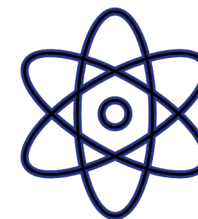


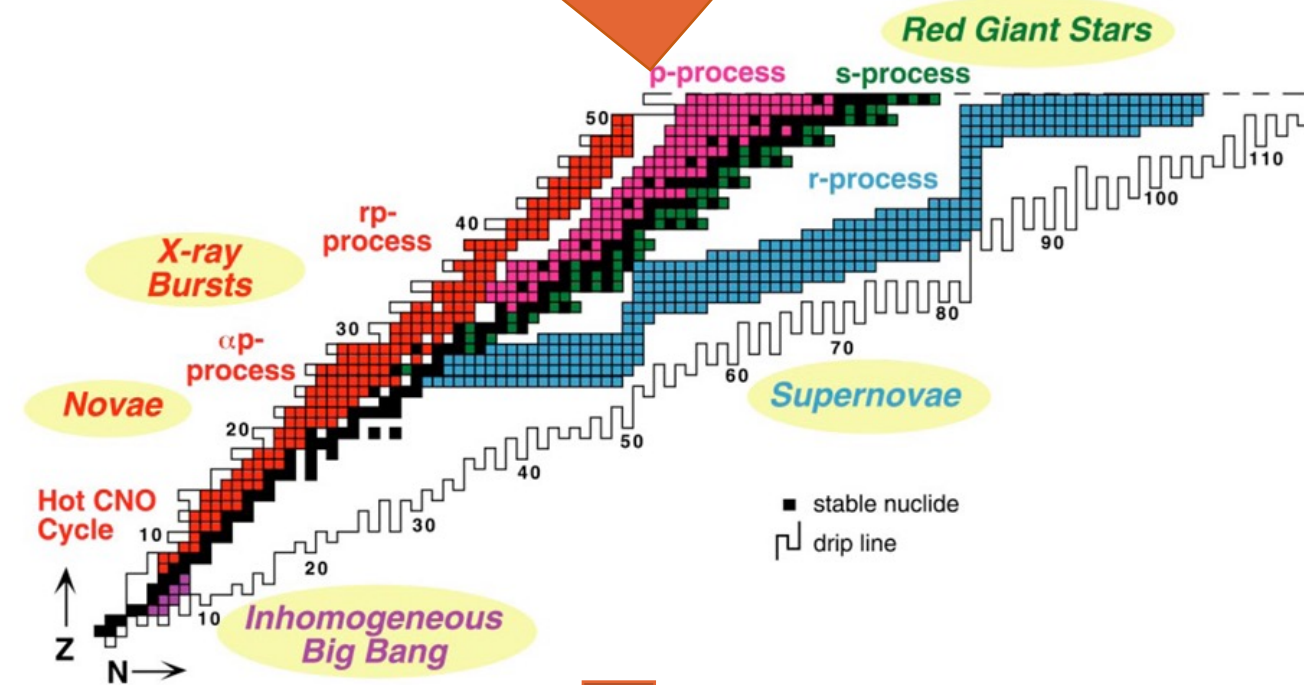
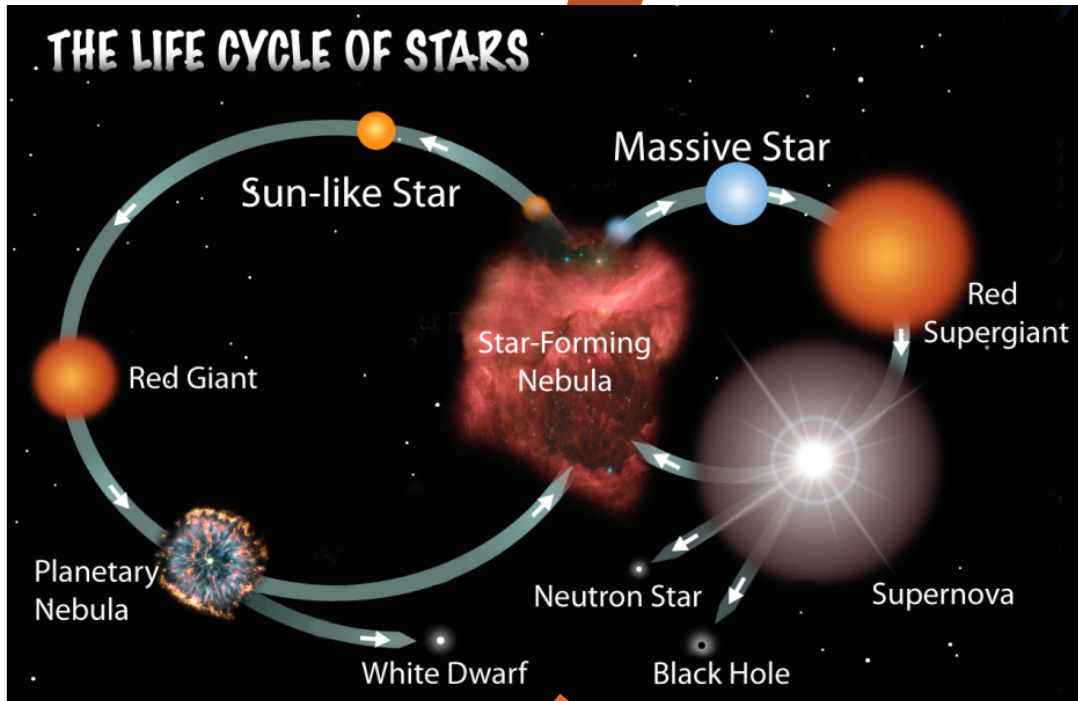


Astrofisica Nucleare @ UniPG

**Workshop di orientamento alla Laurea Magistrale in
Fisica: corsi, curricula, tesi e attività di ricerca a Perugia**

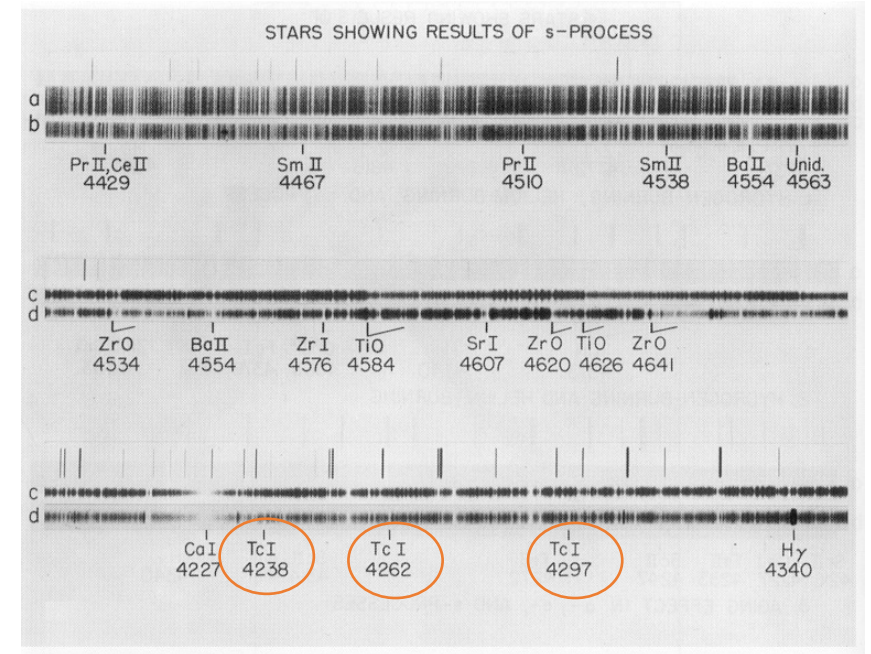


Sara Palmerini – sara.palmerini@unipg.it



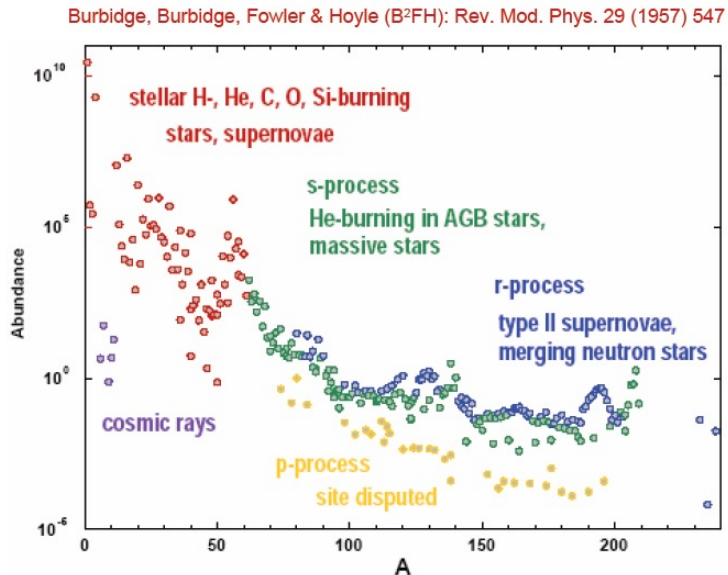
Merrill 1952: s-star contains Tc ($Z=43$ $T_{1/2}= 4$ Gyr)

- Known at the time that Tc is an «artificial» element
- Artificial = someone has to make it
- Merrill 1952: «it is surprising to find an unstable element in stars [...] (1) A stable isotope (of technetium) actually exists although not yet found on Earth; or (2) s-type stars somehow produce technetium as they go along; or (3) s-type stars represent a comparatively transient phase of stellar existence»

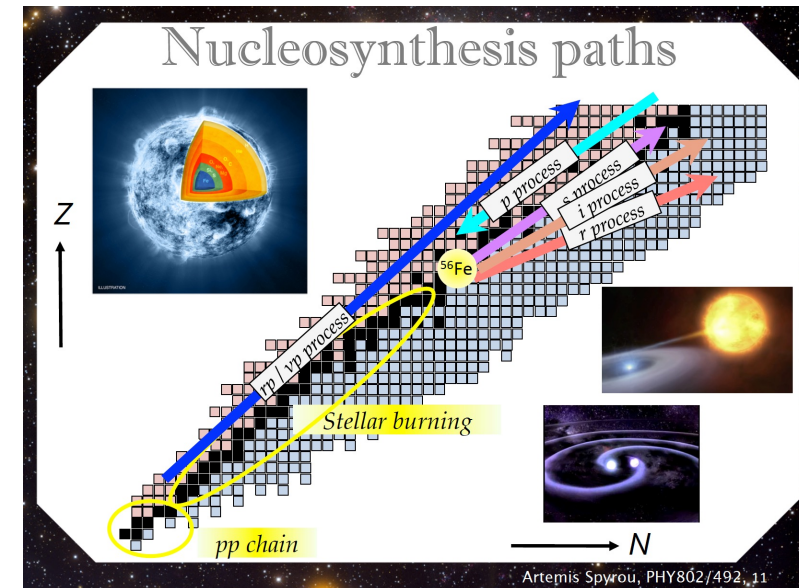


⁹⁷ Ru 2.83 D ε: 100.00%	⁹⁸ Ru STABLE 1.87%	⁹⁹ Ru STABLE 12.76%	¹⁰⁰ Ru STABLE 12.60%	¹⁰¹ Ru STABLE 17.06%	¹⁰² Ru STABLE 31.55%
⁹⁶ Tc 4.28 D ε: 100.00%	⁹⁷ Tc 4.21E+6 Y ε: 100.00%	⁹⁸ Tc 4.2E+6 Y β-: 100.00%	⁹⁹ Tc 2.111E+5 Y β-: 100.00%	¹⁰⁰ Tc 15.46 S ε: 2.6E-3%	¹⁰¹ Tc 14.02 M β-: 100.00%
⁹⁵ Mo STABLE 15.84%	⁹⁶ Mo STABLE 16.67%	⁹⁷ Mo STABLE 9.60%	⁹⁸ Mo STABLE 24.39%	⁹⁹ Mo 65.976 H β-: 100.00%	¹⁰⁰ Mo 7.3E+18 Y 9.82% 2β-: 100.00%

B²FH: the birth of nuclear astrophysics



from: M. Wiescher, JINA lectures on Nuclear Astrophysics



REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4

OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Burbidge



Burbidge



Fowler



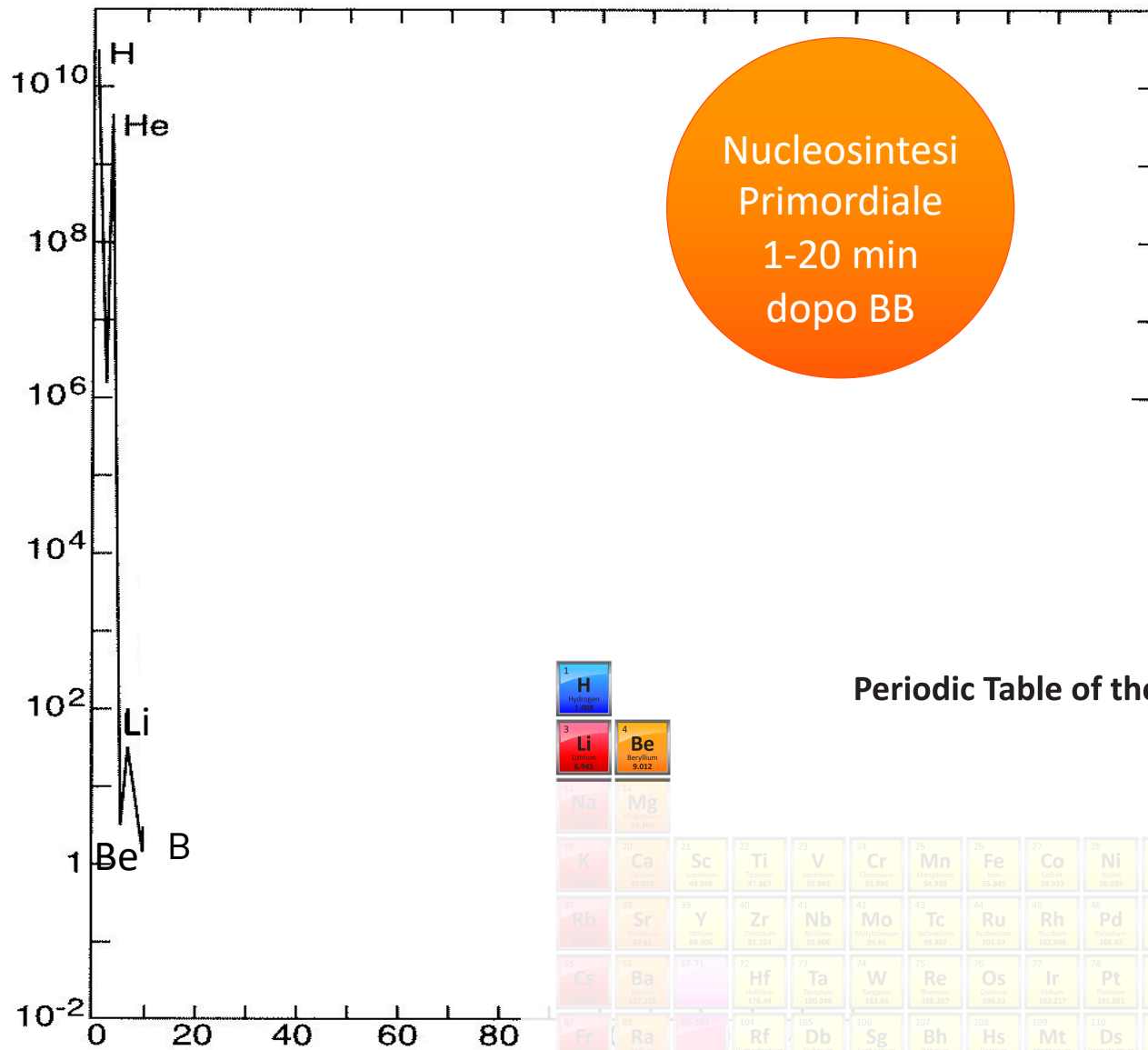
Hoyle



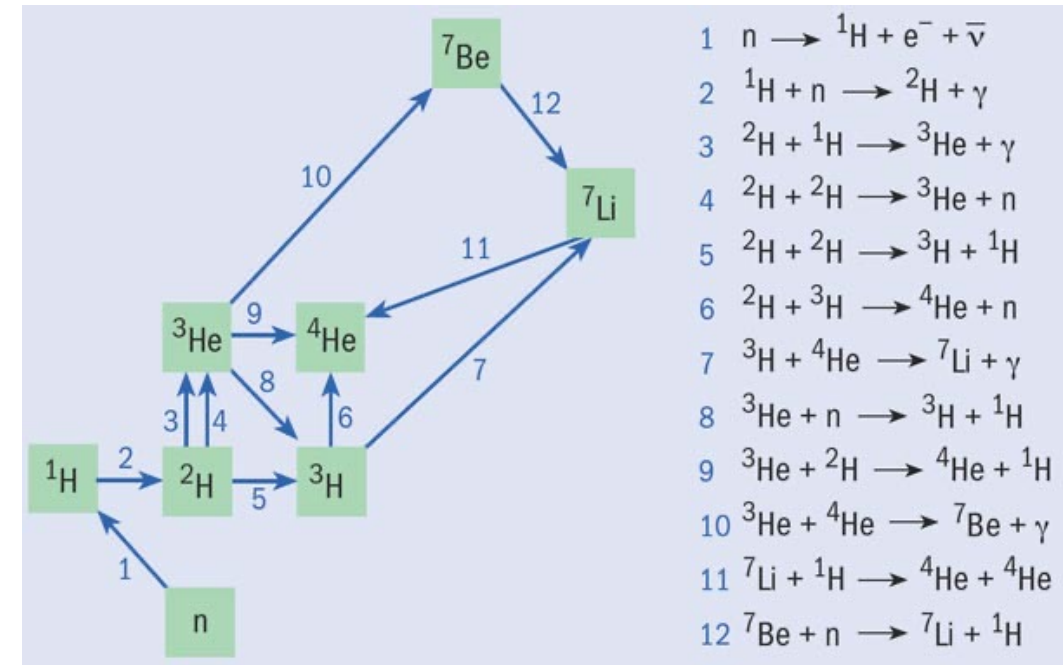
1983
Nobel Prize



"for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"



Nucleosintesi
Primordiale
1-20 min
dopo BB

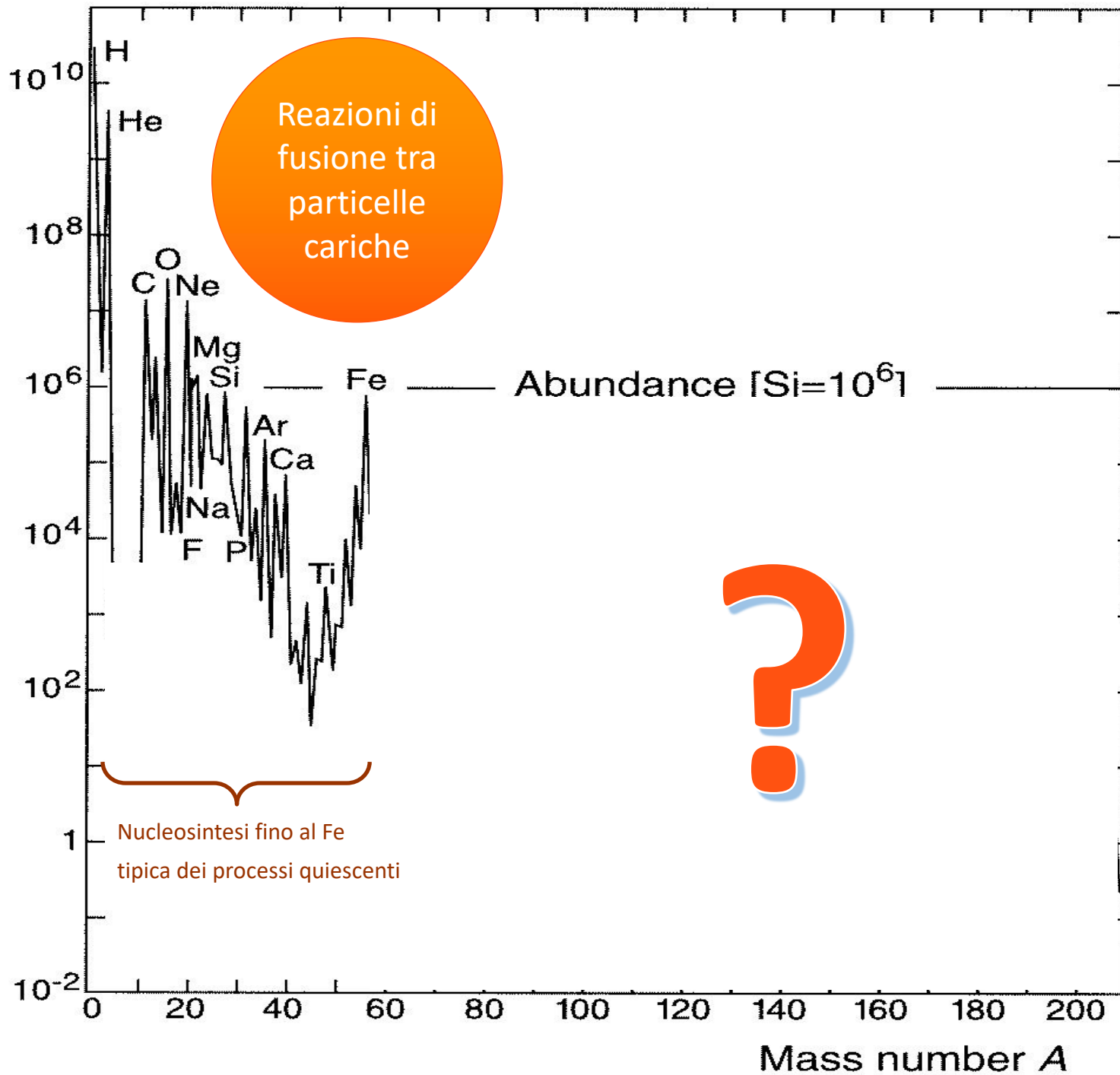


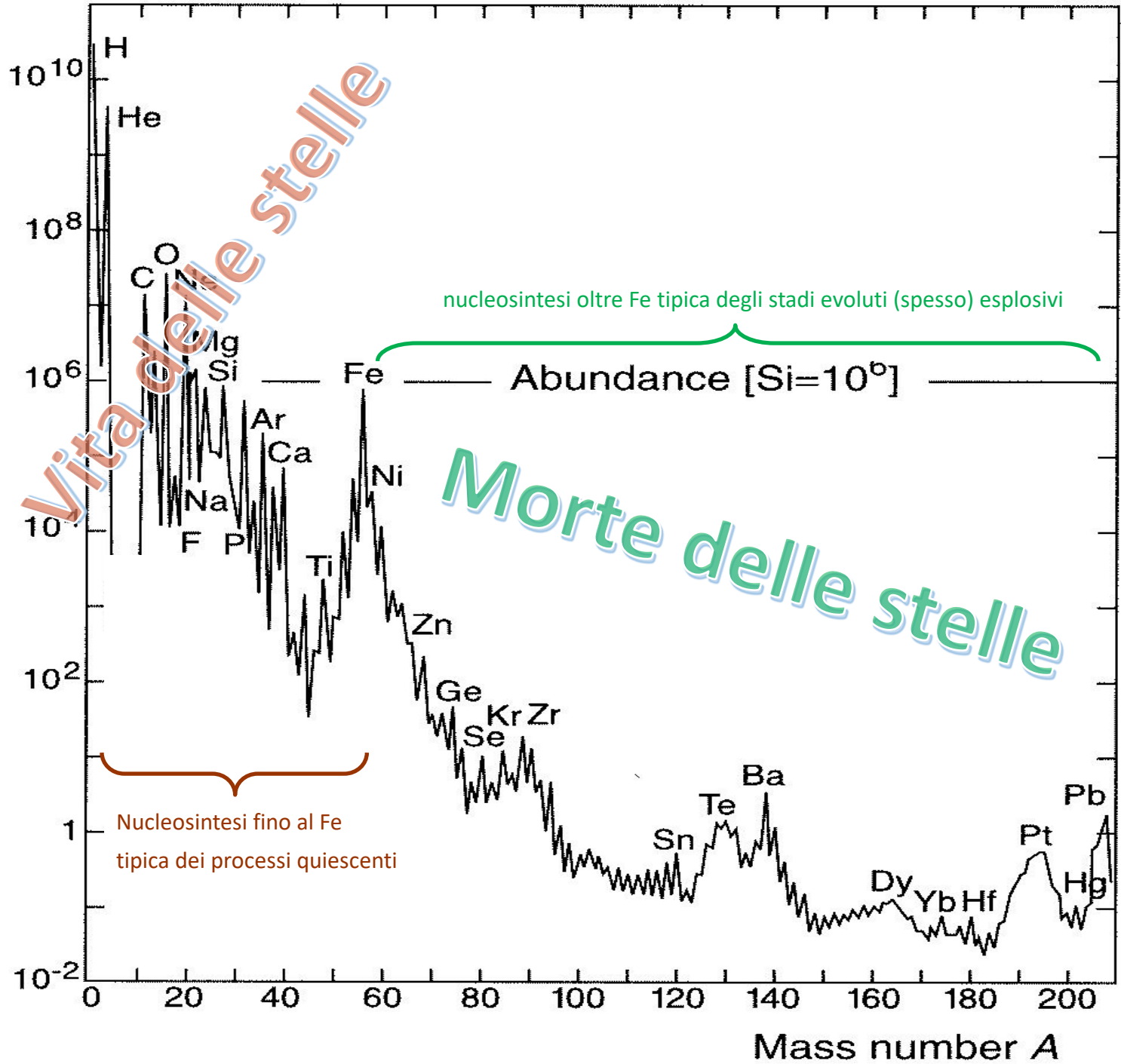
- 1 $n \rightarrow ^1\text{H} + e^- + \bar{\nu}$
- 2 $^1\text{H} + n \rightarrow ^2\text{H} + \gamma$
- 3 $^2\text{H} + ^1\text{H} \rightarrow ^3\text{He} + \gamma$
- 4 $^2\text{H} + ^2\text{H} \rightarrow ^3\text{He} + n$
- 5 $^2\text{H} + ^2\text{H} \rightarrow ^3\text{H} + ^1\text{H}$
- 6 $^2\text{H} + ^3\text{H} \rightarrow ^4\text{He} + n$
- 7 $^3\text{H} + ^4\text{He} \rightarrow ^7\text{Li} + \gamma$
- 8 $^3\text{He} + n \rightarrow ^3\text{H} + ^1\text{H}$
- 9 $^3\text{He} + ^2\text{H} \rightarrow ^4\text{He} + ^1\text{H}$
- 10 $^3\text{He} + ^4\text{He} \rightarrow ^7\text{Be} + \gamma$
- 11 $^7\text{Li} + ^1\text{H} \rightarrow ^4\text{He} + ^4\text{He}$
- 12 $^7\text{Be} + n \rightarrow ^7\text{Li} + ^1\text{H}$

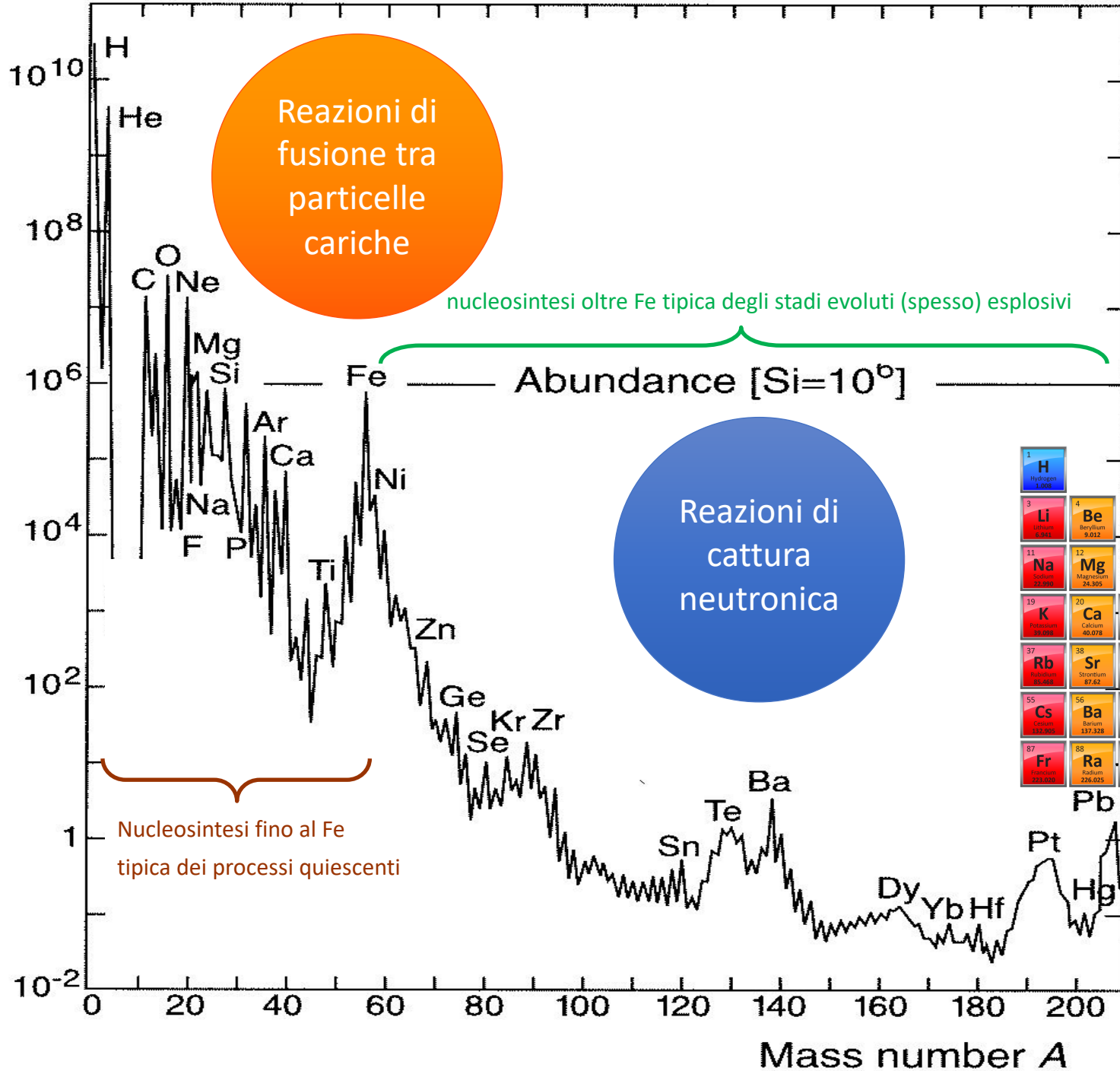
Periodic Table of the Elements

1 H Hydrogen 1.008																	2 He Helium 4.003																	
3 Li Lithium 6.941	4 Be Beryllium 9.012																	5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180											
11 Na Sodium 22.990	12 Mg Magnesium 24.305																	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.06	17 Cl Chlorine 35.453	18 Ar Argon 39.948											
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.798																	
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.94	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.757	52 Te Tellurium 127.6	53 I Iodine 126.905	54 Xe Xenon 131.29																	
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.222	78 Pt Platinum 195.084	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.384	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine [210]	86 Rn Radon [222]																	
87 Fr Francium [223]	88 Ra Radium 226.025	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [277]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [271]	111 Rg Roentgenium [272]	112 Cn Copernicium [285]	113 Nh Nihonium [284]	114 Fl Flerovium [289]	115 Mc Moscovium [288]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]																	
																		57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium [145]	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.255	69 Tm Thulium 168.934	70 Yb Ytterbium 173.054	71 Lu Lutetium 174.967		
																		89 Ac Actinium [227]	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.083	99 Es Einsteinium [252]	100 Fm Fermium [257]	101 Md Mendelevium [258]	102 No Nobelium [259]	103 Lr Lawrencium [260]		

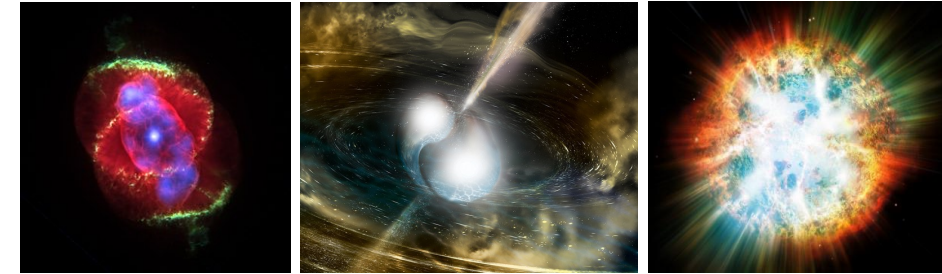
Sara Palmerini







- S-process (lento)
- R-process (rapido)
- i-process (lento)



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Alkali Metal

Alkaline Earth

Transition Metal

Basic Metal

Semimetal

Nonmetal

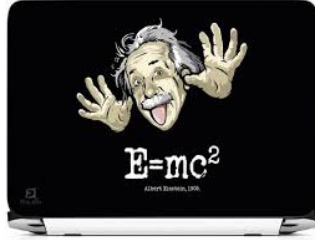
Halogens

Noble Gas

Lanthanide

La fisica nucleare delle stelle

Per la reazione : $A(B,C)D$ cioè $A+B \rightarrow C+D$



Il Q-valore: $Q = [(m_A + m_B) - (m_C + m_D)]c^2$
(energia prodotta per singola reazione)

✓ TASSO (RATE) DI REAZIONE r

(numero di reazioni per unità di tempo e volume)

$$r = \frac{1}{1 + \delta_{AB}} N_A N_B \langle \sigma v \rangle$$

N_i = densità numerica delle specie interagenti

v = velocità relative

$\phi(v)$ = distribuzione della velocità nel plasma

$\sigma(v)$ = sezione d'urto della reazione

$$\langle \sigma v \rangle = \int \sigma(v) \phi(v) v dv$$

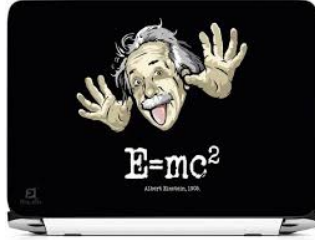
✓ TASSO DI PRODUZIONE DI ENERGIA ε

$$\varepsilon = rQ/\rho$$

unità: $\text{MeV g}^{-1} \text{s}^{-1}$

La fisica nucleare delle stelle

Per la reazione : $A(B,C)D$ cioè $A+B \rightarrow C+D$



Il Q-valore: $Q = [(m_A + m_B) - (m_C + m_D)]c^2$
(energia prodotta per singola reazione)

Misurate
dall'A.N.
sperimentale

✓ TASSO (RATE) DI REAZIONE r
(numero di reazioni per unità di tempo e volume)

$$r = \frac{1}{1 + \delta_{AB}} N_A N_B \langle \sigma v \rangle$$

N_i = densità numerica delle specie interagenti

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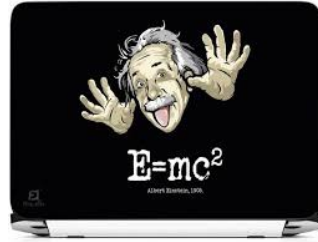
✓ TASSO DI PRODUZIONE DI ENERGIA ε

$$\varepsilon = rQ/\rho$$

unità: $\text{MeV g}^{-1} \text{s}^{-1}$

La fisica nucleare delle stelle

Per la reazione : $A(B,C)D$ cioè $A+B \rightarrow C+D$



Il Q-valore: $Q = [(m_A + m_B) - (m_C + m_D)]c^2$
(energia prodotta per singola reazione)

Usate
nelle
simulazio
ni di
nucleosin
tesi per
spiegare
le
osservazi
one dagli
A.N.
teorica

Misurate
dall'A.N.
sperimentale

✓ TASSO (RATE) DI REAZIONE r
(numero di reazioni per unità di tempo e volume)

$$r = \frac{1}{1 + \delta_{AB}} N_A N_B \langle \sigma v \rangle$$

N_i = densità numerica delle specie interagenti

v = velocità relative

$\phi(v)$ = distribuzione della velocità nel plasma

$$\langle \sigma v \rangle = \int \sigma(v) \phi(v) v dv$$

$\sigma(v)$ = sezione d'urto della reazione

✓ TASSO DI PRODUZIONE DI ENERGIA ϵ

$$\epsilon = rQ/\rho$$

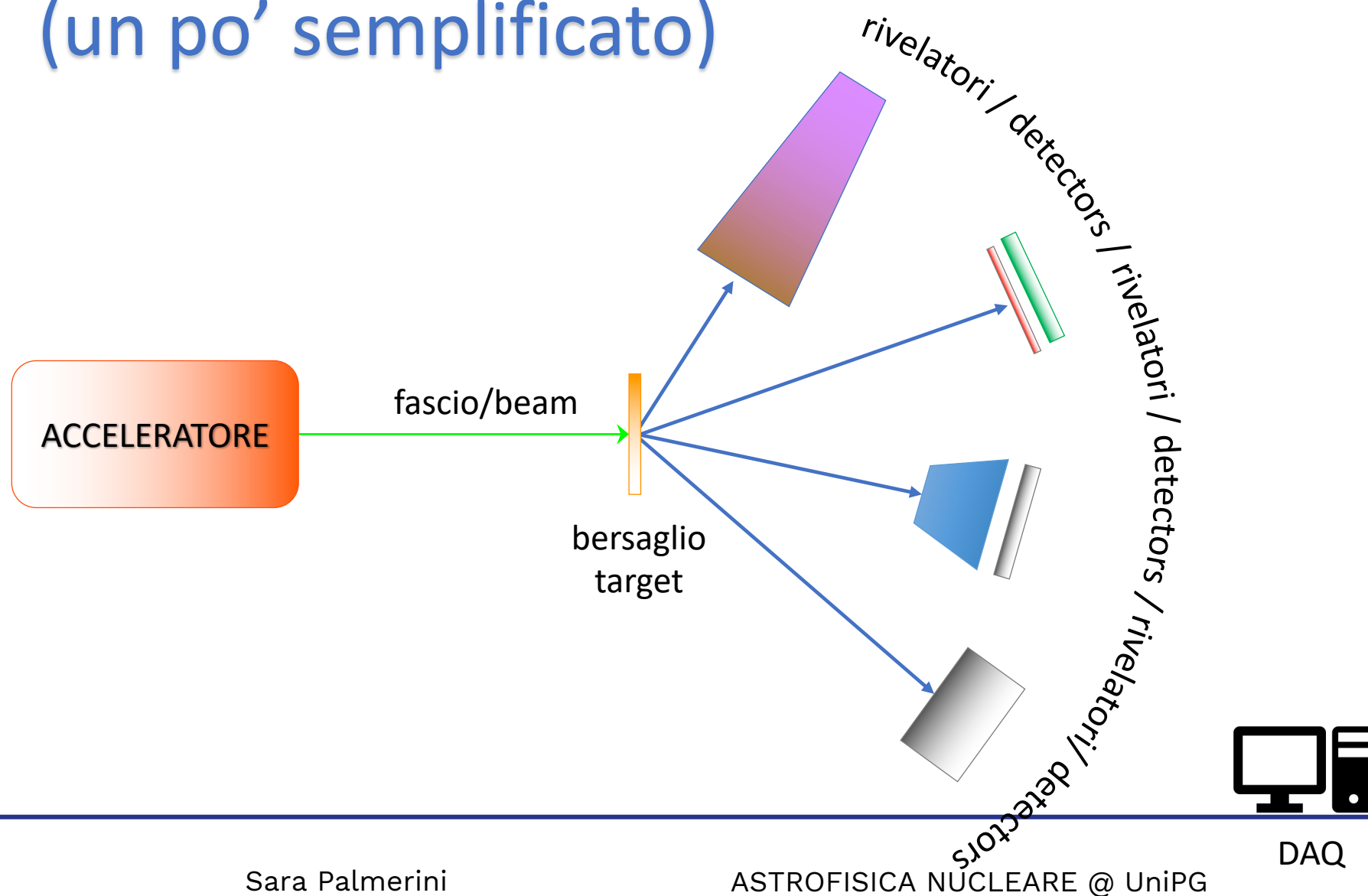
unità: MeV g⁻¹ s⁻¹

Attività e tesi sperimentali



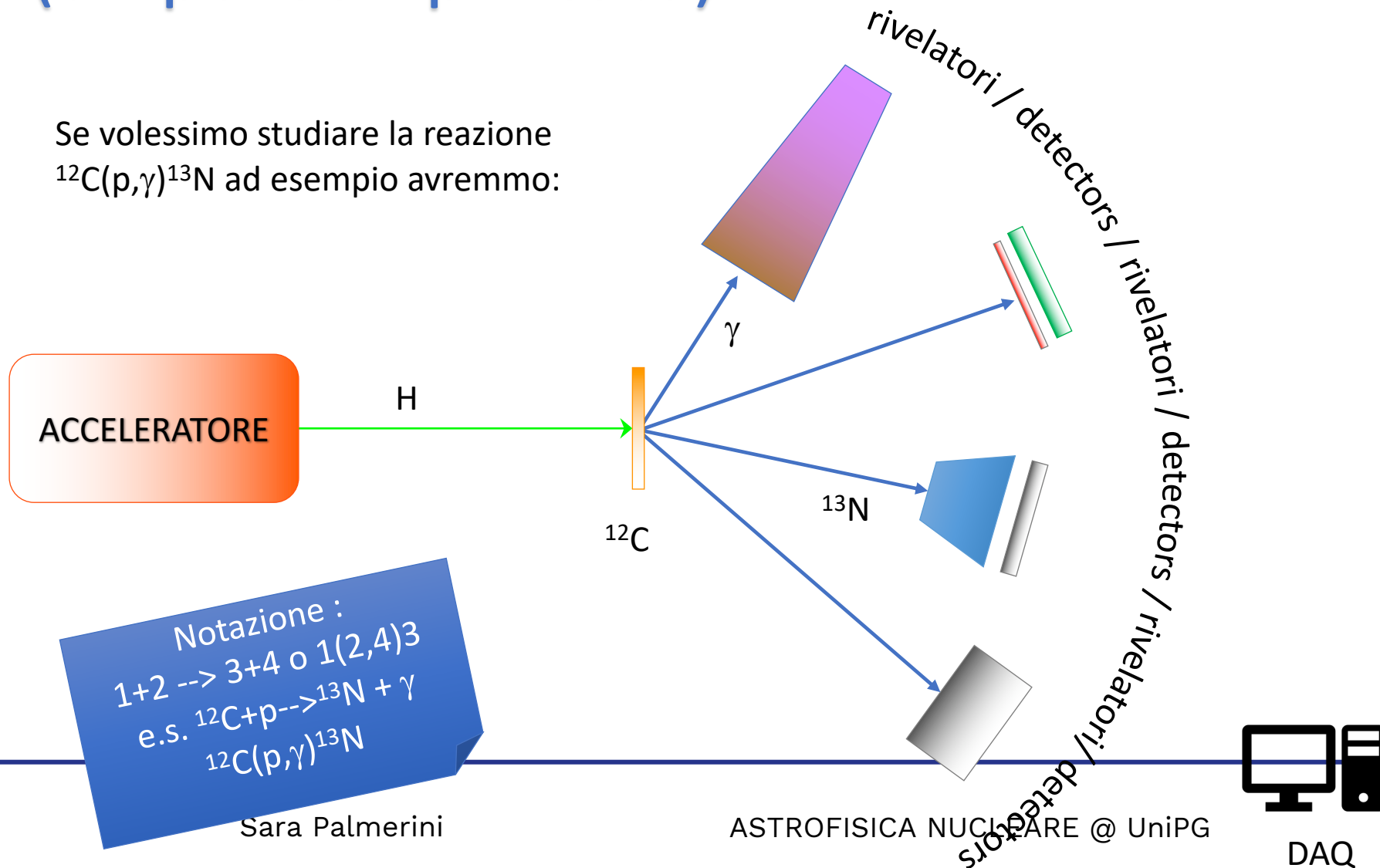
Gli acceleratori

Un esperimento di fisica nucleare (un po' semplificato)



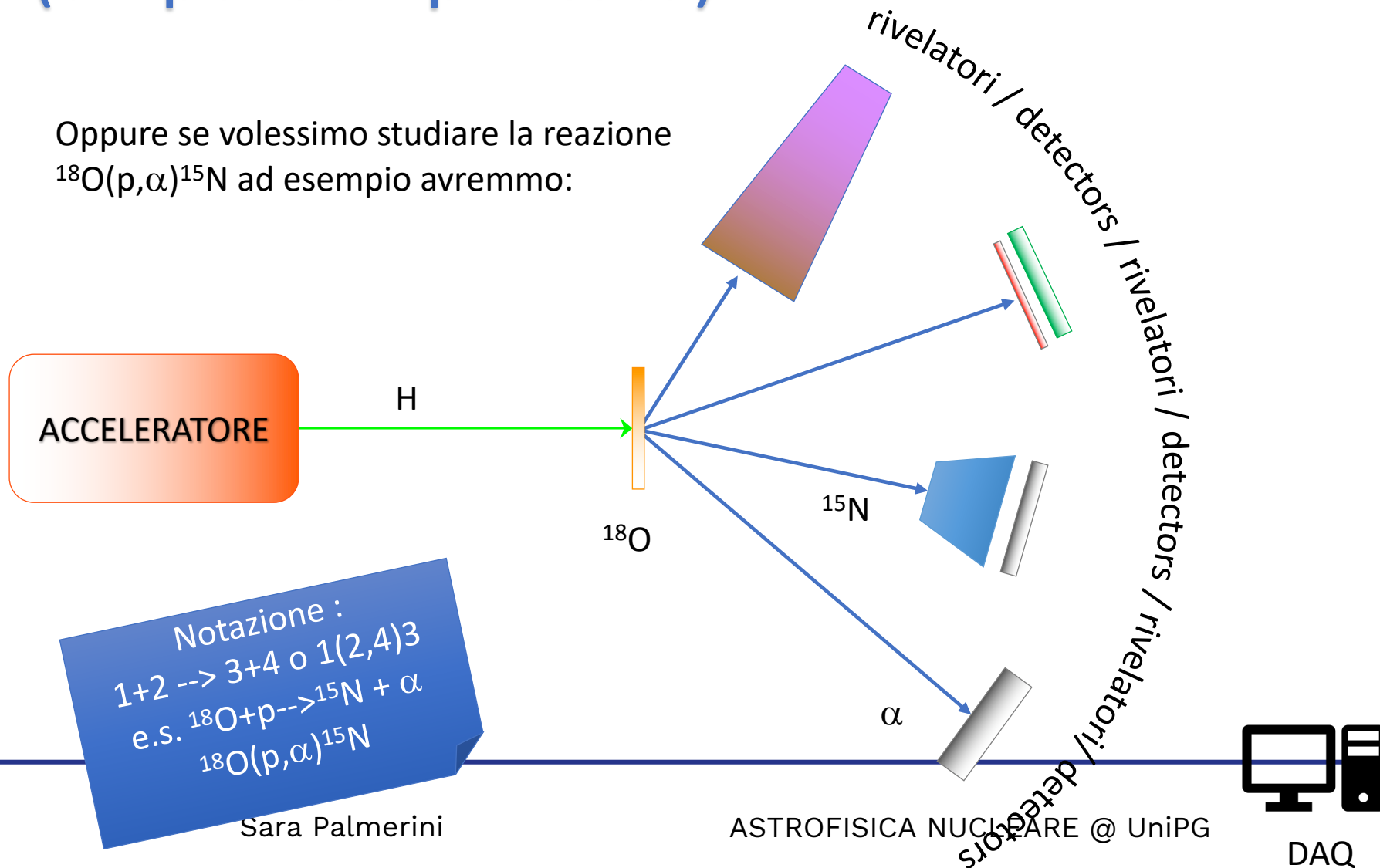
Un esperimento di fisica nucleare (un po' semplificato)

Se volessimo studiare la reazione
 $^{12}\text{C}(p,\gamma)^{13}\text{N}$ ad esempio avremmo:



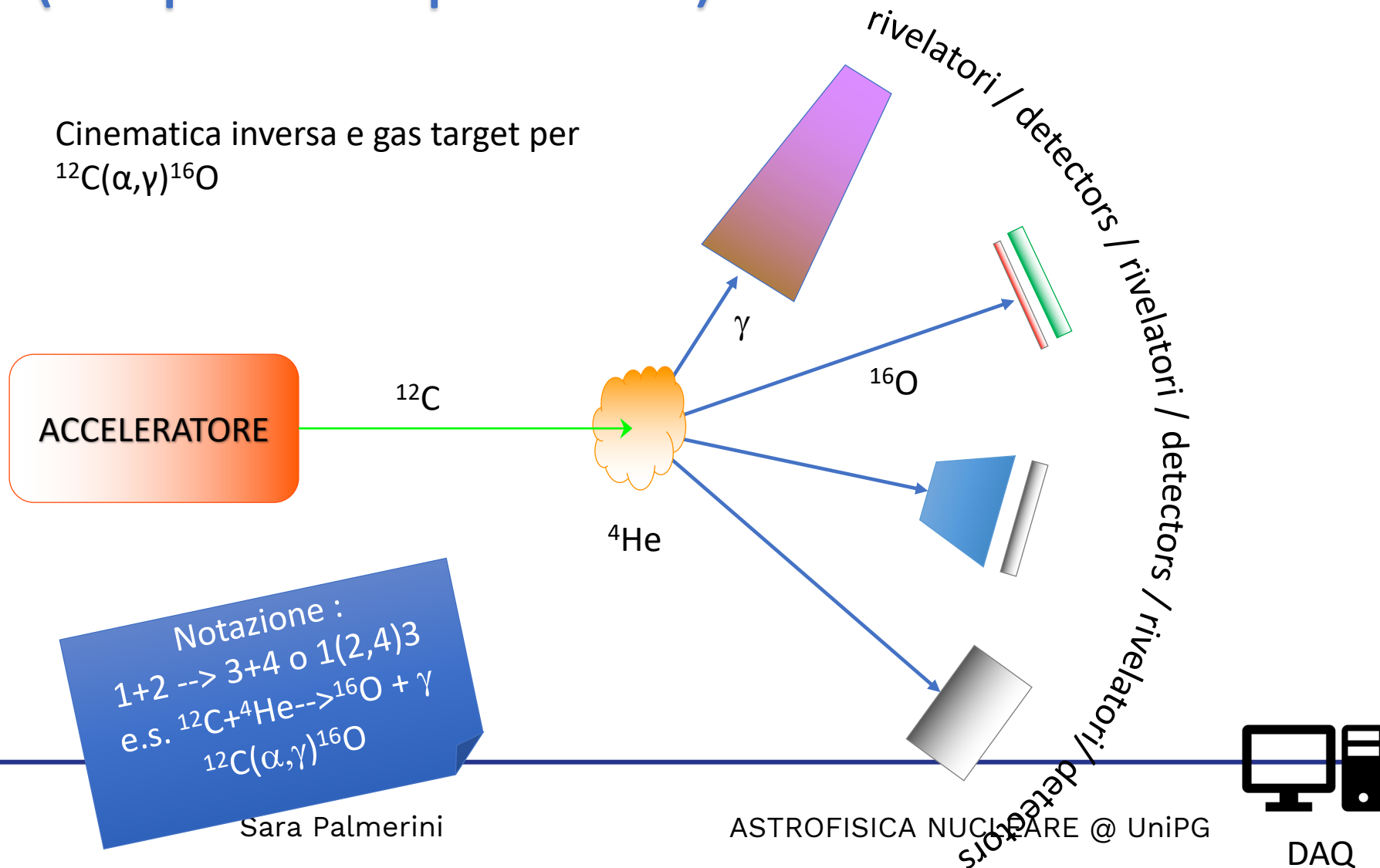
Un esperimento di fisica nucleare (un po' semplificato)

Oppure se volessimo studiare la reazione
 $^{18}\text{O}(p,\alpha)^{15}\text{N}$ ad esempio avremmo:



Un esperimento di fisica nucleare (un po' semplificato)

Cinematica inversa e gas target per
 $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$

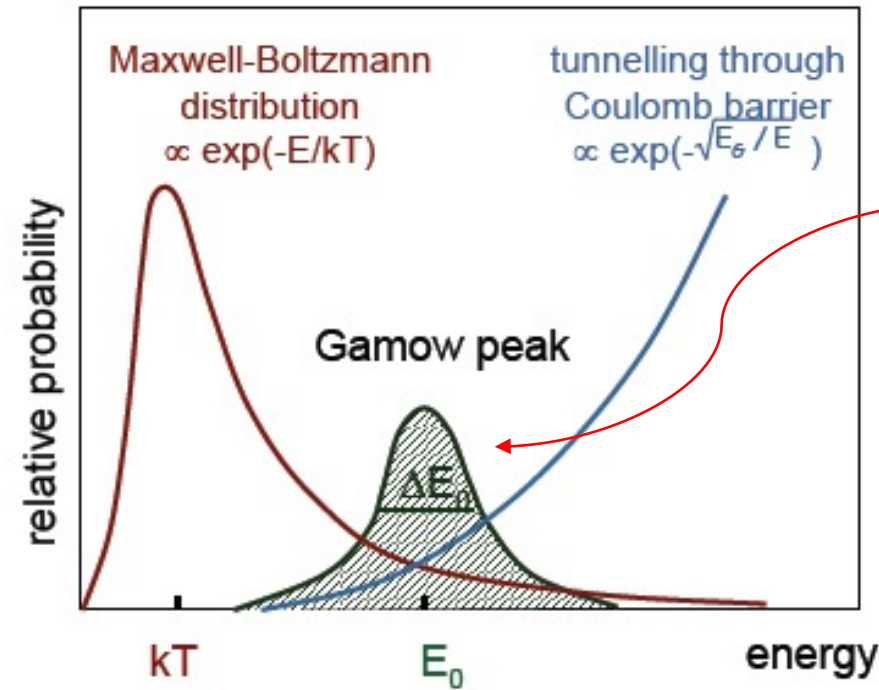
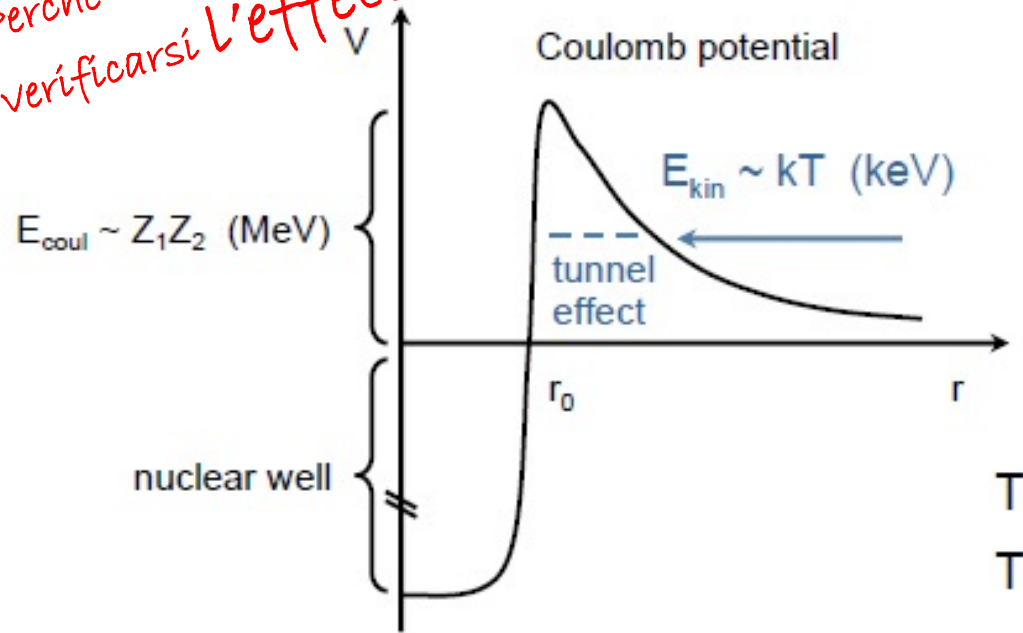


2 problemi da risolvere

- Reazioni di cattura neutronica:
 - REPERIRE TARGET O FASCIO ACCELERATO DI NEUTRONI
- Reazioni tra particelle cariche:
 - LA REPULSIONE COULOMBIANA

Misurare reazioni di fusione tra particelle cariche

Perché una reazione avvenga deve verificarsi l'effetto tunnel



Massima probabilità che avvenga la reazione dipende da T



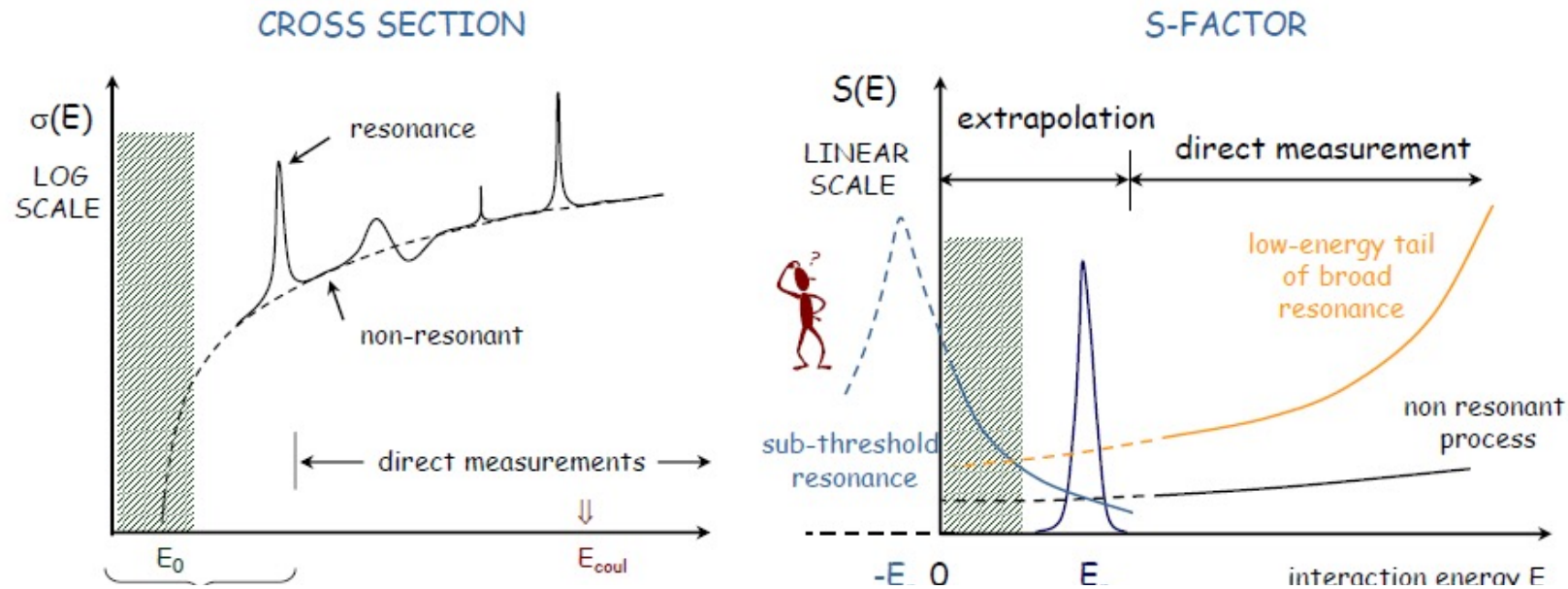
Misurare reazioni di fusione tra particelle cariche

Gamow peak: energy window where information on nuclear processes must be obtained

BUT

$kT \ll E_0 \ll E_{\text{coul}} \Rightarrow 10^{-18} \text{ barn} < \sigma < 10^{-9} \text{ barn} \Rightarrow$ Major experimental difficulties

Procedure: measure $\sigma(E)$ over as wide a range as possible, then extrapolate down to E_0 !



N_p = numero di ioni proiettili
in genere, intensità del
fascio stabile 10^{14} pps

N_t = numero di atomi
bersaglio tipicamente 10^{19}
atoms/cm²

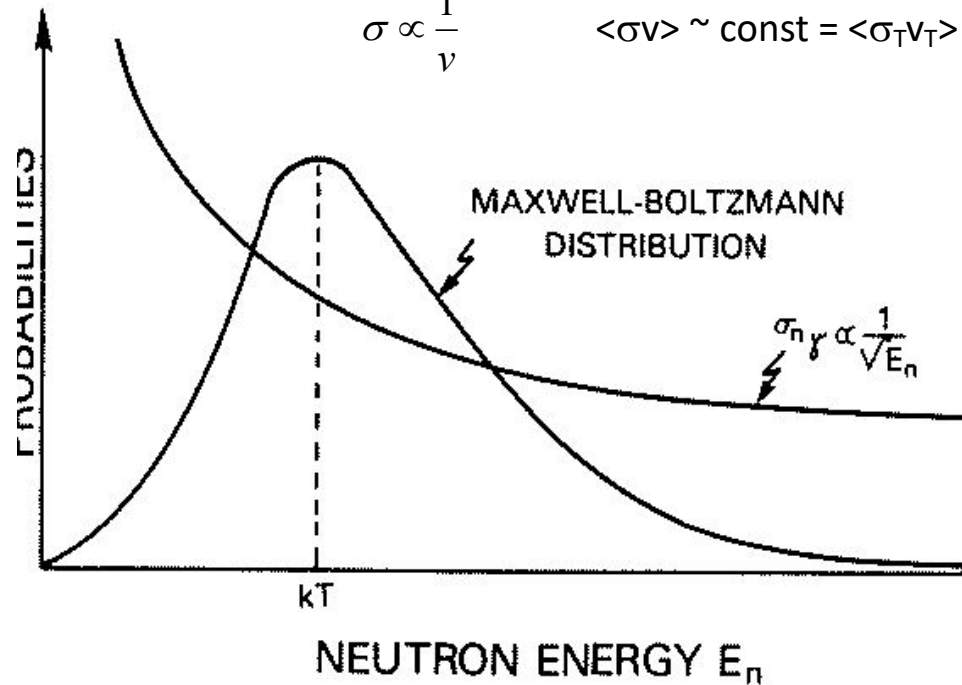
σ = sezione trasversale di
reazione (data dalla
natura) tipicamente, 10^{-15} barn (1 barn = 10^{-24}
cm²)

e = efficienza di rilevamento
in genere, 100% per
particelle cariche ~ 1% per i
raggi

Misurare reazioni di cattura neutronica

$E_0 \sim kT$ = energia di interesse
(e.g. $T \sim 1-6 \times 10^8 \text{ K} \Rightarrow E_0 \sim 30 \text{ keV}$)

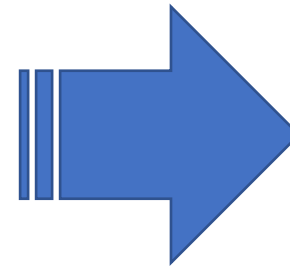
$$\sigma \propto \frac{1}{v} \quad \langle \sigma v \rangle \sim \text{const} = \langle \sigma_T v_T \rangle$$



- Non c'è problema di barriera coulombiana
- Le sezioni d'urto possono essere misurate direttamente alle energie di "astrofisiche"
-basta avere i neutroni all'energia giusta

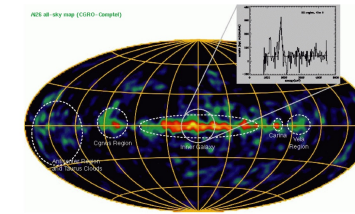
2 proposte di tesi sperimentali

- Misura della sezione d'urto delle reazioni $^{26}\text{Al}(p,\alpha)^{24}\text{Mg}$ e/o $^{26}\text{Al}(n,\alpha)^{23}\text{Mg}$ alle energie tipiche della nucleosintesi stellare



The Astrophysical Case: ^{26}Al

The radioisotope ^{26}Al ($T_{1/2} = 7.17 \times 10^5 \text{ yr}$) is of outstanding importance in astrophysics



Observation of 1808.65 keV γ -rays from the decay of ^{26}Al to ^{26}Mg in the interstellar medium demonstrated that ^{26}Al nucleosynthesis does occur in the **present Galaxy**. The present-day equilibrium mass of ^{26}Al was found to be $2.8 \pm 0.8 M_\odot$.

The irregular distribution of ^{26}Al emission seen along the plane of the Galaxy provided the main argument for the idea that **massive stars** dominate the production of ^{26}Al . (Diehl et al 2006)

In CAIs (the oldest solid of the Solar System):

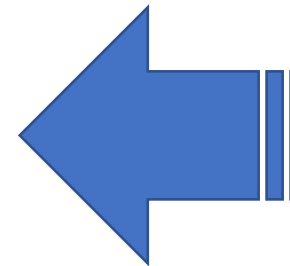
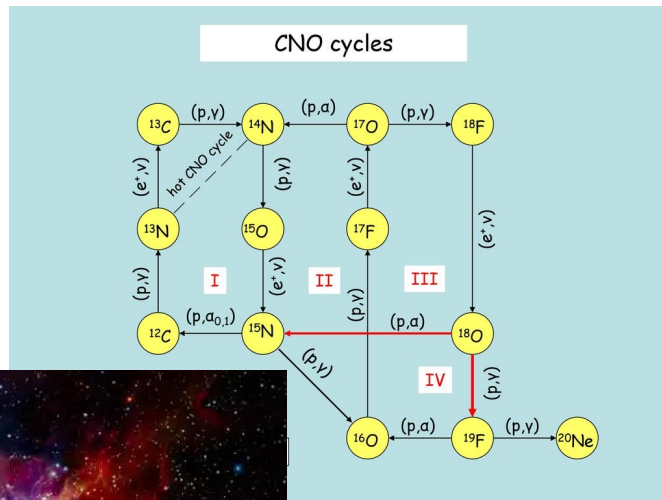
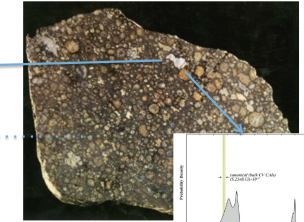
the inferred $6.5 \times 10^{-5} < (^{26}\text{Al}/^{27}\text{Al})_0 < 2 \times 10^{-6}$.

There is no correlation between O- and Mg-isotope compositions.

→ ^{26}Al was injected into the ^{26}Al -poor protosolar nebula, possibly by a wind from a neighboring massive star.

Presolar grains

Corundum, hibonite and carbonaceous chondrites formed before the birth of the solar system show excesses in ^{26}Mg . The highest ratios are found in grains originated in supernova ejecta, but the largest number of grains with $^{26}\text{Al}/^{27}\text{Al} > 3 \times 10^{-8}$ (at least 100 times larger than the solar value) are of the type that come from **low mass stars**.



- Misura della sezione d'urto delle reazioni $^{19}\text{F}(p,\alpha)^{16}\text{O}$ alle energie tipiche della nucleosintesi stellare

Iter dell'esperimento (lavoro tesi)

Selezione problema
«astrofisico»

progetto
esperimento

misura (allestimento
e data taking)

Detector
calibration

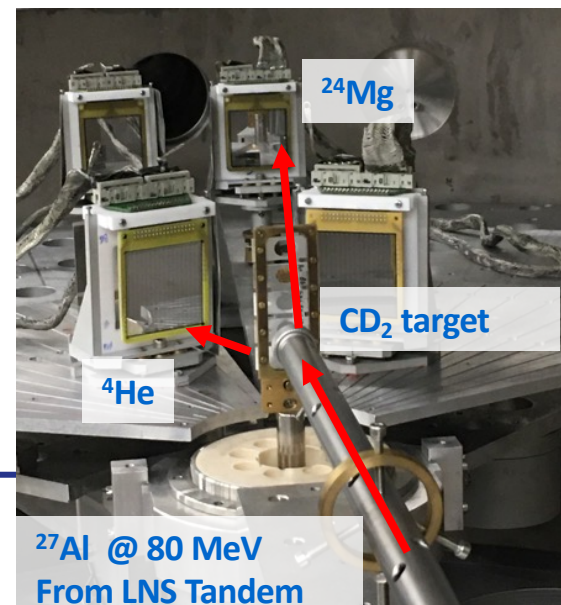
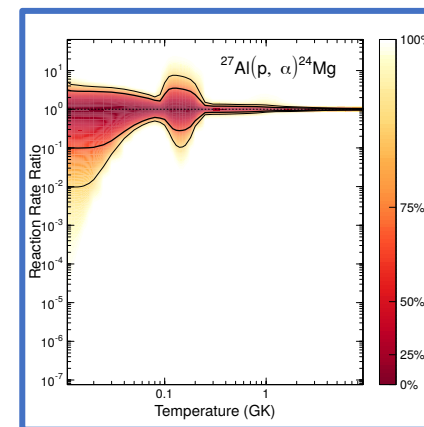
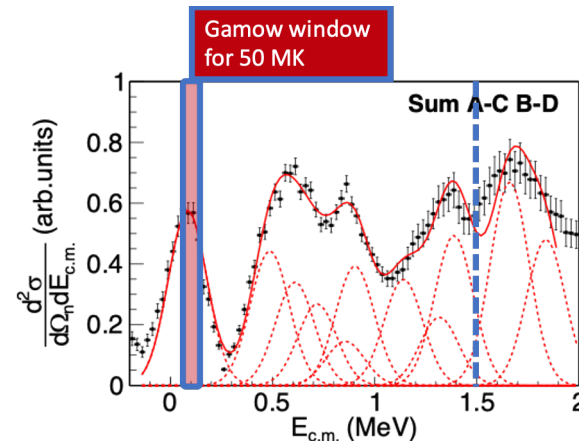
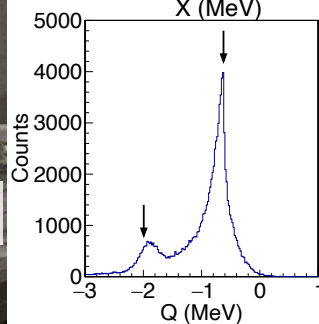
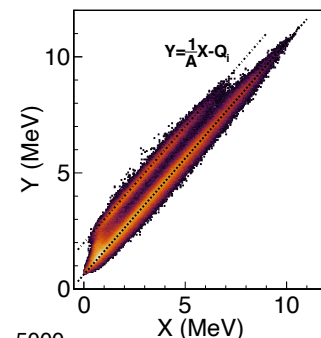
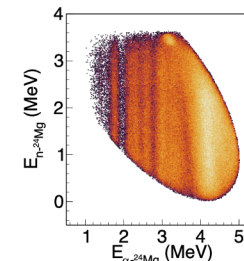
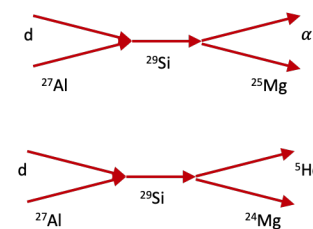
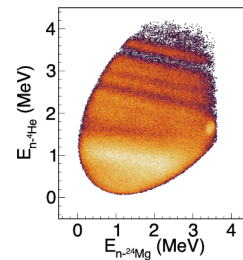
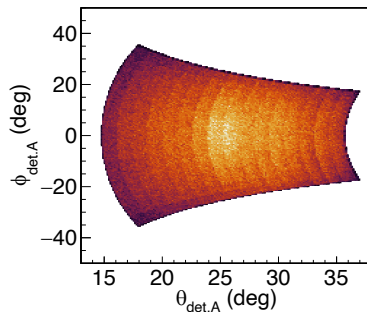
Particle
identification

Reaction channel
selection

QF process
selection

C-M energy
spectra

Reaction rate
extraction



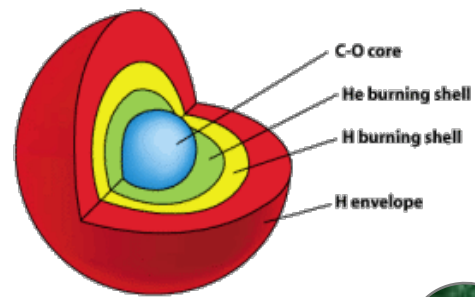
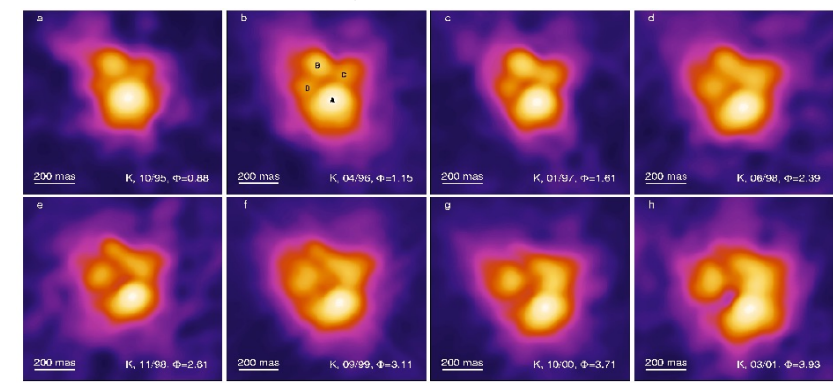
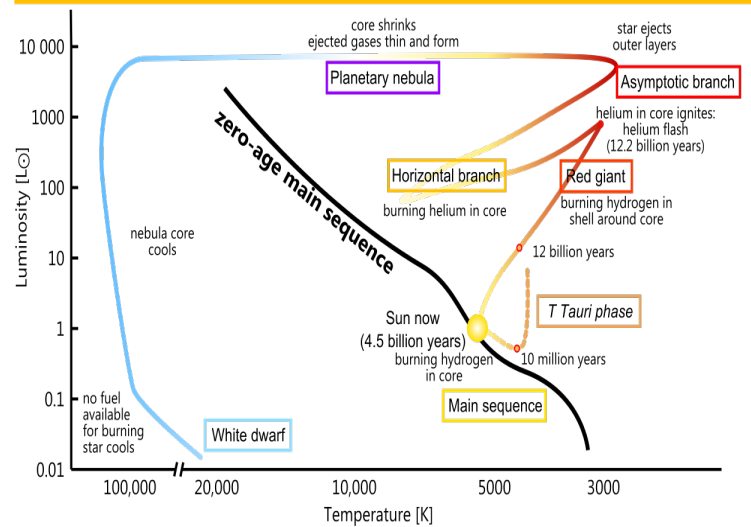
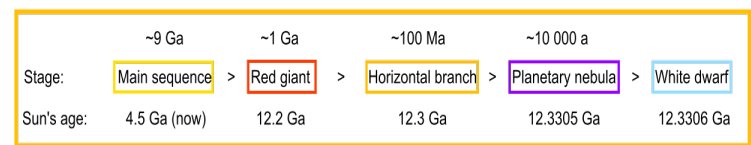
^{27}Al @ 80 MeV
From LNS Tandem

Sara Palmerini

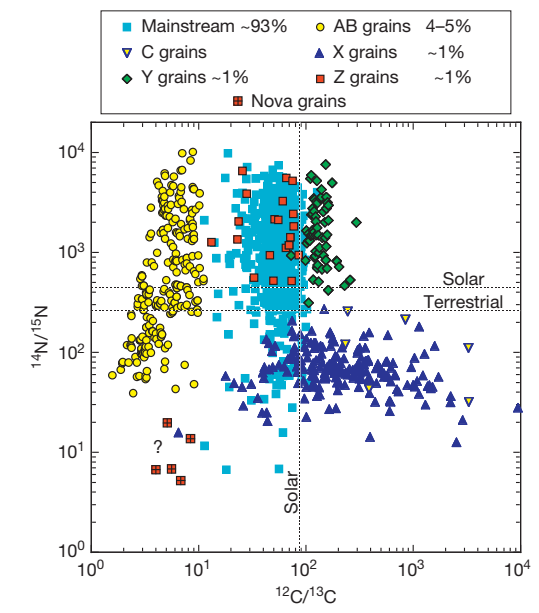
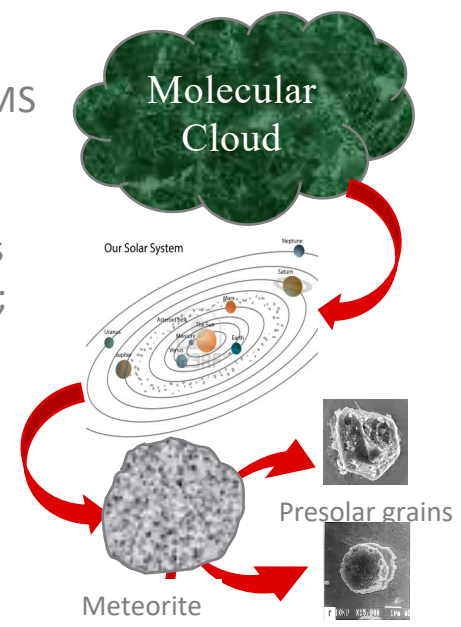
ASTROFISICA NUCLEARE @ UniPG

Attività e tesi teoriche

Stelle del braccio asintotico (AGB) delle giganti e processo s

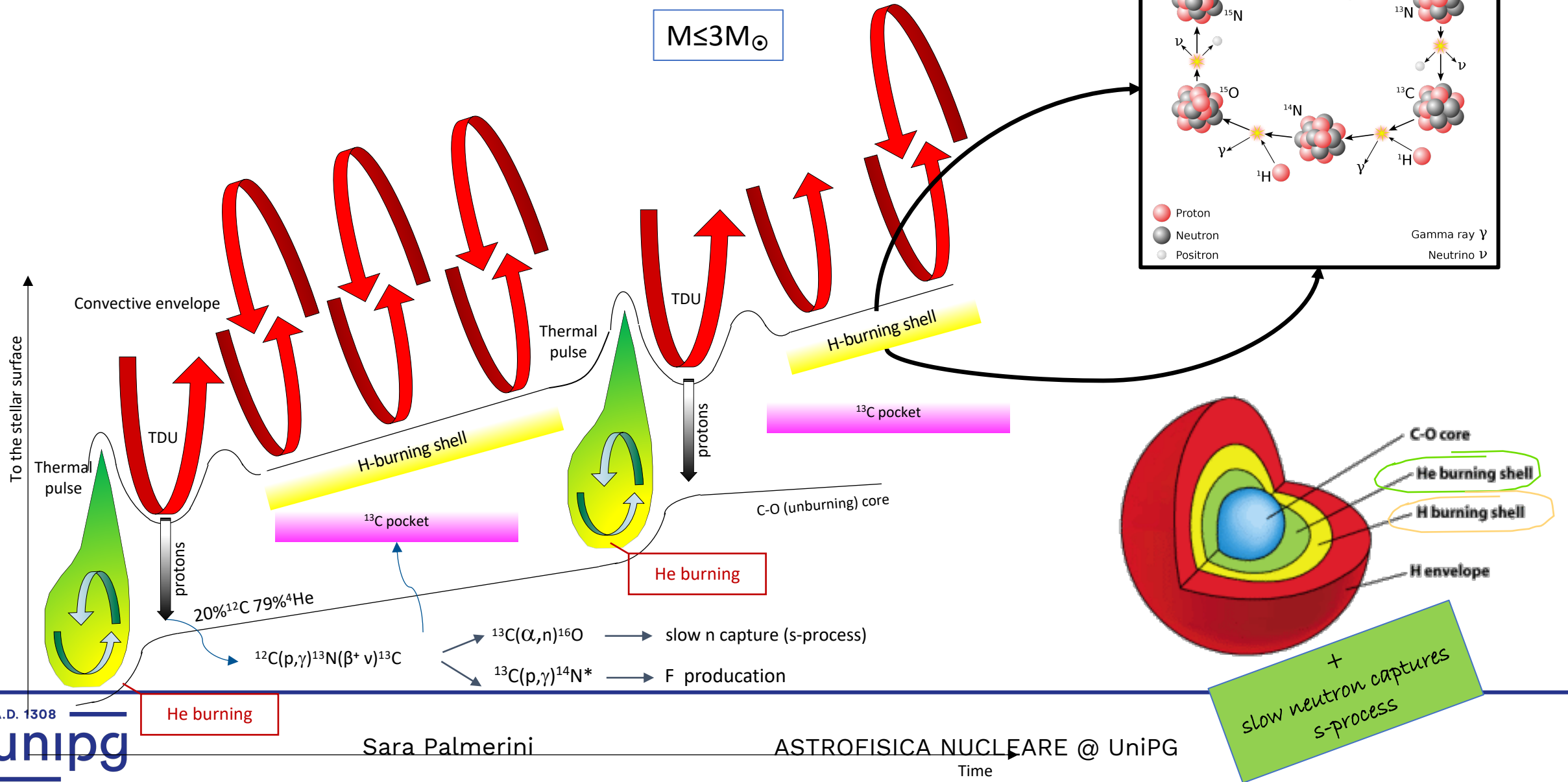


Despite their low masses LMS are so numerous to contribute for 75% to the total mass return from stars to the ISM (Sedlmayr 1994);

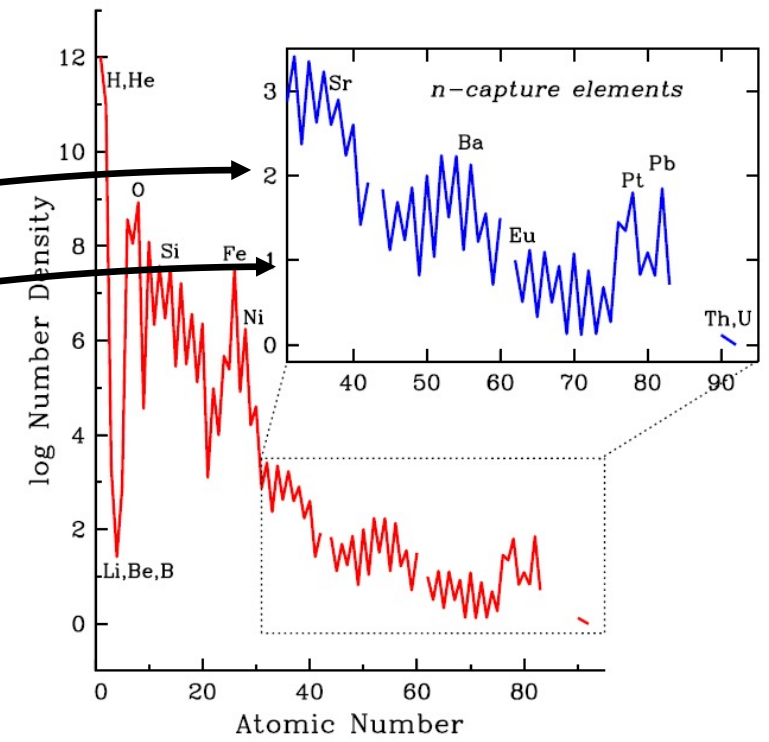
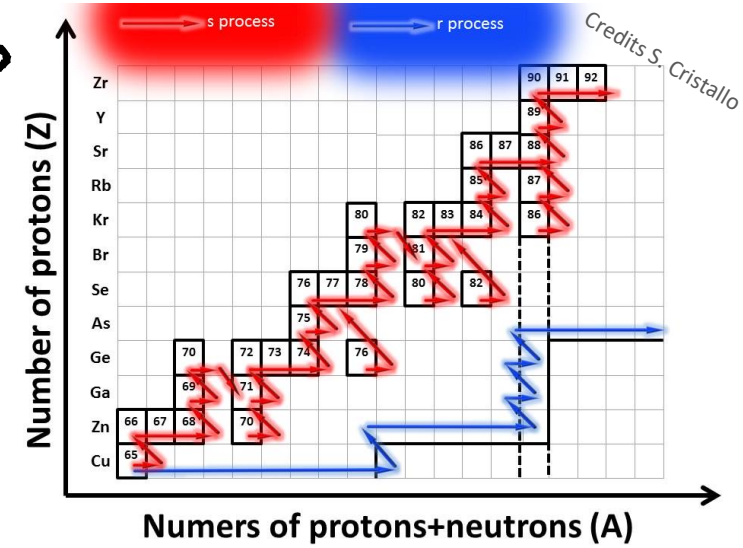
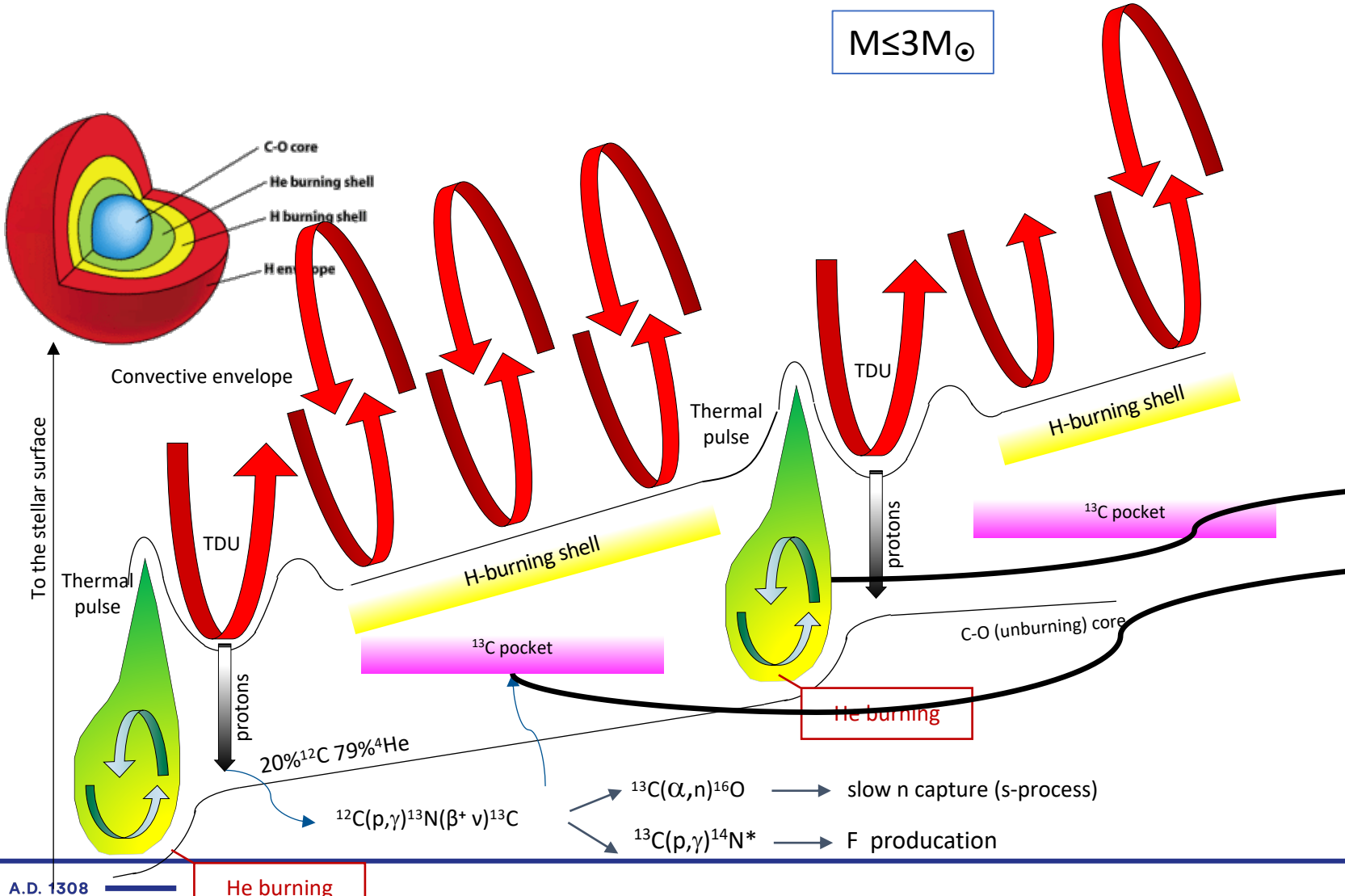


HOW DOES AN AGB STAR WORK?

$M \leq 3M_{\odot}$

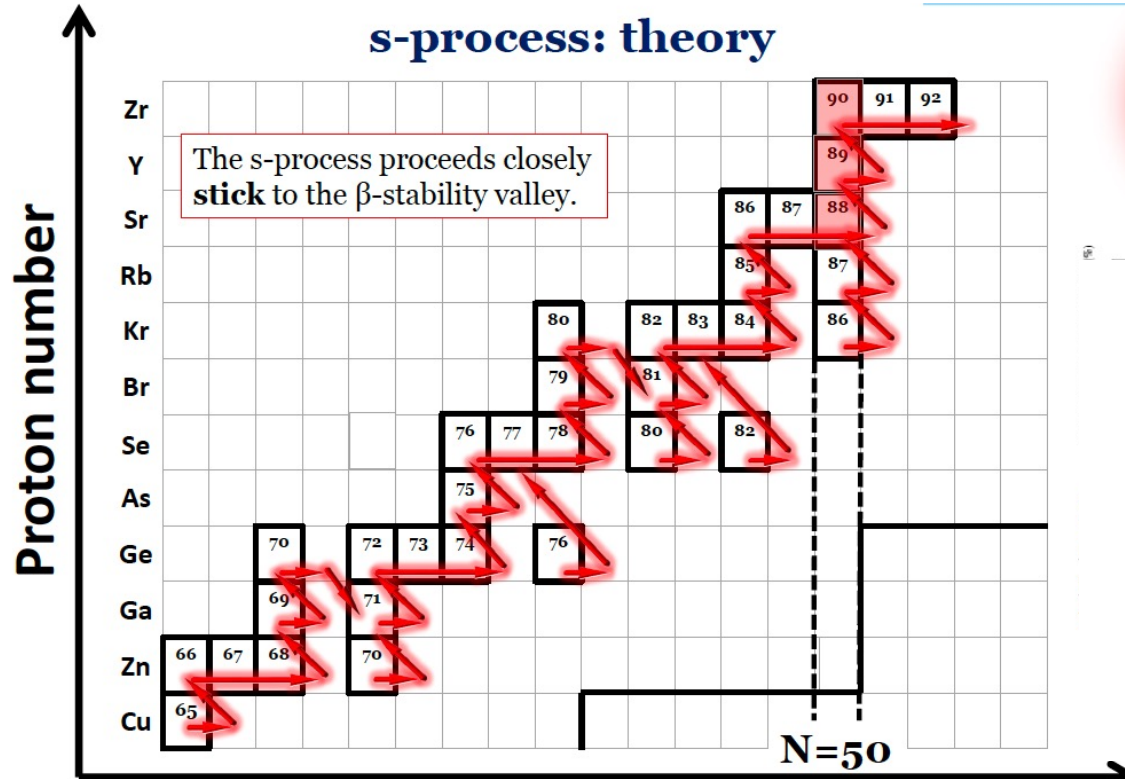


HOW DOES AN AGB STAR WORK?

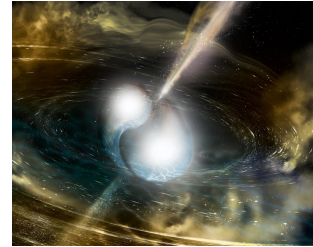


Nucleosintesi da cattura neutronica

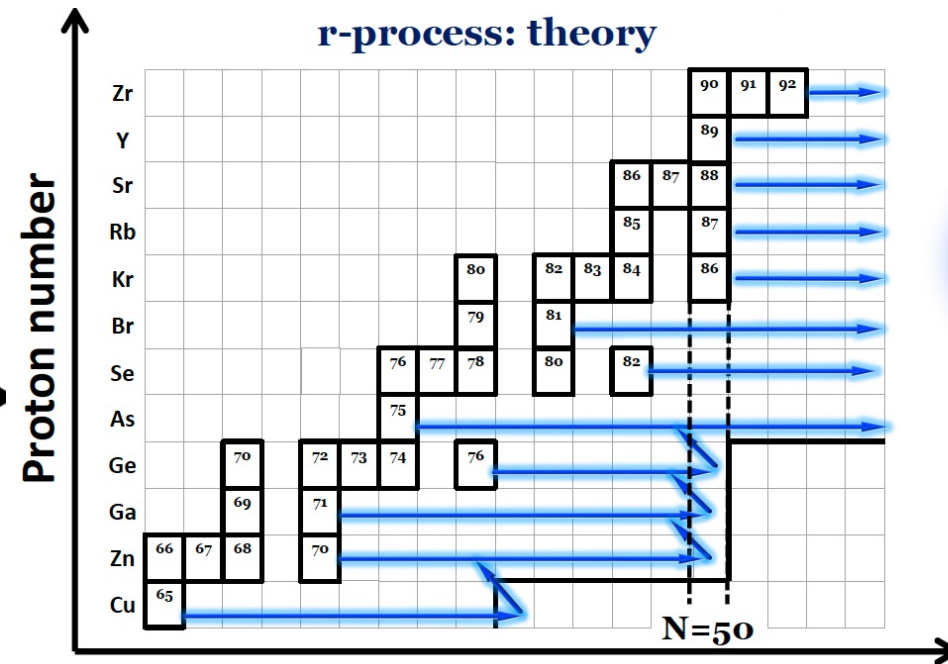
s-process: theory



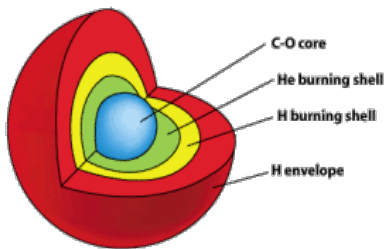
s process
 $N_n \sim 10^7 \text{ n/cm}^3$



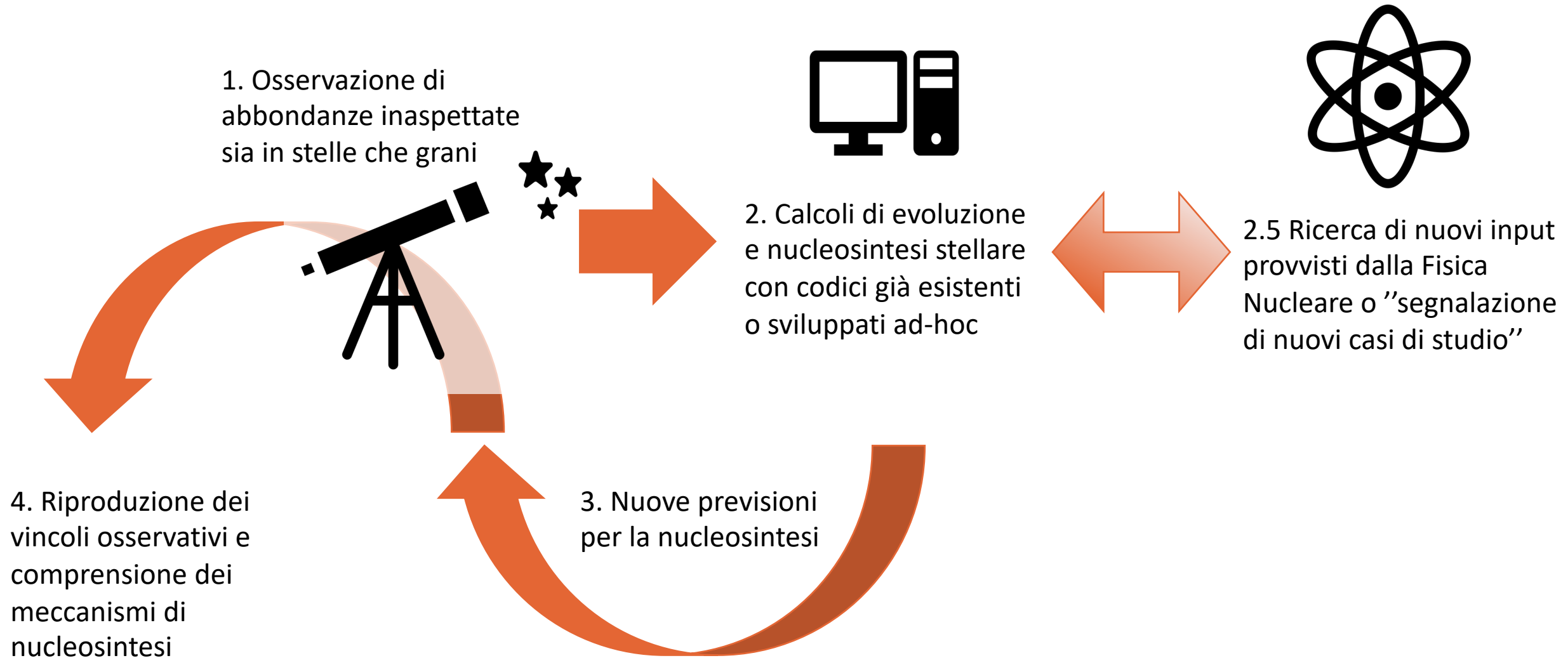
r-process: theory



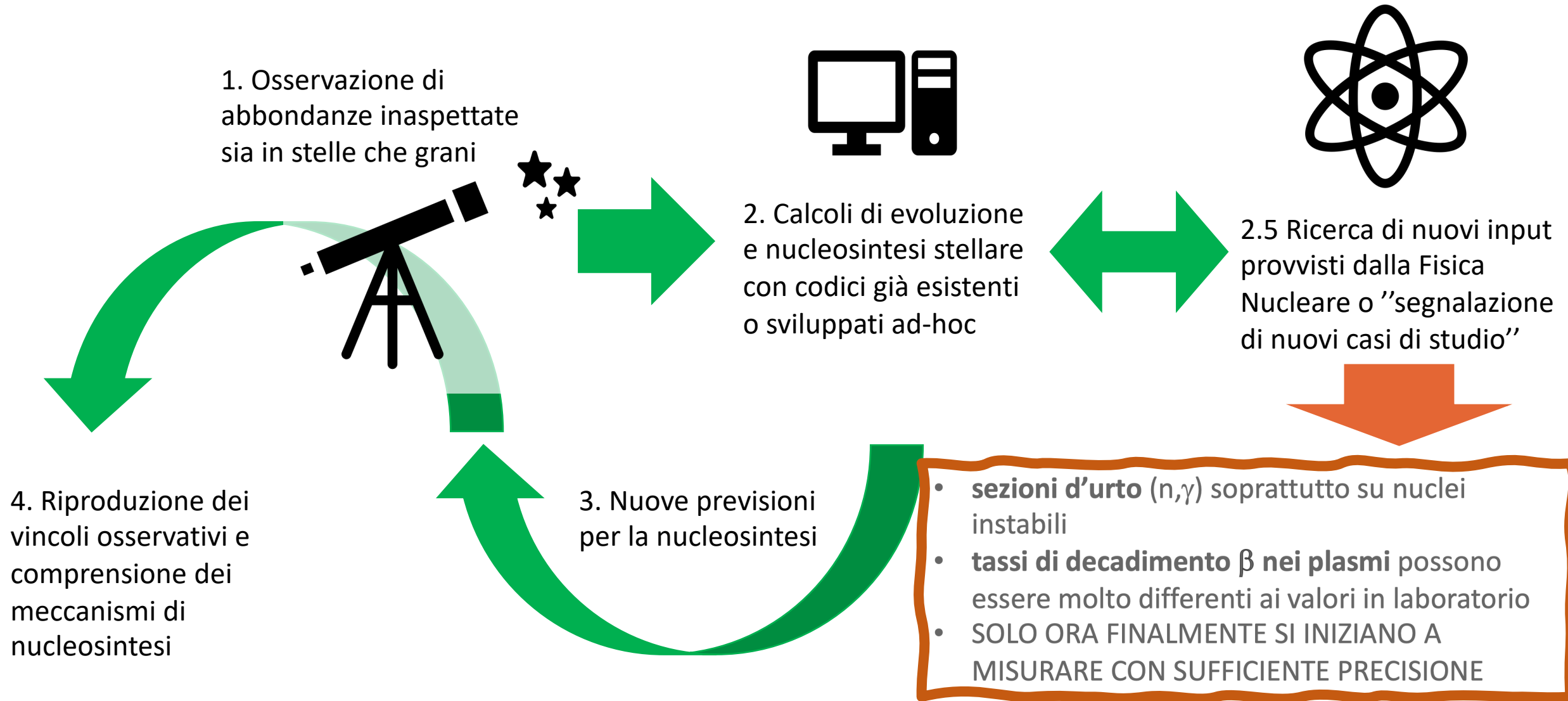
r process
 $N_n > 10^{21} \text{ n/cm}^3$



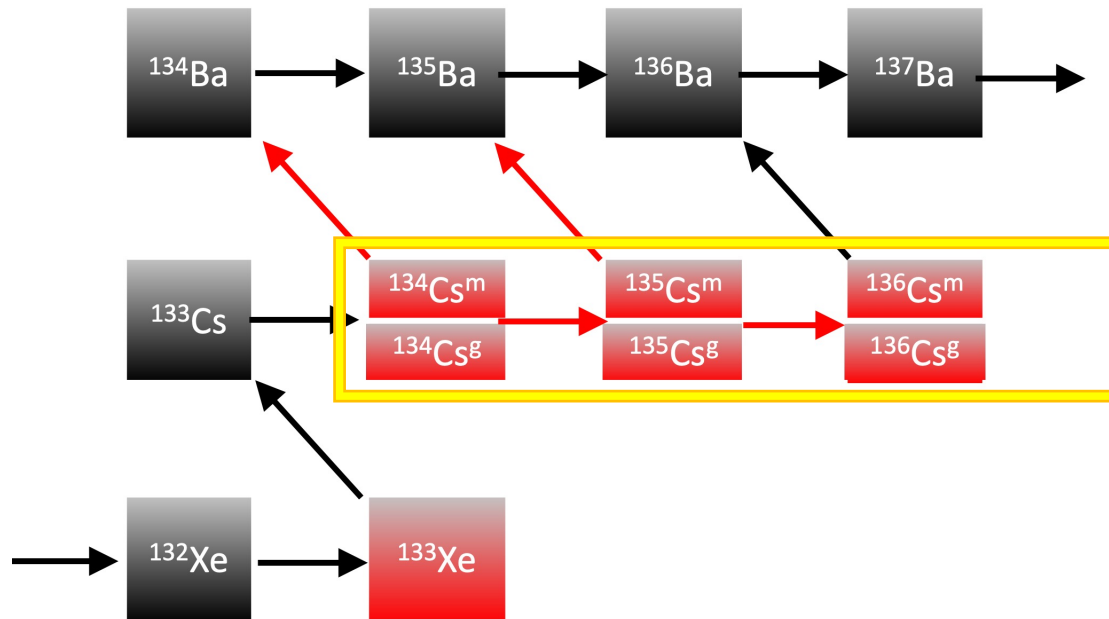
Iter di un lavoro...anche di tesi



Iter di un lavoro...anche di tesi



Un esempio: abbondanze isotopiche dello Ba (da processo s) nei grani presolari di origine AGB



Siamo vicini ad $N=82$

⇒ Decadimenti

⇒ Stati isomerici

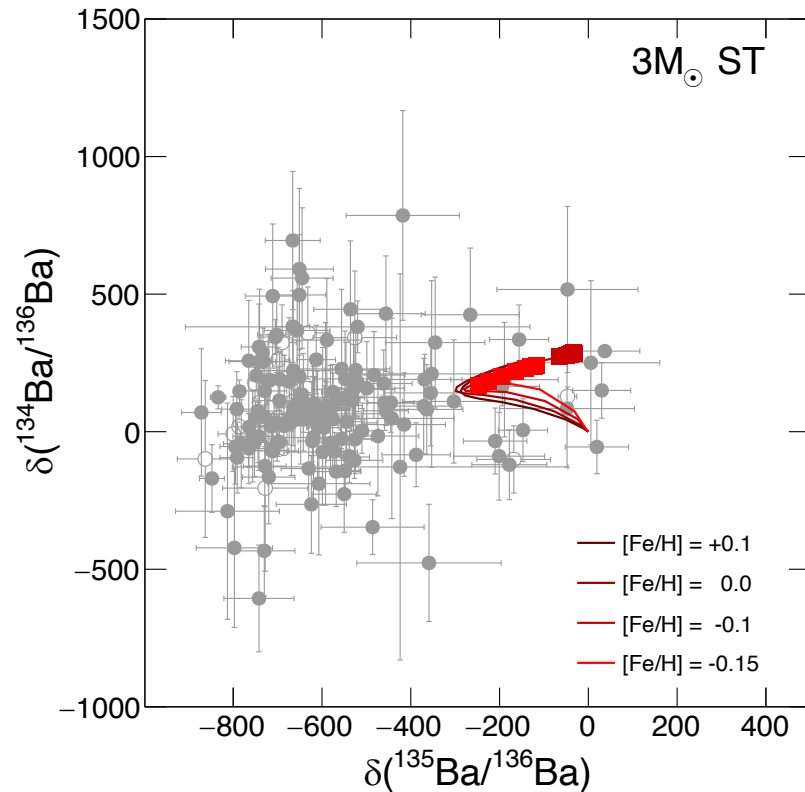
⇒ Branching della nucleosintesi

⇒ Sezioni d'urto «piccole»

⇒ Sezioni d'urto difficilmente misurabili

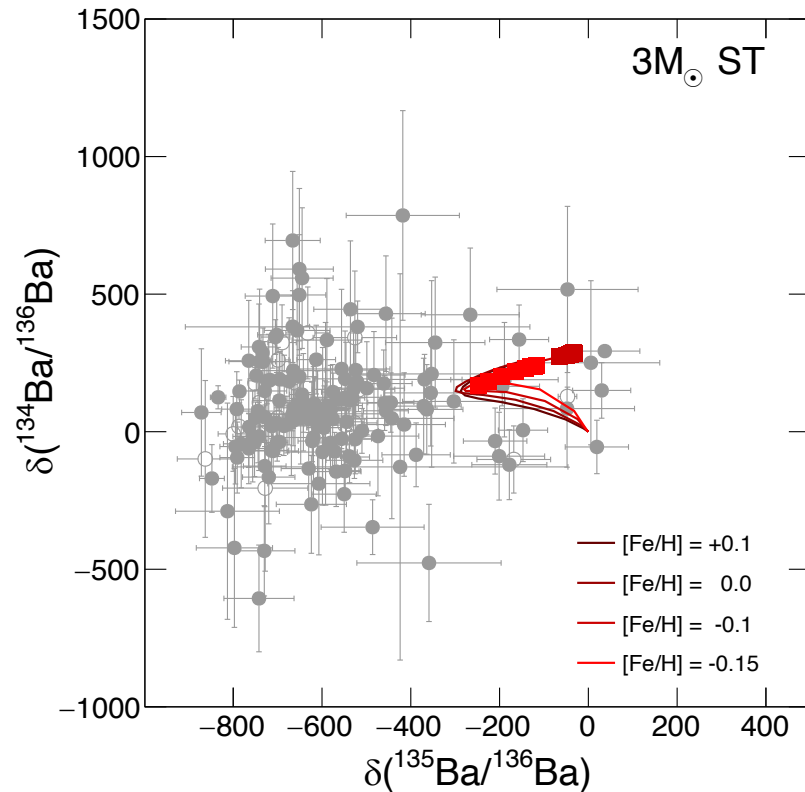
⇒ Input nucleari quasi tutti determinati teoricamente

Un esempio: abbondanze isotopiche dello Ba (da processo s) nei grani presolari di origine AGB: STEP 1 aggiorniamo gli input nucleari

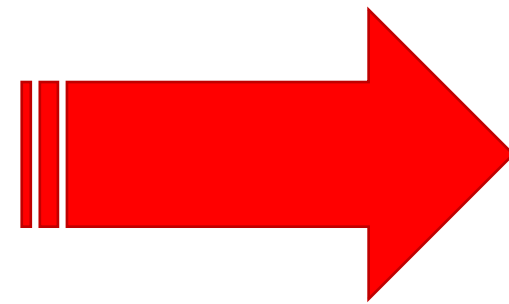


Input nucleari presi dalla letteratura al 2015

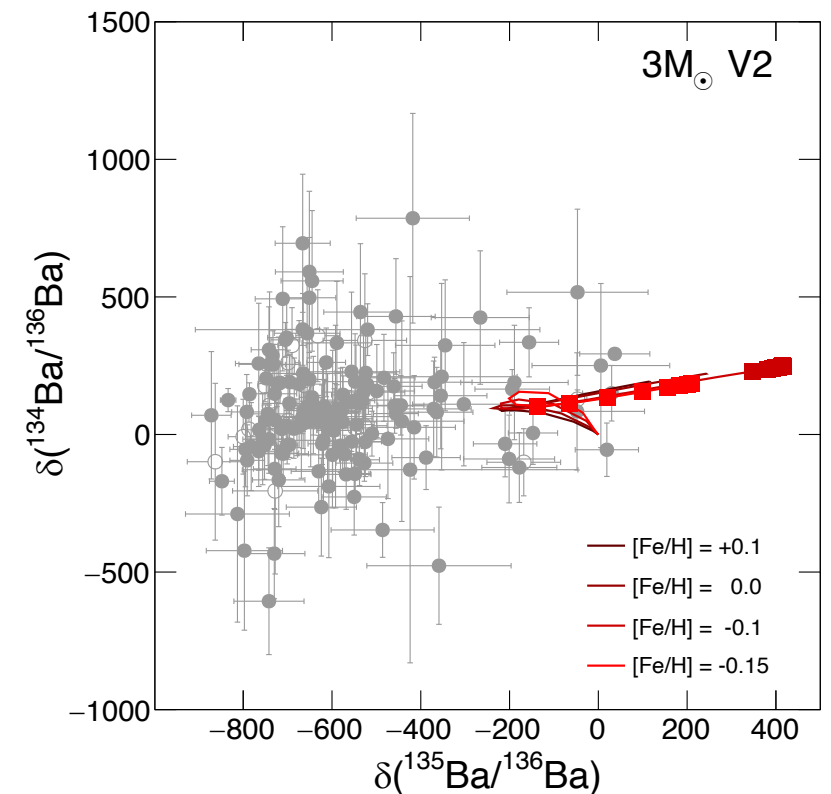
Un esempio: abbondanze isotopiche dello Ba (da processo s) nei grani presolari di origine AGB: STEP 1 aggiorniamo gli input nucleari



Input nucleari presi dalla letteratura al 2015

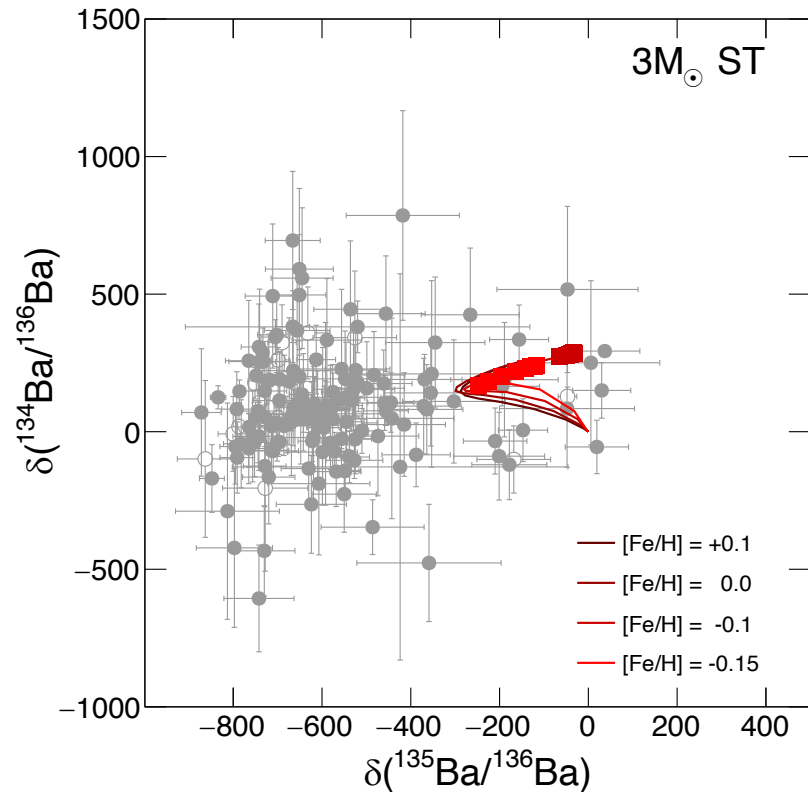


- decay rate of ^{134}Cs enhanced by a factor of 8 respect to TY 1987 (see next talk)
- Similar effects would be induced by variations in the ^{135}Cs neutron-capture cross section

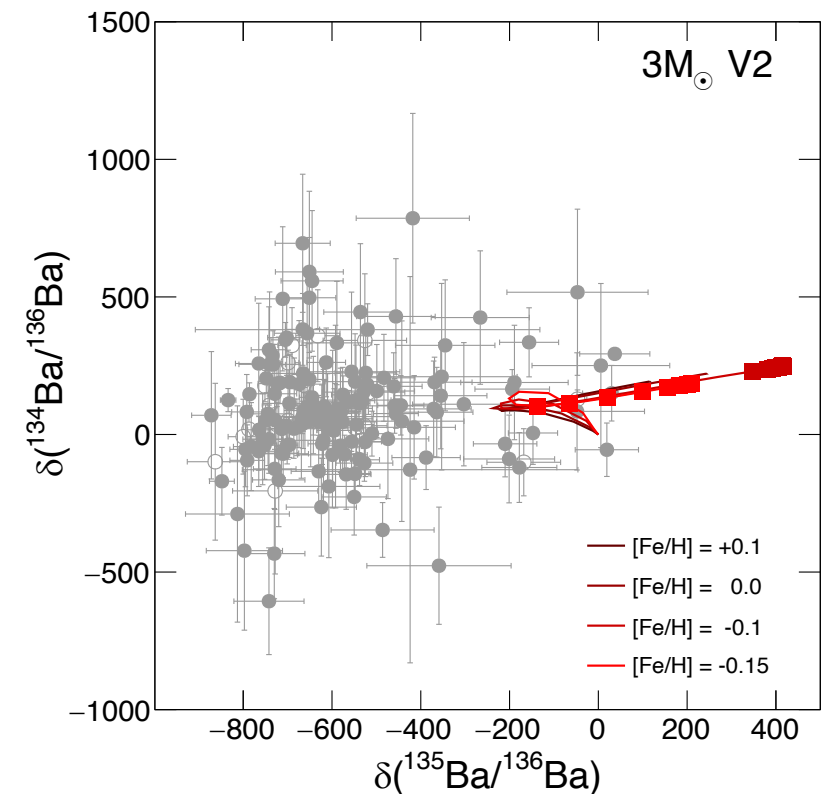


Input nucleari presi dalla letteratura nel 2021

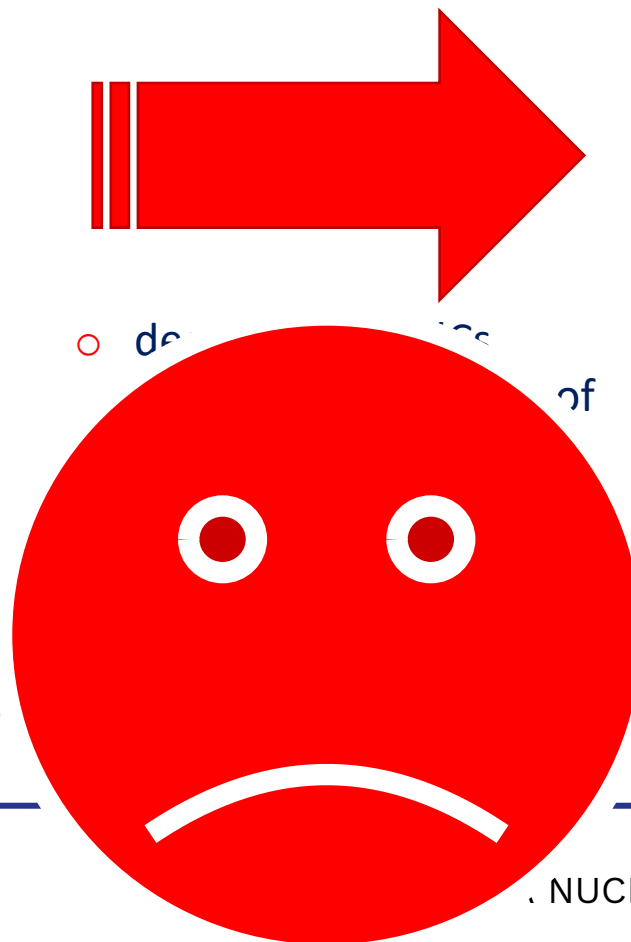
Un esempio: abbondanze isotopiche dello Ba (da processo s) nei grani presolari di origine AGB: STEP 1 aggiorniamo gli input nucleari



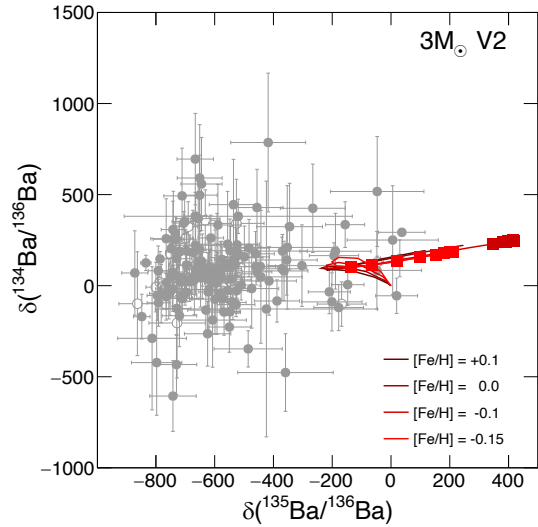
Input nucleari presi dalla letteratura al 2015



Input nucleari presi dalla letteratura nel 2021



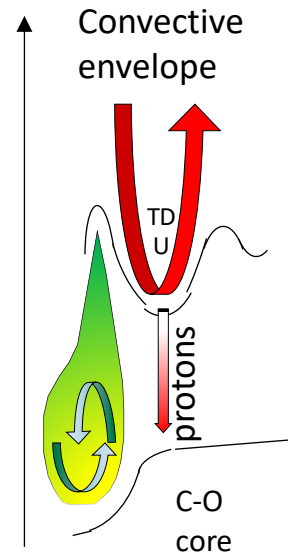
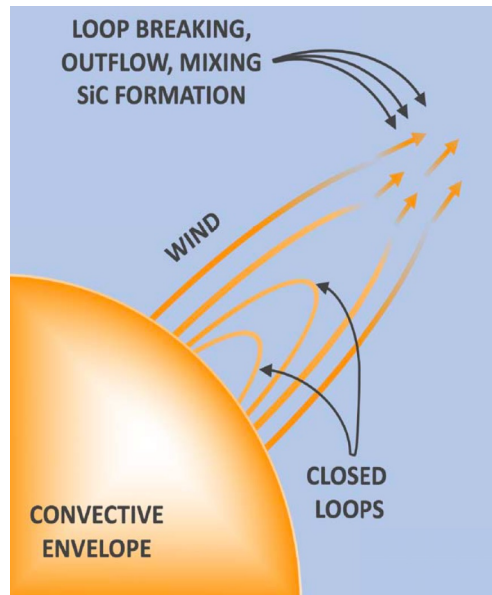
Un esempio: abbondanze isotopiche dello Ba (da processo s) nei grani presolari di origine AGB: STEP 2 cerchiamo la soluzione nella fisica stellare e non nella nucleare



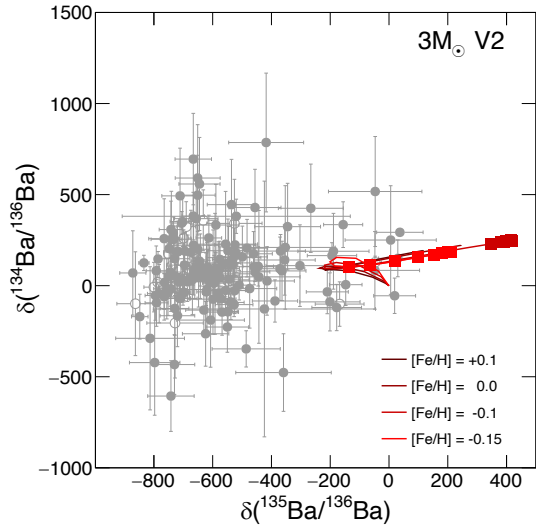
Input nucleari presi
dalla letteratura nel 2021



Nuovo fenomeno: mixing e
vento magnetico



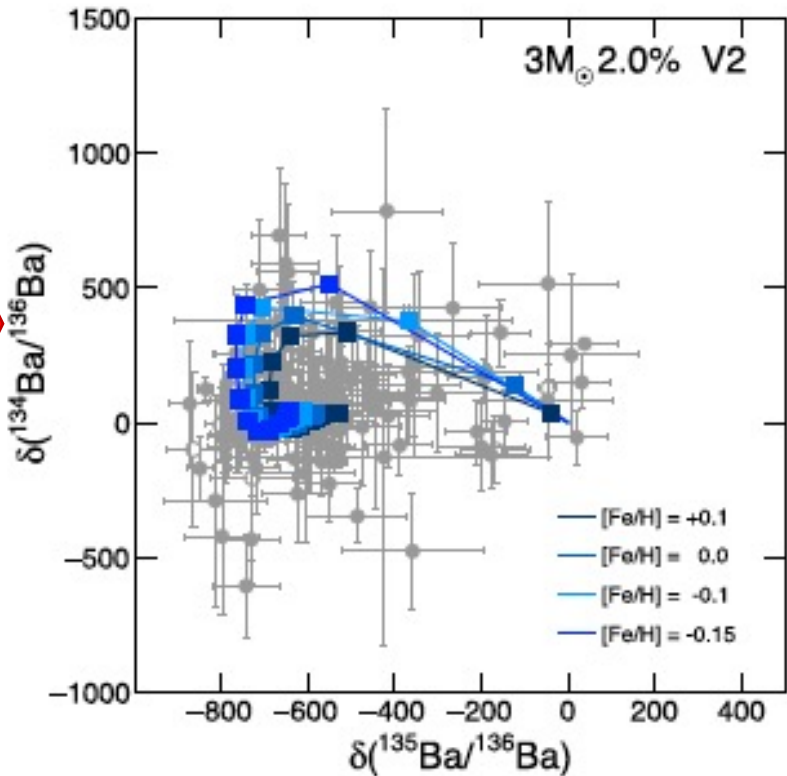
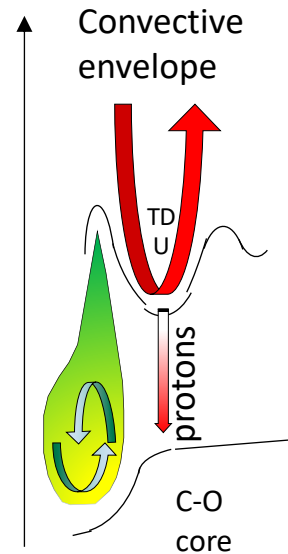
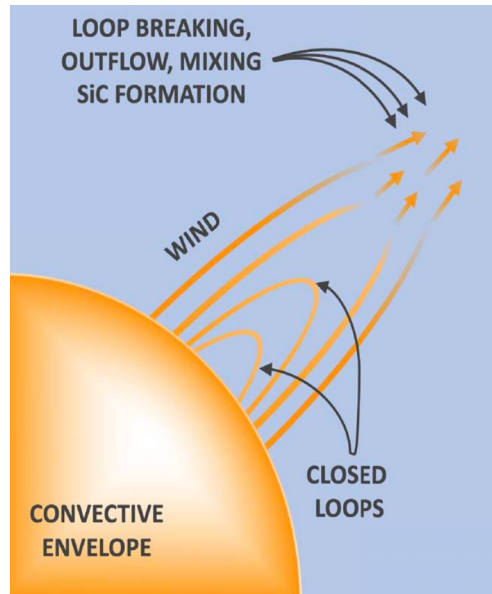
Un esempio: abbondanze isotopiche dello Ba (da processo s) nei grani presolari di origine AGB: STEP 2 cerchiamo la soluzione nella fisica stellare e non nella nucleare



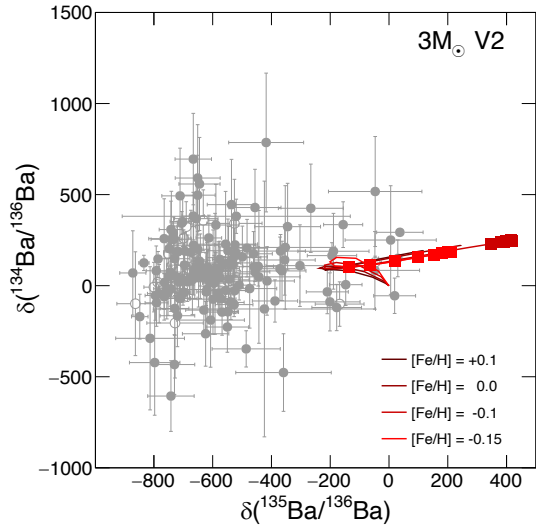
Input nucleari presi dalla letteratura nel 2021



Nuovo fenomeno: mixing e vento magnetico



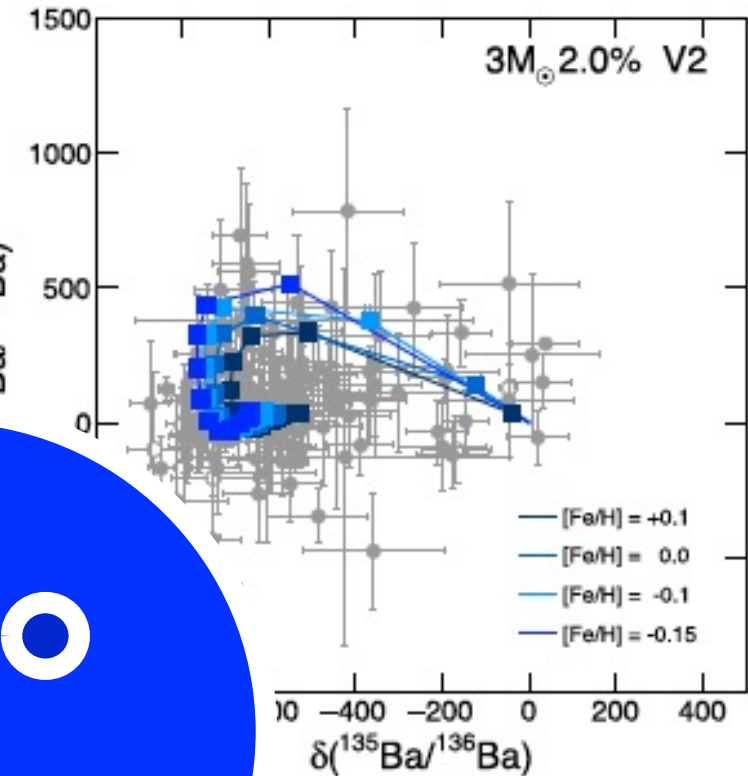
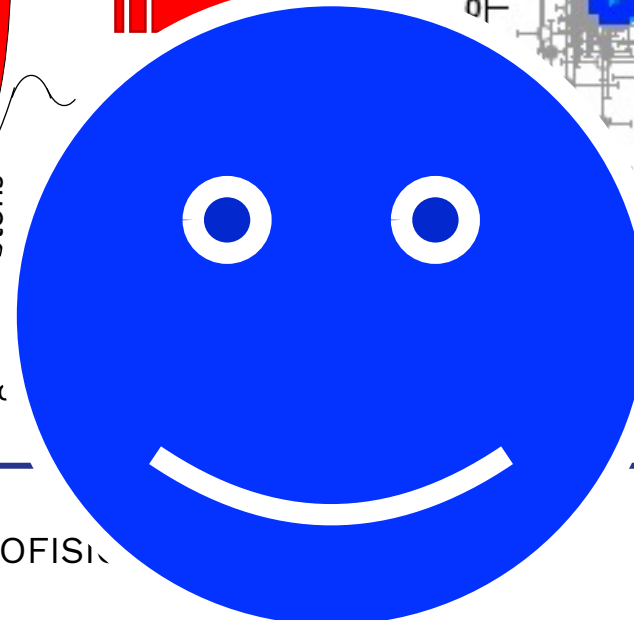
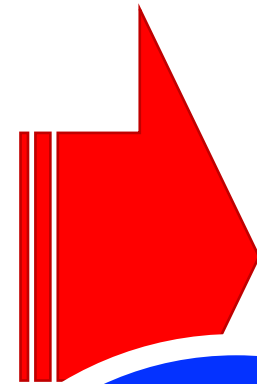
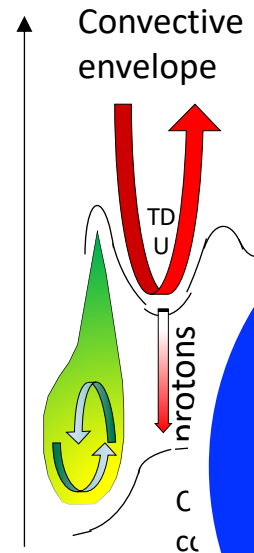
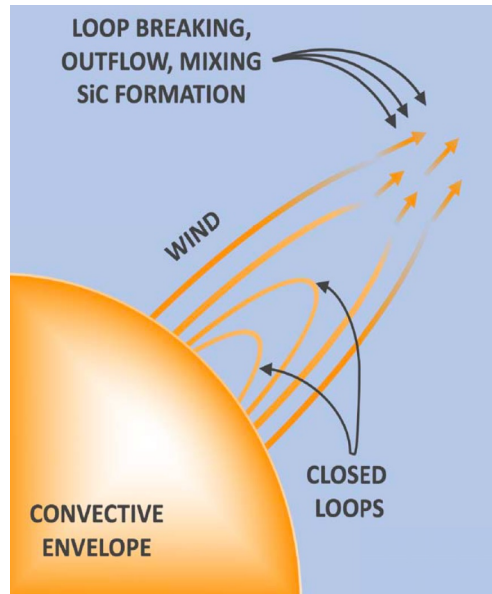
Un esempio: abbondanze isotopiche dello Ba (da processo s) nei grani presolari di origine AGB: STEP 2 cerchiamo la soluzione nella fisica stellare e non nella nucleare



Input nucleari presi dalla letteratura nel 2021



Nuovo fenomeno: mixing e vento magnetico



3 proposte di tesi teoriche

- La nucleosintesi del Ba «spiegata» da nuove stime e misure della vita media del $^{134-137}\text{Cs}$ nei plasmi stellari
- Abbondanze e rapporti isotopici di C e Al nella stelle AGB, la soluzione: nuovi modelli di nucleosintesi o migliori input nucleari?
- Sintesi degli elementi con $A > 180$: competizione e complementarità del processo s e del processo r

collaborazioni

