Studying stars from deep underground: latest news from LUNA

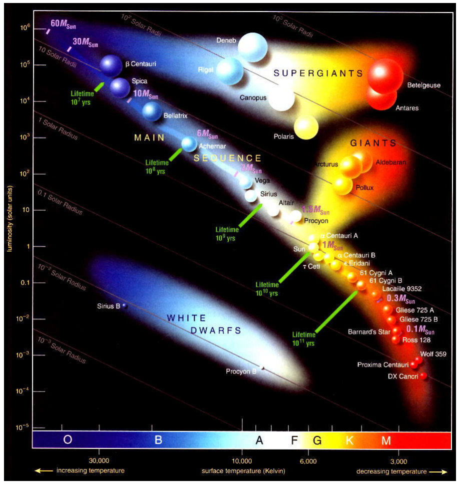
Rosanna Depalo
INFN Padova

Selected Topics in Nuclear and Atomic Physics 2019 – Fiera di Primiero

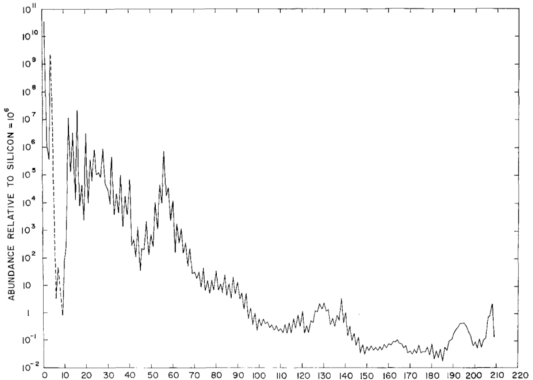
NUCLEAR ASTROPHYSICS

Nuclear reactions cross sections

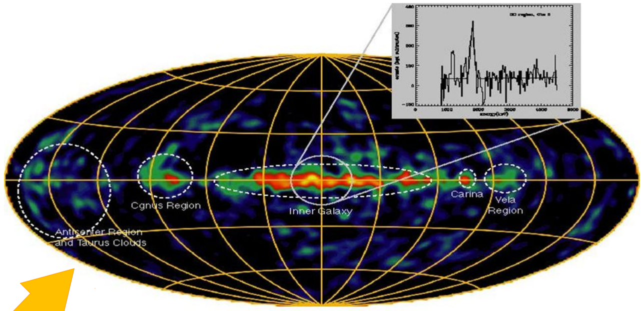
Stellar evolution



Nucleosynthesis

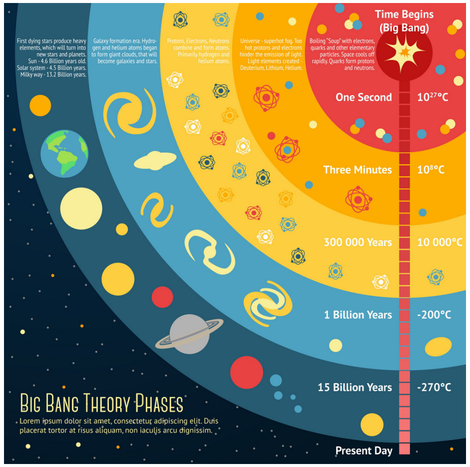


Astronomy with radioactivity

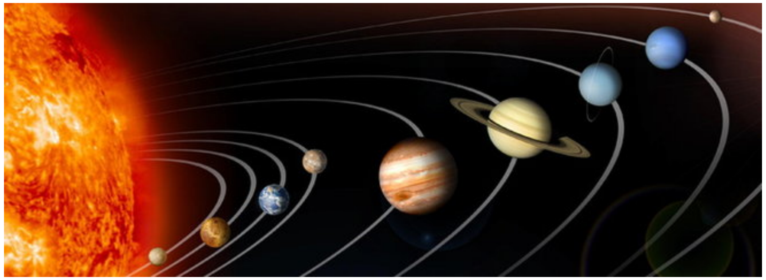


(Oberlack et al., 1996; Pluschke et al., 2001)

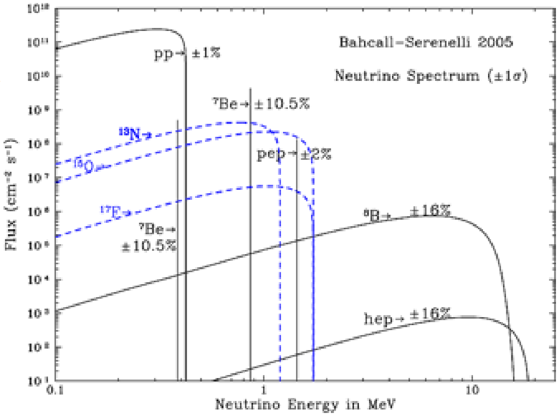
Evolution of early Universe



Solar system formation and evolution



Solar neutrino



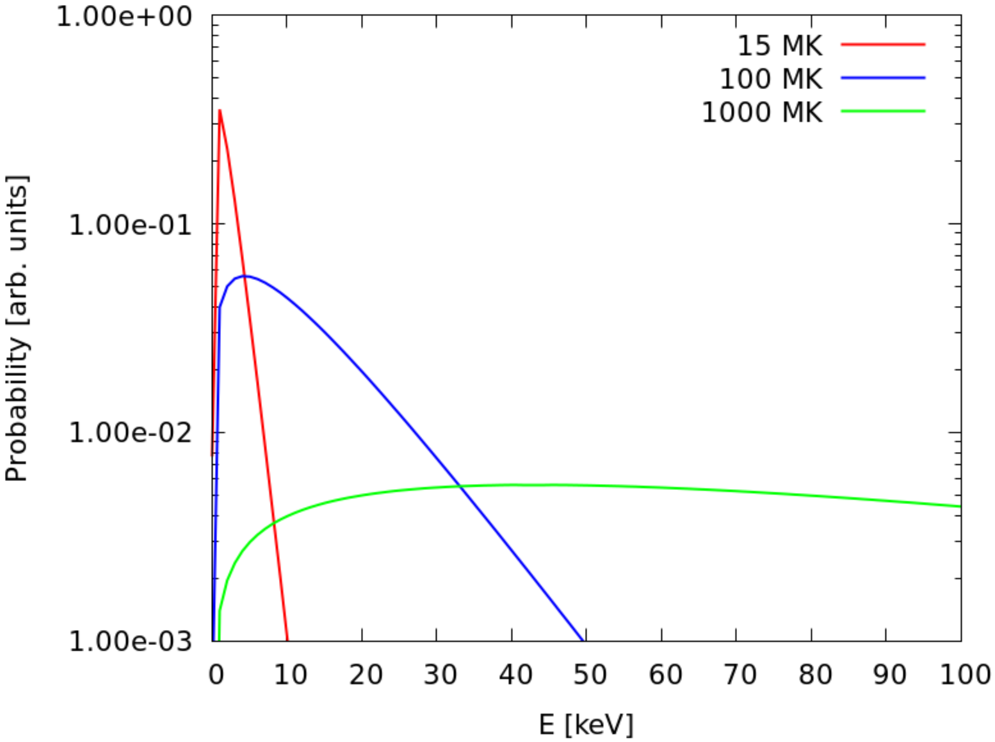
NUCLEAR REACTIONS AT ASTROPHYSICAL ENERGIES

$$\frac{\text{N° Reactions}}{\text{time} \cdot \text{volume}} = N_a \cdot N_b \cdot v \cdot \sigma$$

CROSS SECTION

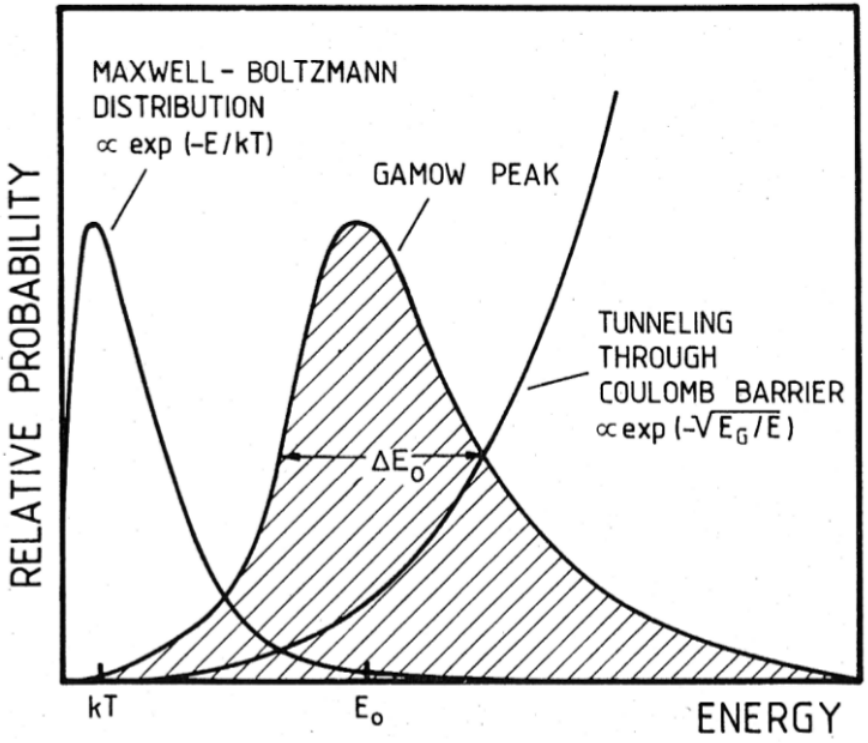
RELATIVE VELOCITY

MAXWELL BOLTZMANN DISTRIBUTION **vs** **COULOMB REPULSION**



$$E_C = \frac{Z_a Z_b e^2}{R} \sim MeV$$

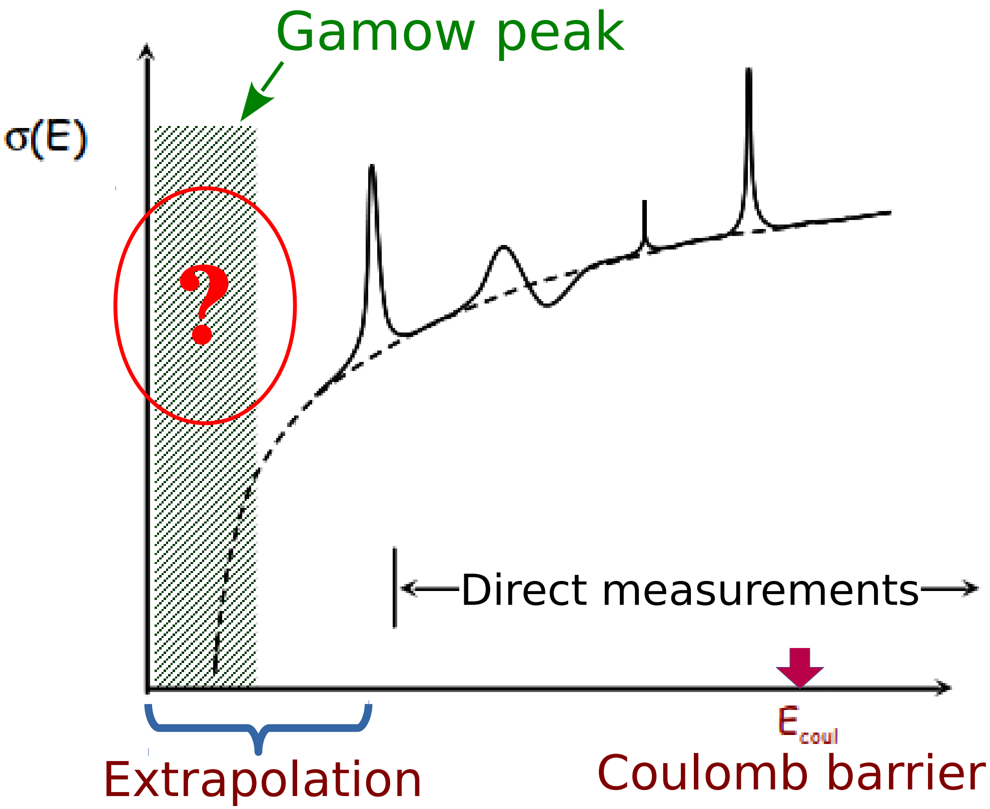
NUCLEAR REACTIONS AT ASTROPHYSICAL ENERGIES



- **Nuclear reactions occur at energies far below the Coulomb barrier**
- **Cross sections are strongly energy-dependent**

At Gamow energies, σ ~ fb - nb

$$\sigma(E) \equiv \frac{1}{E}\, e^{-2\pi\eta}\, S(E)$$



NUCLEAR REACTIONS AT ASTROPHYSICAL ENERGIES

Counting rate = N_p x N_t x cross section x detection efficiency

N_p: 10^{14} pps
(I ~ 100 µA)

N_t: 10^{18} atoms/cm^2
(typical solid-state target)

cross section: 10^{-36} cm^2
(or even smaller)

detection efficiency: 1 - 5% for HPGe

NUCLEAR REACTIONS AT ASTROPHYSICAL ENERGIES

Counting rate = N_p x N_t x cross section x detection efficiency

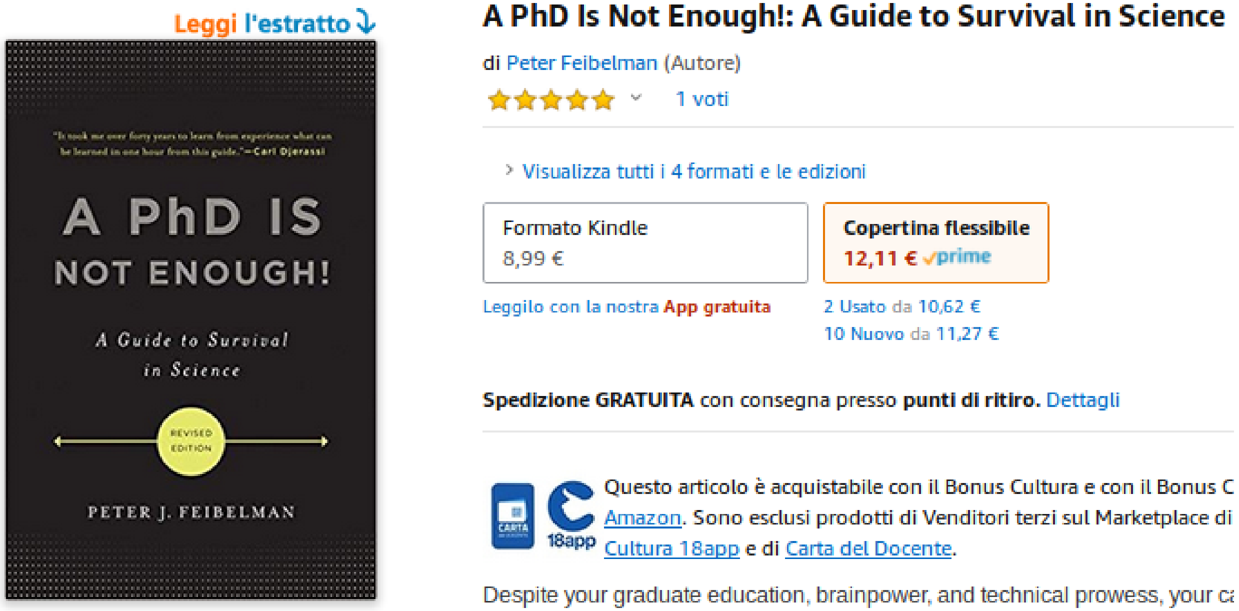
N_p: 10^{14} pps (I ~ 100 μA)

N_t: 10^{18} atoms/cm^2 (typical solid-state target)

cross section: 10^{-36} cm^2 (or even smaller)

detection efficiency: 1 - 5% for HPGe

C = 4 · 10^{-3} counts/hour



Leggi l'estratto

"It took me over forty years to learn from experience what can be learned in one hour from this guide." —Carl Djerassi

A PhD IS NOT ENOUGH!

A Guide to Survival in Science

REVISED EDITION

PETER J. FEIBELMAN

A PhD Is Not Enough!: A Guide to Survival in Science

di Peter Feibelman (Autore)

★★★★★ 1 voti

Visualizza tutti i 4 formati e le edizioni

Formato Kindle	Copertina flessibile
8,99 €	12,11 € prime
Leggilo con la nostra App gratuita	2 Usato da 10,62 € 10 Nuovo da 11,27 €

Spedizione GRATUITA con consegna presso **punti di ritiro.** Dettagli

Questo articolo è acquistabile con il Bonus Cultura e con il Bonus C
Amazon. Sono esclusi prodotti di Venditori terzi sul Marketplace di
Cultura 18app e di Carta del Docente.

Despite your graduate education, brainpower, and technical prowess, your ca

~ 100 counts/PhD

NUCLEAR REACTIONS AT ASTROPHYSICAL ENERGIES

Counting rate = N_p x N_t x cross section x detection efficiency

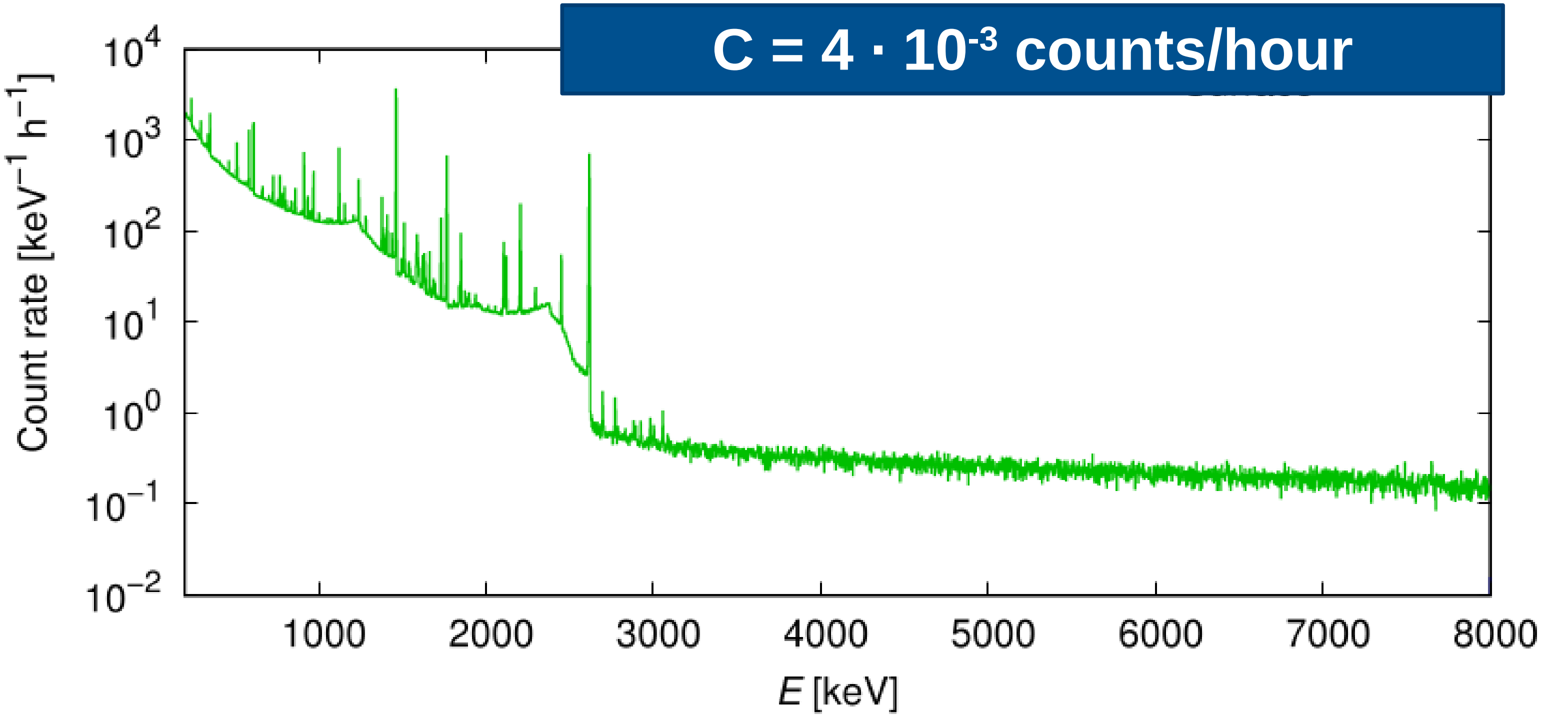
N_p: 10^{14} pps (I ~ 100 μA)

N_t: 10^{18} atoms/cm^2 (typical solid-state target)

cross section: 10^{-36} cm^2 (or even smaller)

detection efficiency: 1 - 5% for HPGe

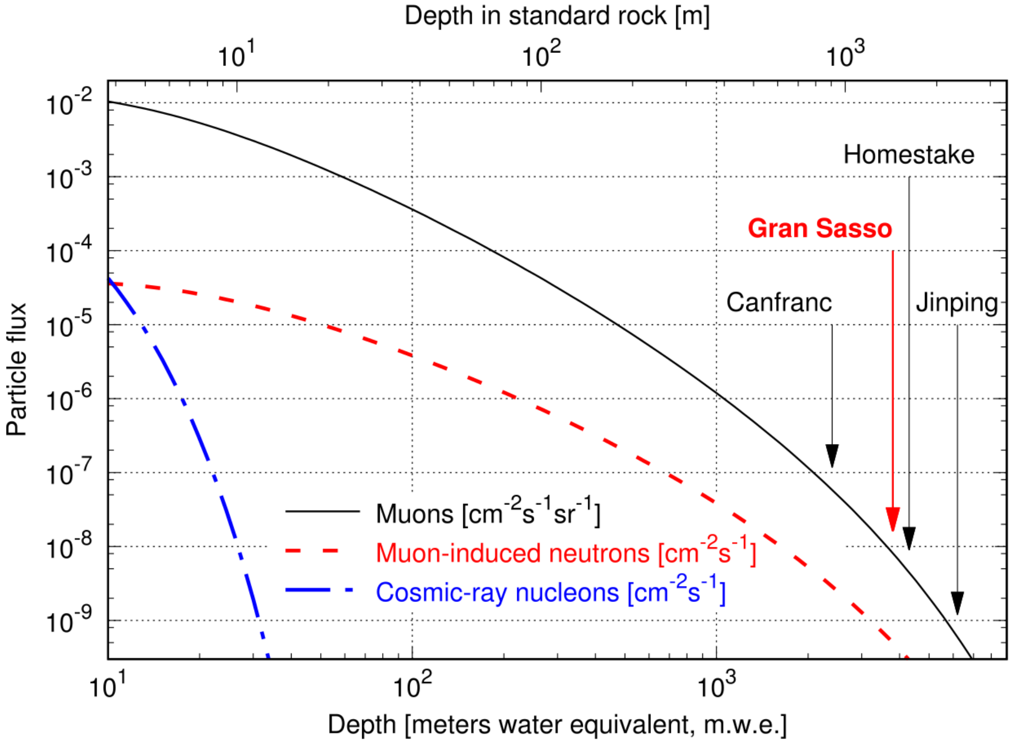
C = 4 · 10^{-3} counts/hour

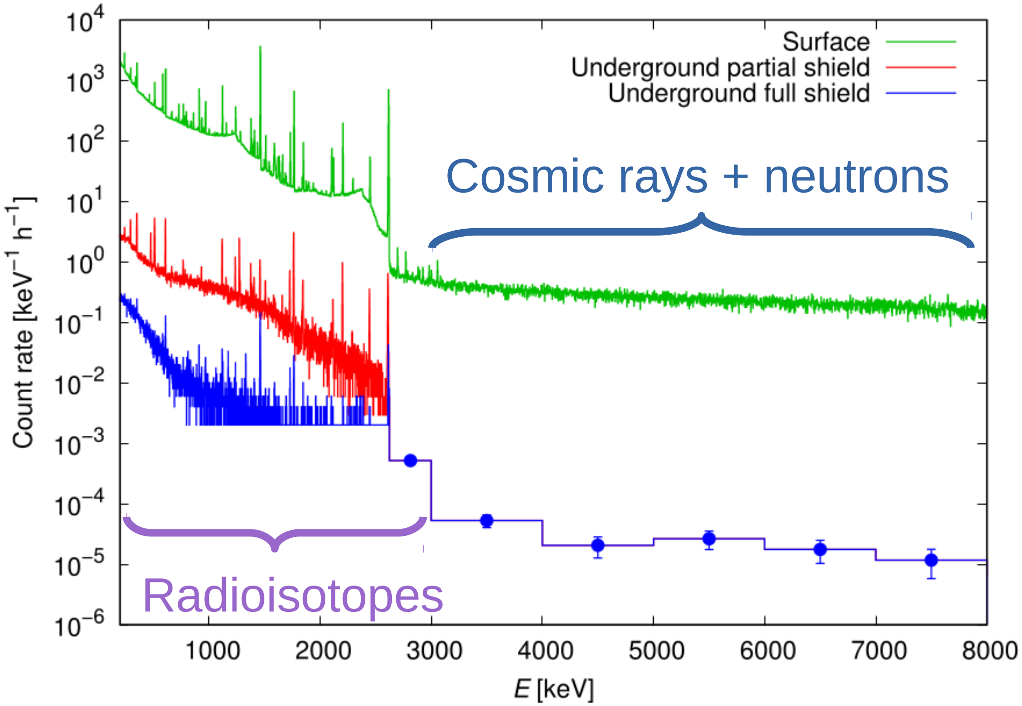


WHY UNDERGROUND?

Main sources of natural background in a gamma ray spectrum:

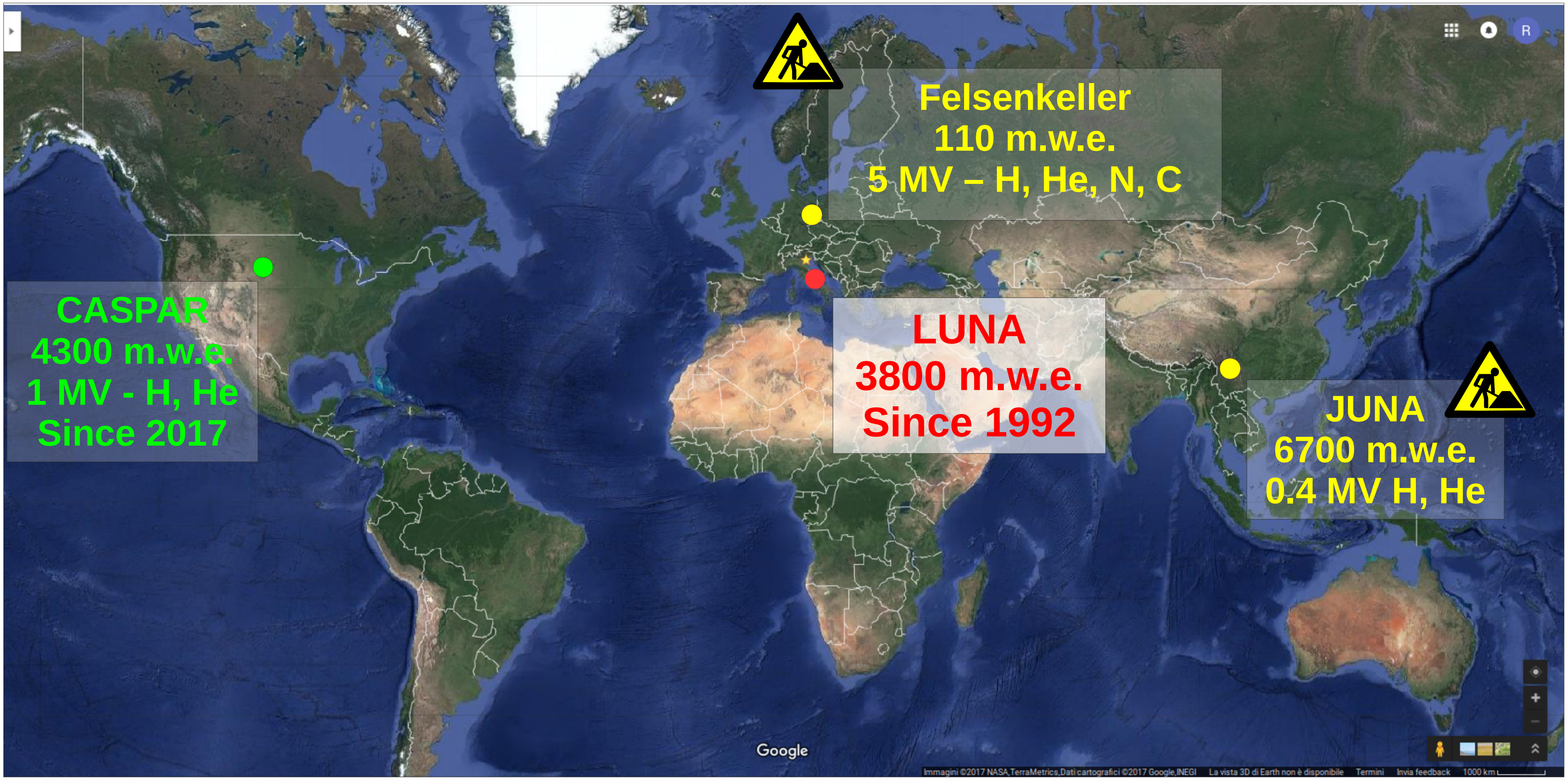
- **Environmental radioactivity**:
  ^{238}U and ^{232}Th chains and ^{40}K
- **Cosmic rays:**
  mainly muons at sea level
- **Neutrons from (α,n) and spallation**





+ More effective passive shielding

UNDERGROUND FACILITIES WORLDWIDE



Felsenkeller
110 m.w.e.
5 MV – H, He, N, C

CASPAR
4300 m.w.e.
1 MV - H, He
Since 2017

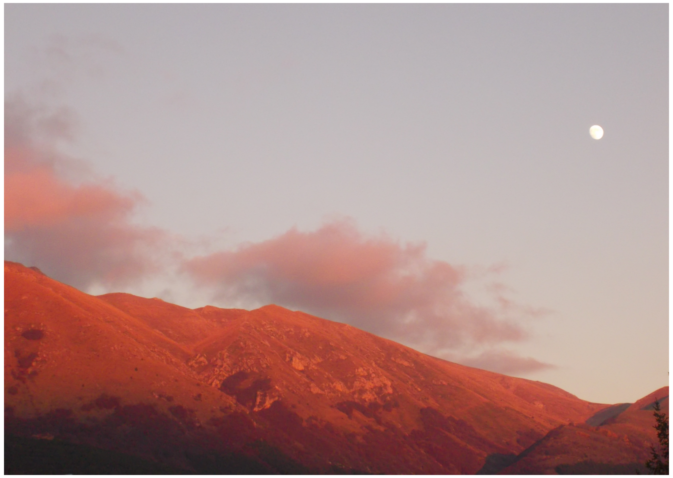
LUNA
3800 m.w.e.
Since 1992

JUNA
6700 m.w.e.
0.4 MV H, He

THE LABORATORY FOR UNDERGROUND NUCLEAR ASTROPHYSICS (LUNA)

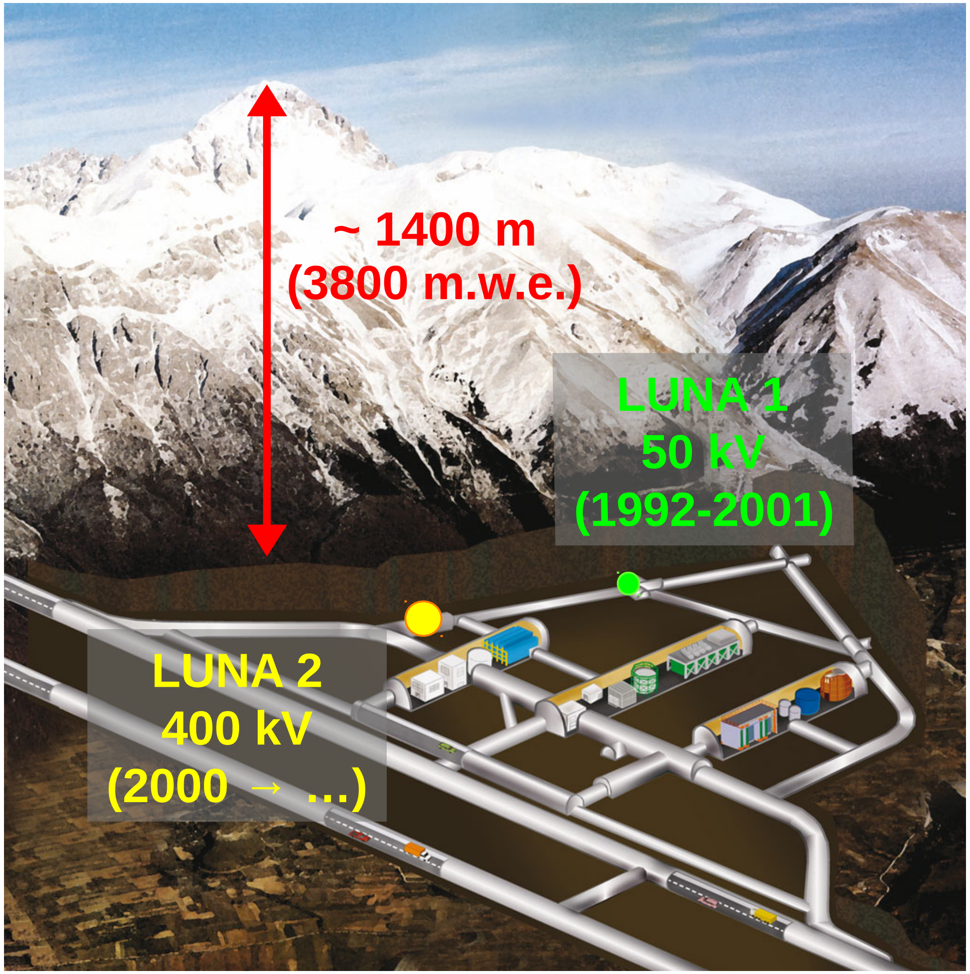
Maps data © 2015 Google

Gran Sasso National Laboratories



THE LABORATORY FOR UNDERGROUND NUCLEAR ASTROPHYSICS (LUNA)

© Franco Fasciolo



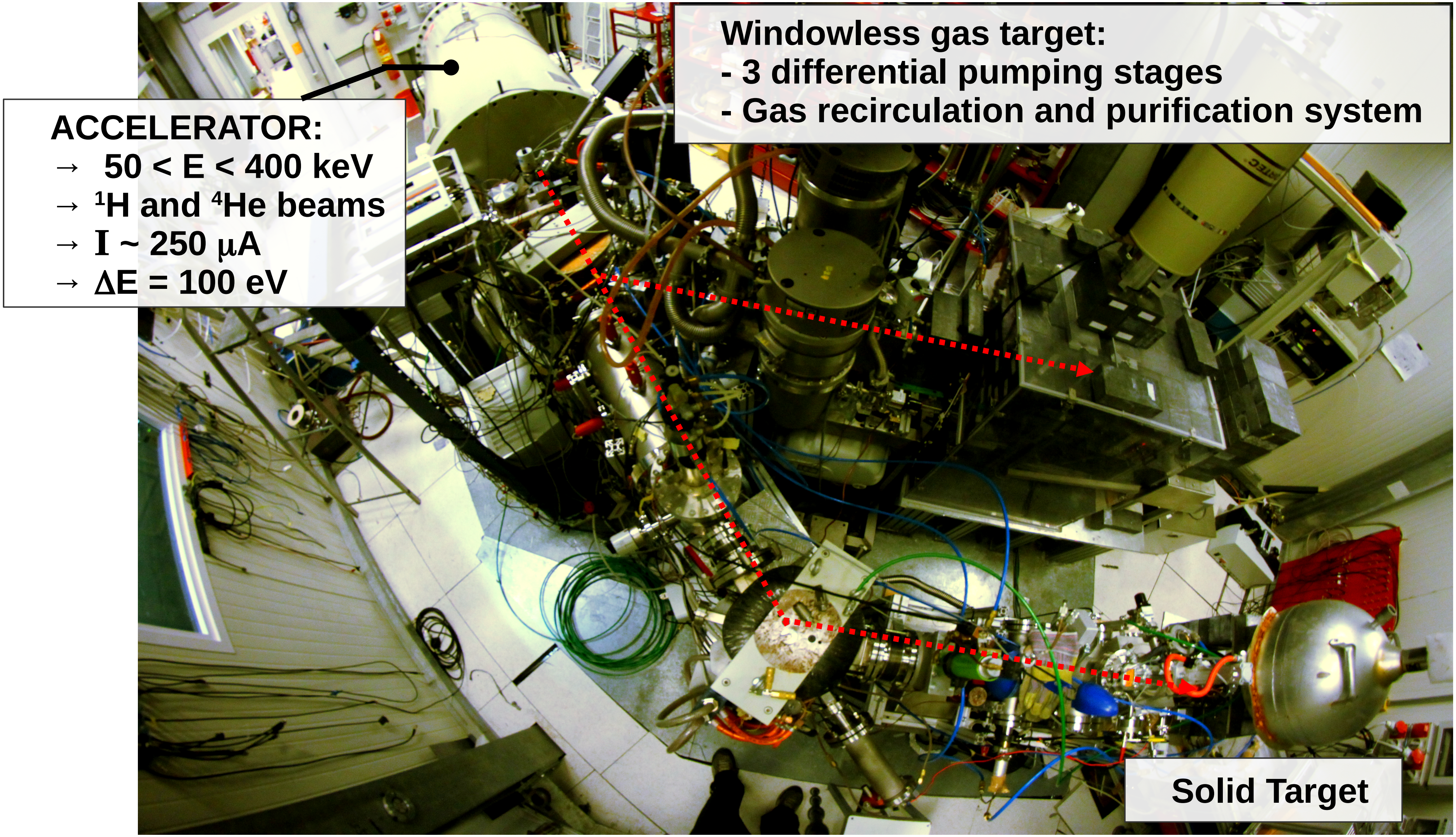
~ 1400 m
(3800 m.w.e.)

LUNA 1
50 kV
(1992-2001)

LUNA 2
400 kV
(2000 → …)

Cosmic ray flux attenuation: μ → 10^{-6}
n → 10^{-3}

THE LABORATORY FOR UNDERGROUND NUCLEAR ASTROPHYSICS (LUNA)

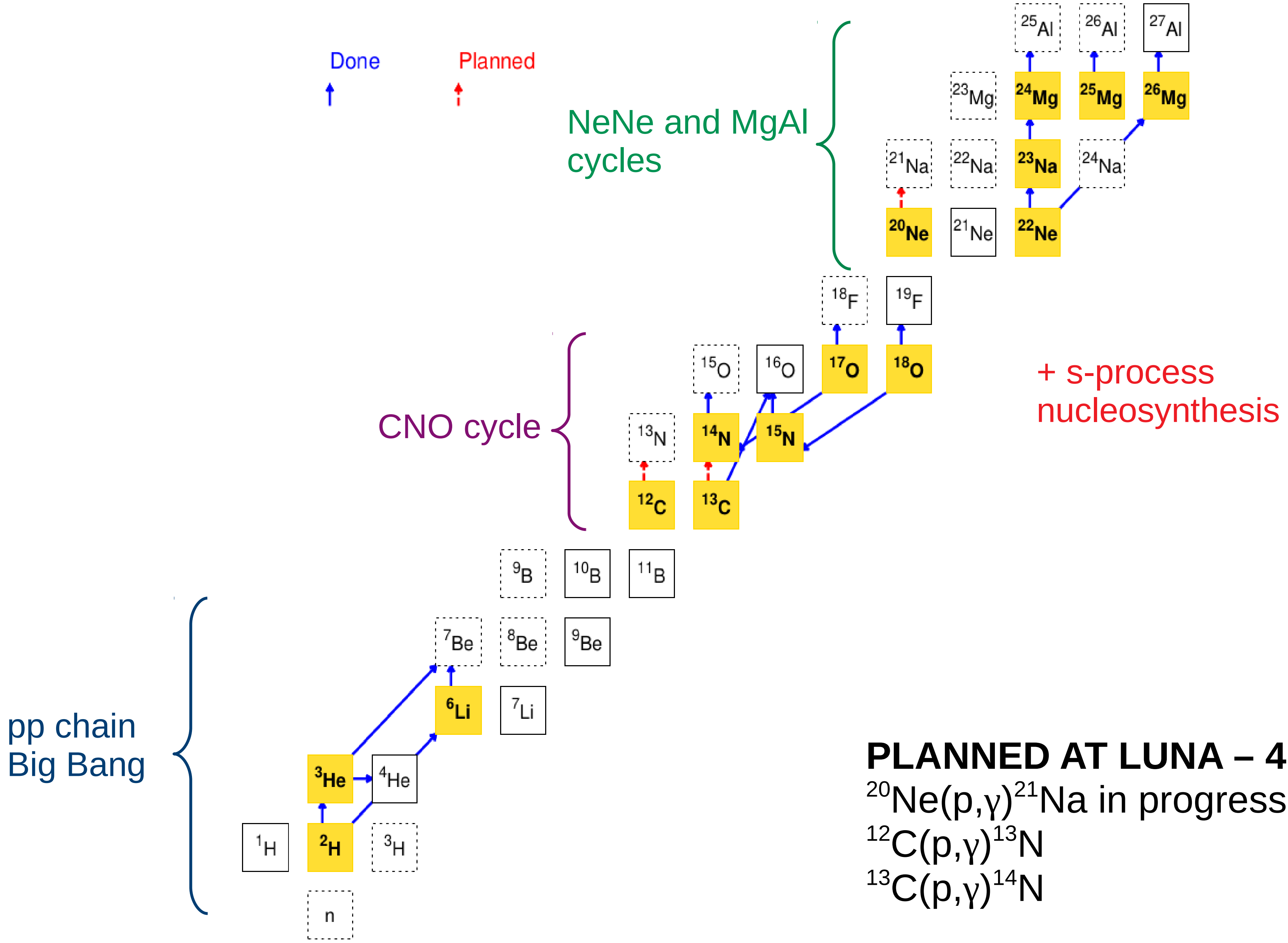


ACCELERATOR:
- → 50 < E < 400 keV
- → ^{1}H and ^{4}He beams
- → I ~ 250 μA
- → ΔE = 100 eV

Windowless gas target:
- 3 differential pumping stages
- Gas recirculation and purification system

Solid Target

REACTIONS STUDIED SINCE 1992



PLANNED AT LUNA – 400 kV:

^{20}Ne(p,γ)^{21}Na in progress

^{12}C(p,γ)^{13}N

^{13}C(p,γ)^{14}N

Big Bang Nucleosynthesis: The $^2H(p,\gamma)^3He$ reaction

$^{2}H(p,\gamma)^{3}He$ REACTION: ASTROPHYSICAL MOTIVATION

PRIMORDIAL ABUNDANCE OF ^{2}H:

- Direct measurements: observation of absorption lines in DLA system

$$\left[\frac{D}{H}\right]_{OBS} = (2.527 \pm 0.030) \cdot 10^{-5}$$

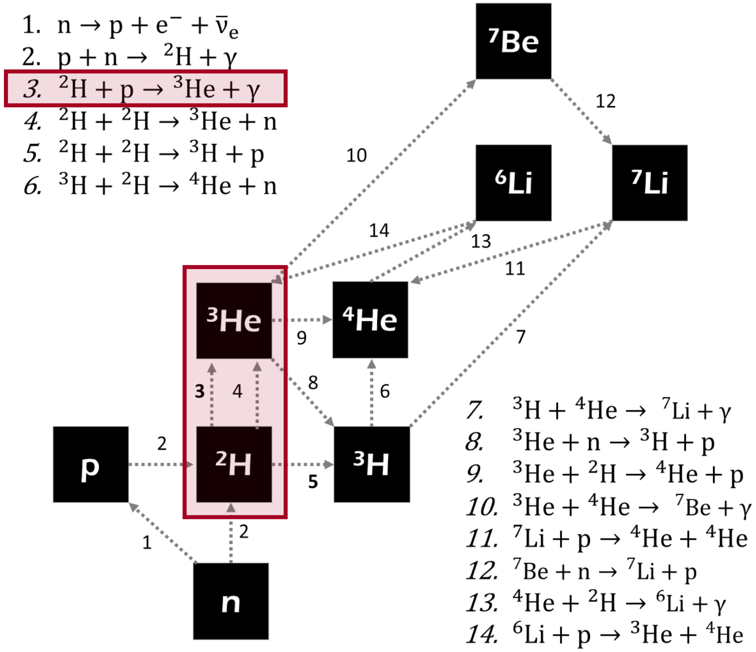
R. Cooke at al., ApJ. 855, 102 (2018)

- BBN theory: from the cosmological parameters and the cross sections of the processes involved in ^{2}H creation and destruction

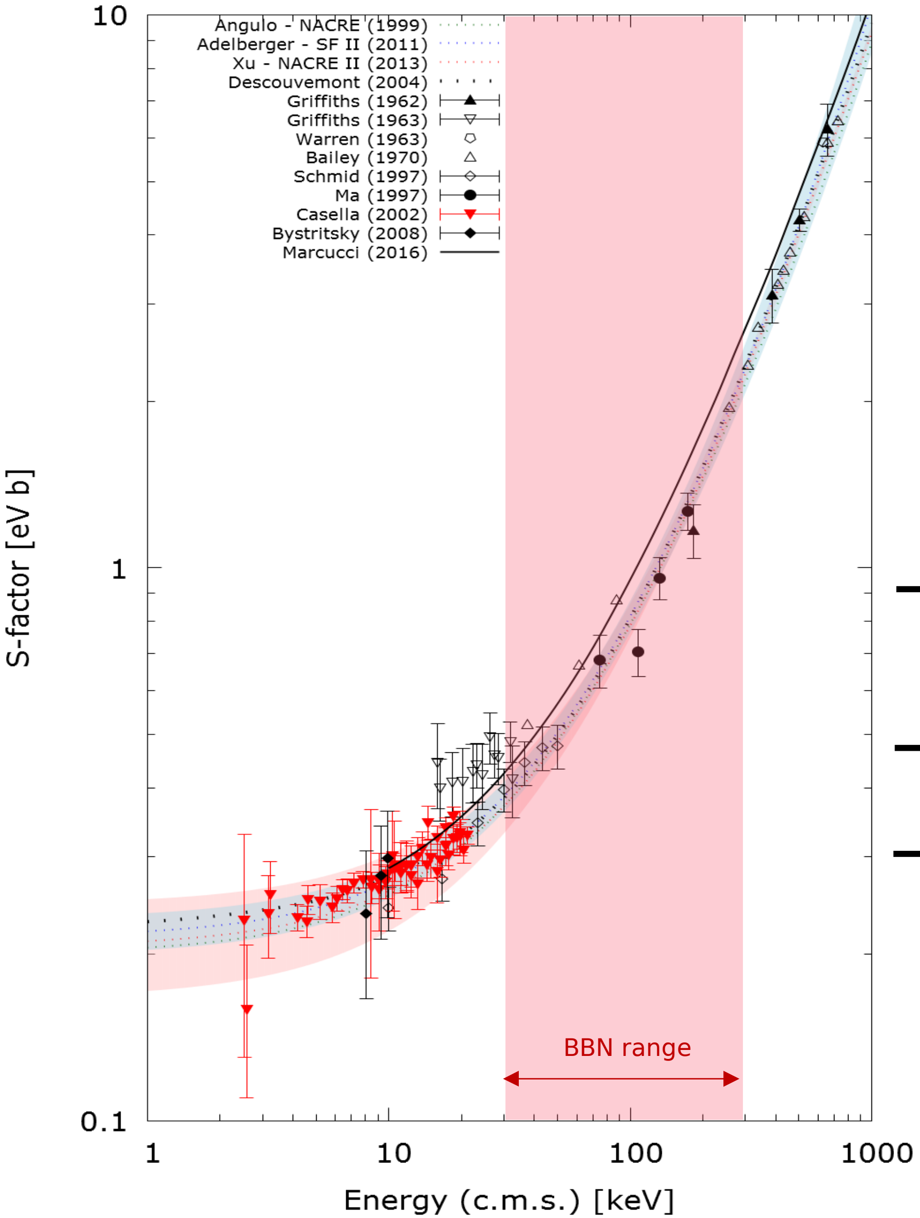
$$\left[\frac{D}{H}\right]_{BBN} = \begin{array}{l} (2.587 \pm 0.055) \cdot 10^{-5} \\ (2.439 \pm 0.052) \cdot 10^{-5} \end{array}$$

Depending on the $^{2}H(p,\gamma)^{3}He$ cross section adopted

Plank 2018 results arXiv:1807.06209v1


1. $n \rightarrow p + e^{-} + \bar{\nu}_e$
2. $p + n \rightarrow\ ^{2}H + \gamma$
3. $^{2}H + p \rightarrow\ ^{3}He + \gamma$
4. $^{2}H + ^{2}H \rightarrow\ ^{3}He + n$
5. $^{2}H + ^{2}H \rightarrow\ ^{3}H + p$
6. $^{3}H + ^{2}H \rightarrow\ ^{4}He + n$
7. $^{3}H + ^{4}He \rightarrow\ ^{7}Li + \gamma$
8. $^{3}He + n \rightarrow\ ^{3}H + p$
9. $^{3}He + ^{2}H \rightarrow\ ^{4}He + p$
10. $^{3}He + ^{4}He \rightarrow\ ^{7}Be + \gamma$
11. $^{7}Li + p \rightarrow\ ^{4}He + ^{4}He$
12. $^{7}Be + n \rightarrow\ ^{7}Li + p$
13. $^{4}He + ^{2}H \rightarrow\ ^{6}Li + \gamma$
14. $^{6}Li + p \rightarrow\ ^{3}He + ^{4}He$

^{2}H(p,γ)^{3}He REACTION: STATE OF THE ART



The cross section of the ^{2}H(p,γ)^{3}He reaction is the main source of uncertainty on the primordial ^{2}H abundance

→ Measurement at solar energies performed at the LUNA – 50 kV accelerator

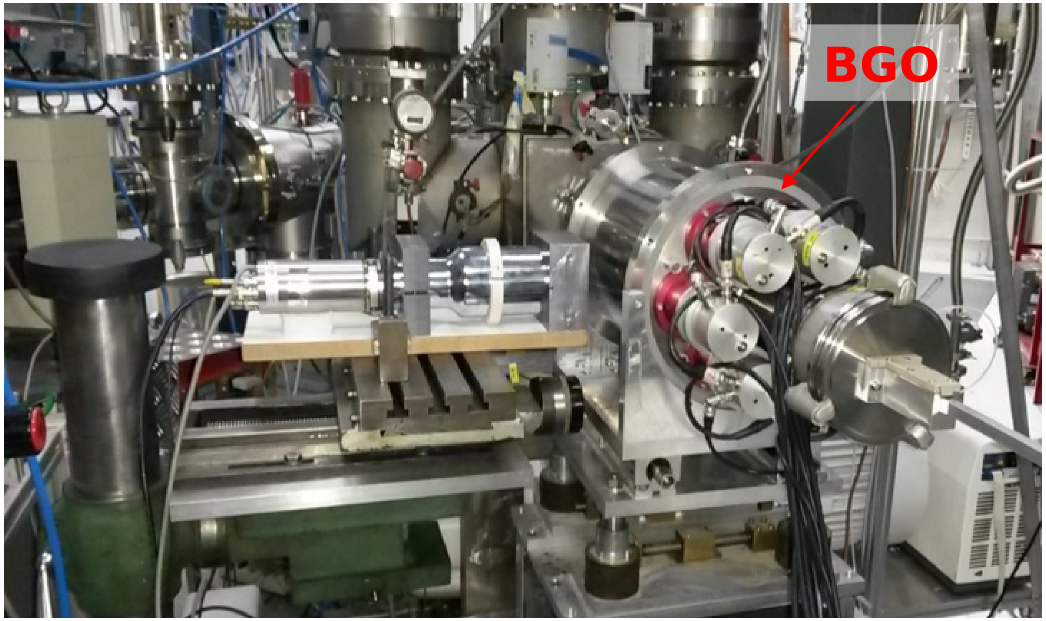
→ Only few data points available at BBN energies

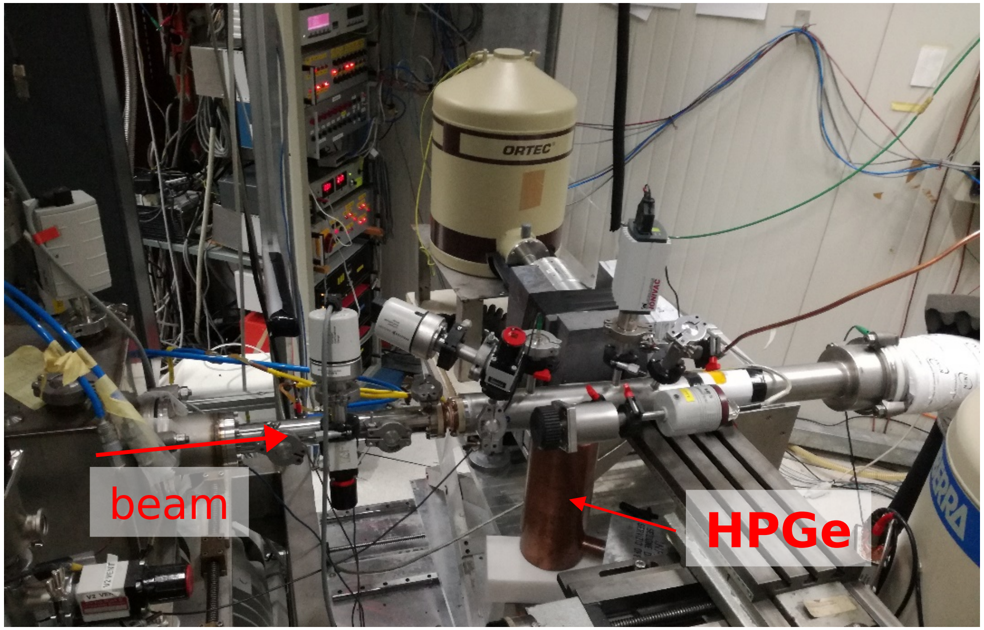
→ Good test case for ab-initio calculations (L. Marcucci et al.)

$^{2}H(p,\gamma)^{3}He$ REACTION: THE EXPERIMENT AT LUNA

The reaction is being studied in two phases with different setups in order to lower the final systematics uncertainties (final goal 3%):

- **BGO** detector setup with high efficiency, to extend data down to E_p = 70keV
- **HPGe** detector setup with extended gas target to study the angular distribution with peak shape analysis



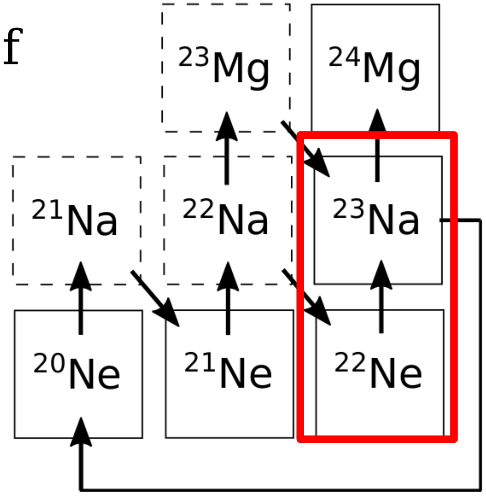


Results will be published soon...

Nucleosynthesis in AGB stars: The ^{22}Ne(p,γ)^{23}Na reaction

^{22}Ne(p,γ)^{23}Na ASTROPHYSICAL MOTIVATION

The Neon - Sodium cycle strongly influences the abundances of Ne, Na, Mg and Al in:



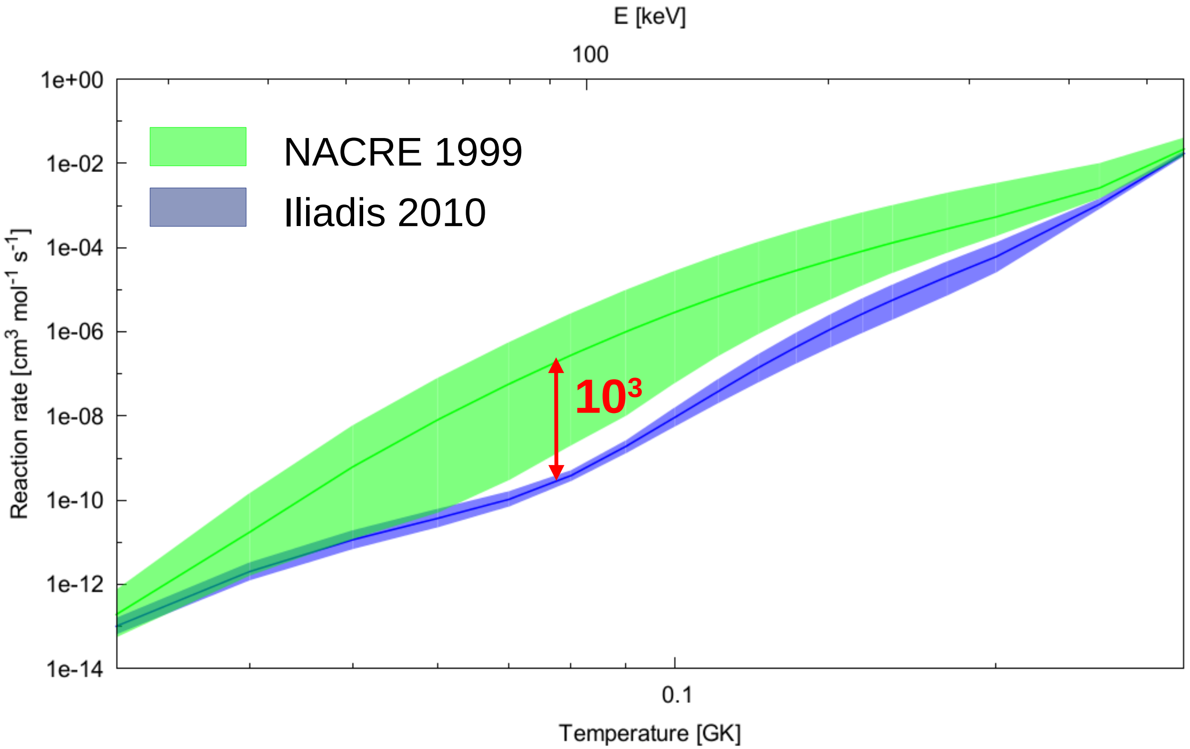
Hydrostatic H burning:

- Core H burning in massive stars
- Shell H burning in RGB and AGB stars

Explosive H burning:

- Classical novae
- Type Ia supernovae

Huge uncertainty due to several poorly-known resonances
+
Two tentative resonances at 70 and 100 keV



THE ^{22}Ne(p,γ)^{23}Na REACTION: EXPERIMENTAL SETUP

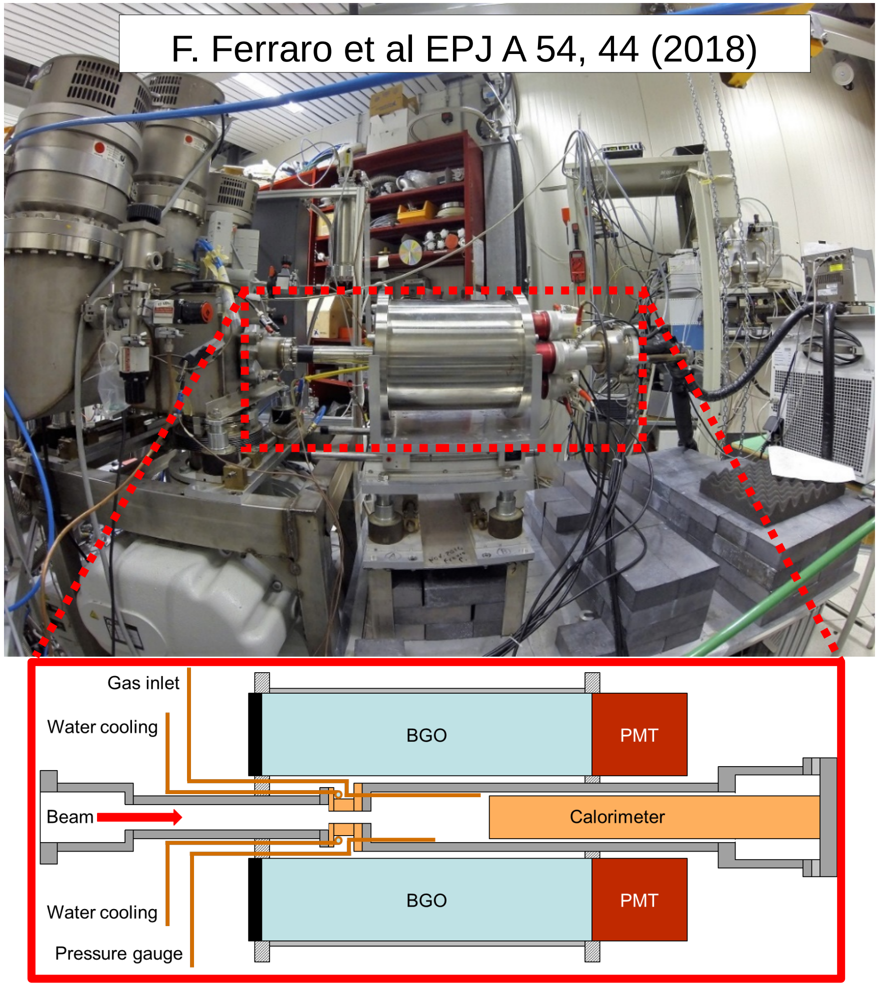
Studied with a windowless gas target with recirculation system, ^{22}Ne gas enriched at 99.9%:

PHASE 1: HPGe detectors

F. Cavanna et al EPJ A 50, 179 (2014)

- 2 HPGe detectors at 55° and 90°
- Pb + Cu shielding (~ 30 cm)

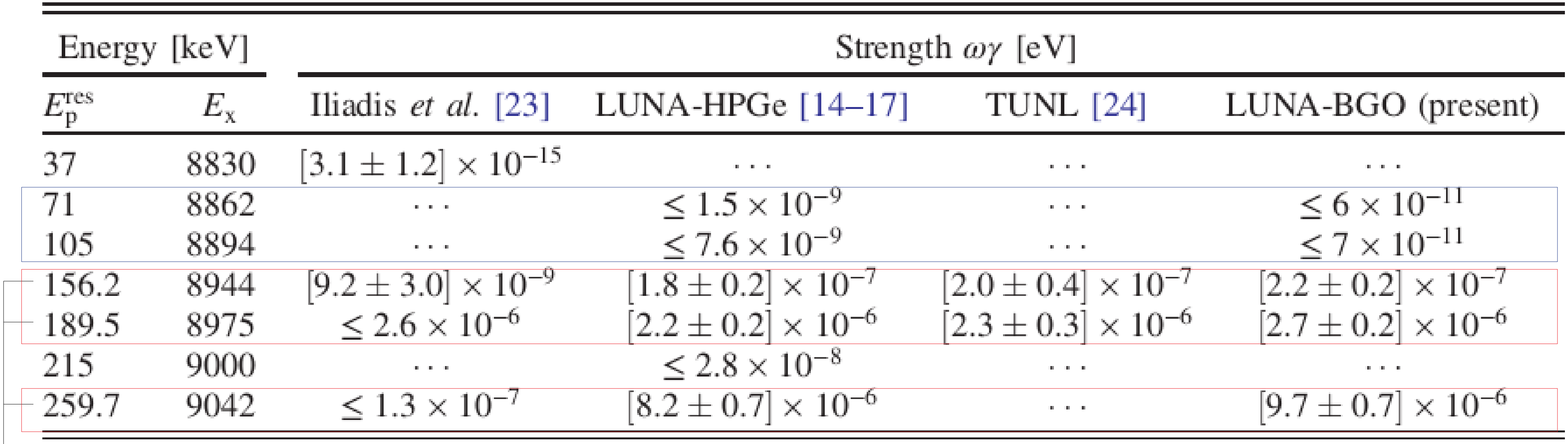
PHASE 2: 4π BGO detector



F. Ferraro et al EPJ A 54, 44 (2018)

Low energy resolution, but detection efficiency 70%

THE $^{22}Ne(p,\gamma)^{23}Na$ REACTION: RESULTS

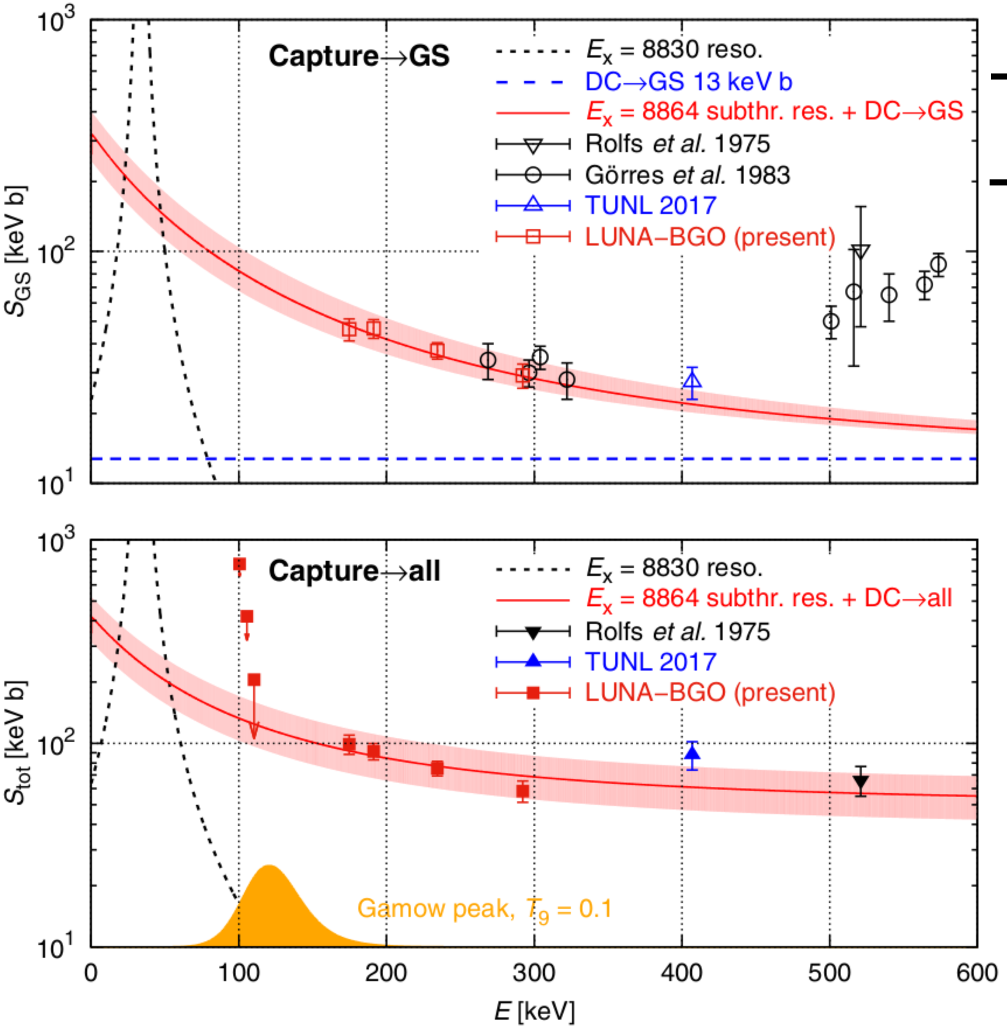


Energy [keV]		Strength $\omega\gamma$ [eV]			
E_p^{res}	E_x	Iliadis *et al.* [23]	LUNA-HPGe [14–17]	TUNL [24]	LUNA-BGO (present)
37	8830	$[3.1 \pm 1.2] \times 10^{-15}$	...	...	...
71	8862	...	$\lesssim 1.5 \times 10^{-9}$	...	$\lesssim 6 \times 10^{-11}$
105	8894	...	$\lesssim 7.6 \times 10^{-9}$	...	$\lesssim 7 \times 10^{-11}$
156.2	8944	$[9.2 \pm 3.0] \times 10^{-9}$	$[1.8 \pm 0.2] \times 10^{-7}$	$[2.0 \pm 0.4] \times 10^{-7}$	$[2.2 \pm 0.2] \times 10^{-7}$
189.5	8975	$\lesssim 2.6 \times 10^{-6}$	$[2.2 \pm 0.2] \times 10^{-6}$	$[2.3 \pm 0.3] \times 10^{-6}$	$[2.7 \pm 0.2] \times 10^{-6}$
215	9000	...	$\lesssim 2.8 \times 10^{-8}$	...	...
259.7	9042	$\lesssim 1.3 \times 10^{-7}$	$[8.2 \pm 0.7] \times 10^{-6}$	...	$[9.7 \pm 0.7] \times 10^{-6}$

► Gamma decay branching ratios and resonance energies also measured

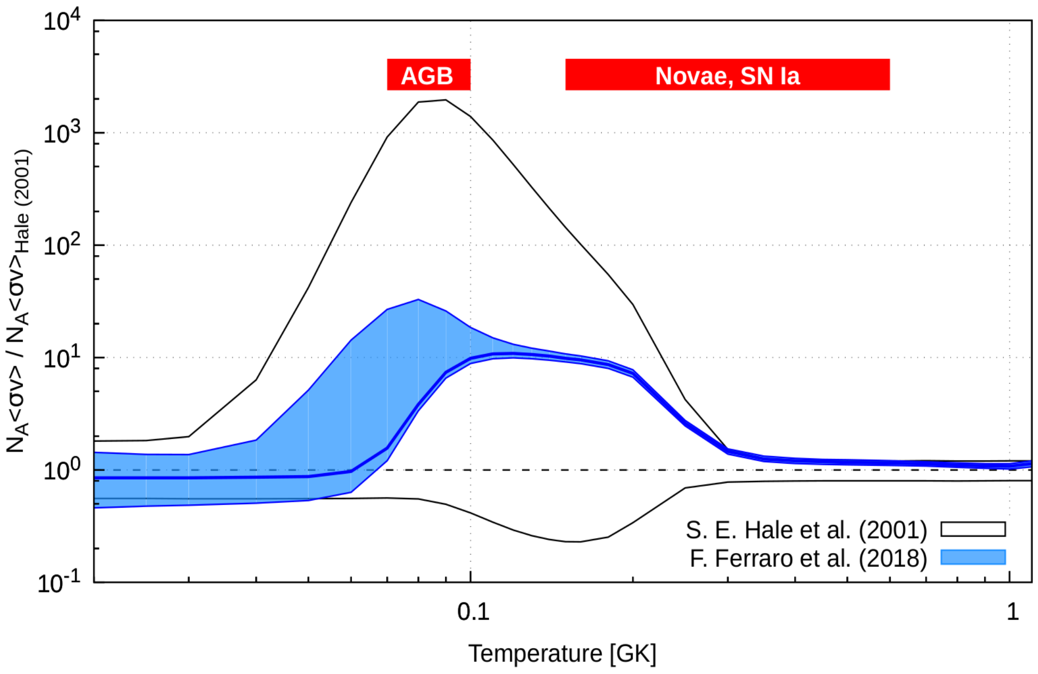
F. Ferraro et al. PRL 121, 172701 (2018)
R. Depalo et al. PRC 94, 055804 (2016)
F. Cavanna et al. PRL 115, 252501 (2015)

THE $^{22}Ne(p,\gamma)^{23}Na$ REACTION: RESULTS



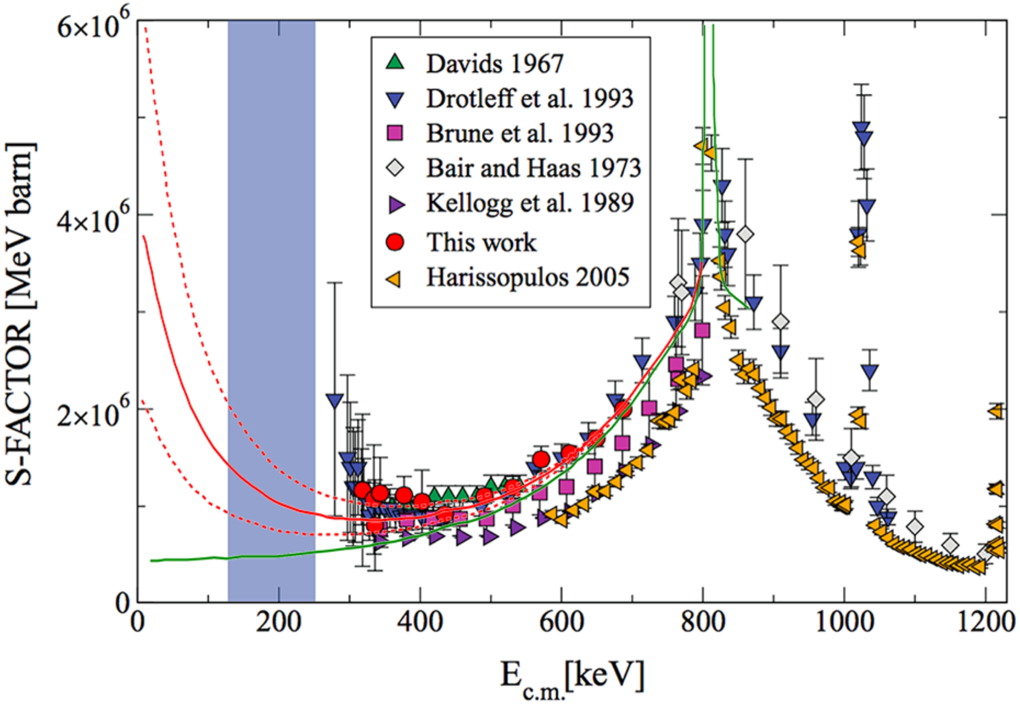
F. Ferraro et al. PRL 121, 172701 (2018)

- → Direct capture measured at Gamow energies
- → Upper limits on 71 and 100 keV resonances decreased by 4 orders of magnitude

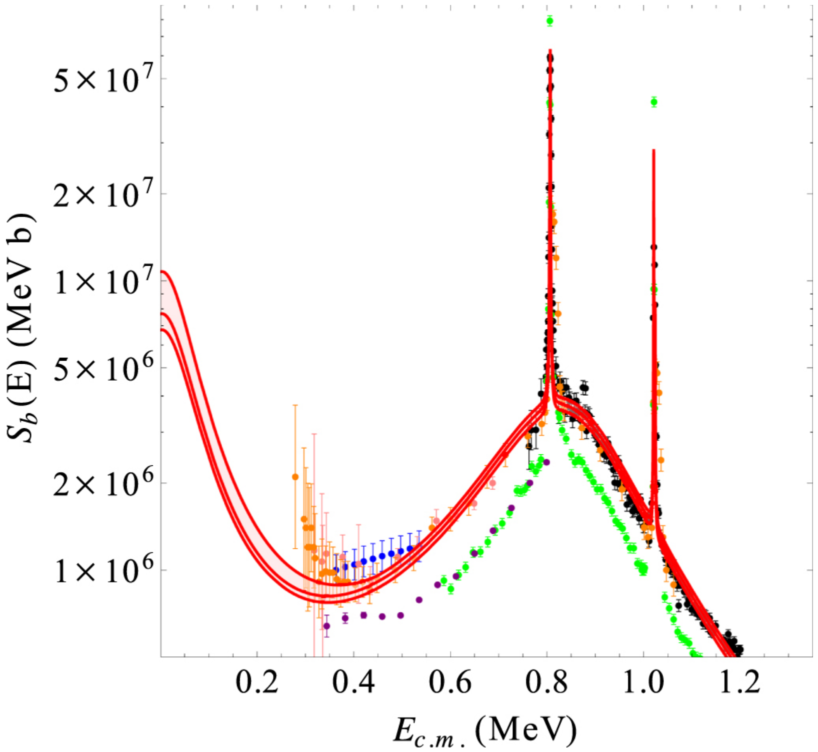


s-process nucleosynthesis:
The $^{13}C(\alpha,n)^{16}O$ reaction

^{13}C(α,n)^{16}O: ASTROPHYSICAL MOTIVATION



M. Heil et al. PRC 78, 025803 (2008)

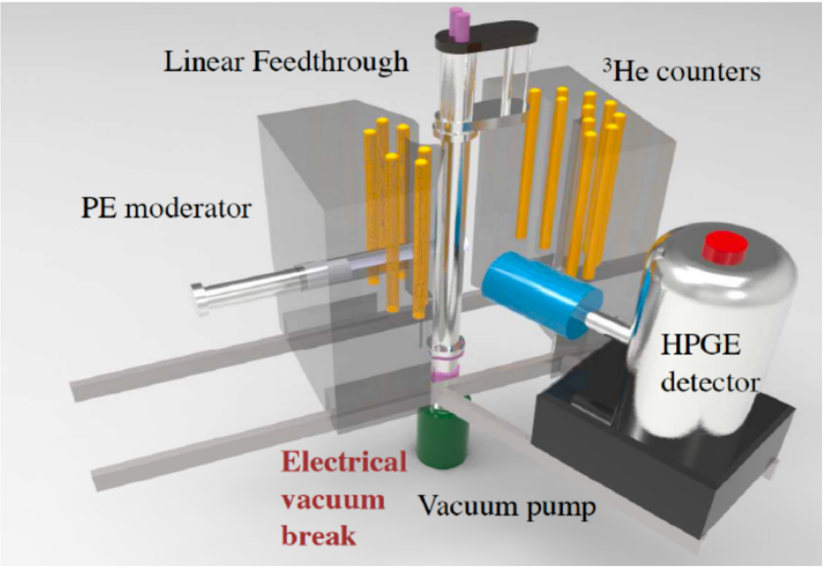


O. Trippella, M. La Cognata ApJ 837, 41 (2017)

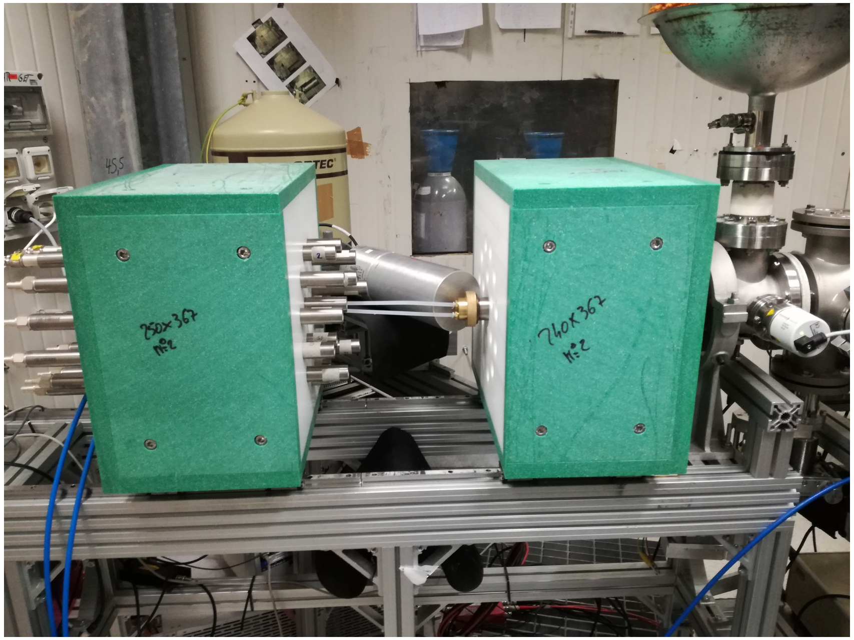
→ Major neutron source for the main component of the s-process in low mass (1-3 M$_\odot$) AGB stars T ~ 10^8 K (E ~ 120-250 keV)

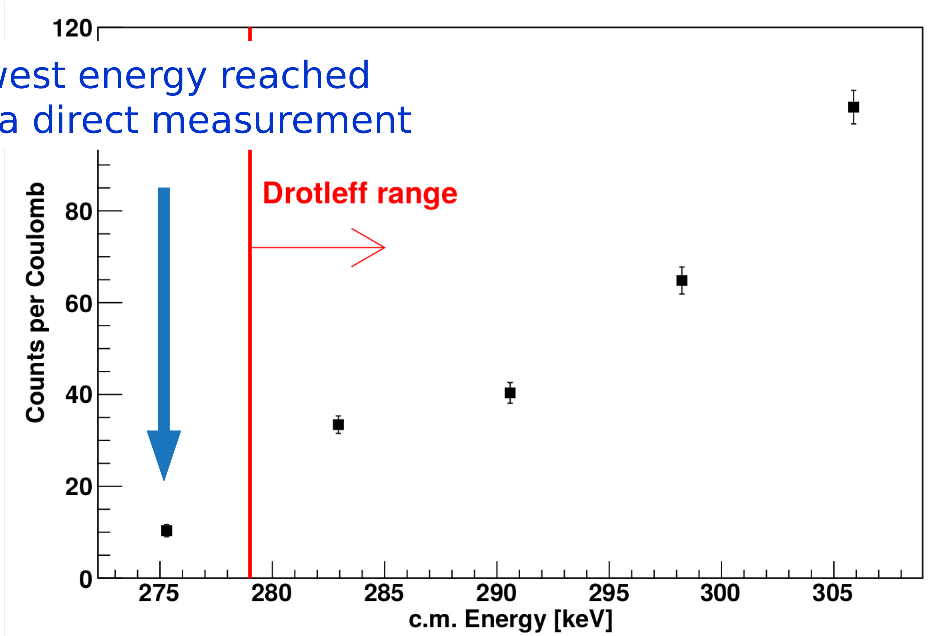
→ No direct data covering this energy range is available yet.

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



Counters arranged in two rings
INNER: 6 tubes (25 cm active length)
OUTER: 12 tubes (40 cm active length)





Lowest energy reached with a direct measurement

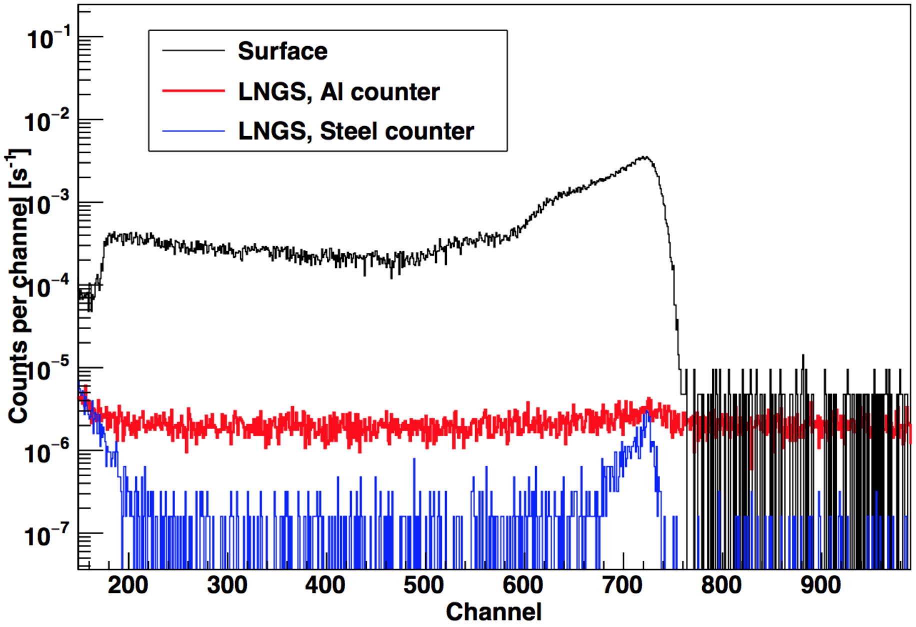
Eα (keV)	charge (C)
360	20.4
380	16.9
390	16.8
400	11.0

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

ENVIRONMENTAL: 1400 m of rock reduce the neutron flux underground by factor 1000 compared to surface.

INTRINSIC: α particles source of intrinsic background from U and Th impurities in the counters' case

10 atm pressurised ^{3}He counters with a stainless steel case with low intrinsic background
Background (n+α): (2.93+-0.09) counts/h in the ROI



POST Processing PULSE SHAPE DISCRIMINATION*
(rejects 90% alpha and 10% neutrons)
Background rate (ROI) for the entire ^{3}He setup:
~ (1.05+-0.06) counts/hour

*J. Balibrea-Correa et al., NIM A 906,103-109, (2018)

Future prospects of LUNA

THE LUNA-MV PROJECT

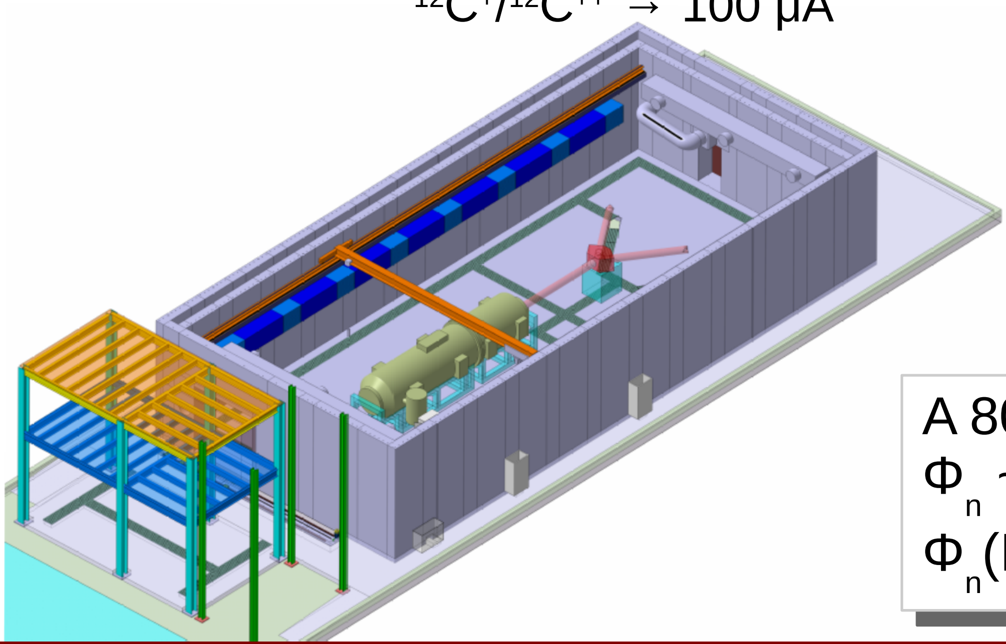
New, higher energy underground accelerator needed to study:

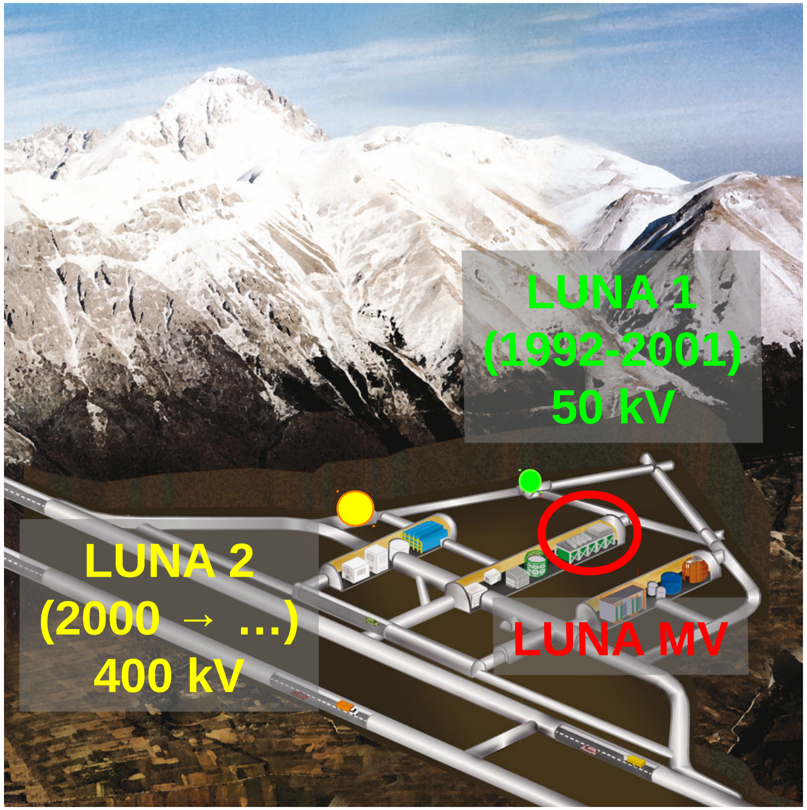
- Stellar Helium and Carbon burning
- Neutron sources for astrophysical s-processes
- Solar fusion reactions

- **Inline Cockcroft Walton accelerator**
- **TERMINAL VOLTAGE:** 0.2 – 3.5 MV
- **Beam current:** $^{1}H^{+}$ → 500 μA – 1mA

  $^{4}He^{+}$ → 300 μA – 500 μA

  $^{12}C^{+}/^{12}C^{++}$ → 100 μA





A 80 cm thick concrete shielding is foreseen.
$\Phi_n \sim 0.1 \times \Phi_n(\mathrm{LNGS})$
$\Phi_n(\mathrm{LNGS}) = 3 \cdot 10^{-6}$ n/(cm^2 s)

THE LUNA-MV PROJECT: SCIENTIFIC PROGRAM

In 2016 a scientific proposal has been presented to the LNGS Scientific Committee, containing key reactions to be studied in the first years of the LUNA-MV machine:

$^{14}\mathrm{N}(p,\gamma)^{15}\mathrm{O}$	Bottleneck of the CNO cycle. Commissioning experiment
$^{12}\mathrm{C}(^{12}\mathrm{C},\alpha)^{20}\mathrm{Ne}$, **$^{12}\mathrm{C}(^{12}\mathrm{C},p)^{23}\mathrm{Na}$**	Main reaction during C burning
$^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{O}$ **$^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$**	→ neutron sources for s-process

Being underground is not always enough...

PREPARATORY WORK: THE $^{12}C+^{12}C$ REACTION

$^{12}C+^{12}C \rightarrow {}^{20}Ne + \alpha\ (+\gamma)\ (Q = 4.62\ MeV)$

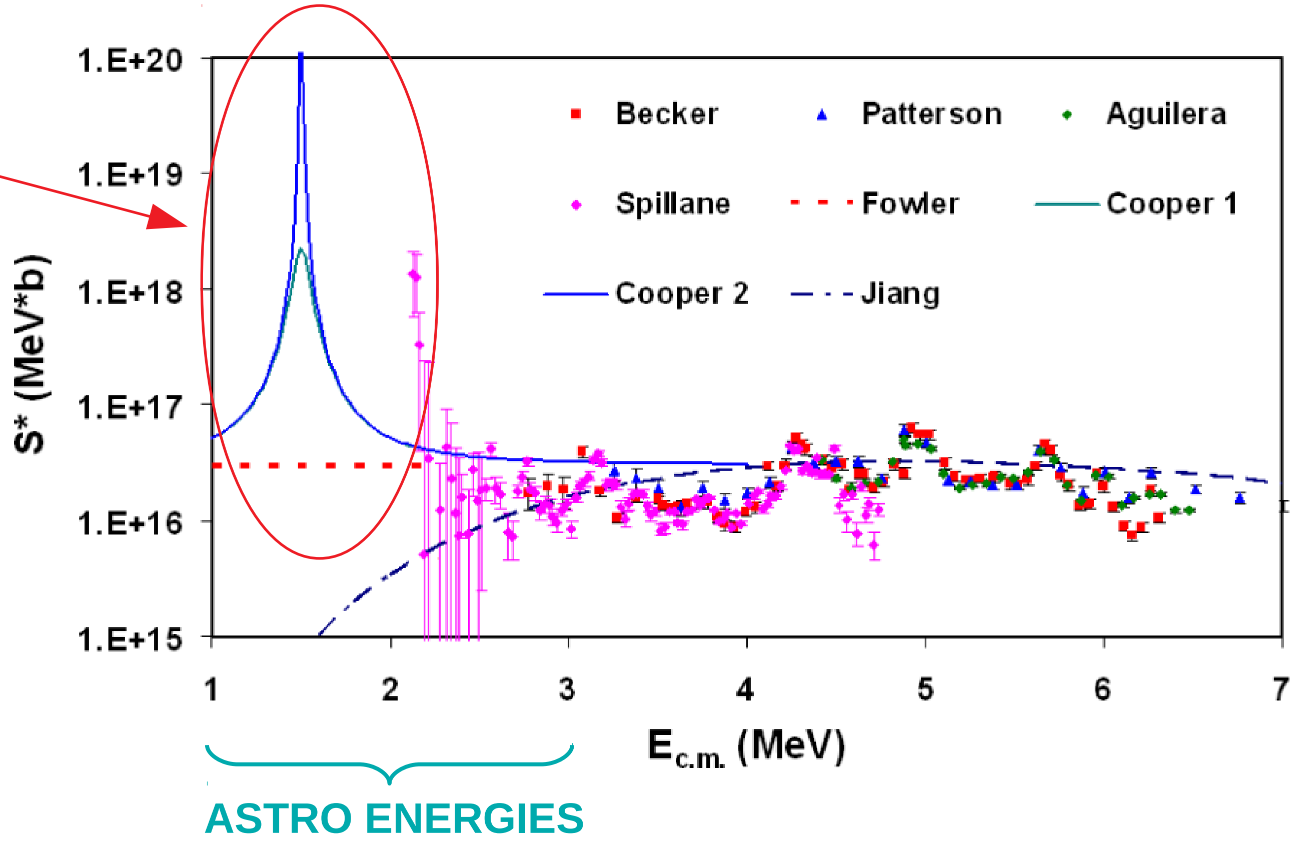
$\rightarrow {}^{23}Na + p\ (+\gamma)\ (Q = 2.24\ MeV)$

Main exit channels

Experiments are performed detecting charged particles and/or gamma rays

IS THERE A LOW-ENERGY RESONANCE?

If so, M_{UP} may decrease by 2 solar masses!



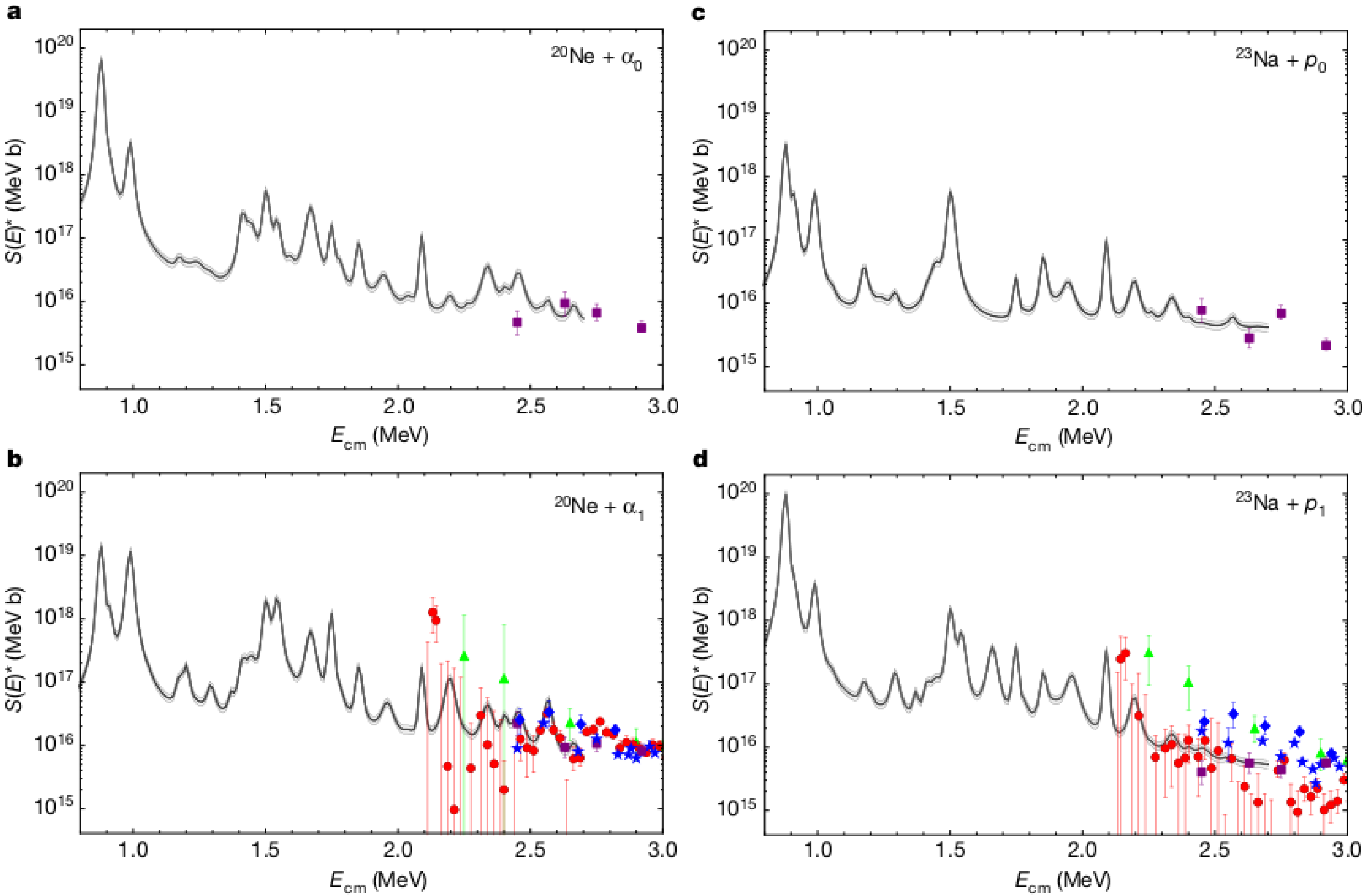
PREPARATORY WORK: THE $^{12}C+^{12}C$ REACTION

$$^{12}C+^{12}C \rightarrow {}^{20}Ne + \alpha\ (+\gamma)\ (Q = 4.62\ MeV)$$
$$\rightarrow {}^{23}Na + p\ (+\gamma)\ (Q = 2.24\ MeV)$$

Main exit channels

Experiments are performed detecting charged particles and/or gamma rays

A. Tumino et al. Nature 557, 687 (2018)



PREPARATORY WORK: THE $^{12}C+^{12}C$ REACTION

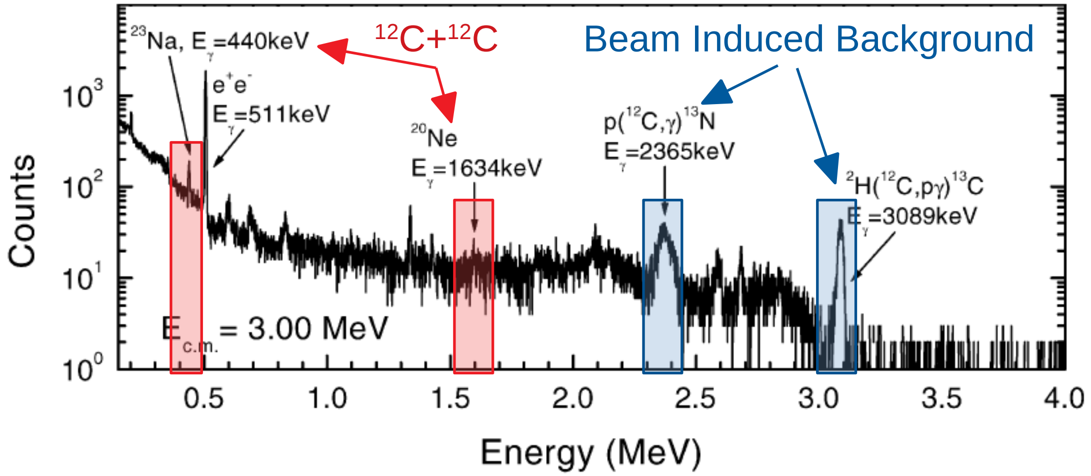
Beam induced background due to ^{1}**H** and ^{2}**H** was a strong limitation in previous measurements

Gamma ray experiments

Background sources:

$^{2}H(^{12}C,p\gamma)^{13}C$ ($E\gamma$ = 3.09 MeV)

$^{1}H(^{12}C,\gamma)^{13}N$ ($E\gamma$ = 2.36 MeV)

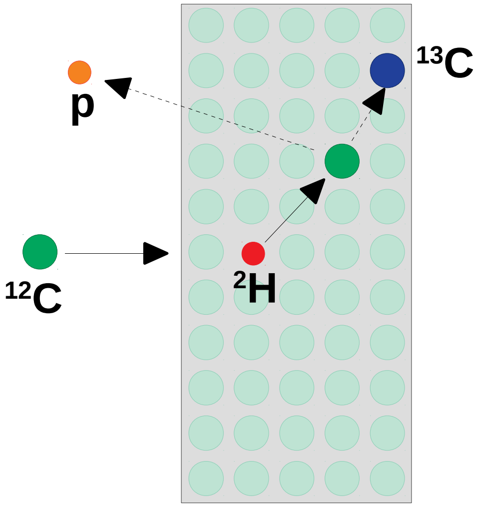


L. Barrón-Palos et al. Nucl. Phys. A 779, 318 (2006)

Charged particles experiments

Background source:

$^{2}H(^{12}C,^{12}C)^{2}H + ^{2}H(^{12}C,p\gamma)^{13}C$



THE HEAT EXPERIMENT @ LEGNARO NATIONAL LAB. (**H**YDROGEN D**E**SORPTION FROM C**A**RBON **T**ARGETS)

1) Determine initial H content through **ion beam analysis** on fresh samples

2) Perform hydrogen **desorption** heating the samples up to different maximum temperatures and with a controlled temperature gradient

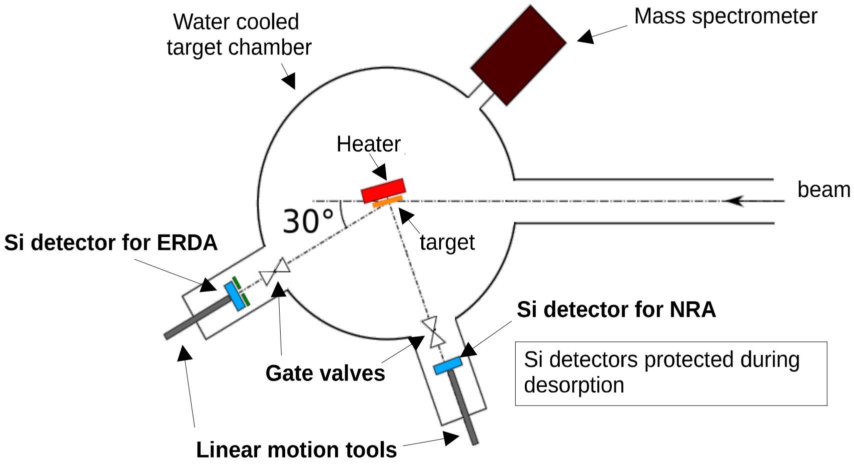
3) Establish effectiveness of the desorption procedure performing **ion beam analysis** of samples after desorption

Ion beam analysis will be performed with two independent approaches:

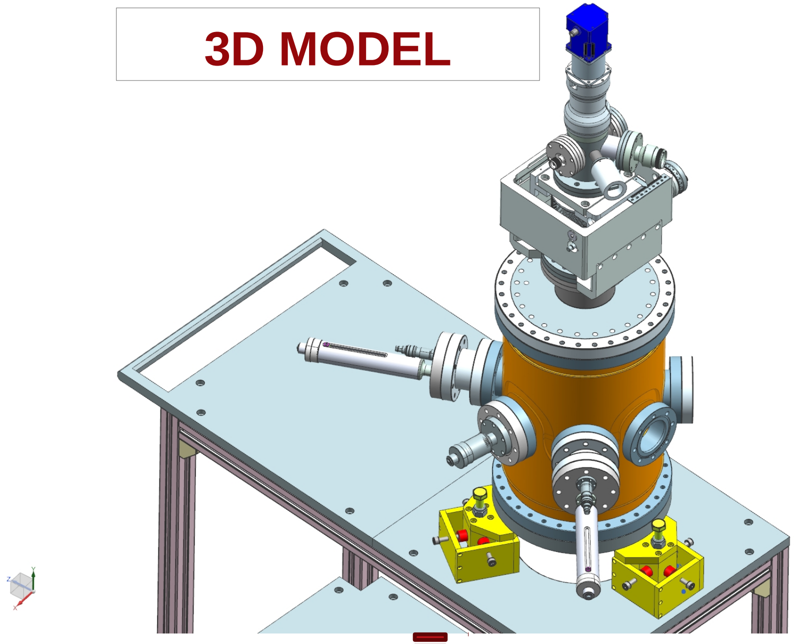
- Nuclear Reaction Analysis (NRA): deuterium profile as a function of the depth exploiting $^{2}H(^{3}He,p)^{4}He$ reaction

- Elastic Recoil Detection Analysis (ERDA): detection of hydrogen scattered by ^{4}He beam (sensitive to sample surface)

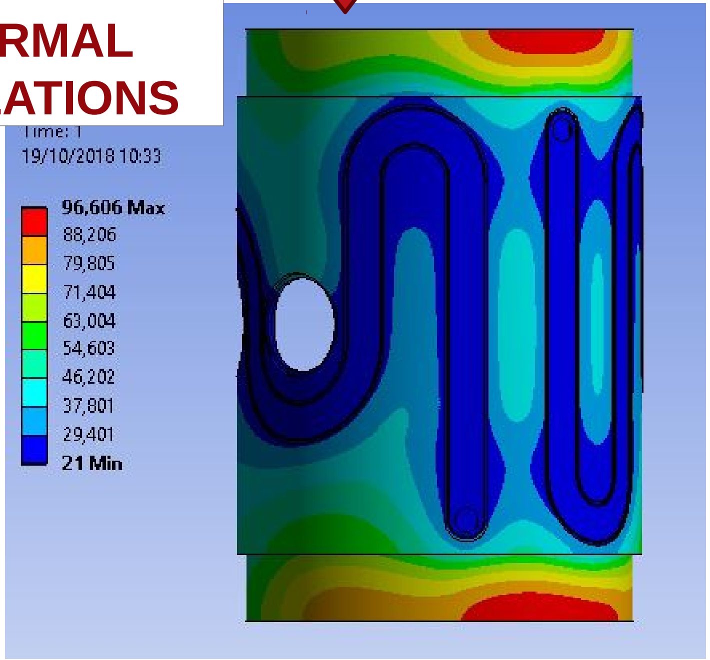
INITIAL IDEA



3D MODEL



THERMAL SIMULATIONS



REAL-LIFE CHAMBER (now at AN2000 accelerator)

"Laboratory Nuclear Astrophysics is often a frustrating science. The desired cross sections are among the smallest measured in the nuclear laboratory, often requiring long data-collection times with painstaking attention to background. From a purely nuclear point of view, the reactions studied are often of comparatively little interest. It is their application to astrophysics that provides the major intellectual motivation. However, on many occasions evaluation of the collected data has provided unexpected intellectual rewards in nuclear physics itself. The grand concept of elemental nucleosynthesis will not be truly established until we attain a deeper and more precise understanding of the many nuclear processes operating in astrophysical environments."

C.E. Rolfs and W.S. Rodney, Cauldrons in the Cosmos

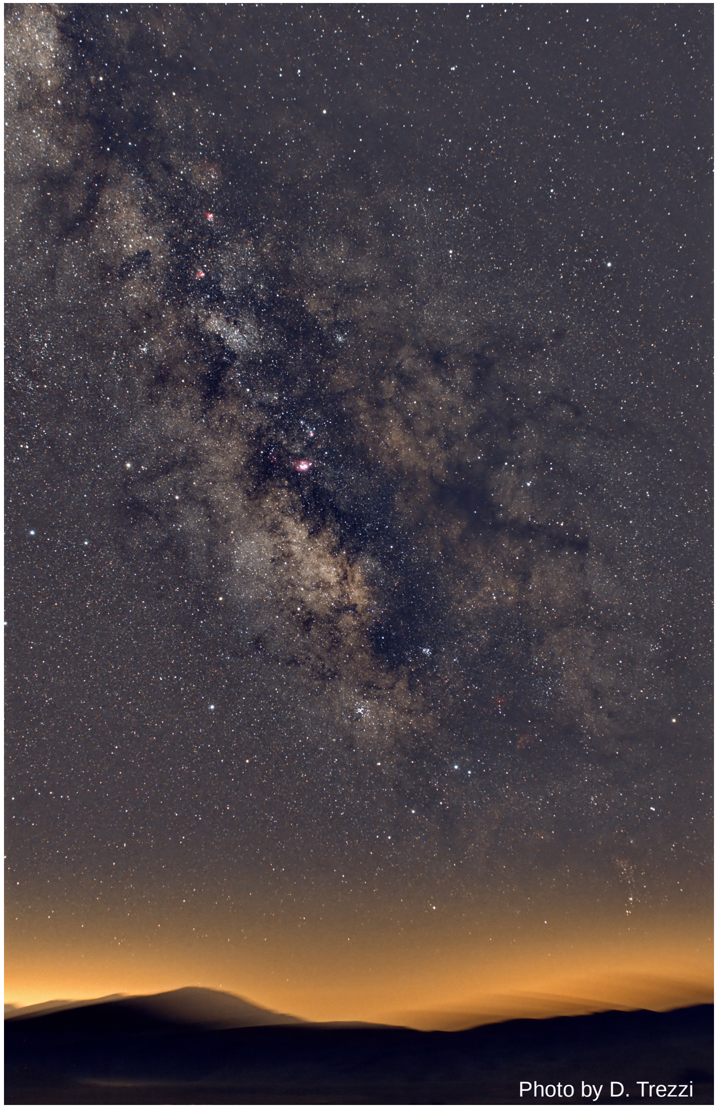


Photo by D. Trezzi

THANK YOU!

The LUNA collaboration

A. Boeltzig, L. Csedreki, L. Di Paolo, A. Formicola, I. Kochanek, M. Junker | **INFN LNGS /*GSSI, Italy**
C. Broggini, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti | **Università di Padova and INFN Padova, Italy**
C. Gustavino | **INFN Roma 1, Italy**
D. Bemmerer, K. Stöckel | **HZDR Dresden, Germany**
G.F. Ciani, Z. Elekes, Zs. Fülöp, Gy. Gyürky, T. Szücs | **MTA-ATOMKI Debrecen, Hungary**
M. Lugaro | **Konkoly Observatory, Hungarian Academy of Sciences, Budapest, Hungary**
O. Straniero | **INAF Osservatorio Astronomico di Collurania, Teramo, Italy**
P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli | **Università di Genova and INFN Genova, Italy**
A. Guglielmetti, E. Masha | **Università di Milano and INFN Milano, Italy**
J. Balibrea, A. Best, A. Di Leva, G. Imbriani | **Università di Napoli and INFN Napoli, Italy**
F. Cavanna, G. Gervino, P. Colombetti | **Università di Torino and INFN Torino, Italy**
M. Aliotta, C. Bruno, T. Chillery, T. Davinson | **University of Edinburgh, United Kingdom**
F. Barile, G. D'Erasmo, E.M. Fiore, V. Mossa, F. Pantaleo, V. Paticchio, R. Perrino,
L. Schiavulli | **Università di Bari and INFN Bari, Italy**
R. Perrino **| INFN Lecce, Italy**