Nuclear Astrophysics at LUNA: Status and Perspectives

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Scottish Universities Physics Alliance

European Nuclear Physics Conference, Bologna 3-7 September 2018

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

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…

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

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

PP-I (86%)

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

(14%)

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

PP-II (99.7%)

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

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

PP-III (0.3%)

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

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

$$\downarrow$$

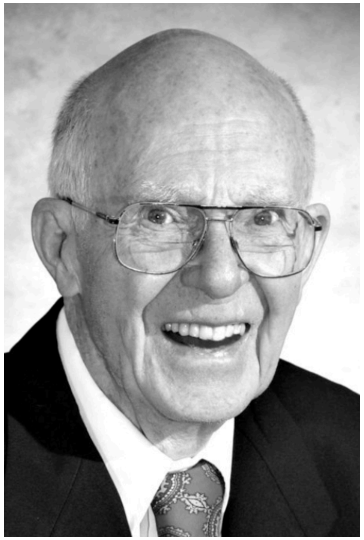
$$2\,{}^4He$$

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% | 14%

PP-I

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

what if this reaction has a resonance at solar energies?

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

99.7% | 0.3%

PP-II

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

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

PP-III

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

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

$\downarrow$

$2\,{}^4He$

a direct measurement of its cross section was necessary

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

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)

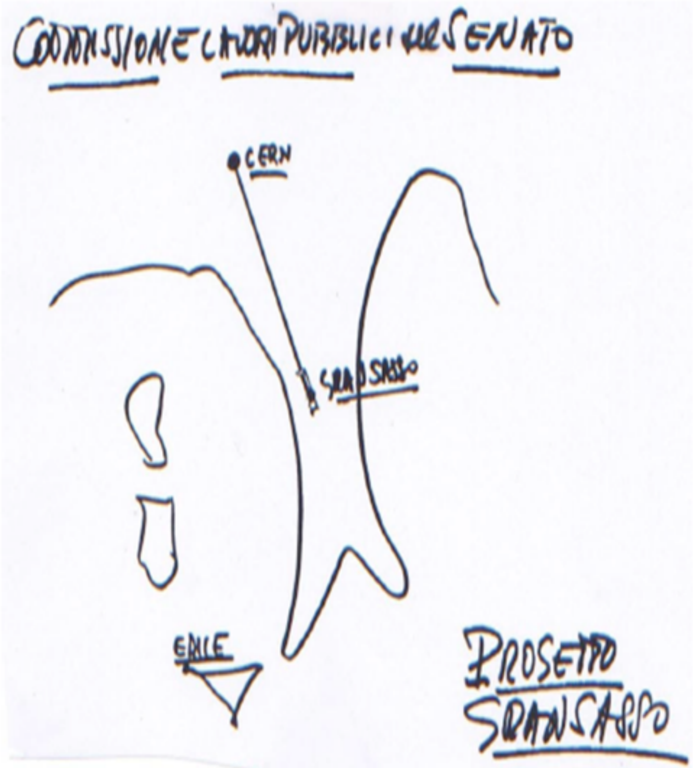
100% for charged particles
~1-10% for gamma rays (HPGe detectors)

Y = 0.3-30 counts/year

~ 1.2-220 counts/PhD

How to improve the signal-to-noise ratio?

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:

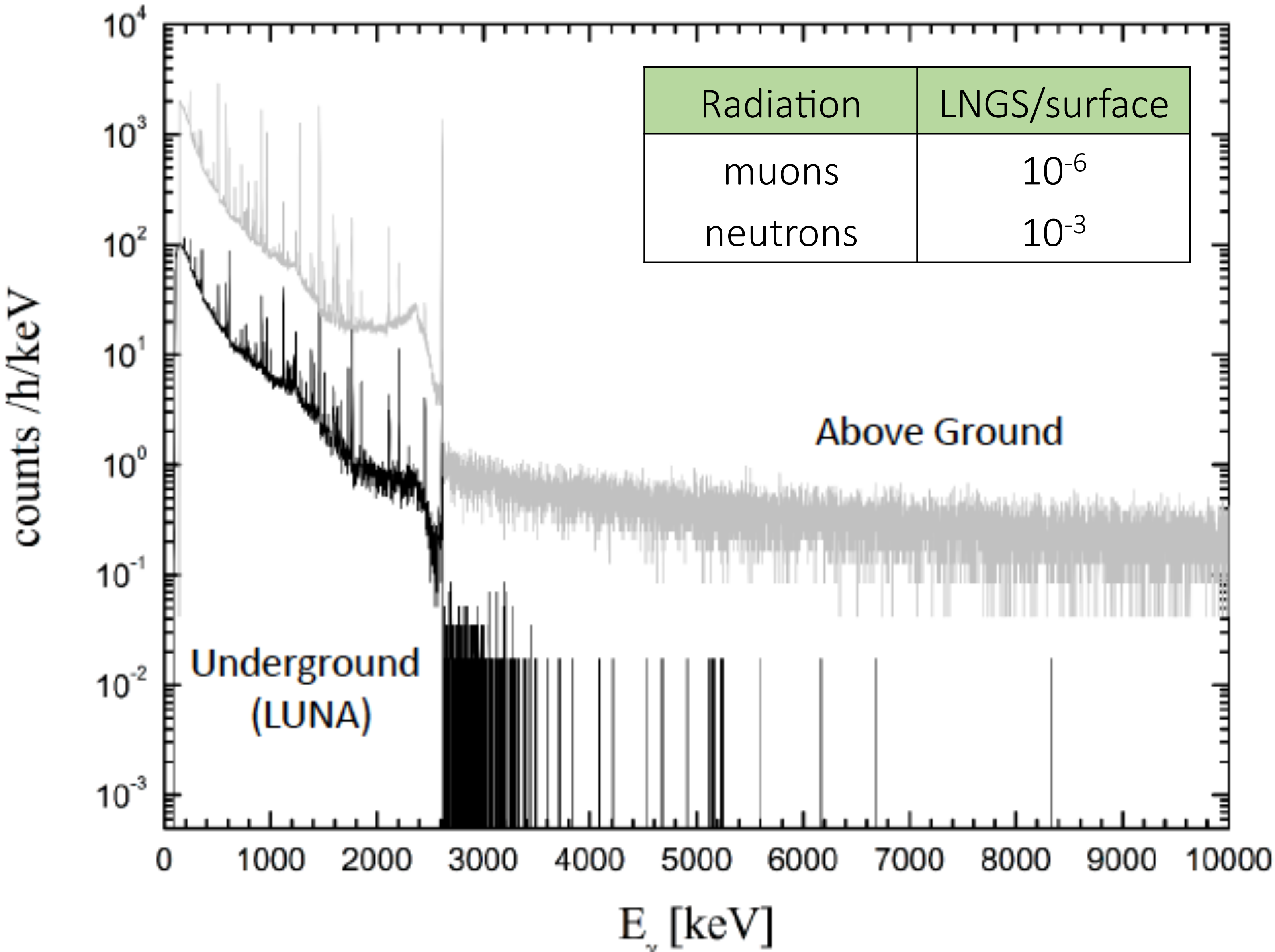
1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

NOT only $\tau_p \neq \infty$

courtesy: C Brpggini

1.4 km rock overburden: million-fold reduction in cosmic background

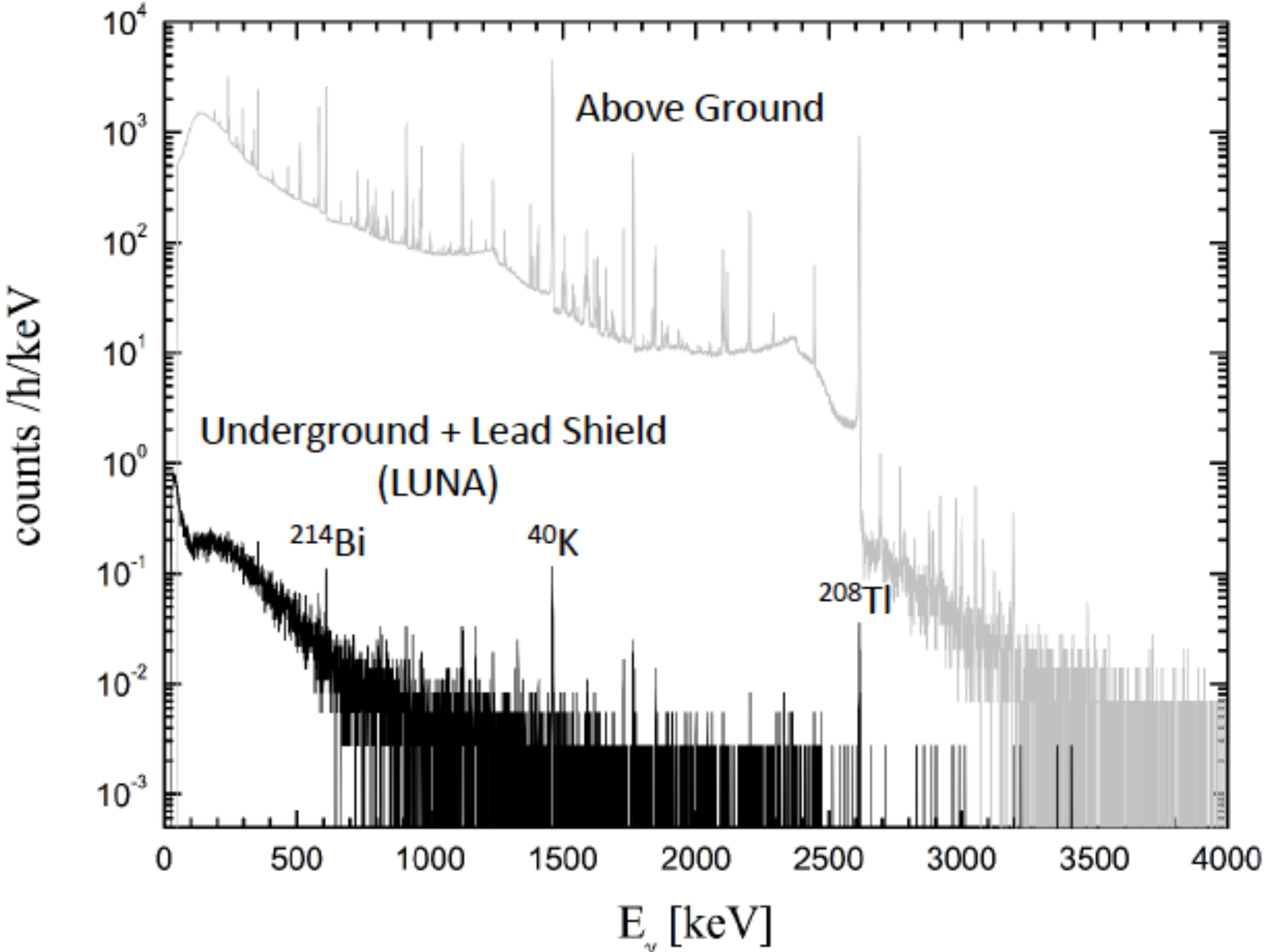
Radiation	LNGS/surface
muons	10^{-6}
neutrons	10^{-3}



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

Gamma-ray background: underground vs overground comparison

1.4 km rock overburden: million-fold reduction in cosmic background



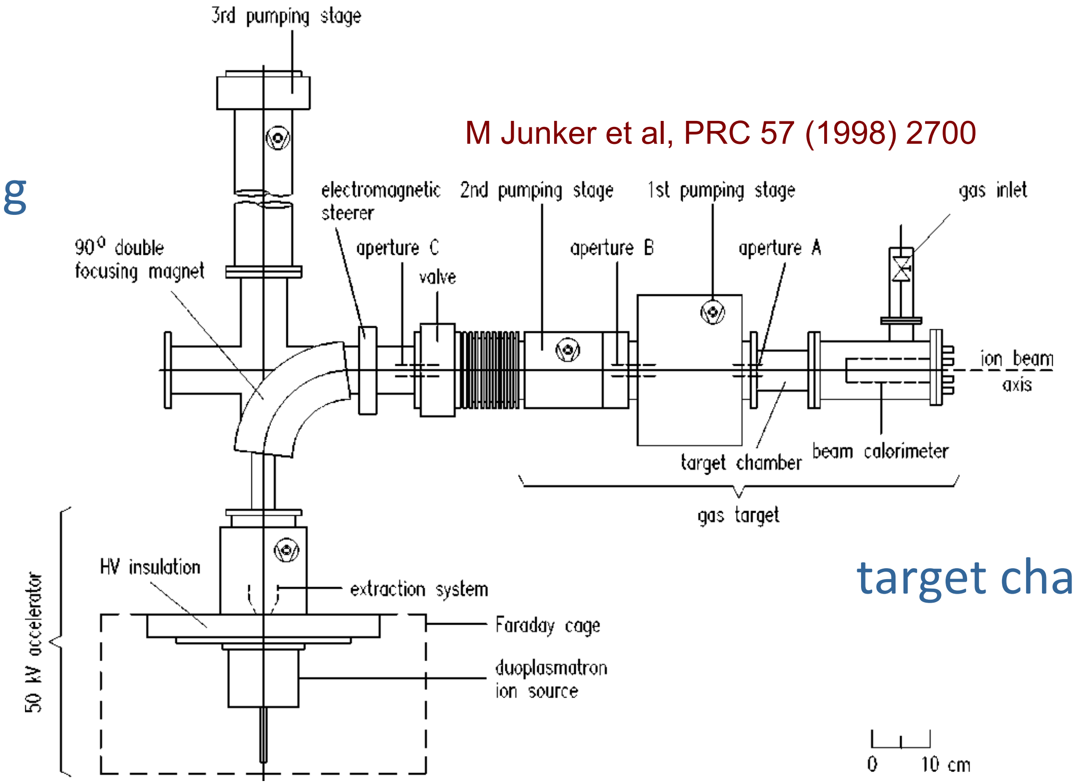
Costantini et al. Rep. Prog. Phys. 72 (2009) 086301

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

first *underground accelerator* in the world

90° analysing magnet

duoplasmatron ion source on 50kV platform



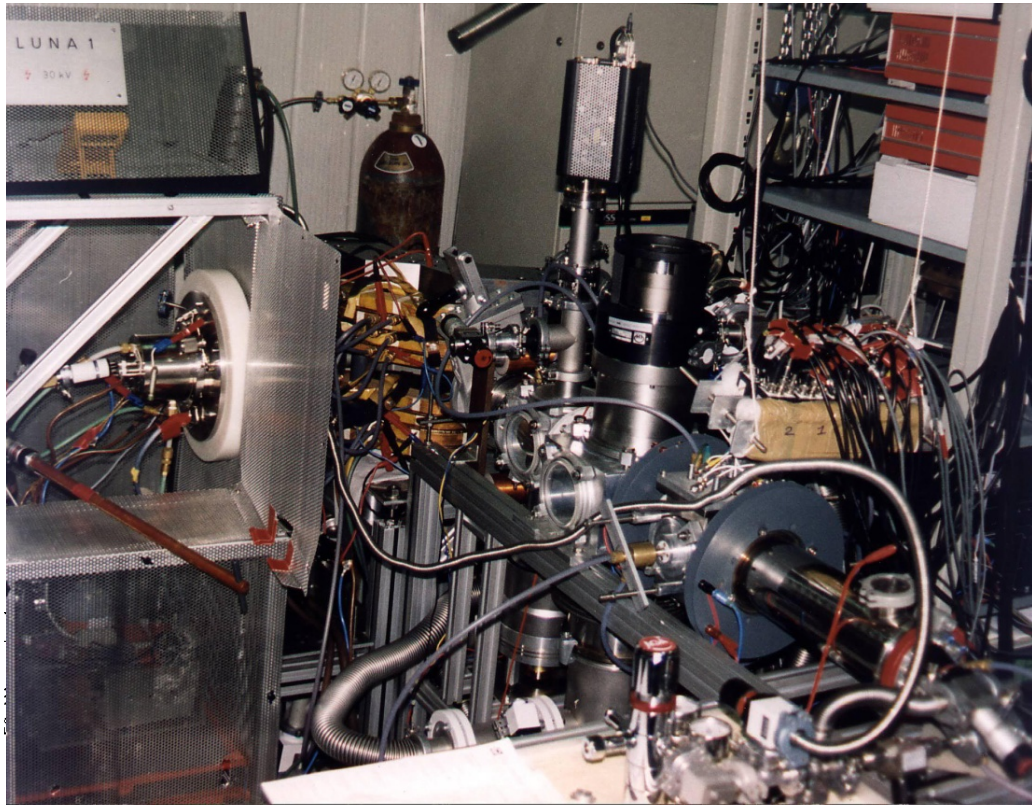
M Junker et al, PRC 57 (1998) 2700

target chamber

entirely built by students!

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

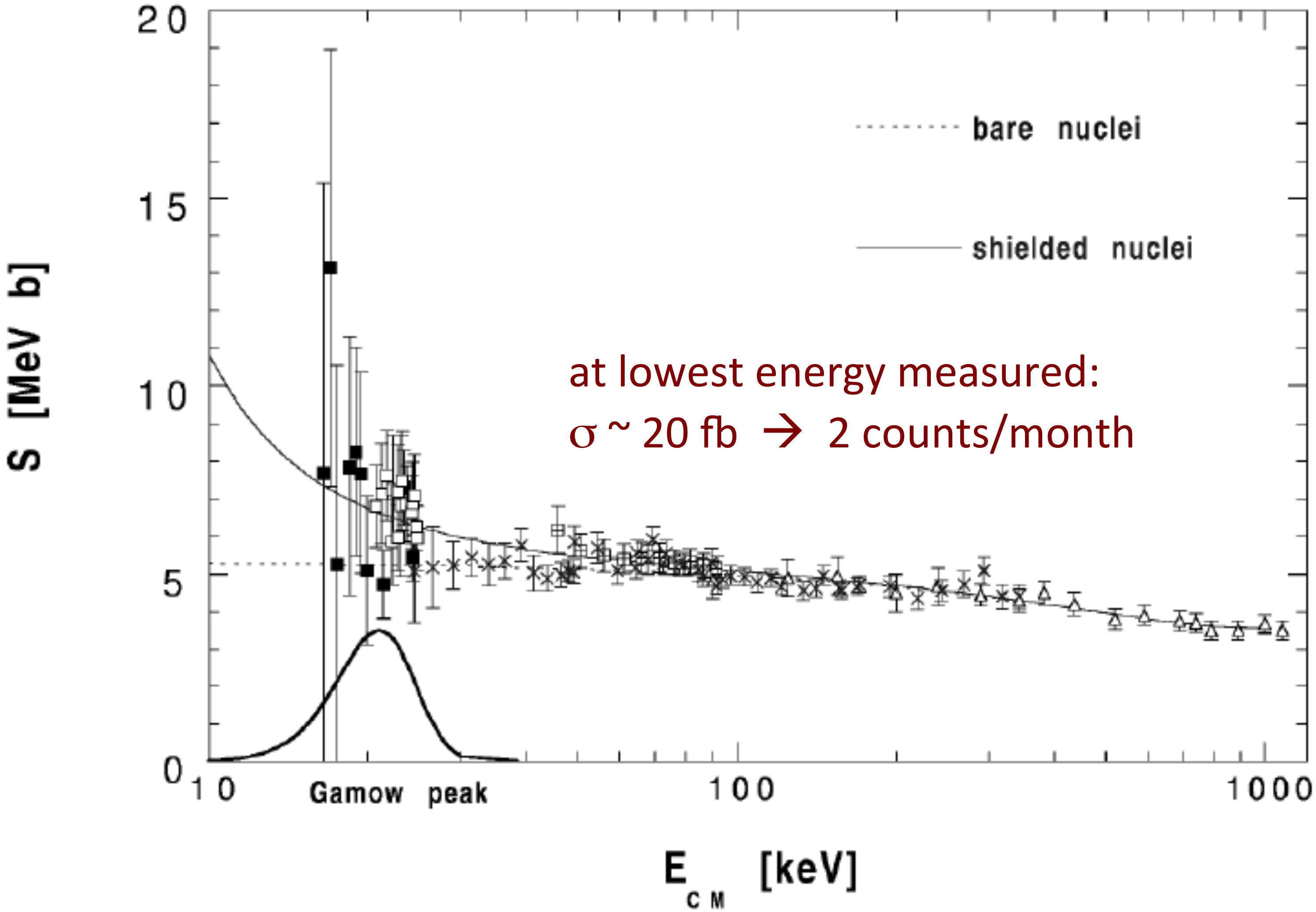
first *underground accelerator* in the world



entirely built by students!

$^3He + ^3He$ at LUNA

First measurement at Gamow peak energies – No resonance found!



Bonetti *et al*. Phys. Rev. Lett. 82 (1999) 5205

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

M. Aliotta

THE INSTITUTE FOR ADVANCED STUDY

PRINCETON, NEW JERSEY 08540

E-mail: jnb@sns.ias.edu FAX: (609)924-7592

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.

THE INSTITU
PRIN
E-mail:

SCHOOL OF NATURAL SCIENCES

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

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
$^3He(^3He, 2p)^4He$ 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
$^3He(\alpha, \gamma)^7Be$, $^7Be(p, \gamma)^8B$, 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.

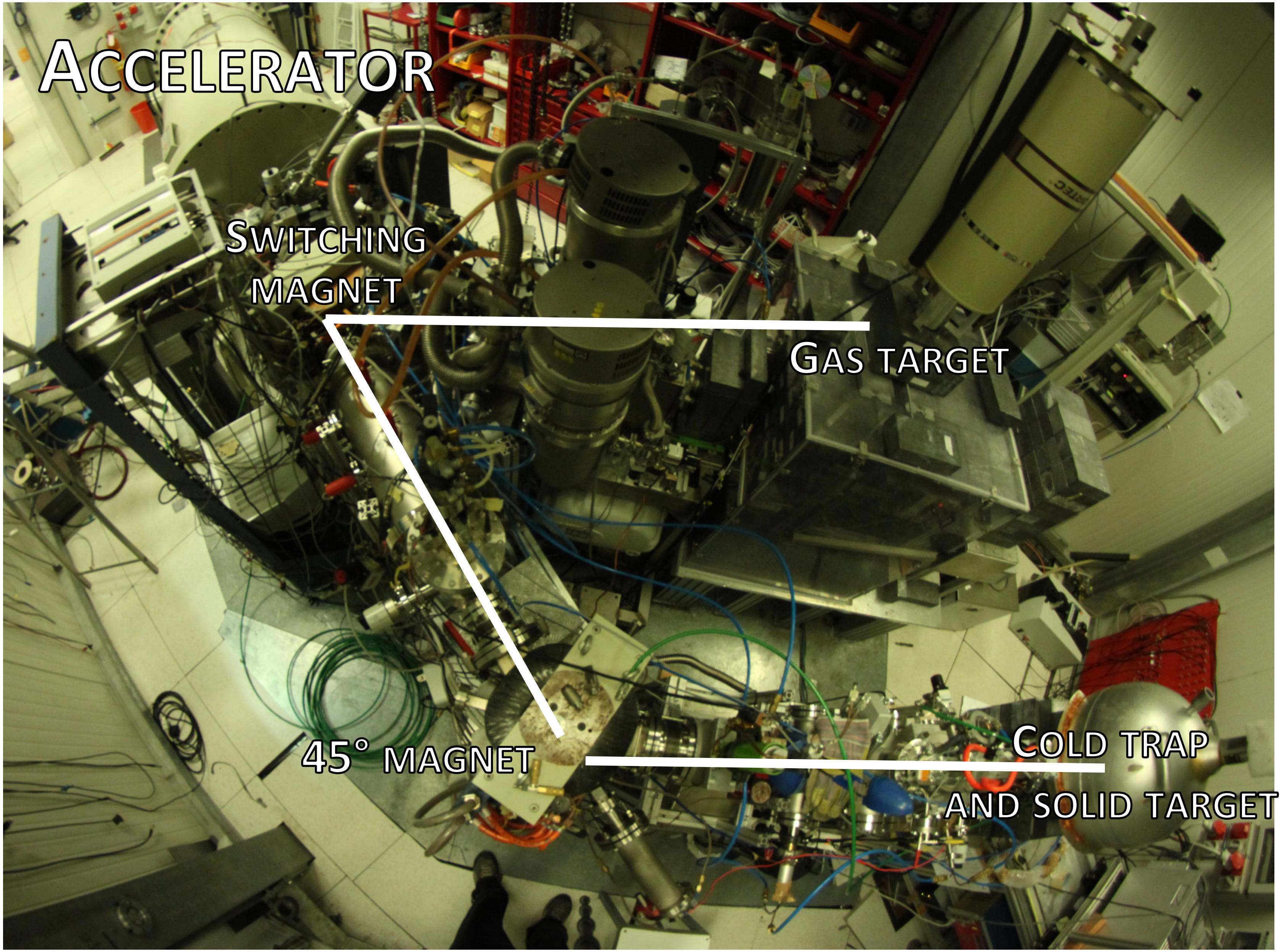
Sincerely yours,

John N. Bahcall
Professor of Natural Science

JNB:jnb

LUNA: 400 kV accelerator

LUNA: 400 kV Accelerator and Beam Lines



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)

18 reactions / 25 year ~ 20 months data taking per reaction!

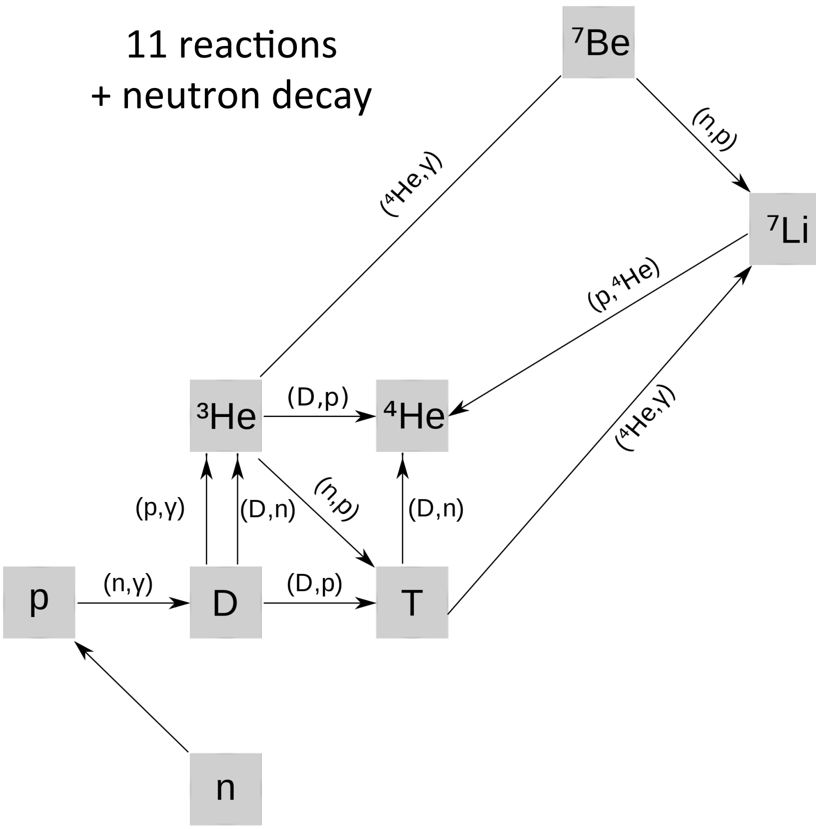
Puzzling Facts and Open Questions

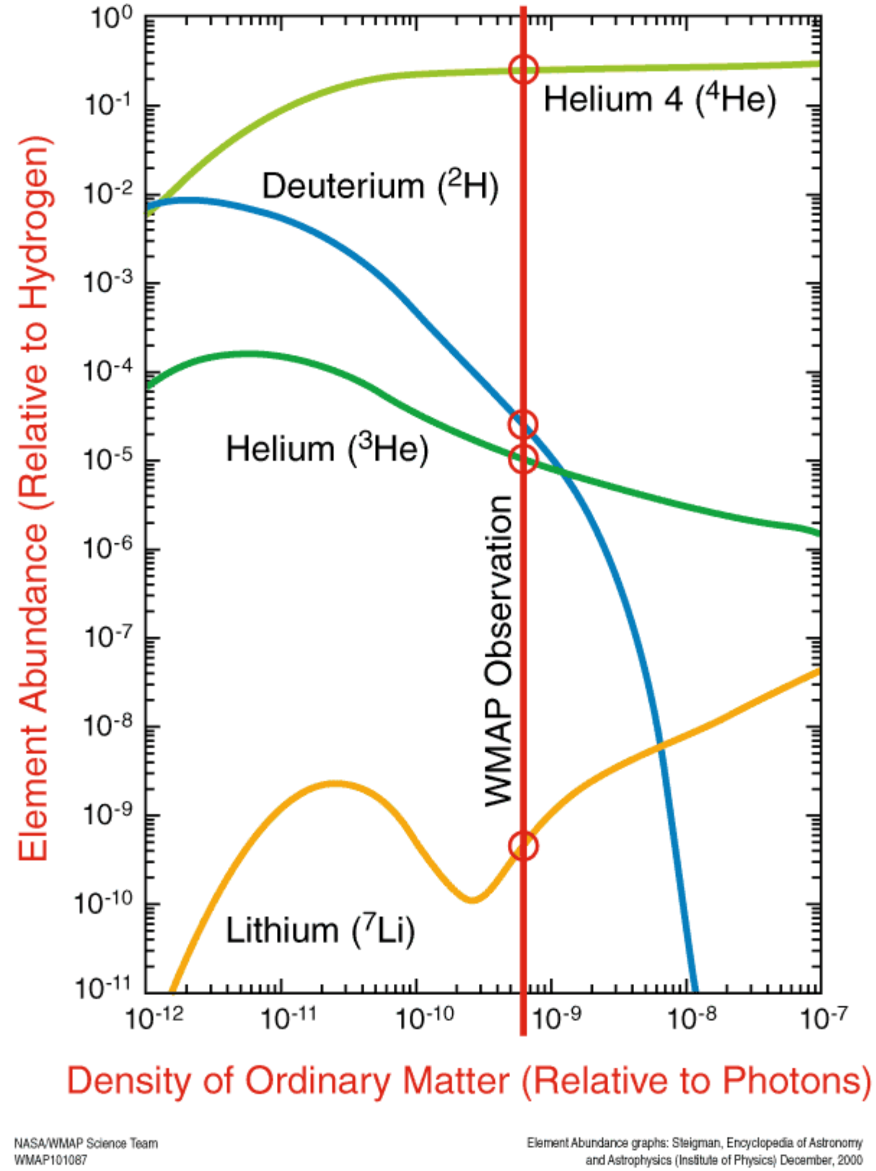
- Big Bang Nucleosynthesis: Li problem(s) and the D abundance
- Core metallicity of the Sun
- Fate of massive stars
- Explosive scenarios: X-ray bursts, novae, SN type Ia
- Pre-solar grains composition/Anomalous abundances
- Origin of heavy elements
- Astrophysical site(s) for the r-process
- …

Big Bang Nucleosynthesis

BBN is only handle to probe state of early universe

Primordial Nucleosynthesis (BBN): 3 minutes after Big Bang





observations of D, ^{3}He, ^{4}He, and ^{7}Li in very old (**metal poor**) stars provide stringent tests of Big Bang theory

LUNA

Primordial Deuterium Abundance: The d(p,γ)^{3}He Reaction

Primordial Deuterium Abundance

about 5% lower than

Observed abundance:

$[D/H] = (2.53 \pm 0.04) \times 10^{-5}$

Cooke et al, APJ 781 (2014) 31

Predicted abundance:

$[D/H] = (2.65 \pm 0.07) \times 10^{-5}$

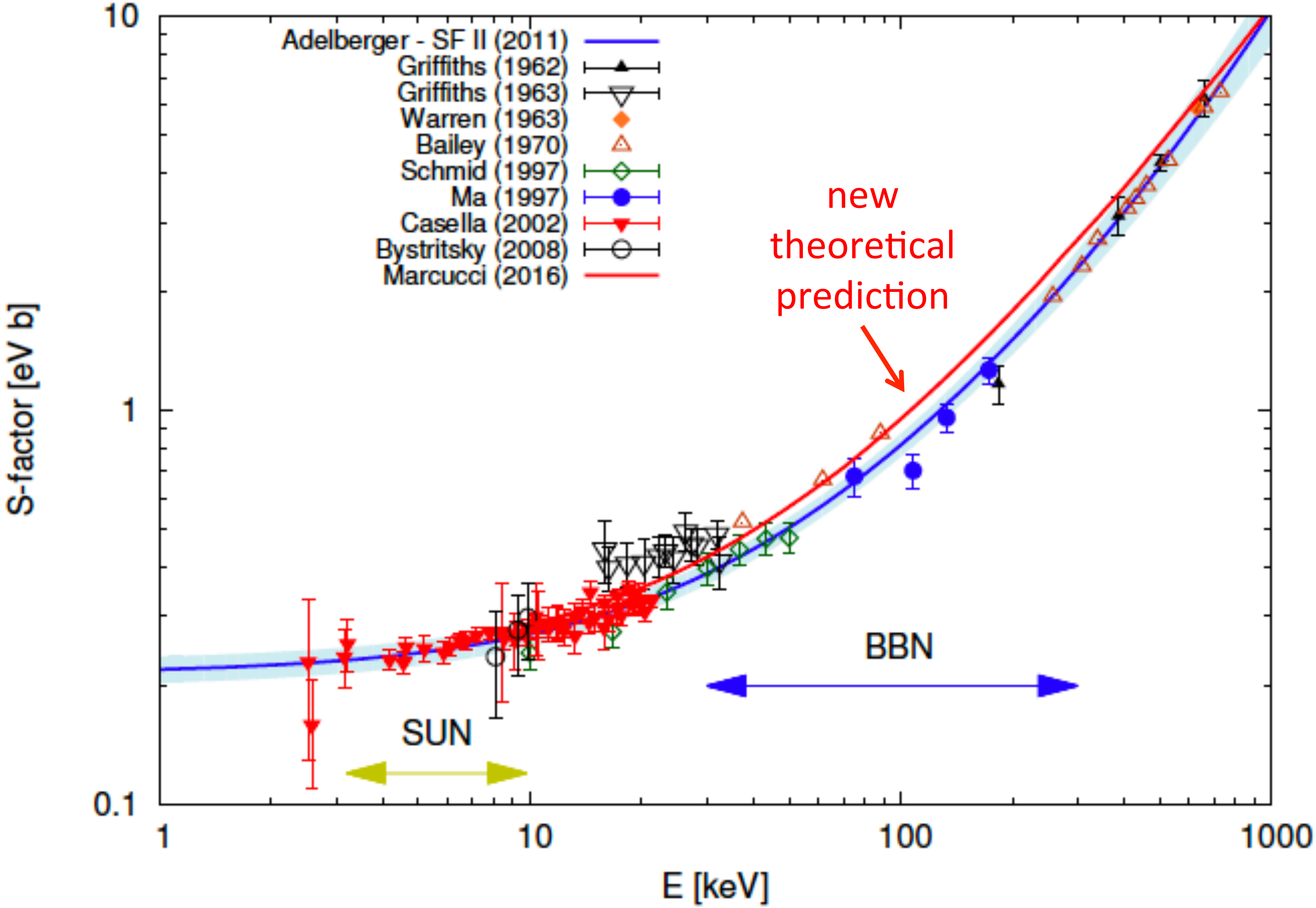
Di Valentino et al, PRD 90 (2014) 023543

main uncertainty in BBN prediction

due to $d(p,\gamma)^3He$ cross section

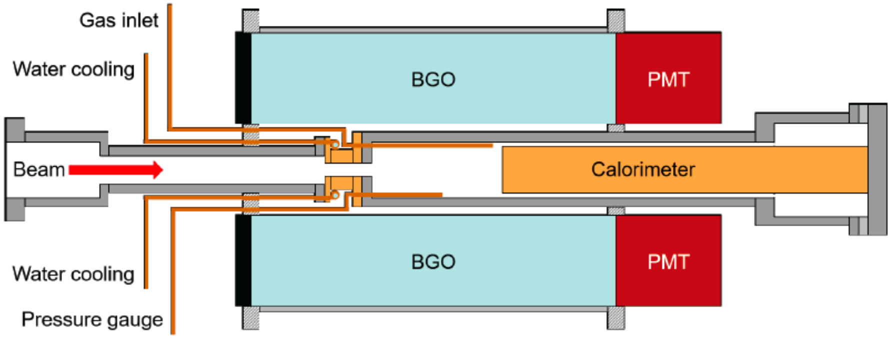
↓

high precision data at BBN energies required


Adelberger - SF II (2011)
Griffiths (1962)
Griffiths (1963)
Warren (1963)
Bailey (1970)
Schmid (1997)
Ma (1997)
Casella (2002)
Bystritsky (2008)
Marcucci (2016)
new theoretical prediction
BBN
SUN
S-factor [eV b]
E [keV]
10
1
0.1
1
10
100
1000

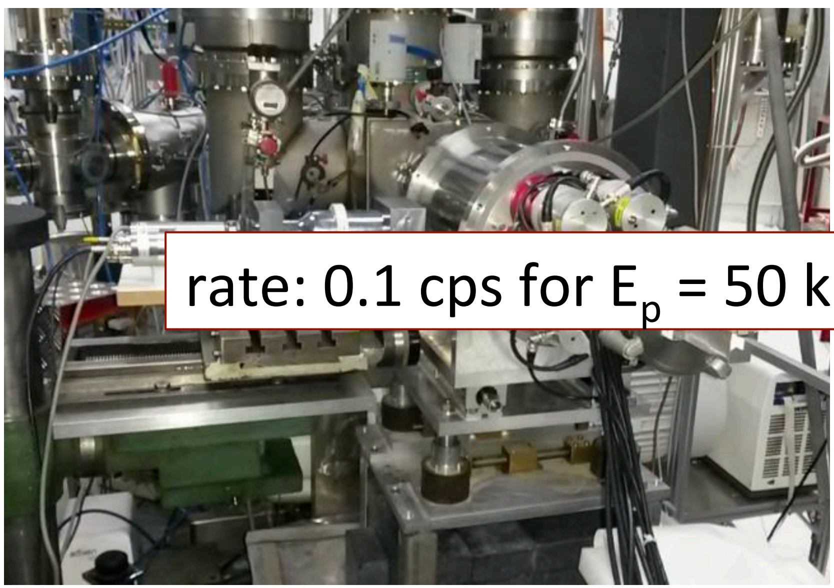
Measurements at LUNA

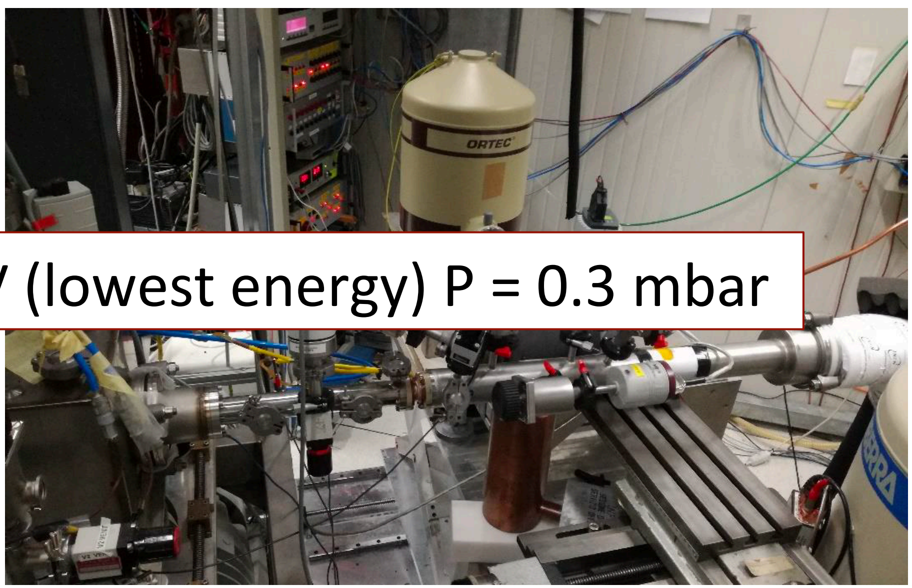
E_{beam} = 50 – 300 keV (full BBN range)



BGO Phase: high efficiency

HPGe Phase: high precision



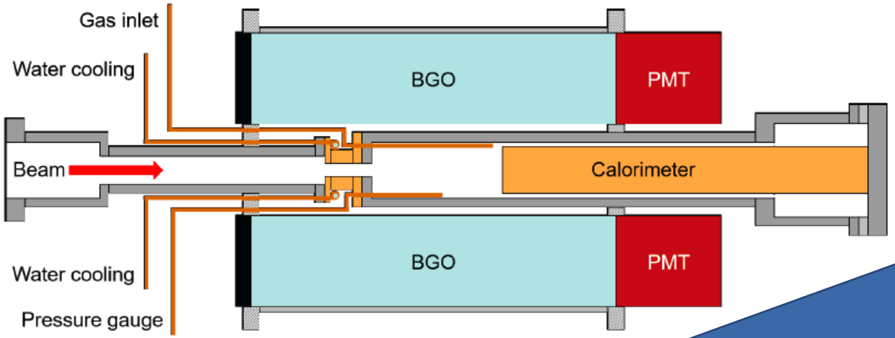


rate: 0.1 cps for E_p = 50 keV (lowest energy) P = 0.3 mbar

Courtesy: V Mossa

Measurements at LUNA

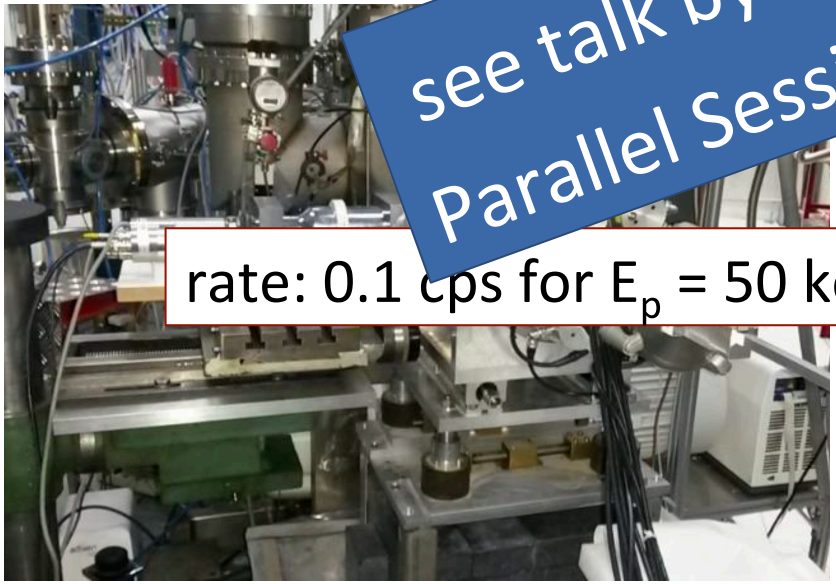
E_{beam} = 50 – 300 keV (full BBN range)

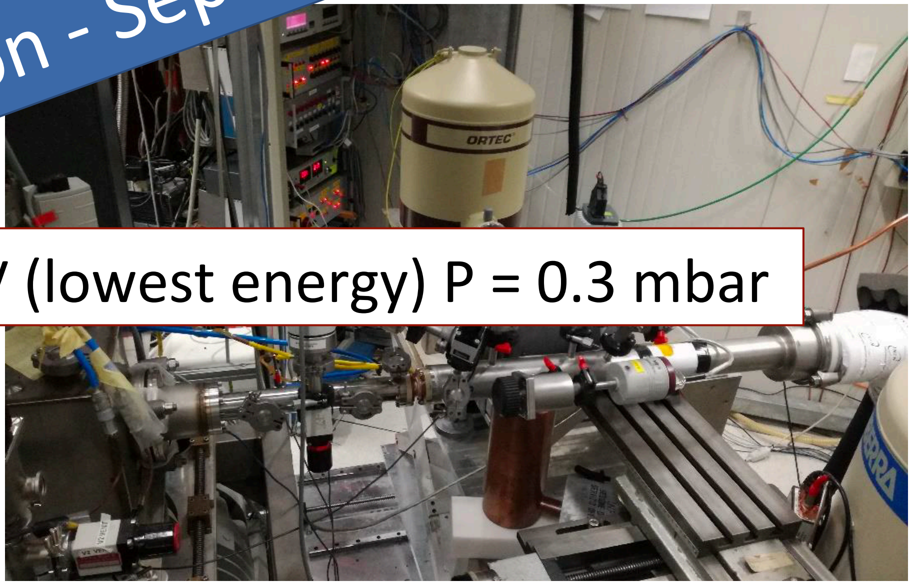


BGO Phas… gh efficiency

…h precision

see talk by Sandra Zavatarelli
Parallel Session - September 4





rate: 0.1 cps for E_p = 50 keV (lowest energy) P = 0.3 mbar

Courtesy: V Mossa

Lithium Problem(s)

a success story:

discrepancy revealed thanks to close interplay among

theory, observation, and experiment

Primordial Lithium Abundances

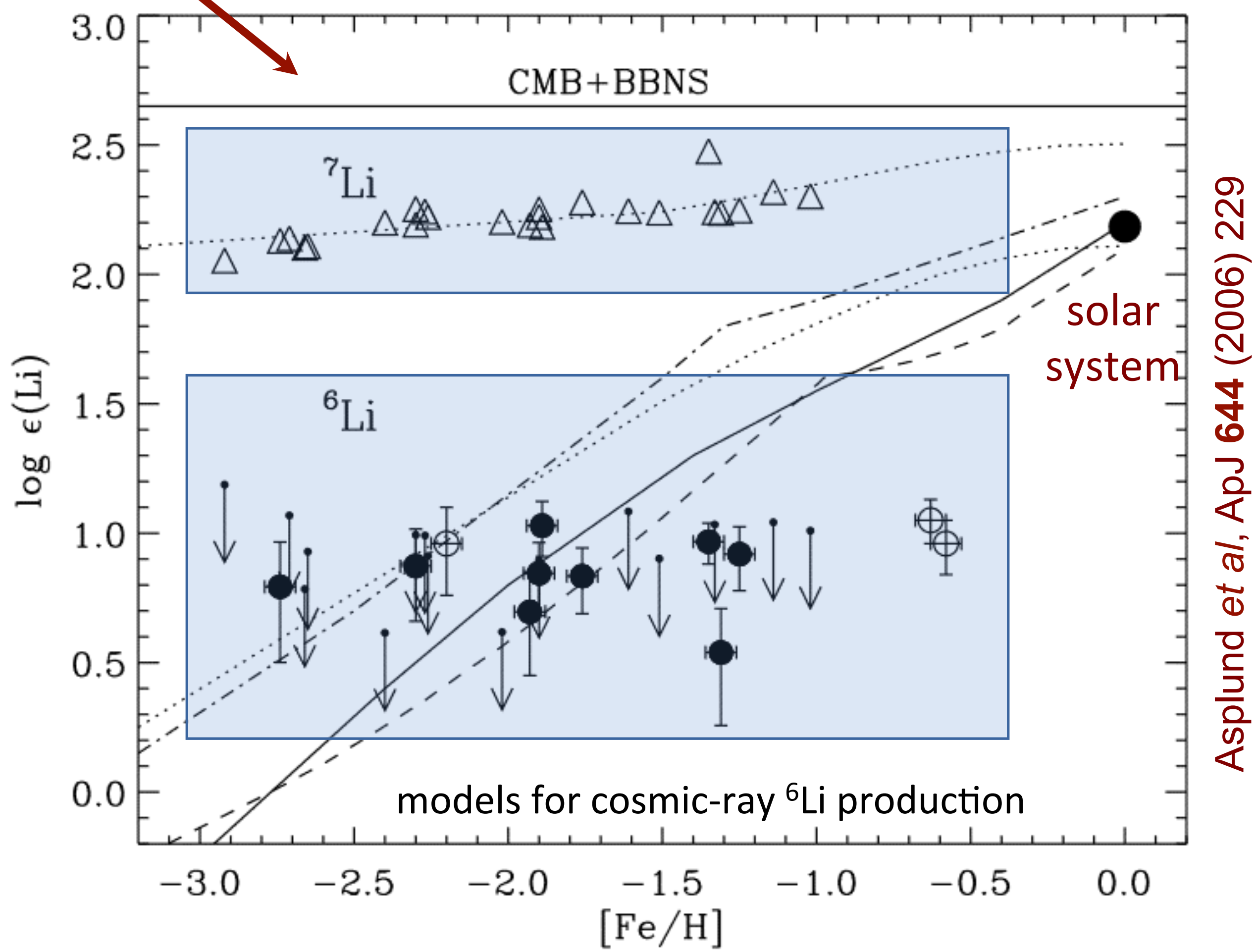
CBM + BBN predictions
^{7}Li abundance (^{6}Li/^{7}Li ~ 10^{-5})

observed ^{7}Li ~ 3x lower than predicted

first Lithium Problem

observed ^{6}Li ~ 10^{2} – 10^{3} higher than predicted

second Lithium Problem



first Lithium Problem

observed ^{7}Li

~ 3x lower than predicted

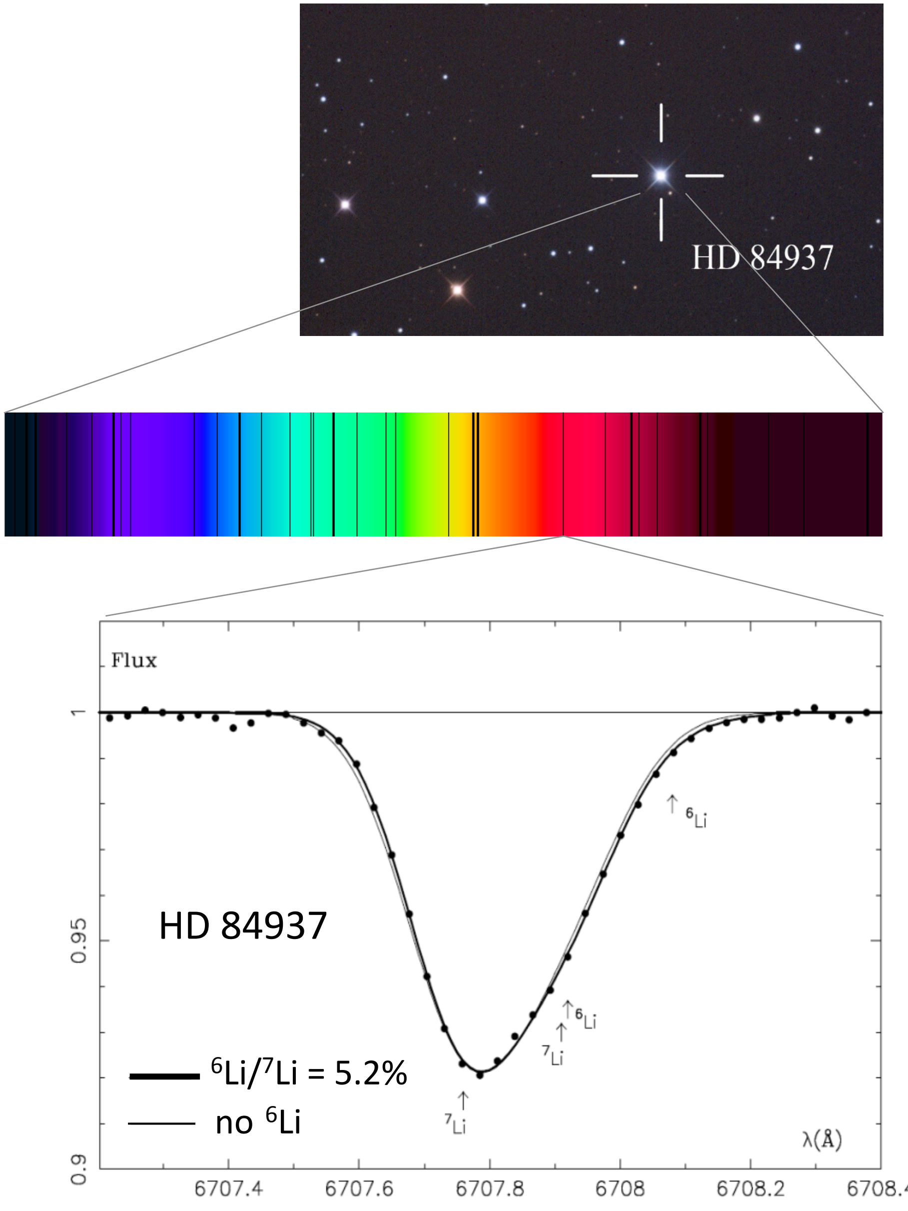
- no nuclear solution
- new (astro)physics?
- physics beyond Standard Model?

second Lithium Problem

observed ^{6}Li

~ $10^{2} - 10^{3}$ higher than predicted

poor nuclear physics inputs
or
challenges with observation?



The Second Lithium Problem

Production and destruction processes affecting ^6Li abundance

^{6}Li production:
The d(α,γ)^{6}Li Reaction

First direct measurement of d(α,γ)^{6}Li cross section at BBN energies

Astroparticle Physics 89 (2017) 57–65
Contents lists available at ScienceDirect
Astroparticle Physics
journal homepage: www.elsevier.com/locate/astropartphys

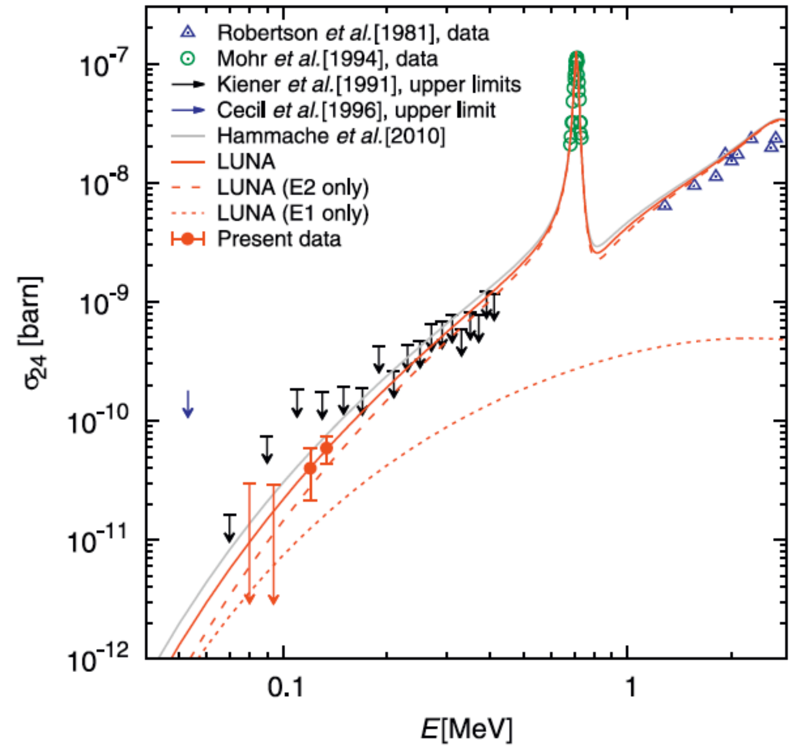
Big Bang ^6Li nucleosynthesis studied deep underground (LUNA collaboration)

D. Trezzi[a], M. Anders[b,c,1], M. Aliotta[d], A. Bellini[e], D. Bemmerer[b], A. Boeltzig[f,g], C. Broggini[h], C.G. Bruno[d], A. Caciolli[h,i], F. Cavanna[e], P. Corvisiero[e], H. Costantini[e,2], T. Davinson[d], R. Depalo[h,i], Z. Elekes[b], M. Erhard[h], F. Ferraro[e], A. Formicola[f], Zs. Fülop[j], G. Gervino[k], A. Guglielmetti[a], C. Gustavino[l,*], Gy. Gyürky[j], M. Junker[f], A. Lemut[e,3], M. Marta[b,4], C. Mazzocchi[a,5], R. Menegazzo[h], V. Mossa[m], F. Pantaleo[m], P. Prati[e], C. Rossi Alvarez[h], D.A. Scott[d], E. Somorjai[j], O. Straniero[n,o], T. Szücs[j], M. Takacs[b]

PRL 113, 042501 (2014) PHYSICAL REVIEW LETTERS week ending 25 JULY 2014

First Direct Measurement of the ^{2}H(α,γ)^{6}Li Cross Section at Big Bang Energies and the Primordial Lithium Problem

M. Anders,[1,2,†] D. Trezzi,[3] R. Menegazzo,[4] M. Aliotta,[5] A. Bellini,[6] D. Bemmerer,[1] C. Broggini,[4] A. Caciolli,[4] P. Corvisiero,[6] H. Costantini,[6,‡] T. Davinson,[5] Z. Elekes,[1] M. Erhard,[4,§] A. Formicola,[7] Zs. Fülöp,[8] G. Gervino,[9] A. Guglielmetti,[3] C. Gustavino,[10,‖] Gy. Gyürky,[8] M. Junker,[7] A. Lemut,[6,*] M. Marta,[1,¶] C. Mazzocchi,[3,**] P. Prati,[6] C. Rossi Alvarez,[4] D. A. Scott,[5] E. Somorjai,[8] O. Straniero,[11,12] and T. Szücs[8]
(LUNA Collaboration)



^{6}Li/^{7}Li = (1.6 ± 0.3) x 10^{-5}

^{6}Li/H = (0.8 ± 0.18) x 10^{-14} (27% lower than previous BBN values)

No nuclear physics solution to second Lithium problem

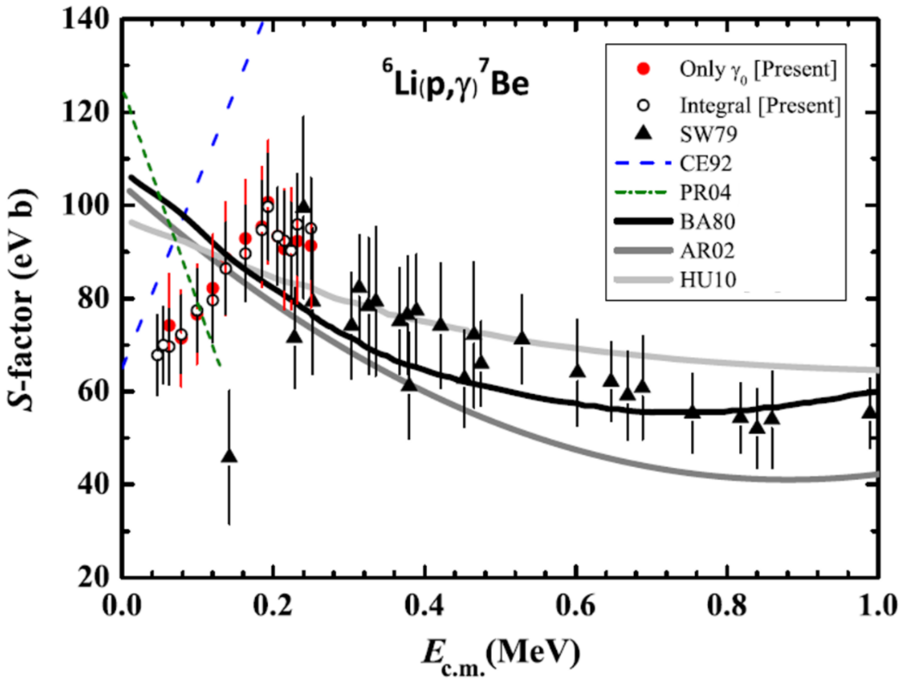
^{6}Li destruction:
The $^{6}Li(p,\gamma)^{7}Be$ and $^{6}Li(p,\alpha)^{3}He$ Reactions

Thomas Chillery's
PhD project

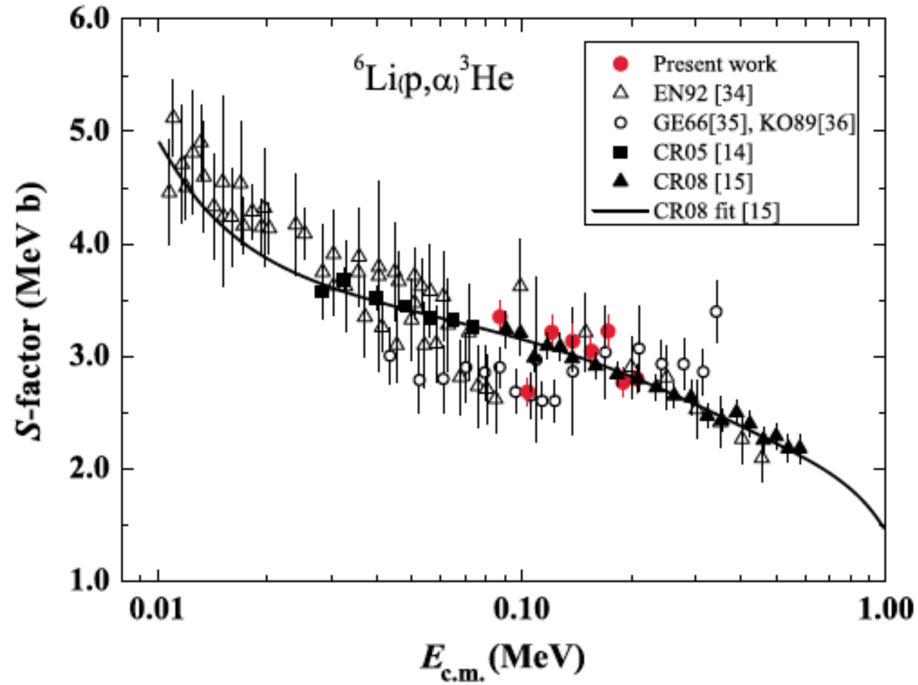
The $^6Li(p,\gamma)^7Be$ and the $^6Li(p,\alpha)^3He$ reactions at LUNA

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

resonance(-like) structure recently reported but never confirmed so far



proposed resonance may also impact angular distribution observed in $^6Li(p,\alpha)^3He$

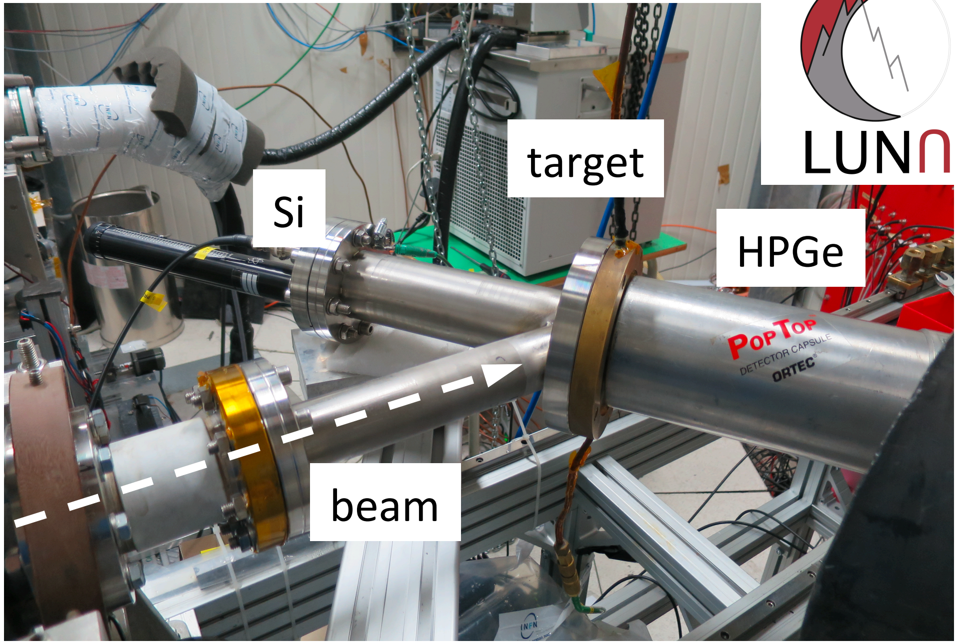


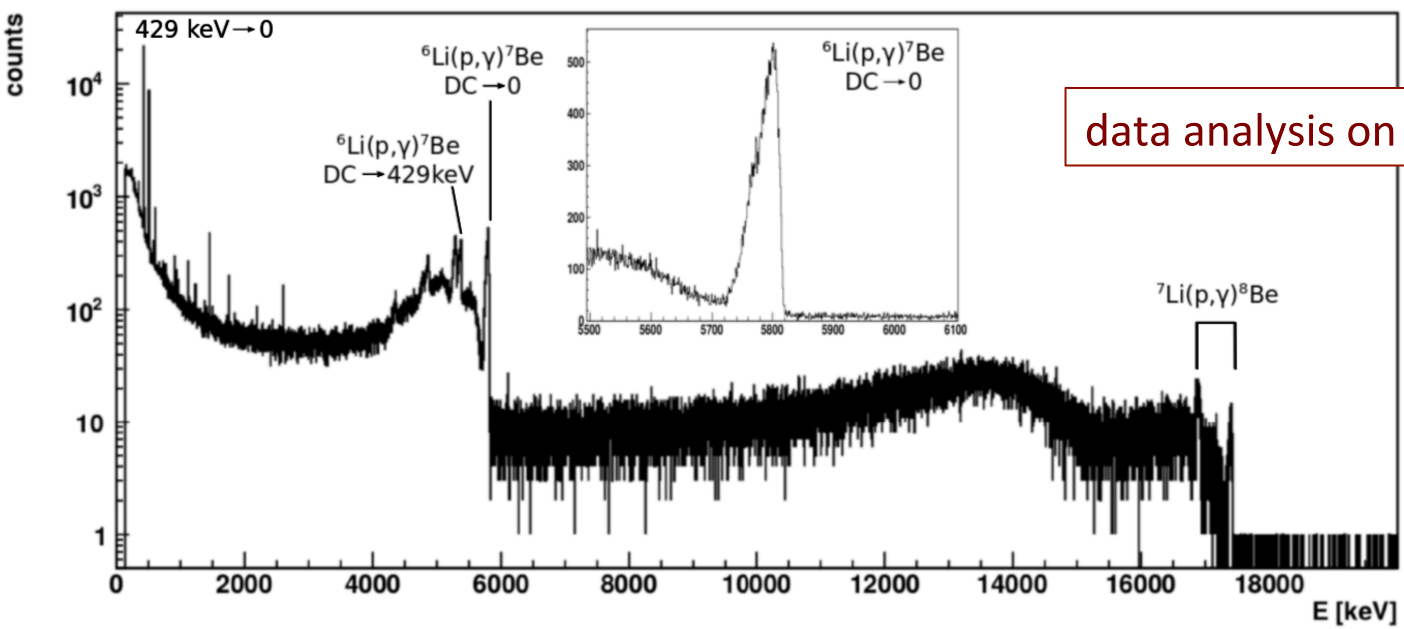
$^6Li(p,\gamma)^7Be$ reaction involved in BBN as well as in ^6Li depletion in early stages of stellar evolution

M. Aliotta

The $^{6}Li(p,\gamma)^{7}Be$ and the $^{6}Li(p,\alpha)^{3}He$ reactions at LUNA

- E_{cm} = 30 – 340 keV
- evaporated ^{6}Li solid targets (95% enrichment)
- $^{6}Li_2O$, $^{6}Li_2WO_4$ and $^{6}LiCl$
- HPGe in close geometry
- silicon detector for $^{6}Li(p,\alpha)^{3}He$





data analysis on going

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

- E_{cm} = 30 – 340 keV
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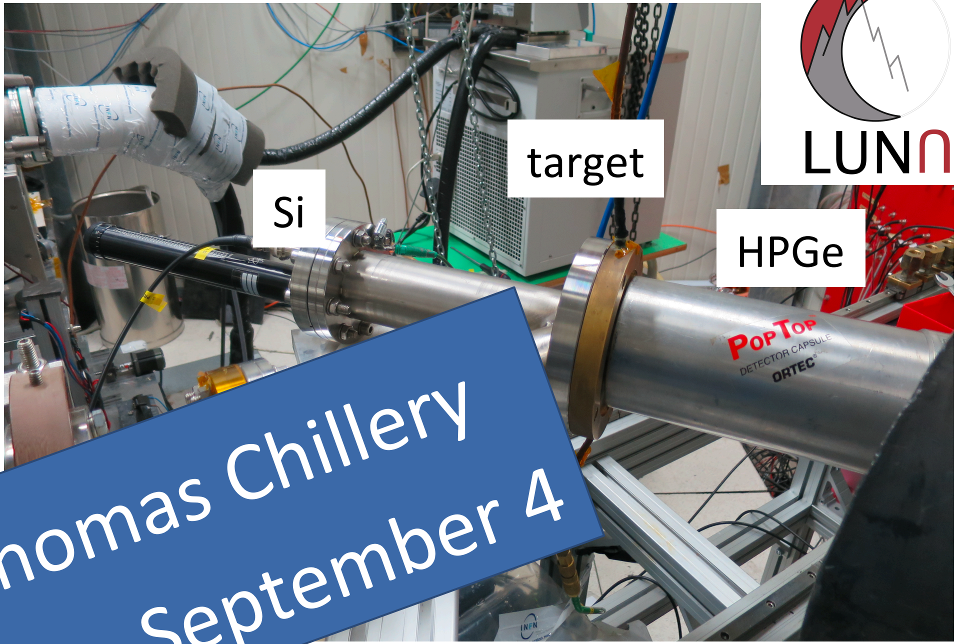
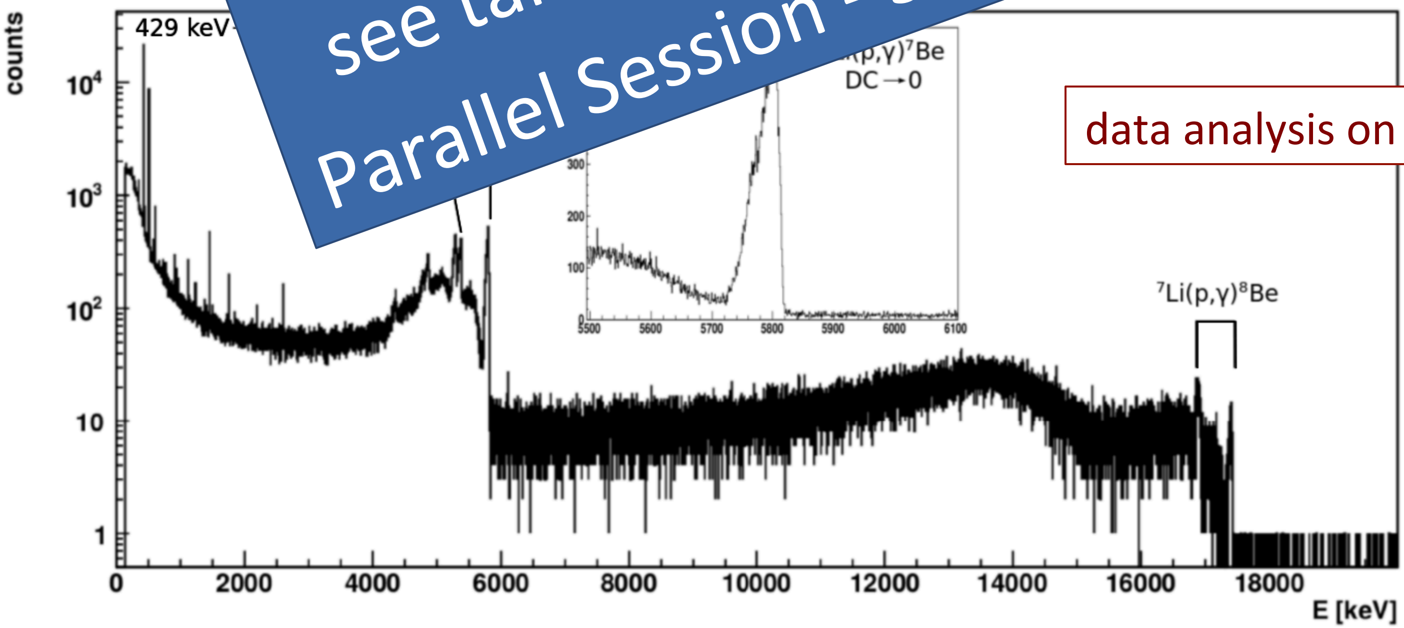


see talk by Thomas Chillery
Parallel Session - September 4



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

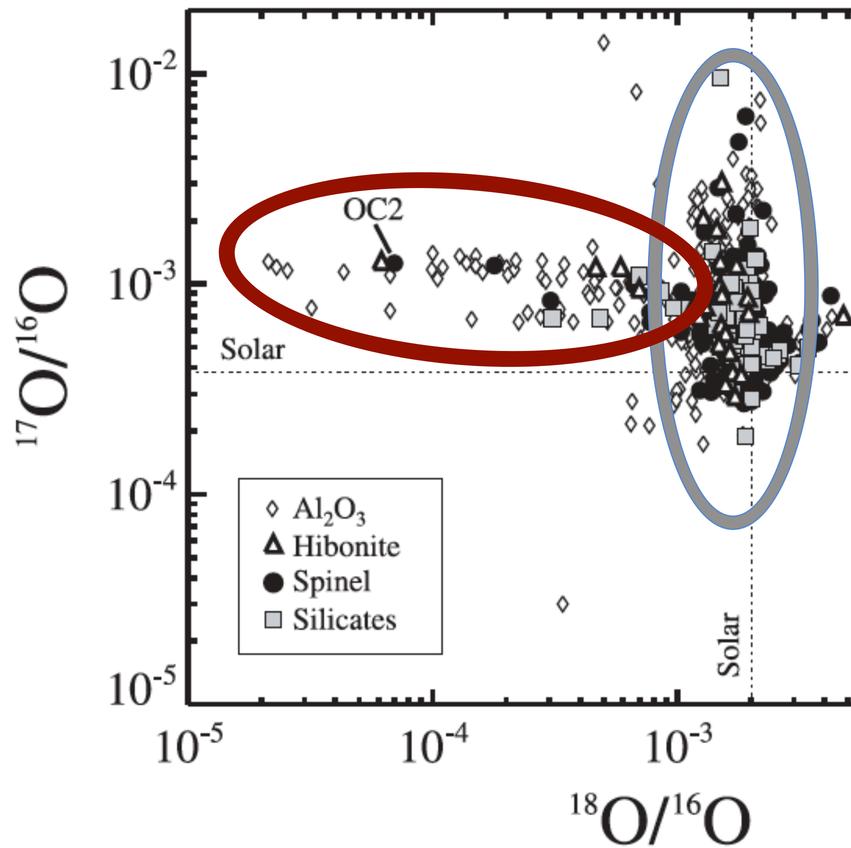
Pre-solar grains in meteorites

- 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 could shed light…

LUNA

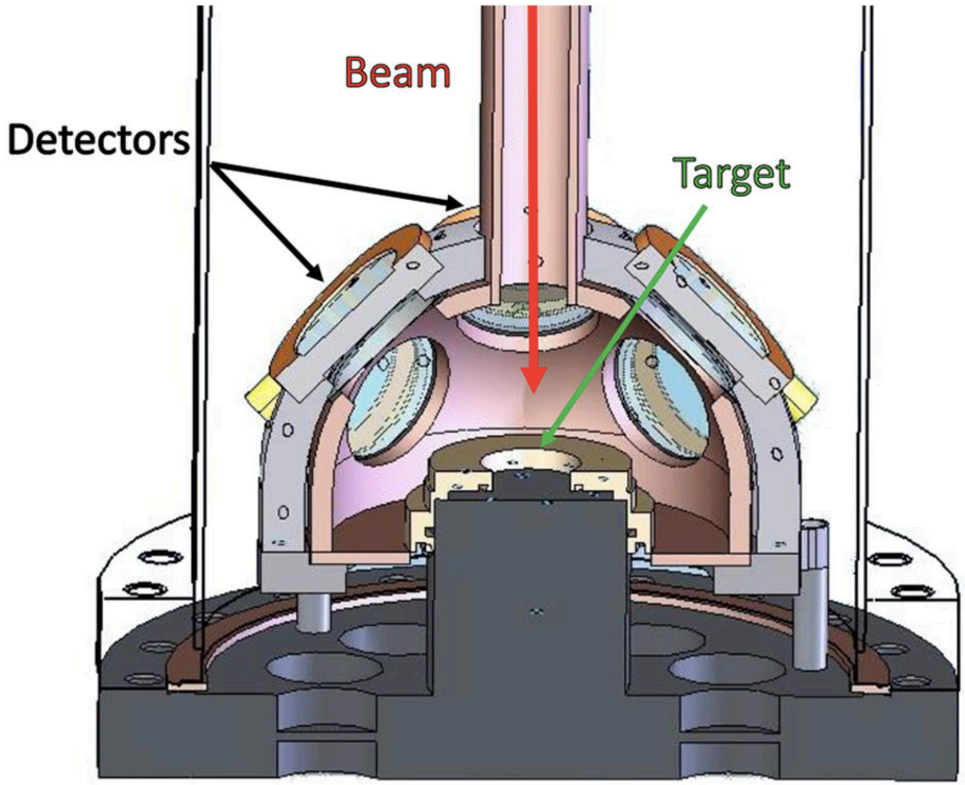
$^{17}O(p,\alpha)^{14}N$ reaction

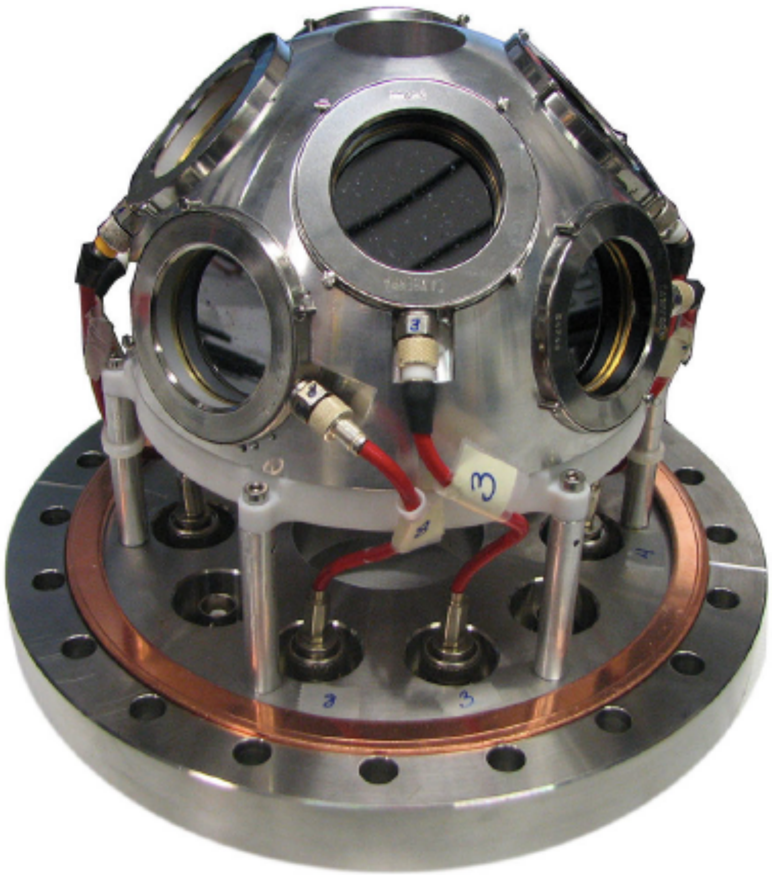
hydrogen burning in various stars + composition of pre-solar grains

PhD project

Carlo Bruno

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



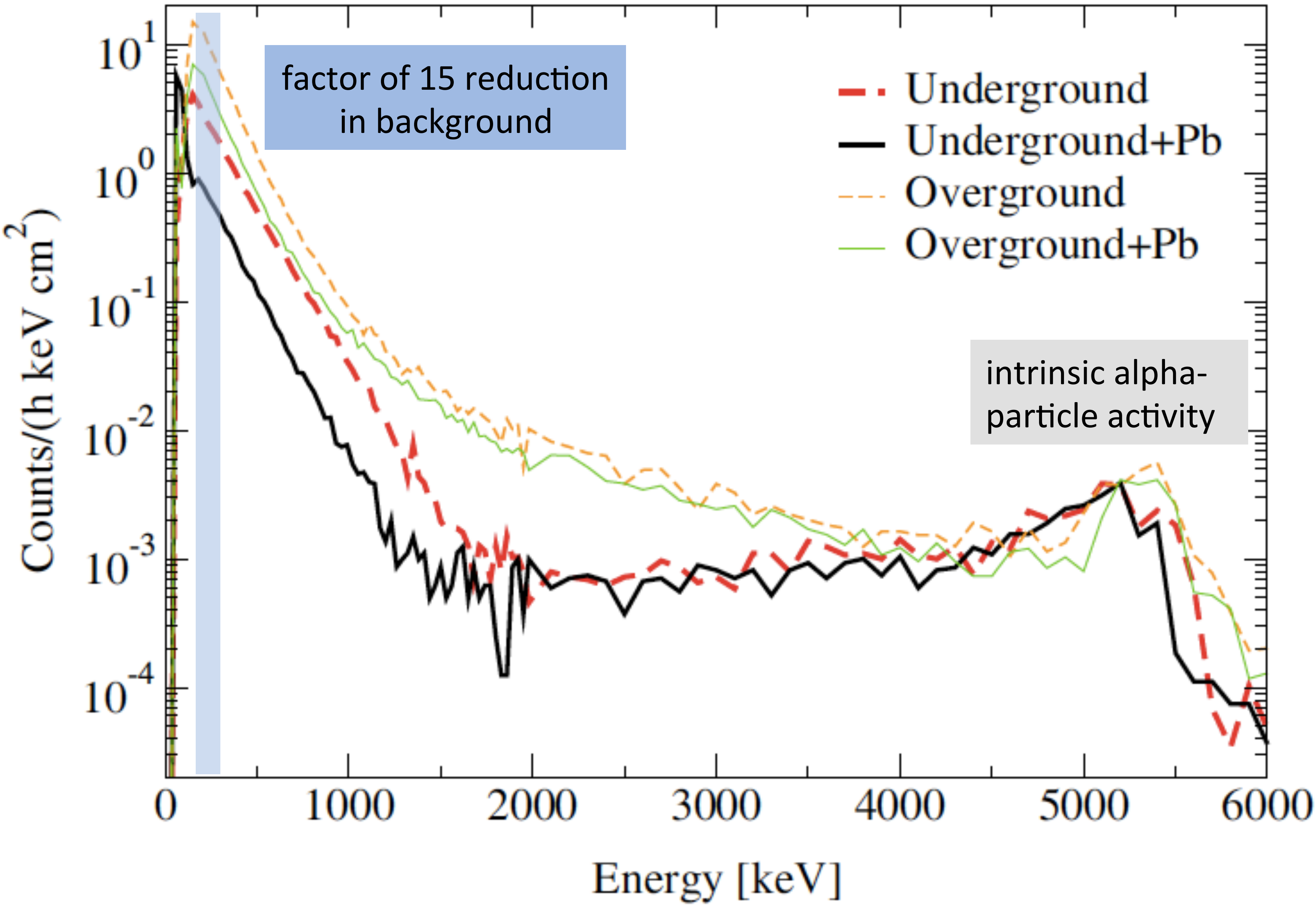


Bruno et al EJPA 51 (2015) 94

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

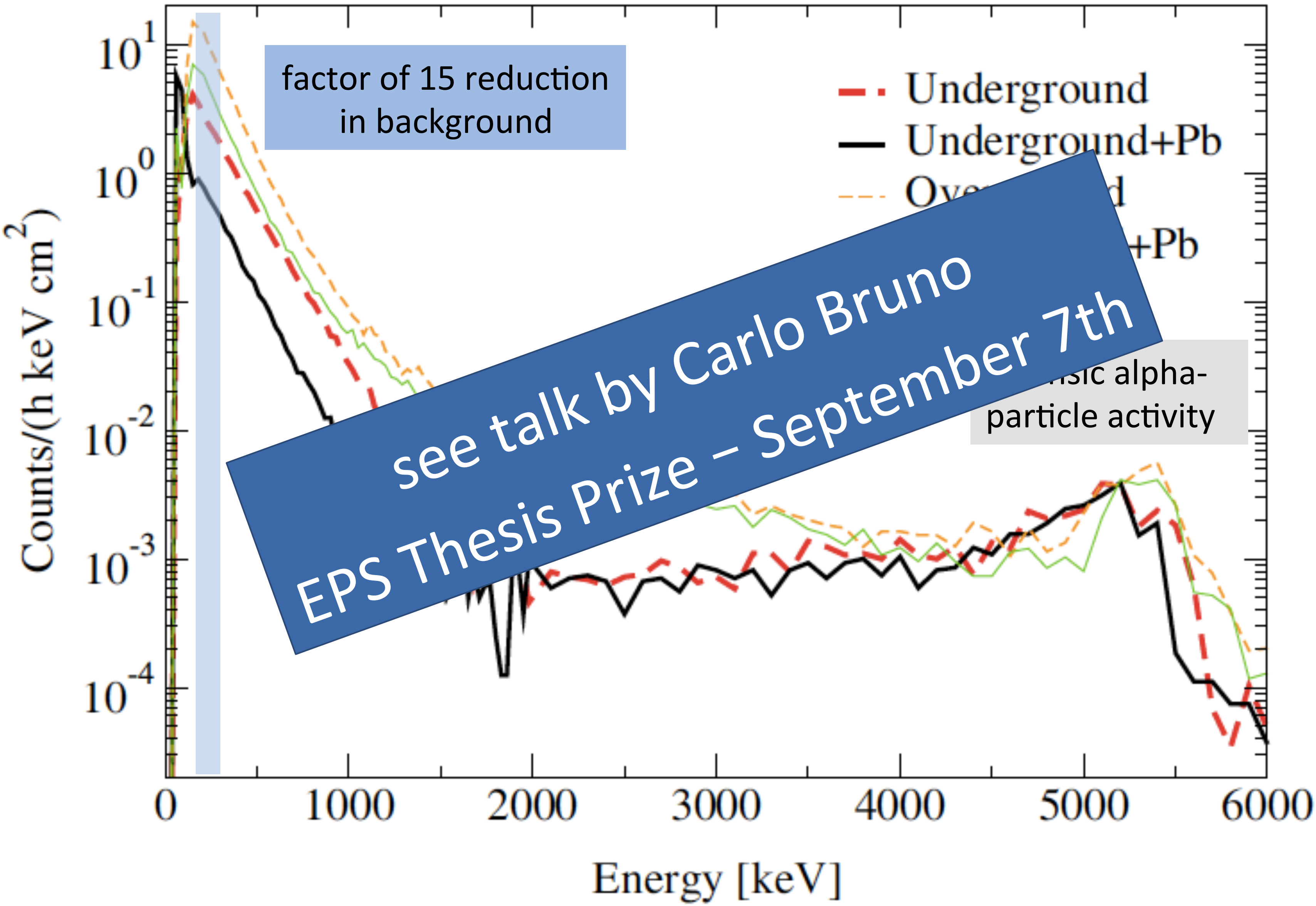
Background Suppression

CG Bruno et al. EPJA 51 (2015) 94



Background Suppression

CG Bruno et al. EPJA 51 (2015) 94



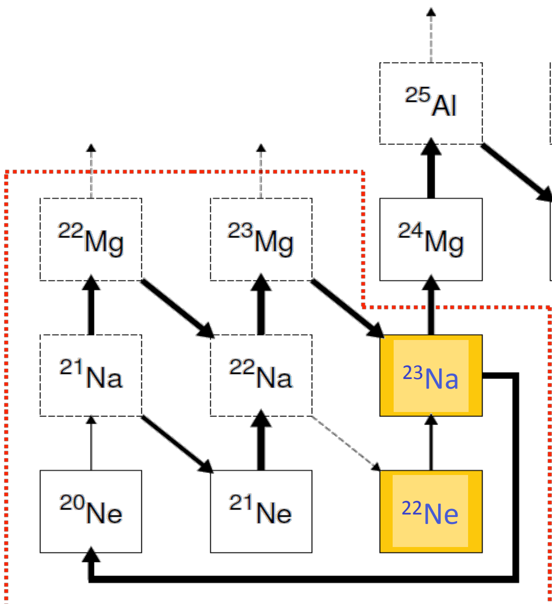
factor of 15 reduction
in background

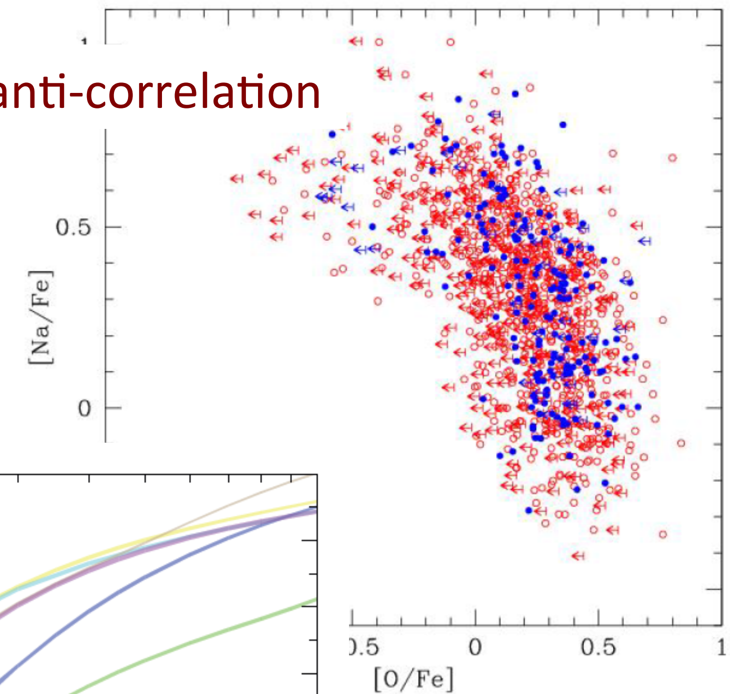
particle activity

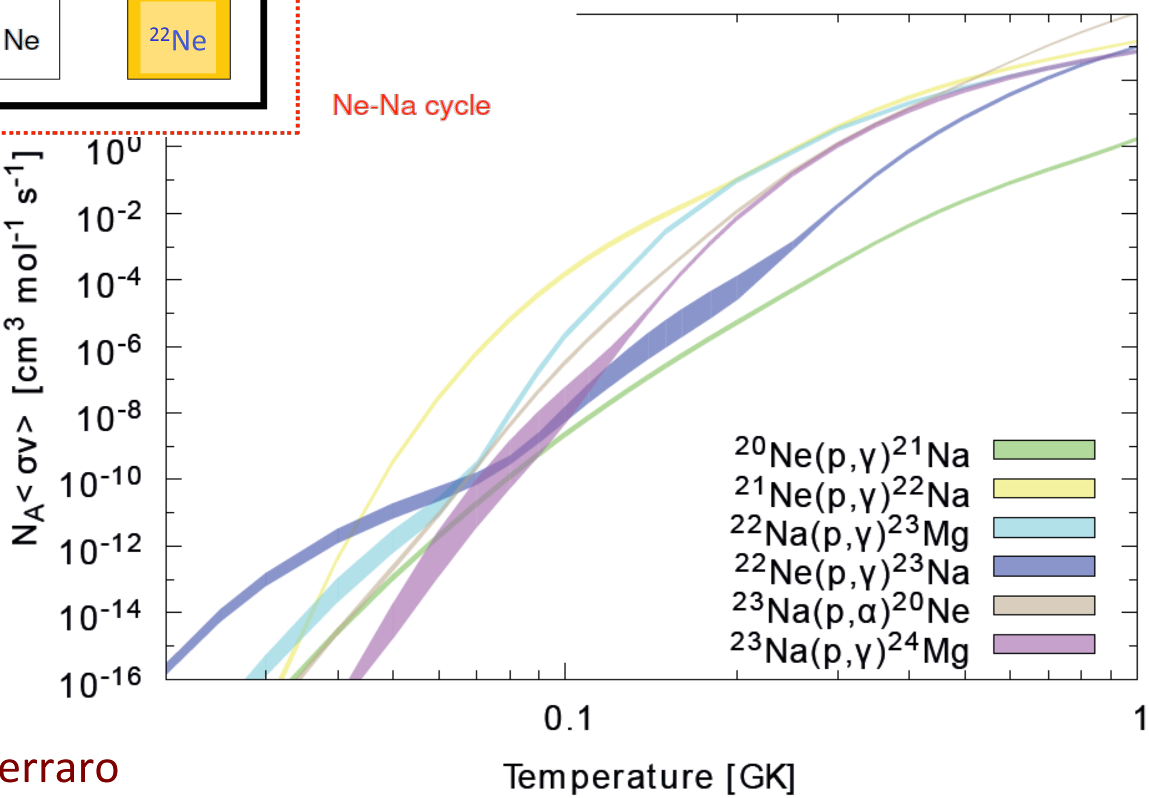
see talk by Carlo Bruno
EPS Thesis Prize – September 7th

The $^{22}Ne(p,\gamma)^{23}Na$ Reaction

$^{22}Ne(p,\gamma)^{23}Na$: The Most Uncertain Reaction in the NeNa-cycle

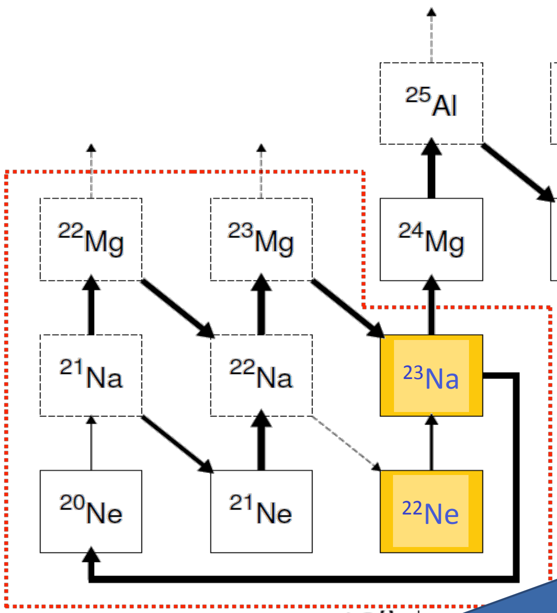




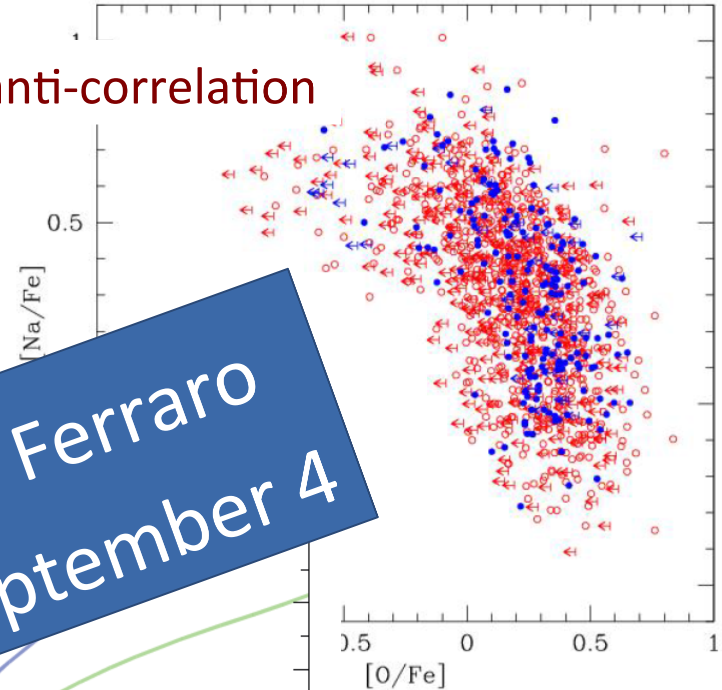


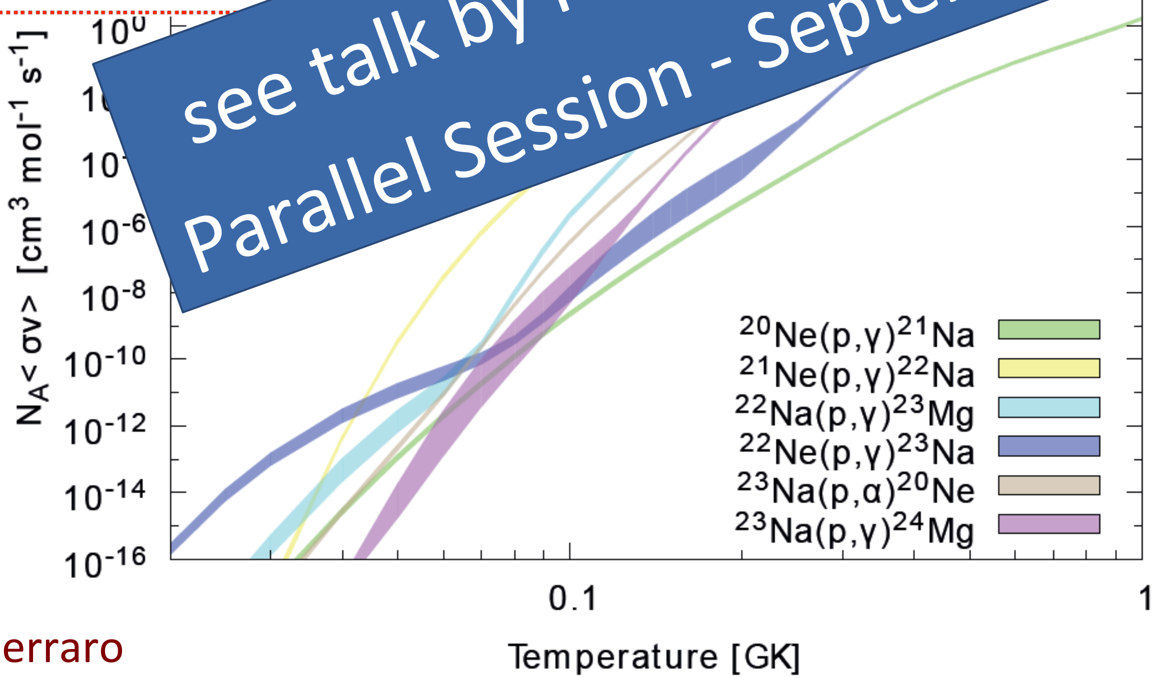
courtesy: F Ferraro

$^{22}Ne(p,\gamma)^{23}Na$: The Most Uncertain Reaction in the NeNa-cycle



Na/O anti-correlation

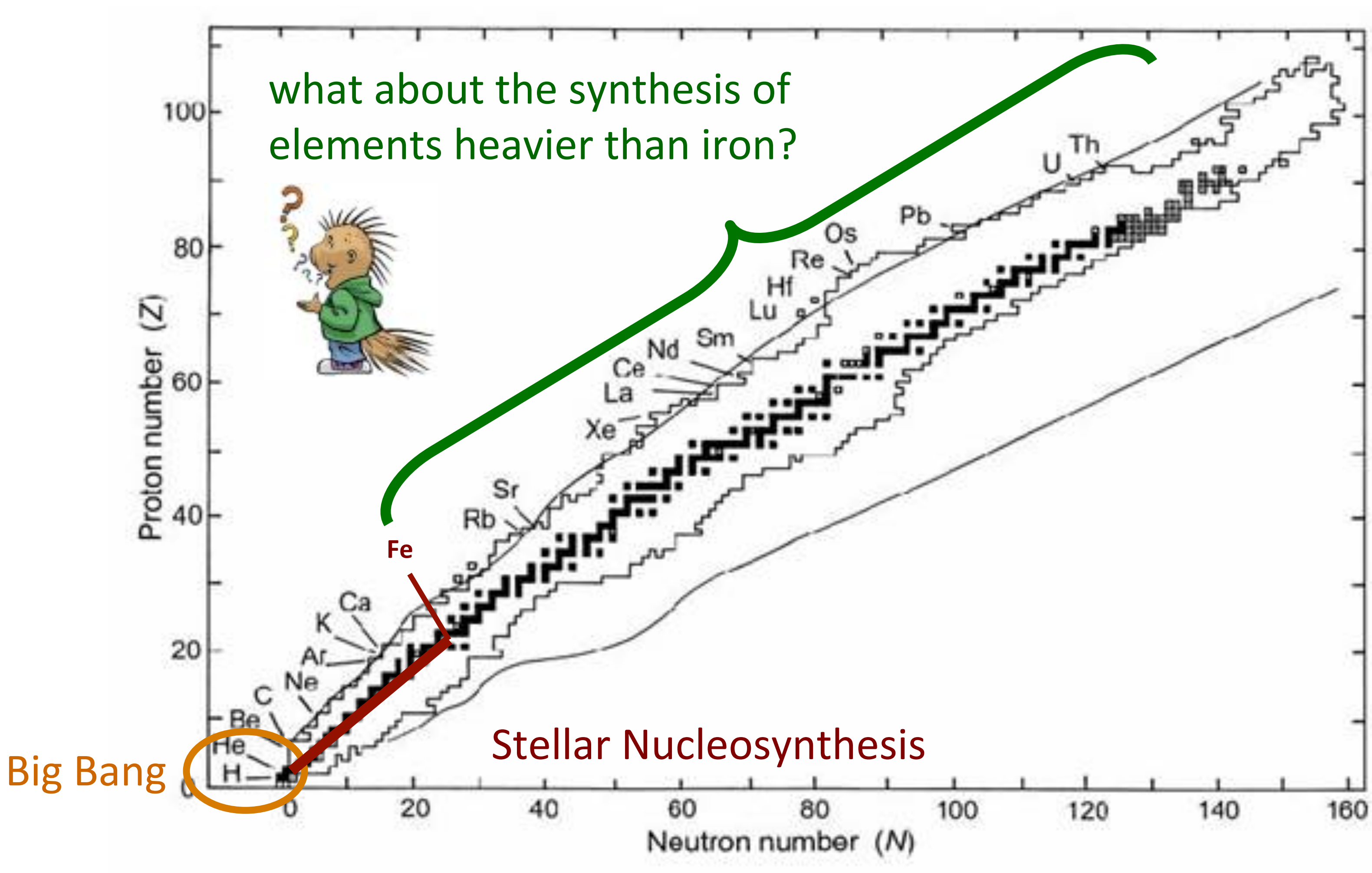




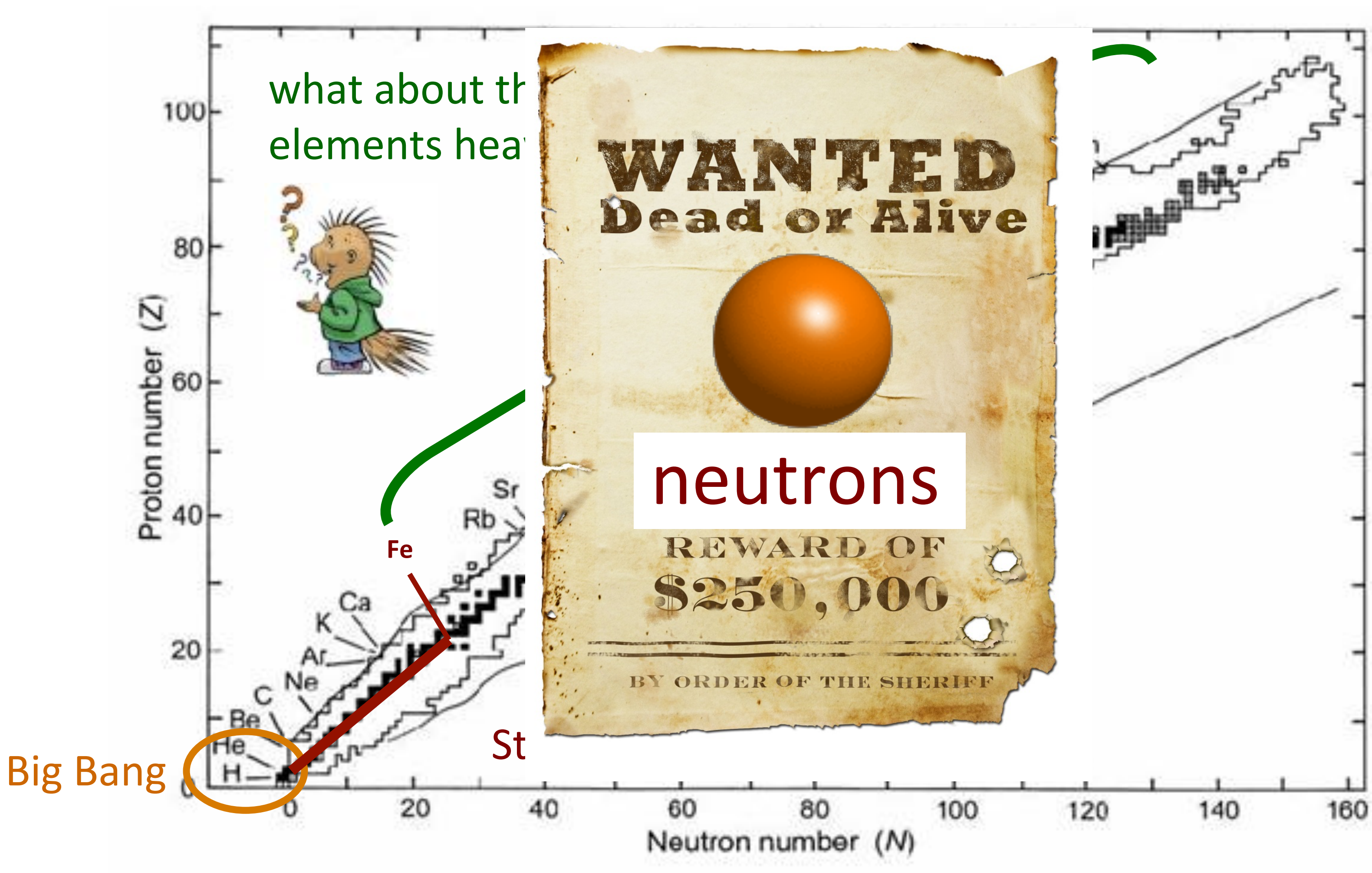
see talk by Federico Ferraro
Parallel Session - September 4

courtesy: F Ferraro

The Creation of Heavy Elements



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

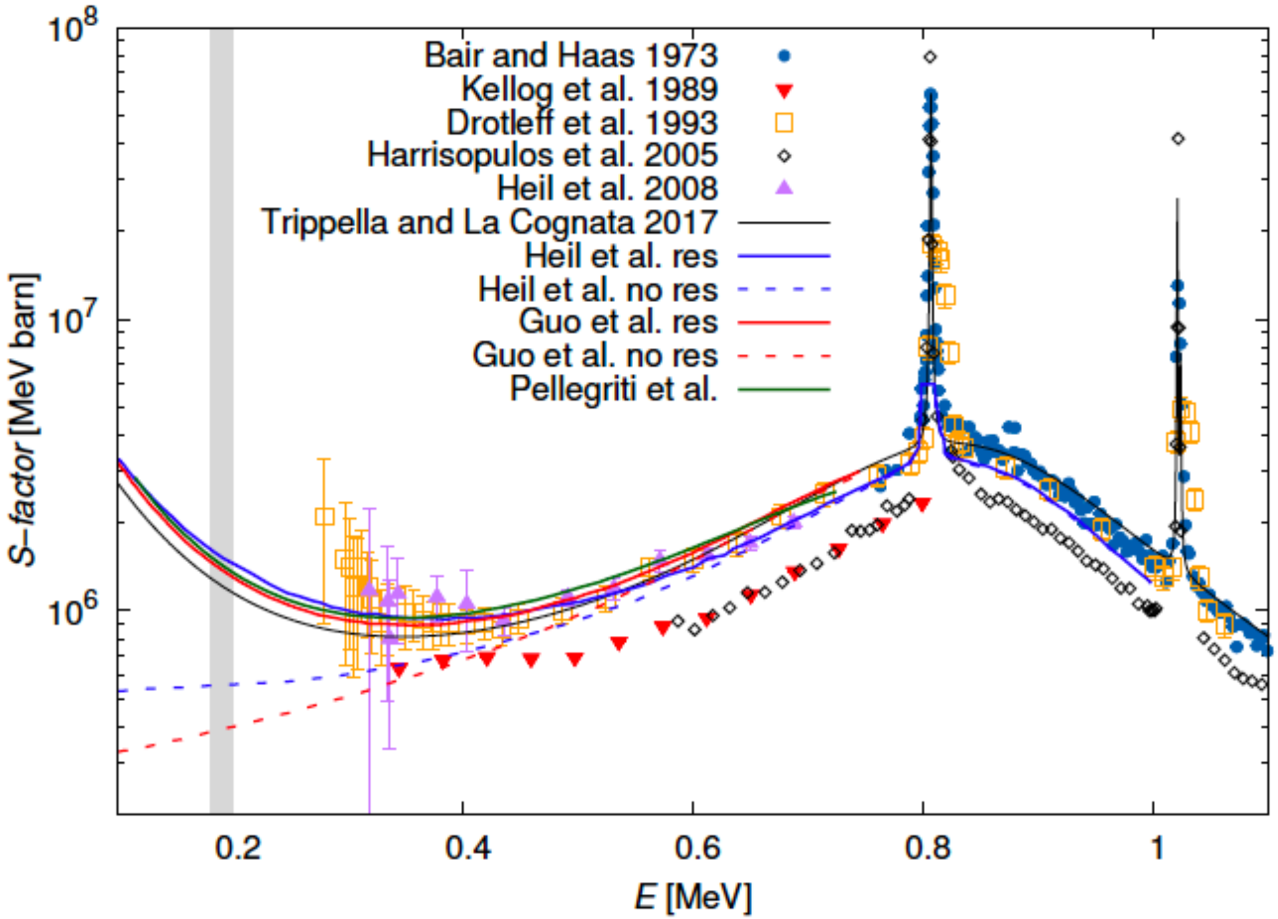


Neutron capture reactions: the s(low) and the r(apid) processes

Neutron Sources for the s-process

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

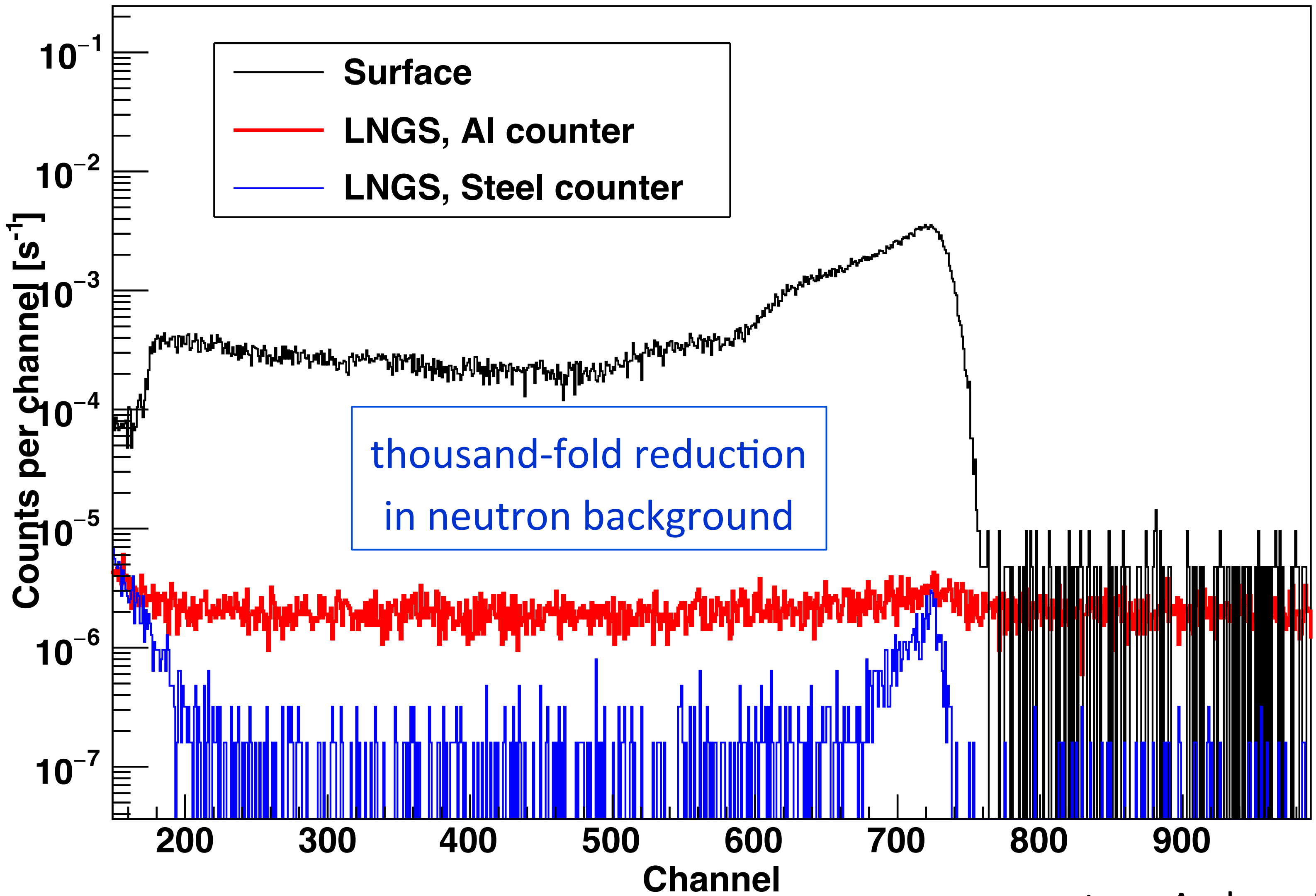
importance: s-process in AGB stars
Gamow region: 130 - 250 keV
min. meas. E_{cm}: 280 keV



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

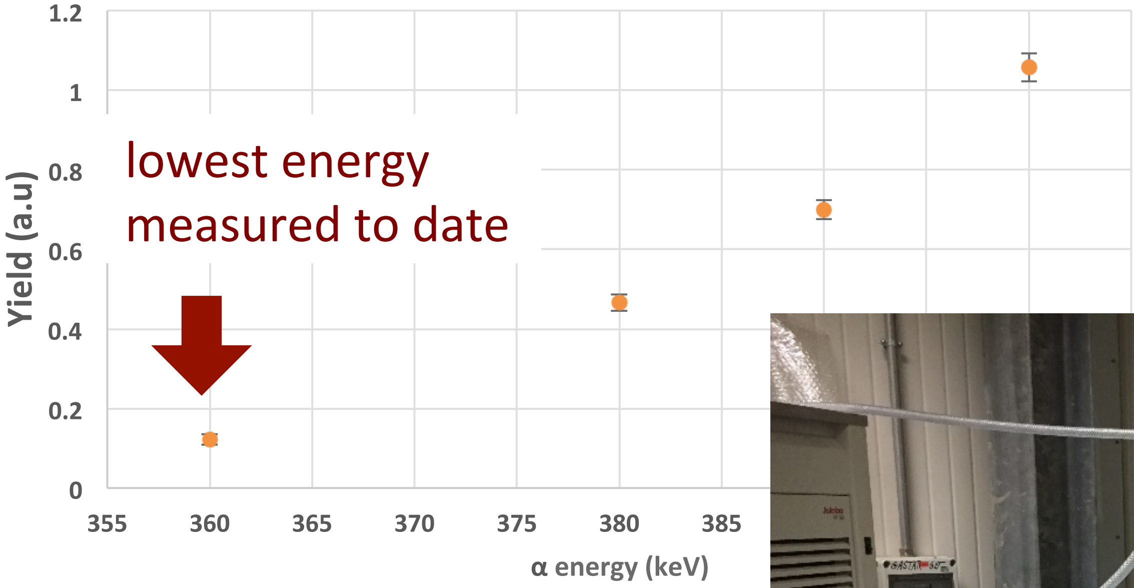
mainly hampered by cosmic background → excellent case for underground study

LUNA: an ideal environment for neutron detection



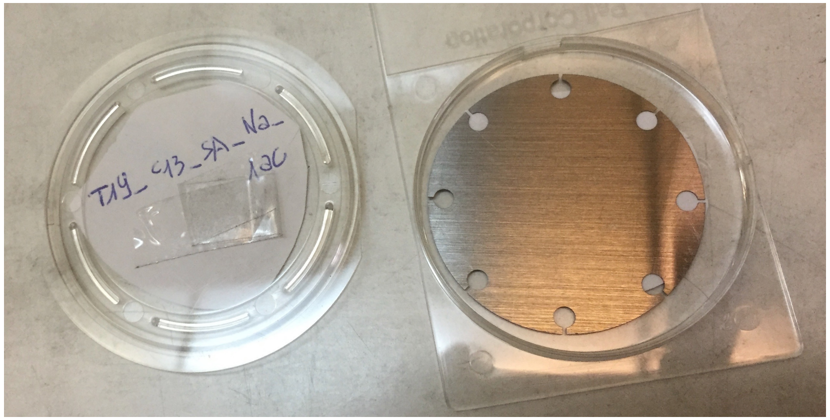
courtesy: Andreas Best

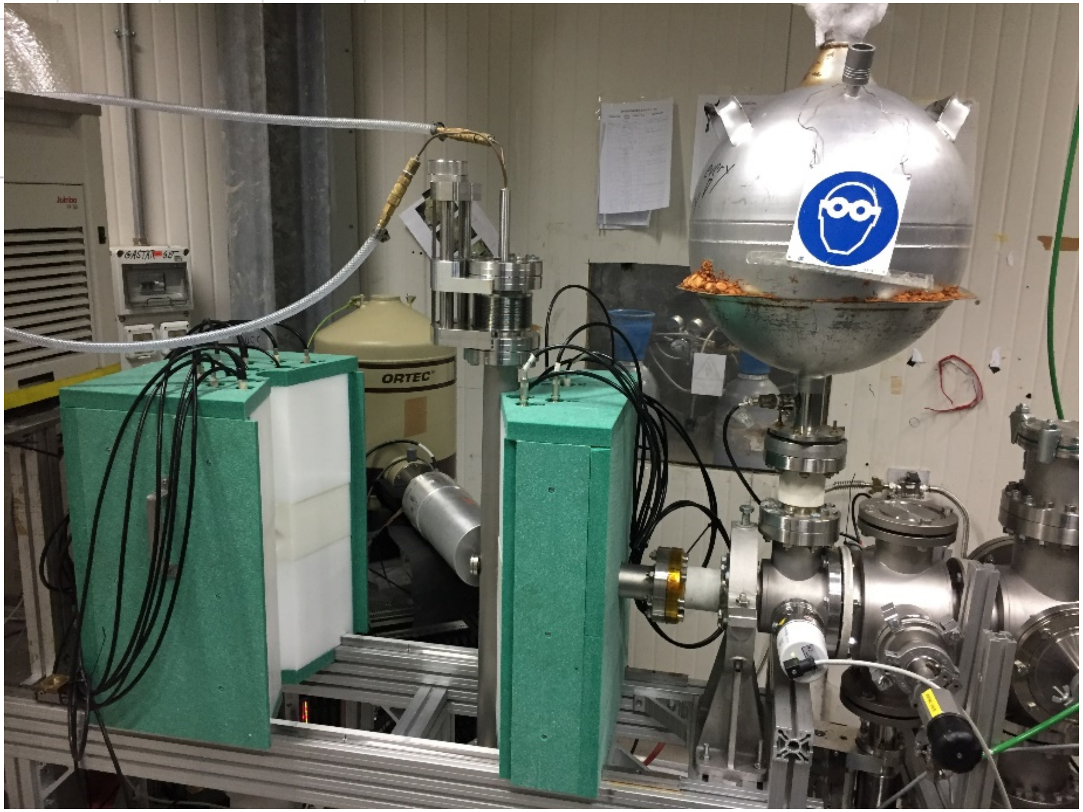
$^{13}C(a,n)^{16}O$ data taking campaign on going at LUNA 400kV



courtesy: A Best

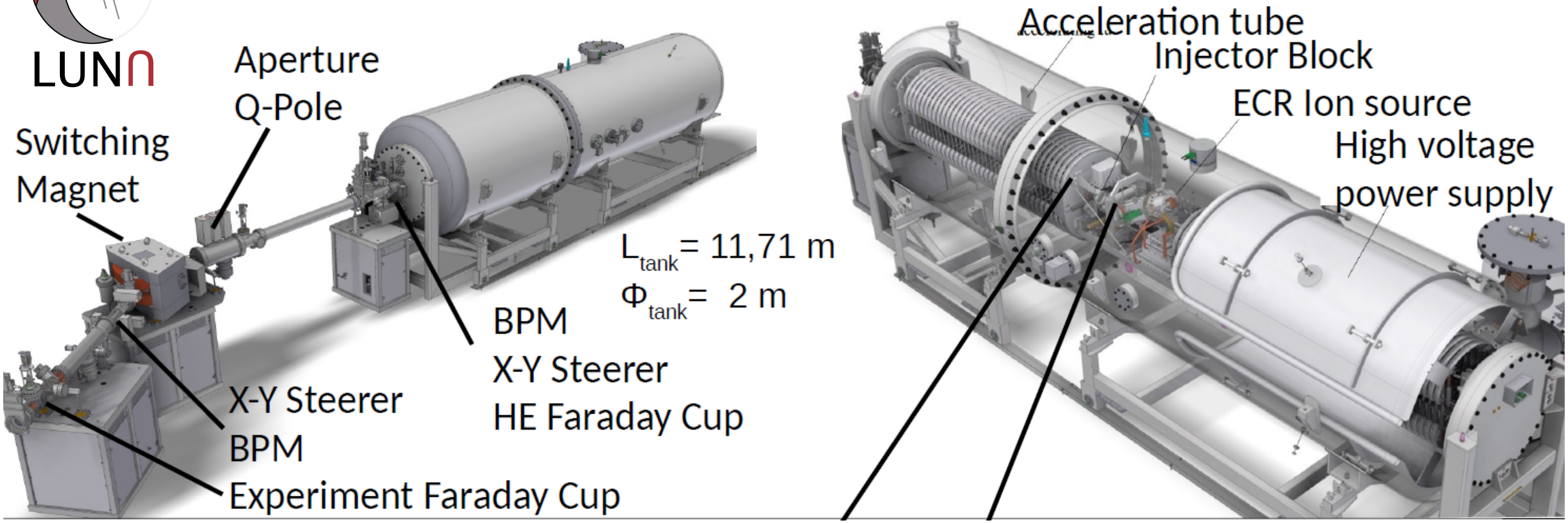
99% enriched 13C targets on Ta backing





Future Opportunities

LUNA MV: A 3.5 MV Accelerator with ECR Ion Source



H

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

He

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

C

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

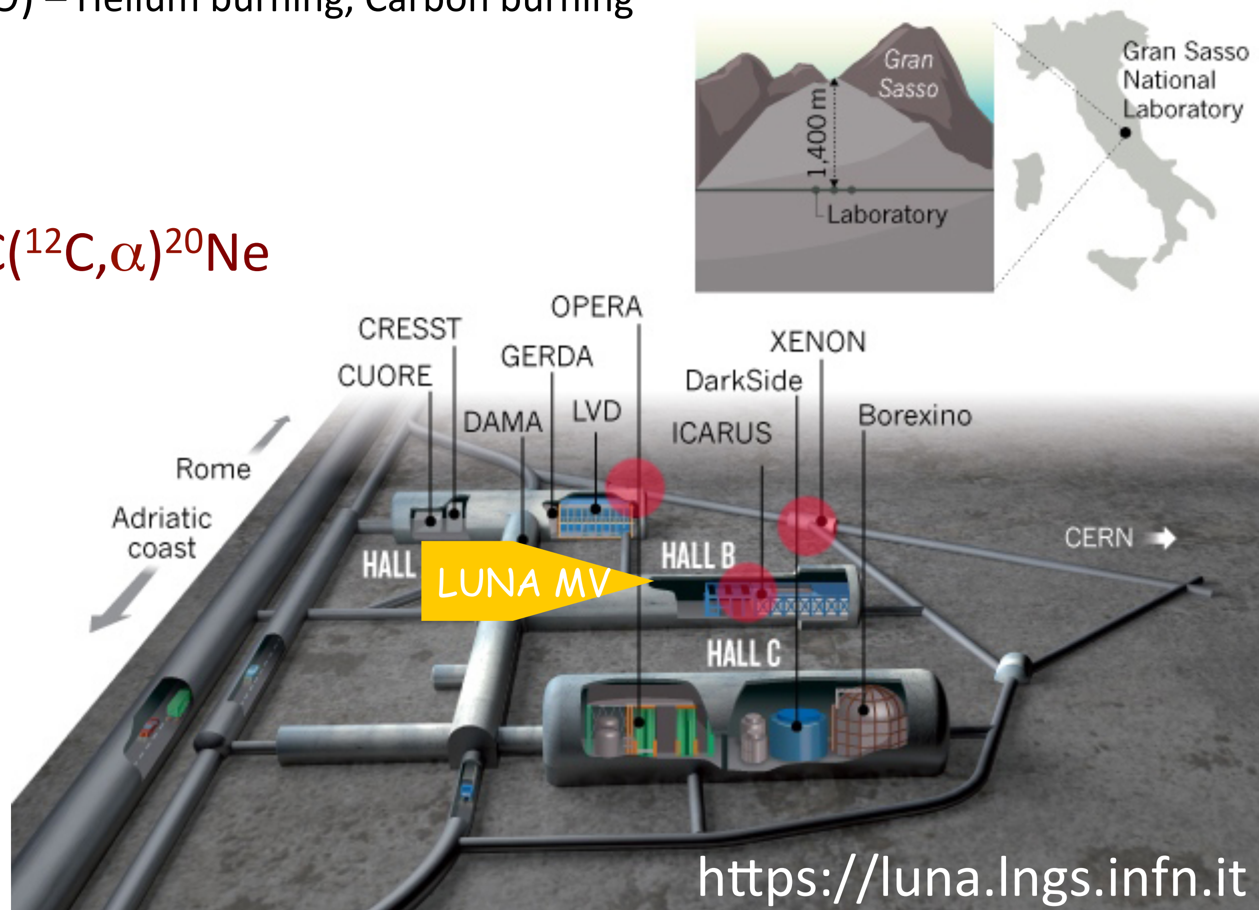
THE LUNA Collaboration

LUNA 50 kV (1992-2001) – Solar Phase

LUNA 400 kV (2000-2018) – CNO, Mg-Al and Ne-Na cycles, BBN

LUNA-MV (from 2019) – Helium burning, Carbon burning

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



LUNA MV – Construction Site

- Accelerator ready at High Voltage Engineering
- Tests in progress
- Installation at LNGS: Fall 2018
- Commissioning: late 2018 – early 2019

CASPAR: Compact Accelerator Systems for Performing Astrophysical Research

SURF: Sanford Underground Laboratory at Homestake (4300 mwe)

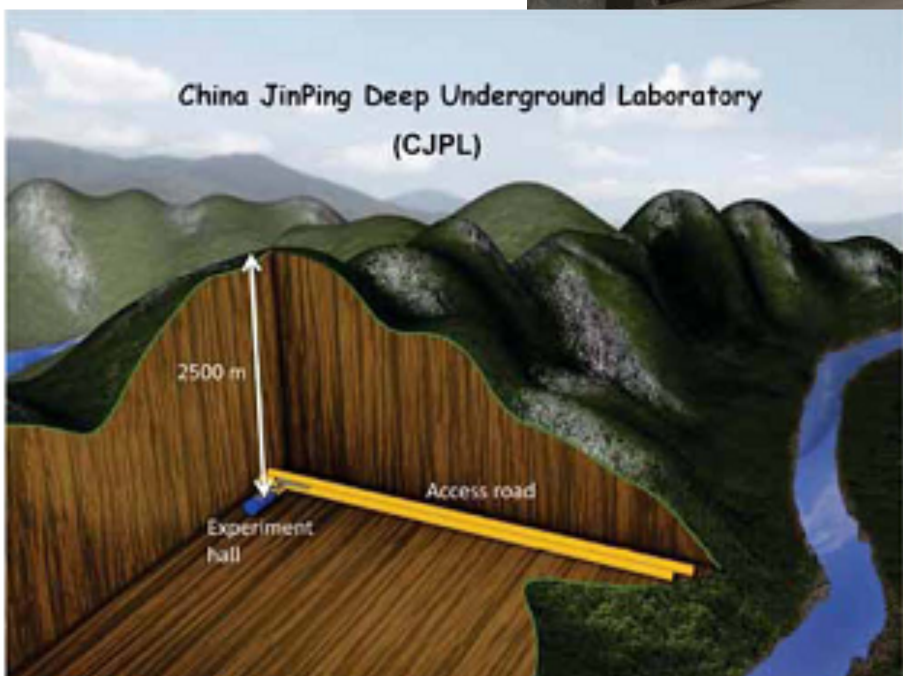
Collaboration between:

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

1 MV Accelerator Inaugurated July 2017

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

Planned for 2019

To Conclude…

LUNA: A Success Story

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, ... G. Gervino,[8] L. Gialanella,[9] U. Greife,[9] A. Guglielmetti,[1] C. Gustavino,[5] G. Imbriani,[3] M. Junker,[5] ... C. Rolfs,[9] M. Romano,[3] F. Schuemann,[9] F. Strieder,[9] F. Terrasi,[3] H.P. Trautvetter,[9] and S. ...
(LUNA Collaboration)

PRL 115, 252501 (2015) — PHYSICAL REVIEW LETTERS

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] ... P. Corvisiero,[1] T. Davinson,[9] A. di Leva, ... C. Gustavino,[14] Gy. Gyürky,[11] ... E. Somorjai,[11] O. Straniero, ... D. A. Scott,[9] ...

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]

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] ... M. Aliotta,[1] M. Anders,[6] D. Bemmerer,[6] C. Broggini,[2] M. Campeggio,[7] P. Corvisiero, ... A. Guglielmetti,[7] C. Gustavino,[5] Gy. Gyürky, ... G. Imbriani,[4] ... Marta,[11] E. Napolitani,[12] P. Prati,[8] ... T. Szücs,[9] F. Terrasi,[15] ...
(LUNA Collaboration)

LUNA has pioneered underground studies in Nuclear Astrophysics for over two decades

Astronomy & Astrophysics

The bottleneck of CNO burning and the age of Globular Clusters

G. Imbriani[1,2,3], H. Costantini[4], A. Formicola[5,6], D. Bemmerer[7], R. Bonetti[8], C. Broggini[9], P. Corvisiero[4], J. Cruz[10], Z. Fülöp[11], G. Gervino[12], A. Guglielmetti[8], C. Gustavino[6], G. Gyürky[11], A. P. Jesus[10], M. Junker[6], A. Lemut[4], R. Menegazzo[9], P. Prati[4], V. Roca[2,3], C. Rolfs[5], M. Romano[2,3], C. Rossi Alvarez[9], F. Schümann[5], E. Somorjai[11], ... F. Terrasi[2,13], H. P. Trautvetter[5], A. Vomiero[14], and S. Zavatarelli[4]

ELSEVIER — Available online at www.sciencedirect.com — SCIENCE @ DIRECT — PHYSICS LETTERS B — Physics Letters B 634 (2006) 483–487 — www.elsevier.com/locate/physletb

First measurement of the $^{14}N(p,\gamma)^{15}O$ cross section down to ...

LUNA Collaboration

A. Lemut[a], D. Bemmerer[b], F. Confortola[a], R. Bonetti[c], C. Broggini[b,*], P. ... H. Costantini[a], J. Cruz[d], A. Formicola[e], Zs. Fülöp[f], G. Gervino[g], A. Guglielmetti ... Gy. Gyürky[f], G. Imbriani[h], A.P. Jesus[d], M. Junker[e], B. Limata[h], R. Menegazzo ... V. Roca[h], D. Rogalla[i], C. Rolfs[j], M. Romano[h], C. Rossi Alvarez[b], F. Schümann ... O. Straniero[k], F. Strieder[j], F. Terrasi[i], H.P. Trautvetter[j]

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]

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

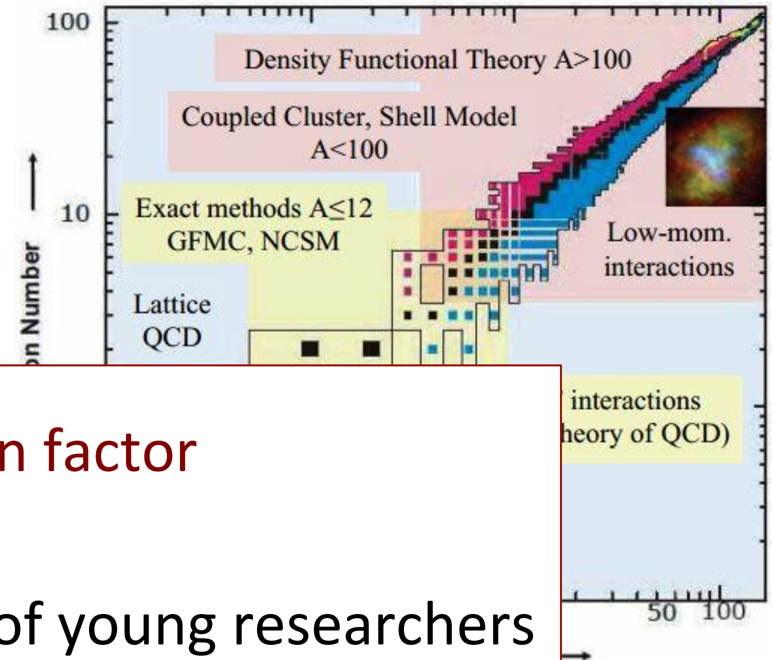
Atomic Physics

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

Ingredients from Future Breakthroughs

experiments

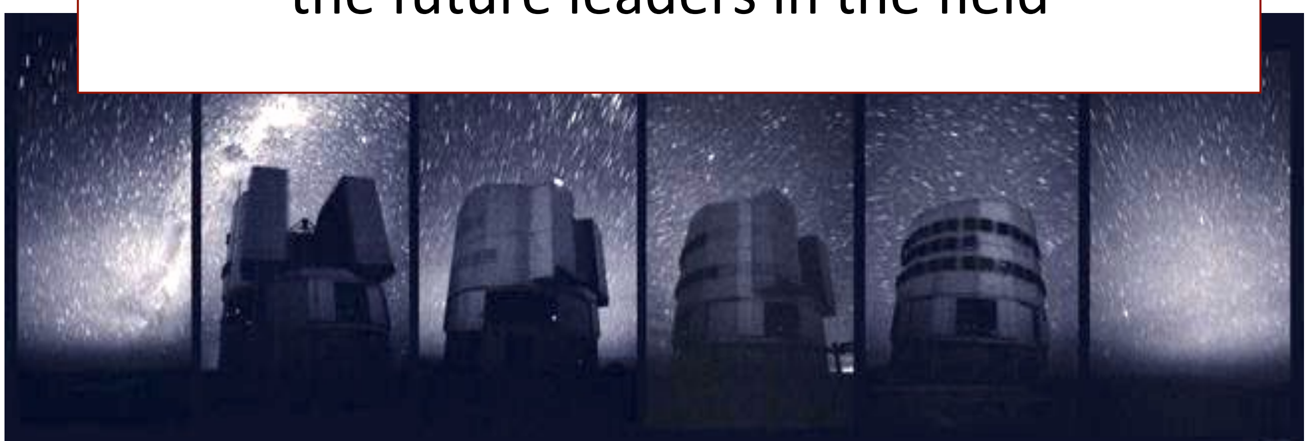
theory



the human factor

training and retention of young researchers

the future leaders in the field



THE LUNA COLLABORATION

LUNA

http://luna.lngs.infn.it

- F. Amodio, G. Ciani, L. Csedreki, L. Di Paolo, A. Formicola, M. Junker| Laboratori Nazionali del Gran Sasso/GSSI, Italy
- D. Bemmerer, K. Stoeckel, M. Takacs | HZDR, Germany
- M. Lugaro | Konkoly Observatory, Hungarian Academy of Sciences, Debrecen, Hungary
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- O. Straniero | Osservatorio Astronomico di Collurania, Teramo, Italy
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- M. Aliotta, C.G. Bruno, T. Chillery, T. Davinson | University of Edinburgh
- F. Cavanna, P. Corvisiero, F. Ferraro, **P. Prati**, S. Zavatarelli | Università di Genova and INFN Genova, Italy
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- G. Gervino | Università di Torino and INFN Torino, Italy
- C. Broggini, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti | Università di Padova and INFN Padova, Italy
- C. Gustavino | INFN Roma1, Italy