LUNA results on deuterium burning and implications for cosmology

Federico Ferraro
(on behalf of the LUNA collaboration)

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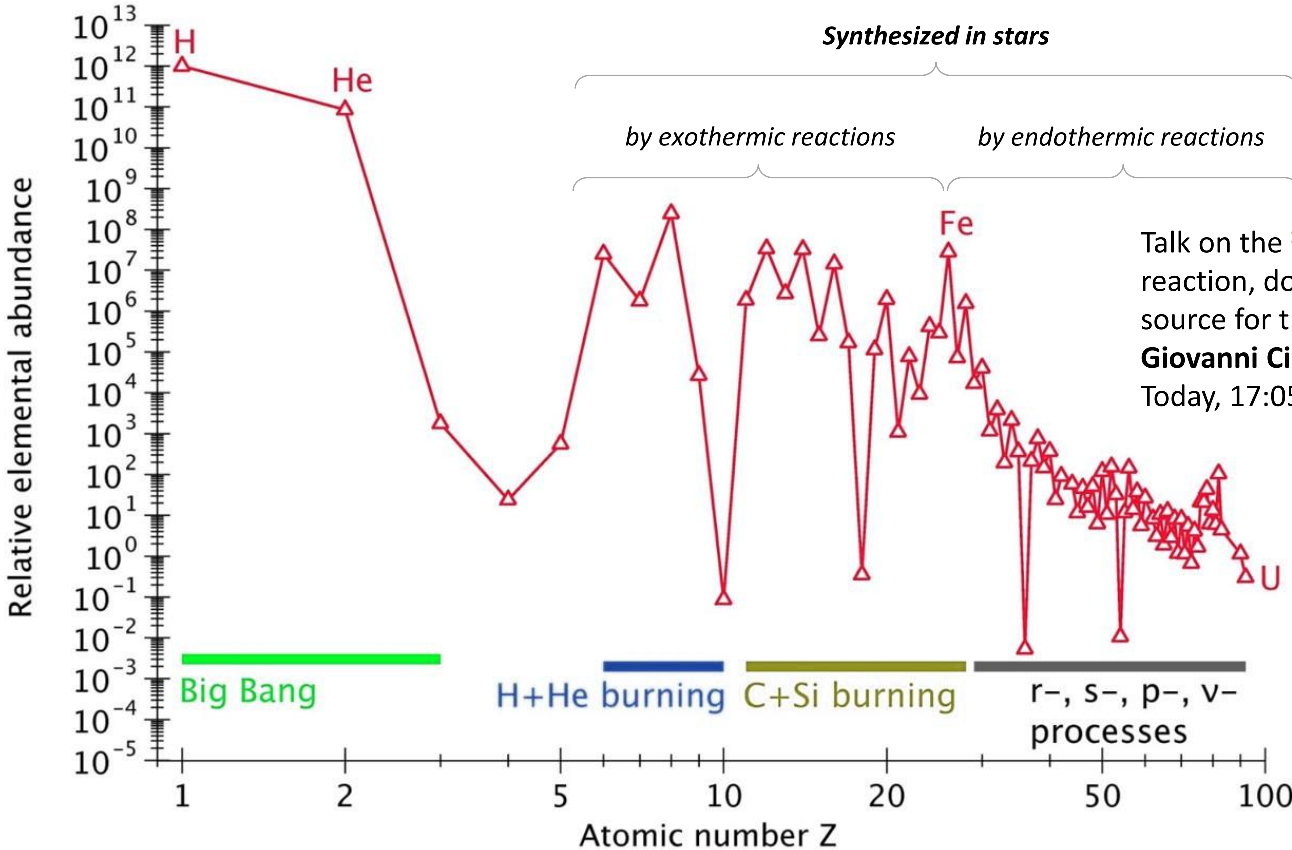
Nuclear Astrophysics in a nutshell

Nuclear reactions determine the **abundances of the elements** and are responsible of **energy production inside stars**



Talk on the $^{13}C(\alpha,n)^{16}O$ reaction, dominant neutron source for the main s process
Giovanni Ciani
Today, 17:05 (Lisbon time)

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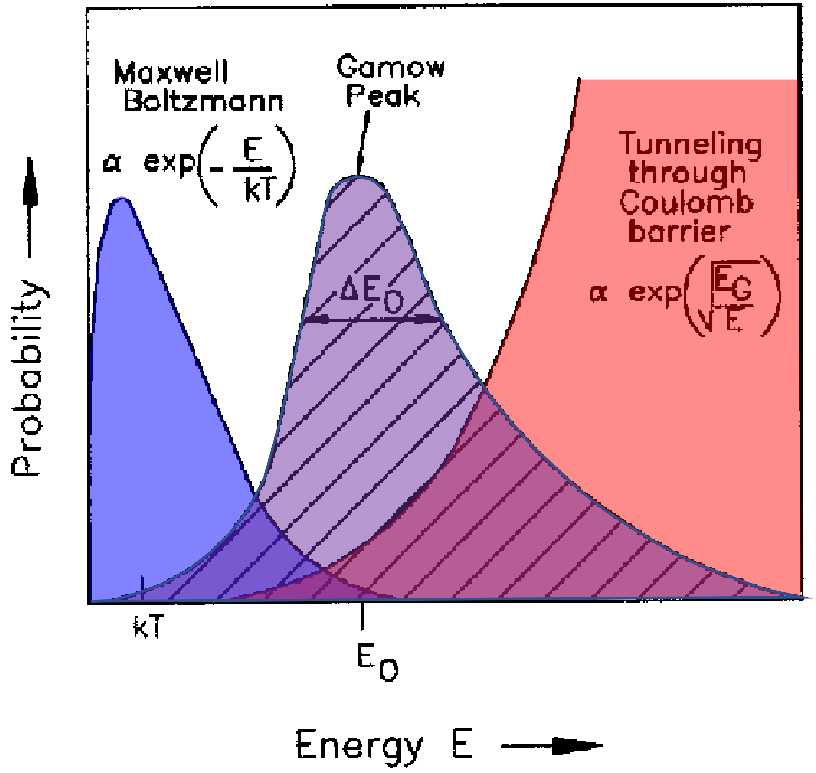
Nuclear Astrophysics in a nutshell



The **Gamow peak** defines the relevant energy range for such reactions to occur

Consider a **radiative capture reaction**

$$A + B \rightarrow C + \gamma$$

The reaction rate is given by

$$\langle r \rangle = N_A N_B \int_0^{\infty} \phi(v)\, \sigma(v)\, v\, dv$$

E_0 is usually so low that the cross section in the Gamow peak is awfully small!

direct measurements on surface are often hampered by cosmic ray induced background

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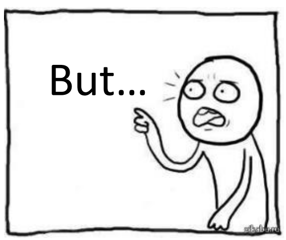
Extrapolation uncertainties

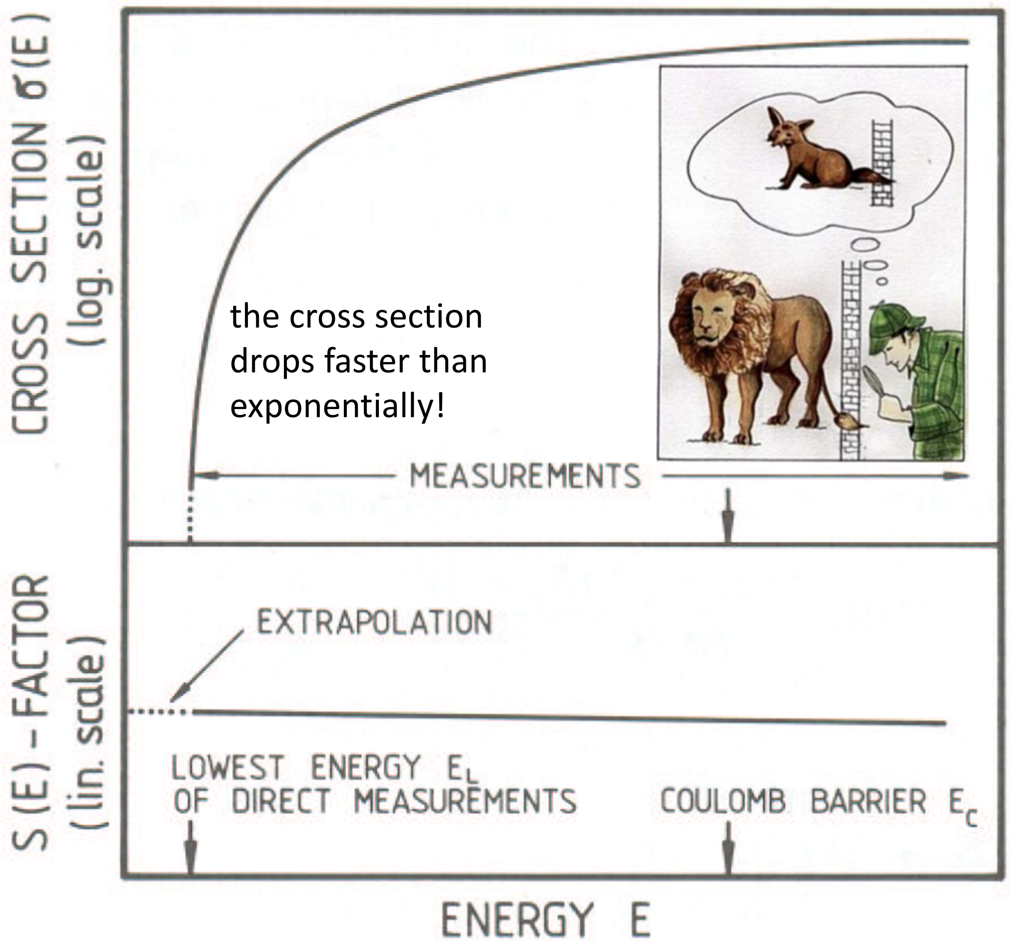
Since it is possible to factorize the cross section:

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

one can measure it at high energy and extrapolate the **astrophysical factor** ***S(E)*** in the interesting energy range



extrapolation uncertainties might be out of control (e.g. because of low-energy resonances, systematics, etc…)



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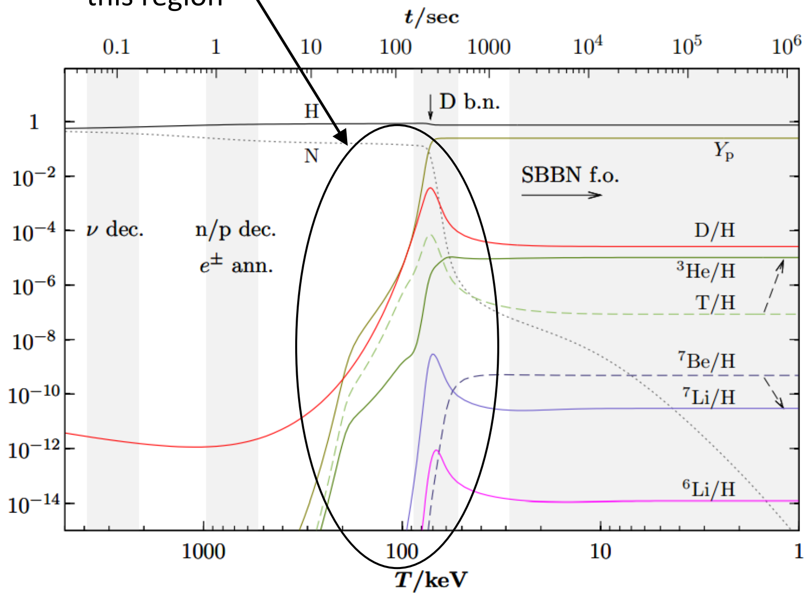
Big Bang Nucleosynthesis

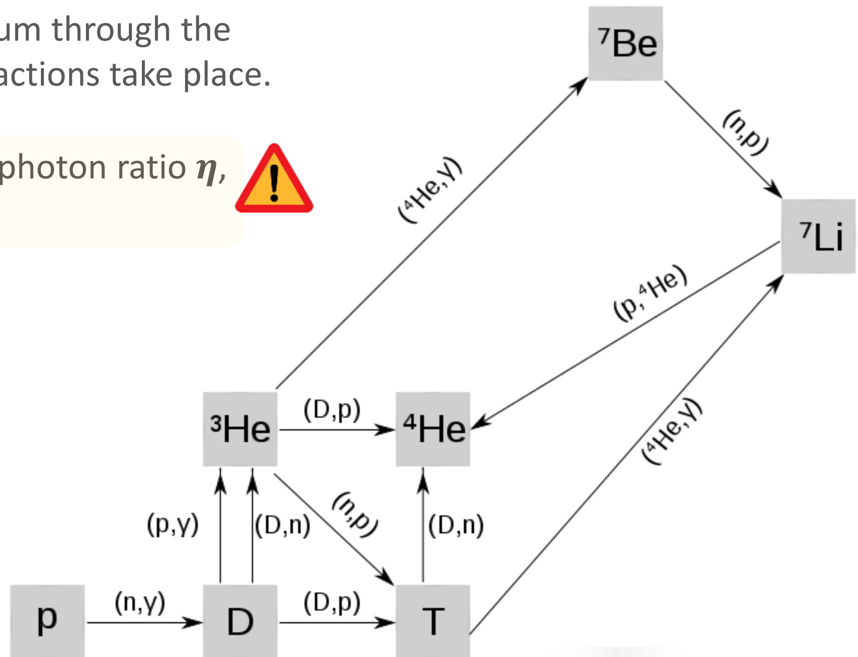
The nucleosynthesis begins with the formation of deuterium through the $p(n,\gamma)\mathrm{D}$ reaction. As soon as some D is present, other reactions take place.

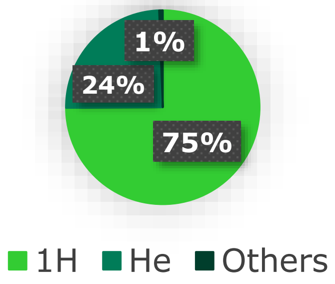
The abundances are strongly influenced by the barion-to-photon ratio $\boldsymbol{\eta}$, which is closely related to the baryon density $\boldsymbol{\Omega_b}$:

$$\boldsymbol{\eta} \equiv \frac{n_b}{n_\gamma} \cong 2.75 \cdot 10^{-8} \boldsymbol{\Omega_b} h^2$$

it greatly influences this region







Primordial abundances

The primordial deuterium abundance [D/H] can be obtained by:

- **observations**

  from direct astronomical observations

  $[D/H]_{OBS} = (2.527 \pm 0.030) \times 10^{-5}$
  Cooke et al, APJ 855 (2018) 102

- **predictions**

  from BBN models (known the cosmological parameters and the cross sections of the processes responsible for D creation and destruction)

  $[D/H]_{BBN} = (2.587 \pm 0.055) \times 10^{-5}$
  $[D/H]_{BBN} = (2.439 \pm 0.052) \times 10^{-5}$
  depending on adopted x-sections
  Planck 2018, A&A 641 (2020) A6

To make a long story short: the comparison $[D/H]_{OBS}$ vs $[D/H]_{BBN}$ allows to determine Ω_b and N_{eff}

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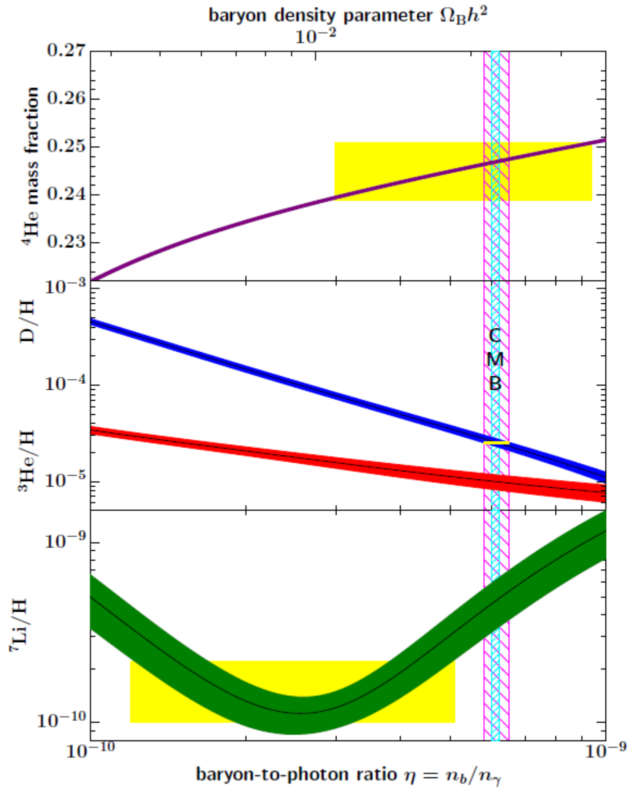
Primordial abundances and barion-to-photon ratio



The "horizontal" **bands** show the standard BBN predictions with state-of-the-art cross sections (95% CL)

Yellow boxes indicate primordial abundances inferred from observations

The **narrow vertical band** is the CMB measure of the baryon density (95% CL)

The **wide vertical band** is the BBN D + ^{4}He concordance range (95% CL)

Recent advances in the observations of D/H and the determination of cosmological parameters by *Planck*, motivate an improvement in BBN calculations (i.e. cross section measurements) → LUNA

M. Tanabashi *et al.* (Particle Data Group), Phys. Rev. D **98**, 030001 (2018) and 2019 update.

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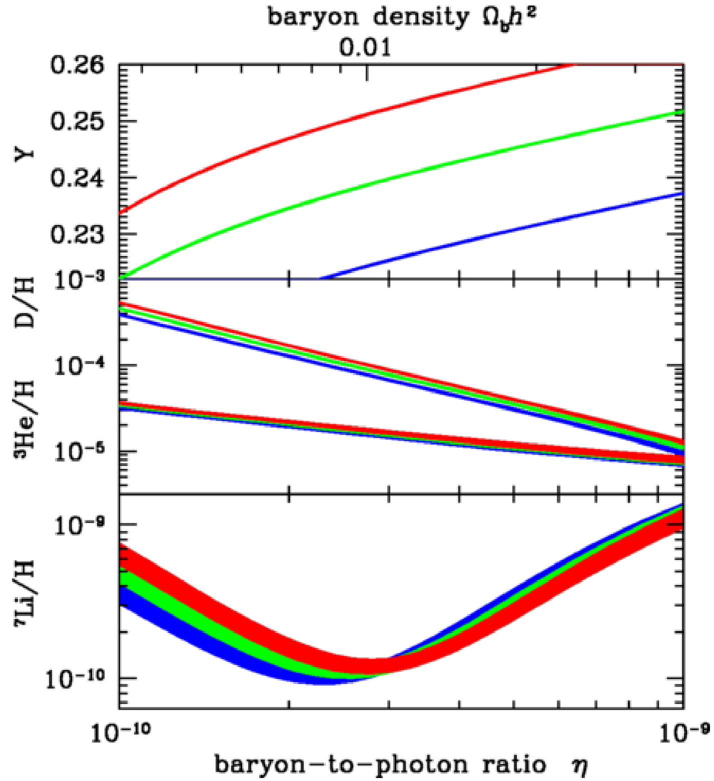
Primordial abundances and effective number of neutrino species



https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.88.015004

Given a certain baryon-to-photon ratio, **primordial abundances of the light-elements are also sensitive to the number of effective neutrino species**.

Abundances shown by different colored bands correspond to calculated abundances assuming $N_{eff} = \mathbf{2}, \mathbf{3}$ and $\mathbf{4}$.

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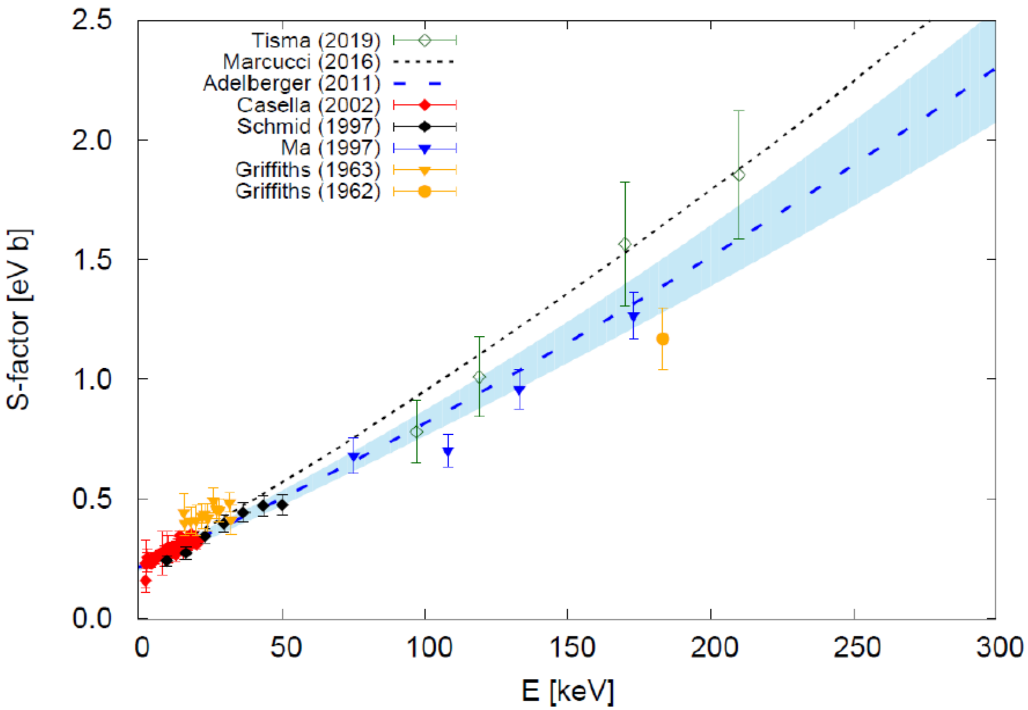
Previous state-of-the-art

Uncertainty on the predicted abundance of deuterium mainly due to the $^{2}H(p,\gamma)^{3}He$ reaction

Only two datasets available at the BBN energy range with a systematic uncertainty of 9-15%

Imperfect agreement with recent *ab-initio* calculations (Marcucci et al. 2016)



Reaction	$\sigma_{^2\mathrm{H/H}} \times 10^5$
$p(n,\gamma)^2\mathrm{H}$	± 0.002
$d(p,\gamma)^3\mathrm{He}$	± 0.062
$d(d,n)^3\mathrm{He}$	± 0.020
$d(d,p)^3\mathrm{H}$	± 0.013

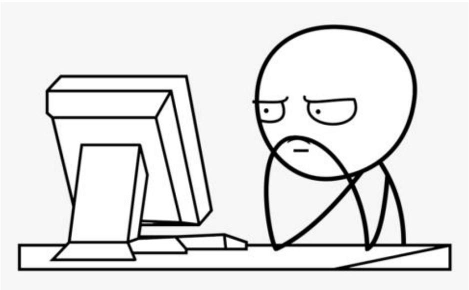
Need for a new, precise and accurate measurement of the $^{2}H(p,\gamma)^{3}He$ cross section!

Towards the measurement: expected counting rate

$$Counting\ rate = beam\ flux \times target\ nuclei\ areal\ density \times cross\ section \times detection\ efficiency$$

- beam flux: 10^{14} pps (100 μA 1^{+} beam)
- target nuclei areal density: 10^{15} atoms/cm^2 (gas target)
- cross section: 10^{-30} cm^2 (often smaller)
- detection efficiency: 1% (HPGe detectors)

1-10 counts/h



It is fundamental to strongly suppress the background!

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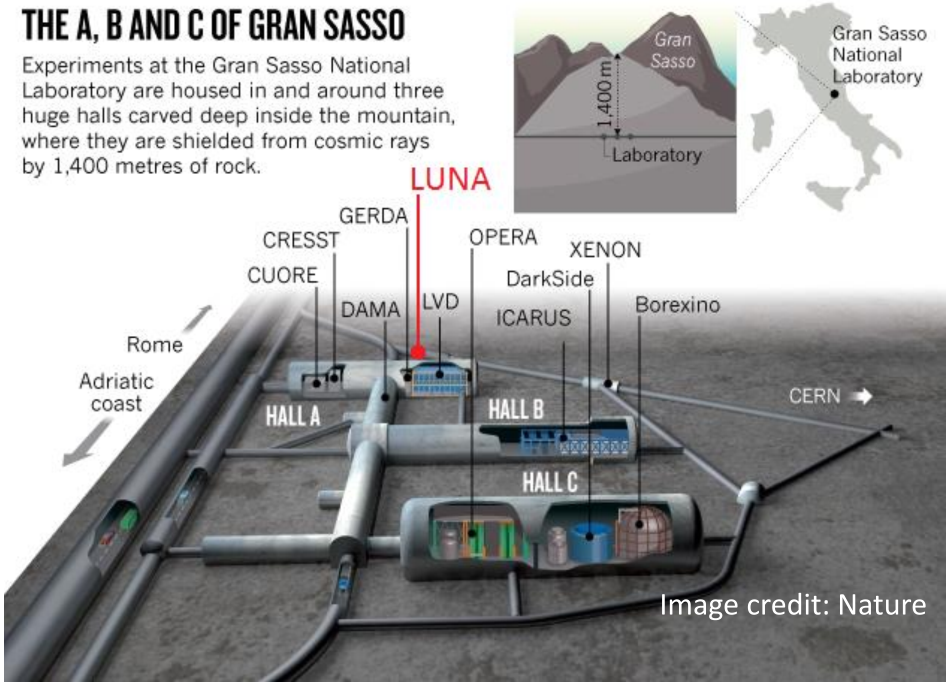
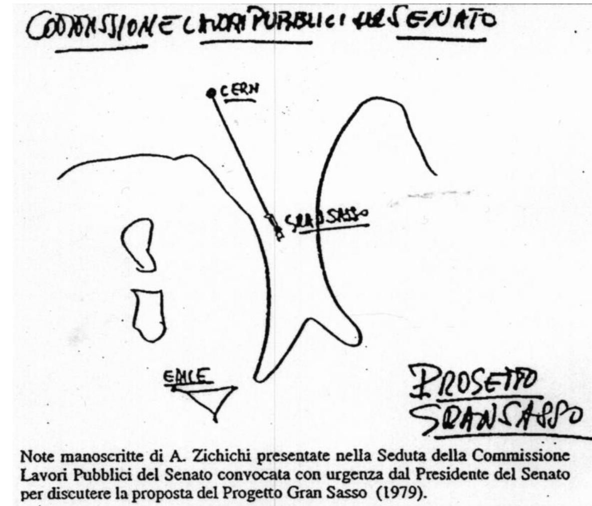
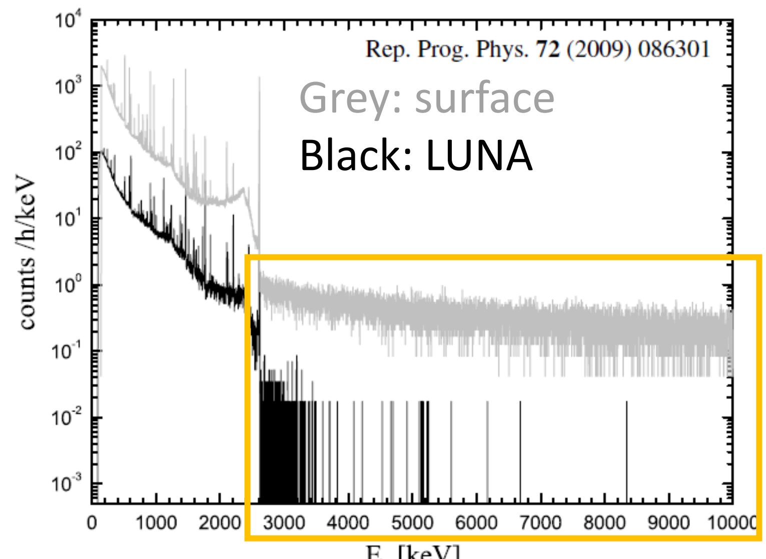
The Gran Sasso National Laboratory (LNGS)





Rock overburden > 1400 m (>3000 m.w.e.)



Reduction of cosmic-ray-induced background

muons: ~ 10^6

neutrons: ~ 10^3 (see G. Ciani's talk)

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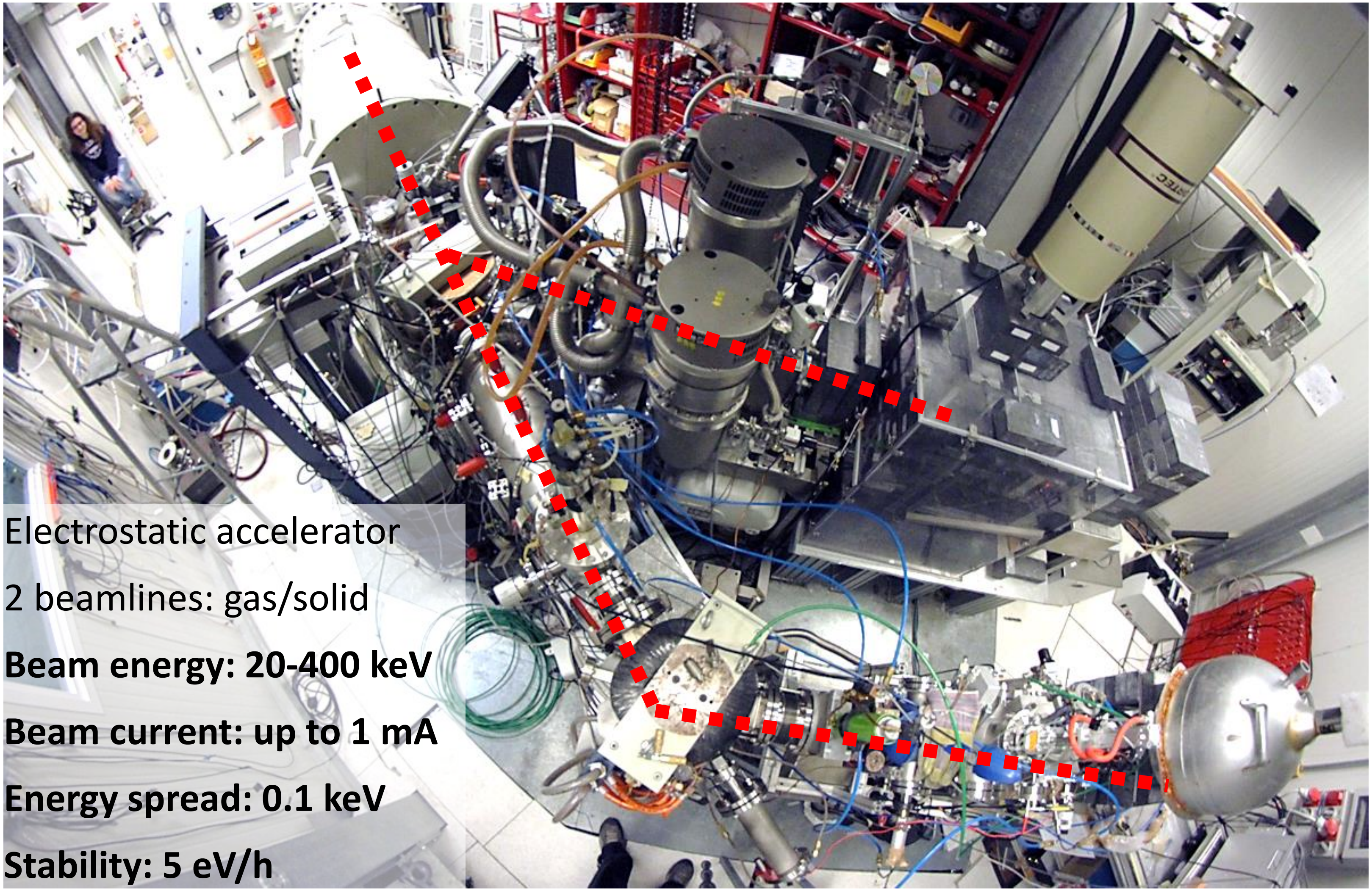
The Laboratory for Underground Nuclear Astrophysics



Electrostatic accelerator

2 beamlines: gas/solid

Beam energy: 20-400 keV

Beam current: up to 1 mA

Energy spread: 0.1 keV

Stability: 5 eV/h

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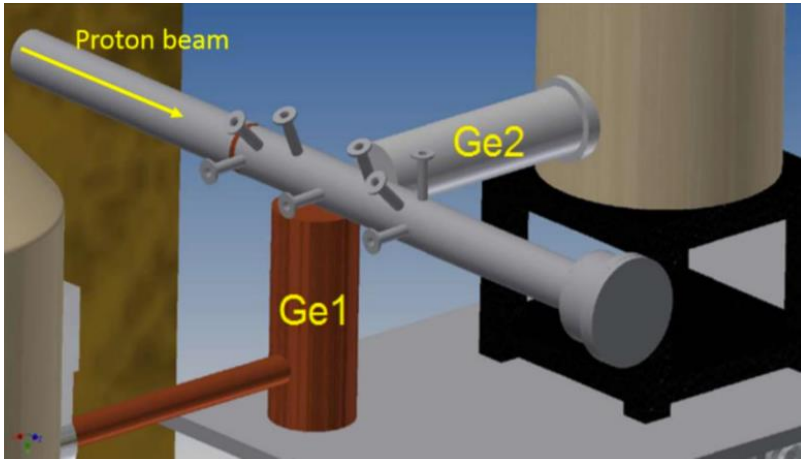
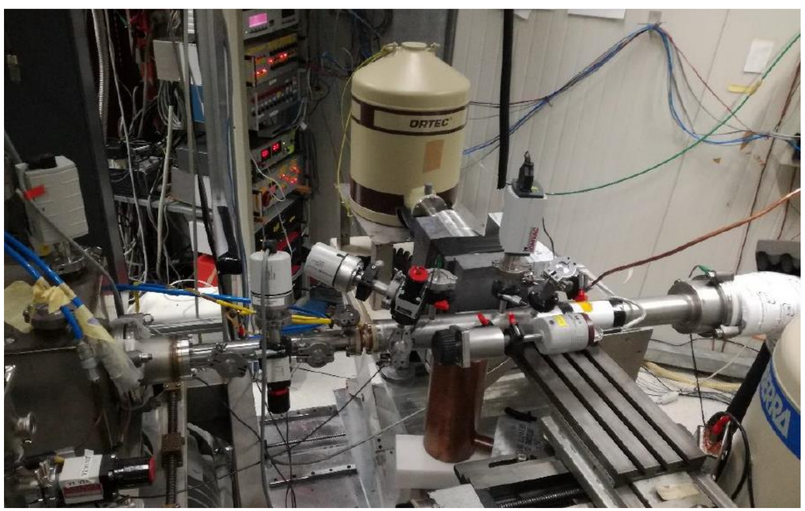
The experiment





GOAL
- measurement of the cross section
- <3% uncertainty
- E_{cm}=30-300 keV

SETUP
- high-intensity proton beam
- D_2 windowless gas target (P=0.3 mbar)
- HPGe detectors

ANCILLARY MEASUREMENTS
- T and P profiles → density profile $\rho(z)$
- HPGe detectors calibration
- calorimeter calibration
- efficiency profile $\varepsilon(z,\gamma)$
- angular distribution effects $W(z)$

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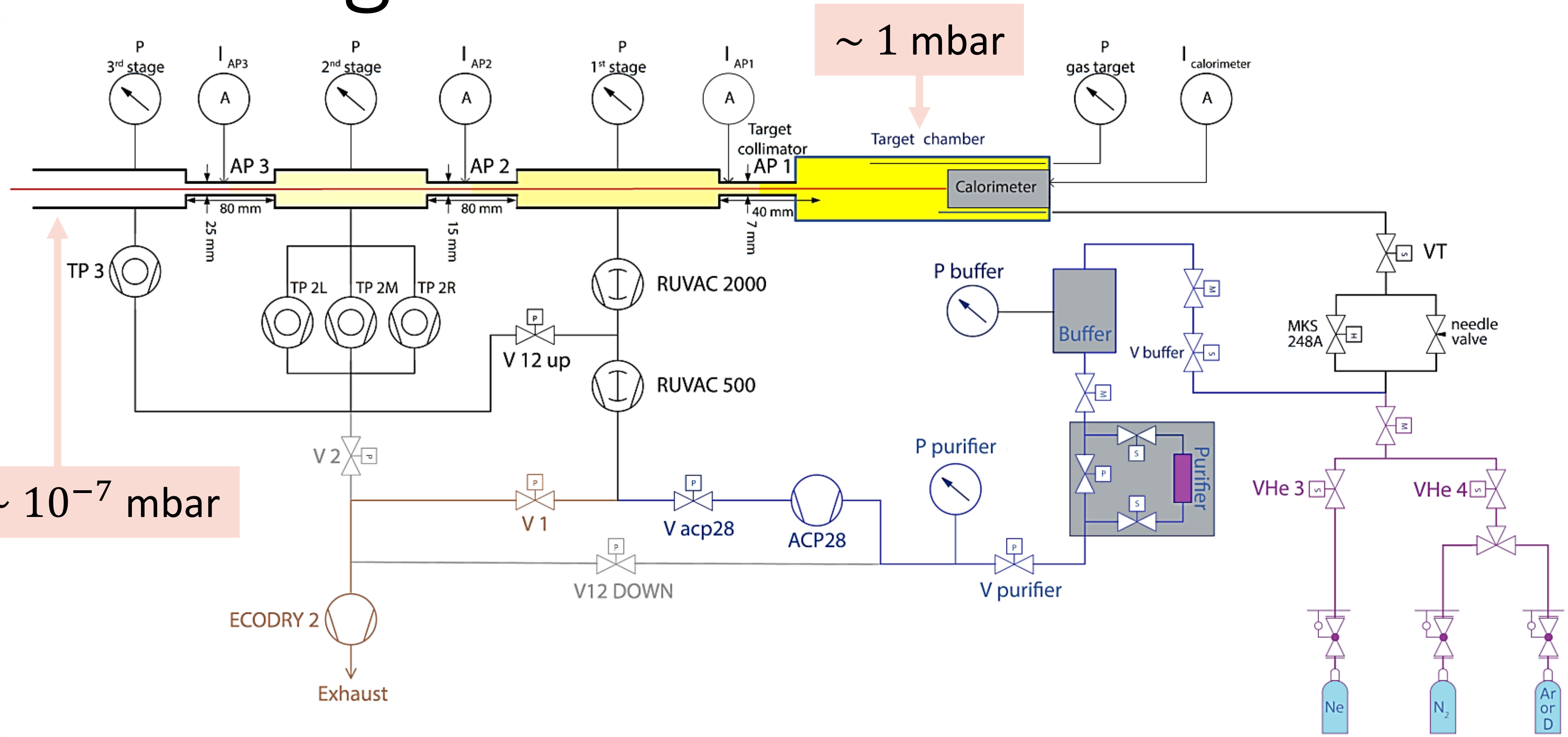
Gas target



- Extended gas target
- 3 differential pumping stages (no entrance window)
- Gas recycling and purification
- Need to measure temperature and pressure profiles -> density profile

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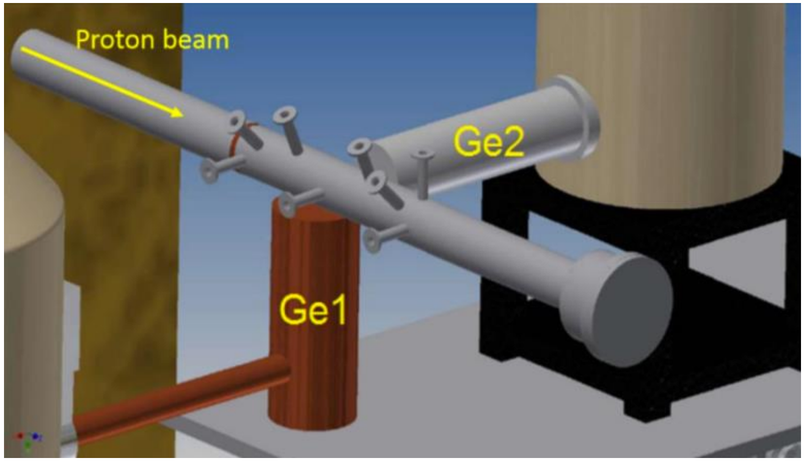
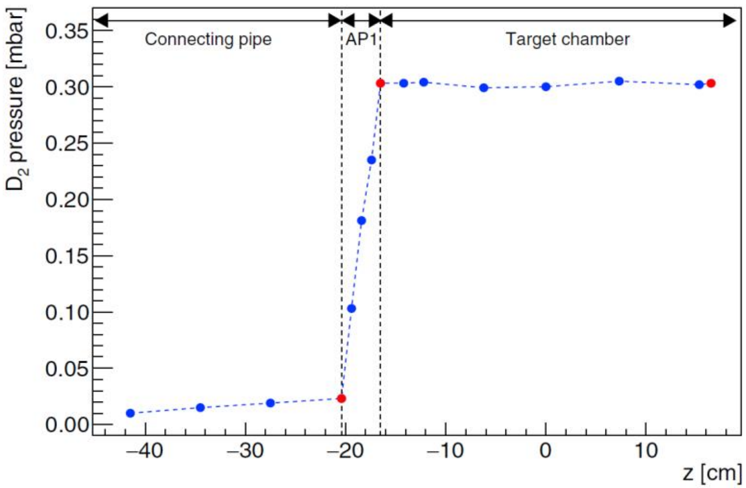
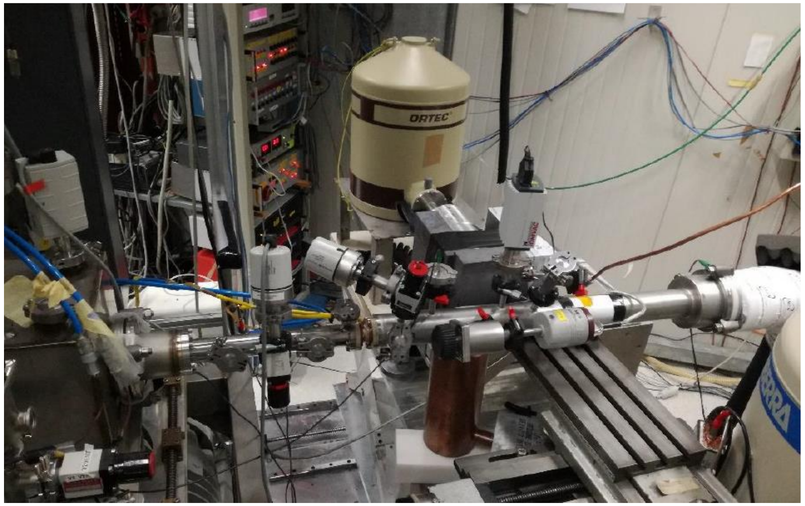
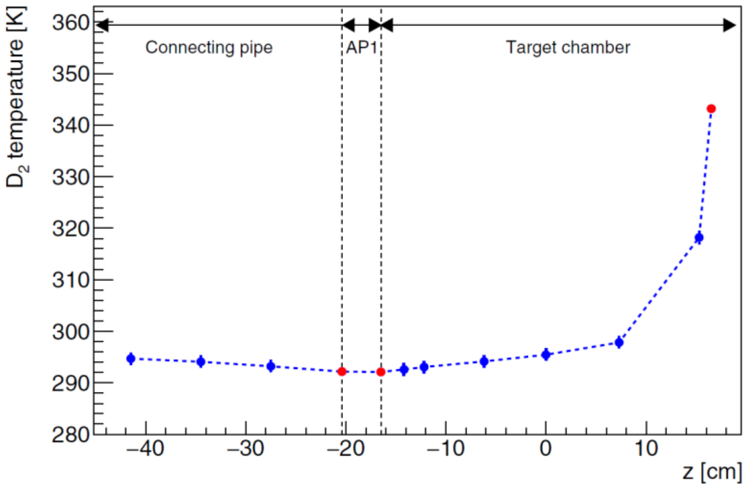
Commissioning – P and T









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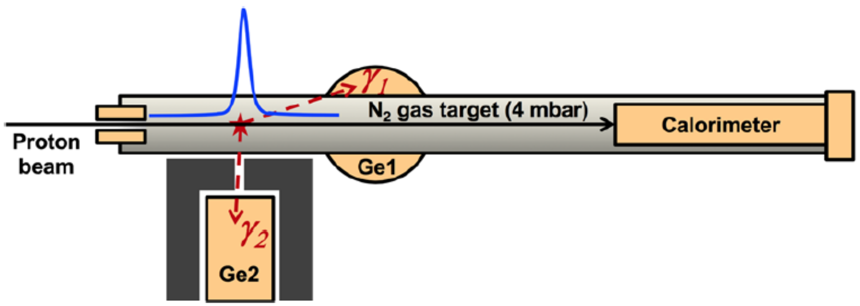
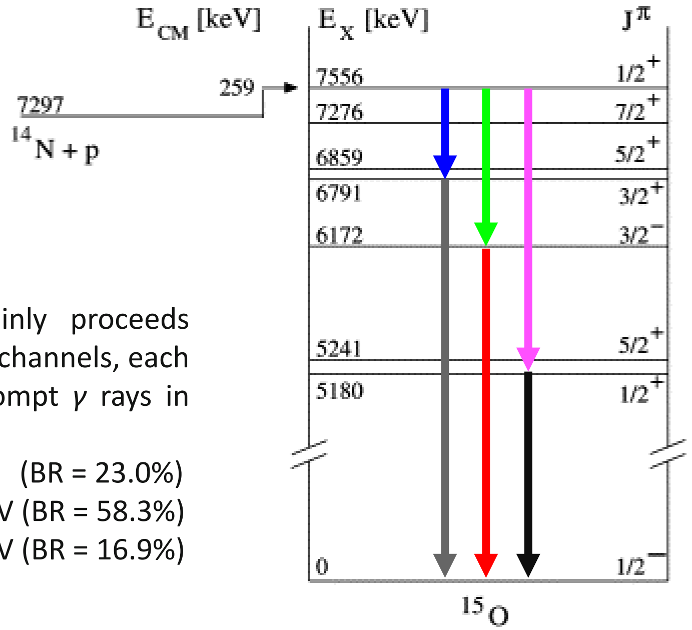
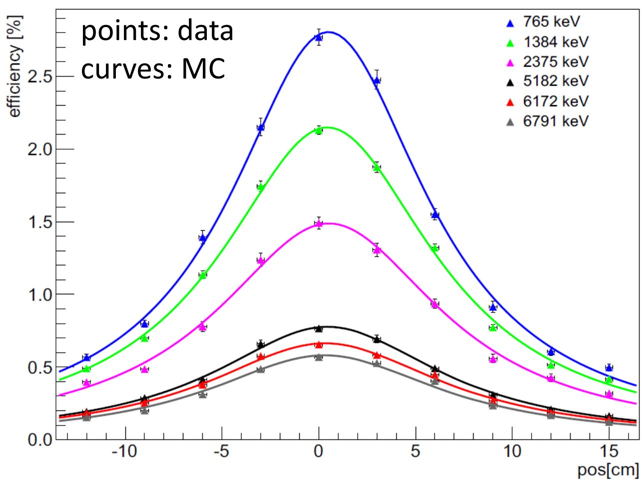
Commissioning – efficiency





This reaction mainly proceeds through three exit channels, each producing two prompt γ rays in cascade:

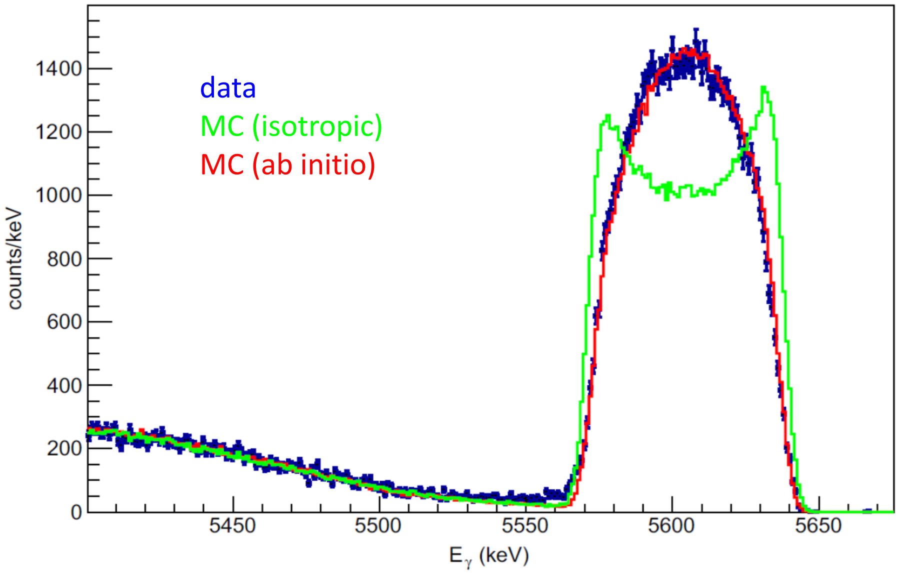
(1) 765 + 6791 keV (BR = 23.0%)
(2) 1384 + 6172 keV (BR = 58.3%)
(3) 2375 + 5182 keV (BR = 16.9%)



$$\epsilon(z, E_\gamma) = \frac{N_\gamma^{Ge1}}{N_\gamma^{Ge2}} \frac{\epsilon^{MC}_{pointlike}}{\epsilon^{MC}_{extended}}$$

Commissioning

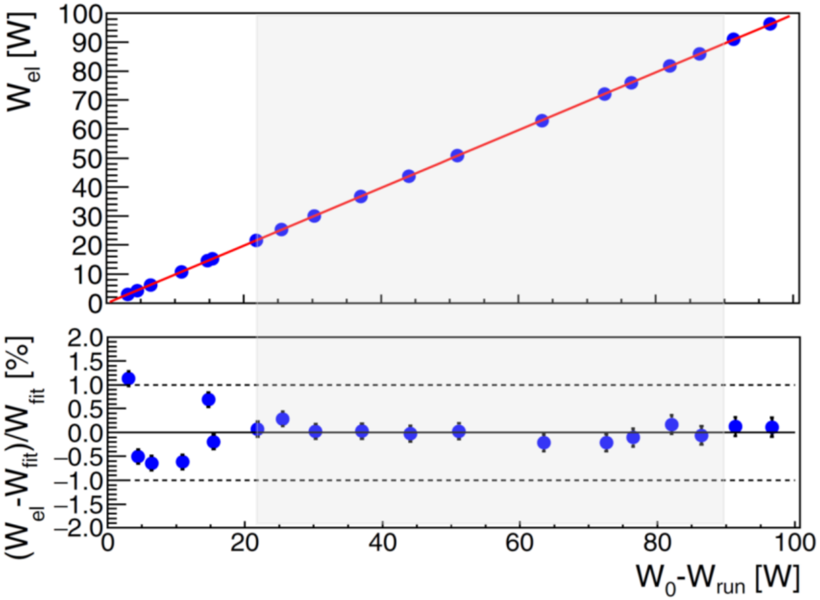
Angular distribution



The full energy peak is broadened by kinematics, while its shape depends on the photon angular distribution

The impact of angular distribution on the error budget has been evaluated by MC simulations assuming both isotropic and ab initio distributions

Current measurement



It is not possible to rely on electrical measurements of the beam current in a gas target

The beam current has been continuously measured with a power-compensation calorimeter calibrated in vacuum

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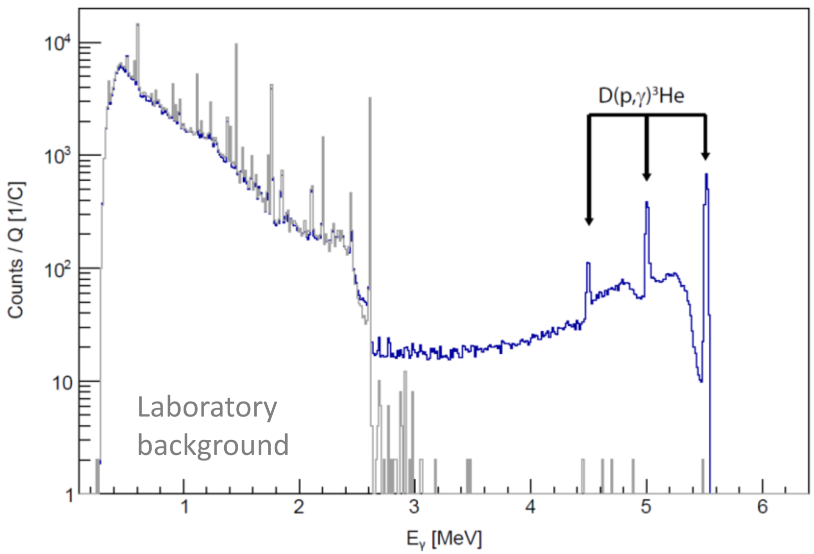
Signal and Background

E_p = 50 keV with D_2 gas target (P=0.3 mbar)

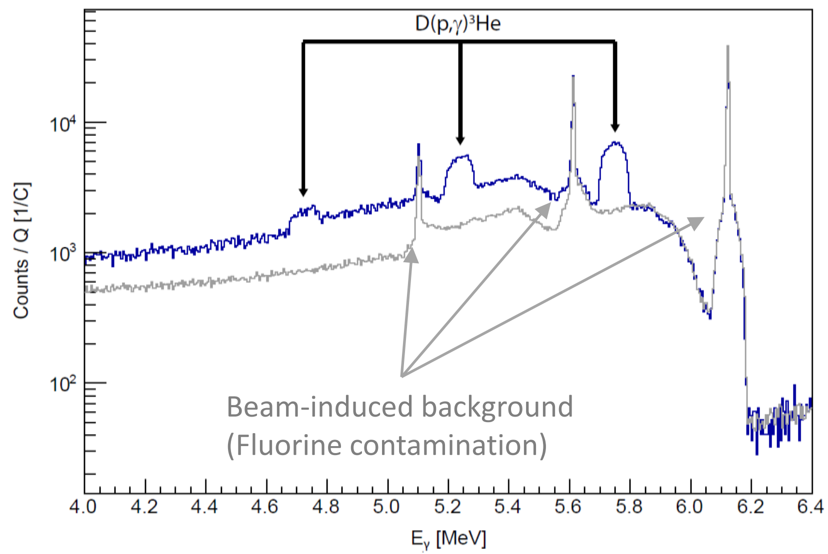
E_p = 50 keV with ^4He gas target (P=0.4 mbar)



E_p = 395 keV with D_2 gas target (P=0.3 mbar)

E_p = 395 keV with ^4He gas target (P=0.4 mbar)

Zoom 4.0-6.4 MeV



Counting statistical error: below 1% at all beam energies

Main source of background: $^{19}F(p,\alpha\gamma)^{16}O$ above E_p=250 keV

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Uncertainty budget (systematics)

cross section

number of detected photons with energy *E*

$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z)\, \varepsilon(z,\gamma)\, W(z)\, dz}$$

number of projectiles

density profile of the target

efficiency profile along the target

angular distribution

Source	Method	ΔS/S
Beam energy	Direct measurement	$\ll 1\%$
Energy loss	Low pressure	$\ll 1\%$
T and P profiles	Direct measurement	1.0%
Beam heating	Direct measurement	0.5%
Gas purity	Data sheet	$\ll 1\%$
Beam current	Calorimeter calibration	1.0%
Efficiency	Direct measurement	2.0%
Instrumental effects	Pulser method	$\ll 1\%$
Angular distribution	Peak shape analysis	0.5%
Total		2.6%

very impressive!

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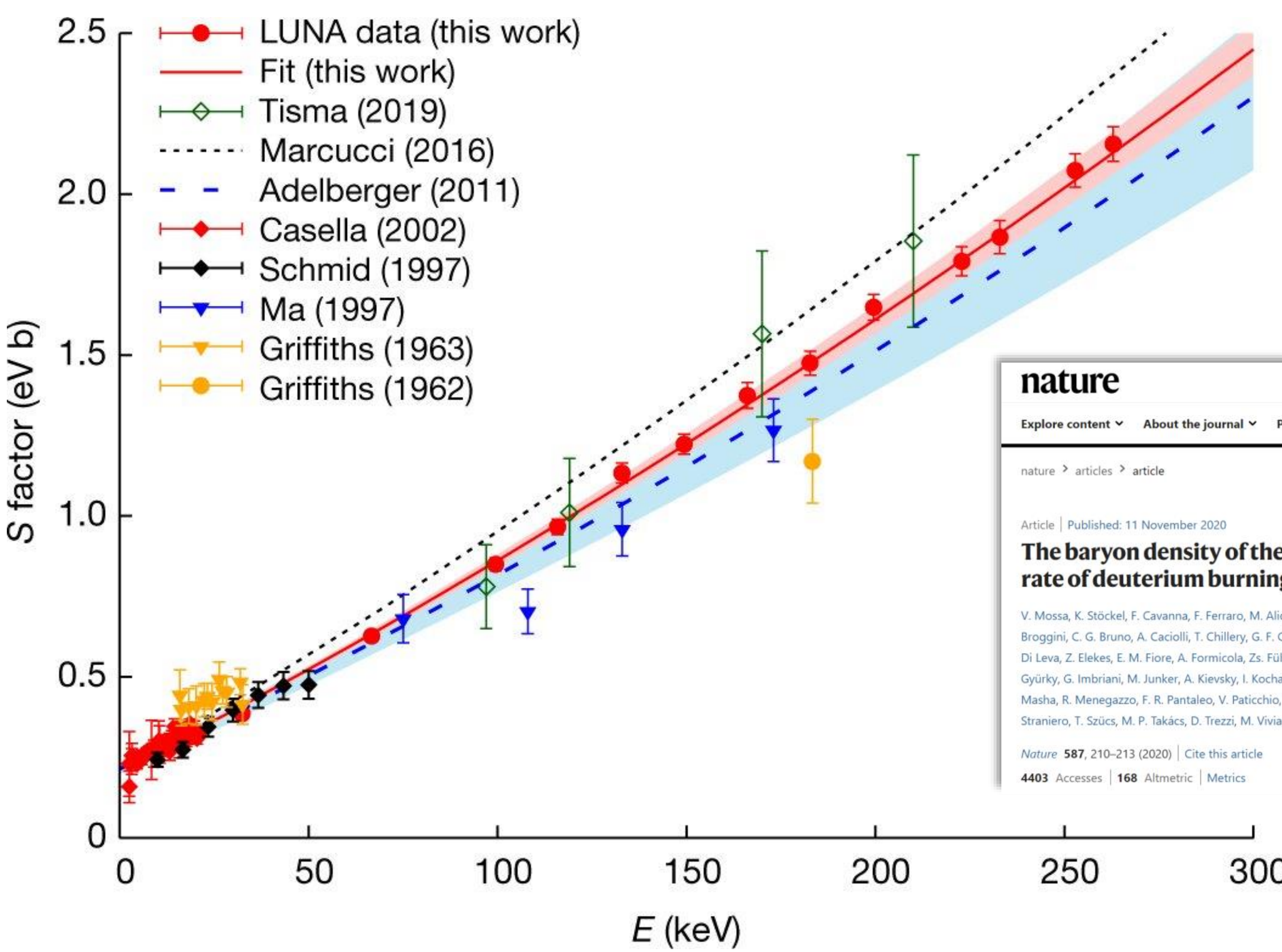
Results – *S*-factor



although the fit includes all experimental data, it is completely dominated by the new results by LUNA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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, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, G. Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli -Show fewer authors

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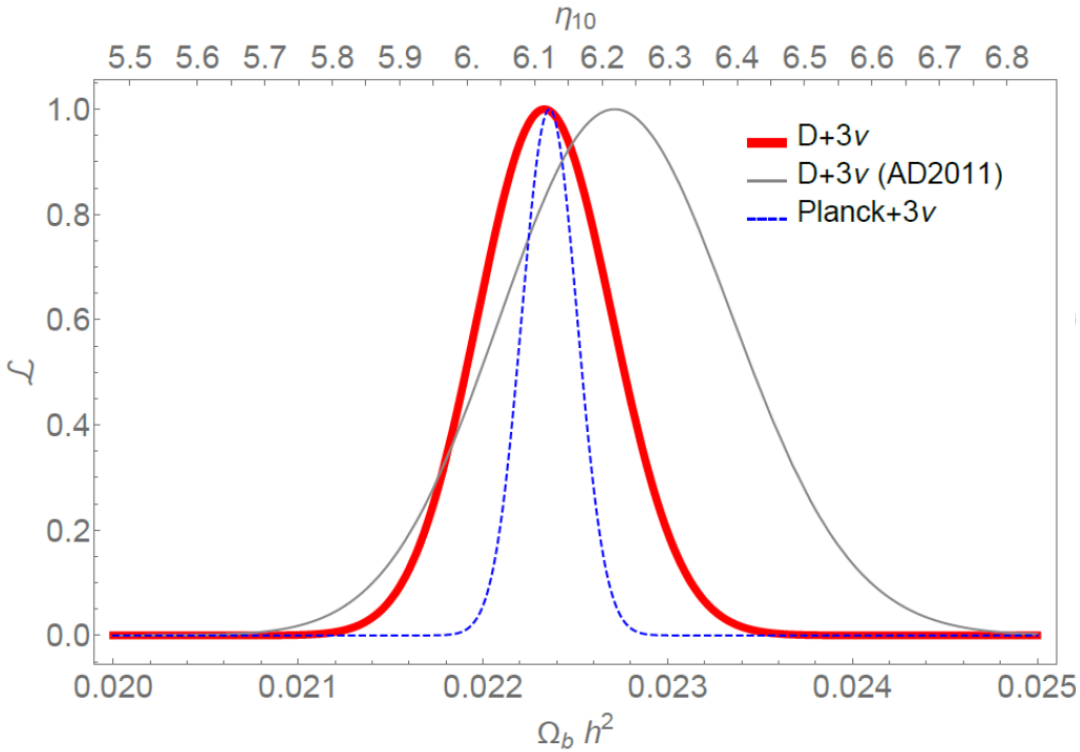
Results – Ω_b

implications of LUNA measurements on BBN have been investigated by Ofelia Pisanti and Gianpiero Mangano

- Baryon density obtained with PARTHENOPE code by comparing $(D/H)_{OBS}$ and $(D/H)_{BBN}$
- **N_{eff} = 3.045, fixed**



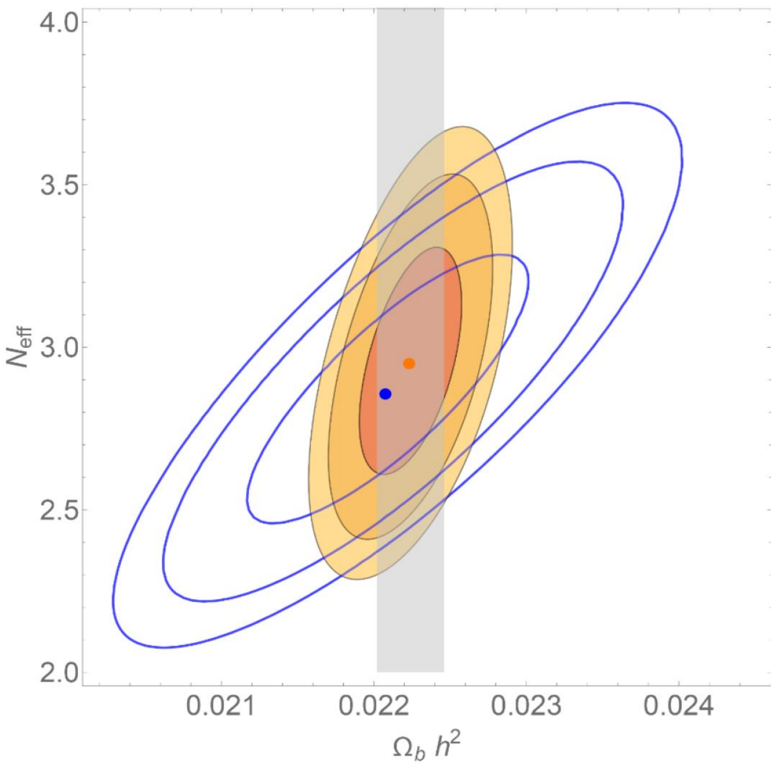
our result is consistent with **Planck** and is more accurate and precise than **previus results** based on preceding measurements

this new, independent determination of Ω_b further supports the ΛCDM model

Results – N_{eff}

To further probe the existence of physics beyond the ΛCDM model: likelihood analysis

- both Ω_b and N_{eff} left as free parameters
- (D + CMB) case: $(\text{D/H})_{\text{obs}}$, **$(\text{D/H})_{\text{BBN}}$**, Ω_b (from Planck, Gaussian distribution, grey band=68% CL)
- (D + Y_p) case: $(\text{D/H})_{\text{obs}}$, **$(\text{D/H})_{\text{BBN}}$**, $(Y_p)_{\text{obs}}$, $(Y_p)_{\text{BBN}}$, Ω_b completely free



$$N_{eff} = 2.95^{+0.61}_{-0.57}$$

$$N_{eff} = 2.86^{+0.75}_{-0.67}$$

No evidence of a sizeable amount of any hypothetical "dark radiation" (e.g. sterile neutrinos, hot axions, etc…)

Conclusions…

By measuring the D(p,γ)^{3}He reaction cross-section to an unprecedented precision of better than 3%, LUNA settled the most uncertain nuclear physics input to BBN calculations and substantially improved the reliability in the use of primordial abundances as probes of the physics of the early Universe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Further reading

Resolving conclusions about the early Universe requires accurate nuclear measurements

Cyril Pitrou, Alain Coc[…] & Elisabeth Vangioni

Nature Reviews Physics (2021)

Deuterium experiments reveal conditions in the early Universe

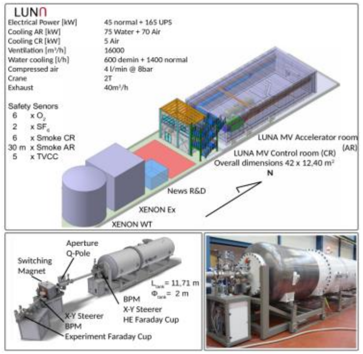
Zoe Budrikis

Nature Reviews Physics (2020)

…and outlook

The future shines bright for LUNA!

- new 3.5 MV accelerator
- rich experimental program



Reaction	Reason of interest
$^{14}N(p,\gamma)^{15}O$	commissioning, Standard Solar Model
$^{12}C(\alpha,\gamma)^{16}O$	Helium burning
$^{13}C(\alpha,n)^{16}O$	n source for the main s-process (zirconium to bismuth)
$^{22}Ne(\alpha,n)^{25}Mg$	n source for the weak s-process (iron to zirconium)
$^{12}C+{}^{12}C$	crucial reactions involved in Carbon burning

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Thank you for your attention!

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Extras

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The Gamow peak

At a given temperature, the average reaction rate per particle pair depends both on the relative velocity distribution (i.e. the temperature) and the cross section:

$$\langle\sigma v\rangle = \left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}} \left(\frac{1}{kT}\right)^{\frac{3}{2}} \int_0^\infty \frac{S(E)}{E}\, e^{-\sqrt{\frac{E_G}{E}}}\, E\, e^{-\frac{E}{kT}}\, dE \quad \Longrightarrow$$

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

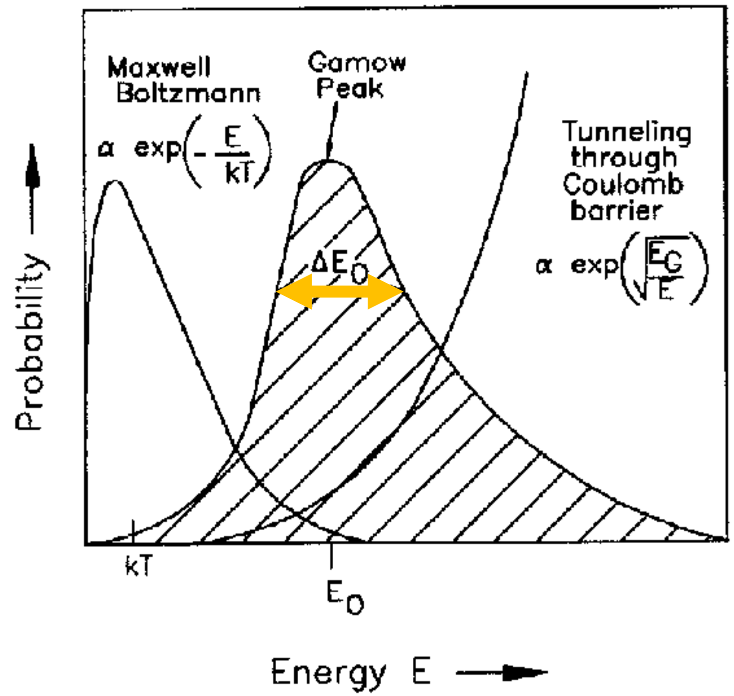
Reactions take place in a certain energy interval: the **Gamow window**

$$E_G = \left(\frac{1}{4\pi\epsilon_0}\frac{\sqrt{2\mu}e^2 Z_x Z_A}{\hbar}\pi\right)^2$$

$$E_0 = \left(\frac{\sqrt{E_G}}{2} kT\right)^{\frac{2}{3}}$$

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

T_9 (GK)	E_0^{lab} (keV)
0.2	55
0.5	101
1	160
2	254
5	467



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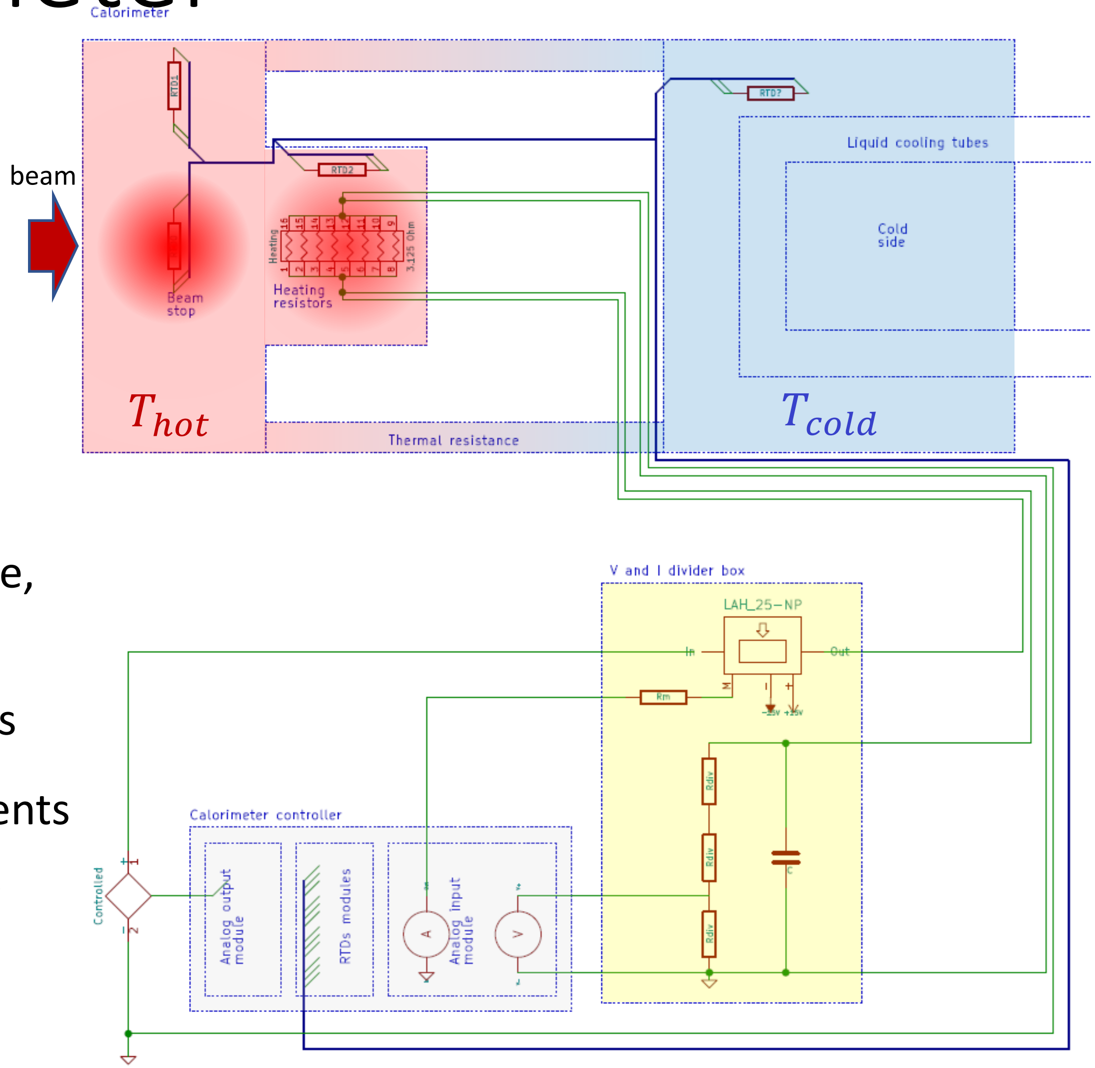
Beam calorimeter

$$W_{cal} = W_0 - W_{run}$$

$$I_{beam} = \frac{p_0 + p_1 W_{cal}}{E_p - \Delta E_{target}} e$$



Power compensation calorimeter

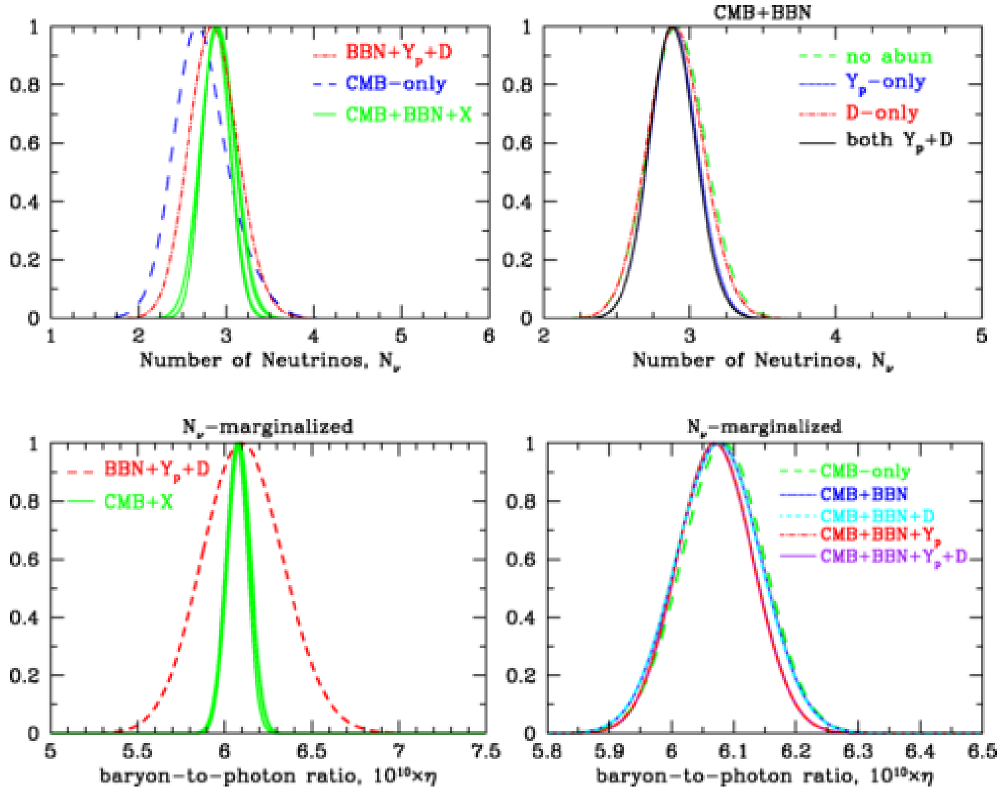
Copper cylinder. Hot side, cold side, constant ΔT

2 heat sources: beam and resistors

beam OFF – beam ON measurements to calculate the beam power W_{cal}

Systematic uncertainty: 1%

Impact of primordial abundances



Precise cross sections and BBN calculations can challenge or confirm the cosmological parameters inferred by CMB

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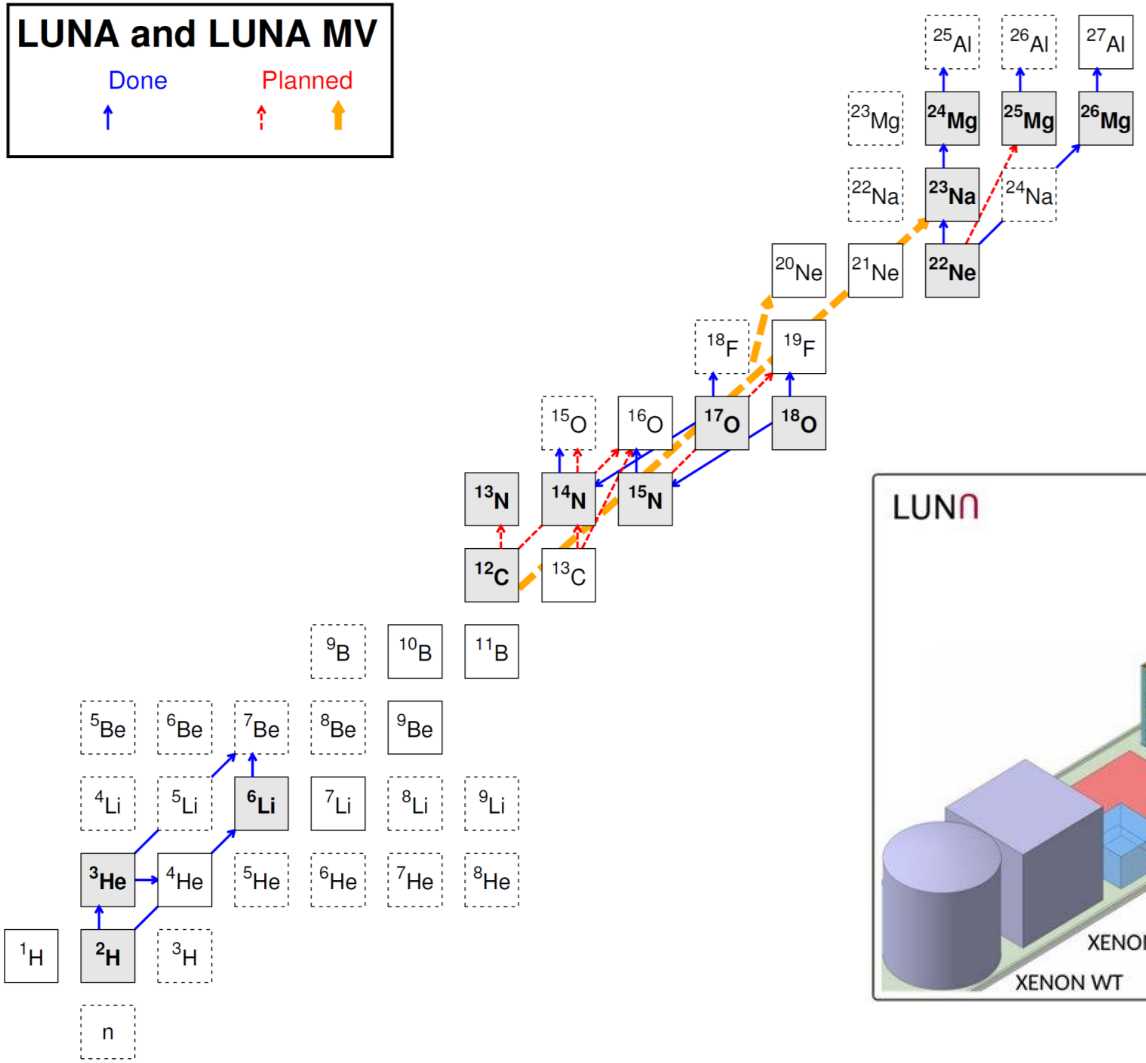
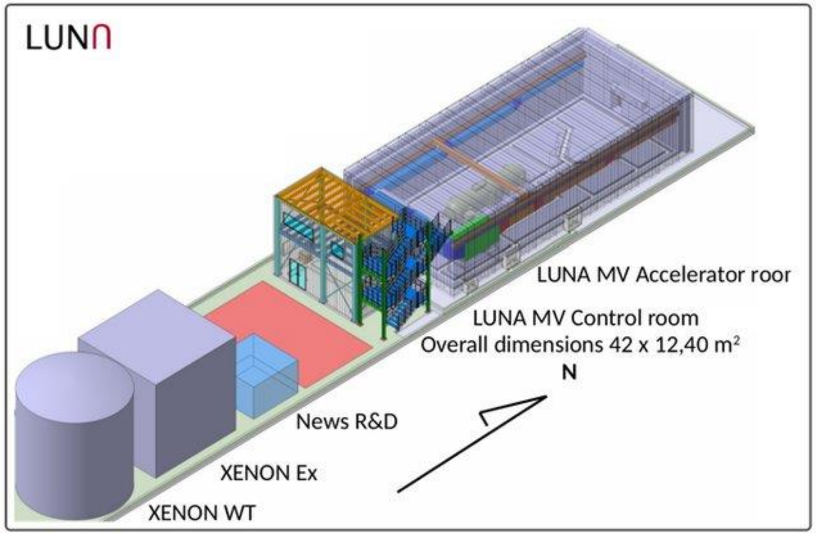
Future measurements





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