The Felsenkeller facility for nuclear astrophysics

Helmholtz International Summer School

"NUCLEAR THEORY AND ASTROPHYSICAL APPLICATIONS"

Dubna, Russia, July 10 – 21, 2017

Tamás Szücs

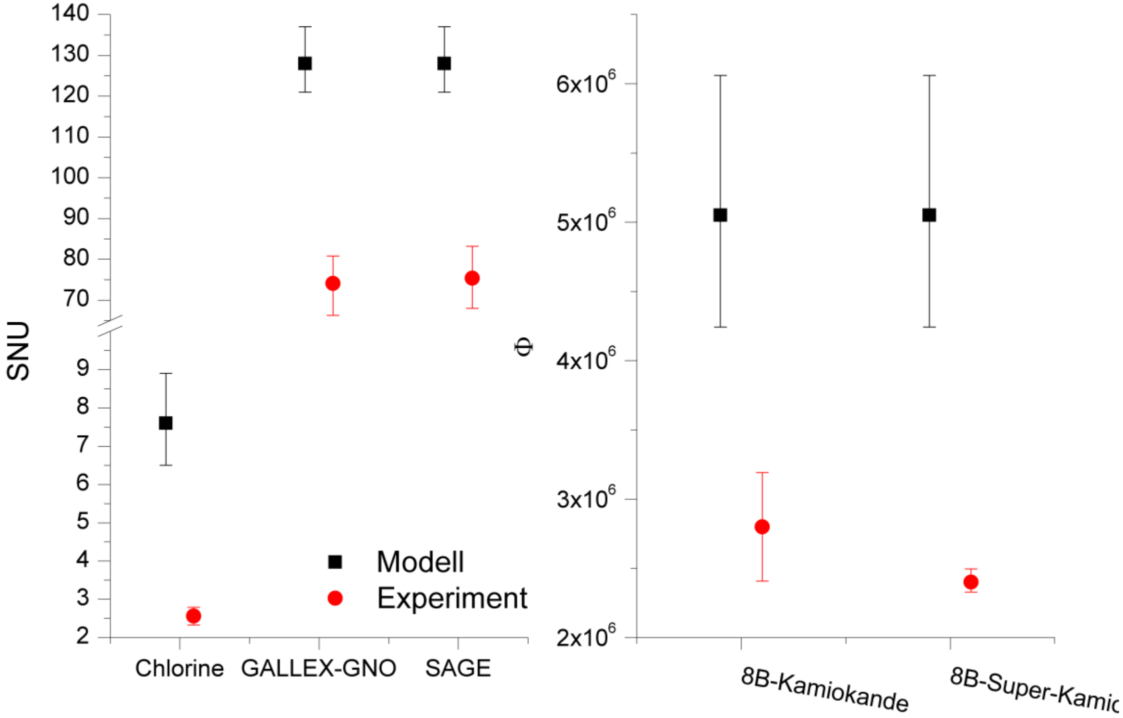
MTA atomki DEBRECEN

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

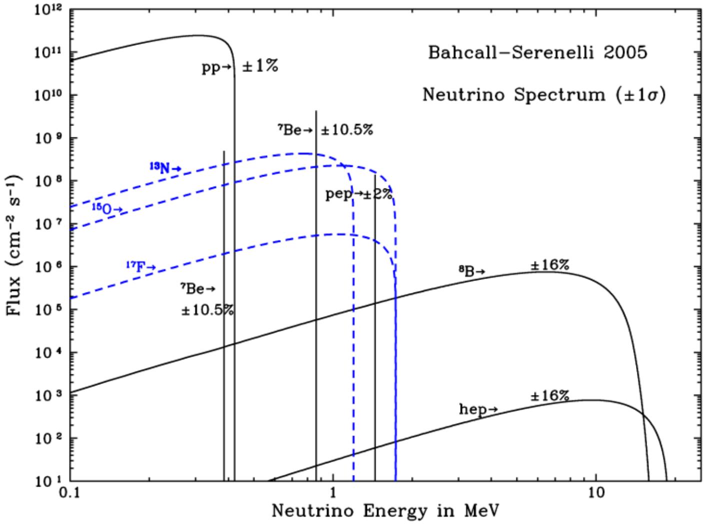
The Felsenkeller facility for nuclear astrophysics

- pp-chain: The $^{3}He(\alpha,\gamma)^{7}Be$ reaction
- CNO cycle: The $^{14}N(p,\gamma)^{15}O$ reaction
- Holy Grail of Nuclear Astrophysics: The $^{12}C(\alpha,\gamma)^{16}O$ reaction
- Capabilities of the new Felsenkeller facility

Solar neutrino fluxes: Solar neutrino problem

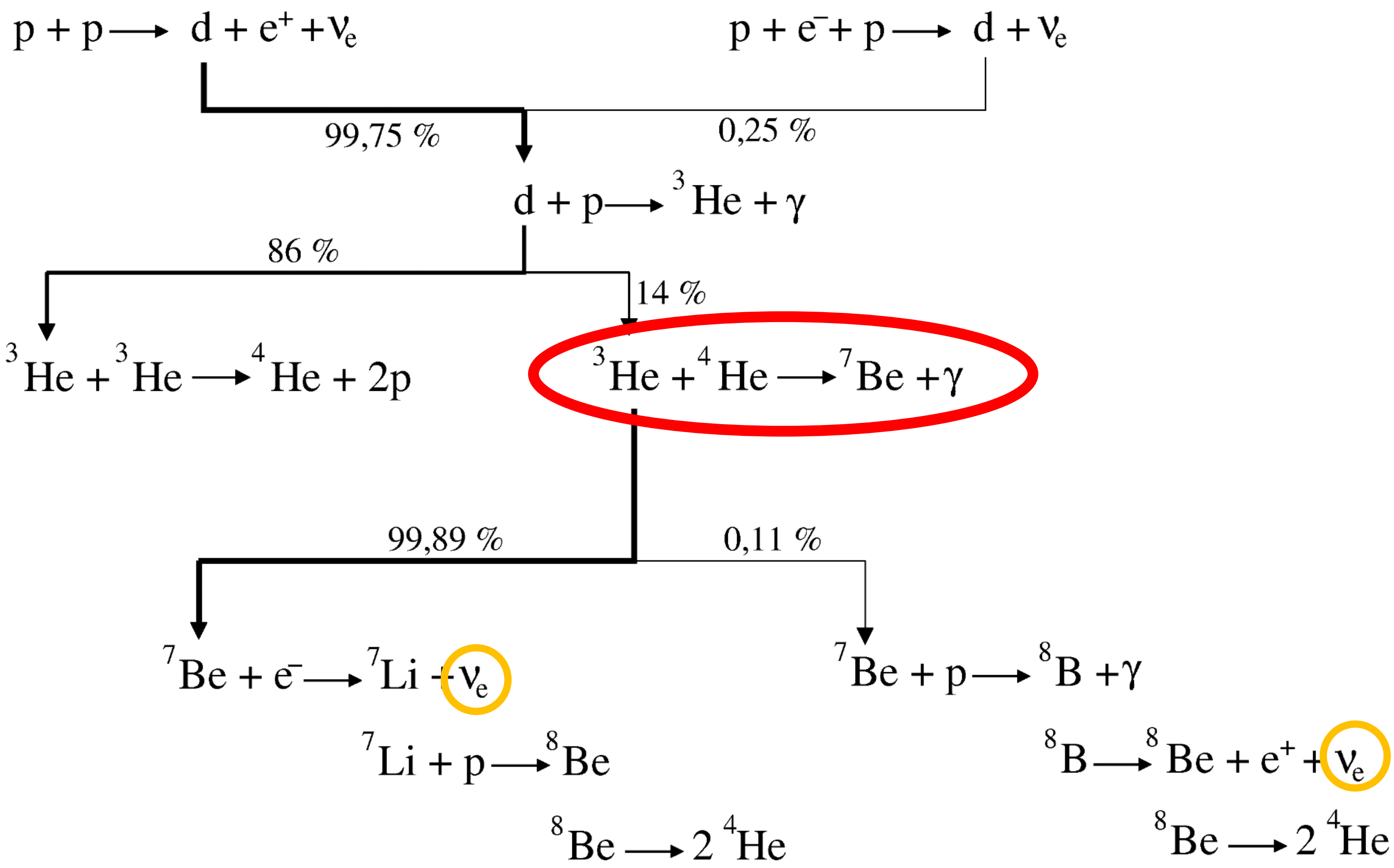


J. N. Bahcall *et al*,
Astrophys. Jour. **555,** 900 (2001)

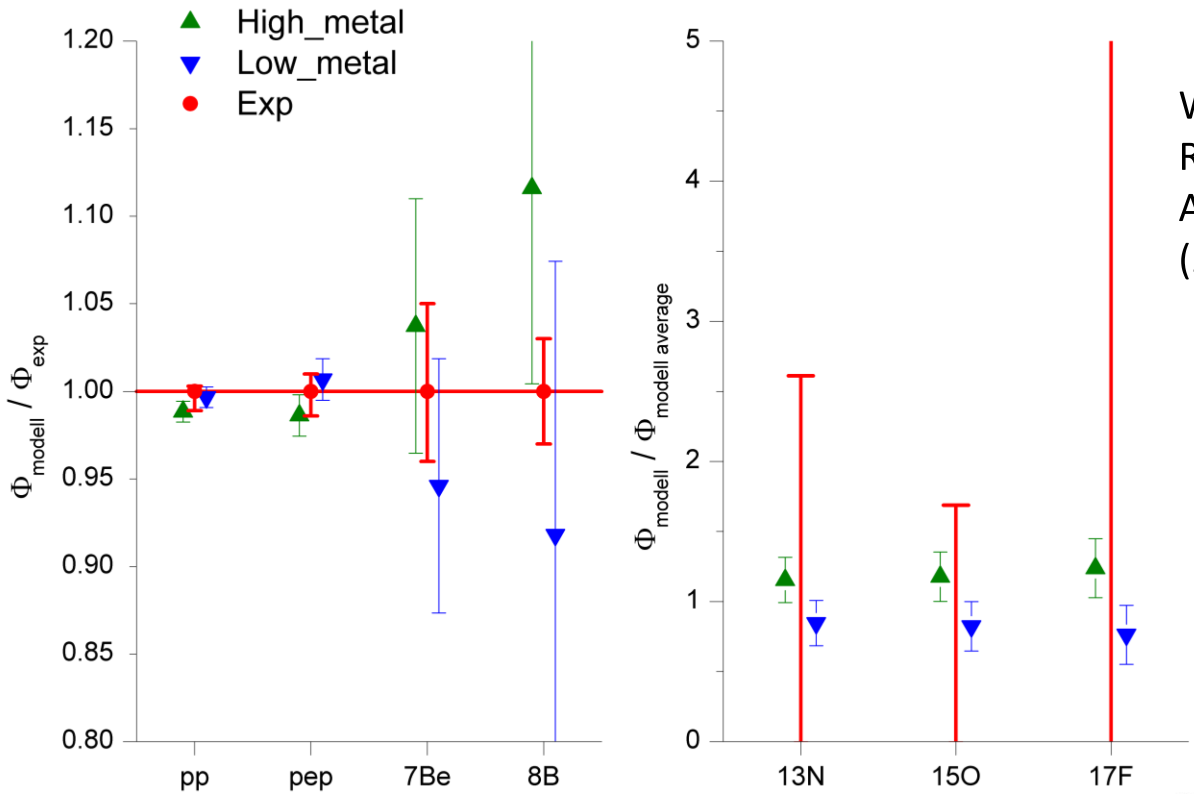


- **No nuclear physics solution**

Solar pp-chain



Solar neutrino fluxes: New solar composition

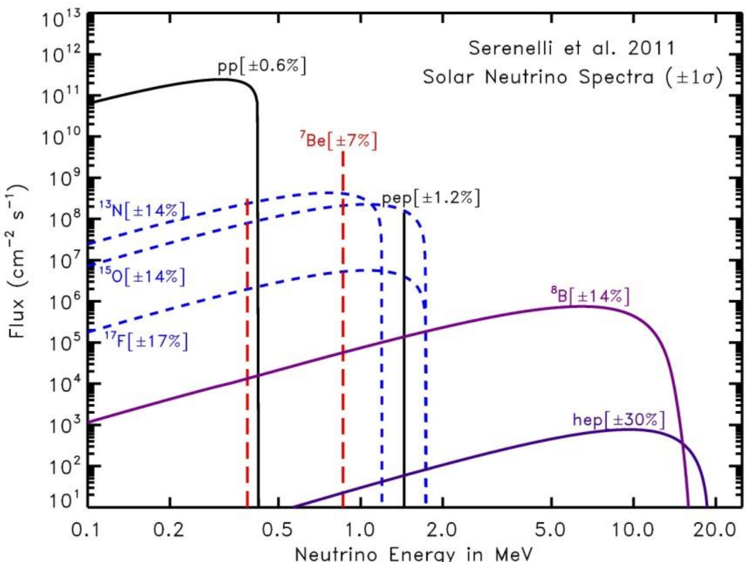


W. C. Haxton, Bahcall, R. G. Hamish Robertson, Aldo M. Serenelli, Annu. Rev. Astron. Astrophys. **51**, 21 (2013)

High_metallicity =
N. Grevesse, A. J. Sauval,
Space Sci. Rev. **85**, 161 (1998)

Low_metallicity =
M. Asplund, N. Grevesse,
A. J. Sauval, P. Scott,
Annu. Rev. Astron. Astrophys. **47**, 481 (2009)

- ^{7}Be, ^{8}B: Data more precise than the models
- ^{13}N, ^{15}O: No data yet, but models are not very precise
- **Need smaller error bars for the models!**
- **→→ More precise input data**



Uncertainties in the predicted solar neutrino fluxes

Nuclear reaction rates

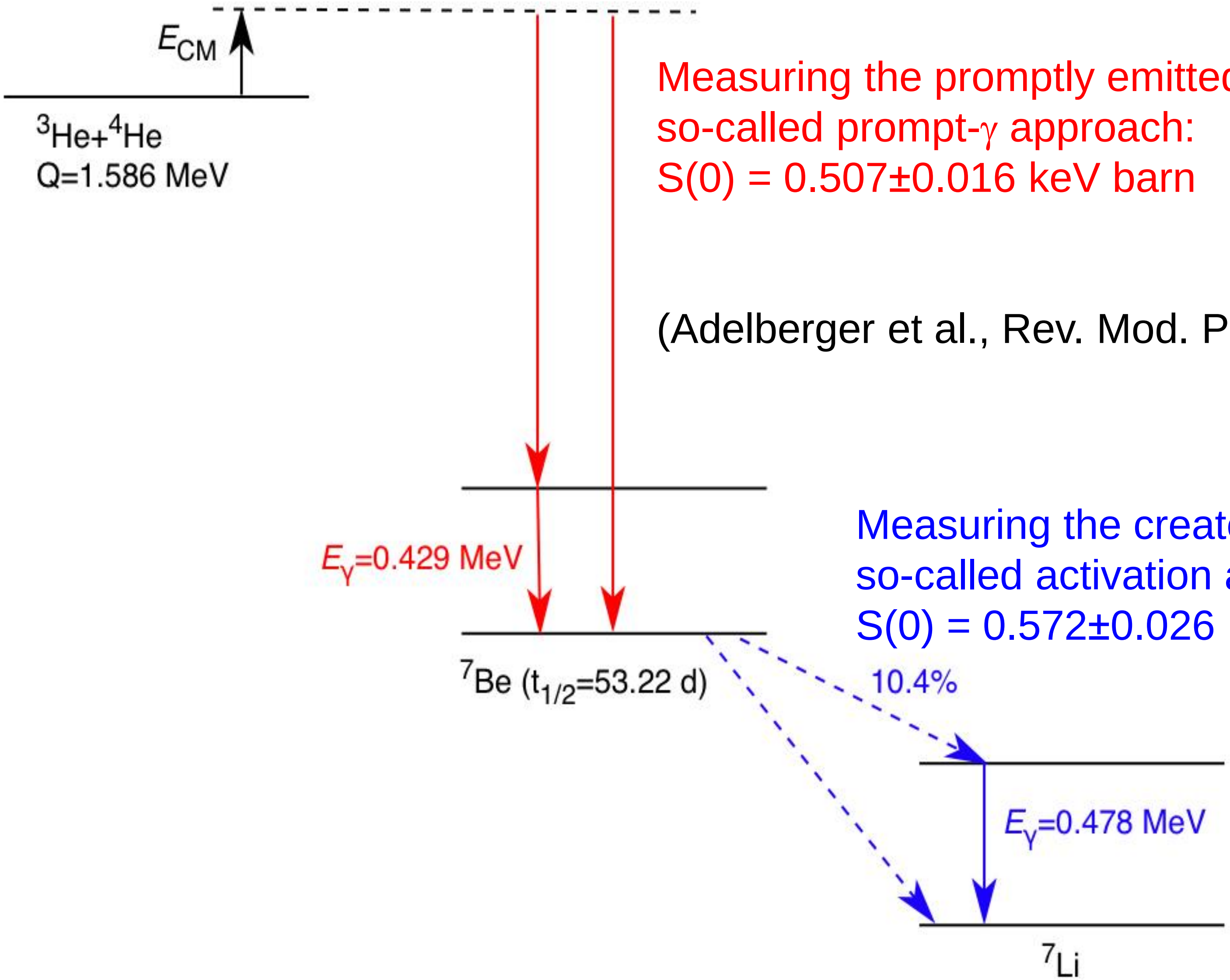
	S_{11}	S_{33}	S_{34}	S_{17}	$S_{1,14}$	Opac	Diff
pp	0.1	0.1	0.3	0.0	0.0	0.2	0.2
pep	0.2	0.2	0.5	0.0	0.0	0.7	0.2
hep	0.1	2.3	0.4	0.0	0.0	1.0	0.5
^{7}Be	1.1	2.2	4.7	0.0	0.0	3.2	1.9
^{8}B	2.7	2.1	4.5	7.7	0.0	6.9	4.0

Uncertainty contributed to neutrino flux, in percent

Antonelli et al., 1208.1356

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

Two method

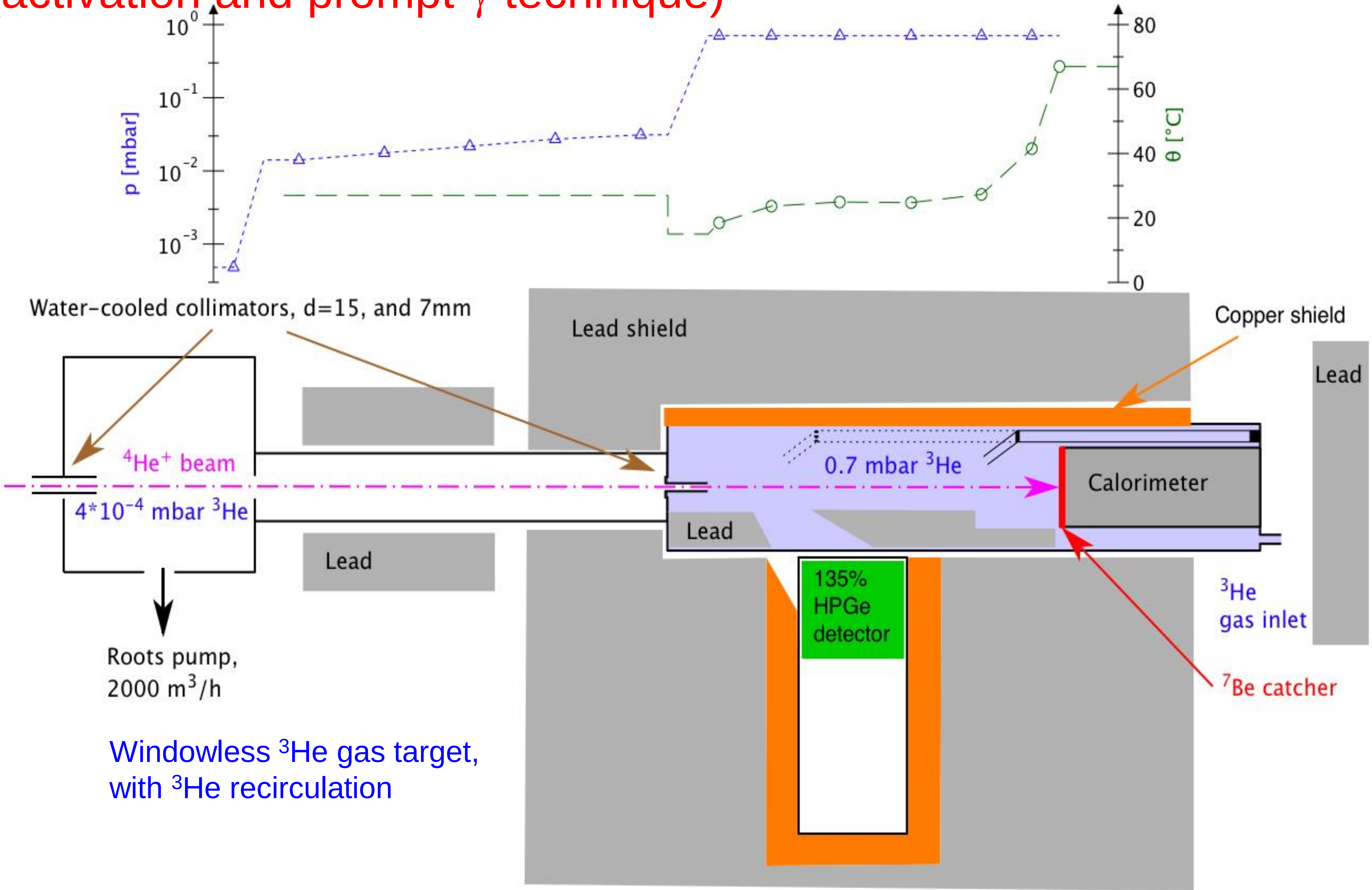


Measuring the promptly emitted γ-rays,
so-called prompt-γ approach:
S(0) = 0.507±0.016 keV barn

(Adelberger et al., Rev. Mod. Phys. 1998)

Measuring the created ^7Be activity,
so-called activation approach:
S(0) = 0.572±0.026 keV barn

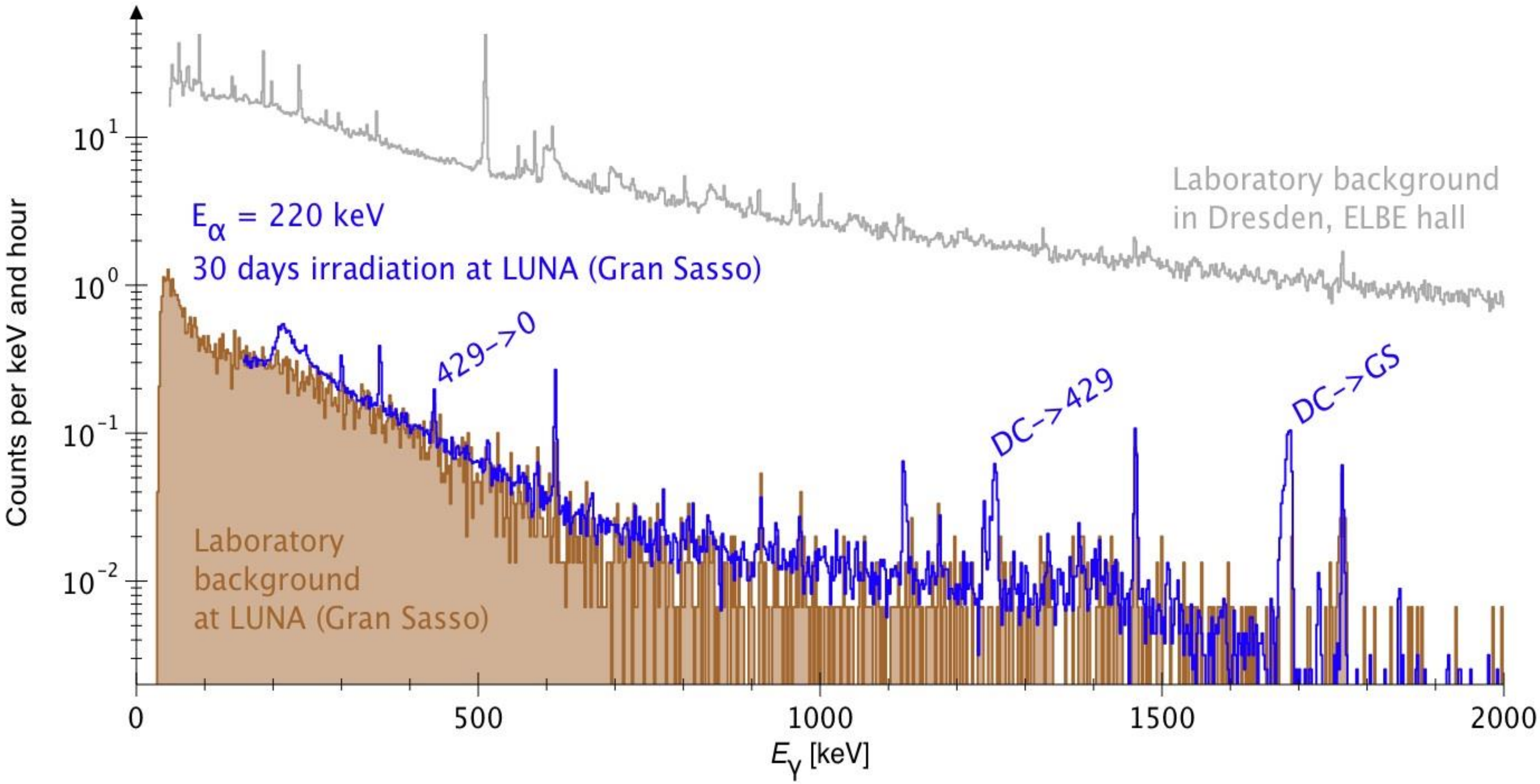
$^3He(\alpha,\gamma)^7Be$ at LUNA (Laboratory for Underground Nuclear Astrophysics) (activation and prompt-γ technique)



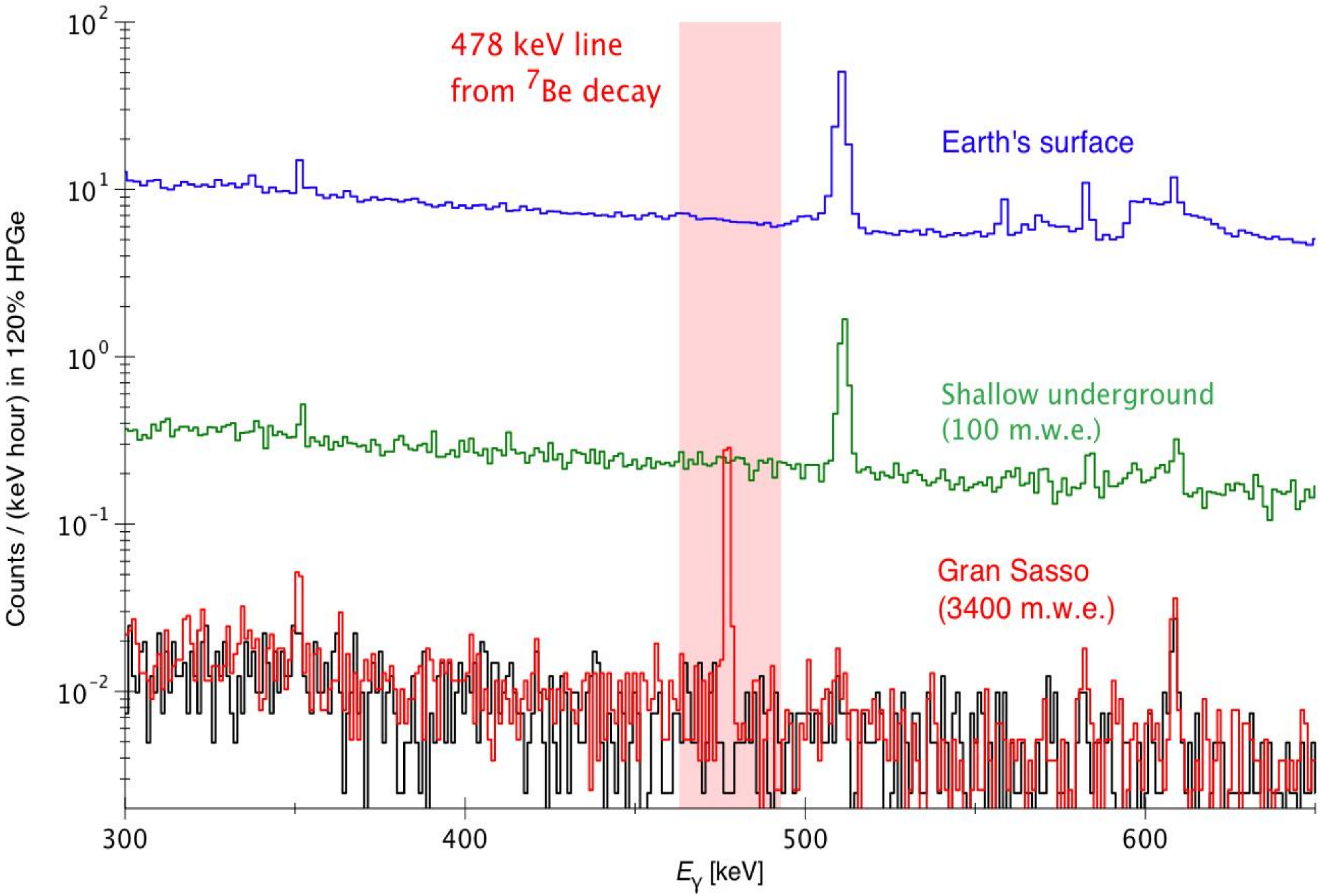
Windowless ^3He gas target, with ^3He recirculation

P. Confortola *et al*, PRC **75,** 065803 (2007)

$^3He(\alpha,\gamma)^7Be$ at LUNA, in-beam γ-spectra

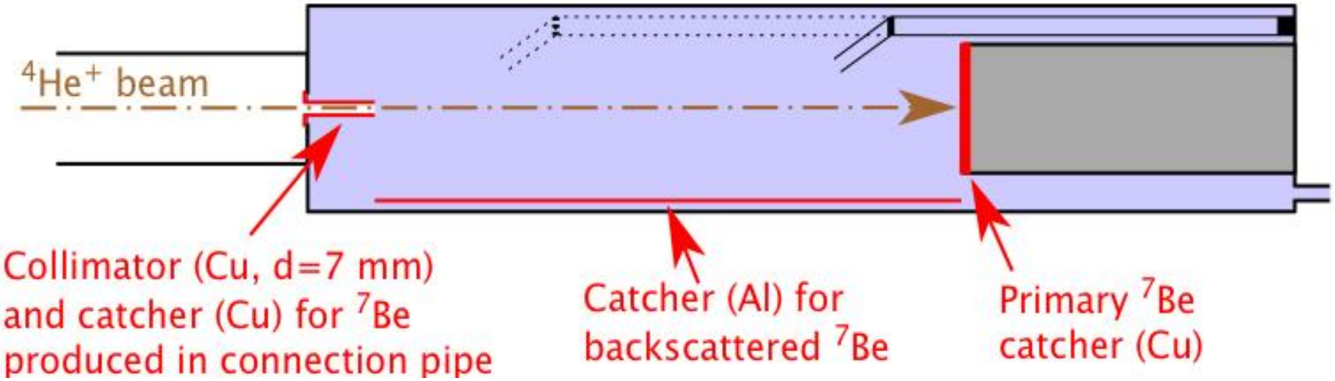


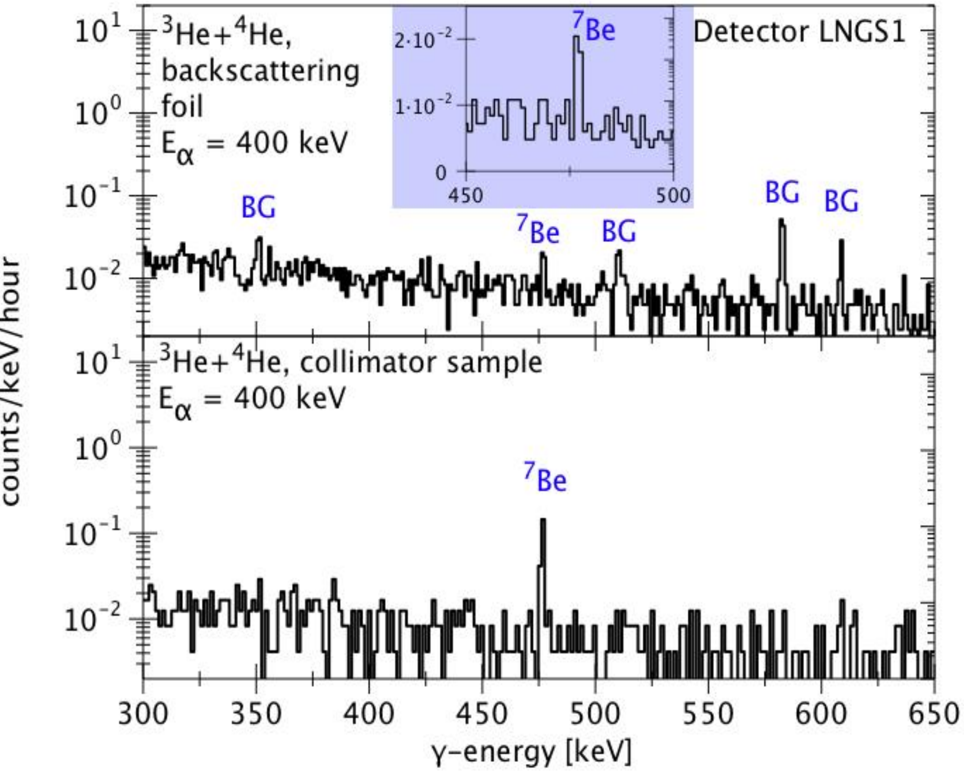
$^3He(\alpha,\gamma)^7Be$ at LUNA, ^7Be activation spectra



Detected ^7Be activities: 0.8 - 600 mBq

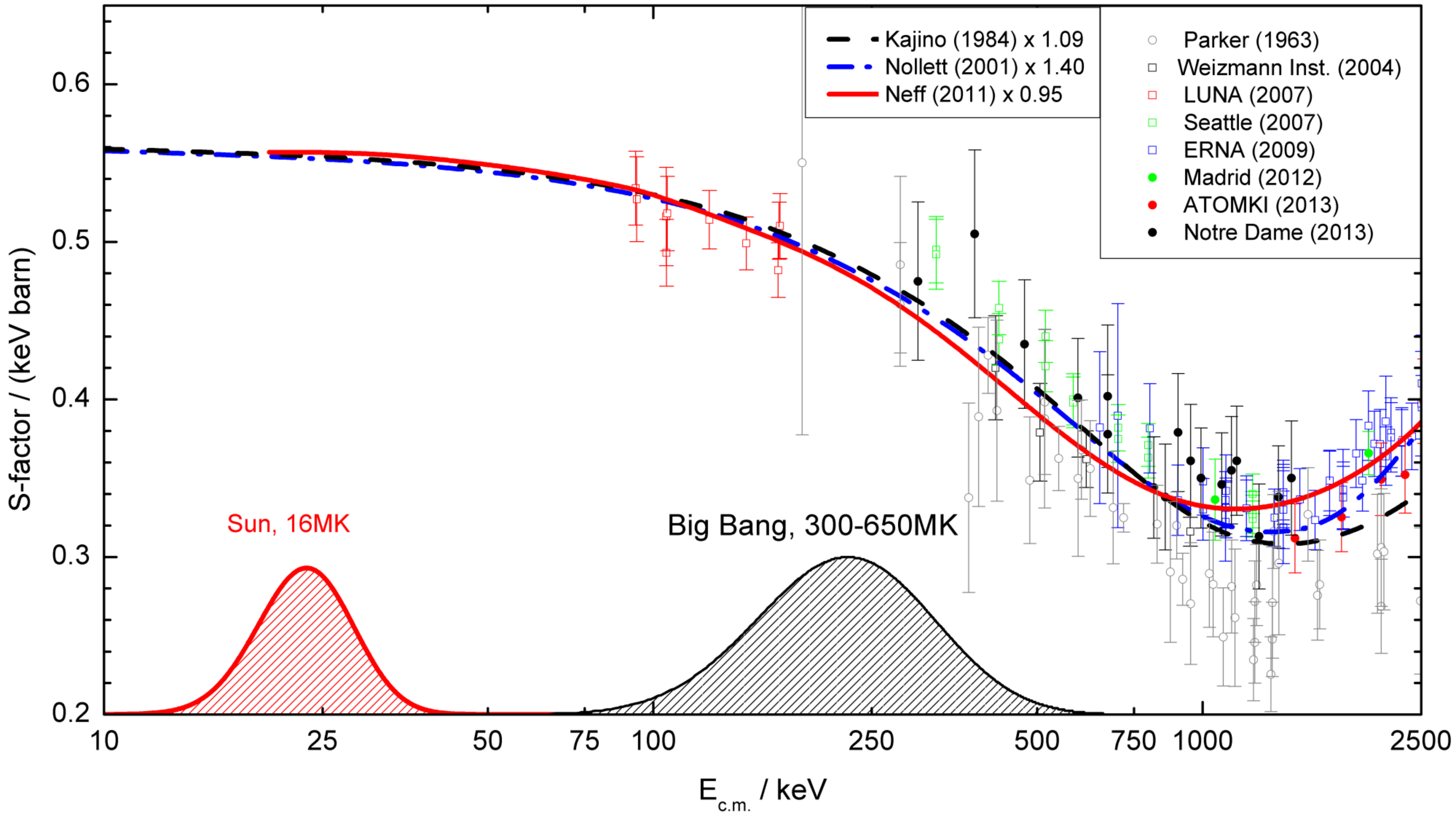
$^3He(\alpha,\gamma)^7Be$ at LUNA, systematic uncertainty



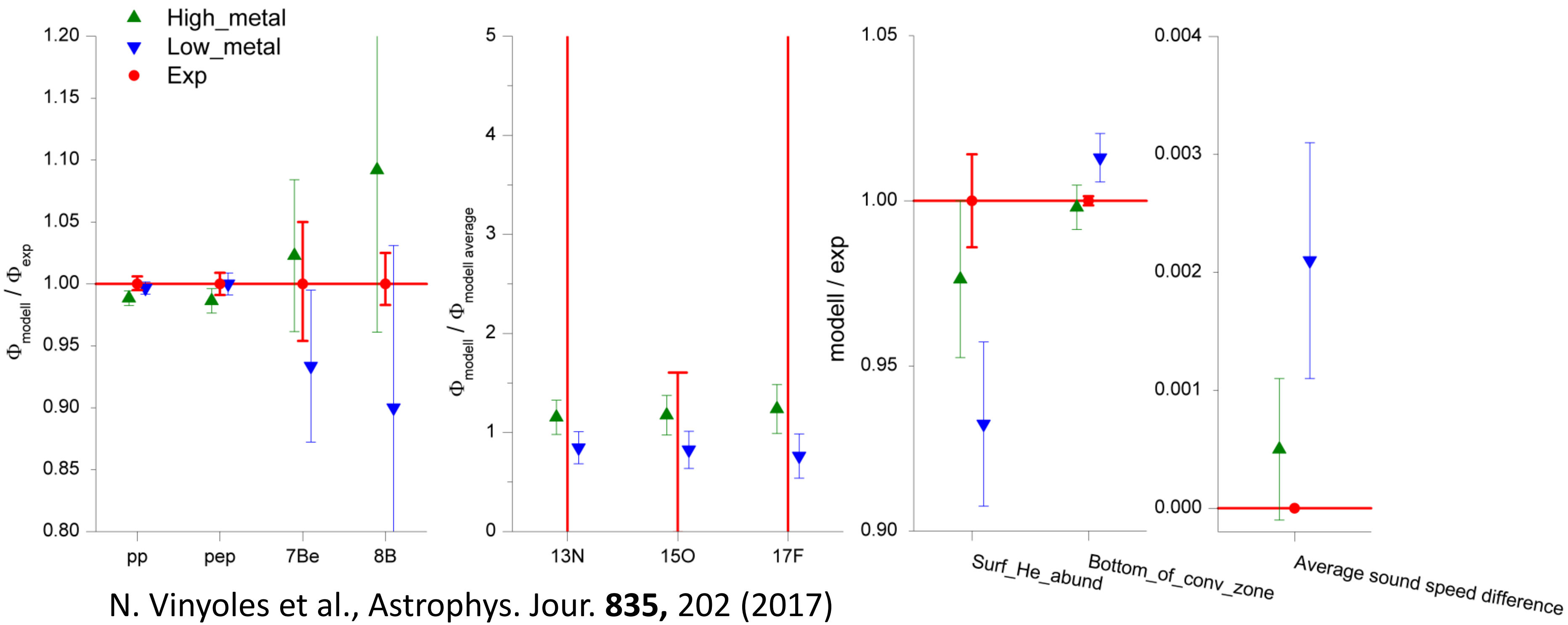


γ-efficiency	1.8%
Beam intensity	1.5%
Target density	1.5%
^{7}Be losses	0.7%
Systematic uncertainty, activation	**3.0%**
Systematic uncertainty, prompt-γ	**3.6%**

$^{3}He(\alpha,\gamma)^{7}Be$ at LUNA, S-factor results



Solar neutrino fluxes: Newer modell



N. Vinyoles et al., Astrophys. Jour. **835,** 202 (2017)

- ^{7}Be, ^{8}B: Data got even more precise
- ^{13}N, ^{15}O: No data yet, but models are not very precise
- Other derived values favours the higher metallicity
- **Still need smaller error bars for the models!**
- **→→ More precise input data**

High_metallicity =
N. Grevesse, A. J. Sauval,
Space Sci. Rev. **85**, 161 (1998)

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Uncertainties in the predicted solar neutrino fluxes?

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Uncertainty contributed to neutrino flux, in percent

Antonelli et al., 1208.1356

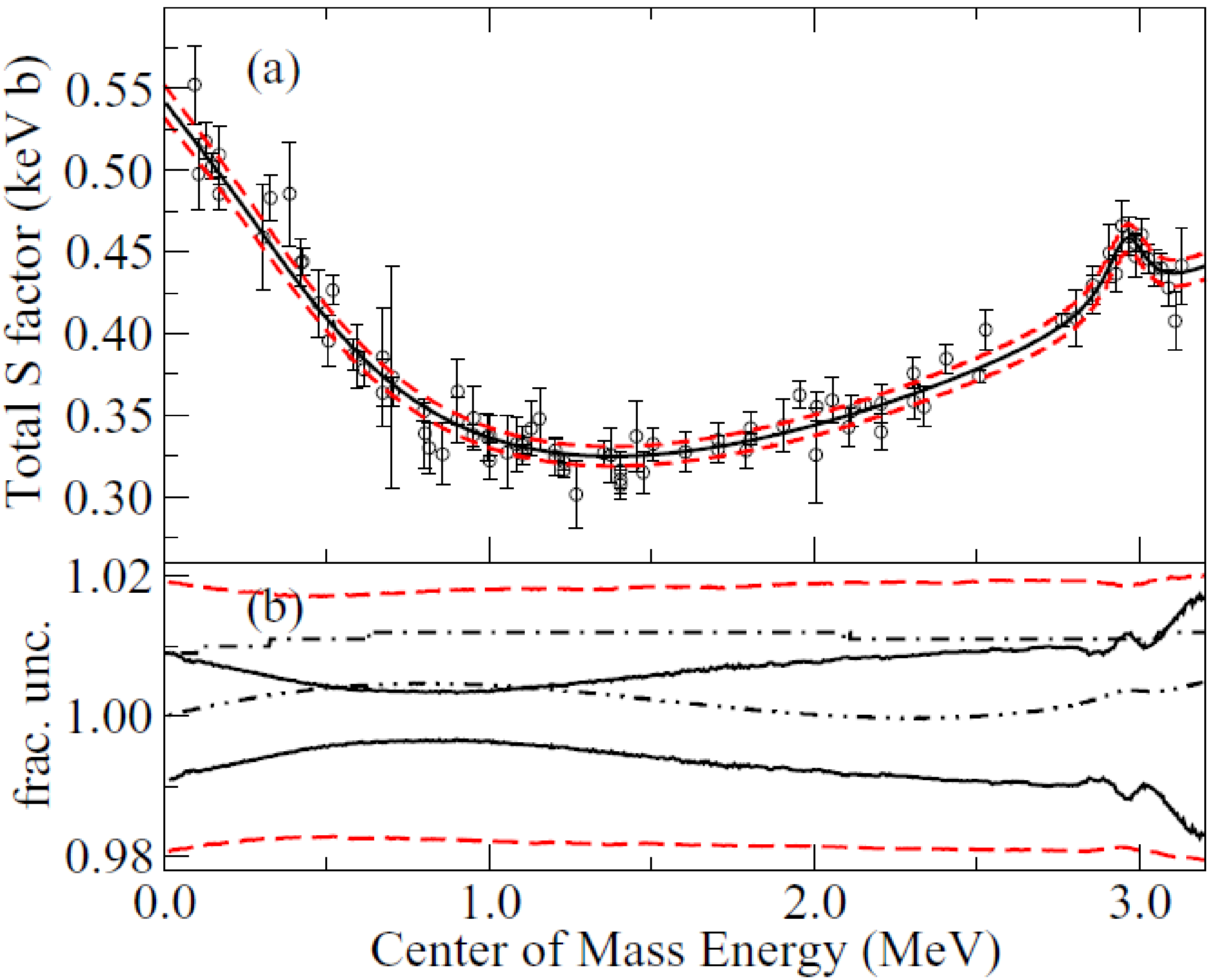
^{3}He(α,γ)^{7}Be

Quant.	Dominant Theoretical Error Sources in %							
Φ(pp)	$L_\odot$:	0.3	S_{34}:	0.3	κ:	0.2	Diff:	0.2
Φ(pep)	κ:	0.5	$L_\odot$:	0.4	S_{34}:	0.4	S_{11}:	0.2
Φ(hep)	S_{hep}:	30.2	S_{33}:	2.4	κ:	1.1	Diff:	0.5
$\Phi(^7$Be)	S_{34}:	4.1	κ:	3.8	S_{33}:	2.3	Diff:	1.9
$\Phi(^8$B)	κ:	7.3	S_{17}:	4.8	Diff:	4.0	S_{34}:	3.9
$\Phi(^{13}$N)	C:	10.0	S_{114}:	5.4	Diff:	4.8	κ:	3.9
$\Phi(^{15}$O)	C:	9.4	S_{114}:	7.9	Diff:	5.6	κ:	5.5
$\Phi(^{17}$F)	O:	12.6	S_{116}:	8.8	κ:	6.0	Diff:	6.0

Newer model

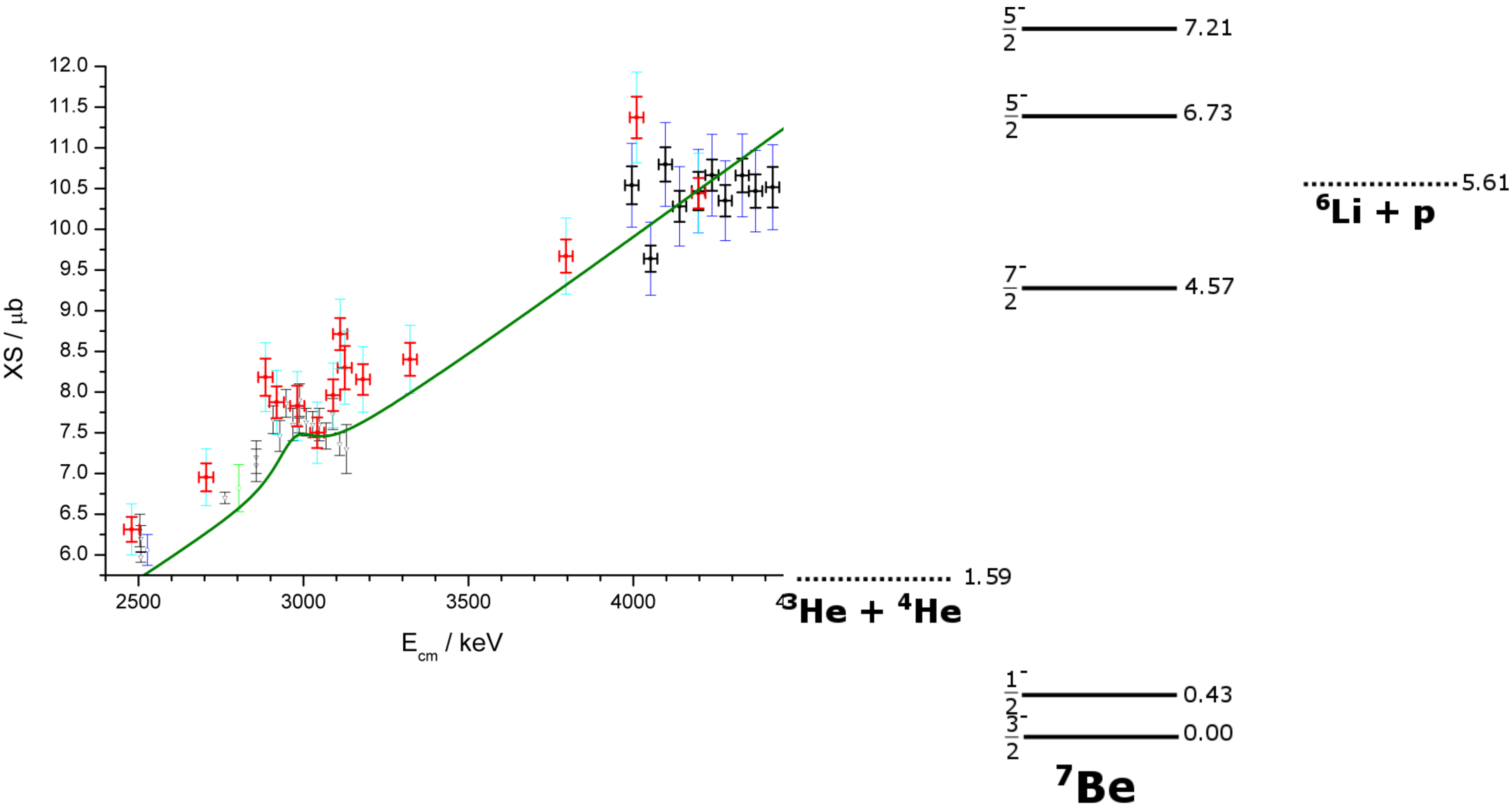
Vinyoles et al., The Astrophysical Journal, **835**, 202 (2017)

R-matrix fit: Monte Carlo approach, and rescaled experimental data



R. J. deBoer *et al*, PRC **90,** 035804 (2014)

New high energy measurement, Preliminary results



Curve from: A. Kontos *et al*, PRC **87,** 065804 (2013)

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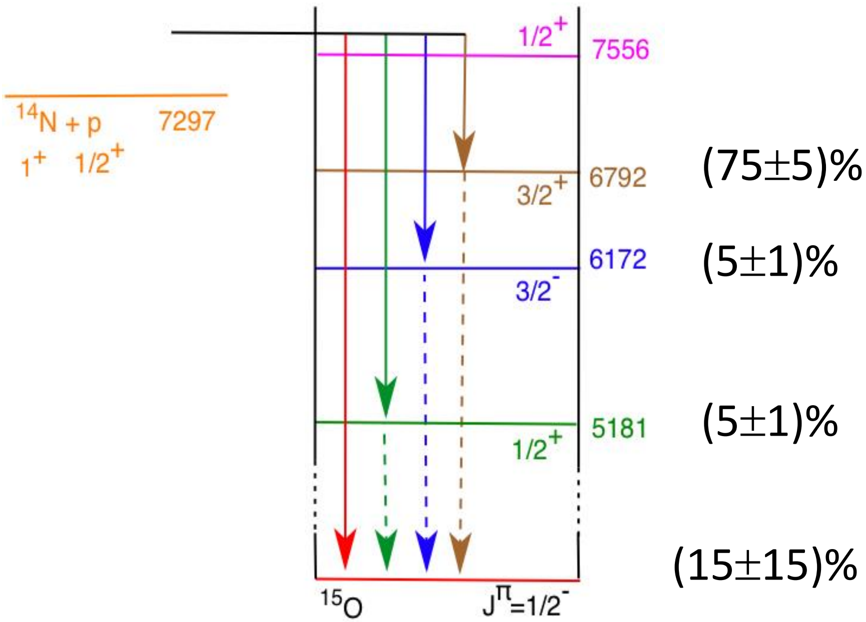
^{13}N	2.1	0.1	0.3	0.0	5.1	3.6	4.9
^{15}O	2.9	0.1	0.2	0.0	7.2	5.2	5.7
^{17}F	3.1	0.1	0.2	0.0	0.0	5.8	6.0

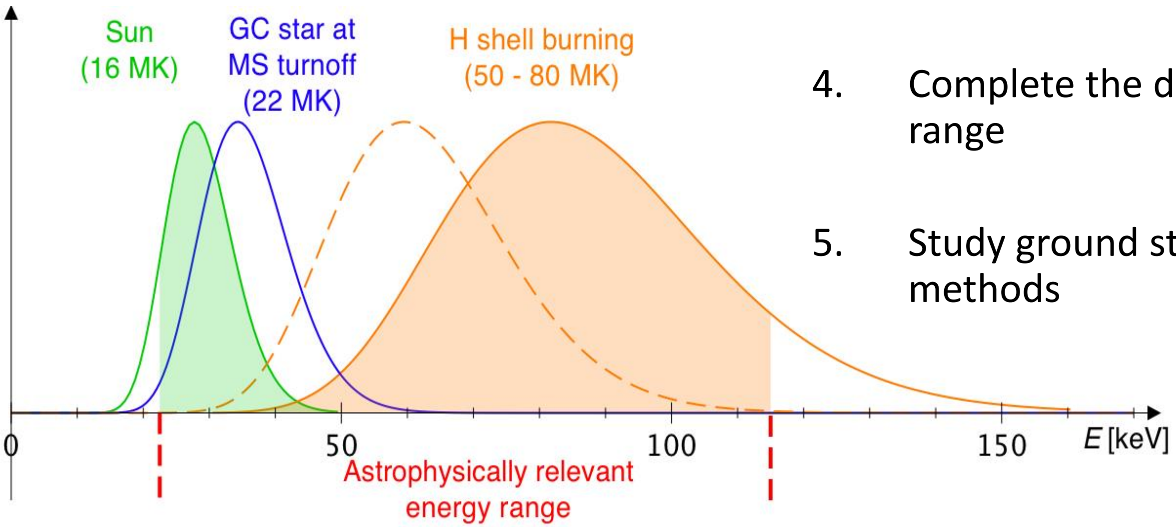
Uncertainty contributed to neutrino flux, in percent

Antonelli et al., 1208.1356

$^{14}N(p,\gamma)^{15}O$

$^{14}N(p,\gamma)^{15}O$, a bit more complex





Some possible experimental approaches:

1. Study capture to each level separately with HPGe detector (~1% efficiency), then extrapolate in the R-matrix framework
2. Study the total cross section with a summing crystal (~70% efficiency) directly at relevant energies
3. Concentrate on the most uncertain component (ground state capture) with precision data and R-matrix fit
4. Complete the data base over a wide energy range
5. Study ground state capture with indirect methods

In-beam experiments, low or high γ-ray detection efficiency?

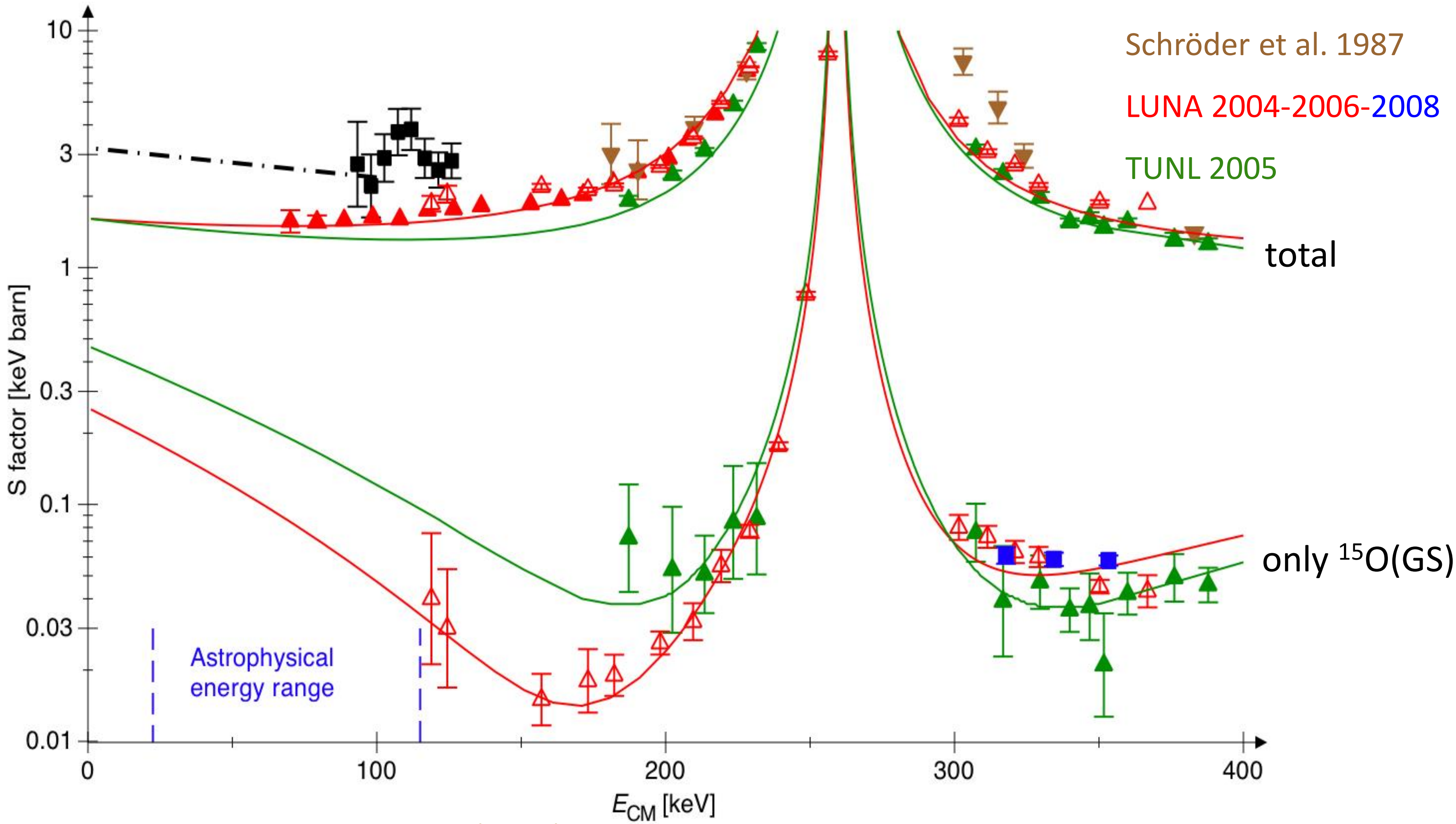
	Germanium	Scintillator
γ-ray resolution	~3 keV + target	~100 keV
γ-ray detection efficiency	~1%	~100%
Level scheme (cascade transitions)	Sensitive	Not sensitive
γ-ray angular distribution	Sensitive	Not sensitive
Beam-induced γ-ray background	Not sensitive	Sensitive

Understand reaction mechanism (direct versus resonant, cascades, interference)

Experimental cross section data at very low energy

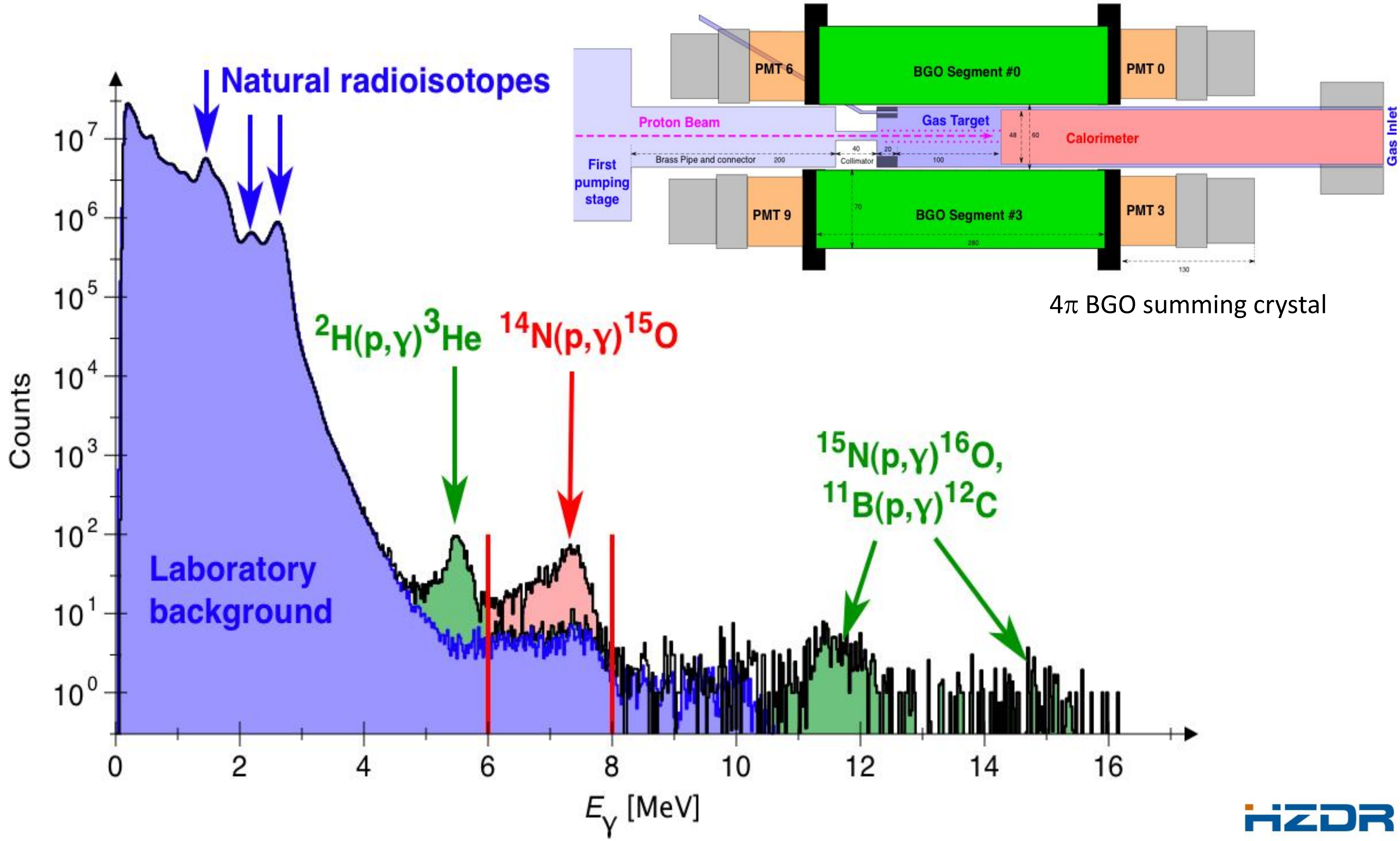
Tamás Szücs | tszucs@atomki.mta.hu | NTAA Summer School, Dubna, 10. - 21. 07. 2017

$^{14}N(p,\gamma)^{15}O$, total S-factor from three LUNA experimental campaigns



U. Schröder *et al*, NPA **467**, 240 (1987);
A. Formicola *et al*, PLB **591**, 61 (2004); D. Bemmerer *et al*, NPA **779**, 297 (2006);
A. Lemut *et al*, PLB **634**, 483 (2006); M. Marta *et al*, PRC **78**, 022802(R) (2008);
R. C. Runkle *et al*, PRL **94**, 082503 (2005)

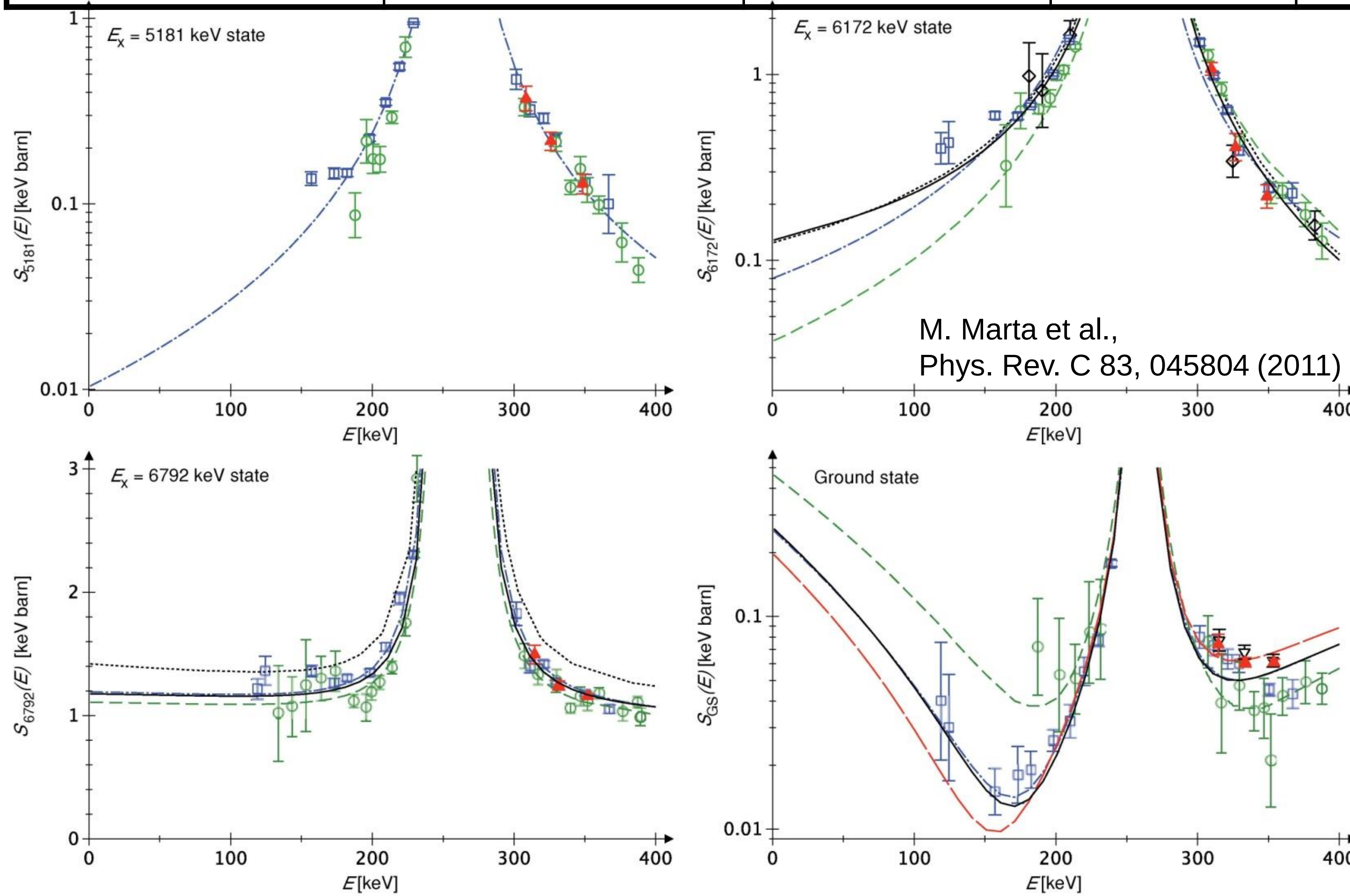
$^{14}N(p,\gamma)^{15}O$, experiment with a summing detector



4π BGO summing crystal

LUNA divided the $^{14}N(p,\gamma)^{15}O$ cross section by 2!

Capture to...	NACRE compilation 1999	LUNA, phase 1 2004	TUNL 2005	LUNA, phase 3 2008+2011
...ground state in ^{15}O	1.55 ± 0.34	0.25 ± 0.06	0.49 ± 0.08	0.27 ± 0.05
...excited states in ^{15}O	1.65 ± 0.05	1.36 ± 0.05	1.27 ± 0.05	(1.39 ± 0.05)
S(0) in keV barn	3.2 ± 0.5 (tot)	1.6 ± 0.2 (tot)	1.8 ± 0.2 (tot)	1.66 ± 0.12 (tot)

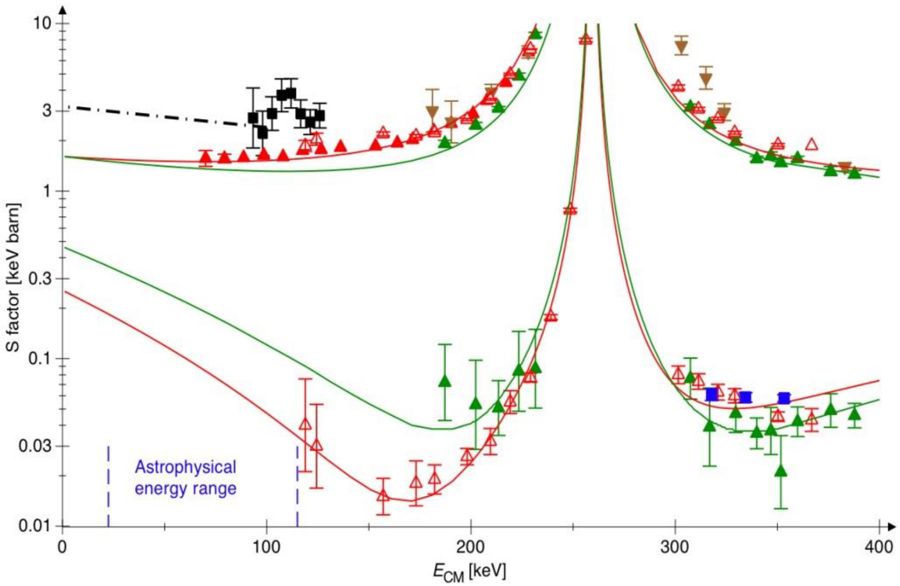


M. Marta et al.,
Phys. Rev. C 83, 045804 (2011)

Adelberger *et al.* 2011 recommended precision 7%...

...but it should be further improved!

Astrophysical implications of the LUNA $^{14}N(p,\gamma)^{15}O$ data



$^{14}N(p,\gamma)^{15}O$ cross section cut in half!

S(0) = 3.2 keV barn (1998)

$\rightarrow$ 1.66±0.12 keV barn (2011)

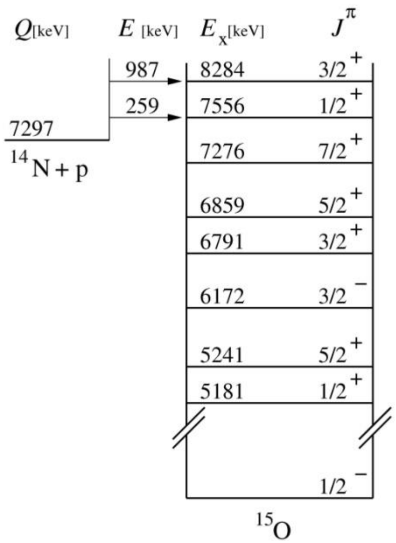
1. Independent lower limit on the age of the universe, through turnoff luminosity of main sequence stars in the oldest globular clusters: 14±2 billion years.

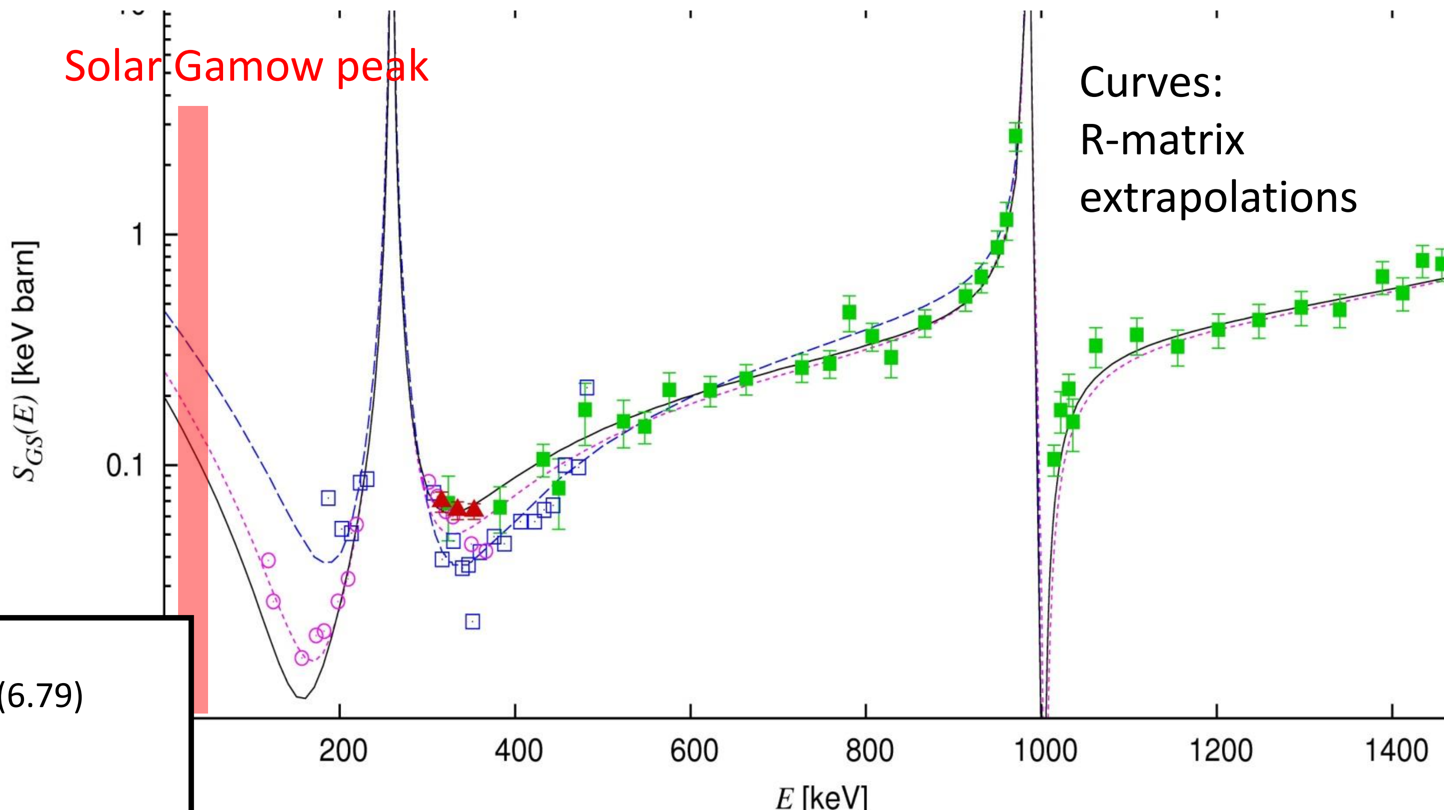
2. CNO contribution to solar burning reduced by a factor 2, now 0.8% of energy production.

3. More efficient dredge-up of carbon to the surface of asymptotic giant branch stars.

4. A chance to now measure carbon+nitrogen content of solar core with neutrinos.

Study of $^{14}N(p,\gamma)^{15}O$ over a wide energy range





Curves:
R-matrix
extrapolations

Important levels in ^{15}O

- E = -0.504 MeV, $^{15}O^*(6.79)$
- E = 0.259 MeV
- E = 0.987 MeV
- E = 2.187 MeV
- "background pole"

Münster 1987

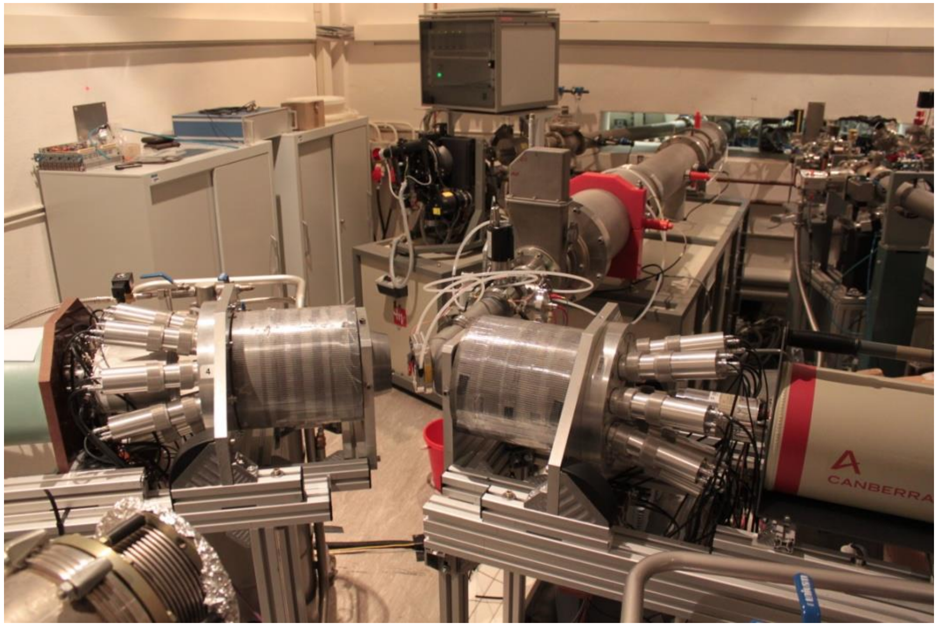
LUNA 2004

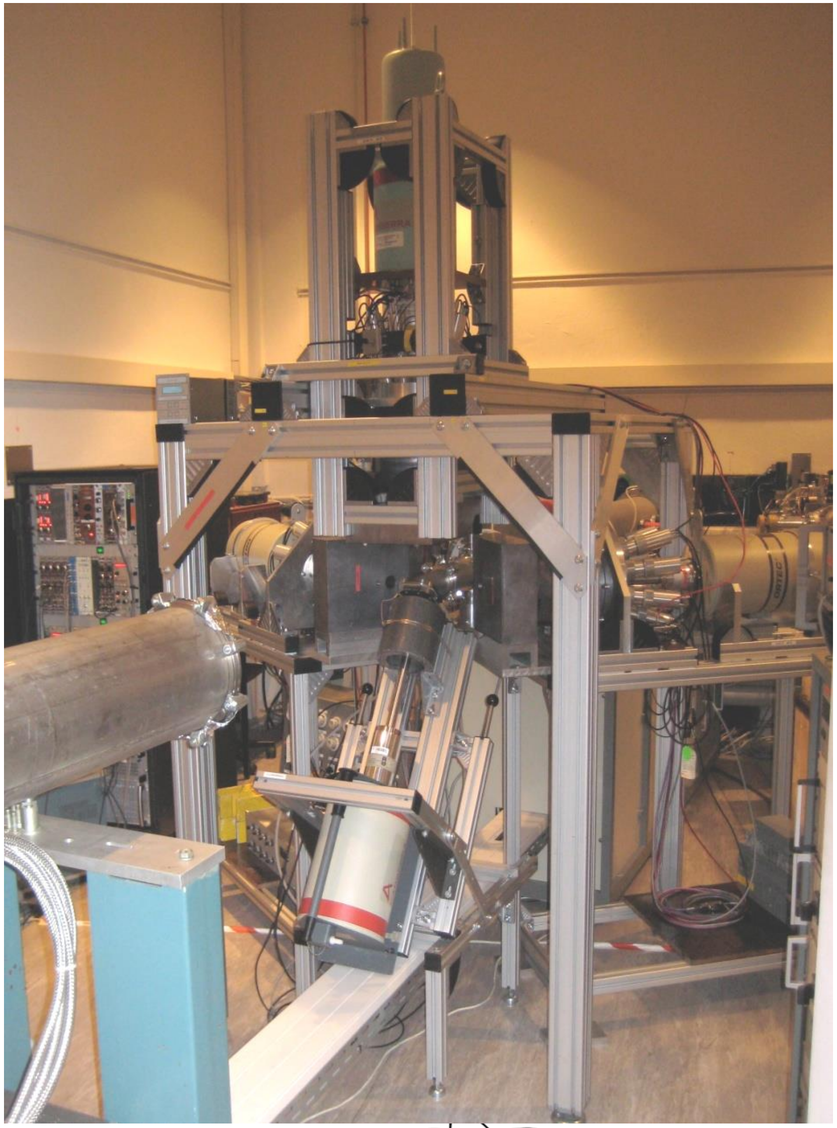
TUNL 2005

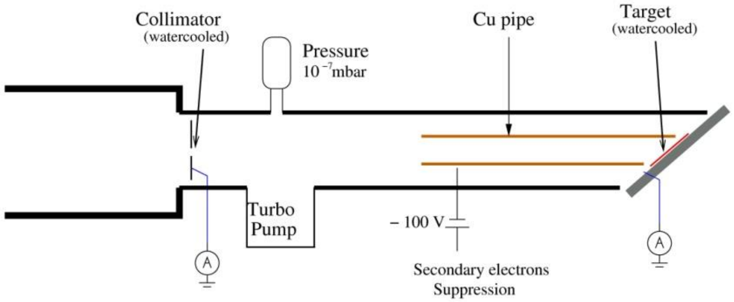
HZDR 2008-

Tamás Szücs | tszucs@atomki.mta.hu | NTAA Summer School, Dubna, 10. - 21. 07. 2017

Experimental setups at the HZDR Tandetron, Dresden

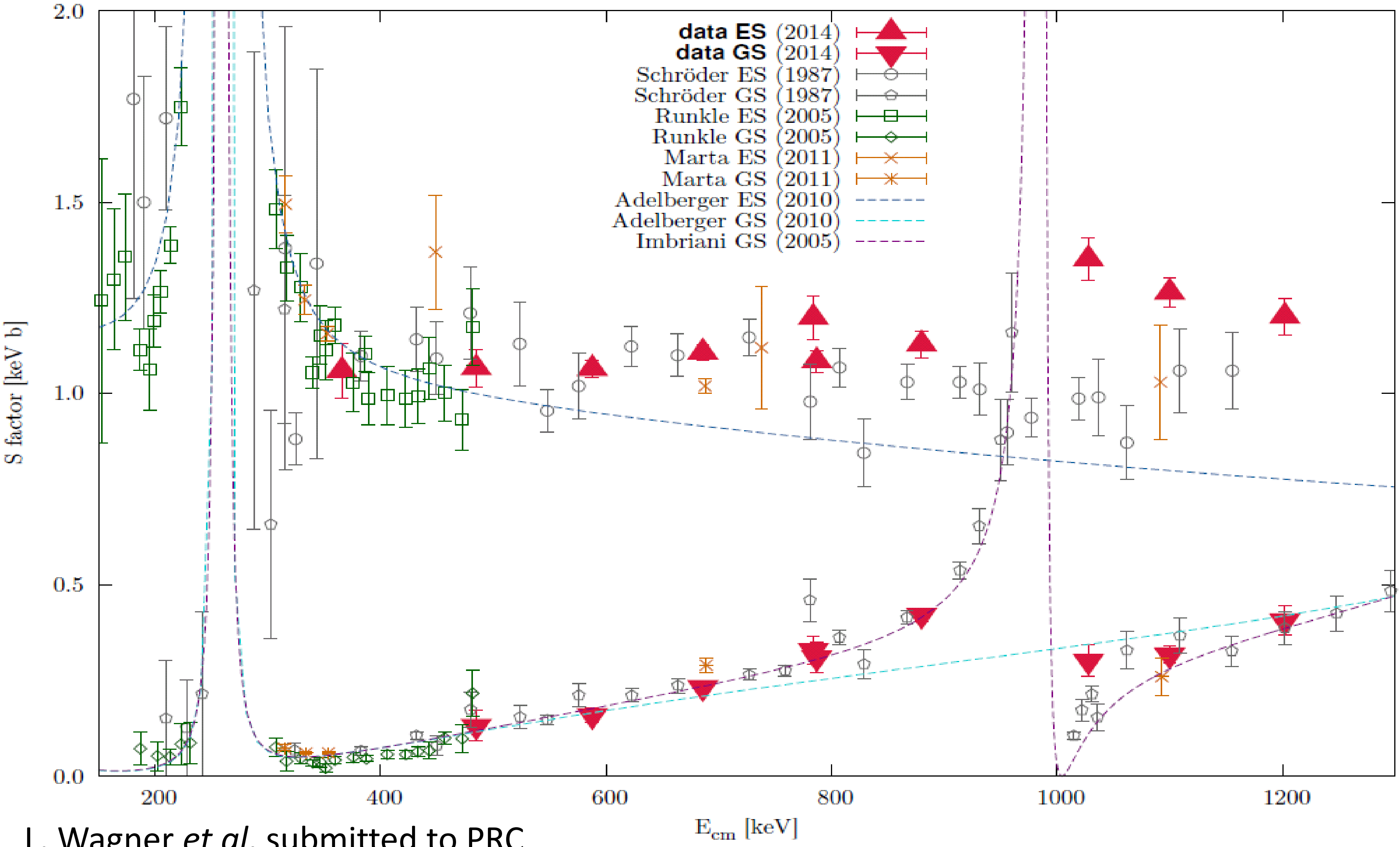






High-energy data on the $^{14}N(p,\gamma)^{15}O$ reaction

- Preliminary data from the Dresden 3 MV Tandetron
- Also high-energy data influence the R-matrix extrapolation to low energy



L. Wagner *et al*, submitted to PRC

High-energy data on the $^{14}N(p,\gamma)^{15}O$ reaction

Q. Li *et al*, PRC **93**, 055806 (2016)

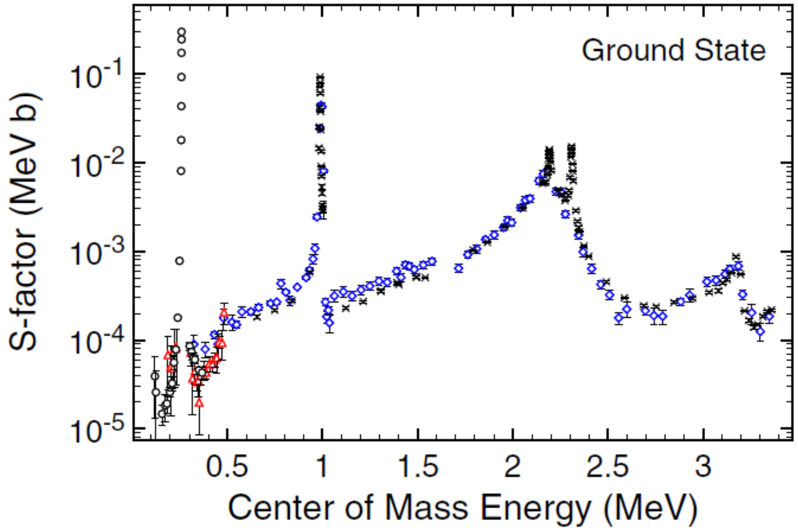


FIG. 6. S factor of the ground-state transition. The data shown are from Ref. [9] (diamonds), Ref. [12] (triangles), Ref. [11] (circles), and the present measurement (crosses). Note that the statistical uncertainties on several of the present measurements are smaller than the symbols.

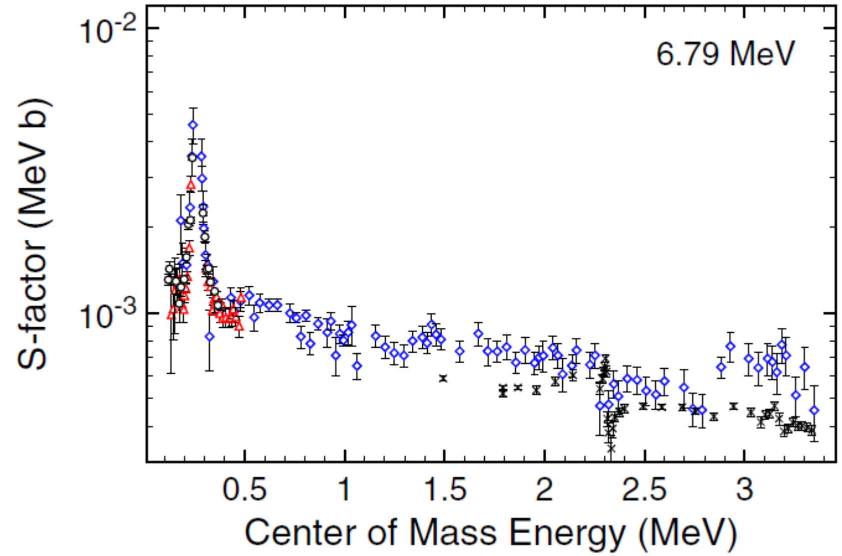
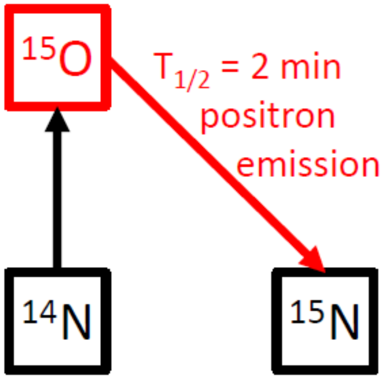


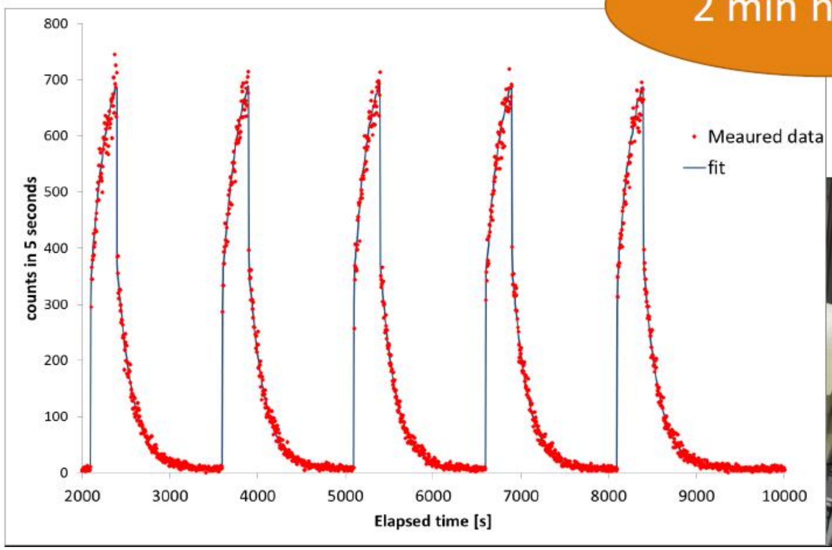
FIG. 5. S factor of the $E_x = 6.79$ MeV primary transition. The data shown are from Ref. [9] (diamonds), Ref. [12] (triangles), Ref. [11] (circles), and the present measurement (crosses). Note that the statistical uncertainties on several of the present measurements are smaller than the symbols.

Activation measurement of the $^{14}N(p,\gamma)^{15}O$ reaction cross section at ATOMKI

- High-energy total cross section data will be provided
- Completely independent method
- Several difficulties experienced by in beam is not present here



2 min half-life!



Courtesy Gy. Gyürky

Uncertainties in the predicted solar neutrino fluxes?

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^{13}N	2.1	0.1	0.3	0.0	5.1	3.6	4.9
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Uncertainty contributed to neutrino flux, in percent

Antonelli et al., 1208.1356

$^{14}N(p,\gamma)^{15}O$

Quant.	Dominant Theoretical Error Sources in %							
$\Phi(pp)$	$L_\odot$:	0.3	S_{34}:	0.3	κ:	0.2	Diff:	0.2
$\Phi(pep)$	κ:	0.5	$L_\odot$:	0.4	S_{34}:	0.4	S_{11}:	0.2
$\Phi(hep)$	S_{hep}:	30.2	S_{33}:	2.4	κ:	1.1	Diff:	0.5
$\Phi(^7Be)$	S_{34}:	4.1	κ:	3.8	S_{33}:	2.3	Diff:	1.9
$\Phi(^8B)$	κ:	7.3	S_{17}:	4.8	Diff:	4.0	S_{34}:	3.9
$\Phi(^{13}N)$	C:	10.0	S_{114}:	5.4	Diff:	4.8	κ:	3.9
$\Phi(^{15}O)$	C:	9.4	S_{114}:	7.9	Diff:	5.6	κ:	5.5
$\Phi(^{17}F)$	O:	12.6	S_{116}:	8.8	κ:	6.0	Diff:	6.0

Newer model

Vinyoles et al.,
The Astrophysical Journal,
835, 202 (2017)

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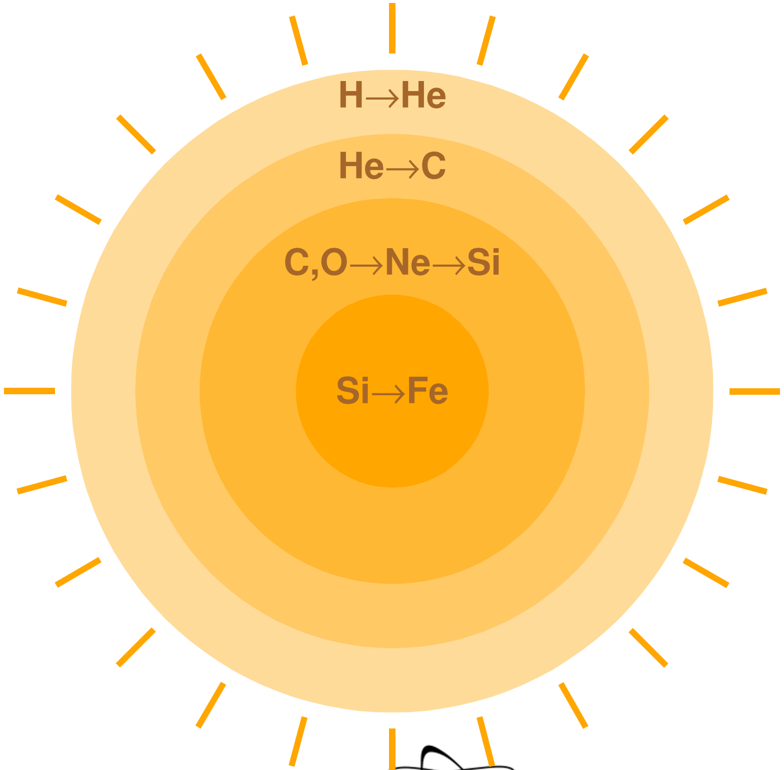
Stellar helium burning and the Holy Grail $^{12}C(\alpha,\gamma)^{16}O$

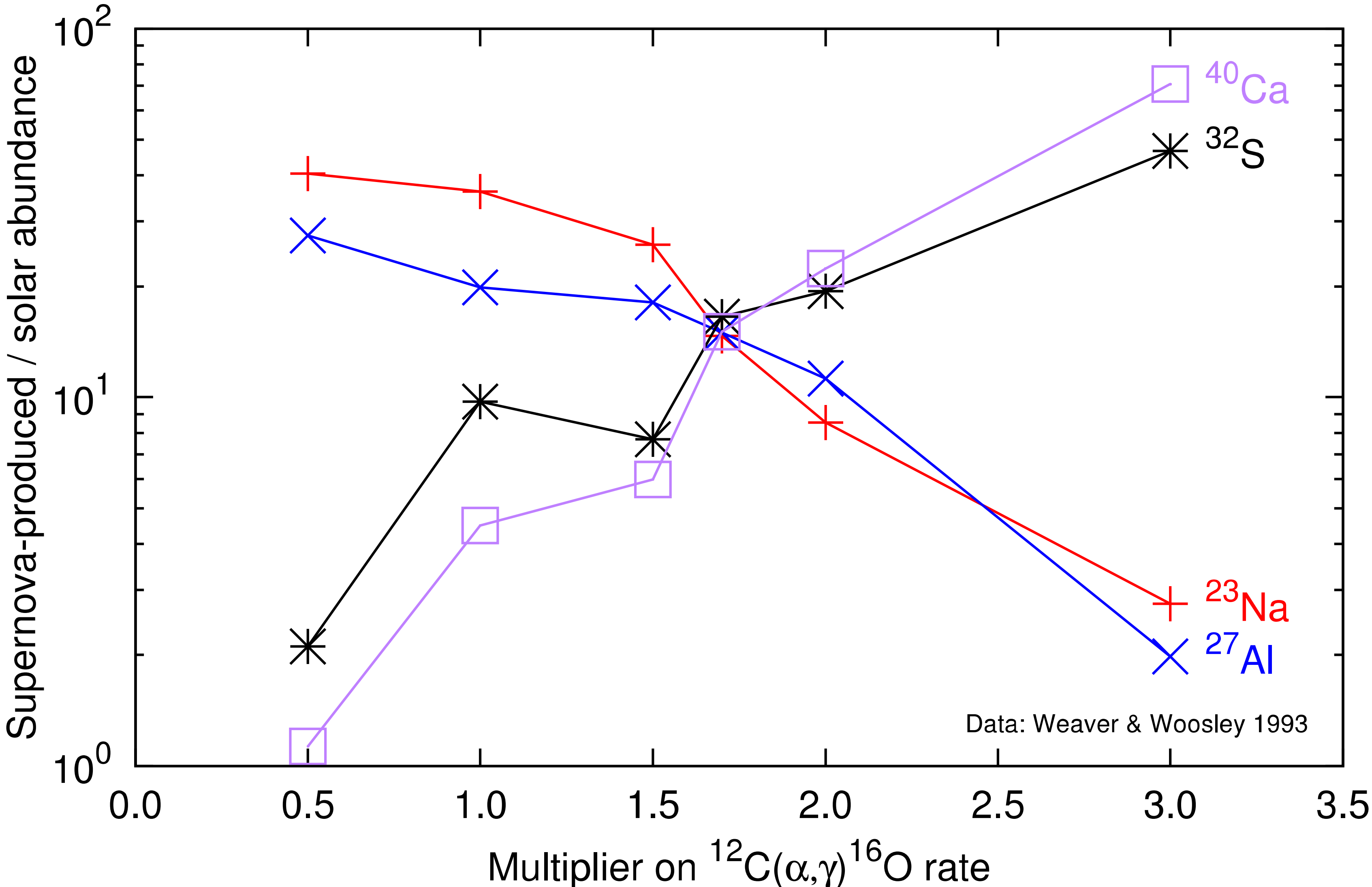
Produce ^{12}C: $$^4\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^8\mathrm{Be} + {}^4\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

Destroy ^{12}C and produce ^{16}O: $$^{12}\mathrm{C} + {}^4\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$$

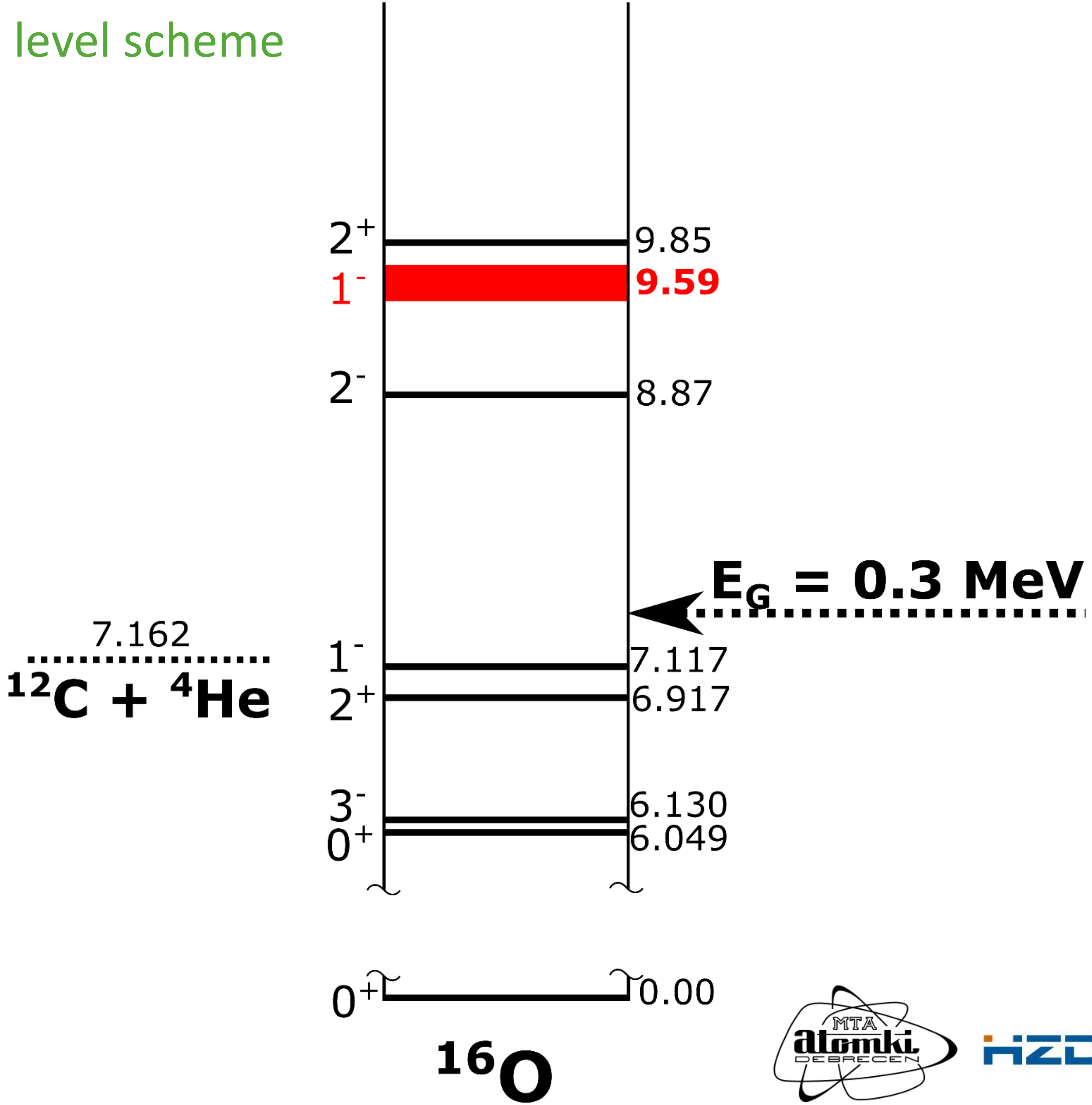
- ^{12}C production and destruction controls the ^{12}C / ^{16}O ratio.
- The $^{12}C(\alpha,\gamma)^{16}O$ reaction was called the "holy grail of nuclear astrophysics" by 1983 Physics Nobel Laureate William A. Fowler.



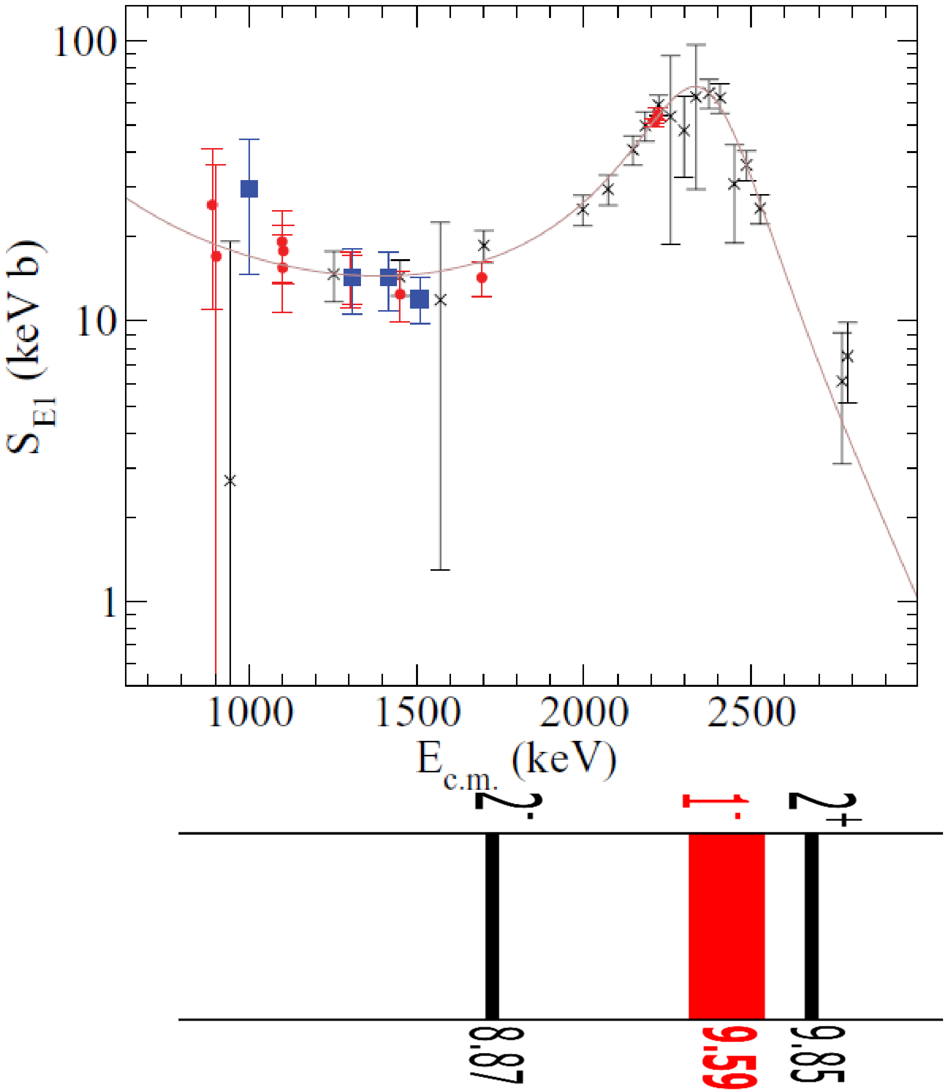
The $^{12}C(\alpha,\gamma)^{16}O$ rate affects the production of many elements!

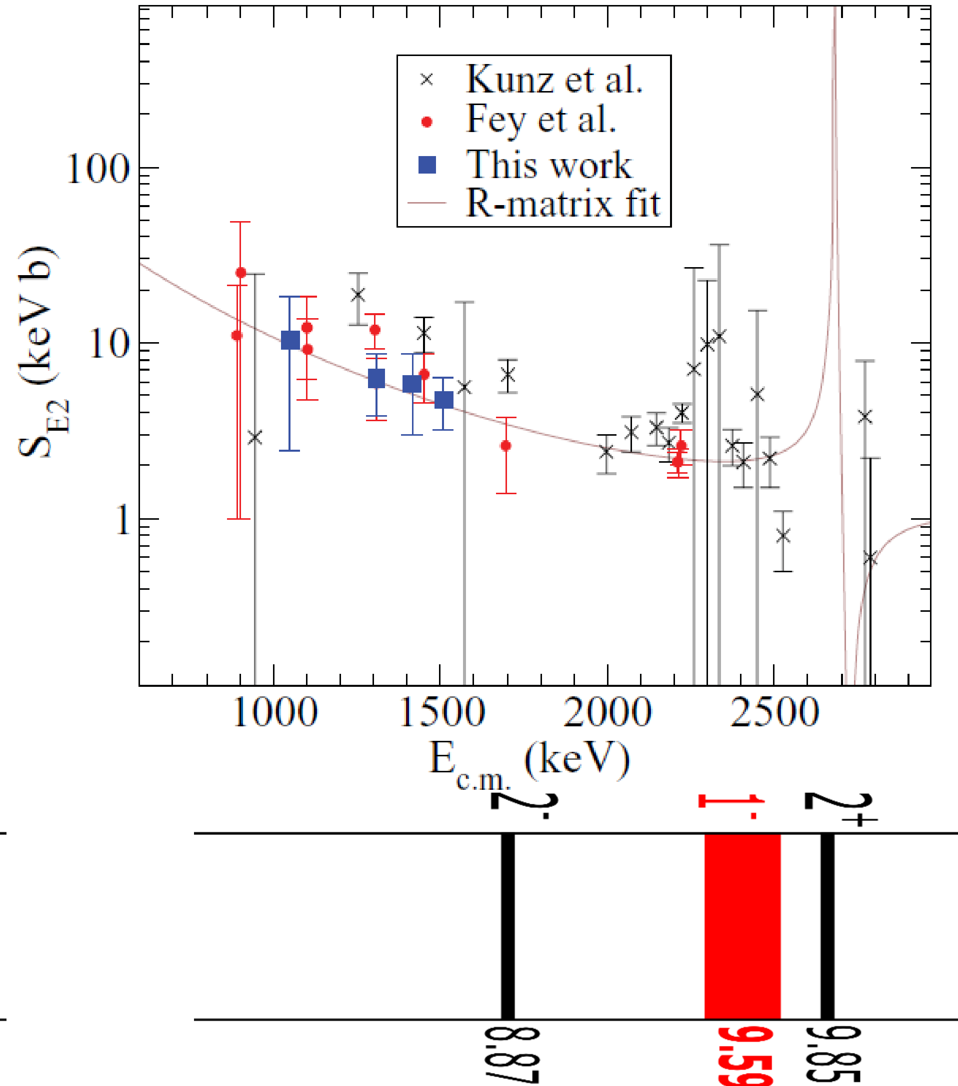


The $^{12}C(\alpha,\gamma)^{16}O$ level scheme



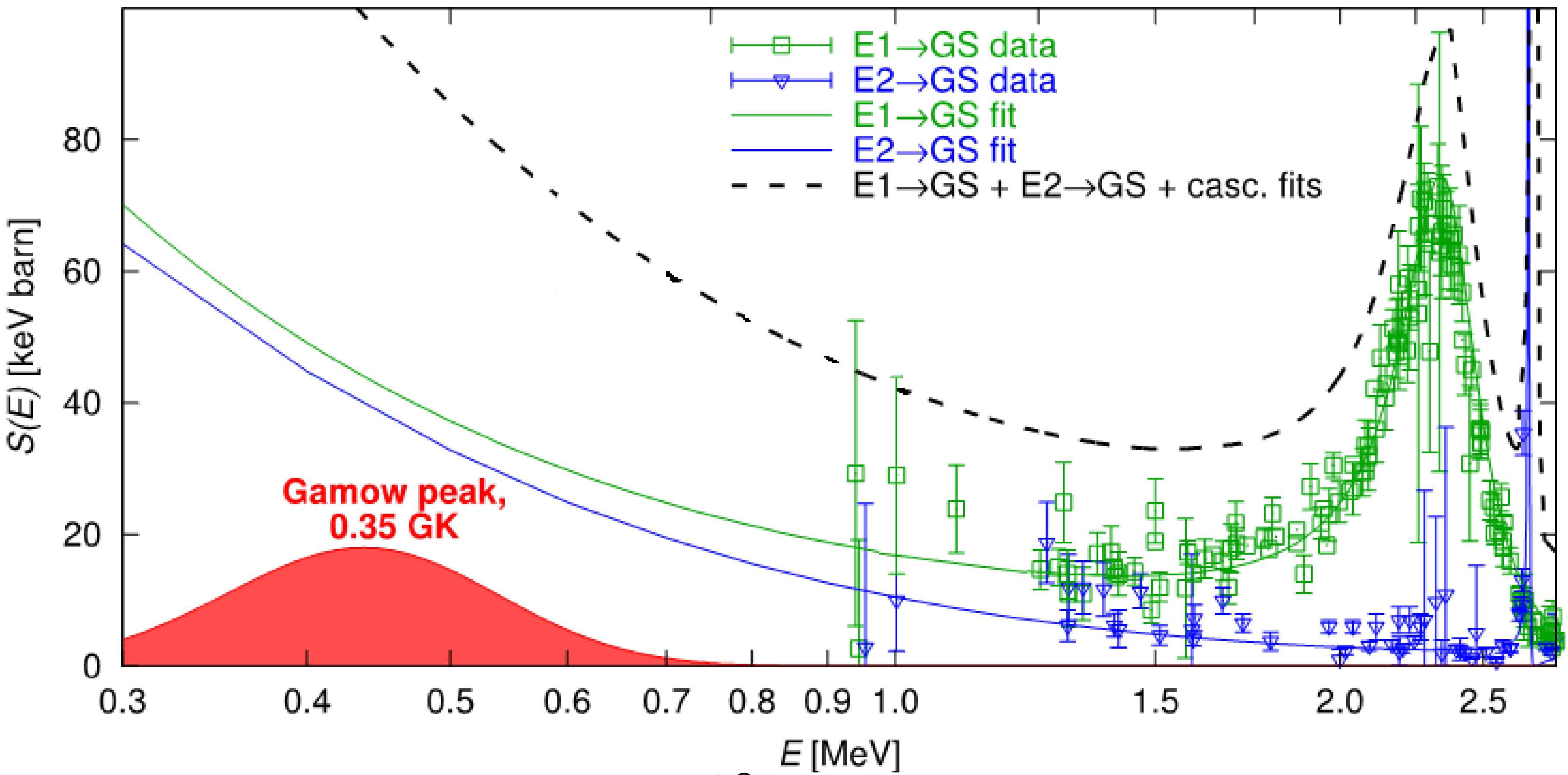
The $^{12}C(\alpha,\gamma)^{16}O$ experimental situation





R. Plag *et al*, PRC **86,** 015805 (2012)

State of the art on $^{12}C(\alpha,\gamma)^{16}O$, major components



$S_{E1} = 84 \pm 21$

X. D. Tang *et al*, PRC **81,** 045809 (2010)

$S_{E2} = 62\,^{+9}_{-6}$

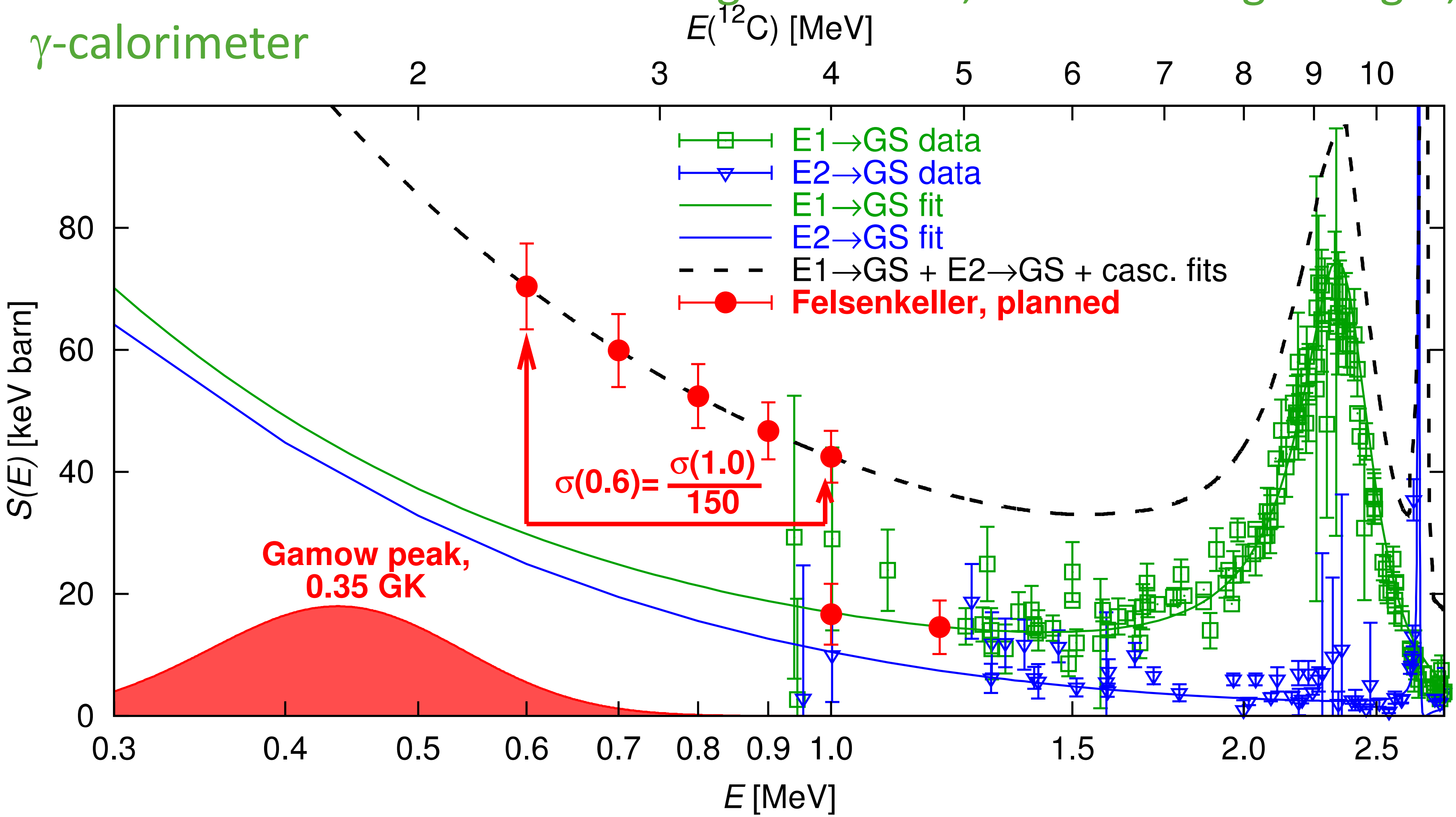
D. B. Sayre *et al*, PRL **109,** 142501 (2012)

$S_{casc} = 11 \pm 3$

M. L. Avila *et al*, PRL **114,** 071101 (2015)

S_{tot} have 15% uncertainty

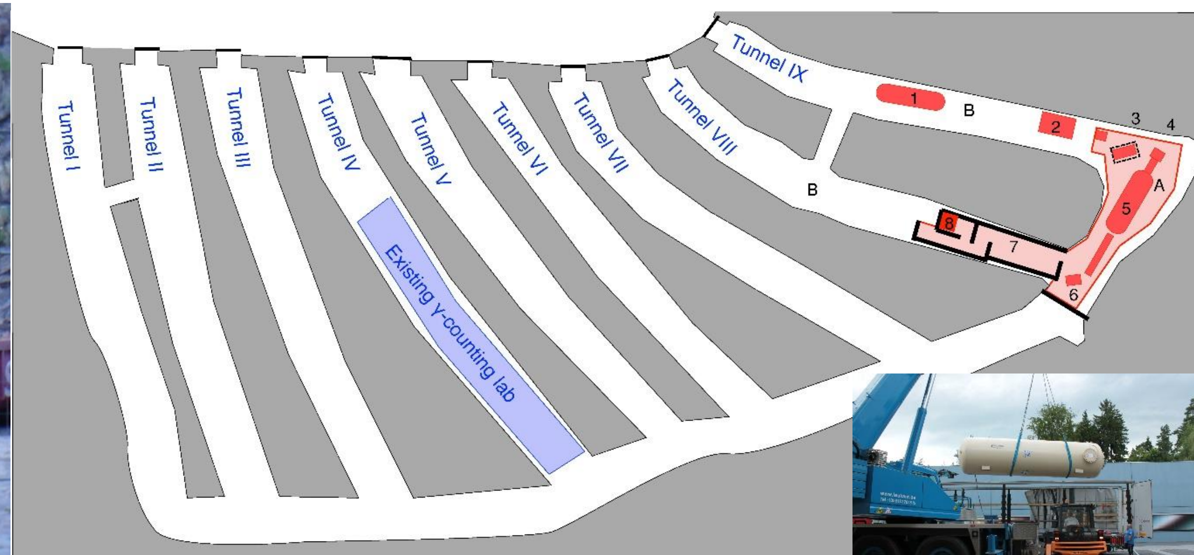
Potential for Felsenkeller… …using $^{12}C^{+}$ beam, windowless gas target, γ-calorimeter



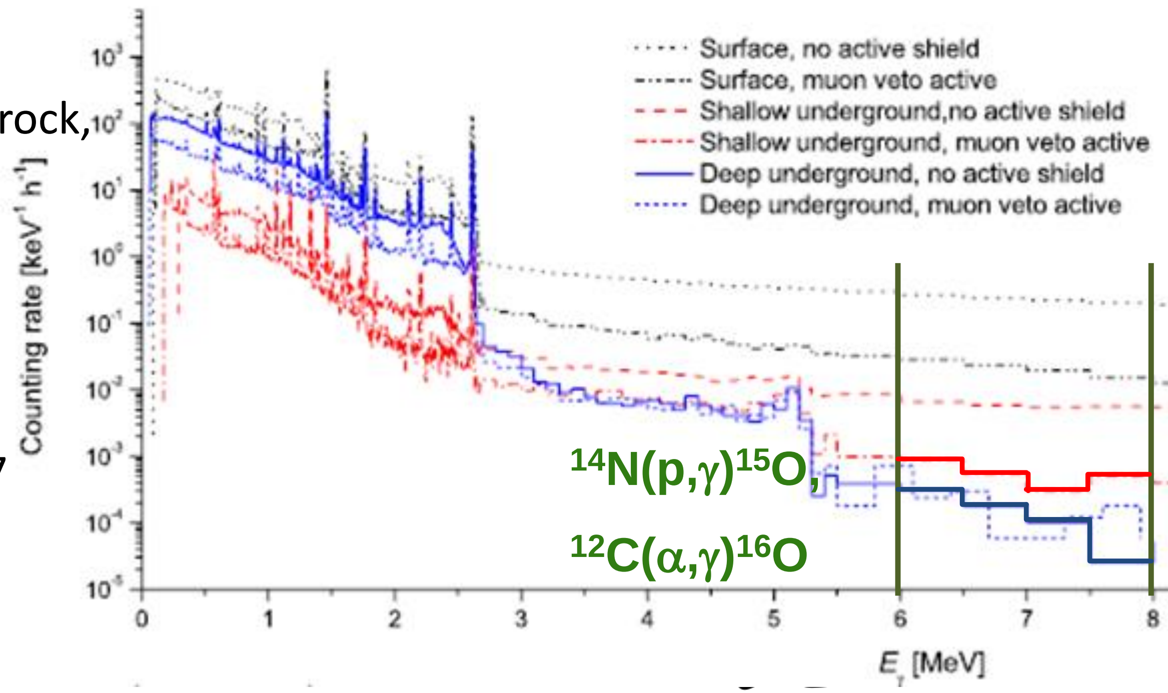
The Felsenkeller facility for nuclear astrophysics

- pp-chain: The $^{3}He(\alpha,\gamma)^{7}Be$ reaction
- CNO cycle: The $^{14}N(p,\gamma)^{15}O$ reaction
- Holy Grail of Nuclear Astrophysics: The $^{12}C(\alpha,\gamma)^{16}O$ reaction
- Capabilities of the new Felsenkeller facility

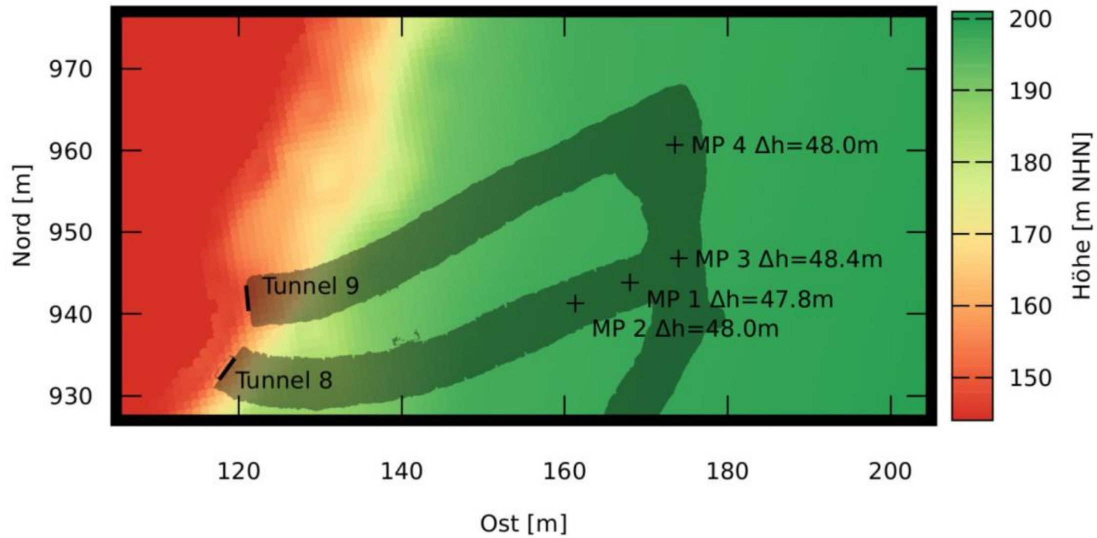
New underground ion beam at Felsenkeller, Dresden

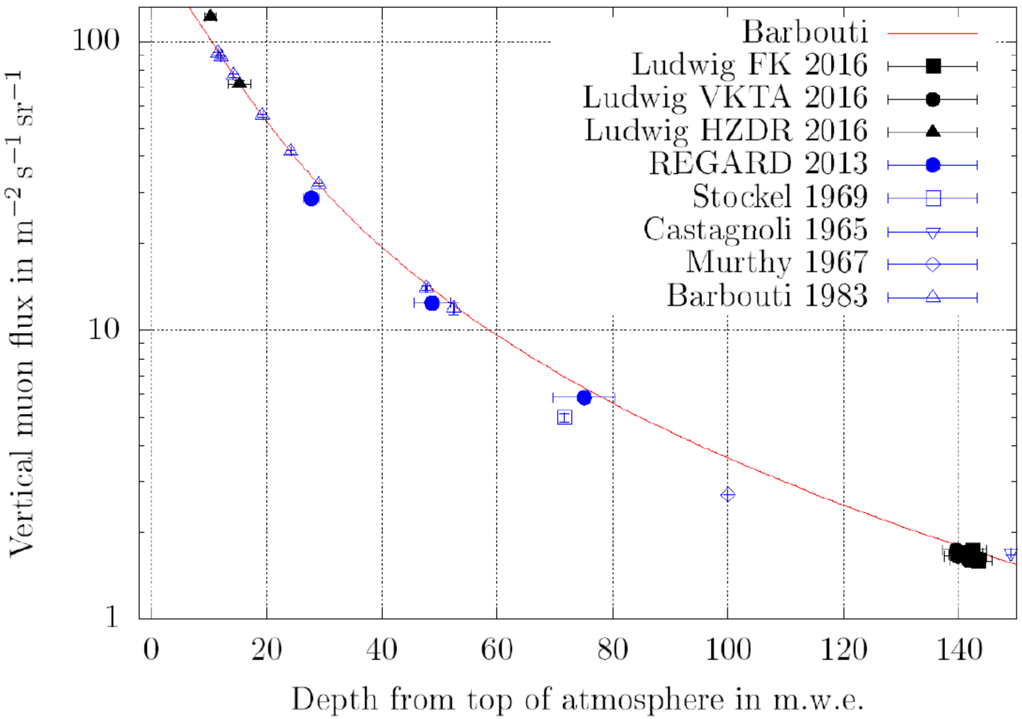


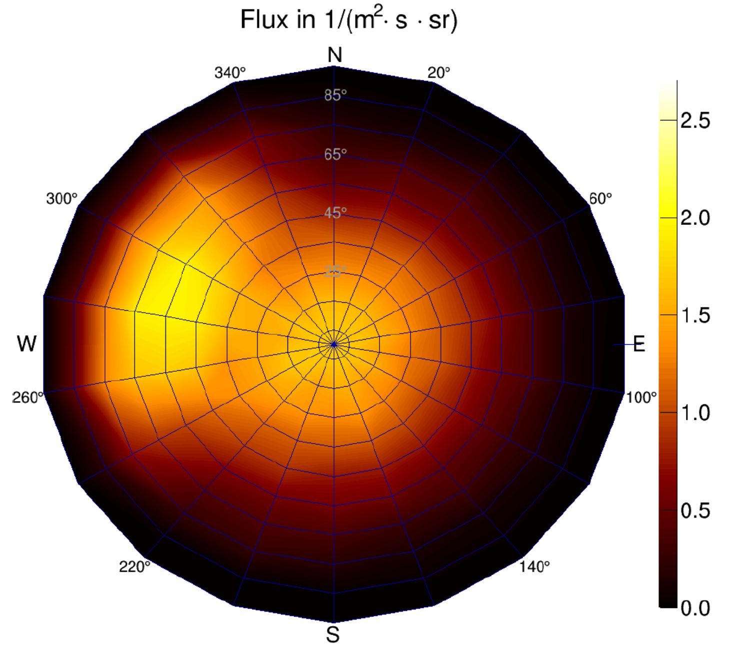
- Cosmic rays attenuated by 45 m rock, additional muon veto then gives ultra-low background
- 5 MV Pelletron ion accelerator
- Installation ongoing, will complete in September 2017



Muon flux measurements (Felix Ludwig, MSc work)

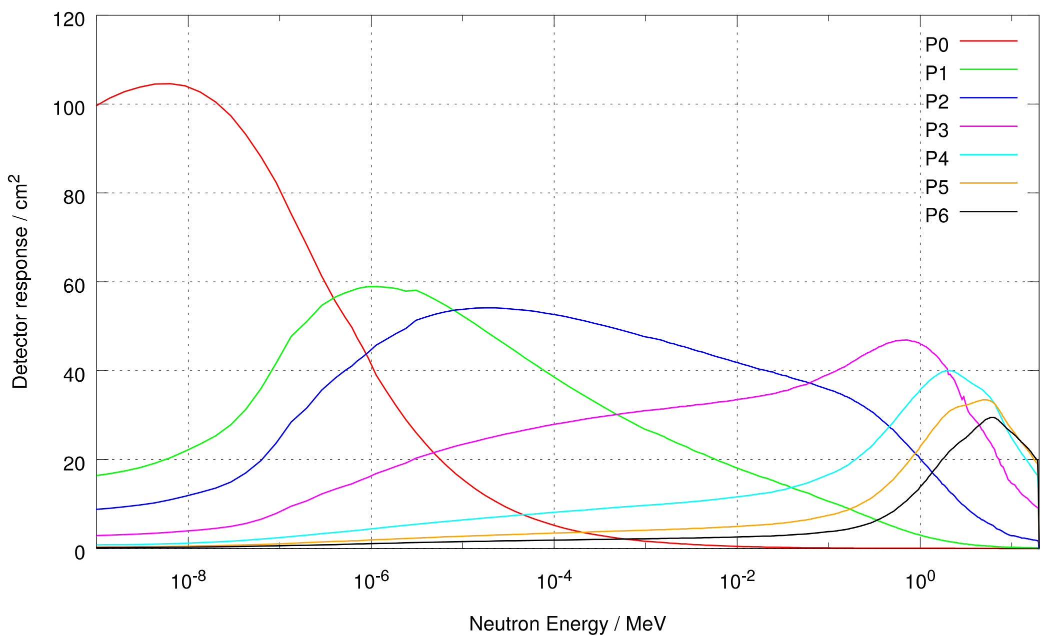


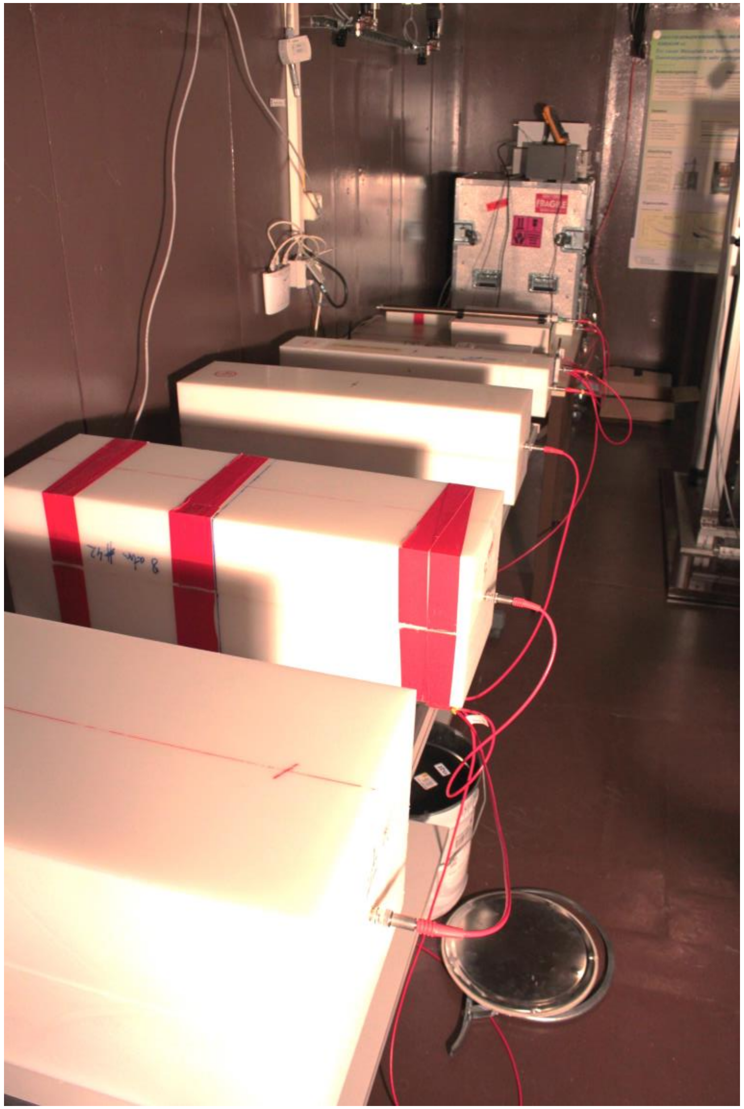




Neutron flux (Marcel Grieger, MSc work)

- ^{3}He counters inside polyethylene moderator blocks of various sizes
- Same setup previously used at Canfranc underground lab, Spain D. Jordan et al., Astropart. Phys. 42, 1 (2013)

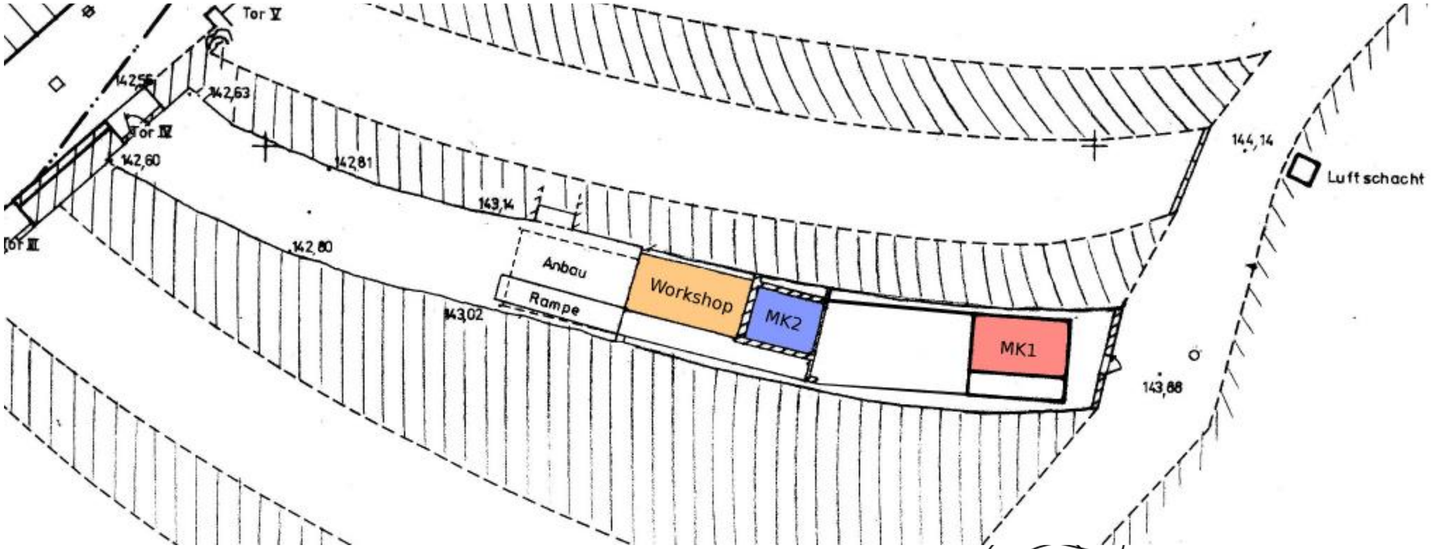




Neutron flux (Marcel Grieger, MSc work)

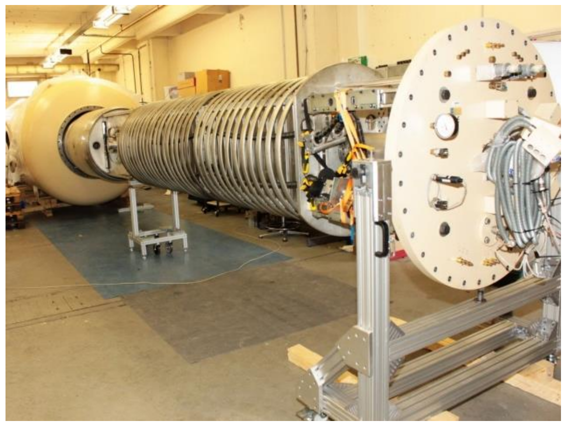
- Three different campaigns show consistent results
- Very different fluxes at three nearby sites (all in tunnel IV) with similar muon flux

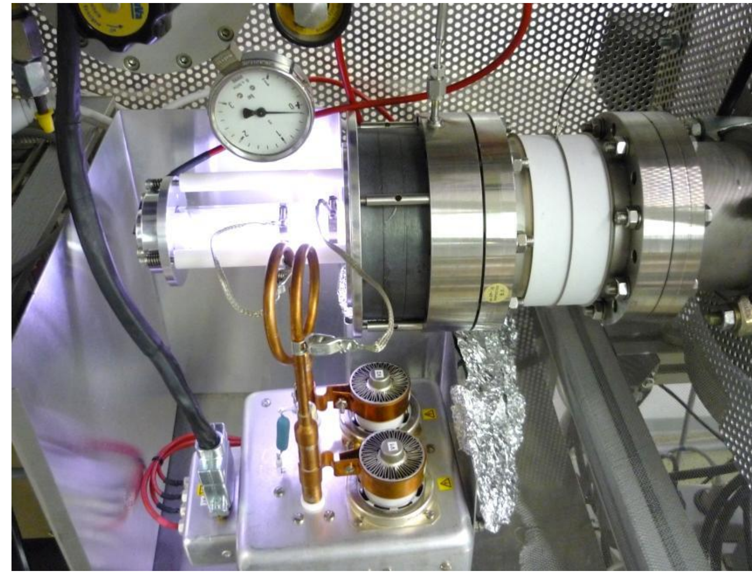
Site	Integrated flux [10^{-4} cm^{-2} s^{-1}]
Workshop	2.1
MK2 (Pb+Fe)	4.6
MK1 (rock)	0.7



5 MV Pelletron from York/UK

- High voltage tank opened
- Pellet chains dismounted and cleaned
- High voltage terminal dismounted
- Control software under re-development





Radio frequency ion source, to be installed on high voltage terminal

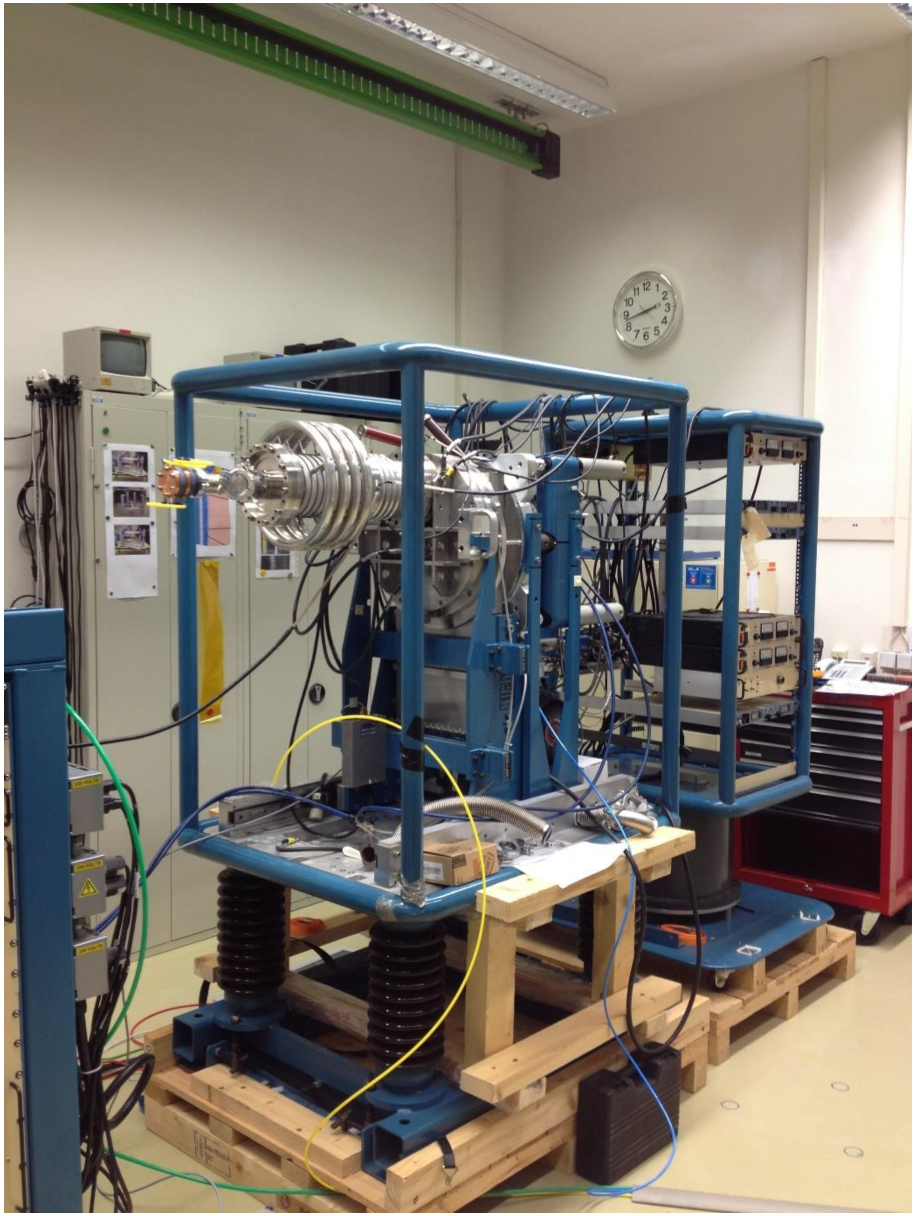
- Commercial NEC RF ion source
- Working plasma discharge
- Tests show successful extraction of 80 µA alpha current
- Electrostatic deflector for coupling RF ion source to beam line

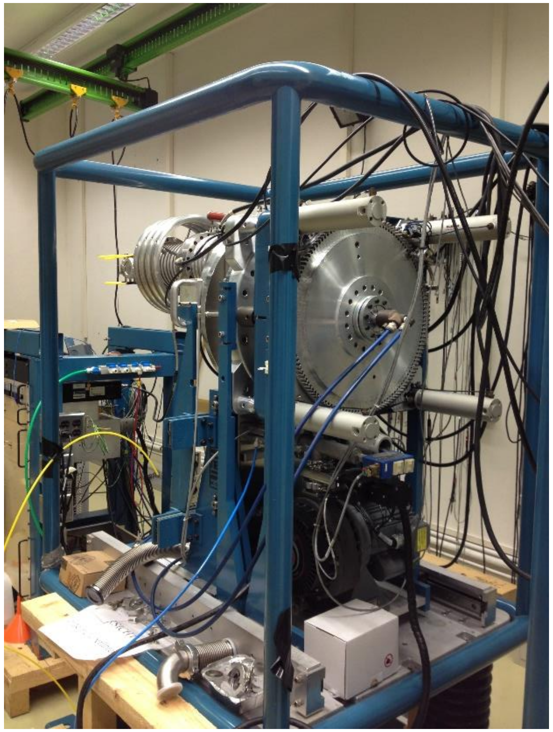
MC-SNICS 134 sputter ion source

- 100 µA C^- beam
- 100 µA H^- beam
- No useful He^- beam
- Has worked well for 12 years

MTA atomki DEBRECEN HZDR

External ion source

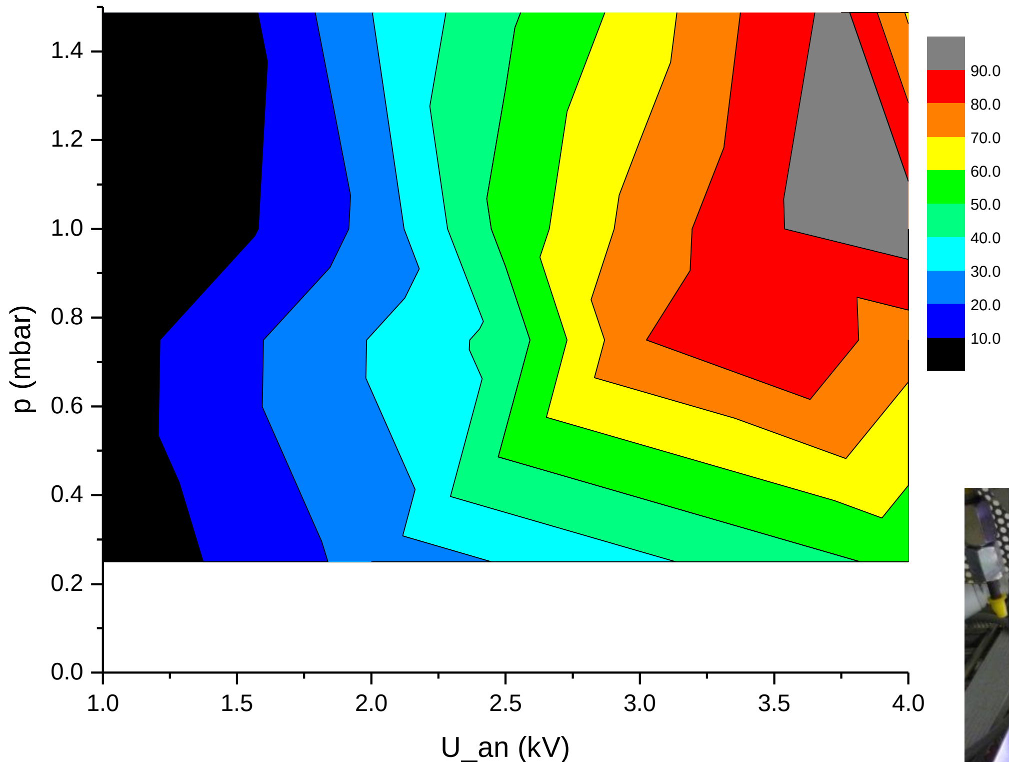




Cesium sputter ion source

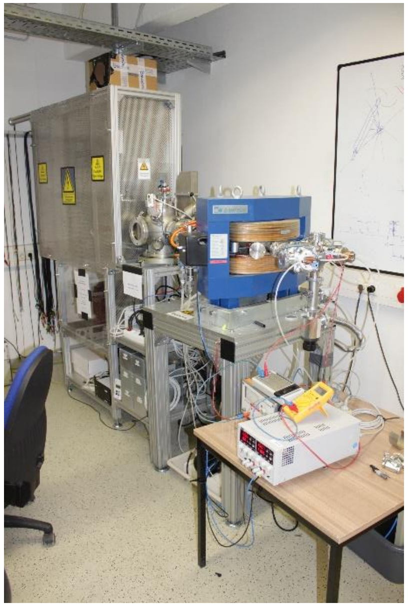
Intensive $^{12}C^{-}$ beam

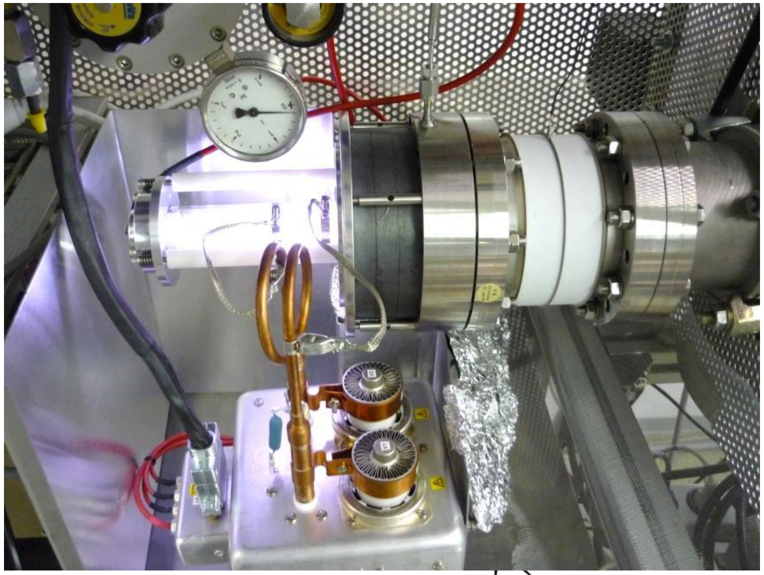
Internal ion source



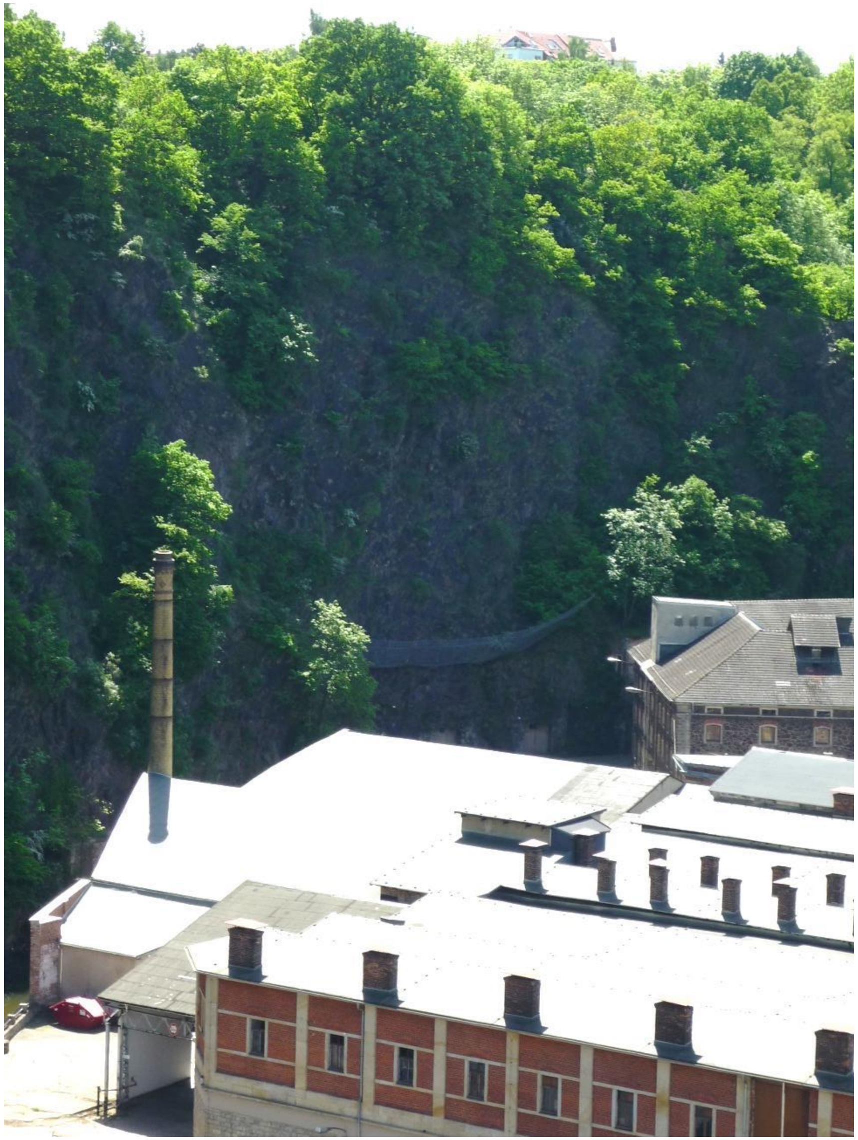
Radio frequency ionization

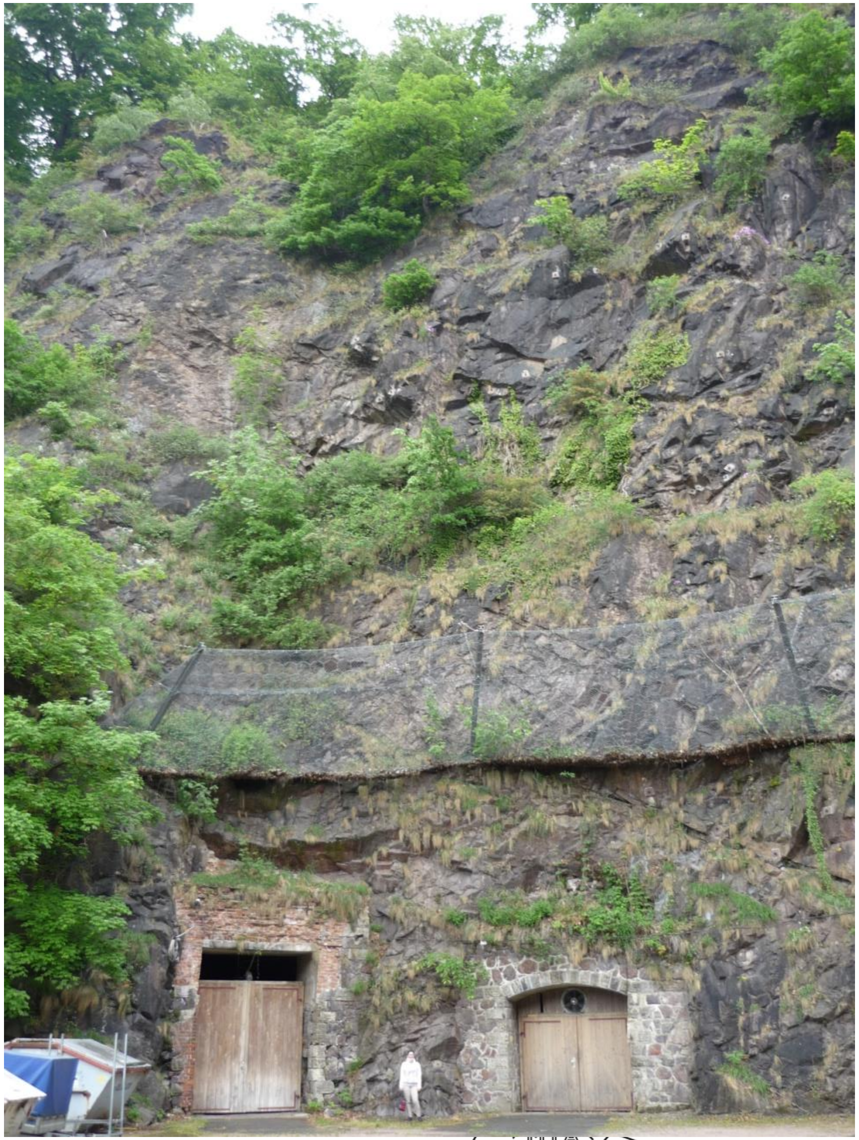
Intensive
He^+, H^+ beams



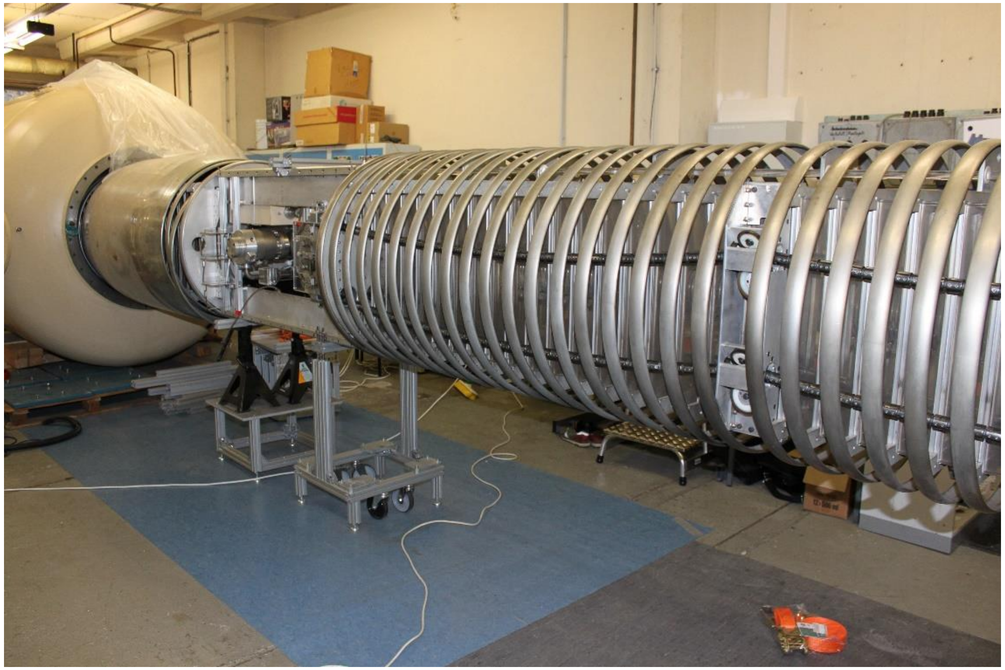


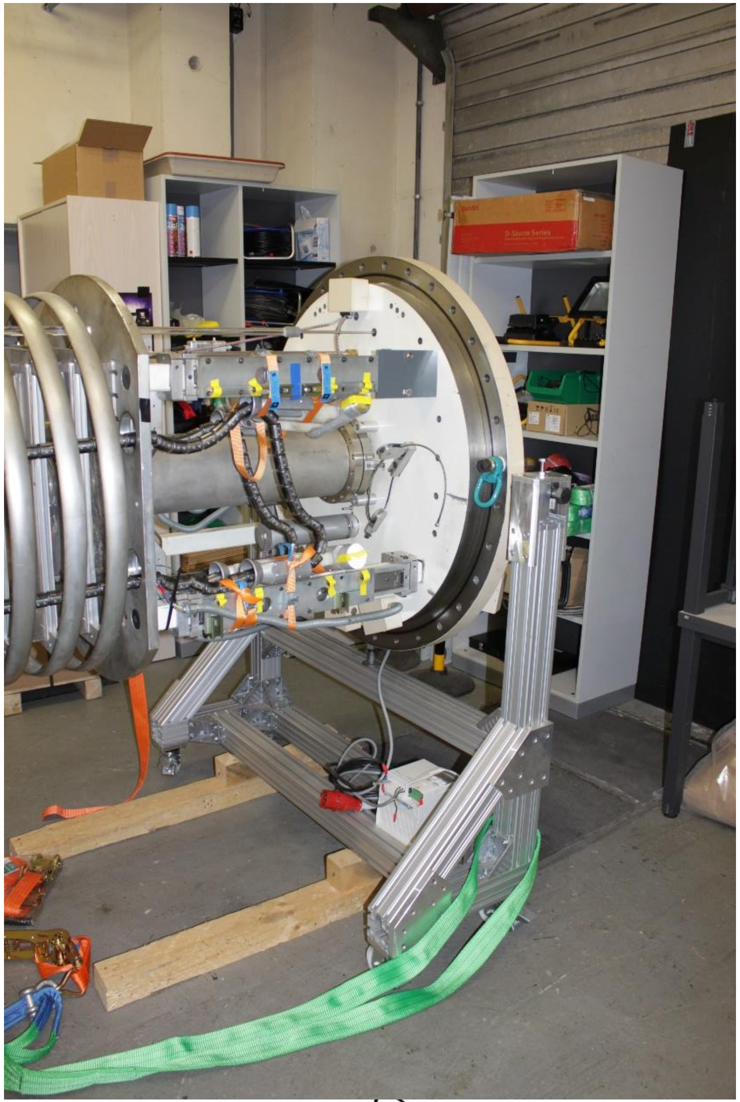
The Felsenkeller site



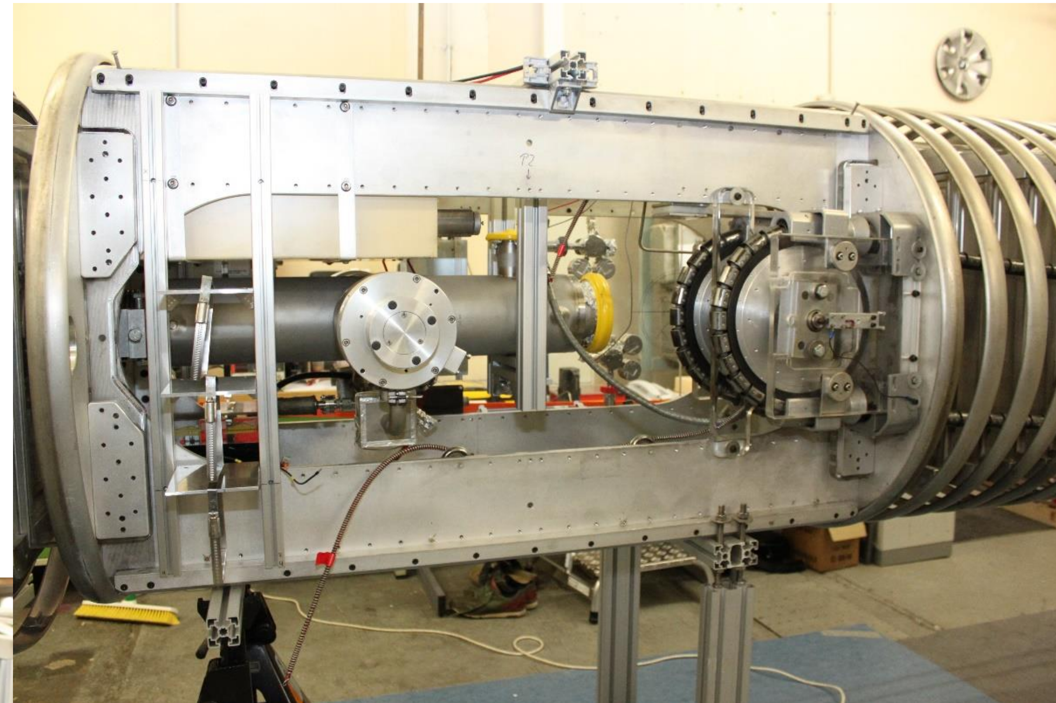


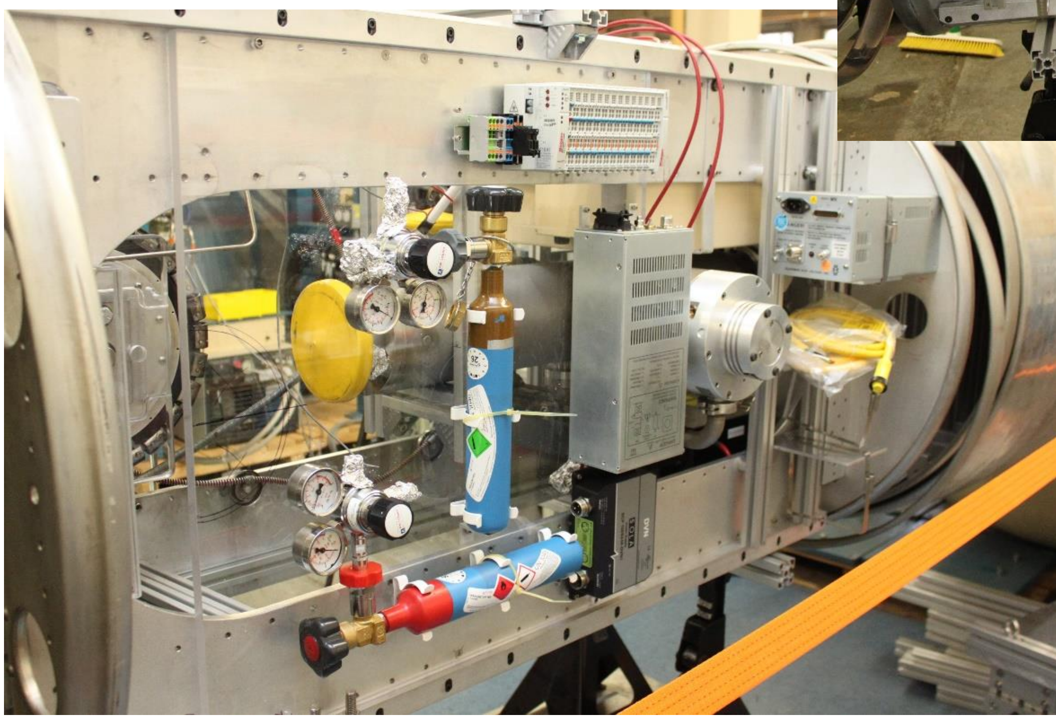
The Pelletron



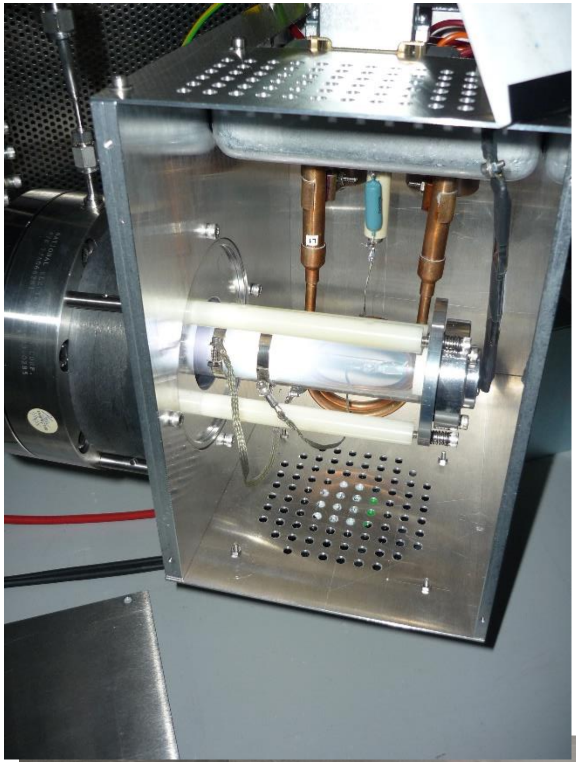


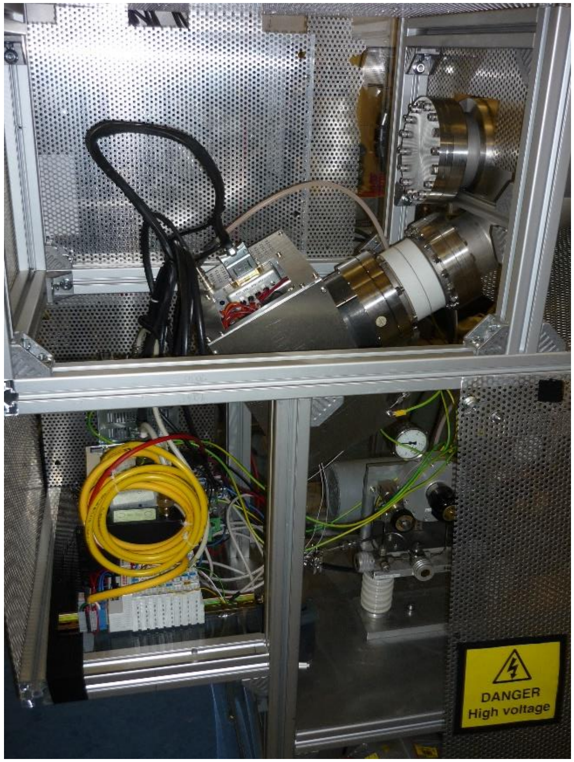
Pelletron terminal

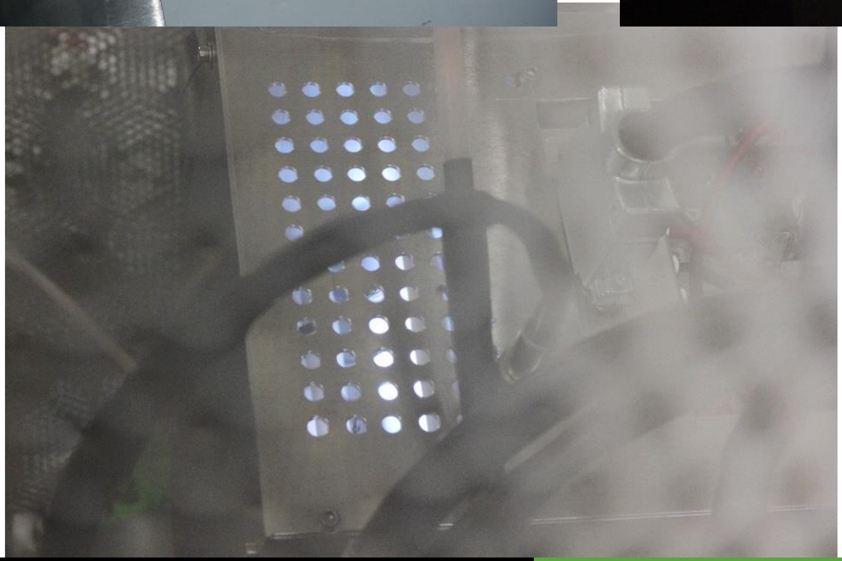




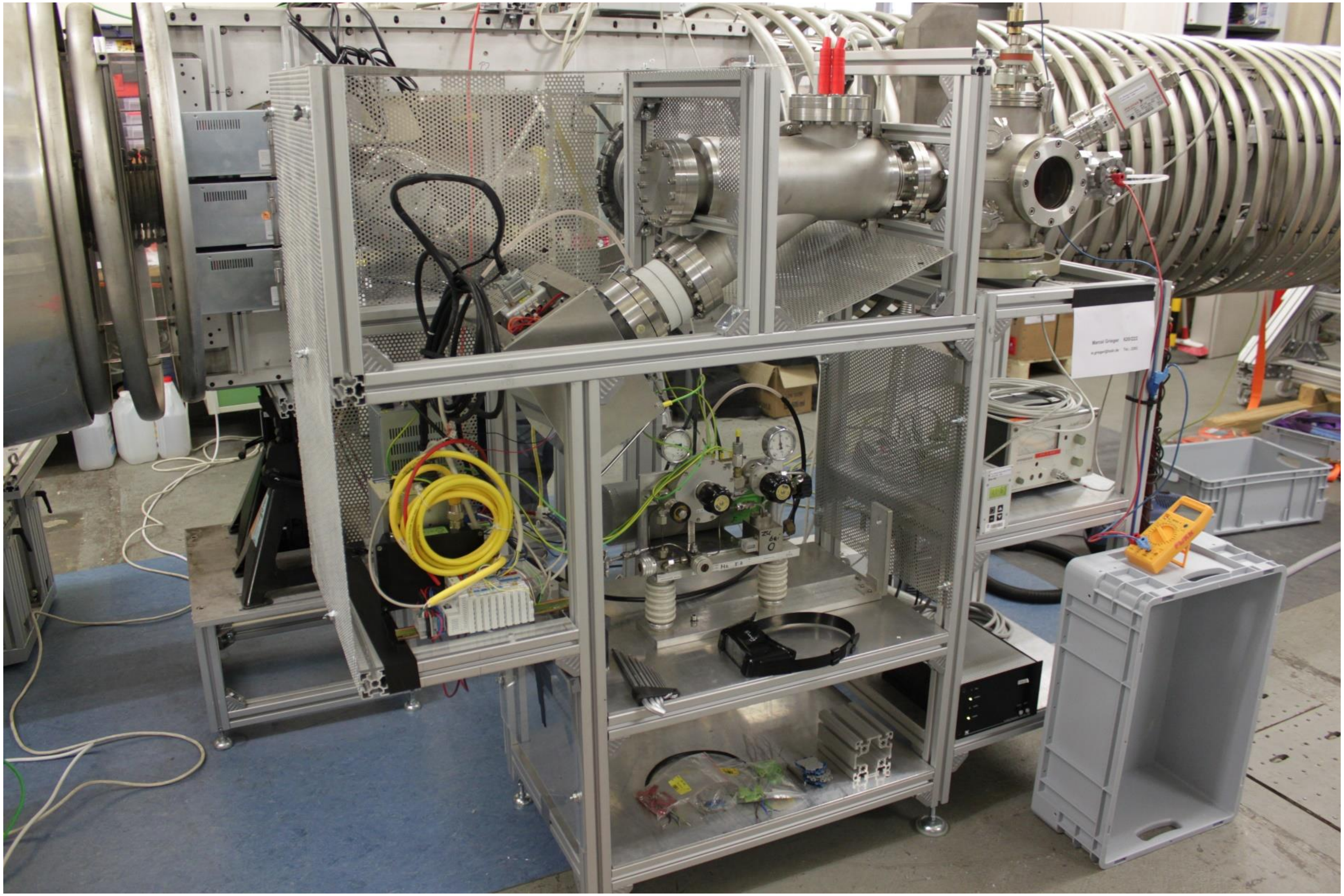
RF Ion source



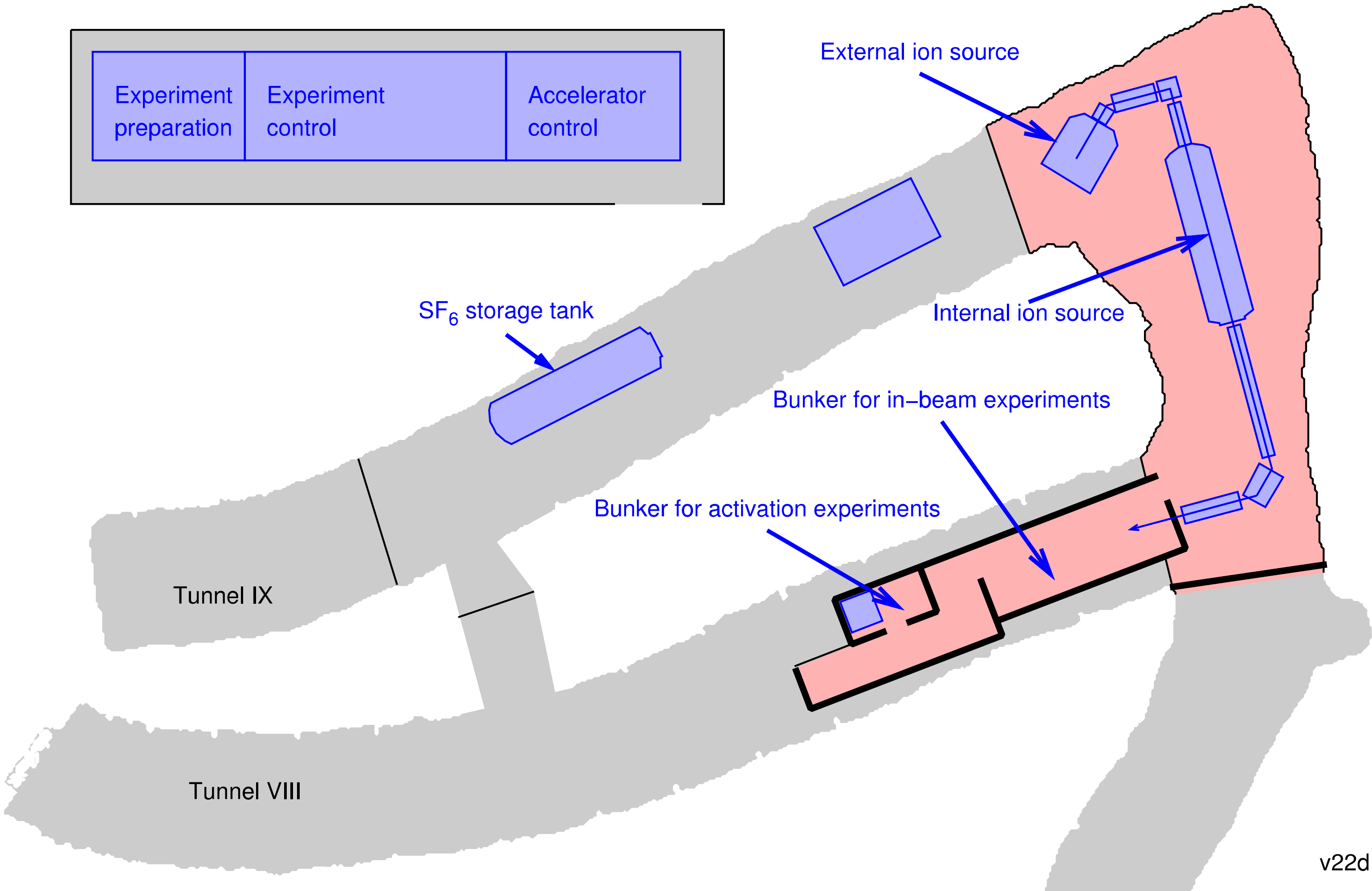




RF Ion source



Map of the planned installations in Felsenkeller



Thank you for your attention!