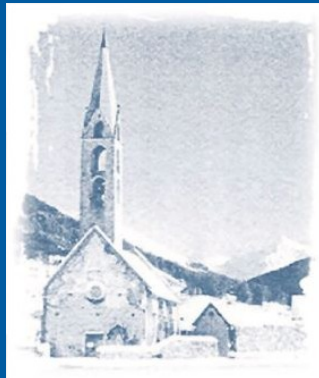


# Exploring Stars in Underground laboratories

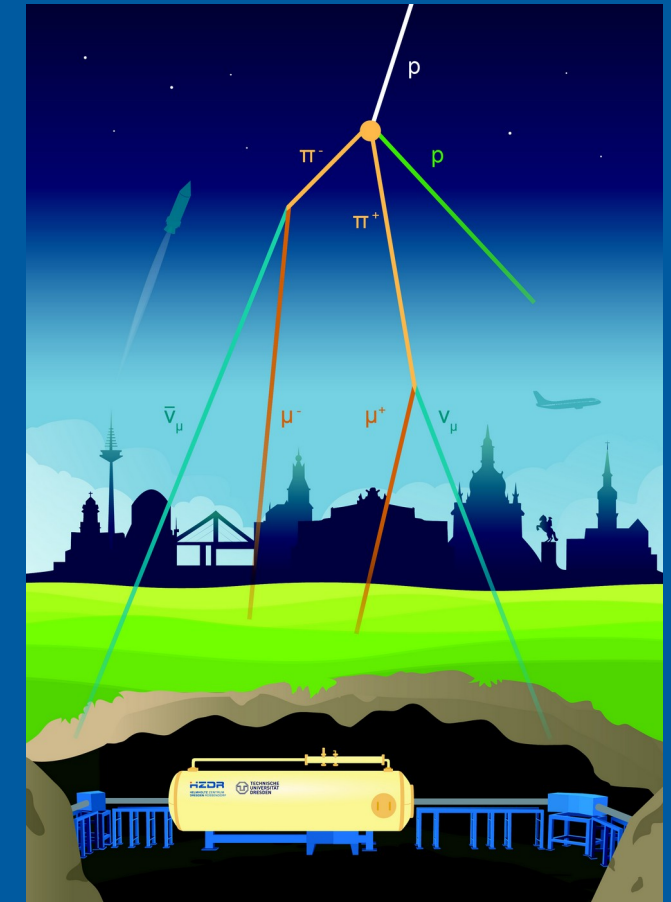
Eliana Masha

Helmholtz-Zentrum Dresden-Rossendorf

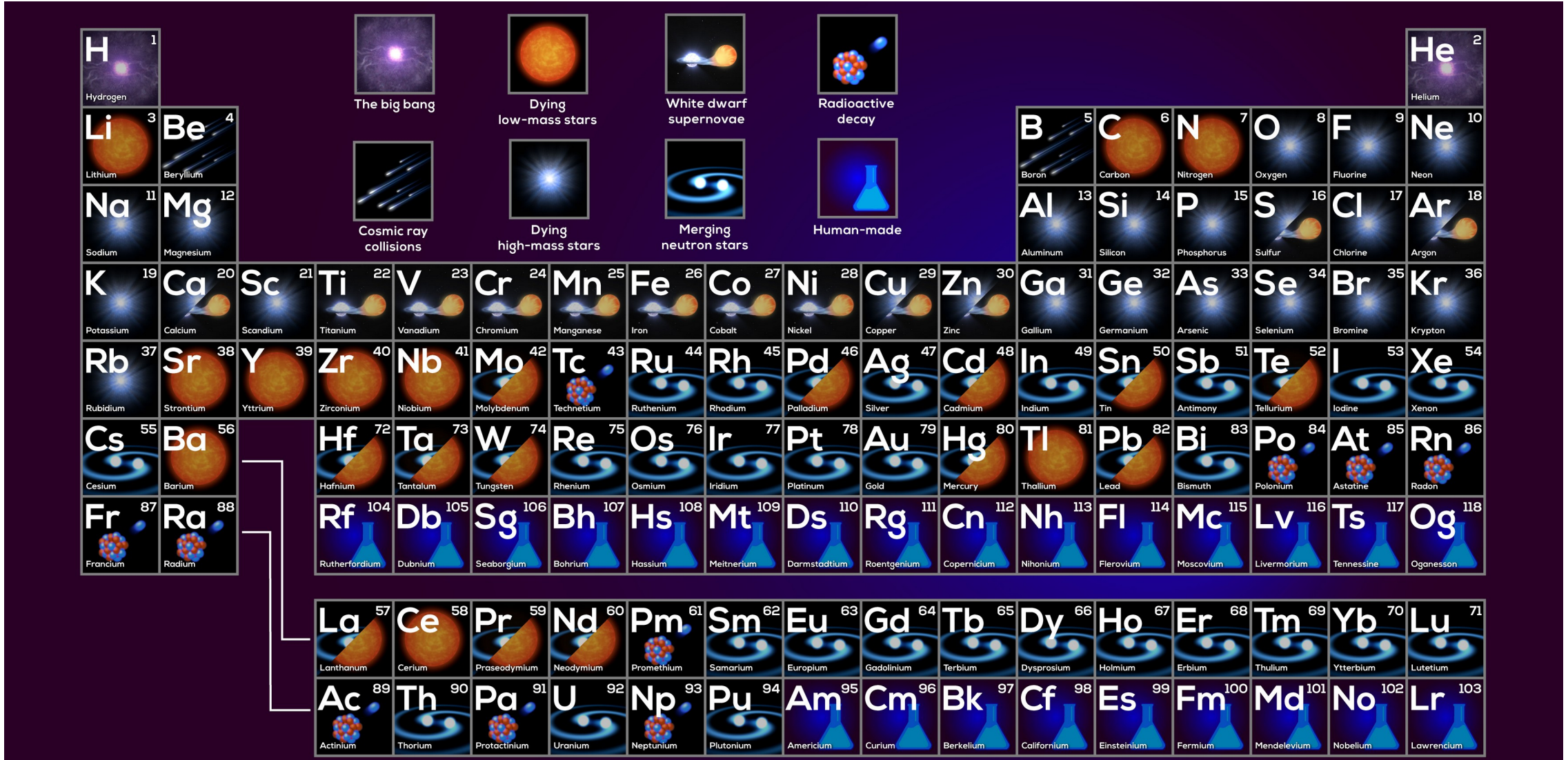


62<sup>nd</sup> International Winter Meeting  
on Nuclear Physics

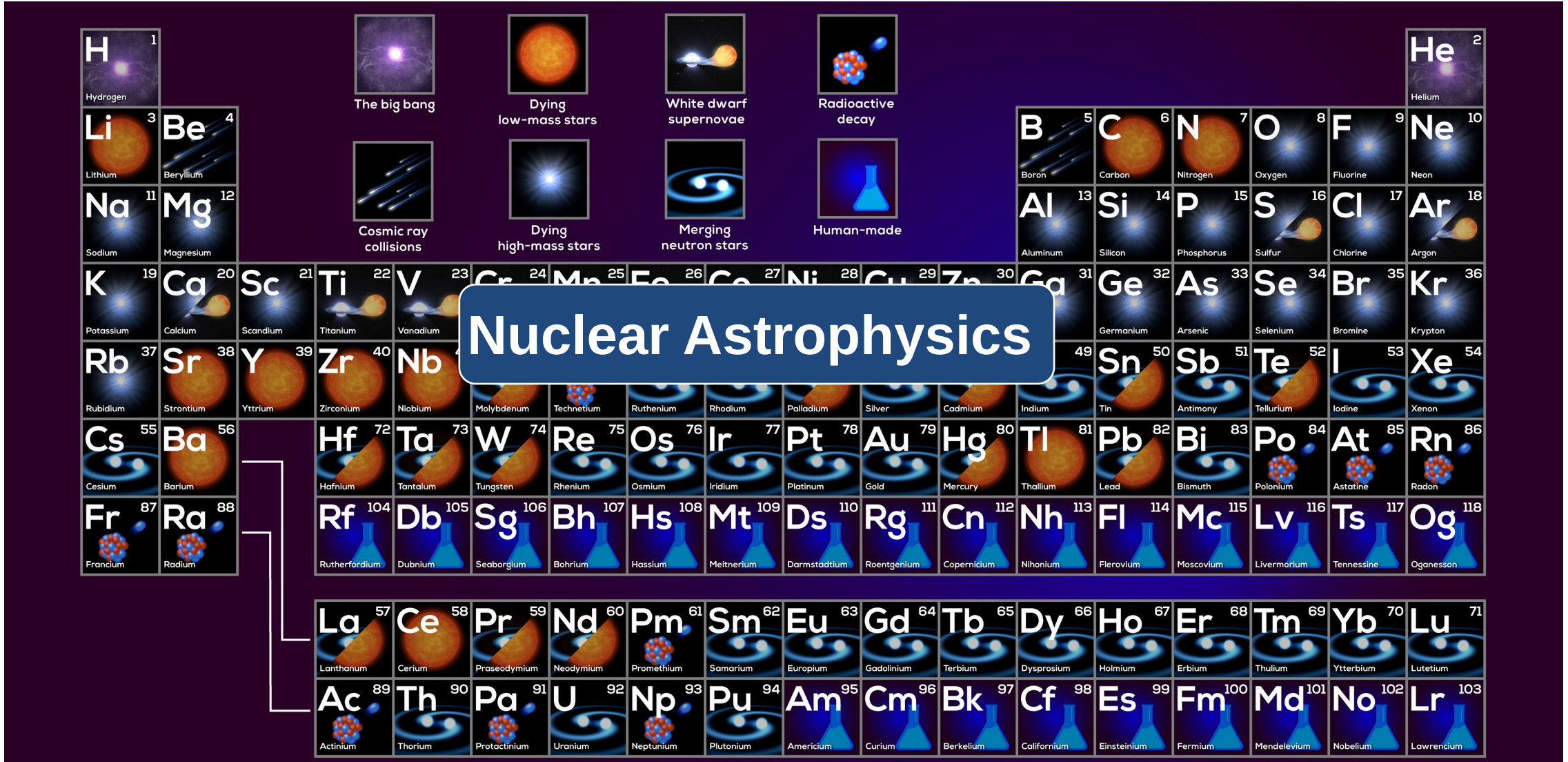
19 - 23 January 2026  
Bormio, Italy



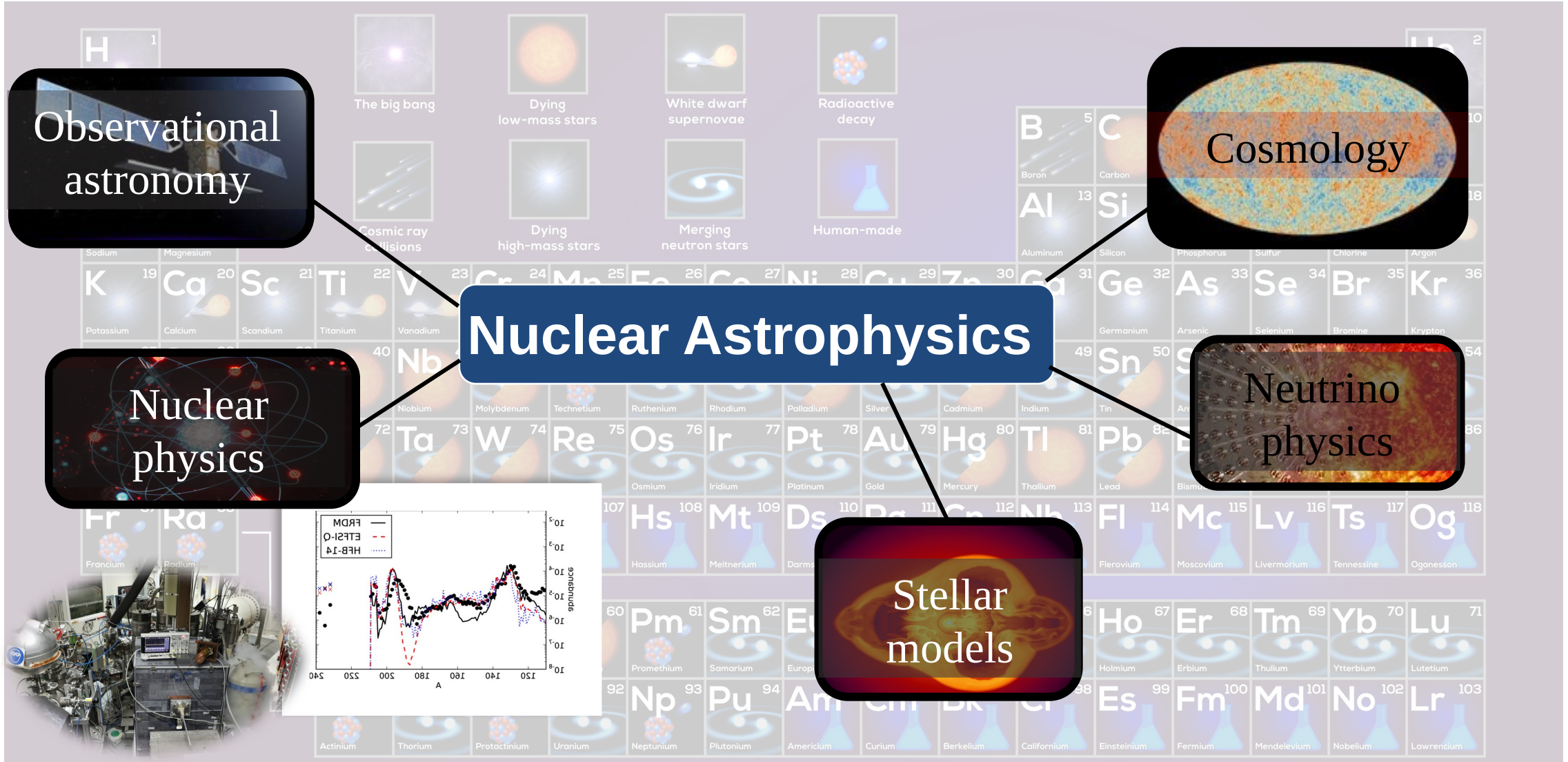
# Where all elements form?



# Where all elements form?



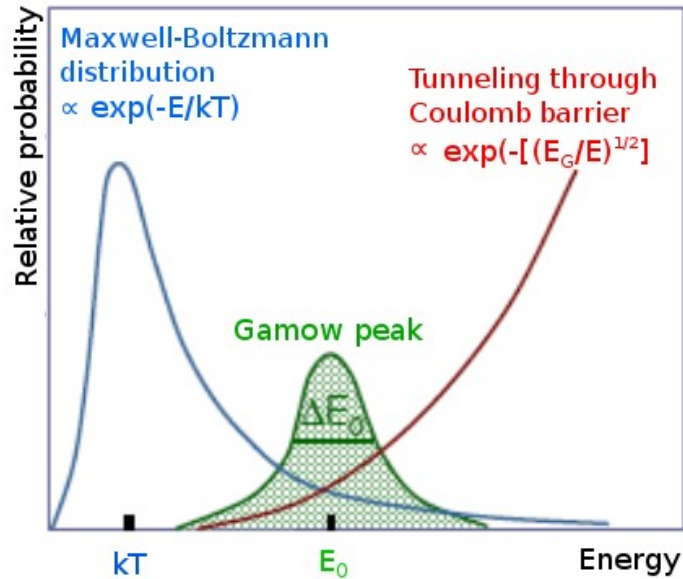
# Where all elements form?



# 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  $\rho_a \rho_A$   
 Relative velocity  $v$   
 Maxwell – Boltzmann distribution  $\phi(v)$   
 Cross section  $\sigma(v)$



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)

# Challenges of direct measurements

$$\text{Counting Rate} = N_p \times N_t \times \text{cross section} \times \text{detection efficiency}$$

$10^{14}$  pps ( $\sim 100 \mu\text{A}$   $q=1+$ ) typical stable beam intensities

$10^{18}$  atoms/cm<sup>2</sup> 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

$$\text{Counting Rate} = N_p \times N_t \times \text{cross section} \times \text{detection efficiency}$$

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

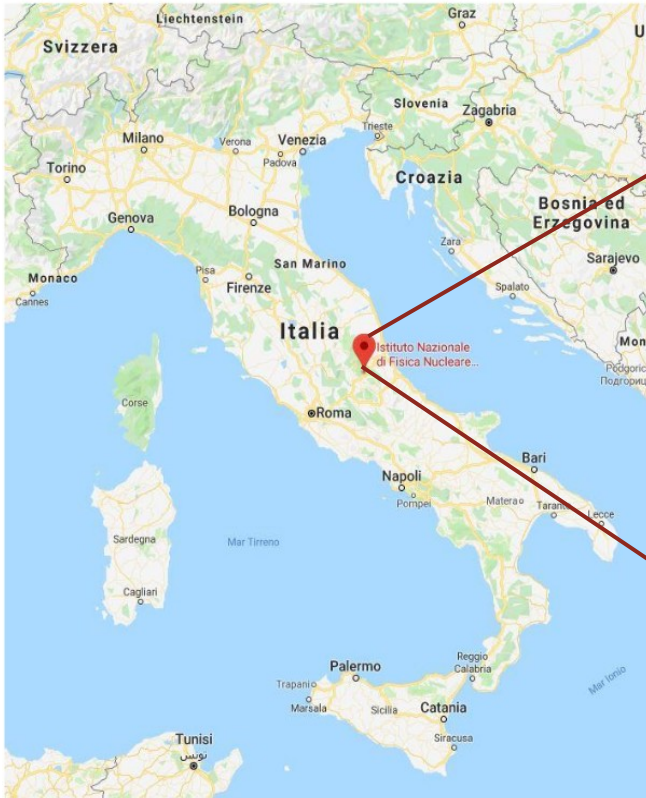
How to improve the signal to noise ratio?

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



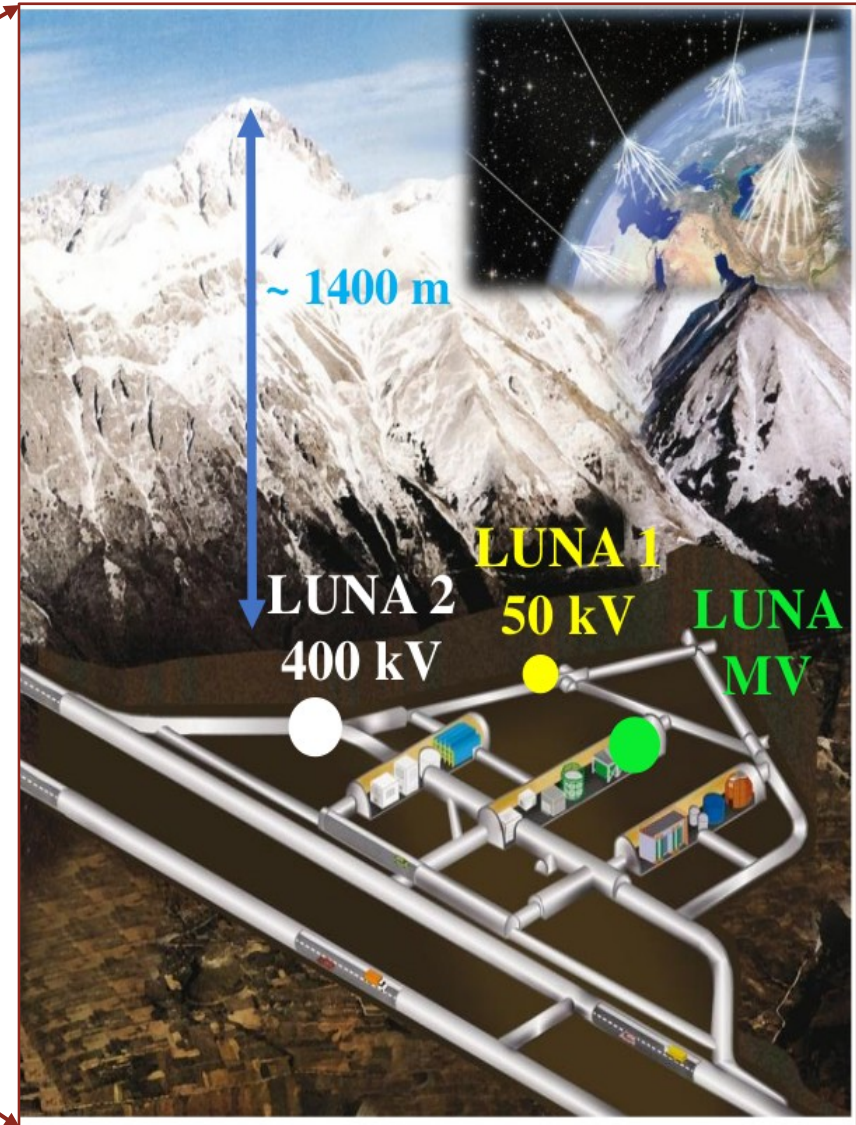
# Underground nuclear astrophysics

First underground laboratory for nuclear astrophysics

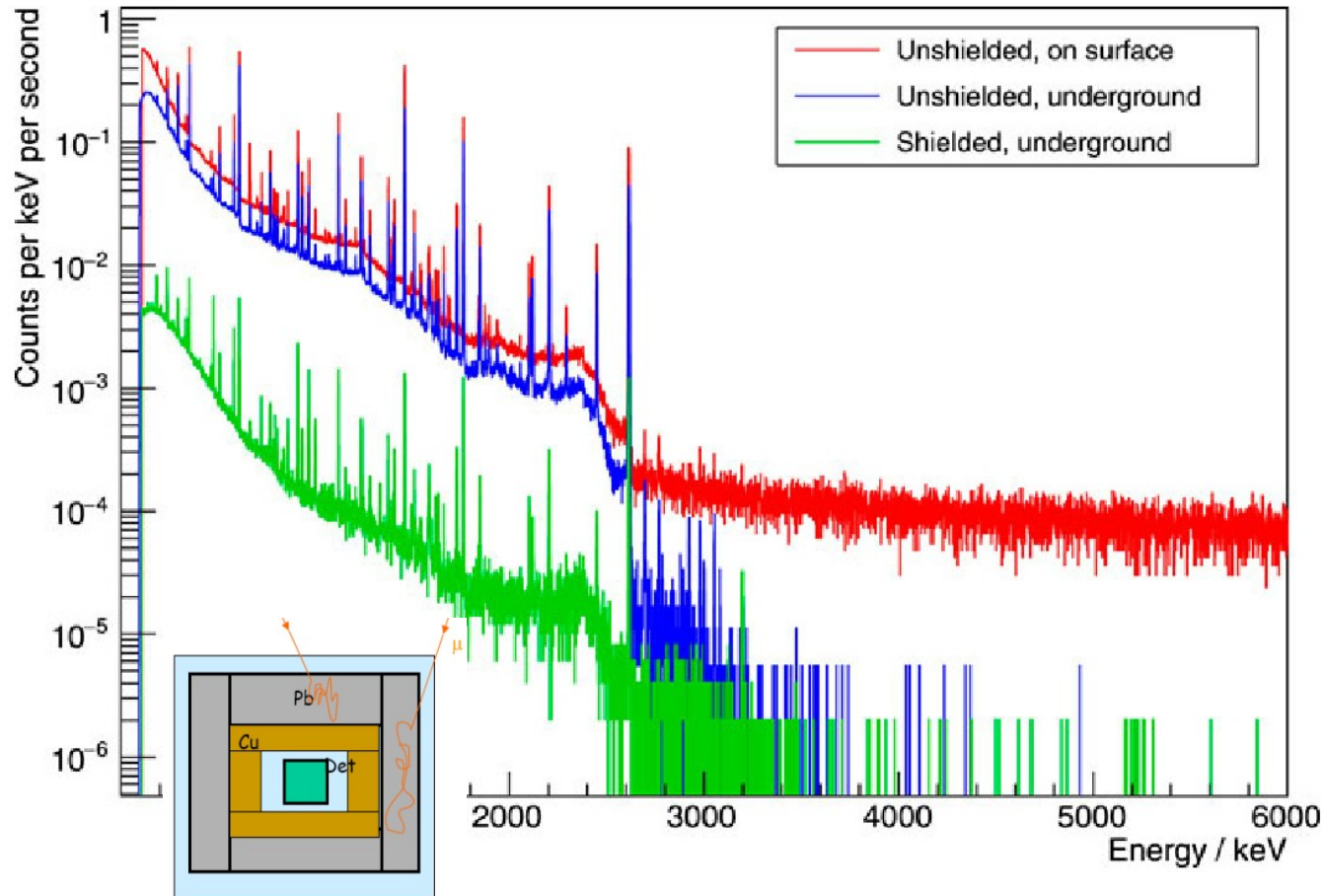


**LUNA@LNGS**

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



# Why Underground?

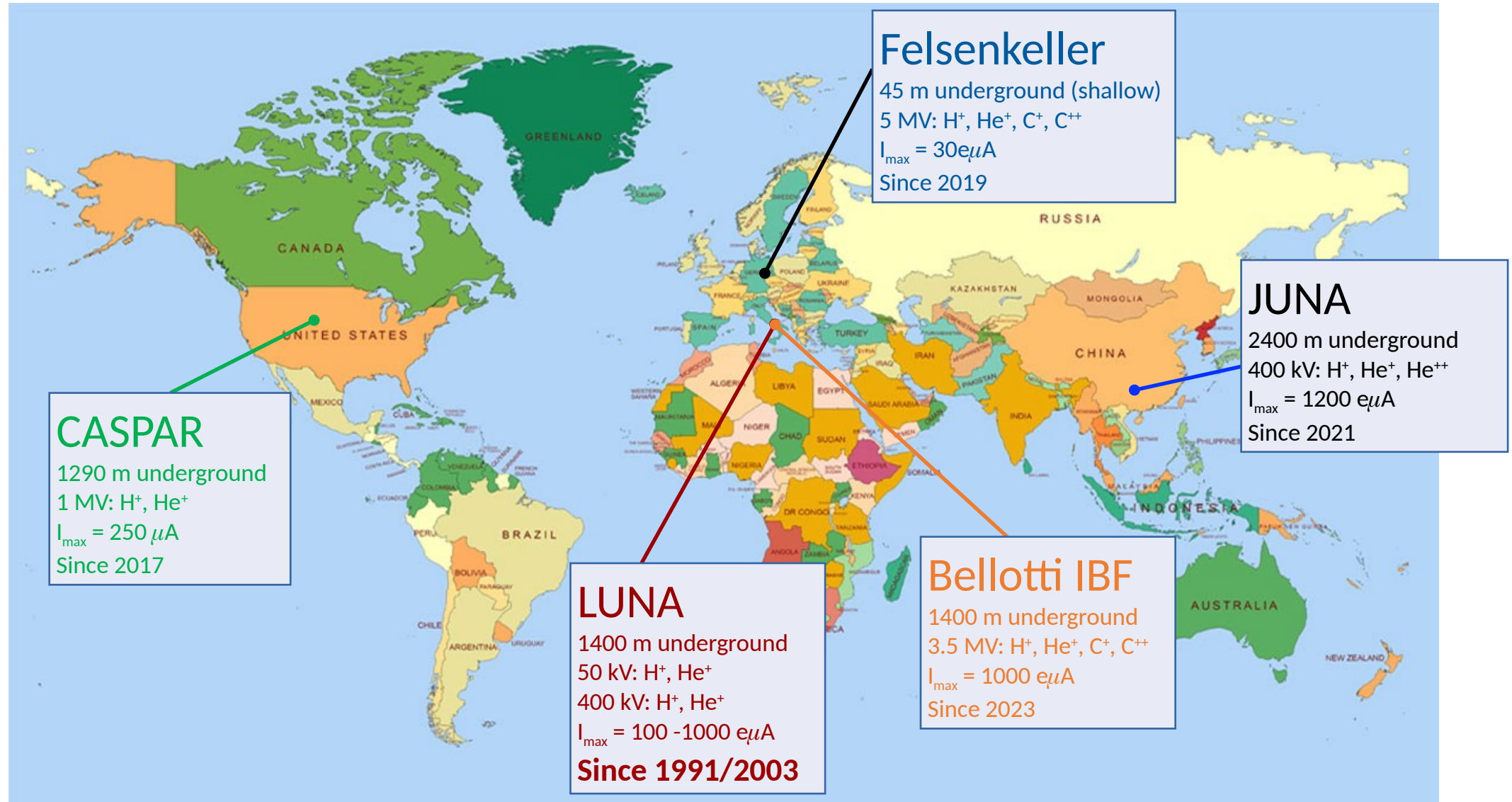


## LUNA/LNGS background reduction:

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

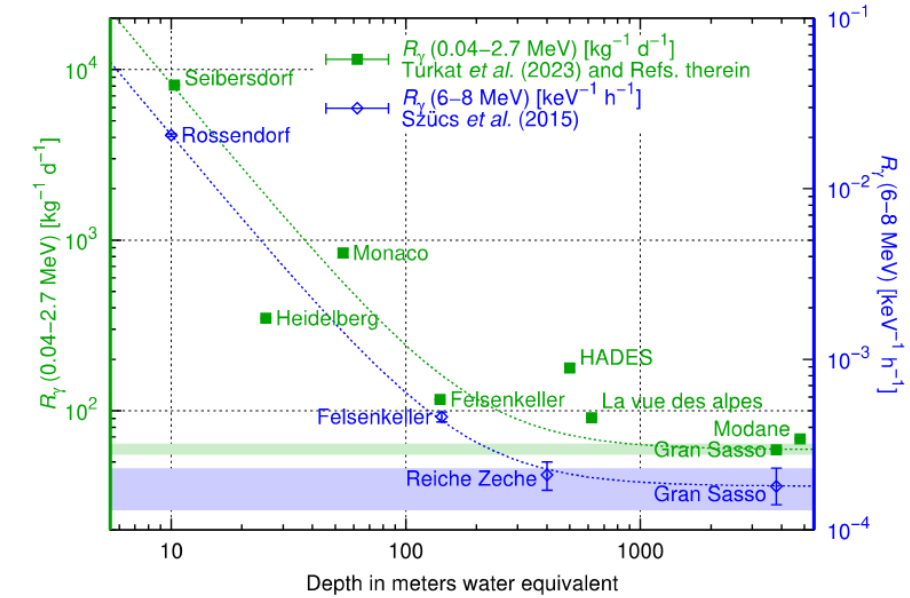
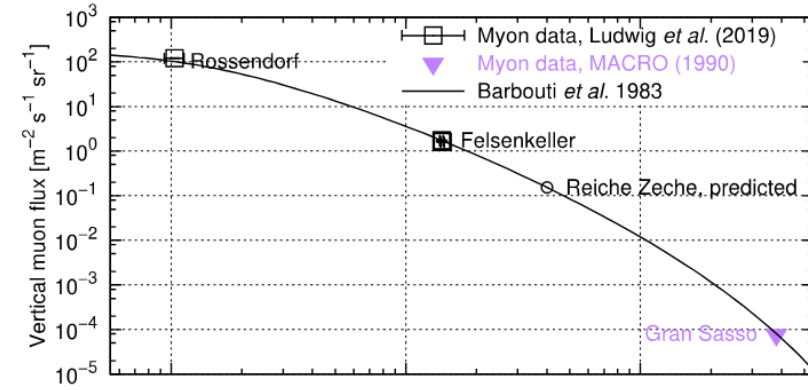
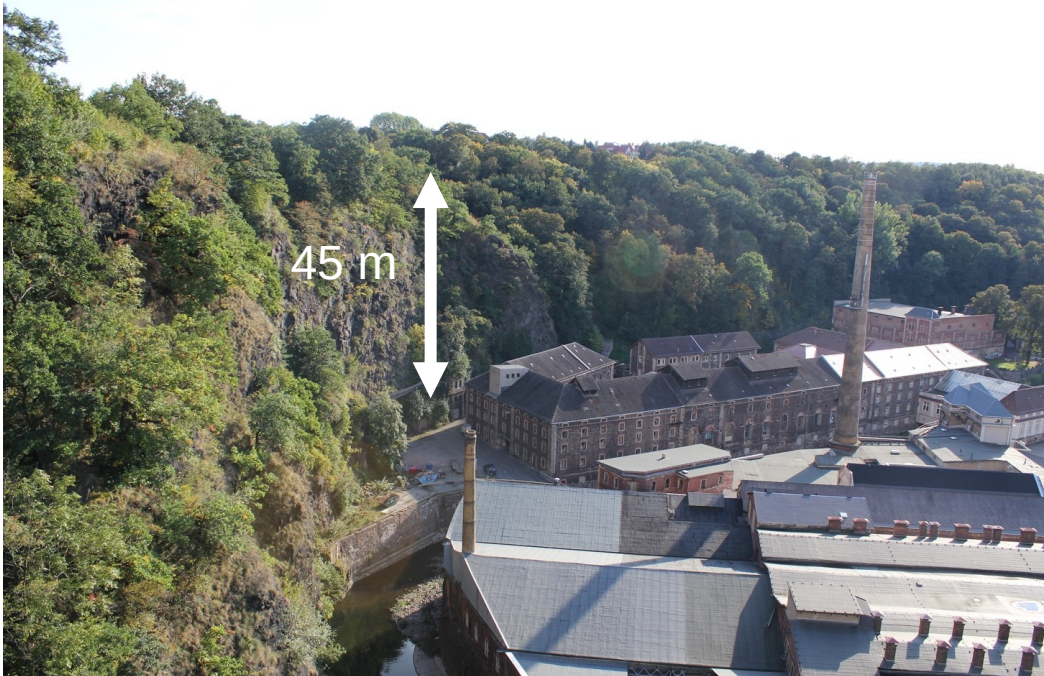
Underground passive shielding is more effective thanks to the suppressed  $\mu$  flux

# Underground accelerators worldwide



# Dresden Felsenkeller underground lab

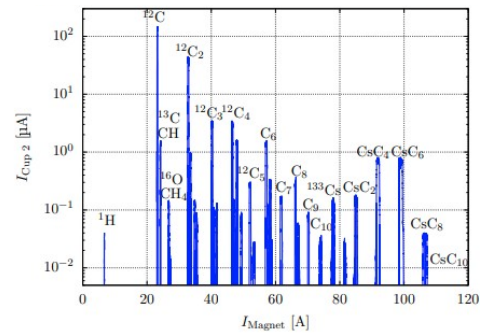
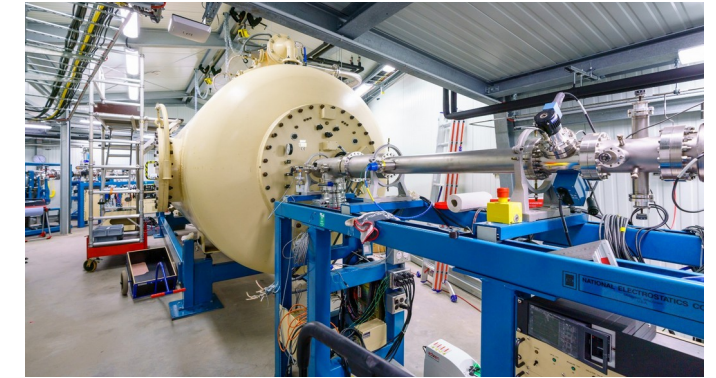
- Joint effort HZDR – TU Dresden, Germany
- ♦ Investment by TU Dresden (Kai Zuber *et al.*) and HZDR (Daniel Bemmerer *et al.*)
  - ♦ Day to day operations by HZDR
  - ♦ 24h operation without operator



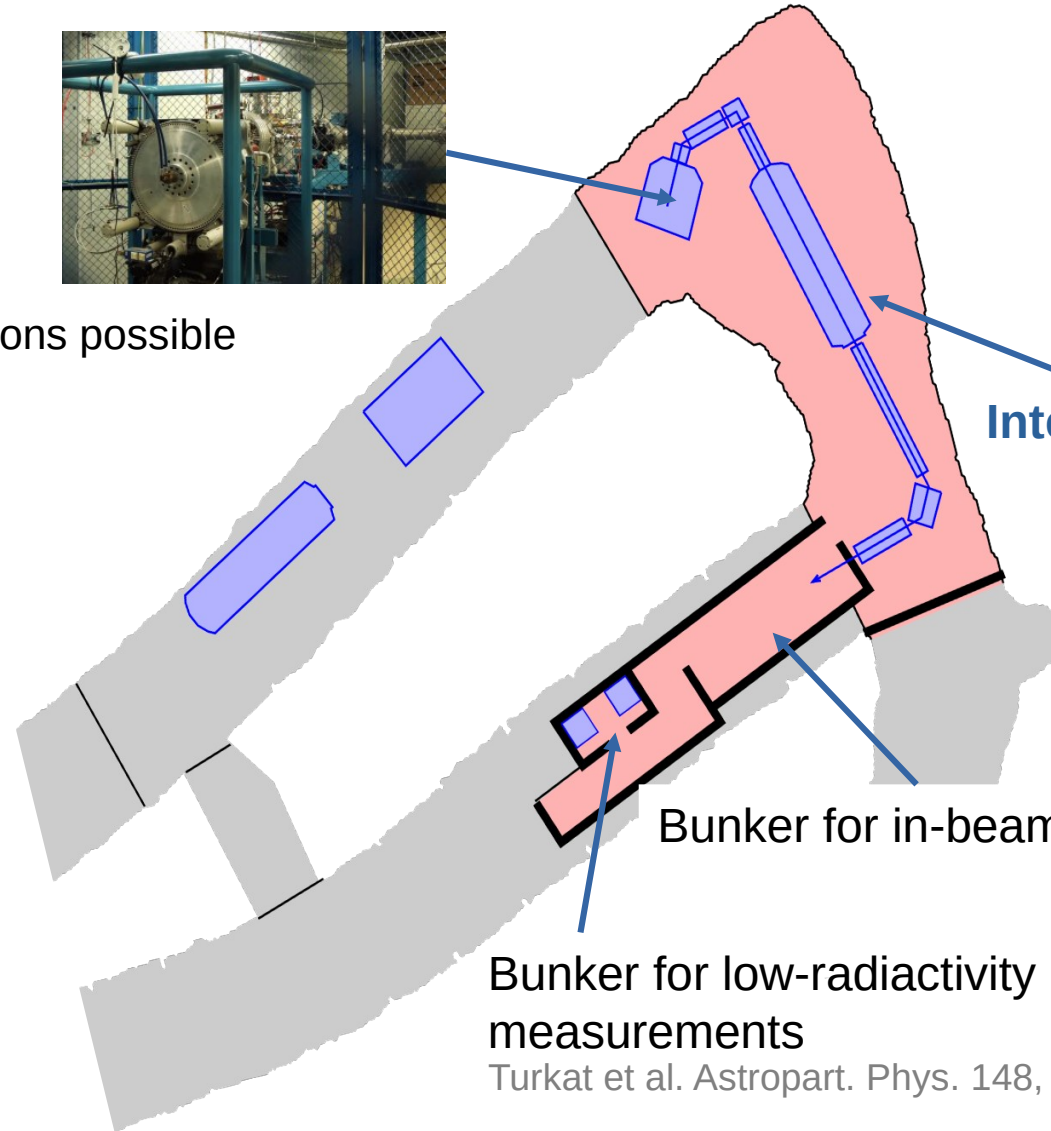
# Dresden Felsenkeller underground lab

## External ion-source

- ◆ Intensive  $^{12}\text{C}$  beam
- ◆ Intensity of 20-30  $\mu\text{A}$
- ◆ Other negatively charged ions possible

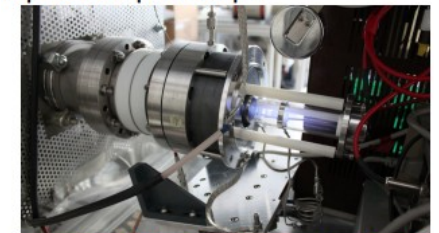


Tunnel IX



## Internal radio frequency ion-source

- ◆ Intensive  $^2\text{H}$  and  $^4\text{He}$  beams
- ◆ Beam current up to 30  $\mu\text{A}$



Bunker for in-beam experiments

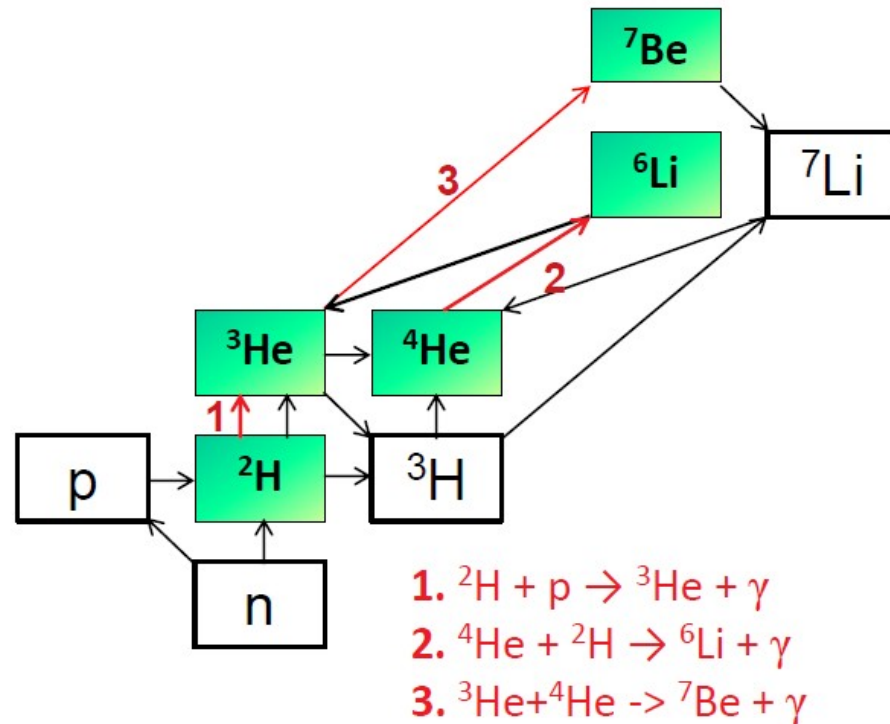
Bunker for low-radiativity measurements

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

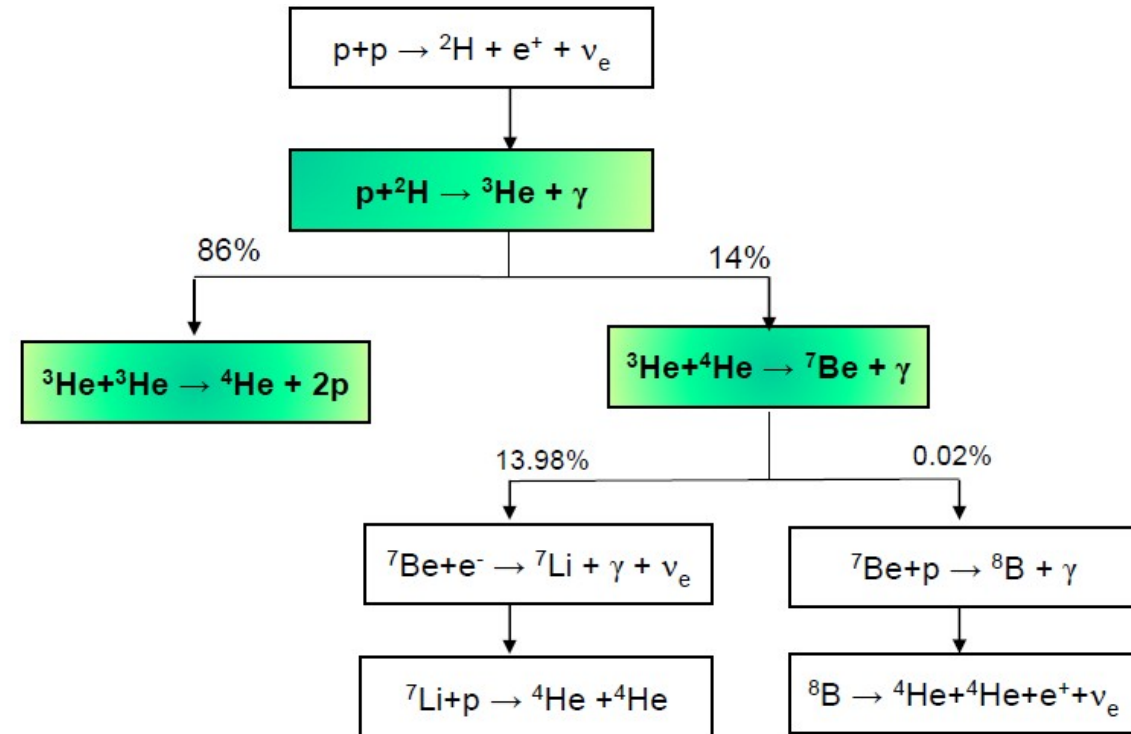


# 30 years of Underground nuclear astrophysics, LUNA

## Big Bang Nucleosynthesis



## Solar H-burning, pp chain

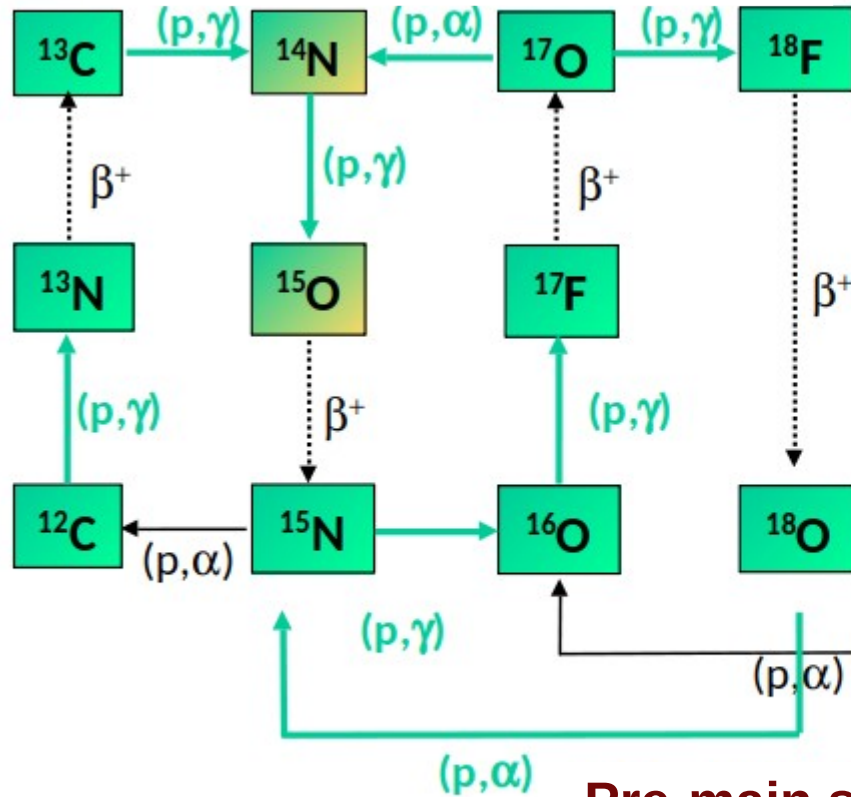


Some of the lowest cross sections ever measured

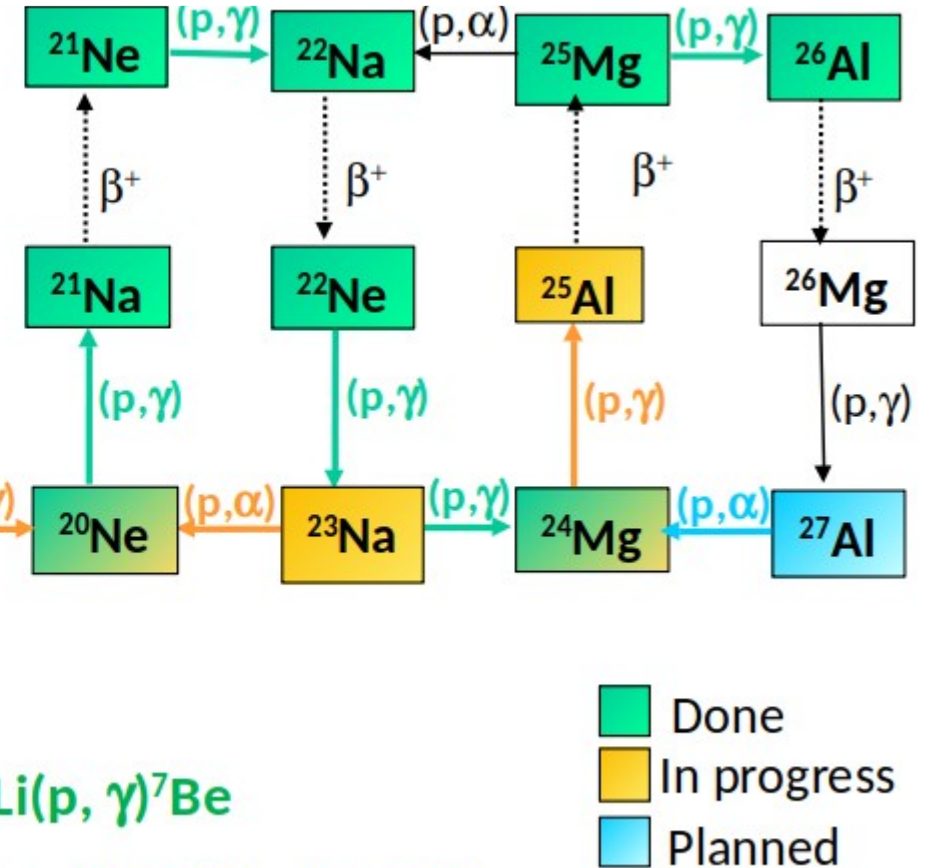
Reaction network credits: F. Cavanna

# 30 years of Underground nuclear astrophysics, LUNA

## H-burning, CNO



## H-burning, NeNa and MgAl cycles



s-process nucleosynthesis:  ${}^{13}\text{C}(\alpha, n){}^{16}\text{O}$ ,  ${}^{22}\text{Ne}(\alpha, \gamma){}^{26}\text{Mg}$

Reaction network credits: F. Cavanna

# Underground nuclear astrophysics at Felsenkeller

## Big Bang Nucleosynthesis

## Hydrogen Burning

## Helium Burning

## Carbon Burning

### Reaction studies with solid target + HPGe detectors

- ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$  Szücs *et al.*
- ${}^2\text{H}(p, \gamma){}^3\text{He}$  Masha, Caciolli *et al.*
- ${}^{12, 13}\text{C}(p, \gamma){}^{13, 14}\text{N}$  Piatti *et al.*
- ${}^{12}\text{C}+{}^{12}\text{C}$  Ferraro *et al.*
- ${}^{15}\text{N}(\alpha, \gamma){}^{19}\text{F}$  Marsh *et al.*

### Reaction studies with gas-jet target + HPGe detectors

- ${}^{14}\text{N}(\alpha, \gamma){}^{18}\text{F}$  Cavanna *et al.*

### Reaction solid target + FELICITAS detector

- ${}^{15}\text{N}(\alpha, \gamma){}^{19}\text{F}$  Marsh, Caciolli *et al.*

### Reaction studies with solid + LaBr3+ particle detection

- ${}^{12}\text{C}+{}^{12}\text{C}$  Heine *et al.*

2022

2025

# Big Bang Nucleosynthesis (BBN): ${}^2\text{H}(p,\gamma){}^3\text{He}$ reaction

## Primordial ${}^2\text{H}$ abundance

**Direct observations:** Absorption lines in DLA systems

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

Cooke et al, APJ 855 (2018) 102

**Predicted abundance:** BBN theory, cosmological parameters and the cross sections of the nuclear reactions responsible for  ${}^2\text{H}$  creation and destruction  $[\text{D}/\text{H}]_{\text{BBN}}$

Different adopted cross sections  $\rightarrow$

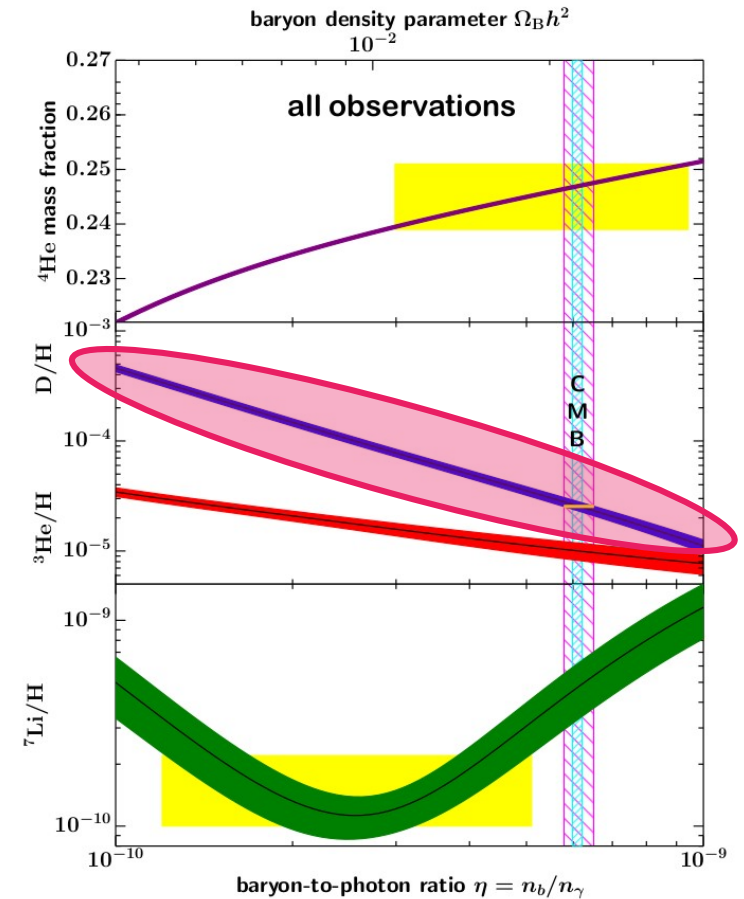
$$[\text{D}/\text{H}]_{\text{BBN}} = (2.587 \pm 0.055) \times 10^{-5}$$

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

Planck, A&A 641 (2018) A6

## Primordial ${}^2\text{H}$ is an excellent baryometer:

Comparison of  $[\text{D}/\text{H}]_{\text{OBS}}$  and  $[\text{D}/\text{H}]_{\text{BBN}} \rightarrow$  Universal Barion density  $\Omega_B$  and/or  $N_{\text{eff}}$



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

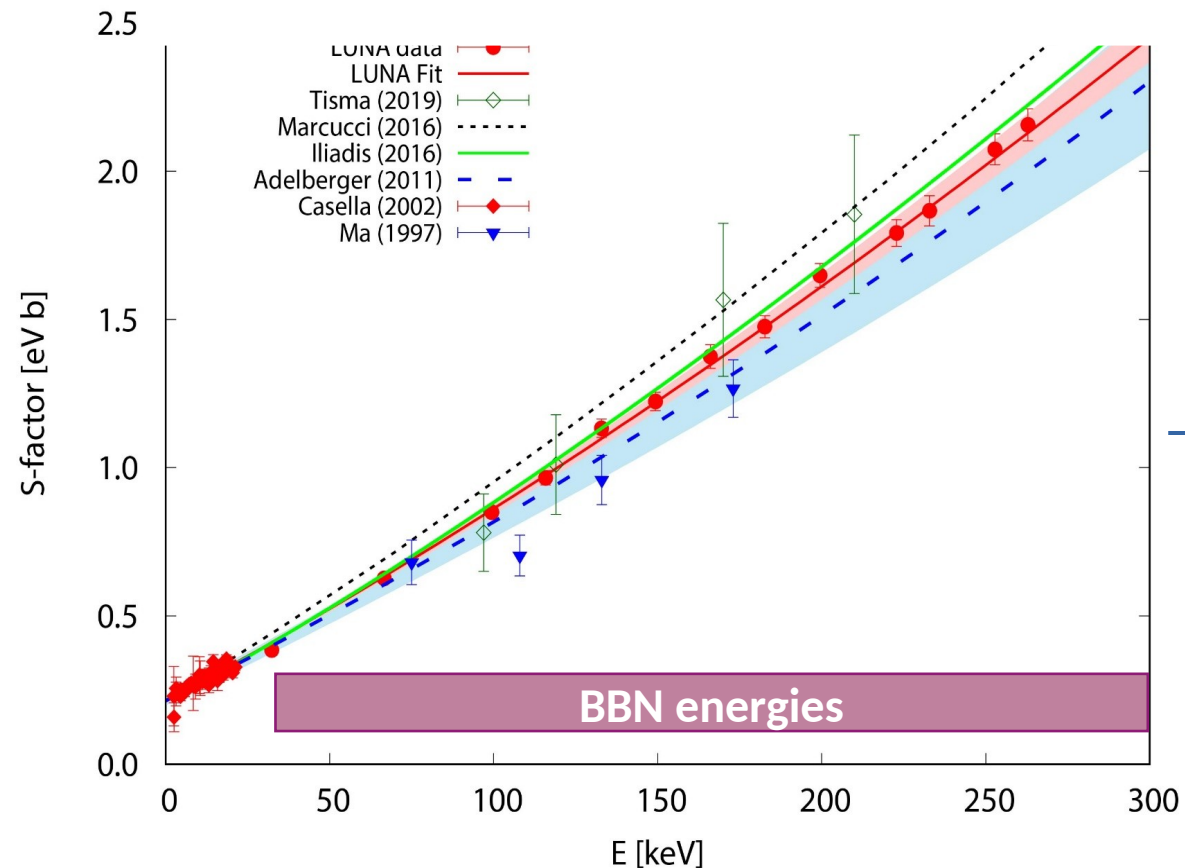
V. Mossa, K. Stöckel, [...] S. Zavatarelli ✉

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

4402 Accesses | 13 Citations | 168 Altmetric | Metrics

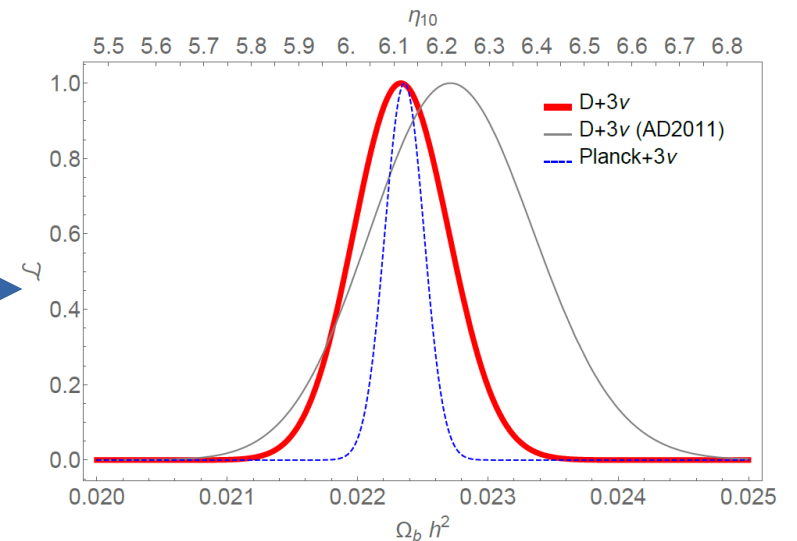
# Big Bang Nucleosynthesis: ${}^2\text{H}(p,\gamma){}^3\text{He}$ reaction

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



Systematic uncertainty  
reduced to **< 3%**

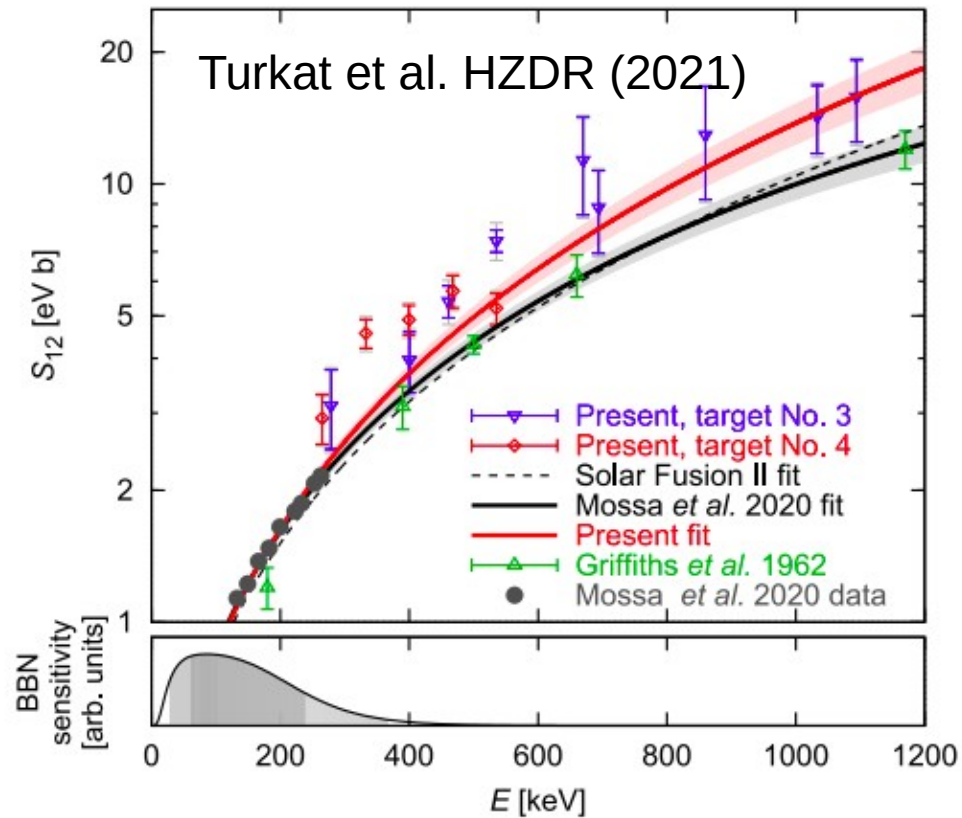
Cosmological  
implications →



### Baryon density

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

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



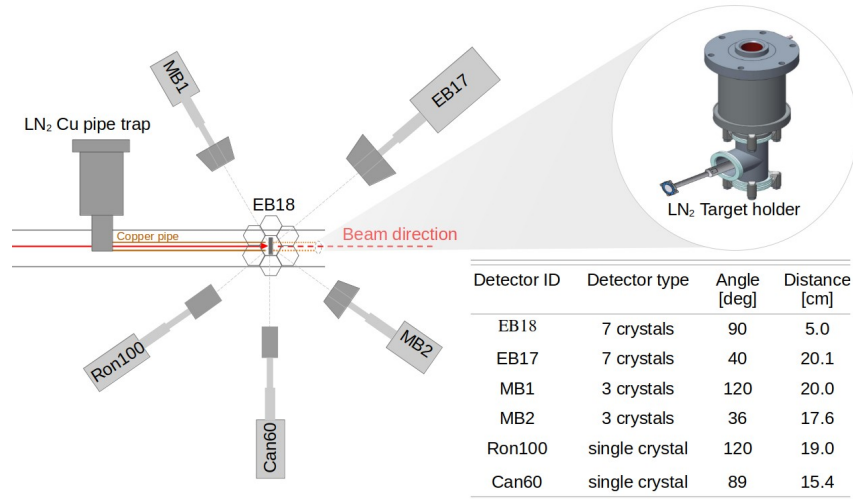
- High energy fit (HZDR) agrees within <1.2 % with LUNA fit in the BBN range
- For  $E_p > 400$  keV discrepancies of 10 % between LUNA and HZDR
- **No direct gamma ray angular measurement** which might effect ab-initio calculation available



**New measurement performed at Felsenkeller lab, Germany**

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

Setup: solid target setup +  $^{21}\text{HPGe}$  detectors for angular coverage

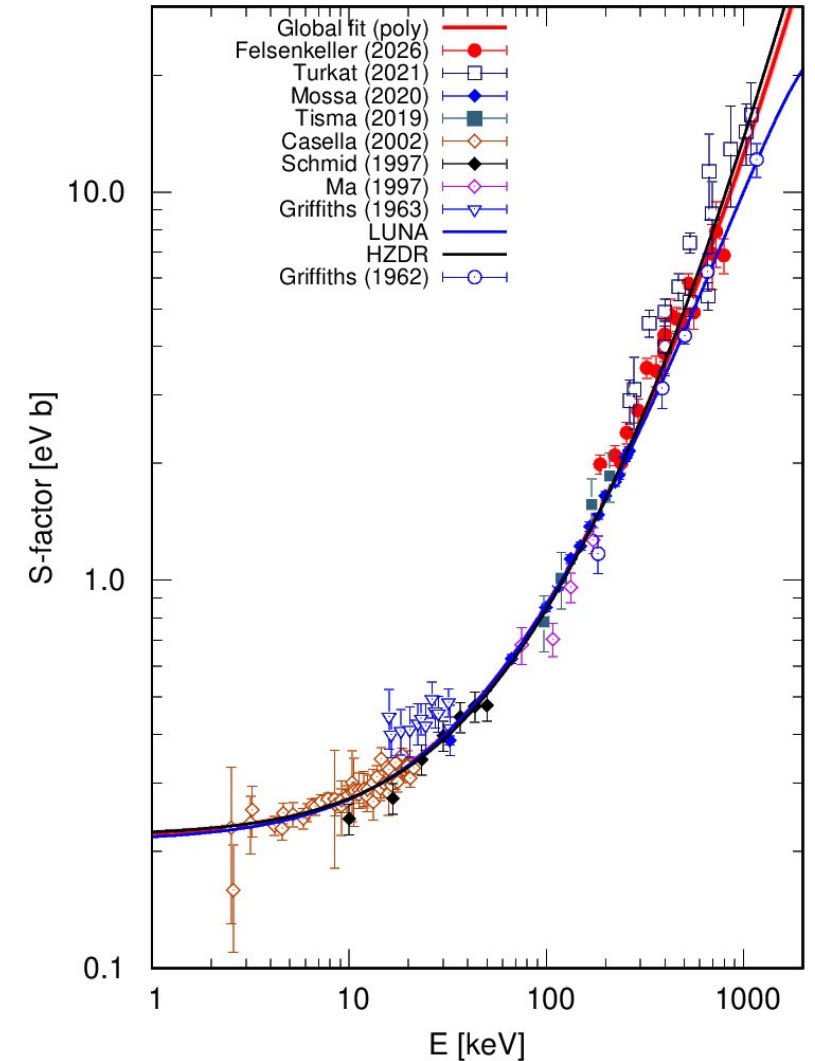
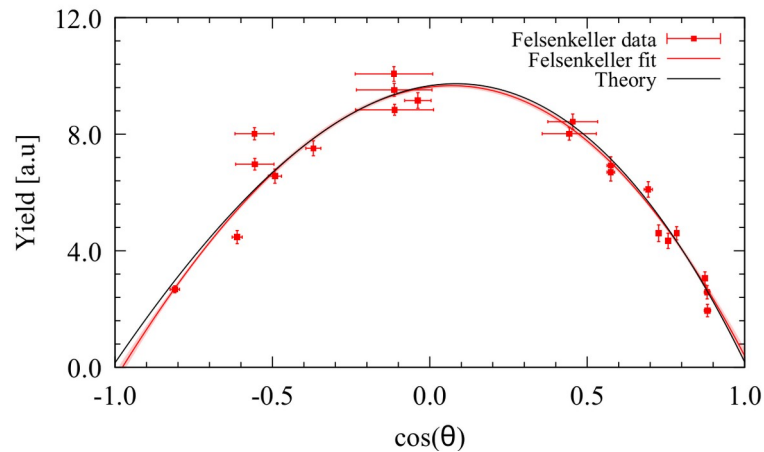


PRELIMINARY



Astrophysical S-factor

Angular distribution

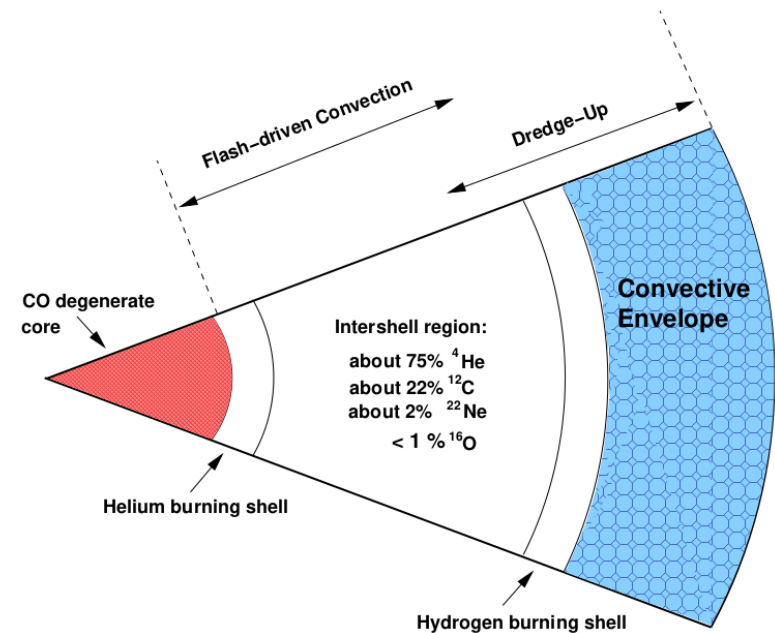
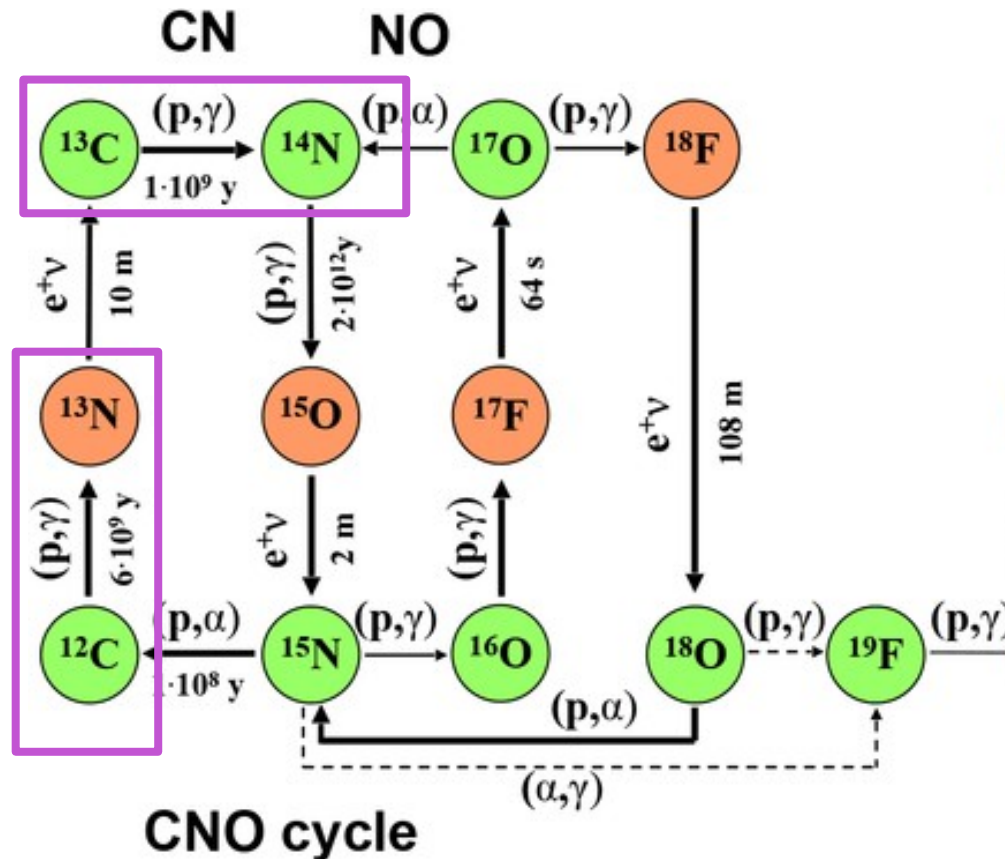


# Hydrogen burning: $^{12,13}\text{C}(p,\gamma)^{13,14}\text{N}$ reactions

## Astrophysical motivation

- Reactions of the **CNO** cycle
- Govern  $^{12}\text{C}$  and  $^{13}\text{C}$  amount in the stellar cores

- The  $^{12}\text{C}/^{13}\text{C}$  ratio: obtained from stellar spectra
- Asymptotic Giant Branch (AGB) undergo heavy mixing
- Precise  $^{12}\text{C}/^{13}\text{C}$  ratio in the core can constrain the mixing models

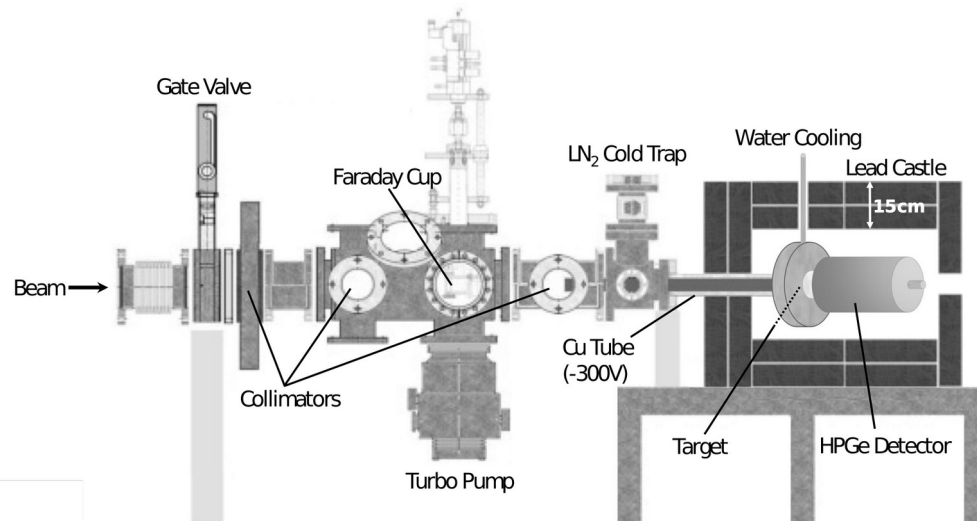


# Hydrogen burning: $^{12,13}\text{C}(p,\gamma)^{13,14}\text{N}$ reactions

## Measurements at low energies at LUNA, Gran Sasso, Italy

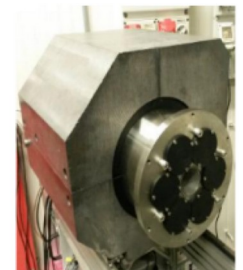
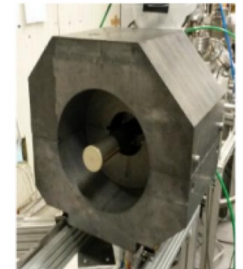
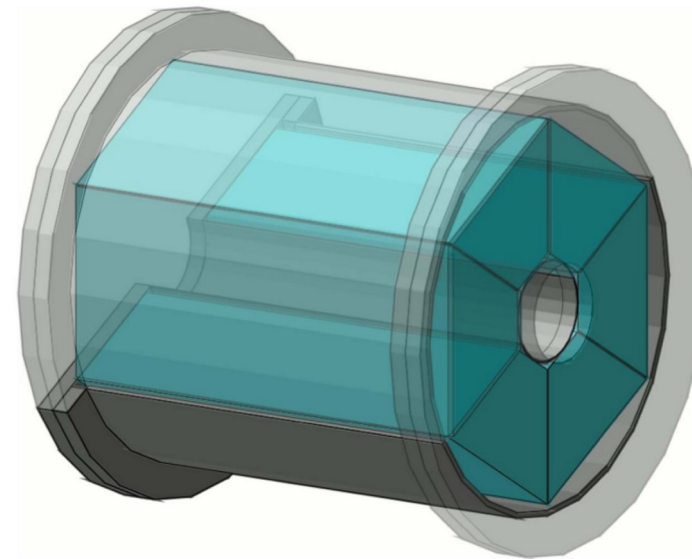
### HPGe setup

- Close geometry (**1.4 cm**) at **0°**
- Far geometry (**15 cm**) at **55°**
- Excellent **energy resolution**



### BGO setup

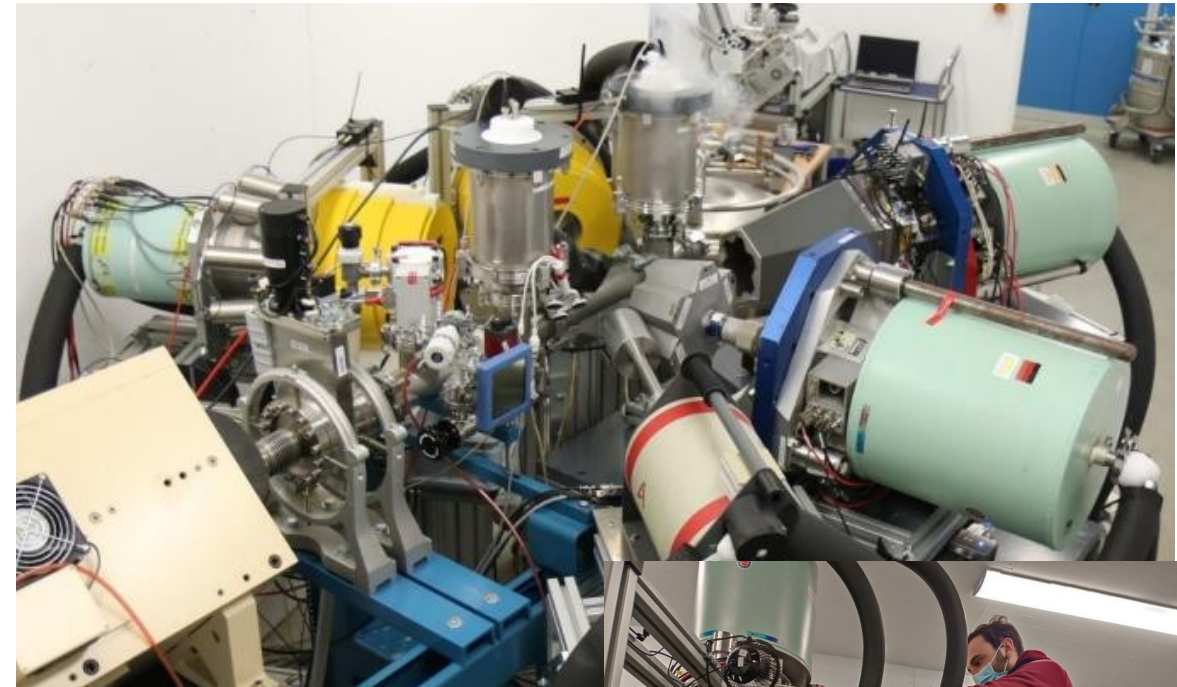
- Almost **4π geometry**
- Segmented in **6 different crystals**
- **Target check** with HPGe at 55°



# Hydrogen burning: $^{12,13}\text{C}(p,\gamma)^{13,14}\text{N}$ reactions

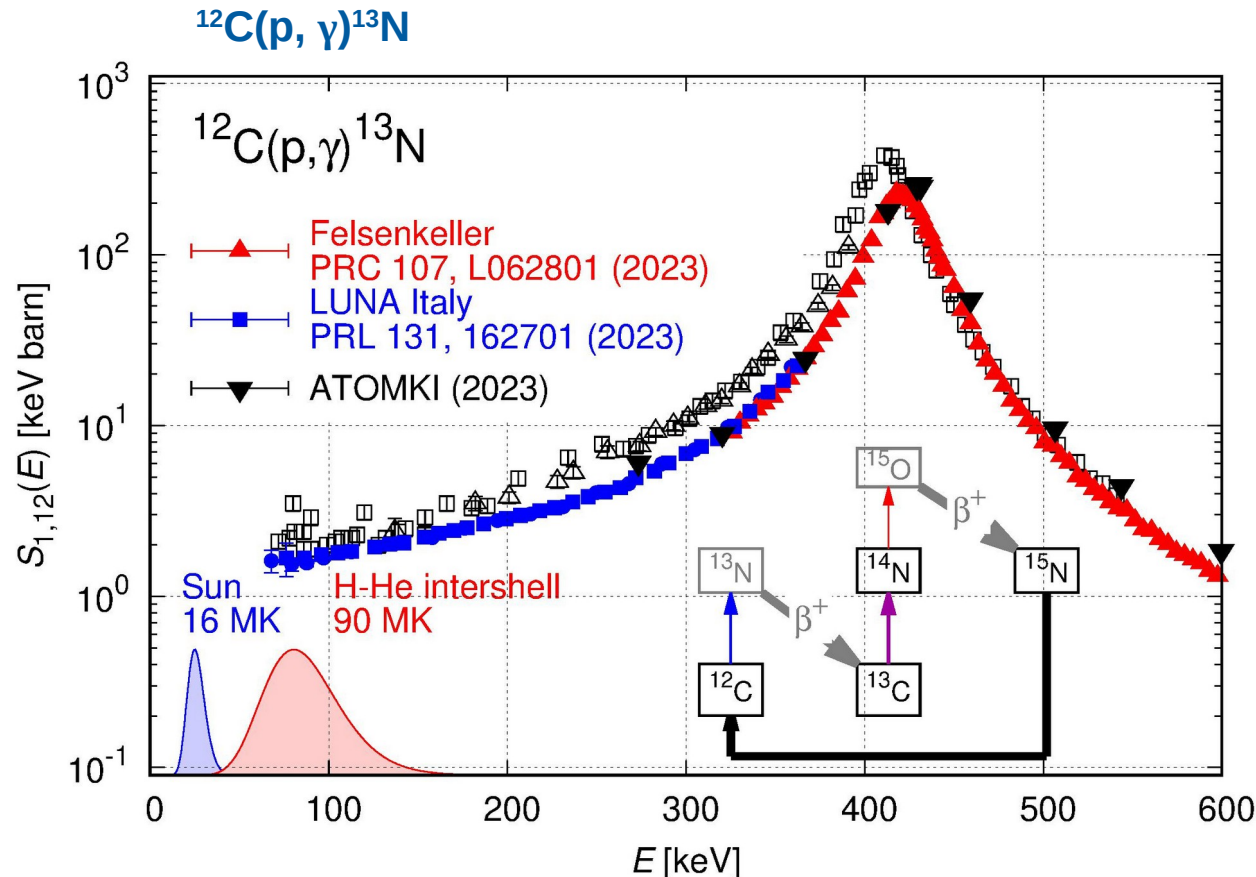
## Measurements at high energies at Felsenkeller

- ◆ Several HPGe detectors at different angle
- ◆  $\text{LN}_2$  cooled targets for the  $p+^{12}\text{C}$  campaign
- ◆ Water cooled targets for the  $p+^{13}\text{C}$  campaign
- ◆ Pb shielding for further background reduction
- ◆ Angular distribution data available



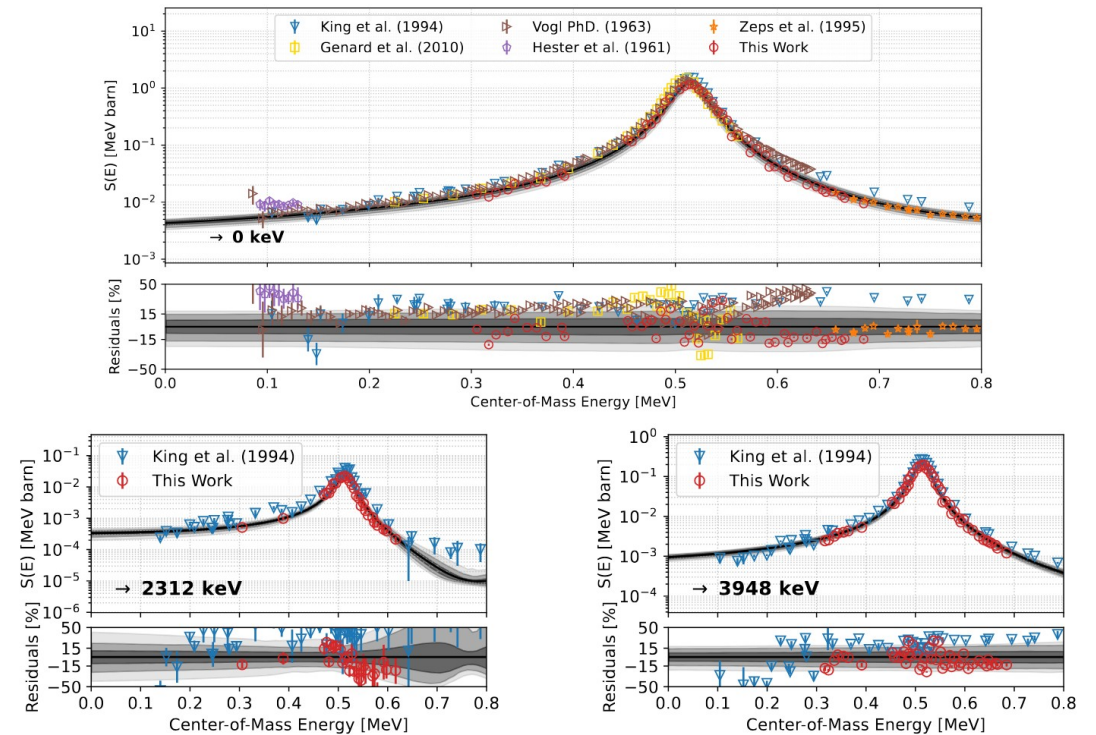
# Hydrogen burning: $^{12,13}\text{C}(p,\gamma)^{13,14}\text{N}$ reactions

## Overall measurements



Good agreement low energy – high energy!

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

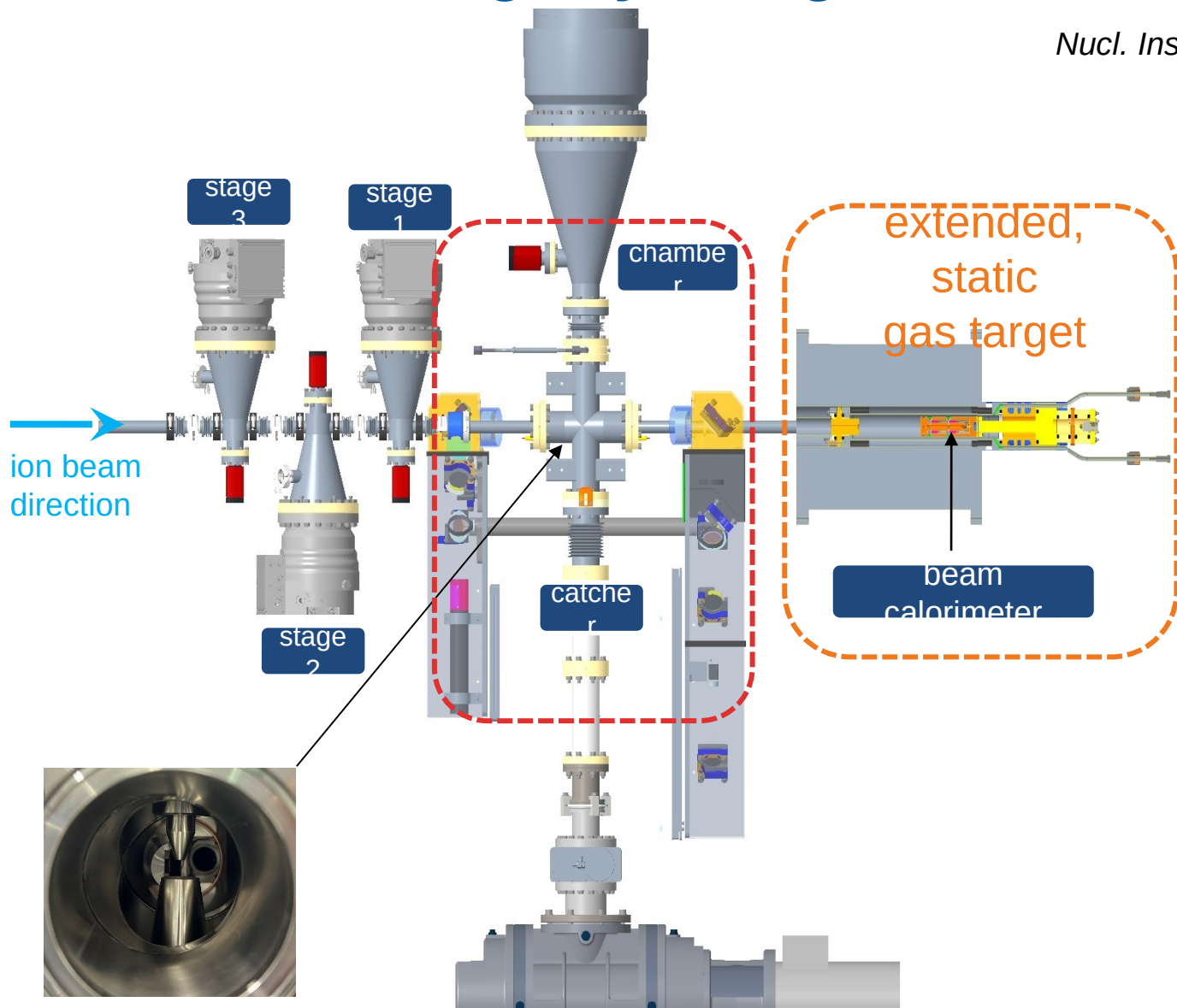


*J. Skowronski et al. Phys. Rev. C 111, 064611 (2025)*

*J. Skowronski et al. (LUNA) Phys. Rev. Lett. 131, 162701 (2023)*

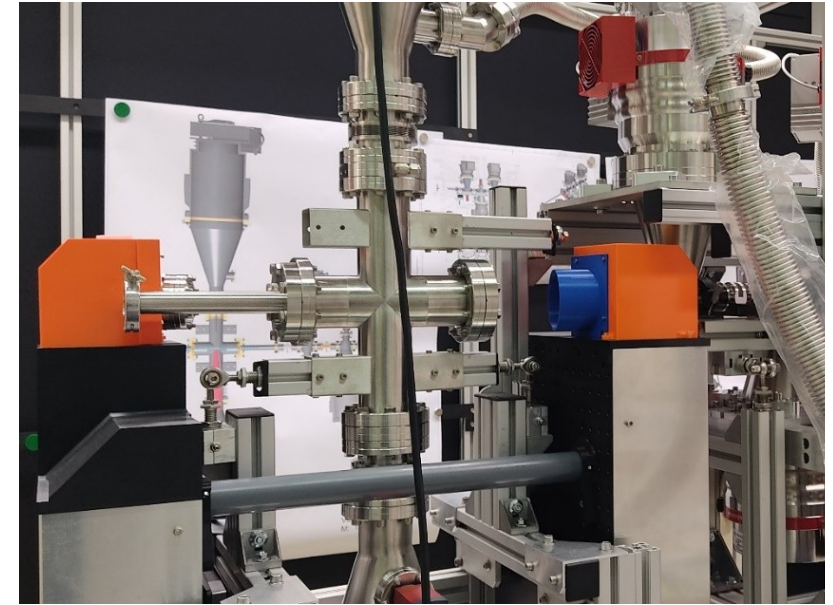
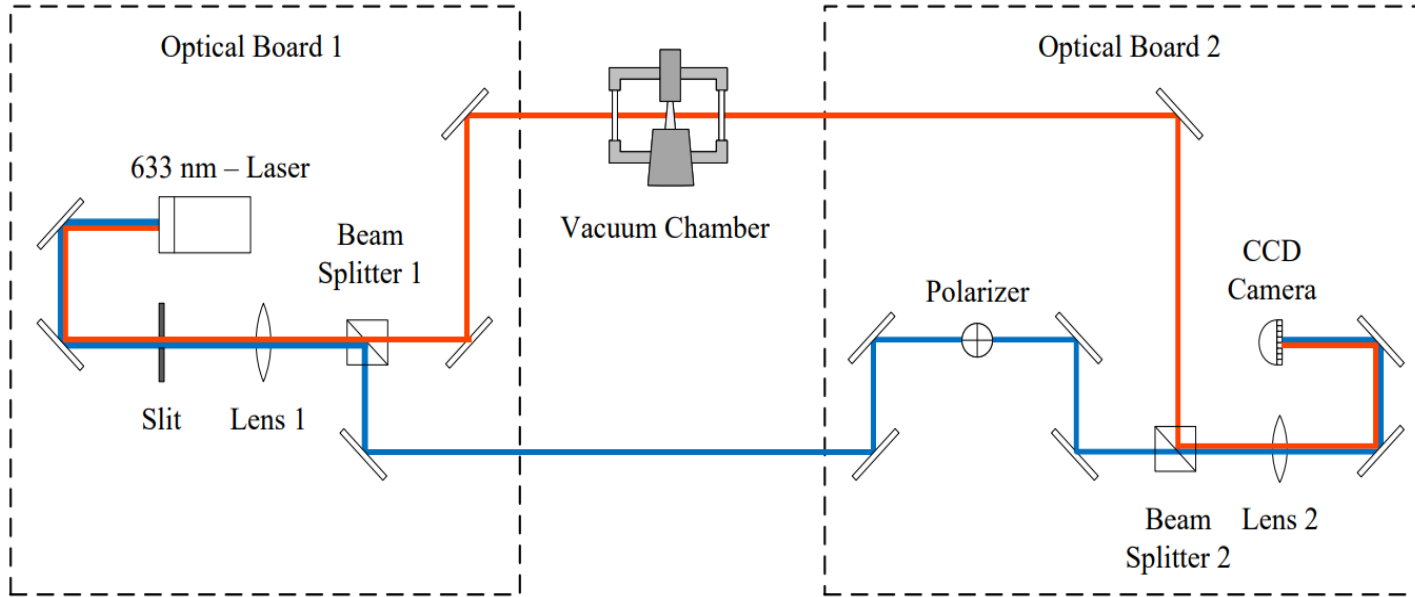
# Felsenkeller gas jet target for nuclear astrophysics

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



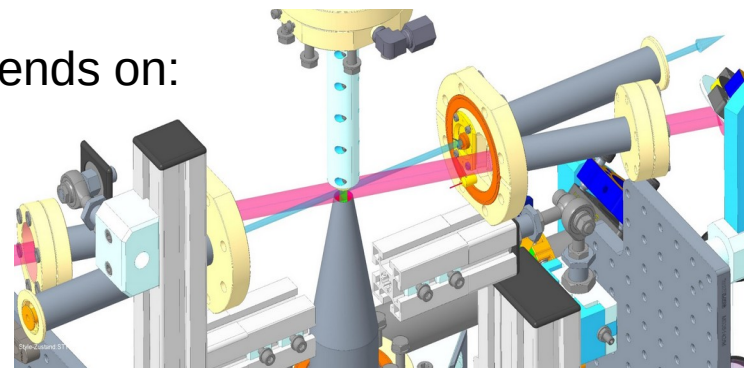
# Jet thickness using laser interferometry

## Mach-Zehnder Interferometer



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

- Optical path length difference depends on:
  - Gas refractive index
  - Density distribution
- Path length shift for  $N_2$  ( $0.11 \mu\text{m}$ )



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](http://www.elsevier.com/locate/nima)

Full Length Article

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

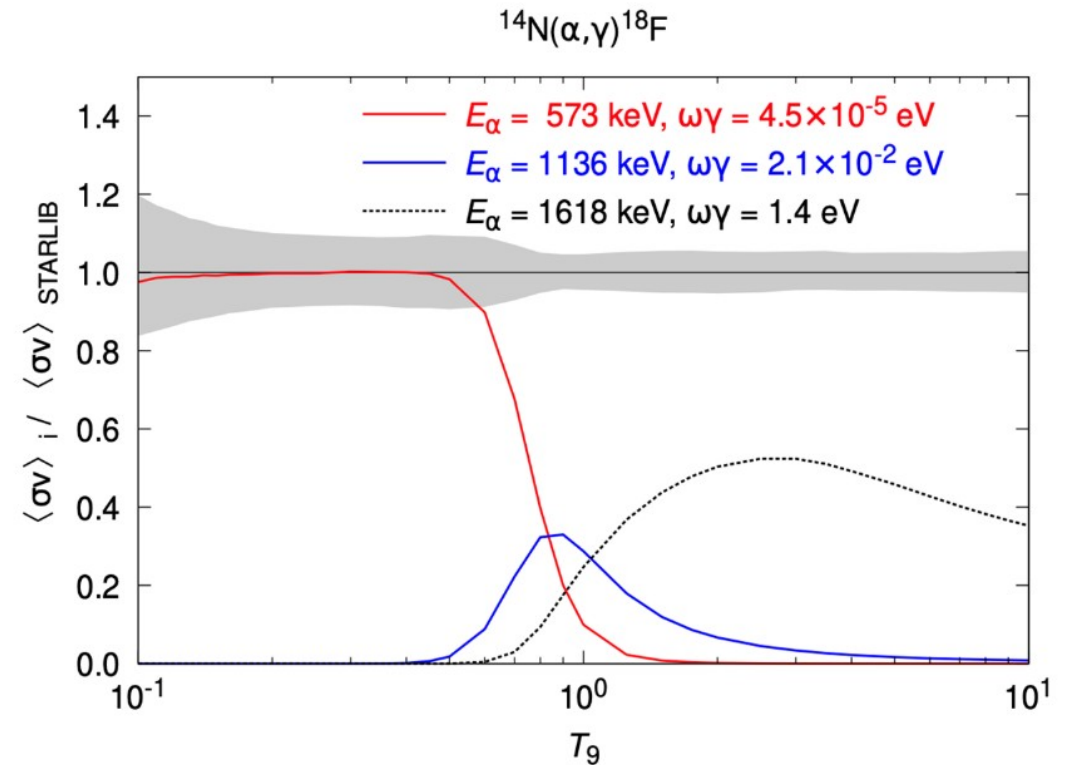
Anup Yadav<sup>a,b</sup>, Daniel Bemmerer<sup>a</sup>, Fabian Donat<sup>a</sup>, Juozas Dudutis<sup>a</sup>, Sören Göhler<sup>a,b</sup>, Maik Görler<sup>a</sup>, Maxim Hiltz<sup>a,b</sup>, Arie Irman<sup>a</sup>, Miglė Mackevičiūtė<sup>a</sup>, Konrad Schmidt<sup>a</sup>, Manfred Sobiella<sup>a</sup>, Vidmantas Tomkus<sup>c</sup>, Kai Zuber<sup>b</sup>

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

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

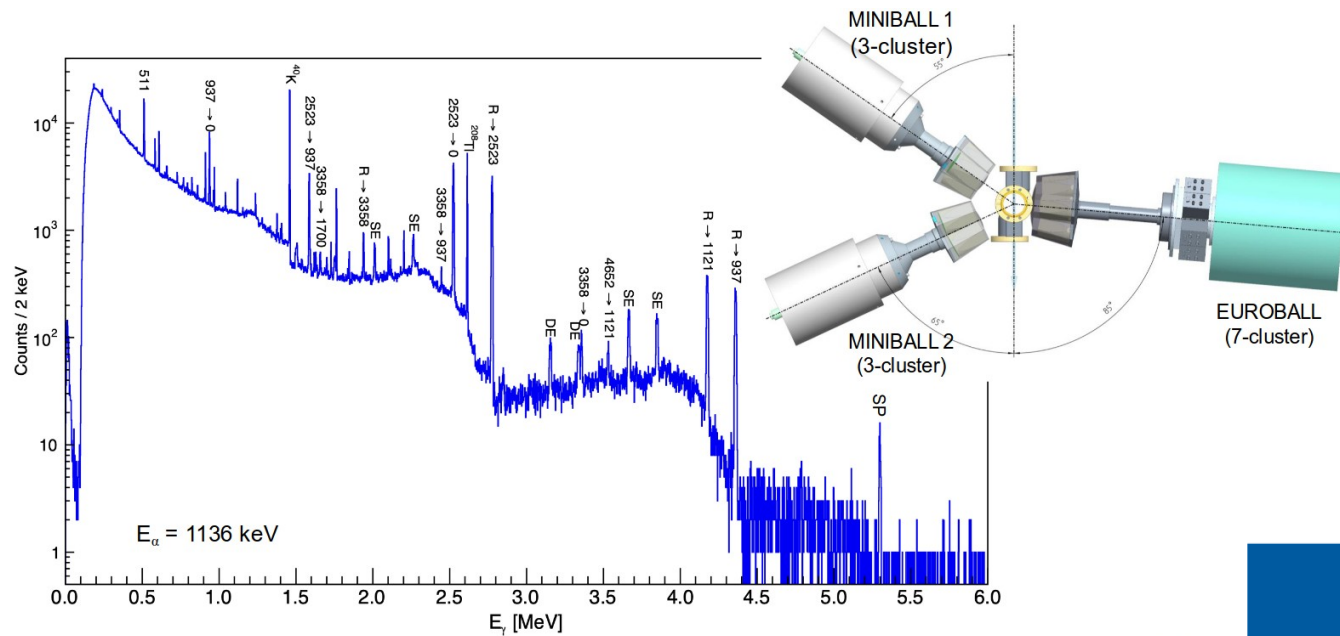
## Helium burning

- Affects the production of  $^{19}\text{F}$
- Influence the synthesis of  $^{22}\text{Ne}$  via  $^{14}\text{N}(\alpha,\gamma)^{18}\text{F}(\beta^\pm)^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$ , main neutron source in massive stars via the  $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$



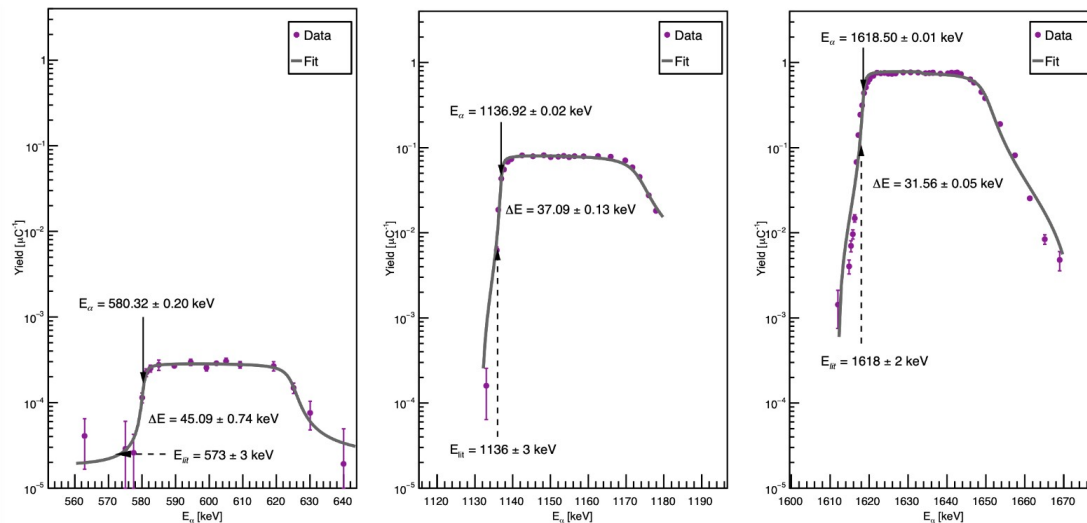
New data of low-energy resonances ( $E_\alpha = 0.4 - 1.6 \text{ MeV}$ ) are still needed

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



**Preliminary results**

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



# The Future: Solar hydrogen burning

## Thesis

<https://doi.org/10.1038/s41567-025-03151-w>

## A star of contradictions



By Mark Buchanan

Check for updates

Recently, physicists in Japan have upgraded the Super-Kamiokande neutrino detector by dissolving a small amount of gadolinium sulfate into its 50,000-ton volume of pure water. Gadolinium absorbs neutrons, and when a neutrino interaction in the detector knocks a neutron free, a gadolinium nucleus captures it within microseconds. This in turn generates a cascade of gamma rays providing an unambiguous signature that distinguishes true neutrino events from background noise. With this improvement, Super-Kamiokande has become one of the most sensitive instruments ever built for observing solar neutrinos, allowing physicists to probe the nuclear chemistry of the Sun with a precision unimaginable only a decade ago. Super-Kamiokande's upgraded phases build on the landmark 2020 detection at the Borexino detector in Italy of elusive CNO neutrinos, produced when hydrogen fuses into helium through the carbon–nitrogen–oxygen catalytic cycle.

As a result, solar neutrinos now play a key role in refining our understanding of stellar interiors. Yet the gains in accuracy have sharpened some predictions while unsettling others. Most dramatically, they have intensified the mismatch between seismic models and spectroscopically inferred surface metallicity – the so-called solar composition problem. Measured CNO neutrino fluxes point toward a solar core richer in heavy elements than the best atmospheric models allow. Meanwhile, updated measurements of other key fusion reactions – such as  ${}^7\text{He} + \alpha \rightarrow {}^7\text{Be}$  and  ${}^7\text{Be} + p \rightarrow {}^8\text{B}$  – combined with improved pp-chain neutrino determinations, have highlighted discrepancies in radiative opacity, the physics governing how energy propagates outward from the core.

This new landscape is at once a crisis and a chance for reinvention. A recent review by Bijaya Acharya and colleagues (*Rev. Mod. Phys.* **97**, 035002:2025) surveys recent progress while laying bare the tensions resulting from this precision revolution. The Sun – long treated as a solved problem – now seems full of subtle contradictions.

In 1938, German physicist Hans Bethe published the first explanation of how the

Sun and other stars generate energy through proton–proton fusion. By the 1980s and 1990s, developments in helioseismology and neutrino physics had refined Bethe's ideas into a standard solar model that reproduced seismic sound-speed profiles with impressive precision. Once researchers understood and incorporated neutrino oscillations, the model accounted for all known neutrino data.

**“The Sun is no longer the tidy, well-understood object it seemed to be a few years ago.”**

But as Acharya and co-authors relate, this sense of completion vanished in the mid-2000s when improved hydrodynamic models of the solar atmosphere triggered revisions to the best estimates of surface abundances. The inferred concentrations of carbon, nitrogen, oxygen, and other heavy elements dropped by nearly 30%. This shift led to immediate inconsistencies: the convection-zone boundary moved to the wrong depth, the sound-speed profile lost its excellent agreement, and the predicted surface helium abundance no longer matched seismic inferences. The Sun no longer fit its own model.

Recent neutrino measurements complicate matters further. The flux of CNO neutrinos scales directly with the core's carbon and nitrogen content and provides the first empirical handle on the Sun's interior metallicity. Intriguingly, the observed flux leans toward a higher metallicity than spectroscopic models predict. This suggests that either our spectroscopic methods are flawed, or our understanding of the physics of the solar interior (including opacity, mixing and diffusion) is significantly incomplete. Future progress will depend on tightening CNO neutrino measurements, improving radiative-opacity calculations, and perhaps revisiting atmospheric models.

A second major issue that the authors highlight is radiative opacity, a quantitative measure of how impenetrable the solar plasma is to

radiation. This impenetrability is determined by the microscopic physics that governs how the solar plasma absorbs, scatters and re-emits photons. For decades, opacity tables were trusted building blocks of solar modeling. Yet helioseismology now suggests that opacities in the radiative zone are 5–15% too low, depending on depth. Laboratory experiments using facilities like Sandia's Z machine have even found that the iron opacity – a crucial contributor – may be substantially higher than theoretical predictions. Because a small increase in opacity deepens the convection zone and alters the temperature profile, opacity underpins the solar composition problem and is rapidly becoming one of the central unknowns in stellar astrophysics.

Acharya and colleagues also revisit the nuclear reaction rates themselves, which have been improved by experiments at advanced underground labs such as LUNA in Italy and Felsenkeller in Germany. Shielded from cosmic rays, experiments at these facilities have refined the low-energy fusion cross sections for critical steps in the pp-chain. Meanwhile, inertial-confinement plasma experiments have begun to probe electron-screening effects directly under near-solar conditions – something previously not possible. Some reaction rates have shifted by a few percent, which is enough to alter predicted neutrino spectra. Even the shape of the  ${}^8\text{B}$  neutrino spectrum, a staple of solar neutrino studies, has been revised downward in energy by tens of keV.

Therefore, the Sun is no longer the tidy, well-understood object it seemed to be a few years ago. The revolution inspired by new neutrino data reveals multiple tensions as neutrinos, seismic waves, opacities, and spectral lines tell slightly different stories. That divergence is what makes the present moment exciting. With new detectors coming online and new laboratory measurements probing previously unreachable regimes, the next twenty years may see Bethe's foundational picture not overturned but enriched. The Sun's simplicity was an illusion born of incomplete data.

Published online: 15 January 2026

# The Future: Solar hydrogen burning

Thesis

Astar

By Mark Buchanan

Recently, physicists in Japan have upgraded the Super-Kamiokande neutrino detector by dissolving a small amount of gadolinium sulfate into its 50,000-ton volume of pure water. Gadolinium absorbs neutrons, and when a neutrino interaction in the detector knocks a neutron free, a gadolinium nucleus captures it within microseconds. This in turn generates a cascade of gamma rays, providing an unambiguous signature that distinguishes true neutrino events from background noise. With this improvement, Super-Kamiokande has become one of the most sensitive instruments ever built for observing solar neutrinos, allowing physicists to probe the nuclear chemistry of the Sun with a precision unimaginable only a decade ago. Super-Kamiokande's upgraded phases build on the landmark 2020 detection at the Borexino detector in Italy of elusive CNO neutrinos, produced when hydrogen fuses into helium through the carbon-nitrogen-oxygen catalytic cycle.

As a result, solar neutrinos now play a key role in refining our understanding of stellar interiors. Yet the gains in accuracy have sharpened some predictions while unsettling others. Most dramatically, they have intensified the mismatch between seismic models and spectroscopically inferred surface metallicity – the so-called solar composition problem. Measured CNO neutrino fluxes point toward a solar core richer in heavy elements than the best atmospheric models allow. Meanwhile, updated measurements of other key fusion reactions – such as  ${}^3\text{He} + \alpha \rightarrow {}^7\text{Be}$  and  ${}^7\text{Be} + p \rightarrow {}^8\text{B}$  – combined with improved pp-chain neutrino determinations, have highlighted discrepancies in radiative opacity, the physics governing how energy propagates outward from the core.

This new landscape is at once a crisis and a chance for reinvention. A recent review by Bijaya Acharya and colleagues (*Rev. Mod. Phys.* **97**, 035002; 2025) surveys recent progress while laying bare the tensions resulting from this precision revolution. The Sun – long treated as a solved problem – now seems full of subtle contradictions.

In 1938, German physicist Hans Bethe published the first explanation of how the

Sun and other stars generate energy through proton-proton fusion. By the 1980s and 1990s, developments in helioseismology and neutrino physics had refined Bethe's ideas into a standard solar model that reproduced seismic sound-speed profiles with impressive precision. Once researchers understood and incorporated neutrino oscillations, the model accounted for all known neutrino data.

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## LUNANOVA

Laboratory Underground for Nuclear Astrophysics  
New Observatory for Solar Neutrino Reactions



Heraeus Workshop on Interdisciplinary Physics of the Sun, June 2025

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

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



nature physics

Volume 22 | January 2026 | 5 | 5



# The Future: Solar hydrogen burning



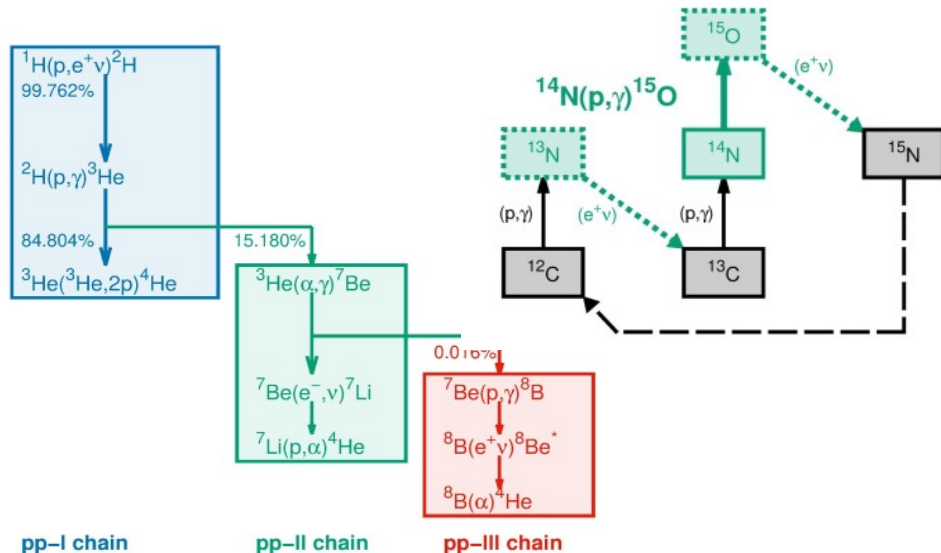
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LUNANOVA

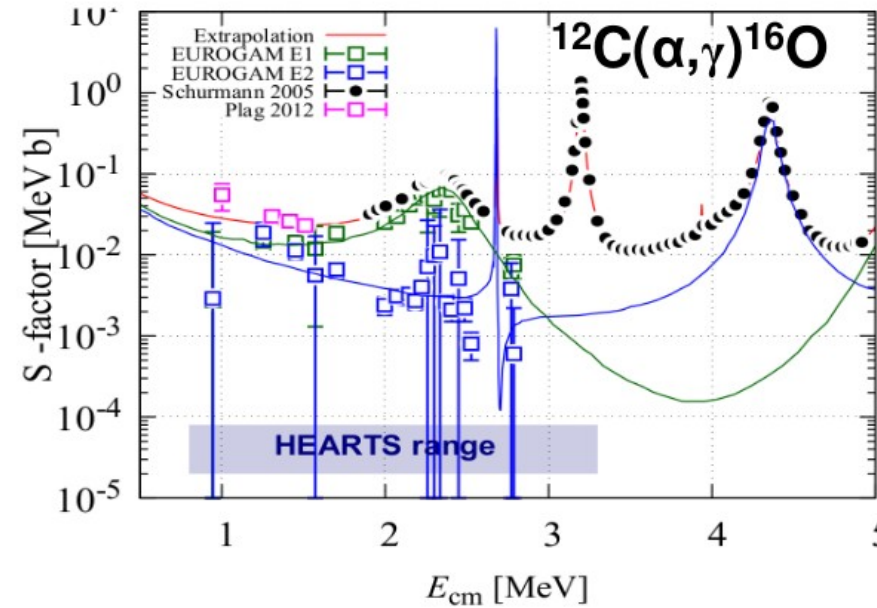


	2026	2027	2028	2029	2030	2031
WP1 Synergy	LUNANOVA cloud (Nextcloud, Mattermost, Jupyter, Gitlab, ELOG, RODARE) @ EOSC					
	2 general meetings/year					
	Synergy stays by PhDs, postdocs					
	Outward look					SF IV meeting
WP2, WP3 Experiments @ LUNANOVA	Procure, install, commission accelerator		${}^3\text{He}(\alpha, \gamma) {}^7\text{Be}$	${}^{14}\text{N}(p, \gamma) {}^{15}\text{O}$	$e^-$ screening	H/He burning
WP4 Experiments elsewhere	${}^{14}\text{N}(p, \gamma) {}^{15}\text{O}$	${}^3\text{He}(\alpha, \gamma) {}^7\text{Be}$	${}^7\text{Be}(p, \gamma) {}^8\text{B}$	CRYRING	ELBE	Bellotti IBF
WP5 Rates	R-Matrix & thermonuclear reaction rate code		He burning react. select.	He burning stellar simulations		C burning stellar simul.
	R-Matrix and rate computation					
WP6 Model	Solar model inputs, code, reaction selection		Solar neutrinos @ dark matter experiments			Solar model update
	Internal structure of solar-like stars			Non-standard solar models		

# The Future: Helium burning

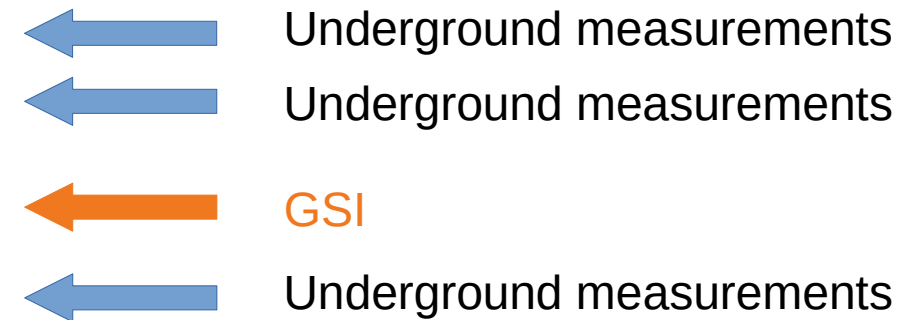
The rate of the  $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$  nuclear reaction (“Holy Grail”) remains highly uncertain

- New  $^4\text{He}$  jet target for angular distribution at high energies
- High efficiency setup at lower energies



Helmholtz Young Investigator  
 PI: E. Masha, HZDR  
 2026-2030

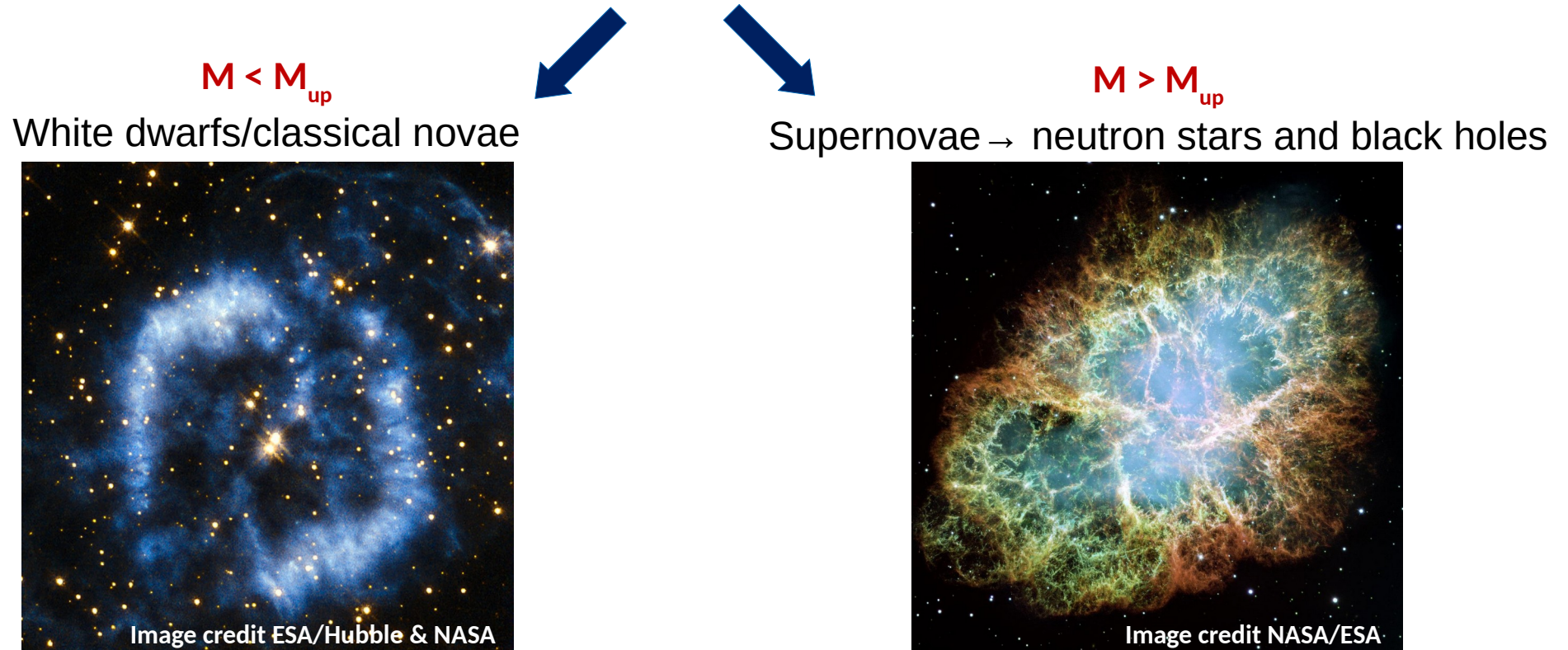
Reaction	T (GK)	Astrophysical Impact
$^{15}\text{N}(\alpha,\gamma)^{19}\text{F}$	0.1 – 0.3	Fluorine production
$^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$	0.1 – 0.3	Seed for the s-process (heavy elements)
$^{18}\text{F}(\alpha,p)^{21}\text{Ne}$	0.4 – 1.0	Fluorine destruction
$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$	0.1 – 0.4	Carbon to oxygen ratio



# The Future: Stellar Carbon burning

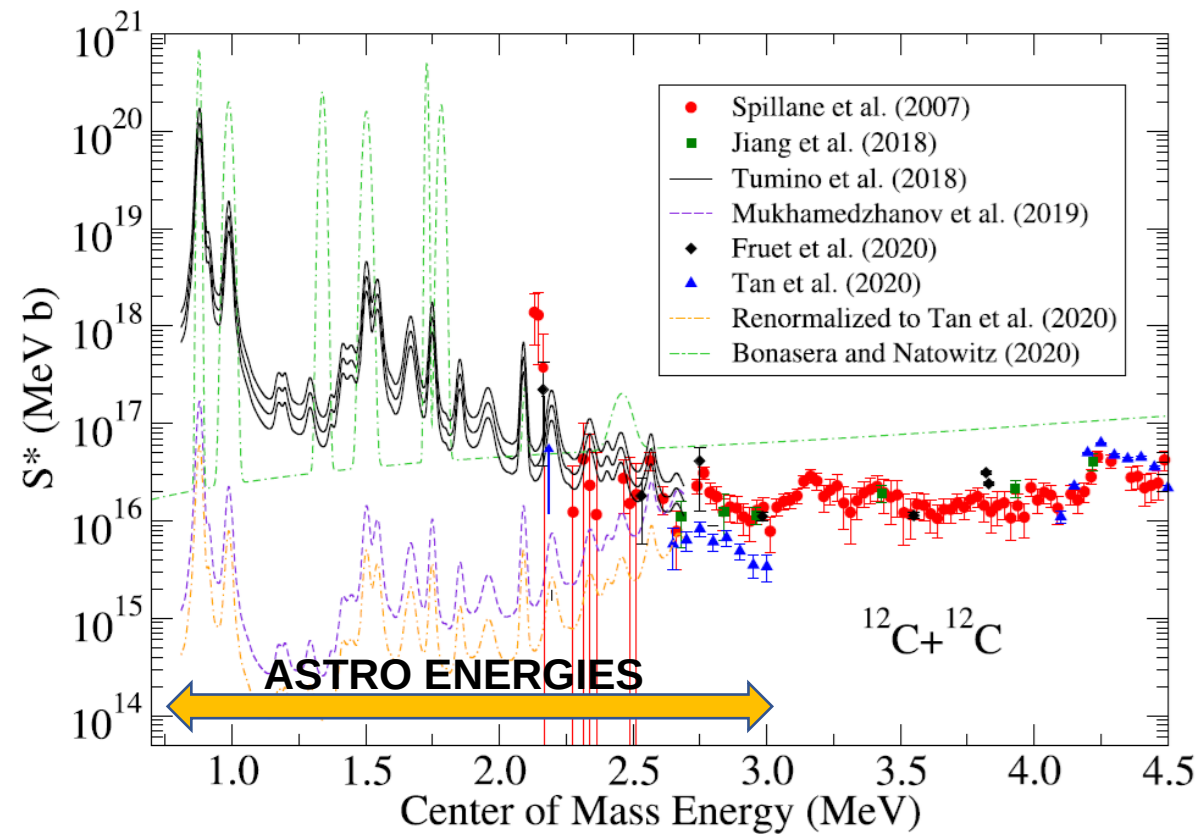
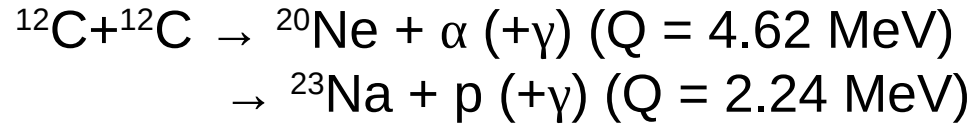
In stars, carbon burning is the first evolutionary stage involving the fusion of heavy ions

Only stars with mass higher than a threshold  $M_{UP}$  ( $\sim 8 M_{SUN}$ ) can ignite carbon burning:



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

# The Future: Stellar Carbon burning



Aliotta et al 2022 J. Phys. G: Nucl. Part. Phys. 49 010501

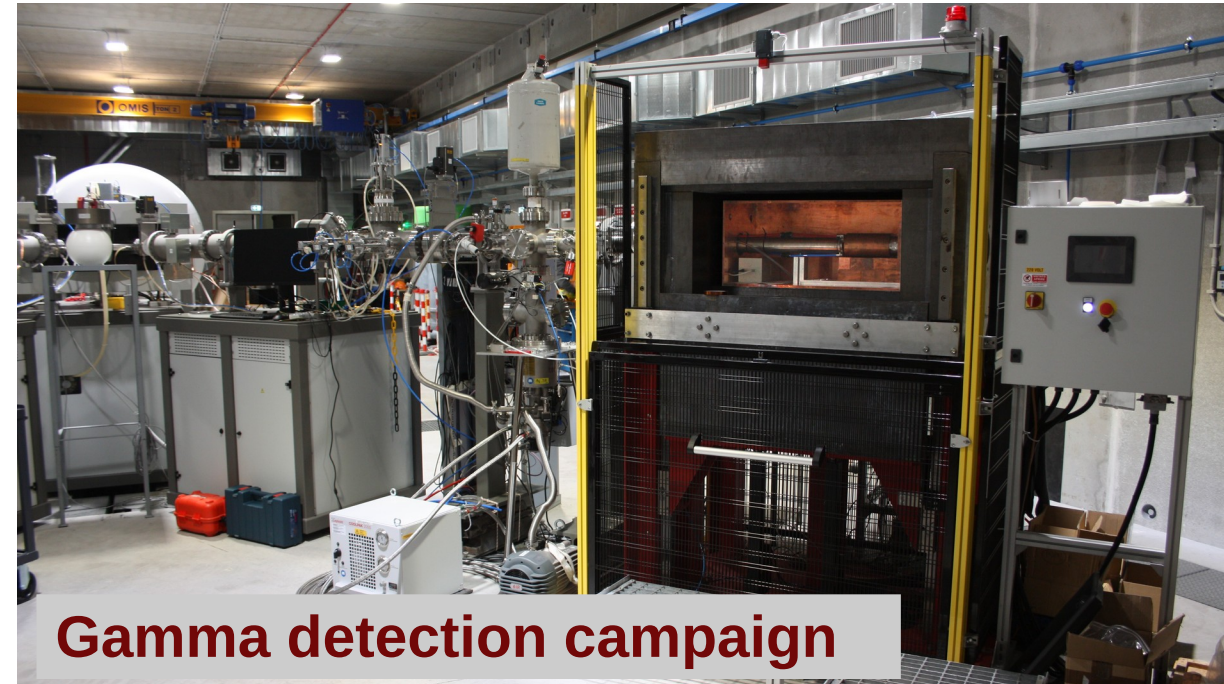
## Measurement started at the Bellotti IBF/LNGS

$^1\text{H}^+$  (TV: 0.3 – 3.5 MV): 500-1000  $\mu\text{A}$

$^4\text{He}^+$  (TV: 0.3 – 3.5 MV): 300-500  $\mu\text{A}$

$^{12}\text{C}^+$  (TV: 0.3 – 3.5 MV): 150  $\mu\text{A}$

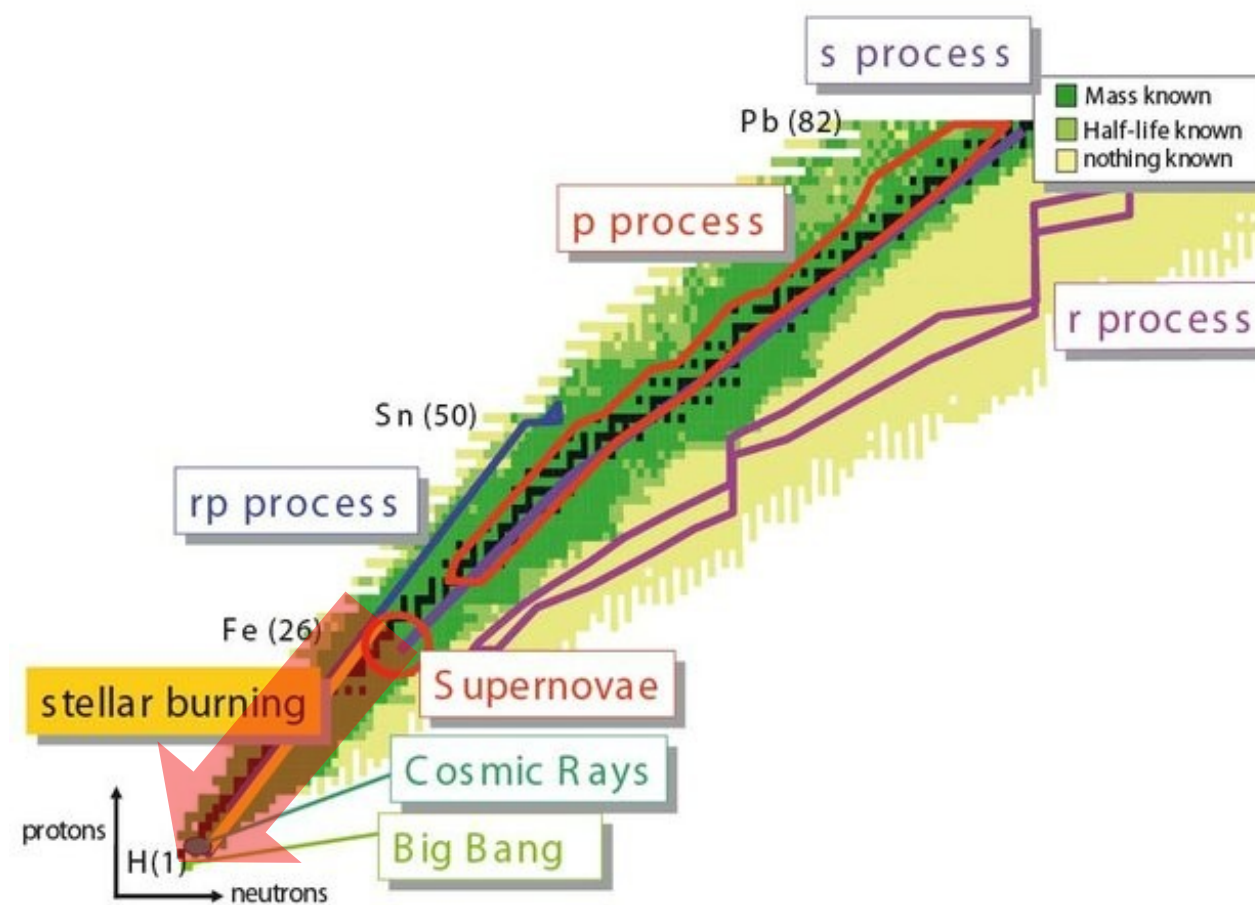
$^{12}\text{C}^{++}$  (TV: 0.5 – 3.5 MV): 100  $\mu\text{A}$



**Gamma detection campaign**

# Summary

- Underground nuclear astrophysics has contributed to the community for over three decades
- LUNA has been leading the field exploring the lowest astrophysical energies
- Underground facilities are expanded worldwide
- Felsenkeller facility has explored several science cases in less than five years and has developed the first jet target in underground lab
- More precision measurements exploring astrophysical scenarios for H burning, He burning, carbon burning, with the effort of collaborative facilities are planned



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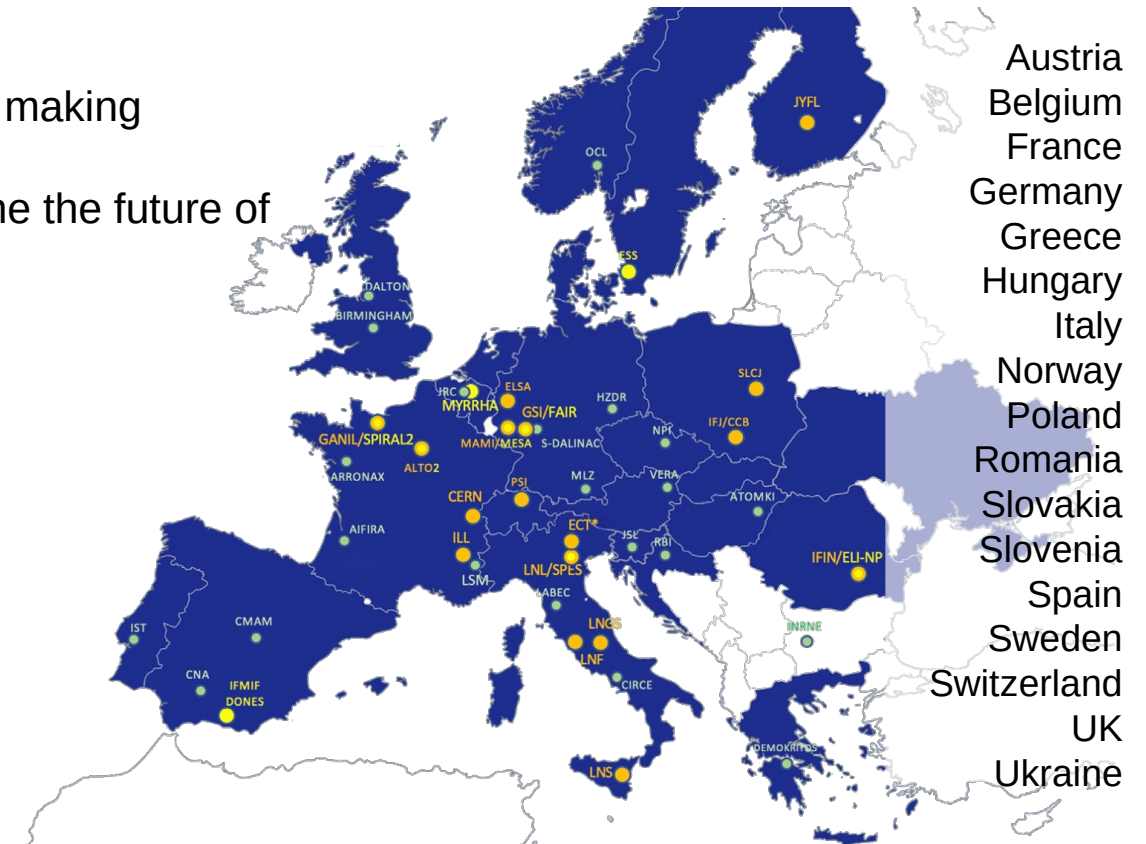
# NuFFER - NuPECC Forum For Early-career Researchers



## Our mission

- Support early-career researchers (ECRs) in nuclear physics across Europe
- Provide visibility and recognition to young scientists
- Represent their needs and interests in the NuPECC decision making
- Encourage participation in strategic discussions that determine the future of nuclear science in Europe
- Inform about opportunities for development

## Current representative members



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