International conference PUMA22 Probing the Universe with Multimessenger Astrophysics
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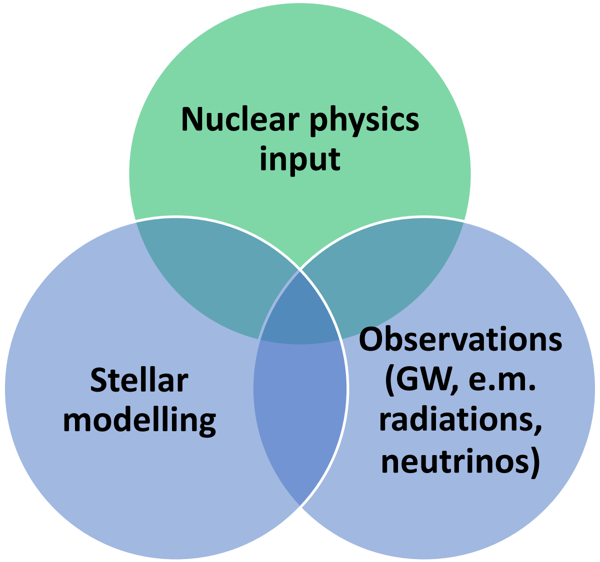
Multimessenger astrophysics at LNS from a nuclear physics point of view

Aurora Tumino

INFN
LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

UNIVERSITAS HENNAE STUDIORUM
LIBERA UNIVERSITÀ KORE ENNA

Nuclear Physics ingredients of Multimessenger Astrophysics



Nuclear physics input

Stellar modelling

Observations (GW, e.m. radiations, neutrinos)

Nuclear physics ingredients: cross sections to determine the reaction rates (in particular for neutron capture reactions), beta-decays, fission rates

Nuclear physics ingredients help access

- the nuclear equation of state, necessary for the description of supernovae explosions, neutron star (NS) structure and dynamical properties, and the dynamics of binary NS mergers.
- r-process yields (determine the heating term of the light curve)

- opacities (determines the optical properties of the expanding plasma) to understand the blast followup.

<u>Some review papers:</u>

Annu. Rev. Nucl. Part. Sci. 67 (2017) 253
Prog. Part. Nucl. Phys. 86 (2016) 86
Prog. Part. Nucl. Phys. 66 (2011) 346

LNS activities involved in this tasks

ASFIN: nuclear reactions of relevance for s-process and r-process nucleosynthesis by means of indirect approaches such as THM and ANC, future activity to tackle ßn emitters

CHIRONE: nuclear reactions to constraint nuclear equation of state and symmetry energy at high density

n-ToF: n-induced reactions to tackle the contribution of fission recycling process to r-process

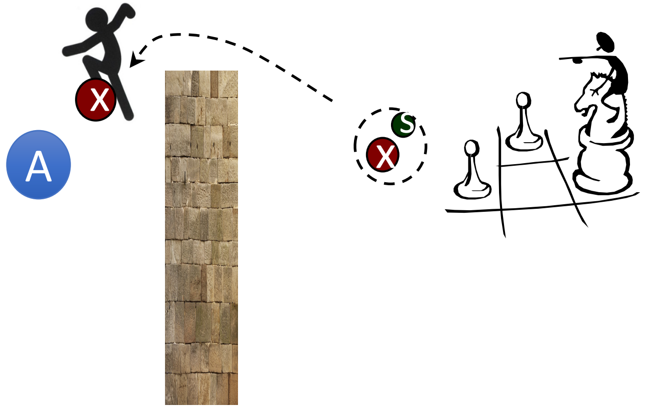
PANDORA: innovative magnetic plasma trap, especially to study ß-decays and opacities under astrophysical conditions

ASFIN and the Trojan Horse Method

Basic principle: astrophysically relevant two-body σ from quasi- free contribution of an appropriate three-body reaction

$A + a \rightarrow c + C + s$ → → → $A + x \rightarrow c + C$

a: $x \oplus s$ clusters

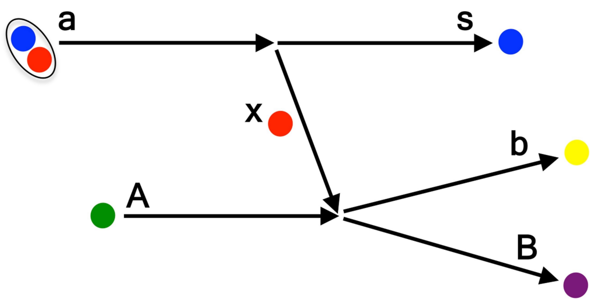


Repulsion wall

Quasi-free mechanism

✓ only *x* - A interaction

✓ *s* = spectator (p_s~0)



$E_A > E_{Coul} \Rightarrow$ NO Coulomb suppression

NO electron screening

$E_{q.f.} = E_{Ax} - B_{x\text{-}s}$ ± intercluster motion → $E_{q.f.} \approx 0$!!!

↓

plays a key role in compensating for the beam energy

PWIA hypotheses:

- beam energy > $a = x \oplus s$ breakup Q-value
- projectile wavelength k^{-1} << x – s intercluster distance

$$\frac{d^3\sigma}{d\Omega_c \, d\Omega_C \, dE_c} \propto KF \cdot \left|\Phi(p_s)\right|^2 \frac{d\sigma^{off}}{d\Omega}$$

Recent Review paper:

Annu. Rev. Nucl. Part. Sci. 71 (2021) 345

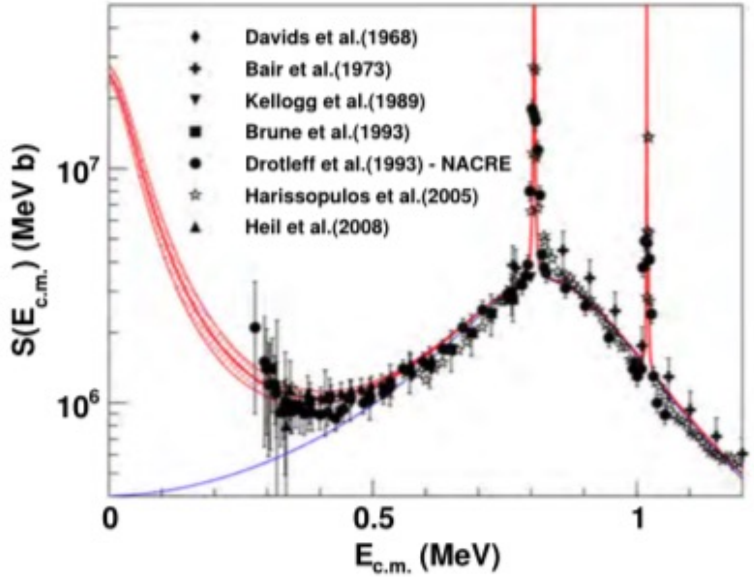
Constraining r-process abundances

The r-process pattern is extracted from the solar system abundances by subtracting the s-process (and p-process) contributions through models

s-process nucleosynthesis plays a crucial to constrain the r-process. At LNS, an intense activity on the s-process is ongoing focusing on:

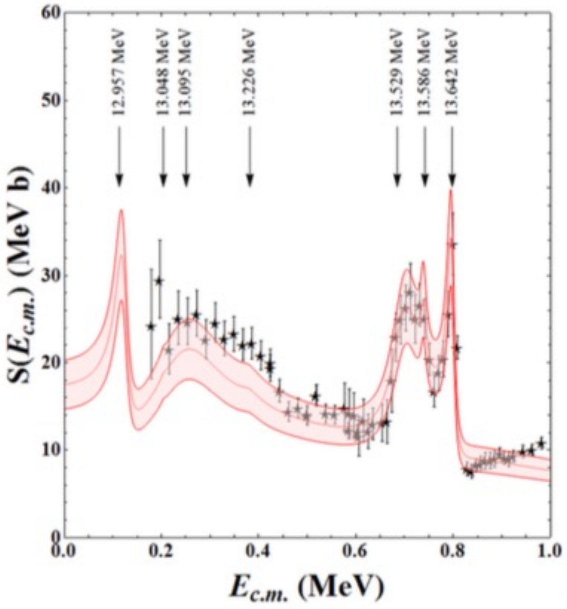
1. Investigating the neutron sources of the s-process: **^{13}C(α,n)^{16}O and ^{22}Ne(α,n)^{25}Mg**

2. Constraining astrophysical models of s-process by studying production and destruction of probe nuclei (mainly ^{19}F)
Fluorine is very sensitive on the stellar physical conditions, so its abundance allows us to see "inside" the s-process site



Red band:
^{13}C(α,n)^{16}O S-factor measured at LNS down to astrophysical energies

Astrophysical Journal 777 (2013) 143
Astrophysical Journal 895 (2018) 105

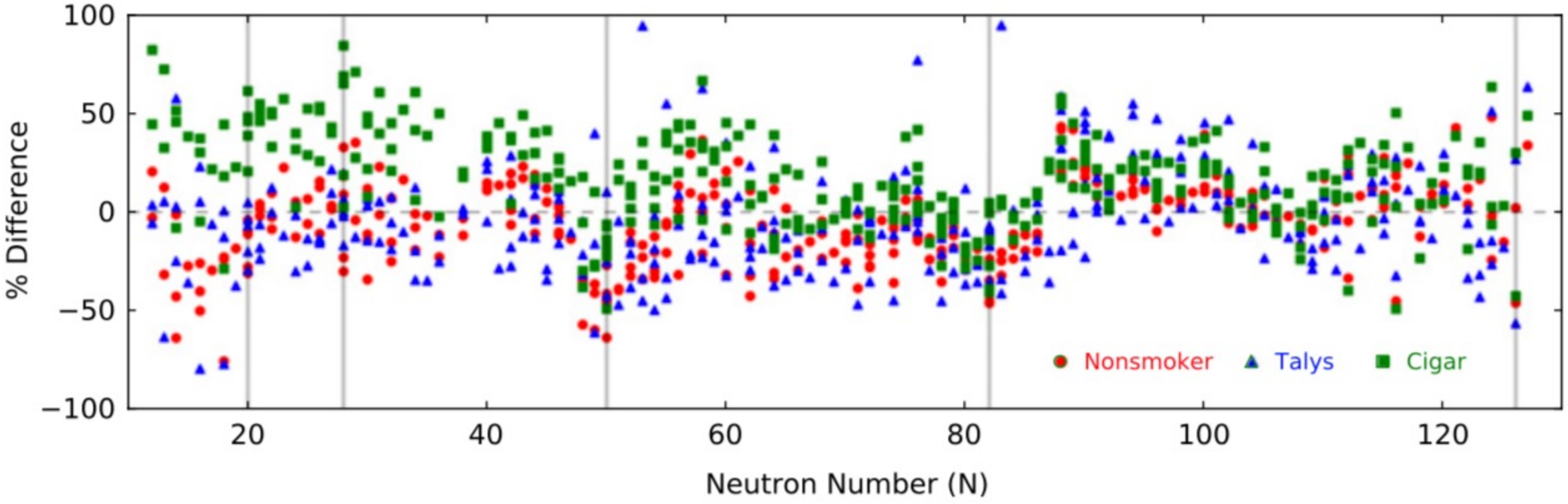


Red band:
^{19}F(p,α)^{16}O S-factor measured at LNS down to astrophysical energies

Astrophysical Journal 845 (2017) 19

Nuclear physics input: n-capture reactions

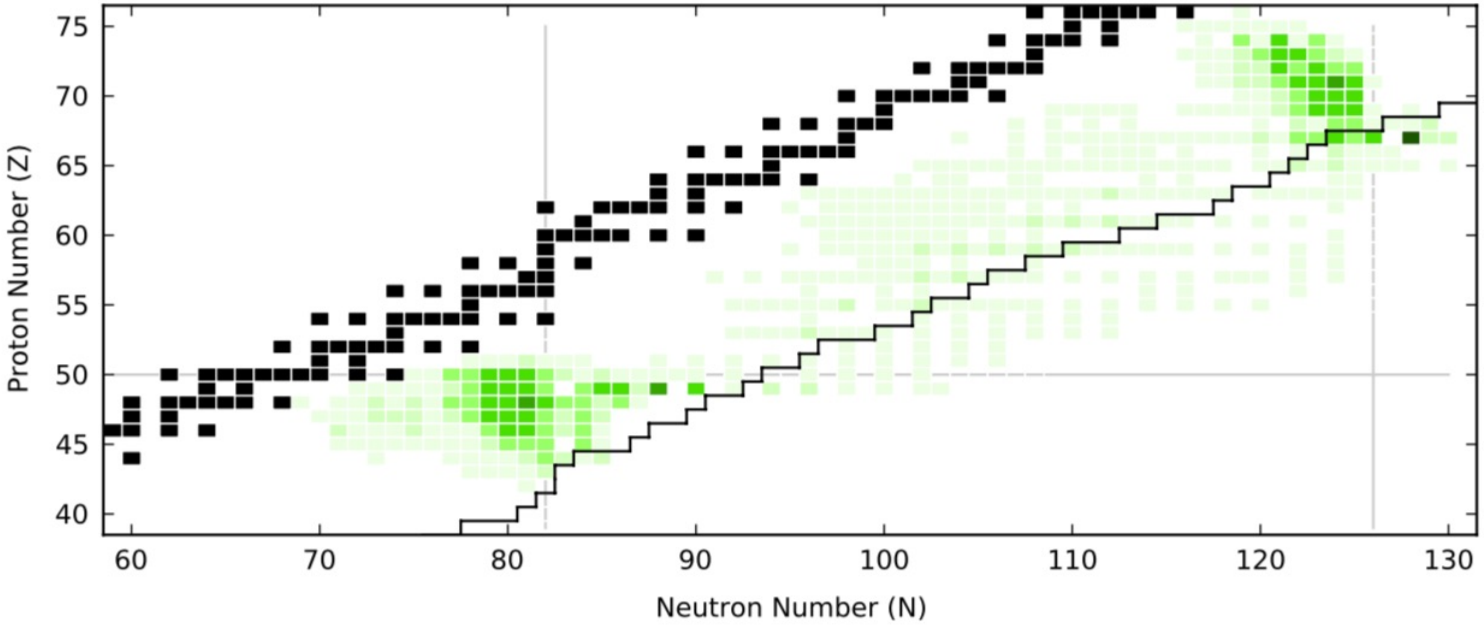
Little or no data on n-capture cross sections available → too short $T_{1/2}$
Cross section calculations necessary.
How reliable?
Often, worse than 1 order of magnitude



How to perform measurements?
→ **Indirect methods**
e.g. Trojan Horse Method, Surrogate reactions

Important <u>neutron capture rates</u> in neutron star mergers

- Along the hot r-process path no sensitivity on cross sections owing to (n,γ)⇔(γ,n) equilibrium
- **Enhanced sensitivity for neutron star mergers** since neutrons are available when (γ,n) reactions become negligible



Prog. Part. Nucl. Phys. 86 (2016) 86

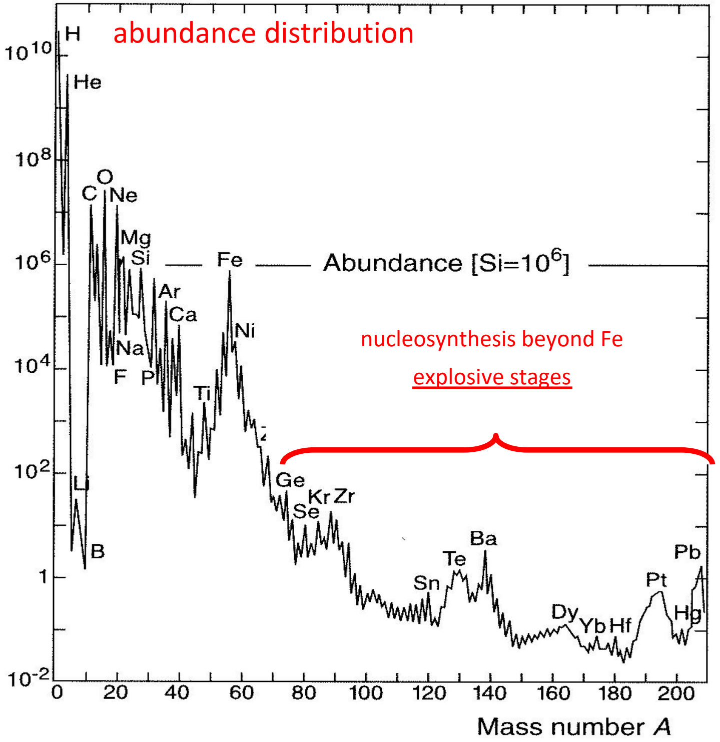
The THM for n+radioactive nucleus reactions

RIB experiments: mostly neutron but also p,a induced reactions to tackle the nucleosynthesis beyond Fe

$T > 10^8$ K ⇒ $E_0 \sim$ 100 keVs - MeVs ≤ E_{coul} → 10^{-6} barn $< \sigma < 10^{-3}$ barn

Experimental Issues:

- low beam intensities (several o.d.m. lower than for stable beams)
- beam energies usually significantly larger than those needed for astrophysical studies
- changing beam energies in small steps to study the excitation function is often impractical.
- n-targets still under development, low density



THM

- Higher beam energies complying with available RIB facilities
- A single beam energy to study the excitation function → intercluster motion used to cover the astrophysical energy region.
- Use of d-targets (CD_2) as virtual n-targets

The THM for n+radioactive nucleus reactions

Benchmarks (stable nuclei or “almost stable”):

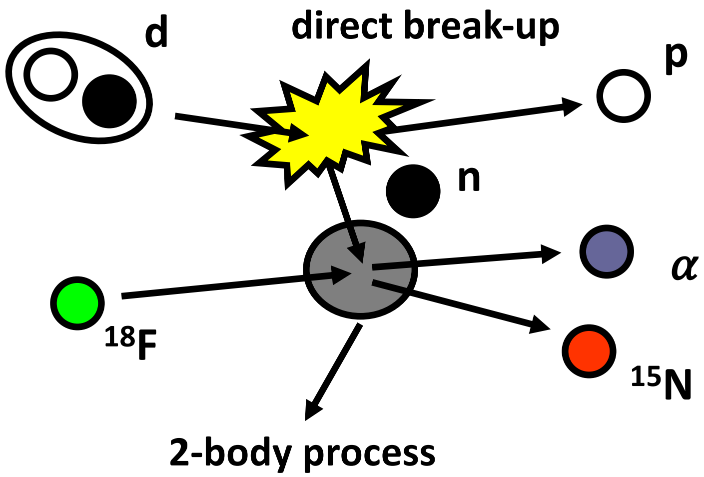
$^{17}O(n,\alpha)^{14}C$ PRC 95 (2017) 025807, PRC 87 (2013) 012801

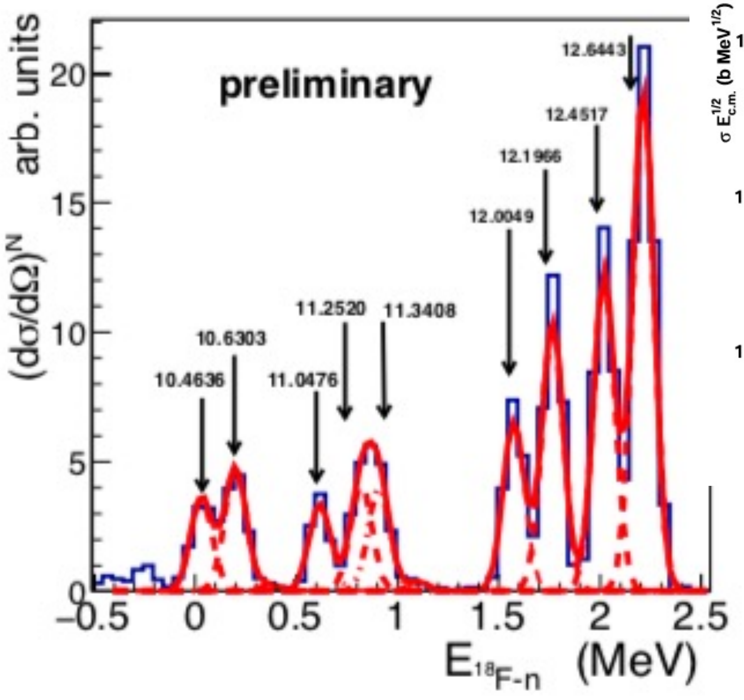
$^{6}Li(n,\alpha)^{3}H$ JPG 37 (2010) 125105, EPJA 25 (2005) 649

$^{7}Be(n,\alpha)^{4}He$ APJ, 879:23 (2019)

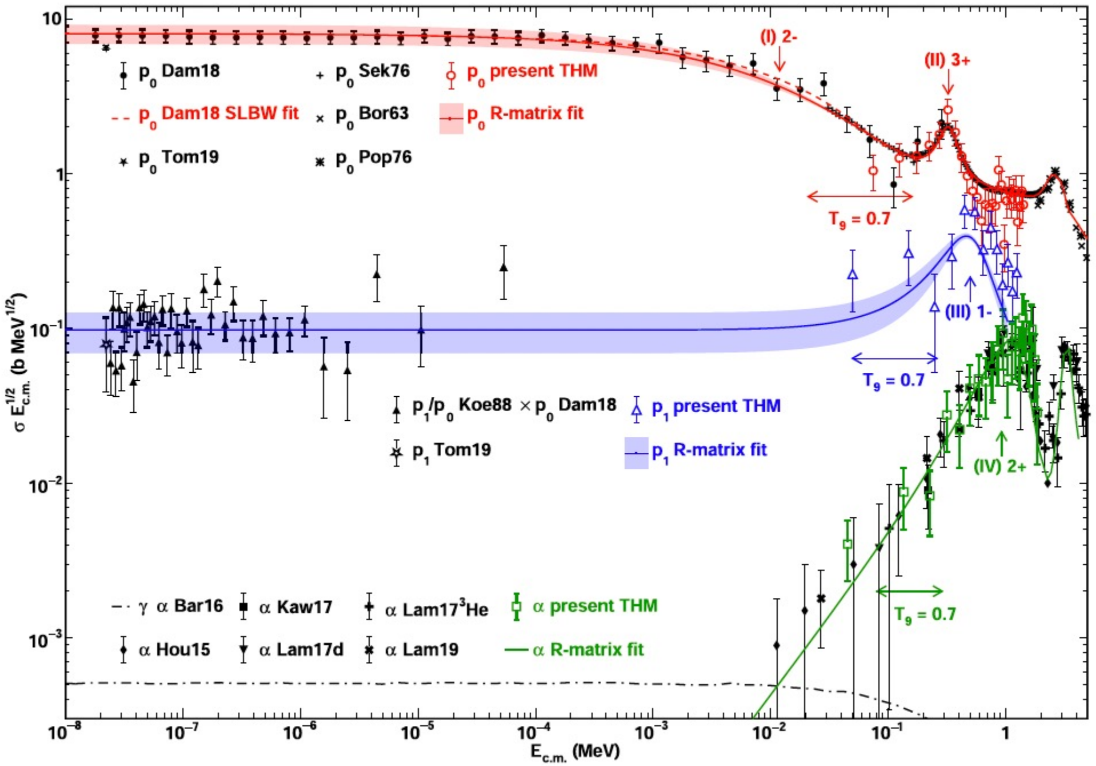
$^{7}Be(n,\alpha)^{4}He$ & $^{7}Be(n,p)^{7}Li$ APJL 915 :L13 (2021)

First measurement of RIB(short lived!!!!!)+neutron: analysis ongoing



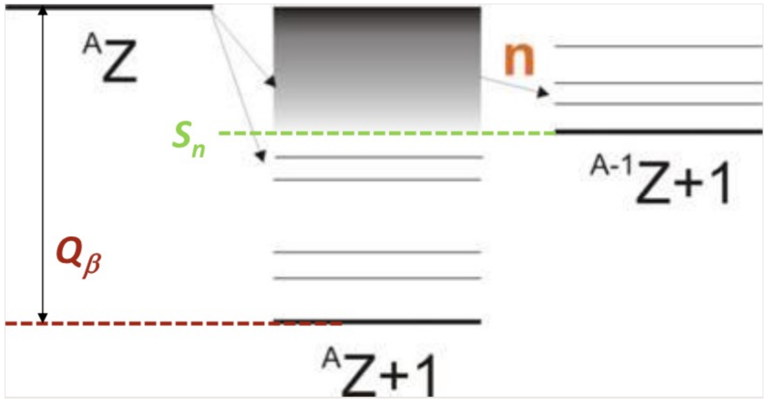


JPS Conf. Proc. 14, 021104 (2017)



$^{7}Be(n,\alpha)^{4}He$ cross section measured with the THM using *d* to transfer a neutron

Nuclear physics input: β-delayed n-emission

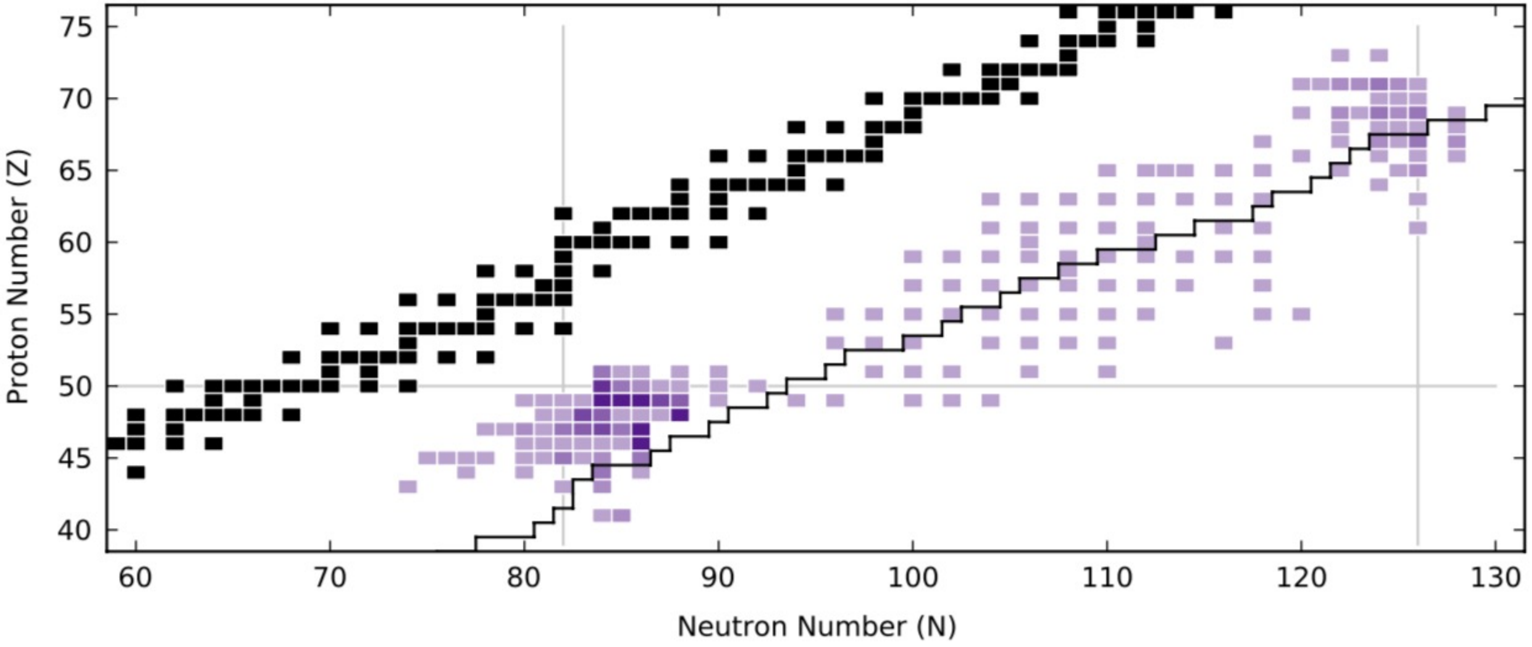


S_n (neutron separation energy) < Q_β (Q-value β-decay)

"Delayed": emission with β-decay half-life of the precursor nucleus ^{A}Z

Important nuclear structure information:

- Time-dependence of n-emission → **$T_{1/2}(^{A}Z)$** ≈ few ms – tens of s
- **Emission probability P_n** and neutron spectrum: β-strength above S_n



Important β-delayed neutron emitters in neutron star mergers

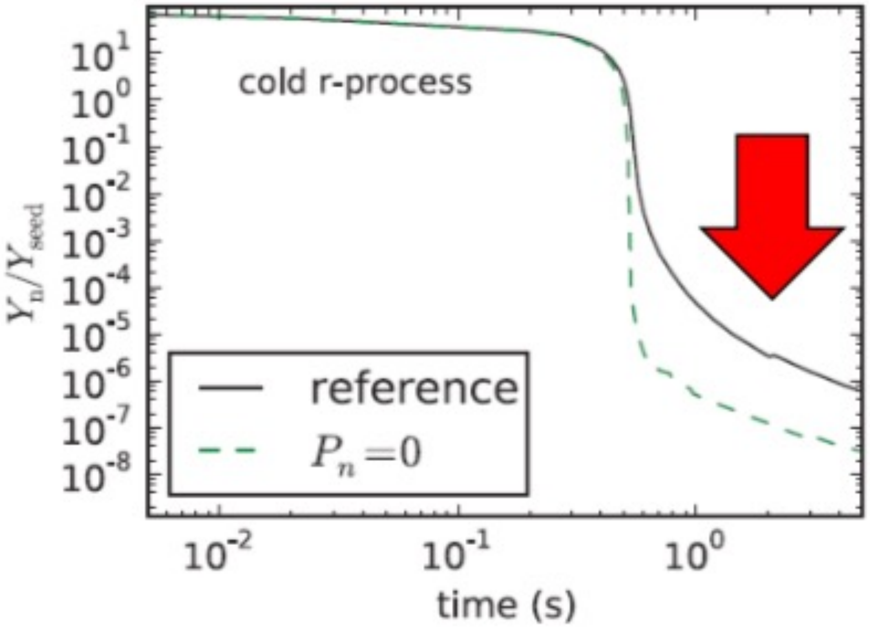
Influence on nucleosynthesis:

- Injection of neutrons during freezeout
- Production of less-neutron-rich nuclei

Reshuffle of r-process yields

Prog. Part. Nucl. Phys. 86 (2016) 86

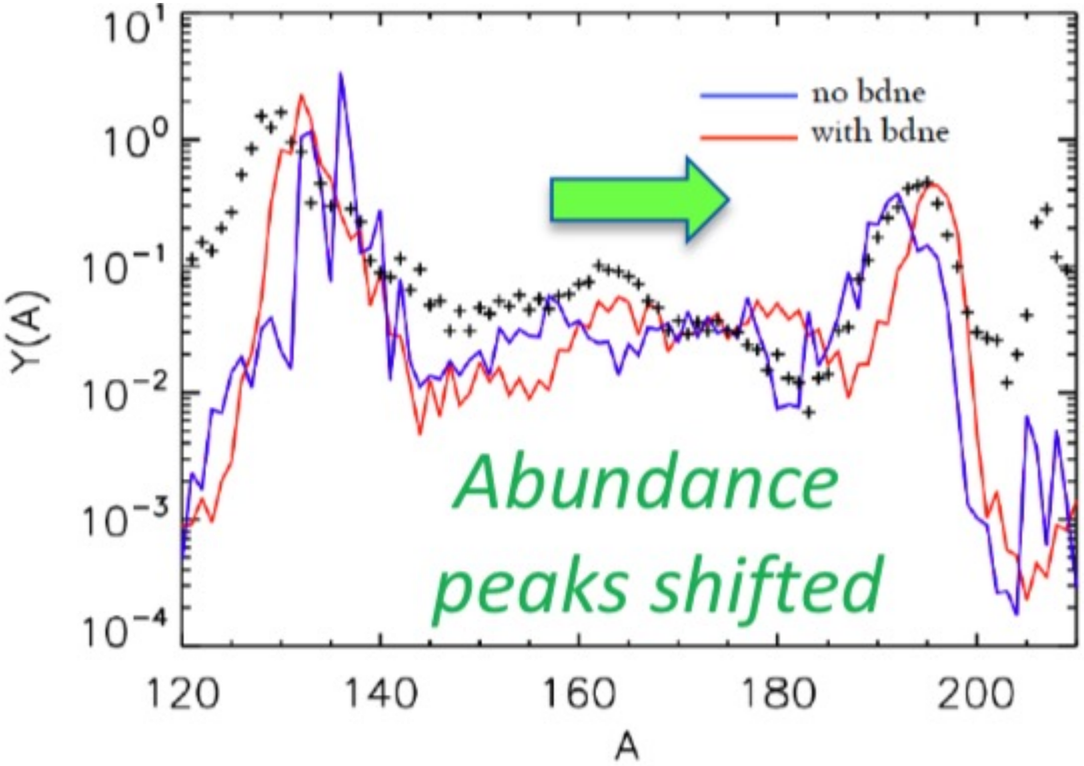
Nuclear physics input: β-delayed n-emission



PRC83, 045809 (2011)

Cold scenario: the case of neutron star mergers

Production of additional neutrons vs. depletion of neutron rich nuclei

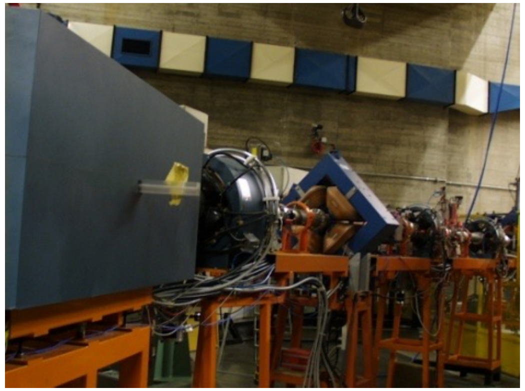


Cold evolutions have a greater availability of neutrons at late times than hot scenarios, from fission and/or from the extra β-delayed neutron emission

Thus we find the most favored solutions tend to initially populate a rare earth peak at lower A, and **late-time neutron captures shift the peak to the correct placement**.

JPG44, 034003 (2017)

POLYFEMO @ LNS to study β-delayed n-emission



FRIBs: in-flight fragment separator

Cocktail beams
→ Possibility to measure many βn emitters at the same time.

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

Journal of Physics: Conf. Series 1014 (2018) 012016

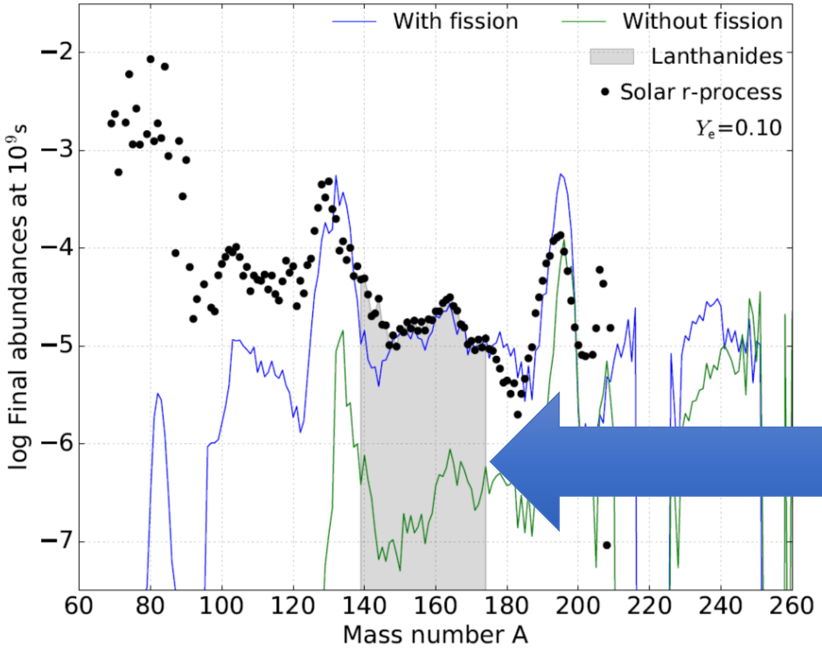
FRIBs will be coupled with the Polycube neutron detector for P_n measurements

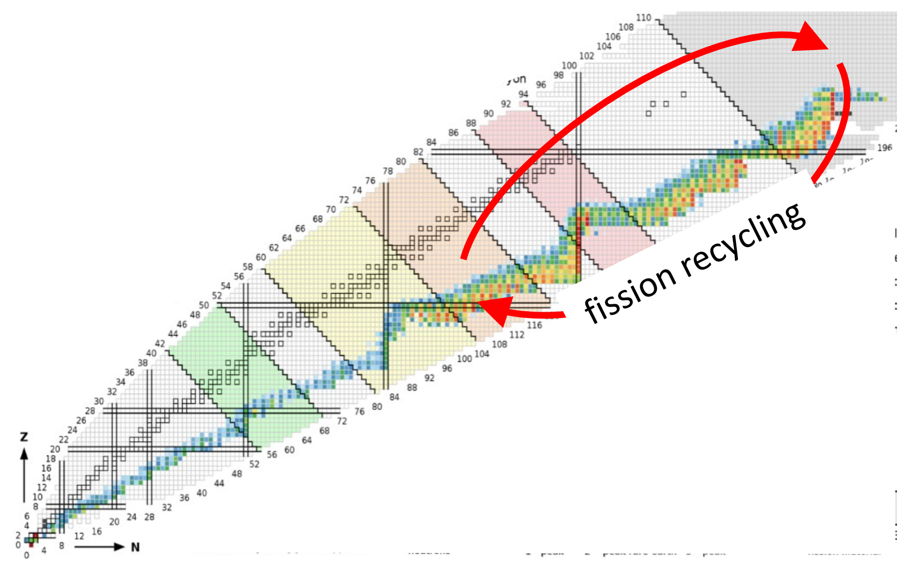
In the next future, improvements in the ECR sources, Cyclotron and FRIBS (FRAISE) upgrade will extend the range of the measured nuclei

n_TOF: Fission Recycling

In explosive scenarios (supernovae and neutron star mergers) the fission products of the heavier elements up to A~250, can be seed for additional r-processing.

N Colonna, et al., The fission experimental programme at the CERN n_TOF facility: status and perspectives, The European Physical Journal A 56 (2), 1-49, 2020

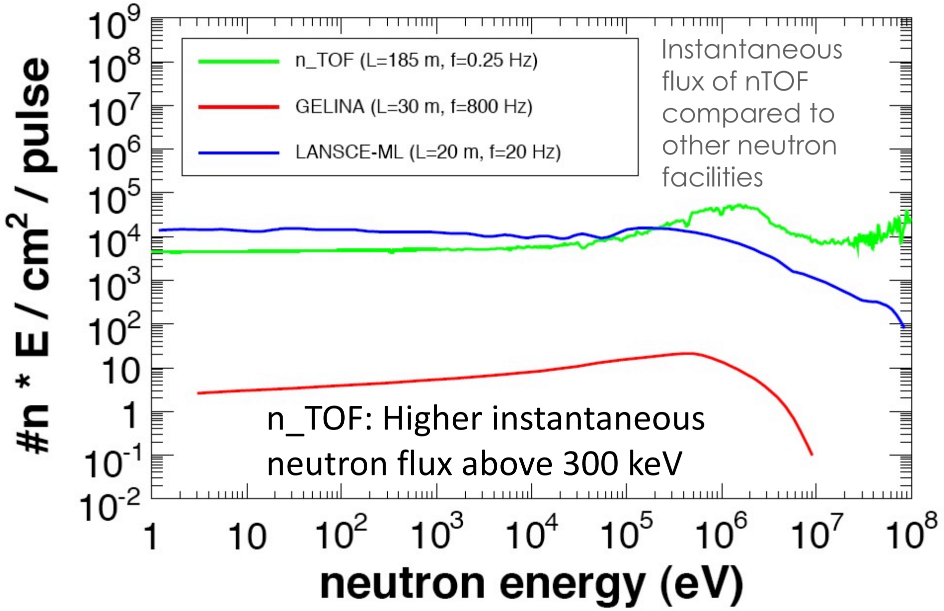




This Fission Recycling process populates the intermediate mass region, with modification of the A~130 r-process abundance peak

FR explains the abundance observed in the solar sistem, in particular in the lanthanides region.

Cross section measurements of neutron induced fission reactions → n_TOF



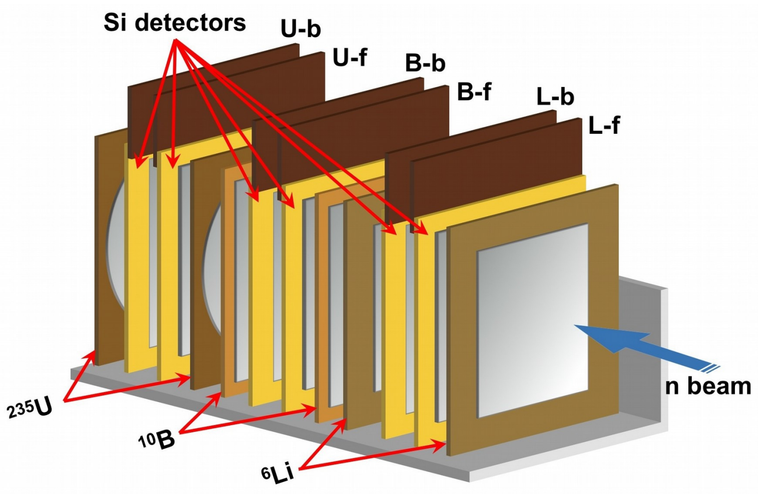
Instantaneous flux of nTOF compared to other neutron facilities

n_TOF: Higher instantaneous neutron flux above 300 keV

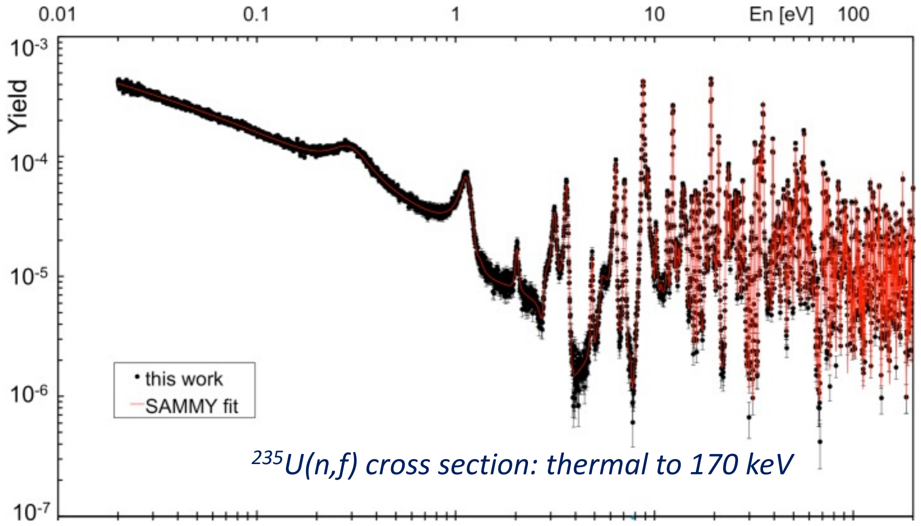
- *Well suitable for radioactive isotopes (actinides)*
- *Possibility of extending the resolved resonances region at higher energy values*
- *To measure fission cross sections up to very high energy (500MeV at least)*

Two Exp. area	**Exp. area 1**	**Exp. area 2**
Neutron flux	**High (10^5 n/bunch)**	**Very high (10^7 n/bunch)**
Energy range	**Very wide (therm. – GeV)**	**Wide (therm. – 100 MeV)**
Energy resolution	**Very good (10^{-4})**	**Good (10^{-3})**
Expecially suitable for:	**Narrow resonances**	**Short lived radioactive isotopes, low cross sections**

LNS-nTOF team: Fission measurements using silicon detectors



Silicon detectors 5x5 cm^2, 200µm



M Mastromarco, S Amaducci et al., The European Physical Journal A 58 (8), 1-13, 2022

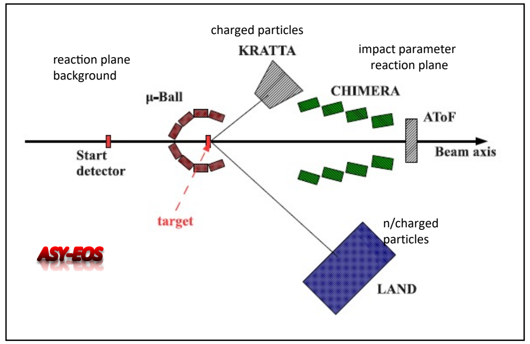
S Amaducci, L Cosentino et al., The European Physical Journal A 55 (7), 1-19, 2019

Measurements by LNS group has led to improvements in 235U standard cross section (used as reference for all fission measurements)

- **High energy resolution** -> To extend the Resolved Resonance Regions
- **Wide energy range** -> From thermal to tens MeV (with suitable configurations possible to reach even up to hundreds MeV)
- **High reliability and high resistance to radiation damage**
- **Modular design** -> High versatility in detector geometry (including annular) and signal readout

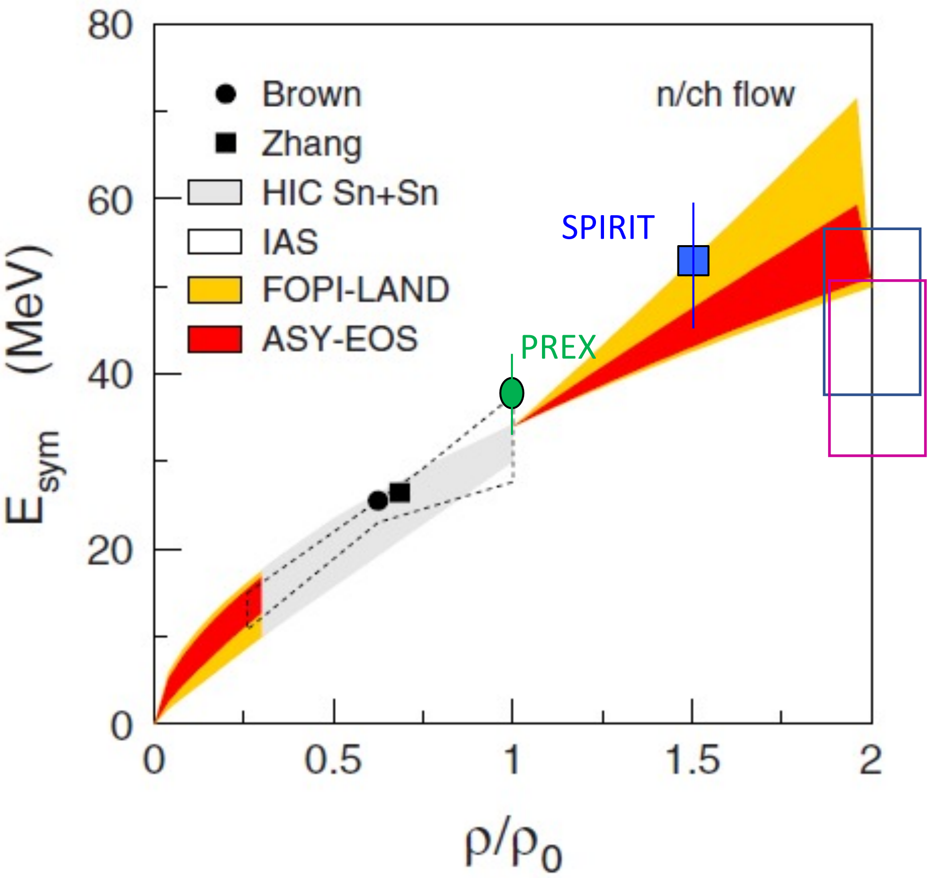
ASY-EOS: a first constraint on high-density symmetry energy

ASY-EOS exp. @ GSI (2011)



Observable:
Elliptic flow ratio of neutrons and protons(charged particles)

P. Russotto et al., PRC 94, 034608 (2016)



neutron star
X-ray observations
Zhang & Li
EPJA 55:39 (2019)
E_{sym} ($2\rho_0$) =
47 ± 10 MeV

Bayesian analysis
GW170817 and
radii of QLMXB
Xie & Li
arXiv:1907.10741
R = 10.8 – 11.9 km
E_{sym} ($2\rho_0$) =
39+12−8 MeV

Bayesian inference to combine data from astrophysical observations of neutron stars and from heavy-ion collisions of gold nuclei at relativistic energies with microscopic nuclear theory calculations to improve our understanding of dense matter.

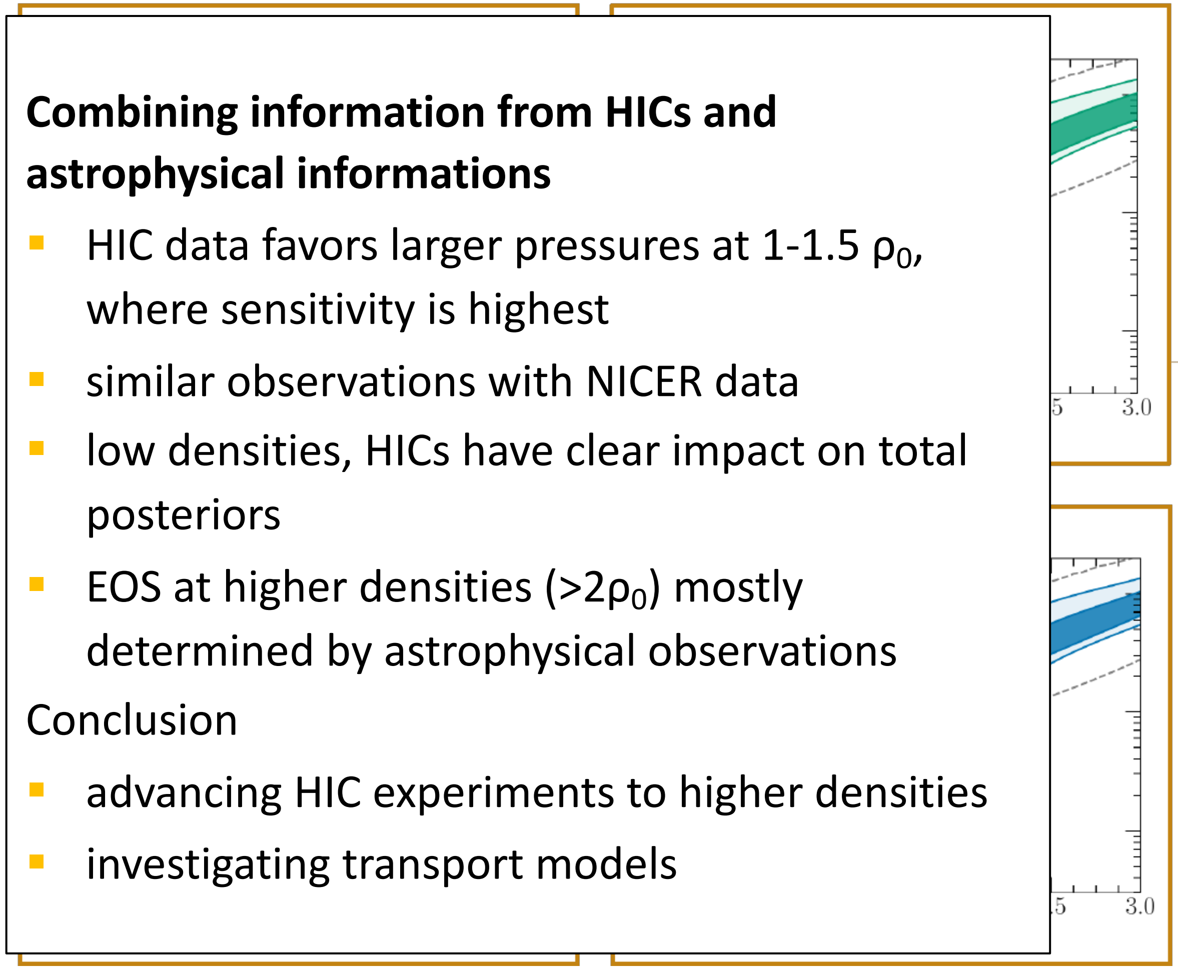
W.G. Lynch, M.B. Zhang, arXIv:2106.10119

PREX, PRL 126, 172502 (2021)

Combining HIC and astrophysical results in the same Bayesian analysis to constrain neutron matter EOS

Constraining Neutron-Star Matter with Microscopic and Macroscopic Collisions
S. Huth et al. **https://www.nature.com/articles/s41586-022-04750-w**

« **HIC** » = FOPI+ASY-EOS+AGS - « **Astro** » = GW, NICER (pulsar X-ray hot spots)

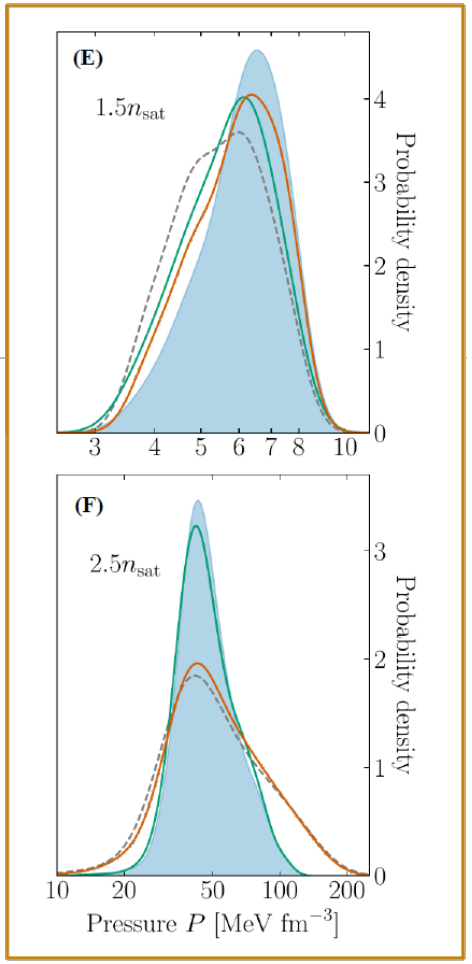


Combining information from HICs and astrophysical informations

- HIC data favors larger pressures at 1-1.5 ρ_0, where sensitivity is highest
- similar observations with NICER data
- low densities, HICs have clear impact on total posteriors
- EOS at higher densities (>2ρ_0) mostly determined by astrophysical observations

Conclusion

- advancing HIC experiments to higher densities
- investigating transport models

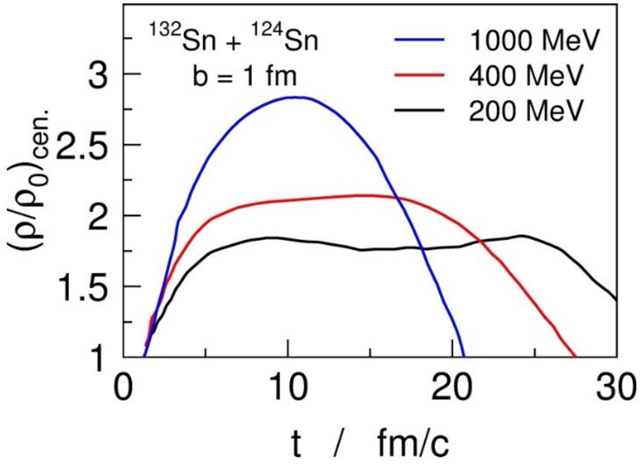


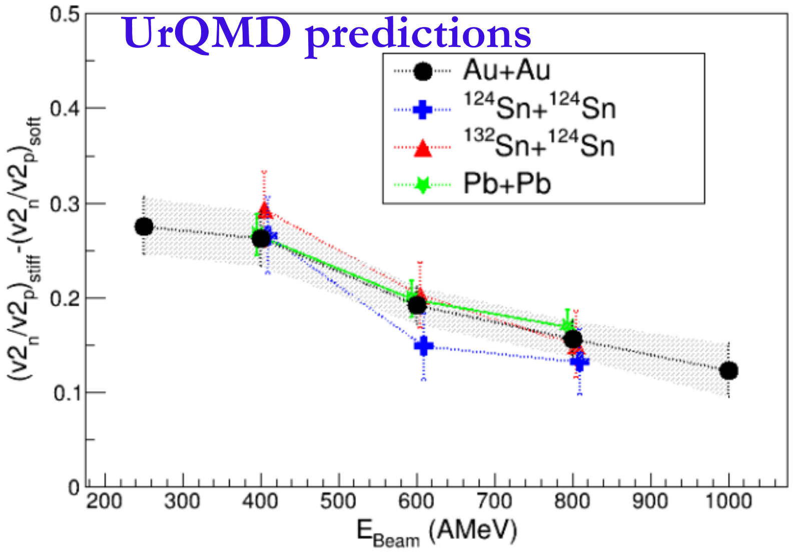
the inclusion of heavy-ion collision data indicates an increase in the pressure in dense matter relative to previous analyses, shifting neutron-star radii towards larger values, consistent with recent observations by the Neutron Star Interior Composition Explorer mission

Advancing to higher densities (towards $2\rho_0$)

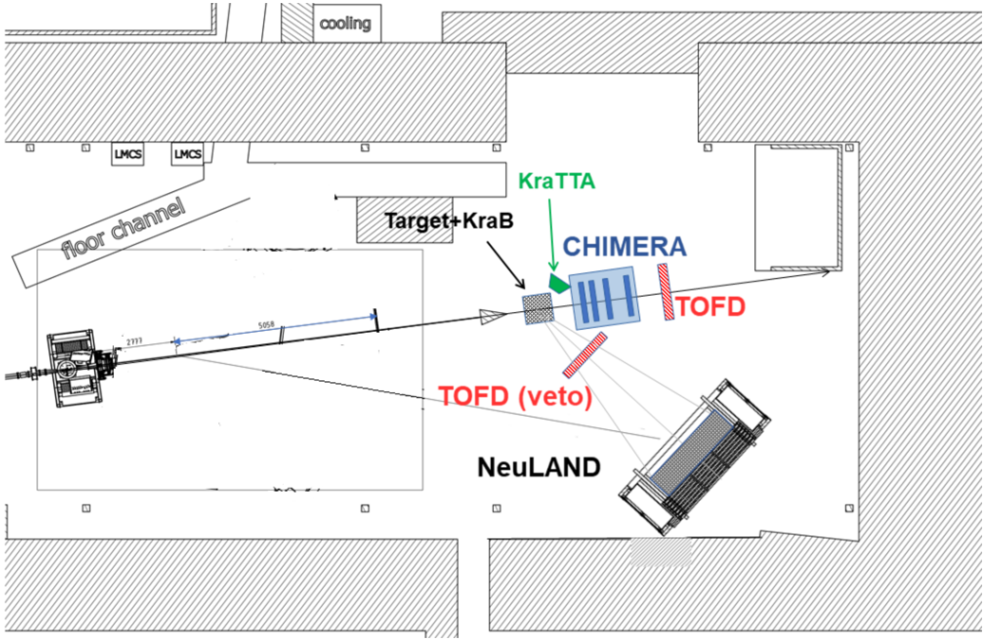
Higher incident energies

Li, Bao-An, NPA 708, 365 (2002)



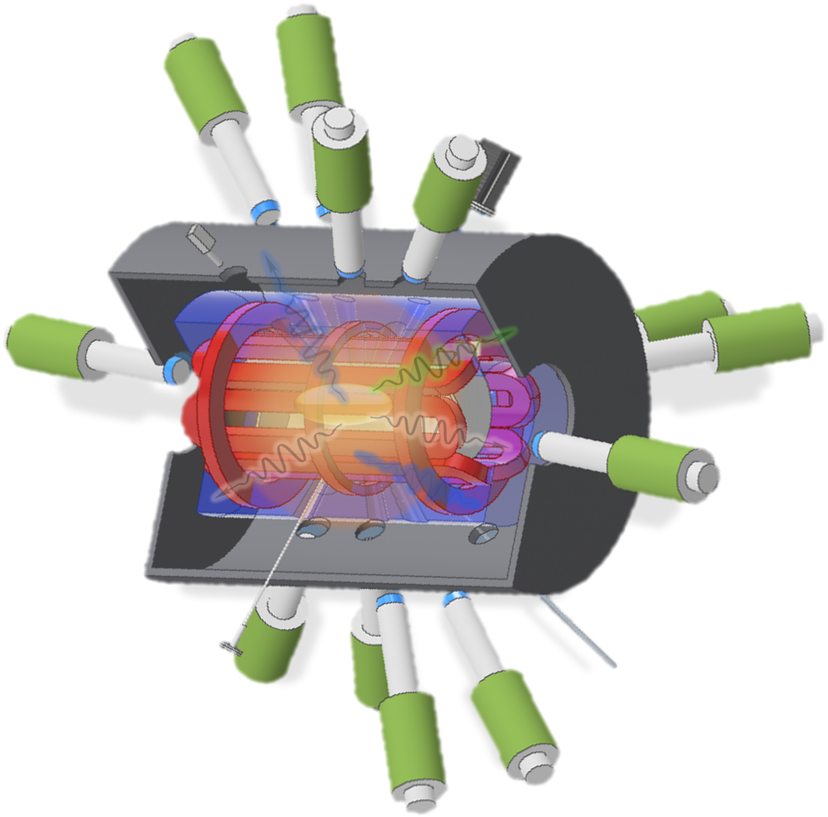


A new experiment (ASY-EOS II) inside the NUSTAR/R3B collaboration, asking to measure excitation function of the n/p elliptic flow in Au+Au collisions (@ 250, 400, 600, and 1000 AMeV), has been recently submitted (June 2022) to the GSI PAC



PANDORA: ECR plasma trap for interdisciplinary studies in nuclear physics and nuclear astrophysics

Plasmas for
Astrophysics
Nuclear
Decay
Observation and
Radiation for
Archaeometry



- **PANDORA concept**: compact **plasma trap** to magnetically confine ions of radioisotopes in a microwave-sustained ECR plasma
- **Goals: nuclear β-decay and spectroscopic measurements** in a plasma resembling **astrophysical conditions** (temperature, ion charge state distribution), BNS ejecta opacity (Pidatella's talk)
- **Plasma diagnostics system**: RF probes, optical and X-ray spectrometers allowing direct **correlation of experimental measurements to plasma density and temperature**
- **Assembling multi-diagnostic setup**: simultaneously monitor plasma parameters and carry measurements under **stable conditions**

- **Electron dens: $10^{12} - 10^{14}$ cm^{-3}**
- **Electron Energy: ~ eV – 100 keV**
- **Ion dens: 10^{11} cm^{-3}**

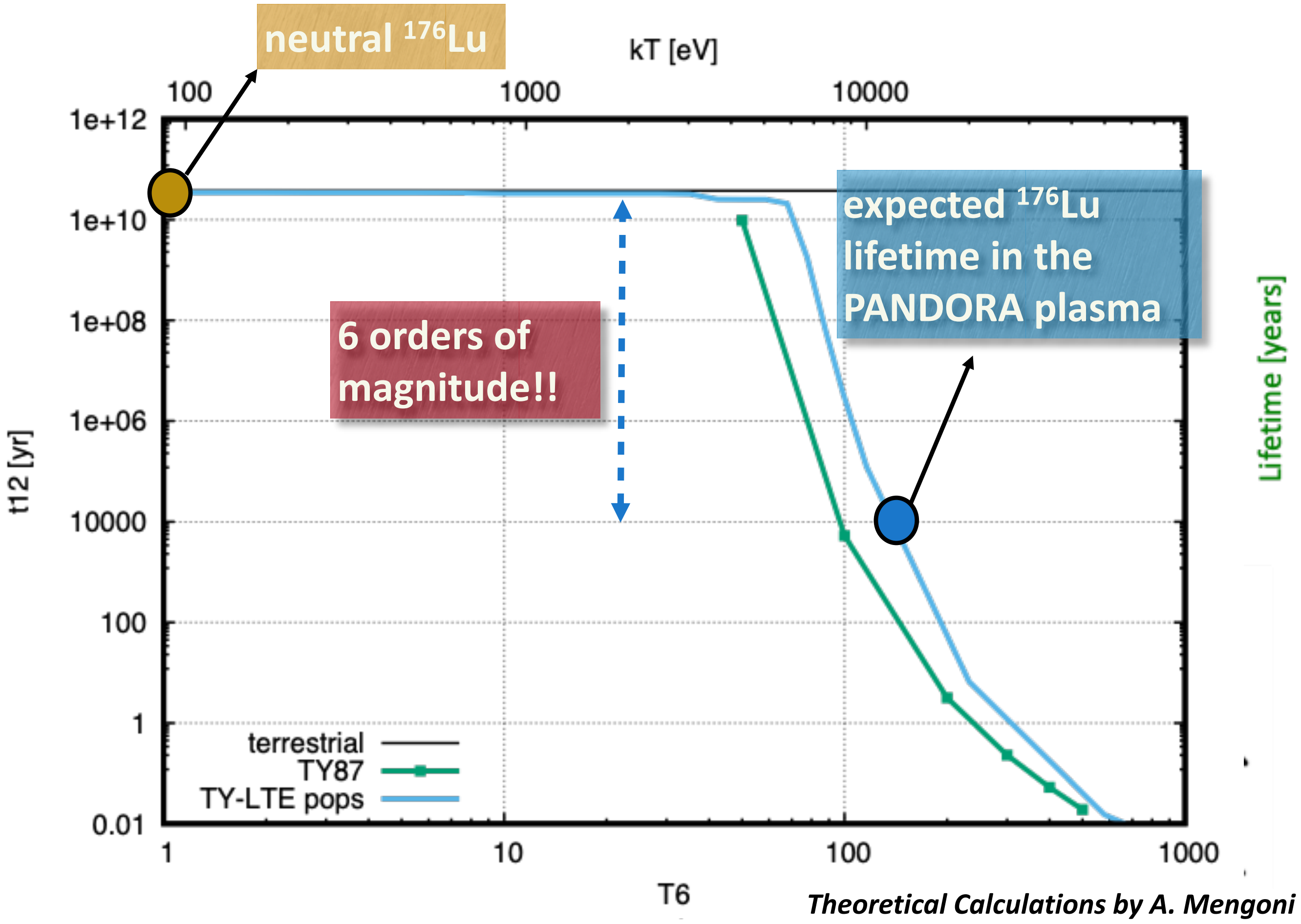
PHYSICS OF INTEREST FOR MMA AND NUCLEAR ASTROPHYSICS

- **s-process nucleosynthesis** + β-decay branching
- **r-process cosmic sites**
- **Nuclear reaction rates in stars**
- Compact binary object **spectroscopy (*kilonova transient*):** to characterize composition and to identify GW events

Mascali,D. et al, Eur. Phys. J. A (2017) 53: 145

Mascali D. et al, Universe 8 (2), 80 (2022)

PANDORA’s challenges: “Collapse” of ^{176}Lu lifetime

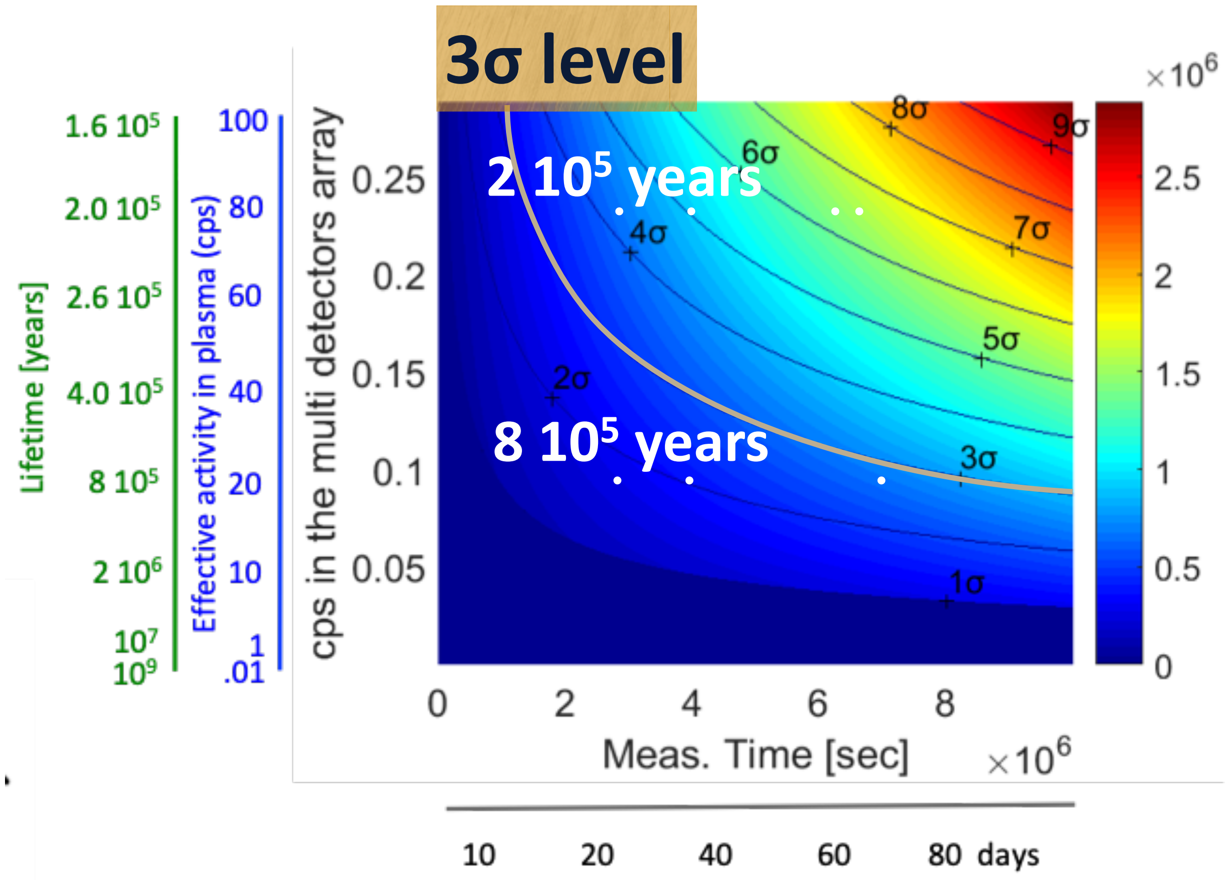

neutral ^{176}Lu

6 orders of magnitude!!

expected ^{176}Lu lifetime in the PANDORA plasma

Theoretical Calculations by A. Mengoni

Estimation of lifetime variation as a function of plasma temperature


3σ level

2 10^5 years

8 10^5 years

“Measurability” of ^{176}Lu lifetime from GEANT-4 simulations (by an array of 14 HpGe-detectors)

Summary

1. Increasingly accurate observations call for more accurate nuclear data on the r-process

→ Constraining the r-process through a better understanding of the s-process:

   a. study of the neutron sources
   b. study of production/destruction of critical elements

→Study of nuclear reactions involved in the r-process

   a. indirect study of n+RIB reactions
   b. Investigation of the beta-delayed neutron emission

2. n-induced reactions to tackle the contribution of fission recycling process to r-process

3. nuclear reactions to constraint nuclear equation of state and symmetry energy at high density → NS radius

4. innovative magnetic plasma trap, especially to study ß-decays and opacities under astrophysical conditions (plasma made up of lanthanides)

THANK YOU VERY MUCH FOR YOUR ATTENTION!