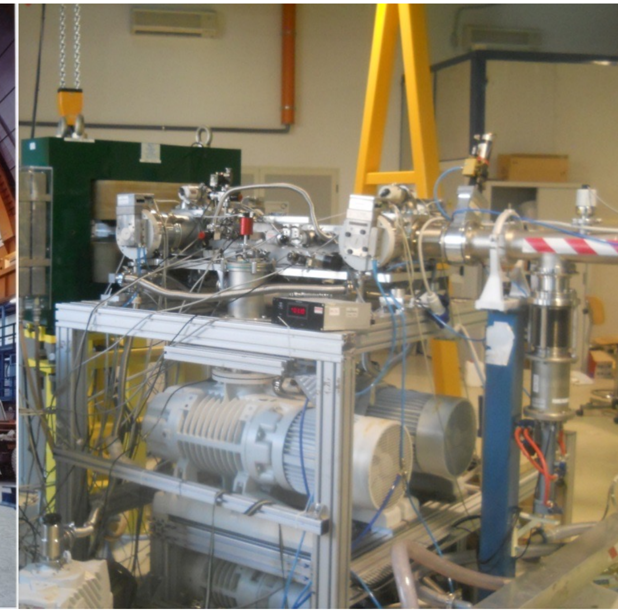
Experimental challenges in Nuclear Astrophysics



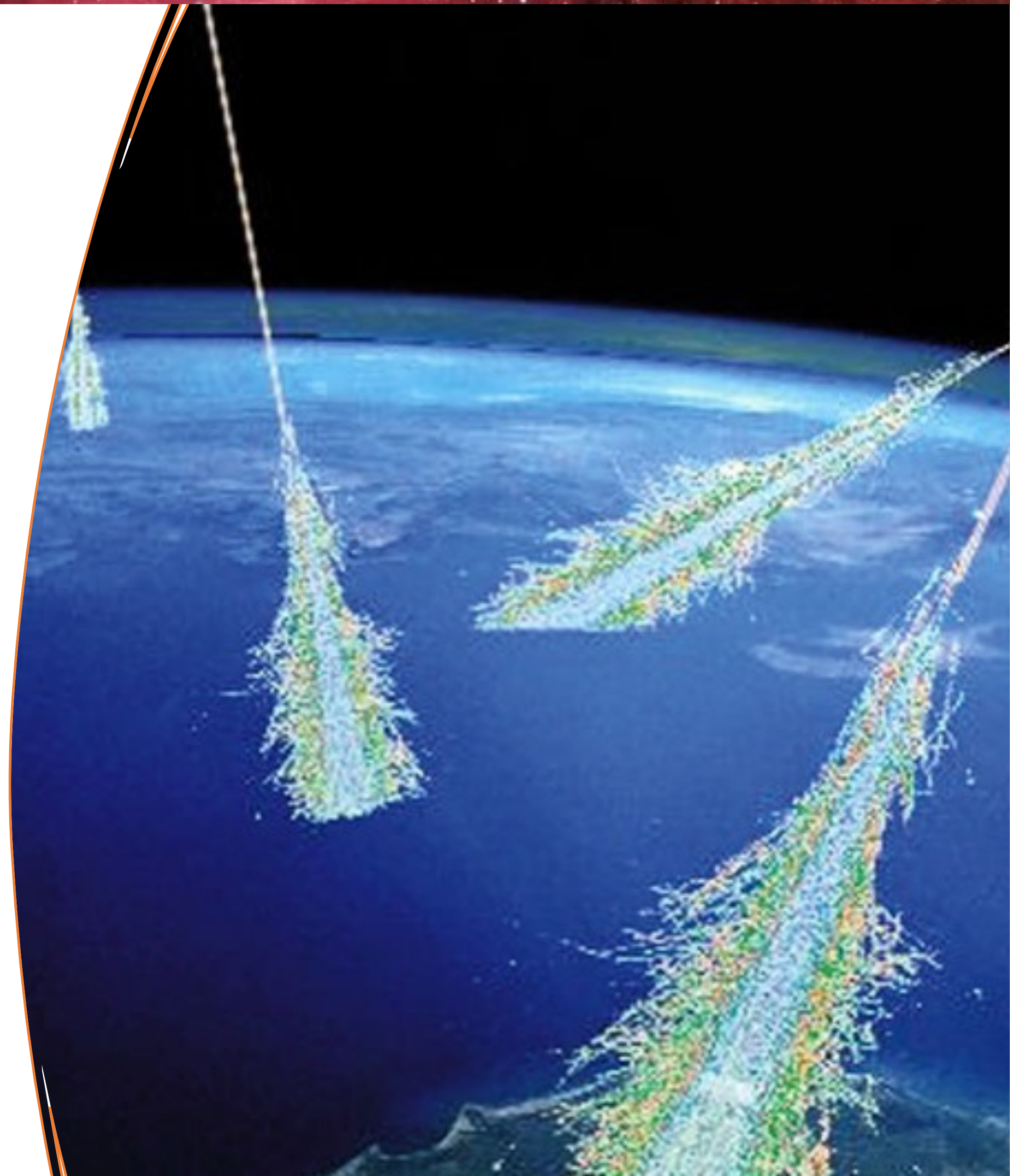
INFN ROMA
Istituto Nazionale di Fisica Nucleare
Sezione di Roma

LUNA

ERNA
European Recoil separator for Nuclear Astrophysics

Alba Formicola

Outline



Why nuclear cross section at lower energies are so challenging?

Highlights from LUNA and ERNA experiments

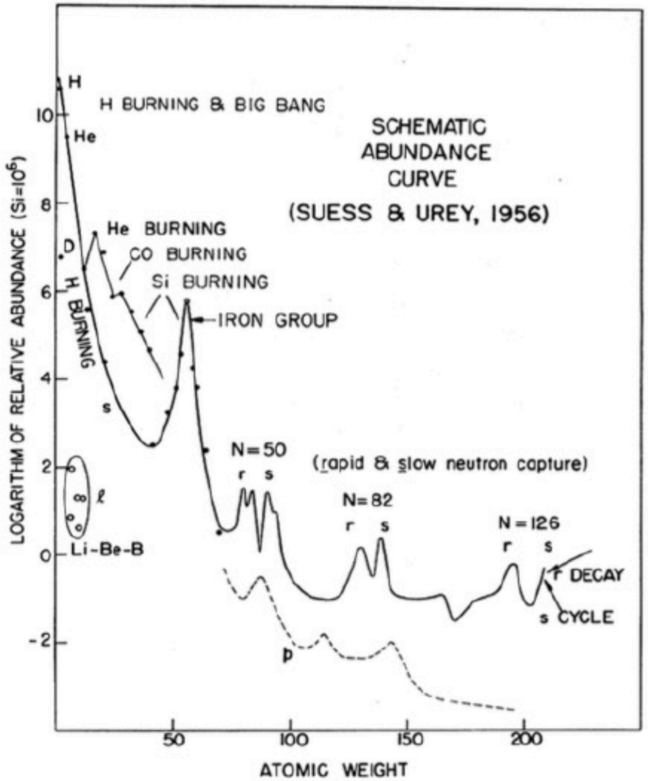
LUNA $^{13}C(\alpha,n)^{16}O$

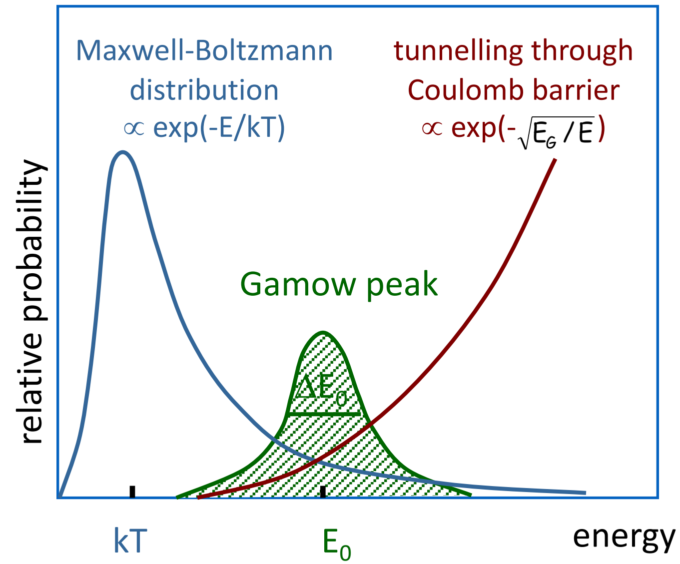
ERNA $^{12}C(\alpha,\gamma)^{16}O$

Future project: LUNA MV facility

LUNA MV $^{14}N(p,\gamma)^{15}O$

Experimental Reaction Rates





$R_{lab} = \boldsymbol{\sigma} \cdot \varepsilon \cdot I_p \cdot \rho \cdot N_{av}/A$

$\sigma(E) = \mathbf{S(E)}/E\exp(-2\eta\pi)$

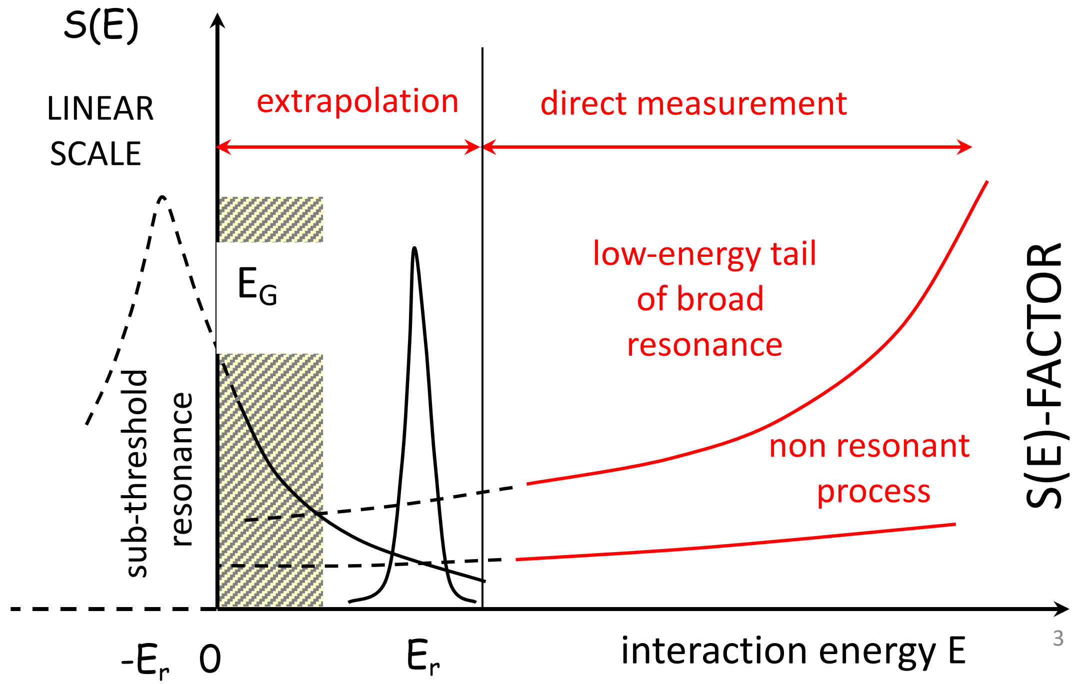
$\varepsilon \sim 10\ \%$

$I_P \sim$ mA

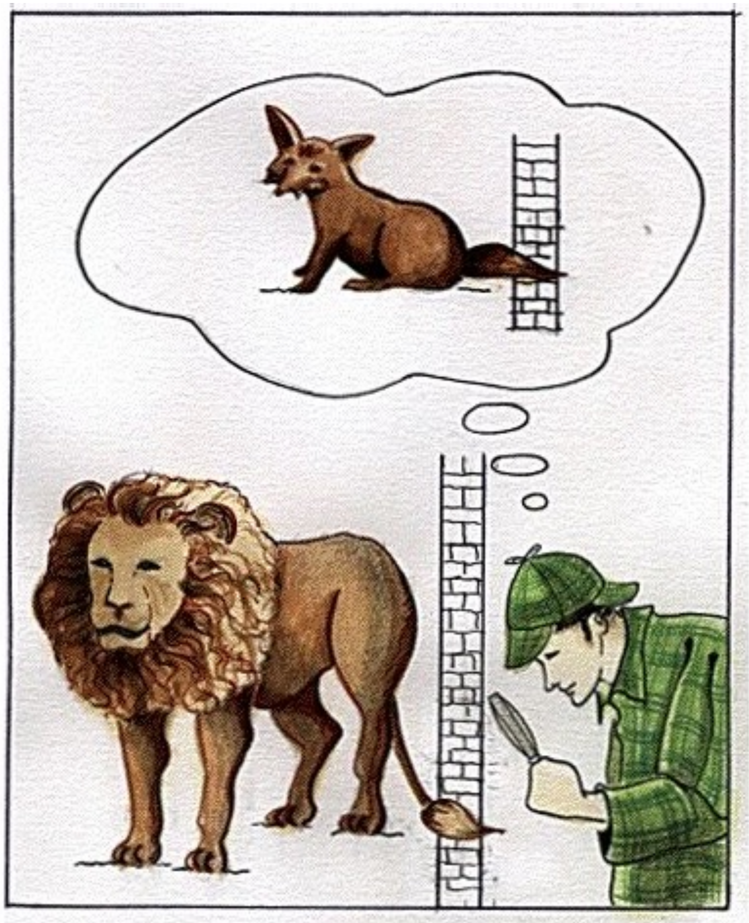
pb < σ < nb

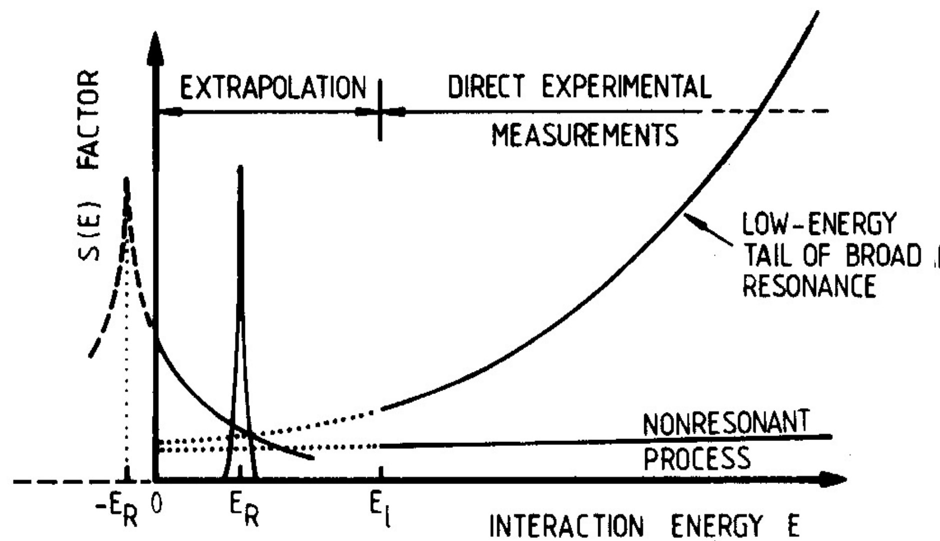
$\rho \sim \mu g/cm^2$

event/month < R_{lab} < event/day



Problem of extrapolation





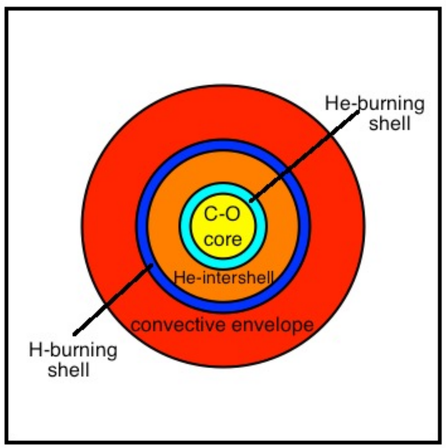
maximising the yield requires:

- improving "signal" (e.g. high beam currents, high target density, high efficiency)
- reducing "noise" (i.e. background)

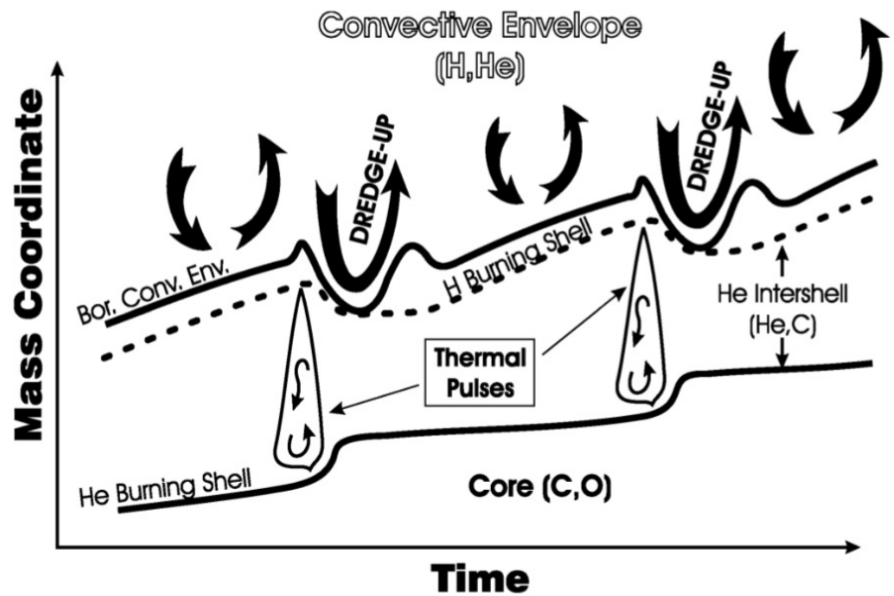
$^{13}C(\alpha,n)^{16}O$ neutron source for s process

About half of the stable isotopes heavier than iron are produced through slow-neutron-capture nucleosynthesis (s process, 90<A<208).

The $^{13}C(\alpha,n)^{16}O$ is active in stars belonging to the asymptotic giant branch (AGB), cool and giant stars with relatively low mass (Straniero et al. 1995, Gallino et al. 1998).

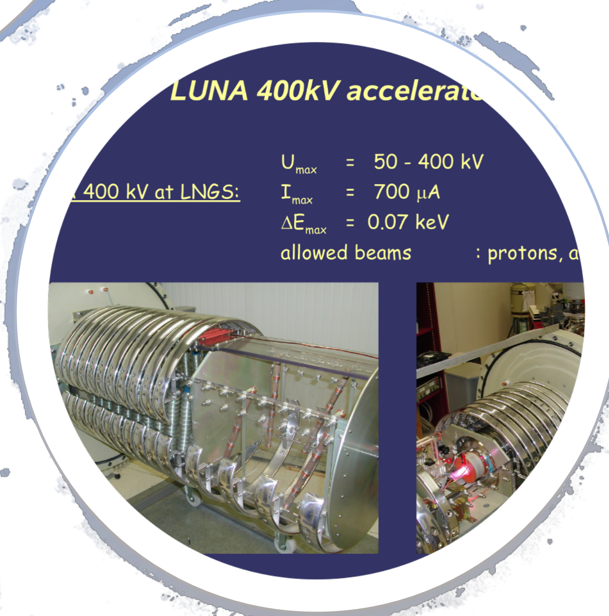


Average temperature
10^8 K → Gamow window 140-250 keV



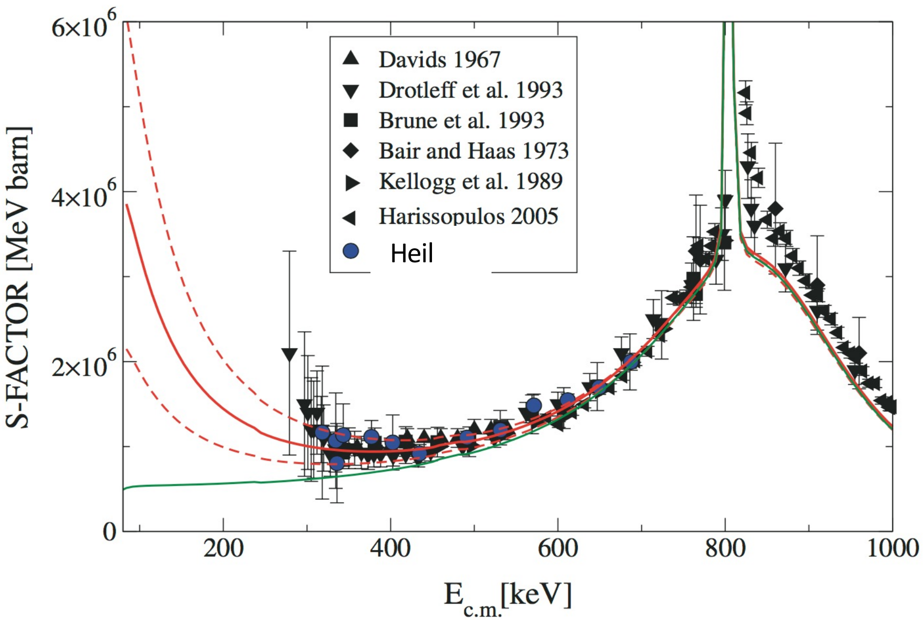
Straniero et al. Nuclear Physics A 777 (2006)

LUNA 400kV accelerator



- $U_{terminal}$ = 50 – 400kV
- I_{max} = 500μA (on target)
- Allowed beams: H^+, ^4He, (^3He)

$^{13}C(\alpha,n)^{16}O$ neutron source for s process

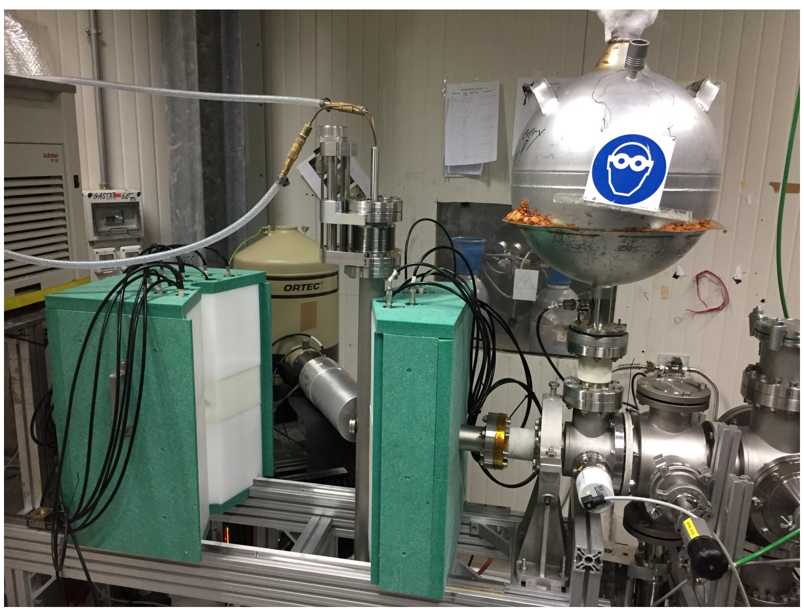


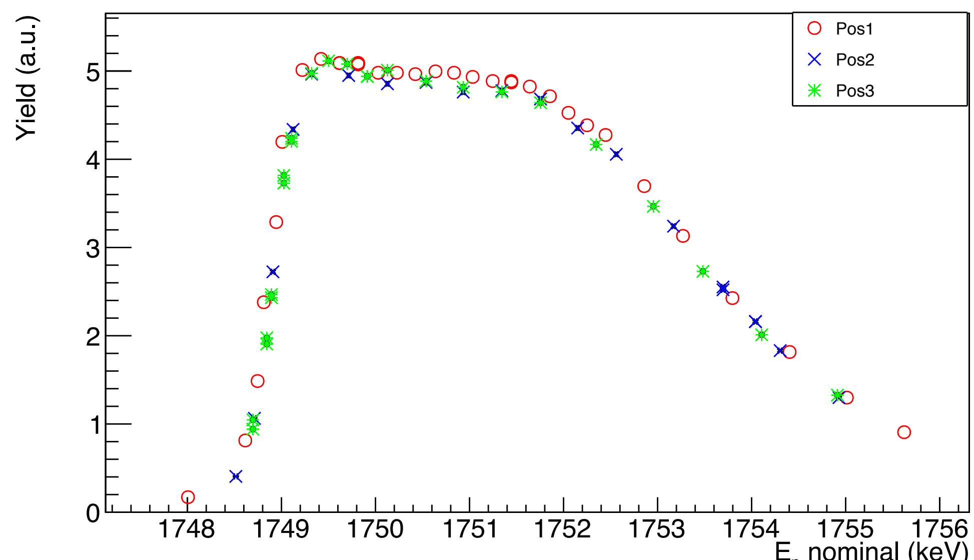
DIRECT MEASUREMENTS

Lowest point at E_{cm} = 280keV by Drotleff et al.

LUNA MAIN GOAL

A direct meauserement of the $^{13}C(a,n)^{16}O$ approaching the Gamow window with a 20% uncertainty.





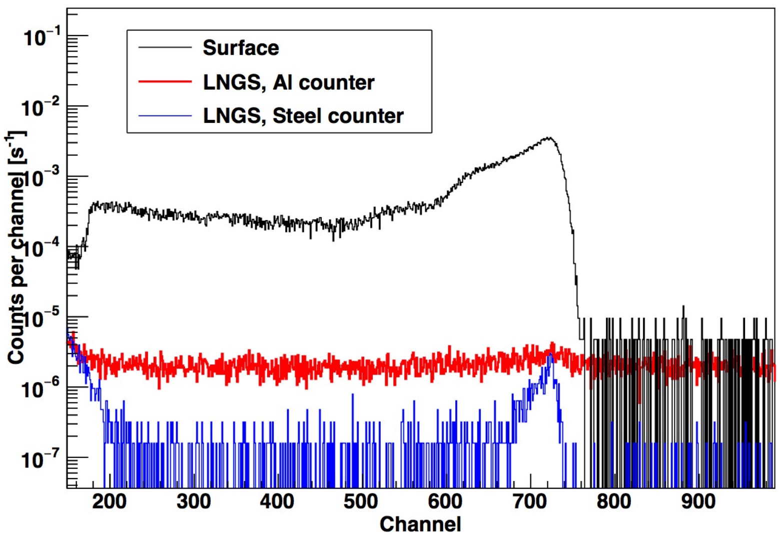
By Ciani PhD thesis 2020

Background Reduction

ENVIRONMENTAL: neutron flux reduction of a factor 1000 **in Underground Laboratory**

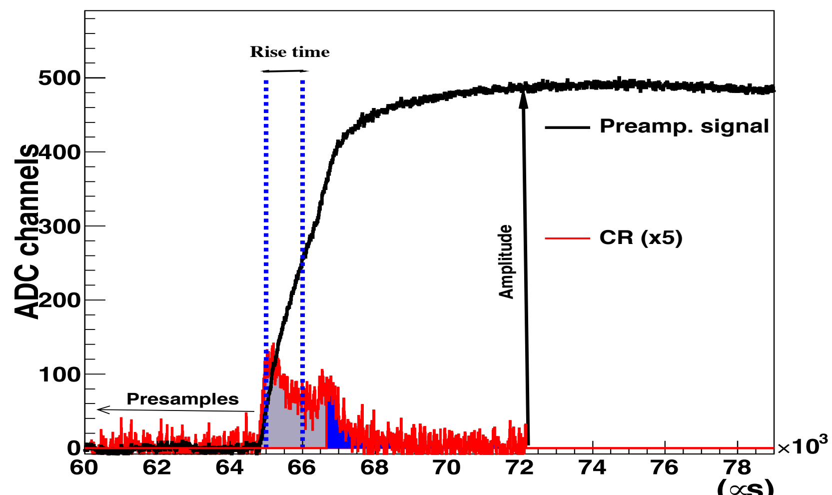
INTRINSIC: α particles source of intrinsic background from U and Th impurities in the counters' case

10 atm pressurised ^{3}He counters with a stainless steel case with low intrinsic background
Background (n+α): (2.93+-0.09) counts/h in the



POST Processing PULSE SHAPE DISCRIMINATION*
(rejects 90% alpha and 10% neutrons)
Background rate (ROI) for the entire ^{3}He setup:
~ (1.05+-0.06) counts/hour

*J. Balibrea-Correa et al., NIM A 906,103-109, (2018)

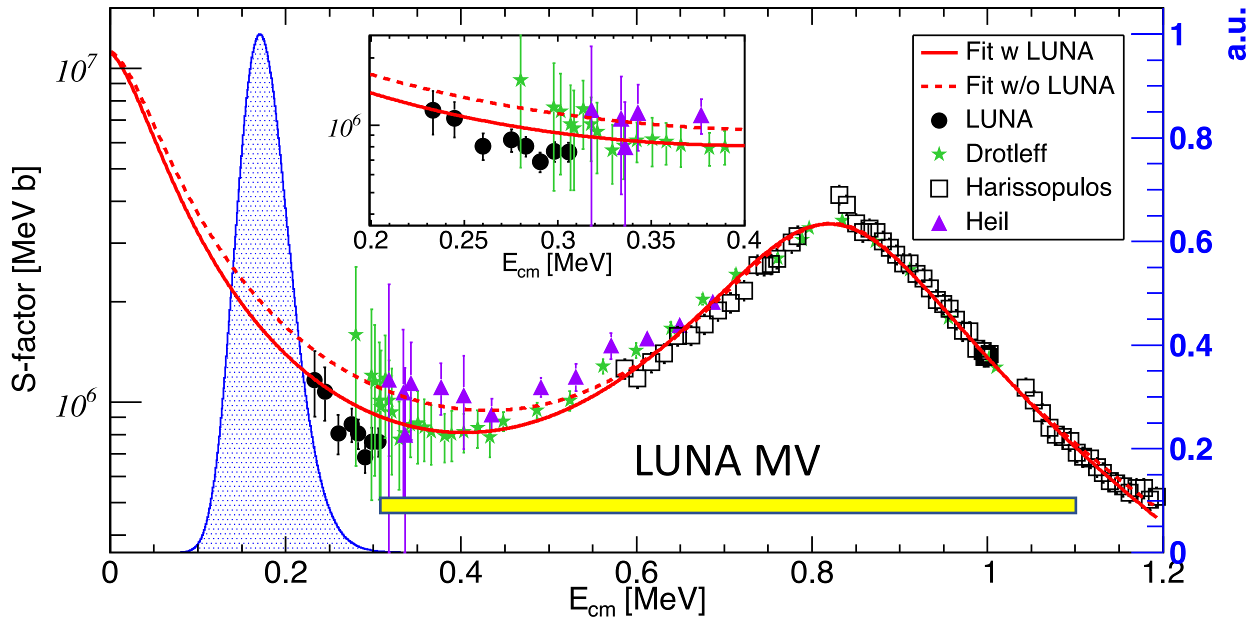


Courtesy of G.F.Ciani

$^{13}C(\alpha,n)^{16}O$ -S(E) factor towards the Gamow window

Statistical uncertainty lower than 10% at E_{cm} 230-305 keV

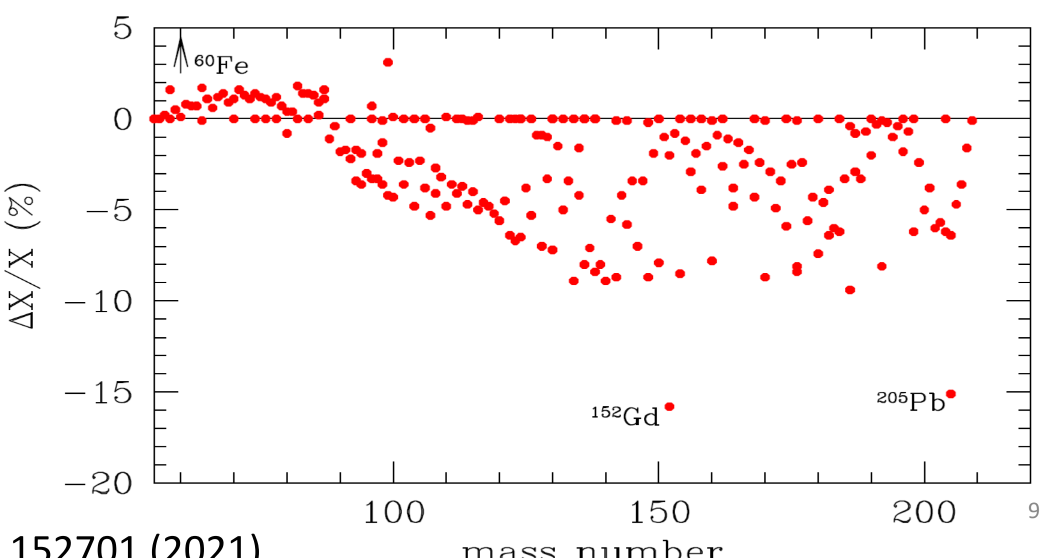
Data at the Gamow window edge of low mass AGB.



M=2M$_\odot$
metallicity Z= 0.02 and Y= 0.27

Calculated percentage variation LOW LUNA/NO LUNA data

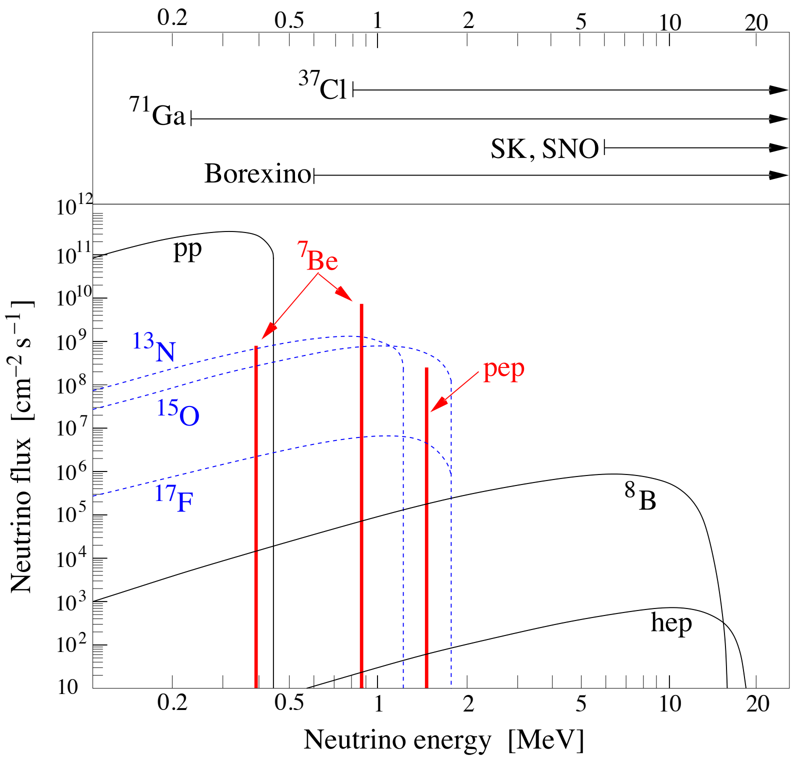
Reduction stronger for A>130.
In general variation smaller than 10% with few exeptions



Ciani et al. PRL 127, 152701 (2021)

Hydrogen burning: the Carbon-Nitrogen-Oxygen (CNO) cycle

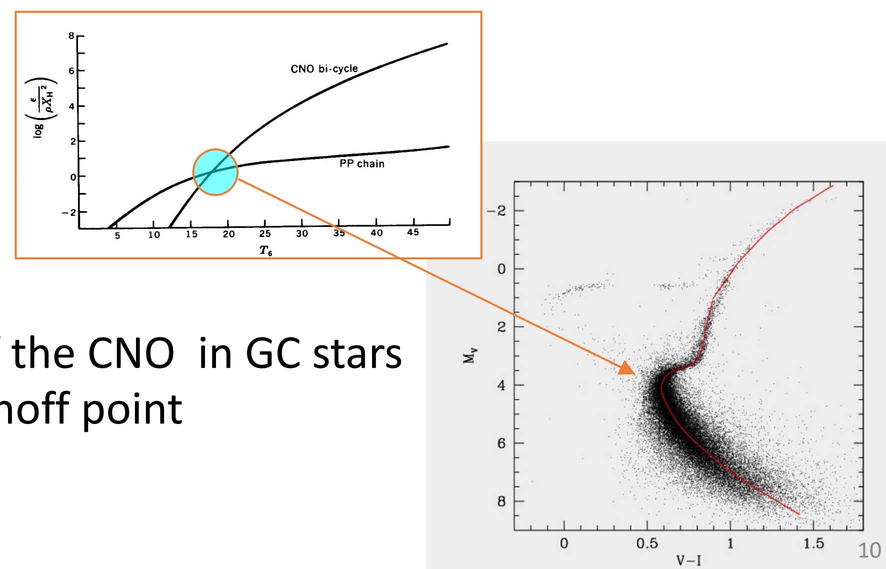
$^{14}N(p,\gamma)^{15}O$ Bottleneck reaction



Astrophysical sites: Massive Stars where CNO more efficient than pp cycle

Sun: CNO contributes only 0.8% to energy, produces detectable neutrino flux

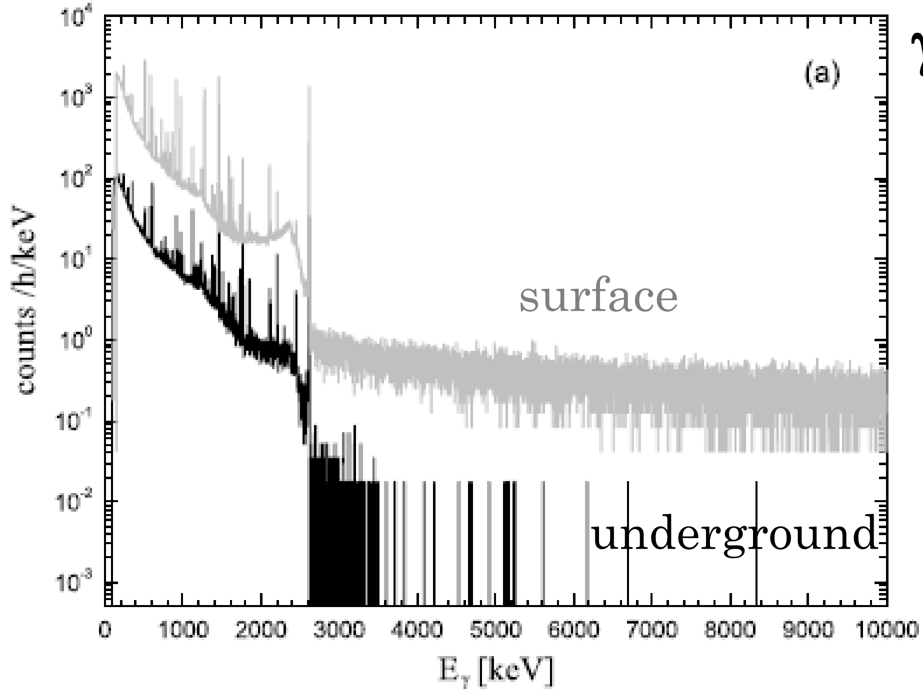
Stars at the turn-off from the main sequence in the Hertzsprung-Russell diagram



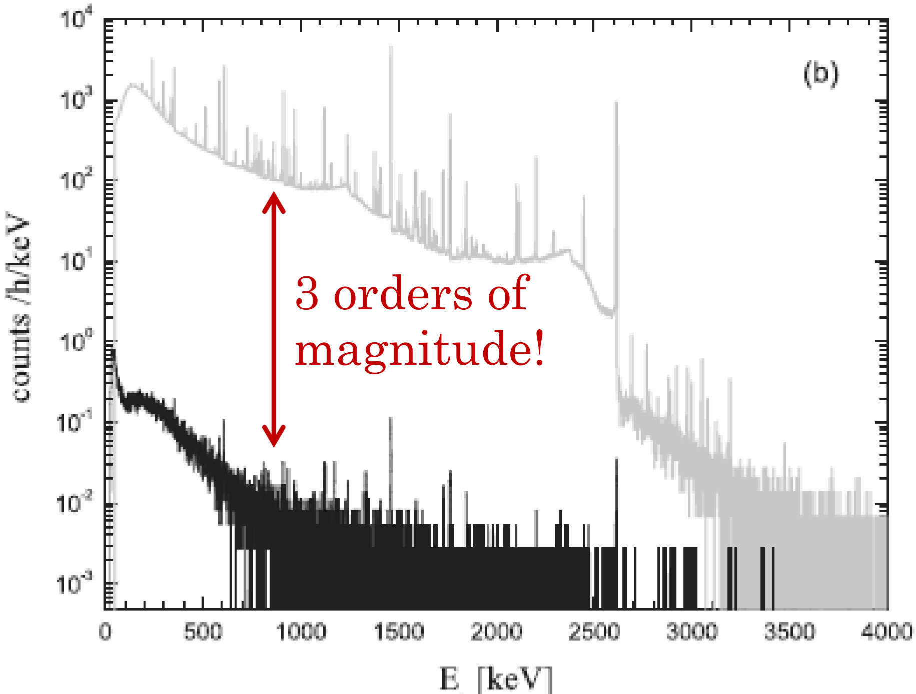
The onset of the CNO in GC stars near the turnoff point

Courtsey of Oscar Straniero

γ-ray natural background



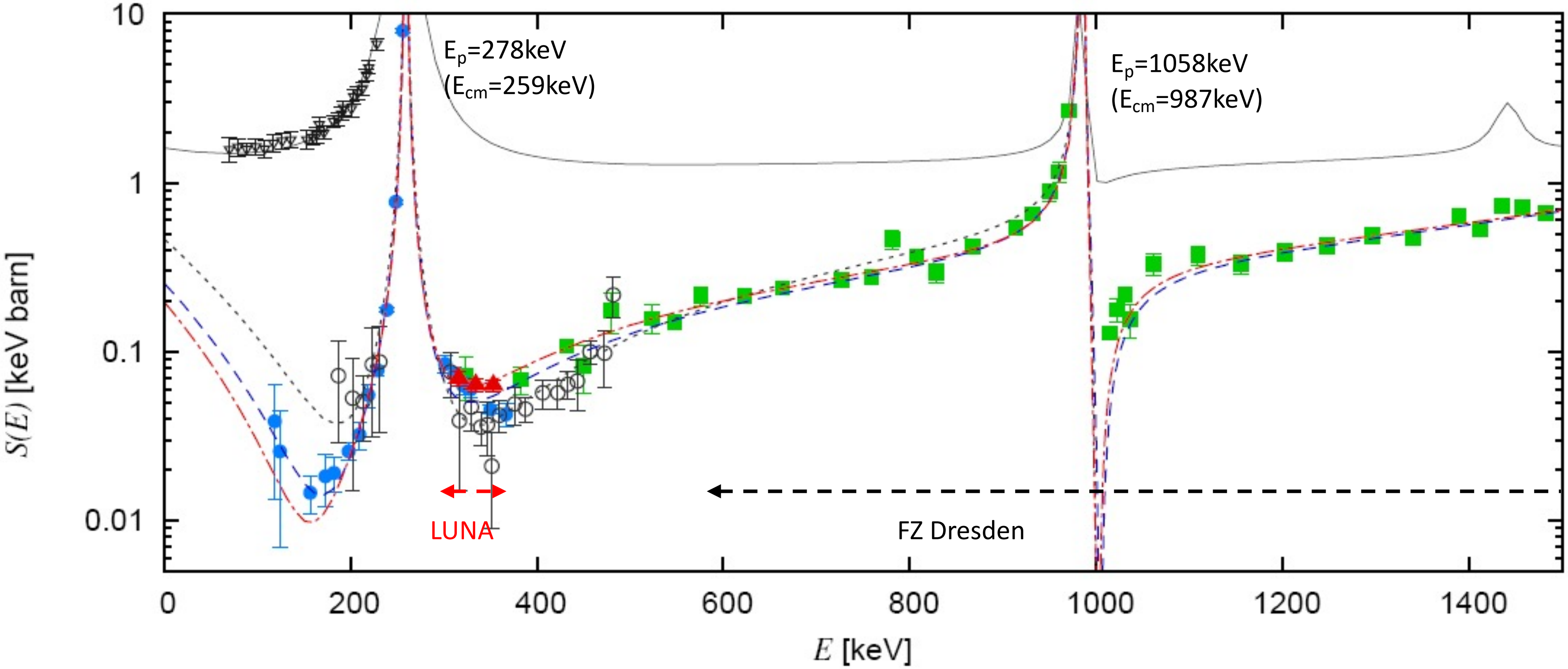
between E_{γ} =7 and 12MeV the bck suppression factor is 100 times



underground passive shielding is more effective since μ flux, that create secondary γ's in the shield, is suppressed

0.3 m^3 Pb-Cu shield suppression three orders of magnitude below 2MeV

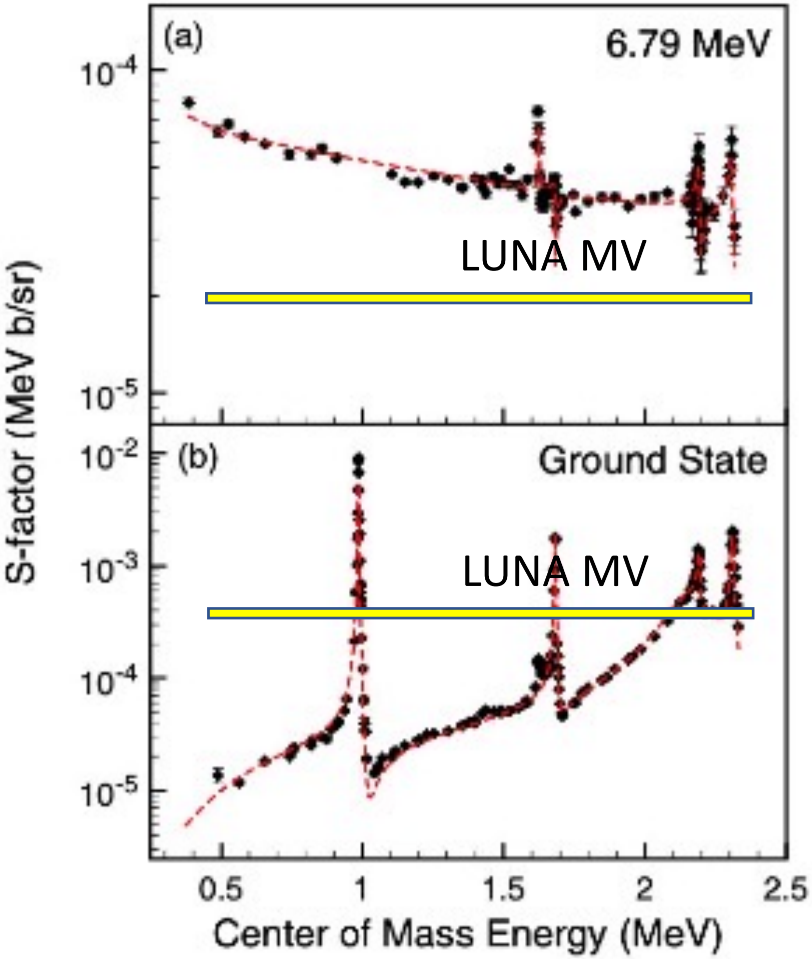
State of the art: $^{14}N(p,\gamma)^{15}O$ S-factor

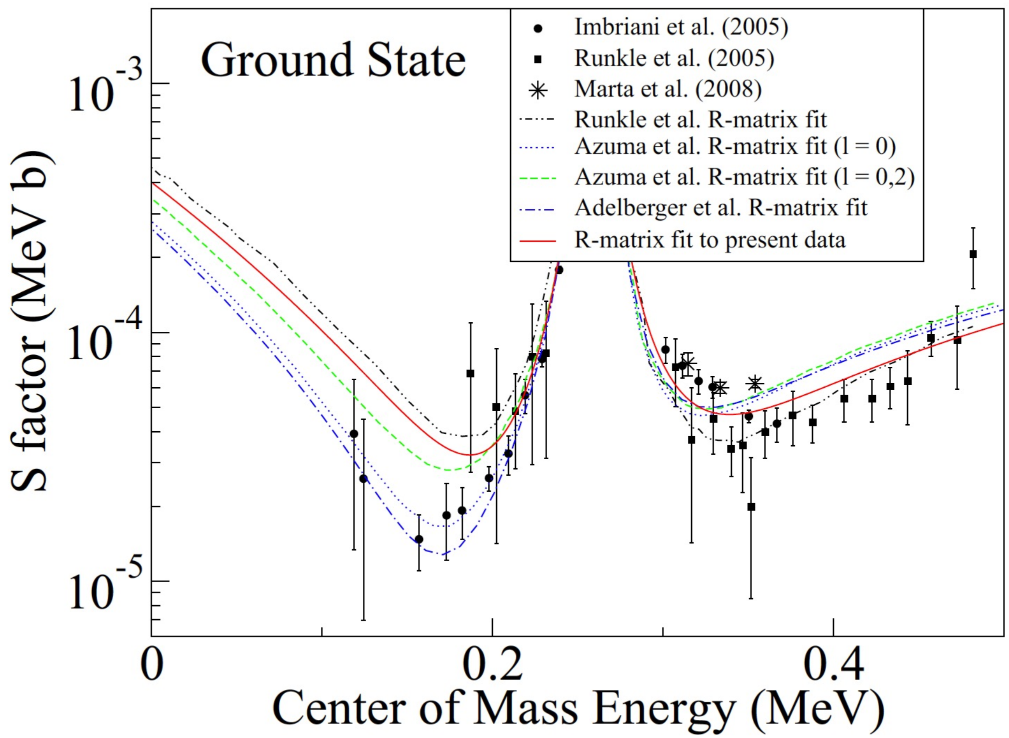


- Before 2001: $S_{tot}(0)$ = 3.1 keV b (1.55 from ground state) Schröder et al. (1987)
- 2004/5: cross section for capture to ground state strongly decreased → $S_{tot}(0)$ = 1.6 keV b Formicola et al. (2004), Imbriani et al. (2005), Runkle et al. (2005)
- 2006: total cross section measured down to 70 keV (T_6=60) Lemut et al. (2006)
- 2008: discrepancy on $S_{GS}(0)$ solved, precision 8% Marta et al. (2008)

$^{14}N(p,\gamma)^{15}O$ S-factor

Energy range E_p = 0.7-3.6MeV
Implanted TiN target
ϑ_{lab}= 0^0–45^0–90^0–135^0–150^0





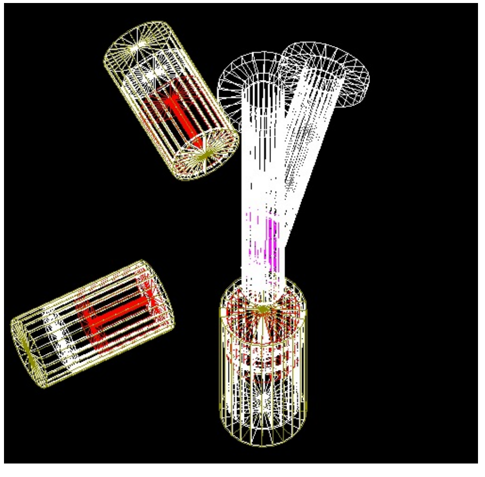
Q. LI et al. Phy. Rev.C 93, 055806 (2016)

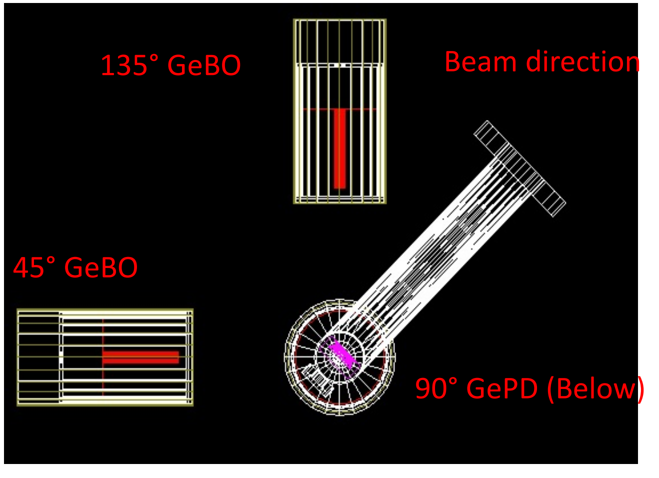
$^{14}N(p,\gamma)^{15}O$ reaction at LUNA MV

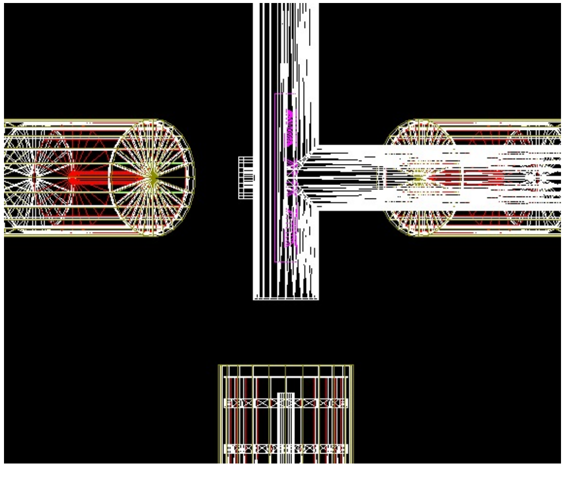
Verify the performance of LUNA-MV accelerator and surrounding setup

Differential cross-section measurement is found critical

- ✓to fit the higher energy data→ Perform the measure over a wide angle range.
- ✓Provide more high-quality higher-energy data over a extensive energy range in order to reduce the error in low-energy extrapolations







(A.Compagnucci-PhD@GSSI)

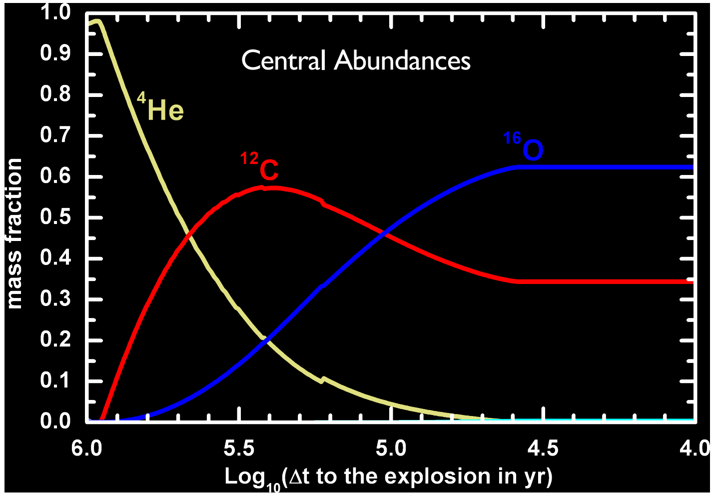
$^{12}C(\alpha,\gamma)^{16}O$ – The Holy Grail of Nuclear Astrophysics

Main Uncertainties in the Presupernova Massive Star Models

$$T \sim 1.5 - 3.5 \cdot 10^8 \ \mathrm{K} \quad \rho \sim 0.2 - 4 \cdot 10^3 \ \mathrm{gcm}^{-3}$$

Primary reactions

$^{12}C(\alpha,\gamma)^{16}O$
$^{3}He(2\alpha,\gamma)^{12}$ C
^{12}C,^{16}O

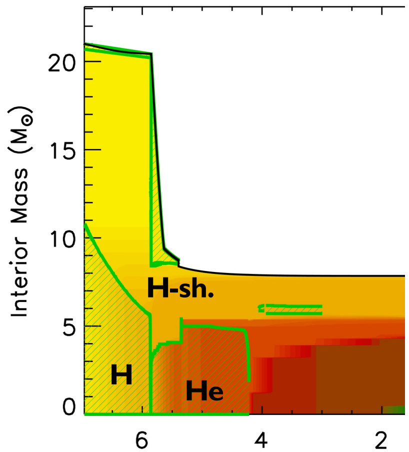


$^{12}C(\alpha,\gamma)^{16}O$ is crucial since it determines the $^{12}C/^{16}O$ ratio at core He depletion that in turn drives all the subsequent nuclear burning stages

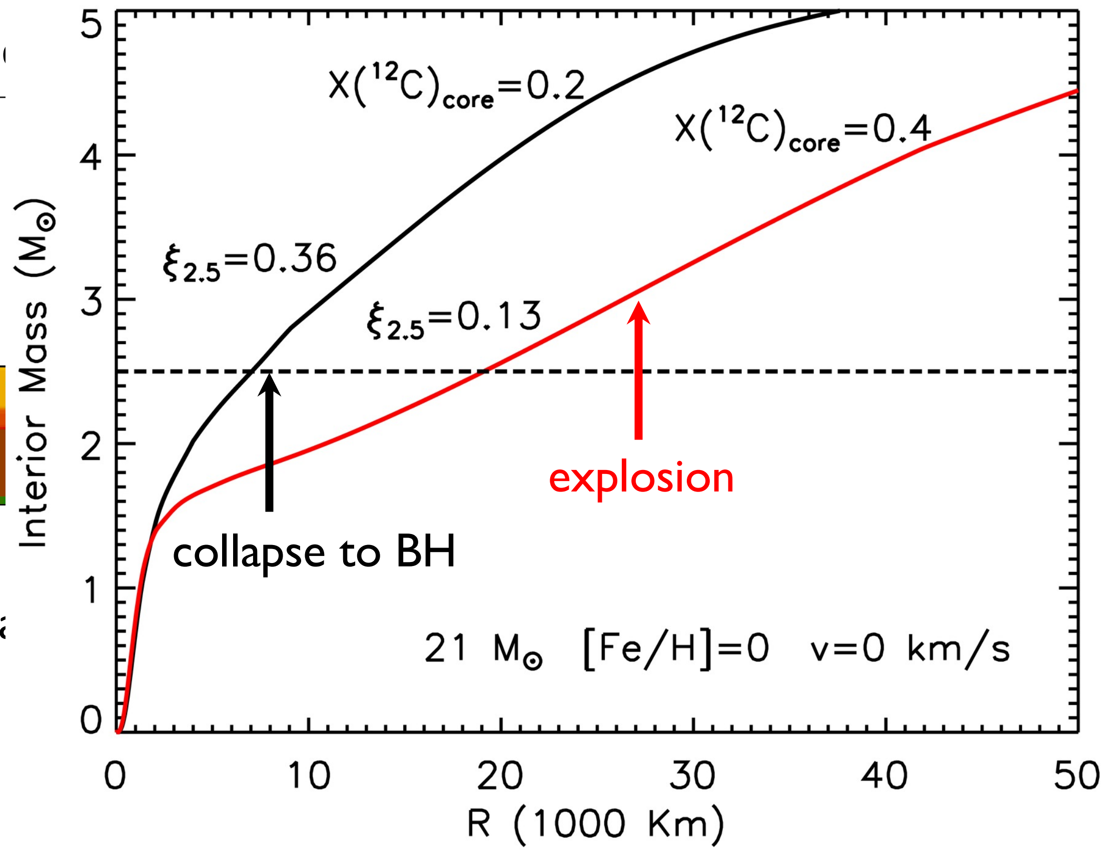
Courtsey of Marco Limongi

Main Uncertainties in the Presupernova Massive Star Models

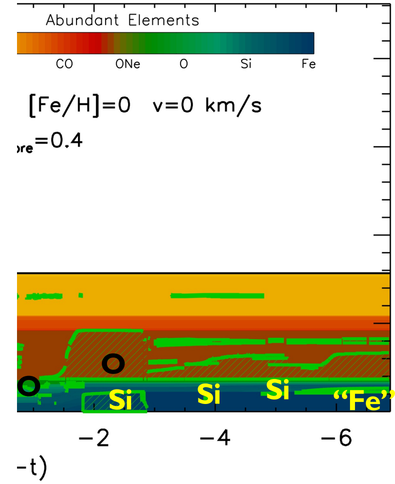
The uncertainties on the ^{12}(



$^{12}C(\alpha,\gamma)^{16}O$ Cross Section



n between ~0.2 and ~0.4



Ba

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ent is

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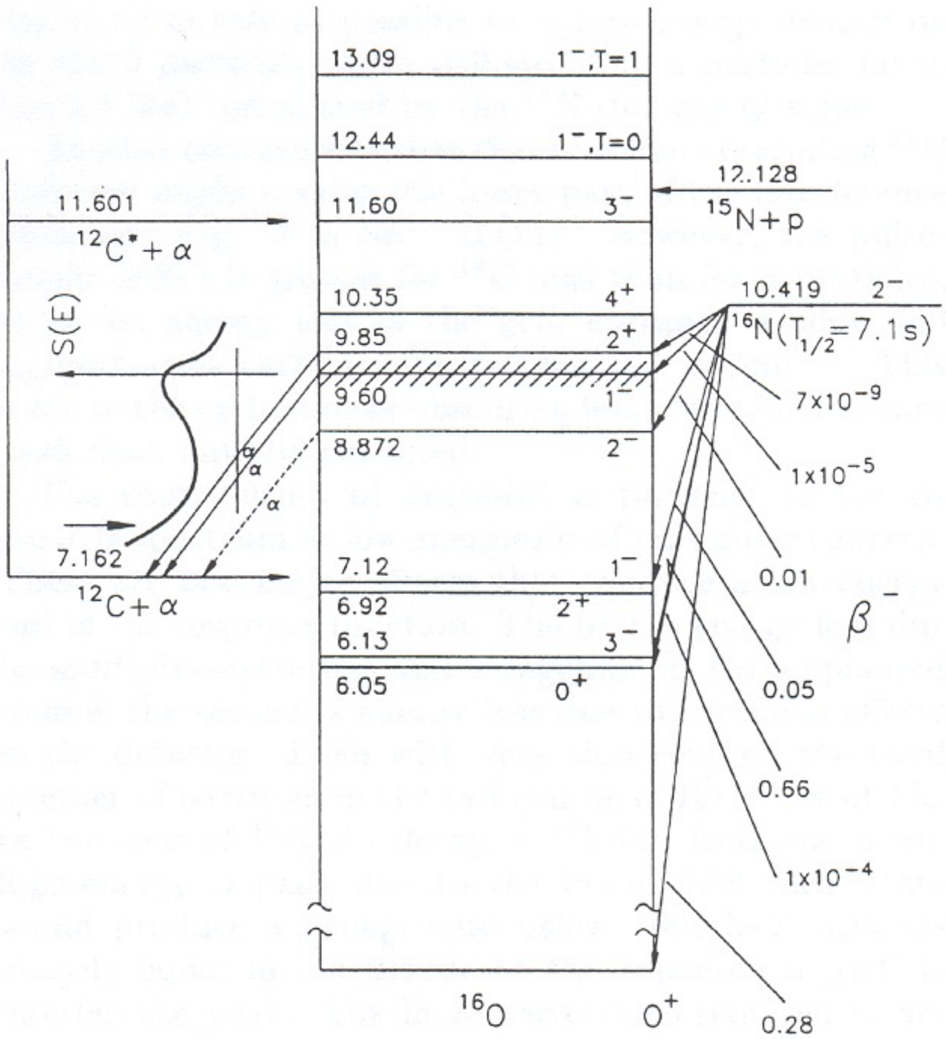
- the stronger is the contraction of the CO core
- the more compact the core at the presupernova stage

Implications on the Initial Mass-Remnant Mass relation → BH/NS forming CCSNe → GW Progenitors

Courtsey of Marco Limongi

Main components to the total cross section of the $^{12}C(\alpha, \gamma)^{16}O$

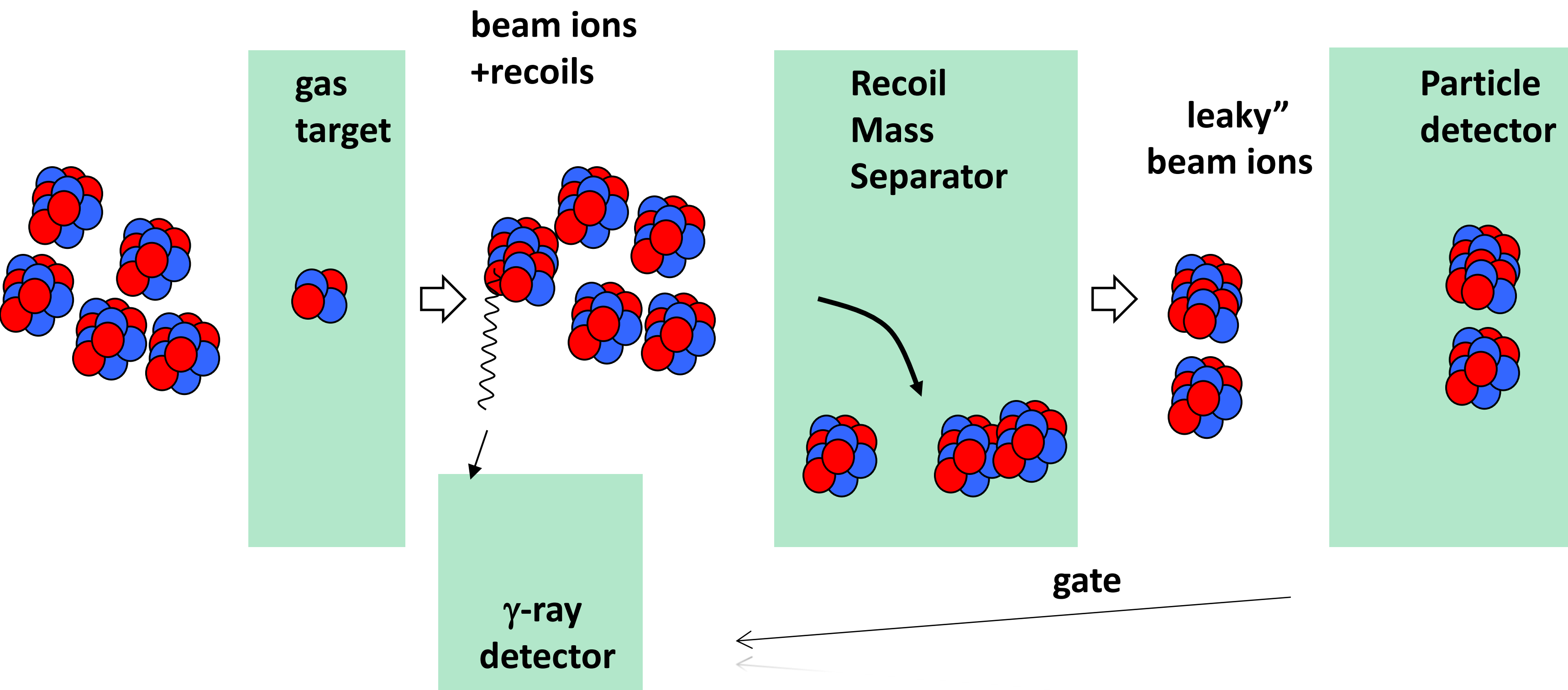


The cross section around the Gamow peak is dominated by ground-state transitions through four different processes:

- E1 amplitudes due to the low-energy tail of the 1^- resonance at E=2.42 MeV and to the subthreshold resonance at-45 keV
- E2 amplitude due to the 2^+ subthreshold resonance at -245 keV
- direct capture to the ^{16}O ground state (plus the relevant interference terms)
- Cascades, the E2 direct capture to the 6.05 MeV and 6.92 MeV states.

ERNA

Recoil Mass Separator : the reaction yield by means of the direct detection of the recoil ions

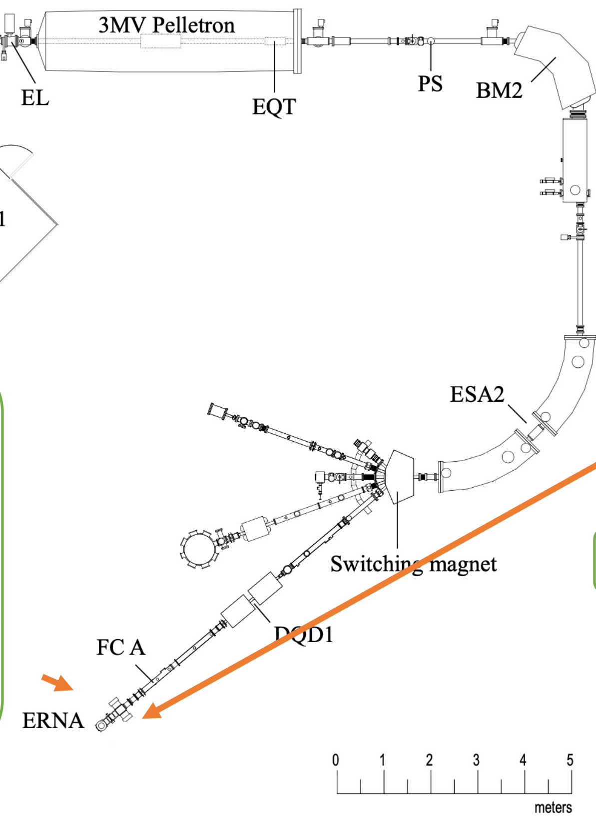


$$N_{recoils} = N_{projectiles} \times n_{target} \times \sigma \times T_{ERNA} \times \Phi_q \times \varepsilon_{part}$$

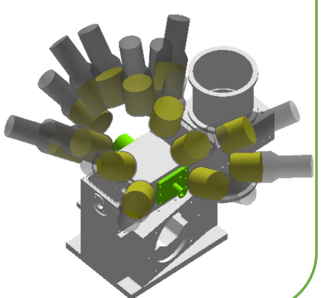
$$N_{gamma} = N_{recoils} \times \varepsilon_\gamma$$

ERNA Experimental setup

Tandem Accelerator Facility



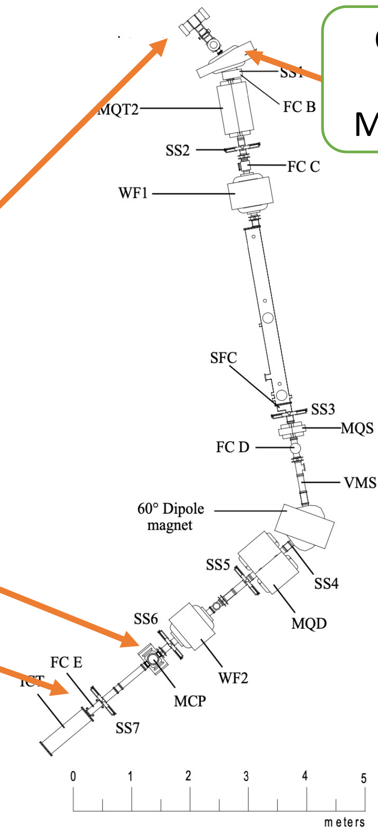
Gamma array detector



Jet He target

Recoil detector

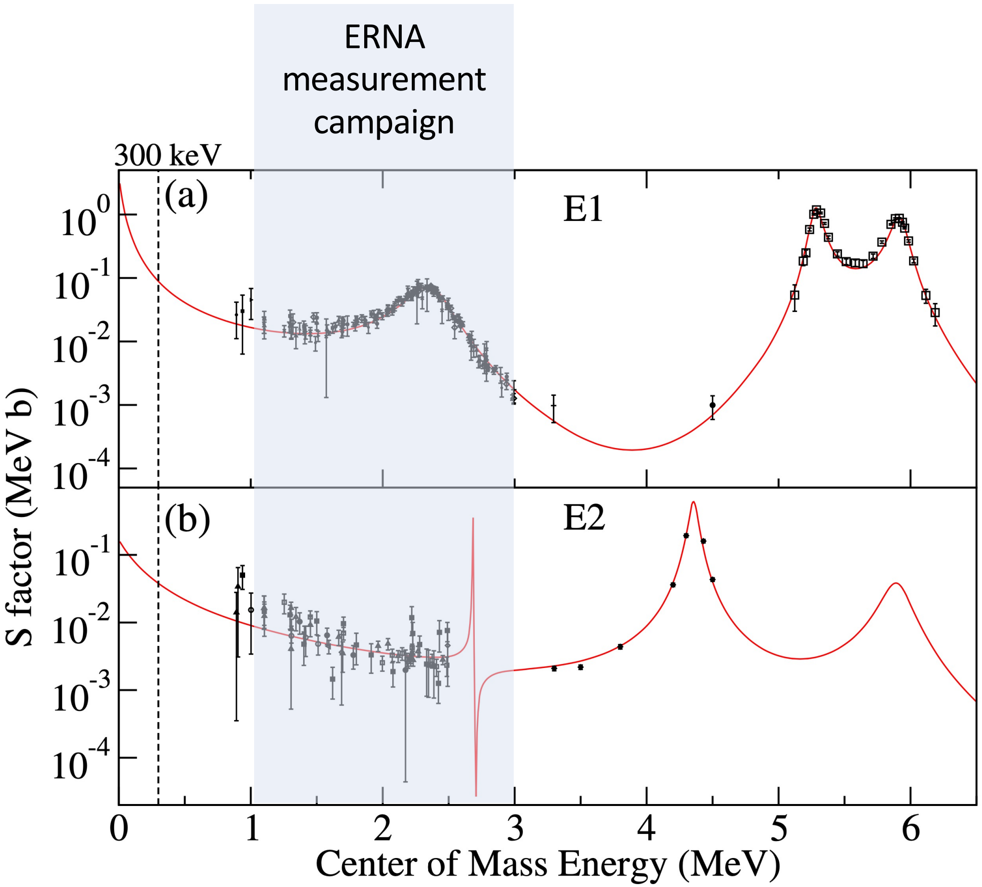
European Recoil Separator for Nuclear Astrophysics

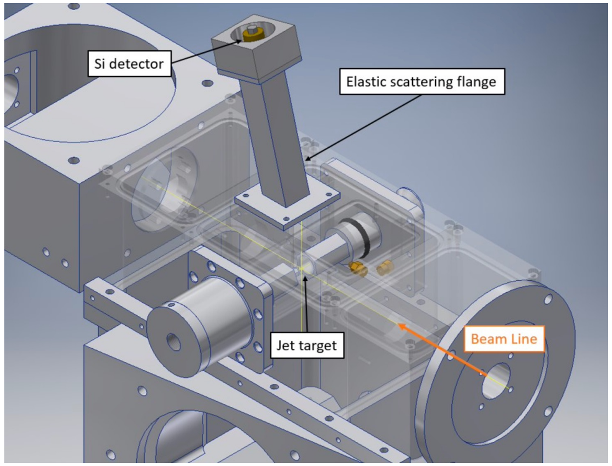


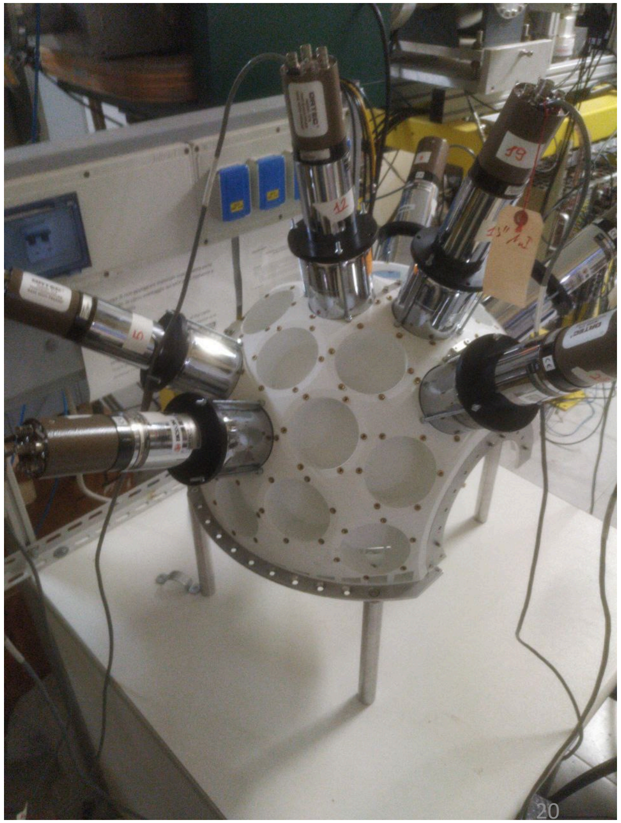
Charge State Selection Magnet (CSSM)

ERNA Goals

- 1 MeV < E_{cm} < 3 MeV
- E1, E2 and cascade contribution

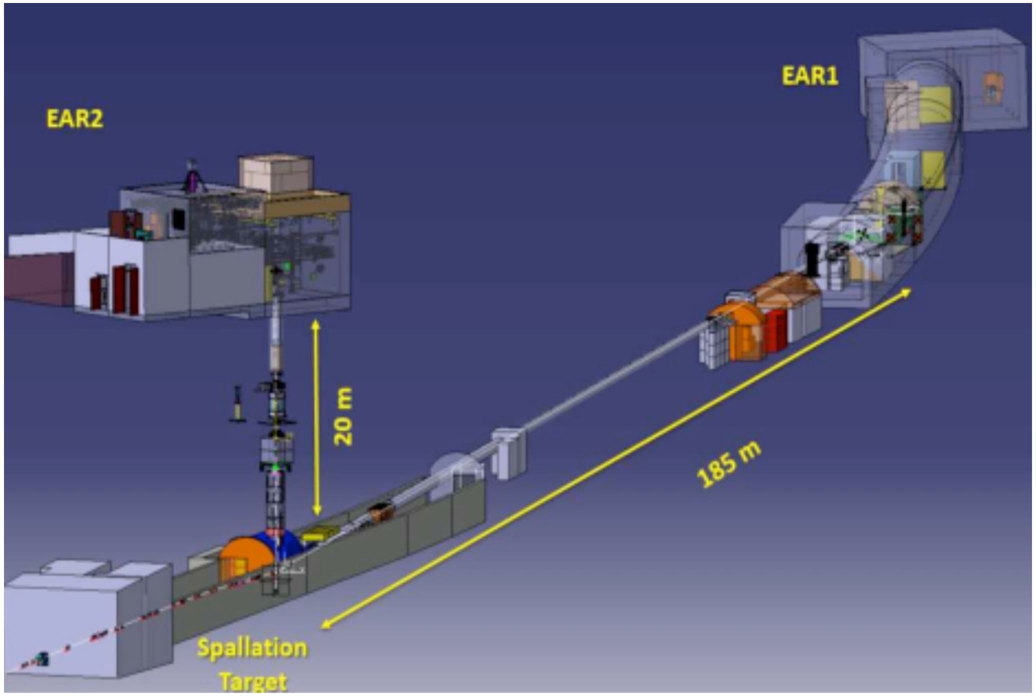






By C. Santonastaso SIF, 13-17 Settembre 2020

X17 initiative (refer to Carlo Gustavino)



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- C. Gustavino (INFN ROMA)
- A. Mengoni (ENEA)
- C. Massimi (UNIBOLOGNA)
- N. Colonna (INFN BARI)
- S. Fiore (ENEA ROMA)
- A. Mazzone (CNR BARI)
- M.C. Petrone (IFIN-HH BUCHAREST)

n_TOF

- M. Viviani (INFN PISA)
- A. Kievsky (INFN PISA)
- L. E. Marcucci (UNIPISA)
- L. Girlanda (UNISALENTO)

Theoretical group

- E. Cisbani (ISS)
- F. Renga (INFN ROMA)

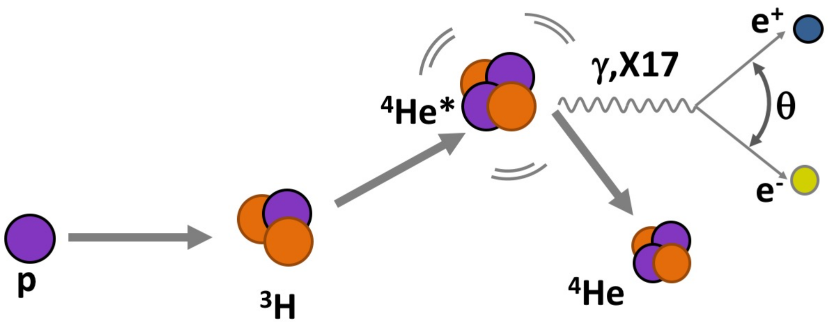
Detector R&D

Working group (in evolution)

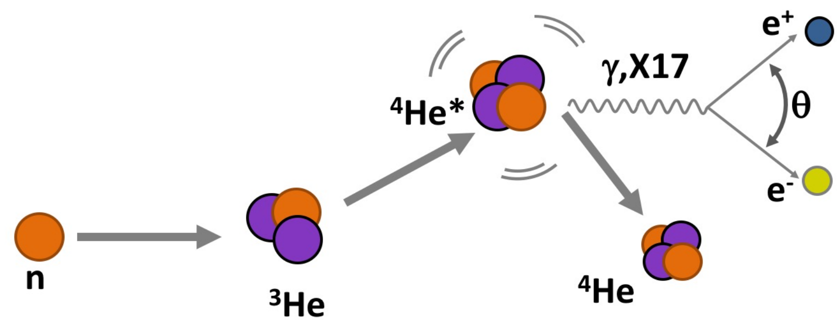
X17 @ nToF

Basic idea: new study of excited ^{4}He exploiting both the conjugated reactions:

$^{3}H(p,e^{+}e^{-})^{4}He$ → $^{3}He(n,e^{+}e^{-})^{4}He$



ATOMKI REACTION



n_TOF REACTION

Physics:

- Probing X17 existence
- X17 Mass, quantic numbers, coupling, life time,..
- proto-phobic nature of the fifth force.
- First measurement of $\sigma(E)$ $^{3}He(n,e^{+}e^{-})^{4}He$
- Data Vs Theoretical nuclear physics

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