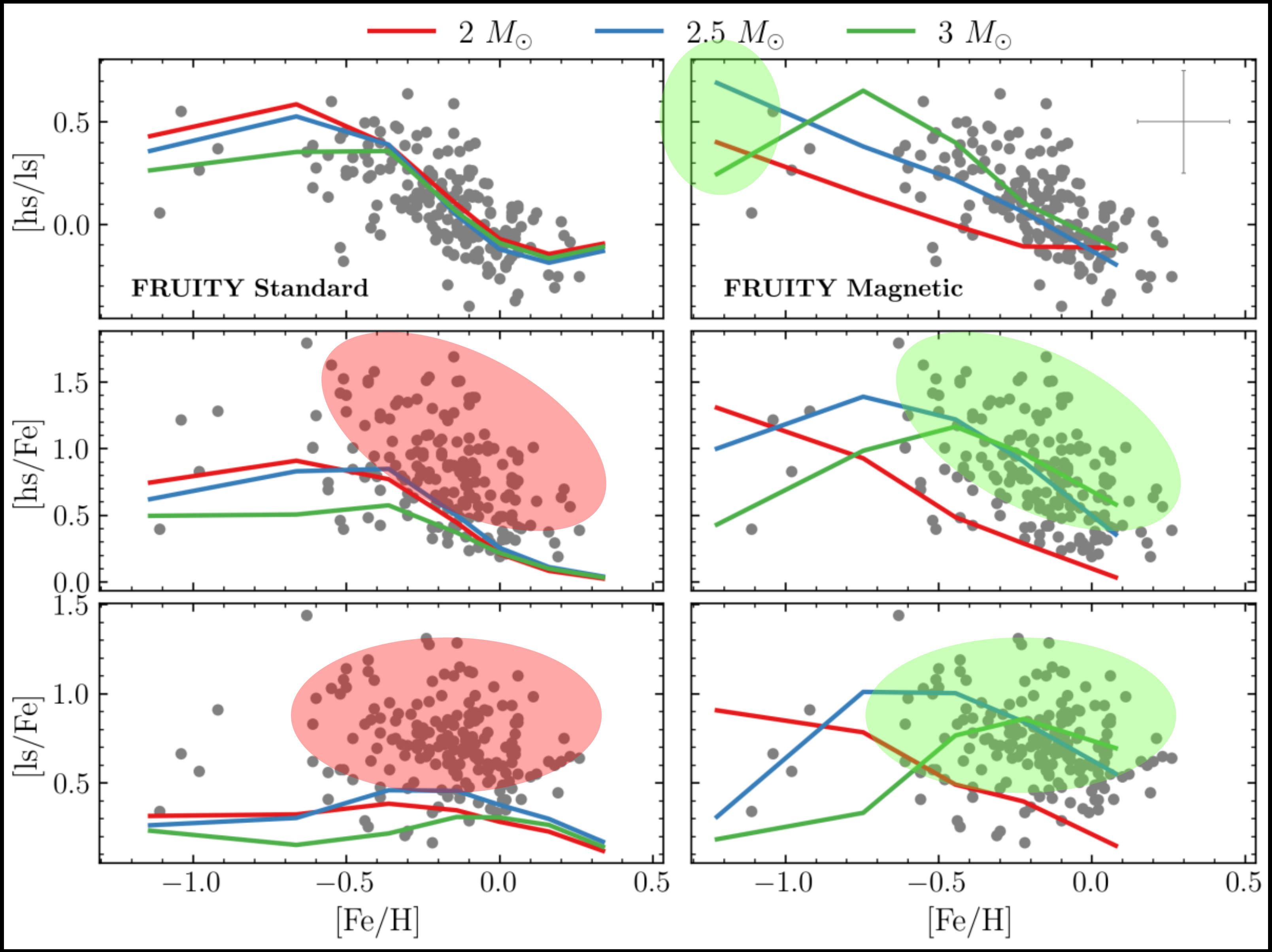
Roriz+21b

Ba-stars



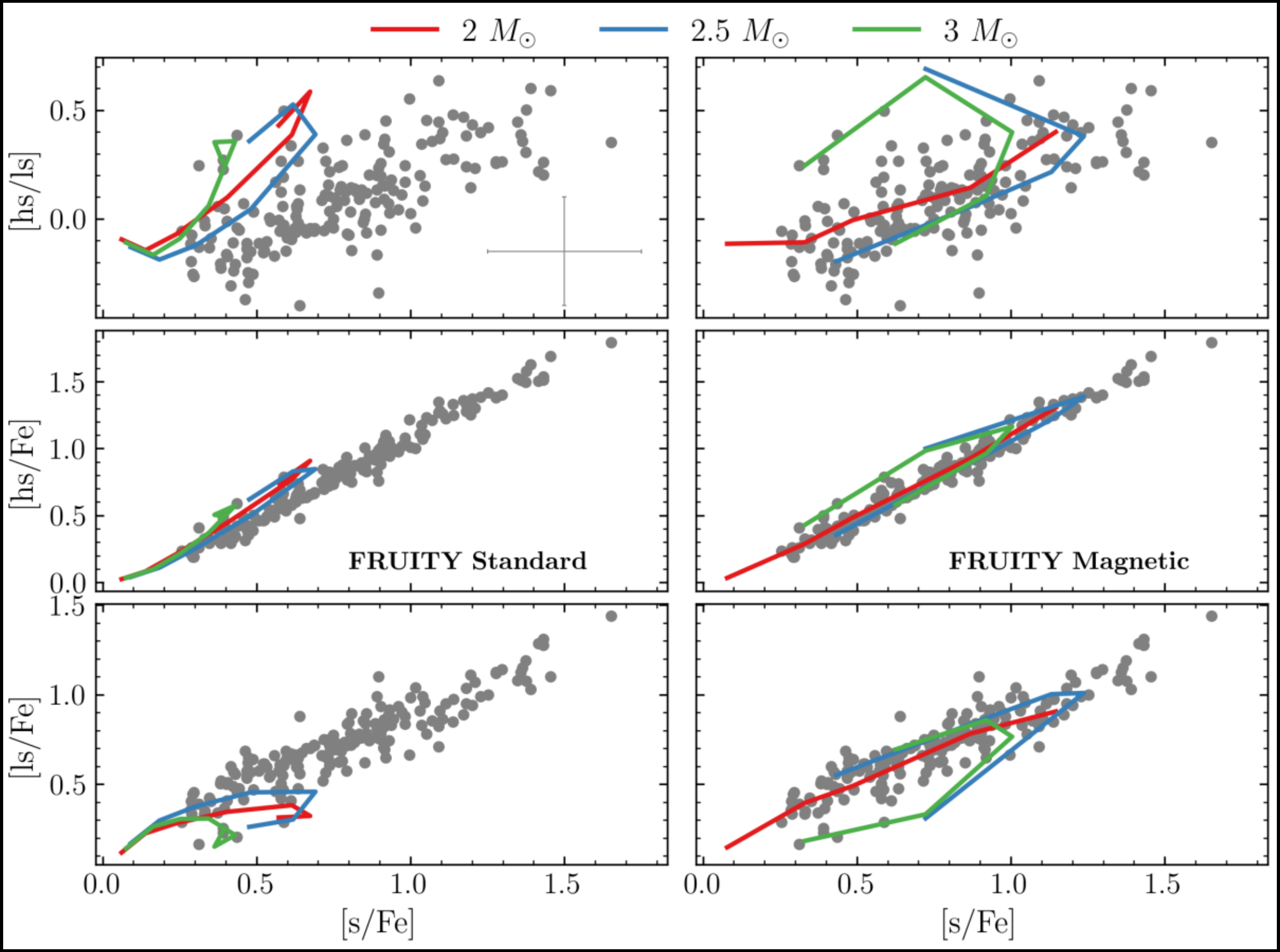
2 $M_\odot$
2.5 $M_\odot$
3 $M_\odot$
[hs/ls]
[hs/Fe]
[ls/Fe]
[Fe/H]
[Fe/H]
FRUITY Standard
FRUITY Magnetic
0.5
0.0
1.5
1.0
0.5
0.0
1.5
1.0
0.5
−1.0
−0.5
0.0
0.5
−1.0
−0.5
0.0
0.5

Ba-stars



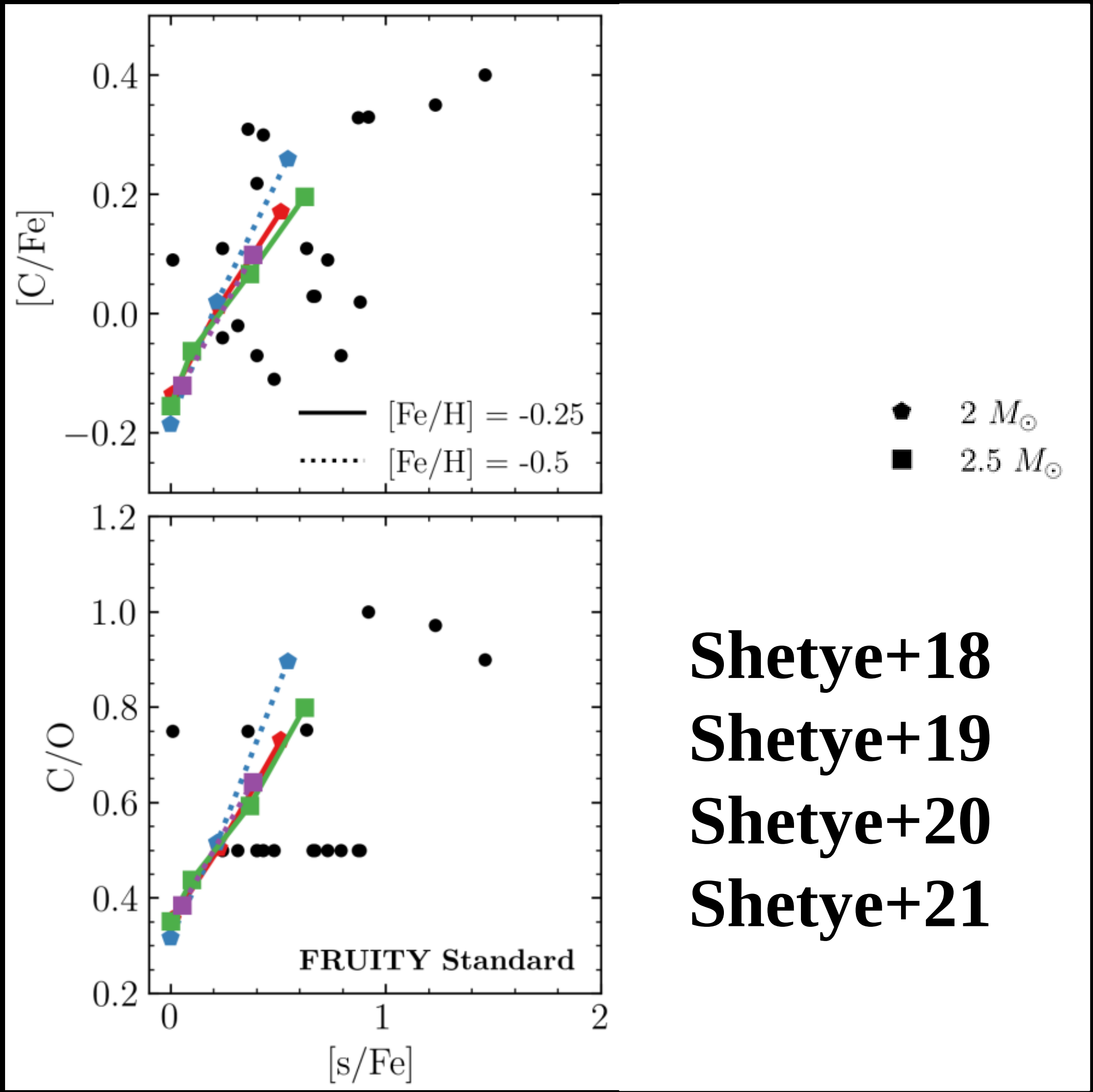
2 $M_\odot$
2.5 $M_\odot$
3 $M_\odot$
FRUITY Standard
FRUITY Magnetic
[hs/ls]
[hs/Fe]
[ls/Fe]
[Fe/H]

Ba-stars



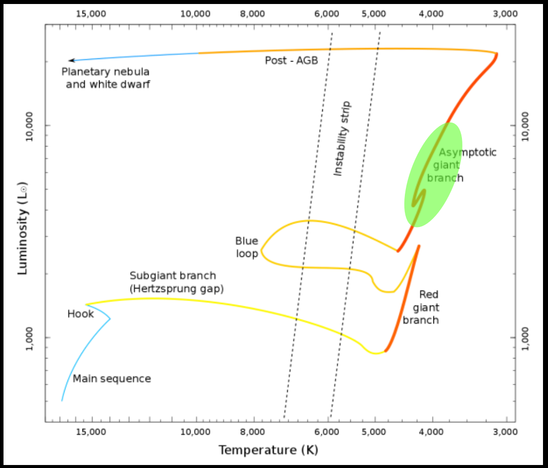
2 $M_\odot$
2.5 $M_\odot$
3 $M_\odot$
[hs/ls]
[hs/Fe]
[ls/Fe]
[s/Fe]
FRUITY Standard
FRUITY Magnetic

S-stars

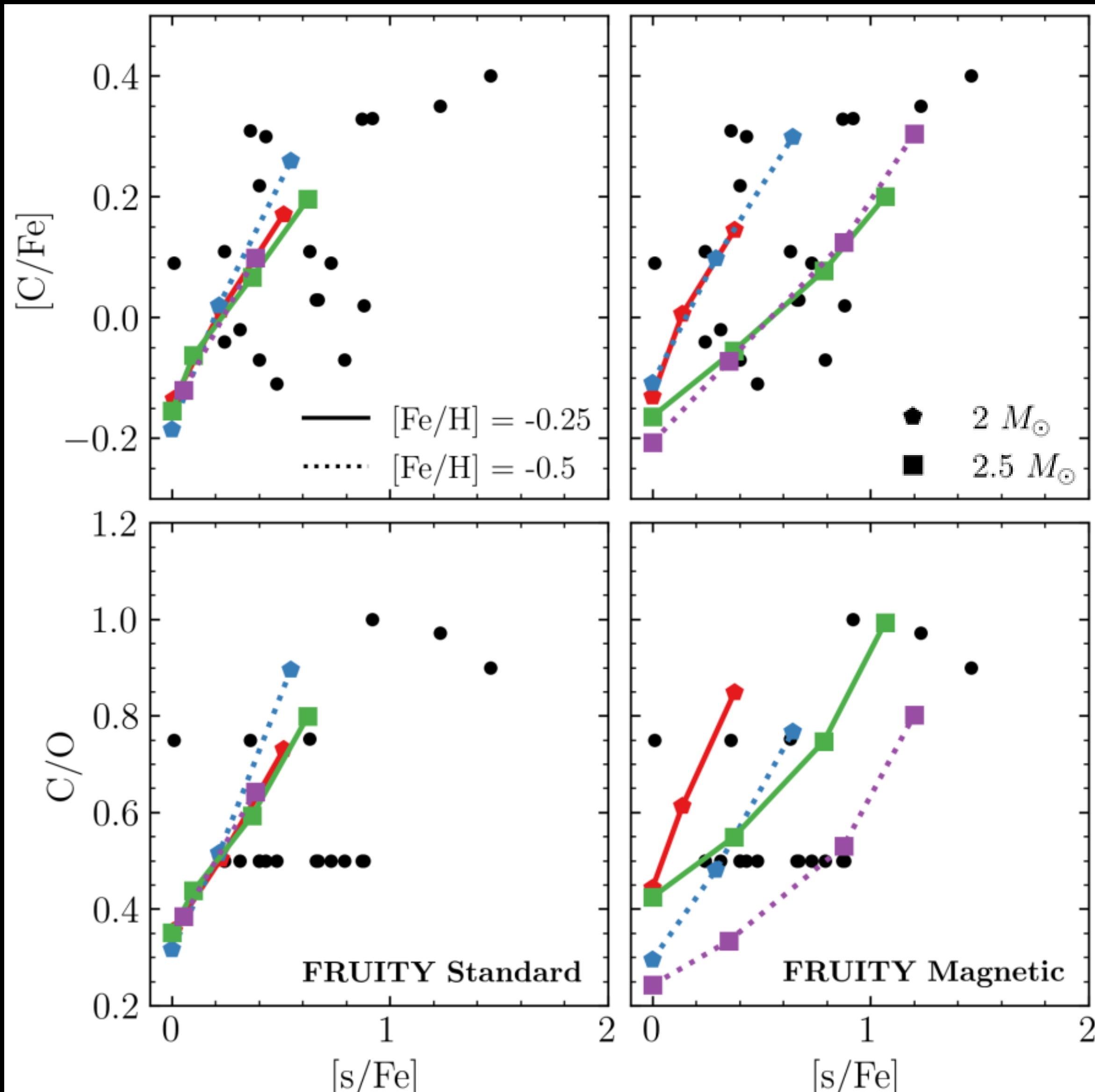


$0.3 < C/O < 1.0$

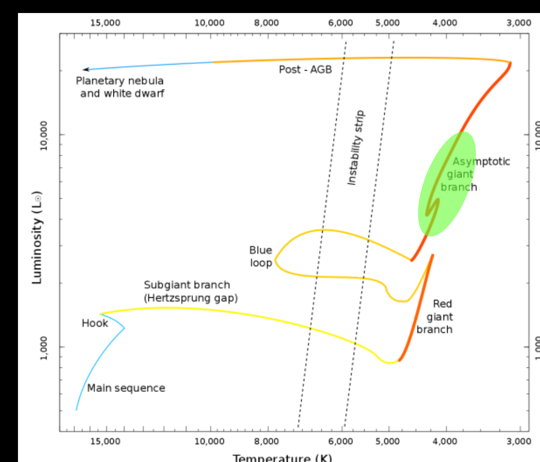
Shetye+18
Shetye+19
Shetye+20
Shetye+21



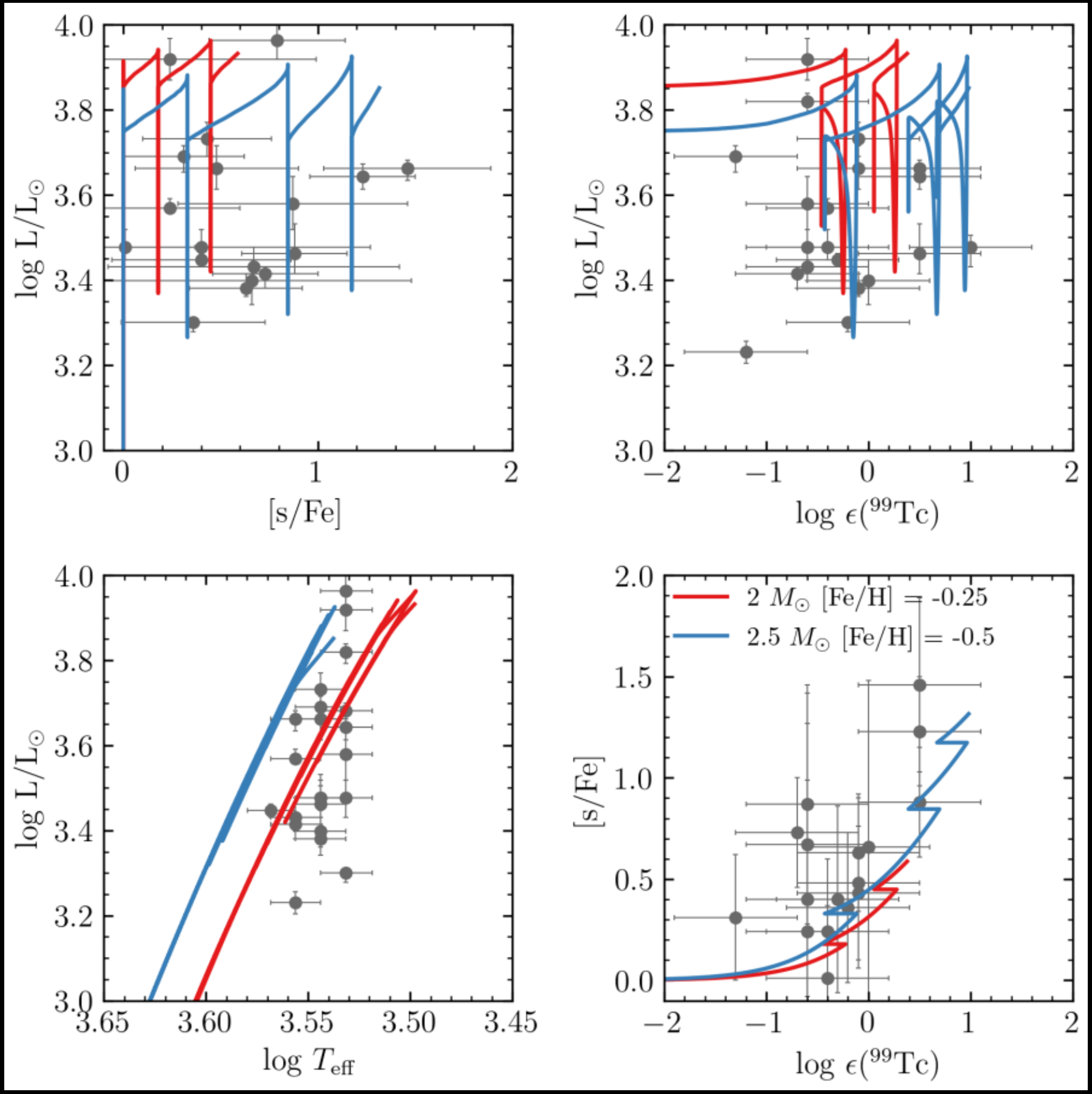
S-stars



0.3 < C/O < 1.0

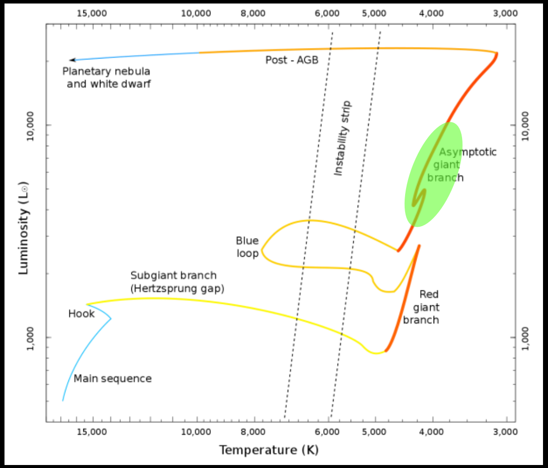


S-stars

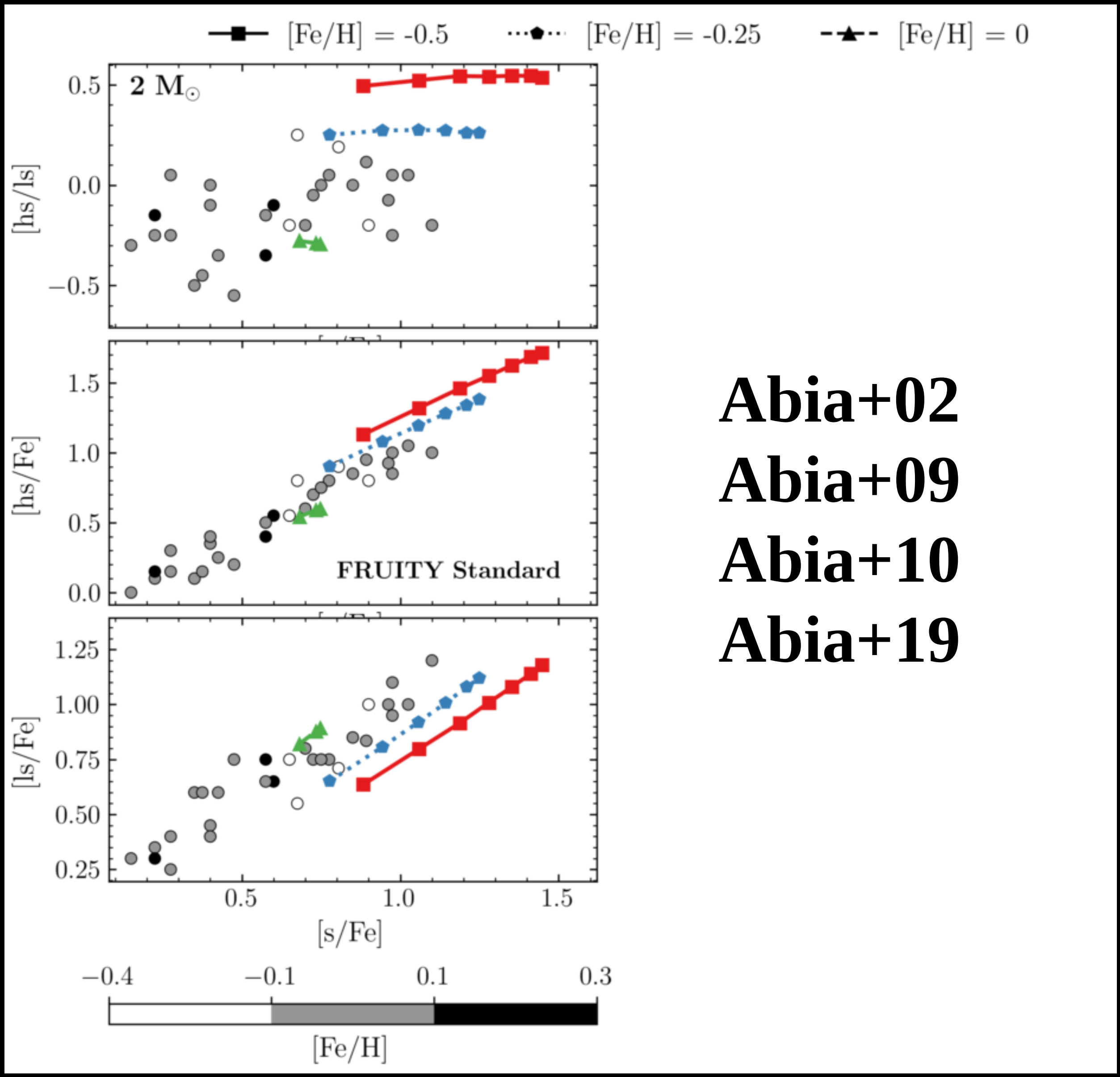


0.3 < C/O < 1.0

Tc is freshly produced by TDU [Merrill 1952]

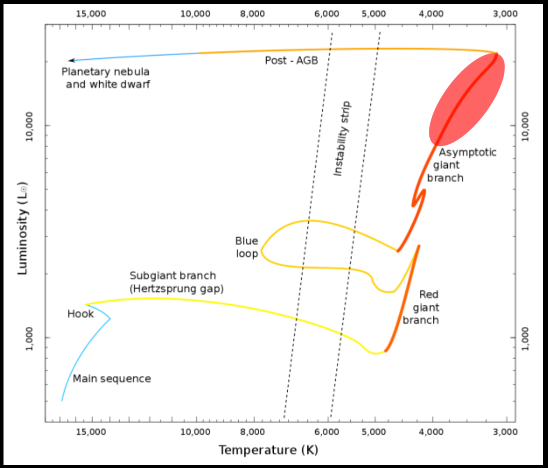


C-stars

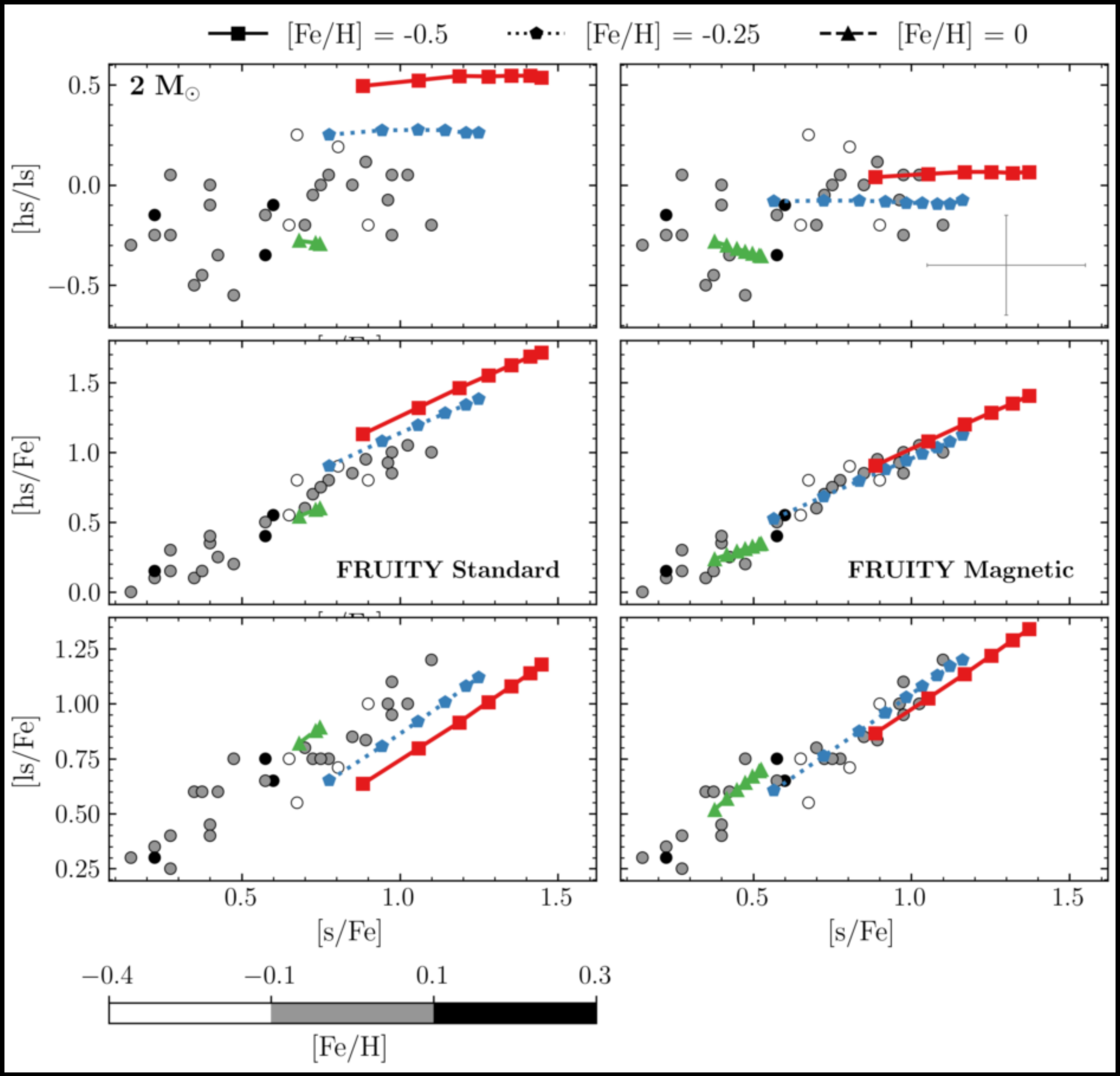


C/O > 1.0

Abia+02
Abia+09
Abia+10
Abia+19

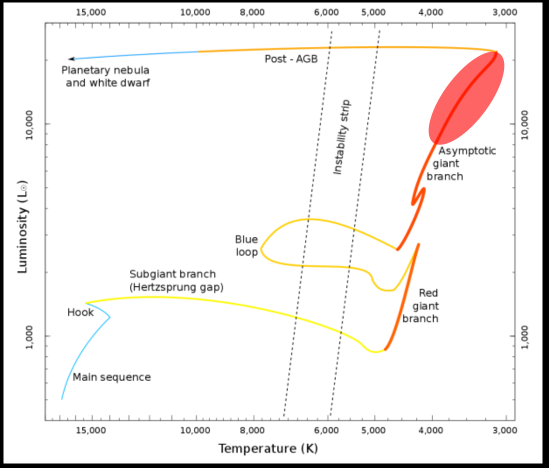


C-stars



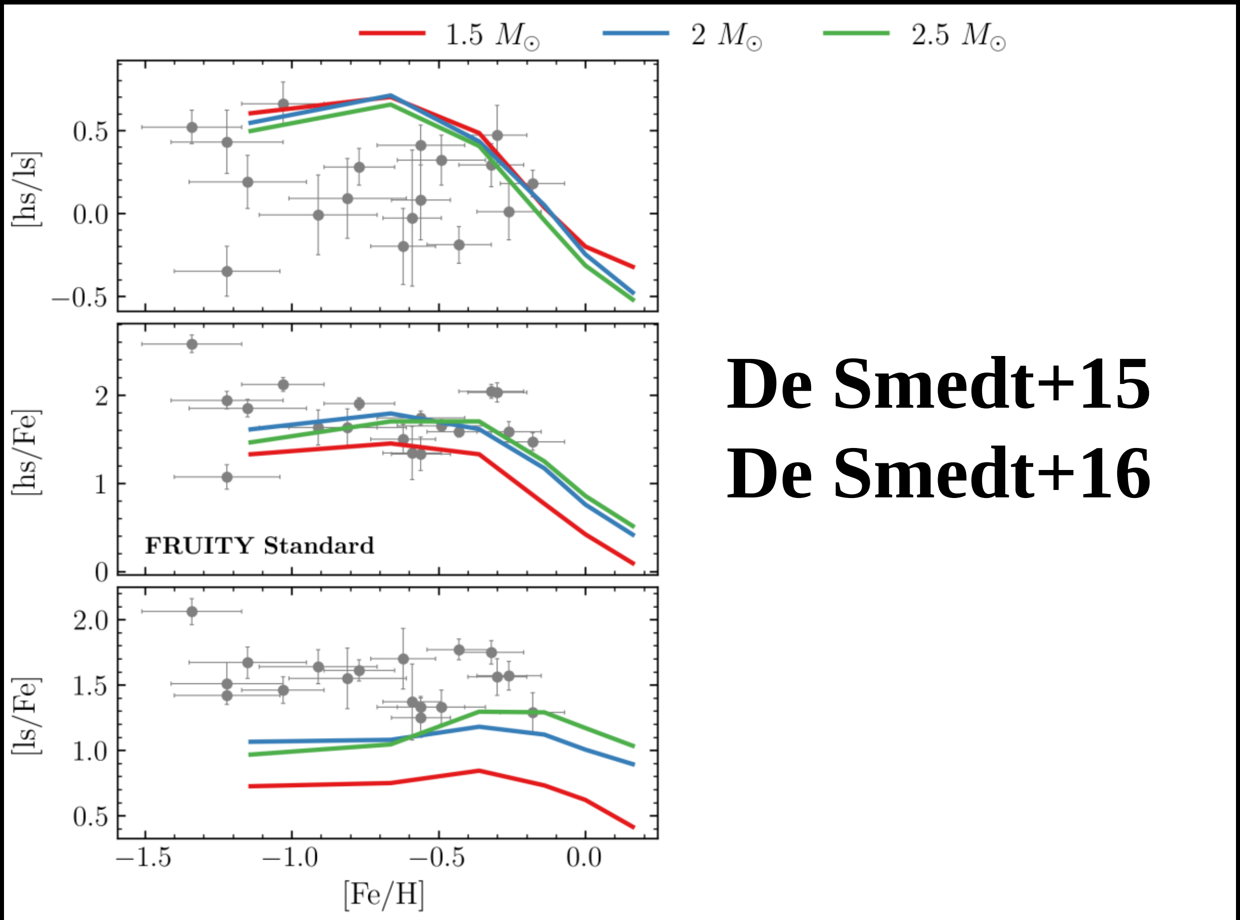
[Fe/H] = -0.5
[Fe/H] = -0.25
[Fe/H] = 0
2 M⊙
[hs/ls]
[hs/Fe]
[ls/Fe]
FRUITY Standard
FRUITY Magnetic
[s/Fe]
[Fe/H]
−0.4
−0.1
0.1
0.3

C/O > 1.0



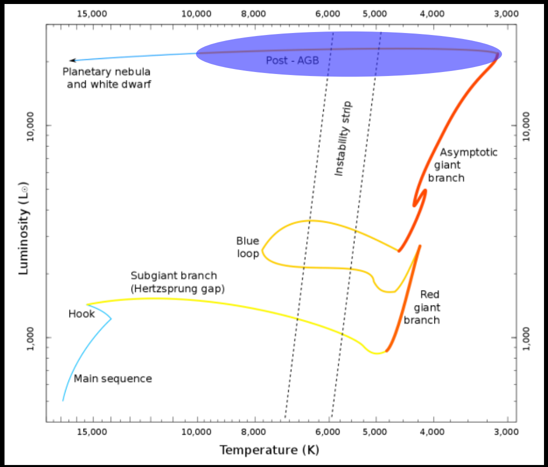
Post - AGB
Planetary nebula and white dwarf
Instability strip
Asymptotic giant branch
Blue loop
Subgiant branch (Hertzsprung gap)
Red giant branch
Hook
Main sequence
Luminosity (L⊙)
Temperature (K)

Post-AGB stars

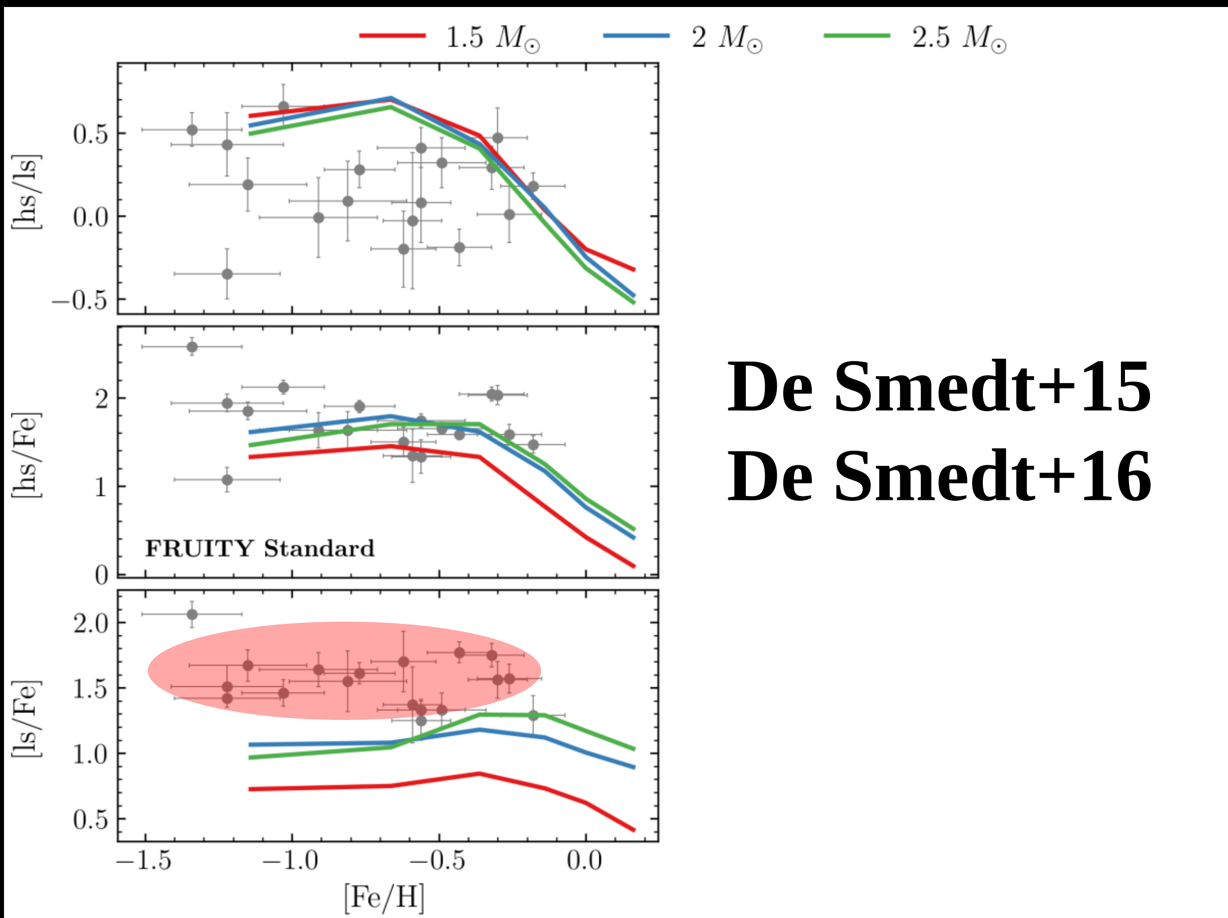


ls & hs

De Smedt+15
De Smedt+16

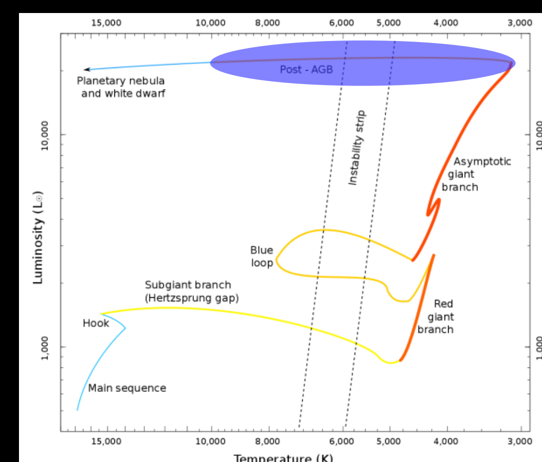


Post-AGB stars

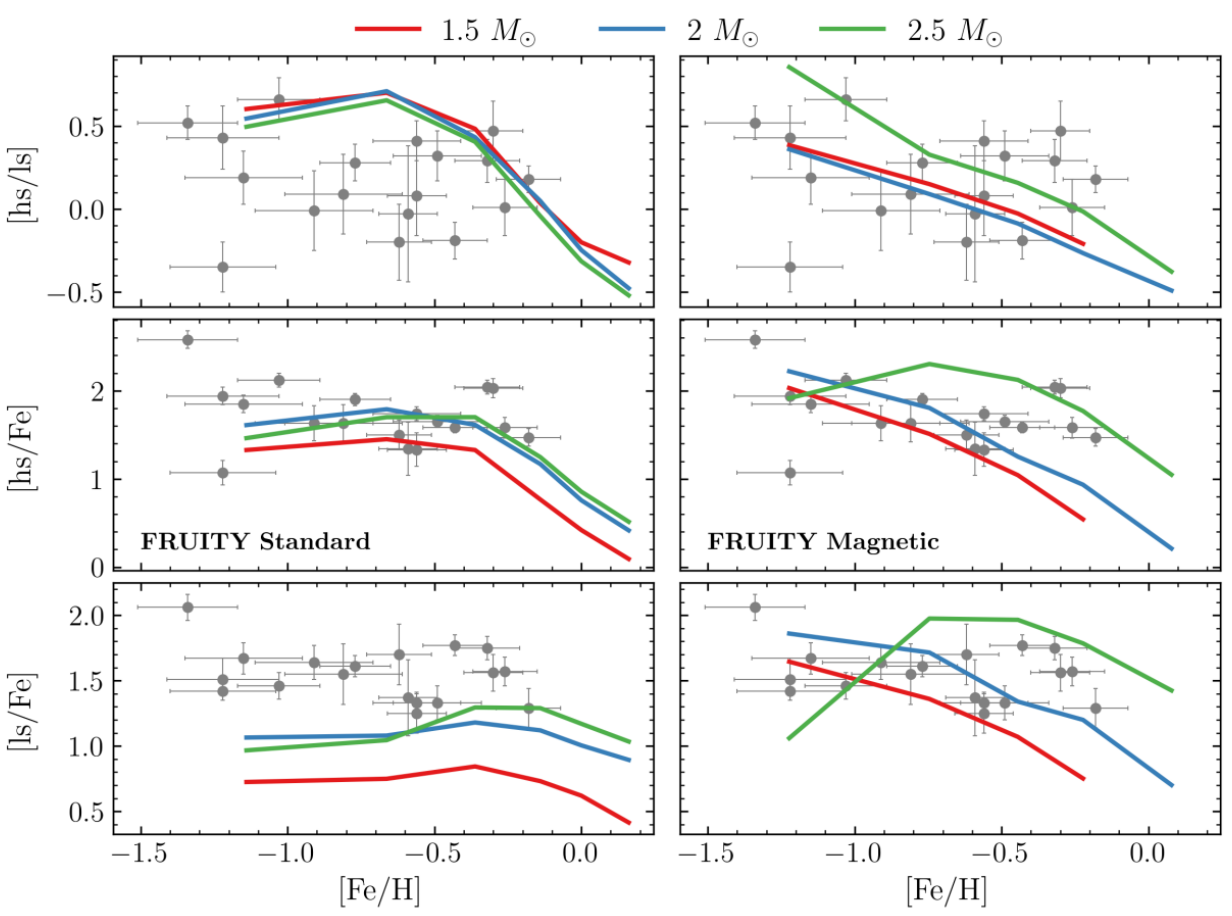


ls & hs

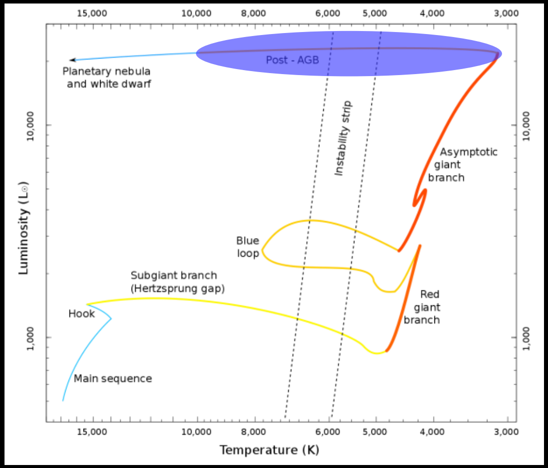
De Smedt+15
De Smedt+16



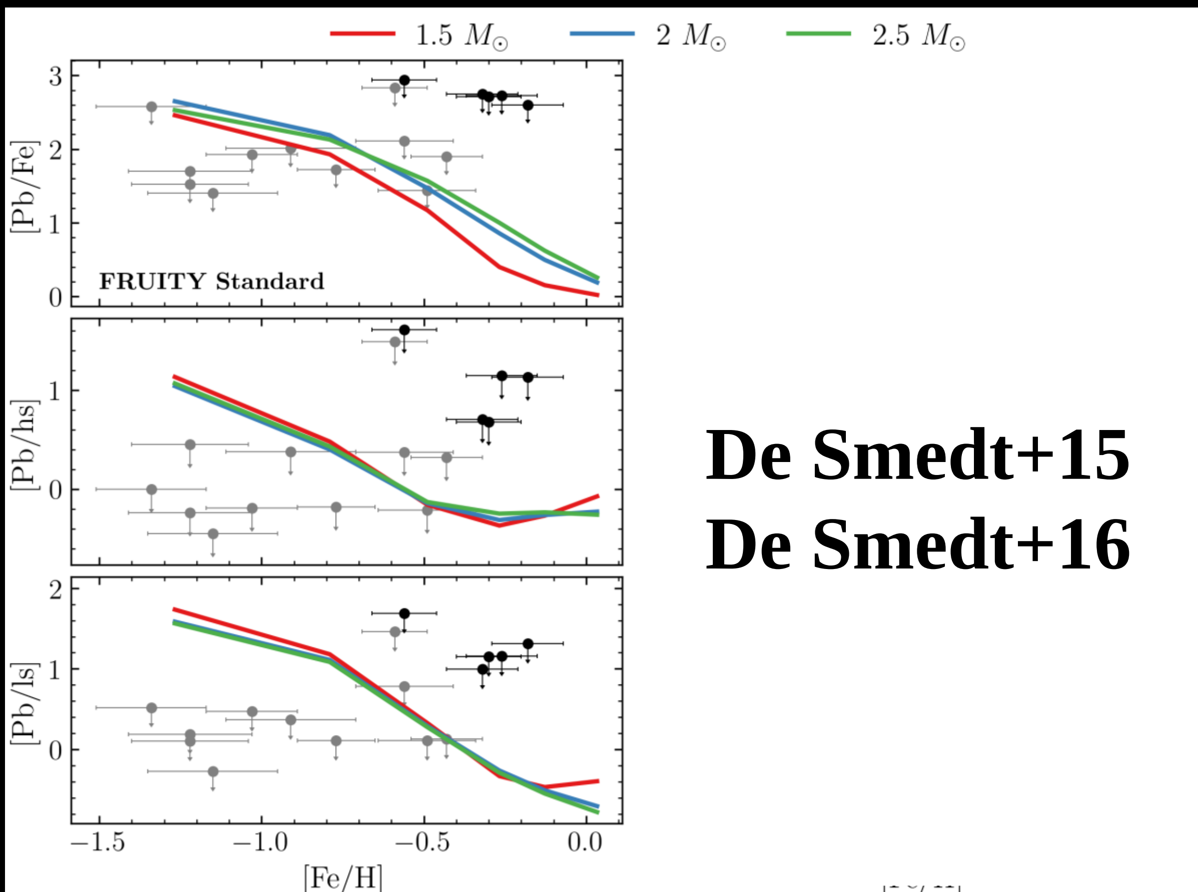
Post-AGB stars



ls & hs

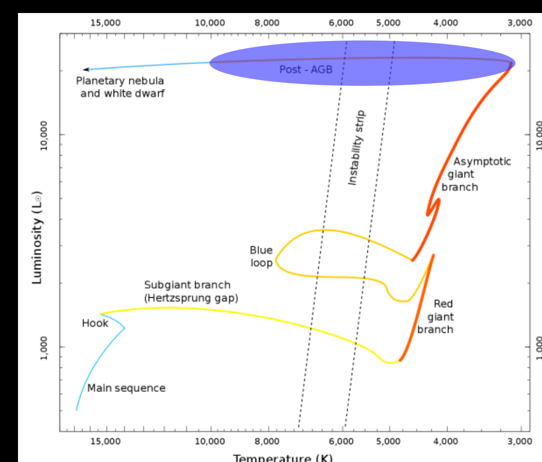


Post-AGB stars

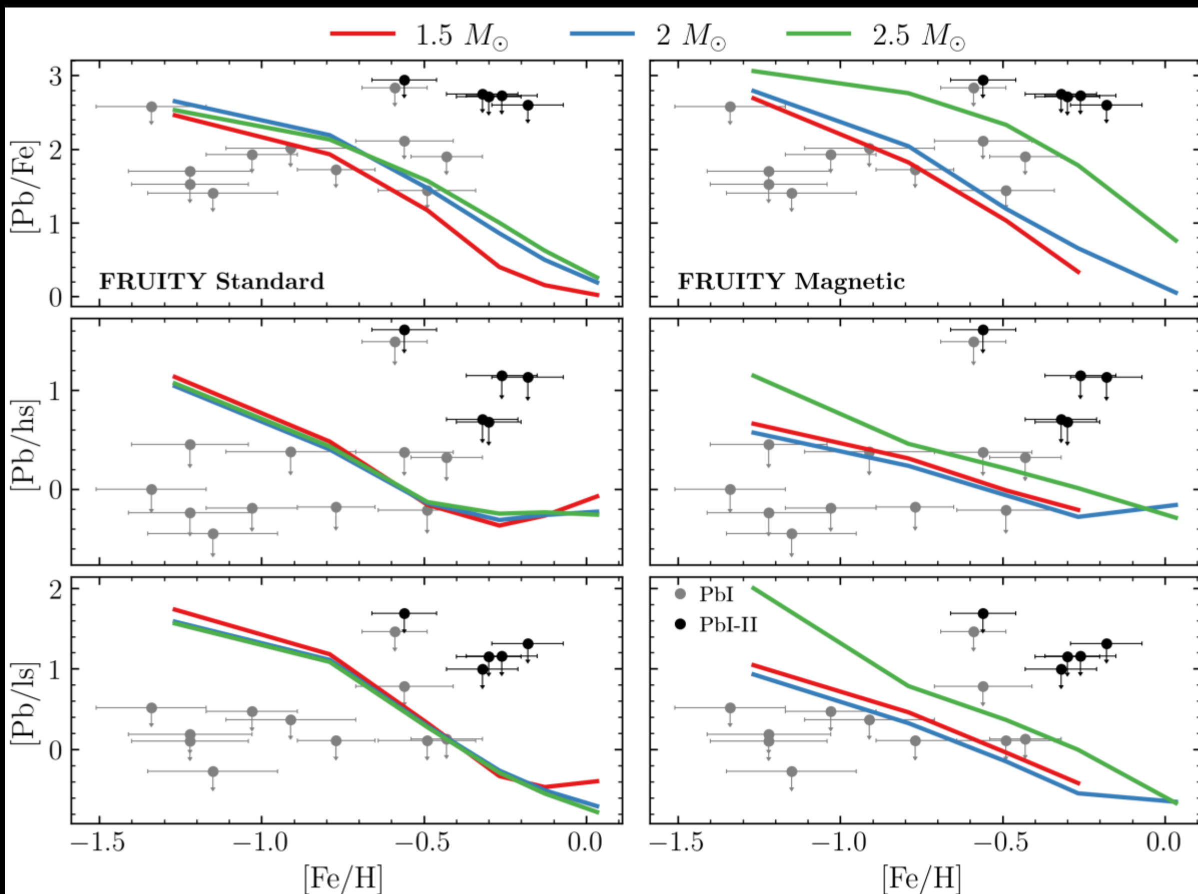


Pb

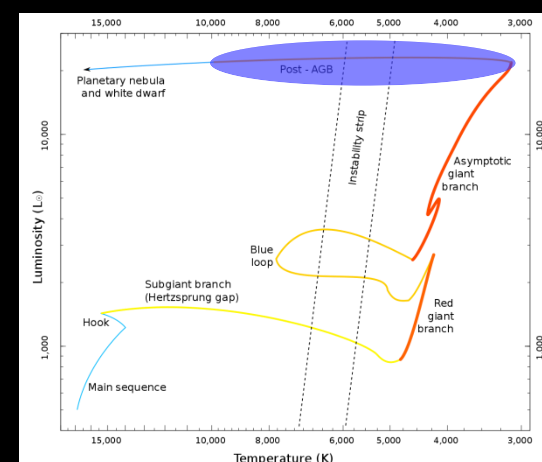
De Smedt+15
De Smedt+16



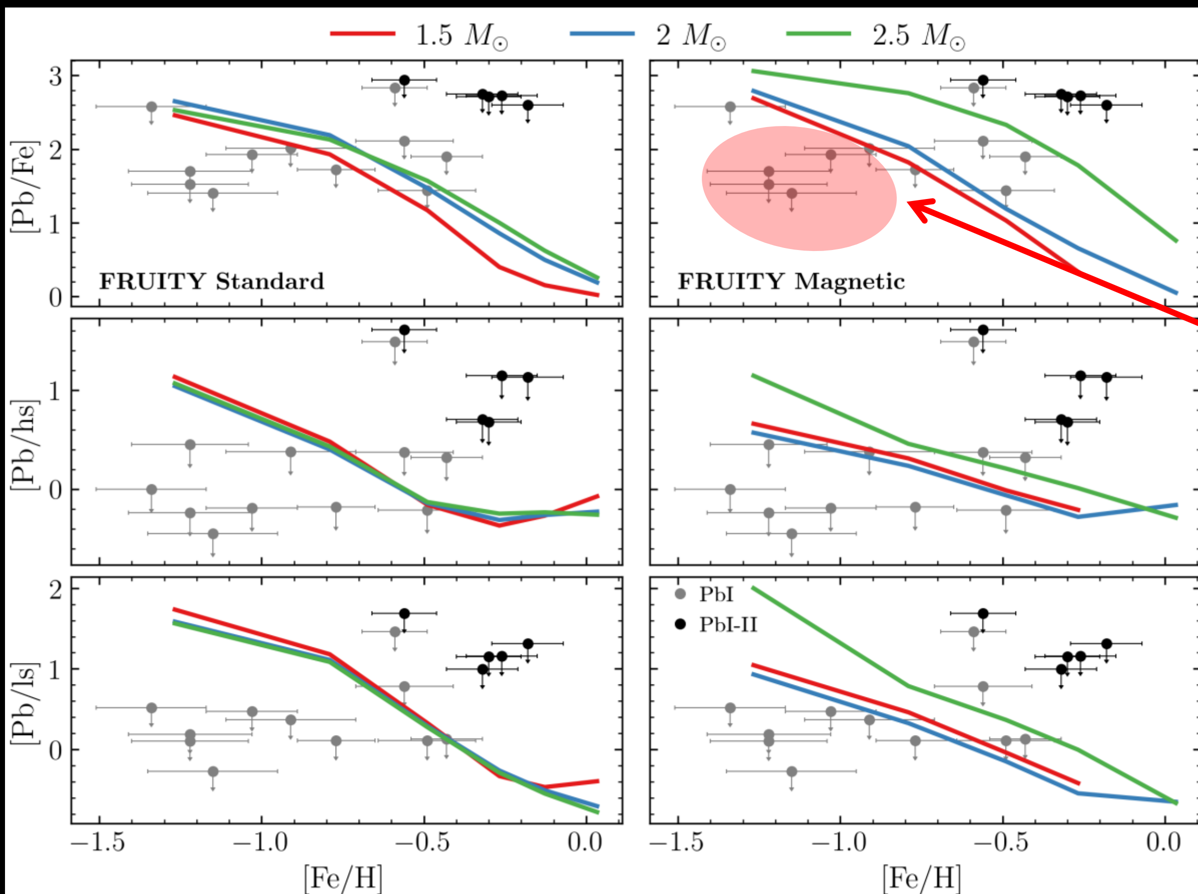
Post-AGB stars



Pb

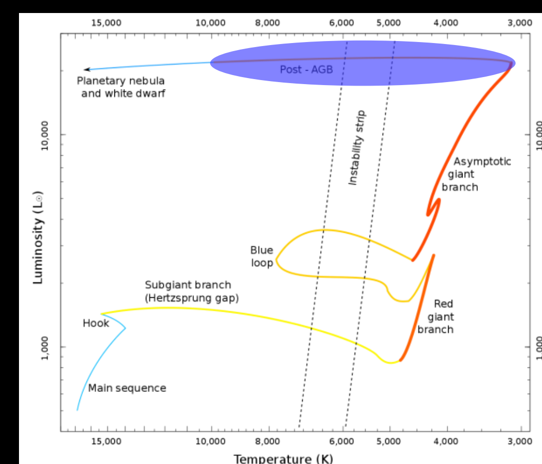


Post-AGB stars

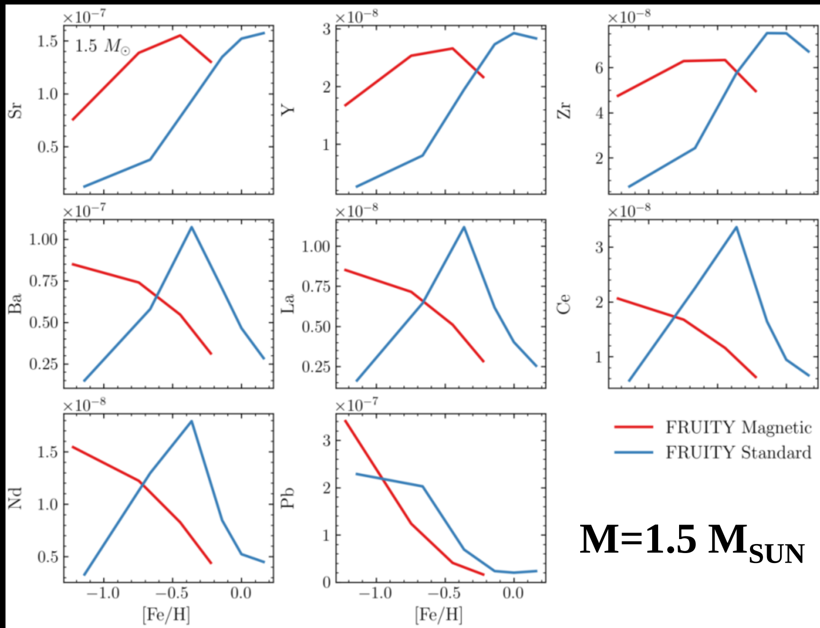


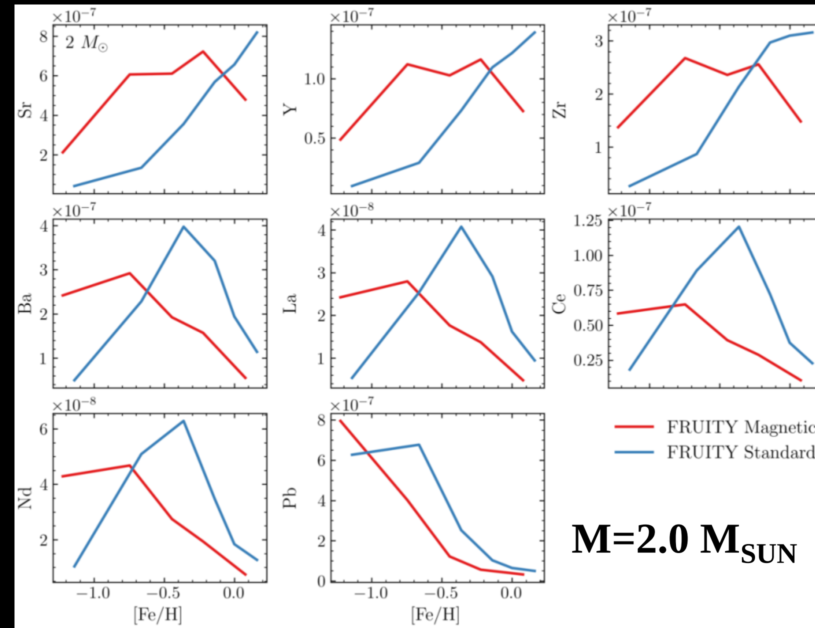
Pb

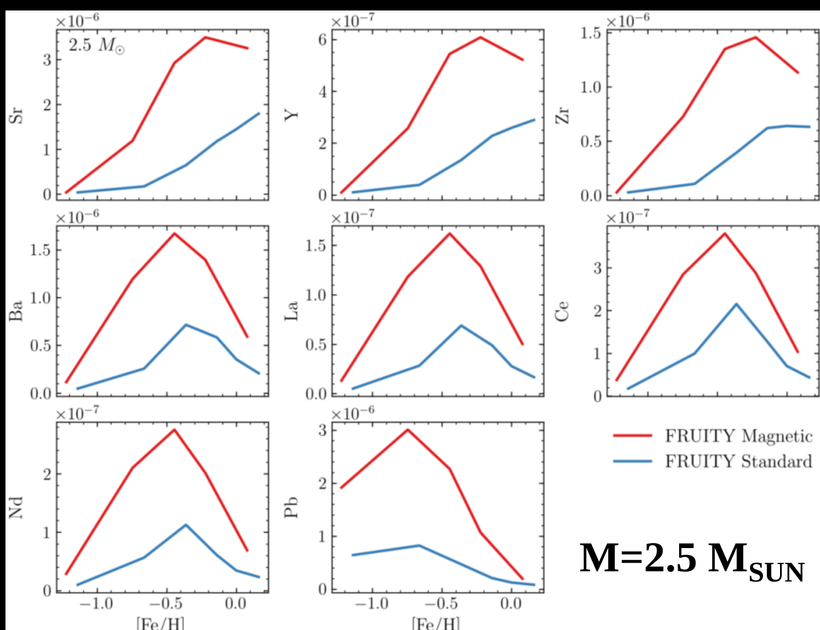
NLTE effects on Pb I @ low Z?

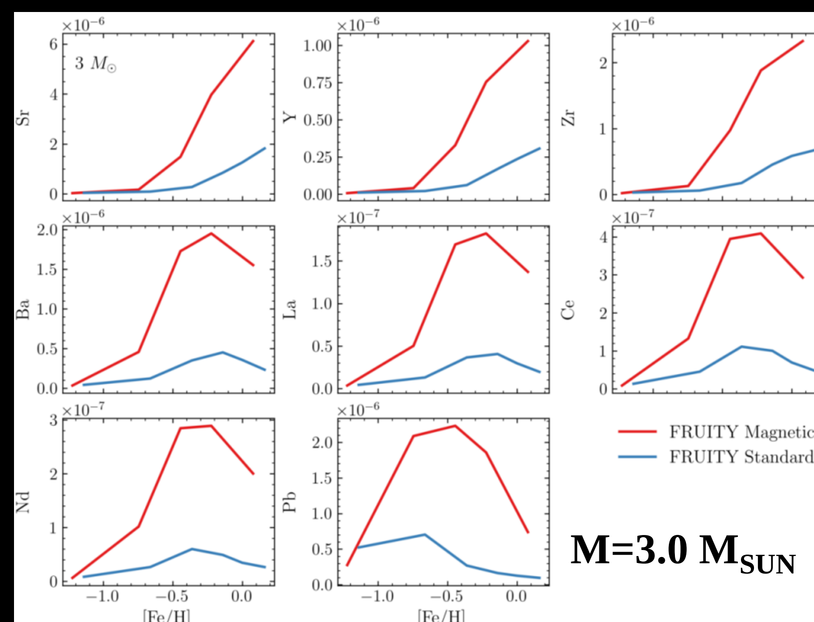


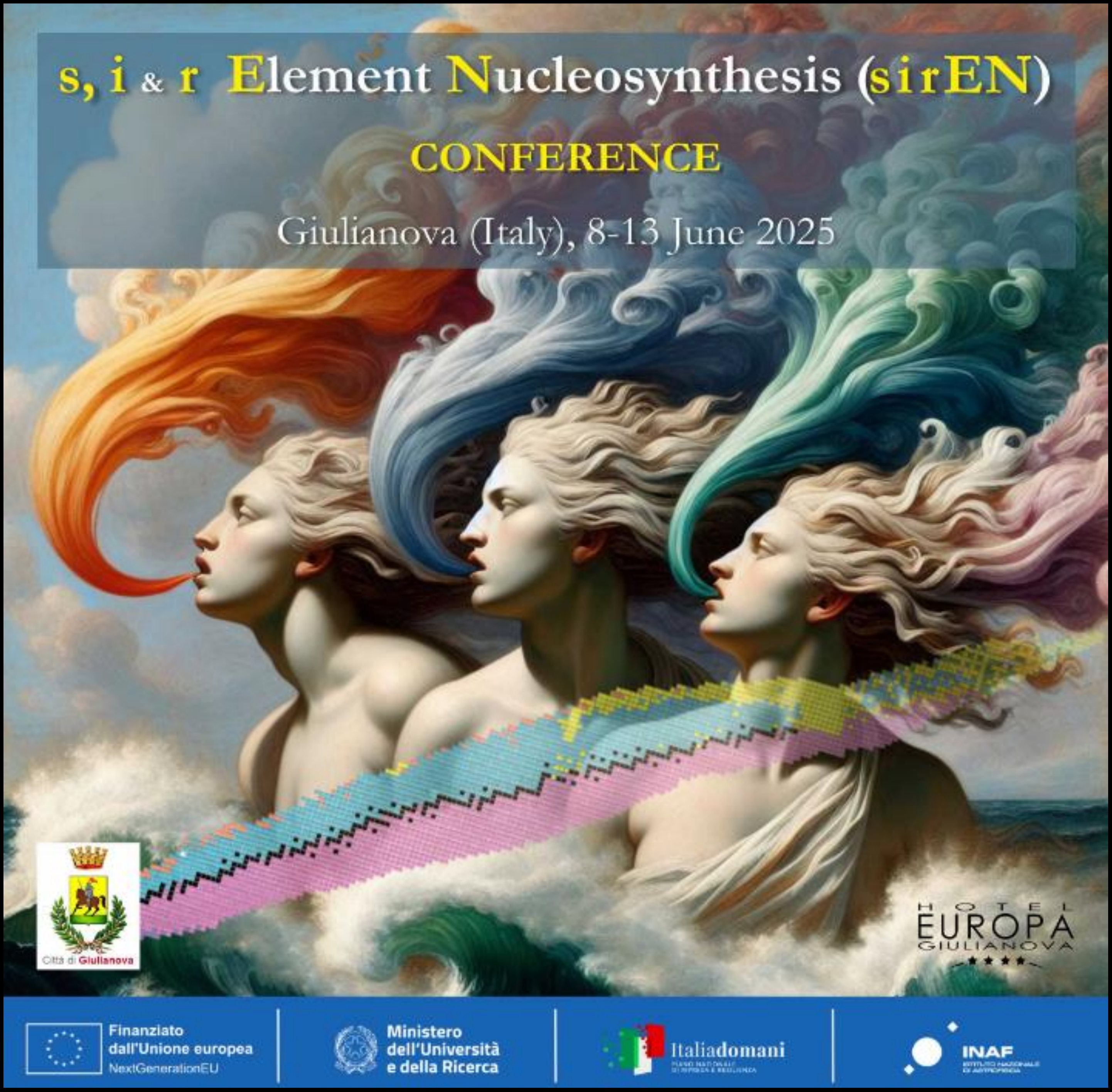
New Magnetic AGB yields







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