Magnetic mixing in AGB stars and branchings in the s-process

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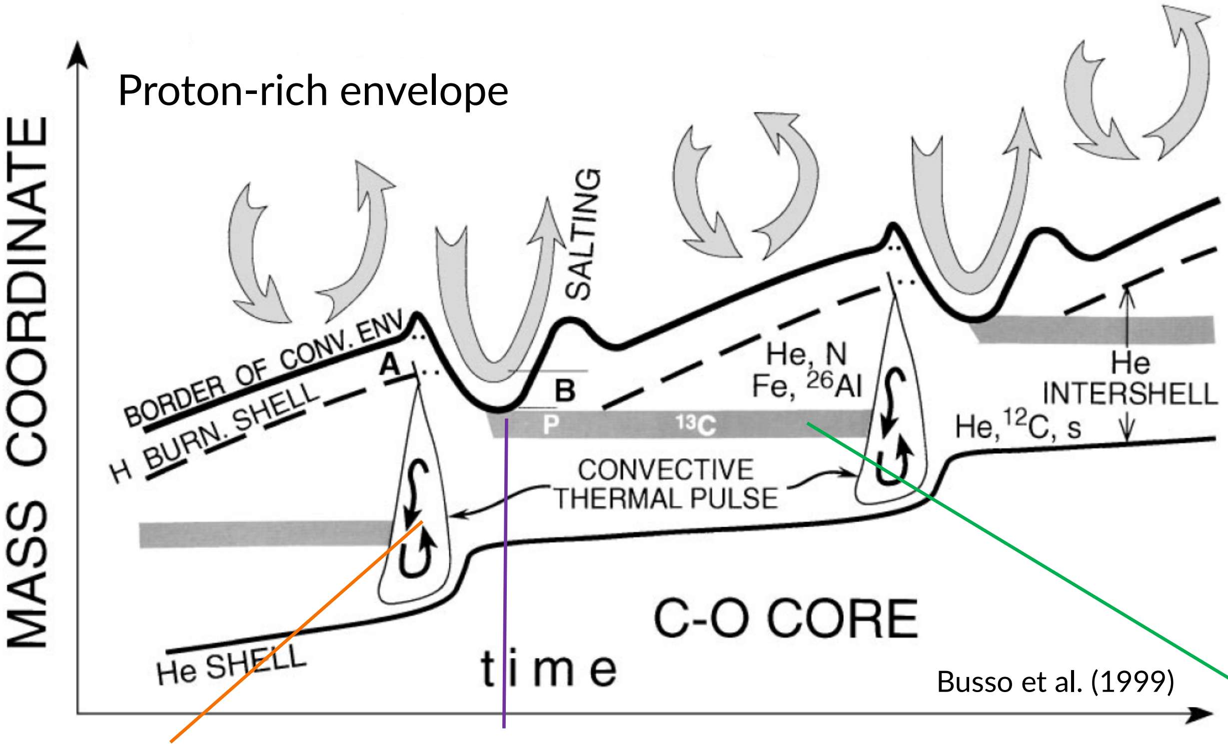
s-Processing in AGB stars



- What?
  Low-Mass Stars
- When?
  Asymptotic Giant Branch (AGB)
- How?
  Thermally Pulsing (TP)

He-flash — Protons — $^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C$ — ^{13}C-pocket

$^{22}Ne(\alpha,n)$ — $^{13}C(\alpha,n)$ → Heavy elements!!

The ^{13}C pocket

Which is the physical mechanism?

TOP-DOWN MECHANISMS

- Opacity-induced overshoot (Straniero+ 06, Cristallo+ 09, 11, 15)
- Overshoot + internal gravity waves (Battino+ 16, 19, 21)

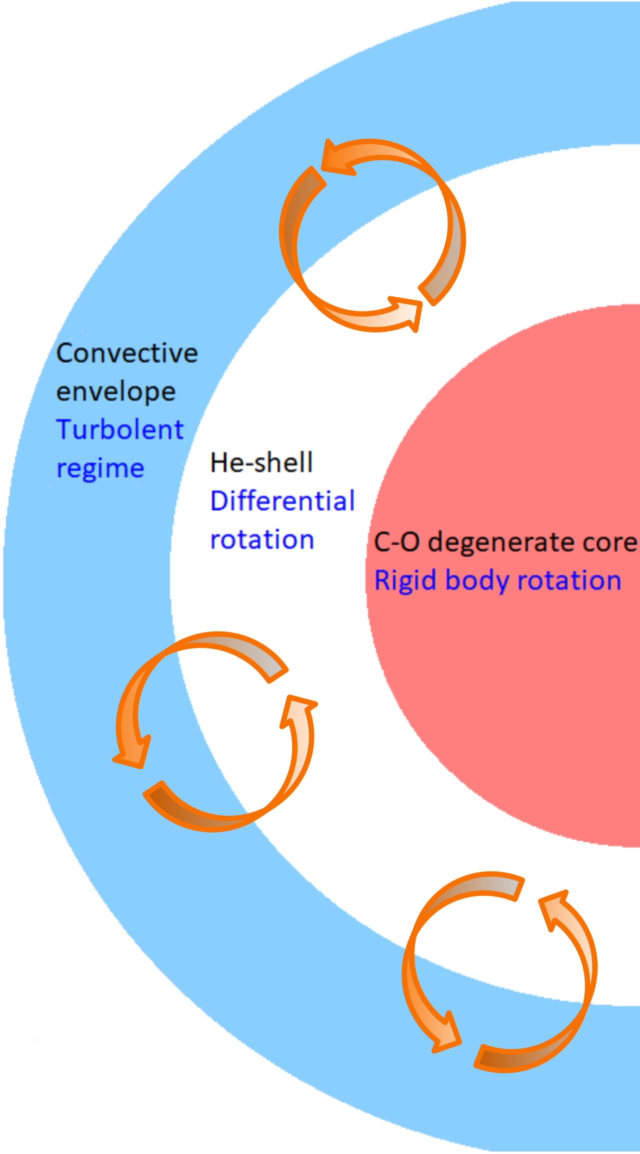
BOTTOM-UP MECHANISMS

- Magnetic fields (Trippella+ 16; Vescovi+ 20; Busso+ 21)

➡ Magnetic buoyancy

➔ Can change due to **rotationally-induced mixing**

(Herwig+ 03; Siess+ 04; Piersanti+ 13)



Magnetic-buoyancy-induced mixing

- **MHD** analytical solutions (Nucci & Busso 14):

- Simple geometry: toroidal magnetic field

- **Magnetic** contribution (Vescovi+ 20) to the dowflow velocity $\boldsymbol{v}_d$, acting when the density distribution is $\rho \propto r^k$:

$$\boxed{v_d(r) = u_\mathrm{p} \left(\frac{r_\mathrm{p}}{r}\right)^{k+2}}$$

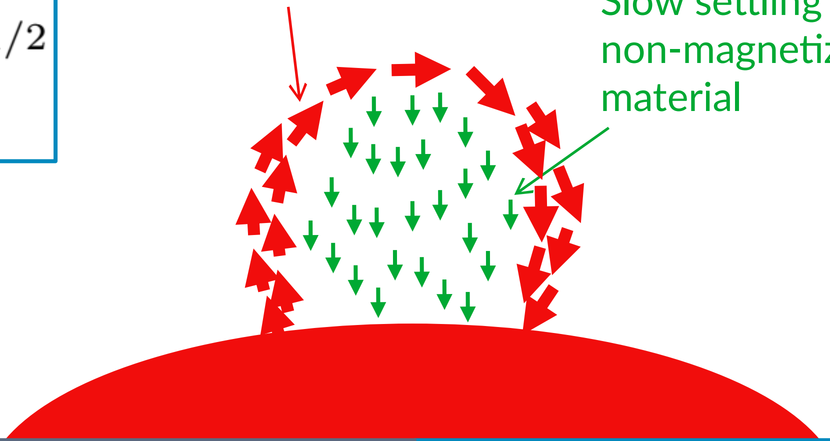
  Parameters:

  - Critical toroidal $\boldsymbol{B}_\varphi$

$$\boxed{B_\varphi \gtrsim \left(4\pi\rho r N^2 H_\mathrm{p} \frac{\eta}{K}\right)^{1/2}}$$

  - Starting velocity $\boldsymbol{u}_p$ of the buoyant material

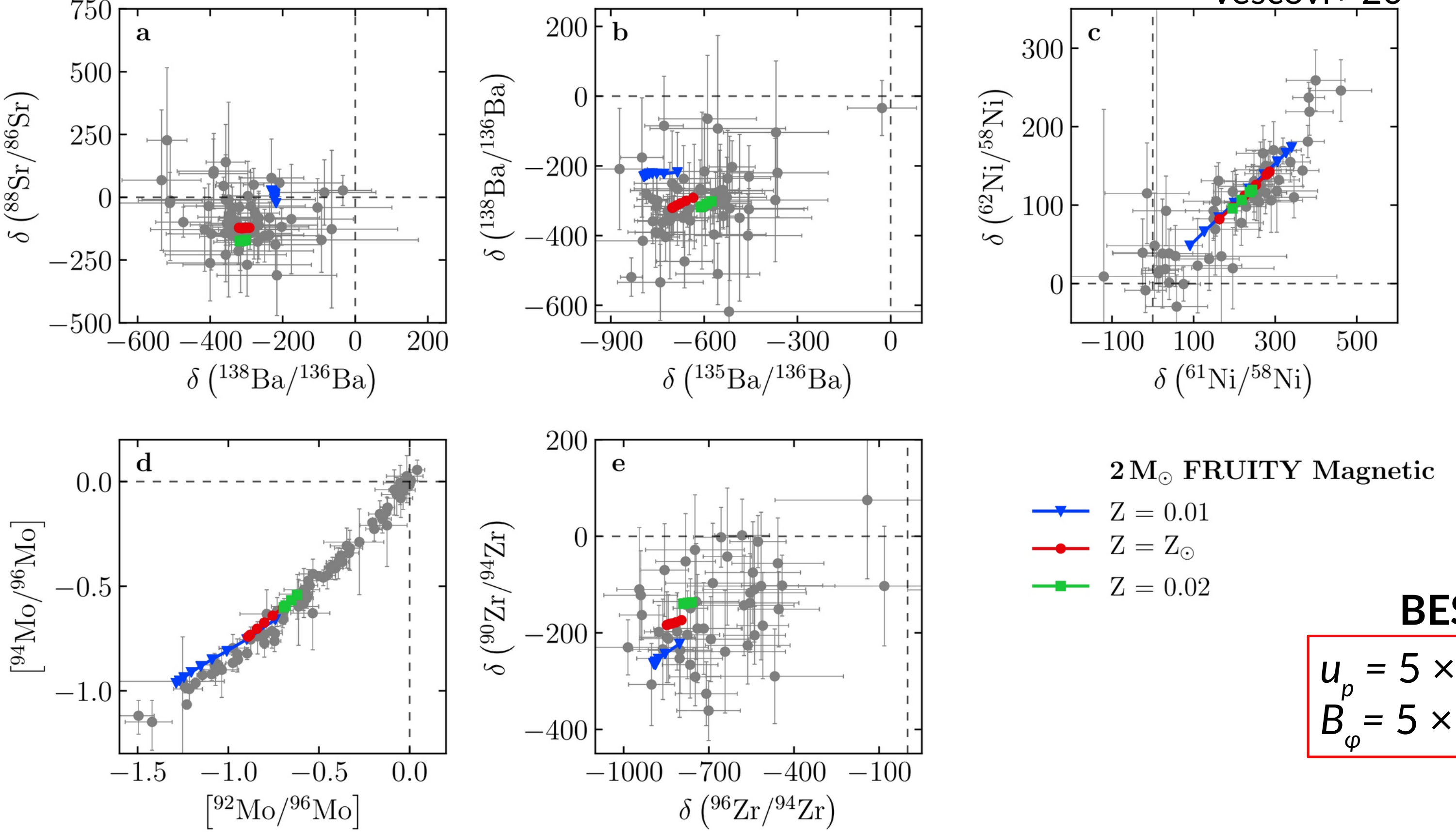
- <u>Calibration</u> is needed!



FRUITY Magnetic: SiC Grains

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

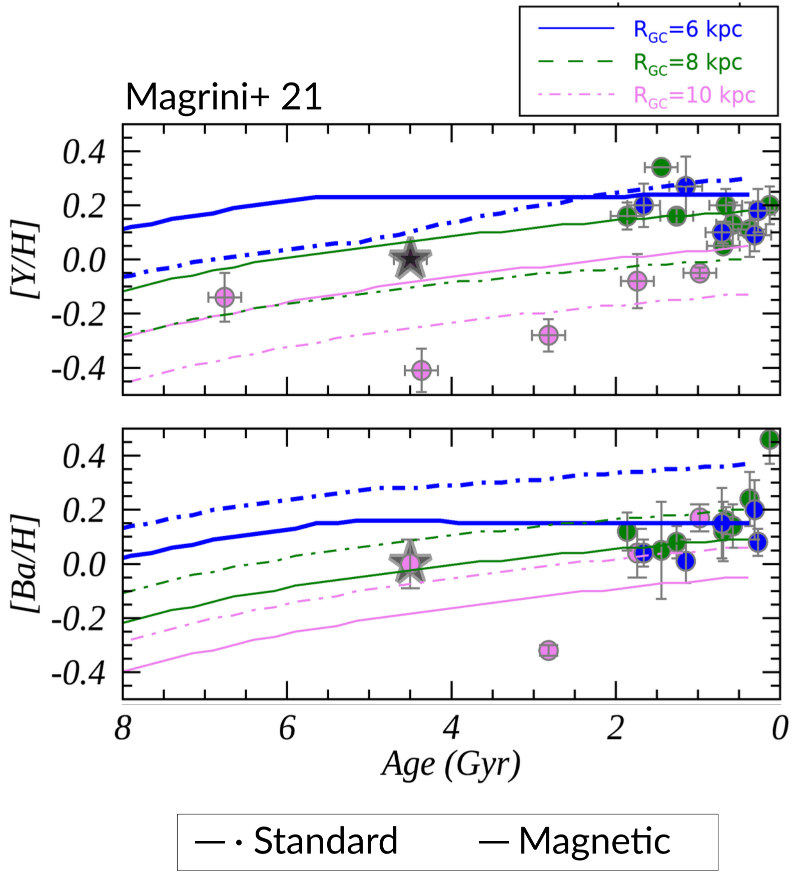
Vescovi+ 20



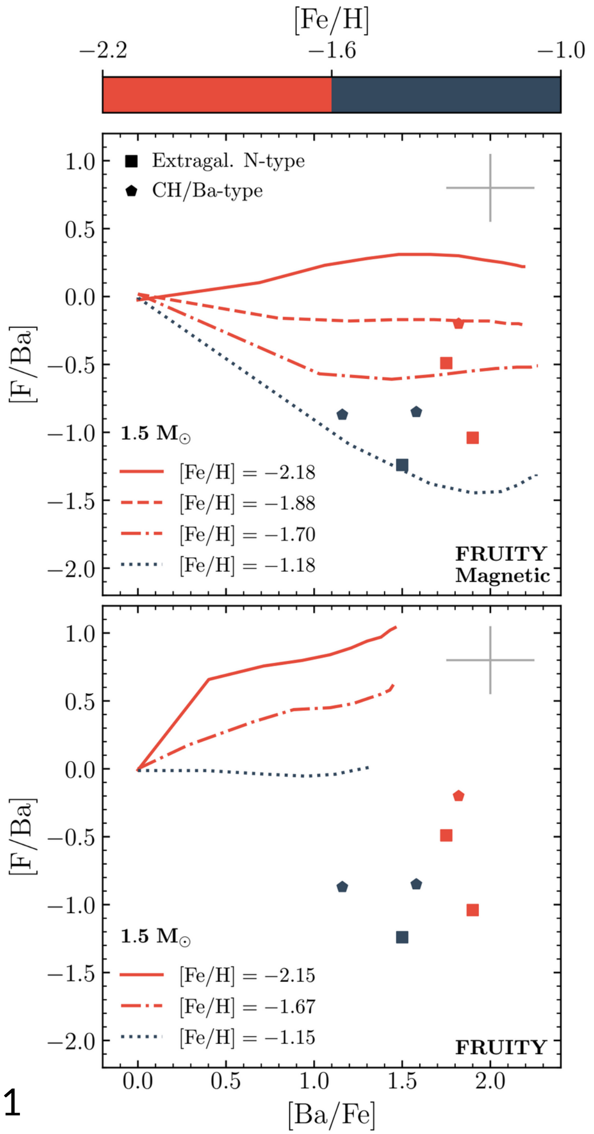
BEST FIT

u_p = 5 × 10^{-5} cm/s
B_φ = 5 × 10^4 G

FRUITY Magnetic: observations vs. models



- **FRUITY Magnetic** models agree with Fluorine spectroscopic observations in very metal-poor AGB stars
- Reproduce the time evolution of the s-process elements for galactic open clusters located in the inner disk



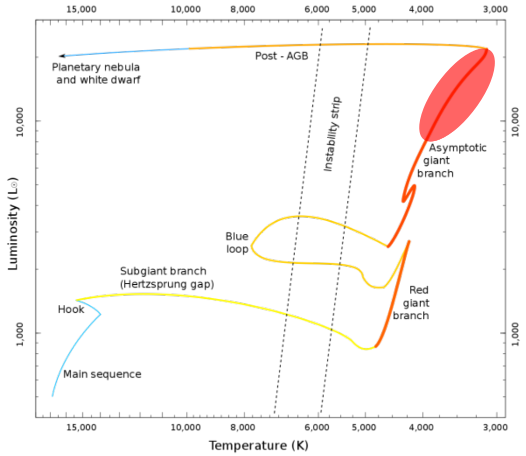
Vescovi+ 21

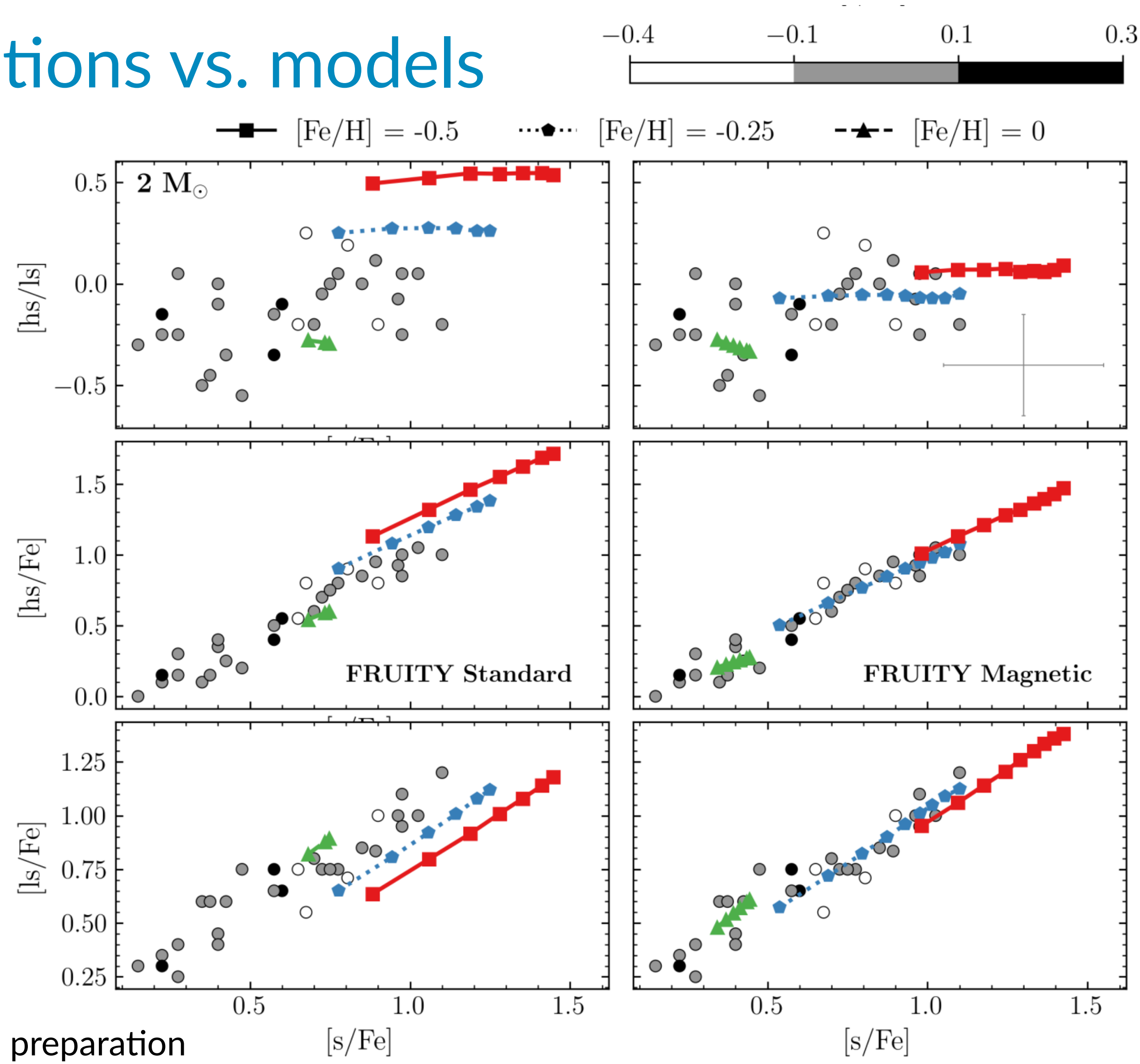
FRUITY Magnetic: observations vs. models

What next?

- Carbon stars ✔

$C/O \geq 1.0$





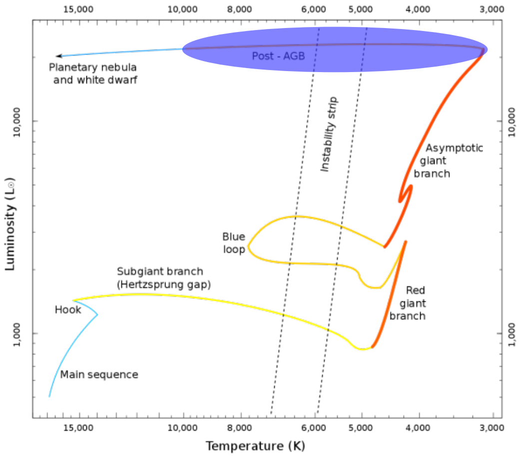
Vescovi+, in preparation

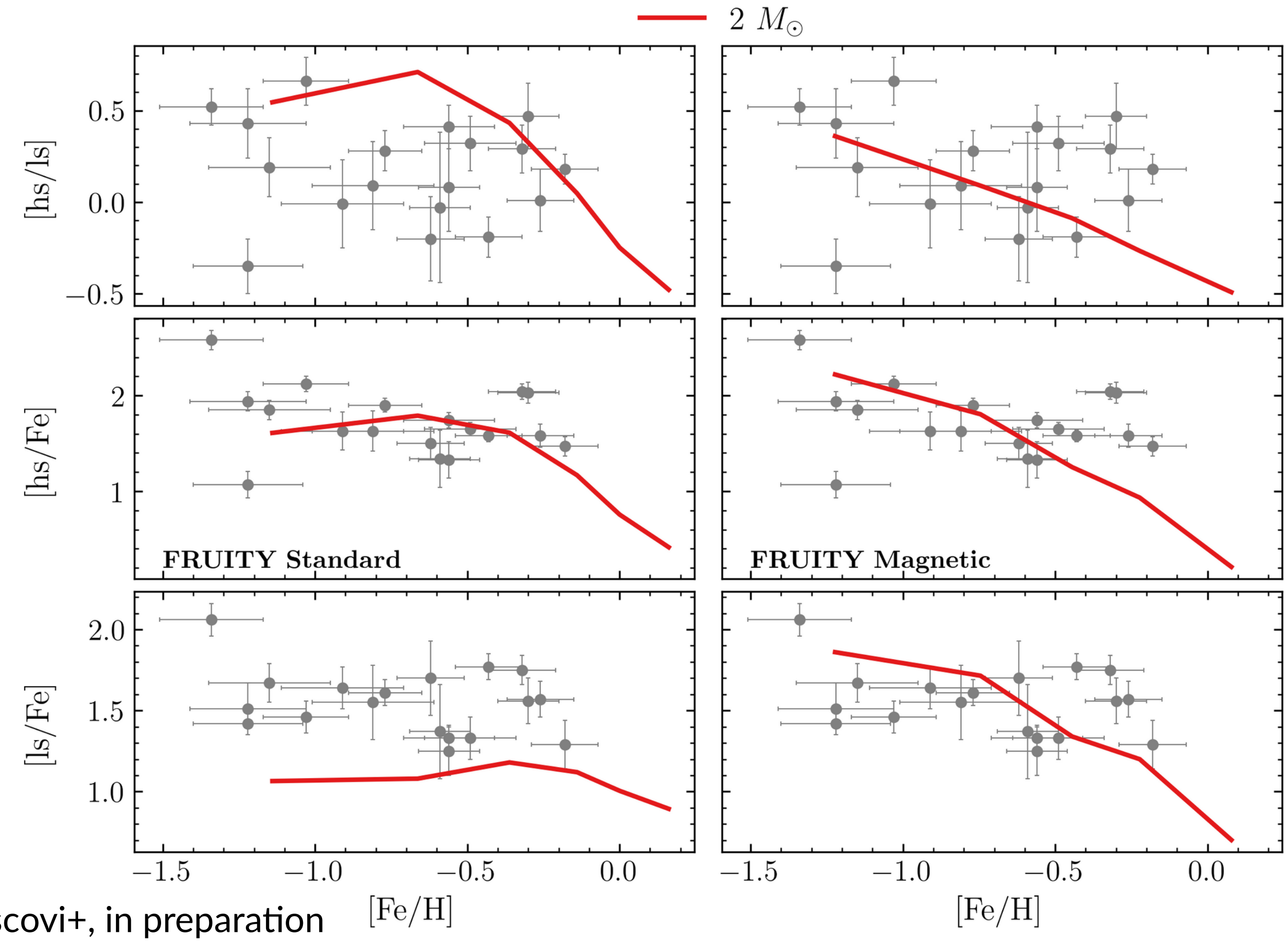
FRUITY Magnetic: observations vs. models

What next?

- Carbon stars ✔
- Post-AGB stars ✔

$\mathrm{C/O} \geq 1.0$

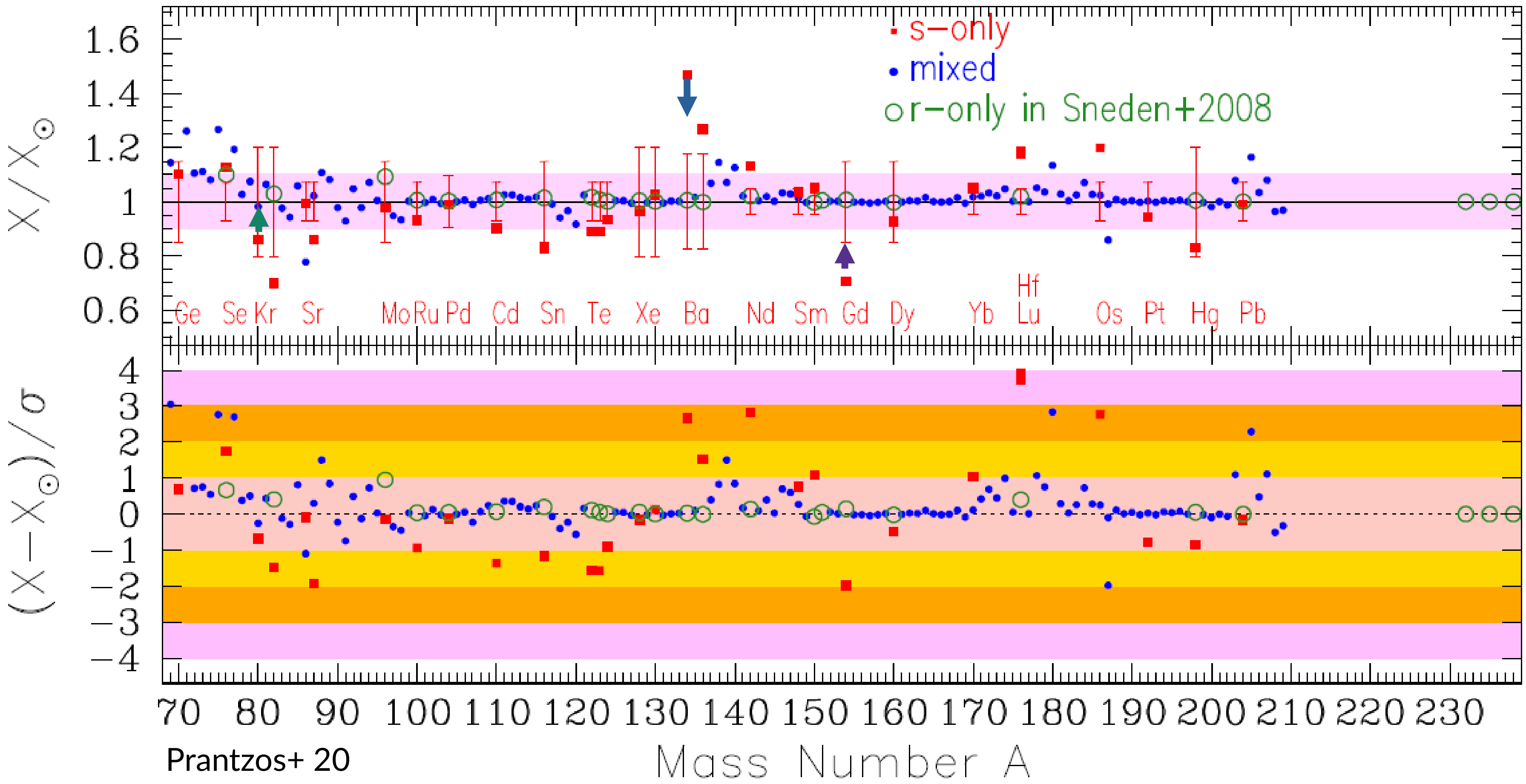




Vescovi+, in preparation

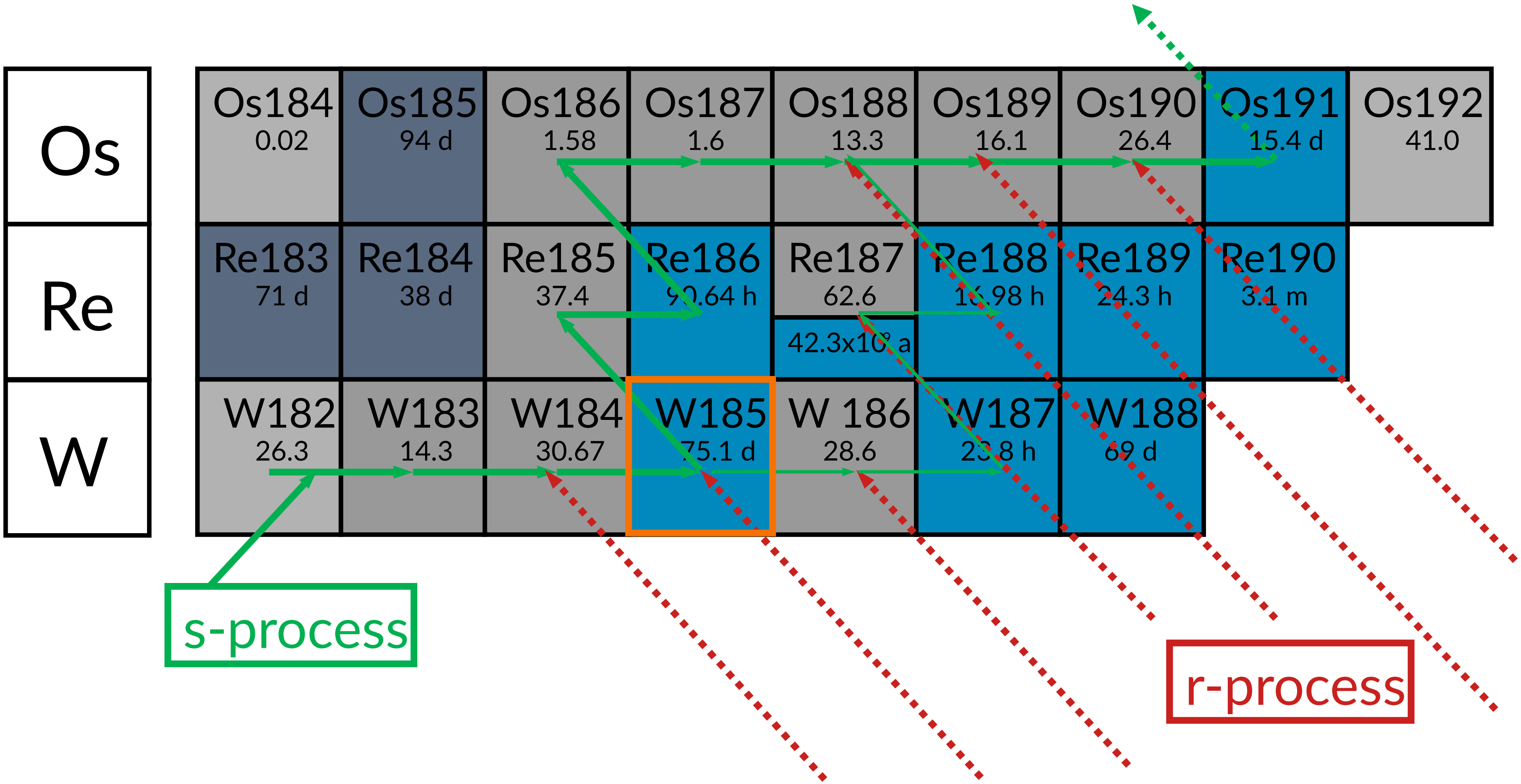
Comparison to solar distribution

Mazzone+ 20   Tessler+ 21   Taioli+ 22



Prantzos+ 20

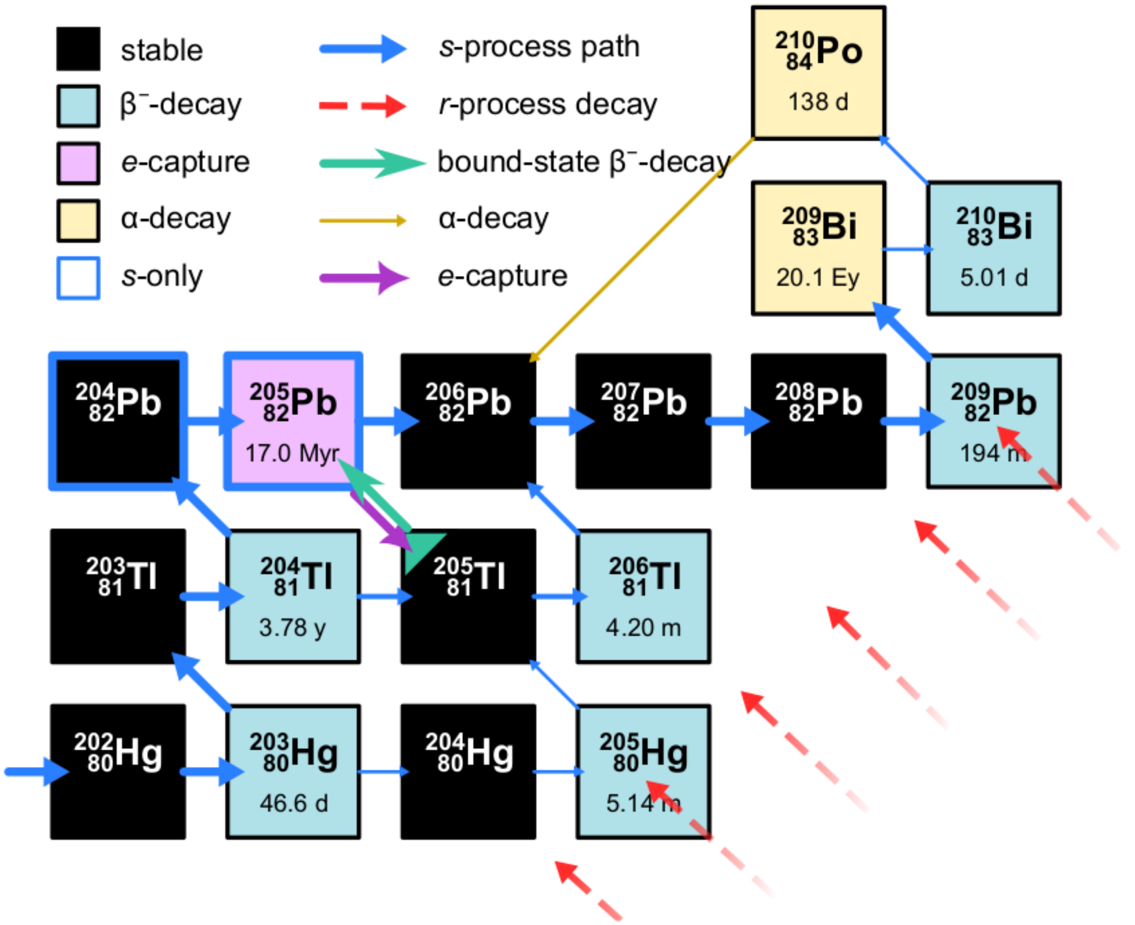
Branchings in the s-process



- **Branching points**: if $\tau_n \sim \tau_\beta$ several paths are possible

Branchings in the s-process: the case of ^{205}Pb

- Galactic production of **^{205}Pb** is exclusive to the s-process
- It was present in the early Solar System, as testified by meteoritic data
- The ^{205}Pb/^{204}Pb abundance ratio provides us information on the nucleosynthetic events prior to the formation of the Solar System
- **Measured for the first time** the bound-state β^- decay of ^{205}Tl
- The measured half-life is **4.7 times larger** than the previous theoretical estimate (291 days vs. 58 days)



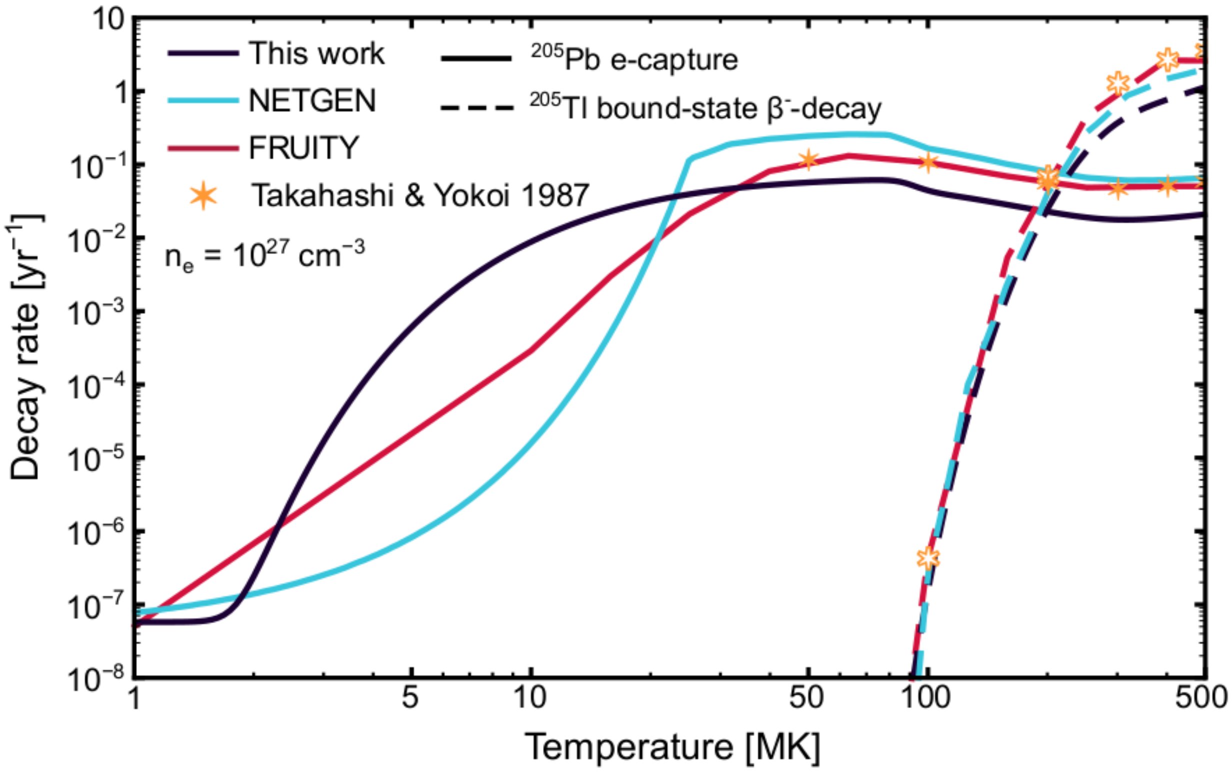
Leckenby+ 24, accepted in Nature

Branchings in the s-process: the case of ^{205}Pb

- Despite its long terrestrial half-life ($T_{1/2}$ = 17 Myr) of **^{205}Pb acts as a branching point** because of the strong dependence on temperature and electron density

- The stable daughter isotope **^{205}Tl becomes unstable during TPs** and its β^- decay is competing with the β^+ decay of ^{205}Pb

- <u>Diverging behavior at low temperatures</u> due to the different extrapolation to the terrestrial value (log versus linear)



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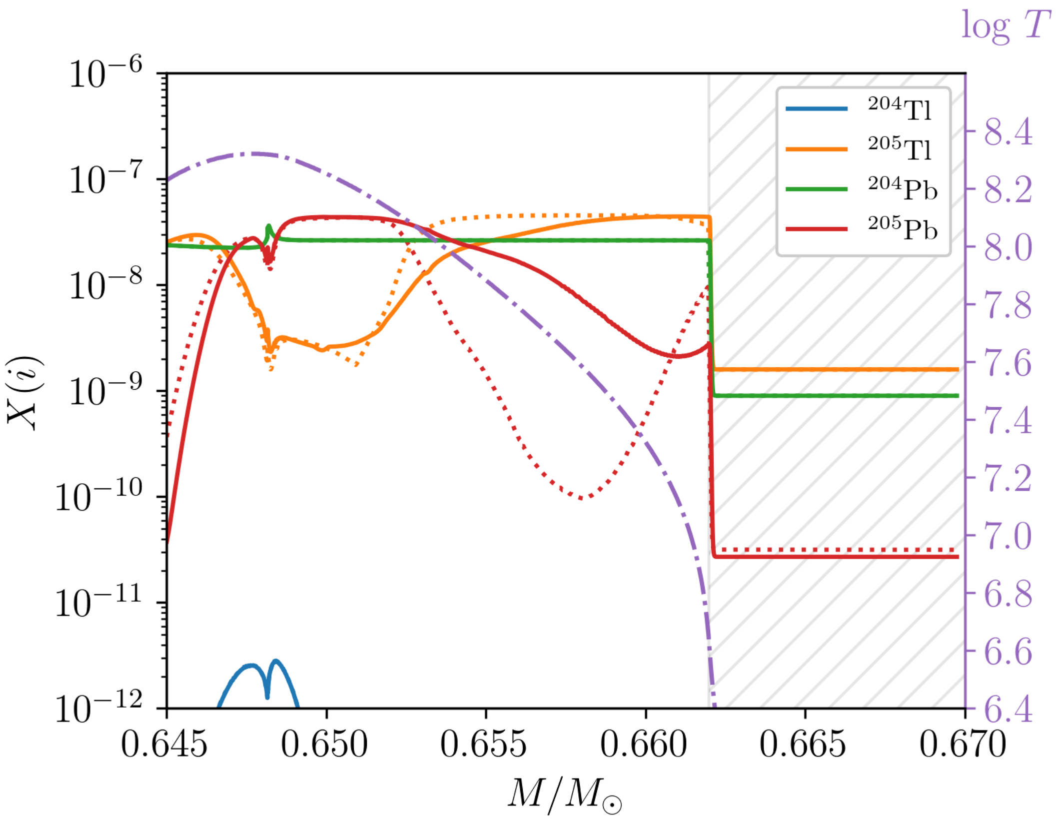
Branchings in the s-process: the case of ^{205}Pb

- The <u>bulk of ^{205}Pb is produced during TPs</u>, resulting in a ^{205}Pb/^{204}Pb ratio of the order of unity.
- During the phase between the end of each TP and the start of the following dredge-up, **^{205}Pb decays** according to the local temperature and electron density, whilst **^{205}Tl decay** doesn't
- Once carried to the convective envelope the ^{205}Pb abundance is <u>preserved and ejected</u> in the interstellar medium via stellar winds
- NEW/FRUITY(TY87) → ^{205}Pb/^{204}Pb ratio **decreased** of a factor ~4
- NEW/NETGEN → ^{205}Pb/^{204}Pb ratio **increased** of a factor ~7



Branchings in the s-process: the case of ^{205}Pb

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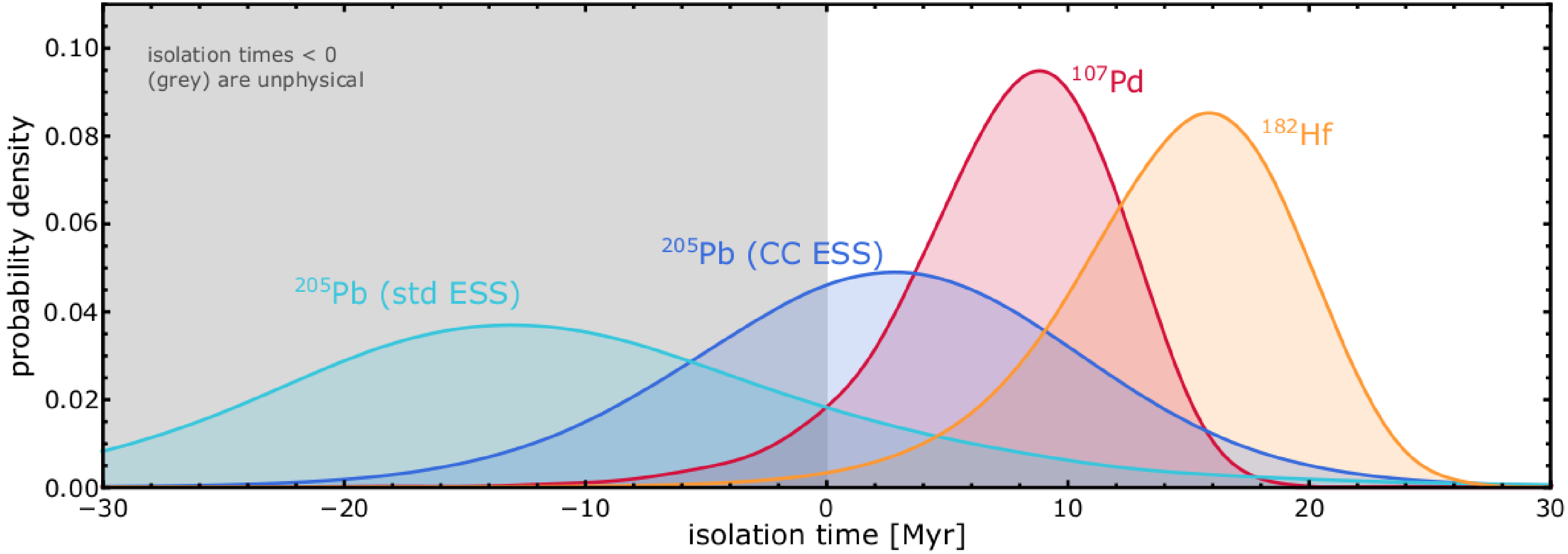


- Plugging in new yields in basic GCE models and comparing to the ^{205}Pb/^{204}Pb ratio from meteorites, the isolation time of Solar material inside its parent molecular cloud can be determined
- **Positive isolation times** that are consistent with the other s-process short-lived radioactive nuclei found in the early Solar System

See posters of Thomas Neff and Iris Dillmann!

Conference Webpage

SCAN ME

Summary and outlook

- The ^{13}**C pocket formation** is a major uncertainty in stellar evolutionary models of AGB stars
- New magnetic models provide a consistent explanation to the **majority of the heavy-element isotope data** detected in presolar SiC grains from AGB stars
- FRUITY Magnetic models provide a theoretical explanation for various spectroscopic observations
- s-process branchings requires accurate nuclear data input
- ^{205}Pb/^{204}Pb ratio is **highly dependent on** temperature dependence of the **weak rates**
- New measurement of ^{205}Tl β^- decay put stellar model predictions in agreement with meteoritic data

Backup Slides

Magnetic buoyancy

- MagnetoHydroDynamics (**MHD**) solutions (Nucci & Busso 2014):
  - No numerical approximations (exact analytic solution)
  - Simple geometry: toroidal magnetic field

Equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \qquad \frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) - \nu_m \Delta \mathbf{B} = 0$$

$$\rho \left[\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} - c_d \mathbf{v} + \nabla \Psi \right] - \mu \Delta \mathbf{v} + \nabla P + \frac{1}{4\pi} \mathbf{B} \times (\nabla \times \mathbf{B}) = 0 \qquad \rho \left[\frac{\partial \epsilon}{\partial t} + (\mathbf{v} \cdot \nabla)\epsilon \right] + P \nabla \cdot \mathbf{v} - \nabla \cdot (\kappa \nabla T) + \frac{\nu_m}{4\pi} (\nabla \times \mathbf{B})^2 = 0$$

Solutions:

$$v_r = v_p \left(\frac{r_p}{r} \right)^{k+1} \qquad B_\varphi = B_{\varphi,p} \left(\frac{r}{r_p} \right)^{k+1}$$

where k is the exponent of the density distribution:

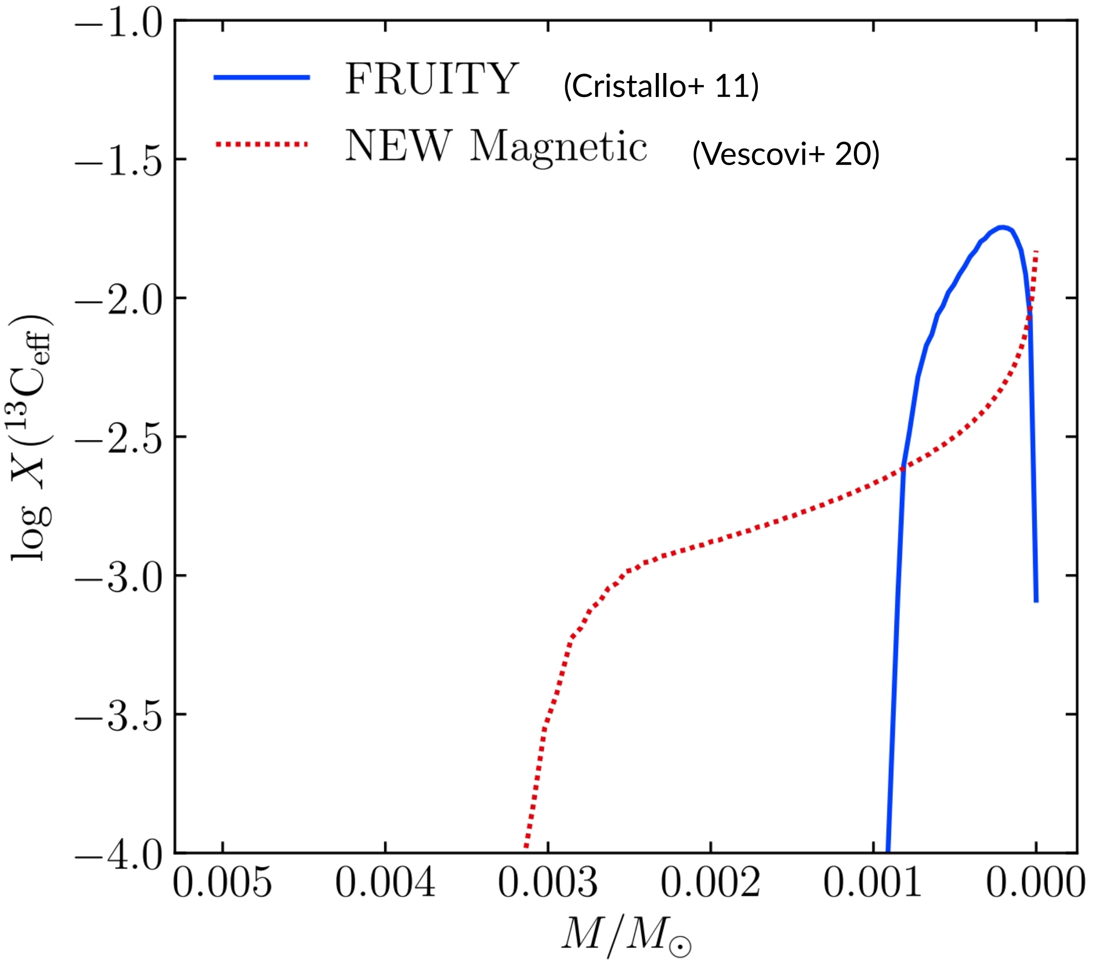
$$\rho(r) = \frac{\rho_p}{r_p^k} r^k$$

The ^{13}C pocket: shape

- Effective ^{13}C in the ^{13}C pocket region –> i.e. the difference between the number fractions of ^{13}C and ^{14}N in the pocket

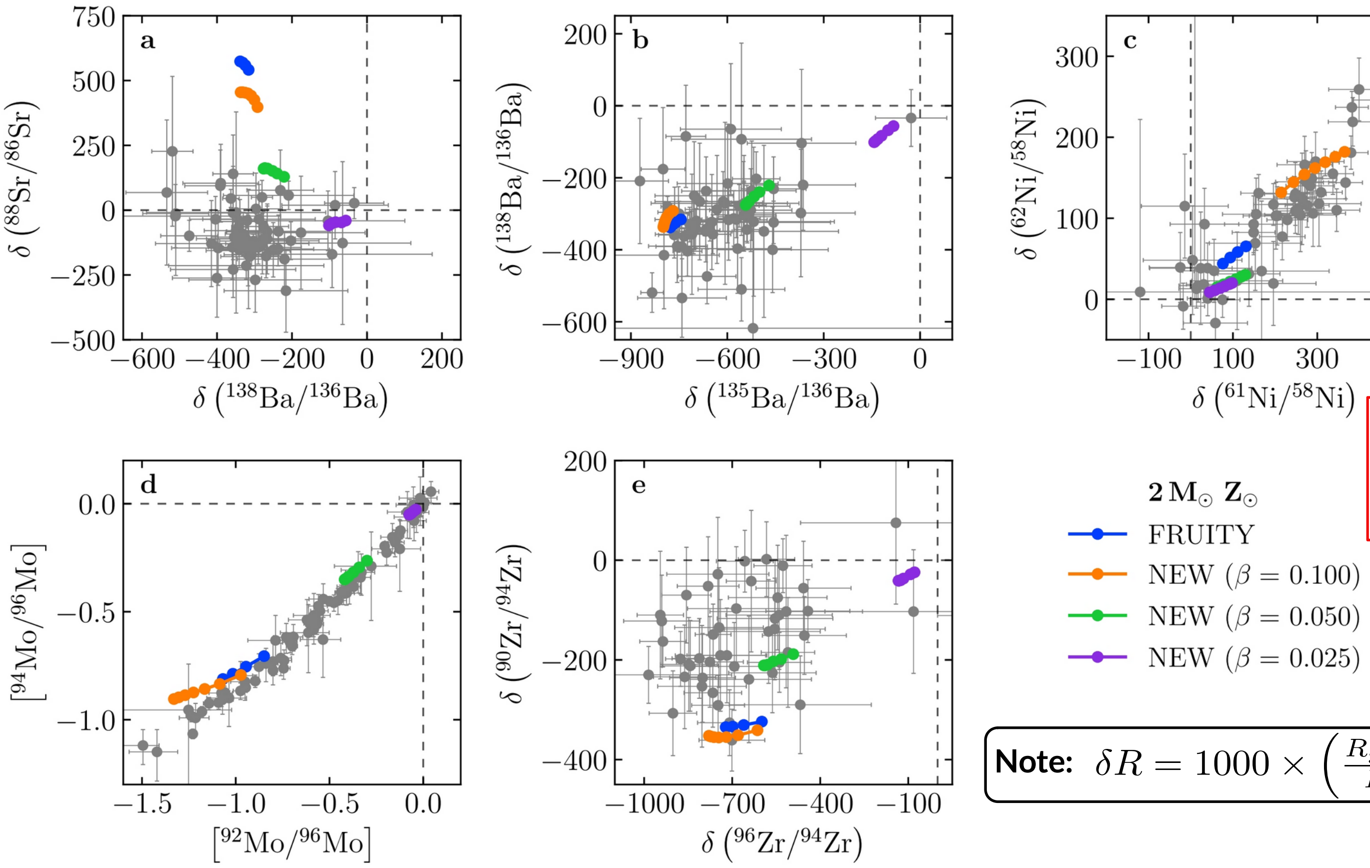
➔ New "Magnetic" pocket presents are **more extended and flatter**

➔ Lower production of isotopes originating from ^{14}N, e.g. **^{19}F**



SiC Grains and FRUITY models

- **Isotopic data** including Ni, Sr, Zr, Mo, and Ba isotope ratios in **presolar SiC grains**
- Stellar models with **same initial mass** (2 $M_\odot$) and **solar metallicity**



$$v = v_{\mathrm{CE}} \exp\left(-\frac{\Delta r}{\beta H_P}\right)$$

Note: $\delta R = 1000 \times \left(\frac{R_{\mathrm{grain}}}{R_\odot} - 1\right)$

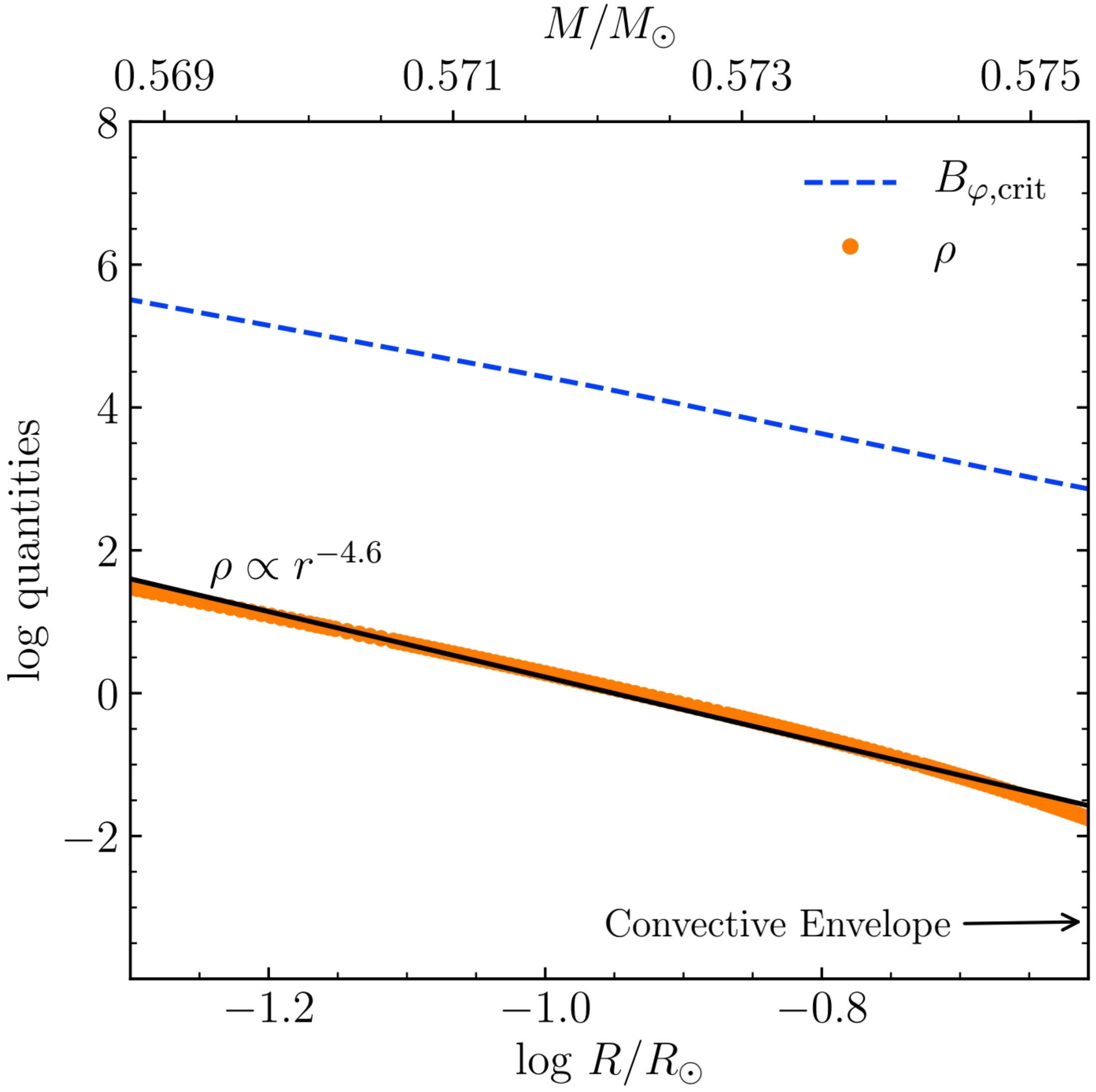
Critical toroidal *B*-field

- <u>Stellar model</u>: $2\ M_\odot$ $Z = Z_\odot$

- **The critical B_φ** necessary for the onset of magnetic buoyancy instabilities, in radiative zone below the convective envelope **varies from ~10^4 G to ~10^6 G**

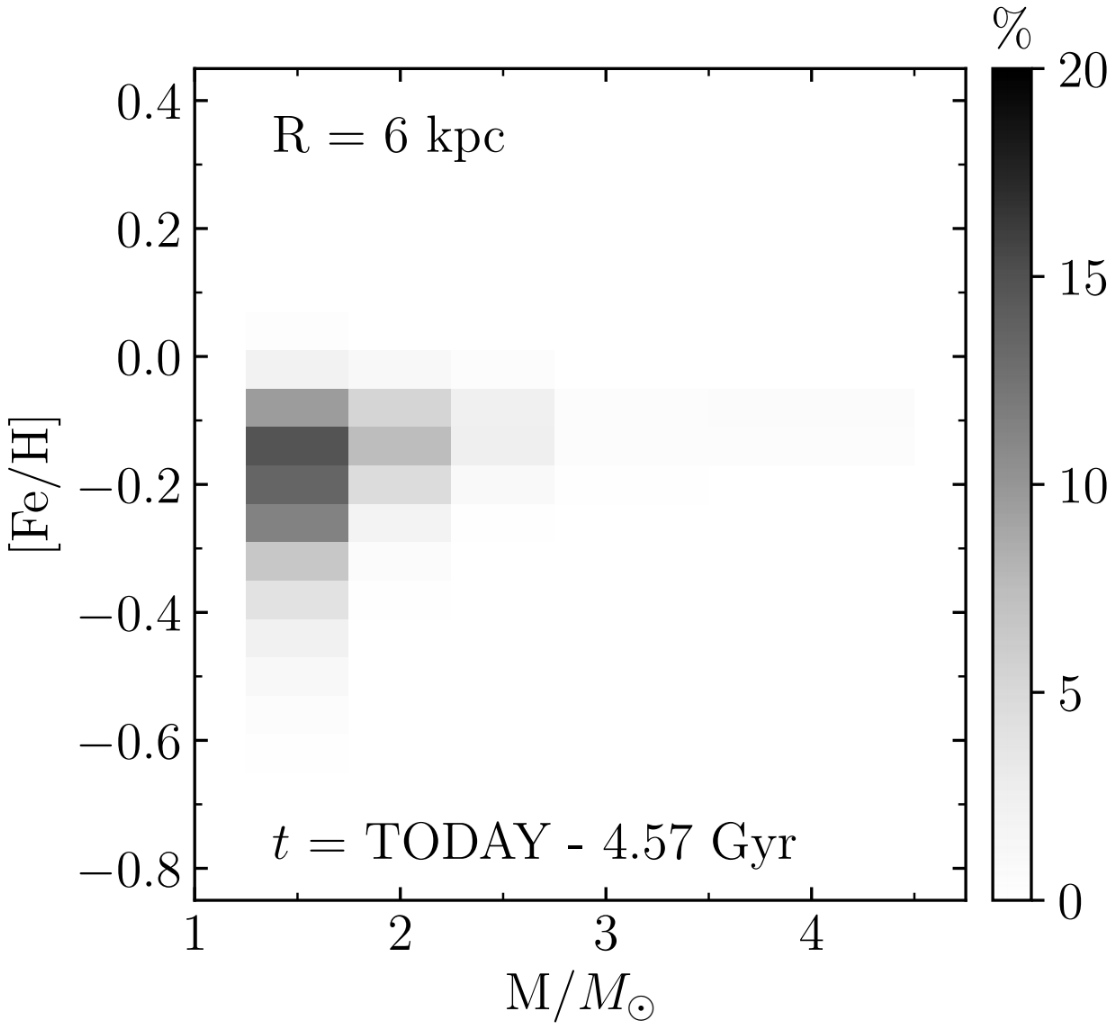
- <u>Different values of B_φ</u> correspond to <u>different values of r_p</u>

→ The strength of B_φ **determines the extension** of the mixed zone and, in turn, **of the ^{13}C-pocket**

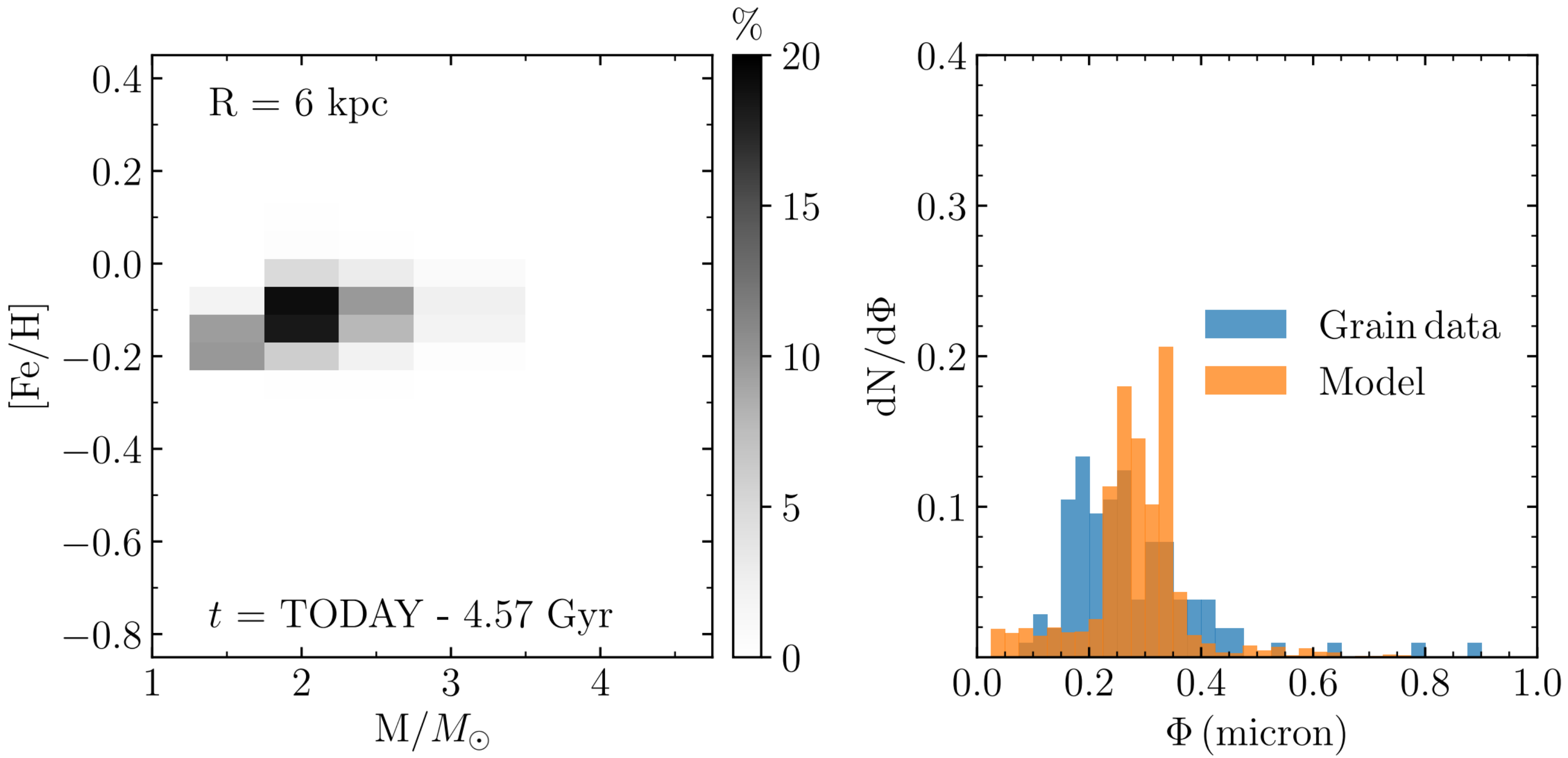


Mass-metallicity distribution

- Mass-metallicity distribution in the solar vicinity at the epoch of Solar System formation (Minchev+ 13 model)



Mass-metallicity distribution weighted



- Mass-metallicity distribution in the solar vicinity at the epoch of Solar System formation **weighted by the SiC grain yields** of the corresponding AGB models
- Corresponding distribution of SiC production vs. grain size (in diameter), compared to SiC grains identified in situ in primitive meteorites