“This presentation is part of a project that has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 101008324 (ChETEC-INFRA)”.

Nuclear Astrophysics in Underground Laboratories

17th Rußbach School for Nuclear Astrophysics 2022

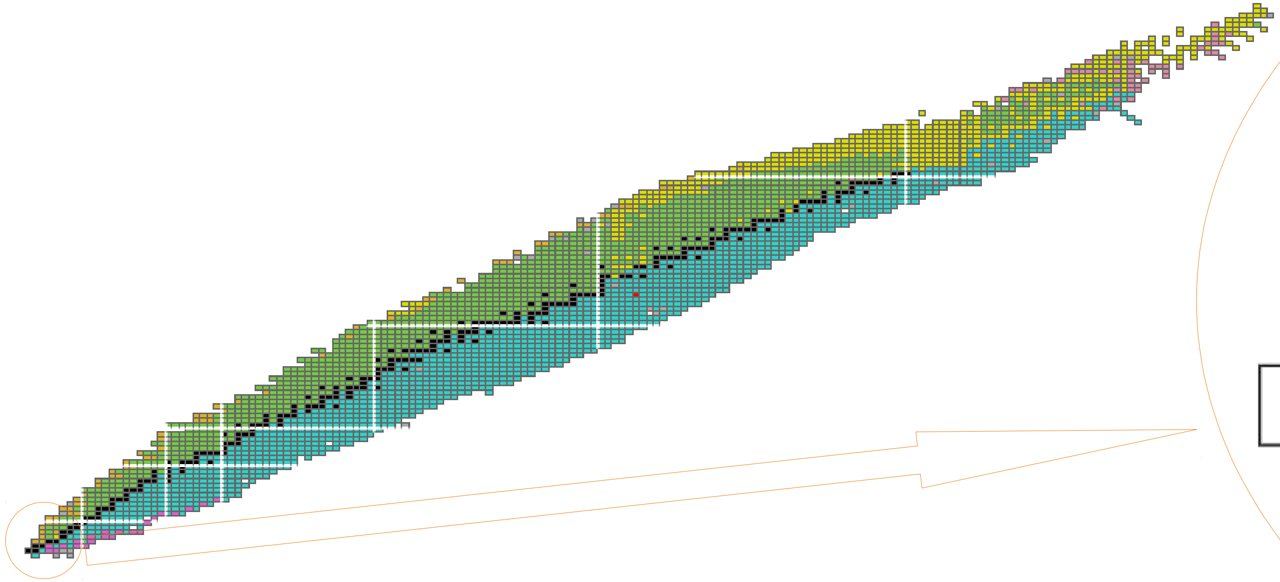
Institute of Radiation Physics · Division of Nuclear Physics · Axel Boeltzig · a.boeltzig@hzdr.de · www.hzdr.de

Introduction

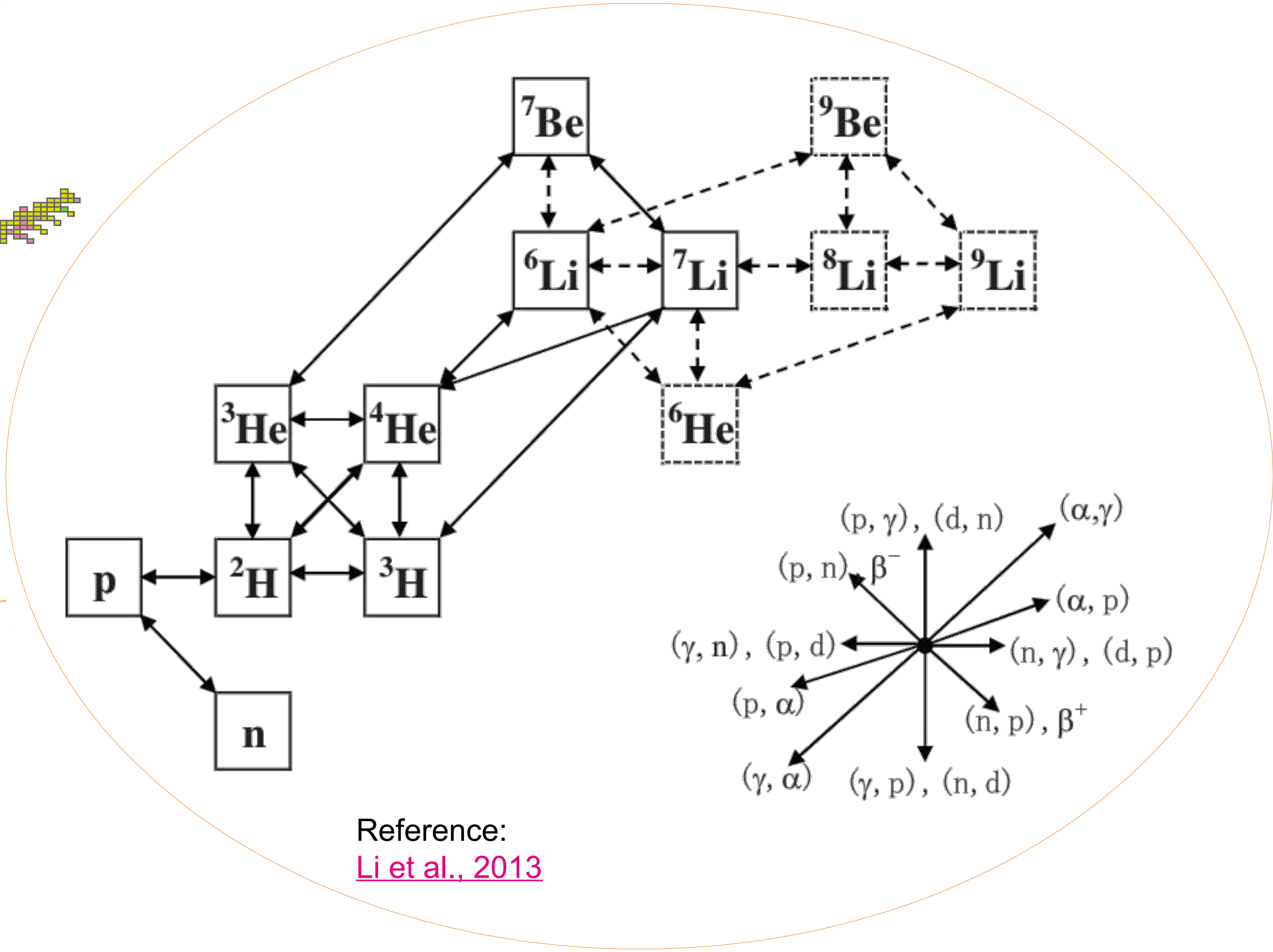
Direct Cross Section Measurements for Nuclear Astrophysics

Cross Sections for Nuclear Astrophysics

Fundamental Input for Nuclear Reaction Networks



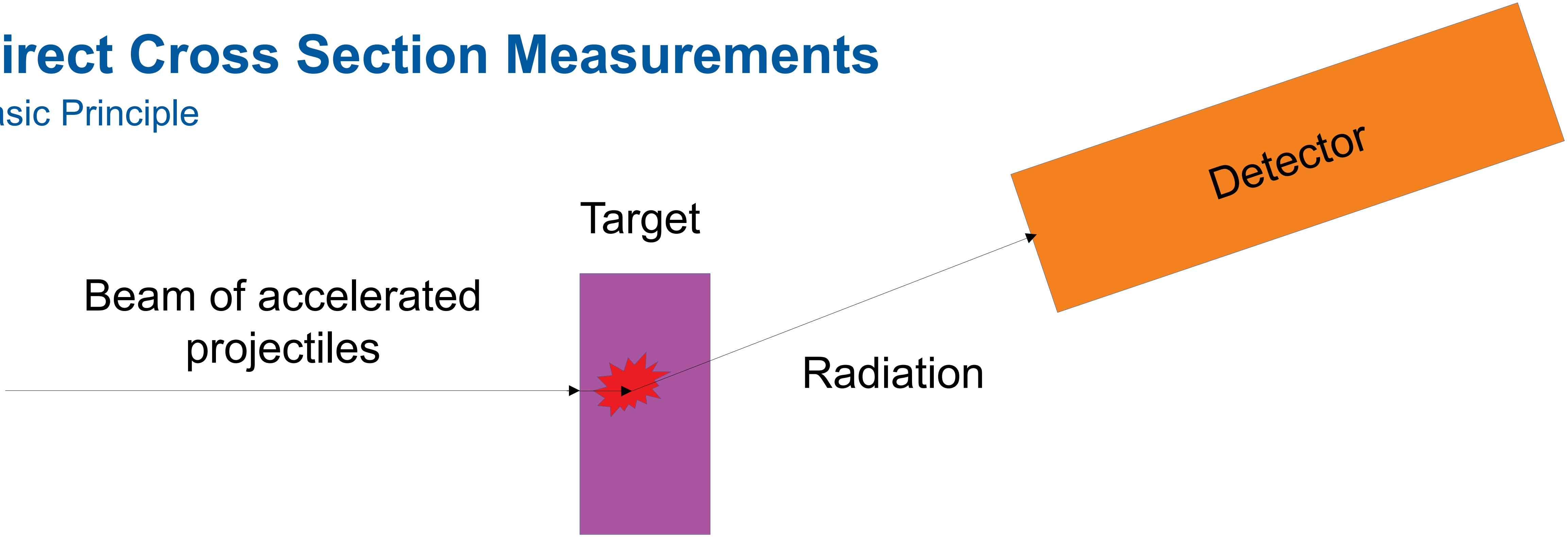
Reference:
IAEA



Reference:
Li et al., 2013

Direct Cross Section Measurements

Basic Principle



Observed Event Rate = Projectile Rate × Reaction Yield × Detection Efficiency

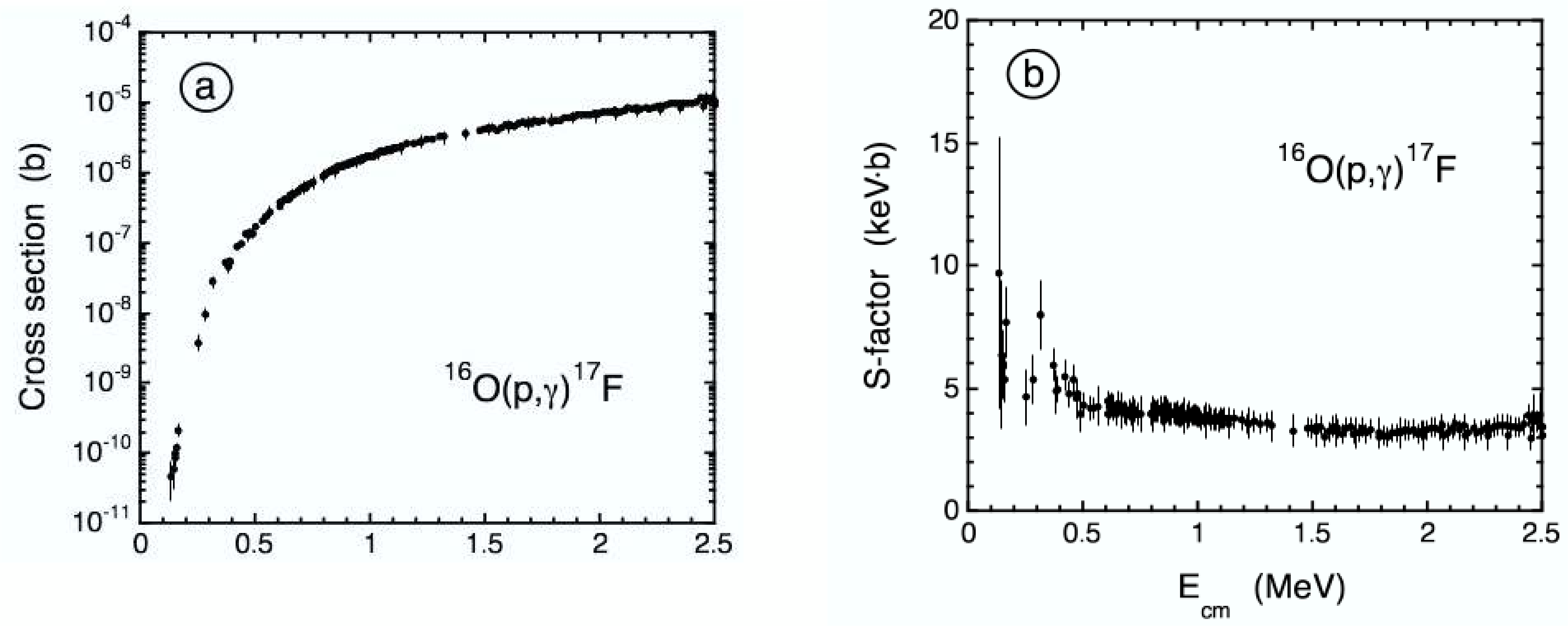
Reaction Yield = ∫ **Cross Section** / Stopping Power

Strategy:
Measure Event Rate as Function of Energy => Deduce Cross Section σ(E)

Cross Sections for Nuclear Astrophysics

Astrophysical S-factor for Charged-Particle Reactions

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

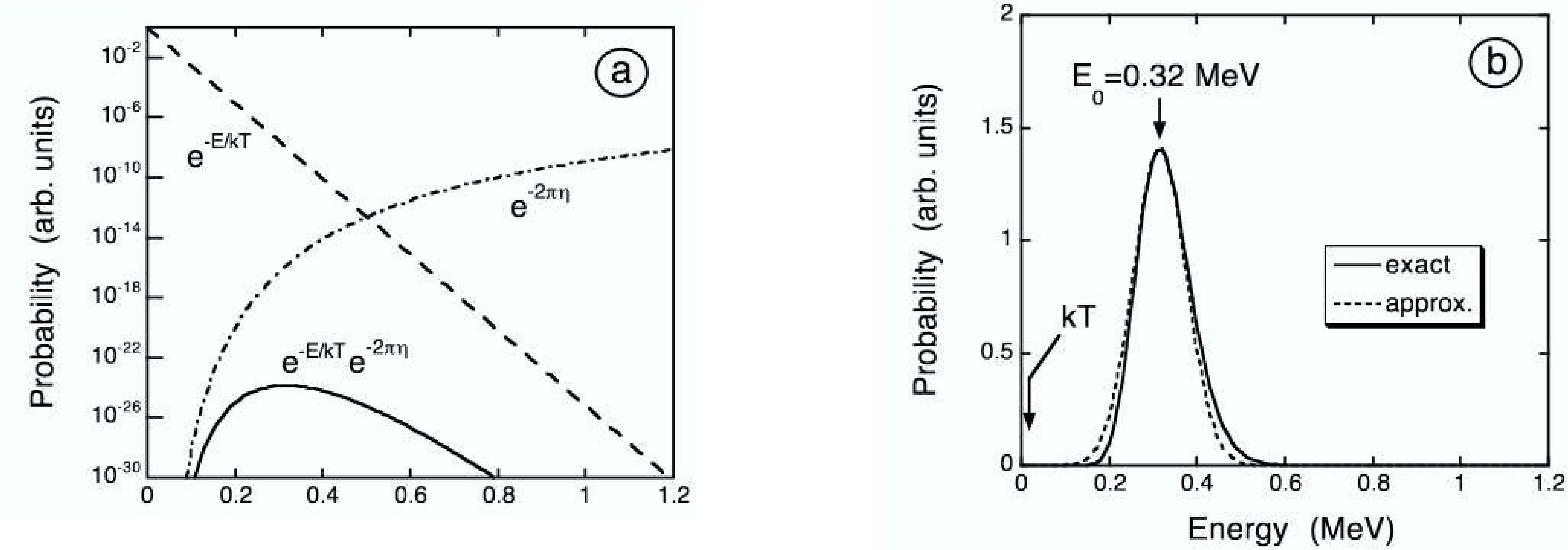


Reference: Iliadis, Nuclear Physics of Stars

Cross Sections for Nuclear Astrophysics

Reaction Rates and the Gamow Window

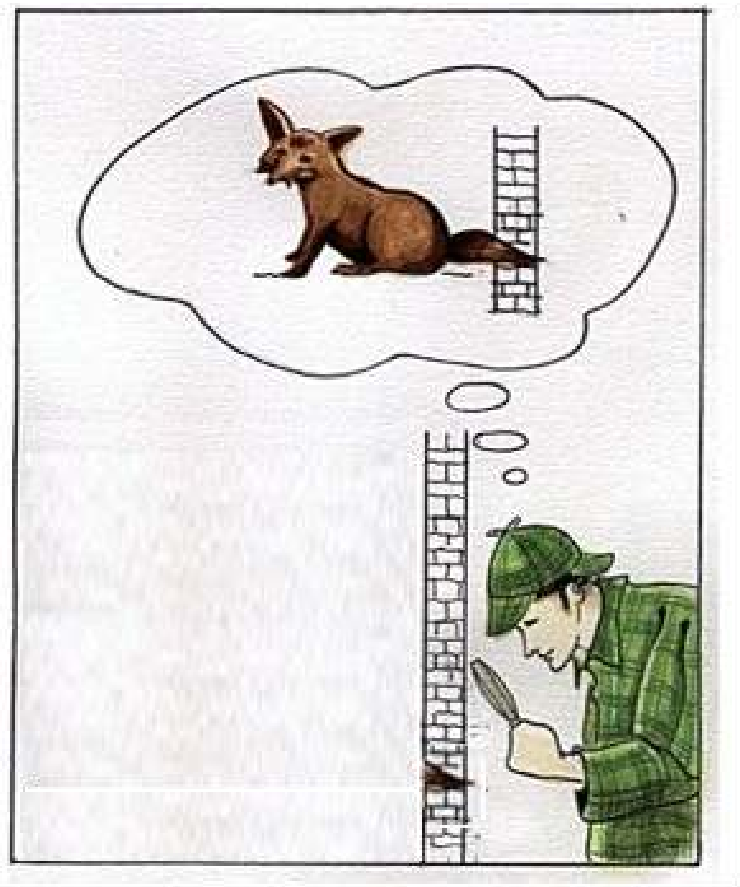
$$N_A \langle \sigma v \rangle = \left(\frac{8}{\pi m_{01}} \right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty E\,\sigma(E)\,e^{-E/kT}\,dE$$

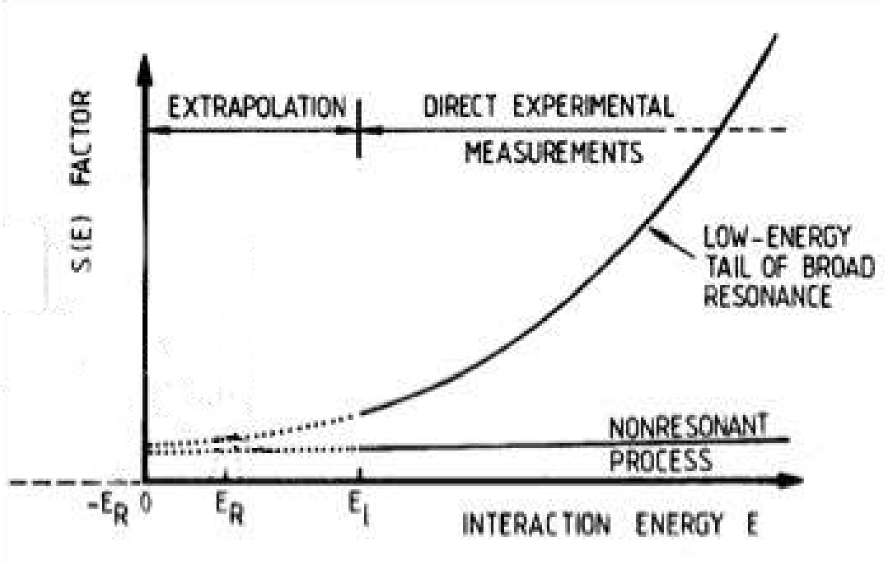


Gamow Peak for 12C(a,g) at 0.2 GK. [Iliadis, Nuclear Physics of Stars]

Cross Sections for Nuclear Astrophysics

Challenges of Extrapolations

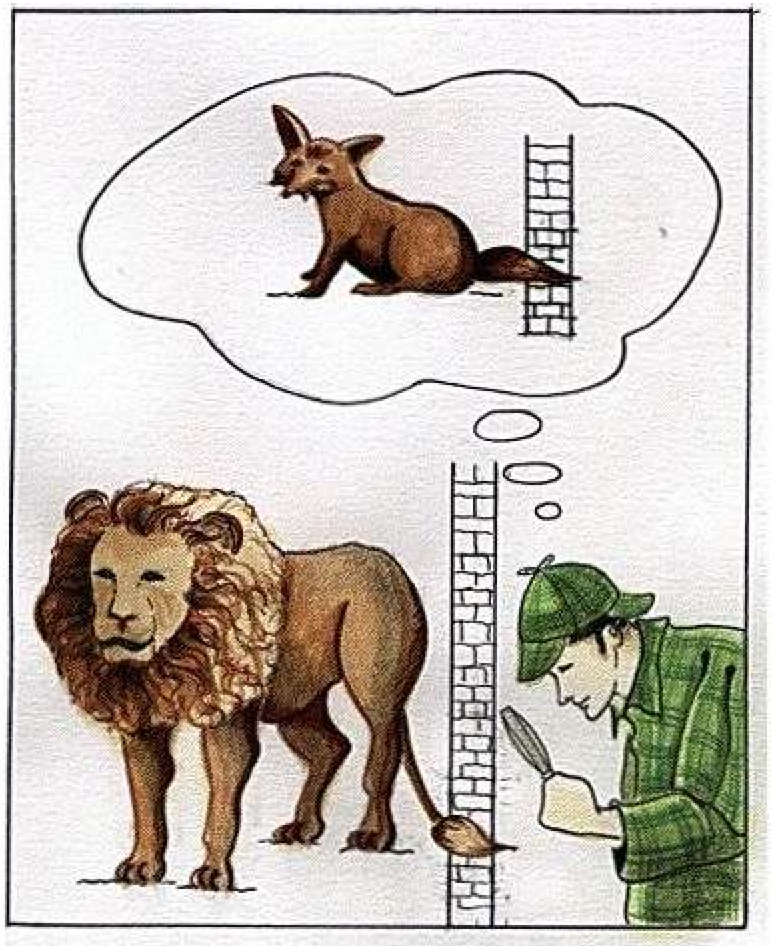


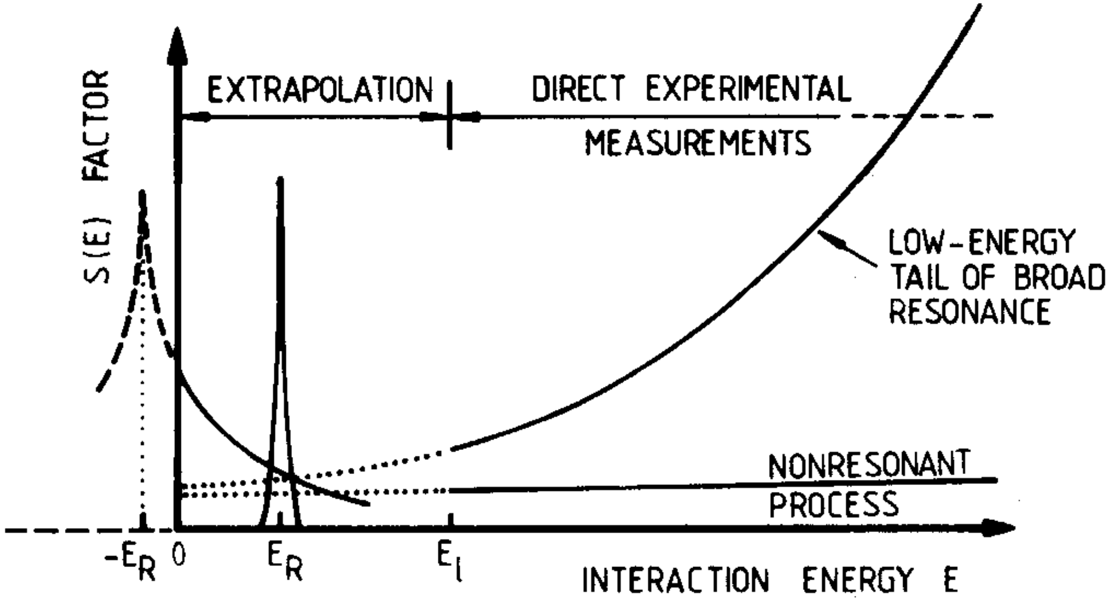


References:
P. Corvisiero,
Rolfs and Rodney: Cauldrons in the Cosmos

Cross Sections for Nuclear Astrophysics

Challenges of Extrapolations





References:
P. Corvisiero,
Rolfs and Rodney: Cauldrons in the Cosmos

Direct Cross Section Measurements

Sensitivity Limits

Background-Limited

Signals which are indistinguishable from the signature of the studied reaction increase the statistical uncertainty of the measured yield.

=> Attenuate / avoid background signals

=> Detector with more specific signatures (e.g. energy resolution)

Yield Limited

Rate of observed reactions in an experiment drops below a reasonable rate.

=> Increase detection efficiency.

=> Increase beam current.

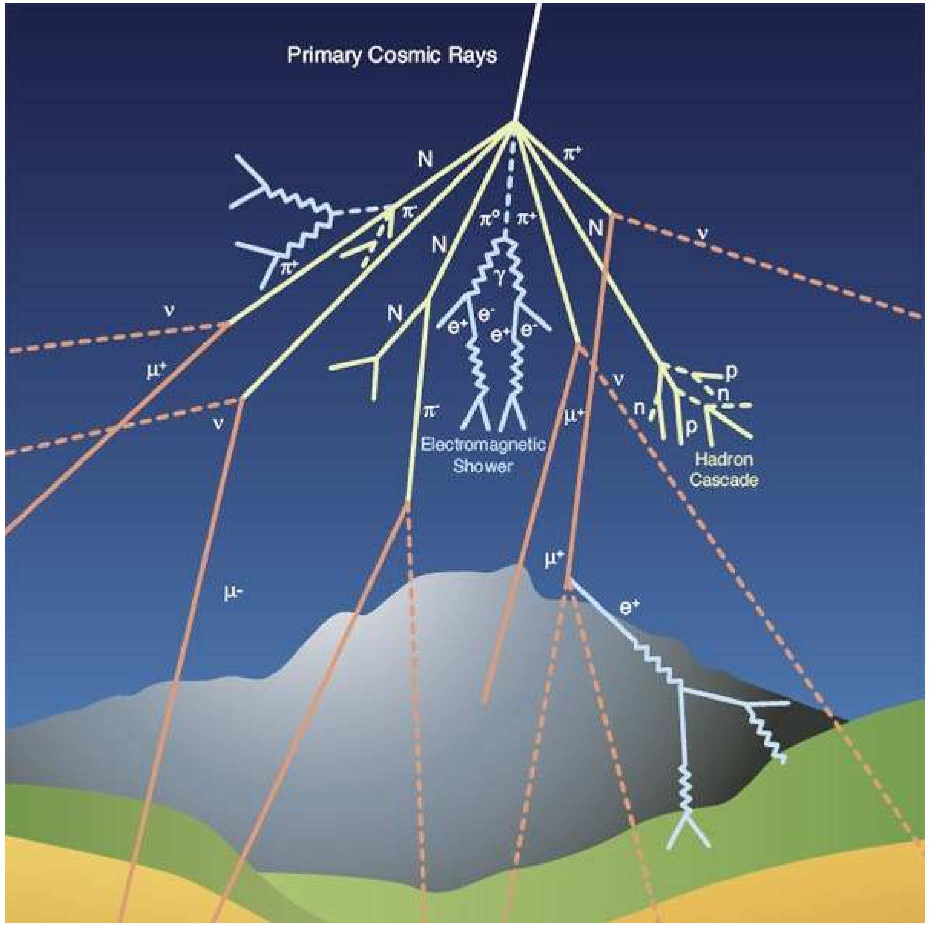
=> (Reduce effective stopping power of target.)

Going Underground

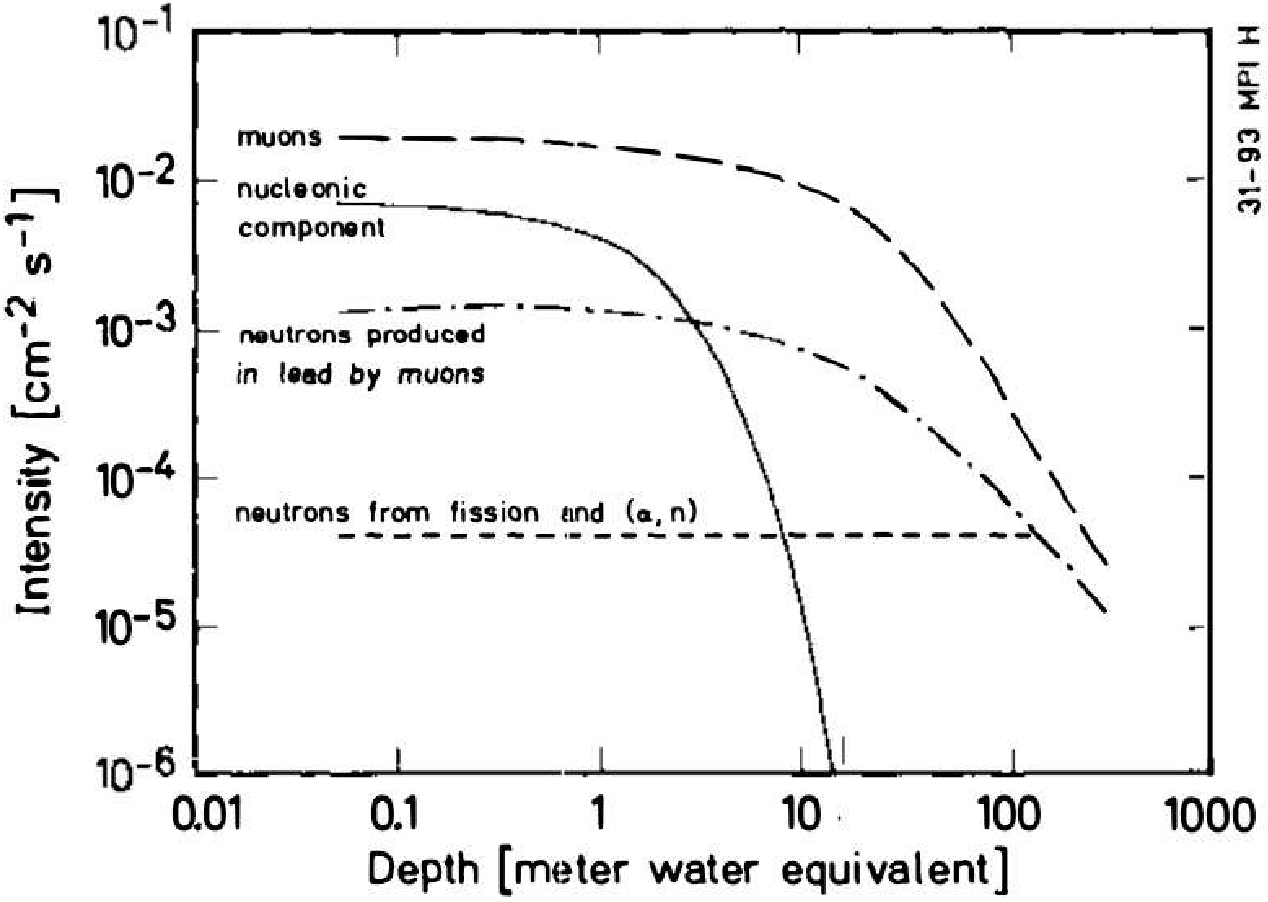
Studying the Stars from Sub-Surface Laboratories

Backgrounds from Cosmic Radiation

Sensitivity and Requirements



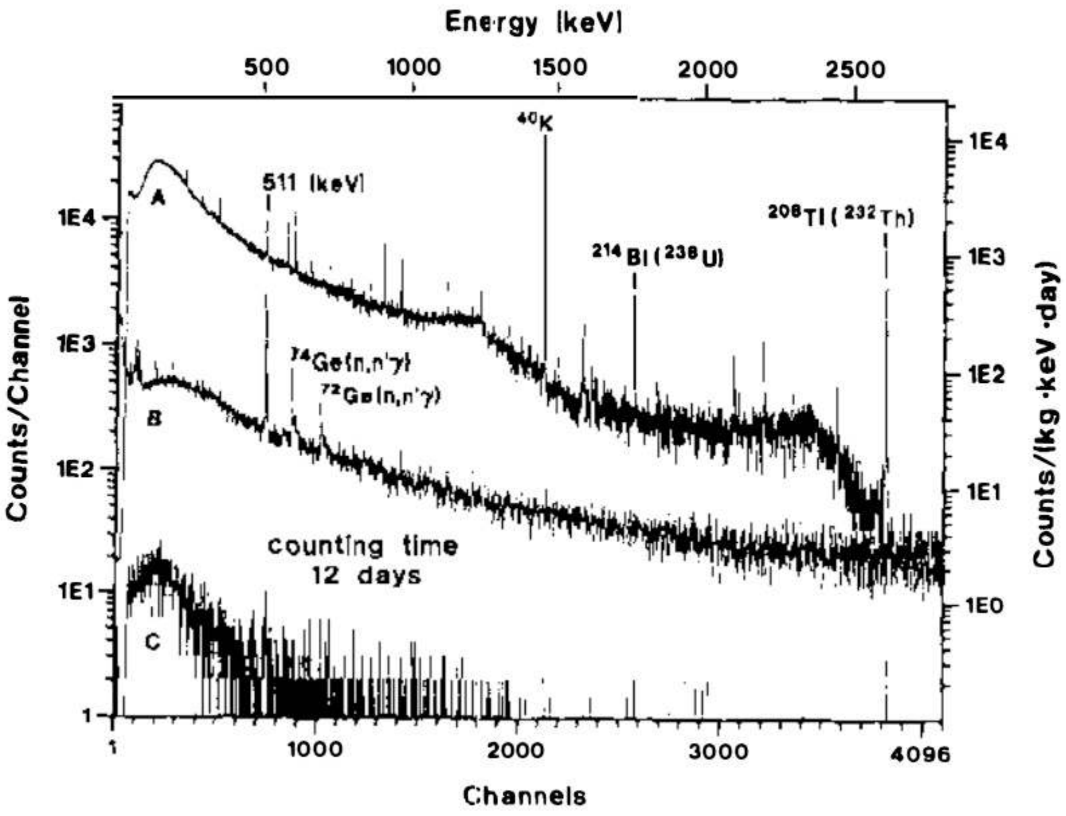
Reference: CERN



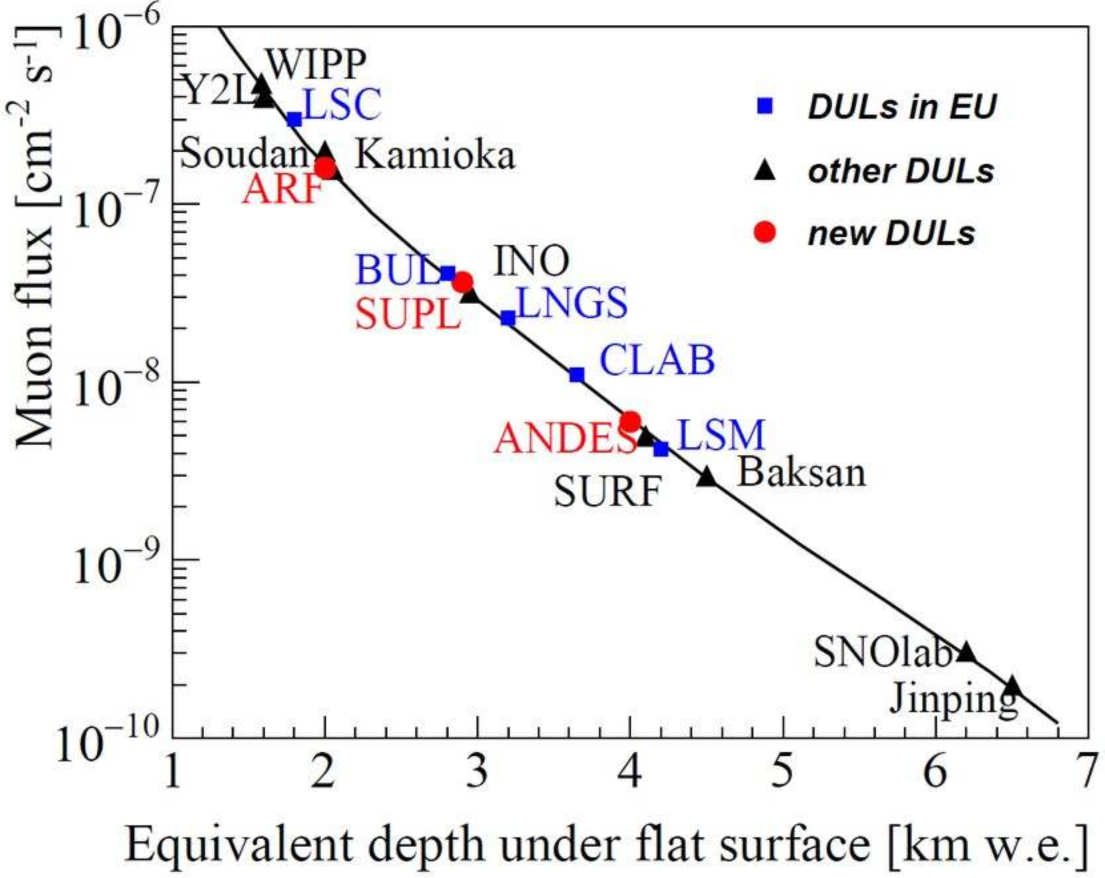
Reference: Heusser, 1995

Backgrounds from Cosmic Radiation

Sensitivity and Requirements



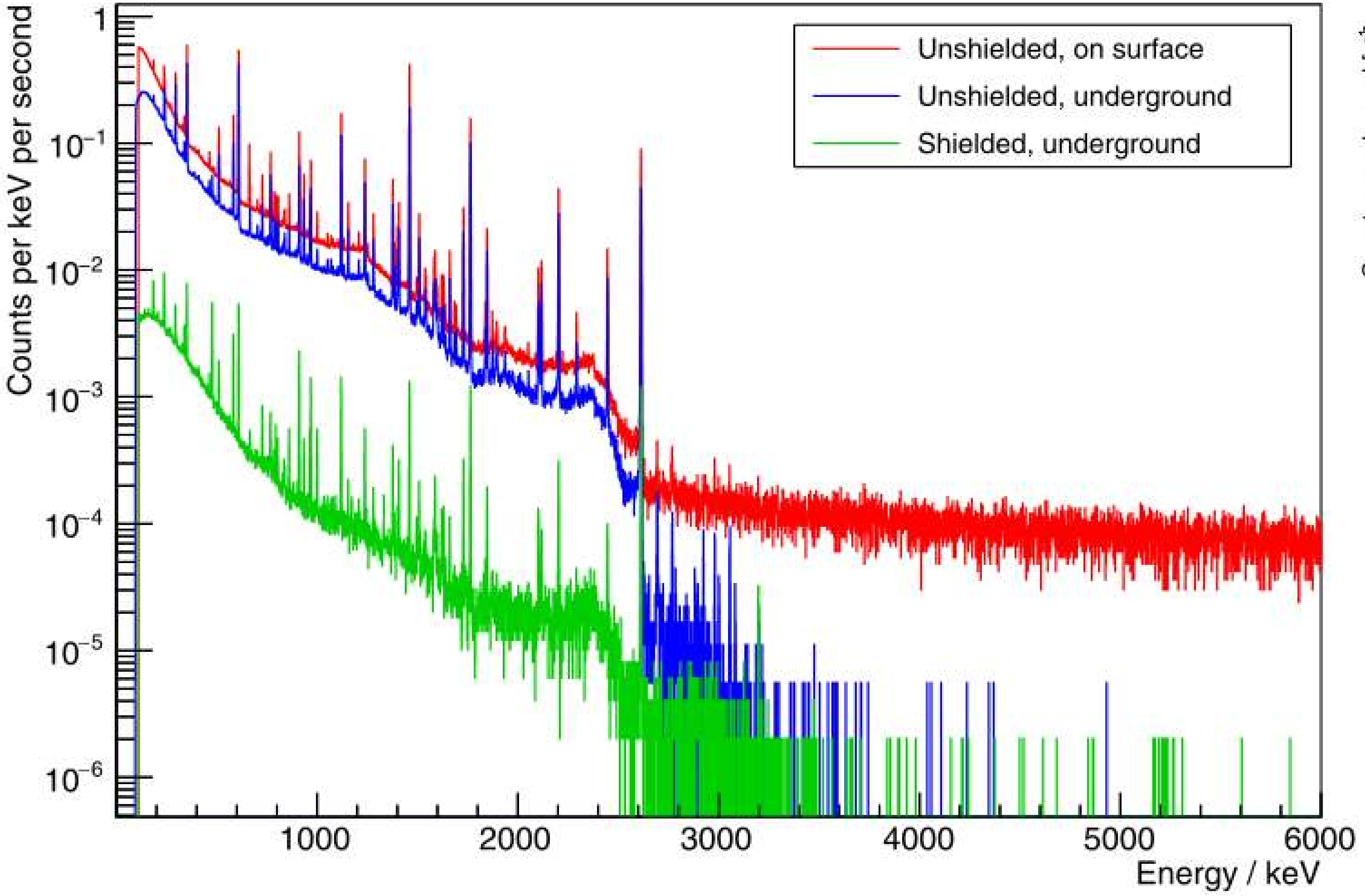
Muon flux on surface: ~10^{-2} $cm^{-2}s^{-1}$

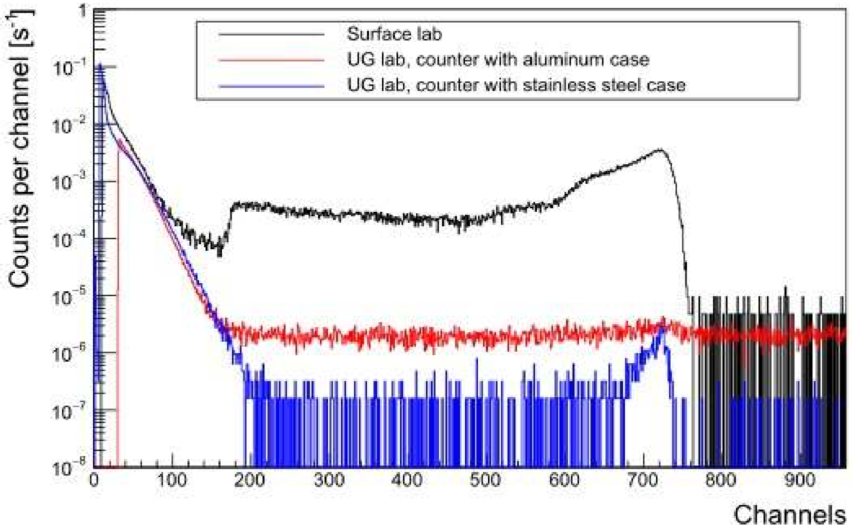


References: Heusser, 1995, Belli et al., 2021

Backgrounds from Cosmic Radiation

Sensitivity and Requirements





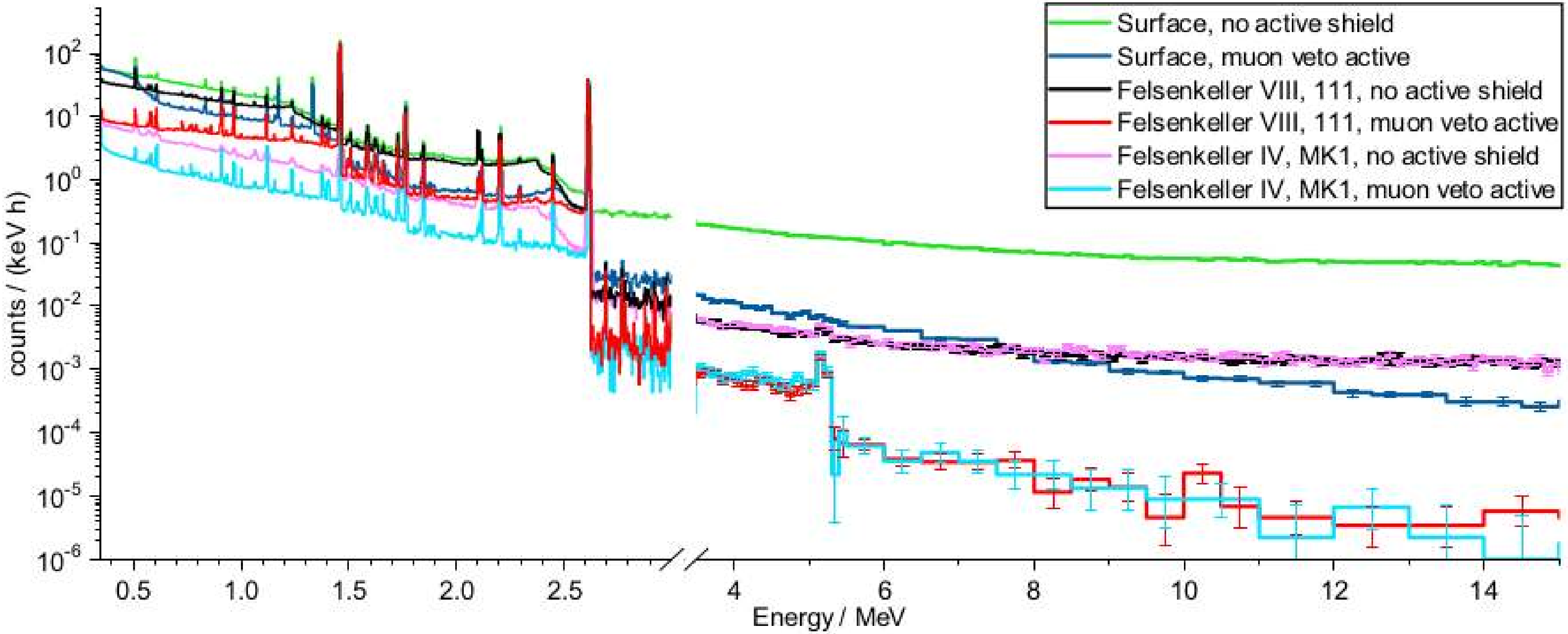
Top: Background 3He Proportional Counter

Left: Backgrounds in a High-Purity Germanium (HPGe) Detector

Reference:
Ferraro et al., 2021

Backgrounds from Cosmic Radiation

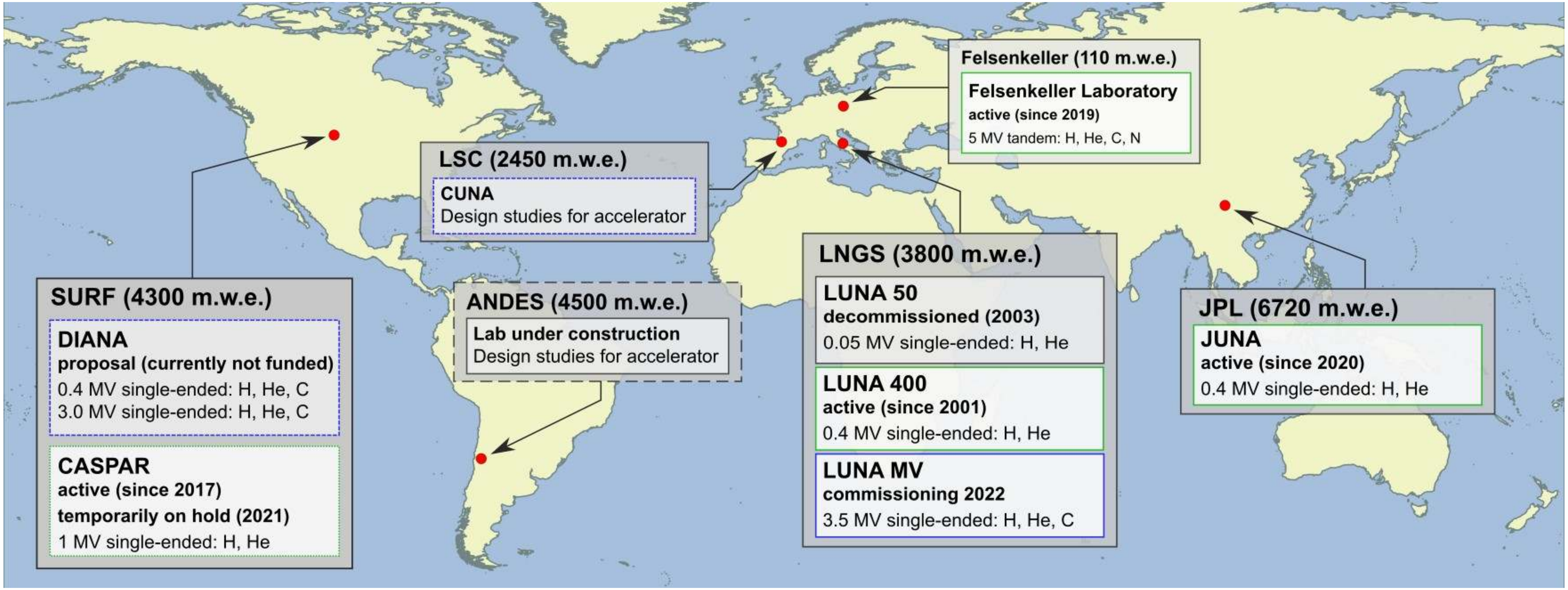
Cosmic Muon Veto / Active Shielding



Reference:
Szücs et al., 2019

Underground Accelerator Facilities Around the World

World Map



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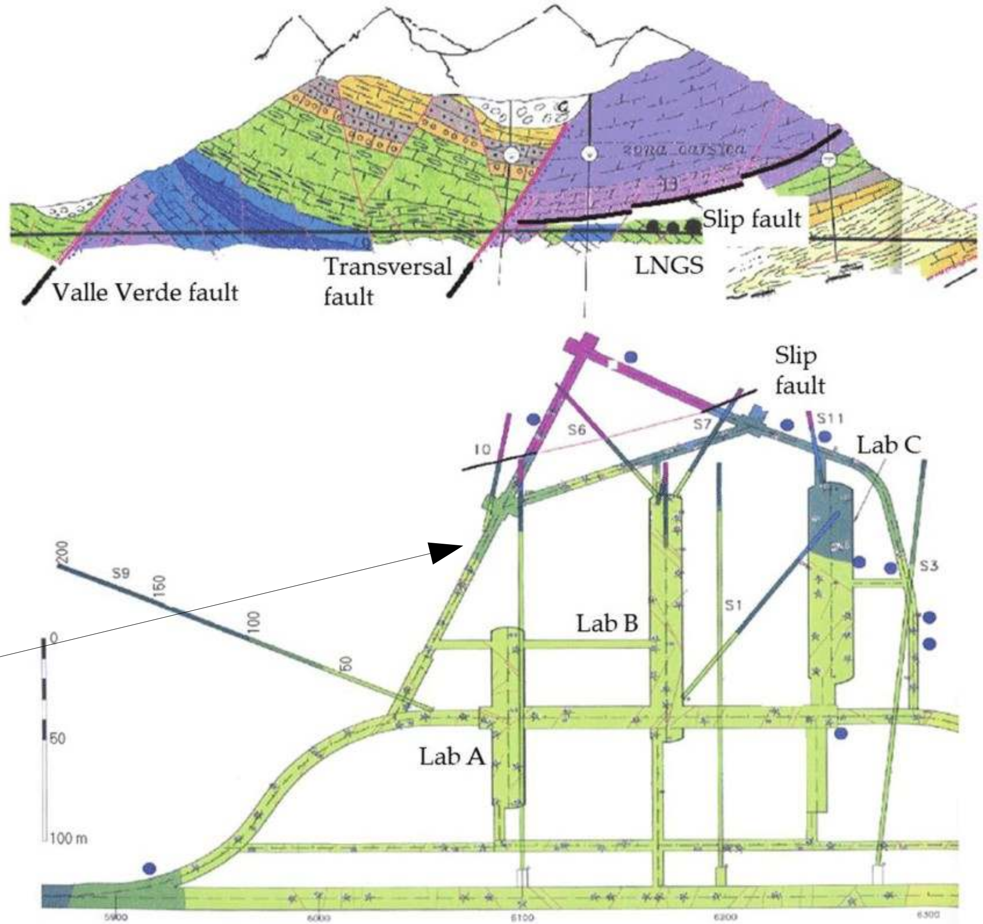
Underground Accelerator Facilities Around the World

LUNA at the Gran Sasso National Laboratory: LNGS and LUNA-50



References:
S. Rosone, P. Corvisiero, Guidotti 2018

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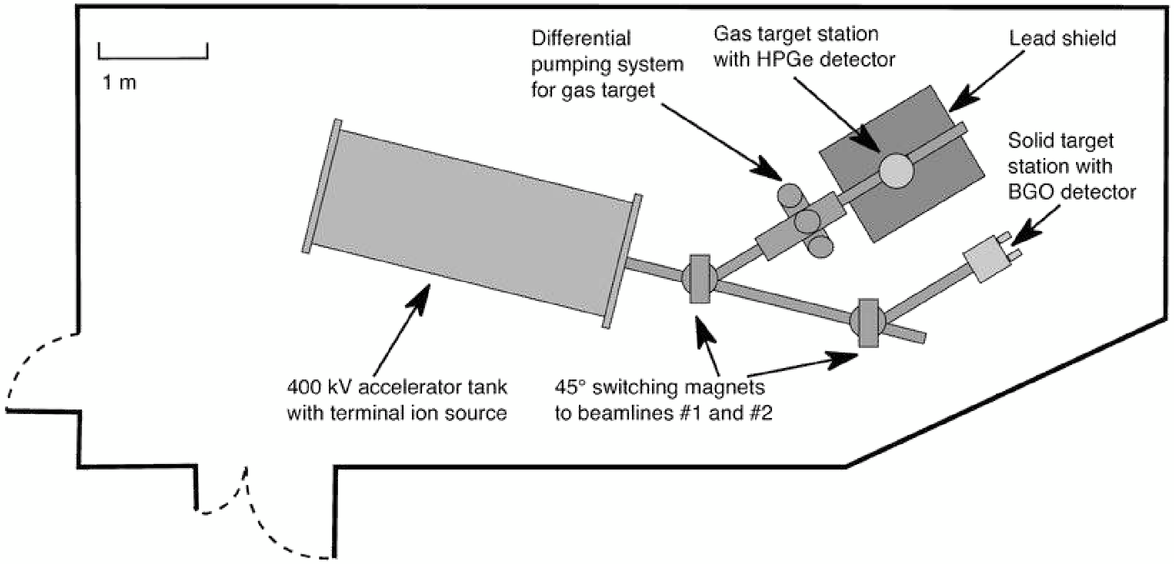
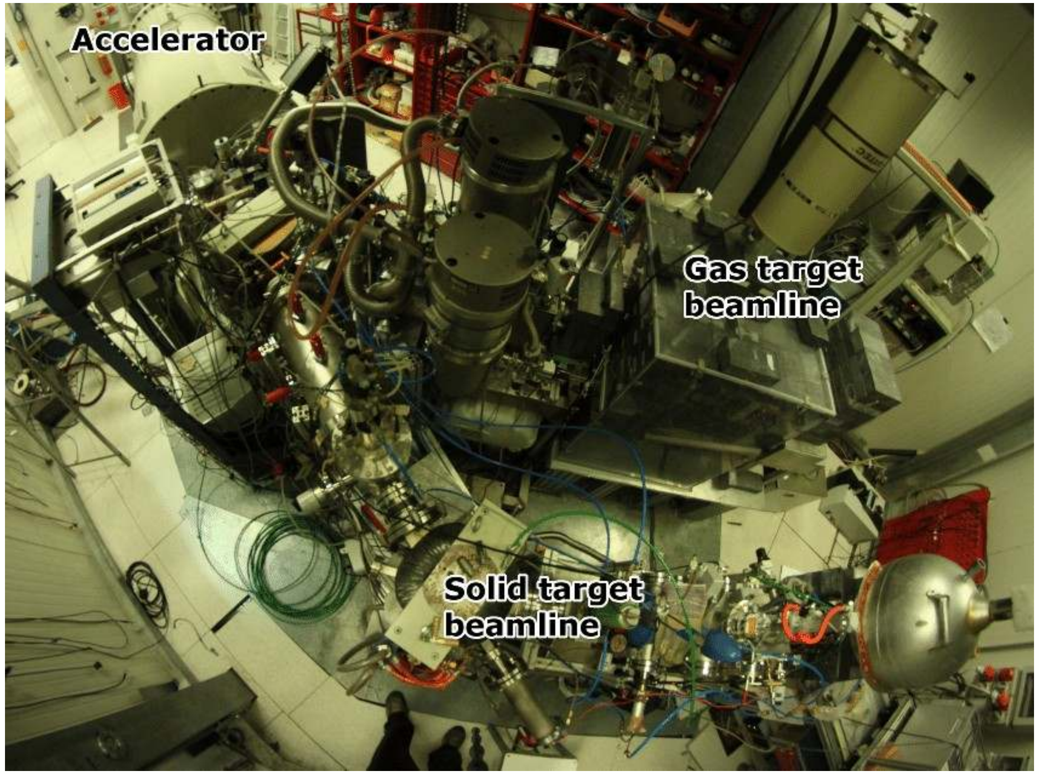
Underground Accelerator Facilities Around the World

LUNA at the Gran Sasso National Laboratory: LUNA-400





High-intensity (~300 uA) beam,
high beam stability,
small energy spread

Two beam lines: equipped with gas and solid target stations

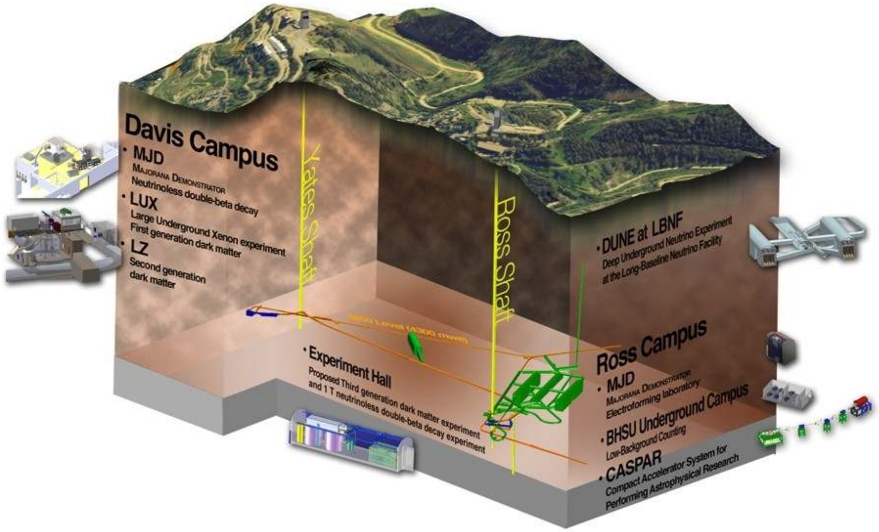
References:
P. Corvisiero, Bruno 2019,
Formicola et al. 2003, Broggini 2016

Underground Accelerator Facilities Around the World

CASPAR at the Sanford Underground Laboratory (SURF)

Refurbished 1 MV accelerator

Single beam line (solid or gas target)



References:
B. Frentz, SDSMT, CASPAR

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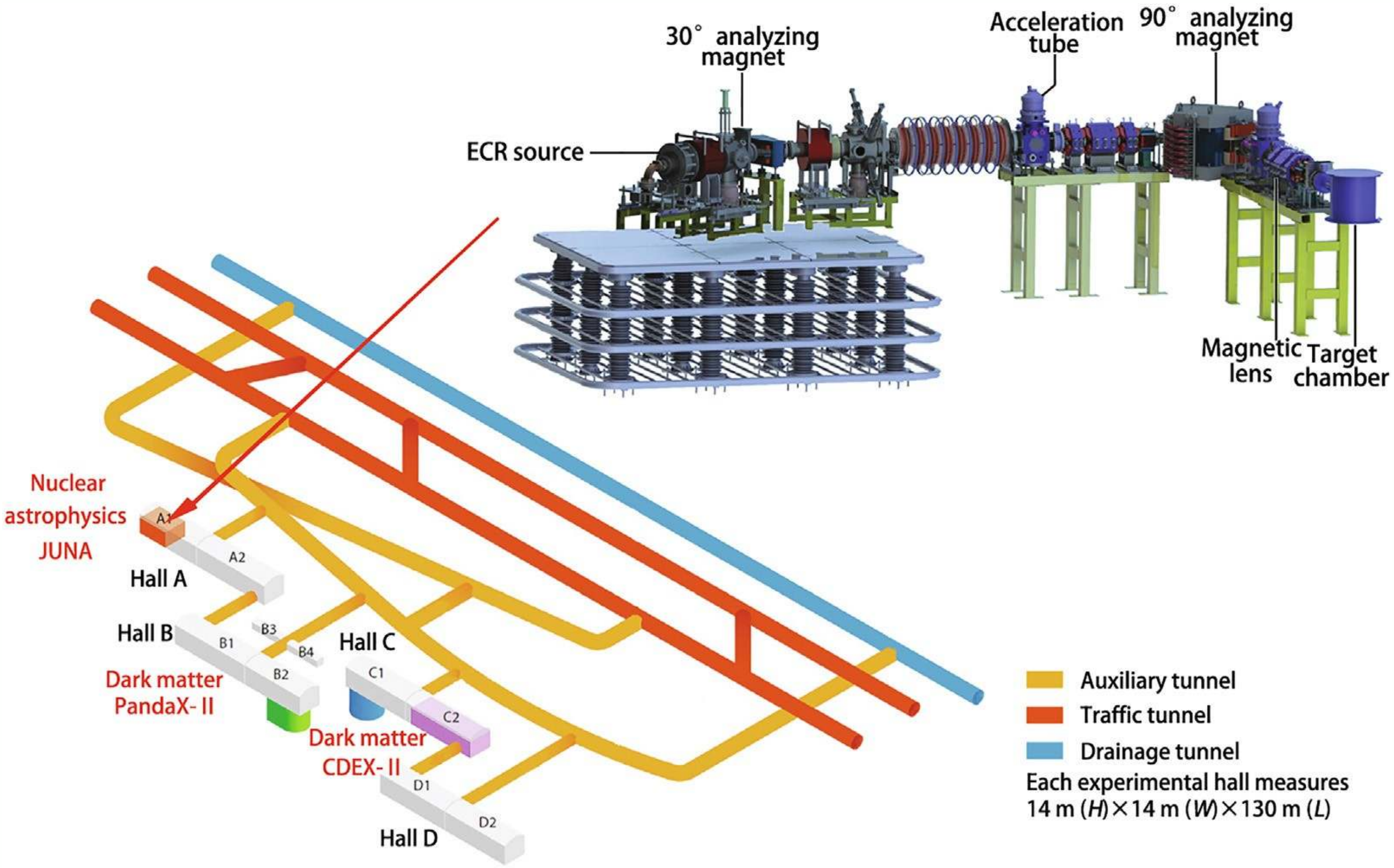
Underground Accelerator Facilities Around the World

JUNA at the China Jinping Underground Laboratory (CJPL)



400 kV terminal voltage

High-intensity beams

Goal

Beam	Intensity, mA	Energy,keV
H^+	10	70-400
He^+	10	70-400
He^{++}	2	140-800

Achieved

Beam	Intensity, mA	Energy,keV
H^+	12	350
He^+	2.5	350
He^{++}	1	800

Reference:
Su et al., 2021,
W. Liu

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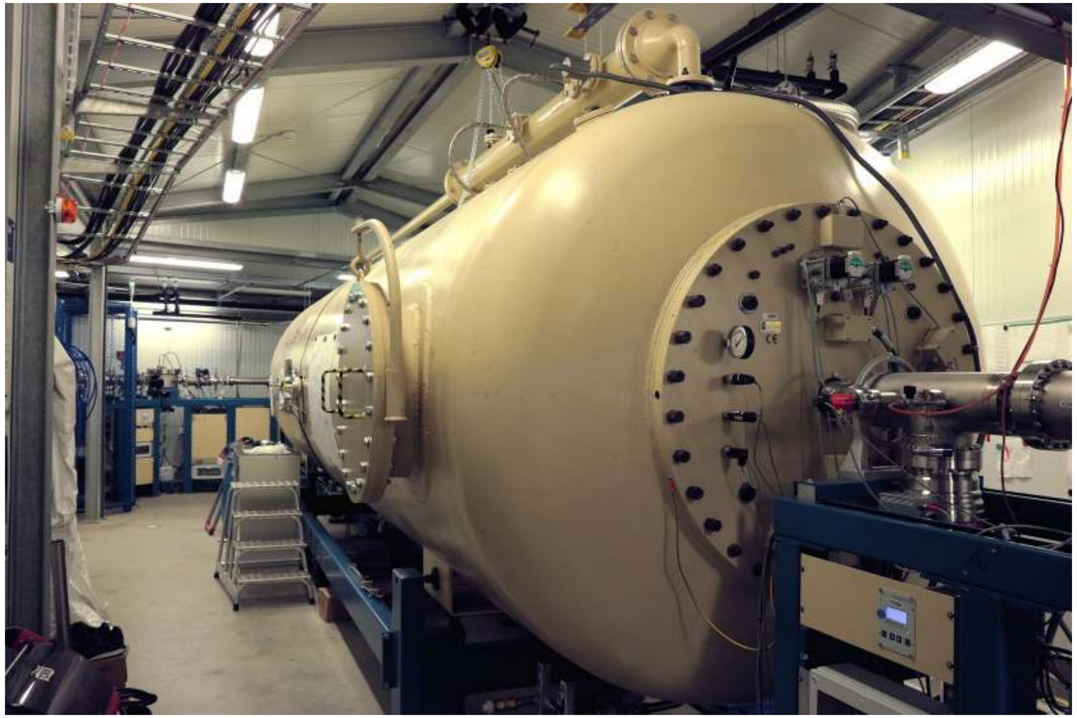
Underground Accelerator Facilities Around the World

Felsenkeller Laboratory



Refurbished 5 MV accelerator

Usable with internal ion source (single-ended), or external SNICS source (tandem)

References: G. Rugel, HZDR

Underground Accelerator Facilities Around the World

The 3.5MV Accelerator at LNGS (LUNA-MV)

H
- $^{1}H^{+}$ (TV: 0.3 – 0.5 MV): 500 μA
- $^{1}H^{+}$ (TV: 0.5 – 3.5 MV): 1000 μA

He
- $^{4}He^{+}$ (TV: 0.3 – 0.5 MV): 300 μA
- $^{4}He^{+}$ (TV: 0.5 – 3.5 MV): 500 μA

C
- $^{12}C^{+}$ (TV: 0.3 – 0.5 MV): 100 μA
- $^{12}C^{+}$ (TV: 0.5 – 3.5 MV): 150 μA
- $^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 μA

inline Cockcroft Walton accelerator

TERMINAL VOLTAGE: 0.2 – 3.5 MV

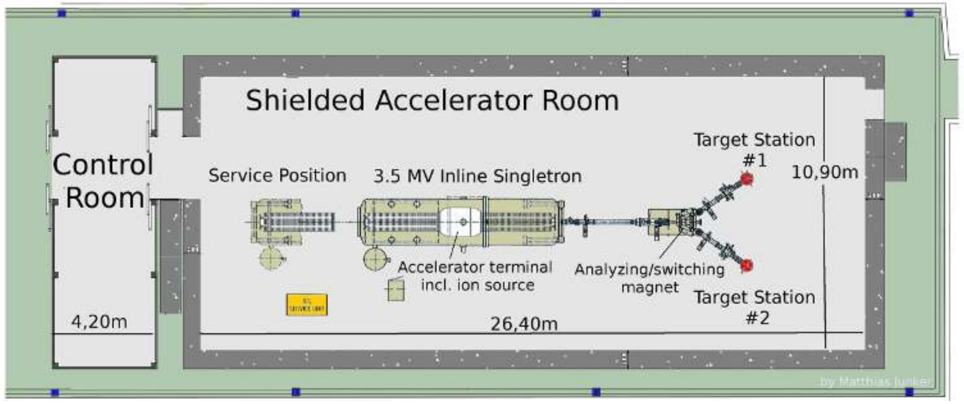
Precision of terminal voltage reading: 350 V

Beam energy reproducibility: 0.01% TV

Beam energy stability: 0.001% TV / hrs

Beam current stability: < 5% / hrs

Currently being set up, commissioning experiments in 2022



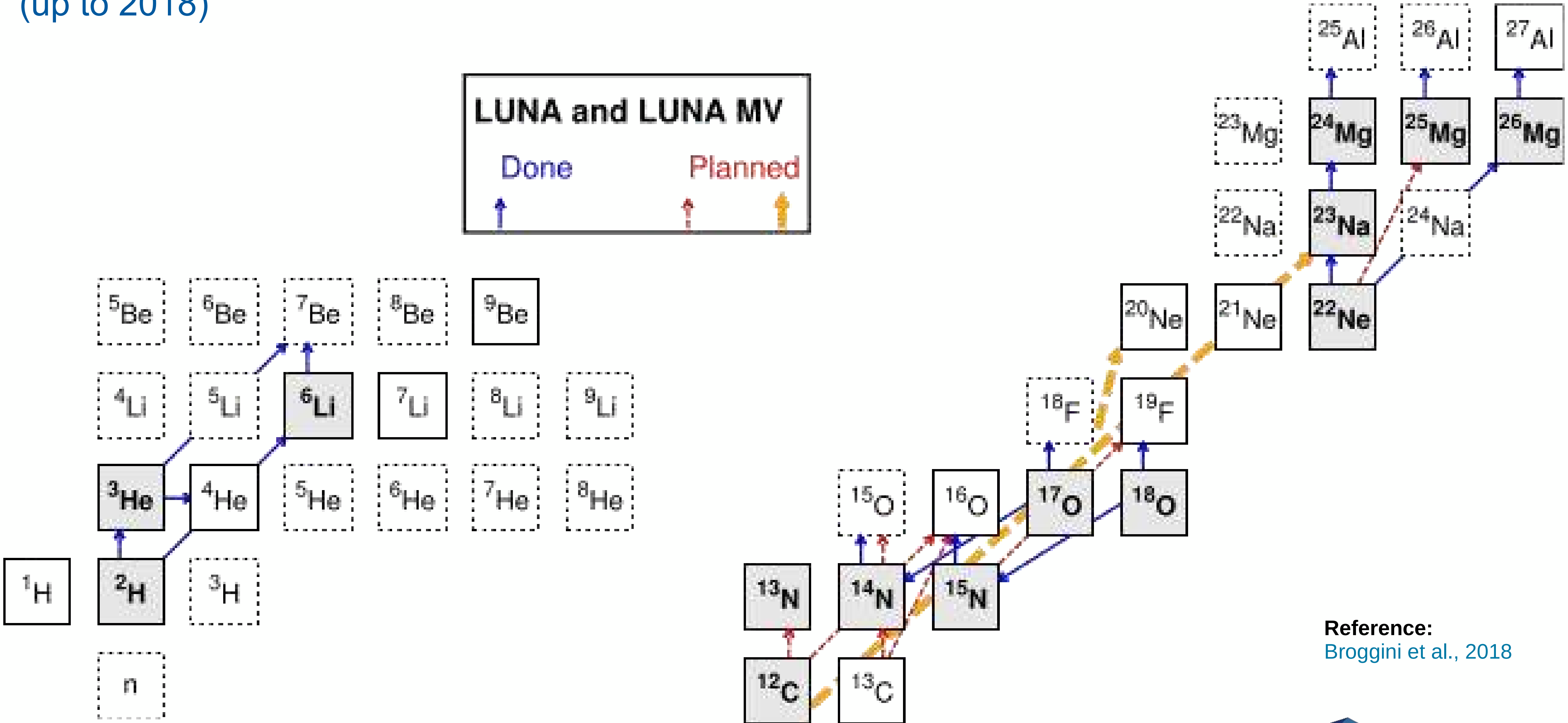
References:
Sen et al., 2019, P. Prati, 2020
LNGS Accelerator Service

Contributions of Underground Measurements

Measurements and Challenges

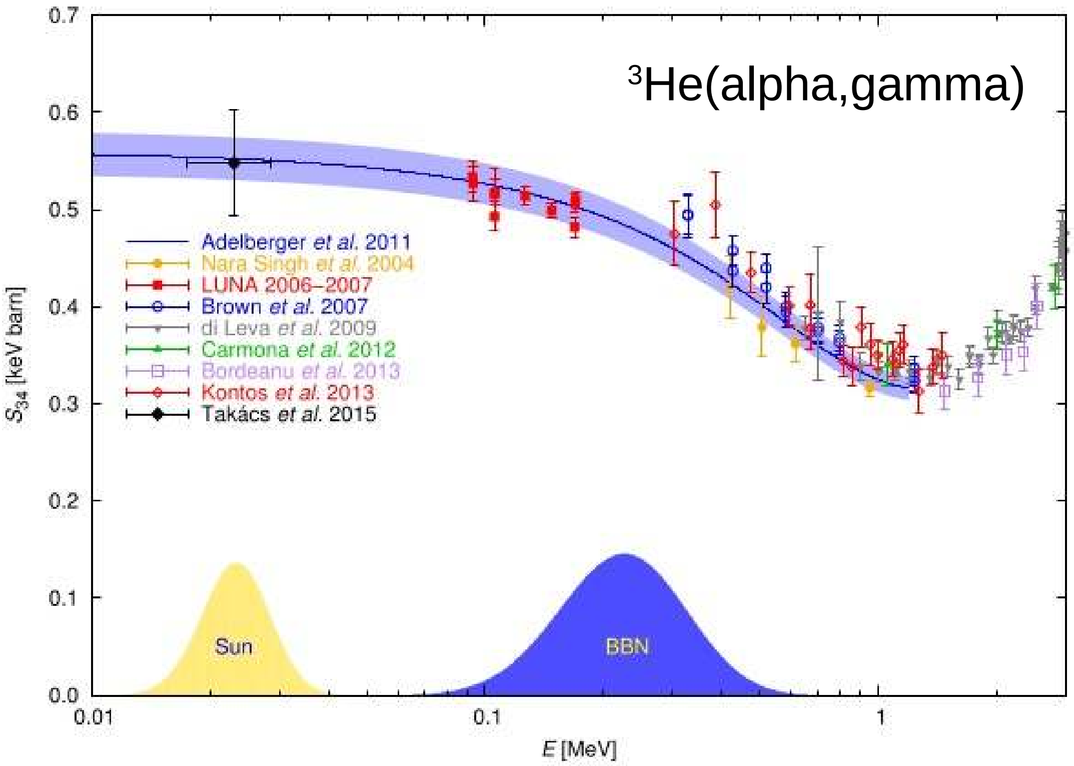
Measurements at LUNA

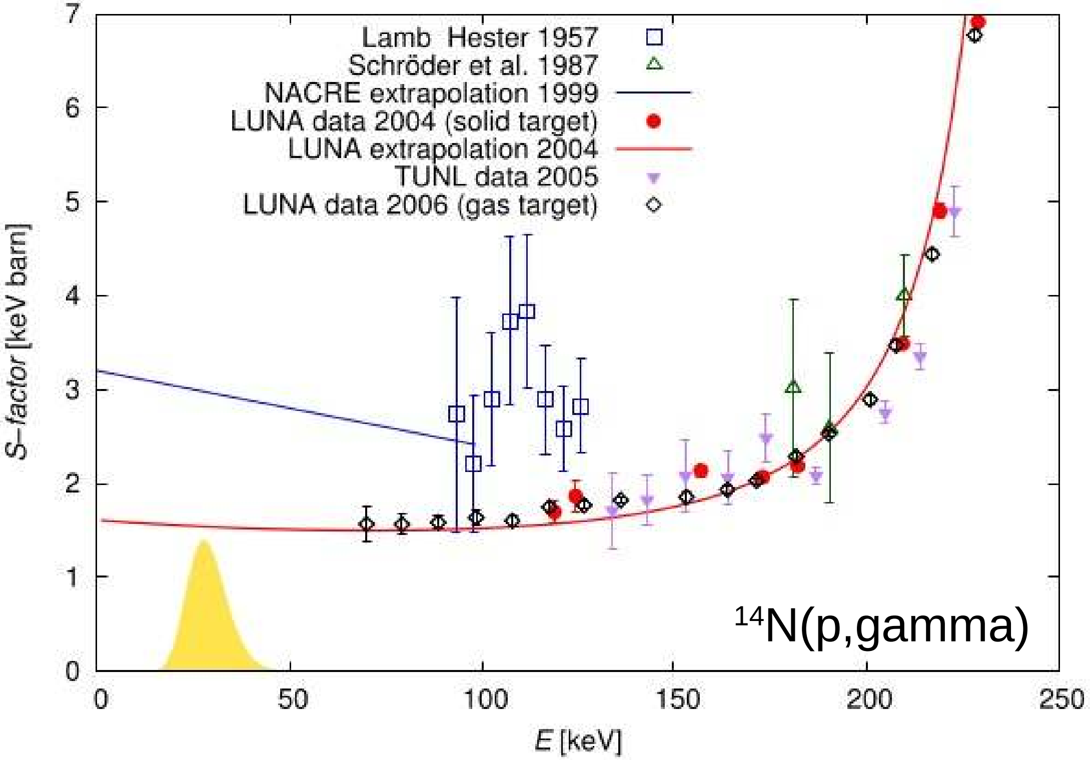
(up to 2018)



Reference:
Broggini et al., 2018

Improved Extrapolations with Low-Energy Data





Reference:
Broggini et al., 2018

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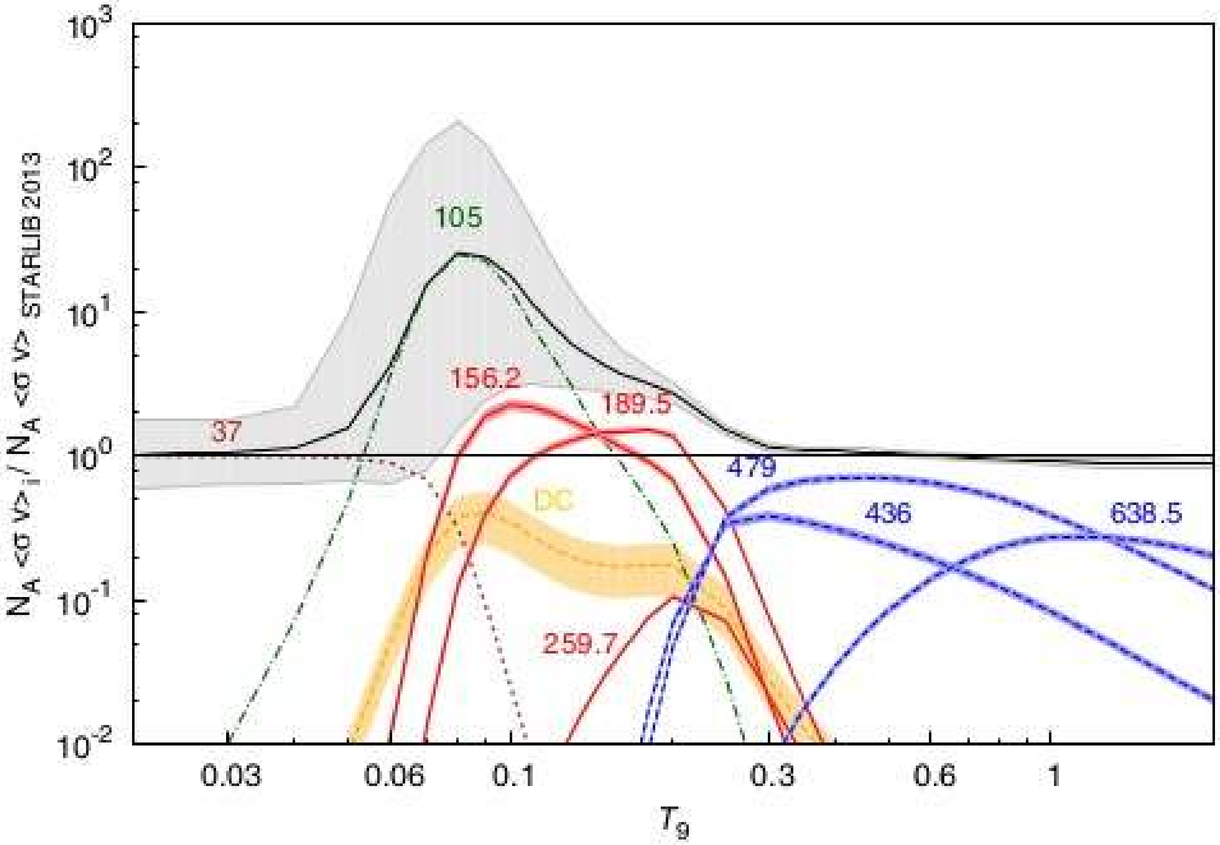
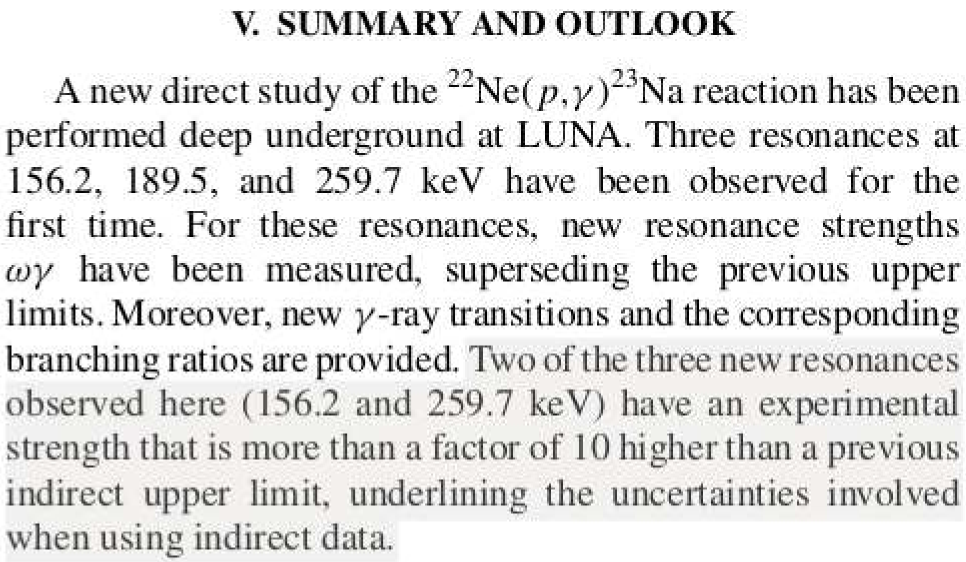
Study of Narrow Resonances

Revised Resonance Strengths in ^{22}Ne(p,γ)




V. SUMMARY AND OUTLOOK

A new direct study of the ^{22}Ne$(p,\gamma)^{23}$Na reaction has been performed deep underground at LUNA. Three resonances at 156.2, 189.5, and 259.7 keV have been observed for the first time. For these resonances, new resonance strengths $\omega\gamma$ have been measured, superseding the previous upper limits. Moreover, new γ-ray transitions and the corresponding branching ratios are provided. Two of the three new resonances observed here (156.2 and 259.7 keV) have an experimental strength that is more than a factor of 10 higher than a previous indirect upper limit, underlining the uncertainties involved when using indirect data.

References:

Cavanna et al. 2015
Depalo et al. 2016
Cavanna et al. 2018

Activation Measurements

Offline Counting

STELLA at LNGS (near LUNA)

TU Counting Stations
at Felsenkeller

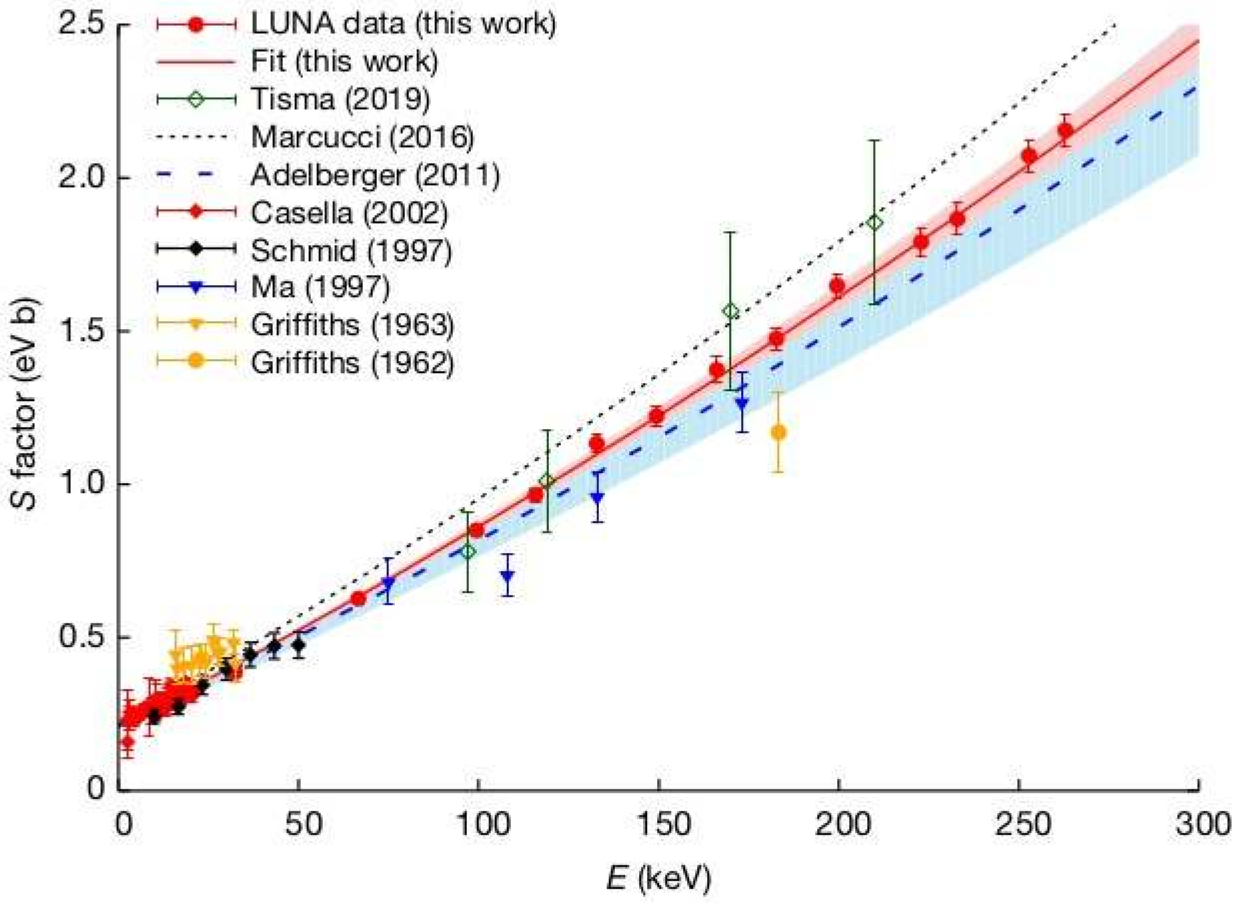
(active veto upgrade not shown)

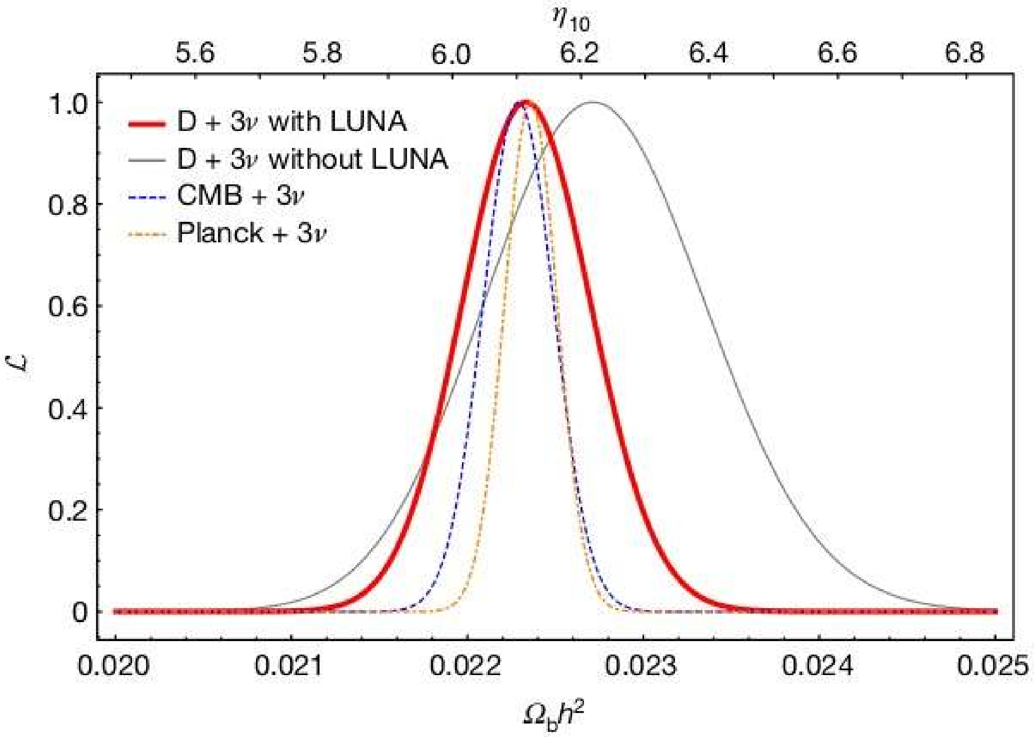
Romanian Underground Laboratory
(~2h Drive from IFIN-HH)

References:
LNGS, HZDR, R.M.Margineanu

Precision Measurements

The case of $^2H+^1H$





Precision cross section data to infer $(D/H)_{BBN}$ and relate to baryon density in the Universe (compared to cosmic microwave background data) – Mossa et al. 2021

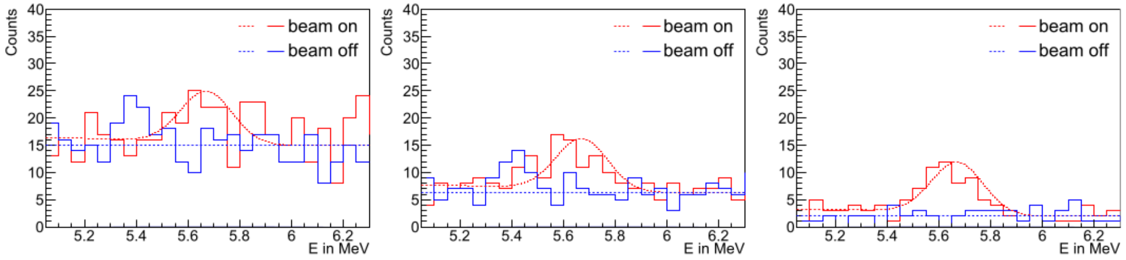
Looking Forward

New Facilities, new possibilities.

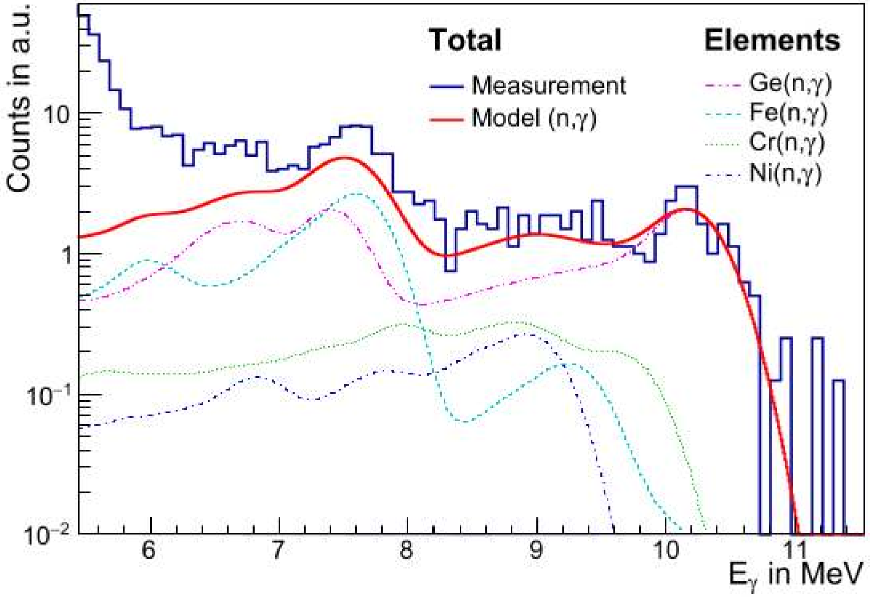
Advances in Background Reduction

Improved Sensitivity to Measure $^{17}O(p,\gamma)$

66 keV resonance in $^{17}O(p,\gamma)$:
Expected yield < 1 reaction / Coulomb



(a) Unshielded. (b) Lead shielding. (c) Lead shielding and borated polyethylene (tests).



Shielding of Lead and borated Polyethylene
=> Background rate $\mathcal{O}$(1 count/day)

References:
Boeltzig et al, 2019
Ciani et al., 2022

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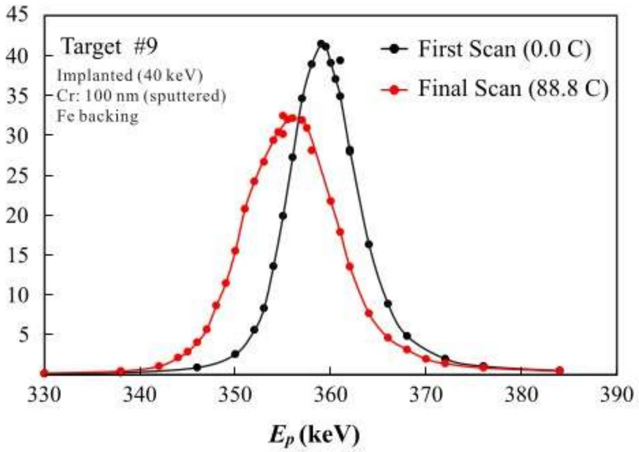
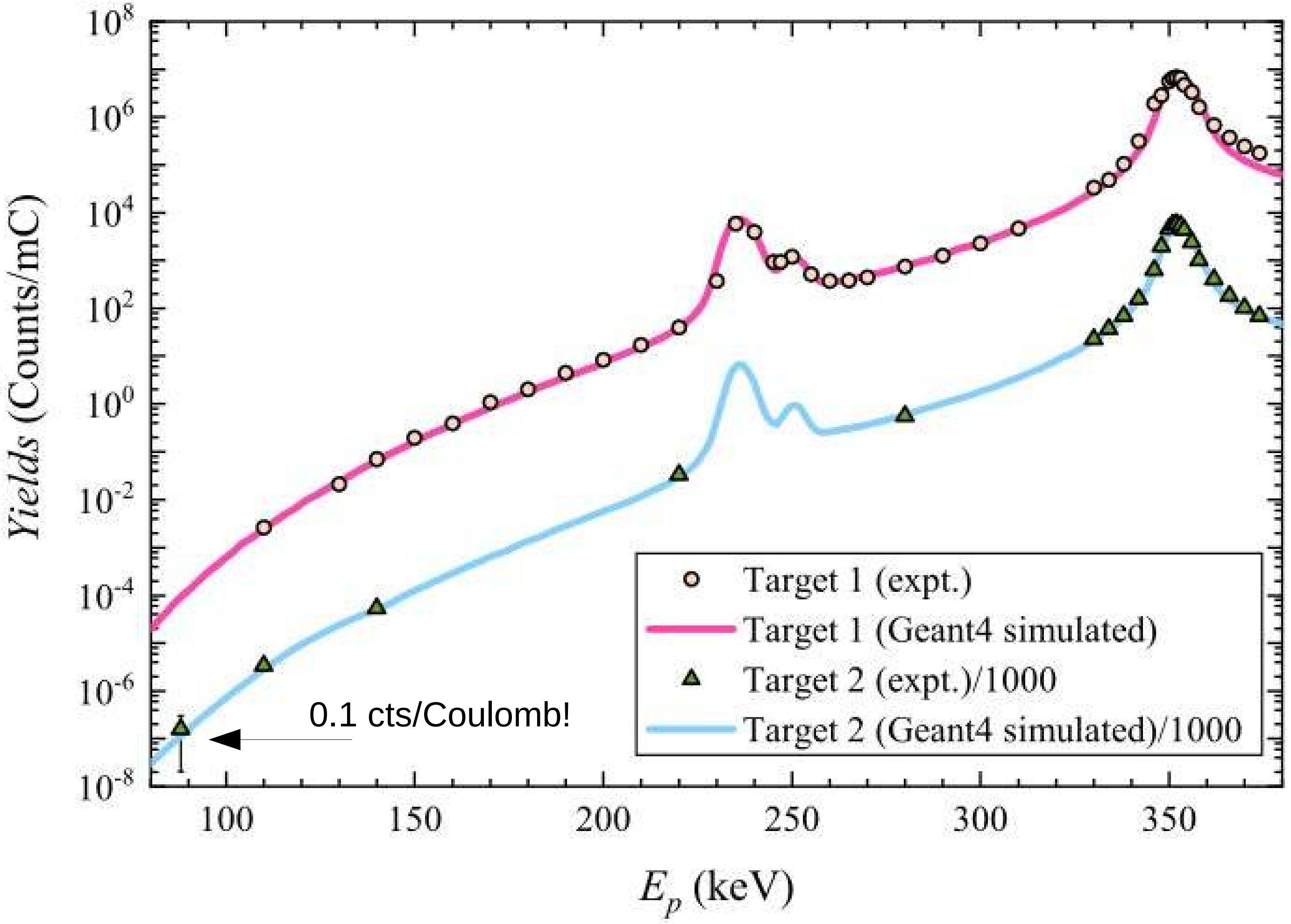
Pushing the Boundaries of Beam Intensity

New Records at JUNA





1 mA of average beam current, 190 Coulomb in ~2 days beam time

References:
Zhang et al. 2021 (NIM A)
Zhang et al. 2021 (PRL)

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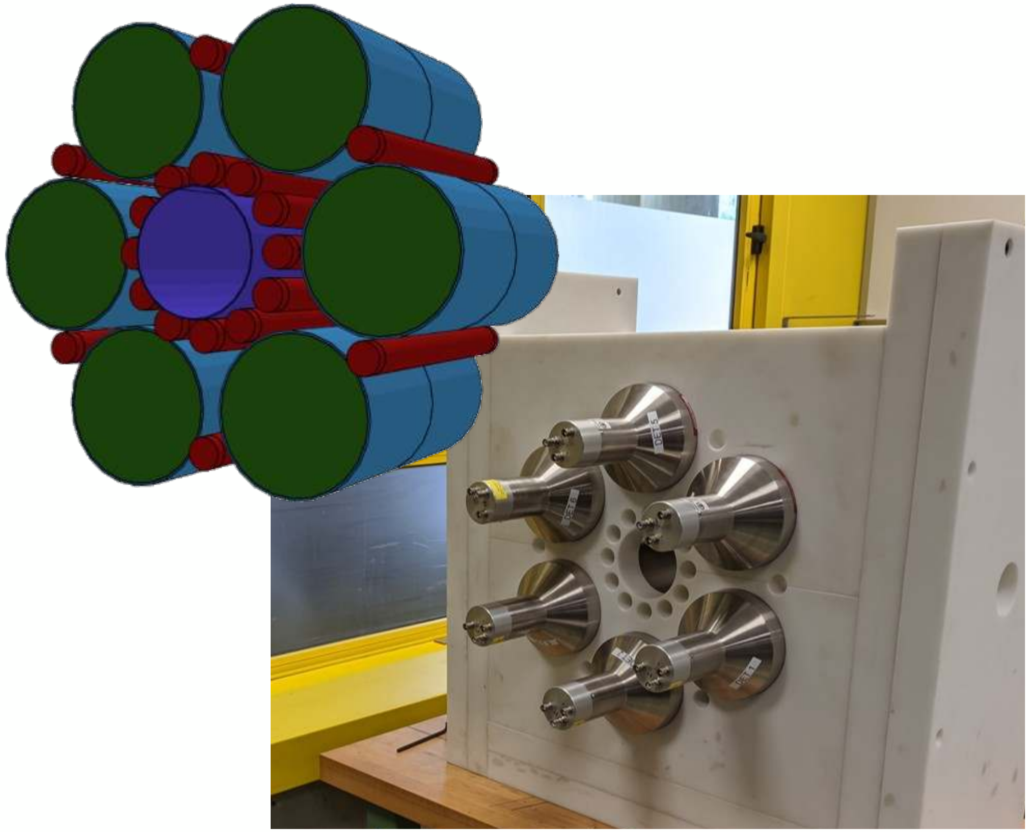
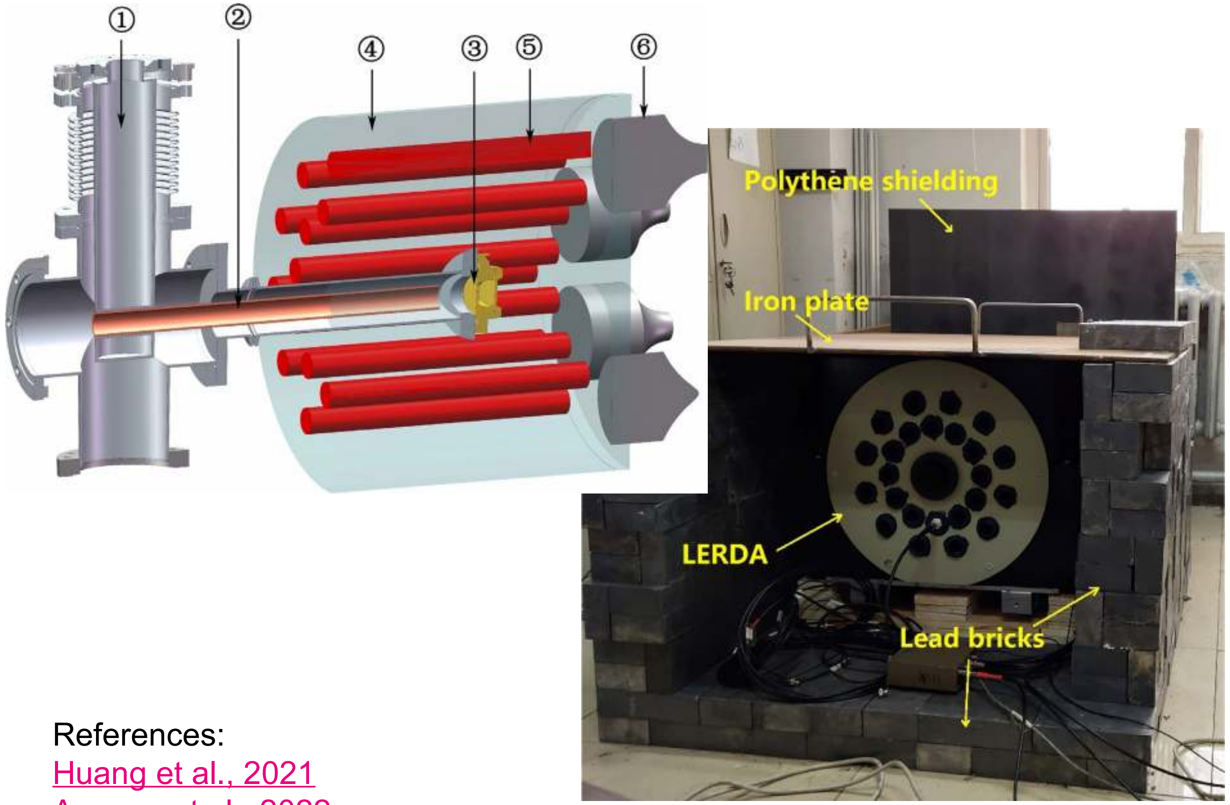
Advances in Background Reduction

Hybrid Neutron Detectors to Study s-process Neutron Sources

SHADES at University of Naples



LERDA at CIAE & CAS



References:
Huang et al., 2021
Ananna et al., 2022

Carbon Fusion Experiments

Carbon-Carbon Fusion at LUNA-MV

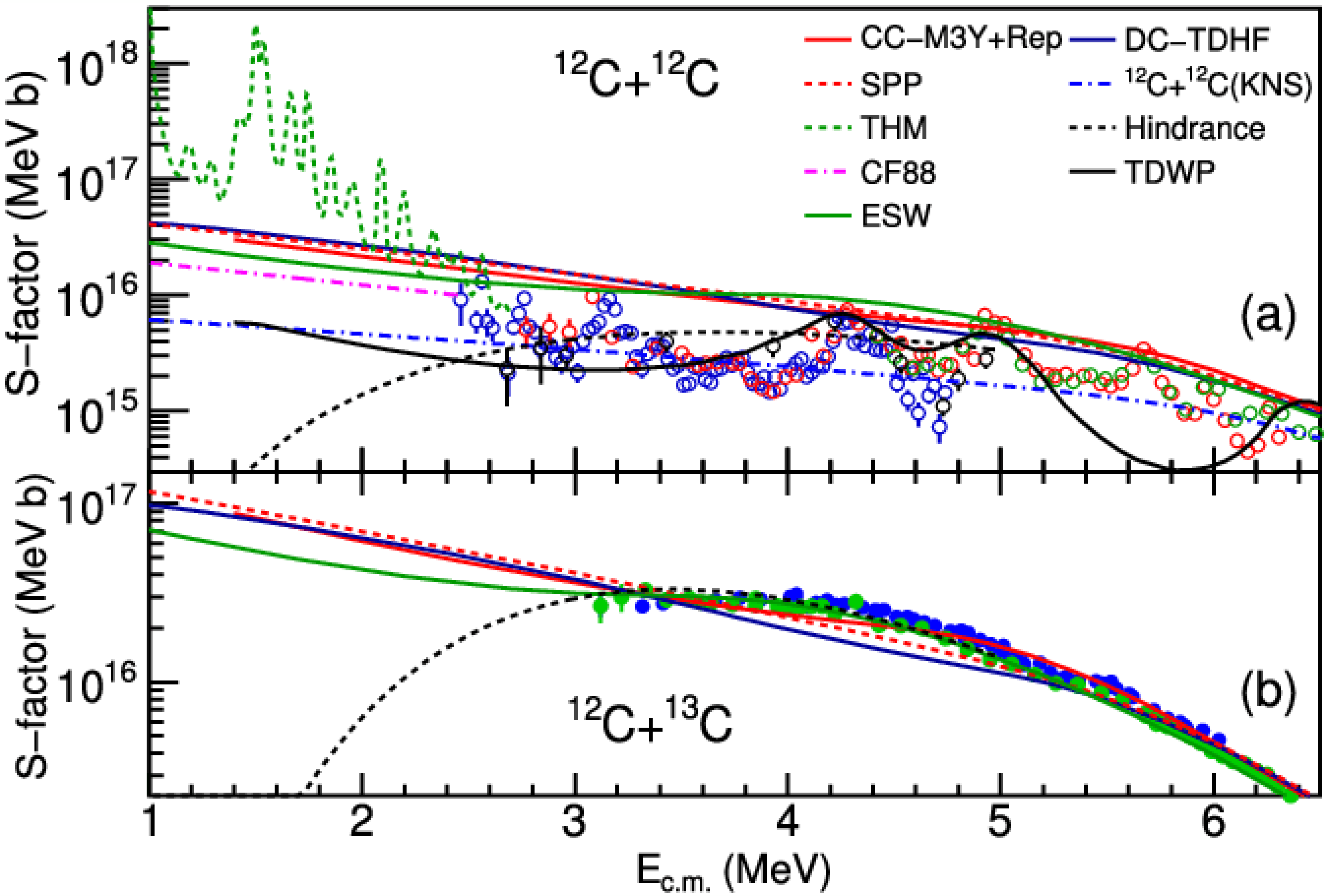
$^{12}C + ^{12}C$ Fusion: Session on Wednesday

$^{12}C + ^{12}C \rightarrow ^{23}Na + p_{0,1,...}$

$^{12}C + ^{12}C \rightarrow ^{20}Ne + \alpha_{0,1,...}$

Intense 12C beam available at 3.5 MV accelerator at LNGS (~100 uA)

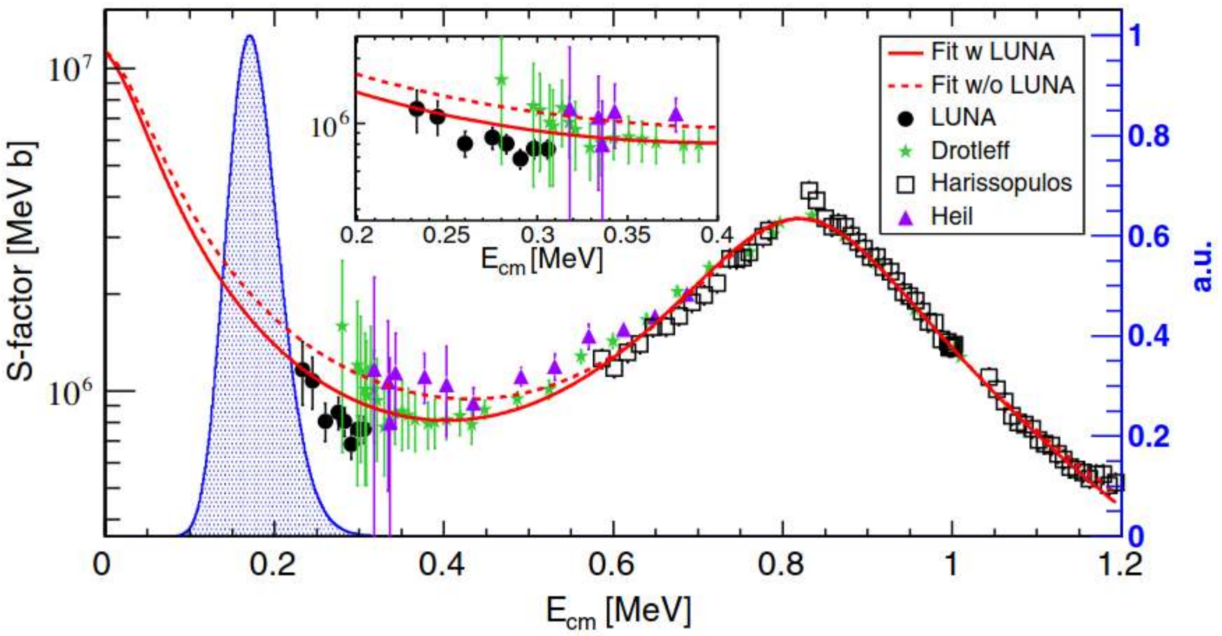
→ Direct measurement of $^{12}C + ^{12}C$ in scientific program for LUNA-MV



References:
Tumino et al. 2018
Zhang et al. 2019

Improved Overlap with Surface Laboratory Data

The example $^{13}C(\alpha,n)$



Measurements on surface and at LUNA (black dots) (Ciani et al., 2021)

Normalization of data under debate

Larger overlap desirable

→ Measurements at JUNA up to 800 kV ($He2^+$) (under evaluation)

→ Measurements of LUNA-MV (planned)

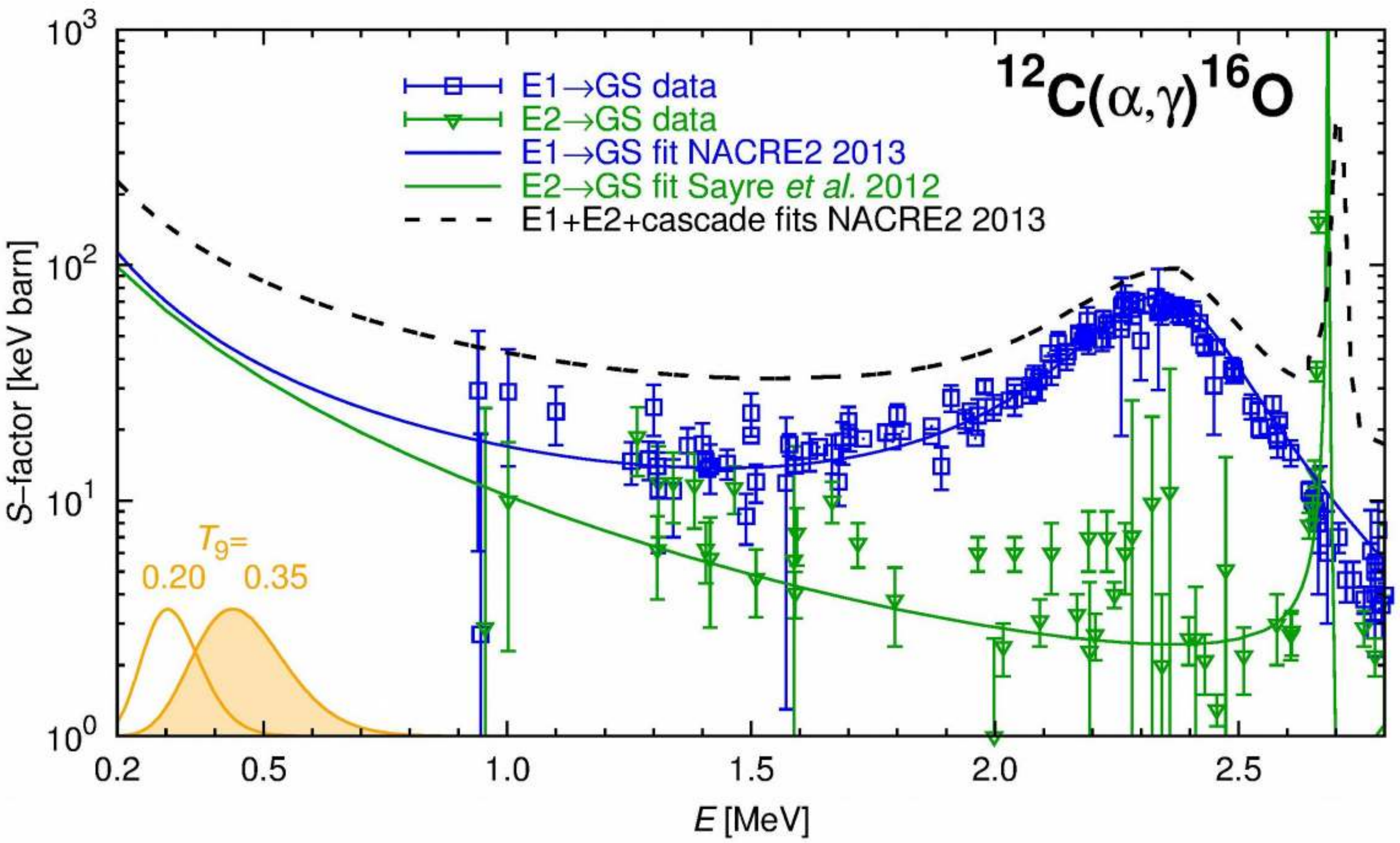
Forward and Inverse Kinematics Underground

Measuring $^{12}C(\alpha,\gamma)$ at JUNA and the Felsenkeller

Highly sought-after reaction data related to carbon/oxygen ratio in the Universe.

JUNA approach: high-intensity alpha beam on carbon target

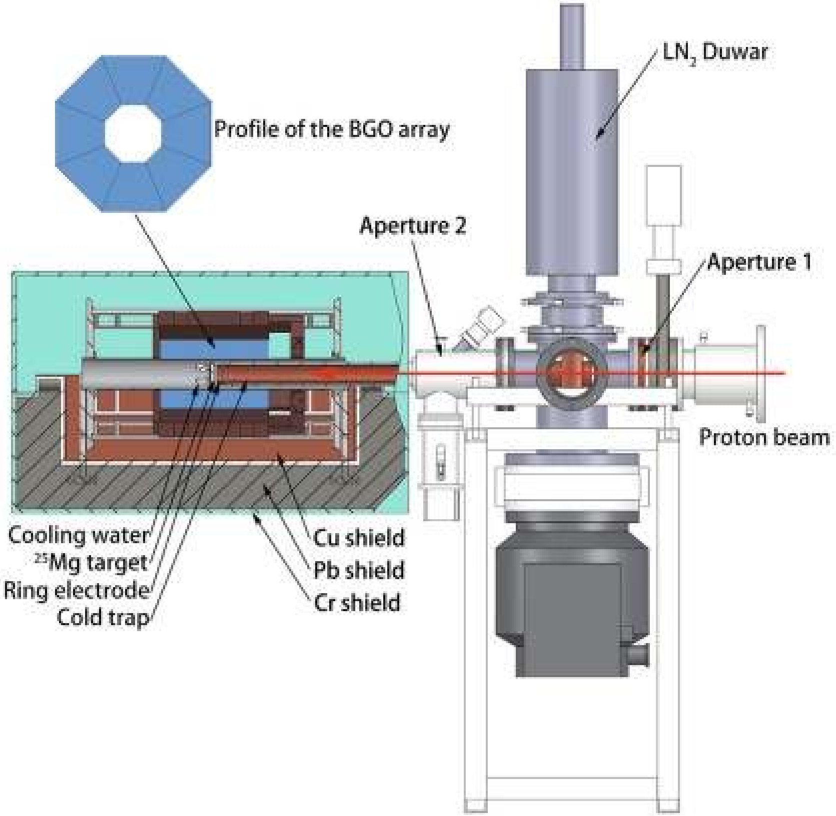
Felsenkeller: carbon beam on helium gas target

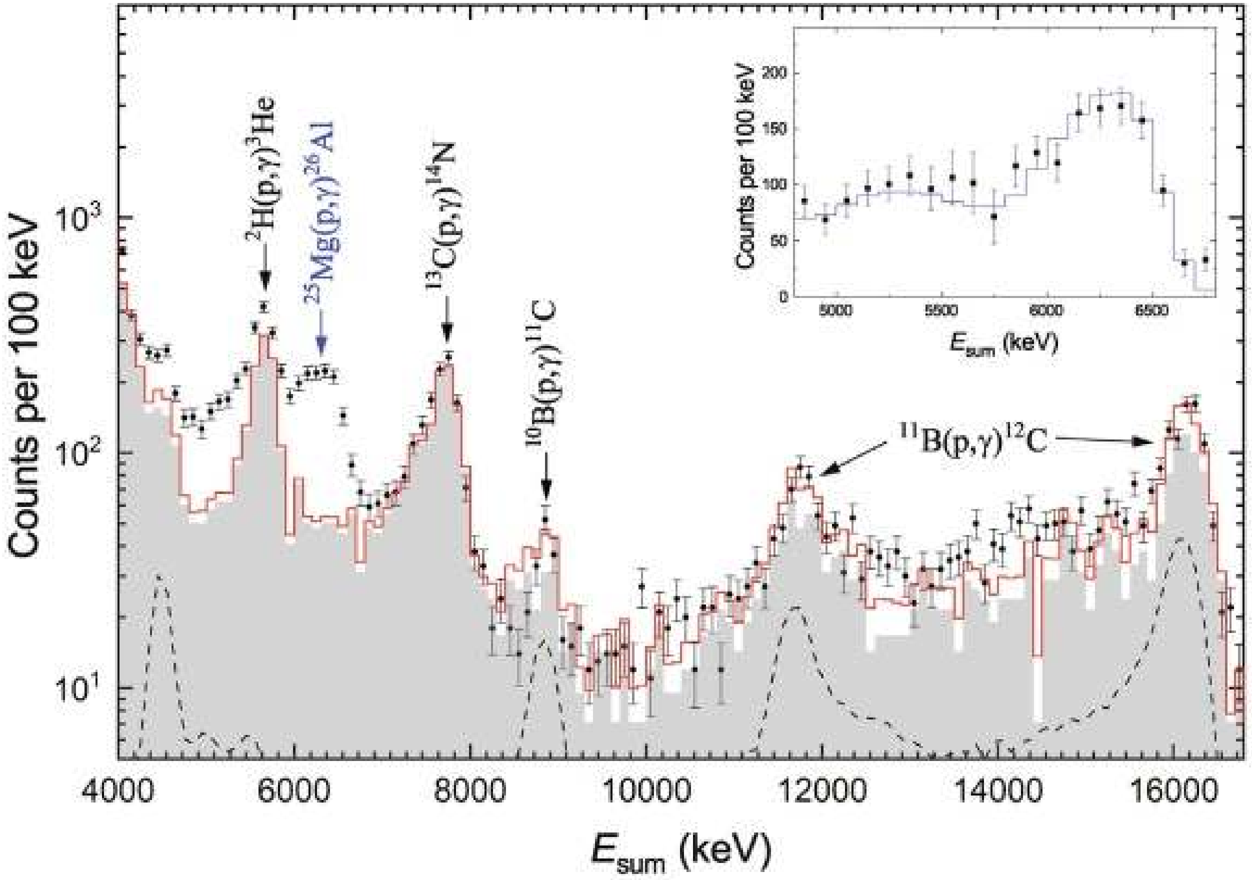


References: HZDR

Beam-induced Backgrounds

A problem above and below ground





Reference: Su et al. 2021

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Challenges Underground

What is not feasible underground (yet)?

Only Available on Surface

Radioactive Beams

Recoil Separators

Storage Rings

Hazardous Materials

Hazardous Materials

(Open) Radioactive

Space Constraints

Complex Detector Arrays

Neighboring Experiments

Practical constraints in laboratory

Rate Limited Experiments

Near or sub-threshold resonances

not accessible to direct measurement

Summary

New Facilities, new possibilities.

Summary

LUNA-50/-400 established underground accelerators as tools for low-energy cross sections for nuclear astrophysics

New underground accelerator facilities have taken up operation, considerably expanding the range of accelerator capabilities underground.

New detector and analysis techniques under development for use underground.

Underground accelerator experiments will continue to provide low-energy cross section data for charged-particle reactions.

Felsenkeller and IFIN-HH are accessible through ChETEC-INFRA's Transnational Access Program!