Recent results from LUNA

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for the LUNA Collaboration
Università degli Studi di Milano and INFN Milano

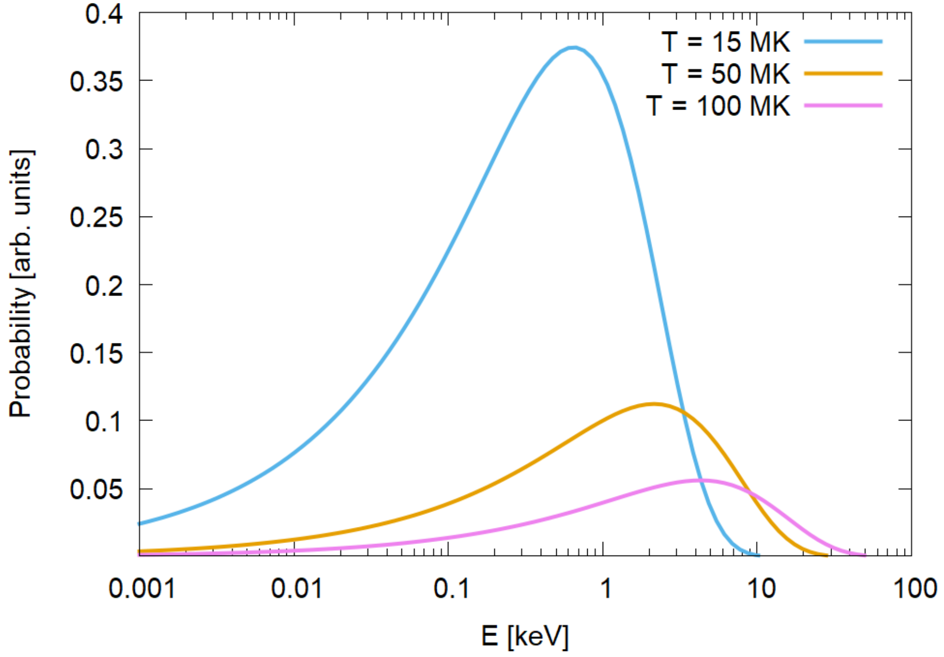
CHARGED-PARTICLE-INDUCED REACTIONS RATES AT ASTROPHYSICAL ENERGIES

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

CROSS SECTION

RELATIVE VELOCITY

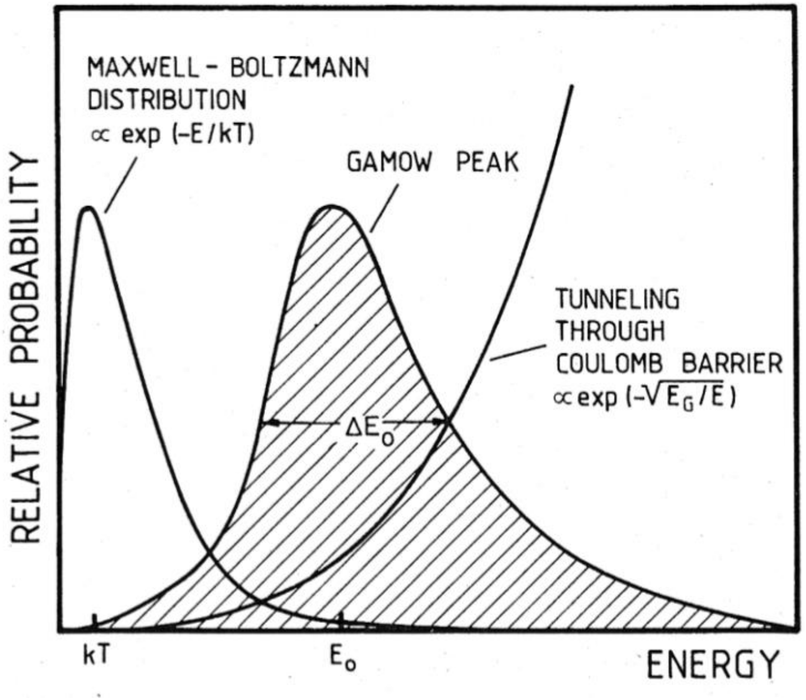
MAXWELL BOLTZMANN DISTRIBUTION **vs** **COULOMB REPULSION**



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

CHARGED-PARTICLE-INDUCED REACTIONS RATES AT ASTROPHYSICAL ENERGIES

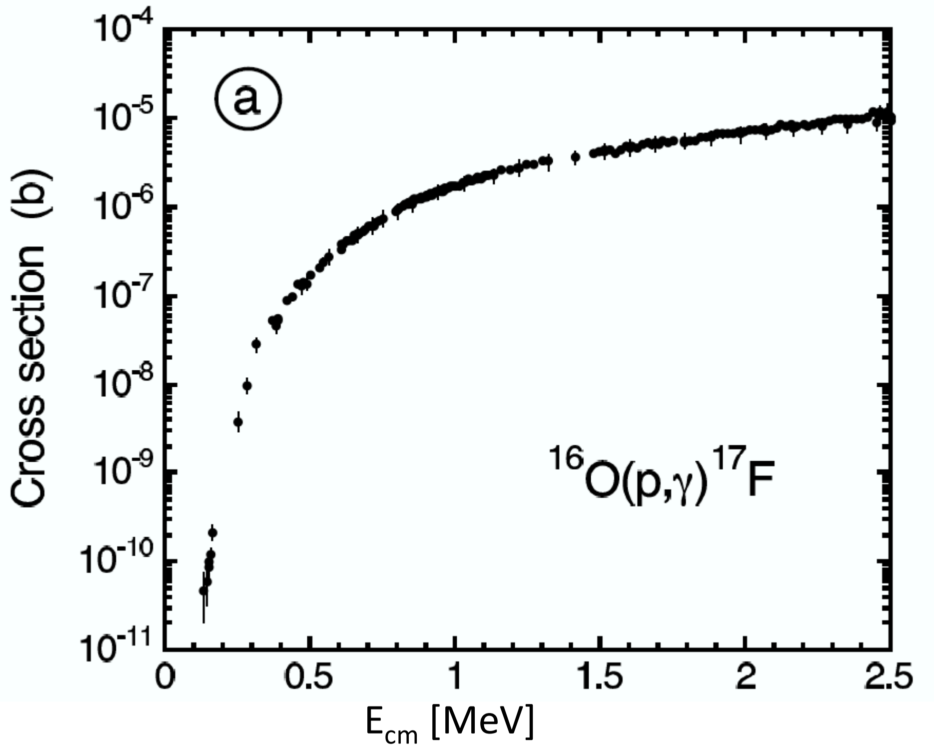
Rolfs, Rodney, Cauldrons in the Cosmos (1988)



→ Nuclear reactions occur at energies far below the Coulomb barrier (quantum-mechanical tunnel)

→ Cross sections are strongly energy-dependent

→ **In the Gamow peak, the cross section can be extremely small**



Iliadis, Nuclear physics of stars (2007)

CHARGED-PARTICLE-INDUCED REACTIONS IN THE LAB

Counting rate in lab = $N_{PROJECTILES}/t$ x $N_{TARGETS}/A$ x **cross section** x **detection efficiency**

- $N_{PROJECTILES}/t$ → 10^{15} pps (I ~ 100 μA)
- $N_{TARGETS}/A$ → 10^{18} atoms/cm^2
- cross section → 10^{-36} cm^2 (1 pb)
- detection efficiency → 1% - 100%

C = 0.03 – 3 counts/hour

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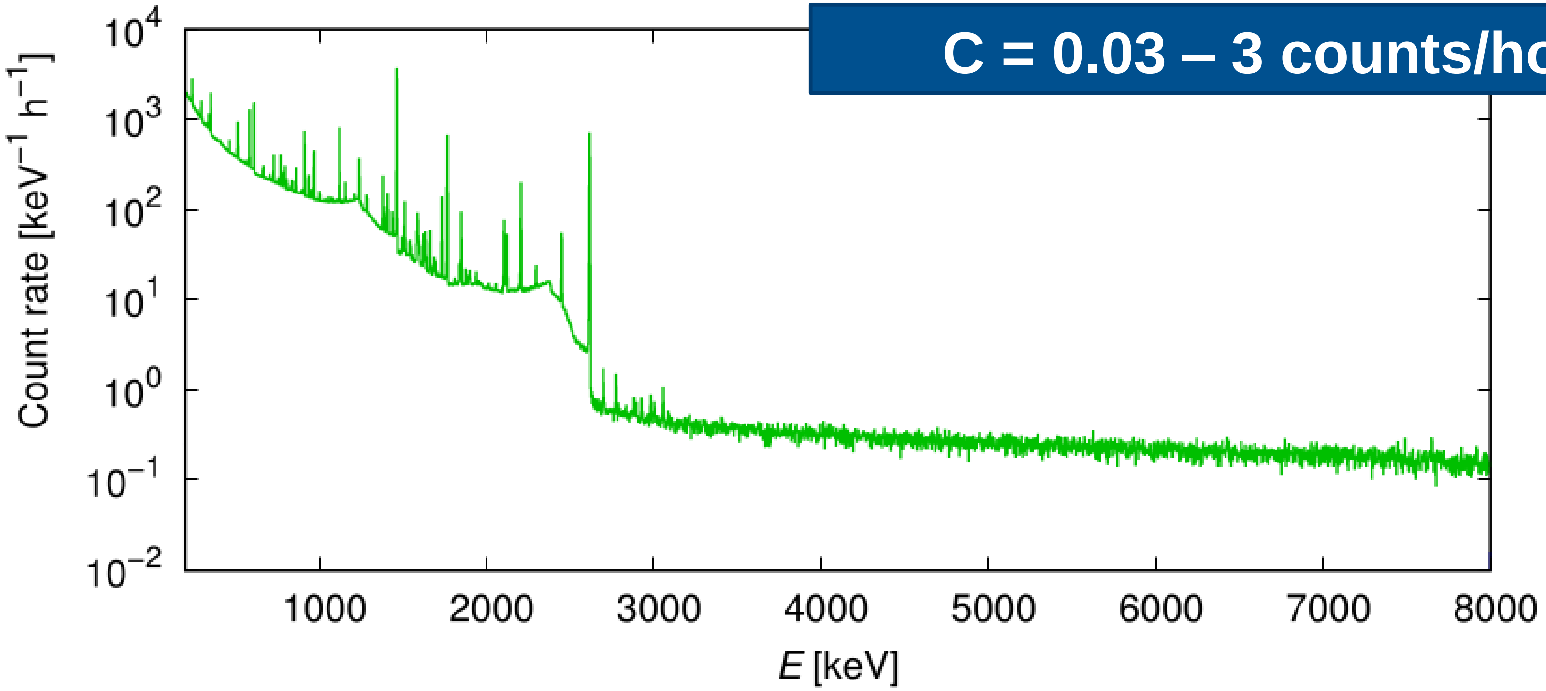

Typical environmental background in HPGe detector

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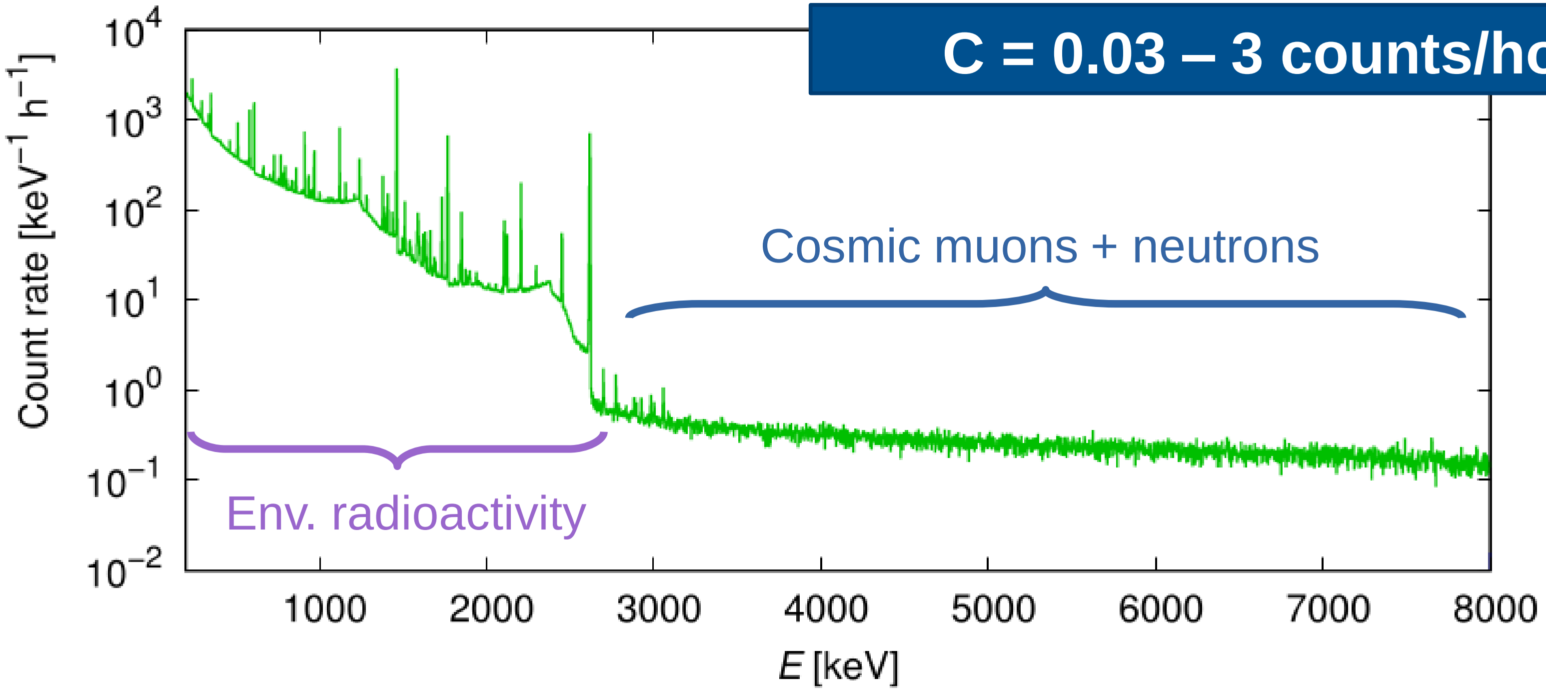
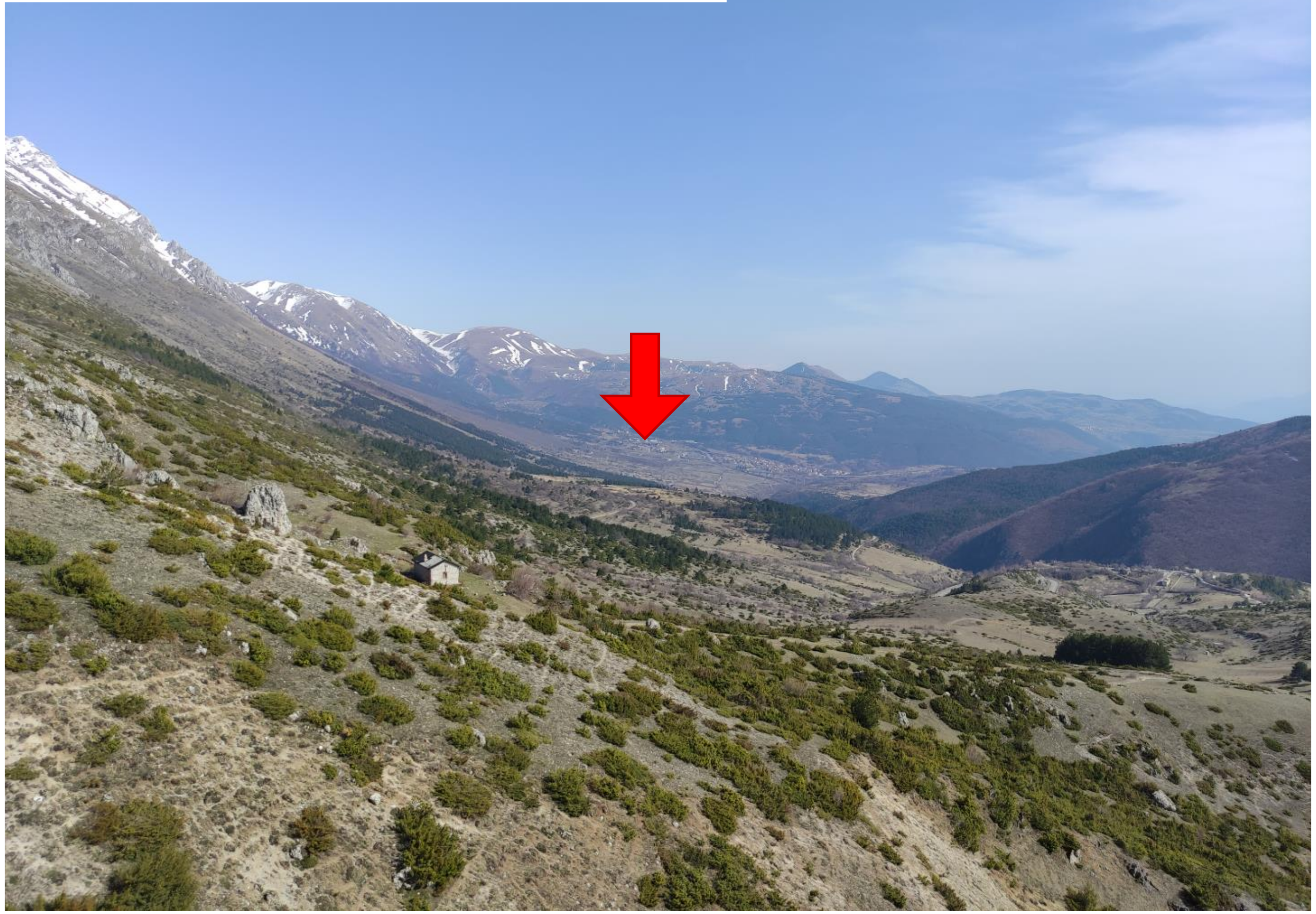


Typical environmental background in HPGe detector

THE LABORATORY FOR UNDERGROUND NUCLEAR ASTROPHYSICS

Laboratori Nazionali del Gran Sasso



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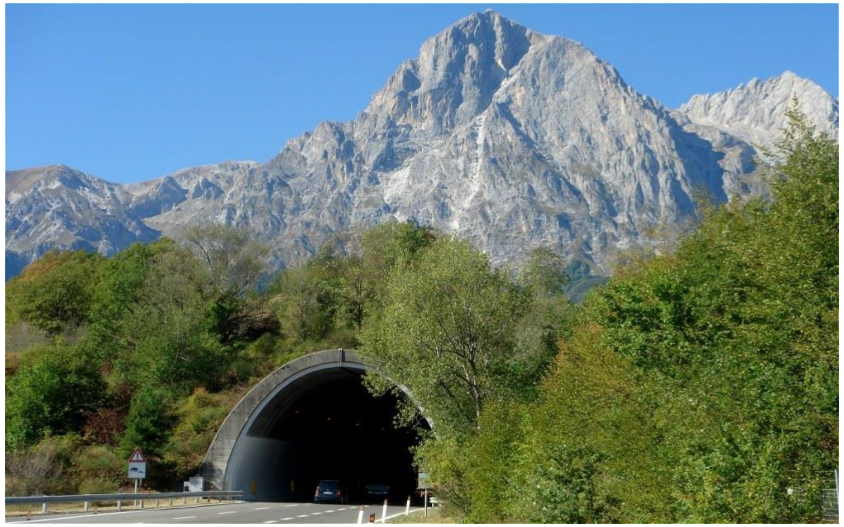
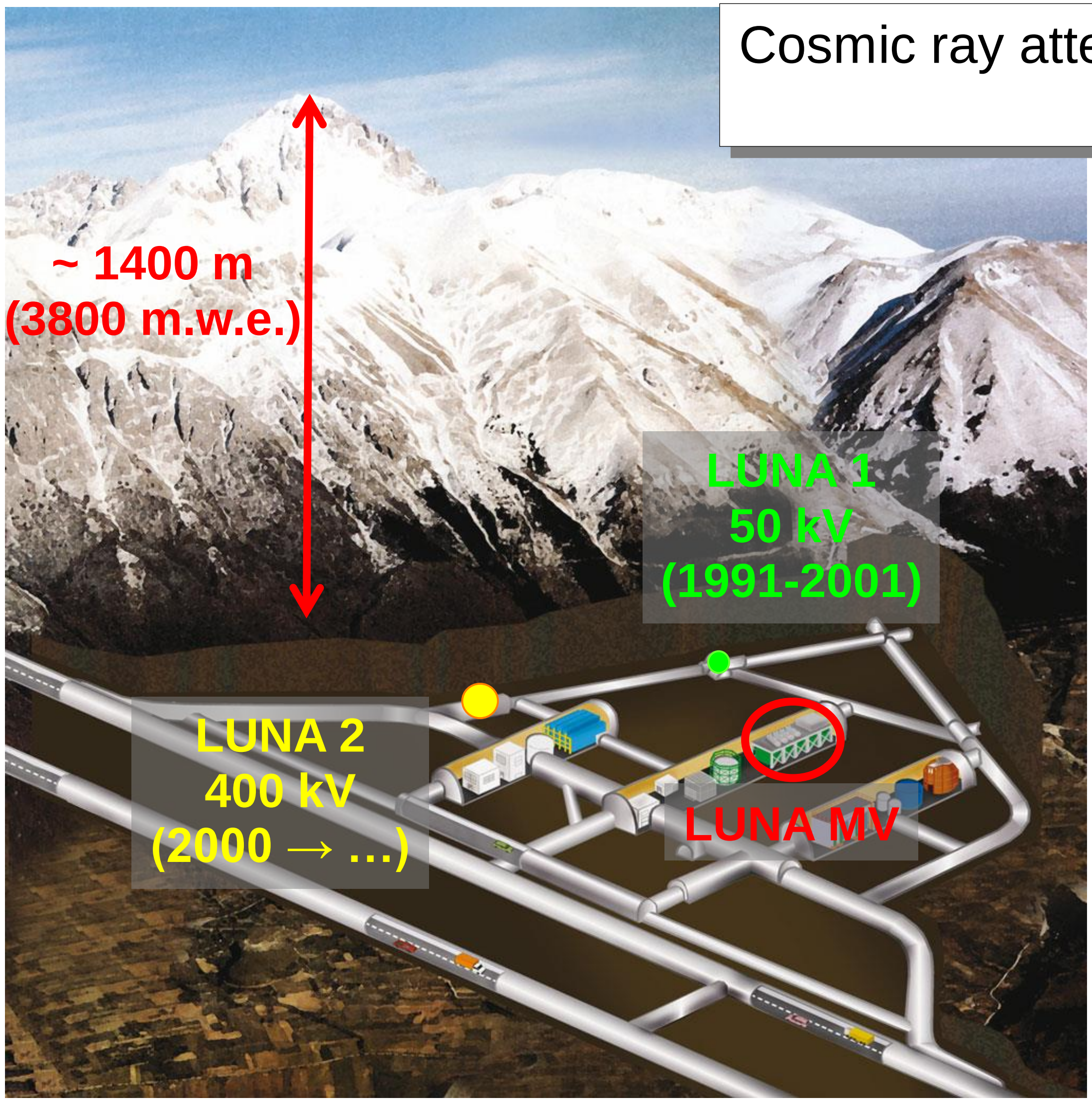
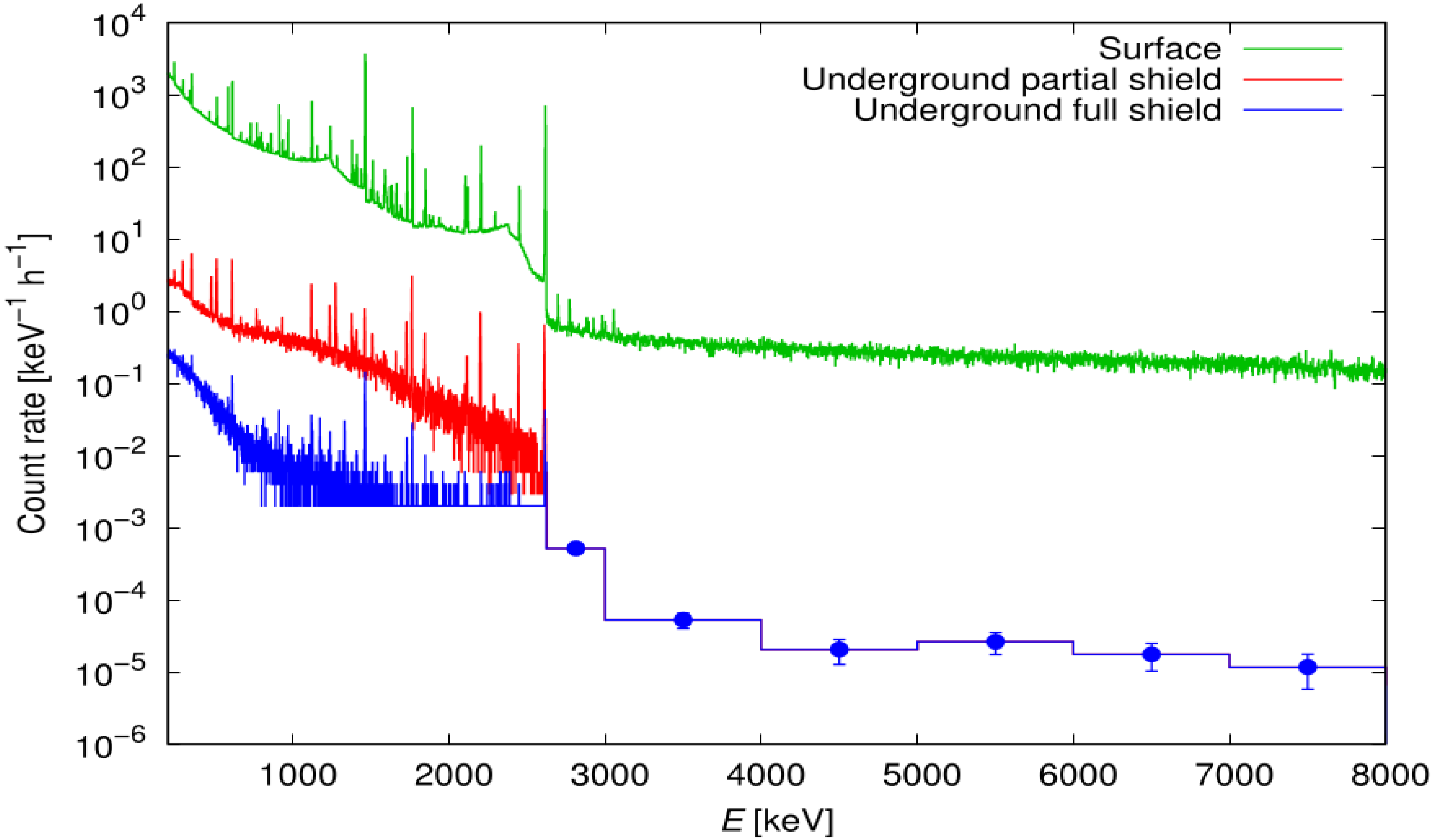


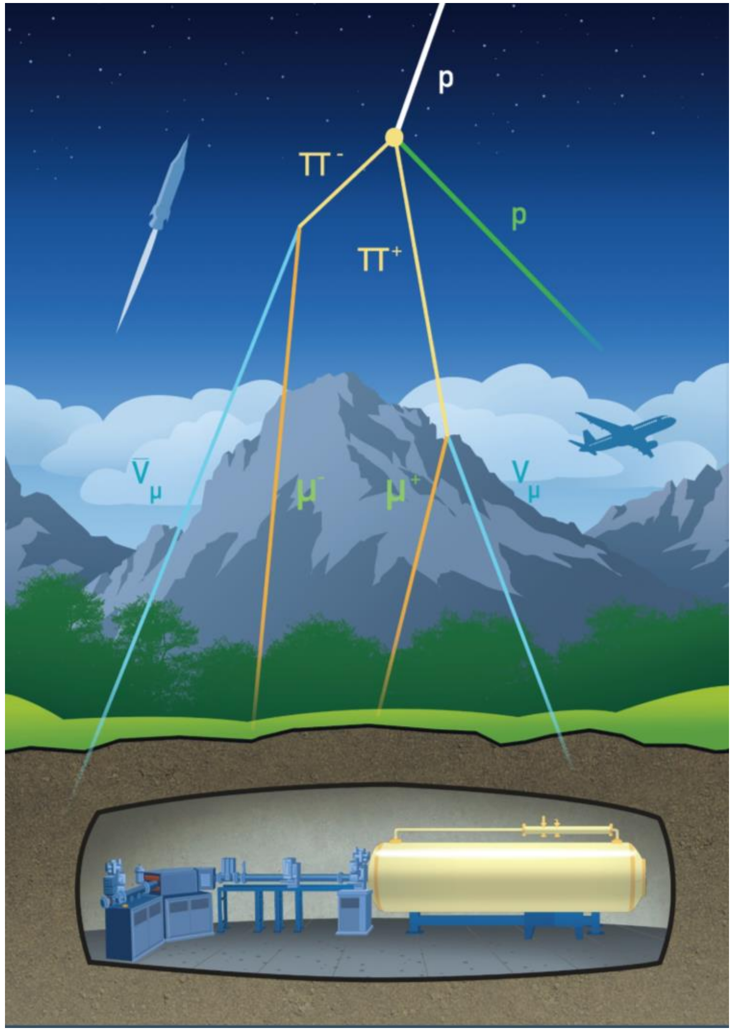


Cosmic ray attenuation: $\mu \rightarrow 10^{-6}$
$n \rightarrow 10^{-3}$

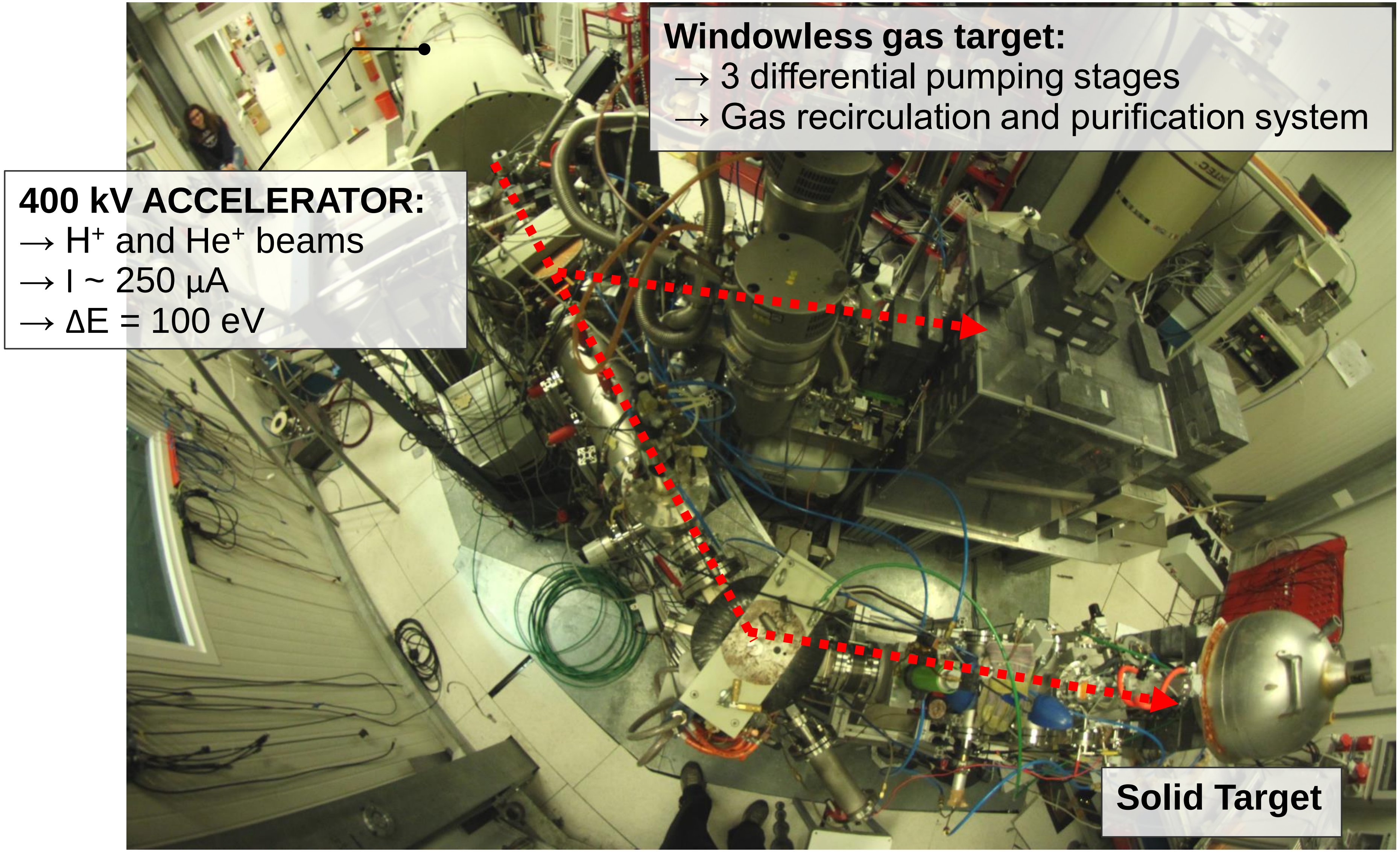
THE LABORATORY FOR UNDERGROUND NUCLEAR ASTROPHYSICS



+ More effective passive shielding

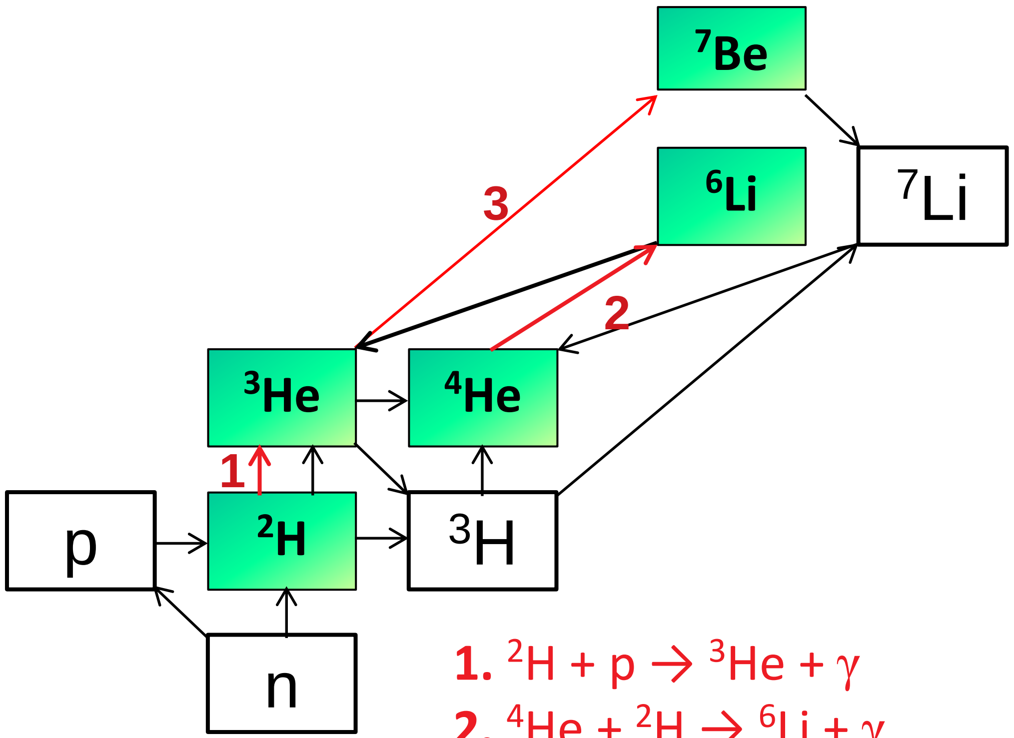


THE LUNA – 400 kV SETUP



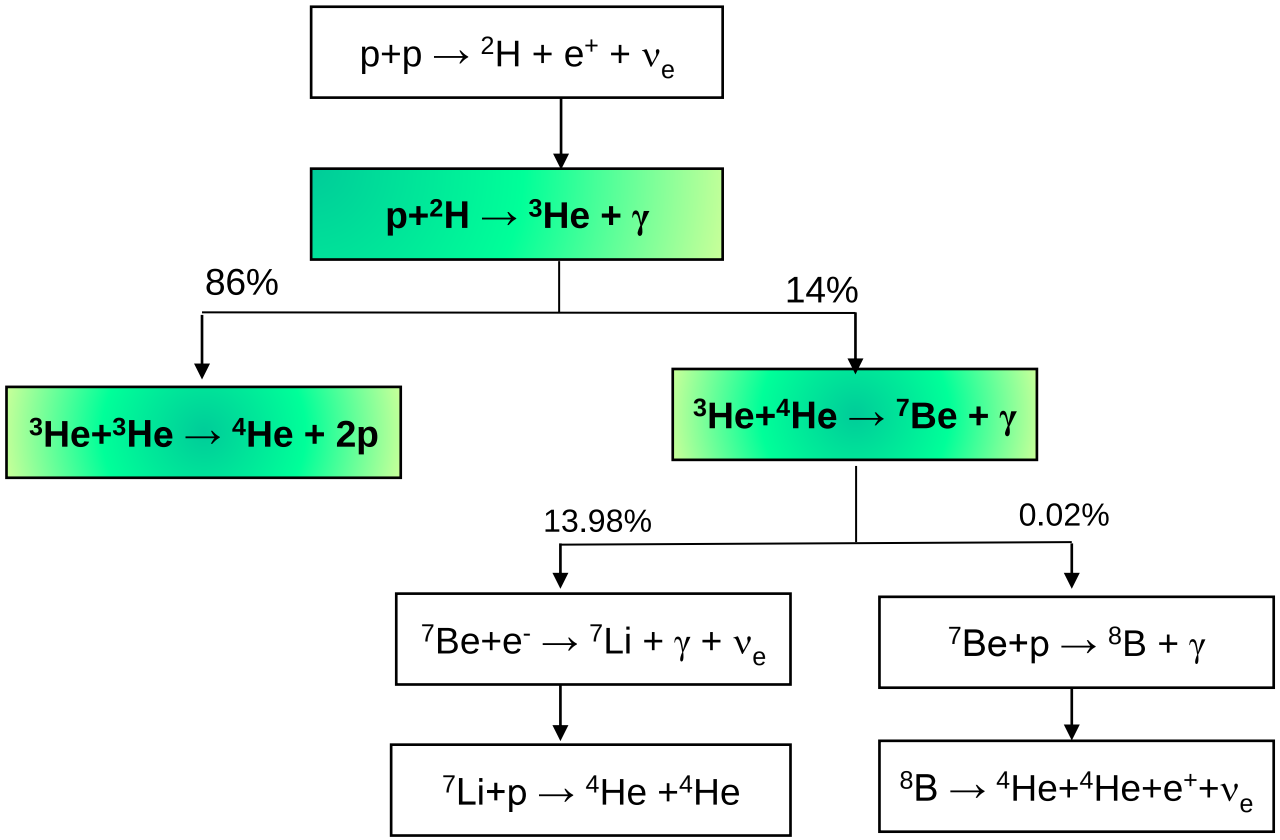
REACTIONS STUDIED SINCE 1991

Big Bang Nucleosynthesis



1. $^2H + p \rightarrow {}^3He + \gamma$
2. $^4He + {}^2H \rightarrow {}^6Li + \gamma$
3. $^3He + {}^4He \rightarrow {}^7Be + \gamma$

pp chain



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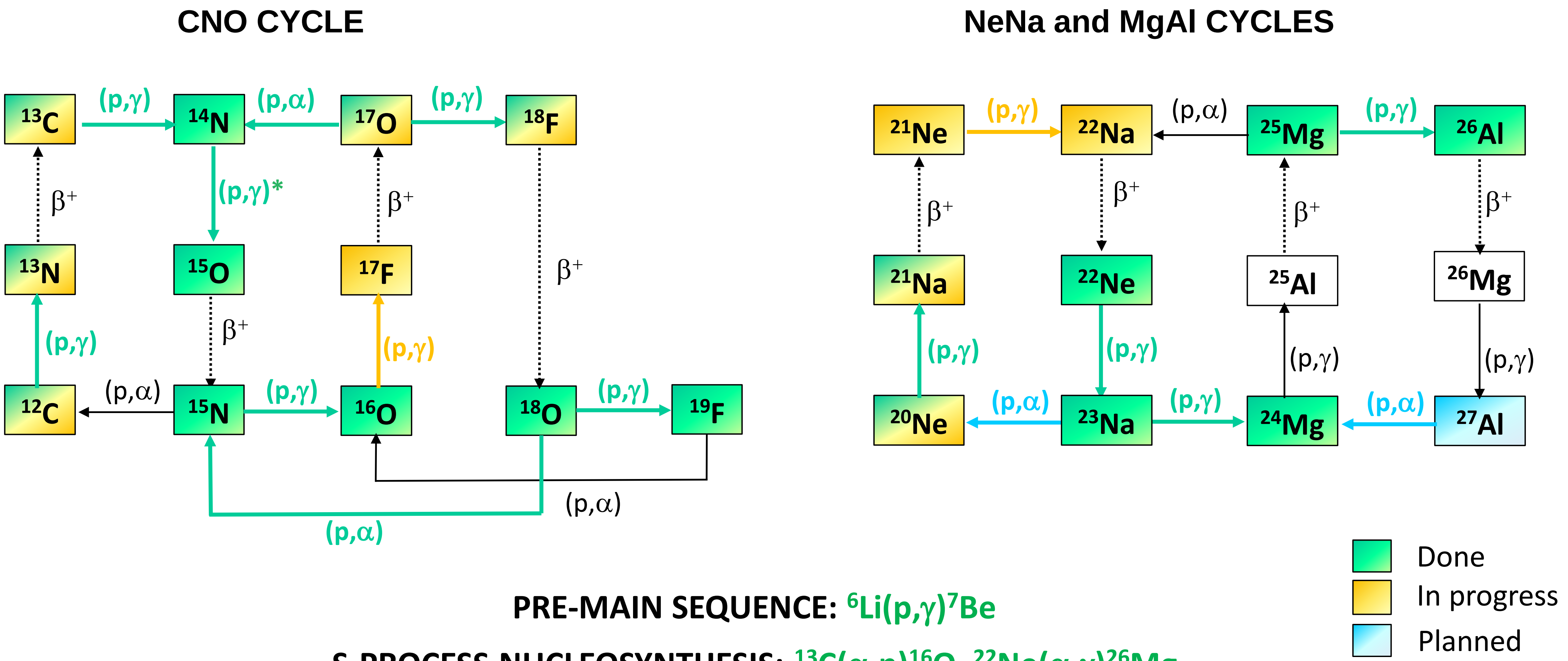


PRE-MAIN SEQUENCE: ^{6}Li(p,γ)^{7}Be

S-PROCESS NUCLEOSYNTHESIS: ^{13}C(α,n)^{16}O, ^{22}Ne(α,γ)^{26}Mg

BIG BANG NUCLEOSYNTHESIS: THE $^{2}H(p,\gamma)^{3}He$ REACTION

THE $^2H(p,\gamma)^3He$ REACTION: ASTROPHYSICAL RELEVANCE

PRIMORDIAL ABUNDANCE OF ^{2}H:

- Direct measurements: observation of absorption lines in DLA system

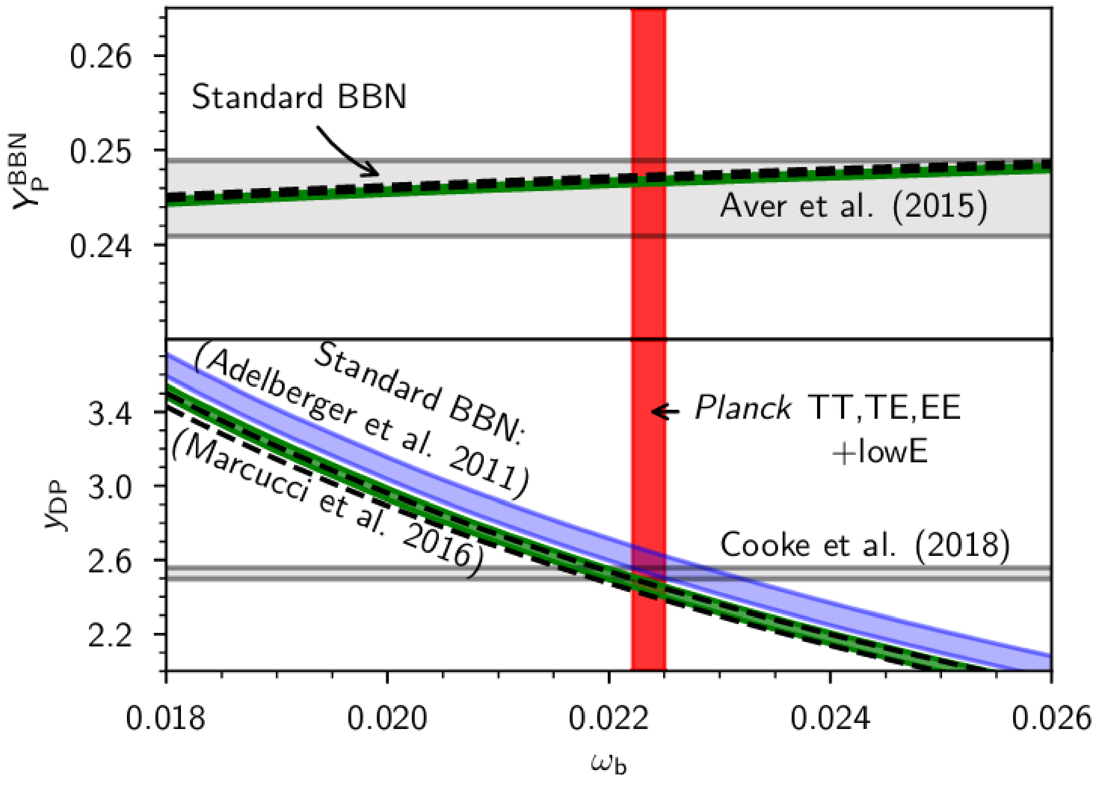
$$\left[\frac{D}{H}\right]_{OBS} = (2.527 \pm 0.030) \cdot 10^{-5}$$

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

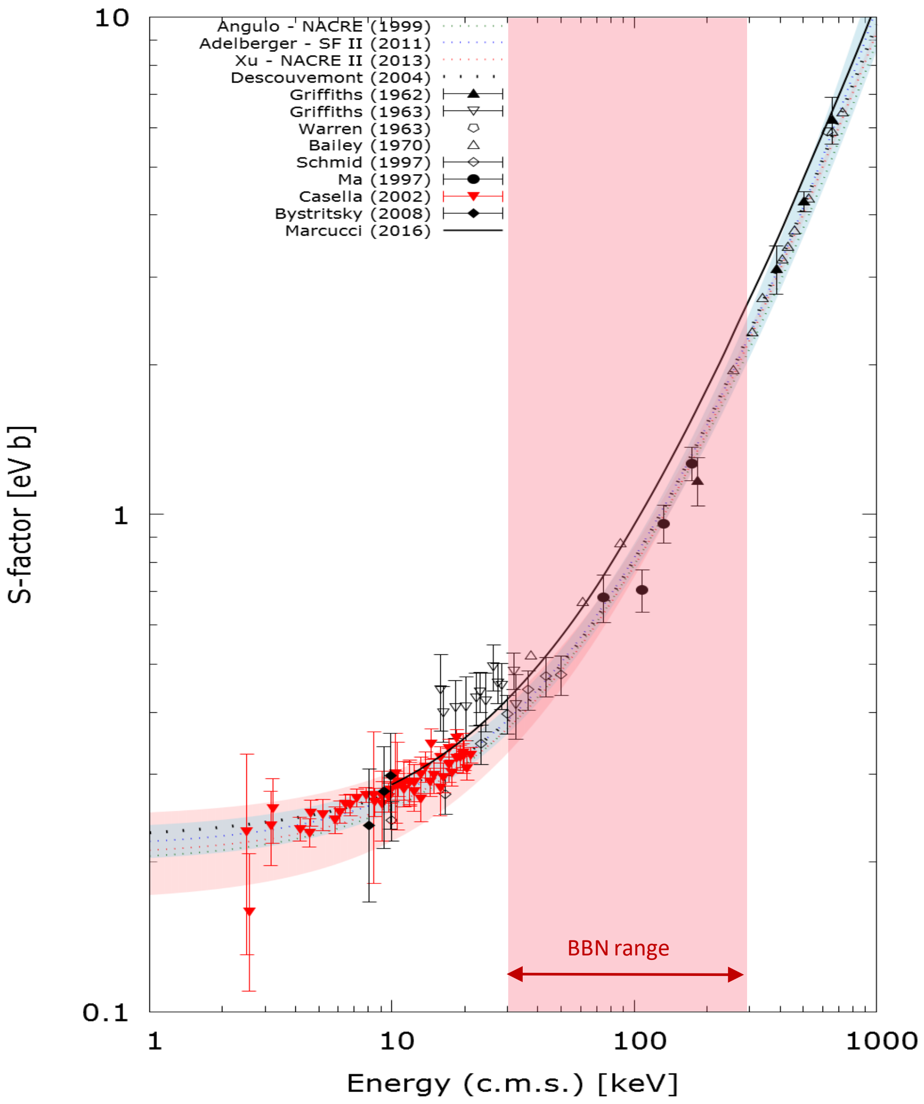
$$\left[\frac{D}{H}\right]_{BBN} = \begin{matrix}(2.587 \pm 0.055) \cdot 10^{-5} \\ (2.439 \pm 0.052) \cdot 10^{-5}\end{matrix}$$

Plank 2018 results arXiv:1807.06209v1



The D/H predicted by BBN changes by 6% depending on the $^2H(p,\gamma)^3He$ cross section adopted

THE $^2H(p,\gamma)^3He$ REACTION: STATE OF THE ART



The cross section of the $^2H(p,\gamma)^3He$ reaction is the main source of uncertainty on the primordial ^2H abundance

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

→ Only few data points available at BBN energies

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

SEE TALK BY F. CAVANNA ON THURSDAY

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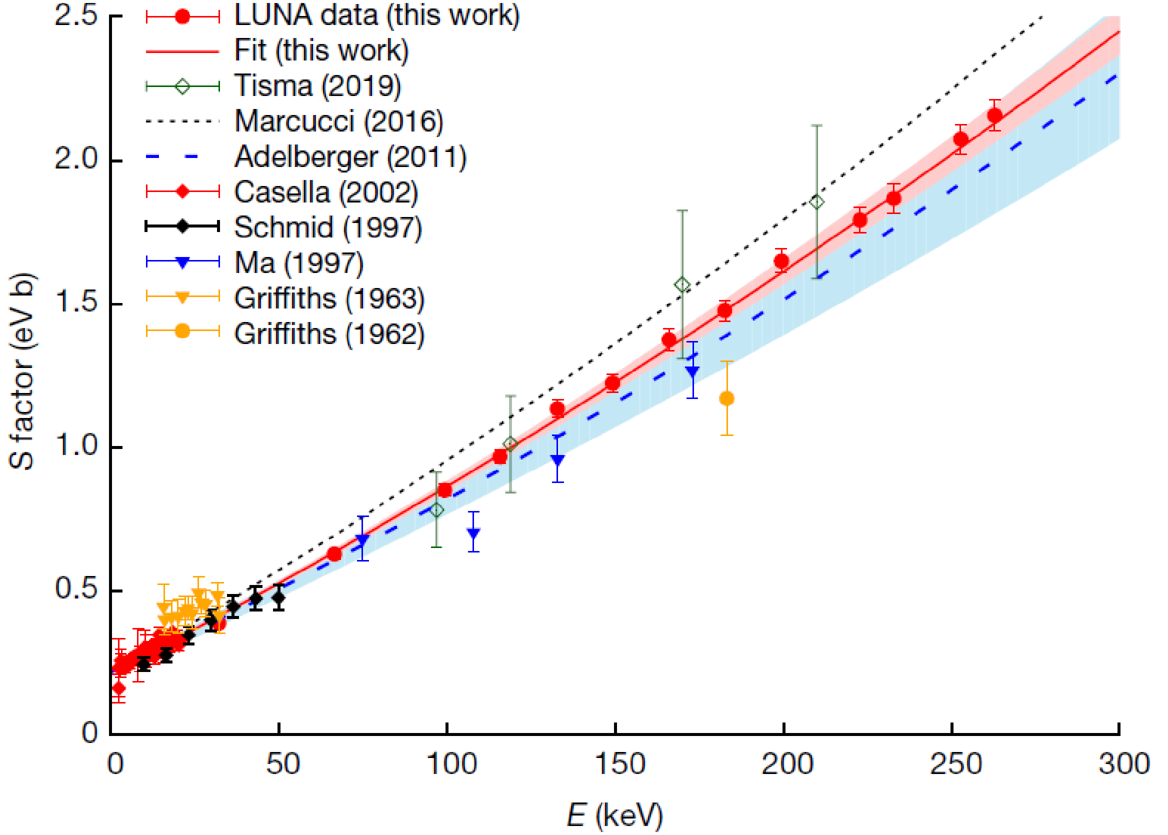
Article | Published: 11 November 2020

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

V. Mossa, K. Stöckel, […]S. Zavatarelli

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



Systematic uncertainty reduced to **< 3%**

HYDROGEN BURNING:

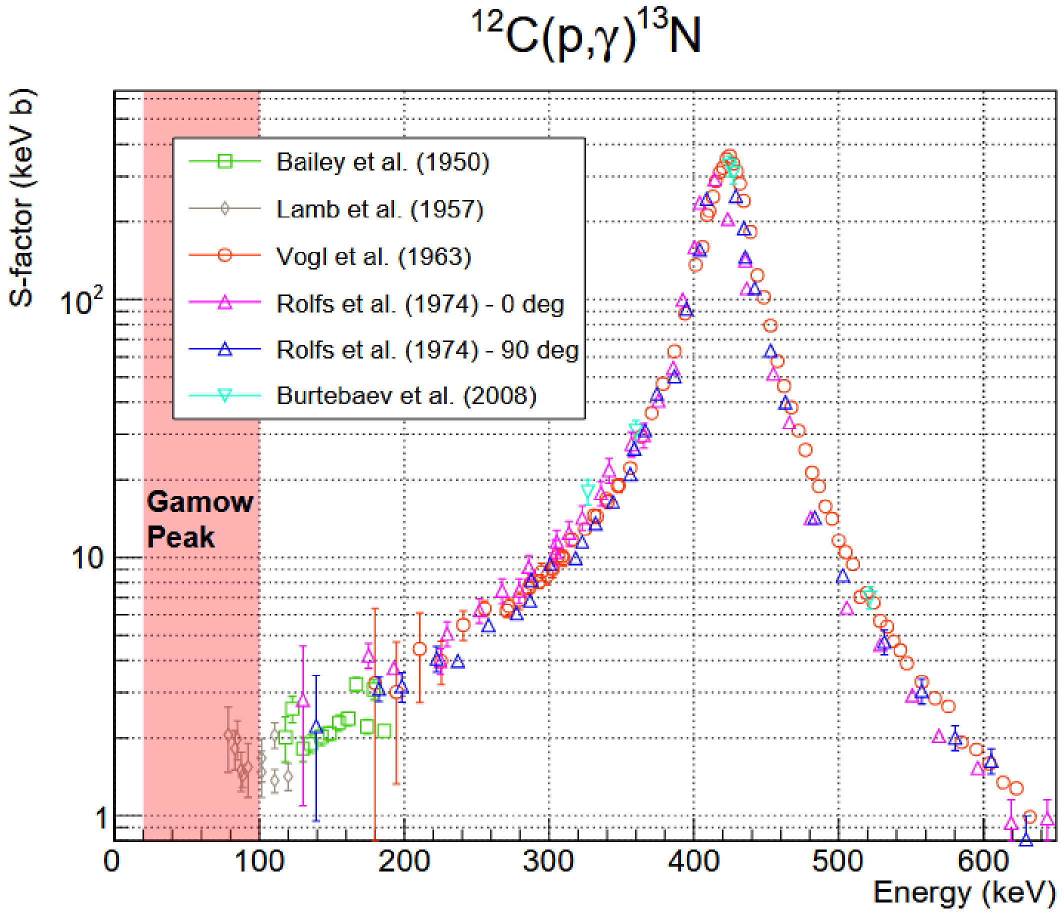
$^{6}Li(p,\gamma)^{7}Be$ -> **POSTER BY D. PIATTI**

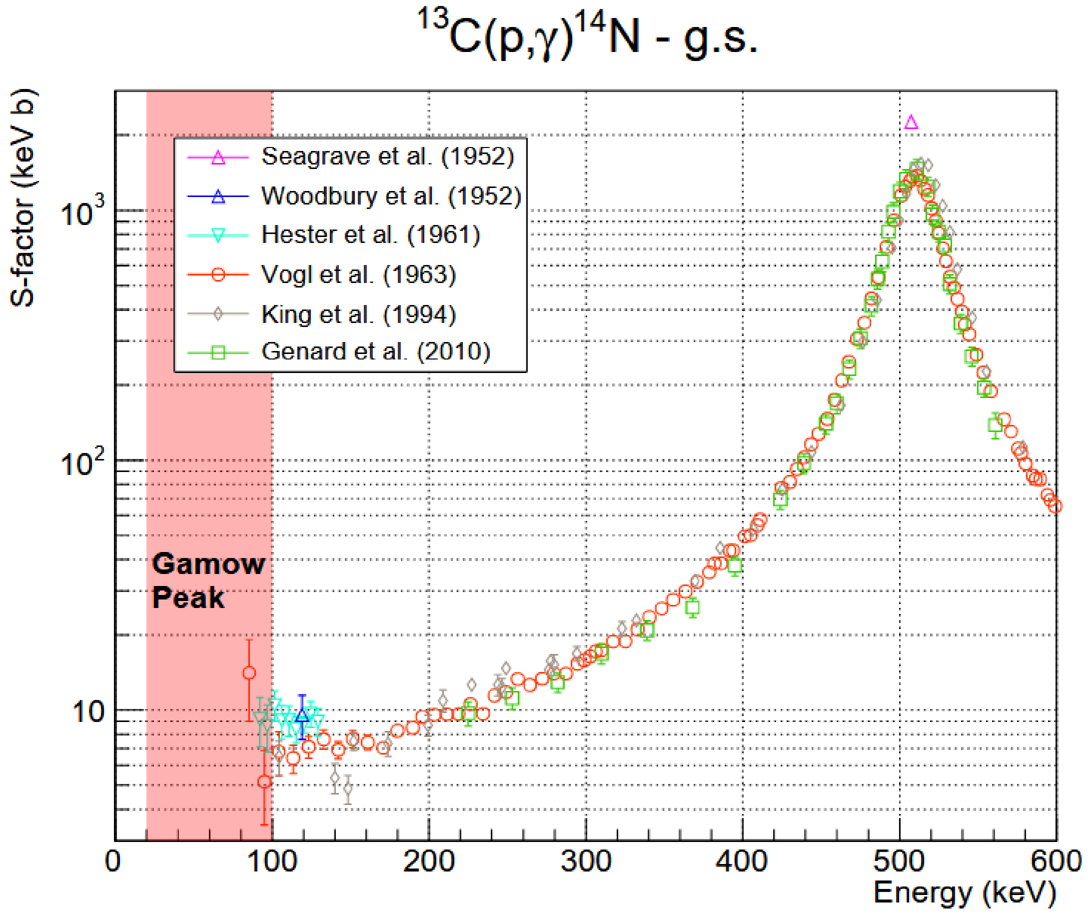
$^{17}O(p,\gamma)^{18}F$ -> **TALK BY D. PIATTI ON WEDNESDAY**

$^{20}Ne(p,\gamma)^{21}Na$ -> **TALK BY S. ZAVATARELLI ON THURSDAY**

$^{12}C(p,\gamma)^{13}N$ and $^{13}C(p,\gamma)^{14}N$ -> **POSTER BY A. BOELTZIG**

$^{12}C(p,\gamma)^{13}N$ and $^{13}C(p,\gamma)^{14}N$: STATE OF THE ART

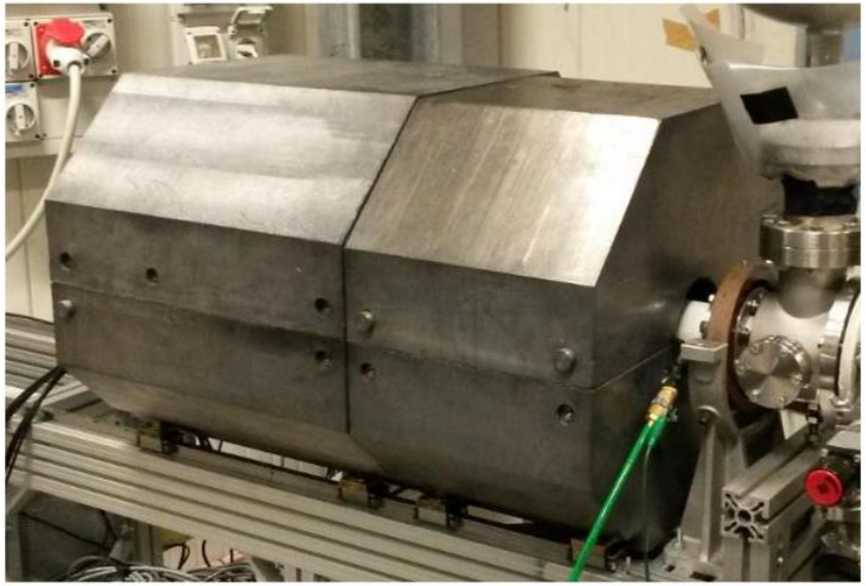


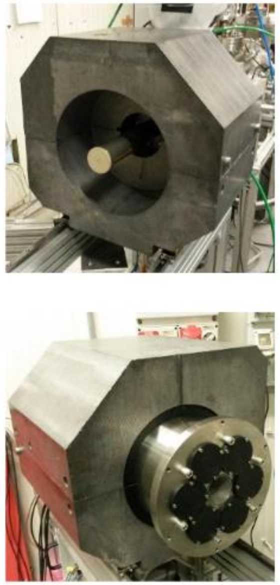


- Large scattering at low energies
- Large uncertainties
- $^{13}C(p,\gamma)^{14}N$ presents 5 minor transitions (~ 29% of total) but only one dataset studied them all

$^{12}C(p,\gamma)^{13}N$ and $^{13}C(p,\gamma)^{14}N$: SETUP AT LUNA

- Intense proton beam impinging on different targets (thin / infinitely thick; nat. abundance or ^{13}C enriched)
- different detection techniques
  - HPGe spectroscopy
  - Total Absorption Spectroscopy with 4π BGO
  - Activation, detecting 511 keV gammas from ^{13}N decay

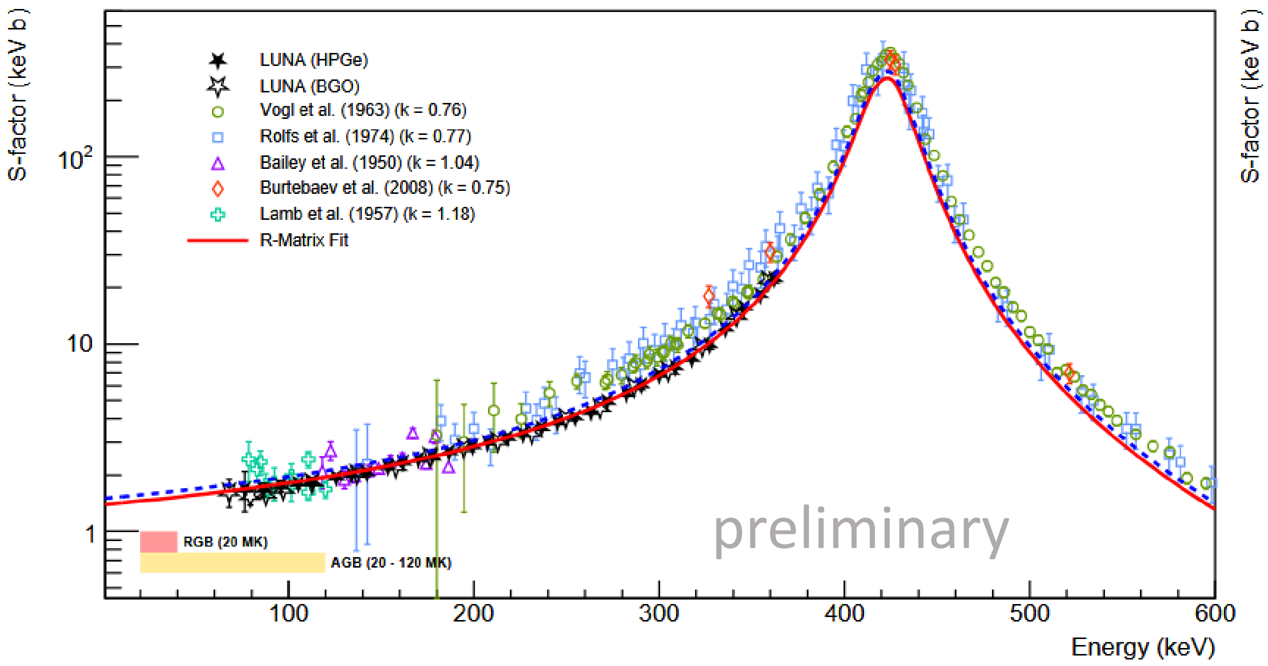




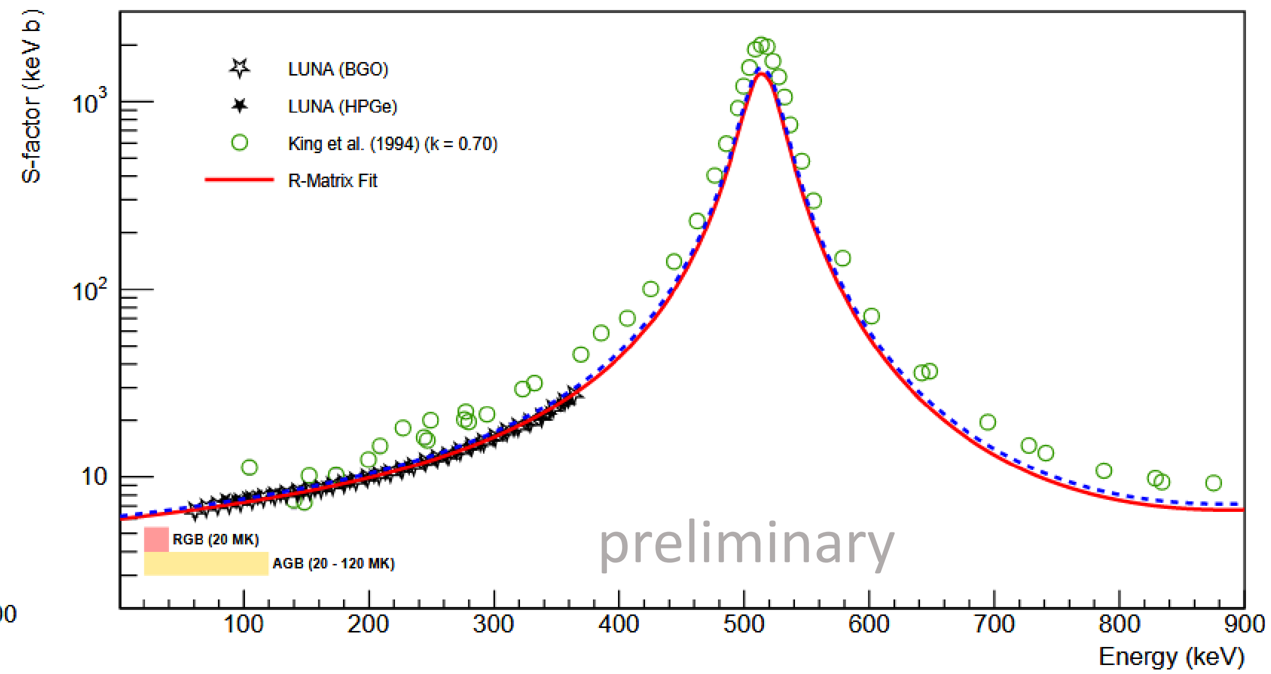
$^{12}C(p,\gamma)^{13}N$ and $^{13}C(p,\gamma)^{14}N$: RESULTS

SEE POSTER BY A. BOELZIG

$^{12}C(p,\gamma)^{13}N$

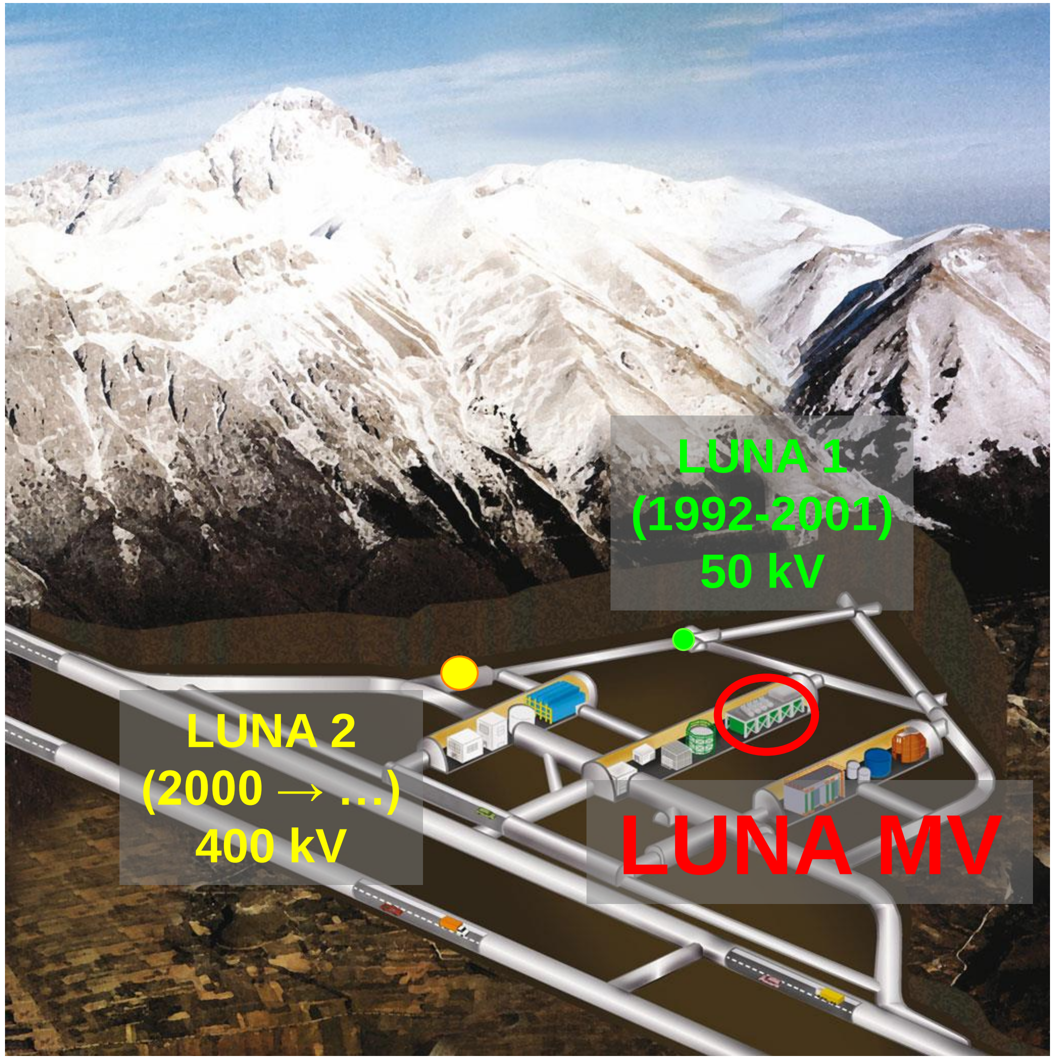


$^{13}C(p,\gamma)^{14}N$

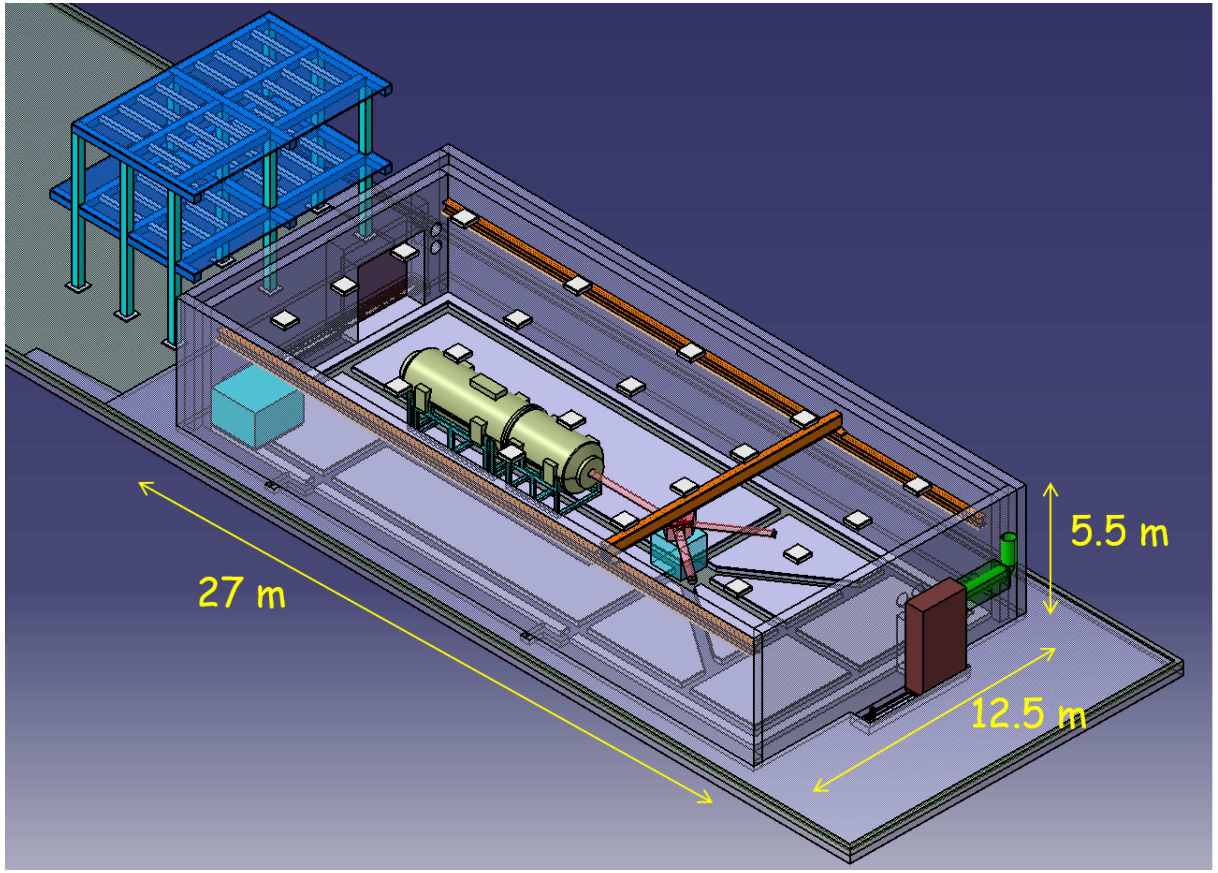


Systematic error (not plotted) ~7%

LUNA-MV



LUNA-MV



- **Inline Cockcroft Walton accelerator**
- **TERMINAL VOLTAGE: 0.2 – 3.5 MV**
- **Beam energy reproducibility:** 0.01% TV or 50V
- **Beam energy stability:** 0.001% TV / h
- **Beam current stability:** < 5% / h

H^+ beam: 500 - 1000 eμA

He^+ beam: 300 - 500 eμA

C^+ beam: 100 - 150 eμA

C^{++} beam: 100 eμA

A. Sen et al. NIM B 450 (2019) 390 - 395

80-cm thick concrete shielding around accelerator room, to reduce the neutron flux just outside the building.

LUNA-MV SCIENTIFIC PROGRAM

$^{14}N(p,\gamma)^{15}O$: bottleneck reaction of the CNO cycle. Also commissioning measurement for the LUNA MV facility

$^{13}C(\alpha,n)^{16}O$ and **$^{22}Ne(\alpha,n)^{25}Mg$:** neutron sources for the s-process (nucleosynthesis beyond Fe)

$^{12}C+^{12}C$: energy production and nucleosynthesis in Carbon burning. Global chemical evolution of the Universe

LUNA-MV

Acceptance tests in September 2022
First experiment in 2023

THANK YOU!

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