Nuclear Astrophysics with Stable Beams: A Biassed Overview

Marialuisa Aliotta
School of Physics and Astronomy - University of Edinburgh, UK
Scottish Universities Physics Alliance

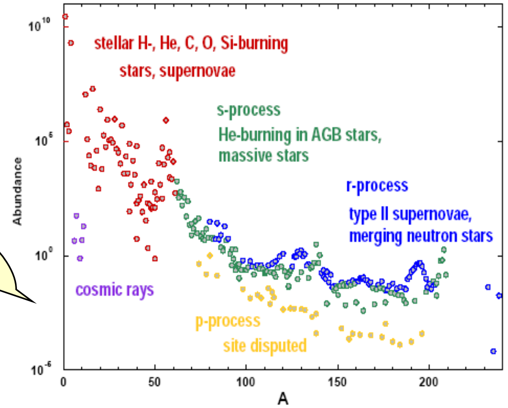
Russbach School, 3-8 March 2024

M. Aliotta

Nuclear Astrophysics: A truly interdisciplinary field

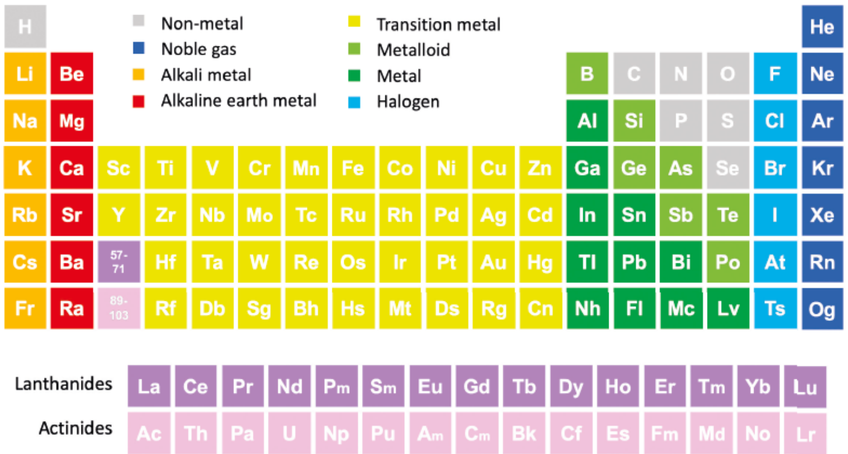
Astrophysics

stellar evolutionary codes
nucleosynthesis calculations
astronomical observations



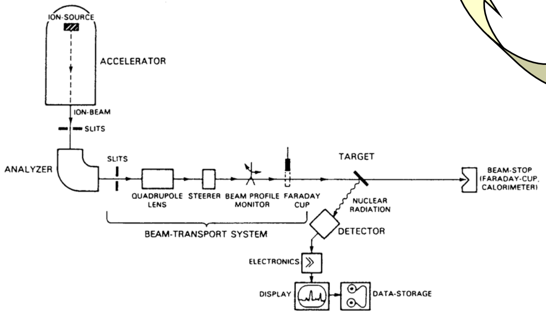
Nuclear Physics

experimental and
theoretical inputs
stable and exotic nuclei



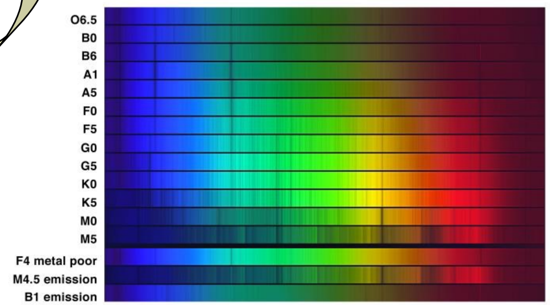
Plasma Physics

degenerate matter
electron screening
equation of state



Atomic Physics

radiation-matter interaction
energy losses, stopping powers, spectral lines
materials and detectors

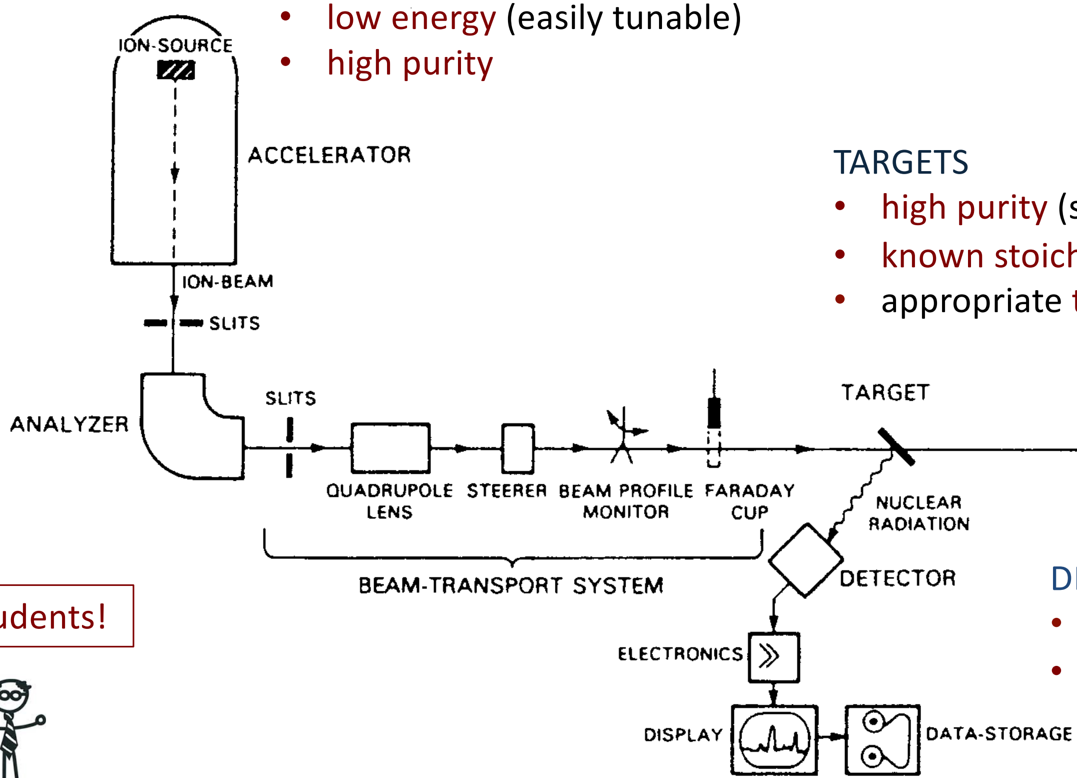


Astrophysical Reaction Studies in the Laboratory: Experimental Challenges

Schematic Layout for Nuclear (Astro-)Physics Experiments

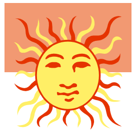
BEAMS
- high beam currents
- low energy (easily tunable)
- high purity

TARGETS
- high purity (solid or gas)
- known stoichiometry
- appropriate thickness and uniformity



DETECTORS
- high efficiency
- good resolution

Excellent Students!



Quiescent stages of stellar evolution

FEATURES

$T \sim 10^6 - 10^8$ K $\Rightarrow$ $E_0 \sim 100$ keV $\ll$ E_{coul} $\Rightarrow$ tunnel effect

$\Rightarrow$ 10^{-18} barn $< \sigma < 10^{-9}$ barn

$\Rightarrow$ average interaction time $\tau \sim \langle \sigma v \rangle^{-1} \sim 10^9$ y

unstable species DO NOT play significant role

CHALLENGES

10^{-18} b $< \sigma < 10^{-9}$ b

$\Rightarrow$ poor signal-to-noise ratio

$\Rightarrow$ major experimental challenge

$\Rightarrow$ extrapolation procedure required

REQUIREMENTS

poor signal-to-noise ratio

$\Rightarrow$ long measurements

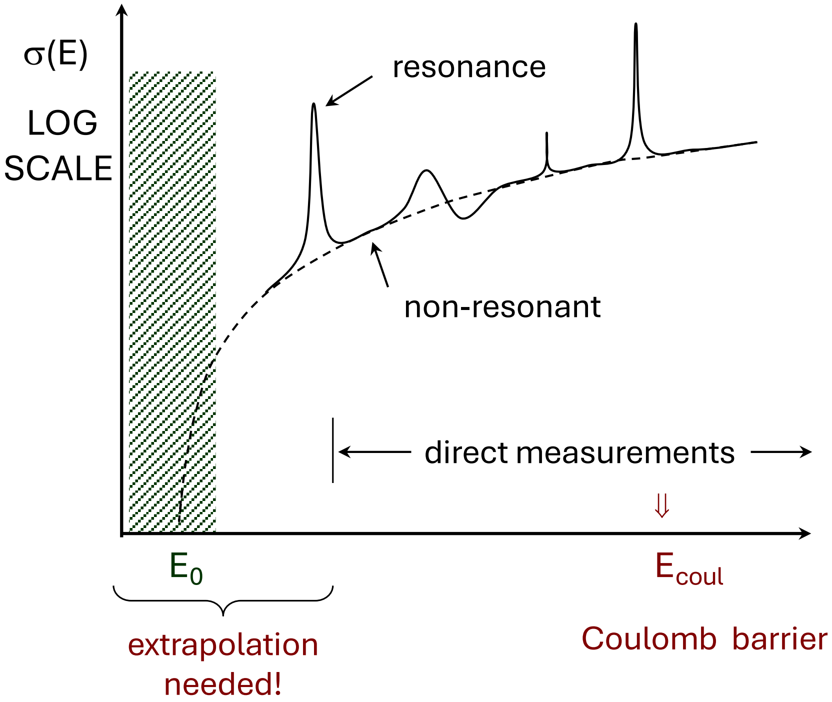
$\Rightarrow$ ultra pure targets

$\Rightarrow$ high beam intensities

$\Rightarrow$ high detection efficiency

Thermonuclear Reactions in Stars occur by Tunnel Effect

e.g. central temperature of the Sun: $T = 15$ MK → average kinetic energy: $kT \sim 1$ keV << Coulomb barrier



Yield = N_p x N_t x σ x η

$N_p = 10^{14}$ pps (~100 μA q=1+)

$N_t = 10^{19}$ atoms/cm^2

$\sigma \sim 10^{-15}$ barn (10^{-39} cm^2)

$\eta = 1 - 100\%$

Y = 0.3 – 30 events/year

~ 1.2-120 counts/PhD

background reduction is critical

Explosive stages of stellar evolution

FEATURES $T > 10^8$ K

⇒ $E_0 \sim 1$ MeV ~ E_{coul}

⇒ 10^{-6} barn < σ < 10^{-3} barn

⇒ cross sections “easy” to measure

CHALLENGES unstable nuclei

⇒ short half-lives ($10^{-6} – 10^{1}$ s)

⇒ unknown nuclear properties

REQUIREMENTS

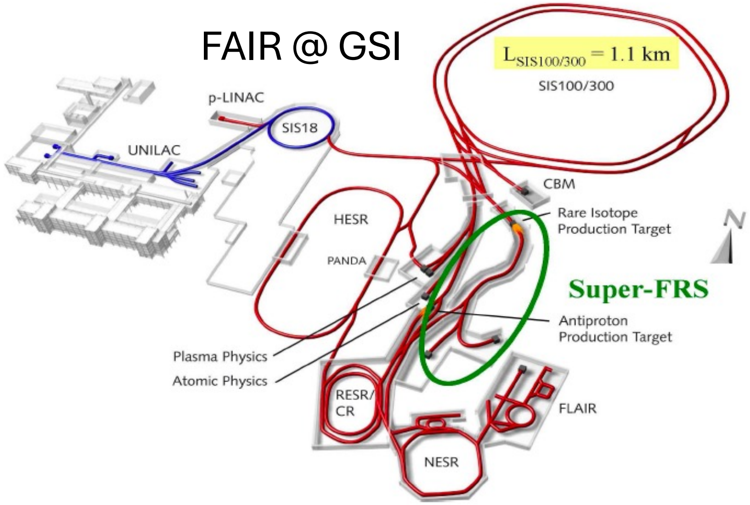
⇒ Radioactive Ion Beam facilities

⇒ produce and accelerate ions of interest

⇒ dedicated detection systems

Radioactive Ion Beam Facilities

FAIR @ GSI



ARIEL @ TRIUMF

FRIB @ MSU

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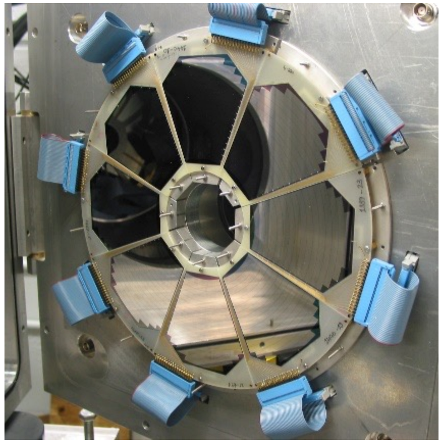
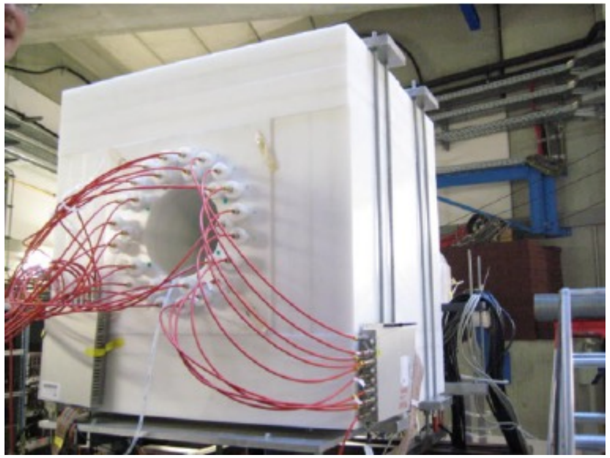
Sophisticated Detector Arrays

Highly Segmented Silicon Detector Arrays



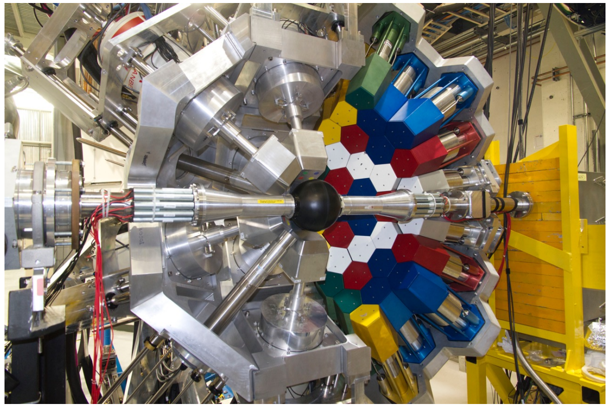
- large solid angle
- advanced electronics & DAQ
- low sensitivity to beam background
- versatile configurations

BELEN Neutron Detector Array



Gamma-Ray Spectrometers and Arrays

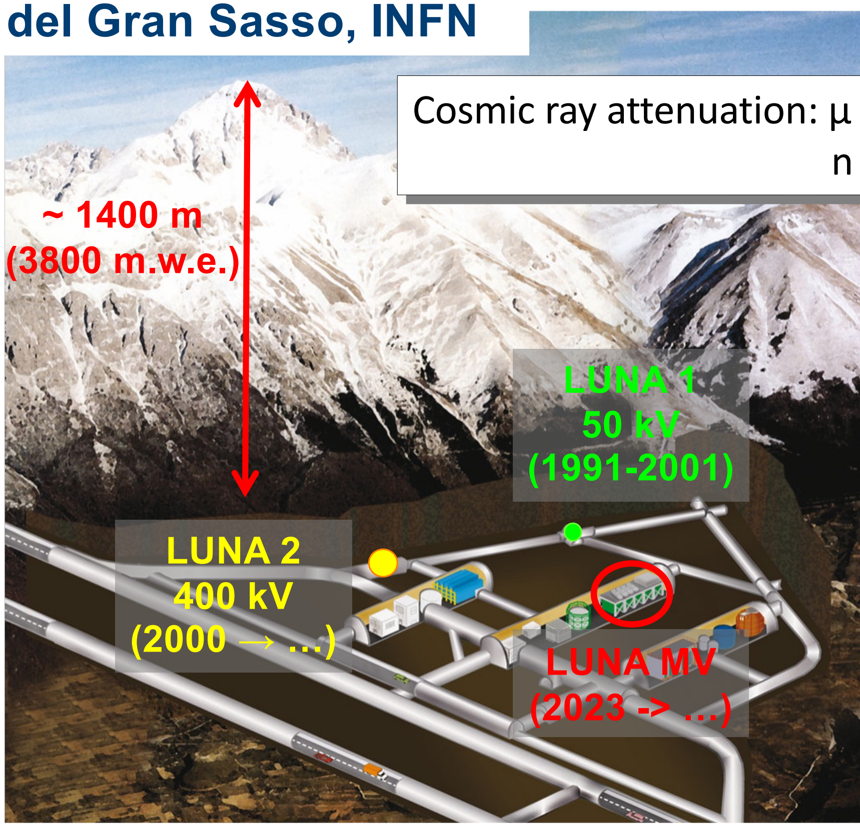
DESCANT neutron detector array



Nuclear Astrophysics with Stable Beams Underground

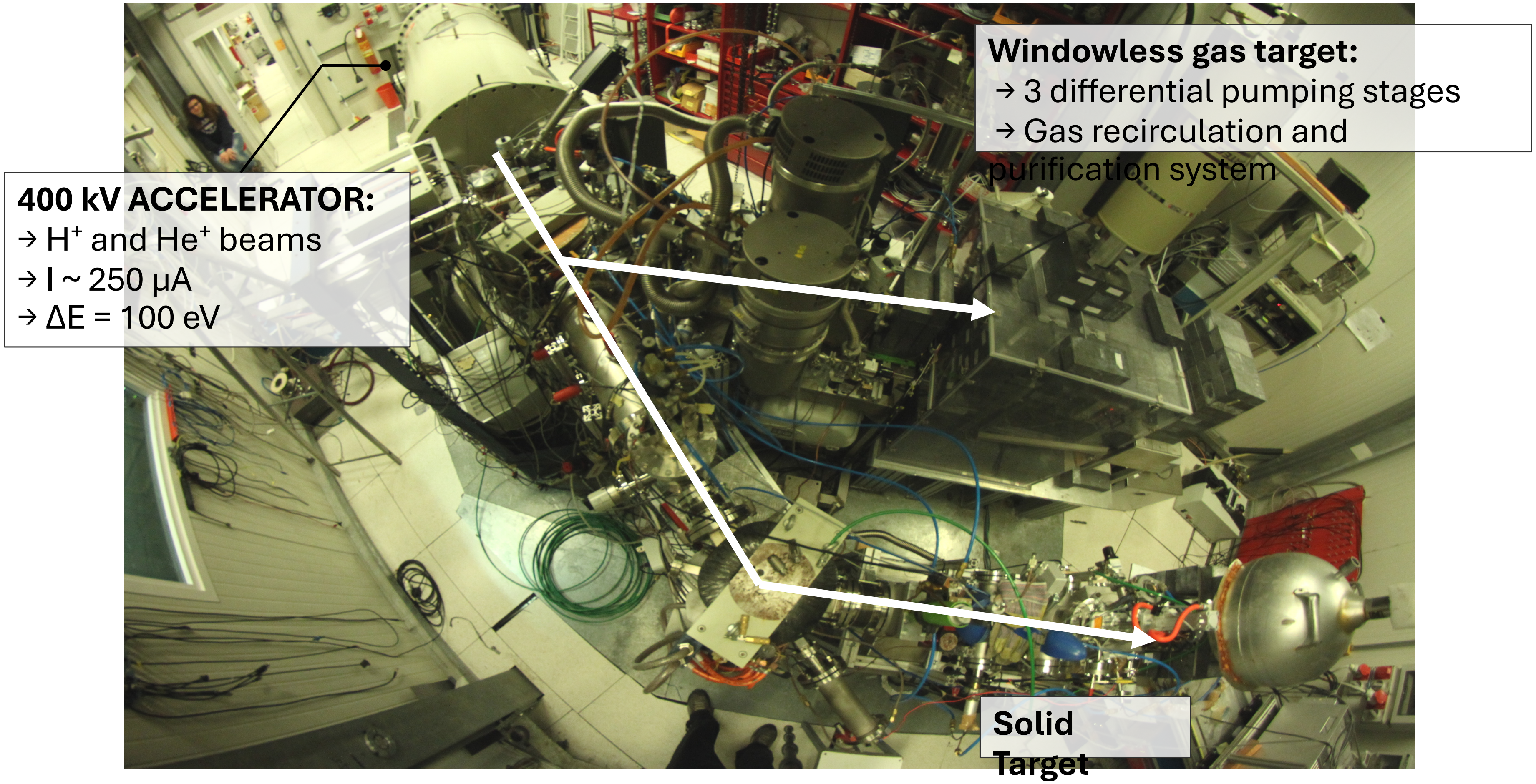
LUNA: Laboratory for **U**nderground **N**uclear **A**strophysics (established early 1990s)

Laboratori Nazionali del Gran Sasso, INFN



Cosmic ray attenuation: $\mu \rightarrow 10^{-6}$
$n \rightarrow 10^{-3}$

The LUNA 400 kV facility



LUNA: The First Underground Laboratory for Nuclear Astrophysics

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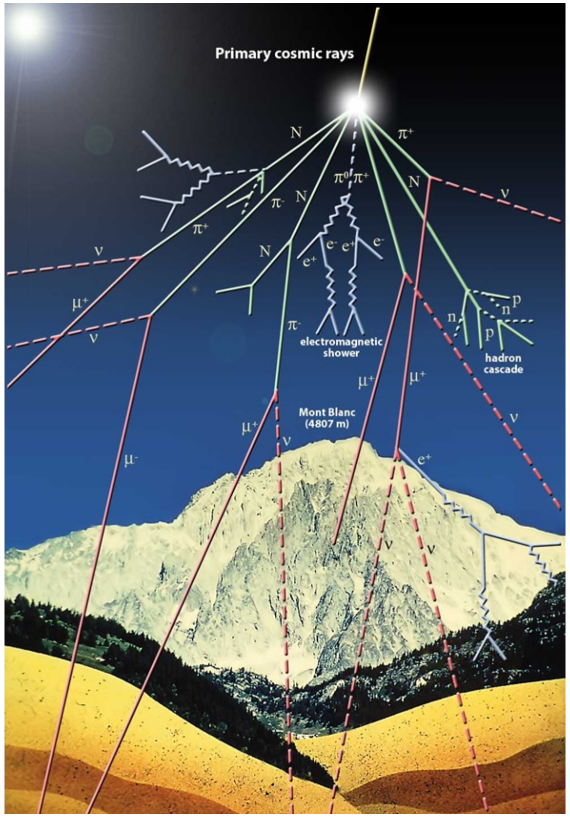
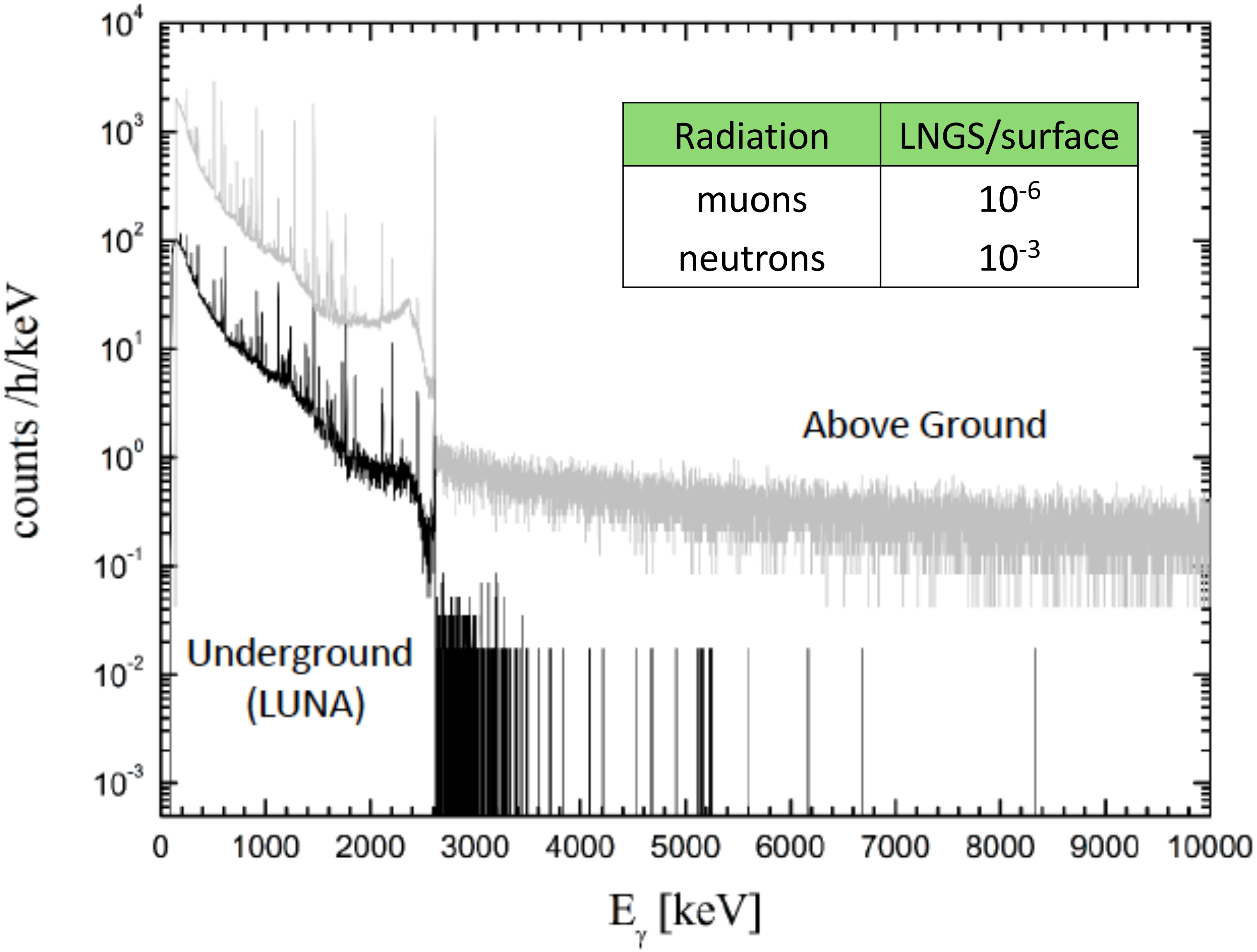
Gamma-ray background: underground vs overground comparison





Radiation	LNGS/surface
muons	10^{-6}
neutrons	10^{-3}

Costantini et al. Rep. Prog. Phys. 72 (2009) 086301

30 years of Nuclear Astrophysics at LUNA (LNGS, INFN)

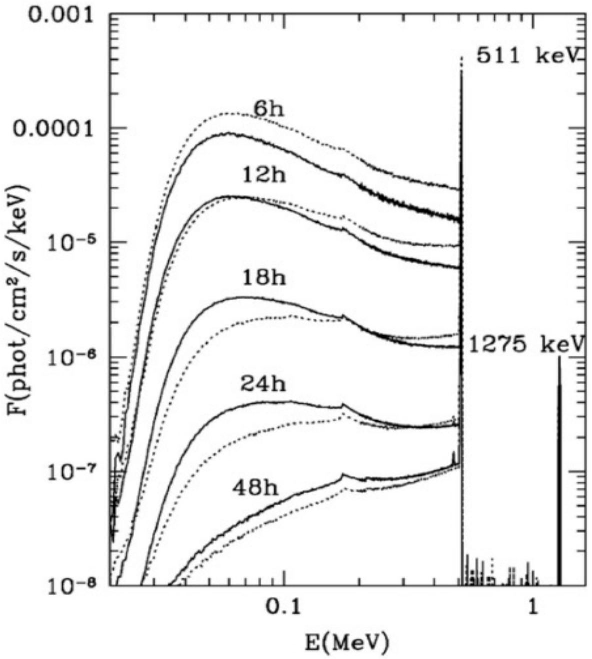
- **solar fusion reactions**
  $^{3}He(^{3}He,2p)^{4}He$ $^{2}H(p,\gamma)^{3}He$ $^{3}He(\alpha,\gamma)^{7}Be$
- **electron screening and stopping power**
  $^{2}H(^{3}He,p)^{4}He$ $^{3}He(^{2}H,p)^{4}He$
- **CNO, Ne-Na and Mg-Al cycles**
  $^{12,13}C(p,\gamma)^{13,14}N$ $^{14,15}N(p,\gamma)^{15,16}O$ $^{16}O(p,\gamma)^{17}F$ $^{20,21,22}Ne(p,\gamma)^{21,22,23}Na$ $^{22}Ne(\alpha,\gamma)^{26}Mg$ $^{23}Na(p,\gamma)^{24}Mg$ $^{25}Mg(p,\gamma)^{26}Al$
- **(explosive) hydrogen burning in novae and AGB stars**
  $^{17}O(p,\gamma)^{18}F$ $^{17}O(p,\alpha)^{14}N$ $^{18}O(p,\gamma)^{19}F$ $^{18}O(p,\alpha)^{15}N$
- **Big Bang nucleosynthesis**
  $^{2}H(\alpha,\gamma)^{6}Li$ $^{2}H(p,\gamma)^{3}He$ $^{6}Li(p,\gamma)^{7}Be$
- **neutron capture nucleosynthesis**
  $^{13}C(\alpha,n)^{16}O$

some of the lowest cross sections ever measured (few counts/month)

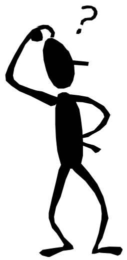
The $^{17}O(p,\gamma)^{18}F$ Reaction in Classical Novae

annihilation radiation (511 keV gamma rays) from β^+ decay of ^{18}F ($t_{½}$ ~ 110 mins)

can provide constraints on novae nucleosynthesis



can be detected by
space-borne telescopes



no 511 keV radiation observed to date!
uncertain $^{17}O(p,\gamma)^{18}F$ rate?

David Scott's
PhD project

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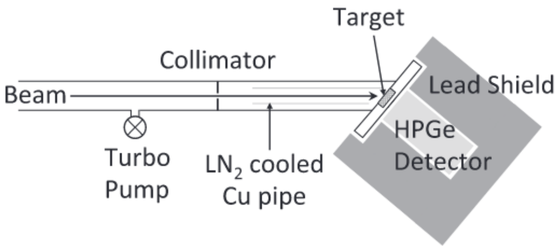
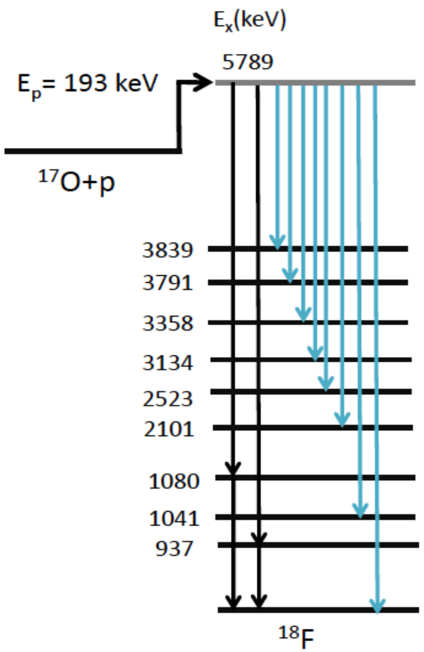
$^{17}O(p,\gamma)^{18}F$ reaction in novae





PHYSICAL REVIEW C **89**, 015803 (2014)

Underground study of the $^{17}O(p,\gamma)^{18}F$ reaction relevant for explosive hydrogen burning

A. Di Leva,[1,2,*] D. A. Scott,[3] A. Caciolli,[4,5] A. Formicola,[6,†] F. Strieder,[7] M. Aliotta,[3] M. Anders,[8] D. Bemmerer,[8] C. Broggini,[4] P. Corvisiero,[9,10] Z. Elekes,[8] Zs. Fülöp,[11] G. Gervino,[12] A. Guglielmetti,[13,14] C. Gustavino,[15] Gy. Gyürky,[11] G. Imbriani,[1,2] J. José,[16] M. Junker,[6] M. Laubenstein,[6] R. Menegazzo,[4] E. Napolitani,[17] P. Prati,[9,10] V. Rigato,[5] V. Roca,[1,2] E. Somorjai,[11] C. Salvo,[6,10] O. Straniero,[2,18] T. Szücs,[11] F. Terrasi,[2,19] and D. Trezzi[13,14]
(LUNA Collaboration)

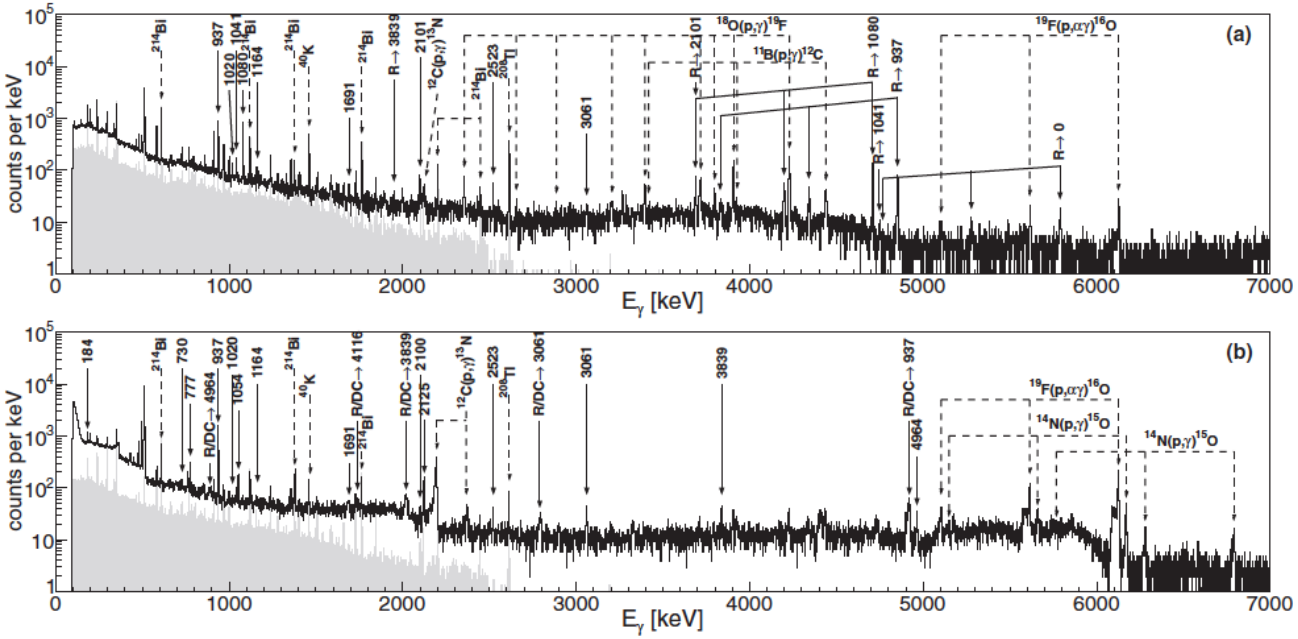


FIG. 5. (a) Sample spectrum of an on-resonance measurement at energy $E_{c.m.} = 183$ keV. (b) Sample spectrum for an off-resonance measurement at $E_{c.m.} = 250$ keV. In gray is the time-normalized room background with 10 cm of lead surrounding the detector.

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$^{17}O(p,\gamma)^{18}F$ reaction in novae

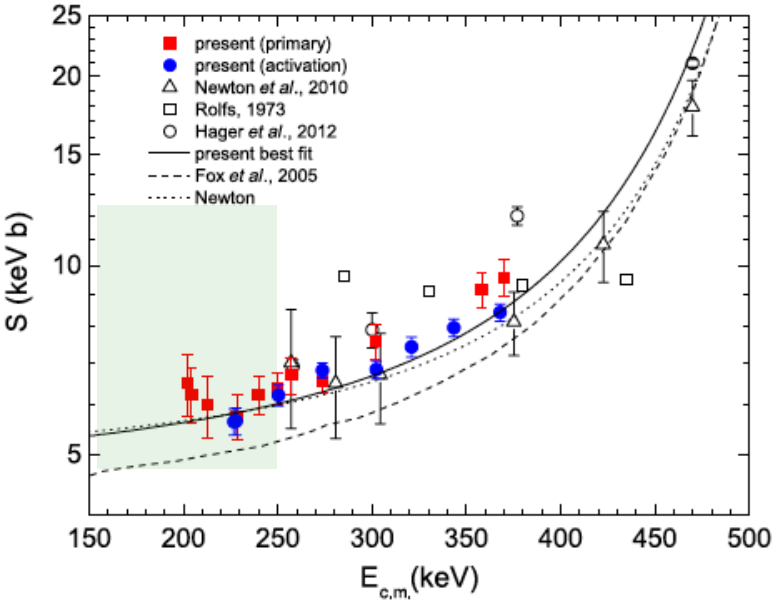
PRL **109,** 202501 (2012) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2012

First Direct Measurement of the $^{17}O(p,\gamma)^{18}F$ Reaction Cross Section at Gamow Energies for Classical Novae

D. A. Scott,[1] A. Caciolli,[2,3] A. Di Leva,[4] A. Formicola,[5,*] M. Aliotta,[1] M. Anders,[6] D. Bemmerer,[6] C. Broggini,[2] M. Campeggio,[7] P. Corvisiero,[8] Z. Elekes,[6] Zs. Fülöp,[9] G. Gervino,[10] A. Guglielmetti,[7] C. Gustavino,[5] Gy. Gyürky,[9] G. Imbriani,[4] M. Junker,[5] M. Laubenstein,[5] R. Menegazzo,[2] M. Marta,[11] E. Napolitani,[12] P. Prati,[8] V. Rigato,[3] V. Roca,[4] E. Somorjai,[9] C. Salvo,[5,8] O. Straniero,[14] F. Strieder,[13] T. Szücs,[9] F. Terrasi,[15] and D. Trezzi[16]

(LUNA Collaboration)

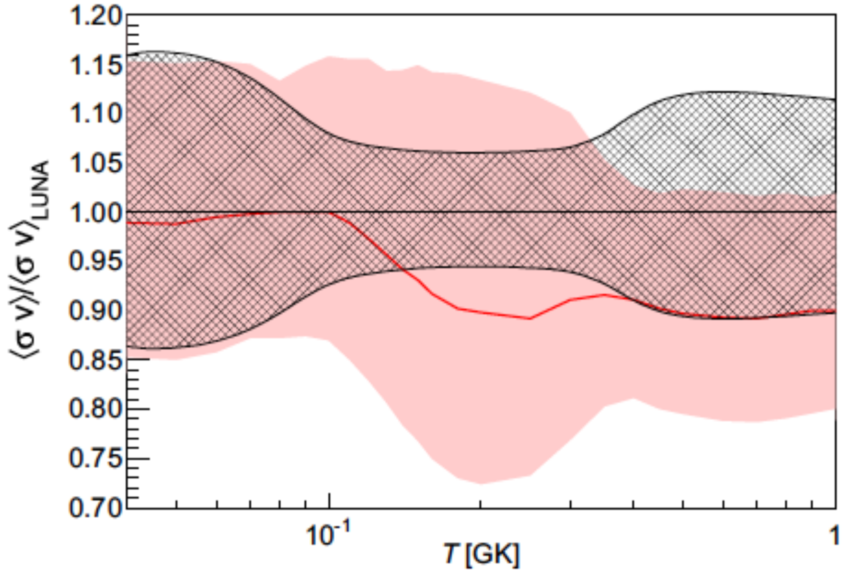
first measurement within Gamow window



firmer constraints on amount of ^{18}F produced in novae

new limits to satellite detection of 511keV γ rays

improved reaction rate

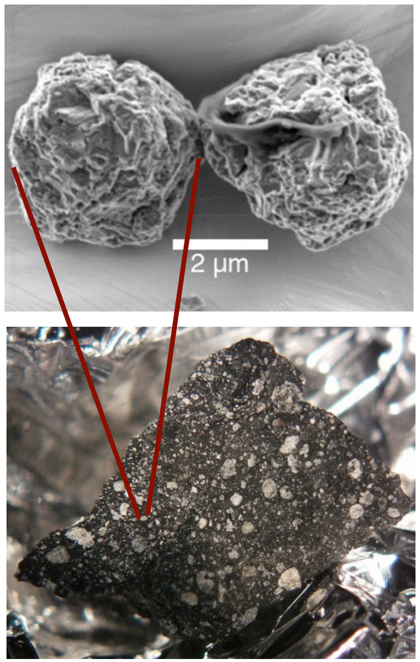


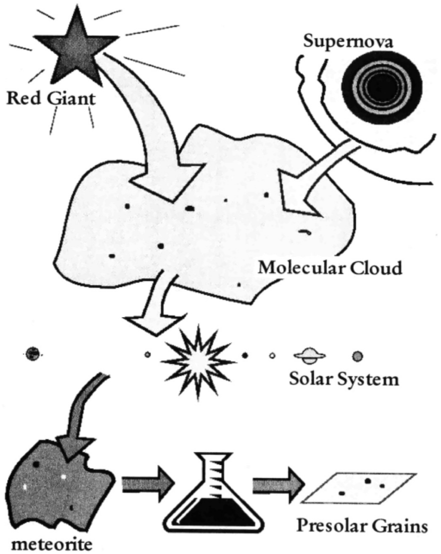
The $^{17}O(p,\alpha)^{14}N$ Reaction: Puzzling Origin of Pre-Solar Grains

LUNA

Carlo Bruno's
PhD project

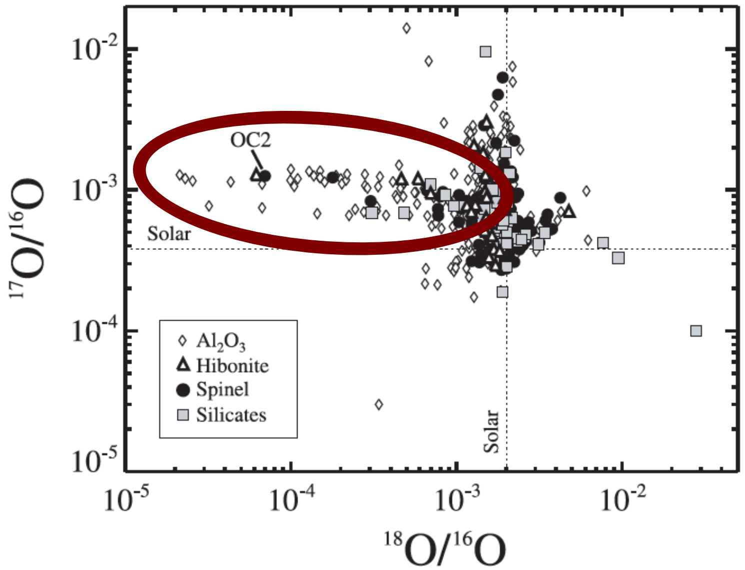
Pre-solar grains: stellar dust trapped in meteorites





isotopic anomalies can reveal
clues on site of formation

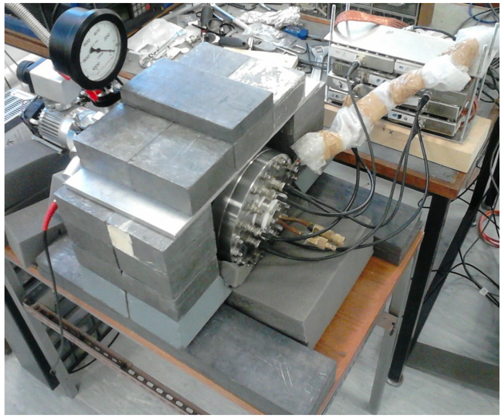
puzzling origin of Oxygen-rich grains



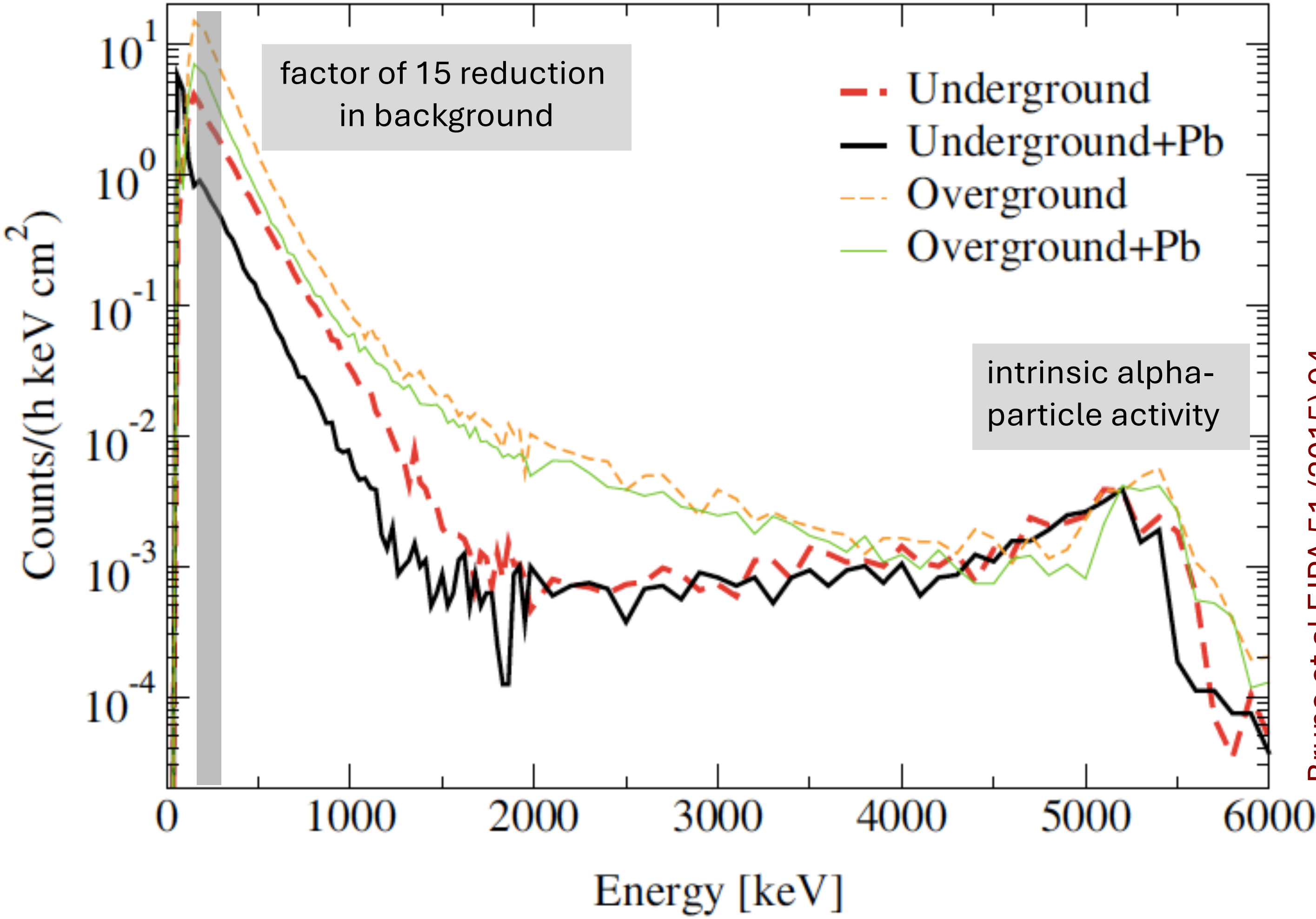
improved knowledge on
$^{17}O(p,\alpha)^{14}N$ reaction needed

Background Suppression

Edinburgh



Gran Sasso



Bruno et al EJPA 51 (2015) 94

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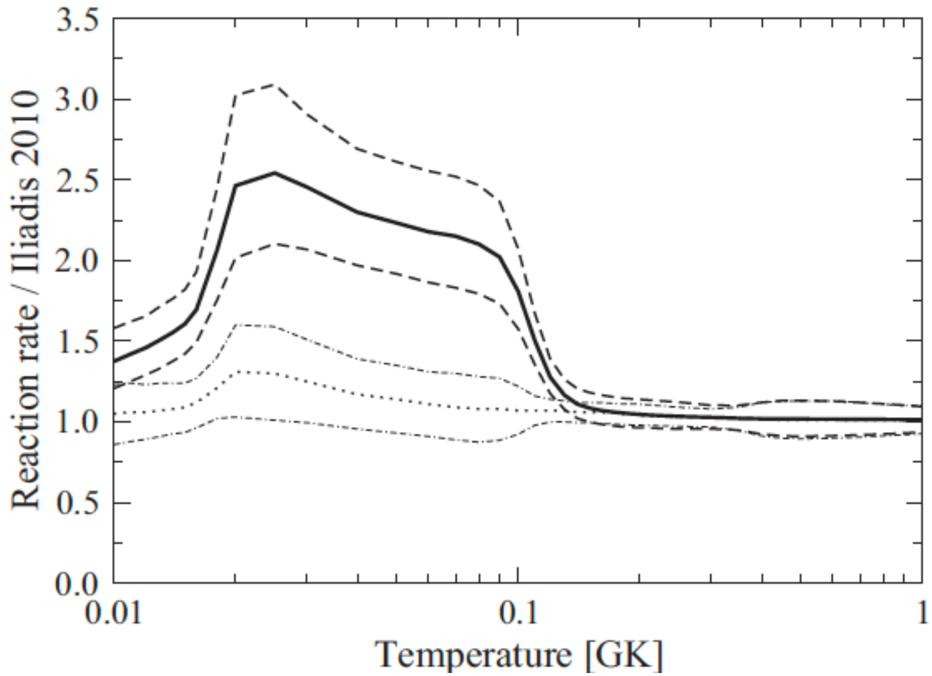
$^{17}O(p,\alpha)^{14}N$ Results

PRL **117,** 142502 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

Improved Direct Measurement of the 64.5 keV Resonance Strength in the $^{17}O(p,\alpha)^{14}N$ Reaction at LUNA

C. G. Bruno,[1,*] D. A. Scott,[1] M. Aliotta,[1,†] A. Formicola,[2] A. Best,[3] A. Boeltzig,[4] D. Bemmerer,[5] C. Broggini,[6] A. Caciolli,[7] F. Cavanna,[8] G. F. Ciani,[4] P. Corvisiero,[8] T. Davinson,[1] R. Depalo,[7] A. Di Leva,[3] Z. Elekes,[9] F. Ferraro,[8] Zs. Fülöp,[9] G. Gervino,[10] A. Guglielmetti,[11] C. Gustavino,[12] Gy. Gyürky,[9] G. Imbriani,[3] M. Junker,[2] R. Menegazzo,[6] V. Mossa,[13] F. R. Pantaleo,[13] D. Piatti,[7] P. Prati,[8] E. Somorjai,[9] O. Straniero,[14] F. Strieder,[15] T. Szücs,[5] M. P. Takács,[5] and D. Trezzi[11]

15x lower background underground



reaction rate ~ 2x higher than previously assumed

reaction can occur at lower temperatures, i.e. those attained in IM AGB stars

On the origin of Group II grains

nature astronomy
LETTERS
PUBLISHED: 30 JANUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0027

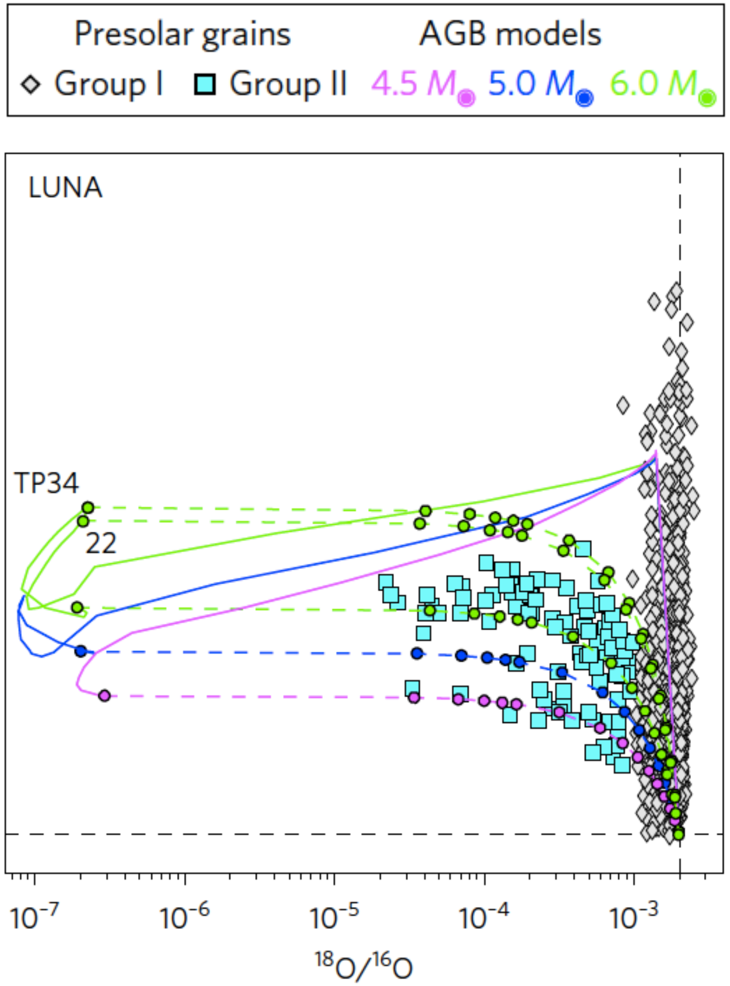
Origin of meteoritic stardust unveiled by a revised proton-capture rate of ^{17}O

M. Lugaro[1,2*], A. I. Karakas[2-4], C. G. Bruno[5], M. Aliotta[5], L. R. Nittler[6], D. Bemmerer[7], A. Best[8], A. Boeltzig[9], C. Broggini[10], A. Caciolli[11], F. Cavanna[12], G. F. Ciani[9], P. Corvisiero[12], T. Davinson[5], R. Depalo[11], A. Di Leva[8], Z. Elekes[13], F. Ferraro[12], A. Formicola[14], Zs. Fülöp[13], G. Gervino[15], A. Guglielmetti[16], C. Gustavino[17], Gy. Gyürky[13], G. Imbriani[8], M. Junker[14], R. Menegazzo[10], V. Mossa[18], F. R. Pantaleo[18], D. Piatti[11], P. Prati[12], D. A. Scott[5,†], O. Straniero[14,19], F. Strieder[20], T. Szücs[13], M. P. Takács[7] and D. Trezzi[16]

new LUNA rate allows to reproduce correct abundances

confirms intermediate mass AGB as likely site of production

for oxygen-rich pre-solar grains



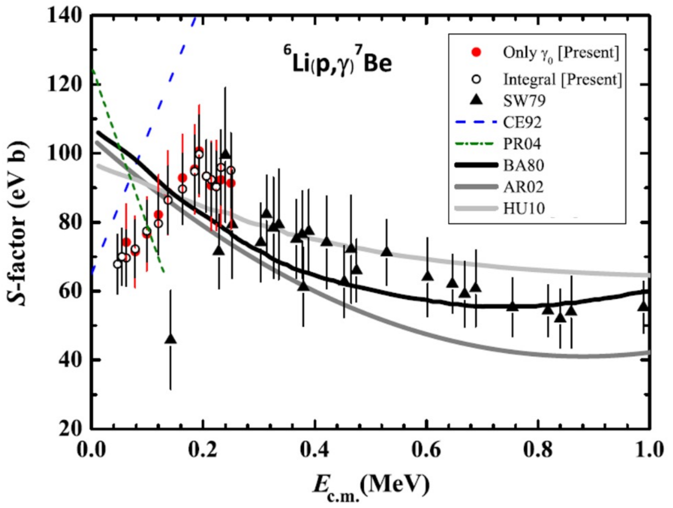
^{6}Li destruction:
The $^{6}Li(p,\gamma)^{7}Be$ and $^{6}Li(p,\alpha)^{3}He$ Reactions

LUNA

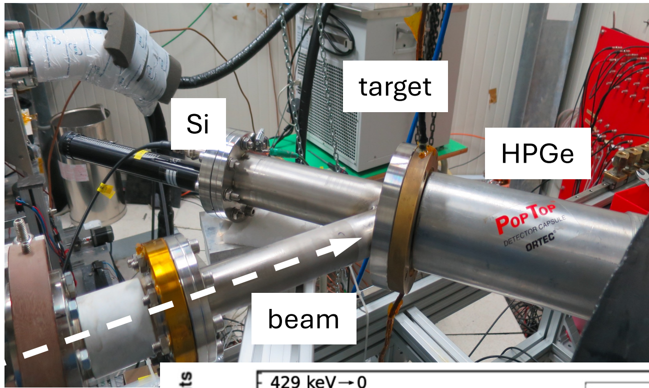
$^{6}Li(p,\gamma)^{7}Be$ reaction involved in BBN as well as in ^{6}Li depletion in early stages of stellar evolution

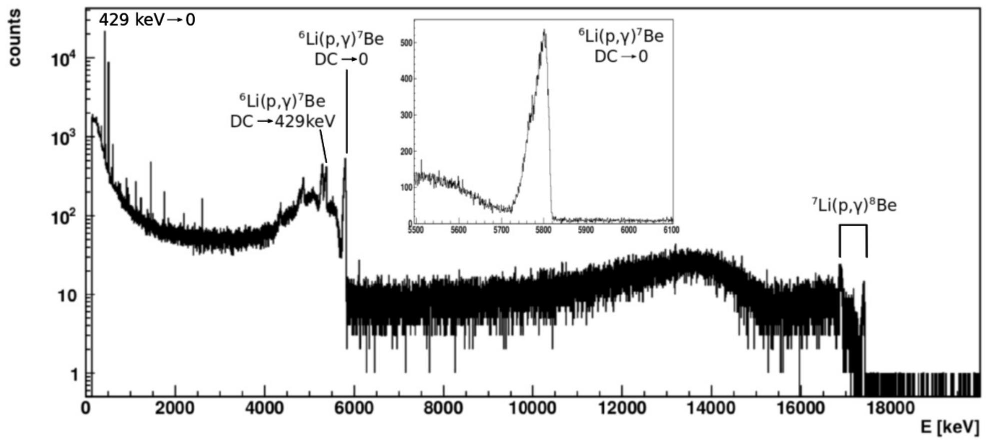
Thomas Chillery's PhD project

J. He *et al*, Physics Letters B, **725** (2013) 287



resonance(-like) structure reported but never independently confirmed





The ^{6}Li(p,γ)^{7}Be and the ^{6}Li(p,α)^{3}He reactions at LUNA

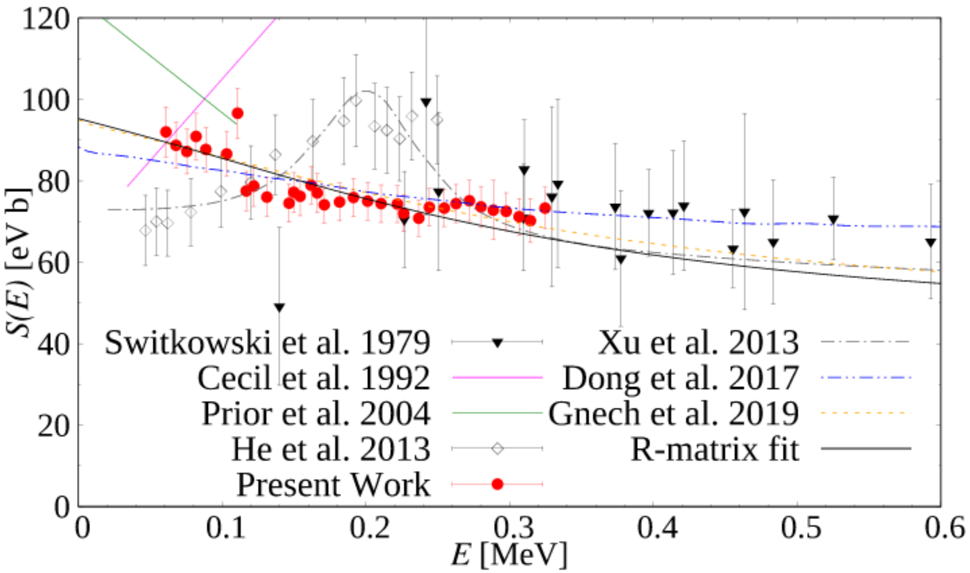
PHYSICAL REVIEW C **102**, 052802(R) (2020)

Rapid Communications

Underground experimental study finds no evidence of low-energy resonance in the ^{6}Li$(p, \gamma)^7$Be reaction

D. Piatti,[1] T. Chillery,[2] R. Depalo,[1,*] M. Aliotta,[2] D. Bemmerer,[3] A. Best,[4] A. Boeltzig,[5] C. Broggini,[6] C. G. Bruno,[2] A. Caciolli,[1] F. Cavanna,[7] G. F. Ciani,[5] P. Corvisiero,[7] L. Csedreki,[5] T. Davinson,[2] A. Di Leva,[4] Z. Elekes,[8] F. Ferraro,[7] E. M. Fiore,[9] A. Formicola,[10] Zs. Fülöp,[8] G. Gervino,[11] A. Gnech,[12] A. Guglielmetti,[13] C. Gustavino,[14] Gy. Gyürky,[8] G. Imbriani,[4] M. Junker,[10] I. Kochanek,[10] M. Lugaro,[15] L. E. Marcucci,[16] P. Marigo,[17] E. Masha,[13] R. Menegazzo,[6] V. Mossa,[9] F. R. Pantaleo,[9] V. Paticchio,[18] R. Perrino,[18] P. Prati,[7] L. Schiavulli,[9] K. Stöckel,[19] O. Straniero,[20] T. Szücs,[3] M. P. Takács,[19] and S. Zavatarelli[7]
(LUNA Collaboration)

ruled out previously suggested resonance



^{22}Na Production in Novae: the ^{21}Ne(p,γ)^{22}Na reaction

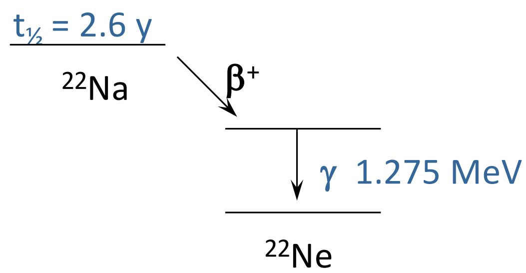
Ragandeep Sidhu, PDRA

The $^{21}Ne(p,\gamma)^{22}Na$

novae models ⇒ measurable γ-ray fluxes observable within few kilo-parsecs

idea: observe γ-ray signature to test nova models

^{22}Na: the fingerprint of a nova outburst — Clayton & Hoyle, ApJ L101 (1974) 187



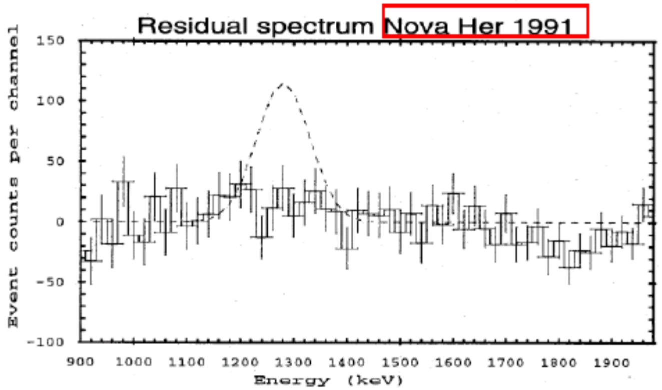
why ^{22}Na?

- novae (ONe WDs) are main galactic production site for ^{22}Na
- ^{22}Na decay has conveniently short half-life

  ⇒ hence spatial and temporal limits to its detection

no observation to date

unclear (nuclear) inputs?

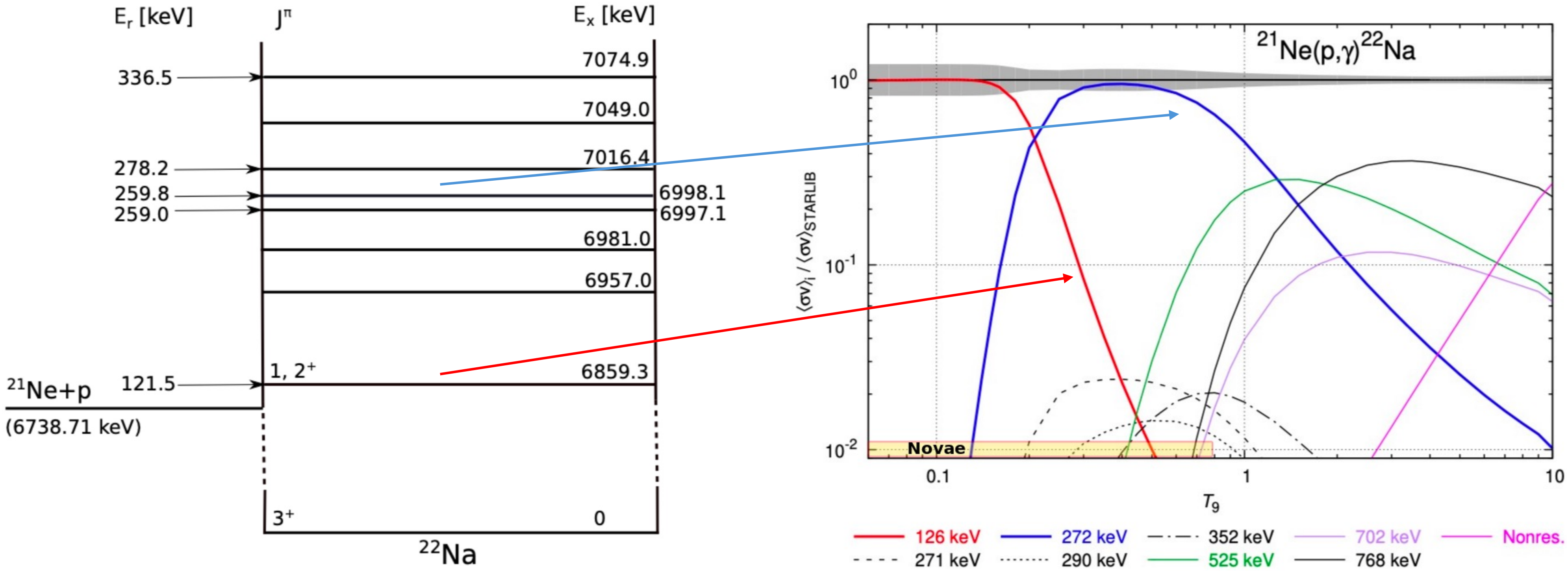


- Sensitivity study [Iliadis+, ApJ 142 (2002) 105]:

  20% variation in reaction rate →
  factor of 6 change in ^{22}Na abundance)

The $^{21}Ne(p,\gamma)^{22}Na$ reaction

main resonances: E_p = 126 and 272 keV



Other resonances: E_p = 271, 290 and 352 keV (< 5% contribution to stellar rate)

Experimental Setup

- windowless Ne-gas target

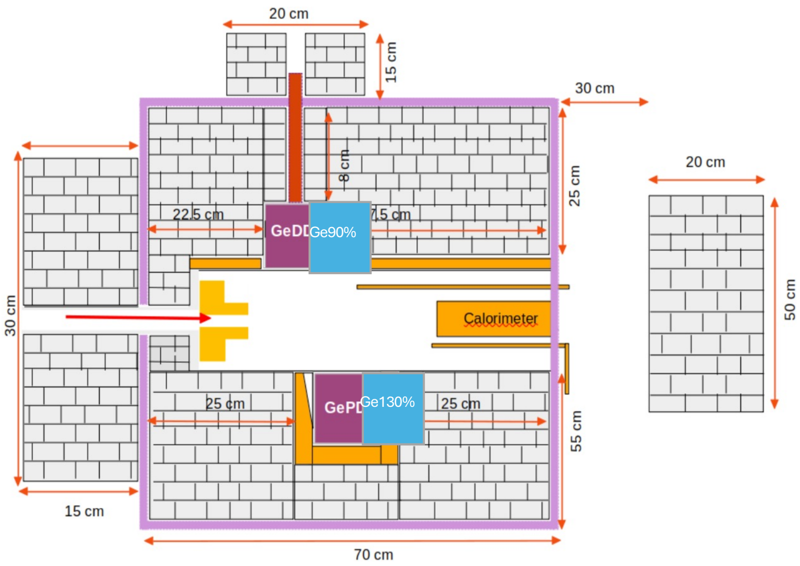
  P = 2 mbar

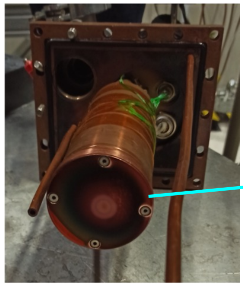
- HPGe detectors:
  - Relative efficiency 130%
  - Relative efficiency 90%

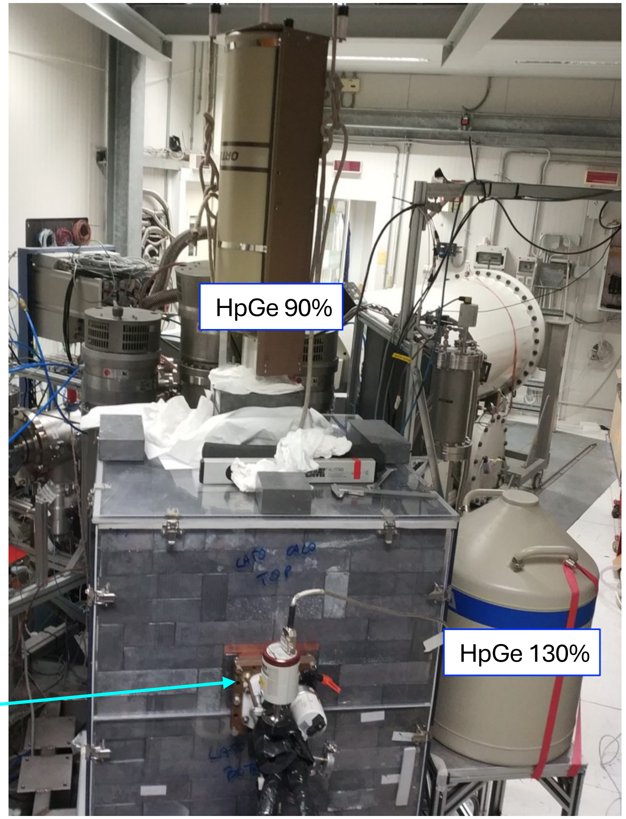
- Lead + copper shield
- Anti-Radon box

- 260 keV < E_p < 400 keV
- thick-target condition

  fulfilled for all resonances



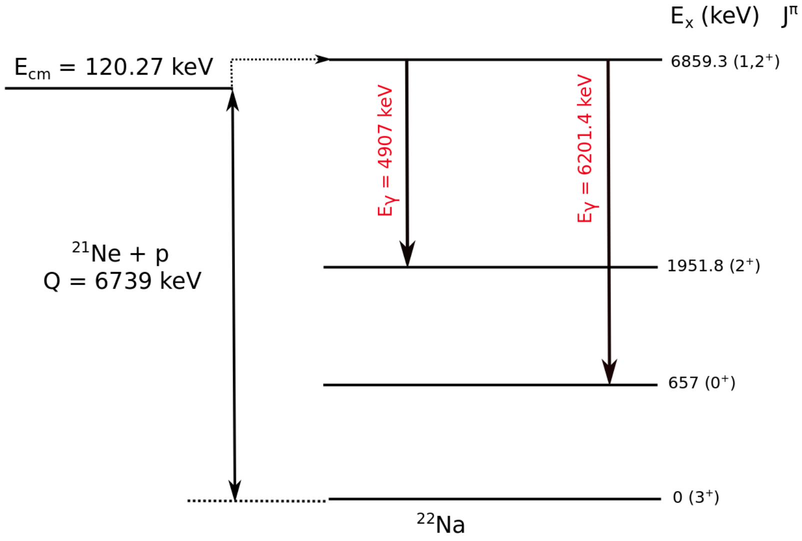


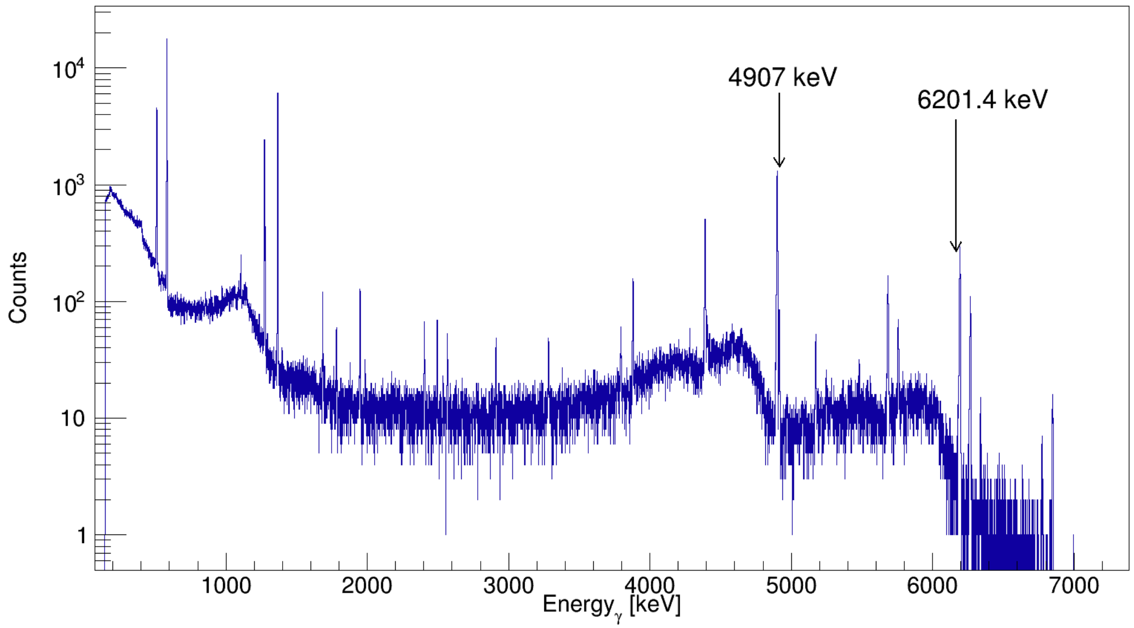


calorimeter to measure beam current (see later)

The $^{21}Ne(p,\gamma)^{22}Na$

E_p = 126 keV resonance, using ^{21}Ne enriched gas (59.1%)





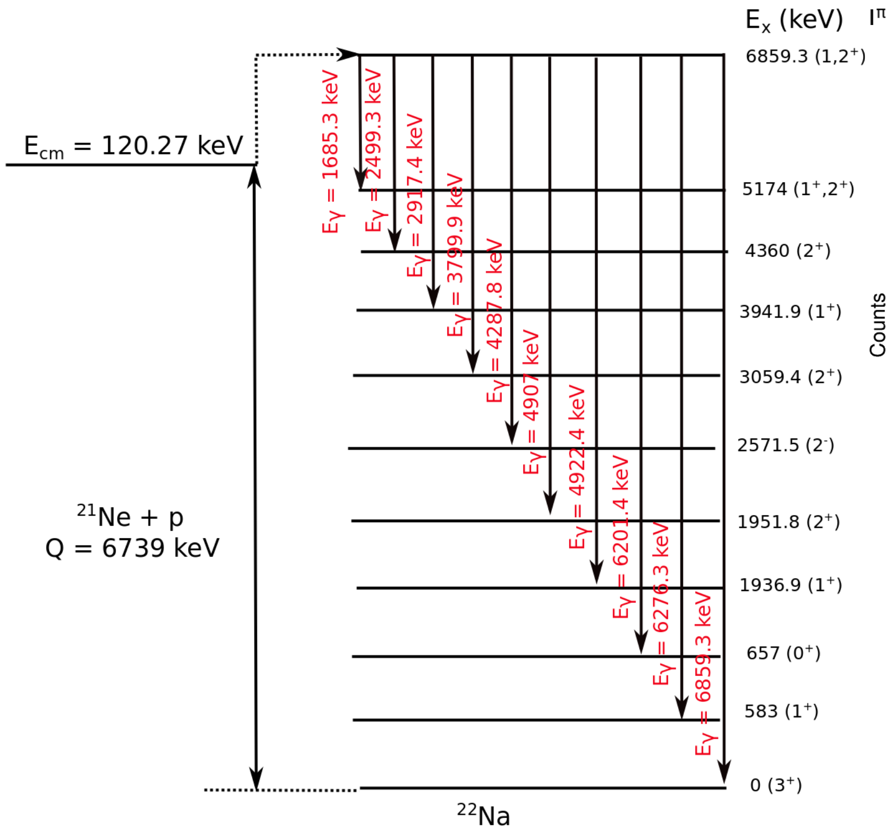
previous studies:

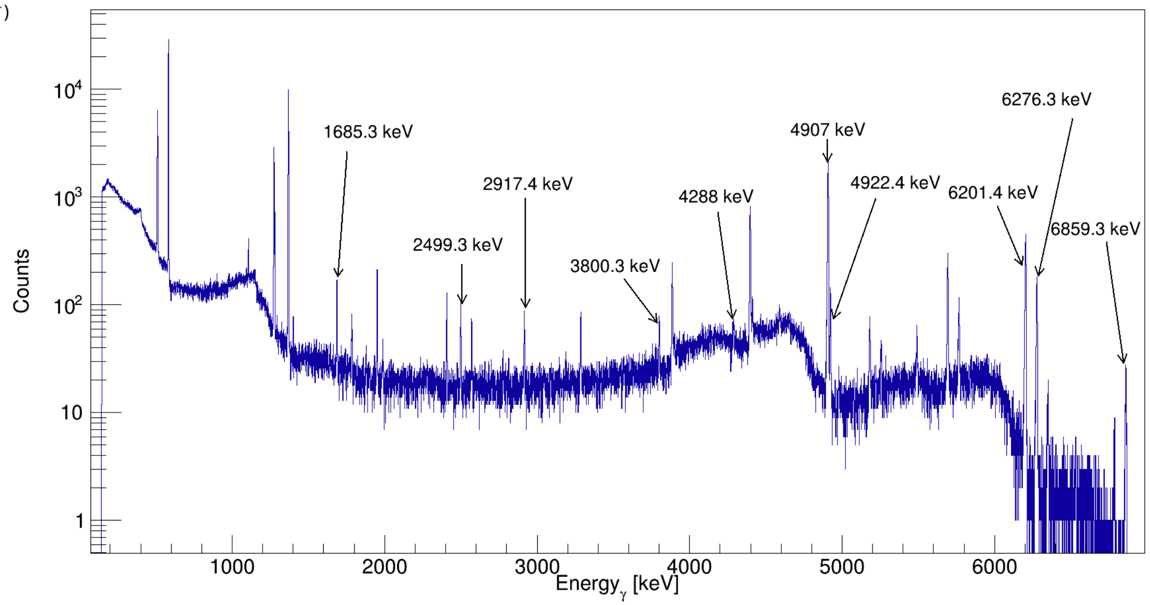
only two transitions reported (NNDC)

E(level) (keV)	J^{π}(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final Levels	
6834 7	(0+,1+)						
6859.3 6	1,2+	< 12 eV	4907.0 6201.4	100 11 25 11		1951.8 657.00	2+ 0+

The $^{21}Ne(p,\gamma)^{22}Na$

E_p = 126 keV resonance, using ^{21}Ne enriched gas (59.1%)





eight new primary transitions identified

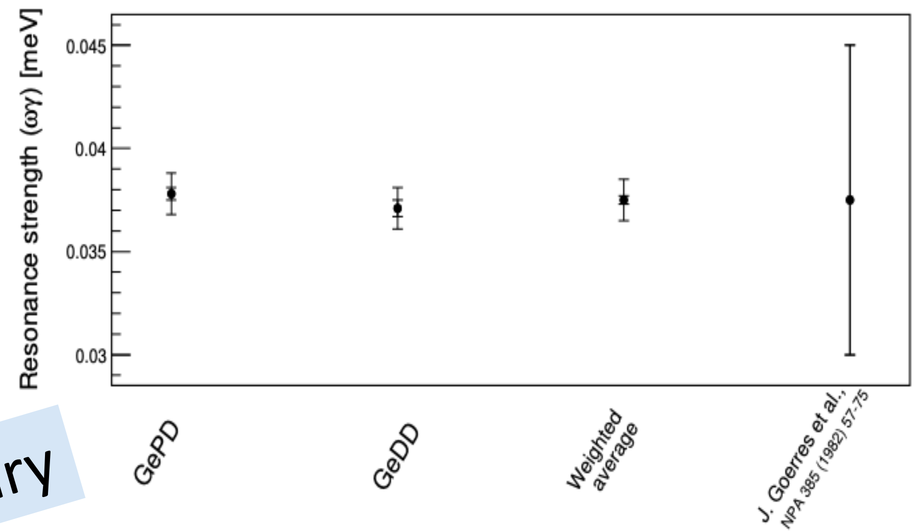
The $^{21}Ne(p,\gamma)^{22}Na$

E_p = 126 keV resonance, using ^{21}Ne enriched gas (59.1%)

Branching ratios (→ new!)

	E_γ	BR [%]	stat. error [%]	syst. error [%]
→	1685.2	1.25	0.04	0.07
→	2499.1	1.16	0.05	0.06
→	2917.2	0.98	0.06	0.05
→	3799.5	1.09	0.08	0.07
→	4287.4	0.57	0.10	0.04
	4907.0	64.2	0.4	3.0
→	4921.8	3.18	0.09	0.18
	6201.4	19.6	0.2	1.0
→	6275.3	6.8	0.1	0.4
→	6858.2	1.16	0.05	0.06

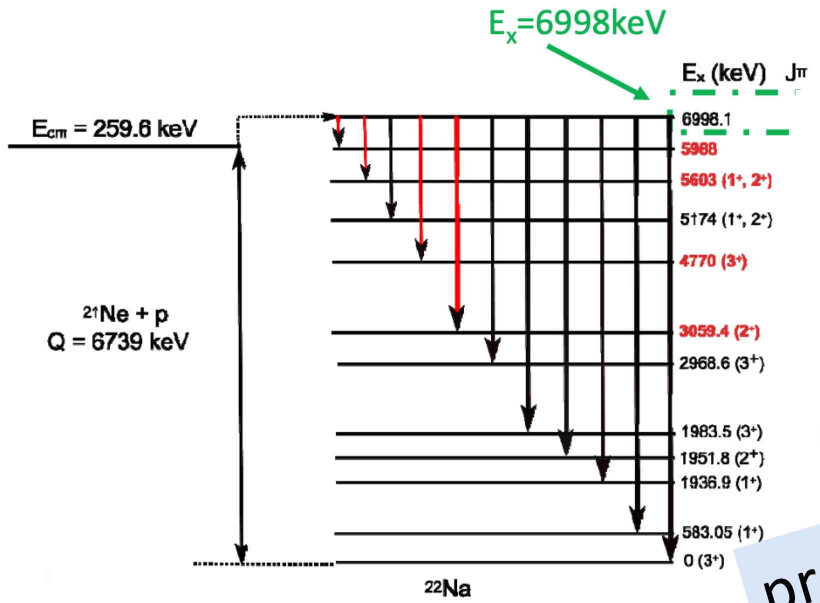
Resonance strength



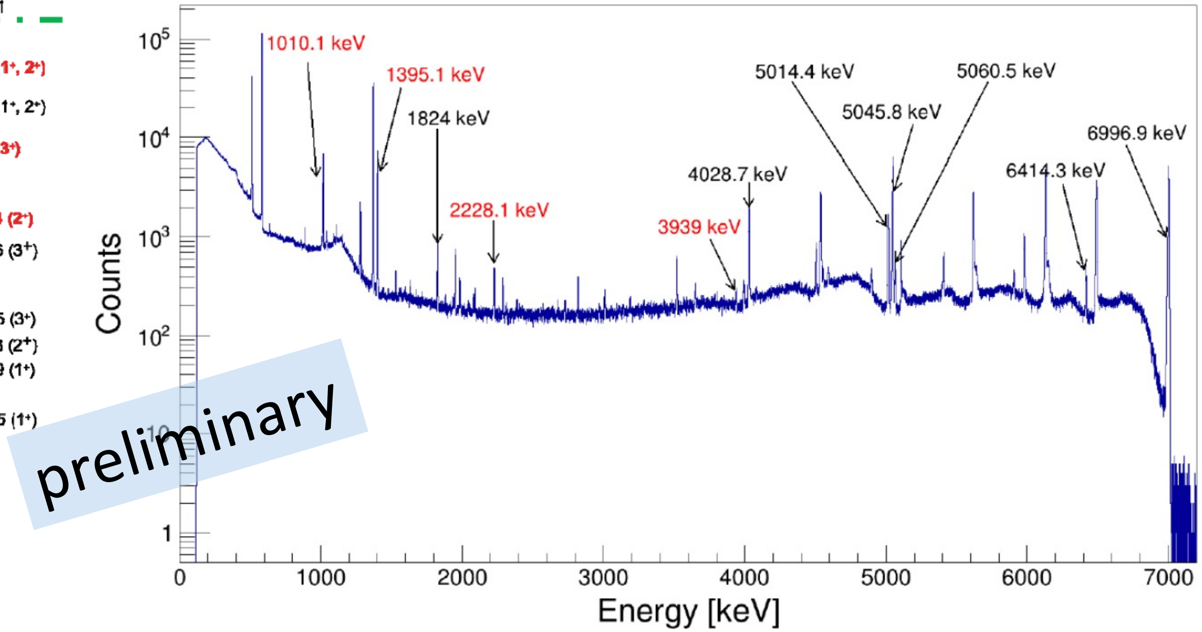
preliminary

$$\omega\gamma \text{ [meV]} = 0.0375 \pm 0.0002_{stat} \pm 0.0010_{syst}$$

E_p = 272 keV resonance, using natural Ne gas



four new transitions observed



resonance strength

$\omega\gamma$ [meV] = $129.9 \pm 0.4_{stat} \pm 3.8_{syst}$

ca. 50% higher than previously reported

The $^{21}Ne(p,\gamma)^{22}Na$ reaction: Summary

- resonance strengths of all resonances of interest for novae measured at LUNA with < 7% uncertainty (19% for E_p = 271 keV resonance)
- new primary gamma transitions found in E_p = 126, 272, and 291 keV resonances
- the E_p = 272 keV resonance (dominant at novae temperatures) is 1.5x larger than previously found

E_p [keV]	$\omega\gamma$ [meV]
126	$0.0375 \pm 0.0002_{stat} \pm 0.0010_{syst}$
271	$2.7 \pm 0.3_{stat} \pm 0.4_{syst}$
272	$129.9 \pm 0.4_{stat} \pm 3.8_{syst}$
291	$1.99 \pm 0.01_{stat} \pm 0.05_{syst}$
352	$14.9 \pm 0.4_{stat} \pm 0.5_{syst}$

preliminary

reaction rate and impact under evaluation

special thanks for Ragan Sidhu, Eliana Masha, Francesca Cavanna, Sandra Zavatarelli

The ^{23}Na(p,α)^{18}F Reaction for Globular Clusters

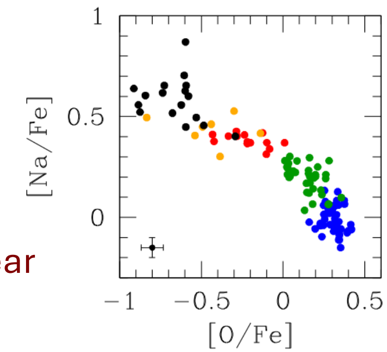
Globular Clusters:

spheroidal ensembles of stars held together by gravity

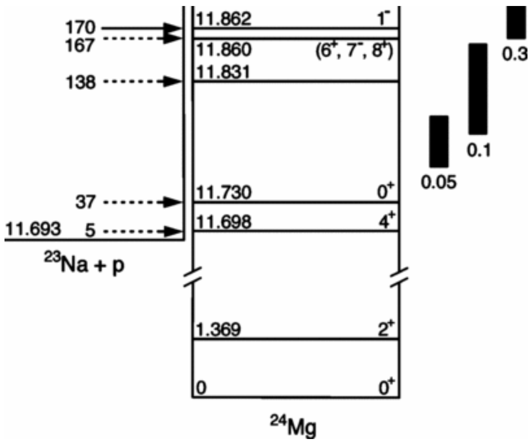
thousands of stars with varying masses and compositions

+ characteristic light element abundances:

Na-O anti-correlation: origin still unclear



Lucia Barbieri's
PhD project



A reduction by a factor of 3-5 in the ^{23}Na(p,α)^{20}Ne reaction rate may solve this problem

Main uncertainty comes from contribution of possible low-energy resonance

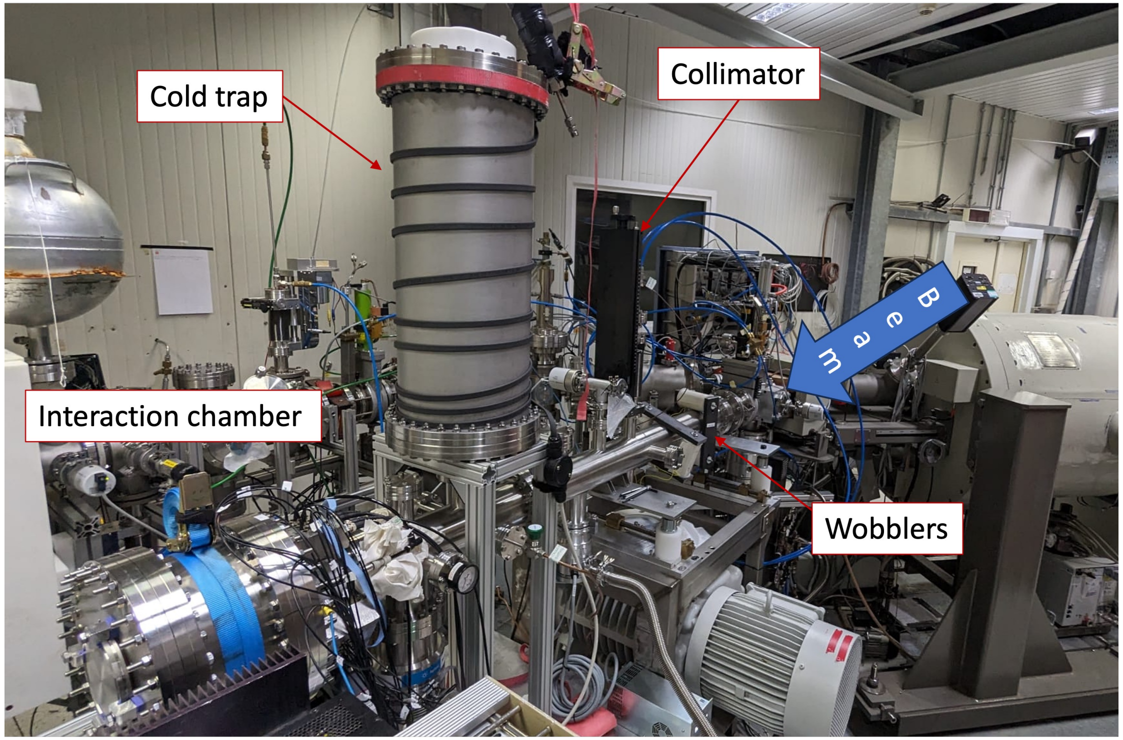
E_r [keV]	J^π	$\omega\gamma$ [eV]
37	0^+	$< 3.3 \times 10^{-20}$
138	? (l_p=0)	$< 1.6 \times 10^{-6}$
	? (l_p=1)	$< 7.5 \times 10^{-8}$
	? (l_p=2)	$< 2.8 \times 10^{-9}$
	? (l_p=3)	$< 5.4 \times 10^{-11}$
167	$(6,7,8)^+$	? (negligible)
170	1^-	$(23 \pm 5) \times 10^{-3}$

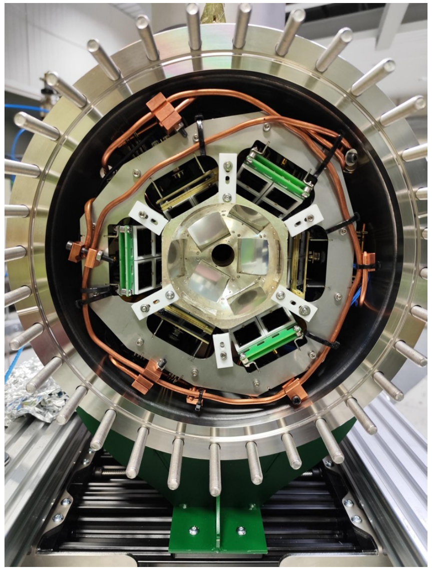
The $^{23}Na(p,\alpha)^{20}Ne$ reaction

European Research Council
Established by the European Commission

ELDAR ERC (PI Carlo Bruno)

A new beam line designed in Edinburgh recently installed & commissioned at LUNA (in place of gas target)

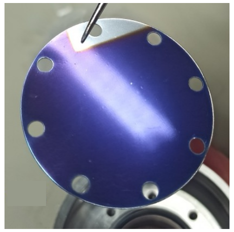




new silicon detector array

^{23}Na target tests currently ongoing at LUNA

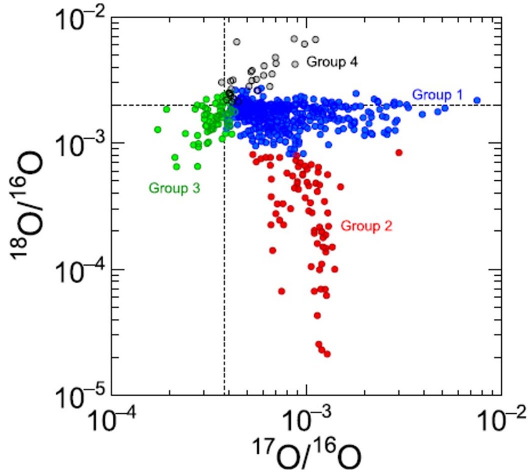
evaporated



sputtered

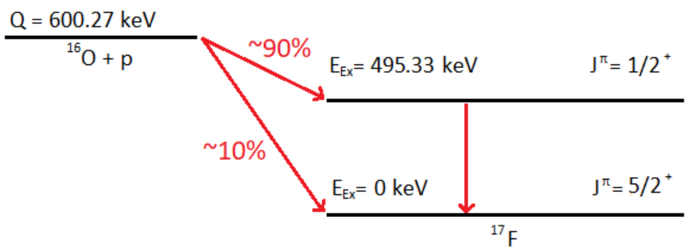
The $^{16}O(p,\gamma)^{17}F$ Reaction: $^{17}O/^{17}O$ in pre-solar grains

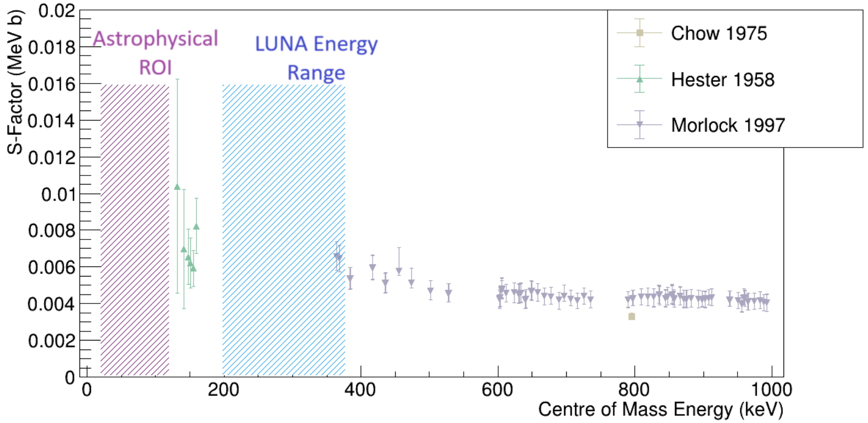
- **Group 2 pre-solar grains** predicted to originate in **AGB** stars
- Standard stellar models required additional mixing process to reproduce observed $\mathbf{^{17}O/^{16}O}$ ratios
- **Hot Bottom Burning** may provide solution, depending on the rate of the **$^{16}O(p,\gamma)^{17}F$ reaction**



Duncan Robb's PhD project

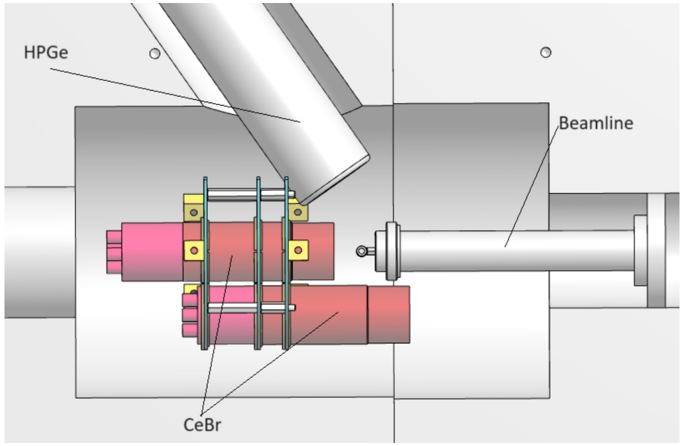
direct capture reaction



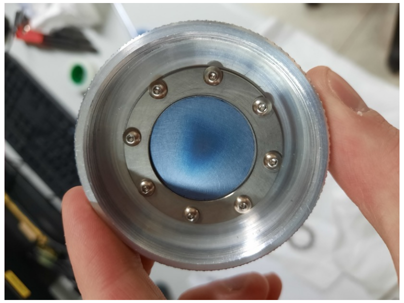


The $^{16}O(p,\gamma)^{17}F$ reaction

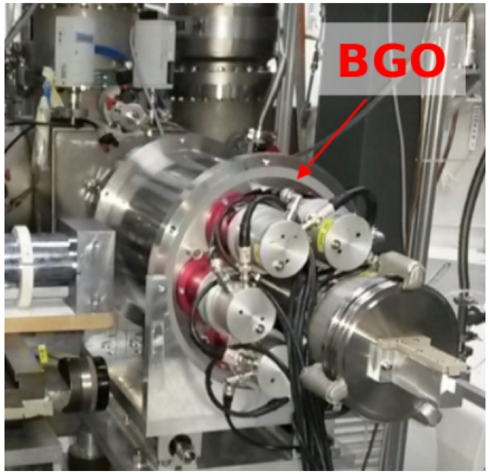
prompt γ-ray measurement (HPGe, 2x $CeBr_3$)

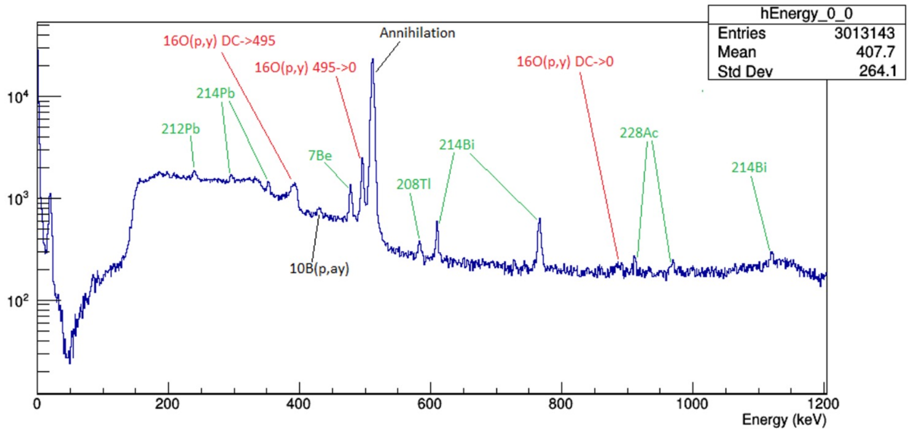


Ta_2O_5 targets



activation technique (beta decay of ^{17}F)





preliminary results
analysis of activation data ongoing

Plans for the Future…

NUclear **CL**ustering **E**ffects in **A**strophysical **R**eactions

NUCLEAR

European Research Council
Established by the European Commission

UK Research
and Innovation

Nucleosynthesis in First Stars and Other Puzzles

Long-Standing Questions in Nuclear Astrophysics

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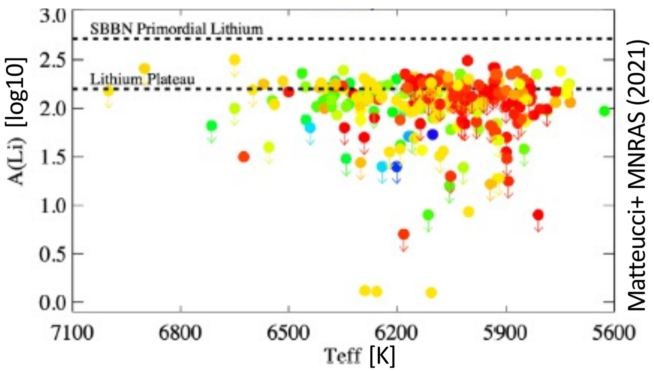
Q1. Cosmological Lithium Problem



factor of 3 discrepancy between observed and predicted Li abundance

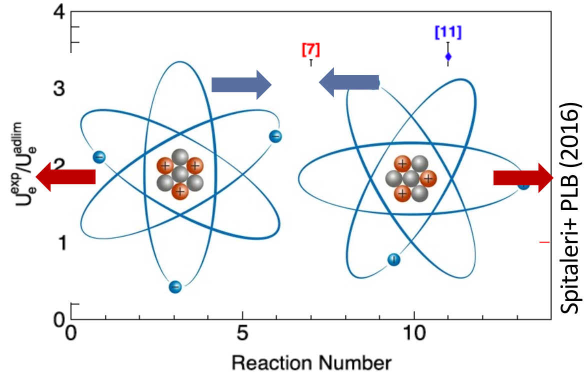
Standard Model of Particle Physics + Cosmology

Q2. Nucleosynthesis in First Stars

made of pristine H and He
very massive → need CNO nuclei

Chemical Evolution of Early Universe + Astronomical Observations (JWST)

Q3. Electron Screening Puzzle



discrepancy between experiment and theory remains unexplained

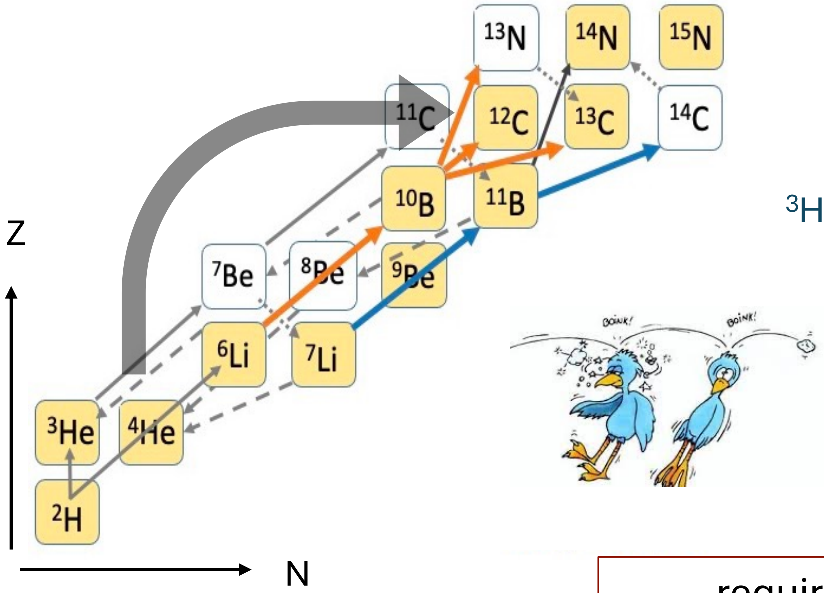
Reactions in Plasmas
Fusion-driven Energy Generation

Nuclear Clustering: A Possible Solution?

Eur. Phys. J. A (2021) 57:24
https://doi.org/10.1140/epja/s10050-020-00339-x
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Theoretical Physics

Nuclear clusters as the first stepping stones for the chemical evolution of the universe

Michael Wiescher[1,a], Ondrea Clarkson[2], Richard J. deBoer[1], Pavel Denisenkov[2]
[1] Department of Physics, The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA
[2] Department of Physics & Astronomy, University of Victoria, Victoria, BC V8W 2Y2, Canada



^{4}He(d,γ)^{6}Li(α,γ)^{10}B(α,d)^{12}C — deuterons as catalyst isotope
^{10}B(α,p)^{13}C
^{10}B(α,n)^{13}N — possible neutron source

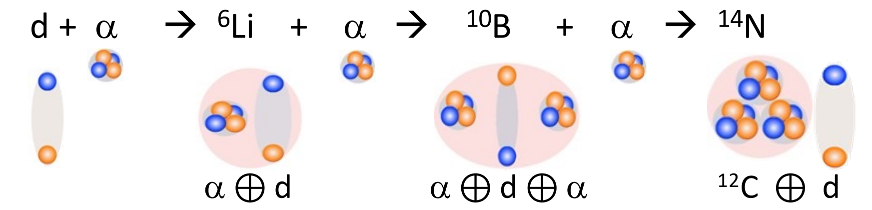
^{3}He(α,γ)^{7}Be(e,γ)^{7}Li(α,γ)^{11}B(α,p)^{14}C
^{11}B(α,n)^{14}N — possible neutron source

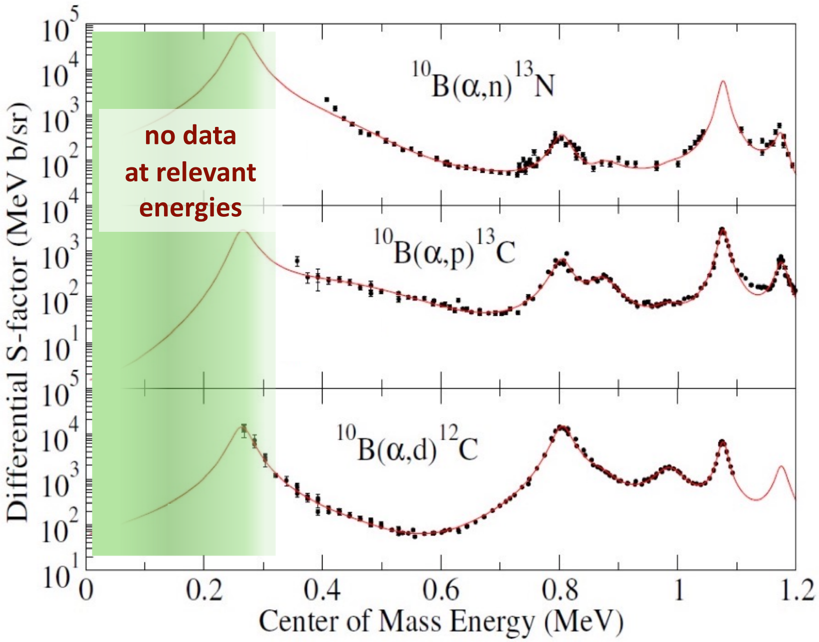
NOTE: 3α process forms C but completely by-passes Li; instead, proposed reaction sequences would also alter Li abundances → solution to CLiP?

requirement: strong enhancement of (α,γ) reaction rates

Current Status

proposed reactions involve strong cluster configurations





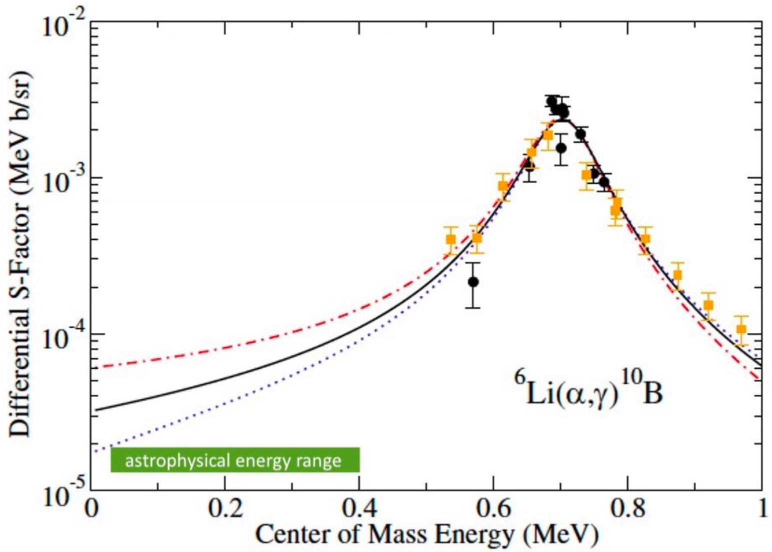
tantalizing new evidence for broad cluster resonances

PHYSICAL REVIEW C **106**, 065801 (2022)

Excitation function for the ^{6}Li + α reaction between 0.5 and 1.4 MeV

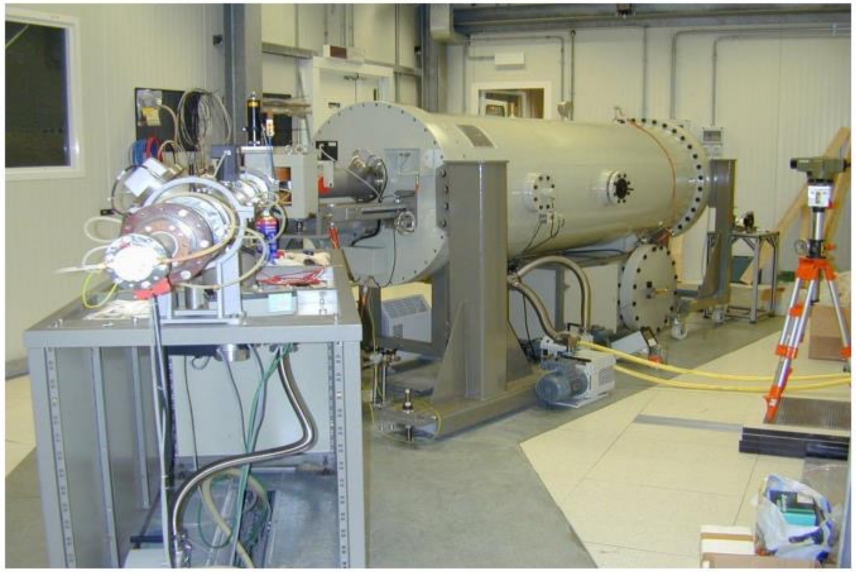
A. Gula, R. J. deBoer, R. Kelmar, J. Görres, K. V. Manukyan, E. Stech, W. Tan, and M. Wiescher

Department of Physics and the Joint Institute for Nuclear Astrophysics, Notre Dame, Indiana 46556, USA



new measurements UNDERGROUND needed

$^{10}B + \alpha$ Reaction Studies at LUNA 400kV



Upcoming measurements at LUNA

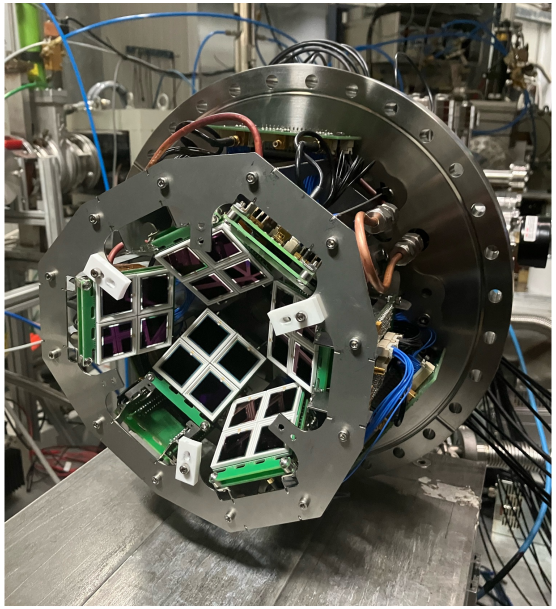
$^{10}B(\alpha,d)^{12}C$
$^{10}B(\alpha,p)^{13}C$ } charged particle detection

$^{10}B(\alpha,n)^{13}N$ activation measurement

silicon detector array

$^{23}Na(p,\alpha)^{20}Ne$ ELDAR ERC – Bruno (UoE)

segmented BGO detector



Jamie Jones, PhD

Rhys Bonnell, PhD

^{6,7}Li + α Reaction Studies at Bellotti Facility

3.5 MV accelerator

$^{4}He^{+}$ (TV: 0.3 – 0.5 MV): 300 μA
$^{4}He^{+}$ (TV: 0.5 – 3.5 MV): 500 μA

$^{6,7}Li(\alpha,\gamma)$ reactions: prompt γ-ray measurements

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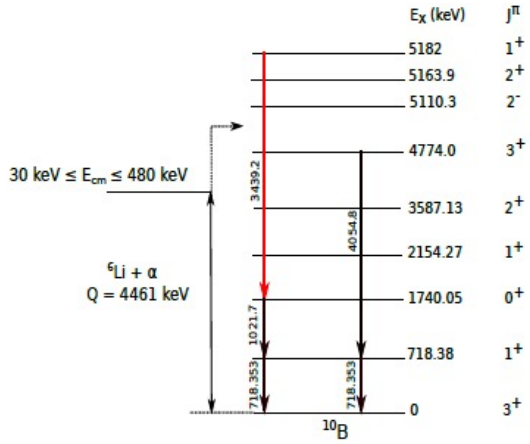
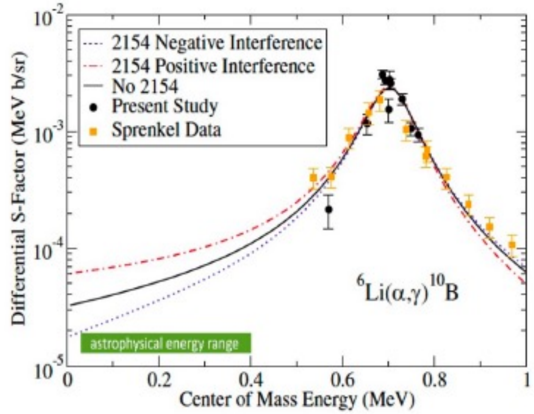
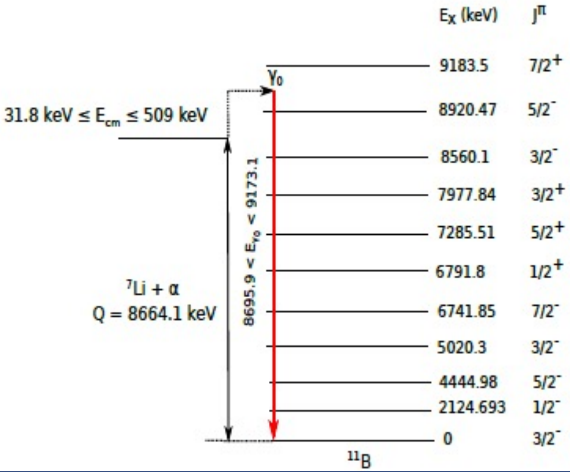
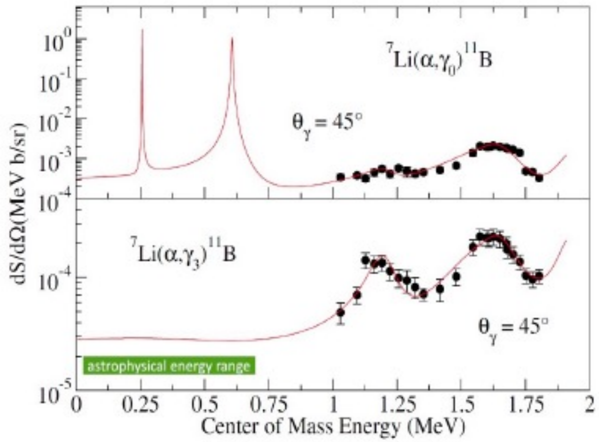
prompt γ-ray detection with either

HPGe detectors or the BGO detector









push measurements

to lowest accessible energies

Grant Start Date: 2 December 2024

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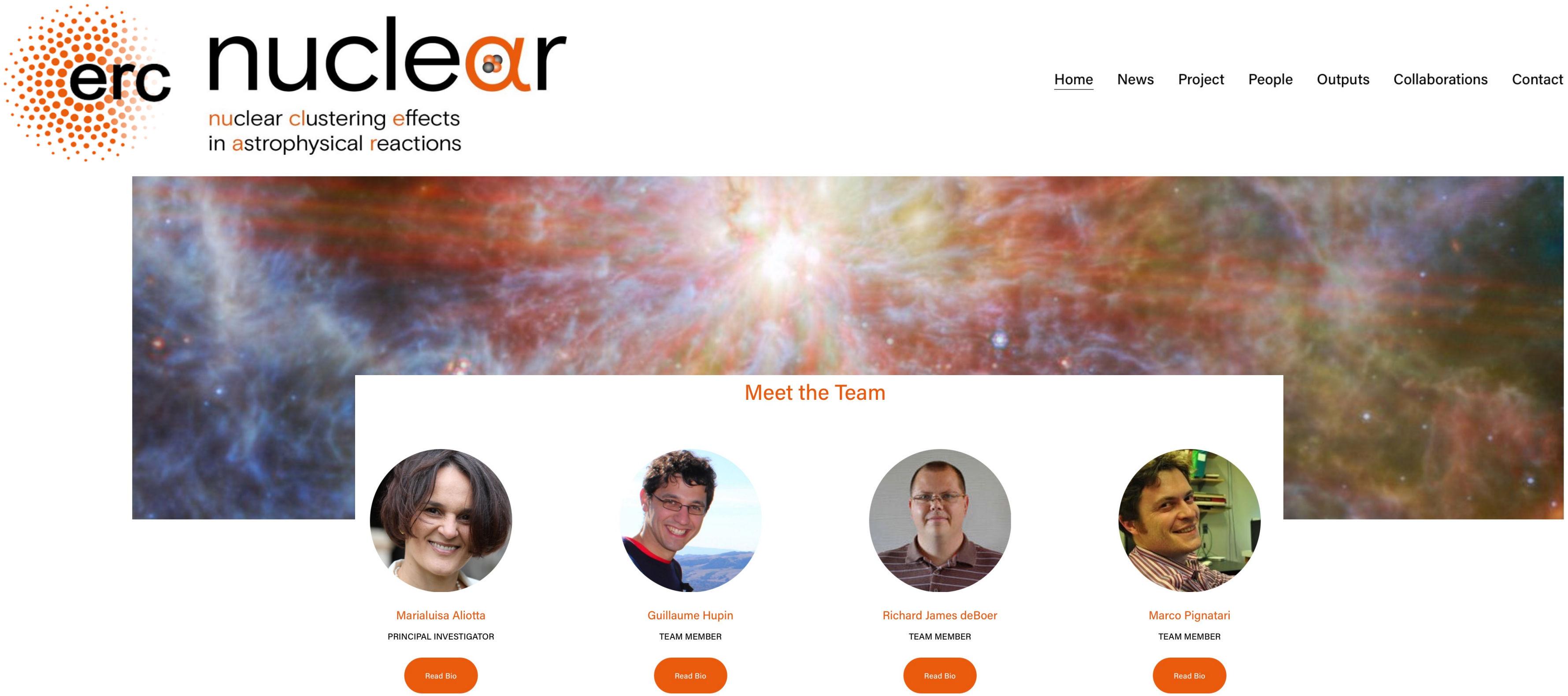

Just recruited: 1 PhD student (December), 1 PDRA Exp (February), 1 PDRA Theo (TBC)

Summary & Outlook

Nuclear Astrophysics a very vibrant research field

much remains to be done with **stable beams**, both at surface and underground facilities

Edinburgh playing a leading role in this area

exciting new results in the future


THANK YOU

the LUNA Collaboration