Nuclear Astrophysics Experiments Deep Underground at LUNA
part 2

Marialuisa Aliotta

School of Physics and Astronomy - University of Edinburgh, UK

XVI Nuclei in the Cosmos School – September 2021

Nuclei in the Cosmos I, 1990 – Baden/Vienna, Austria

Gianni Fiorentini & Claus Rolfs

Our Sun has been shining at a constant rate for 5 billion years

converting 700 million tonnes of H into He each second

According to the Standard Solar Model…

$$p + p \rightarrow d + e^{+} + \nu$$

$$p + d \rightarrow {}^{3}He + \gamma$$

86% | 14%

PP-I (86%)

$$ {}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$$

(14%)

$$ {}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$$

99.7% | 0.3%

PP-II (99.7%)

$$ {}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$$

$$ {}^{7}Li + p \rightarrow 2\,{}^{4}He$$

PP-III (0.3%)

$$ {}^{7}Be + p \rightarrow {}^{8}B + \gamma$$

$$ {}^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$$

$$\downarrow$$

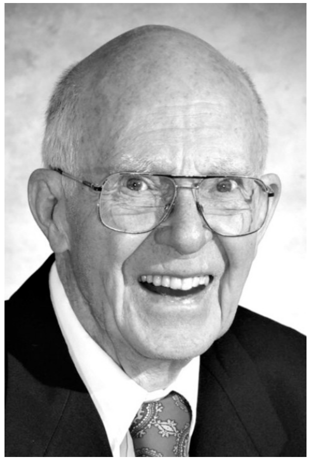
$$2\,{}^{4}He$$

No way of "seeing" what happens in the core of the Sun except if we…

detect neutrinos

Solar Neutrino Detection at Homestake in 1960s

FIRST DIRECT EVIDENCE FOR NUCLEAR REACTIONS IN OUR SUN



Ray Davis Jr.
2002 Nobel Prize

http://sanfordlab.org/article/270

1965: Ray Davis inside chlorine tank used for solar neutrino detection
Credit: Anna Davis

for 30 years
all neutrino detection efforts consistently
measured **1/3 of expected neutrinos flux**
based on **Standard Solar Model**

Solar Neutrino Problem

- wrong assumptions of SSM?
- poor understanding of neutrinos properties?
- unclear nuclear inputs?

$p + p \rightarrow d + e^+ + \nu$

$p + d \rightarrow {}^3He + \gamma$

86% PP-I

${}^3He + {}^3He \rightarrow {}^4He + 2p$

14%

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

99.7% PP-II

${}^7Be + e^- \rightarrow {}^7Li + \nu$

${}^7Li + p \rightarrow 2\,{}^4He$

0.3% PP-III

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^8B \rightarrow {}^8Be + e^+ + \nu$

$\downarrow$

$2\,{}^4He$

what if this reaction has a resonance at solar energies?

a direct measurement of its cross section was necessary

Yield = N_p x N_t x cross section x detection efficiency

10^{14} pps (~100 μA q=1+) typical stable beam intensities

10^{19} atoms/cm^2 typical solid-state targets

10^{-15} barn (often even smaller)

100% for charged particles
~1-10% for gamma rays (HPGe detectors)

Y = 0.3-30 counts/year

~ 1.2-120 counts/PhD

low cross sections → low yields → poor signal-to-noise ratio

Yield = $N_{projectiles}$ x N_{target} x cross section x detection efficiency

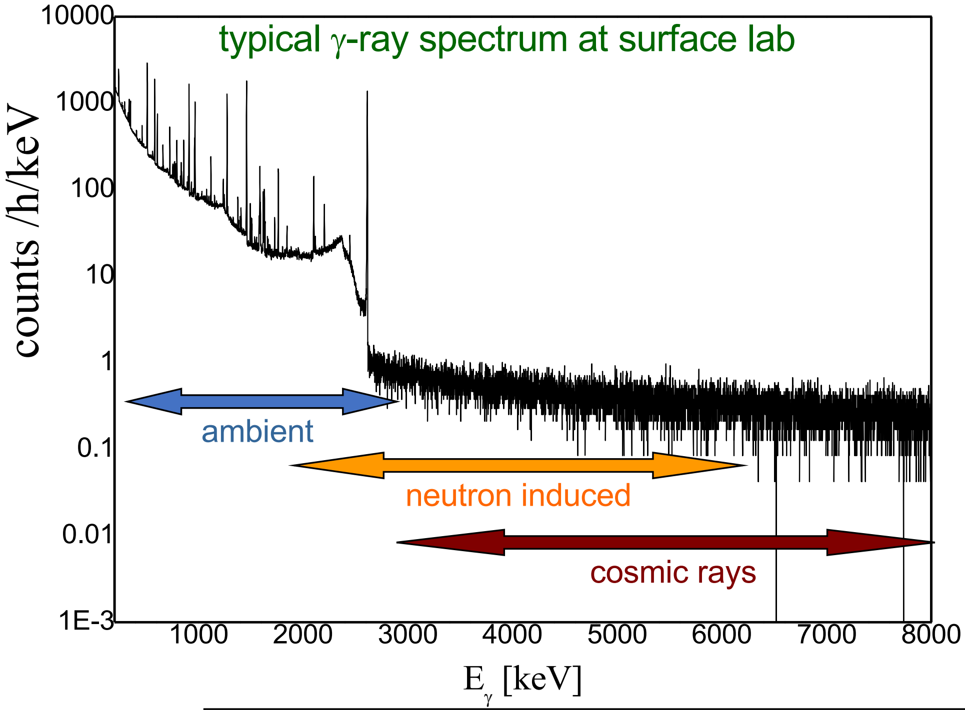
maximising the yield requires:

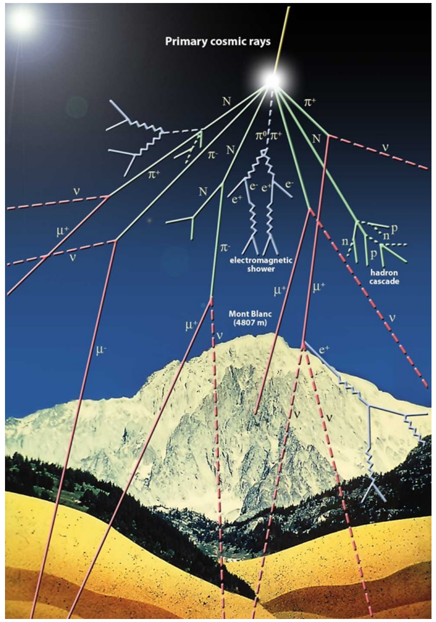
- improving "signal" (e.g. high beam currents, high target density, high efficiency)
- reducing "noise" (i.e. background)
- combination of both

How to improve the signal-to-noise ratio?

Main Sources of Background:

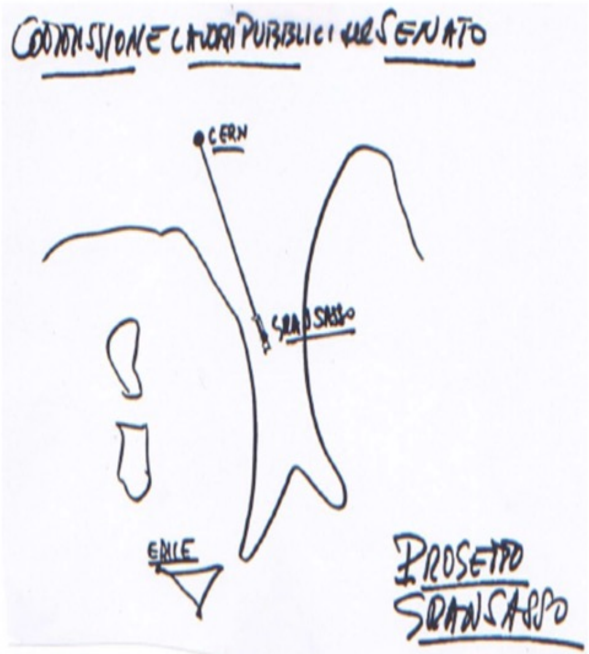
- natural radioactivity (mainly from U and Th chains and from Rn)
- cosmic rays (muons, $^{1,3}H$, ^{7}Be, ^{14}C, …)
- neutrons from (α,n) reactions and fission





ideal location: underground + low concentration of U and Th

Laboratori Nazionali del Gran Sasso: An Ideal Location



Note manoscritte di A. Zichichi presentate nella Seduta della Commissione Lavori Pubblici del Senato convocata con urgenza dal Presidente del Senato per discutere la proposta del Progetto Gran Sasso (1979).

To summarize, the scientific aims of the "Gran Sasso" laboratory are the study of:

1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

NOT only $\tau_p \neq \infty$

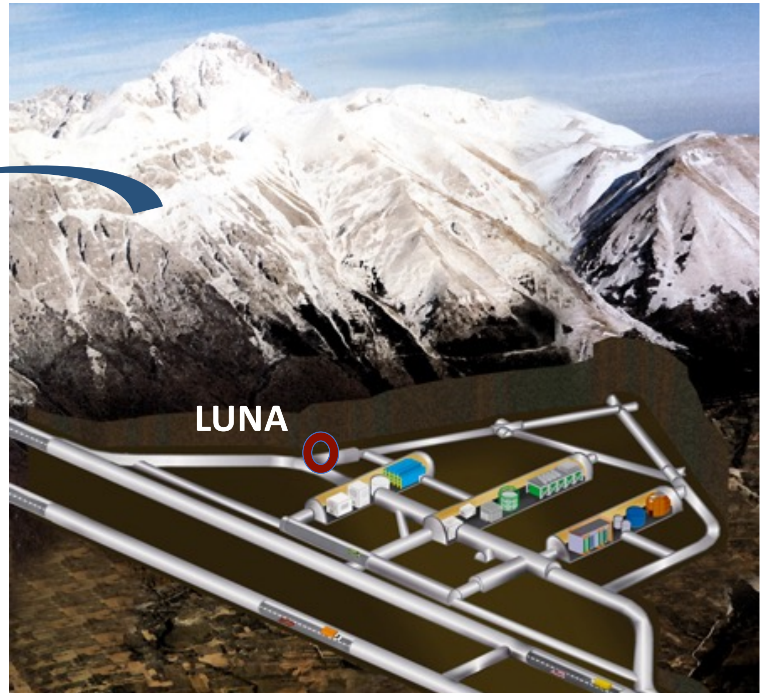
Antonino Zichichi

courtesy: C Broggini

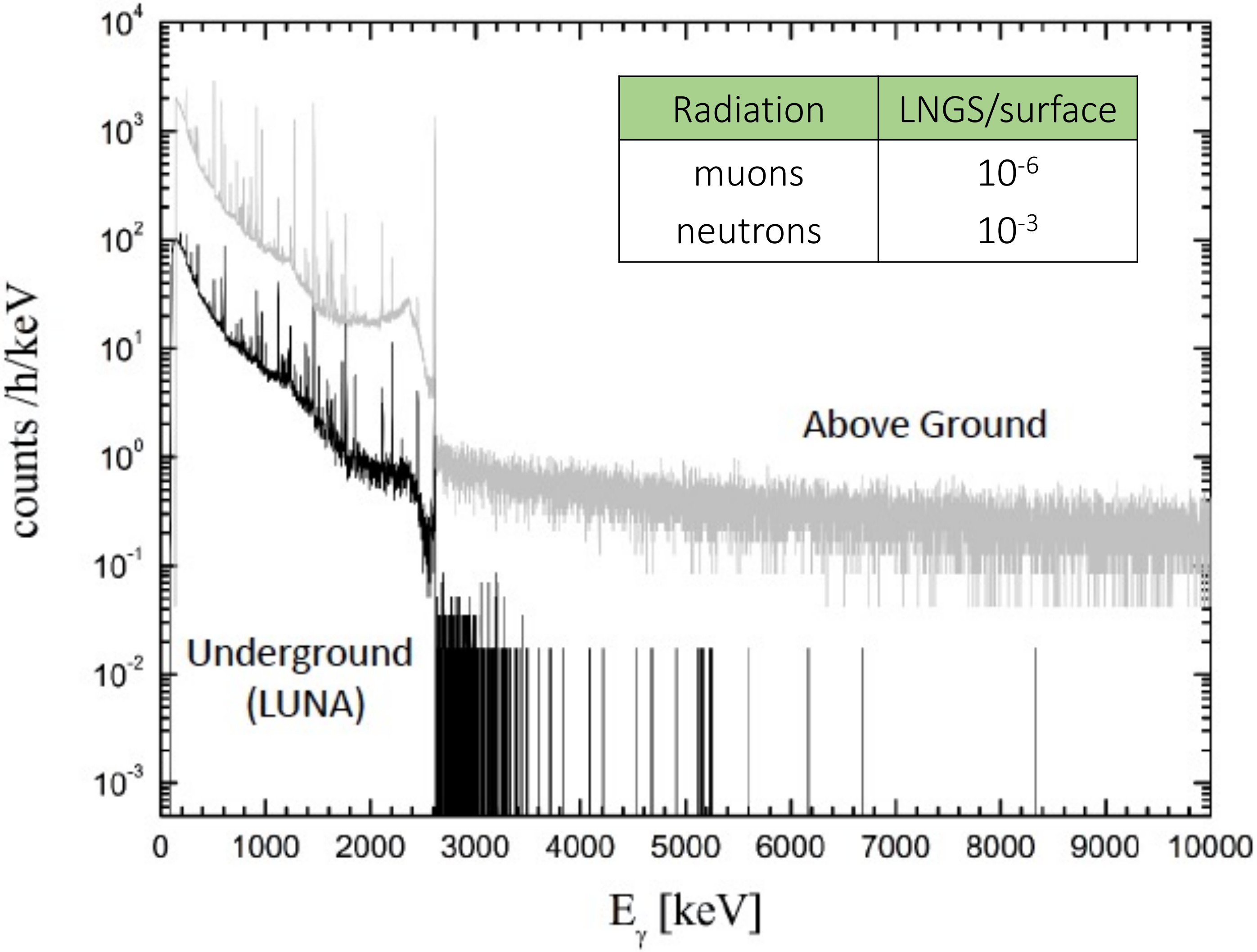
LUNA: Laboratory for Underground Nuclear Astrophysics

INFN - Laboratori Nazionali del Gran Sasso (Italy)

first underground accelerator in the world for Nuclear Astrophysics studies



Gamma-ray background: underground vs overground comparison



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

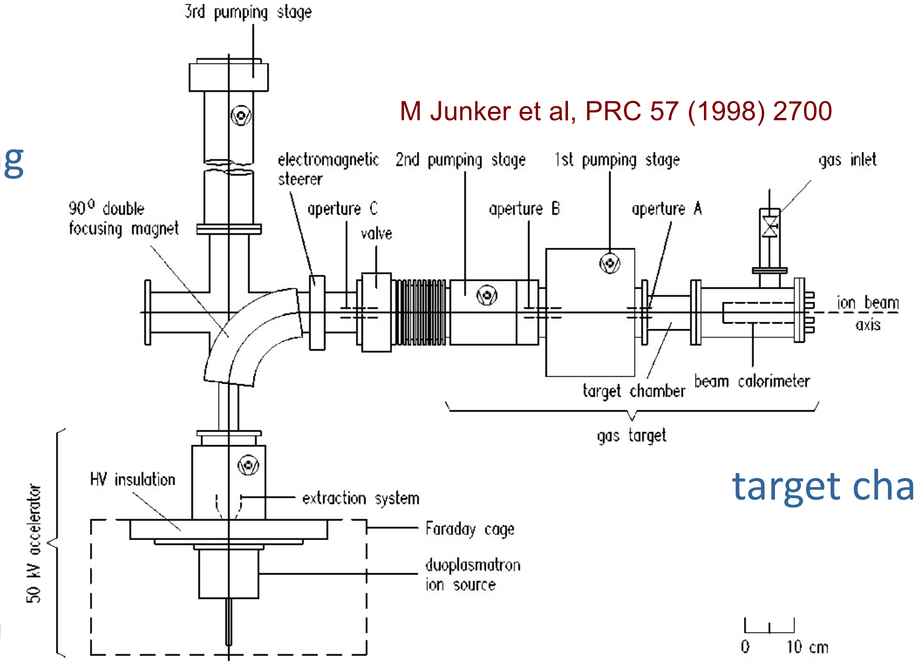
Costantini et al. Rep. Prog. Phys. 72 (2009) 086301

LUNA – Phase I: 50 kV accelerator (1992-2001)

investigate reactions in solar pp chain

90° analysing magnet

duoplasmatron ion source on 50kV platform



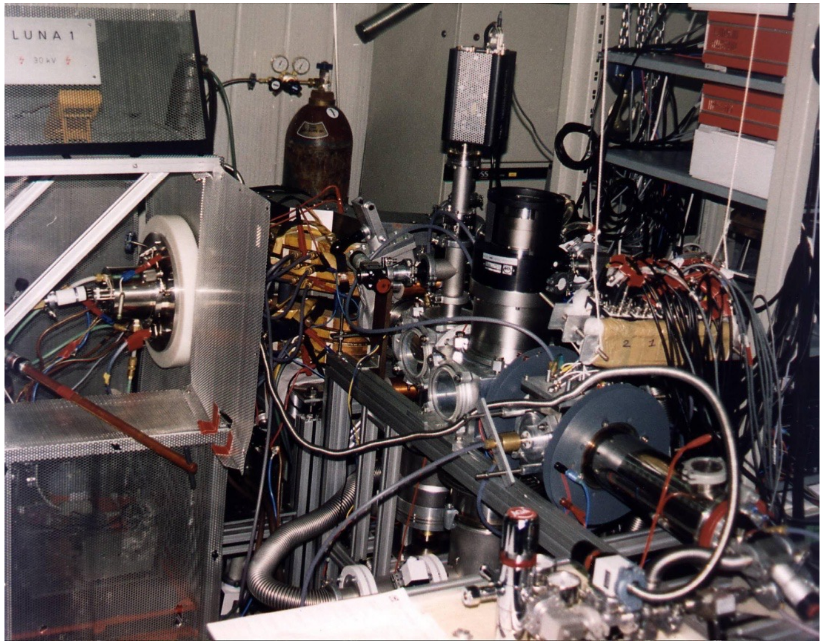
M Junker et al, PRC 57 (1998) 2700

target chamber

entirely built by students!

LUNA – Phase I: 50 kV accelerator (1992-2001)

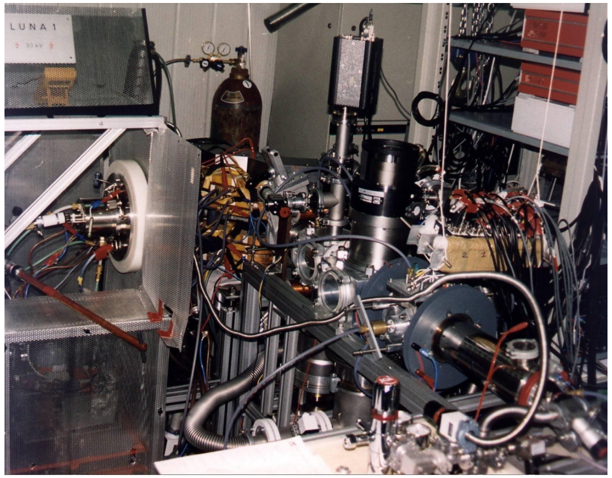
investigate reactions in solar pp chain



LUNA

The $^3He(^3He,2p)^4He$ Reaction and the Solar Neutrino Puzzle

LUNA 50 kV accelerator

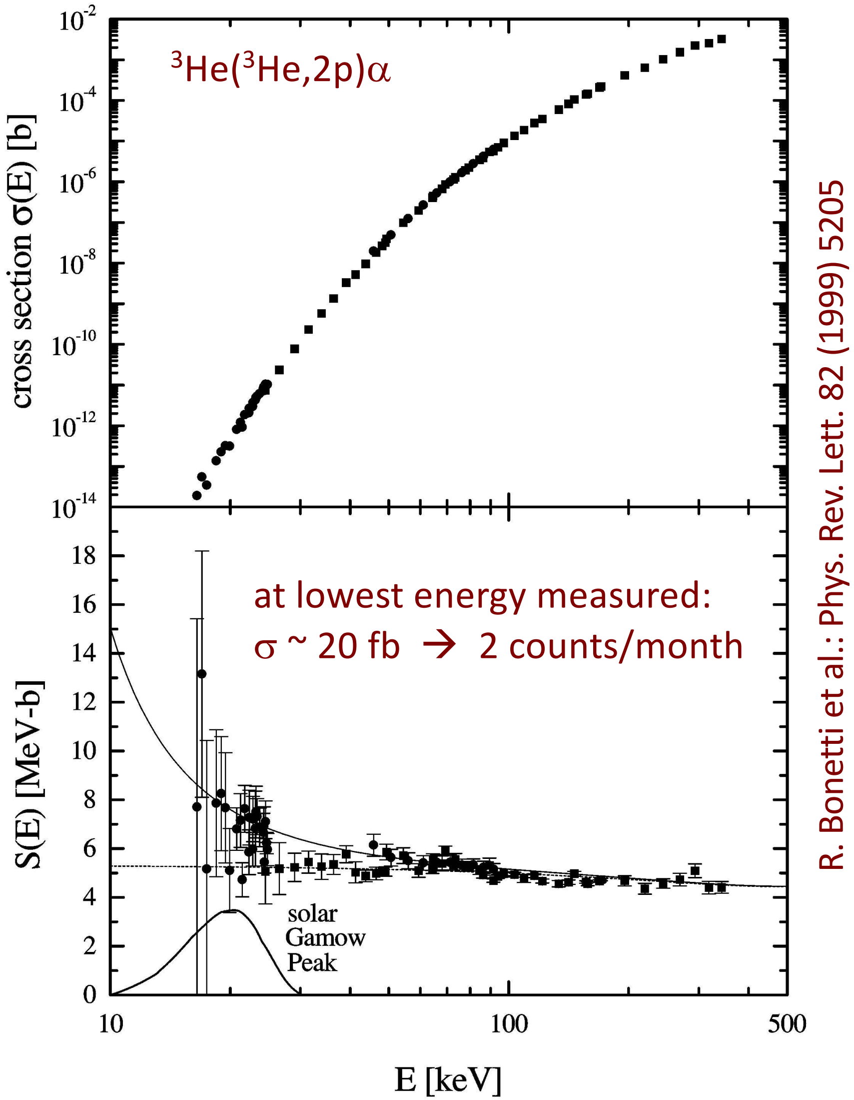


the first reaction to be

measured directly

at astrophysical energies:

no resonance found



VOLUME 82, NUMBER 26 PHYSICAL REVIEW LETTERS 28 JUNE 1999

First Measurement of the $^3He(^3He, 2p)^4He$ Cross Section down to the Lower Edge of the Solar Gamow Peak

R. Bonetti,[1] C. Broggini,[2,*] L. Campajola,[3] P. Corvisiero,[4] A. D'Alessandro,[5] M. Dessalvi,[4] A. D'Onofrio,[6] A. Fubini,[7] G. Gervino,[8] L. Gialanella,[9] U. Greife,[9] A. Guglielmetti,[1] C. Gustavino,[5] G. Imbriani,[3] M. Junker,[5] P. Prati,[4] V. Roca,[3] C. Rolfs,[9] M. Romano,[3] F. Schuemann,[9] F. Strieder,[9] F. Terrasi,[3] H.P. Trautvetter,[9] and S. Zavatarelli[4]
(LUNA Collaboration)

excluded a "nuclear solution" to the missing neutrino problem

photo: A. Mahmoud

T. Kajita

A. McDonald

photo: A. Mahmoud

2015 Nobel Prize in Physics
Discovery of Neutrinos Oscillations

THE INSTITU

PRI

E-mail:

SCHOOL OF NATURAL SCIENCES

Professor P. Corvisiero
Professor C. Rolfs
Spokesmen for the LUNA-Collal

Dear Professors Corvisiero and I

I am writing to you about a his
recent meeting on Solar Fusion R
University. At this meeting, I ha
the LUNA measurements of the
a significant part of the Gamow
had never believed possible. The
nuclear astrophysics in three dec

With the LUNA results, debates
energy that were ignited by the
tions of solar neutrinos can now
$^{3}He(^{3}He,2p)^{4}He$ reaction, it is
tributed to our nuclear physics
in order to clarify some systema
energy part of the Gamow peak.

There are a number of other r
lar neutrino experiments and fo
$^{3}He(\alpha,\gamma)^{7}Be$, $^{7}Be(p,\gamma)^{8}B$, and
tions at or near the energies at
stars.

The LUNA collaboration is supe
an improved facility, a 200 kV h
ment of the Gran Sasso Undergr

I have had some experience in helping to set priorities for research in physics and in astronomy, most recently as Chair of the Decade Survey for Astronomy and Astrophysics of the National Academy of the United States and as President (now emeritus) of the American Astronomical Society. I can say, with the perspective provided by these previous assignments, that the work of the LUNA collaboration is unique and essential for further progress in solar neutrino studies and for understanding how main sequence stars evolve. I personally would rank the LUNA project among the highest priorities internationally for research in nuclear astrophysics, in stellar evolution, in solar neutrinos, and in particle phenomenology.

JNB:jnb

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SCHOOL OF NATURAL SCIENCES JOHN N. BAHCALL

28 May 1997

Professor P. Corvisiero
Professor C. Rolfs
Spokesmen for the LUNA-Collaboration

Dear Professors Corvisiero and Rolfs:

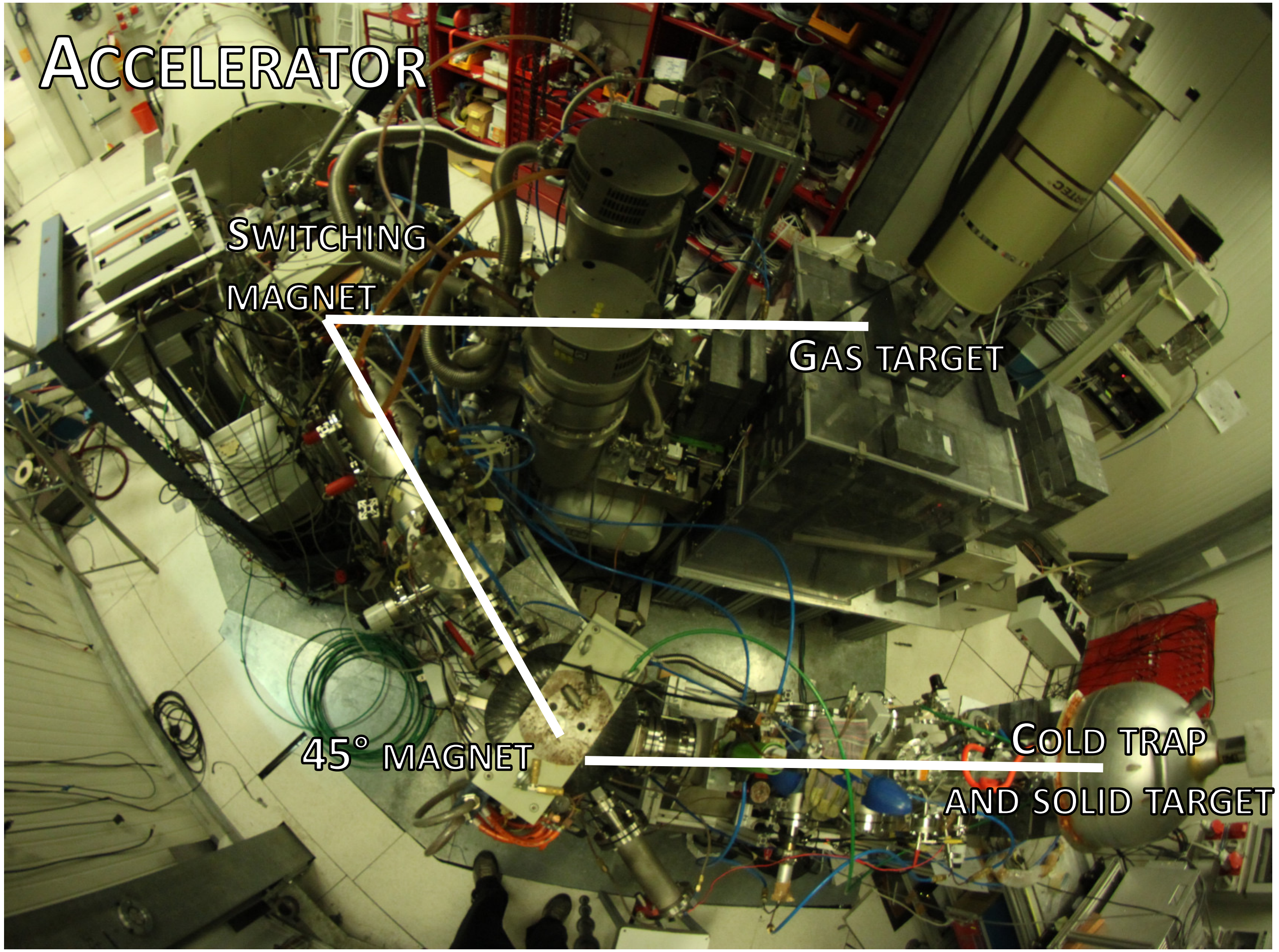
I am writing to you about a historic opportunity of which I first became aware at the recent meeting on Solar Fusion Reactions at the Institute of Nuclear Theory, Washington University. At this meeting, I had the opportunity to see for the first time the results of the LUNA measurements of the important $3He-3He$ reaction in a region that covers a significant part of the Gamow energy peak for solar fusion. This was a thrill that I had never believed possible. These measurements signal the most important advance in nuclear astrophysics in three decades.

Sincerely yours,

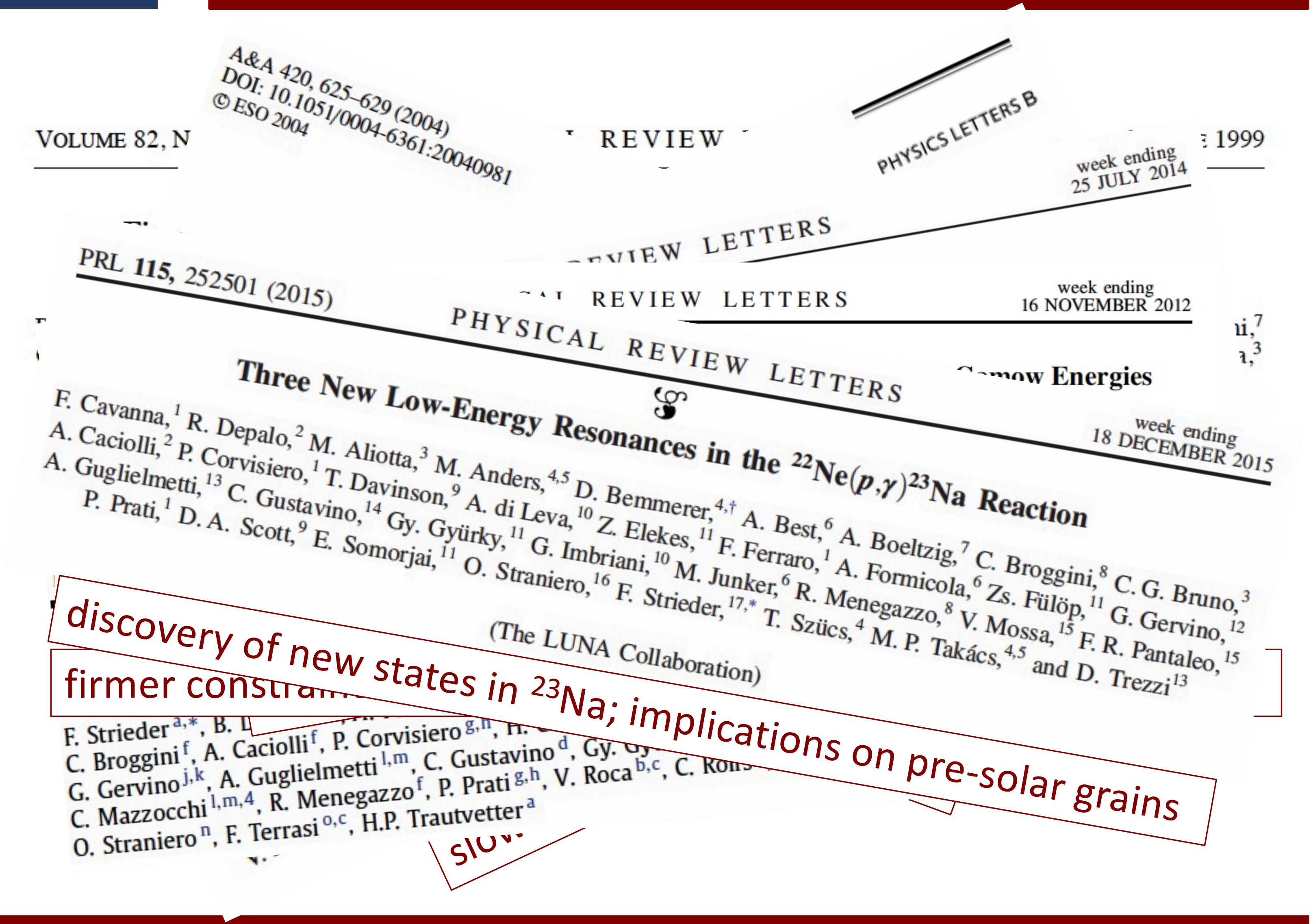
John N. Bahcall
Professor of Natural Science

LUNA: 400 kV accelerator

LUNA: 400 kV Accelerator and Beam Lines



Past and Recent Highlights from LUNA



VOLUME 82, N

1999

A&A 420, 625–629 (2004)
DOI: 10.1051/0004-6361:20040981
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PHYSICS LETTERS B

week ending
25 JULY 2014

REVIEW LETTERS

REVIEW LETTERS

week ending
16 NOVEMBER 2012

Gamow Energies

PRL 115, 252501 (2015)

PHYSICAL REVIEW LETTERS

week ending
18 DECEMBER 2015

Three New Low-Energy Resonances in the $^{22}Ne(p,\gamma)^{23}Na$ Reaction

F. Cavanna,[1] R. Depalo,[2] M. Aliotta,[3] M. Anders,[4,5] D. Bemmerer,[4,†] A. Best,[6] A. Boeltzig,[7] C. Broggini,[8] C. G. Bruno,[3] A. Caciolli,[2] P. Corvisiero,[1] T. Davinson,[9] A. di Leva,[10] Z. Elekes,[11] F. Ferraro,[1] A. Formicola,[6] Zs. Fülöp,[11] G. Gervino,[12] A. Guglielmetti,[13] C. Gustavino,[14] Gy. Gyürky,[11] G. Imbriani,[10] M. Junker,[6] R. Menegazzo,[8] V. Mossa,[15] F. R. Pantaleo,[15] P. Prati,[1] D. A. Scott,[9] E. Somorjai,[11] O. Straniero,[16] F. Strieder,[17,*] T. Szücs,[4] M. P. Takács,[4,5] and D. Trezzi[13]

(The LUNA Collaboration)

F. Strieder[a,*], B. L..., C. Broggini[f], A. Caciolli[f], P. Corvisiero[g,h], ..., G. Gervino[j,k], A. Guglielmetti[l,m], C. Gustavino[d], Gy. Gy..., C. Mazzocchi[l,m,4], R. Menegazzo[f], P. Prati[g,h], V. Roca[b,c], C. Rol..., O. Straniero[n], F. Terrasi[o,c], H.P. Trautvetter[a]

firmer constrai...

discovery of new states in ^{23}Na; implications on pre-solar grains

25 year 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**
  $^{14}N(p,\gamma)^{15}O$ $^{15}N(p,\gamma)^{16}O$ $^{22}Ne(p,\gamma)^{23}Na$ $^{22}Ne(\alpha,\gamma)^{26}Mg$ $^{23}Na(p,\gamma)^{24}Mg$ $^{25}Mg(p,\gamma)^{26}Al$
- **(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)

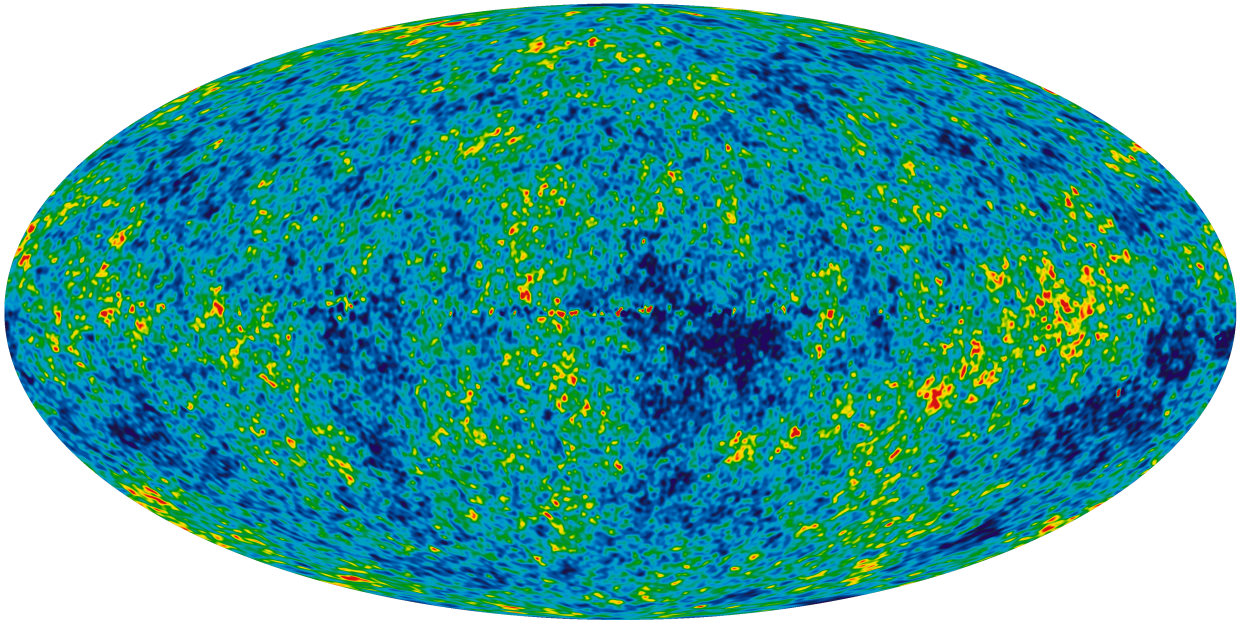
LUNA

Recent Selected Highlights

- Big Bang Nucleosynthesis: $^{2}H(p,\gamma)^{3}He$ gamma rays
- Origin of pre-solar grains: $^{17}O(p,\alpha)^{14}N$ charged particles
- Origin of heavy elements: $^{13}C(\alpha,n)^{16}O$ neutrons

Cosmic Microwave Background (CMB) radiation

oldest electromagnetic radiation in the Universe (~ 380,000 y after Big Bang)

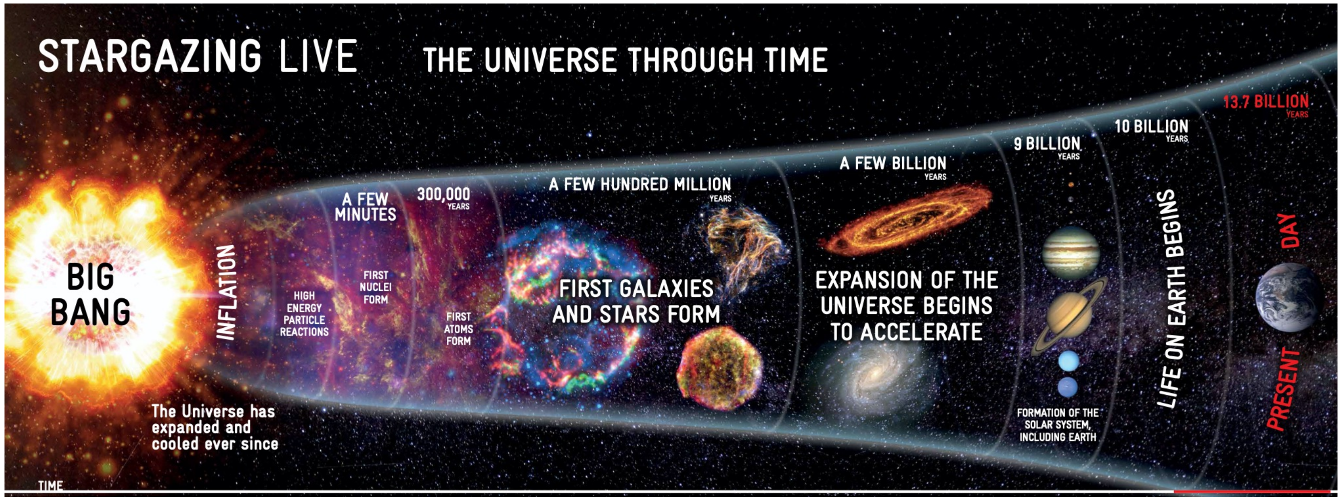


NASA - http://wmap.gsfc.nasa.gov/media/101080

accidental discovery by Penzias and Wilson in 1965 (Nobel Prize in 1978)

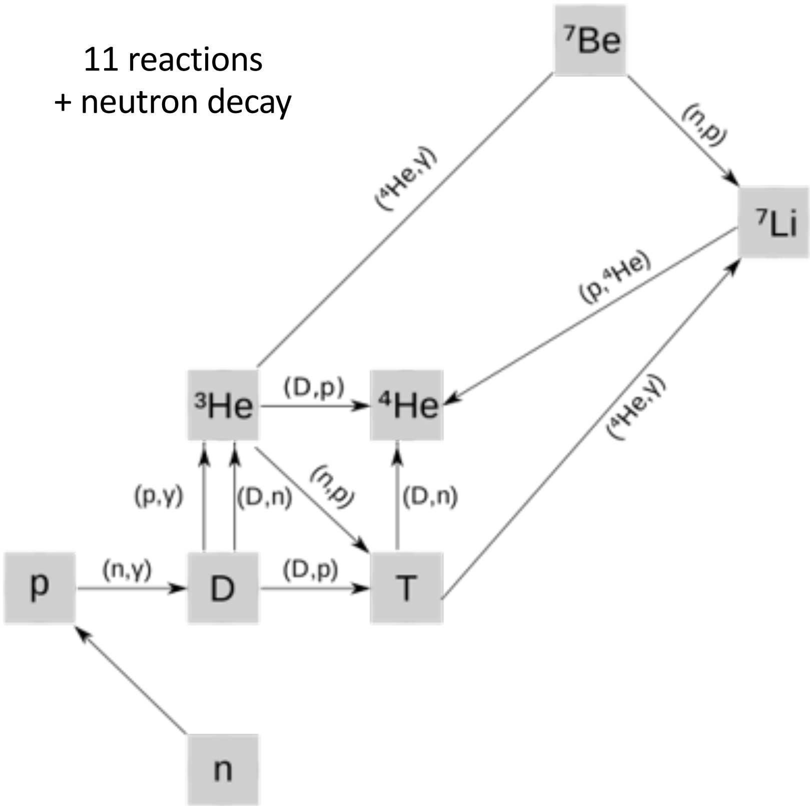
Big Bang Nucleosynthesis

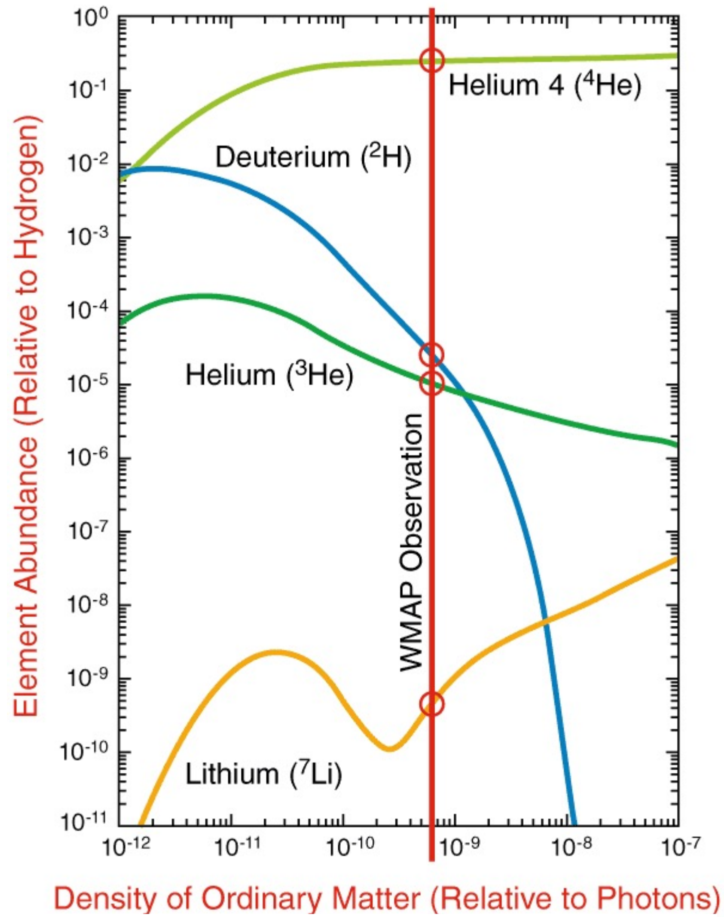
BBN is only handle to probe state of early universe



Primordial Nucleosynthesis (BBN): 3 minutes after Big Bang

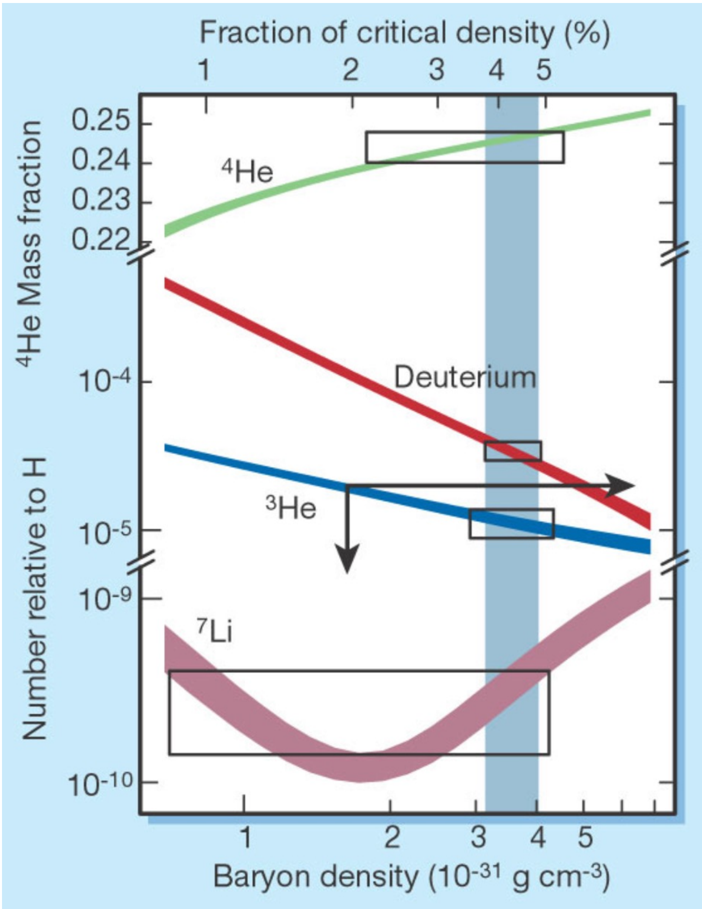
11 reactions
+ neutron decay





(assuming only 3 neutrino species)

Primordial Abundances to determine Baryon Density



Deuterium is an excellent baryometer

- D is produced only during Big Bang Nucleosynthesis
- D is destroyed easily in stars
- D abundance is the most sensitive to the baryon density $\Omega_b h^2$
- D abundance also depends on the effective number N_{eff} of neutrino species

- baryon density inferred from BBN → early epoch
- baryon density inferred from CMB → recombination epoch (380000 years later)

according to Standard Model of Cosmology (ΛCDM)

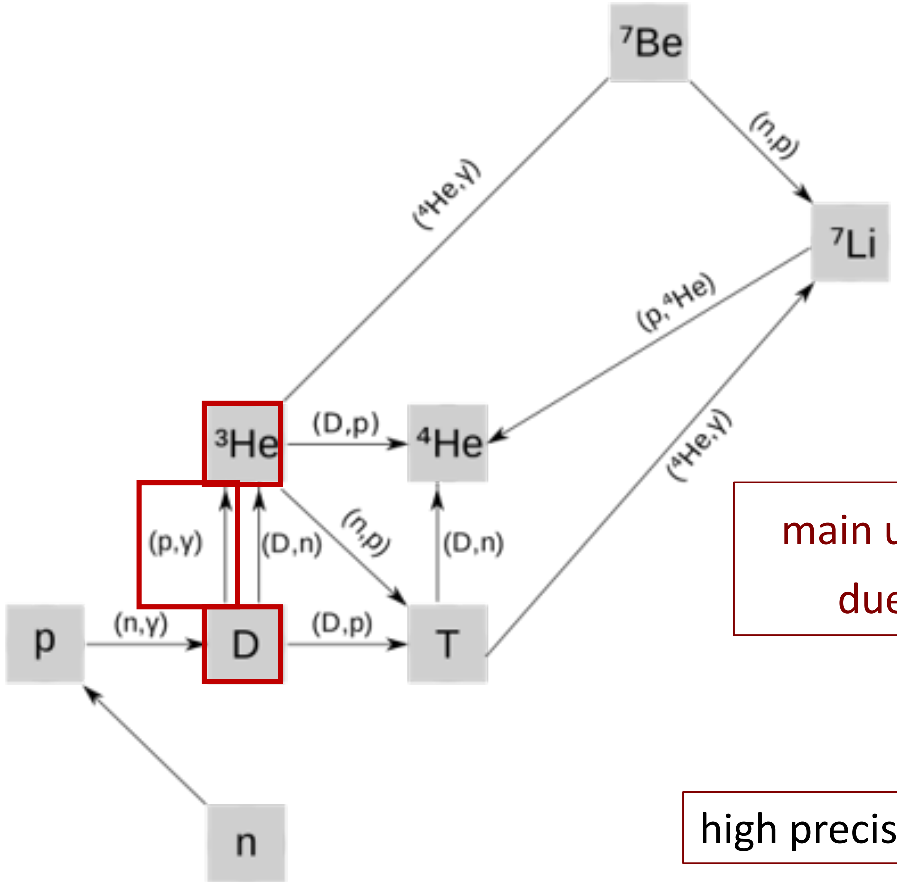
baryon density can only vary as a result of Universe expansion

if present-day value of Ω_b (BBN) = Ω_b (CMB) → validity of ΛCDM

if present-day value of Ω_b (BBN) ≠ Ω_b (CMB) → new physics beyond ΛCDM

independent determinations of Ω_b can provide useful tests

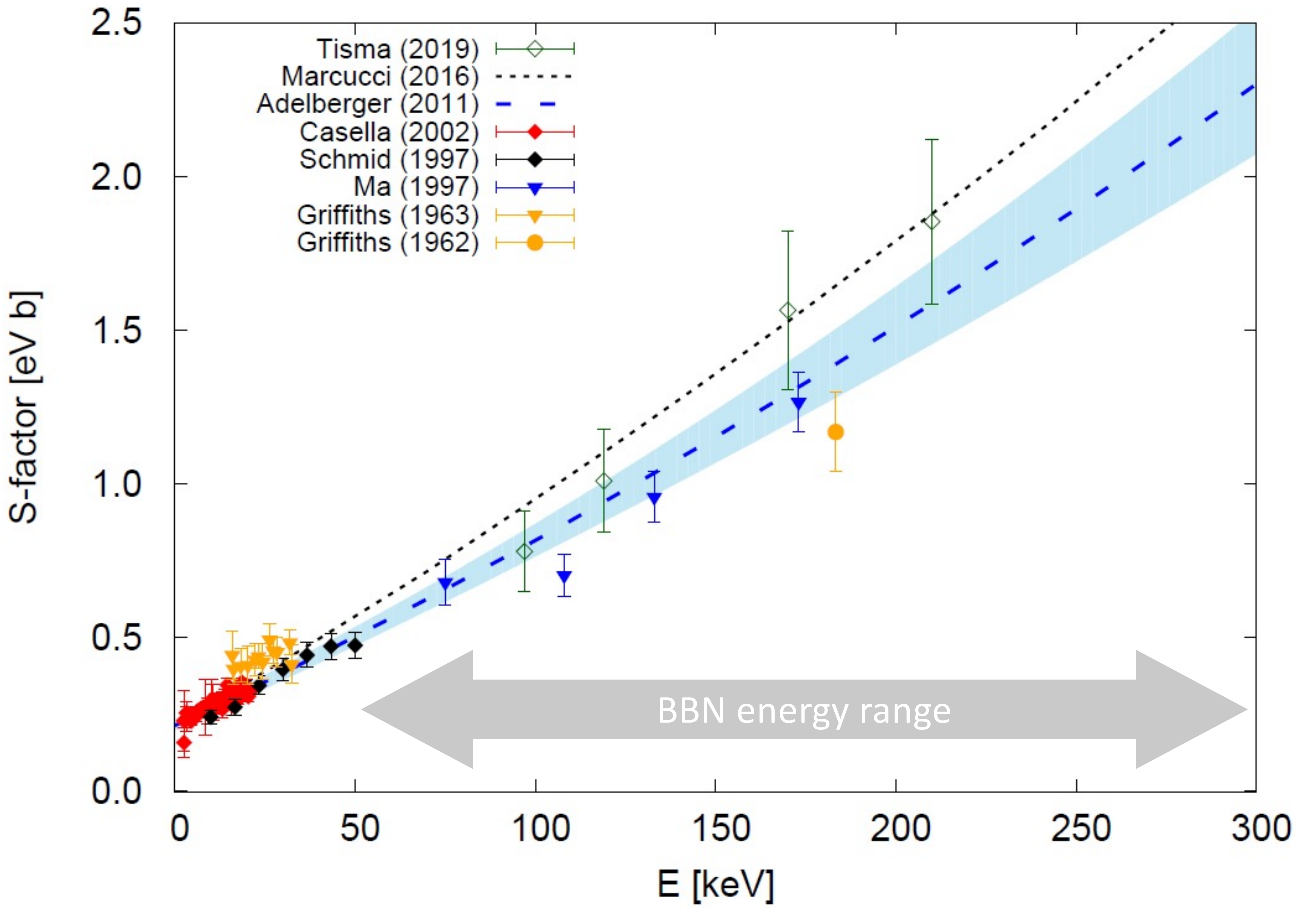
- Astronomical observations of deuterium abundance have reached % accuracy
- BBN predictions of deuterium abundance still affected by large uncertainties



main uncertainty in BBN predictions due to **d(p,γ)^{3}He** cross section

high precision data at BBN energies required

State of the Art before LUNA measurement



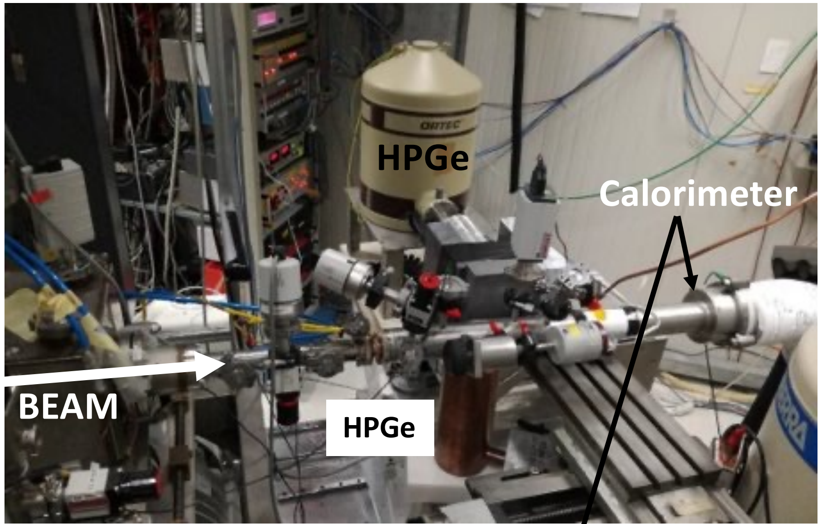
courtesy: F Cavanna

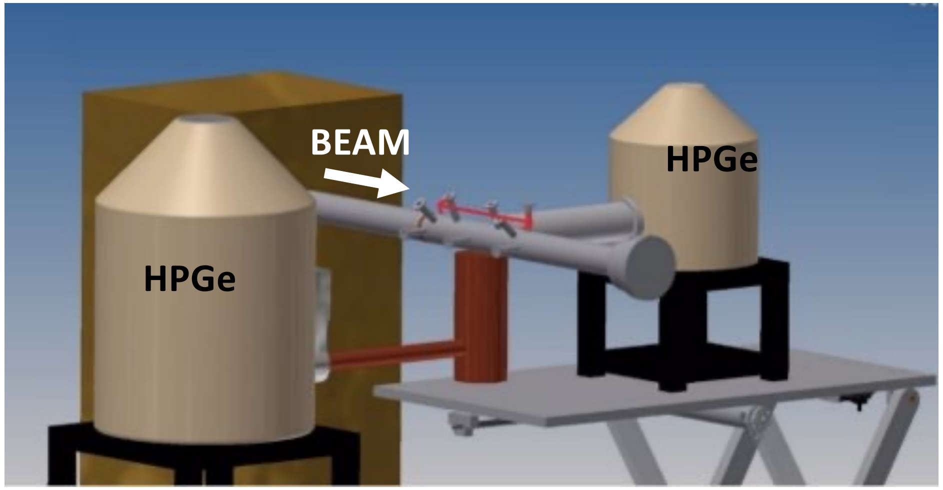
LUNA

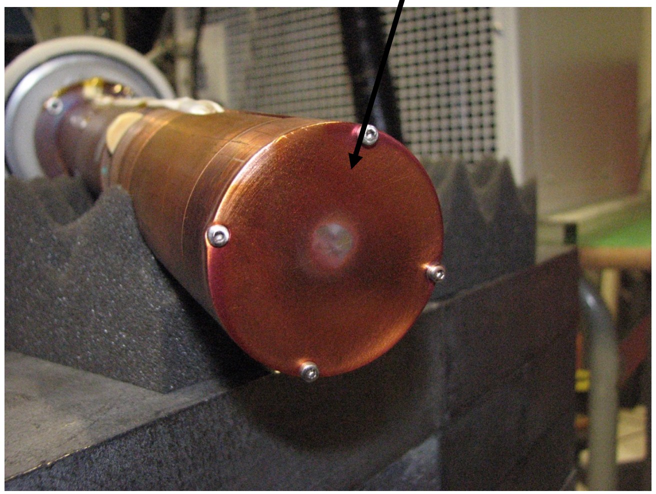
Primordial Deuterium Abundance: The $d(p,\gamma)^3He$ Reaction

Experimental Setup

- proton beam (100 uA)
- E_{beam} = 50 - 300 keV (full BBN range)
- extended D_2 gas target (99.99% isotopic purity)
- P = 0.3 mbar (0.25% accuracy)
- Beam stop = calorimeter
  -> current measurement
- HPGe detector for prompt γ-ray detection



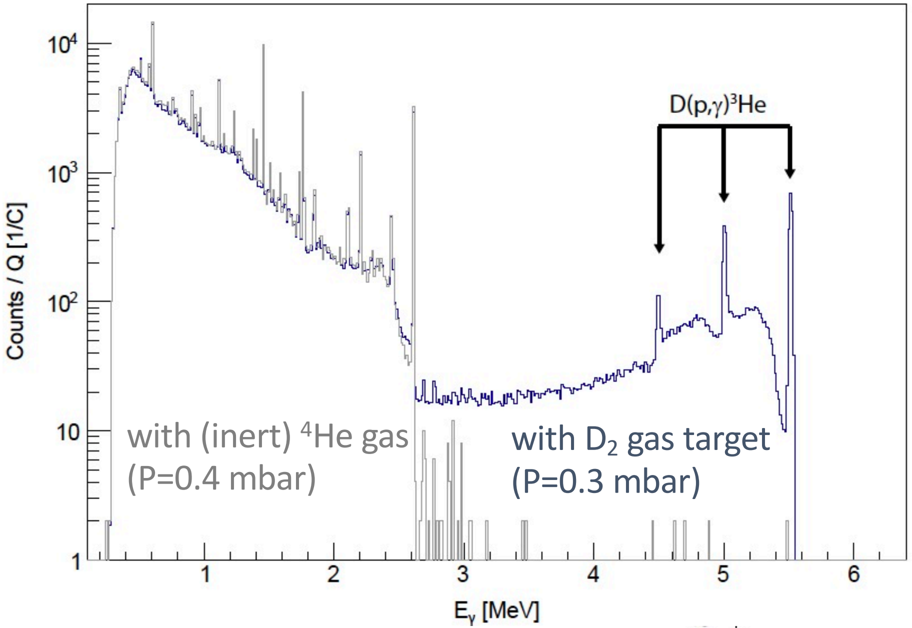




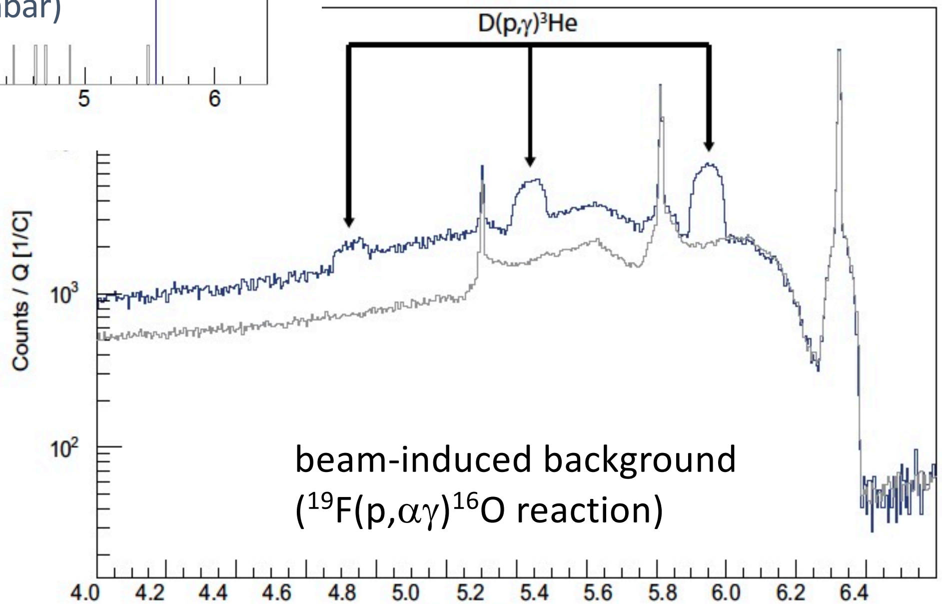
M. Aliotta

The d(p,γ)^{3}He reaction at LUNA

E_p = 50 keV



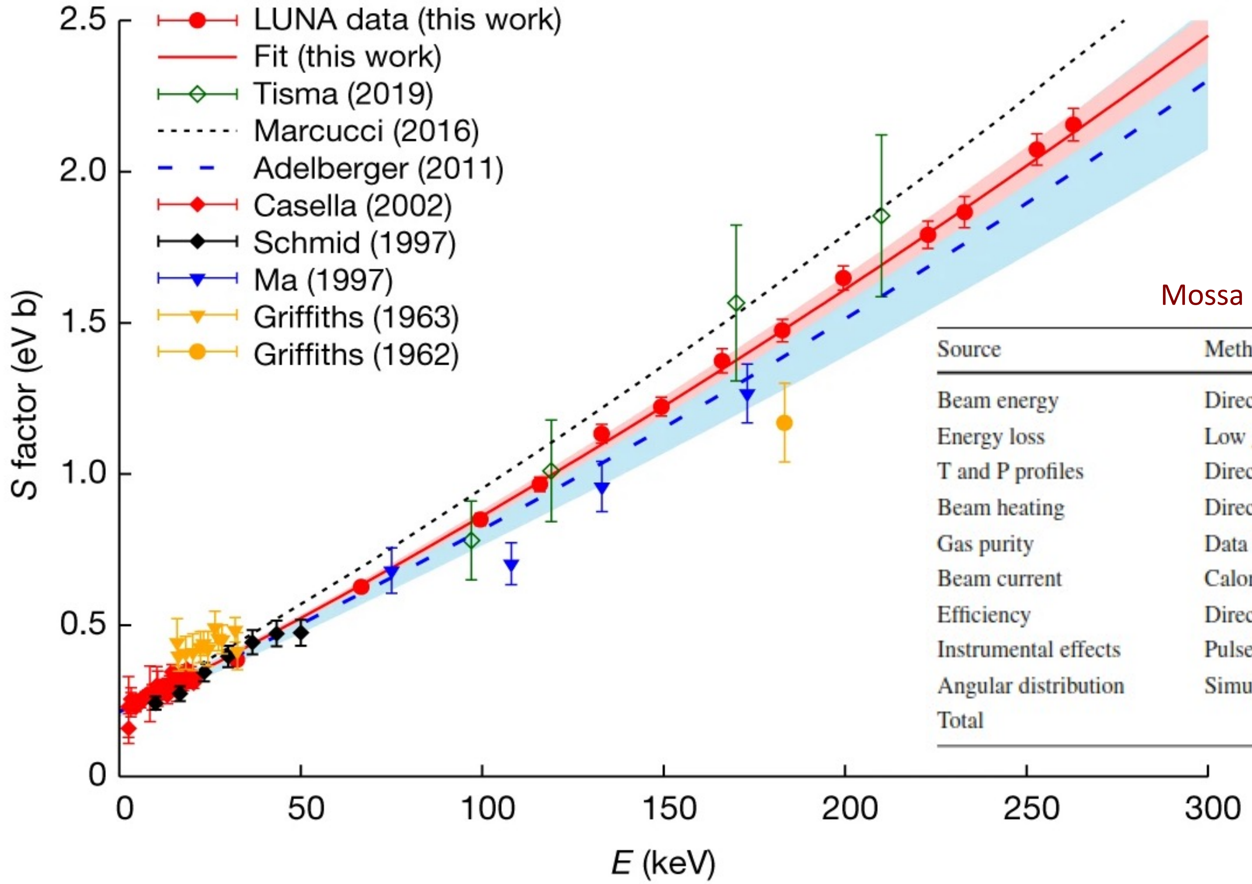
E_p = 395 keV



significant background

suppression underground

Astrophysical S factor



Mossa et al. EPJA, 56 (2020) 144

Source	Method	ΔS/S (%)
Beam energy	Direct measurement	0.2
Energy loss	Low gas pressure	0.04
T and P profiles	Direct measurement	1.0
Beam heating	Direct measurement	0.5
Gas purity	Data sheet	0.1
Beam current	Calorimeter calibration	1.0
Efficiency	Direct measurement	2.0
Instrumental effects	Pulser method	0.2
Angular distribution	Simulations	0.5
Total		2.6

Mossa et al. Nature, 587 (2020) 210

Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, G. Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli

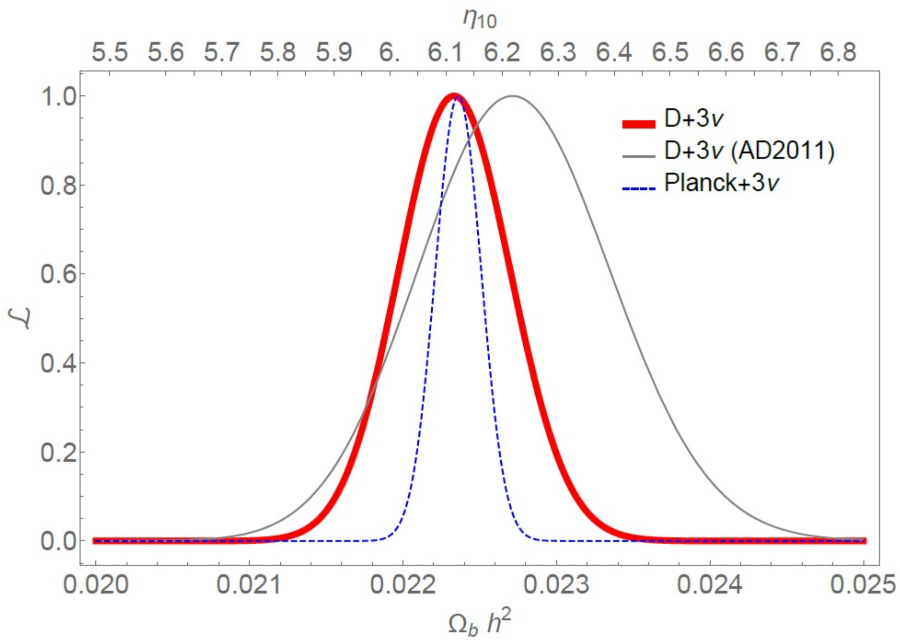
-Show fewer authors

Nature **587**, 210–213(2020) | Cite this article

standard cosmological model seems safe for now...

baryon density ($\Omega_b h^2$)
now in excellent
agreement with Planck
and with comparable
uncertainty

analysis by
Gianpiero Mangano and Ofelia Pisanti

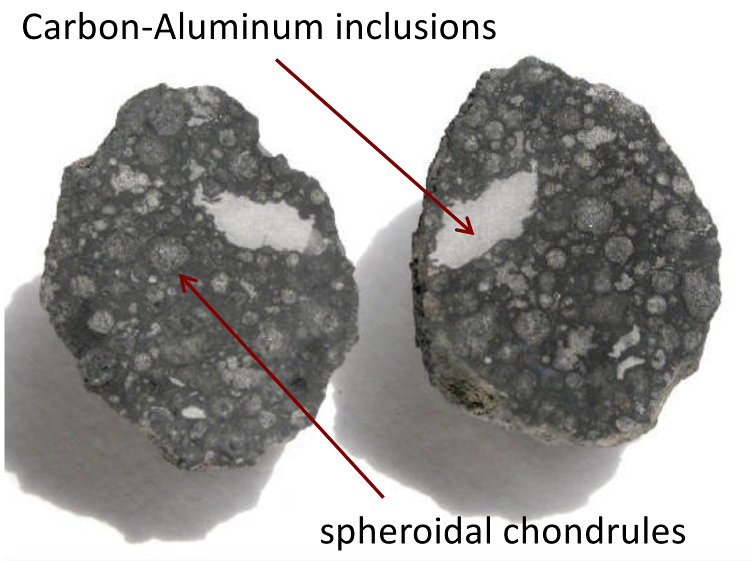


Pre-Solar Grains Composition

Rocks from Space: the Importance of Meteorites

fragment of Allende Meteorite
(named after nearest post office)
8 February 1969 – Mexico

- best known and most studied meteorite in history



isotopic composition different from solar

⬇

anomalies pinpoint to extra-solar origins

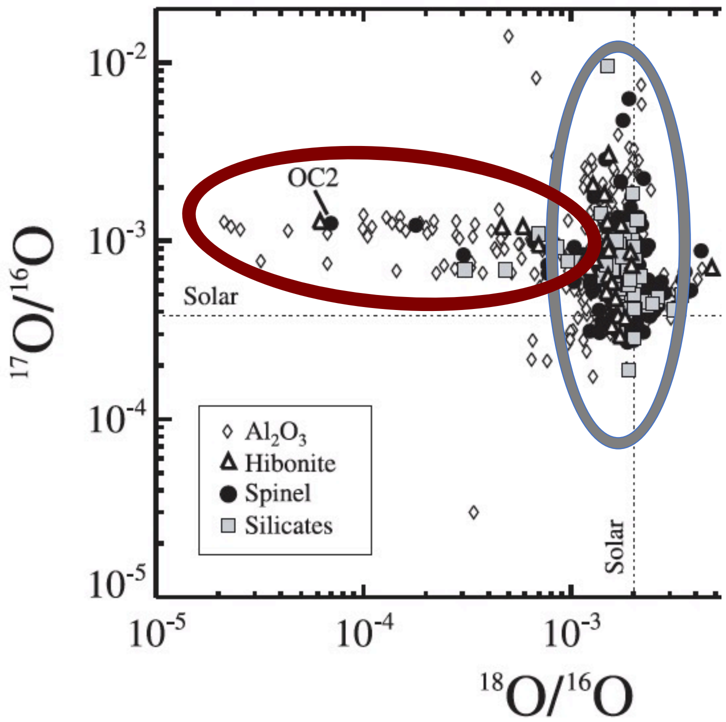
http://www.marmet-meteorites.com/id46.html

Pre-solar grains in meteorites

- Carbon-rich (diamond, graphite, silicon carbide)
- Oxygen-rich (silicates, Al-rich oxides, …)

Group I (about 75%): show excess in ^{17}O compared to solar values;
origin well-understood: red giants (1-3 $M_{\odot}$)

Group II (about 10%): excess in ^{17}O, but depleted in ^{18}O (up to 2 o.o.m. less than in solar system)
origin highly debated!



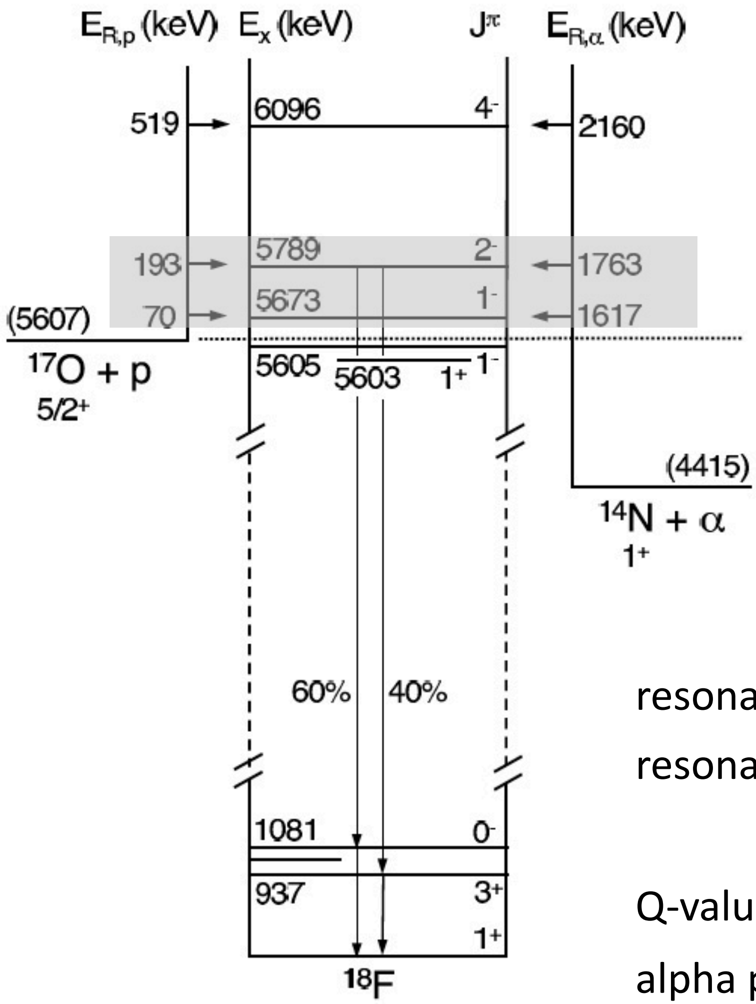
a renewed study of $^{17}O(p,\alpha)^{14}N$ reaction needed…

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

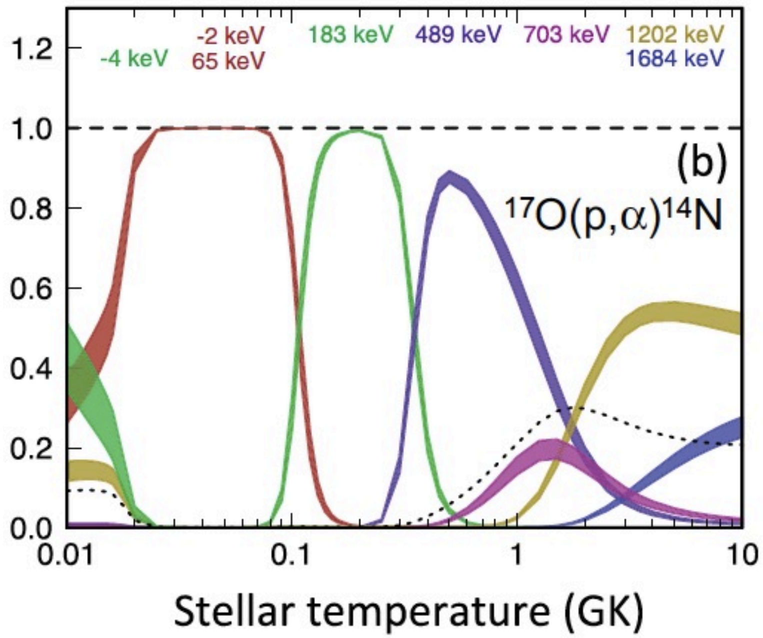
hydrogen burning in various stars + composition of pre-solar grains

PhD project

Carlo Bruno



Buckner et al, PRC 91 (2015) 015812



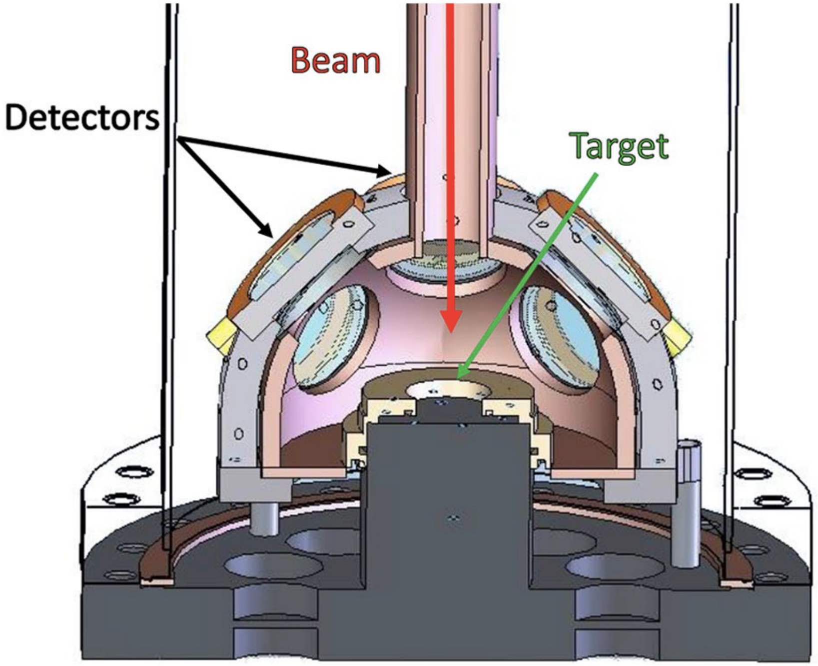
resonance strength of 193keV state well known

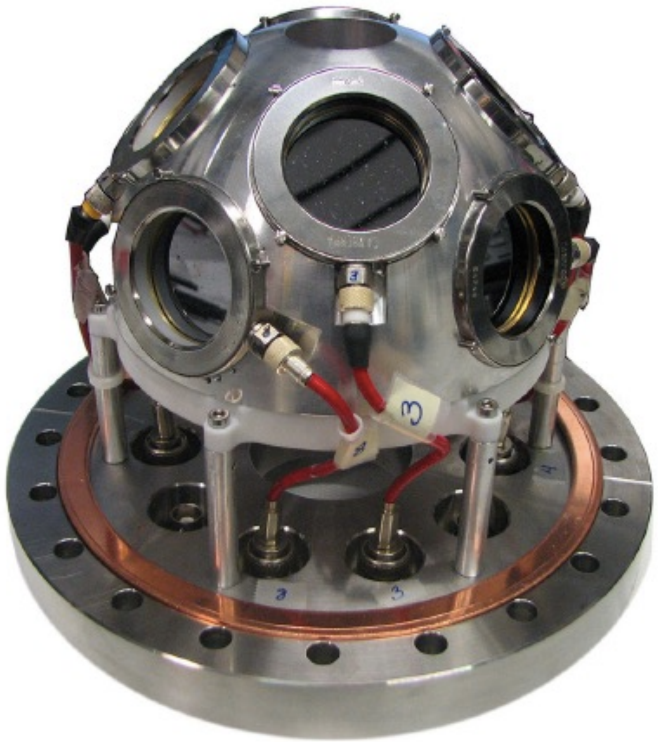
resonance strength of 70keV state largely uncertain

Q-value (p,α) reaction = 1.2 MeV

alpha particles energy at backward angles ~ 1MeV

Purpose-built scattering chamber to host array of 8 silicon detectors





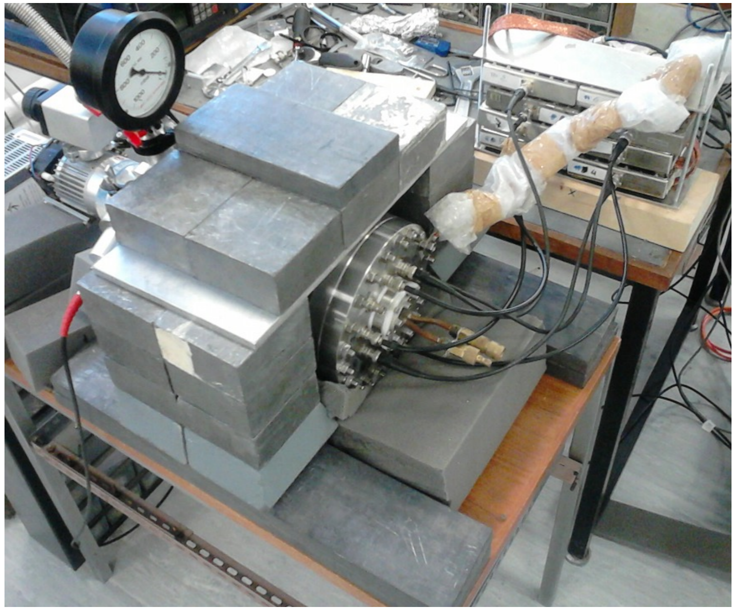
Bruno et al EJPA 51 (2015) 94

- protective aluminized Mylar foils before each detector
- expected alpha particle energy E ~ 200 keV (from 70 keV resonance in $^{17}O(p,\alpha)^{14}N$)

Commissioning Phase

- background measurements above- and under-ground; with and w/o shielding
- detector calibration + foils thickness measurement
- detection efficiency (simulations + measurements)
- re-determination of 193keV resonance strength

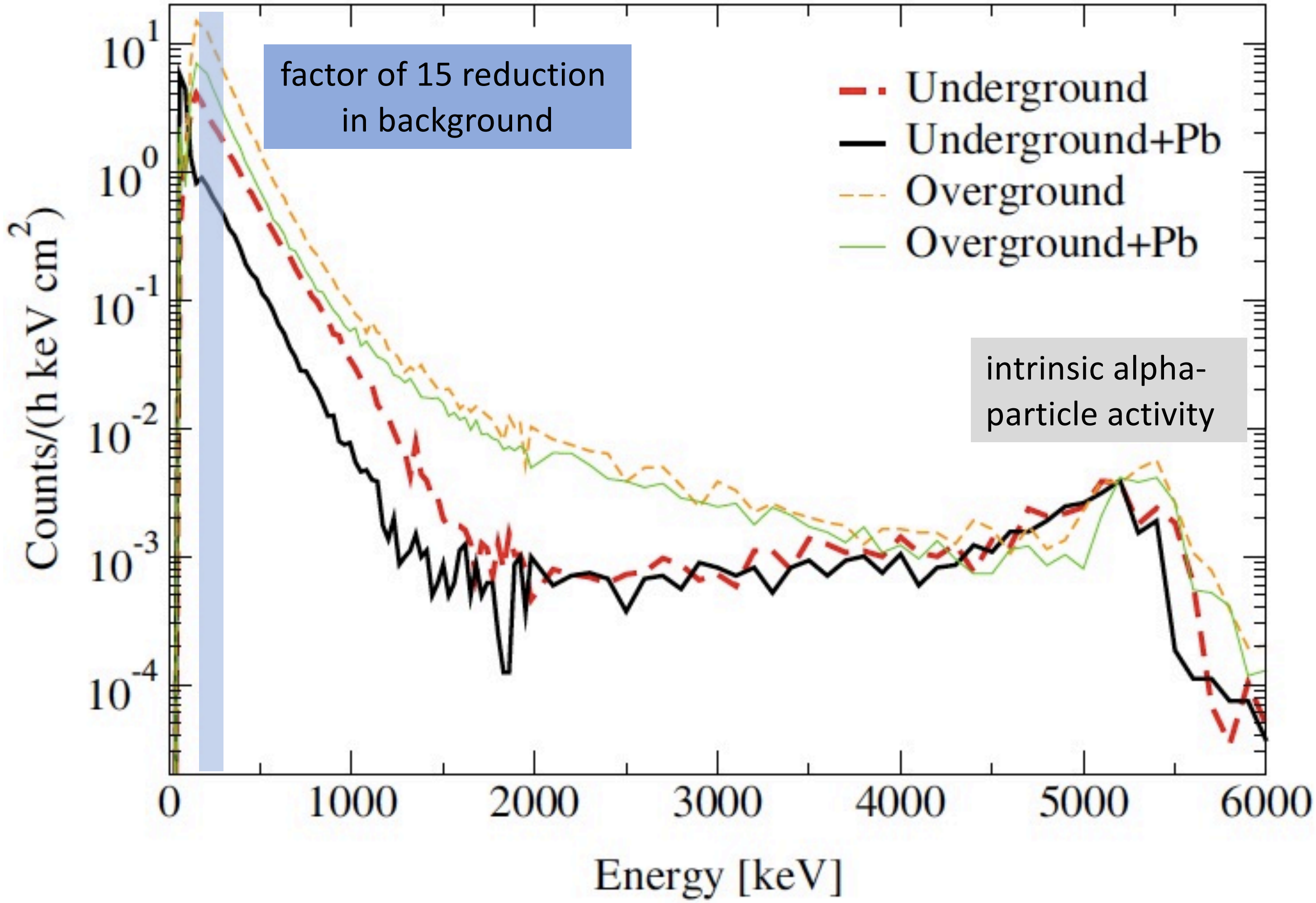
Edinburgh



Gran Sasso

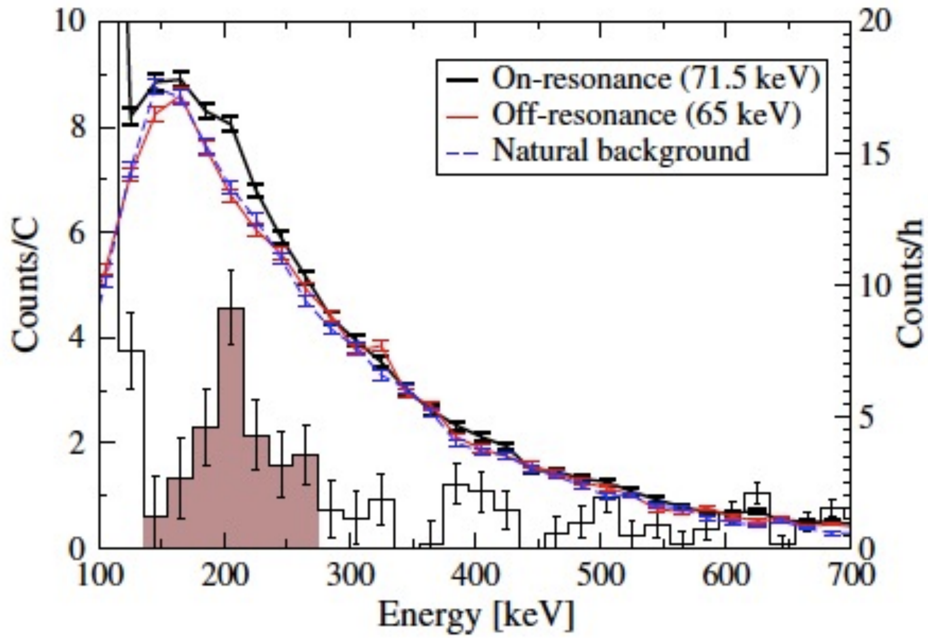
Background Suppression

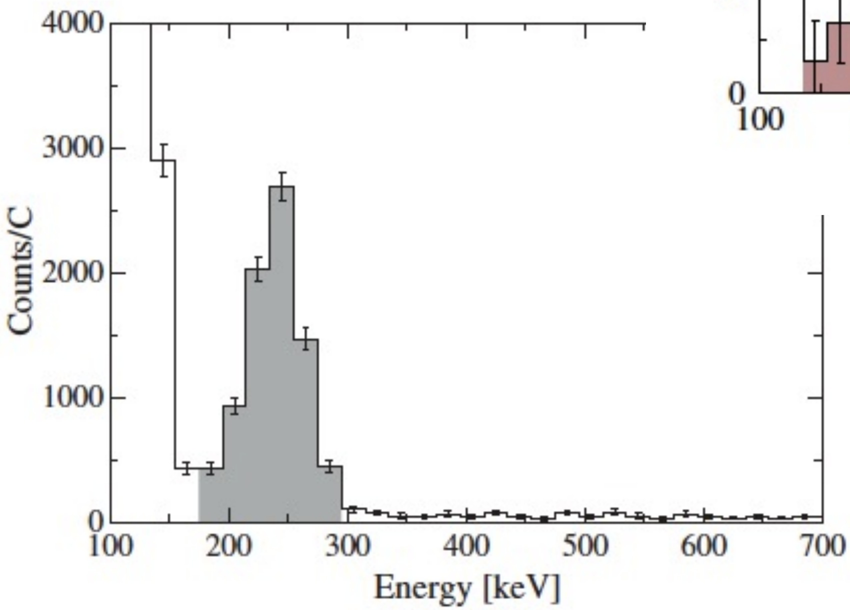
CG Bruno et al. EPJA 51 (2015) 94



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

use stronger 193keV resonance to identify ROI for expected alpha particles from 70keV state





$\omega\gamma$ = 10.0 ± 1.4 (stat) ± 0.7 (sys) neV

most accurate result to date

M Aliotta

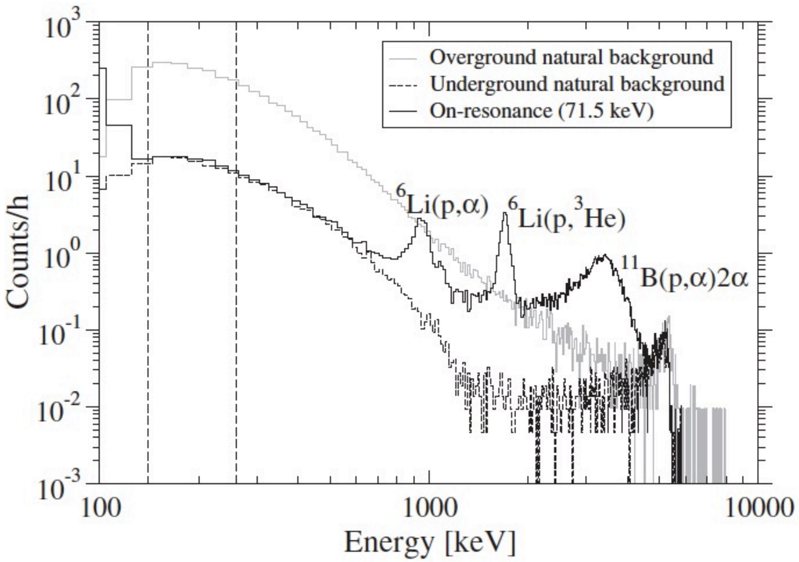
$^{17}O(p,\alpha)^{14}N$ Results

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

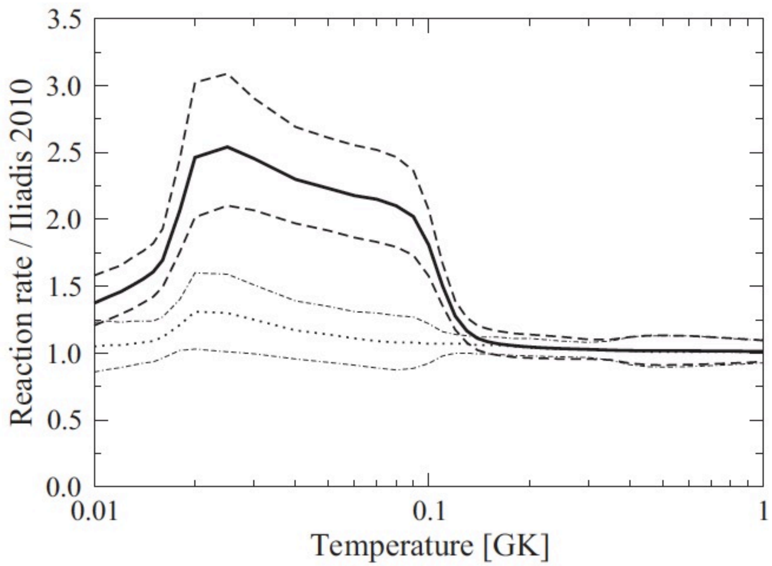
Improved Direct Measurement of the 64.5 keV Resonance Strength in the $^{17}O(p,\alpha)^{14}N$ Reaction at LUNA

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]

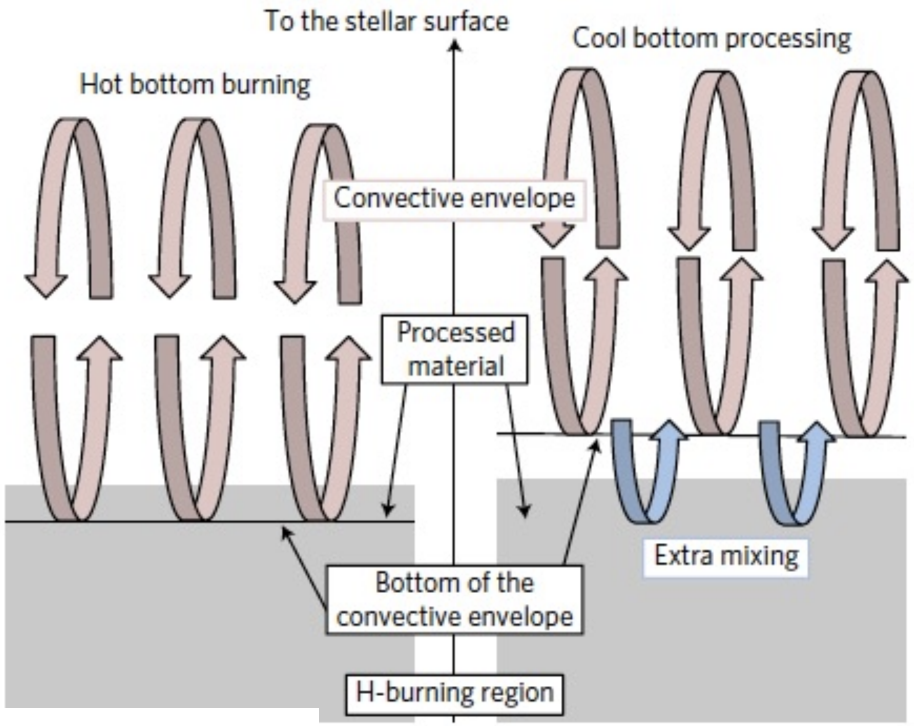
15x background reduction in ROI
+ improved experimental conditions



reaction rate ~ 2-2.5x higher
than previously assumed



Massive (4-8 $M_\odot$) AGB stars expected to produce large amounts of dust, BUT…



M Lugaro et al., Nature Astronomy 1 (2017) 0027

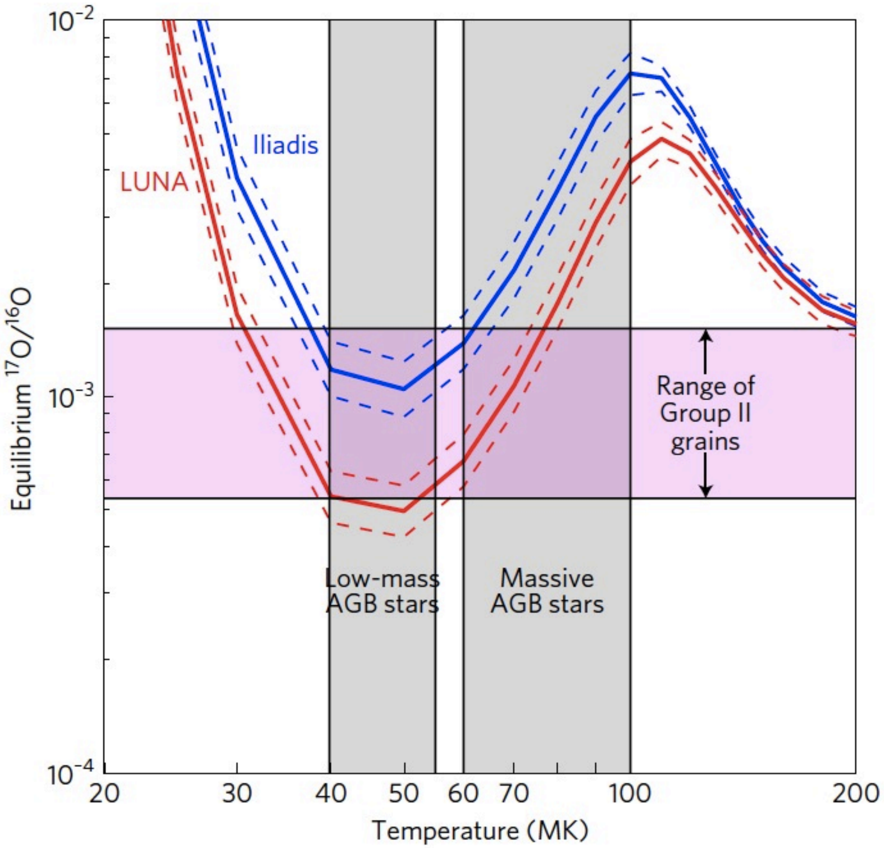
massive AGB stars
Hot Bottom Burning

low-mass AGB stars
Cool Bottom Processing

higher temperatures (60-100 MK)
mixing due to convection

lower temperatures (40-55 MK)
mixing due to *ad-hoc* “extra mixing”

On the origin of Group II grains



with previous $^{17}O(p,\alpha)^{14}N$ reaction rate (Iliadis, 2010):

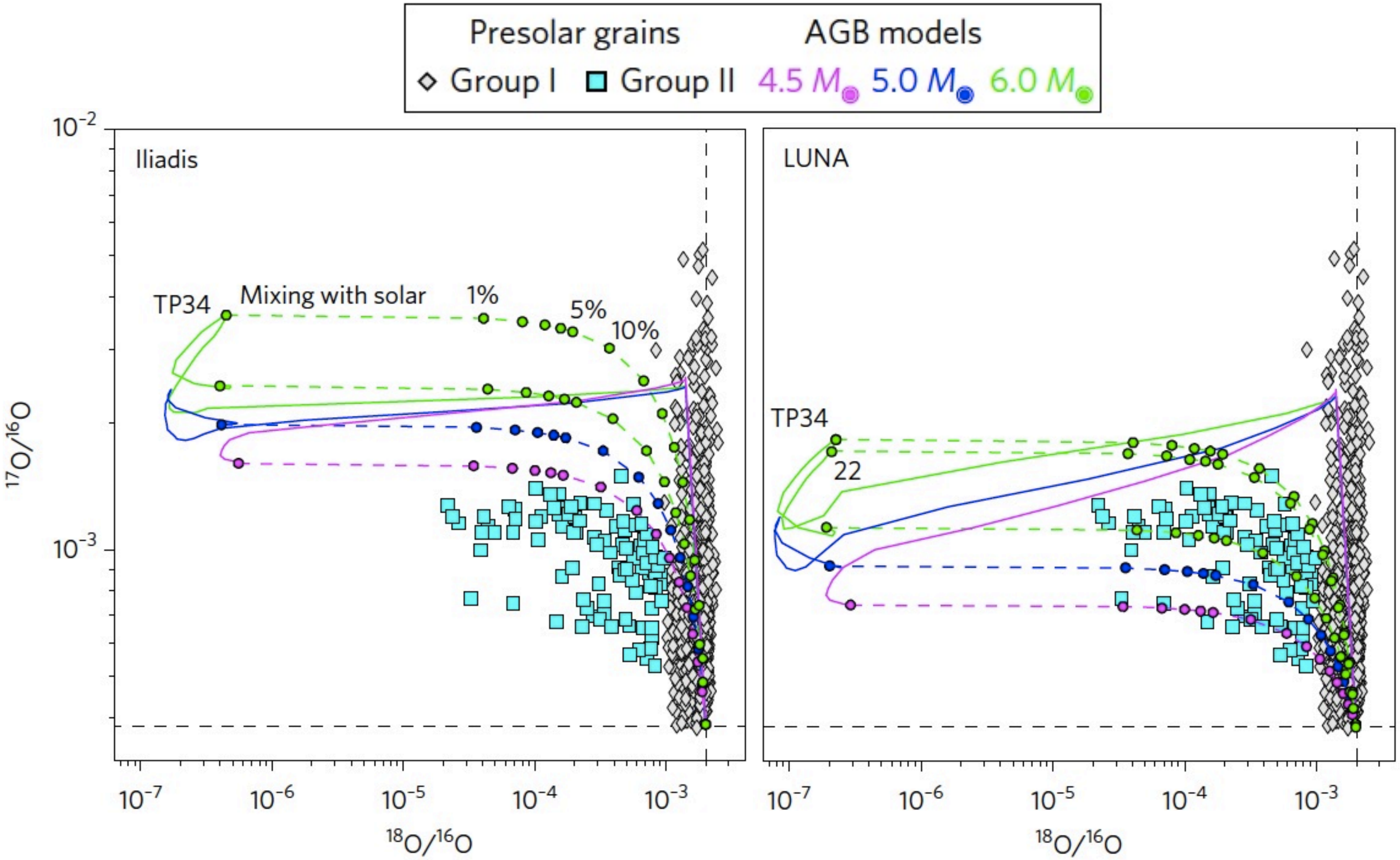
- massive AGB stars excluded as possible sites of origin
- low-mass AGB stars can be a possible site, but extra mixing process unclear

with new reaction rate (LUNA , 2016):

- massive AGB stars become likely site of origin (as expected)
- no need to invoke "extra mixing"

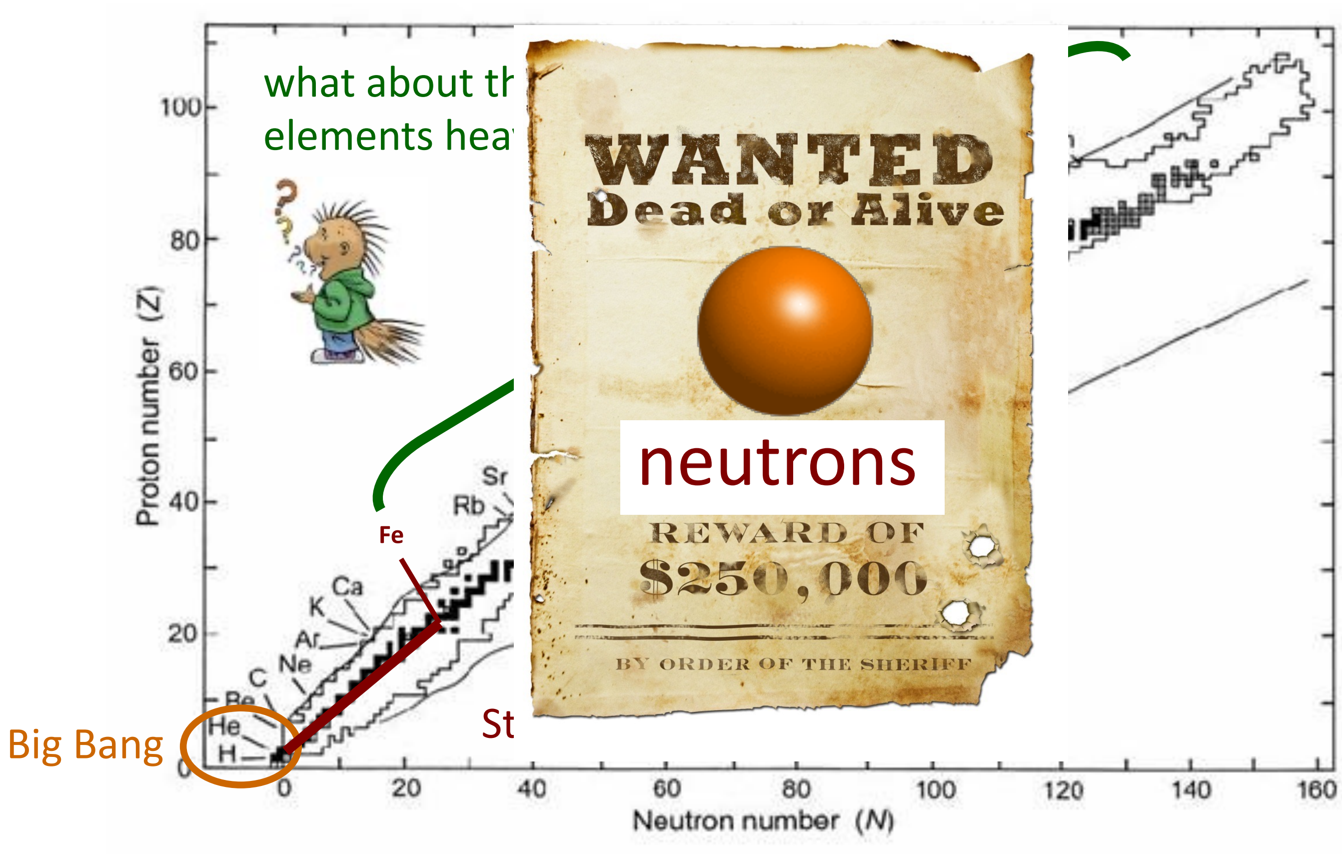
M Lugaro et al., Nature Astronomy 1 (2017) 0027

On the origin of Group II grains



M Lugaro et al., Nature Astronomy 1 (2017) 0027

The Creation of Heavy Elements

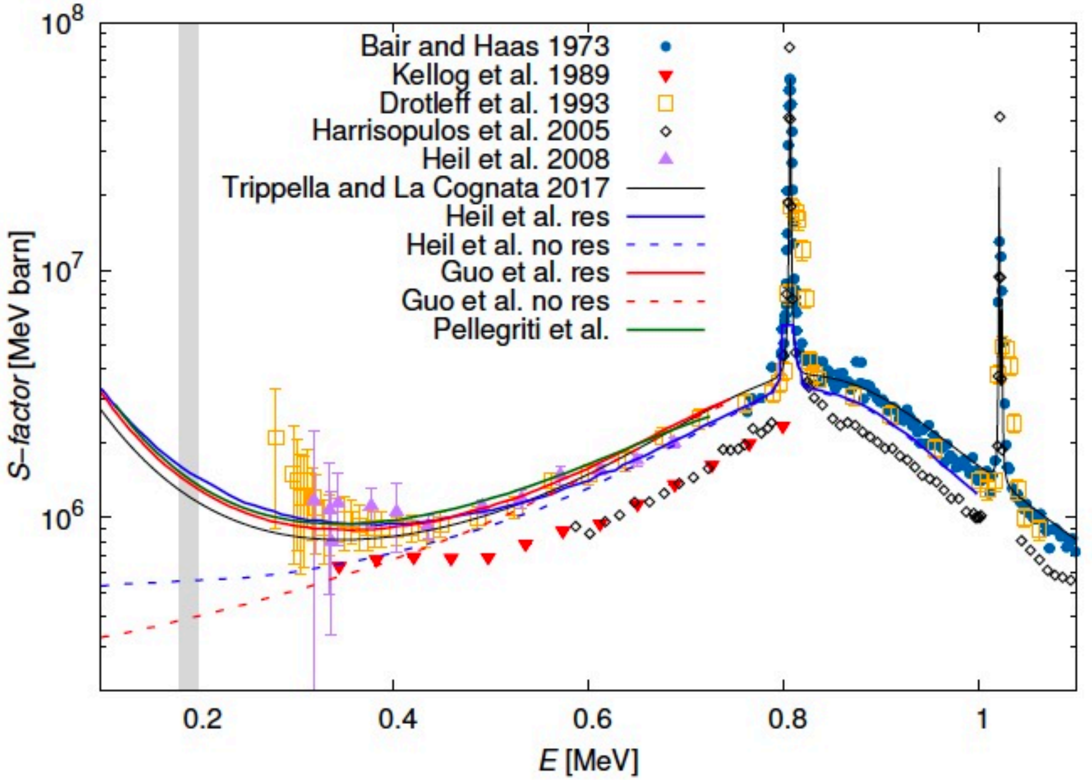


Neutron capture reactions: the s(low) and the r(apid) processes

Neutron Sources for the s-process

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

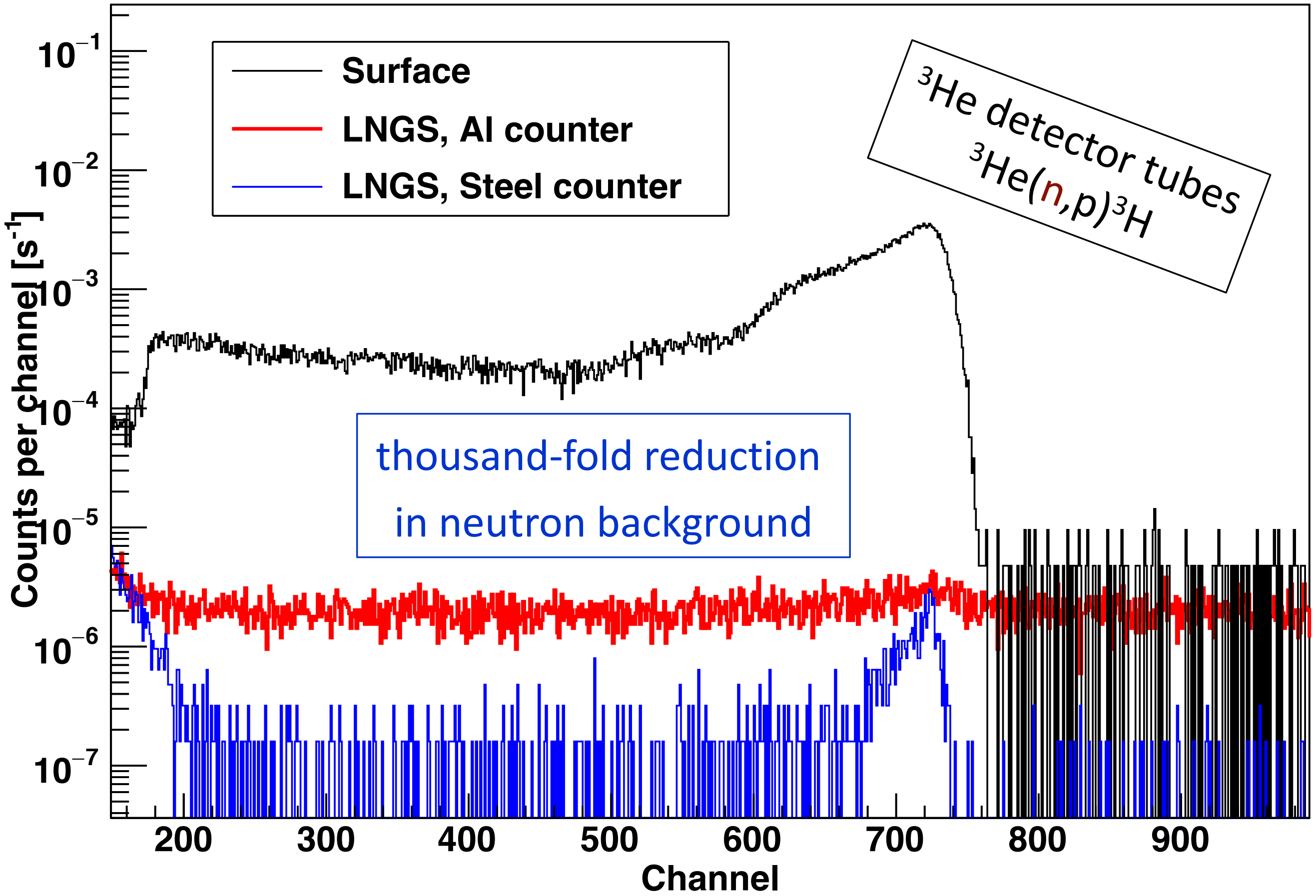
importance: s-process in AGB stars
Gamow region: 130 - 250 keV
min. meas. E_{cm}: 280 keV



Broggini et al. Progr. Part. Nucl. Phys. 98 (2018) 55

mainly hampered by cosmic background → excellent case for underground study

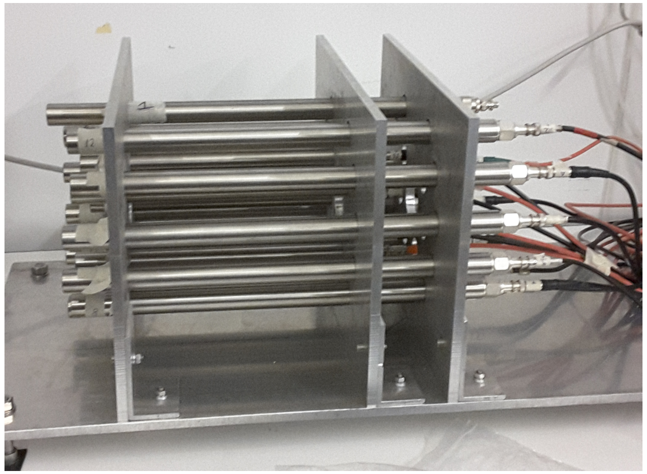
LUNA: an ideal environment for neutron detection



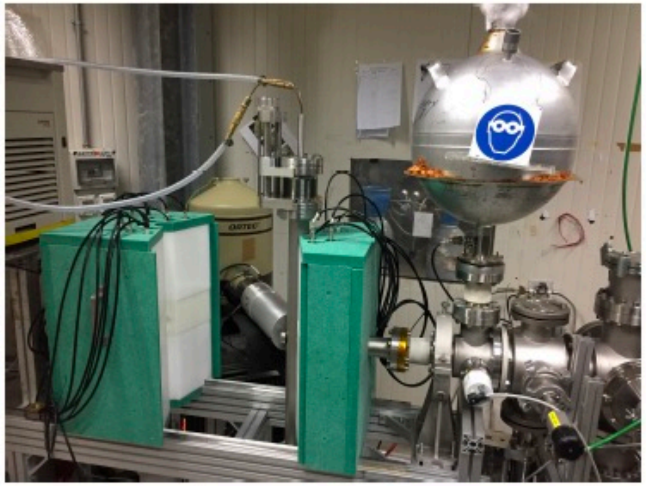
courtesy: Andreas Best

$^{13}C(a,n)^{16}O$ reaction at LUNA; Experimental Setup

- H^+ and He^+ beams (300 μA)
- E_{beam} < 400 keV
- 18 stainless steel ^3He counters (P = 10 bar)
- PE moderator + 1” borated PE shield
- Digital DAQ for Pulse Shape Discrimination
- neutron background [ROI]: 1.2±0.1 n/h



multi-target, vertical arrangement:
detector commissioning, target characterization



single-target, horizontal arrangement:
low-energy cross section measurements

$^{13}C(a,n)^{16}O$ reaction at LUNA: Detection Efficiency

Efficiency measurements

- $^{51}V(p,n)^{51}Cr$
- AmBe source
- simulations

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

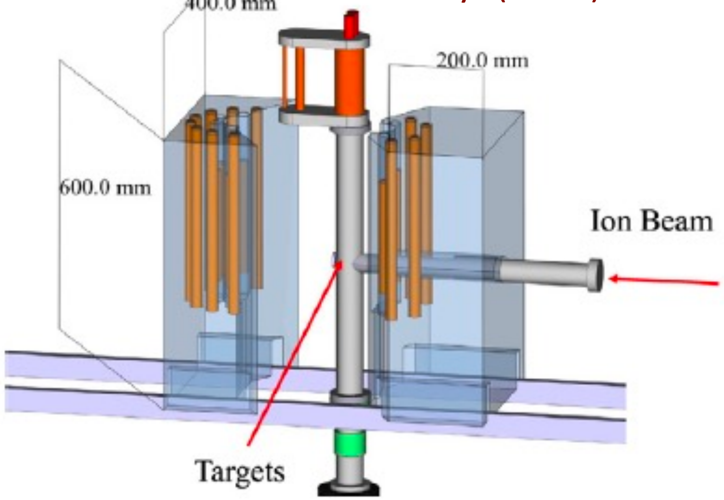
journal homepage: www.elsevier.com/locate/nima

ELSEVIER

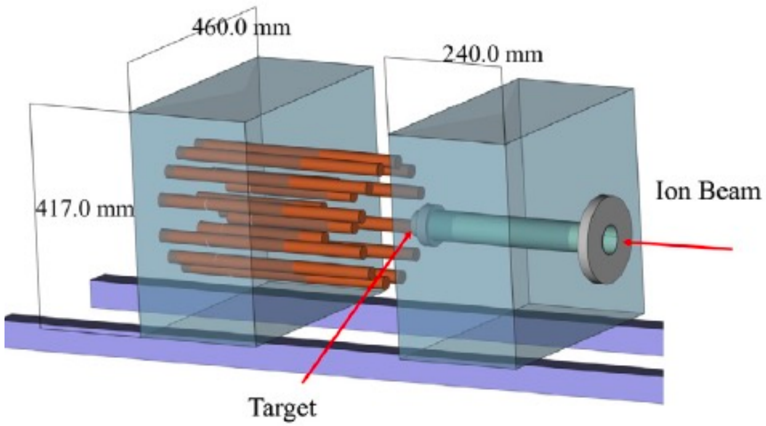
Characterization of the LUNA neutron detector array for the measurement of the $^{13}C(\alpha, n)^{16}O$ reaction

L. Csedreki [a,b,c,*], G.F. Ciani [a,b,c], J. Balibrea-Correa [d], A. Best [d], M. Aliotta [e], F. Barile [f], D. Bemmerer [g], A. Boeltzig [a], C. Broggini [h], C.G. Bruno [e], A. Caciolli [h,i], F. Cavanna [j], T. Chillery [e], P. Colombetti [j,k], P. Corvisiero [l,m], T. Davinson [e], R. Depalo [h,i], A. Di Leva [d], Z. Elekes [c], F. Ferraro [l,m], E.M. Fiore [f,n], A. Formicola [a], Zs. Fülöp [c], G. Gervino [j,k], A. Guglielmetti [o], C. Gustavino [p], Gy. Gyürky [c], G. Imbriani [d], Z. Janas [q], M. Junker [a], I. Kochanek [a], M. Lugaro [r,w], P. Marigo [h,i], E. Masha [o], C. Mazzocchi [q], R. Menegazzo [h], V. Mossa [f], F.R. Pantaleo [f,s], V. Paticchio [f], R. Perrino [f], D. Piatti [h,i], P. Prati [l,m], L. Schiavulli [f,n], K. Stöckel [g,t], O. Straniero [a,u], T. Szücs [c], M.P. Takács [g,t], F. Terrasi [v], S. Zavatarelli [l]

efficiency: (34±3)%



efficiency: (38±3)%



M. Aliotta

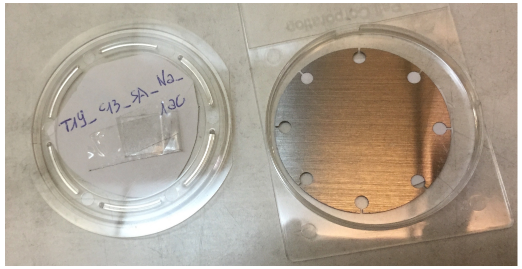
$^{13}C(a,n)^{16}O$ reaction at LUNA: Target Degradation

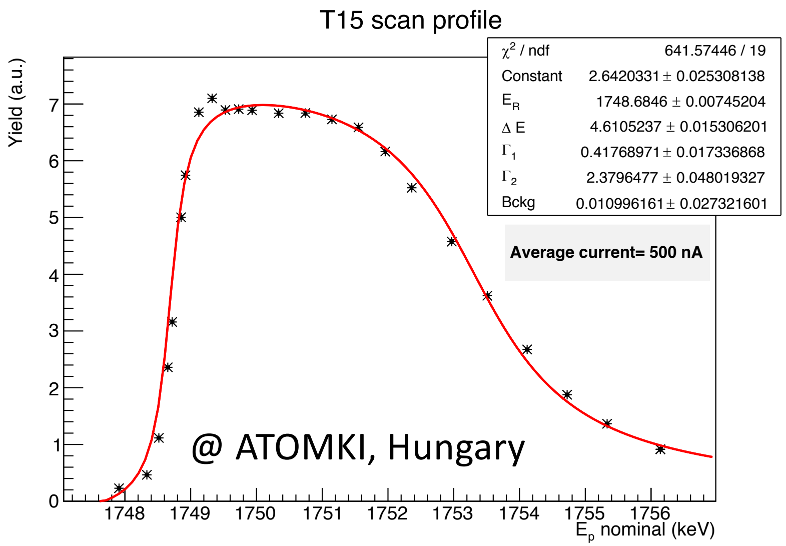
Eur. Phys. J. A (2020) 56:75
https://doi.org/10.1140/epja/s10050-020-00077-0
THE EUROPEAN PHYSICAL JOURNAL A
Special Article - New Tools and Techniques

A new approach to monitor ^{13}C-targets degradation in situ for $^{13}C(\alpha, n)^{16}O$ cross-section measurements at LUNA

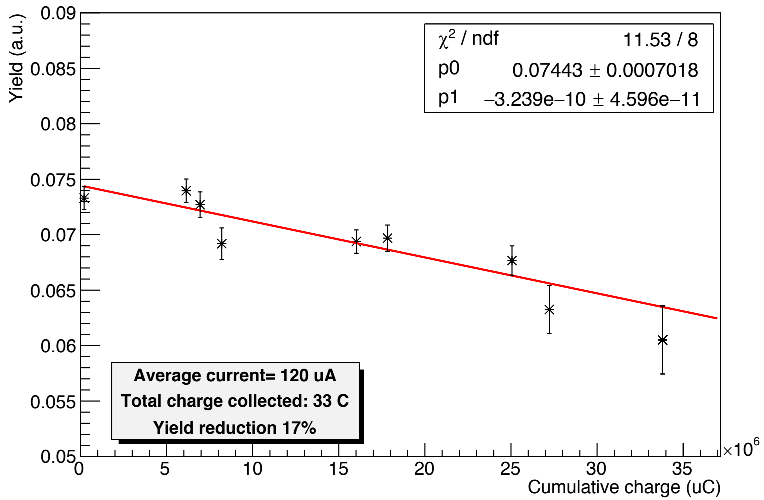
G. F. Ciani[1,2,3,a], L. Csedreki[1,2,b], J. Balibrea-Correa[4,5], A. Best[4,5], M. Aliotta[6], F. Barile[7], D. Bemmerer[8], A. Boeltzig[1,2], C. Broggini[9], C. G. Bruno[6], A. Caciolli[9,10], F. Cavanna[11], T. Chillery[6], P. Colombetti[12,13], P. Corvisiero[11,14], T. Davinson[6], R. Depalo[9], A. Di Leva[4,5], L. Di Paolo[2], Z. Elekes[3], F. Ferraro[11,14], E. M. Fiore[7,15], A. Formicola[2], Zs. Fülöp[3], G. Gervino[12,13], A. Guglielmetti[16,17], C. Gustavino[18], Gy. Gyürky[3], G. Imbriani[4,5], M. Junker[2], I. Kochanek[2], M. Lugaro[19], P. Marigo[9,10], E. Masha[16,17], R. Menegazzo[9], V. Mossa[7], F. R. Pantaleo[7,20], V. Paticchio[7], R. Perrino[7,24], D. Piatti[9,10], P. Prati[11,14], L. Schiavulli[7,15], K. Stöckel[8,21], O. Straniero[2,22], T. Szücs[8], M. P. Takács[8,21,25], F. Terrasi[23], D. Trezzi[16,17], S. Zavatarelli[11]

99% enriched ^{13}C targets on Ta backing





17% yield reduction after 33C



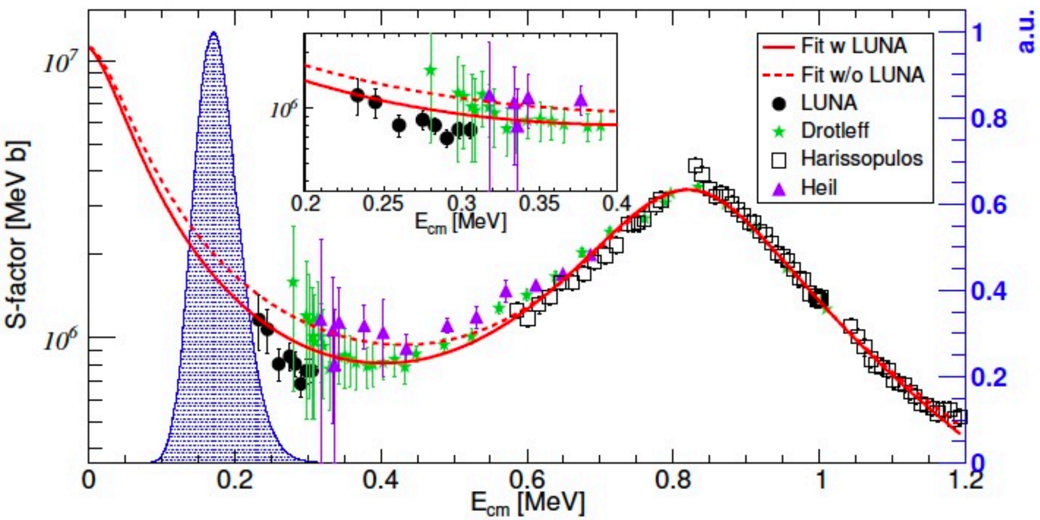
M. Aliotta

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

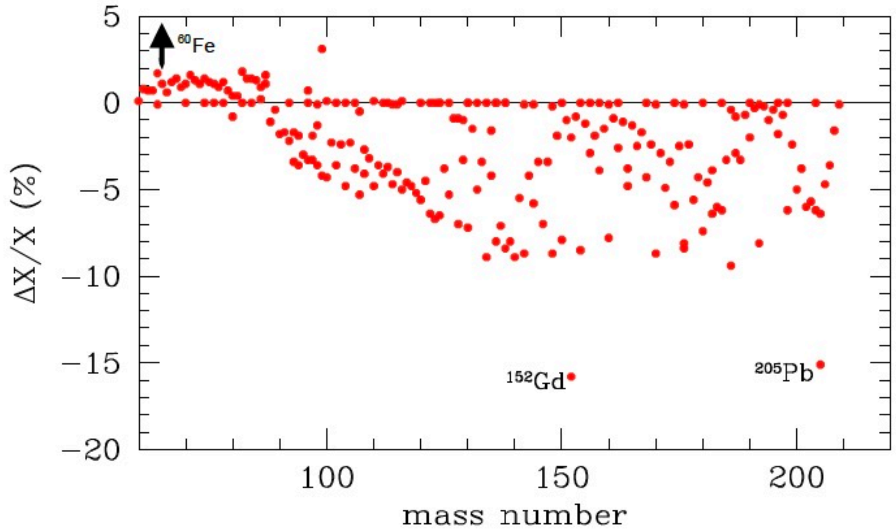
Direct measurement of the $^{13}C(\alpha,n)^{16}O$ cross section into the *s*-process Gamow peak

G.F. Ciani,[1,2,3] L. Csedreki,[1,2,3] D. Rapagnani,[4,5] M. Aliotta,[6] J. Balibrea-Correa,[4,5] F. Barile,[7,8] D. Bemmerer,[9] A. Best,[4,5,*] A. Boeltzig,[1,2] C. Broggini,[10] C.G. Bruno,[6] A. Caciolli,[10,11] F. Cavanna,[12] T. Chillery,[6] P. Corvisiero,[13,14] S. Cristallo,[15,16] T. Davinson,[6] R. Depalo,[11,10] A. Di Leva,[17] Z. Elekes,[3] F. Ferraro,[13,14] E. Fiore,[7,8] A. Formicola,[2,†] Zs. Fülöp,[3] G. Gervino,[18] A. Guglielmetti,[19] C. Gustavino,[20] Gy. Gyürky,[3] G. Imbriani,[17] M. Junker,[2] M. Lugaro,[21,22] P. Marigo,[10,11] E. Masha,[19] R. Menegazzo,[10] V. Mossa,[8] F.R. Pantaleo,[7,8] V. Paticchio,[8] R. Perrino,[8,‡] D. Piatti,[10,11] P. Prati,[13,14] L. Schiavulli,[7,8] K. Stöckel,[9,23] O. Straniero,[15,2] T. Szücs,[3] M.P. Takács,[9,23] F. Terrasi,[24] D. Vescovi,[16,25] and S. Zavatarelli[14]
(LUNA Collaboration)

PRL, 2021 (accepted)



- reached Gamow peak for the first time
- 50 keV below lowest direct measurement to date



- sizeable percentage variations in abundances, especially ^{60}Fe (+102%)

Other Recent Studies

The $^{22}Ne(p,\gamma)^{23}Na$ reaction at LUNA

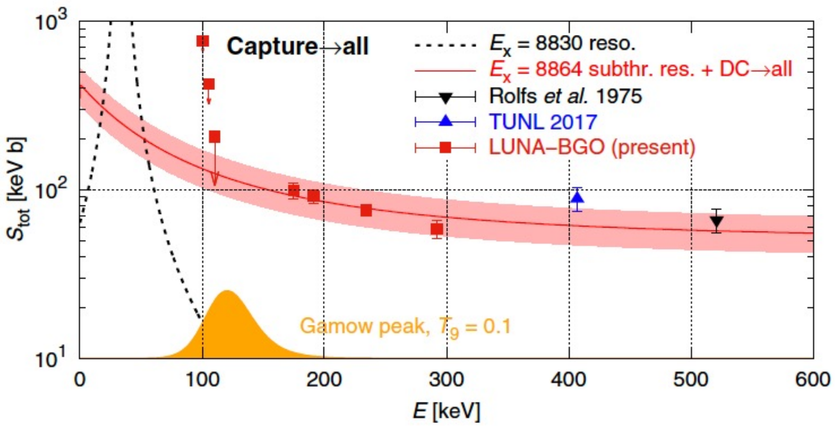
PHYSICAL REVIEW LETTERS **121,** 172701 (2018)

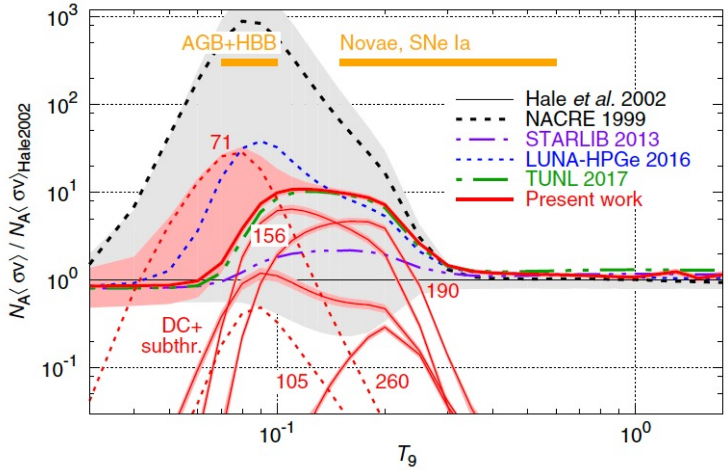
Direct Capture Cross Section and the $E_p = 71$ and 105 keV Resonances in the $^{22}Ne(p,\gamma)^{23}Na$ Reaction

F. Ferraro,[1,2] M. P. Takács,[3,4,§] D. Piatti,[5,6] F. Cavanna,[2] R. Depalo,[5,6] M. Aliotta,[7] D. Bemmerer,[3,*] A. Best,[8,9] A. Boeltzig,[10] C. Broggini,[6] C. G. Bruno,[7] A. Caciolli,[5,6,†] T. Chillery,[7] G. F. Ciani,[10,11] P. Corvisiero,[1,2] T. Davinson,[7] G. D'Erasmo,[12,13] A. Di Leva,[8,9] Z. Elekes,[14] E. M. Fiore,[12,13] A. Formicola,[11] Zs. Fülöp,[14] G. Gervino,[15,16] A. Guglielmetti,[17,18] C. Gustavino,[19] Gy. Gyürky,[14] G. Imbriani,[8,9] M. Junker,[11] A. Karakas,[20] I. Kochanek,[11] M. Lugaro,[21] P. Marigo,[5,6] R. Menegazzo,[6] V. Mossa,[12,13] F. R. Pantaleo,[12,13] V. Paticchio,[13] R. Perrino,[13,‡] P. Prati,[1,2] L. Schiavulli,[12,13] K. Stöckel,[3,4] O. Straniero,[22,9] T. Szücs,[3,14] D. Trezzi,[17,18] and S. Zavatarelli[2]

(LUNA Collaboration)

NeNa cycle and Na/O anticorrelation in globular clusters





M Aliotta

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

Physics Letters B 790 (2019) 237

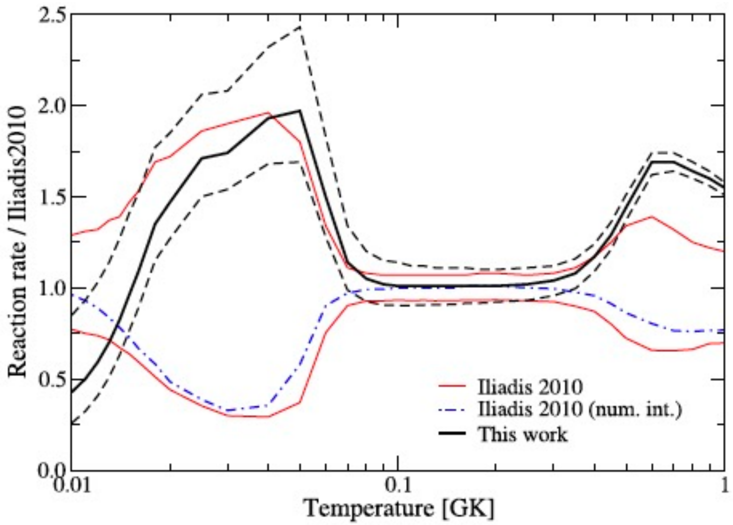
ELSEVIER

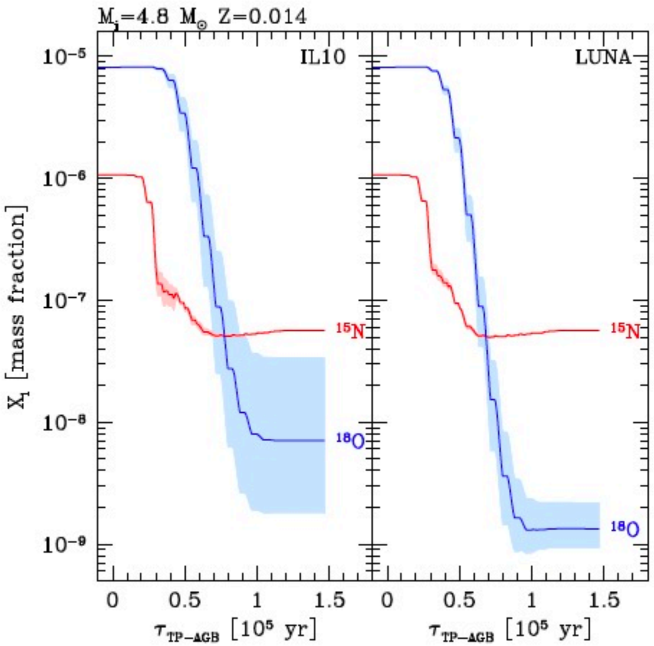
Improved astrophysical rate for the $^{18}O(p,\alpha)^{15}N$ reaction by underground measurements

C.G. Bruno [a,*], M. Aliotta [a,*], P. Descouvemont [b], A. Best [c], T. Davinson [a], D. Bemmerer [d], A. Boeltzig [e,f,1], C. Broggini [g], A. Caciolli [h], F. Cavanna [i], T. Chillery [a], G.F. Ciani [e], P. Corvisiero [i,j], R. Depalo [h], A. Di Leva [c], Z. Elekes [k], F. Ferraro [i,j], A. Formicola [f], Zs. Fülöp [k], G. Gervino [l], A. Guglielmetti [m], C. Gustavino [n], Gy. Gyürky [k], G. Imbriani [c], M. Junker [f], M. Lugaro [o], P. Marigo [g,h], R. Menegazzo [h], V. Mossa [p], F.R. Pantaleo [p], D. Piatti [h], P. Prati [i,j], K. Stöckel [d,q], O. Straniero [f,r], F. Strieder [s], T. Szücs [d,k], M.P. Takács [d,q], D. Trezzi [m]

nucleosynthesis and mixing processes in AGB stars

improved reaction rate



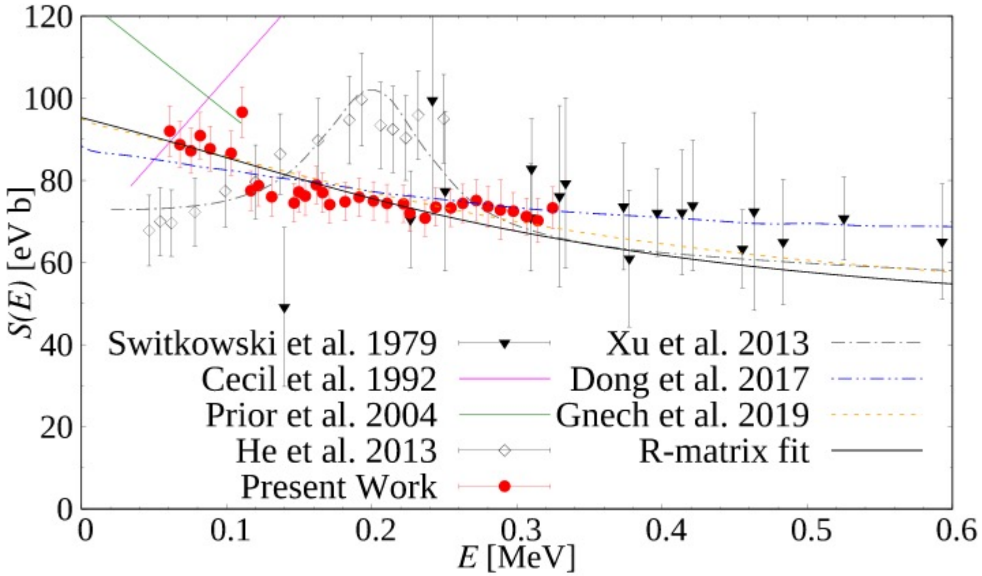


PHYSICAL REVIEW C **102**, 052802(R) (2020)

Rapid Communications

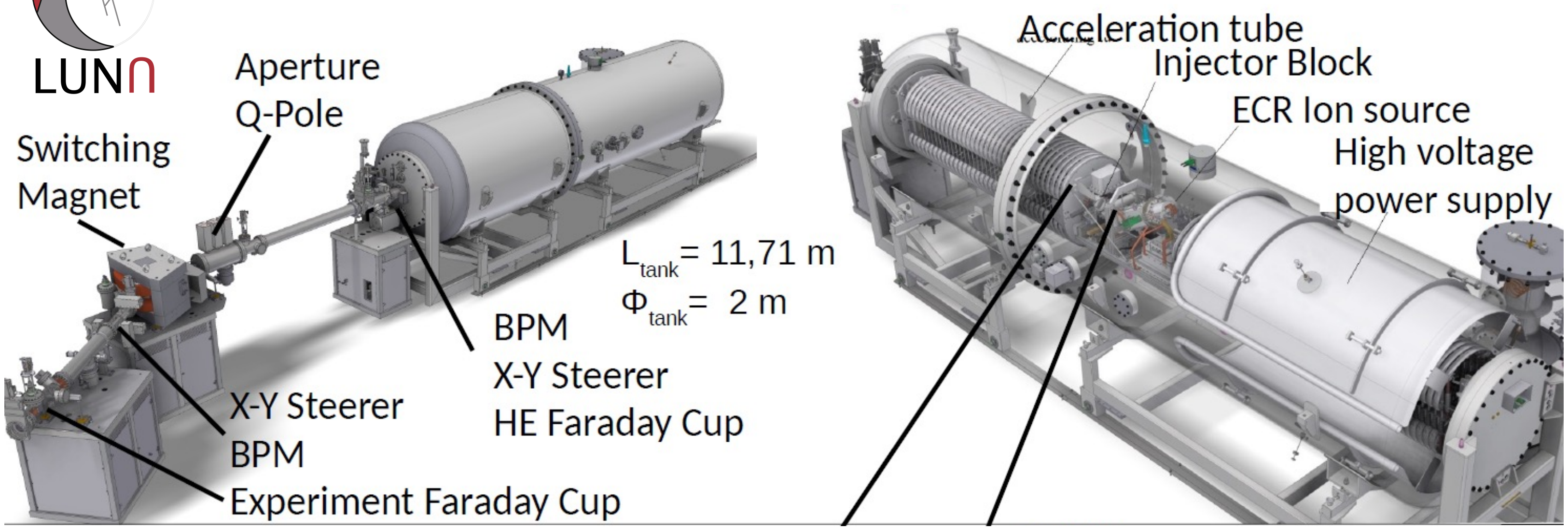
Underground experimental study finds no evidence of low-energy resonance in the ^{6}Li(p, γ)^{7}Be reaction

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)



Future Opportunities: LUNA MV

LUNA MV: A 3.5 MV Accelerator with ECR Ion Source



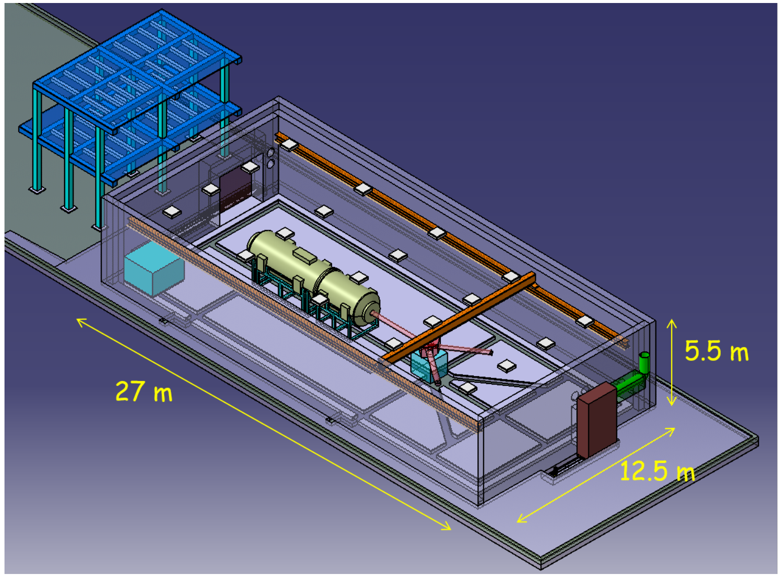
$^{1}H^{+}$ (TV: 0.3 – 0.5 MV): 500 μA
$^{1}H^{+}$ (TV: 0.5 – 3.5 MV): 1000 μA

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

$^{12}C^{+}$ (TV: 0.3 – 0.5 MV): 100 μA
$^{12}C^{+}$ (TV: 0.5 – 3.5 MV): 150 μA
$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 μA

LUNA MV - Construction Site

- Accelerator by High Voltage Engineering
- Tests completed
- Site at LNGS under completion
- Installation at LNGS: 2021
- Commissioning: 2021-2022

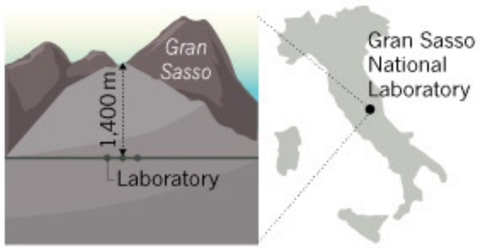


THE LUNA Collaboration

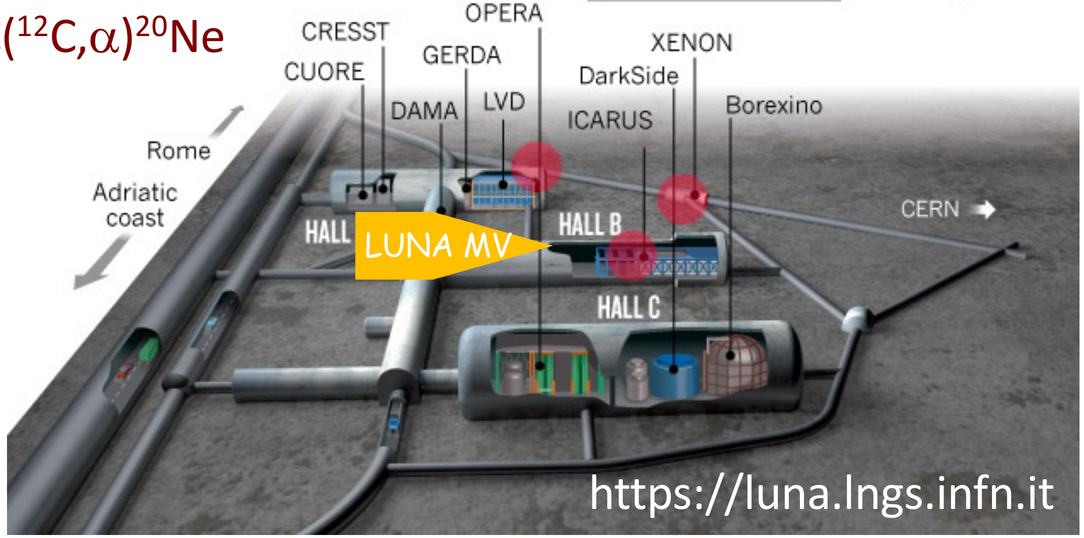
LUNA 50 kV (1992-2001) – Solar Phase

LUNA 400 kV (2000-present) – CNO, Mg-Al and Ne-Na cycles, BBN

LUNA-MV (from 2022) – Helium burning, Carbon burning



- $^{14}N(p,\gamma)^{15}O$ (commissioning)
- $^{12}C(^{12}C,p)^{23}Na$ and $^{12}C(^{12}C,\alpha)^{20}Ne$
- $^{13}C(\alpha,n)^{16}O$
- $^{22}Ne(\alpha,n)^{25}Mg$



M. Aliotta

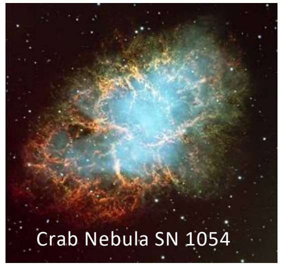
The $^{12}C+^{12}C$ fusion reactions: Current status

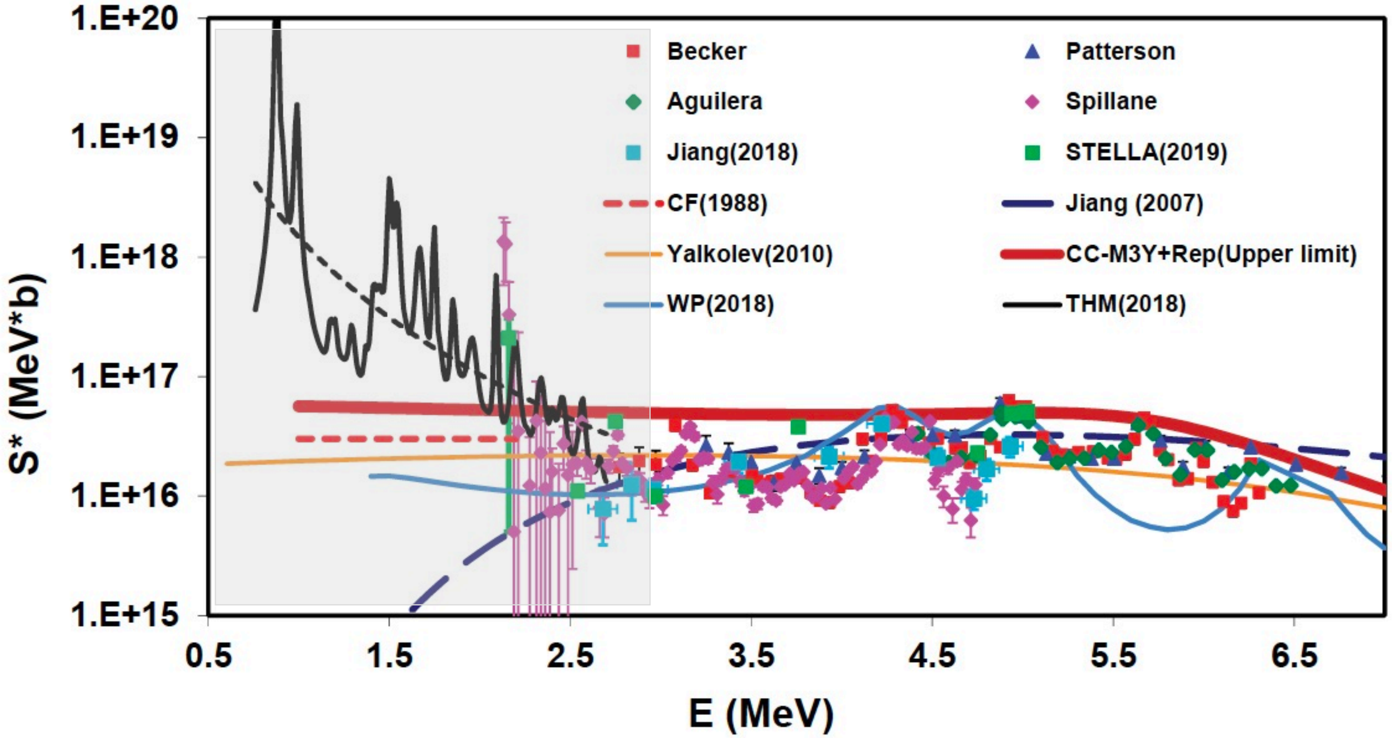
$^{12}C+^{12}C$

importance: evolution of massive stars

Gamow region: 1 – 3 MeV

min. measured E: 2.1 MeV (by γ-ray spectroscopy)





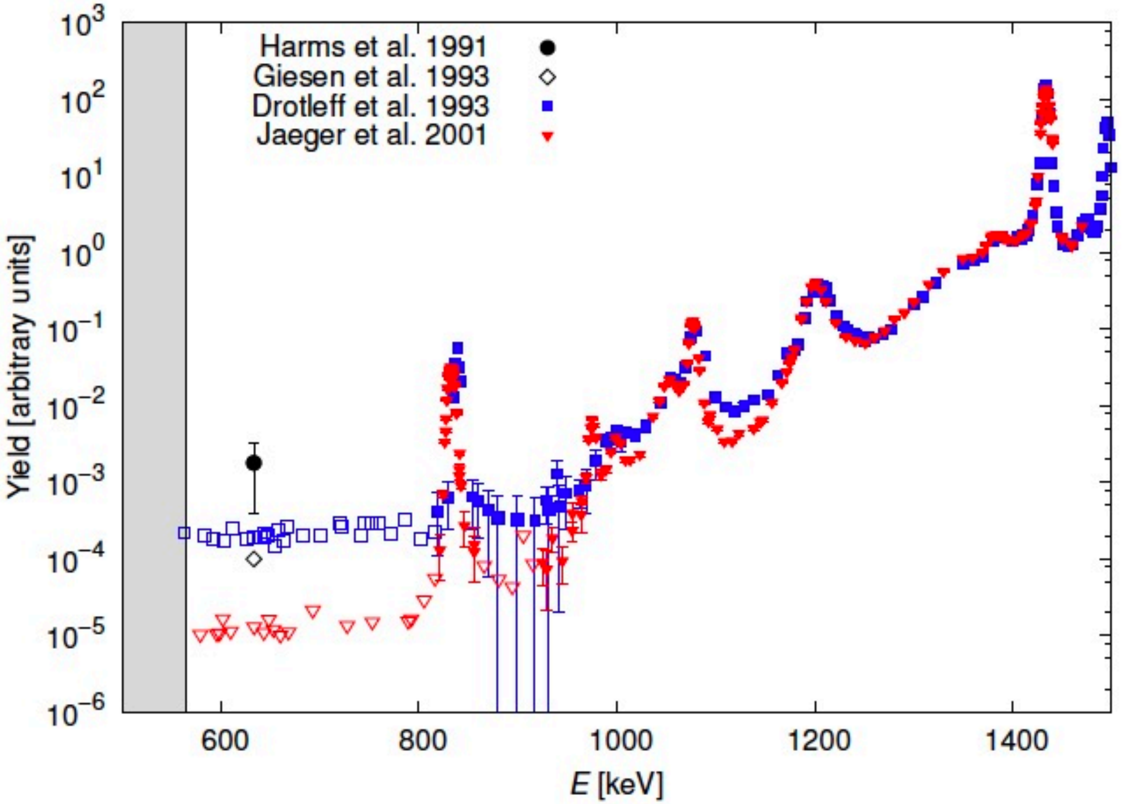
Beck et al. arXiv: 1909.06021v1

$^{22}Ne(\alpha,n)^{25}Mg$

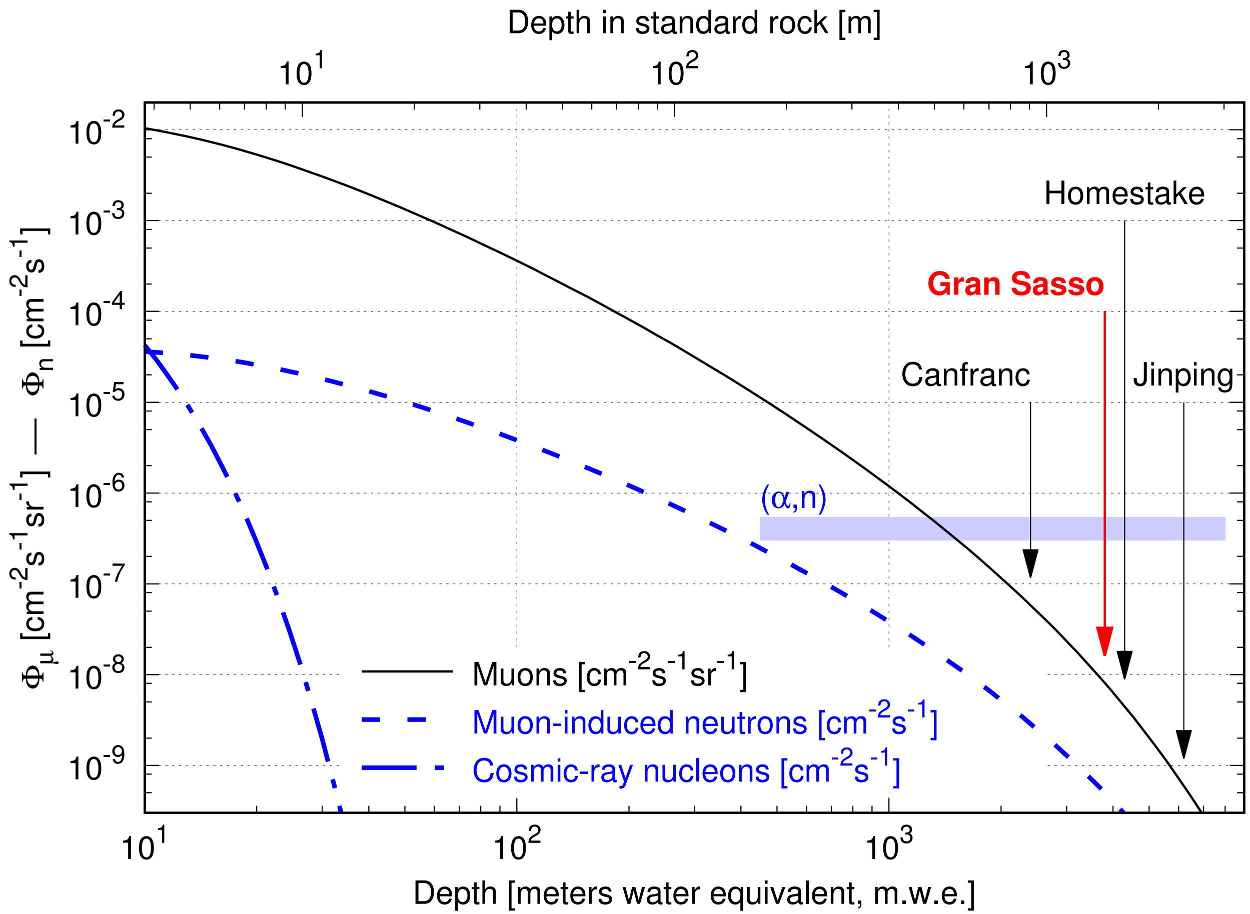
importance: weak s-process component

Gamow region: 360-690 keV

min. measured E: 700 keV



Broggini et al. Progr. Part. Nucl. Phys. 98 (2018) 55



courtesy: A Caciolli

CASPAR: Compact Accelerator Systems for Performing Astrophysical Research

SURF: Sanford Underground Laboratory at Homestake (4300 mwe)

Collaboration between:

- University of Notre Dame
- Colorado School of Mines
- South Dakota School of Mines and Technology

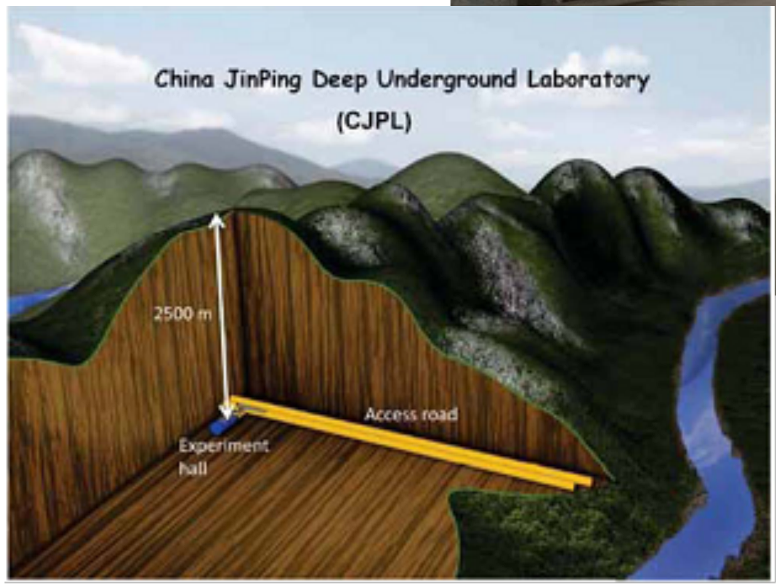
1 MV Accelerator Inaugurated July 2017

JUNA

Jinping Underground lab for Nuclear Astrophysics

锦屏深地核天体物理实验室

China Institute of Atomic Energy

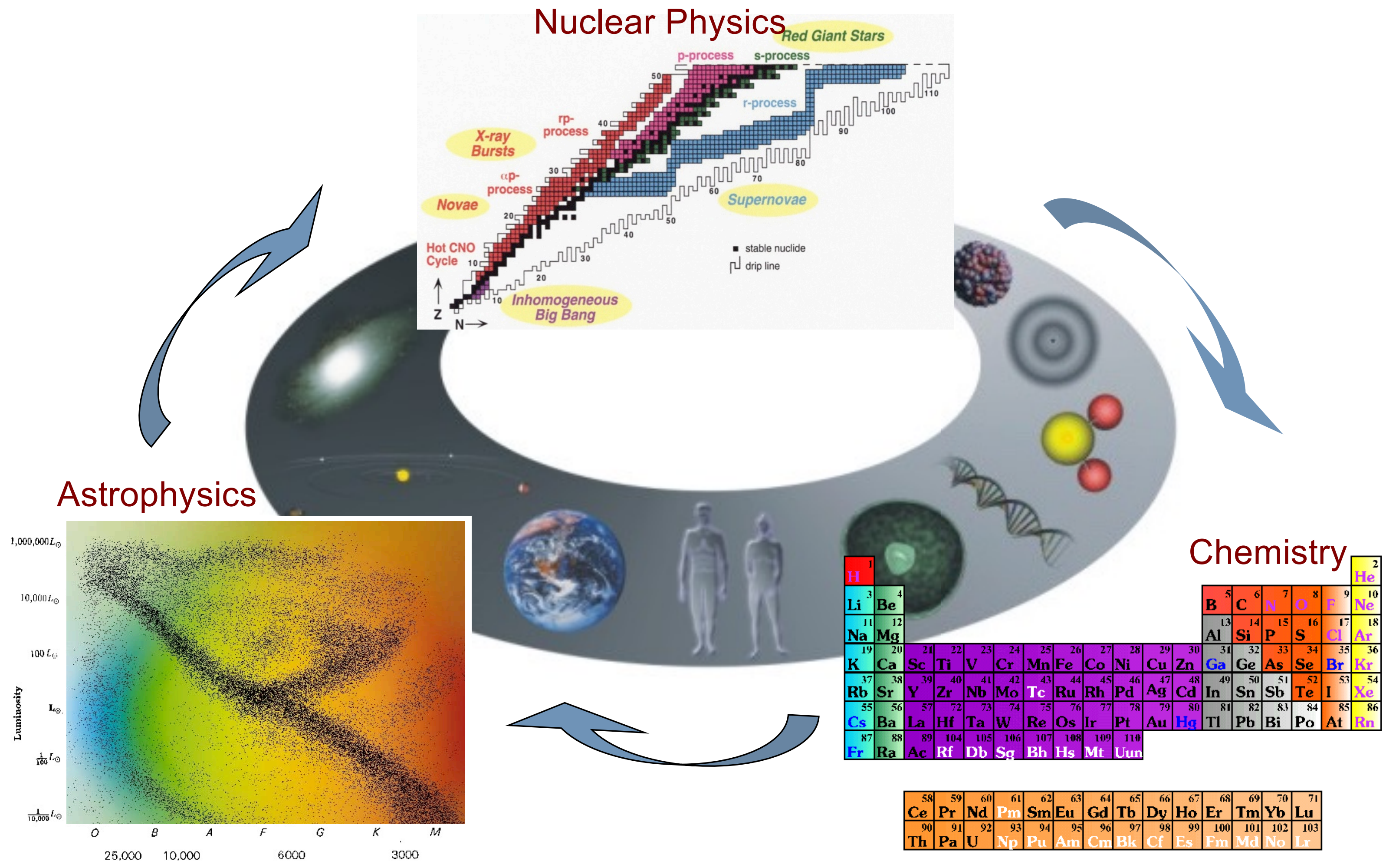


2,400 meters deep in a mountain in Sichuan Province

Operating since 2020

Summary and Outlook

The Role of Nuclear Physics



Central image credit:
Mackintosh, Al-Khalili, Jonson, Pena: Nucleus - A trip into the Heart of Matter, 2nd edition - Dundee University Press, 2011

Nuclear Astrophysics Underground

- low-energy nuclear astrophysics → experimental challenges
- underground accelerators essential for major advances
- pioneering work of LUNA

  major progress: H burning, CNO, NeNa, MgAl cycles
- much work still remains: helium and carbon burning
- new opportunities for a bright future


THANK YOU