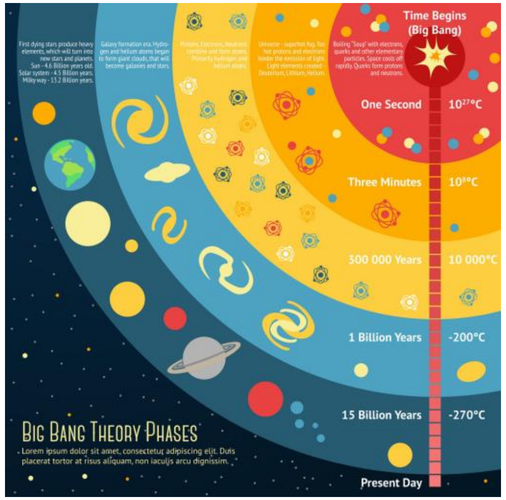
Why to study stars underground?

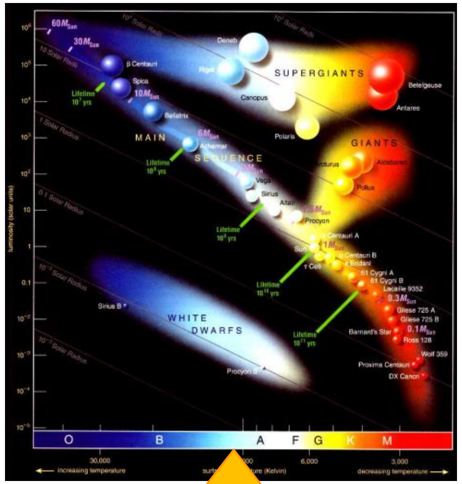
R. Depalo
Università degli Studi di Milano and INFN Milano

Nuclear reactions in Astrophysics

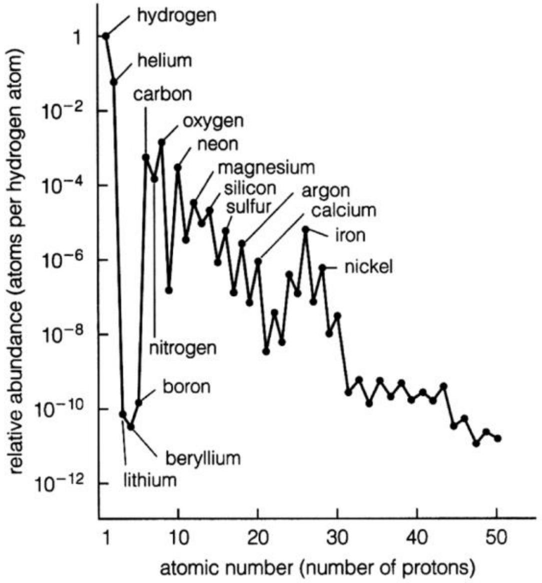
Evolution of early Universe



Stellar evolution

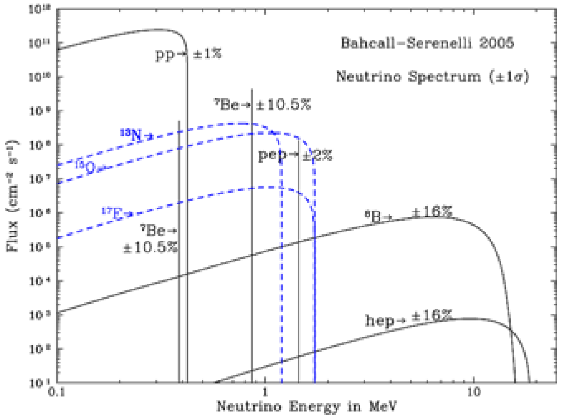


Nucleosynthesis

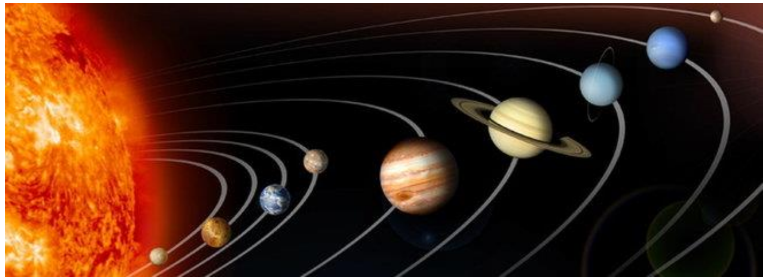


Nuclear reactions cross sections

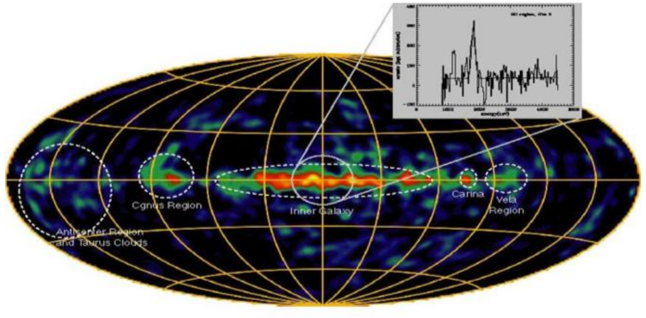
Solar neutrinos



Solar system formation and evolution



Astronomy with radioactivity



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

Nuclear reactions at astrophysical energies

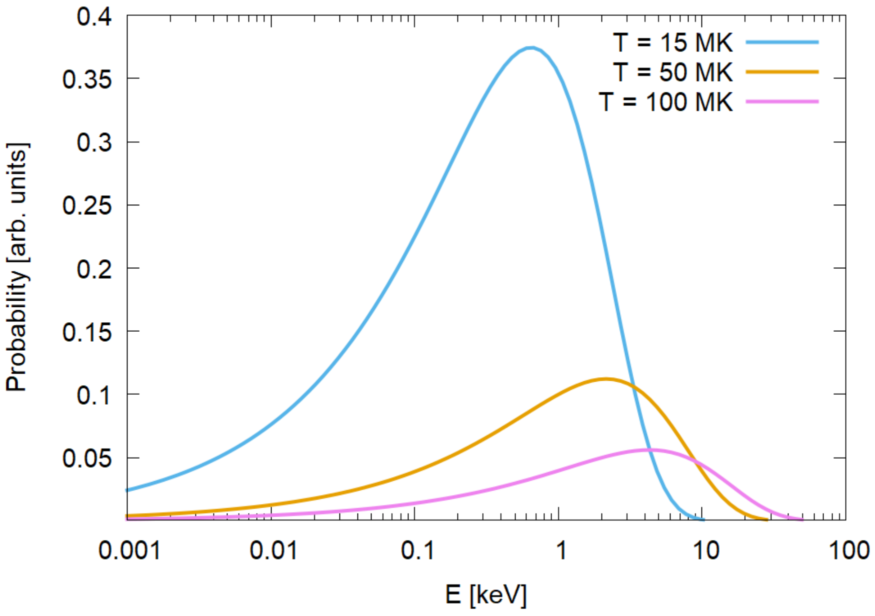
$$\frac{\text{N° Reactions}}{\text{time} \cdot \text{volume}} = n_a \cdot n_b \cdot v \cdot \sigma(v)$$

Nuclear reactions at astrophysical energies

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

RELATIVE VELOCITY OF INTERACTING NUCLEI

MAXWELL - BOLTZMANN DISTRIBUTION



$$P(v)dv = \left(\frac{m_{ab}}{2\pi kT}\right)^{3/2} e^{-m_{ab}v^2/(2kT)} 4\pi v^2 dv$$

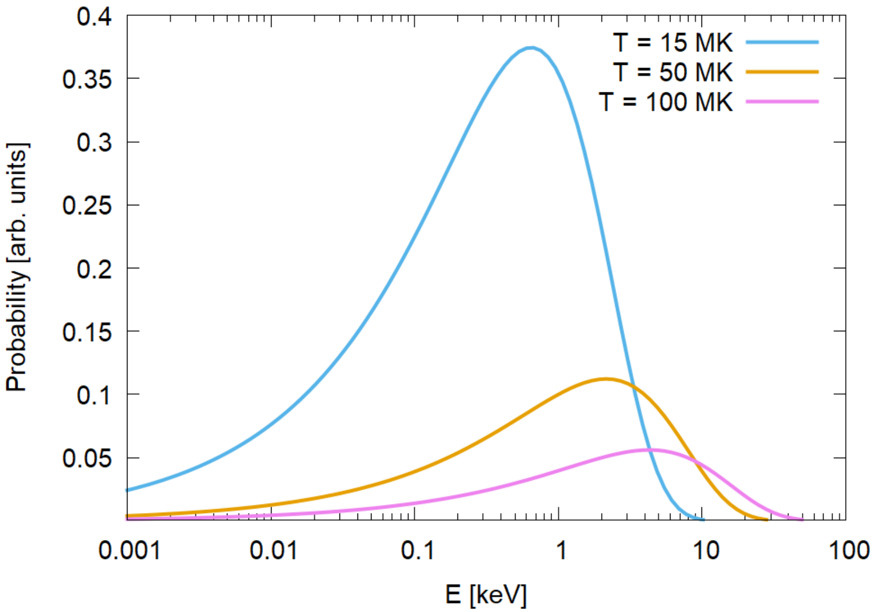
Nuclear reactions at astrophysical energies

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

CROSS SECTION

RELATIVE VELOCITY OF INTERACTING NUCLEI

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

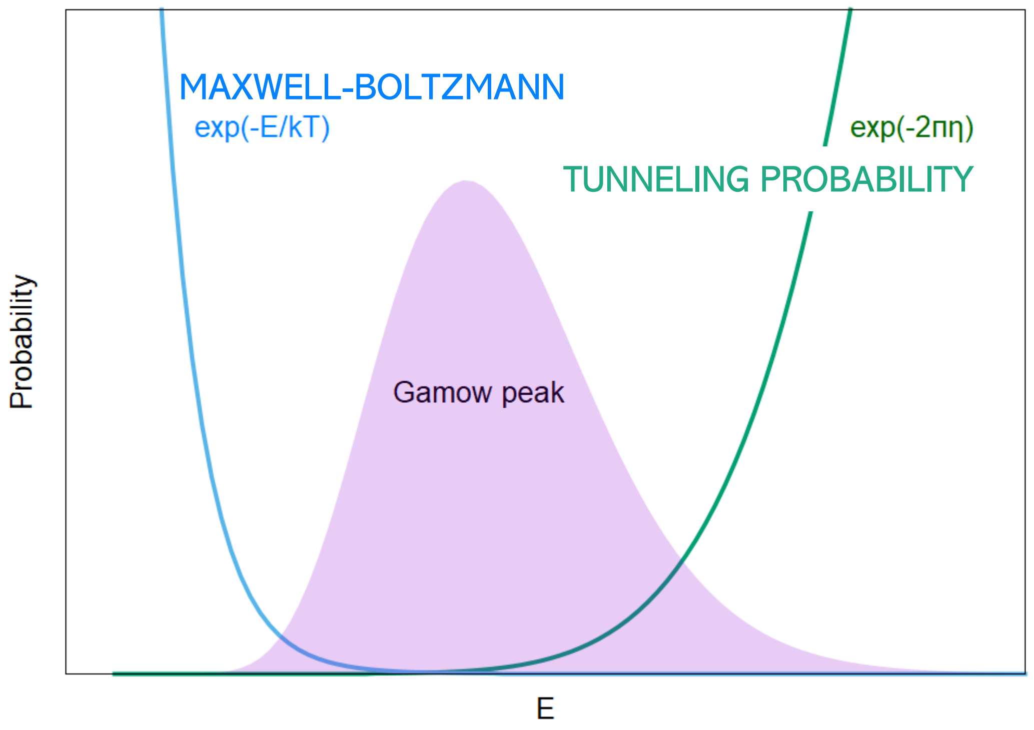


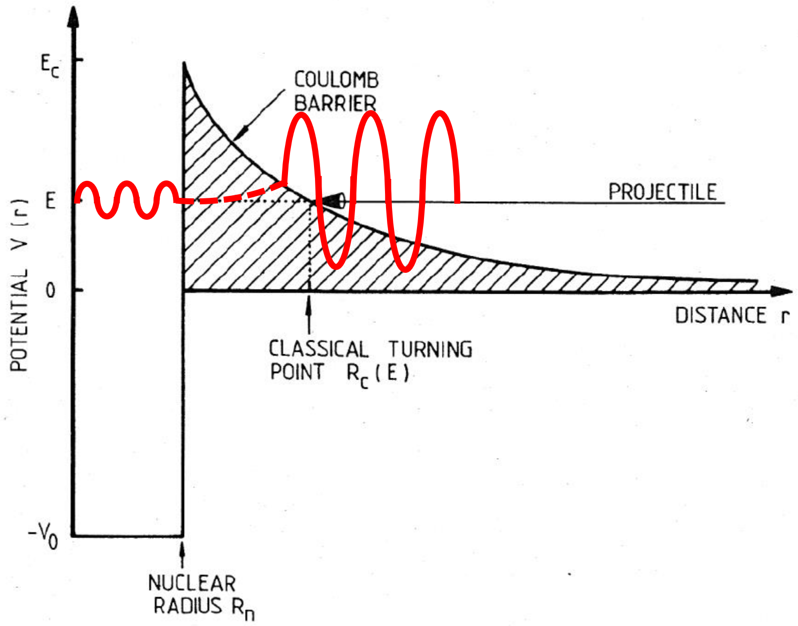
$$E_C = \frac{Z_a Z_b e^2}{R} \sim MeV$$

Nuclear reactions at astrophysical energies

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

The barrier penetration probability is steeply energy-dependent





$$\sigma(E) = \frac{1}{E} S(E) \exp\left(-cZ_0Z_1\sqrt{\frac{\mu}{E}}\right)$$

At Gamow peak energies
σ ~ fb – nb (1b = 10^{-24} cm^2)

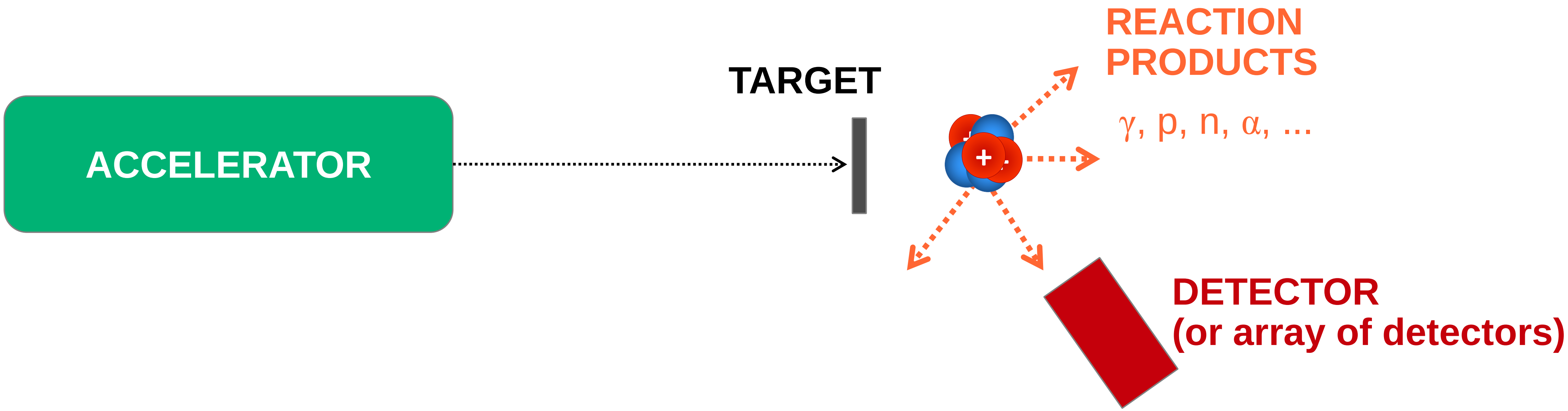
How to measure a nuclear cross section in the lab?

- High intensity
- High stability
- Small energy spread

How to measure a nuclear cross section in the lab?

- High purity
- Stable against irradiation

How to measure a nuclear cross section in the lab?



- Best compromise between detection efficiency and energy resolution

Expected counting rate in the detector

Counting rate = N_p/t x N_t/A x cross section x detection efficiency

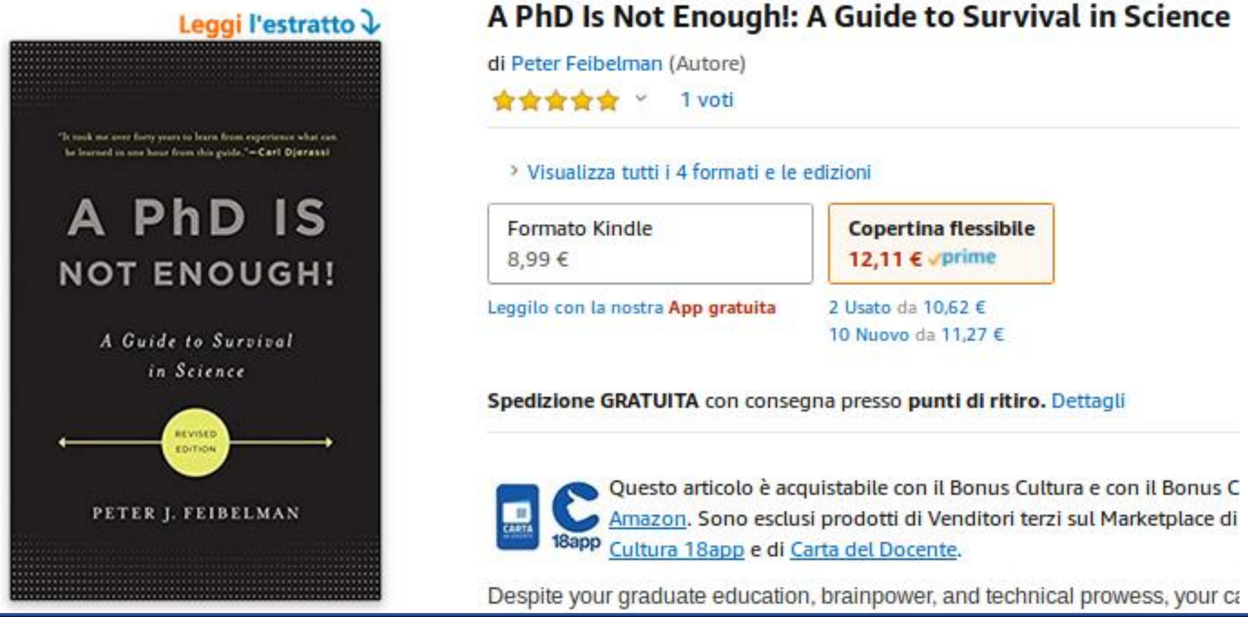
- N_p/t: 10^{14} pps (I ~ 100 μA)
- N_t/A: 10^{18} atoms/cm^2 (typical solid-state target)
- cross section: 10^{-36} cm^2 (or even smaller)
- detection efficiency: 1 - 5% for HPGe

Expected counting rate in the detector

Counting rate = N_p/t x N_t/A x **cross section** x **detection efficiency**

- N_p/t → 10^{14} pps (I ~ 100 μA)
- N_t/A → 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



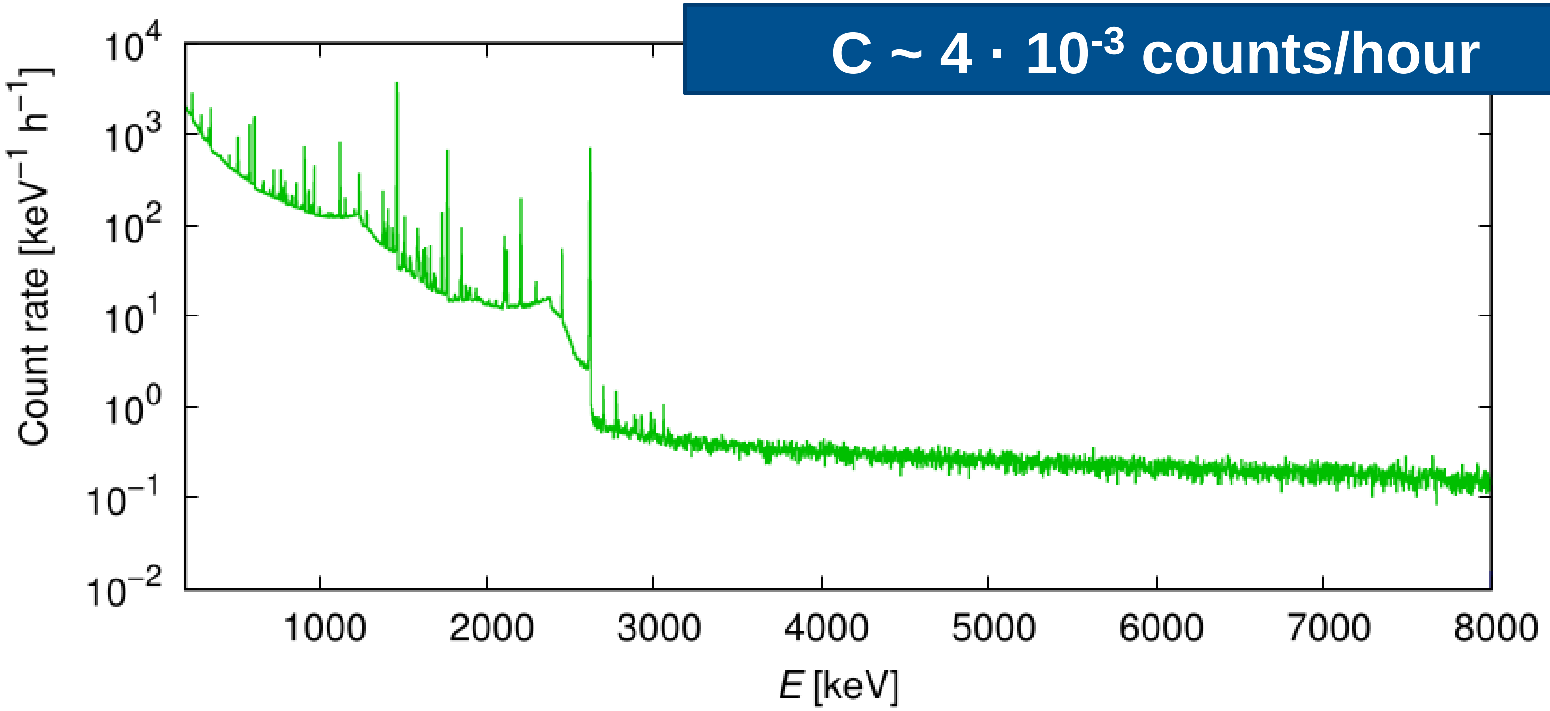
~ 100 counts/PhD

Expected counting rate in the detector

Counting rate = N_p/t x N_t/A x cross section x detection efficiency

- N_p/t → 10^{14} pps (I ~ 100 μA)
- N_t/A → 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

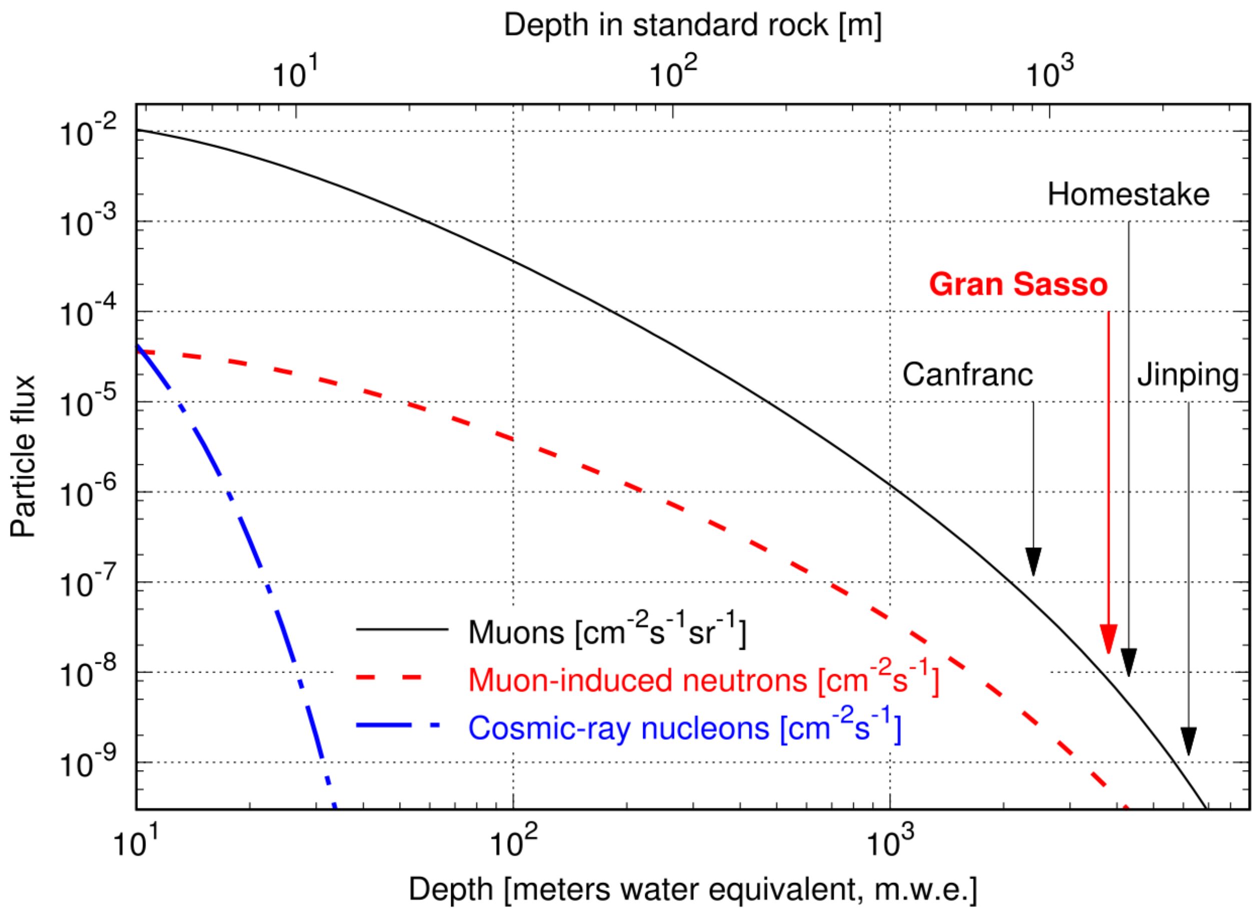


Environmental background in gamma-ray detector

Why underground?

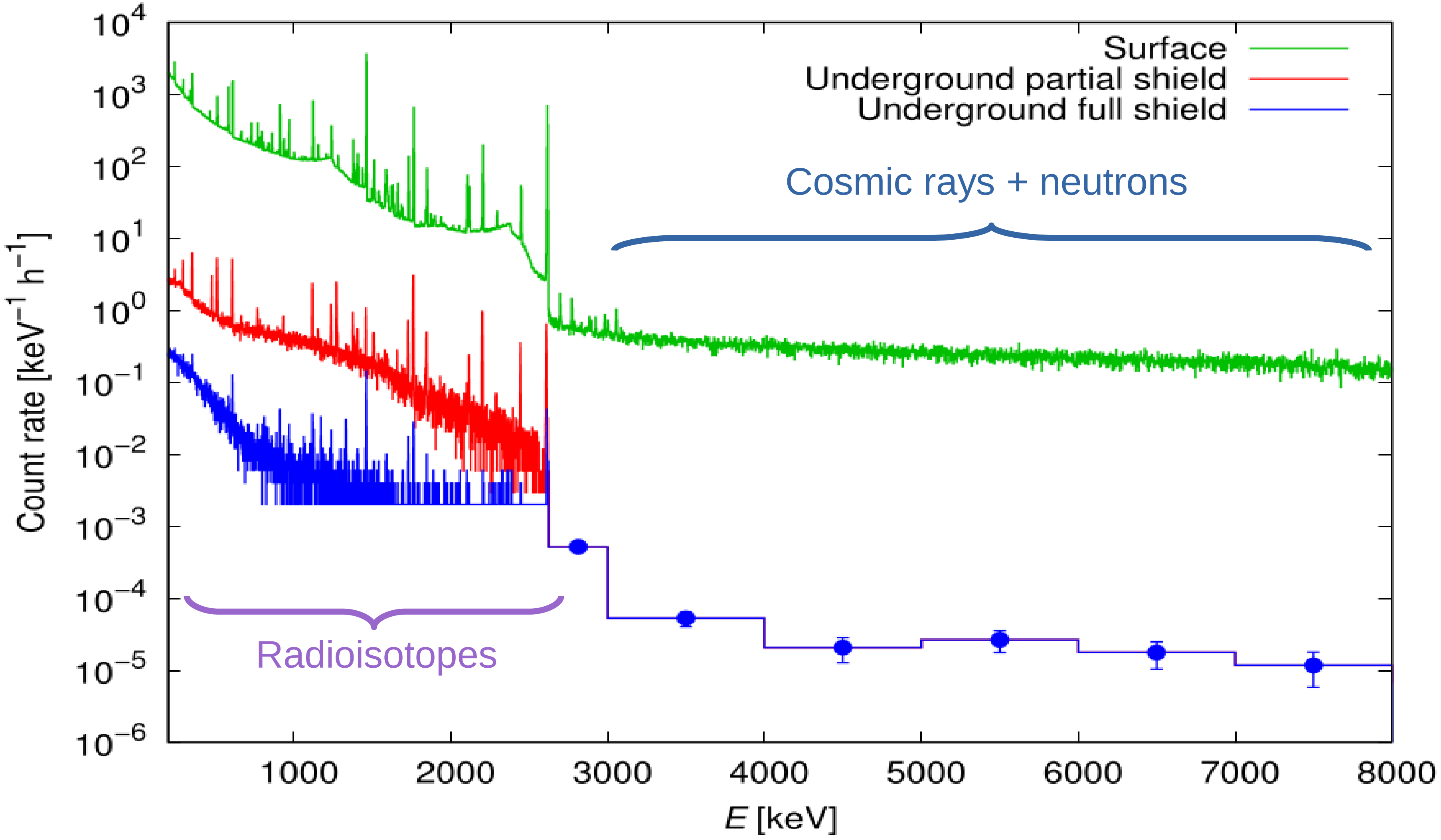
Main sources of environmental background in a gamma ray spectrum:

- **Naturally-occurring radionuclides**:
  $^{235,\,238}U$, ^{232}Th chains and ^{40}K
- **Cosmic rays:**
  mainly muons at sea level
- **Neutrons:**
  from fission of ^{238}U, (α,n) reactions and muon-induced spallation



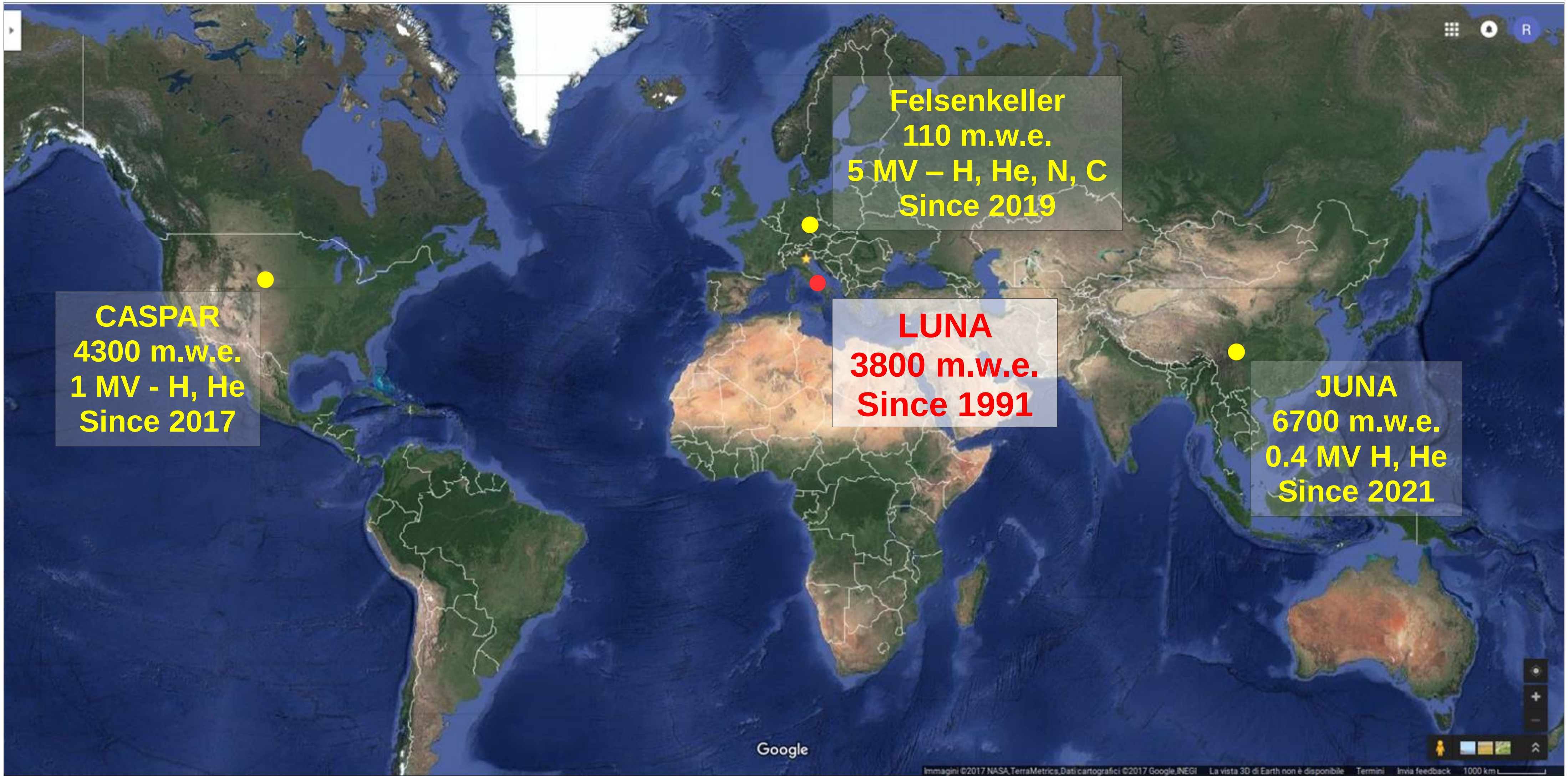
C. Broggini et al. Progress in Particle and Nuclear Physics 98 (2018) 55–84

Why underground?



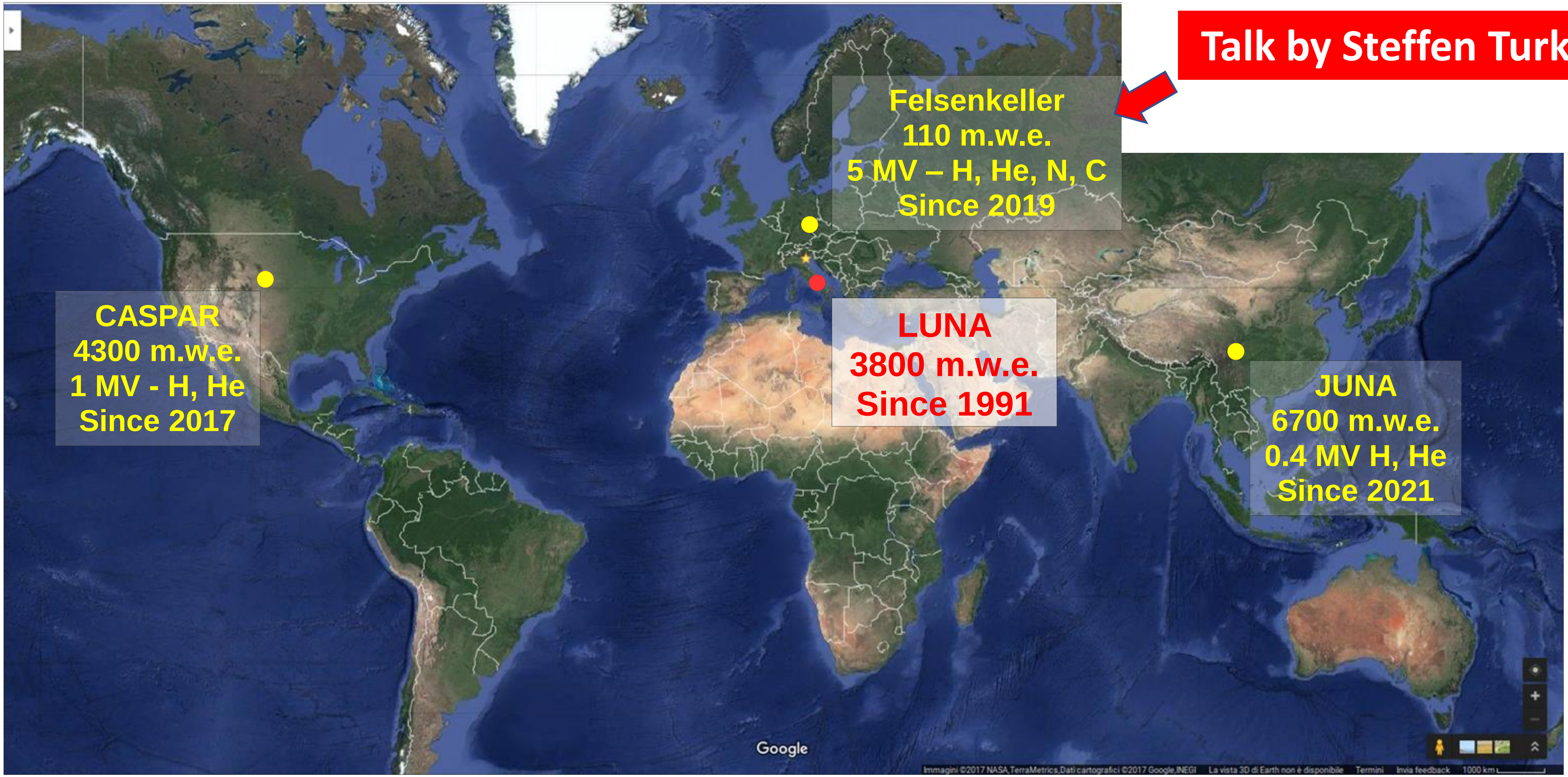
+ More effective passive shielding

Underground nuclear astro labs worldwide



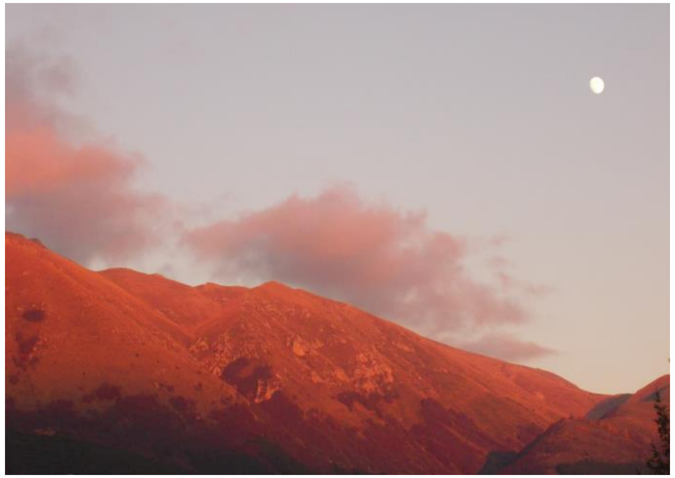
Underground nuclear astro labs worldwide

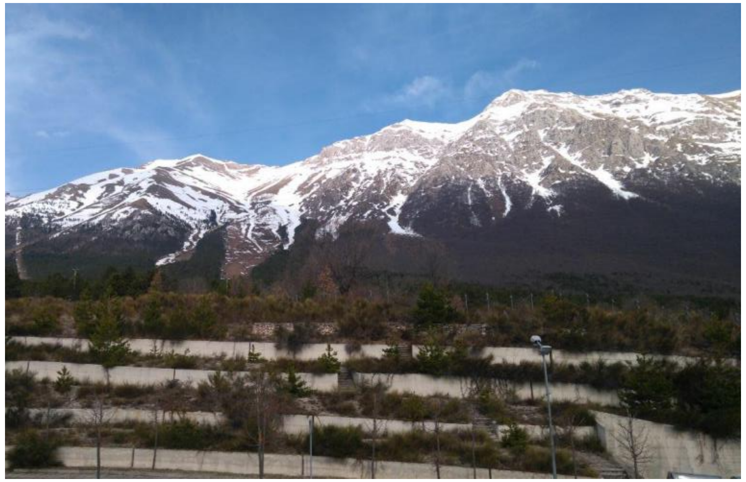
Talk by Steffen Turkat!



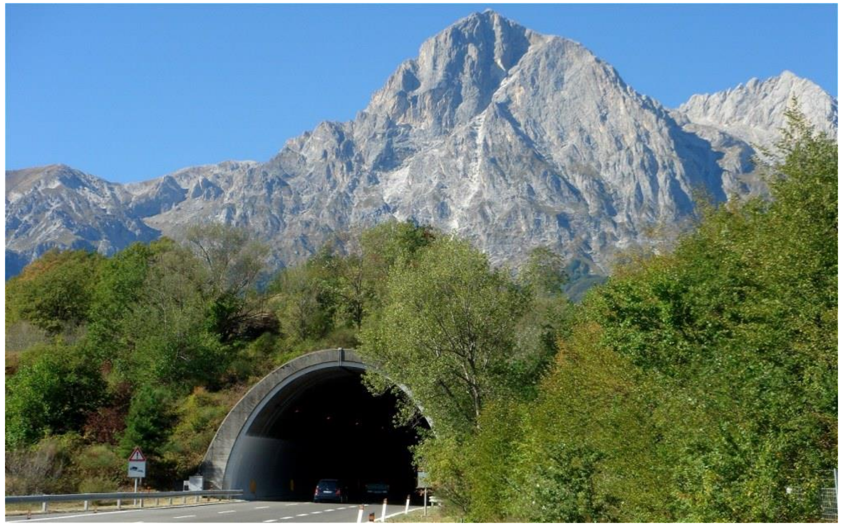
The Laboratory for Underground Nuclear Astrophysics

Laboratori Nazionali del Gran Sasso

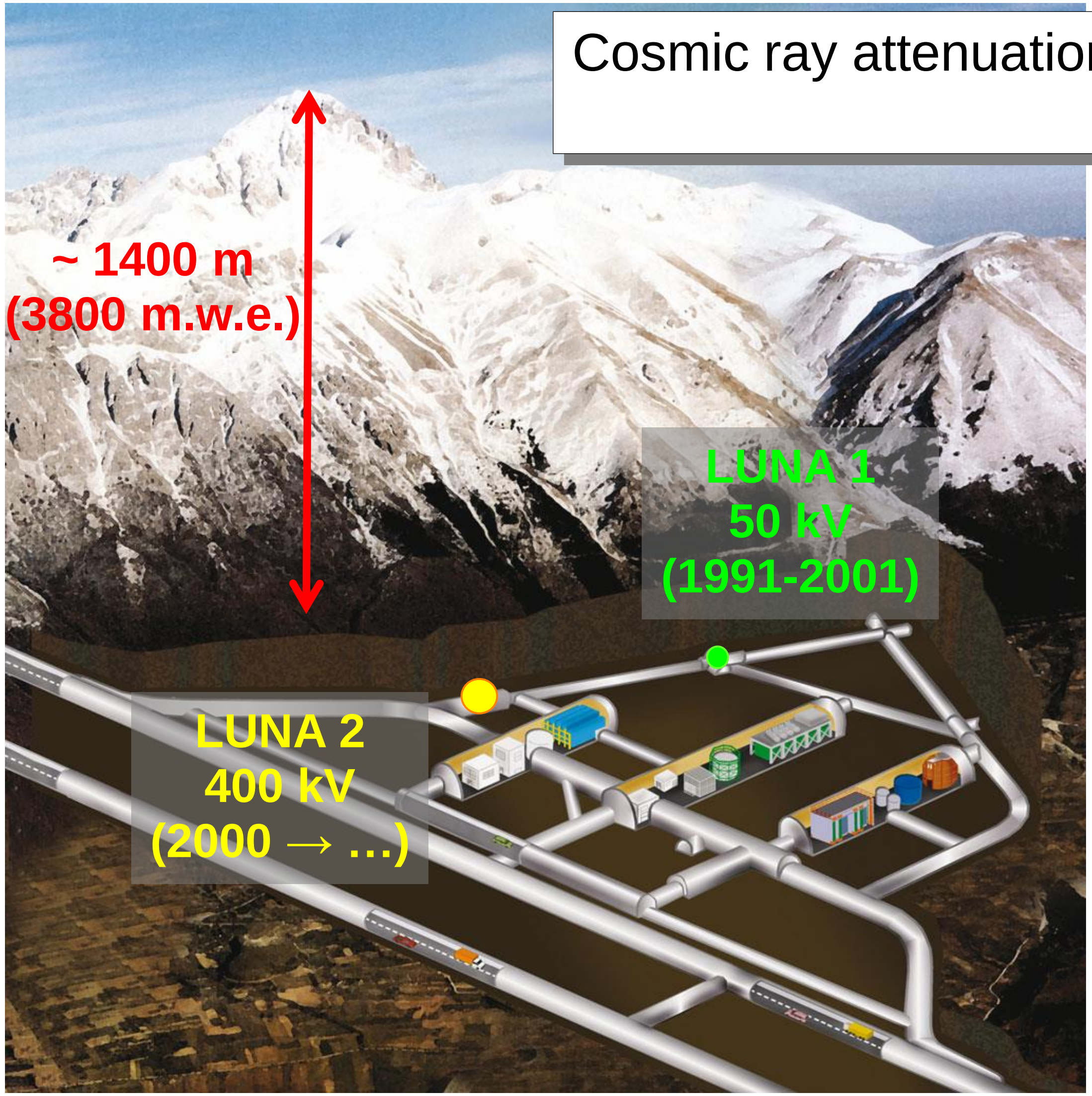




The Laboratory for Underground Nuclear Astrophysics



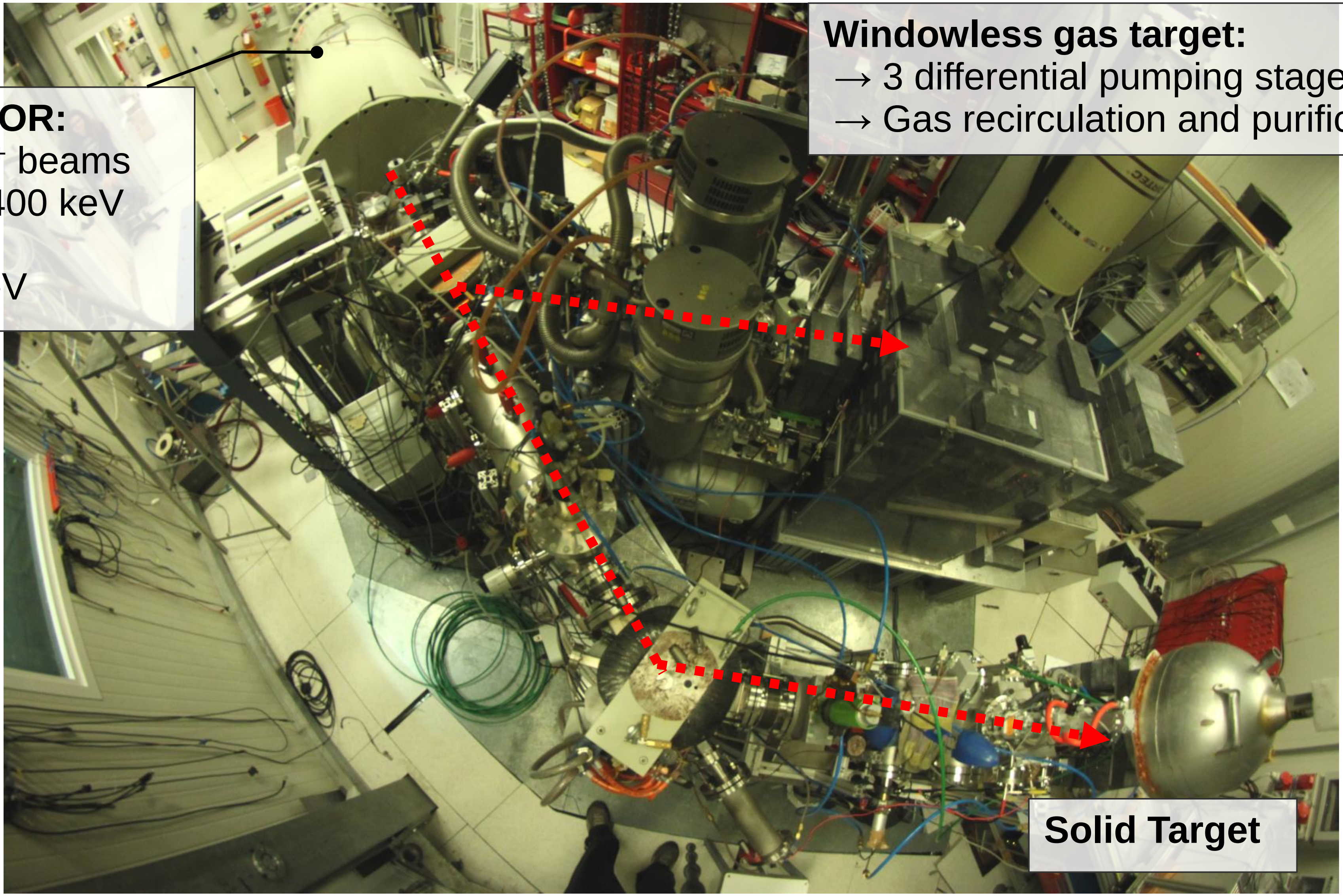
Cosmic ray attenuation: $\mu \rightarrow 10^{-6}$
$n \rightarrow 10^{-3}$



The Laboratory for Underground Nuclear Astrophysics

ACCELERATOR:
→ H^+ and He^+ beams
→ 50 < E < 400 keV
→ I ~ 250 μA
→ ΔE = 100 eV

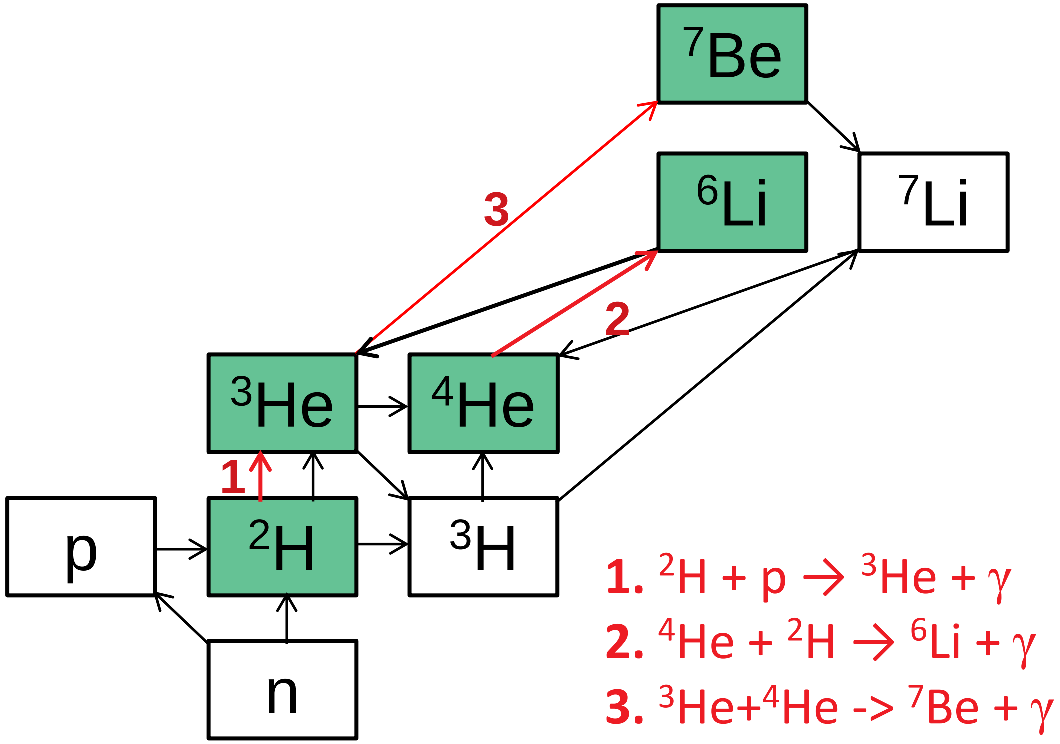
Windowless gas target:
→ 3 differential pumping stages
→ Gas recirculation and purification system



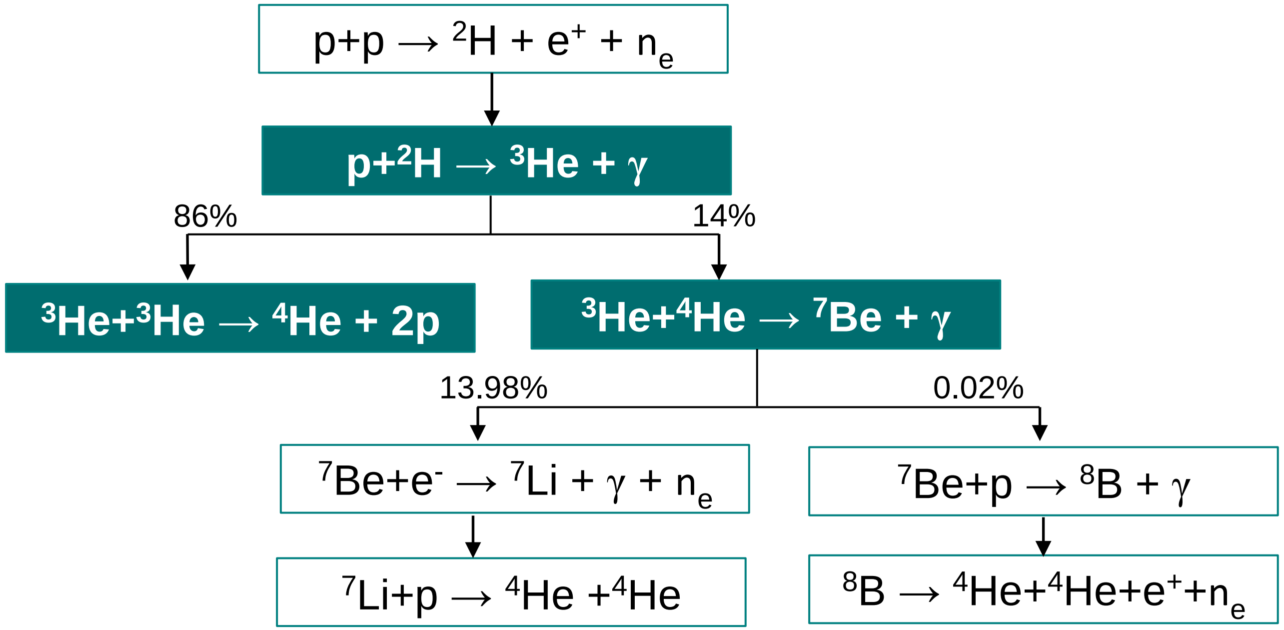
Solid Target

LUNA legacy: Reactions studied since 1991

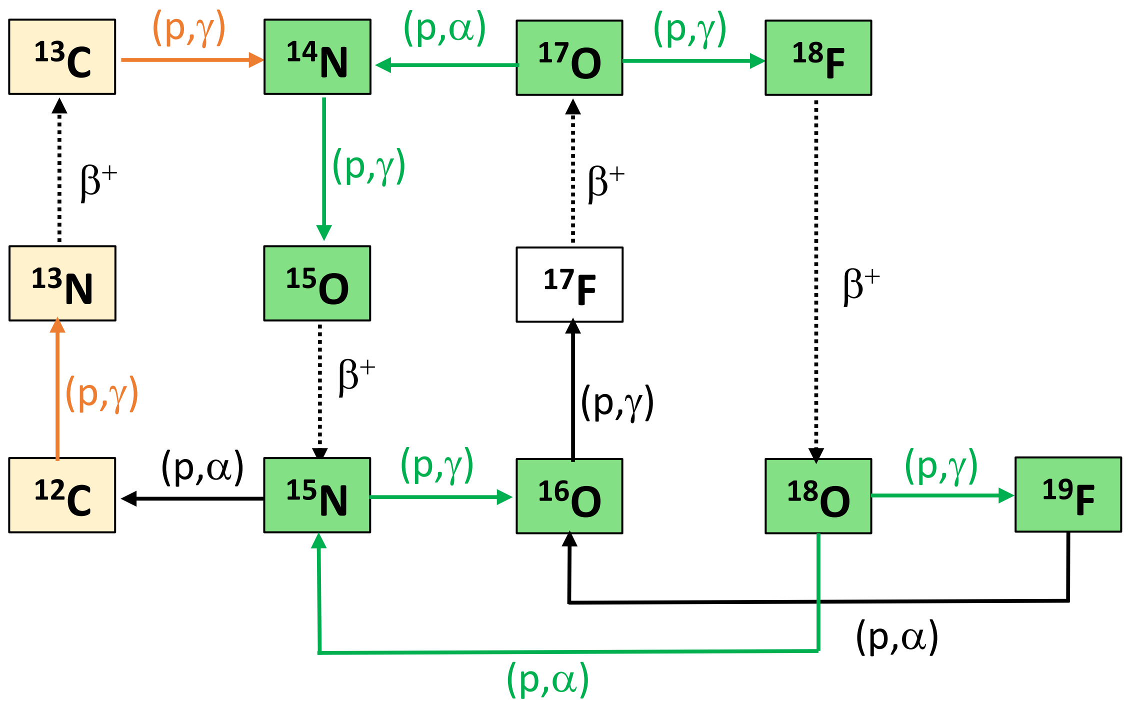
Big Bang Nucleosynthesis



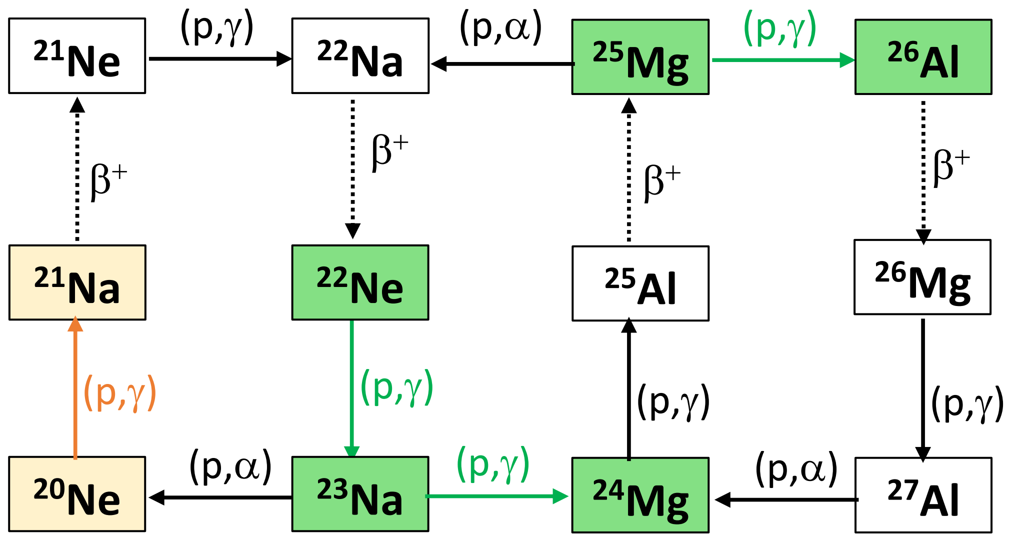
pp CHAIN



CNO CYCLE



NeNa and MgAl CYCLES



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

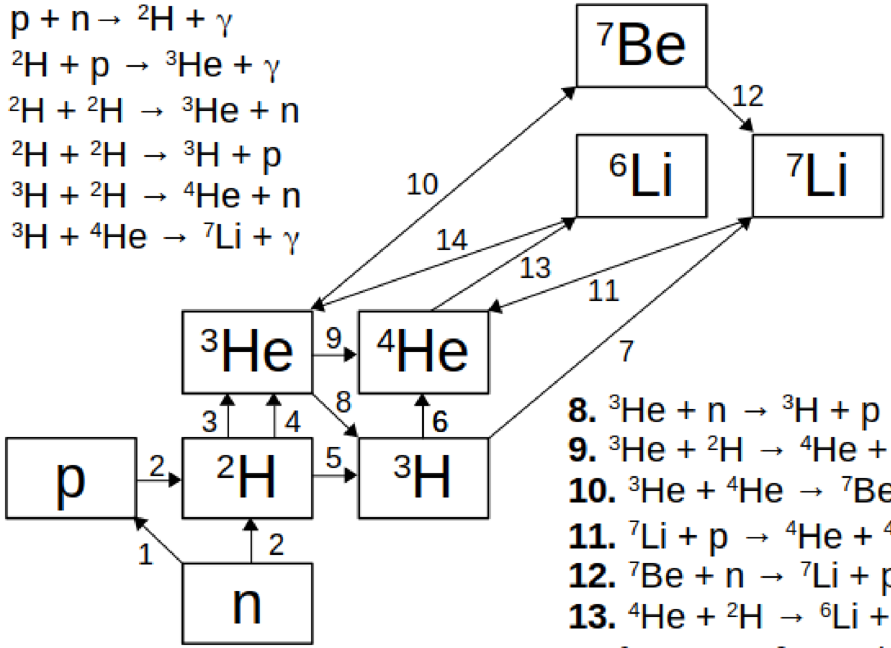
S-PROCESS NUCLEOSYNTHESIS: $^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,\gamma)^{26}Mg$

Recent results by the LUNA Collaboration

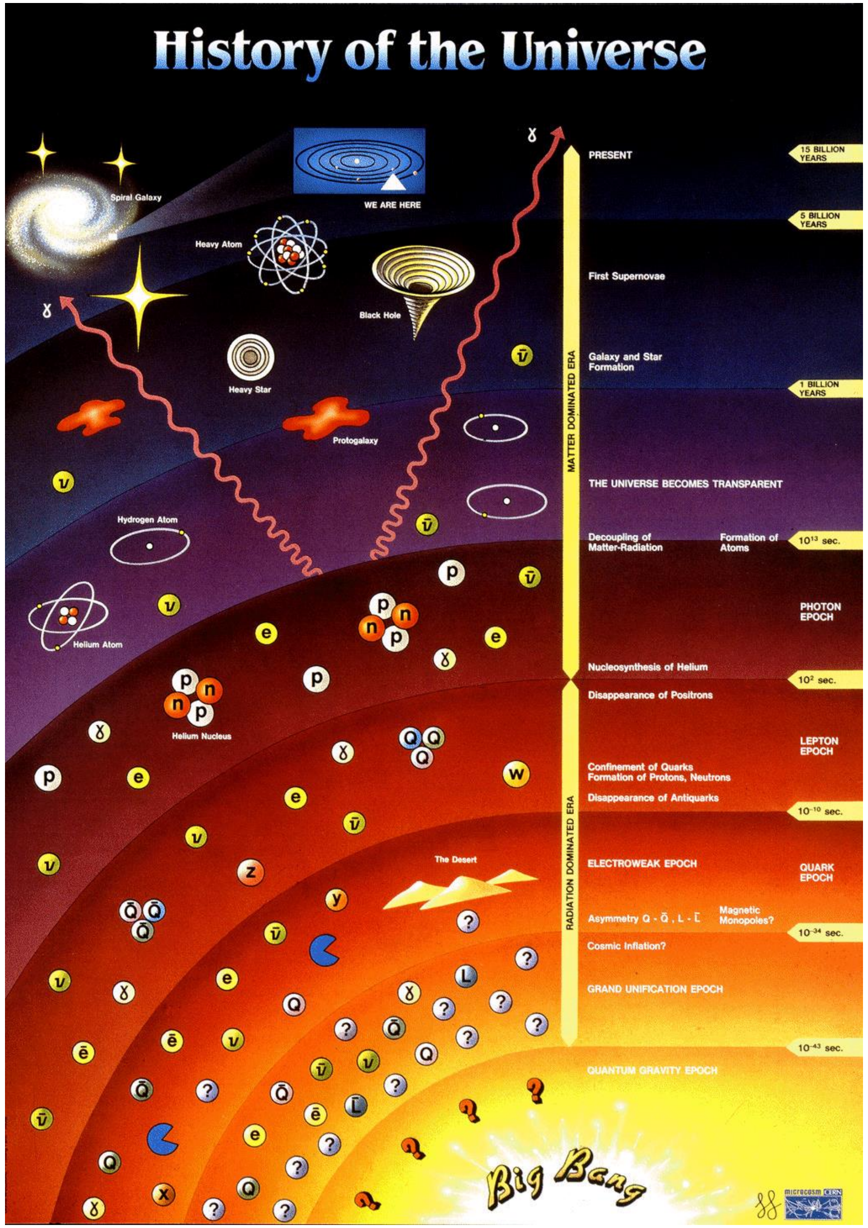
Big Bang Nucleosynthesis

The first nucleosynthesis event dates back to ~ 3 min after the Big Bang

1. $n \rightarrow p + e^- + \nu^*_e$
2. $p + n \rightarrow {}^2H + \gamma$
3. ${}^2H + p \rightarrow {}^3He + \gamma$
4. ${}^2H + {}^2H \rightarrow {}^3He + n$
5. ${}^2H + {}^2H \rightarrow {}^3H + p$
6. ${}^3H + {}^2H \rightarrow {}^4He + n$
7. ${}^3H + {}^4He \rightarrow {}^7Li + \gamma$

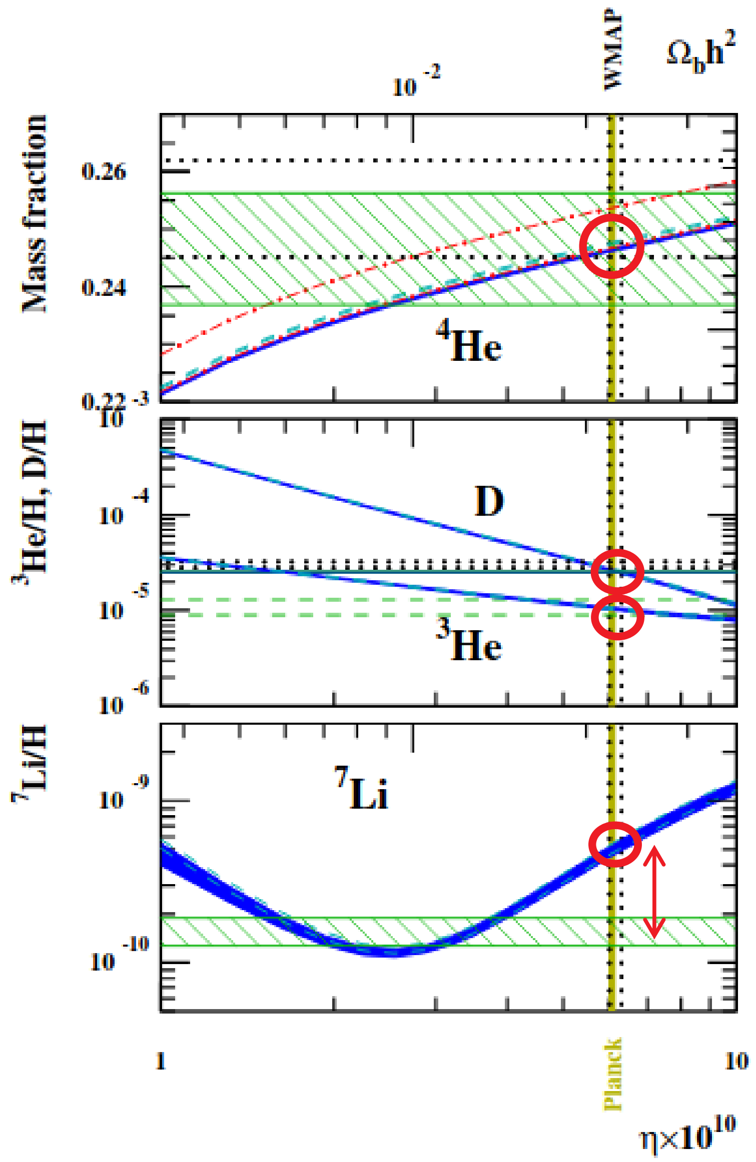


8. ${}^3He + n \rightarrow {}^3H + p$
9. ${}^3He + {}^2H \rightarrow {}^4He + p$
10. ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$
11. ${}^7Li + p \rightarrow {}^4He + {}^4He$
12. ${}^7Be + n \rightarrow {}^7Li + p$
13. ${}^4He + {}^2H \rightarrow {}^6Li + \gamma$
14. ${}^6Li + p \rightarrow {}^3He + {}^4He$



Big Bang Nucleosynthesis

The comparison of observed primordial elemental abundances with the abundances predicted by BBN (intersection of blue curves with vertical line)provides stringent constraints to cosmological parameters and the Big Bang model



Alain Coc et al JCAP 10 (2014) 050

The $^2H(p,\gamma)^3He$ reaction

PRIMORDIAL ABUNDANCE OF ^2H:

- Direct measurements: observation of absorption lines in DLA system

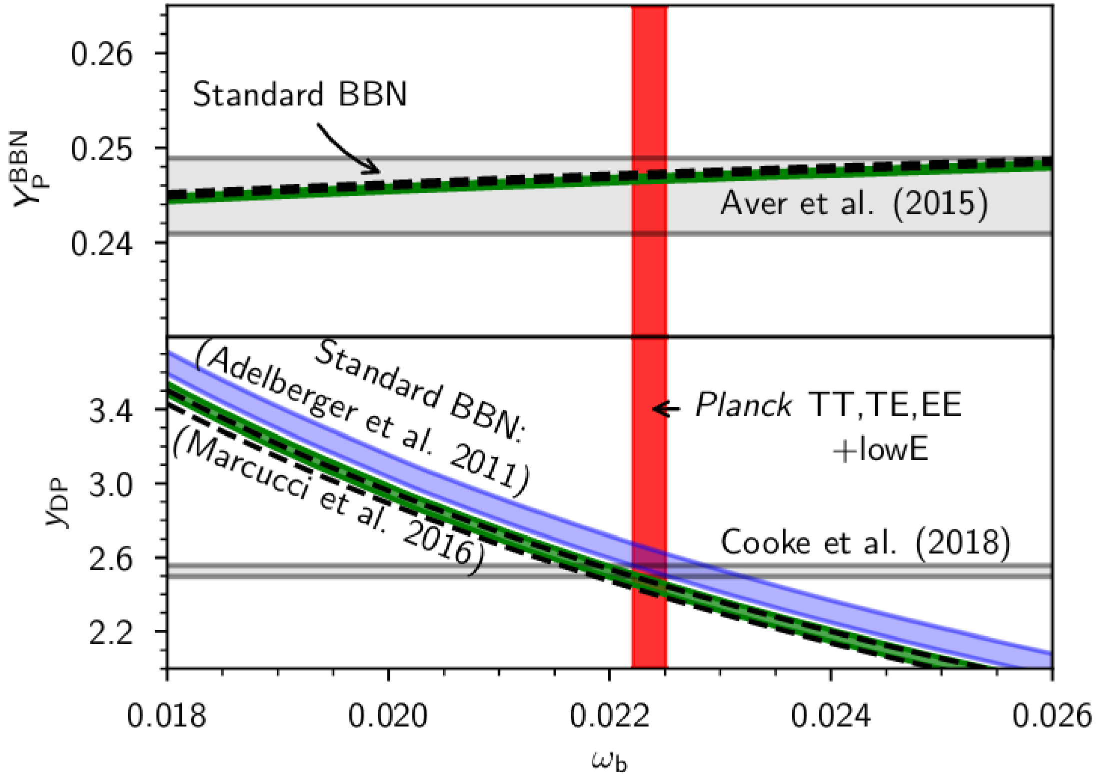
$$\left[\frac{D}{H}\right]_{OBS} = (2.527 \pm 0.030) \cdot 10^{-5}$$

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

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

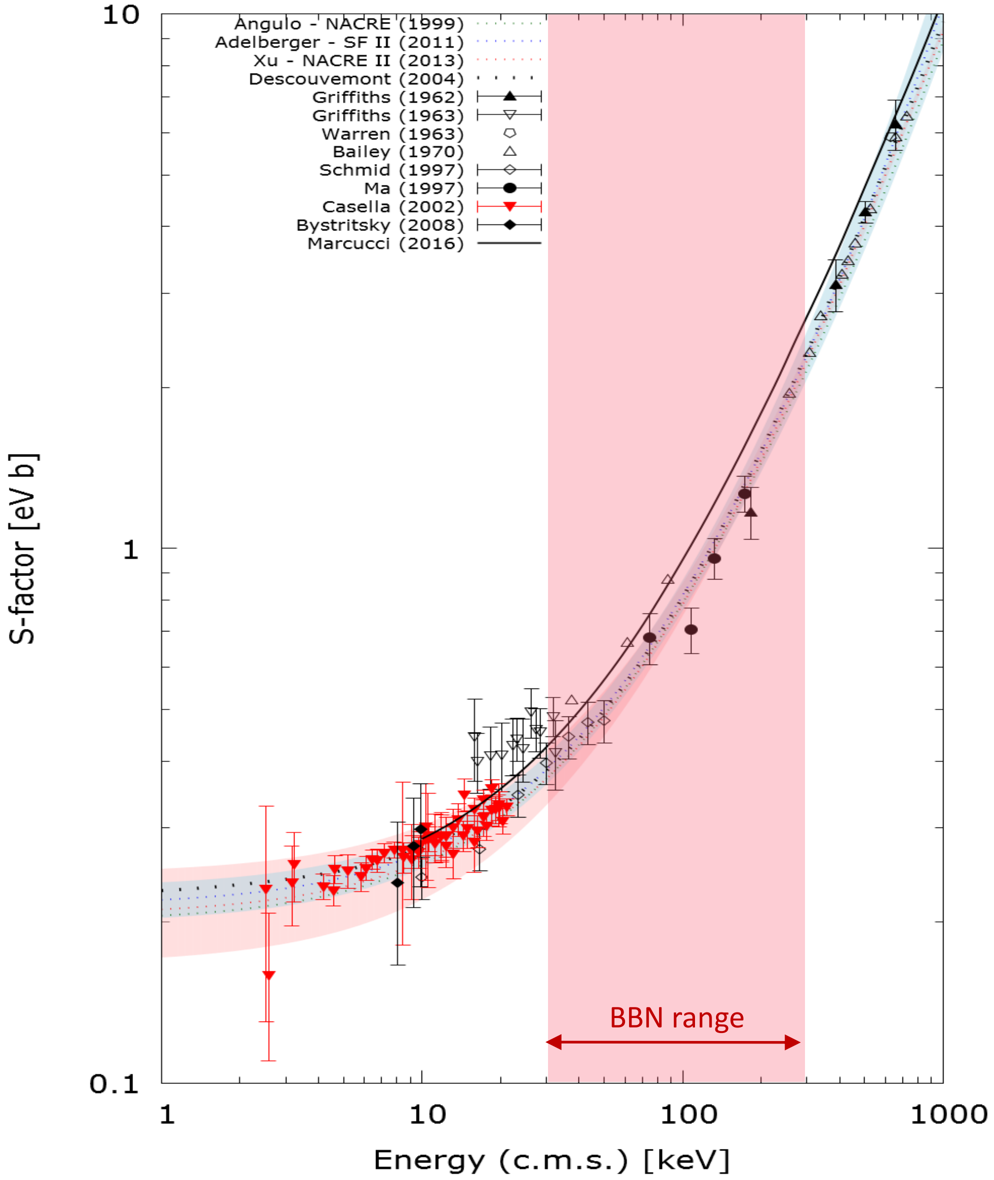
$$\left[\frac{D}{H}\right]_{BBN} = \begin{matrix} (2.587 \pm 0.055) \cdot 10^{-5} \\ (2.439 \pm 0.052) \cdot 10^{-5} \end{matrix}$$

Plank 2018 results A&A 641, A6 (2020)



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

$^{2}H(p,\gamma)^{3}He$ reaction: State of the art

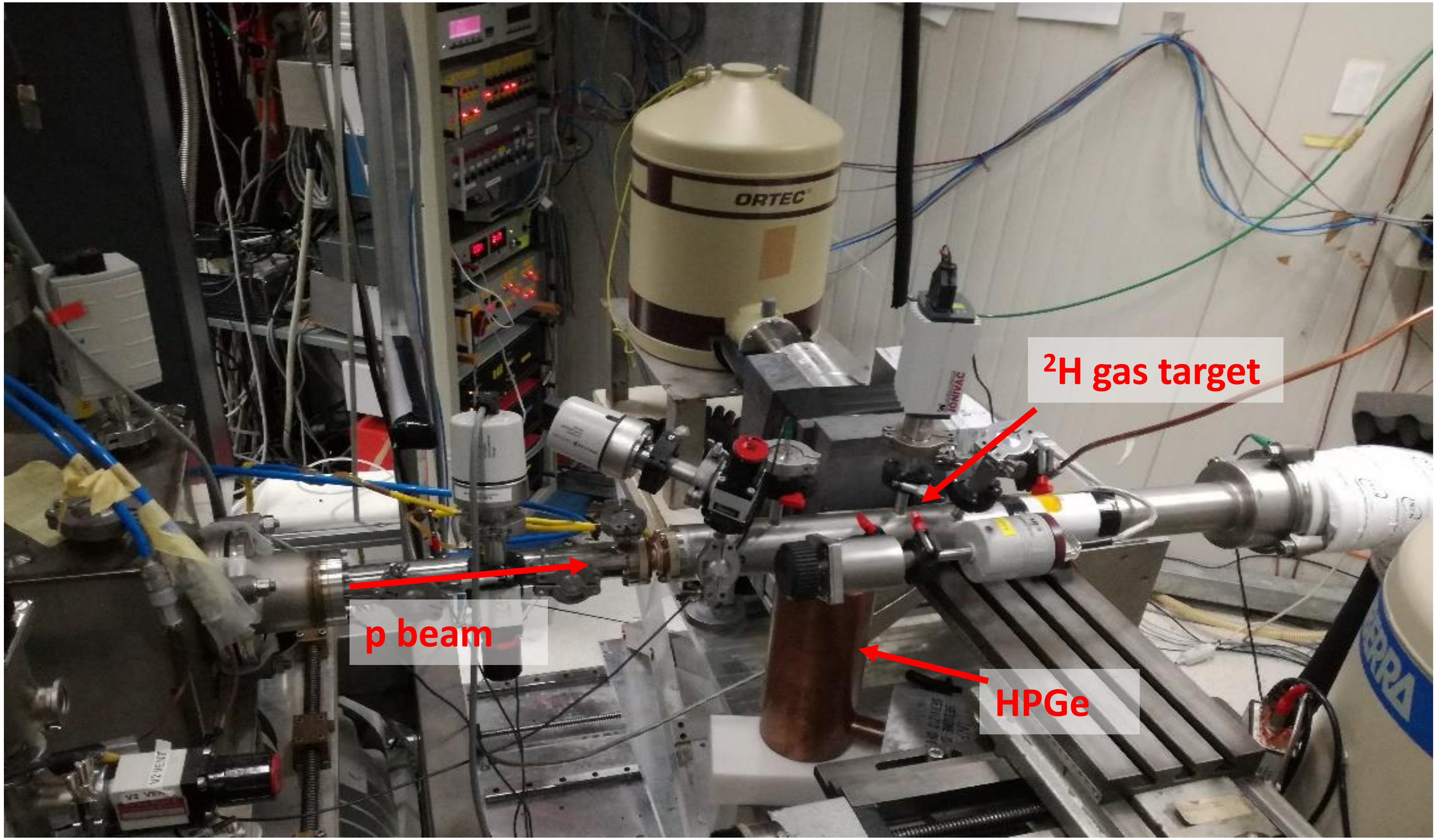


The cross section of the $^{2}H(p,\gamma)^{3}He$ reaction is the main source of uncertainty on the primordial ^{2}H abundance

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

→ Only few data points available at BBN energies

$^2H(p,\gamma)^3He$ reaction: setup at LUNA



V. Mossa et al. EPJ A 56,144 (2020)

$^{2}H(p,\gamma)^{3}He$ reaction: Results

nature

Explore content ⌄ About the journal ⌄ Publish with us ⌄

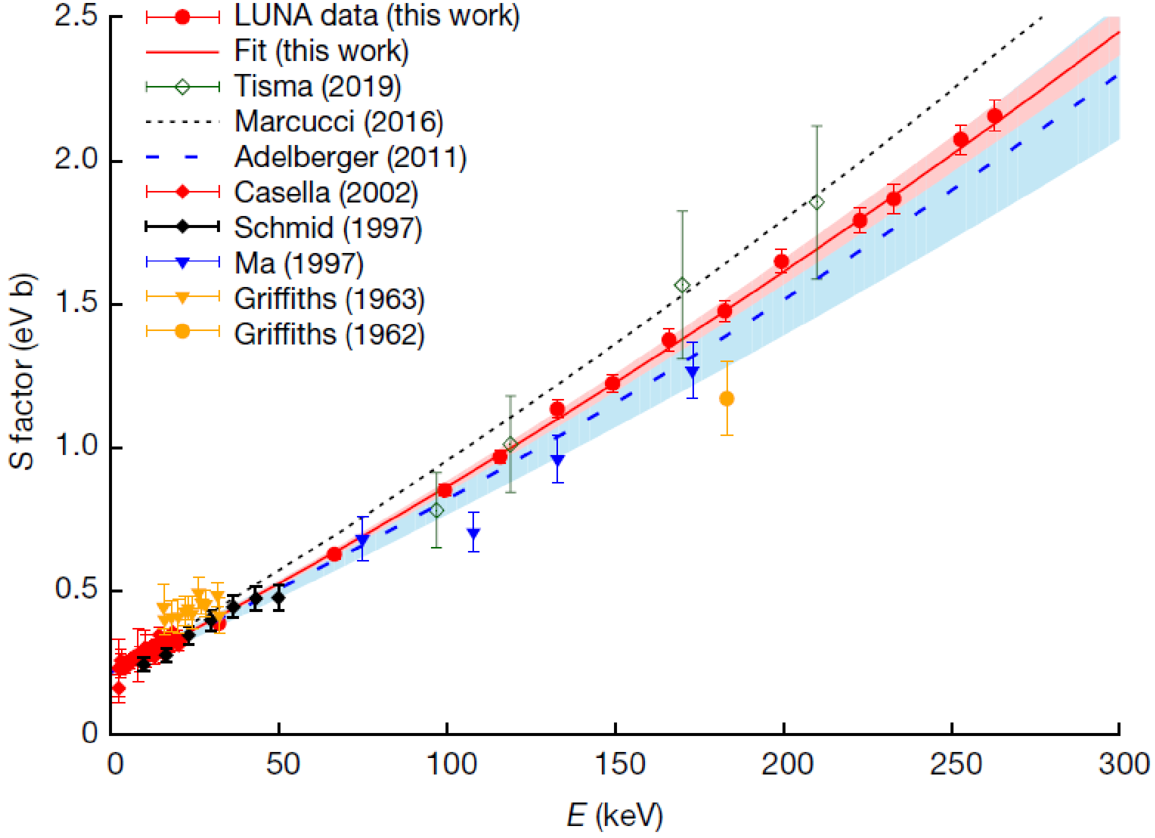
nature › articles › article

Article | Published: 11 November 2020

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

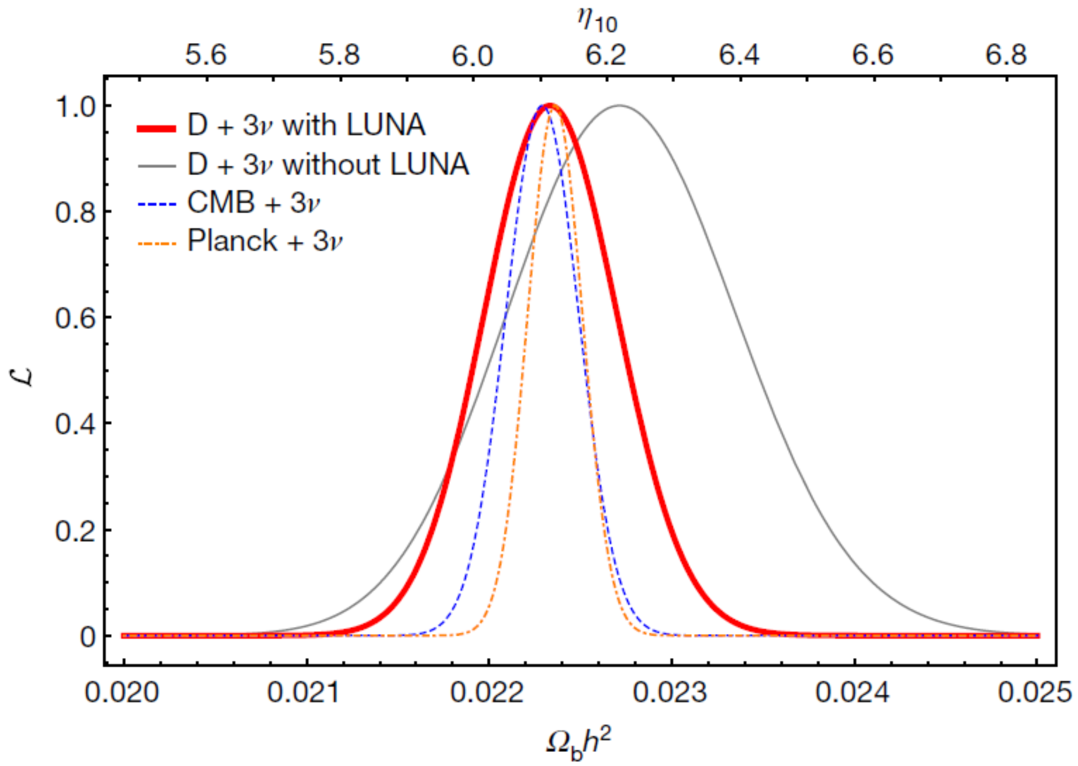
V. Mossa, K. Stöckel, [...]S. Zavatarelli

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



Systematic uncertainty reduced to **< 3%**

$^2H(p,\gamma)^3He$ reaction: Results



Using the baryon density provided by Planck, we derive

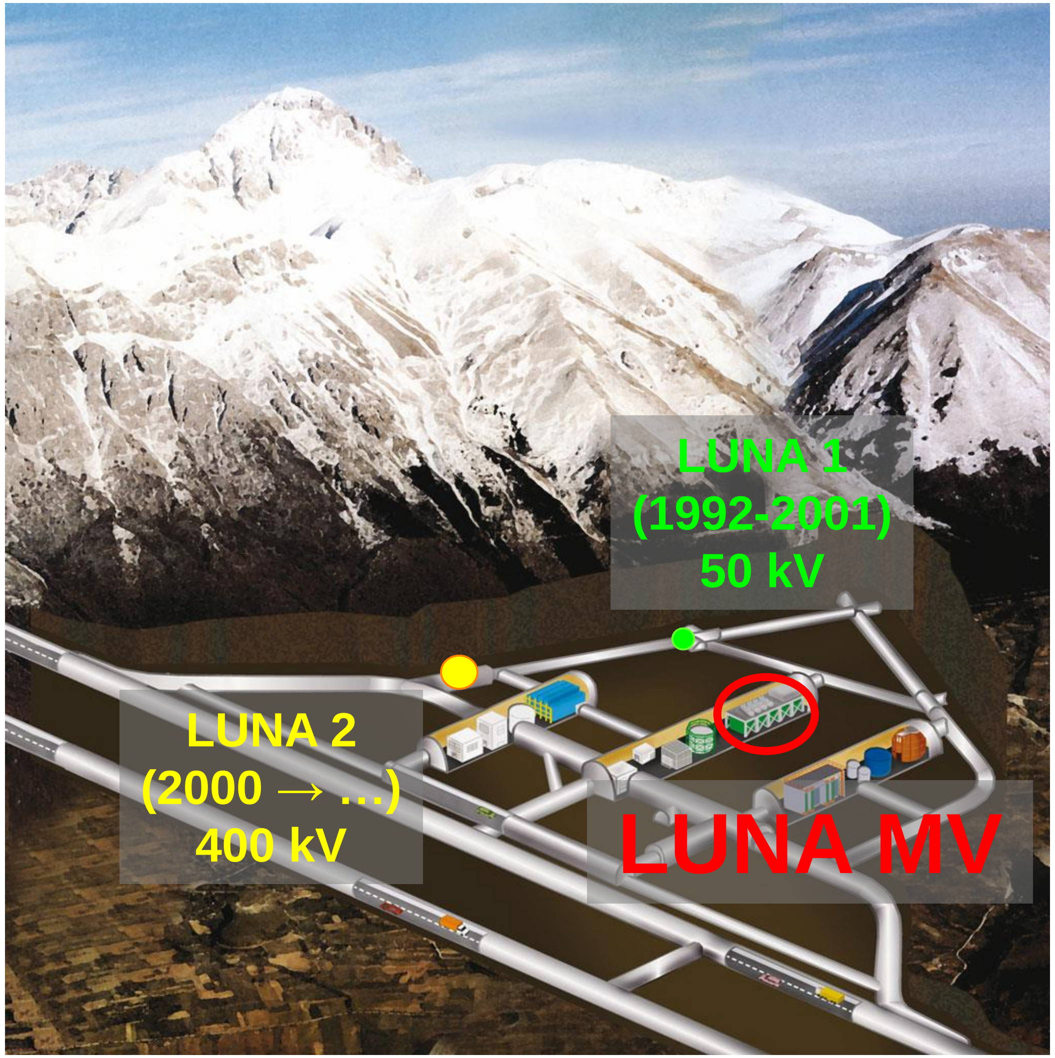
$$\left[\frac{D}{H}\right]_{BBN} = (2.52 \pm 0.07) \cdot 10^{-5}$$

In excellent agreement with astronomical observations

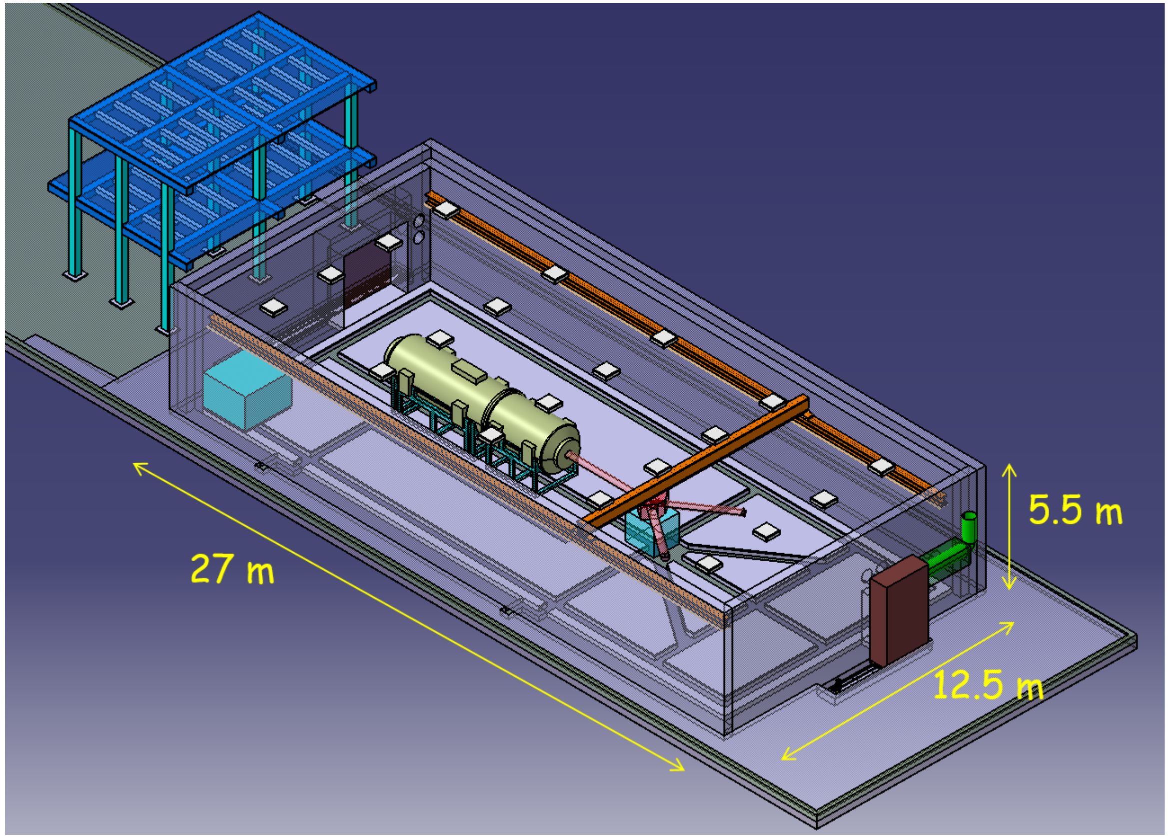
$$\left[\frac{D}{H}\right]_{OBS} = (2.527 \pm 0.030) \cdot 10^{-5}$$

V. Mossa et al. Nature 587, 210–213 (2020)

The LUNA-MV project



The LUNA-MV project



- **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: 60 - 100 eμA

80 cm-thick concrete shielding around accelerator room. This will reduce the neutron flux just outside the shielding to a value about one order of magnitude lower than the neutron flux at LNGS

LUNA-MV: 5yr scientific program

Scientific program for the first 5 years

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

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

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

The LUNA-MV project

Accelerator being installed right now!

THANK YOU!

The LUNA collaboration

A. Compagnucci, M. Junker | **INFN LNGS /*GSSI, Italy**

C. Broggini, A. Caciolli, P. Marigo, R. Menegazzo, D. Piatti, J. Skowronski | **Università di Padova and INFN Padova , Italy**

A. Formicola, C. Gustavino | **INFN Roma 1, Italy**

D. Bemmerer, A. Boeltzig | **HZDR Dresden , Germany**

L. Csedreki, Z. Elekes, Zs. Fülöp, Gy. Gyürky, T. Szücs | **MTA-ATOMKI Debrecen, Hungary**

M. Lugaro | **Konkoly Observatory,n) and spallation Hungarian Academy of Sciences,n) and spallation Budapest, Hungary**

O. Straniero | **INAF Osservatorio Astronomico di Collurania, Italy**

P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli | **Università di Genova and INFN Genova, Italy**

R. Depalo, F. Ferraro, A. Guglielmetti, E. Masha | **Università di Milano and INFN Milano, Italy**

C. Ananna, A. Best, A. Di Leva, G. Imbriani, D. Rapagnani | **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. Davinson | **University of Edinburgh, United Kingdom**

F. Barile, G.F. Ciani, V. Paticchio, L. Schiavulli | **Università di Bari and INFN Bari, Italy**

R. Perrino | **INFN Lecce, Italy**

M. Campostrini, V. Rigato | **INFN LNL, Italy**