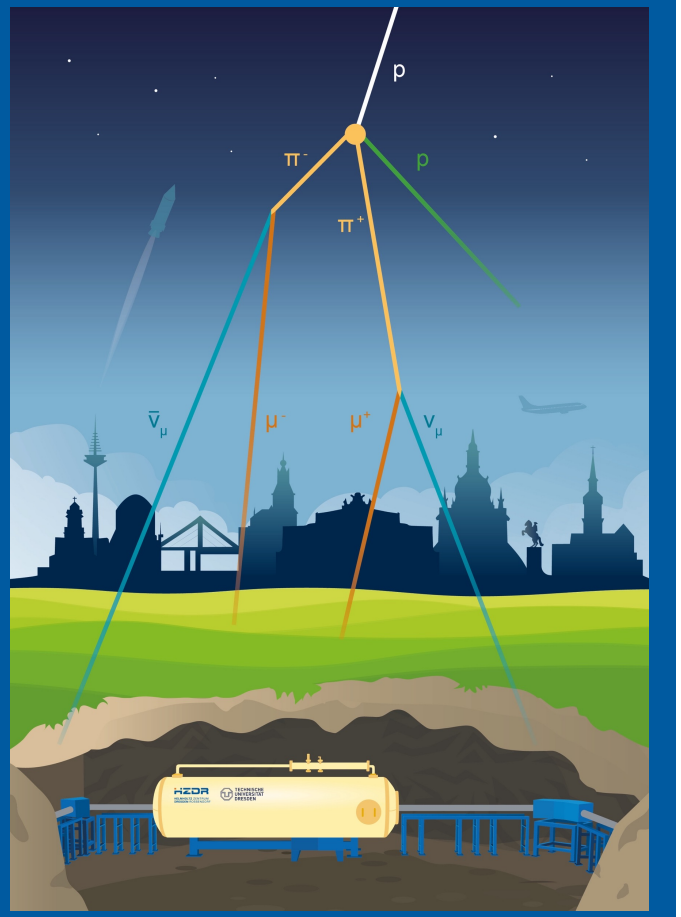
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101008324 (ChETEC-INFRA).

Nuclear reaction experiments with stable nuclei

61st Karpacz Winter School of Theoretical Physics
and
ChETEC-INFRA Training School
„Multi-messenger nuclear astrophysics in the 21st century"

Karpacz, 03.03.2025



Daniel Bemmerer
Helmholtz-Zentrum Dresden-Rossendorf

Institute of Radiation Physics · Nuclear Physics Division · Prof. Dr. Daniel Bemmerer · d.bemmerer@hzdr.de · www.hzdr.de

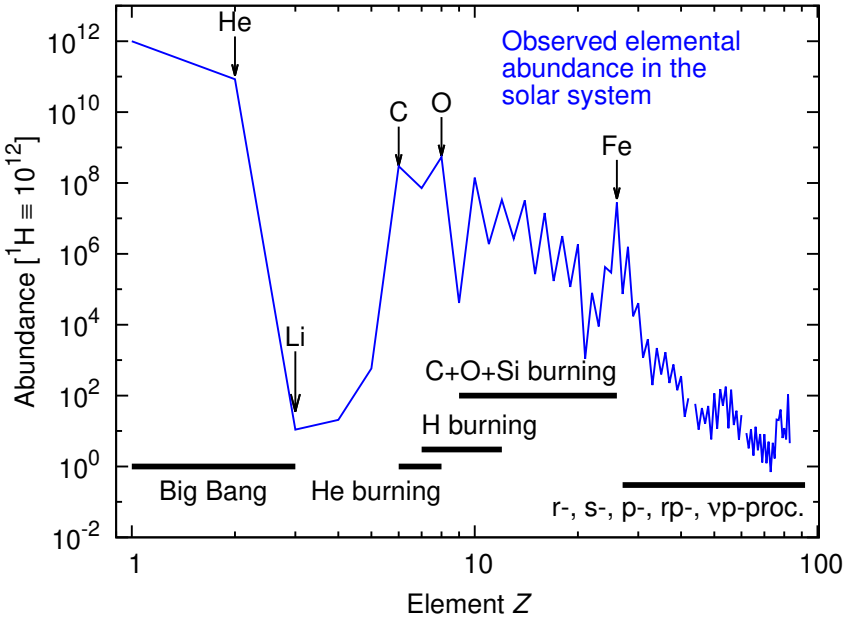
The quest for the origin of the chemical elements

H																He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
Th	Pa	U												

Big Bang
Cosmic
Stellar
r-process
s-process

Further contributions: p-, i-, rp-, ν-processes



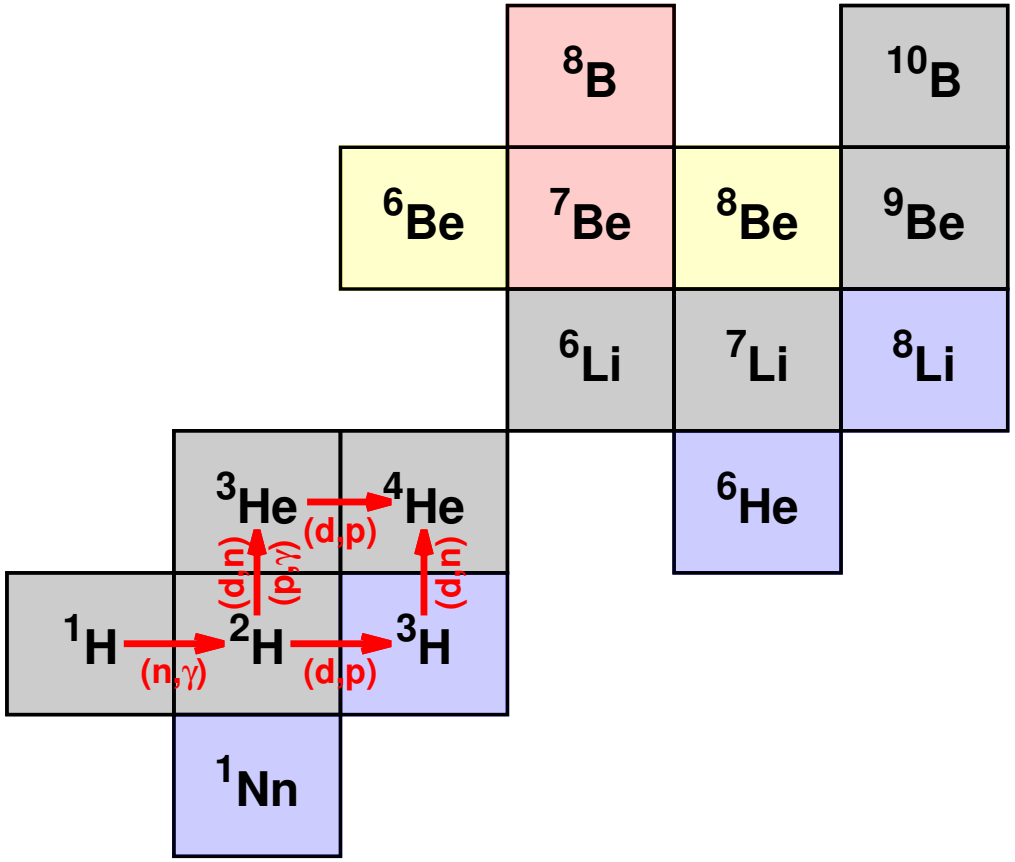
The periodic table: Big Bang Nucleosynthesis

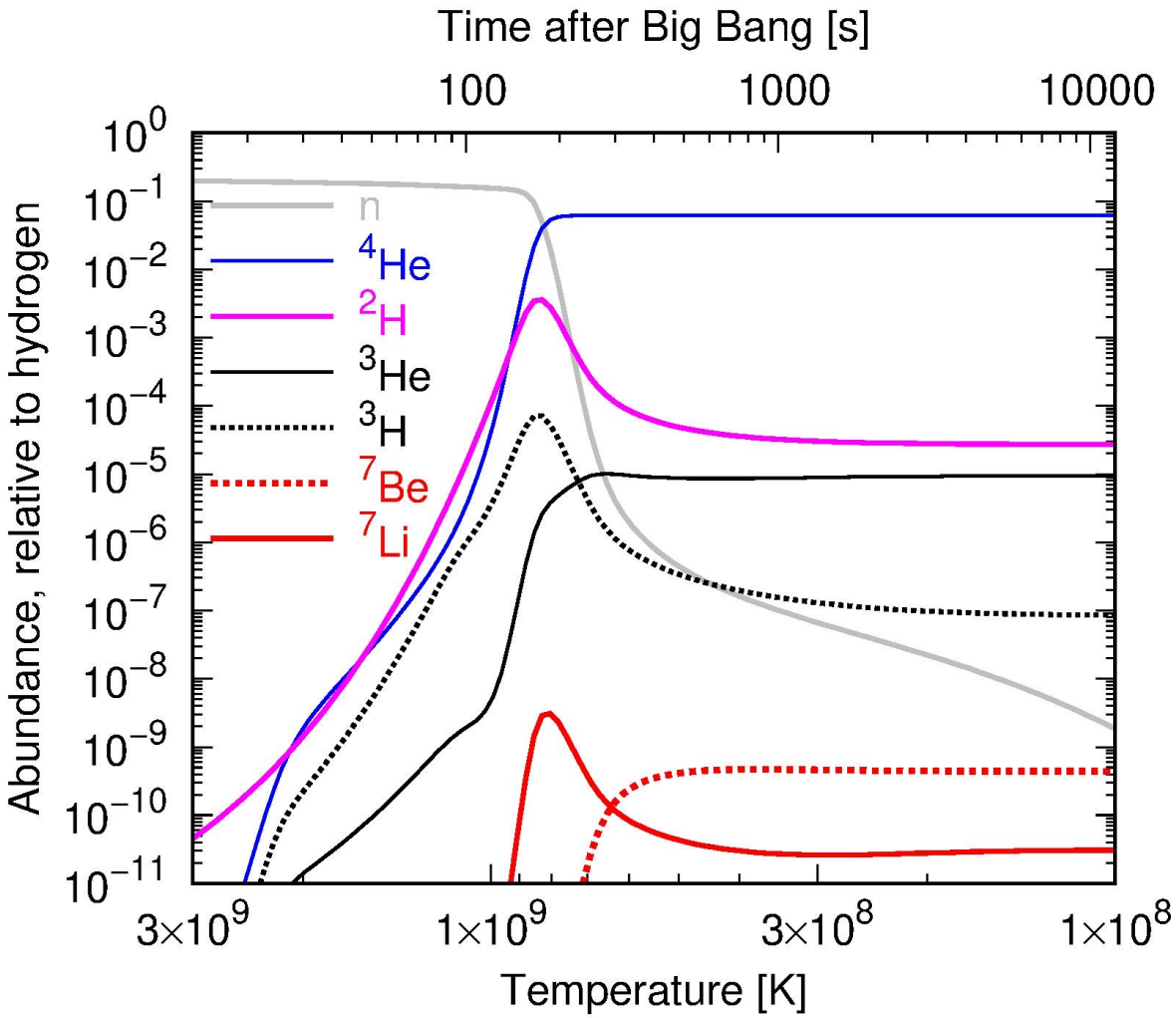
H														He
Li	Be									B	C	N	O	F	Ne
Na	Mg									Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

Big Bang

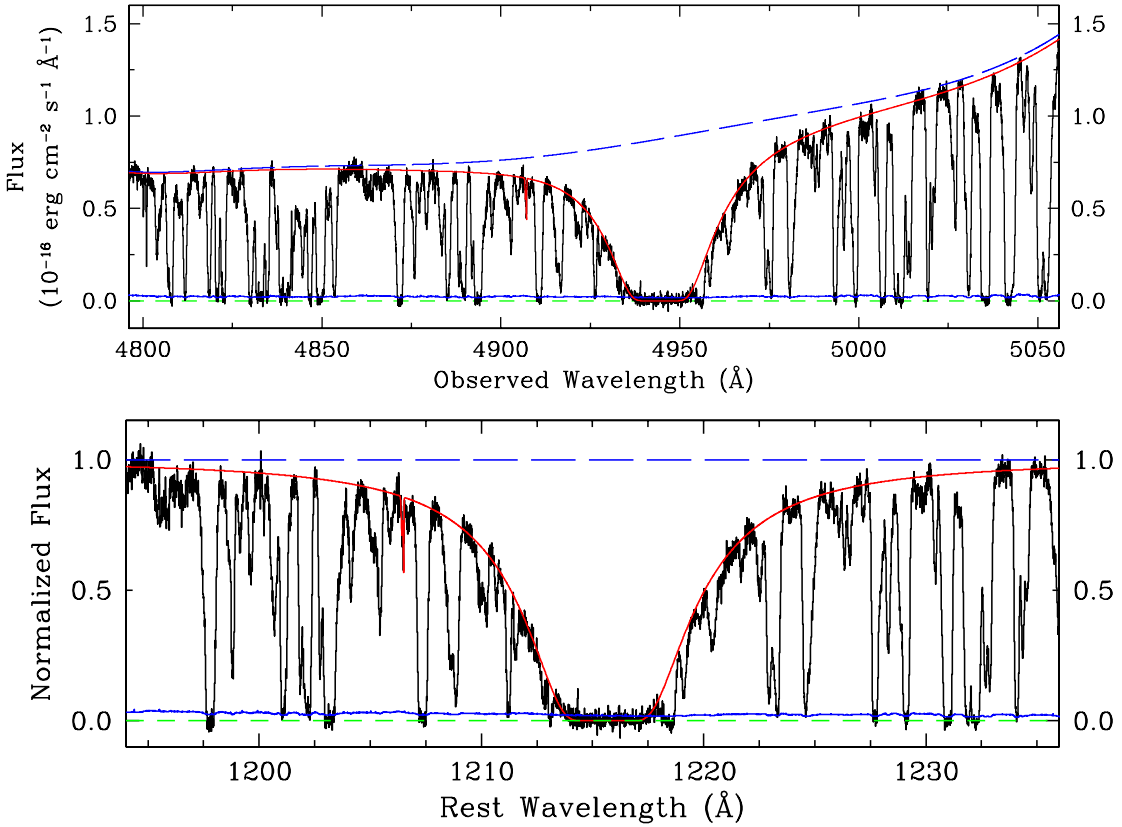
Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U											

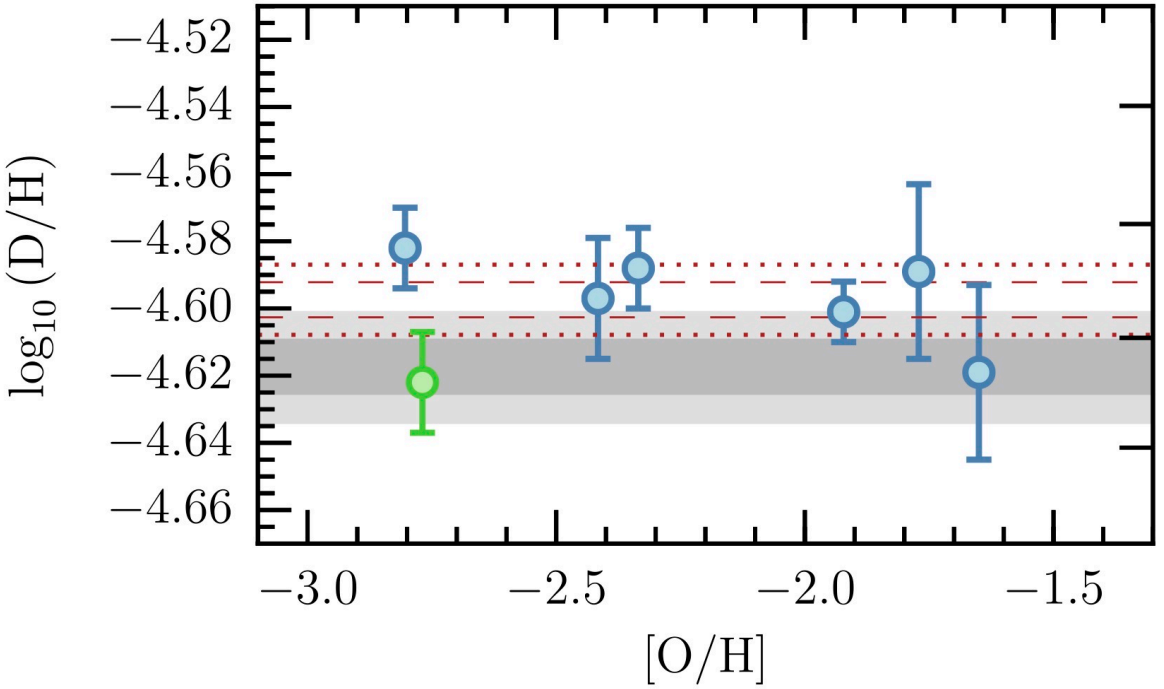
Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe





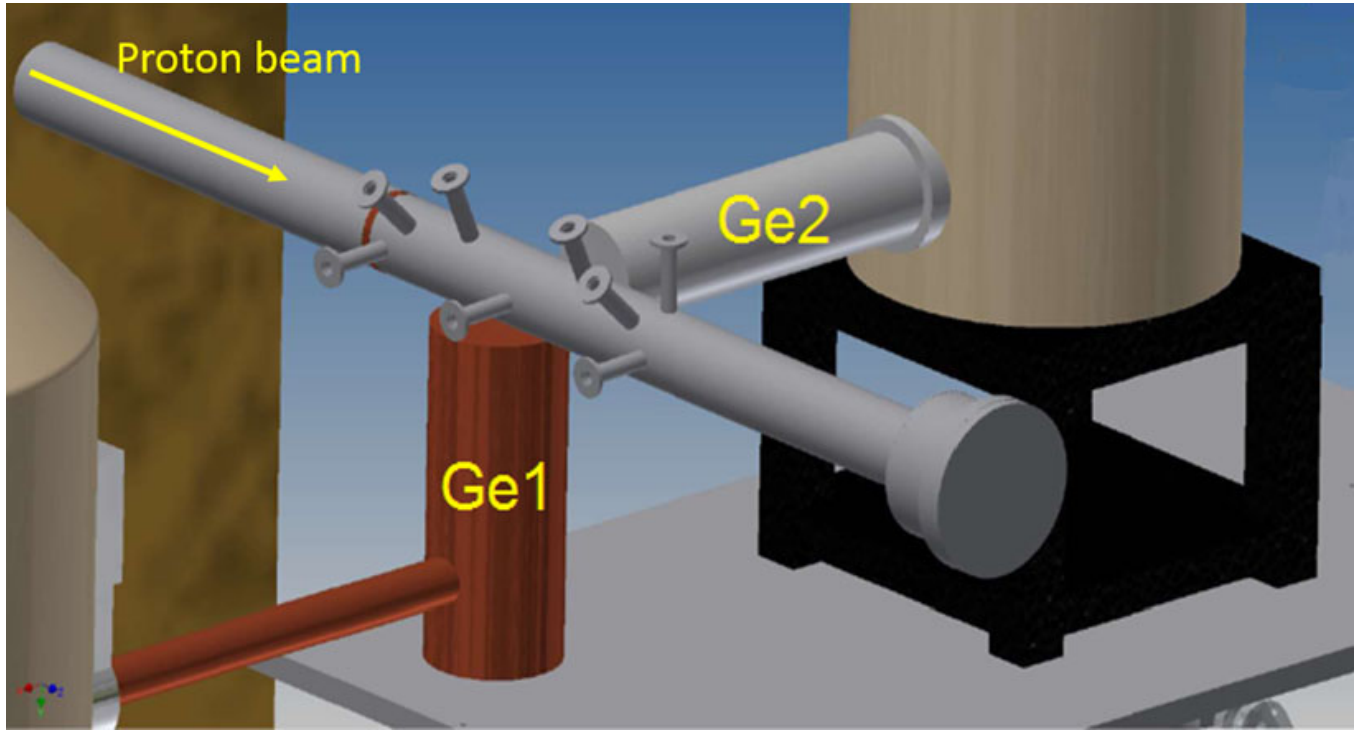
Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe





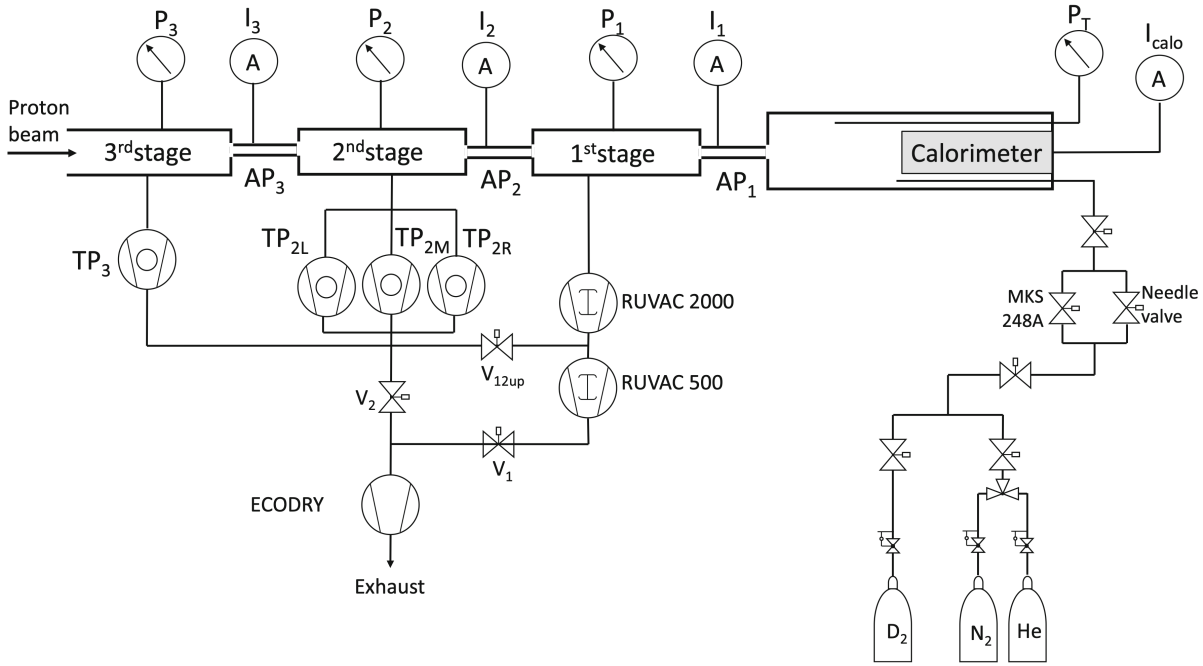
Astronomical ^{2}H observations:
Cooke *et al*. ApJ 855, 102 (2018)

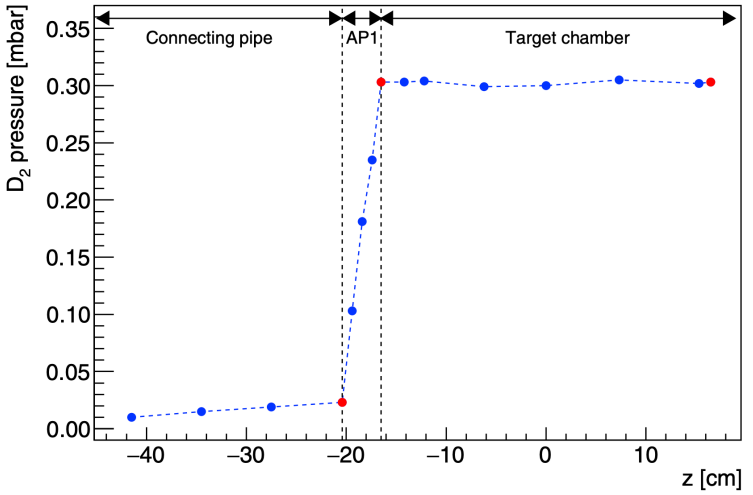
Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe

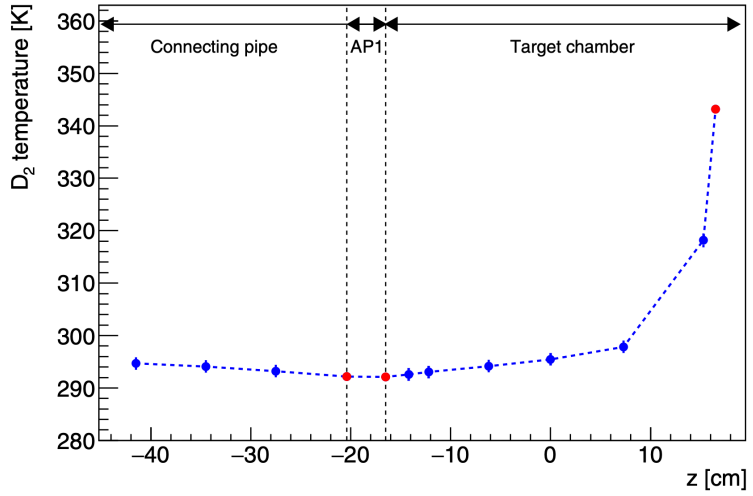


Mossa *et al.* (LUNA), Nature 587, 210 (2020)
K. Stöckel *et al.* (LUNA), Phys. Rev. C 110, L032801 (2024)

Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe







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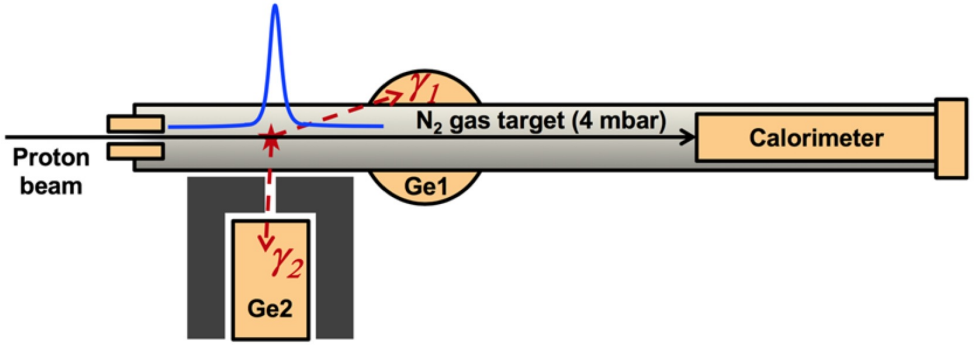
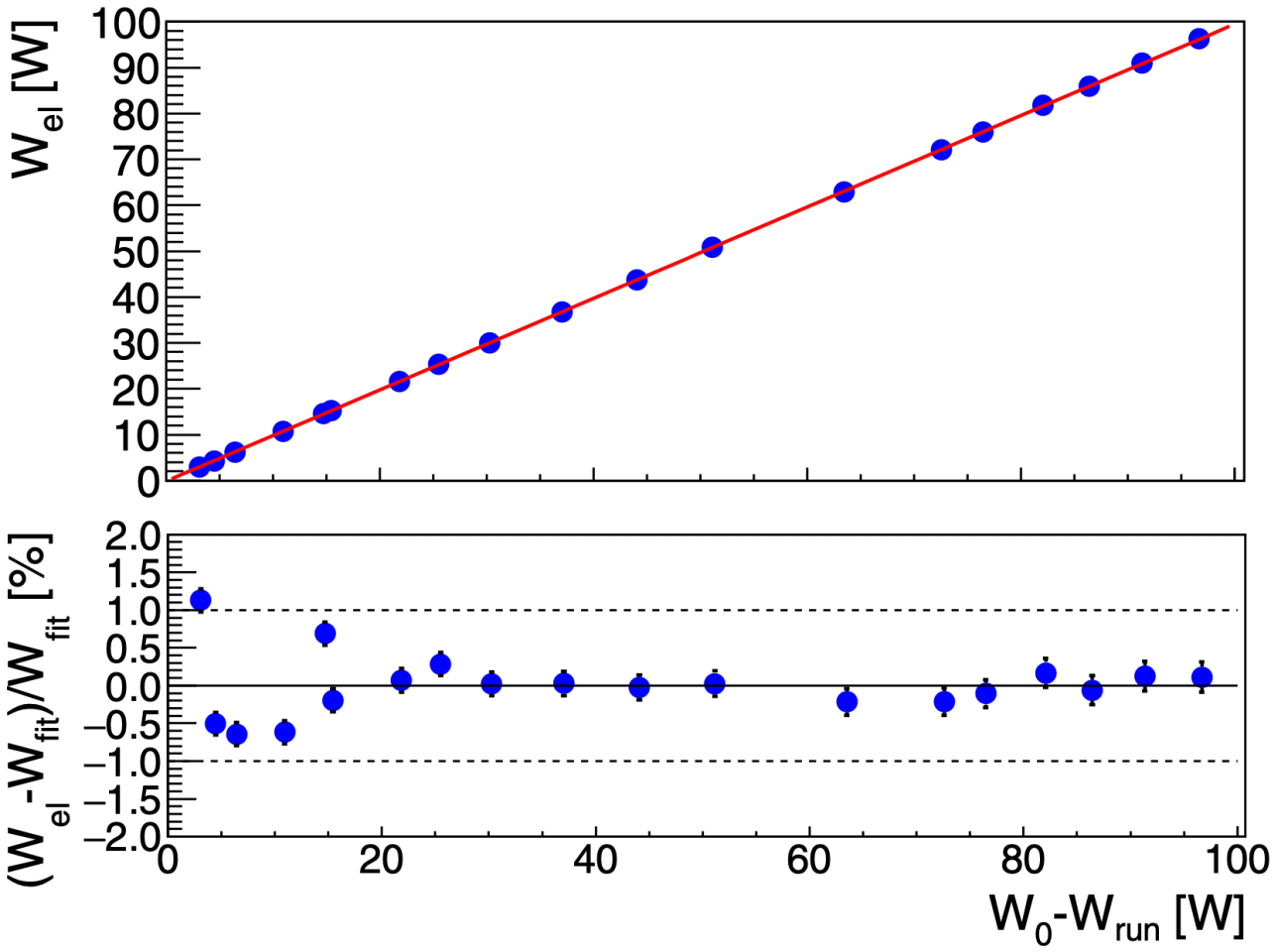
Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe



$$I = \frac{e \cdot W_{\mathrm{cal}}}{E_{\mathrm{p}} - \Delta E},$$



Mossa *et al.* (LUNA), Nature 587, 210 (2020)
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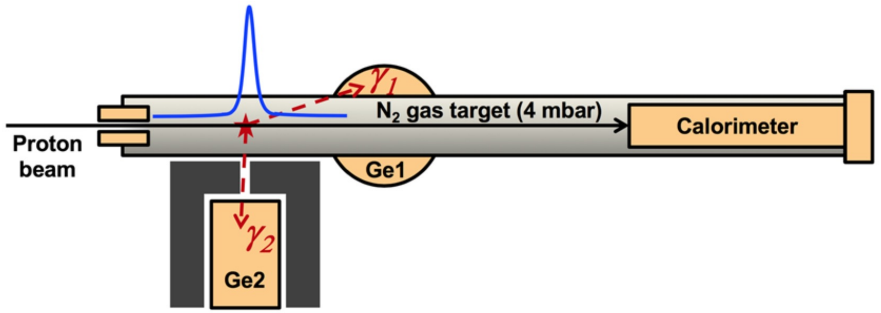
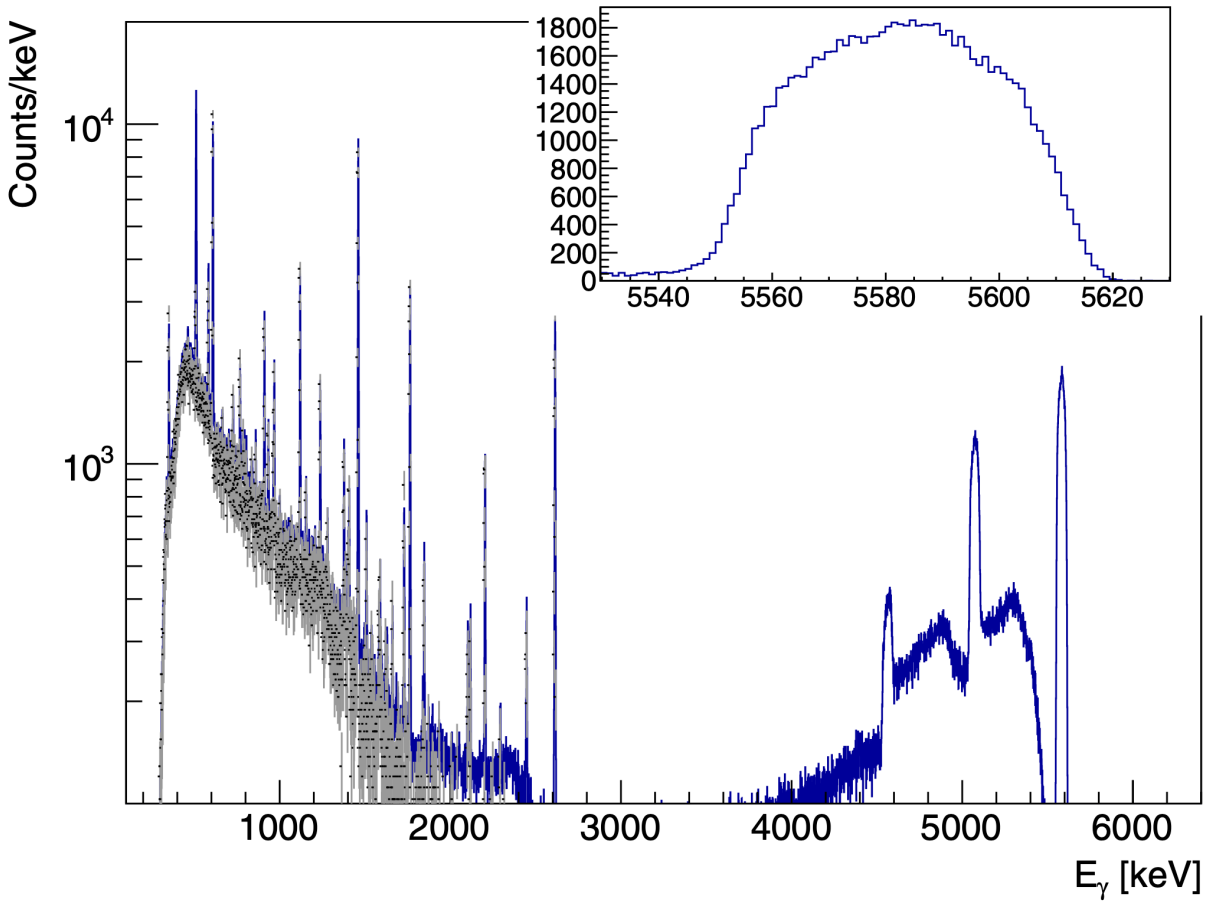
Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe



$$E_\gamma = (Q + E_{\text{beam, c.m.}} - \Delta E_{\text{recoil}}) \times \left(1 + \frac{v}{c}\cos\theta_{\text{c.m.}}\right)$$

$$\frac{d\sigma}{d\Omega_{\text{c.m.}}} = A_0\left(1 + \sum_{l=1}^{3} a_l P_l(\cos\theta_{\text{c.m.}})\right)$$

$$= A_0\left(1 + \sum_{l=1}^{3} a_l P_l(E_\gamma)\right).$$



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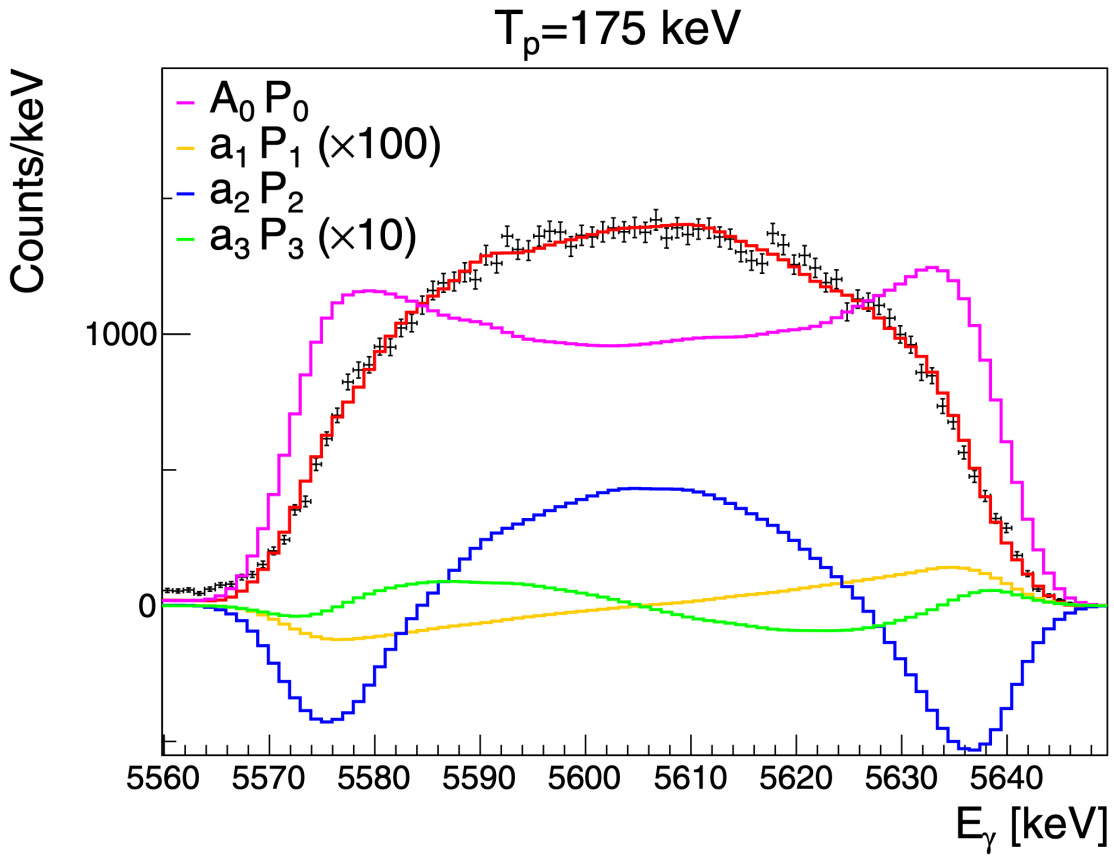
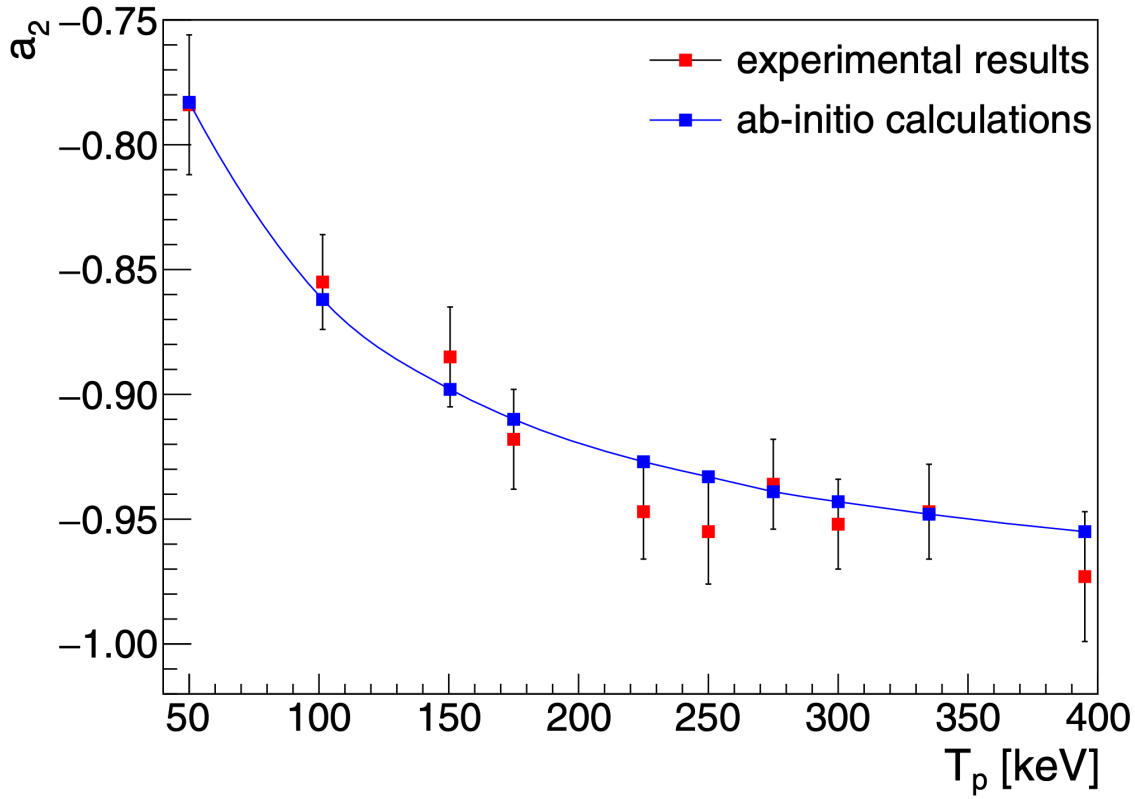
Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe

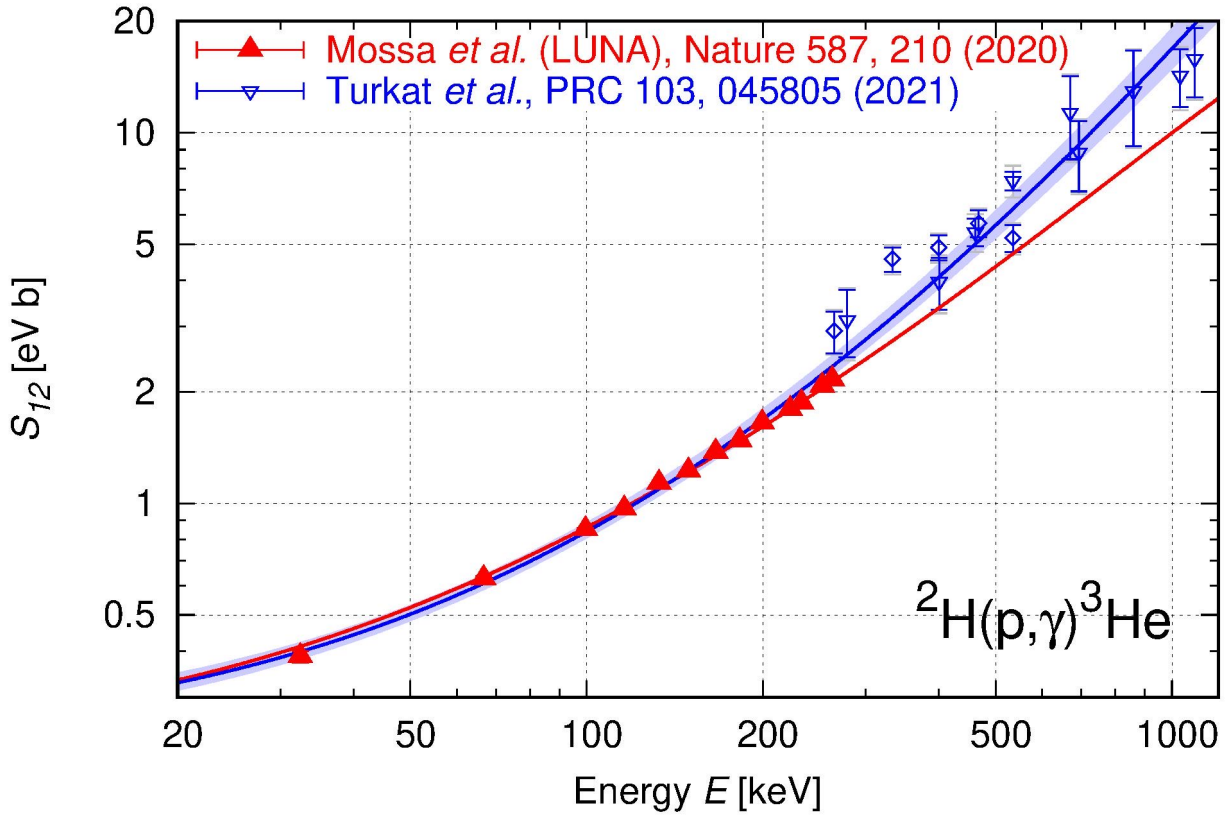




Mossa *et al.* (LUNA), Nature 587, 210 (2020)
K. Stöckel *et al.* (LUNA), Phys. Rev. C 110, L032801 (2024)

Big Bang Nucleosynthesis (BBN) and ^{2}H (D) as a cosmological probe

$$S_{12}(E) = \sigma(E) \times E \times \exp\left(Z_1 Z_2 \alpha \sqrt{\frac{\mu c^2}{2E}}\right)$$



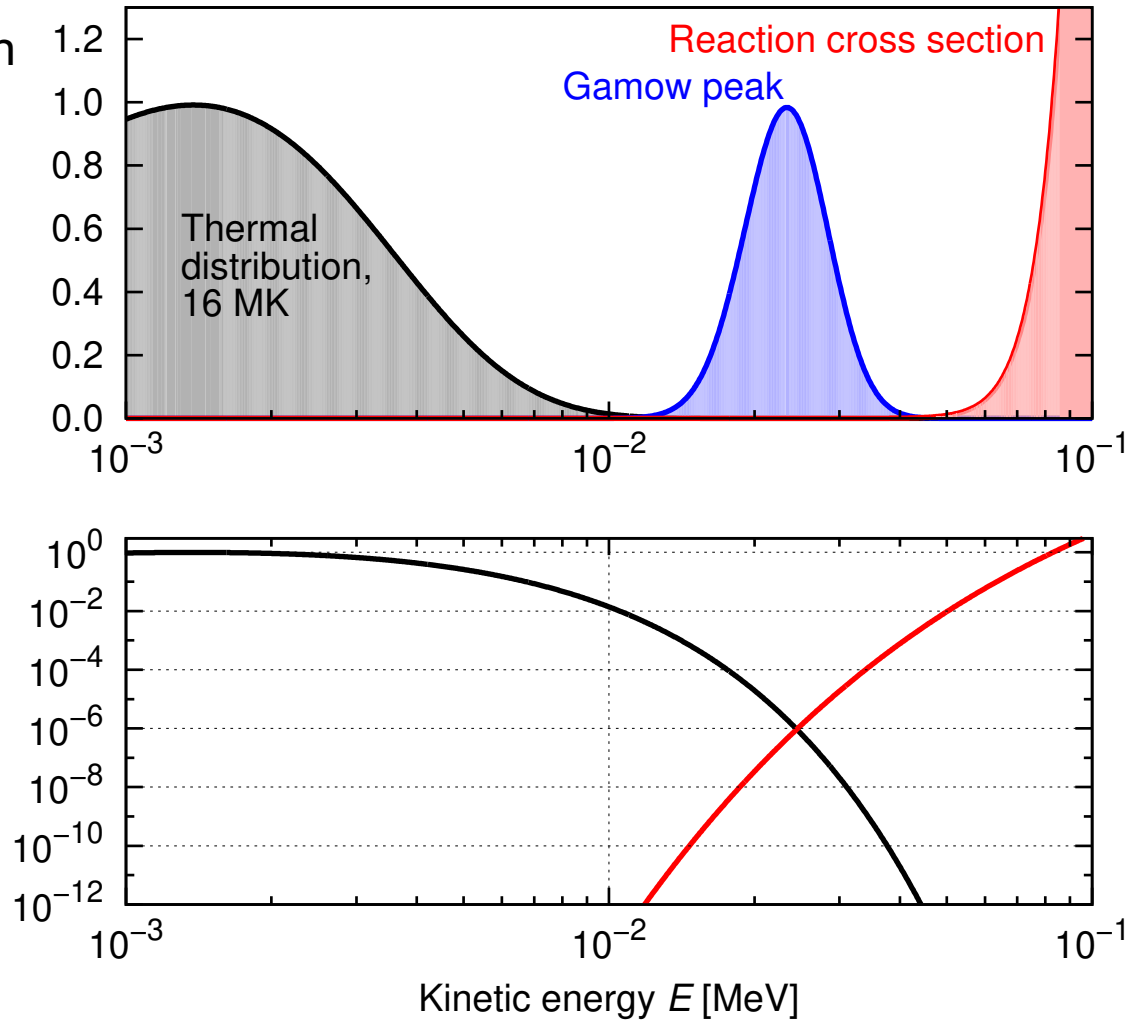
Using ^{2}H from BBN to determine the cosmic baryon density:

$$\Omega_b h^2 = 0.02271 \pm 0.00062 \quad \text{BBN, before new LUNA data}$$
$$\Omega_b h^2 = 0.02233 \pm 0.00036 \quad \text{BBN, including new LUNA data}$$
$$\Omega_b h^2 = 0.02236 \pm 0.00015 \quad \text{Cosmic Microwave Background}$$

Charged-particle induced nuclear reactions in a plasma

Thermal distribution of particles in a stellar plasma

$$P(E) = \frac{2\sqrt{E}}{\sqrt{\pi}(k_\mathrm{B}T)^{\frac{3}{2}}} \times \exp\left[-\frac{E}{k_\mathrm{B}T}\right]$$



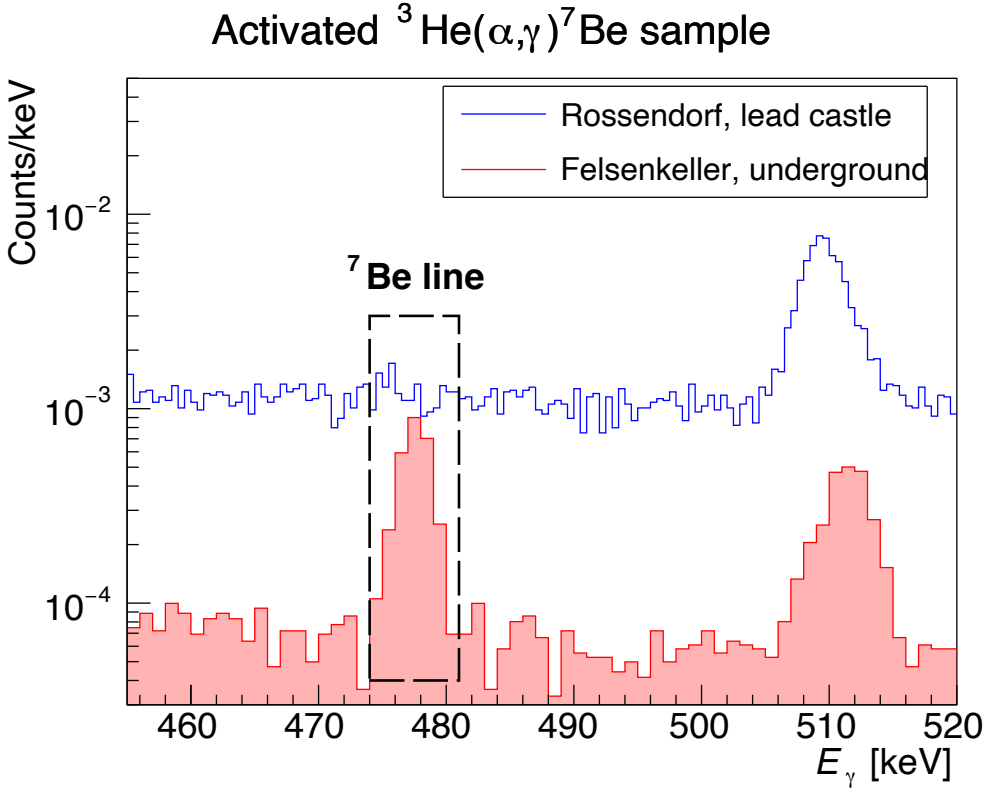
Nuclear reaction cross section far below the repulsive Coulomb barrier

picobarn – nanobarn

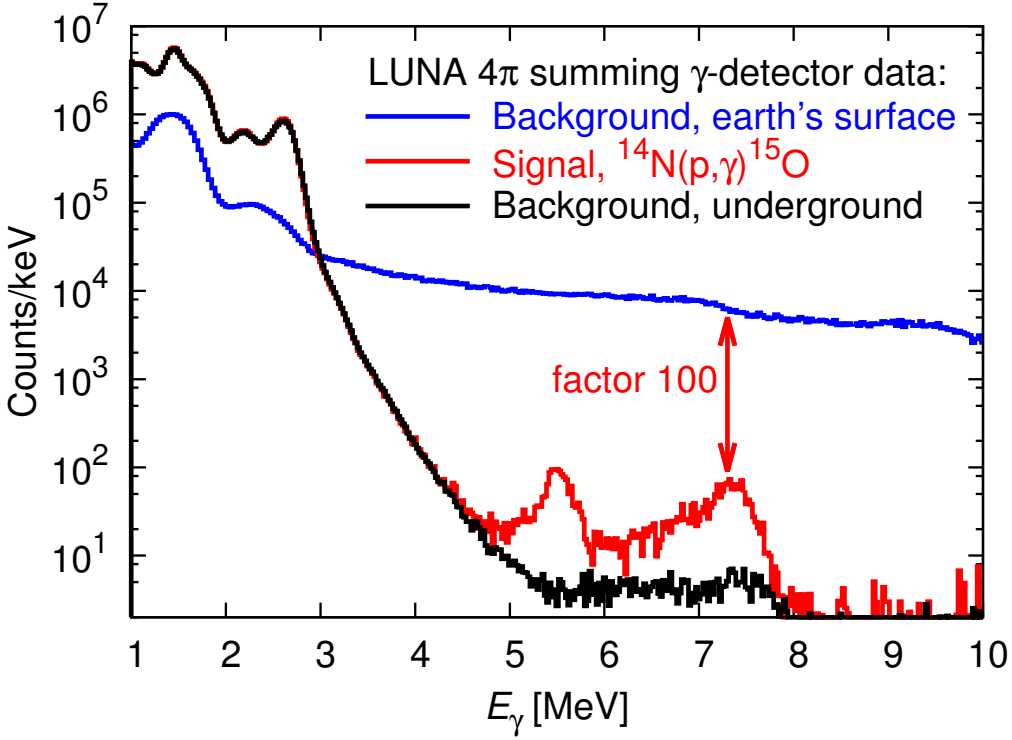
$$\sigma(E) = \frac{S(E)}{E} \exp\left[-\frac{b}{\sqrt{E}}\right]$$

S(E) = astrophysical S-factor

Measuring very small cross sections, two examples



Felsenkeller Dresden



LUNA, below the Gran Sasso mountain, Italy

The periodic table: Hydrostatic stellar burning

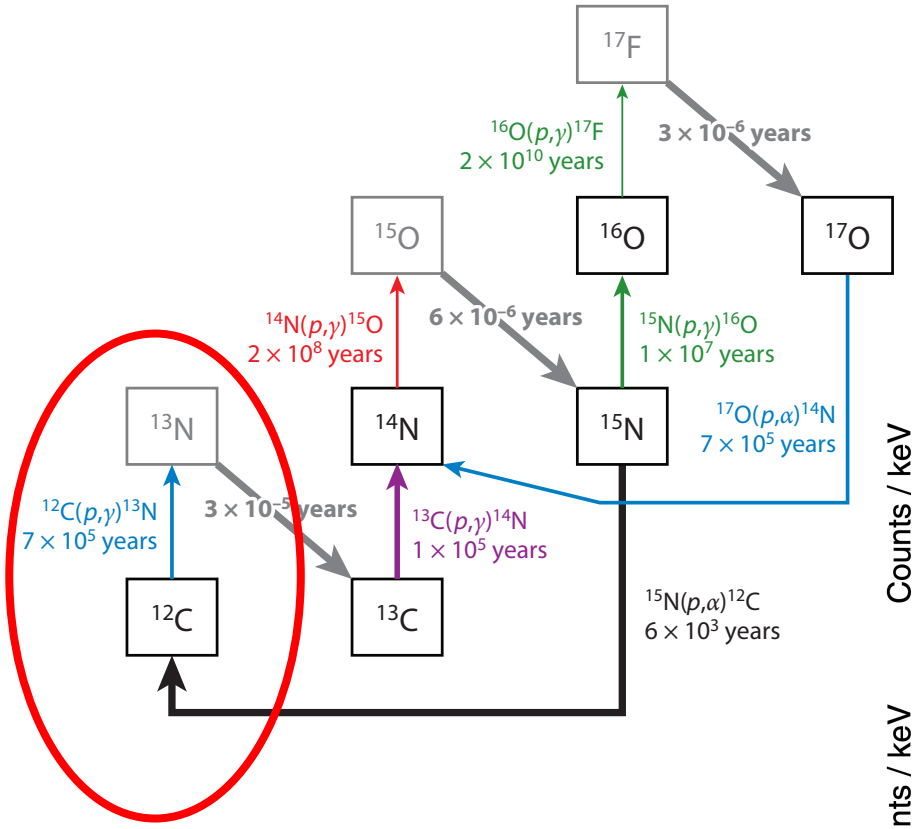
H														He
Li	Be								B	C	N	O	F	Ne
Na	Mg								Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac															

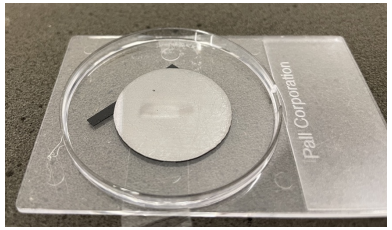
Big Bang

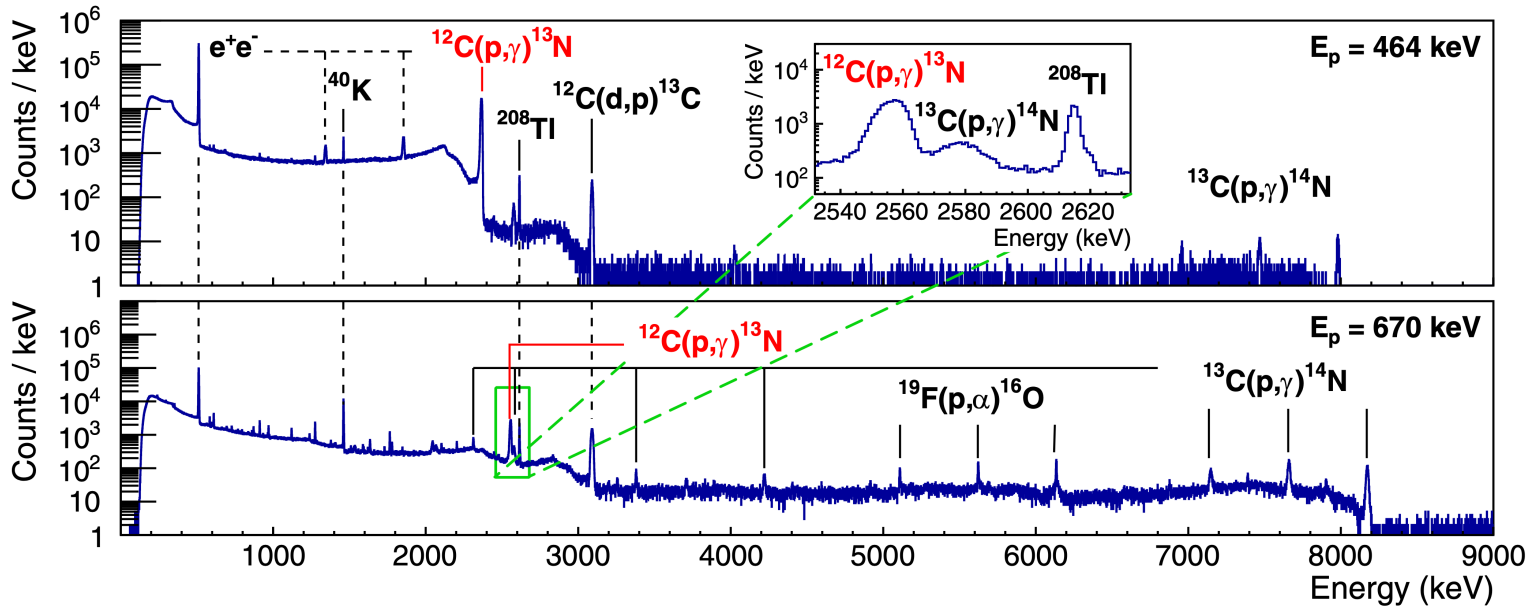
Stellar

Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Th	Pa	U											

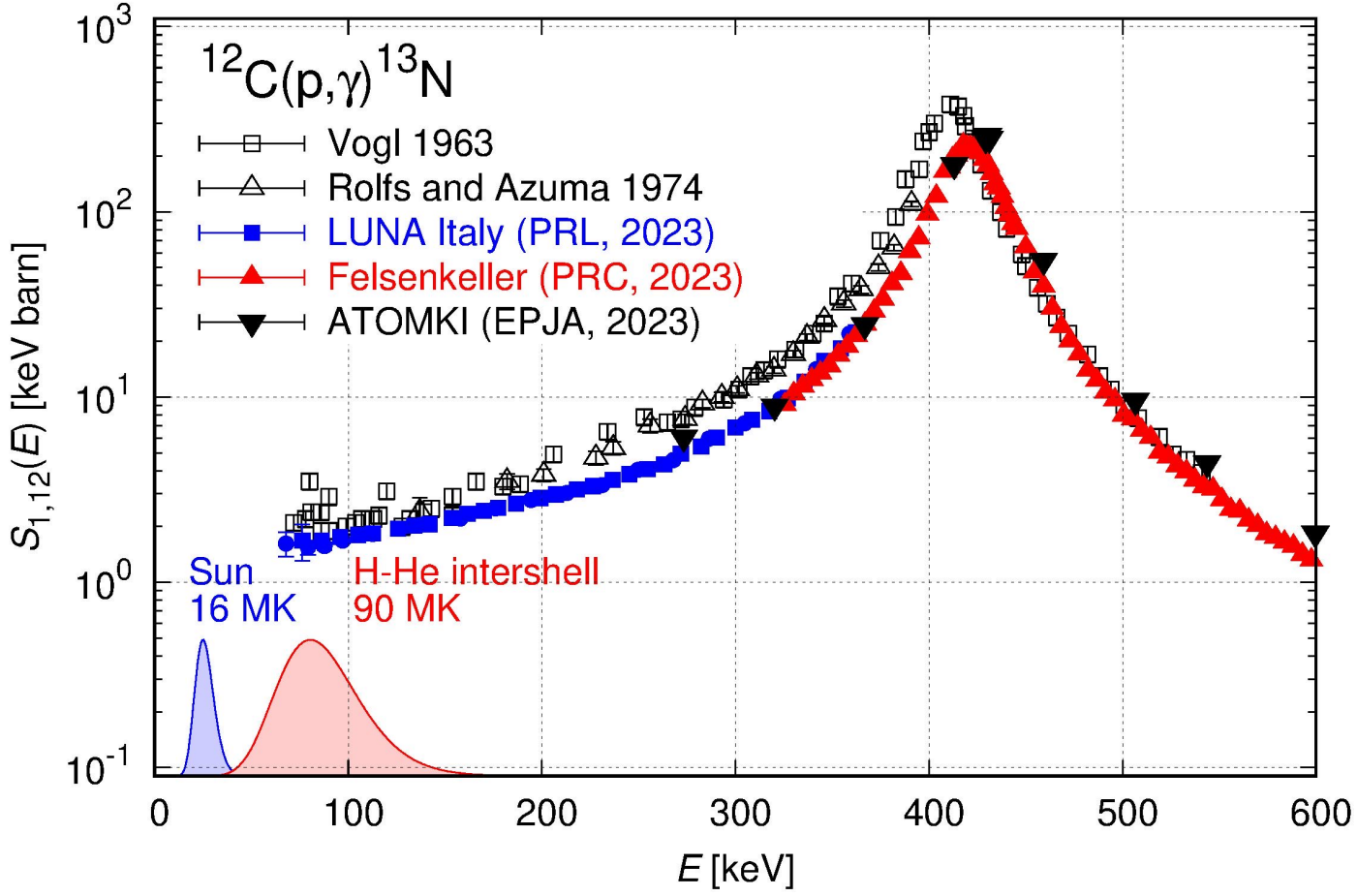
Study of the $^{12}C(p,\gamma)^{13}N$ reaction at Felsenkeller and at LUNA

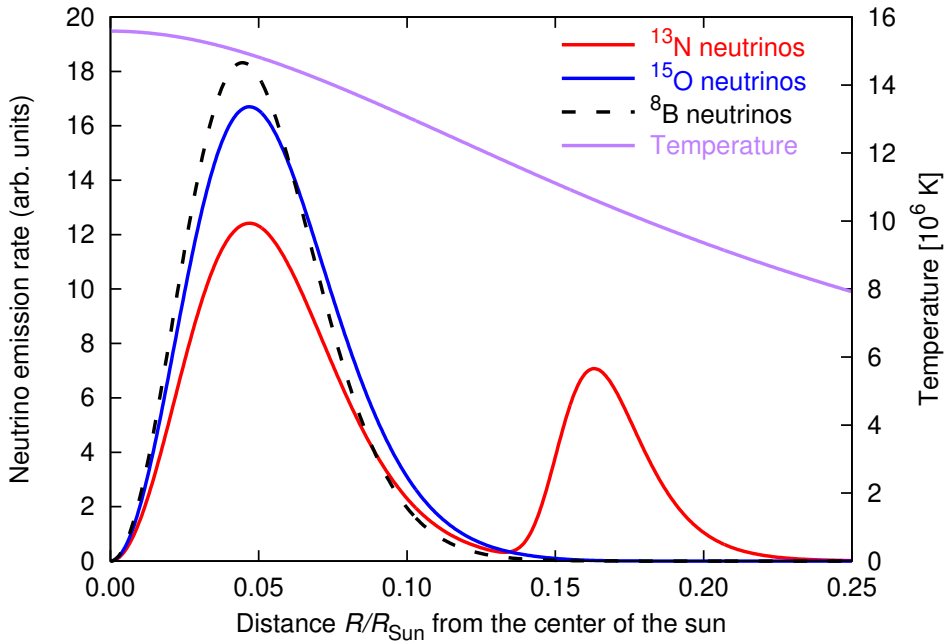




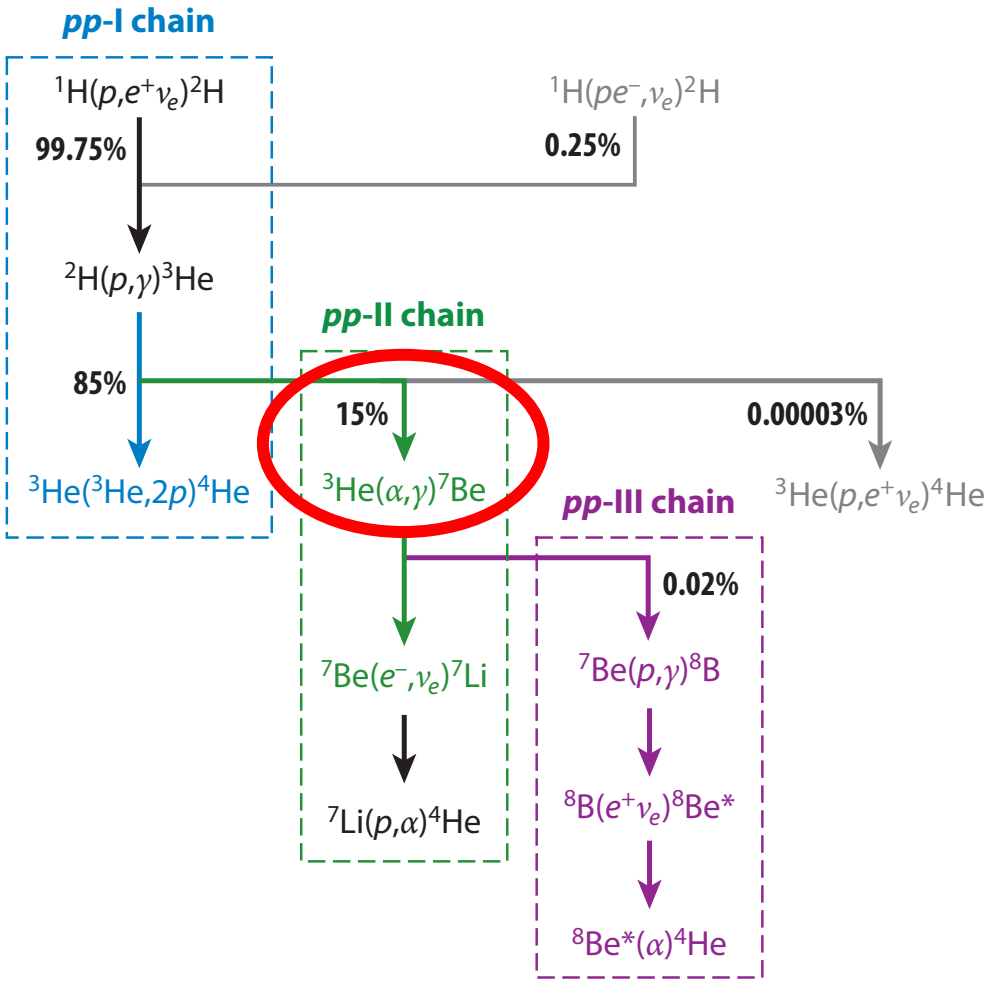


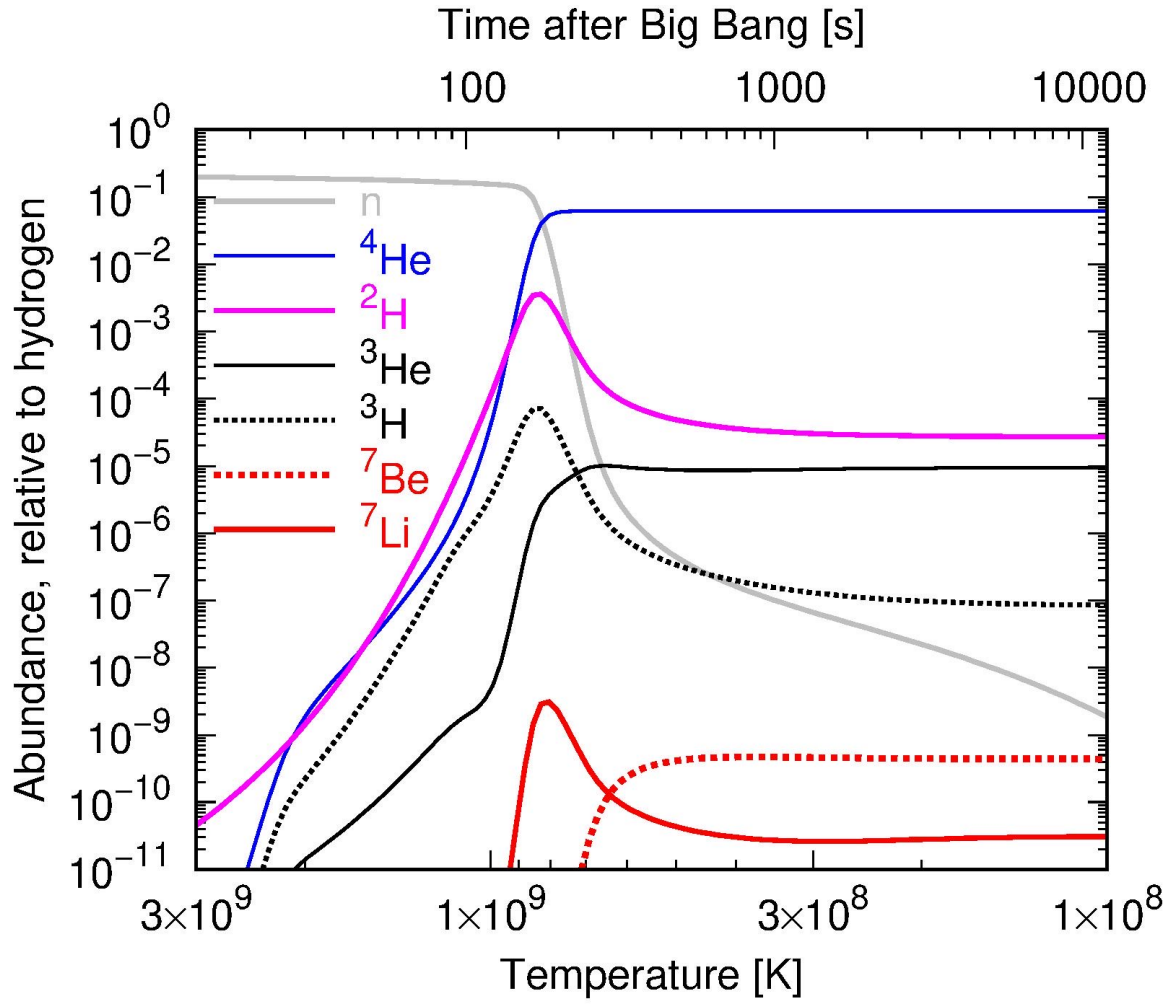
Study of the $^{12}C(p,\gamma)^{13}N$ reaction at Felsenkeller and at LUNA



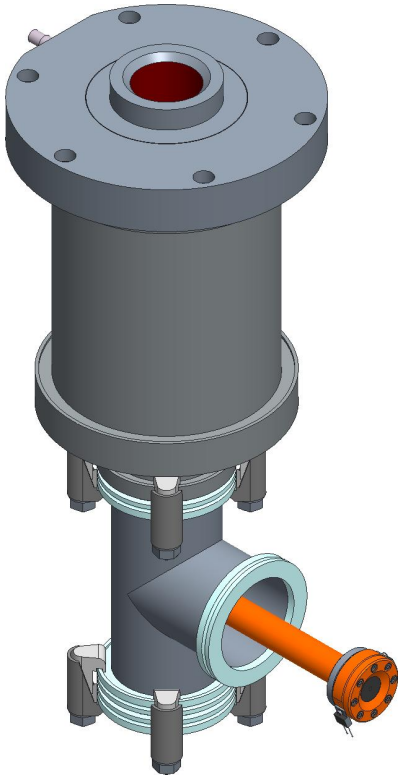


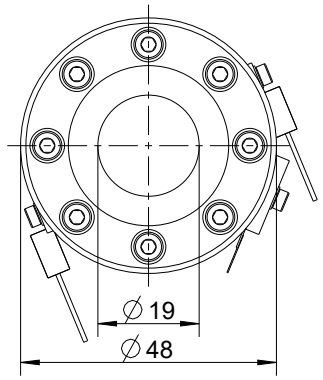
Study of the $^3He(\alpha,\gamma)^7Be$ γ-ray angular distribution at Felsenkeller

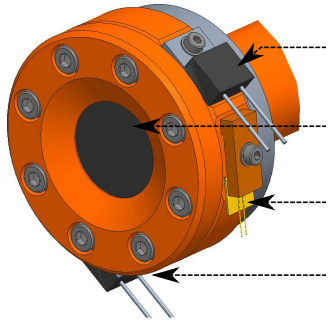




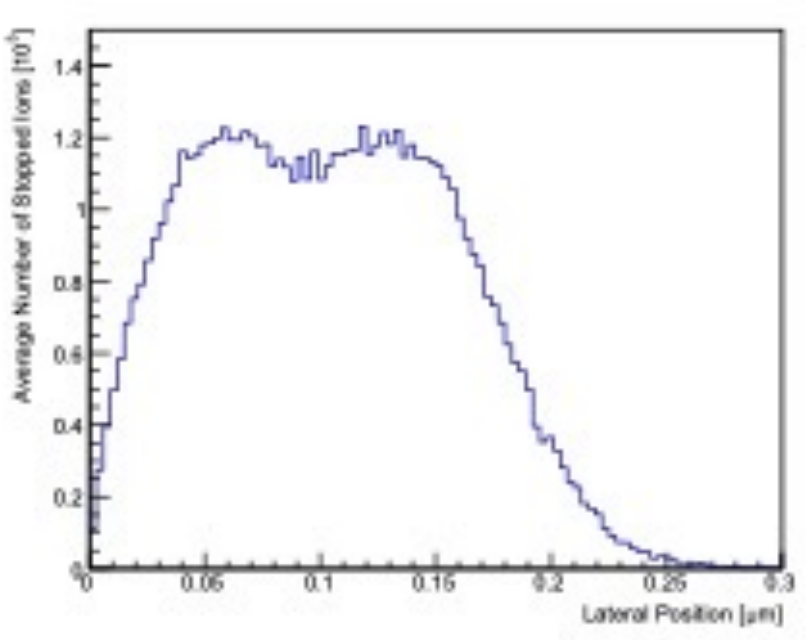
$^{3}He(\alpha,\gamma)^{7}Be$ γ-ray angular distribution: Targets







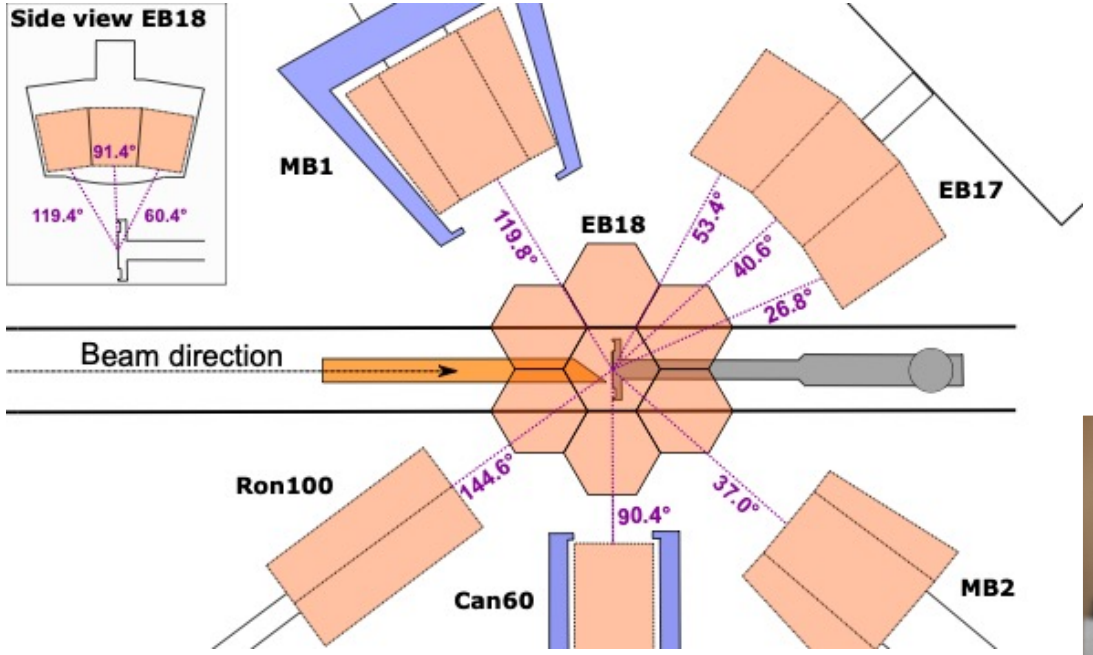
LN_2 cooling of the target to reduce target degradation, effective target temperature -100 °C.

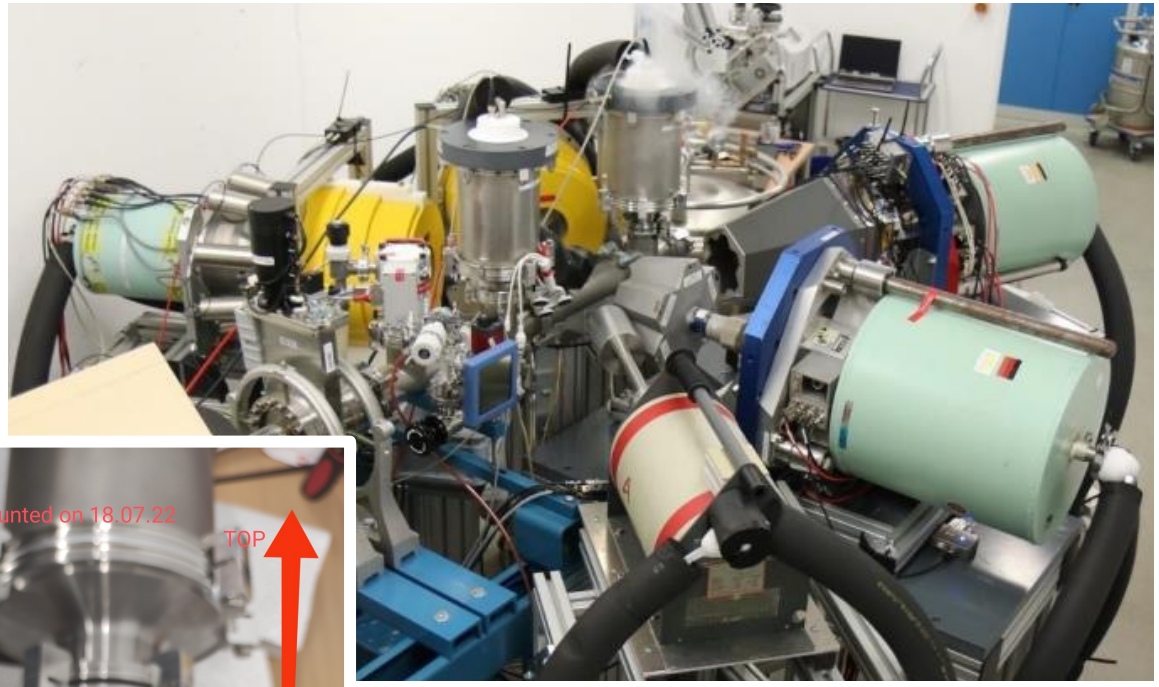


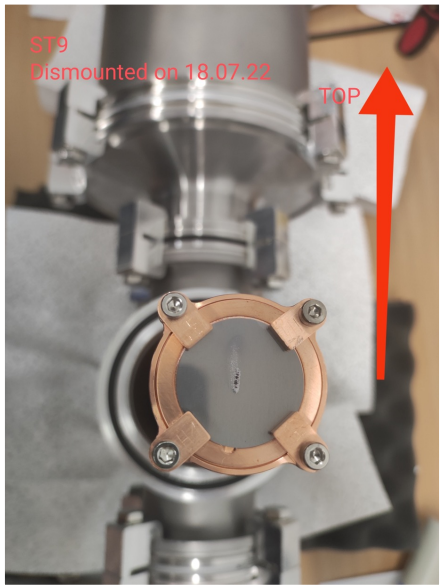
^{3}He implanted (15 keV and 35 keV) into chemically treated tantalum backings, implantation done at HZDR Rossendorf.

^{4}He irradiation (1.5 – 3.0 MeV) of targets at Felsenkeller for main experiment

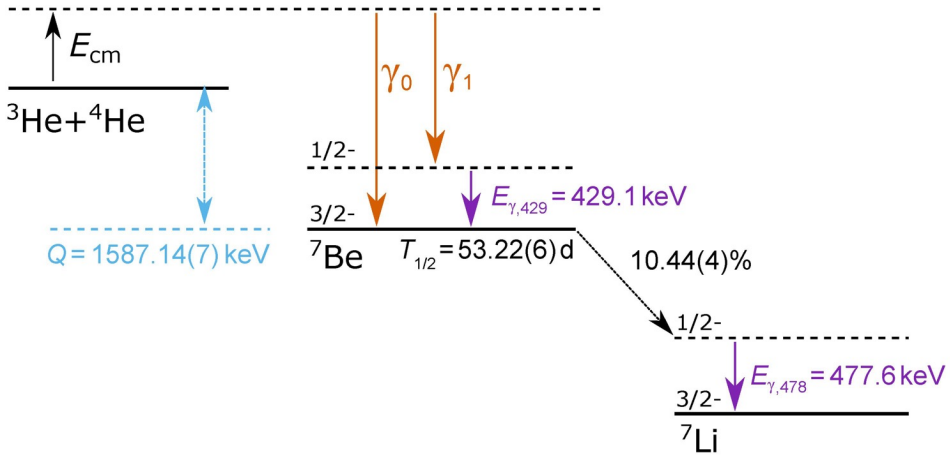
Study of the $^{3}He(\alpha,\gamma)^{7}Be$ γ-ray angular distribution at Felsenkeller

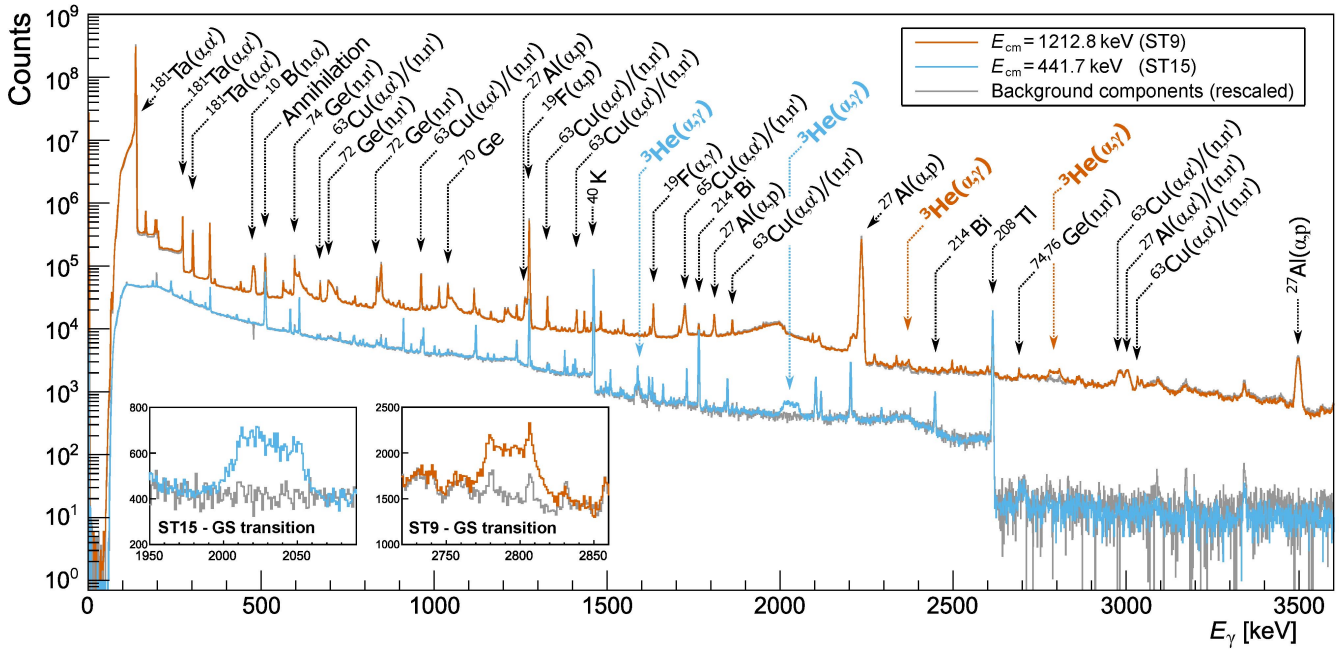




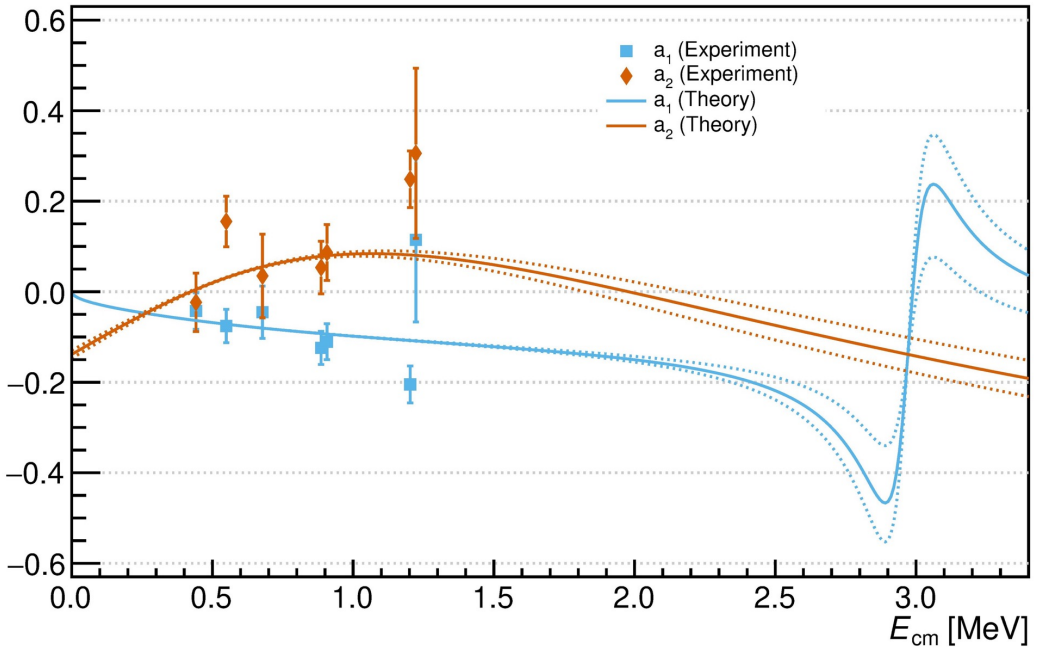


Study of the $^3He(\alpha,\gamma)^7Be$ γ-ray angular distribution at Felsenkeller



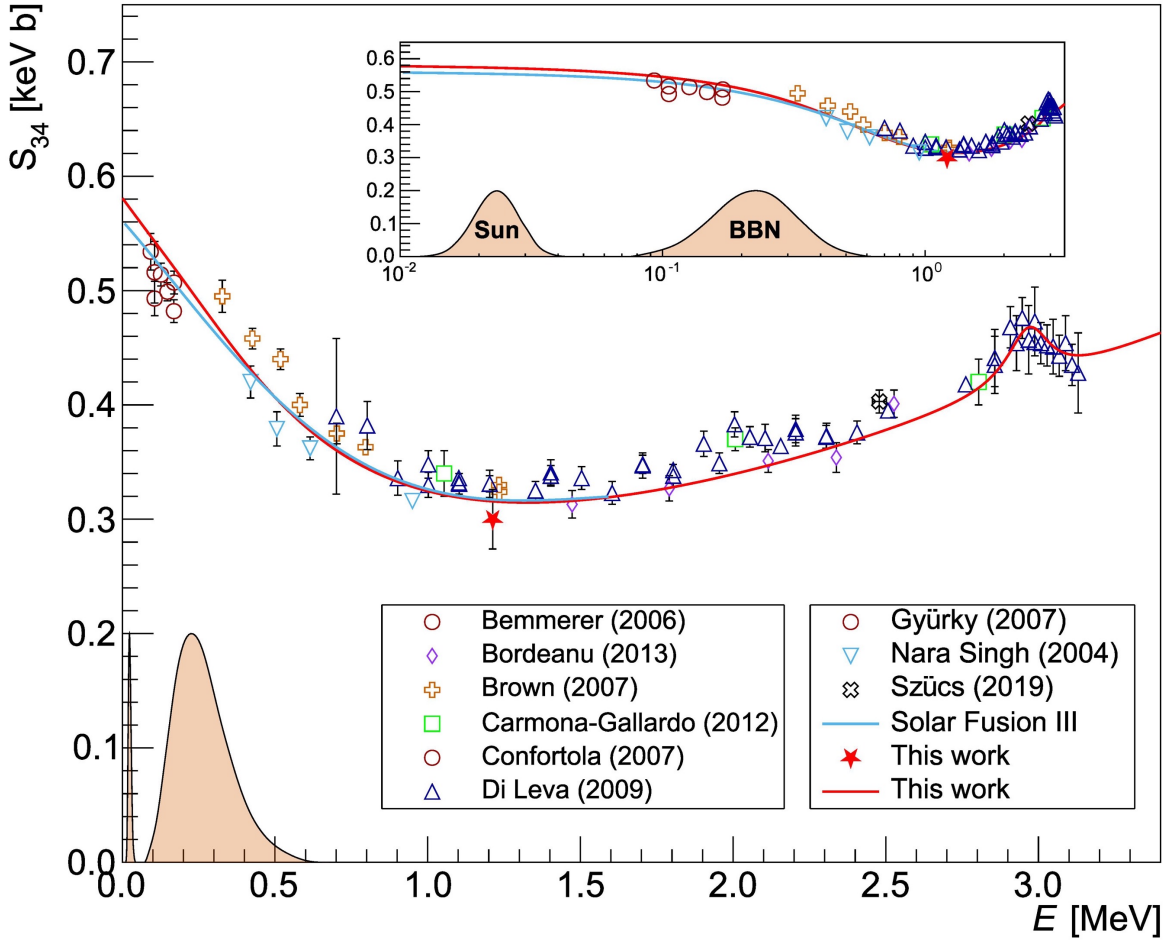


Study of the ^{3}He(α,γ)^{7}Be γ-ray angular distribution at Felsenkeller

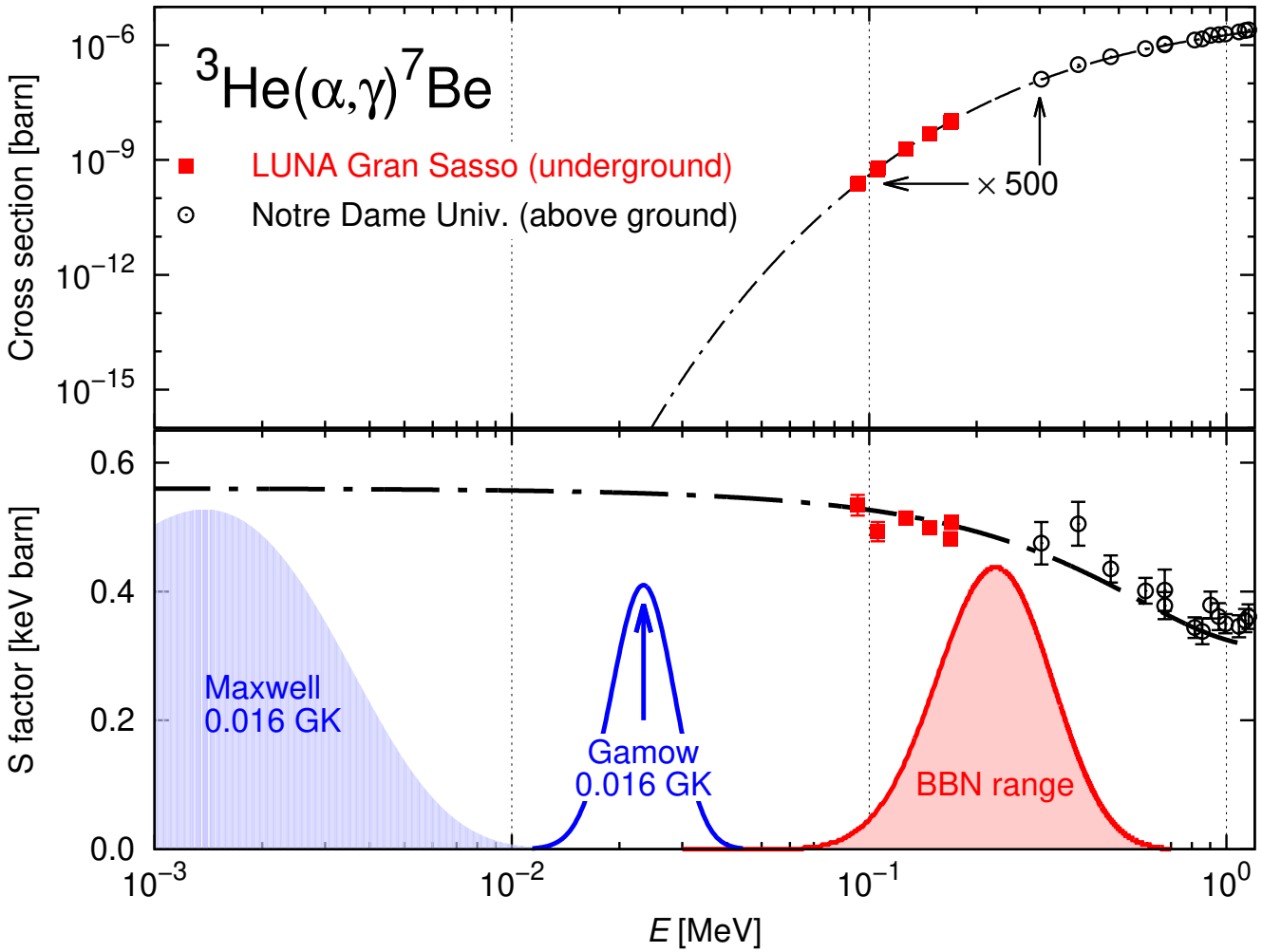


$$\frac{d\sigma}{d\Omega_{\text{c.m.}}} = A_0\left(1+\sum_{l=1}^{3} a_l P_l(\cos\theta_{\text{c.m.}})\right)$$

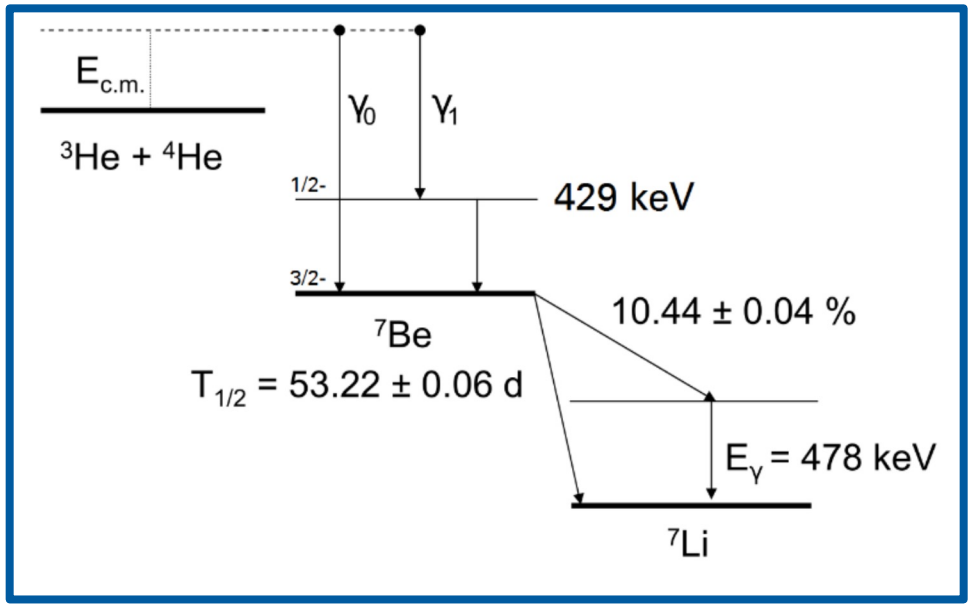
$$= A_0\left(1+\sum_{l=1}^{3} a_l P_l(E_\gamma)\right).$$



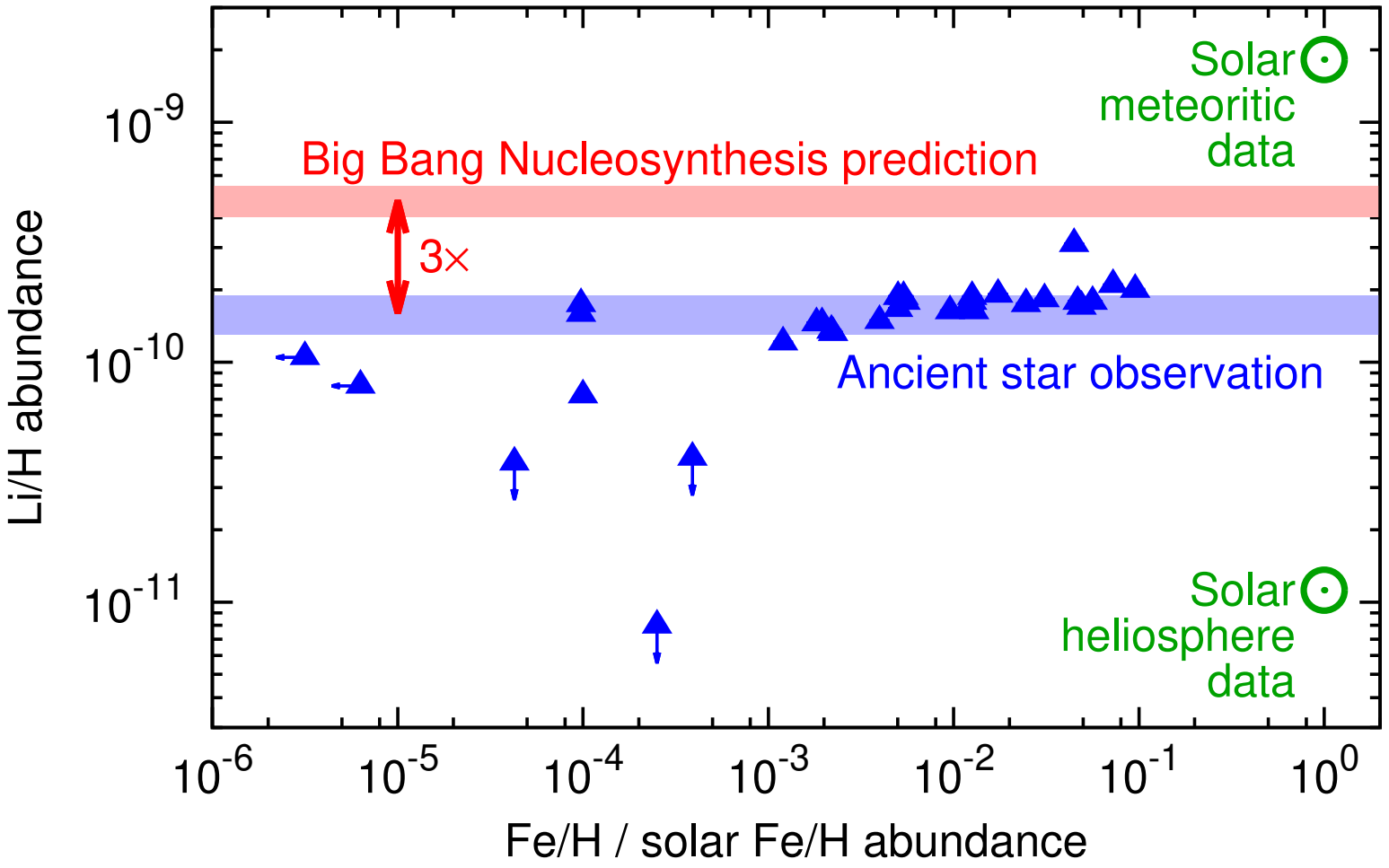
$^3He(\alpha,\gamma)^7Be$: above ground and underground data



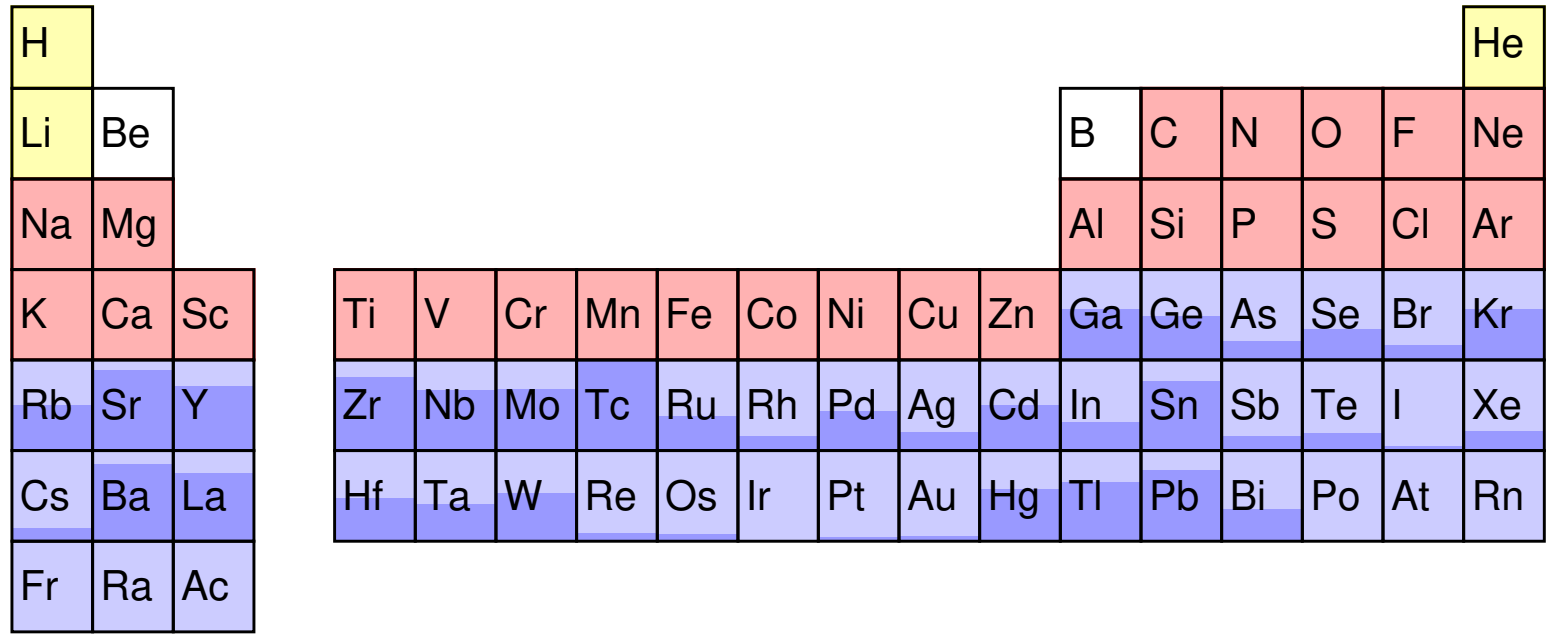
- Big Bang 0.3-0.9 GK
- Sun 0.016 GK



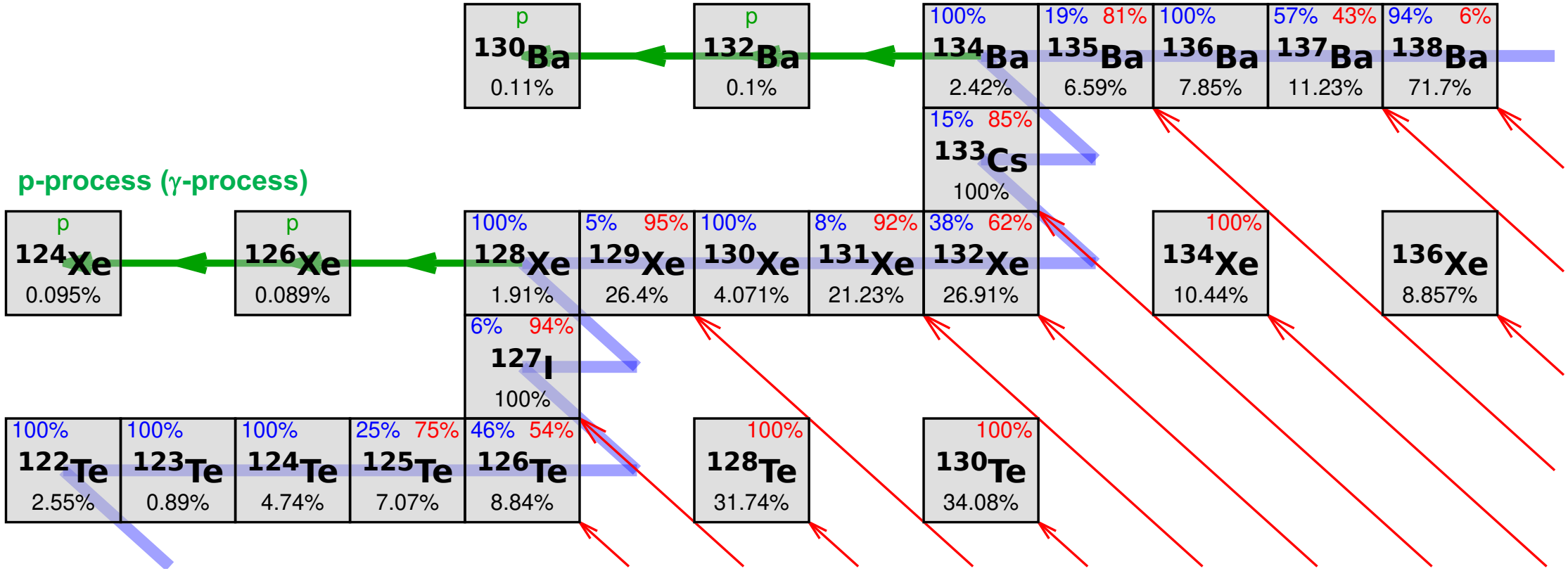
^{7}Be and ^{7}Li – wide scope for future study



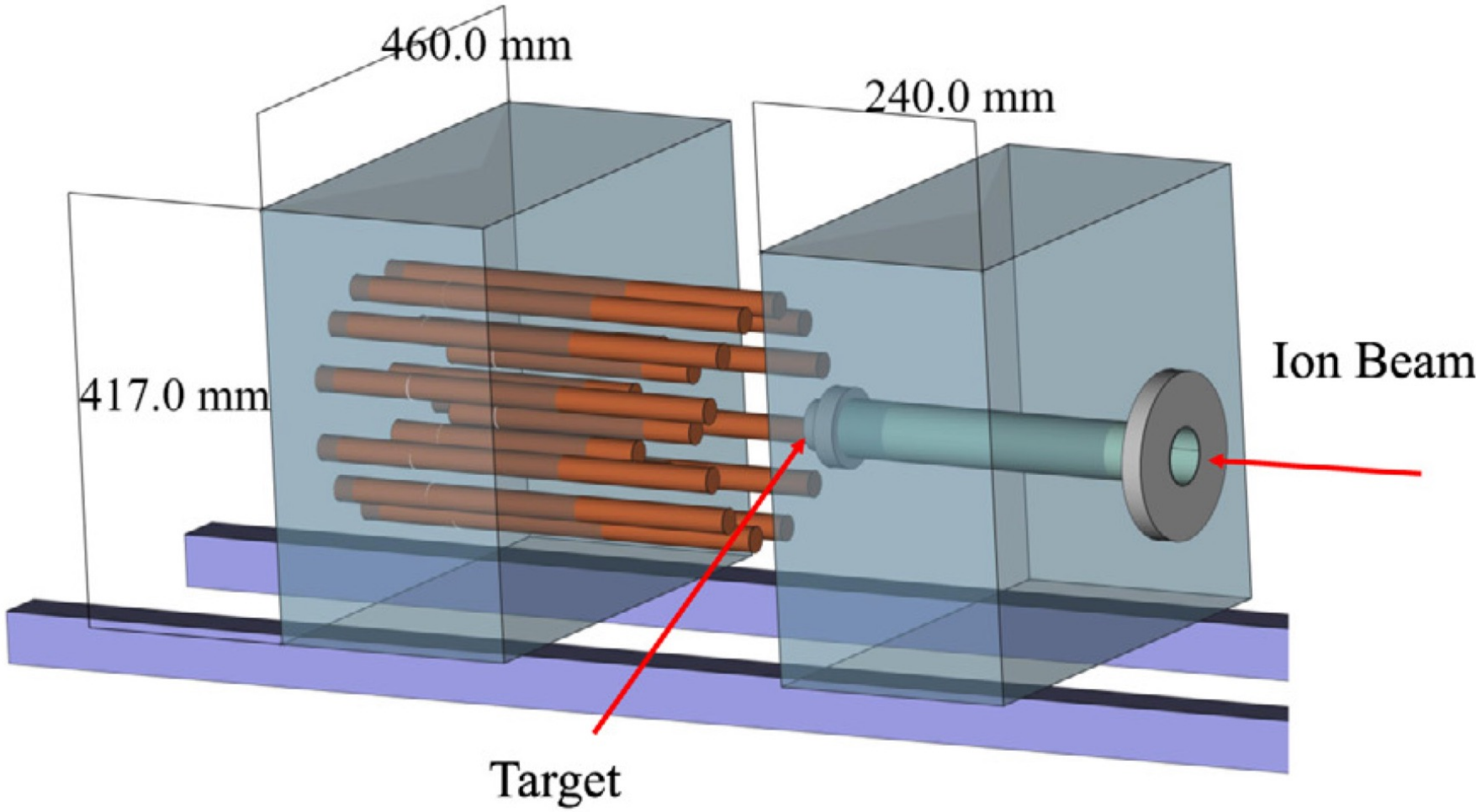
The periodic table: Neutron capture: rapid and slow processes



The two astrophysical neutron capture processes, and the γ-process

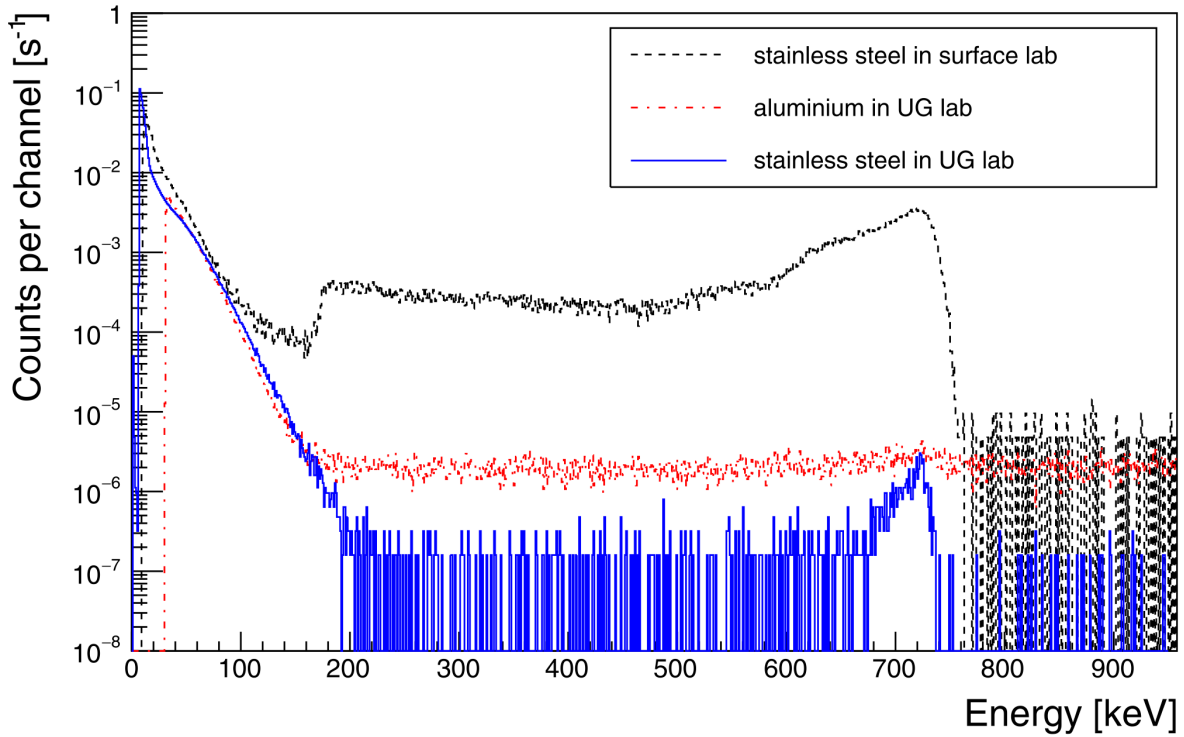


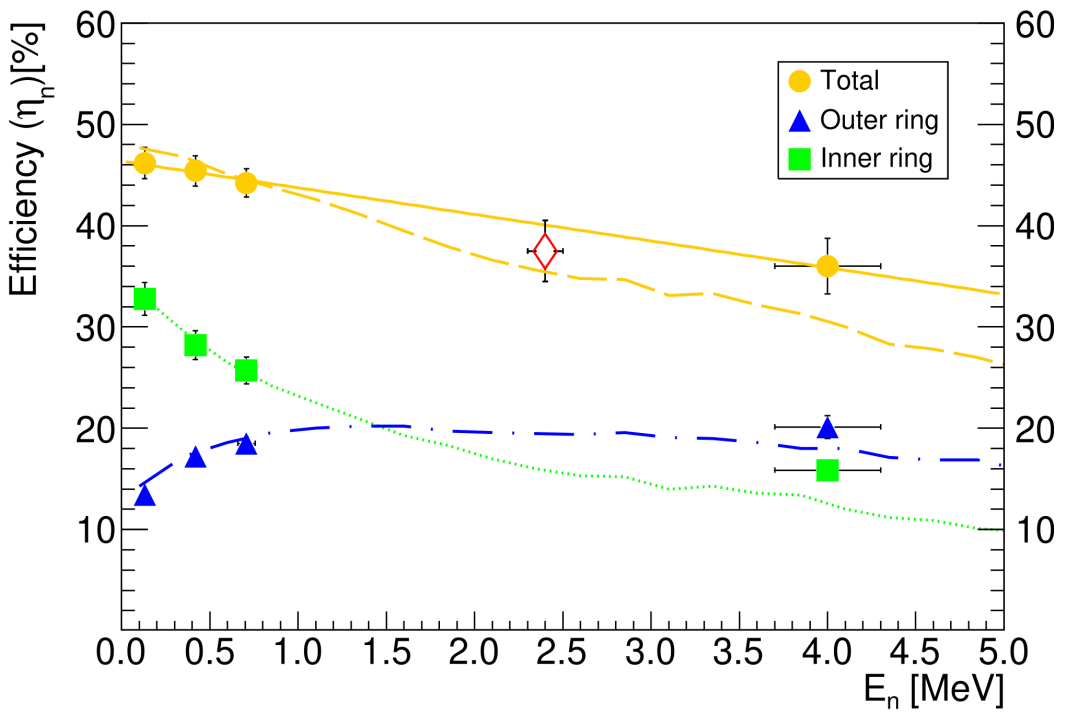
$^{13}C(\alpha,n)^{16}O$ neutron source for the astrophysical s-process



Ciani *et al*. (LUNA), Phys. Rev. Lett. 127, 152701 (2021)

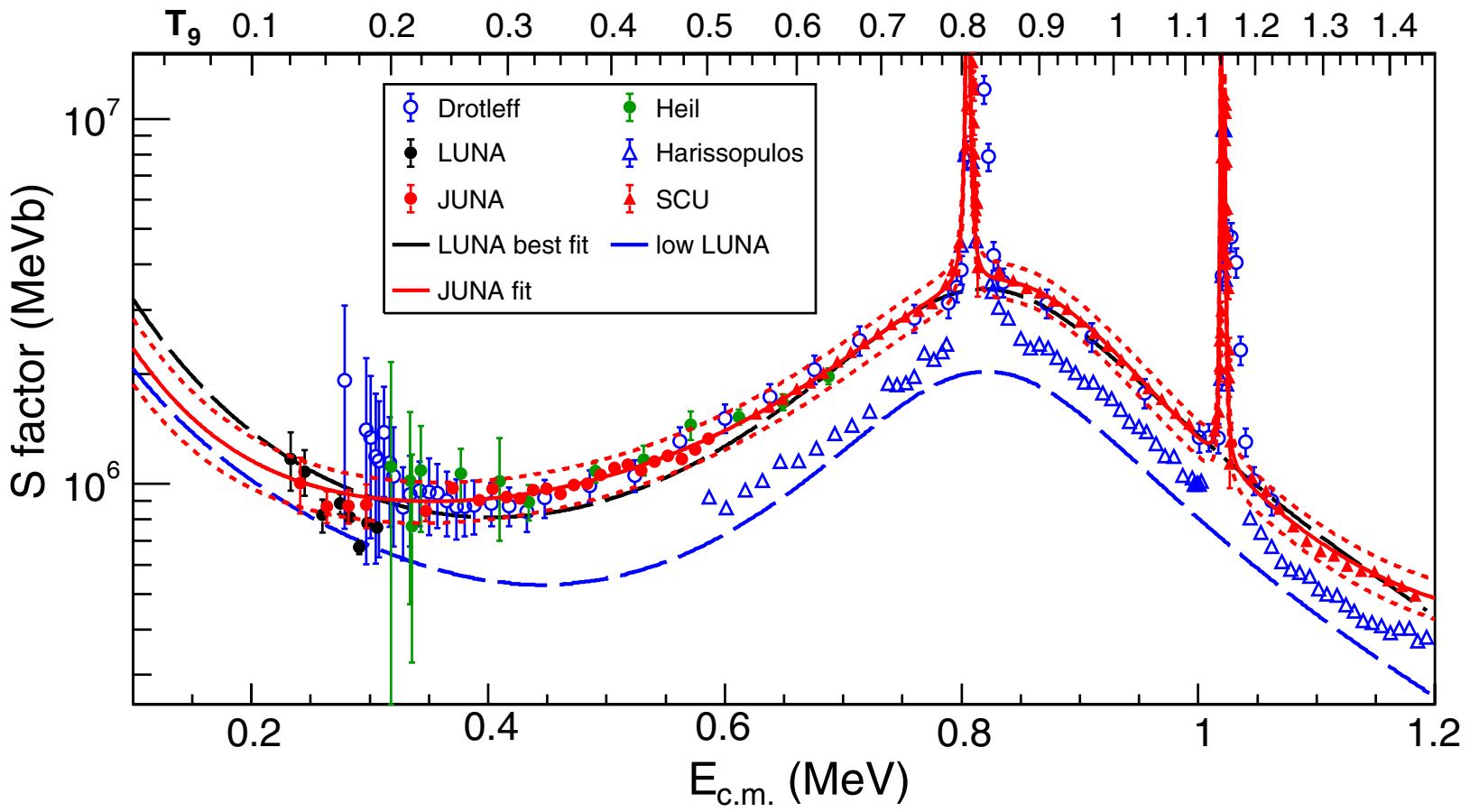
$^{13}C(\alpha,n)^{16}O$ neutron source for the astrophysical s-process





Ciani *et al*. (LUNA), Phys. Rev. Lett. 127, 152701 (2021)

$^{13}C(\alpha,n)^{16}O$ neutron source for the astrophysical s-process

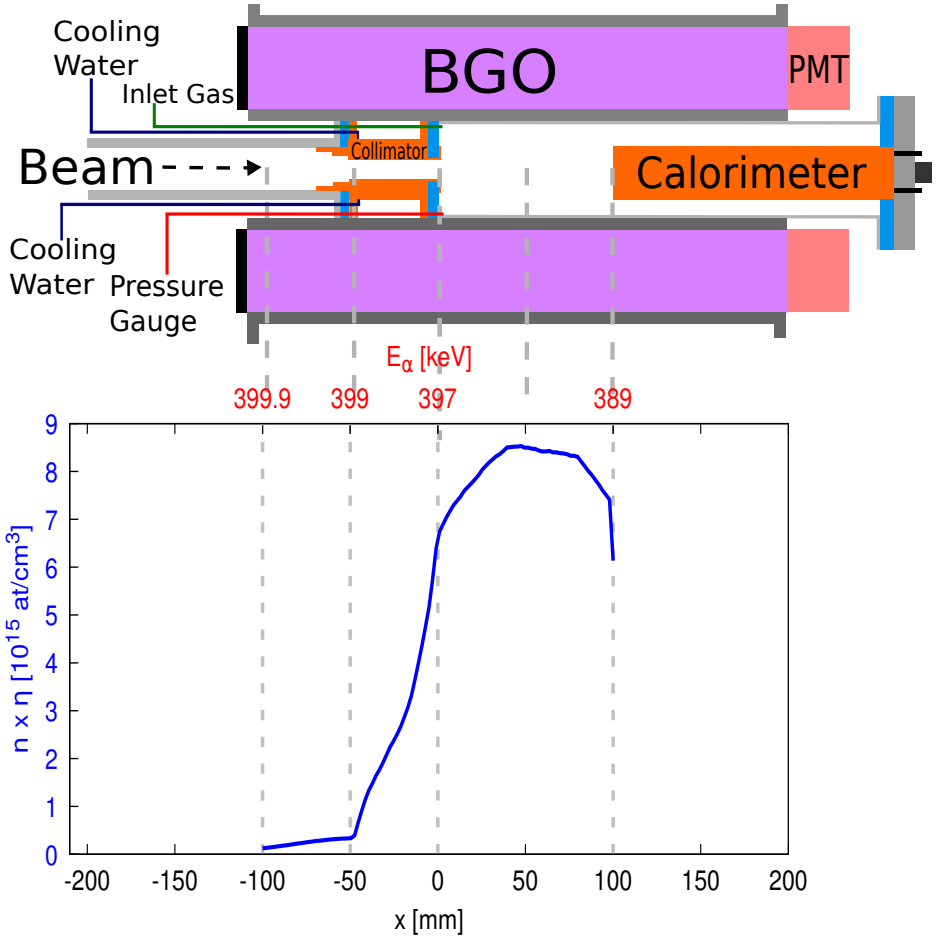


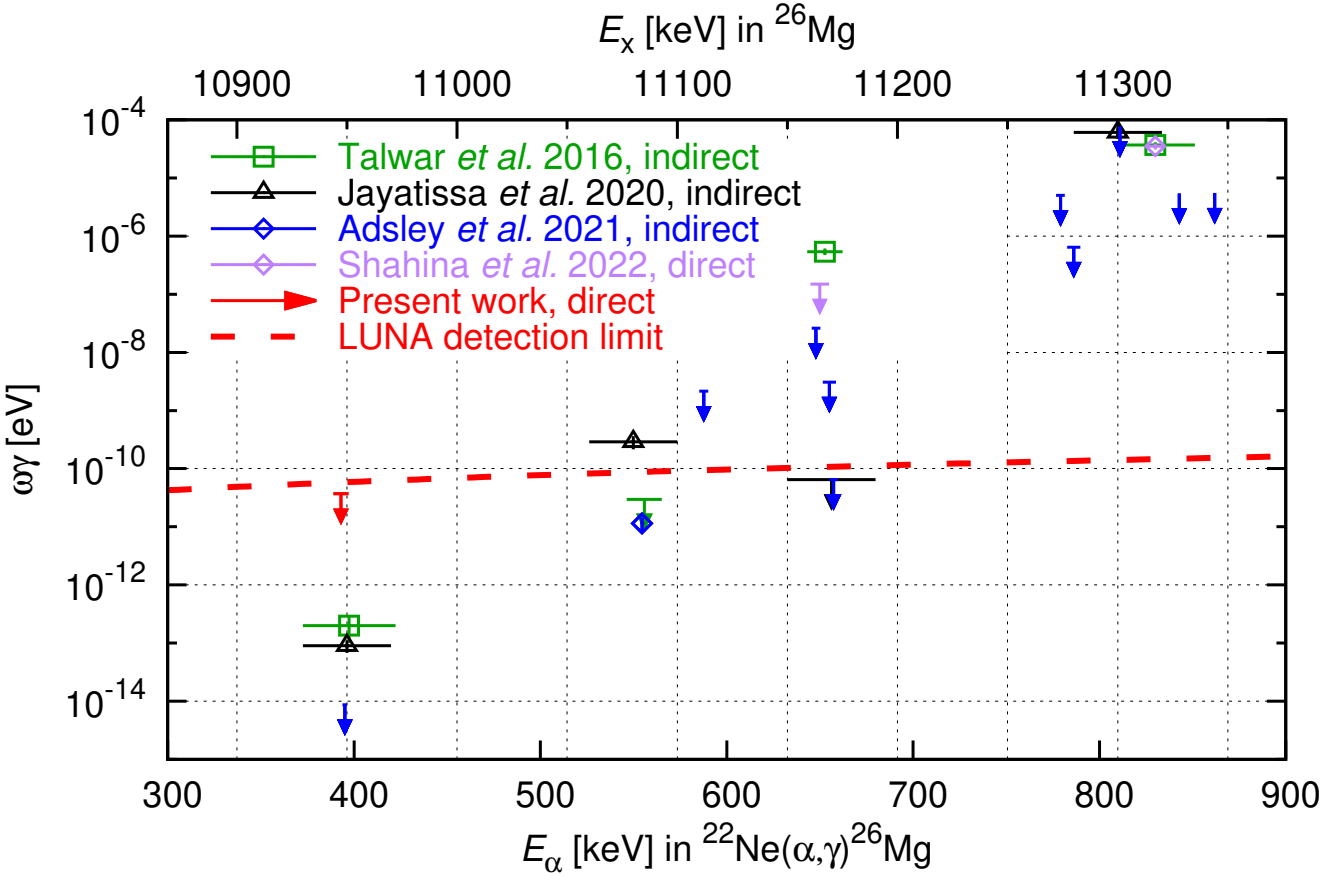
LUNA = deep underground
Gran Sasso/Italy
Ciani *et al.*
PRL 127, 152701 (2021)

JUNA = deep underground
Jinping/China
Gao *et al.*
PRL 129, 132701 (2022)

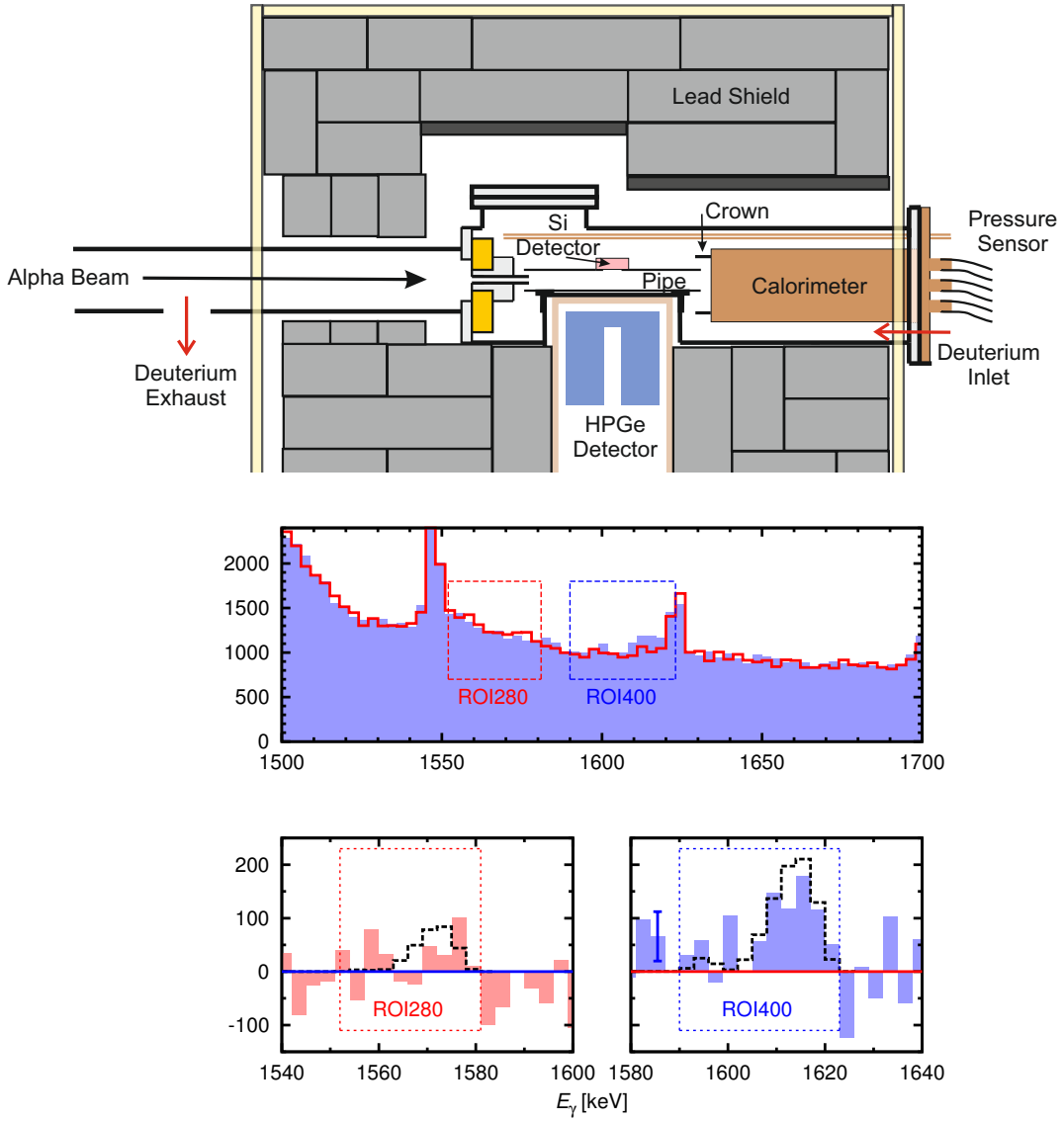
^{22}Ne(α,n)^{25}Mg neutron source for the astrophysical s-process

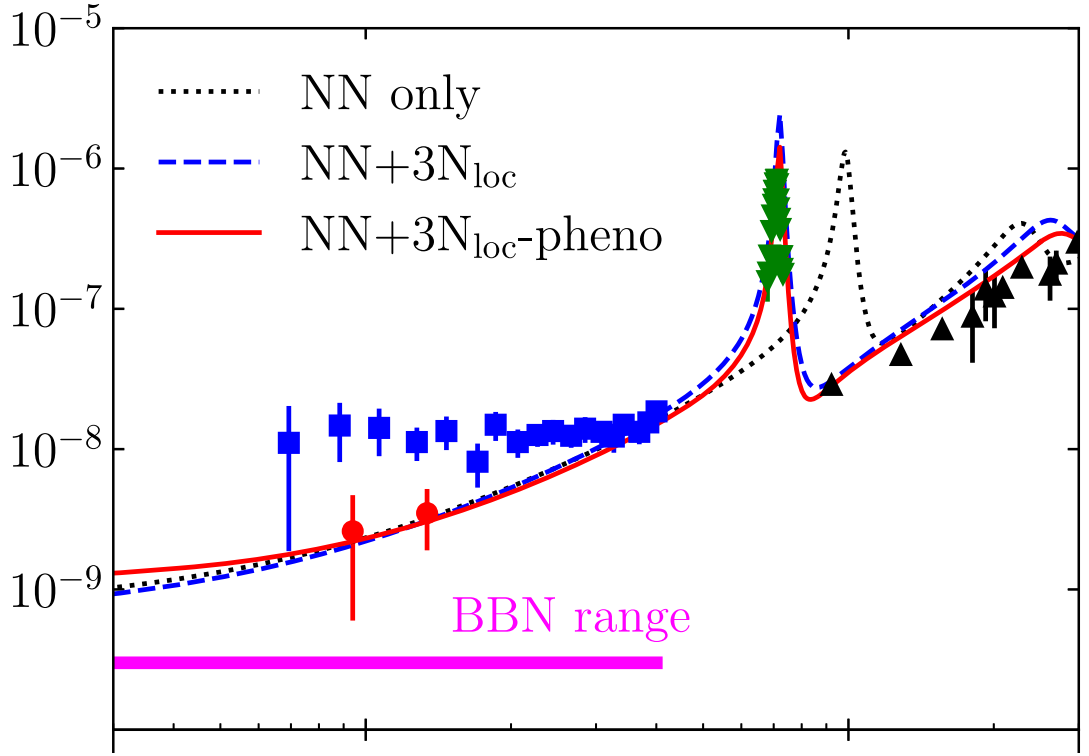
LUNA = deep underground Gran Sasso
Piatti *et al.* EPJA 58, 194 (2022)





Lithium-6, between cosmic-ray and Big Bang production





Experiment Anders, DB *et al.* PRL 113, 042501 (2014)

New theory Hebburn *et al.* PRL 129, 042503 (2022)

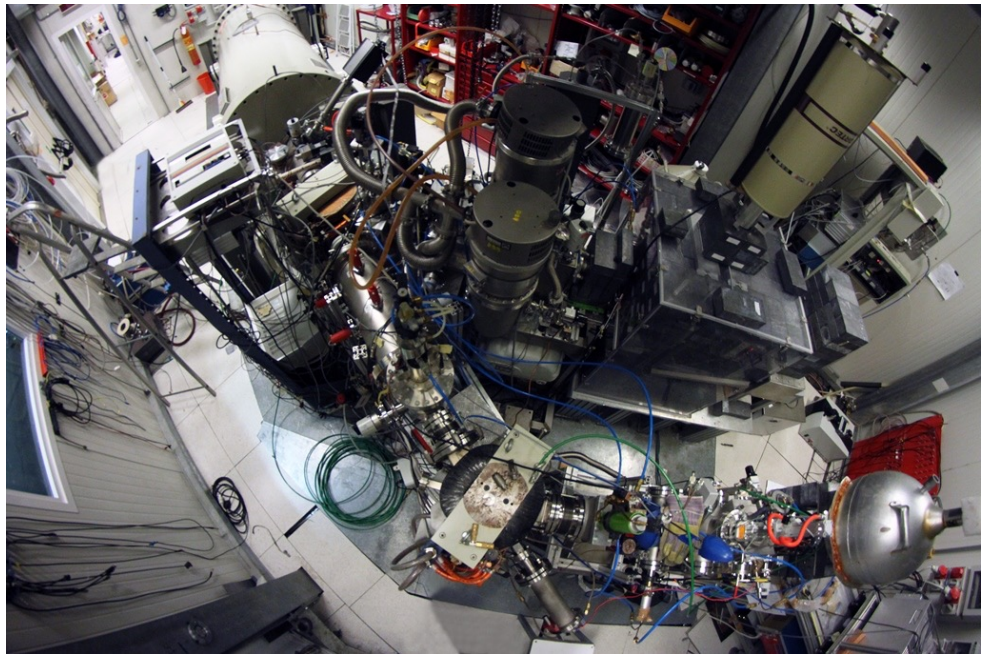
Underground ion accelerators worldwide – starting from LUNA

The workhorse, commissioned in 2001 and still going strong:

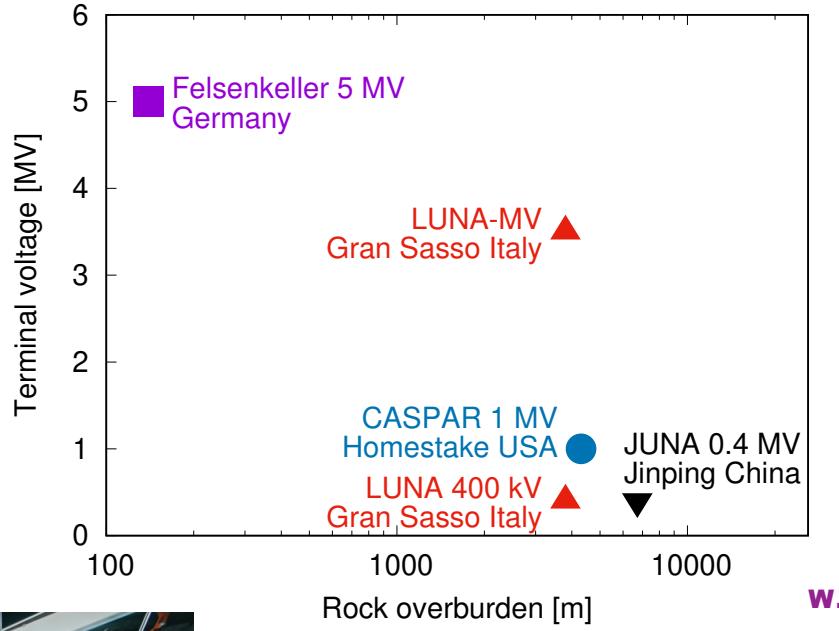
LUNA 400 kV ion accelerator for $^{1}H^{+}$ and $^{4}He^{+}$ ions

- Solar hydrogen burning
- Big Bang nucleosynthesis

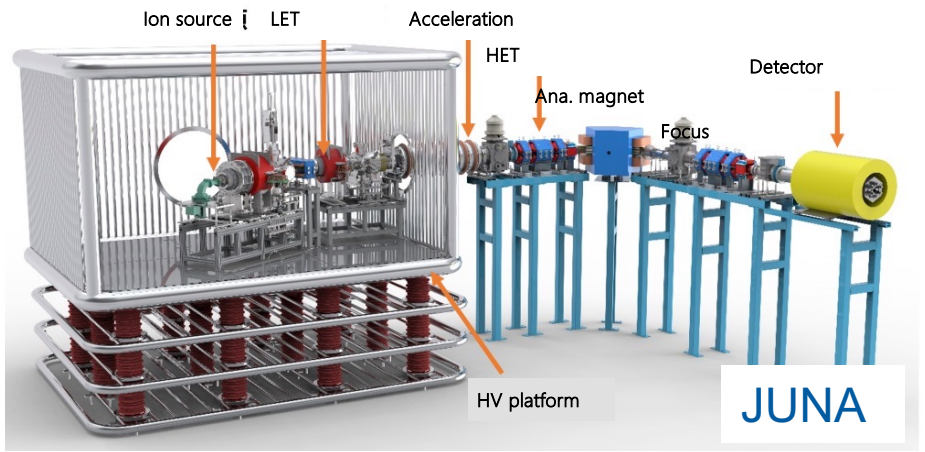
Gran Sasso lab, Italy – 1400 m rock equivalent to 3800 m water



Underground ion accelerators – new players on three continents



W. P. Liu et al., Sci. China 59(2016)5785.



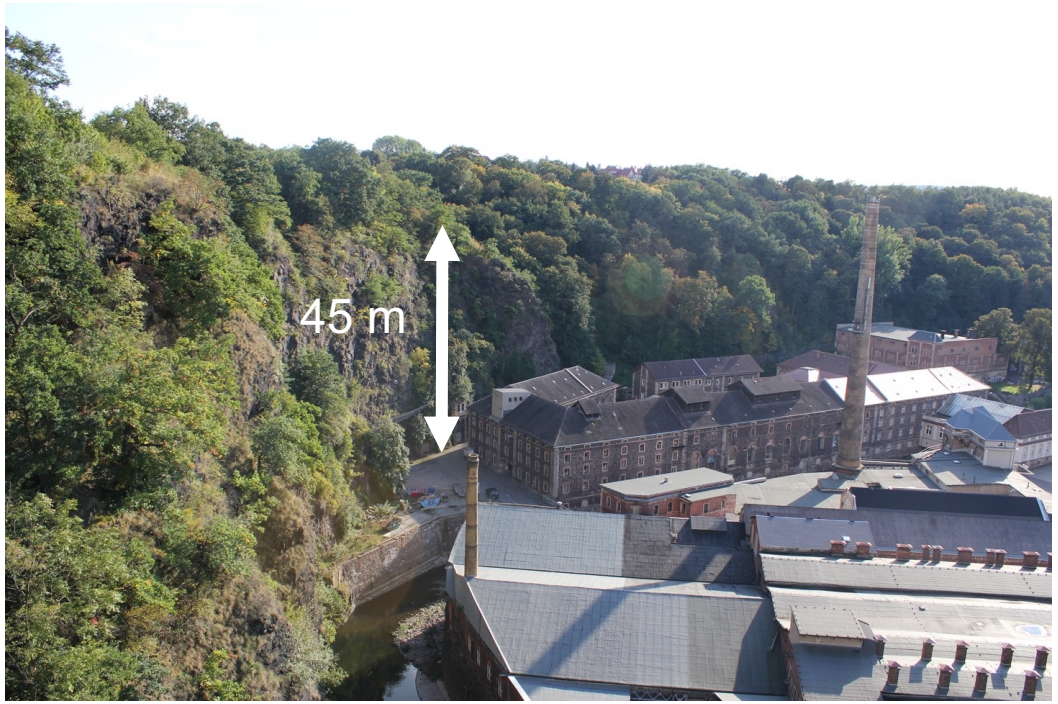
Dresden Felsenkeller underground lab, below 45 m of rock

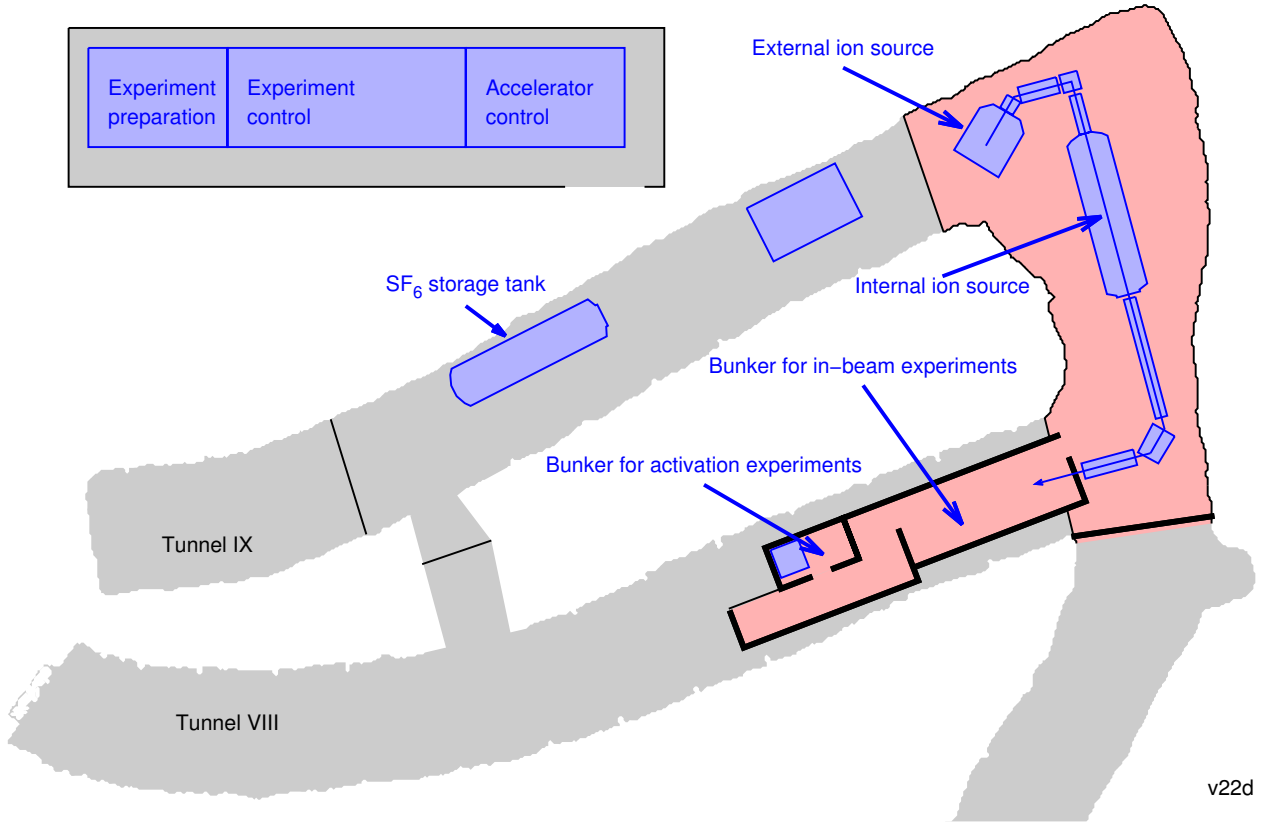
Joint effort HZDR – TU Dresden

- Investment by TU Dresden (Kai Zuber *et al.*) and HZDR (Daniel Bemmerer *et al.*)
- Day to day operations by HZDR

Two main instruments

- **HZDR:** 5 MV Pelletron, 30 µA beams of $^{1}H^{+}$, $^{4}He^{+}$, $^{12}C^{+}$, ...
- **TU Dresden:** 163% ultra-low-background HPGe detector for offline radioactivity measurements

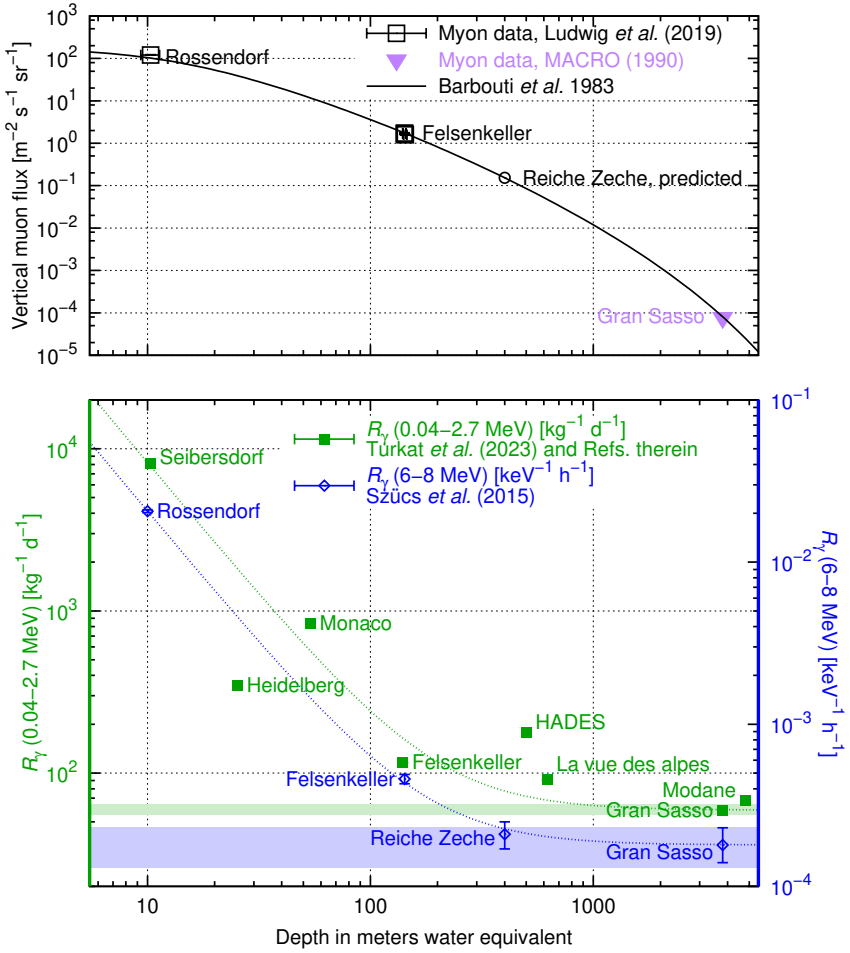




Felsenkeller: Studying low cross sections with low background

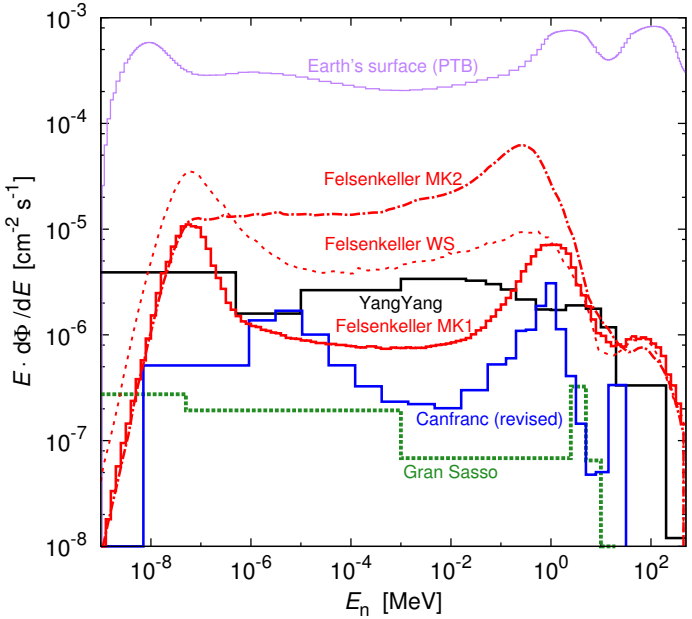
40× lower muon background

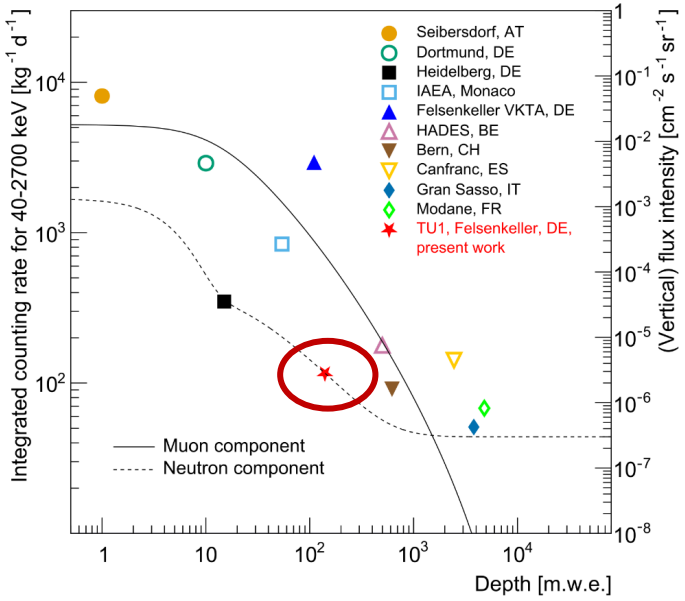
Astropart. Phys. 112, 24 (2019)



200× lower neutron background

Phys. Rev. D 101, 123027 (2020)



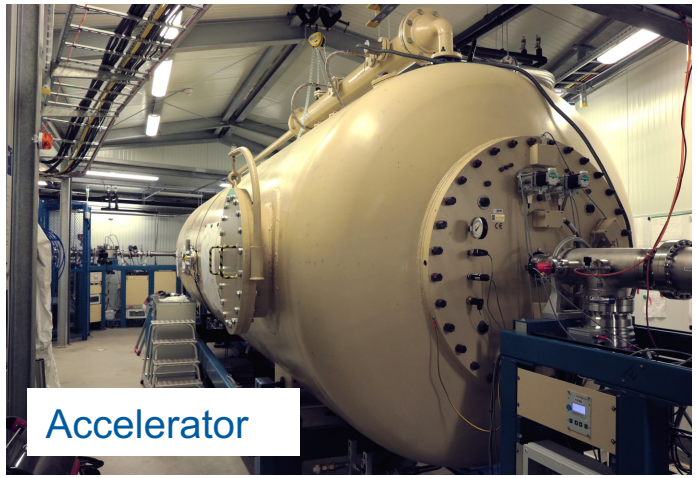


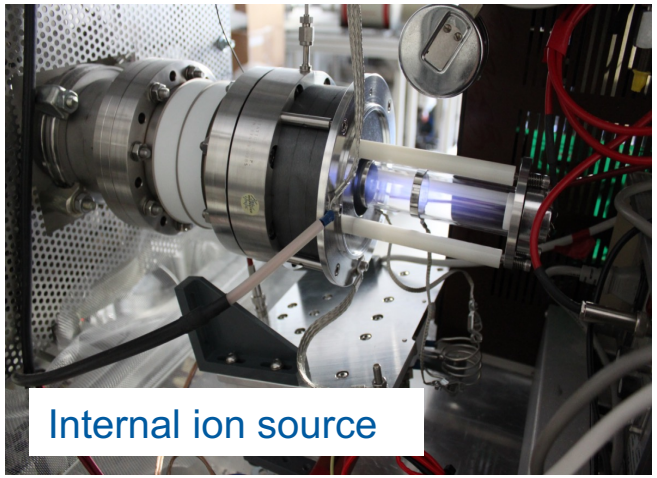
100× lower γ-background

Eur. Phys. J. A 51, 33 (2015)

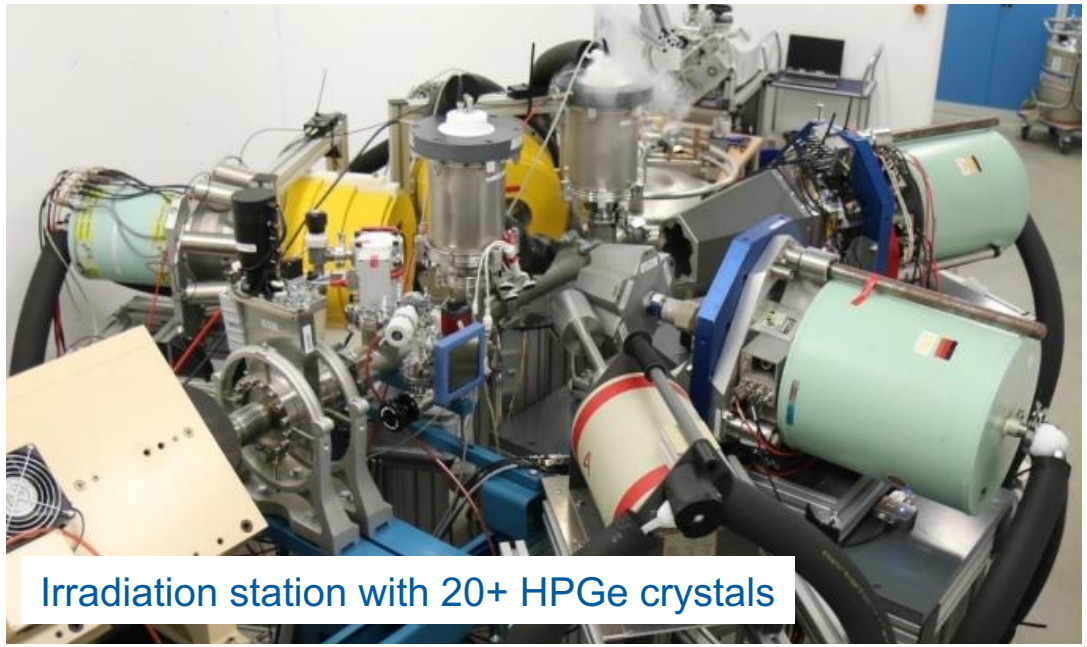
Astropart. Phys. 148, 102816 (2023)

Felsenkeller 5 MV underground ion accelerator


Accelerator


Internal ion source


External ion source

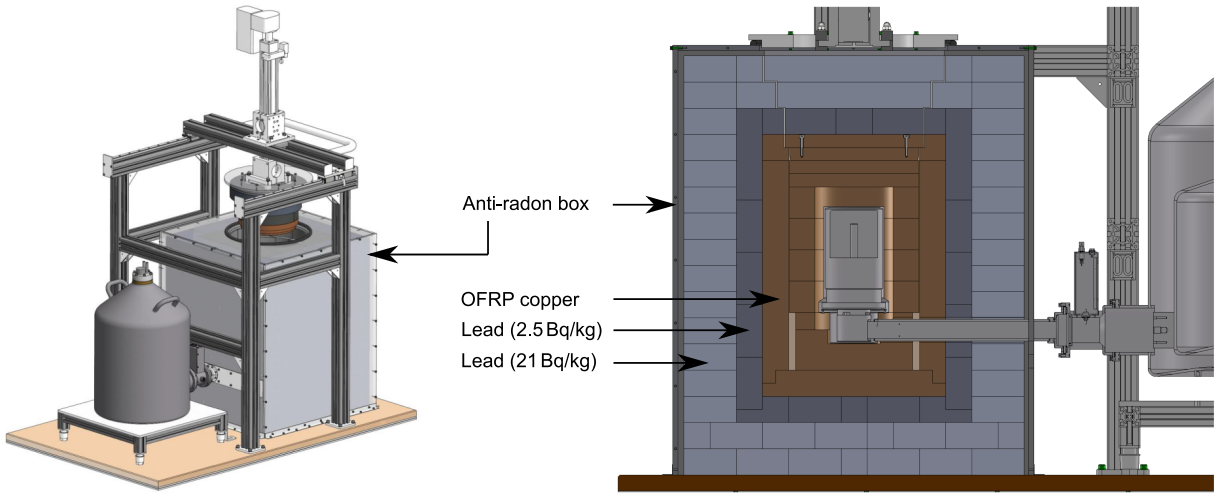

Irradiation station with 20+ HPGe crystals

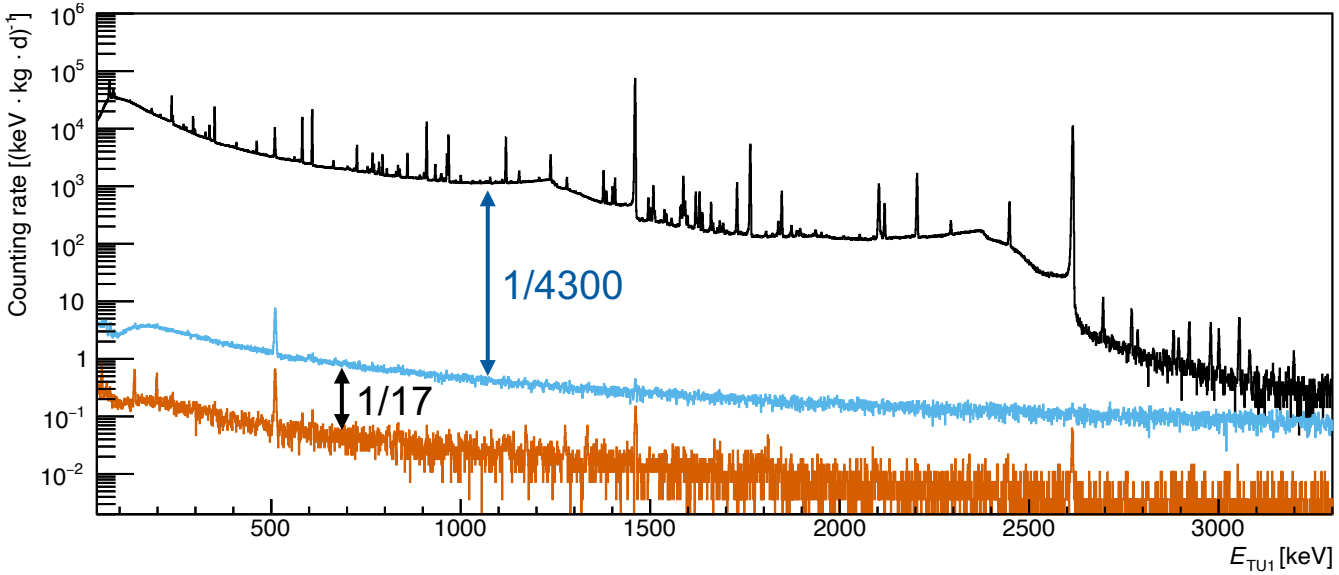
5 MV accelerator (0.4-3.8 MV), two alternative ion sources

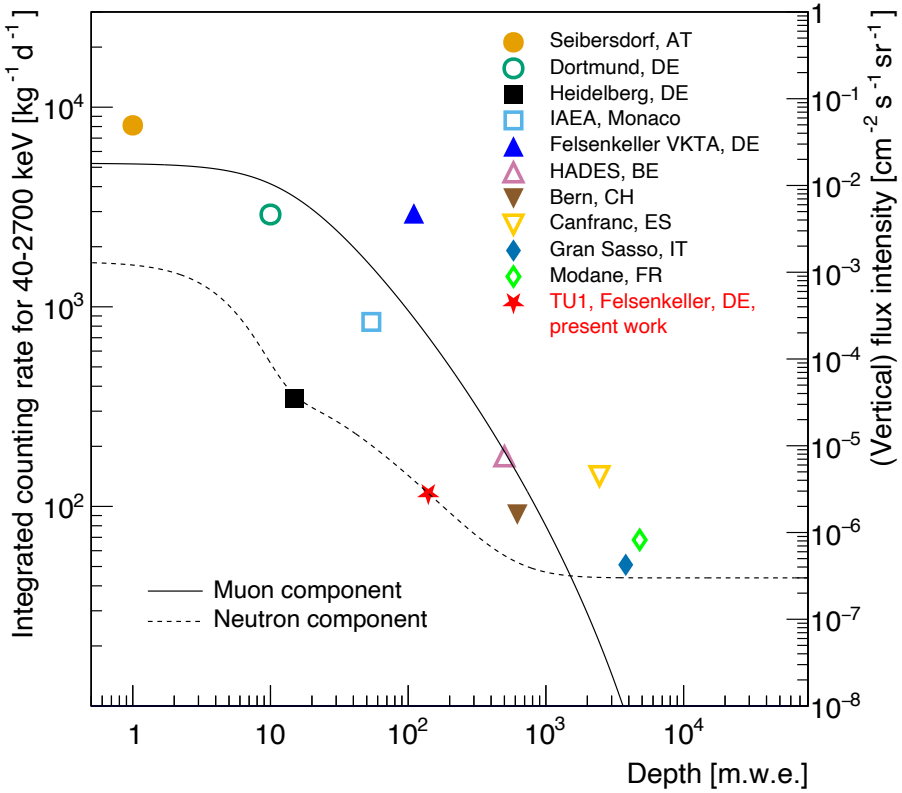
- Internal RF ion source: 30 μA ^{1}H, ^{4}He
- SNICS sputter ion source: 30 μA ^{12}C

- 24 hour operation permitted even without operator
- Personnel is allowed at target while beam is on
- Control and counting rooms at surface
- EU-supported transnational access available

Germany‘s most sensitive radioactivity measurement setup “TU1”



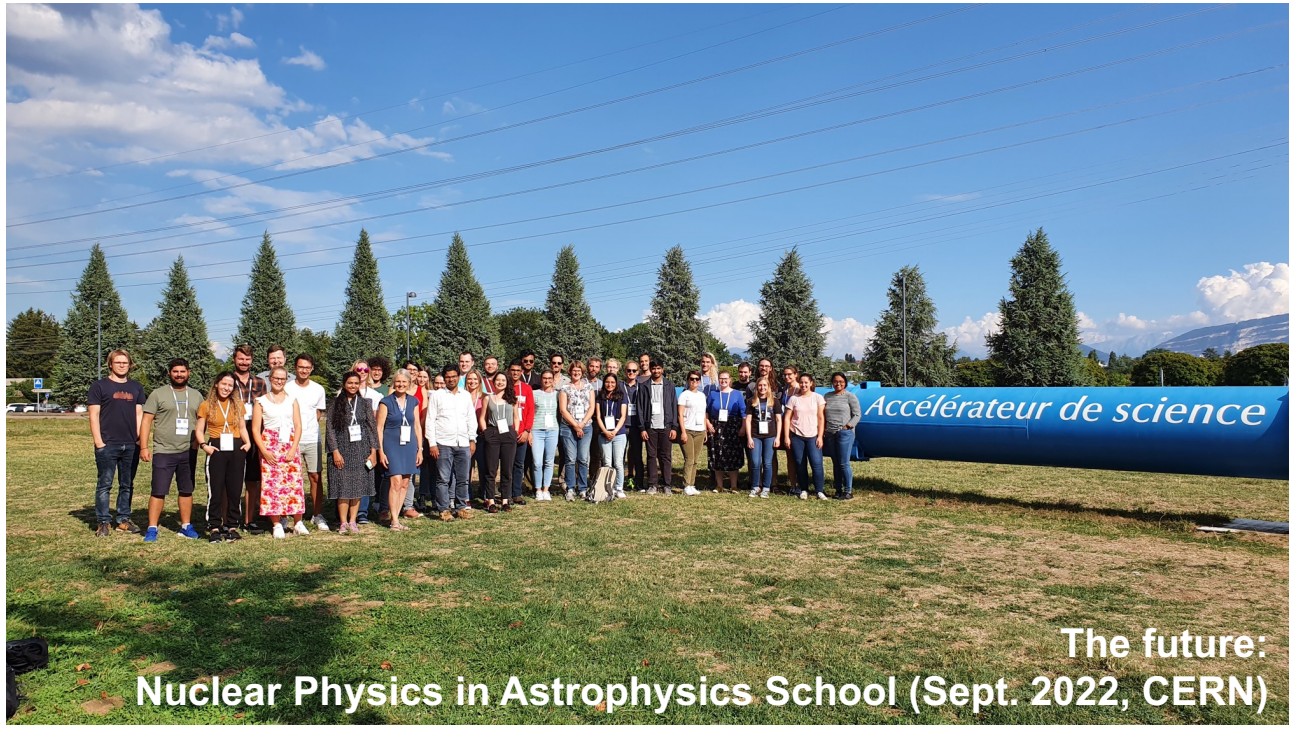




Steffen Turkat, Kai Zuber *et al.*,
Astropart. Phys. 148 (2023) 102816

ChETEC-INFRA EU project for nuclear astrophysics [ketek-infra]

The present:
General Assembly (June 2022, Padova)



The future:
Nuclear Physics in Astrophysics School (Sept. 2022, CERN)

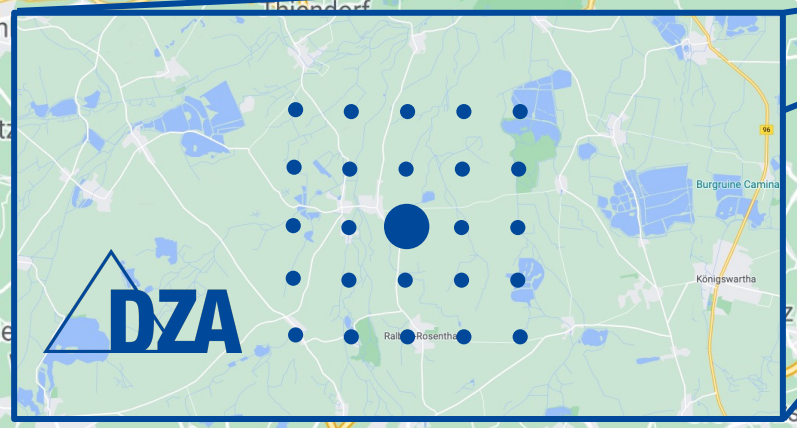
https://www.chetec-infra.eu

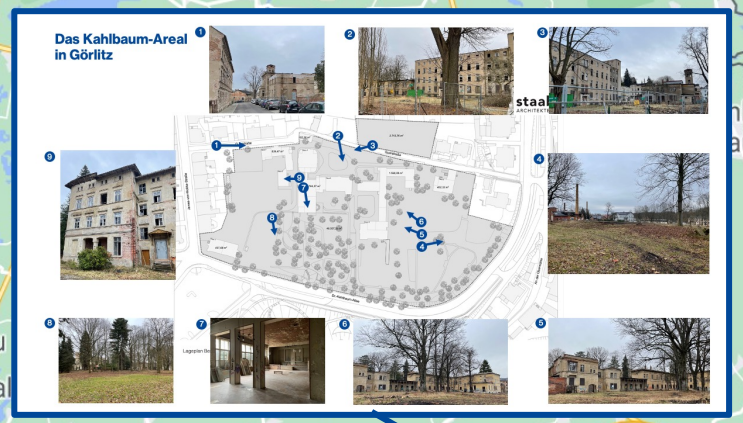
- **Starting Community** of research infrastructures
- **31 partners** in 17 EU+ countries
- May 2021 – October 2025
- 5 M€ support by EU

Courtesy Christian Stegmann / DESY

Eine Region für Astrophysik, Technologie und Digitalisierung

Möglicher Standort des Einstein-Teleskop mit dem unterirdischen Low-Seismic-Lab





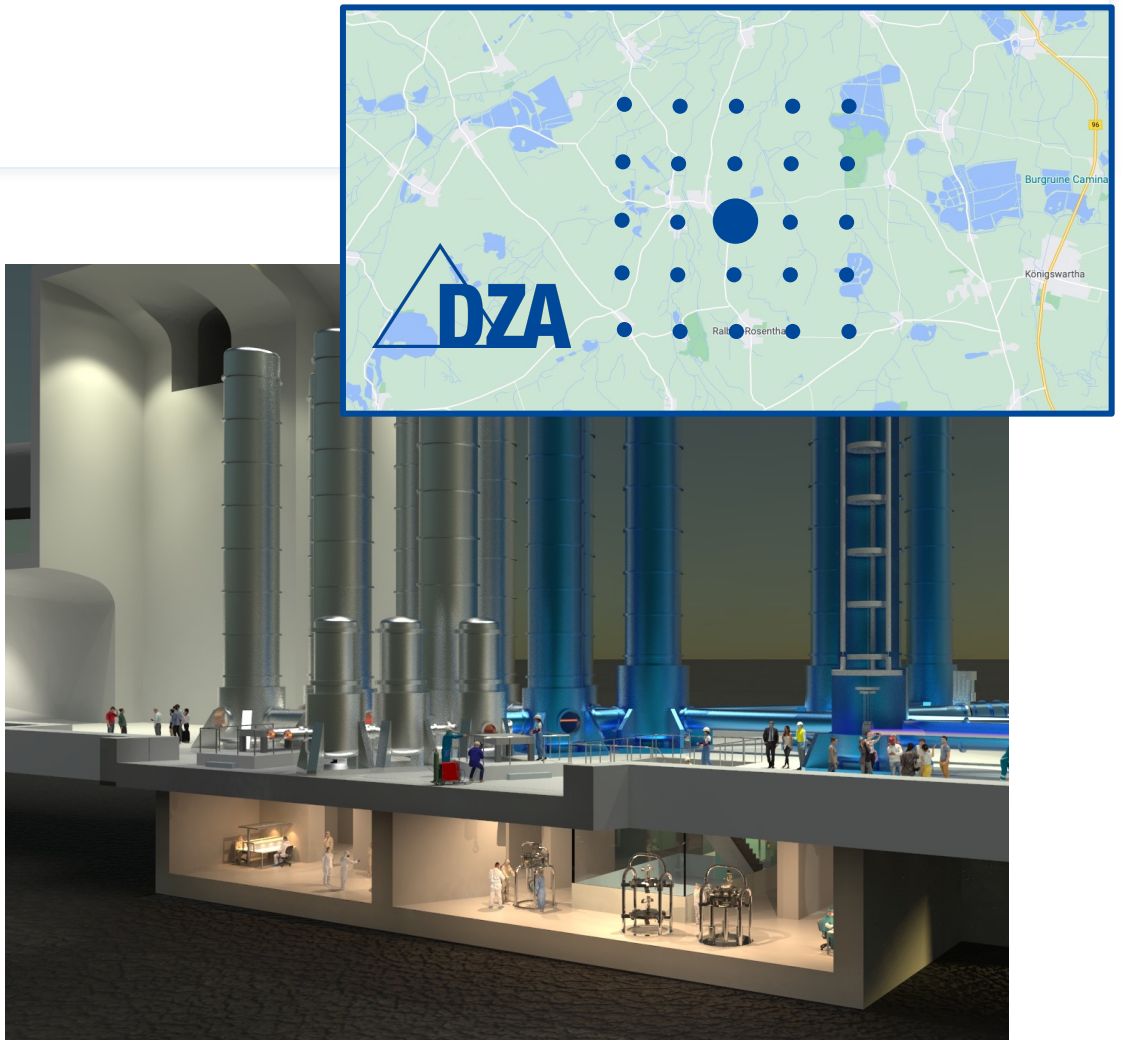
Ein Zentrum für Astrophysik mit fortschrittlicher Computertechnik und Technologieentwicklung

DZA

TECHNISCHE UNIVERSITÄT DRESDEN

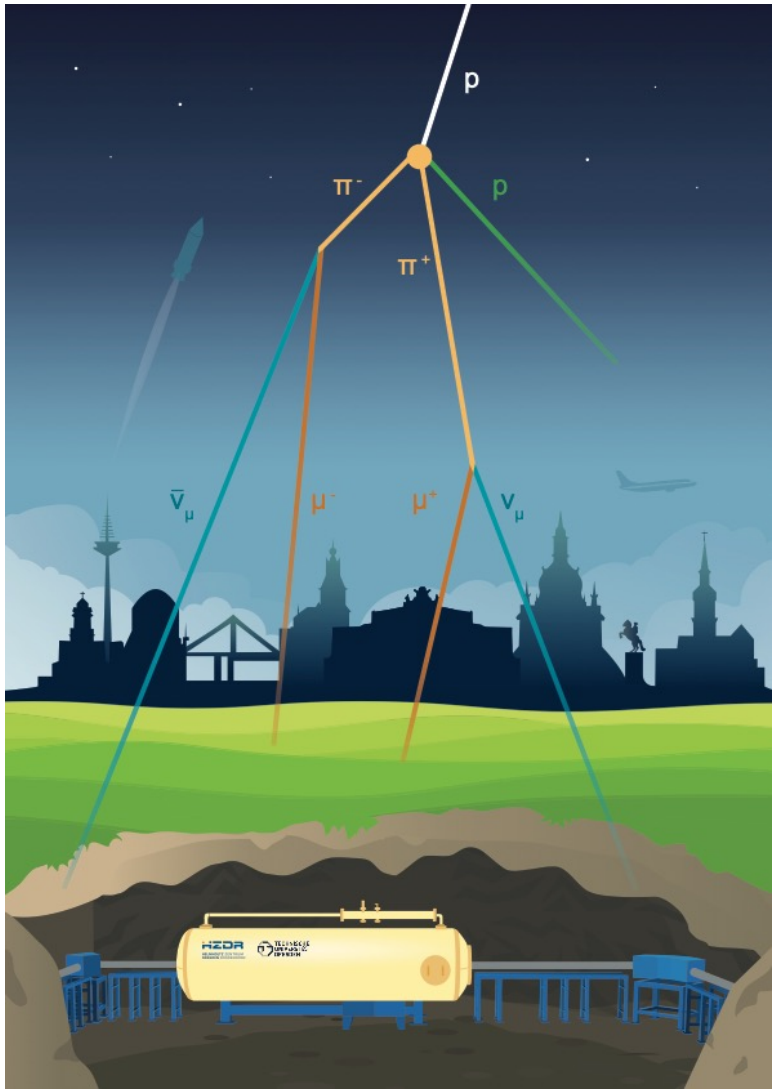
Das Low-Seismic-Lab

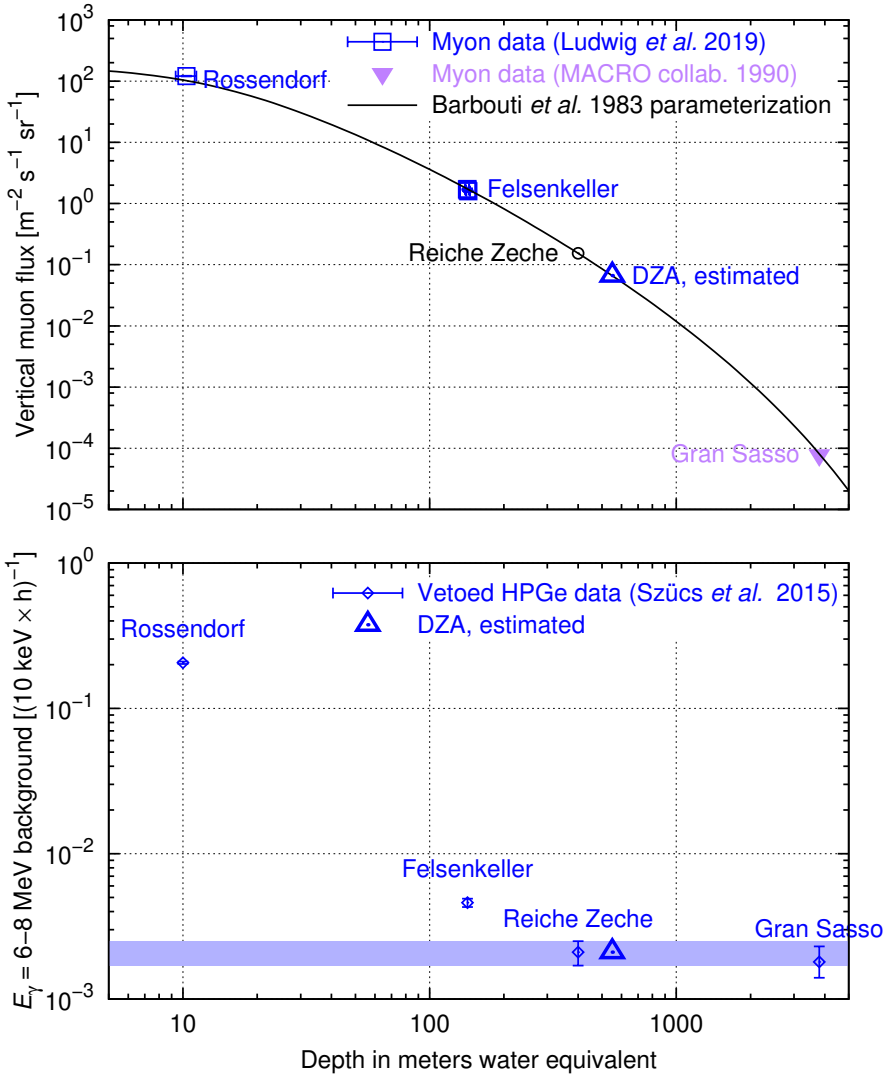
- Technologieentwicklung für die Gravitationswellenastronomie
- Adaptive seismische Rauschunterdrückung
- Sub-Nanometer-Mikroskopie und Photolithographie
- Astrophysik mit Beschleunigern

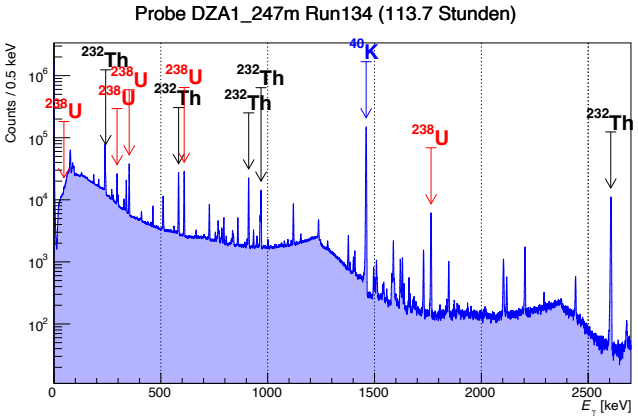


Courtesy Christian Stegmann / DESY

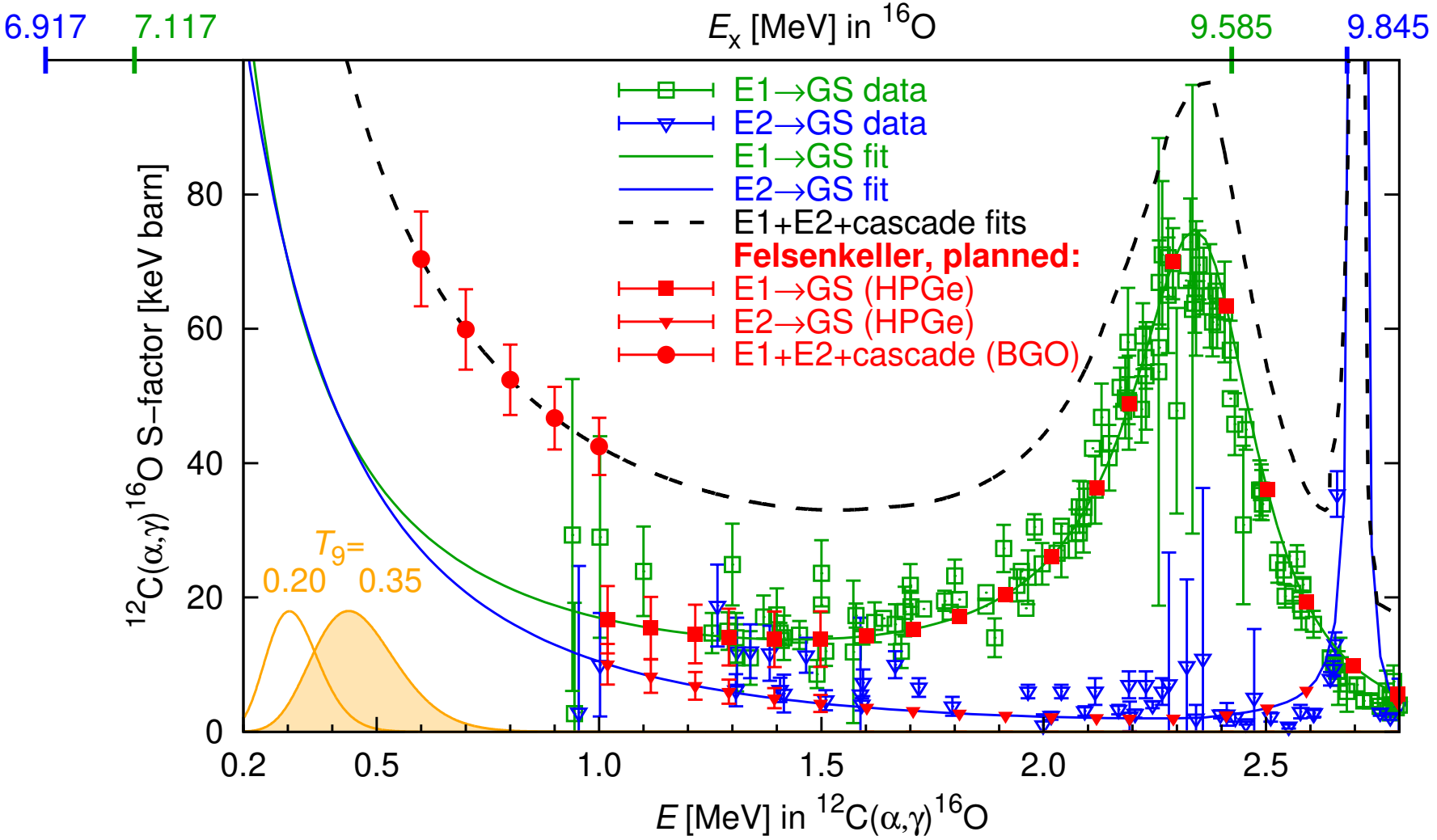
DZA Low Seismic Lab, at the „sweet spot“ for nuclear astrophysics







State of the art on $^{12}C(\alpha,\gamma)^{16}O$ and potential for Felsenkeller…
…using $^{12}C^{+}$ beam, gas target



31 partners in ChETEC-INFRA