Nuclear Physics Mid Term Plan in Italy

LNS – Session

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Nuclear Physics
Mid Term Plan in Italy

r and s processes

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INFN
Istituto Nazionale di Fisica Nucleare

Outline

- Brief introduction to the *r* and *s* processes nucleosynthesis
- Details on proposed research activities:

s-process

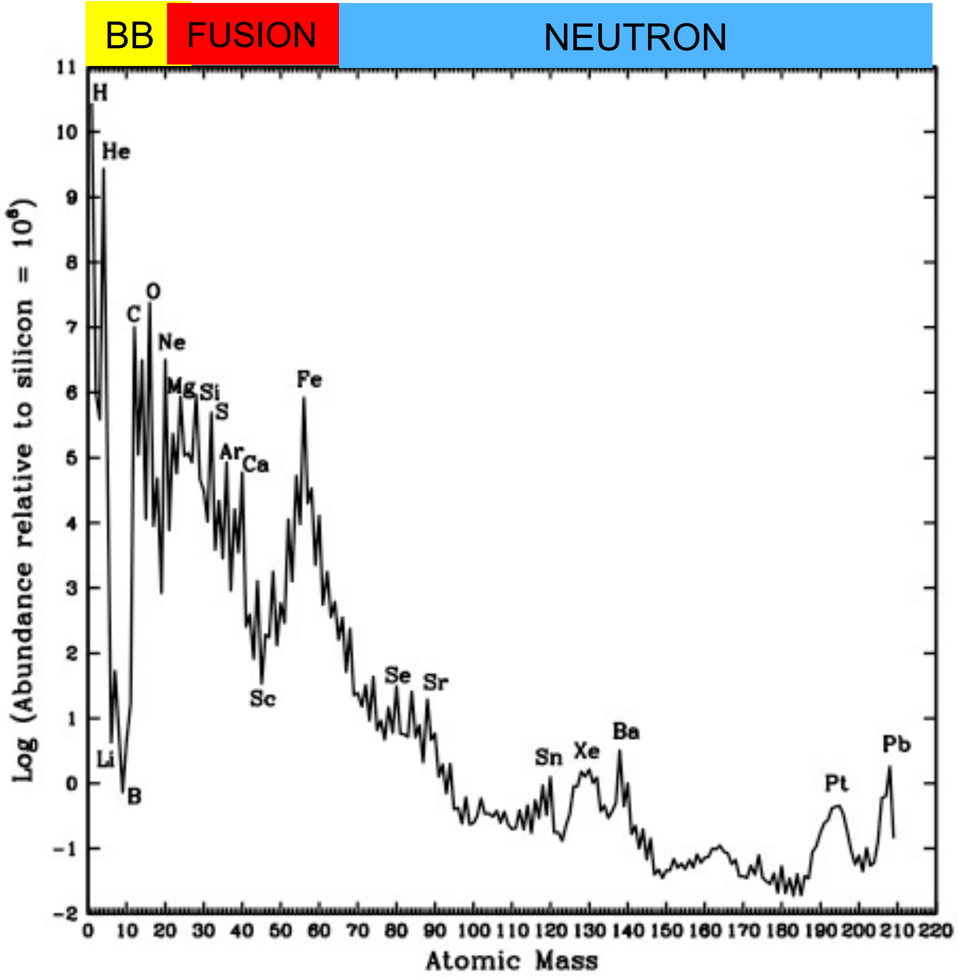
- neutron poisons and neutron sources reactions:
  - the ^{22}Ne(α,n)^{25}Mg, ^{17}O(α,n)^{20}Ne, ^{16}O(n,γ)^{17}O, ^{25}Mg(n,γ)^{26}Mg, ^{22}Ne(n,γ)^{23}Ne, ^{18}O(α,n)^{21}Ne reactions;
  - low-energy proton inelastic scattering ^{21}Ne(p,p')^{21}Ne;
- New experimental inputs on branching ratios for s-process:
  - the cases of ^{176}Lu, ^{187}Os, ^{85}Kr, ^{86}Rb, ^{134}Cs, ^{135}Cs;
- Continuous and pulsed neutron sources driven by Laser and Ion beams for Nuclear Astrophysics;

r-process

- Neutron star merger & r-process nucleosynthesis in the multi-messenger era: in-laboratory experimental measurements of Binary Neutron Stars merger ejecta opacity;
- POLYcube detector system For Experimental Multimessenger astrOnomy (POLYFEMO);
- Study the αOMP parameterizations by inverse elastic scattering experiments using neutron-rich RI beams.

- Summary

Solar System abundances: r- and s- processes nucleosynthesis



The abundances of elements in the Sun indicate that the matter evolved from rather simple forms to much more complex ones.

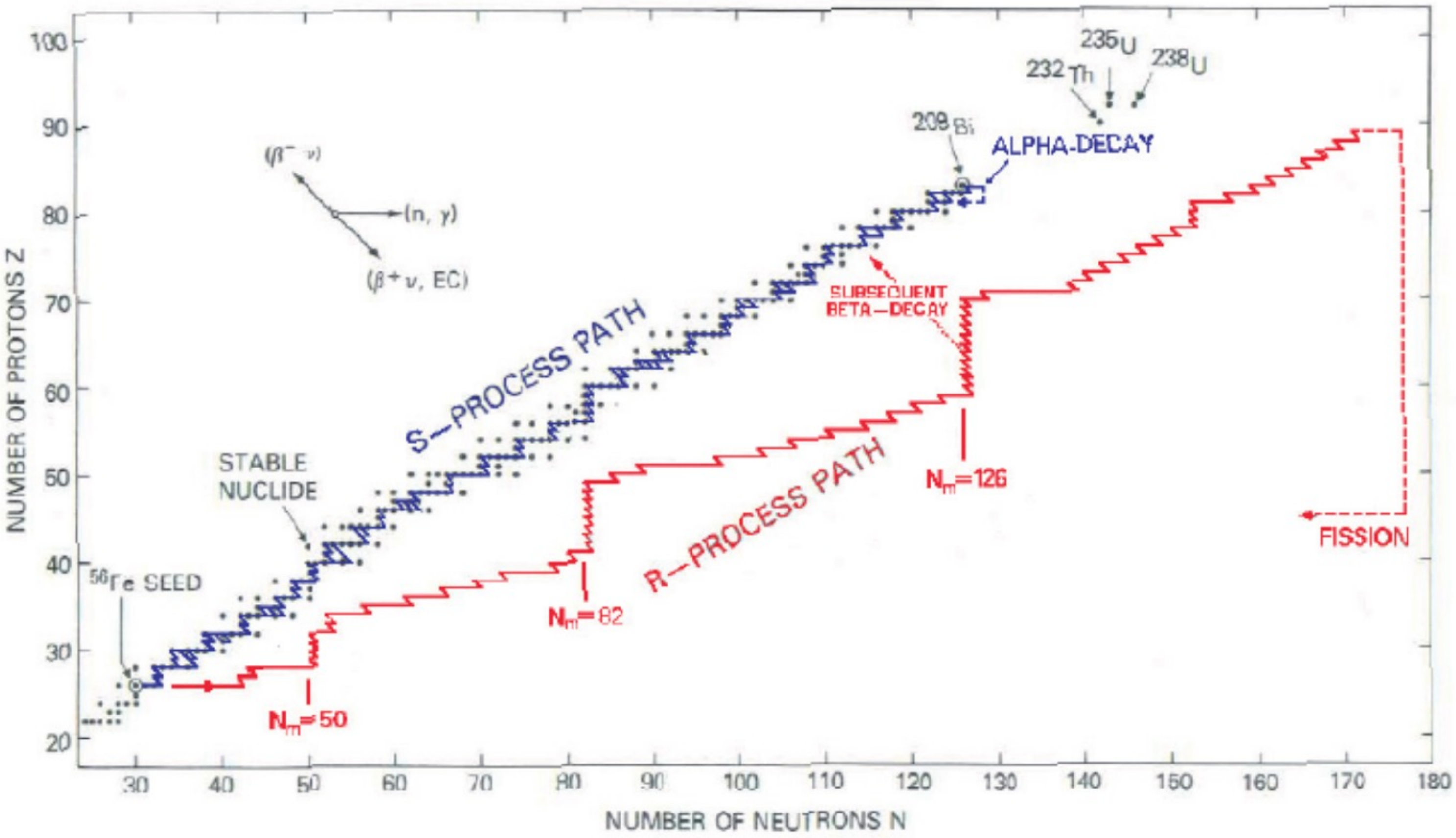
The stellar evolutionary process begins with H and He atoms from the Big Bang, which combine to form more complex atoms via nuclear reactions that transform one element into another.

The entire process is referred to as NUCLEOSYNTHESIS

How are heavy elements formed?

Because of their high number of protons, elements heavier than Fe have a large Coulomb barrier and can be produced only by **capturing neutrons**.
The synthesis proceeds in steps of 1 mass unit and occurs either at a slow rate (s-process) or at rapid rate (r-process).

For unstable nuclei, when the time between successive neutron capture $\tau_{n,\gamma}$ is much larger than the β-decay lifetimes τ_β the network of processes involved is called **s-process.**

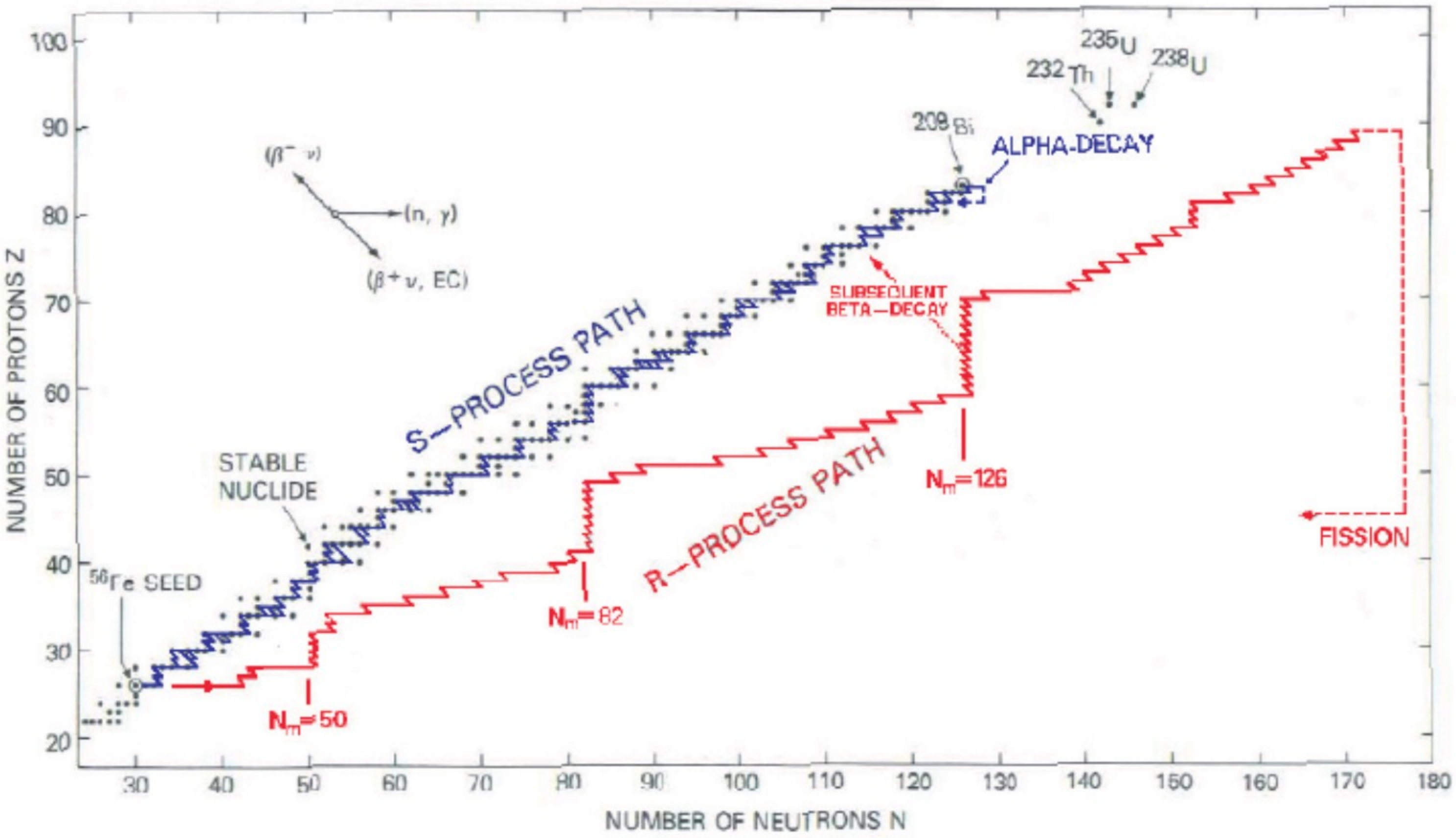


Path of the s- and r processes in the N-Z plan.
Both processes start with the nuclides of the iron peak region as seeds.

During the s-process

- AGB stars, massive stars
- $\tau_{n,\gamma} >> \tau_\beta$
- $\tau_{n,\gamma}$ (~ 1 yr) > $t_{1/2}$
- N_n ~ 10^8 cm^{-3}
- close to valley of stabillity

If neutron capture proceeds on a rapid time scale $\tau_{n,\gamma}$ compared with β-decay lifetimes τ_β, due to the very high densities of free neutrons, the network of reactions involved is called **r-process.**



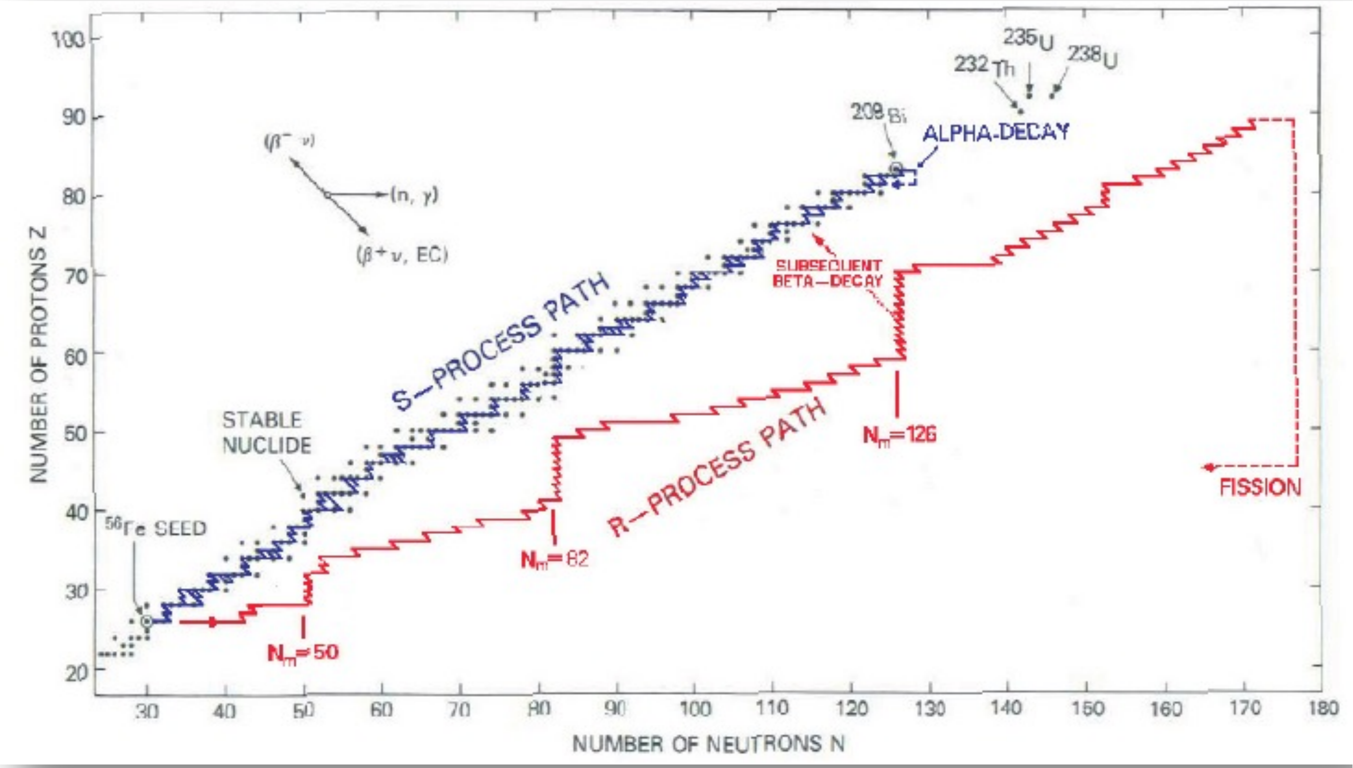
Path of the s- and r processes in the N-Z plan.
Both processes start with the nuclides of the iron peak region as seeds.

During the r-process

- explosive scenarios
- $\tau_{n,\gamma} << \tau_\beta$
- $\tau_{n,\gamma}$ (10^{-4} s) < $t_{1/2}$
- $N_n \sim 10^{21}$ cm^{-3}
- far from valley of stabillity

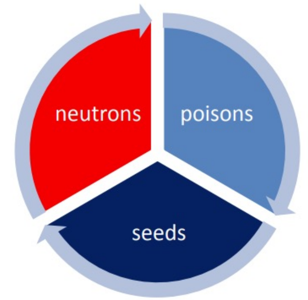
s-process: neutron poisons and neutron sources reactions

The main site of the slow neutron captures is the final **Asymptotic Giant Branch (AGB)** phase of low- and intermediate-mass stars, being the weak component due to massive stars ($M > 8M_\odot$).
Pignatari et al.; APJ,1557 710 (2010)



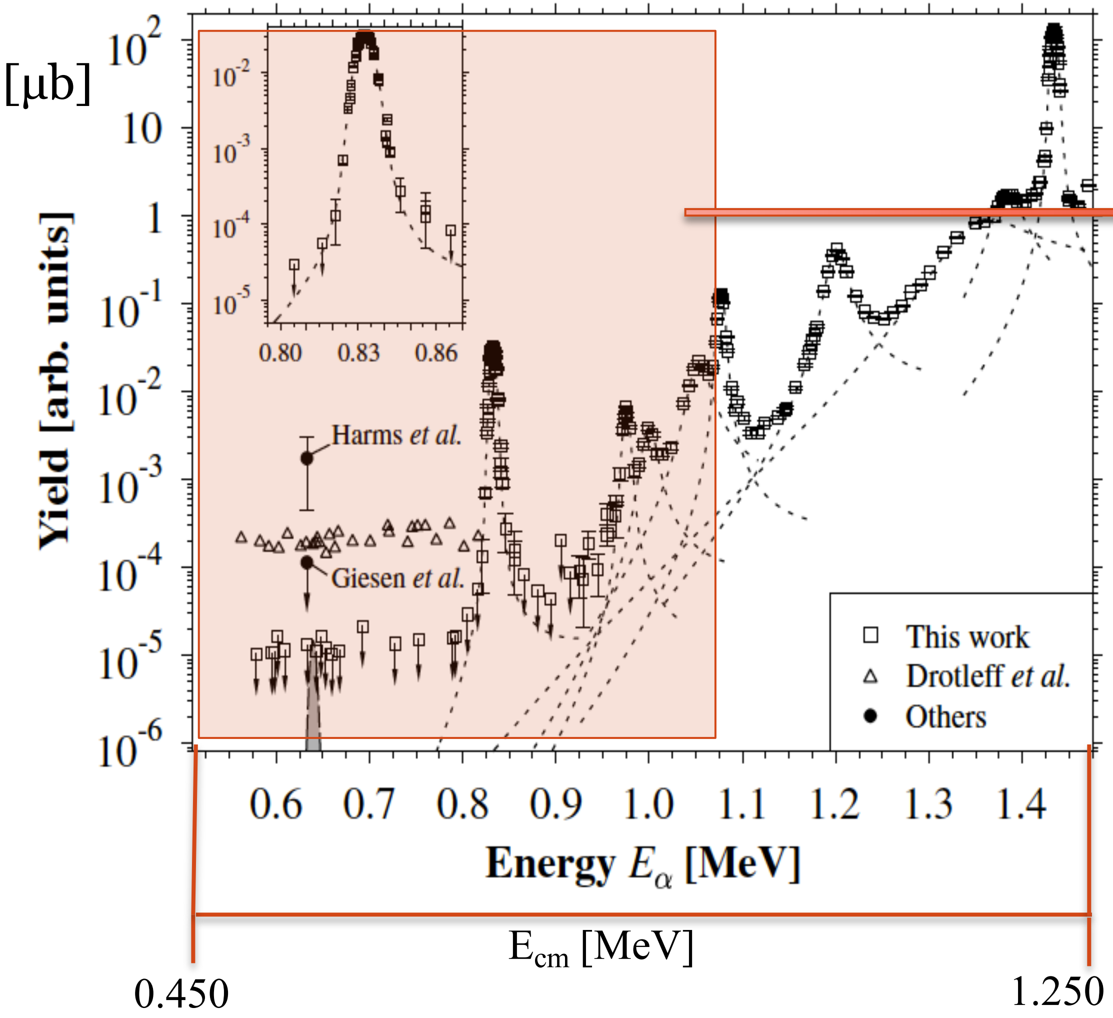
The main sources of neutrons for s-process nucleosynthesis are the **$^{13}C(\alpha,n)^{16}O$** and the **$^{22}Ne(\alpha,n)^{25}Mg$** reactions.

Since light nuclei are relatively abundant with respect to the heavier ones, a large fraction of the neutrons produced are captured by light nuclei and removed from the s-process nucleosynthesis path: these are the so-called **neutron poisons reactions.**
Kappeler et al.; Rev. Mod. Phys., 83,157 (2011).
Pignatari et al.; APJ,1557 710 (2010)



A specific research program about the role of the neutron poisons and neutron source reactions can benefit from the expertise of the INFN-LNS facilities and knowledge.

The ^{22}**Ne**$(\alpha$**,n**$)^{25}$**Mg** reaction is a source of neutrons for the s-process.



Jaeger et al.; Phys. Rev. Lett. 87, 202501 (2001)

Status of the art

Large uncertainties come from the unknown α-particle partial width of ^{26}Mg excited levels, especially at energies lower than E_{cm}= 800 keV

Below 1.2 MeV, the cross section values are significatively smaller than 1 μb
→ very difficult to perform direct measurements

Indirect measurements is needed @low energy to cover the whole range and complement the already available information from direct measurements.

i.e.: THM, ANC, transfer reaction ….

The measurement of the **^{22}Ne(α,n)^{25}Mg** will be studied using the Trojan Horse Method (THM).

One of this way will involve the possible expansion of the THM to the use of TH nuclei with p-wave intercluster motion inside.

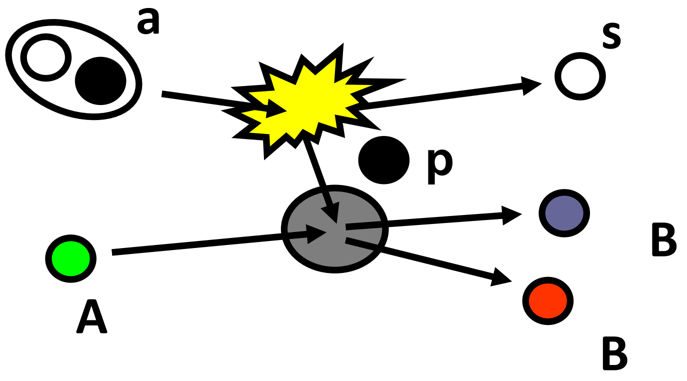
+

ECR ion source NESTOR:

- **Production of ^{4}He implanted solid targets;**
- **Production of ^{22}Ne beam**

one of the key challenges for the next advancements of NA to avoid the huge angular spread in gas targets (measurements almost useless for astrophysical applications)

TROJAN HORSE METHOD (see talk by G.G. Rapisarda)



α(^{26}Mg,αn)^{25}Mg THM + solid α targets **(NESTOR)** (^{26}Mg =^{22}Ne+ α)

α(^{23}Na,pn)^{25}Mg THM + solid α targets **(NESTOR)** (^{23}Na =^{22}Ne+ p)

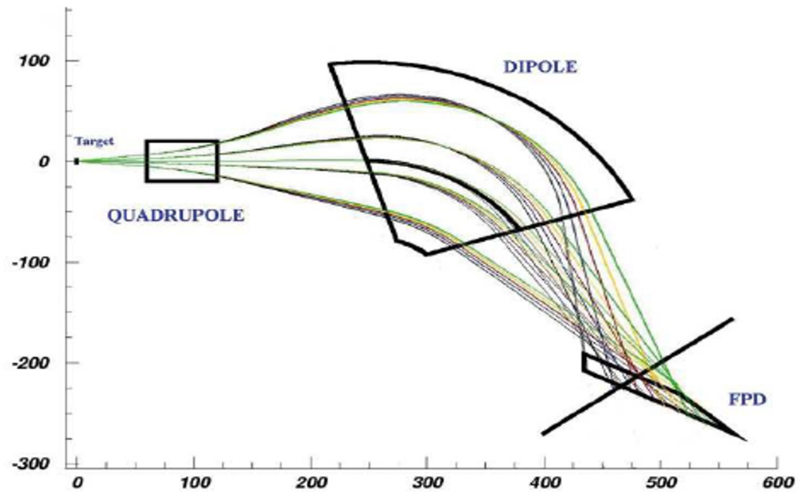
^{6}Li(^{22}Ne,dn)^{25}Mg THM + solid ^{6}LiF targets (^{6}Li= α+d)

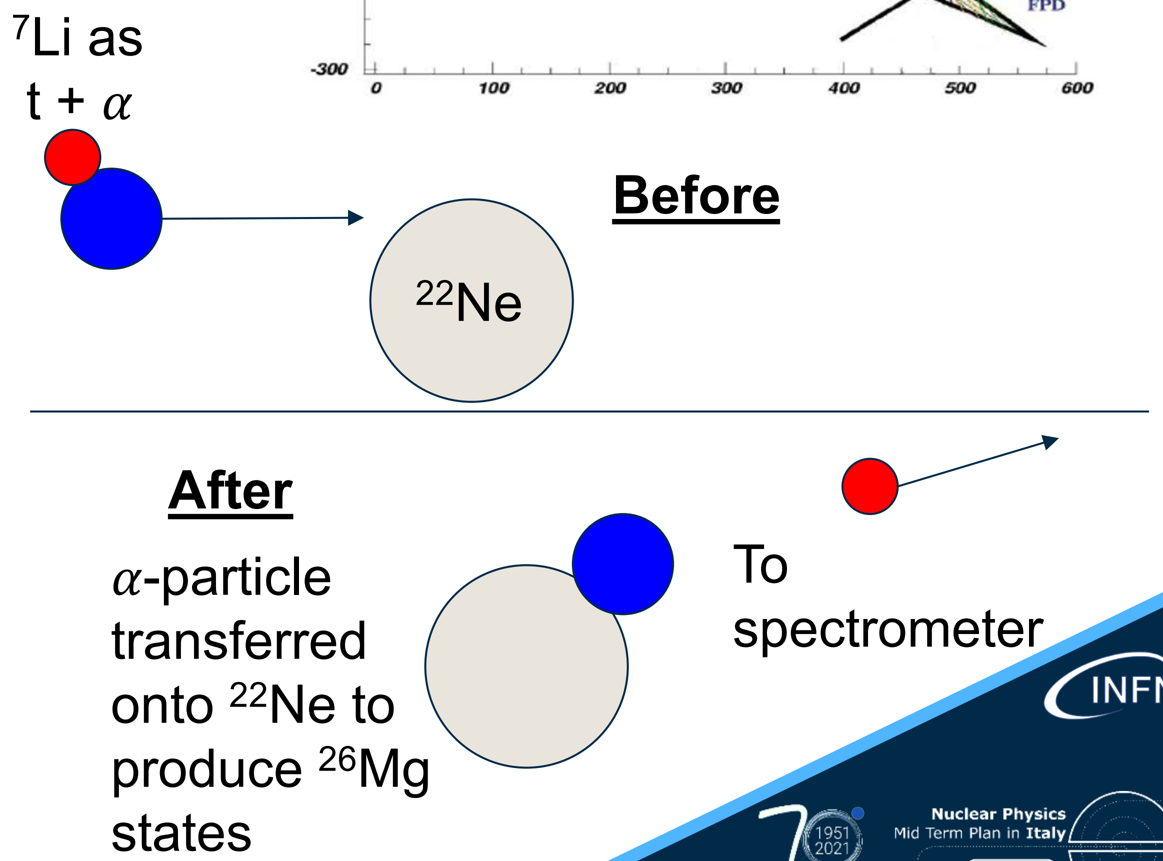
α-cluster transfer reactions such as **^{22}Ne(^{6}Li,d)^{26}Mg** and **^{22}Ne(^{7}Li,t)^{26}Mg** provide a means to indirectly determine the unknown α-particle partial width of ^{26}Mg excited levels.

LNS can fulfill this task thanks to the combination of a **noble-gas implantation source NESTOR and a large-acceptance magnetic spectrograph MAGNEX.**

Neon implanted in a heavy metal (e.g. tungsten). The reactions induced by the tandem beams on the metal are suppressed by the Coulomb barrier while reactions on the ^{22}Ne may still occur.

Possible experiments will be planned in the agreement with Magnex activities.



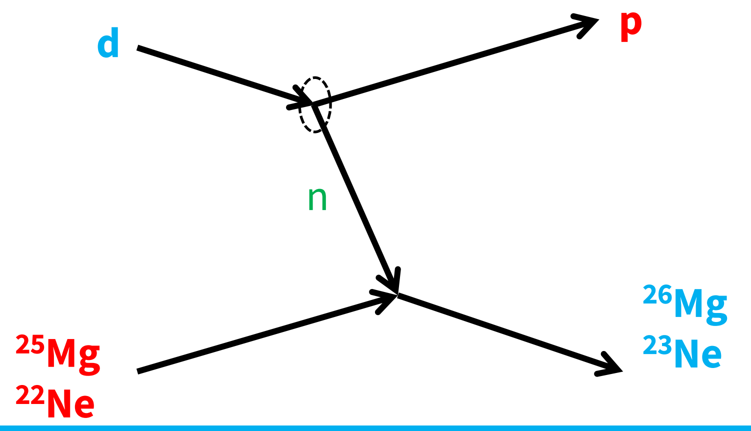


The amount of neutrons expected by the ignition of the $^{22}Ne(\alpha,n)^{25}Mg$ can be depleted by two principal neutron poisons reactions: **$^{25}Mg(n,\gamma)^{26}Mg$** and the **$^{22}Ne(n,\gamma)^{23}Ne$**.

^{25}Mg is the most important neutron poison due to neutron capture on ^{25}Mg in competition with neutron capture on ^{56}Fe that is the basic s-process seed for the production of heavy isotopes.

For this reason, a precise knowledge of the **$^{25}Mg(n,\gamma)^{26}Mg$** cross section is required to properly simulate s-process nucleosynthesis in stars.

The main uncertainty of the reaction rate comes from the poorly known property of the states in ^{26}Mg. Information can come from neutron measurements (knowledge of J^{π} for the ^{26}Mg states).



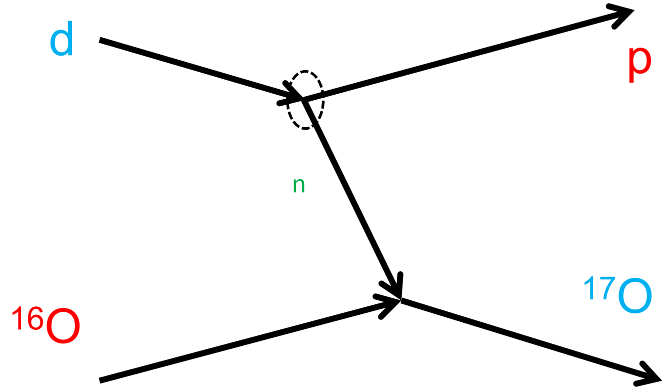
Asymptotic Normalization Coefficient (ANC) method: $^{25}Mg(n,\gamma)^{26}Mg$ and **$^{22}Ne(n,\gamma)^{23}Ne$**, *principal depleting channels in case of ^{22}Ne source*

The ANC method is useful to deduce the direct radiative capture part of the cross-section for an $A(a,\gamma)B$ reaction from the analysis of the direct peripheral transfer process A(X,Y)B.
Mukhamedzhanov, J. Exp. Theor. Phys. Lett. 1990, 51, 282.
Burjan, Front. Astron. Space Sci., 10 November 2020

The ratio between the rates of the reactions **^{17}O(α,n)^{20}Ne** and **^{17}O(α,γ)^{21}Ne** determines whether ^{16}O is an efficient neutron poison for the s process in massive stars, or if most of the neutrons captured by **^{16}O(n,γ)^{17}O** are recycled into the stellar environment. This ratio is of particular relevance to constrain the s process yields of fast rotating massive stars at low metallicity.
(A. Best et al., PRC 87, 045805 (2013)

- ✓ **THM: ^{17}O(α,n)^{20}Ne** via the ^{20}Ne(d,α^{17}O)p *using the **NESTOR** source and **TANDEM** beam*

- ✓ **ANC:** (especially with a dedicated deuterium beam): **^{16}O(n,γ)^{17}O,**



Many recent studies on the **^{17}O(α,γ)^{21}Ne** reactions. Lack of clarity about number of levels in ^{21}Ne, the compound nucleus.

Low-energy proton inelastic-scattering ^{21}Ne(p,p')^{21}Ne is a good way to indiscriminately populate levels in ^{21}Ne. This will help to implement the information already obtained in the previous ^{20}Ne(d,p)^{21}Ne and ^{17}O(^{7}Li,t)^{21}Ne studies.

Metodology: ^{21}Ne implanted (**NESTOR**) in a substrate (e.g. carbon) to make a ^{21}Ne-containing target.

Adsley et al.; Phys. Rev. C 97, 045807 (2018)

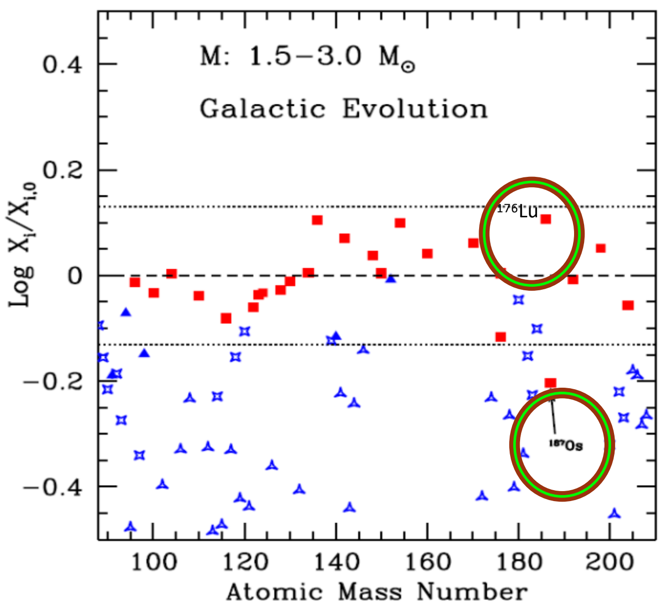
New data needed to understand the cosmic clocks

Several branching points along the s-process path require revisions through so-far **unexplored measurements of β-decay rates in plasmas**.

For the inspection of the predicted solar-system *s*-process abundances, adopted models has been specifically run for the **PANDORA** collaboration (*Palmerini et al., APJ 921:7 (2021))* **and two choices of cross sections**, from the online compilation Kadonis 0.3 and 1.0, have been done.

Predicted s-process contributions to the solar abundances (for nuclei with A>88) computed from a simulation of Galactic Evolution. Red dots are s-only nuclei, that should be at «0»

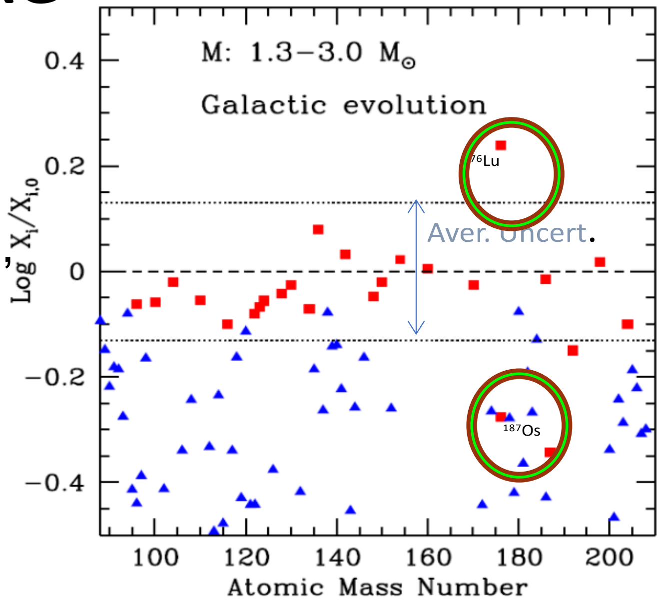
Busso et. al 2021 (n,γ) from Kadonis 0.3



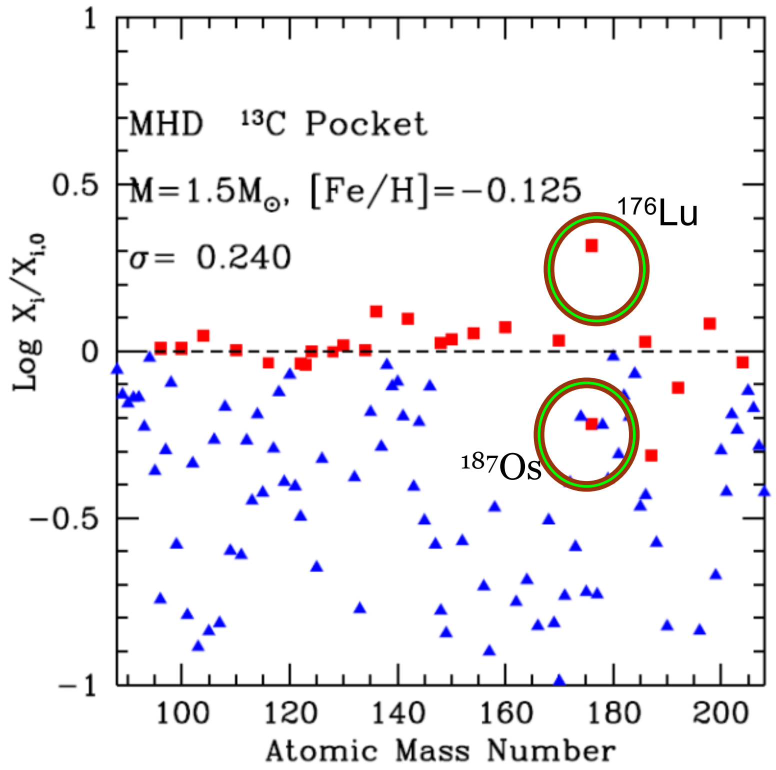
^{176}Lu-^{176}Hf and ^{187}Os-^{187} Re

Inclusion of cross sections from Kadonis 1.0 (in computing low mass AGB stars nucleosynthesis) improves the fit up to A=140, but it worsens the quality of the fit for the highest mass nuclei, in particular for ^{176}Lu-^{176}Hf and for ^{187}Os-^{187}Re. **The knowledge of the nuclear data for the branchings involved at high atomic mass is in general poor.**

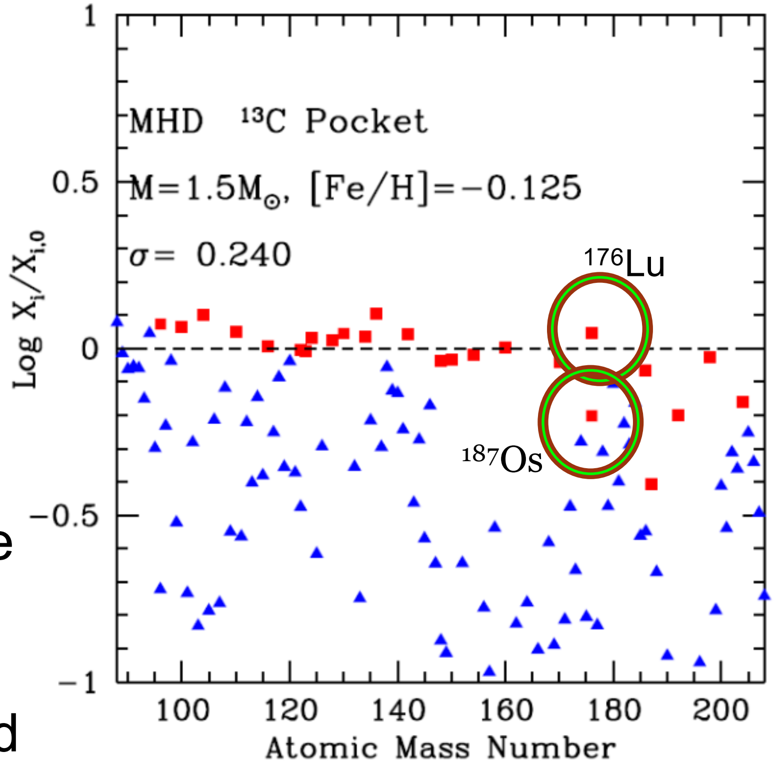
Work in progress Kadonis 1.0



IMPACT OF the beta-decay rate!



By enhancing the decay rate of ^{176}Lu^{m} (at T>2.5 10^8K) by a factor of 2, as a guess to the action of plasma physics.



Situation improves:

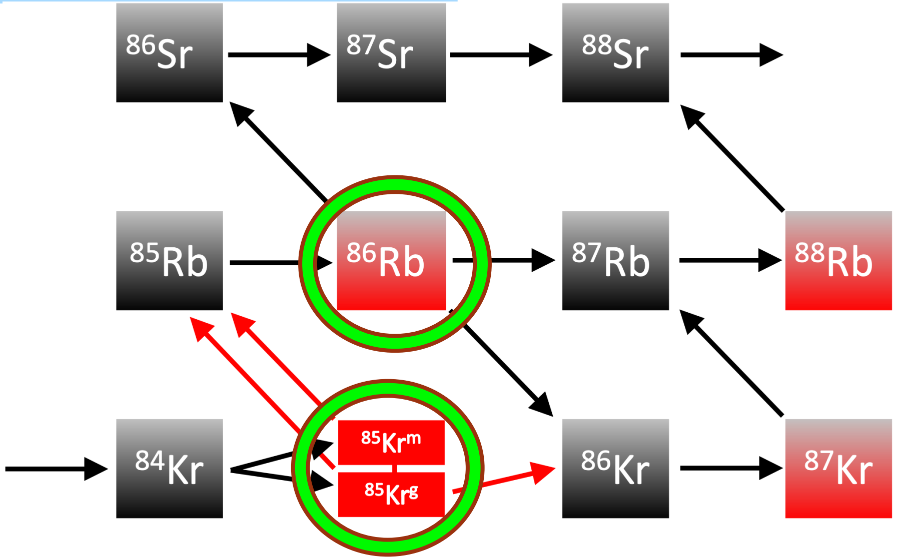
- ^{176}Lu would be reproduced inside the remaining uncertainties,
- the production of its daughter ^{176}Hf would be almost unchanged

Calculation refers to a 1.5 M_8, [Fe/H] = -0.125 AGB model, the one mimick rather well the average galactic contribution.

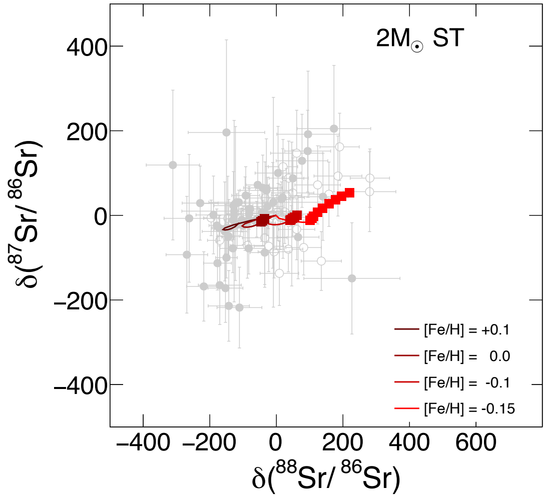
PANDORA APPROACHES APPEAR NECESSARIES

(see talk by A. Pidatella)

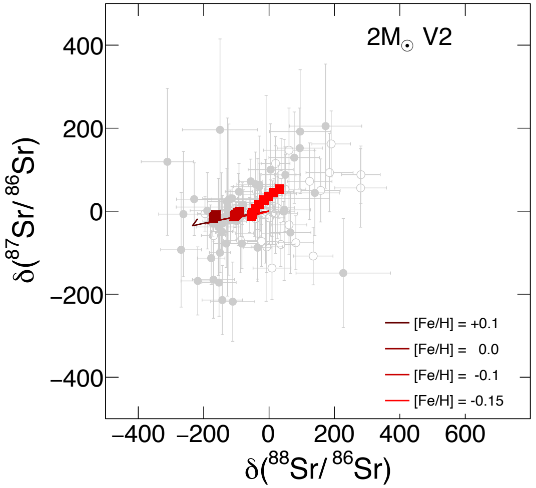
2 brancing points affects the s-process path to Sr production: ^{85}Kr (which is populated in both ground and isomeric state) and ^{86}Rb



Palmerini et al., APJ 921:7 (2021)



^{84}Kr(n,γ)^{85}Kr cross section:
Kadonis 0.3
-> Kadonis 1.0



The flux of neutrons on ^{85}Kr^m pass from 40% to 60% by modifying the cross section on ^{84}Kr . The same effect will occur if the ^{85}Kr^m decay rate will be found too smaller.

- **Measurements of decay rates of ^{86}Rb and ^{85}Kr (both gs and ms) in plasma conditions are needed → PANDORA**
- High precision determination of (n,γ) cross section of ^{86}Rb and ^{85}Kr are crucial too.

Similarly, the cases of ^{134}Cs and ^{135}Cs

- Branching ratios on Cs isotopes affect the Ba nuclesoynthesis.
- one of the new experimental inputs on branching ratios for s-process chain is the **measurements of the ^{134,135}Cs half-life in stellar plasma conditions**

→ **PANDORA**

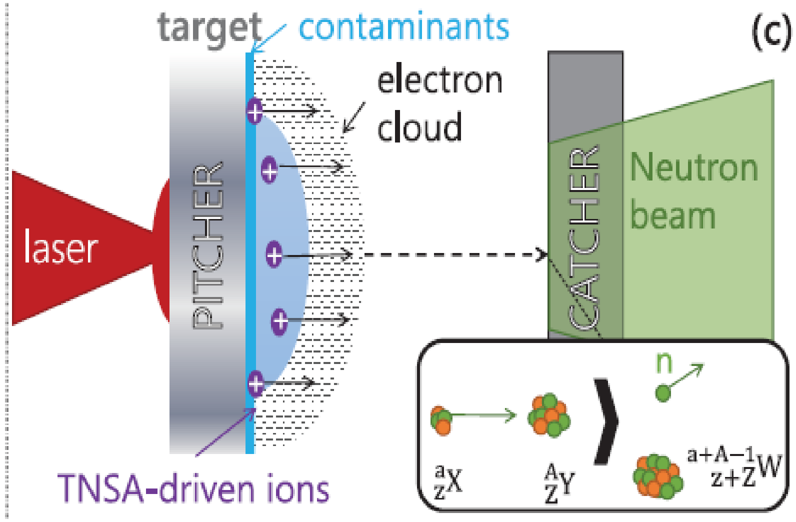
Palmerini et al., APJ 921:7 (2021)

In next years a 250 TW laser will be available at LNS.

→ Forward peaked neutrons may be produced by a double-target configuration (named pitcher-catcher):

(see talk by G.A Cirrone)

- ***Projectile light ions*** *by Target Normal Sheath Acceleration (TNSA)*
- ***Fusion reactions*** *in the converter target*



- **Pulse rep. rate 1Hz – 5Hz**
- **Φ < 20 µm**
- **Intensity ~10^{19} W/cm²**

From the literature, **a total neutron number up to 10^9 - 10^{10} per laser pulse** can be produced **with laser intensity of 10^{19} W/cm²**

	p-driven(this work)	γ-driven(this work)	ion-driven[48,49]
laser intensity I_{laser}	~$10^{19} \frac{W}{cm^2}$	~$10^{19} \frac{W}{cm^2}$	$5 \times 10^{20} \frac{W}{cm^2}$
focused energy E_{laser}	20 J	20 J	52 J
target system	CHO foam	CHO foam	CD_2 foil
neutron production	(p,xn)	(γ,xn)	(d,n)
primaries (>10 MeV)	~3×10^{11}, proton	3×10^{11}, e^-	>10^{11}, d
laser-primary conversion eff.	–	10%	0.5%
laser-γ conversion eff.	–	1.4% (>10 MeV)	–
total neutron number	6.2×10^{10}	1.4×10^{10}	7.2×10^9
neutron direction	isotropic	isotropic	16% directed
mean neutron energy	500 keV-1 MeV	2 MeV	>10 MeV directed 2-4 MeV isotropic
laser-neutron conversion eff.	0.05%	0.02%	0.01%
neutrons per laser energy	3.1×10^9 n/J	7×10^8 n/J	1.3×10^8 n/J

M. M. Günther et al., NATURE COMMUNICATIONS, (2022) 13:170 | https://doi.org/10.1038/s41467-021-27694-7 |

- Adopting **different target systems**, the neutron energy spectra can be modified. The final energy spectra can be additionally shaped with **moderators to reproduce a Maxwellian distribution**.
- Measurements of **Integral cross sections** may be potentially performed by **Neutron Activation**.
- Maxwell-Boltzmann neutron energy distributions for astrophysics research?
- Radioactive isotope targets produced by available ion beams (FRAISE, other..)?

EXAMPLES OF POSSIBLE FUTURE NUCLEAR ASTROPHYSICS APPLICATIONS:

✓ measurement of ^{140}**Ce(n,γ)**^{141}**Ce** (^{141}Ce $T_{1/2}$= 32.5 days): it represents a bottleneck for the s-process nucleosynthesis and determines to a large extent the cerium abundance in stars.

→ Significant difference between the cerium abundance measured in globular clusters and the value predicted by theoretical stellar models.

Amaducci, Universe 2021, *7*(6), 200

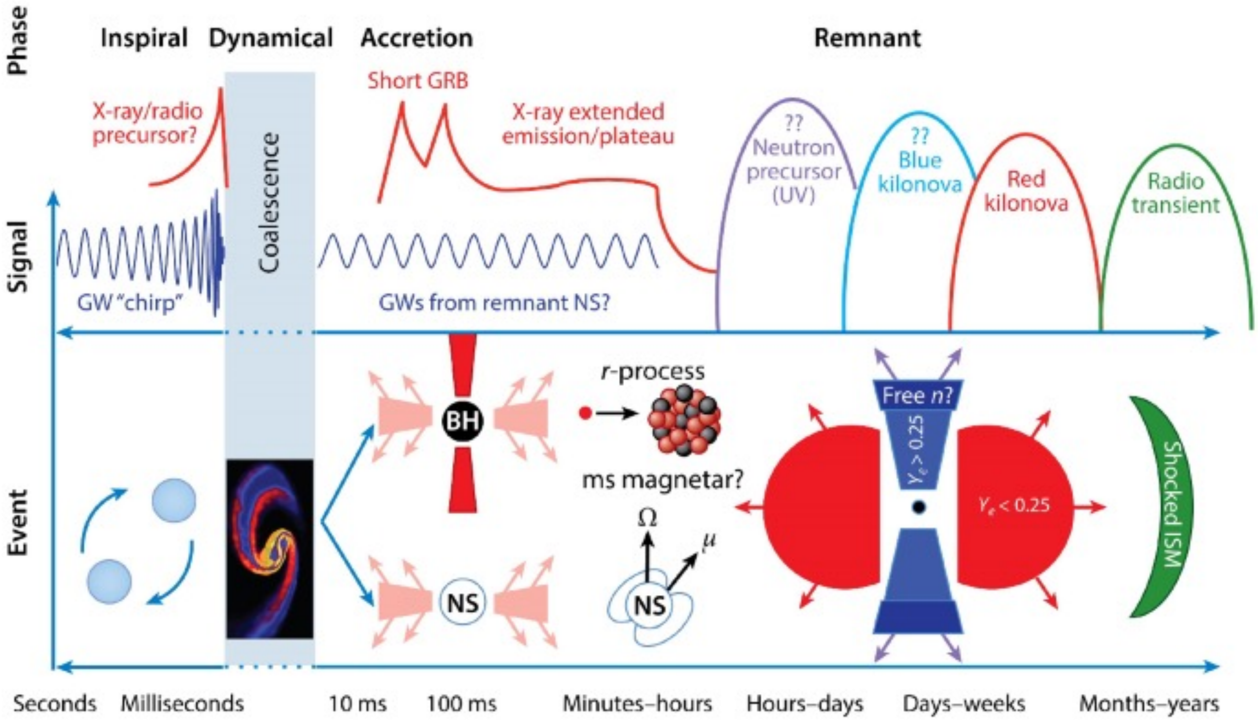
✓ measurement of ^{94}**Zr(n,γ)**^{95}**Zr** (^{95}Zr $T_{1/2}$= 64 days): is crucial in the modelling of s-process nucleosynthesis in asymptotic giant branch stars because Zr is situated at a crucial point, where the two s components (weak and main) match.

Tagliente, PHYSICAL REVIEW C 84, 015801 (2011)

FOCUS: complementarity of activation and TOF measurements!

Binary Neutron Stars (BNS) mergers are predicted to give rise to three major detectable phenomena: a short burst of γ-rays, a gravitational-wave signal, and a transient optical–near-infrared source powered by the **synthesis of large amounts of very heavy elements via the r-process**. Such transients, named **'kilonovae',** are believed to be centres of production of rare elements such as gold and platinum.

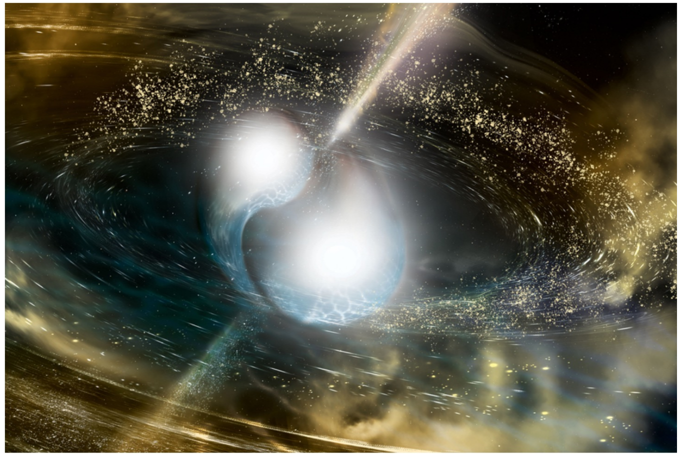
- The **GW170817 event** has given the unquestionable evidence that coalescences of binary neutron stars systems are at the origin of r-process nucleosynthesis of heavy elements.
  Pian et al.; Nature, 551, 67 (2017)
- After the merger, the ejected material, released from the huge internal pressure of the neutron stars, expands and forms seeds of heavy nuclei that rapidly capture free neutrons and radiate optical light which can be detected for about one week.



- The bulk of the ejected material seems to consist of two distinct mass regions (A<140, A>140)
  - ➢ Hot blue masses of highly radiactive r-process matter of lower-mass-range heavy nuclei (A<140)
  - ➢ Cooler red masses of higher mass-number r-processes nuclei (A>140) rich in actinides

Experimental data on neutron-rich isotopes from these new capabilities will be essential for answering many important still open questions such as:

- What elements are created in NS mergers ?
- How much do they contribute to the total inventory of r-process elements ?
- Can we identify particular r-process elements in future mergers ?
- Why is the fundamental abundance pattern of heavy r-process so robust ?
- Why this robustness do not extend to the actinides ?

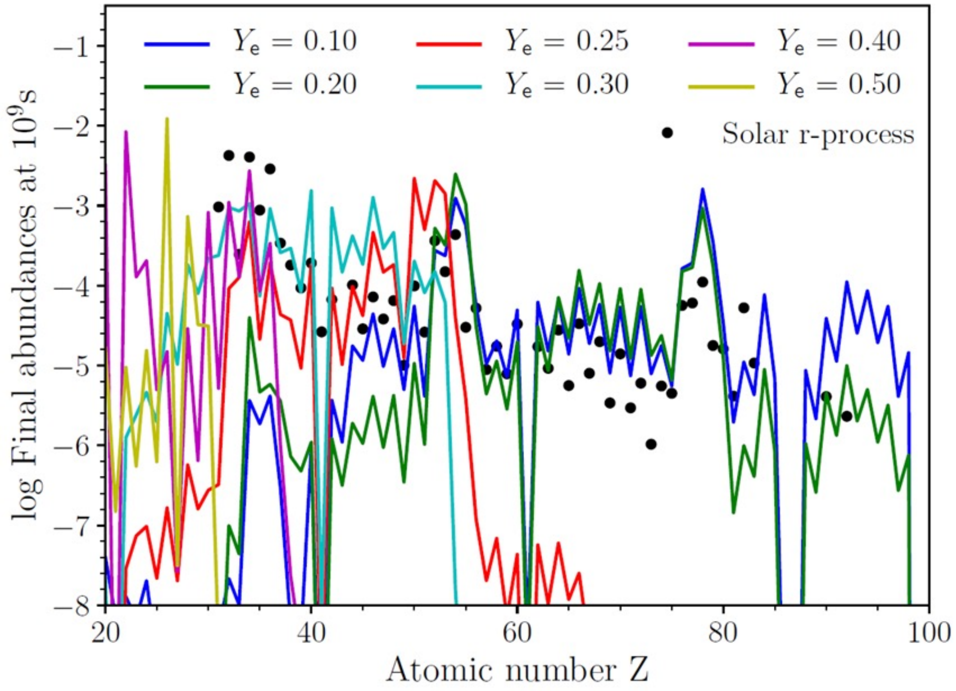


National Science Foundation/LIGO/Sonoma State University/A. Simonnet, edited by MIT News

r-process nucleosynthesis in compact binary object

- **Plasma opacity** : great impact on energy transport and spectroscopic observations.
- Opacity from **theoretical models**: **large uncertainty** factor, blending of many millions atomic transition lines, experimental data are largely desired!
- *r*-process nucleosynthesis in BNS mergers: impact of plasma opacity
  - Electron fraction, $Y_e \sim \frac{n_p}{n_p+n_n}$ → dominant parameter (composition)

Pidatella et al.; Nuovo Cimento C 44, 65 (2021)



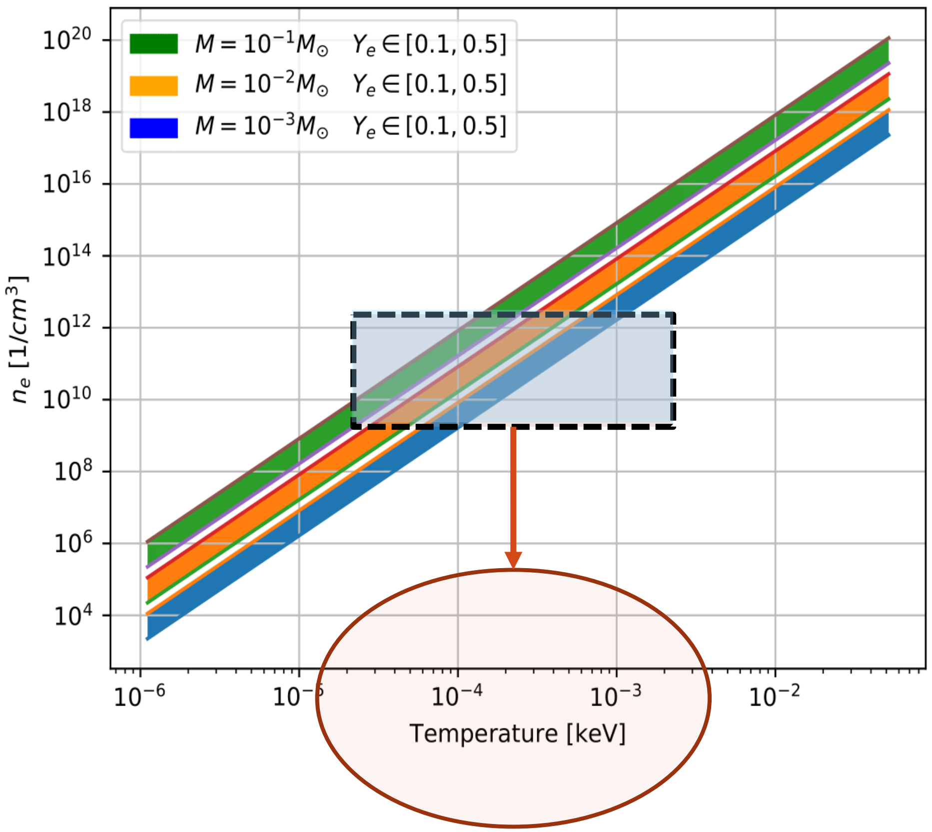
Comparison between simulation and solar r-process element abundances

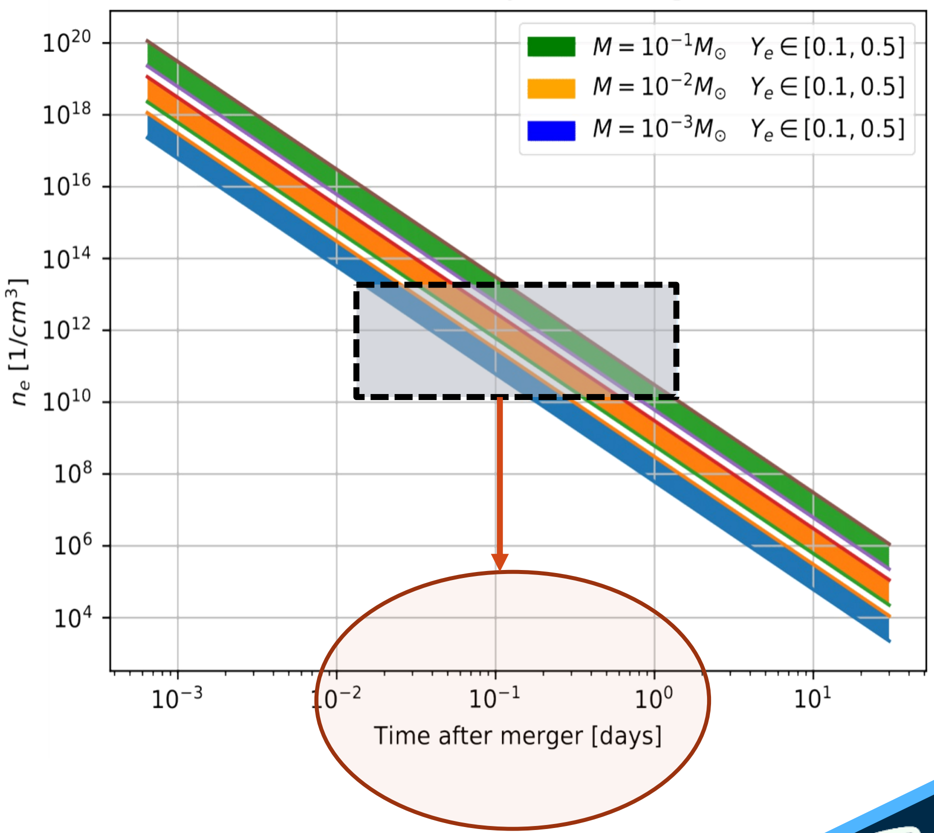
- Production of lanthanides dramatically changes photon opacity κ_ν
- No lanthanides ($Y_e > 0.2$): low opacity, blue-KN emission
- Presence of lanthanides ($Y_e \leq 0.2$): larger opacity, red-KN emission

PANDORA: in-laboratory experimental measurements of BNS ejecta opacity

- **Trapped magneto-plasmas conceived in PANDORA**: experimental **in-laboratory measurements of opacities** at electron densities and temperatures resembling some **ejecta plasma conditions**

- **Feasibility study**: astrophysical modelling BNS ejecta, nuclear network for nucleosynthesis yields, and population kinetics code for synthetic spectra





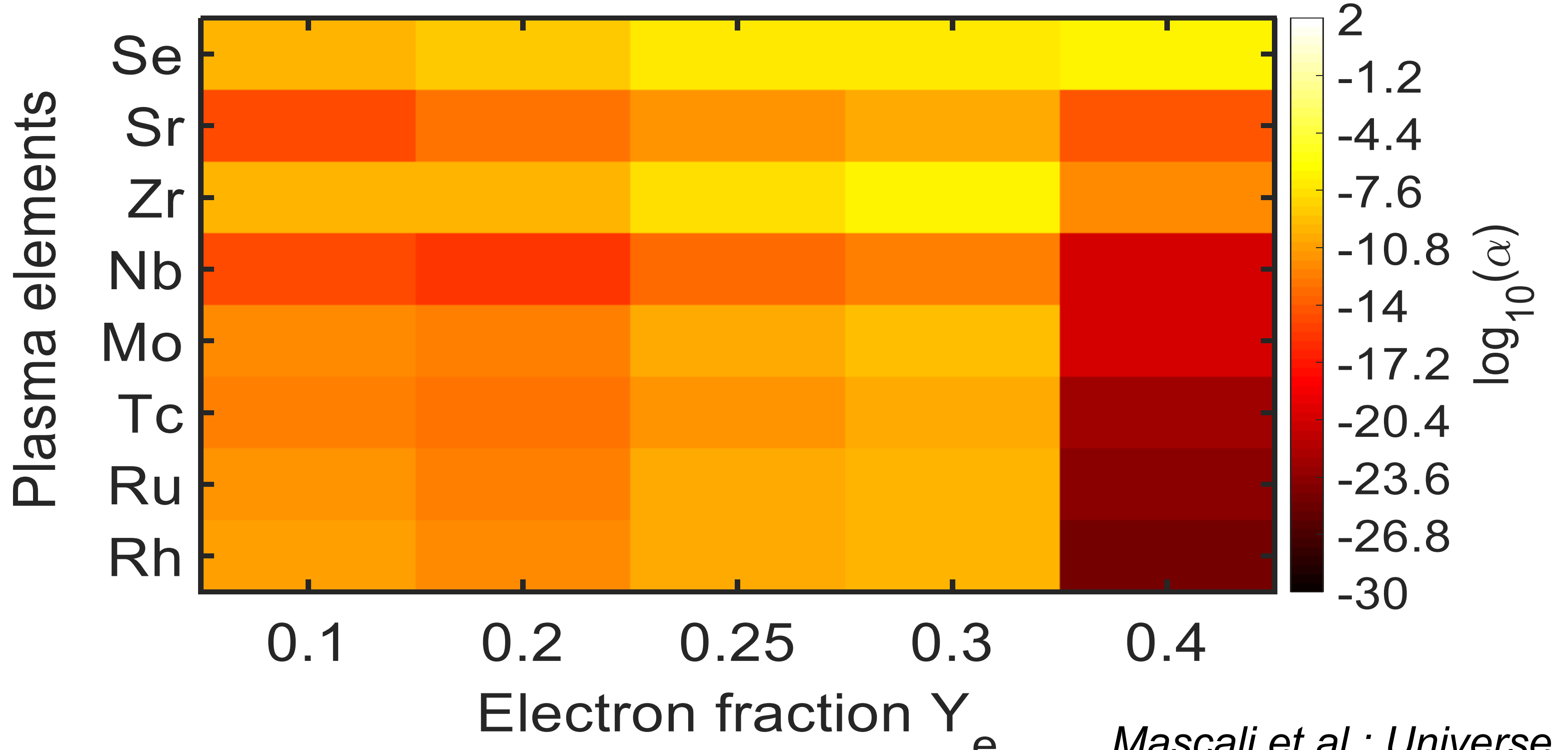
blue-KN stage

- **PANDORA** is a multi-diagnostic facility: optical emission spectroscopy (OES) to probe plasma emission in the blue-KN stage, supported by ancillary non-invasive diagnostics

- Monitoring/measuring plasma parameters, plasma stability.

- **Experimental setup and measurement design**: w.i.p. on the Flexible Plasma Trap, first campaign of OES measurements, closely reproducing KN conditions – few eV, and 10^{11} cm^{-3}

Opacity weighted on abundances from SKYNET



➔ **Suitable species for opacity measurements** at blue-KN stage, **light-r process elements** (first peak)

Pidatella et al.; Nuovo Cimento C 44, 65 (2021)

- Perspectives: light-*r process* elements plasmas **(Se, Sr, Nb) opacity** measurements via OES.

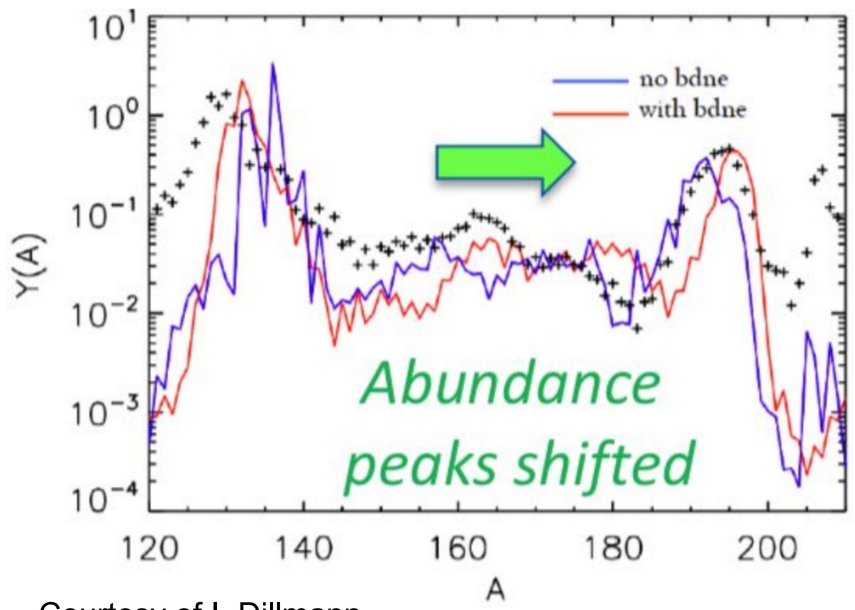
Mascali et al.; Universe, 8, 80 (2022)

Are a gravitational wave events as GW170817 partially or entirely able to reproduce the *r*-process abundance pattern observed throughout the galaxy?

Heavy element abundance predictions, via accurate reaction network calculations, are especially sensitive to the values of:

- nuclear masses;
- *β*-decay half-lives: $\mathbf{T_{1/2}(^{A}Z)}$ ≈ few ms – tens of s
- and ***β*-delayed neutron emission probabilities P_n** of very neutron-rich nuclei;

Mumpower et al., Phys. Rev. C, 92 (3) (2015), Article 035807 and Prog. Part. Nucl. Phys., 86 (2016), pp. 86-126,



Courtesy of I. Dillmann

Example of the effect on the r-process yield of the β-delay n emission: the sizeable effect of P_n is clear.

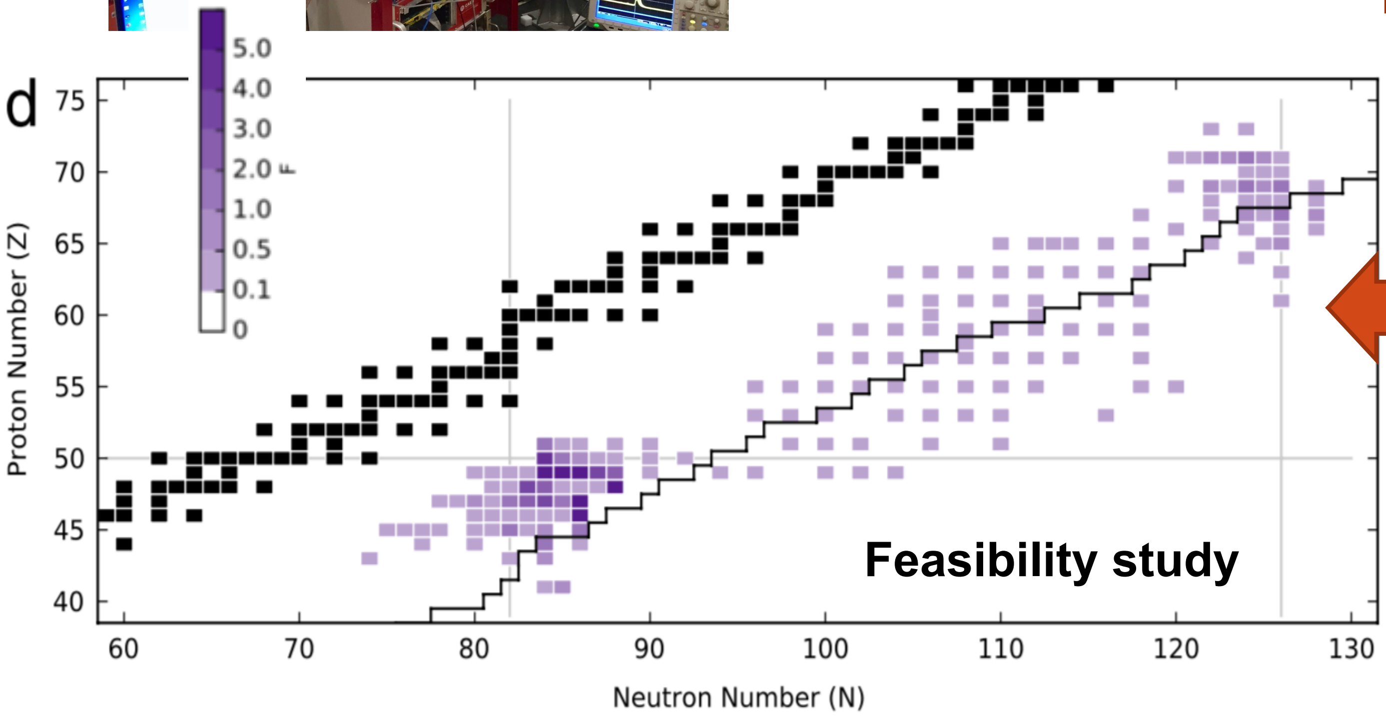
Influence on nucleosynthesis:

- secondary source of neutrons during freeze-out
- Production of less-neutron-rich nuclei

Reshuffle of r-process yields!

Thank to the availability of a **high efficiency neutron counter (polycube)**, successfully used in the past in the ^{8}Li(α,n)^{11}B measurement *(La Cognata,Physics Letters B 664 (2008) 157–161)*, and of the **FRAISE** facility for the production of short lived radioactive nuclei, LNS can play an important role in the accurate determination of P_n

FRAISE could be coupled with the Polycube neutron detector for P_n measurements (**POLYFEMO**)



Important *β*-delayed neutron emitters in neutron star mergers
—— **calculated production limit with FRIB**

Candidate nuclei to test the approach: ^{66}Co ($T_{1/2}$ ~ 0.2 s) and ^{72}Ni ($T_{1/2}$ ~ 1.6 s)

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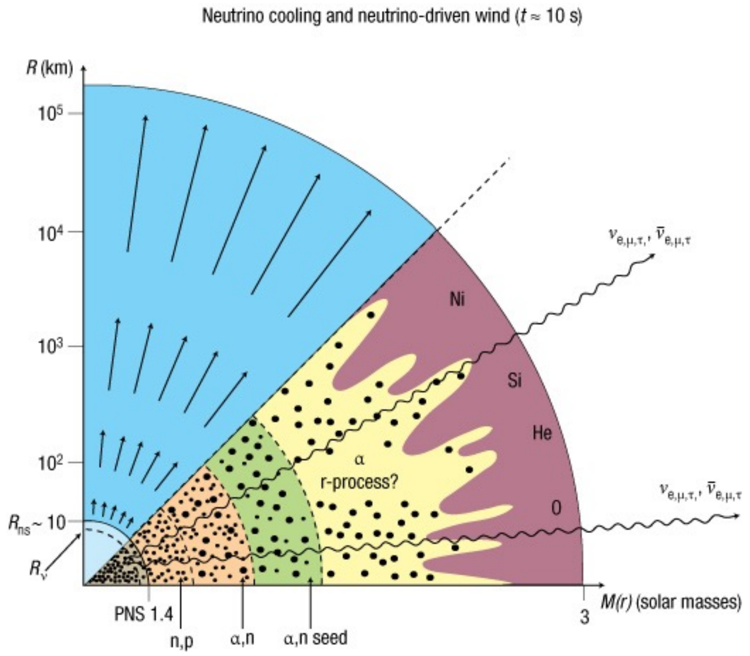
Weak r-process nucleosynthesis: study of the αOMP



Low mass (38 [Sr] ≤ Z ≤ 47 [Ag]) might be synthesized by charged particle-induced reactions in neutrino driven winds.

Nuclear reaction network
Astrophysical input:
→ Key **(α,n)** reactions
Nuclear physics input from Hauser-Feshbach model (Talys code)
→ Key inputs

The α+nucleus optical potential parameter sets (αOMP's) represents the main source of uncertainty.

Experiments are critical to determine the parameters of the αOMP, to reduce the uncertainties of the (α,n) rates

*Arcones & Bliss, Phys. G **41** (2014) 044005, Bliss et al., J. Phys. G **44** (2017) 054003, Bliss et al., PRC **101** (2020) 055807 Mohr, PRC **94** 035801 (2016), Palumbo et al., PRC **85** 035808 (2012).*

EXAMPLE OF POSSIBILE APPLICATION (FRAISE)

- By inverse elastic scattering angular distribution and excitation function measurements of the **α(^{63}Co,^{63}Co)α**, the existing αOMP parameterizations can be evaluated → ^{63}Co(α,n)^{66}Cu
- Position-sensitive silicon detectors are available at LNS, thin Si films containing ~10^{18} ^{4}He atoms can be purchased.

Feasibility study was already performed at LNS using stable ^{58}Ni beams, position-sensitive silicon detectors and thin Si films containing large quantities of ^{4}He.

WG3 r- and s- processes summary

ACTIVITY	PROPOSER	AFFILIATIONS
Measurement of ^{22}Ne(α,n)^{25}Mg via the THM	R. Spartà, , A. Tumino, S. Romano	LNS-INFN, Catania, Dip. di Fisica e Astronomia «Ettore Majorana», UniCt, UniKore Enna
Measurement of ^{22}Ne(^{6}Li,d)^{26}Mg, ^{22}Ne(^{7}Li,t)^{26}Mg α-cluster transfer reactions	P. Adsley	Texas A&M University, College Station, Texas, USA
Measurement of ^{25}Mg(n,γ)^{26}Mg and ^{22}Ne(n,γ)^{23}Ne via ANC	L. Guardo, G. D'Agata J. Mrazek	Dip. di Fisica e Astronomia «Ettore Majorana», UniCt & LNS-INFN NPI of the Czech Academy of Sciences, Řež, Czech Republic
Measurement of low-energy proton inelastic-scattering ^{21}Ne(p,p')^{21}Ne	P. Adsley	Texas A&M University, College Station, Texas, USA
Measuremnet of beta decays of the isomeric state of ^{176}Lu	M.Busso, S. Palmerini	Dip. di Fisica e Geologia, UniPG, Perugia (Italy) & INFN, sezione di Perugia,
Measurements of decay rates of ^{86}Rb and ^{85}Kr (both gs and ms) in plasma conditions	M.Busso, S. Palmerini	Dip. di Fisica e Geologia, UniPG, Perugia (Italy) & INFN, sezione di Perugia,
measurements of the ^{134,135}Cs half-life in stellar plasma conditions	M.Busso, S. Palmerini,	Dip. di Fisica e Geologia, UniPG, Perugia (Italy) & INFN, sezione di Perugia,
Neutron star merger & r-process nucleosynthesis in the multi-messenger era	I. Vidana Haro	Dip. di Fisica e Astronomia «Ettore Majorana», UniC Catania
In-laboratory experimental measurements of BNS ejecta opacity	A. Pidatella, B. D. Mascali	LNS-INFN, Catania
POLYcube detector system For Experimental Multimessenger astrOnomy	M. La Cognata, R.G. Pizzone	LNS-INFN, Catania
Study the αOMP parameterizations by inverse elastic scattering experiments using neutron-rich RI beams	G. Kiss, Z. Fulop	Institute for Nuclear Research (MTA Atomki), Debrecen, Hungary
Continuous and pulsed neutron sources driven by Laser and Ion beams for Nuclear Astrophysics	S. Amaducci, G. Cosentino	LNS-INFN, Catania

THANK YOU