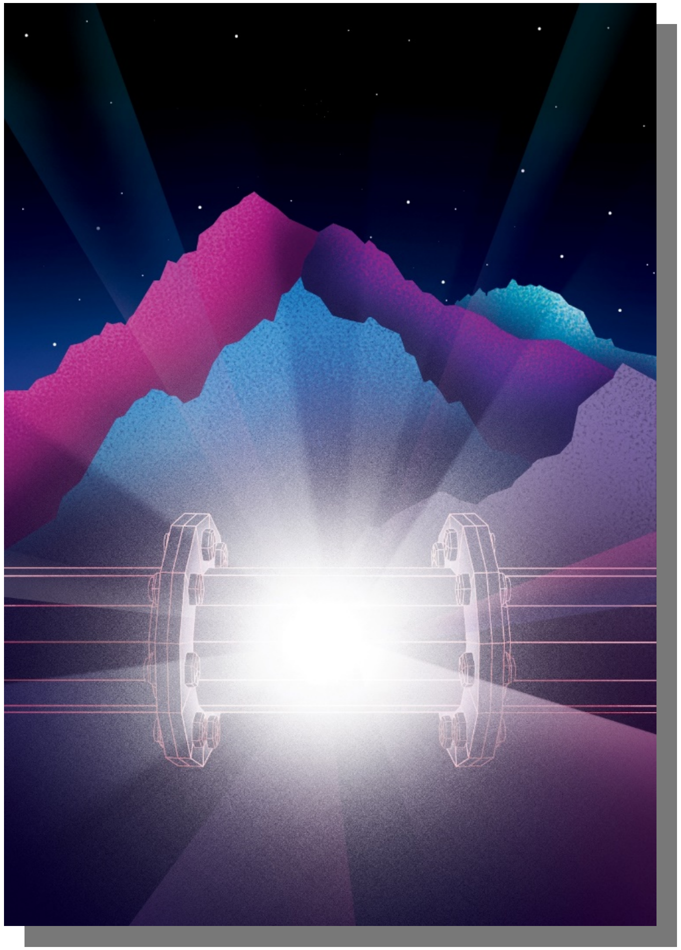
The baryon density of the Universe from an improved rate of deuterium burning



Francesca Cavanna

INFN Torino

LUNA Laboratory for Underground Nuclear Astrophysics

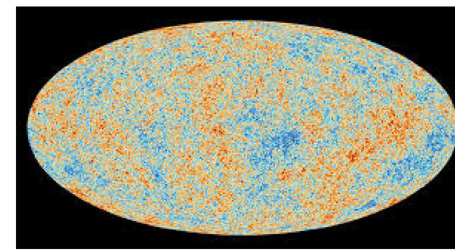
INFN Istituto Nazionale di Fisica Nucleare

Nuclear Astrophysics: an interdisciplinary field

Observational astronomy

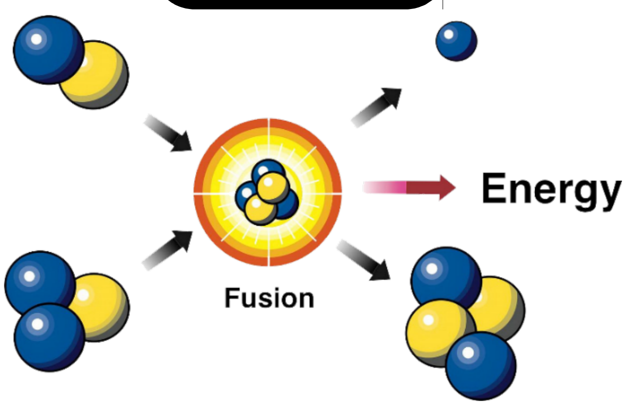
Cosmology

Nuclear astrophysics

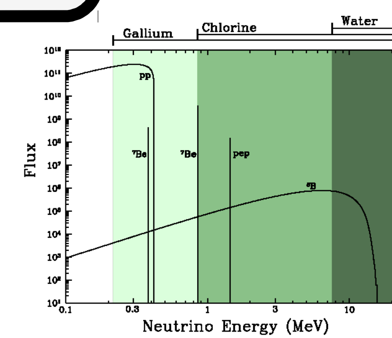


Nuclear physics

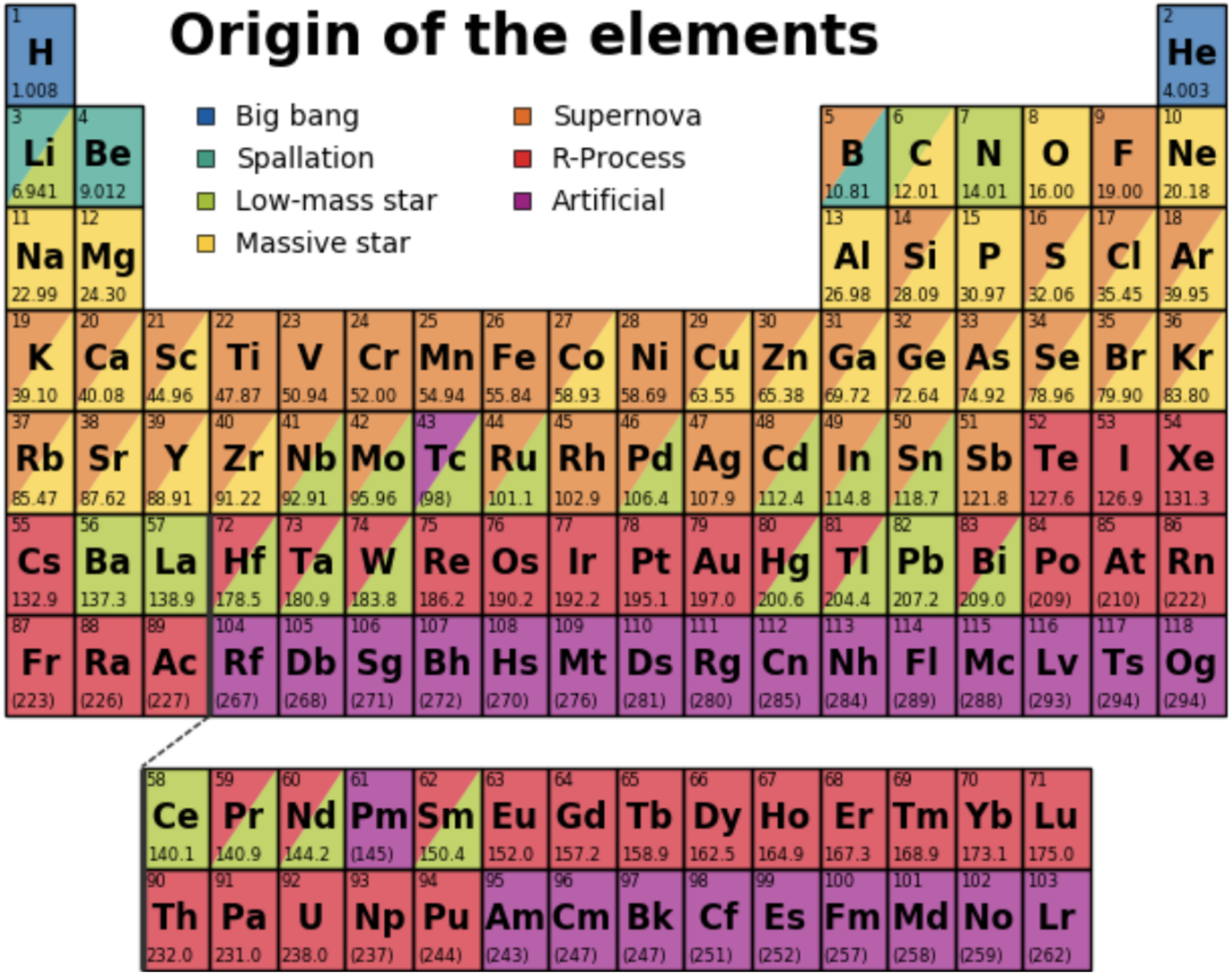
Neutrino physics



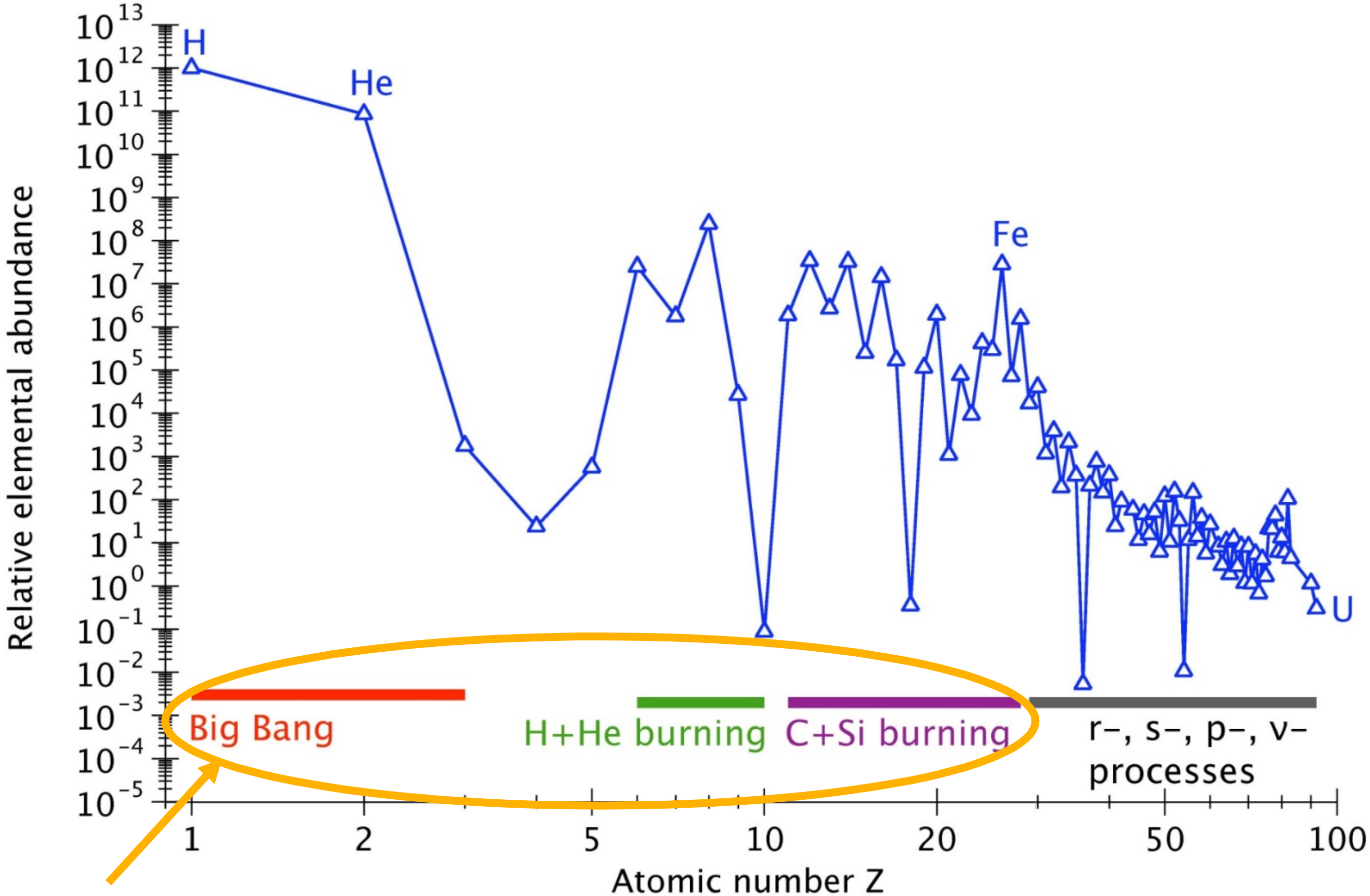
Stellar Models



The Origin of the Elements



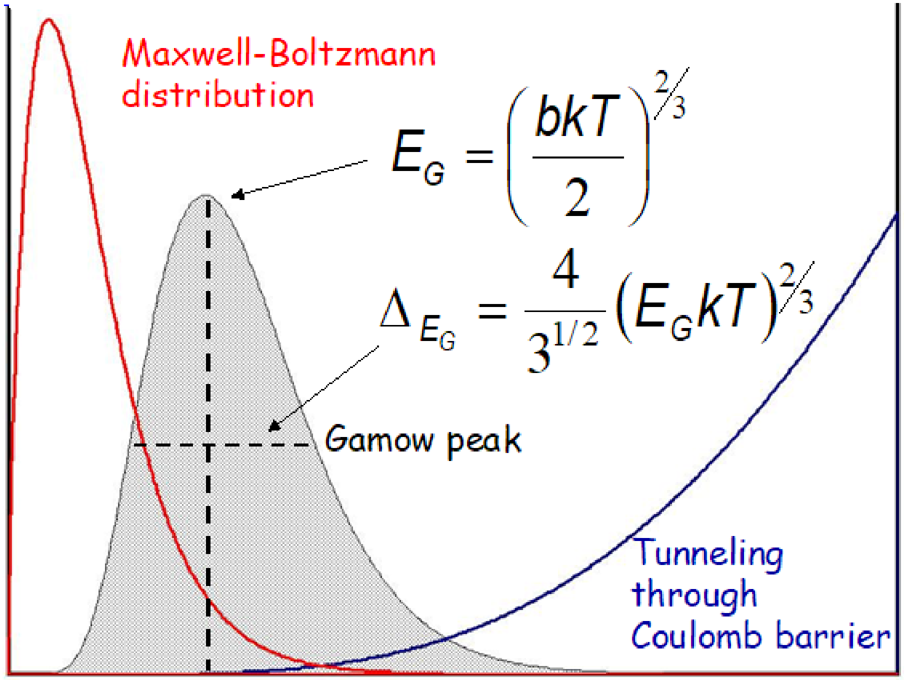
The Origin of the Elements



Charged-particle induced reactions

Challenges of
nuclear astrophysics experiments

Relevant energy range



Low energies ⟹ small cross sections

Experimental Challenges of Direct Measurement

Counting Rate = N_p x N_t x cross section x detection efficiency

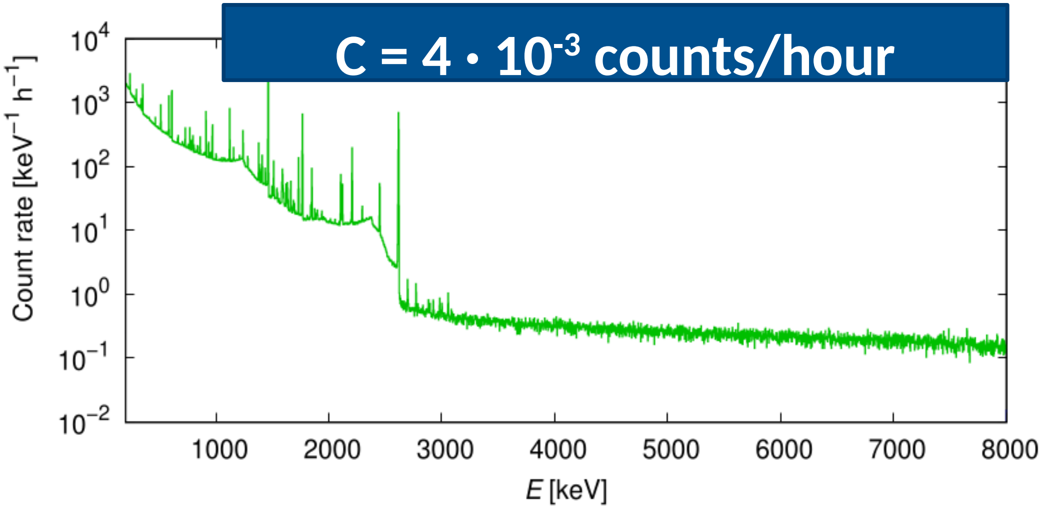
10^{14} pps (~100 μA q=1+) typical stable beam intensities

10^{18} atoms/cm^2 typical solid state targets

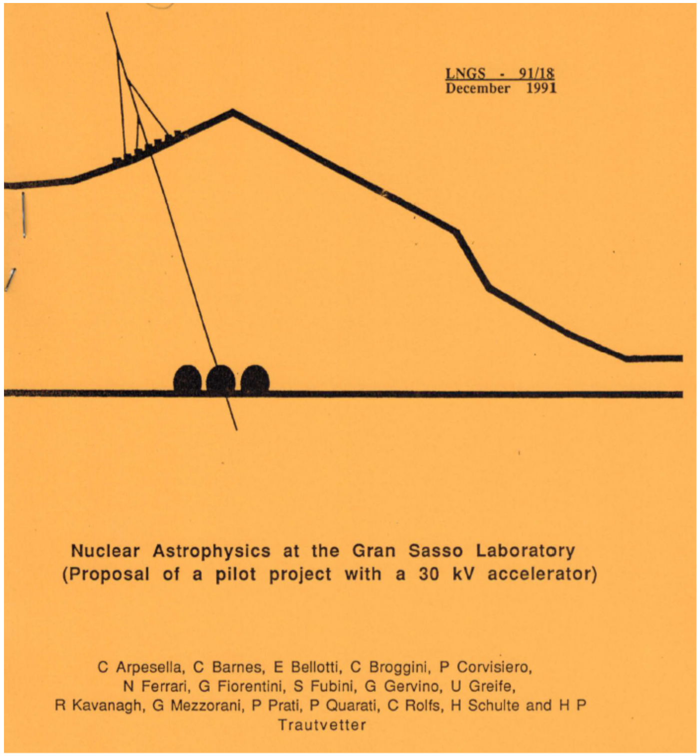
10^{-36} cm^2 (often even smaller)

~1-5% for gamma rays (HPGe detectors)

C = 4 · 10^{-3} counts/hour



How to improve the signal-to-noise ratio?

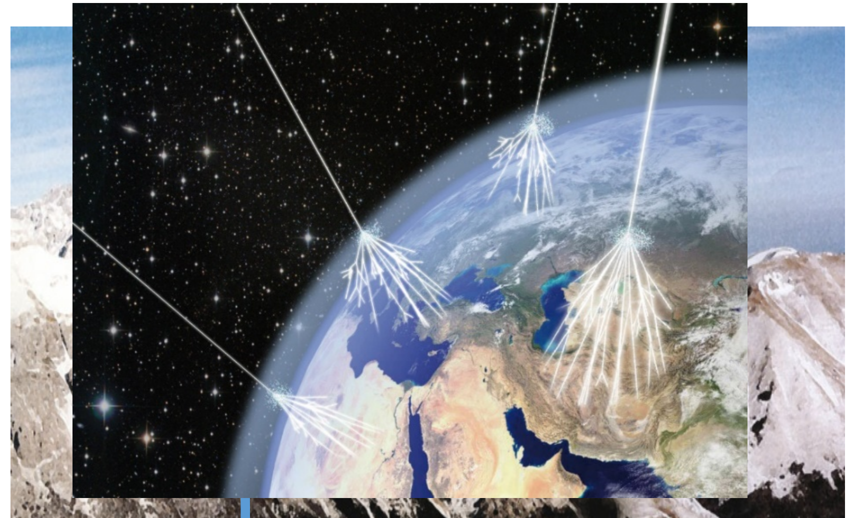

LNGS - 91/18
December 1991

Nuclear Astrophysics at the Gran Sasso Laboratory
(Proposal of a pilot project with a 30 kV accelerator)

C Arpesella, C Barnes, E Bellotti, C Broggini, P Corvisiero,
N Ferrari, G Fiorentini, S Fubini, G Gervino, U Greife,
R Kavanagh, G Mezzorani, P Prati, P Quarati, C Rolfs, H Schulte and H P
Trautvetter

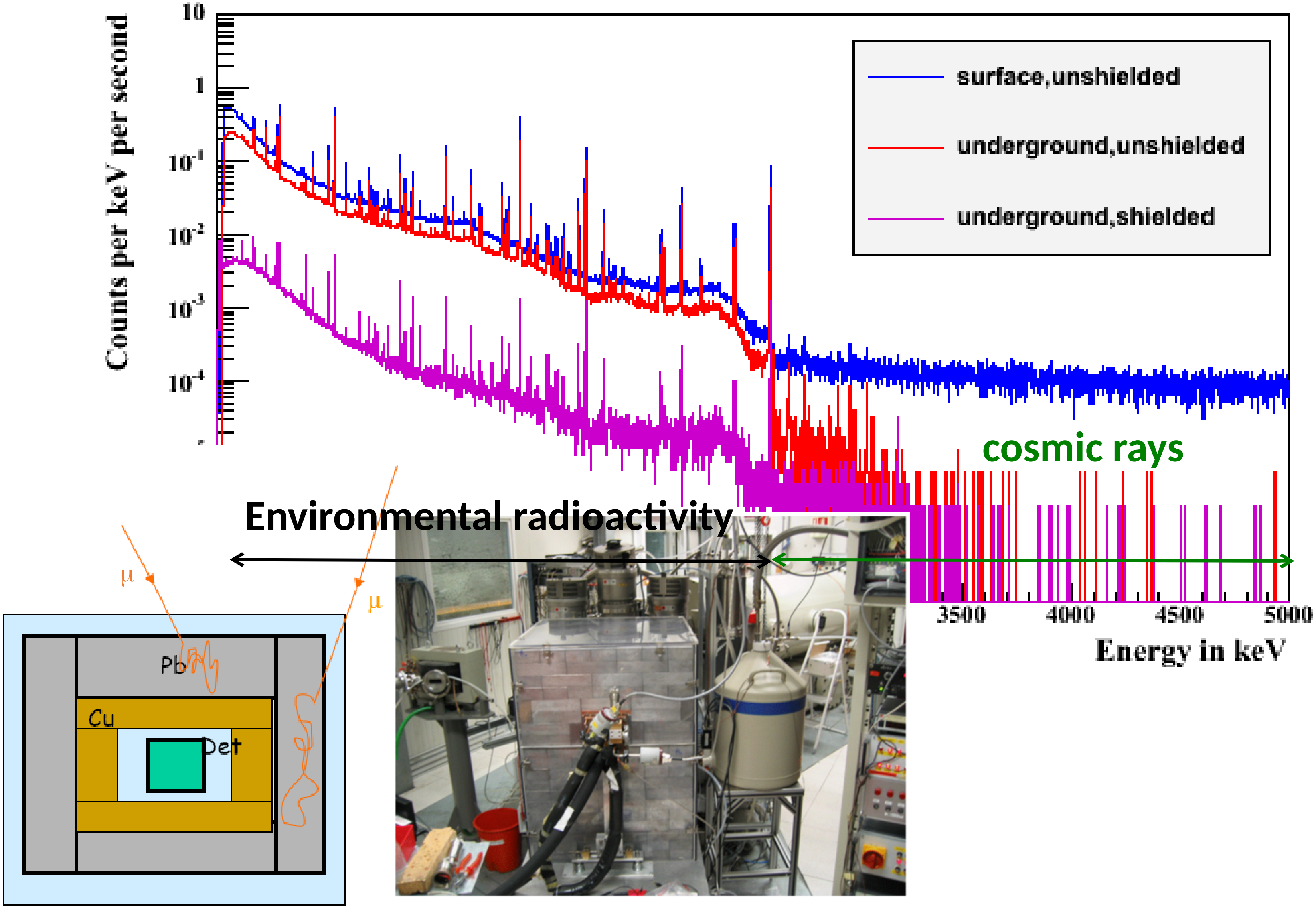
Laboratory for Underground Nuclear Astrophysics

Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}

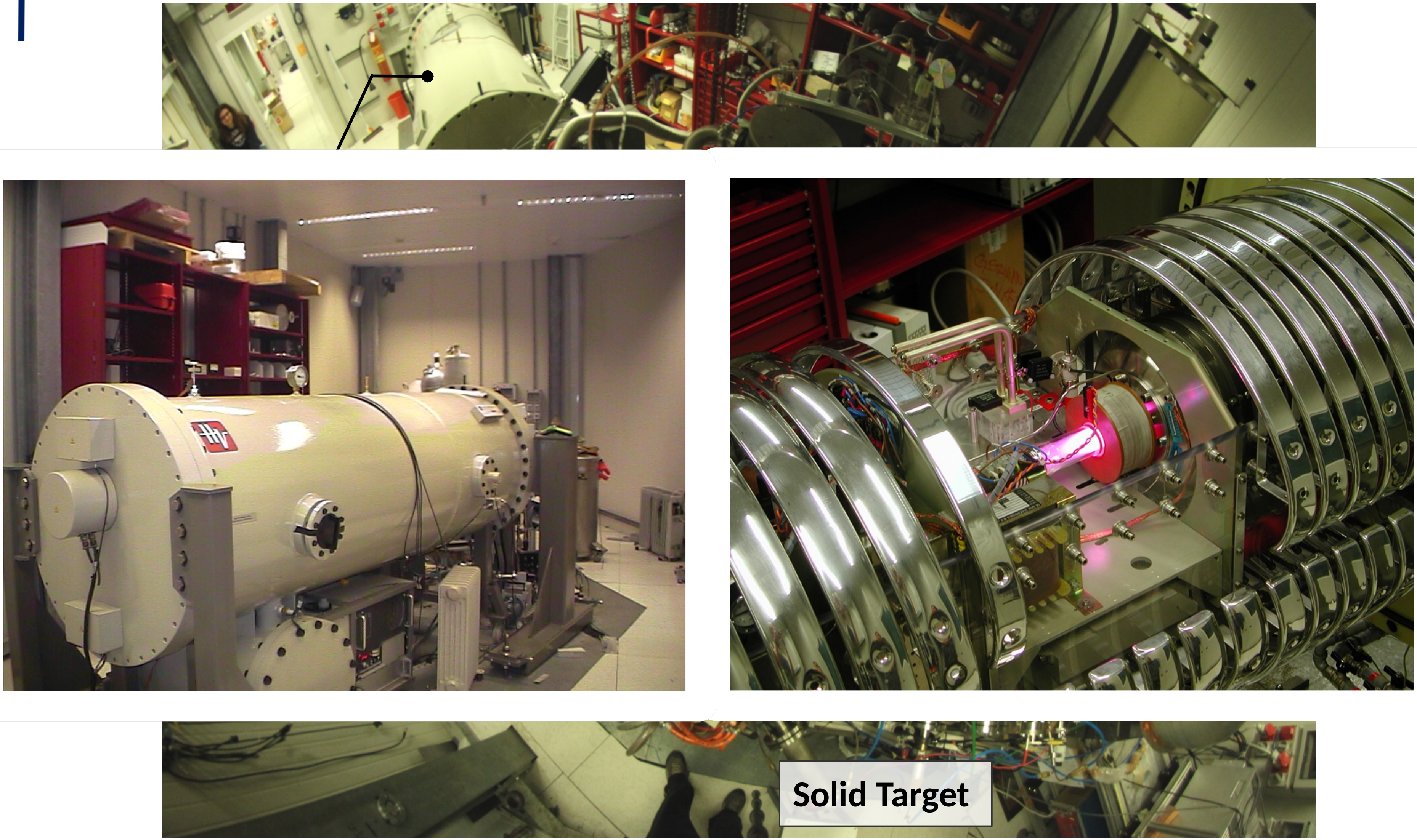


LNGS (1400 m rock shielding ≡ 4000 m w.e.)

Gamma background reduction at LNGS



LUNA experimental setup



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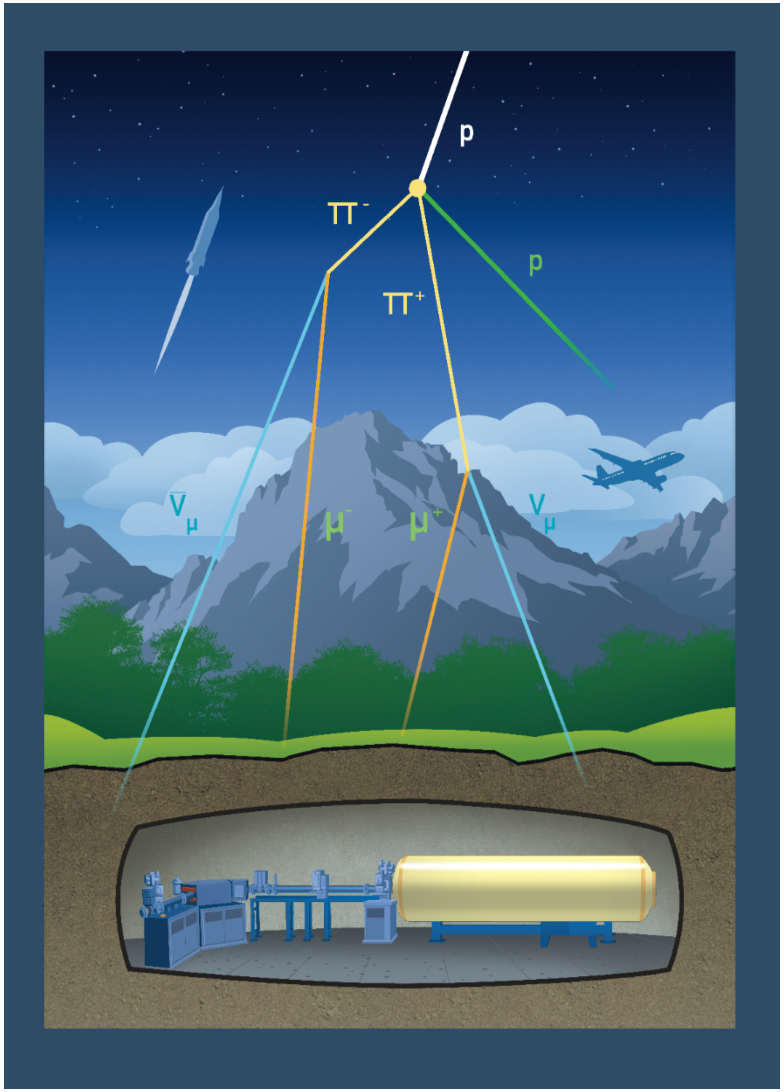
Article | Published: 11 November 2020

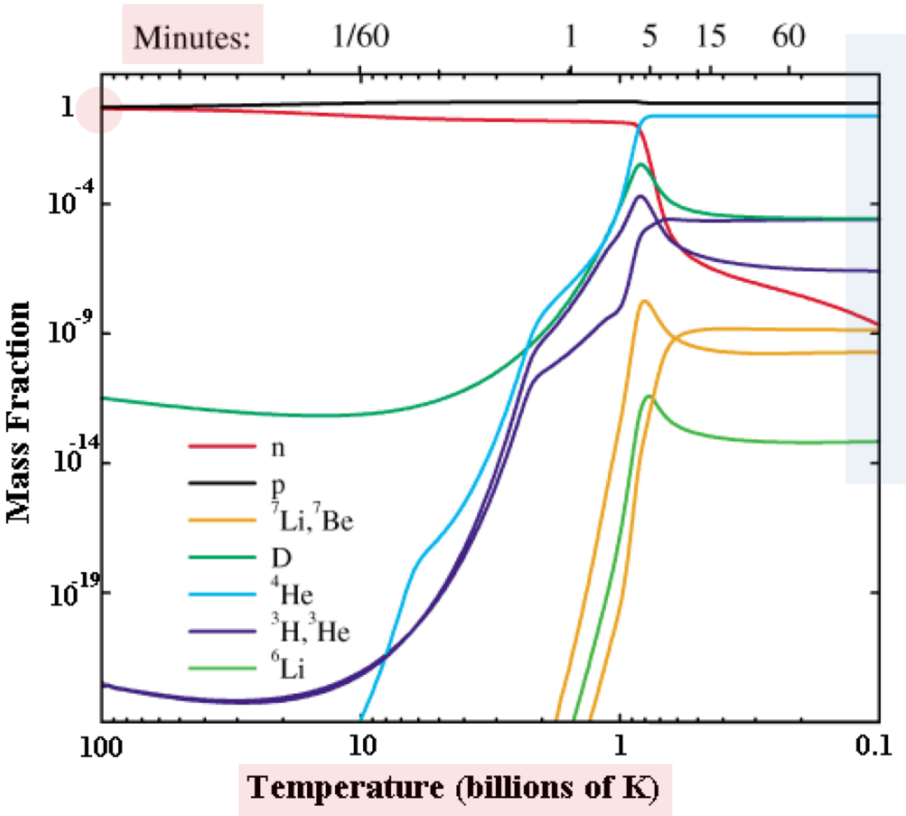
The baryon density of the Universe from an improved rate of deuterium burning

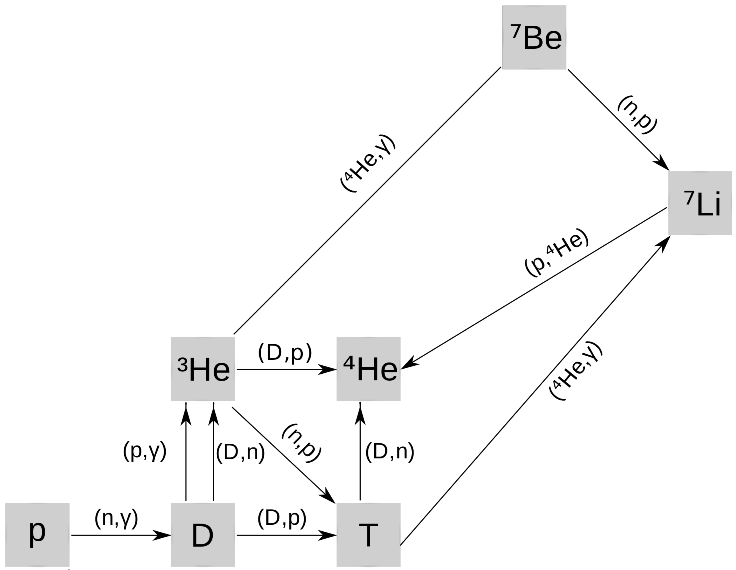
V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, 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

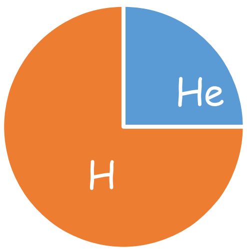
Nature **587**, 210–213(2020) | Cite this article



Big Bang Nucleosynthesis







- ✓ BBN occurs 3 minutes after Big Bang
- ✓ After BBN we have mainly H and ^{4}He plus small amounts of D, ^{3}He, ^{6}Li and ^{7}Li

The primordial deuterium abundance

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

- **Observed abundance**

  Direct astronomical observations

  $[D/H]_{OBS} = (2.527 \pm 0.030) \times 10^{-5}$

  Cooke et al, APJ 855 (2018) 102

  1% accuracy

- **Predicted abundance (BBN theory)**:

  From BBN theory, knowing the cosmological parameters and the cross sections of the processes responsible for D creation and destruction $[D/H]_{BBN}$

  Depending on the adopted cross sections →

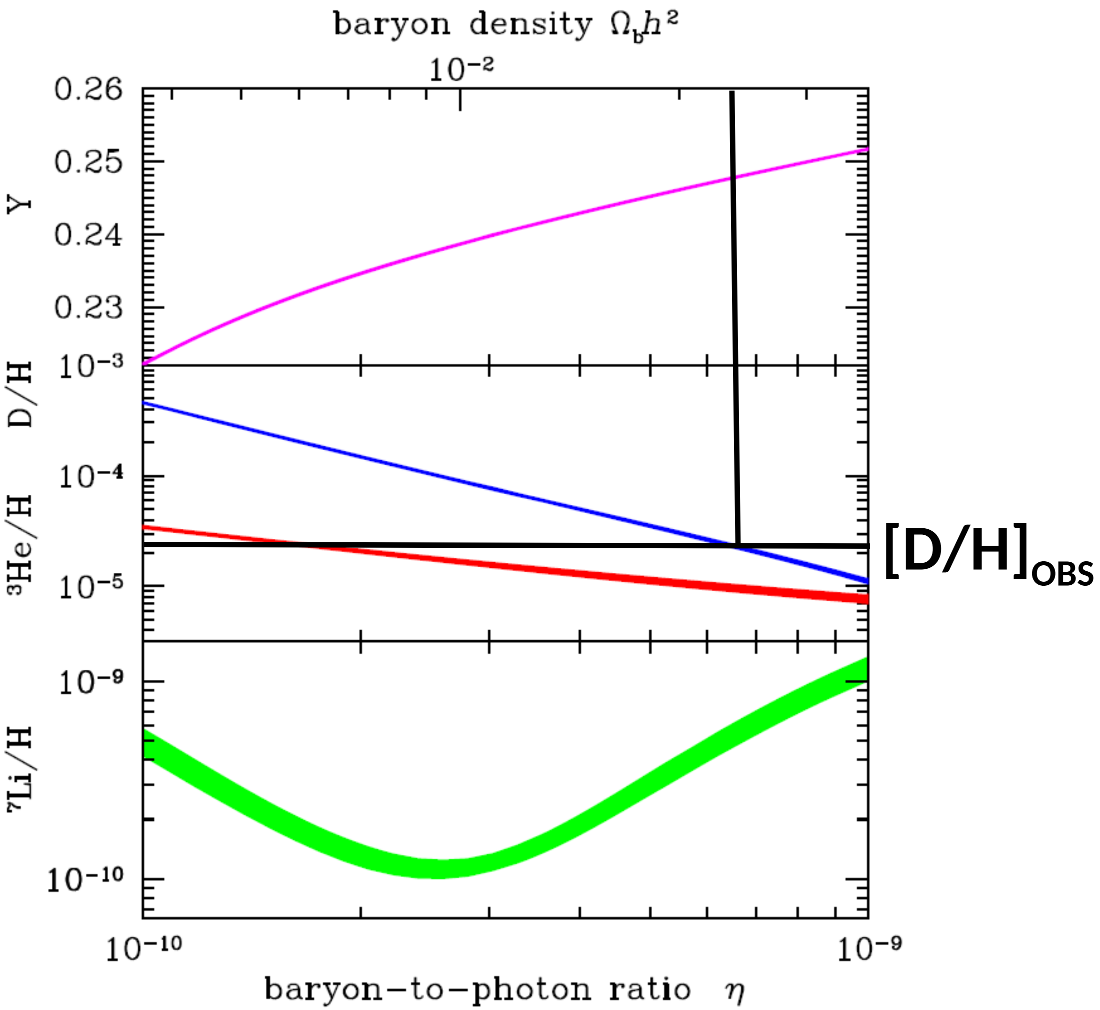
  $[D/H]_{BBN} = (2.587 \pm 0.055) \times 10^{-5}$

  $[D/H]_{BBN} = (2.439 \pm 0.052) \times 10^{-5}$

  Planck 2018, A&A 641 (2020) A6

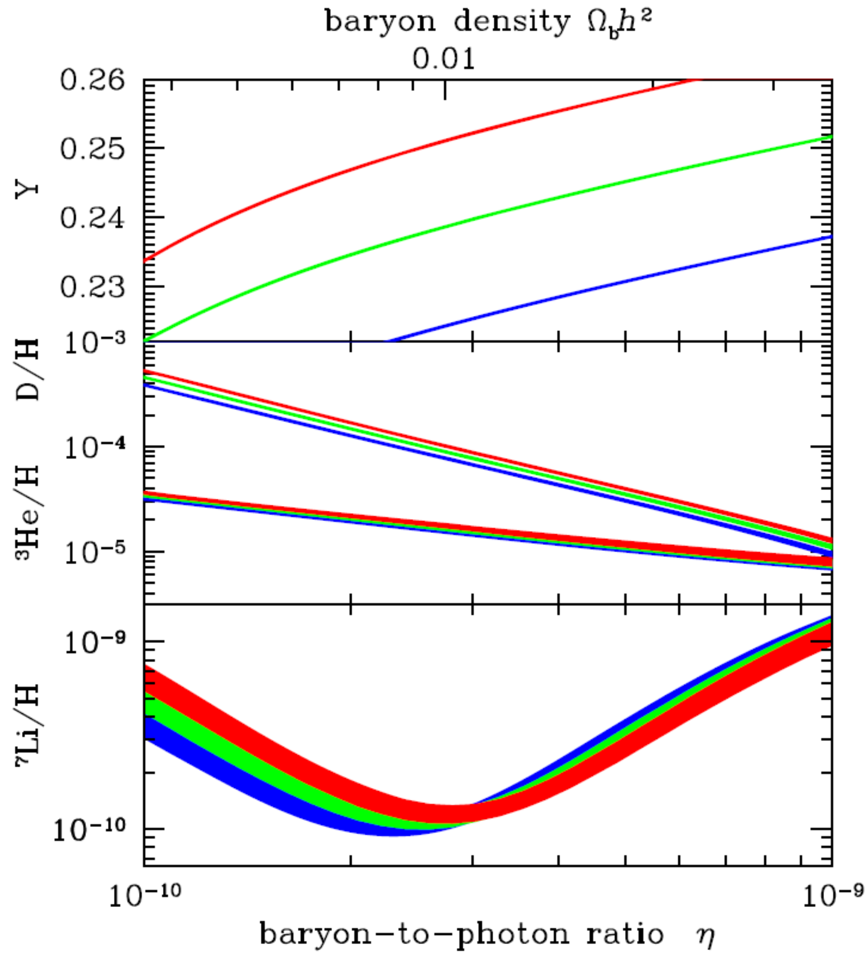
✓ By comparing $[D/H]_{OBS}$ and $[D/H]_{BBN}$ → the universal barion density Ω_B and/or N_{eff} can be derived

The primordial deuterium abundance



The primordial deuterium abundance is sensitive to the baryon density of the Universe

The primordial deuterium abundance



The primordial deuterium abundance is also sensitive to the number of neutrino species, N_{eff}= 2, 3 and 4

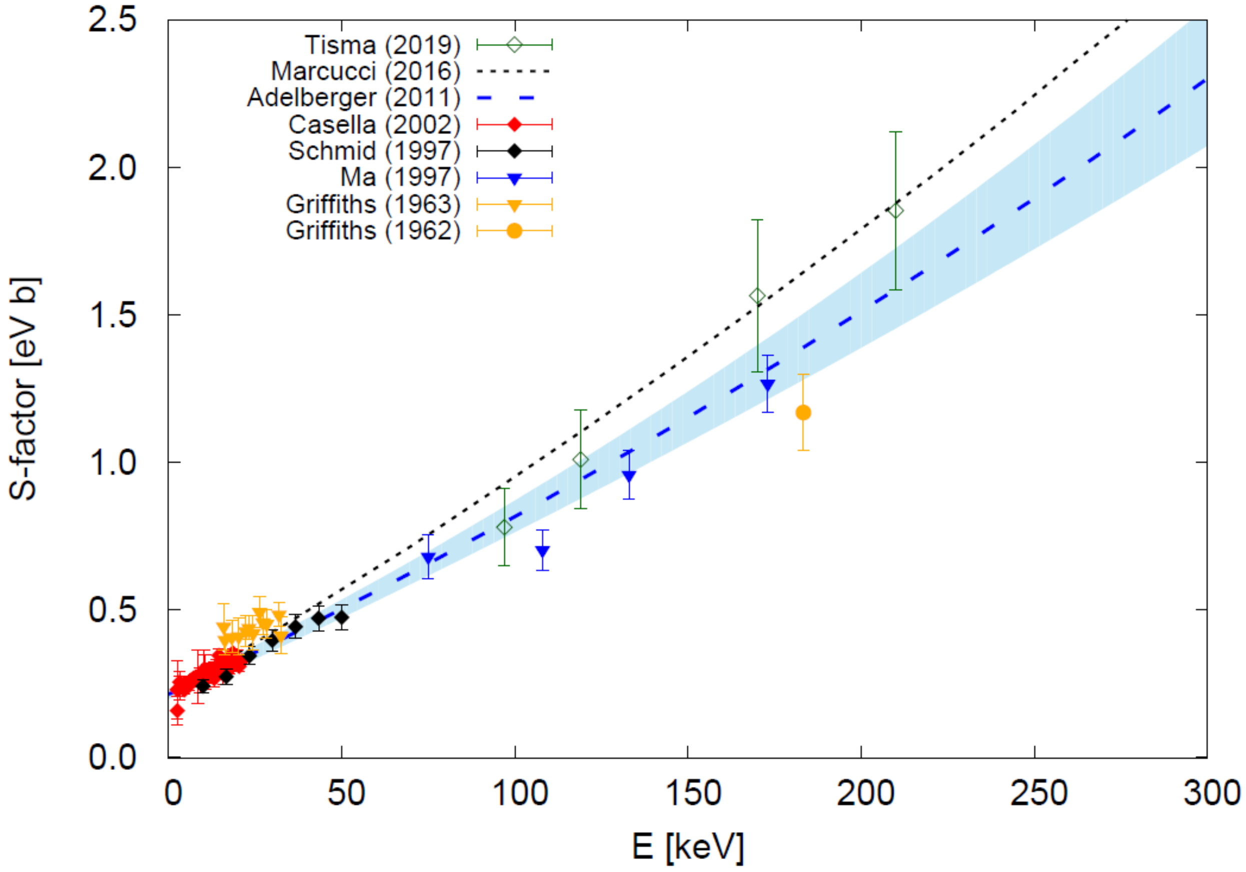
$D(p,\gamma)^3He$: State of the art

- The uncertainty on $[D/H]_{BBN}$ is related to the knowledge of the reactions involved in the deuterium production and distruction

Reaction	$\sigma_D\ 10^5$
$p(n,\gamma)D$	0.002
$D(p,\gamma)^3He$	0.062
$D(d,n)^3He$	0.020
$D(d,p)^3H$	0.013

- The uncertainty on $[D/H]_{BBN}$ is dominated by the uncertainty on the $D(p,\gamma)^3He$ S-factor

D(p,γ)^{3}He: State of the art



- ✓ Experimental data: two datasets currently available in the BBN energy range with a systematic error of 9-15%
- ✓ Ab initio calculations disagree with experimental data

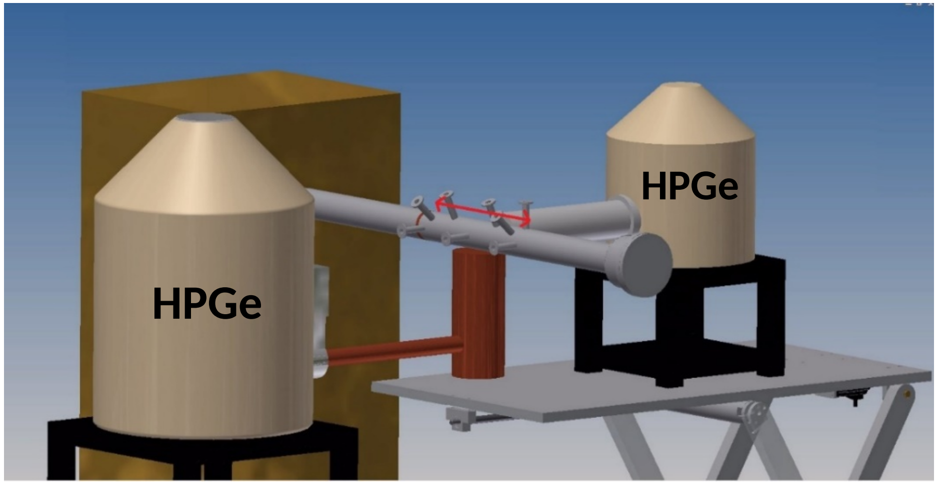
D(p,γ)^{3}He: experimental setup

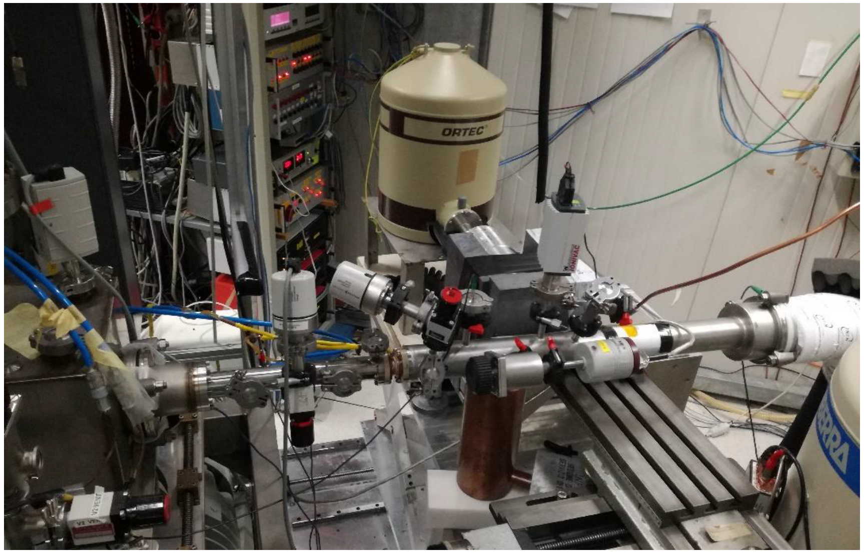
Measurement goal:

- ✓ Cross section measurement with ~3% accuracy
- ✓ E_{cm}= 30-300 keV

Experimental setup:

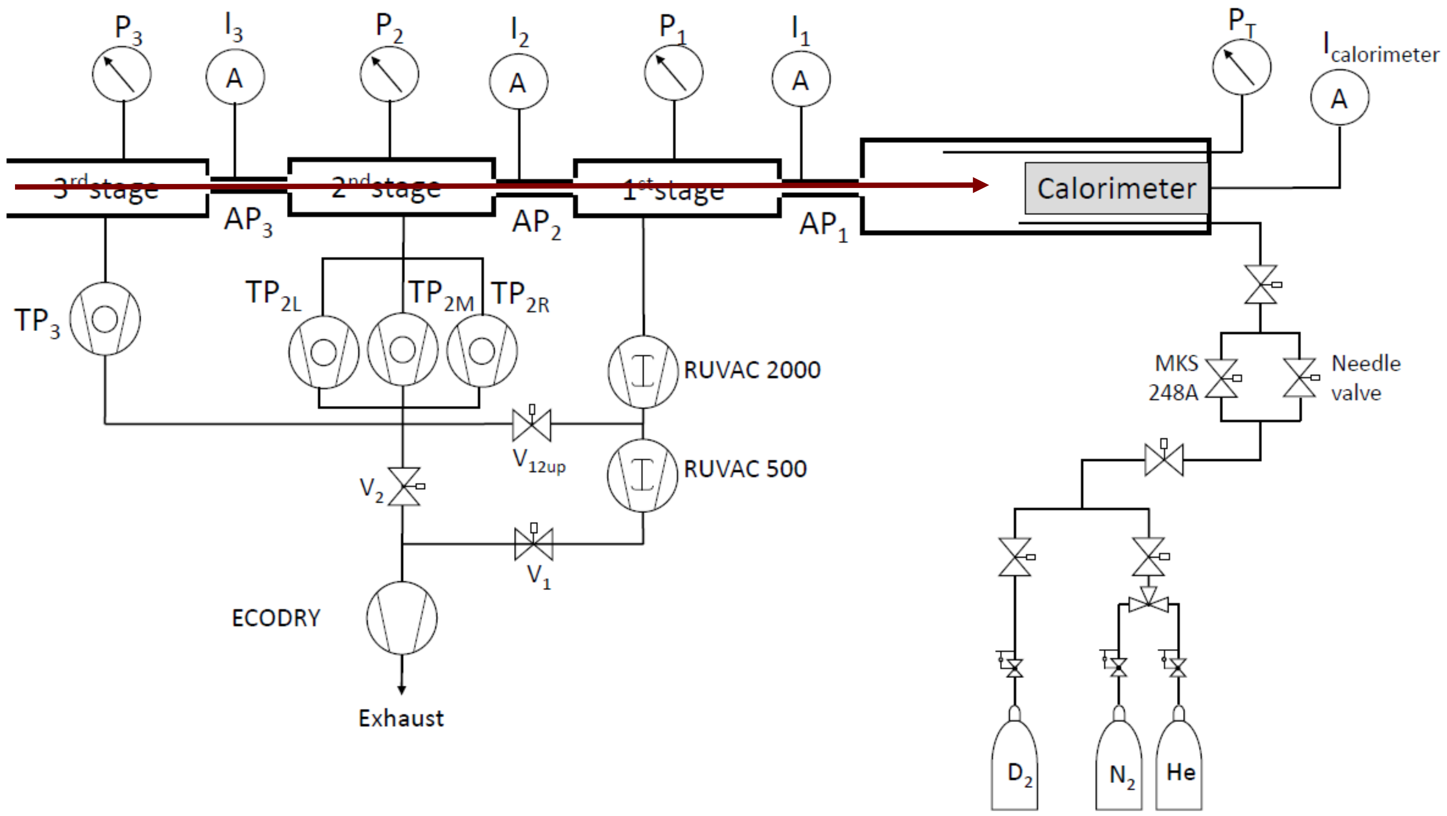
- ✓ Proton beam
- ✓ D_2 windowless gas target (P=0.3 mbar)
- ✓ HPGe detectors for γ-rays





D(p,γ)³He: experimental setup

✓ Windowless gas target setup

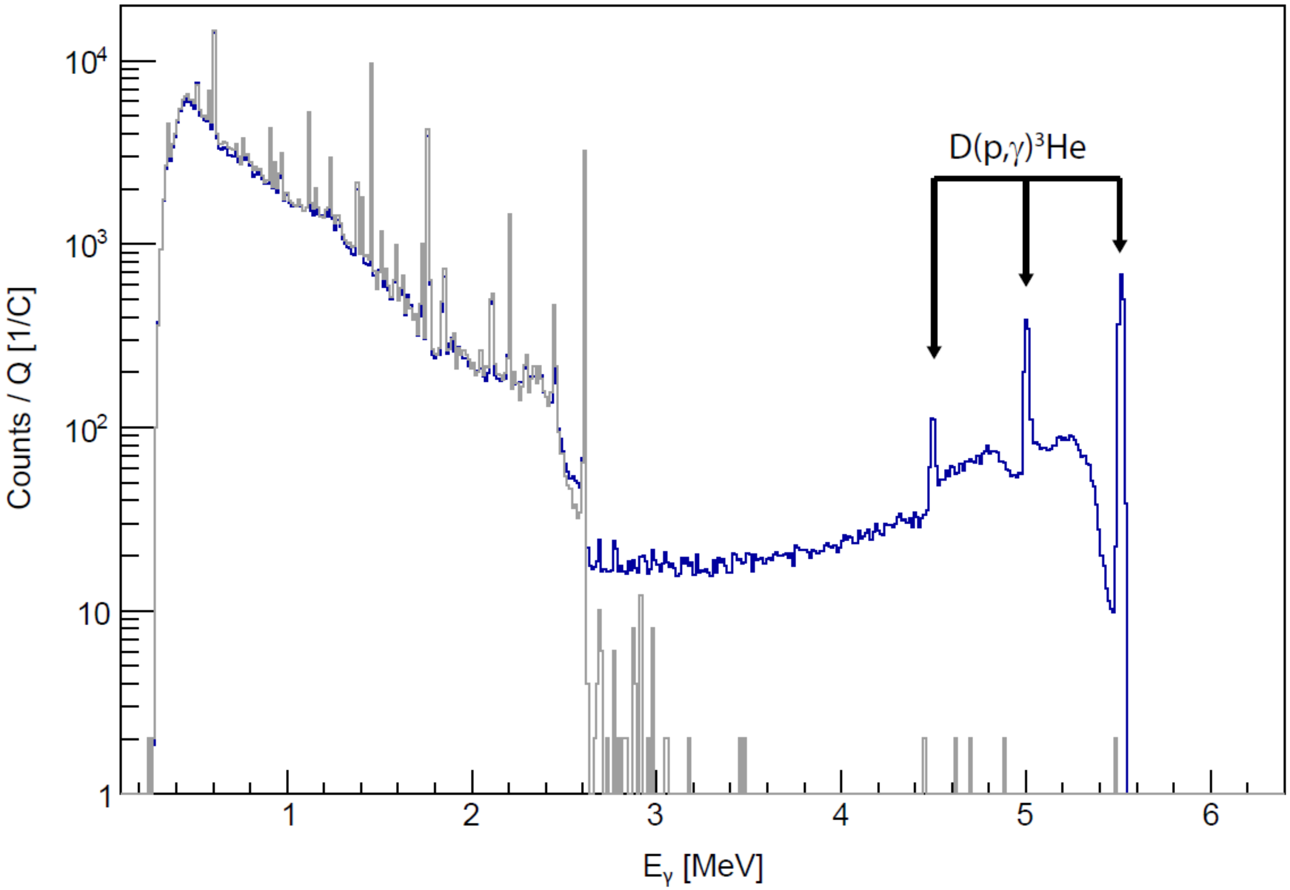


$D(p,\gamma)^3He$: study of systematic uncertainties

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

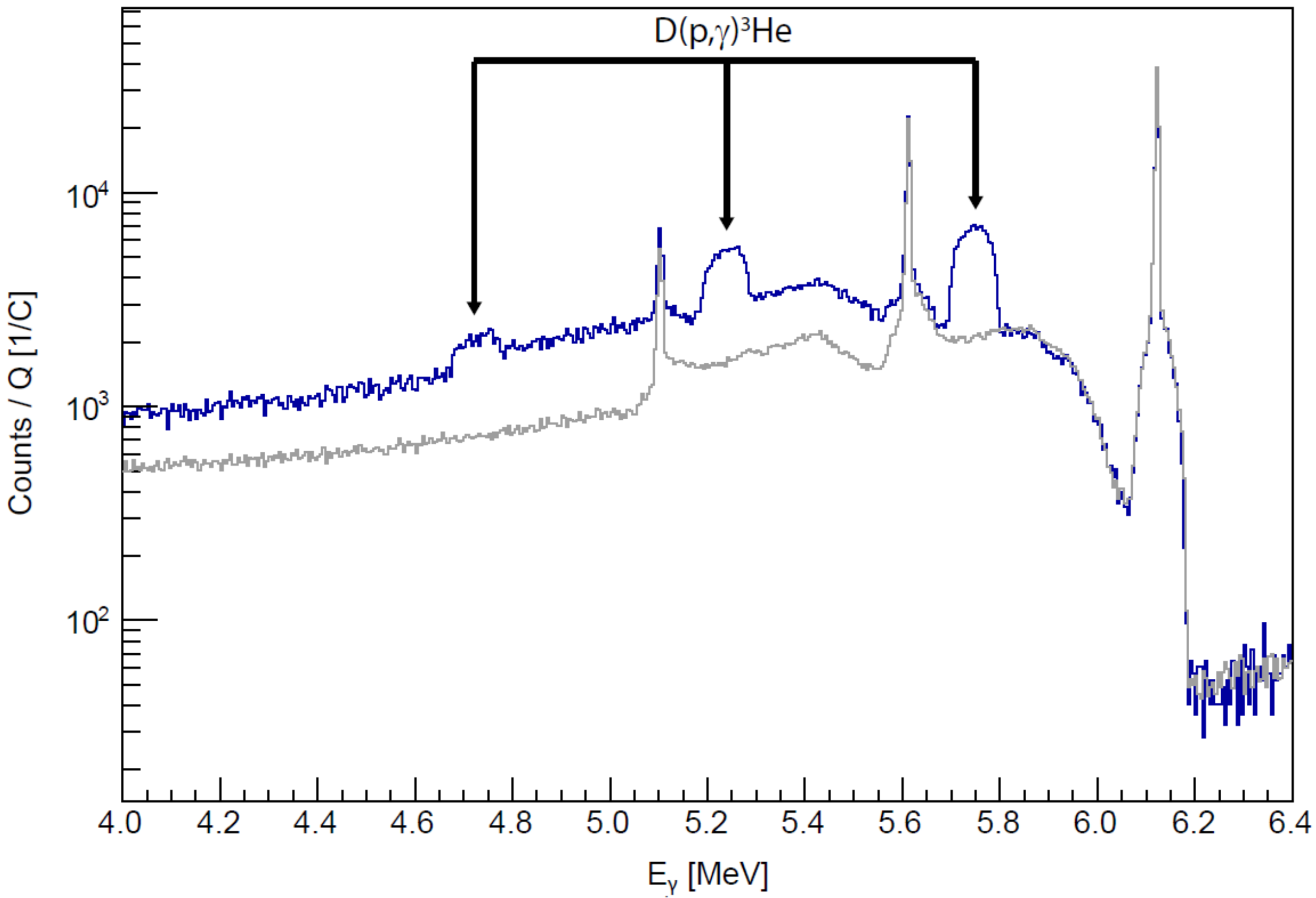
Source	Method	ΔS/S
Beam energy	Direct measurement	$\ll 1\%$
Energy loss	Low pressure	$\ll 1\%$
T and P profiles	Direct measurement	1.0%
Beam heating	Direct measurement	0.5%
Gas purity	Data sheet	$\ll 1\%$
Beam current	Calorimeter calibration	1.0%
Efficiency	Direct measurement	2.0%
Instrumental effects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

$D(p,\gamma)^3He$: spectra



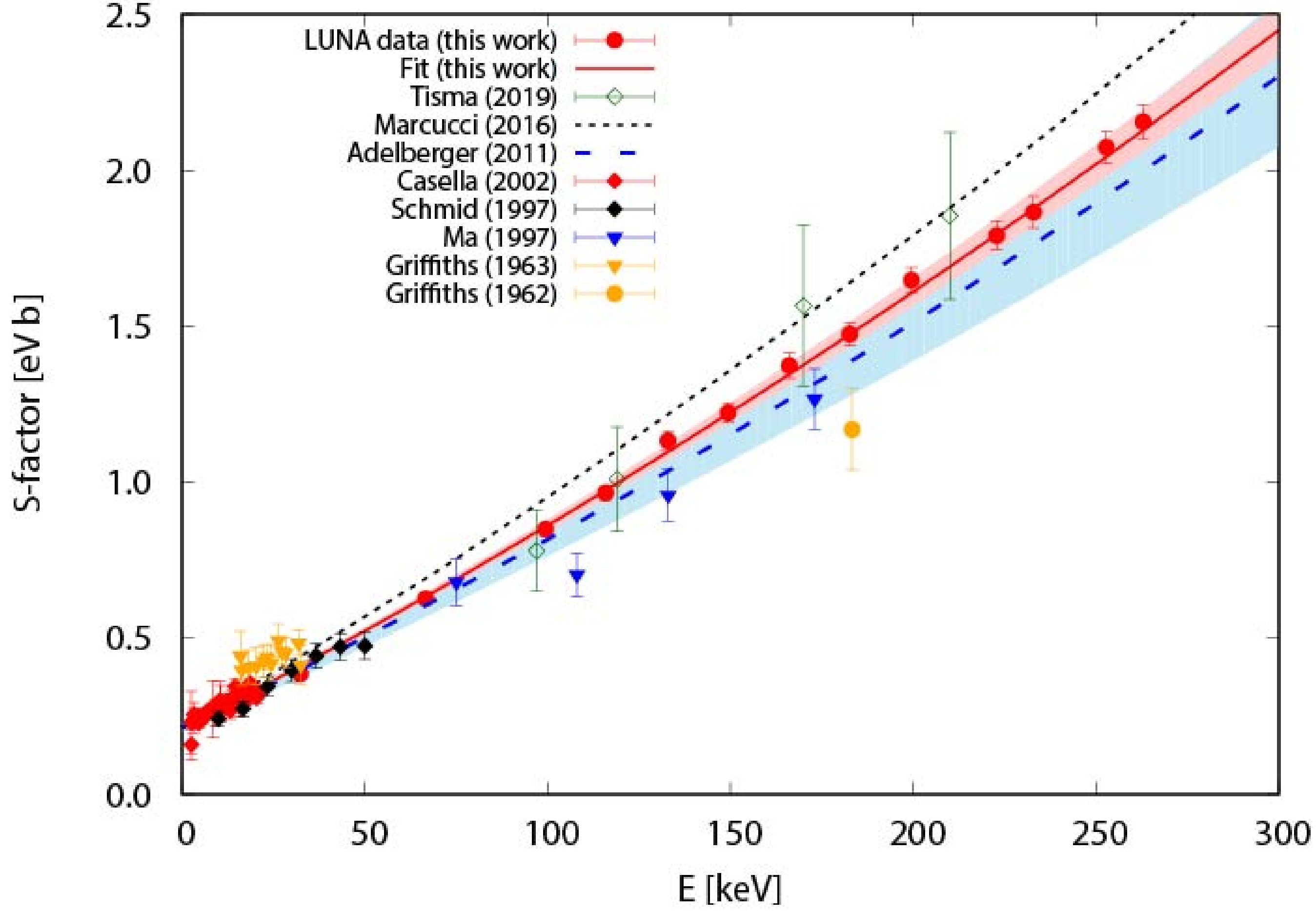
- Spectrum obtained @ E_p = 50 keV with D_2 gas target (P=0.3 mbar)
- Spectrum obtained @ E_p = 50 keV with ^4He gas target (P=0.4 mbar)

D(p,γ)^{3}He: spectra



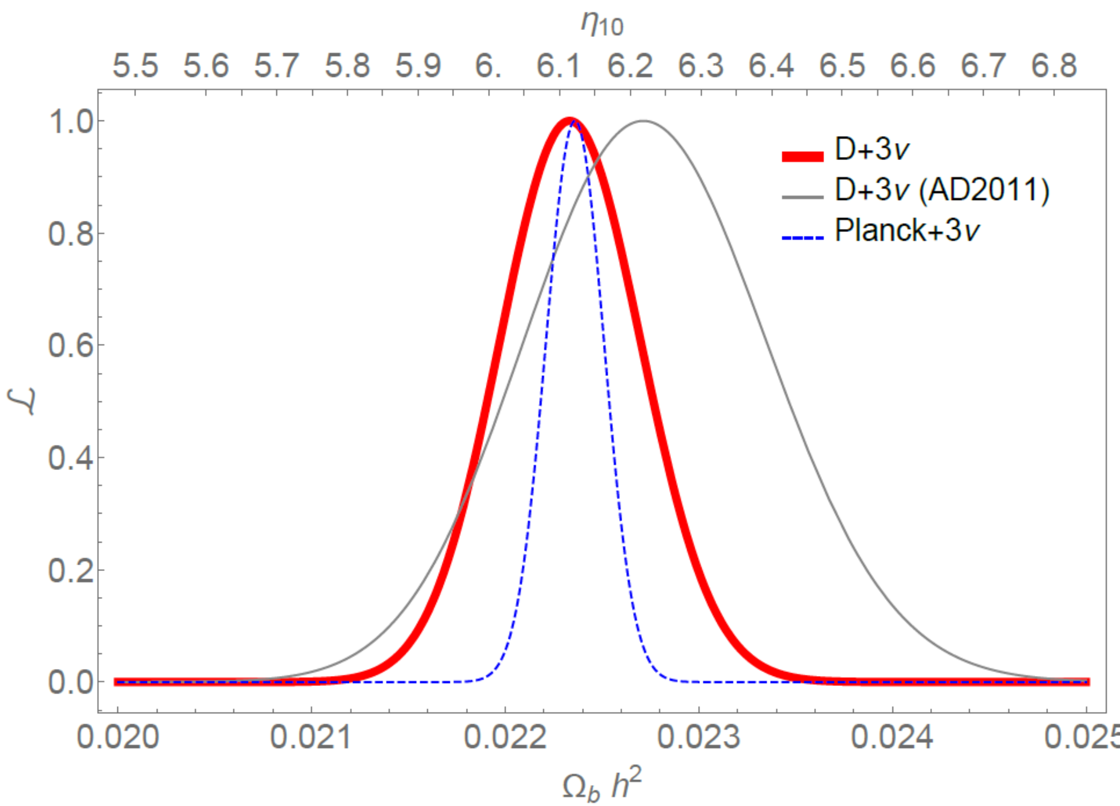
- ✓ Spectrum obtained @ E_p = 395 keV with D_2 gas target (P=0.3 mbar)
- ✓ Spectrum obtained @ E_p = 395 keV with ^{4}He gas target (P=0.3 mbar)

D(p,γ)^{3}He: S-factor results



The baryon density of the Universe

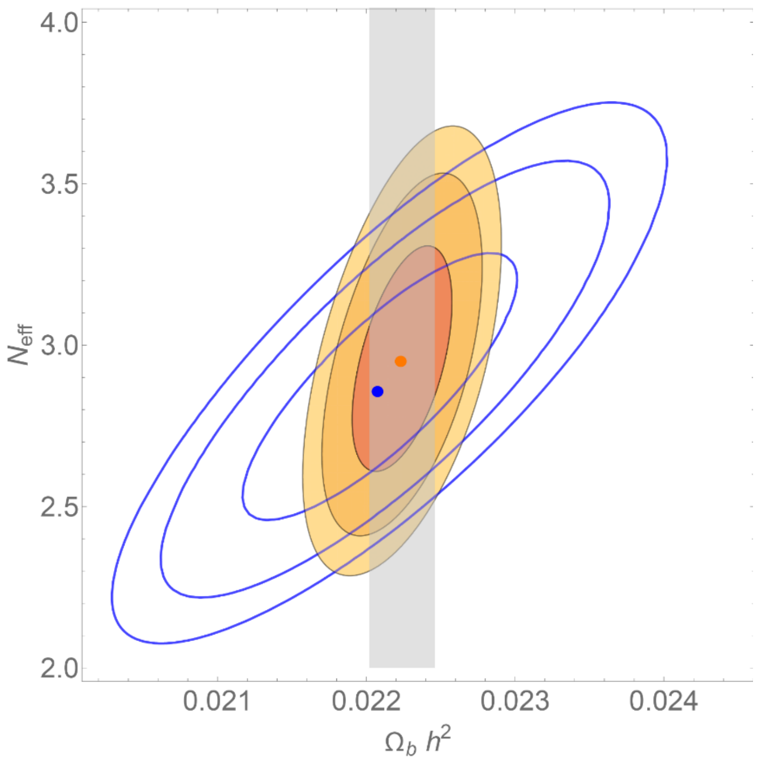
- Baryon density obtained with PARTHENOPE code by comparing $[D/H]_{OBS}$ and $[D/H]_{BBN}$
- N_{eff} = 3.045, fixed
- Comparison with Planck results



Analysis performed by Ofelia Pisanti and Gianpiero Mangano

Evidence of new physics?

- ✓ Likelihood analysis in wich both $\Omega_b h^2$ and N_{eff} were left as free parameters
  - D+CMB case with $(D/H)_{obs}$ and $(D/H)_{BBN}$, combined with the CMB baryon density from Planck
  - D+Y_p case with observed and predicted values of both the deuterium abundance and the ^{4}He mass fraction, Y



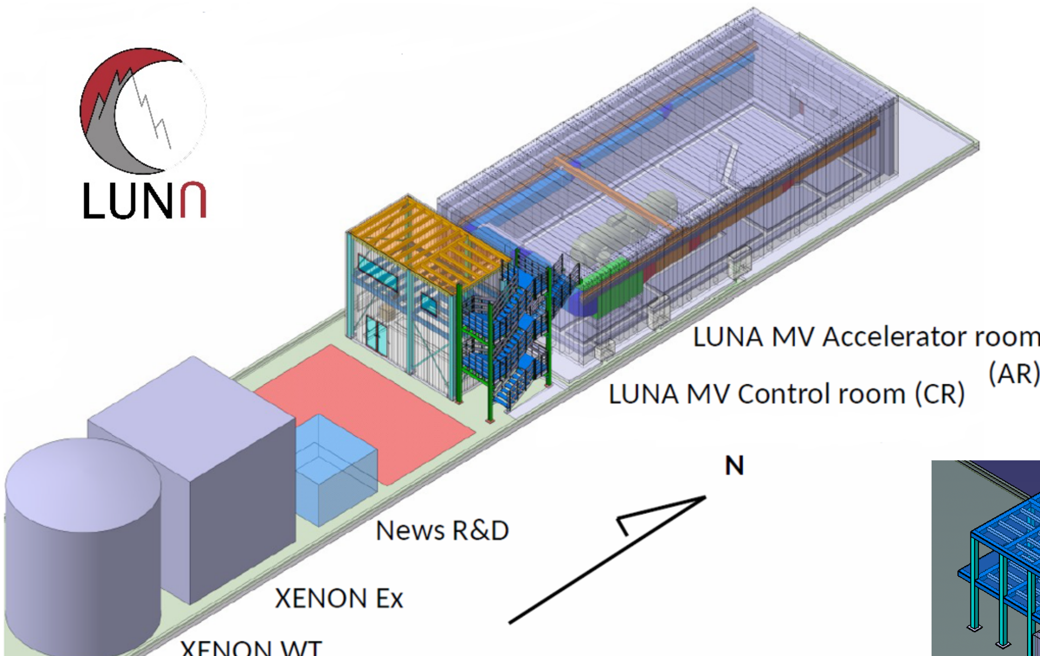
$$N_{eff} = 2.95^{+0.61}_{-0.57}$$

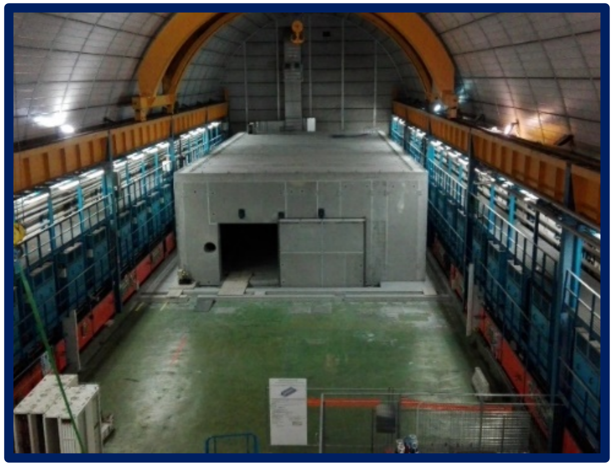
$$N_{eff} = 2.86^{+0.75}_{-0.67}$$

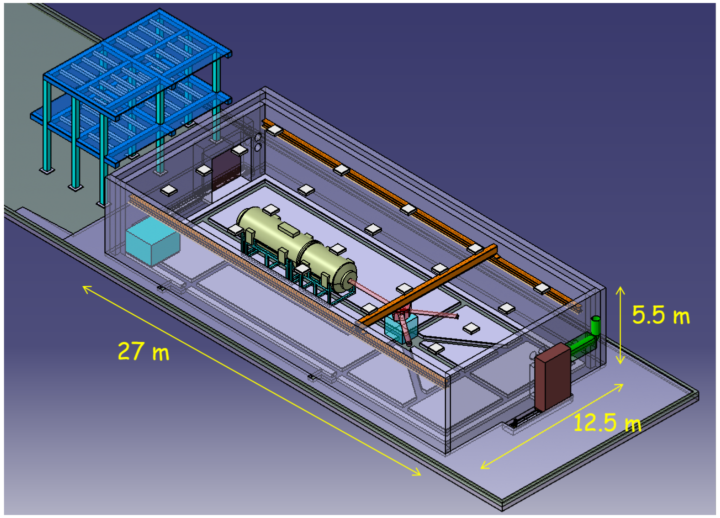
Our largest value of N_{eff} deviates by at most 20% from N_{eff} = 3.045

The future

LUNA MV: A 3.5 MV accelerator







H

$^{1}H^{+}$ (TV: 0.3 – 3.5 MV): 500-1000 μA

He

$^{4}He^{+}$ (TV: 0.3 – 3.5 MV): 300-500 μA

C

$^{12}C^{+}$ (TV: 0.3 – 3.5 MV): 150 μA

$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 μA

LUNA MV: scientific program (first five years)

- ✓ $^{14}N(p,\gamma)^{15}O$ reaction: commisioning measurement
  - Already studied at LUNA
  - High scientific interest: Solar Standard Model prediction for the solar composition → a measurement in a wide energy range is needed
- ✓ Neutron sources for the weak and main s-process: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$
  - $^{13}C(\alpha,n)^{16}O$: for a better extrapolation at low energies a measurement in a wide energy range is needed
  - $^{22}Ne(\alpha,n)^{25}Mg$: in the energy region of interest 570 keV < E_α < 800 keV no direct experimental data are available
- ✓ $^{12}C + ^{12}C$: of crucial importance for C burning. It influences the chemical composition of the Universe

Conclusions

The LUNA result settles the most uncertain nuclear physics input to BBN calculations and substantially improve the reliability of using primordial abundances as probes of the physics of the early Universe

The LUNA collaboration

- A. Boeltzig, A. Formicola, M. Junker | INFN LNGS
- D. Bemmerer, K. Stoeckel | HZDR Dresden, Germany
- C. Broggini, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti | Università di Padova and INFN Padova, Italy
- C. Gustavino | INFN Roma1, Italy
- L. Csedreki, Z. Elekes, Zs. Fülöp, Gy. Gyurky, T. Szucs | MTA-ATOMKI Debrecen, Hungary
- M. Lugaro | Konkoly Observatory, Hungarian Academy of Sciences, Budapest, Hungary
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- P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli | Università di Genova and INFN Genova, Italy
- A. Guglielmetti, E. Masha | Università di Milano and INFN Milano, Italy
- A. Best, G.F. Ciani, A. Di Leva, G. Imbriani, | Università di Napoli and INFN Napoli, Italy
- F. Cavanna, P. Colombetti, G. Gervino | Università di Torino and INFN Torino, Italy
- M. Aliotta, C. Bruno, T. Davinson | University of Edinburgh, United Kingdom
- F. Barile, V. Mossa, V. Paticchio, R. Perrino*, L. Schiavulli | Università di Bari and INFN Bari/*Lecce, Italy