A.D. 1308 unipg

DIPARTIMENTO
DI FISICA E GEOLOGIA

INFN PERUGIA

Nucleosintesi delle stelle AGB tra modelli idrostatici, reazioni nucleari, polveri e plasmi

Kick-off Meeting del Piano Triennale della Ricerca e Terza Missione del Dipartimento di Fisica e Geologia

10/01/2022

Sara Palmerini

Ambito di ricerca già attivato: 1
TITOLO: Astrofisica Nucleare

DESCRIZIONE: In quest'ambito viene affrontato lo studio dell'evoluzione e nucleosintesi stellare mediante lo sviluppo di modelli teorici di carattere astrofisico e lo studio sperimentale e teorico di sezioni d'urto nucleari necessari come input ai modelli. La descrizione idrodinamica alla base dei modelli sviluppati, con instabilità secolari magnetoidrodinamiche e/o doppio diffusive di tipo thermohaline mixing trova anche applicazioni in ambiti oceanografici.

Tematiche già attive:

Astrofisica Nucleare idrostatica, modelli di nucleosintesi, mescolamento e dinamica del plasma nelle fasi avanzate dell'evoluzione stellare

Misure sperimentali di sezioni d'urto di interesse per Astrofisica Nucleare (n-TOF, ERNA, ASFIN).

Analisi della composizione isotopica dei meteoriti come vincolo alla nucleosintesi stellare.

Tematiche nuove:

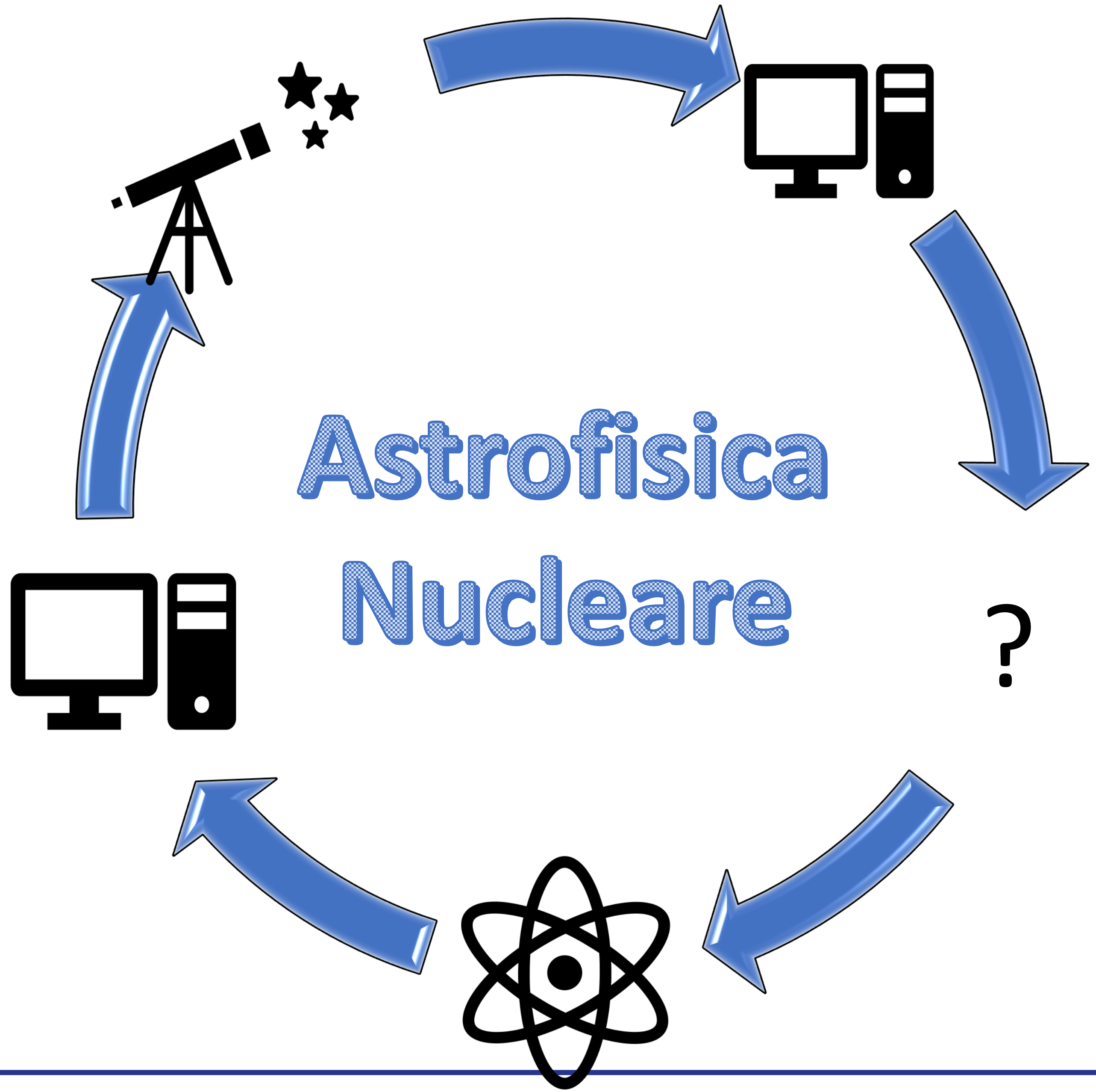
Studio delle applicazioni all'evoluzione della Galassia, con modelli chemo-dinamici multi-body ed SPH.

Studio teorico e misura sperimentale delle interazioni deboli in condizioni di ionizzazione e temperatura tipiche delle stelle (esperimento INFN PANDORA).

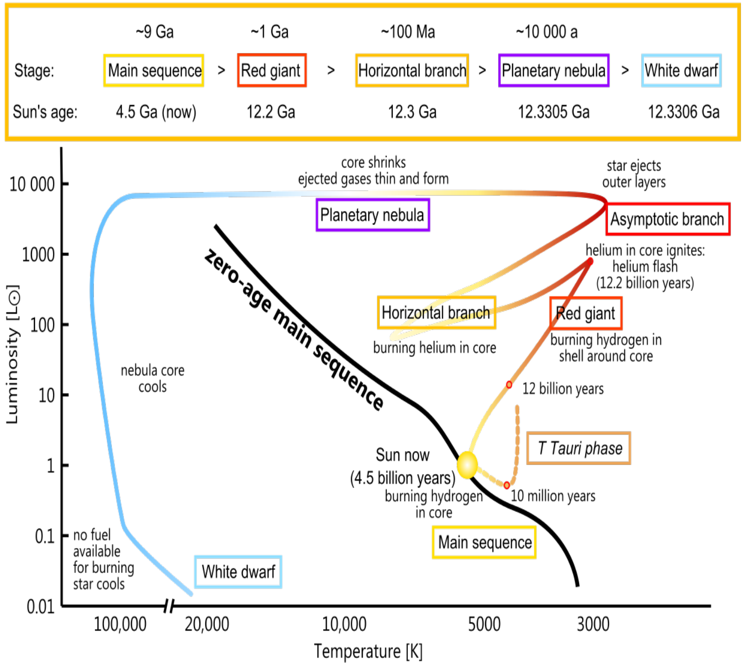
Chimica del mezzo interstellare.

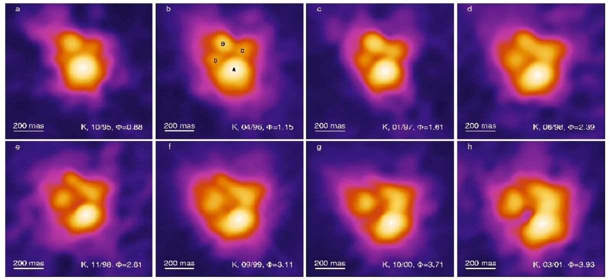
SSD: FIS/05, FIS/04, FIS/01, GEO/07, GEO/08

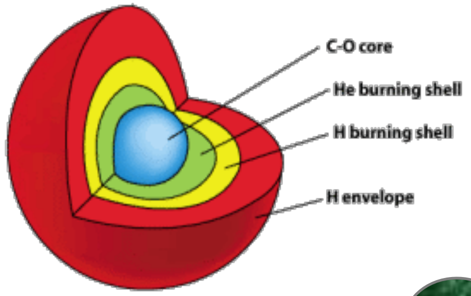
SETTORI ERC: PE2_4, PE2_3, PE2_6, PE2_5


Astrofisica
Nucleare
?

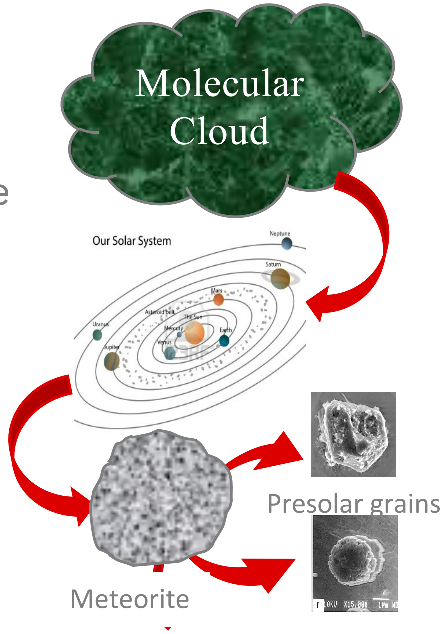
AGB STARS: A VERY BRIEF INTRODUCTION

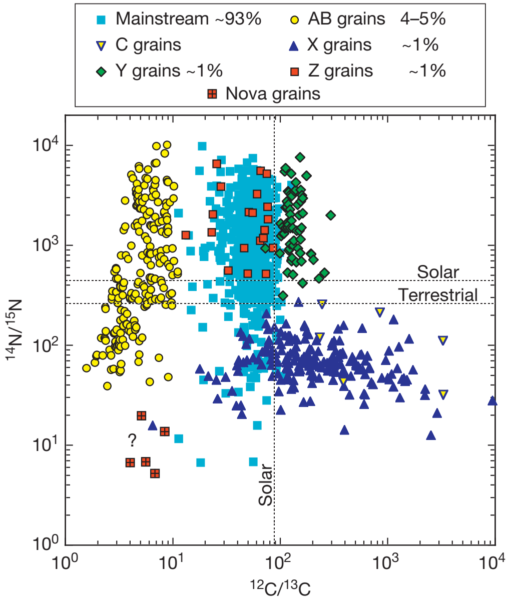


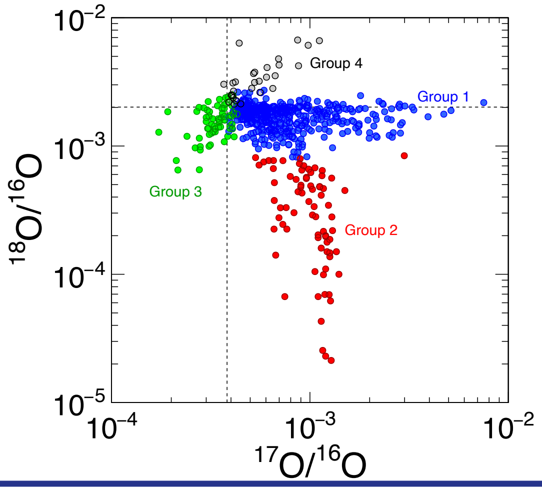




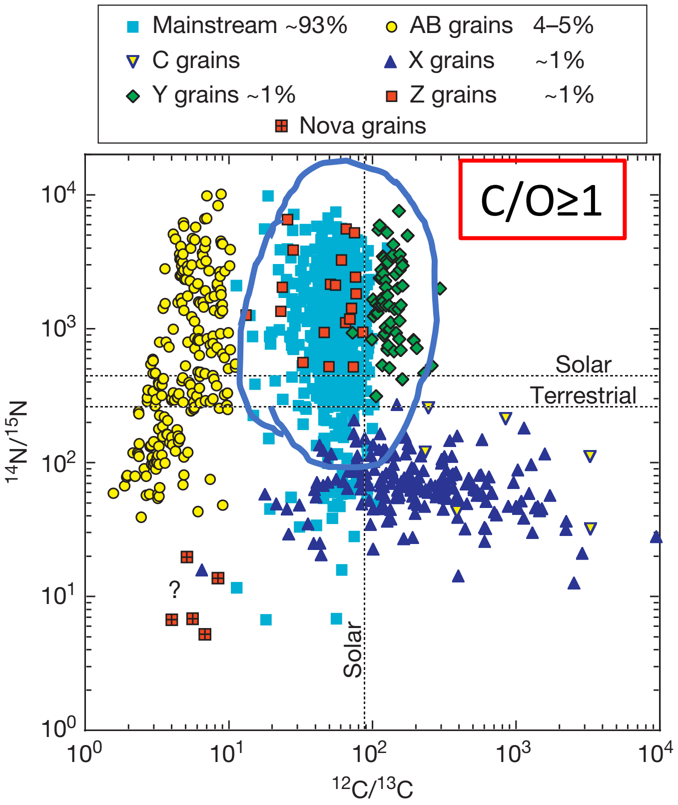
Despite their low masses LMS are so numerous to contribute for 75% to the total mass return from stars to the ISM (Sedlmayr 1994);

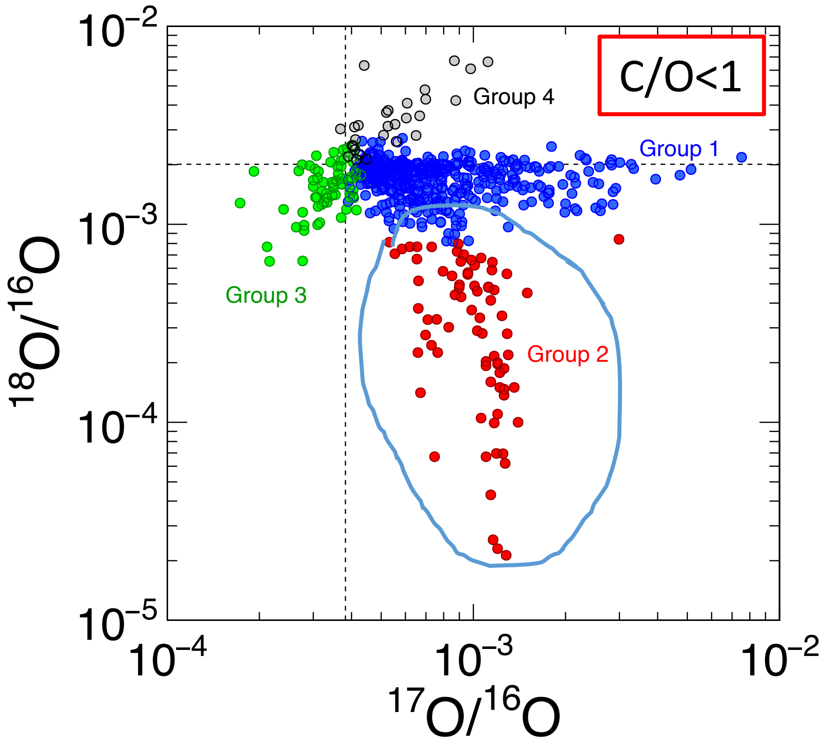






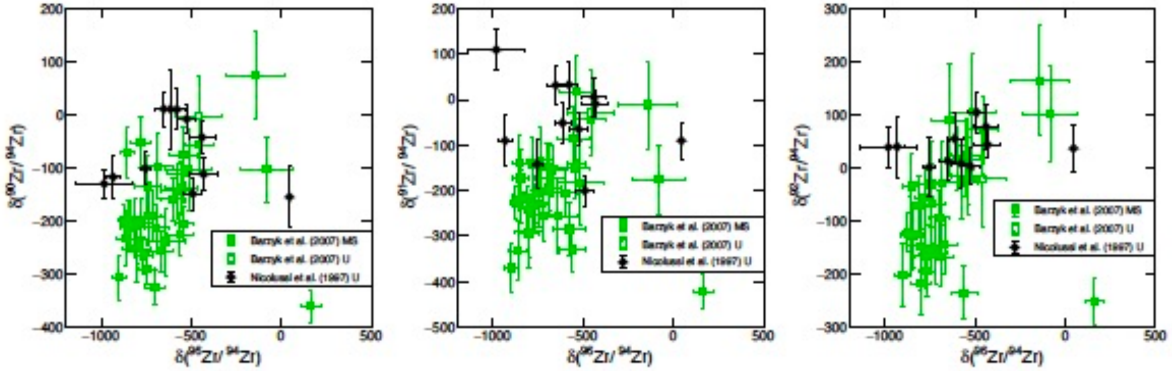
PRESOLAR GRAINS FROM AGB STARS

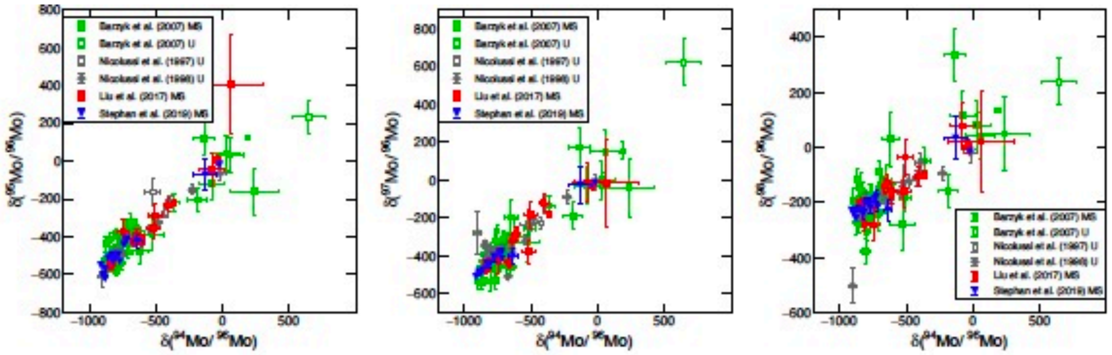


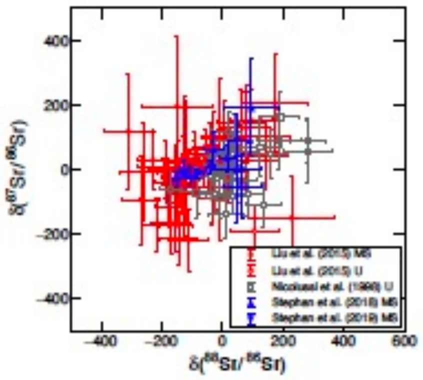


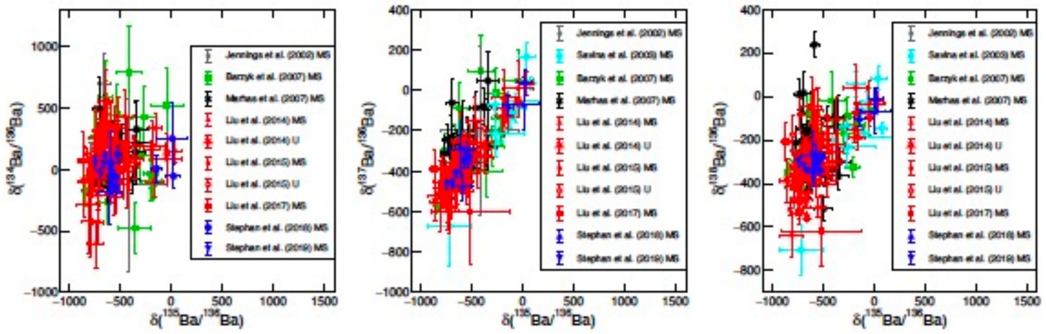
we have samples in our department too!

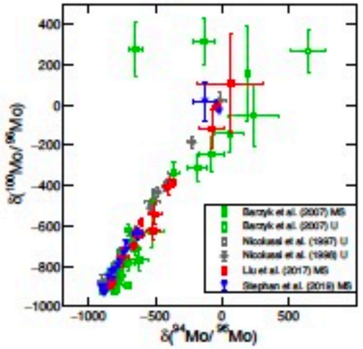
MAIN STREAM SIC GRAINS







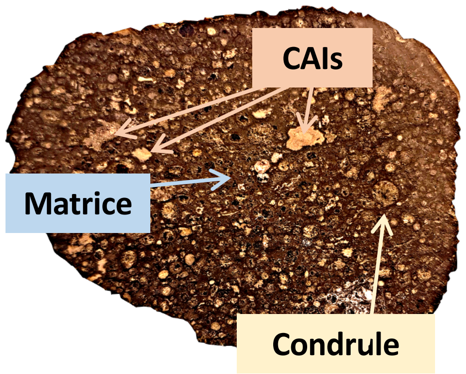




…VORREMMO DARE ANCHE IL NOSTRO CONTRIBUTO!

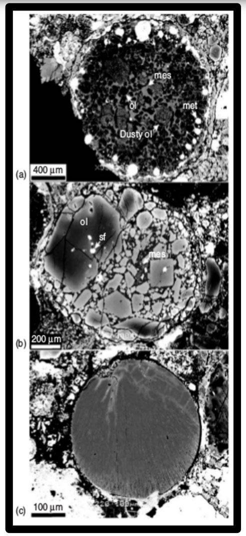
ERNA2@PG Caso scientifico

Caratterizzazione della composizione isotopica di meteoriti finalizzata alla determinazione di vincoli per i modelli di nucleosintesi

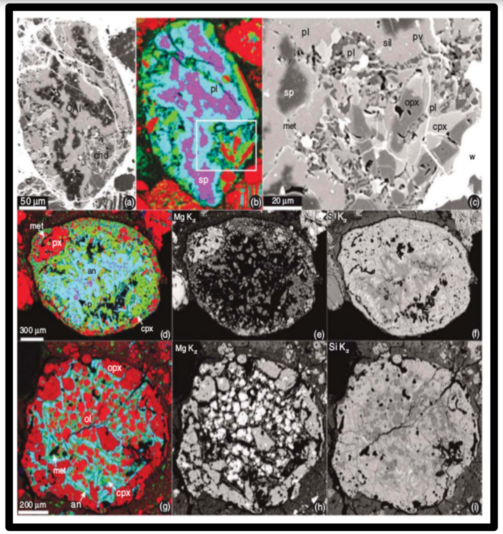


Meteoriti primitive: **Condriti**

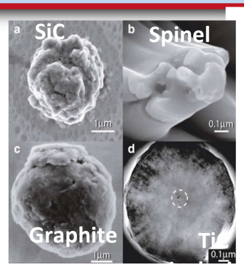
Condrule



CAIs dentro le condrule

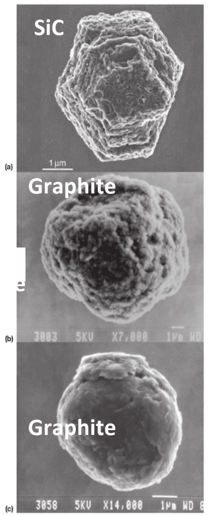


Grani presolari



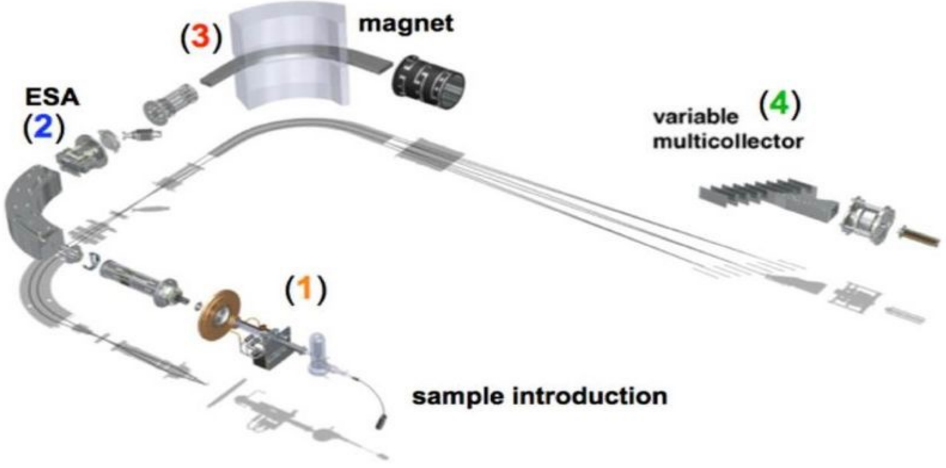
Nittler (2003)

Lodders and Amari (2005)



Zinner (2014)

Evaluation of Ni/Fe isotopic ratios by MC-ICPMS @ CIRCE lab

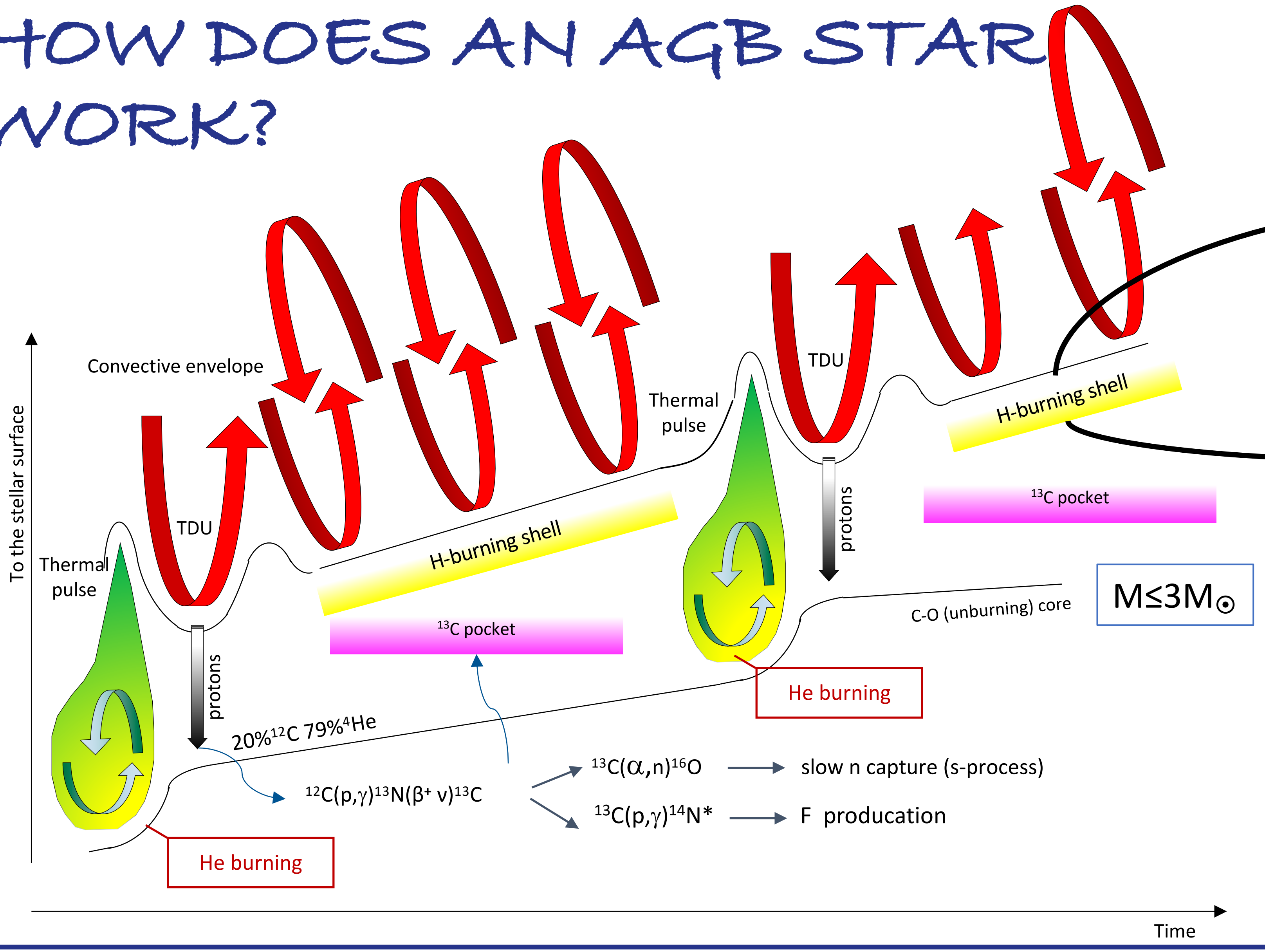


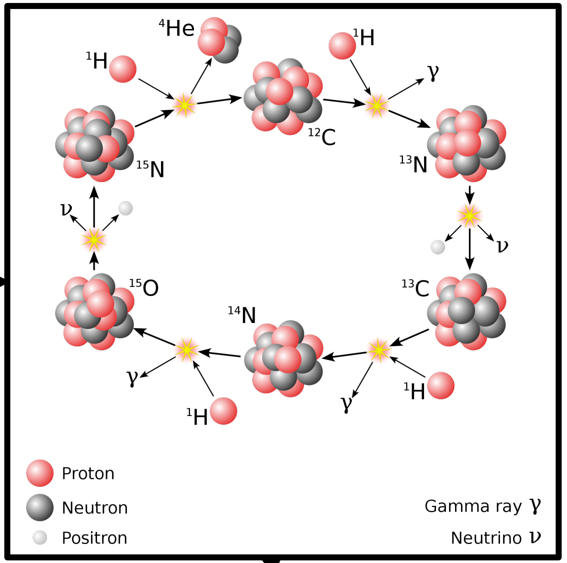
- ✓ 2018-2019 Messa a punto della metodica di separazione chimica del campione
- ✓ 2019 Misura rapporti isotopici del Ni (d^{60}Ni) su campioni di Pallasiti
- ✓ 2020 Misura rapporti isotopici del Fe (d^{60}Ni) su campioni di Pallasiti

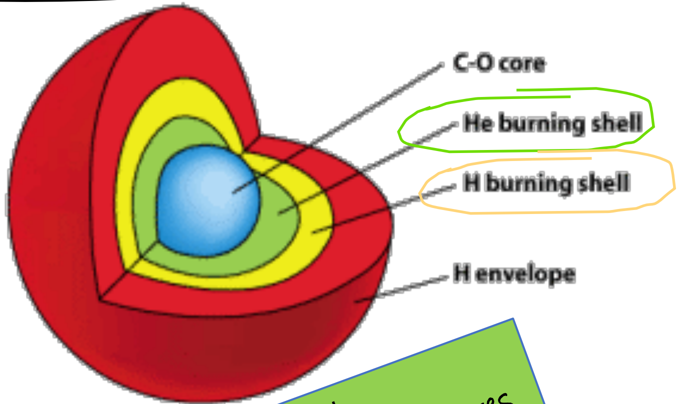
	$\delta\,^{60}$Ni (‰)	unc (‰)
Brenham	0.9	0.1
Mineo	0.5	0.3

Le prime misure di Fe/Ni mostrano contaminazioni Fe più alte della media solare. Sono in corso ulteriori analisi per le misurazioni del rapporto isotopico Fe .

HOW DOES AN AGB STAR WORK?

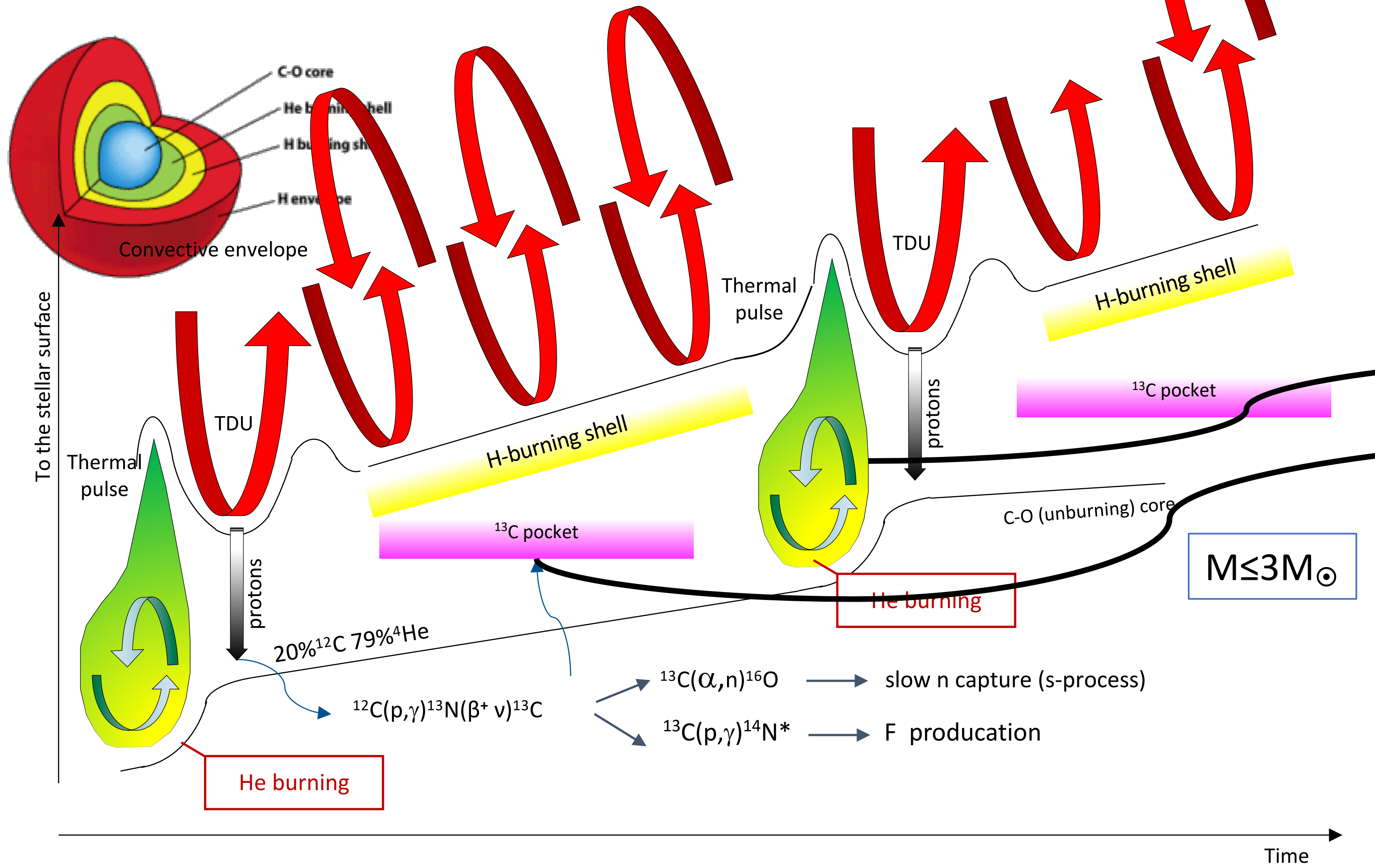


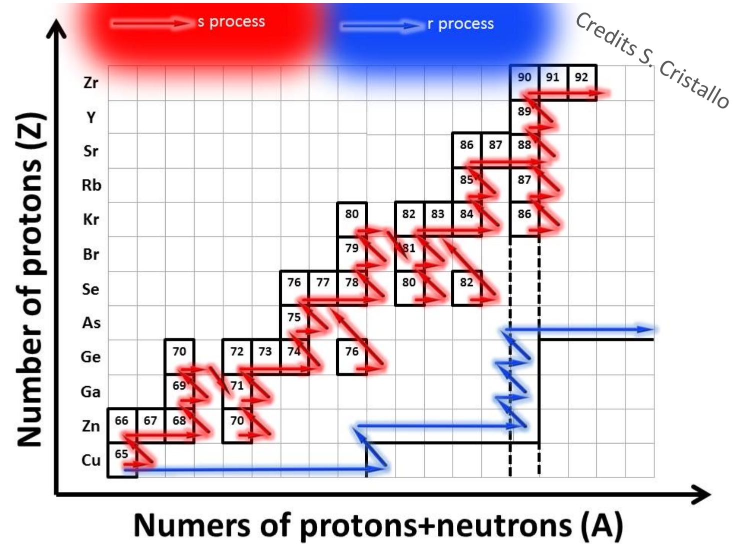


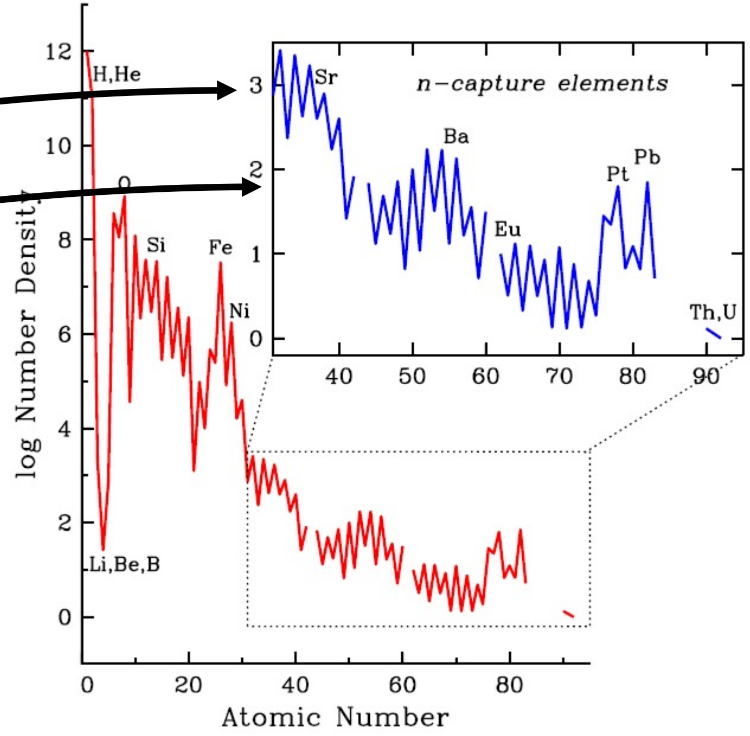


+ slow neutron captures s-process

HOW DOES AN AGB STAR WORK?





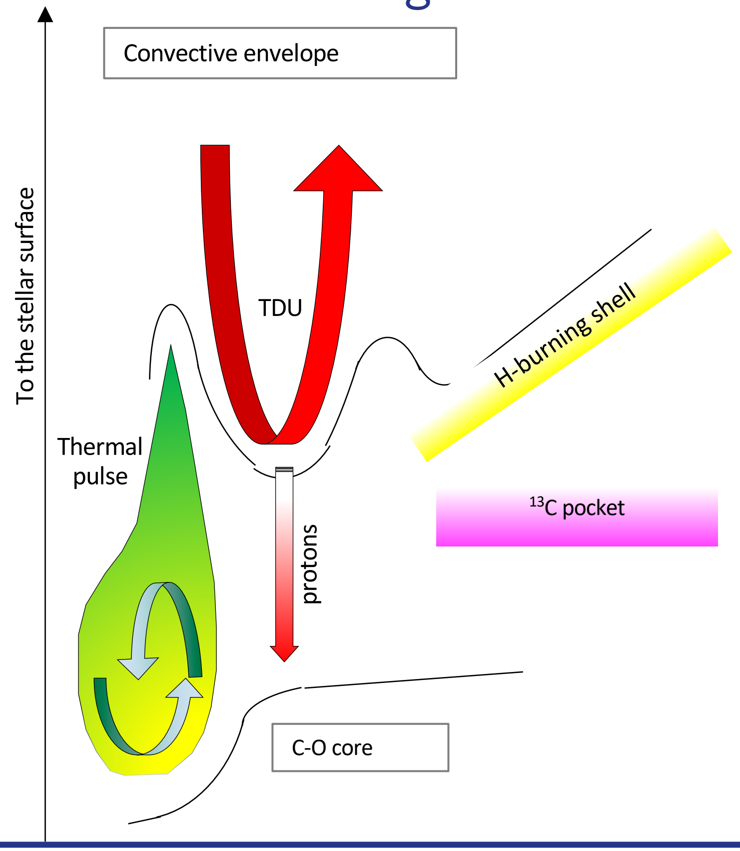


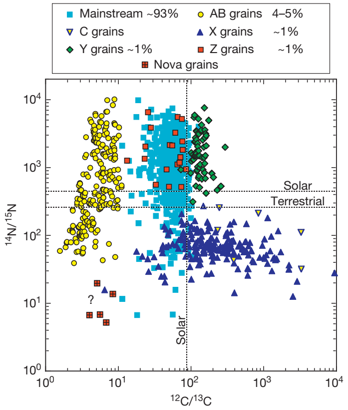
WE ARE LOOKING FOR A PHYSICAL MECHANISM DRIVING...

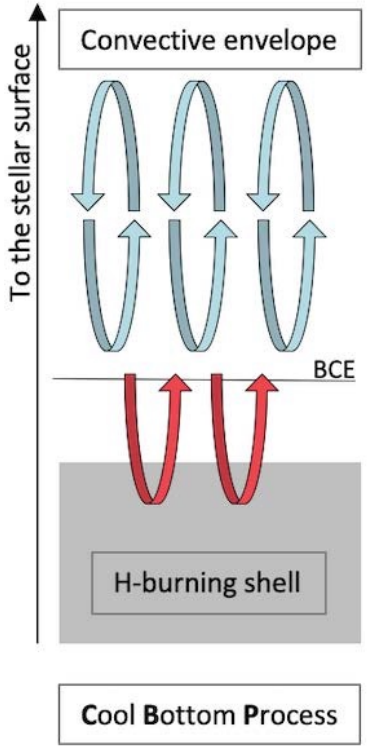
1. the formation of the ^{13}C pocket,

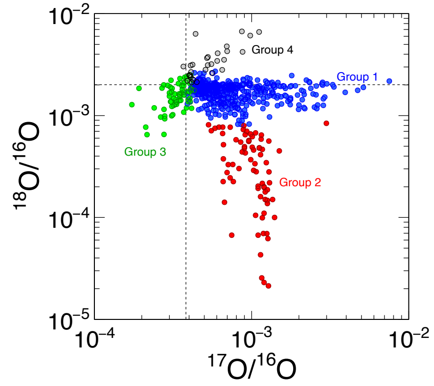
whose resulting s-process nucleosynthesis reproduces the isotopic abundances in MS-SiC grains

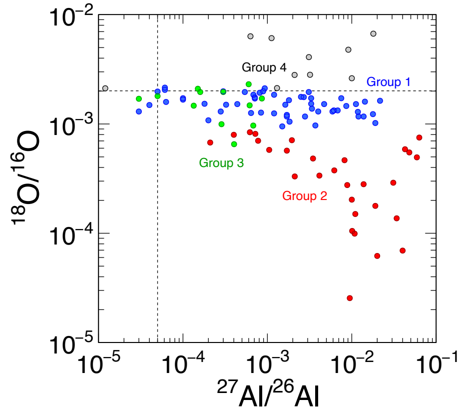
2. a deep (non convective) mixing accounting for the large ^{18}O depletion and ^{26}Al enrichment found in group 2 oxide grains











MIGHT STELLAR MAGNETIC FIELDS TRIGGER SUCH A MIXING?

THE MHD MODEL BY NUCCI & BUSSO 2014 (APJ,787,141 2014)

The full MHD equations

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

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

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

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

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

Their “simple” analytical solution

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

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

THE MHD MODEL BY NUCCI & BUSSO 2014 (ApJ,787,141 2014)

whenever a set of three peculiar situations occurs:

1. the plasma density distribution has the simple form $\rho \propto r^k$, with k is smaller than -1;
2. a small dynamic viscosity μ;
3. Magnetic Prandtl number $P_m >> 1$

The full MHD equations

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

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

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

$$\nabla \cdot \mathbf{B} = 0 \tag{4}$$

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

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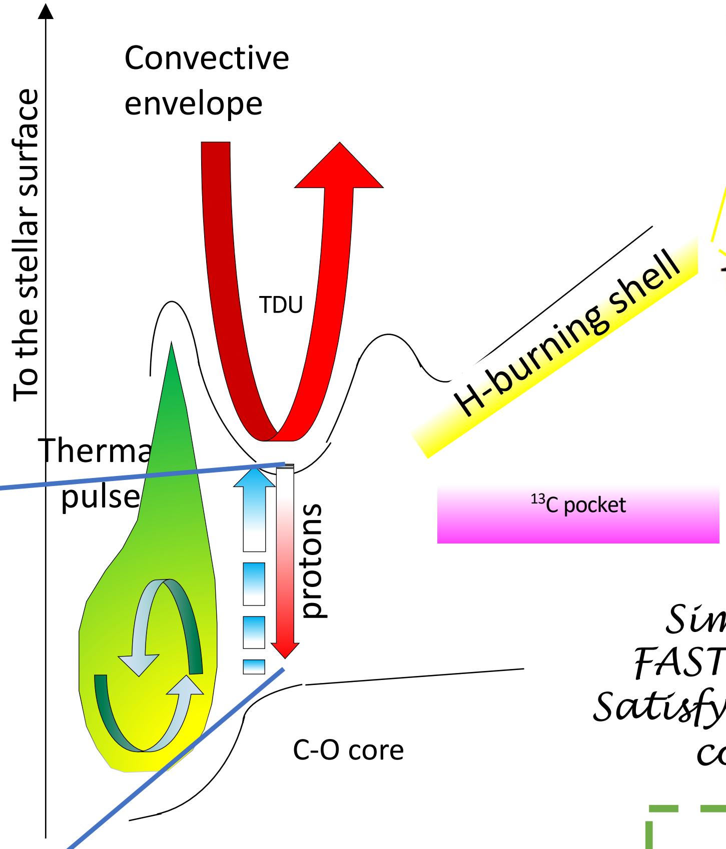
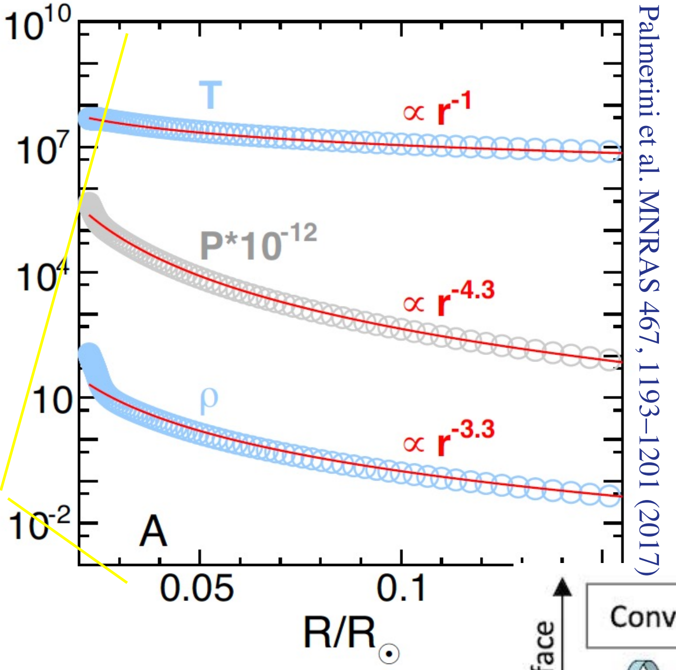
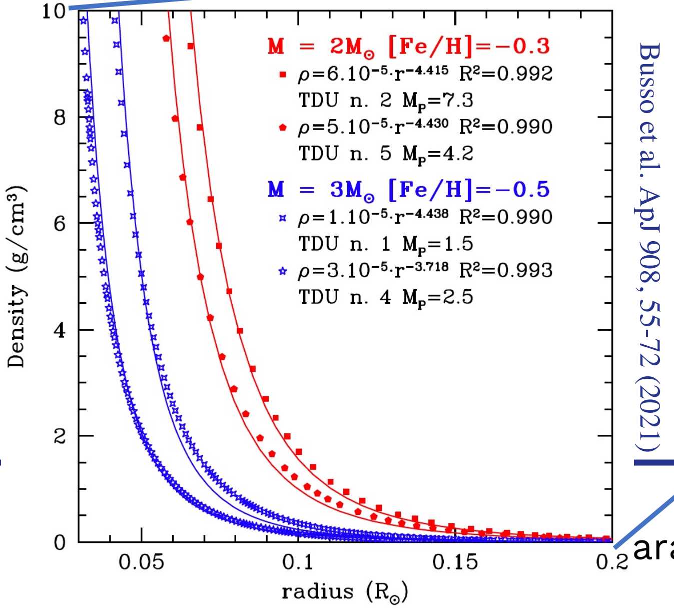
MAGNETIC EXTRA- MIXING AND THE ^{13}C-POCKET FORMATION

- ✓ N&B conditions are satisfied;
- ✓ the exact analytical solutions of the MHD equations are held;
- ✓ the formation of ^{13}C-pocket is allowed
- ✓ an advective mixing occurs from the H-burning shell to the BCE

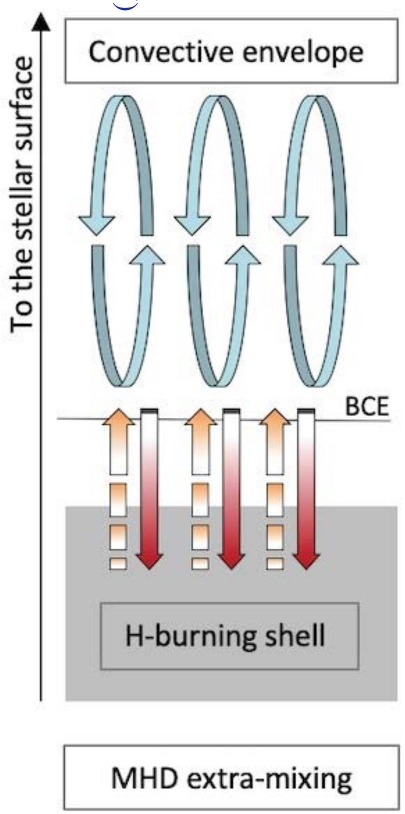




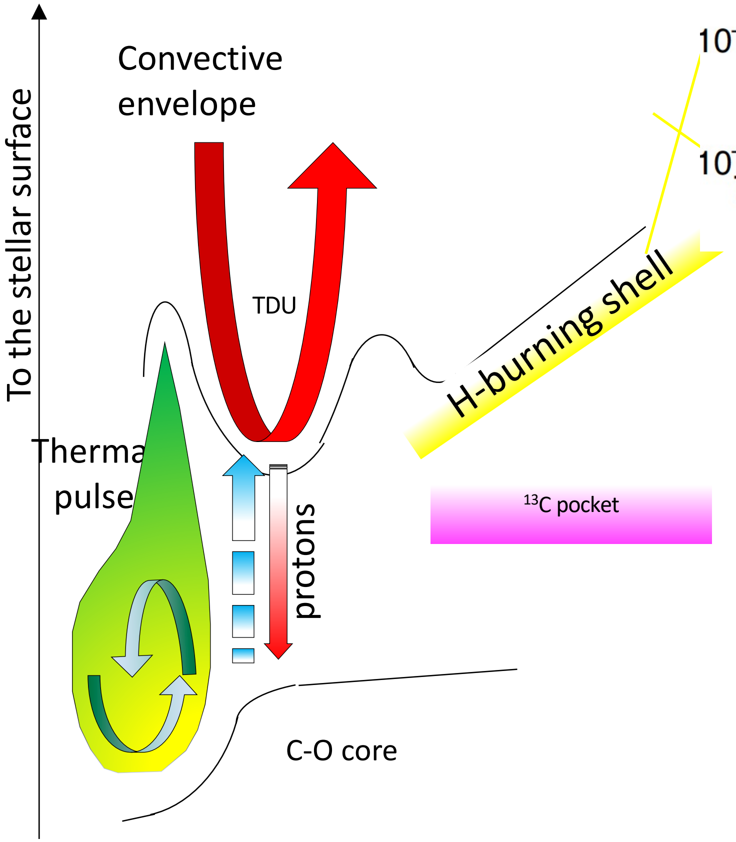


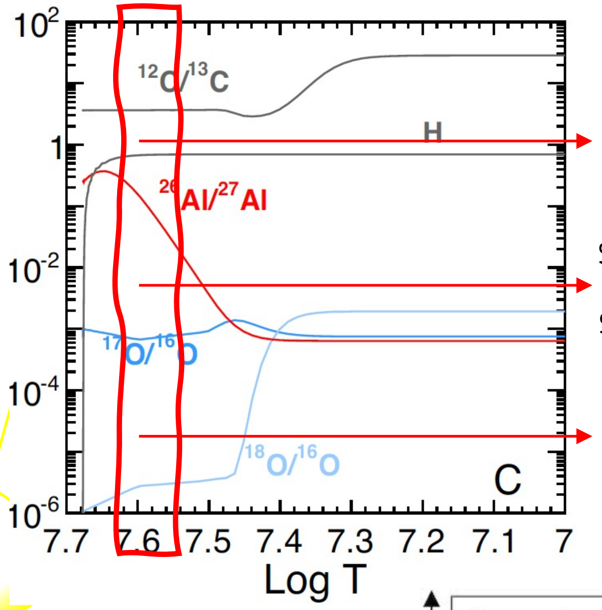
Simplest and FASTEST solution Satisfying boundary conditions

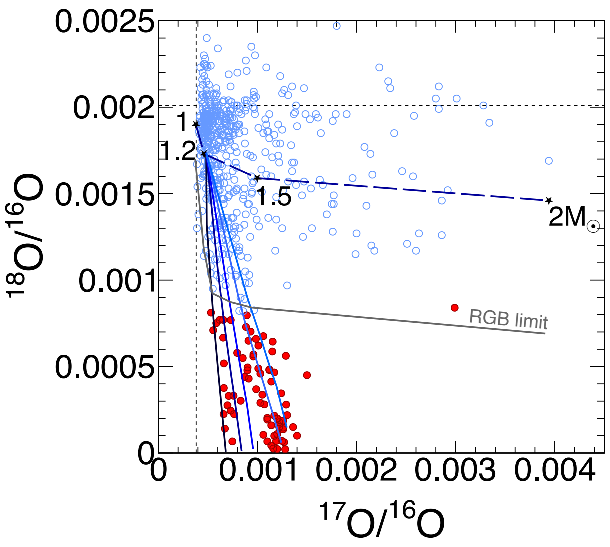
$$v_r = v_P \left(\frac{r_P}{r} \right)^{-(k+1)}$$

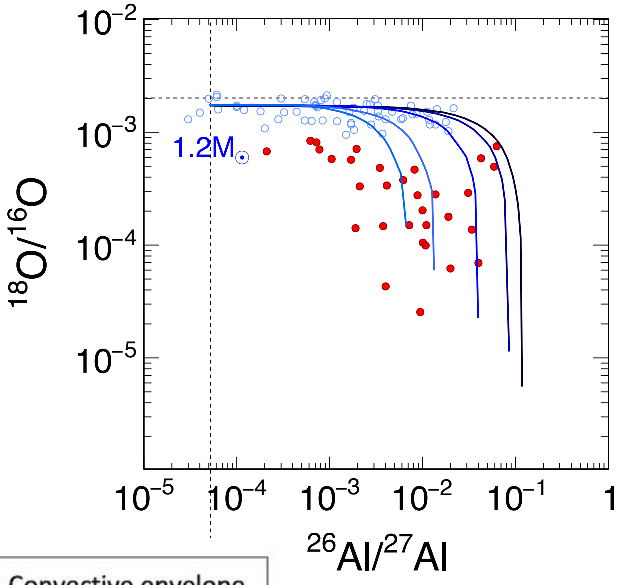


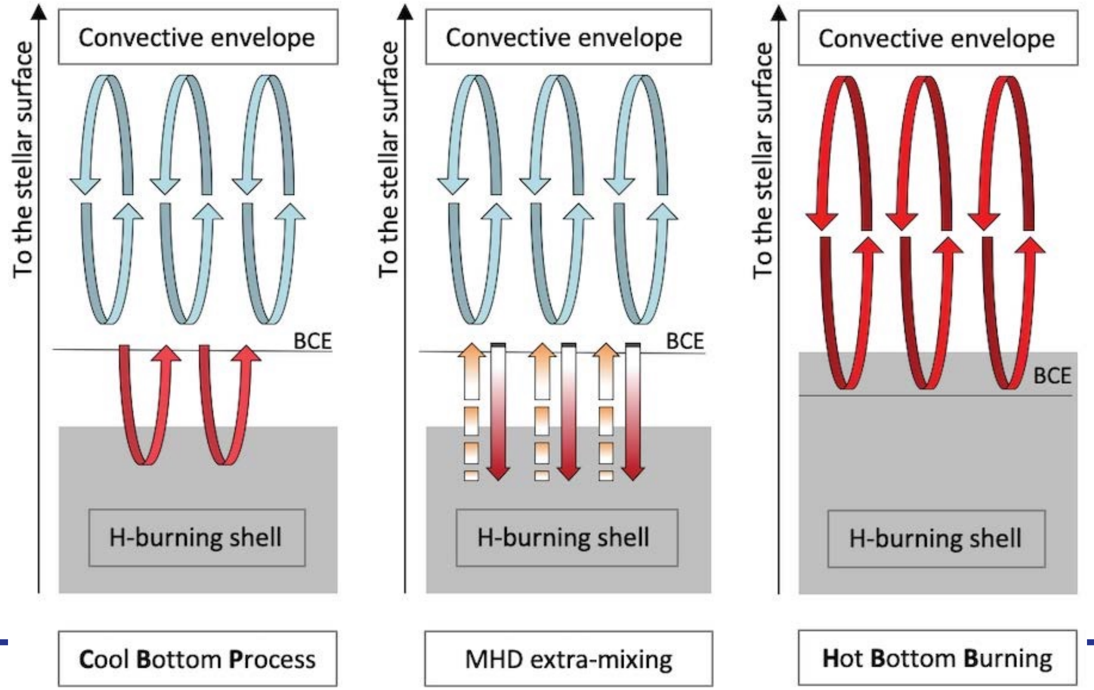
MAGNETIC EXTRA-MIXING









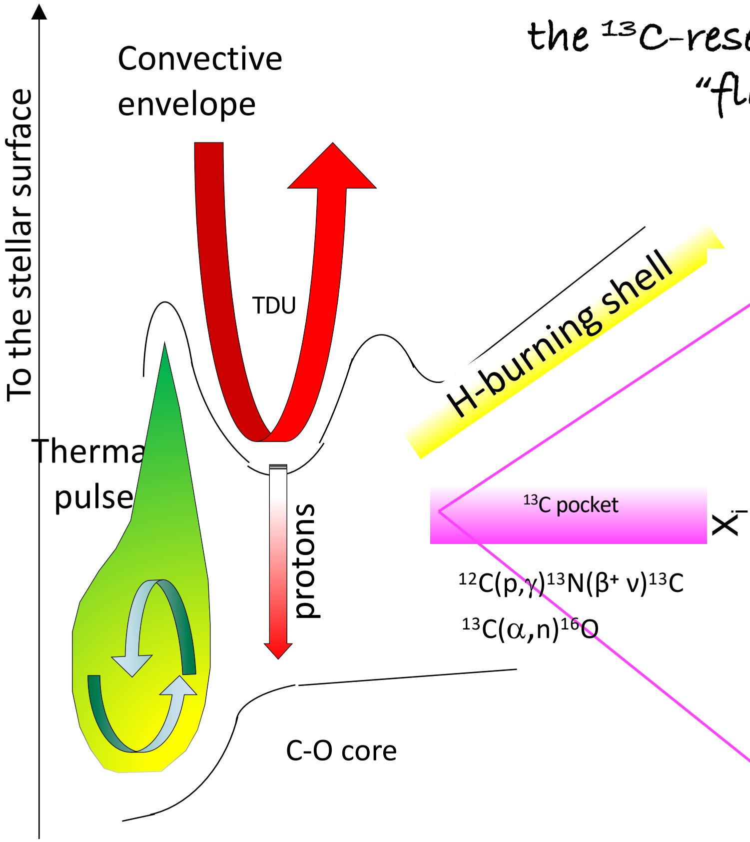


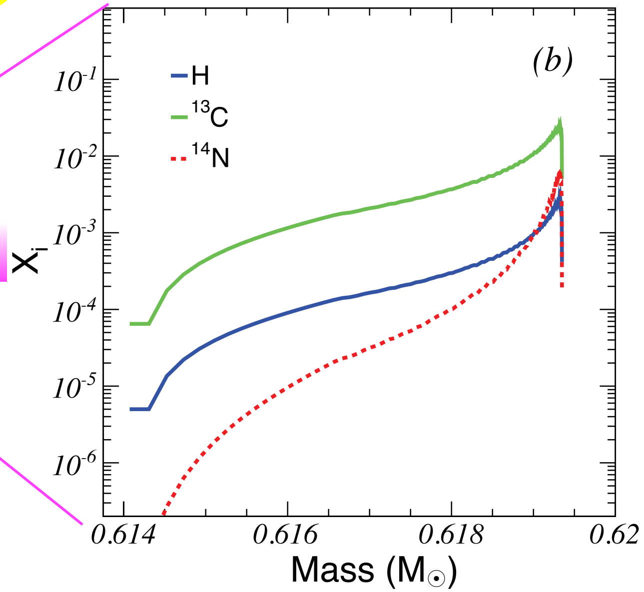
Low mass AGB stars | Low mass AGB stars | Intermediate mass AGB stars

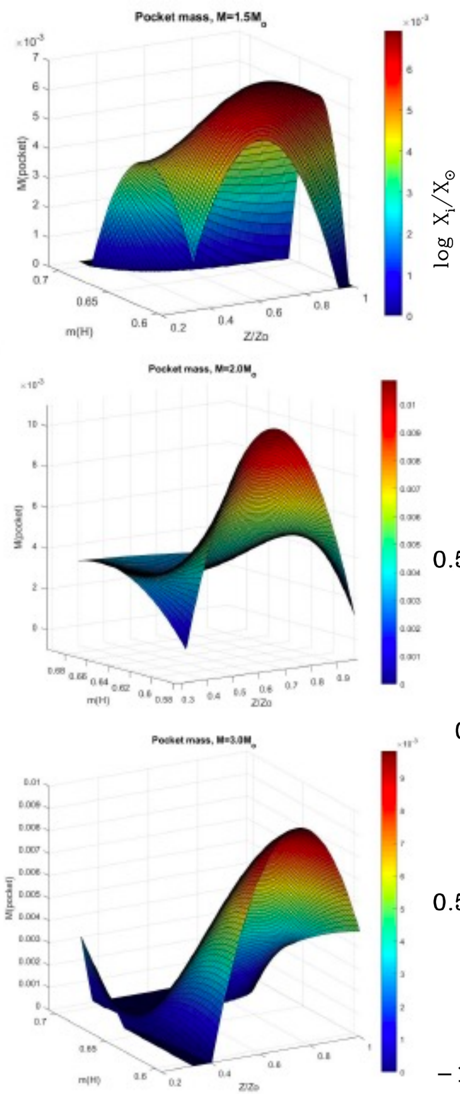
MAGNETIC ^{13}C-POCKET

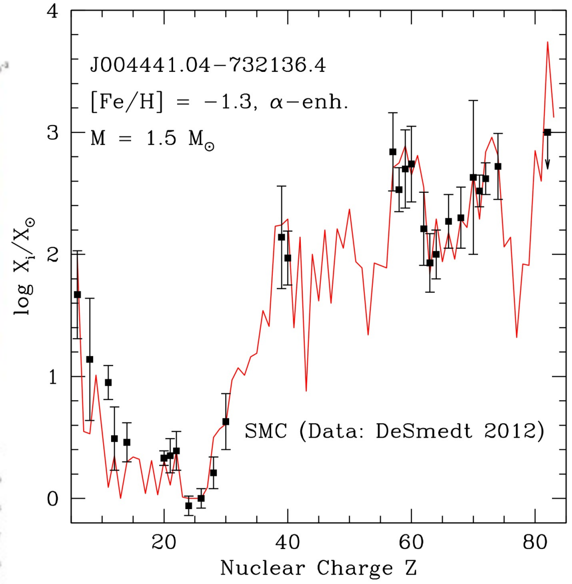
the ^{13}C-reservoir formed is an almost "flat" pocket of about

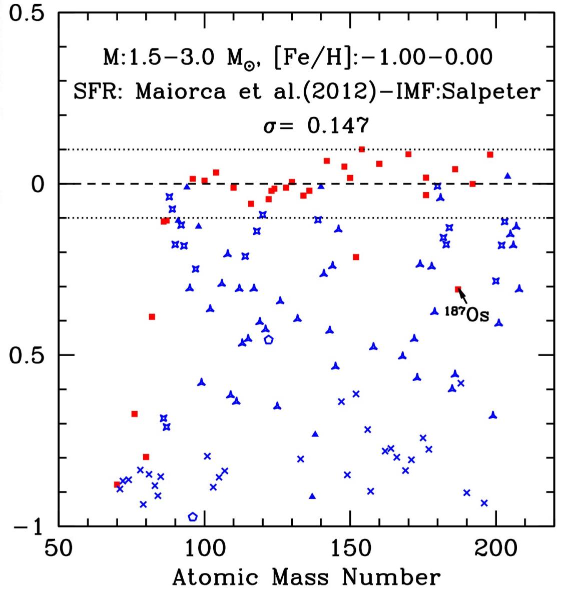
5×10^{-3} M$_\odot$





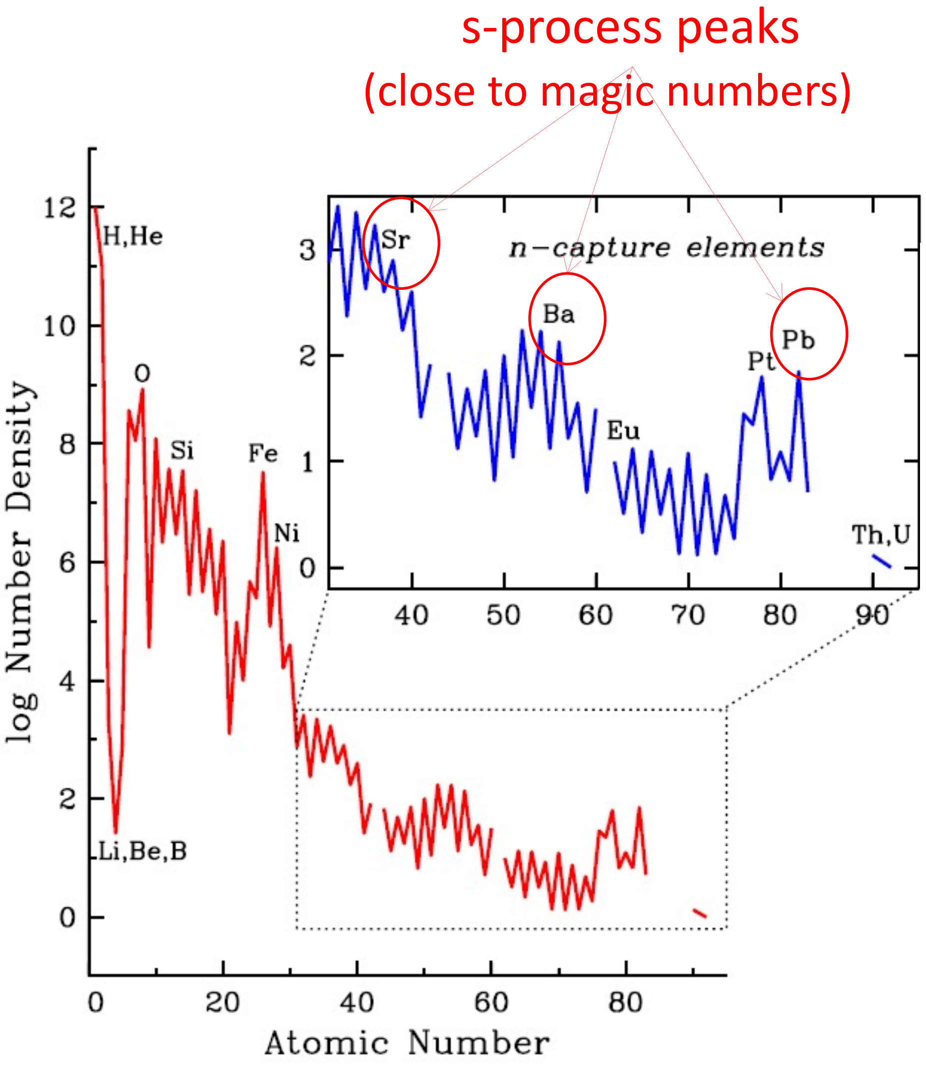


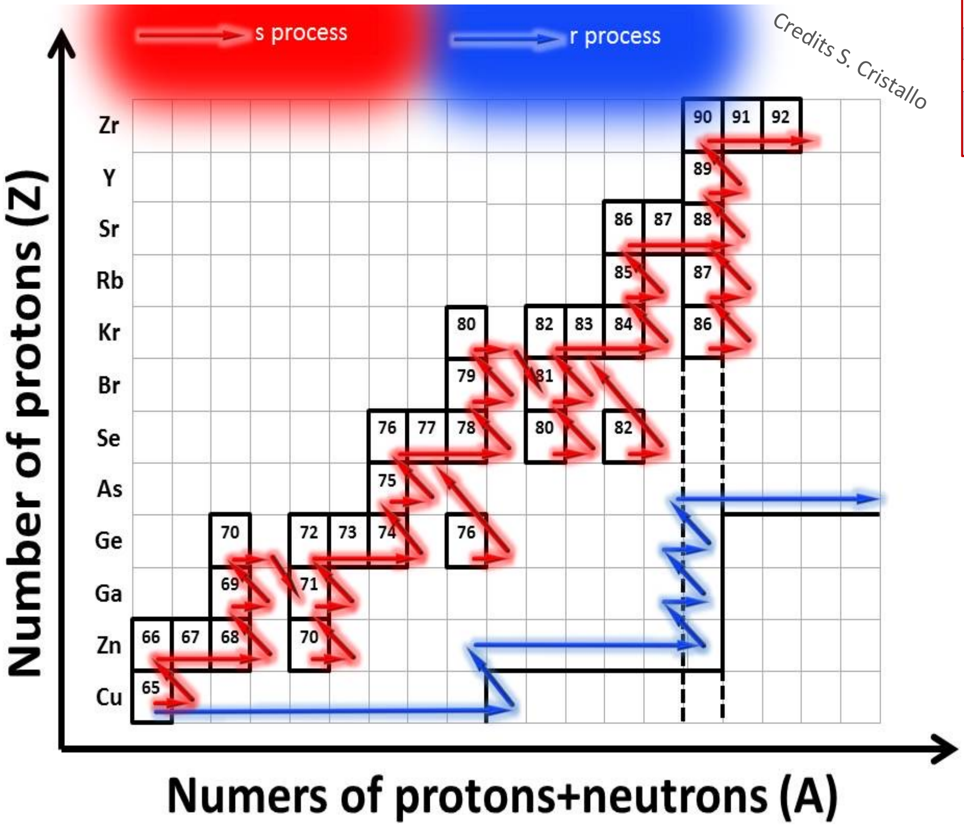




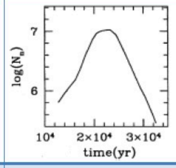
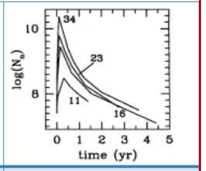
THE SLOW NEUTRON-CAPTURE PROCESS

The s process is responsible for the production of about half the abundances of elements heavier than iron in the Galaxy.

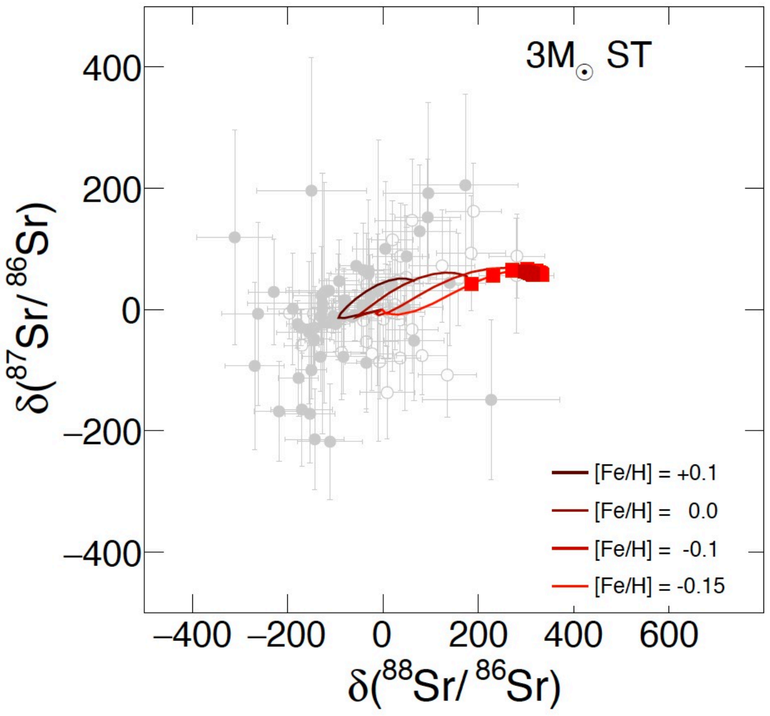


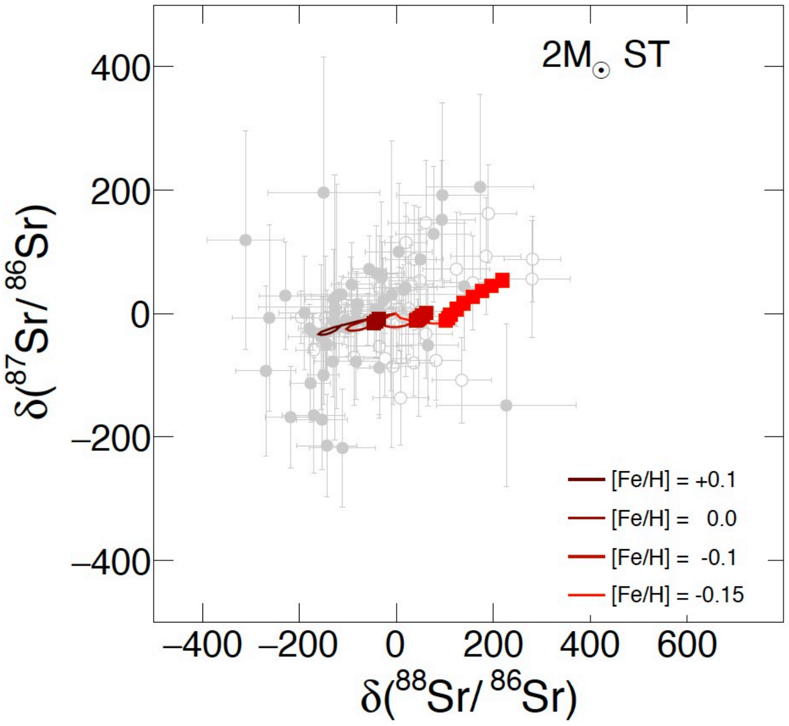


Neutron sources in AGB stars

Typical neutron density profile in time:		
Neutron source	$^{13}C(\alpha,n)^{16}O$	$^{22}Ne(\alpha,n)^{25}Mg$
Activation	Interpulse phase (radiative conditions) $T \cong 10^8$ K	Thermal pulse (convective conditions) $T \gtrsim 2.5\ 10^8$ K
Timescale	10^4 yr	10 yr
Neutron exposure	0.3 $mbarn^{-1}$	0.02 $mbarn^{-1}$
Note	It is the MAIN neutron source	Important for key branching points (e.g. ^{87}Rb and ^{96}Zr production)

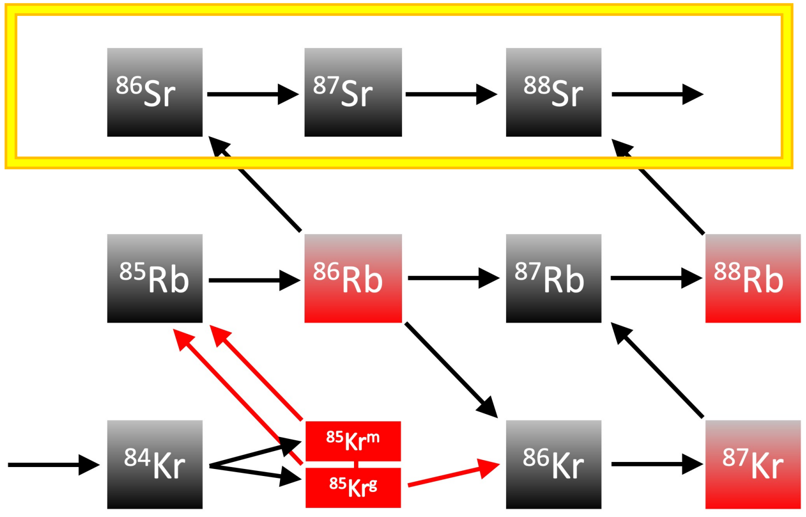
The ^{85}Kr Branching…around N = 50





ST nuclear input

- (n,γ) MACS are from KADONIS 1.0
- (n,γ) theoretical Hauser–Feshbach computations TALYS 2008 for unstable nuclei
- rates for weak interactions from Takahashi & Yokoi (1987)

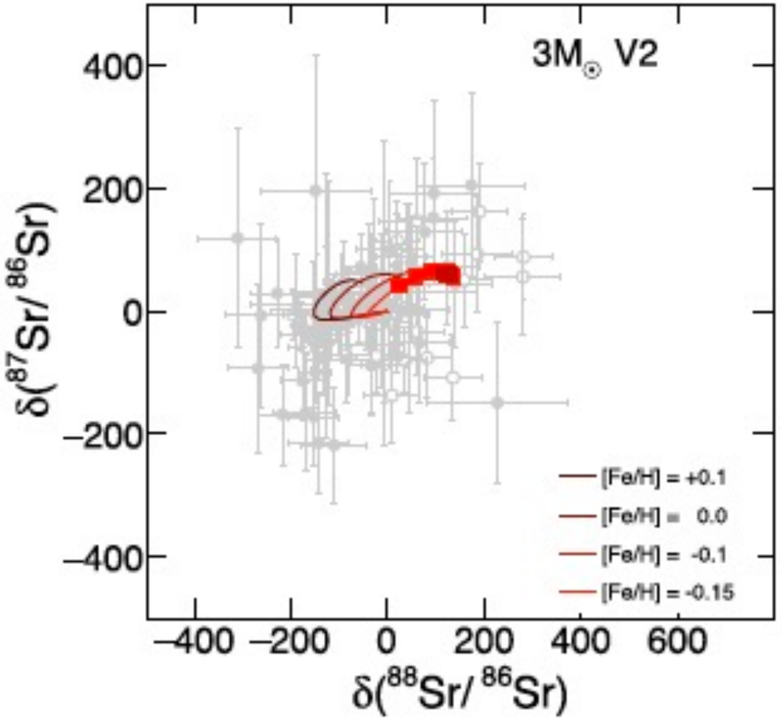


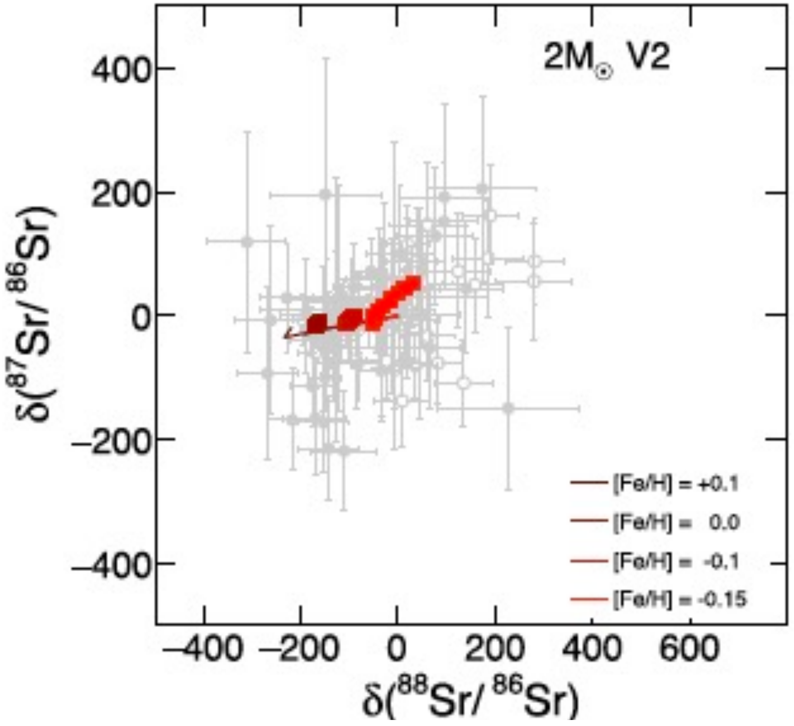
The ^{85}Kr Branching…around N = 50

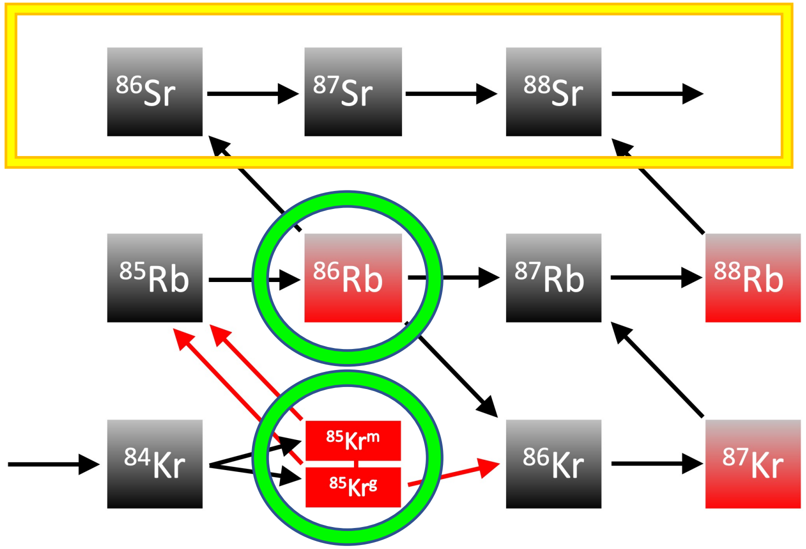
the ratio of Sr isotopes depends on their own cross sections, but also on those of ^{84,85}Kr, on the branching ratio to ^{85}Kr^{m}
→ We NEED new nuclear physics measurements on the chains departing from ^{84}Kr , proceeding through ^{85}Kr^{m}, ^{85}Rb, ^{86}Rb and ^{86,87}Sr.

V2 nuclear input

- ^{85}Kr b.r. = 0. 6, (60% of the n flux to the ^{85}Kr^{m}) K1
- ^{85}Kr b.r. = 0.4, (40% of the n flux to the ^{85}Kr^{m}) K0.3 -> more ^{88}Sr
- Same effect occurs with the ^{84}Kr(n,γ) in K1 and a «new» ^{85}Kr^{m} decay rate

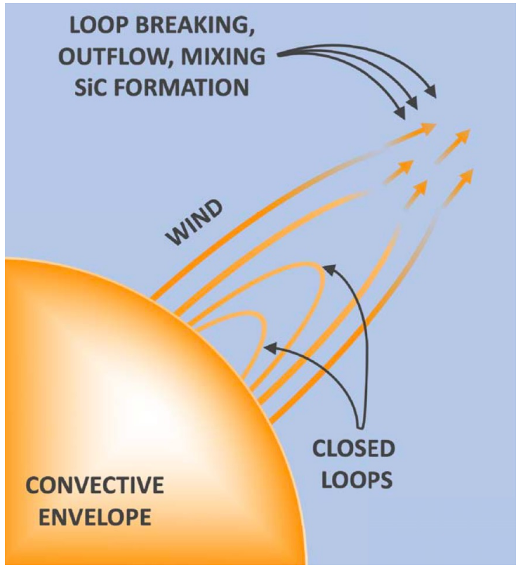


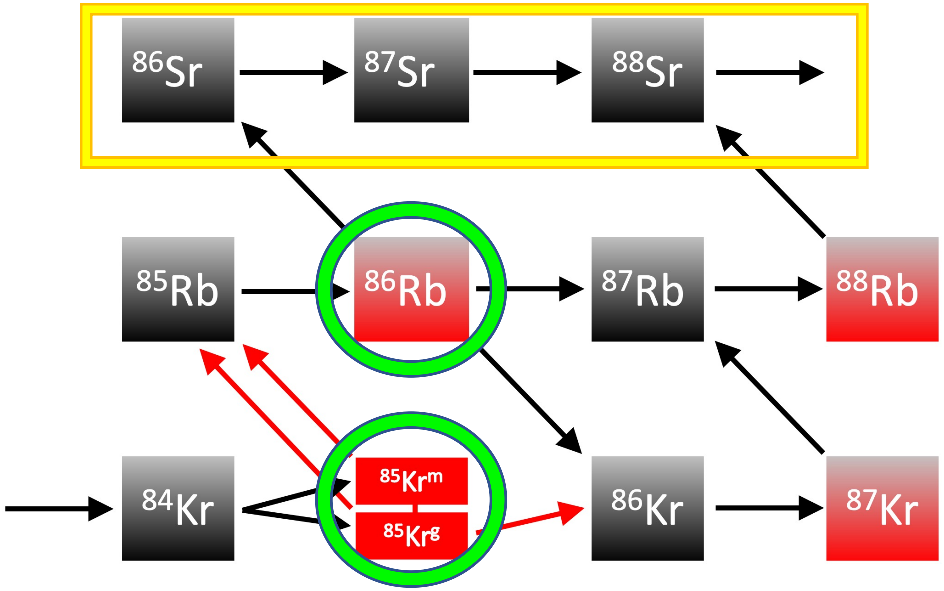


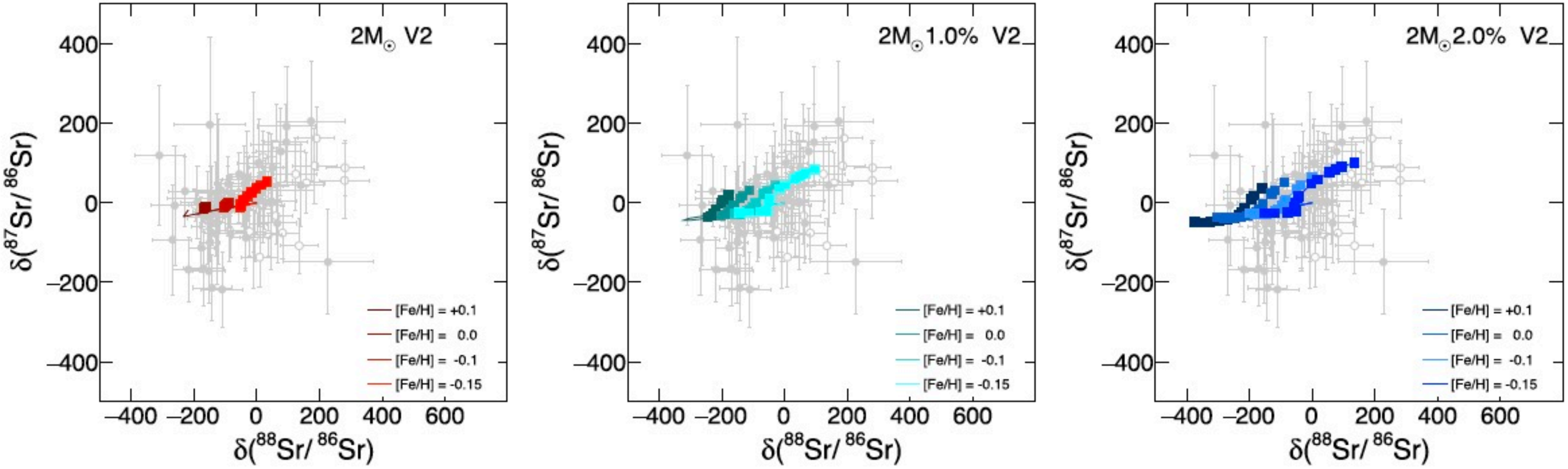


ADDING "WIND"

The advection of magnetic bubble in the stellar envelope may allow the existence of C-rich domains, isolated by magnetic tension, even when the average envelop composition is still O-rich.







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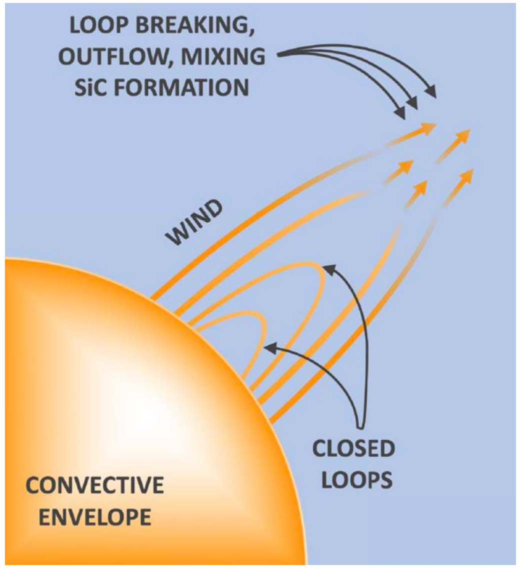
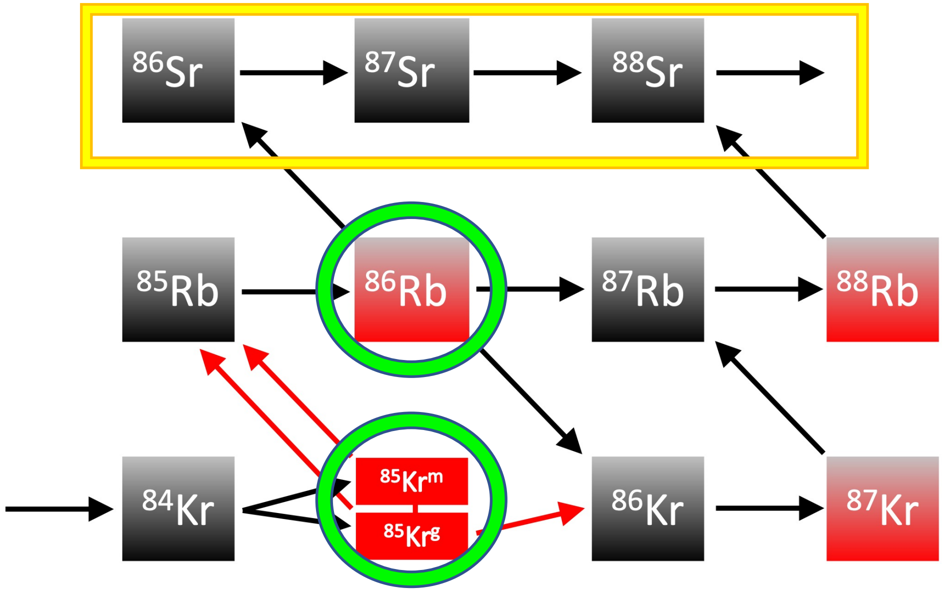
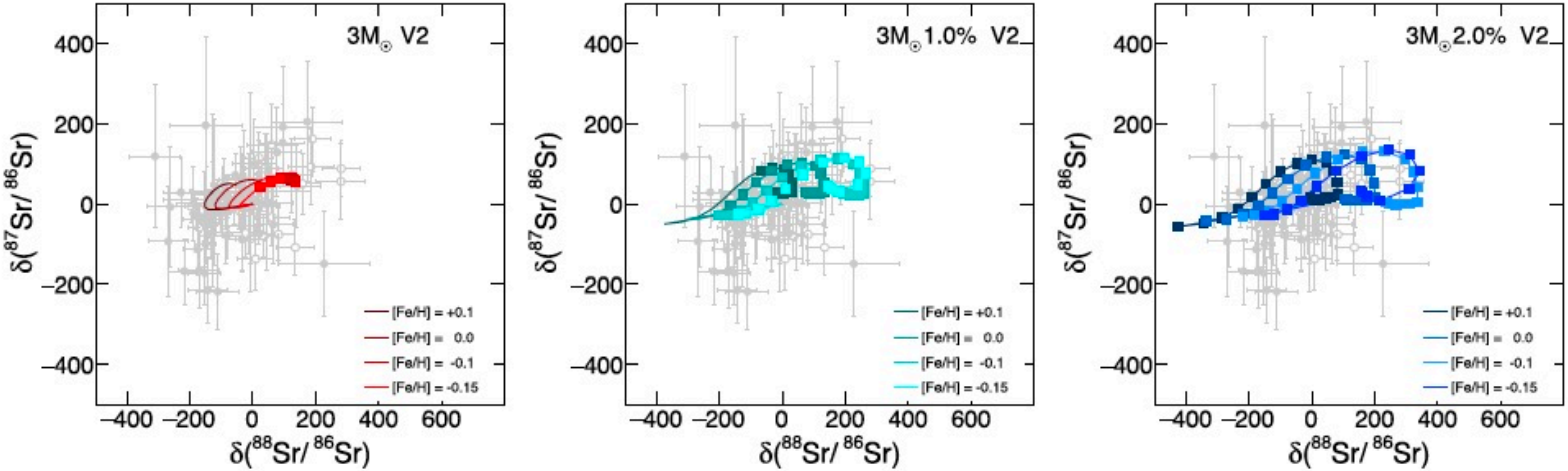
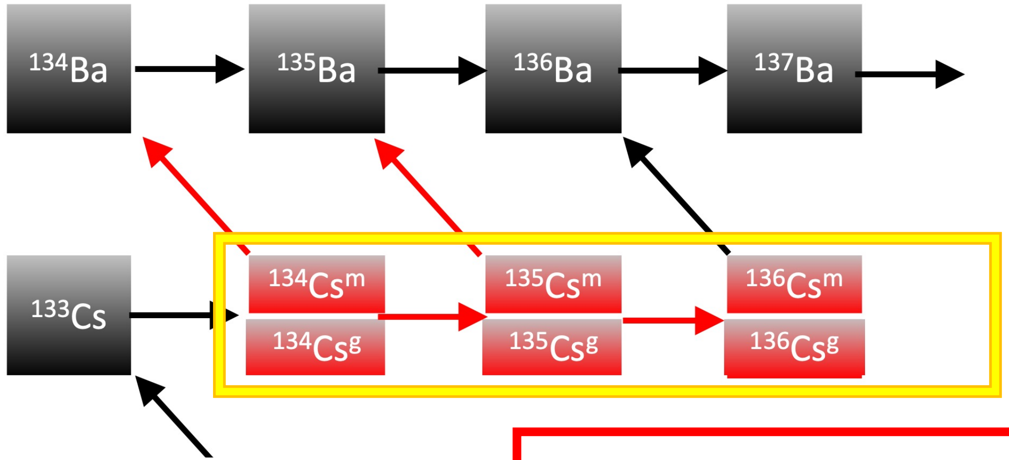
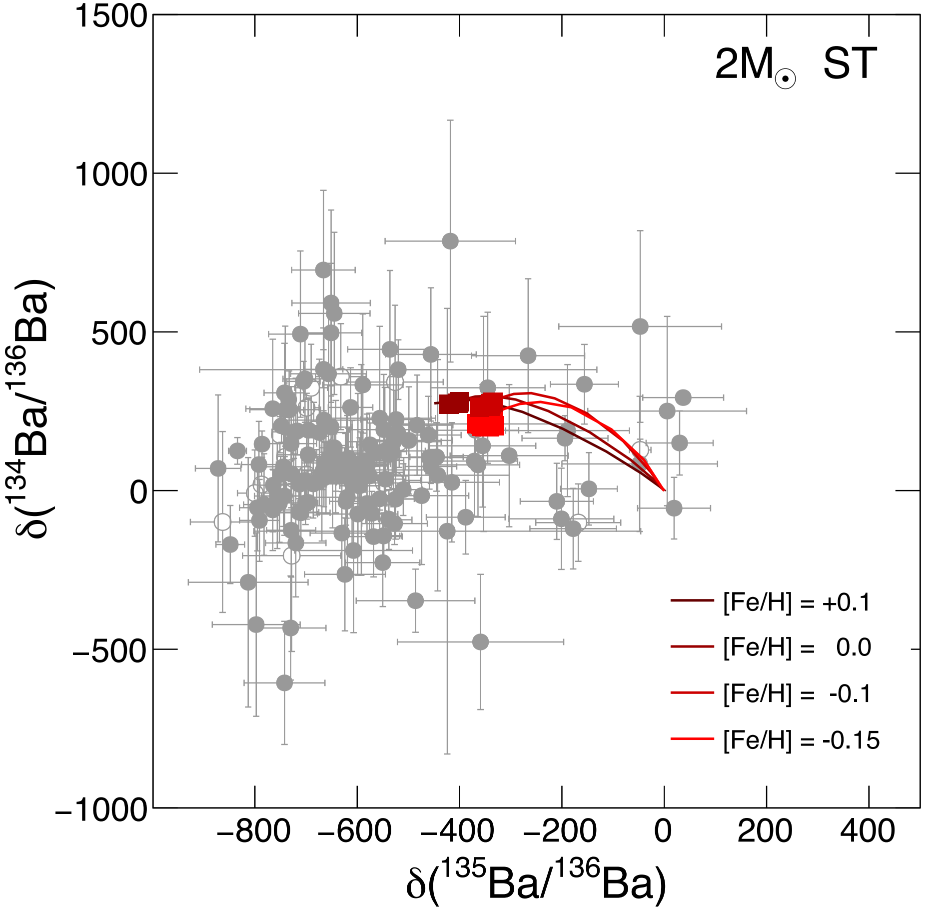


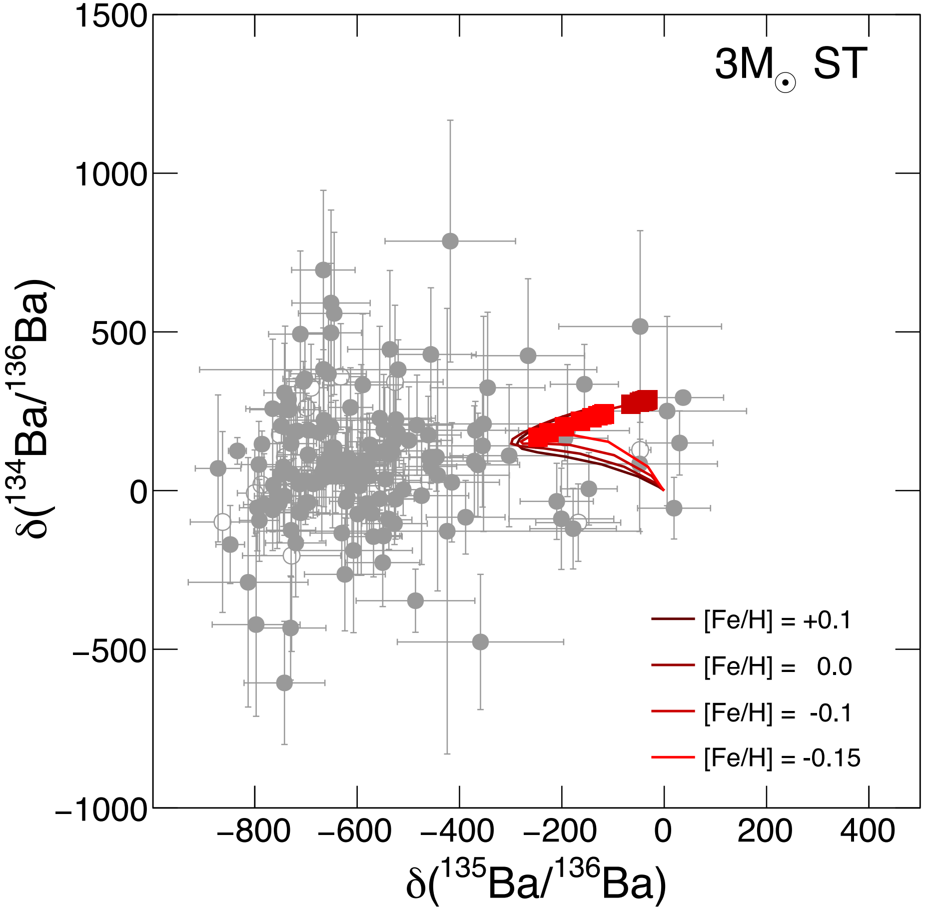




The Cs Branchings and Ba nucleoynthesis ...around N = 82





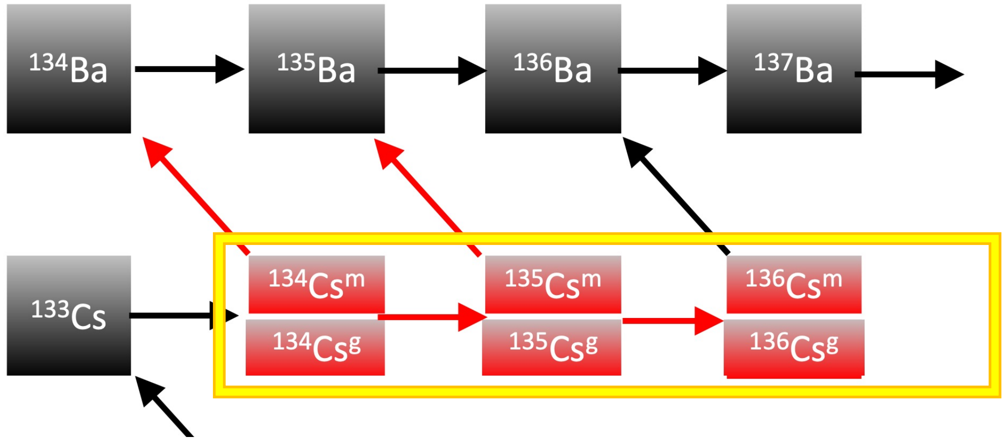


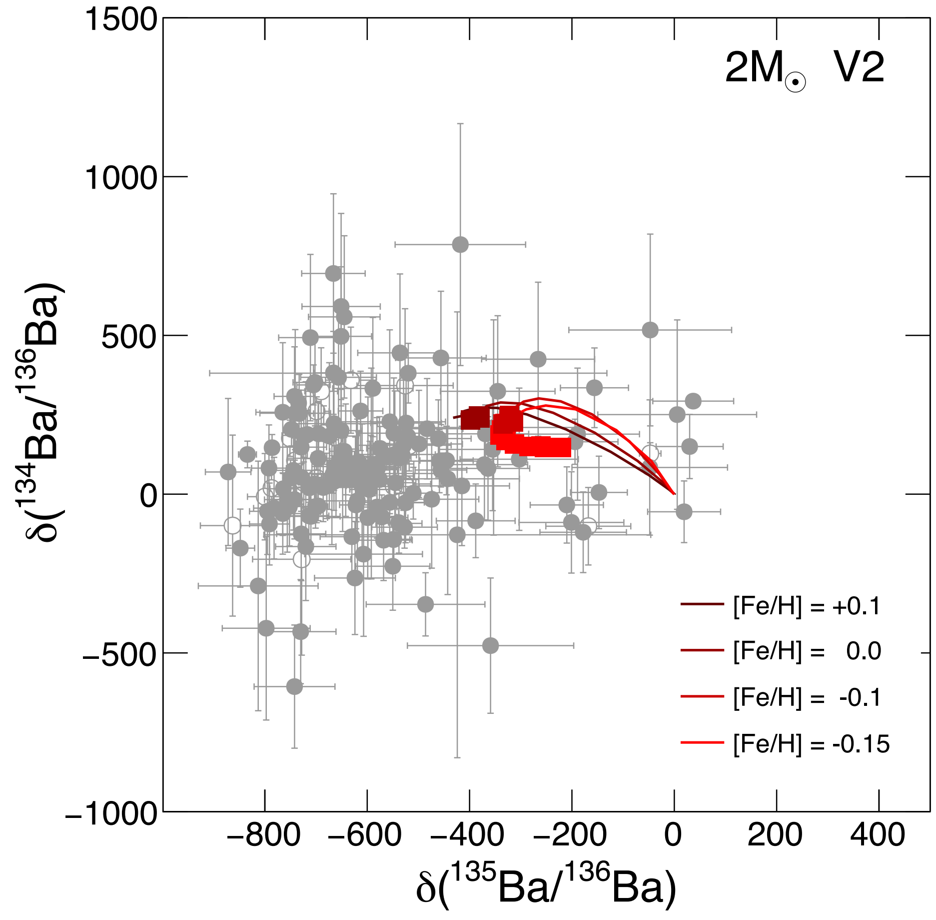
ST nuclear input

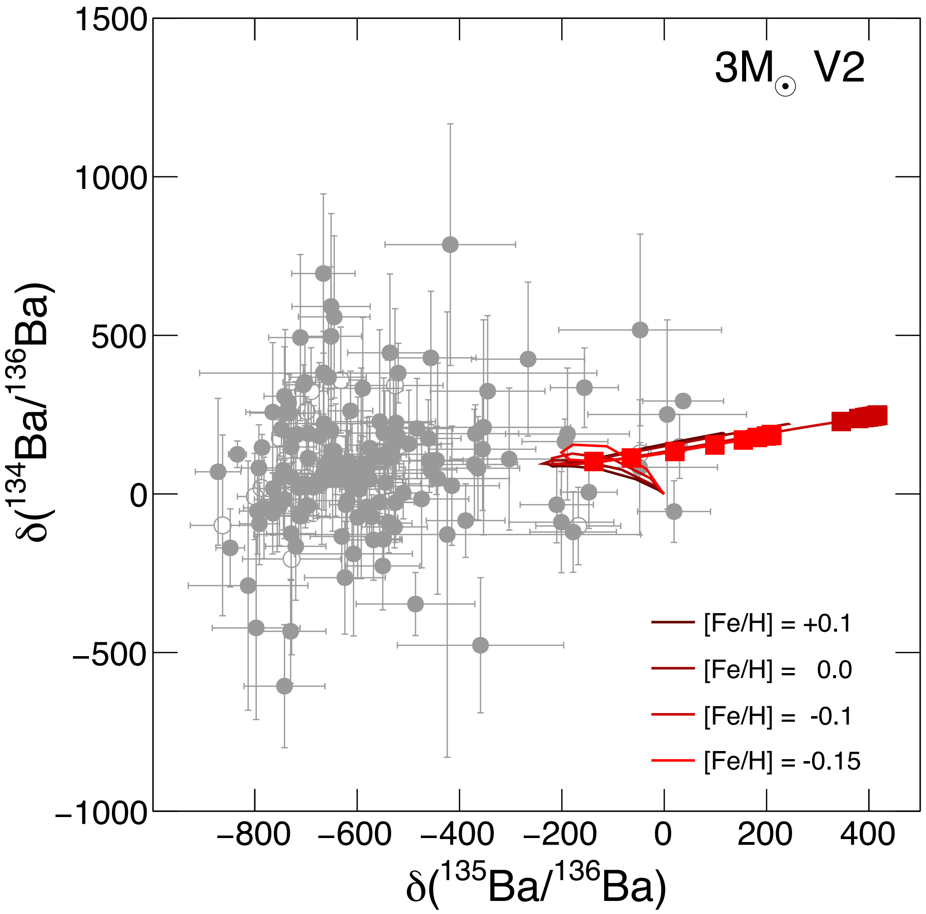
- (n,γ) MACS are from KADONIS 1.0
- (n,γ) theoretical Hauser–Feshbach computations TALYS 2008 for unstable nuclei
- rates for weak interactions from Takahashi & Yokoi (1987)

The Cs Branchings

Ba isotopic ratios are sensitive to the (n,γ) cross sections (only theoretical values exist) and β–decay of ^{134}Cs and ^{135}Cs at T > 2 10^8K.



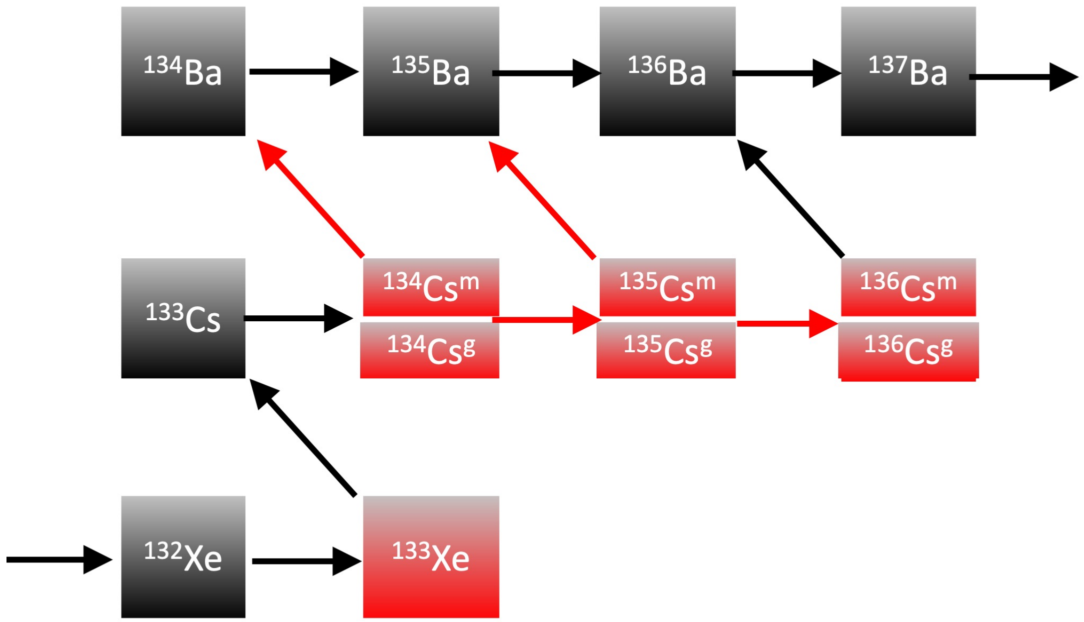




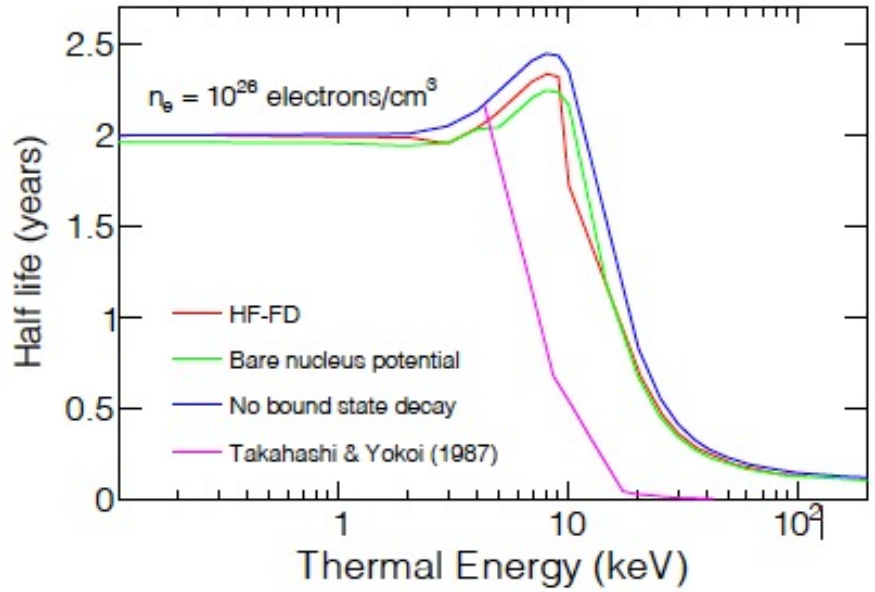
V2 nuclear input

- decay rate of ^{134}Cs enhanced by a factor of 8 respect to TY 1987 (see next talk)
- Similar effects would be induced by variations in the ^{135}Cs neutron-capture cross section

The $^{134\text{-}135}$Cs Branchings and Ba nucleoynthesis ...around N = 82

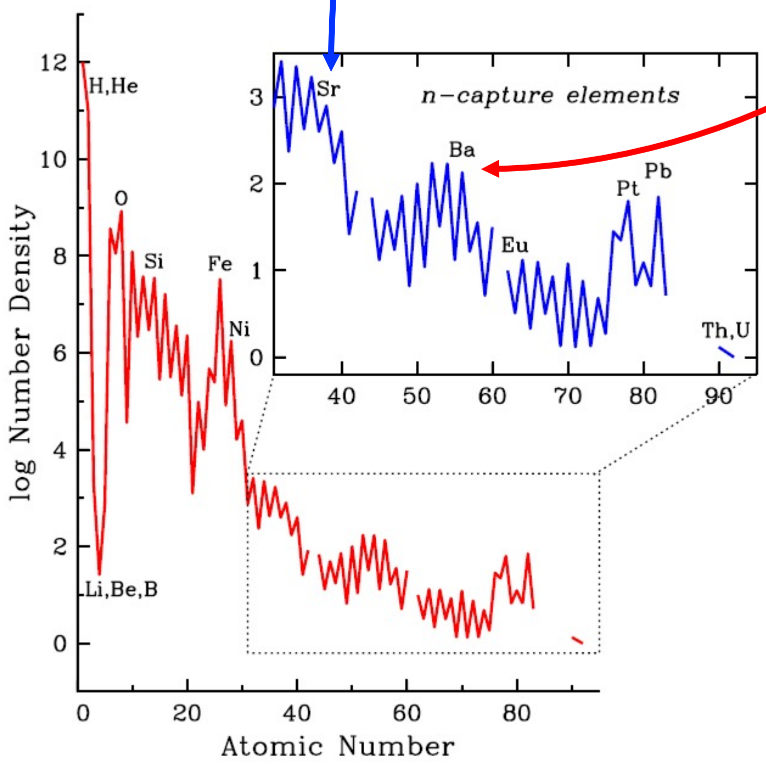


- ^{134}Cs (β^-) $t_{1/2} \approx 2$ yr (lab.)
- @ 3 10^8K the decay rate of ^{134}Cs is enhanced by a factor of about 200. (TY 1987)



Taioli et al 2021 ArXive2109.14230

LIGHT S AND HEAVY S TOGHETER



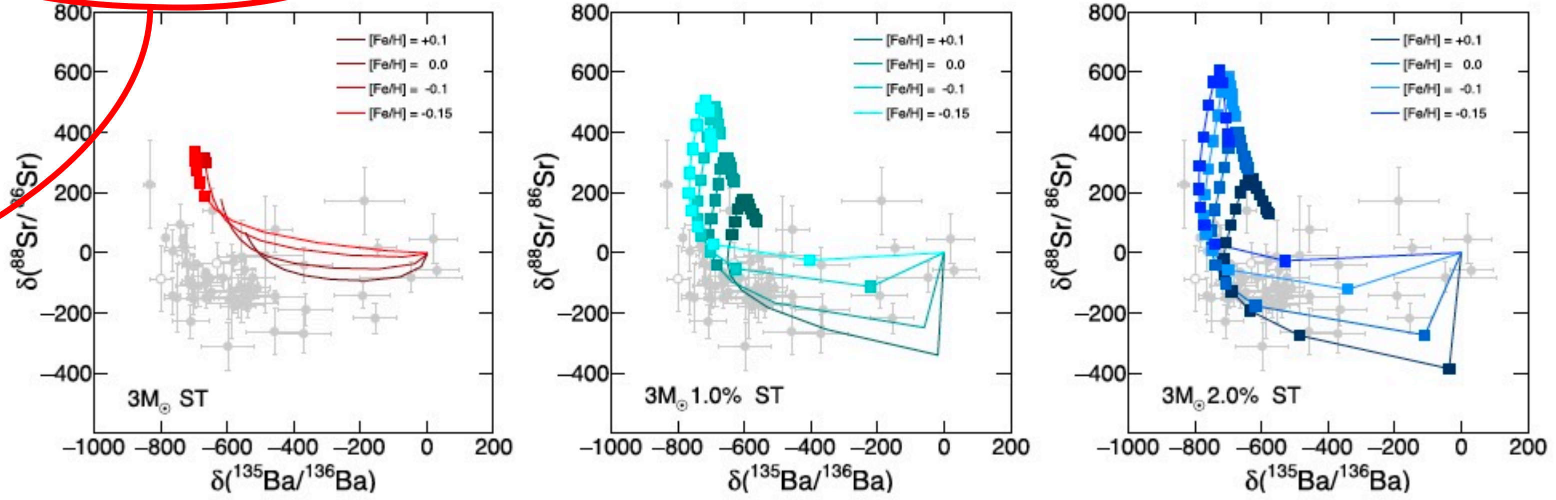


Figure 12. Same as Figure 11, but for models of 3 $M_{\odot}$ stars.

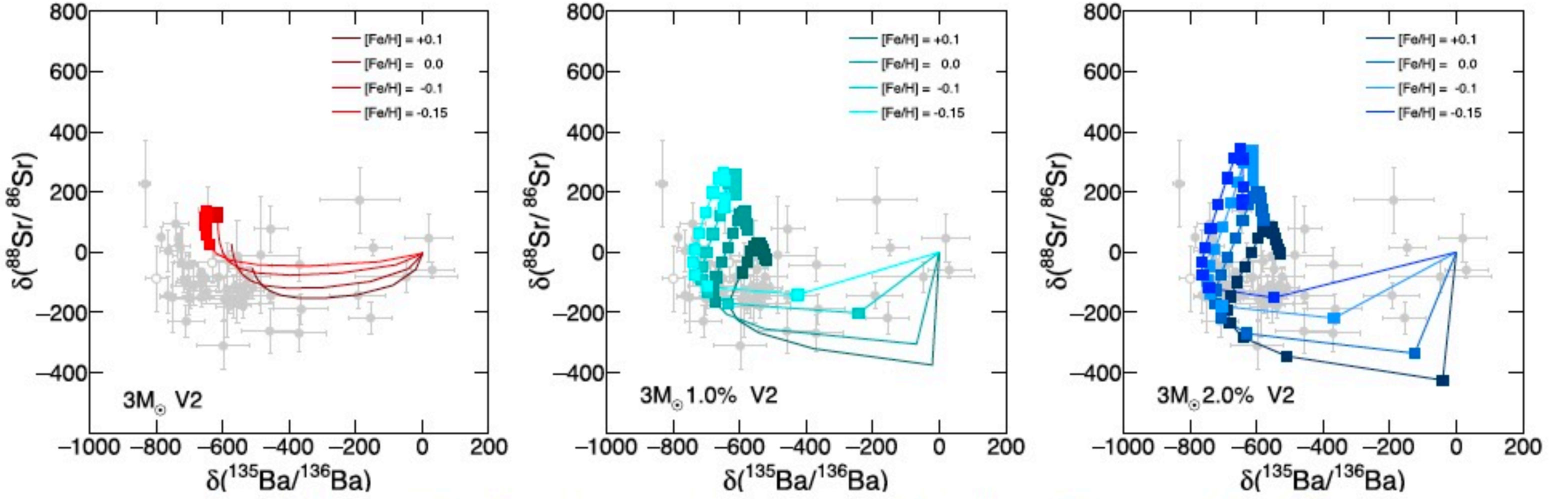


Figure 13. Same as Figure 12, but for the test models V2, with tentatively modified nuclear inputs (see Section 3).

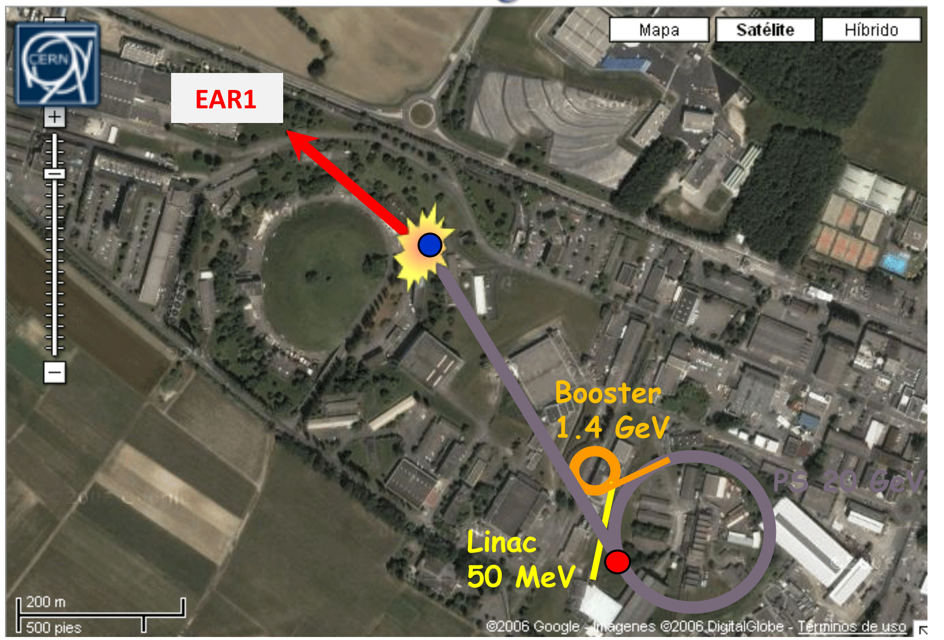
MIGHT STELLAR MAGNETIC FIELDS TRIGGER SUCH A MIXING?

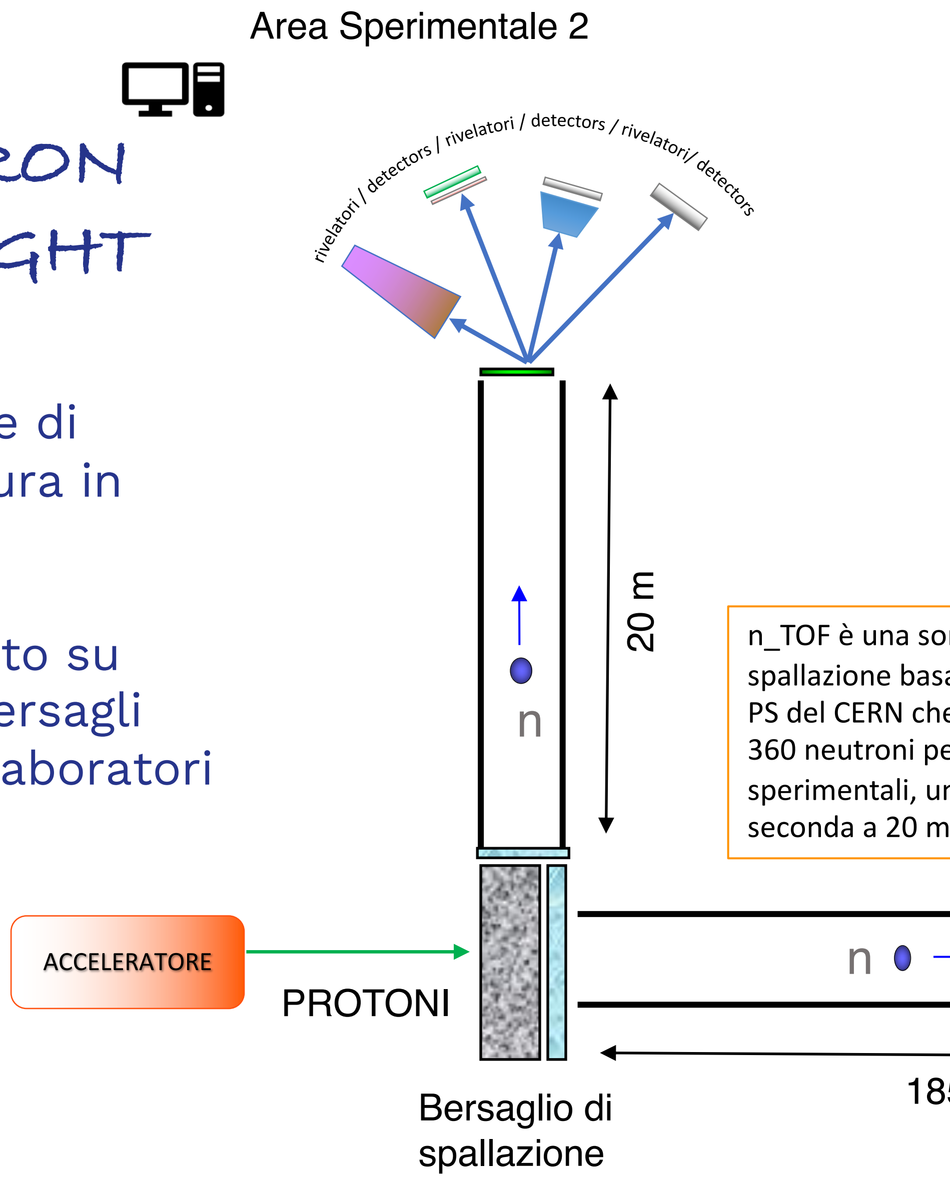
YES, THEY MIGHT,

but more precise nuclear physics input are needed, in particular for beta decay in plasma conditions and fusion cross section of reactions involving instable nuclei.

nTOF NEUTRON TIME OF FLIGHT

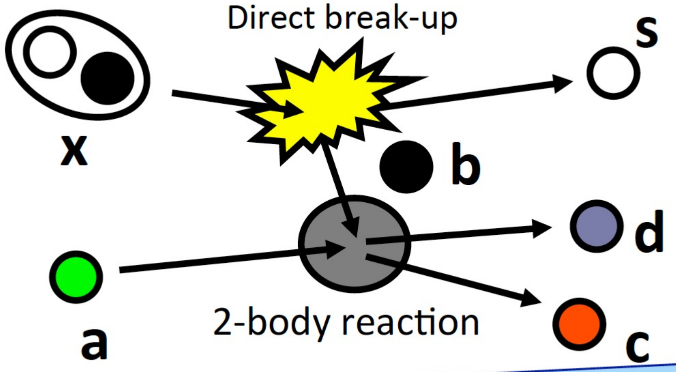
- ✓ ^{140}Ce, ^{88}Sr, ^{89}Y misure di sezioni d'urto di cattura in corso
- ✓ Misure di sezioni d'urto su nuclei instabili con bersagli prodotti a ISOLDE o laboratori radiochimica "vicini".





n_TOF è una sorgente di neutroni di spallazione basata su 20 protoni GeV / c dal PS del CERN che colpisce un blocco Pb (~ 360 neutroni per protone). Due aree sperimentali, una a 185 m (EAR1) e la seconda a 20 m (EAR2)

MEASUREMENT OF ASTROPHYSICAL RELEVANT REACTIONS INDUCED BY ALPHA, PROTONS AND NEUTRONS AT THE GAMOW PEAK USING THE TROJAN HORSE METHOD



The applicability of the pole approximation is limited to small momentum p_s

The cross section of the

$$a + b \rightarrow c + d$$

two-body reaction (not involving photons) can be determined from the quasi-free contribution of an appropriate three-body reaction:

$$a + x \rightarrow c + d + s$$

$$\downarrow$$

$$x = b \oplus s \text{ (cluster)}$$

TH nucleus breaks up inside the nuclear field of nucleus a

- ✓ b interacts with a
- ✓ s is considered to be spectator to the reaction

$$E_{c.m.(a,b)} = E_{c,d} - Q_{a+b \to c+d}$$

- ✓ Astrophysical energies can be achieved with 1-10 AMeV energy beams.
- ✓ Measurements at deep sub-Coulomb energies are possible as the THM cross section is not damped by the penetration of the a-b Coulomb barrier, being b a virtual particle.

From the experiment

Evaluated through a MC code

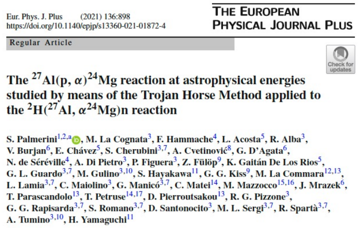
[Tribble et al. 2015]

$$\frac{d^3\sigma}{dE_c d\Omega_c d\Omega_d} \propto KF\left|\phi(p_s)\right|^2 \left(\frac{d\sigma}{d\Omega}\right)^{a+b\to c+d}_{cm}$$

HOES 2-body cross section

STUDYNG NEUTRON AND PROTON CAPTURE REACTIONS OF UNSTABLE NUCLEI BY THE THM IN RIBS FACILITIES….

….STARTING FROM $^{26}Al^*$



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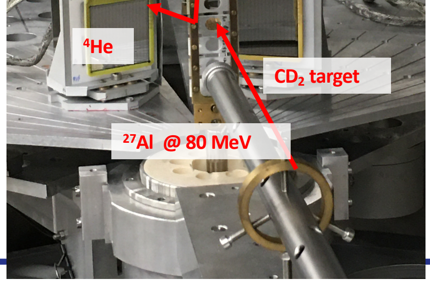
THE EUROPEAN PHYSICAL JOURNAL PLUS

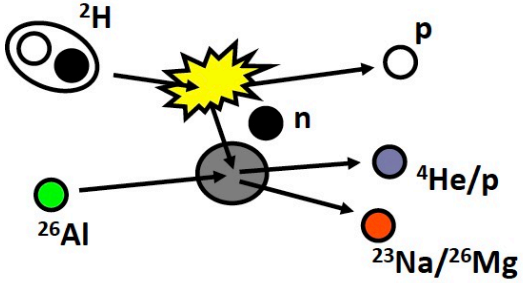
Regular Article

The $^{27}Al(p,\alpha)^{24}Mg$ reaction at astrophysical energies studied by means of the Trojan Horse Method applied to the $^{2}H(^{27}Al,\alpha^{24}Mg)n$ reaction

S. Palmerini[1,2,a], M. La Cognata[3], F. Hammache[4], L. Acosta[5], R. Alba[3], V. Burjan[6], E. Chávez[5], S. Cherubini[3,7], A. Cvetinović[8], G. D'Agata[6], N. de Séréville[4], A. Di Pietro[3], P. Figuera[3], Z. Fülöp[9], K. Gaitán De Los Rios[5], G. L. Guardo[3,7], M. Gulino[3,10], S. Hayakawa[11], G. G. Kiss[9], M. La Commara[12,13], L. Lamia[3,7], C. Maiolino[3], G. Manicó[3,7], C. Matei[14], M. Mazzocco[15,16], J. Mrazek[6], T. Parascandolo[13], T. Petruse[14,17], D. Pierroutsakou[13], R. G. Pizzone[3], G. G. Rapisarda[3,7], S. Romano[3,7], D. Santonocito[3], M. L. Sergi[3,7], R. Spartà[3,7], A. Tumino[3,10], H. Yamaguchi[11]

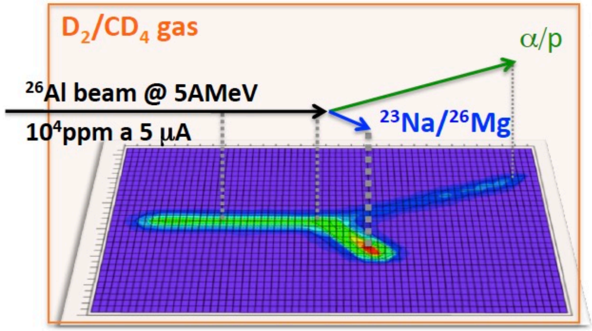


$^{26}Al^*(n,\alpha)^{23}Na$ via $^{26}Al^*(d,\alpha^{23}Na)p$
$^{26}Al^*(n,p)^{26}Mg$ via $^{26}Al^*(d,p^{26}Mg)p$



- ✓ Only events occurring at the energy of interest can be selected
- ✓ Two-rays events will be singled out to select reactions with p_s=0 (QF contribution is maximum)

$$E_{QF} = \frac{M_n}{M_n + M_{26Al}} E_{26Al} - Q_d$$



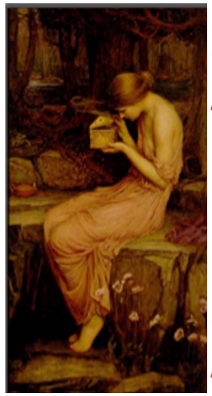
E_{beam} E_{cm}	113MeV 2MeV	60MeV 0 MeV
400 mbar CD_4	17.5mm	68mm
1000 mbar D_2	51 mm	240mm

TPC might be very well suited to measure THM reactions

STUDIO DEI DECADIMENTI $\beta^{\mp}$ IN PLASMI MAGNETIZZATI

PANDORA: Plasmas for Astrophysics, Nuclear Decays Observation and Radiation for Archaeometry → A New ECRIT – ECR Ion Trap for β-decay measurements in plasmas

INFN LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud



Plasmas for
Astrophysics,
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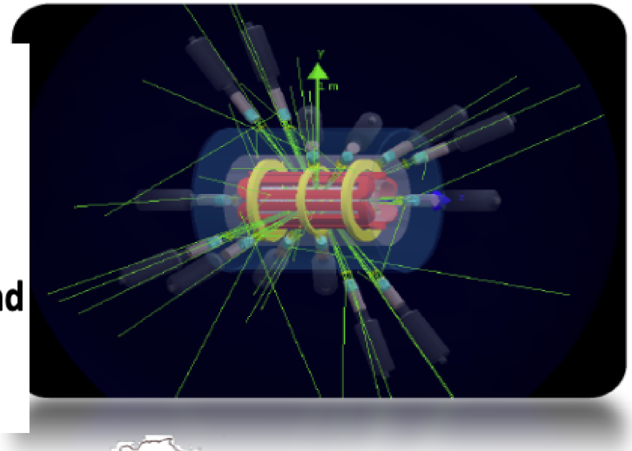
Radiation for
Archaeometry



MAIN GOAL:* Make β–decay measurements in plasmas of astrophysical interest: *many isotopes can change their lifetime of several order of magnitude when ionized!!

Isotope	$T_{1/2}$ (yr)	Eγ (keV)
^{176}Lu	3.78×10^{10}	88-400
^{134}Cs	2.06	>600
^{94}Nb	2.03×10^{4}	>700

→ COSMO-CHRONOMETER

→ reproduction of the two s-only isotopes ^{134}Ba, ^{136}Ba in suitable proportions

→ Solving the puzzle about the the exact contribution of s-processing to ^{94}Mo: β-decay or binary stars

^{7}Be, ^{85}Kr, $^{134\text{-}135}$Cs

Experiments driving feasibility study carried out in the frame of an international partnership:

- **ATOMKI – Debrecen (Hungary)** → multi-diagnostics setups
- **LPSC-Grenoble (France)** → radio-isotopes injection
- **Max Planck Institute – Inst. Plasma Physics (Germany)** → Optical Spectroscopy of magnetoplasmas
- **GANIL (France)** → theoretical studies on multi-ionisation
- **University Jyvaskyla (Finland)** → Ion Cyclotron Heating studies
- **GSI – Darmstadt (Germany)** → Vaporizing ovens
- INAF: the spectropolarimeter SARG was moved from TNG-Canary Island to LNS

>30 Researchers and Technologists INFN involved in 2020 with > 15 FTE, 2 Nat. Labs and 2 Sections

STUDIO DEI DECADIMENTI $\beta^{\mp}$ IN PLASMI MAGNETIZZATI

L'esperimento PANDORA è basato su una trappola magnetica in grado di confinare plasmi ad alta temperatura (fino a 10^8 K) e densità dell'ordine di 10^{13} cm^{-3}, contenenti isotopi radioattivi multi-ionizzati al fine di studiarne la variazione del decadimento β in condizioni astrofisiche. Tale variazione è predetta teoricamente (bound-state β decay) ed è stata finora osservata in forma preliminare per pochi isotopi in condizioni di massima ionizzazione (in un esperimento allo Storage Ring del GSI, effettuato sul ^{187}Re totalmente ionizzato, la vita media è collassata di 9 ordini di grandezza).

La probabilità di una interazione debole è funzione dello stato di plasma attraverso un fattore P_{em} in cui possiamo immaginare di far confluire tutti i termini dipendenti dall'ambiente, dalle condizioni che inducono la ionizzazione alla densità delle cariche (elettroni) nel plasma circostante (entro un raggio di Debye, anche per plasmi di conducibilità elettrica quasi infinita, la condizione di neutralità elettrica non vale). Il progetto Pandora potrà fornire in particolare **la dipendenza del decadimento dalla ionizzazione.**

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