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UNIVERSITÀ DEGLI STUDI DI MILANO
INFN

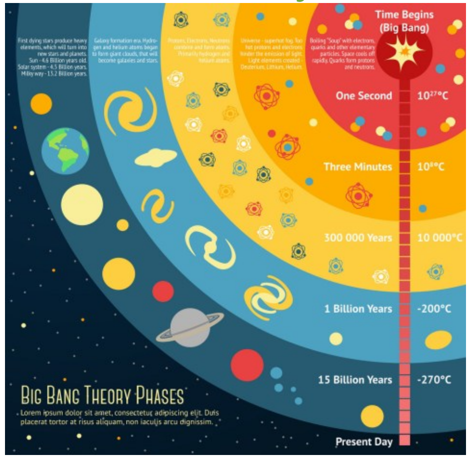
Nuclear Astrophysics deep underground: the LUNA experiment

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

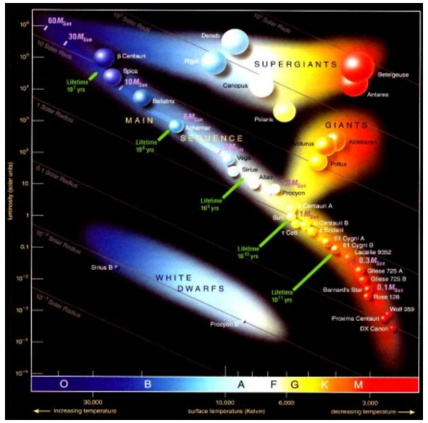
Nuclear reactions in Astrophysics

Nuclear reactions cross sections

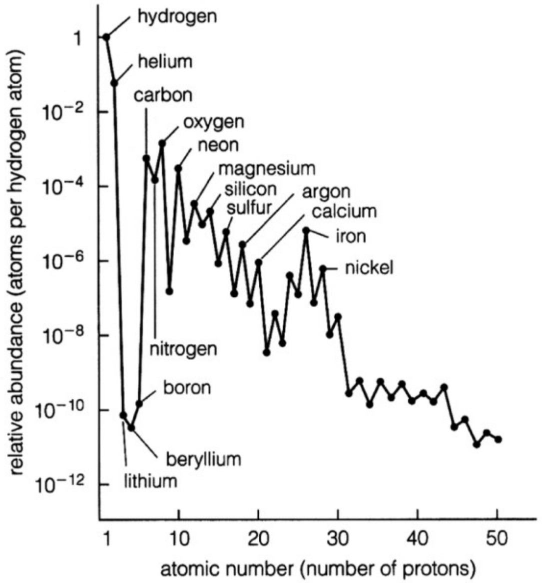
Evolution of early Universe



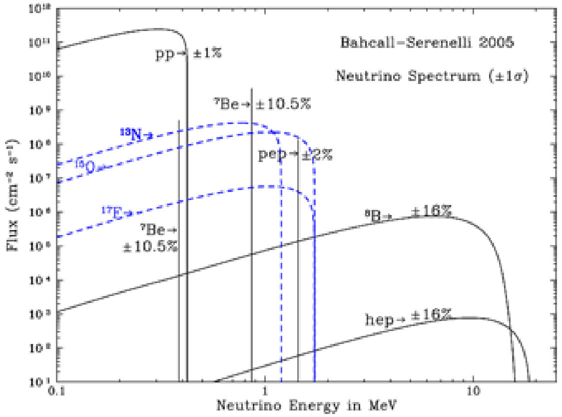
Stellar evolution



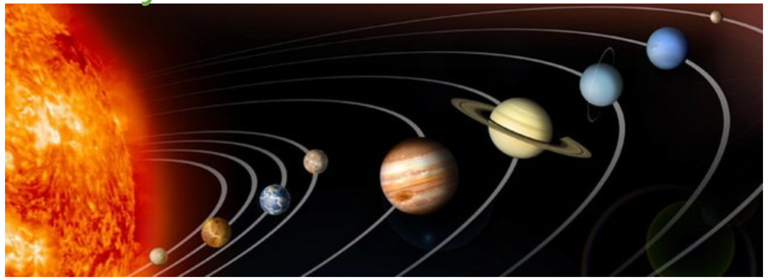
Nucleosynthesis



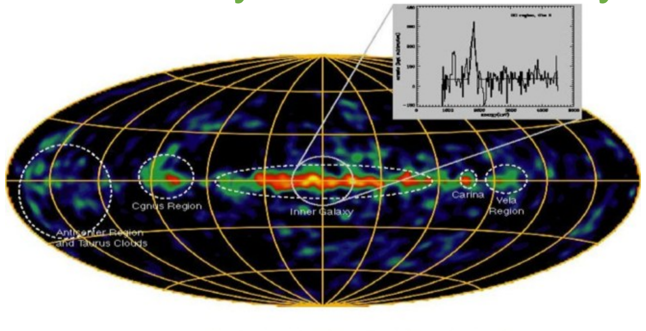
Solar neutrinos



Solar system formation and evolution



Astronomy with radioactivity



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

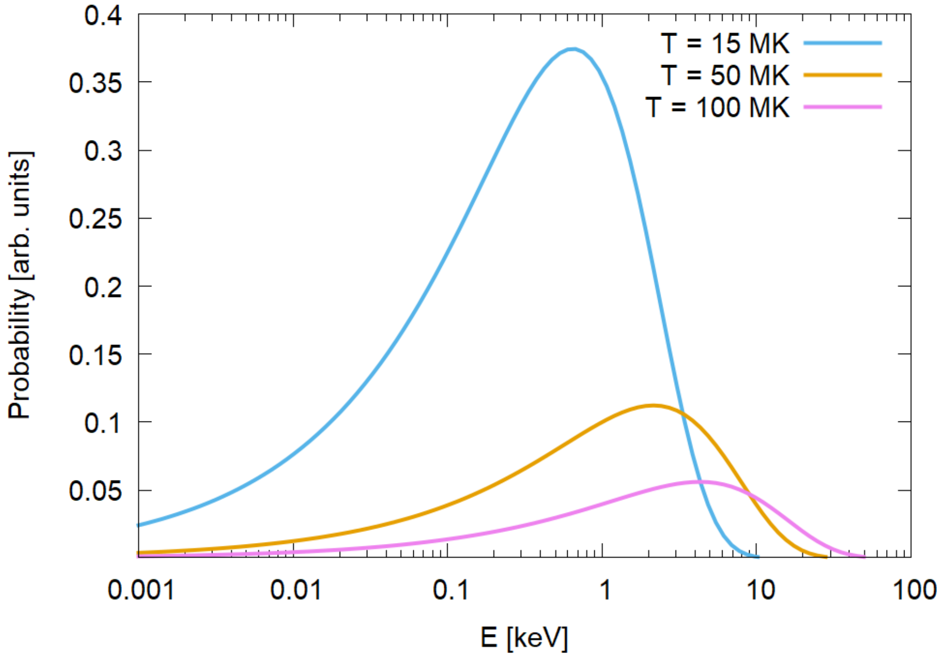
Charged-particle-induced reactions at astro energies

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

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 at astro energies

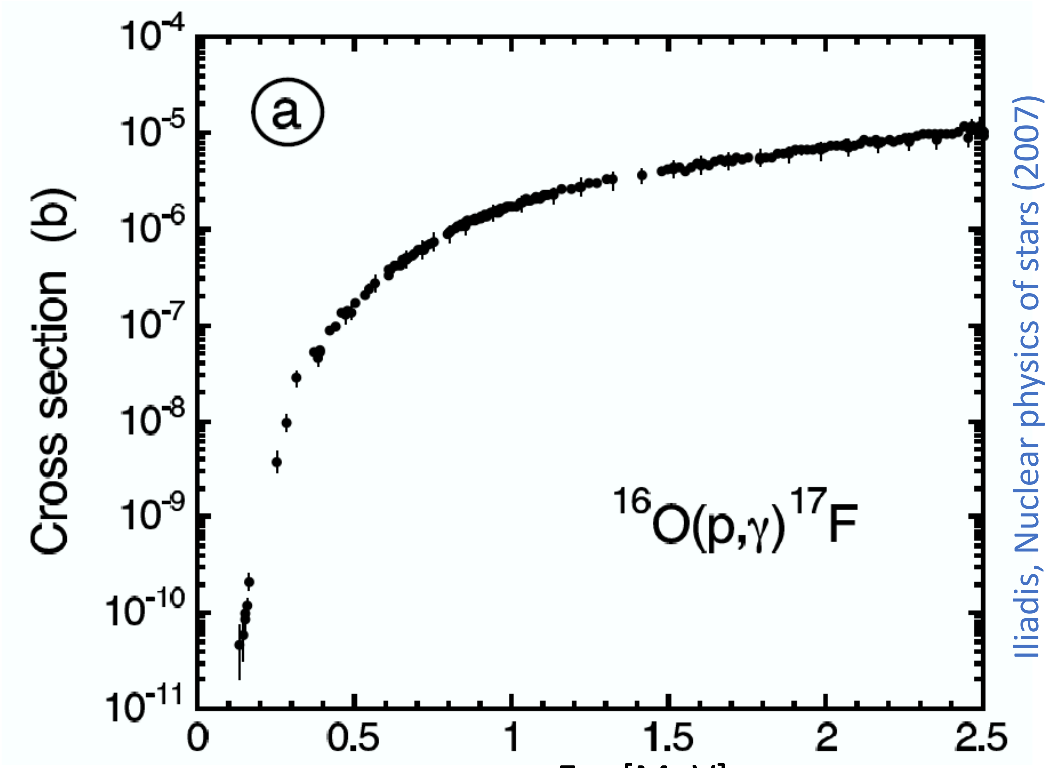
In most astrophysical scenarios, the kinetic energy of interacting nuclei is much lower than Coulomb repulsive potential:

⟶ Nuclear reactions occur through quantum-mechanical tunnel

⟶ Cross sections decreases steeply with energy

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

At astrophysical energies, the cross section can be extremely small (fb – nb)



E_{cm} [MeV]

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^{14} 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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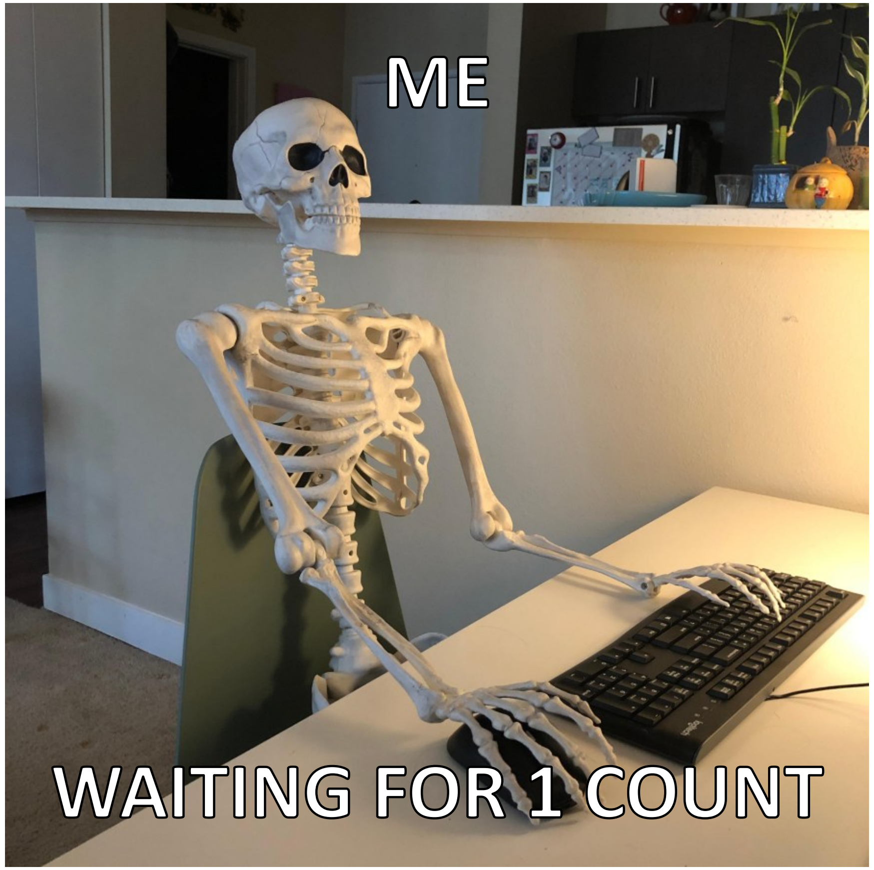
C = 4E-3 –> 4E-1 counts/hour



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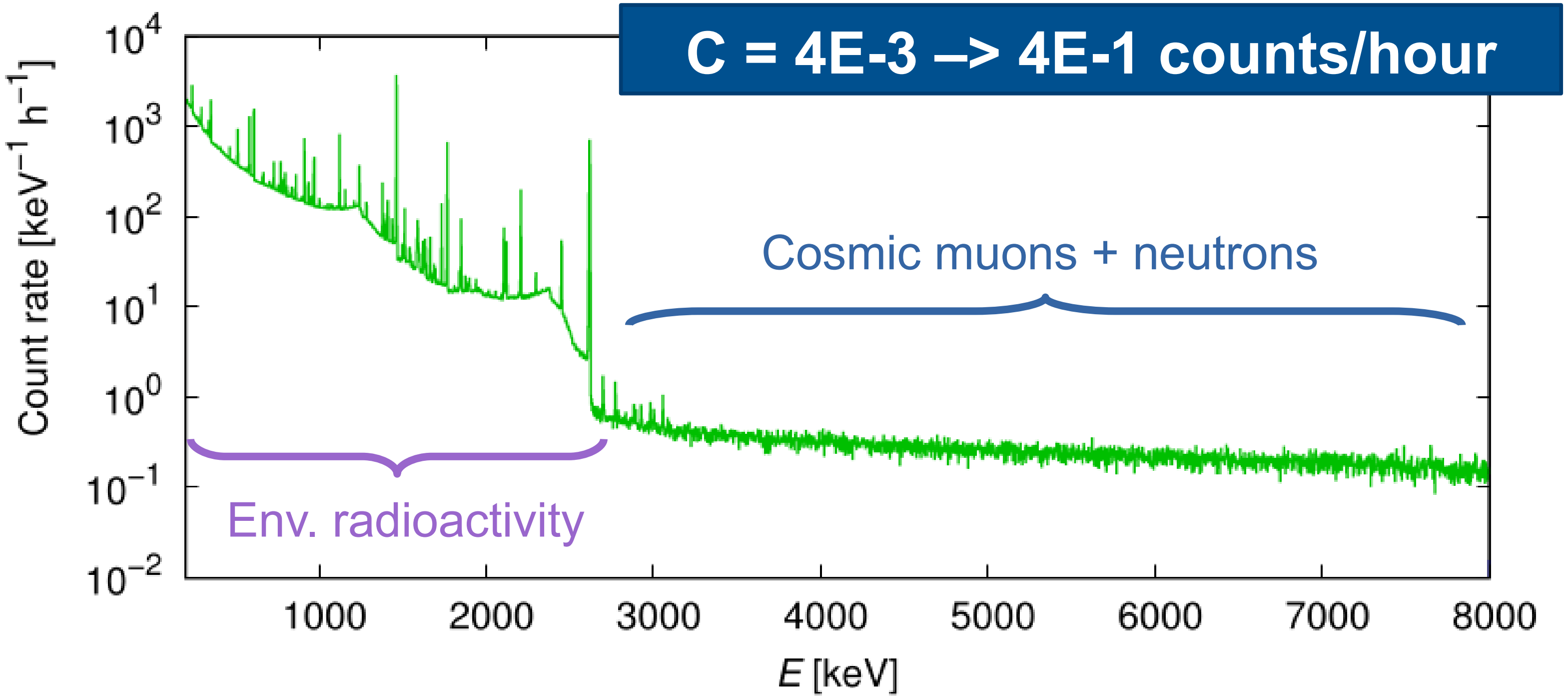
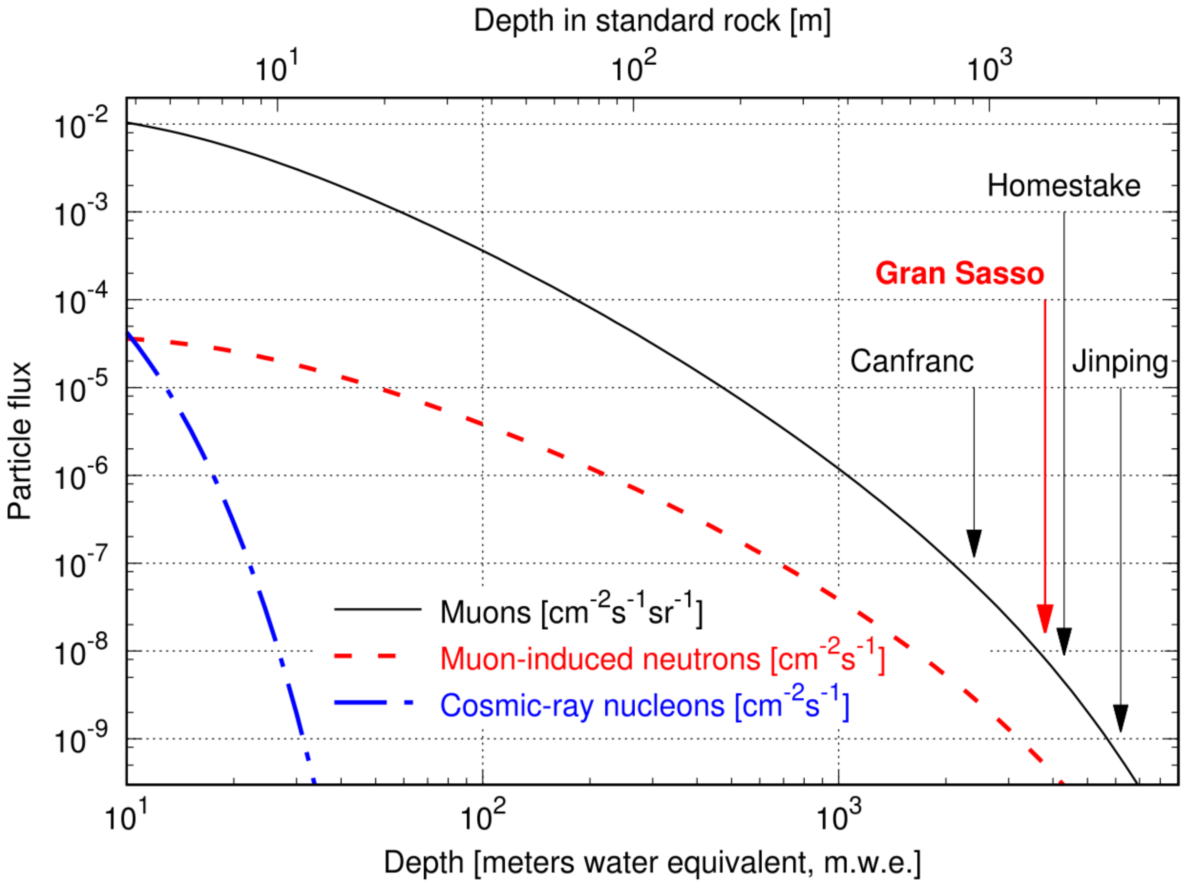


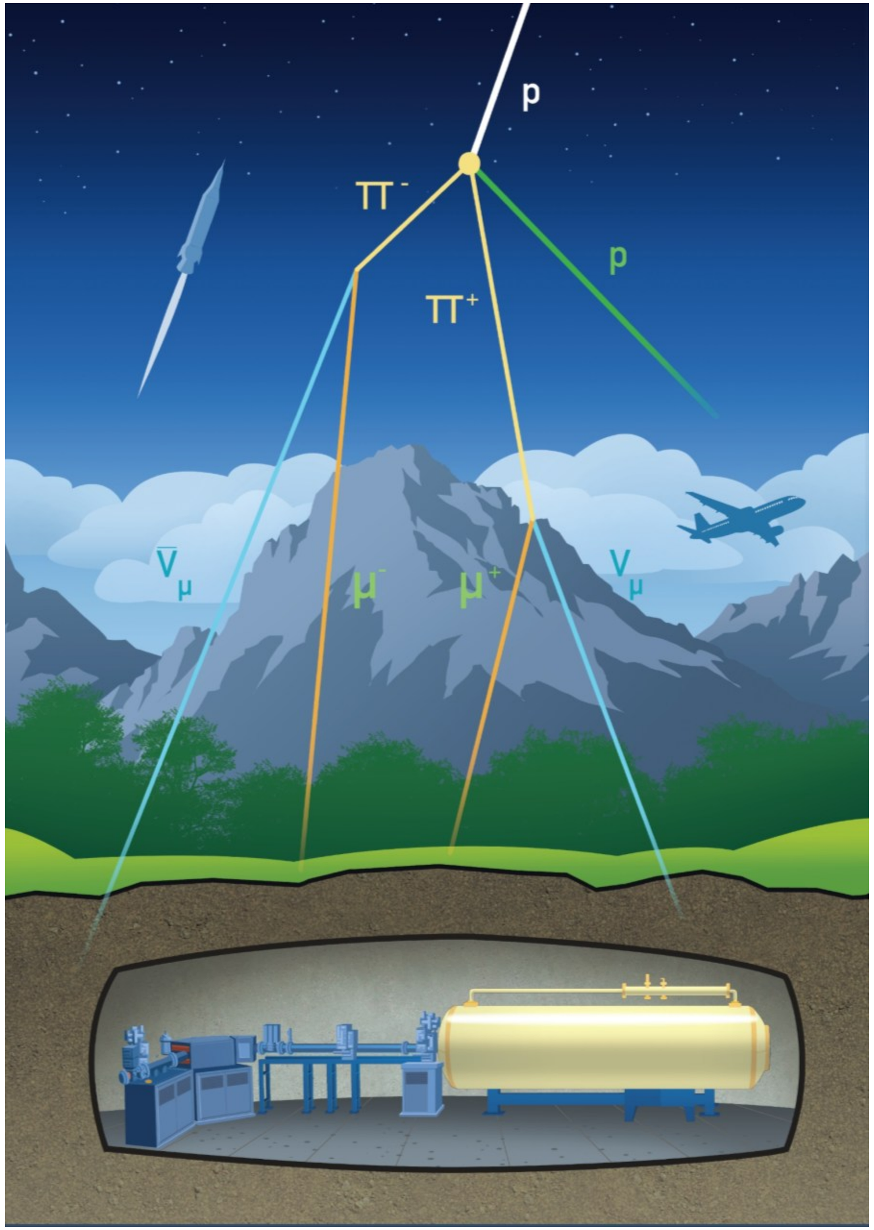
Typical environmental background in HPGe detector

Why underground?

Rocks can efficiently suppress cosmic ray flux



C. Broggini+, Prog. Part. Nuc. Phys. 98 (2018) 55–84

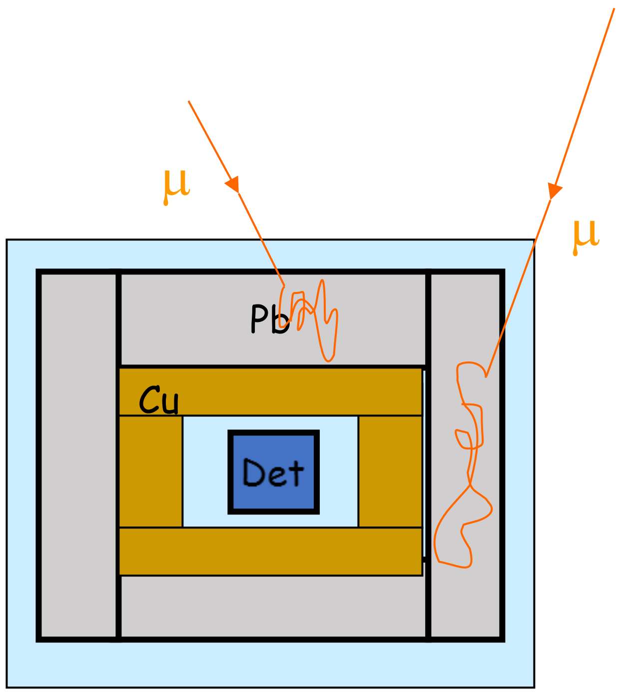


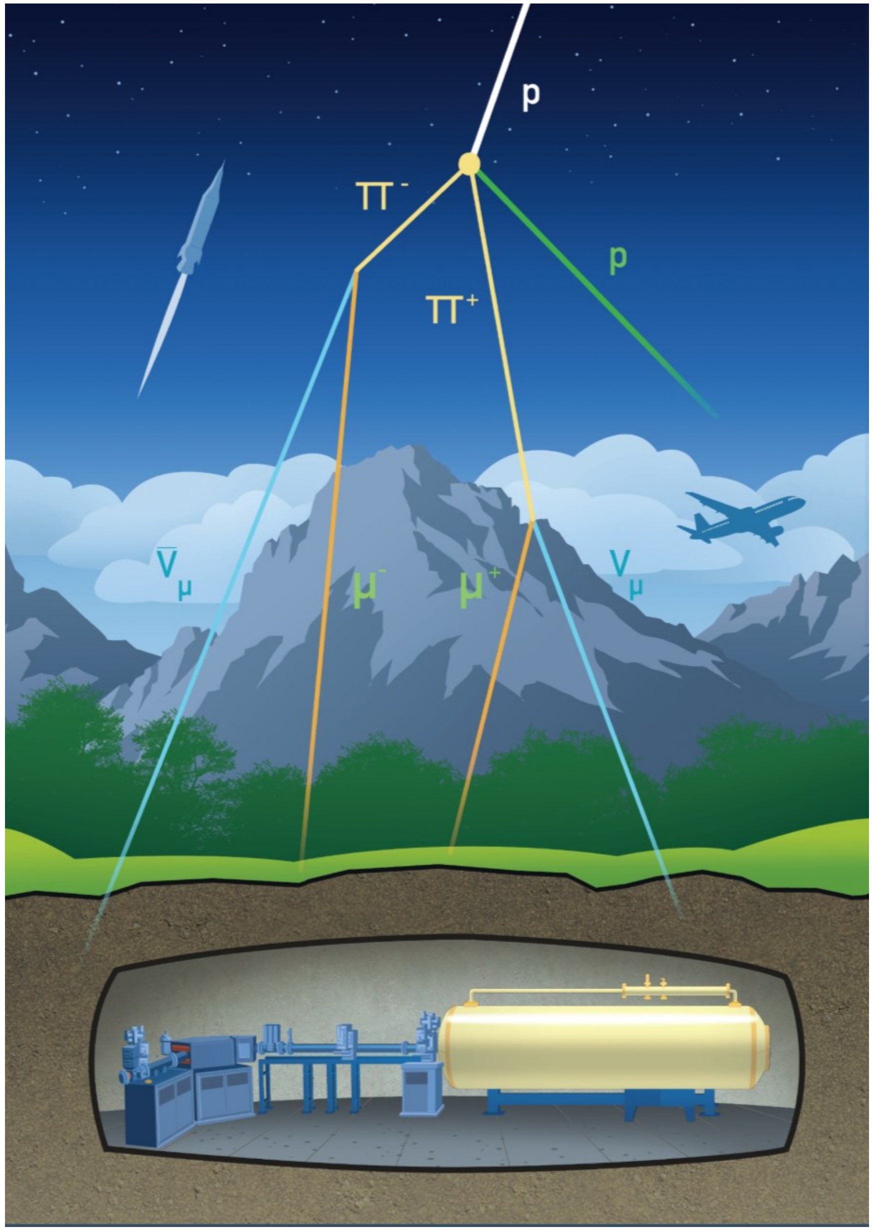
Why underground?

+ More effective passive shielding for Eγ < 3 MeV

Underground passive shielding is more effective since μ flux, that create secondary γ's in the shield, is suppressed.

Background reduction as high as a factor of 10^5





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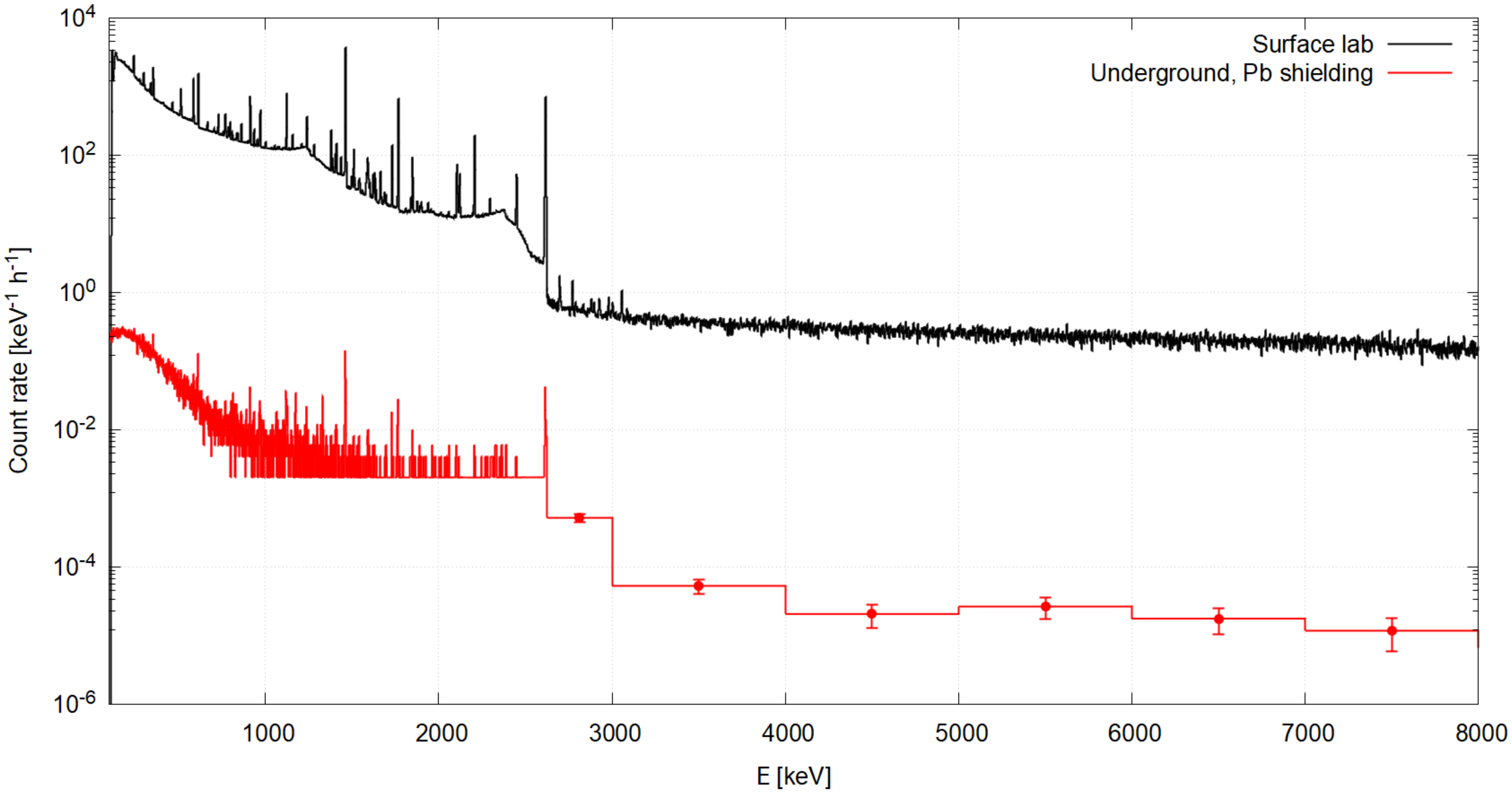
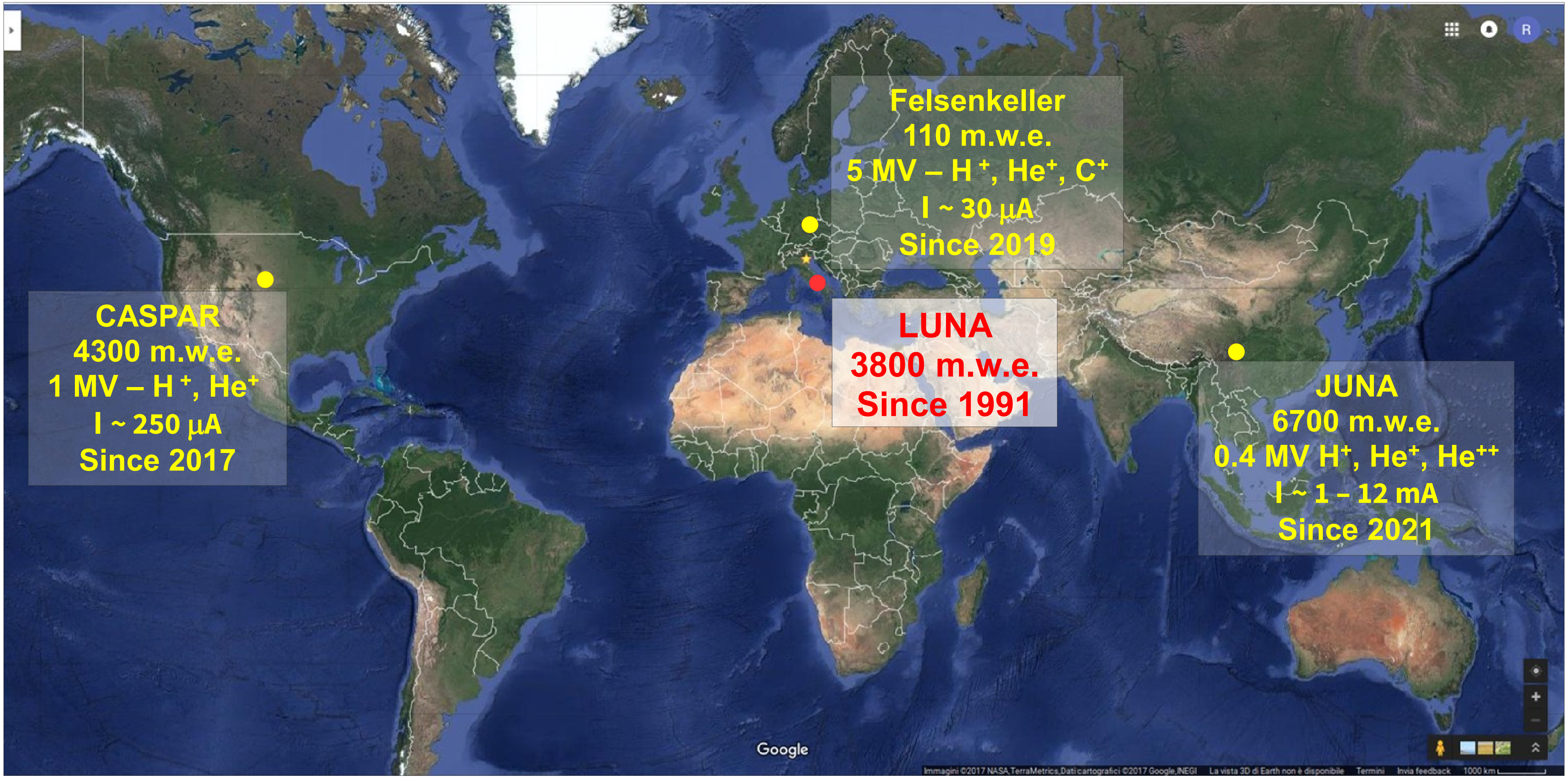


Underground Nuclear Astrophysics worldwide



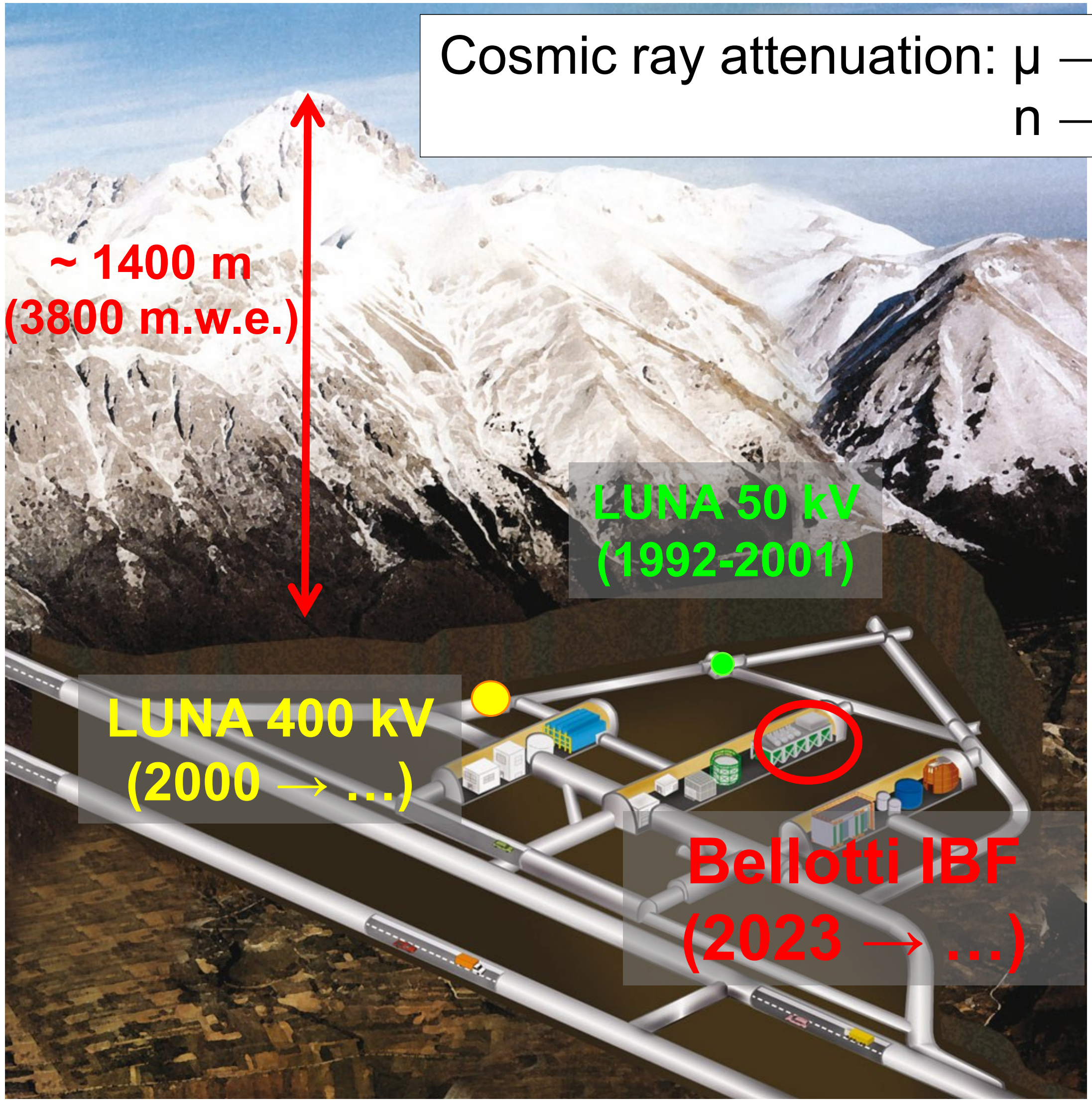
The Laboratory for Underground Nuclear Astrophysics

Laboratori Nazionali del Gran Sasso

The Laboratory for Underground Nuclear Astrophysics

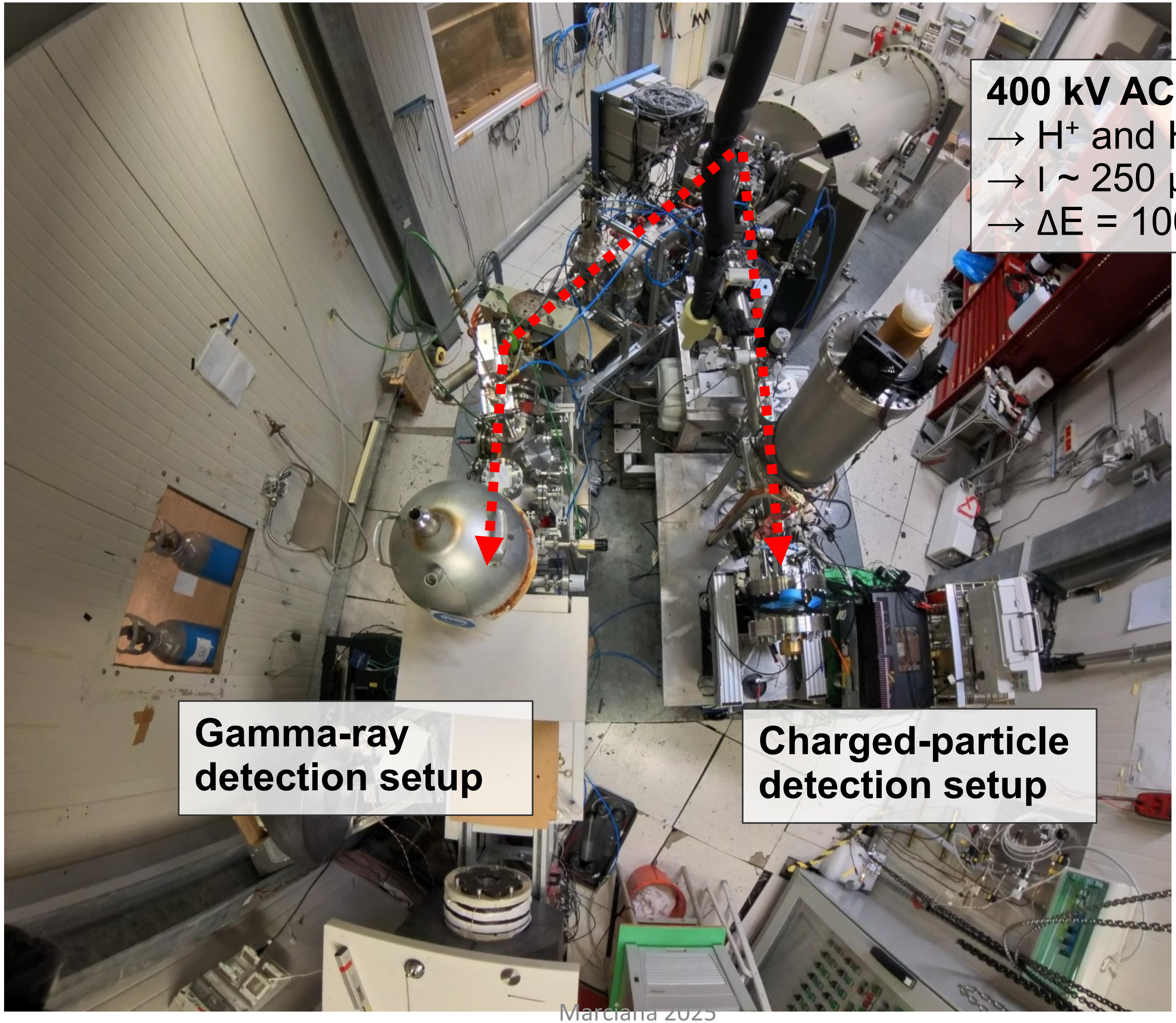
Virtual tour of LNGS
available on Google Maps

The Laboratory for Underground Nuclear Astrophysics



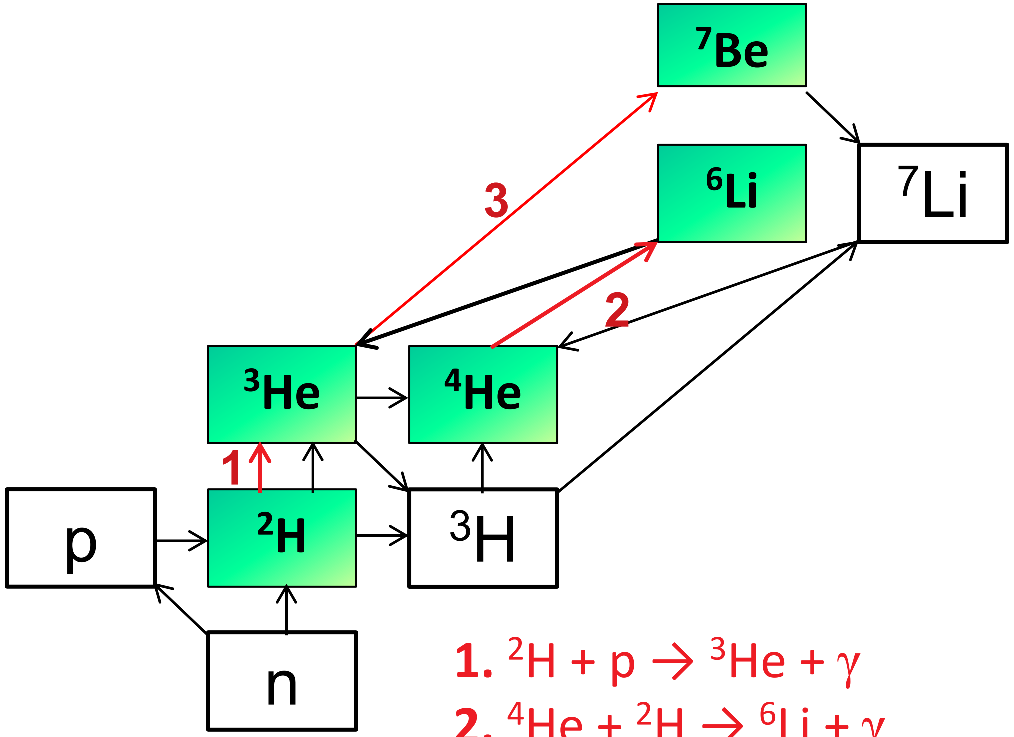
Cosmic ray attenuation: $\mu \rightarrow 10^{-6}$
$n \rightarrow 10^{-3}$

LUNA-400 kV


400 kV ACCELERATOR:
→ H^+ and He^+ beams
→ I ~ 250 µA
→ ΔE = 100 eV
Gamma-ray detection setup
Charged-particle detection setup

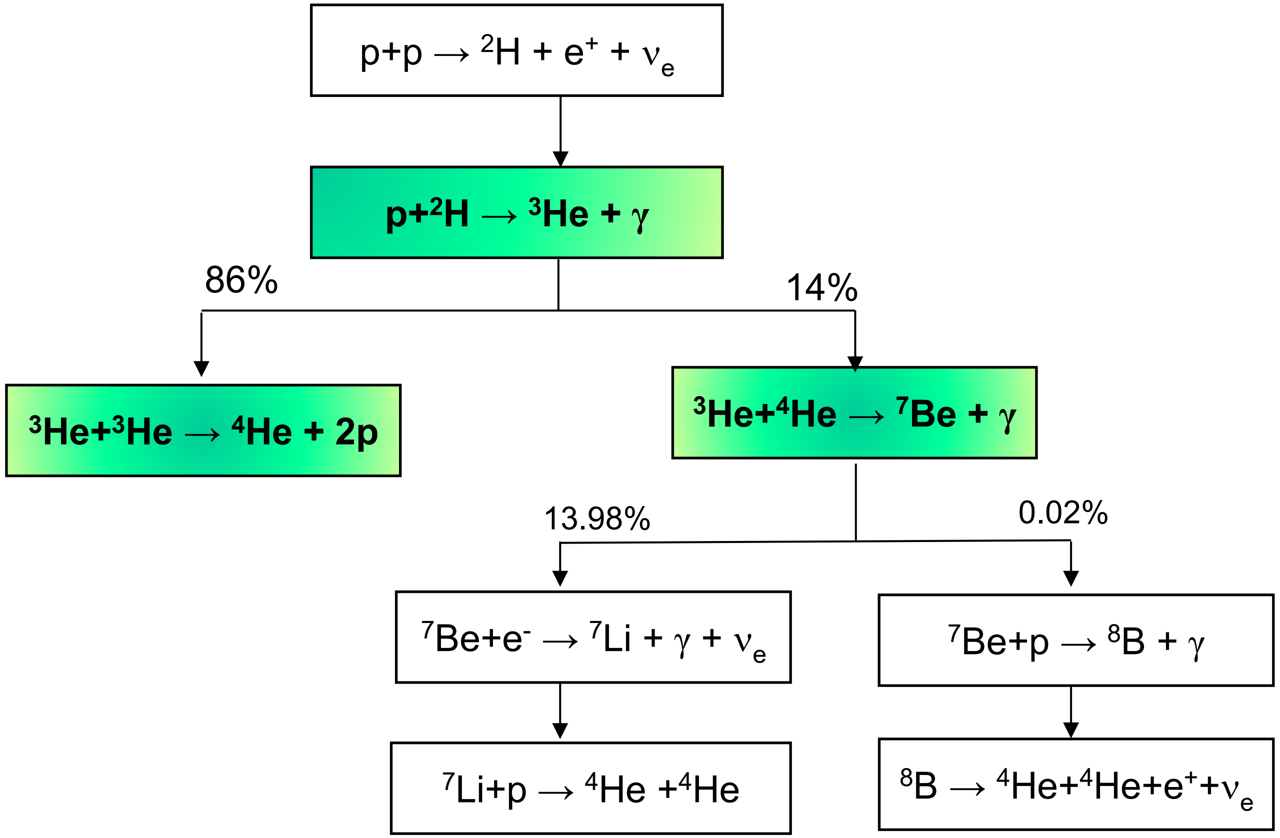
Reactions studied at LUNA since 1991

Big Bang Nucleosynthesis



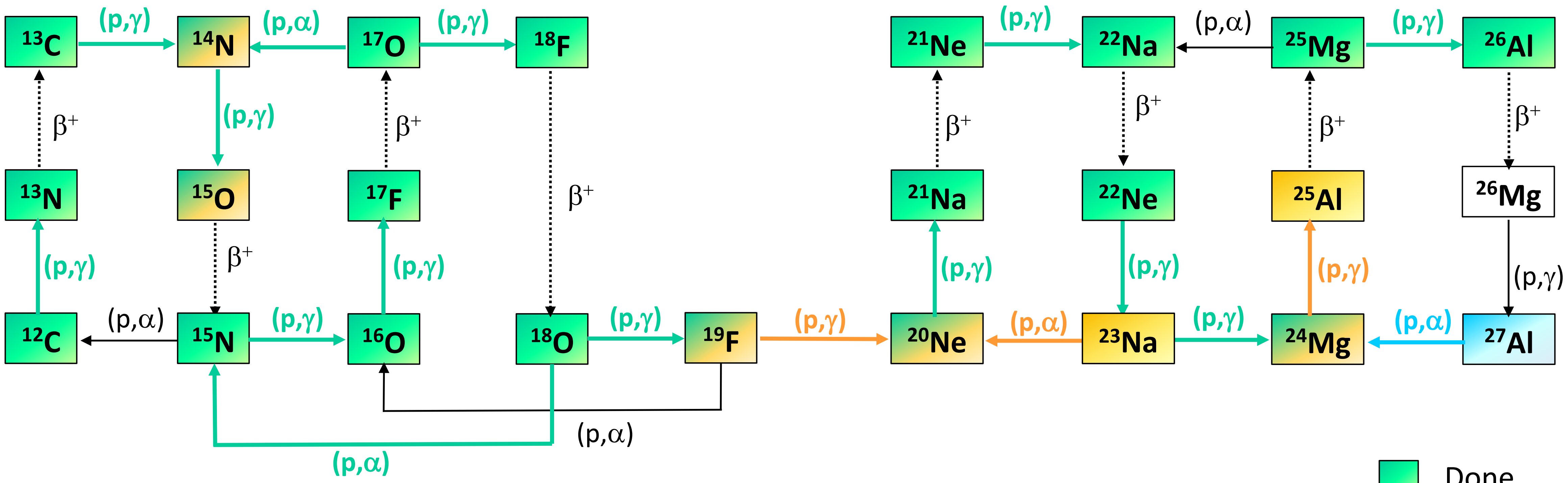
1. $^{2}H + p \rightarrow {}^{3}He + \gamma$
2. $^{4}He + {}^{2}H \rightarrow {}^{6}Li + \gamma$
3. $^{3}He + {}^{4}He$ -> $^{7}Be + \gamma$

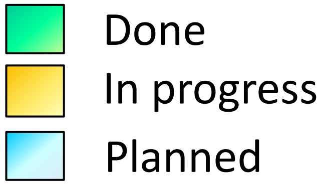
pp chain



Reactions studied at LUNA since 1991

CNO CYCLE **NeNa and MgAl CYCLES**



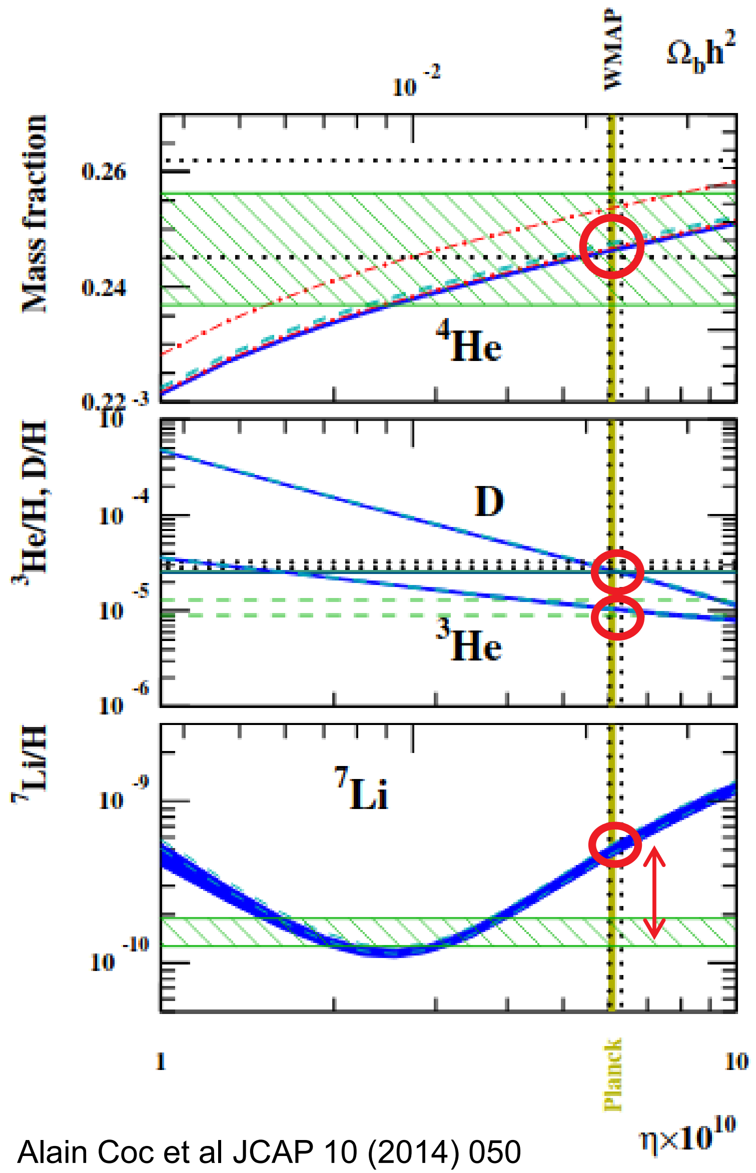


PRE-MAIN SEQUENCE: $^{6}Li(p, \gamma)^{7}Be$

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

Big bang nucleosynthesis: $^2H(p,\gamma)^3He$ reaction

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

Big bang nucleosynthesis: $^2H(p,\gamma)^3He$ reaction

PRIMORDIAL ABUNDANCE OF ^{2}H:

- Direct measurements: observation of absorption lines in DLA system

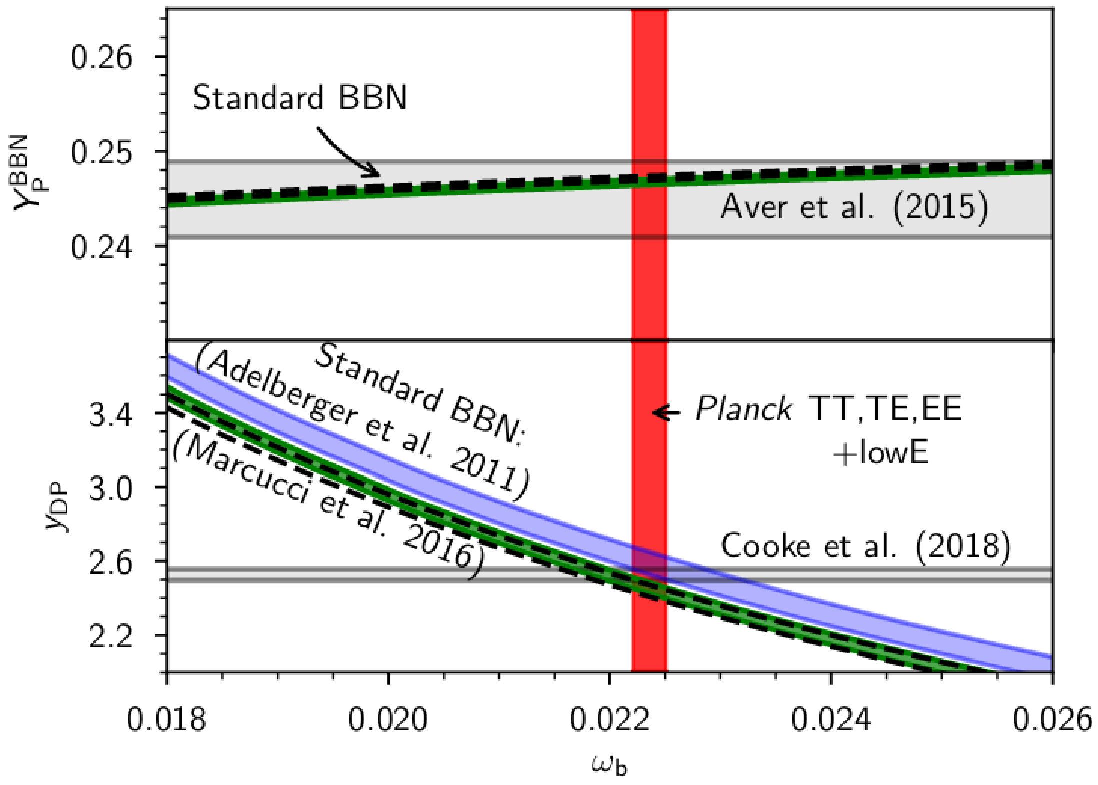
$$\left[\frac{D}{H}\right]_{OBS} = (2.527 \pm 0.030) \cdot 10^{-5}$$

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

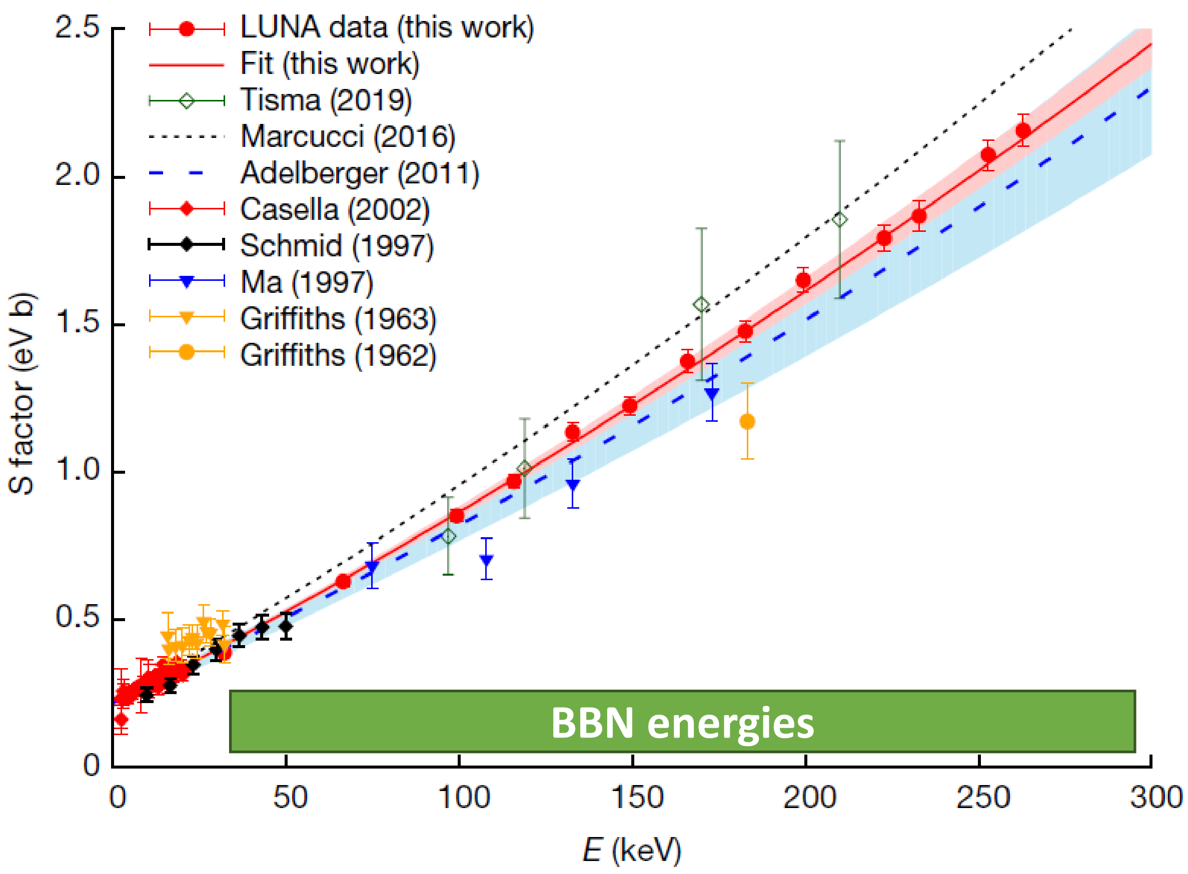
$$\left[\frac{D}{H}\right]_{BBN} = \begin{matrix} (2.587 \pm 0.055) \cdot 10^{-5} \\ (2.439 \pm 0.052) \cdot 10^{-5} \end{matrix}$$

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

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



Systematic uncertainty reduced to **< 3%**

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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

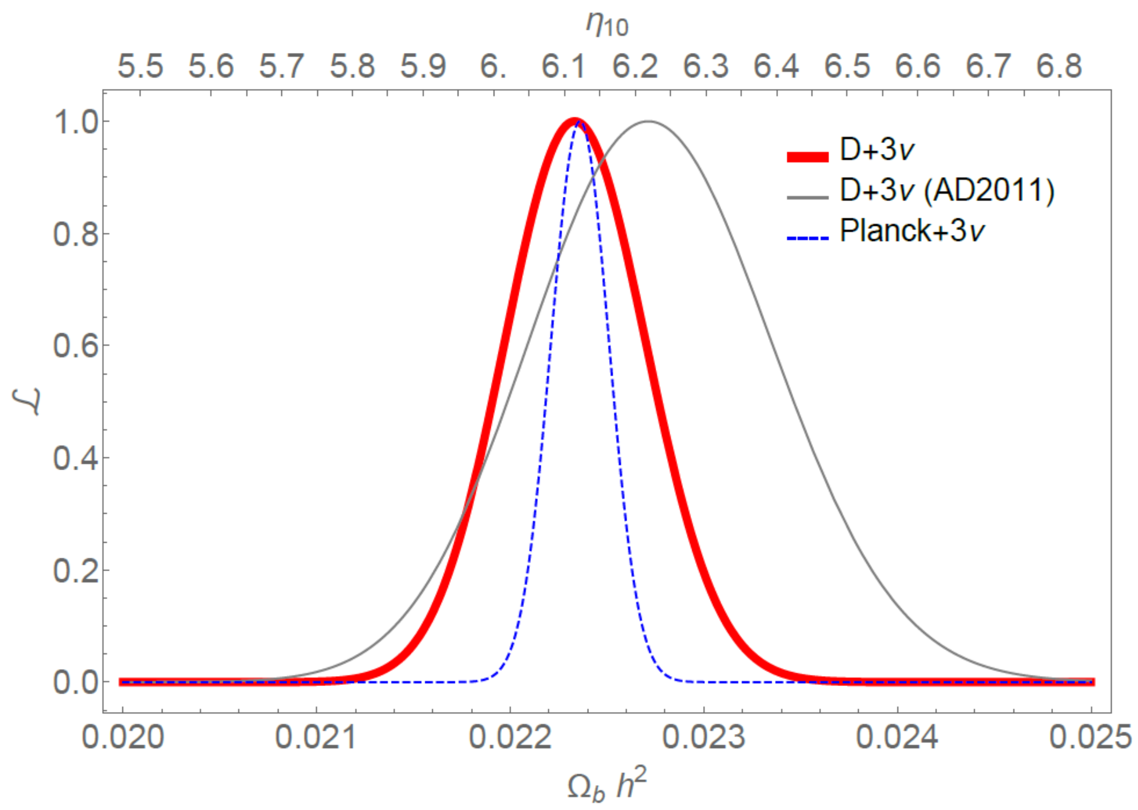
Nature **587**, 210–213 (2020) | Cite this article

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

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

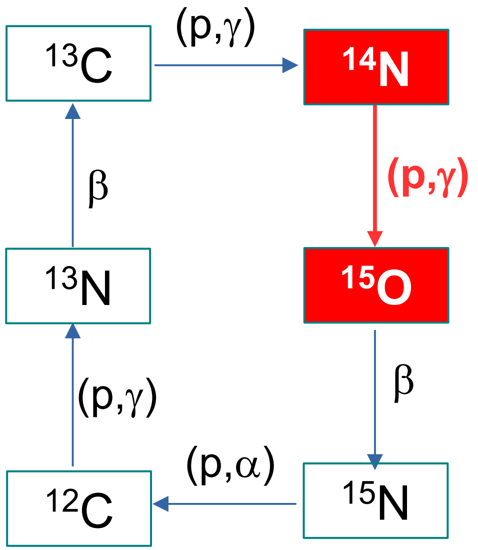
Baryon density of the Universe:

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



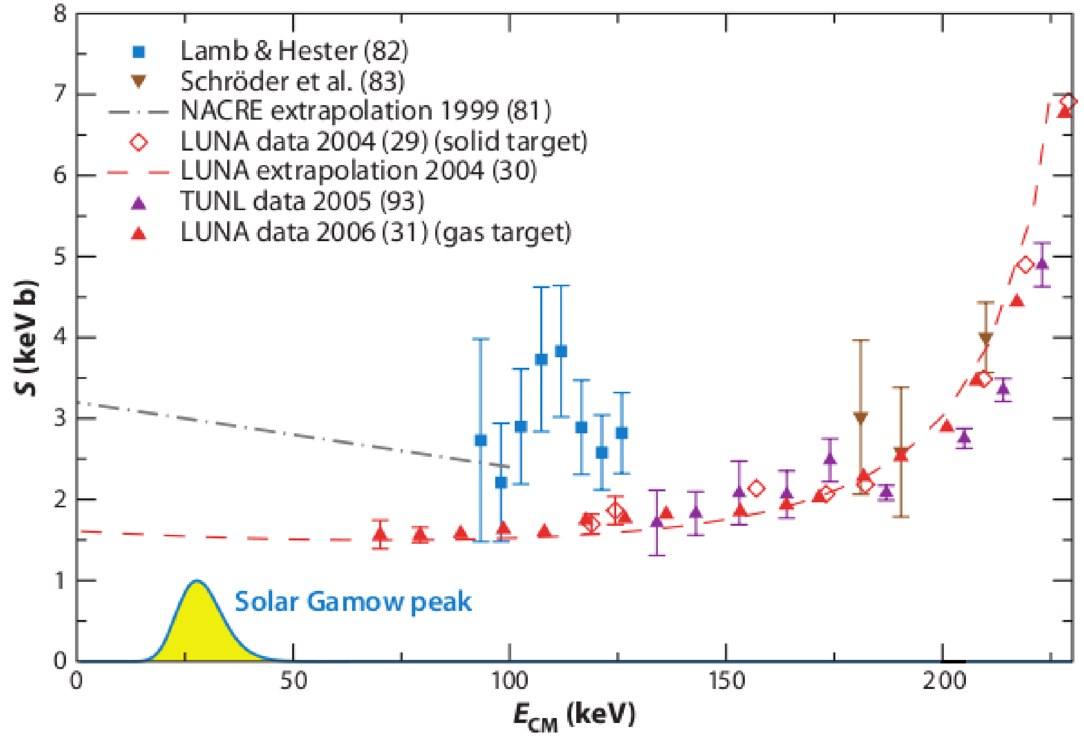
Analysis performed by Ofelia Pisanti and Gianpiero Mangano

$^{14}N(p,\gamma)^{15}O$ reaction: Bottleneck of the CNO cycle



$^{14}N(p,\gamma)^{15}O$ is the slowest reaction of the CNO cycle

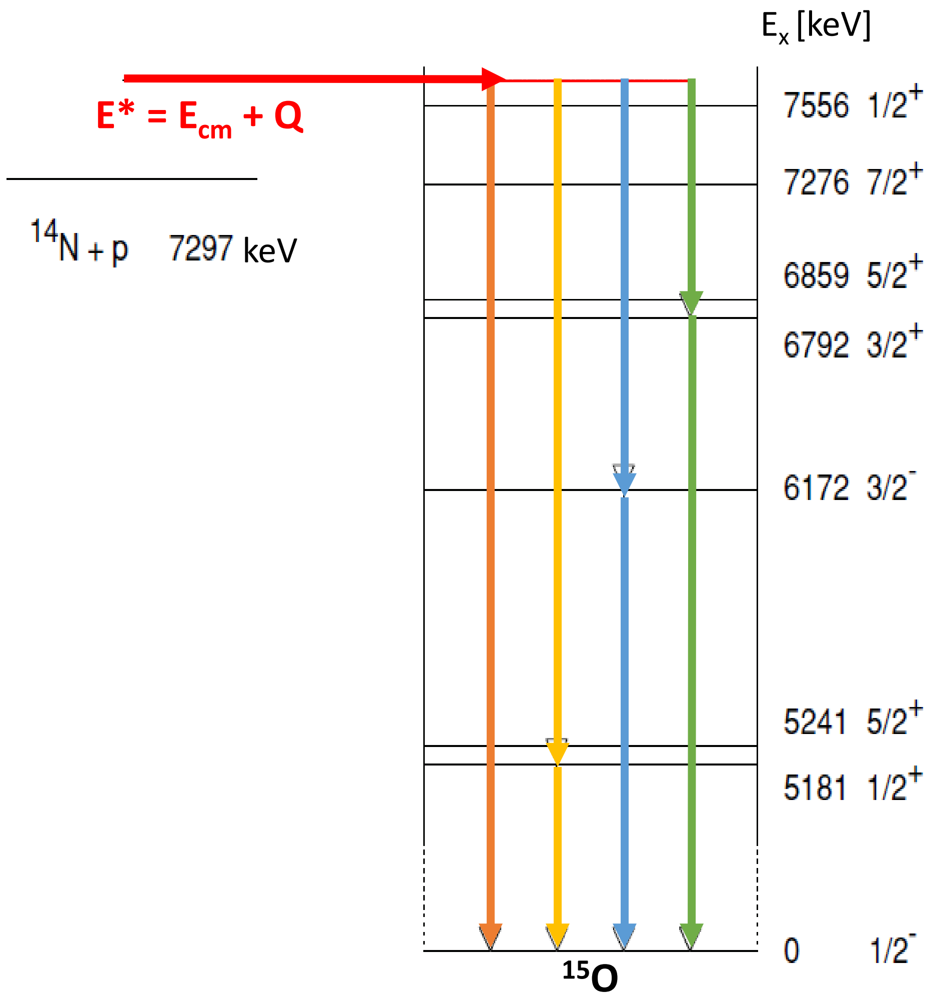
It determines the overall rate of the cycle

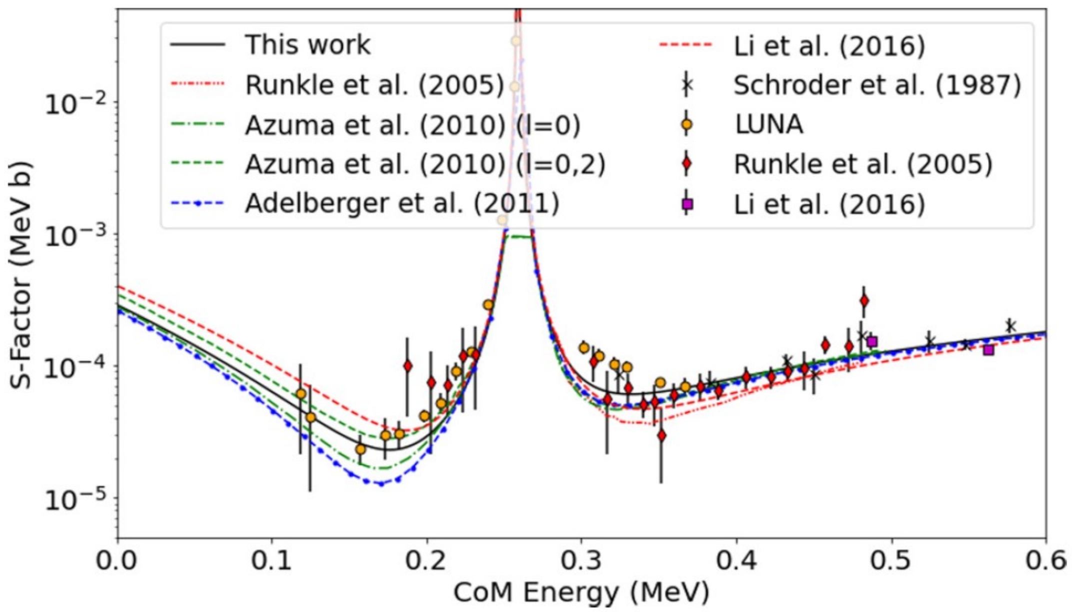


→ Determine age of the Universe from globular clusters

→ Use CNO neutrino flux to probe the interior of the Sun

$^{14}N(p,\gamma)^{15}O$ reaction: Bottleneck of the CNO cycle





Frentz et al. PRC 103, 045802 (2021)

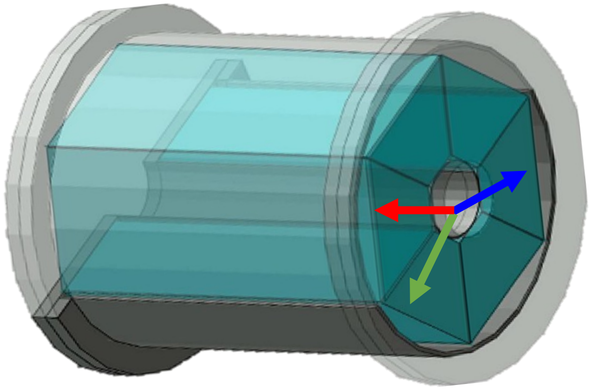
TABLE IX $S_{1\,14}(0)$ as the sum of the different transitions.

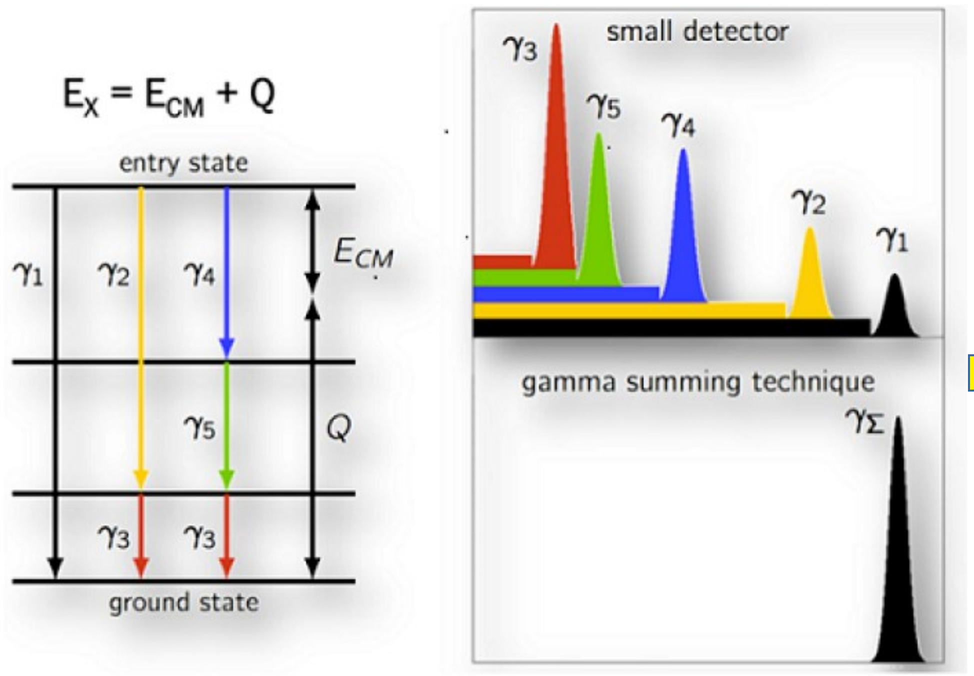
Transition	$S_{1\,14}(0)$ (keV b)	$\Delta S_{114}(0)$	Reference
tr → 0	0.30 ± 0.11	37%	Present
tr → 6.79	1.17 ± 0.03	2.9%	Present
tr → 6.17	0.13 ± 0.05	38%	SF II
tr → 5.18	0.010 ± 0.003	30%	SF II
tr(5.24) → 0	0.068 ± 0.020	30%	SF II
R-matrix sum	1.68 ± 0.13	7.6%	
Additional syst. uncert.		3.5%	
Total	1.68 ± 0.14	8.4%	

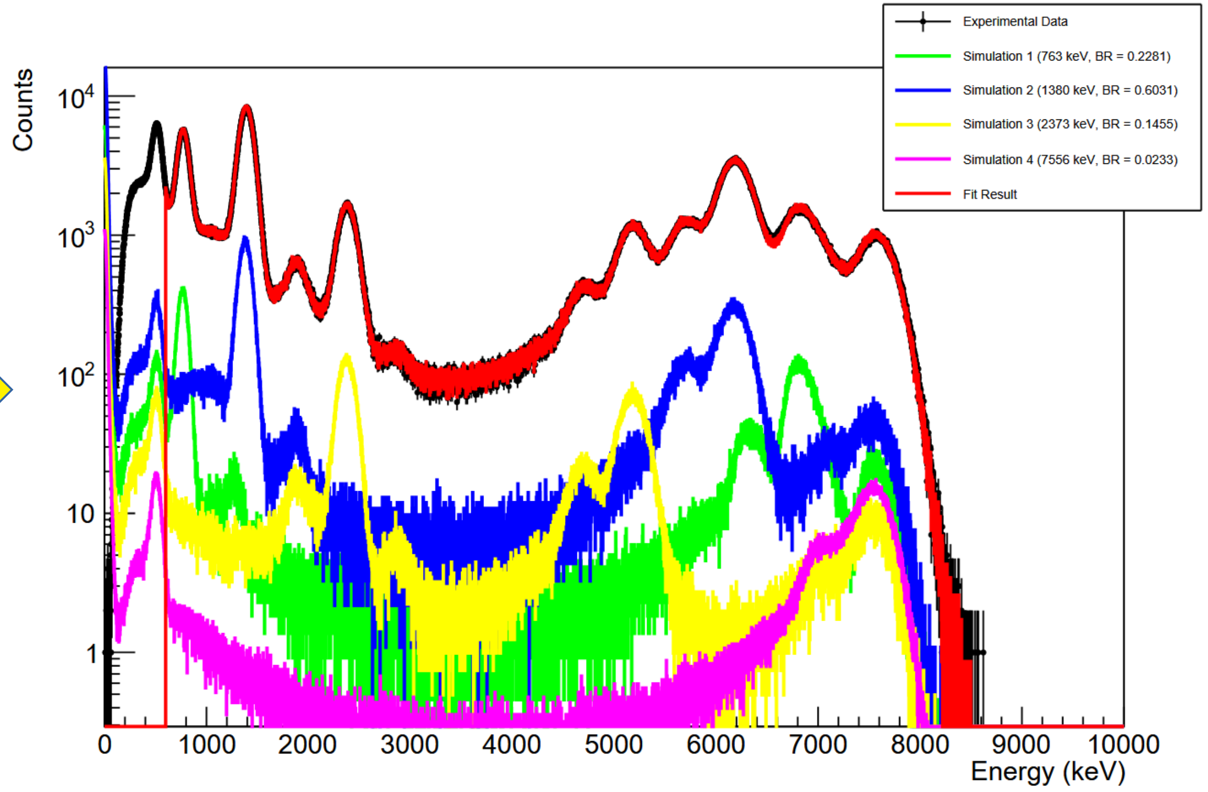
Solar Fusion III arXiv:2405.06470v1 (2024)

$^{14}N(p,\gamma)^{15}O$ reaction: Bottleneck of the CNO cycle

New experimental campaign, same detector, more advanced analysis technique!







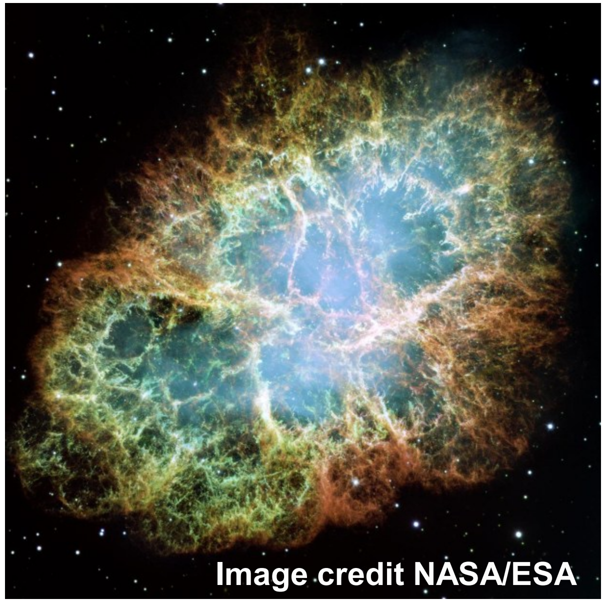
Stellar carbon burning

In stars, carbon burning is the first evolutionary stage involving the fusion of heavy ions.

Only stars with mass higher than a threshold M_{UP} (~ 8 M_{SUN}) can ignite carbon burning:

$M < M_{up}$
White dwarfs/classical novae

$M > M_{up}$
Supernovae→ neutron stars and black holes



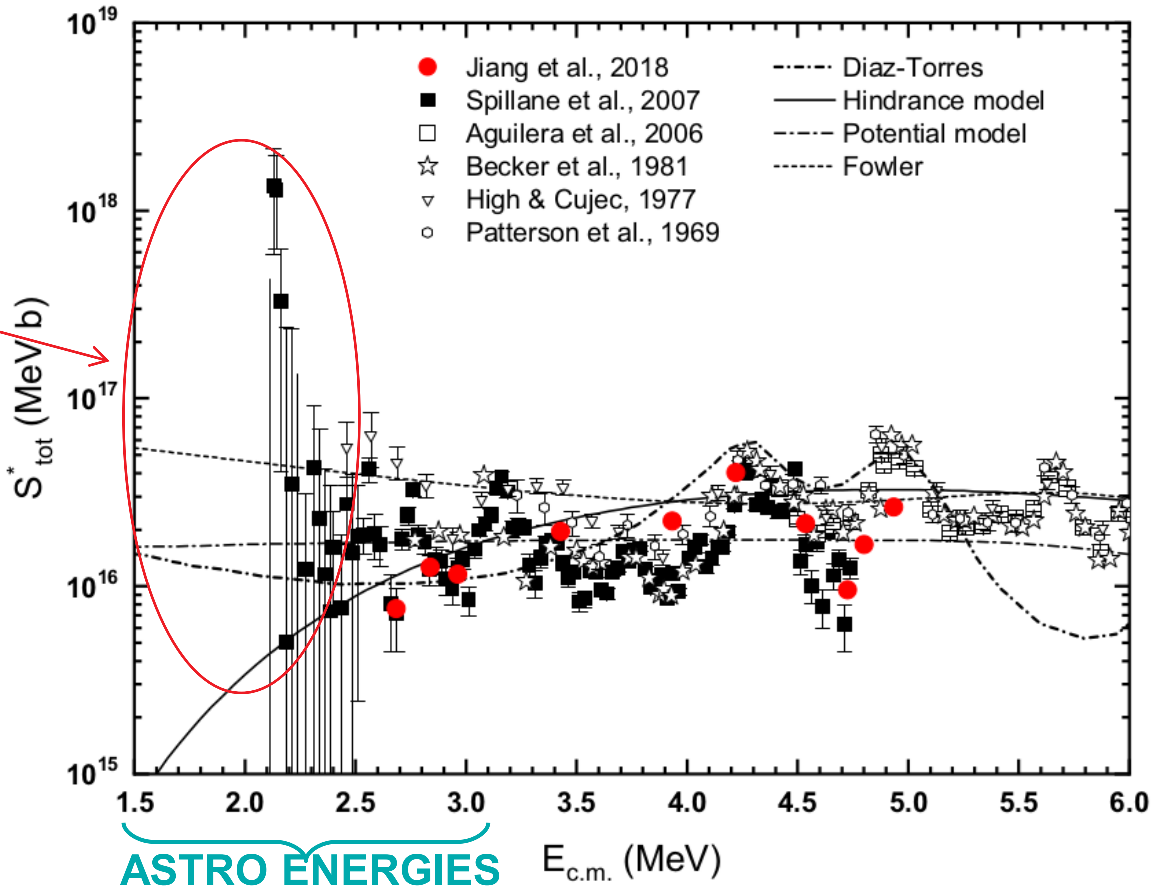
M_{UP} (and hence the whole life and fate of a star) depends on the $^{12}C+^{12}C$ cross section

Stellar carbon burning

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

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!



J. Zickefoose et al. PRC97, 065806 (2018)

Stellar carbon burning

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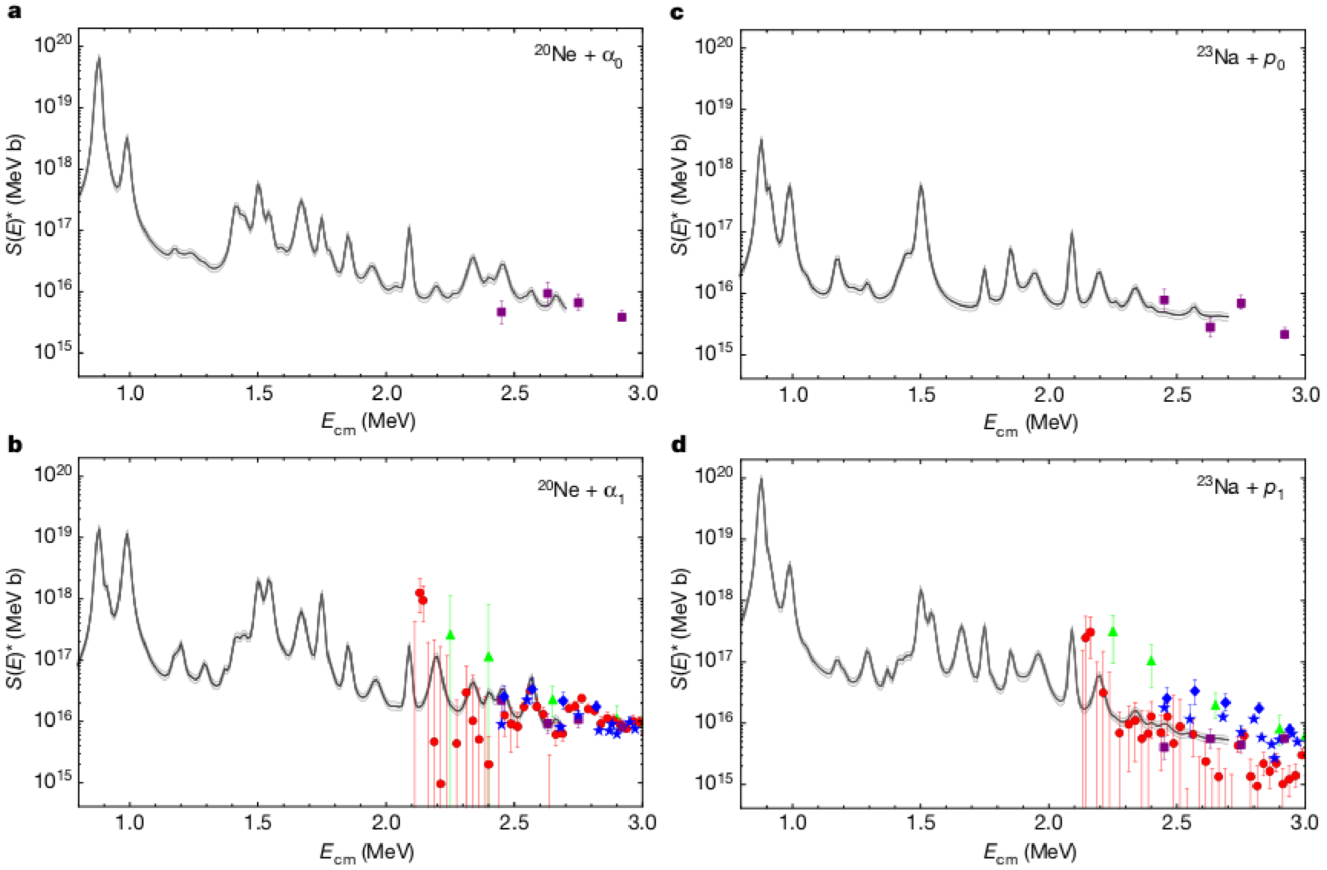
A. Tumino et al. Nature 557, 687 (2018)



Bellotti Ion Beam Facility

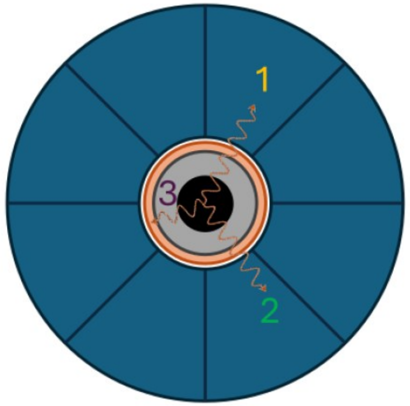
- **Inline Cockcroft Walton accelerator**
- **TERMINAL VOLTAGE: 0.2 – 3.5 MV**
- **Beam energy reproducibility:** 0.01% TV or 50V
- **Beam energy stability:** 0.001% TV / h
- **Beam current stability:** < 5% / h

H^+ beam: 500 - 1000 eμA
He^+ beam: 300 - 500 eμA
C^+ beam: 100 - 150 eμA
C^{++} beam: 100 eμA

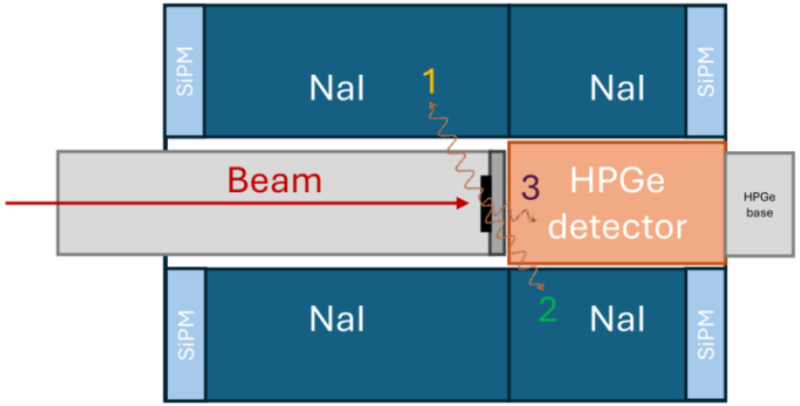
A. Sen et al. NIM B 450 (2019) 390 - 395

$^{12}C + ^{12}C$ experiment at the Bellotti IBF

- ^{12}C beam on thick graphite target
- gamma-rays detected by one large-volume HPGe
- detector surrounded by 7cm Cu + 25cm Pb shielding to suppress background
- NaI detectors to suppress Compton continuum
- Data taking just started!



Front view



Lateral view

THANK YOU!

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