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 and unstable nuclei

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

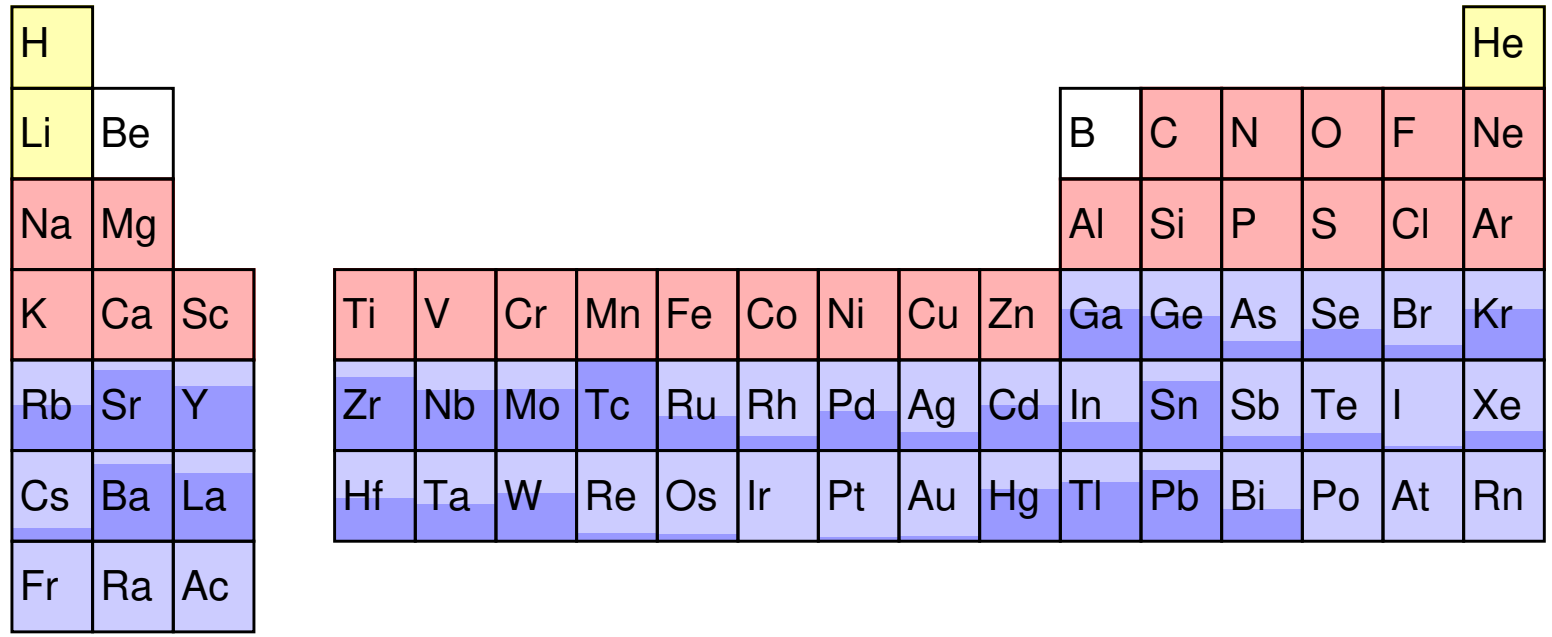
Karpacz, 04.03.2025

Daniel Bemmerer

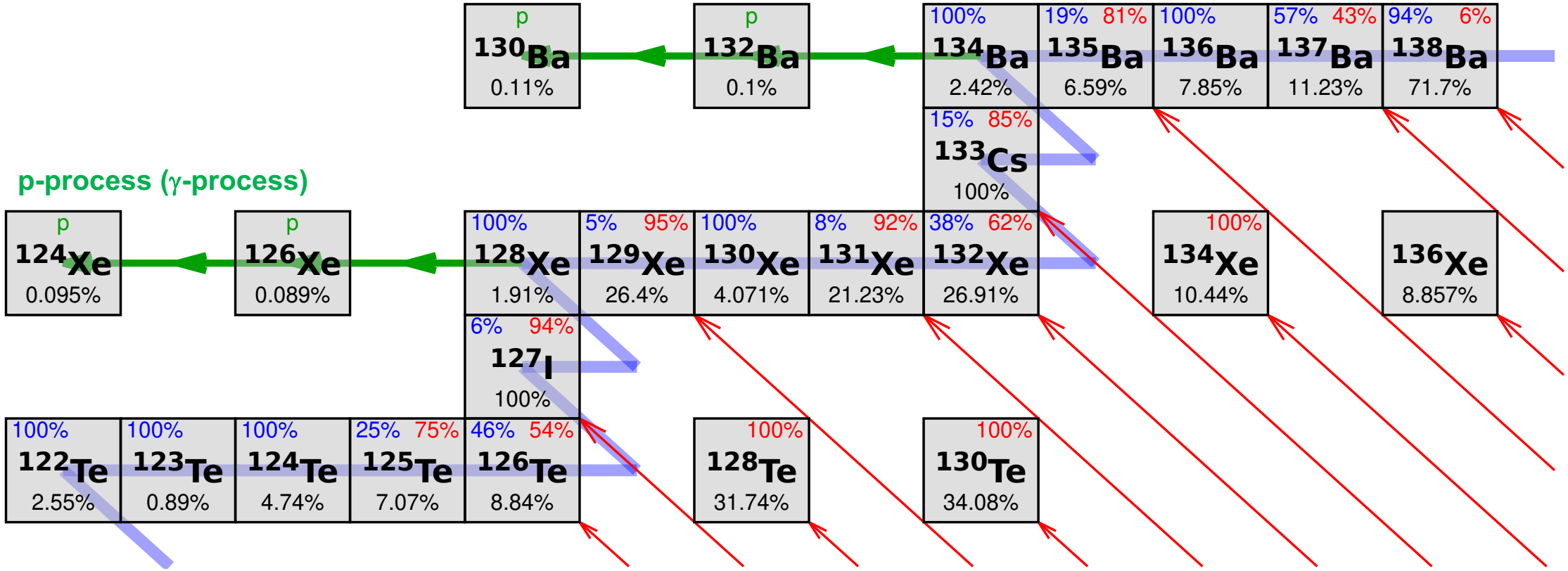
Helmholtz-Zentrum Dresden-Rossendorf

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

The periodic table: Neutron capture: rapid and slow processes



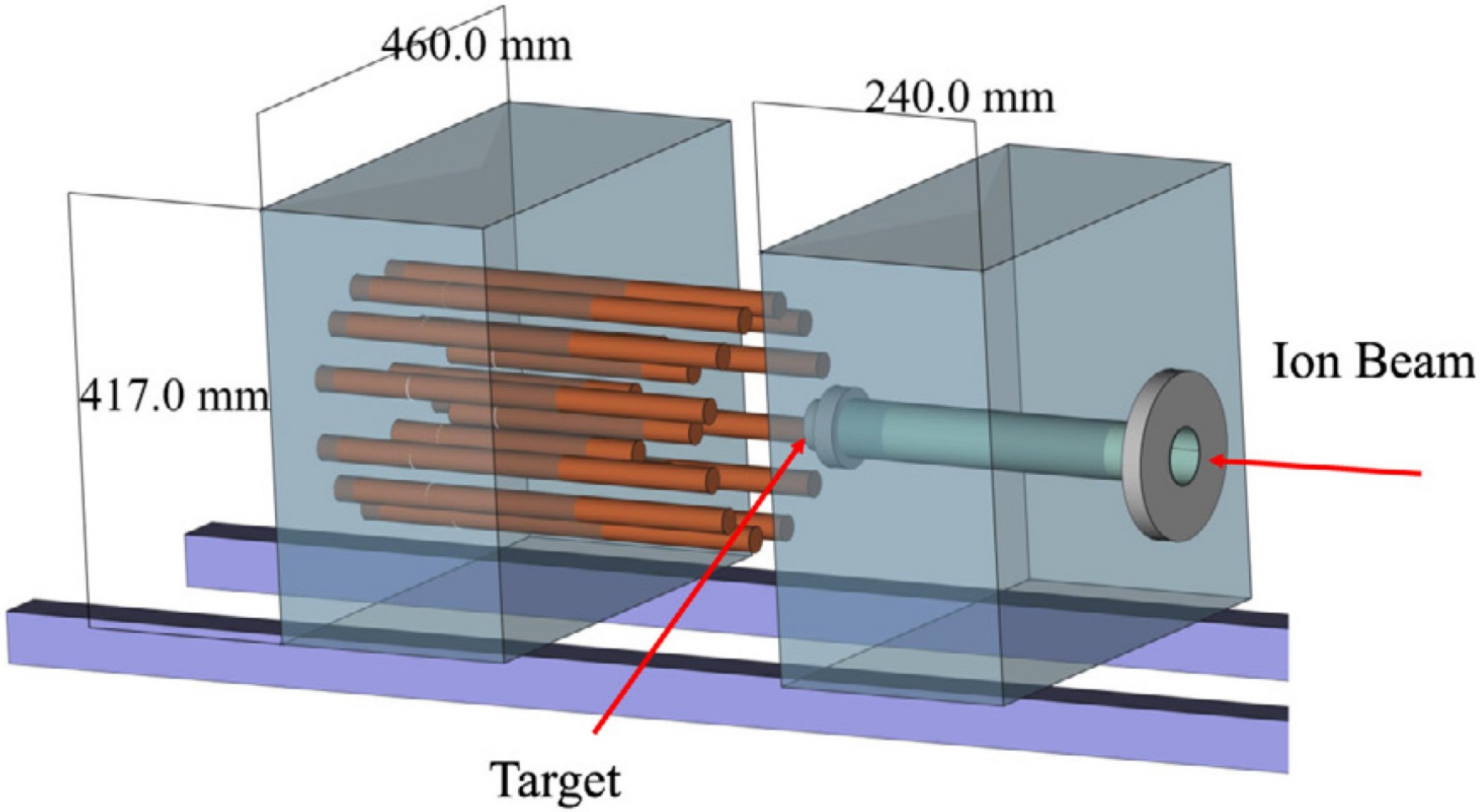
The two astrophysical neutron capture processes, and the γ-process



Neutron capture, immediately followed by β^- decay

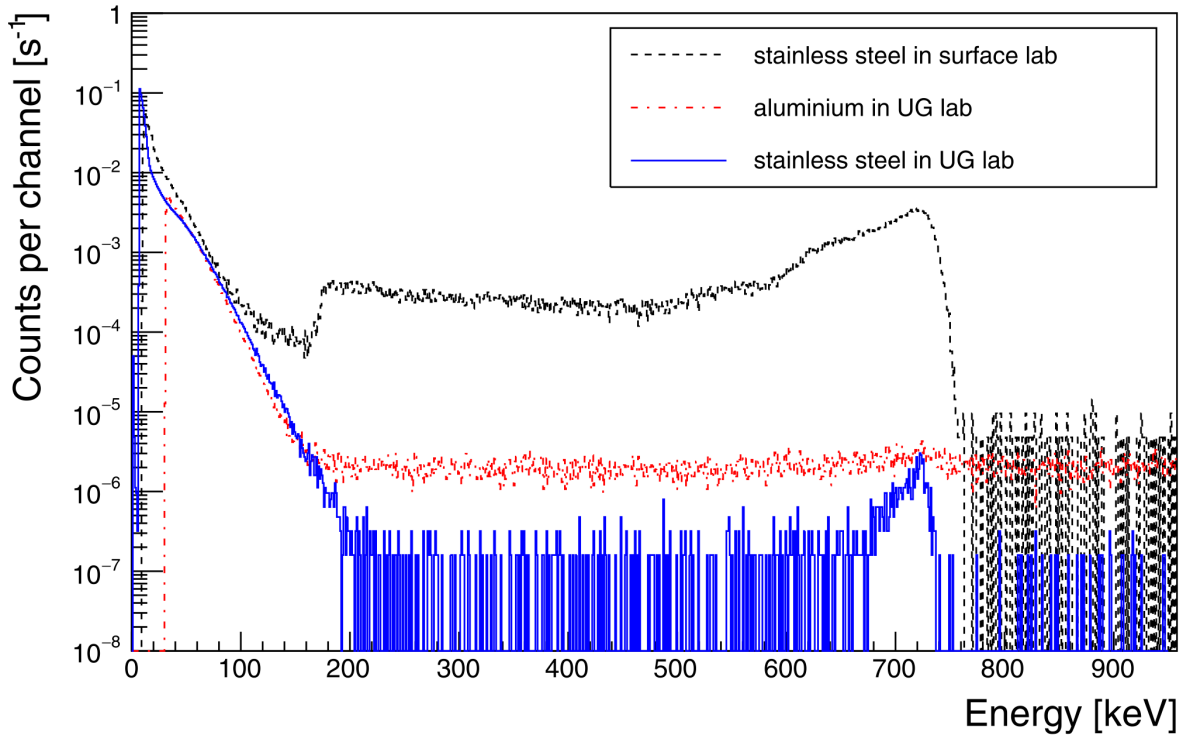
Series of neutron captures, followed by a series of β^- decays

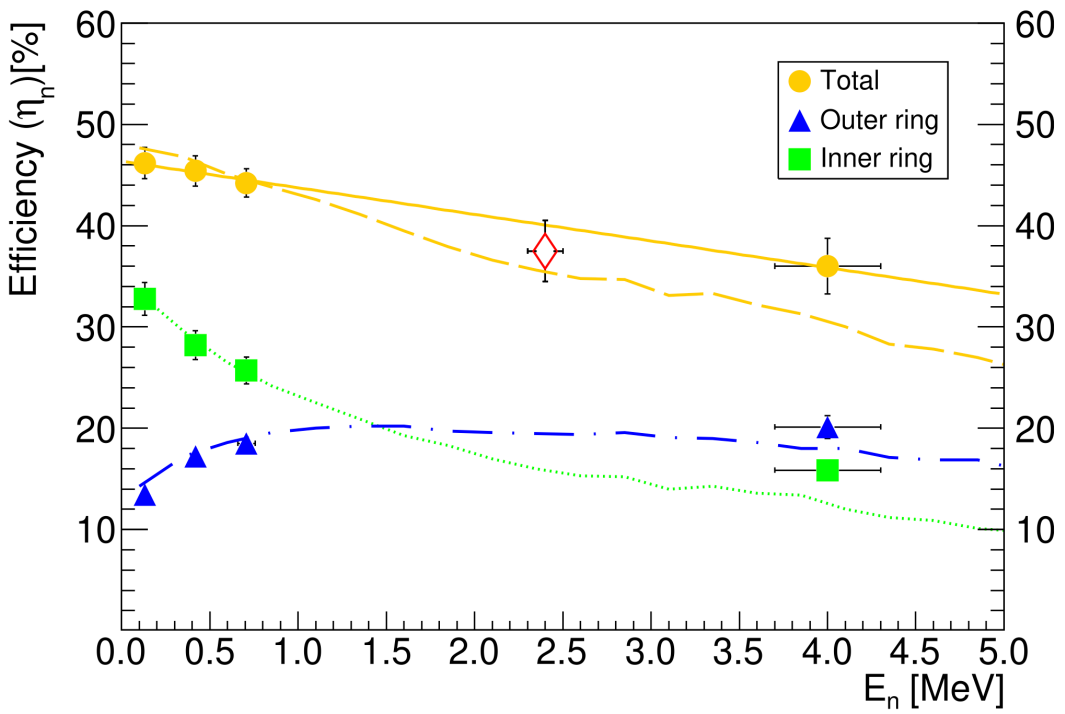
$^{13}C(\alpha,n)^{16}O$ neutron source for the astrophysical s-process



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

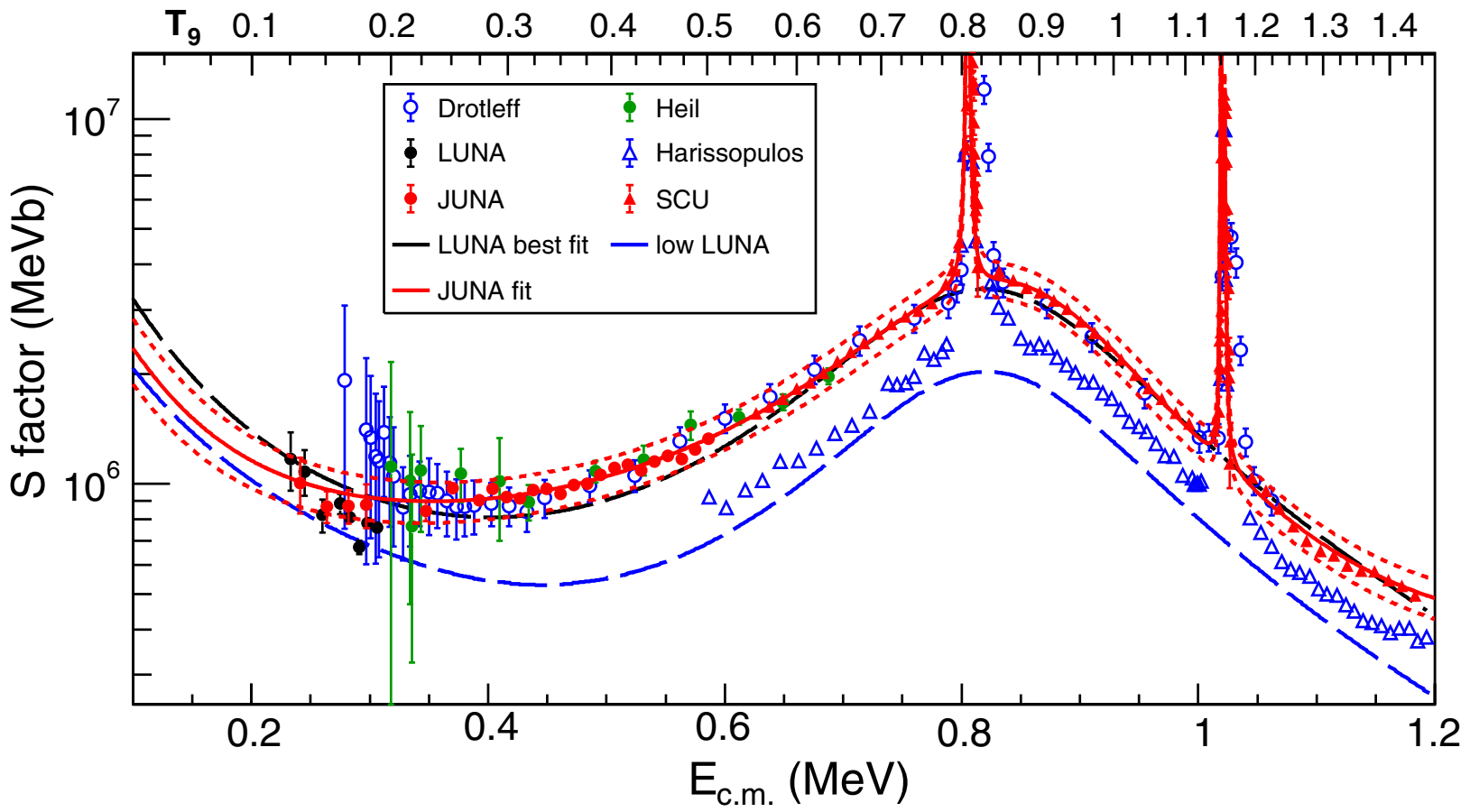
$^{13}C(\alpha,n)^{16}O$ neutron source for the astrophysical s-process





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

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

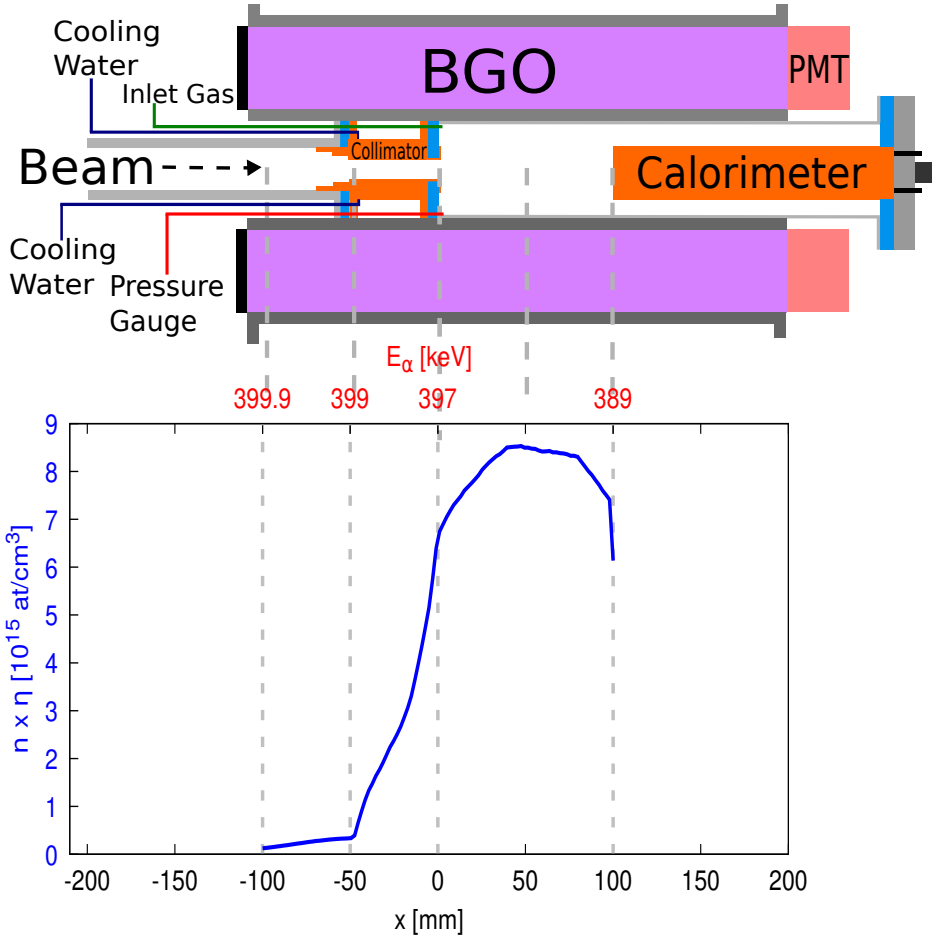


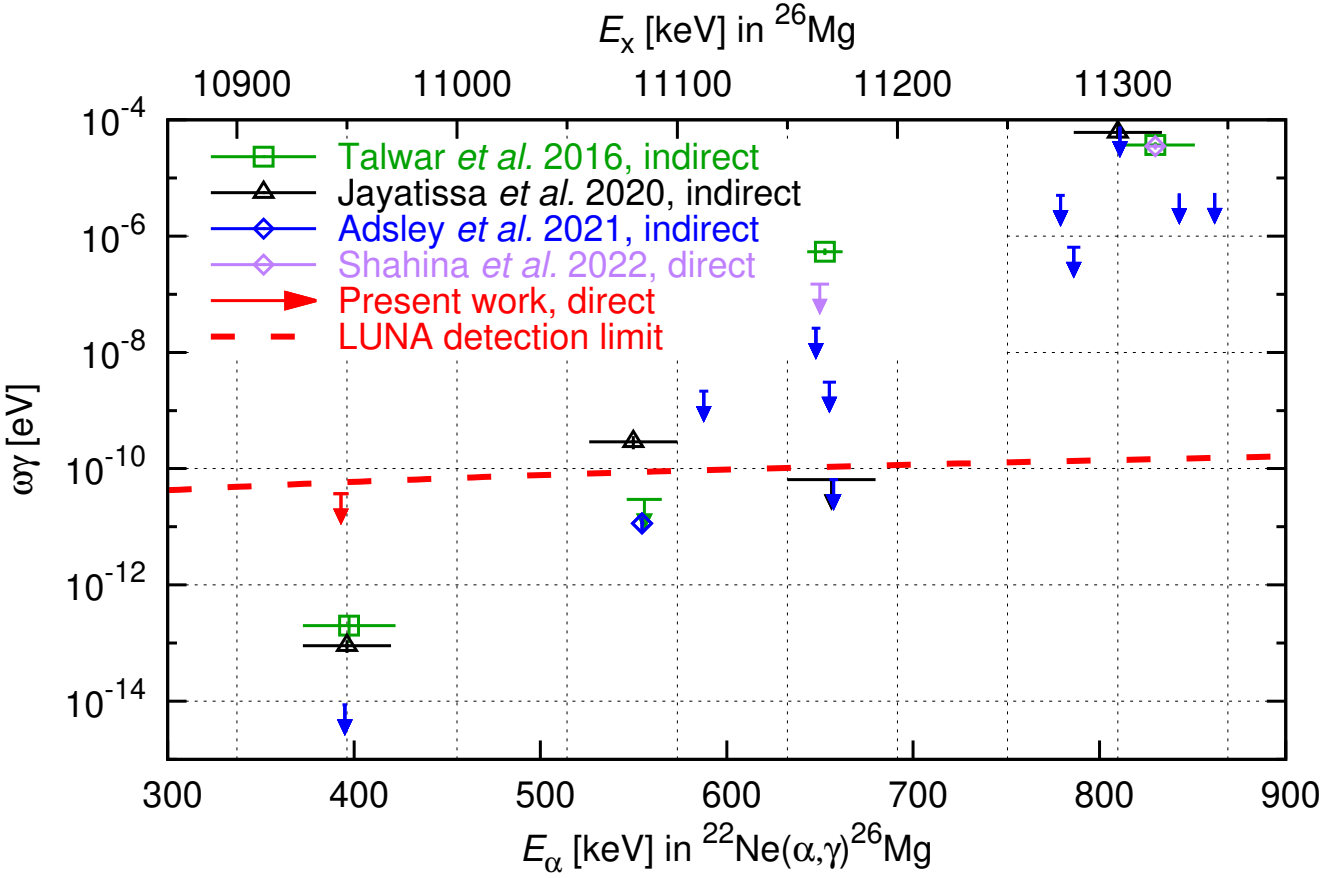
LUNA = deep underground
Gran Sasso/Italy
Ciani *et al*.
PRL 127, 152701 (2021)

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

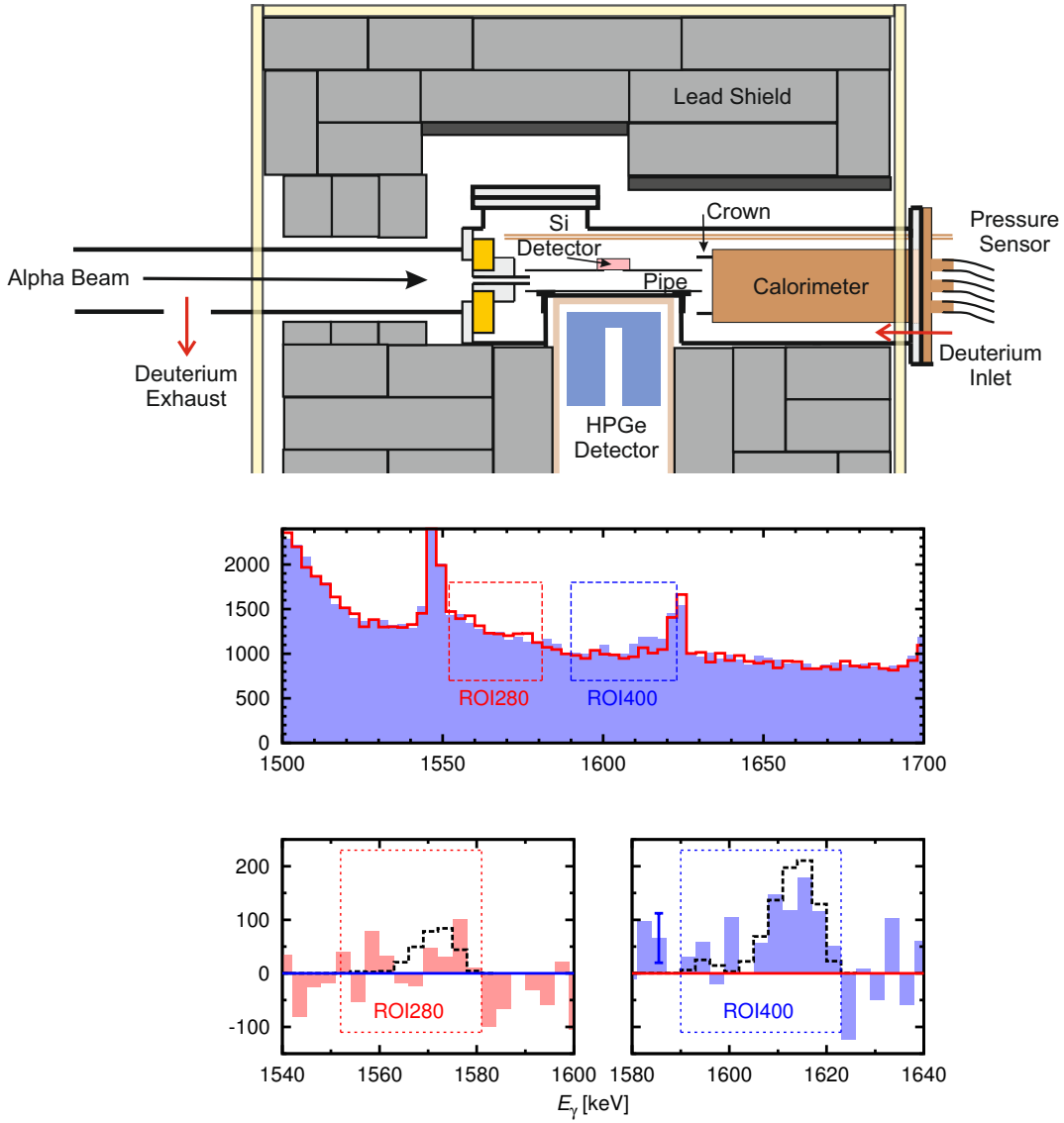
^{22}Ne(α,n)^{25}Mg neutron source for the astrophysical s-process

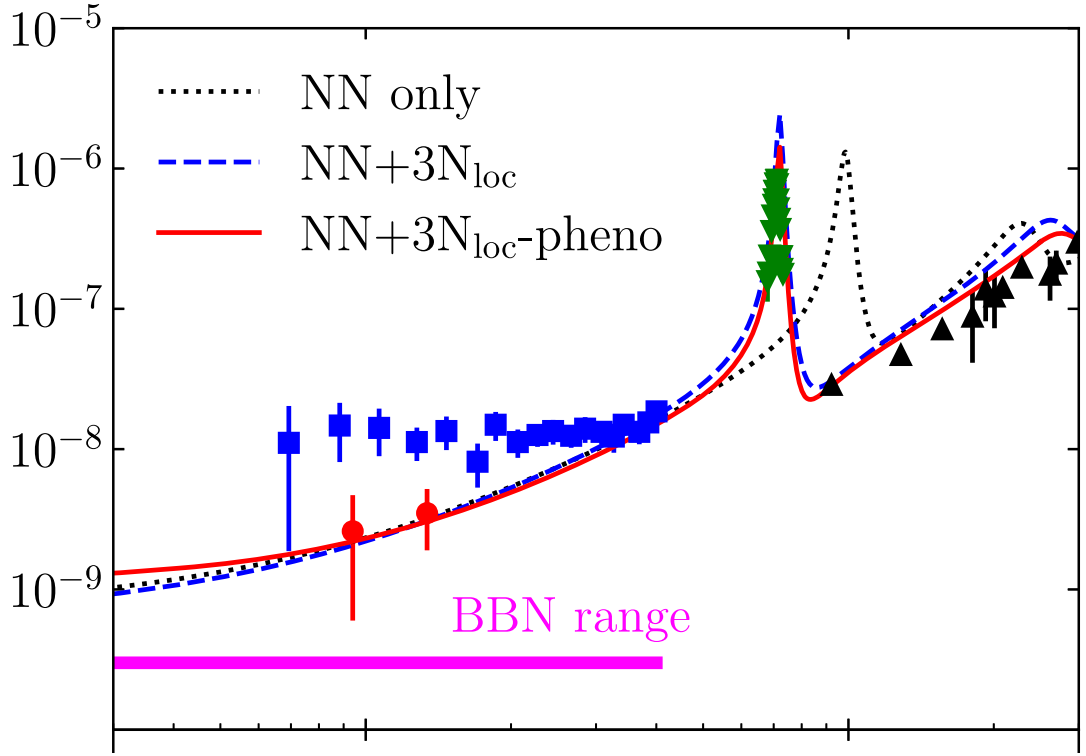
LUNA = deep underground Gran Sasso
Piatti *et al.* EPJA 58, 194 (2022)





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





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

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

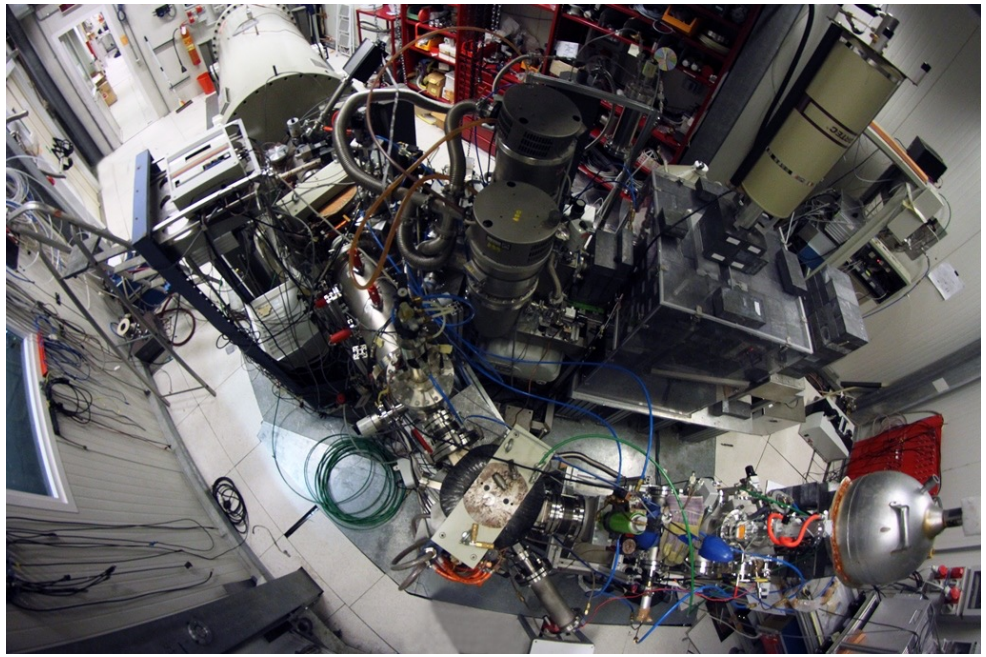
Underground ion accelerators worldwide – starting from LUNA

The workhorse, commissioned in 2001 and still going strong:

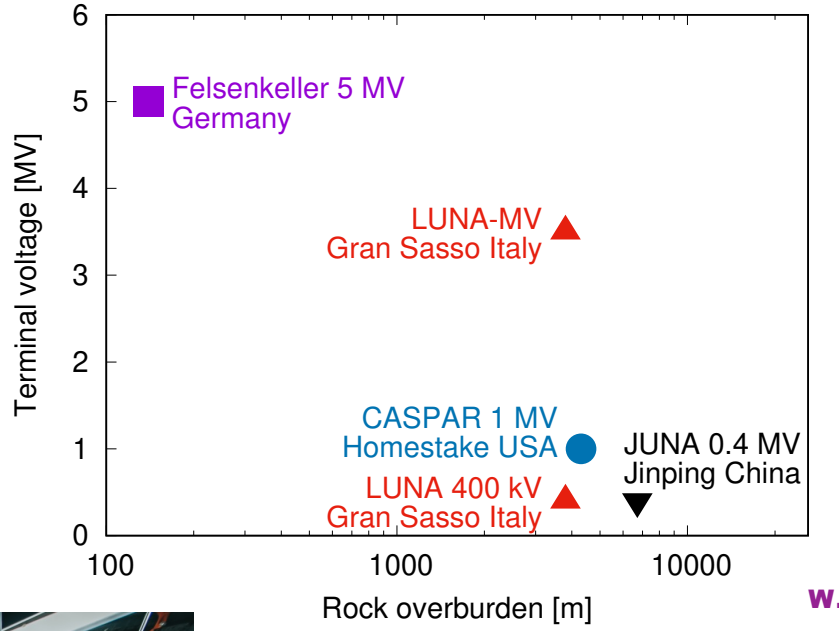
LUNA 400 kV ion accelerator for $^{1}H^{+}$ and $^{4}He^{+}$ ions

- Solar hydrogen burning
- Big Bang nucleosynthesis

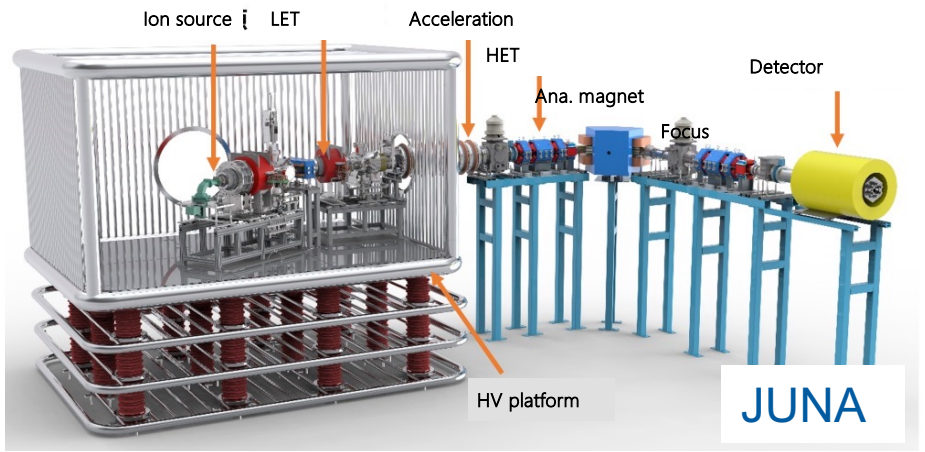
Gran Sasso lab, Italy – 1400 m rock equivalent to 3800 m water



Underground ion accelerators – new players on three continents



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



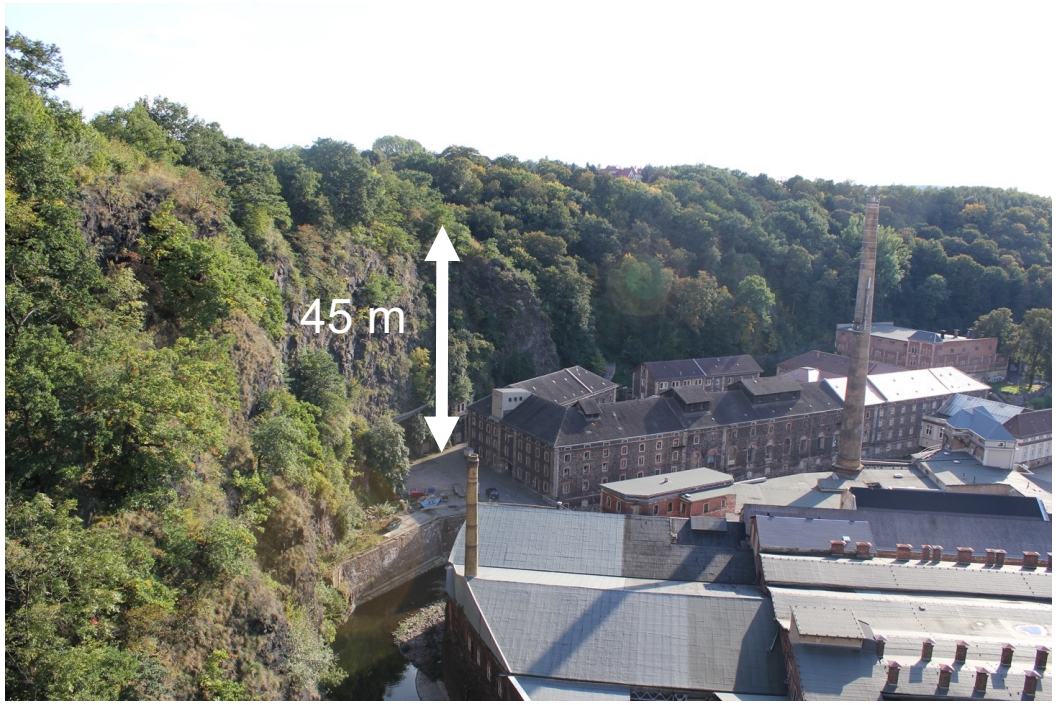
Dresden Felsenkeller underground lab, below 45 m of rock

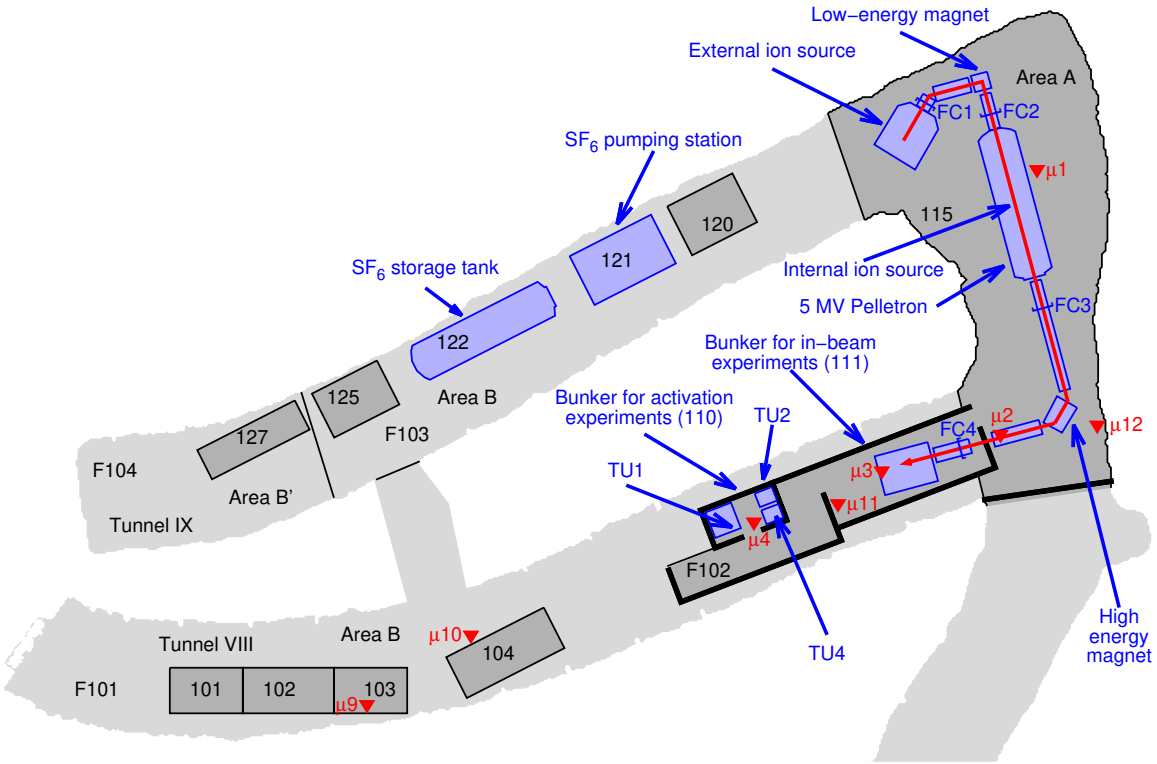
Joint effort HZDR – TU Dresden

- 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



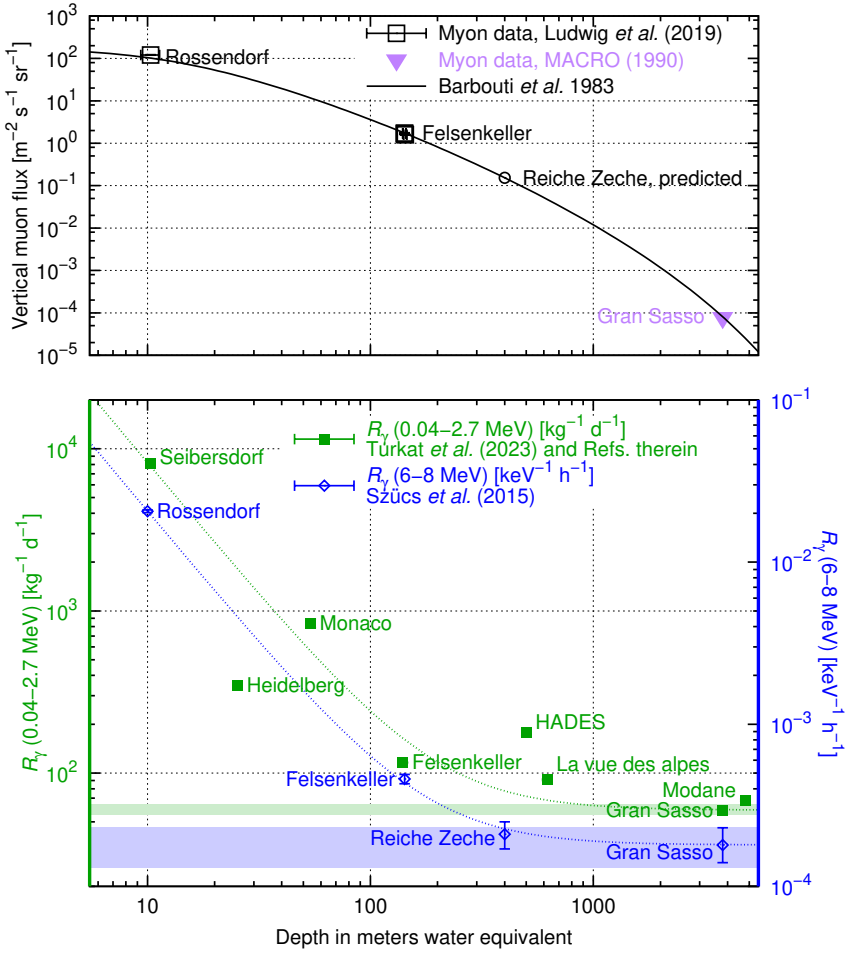


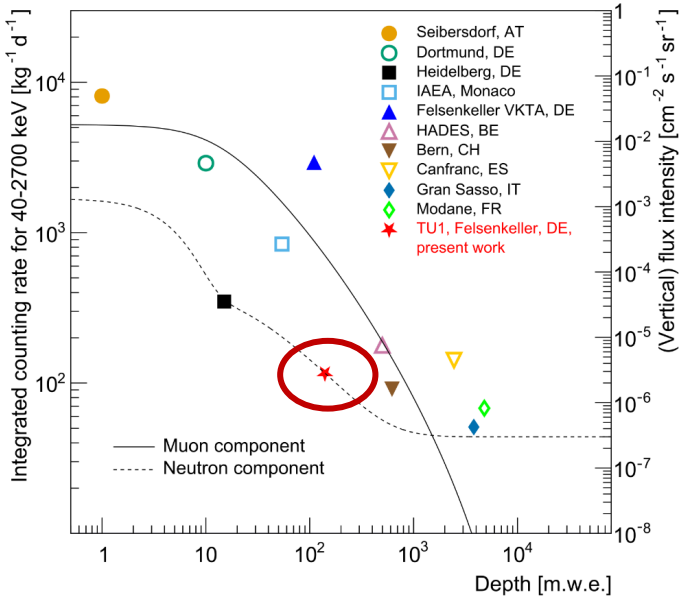
Eur. Phys. J. A 61, 19 (2025)

Felsenkeller: Studying low cross sections with low background

40× lower muon background

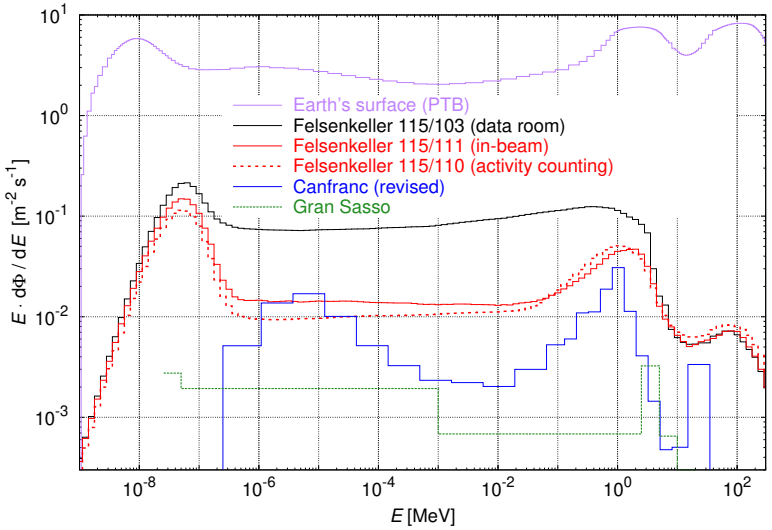
Astropart. Phys. 112, 24 (2019)





200× lower neutron background

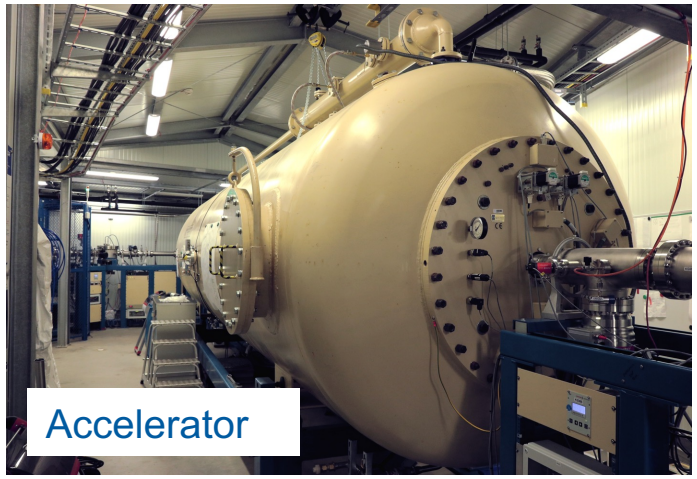
Phys. Rev. D 101, 123027 (2020)

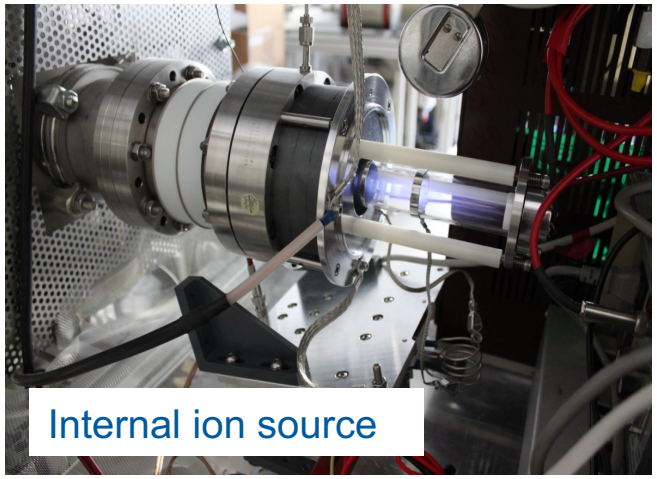


100× lower γ-background

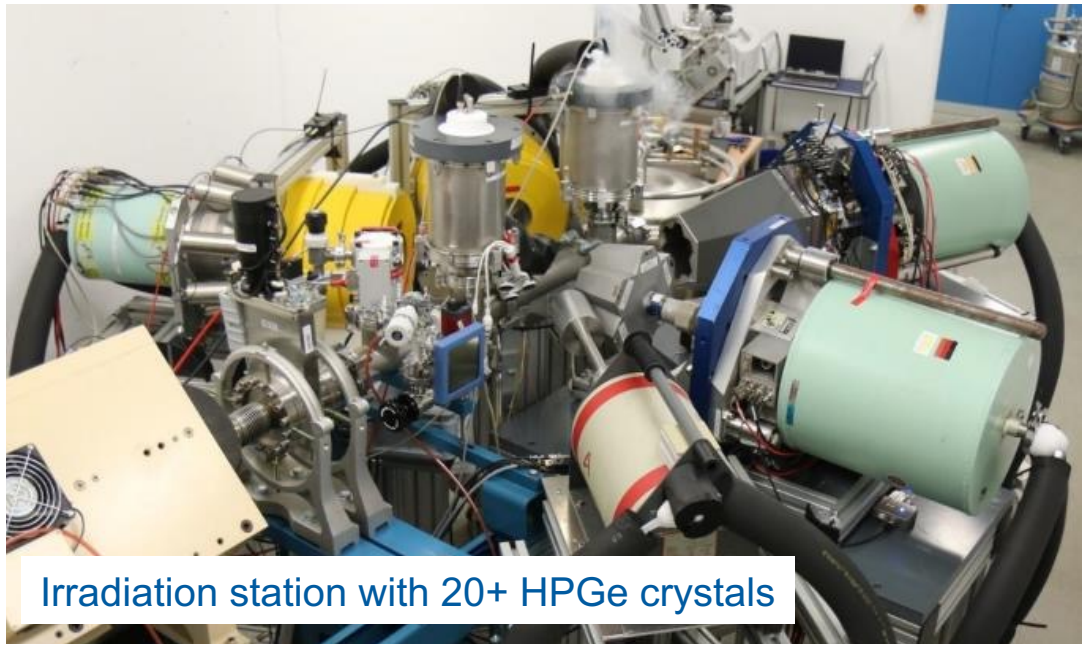
Eur. Phys. J. A 51, 33 (2015)
Astropart. Phys. 148, 102816 (2023)
Eur. Phys. J. A 61, 19 (2025)

Felsenkeller 5 MV underground ion accelerator


Accelerator


Internal ion source


External ion source

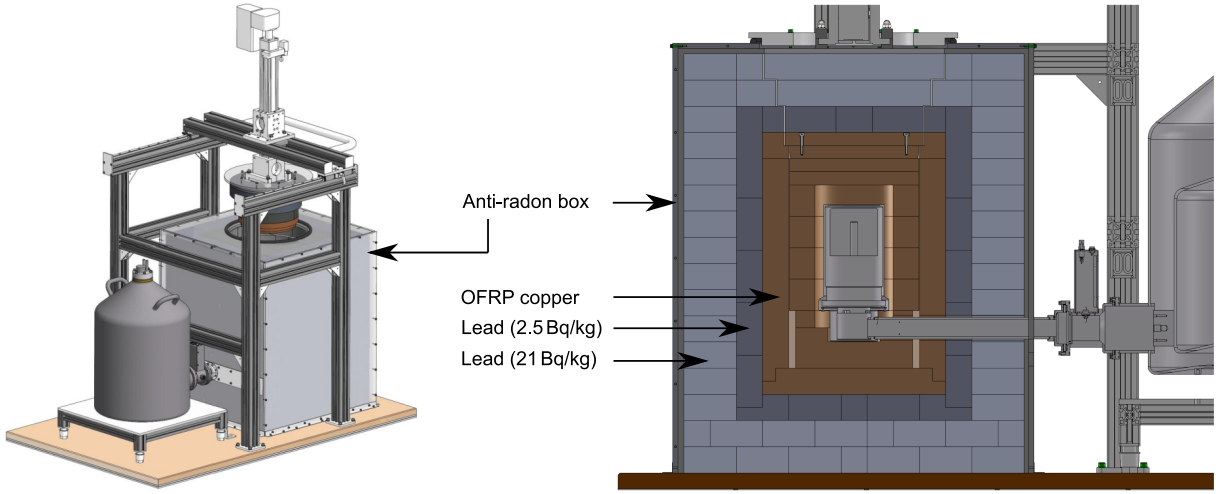

Irradiation station with 20+ HPGe crystals

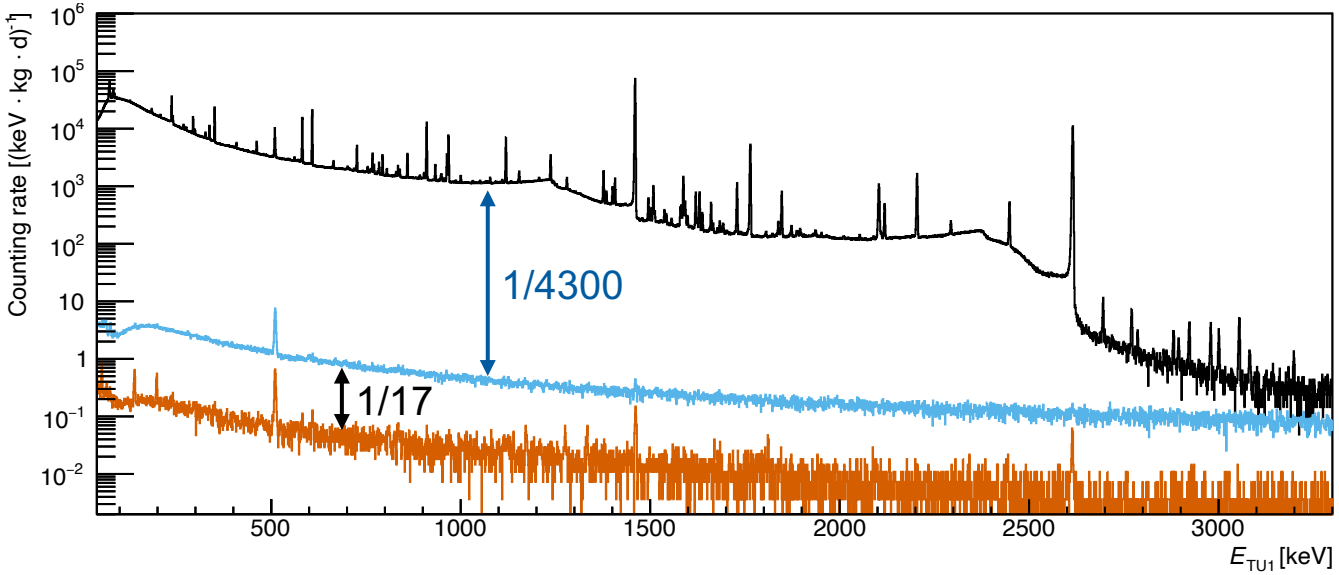
5 MV accelerator (0.4-3.8 MV), two alternative ion sources

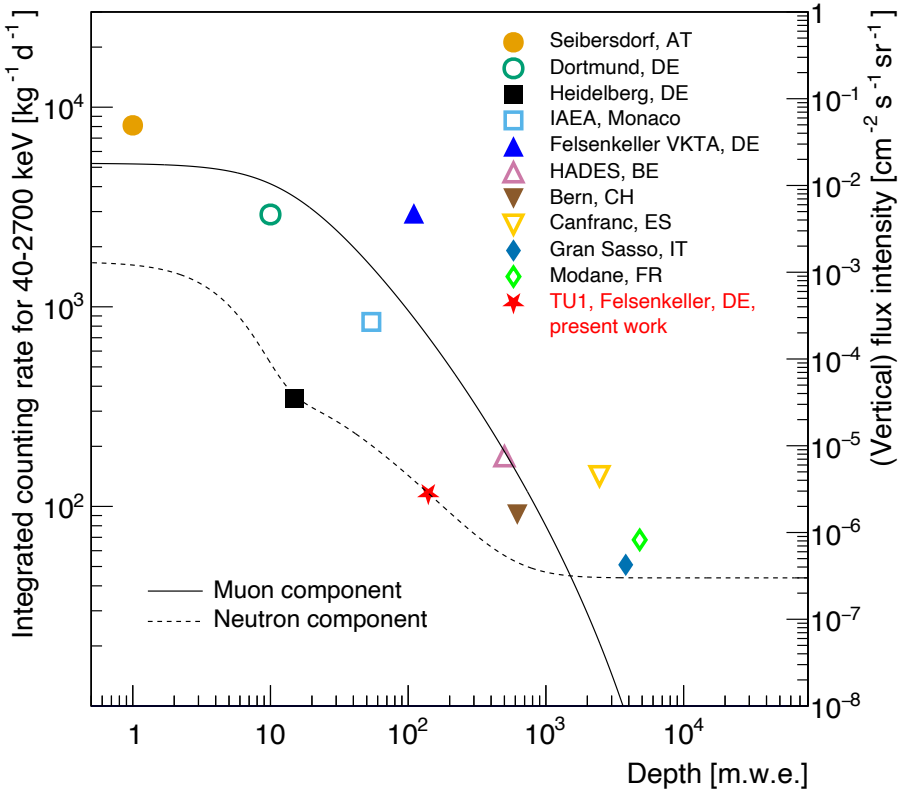
- Internal RF ion source: 30 μA ^{1}H, ^{4}He
- SNICS sputter ion source: 30 μA ^{12}C

- 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

Germany‘s most sensitive radioactivity measurement setup “TU1”

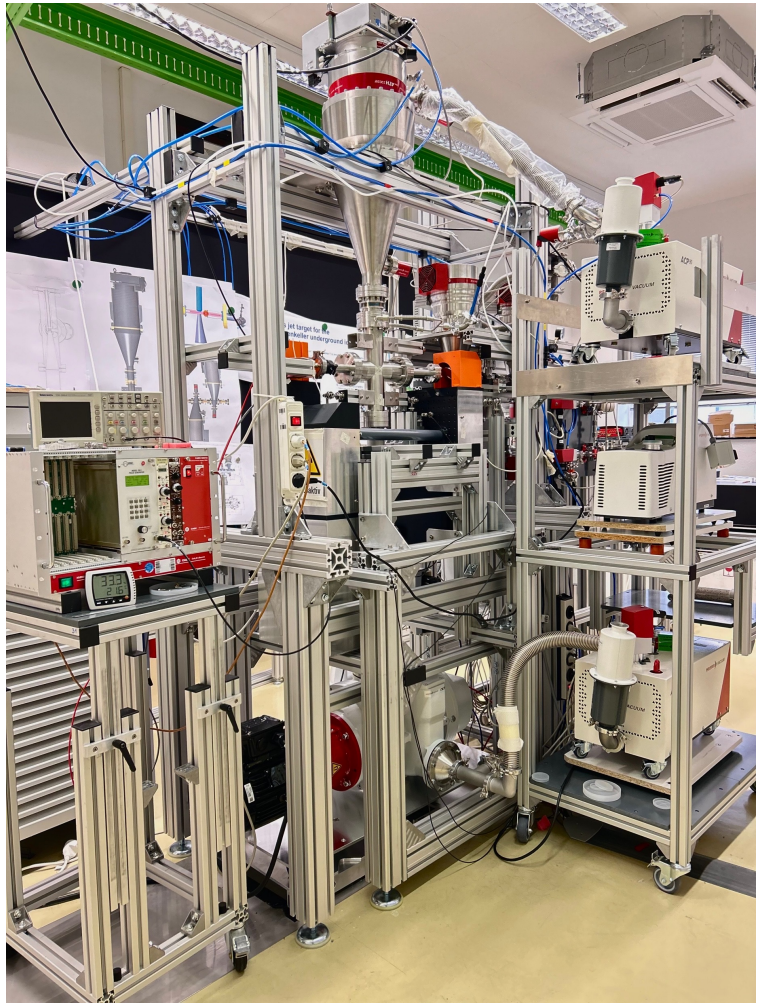


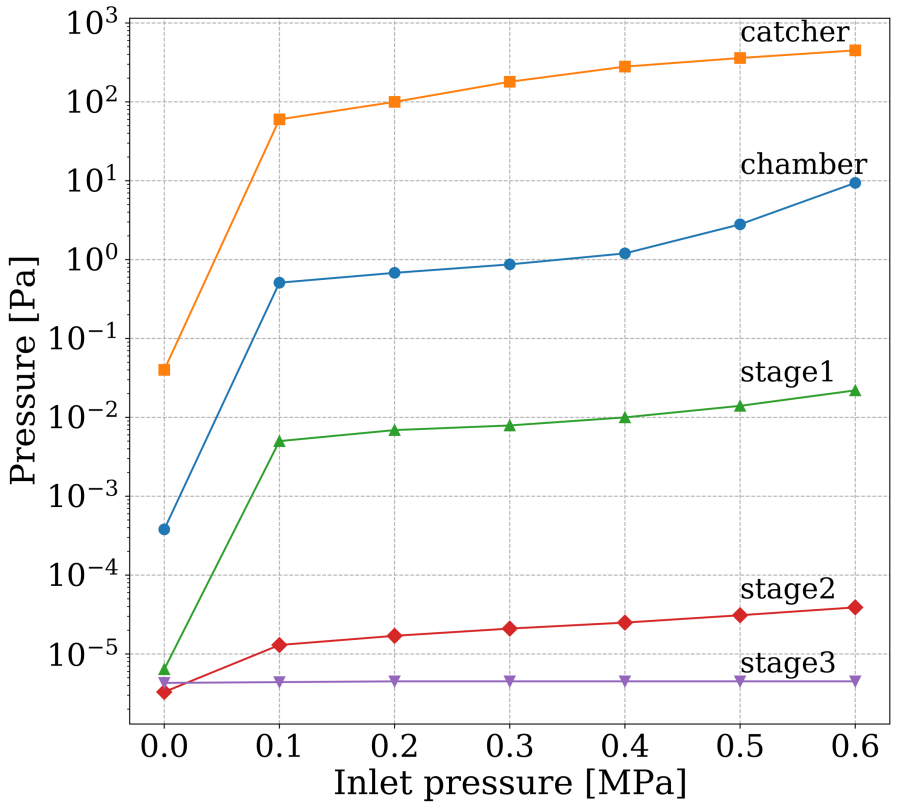


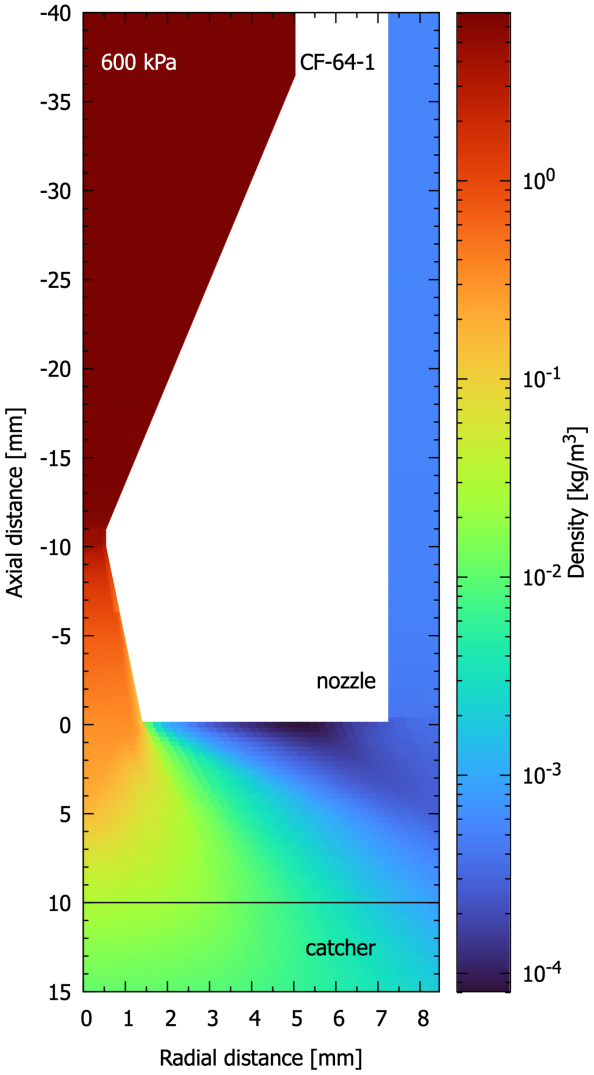


Steffen Turkat, Kai Zuber *et al.*,
Astropart. Phys. 148 (2023) 102816

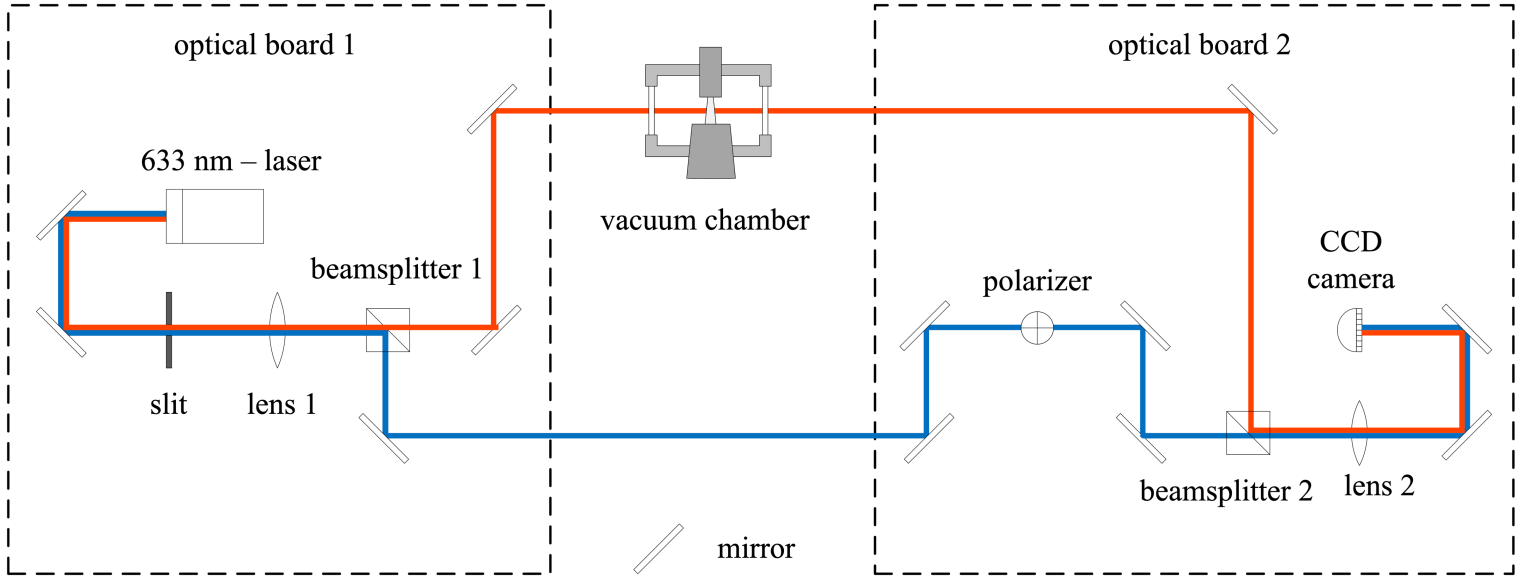
Jet gas target system at Felsenkeller

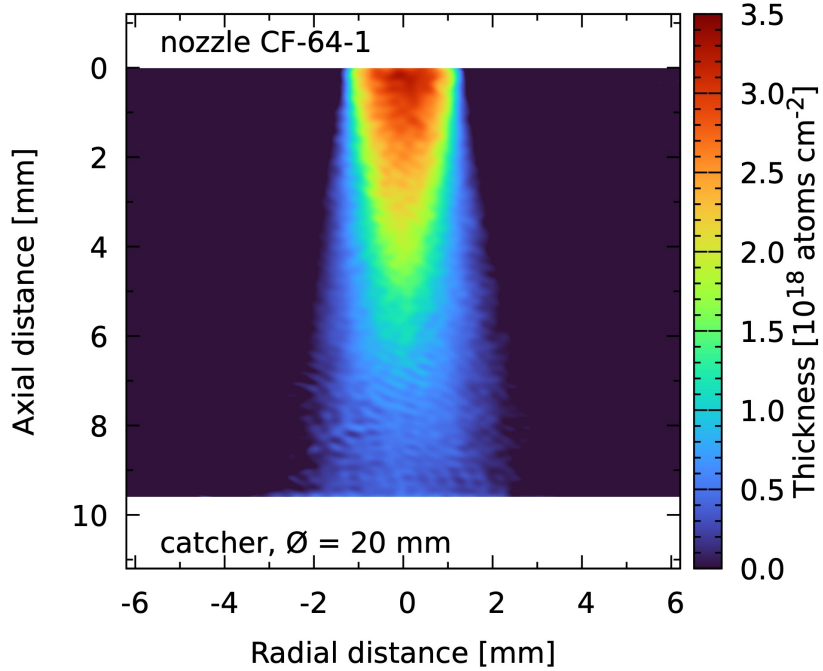


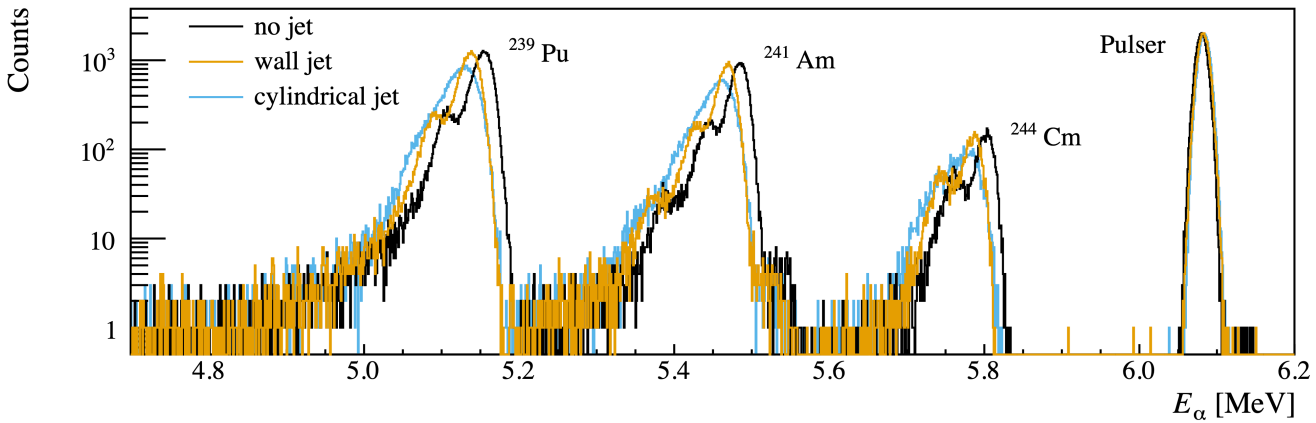




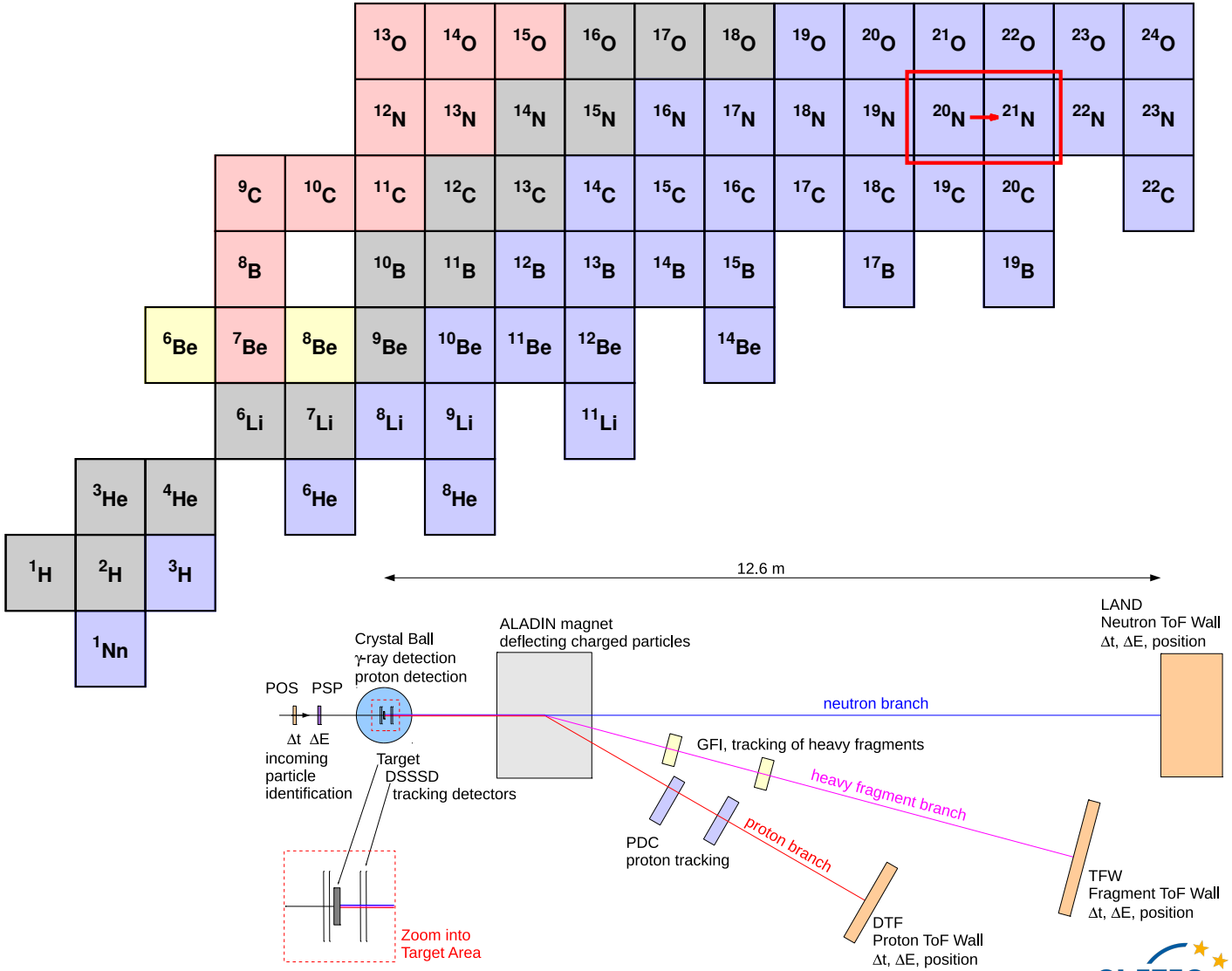
Jet gas target system at Felsenkeller

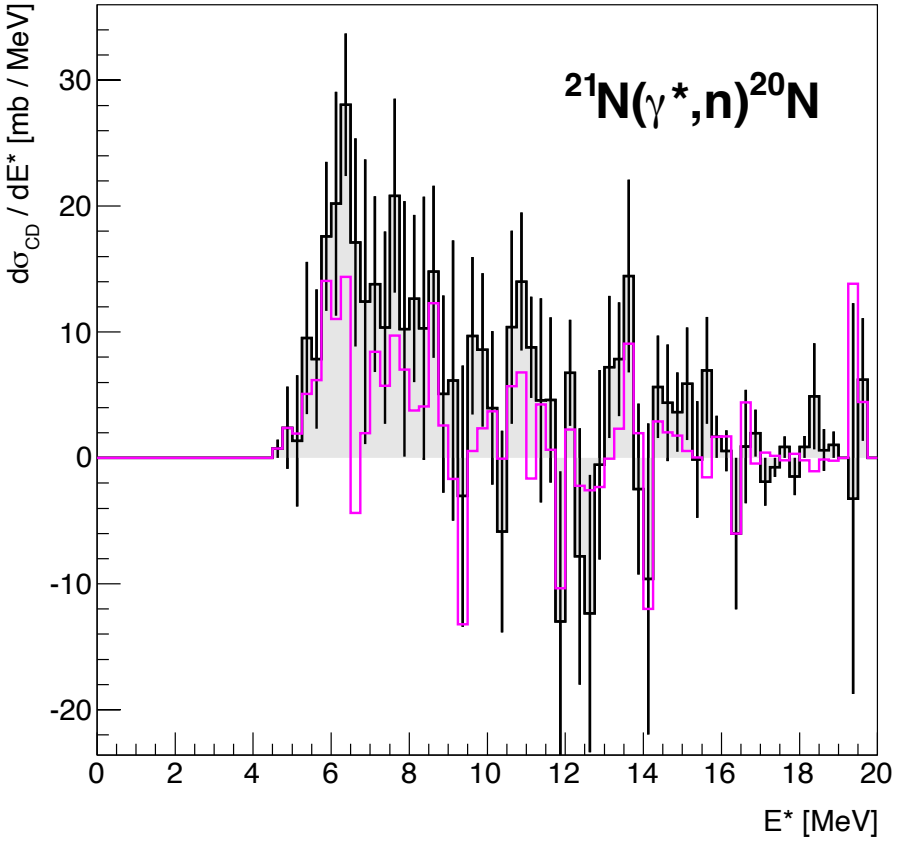






Time-inverted experiments for the r-process at the R³B experiment, GSI

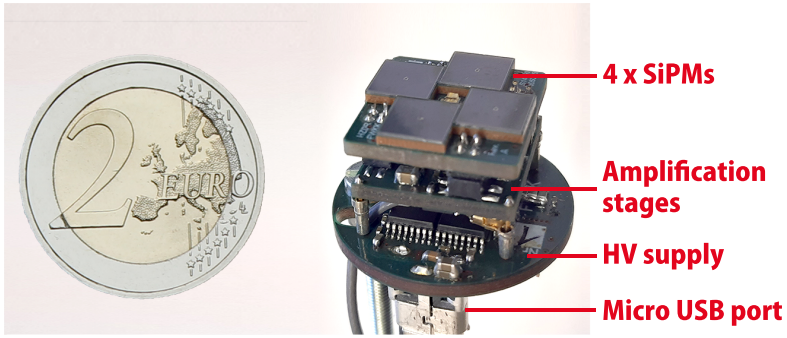


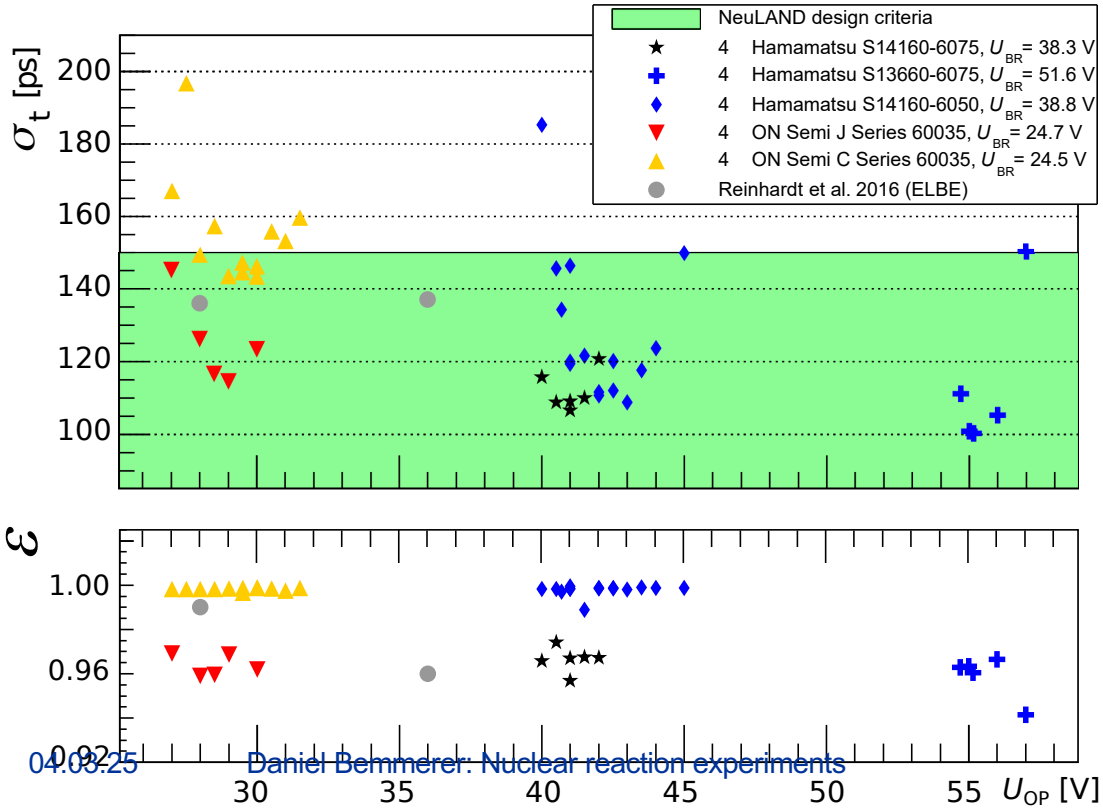


R³B = Reactions with Relativistic Radioactive Beams @ GSI and FAIR

Röder, DB *et al.* PRC 93, 065807 (2016)

Collaboration with R³B @ FAIR

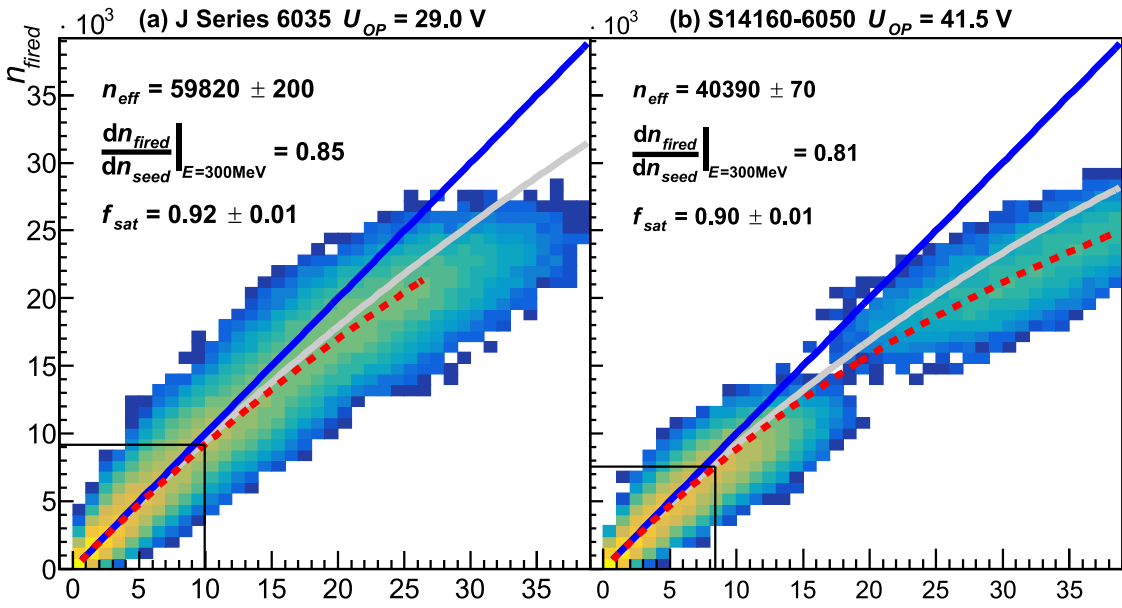




Study of a possible re-instrumentation of NeuLAND with SiPMs, experiments at HZDR ELBE electron beam

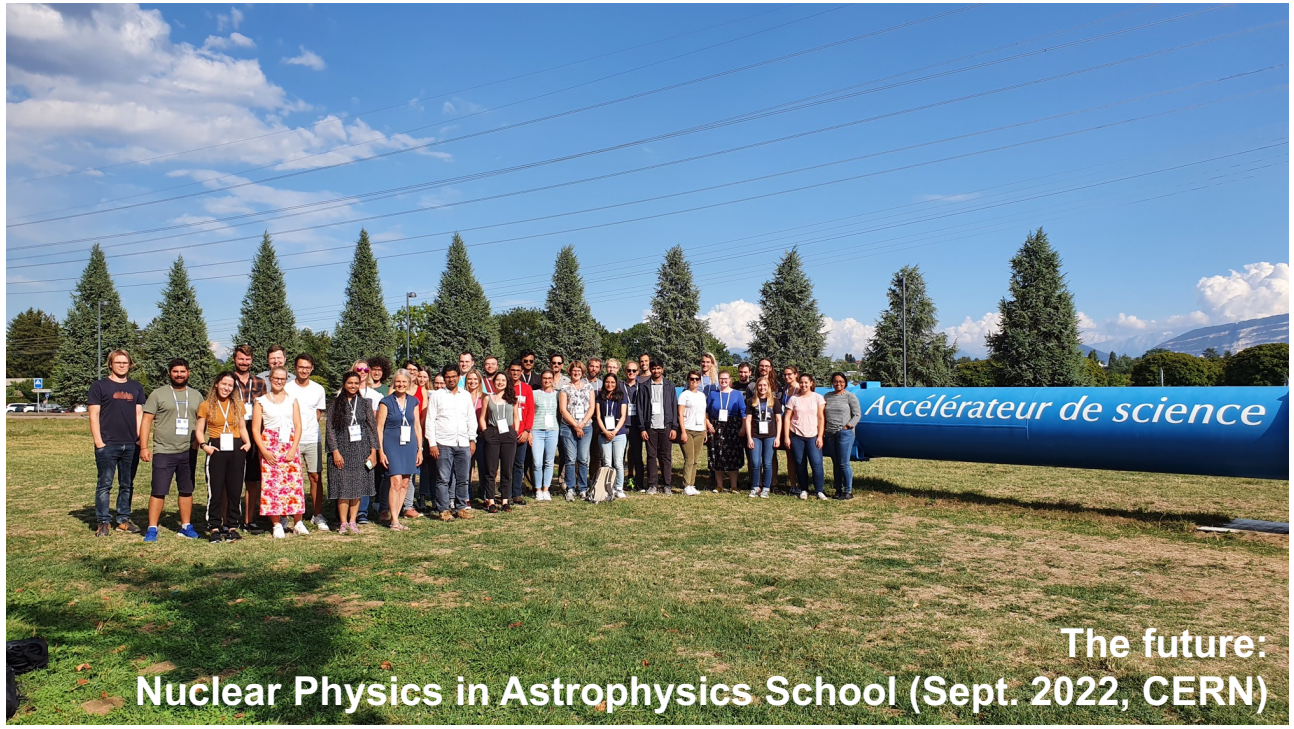
- Linearity (<10% deviation)
- Dark count rate (< cosmic rate)
- Time resolution (< 100 ps)

T. Hensel *et al.* Nucl. Inst. Meth. A 1048 (2023) 167972



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)

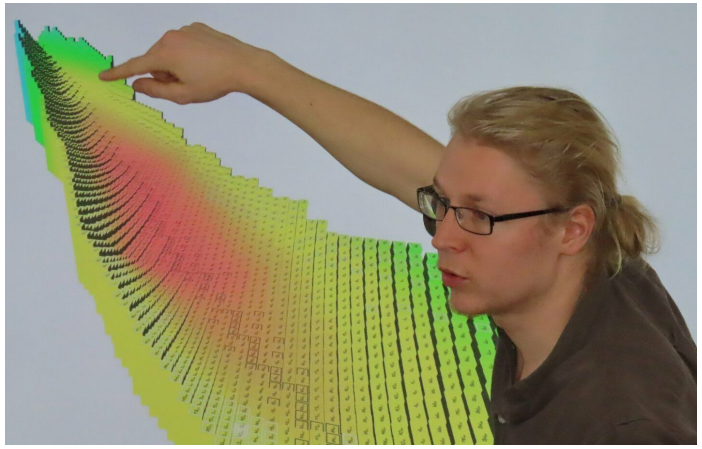
https://www.chetec-infra.eu

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

Nuclear astrophysics masterclasses http://mc.chetec-infra.eu

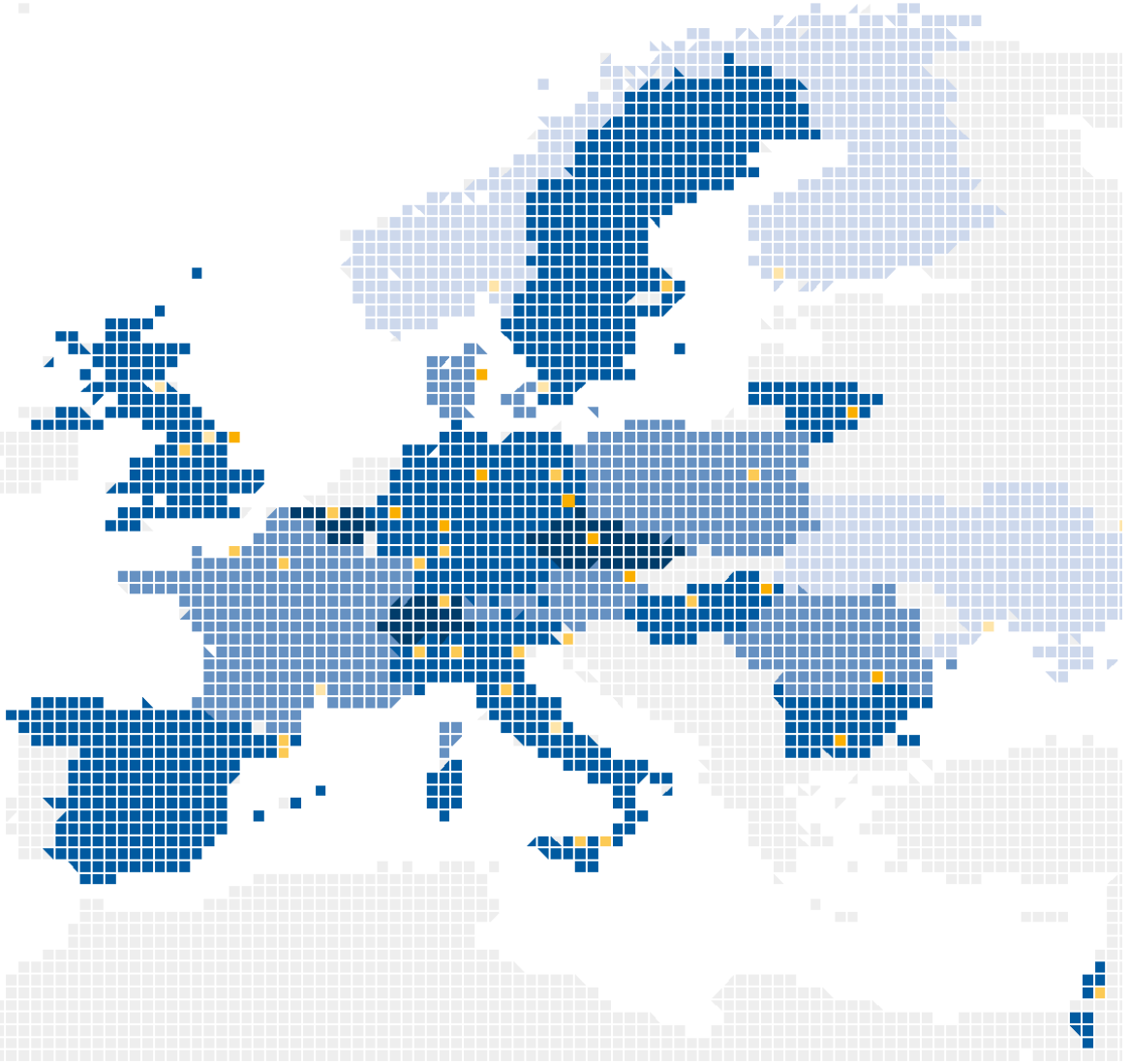
- 1 full day outreach to secondary school students
- Ready-made solution, available in 7 languages, more to come
- Based on model from ATLAS@CERN outreach

- English (master copy)
- German
- French
- Italian
- Czech
- Bulgarian
- Upper Sorbian



- Looking for nuclear astrophysics PhD students to teach 1-day masterclasses in their native language!
- Looking for translators to add new languages!
- Topic 1 $^{14}N(\alpha,\gamma)^{18}F$ – experimental nuclear physics
- Topic 2 Fingerprints of the stars – Li astronomy

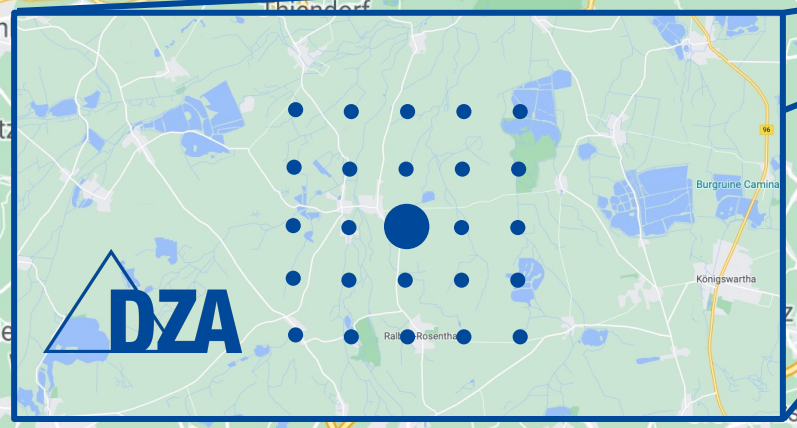
31 partners in ChETEC-INFRA

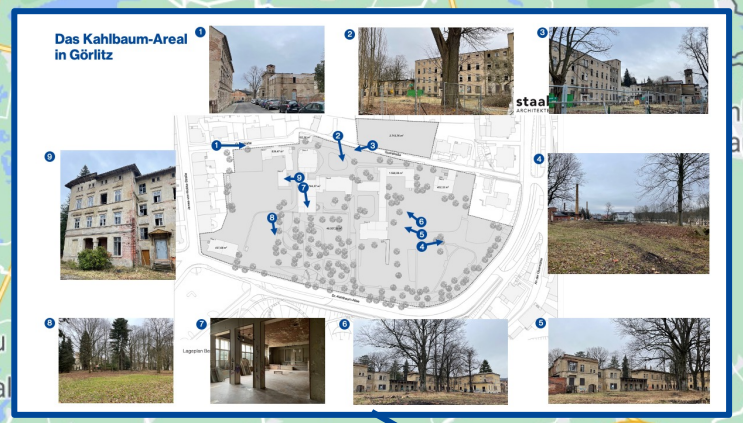


Courtesy Christian Stegmann / DESY

Eine Region für Astrophysik, Technologie und Digitalisierung

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





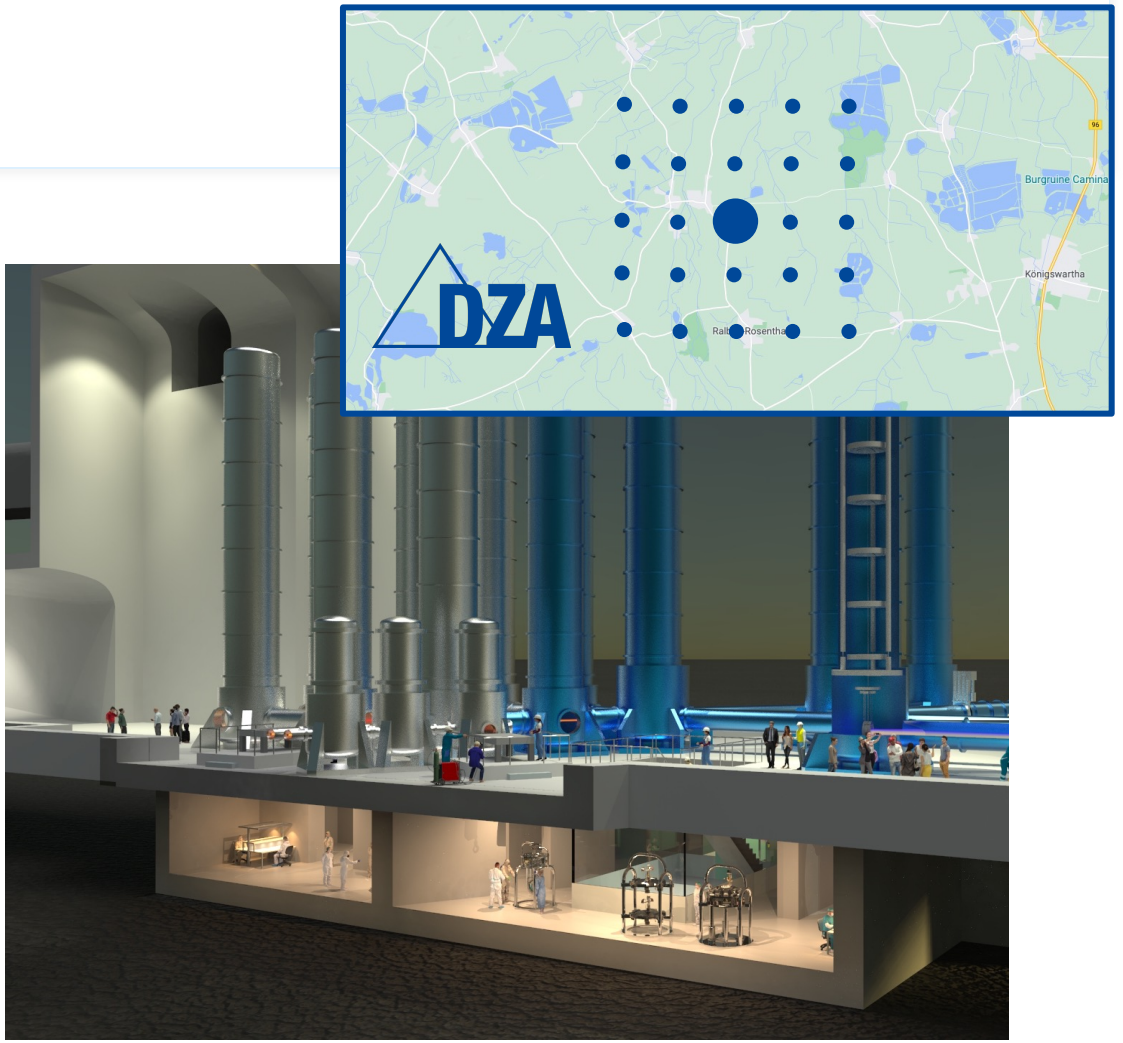
Ein Zentrum für Astrophysik mit fortschrittlicher Computertechnik und Technologieentwicklung

DZA

TECHNISCHE UNIVERSITÄT DRESDEN

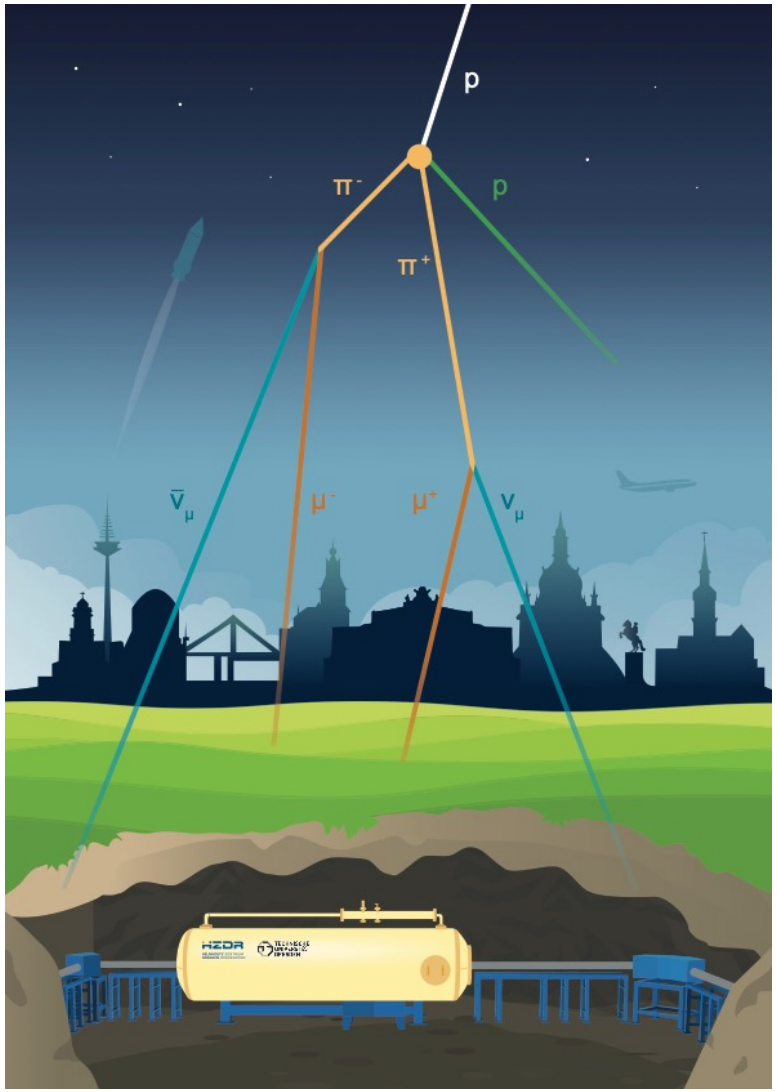
Das Low-Seismic-Lab

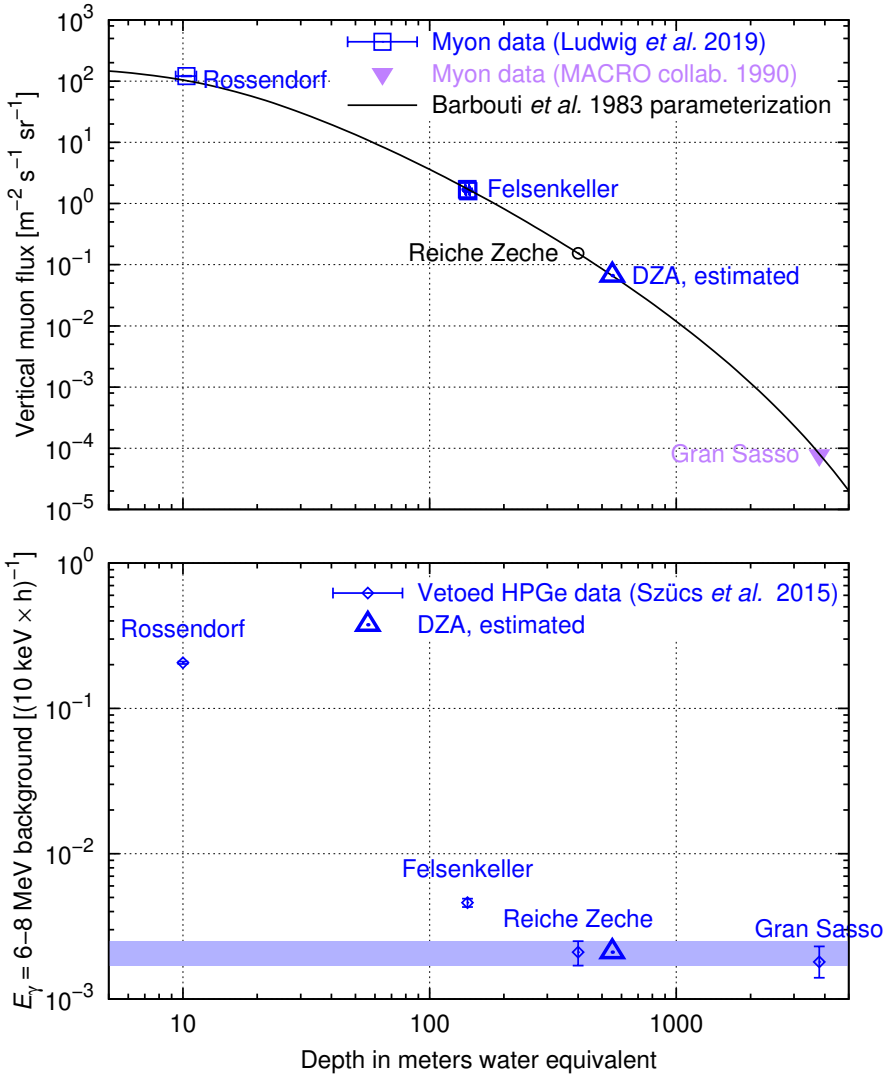
- Technologieentwicklung für die Gravitationswellenastronomie
- Adaptive seismische Rauschunterdrückung
- Sub-Nanometer-Mikroskopie und Photolithographie
- Astrophysik mit Beschleunigern

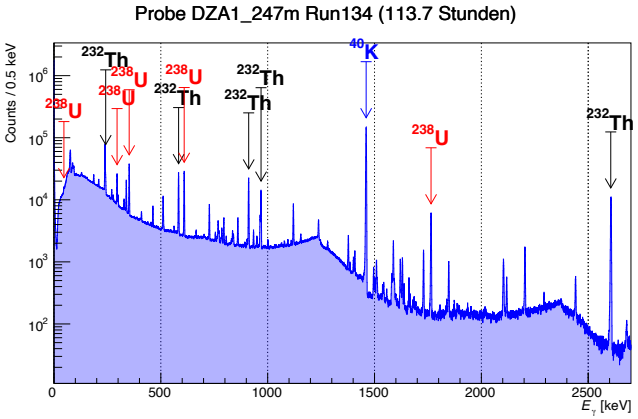


Courtesy Christian Stegmann / DESY

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