Nuclear Reactions in Stars:
A Personal Journey through Nuclear Astrophysics

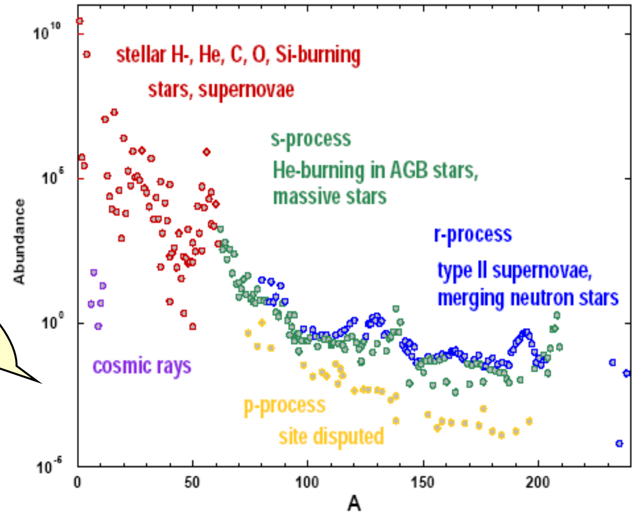
Marialuisa Aliotta
School of Physics and Astronomy - University of Edinburgh, UK
Scottish Universities Physics Alliance

CRC 1660 Kick-off Meeting – Mainz 9-10 December 2024

Nuclear Astrophysics: A truly interdisciplinary field

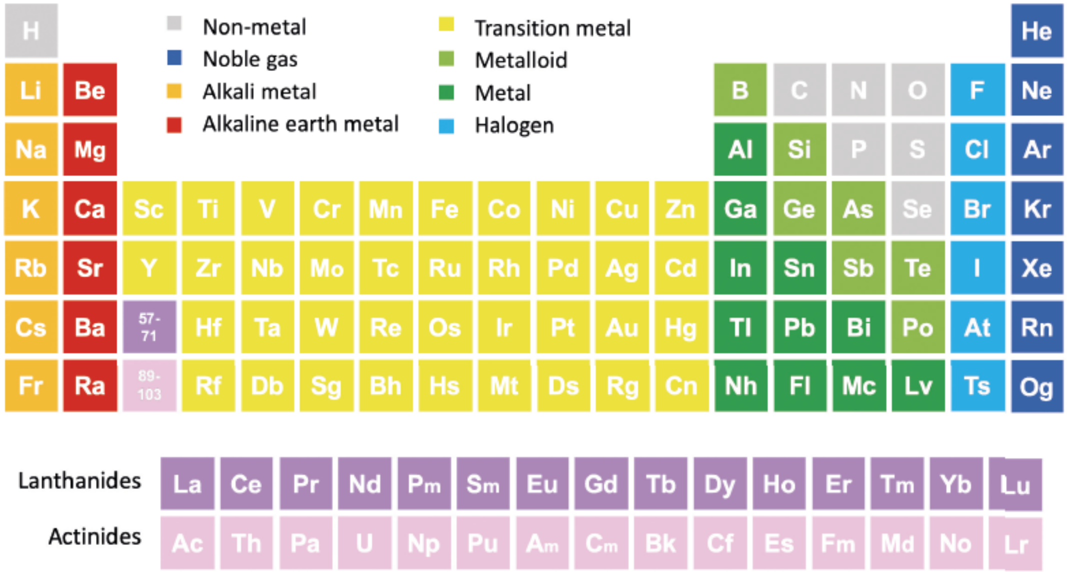
Astrophysics

stellar evolutionary codes
nucleosynthesis calculations
astronomical observations



Nuclear Physics

experimental and
theoretical inputs
stable and exotic nuclei



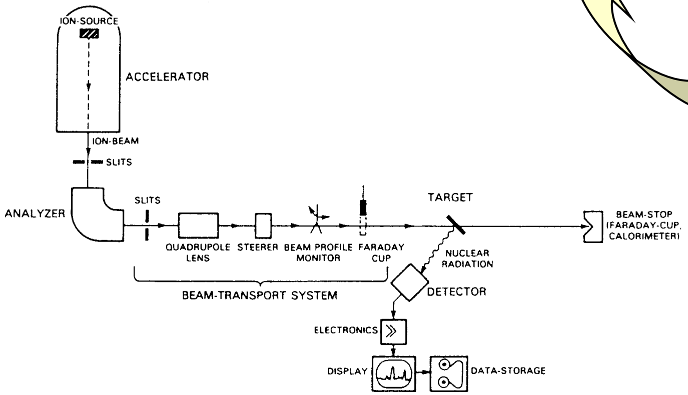
⬜ Non-metal
🟦 Noble gas
🟧 Alkali metal
🟥 Alkaline earth metal
🟨 Transition metal
🟩 Metalloid
🟩 Metal
🟦 Halogen

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	57-71	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	89-103	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og

Lanthanides	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Actinides	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

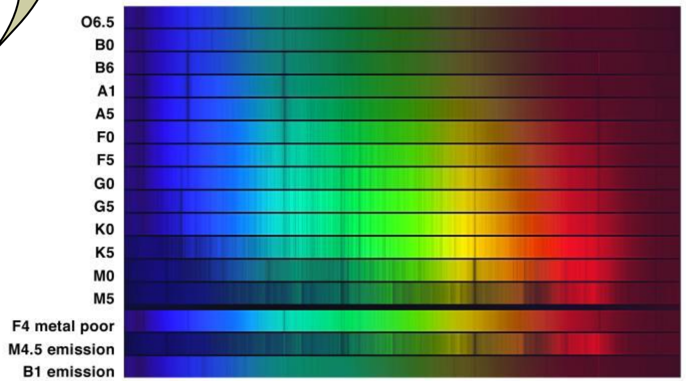
Plasma Physics

degenerate matter
electron screening
equation of state



Atomic Physics

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



University of Catania (founded in 1434)
one of the oldest in the world

1994-1995: Postgraduate Fellowship

Ruhr-Universität Bochum (Germany)

Prof. Claus Rolfs

1996 – 1999: PhD at University of Catania (Italy)

Laboratori Nazionali del Sud (INFN)

PhD Project:

The quasi-free ^{4}He(^{12}C,^{12}C)^{4}He scattering: A test measurement

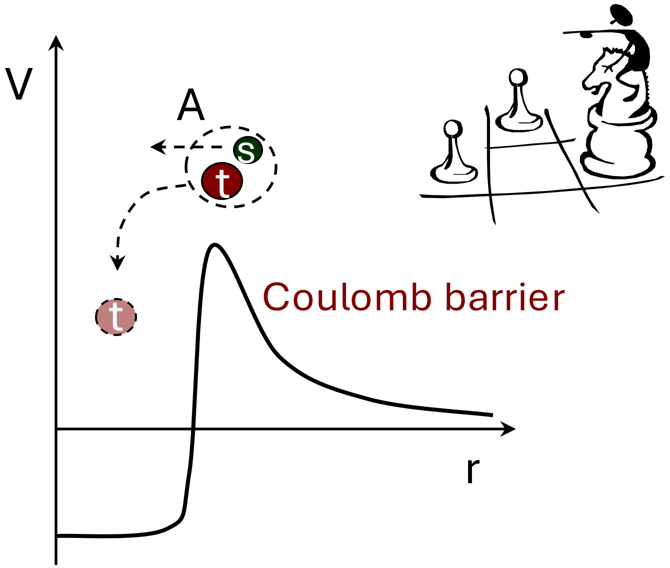
Supervisor
Prof Spitaleri

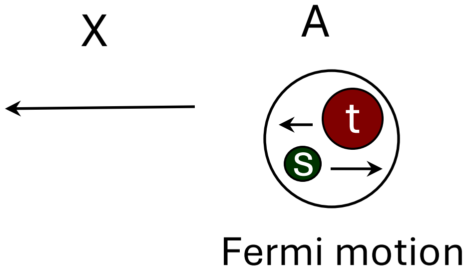
ASFIN Proposal: The ^{12}C(α,γ)^{16}O with the THM

Trojan Horse Method: Basic Idea

Baur (1986)

study a reaction of interest X(t,b)Y using a suitable three-body reaction: X(A,bs)Y with A = t + s





Advantages:

- reaction within nuclear field (‘no’ Coulomb, no screening)
- different projectile-target combinations possible

BUT…

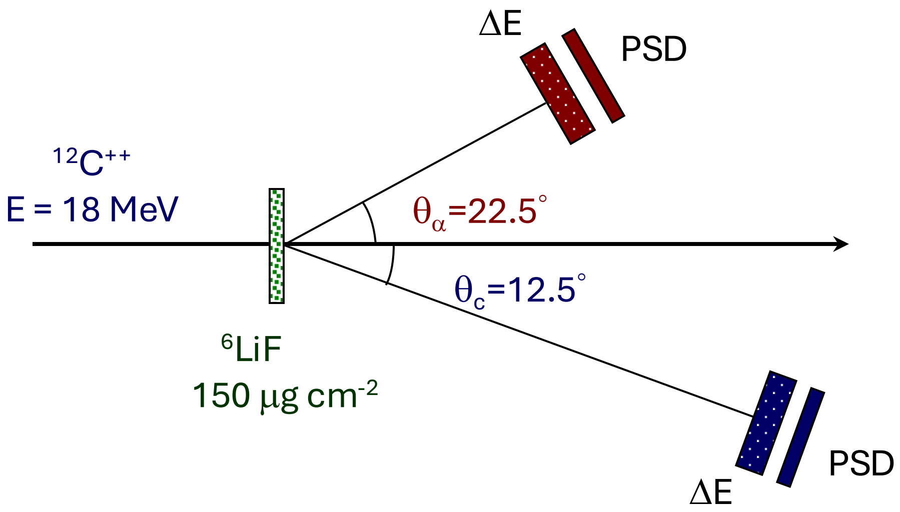
- complex formalism and data analysis
- validity tests required

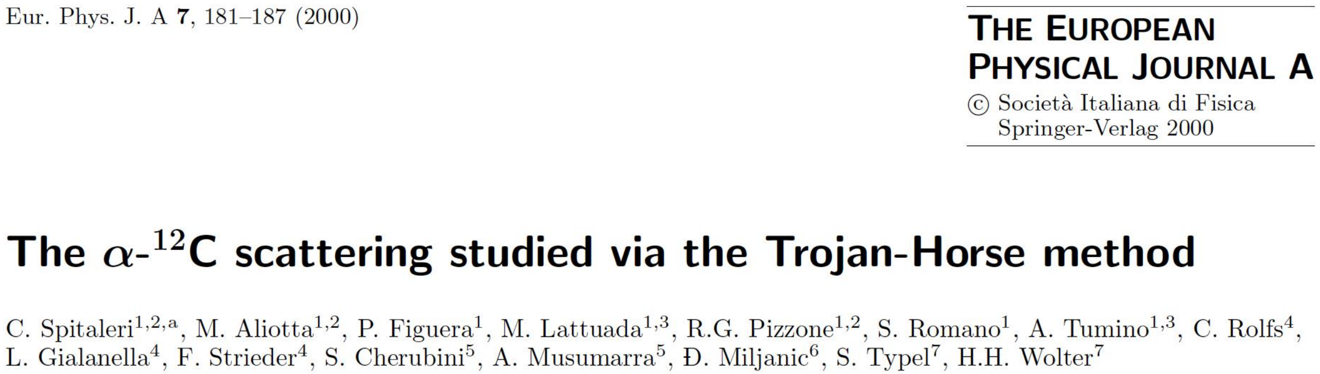
The quasi-free $^{4}He(^{12}C,^{12}C)^{4}He$ scattering: A test measurement

$$^{6}Li(^{12}C,\alpha^{12}C)^{2}H \Leftrightarrow {}^{4}He(^{12}C,^{12}C)^{4}He$$

Experimental setup

Laboratori Nazionali del Sud – Catania

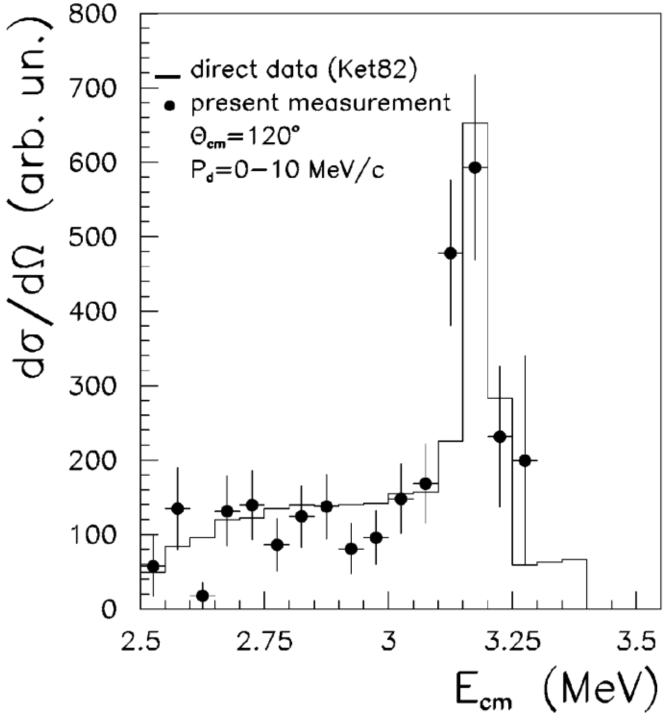



Eur. Phys. J. A 7, 181–187 (2000)

THE EUROPEAN PHYSICAL JOURNAL A

The α-^{12}C scattering studied via the Trojan-Horse method

C. Spitaleri[1,2,a], M. Aliotta[1,2], P. Figuera[1], M. Lattuada[1,3], R.G. Pizzone[1,2], S. Romano[1], A. Tumino[1,3], C. Rolfs[4], L. Gialanella[4], F. Strieder[4], S. Cherubini[5], A. Musumarra[5], Đ. Miljanic[6], S. Typel[7], H.H. Wolter[7]



after much data analysis, checks and cross-checks…

cross section in good agreement with direct data

1999 – 2001: Alexander von Humboldt Fellowship
Ruhr-Universität Bochum (Germany)

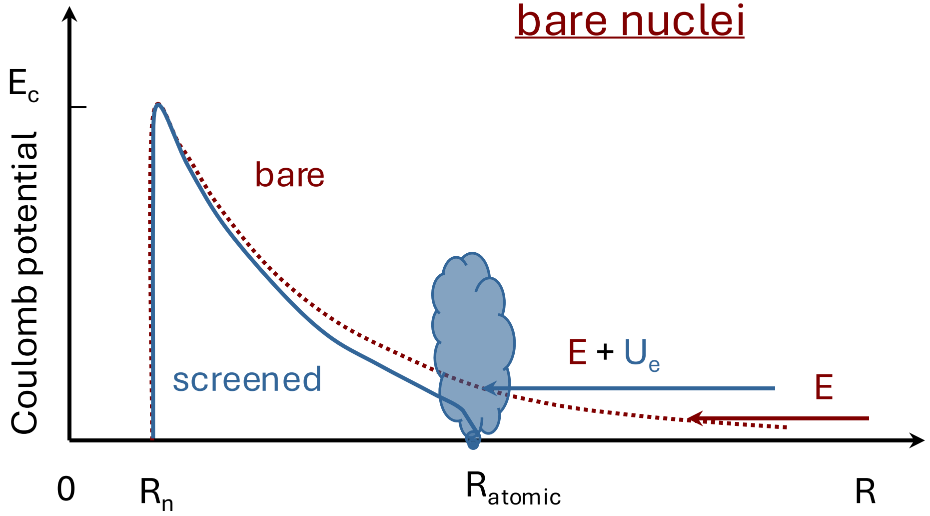
Electron Screening

Electron Screening

$\sigma(E) = \frac{1}{E} \exp(-2\pi\eta)\, S(E)$

assumption: $2\pi\eta \sim Z_1 Z_2 (\mu/E)^{1/2}$

bare nuclei



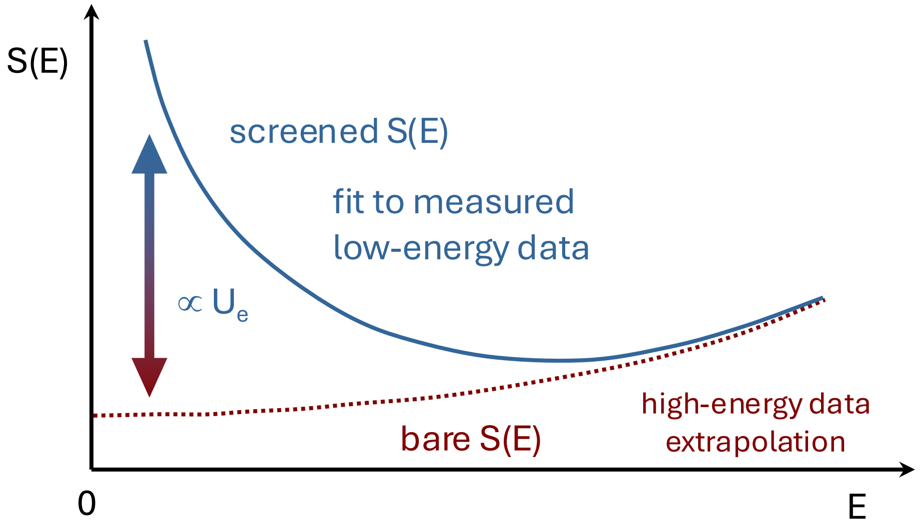
in the lab and in stellar plasmas

interaction affected by electrons

SCREENING POTENTIAL U_e

corrections typically negligible, except at ultra-low energies

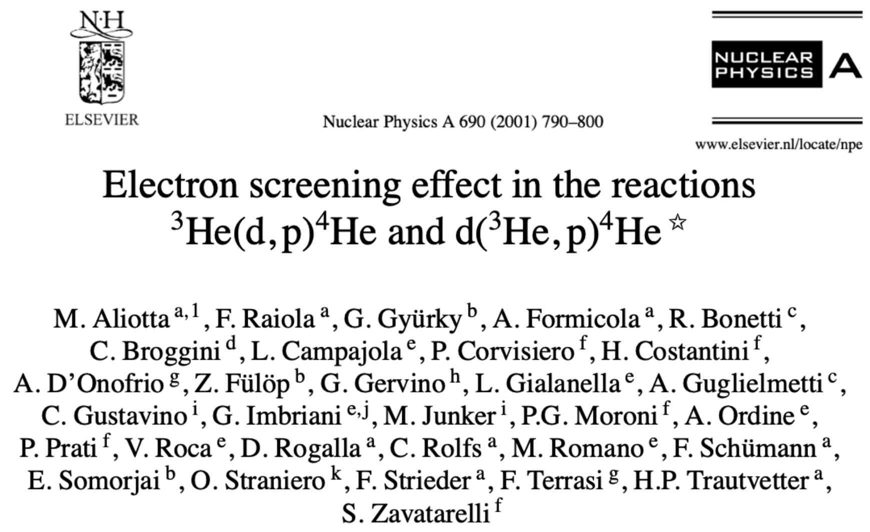
$f_{lab}(E) = \frac{S_{screen}(E)}{S_{bare}(E)} \sim \exp(\pi\eta U_e/E)$



experimental U_e values in excess of theoretical limit !

ELECTRON SCREENING PUZZLE

Electron Screening



ELSEVIER

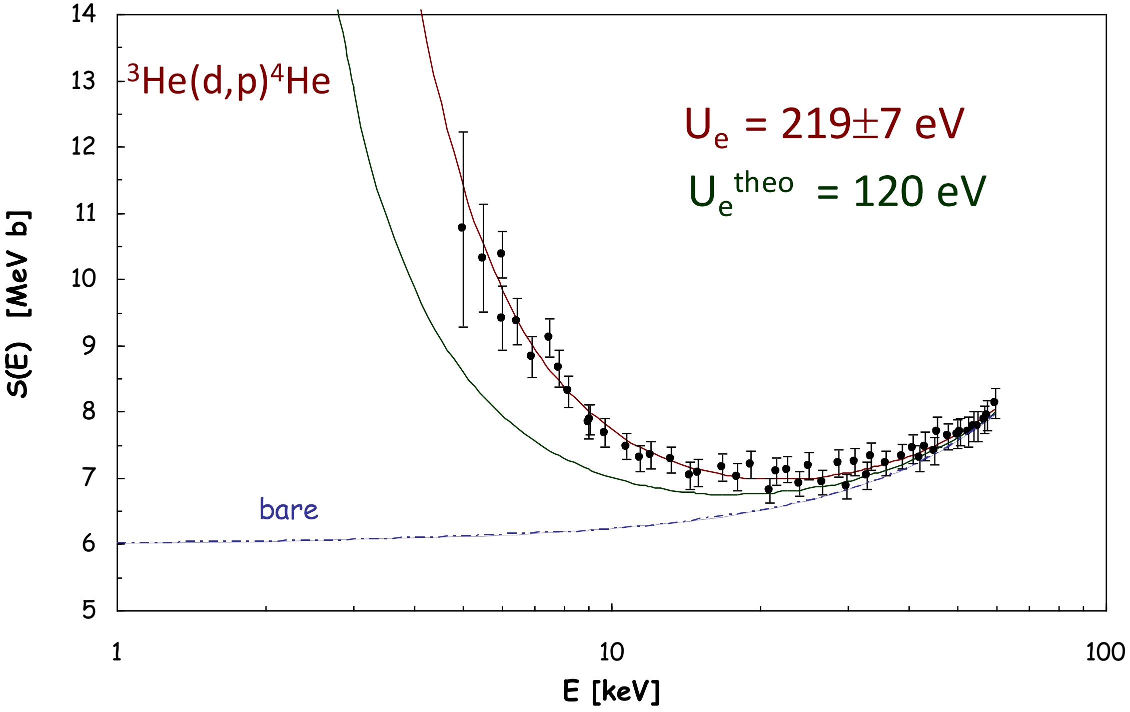
Nuclear Physics A 690 (2001) 790–800

NUCLEAR PHYSICS A

www.elsevier.nl/locate/npe

Electron screening effect in the reactions $^3He(d,p)^4He$ and $d(^3He,p)^4He$ ☆

M. Aliotta[a,1], F. Raiola[a], G. Gyürky[b], A. Formicola[a], R. Bonetti[c], C. Broggini[d], L. Campajola[e], P. Corvisiero[f], H. Costantini[f], A. D'Onofrio[g], Z. Fülöp[b], G. Gervino[h], L. Gialanella[e], A. Guglielmetti[c], C. Gustavino[i], G. Imbriani[e,j], M. Junker[i], P.G. Moroni[f], A. Ordine[e], P. Prati[f], V. Roca[e], D. Rogalla[a], C. Rolfs[a], M. Romano[e], F. Schümann[a], E. Somorjai[b], O. Straniero[k], F. Strieder[a], F. Terrasi[g], H.P. Trautvetter[a], S. Zavatarelli[f]



Eur. Phys. J. A 8, 443–446 (2000)

THE EUROPEAN PHYSICAL JOURNAL A
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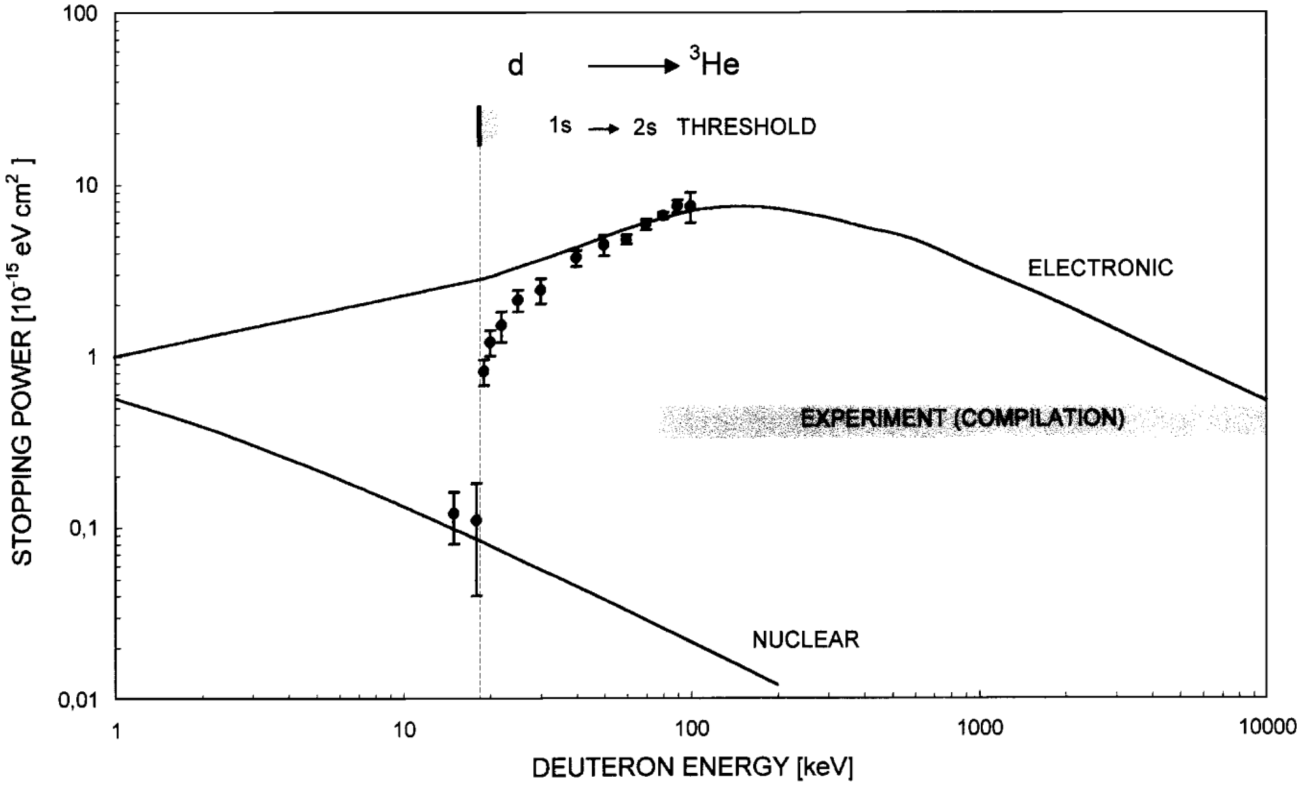
Springer-Verlag 2000

Short note

Energy loss of deuterons in ^3He gas: a threshold effect

A. Formicola[1], M. Aliotta[1,a], G. Gyürky[2], F. Raiola[1], R. Bonetti[3], C. Broggini[4], L. Campajola[5], P. Corvisiero[6], H. Costantini[6], A. D'Onofrio[7], Z. Fülöp[2], G. Gervino[8], L. Gialanella[5], A. Guglielmetti[3], C. Gustavino[9], G. Imbriani[5,10], M. Junker[9], A. Ordine[5], P. Prati[6], V. Roca[5], D. Rogalla[1], C. Rolfs[1,b], M. Romano[5], F. Schümann[1], E. Somorjai[2], O. Straniero[11], F. Strieder[1], F. Terrasi[7], H.P. Trautvetter[1], and S. Zavatarelli[6]

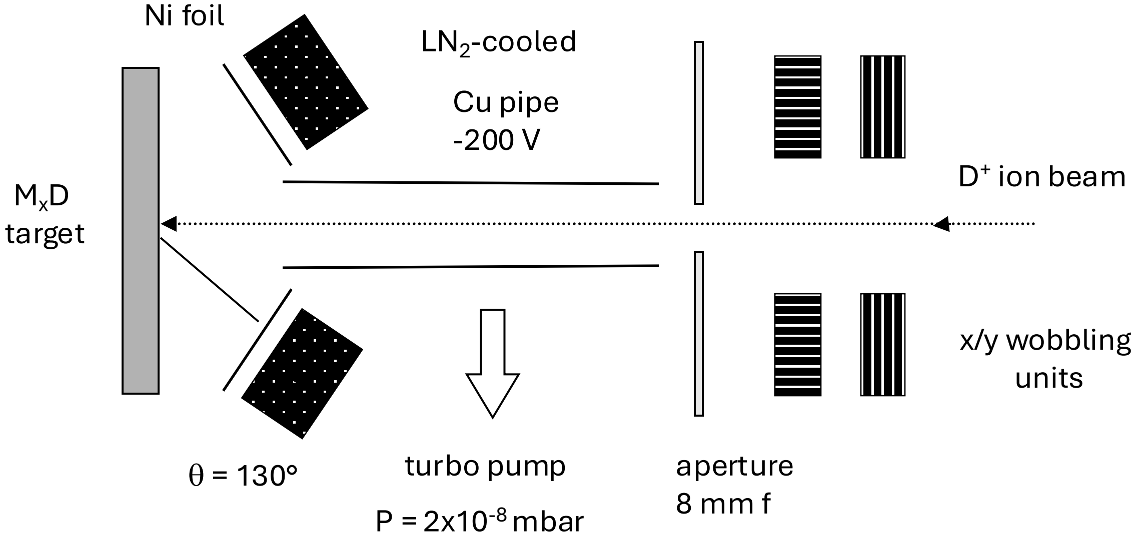


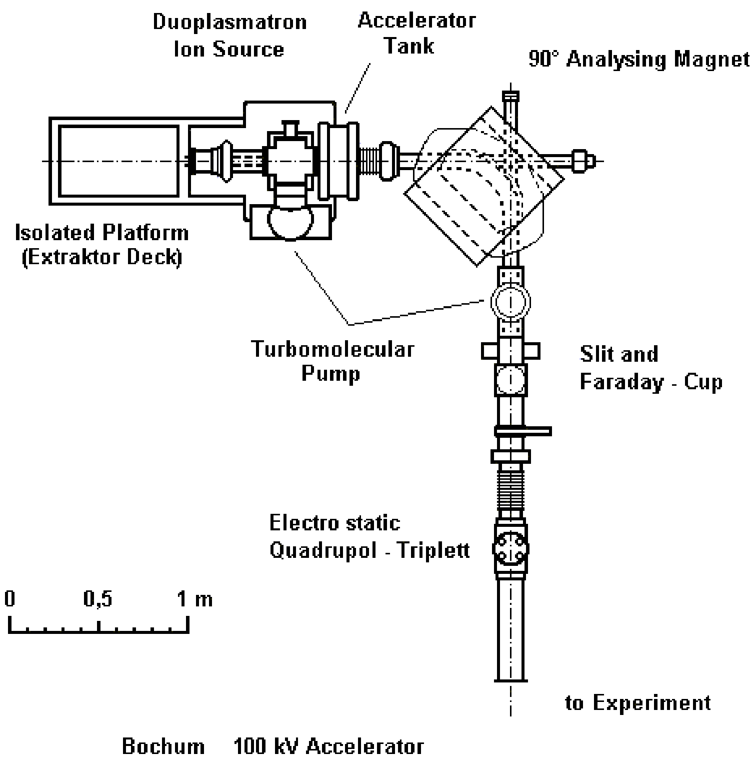
Electron Screening Studies at RUB

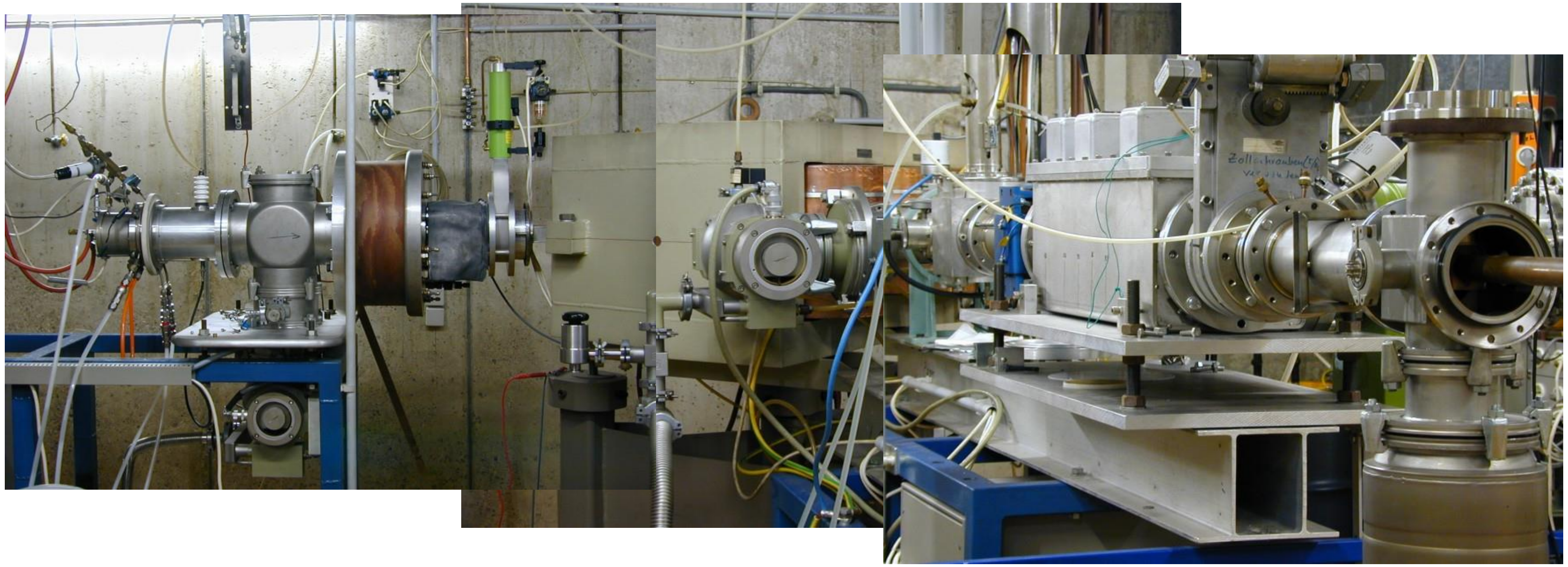
systematic study of

d(d,p)t reaction

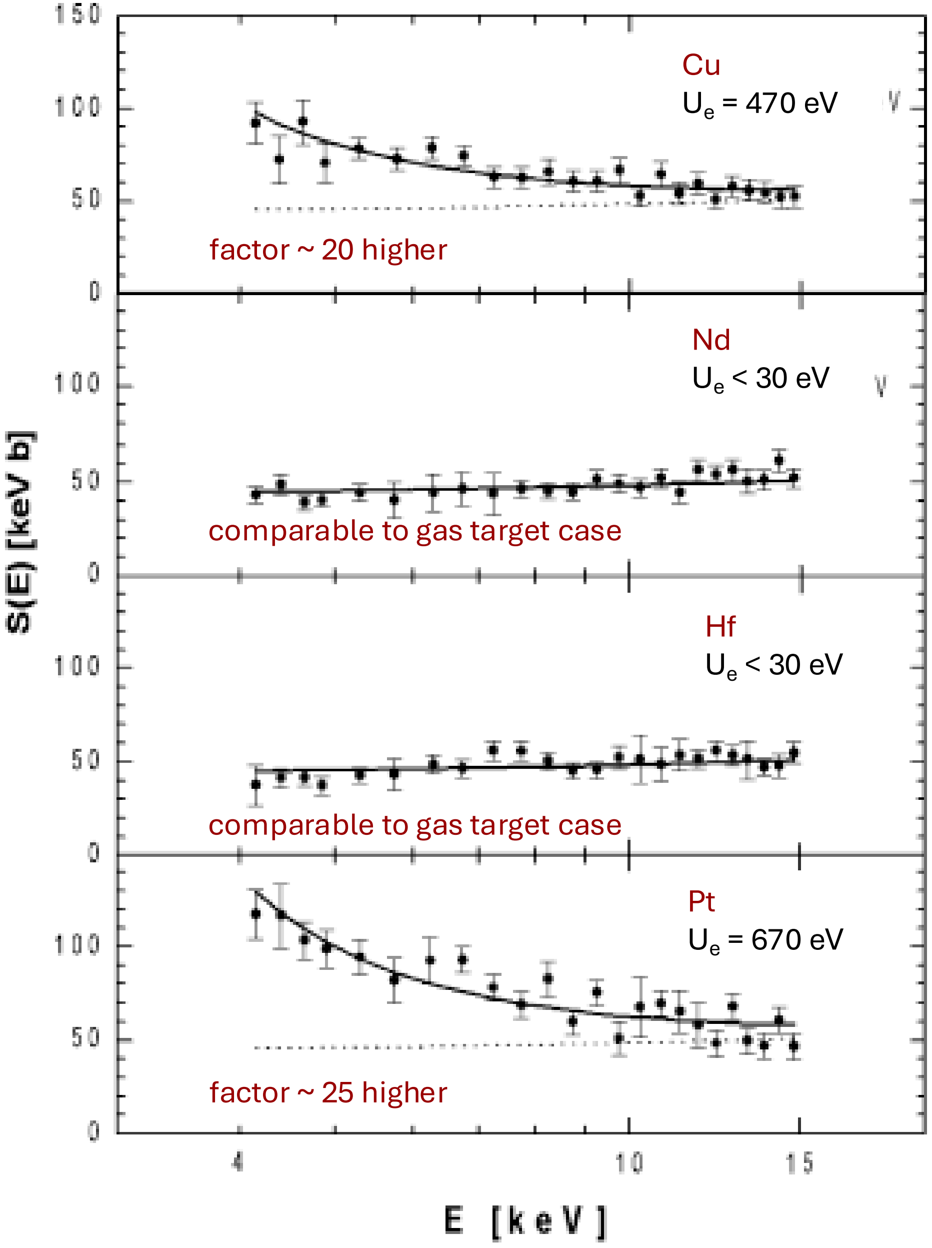
on various hosts







Electron Screening: Anomalous U_e Behaviour for d(d,p)t Reactions in Metals

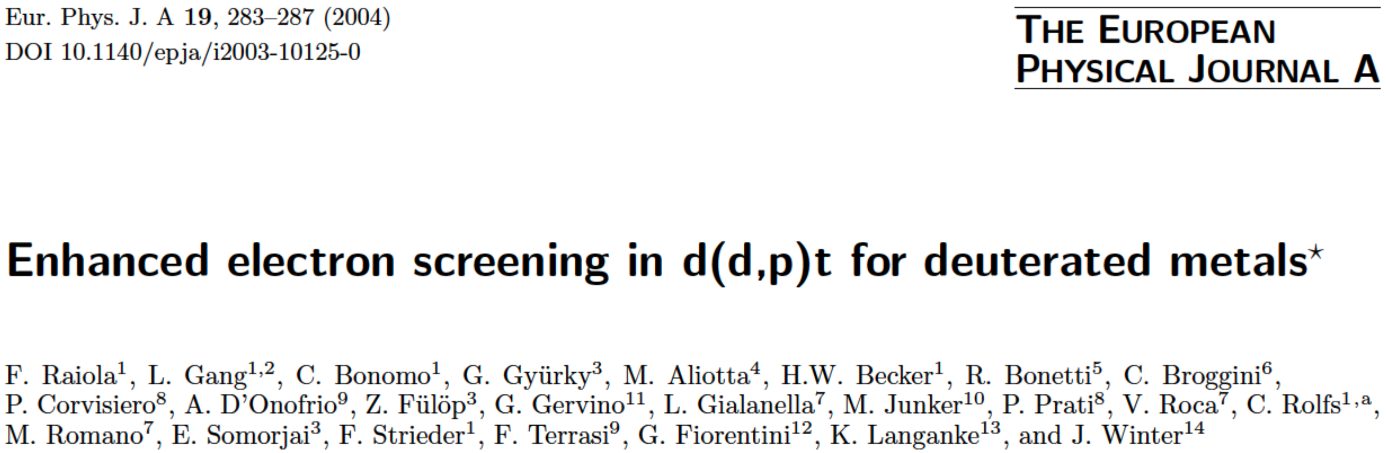


Cu
$U_e = 470$ eV
factor ~ 20 higher

Nd
$U_e < 30$ eV
comparable to gas target case

Hf
$U_e < 30$ eV
comparable to gas target case

Pt
$U_e = 670$ eV
factor ~ 25 higher



Eur. Phys. J. A **19**, 283–287 (2004)
DOI 10.1140/epja/i2003-10125-0

THE EUROPEAN
PHYSICAL JOURNAL A

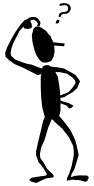
Enhanced electron screening in d(d,p)t for deuterated metals*

F. Raiola[1], L. Gang[1,2], C. Bonomo[1], G. Gyürky[3], M. Aliotta[4], H.W. Becker[1], R. Bonetti[5], C. Broggini[6], P. Corvisiero[8], A. D'Onofrio[9], Z. Fülöp[3], G. Gervino[11], L. Gialanella[7], M. Junker[10], P. Prati[8], V. Roca[7], C. Rolfs[1,a], M. Romano[7], E. Somorjai[3], F. Strieder[1], F. Terrasi[9], G. Fiorentini[12], K. Langanke[13], and J. Winter[14]

compared to screening in gas D_2 target ($U_e \cong 30$ eV)

anomalous enhancements observed for

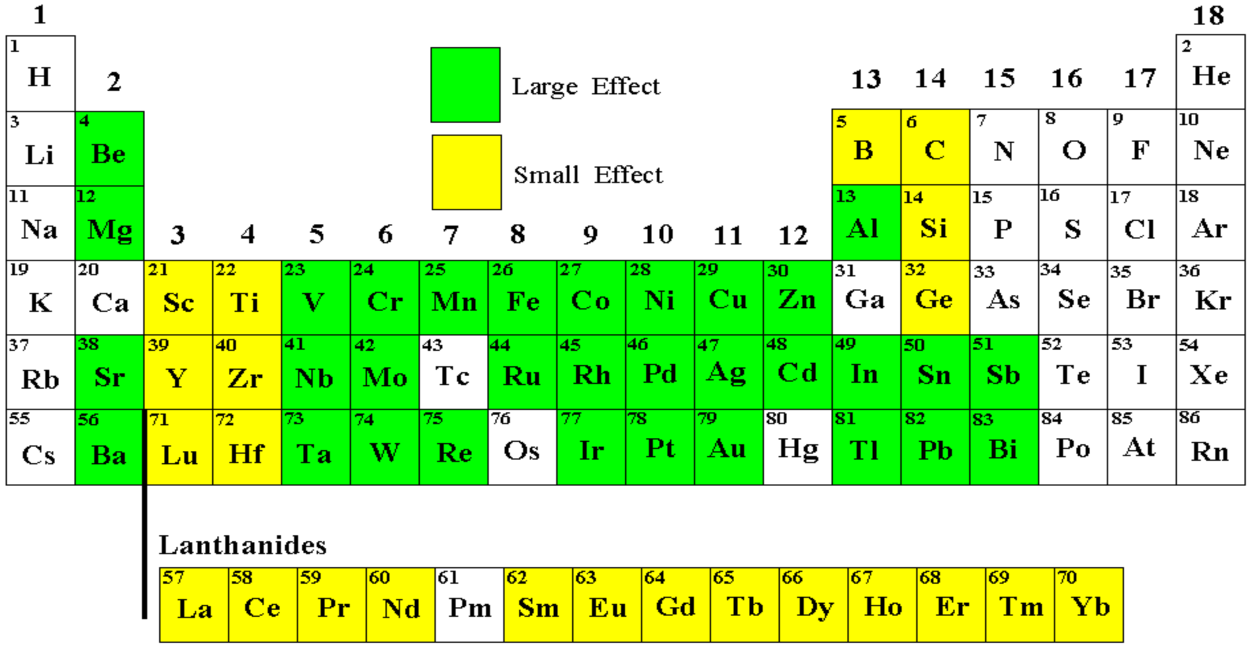
some materials but not for others



WHY?

Electron Screening

55 samples
in total



F. Raiola et al.: Eur. Phys. J A19 (2004) 283

Key Results:

- elements in same group show similar U_e values
  - large effect ~ 300 eV
  - small effect ~ 30 eV
- exceptions: group 13 (B = metalloid) and group 14 (C, Si, Ge = semiconductors)

2001: Lectureship at the University of Edinburgh

2008: Senior Lecturer

2013: Reader

2016: Full Professor

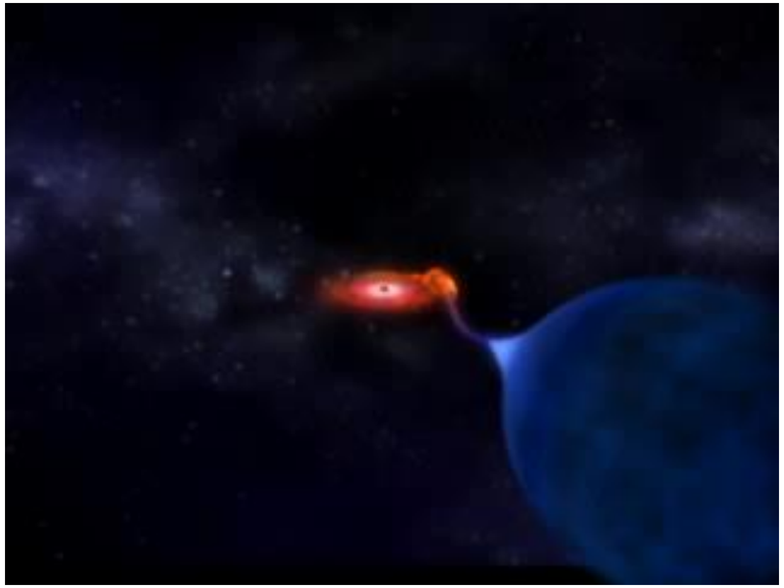
2021 – present: Head of Nuclear Physics Group

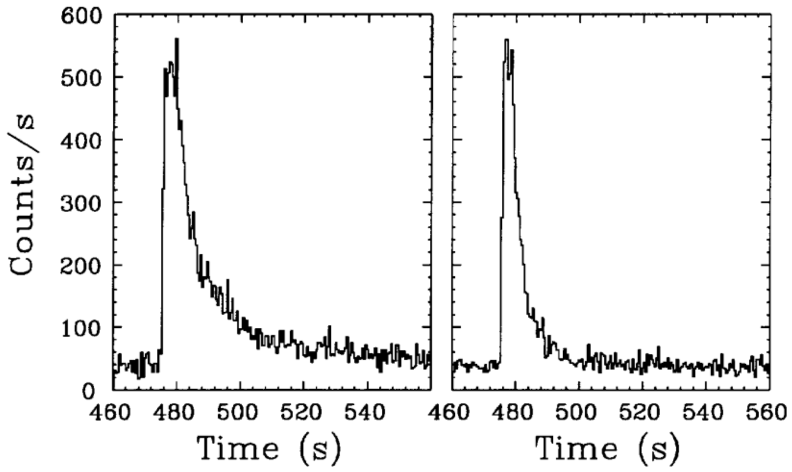
School of Physics and Astronomy
James Clerk Maxwell Building

Nuclear Astrophysics with Radioactive Ion Beams

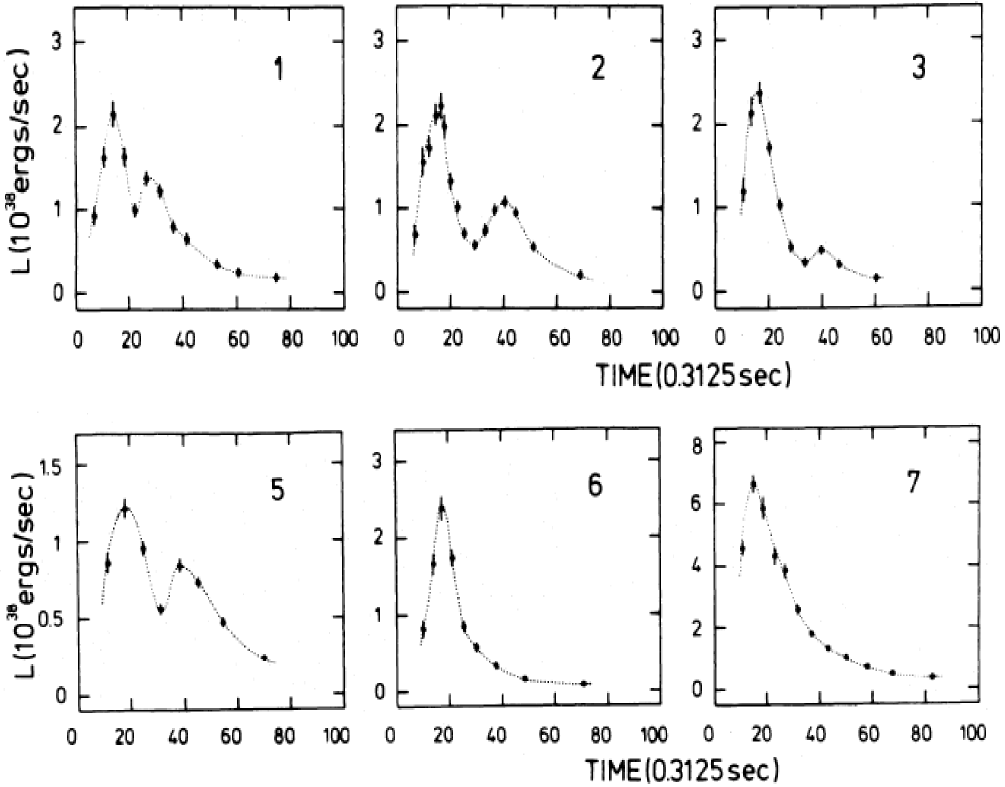
X-ray bursts

thermonuclear explosion in binary systems with neutron star + LEC





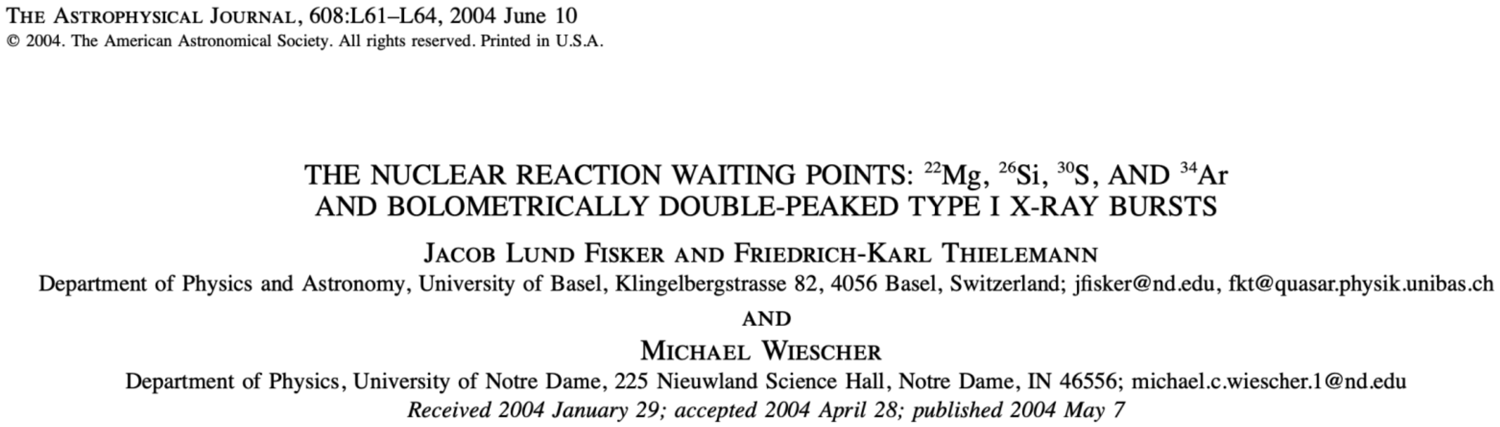
some Type I X-ray bursts show double peak in luminosity separated by a few seconds



Szatjano et al. ApJ 299 (1985) 487-495

origin of double-peak structures unclear

X-ray bursts



The Astrophysical Journal, 608:L61–L64, 2004 June 10

THE NUCLEAR REACTION WAITING POINTS: ^{22}Mg, ^{26}Si, ^{30}S, AND ^{34}Ar AND BOLOMETRICALLY DOUBLE-PEAKED TYPE I X-RAY BURSTS

Jacob Lund Fisker and Friedrich-Karl Thielemann
Department of Physics and Astronomy, University of Basel, Klingelbergstrasse 82, 4056 Basel, Switzerland; jfisker@nd.edu, fkt@quasar.physik.unibas.ch
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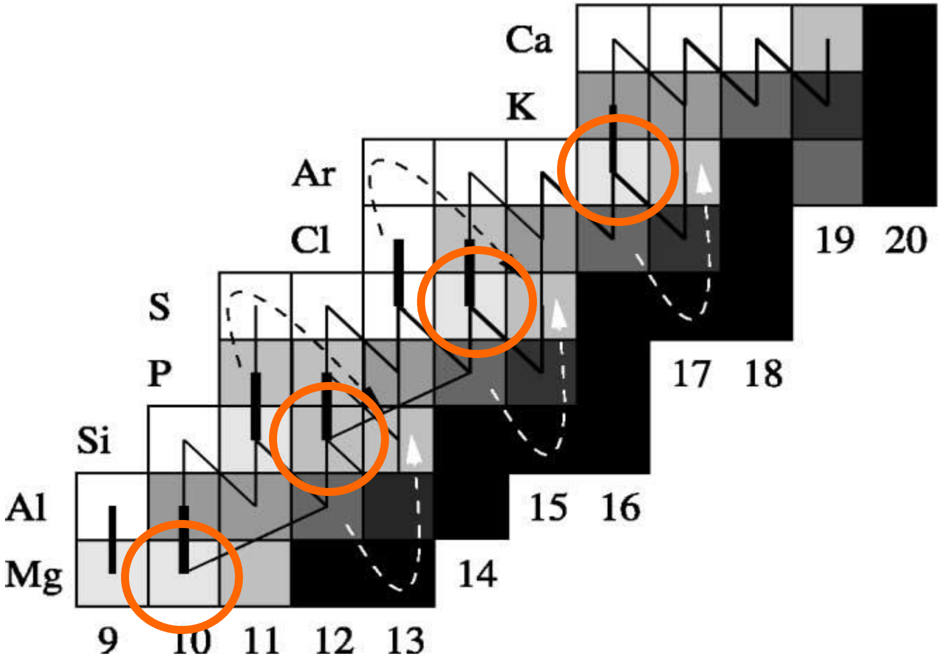


possible cause: waiting points in thermonuclear reaction flow ?

waiting points: ^{22}Mg, ^{26}Si, ^{30}S, and ^{34}Ar ?

(p,γ)-reaction quenched by photodisintegration

(α,p) reactions too weak because of Coulomb barrier

short-lived unstable nuclei

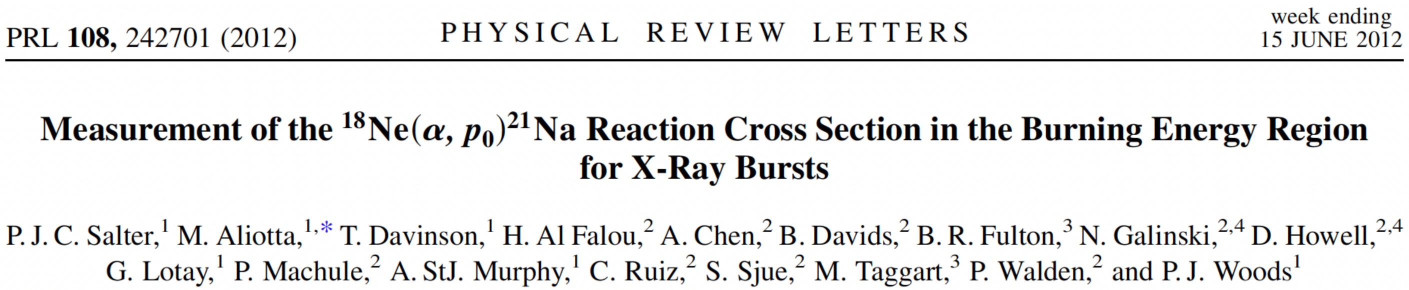
	^{22}Mg,	^{26}Si,	^{30}S,	and ^{34}Ar
$T_{1/2}$ (s)	3.9	2.2	1.18	0.8

However: no relevant RIBs available at that time...

^{18}Ne(α,p)^{21}Na breakout from HCNO cycle

by time reversal approach: ^{21}Na(p,α)^{18}Ne as proof of principle for further (α,p) reactions

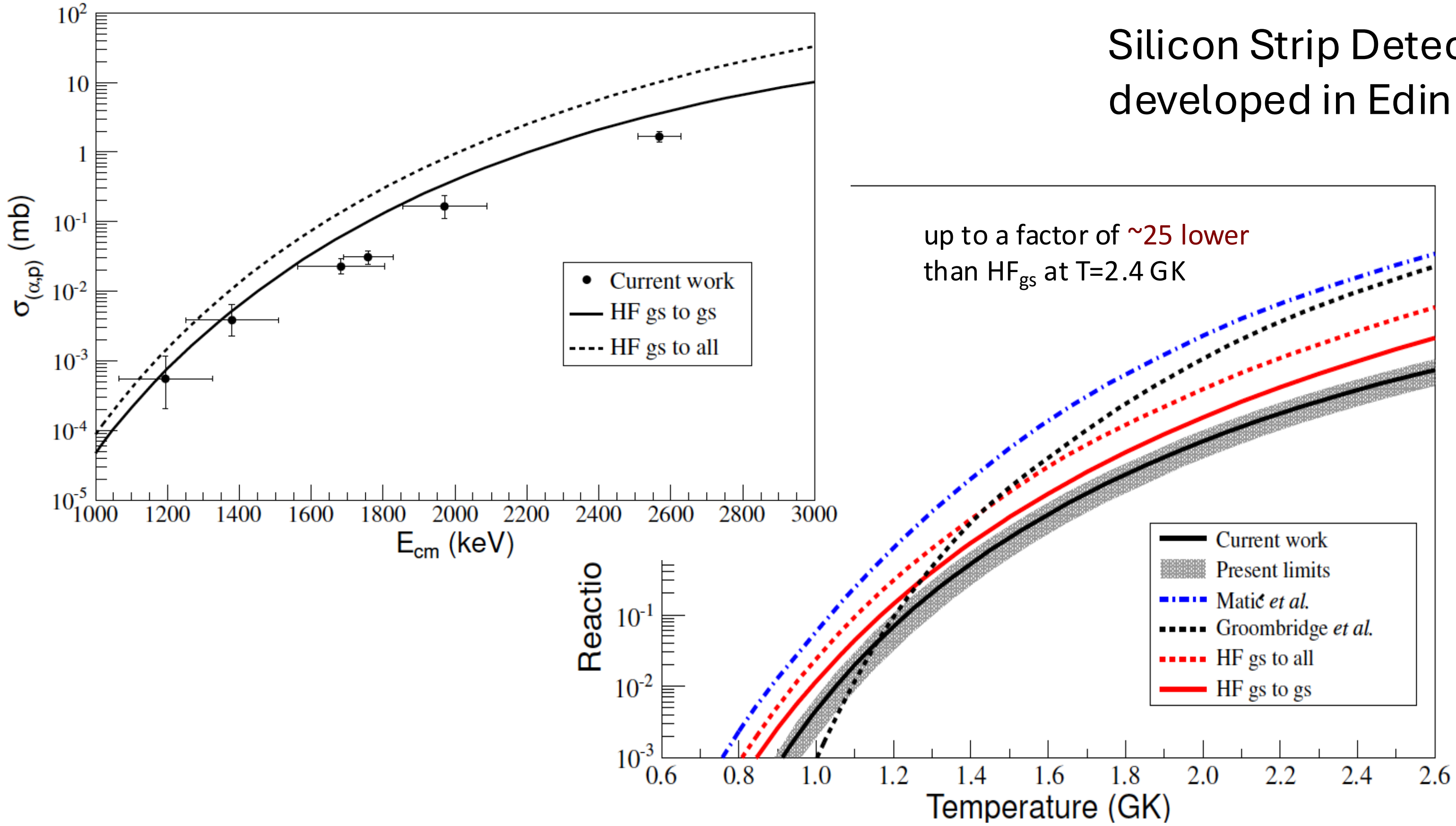
X-ray bursts



PRL **108,** 242701 (2012) PHYSICAL REVIEW LETTERS week ending 15 JUNE 2012

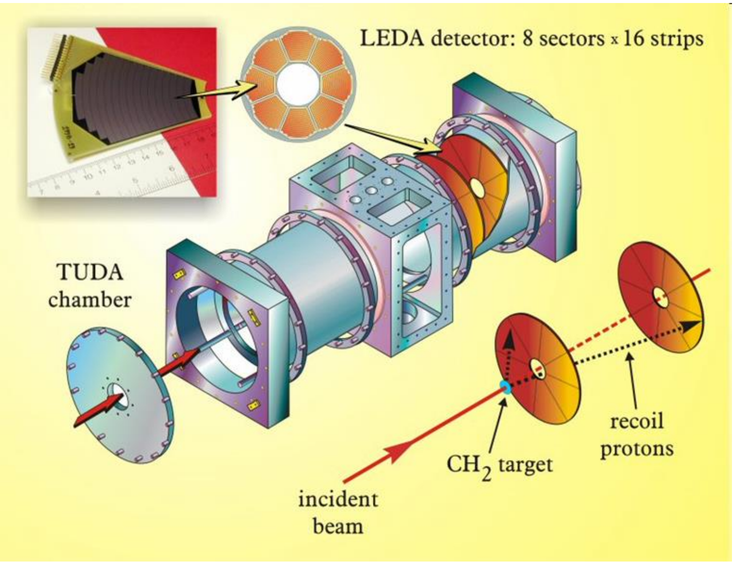
Measurement of the ^{18}Ne(α, p_0)^{21}Na Reaction Cross Section in the Burning Energy Region for X-Ray Bursts

P. J. C. Salter,[1] M. Aliotta,[1,*] T. Davinson,[1] H. Al Falou,[2] A. Chen,[2] B. Davids,[2] B. R. Fulton,[3] N. Galinski,[2,4] D. Howell,[2,4] G. Lotay,[1] P. Machule,[2] A. StJ. Murphy,[1] C. Ruiz,[2] S. Sjue,[2] M. Taggart,[3] P. Walden,[2] and P. J. Woods[1]



up to a factor of ~25 lower than HF_{gs} at T=2.4 GK

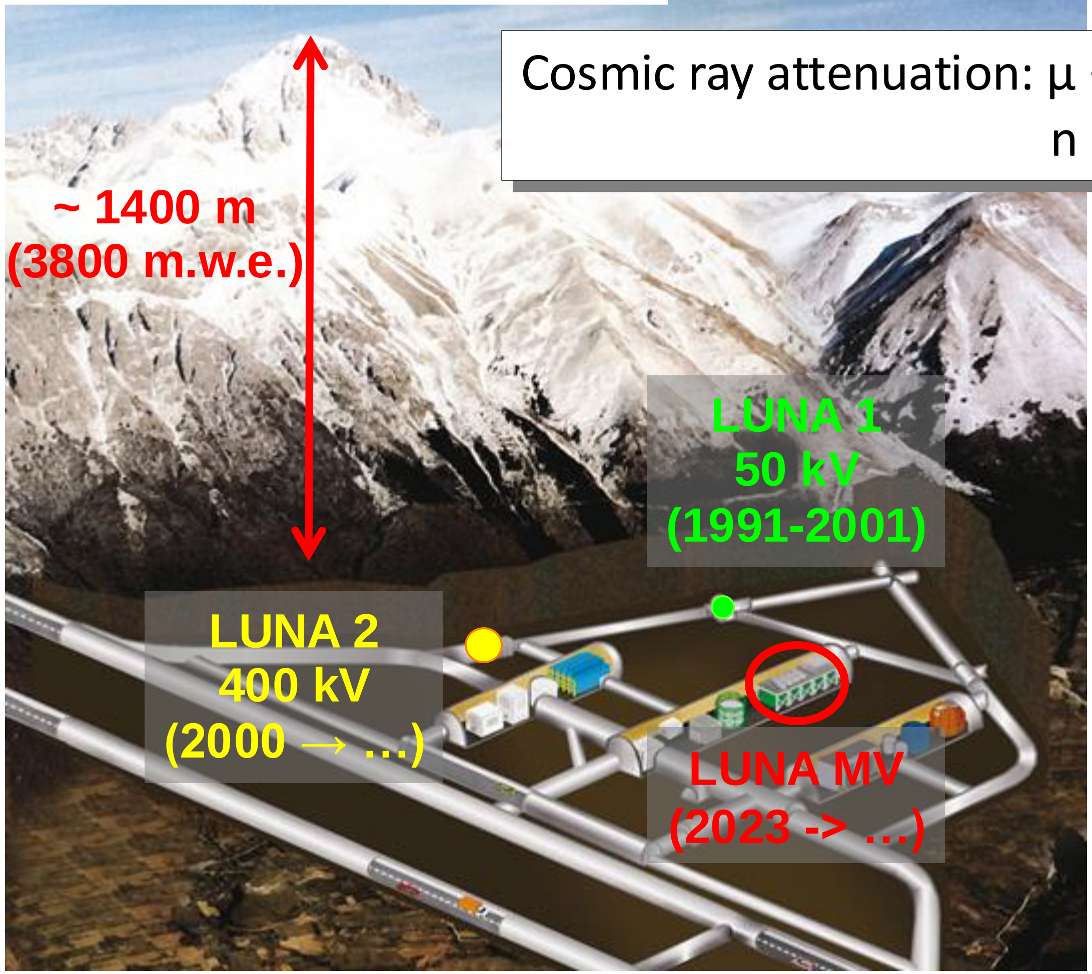
Silicon Strip Detectors developed in Edinburgh



Nuclear Astrophysics with Stable Beams Underground

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

Laboratori Nazionali del Gran Sasso, INFN



~ 1400 m
(3800 m.w.e.)

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

LUNA 1
50 kV
(1991-2001)

LUNA 2
400 kV
(2000 → …)

LUNA MV
(2023 -> …)

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

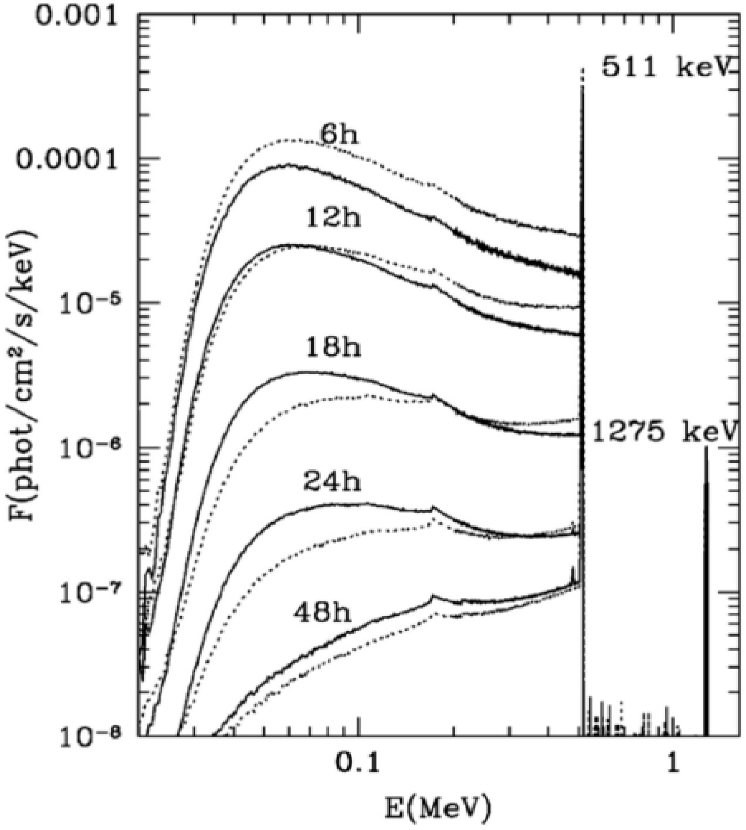
- **solar fusion reactions**
  $^{3}He(^{3}He,2p)^{4}He$ $^{2}H(p,\gamma)^{3}He$ $^{3}He(\alpha,\gamma)^{7}Be$
- **electron screening and stopping power**
  $^{2}H(^{3}He,p)^{4}He$ $^{3}He(^{2}H,p)^{4}He$
- **CNO, Ne-Na and Mg-Al cycles**
  $^{12,13}C(p,\gamma)^{13,14}N$ $^{14,15}N(p,\gamma)^{15,16}O$ $^{16}O(p,\gamma)^{17}F$ $^{20,21,22}Ne(p,\gamma)^{21,22,23}Na$ $^{22}Ne(\alpha,\gamma)^{26}Mg$ $^{23}Na(p,\gamma)^{24}Mg$ $^{25}Mg(p,\gamma)^{26}Al$
- **(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)

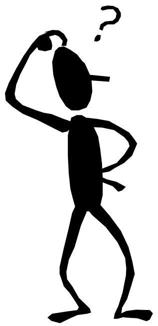
The $^{17}O(p,\gamma)^{18}F$ Reaction in Classical Novae

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

can provide constraints on novae nucleosynthesis



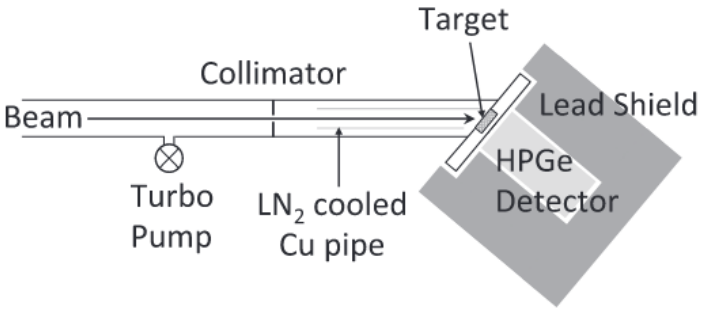
can be detected by
space-borne telescopes

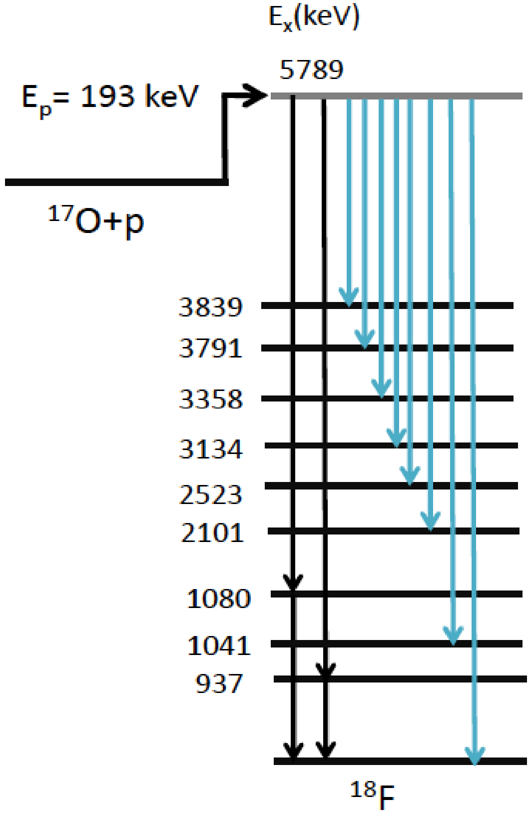


no 511 keV radiation observed to date!
uncertain $^{17}O(p,\gamma)^{18}F$ rate?

David Scott's
PhD project

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

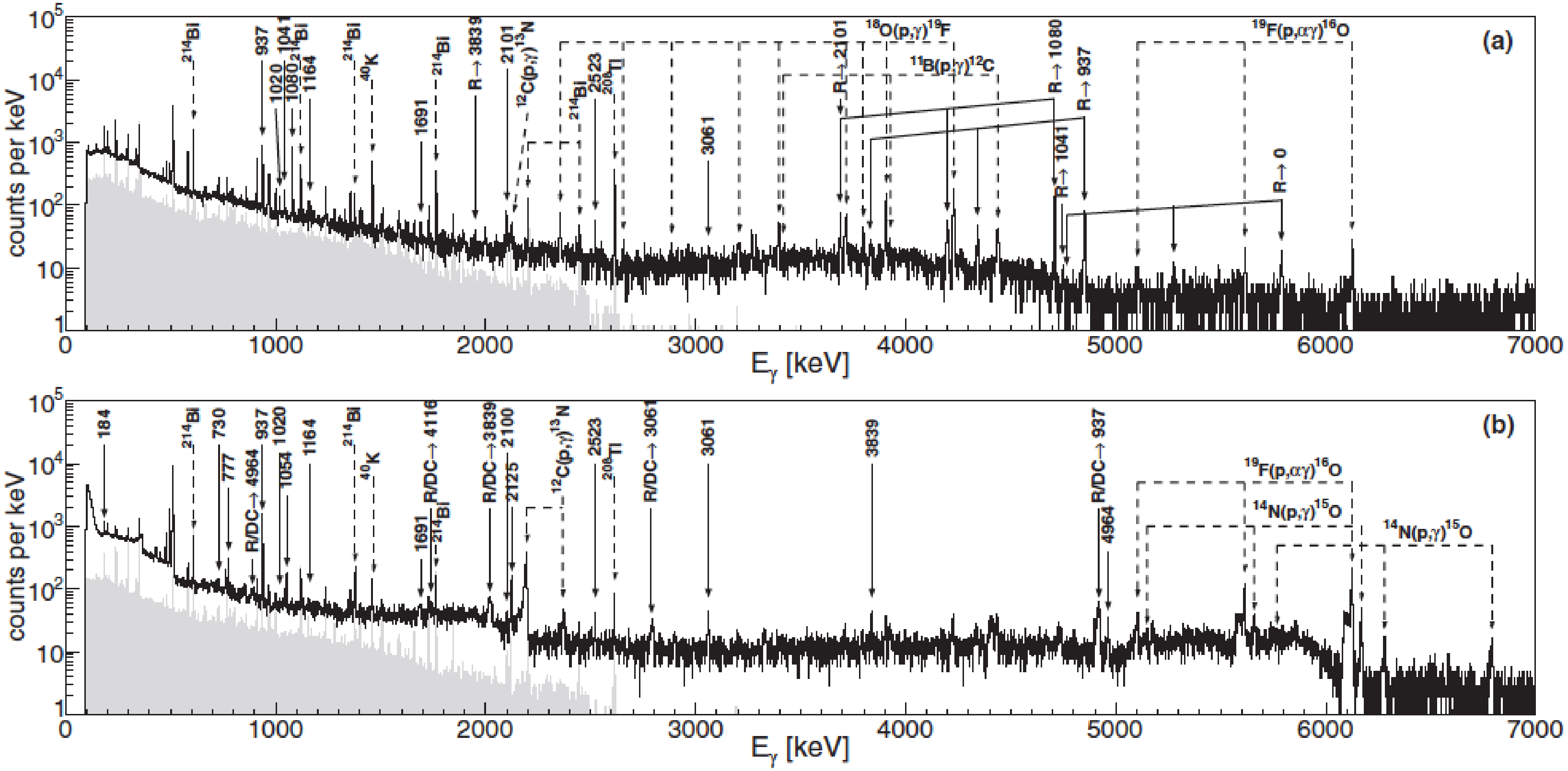
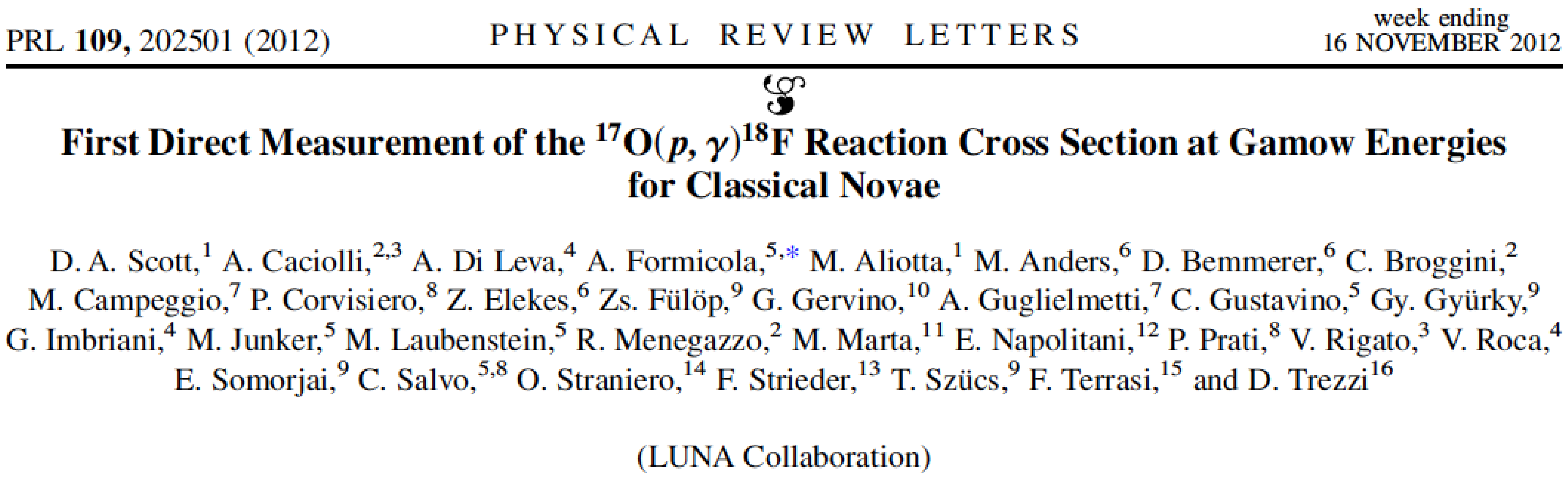


FIG. 5. (a) Sample spectrum of an on-resonance measurement at energy $E_{c.m.} = 183$ keV. (b) Sample spectrum for an off-resonance measurement at $E_{c.m.} = 250$ keV. In gray is the time-normalized room background with 10 cm of lead surrounding the detector.

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



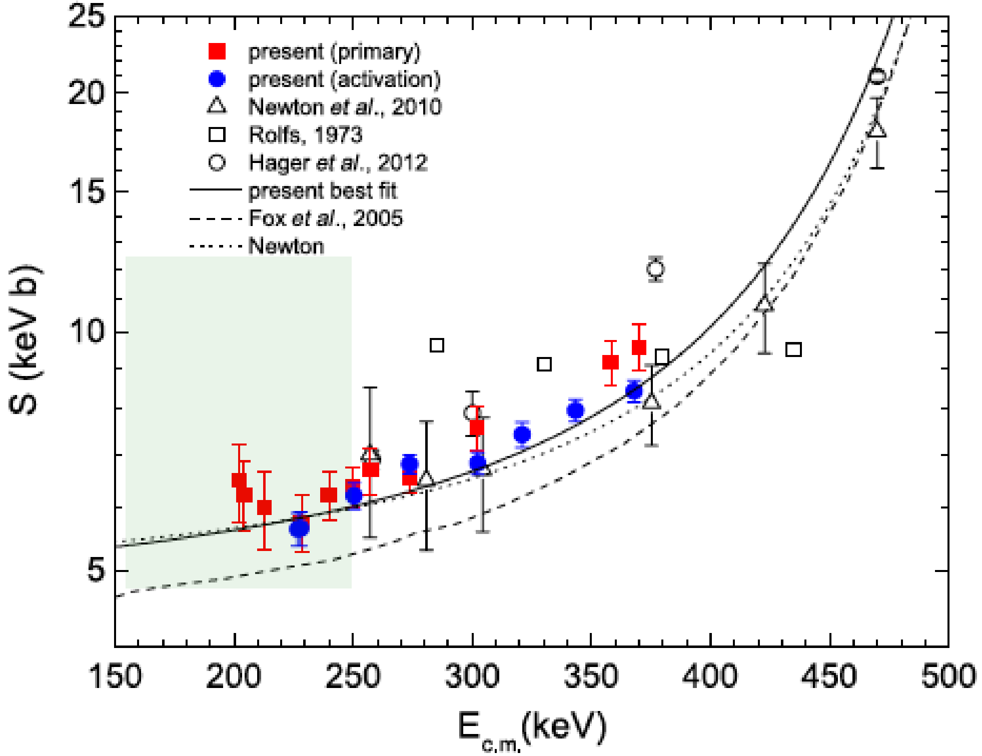
PRL **109,** 202501 (2012) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2012

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

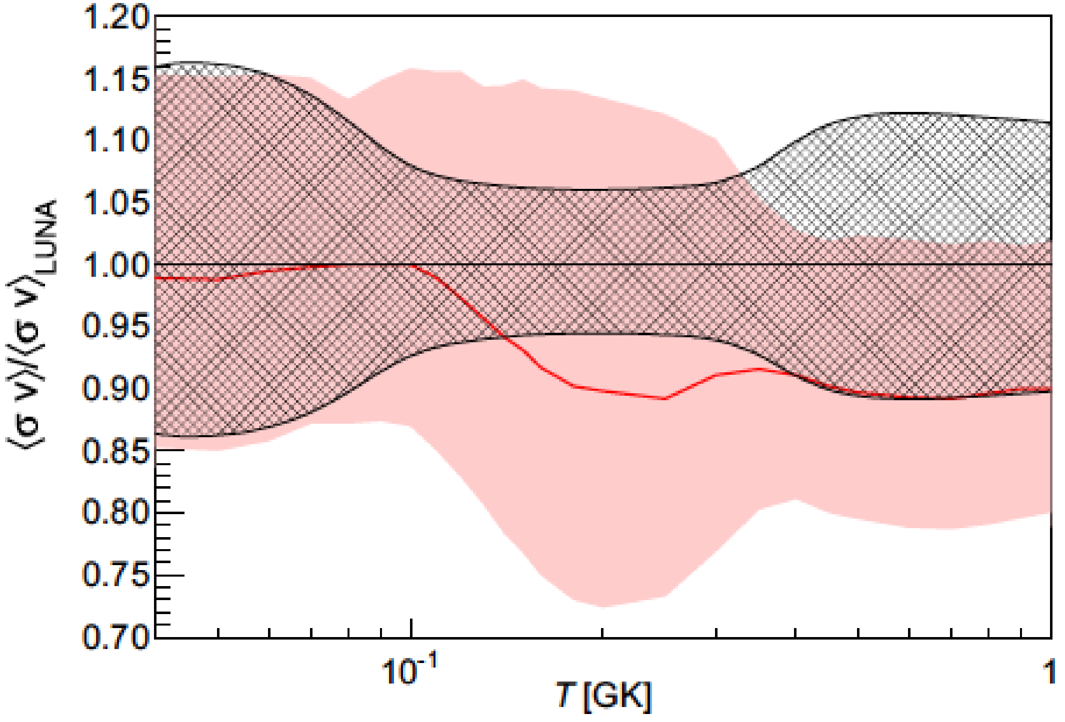


firmer constraints on amount of ^{18}F produced in novae

↓

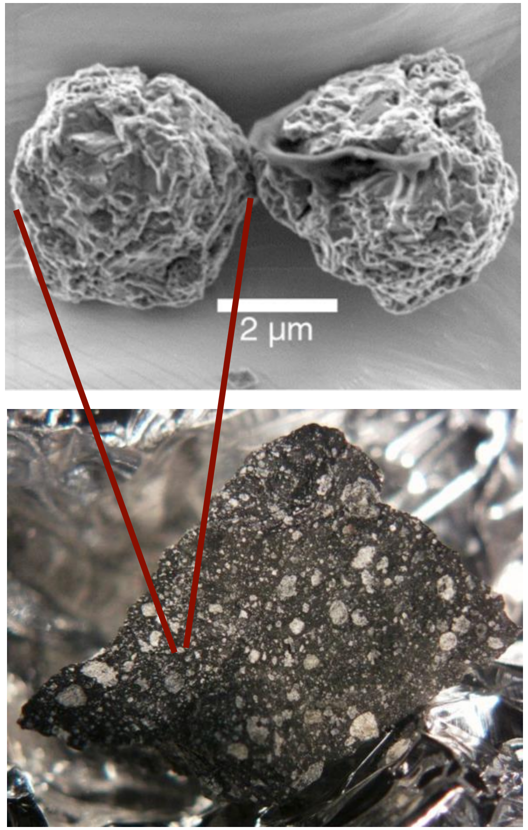
new limits to satellite detection of 511keV γ rays

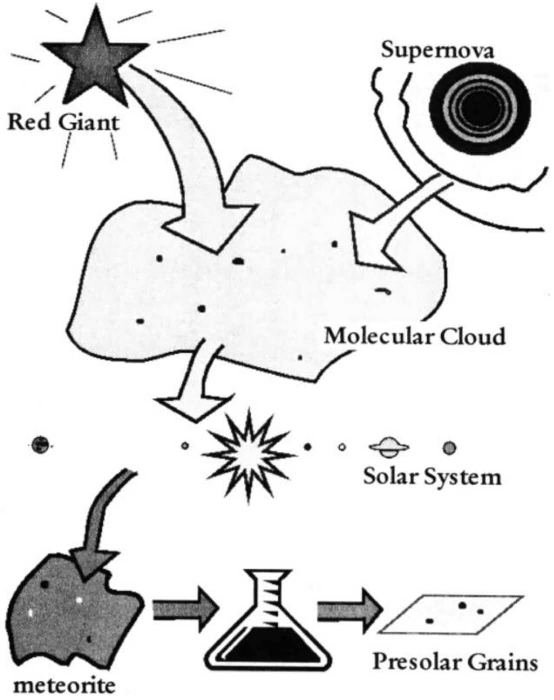
improved reaction rate



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

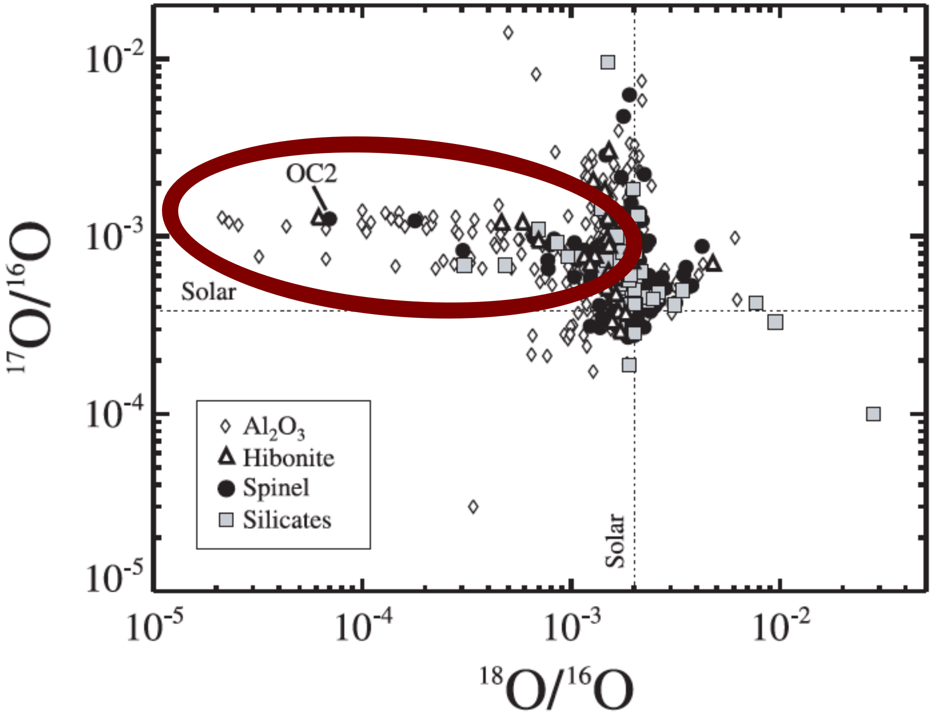
Pre-solar grains: stellar dust trapped in meteorites





isotopic anomalies can reveal
clues on site of formation

puzzling origin of Oxygen-rich grains

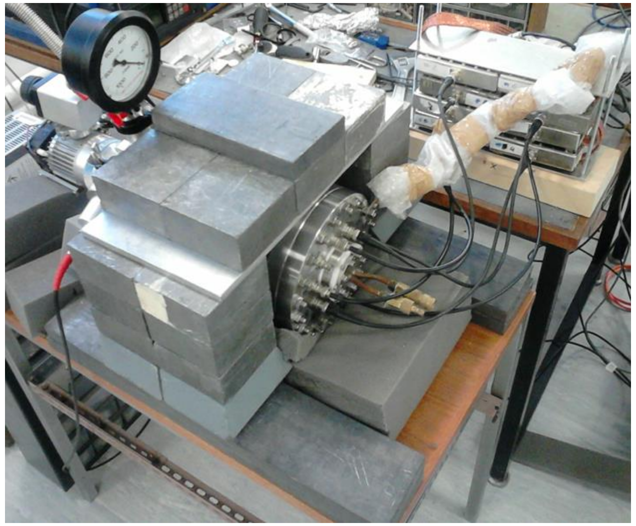


improved knowledge on
^{17}O(p,α)^{14}N reaction needed

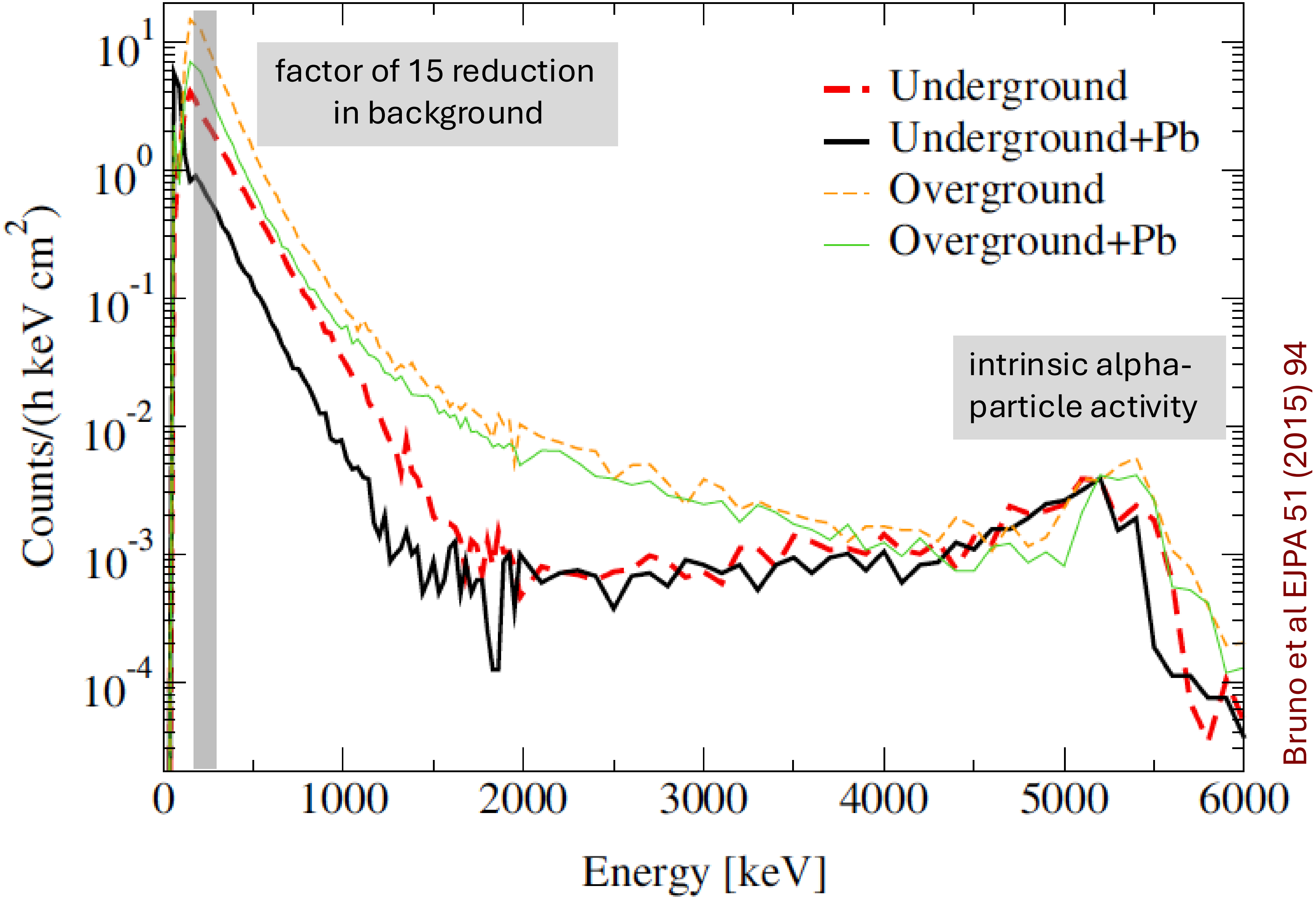
Carlo Bruno's
PhD project

Background Suppression

Edinburgh



Gran Sasso

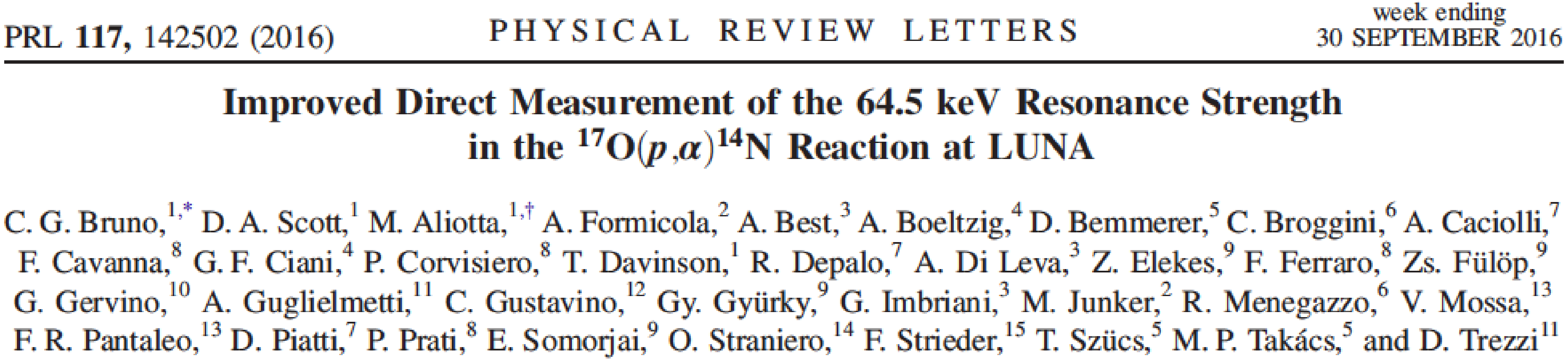


factor of 15 reduction in background

intrinsic alpha-particle activity

Bruno et al EJPA 51 (2015) 94

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

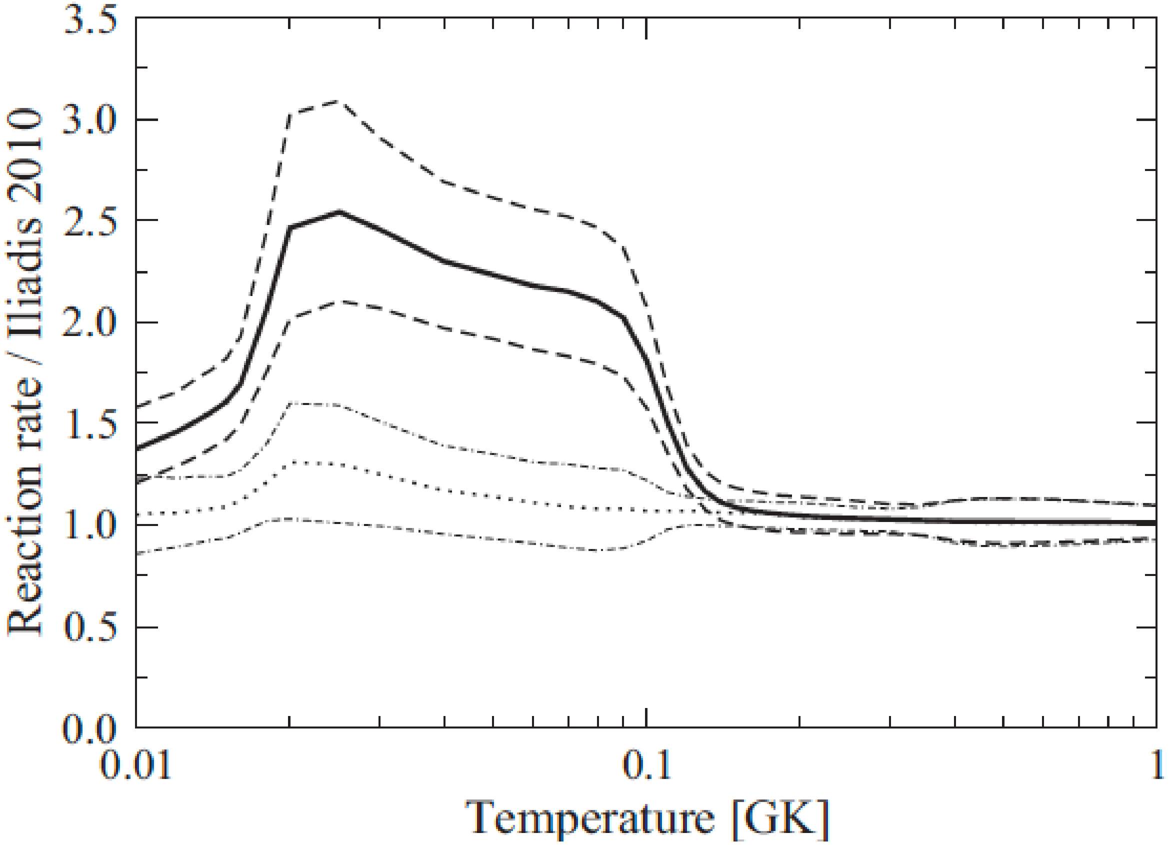


PRL **117,** 142502 (2016) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2016

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]

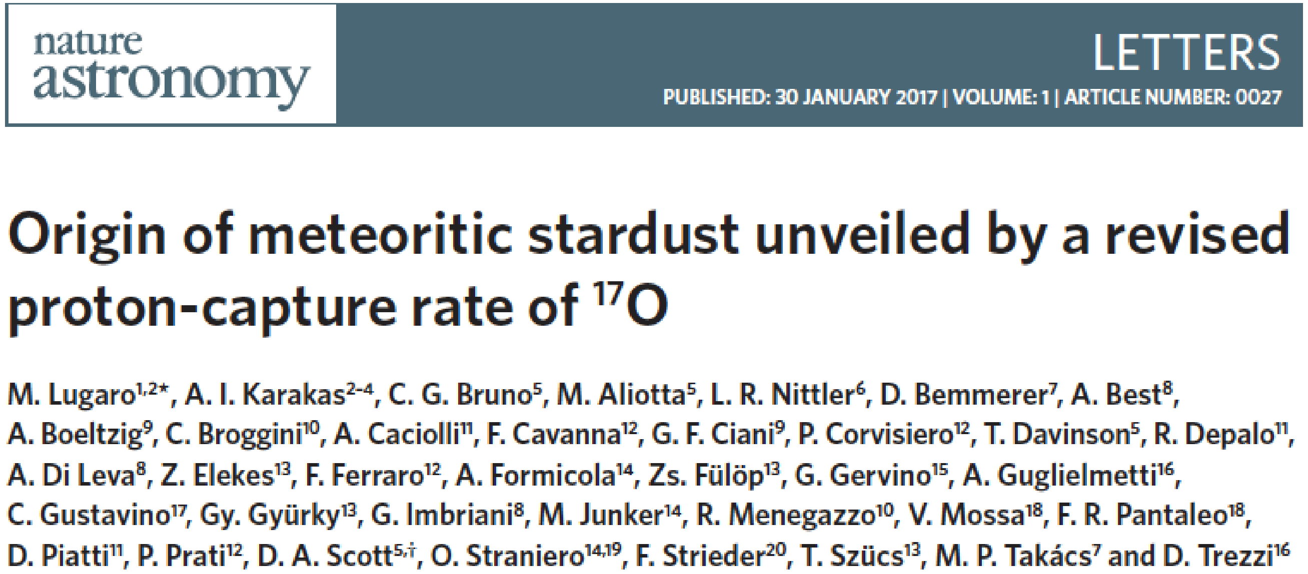
15x lower background underground



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

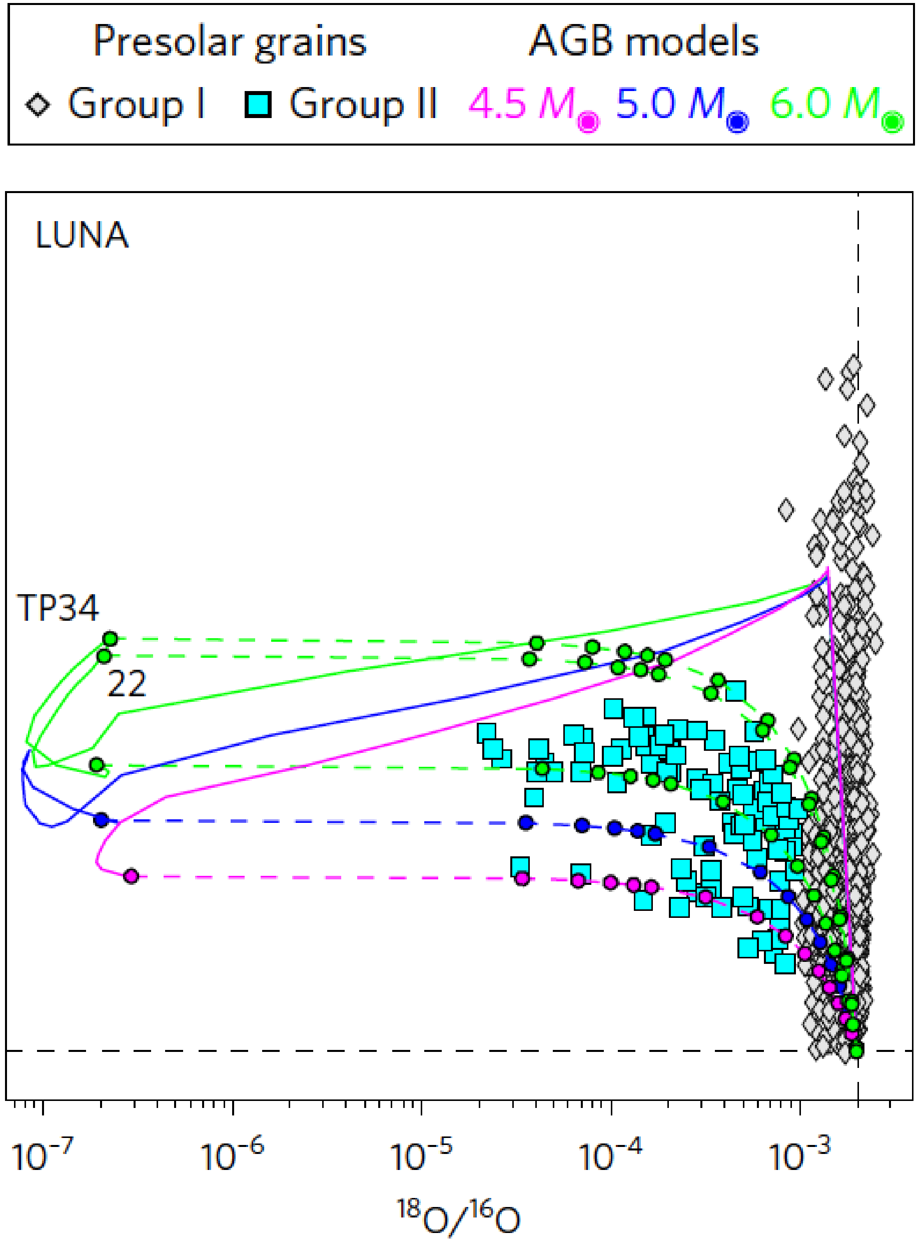
Origin of meteoritic stardust unveiled by a revised proton-capture rate of ^{17}O

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

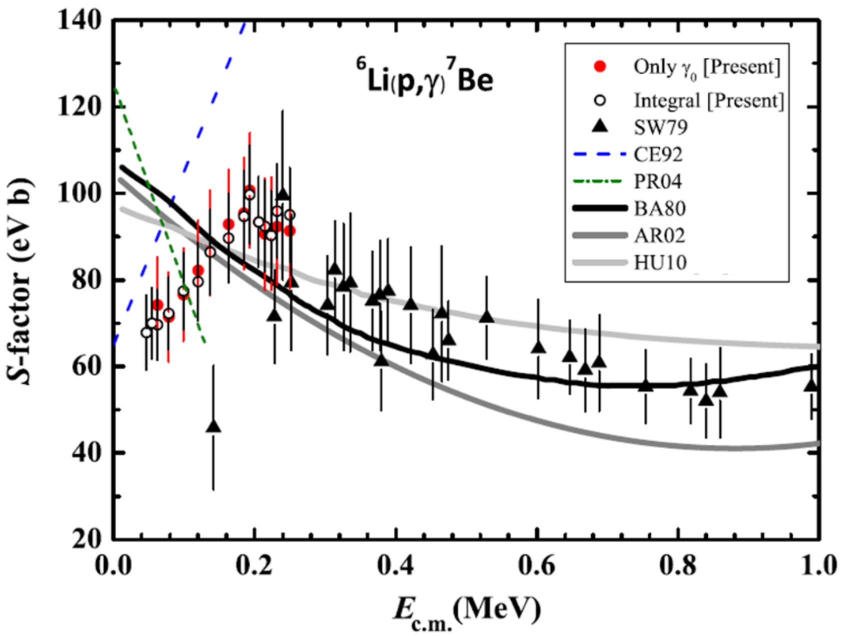
for oxygen-rich pre-solar grains



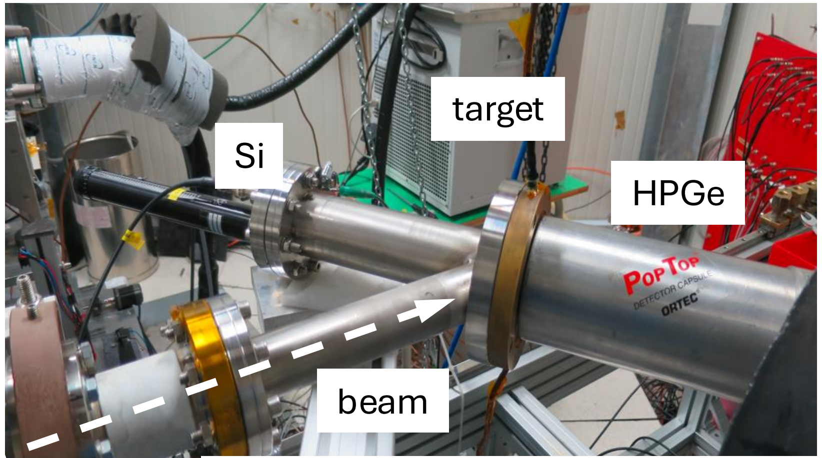
^{6}Li destruction:
The ^{6}Li(p,γ)^{7}Be and ^{6}Li(p,α)^{3}He Reactions

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

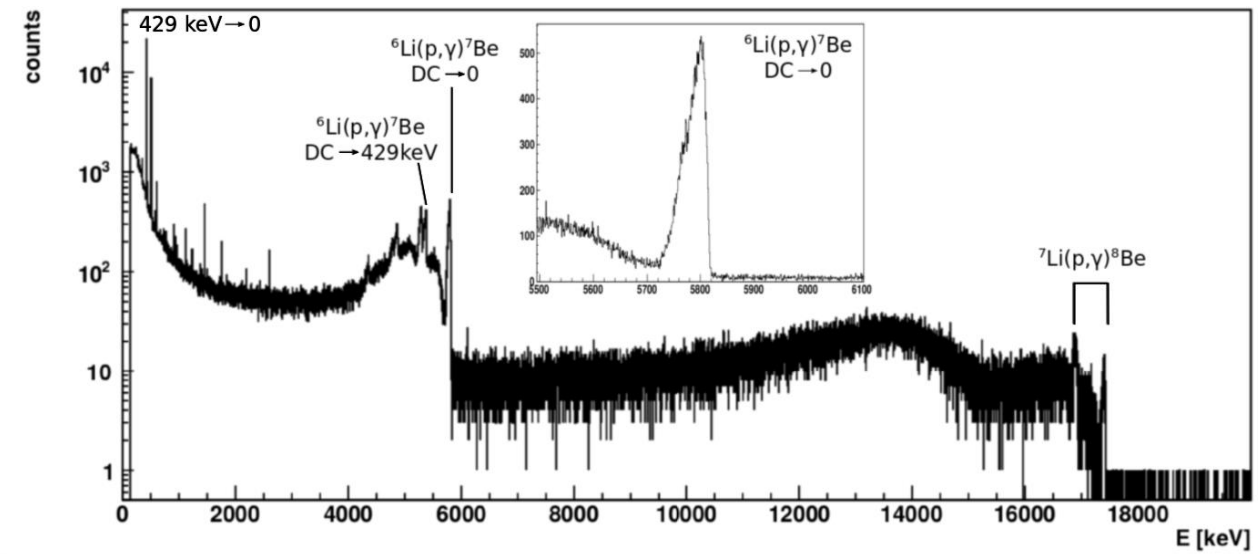
J. He *et al*, Physics Letters B, **725** (2013) 287



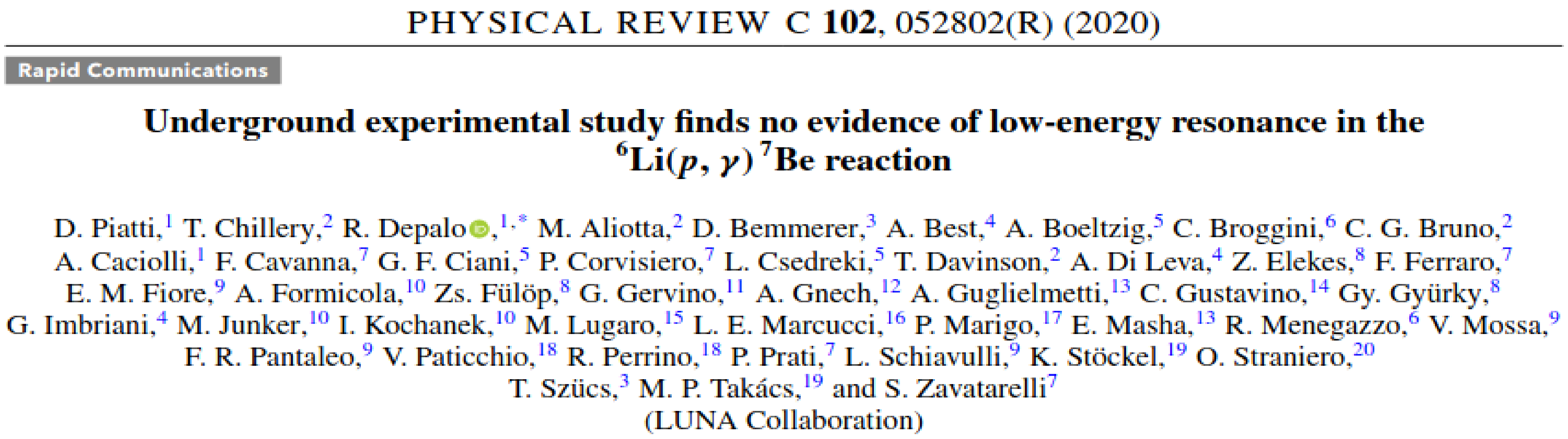
resonance(-like) structure reported but never independently confirmed



Thomas Chillery's PhD project



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

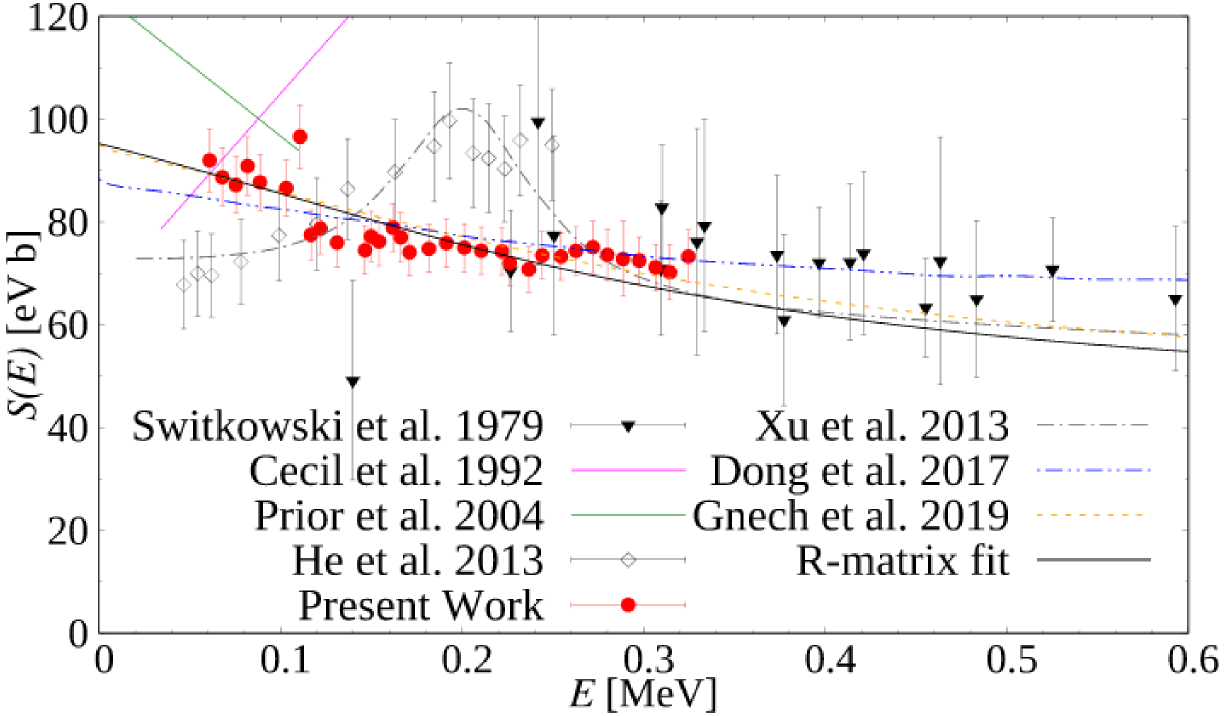


PHYSICAL REVIEW C **102**, 052802(R) (2020)

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

Plans for the Future...

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

NUCLEAR

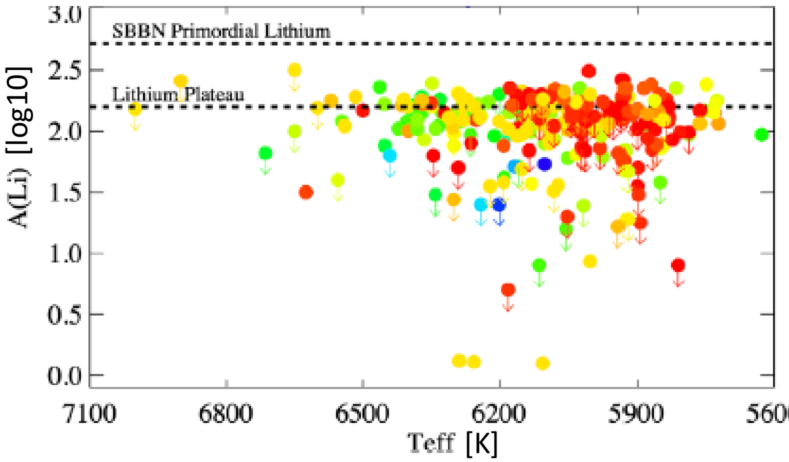
European Research Council
Established by the European Commission

UK Research and Innovation

Nucleosynthesis in First Stars and Other Puzzles

Long-Standing Questions in Nuclear Astrophysics

Q1. Cosmological Lithium Problem



Matteucci+ MNRAS (2021)

factor of 3 discrepancy between observed and predicted Li abundance

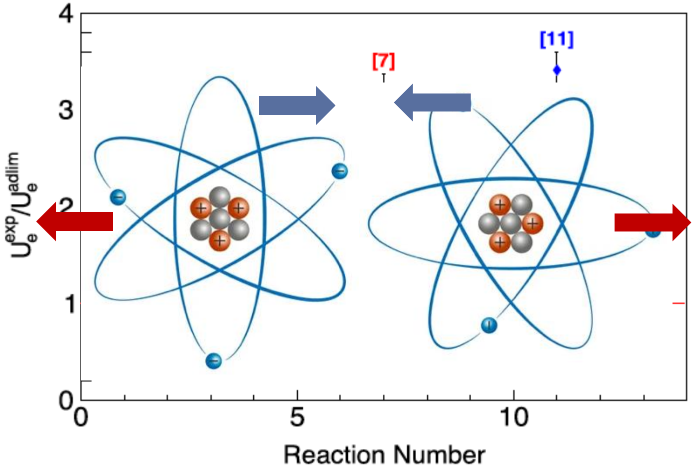
Standard Model of Particle Physics + Cosmology

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



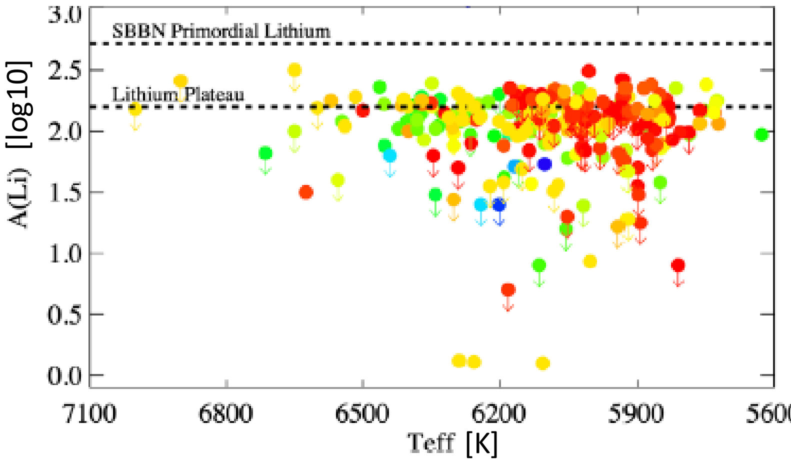
Spitaleri+ PLB (2016)

discrepancy between experiment and theory remains unexplained

Reactions in Plasmas Fusion-driven Energy Generation

Long-Standing Questions in Nuclear Astrophysics

Q1. Cosmological Lithium Problem



Matteucci+ MNRAS (2021)

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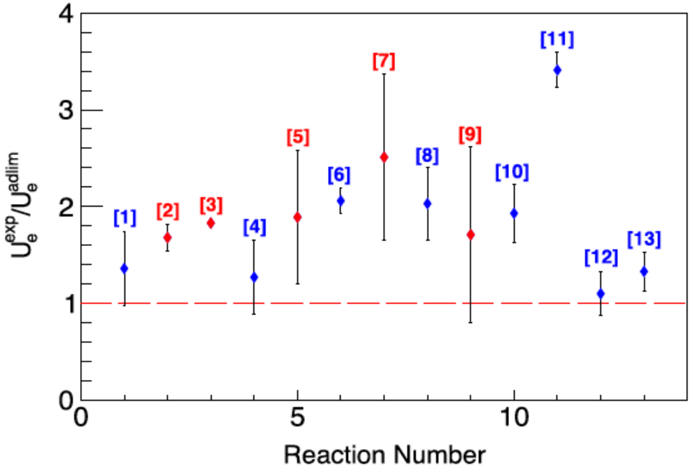


Spitaleri+ PLB (2016)

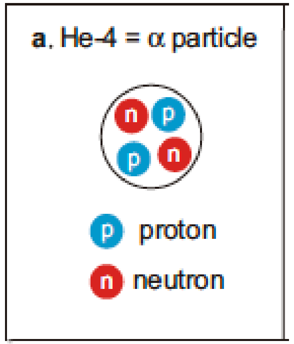
discrepancy between experiment and theory remains unexplained

key idea:

Nuclear Clustering

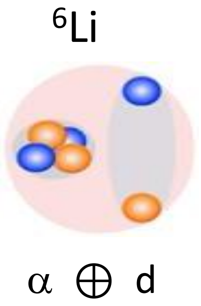
key to unlock all three puzzles

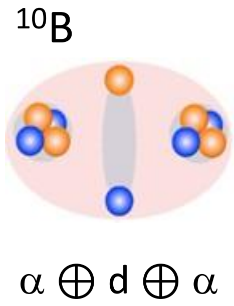
Nuclear Clustering



very stable configurations

→ building blocks for other nuclei



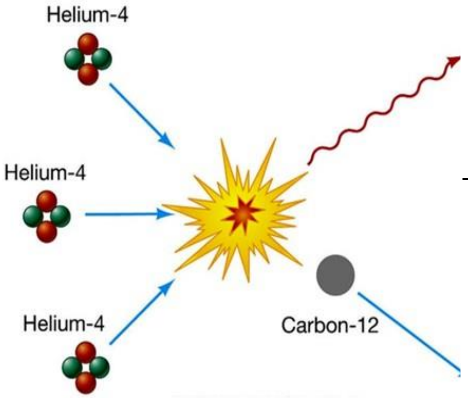


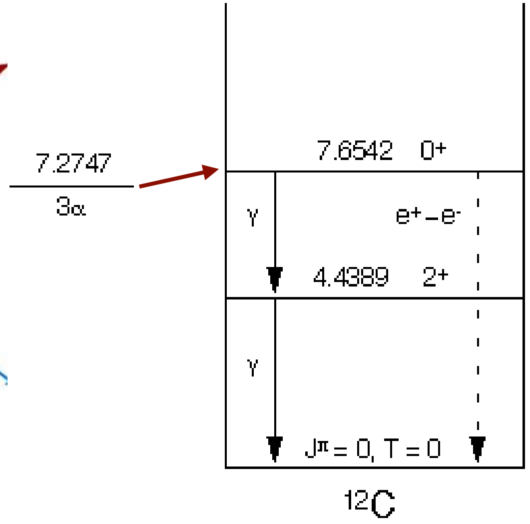
nuclear clustering may greatly

enhance fusion probabilities

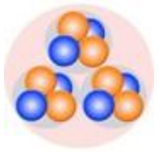
at low (i.e. astrophysical) energies

triple alpha process



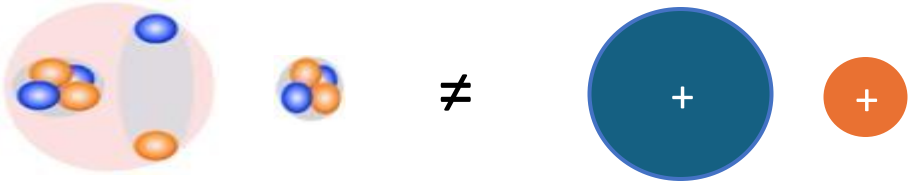


Hoyle state



~10^7 times faster

electron screening puzzle



lower Coulomb barrier → enhanced fusion

Nuclear Clustering: A Possible Solution?

Eur. Phys. J. A (2021) 57:24
https://doi.org/10.1140/epja/s10050-020-00339-x

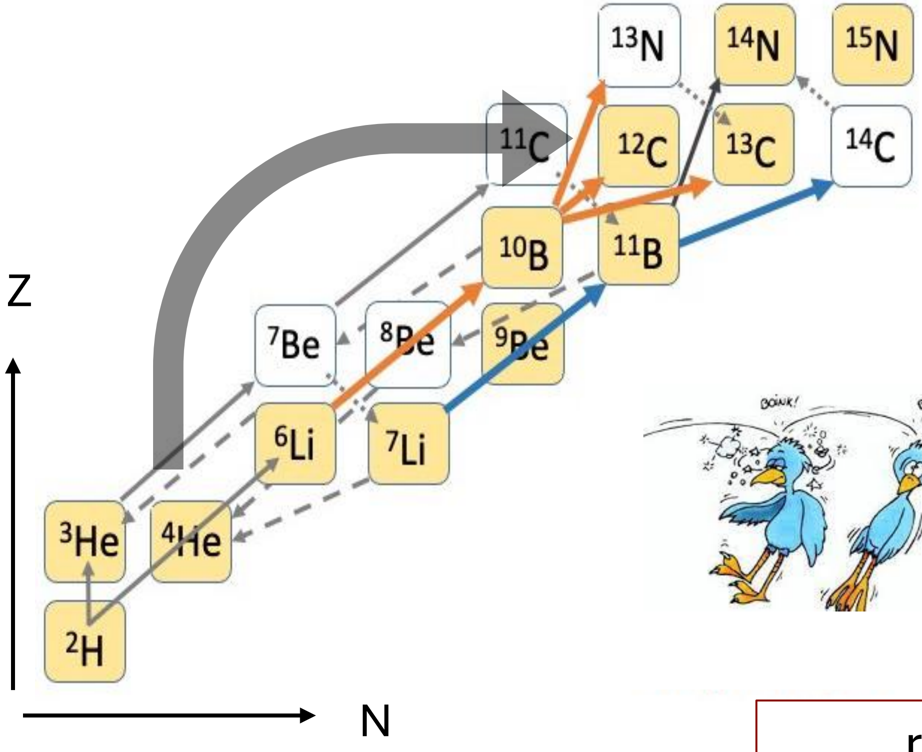
THE EUROPEAN PHYSICAL JOURNAL A

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



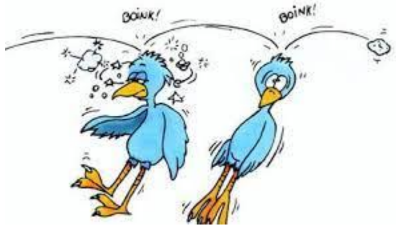
^{4}He(d,γ)^{6}Li(α,γ)^{10}B(α,d)^{12}C deuterons as catalyst isotope

^{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(a,p)^{14}C

^{11}B(α,n)^{14}N possible neutron source

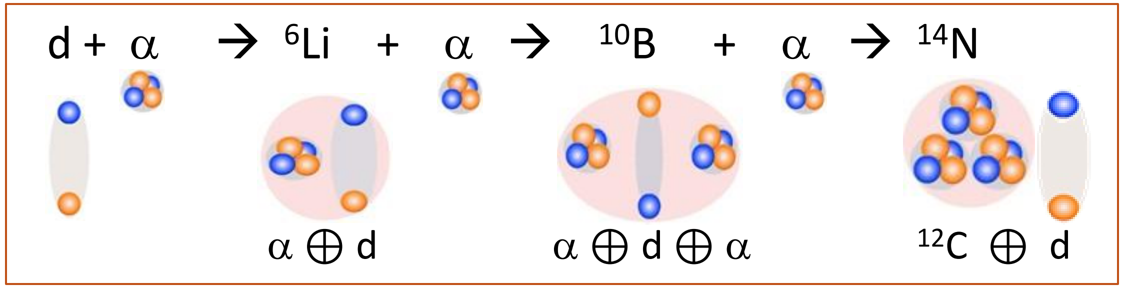


NOTE: 3α process forms C but completely by-passes Li; instead, proposed reaction sequences would also alter Li abundances → solution to CLiP?

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

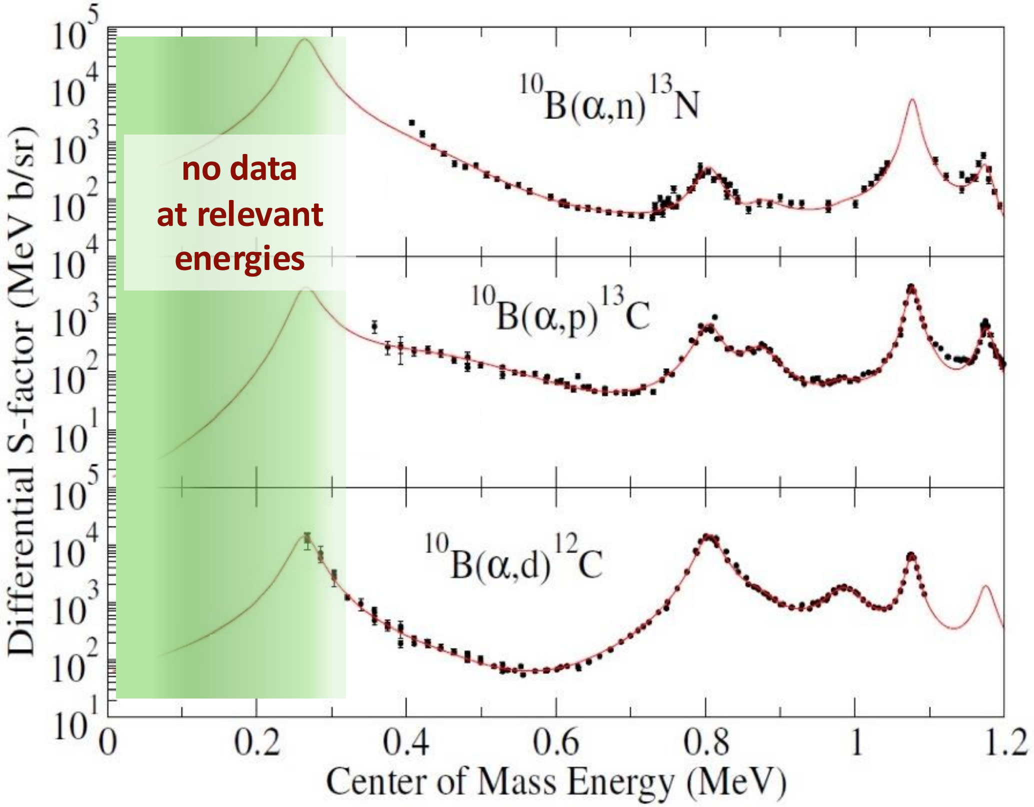
Current Status

proposed reactions involve strong cluster configurations



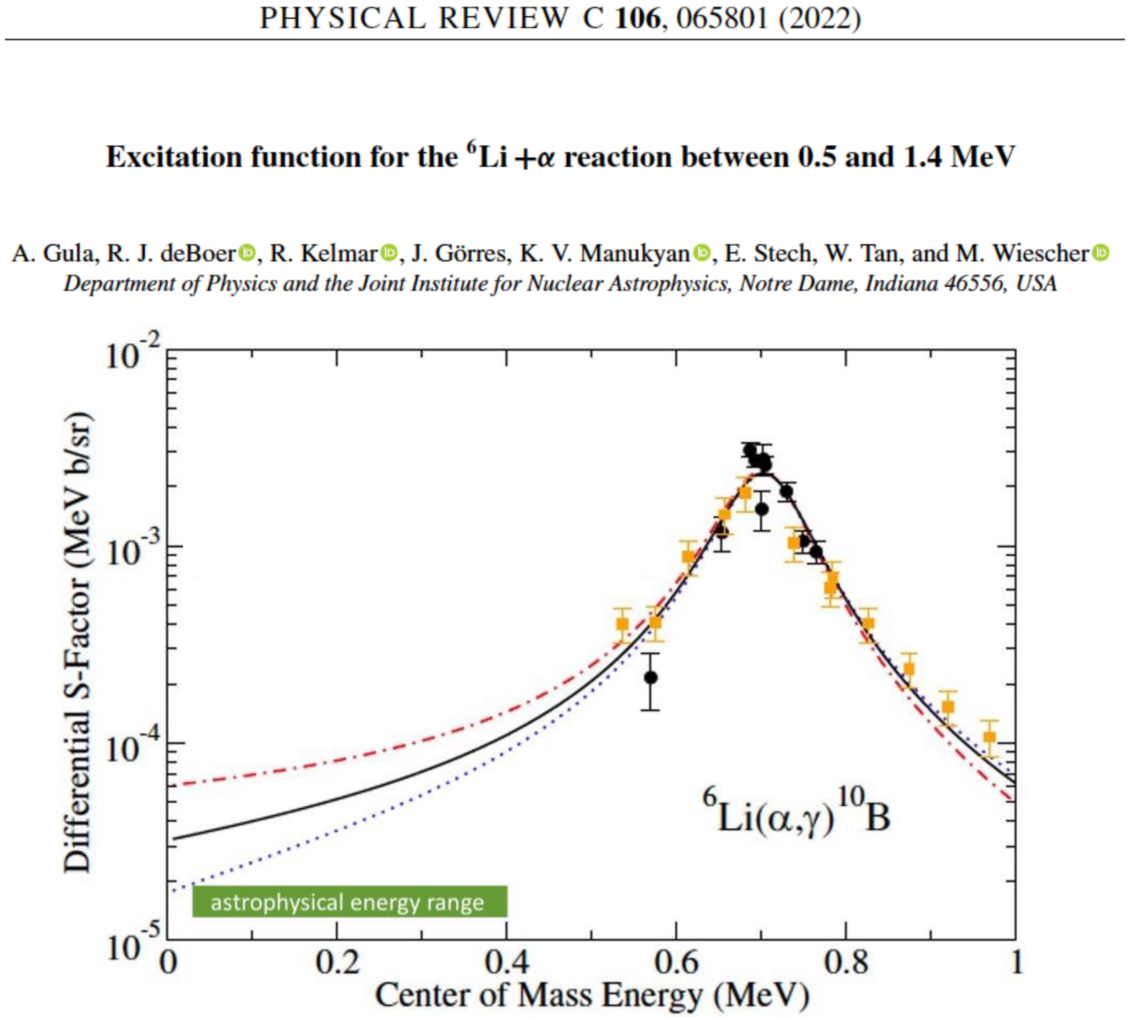
$d + \alpha \rightarrow {}^{6}\mathrm{Li} + \alpha \rightarrow {}^{10}\mathrm{B} + \alpha \rightarrow {}^{14}\mathrm{N}$

$\alpha \oplus d$ $\quad \alpha \oplus d \oplus \alpha$ $\quad {}^{12}\mathrm{C} \oplus d$



no data
at relevant
energies

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

astrophysical energy range

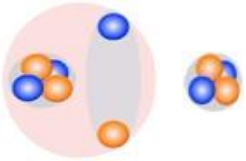
new measurements UNDERGROUND needed

Work Programme and Outcomes

Theoretical Programme

WP2a: PDRA2

G Hupin
[10%]



- cluster structures at low energies
- impact on astrophysical reactions & electron screening

RJ deBoer
[10%]

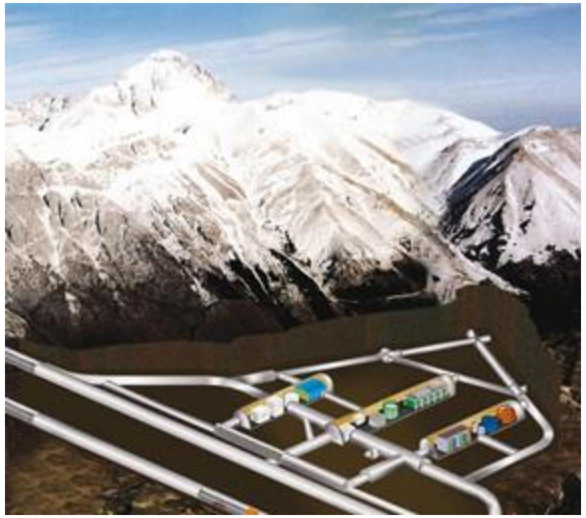
WP2b: **PI**, PDRA2

- improved R-matrix capabilities
- robust reaction rates

Experimental Programme

WP1: **PI**, PDRA1, PhD1,PhD2

Laboratory for Underground Nuclear Astrophysics

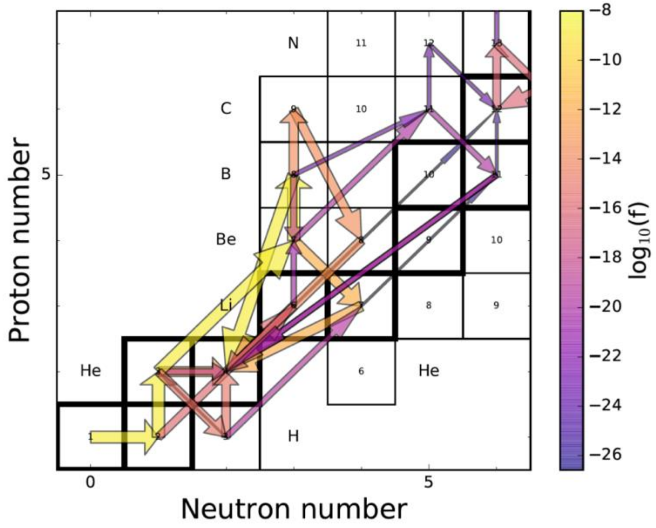


- α+Li and α+B reactions (Q1-Q3)
- ultra-low background @LUNA
- lowest-energy data (world best)

Computational Programme

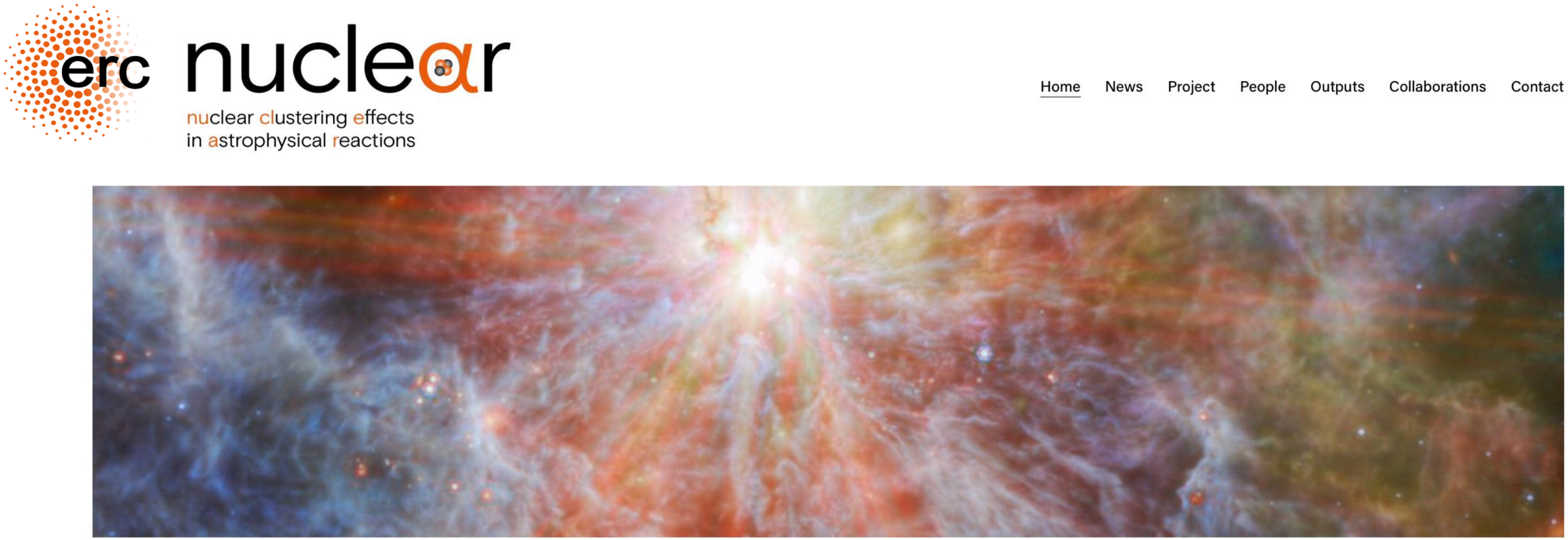
WP3: **PI**, PDRA3

M Pignatari
[20%]



- stellar models for first stars (MESA)
- nucleosynthesis networks (NuGRID)
- impact on Q1 and Q2

Grant started on 2 December 2024



2 PhD students just started, 1 PDRA Exp (Feb 2025), 1 PDRA Theo (recruiting)

In Summary…

- Experience with Direct and Indirect Methods in Nuclear Astrophysics
- Radioactive and Stable Beam Experiments
- Surface and Underground Laboratories

Enjoyed many fruitful collaborations throughout my career

Look forward to further collaborations with the Mainz group


THANK YOU