Nuclear Astrophysics at Gran Sasso : the present and the future

S. Zavatarelli
INFN- Genoa (Italy)

A pivotal encounter..

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

Energy production in the Sun

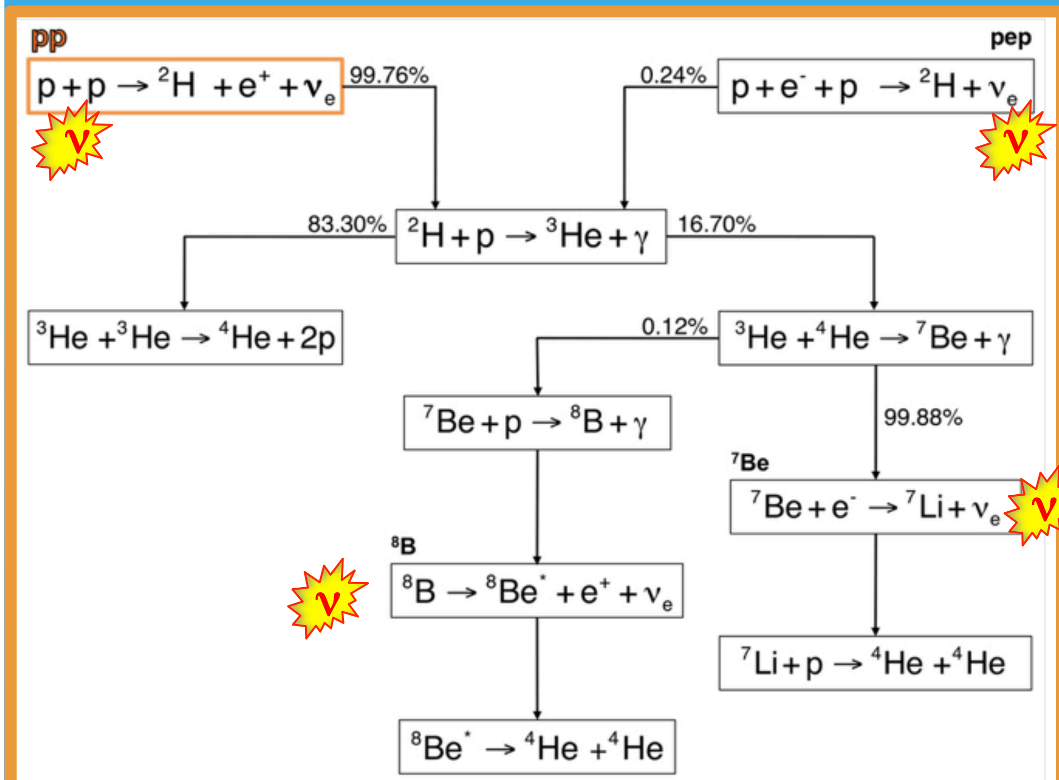
Our Sun has been shining at a constant rate for 5 billion years converting 700 million tonnes of H into He each second

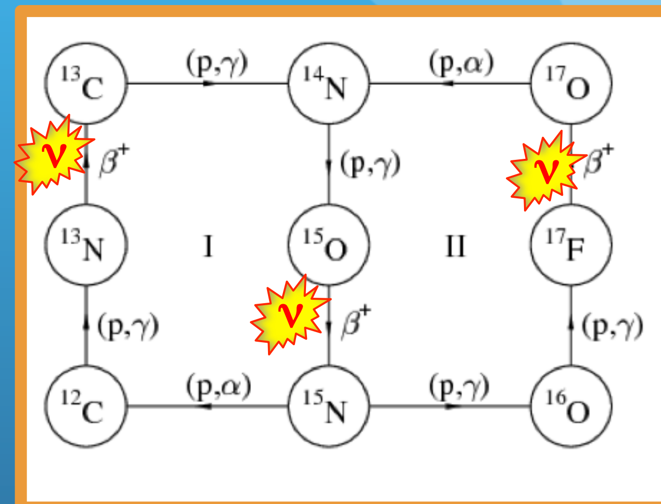
Converting H into He: The Proton-Proton Chain

According to the Standard Solar Model…

pp chain: 99 % of Sun Energy

CNO cycle: <1 % of Sun Energy

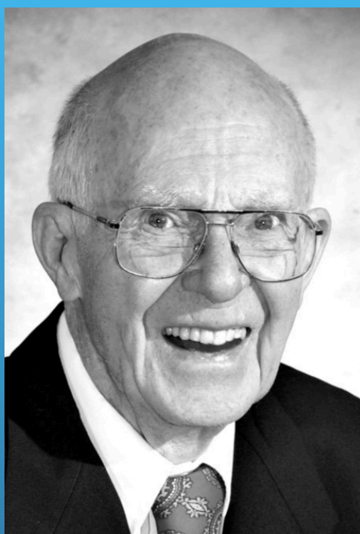




No way of "seeing" what happens in the core of the Sun except if we…
detect neutrinos

Direct evidence of nucleosynthesis in stars

FIRST DIRECT EVIDENCE FOR NUCLEAR REACTIONS IN OUR SUN

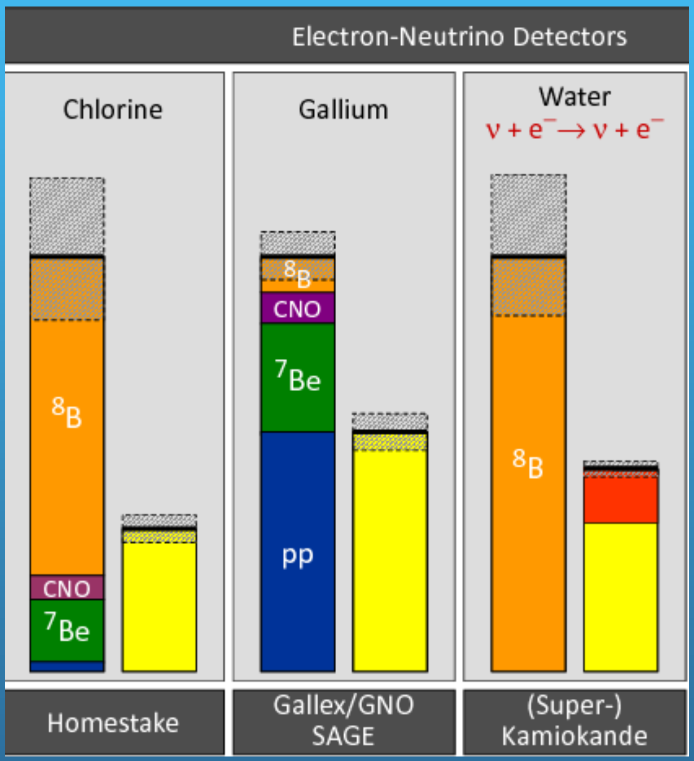


Ray Davis Jr.
2002 Nobel Prize

http://sanfordlab.org/article/270

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

Solar Neutrino Problem



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

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

A Resonance in $^3He+^3He$ to Solve the Solar Neutrino Problem?

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

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

86% | 14%

PP-I

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

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

99.7% | 0.3%

PP-II

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

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

PP-III

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

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

$\downarrow$

$2\,{}^4He$

what if this reaction has a resonance at solar energies?

a direct measurement of its cross section was necessary

Thermonuclear Reactions in Stars

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)

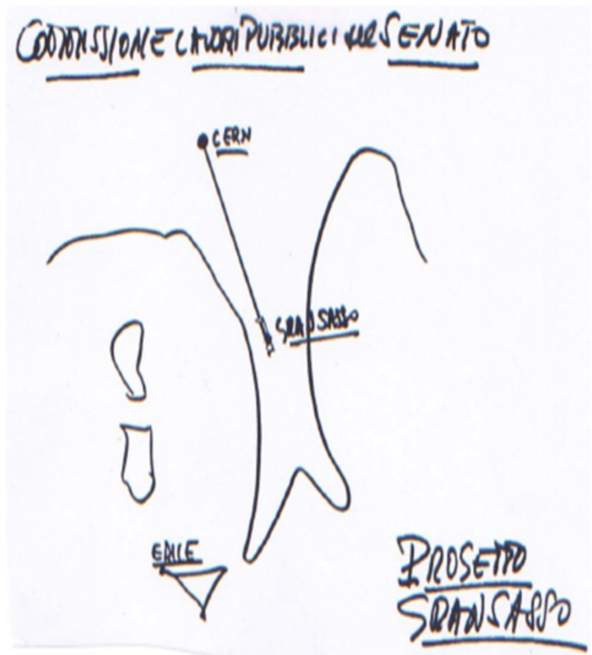
Y = 0.3-30 counts/year

~ 1.2-220 counts/day (background)

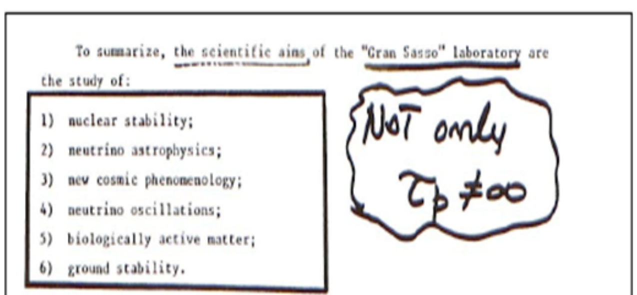
How to improve the signal-to-noise ratio?

Gianni Fiorentini & Claus Rolfs

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:

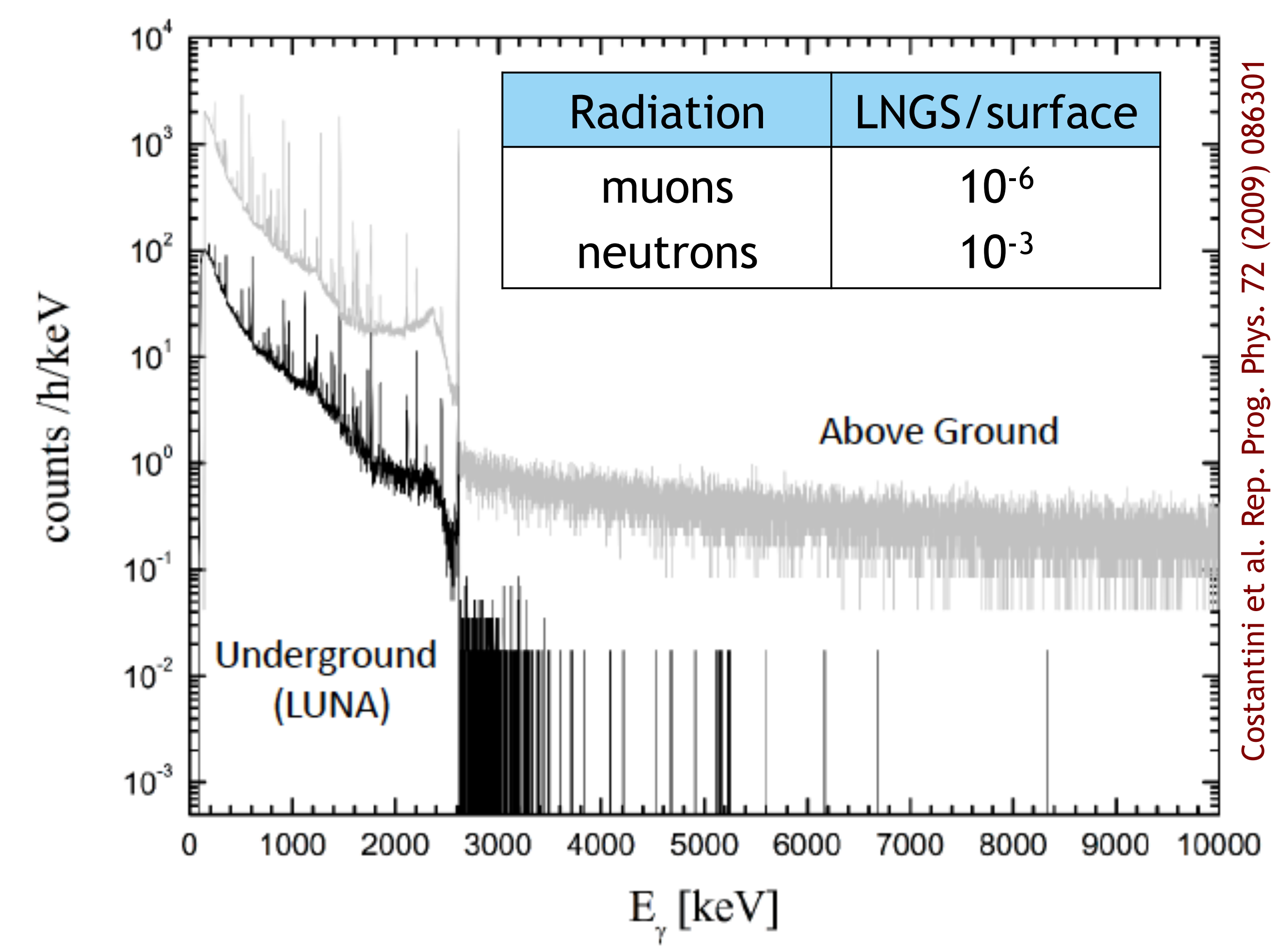
1) nuclear stability;
2) neutrino astrophysics;
3) new cosmic phenomenology;
4) neutrino oscillations;
5) biologically active matter;
6) ground stability.

courtesy: C. Broggini

Antonino Zichichi

Gamma-ray background: underground vs overground comparison

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



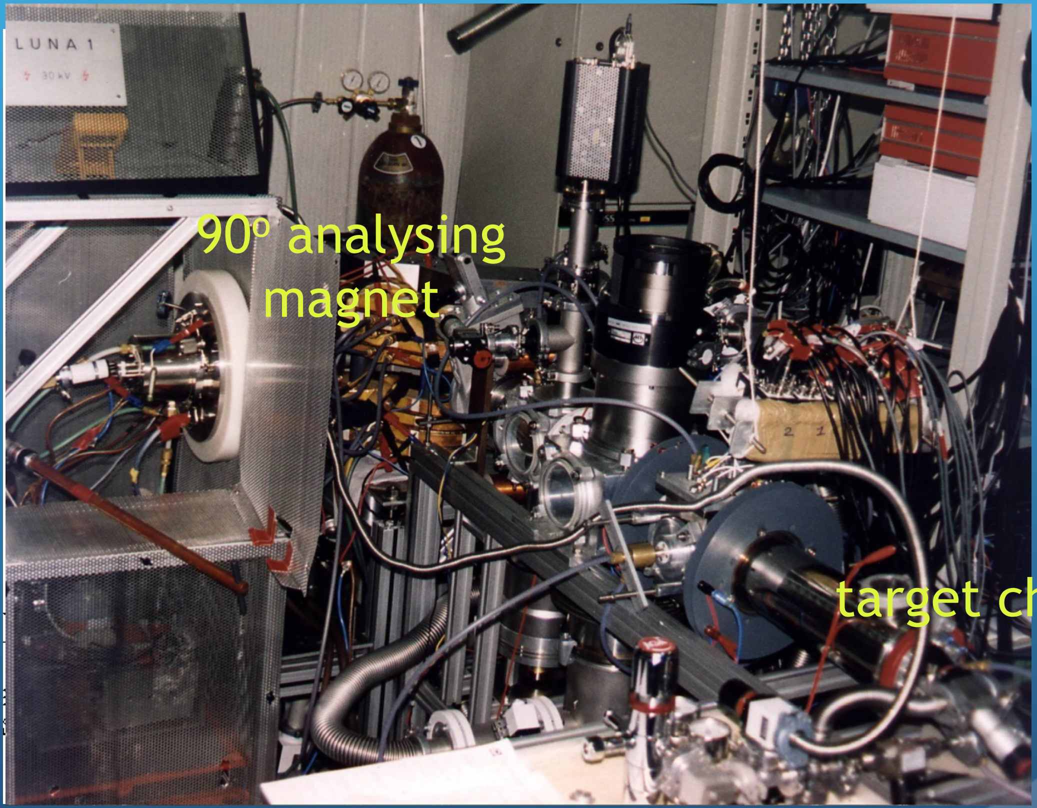
Radiation	LNGS/surface
muons	10^{-6}
neutrons	10^{-3}

LUNA:
Laboratory for Underground Nuclear Astrophysics

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

first *underground accelerator* in the world

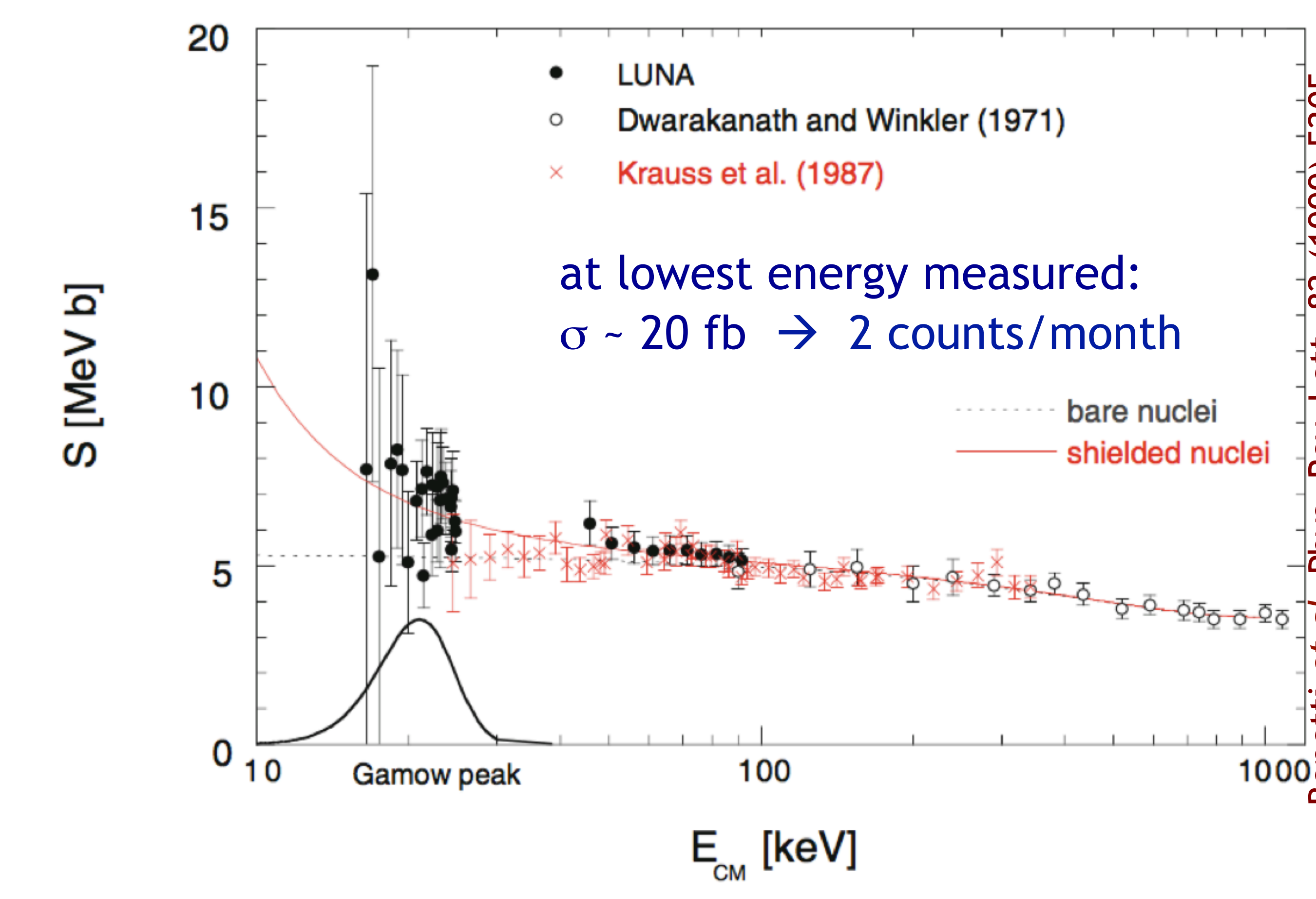
duoplasmatron ion source on 50kV platform



entirely built by students!

The $^3He+^3He$ Reaction at LUNA and the Solar Neutrino Problem

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 $^{3}He(^{3}He, 2p)^{4}He$ 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-Colla

Dear Professors Corvisiero and

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

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.

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

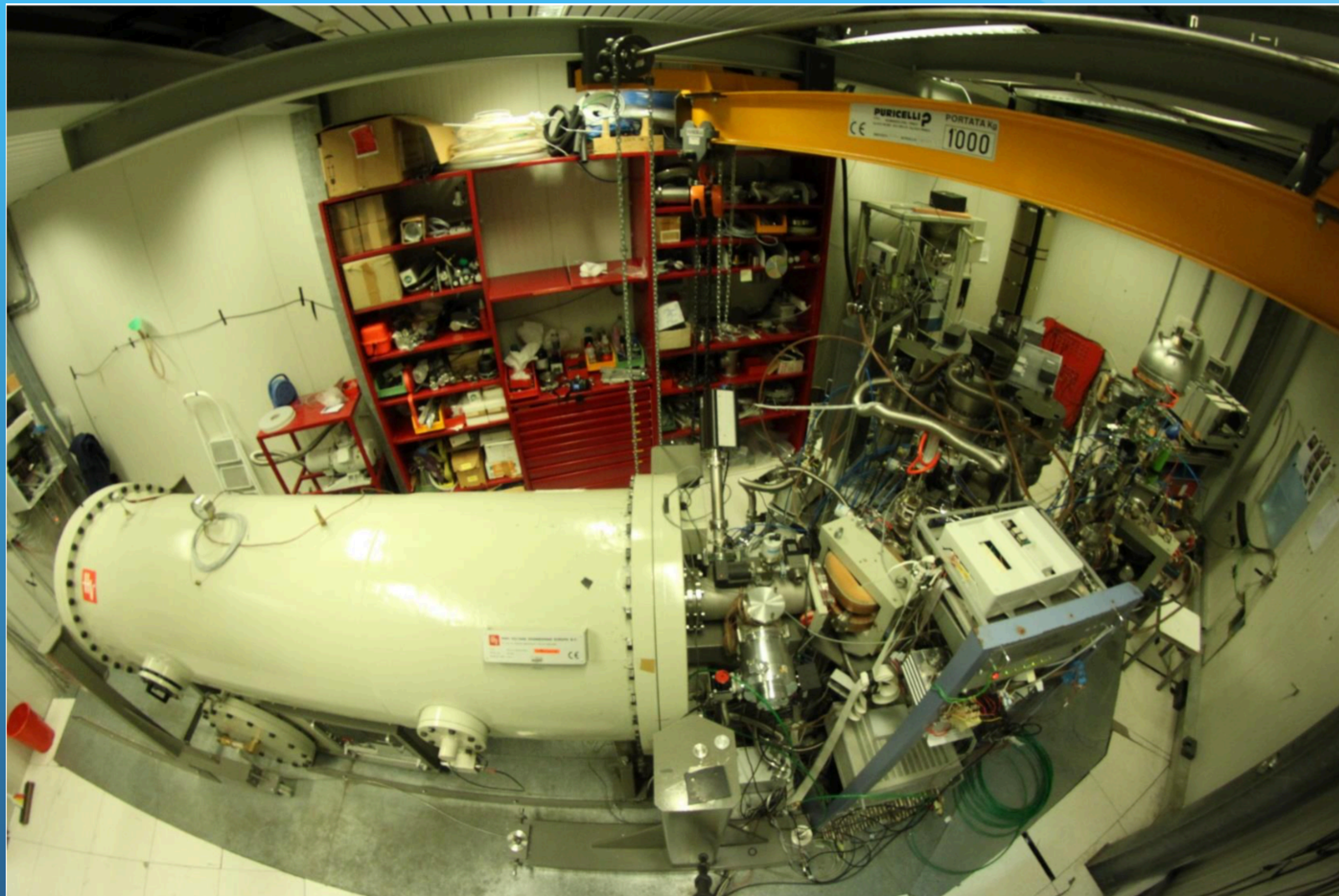
I have had some experience in helping to set priorities for research in physics and in astronomy, most recently as Chair of the Decade Survey for Astronomy and Astrophysics of the National Academy of the United States and as President (now emeritus) of the American Astronomical Society. I can say, with 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

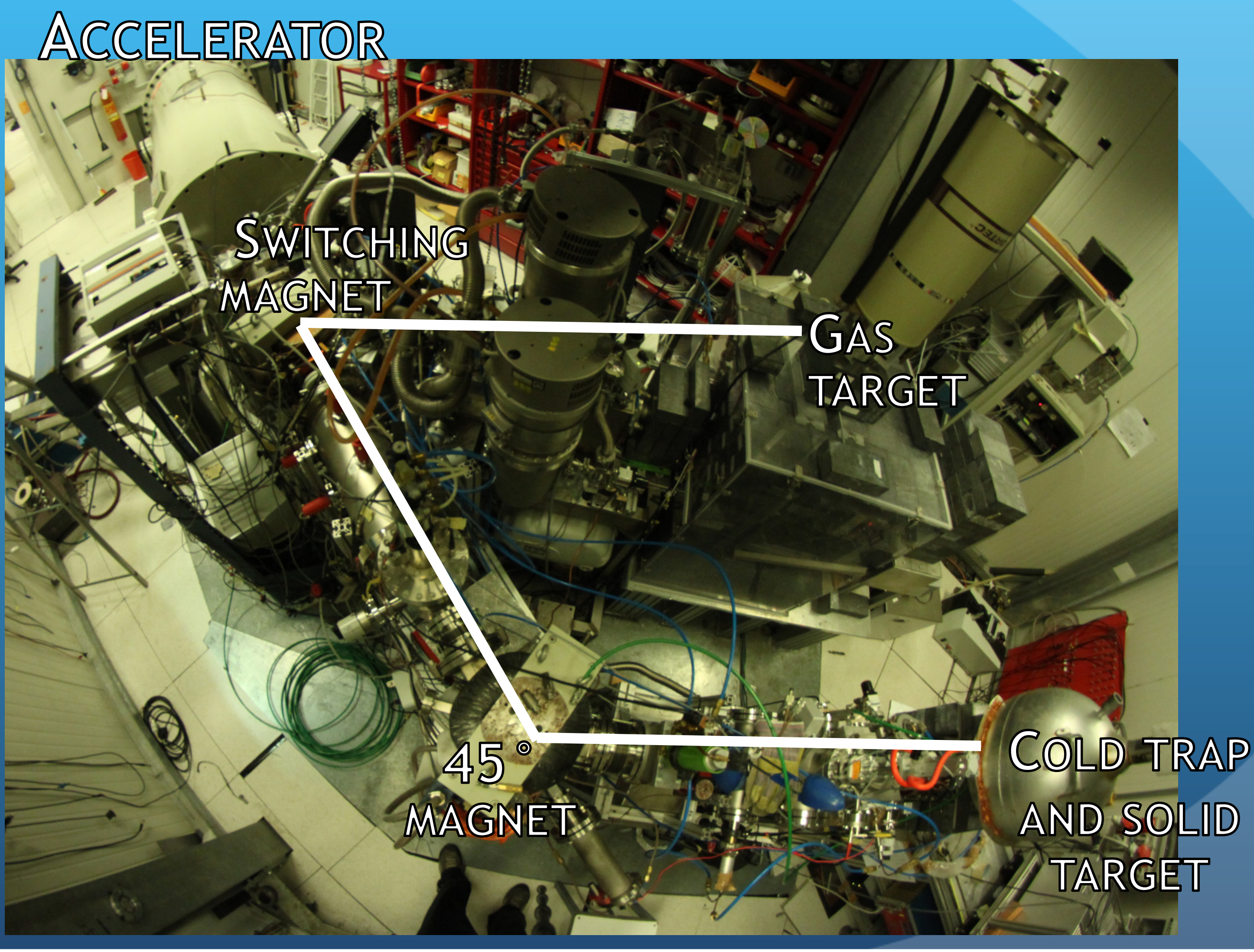
JNB:jnb

The LUNA 400 KV accelerator



E_{beam} ≈50–400keV
I max ≈ 500 μA protons, I_{max} ≈ 250 μA alphas ; Energy spread ≈ 70 eV
Long term stability ≈ 5eV/h

The LUNA 400 KV accelerator and beam lines



25 year of Nuclear Astrophysics at LUNA (LNGS)

- **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!

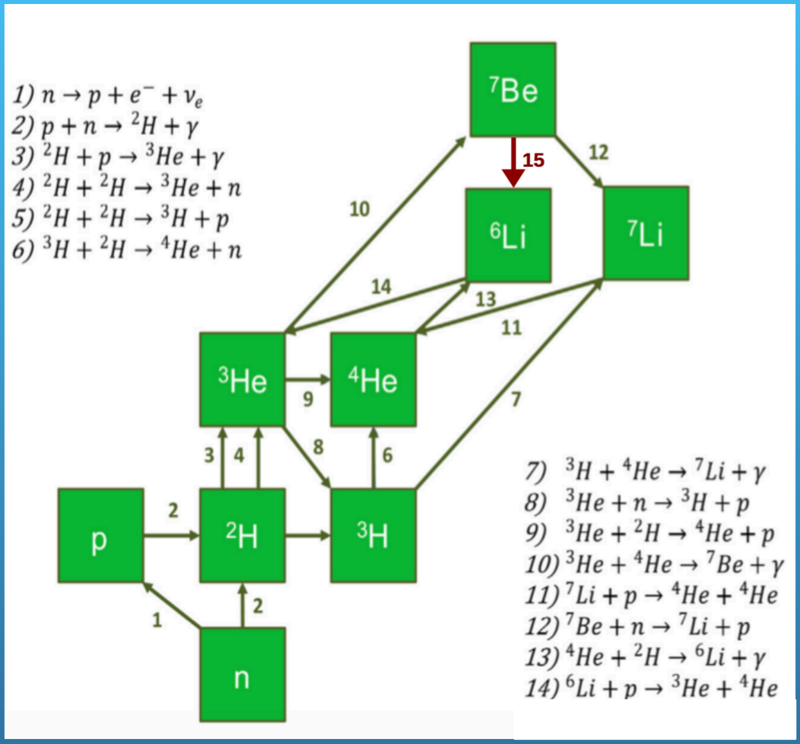
Puzzling Facts and Open Questions

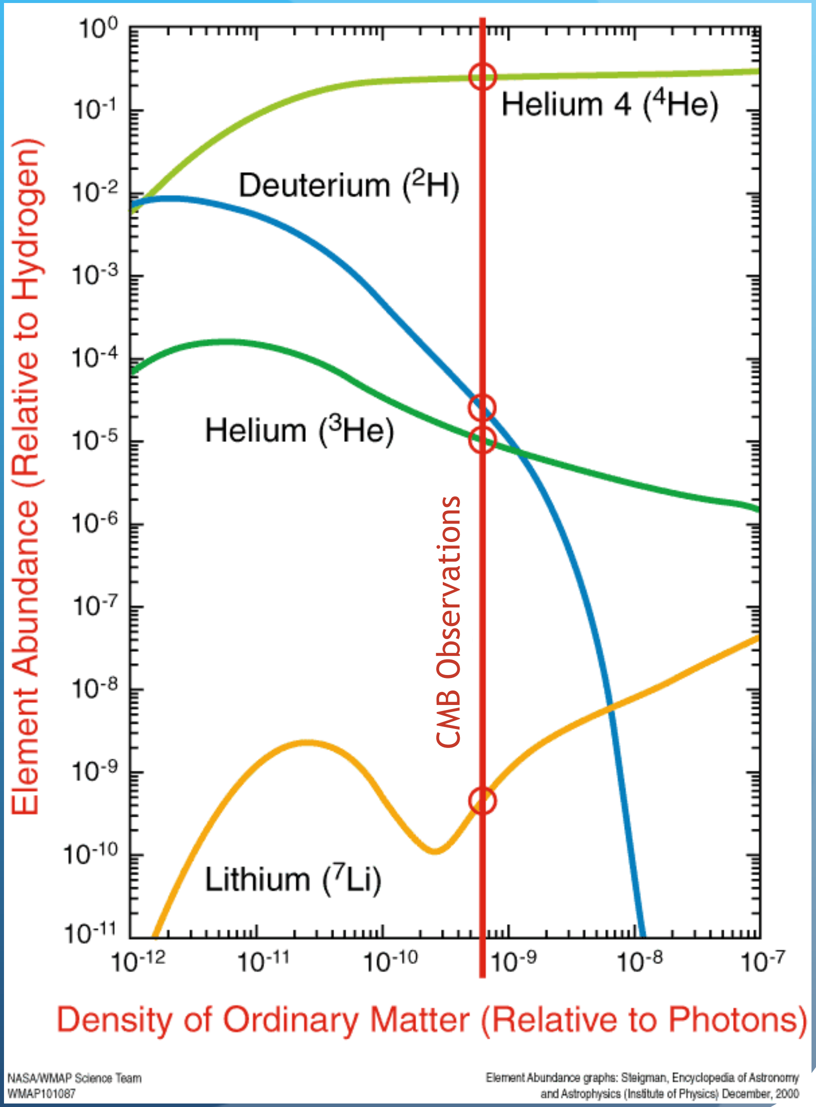
- Big Bang Nucleosynthesis: Li problem(s) and the D abundance
- Core metallicity of the Sun
- Fate of massive stars
- Explosive scenarios: X-ray bursts, novae, SN type Ia
- Pre-solar grains composition/Anomalous abundances
- Origin of heavy elements
- Astrophysical site(s) for the r-process
- …

Big Bang Nucleosynthesis

BBN is only handle to probe state of early universe

Primordial Nucleosynthesis (BBN): 3 minutes after Big Bang

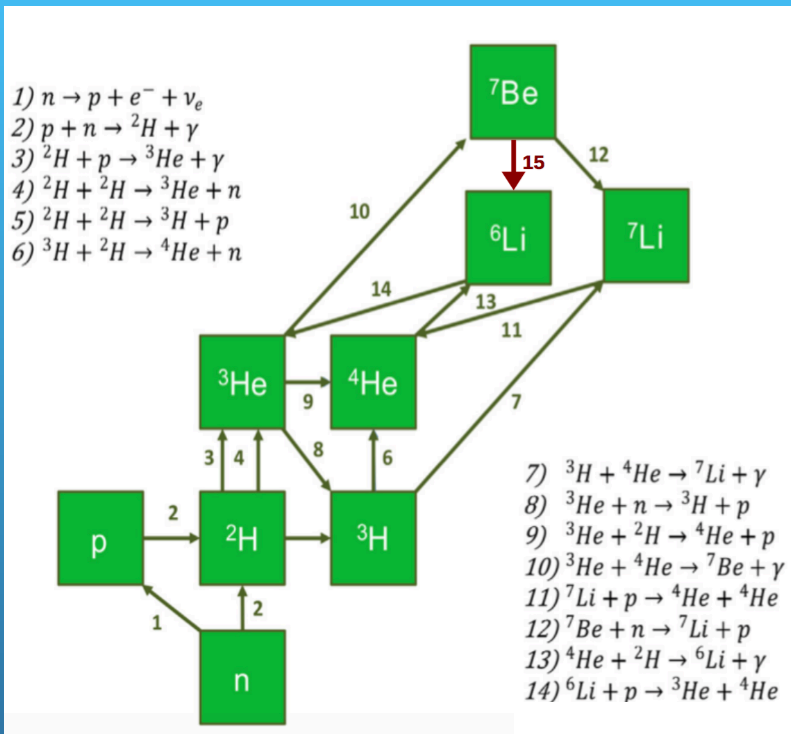


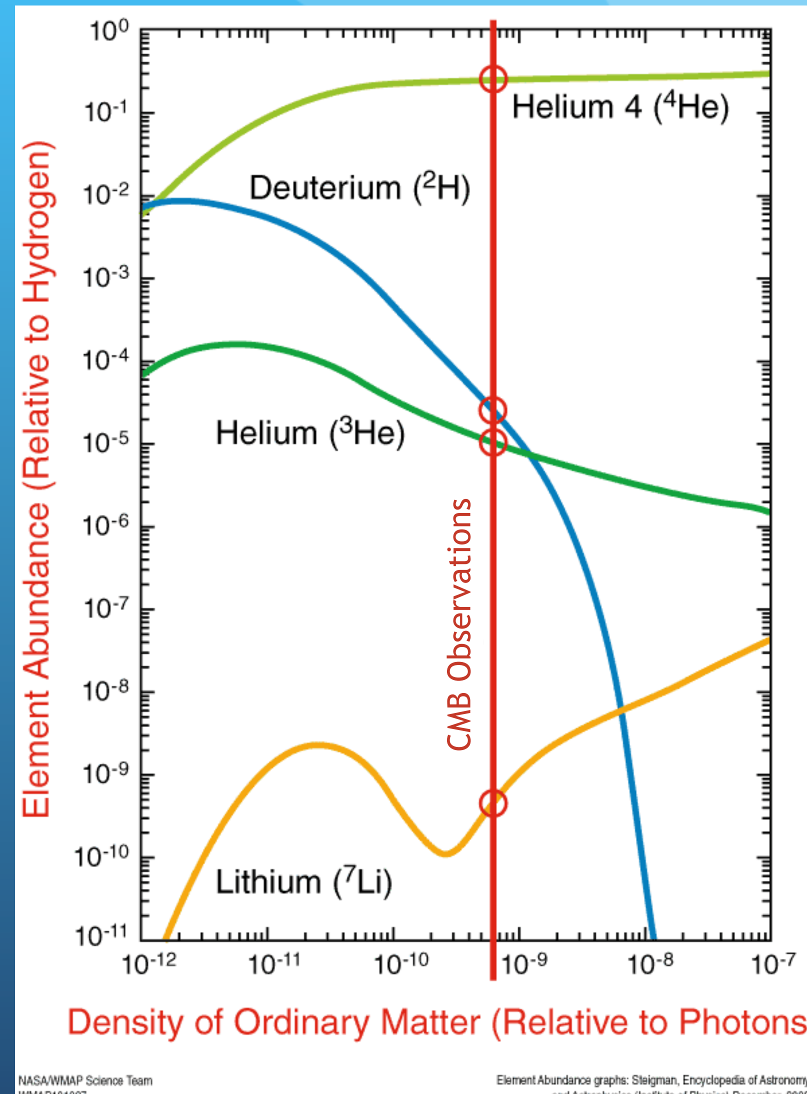


Calculation of primordial abundances only depends on:

- Nuclear Astrohysics, i.e. cross sections of relevant processes at BBN energies
- Particle Physics (N_{eff},..)
- Baryon density Ω_b

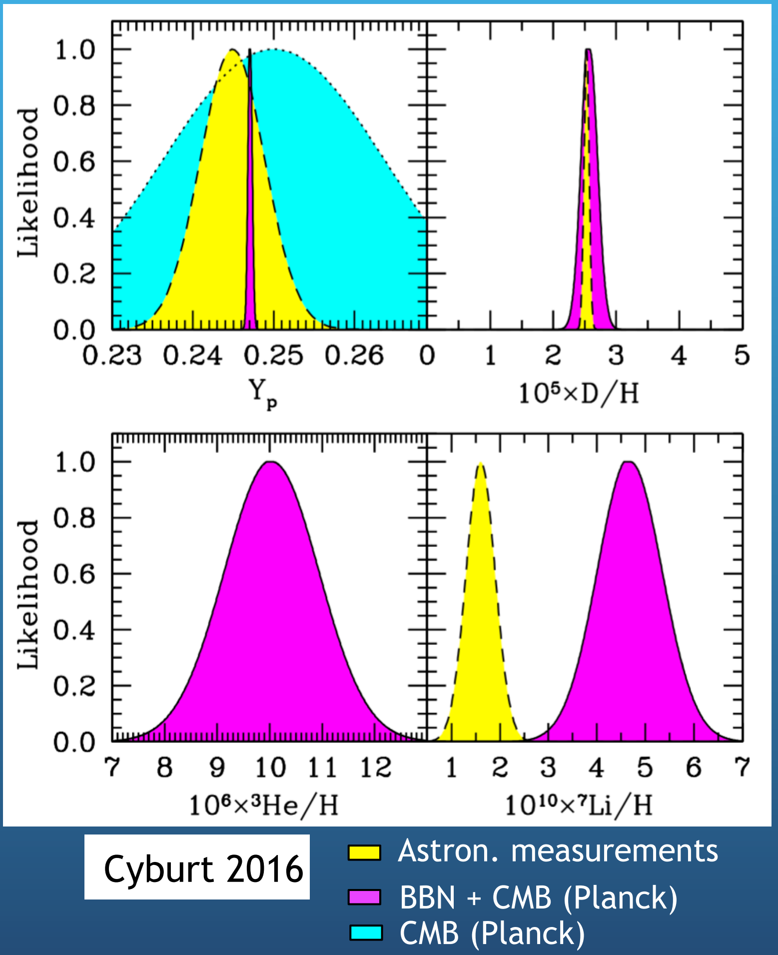
Primordial Nucleosynthesis (BBN): 3 minutes after Big Bang





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

Primordial Nucleosynthesis (BBN): light element abundances



Cyburt 2016

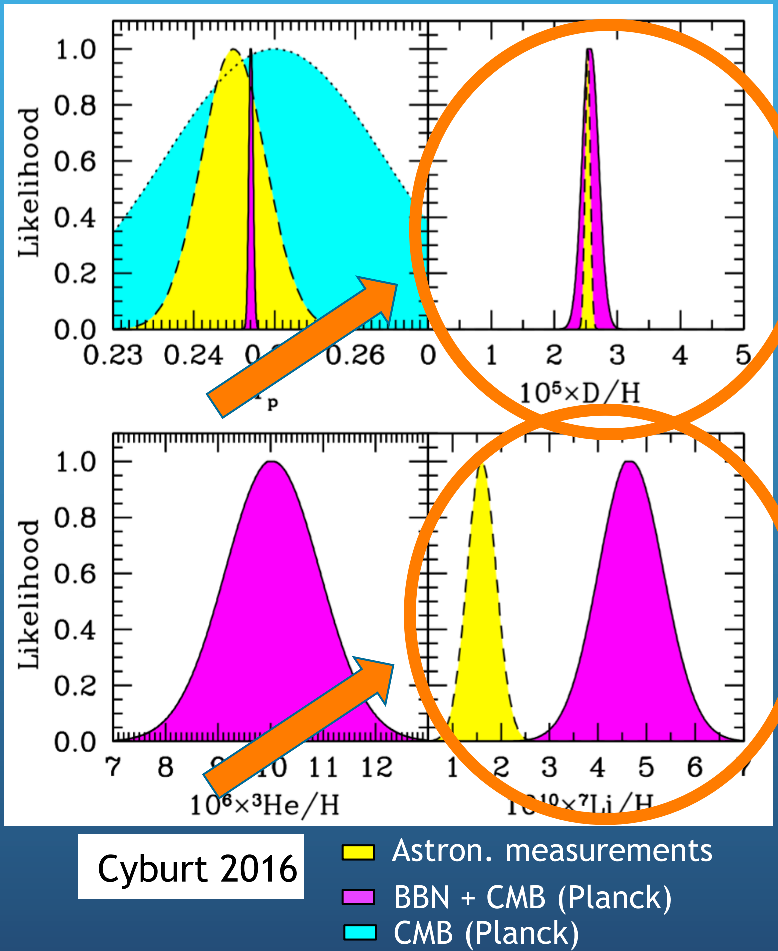
Isotope	BBN Theory	Observations
Yp	0.24771±0.00014	0.254±0.003
D/H	$(2.41\pm0.05)\times10^{-5}$	$(2.53\pm0.03)\times10^{-5}$
$^3He/H$	$(1.00\pm0.01)\times10^{-5}$	$(0.9\pm1.3)\times10^{-5}$
$^7Li/H$	$(4.68\pm0.67)\times10^{-10}$	$(1.23\ ^{+0.68}_{-0.32})\times10^{-10}$
$^6Li/^7Li$	$(1.5\pm0.3)\times10^{-5}$	$\sim10^{-2}$

^{4}He, D, ^{3}He abundances measurements are (broadly) consistent with expectations.

^{7}Li: Long standing “Lithium problem”

^{6}Li: “Second Lithium problem”?

Primordial Nucleosynthesis (BBN): light element abundances



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^{4}He, D, ^{3}He abundances measurements are (broadly) consistent with expectations.

^{7}Li: Long standing "Lithium problem"

^{6}Li: "Second Lithium problem"?

Lithium Problem(s)

a success story:

discrepancy revealed thanks to close interplay among

theory, observation, and experiment

Primordial Lithium Abundances

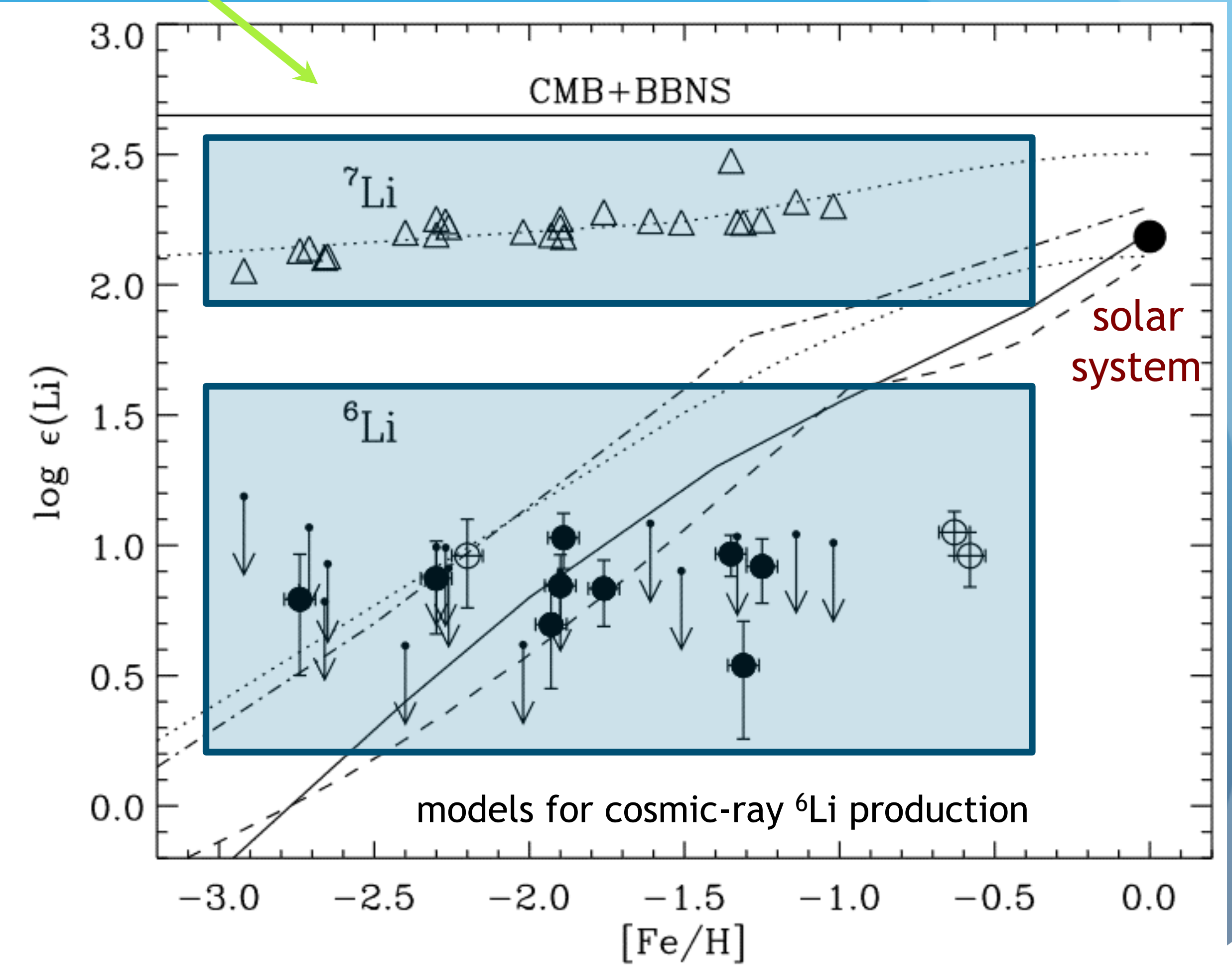
CBM + BBN predictions
^{7}Li abundance (^{6}Li/^{7}Li ~ 10^{-5})

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

first Lithium Problem

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

second Lithium Problem



Asplund *et al*, ApJ **644** (2006) 229

first Lithium Problem

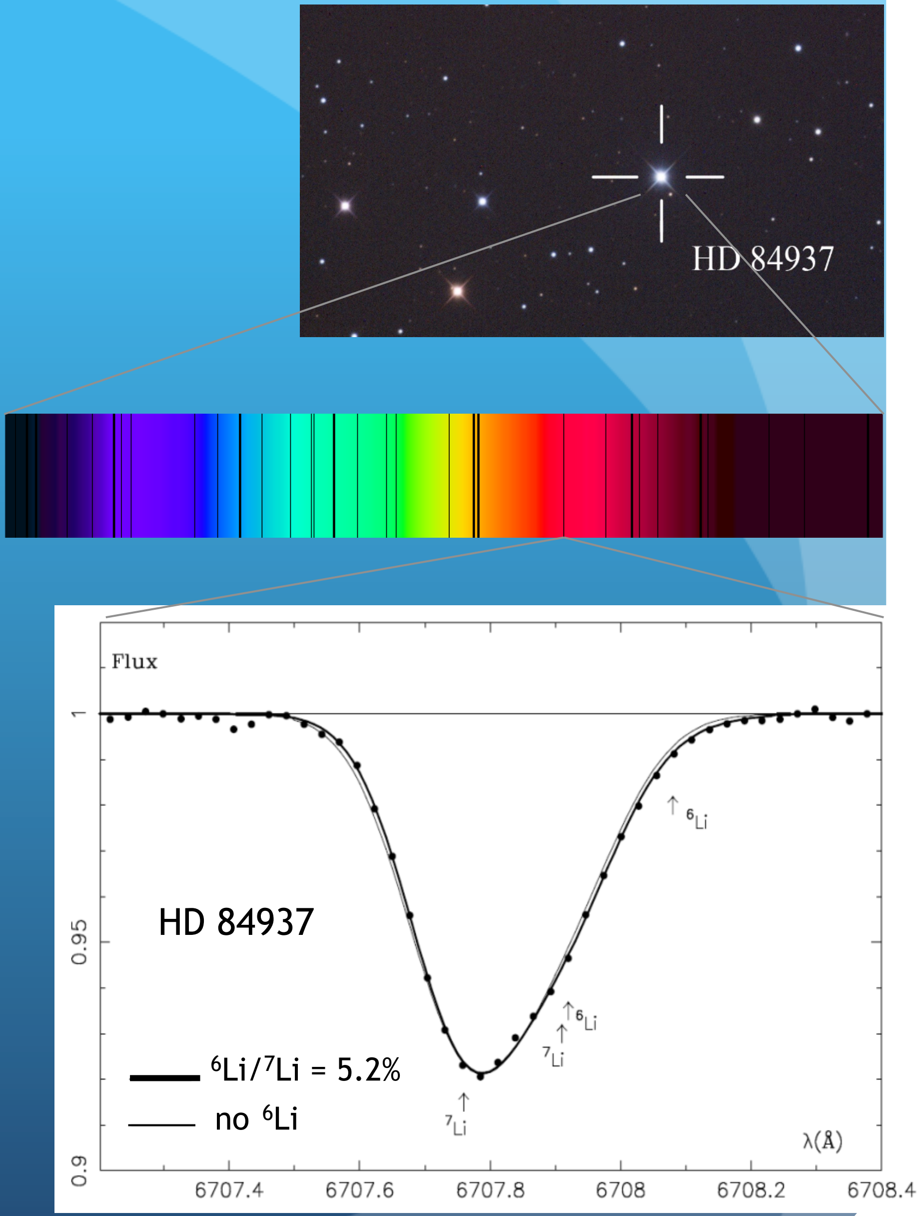
observed ^{7}Li
~ 3x lower than predicted

- 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

LUNA

^{6}Li production:
The $d(\alpha,\gamma)^{6}$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

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

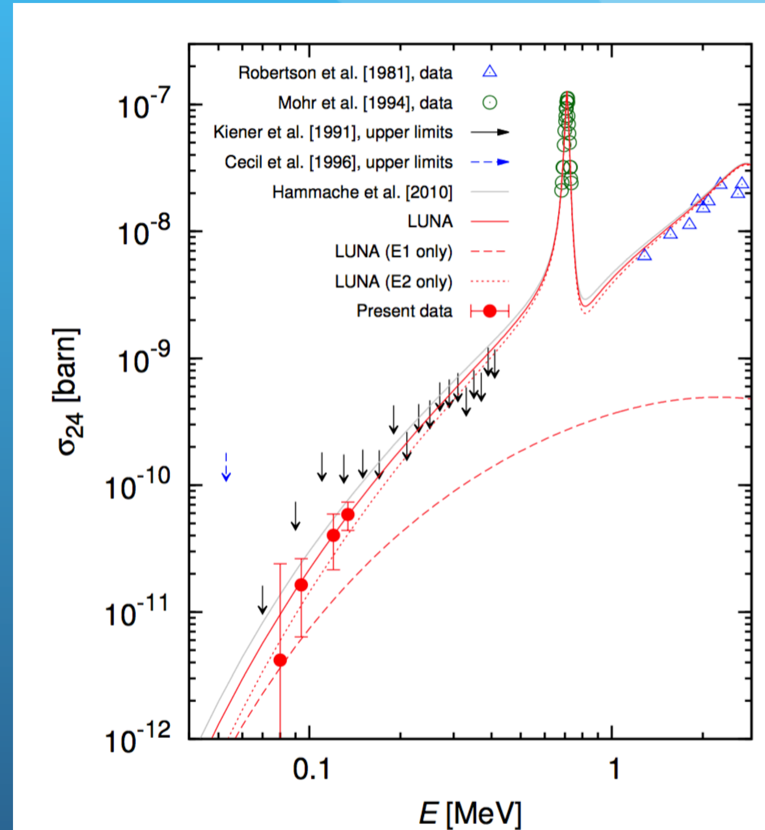
CrossMark

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 $^2H(\alpha,\gamma)^6Li$ 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)



$^6Li/^7Li = (1.6 \pm 0.3) \times 10^{-5}$

$^6Li/H = (0.8 \pm 0.18) \times 10^{-14}$ (27% lower than previous BBN values)

No nuclear physics solution to second Lithium problem

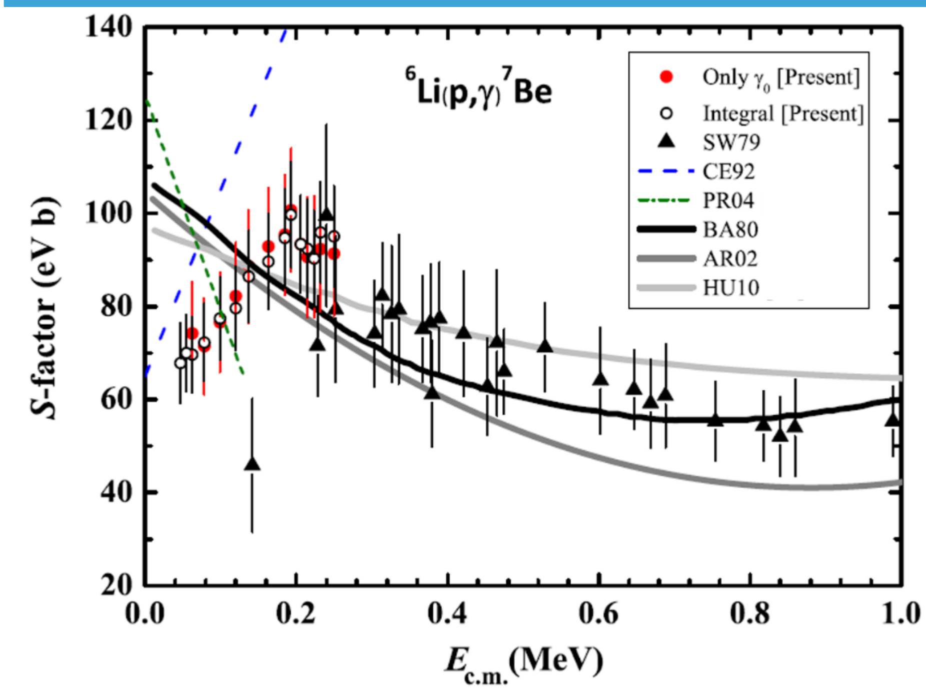
^{6}Li destruction:
The ^{6}Li(p,γ)^{7}Be and ^{6}Li(p,α)^{3}He Reactions

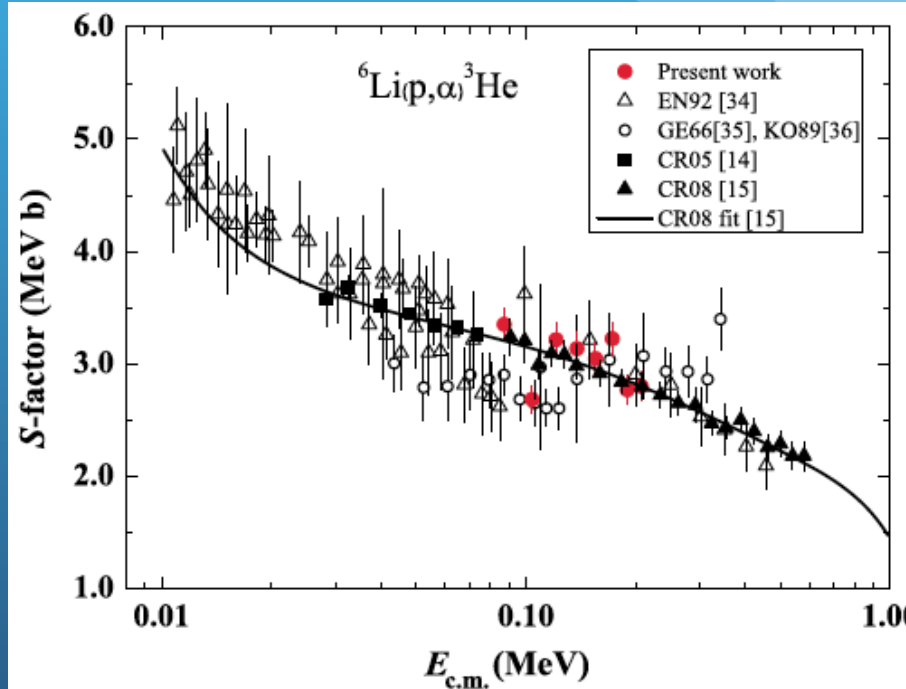
The $^{6}Li(p,\gamma)^{7}Be$ and the $^{6}Li(p,\alpha)^{3}He$ reactions in literature

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 $^{6}Li(p,\alpha)^{3}He$

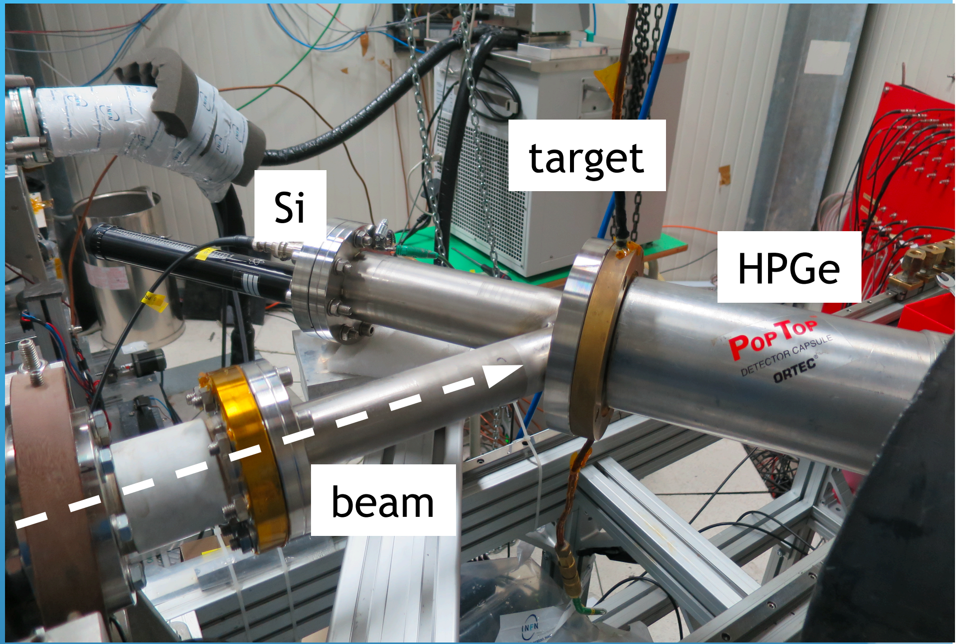


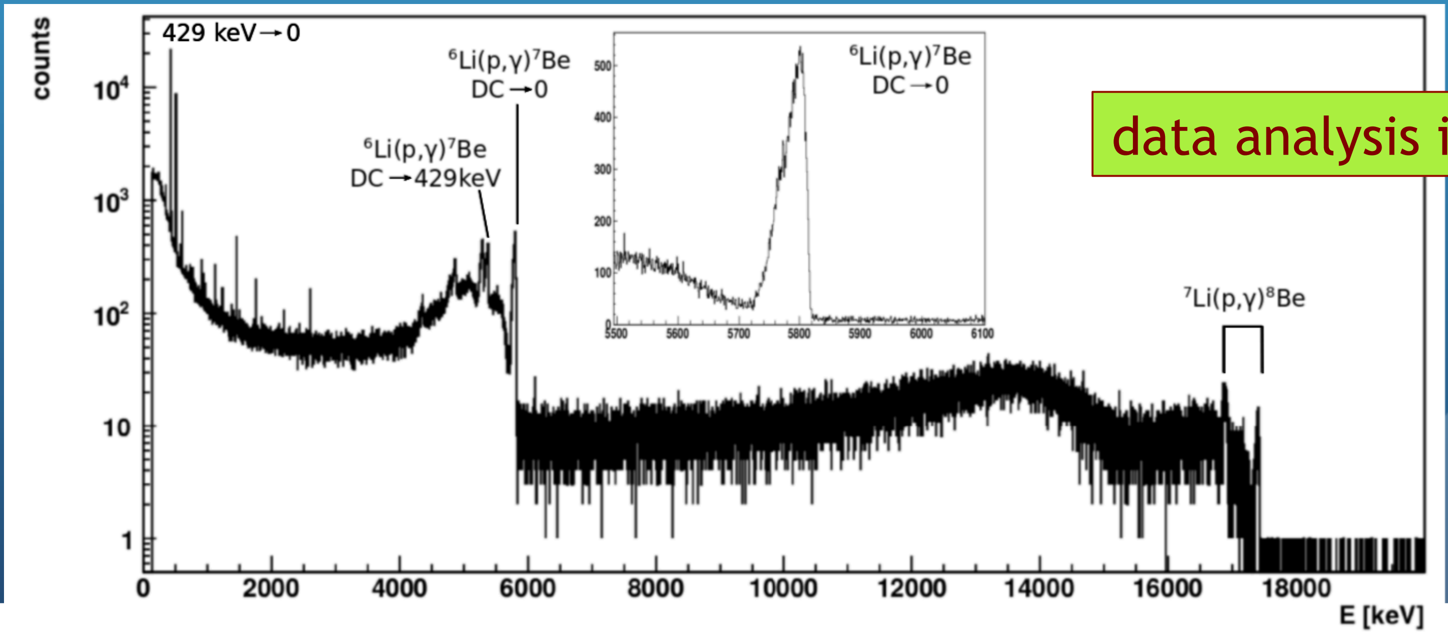


$^{6}Li(p,\gamma)^{7}Be$ reaction involved in BBN as well as in ^{6}Li depletion in early stages of stellar evolution

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 in progress

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

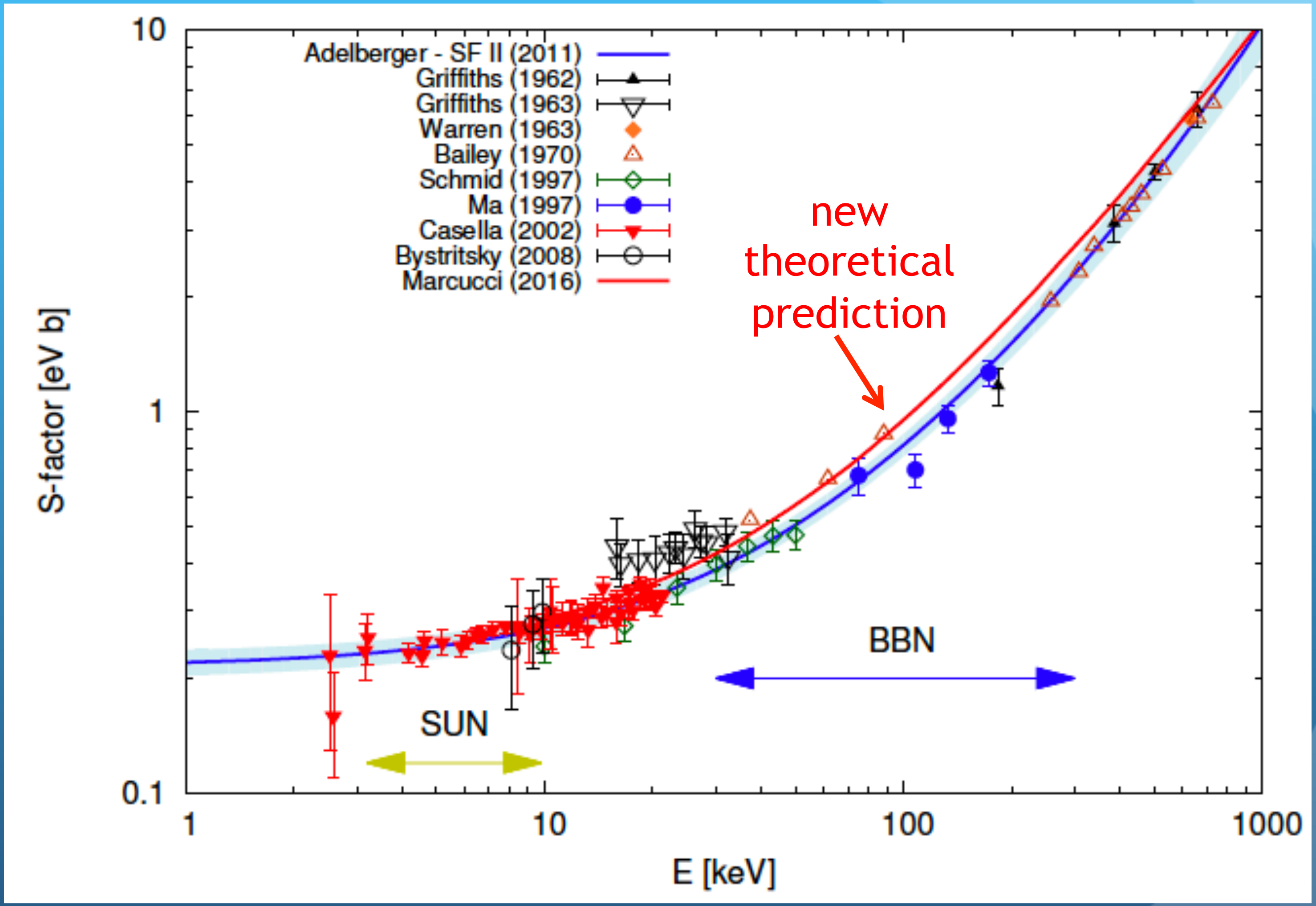
main uncertainty in BBN prediction due

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

⇩

high precision data at BBN energies required

The d(p,γ)^{3}He reaction : theory vs experiments



New theoretical models based on an ab-initio approach (Marcucci et al PRL 116, 102501 - 2016), predict higher values for the cross section, at the level of 20%.

D/H ratio and cosmology

$10^5(D/H)_{obs}$ =(2.527±0.030) *R. Cooke et al., Ap. J. 855 (2018) 102*

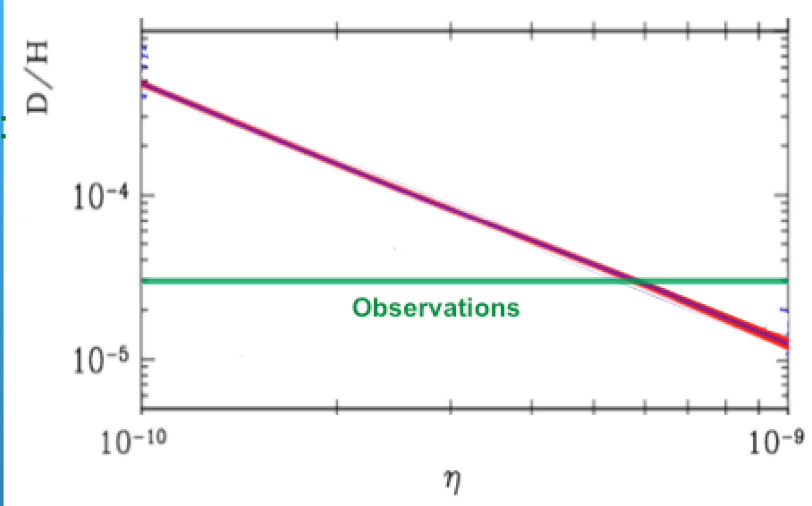
-BBN provides a precise estimate of Baryon density Ω_b, through the comparison of $(D/H)_{BBN}$ and $(D/H)_{obs}$:

D(p,γ) data fit

$100\Omega_{b,0}h^2$(BBN)=2.26±0.03±0.02 *R. Cooke et al., Ap. J. 830 (2016) 148*

$100\Omega_{b,0}h^2$(BBN)=2.16±0.01±0.02

D(p,γ) "ab-initio" *D/H observations*



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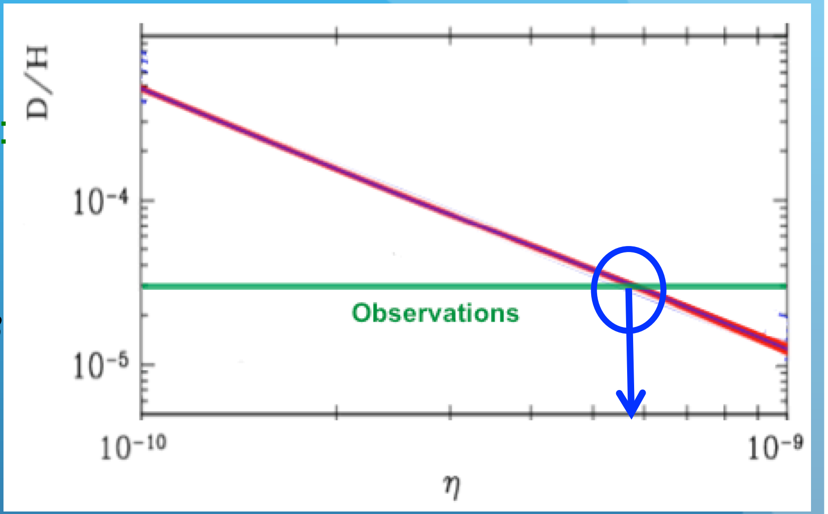

From CMB data:
$100\Omega_{b,0}h^2(CMB) = 2.23 \pm 0.02$ (PLANCK2015)

D/H ratio and cosmology

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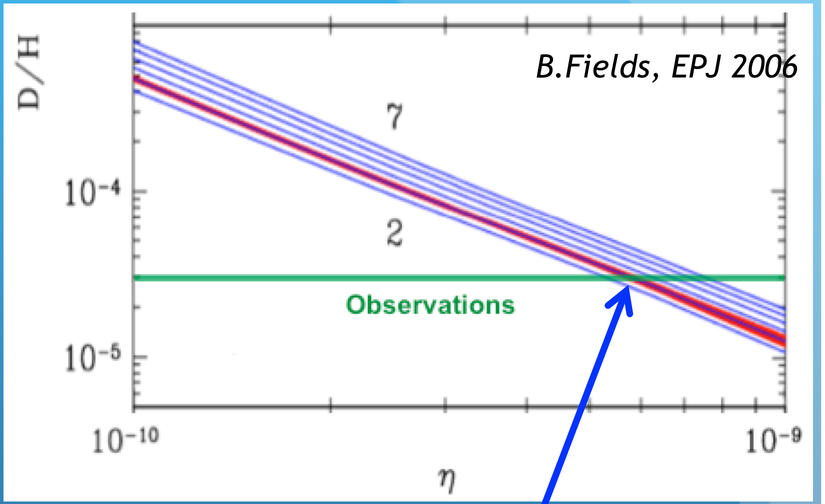
R. Cooke et al., Ap. J. 830 (2016) 148

D(p,γ) "ab-initio" *D/H observations*

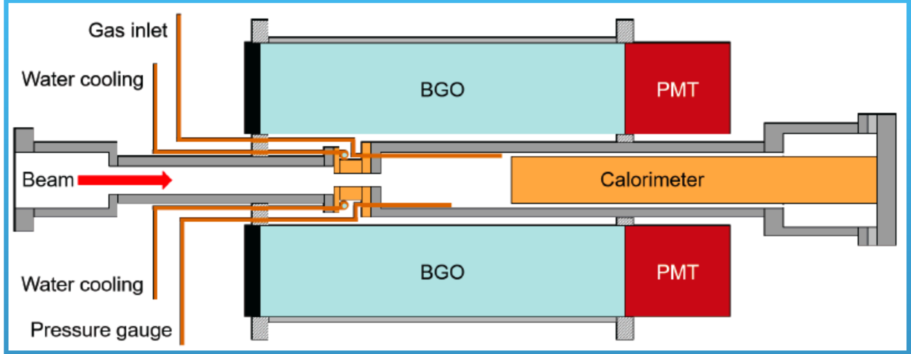
From CMB data:
$100\Omega_{b,0}h^2(CMB) = 2.23 \pm 0.02$ (PLANCK2015)



-Deuterium abundance also depends on the density of relativistic particles (photons and 3 neutrinos in SM). Therefore it is a tool to constrain the "dark radiation".

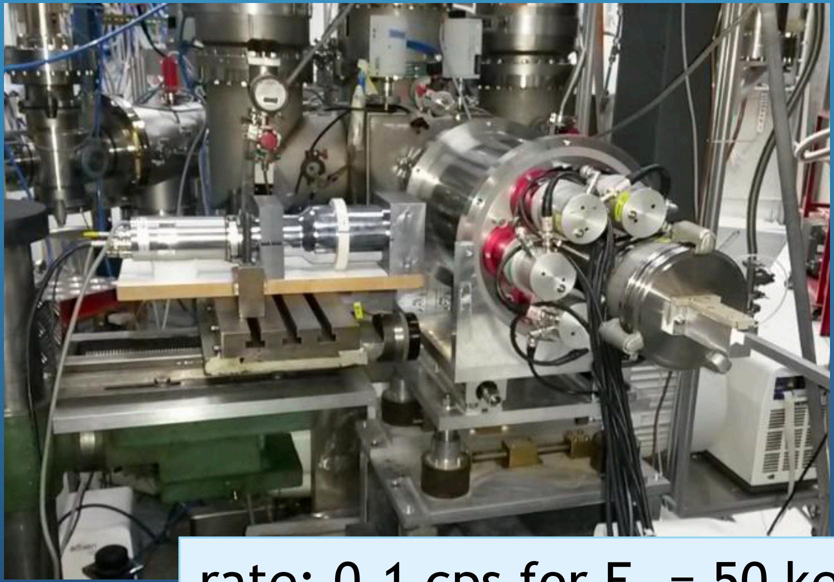
Measurements at LUNA

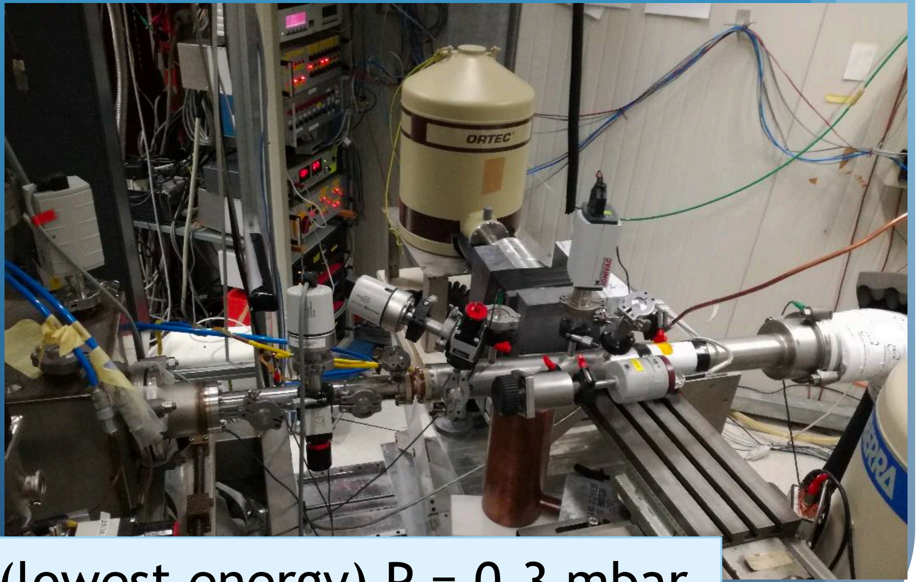
$D(p,\gamma)^3He$: Q-value = 5.493 MeV E_{beam} = 50 – 300 keV (full BBN range)



BGO Phase: high efficiency

HPGe Phase: high precision

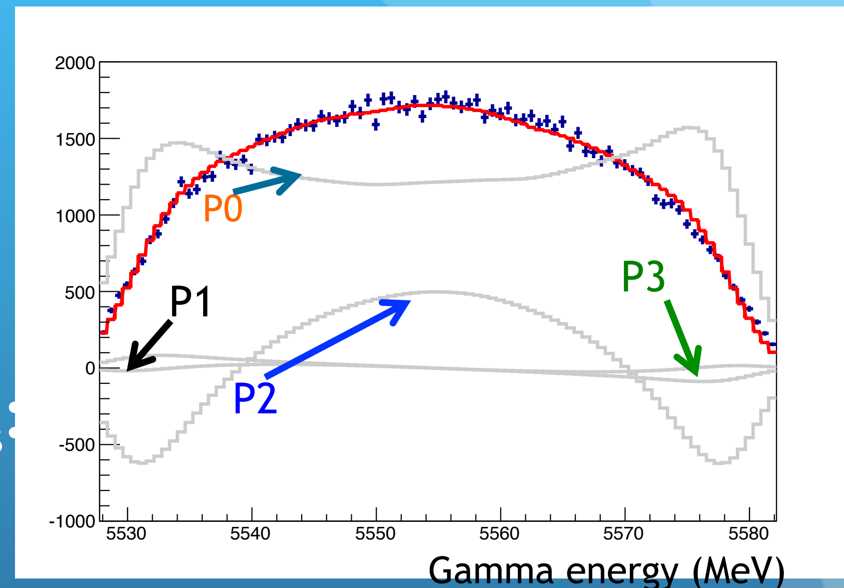




rate: 0.1 cps for E_p = 50 keV (lowest energy) P = 0.3 mbar

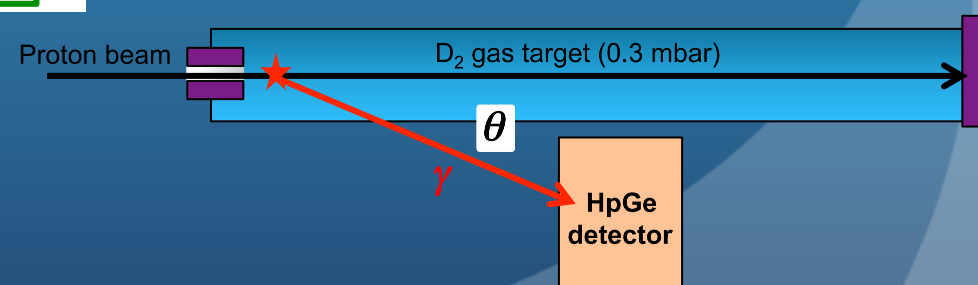
Angular distribution: peak shape analysis

$$\overline{\sigma} = \frac{N_\gamma}{\frac{t \cdot I_{beam}}{e} \int_0^L \rho(z) \cdot \eta(z) \cdot W(z) \cdot dz}$$

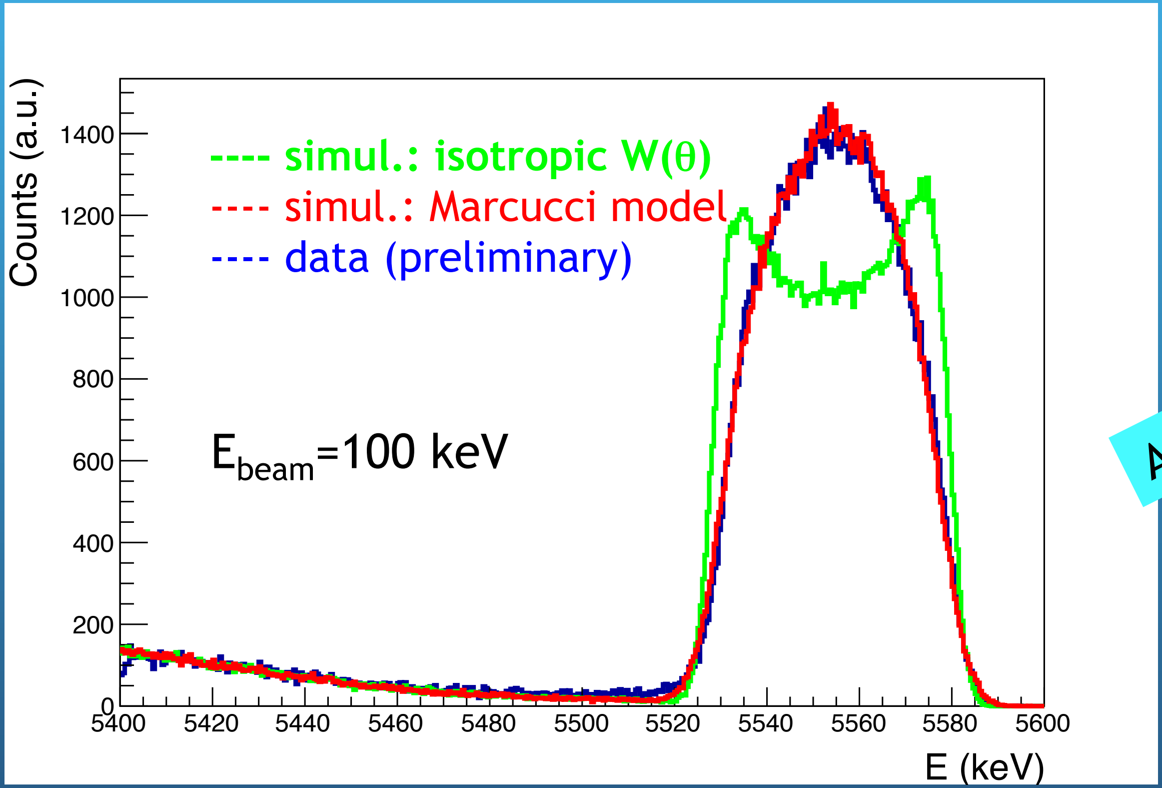


Doppler effect for the emitted γ_s:

$$E_\gamma = \frac{m_p^2 + m_d^2 - m_{He}^2 - 2E_p m_d}{2\left(E_p + m_d - p_p \cos(\theta_{lab})\right)}$$



D(p,γ)^{3}He energy spectrum: full absorption peak shape



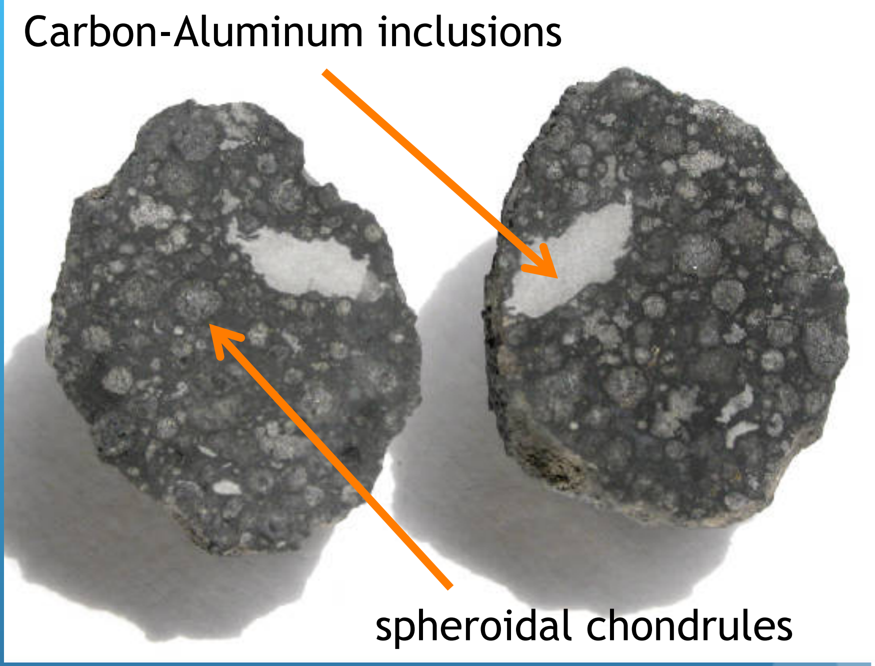
Analysis in progress

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

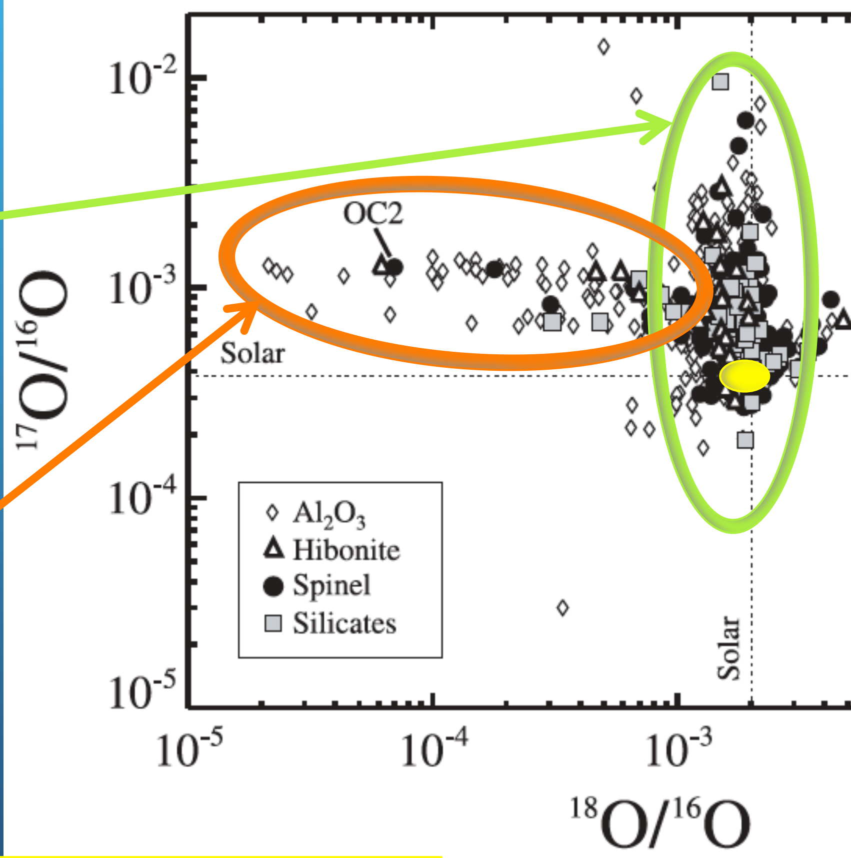
http://www.marmet-meteorites.com/id46.html

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!

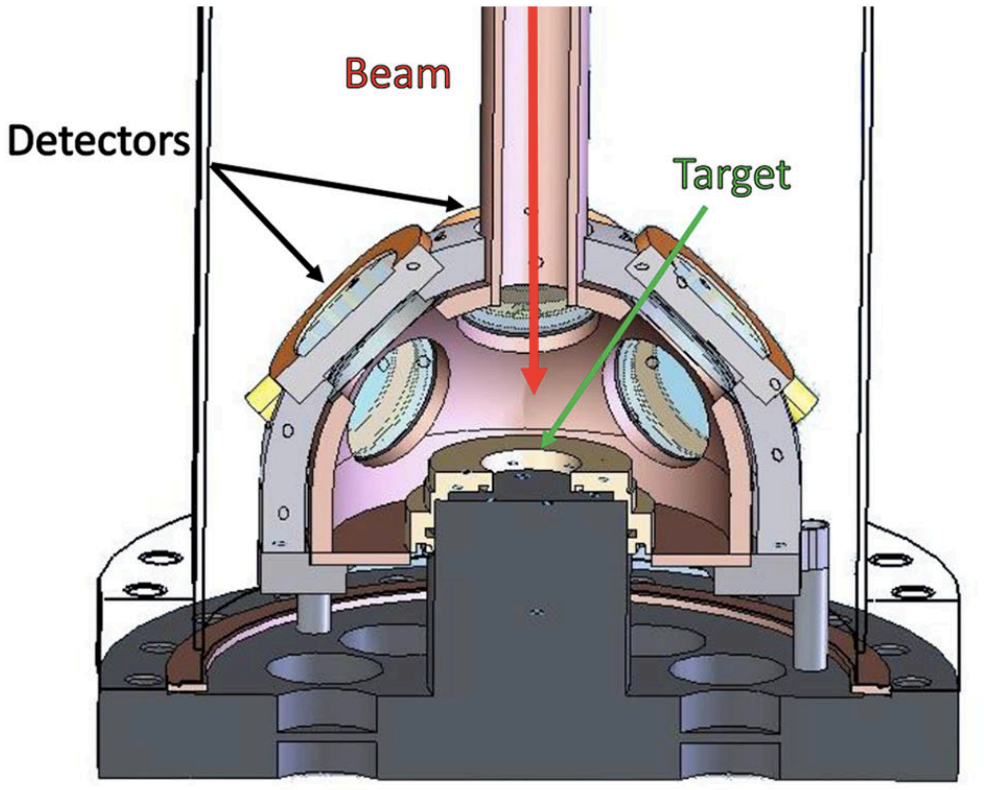


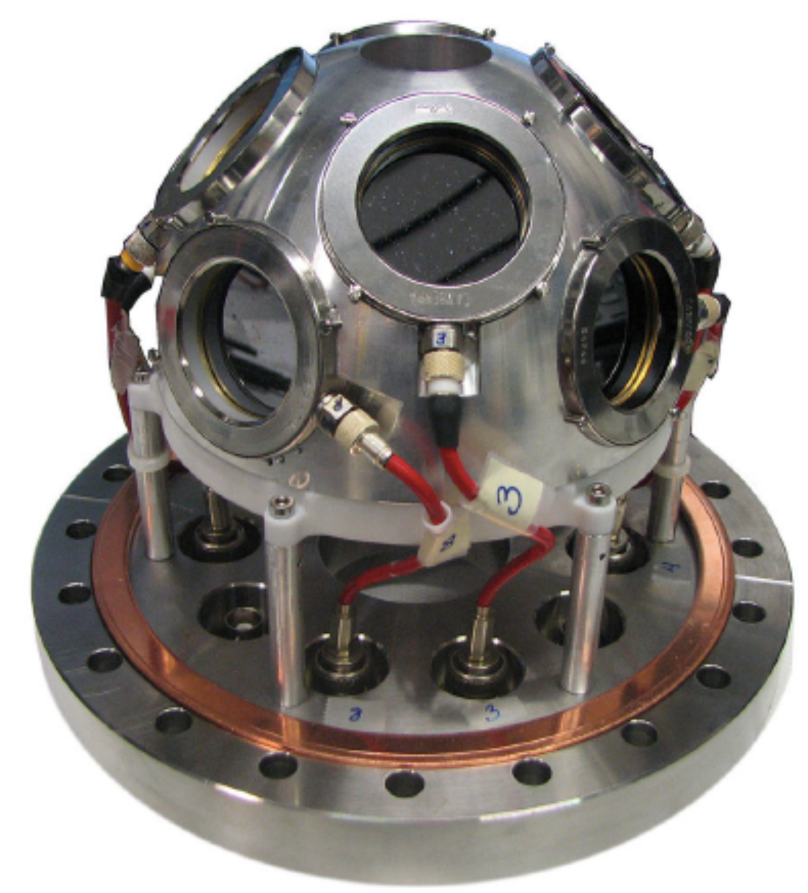
a renewed study of $^{17}O(p,\alpha)^{14}N$ reaction needed…

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

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

Scattering Chamber for the $^{17,18}O(p,\alpha)^{14,15}N$ reactions at LUNA



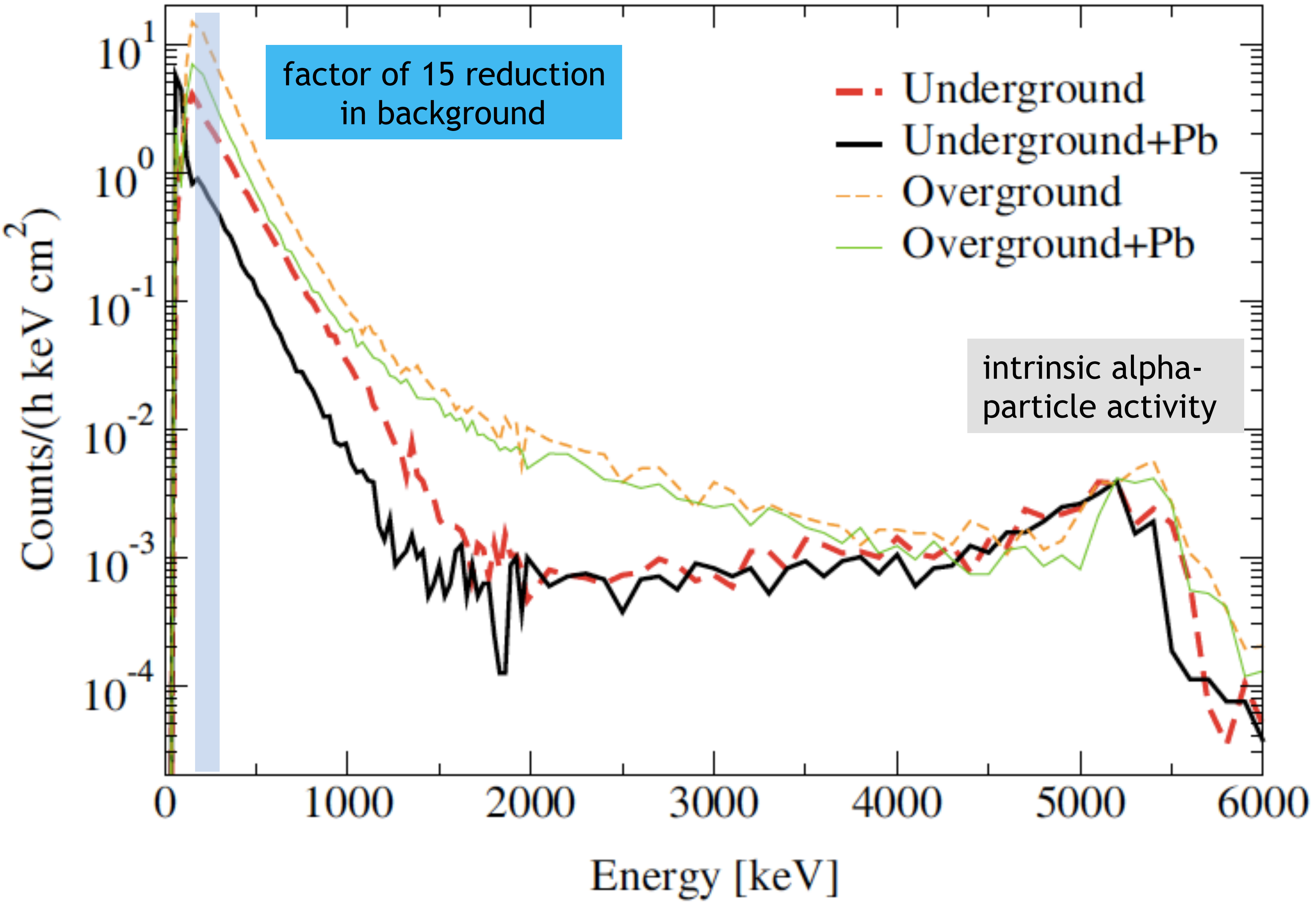


Bruno et al EJPA 51 (2015) 94

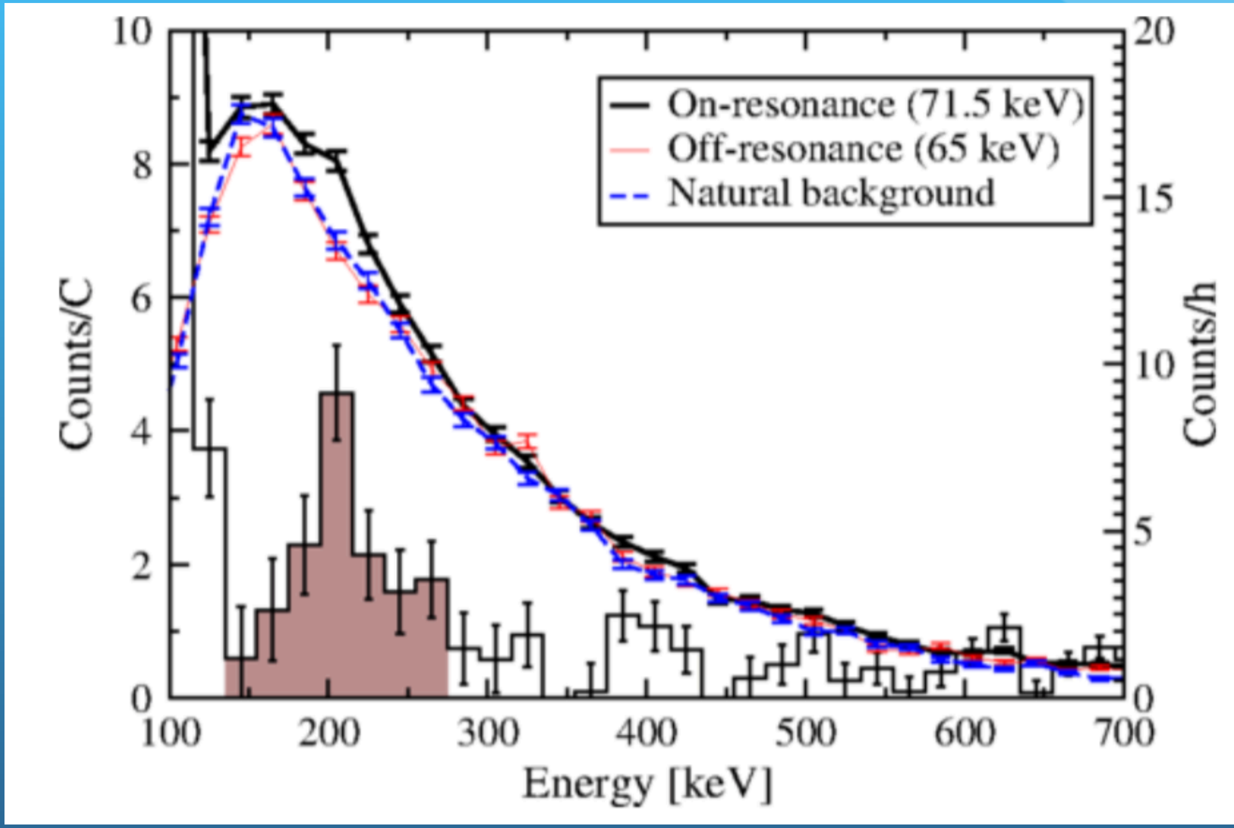
- Ta_2O_5 targets isotopically enriched (80-85% ca.)
- protective aluminized Mylar foils before each detector
- expected alpha particle energy E ~ 200 keV (from 70 keV resonance in $^{17}O(p,\alpha)^{14}N$)

Background Suppression

CG Bruno et al. EPJA 51 (2015) 94



New measurement of the 64.5 keV resonance strenght

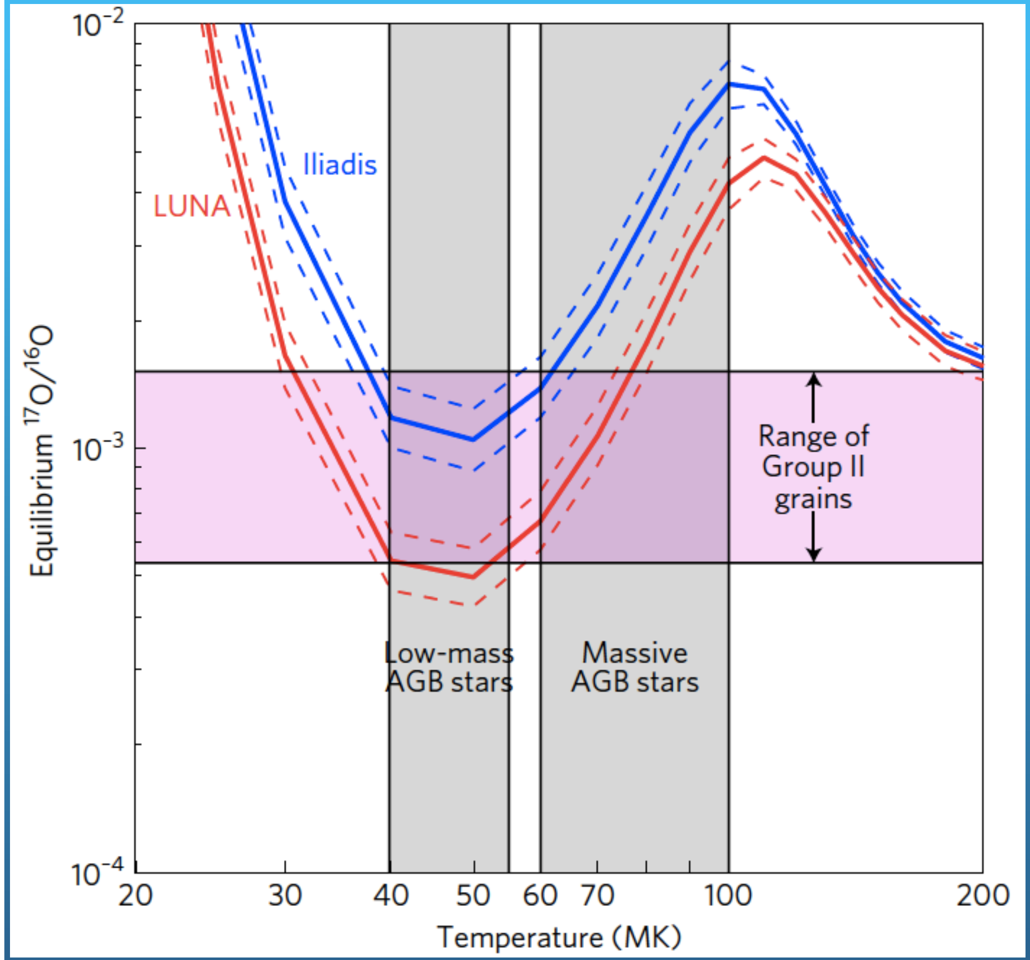


C. Bruno et al. Phys Rev Lett. 117 (2016) 142502

$$\omega\gamma = 10.0 \pm 1.4_{\mathrm{stat}} \pm 0.7_{\mathrm{syst}}\ \mathrm{neV}$$

Stellar reaction rate higher by a factor 2-2.5

Pre- solar grains sources



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

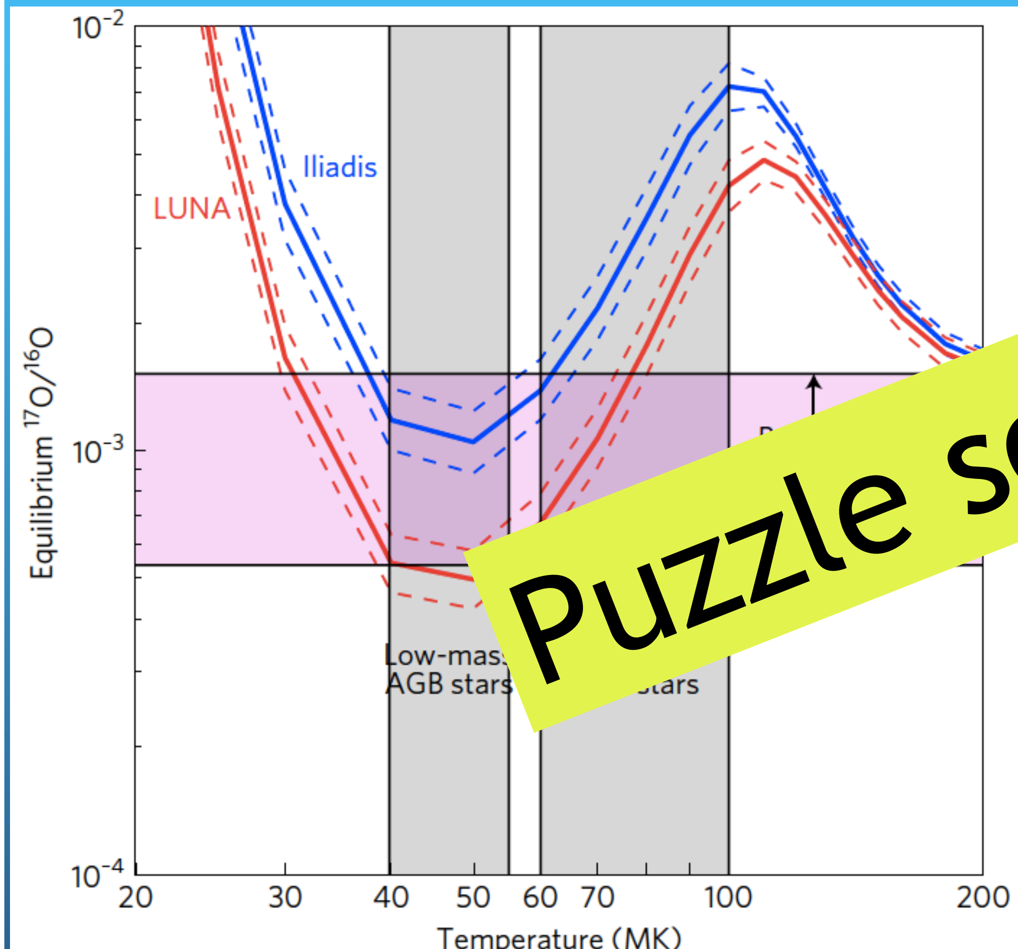
- massive AGB stars excluded as possible sites of origin
- low-mass AGB stars can be a possible site, but extra mixing process unclear

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

Pre- solar grains sources



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

- massive AGB stars excluded as possible sites of ori
- lo s can be a possible ng process unclear

Puzzle solved!!

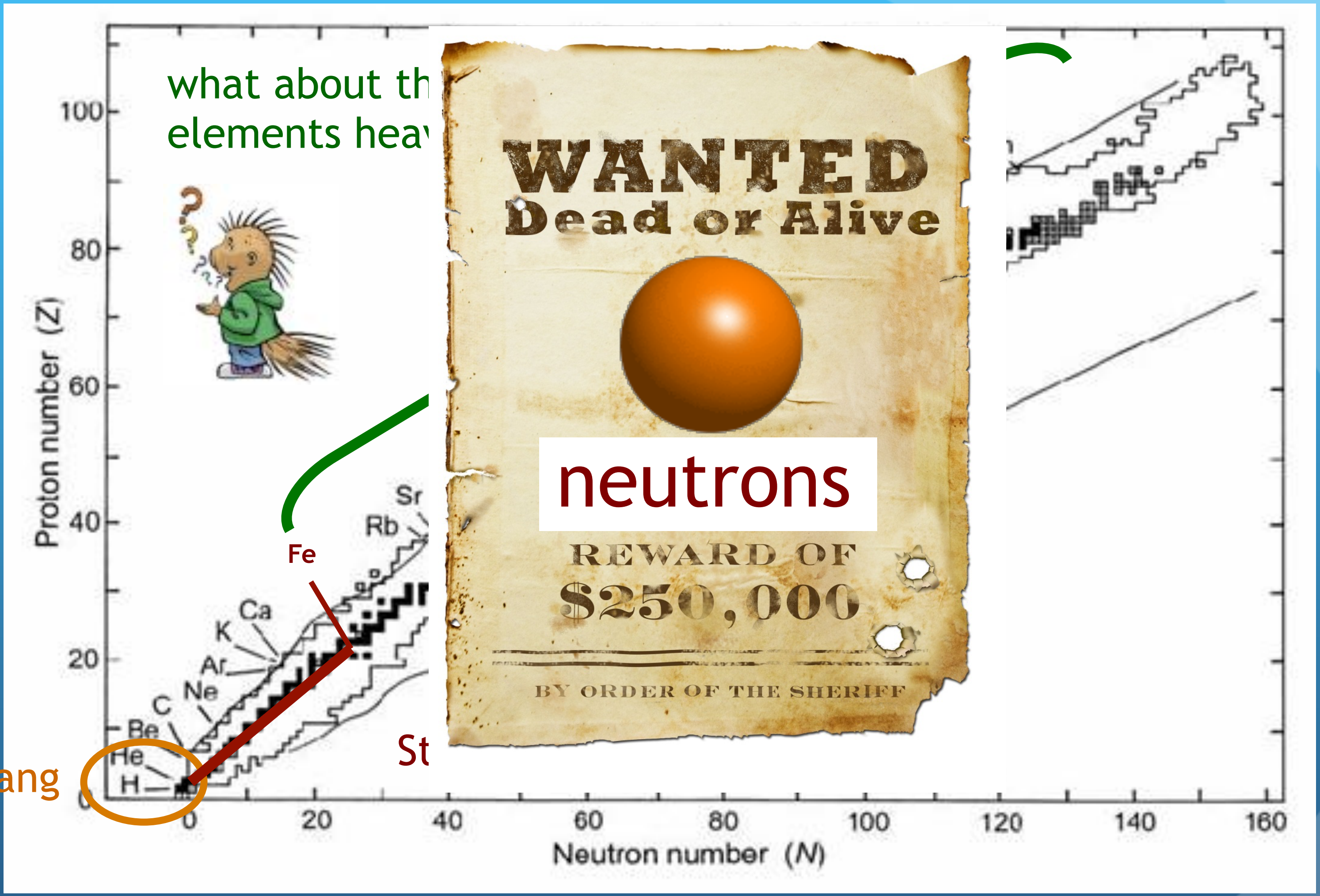
with new reaction rate (LUNA , 2016):

- 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

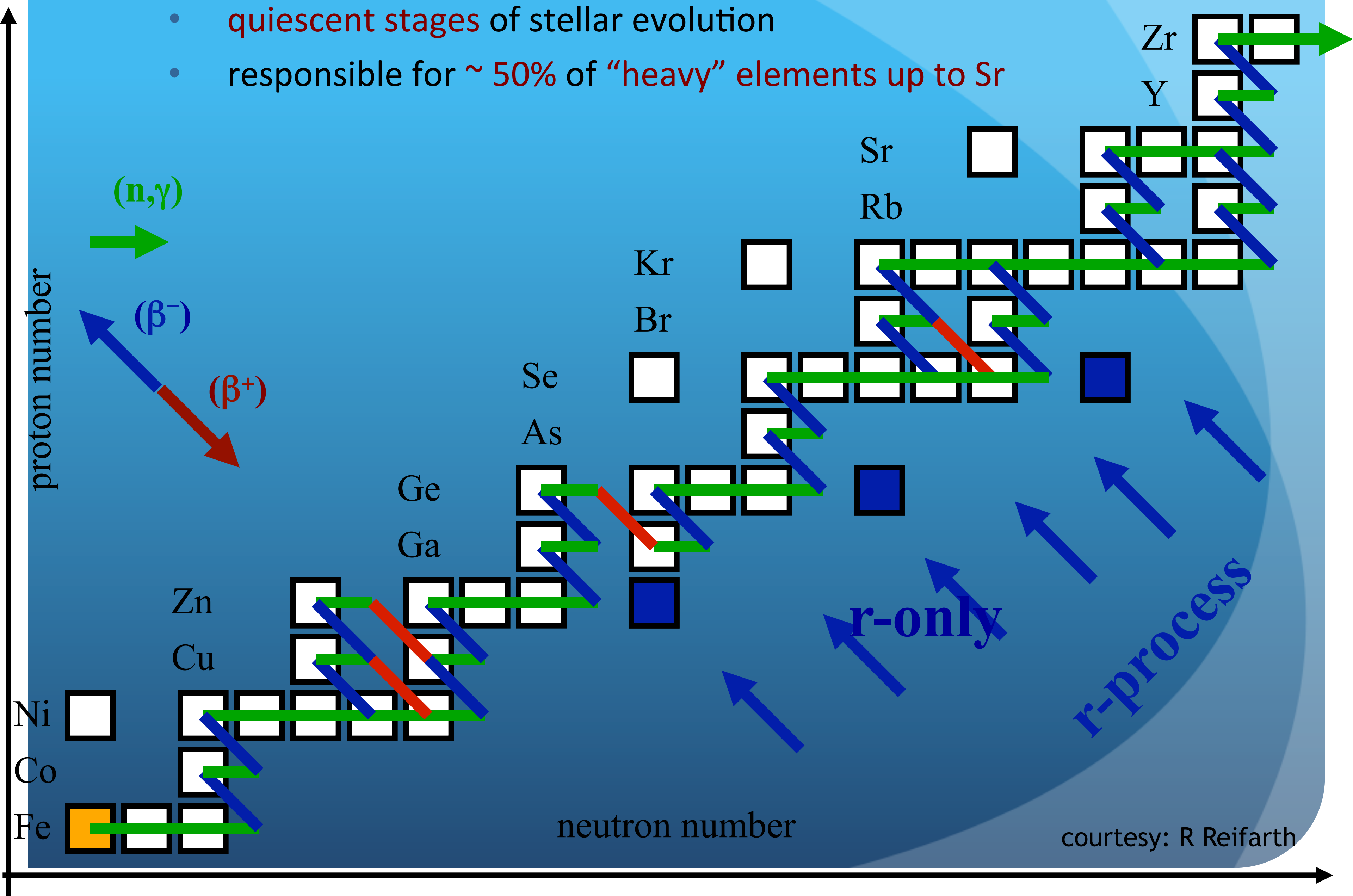
The Creation of Heavy Elements

Nucleosynthesis beyond iron



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

- s (slow) process
- quiescent stages of stellar evolution
- responsible for ~ 50% of "heavy" elements up to Sr



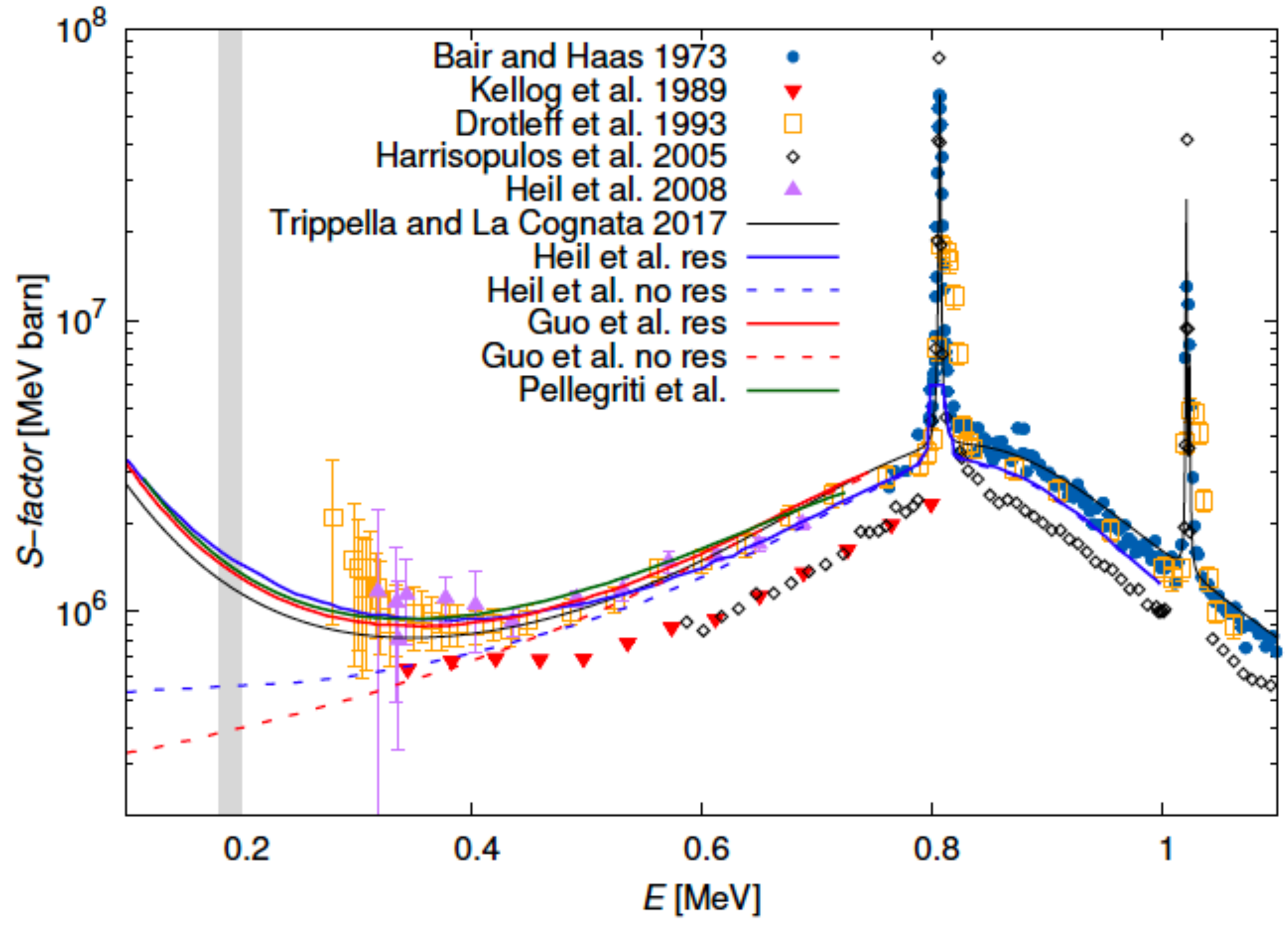
courtesy: R Reifarth

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

importance: main s-process in AGB stars ~90<A<210

Gamow region: 130 - 250 keV

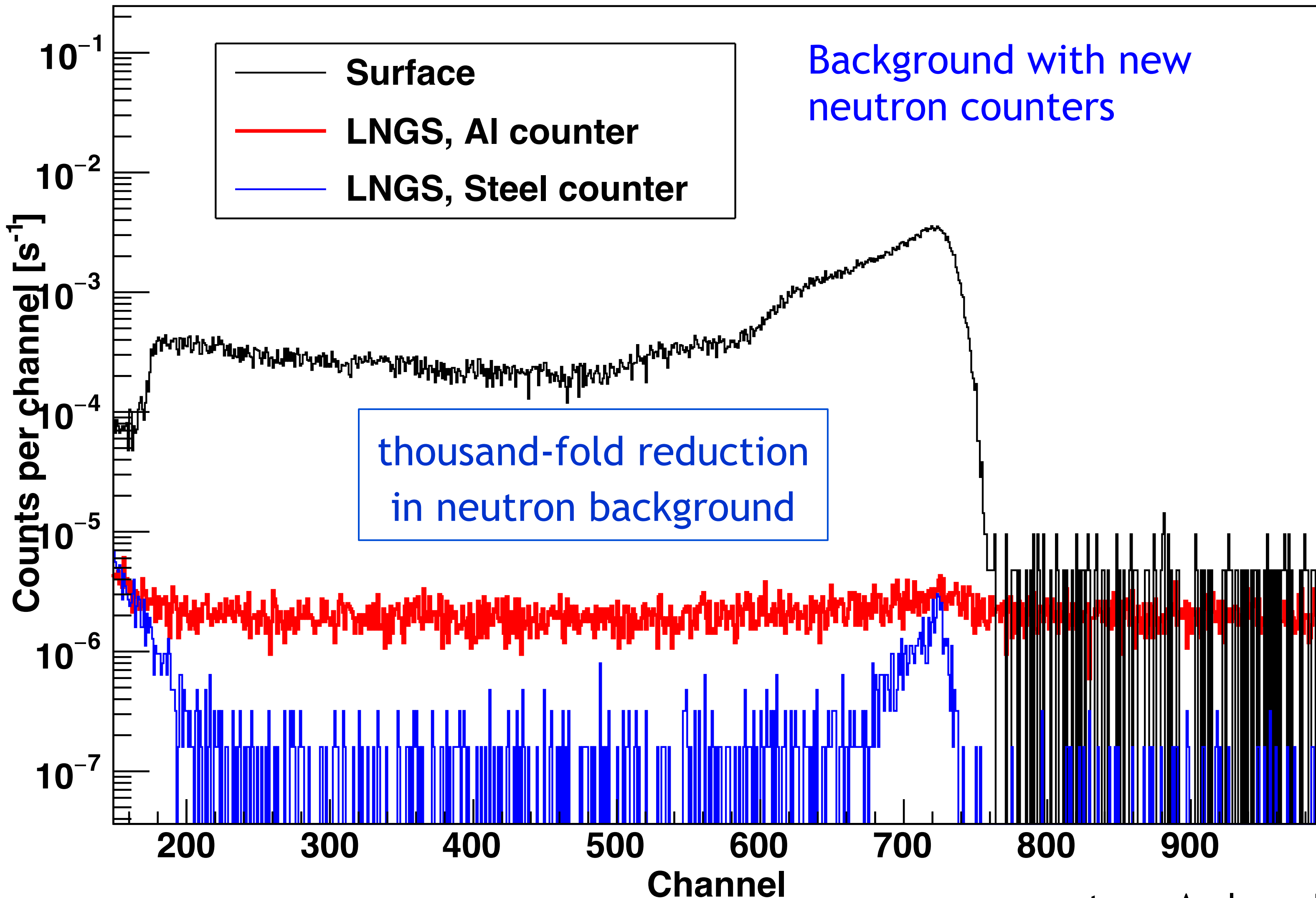
min. meas. E_{cm}: 280 keV



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

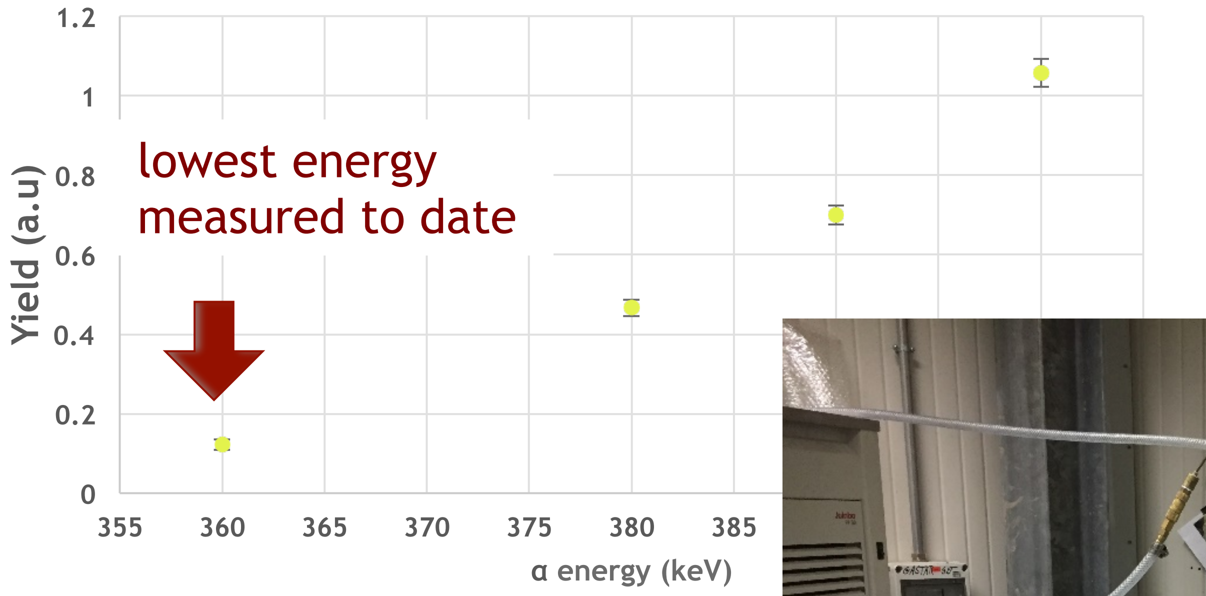
mainly hampered by cosmic background → excellent case for underground study

LUNA: an ideal environment for neutron detection



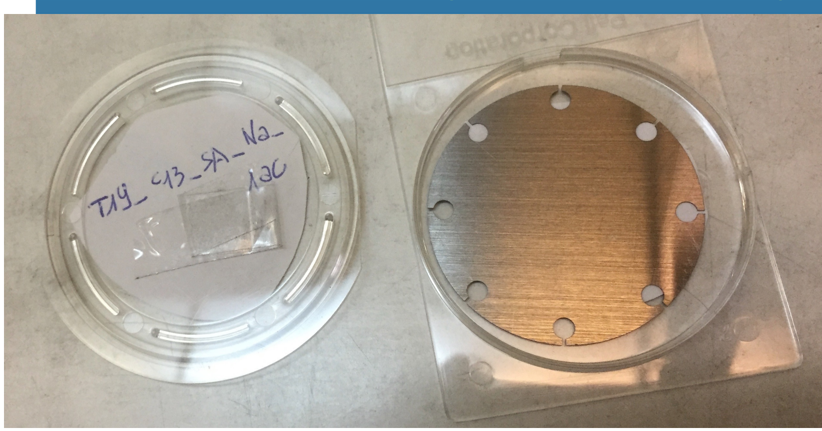
courtesy: Andreas Best

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



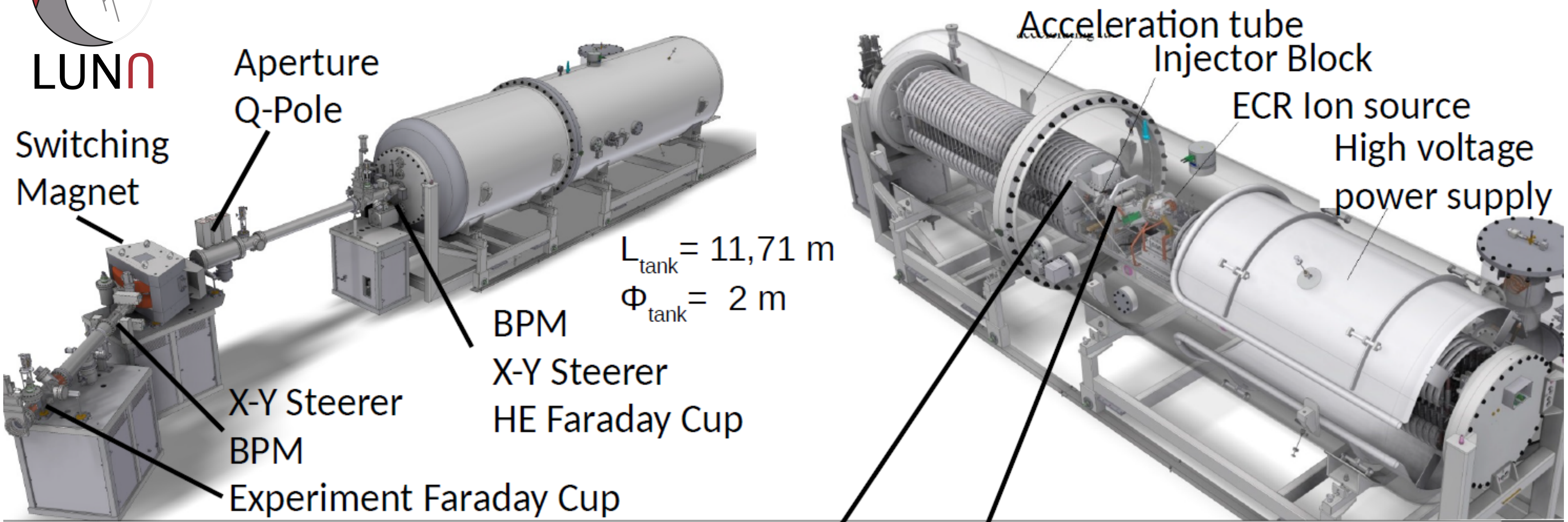
courtesy: A Best

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



Future Facilities

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

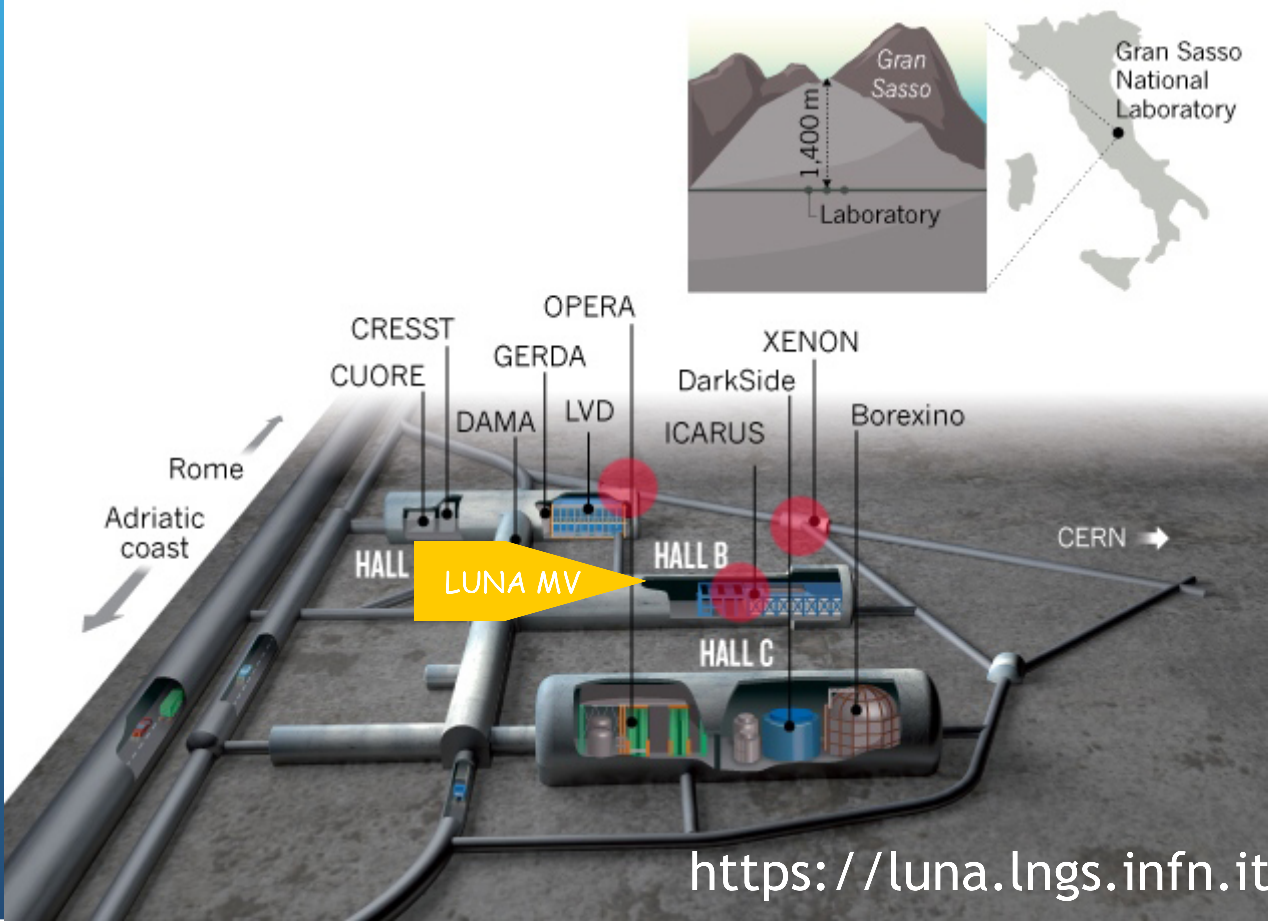
THE LUNA Collaboration

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

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



https://luna.lngs.infn.it

LUNA

- Accelerator ready at High Voltage Engineering
- Tests in progress
- Installation at LNGS: 2019
- Commissioning: 2019-20

CASPAR: Compact Accelerator Systems for Performing Astrophysical Research

SURF: Sanford Underground Laboratory at Homestake (4300 mwe)

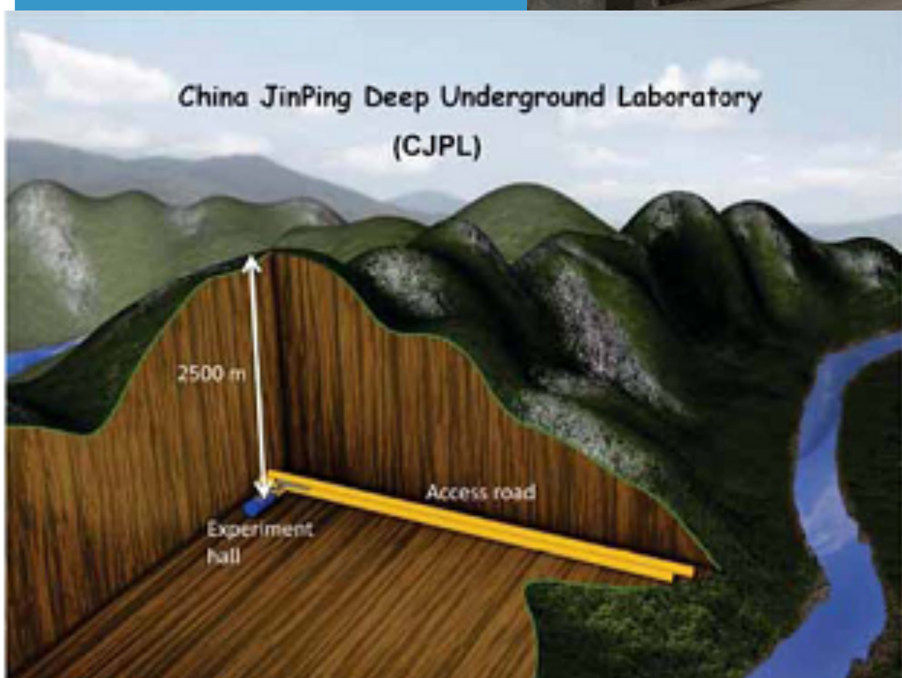
Collaboration between:

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

Future Underground Facilities for Nuclear Astrophysics

JUNA Jinping Underground lab for Nuclear Astrophysics
锦屏深地核天体物理实验室

China Institute of Atomic Energy

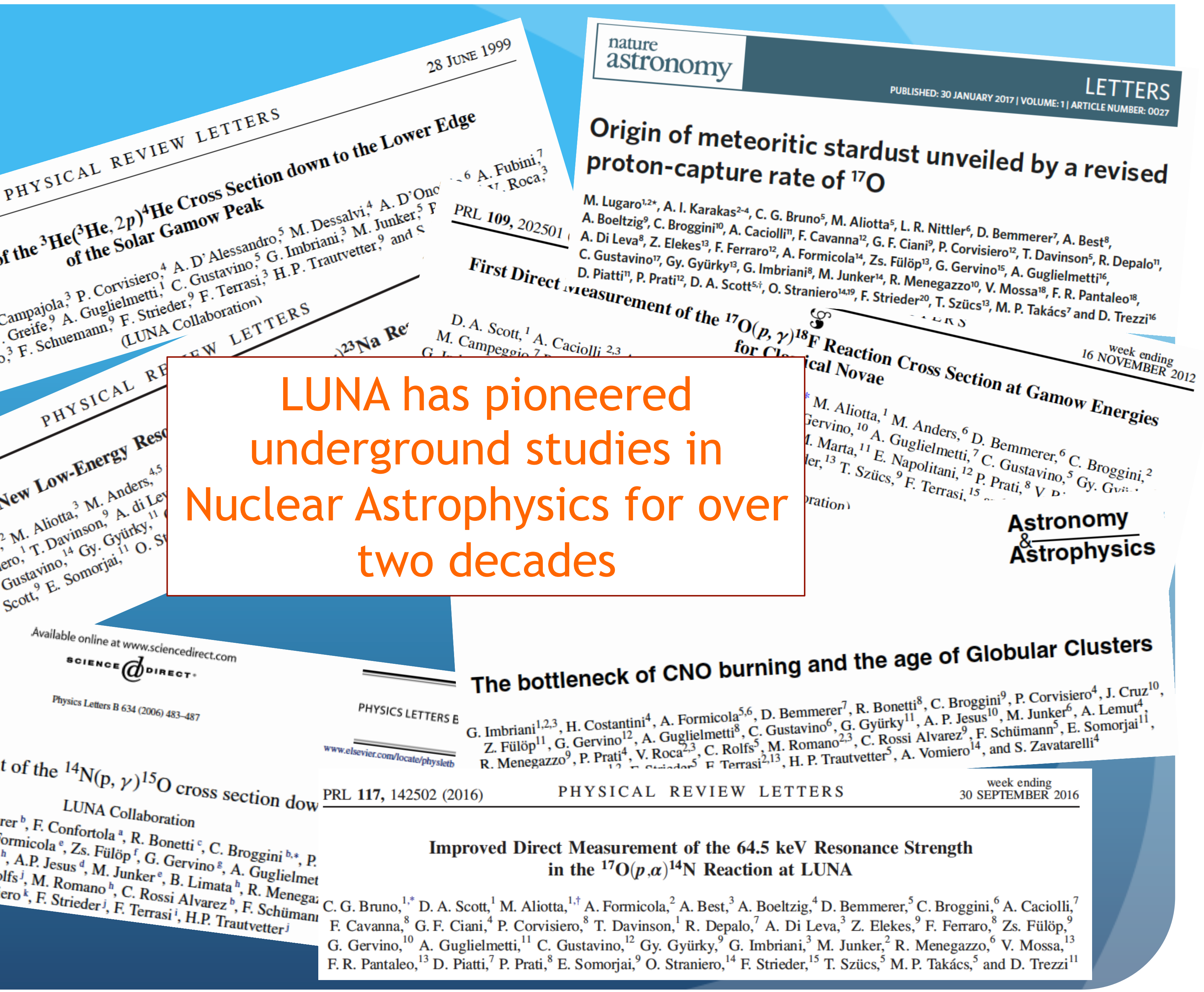


2,400 meters deep in a mountain in Sichuan Province

Planned for 2019

To Conclude…

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



Nuclear Astrophysics: A Truly Interdisciplinary Effort

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

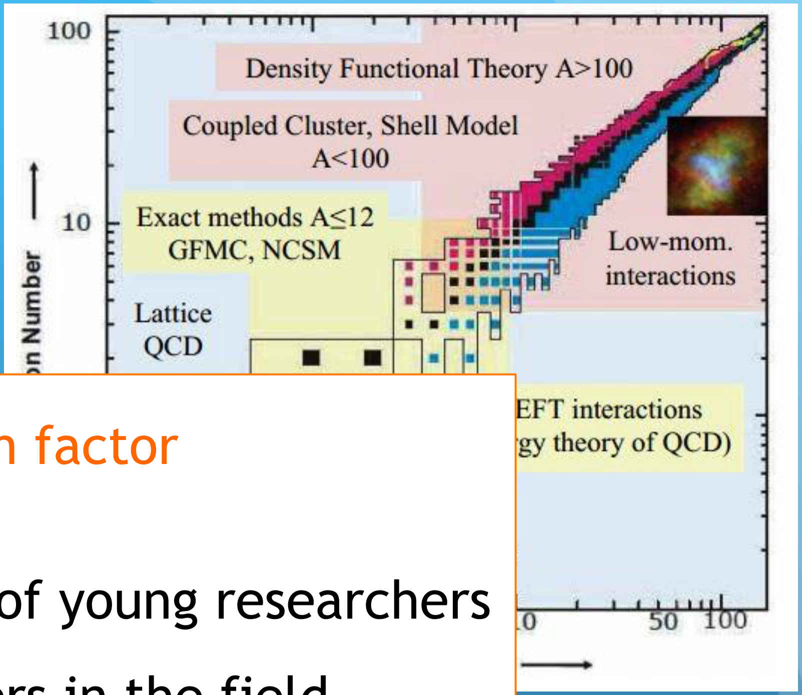
Atomic Physics

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


Many thanks to MariaLuisa Aliotta
(Edinburgh University) for many
many slides !! ☺ ☺ ☺
RUSSELL
R
Courtesy: H.P. Trautvetter


Many thanks to MariaLuisa Aliotta
(Edinburgh University) for many
many slides !! ☺ ☺ ☺
Thanks!!!!
Courtesy: H.P. Trautvetter

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http://luna.lngs.infn.it

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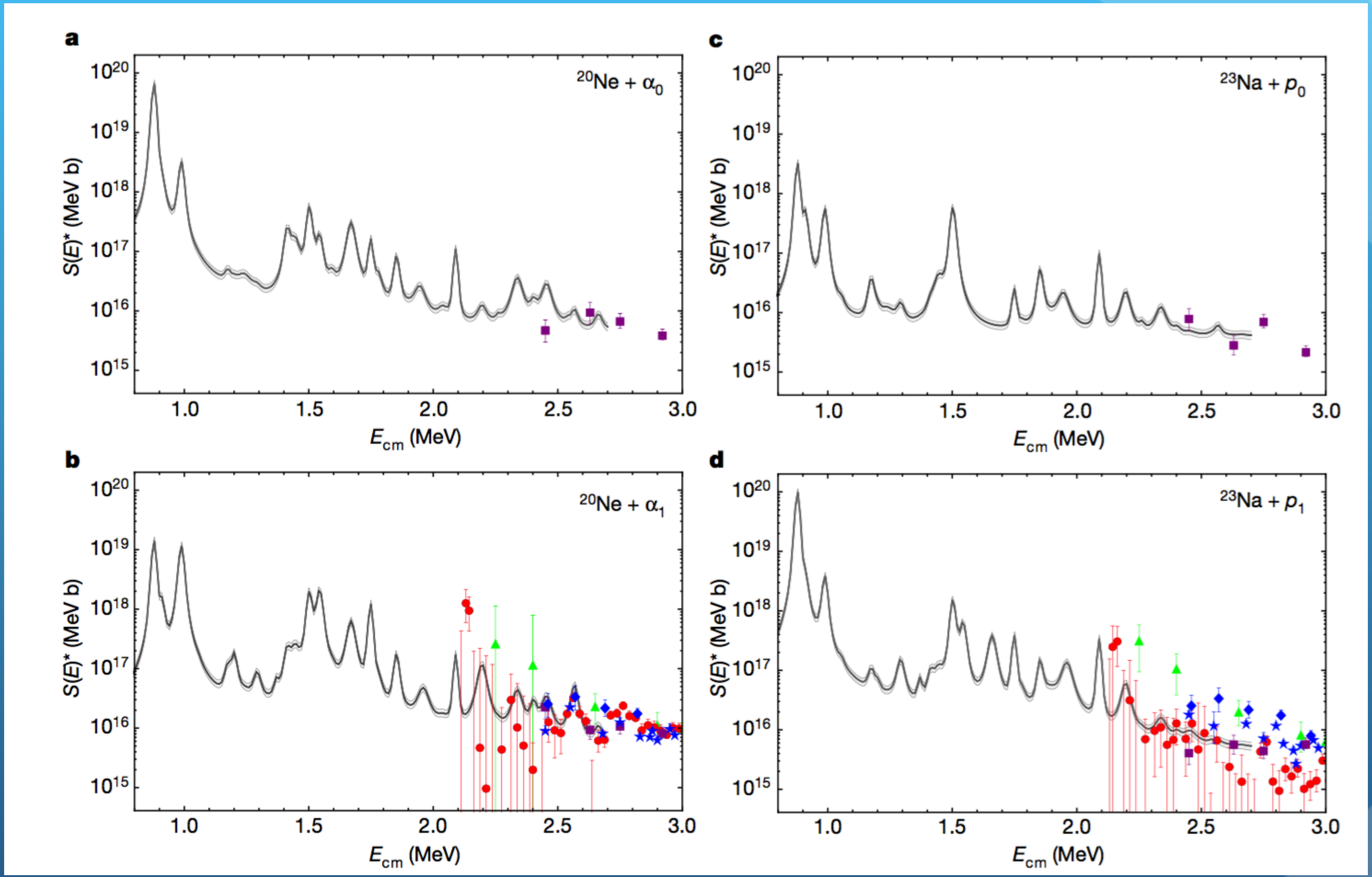
- C. Gustavino | INFN Roma1, Italy

$^{12}C+^{12}C$: need for precise direct measurements and cross checks



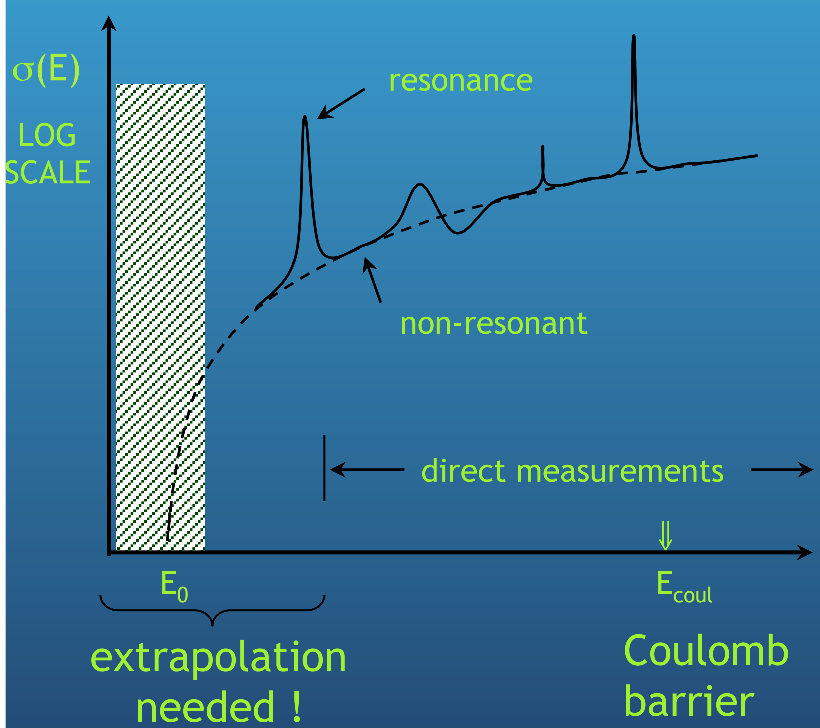
Al low energies only data with Trojan horse method: $^{12}C(^{14}N, \alpha\ ^{20}Ne)^{2}H$ and $^{12}C(^{14}N, p\ ^{23}Na)^{2}H$

Gamow peak: energy window where information on nuclear processes is needed

$kT \ll E_0 \ll E_{coul}$ ⇒ 10^{-18} barn < σ < 10^{-9} barn ⇒ Major experimental difficulties

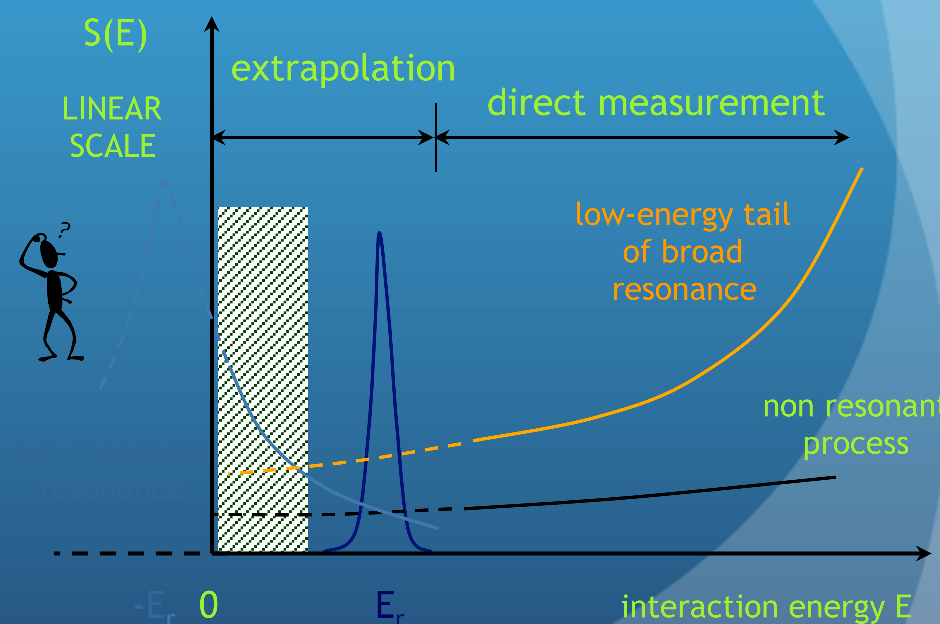
Procedure: measure $\sigma(E)$ over wide energy, then extrapolate down to E_0!

CROSS SECTION



S-FACTOR

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



DANGER OF EXTRAPOLATION !

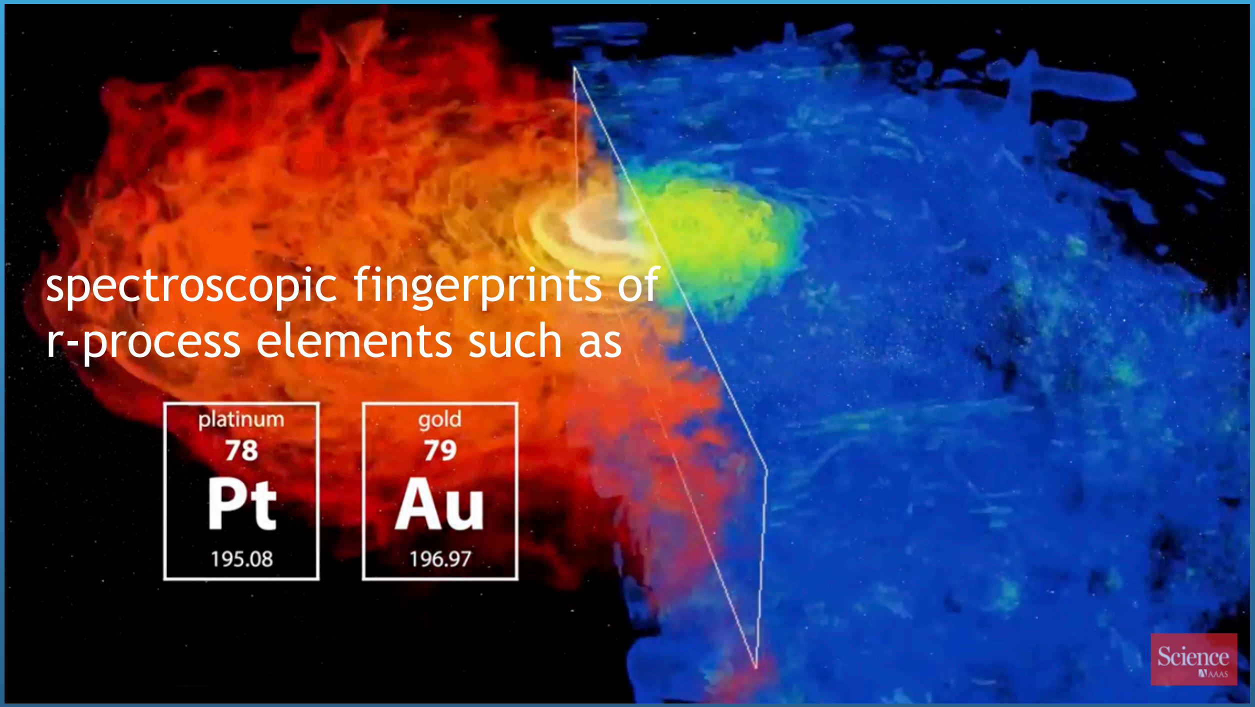
17 August 2017

130 million light years from Earth

LIGO and VIRGO: first observation of gravitational waves from merging neutron stars

event observed by 70 ground- and space-based observatories

including in visible light 11h after GW detection



neutron star mergers could well be the main source for r-process elements

A new era in Astronomy has just begun…

Ingredients for Future Advances

- nuclear masses and reaction rates far from stability
- weak interactions and neutrino interaction rates (supernovae & neutron star mergers)
- equation of state of dense neutron matter
- multi-D models of astrophysical sites (novae, X-ray bursts, SNIa, ccSN, neutron star mergers, low-metallicity stars)
- spectroscopic stellar surveys (across electromagnetic spectrum)
- asteroseismology
- gravitational-wave astronomy (ccSN, compact object mergers)
- data and codes (adapted to extreme astrophysical conditions)

Converting H into He: The Proton-Proton Chain

According to the Standard Solar Model…

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

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

86% — PP-I

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

14%

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

99.7% — PP-II

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

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

0.3% — PP-III

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

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

$\downarrow$

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

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