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

Solar pp-chain reactions studied underground

Interdisciplinary Physics of the Sun
Spanish-German WE-Heraeus-Seminar

29 June – 04 July 2025

WILHELM UND ELSE HERAEUS-STIFTUNG

Eliana Masha

Helmholtz Zentrum Dresden-Rossendorf

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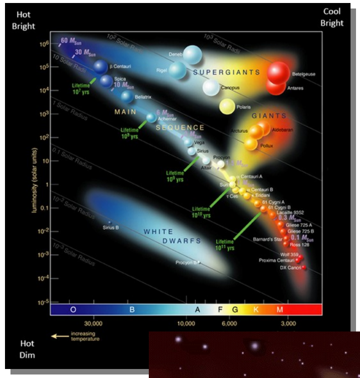
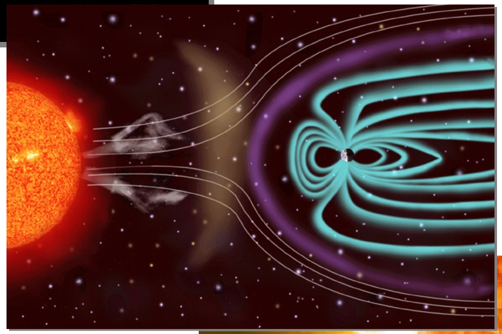
Why still study the Sun?

- Fundamental to understand stellar evolution
- Direct Impact on Earth
- The closest natural lab for nuclear and plasma physics

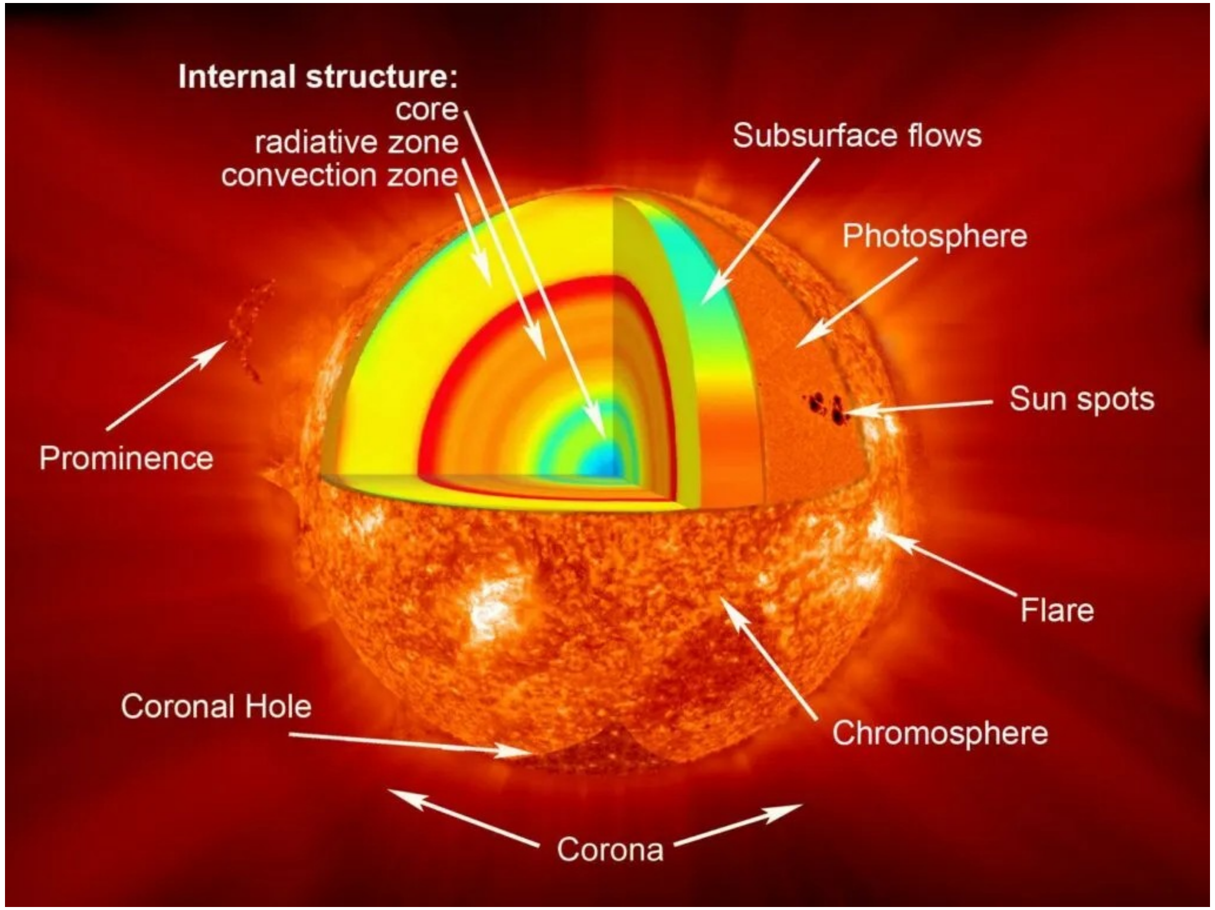




Structure of the Sun

- Sun’s energy is produced in the core

- Energy is transported outward through the radiative and convective zones.



Structure of the Sun

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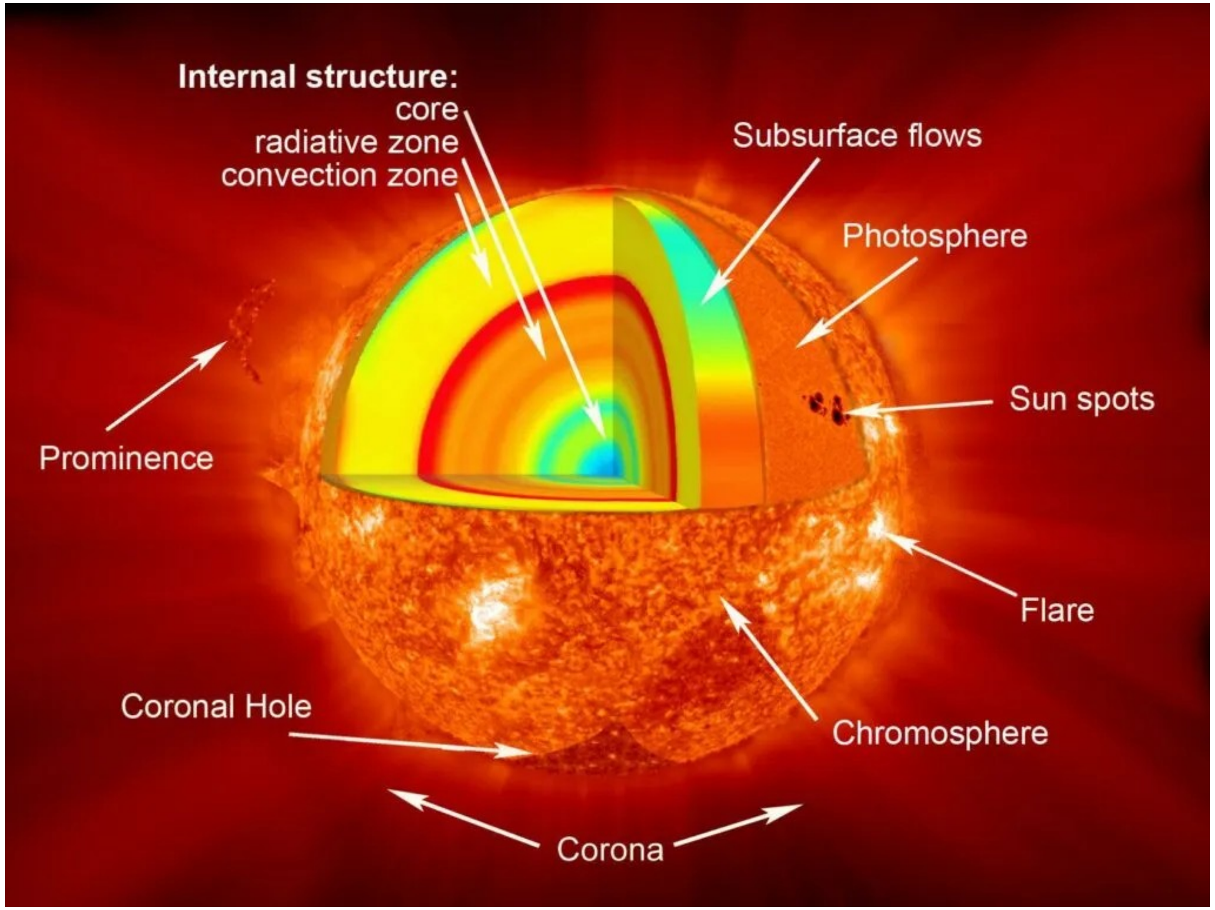
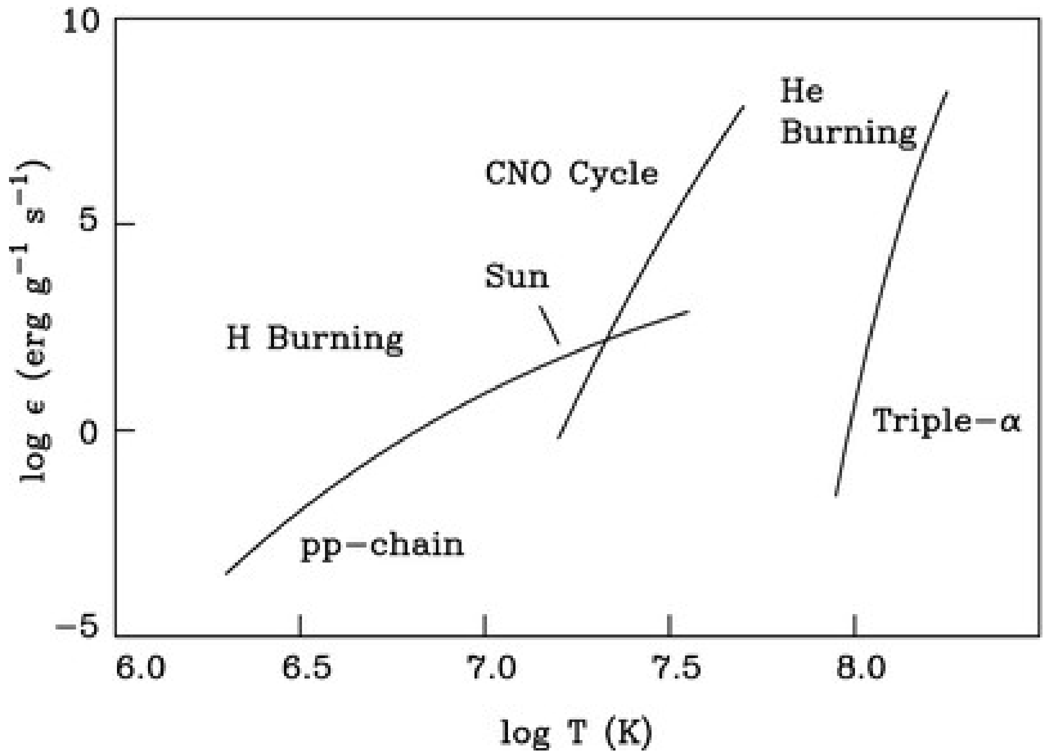
⇒ **Nuclear reactions in the core of the Sun**



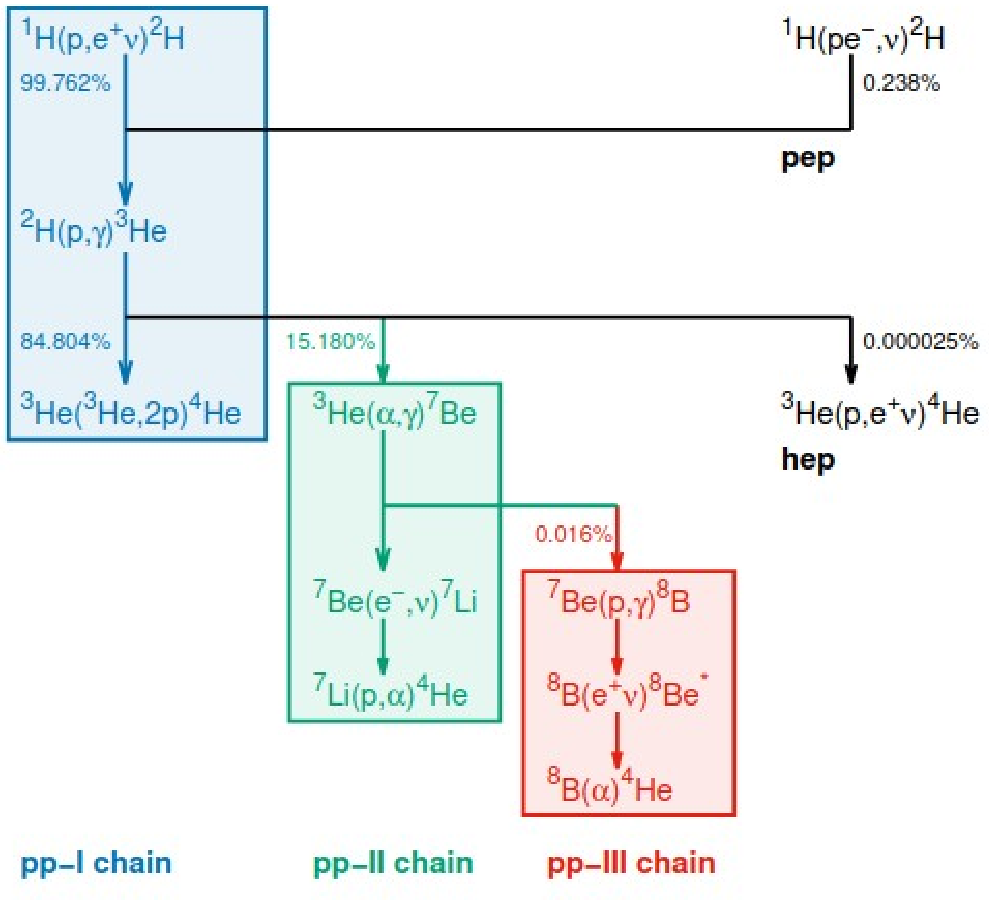
Solar proton-proton chain

Fundamental energy source

- Powers the Sun and similar main-sequence stars
- Responsible for ~99% of solar energy output



Step by step: The pp-chain reactions



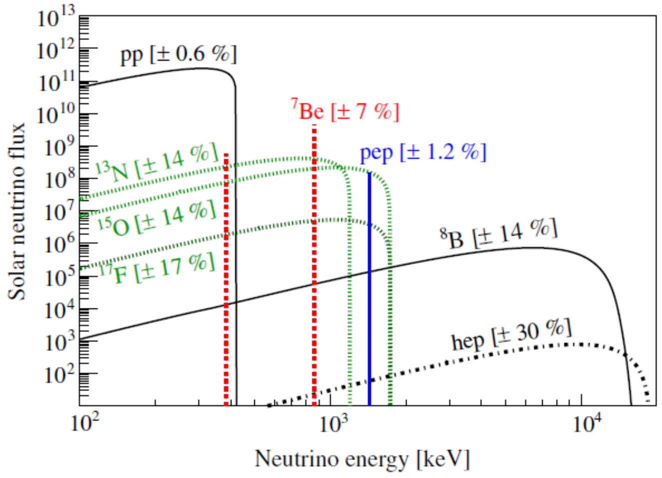
A cornerstone of stellar evolution models

- Determine the rate of hydrogen burning the sun’s life
- Affect stellar structure, luminosity and temperature
- Provides the basis of SSM
- Precise reactions rate crucial for the models

Observational evidence and diagnostics

Neutrino detection

- Solar neutrinos provide direct evidence of core fusion processes.

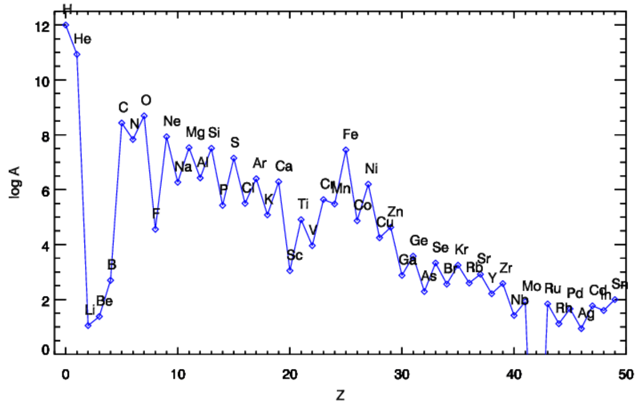


Helioseismology

- Solar oscillations provide info on the internal structure and validate theoretical models of the Sun's core conditions and energy transport mechanisms.

Abundance analysis

- Spectroscopic measurements of isotopic ratios and element abundances trace nucleosynthesis pathways and confirm reaction rates predicted by theory.



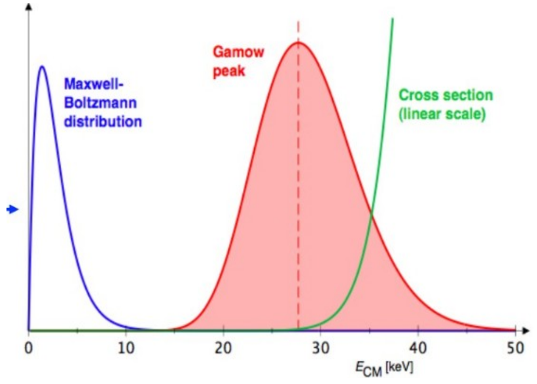
Precise nuclear reaction rate

Yesterday from
A. Formicola

- Direct cross section at stellar energies $N_A\langle\sigma v\rangle = N_A\sqrt{\frac{8}{\pi A}}(k_B T)^{-3/2}\int \sigma(E) E \exp\left(-\frac{E}{k_B T}\right) dE$

- Very low cross section

- Deal with low signal-to-noise ratio



Reaction	E_0 [keV]
p+p	6
^{3}He+^{3}He	22
^{3}He+^{4}He	23
^{7}Be+p	18
^{14}N+p	27

R_{lab} = 1-10 counts/day

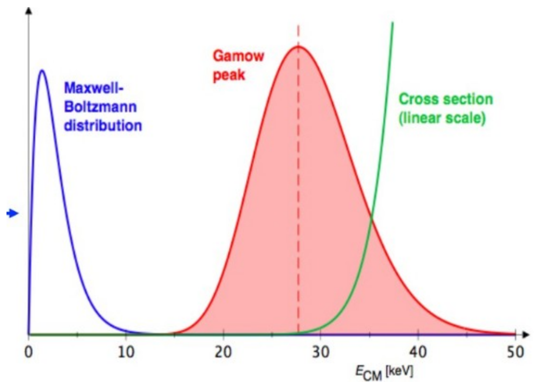
Precise nuclear reaction rate

Yesterday from
A. Formicola

LUNA

- Direct cross section at stellar energies $N_A\langle\sigma v\rangle = N_A\sqrt{\frac{8}{\pi A}}(k_B T)^{-3/2}\int \sigma(E)E\exp\left(-\frac{E}{k_B T}\right)dE$
- Very low cross section
- Deal with low signal-to-noise ratio

Underground measurements



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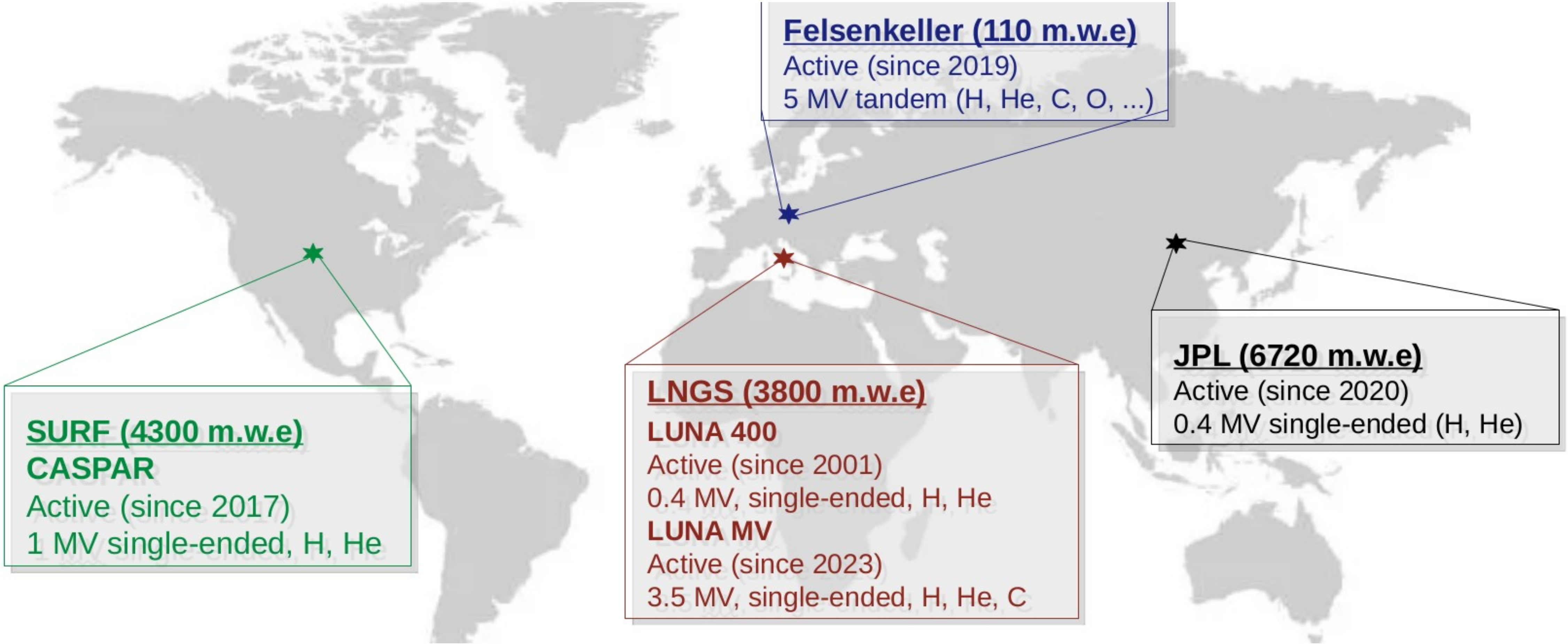
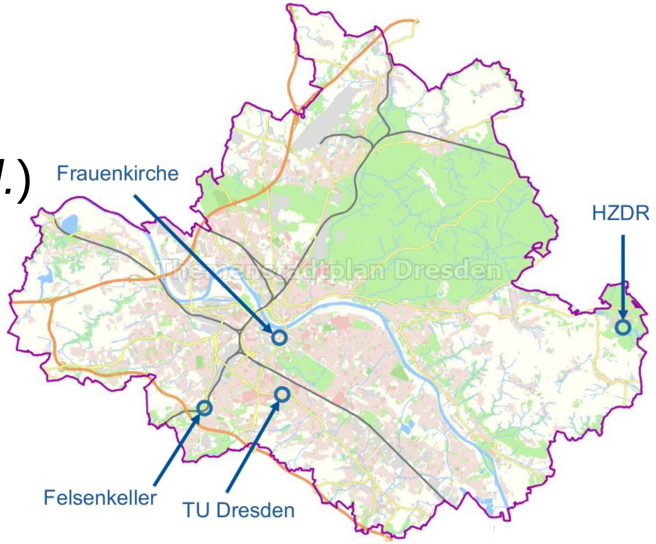
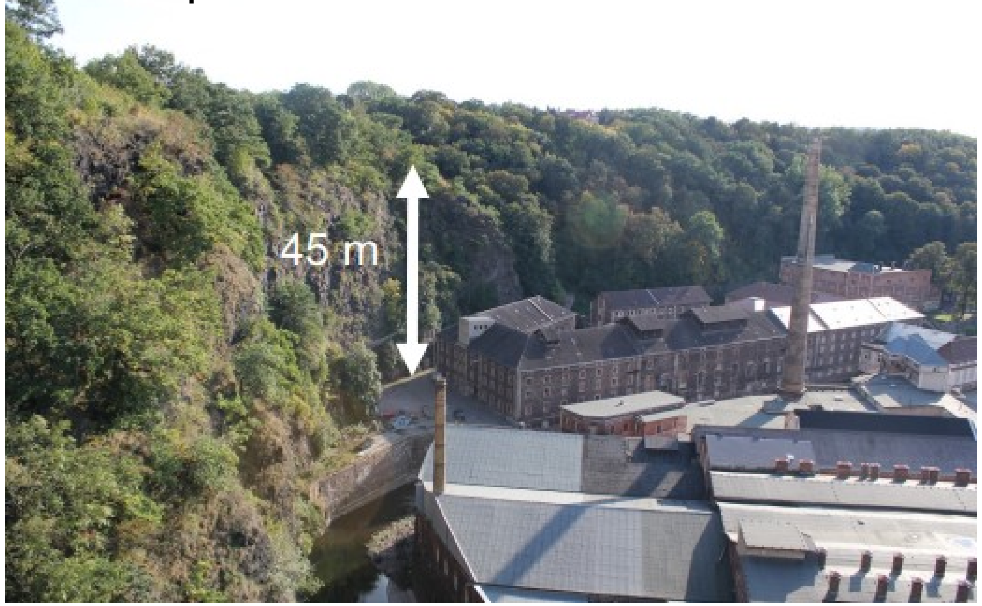
Underground accelerator facilities

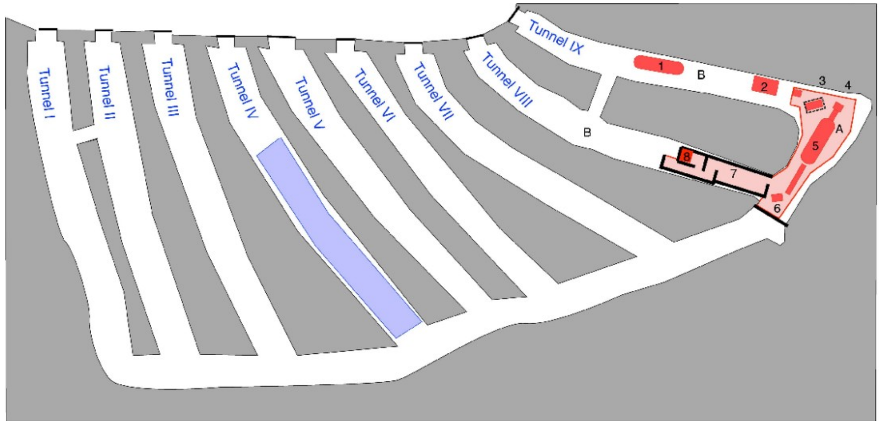


Felsenkeller shallow underground lab

- Located in Dresden, Germany
- System of nine tunnels
- Joint project: TU Dresden (Kai Zuber *et al.*) and HZDR (Daniel Bemmerer *et al.*)
- 24 h beam operation
- Surface operator room / offices
- Experimental room accessible with beam on target



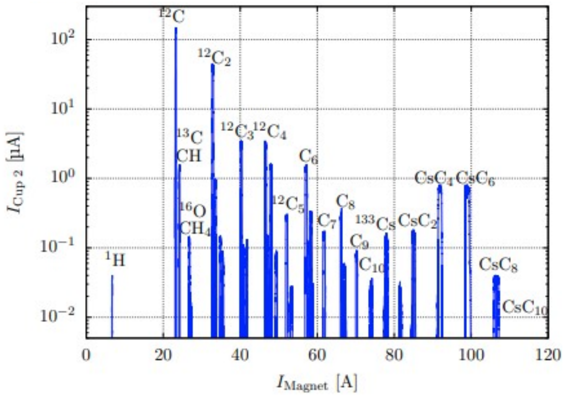


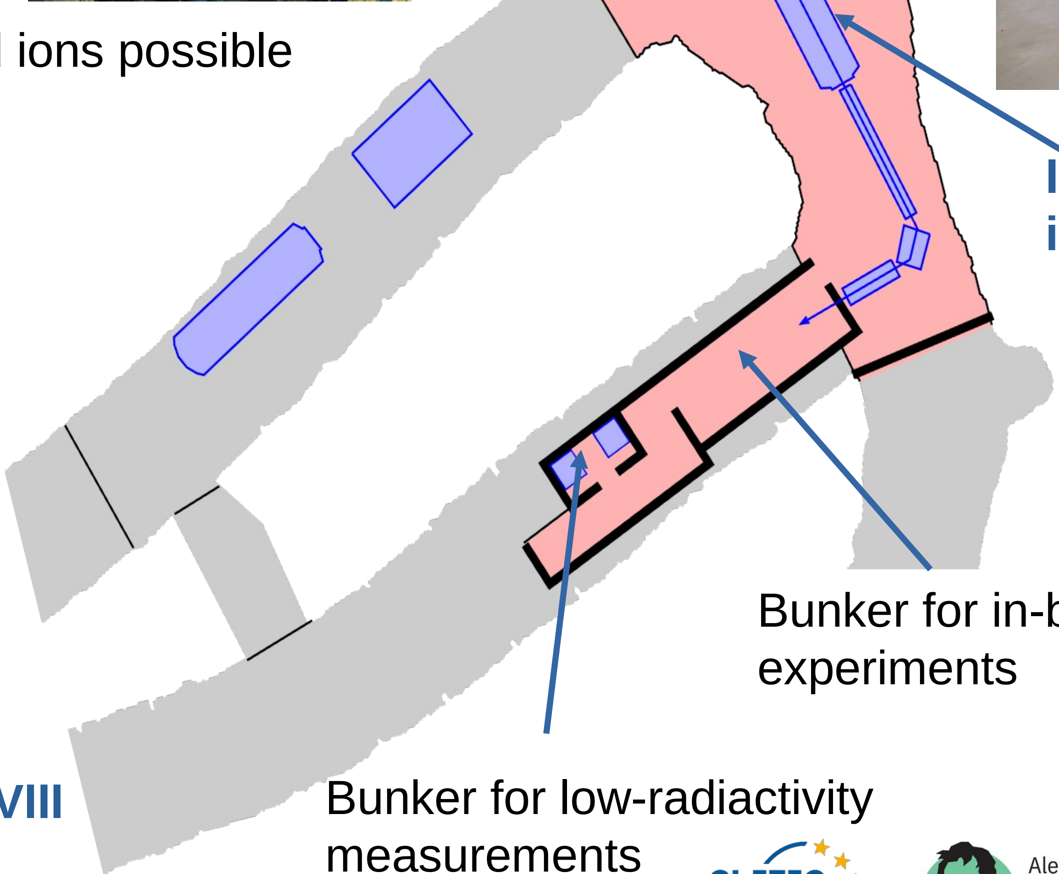


Felsenkeller shallow underground lab

External ion-source

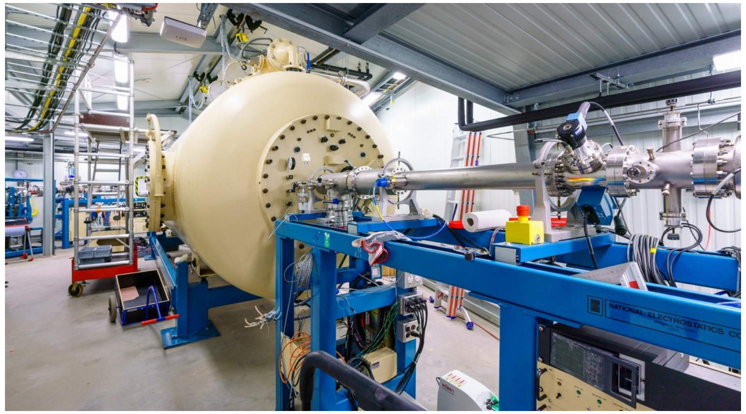
- Intensive ^{12}C beam
- Intensity of 20-30 µA
- Other negatively charged ions possible





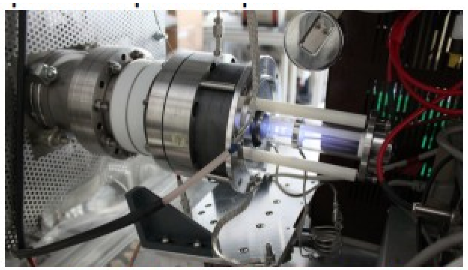
Tunnel IX

Tunnel VIII



Internal radio frequency ion-source

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

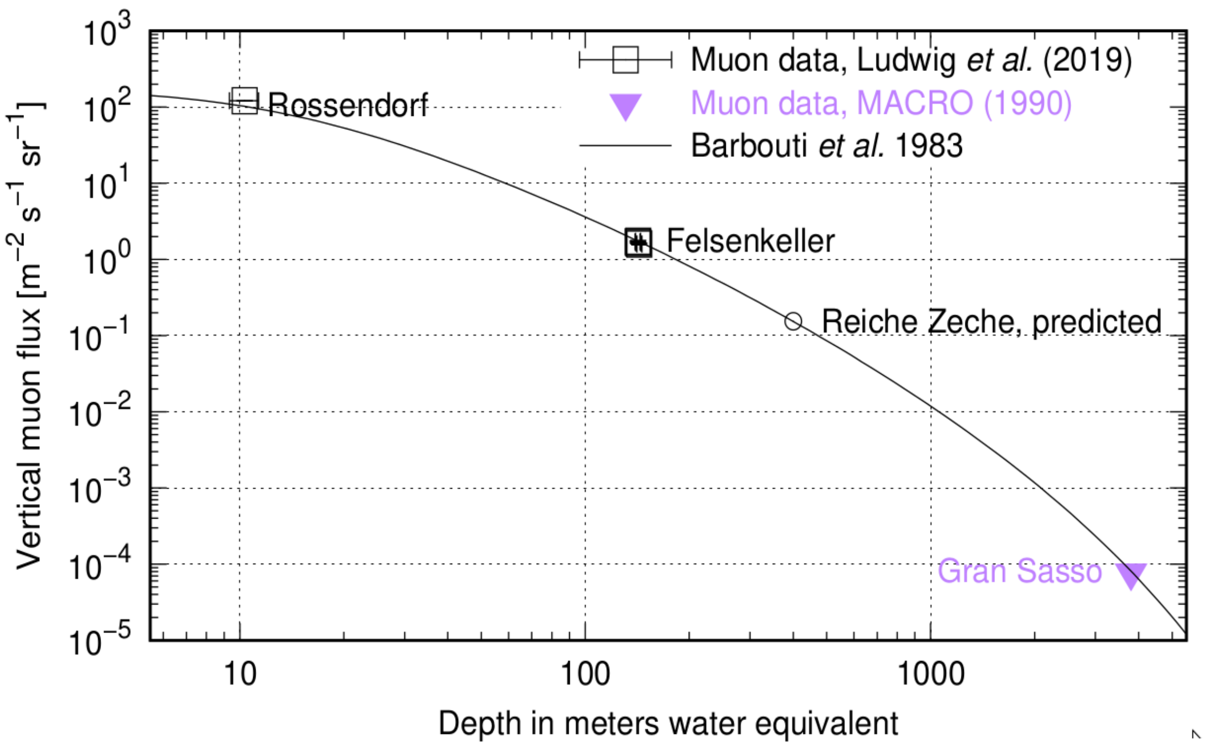


Bunker for in-beam experiments

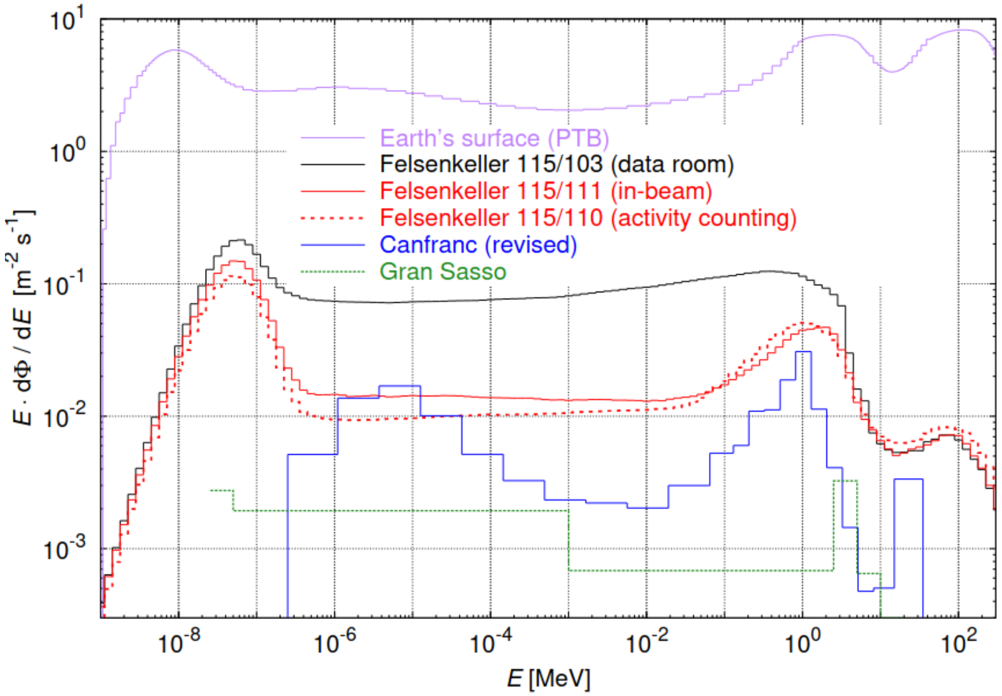
Bunker for low-radiactivity measurements

Felsenkeller shallow underground lab

Muon flux: 40x reduction



Neutron flux: 180x reduction

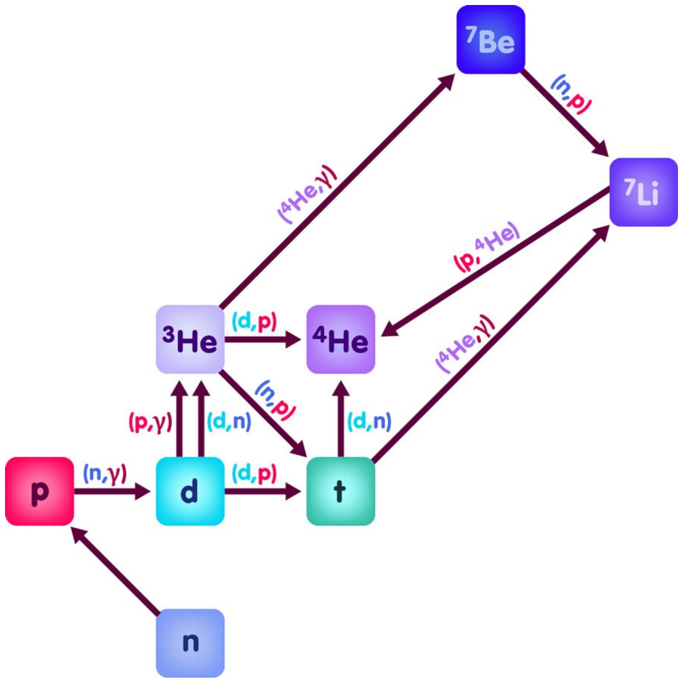


D. Bemmerer et al. Eur. Phys. J. A (2025) 61: 19

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

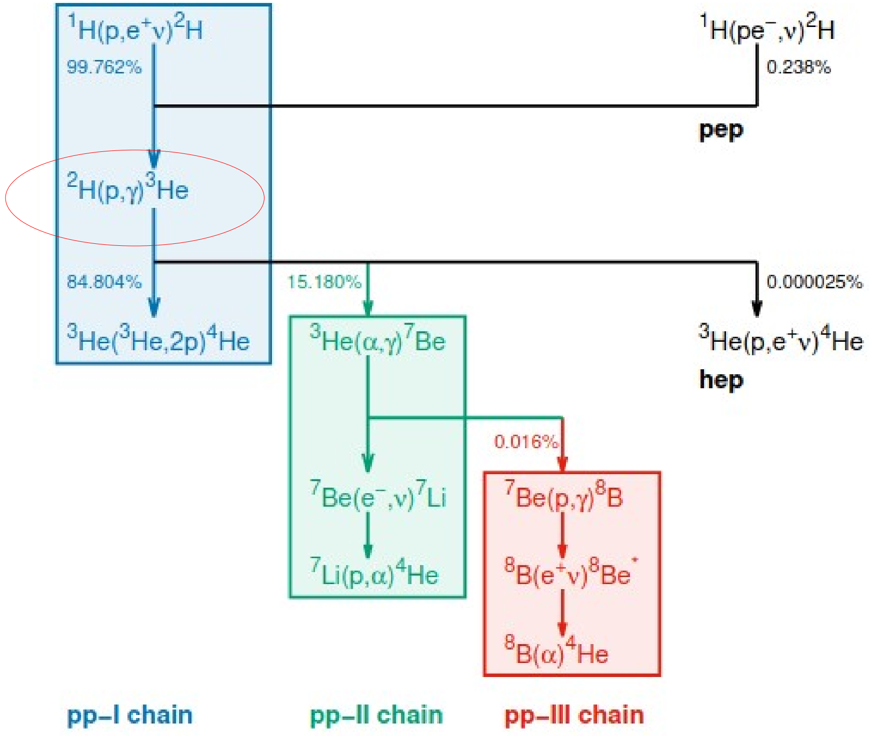
Astrophysical motivation

- Big Bang nucleosynthesis



Deuterium abundance, constrains on cosmological constants. High precision nuclear data required

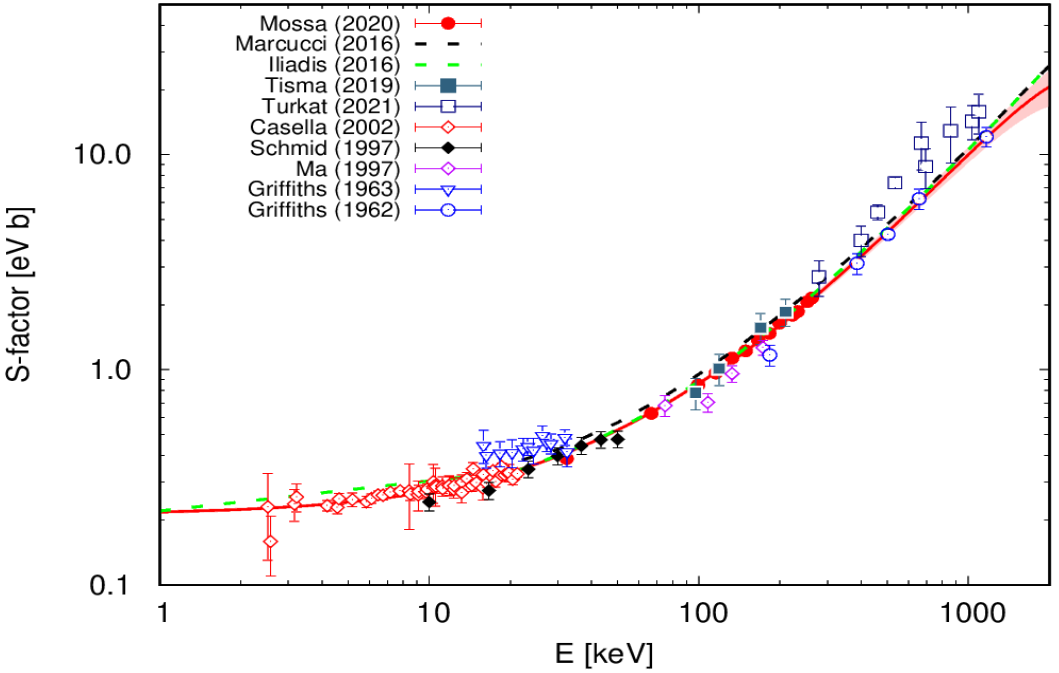
- Sun: Energy production



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

State of the art

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



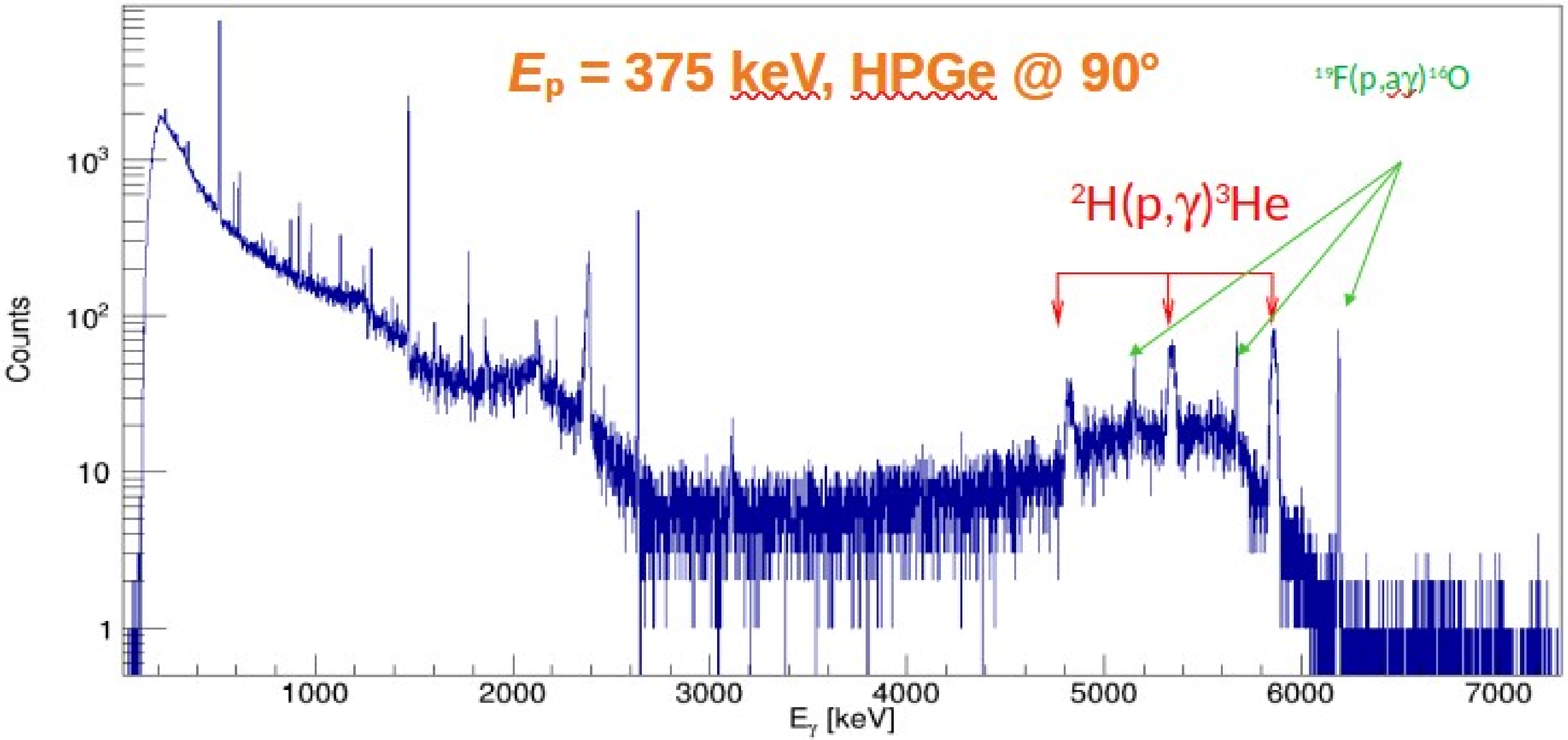
^{2}H(p, γ)^{3}He reaction at Felsenkeller

Measurements

- ✓ Wide energy range measurement for overlap with low and hig -energy data
- ✓ Solid target
- ✓ Several HPGe detectors
- ✓ Direct angular distribution data

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

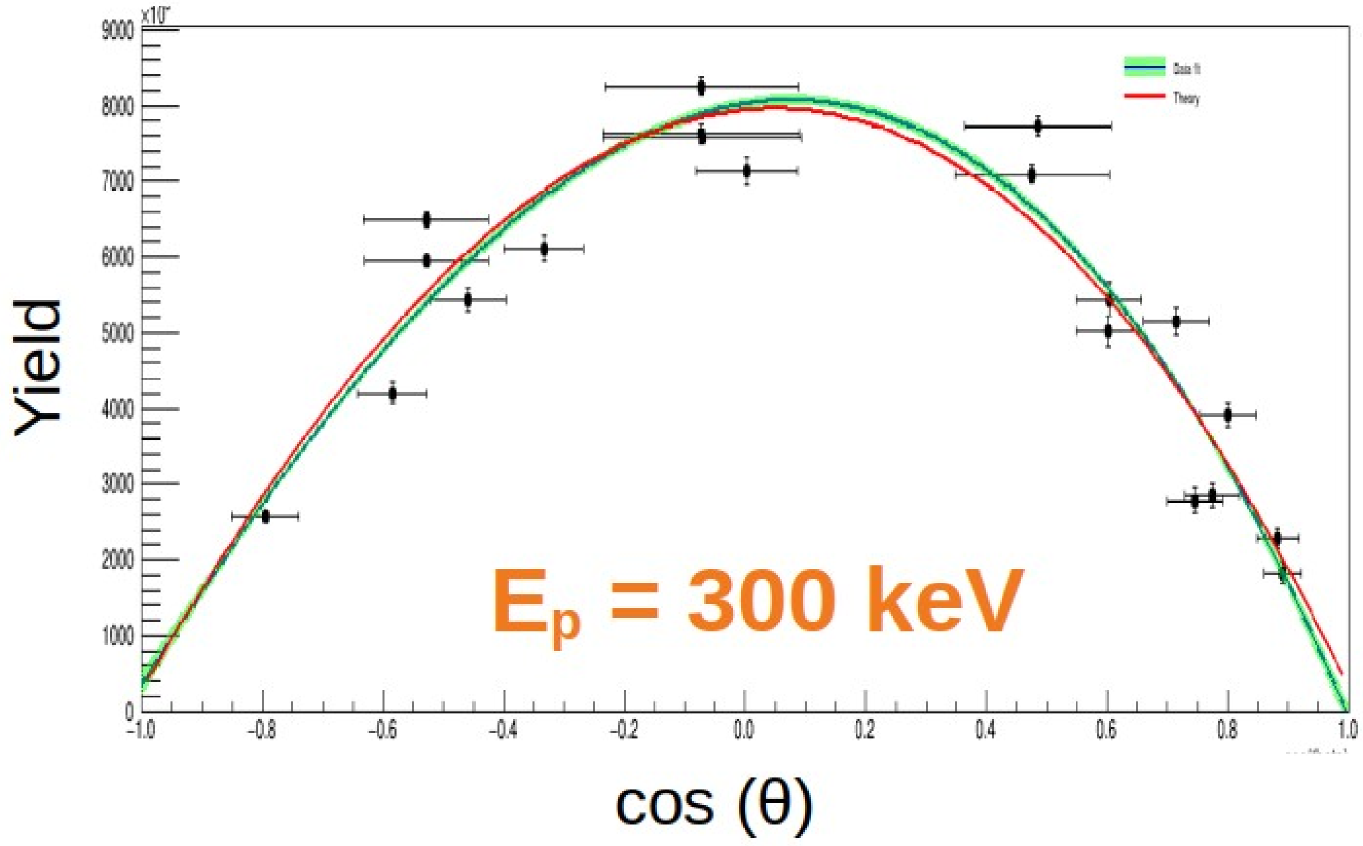
Measurements



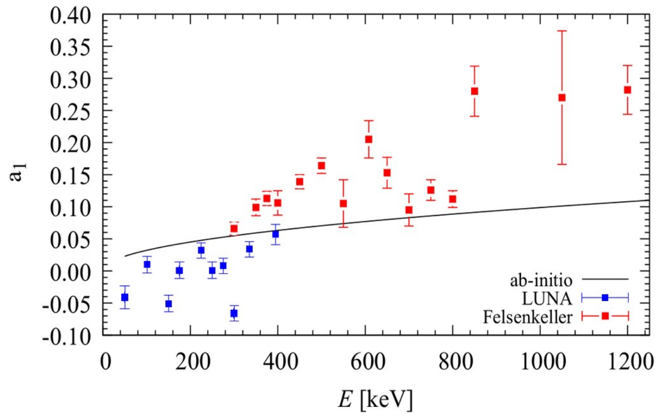
$^{2}H(p, \gamma)^{3}He$ reaction at Felsenkeller

Preliminary results

See poster
M. Lukyanova



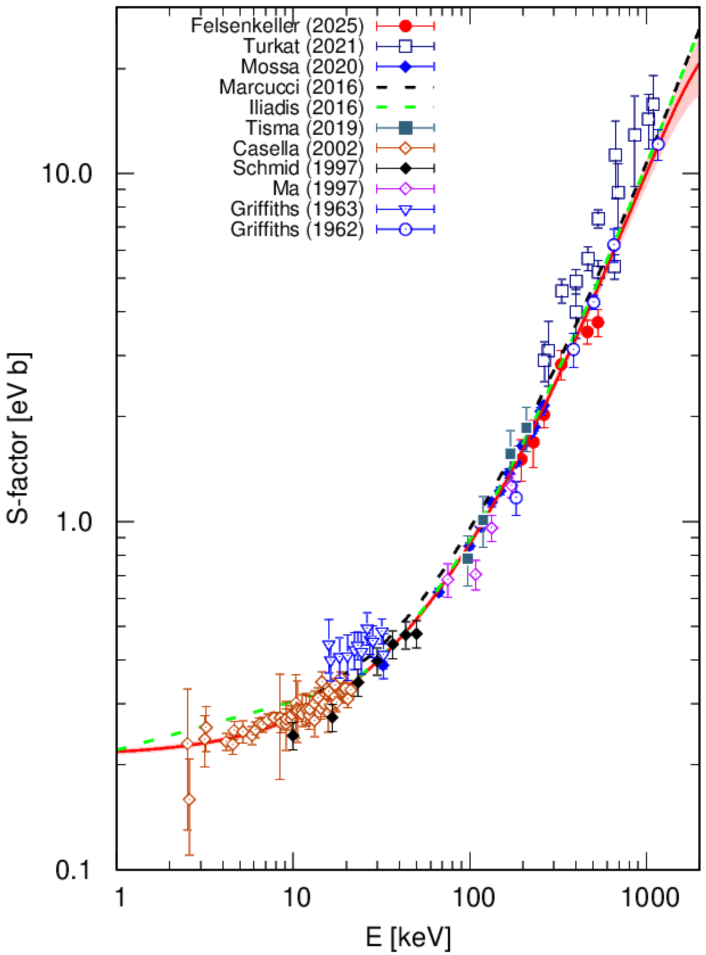
Data points from 300 keV to 1200 keV



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

See poster
M. Lukyanova

Preliminary results



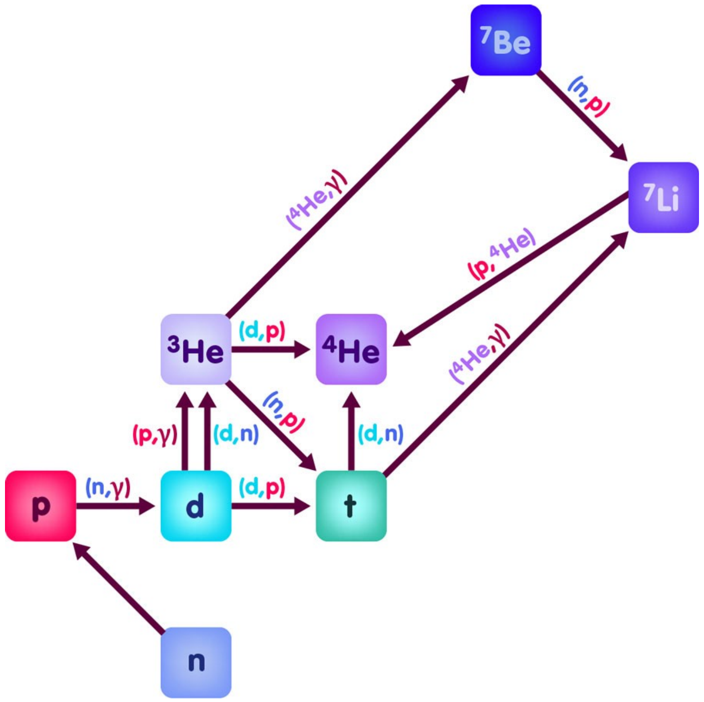
- Further analysis are ongoing to define target degradation and error budged
- Comparison with new ab-initio calculations

$^3He(^4He, \gamma)^7Be$ reaction

Astrophysical motivation

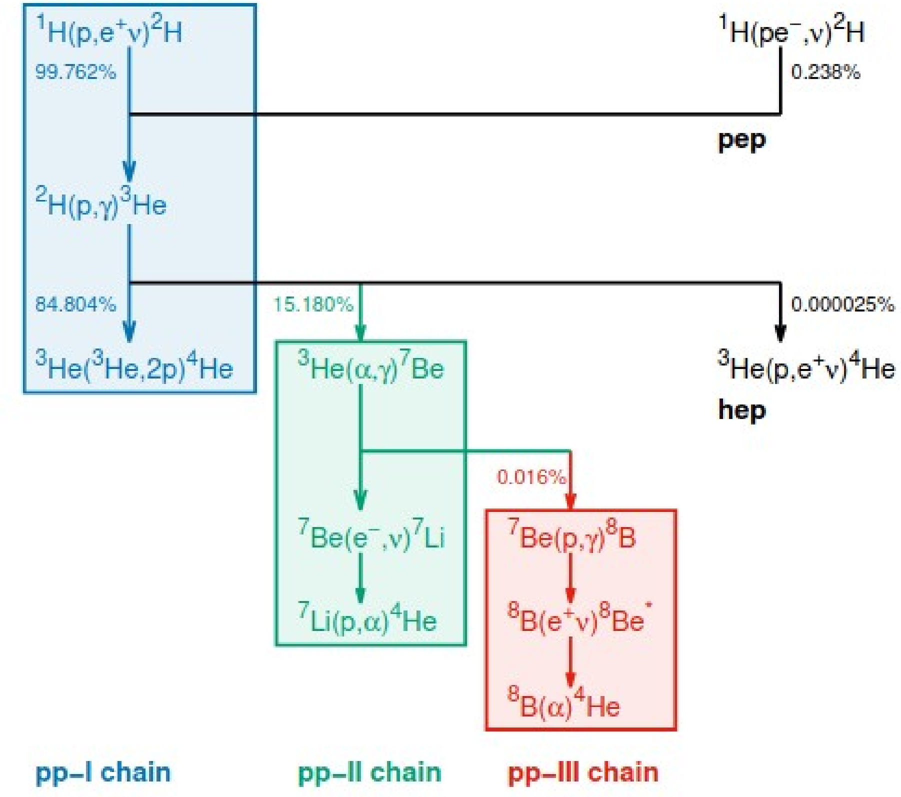
- Big Bang nucleosynthesis

^7Li production



$E_{BBN} \approx$ 160 – 380 keV

- Solar neutrino flux



$E_{Sun} \approx$ 19 – 30 keV

$^{3}He(^{4}He, \gamma)^{7}Be$ reaction

Astrophysical motivation

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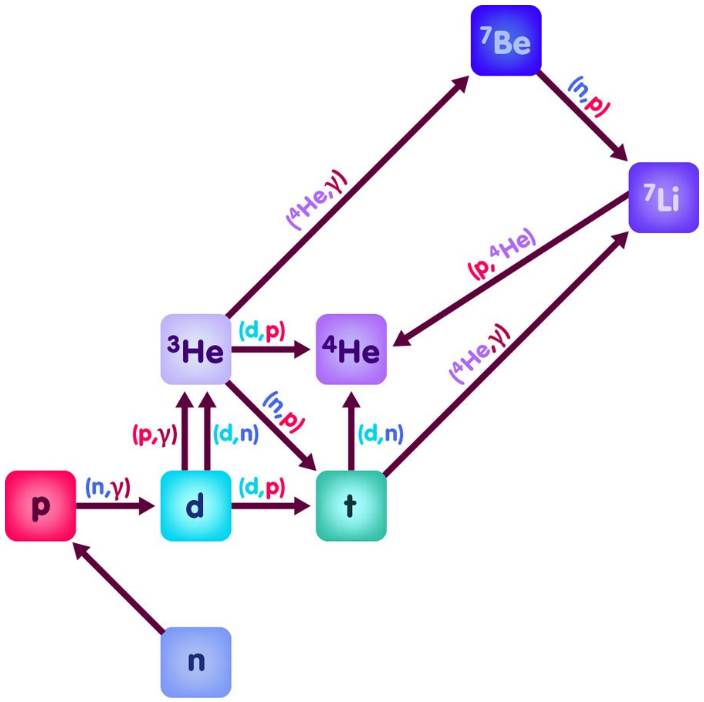

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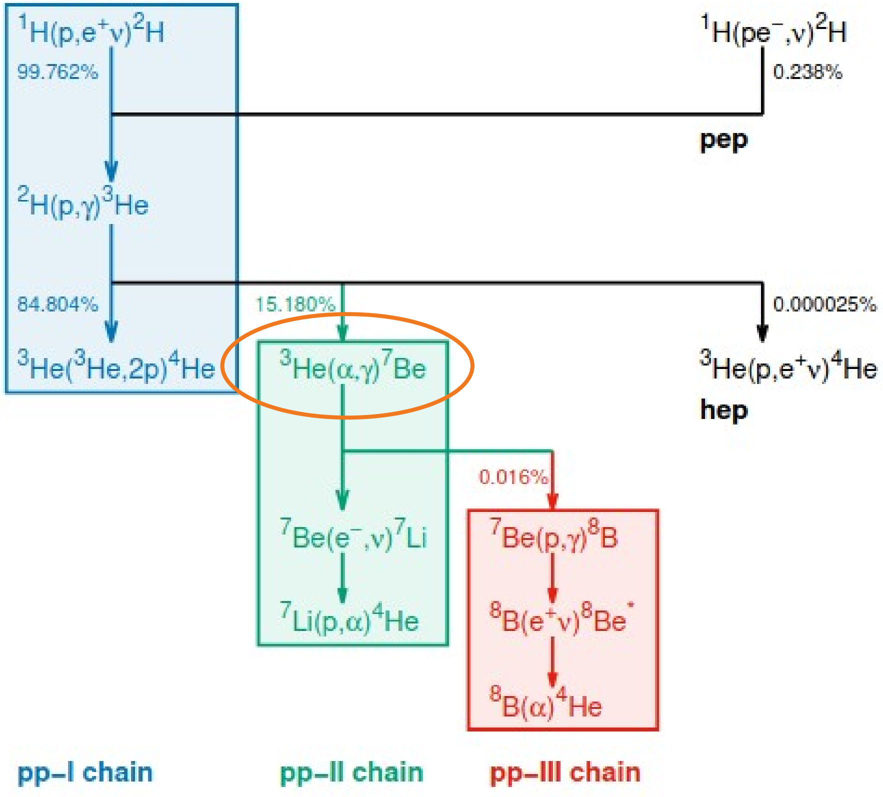

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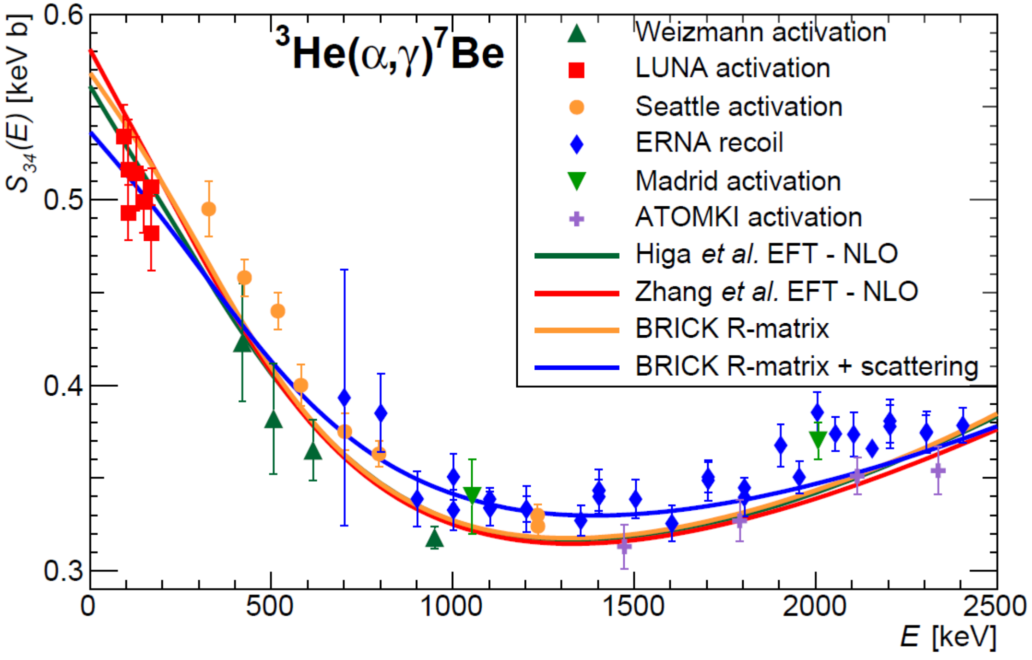
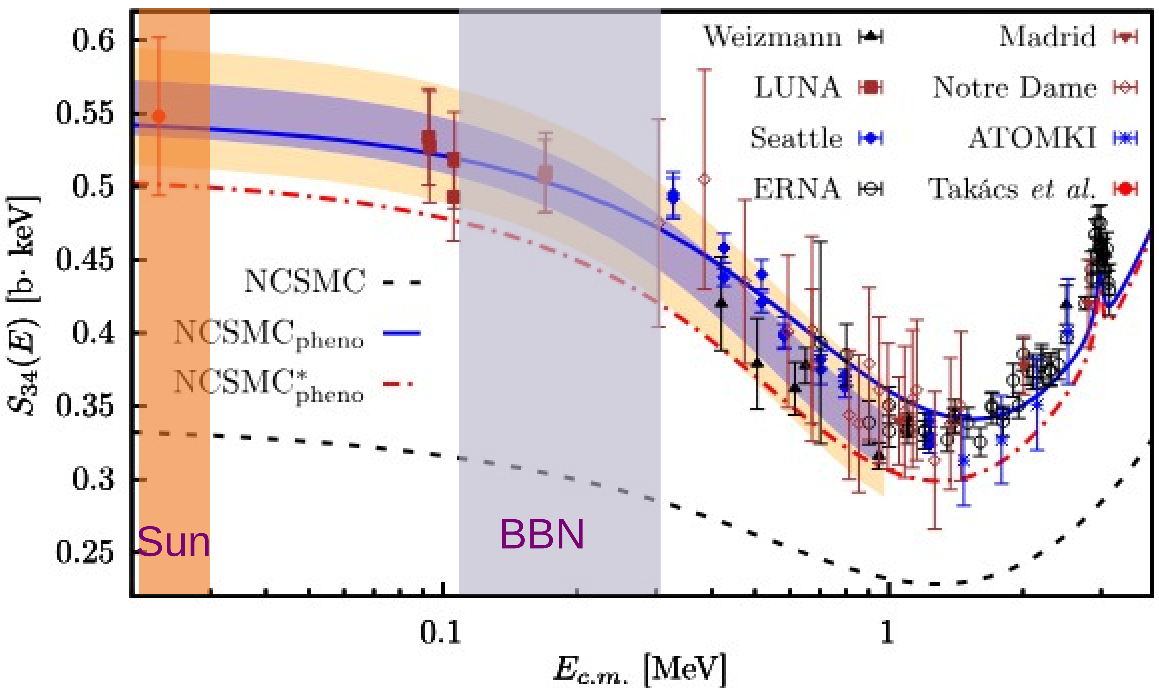
$^3He(^4He, \gamma)^7Be$ reaction

State of the art



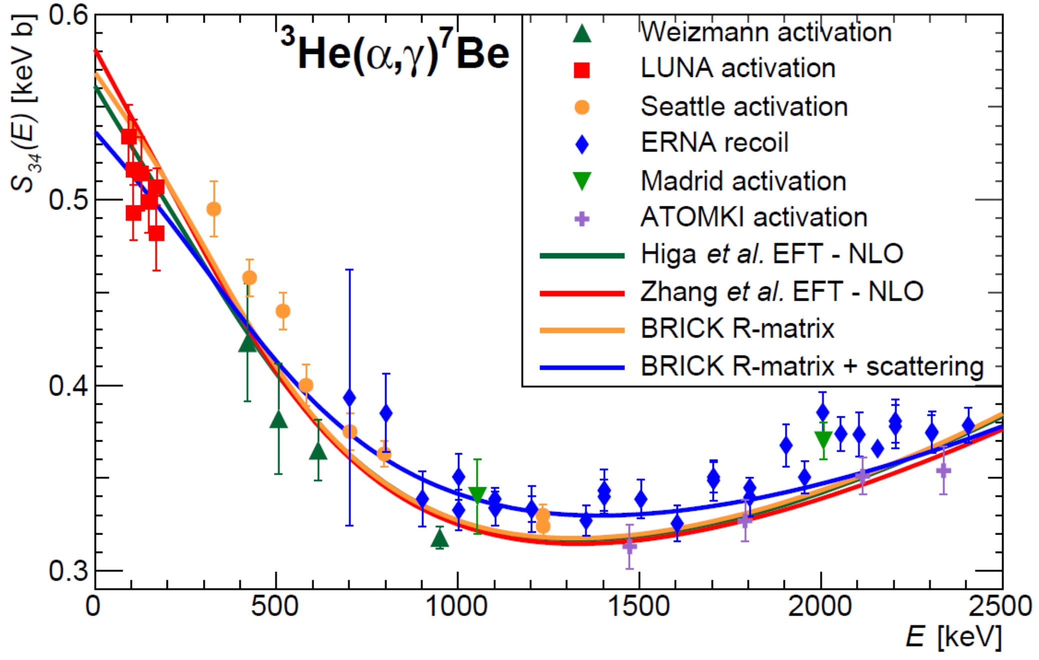
Solar Fusion III arXiv:2405.06470v1 (2024)



M.C. Atkinson et al. PLB 860 (2025) 139189

$^{3}He(^{4}He, \gamma)^{7}Be$ reaction

State of the art



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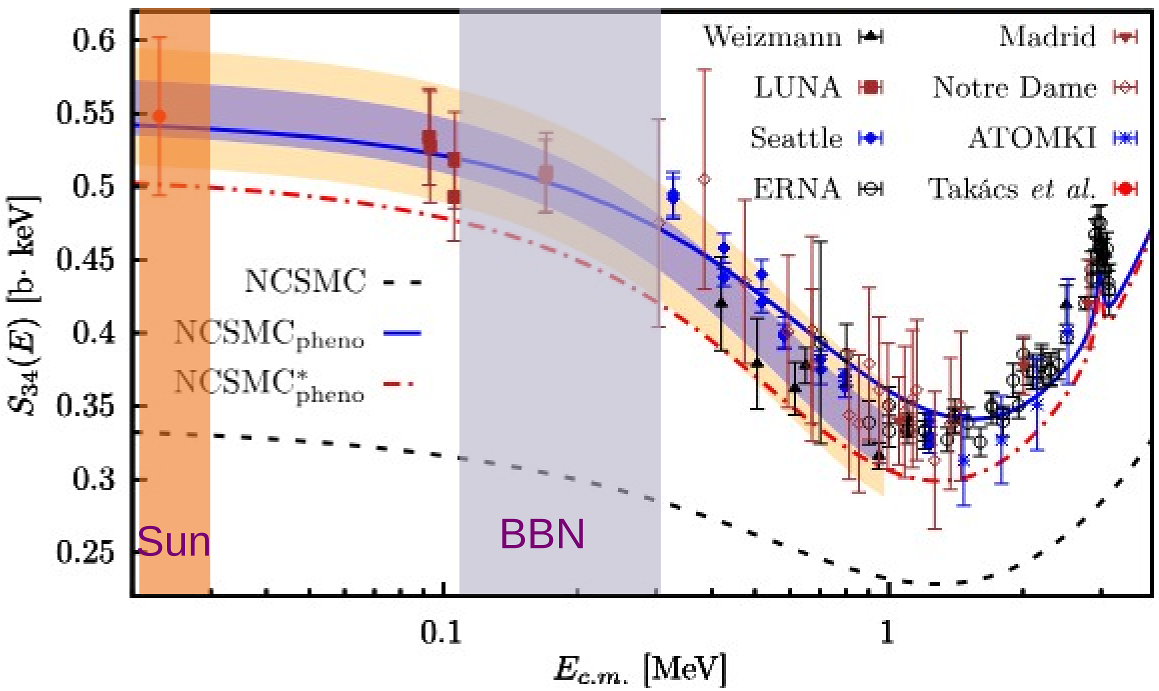


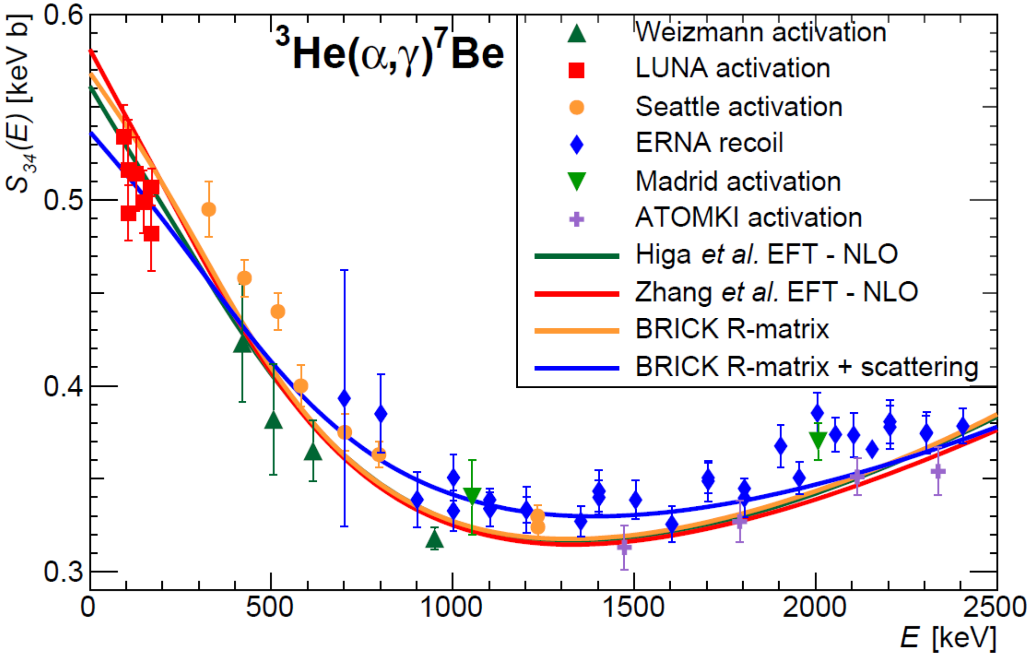
M.C. Atkinson et al. PLB 860 (2025) 139189

No data at E_{Sun}

S factor extrapolations form high energies

$^{3}He(^{4}He, \gamma)^{7}Be$ reaction

State of the art



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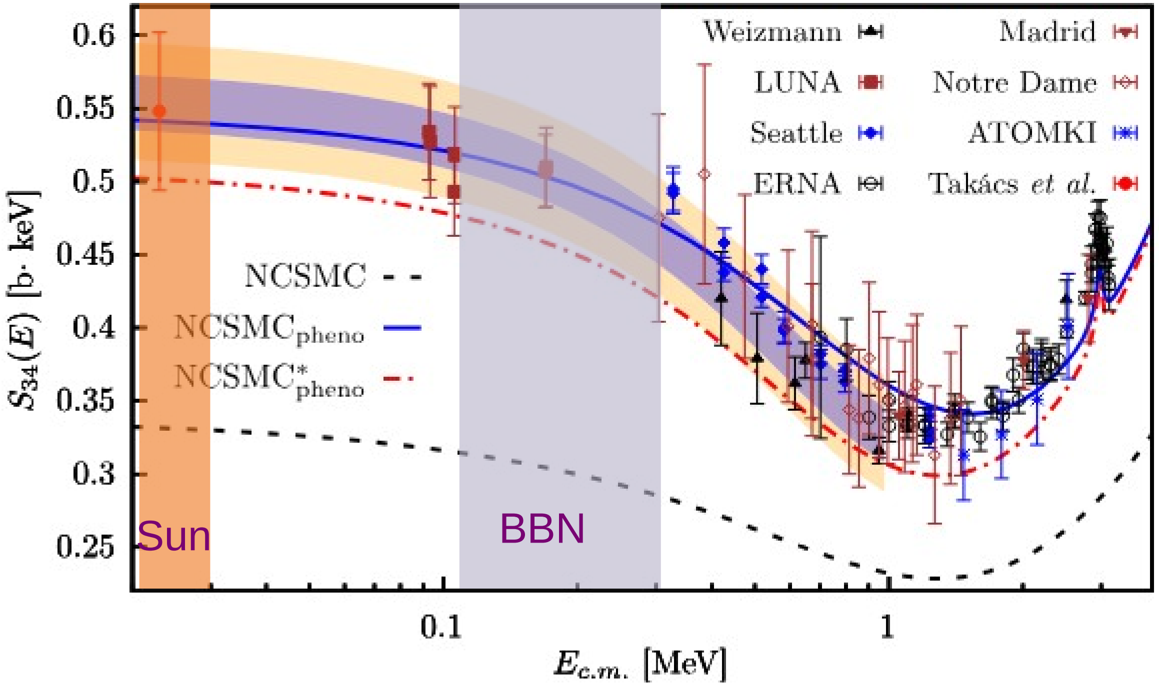

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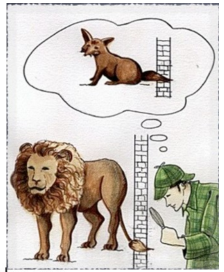

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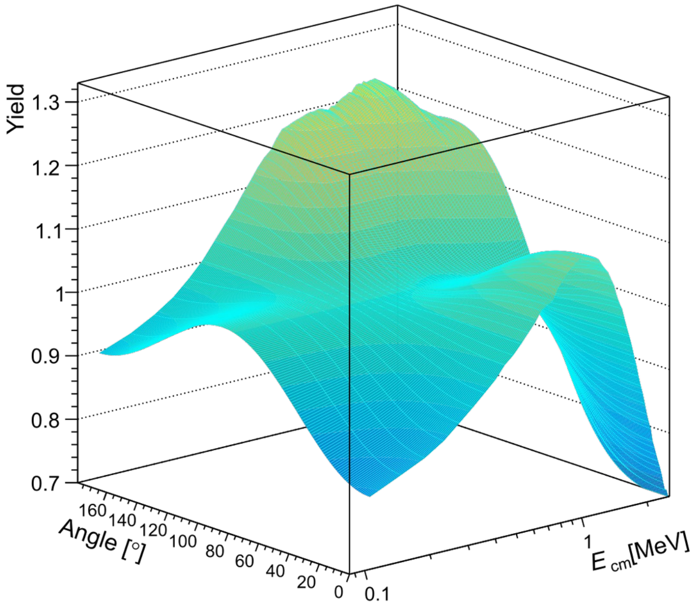
DRESDEN concept SCIENCE AND INNOVATION CAMPUS
HZDR
LUNA

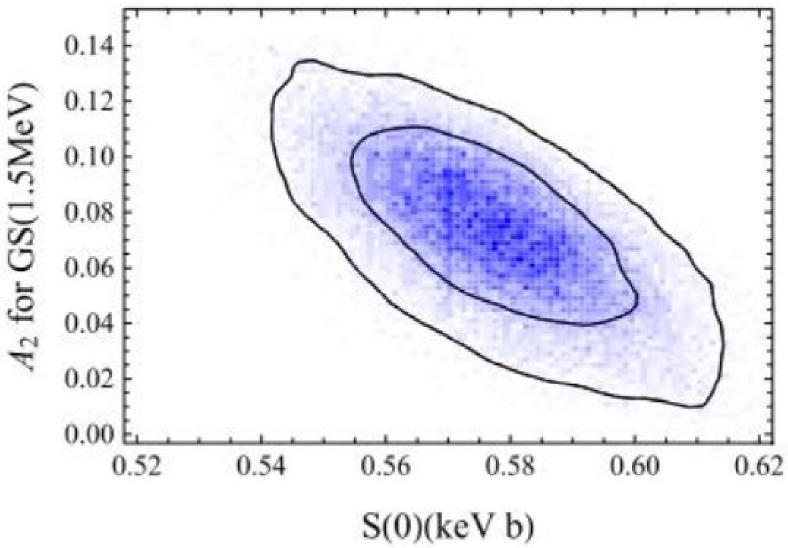
$^3He(^4He, \gamma)^7Be$ reaction

State of the art

Theory show correlation of the angular distribution coefficients and S(0)



$$\sigma^i(E,\theta) = \sigma^i(E)\,[1 + a_2^i(E)\,P_2(\cos\theta)]$$



Tombrello et al., Phys. Rev. 131, 2582 (1963)

Xilin Zhang et al 2020 J. Phys. G: Nucl. Part. Phys. 47 054002

Angular distribution measurements needed!

$^{3}He(^{4}He, \gamma)^{7}Be$ reaction

State of the art

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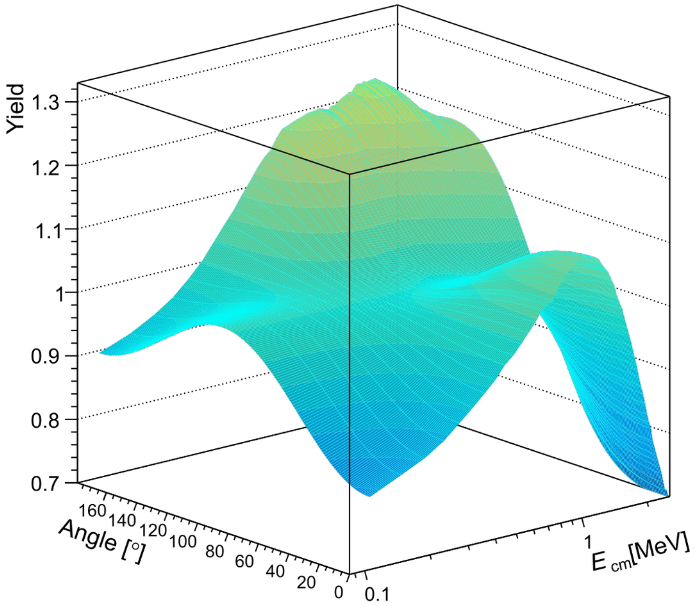
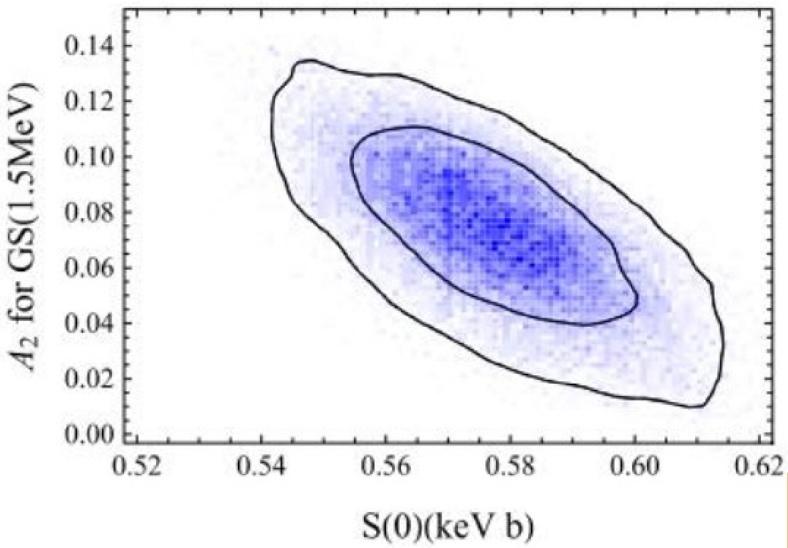
$$\sigma^{i}(E,\theta) = \sigma^{i}(E)\,[1 + a_2^{i}(E)\,P_2(\cos\theta)]$$



Tombrello et al., Phys. Rev. 131, 2582 (1963)



Xilin Zhang et al 2020 J. Phys. G: Nucl. Part. Phys. 47 054002

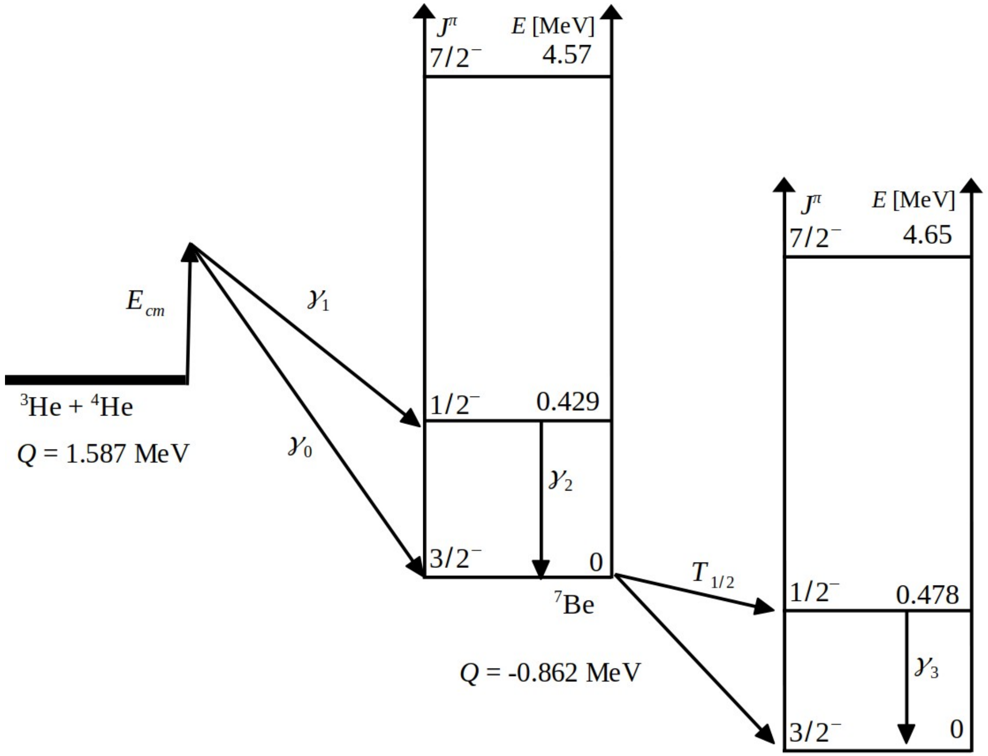
See Talk from
A. Guglielmetti

Angular distribution measurements needed!

$^{3}He(^{4}He, \gamma)^{7}Be$ reaction

How can we deal experimentally?

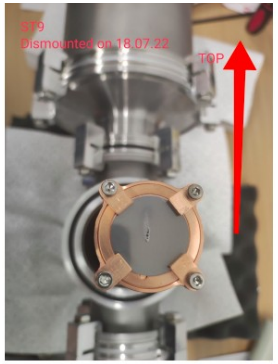
- Measuring directly the prompt γ-rays from the de-excitation into the ground state of ^{7}Be
- Activation analysis of the radioactive ^{7}Be at low-background counting facility
- Indirect approaches

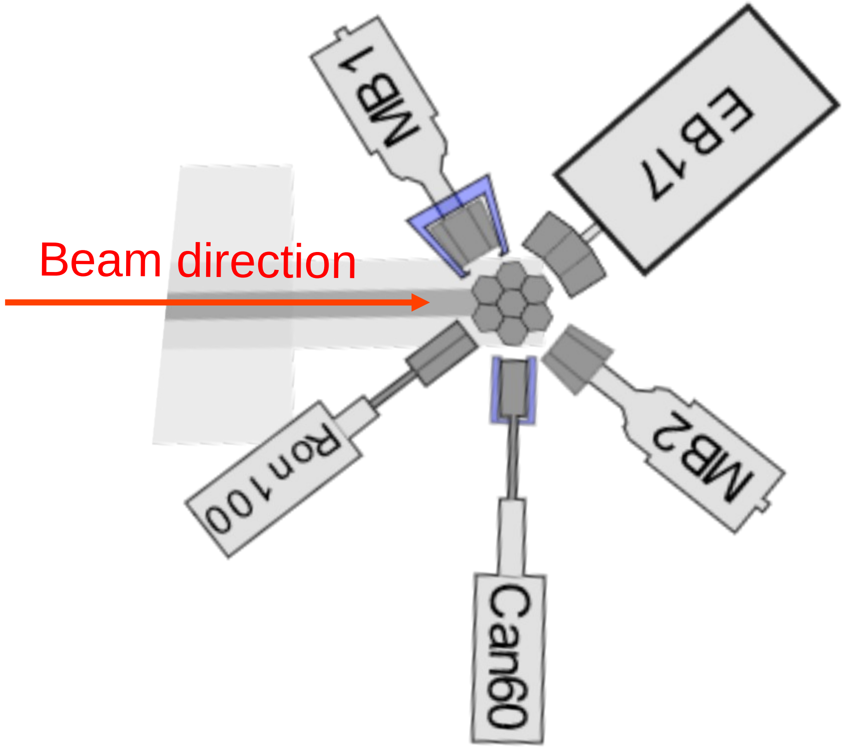


^{3}He(^{4}He, γ)^{7}Be reaction at Felsenkeller

Experimental setup

- ^{4}He beam (I = 13-15 μA)
- 22 HPGe detectors (four HPGe cluster + 2 single crystal)
- LN_2 target cooling.
- Implanted ^{3}He target on Ta backing (2.7E17 atoms/cm2)
- Lead shielding for lab background reduction

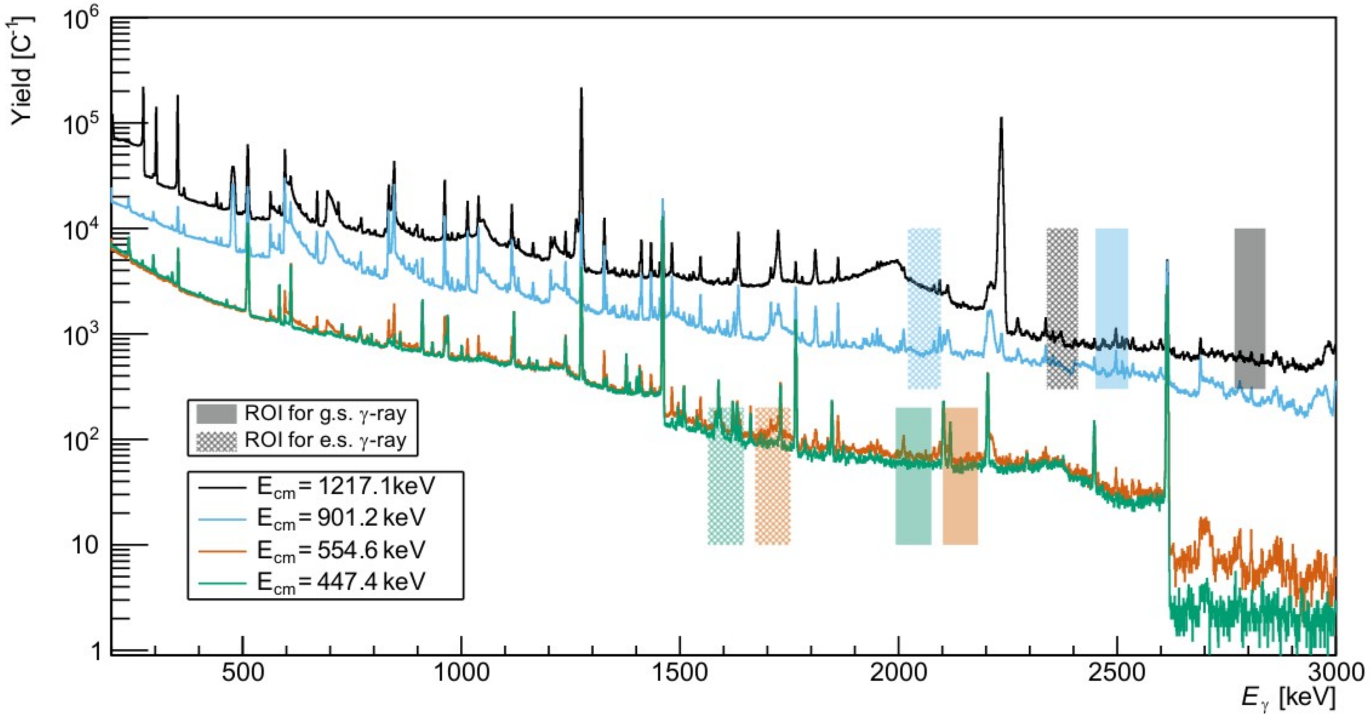




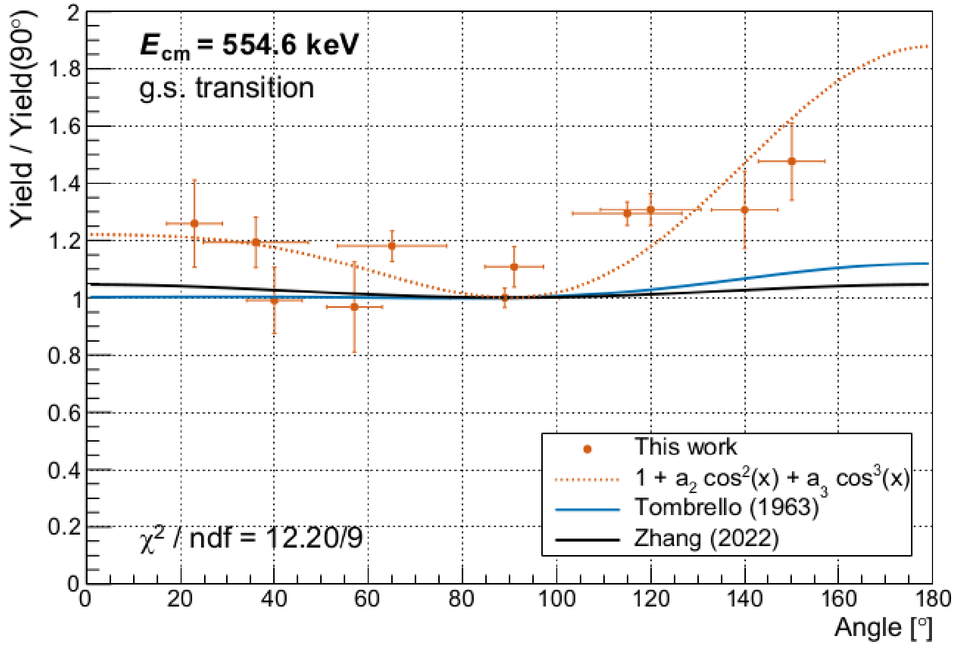
- E_{α} = *0.470 MeV, 0.580 MeV, 0.92 MeV*
- θ = 36, 57, 90, 120 and 145 degree

$^{3}He(^{4}He, \gamma)^{7}Be$ reaction at Felsenkeller

Experimental spectra

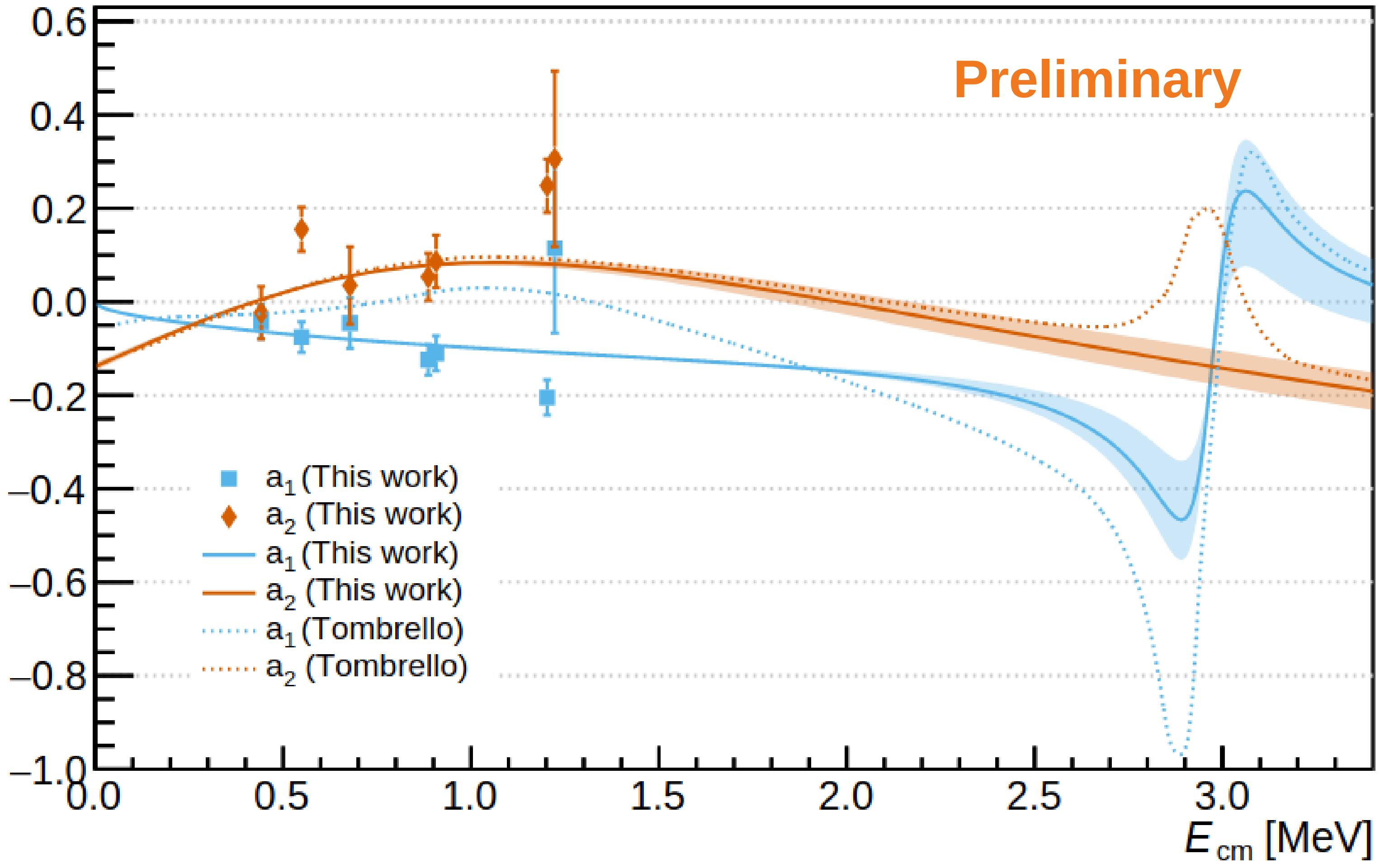


Angular distributions



S. Turkat, PhD thesis (2024)

$^{3}He(^{4}He, \gamma)^{7}Be$ reaction at Felsenkeller



- Good agreement with theory for a_1
- Larger discrepancies for a_2

See poster
P. Hempel

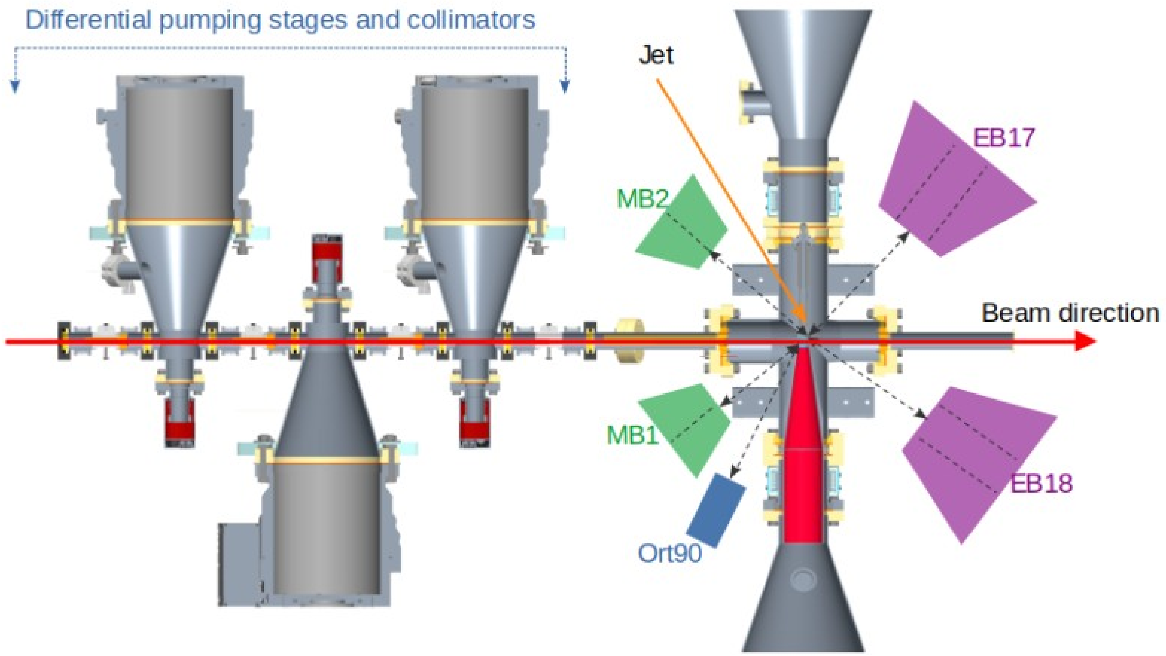
$^{3}He(^{4}He, \gamma)^{7}Be$ reaction at Felsenkeller

What else experimentally?

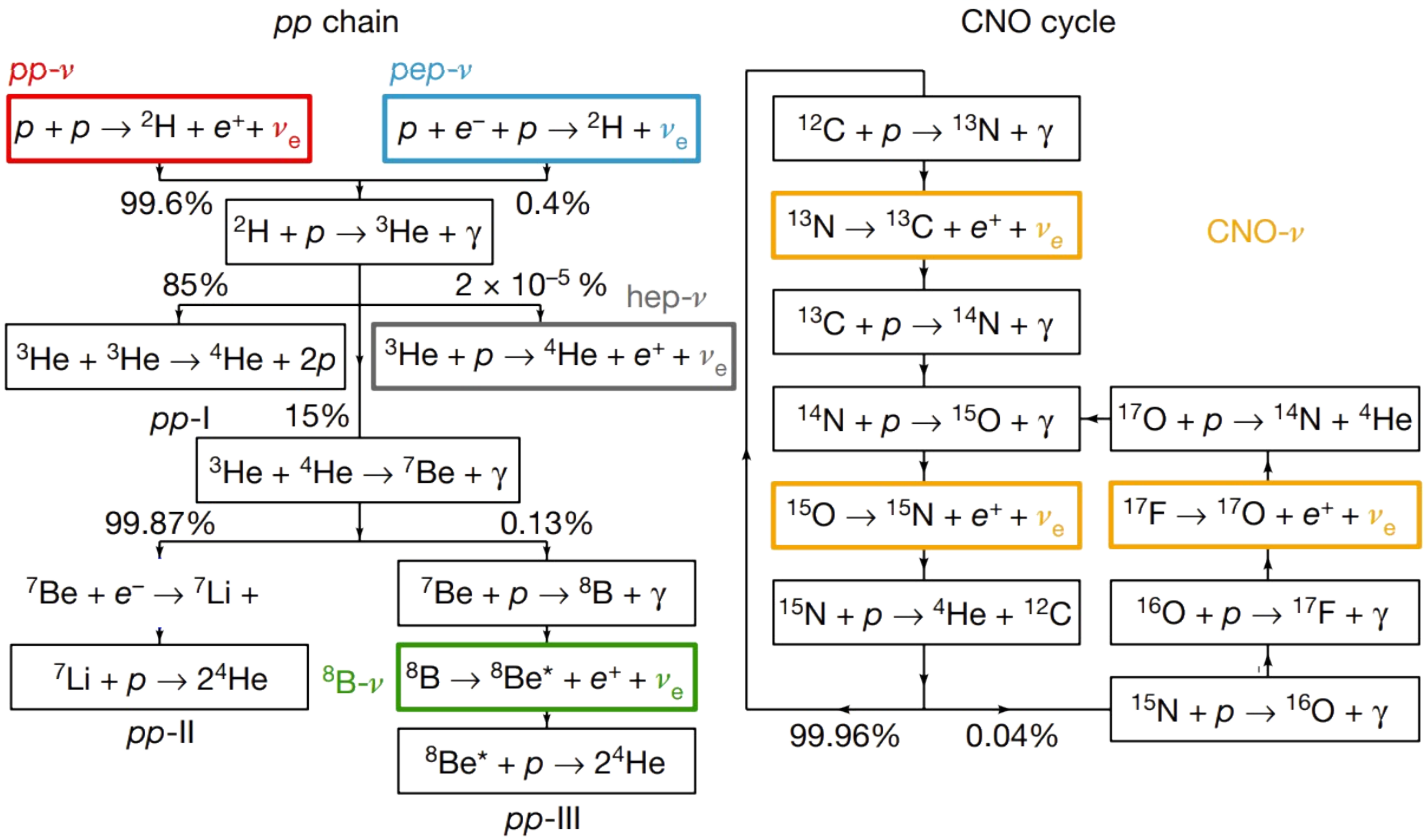
See talk
G. Imbriani

- Cross-section measurements at lower energies (intense alpha beams + stable targets)
- Gas-jet target for cross section and angular distribution measurements

See poster
K. Schmidt



Solar pp-chain and other H-burning



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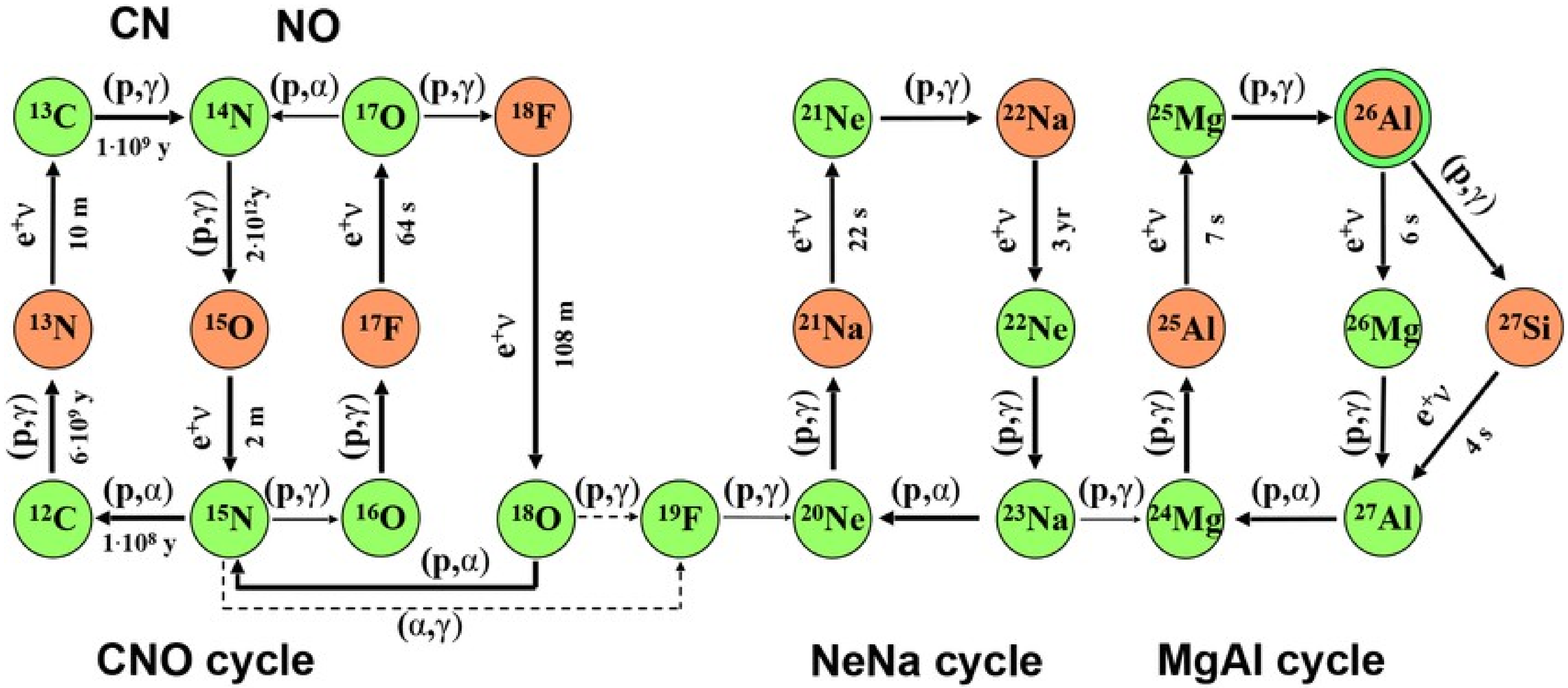
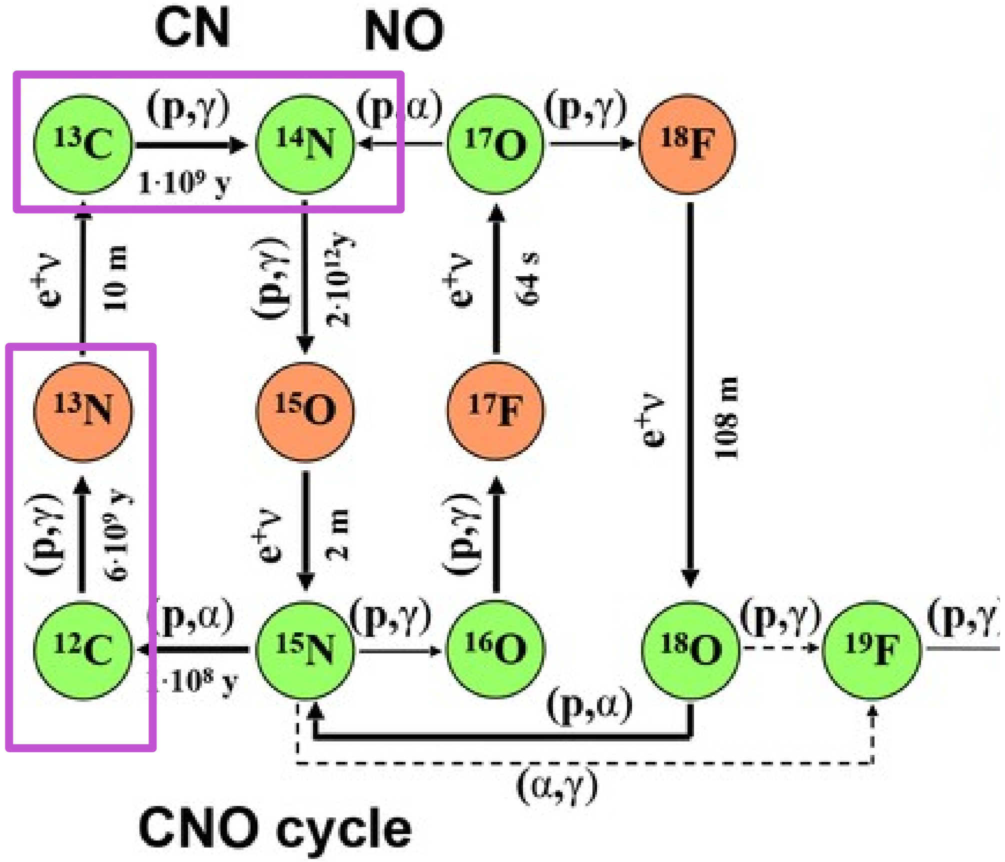


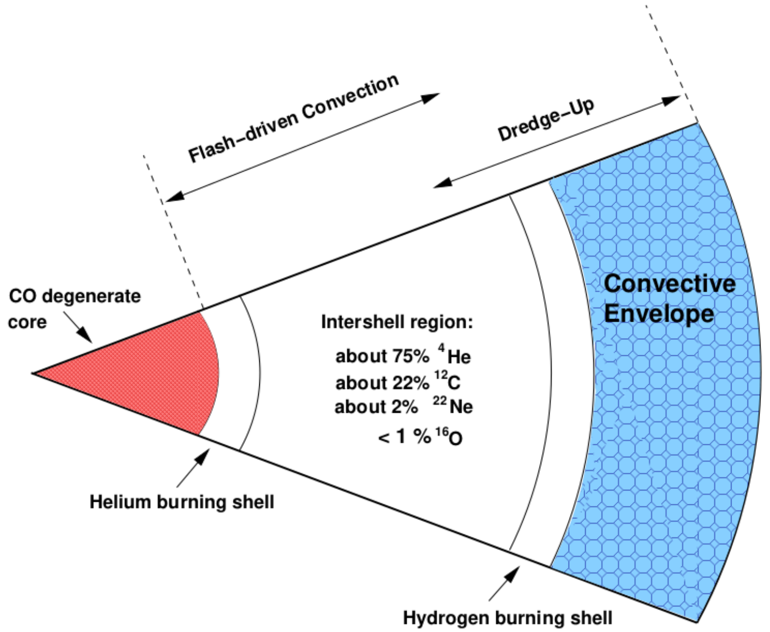
$^{12,13}C(p,\gamma)^{13,14}N$ reaction

Astrophysical motivation

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



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



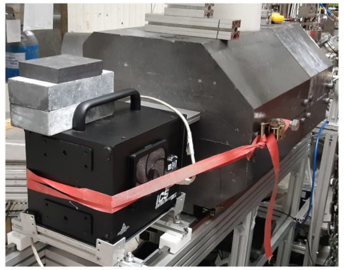
$^{12,13}C(p,\gamma)^{13,14}N$ reaction

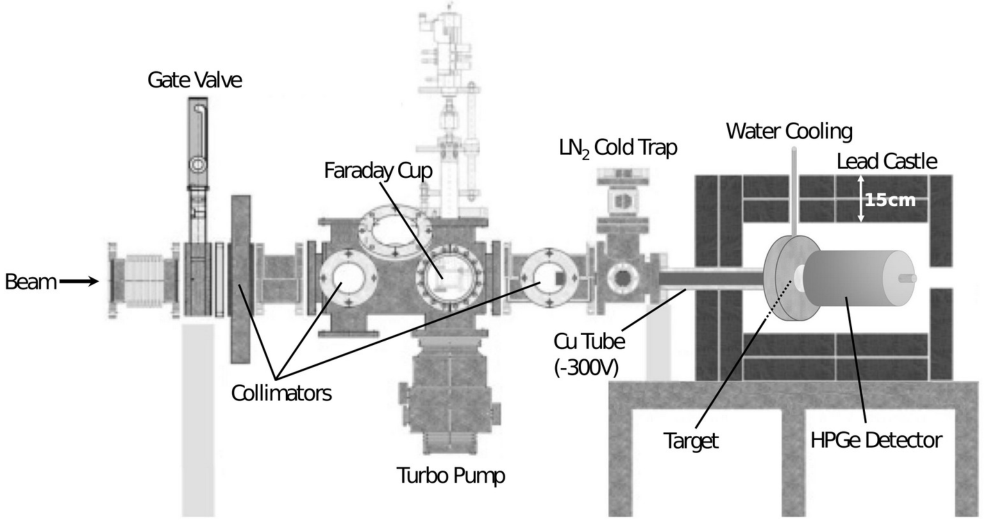
Measurements

- At low energies at LUNA, Gran Sasso, Italy

HPGe setup

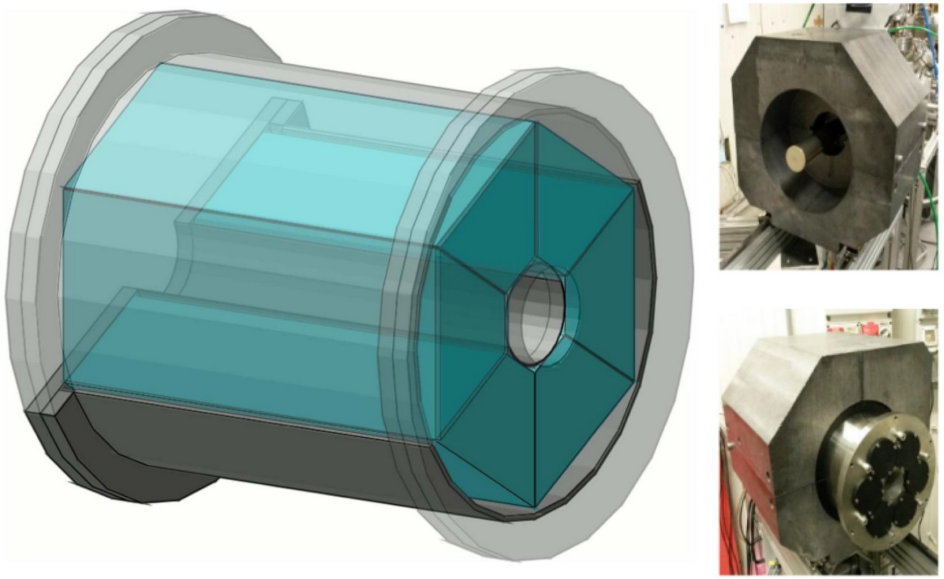
- Close geometry (**1.4 cm**) at **0°**
- Far geometry (**15 cm**) at **55°**
- Excellent **energy resolution**





BGO setup

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



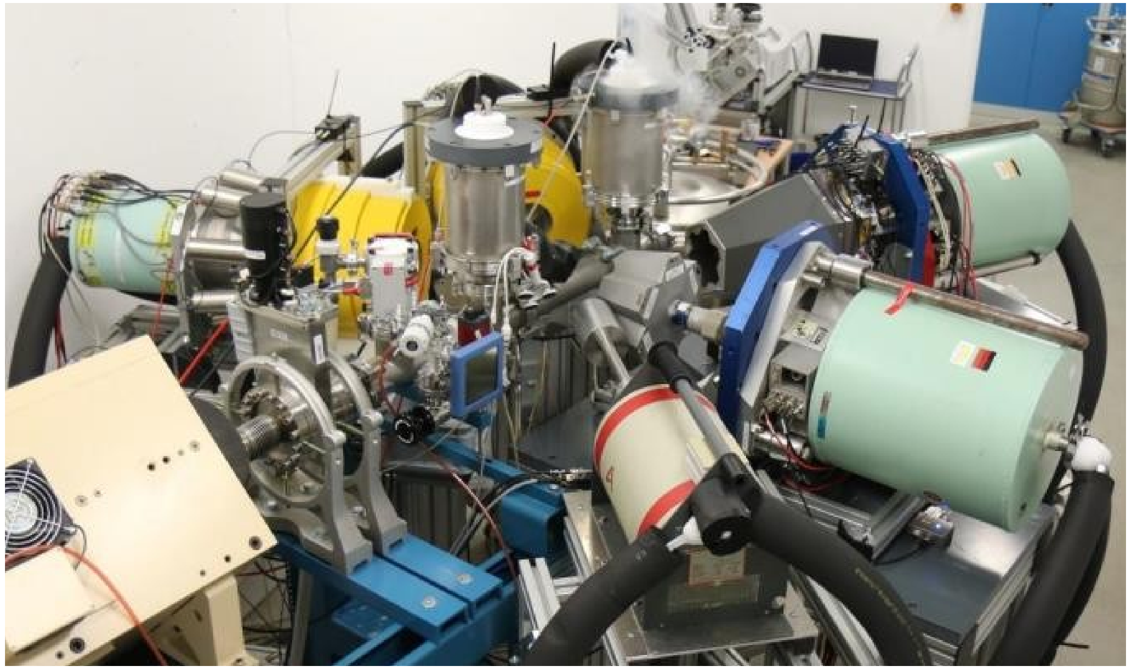
J Skowronski et al 2023 J. Phys. G: Nucl. Part. Phys. 50 045201

$^{12,13}C(p,\gamma)^{13,14}N$ reaction

Measurements

- At E_p > 400 keV energies at Felsenkeller, Germany

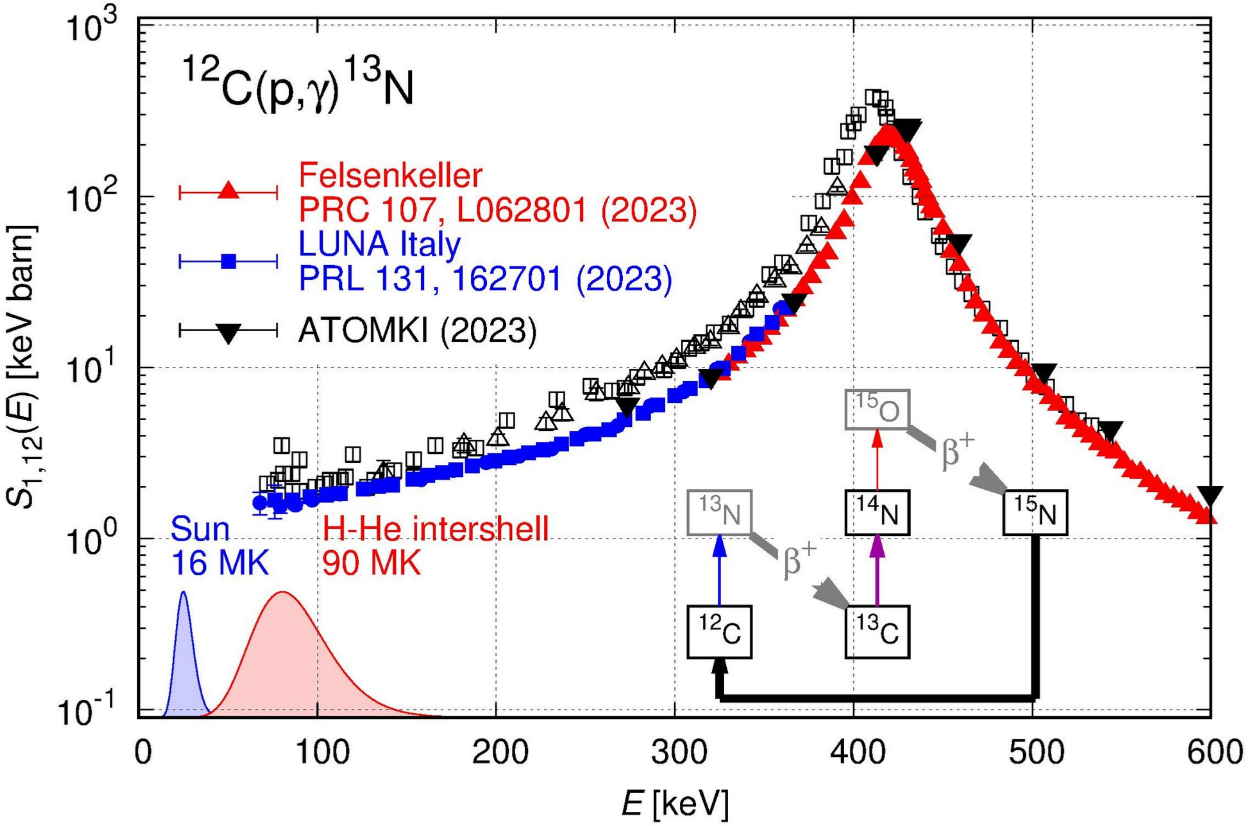
- Sever HPGe detectors at different angle
- LN_2 cooled targets for the p+ ^{12}C campaign
- Water cooled targets for the p+^{13}C campaign
- Pb shielding for further background reduction
- Angular distribution data available



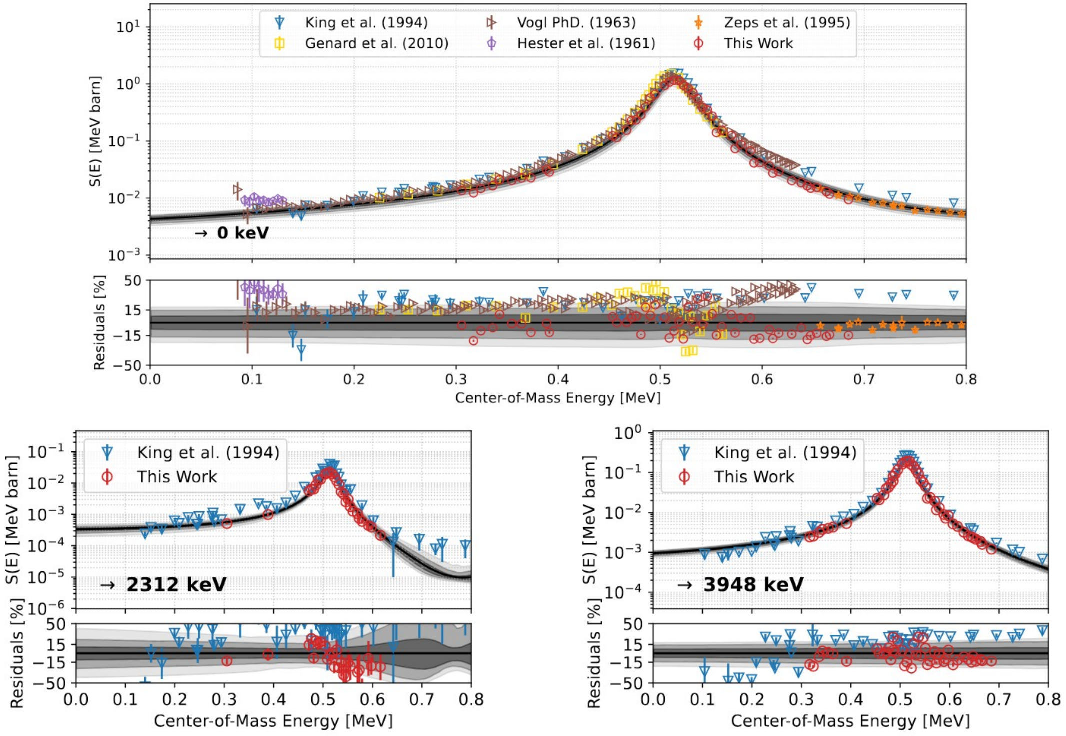
$^{12,13}C(p,\gamma)^{13,14}N$ reaction

Results

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



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



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

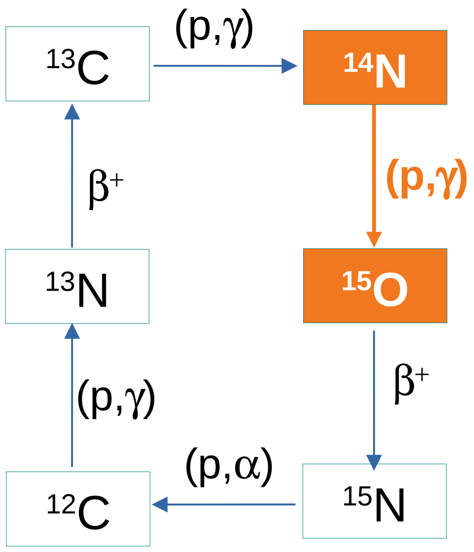
Good agreement low energy – high energy!

Systematic uncertainties of **7 - 9 %** (**stopping power** dominated) → **Experimental effort needed**

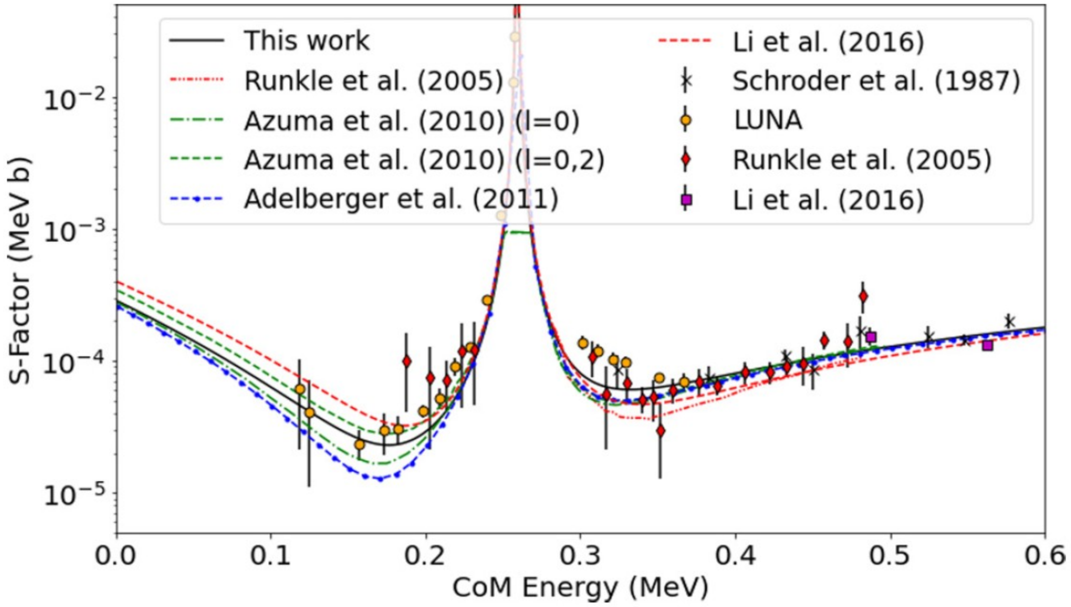
$^{14}N(p,\gamma)^{15}O$ reaction: Bottleneck of the CNO cycle

LUNA

Astrophysical motivation



$^{14}N(p,\gamma)^{15}O$ is the slowest reaction of the CNO cycle



Frentz et al. PRC 103, 045802 (2021)

- Determine age of the Universe from globular clusters
- Use CNO neutrino flux to probe the interior of the Sun

Courtesy R. Depalo, R. Sariyal

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$^{14}N(p,\gamma)^{15}O$ reaction: Bottleneck of the CNO cycle

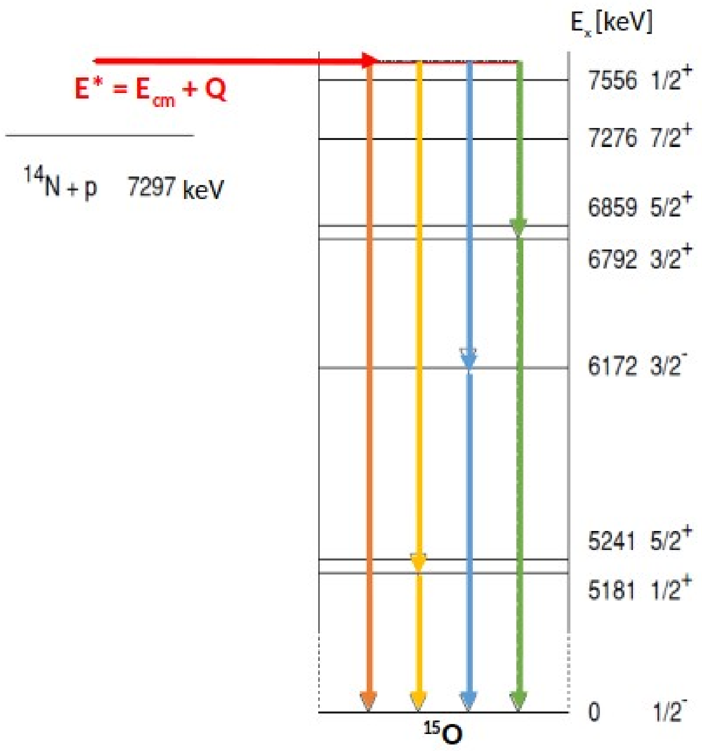

TABLE IX $S_{1\,14}(0)$ as the sum of the different transitions.

Transition	$S_{1\,14}(0)$ (keV b)	$\Delta S_{114}(0)$	Reference
tr → 0	0.30 ± 0.11	37%	Present
tr → 6.79	1.17 ± 0.03	2.9%	Present
tr → 6.17	0.13 ± 0.05	38%	SF II
tr → 5.18	0.010 ± 0.003	30%	SF II
tr(5.24) → 0	0.068 ± 0.020	30%	SF II
R-matrix sum	1.68 ± 0.13	7.6%	
Additional syst. uncert.		3.5%	
Total	1.68 ± 0.14	8.4%	

Solar Fusion III arXiv:2405.06470v1 (2024)

Courtesy R. Depalo, R. Sariyal

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$^{14}N(p, \gamma)^{15}O$ reaction: Bottleneck of the CNO cycle

LUNA

See Talk from
A. Formicola

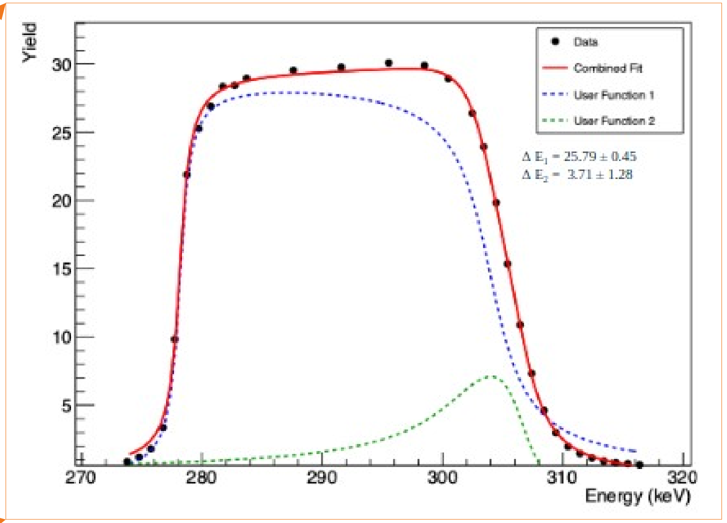
New experimental measurements

- At high energies, providing also angular distributions by **LUNA @IBF, Gran Sasso, Italy**
- At low energies (125 – 400 keV) at LUNA 400 kV

- **4π geometry**
- **6 different crystals**
- **Target degradation under control**

LUNA 400 kV accelerator

TiN targets



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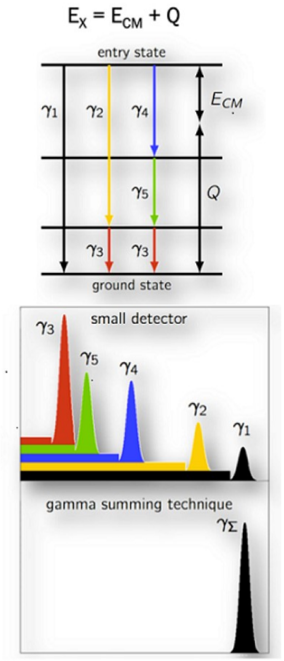
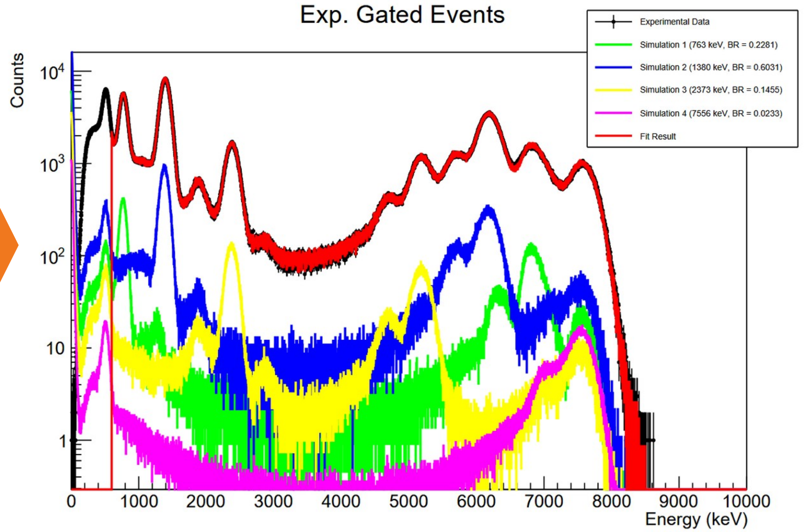
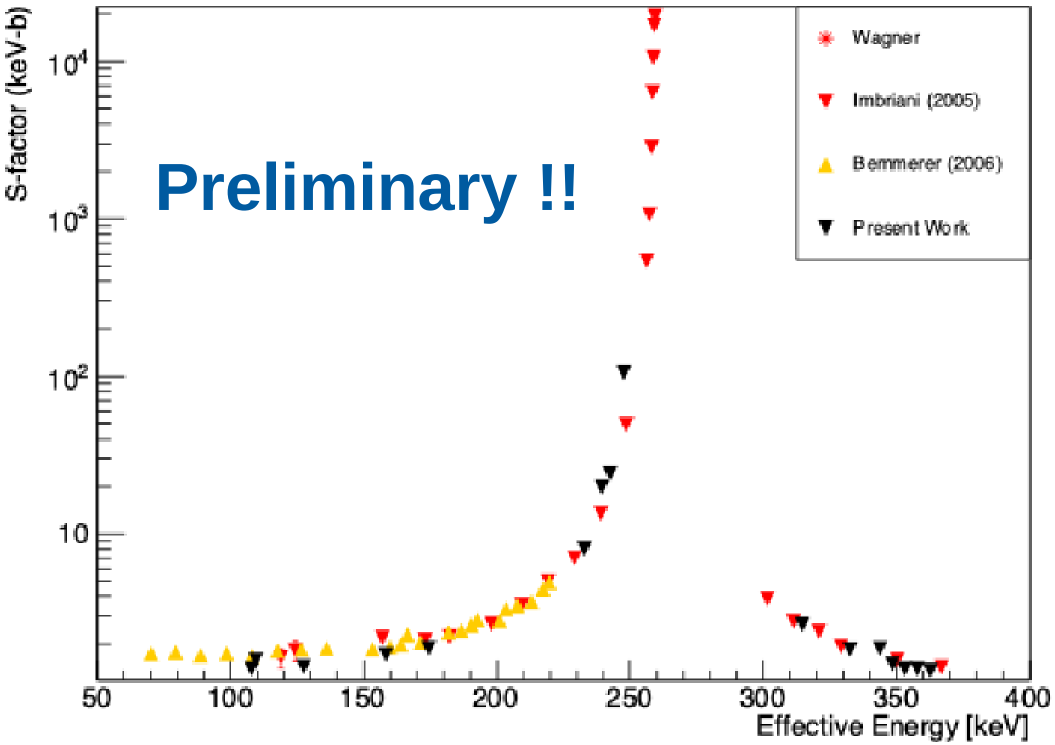
$^{14}N(p,\gamma)^{15}O$ reaction: Bottleneck of the CNO cycle

New experimental measurements

- At low energies (125 – 400 keV) at LUNA 400 kV







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$^{14}N(p,\gamma)^{15}O$ reaction: Bottleneck of the CNO cycle

New experimental measurements

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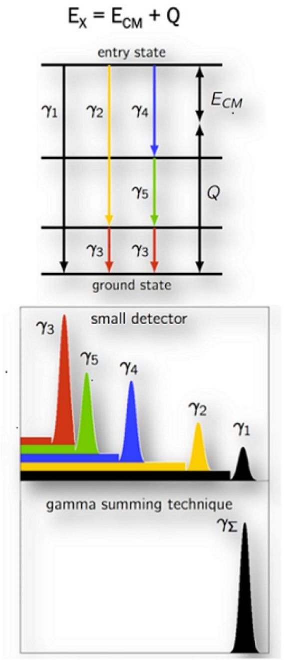

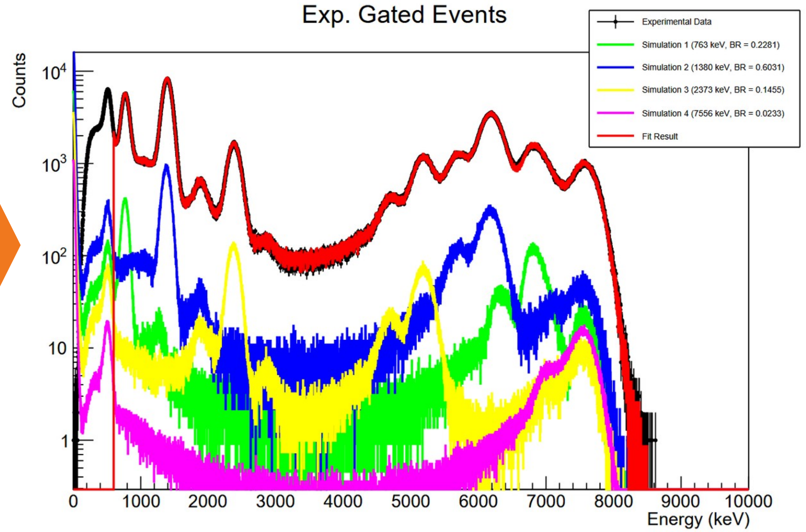

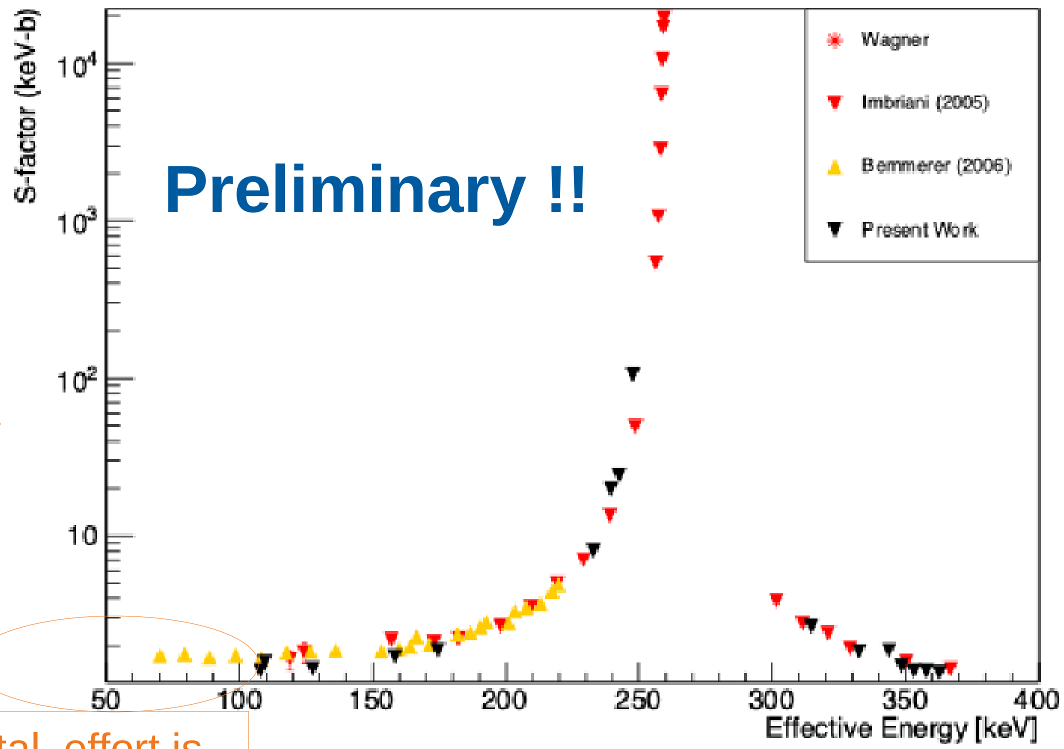

Further experimental effort is still needed to push down

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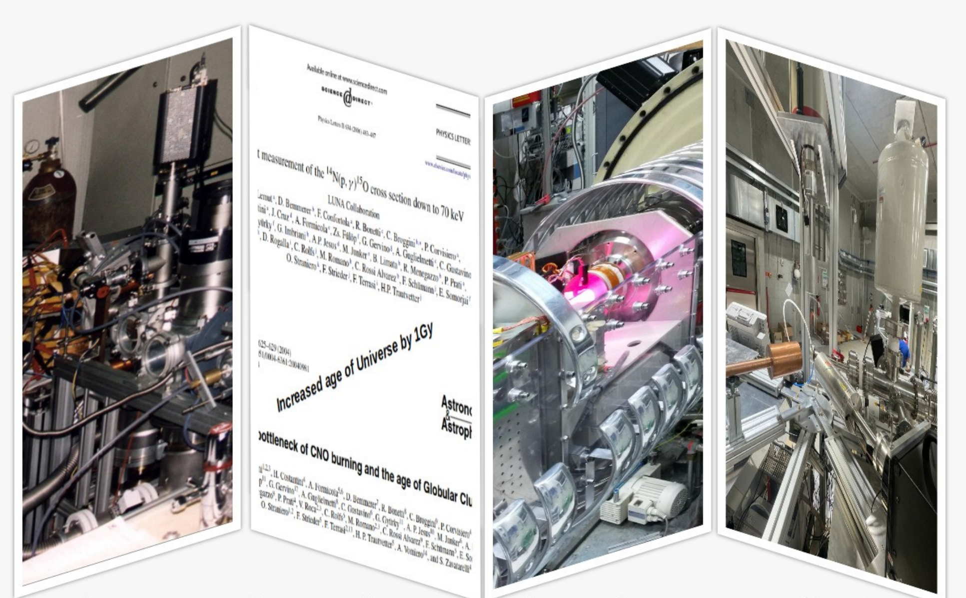
Summary

Solar pp chain is the main source of energy in the Sun

Precise nuclear reaction rates are at stellar energies are essential to understand energy production and evolution

Underground experiments (LUNA, Felsenkeller and others) provide direct measurements at stellar energies.

Efforts aim to extend measurements to lower energies, improve angular distributions are needed



Laboratory for Underground Nuclear Astrophysics