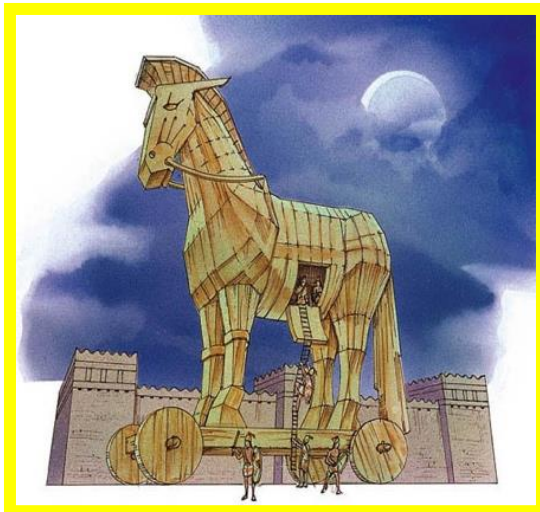




Nuclear Astrophysics with Indirect Methods

Marco Mazzocco



Nuclear Astrophysics

Nuclear Astrophysics investigates how nuclear processes **generate** the **energy of stars** over their **lifetime** and, in doing so, **synthesize heavier elements** from the **primordial hydrogen** and **helium** produced in the **Big Bang**.

We **humans** are mostly **(83%) oxygen** and **carbon**. We **understand** in a general way the **chemistry** and **biology** involved, but we certainly **do not understand** the **nuclear astrophysics** which produced the oxygen and carbon in our bodies.

Each of **us**, in a sense, has been **inside a star** and truly and literally **consists of stardust**. Every molecule in our bodies contains matter that once was subjected to the **tremendous temperatures** and **pressures** at the **center** of a **star**.

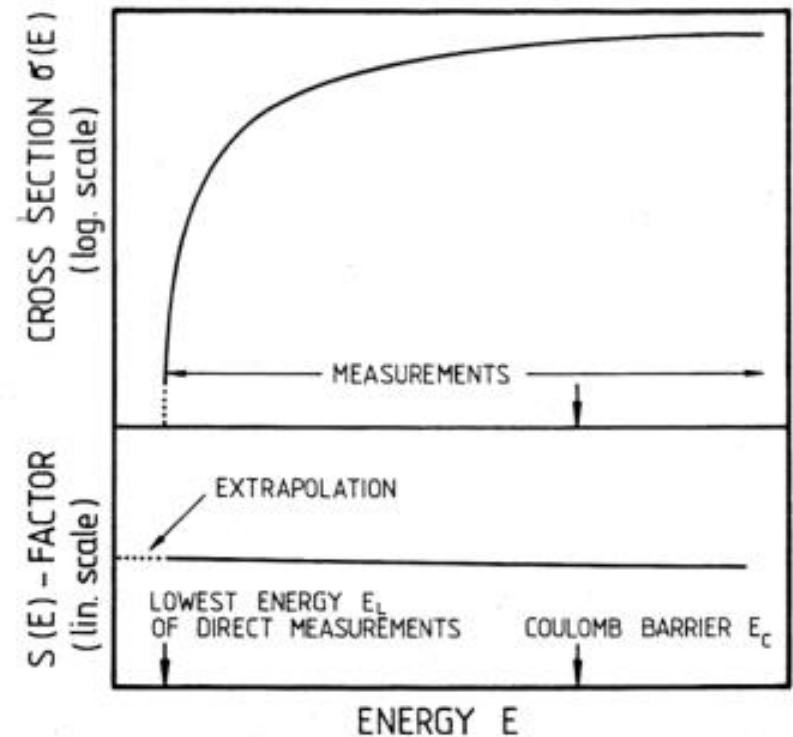
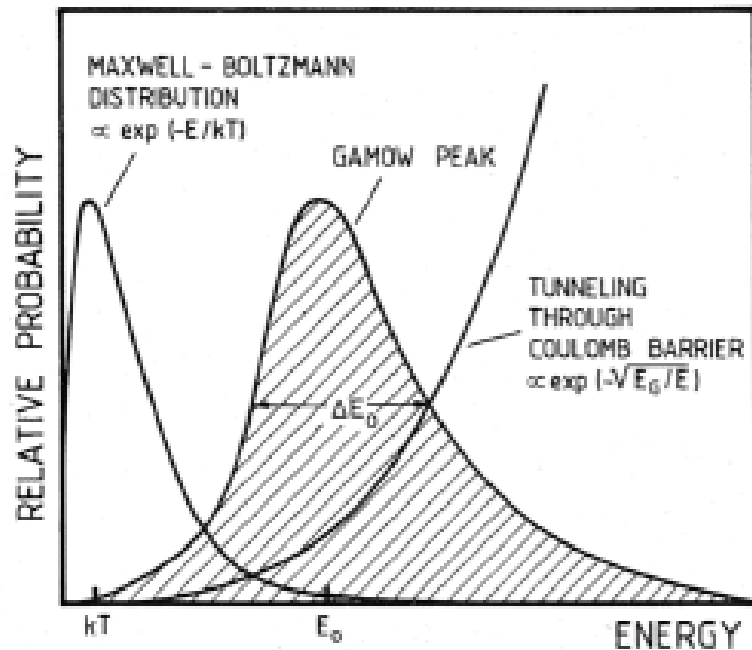
This is where the **iron** in our **blood cells** originated, the **oxygen** we **breathe**, the **carbon** and **nitrogen** in our **tissues** and the **calcium** in our **bones**.

(W.A. Fowler – Nobel Price in Physics 1983)



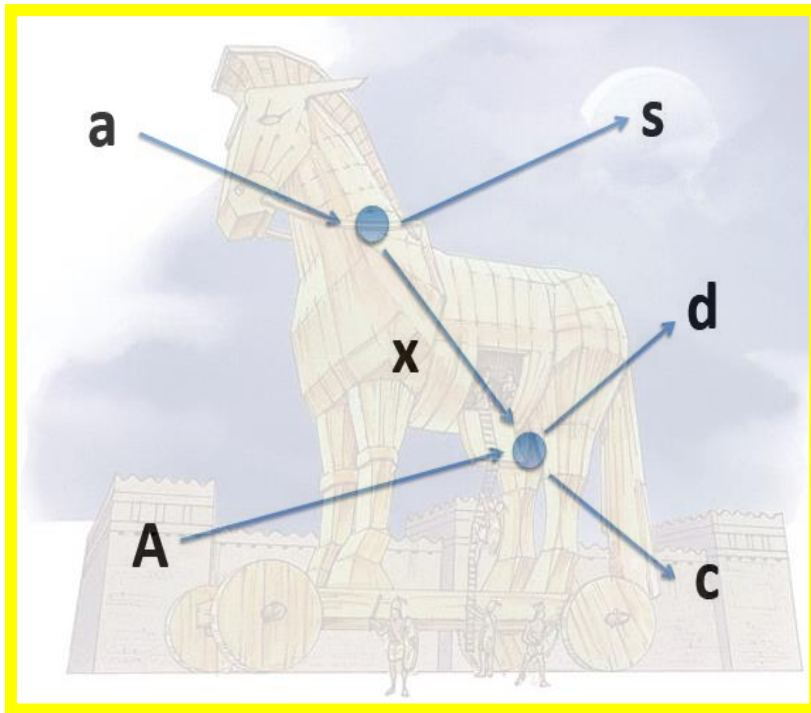
ThermoNuclear Reactions

Gamow Energy Peak



Nuclear reactions of astrophysical interest occur at energies **deeply below the Coulomb barrier**, their **cross sections** (i.e. probabilities) might be extremely **small** and **background** might be very **high**.

Trojan Horse Method



Basic Concept:

It is possible to extract the astrophysically relevant **two-body cross section**:



from the quasi-free contribution of a suitable **three-body reaction**:



Method: to hide the **projectile** x inside a **Trojan Horse Nucleus** a , with a prominent cluster structure $x + s$, and to make sure that **particle** s acts as a **spectator** in the nuclear reaction (quasi-free mechanism)

Recent Measurements

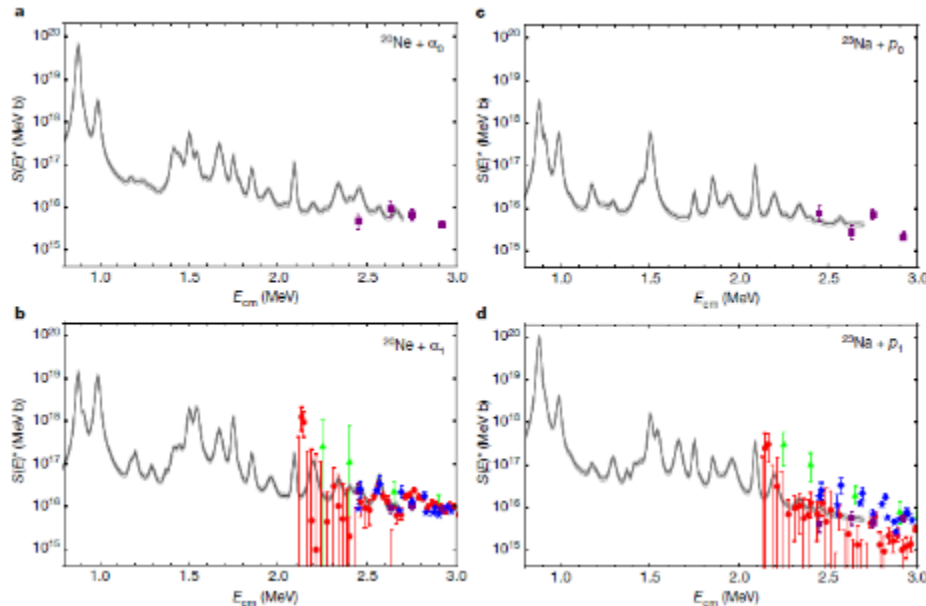
Massive Star Evolution (LNS)

LETTER

<https://doi.org/10.1038/s41586-018-0149-4>

An increase in the $^{12}\text{C} + ^{12}\text{C}$ fusion rate from resonances at astrophysical energies

A. Tumino^{1,2*}, C. Spitaleri^{1,3}, M. La Cognata², S. Cherubini^{1,2,7}, G. L. Guardo^{2,4}, M. Gulino^{1,2}, S. Hayakawa^{1,2,5}, I. Indelicato², L. Lamia^{1,2}, H. Petrascu⁴, R. G. Pizzone², S. M. R. Puglia², G. G. Rapisarda², S. Romano^{2,2}, M. L. Sergi², R. Spartà² & L. Trache⁴



Big-Bang Nucleosynthesis (LNL)

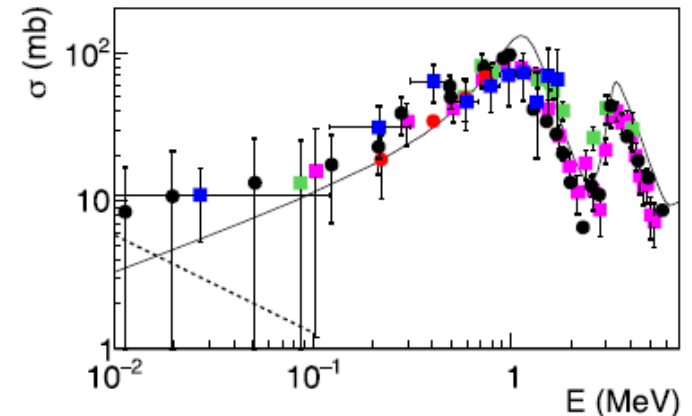
THE ASTROPHYSICAL JOURNAL, 879:23 (5pp), 2019 July 1
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<https://doi.org/10.3847/1538-4357/ab2234>



Cross-section Measurement of the Cosmologically Relevant $^7\text{Be}(n, \alpha)^4\text{He}$ Reaction over a Broad Energy Range in a Single Experiment

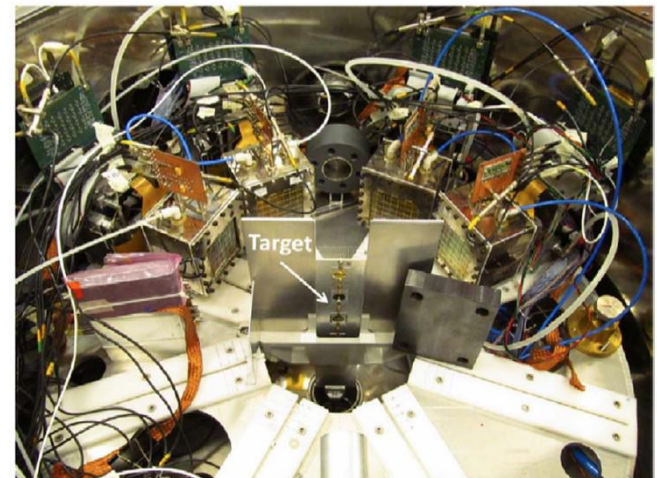
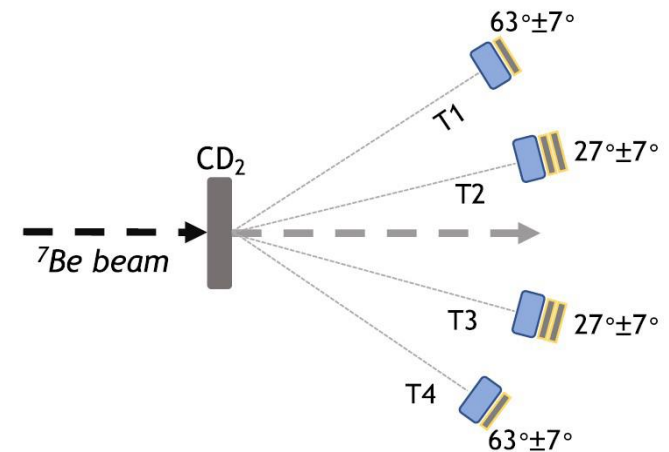
L. Lamia^{1,2}, M. Mazzocco^{3,4}, R. G. Pizzone², S. Hayakawa³, M. La Cognata², C. Spitaleri^{1,2}, C. A. Bertulani⁶, A. Botano⁷, C. Boiano⁸, C. Broggini⁴, A. Cacioli^{3,4}, S. Cherubini^{1,2}, G. D'Agata^{7,13}, H. da Silva⁹, R. Depalo^{3,4}, F. Galtarossa¹⁰, G. L. Guardo^{3,2}, M. Gulino^{2,11}, I. Indelicato^{1,2}, M. La Comara^{7,12}, G. La Rana^{7,12}, R. Menegazzo⁴, J. Mrazek¹³, A. Pakou¹⁴, C. Panascandolo⁷, D. Piarri^{3,4}, D. Pierrotsakou², S. M. R. Puglia², S. Romano^{1,7}, G. G. Rapisarda², A. M. Sánchez-Benítez¹⁵, M. L. Sergi², O. Sgouros^{2,14}, F. Soramel^{3,4}, V. Soukemen^{2,14}, R. Spartà², E. Strano^{3,4}, D. Torresi², A. Tumino^{2,11}, H. Yamaguchi⁵, and G. L. Zhang¹⁶



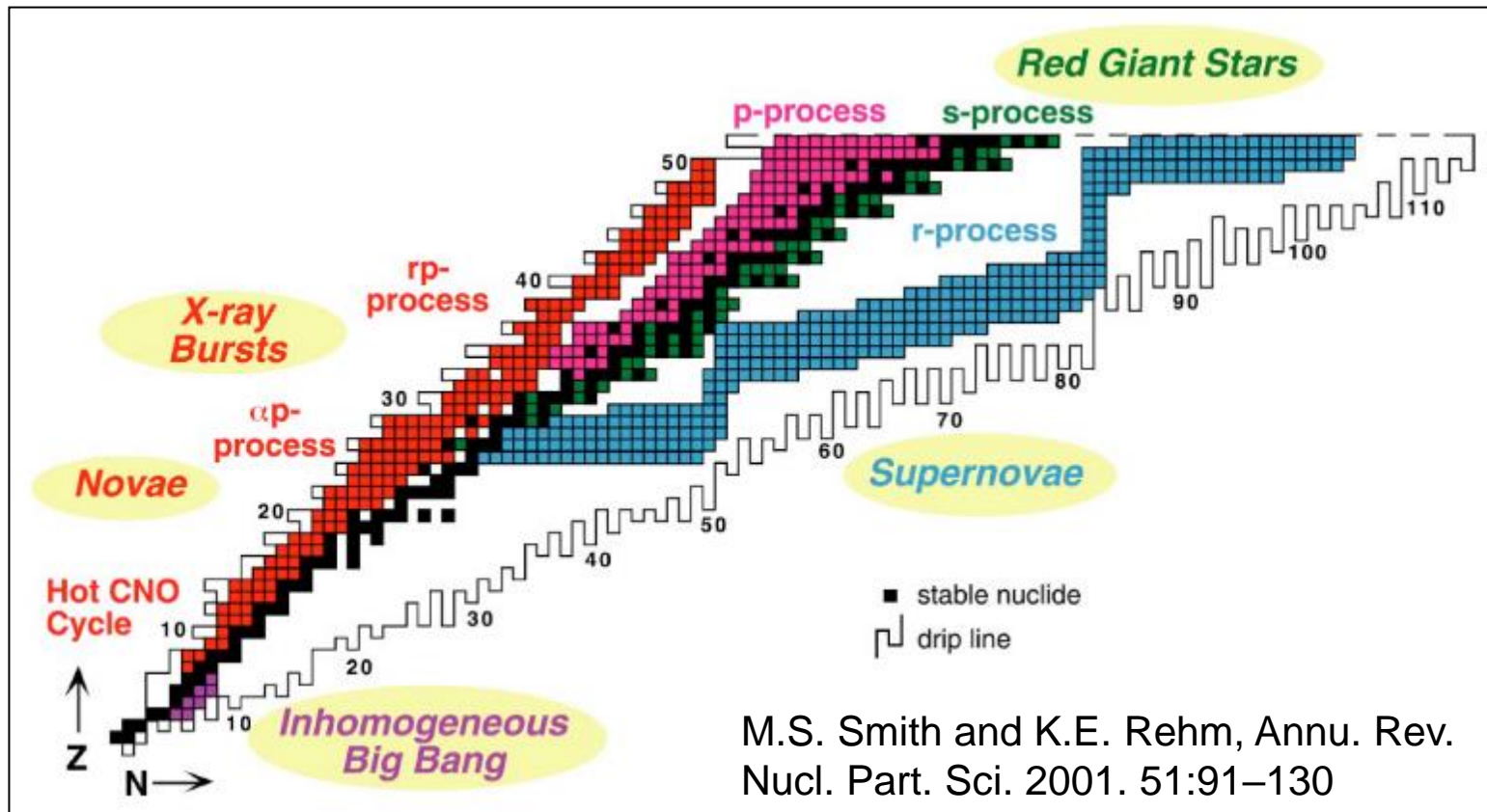
Thesis Activity (I)

- Setup design and construction,
- Setup characterization,
- Data taking,
- Data analysis,
- Study the impact of the cross section results in astrophysical models.

Join experimental runs performed at the RIB facility EXOTIC located at the Legnaro National Laboratories, Laboratori Nazionali del Sud (Catania) or abroad (France, Czech Republic, Canada, Romania, Japan, ...)



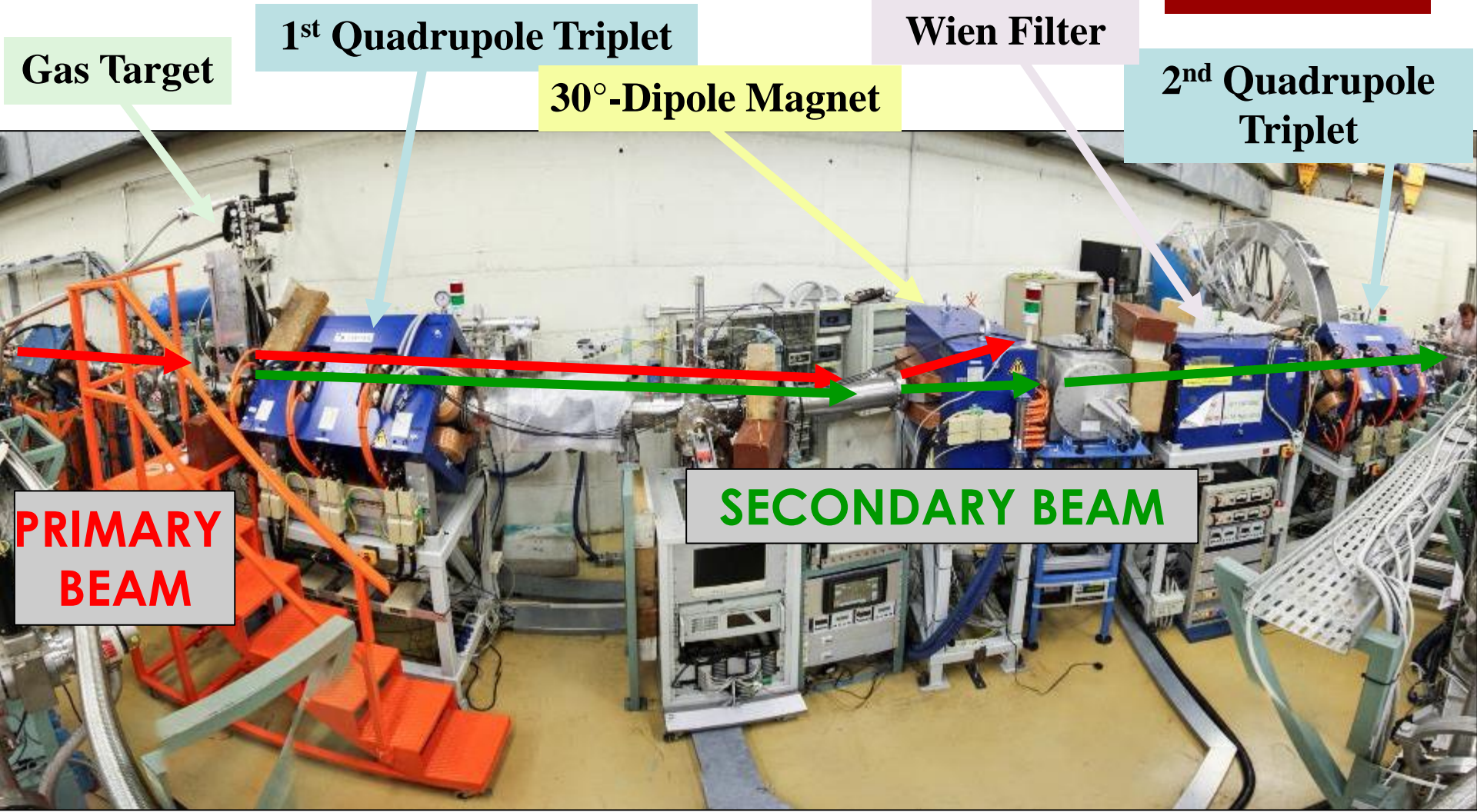
Nuclear Astrophysics and Radioactive Ion Beams



Radioactive Ion Beams (RIBs) are deeply involved in **several scenarios** of interest for **Nuclear Astrophysics**.

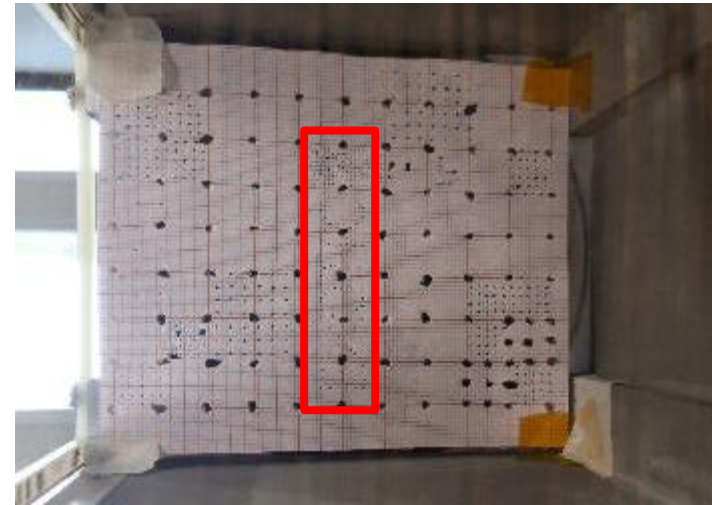
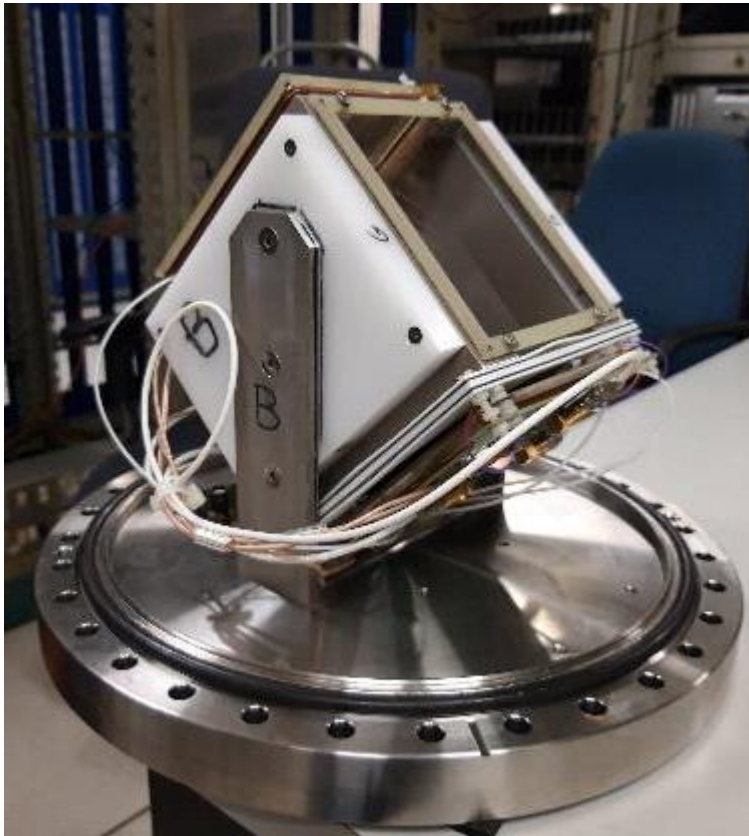
Thesis Activity (II)

- Study of the ion-optics for the connection of EXOTIC and AGATA



Thesis Activity (III)

- Development and characterization of a MCP tracking detector.



ASFIN partnerships and collaborations



@ Catania/LNS: A. Bonasera, S. Cherubini, G. D'Agata, A. Di Pietro, P. Figuera, G.L. Guardo, M. Gulino, M. La Cognata, L. Lamia, D. Lattuada, A.A. Oliva, G.G. Rapisarda, R.G. Pizzone, S. Romano, D. Santonocito, M.L. Sergi, R. Spartà, A. Tumino
@ Padova M. Mazzocco, S. Pigliapoco, F. Soramel
@ Perugia M. Busso, S. Palmerini, M. Limongi, A. Chieffi, M.C. Nucci. N. Vukman
@ Napoli M. La Commara

International Collaborations



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- Texas A&M Commerce USA: C. Bertulani
- Florida State University USA: I. Wiedenhofer
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- CSNSM, Orsay, France : A. Coc , F. Hammache, N. De Sereville
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- University of Pisa: S. Degl'Innocenti, P. Prada Moroni

