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Solar fusion cross sections III – a nuclear physics perspective

Reviews of Modern Physics 97, 035002 (2025)

European Nuclear Physics Conference, 23.09.2025 Caen/France

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Solar fusion III: New data and theory for hydrogen-burning stars

B. Acharya, M. Aliotta, A. B. Balantekin, D. Bemmerer, C. A. Bertulani, A. Best, C. R. Brune, R. Buompane, L. Gialanella *et al.*

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Rev. Mod. Phys. **97**, 035002 – **Published 4 September, 2025**

DOI: https://doi.org/10.1103/8lm7-gs18

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Abstract

In stars that lie on the main sequence in the Hertzsprung-Russell diagram, like our Sun, hydrogen is fused to helium in a number of nuclear reaction chains and series, such as the proton-proton chain and the carbon-nitrogen-oxygen cycles. Precisely determined thermonuclear rates of these reactions lie at the foundation of the standard solar model. This review, the third decadal evaluation of the nuclear physics of hydrogen-burning stars, is motivated by the great advances made in recent years by solar neutrino observatories, putting experimental knowledge of the proton-proton (pp)-chain neutrino fluxes in the few-percent precision range. The basis of the review is a one-week community meeting held in July 2022 in Berkeley, California, and many subsequent digital meetings and exchanges. The relevant reactions of solar and stellar hydrogen burning are reviewed here from both theoretical and experimental perspectives. Recommendations for the state of the art of the astrophysical S factor and its uncertainty are formulated for each of them. Several other topics of paramount importance for the solar model are reviewed as well: recent and future neutrino experiments, electron screening, radiative opacities, and current and upcoming experimental facilities. In addition to reaction-specific recommendations, general recommendations are also formed.

See 8 more figures

Solar Fusion Cross Sections – series of conferences

National Institute of Nuclear Theory, at University of Washington

N3AS, at UC Berkeley

Solar Fusion Cross Sections

17.-20.02.1997
Institute of Nuclear Theory
Seattle

Adelberger *et al.*
Rev. Mod. Phys. 70, 1265 (1998)

Solar Fusion Cross Sections II

21.-23.01.2009
Institute of Nuclear Theory
Seattle

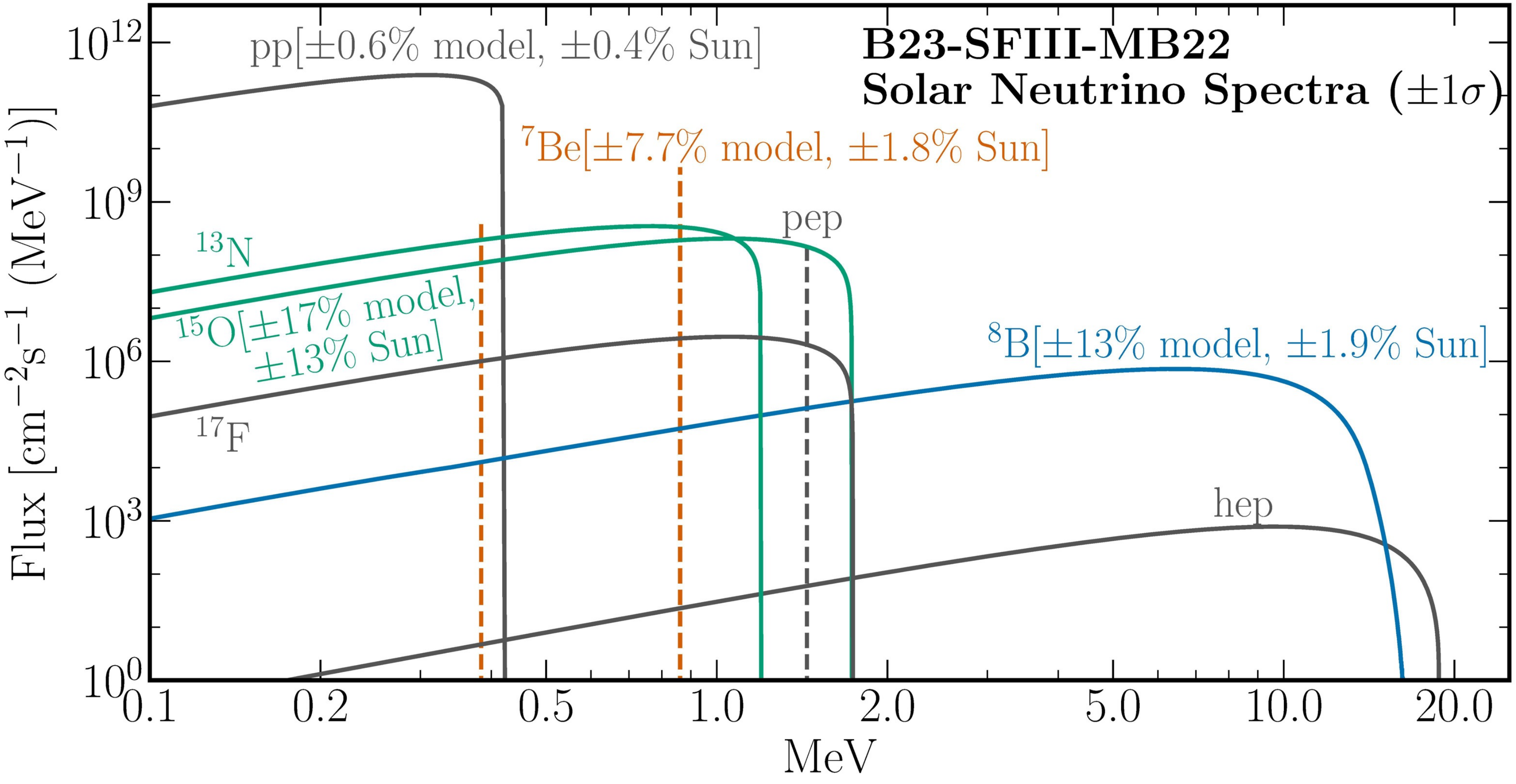
Adelberger *et al.*
Rev. Mod. Phys. 83, 195 (2011)

Solar Fusion Cross Sections III

26.-29.07.2022
David Brower Center
Berkeley

Acharya *et al.*
Rev. Mod. Phys. 07, 035002 (2025)

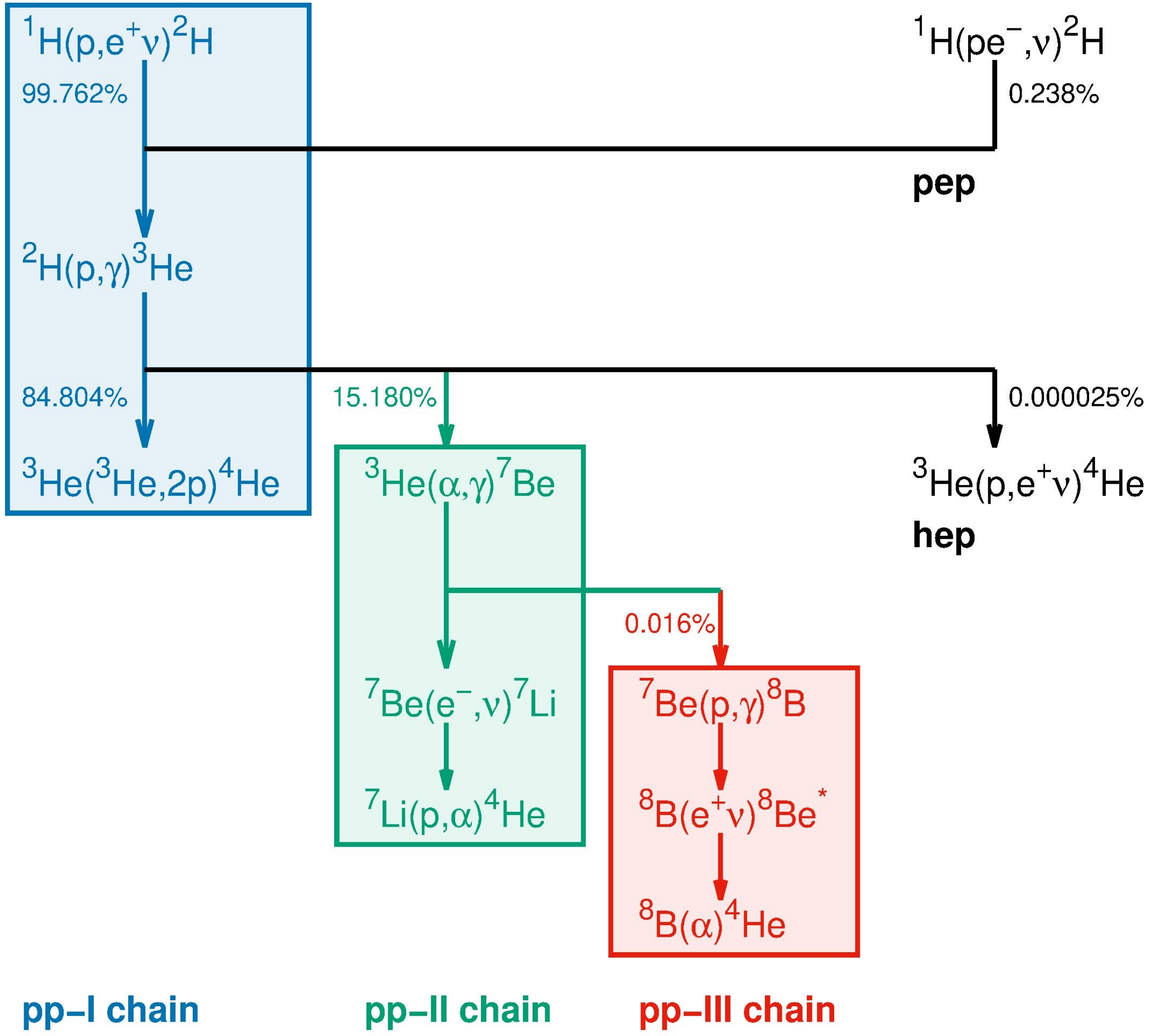
State of the art on solar neutrino fluxes



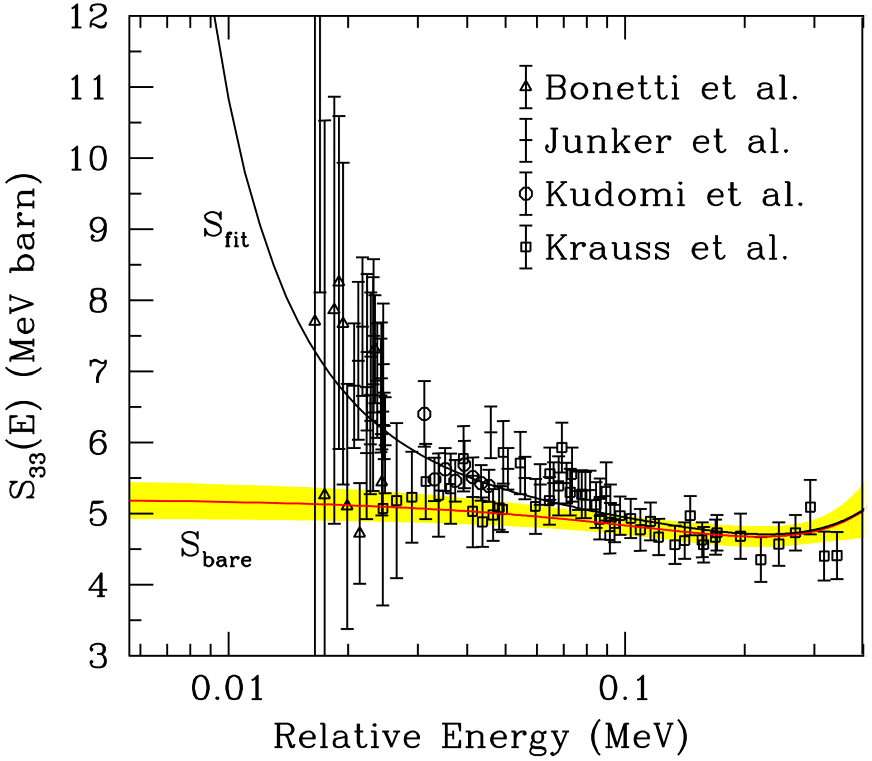
Measured solar ν fluxes:

- ν(pp) ± 0.4%
- $\nu(^{7}Be)$ ± 1.8%
- $\nu(^{8}B)$ ± 1.9%
- $\nu(^{13}N+^{15}O)$ ± 13%

The proton-proton chain



$^3He(^3He,2p)^4He$ – pp-I chain

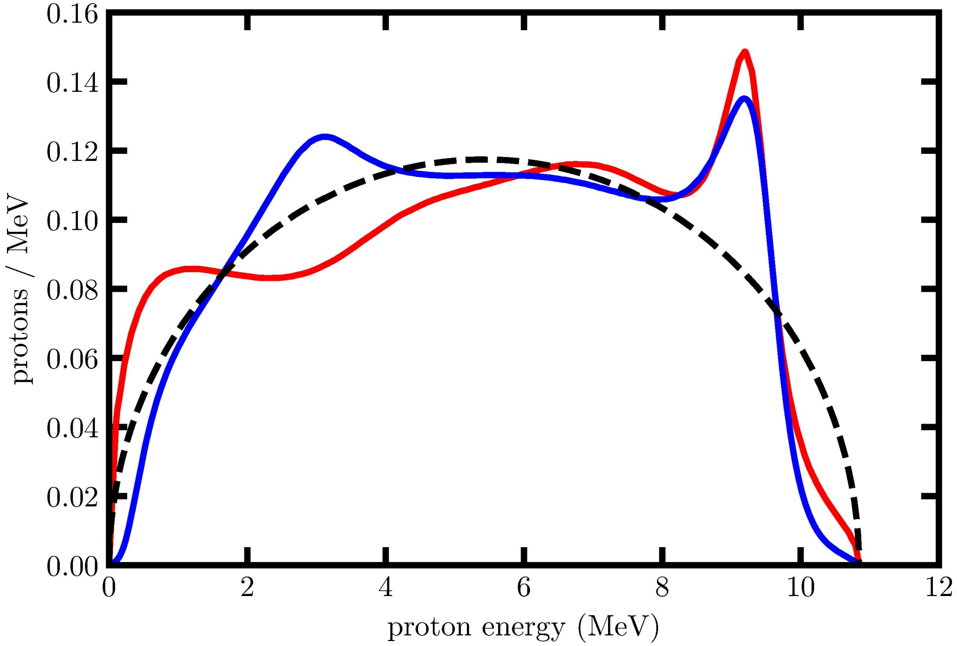


Evaluated S-factor normalization:

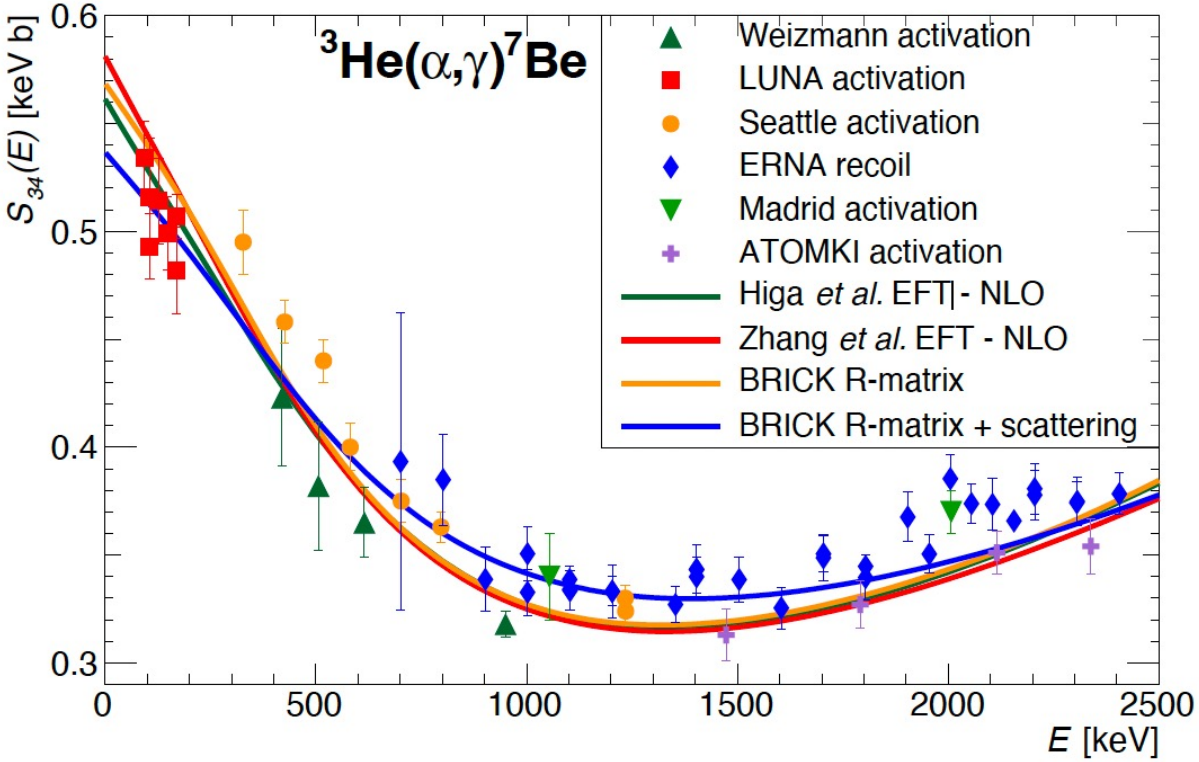
$S_{33}(0) = (5.21 \pm 0.34)$ MeV b

6.5% uncertainty – higher than in 2011!

The reason: Uncertainty on the assumed shape of the energy spectrum of emitted protons.



$^{3}He(\alpha,\gamma)^{7}Be$ – pp-II chain



Recommendations for future work:

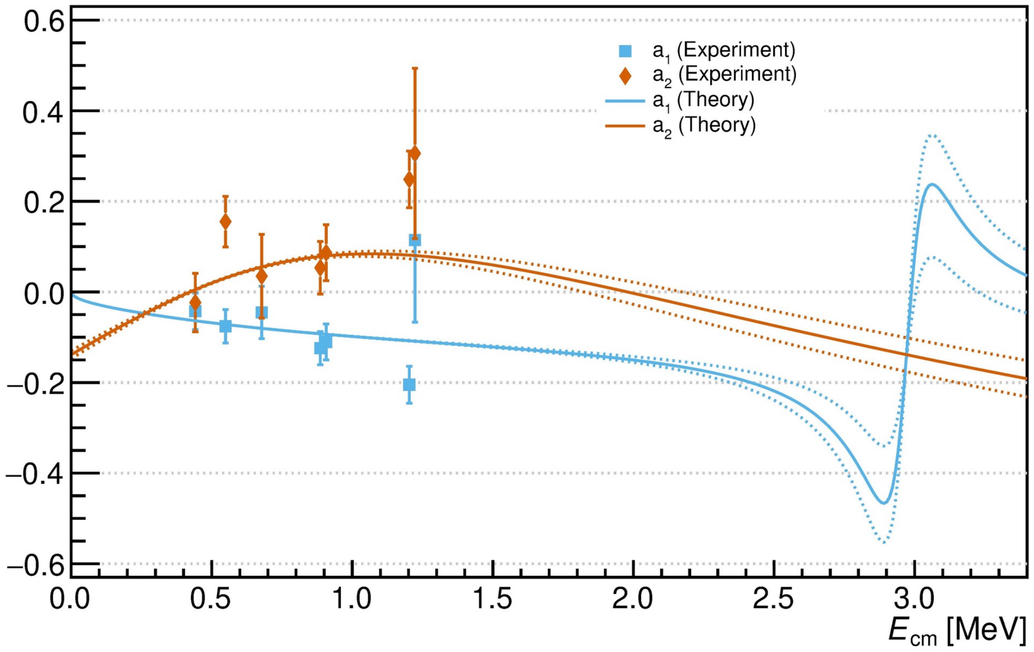
- Elastic scattering data below 2 MeV
- γ-ray angular distribution data
- Study of the S-factor over a wide energy range, 50-1500 keV.
- Further development of *ab initio* techniques.

Evaluated S-factor normalization:

$S_{34}(0) = (0.561 \pm 0.018_{\mathrm{expt}} \pm 0.022_{\mathrm{theor}})$ keV b

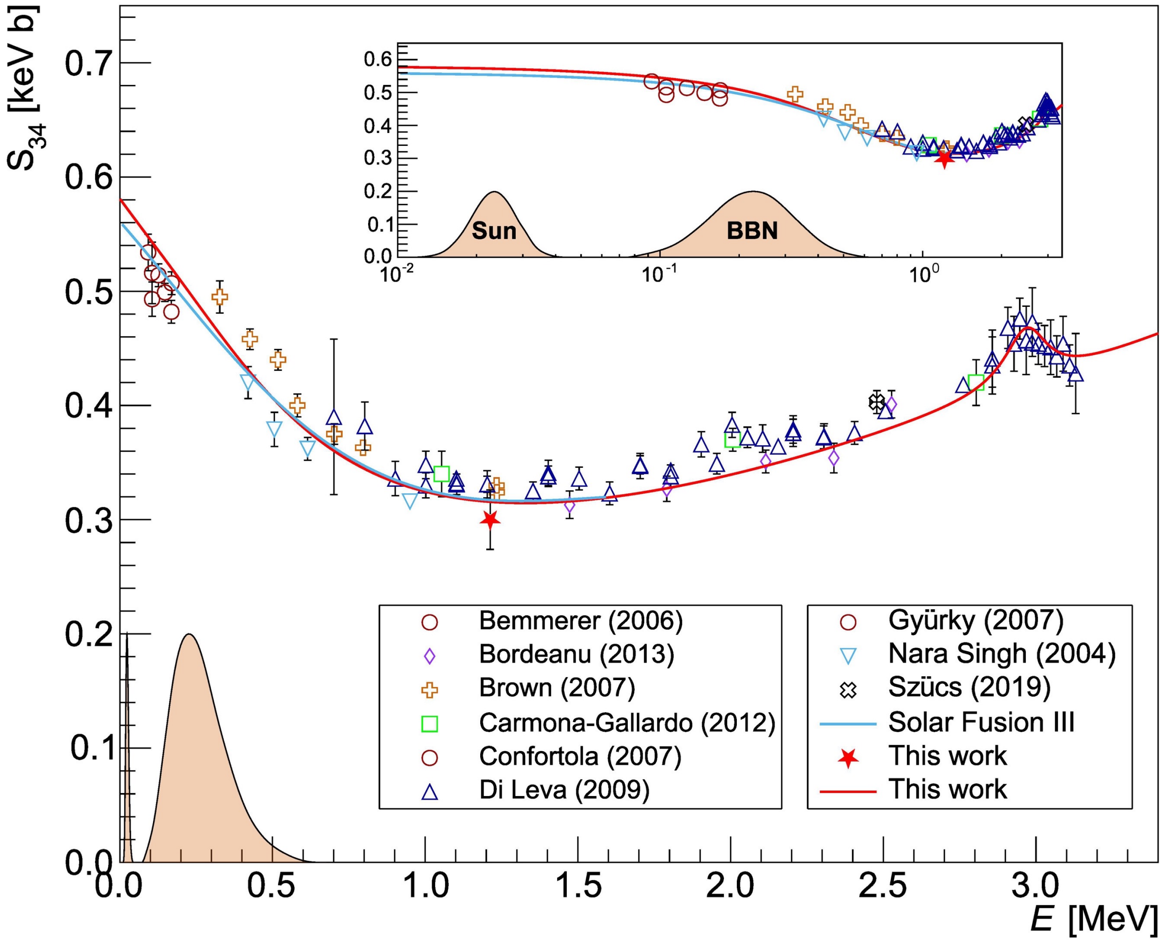
5.1% precision

Study of the $^{3}He(\alpha,\gamma)^{7}Be$ γ-ray angular distribution at Felsenkeller



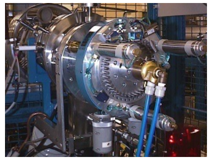
$$\frac{d\sigma}{d\Omega_{\mathrm{c.m.}}} = A_0\left(1+\sum_{l=1}^{3} a_l P_l(\cos\theta_{\mathrm{c.m.}})\right)$$

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

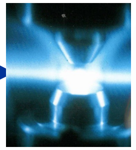


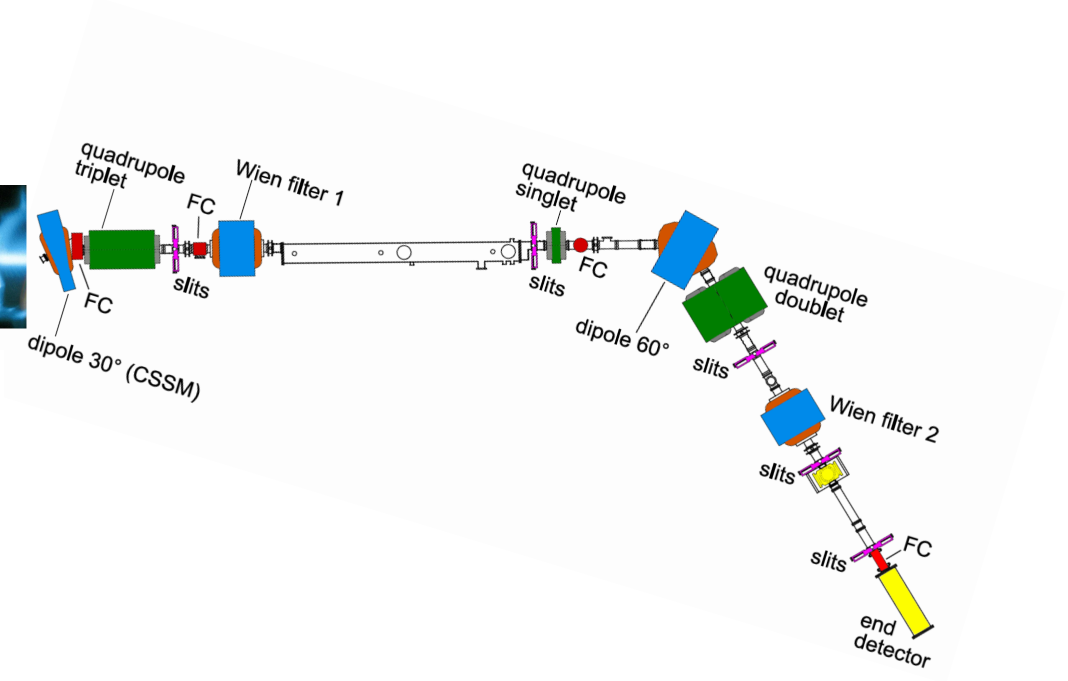
$^7Be(p,\gamma)^8B$ – pp-III chain

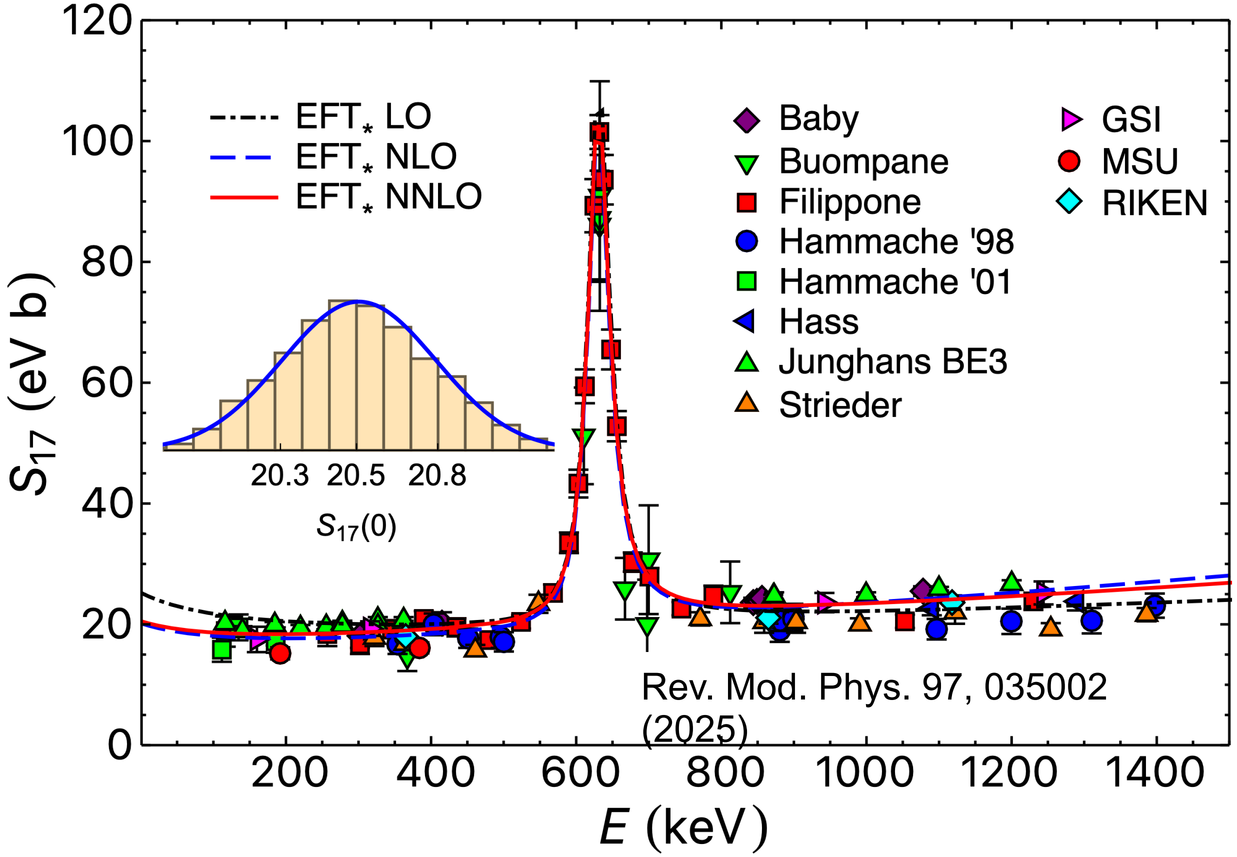
SNICS-40 ions source



^{7}Be beam





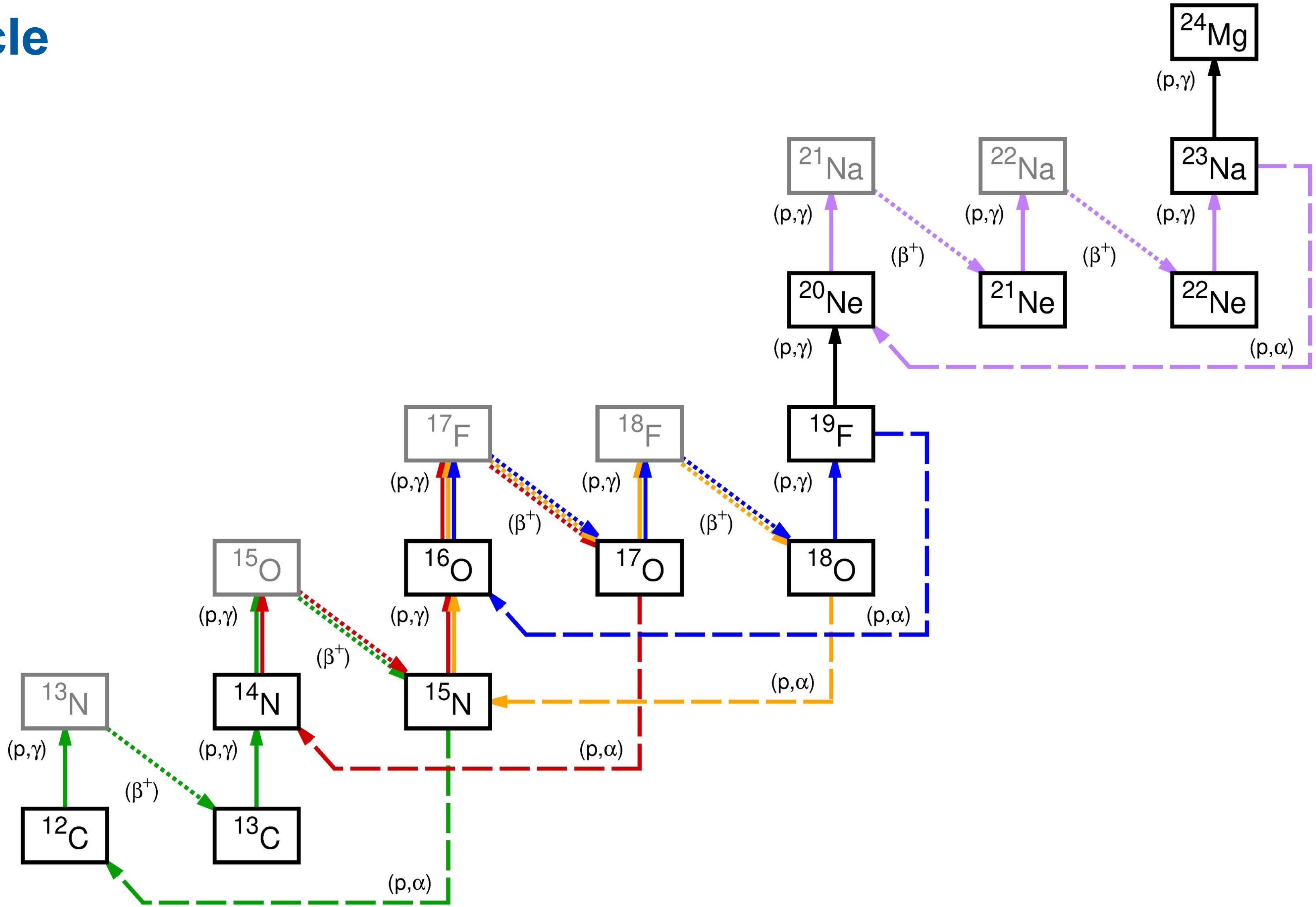


Evaluated S-factor normalization:

$S_{17}(0) = (20.5 \pm 0.3_{\mathrm{expt}} \pm 0.6_{\mathrm{theor}})$ eV b

3.5% precision

The CNO cycle



$^{14}N(p,\gamma)^{15}O$ – CNO cycle rate

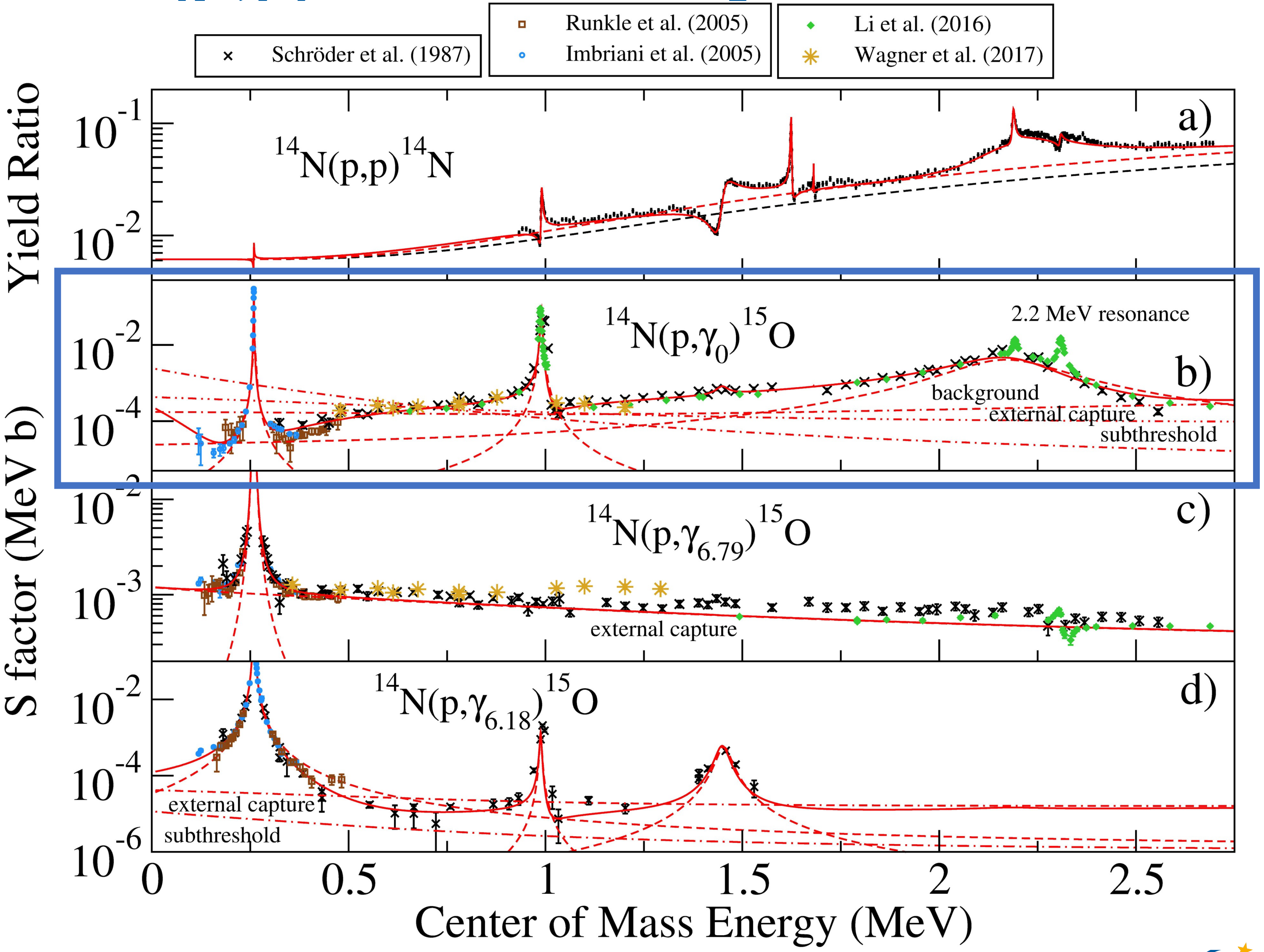


TABLE X. Total $S_{114}(0)$ values as the sum of the partial transitions.

Transition	$S_{114}(0)$ (keV b)	$\Delta S_{114}(0)$	Reference
tr → 0	0.30 ± 0.11	37%	This review
tr → 6.79	1.17 ± 0.03	2.9%	This review
tr → 6.17	0.13 ± 0.05	38%	Adelberger *et al.* (2011)
tr → 5.18	0.010 ± 0.003	30%	Adelberger *et al.* (2011)
tr(5.24) → 0	0.068 ± 0.020	30%	Adelberger *et al.* (2011)
R-matrix sum	1.68 ± 0.13[a]	7.6%	
Additional system uncertainty[b]		3.5%	
Total	1.68 ± 0.14	8.4%	

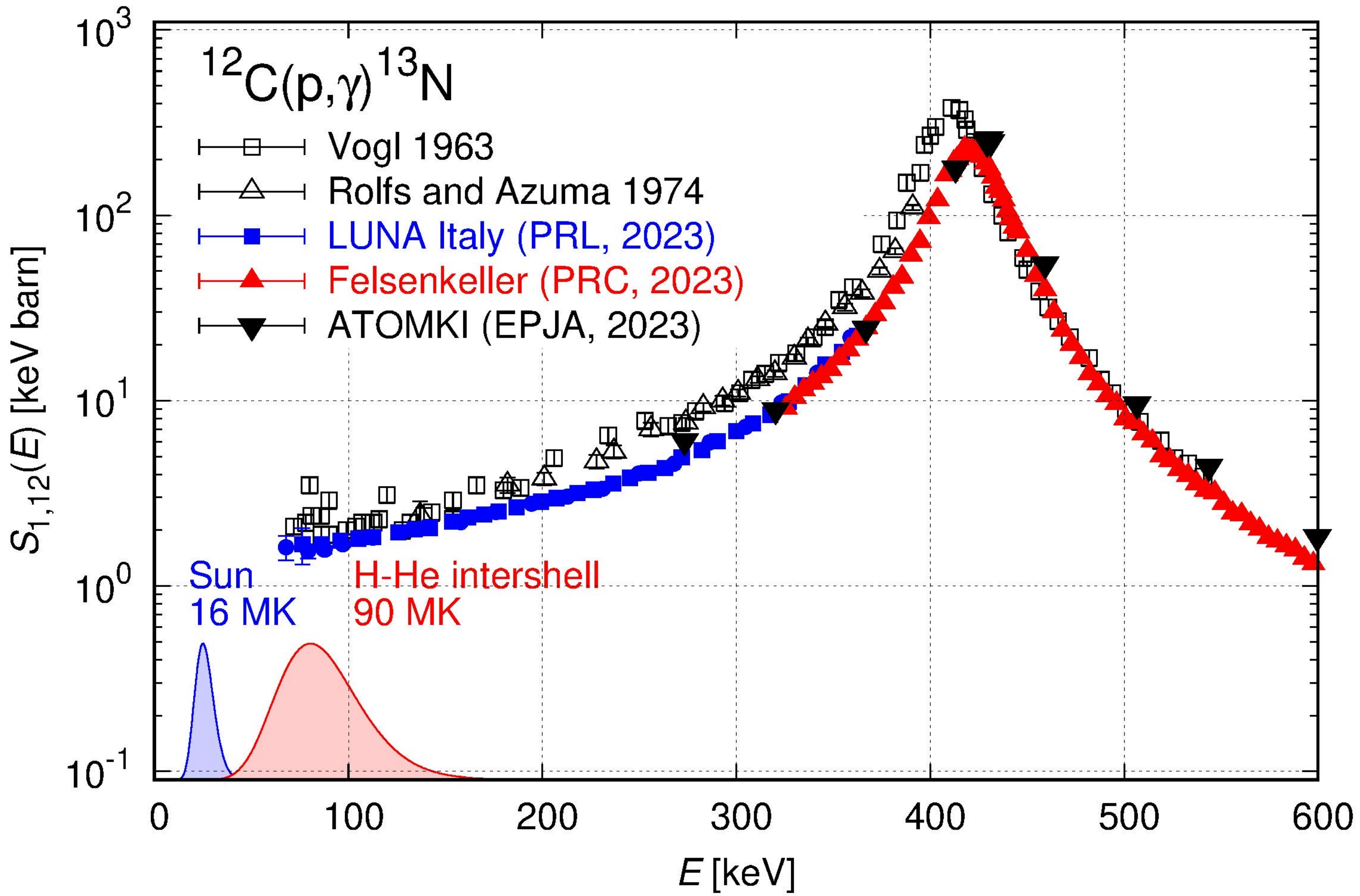
8.4% uncertainty – higher than in 2011!

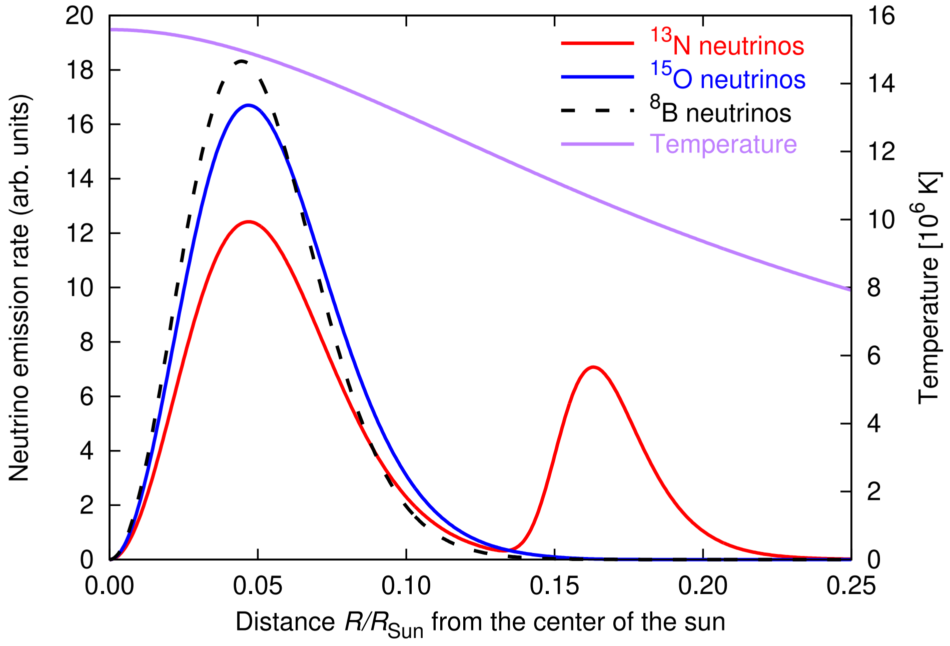
$^{14}N(p,\gamma)^{15}O$ – CNO cycle rate

Recommendations for future work:

- γ-ray angular distribution for the ground state transition
- Study of the S-factor over a wide energy range, 100-2500 keV.
- Measurements at very low energies, 100 keV, with high precision.
- Measurement of the lifetime of the 6.79 MeV excited state in ^{15}O.
- Cross section measurements for the 6.18 and 7.56 MeV transitions.

Study of the $^{12}C(p,\gamma)^{13}N$ reaction at Felsenkeller, LUNA, and ATOMKI





Solar model uncertainties

Table 7
Dominant Theoretical Error Sources for Neutrino Fluxes and the Main Characteristics of the SSM

Quant.	Dominant Theoretical Error Sources in %							
$\Phi(\mathrm{pp})$	$L_\odot$:	0.3	S_{34}:	0.3	κ:	0.2	Diff:	0.2
$\Phi(\mathrm{pep})$	κ:	0.5	$L_\odot$:	0.4	S_{34}:	0.4	S_{11}:	0.2
$\Phi(\mathrm{hep})$	S_{hep}:	30.2	S_{33}:	2.4	κ:	1.1	Diff:	0.5
$\Phi(^7\mathrm{Be})$	S_{34}:	4.1	κ:	3.8	S_{33}:	2.3	Diff:	1.9
$\Phi(^8\mathrm{B})$	κ:	7.3	S_{17}:	4.8	Diff:	4.0	S_{34}:	3.9
$\Phi(^{13}\mathrm{N})$	C:	10.0	S_{114}:	5.4	Diff:	4.8	κ:	3.9
$\Phi(^{15}\mathrm{O})$	C:	9.4	S_{114}:	7.9	Diff:	5.6	κ:	5.5
$\Phi(^{17}\mathrm{F})$	O:	12.6	S_{116}:	8.8	κ:	6.0	Diff:	6.0
α_{MLT}	O:	1.3	Diff:	1.2	κ:	0.7	Ne:	0.7
Y_{ini}	κ:	1.9	Ne:	0.5	Diff:	0.4	Ar:	0.3
Z_{ini}	O:	4.7	C:	2.0	Ne:	1.7	Diff:	1.6
Y_{S}	κ:	2.2	Diff:	1.1	Ne:	0.6	O:	0.3
Z_{S}	O:	4.8	C:	2.0	Ne:	1.8	κ:	0.7
R_{CZ}	κ:	0.6	O:	0.3	Diff:	0.3	Ne:	0.2

A biased takeaway, and some recommendations

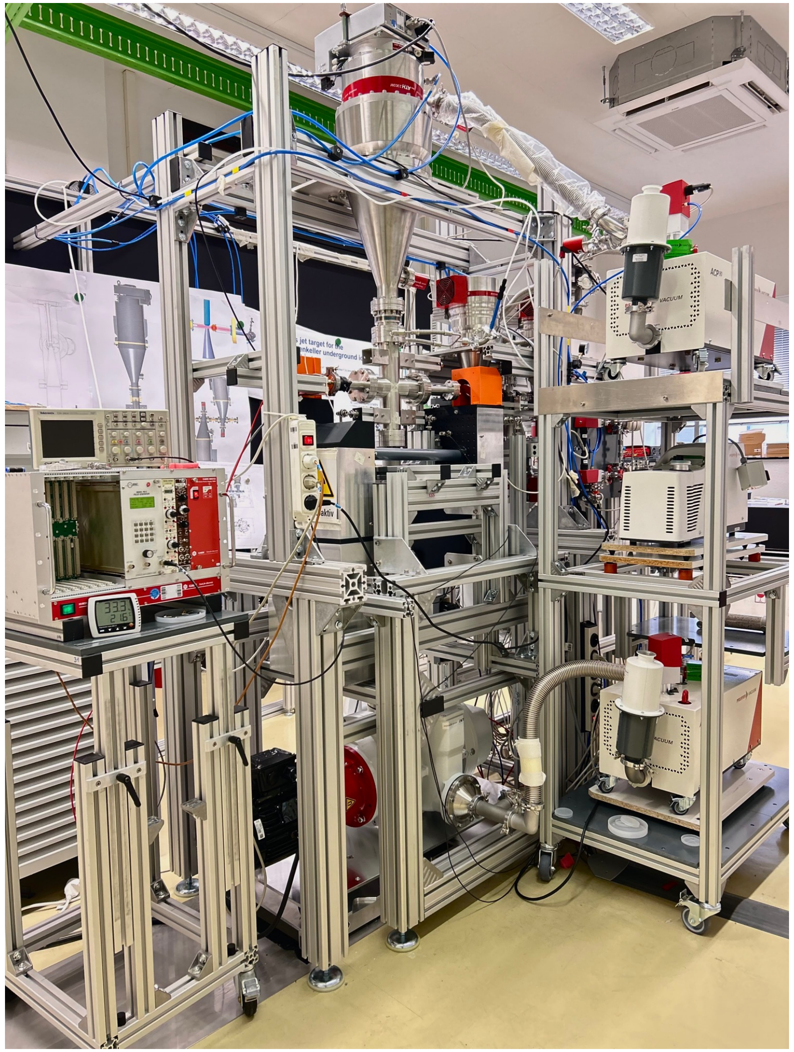
Solar fusion cross sections need more work, by the community!

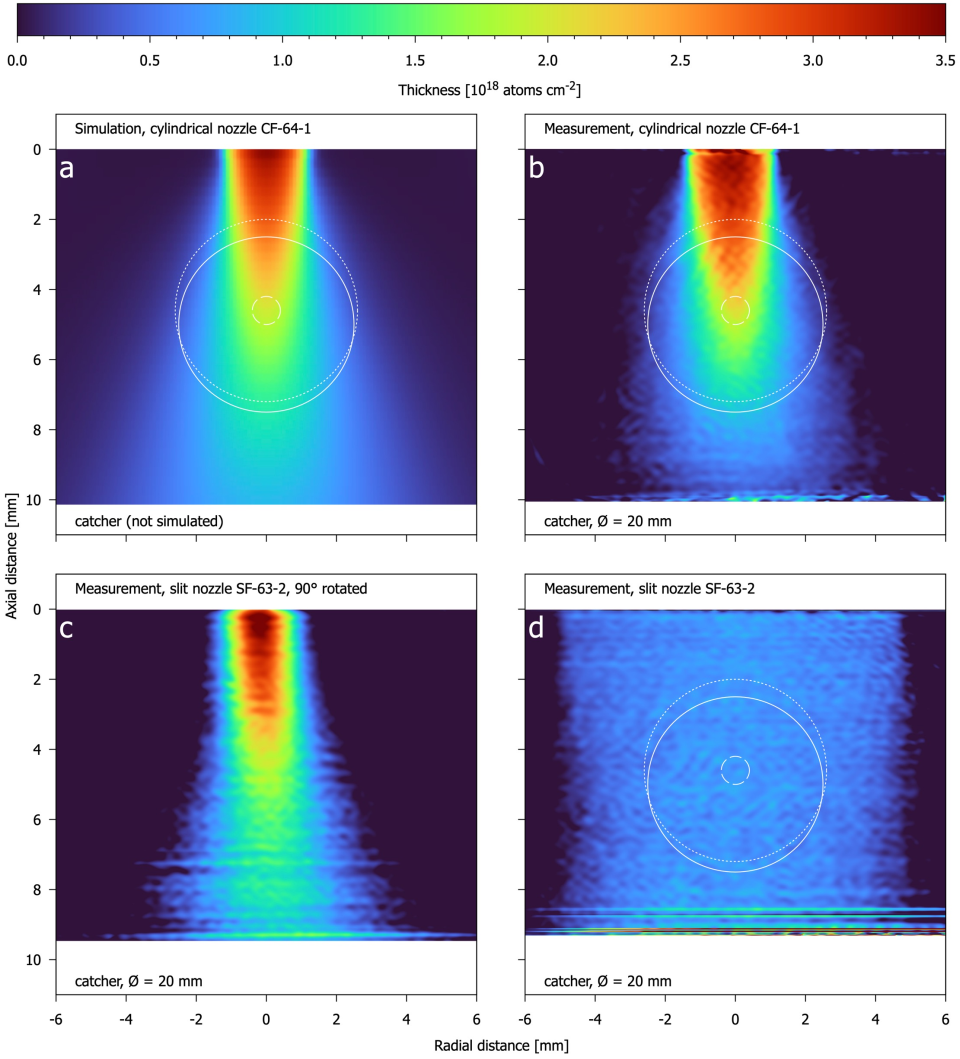
- Cross section measurements - but over a wide energy range.
- Elastic scattering plays a role, by constraining theory.
- γ-ray angular distributions would better constrain several extrapolated cross sections.
- Coordinated, interleaved approaches are necessary.

Use the new tools that are available now.

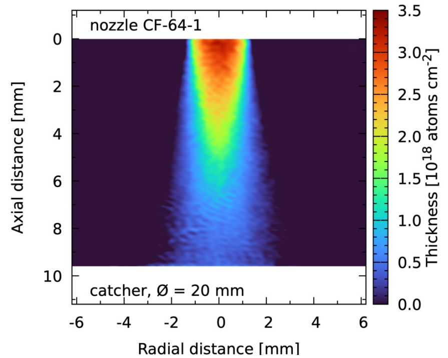
- Underground ion accelerators - Bellotti (Gran Sasso Italy), Felsenkeller (Germany), China, US
- AGATA – for lifetime measurement of the ^{15}O excited states (under analysis / Legnaro)
- Ion storage rings (CRYRING @ FAIR)
- Elastic scattering experiments
- Jet gas targets

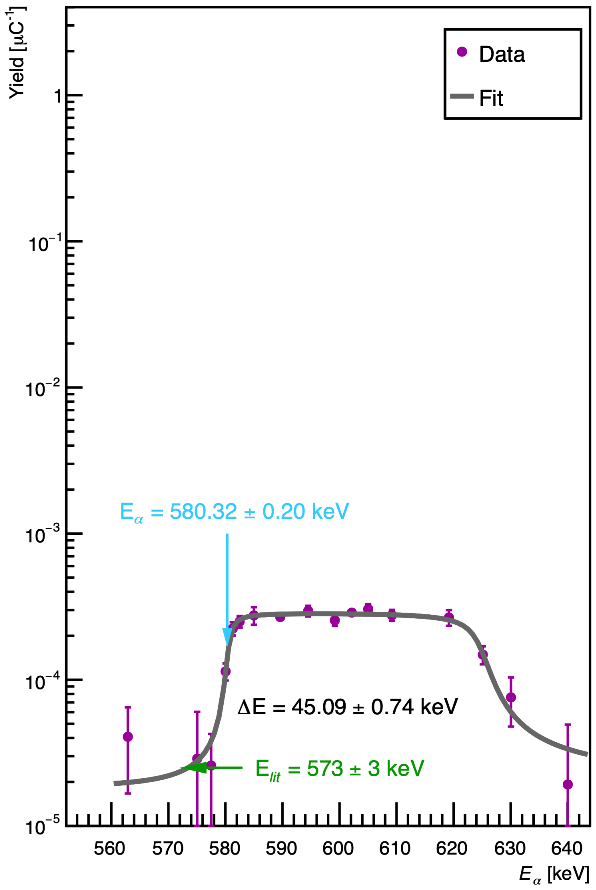
New tool at Felsenkeller: Gas target with interferometric measurement

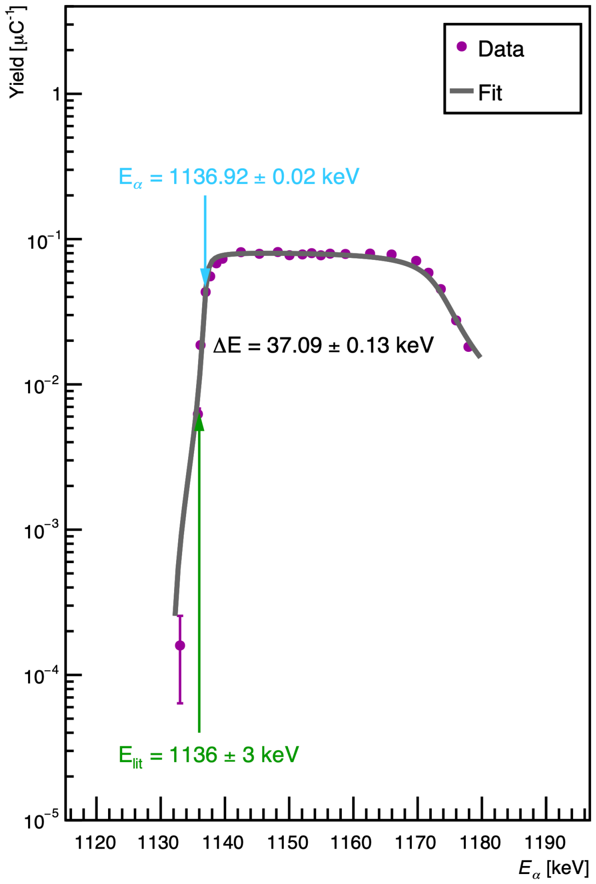


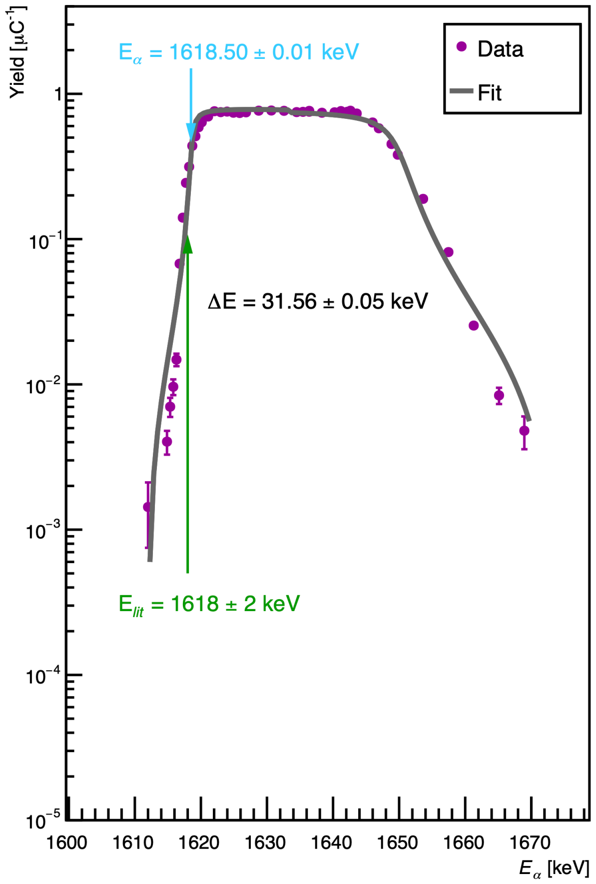


Jet gas target system at Felsenkeller





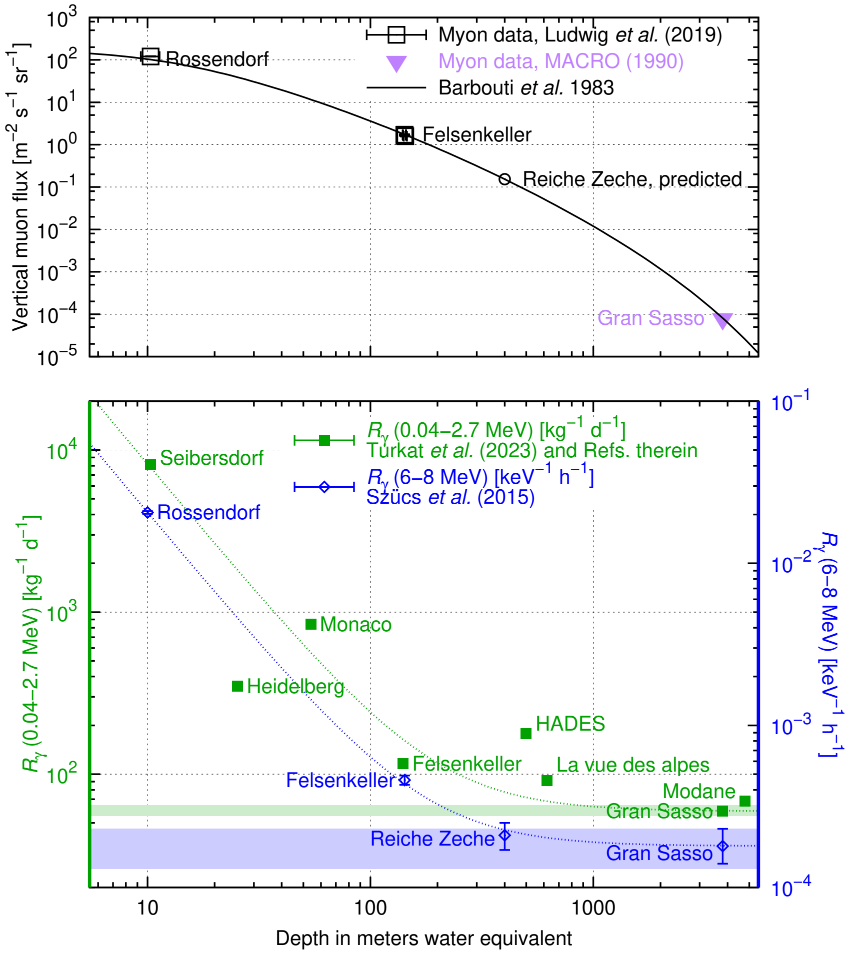


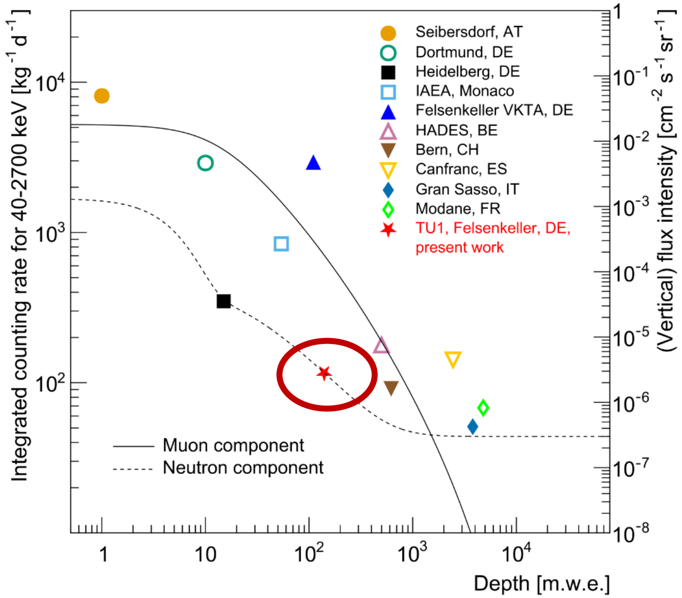


Felsenkeller: Studying low cross sections with low background

40× lower muon background

Astropart. Phys. 112, 24 (2019)





100× lower γ-background

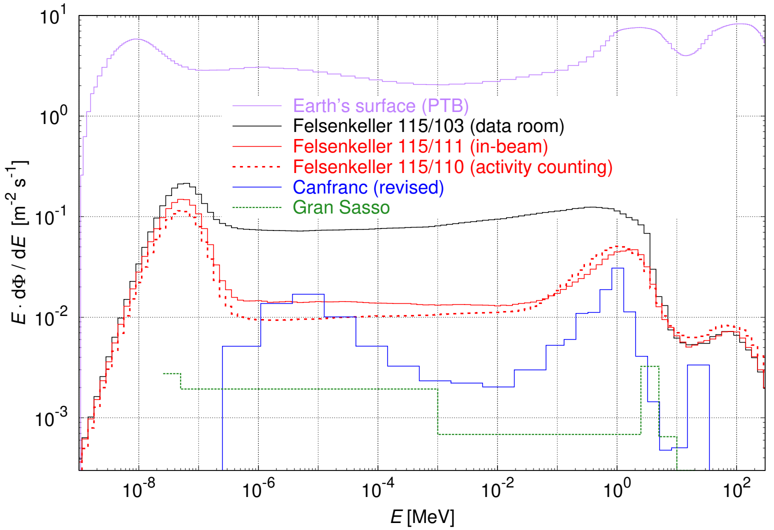
Eur. Phys. J. A 51, 33 (2015)

Astropart. Phys. 148, 102816 (2023)

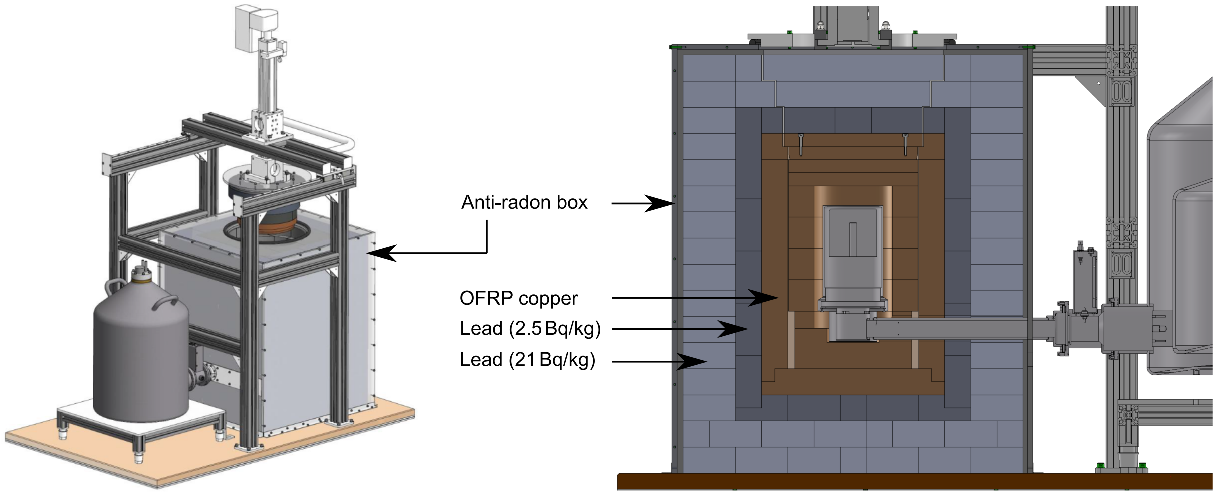
Eur. Phys. J. A 61, 19 (2025)

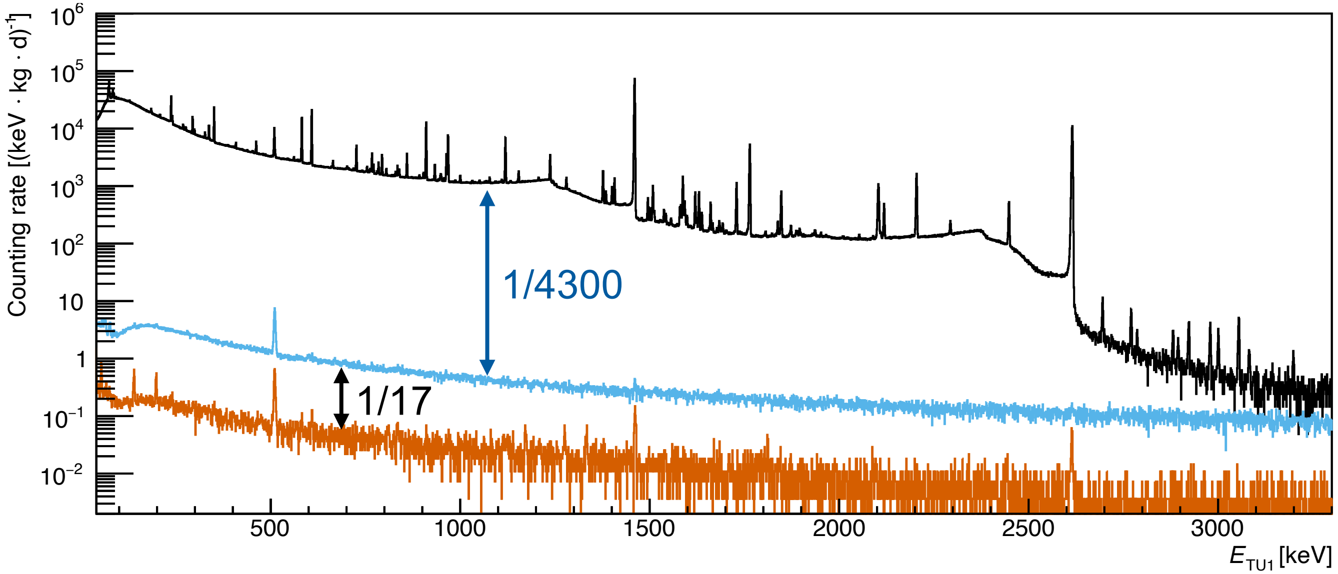
200× lower neutron background

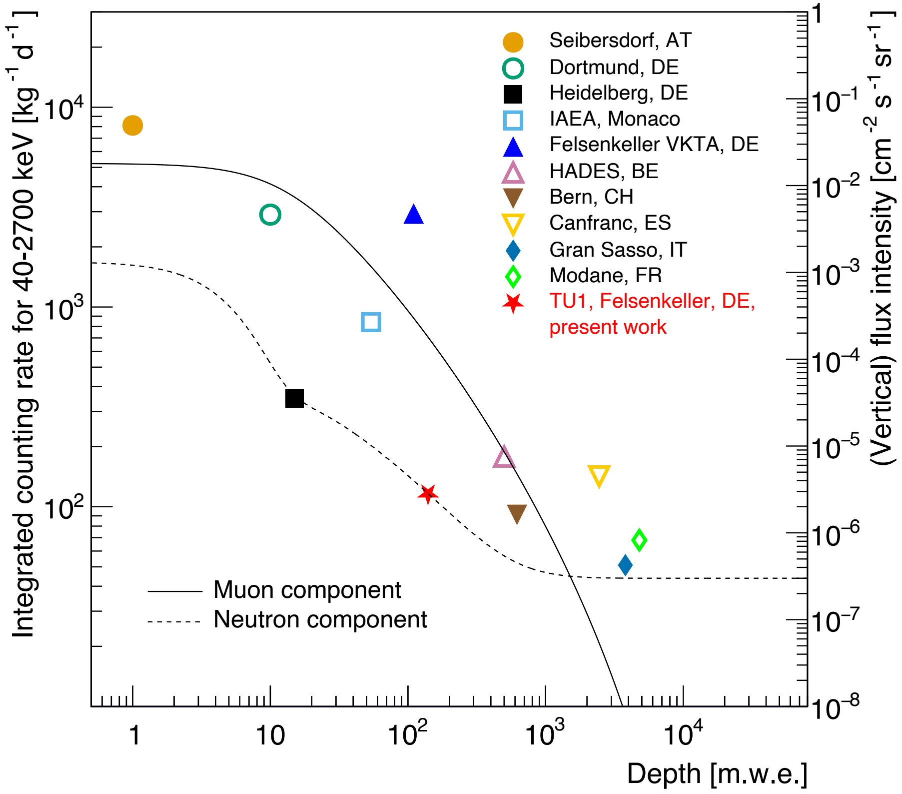
Phys. Rev. D 101, 123027 (2020)



Germany's most sensitive radioactivity measurement setup "TU1"

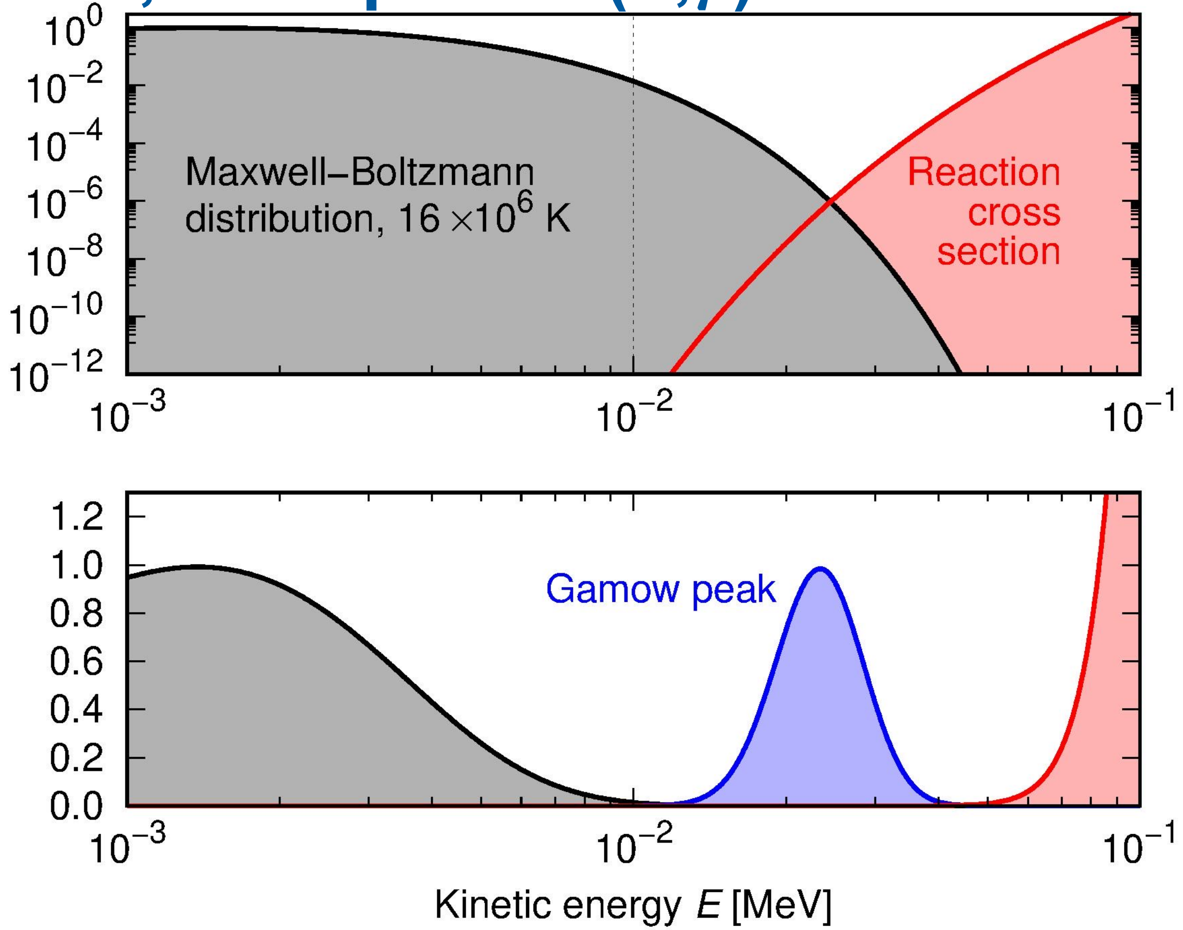






Steffen Turkat, Kai Zuber *et al.*,
Astropart. Phys. 148 (2023) 102816

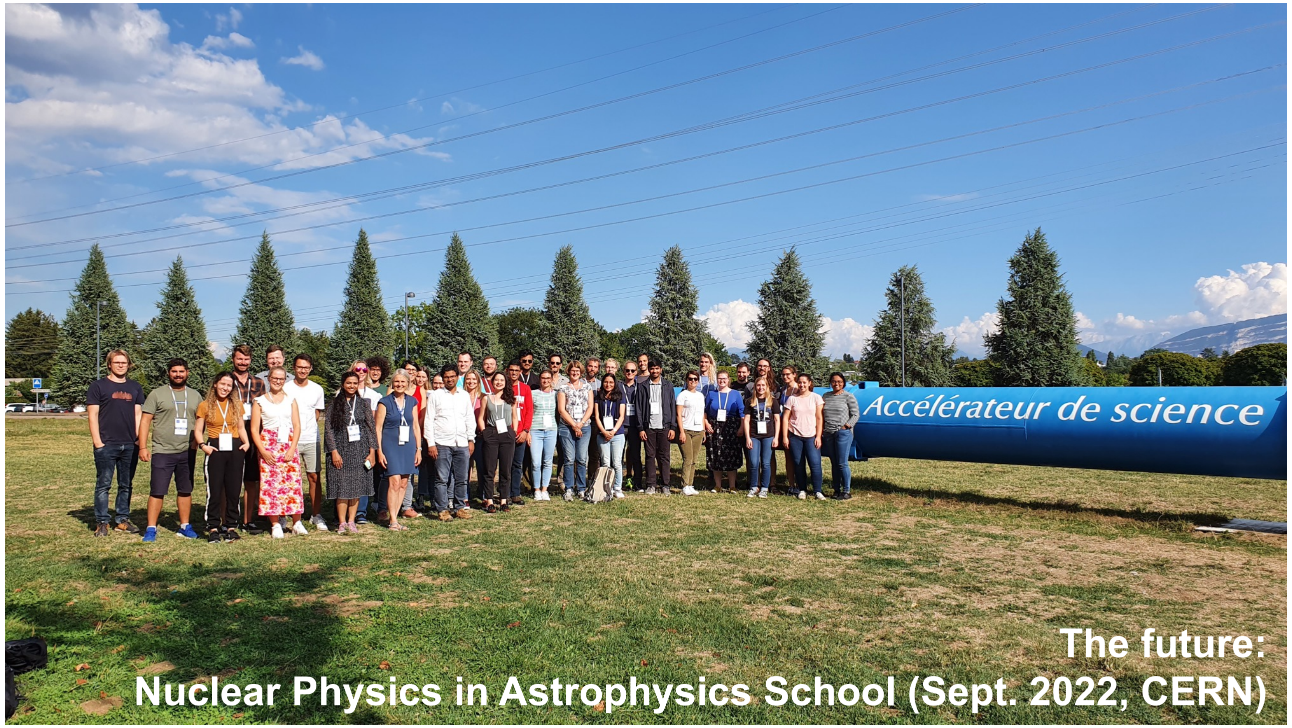
The Gamow peak, example $^3He(\alpha,\gamma)^7Be$



Sensitive, underground experiments needed

Thermonuclea r reaction rate $\propto \int_0^\infty \boxed{\exp\left[-\frac{E}{k_B T}\right]} \boxed{S(E)\exp\left[-\frac{b}{\sqrt{E}}\right] dE}$

ChETEC-INFRA EU project for nuclear astrophysics [ketek-infra]



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- **5 M€ support** by EU (2021 – 2025)

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HZDR Felsenkeller Underground / DE


HZDR DREAMS AMS / DE


Vienna University VERA AMS / AT

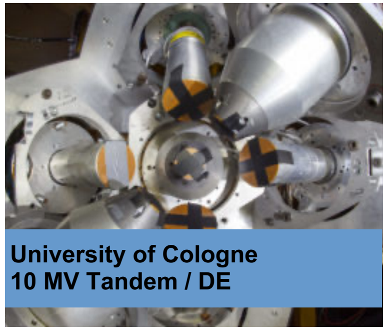

IANAO National Astronomical Observatory / BG


ASU Perek Telescope / CZ


Nordic Optical Telescope La Palma / ES (Arhus / DK)


Frankfurt University van de Graaf n-source / DE


PTB Ion Accelerator Facility / DE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Vilnius University Moletai Astronical Observatory / LT


IFIN-HH 3 MV Tandetron accelerator / RO


Hull University VIPER cluster


Bellotti IBF, IT
Underground ion accelerator