Prospects of present and future underground labs for nuclear astrophysics

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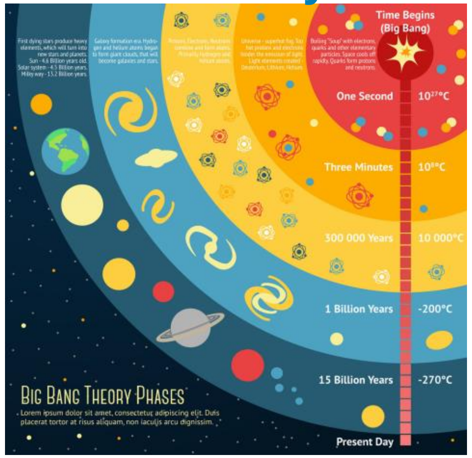
for the LUNA Collaboration

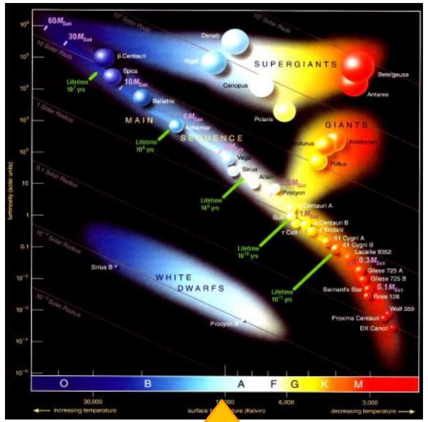
Università degli Studi di Milano and INFN Milano

NUCLEAR REACTIONS IN ASTROPHYSICS

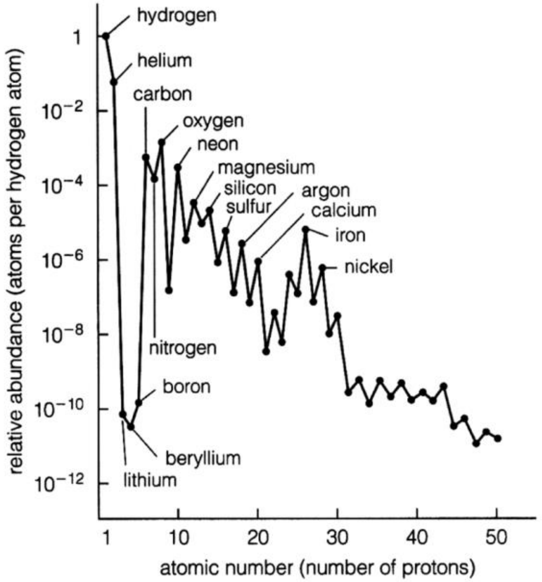
Evolution of early Universe



Stellar evolution

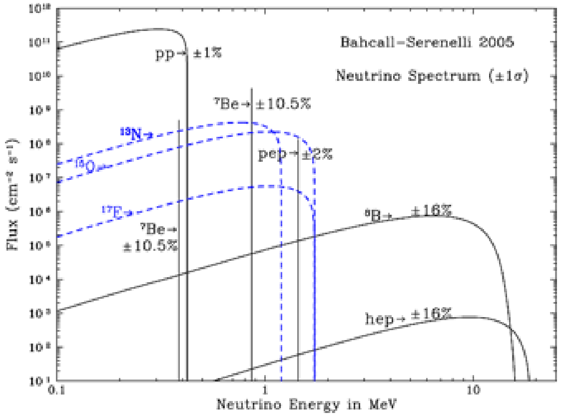


Nucleosynthesis

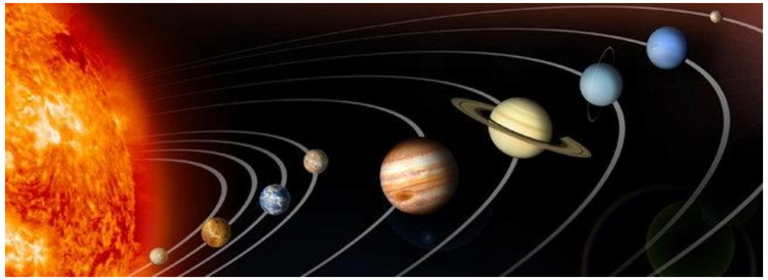


Nuclear reactions cross sections

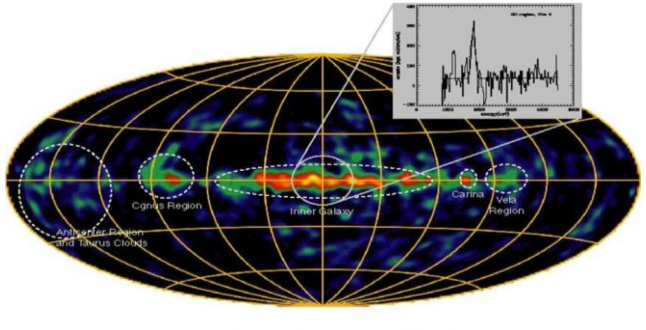
Solar neutrinos



Solar system formation and evolution



Astronomy with radioactivity



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

CHARGED-PARTICLE-INDUCED REACTIONS RATES AT ASTROPHYSICAL ENERGIES

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

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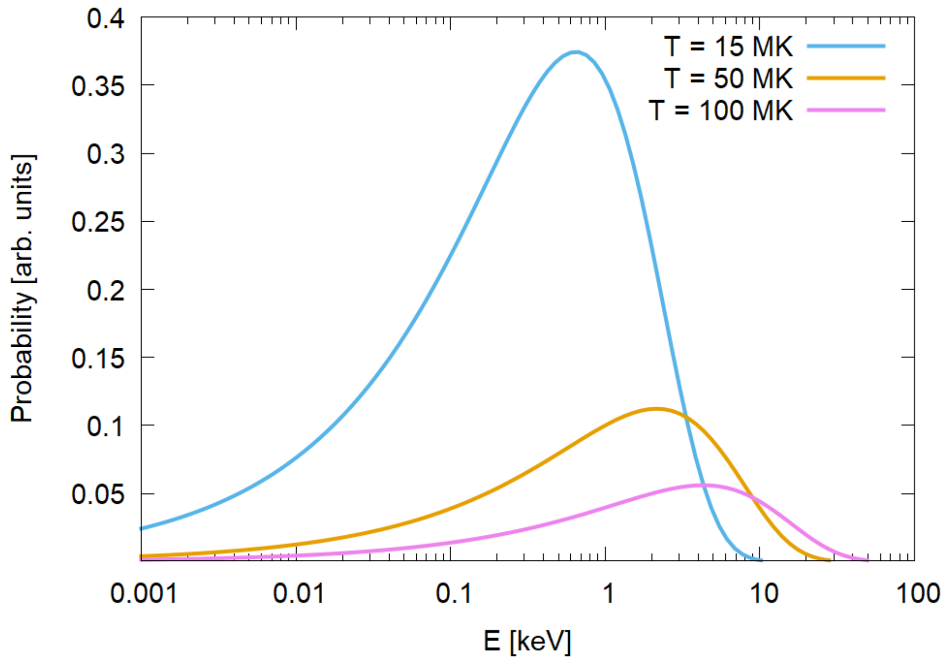
RELATIVE VELOCITY

MAXWELL BOLTZMANN DISTRIBUTION



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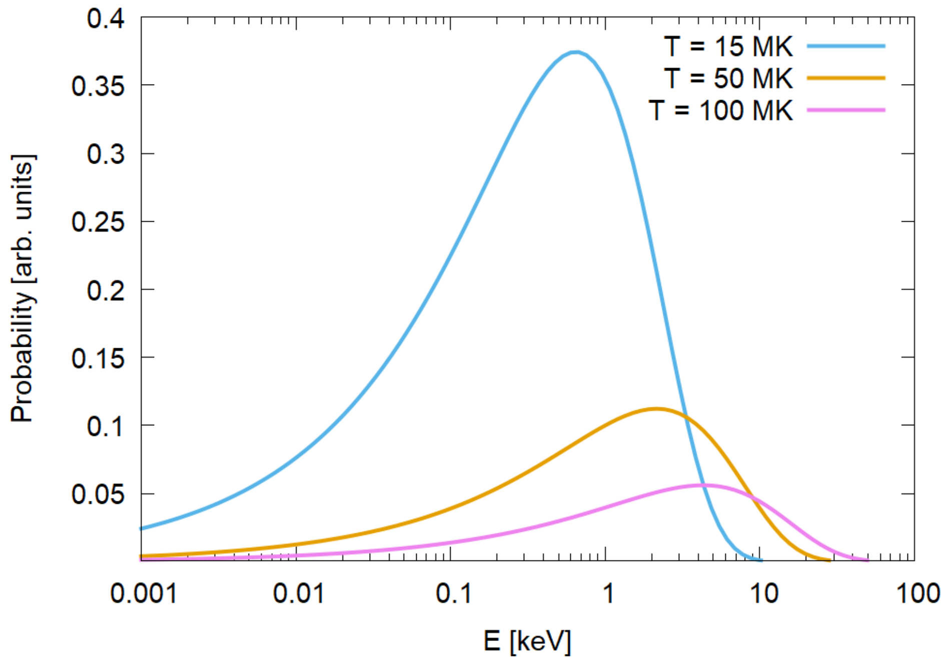
CROSS SECTION → $\sigma(v)$

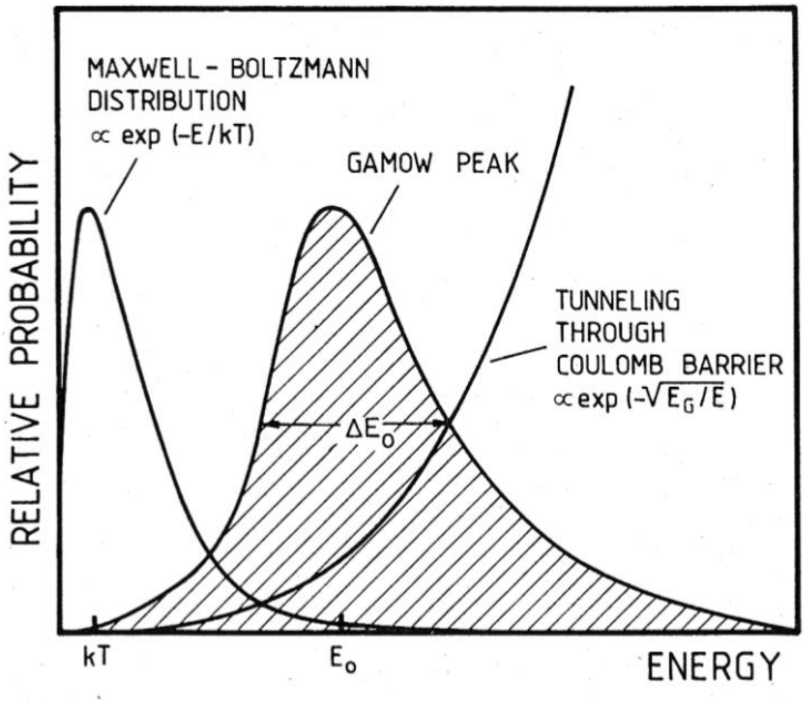
RELATIVE VELOCITY → v

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

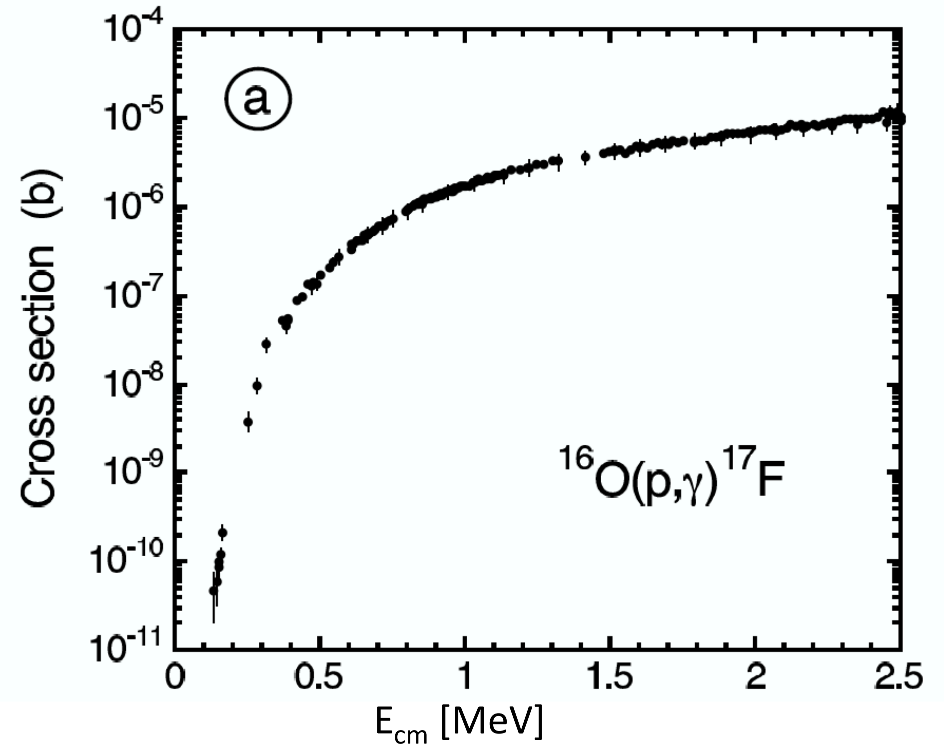


Rolfs, Rodney, Cauldrons in the Cosmos (1988)

→ 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%

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C = 3e-3 –> 0.3 counts/hour

~100 counts/PhD*
***3 years, 365 days/year**

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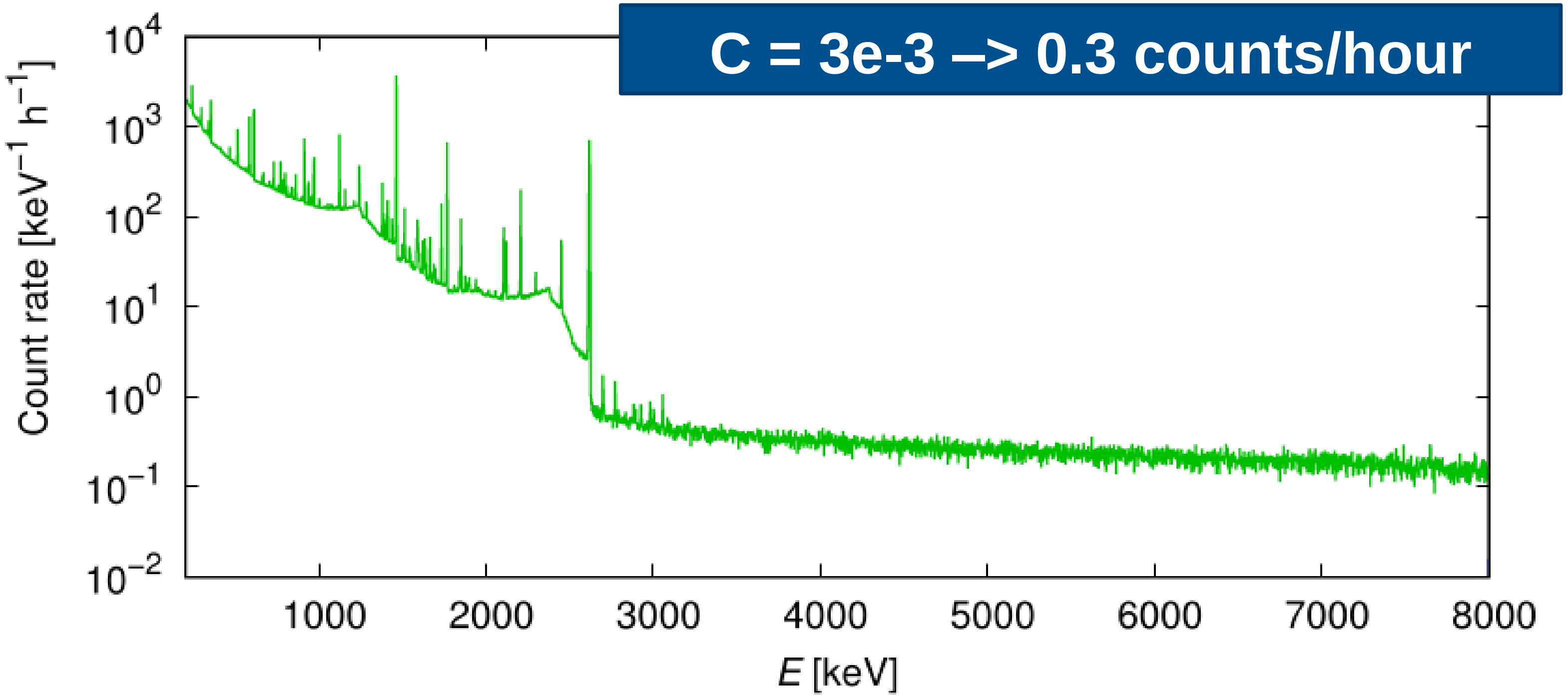

Typical environmental background in HPGe detector

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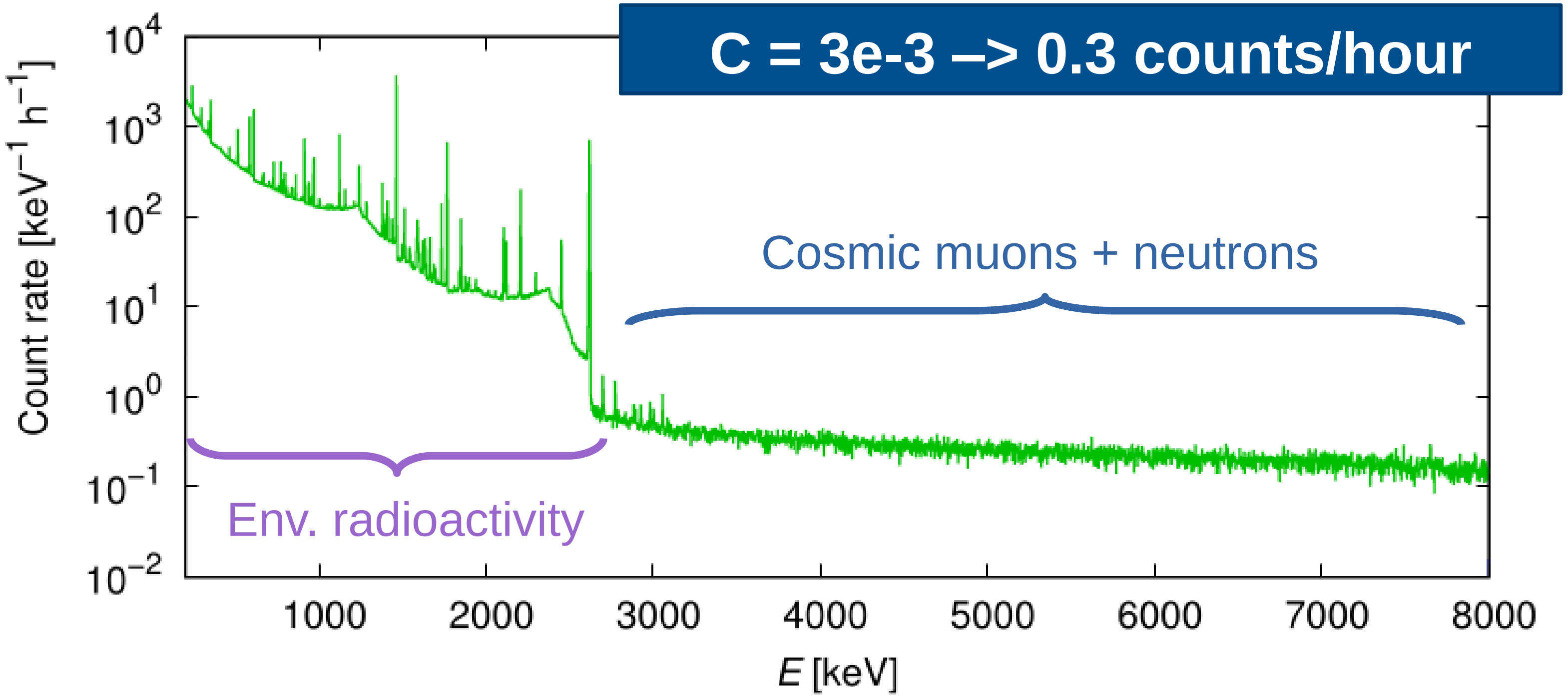

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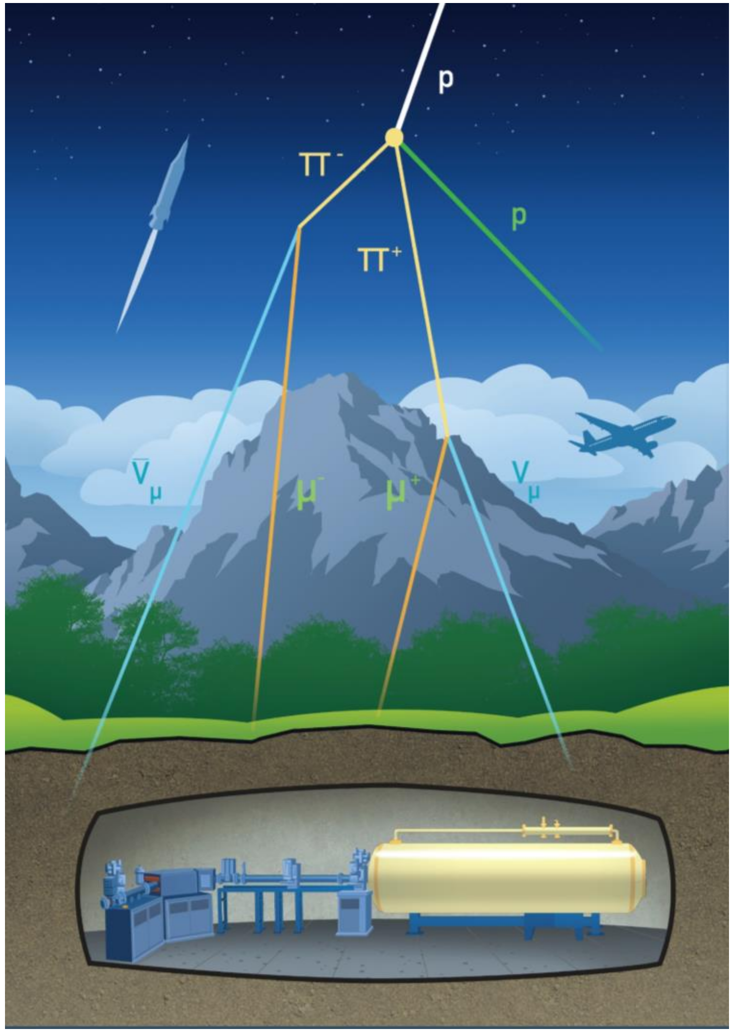
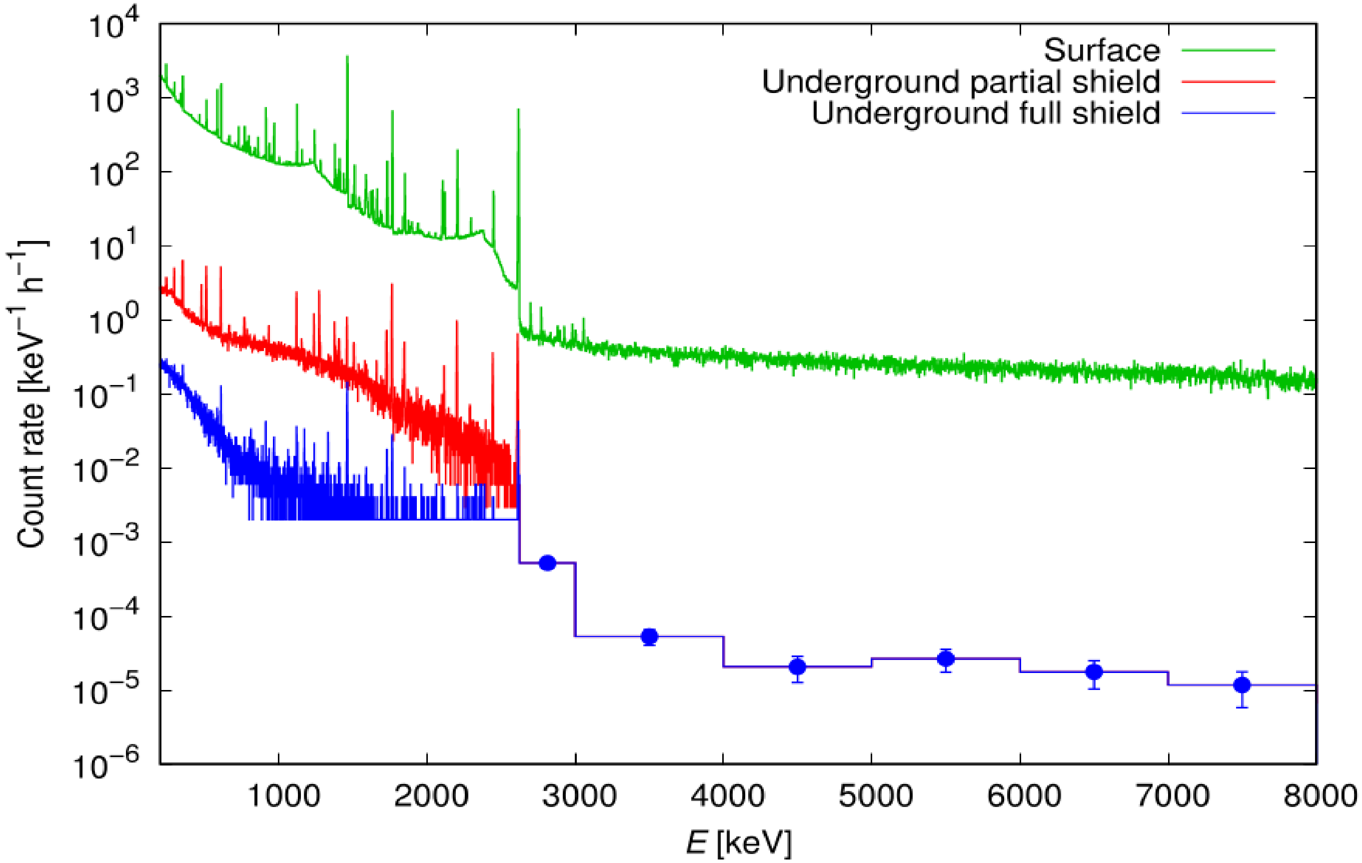
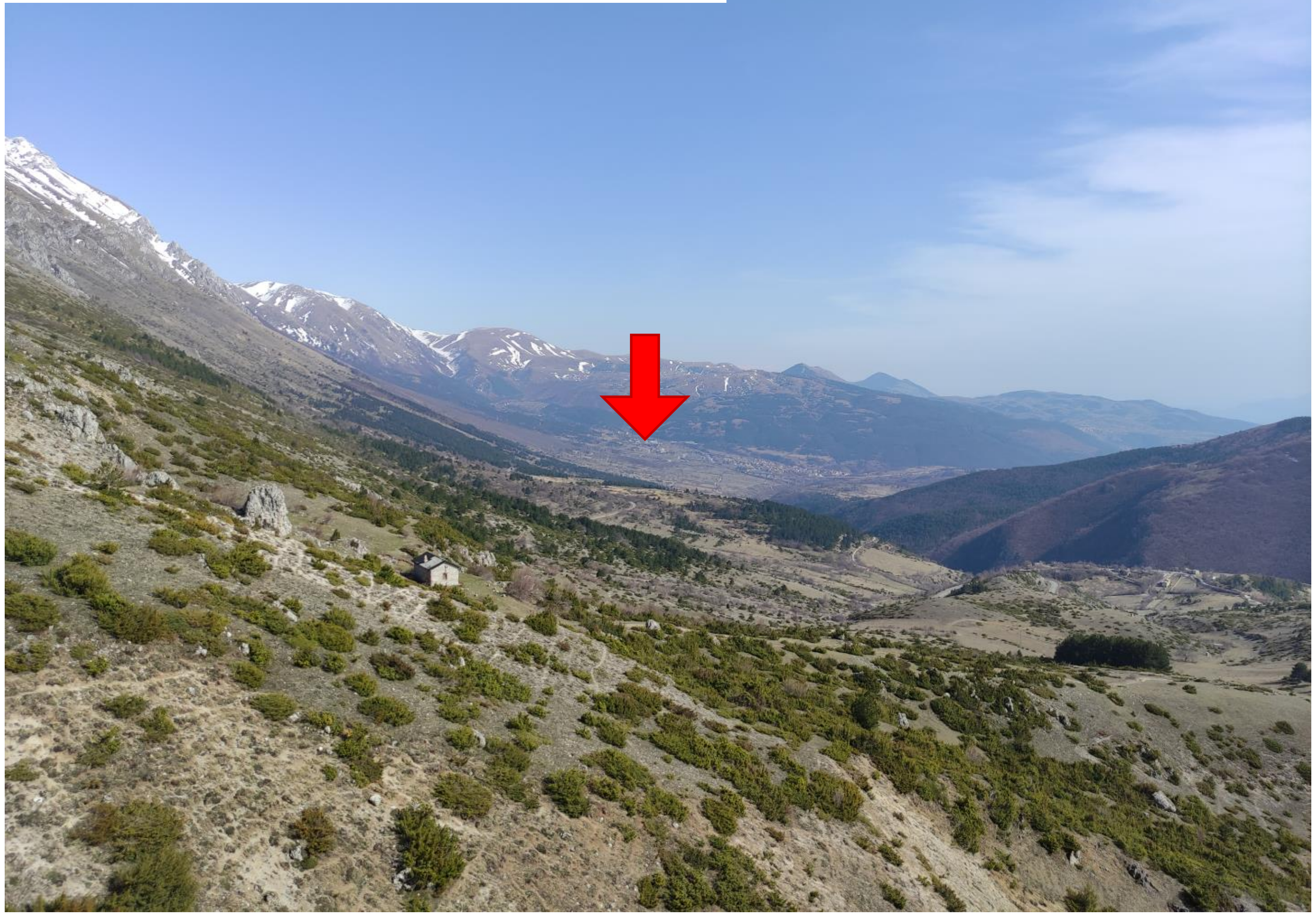
WHY UNDERGROUND?





THE LABORATORY FOR UNDERGROUND NUCLEAR ASTROPHYSICS

Laboratori Nazionali del Gran Sasso



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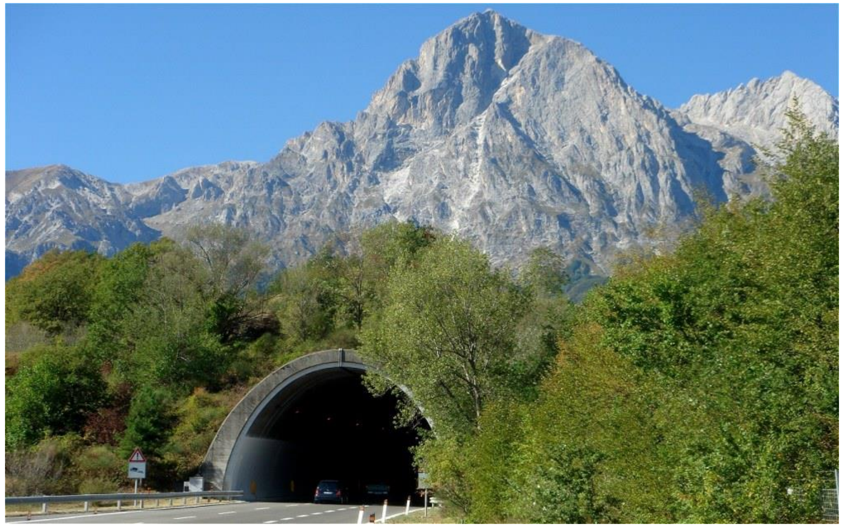
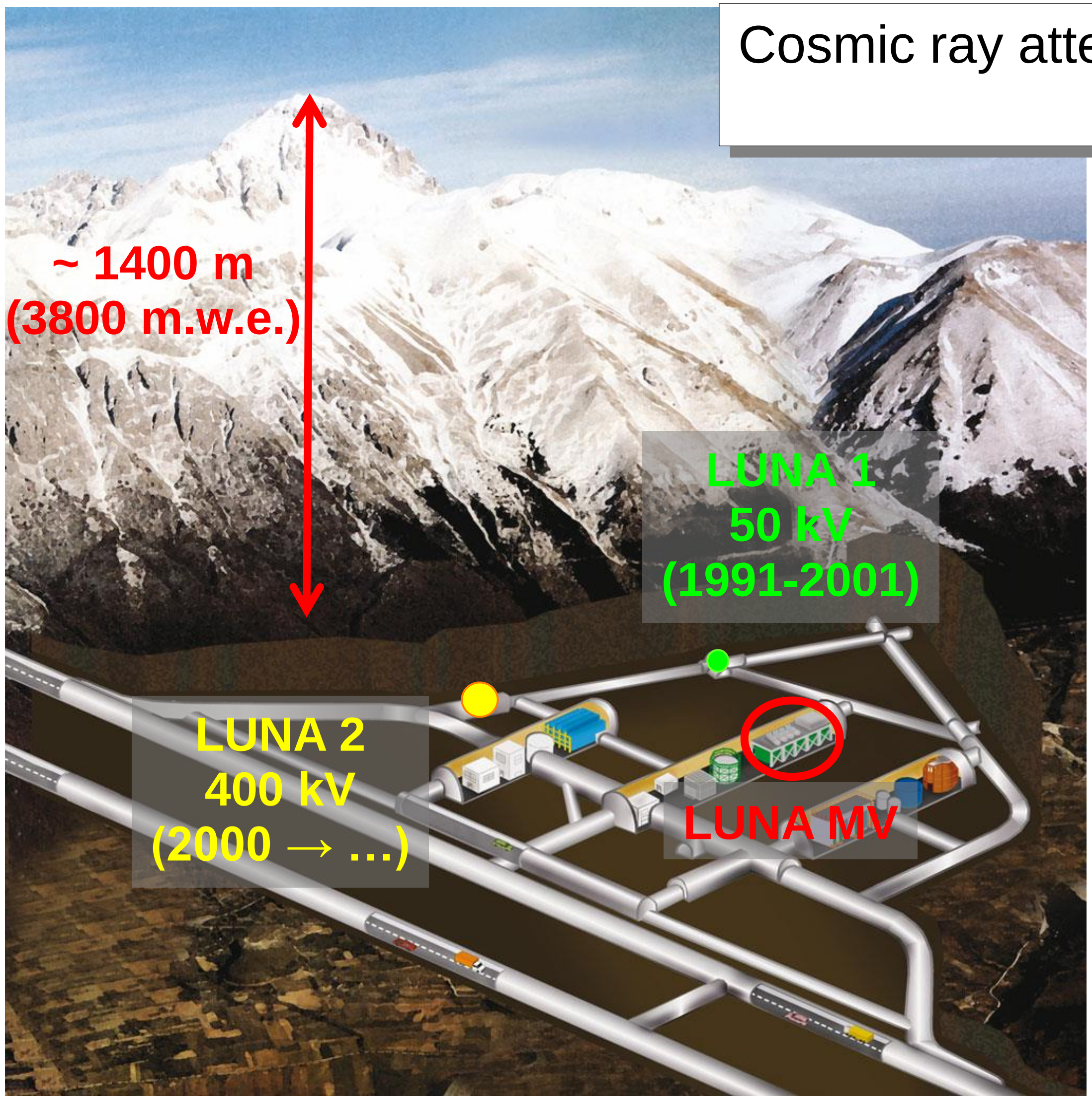
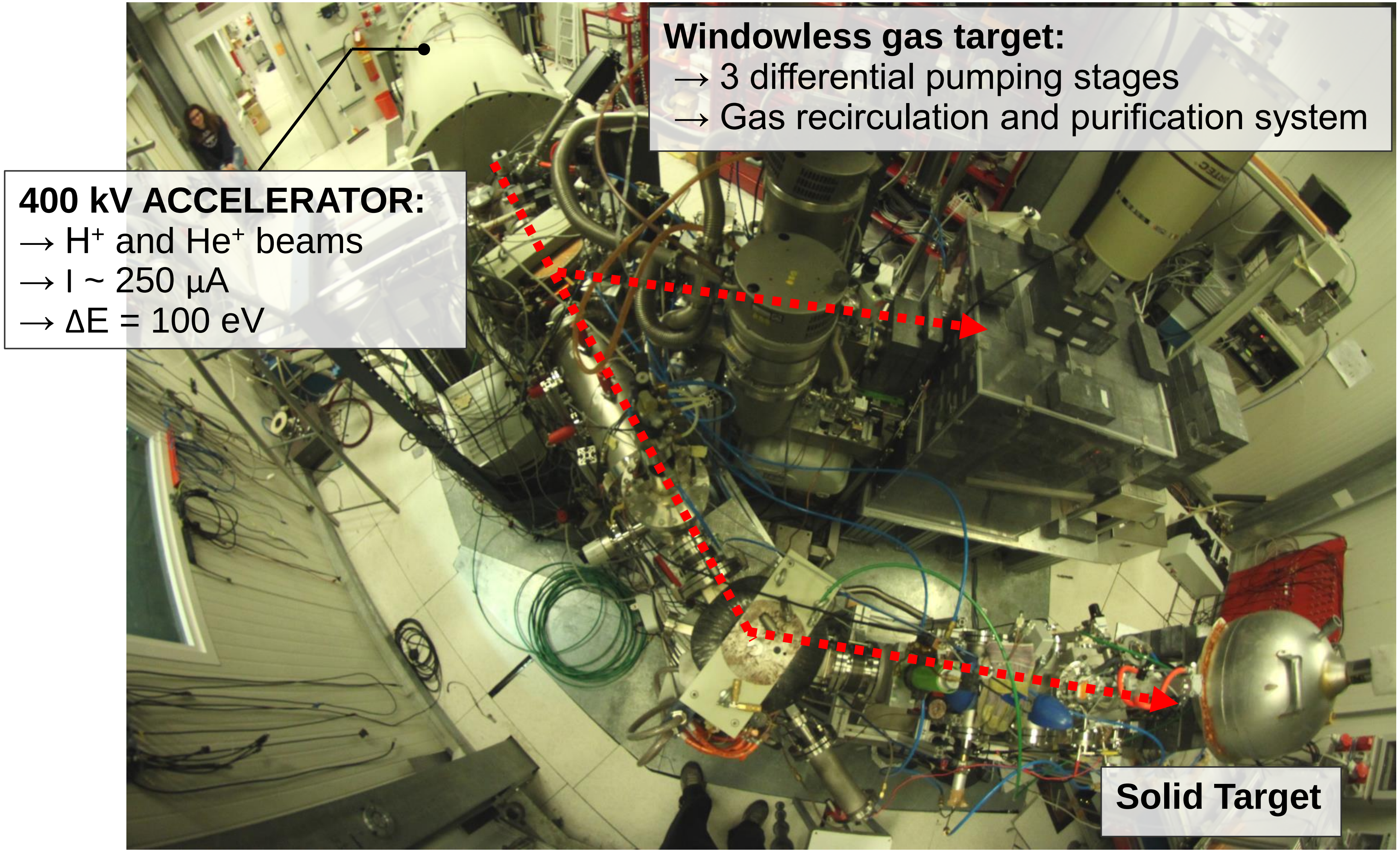




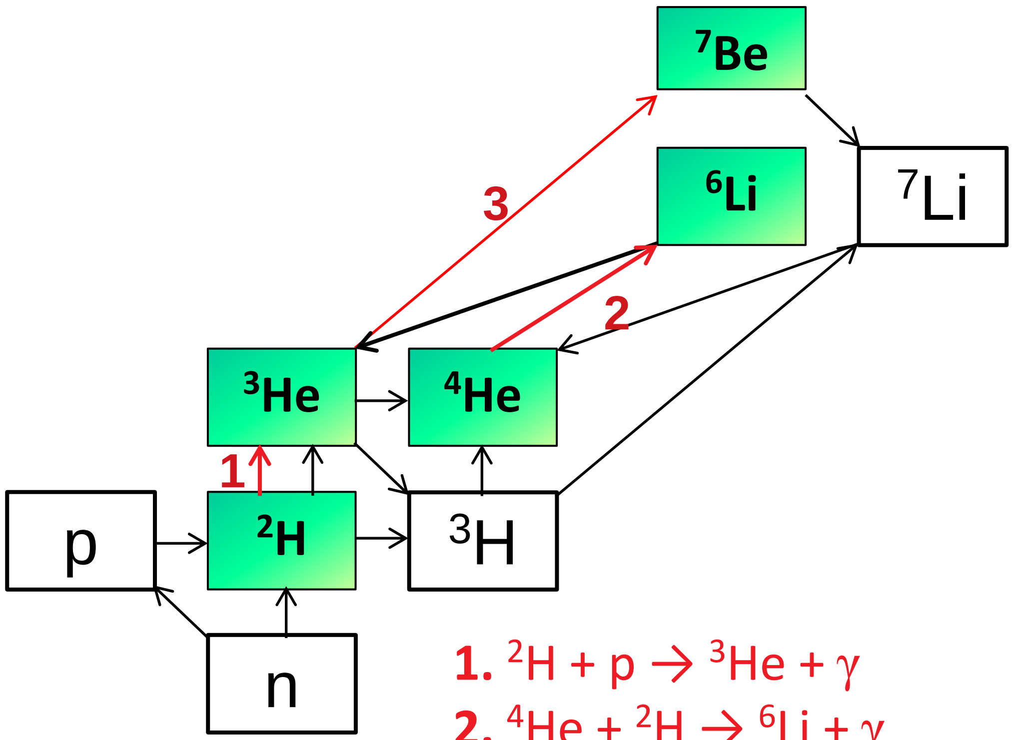
Cosmic ray attenuation: $\mu \rightarrow 10^{-6}$
$n \rightarrow 10^{-3}$

THE LUNA – 400 kV SETUP



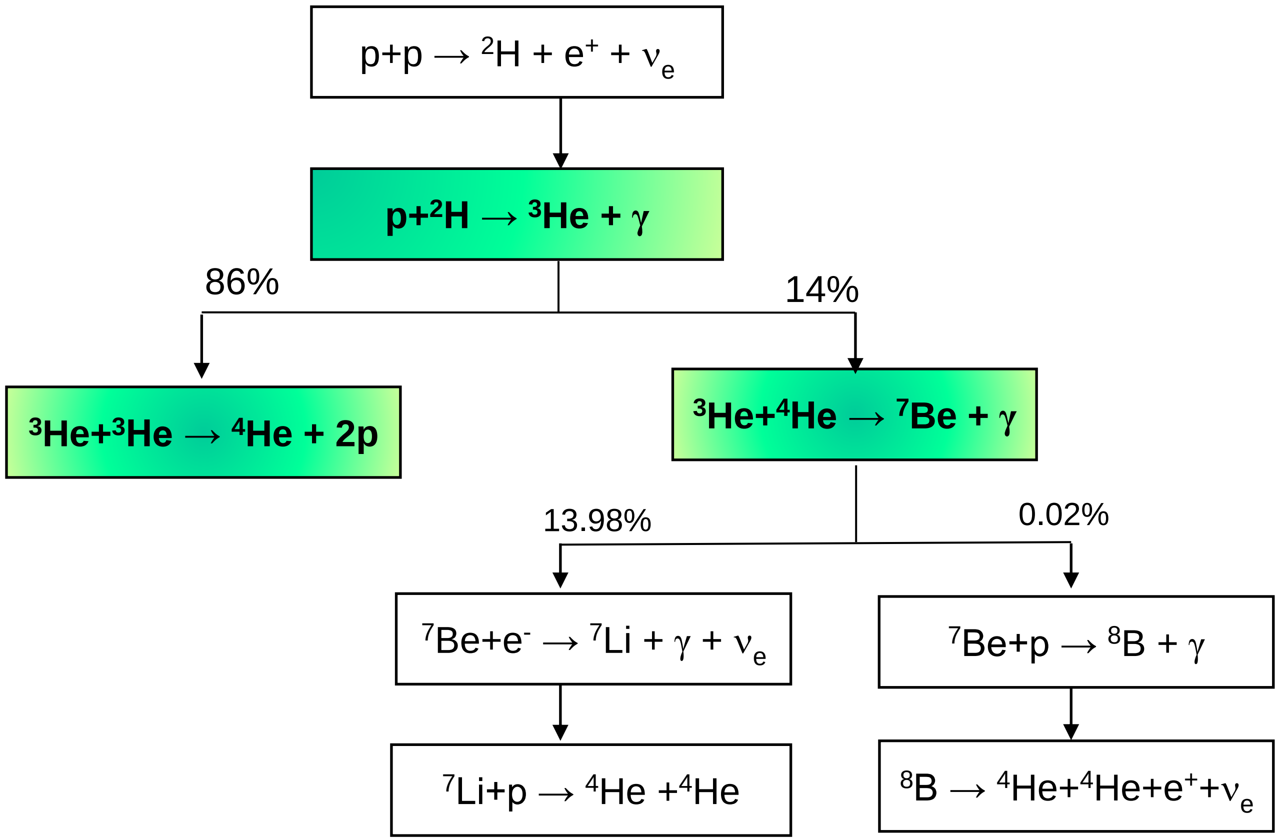
REACTIONS STUDIED SINCE 1991

Big Bang Nucleosynthesis



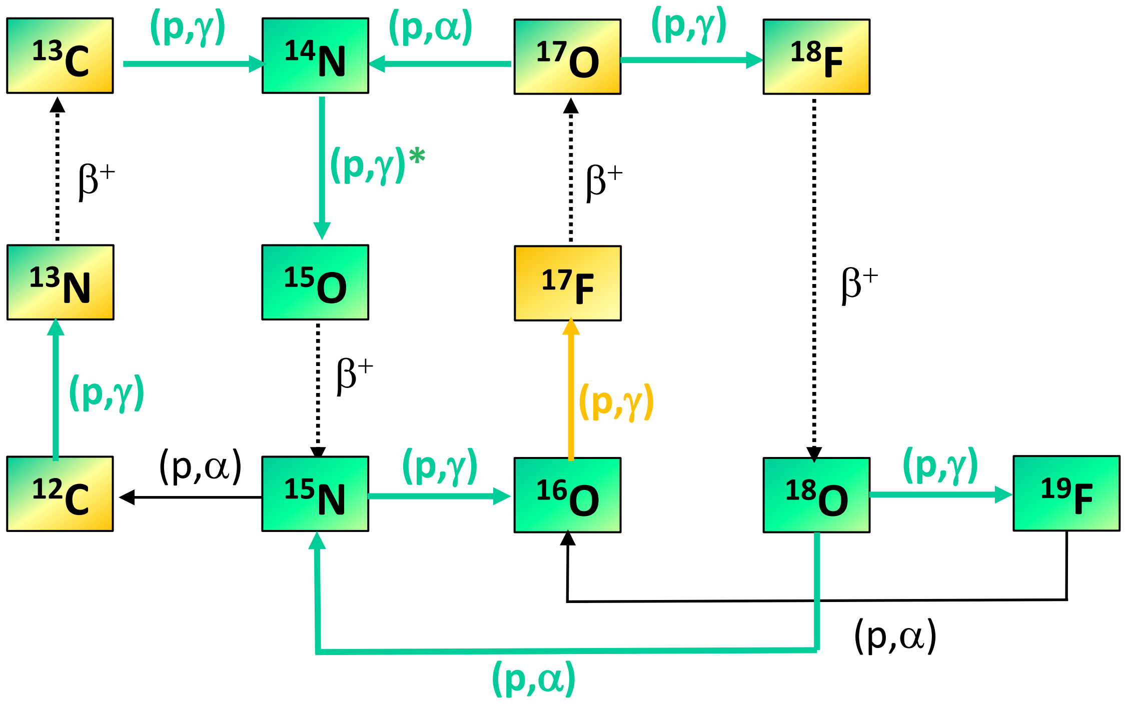
1. $^{2}H + p \rightarrow {}^{3}He + \gamma$
2. $^{4}He + {}^{2}H \rightarrow {}^{6}Li + \gamma$
3. $^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

pp chain

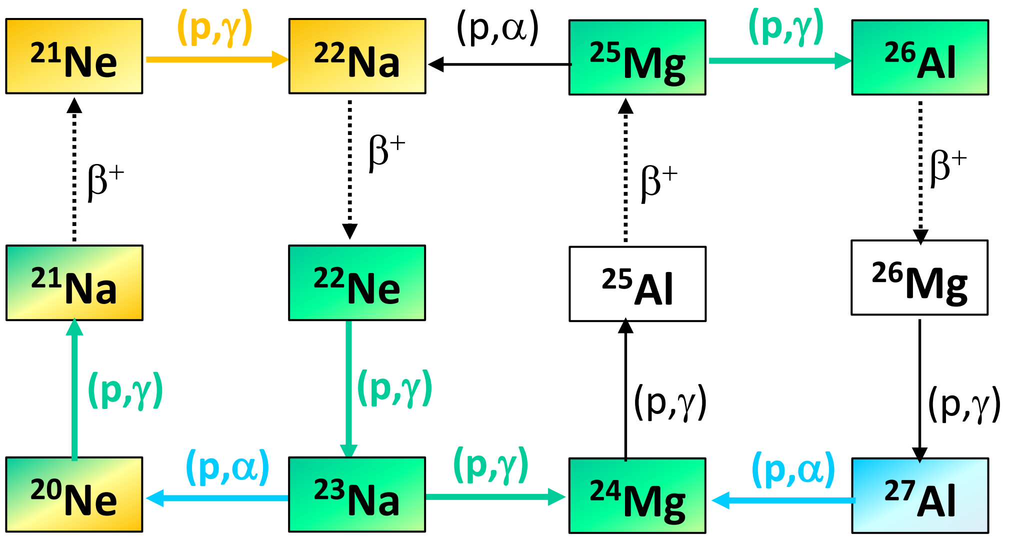


REACTIONS STUDIED SINCE 1991

CNO CYCLE



NeNa and MgAl CYCLES



Done
In progress
Planned

PRE-MAIN SEQUENCE: $^{6}Li(p,\gamma)^{7}Be$

S-PROCESS NUCLEOSYNTHESIS: $^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,\gamma)^{26}Mg$

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

THE ^{2}H(p,γ)^{3}He REACTION: ASTROPHYSICAL RELEVANCE

PRIMORDIAL ABUNDANCE OF ^{2}H:

- Direct measurements: observation of absorption lines in DLA system

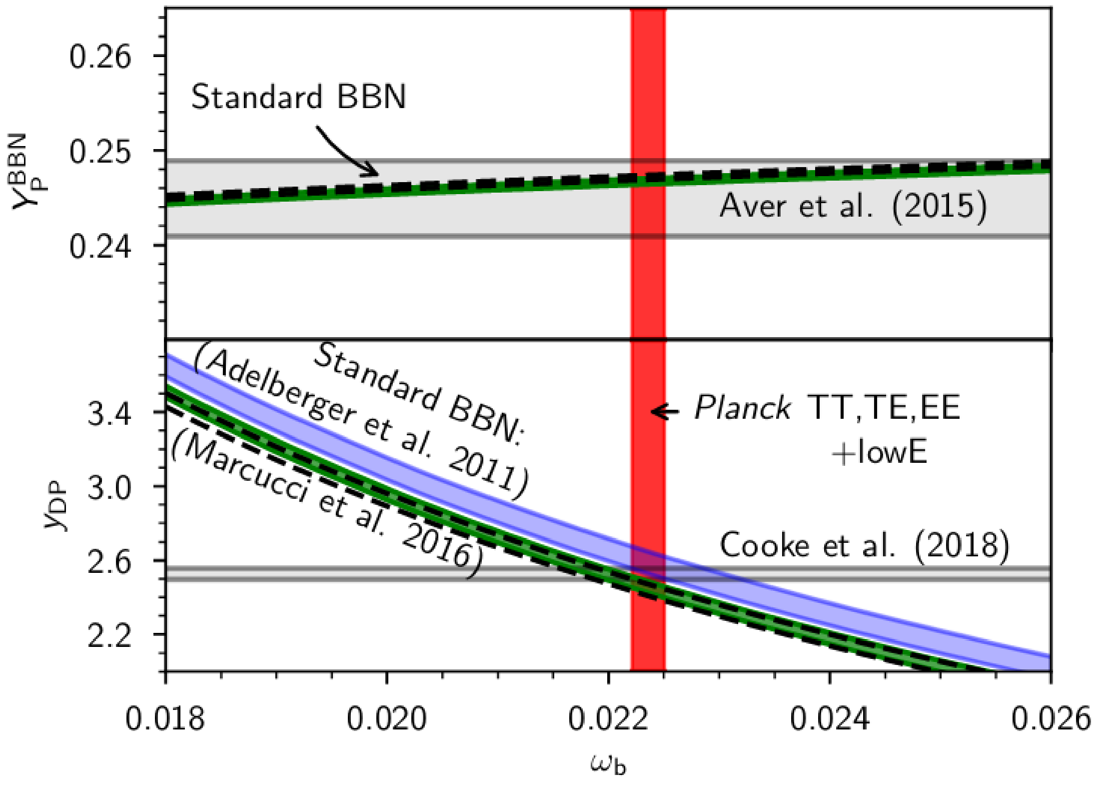
$$\left[\frac{D}{H}\right]_{OBS} = (2.527 \pm 0.030) \cdot 10^{-5}$$

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

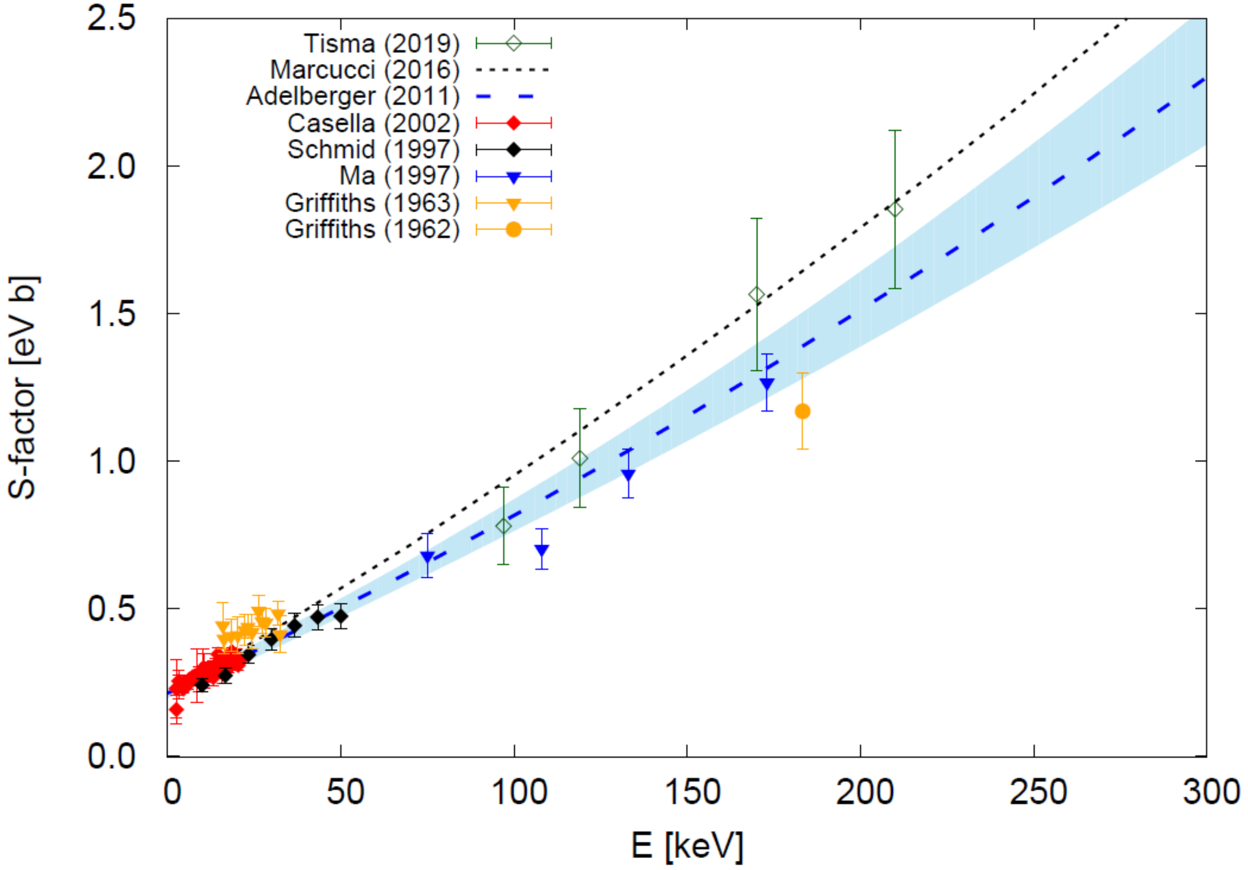
$$\left[\frac{D}{H}\right]_{BBN} = \begin{matrix} (2.587 \pm 0.055) \cdot 10^{-5} \\ (2.439 \pm 0.052) \cdot 10^{-5} \end{matrix}$$

Plank 2018 results arXiv:1807.06209v1



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

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

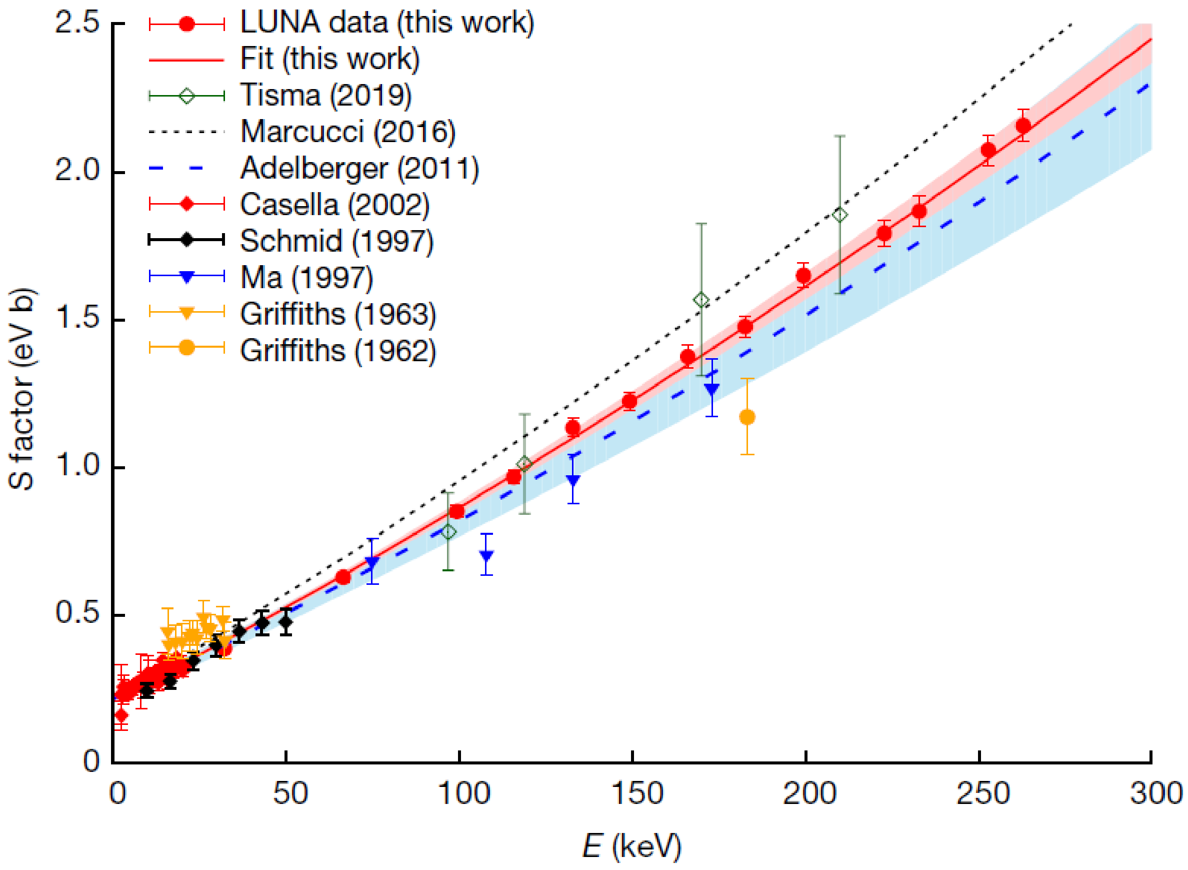


$^2H(p,\gamma)^3He$ is the main source of uncertainty on the primordial ^2H abundance

→ 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



Systematic uncertainty reduced to **< 3%**

nature

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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

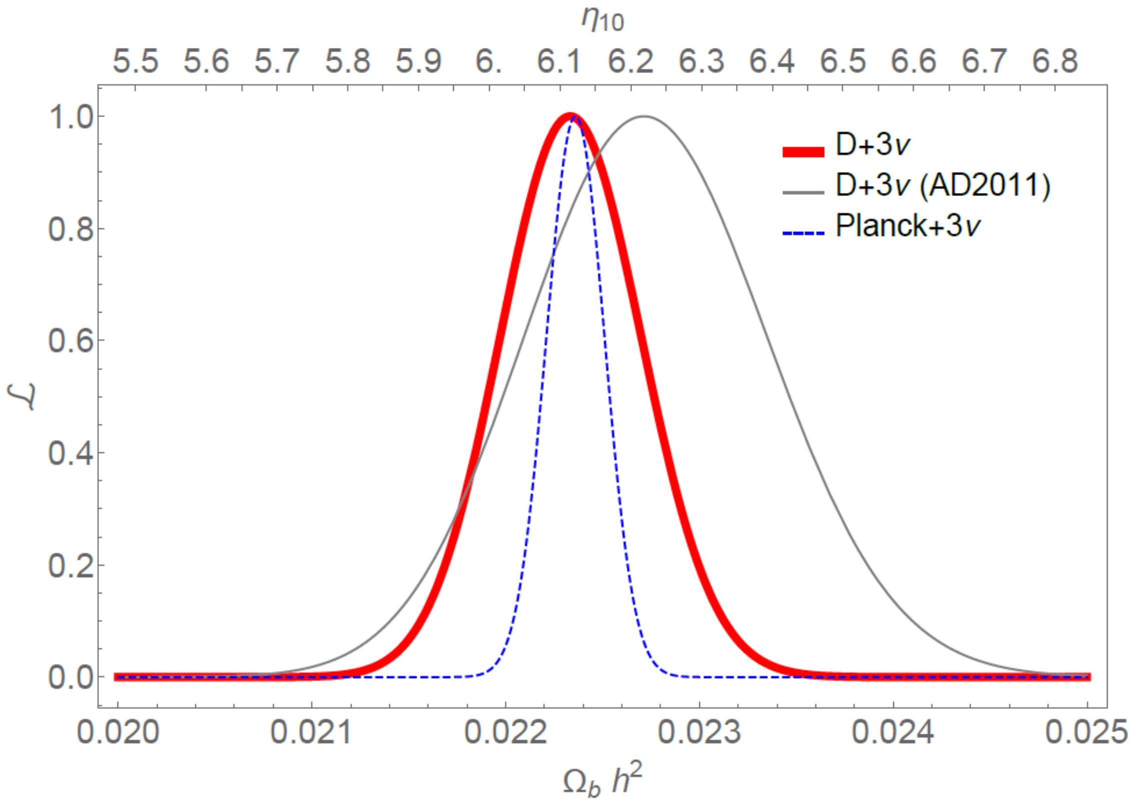
Nature **587**, 210–213 (2020) | Cite this article

4402 Accesses | **13** Citations | **168** Altmetric | Metrics

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

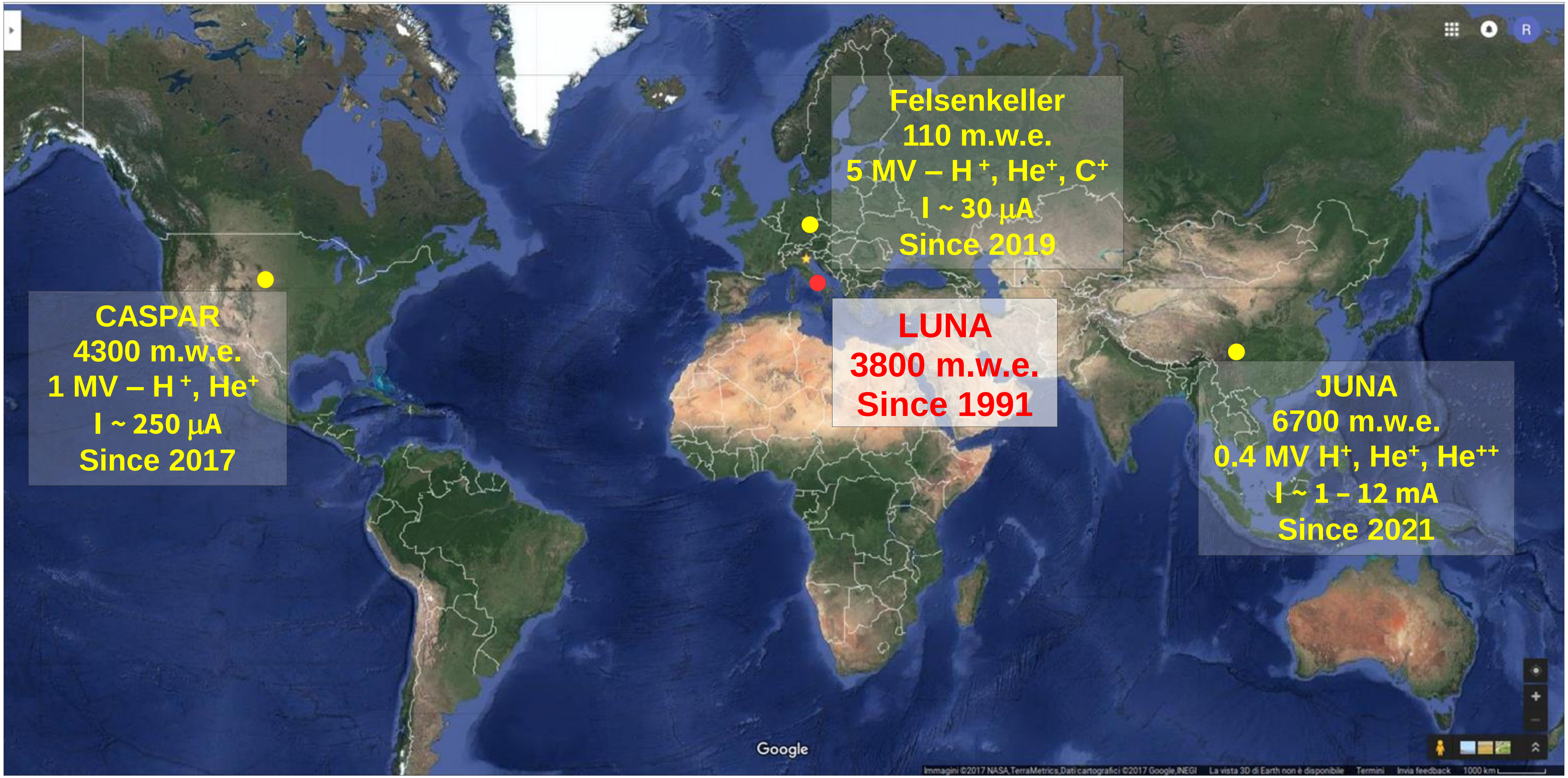
Baryon density of the Universe:

- ✓ Obtained with PArthENoPE code by comparing $[D/H]_{OBS}$ and $[D/H]_{BBN}$
- ✓ N_{eff} = 3.045, fixed
- ✓ Comparison with Planck results

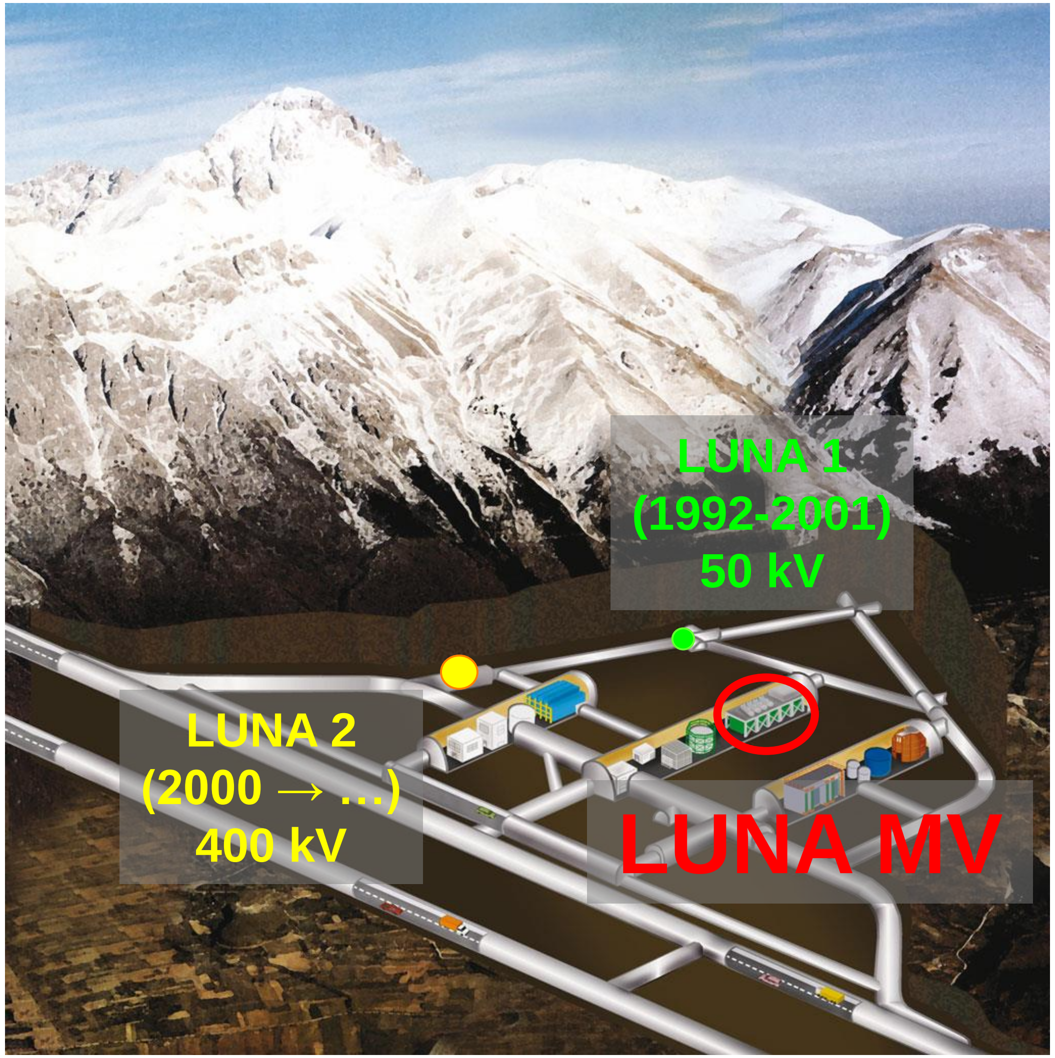


Analysis performed by Ofelia Pisanti and Gianpiero Mangano

UNDERGROUND NUCLEAR ASTROPHYSICS WORLDWIDE



NEW ACCELERATOR AT LNGS: LUNA-MV



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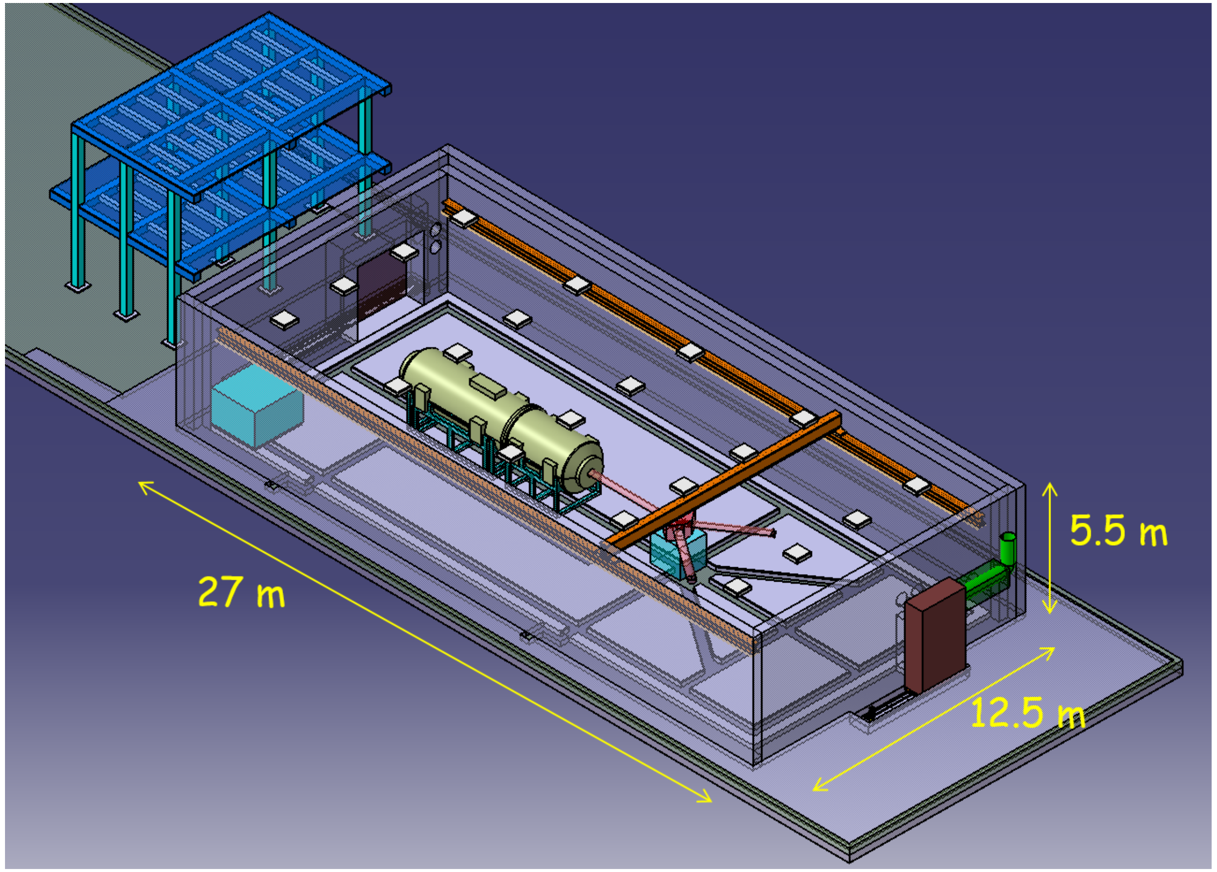

- **Inline Cockcroft Walton accelerator**
- **TERMINAL VOLTAGE: 0.2 – 3.5 MV**
- **Beam energy reproducibility:** 0.01% TV or 50V
- **Beam energy stability:** 0.001% TV / h
- **Beam current stability:** < 5% / h

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, important for CNO neutrino flux. Also commissioning experiment 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 are now ongoing!
First experiment in 2023

THANK YOU!

LUNA COLLABORATION:

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