A unique mechanism to account for well known peculiarities of AGB star nucleosynthesis

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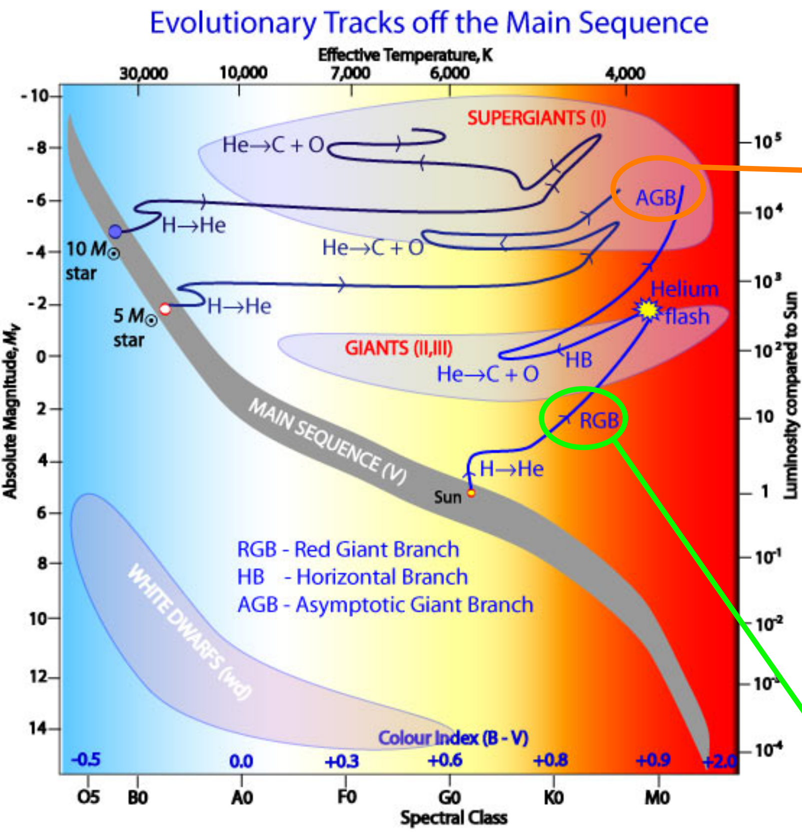
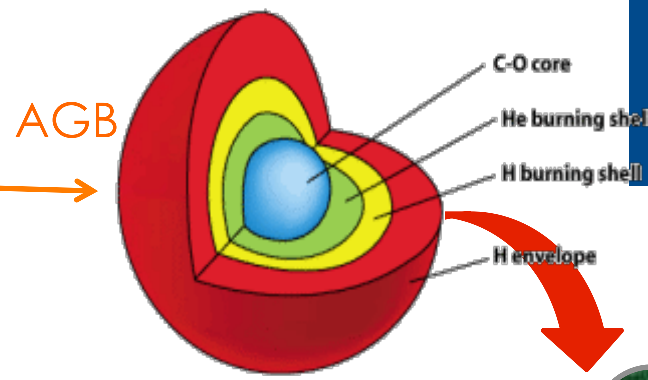
ITALY

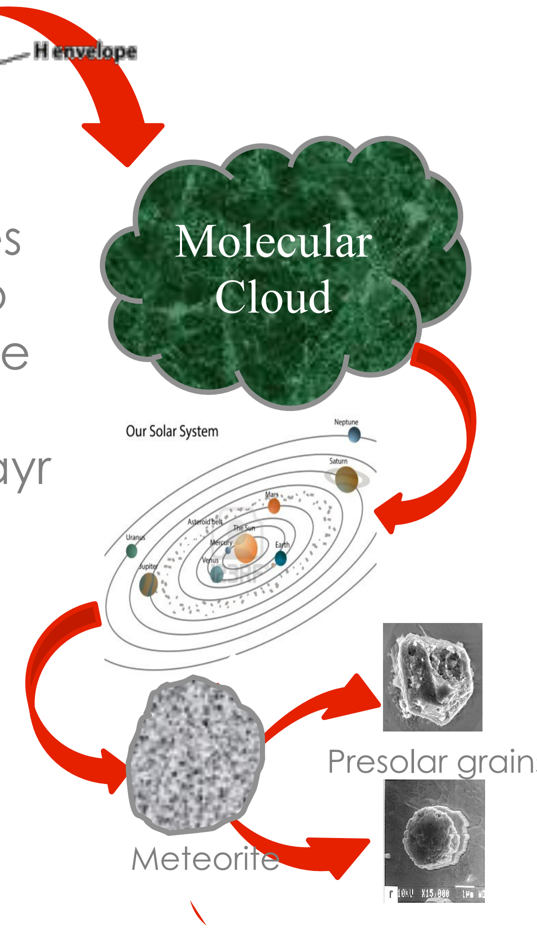
Workshop on Nuclear Astrophysics at the Dresden Felsenkeller

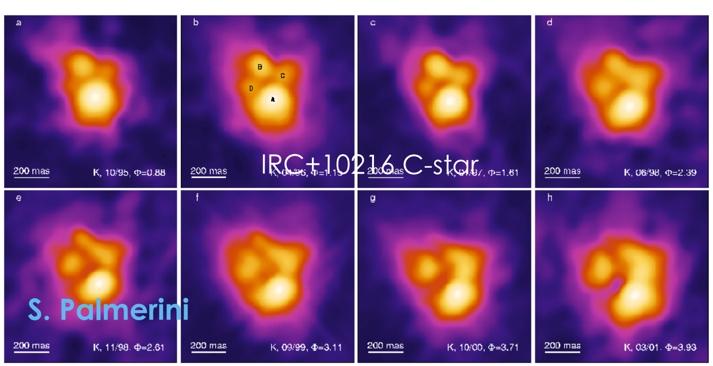
Contribution of LMS to GCE

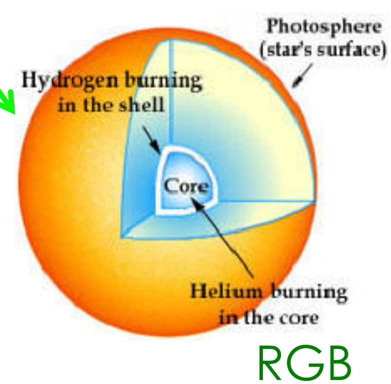




Despite their low masses LMS are so numerous to contribute for 75% to the total mass return from stars to the ISM (Sedlmayr 1994);

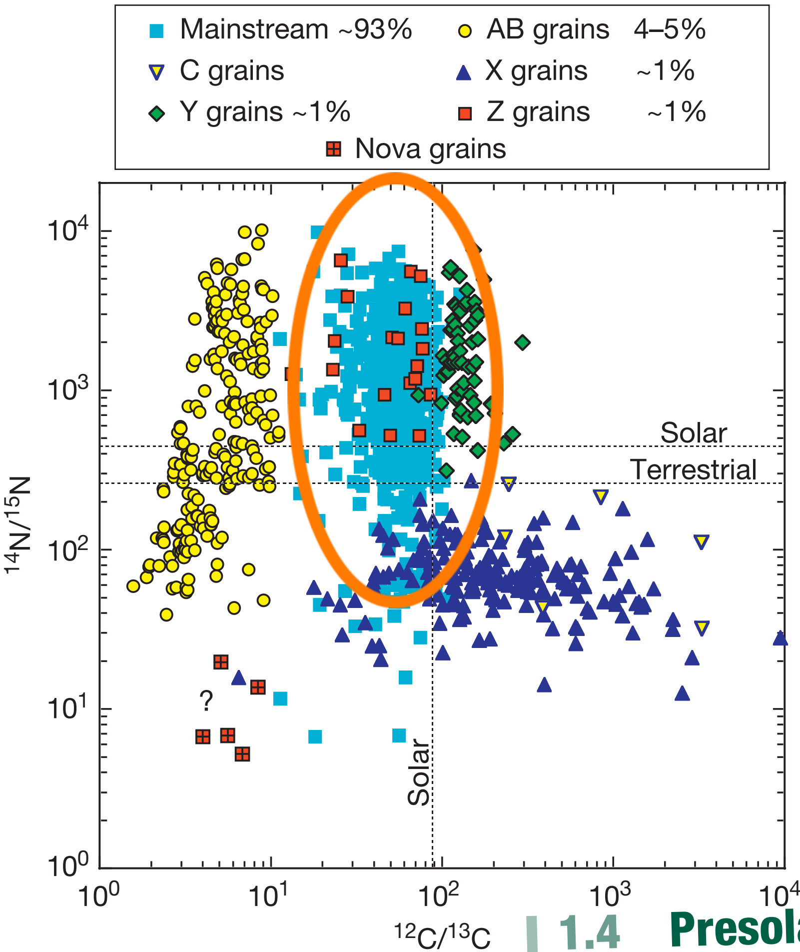




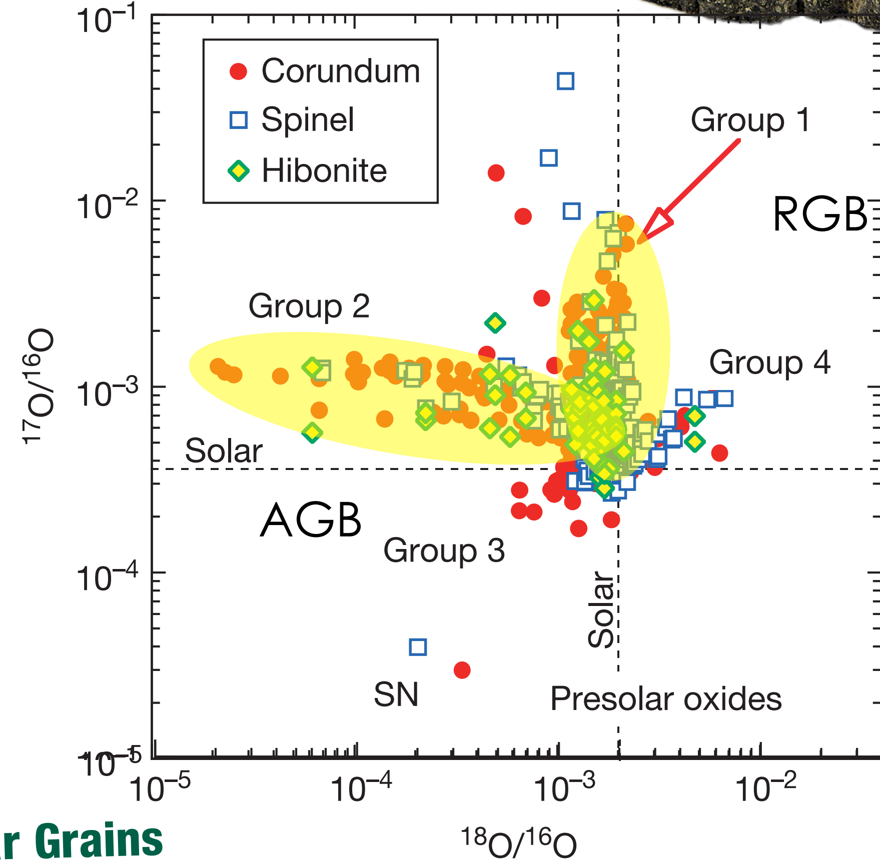


Presolar grains from AGB stars

C/O≥1 SiC grains



C/O<1 Oxide grains



1.4 Presolar Grains

E Zinner, Washington University, St. Louis, MO, USA

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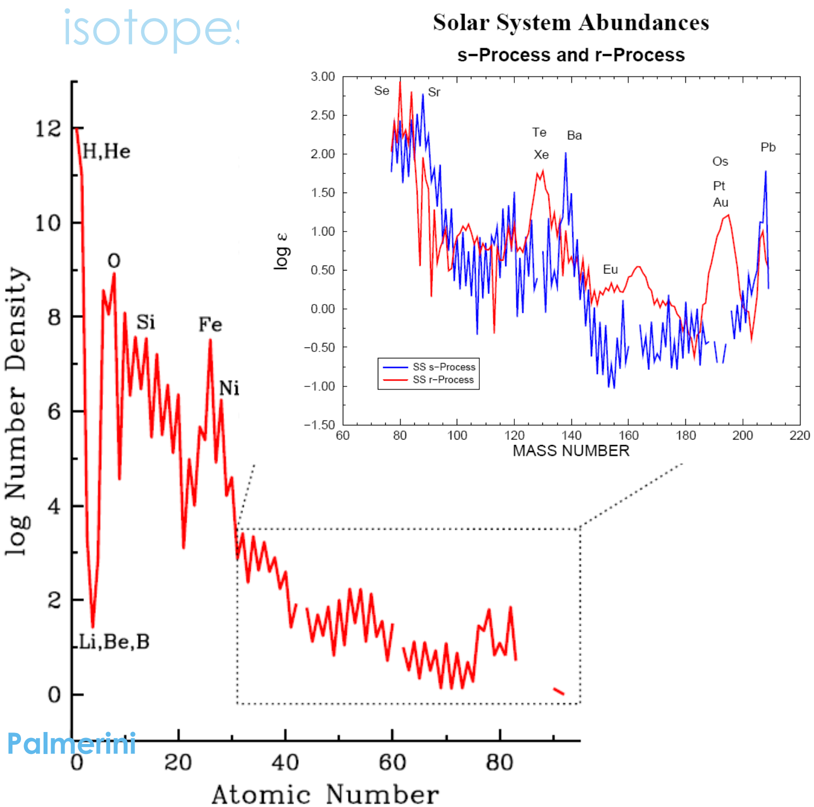
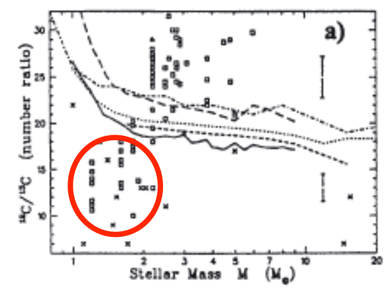
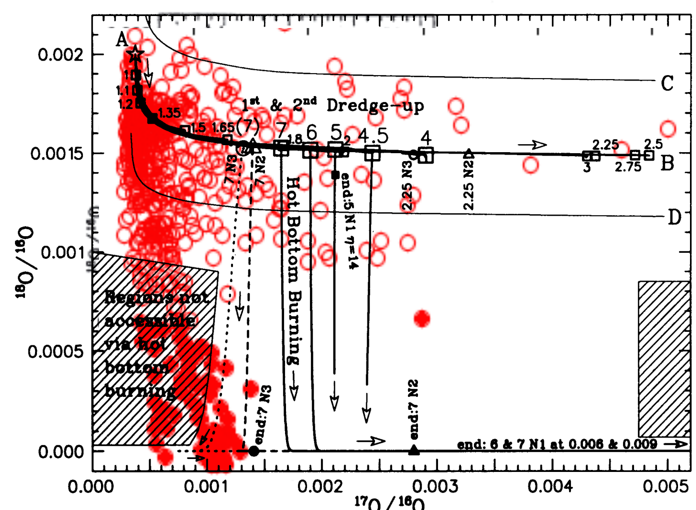
Contribution of LMS to GCE

- Through slow neutron capture nucleosynthesis AGB strongly contribute to the amount of elements heavier than Fe. They are the sole parents of the s-only isotopes

- Meteorites grains of AGB origin and envelopes of low mass giants show unexpected abundances of light nuclei (^{7}Li, ^{12}C, ^{13}C, ^{16}O, ^{17}O, ^{18}O, ^{26}Al) .







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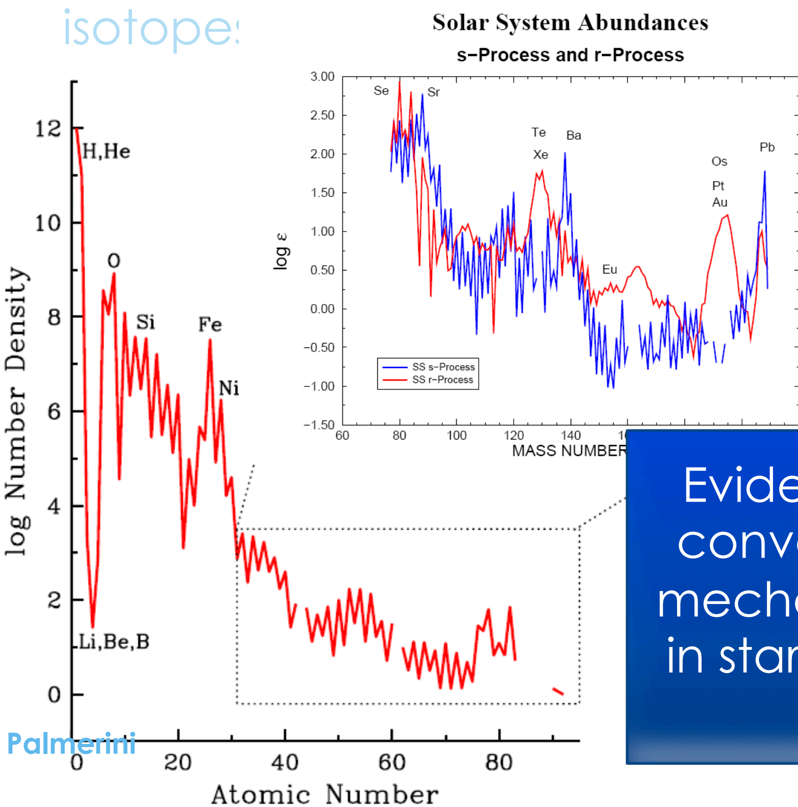
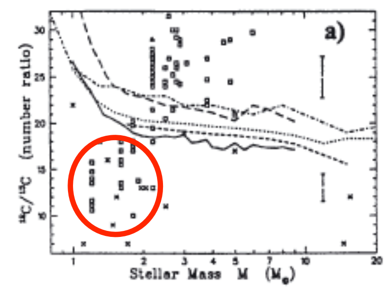
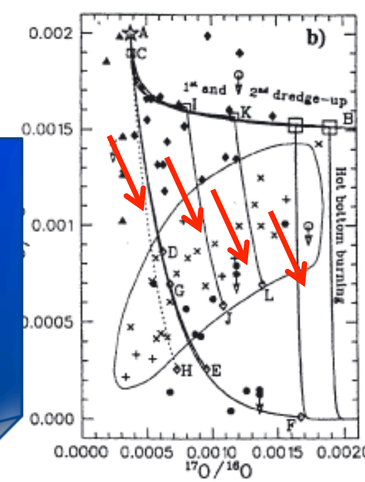


Evidences of non-convective mixing mechanisms at play in stars with M<3M$_\odot$





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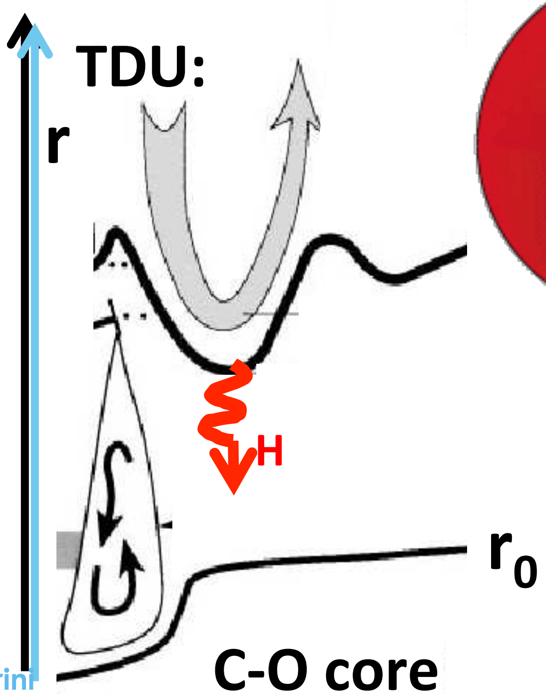
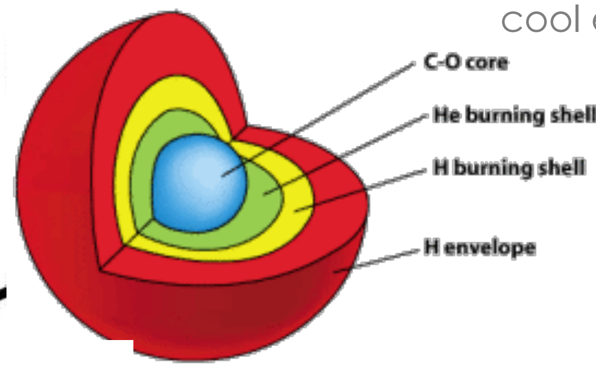
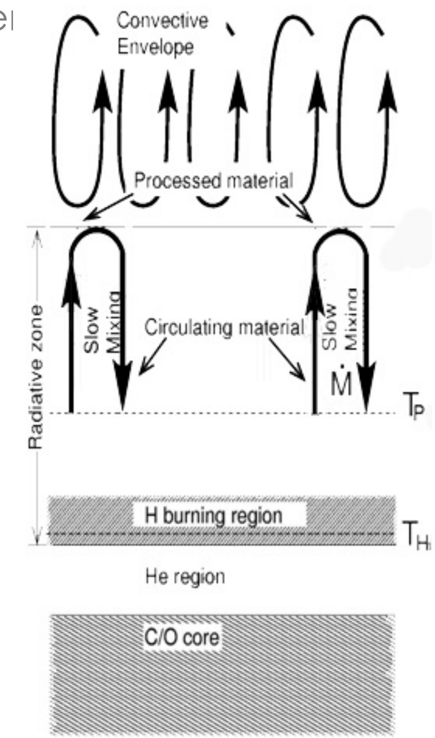
A physical mechanism that allows:

- the formation of the ^{13}C reservoir (or pocket):
  - proton penetration from the envelop during the TDU→ $^{12}C(p,\gamma)^{13}N(\beta^{+}\nu)^{13}C$; – ^{14}N is the most important neutron poison.
- the enrichment of the stellar surface with fresh products of the H-burning
  - currents transport matter upward/ downward from regions where H-burning occurs to the bottom of the cool e

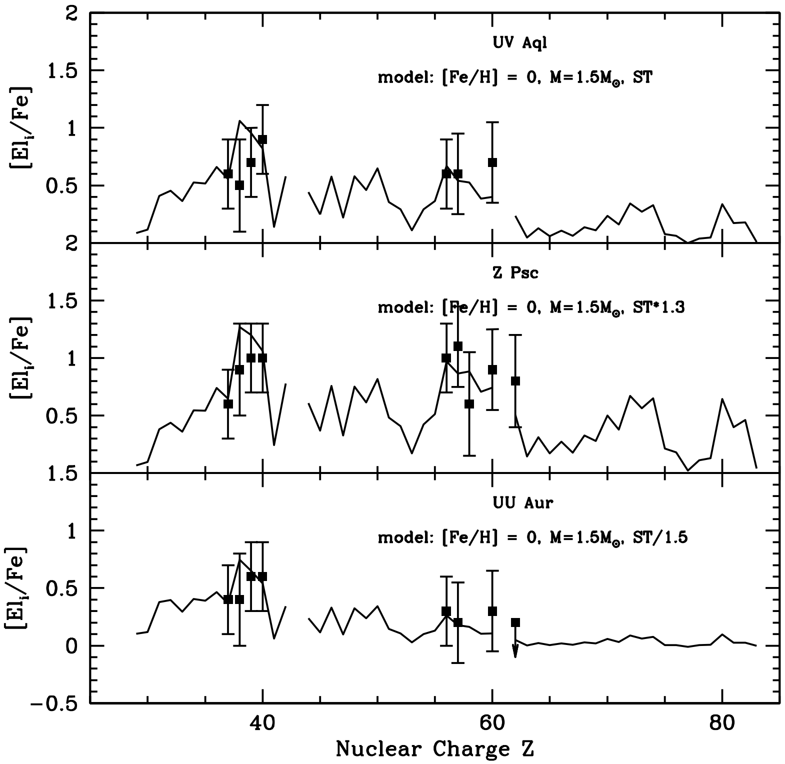




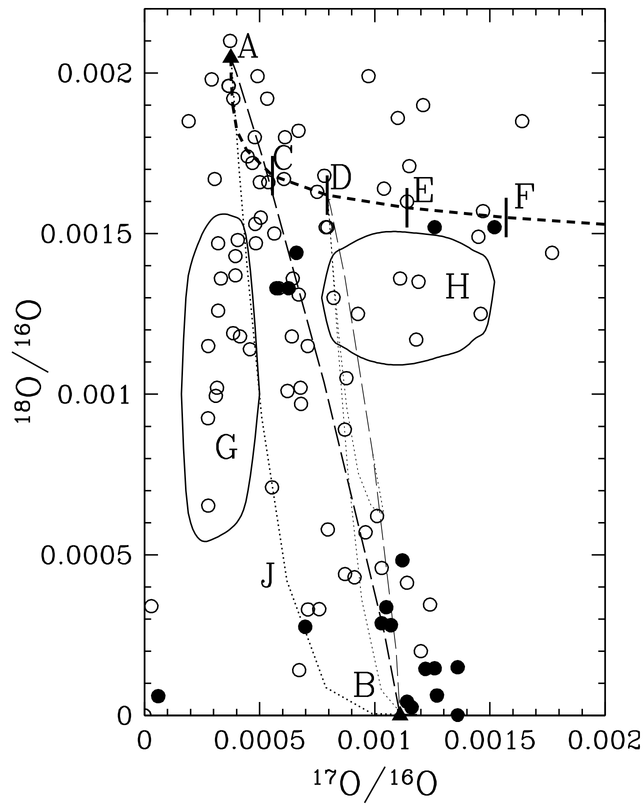


Parametric models have been working for almost twenty years (perhaps more)

Abia et al. 2002



Nollet et al.2004



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Where is the problem?

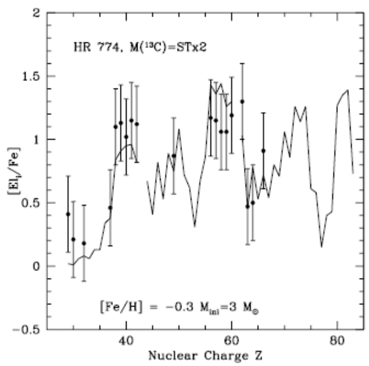


FIG. 13a

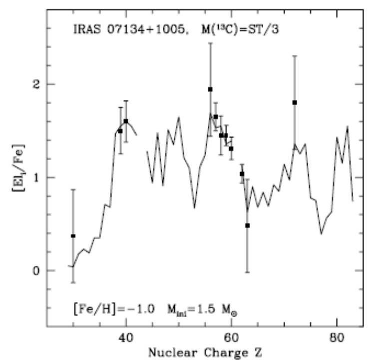
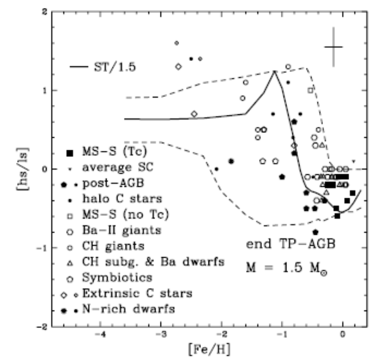
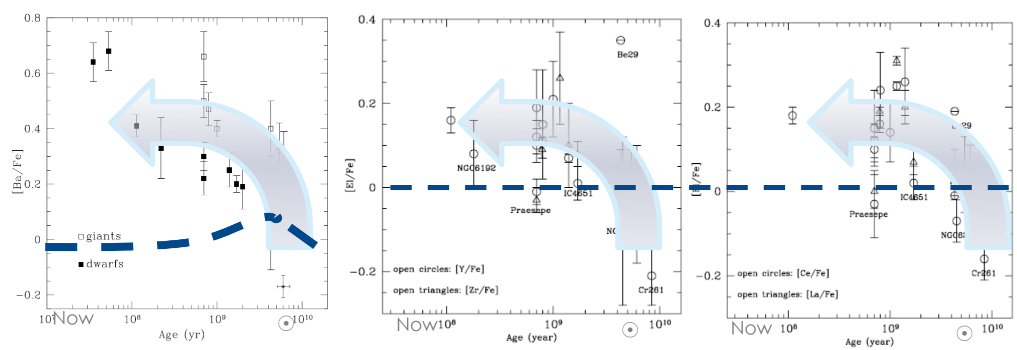


FIG. 13b



"Classical" s-process scenario built in the '90s (e.g. Busso et al., 2001) worked fine in reproducing stellar abundances from the $^{13}C(\alpha,n)^{16}O$ source

Since 2009 measurements of s-process elements (Y, Zr, Ba, La, Ce) in young Galactic stellar systems have indicated that the neutron-rich nuclei Y, Zr, Ba, La and Ce are enhanced by a factor of ≃ 0.2 dex as compared to the Sun (D'Orazi et al. 2009; Jacobson et al. 2011; Maiorca et al. 2011….) .



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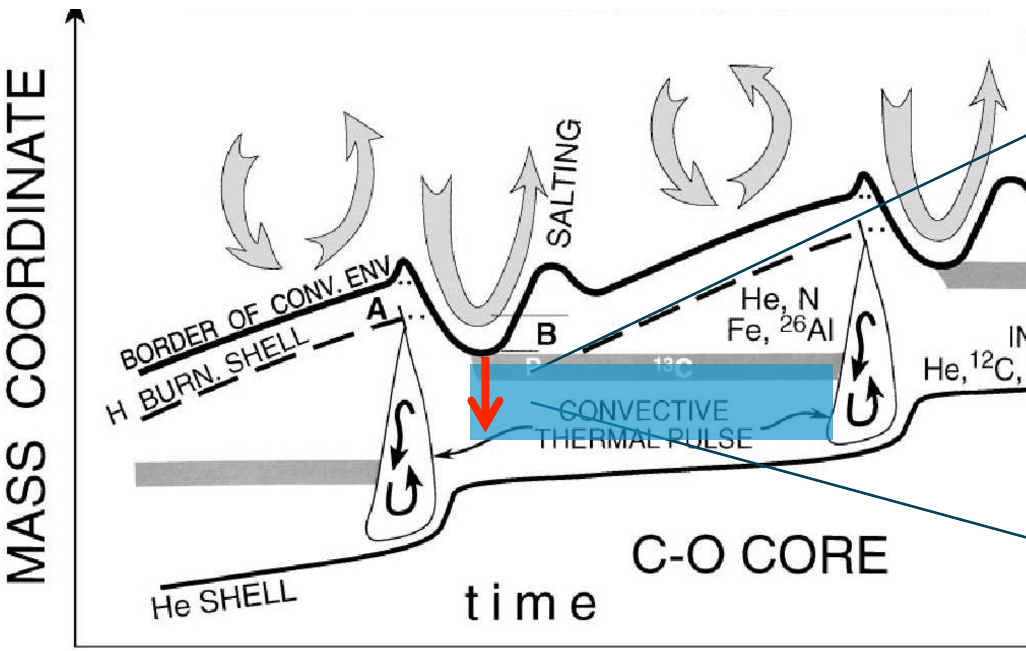
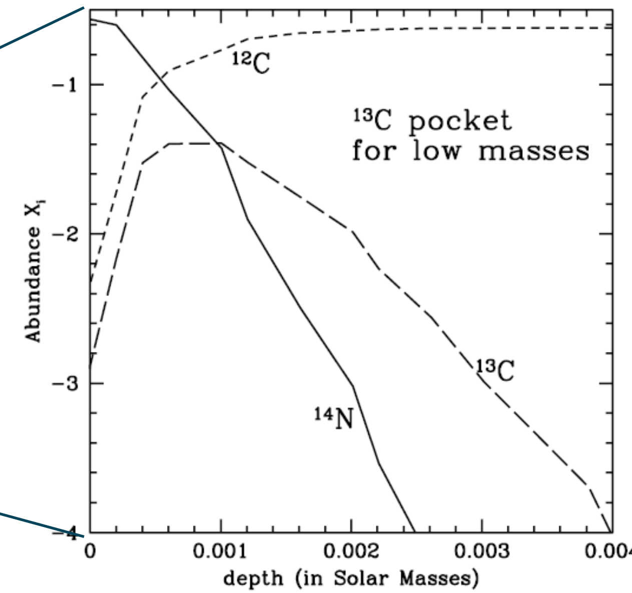
The parametric solution: a larger/ deeper ^{13}C pocket for M<1.5M$_\odot$

Maiorca et al. 2012





- The extension of the ^{13}C reservoir depends on how many protons enter the He-rich layers at dredge-up. This is related to a mixing mechanisms. In a **parametric** model we can assume that these mechanisms (proton penetration) are deeper in stars less massive than 1.5 M$_\odot$→ a few 10^{-3}M$_\odot$ Reasons for guessing a more efficient mixing in very LMS exist

- A few 10^{-3}M$_\odot$ pocket would be adequate to explain the enhancements observed in very young open clusters of the galactic thin disk.

Classical scenario for slow neutron capture nucleosynthesis in low mass AGB

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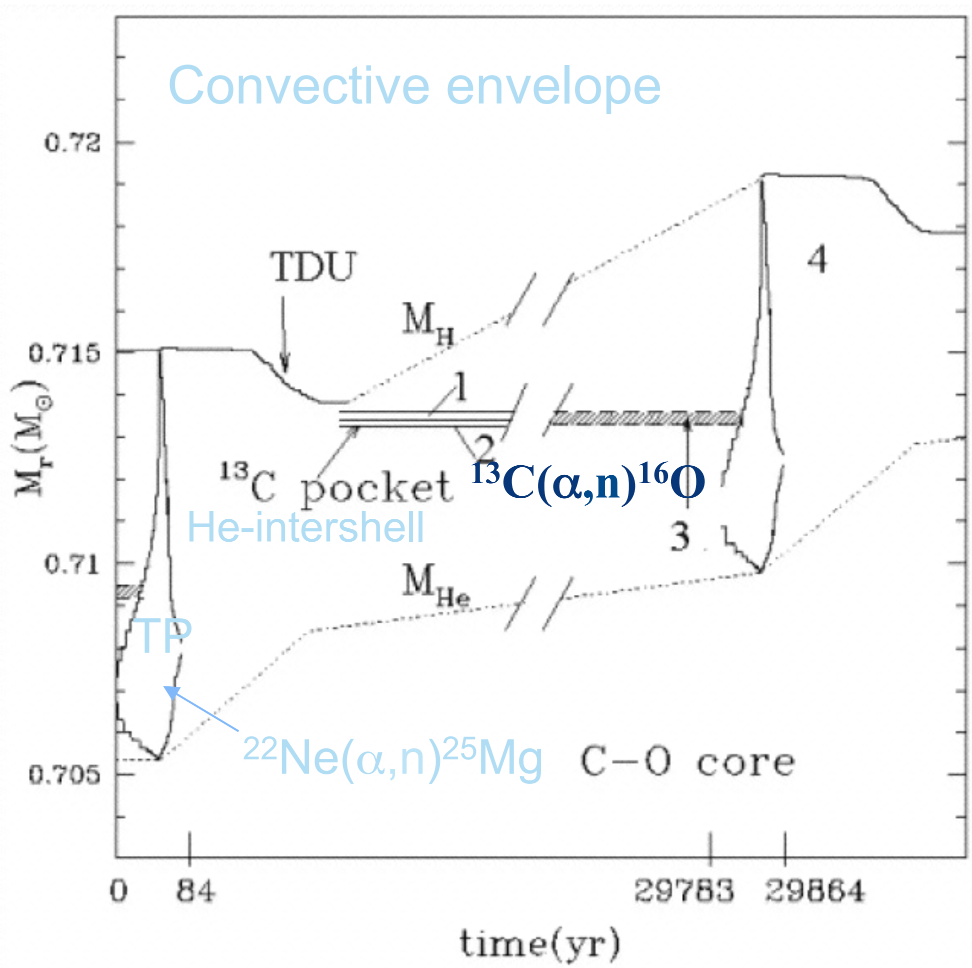


Neutron source:

$^{12}C(p,\gamma)^{13}N(\beta^+)^{13}C(\alpha,n)$.

Type: primary

When: interpulse T_6>90.

Where: He-intershell

Density: 10^6-10^7 (n/cm^3)

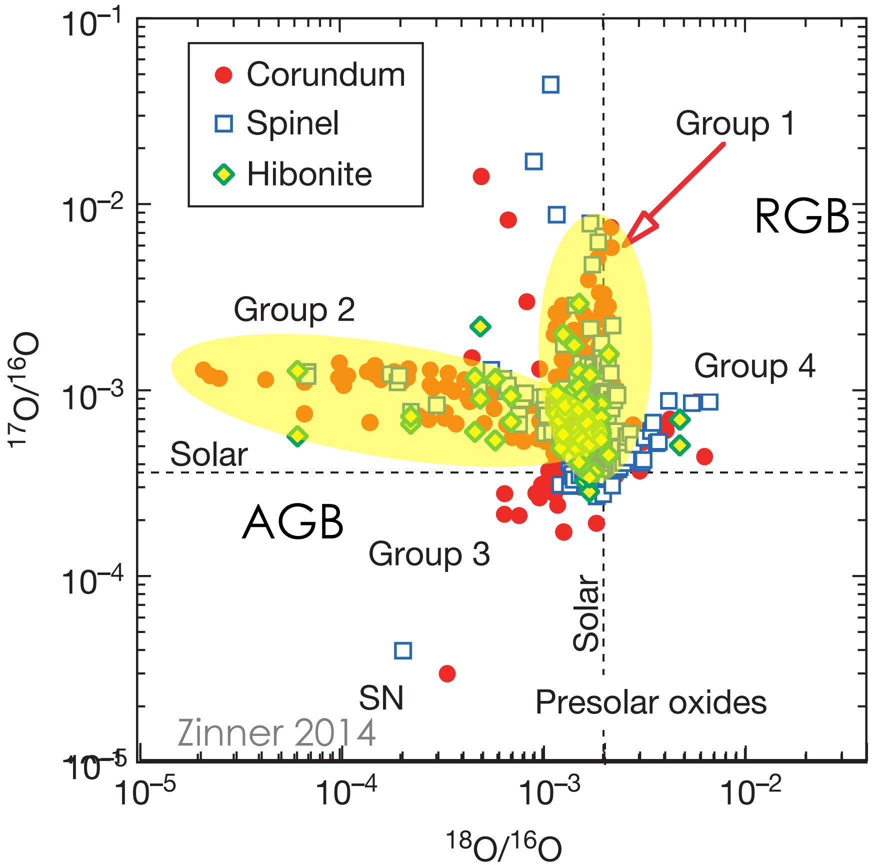
During the TDU → p ingestion at the top of He-intershell (few p's).
At H-shell ignition → ^{13}C-pocket formation via
$^{12}C\ (p,\gamma)^{13}N(\beta^+\nu)^{13}C$
At T~ 10^8 K → $^{13}C(a,n)^{16}O$ in radiative conditions → s-process.

What are we looking for?

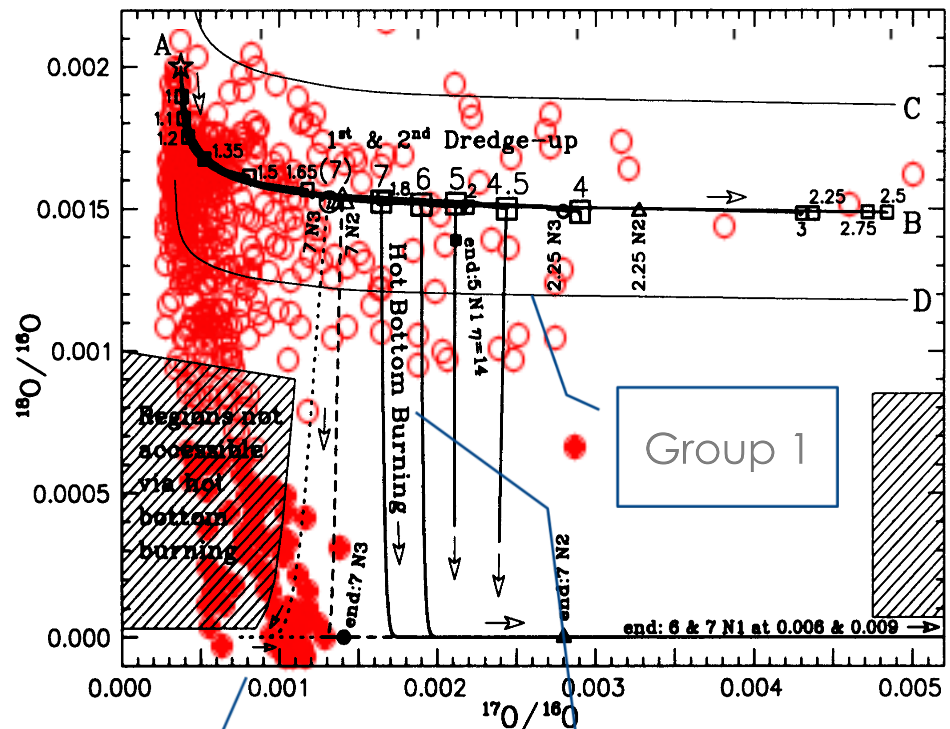
- A mechanism for **injecting protons** into the H-exhausted region must be found, so that interacting with the abundant ^{12}C they can produce fresh ^{13}C locally;
- the abundance of the injected protons in each layer must **be low enough** not to induce further proton captures on ^{13}C; indeed, this would inevitably produce large amounts of ^{14}N, which is an efficient neutron absorber and would hamper n-captures on heavy seeds;
- the total amount of **^{13}C produced must be rather large**, hence the proton injection must reach down to **deep** layers of the He-rich zone to form a ^{13}C reservoir (or "pocket") adequate to explain the chemical evolution of the Galaxy in s-elements, including the enhancements observed in very young open clusters of the galactic thin disk.

Cool Bottom Process from an idea
by Boothroyd, A.I., Sackmann, I.J. & Wasserburg, G.J. (1994)

C/O<1   Oxide grains



Boothroyd, Sackmann & Wasserburg 1995

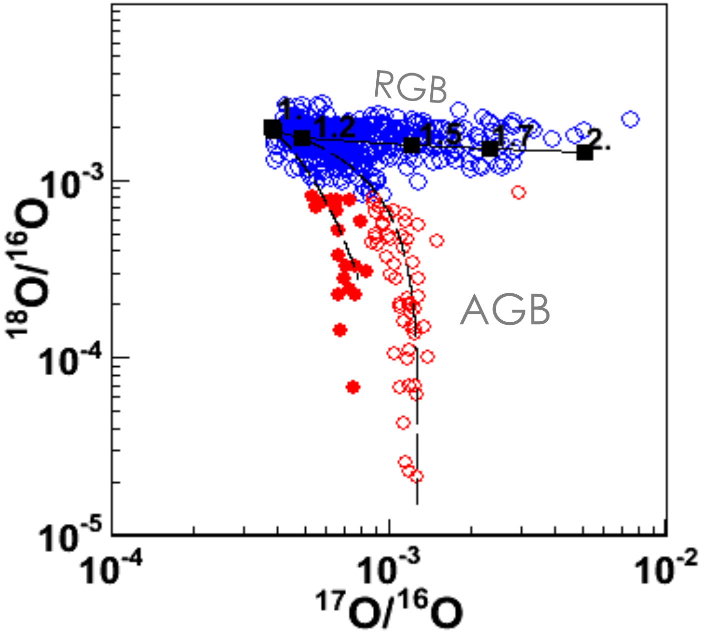


Group 1

Group 2

Area not accessible to nucleosynthesis from massive AGBs (Iliadis et al. 2008).

By improving stellar models and nuclear physics inputs...



- ✓ New reaction rates and opacities tell us that oxide grains (group 1 and 2) come from stars with mass $<1.7M_{\odot}$ where CBP take place.

- ✓ BUT $^{26}Al/^{27}Al$ in oxyde grains requires CBP from warm and (too) deep regions during AGB phases .

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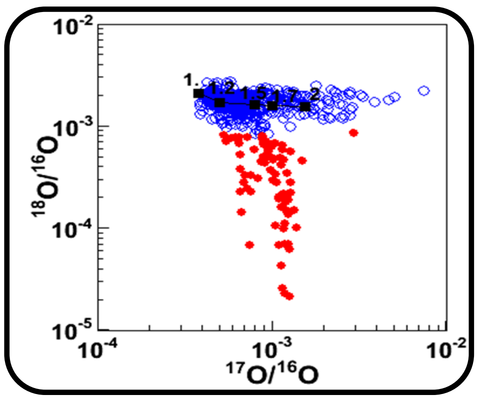
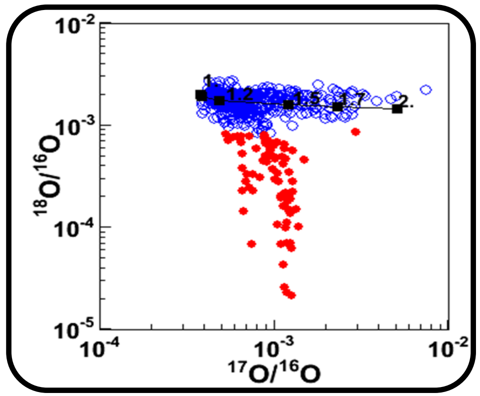
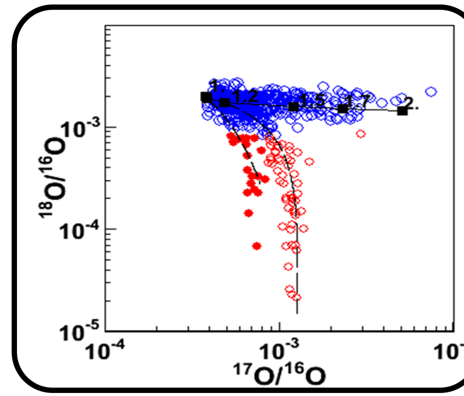
Improving nuclear physics input

- ✓ Extra-mixing in RGB stars ($M_\star < 2M_\odot$) account for by oxygen isotopic mix shown by group 1 grains

$^{17}O(p,\alpha)^{14}N$ (Sergi et al.2011)
$^{18}O(p,\alpha)^{15}O$ (La Cognata et al 2009)
Palmerini et al.2013



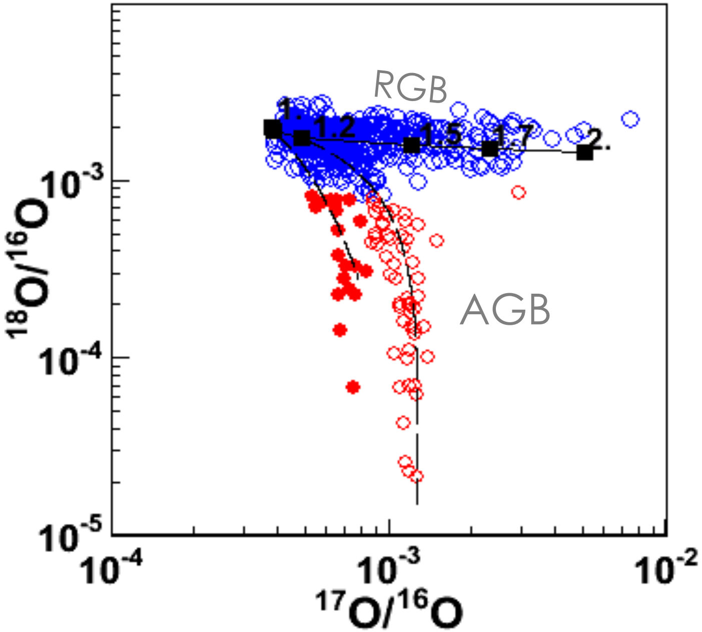




$^{14}N(p,\gamma)^{15}O$ (Imbriani et al 2004, Adelberger et al 2011)
Palmerini et al. 2011

- ✓ Group 2 oxide grains need extra-mixing during AGB phase (deep and efficient Δ=0.1 $\dot{M}$ = $10^{-6} M_\odot$/yr), the RGB is not warm enough
- ✓ Mass range of stellar progenitors of group 2 oxide grains is significantly reduced from 1-2 $M_\odot$ to 1- 1.5 (1.2)$M_\odot$
- ✓ Maybe group 2 grains might be divided in 2 subgroups because of the progenitor mass.

By improving stellar models and nuclear physics inputs...



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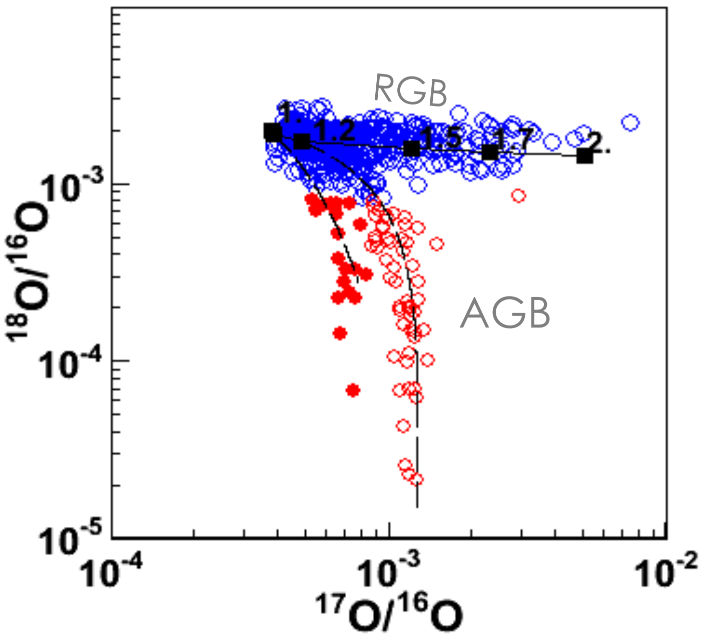
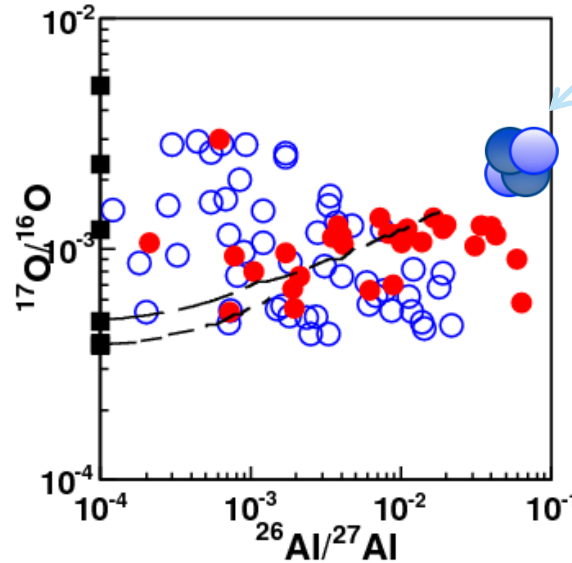
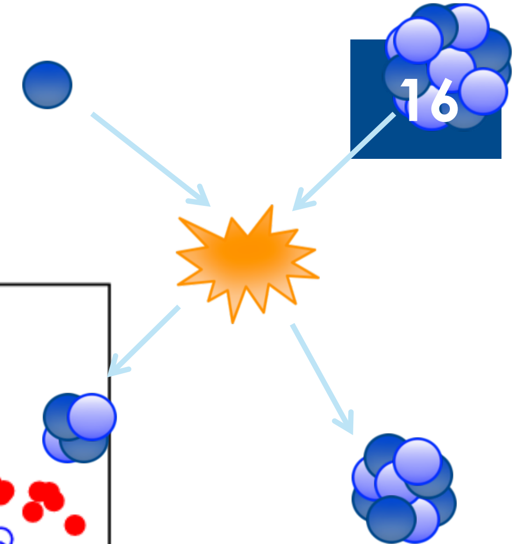
The ^{26}Al puzzle







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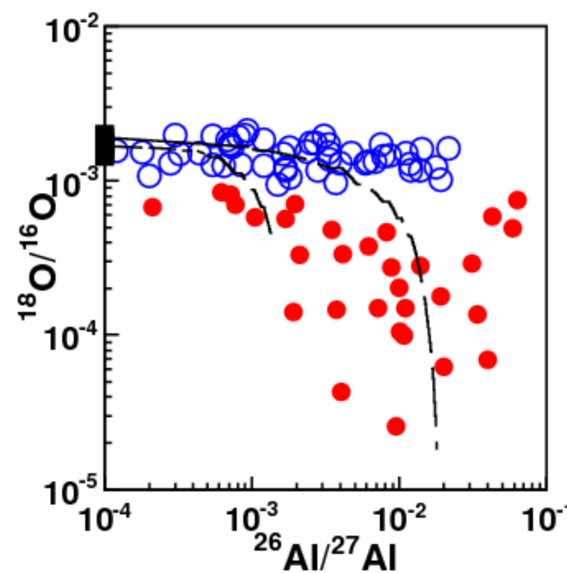
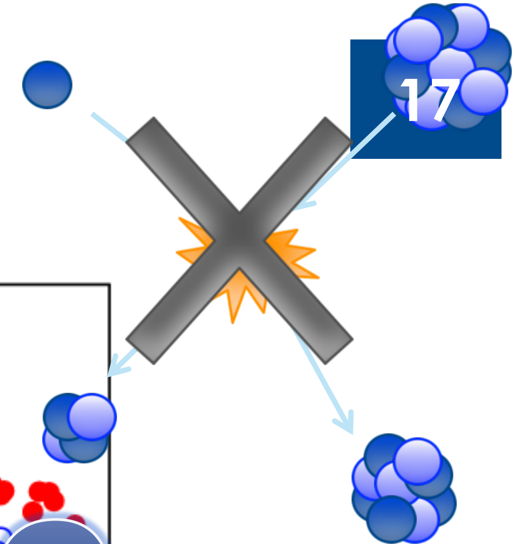


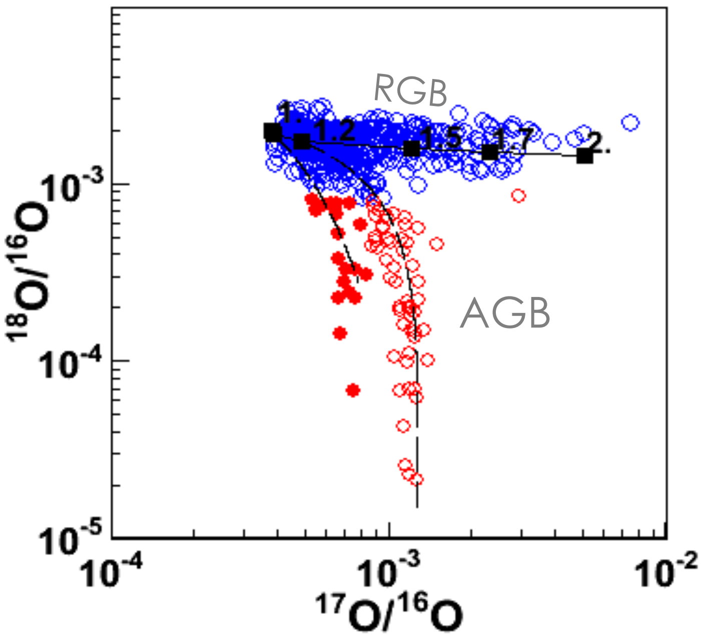
^{26}Al/^{27}Al>0.02 shown by part of group 2 grains

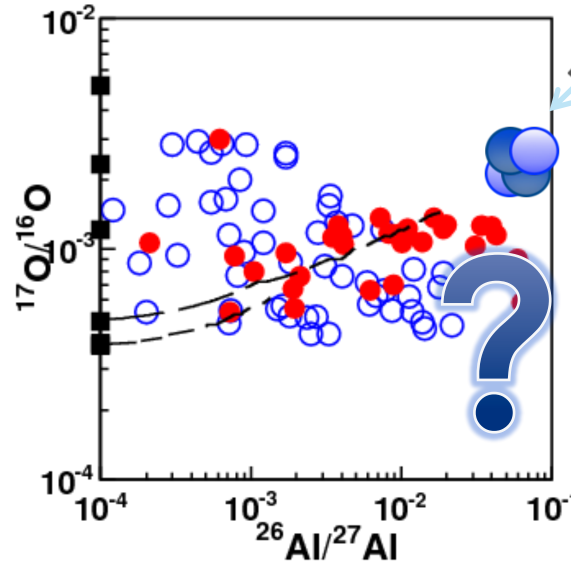
Might news from nuclear physics help? NO

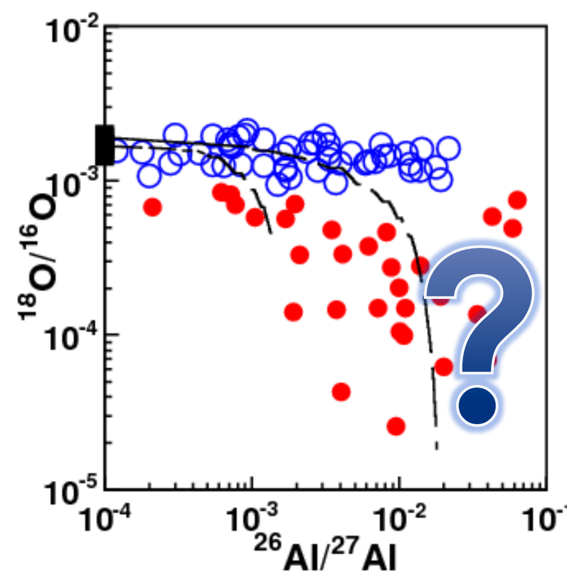
^{25}Mg(p,g)^{26}Al measurement by LUNA collaboration, Straniero et al 2013 and a^{26}Al(p,g) by Pain et al 201.

The ^{26}Al puzzle









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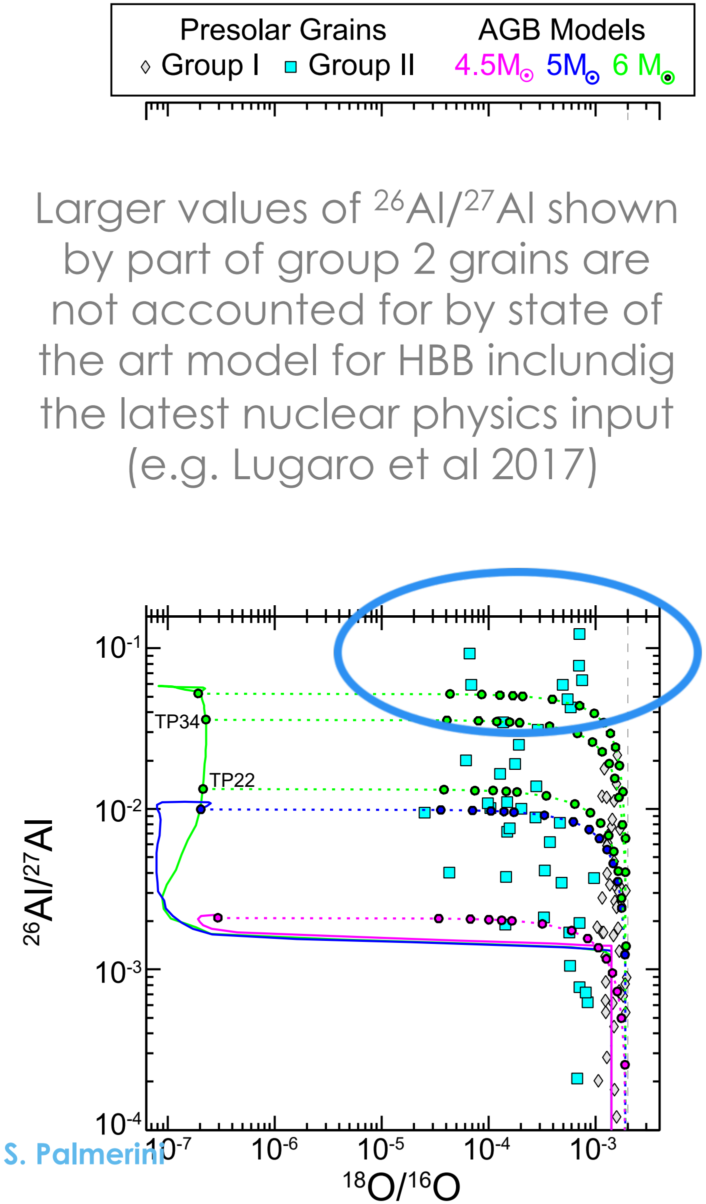

Larger values of $^{26}Al/^{27}Al$ shown by part of group 2 grains are not accounted for by state of the art model for HBB inclundig the latest nuclear physics input (e.g. Lugaro et al 2017)

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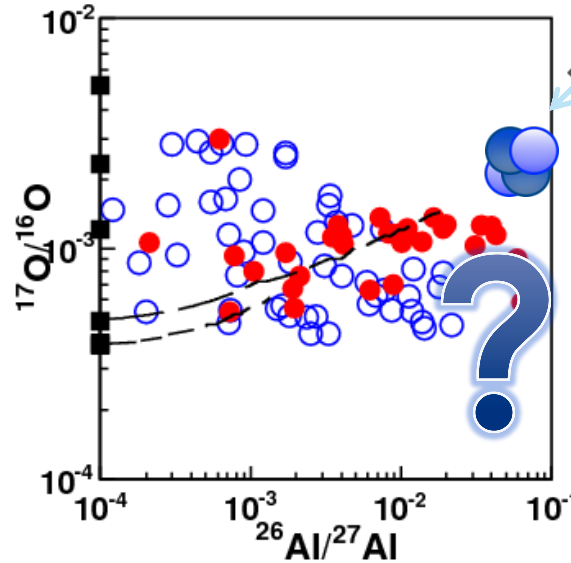

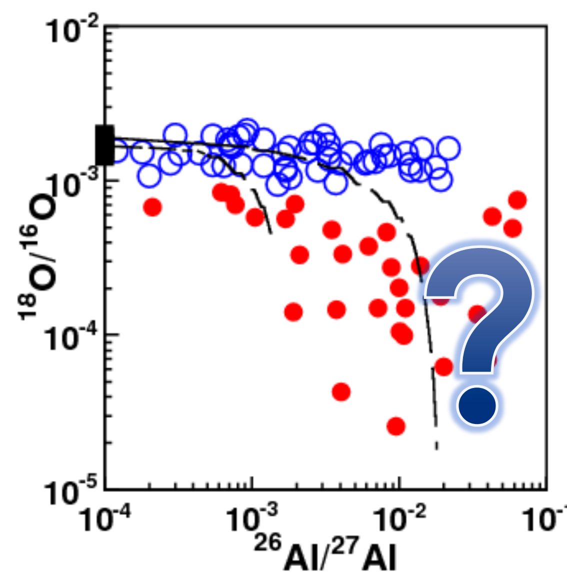

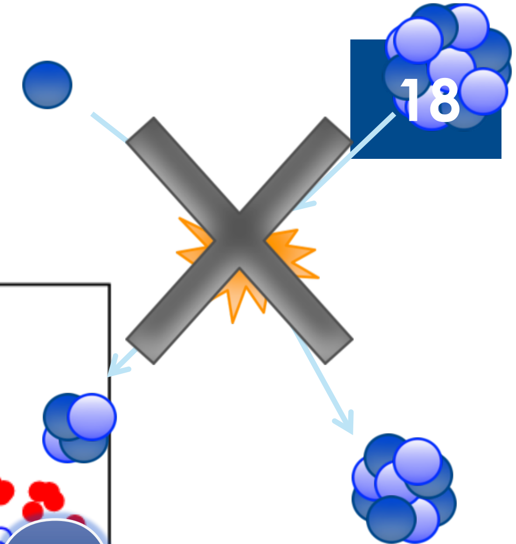

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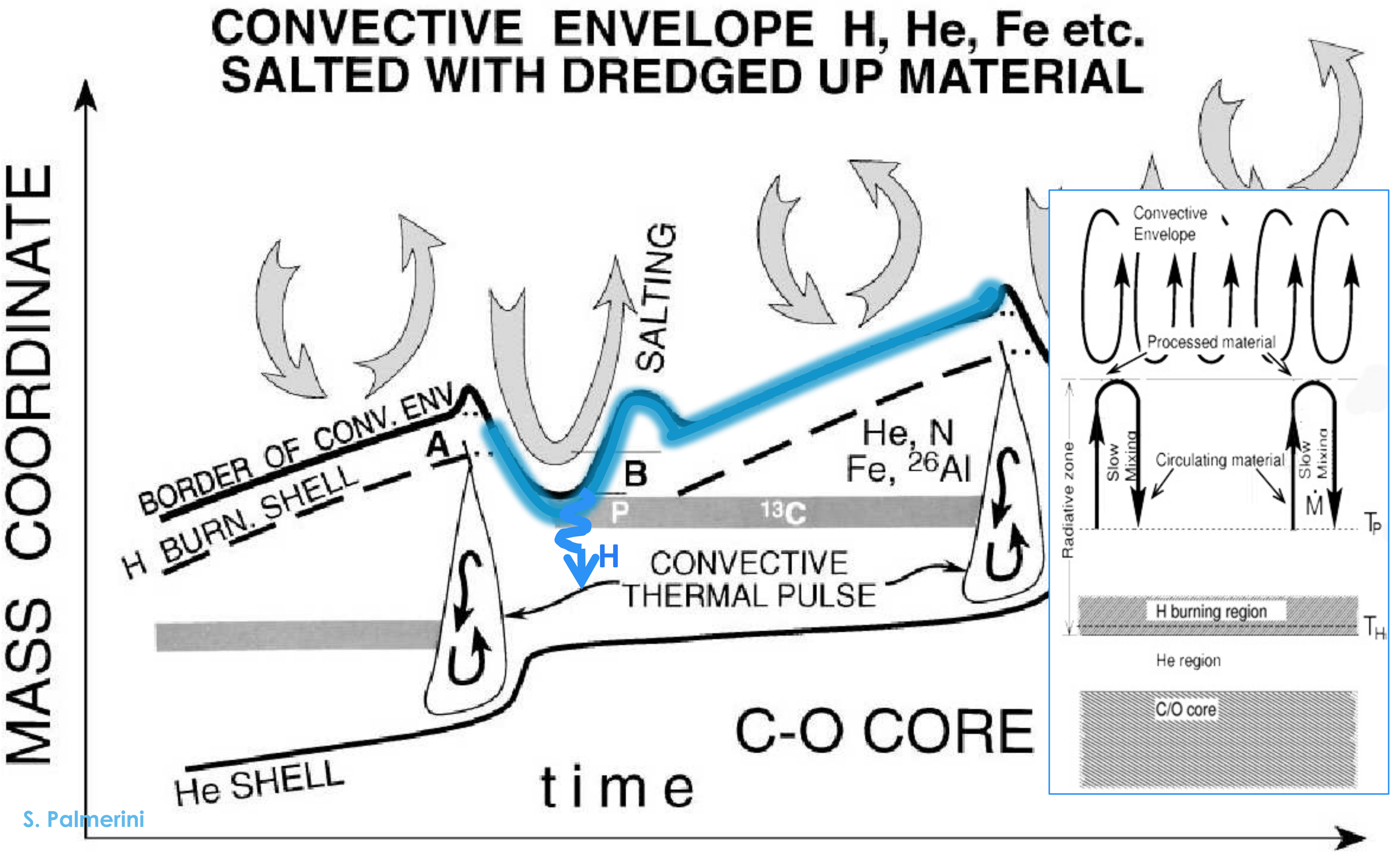
A physical mechanism that allows:



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What physical mechanism?

A few of the many models presented:

Cool Bottom Process (Wasserburg, Boothroyd & Sackmann & 1995) a "conveyor belt" model

Rotation (shear instabilities and diffusion, meridional circulation) Charbonnel 1994; Charbonnel & Do Nascimiento 1998, Denissenkov & Van den Berg 2003 and Palacios et al. 2003

Gravitational waves (Denissenkov & Tout 2000).

Magnetic buoyancy (Busso et al. 2006, Denissenkov et al. 2009….)

Rotation + Thermohaline (Charbonnel et al. 2010)

"**Thermohaline mixing**", (Eggleton et al. 2006; Stancliffe 2010; Angelou et al. 2012)

Magnetic + Thermohaline (Denissenkov and Merryfield 2011)

The MHD model by Nucci & Busso 2014 (ApJ,787,141 2014)

The full MHD equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \qquad (1)$$

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

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla\times(\mathbf{v}\times\mathbf{B}) - \nu_m\Delta\mathbf{B} = 0 \qquad (3)$$

$$\nabla\cdot\mathbf{B} = 0 \qquad (4)$$

$$\rho\left[\frac{\partial \epsilon}{\partial t} + (\mathbf{v}\cdot\nabla)\epsilon\right] + P\nabla\cdot\mathbf{v} - \nabla\cdot(\kappa\nabla T) + \frac{\nu_m}{4\pi}(\nabla\times\mathbf{B})^2 = 0. \qquad (5)$$

Their “simple” analytical solution

$$v_r = \frac{dw(t)}{dt} r^{-(k+1)} \qquad (6)$$

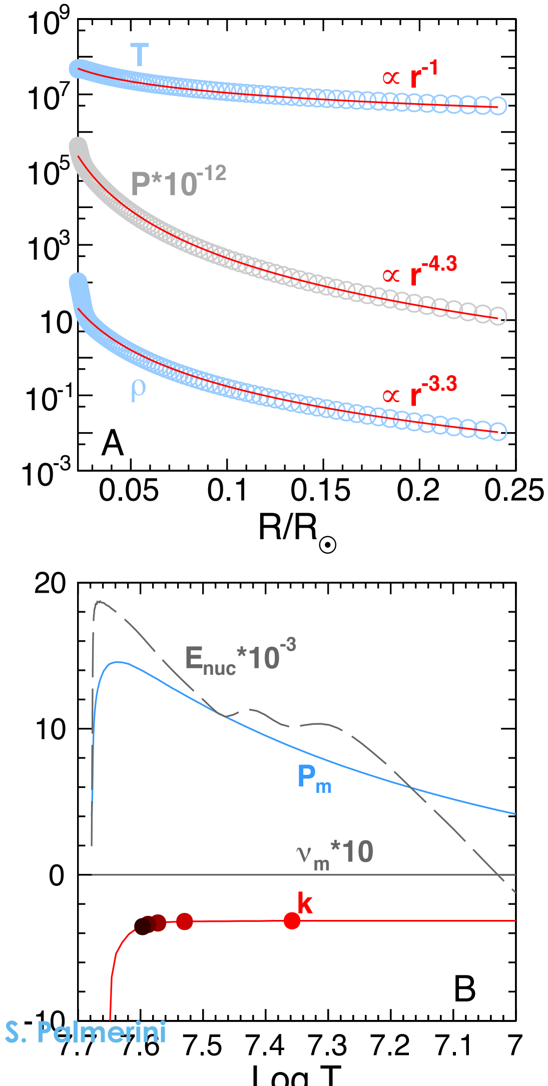
$$B_\varphi = \Phi(\xi) r^{k+1}, \quad [\xi = -(k+2)w(t) + r^{k+2}]. \qquad (7)$$

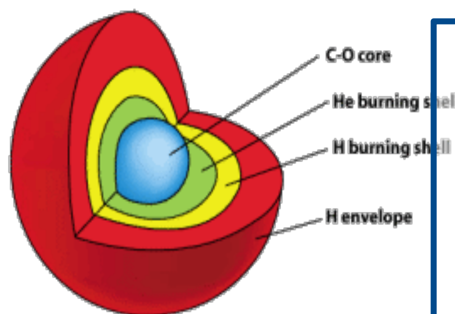
…. whenever a set of three peculiar situations occurs:

1. the plasma density distribution has the simple form $\rho \propto r^k$, where r is the stellar radius and k is smaller than -1;
2. Magnetic Prandtl number $P_m > 1$ (namely the ratio between the kinematic viscosity $\eta = \mu / \rho$ and the magnetic diffusivity ν_m, see Spitzer 1962);
3. Small magnetic diffusivity ν_m (the kinematic viscosity η cannot be really neglected,but the dynamic viscosity μ remains rather small)

The solution for the radiative layer above the H-burning shell of an AGB star

$1.5M_{\odot}\ Z_{\odot}$





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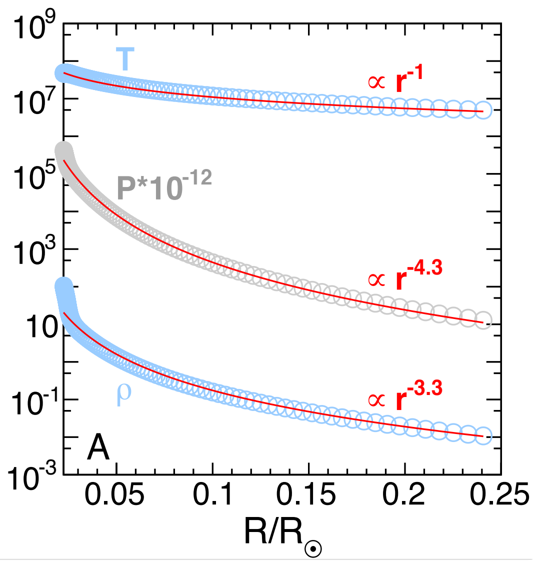
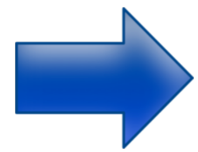
The solution for the radiative layer above the H-burning shell of an AGB star

$1.5 M_{\odot}\ Z_{\odot}$



In the radiative layer above the H-burning shell of an AGB star

$$\rho \propto r^k, \qquad P \propto \rho^{4/3}$$

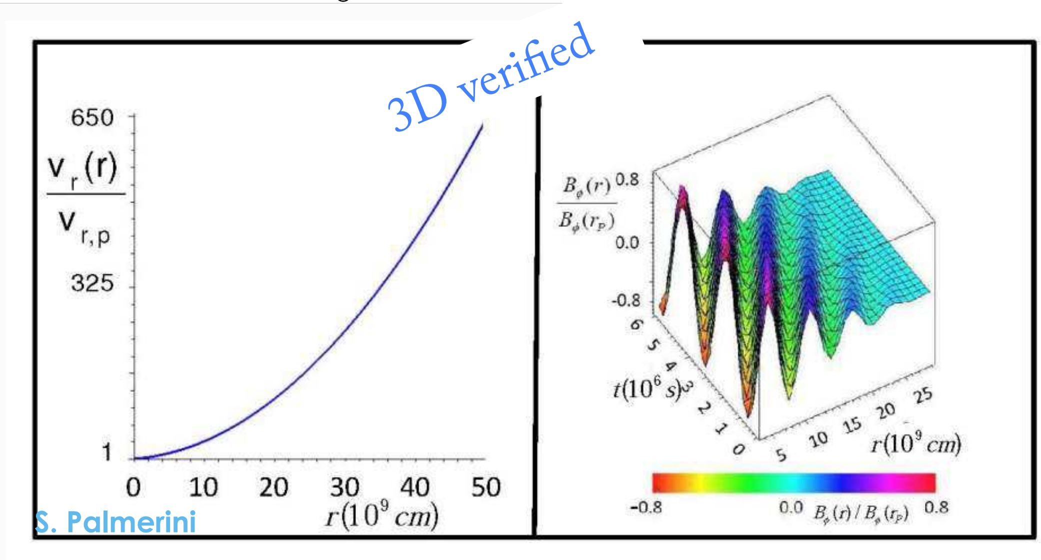


$$v_r = \Gamma r^{-(k+1)}$$

$$\Gamma = v_p r_p^{k+1}.$$

$$v_r = v_P \left(\frac{r_P}{r}\right)^{-(k+1)}$$

Simplest solution satisfieng the bonduary conditions

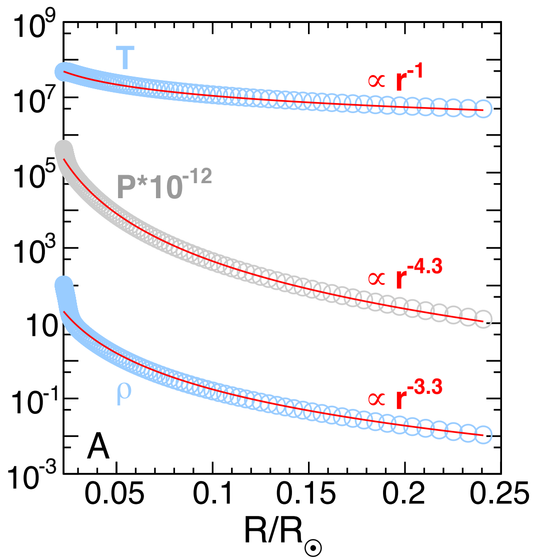


Below the convective envelope of a red giant star, magnetic fields induce a natural expansion, permitted by the almost ideal MHD conditions, in which the radial velocity grows as a power of the radius.

Building the MHD mixing model

(for the radiative layer above the H-burning shell of an AGB star1.5$M_\odot$ $Z_\odot$)

Palmerini et al. 2017a



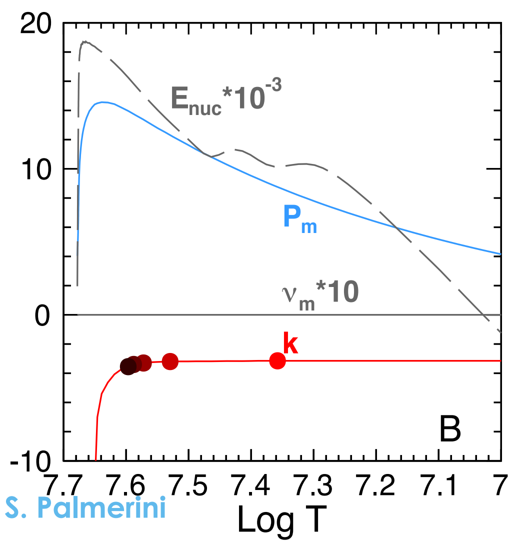
1.5$M_\odot$ $Z_\odot$ AGB

$$\varrho = \varrho_P (r/r_P)^k$$ ← $\rho \propto r^k,$

$$v_r = v_P \left(\frac{r_P}{r}\right)^{-(k+1)}$$

Where is r_P?

$k = -3.5, -3.4, -3.3, -3.2$ and -3.1.



Here is r_P

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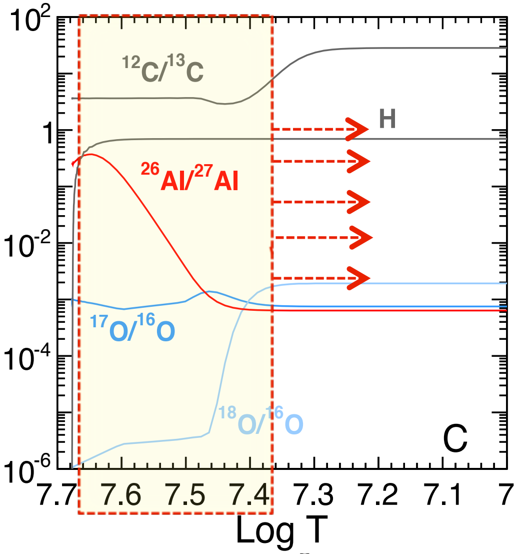
The magnetic (extra-) mixing model

Palmerini et al. 2017a

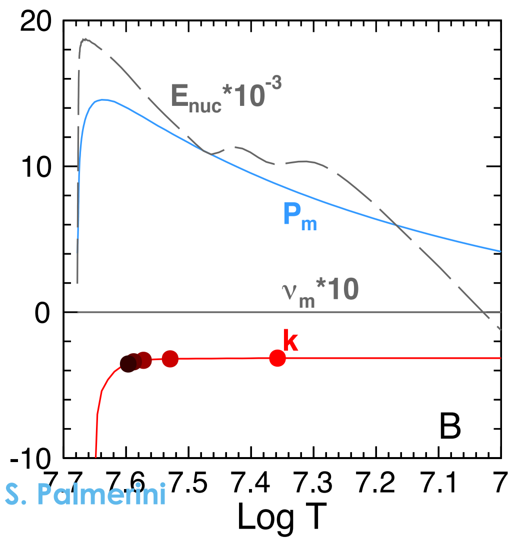


$$\varrho = \varrho_P (r/r_P)^k$$

$$v_r = v_P \left(\frac{r_P}{r}\right)^{-(k+1)}$$

1.5M$_\odot$ Z$_\odot$ AGB

…the magnetic buoyance might promote the mixing n between the H-burning shell and the base of the convective envelope



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- Mixing depth:

$\rho \propto r^k,$

$k = -3.5, -3.4, -3.3, -3.2$ and $-3.1.$

- Mixing velocity:

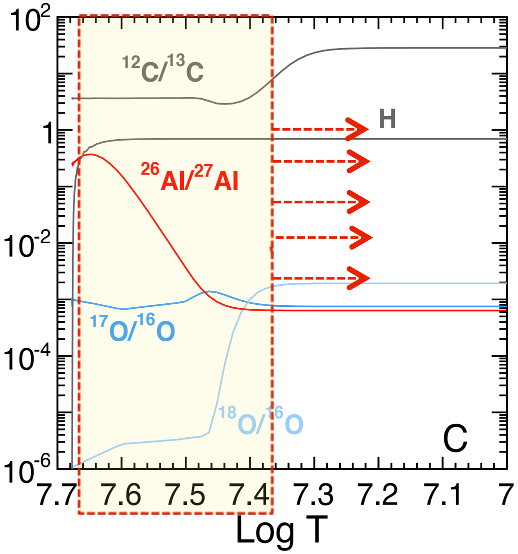
$$v_r = v_P \left(\frac{r_P}{r}\right)^{-(k+1)}$$

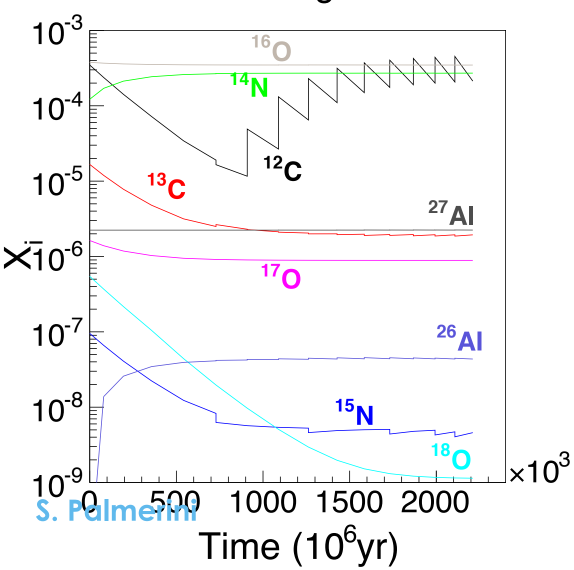
- Mixing rate:

$$\dot{M} = 4\pi \rho_e r_e^2 v_e f_1 f_2$$

The magnetic (extra-) mixing model

Palmerini et al. 2017a





$$\varrho = \varrho_P (r/r_P)^k$$

$$v_r = v_P \left(\frac{r_P}{r} \right)^{-(k+1)}$$

$1.5 M_\odot$ $Z_\odot$ AGB

...the magnetic buoyance might promote the mixing n between the H-burning shell and the base of the convective envelope

- Mixing depth:

$\rho \propto r^k,$

$$k = -3.5, -3.4, -3.3, -3.2 \text{ and } -3.1.$$

- Mixing velocity:

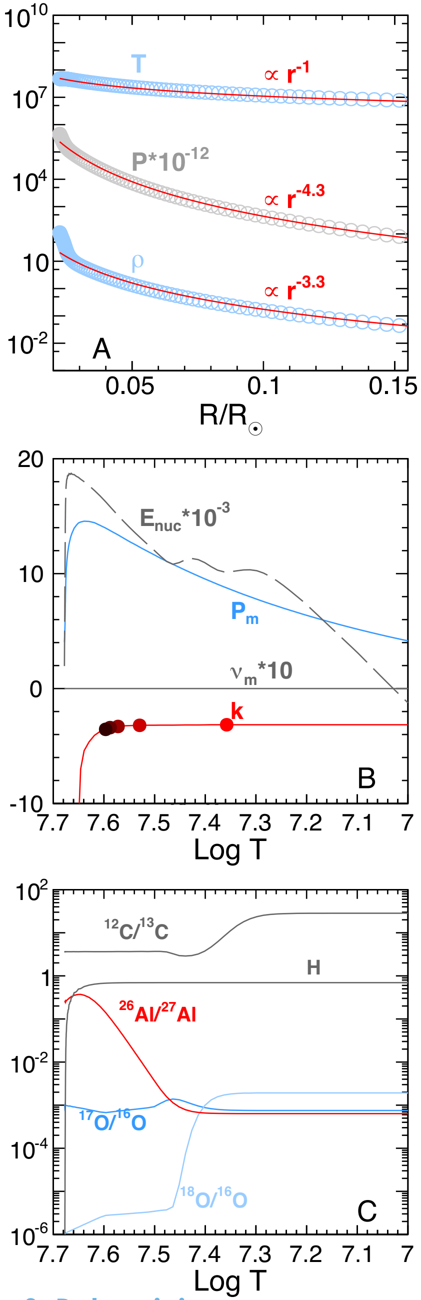
$$v_r = v_P \left(\frac{r_P}{r} \right)^{-(k+1)}$$

- Mixing rate:

$$\dot{M} = 4\pi \rho_e r_e^2 v_e f_1 f_2$$

Results for oxide grains

Palmerini et al. 2017a



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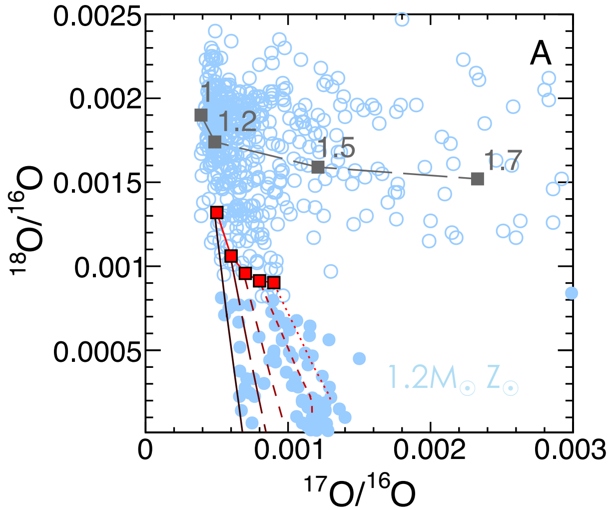
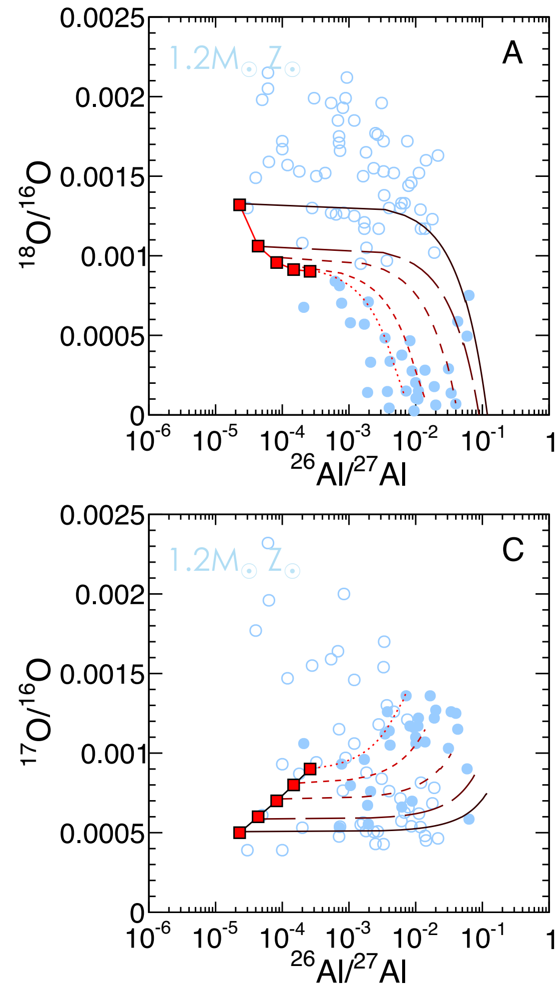
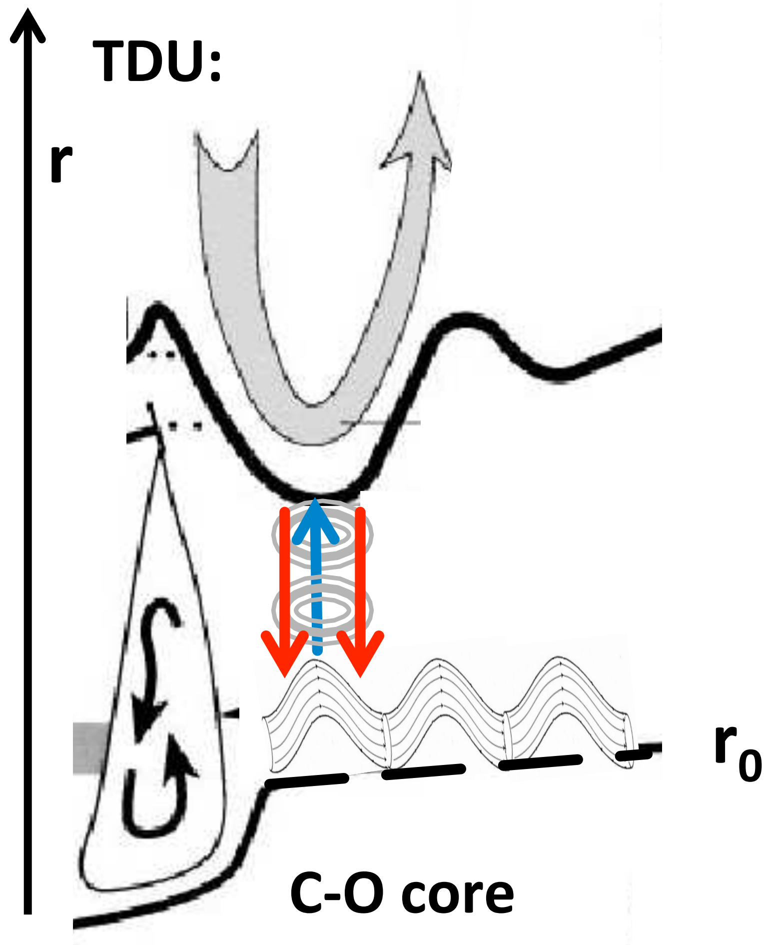


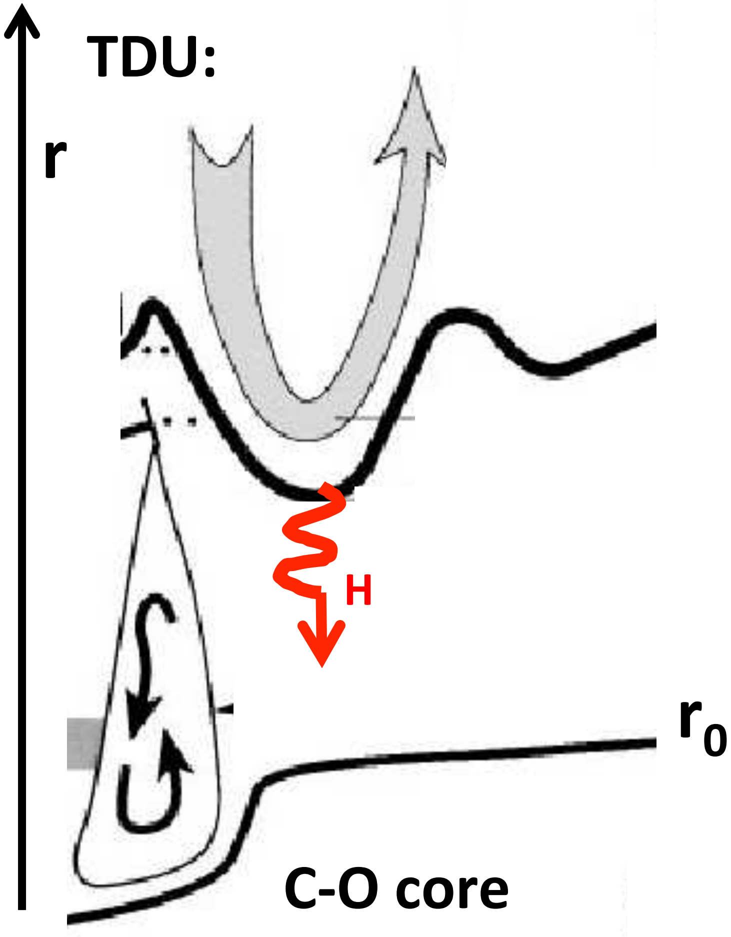
Table 1. C/O and $^{12}C/^{13}C$ ratios predicted by our most massive model with CBP, that of a 1.5 $M_\odot$ star, up to the end of the AGB phase. They are compared to results from the same stellar code with no CBP.

	$^{12}C/^{13}C$		C/O	
FDU	25		0.30	
	$k = -3.3$	No CBP	$k = -3.3$	No CBP
Early AGB	19	25	0.24	0.30
Mid-TP-AGB	35	53	0.43	0.63
End TP-AGB	51	79	0.63	0.94



^{13}C-pocket formation due to Magnetic Instabilities





The ^{13}C-pocket formation - Calculations

Trippella et al. 2016

The **density of envelope** material injected (downflow mass) into the He-layers will vary as:

$$d\rho_d/\rho_d = +\alpha dr$$

corresponding to an **exponential profile**:

$$\rho_d(r) = \rho_{d,0}e^{-\alpha(r_e-r)}$$

We multiplied for the infinitesimal **element of volume**:

$$dM_d(r) = 4\pi r^2 \rho_e e^{-\alpha(r_e-r)} dr.$$

After **integration** between envelope border and the innest layer, we obtain:

$$\Delta M_d^H \simeq 0.714 \frac{4\pi\rho_E}{\alpha} \left\{ \left[r_e^2 - \frac{2}{\alpha} r_e + \frac{2}{\alpha^2} \right] - \left[r_p^2 - \frac{2}{\alpha} r_p + \frac{2}{\alpha^2} \right] e^{-\alpha(r_e-r_p)} \right\}$$

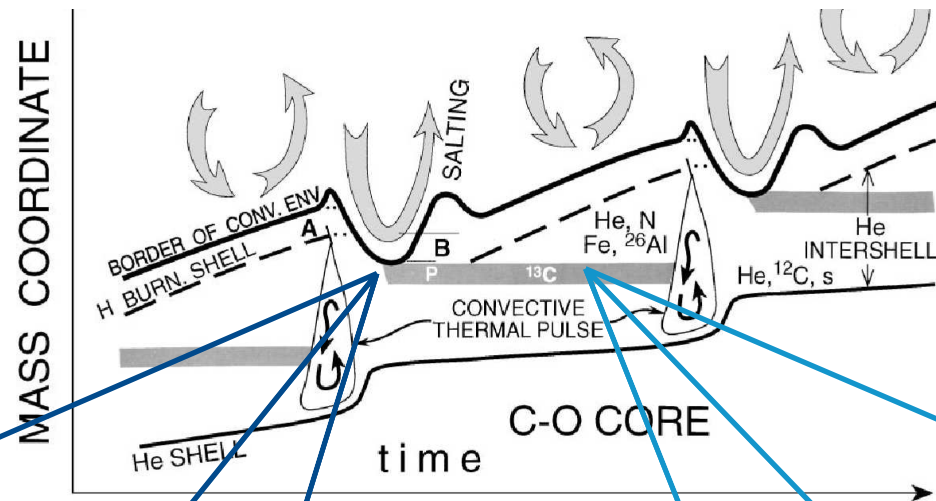
Comparing this result with the **mass transported** by magnetic buoyancy

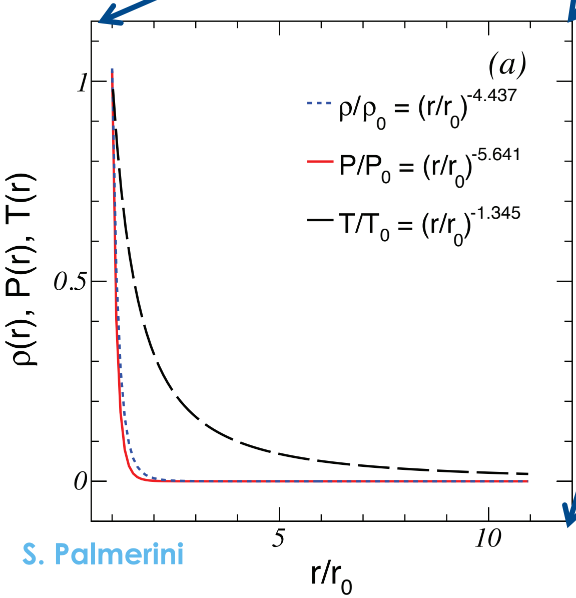
$$M_{up} = \dot{M} \cdot \Delta t = 4\pi r_e^2 \rho_e v_e f_1 f_2 \Delta t$$

we obtain the **amount of proton injested** in the He-rich region for the formation of the ^{13}C-pocket

Courtesy of O. Trippella

The ^{13}C-pocket formation :





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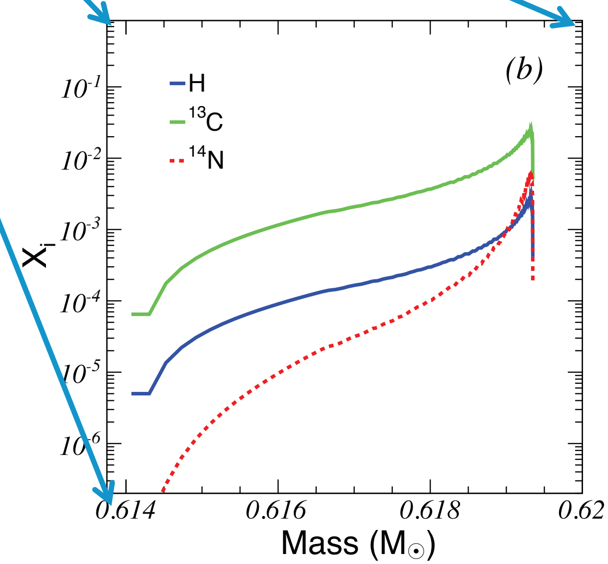
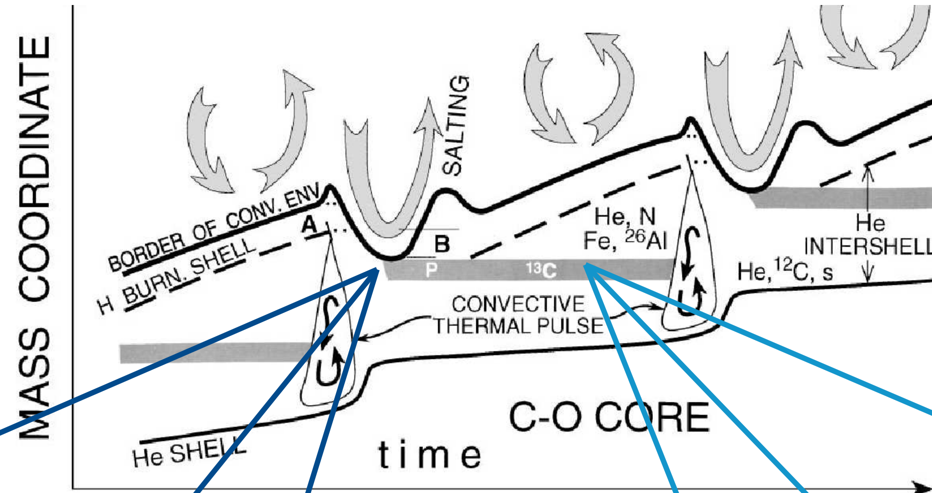
N&B conditions are satisfied

the exact analytical solutions of the MHD equations are held.

the formation of ^{13}C-pocket is allowed



The ^{13}C-pocket formation :

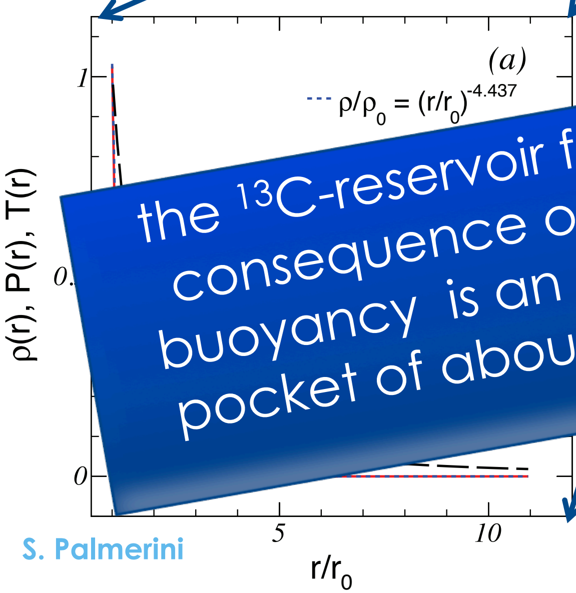


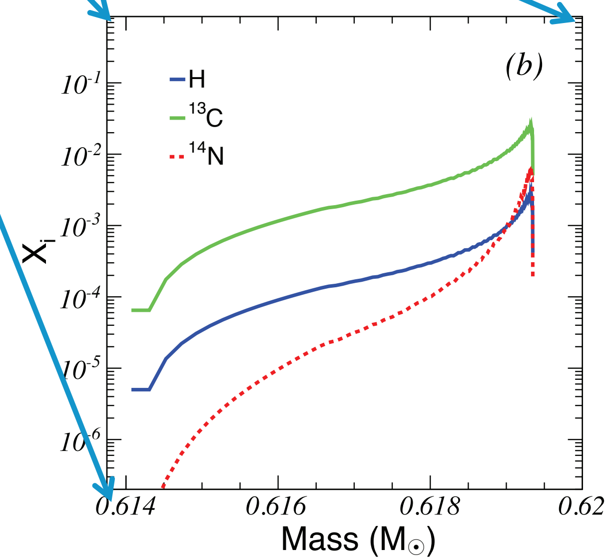
N&B conditions are satisfied

... analytical ... the MHD ... are held.

the formation of ^{13}C-pocket is allowed

the ^{13}C-reservoir formed as a consequence of magnetic buoyancy is an almost "flat" pocket of about 5×10^{-3} $M_{\odot}$





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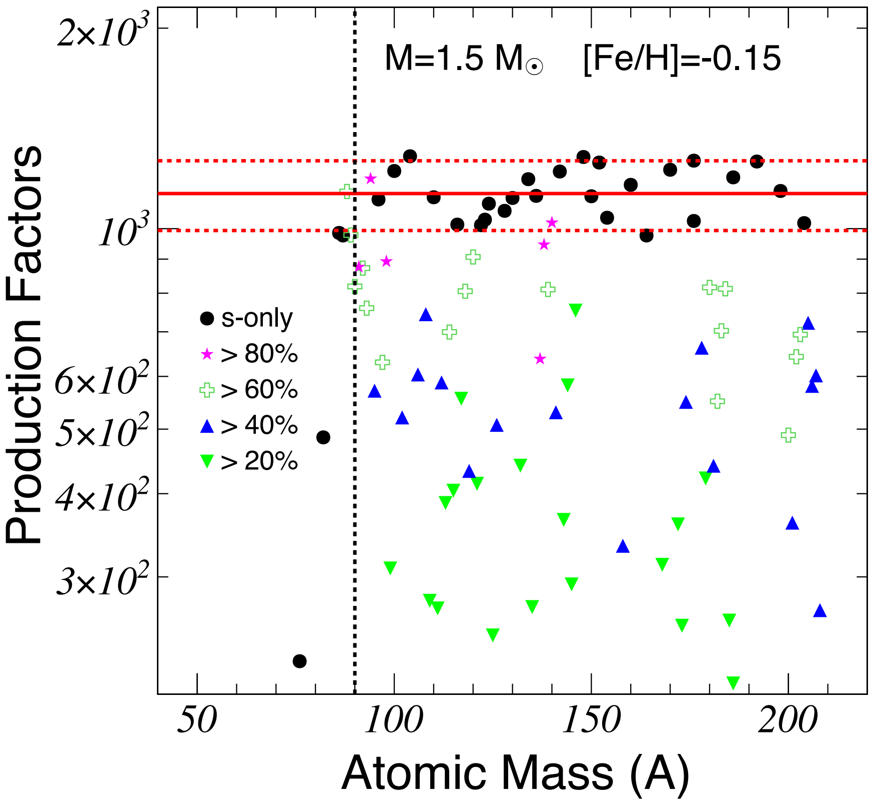
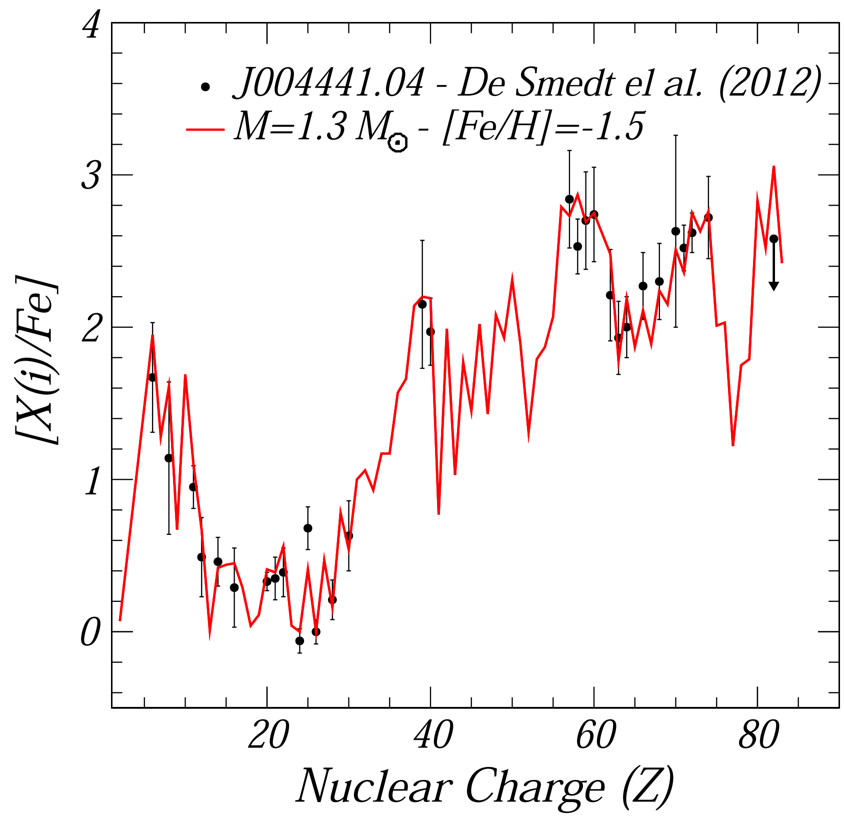
Two tests for our results

Trippella et al. 2016

The solar main component



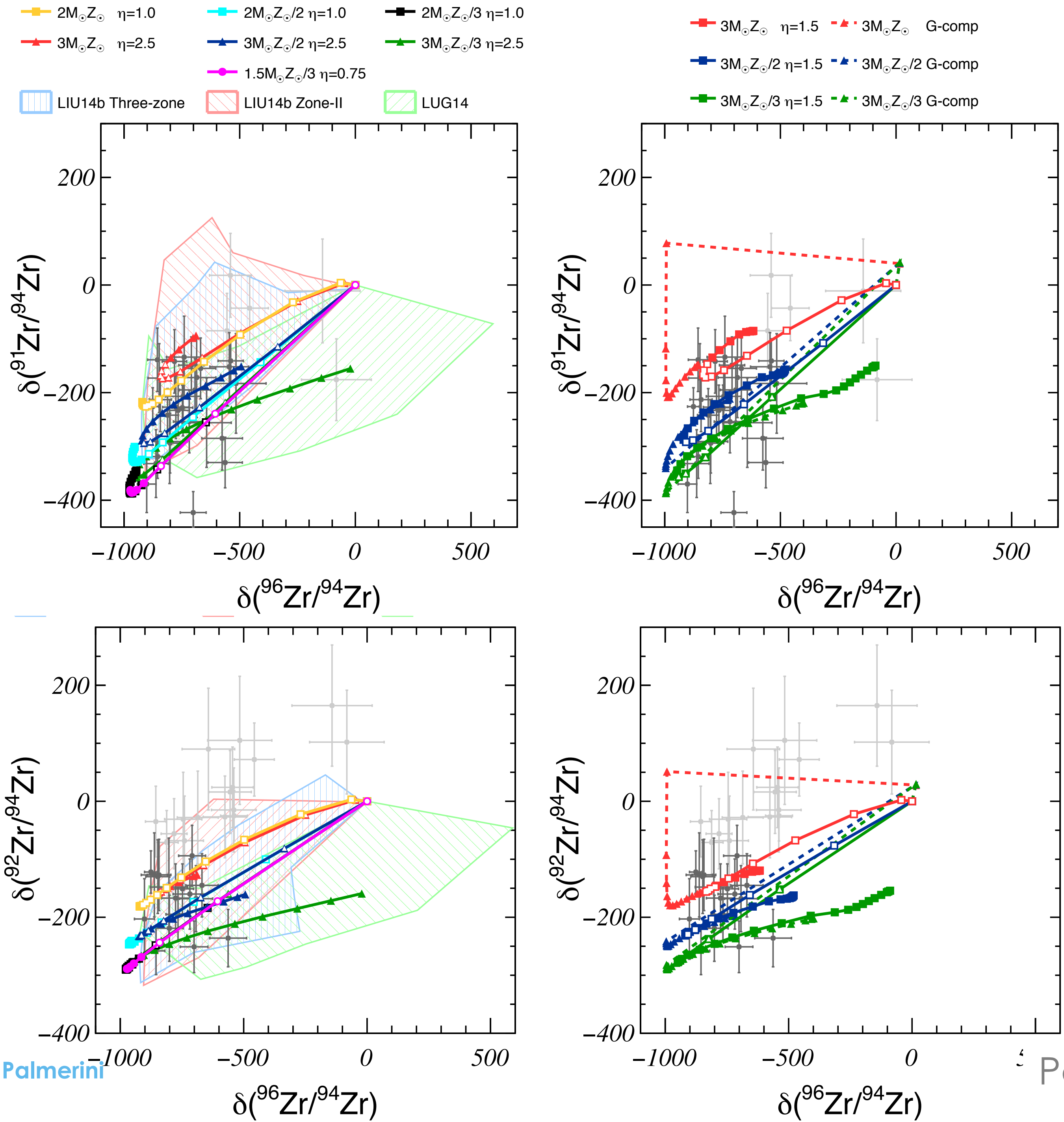
The [X(i)/Fe] abundances in a post-AGB



...without invoking free parameterizations.

A few results: Zirconium

$$\delta({}^{i}X/{}^{k}X) = \left[\frac{({}^{i}X/{}^{k}X)_{\star}}{({}^{i}X/{}^{k}X)_{\odot}} - 1\right] \times 1000$$



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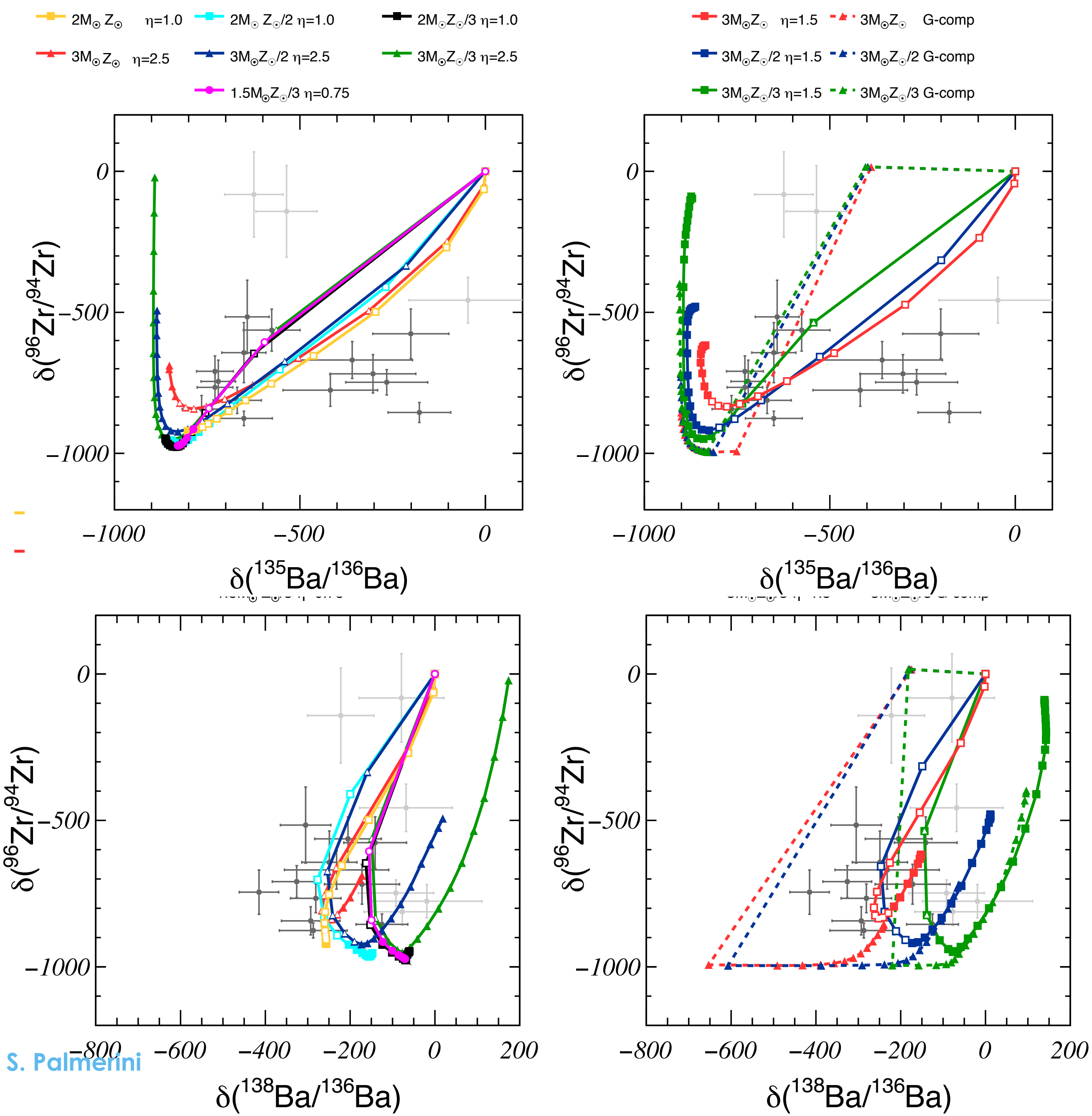
Palmerini et al. 2017b

A few results: Zirconium and Barium

$$\delta(^iX/^kX) = \left[\frac{(^iX/^kX)_\star}{(^iX/^kX)_\odot} - 1\right] \times 1000$$



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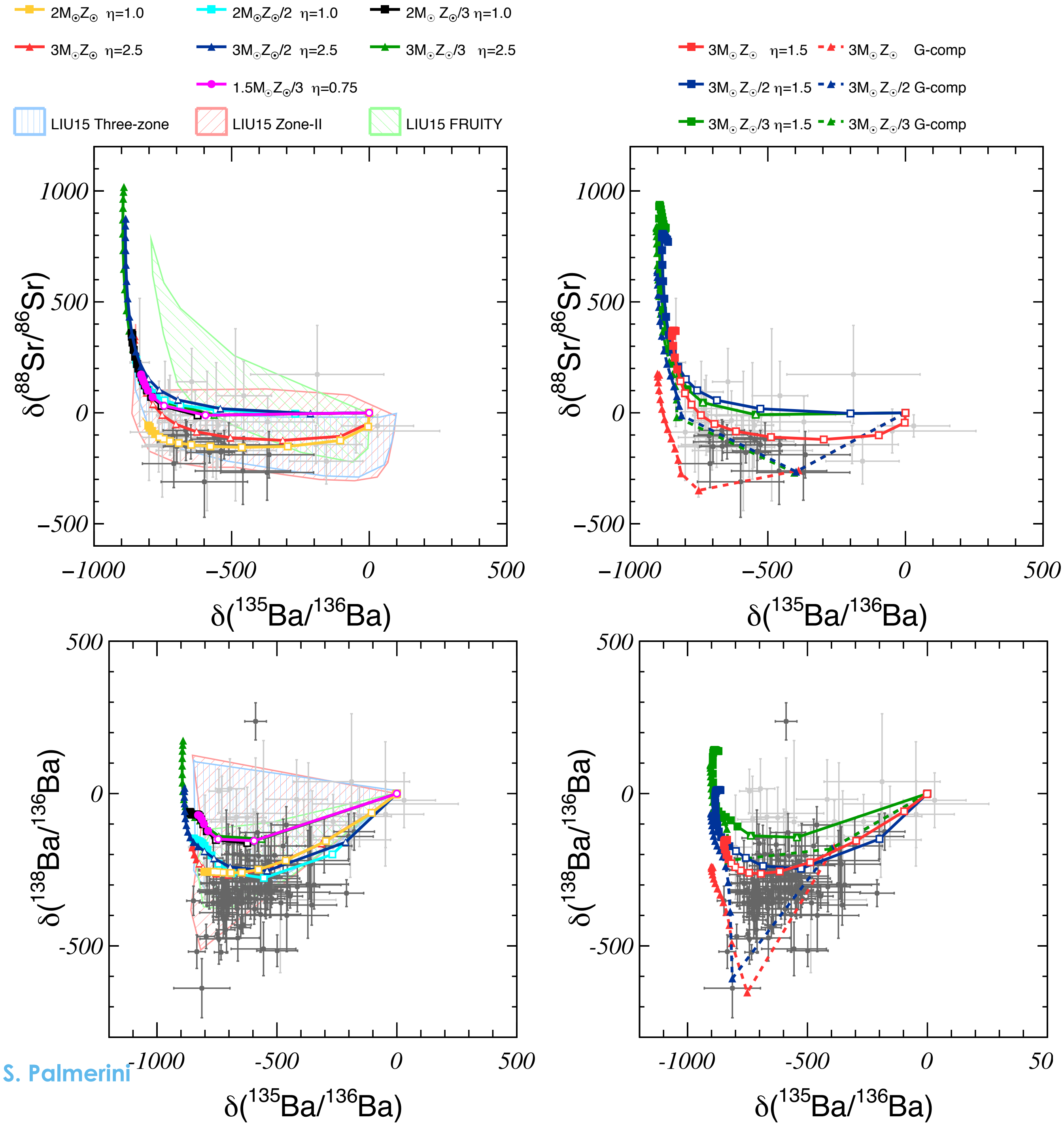
A few results: Strontium & Barium

$$\delta({}^iX/{}^kX) = \left[\frac{({}^iX/{}^kX)_\bigstar}{({}^iX/{}^kX)_\odot} - 1\right] \times 1000$$



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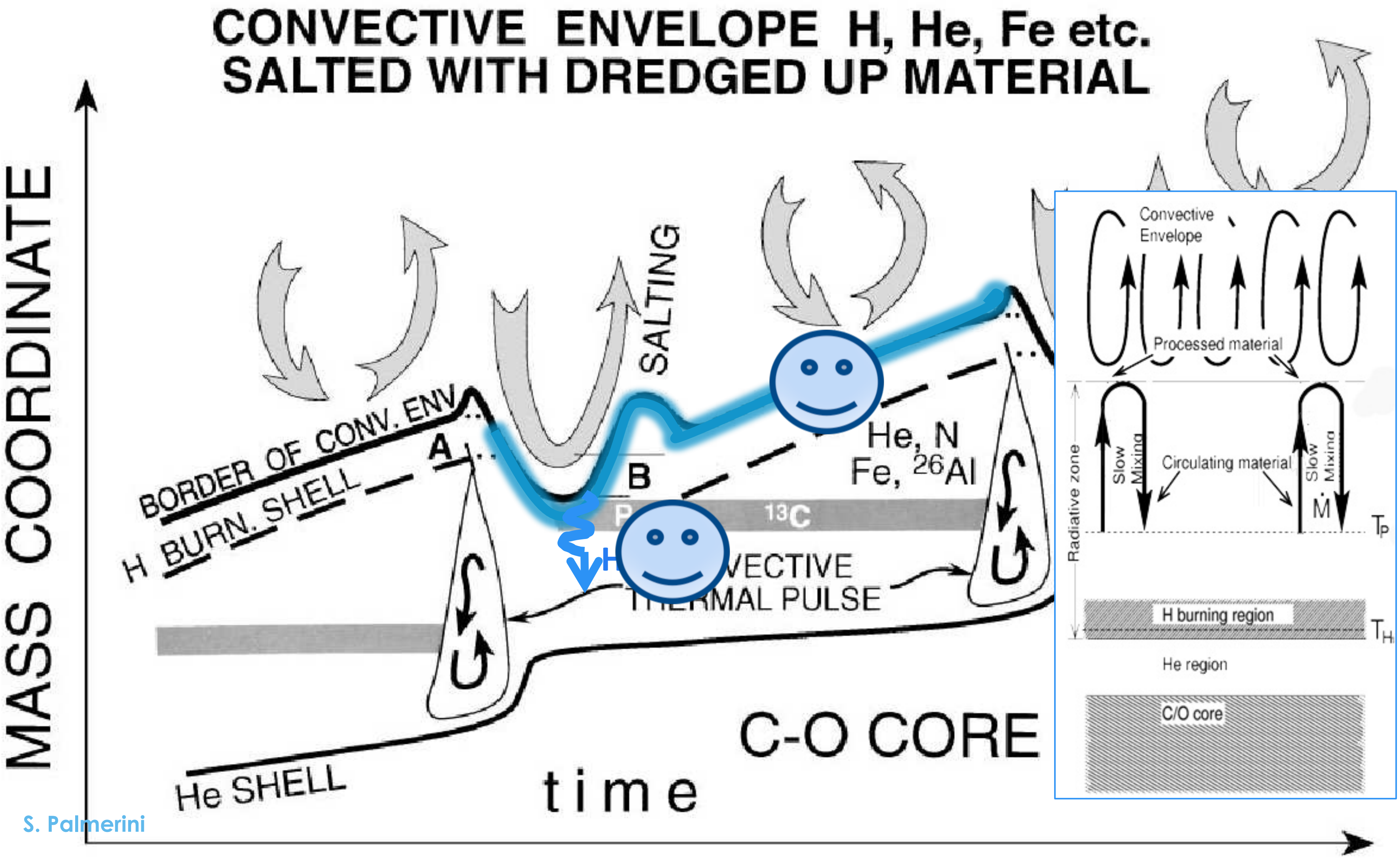
A physical mechanism that allows:



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Remarks

- ✓ Below the convective envelopes of low mass red giant stars (AGB and RGB) the exact analytical solutions of the MHD equations are held.
- ✓ The physical conditions of those regions above the H shell are such that the buoyancy of magnetized structures can occur as a natural expansion, which can drive a non-convective mixing and account for ‘anomalies’ in isotopic abundances of AGB stars and the composition of oxide grains of AGB origin, in particular.
- ✓ The same mechanism would also drive the formation of the ^{13}C-pocket.
- ✓ The MHD mixing parameters are not free but related to the intrinsic property of the stellar structure and linked to the particular polytropic transformation that best represents the thermodynamics of the environment .
- ✓ Kepler observatory demonstrated the presence of strong internal magnetic fields in a sample of low mass red giants, through their effects in suppressing dipole oscillatory modes (Fuller et al. 2015). Many of the field values inferred were in the range originally suggested to produce the required mixing (10^5 Gauss) .

Thank you!