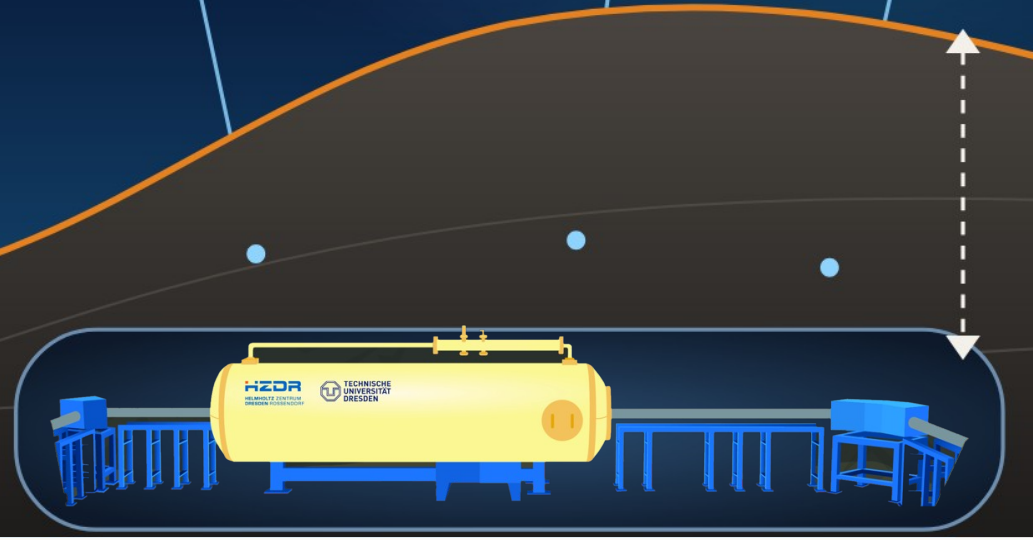
The origin of the chemical elements

From stars to underground labs and back

Eliana Masha
Helmholtz-Zentrum Dresden-Rossendorf

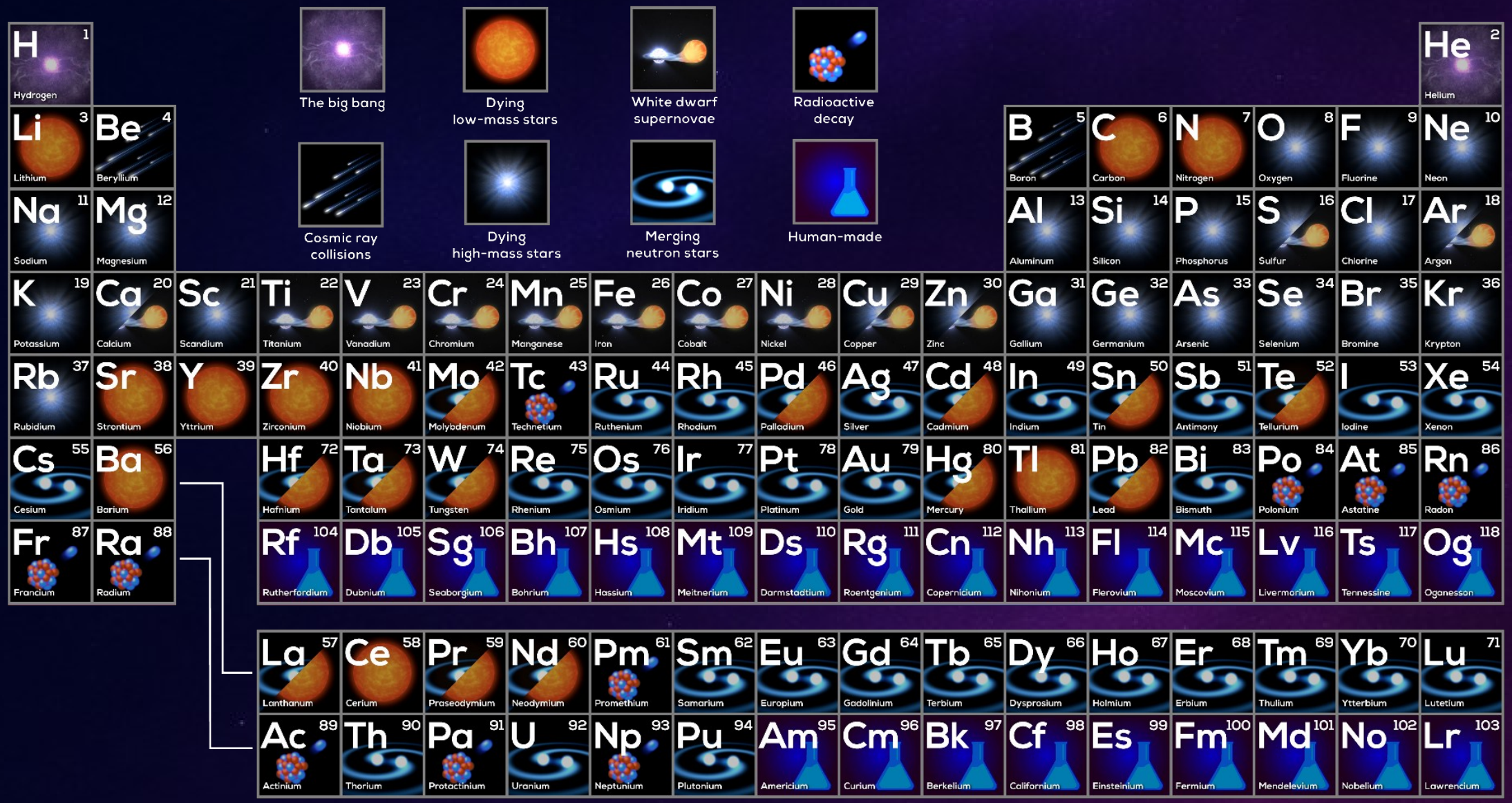
PSI THURSDAY COLLOQUIUM
November 5, 2026



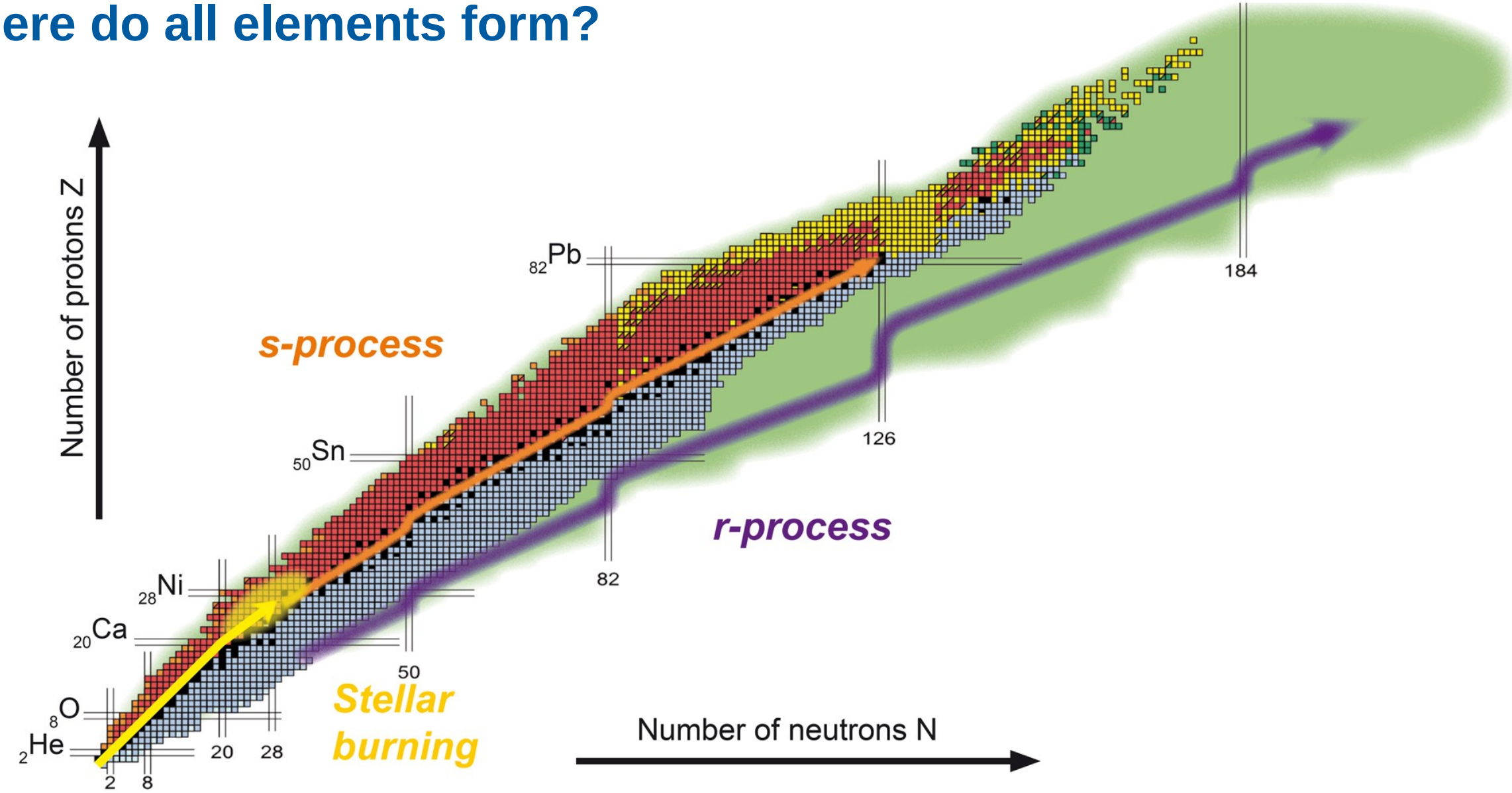
Institute of Radiation Physics · Nuclear Physics Division · Eliana Masha· e.masha@hzdr.de · www.hzdr.de

Alexander von HUMBOLDT STIFTUNG
CHETEC INFRA
LUNA NOVA
erc European Research Council Established by the European Commission
HEARTS
Technische Universität Dresden
HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Where do all elements form?

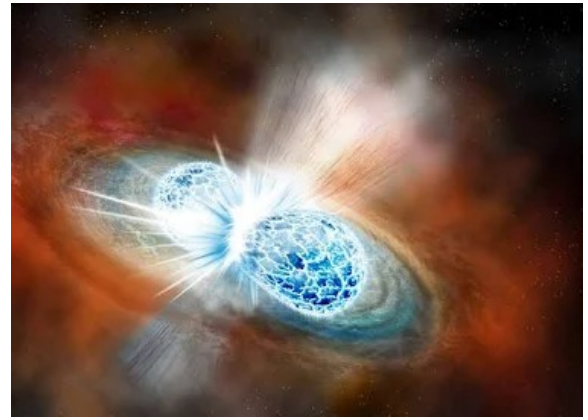


Where do all elements form?



Where do all elements form?





Number of protons Z

Number of neutrons N

Big Bang Nucleosynthesis
^{2}H, ^{4}He, Li

Cosmic Rays
Li, Be, B ,..

s-process
AGB stars

r-process

Stellar burning

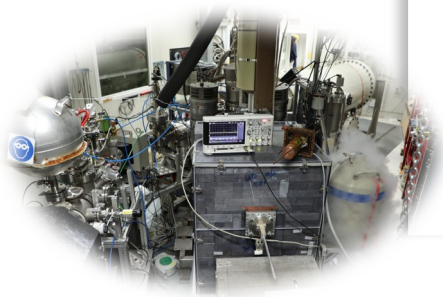
$_{2}$He $_{8}$O $_{20}$Ca $_{28}$Ni $_{50}$Sn $_{82}$Pb

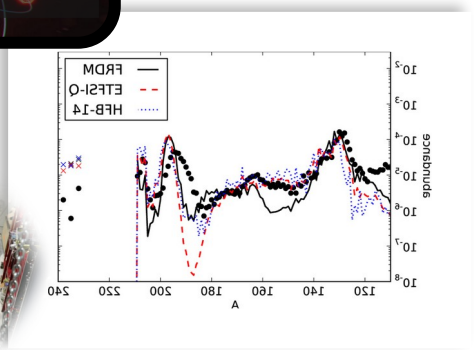
2 8 20 28 50 82 126 184

Nuclear Astrophysics

Observational astronomy

Nuclear physics







Cosmology

Neutrino physics

Stellar models

Charged-particle nuclear reactions at stellar energies

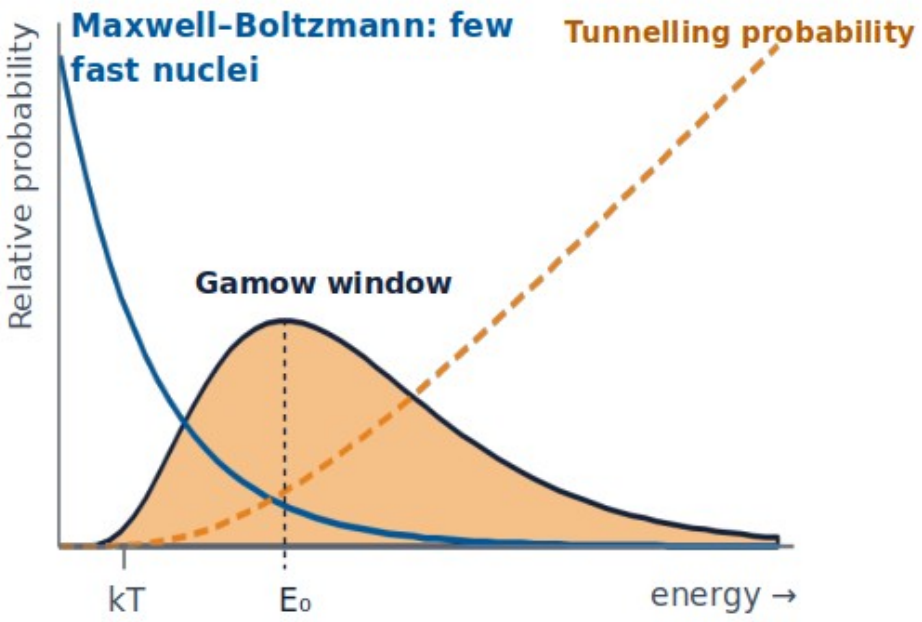
$$r = \frac{N_r}{Vt} = \rho_a \rho_A \int_0^\infty \sigma(v)\, v\, \phi(v)\, d(v) = \rho_a \rho_A \langle \sigma v \rangle$$

Density of interacting nuclei

Relative velocity

Maxwell – Boltzmann distribution

Cross section



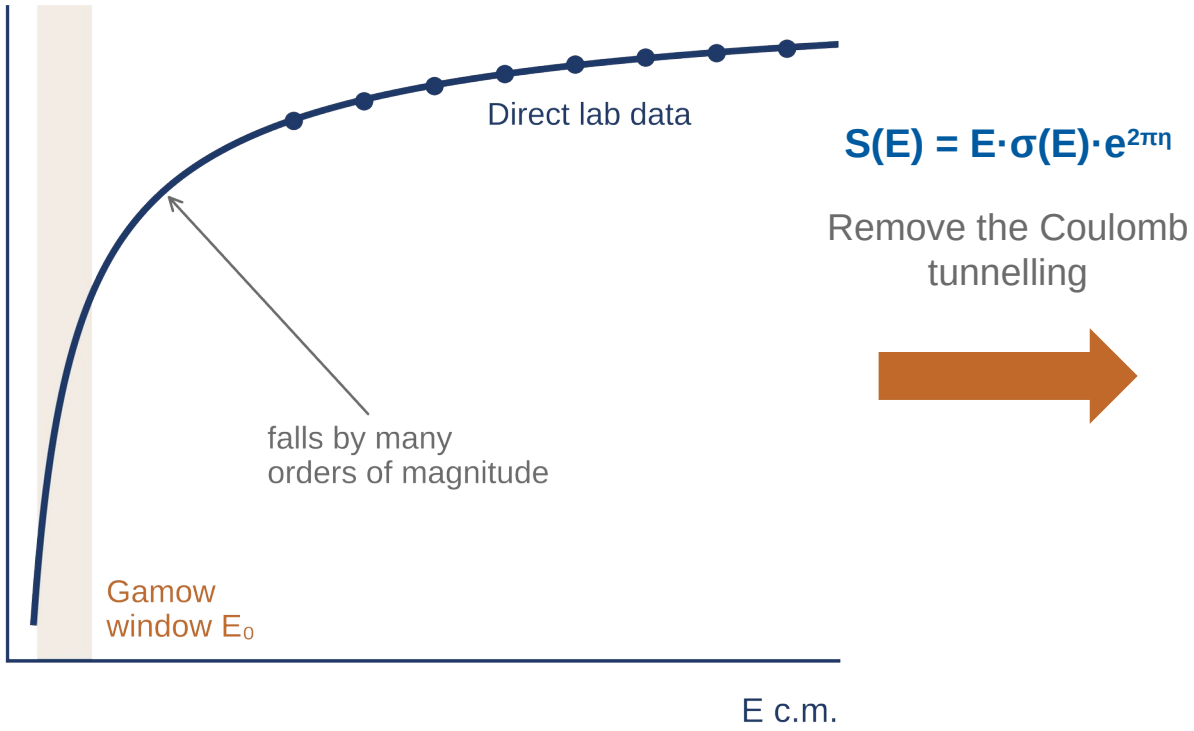
Energy dependent cross-section

$$\sigma(E) = \frac{1}{E} \exp\left(-31.29\, Z_1 Z_2 \sqrt{\frac{\mu}{E}} \right) S(E)$$

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

From cross section to astrophysical S factor

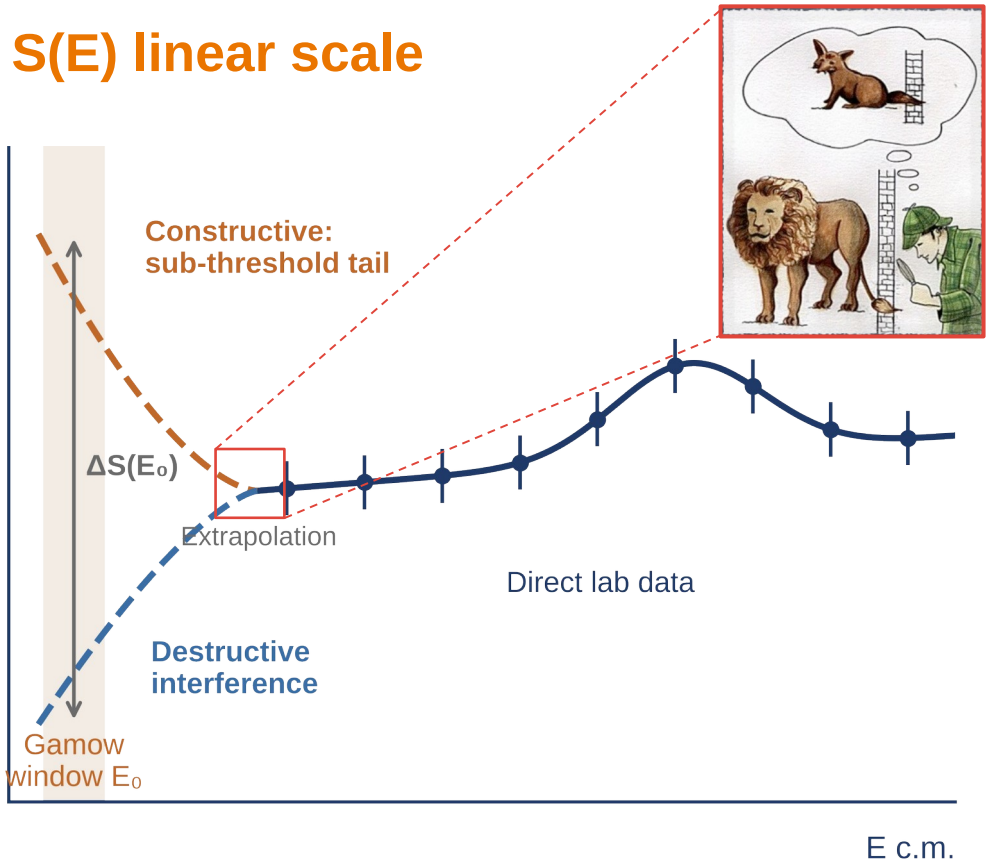
σ(E) linear scale



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

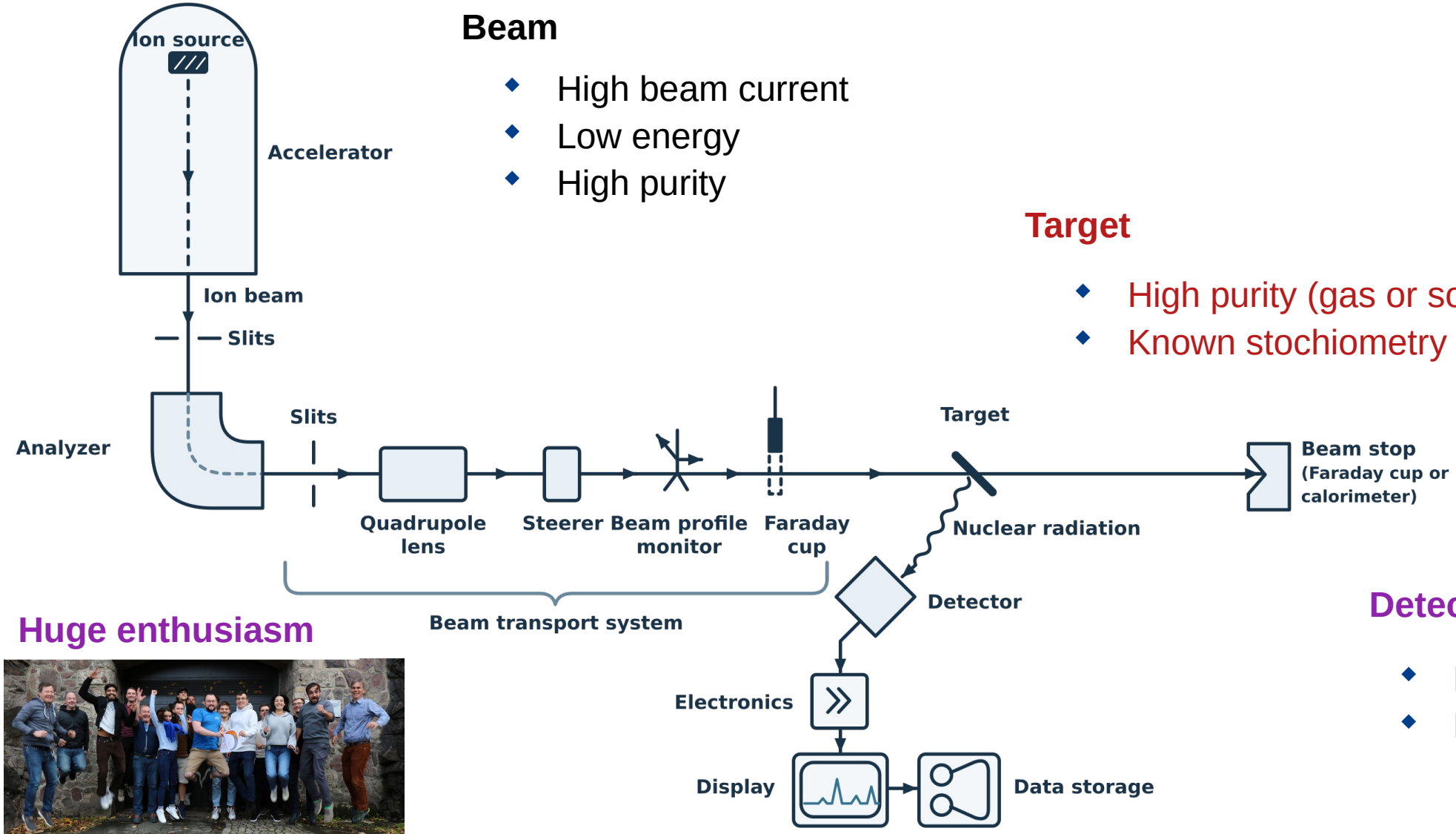
Remove the Coulomb tunnelling

S(E) linear scale



Danger of extrapolation → Measure as close to E_{Gamow} as possible

Challenges of direct measurements



Beam

- High beam current
- Low energy
- High purity

Target

- High purity (gas or solid)
- Known stochiometry and thickness

Detector

- High resolution
- High efficiency

Huge enthusiasm

Challenges of direct measurements

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^{-13} barn (often even smaller)

100% for charged particles

~1-10% for gamma rays (HPGe detectors)

Counting Rate = 0.1- 10 counts/day

Signal to noise ratio extremely low

Challenges of direct measurements

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

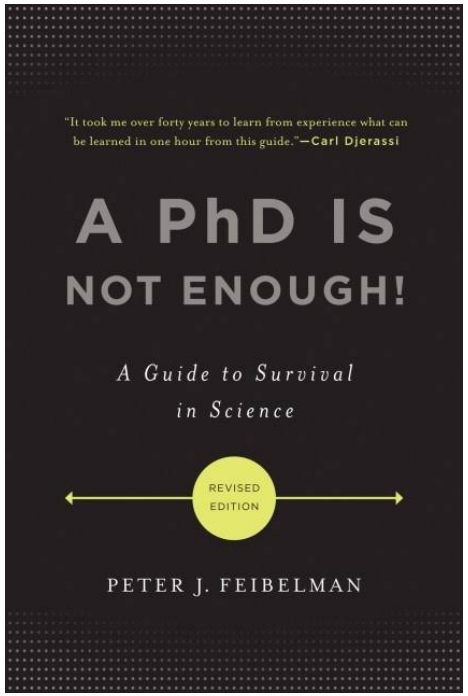
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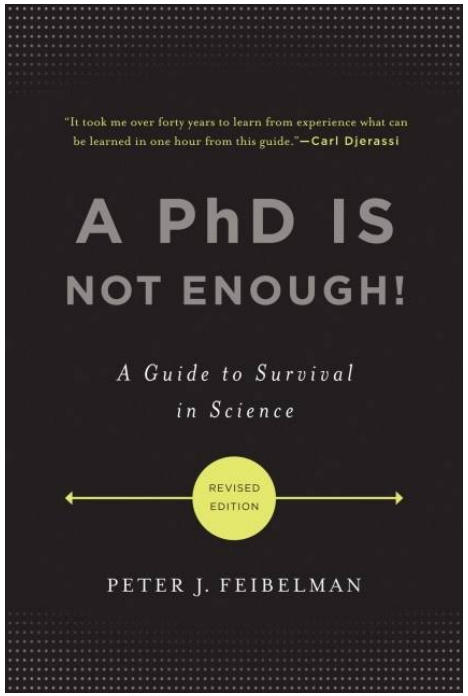
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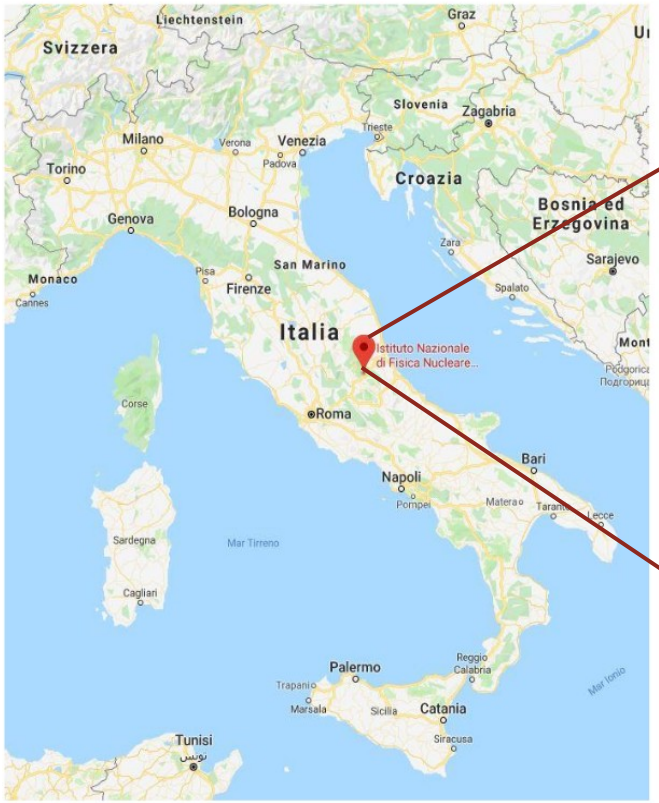


How to improve the signal to noise ratio?

- Improving "signal" (high beam currents, high target density, high efficiency)
- Reducing "noise" (background)
- Combination of both

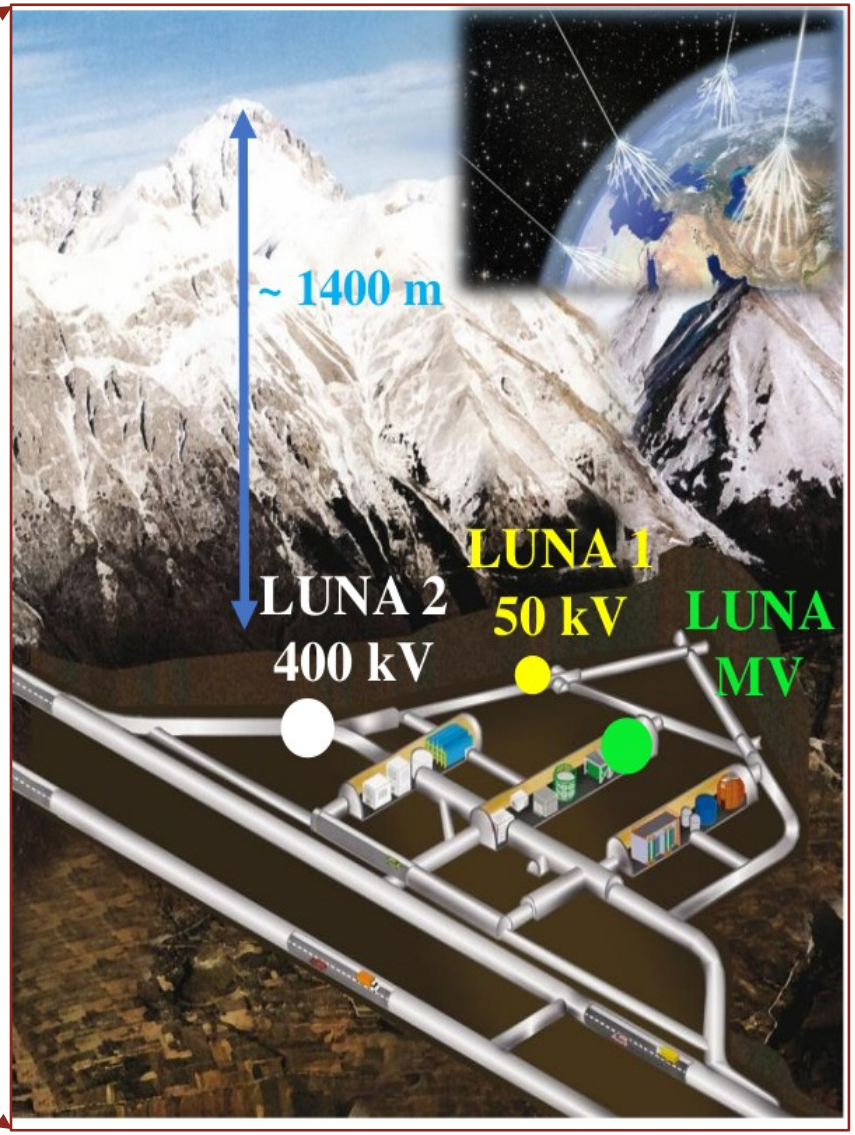
Underground nuclear astrophysics

First underground laboratory for nuclear astrophysics

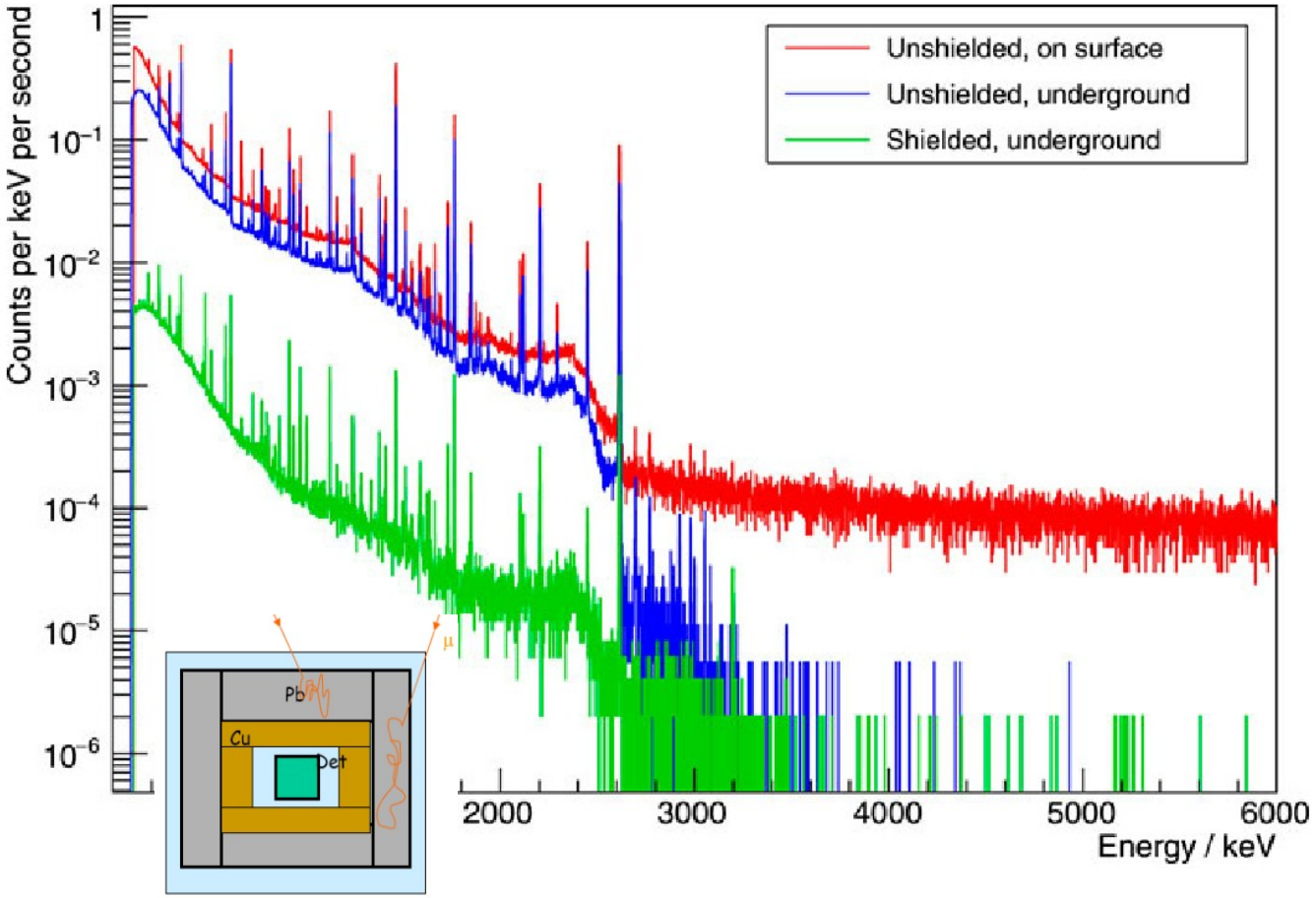


LUNA@LNGS

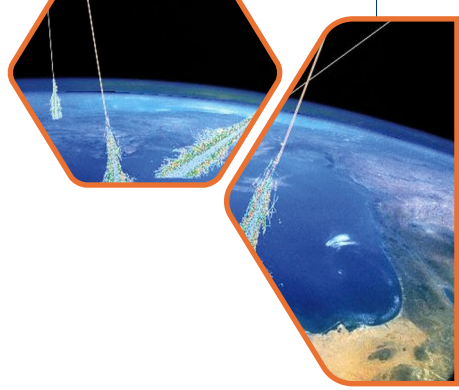
(**Gran Sasso mountain** in Abruzzo, Italy)
Italy, Germany, UK, Hungary



Why Underground?



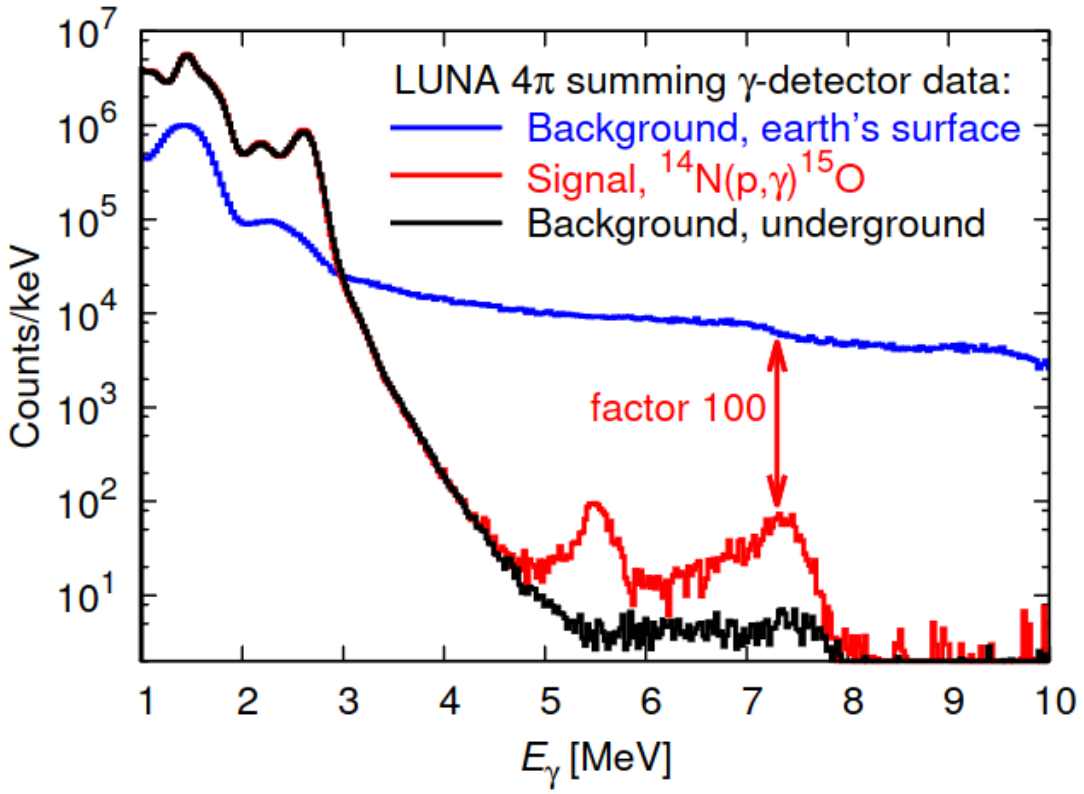
Underground passive shielding is more effective thanks to the suppressed μ flux

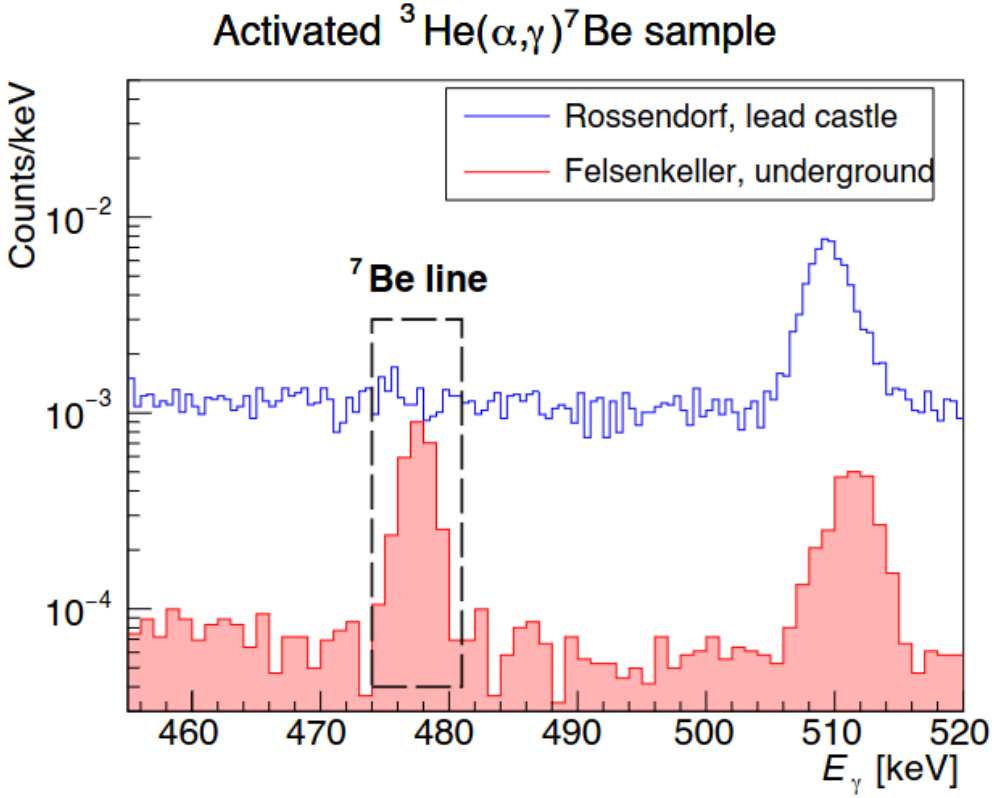


LUNA/LNGS background reduction:

- Muon flux ~ 6 orders of magnitude
- Neutron flux~ 3 orders of magnitude
- Gamma ~ factor of 3

Why Underground? - Two different case study





LUNA, Gran Sasso, Italy

Felsenkeller, Dresden, Germany

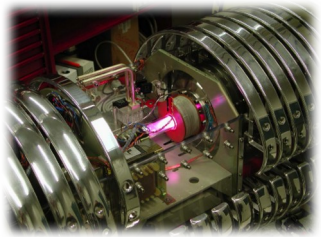
Underground accelerators worldwide

DZA low seismic lab

CASPAR
1290 m underground
1 MV: H^+, He^+
I_{max} = 250 μA
Since 2017

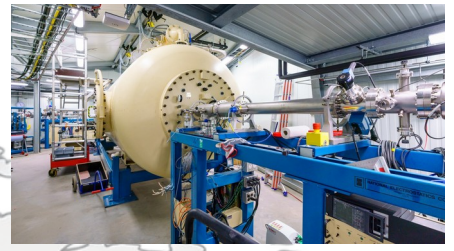


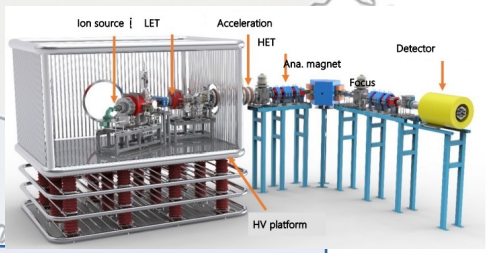
LUNA
1400 m underground
50 kV: H^+, He^+
400 kV: H^+, He^+
I_{max} = 100 -1000 eμA
Since 1991/2003



LUNANOVA
1400 m underground

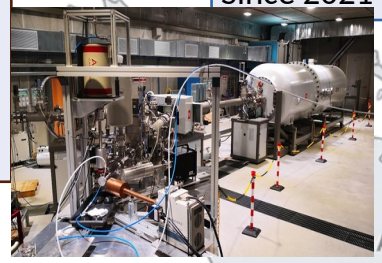
Felsenkeller
45 m underground (shallow)
5 MV: H^+, He^+, C^+, C^{++}
I_{max} = 30eμA
Since 2019





JUNA
2400 m underground
400 kV: H^+, He^+, He^{++}
I_{max} = 1200 eμA
Since 2021

Bellotti IBF
1400 m underground
3.5 MV: H^+, He^+, C^+, C^{++}
I_{max} = 1000 eμA
Since 2023



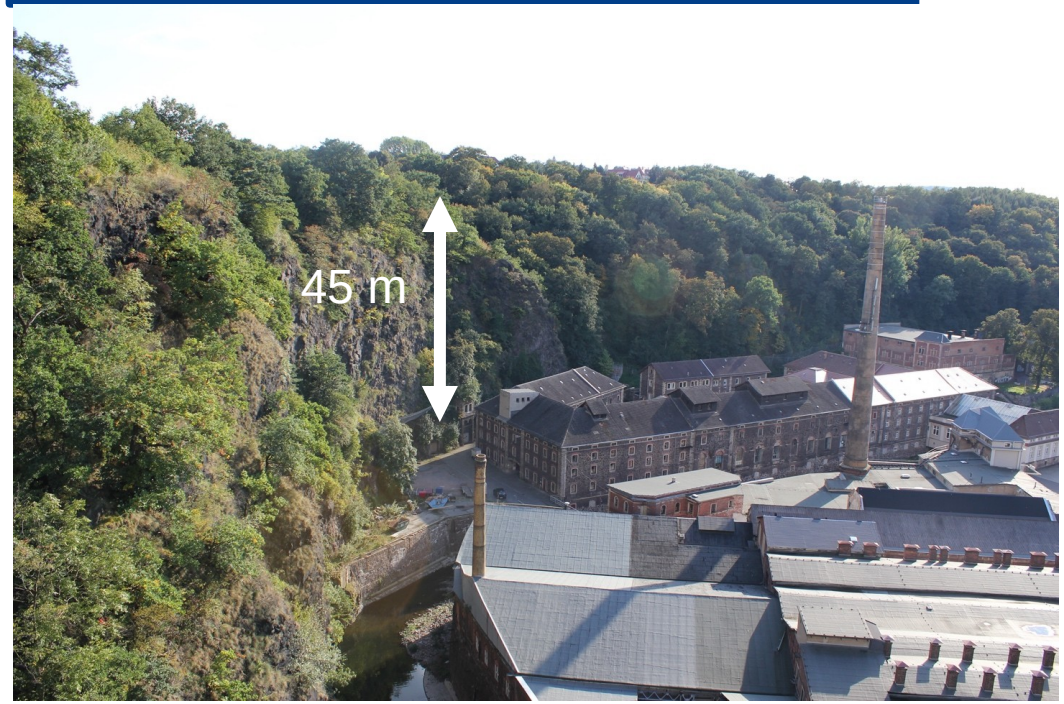
Dresden Felsenkeller underground lab

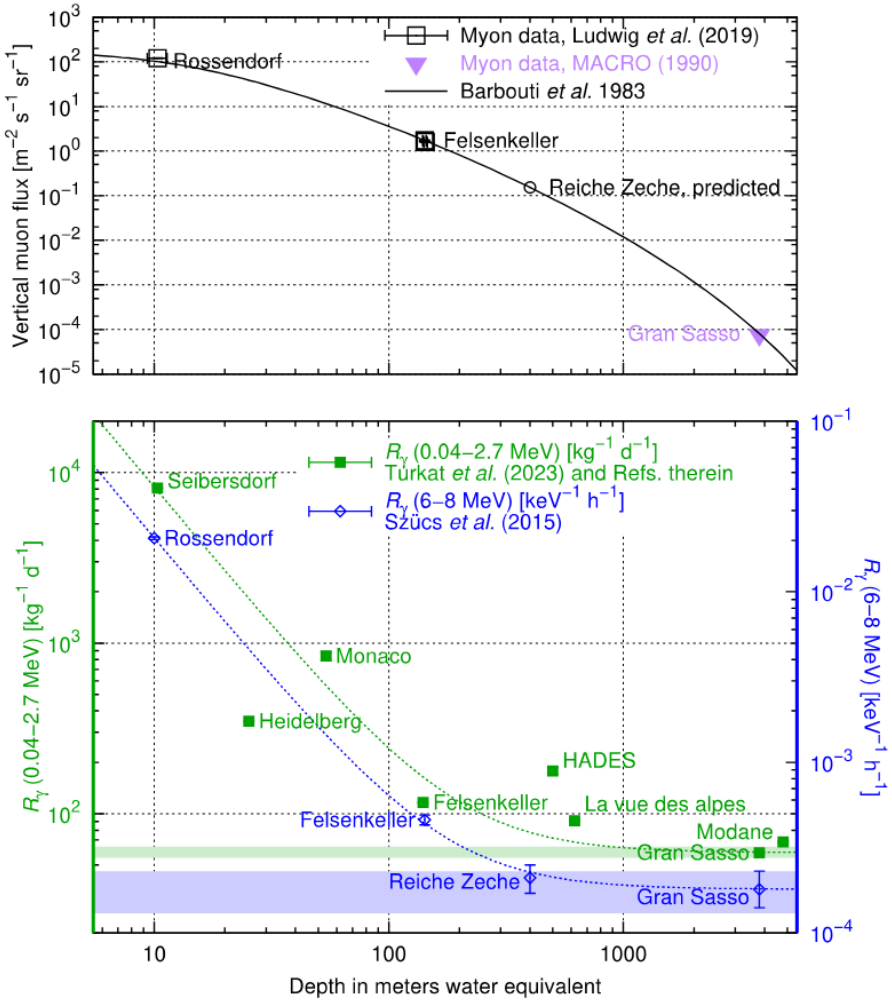


Dresden Felsenkeller underground lab

Joint effort HZDR – TU Dresden, Germany

- Investment by TU Dresden (Kai Zuber *et al.*) and HZDR (Daniel Bemmerer *et al.*)
- Day to day operations by HZDR
- 24h operation without operator





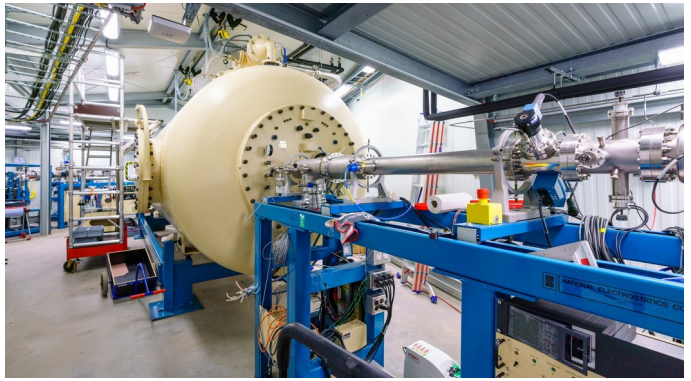
Eur. Phys. J. A 61, 19 (2025)

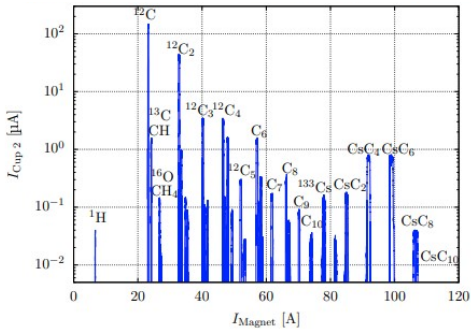
Dresden Felsenkeller underground lab

External ion-source

- Intensive ^{12}C beam
- Intensity of 20-30 μA
- Other negatively charged ions possible

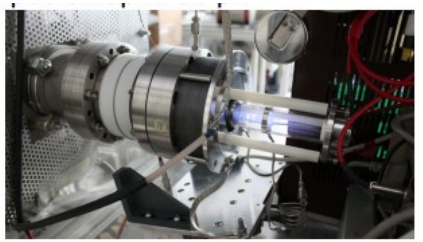






Internal radio frequency ion-source

- Intensive ^2H and ^4He beams
- Beam current up to 30 μA



Tunnel IX

Bunker for in-beam experiments

Bunker for low-radiactivity measurements

Turkat et al. Astropart. Phys. 148, 102816 (2023)



Nuclear astrophysics at Felsenkeller

Big Bang Nucleosynthesis

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

New data from 0.3 – 2 MeV
Angular distribution data
Cross section data

Hydrogen Burning

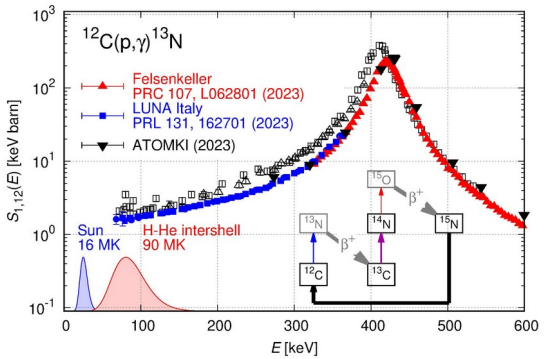
$^{3}He(\alpha,\gamma)^{7}Be$

$^{12}C(p,\gamma)^{13}N$

$^{13}C(p,\gamma)^{14}N$

Phys. Rev. C 111, 064611 (2025)

Phys. Rev. Lett. 131, 162701 (2023)



Helium Burning

$^{15}N(\alpha,\gamma)^{19}F$

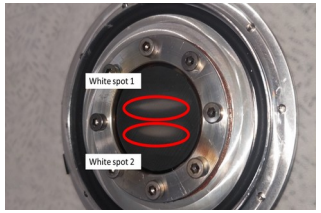
$^{14}N(\alpha,\gamma)^{18}F$

New gas jet target system for underground nuclear astrophysics

Carbon Burning

$^{12}C+^{12}C$
Target tests
Particle detection

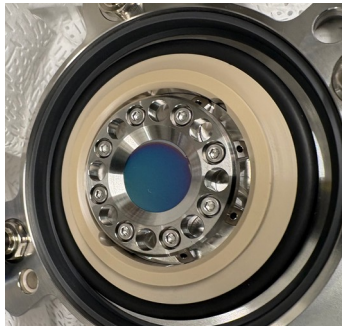
French collaboration
INFN collaboration



Explosive scenarios

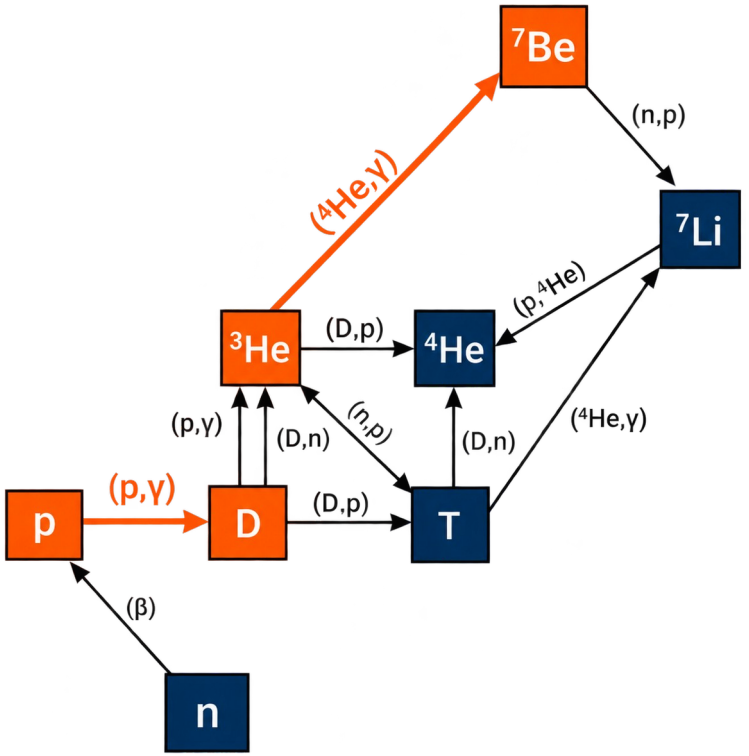
$^{40}Ca(\alpha,\gamma)^{44}Ti$

Ongoing

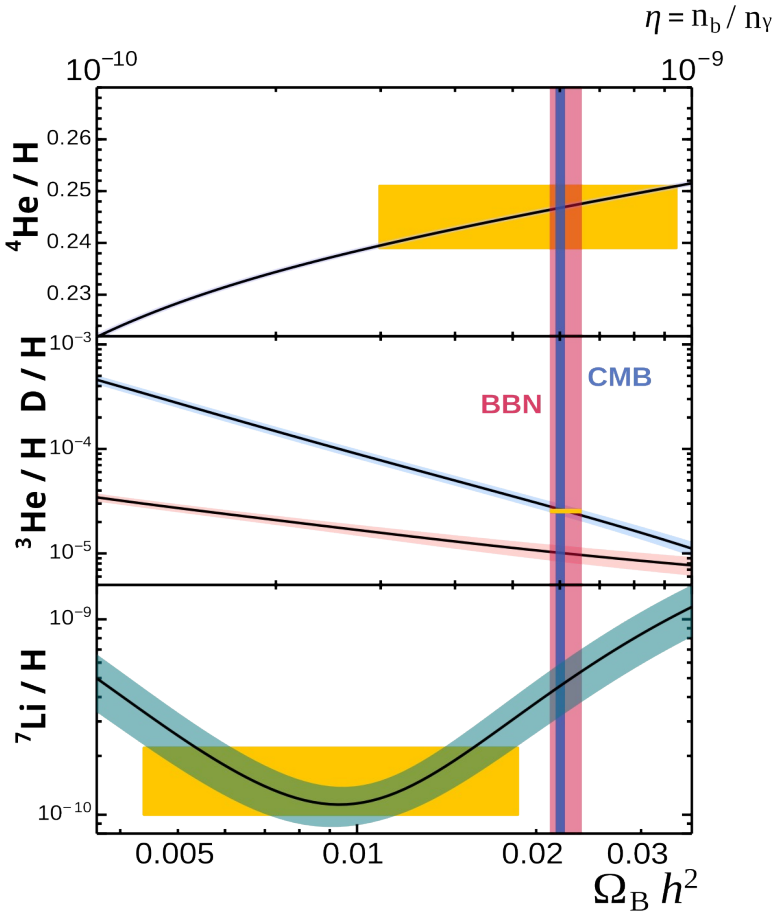


Big Bang Nucleosynthesis as a precision probe

BBN reaction network



Primordial abundances

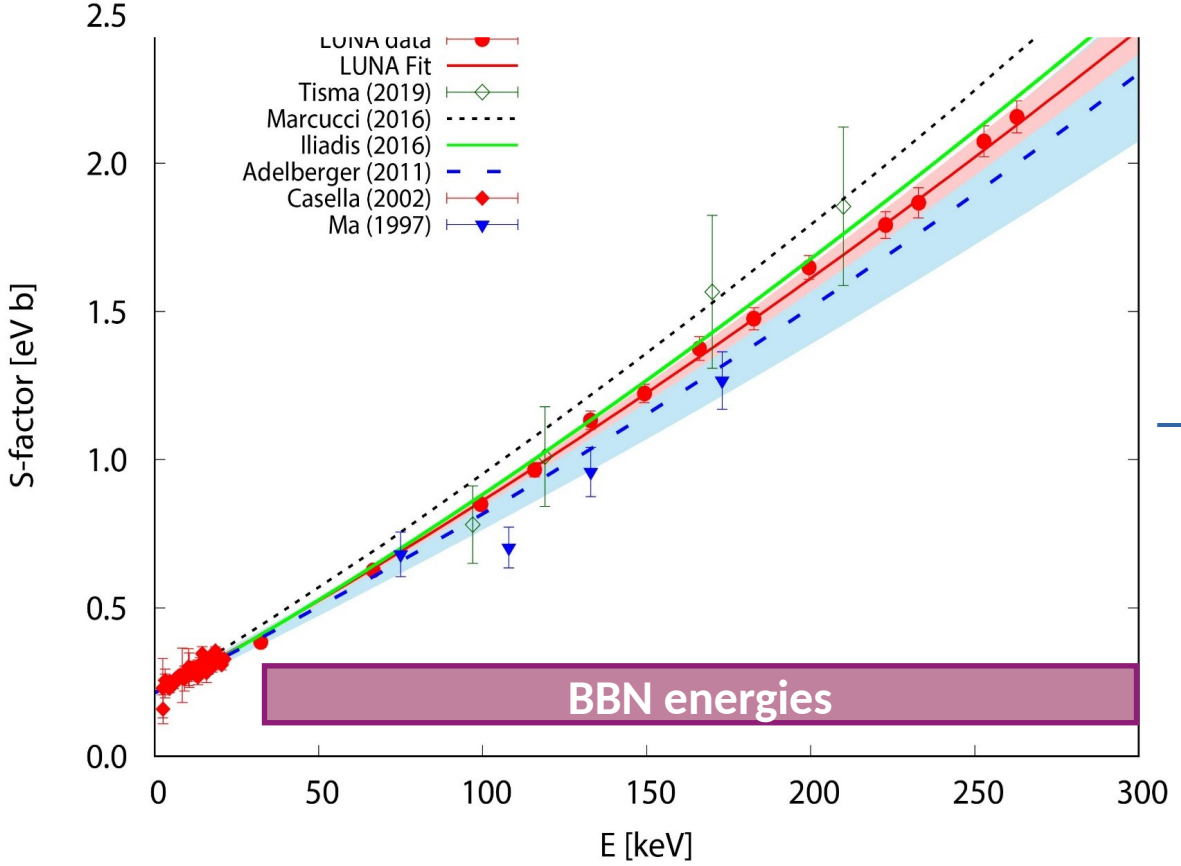


What we can learn?

- $\Omega_\beta h^2$ — **Baryon Density**
- N_{eff} — **Early-Universe physics**
- CMB ↕ BBN — **Independent consistency test**

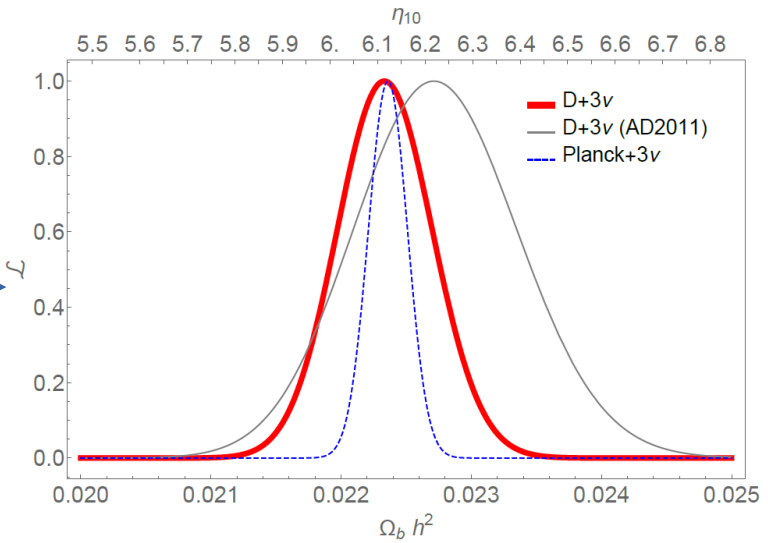
Big Bang Nucleosynthesis: $^2H(p,\gamma)^3He$ reaction

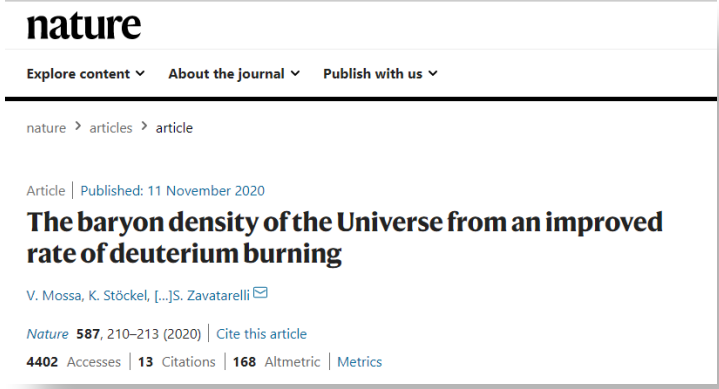
First direct measurement at BBN energies at LUNA, Italy (2020)



Systematic uncertainty reduced to **< 3%**

Cosmological implications




nature

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nature › articles › article

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

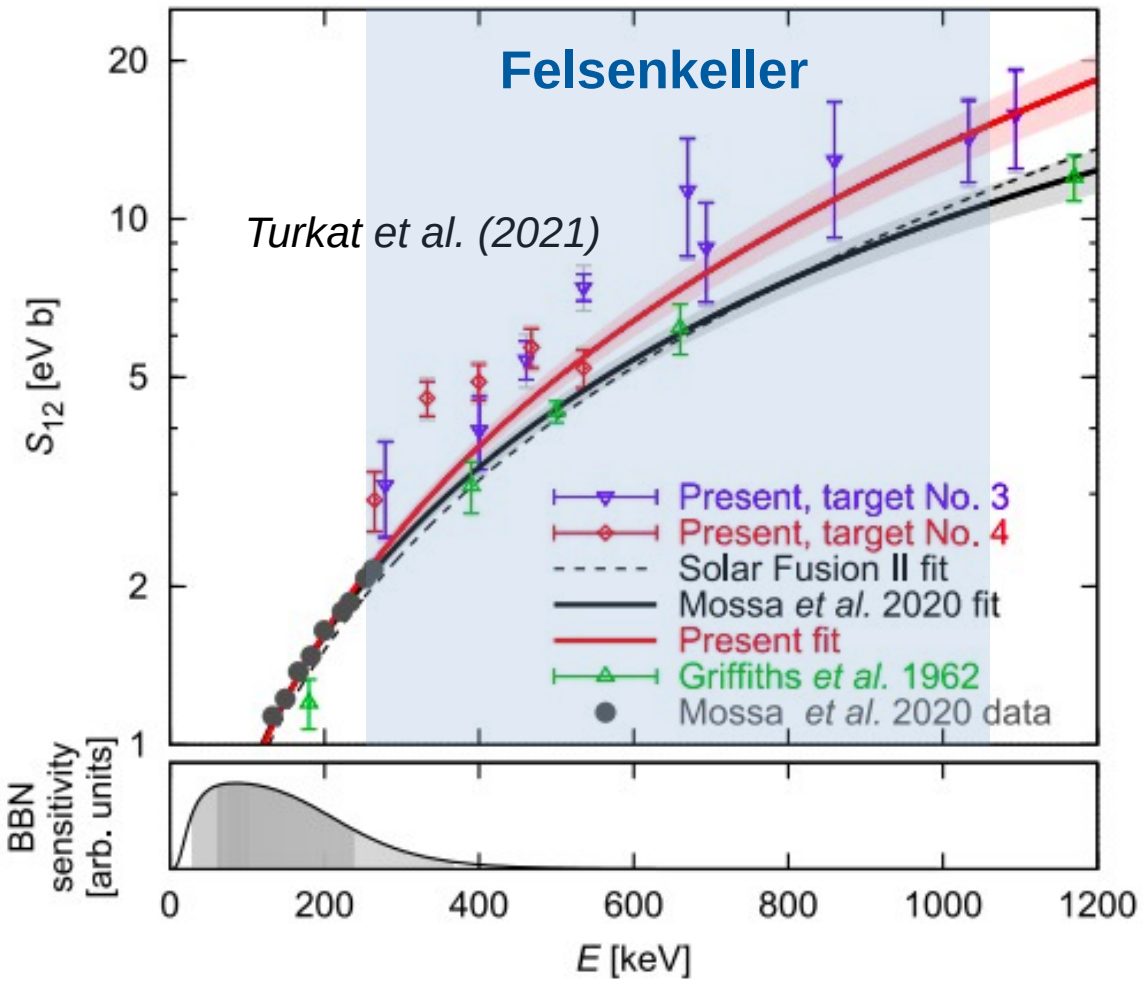
4402 Accesses | **13** Citations | **168** Altmetric | Metrics

Baryon density

- Using PARTHENOPE code comparing $[D/H]_{OBS}$ and $[D/H]_{BBN}$
- N_{eff} from Standard Model
- Comparison with Planck results

DRESDEN concept SCIENCE AND INNOVATION CAMPUS HZDR

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



Why another measurement?

Energy dependence

- ~10% tension above 400 keV

Angular distribution

- Extend direct constraints to higher energies
- Benchmark ab-initio calculations

Felsenkeller goal

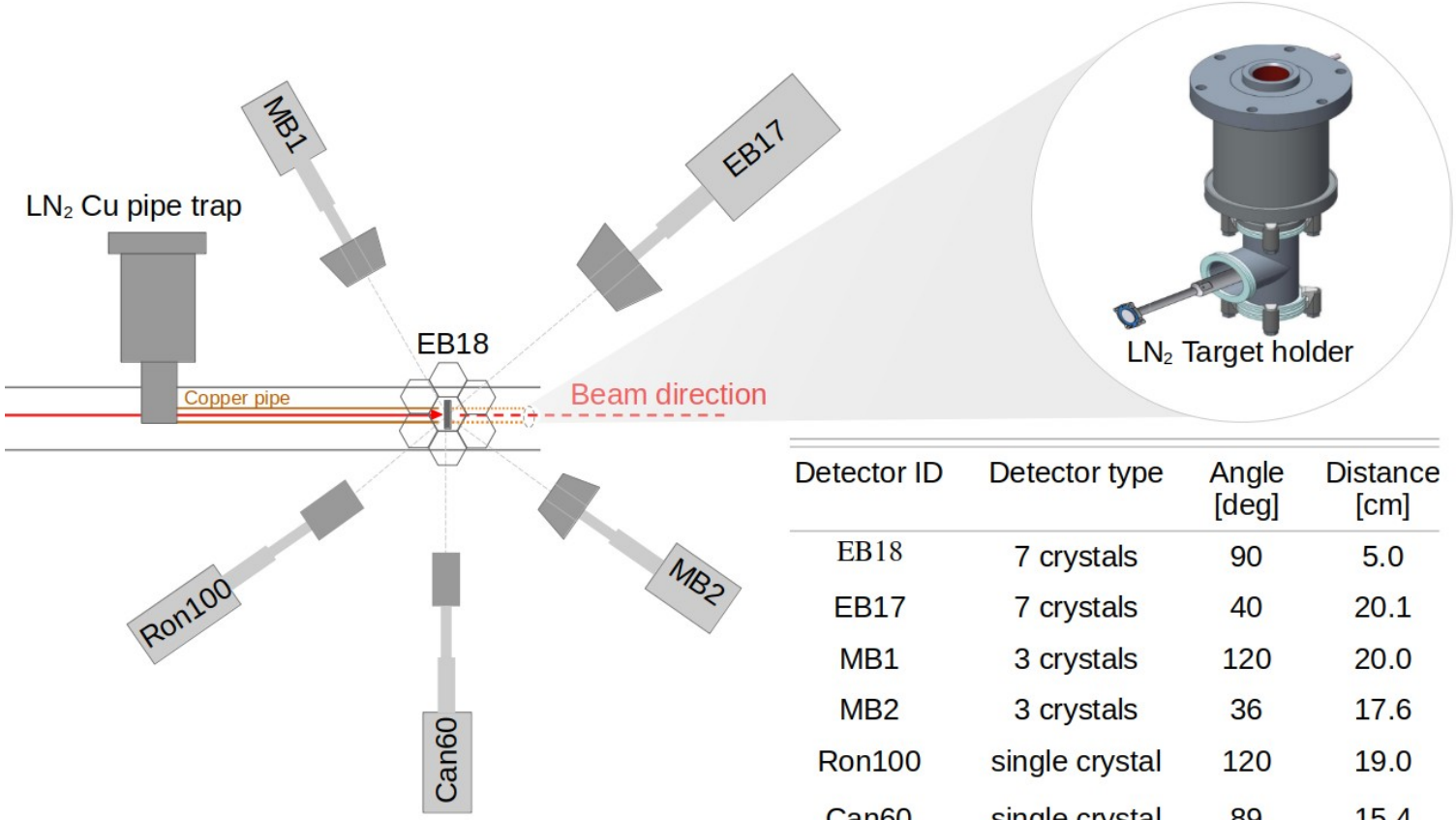
- Bridge low- and high- energy data
- Direct multi angle γ-ray measurements

Study of the $^{2}H(p,\gamma)^{3}He$ at Felsenkeller

Experimental setup

- E_p = 300 – 1200 keV
- ZrD_2 solid targets (LNL, INFN, Italy)
- 21HPGe crystals at multiple angles



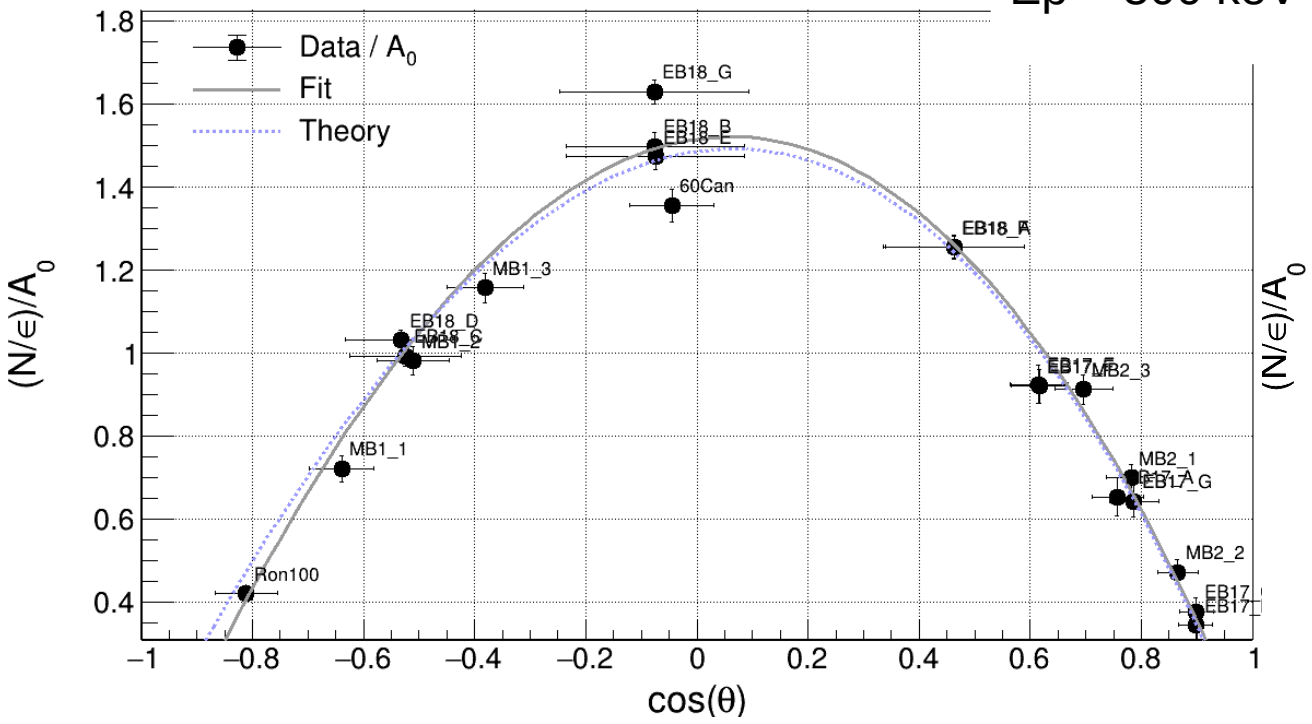


Detector ID	Detector type	Angle [deg]	Distance [cm]
EB18	7 crystals	90	5.0
EB17	7 crystals	40	20.1
MB1	3 crystals	120	20.0
MB2	3 crystals	36	17.6
Ron100	single crystal	120	19.0
Can60	single crystal	89	15.4

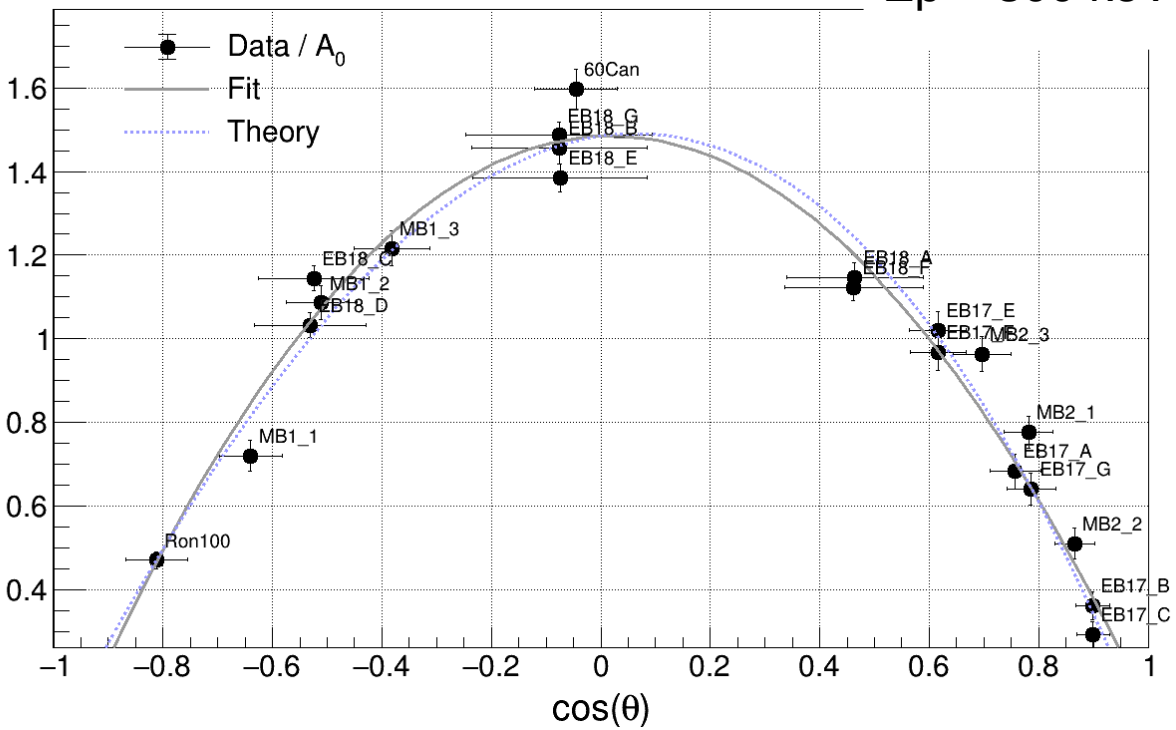
$^2H(p,\gamma)^3He$ at Felsenkeller

Direct γ- ray angular distributions - preliminary

Ep = 500 keV



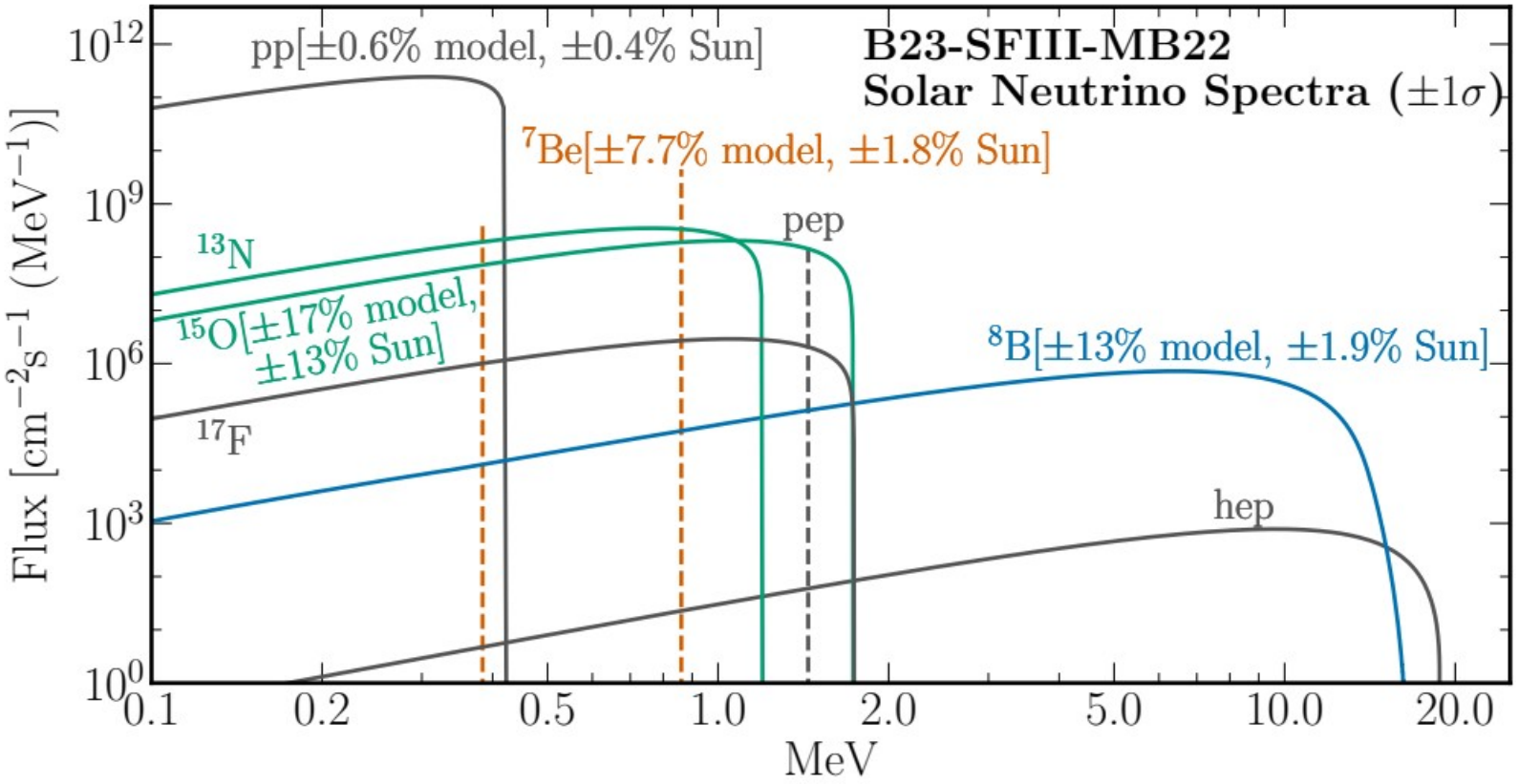
Ep = 800 keV



Direct measurements up to E_p = 1200 keV, test of ab-initio beyond the BBN range

New S-factor data over a wide energy range under evaluation ➡ **Stay tuned!!!**

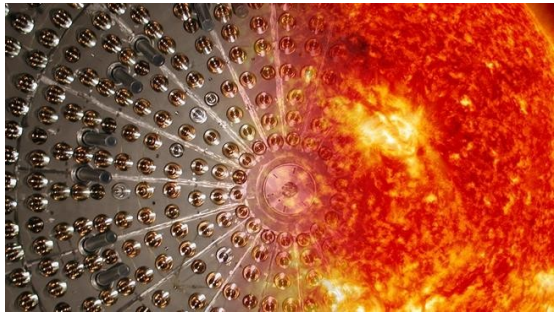
Solar neutrinos: the model is less precise than the data



SSM model ν fluxes...		and data
ν(pp)	± 0.6%	± 0.4%
ν(^{7}Be)	± 7.7%	± 1.8%
ν(^{8}B)	± 13%	± 1.9%
ν(^{13}N+^{15}O)	± 17%	± 13%

Model not precise

Data precise



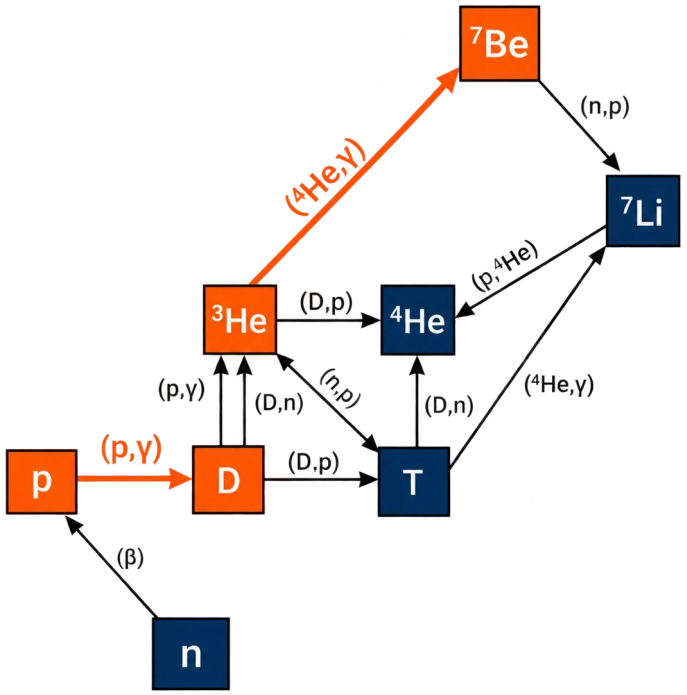
M. Agostini et al., Nature (2018)
S. Appel et al. PRL (2022)

Model uncertainties >> experimental uncertainties!

Solar hydrogen burning: $^{3}He(^{4}He,\gamma)^{7}Be$ reaction

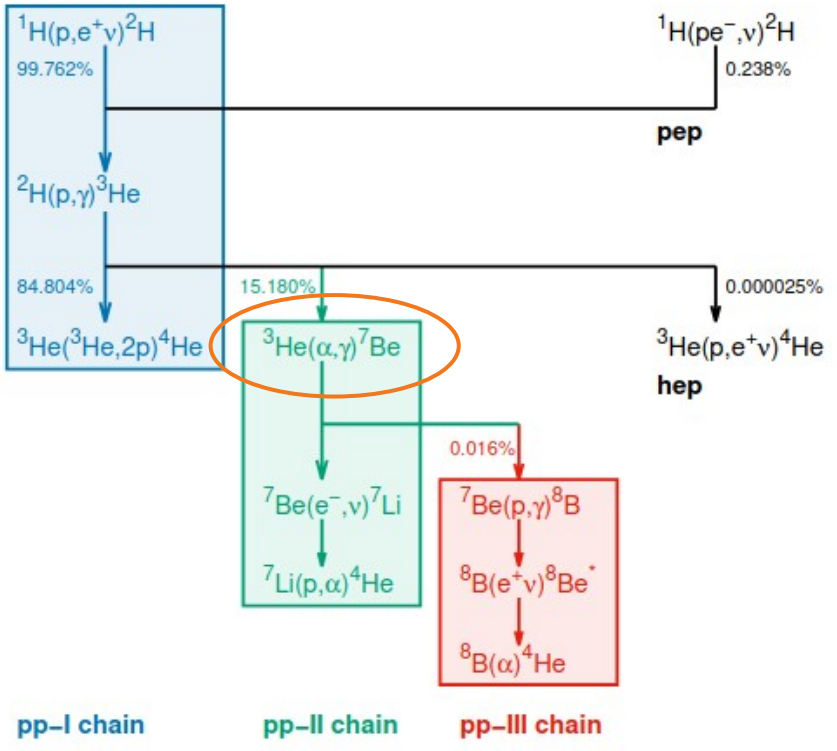
Big Bang nucleosynthesis

^{7}Li production



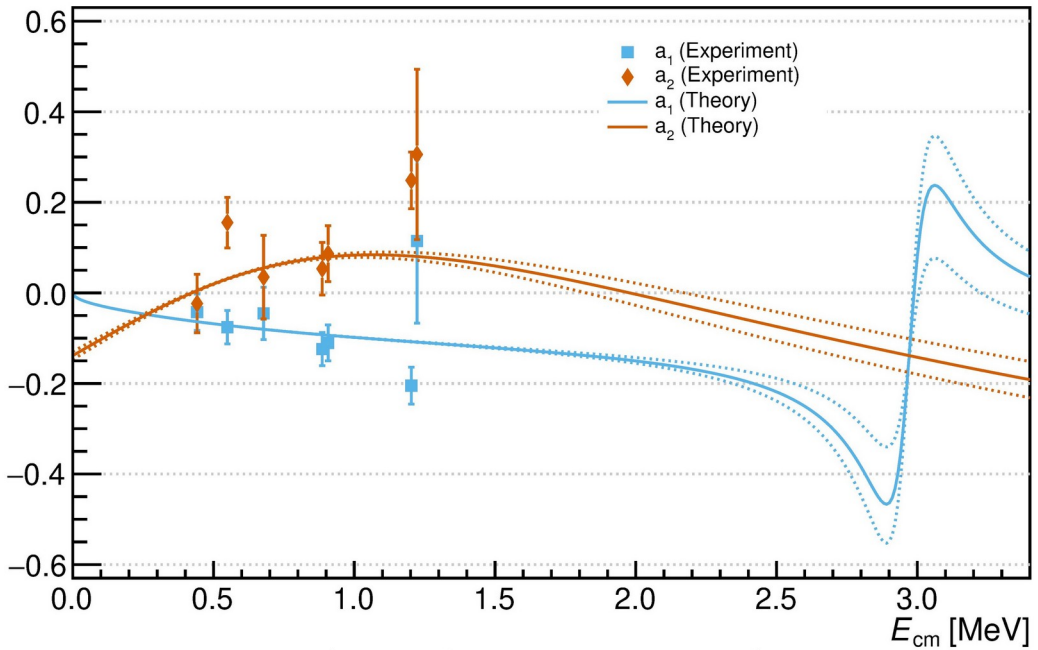
$E_{BBN} \approx$ 160 – 380 keV

Solar neutrino flux



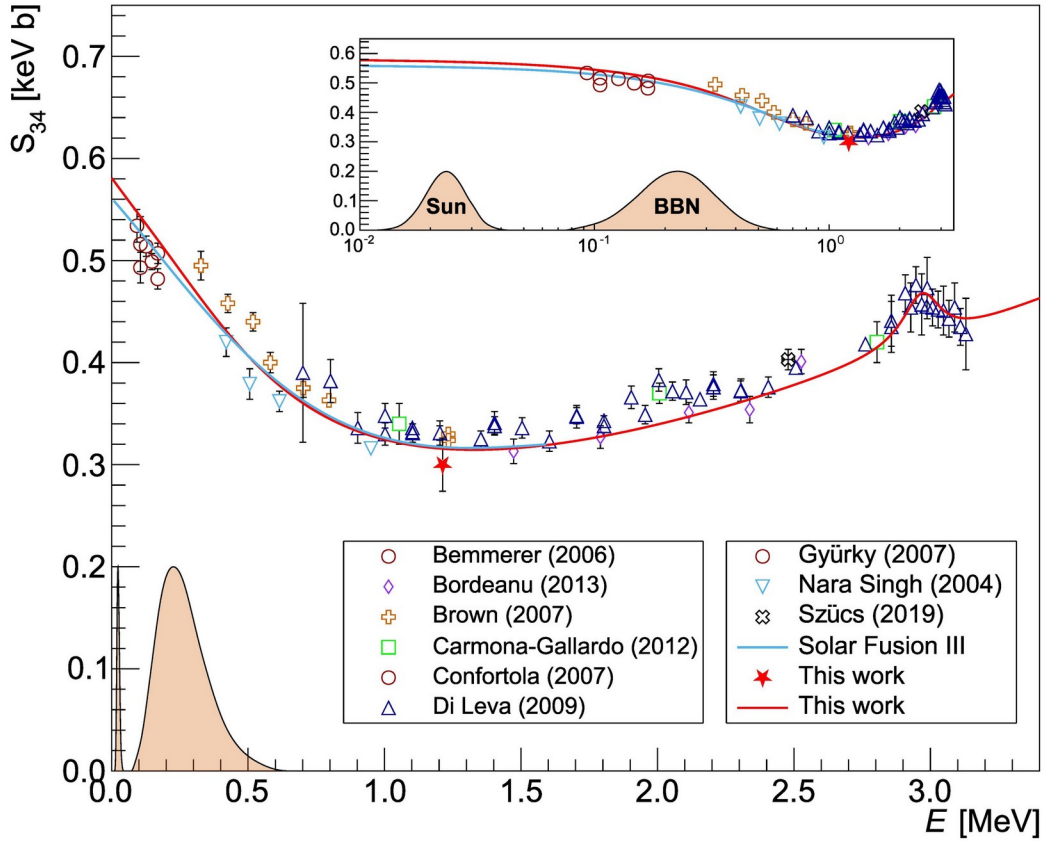
$E_{Sun} \approx$ 19 – 30 keV

Study of the ^{3}He(α,γ)^{7}Be γ-ray angular distribution at Felsenkeller (2)



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

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



New data are still needed!

S. Turkat, P. Hempel *et al., PRC (letter), 2026, Accepted*

European Research Council
Established by the European Commission

LUNANOVA

Laboratory **U**nderground for **N**uclear **A**strophysics
New **O**bserv**a**tory for Solar Neutrino Reactions

Daniel Bemmerer (cPI)
Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Germany

Alba Formicola (PI)
Istituto Nazionale di Fisica Nucleare (INFN), Italy

Aldo Serenelli (PI,
Instituto de Ciencias del Espacio (ICE-CSIC), Spain

Gianluca Imbriani (PI)
Università degli studi di Napoli Federico II, Italy



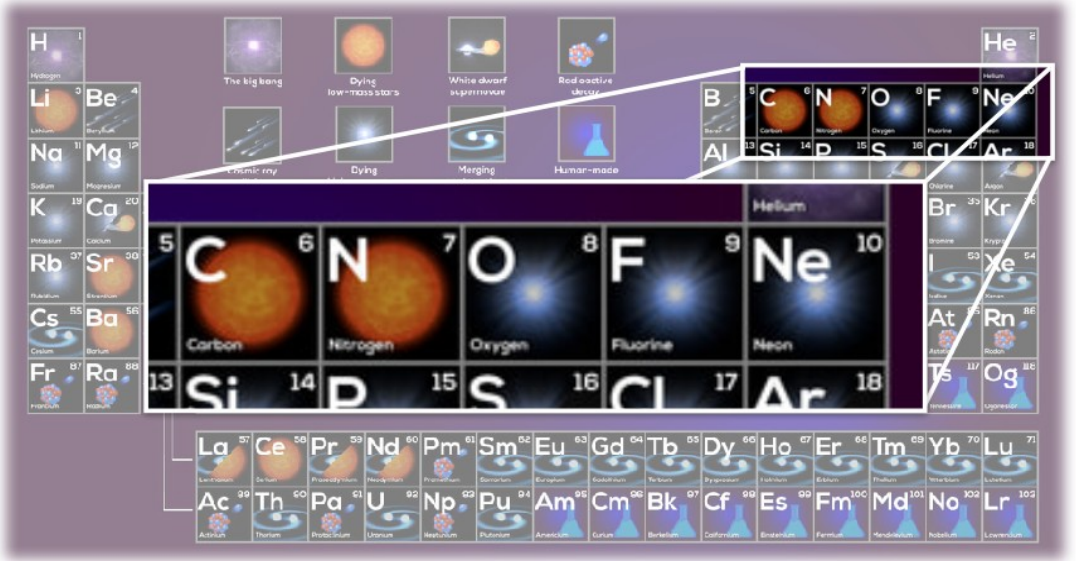
Heraeus Workshop on Interdisciplinary Physics of the Sun, June 2025

...ERC Synergy Grant, 01.09.2026 – 31.08.2032, 14 M€

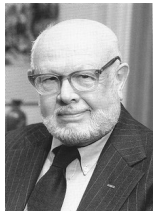
Goal: Precise measurements of solar hydrogen burning reactions

Stellar Helium burning

- **Temperature:** 0.1 – 0.4 GK
- Red Giant and Asymptotic Giant Branches stars,
- Massive stars
- Core-collapse supernova progenitors



➡ **Carbon to oxygen ratio**, hence, heavy-element production

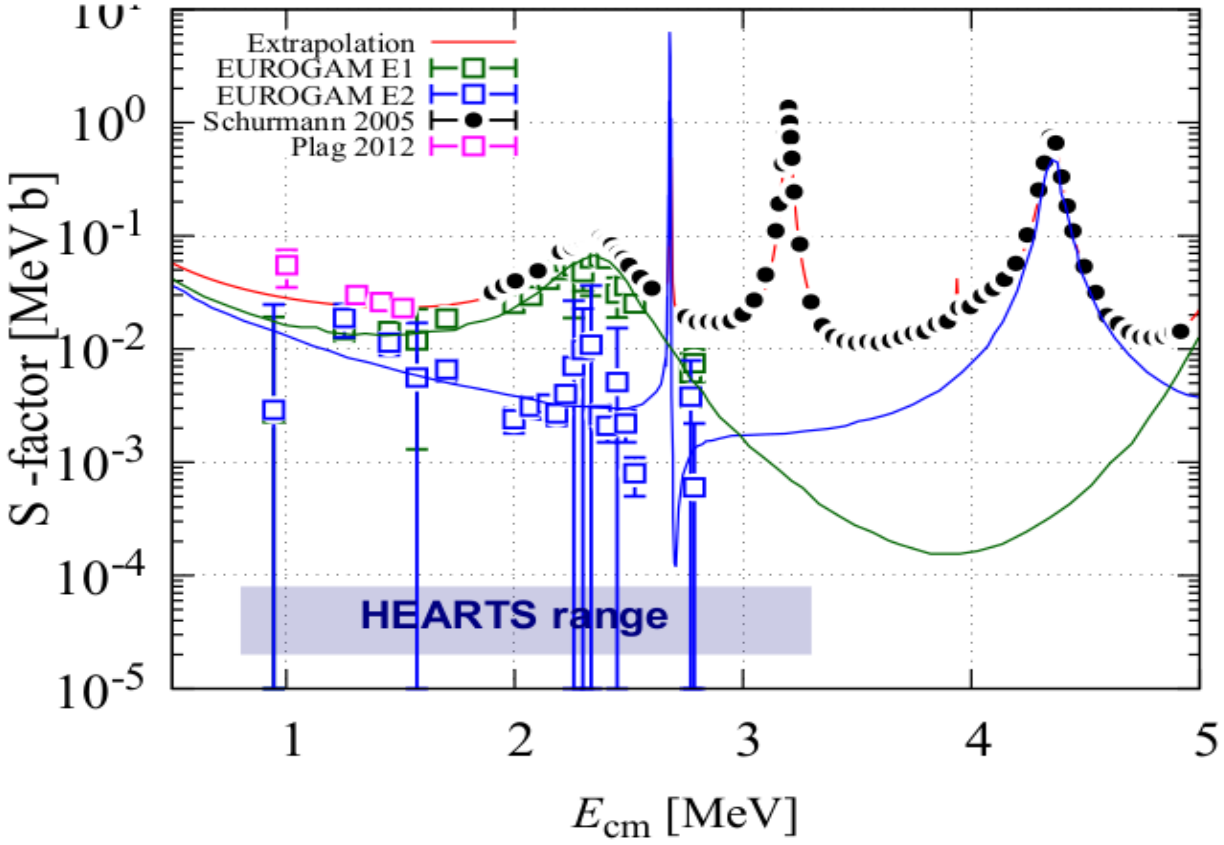


"The Holy Grail of Nuclear astrophysics: $^{12}C(\alpha, \gamma)^{16}O$ reaction"
William A. Fowler
1983 Nobel Prize in Physics

"For his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"a

Stellar Helium burning: $^{12}C(\alpha,\gamma)^{16}O$ reaction

The $^{12}C(\alpha,\gamma)^{16}O$ nuclear reaction ("Holy Grail") remains **highly uncertain**



What we have:
30% uncertainty

What we need:
10% uncertainty

HEARTS

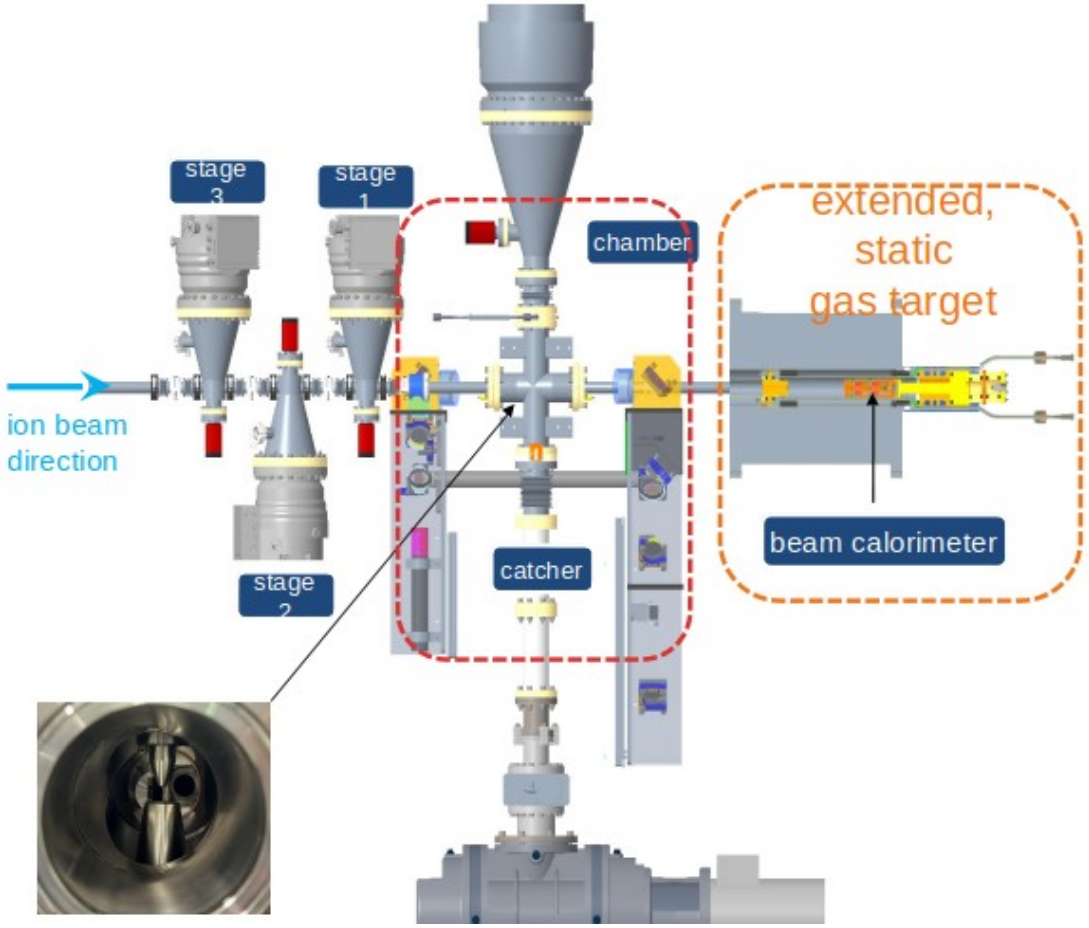
Helmholtz Young Investigator Group
PI: Eliana Masha (2026-2031) on
HELIUM BURNING at **Felsenkeller,**
CRYRING, **LUNA**

Goal

- $^{12}C(\alpha,\gamma)^{16}O$ angular distribution and cross-section
- Measure and reduce the reaction rate uncertainties, for α-induced reaction on N, O, F ^{25}Mg isotopes

Stellar Helium burning: α- induced on Nitrogen isotopes

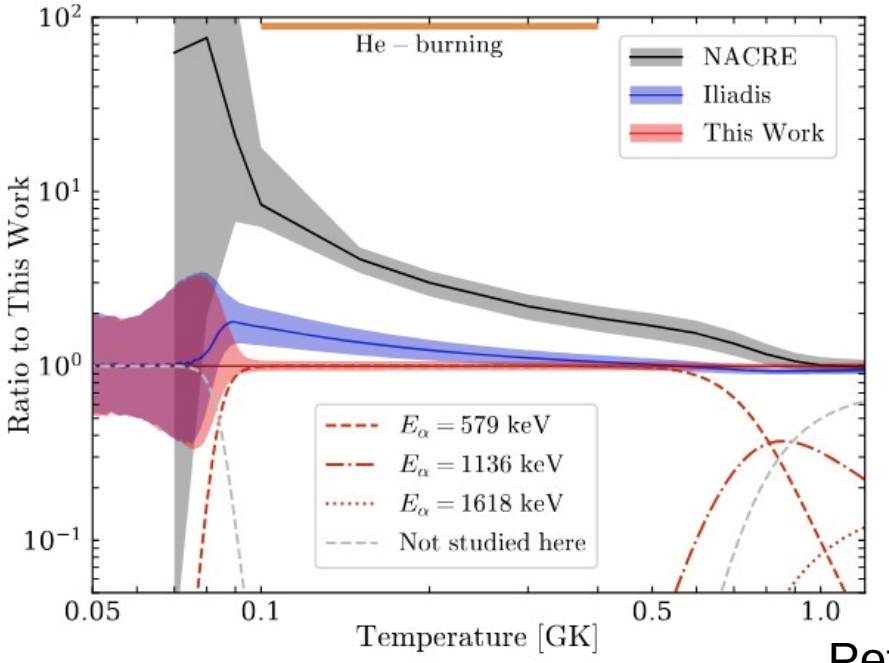
Felsenkeller gas-jet target



Nucl. Inst. Meth. A 1082, 171034 (2025)

A. Yadav PhD project

$^{14}N(\alpha,\gamma)^{18}F$: commissioning and first science case



Yadav, PRL,, Under review (2026)

Peter Hempel



Maria Lukyanova



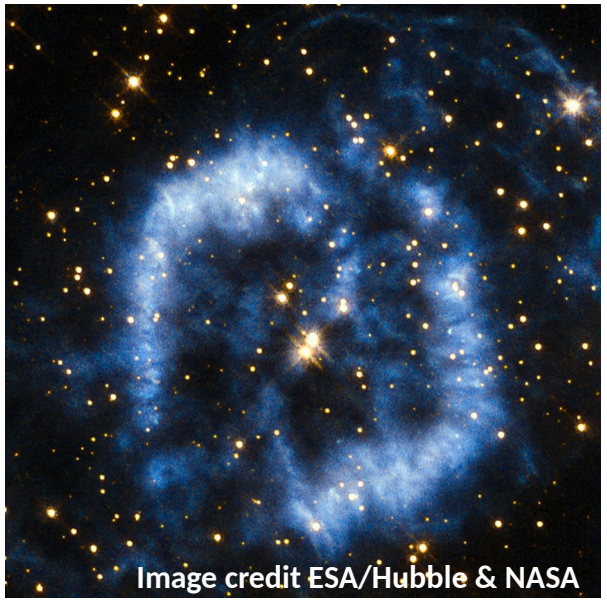
Stellar Carbon burning

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:

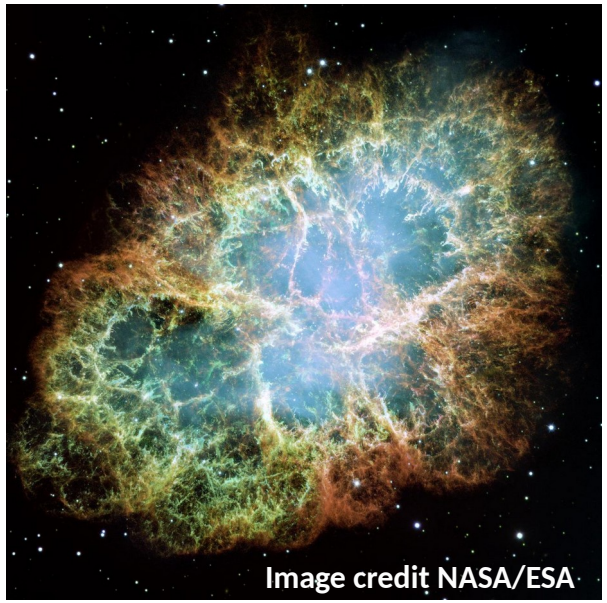
$M < M_{up}$

White dwarfs/classical novae



$M > M_{up}$

Supernovae → neutron stars and black holes

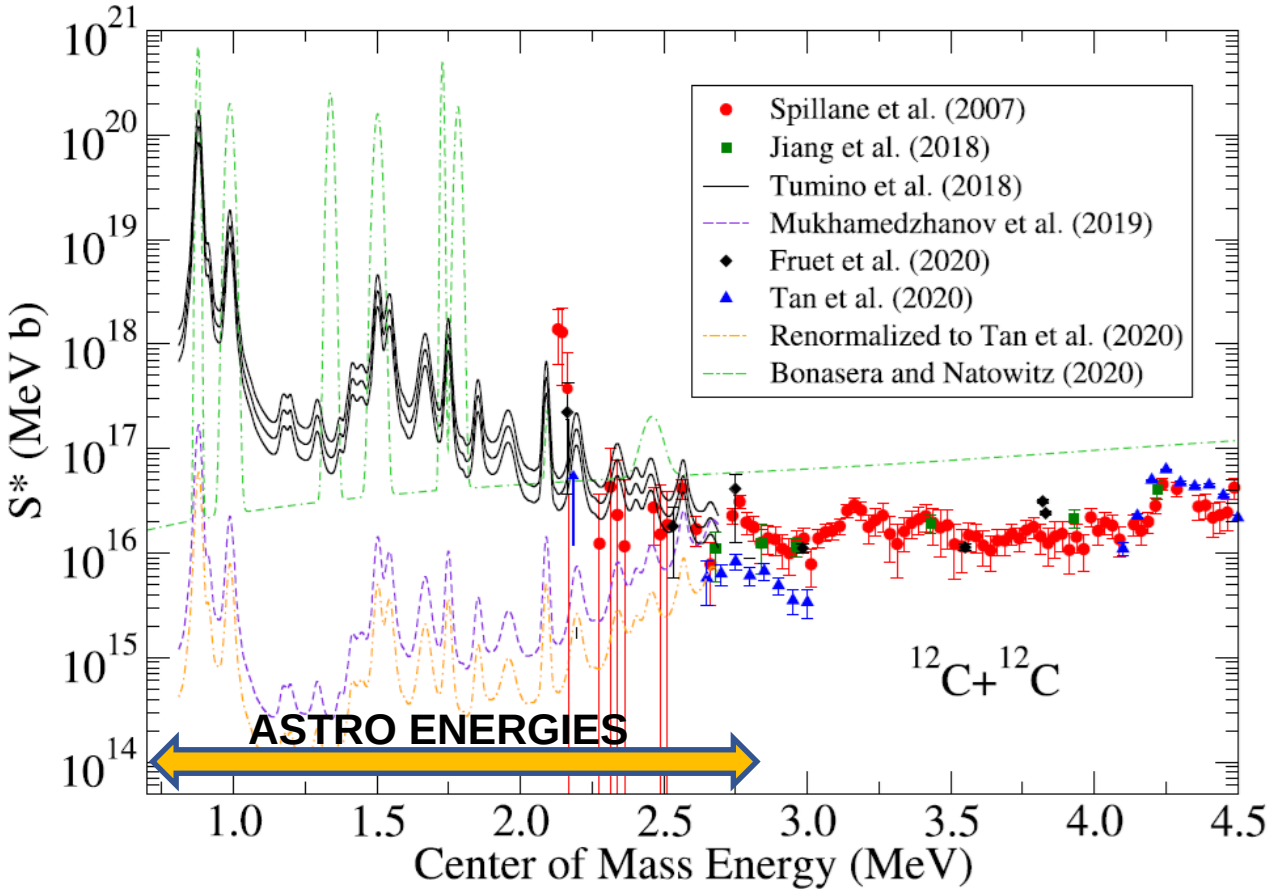


M_{UP} (and hence the whole life and fate of a star) depends on the $^{12}C+^{12}C$ cross section

Stellar Carbon burning

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

$\rightarrow {}^{23}Na + p\ (+\gamma)\ (Q = 2.24\ MeV)$



Ongoing studies

- Measurements at Bellotti IBF/LNGS
  - Gamma detection
  - LUNA collaboration
- Measurement at Felsenkeller
  - gamma-particle detection
  - STELLA collaboration, Strasbourg (S. Courtin, M. Heine et al.)

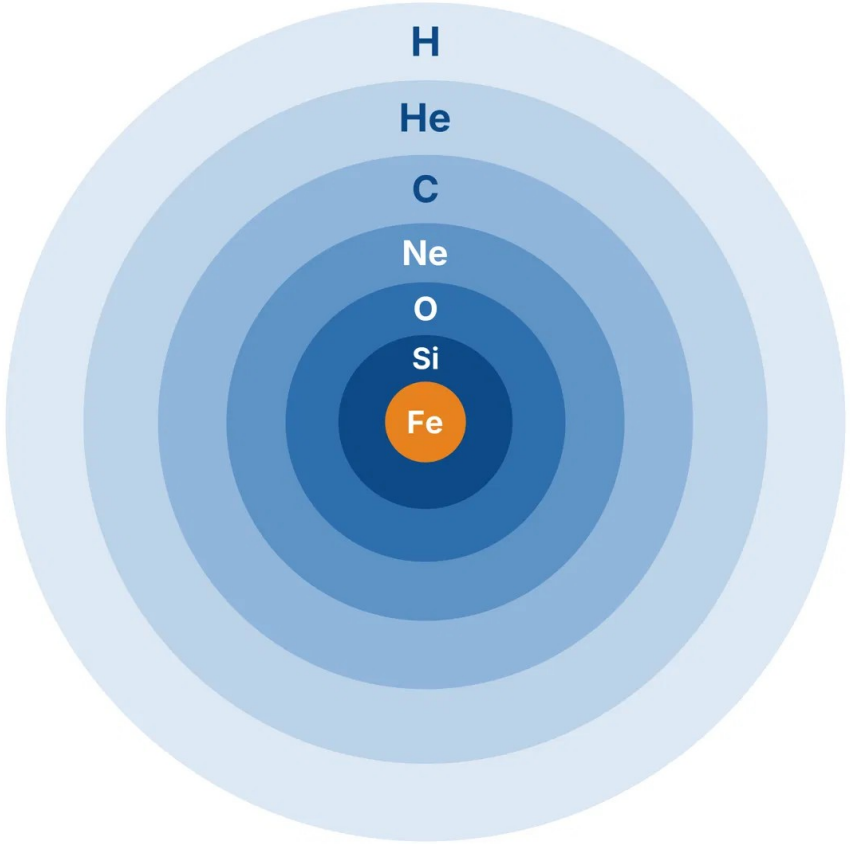
Summary

- Elements are produced in the Big Bang, in stars and in stellar explosions, and nuclear reaction rates are the key input to understanding them
- Underground nuclear astrophysics has contributed to the community for over three decades
- Underground facilities are expanding worldwide
- In less than five years, Felsenkeller has explored several science cases and developed the first gas-jet target in an underground lab
- Precision measurements for hydrogen and helium burning are ongoing with LUNANOVA and HEARTS project



Backup slides

Burning stages: Each ash is the next fuel

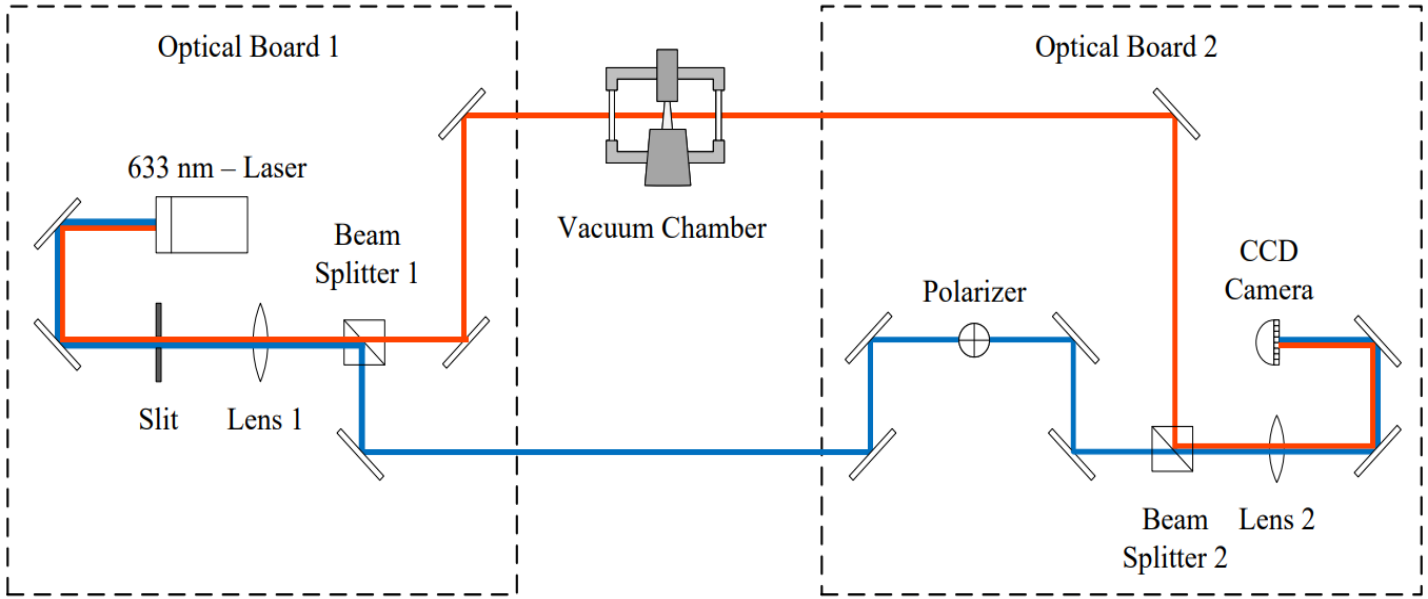


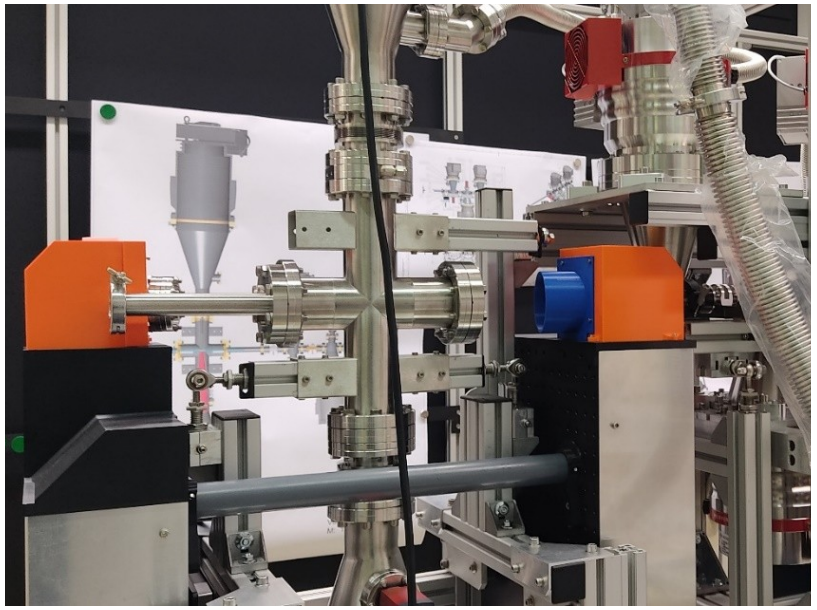
Stage	Fuel → main products
Hydrogen	H → He
Helium	He → C, O
Carbon	C → Ne, Na, Mg
Neon	Ne → O, Mg
Oxygen	O → Si, S
Silicon	Si → Fe-group

Only massive stars (≳ 8 M☉) go beyond helium. Iron is the end of the line: fusion no longer releases energy.

Jet thickness using laser interferometry

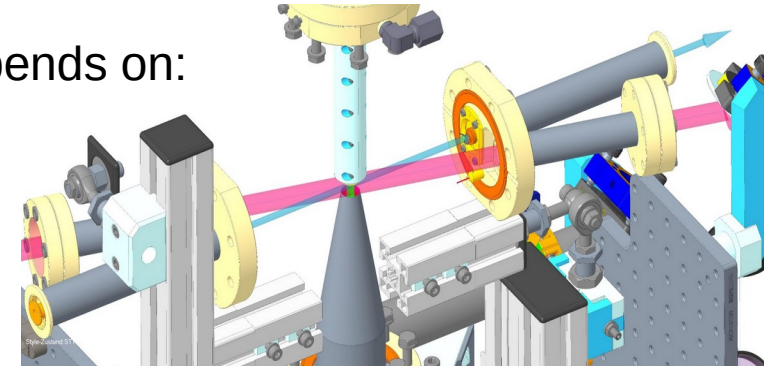
Mach-Zehnder Interferometer

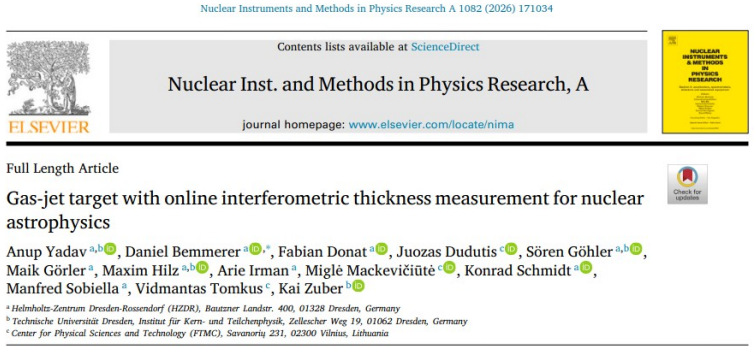




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- Optical path length difference depends on:
  - Gas refractive index
  - Density distribution
- Path length shift for N_2 (0.11 μm)





Nuclear Instruments and Methods in Physics Research A 1082 (2026) 171034

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

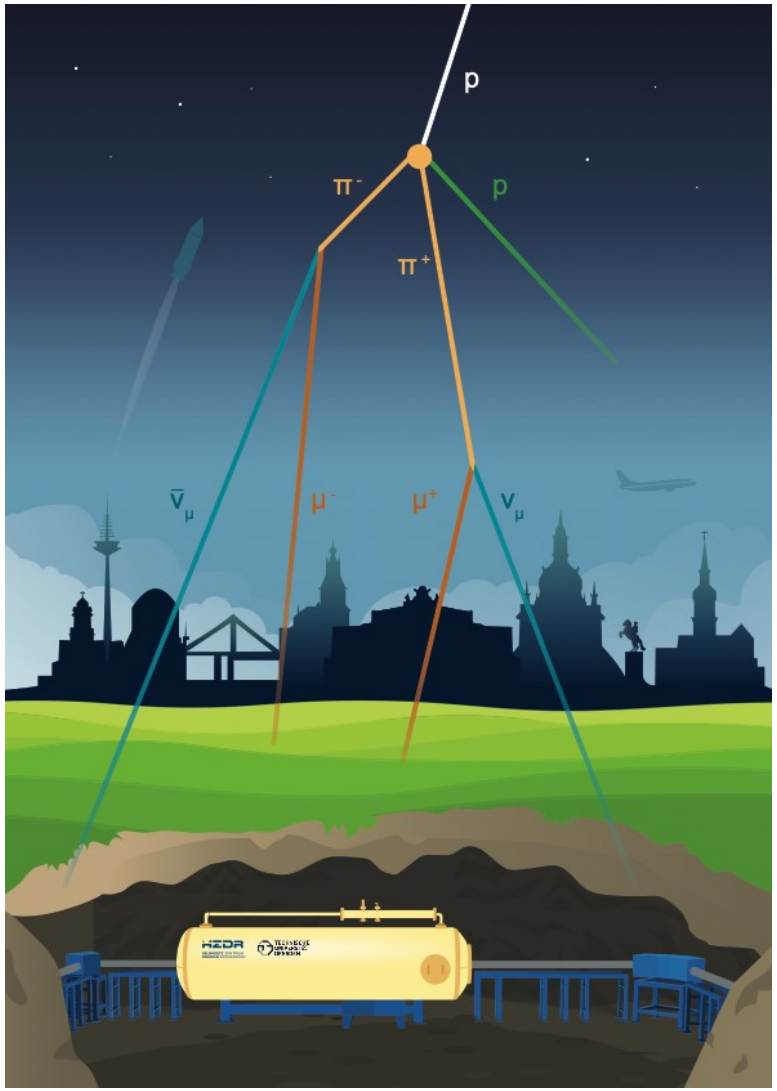
Full Length Article

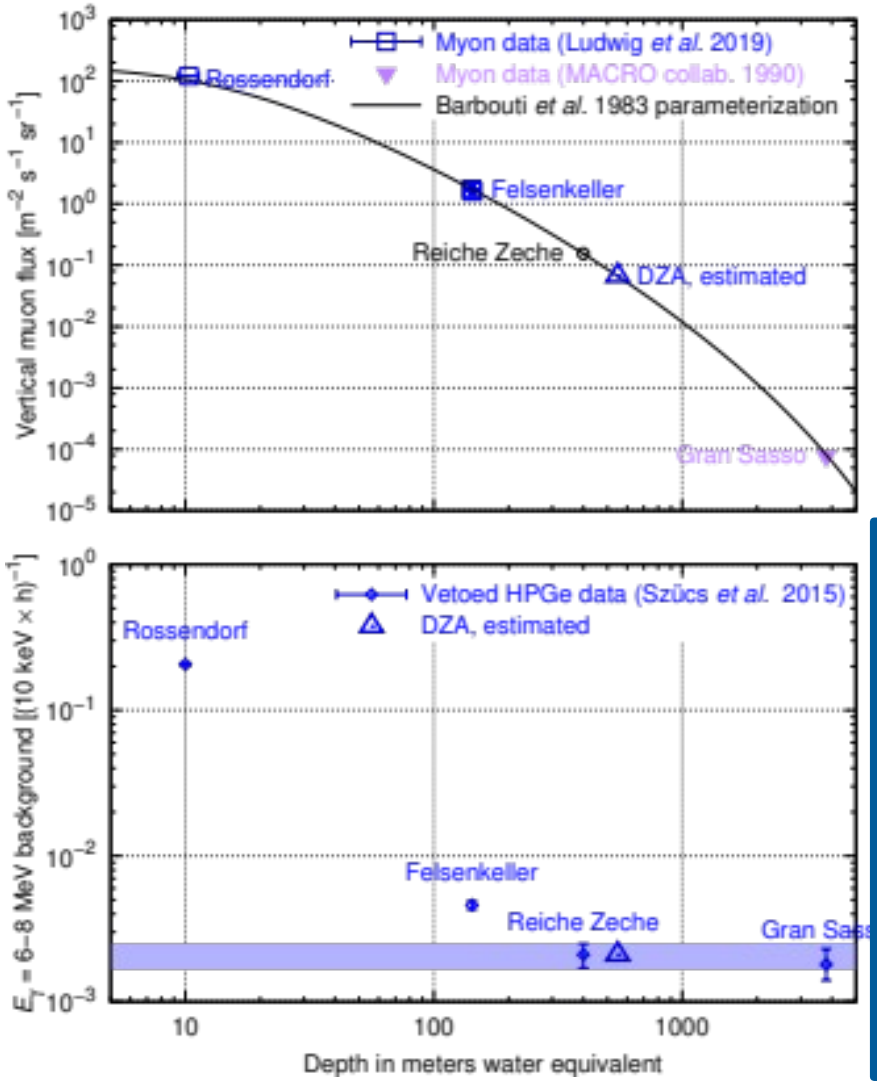
Gas-jet target with online interferometric thickness measurement for nuclear astrophysics

Anup Yadav [a,b], Daniel Bemmerer [a,*], Fabian Donat [a], Juozas Dudutis [c], Sören Göhler [a,b], Maik Görler [a], Maxim Hilz [a,b], Arie Irman [a], Miglė Mackevičiūtė [c], Konrad Schmidt [a], Manfred Sobiella [a], Vidmantas Tomkus [c], Kai Zuber [b]

[a] Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Bautzner Landstr. 400, 01328 Dresden, Germany
[b] Technische Universität Dresden, Institut für Kern- und Teilchenphysik, Zellescher Weg 19, 01062 Dresden, Germany
[c] Center for Physical Sciences and Technology (FTMC), Savanorių 231, 02300 Vilnius, Lithuania

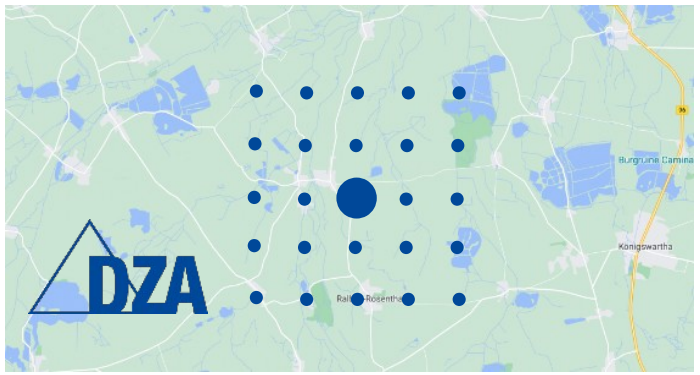
DZA Low Seismic Lab, at the „sweet spot“ for nuclear astrophysics



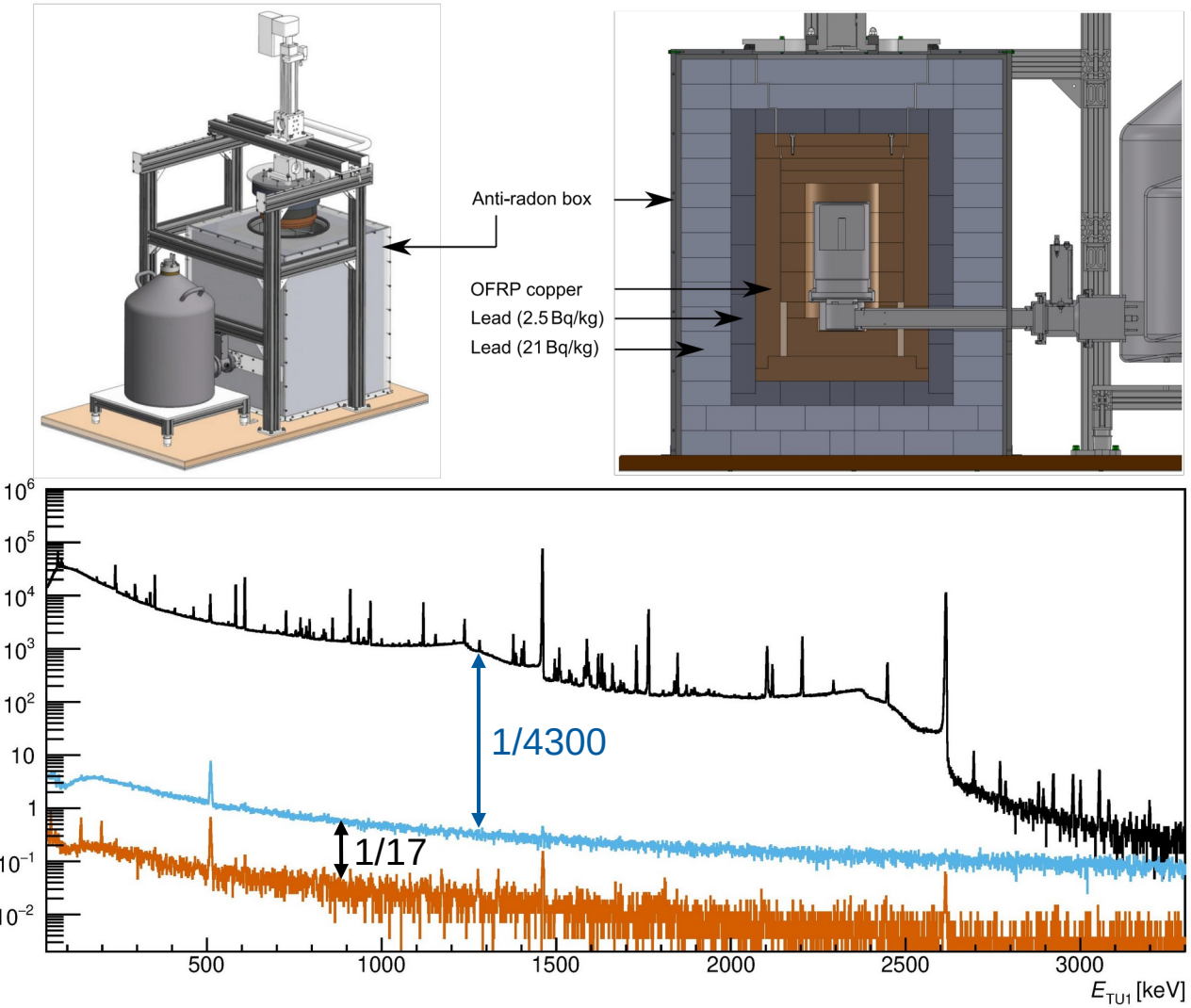


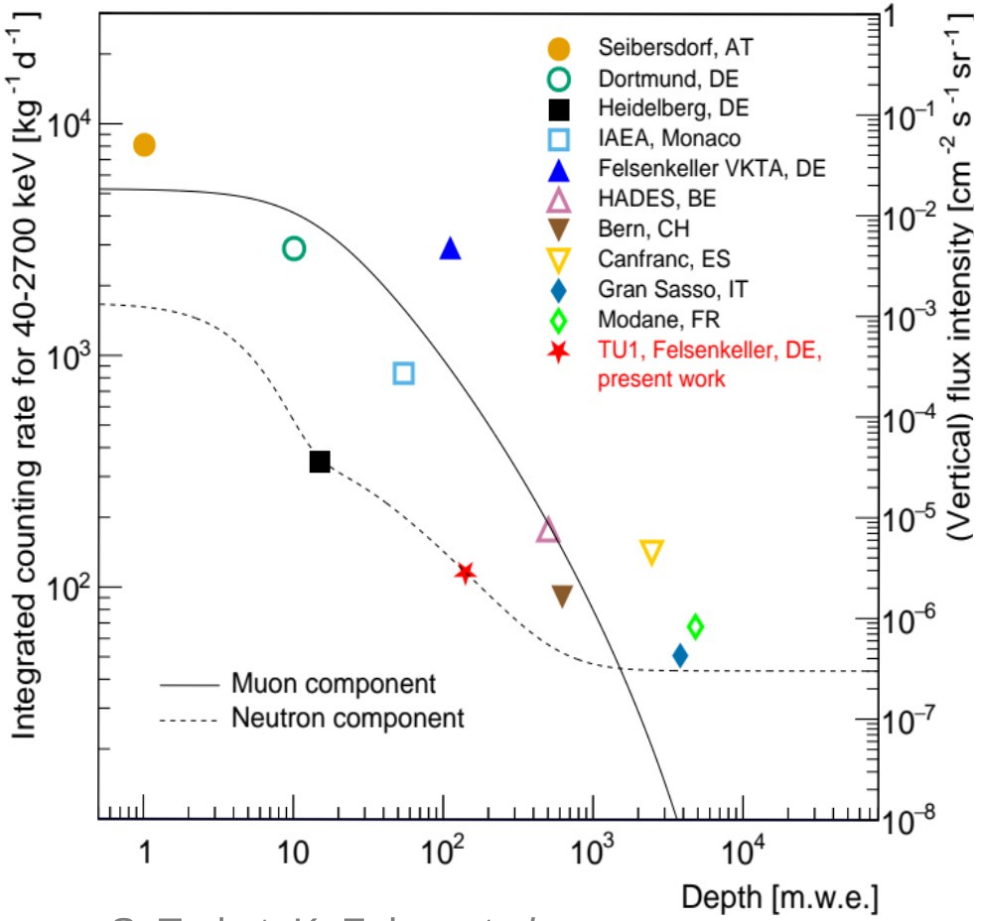


Deutsches Zentrum für Astrophysik
new underground Low Seismic Lab, Lusatia



Low-radioactivity HPGe detector (TU1)





S. Turkat, K. Zuber *et al.*,
Astropart. Phys. 148 (2023) 102816

Possible sources of fluorine in the Universe

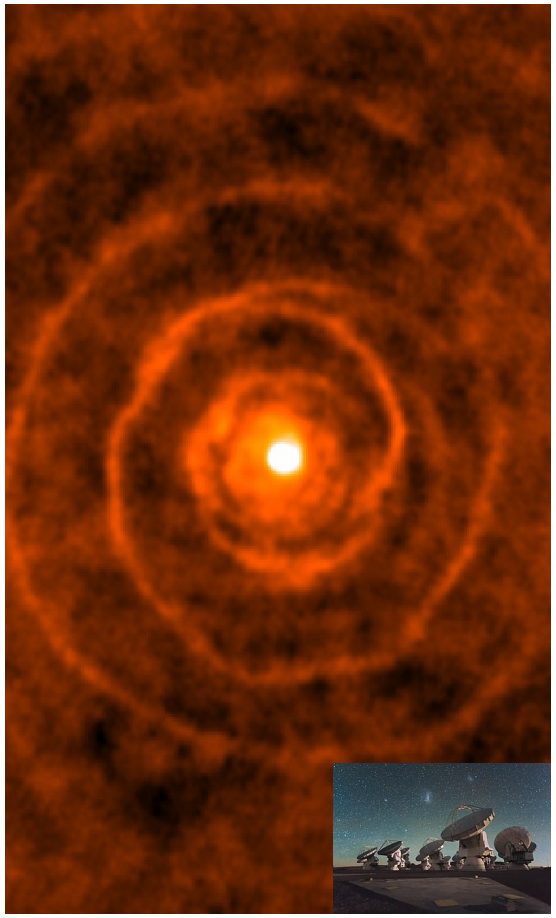
Type II Supernova



Credit: NASA, ESA, CSA, STScI, D. Milisavljevic, I. De Looze, T. Temim

James Webb Space Telescope Cold Side

Asymptotic Giant Branch star



Credit: Kim *et al.* Nature Astronomy (2017)

Atacama Large Millimeter /submillimeter Array (ALMA)

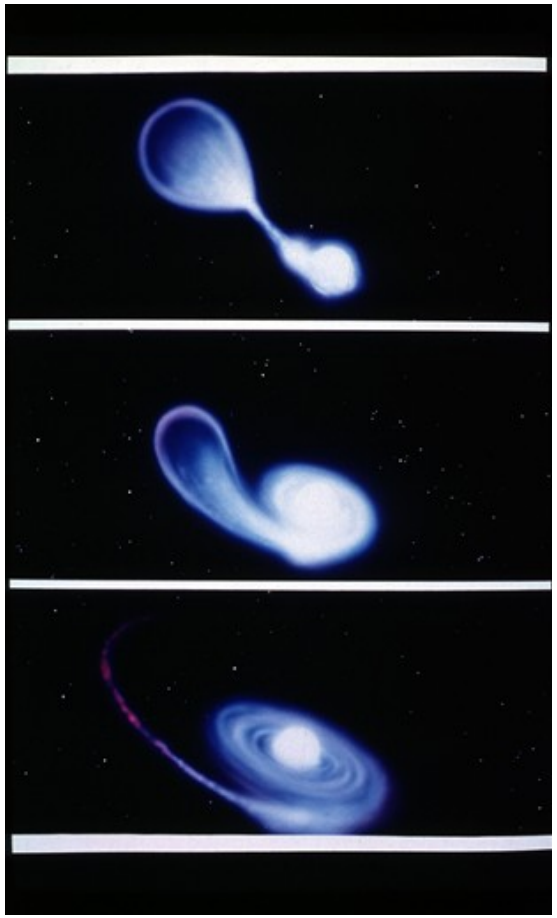
Wolf-Rayet star



Credit: NASA, ESA, CSA, STScI, Webb ERO Production Team

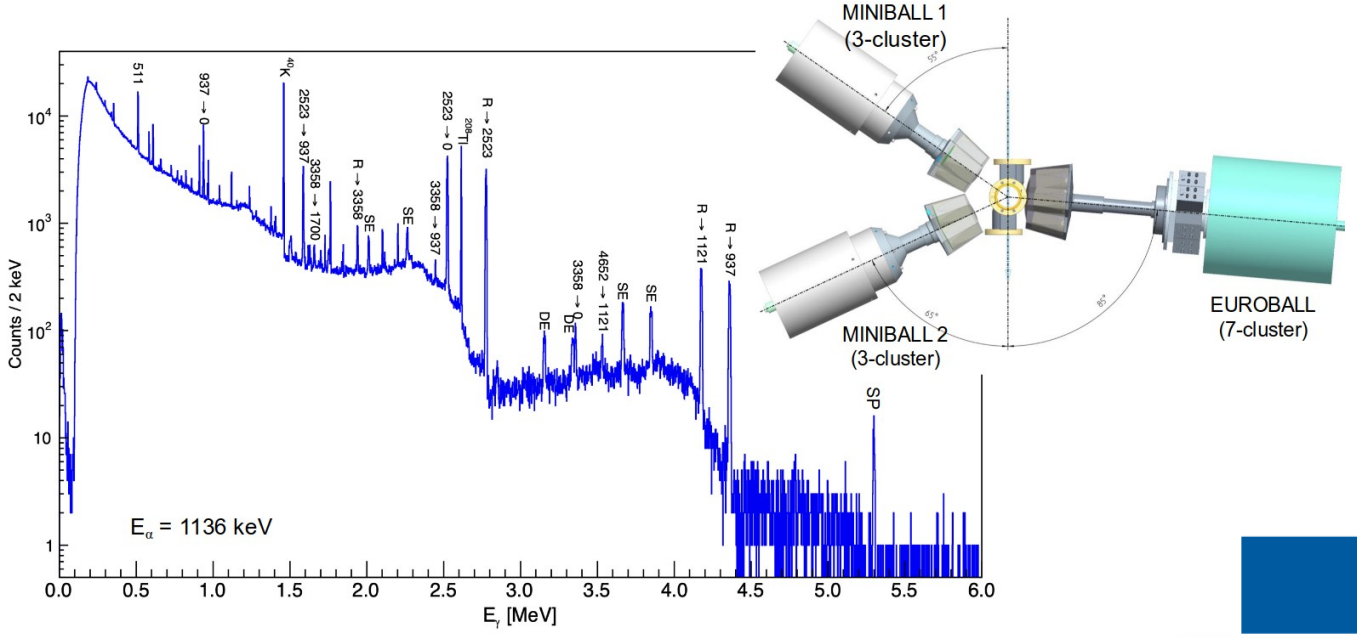
James Webb Space Telescope Hot Side

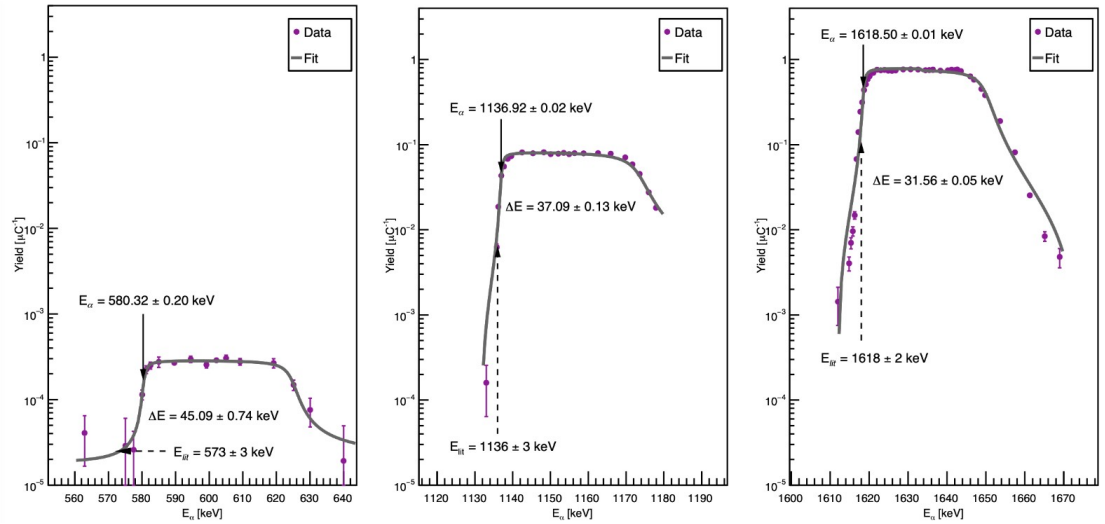
White Dwarf Merger



Credit: STScI, Dana Berry

First gas-jet target experiment: $^{14}N(\alpha,\gamma)^{18}F$ reaction





Preliminary results

Resonance energy [keV]		Resonance strength ωγ [meV]	
this work	literature	this work	literature
580.3 ± 0.2[1]	573 ± 3	4.6 ± 0.3 × 10^{-2}	4.6 ± 0.3 × 10^{-2}
1136.9 ± 0.2[1]	1136 ± 3	23.5 ± 0.6 × 10^{0}	21.1 ± 0.3 × 10^{0}
1618.1 ± 0.1[1]	1618 ± 2	4.55 ± 0.07 × 10^{2}	4.5 ± 0.5 × 10^{2}

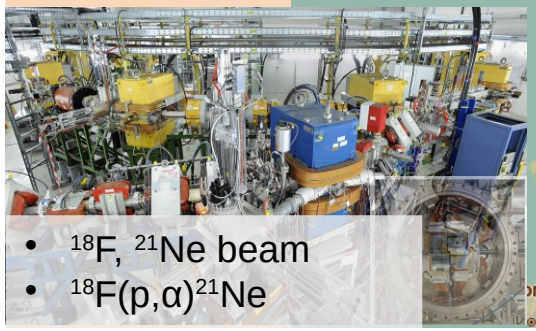
HEARTS facilities

Felsenkeller@HZDR

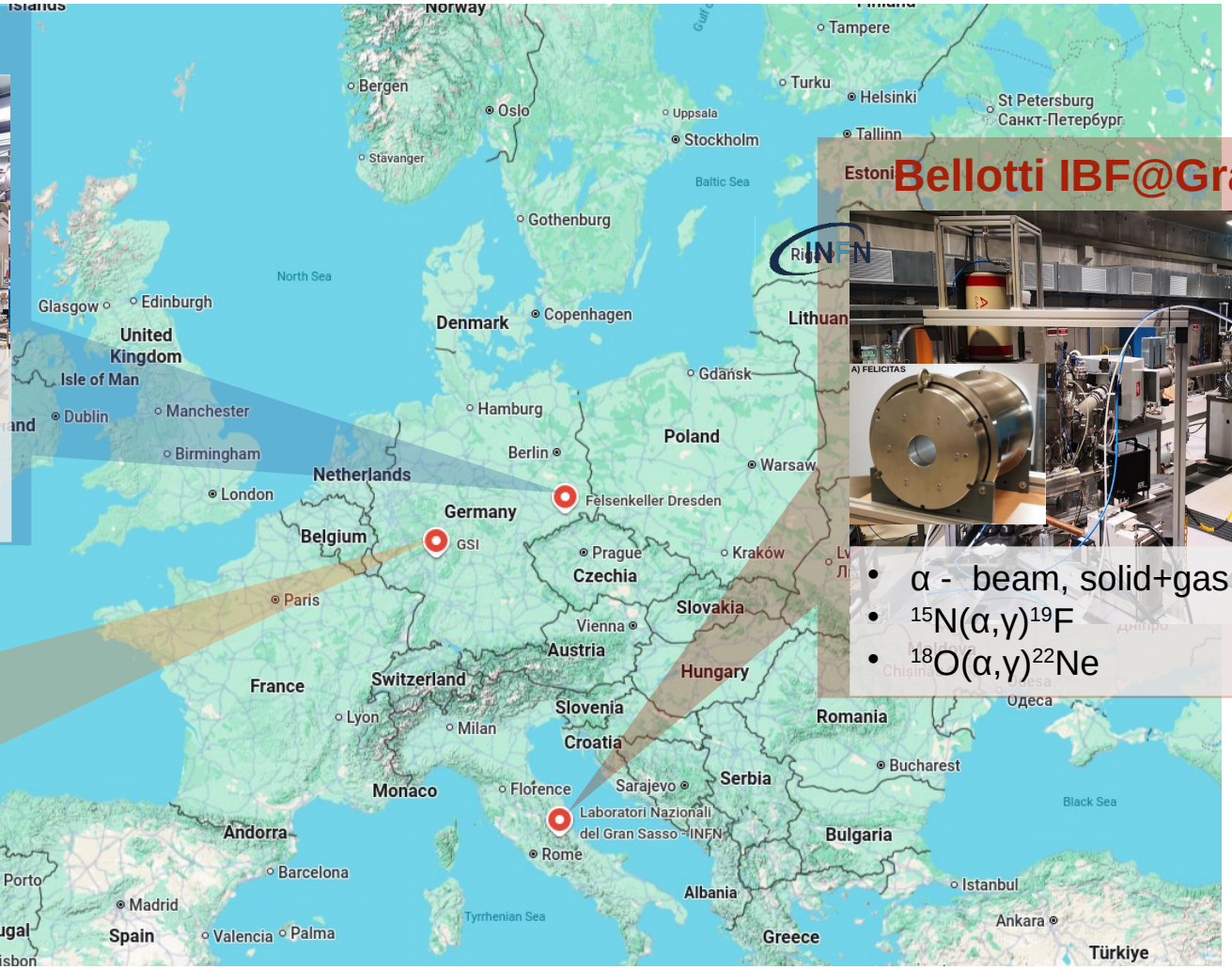


- α, ^{12}C beams
- solid+ gas-jet target
- $^{12}C(\alpha,\gamma)^{16}O$
- $^{25}Mg(\alpha,n)^{28}Si$

CRYRING@GSI



- ^{18}F, ^{21}Ne beam
- $^{18}F(p,\alpha)^{21}Ne$



Bellotti IBF@Gran Sasso

- α - beam, solid+gas target
- $^{15}N(\alpha,\gamma)^{19}F$
- $^{18}O(\alpha,\gamma)^{22}Ne$