Felsenkeller shallow-underground 5 MV accelerator for nuclear astrophysics, status and outlook

2nd Workshop on Nuclear Astrophysics
at the Canfranc Underground Laboratory

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HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Felsenkeller shallow-underground accelerator laboratory for nuclear astrophysics

1. The science case for new underground accelerators

2. Status quo at Felsenkeller

3. Background suppression and background intercomparison

4. Project status

5. Scientific outlook

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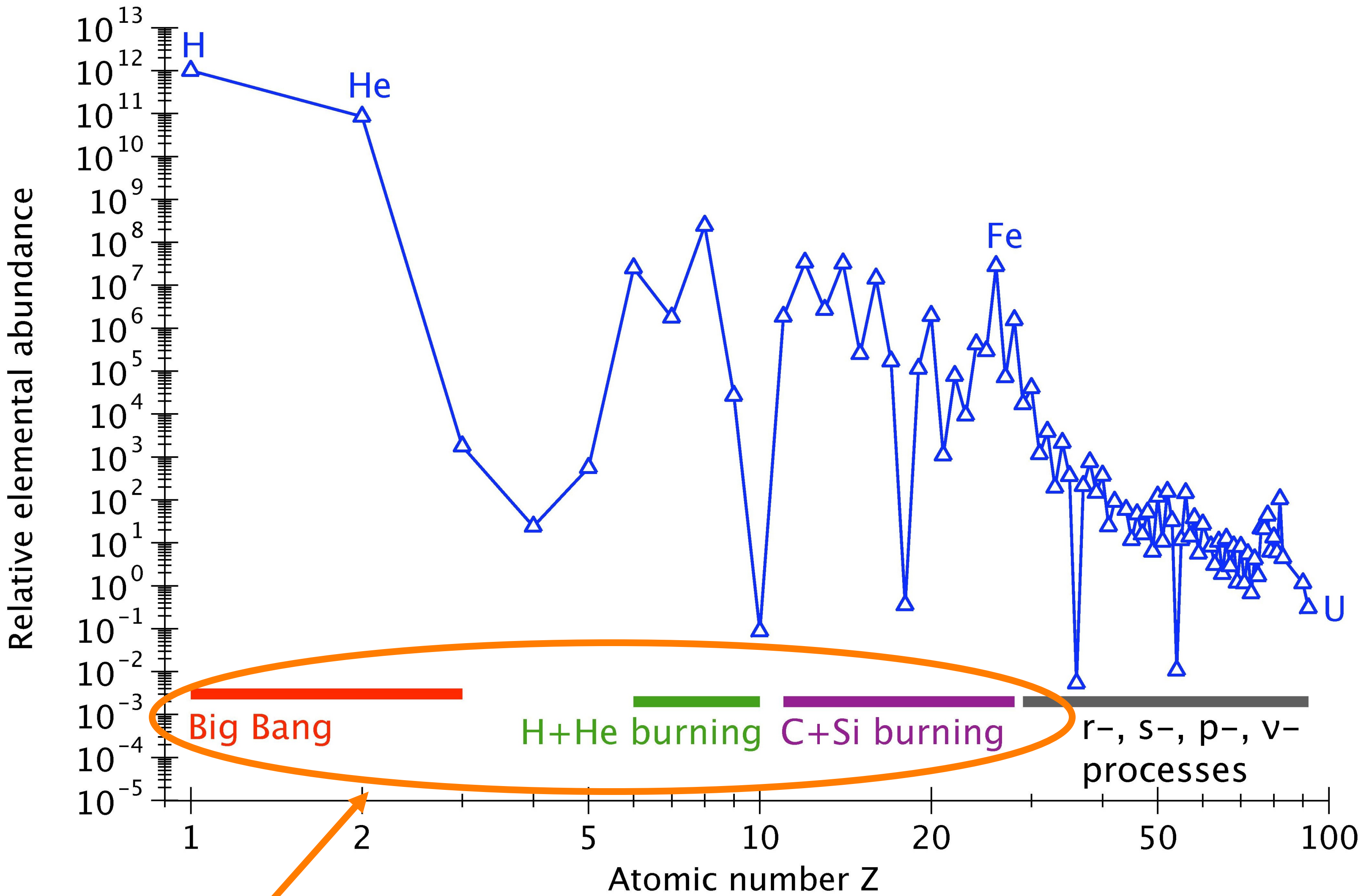
Stable-beam, stable-target accelerators: Why are they needed?



Charged-particle induced reactions on stable nuclei

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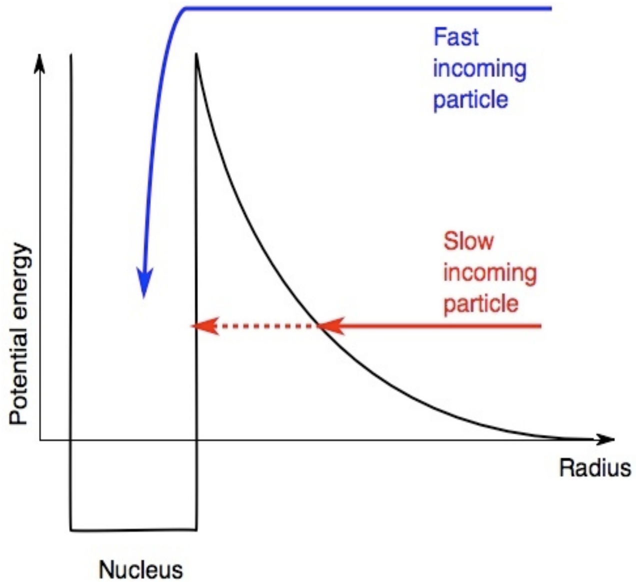
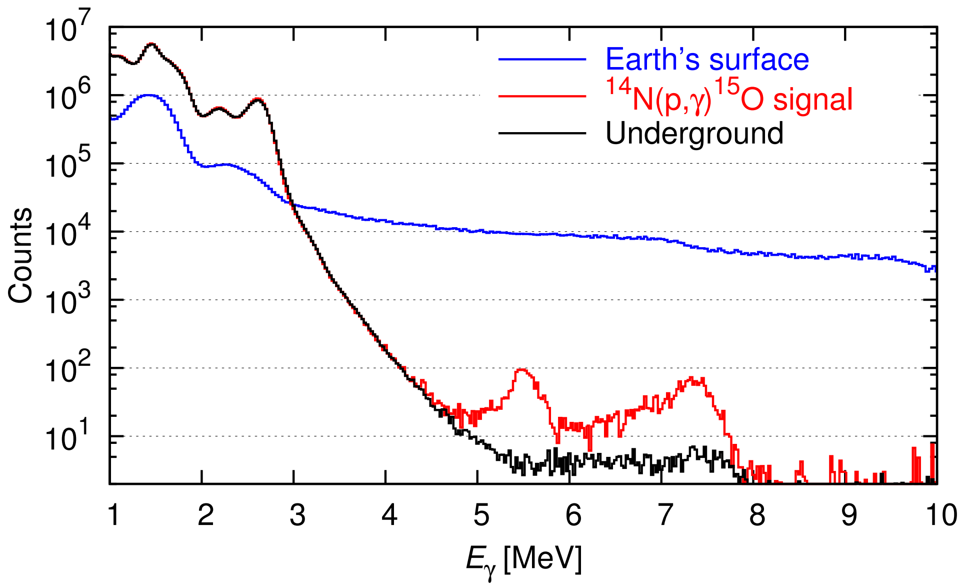
Stable-beam, stable-target accelerators: The problem



- Very low cross section at the relevant energies for hydrostatic stellar burning.
- Thus, very low signal counting rate in a detector, thus very sensitive to background
- Thus, very long running time (1-3 years per nuclear reaction)

Stable-beam, stable-target accelerators: The solution

- High-intensity, low beam energy accelerator
- Ultra-low background environment, deep underground.
- LUNA 0.4 MV accelerator in Italy = a success story!
  See previous talk by Rosanna Depalo for the latest discoveries at LUNA.

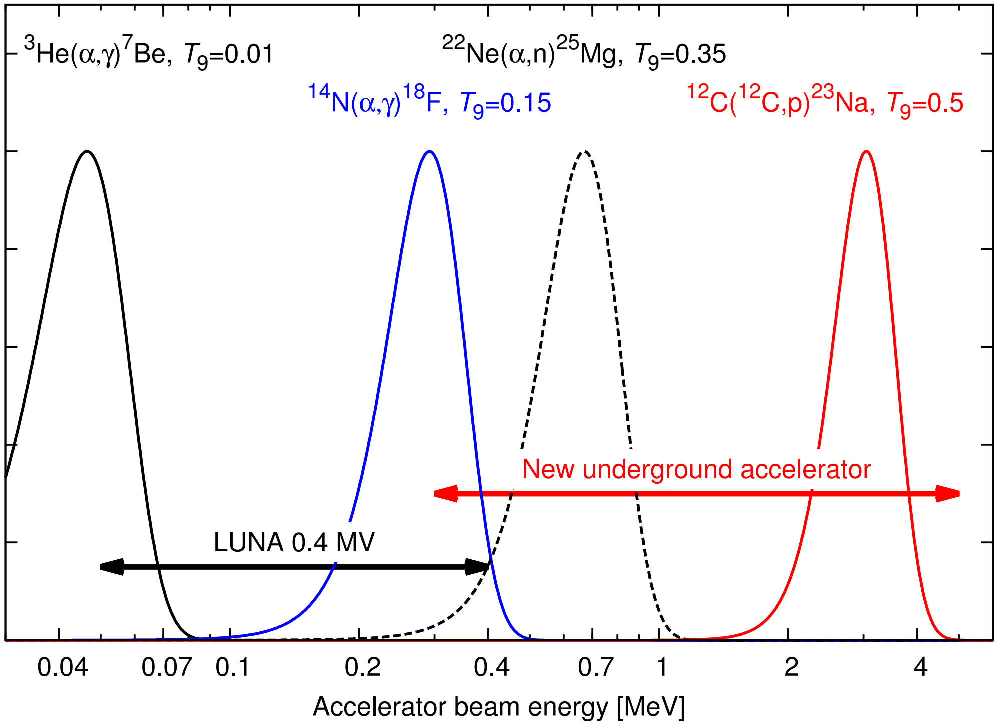


LUNA 0.4 MV accelerator and higher-energy accelerators

NuPECC Long Range Plan 2010-2016:

"An immediate, pressing issue is to select and construct the next generation of underground accelerator facilities. (…) There are a number of proposals being developed in Europe and it is vital that construction of one or more facilities starts as soon as possible."

Gamow peak for selected stable-ion reactions:



LUNA 0.4 MV

- Solar fusion
- Big-Bang nucleosynthesis
- Hydrogen burning

Higher-energy underground accelerators

- Solar fusion
- Big-Bang nucleosynthesis
- Helium burning
- Carbon burning
- ^{26}Al, ^{44}Ti production and destruction

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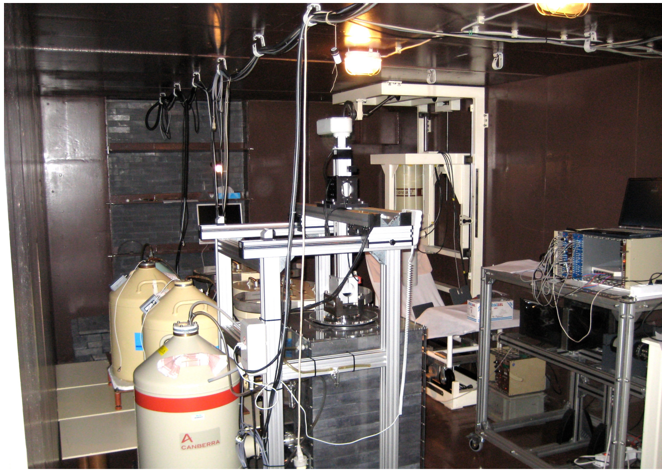
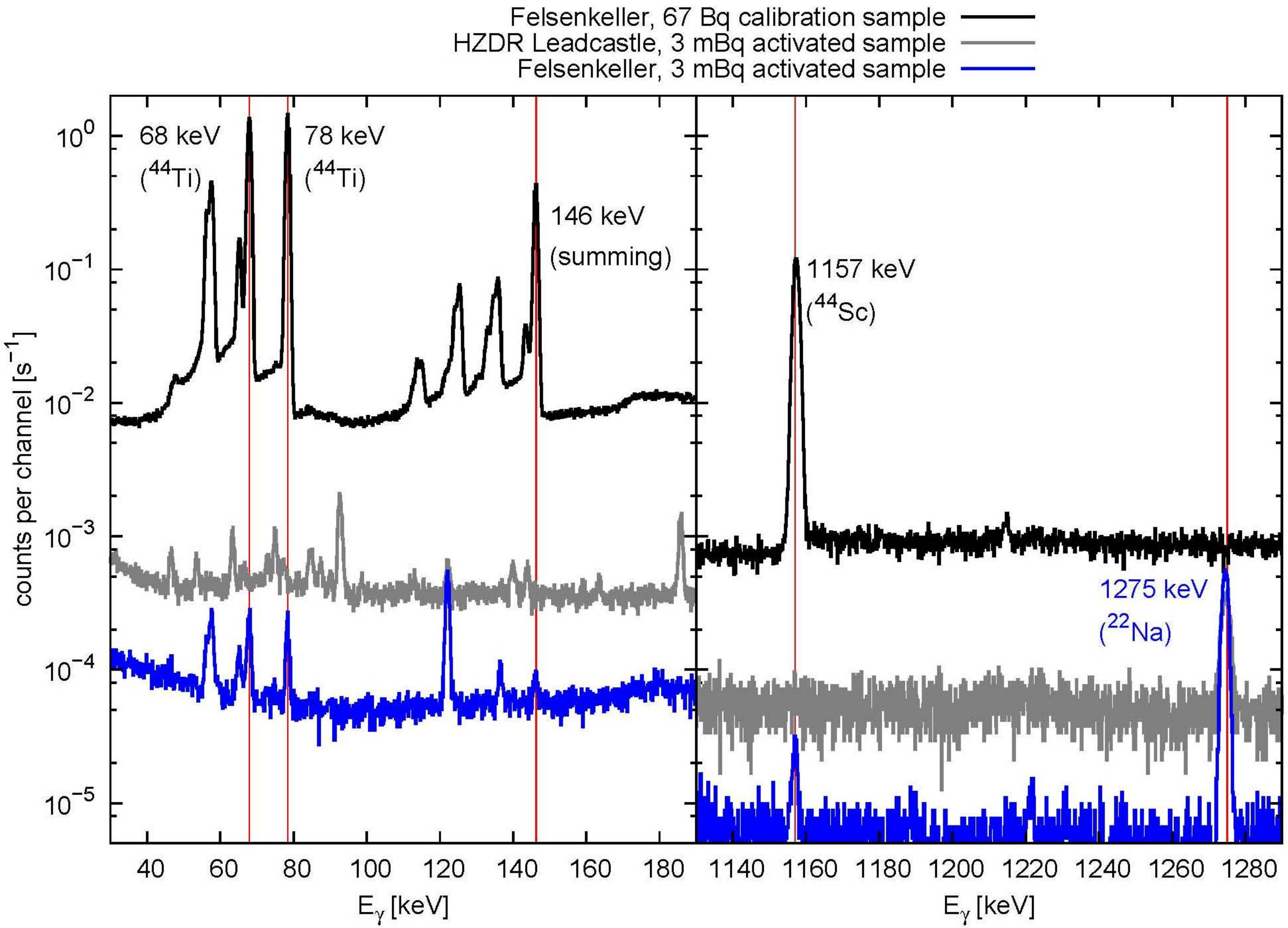
Dresden Felsenkeller, below 47 m of rock

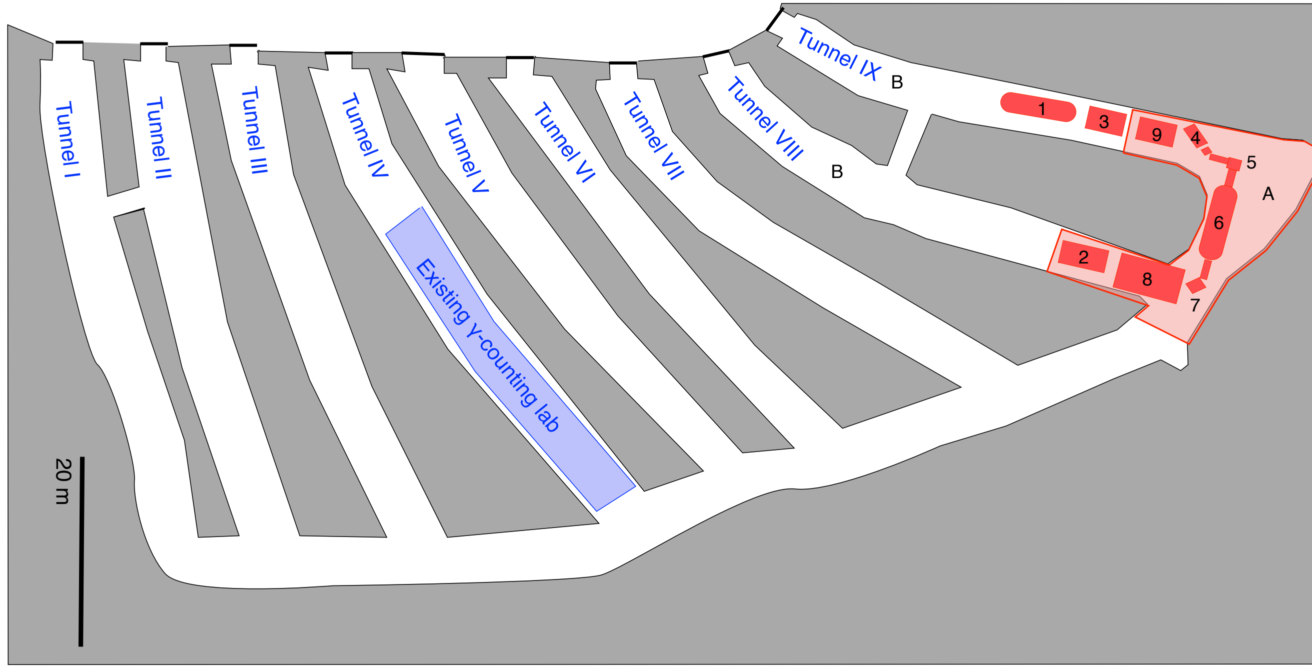
- γ-counting facility for analytics, established 1982
- Deepest underground γ-counting lab in Germany
- Contract enabling scientific use (since 2009)
- 4 km from TU Dresden, and from city center
- 25 km from HZDR campus





^{44}Ti production study:
Konrad Schmidt *et al.*
Phys. Rev. C 88, 025803 (2013)
Phys. Rev. C 89, 045802 (2014)

Why not place a surplus accelerator in Felsenkeller?



- Industrial area (former Felsenkeller brewery)
- Tunnels driven in the 1850s into the wall of a former quarry
- Additional space available underground

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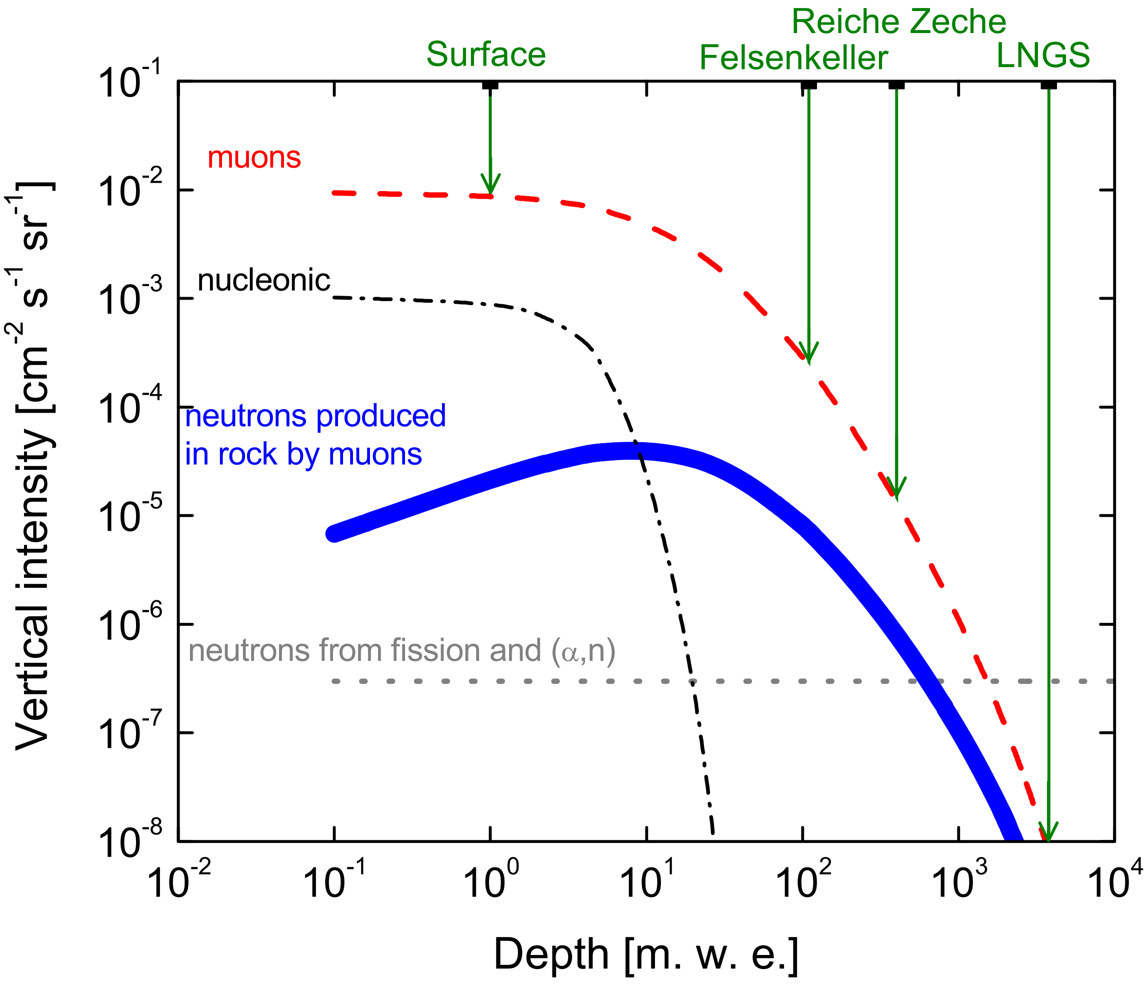
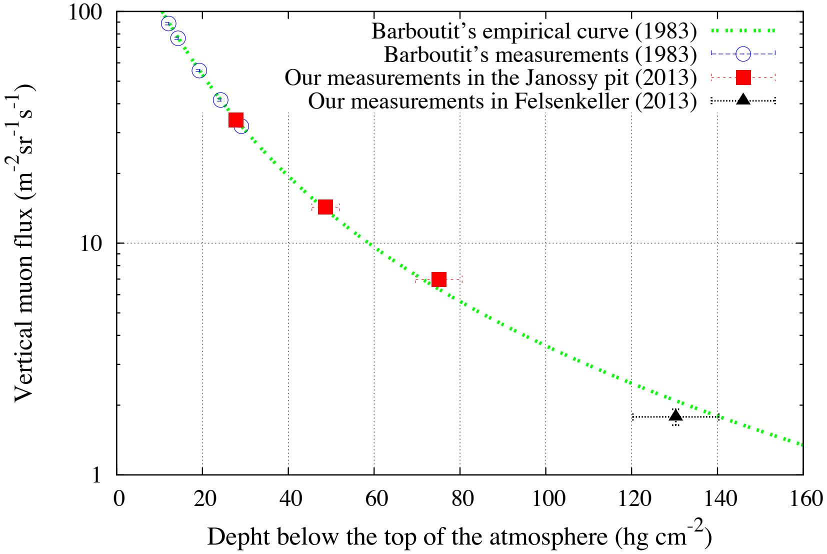
Background suppression approach in Felsenkeller



„First passive, then active“

1. First 30 m.w.e. of rock completely remove nucleonic component of cosmic rays.
2. Subsequent rock thickness attenuates the muon flux, and thus muon-produced neutrons (110 m.w.e. = factor of 30)
3. Active muon veto removes most of the remaining muon-induced effects

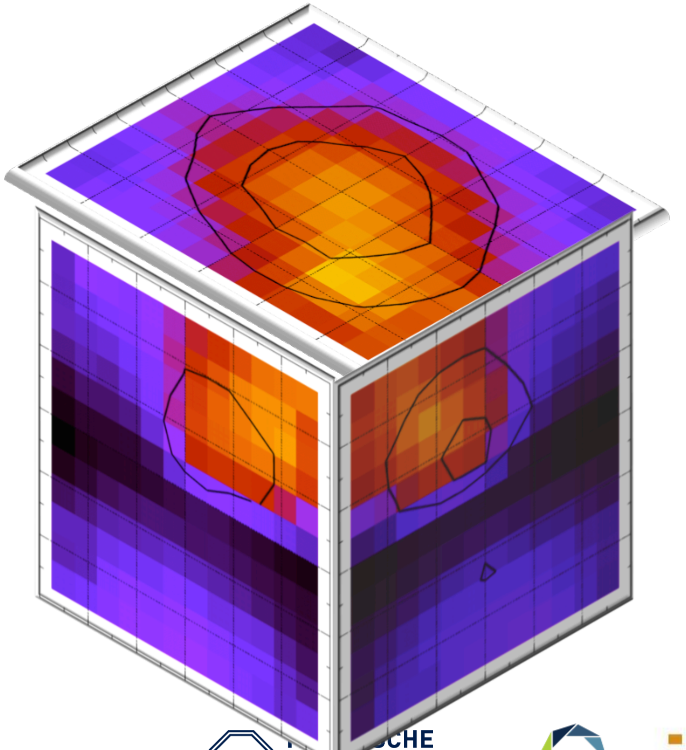
Muon flux measurement (Budapest REGARD muon tomograph)



- Rock overburden 130 m.w.e., slightly higher than in the nearby existing low-activity lab (110 m.w.e.)
- Laszlo Oláh (MTA Wigner) et al.,
  PoS (NIC XIII) 129 (2015)
  J. Phys. Conf. Series 665 (2016) 012032

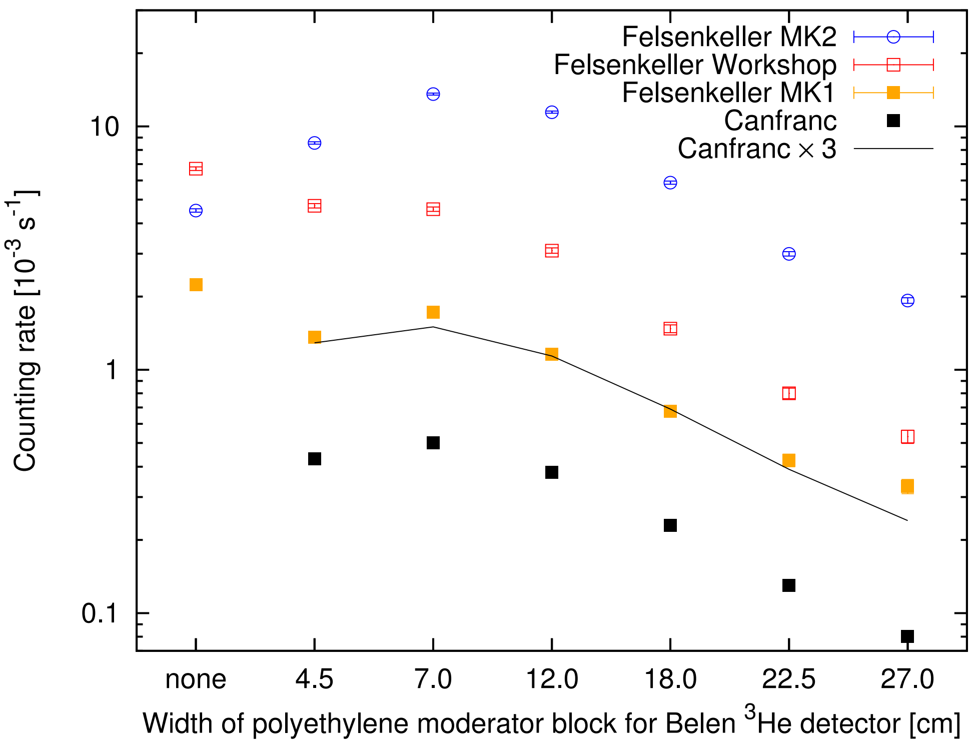
Work in progress:

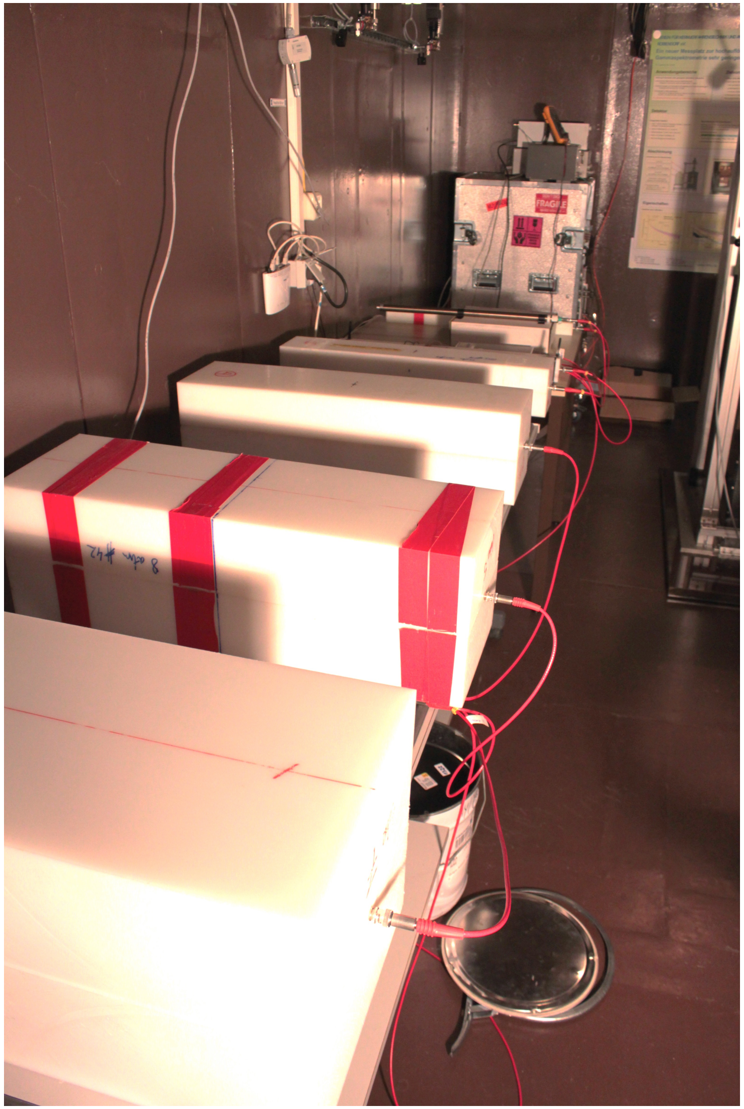
- Complete mapping of tunnels underway (Master‘s thesis Felix Ludwig, started Nov. 2015)



Neutron flux measurement (BELEN ^{3}He counters)

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





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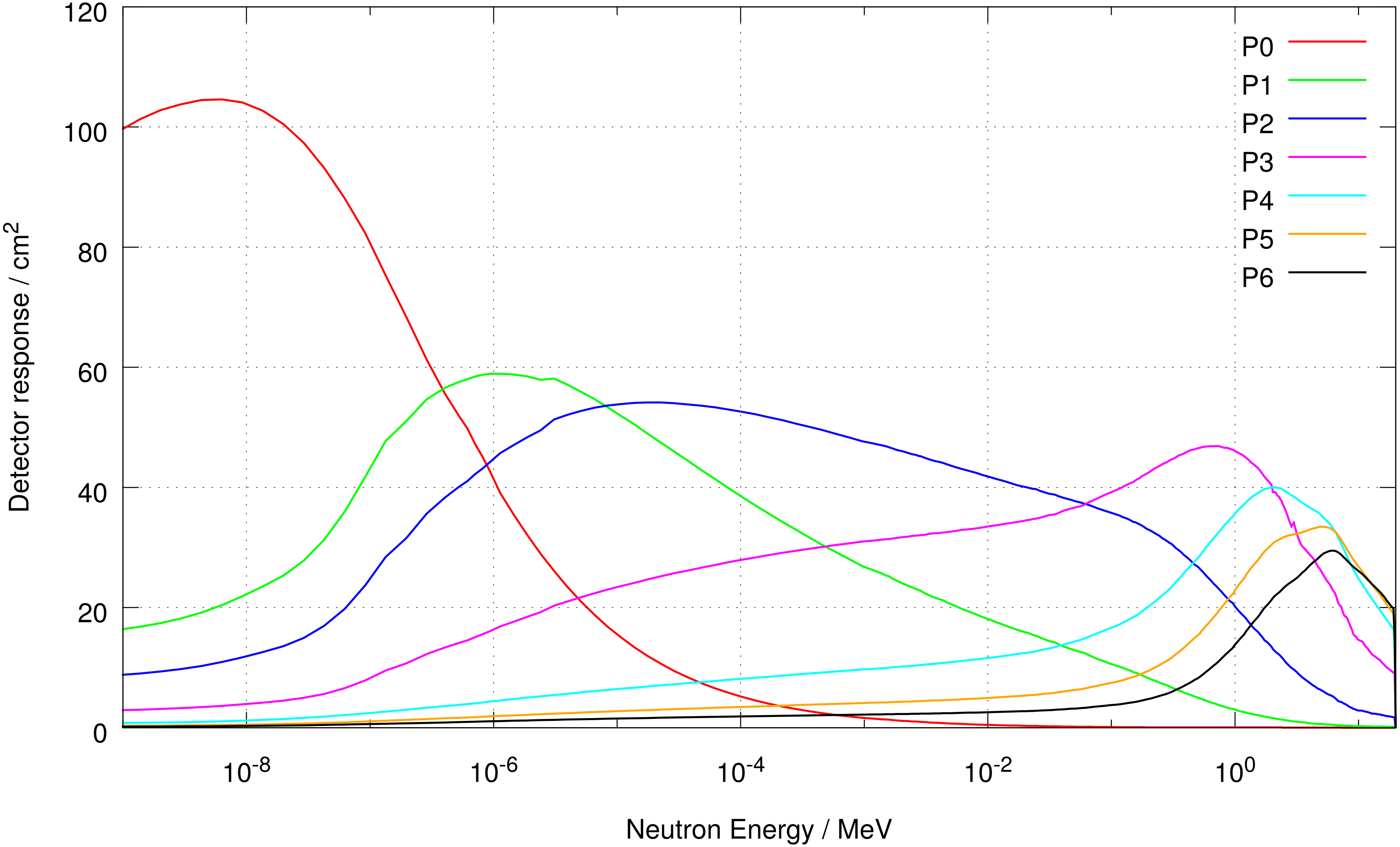
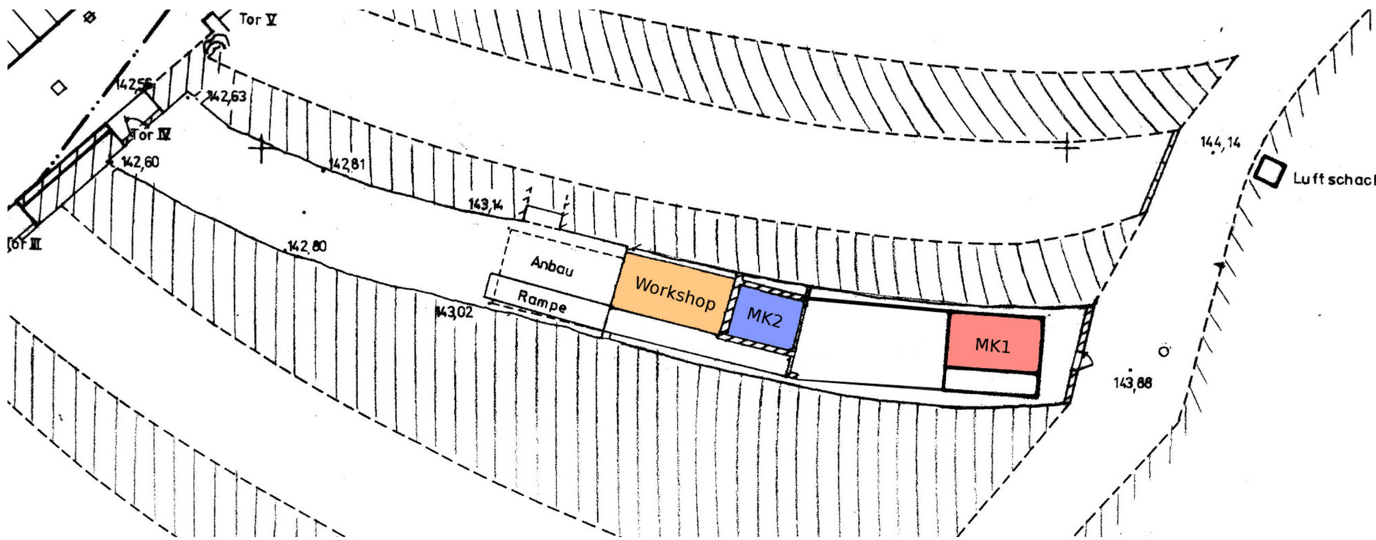
Calculated response functions (FLUKA)



Neutron flux strongly differs between sites with very similar muon flux

- Three different campaigns show consistent results
- 5“ Bonner sphere with almost flat response function shows similar results
- Very different fluxes at three nearby sites (all in tunnel IV) with similar muon flux
- Characterization of tunnels VIII and IX will follow

Place	PTB set of Bonner spheres 2013 [10^{-4} cm^{-2} s^{-1}]	BELEN ^{3}He counters 2015 prelim. [10^{-4} cm^{-2} s^{-1}]	PTB 5” Bonner sphere 2015 prelim. [10^{-4} cm^{-2} s^{-1}]
Workshop		2.0	2.2
MK2 (Pb+Fe)	5.7	4.6	5.6
MK1 (rock)		0.7	0.7



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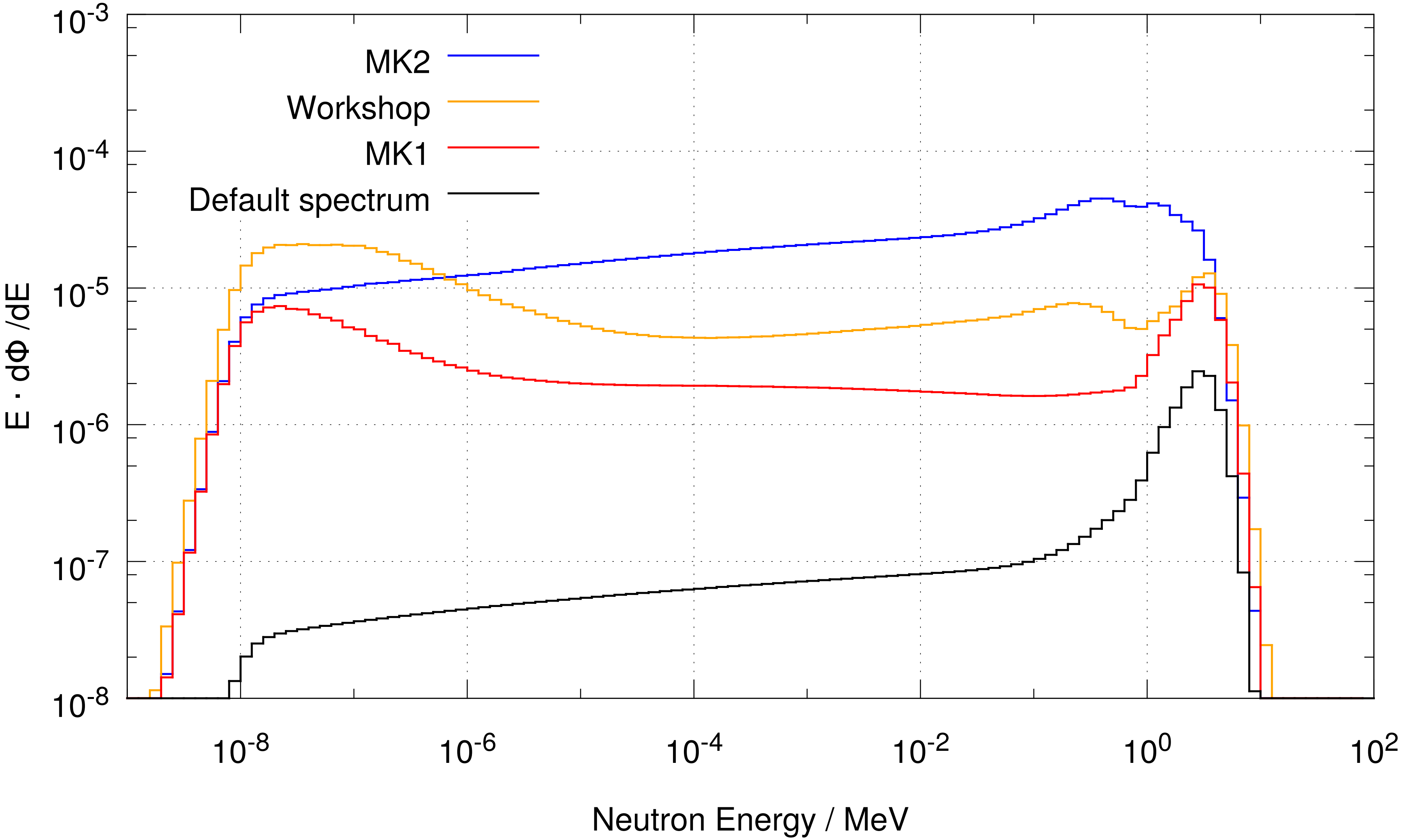
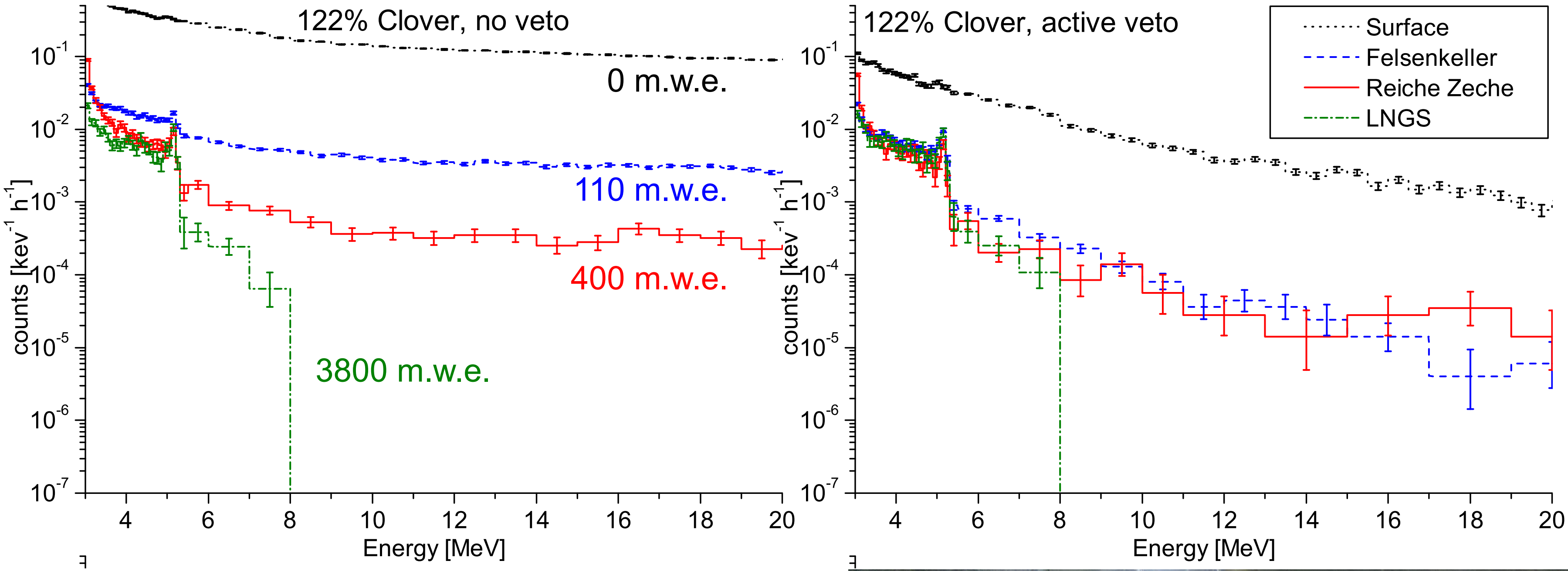
Deconvoluted energy spectrum (MAXED and GRAVEL algorithms)



Background in γ-detectors (HPGe with active veto)



- One and the same HPGe detector (Eurisys Clover with active veto) used subsequently at different laboratories
- Background rate at 6-8 MeV γ-ray energy only a factor of 3 higher at Felsenkeller (110 m.w.e.) than at Gran Sasso
- Conclusions recently confirmed in a 400 m.w.e. deep mine (Freiberg/Sachsen, Germany)
- Explanation: active veto suppresses remaining muon-induced effects

Tamás Szücs *et al.*
Eur. Phys. J. A 48, 8 (2012)
Eur. Phys. J. A 51, 33 (2015)

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12 year old 5 MV Pelletron system from York/UK

- Spin-off company of York University doing ^{14}C analyses by accelerator mass spectrometry
- Magnets, beamline, pumps, fully digital control

- MC-SNICS sputter ion source (C^- and H^- ions)
- 250 μA upcharge current (double pellet chains)

➔ Well-suited for low-energy nuclear astrophysics

- Purchased by HZDR, brought to Dresden

12 July 2012: Still assembled, in York

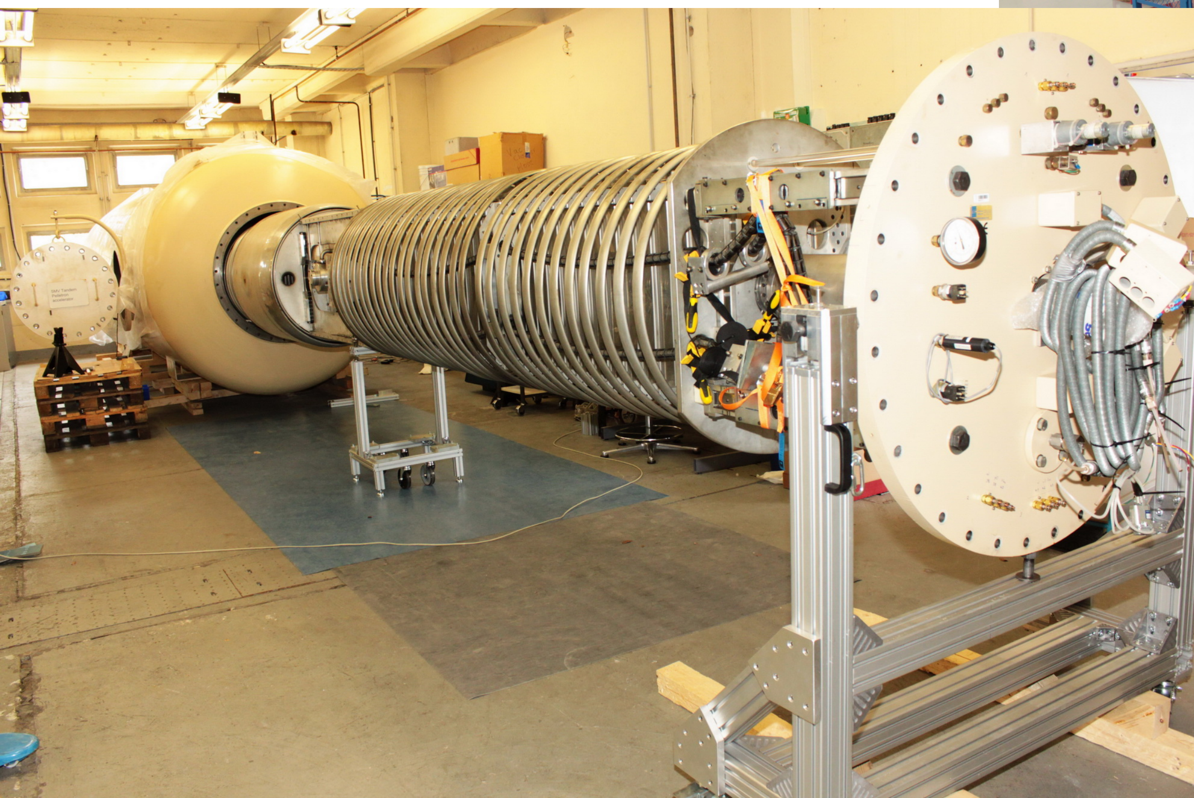
24 July 2012: Loading of components in York

30 July 2012: Unloading of last component in Dresden

5 MV Pelletron

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

Louis Wagner

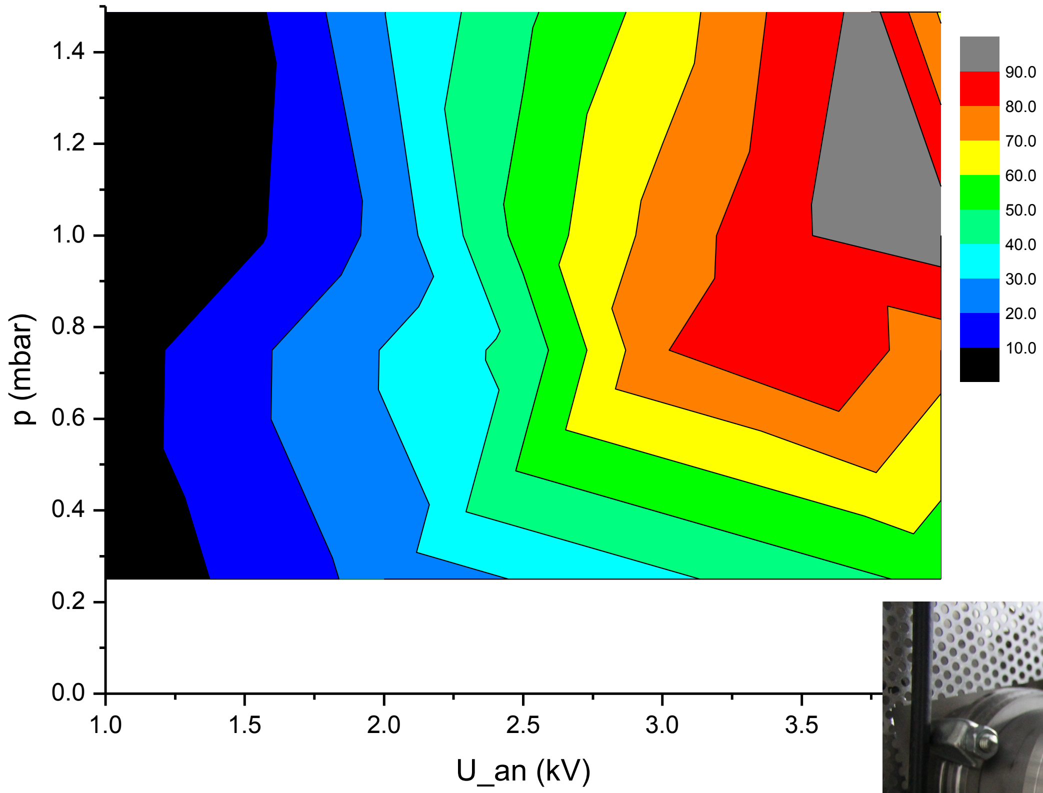


MC-SNICS 134 sputter ion source

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

Marcell Takács

Radio frequency ion source, results of offline tests



HZDR-made ion source:

Extracted ion current (µA)
as a function of anode voltage and
gas pressure.

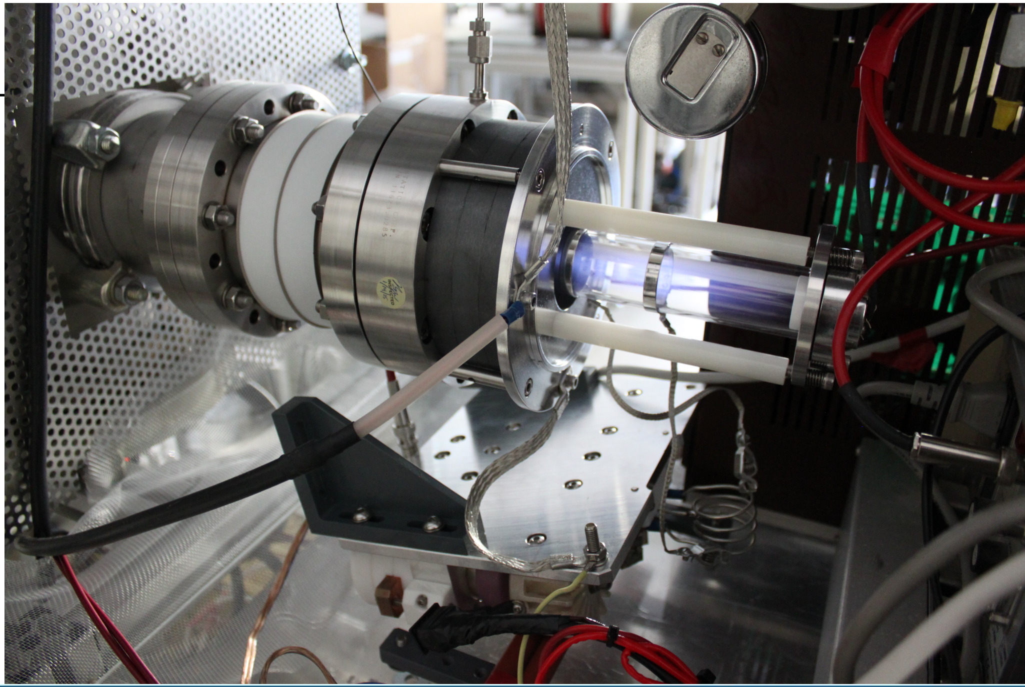
Commercial ion source (NEC):

First plasma, promising current

Tamás Szücs
Stefan Reinicke

To do:

- Analysis of extracted beam species
- Decision which of the two RF ion sources to use
- Electrostatic deflector for coupling RF ion source to beam line



Felsenkeller accelerator, technical capabilities

Existing capabilities

- 100 μA carbon beam (MC-SNICS)
- 100 μA hydrogen beam (MC-SNICS)
- Solid target setup
- Two in-beam HPGe detectors
- One offline HPGe detector in Pb castle

Capabilities that are under construction

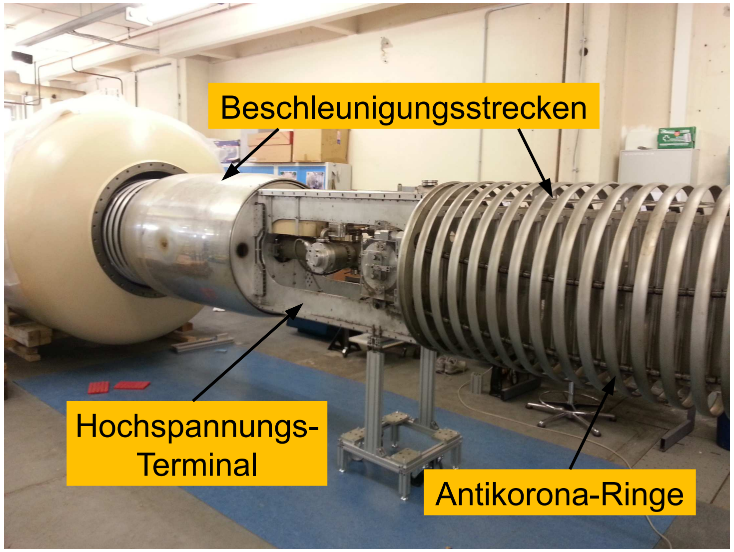
- Two triple HPGe clusters (EUROBALL HPGe crystals in MINIBALL capsules) with BGO shields
- 100 μA helium beam (RF ion source)

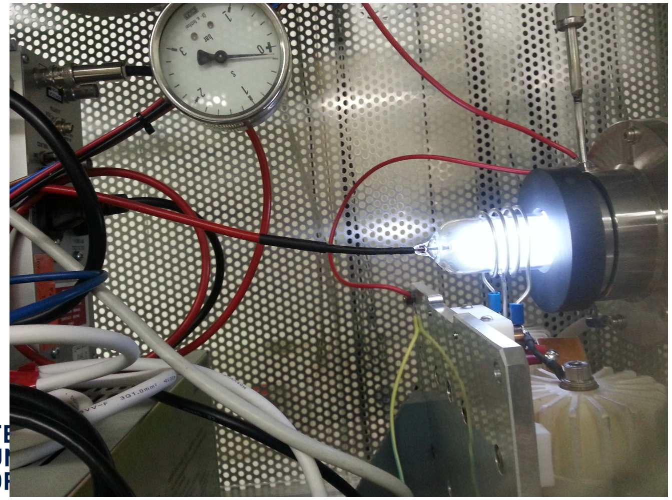
Temporarily available (setups at HZDR ELBE)

- 4 additional BGO-shielded HPGe detectors
- 4 additional 3'' $LaBr_3$ detectors

To be applied for

- Windowless gas target





Construction, funding, staff

Total investment needed+funded 1.5 M€

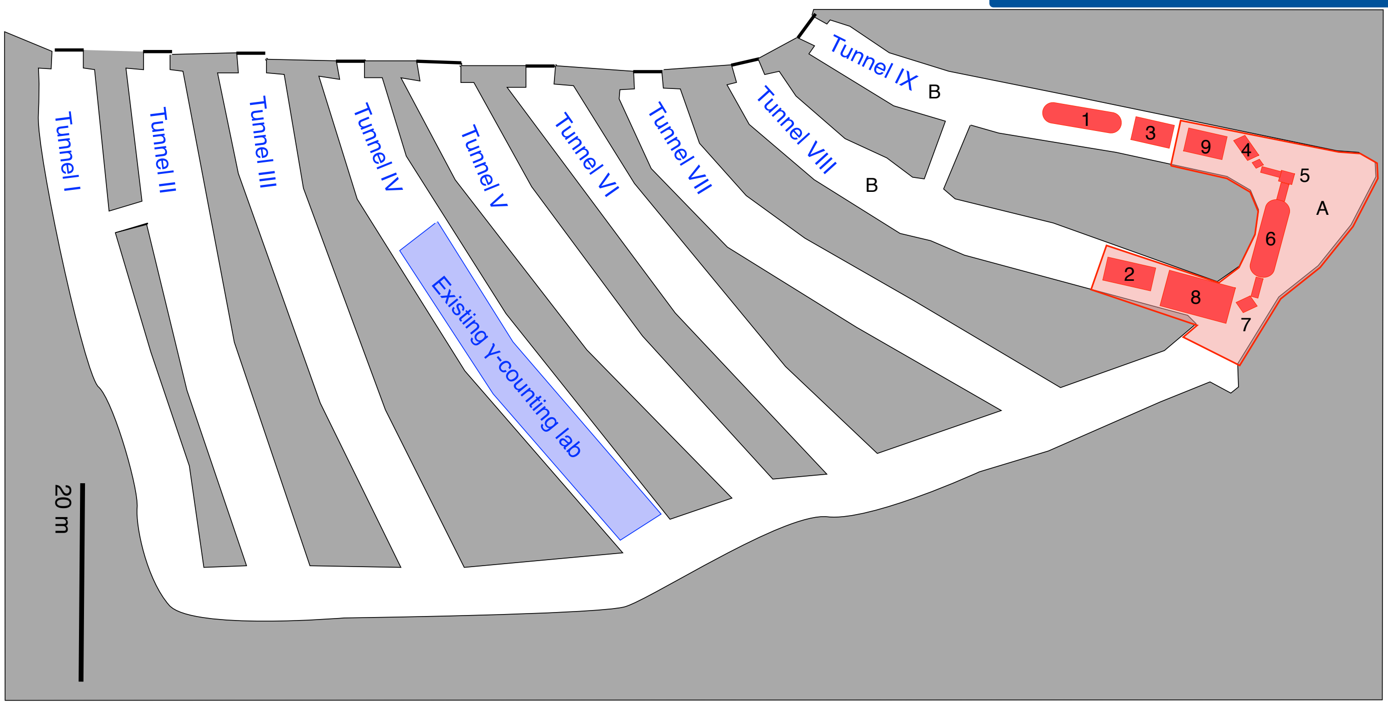
- Purchase and transport of Pelletron (spent)
- Construction (TU Dresden, Excellence Initiative „support the best“, K. Zuber, approved 2014)
- Planning, infrastructure, reserve (HZDR)

Running cost will be covered by HZDR

- Rent for the tunnel
- Electricity, liquid nitrogen
- 1 scientist and 1 engineer

Executive project

- Detailed drafts updated in August 2015
- Full planning started in November 2015
- Construction starts fall 2016
- Opening of the facility September 2017



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Felsenkeller accelerator: access, use, program

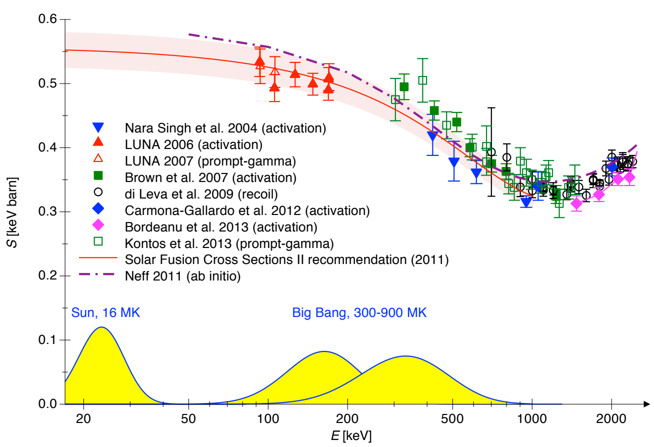
Collaboration between HZDR and TU Dresden

- Kai Zuber et al. (TU Dresden)
- Daniel Bemmerer et al. (HZDR)
- Independent scientific advisory board to advise on program, users, and facility development

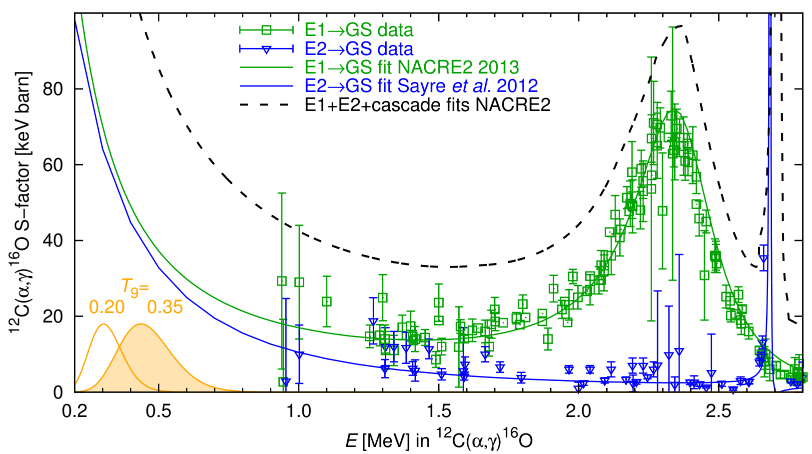
Planned use

- In-house research by HZDR and TU Dresden
  - Solar fusion — $^{3}He(\alpha,\gamma)^{7}Be$ over a wide energy range
  - Helium burning — $^{4}He(^{12}C,\gamma)^{16}O$
- Outside scientific users from any field of science welcome, no charge for beam time

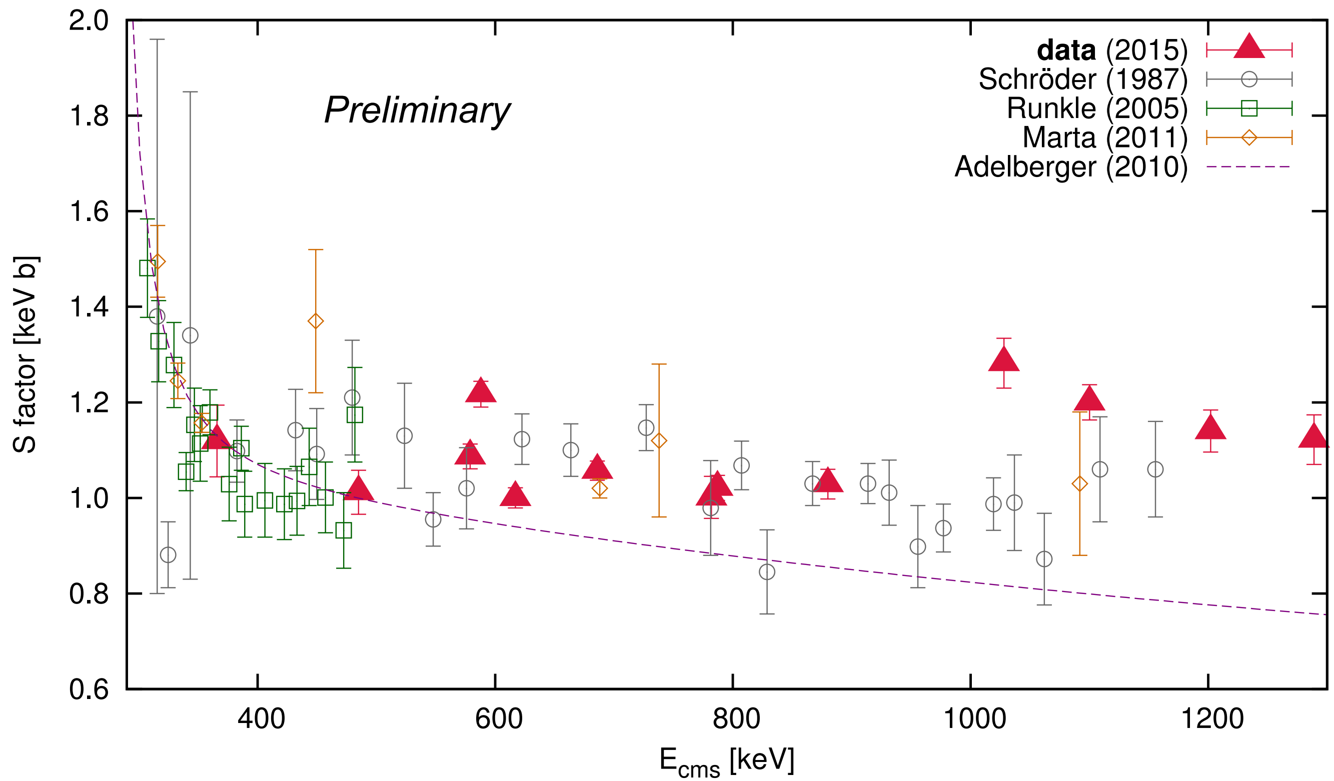
Solar fusion

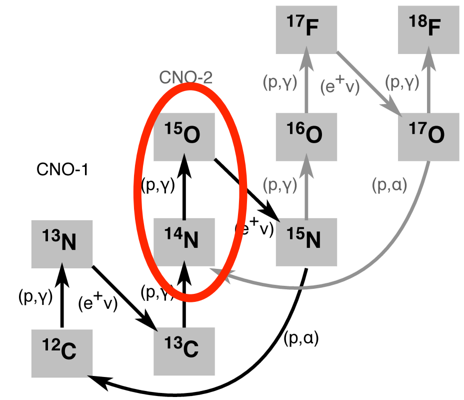


Helium burning



CNO neutrinos (^{13}N, ^{15}O, ^{17}F) and the ^{14}N(p,γ)^{15}O reaction





- Measurement of the two strongest transitions (6.79, GS) done, at the HZDR 3MV Tandetron at the Earth's surface
- Measurement of the two weaker transitions (6.17, 5.18) needs much higher beam intensity and lower background
- Felsenkeller accelerator will offer both.

Poster # 59 (Louis Wagner)

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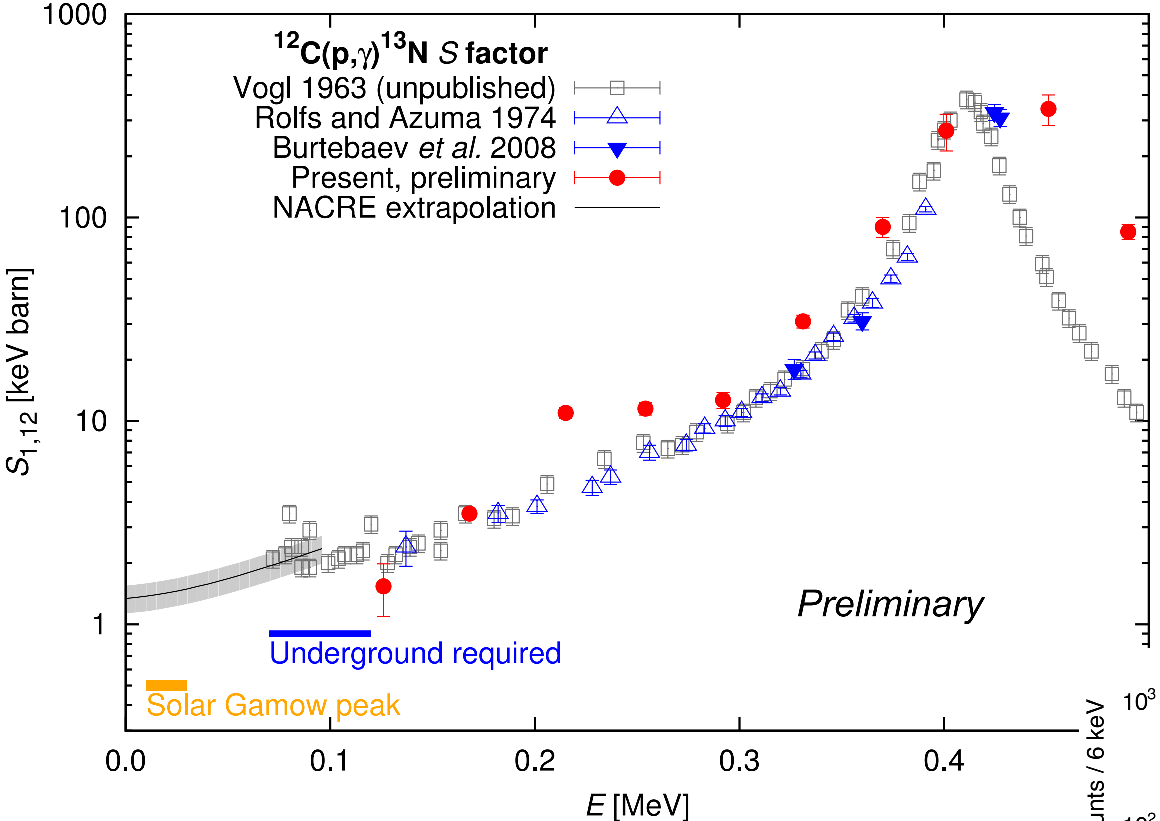
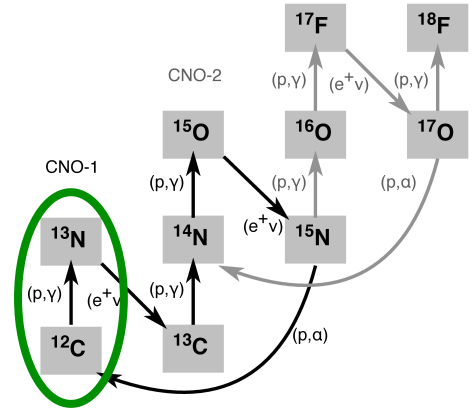
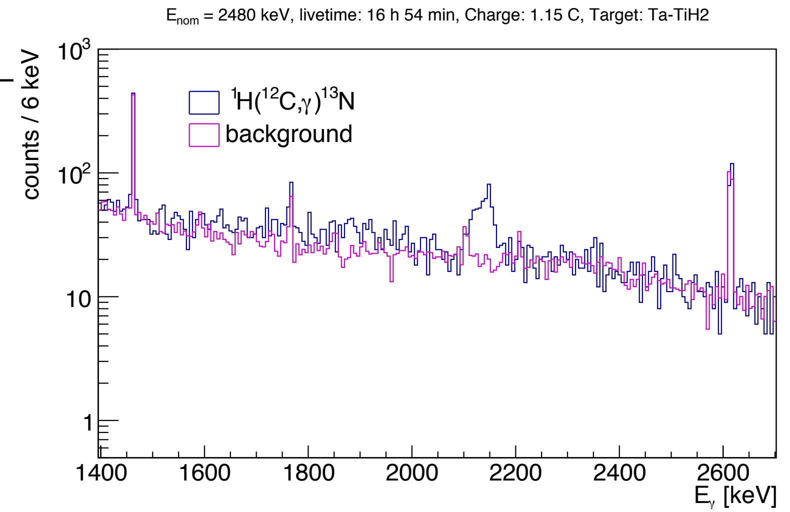
CNO neutrinos (^{13}N, ^{15}O, ^{17}F) and the $^{12}C(p,\gamma)^{13}N$ reaction







- Inverse-kinematics measurement recently completed, at the HZDR 3MV Tandetron at the Earth's surface
- Cosmic-ray background limits further progress.
- Felsenkeller will offer high ^{12}C beam intensity and lower background.

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Felsenkeller shallow-underground accelerator laboratory for nuclear astrophysics

- Stable-beam, stable-target accelerators are needed for the progress of nuclear astrophysics.
- Shallow-underground sites offer good background conditions, if an additional active veto is used.
- Felsenkeller underground accelerator will be running late in 2017:
  50 µA H, 50 µA C, 50 µA He
- Wide open for scientific users
  from Europe and from the rest of the world!
- What about a European network of underground nuclear astrophysics laboratories (both accelerator-based and offline γ-counting based)?

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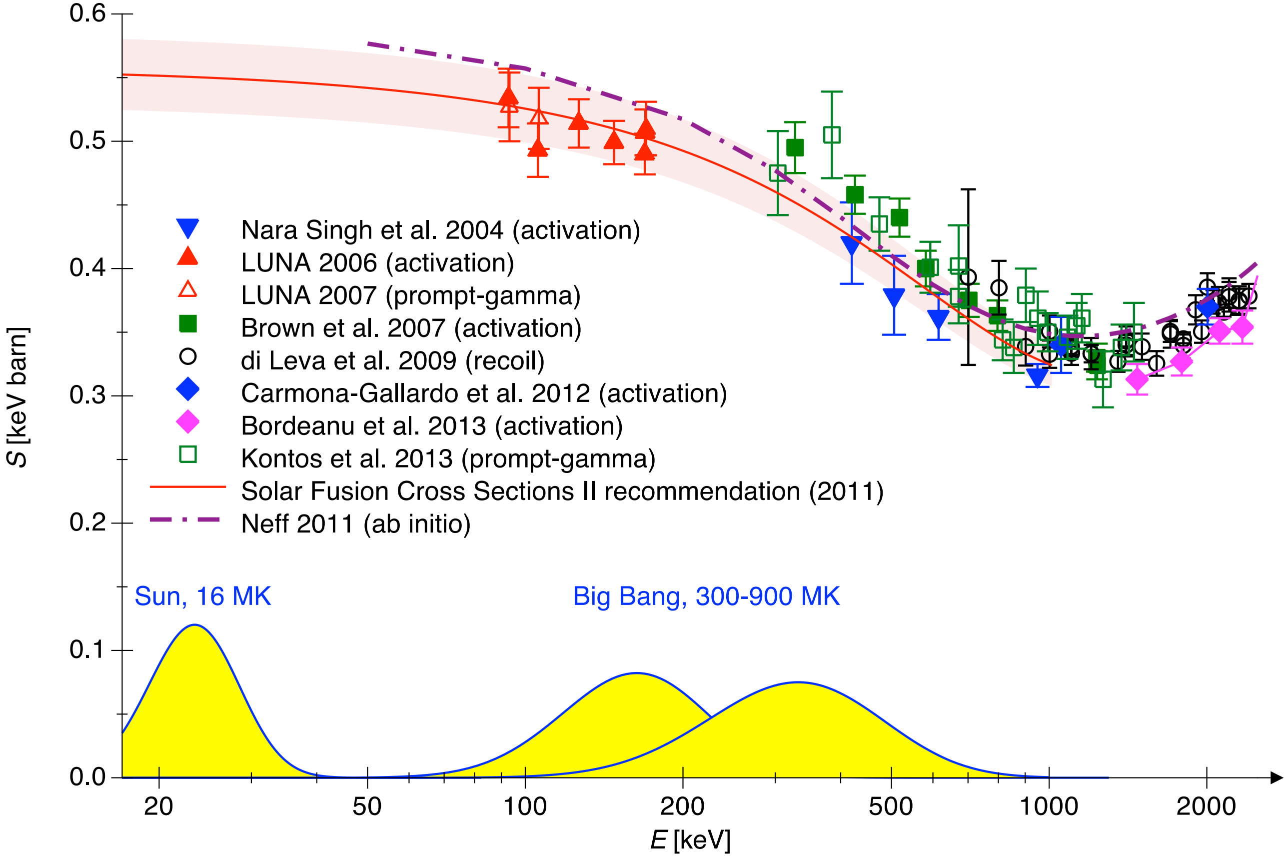
The power of the deep: $^3He(\alpha,\gamma)^7Be$, controlling Big Bang ^7Li and solar ^7Be



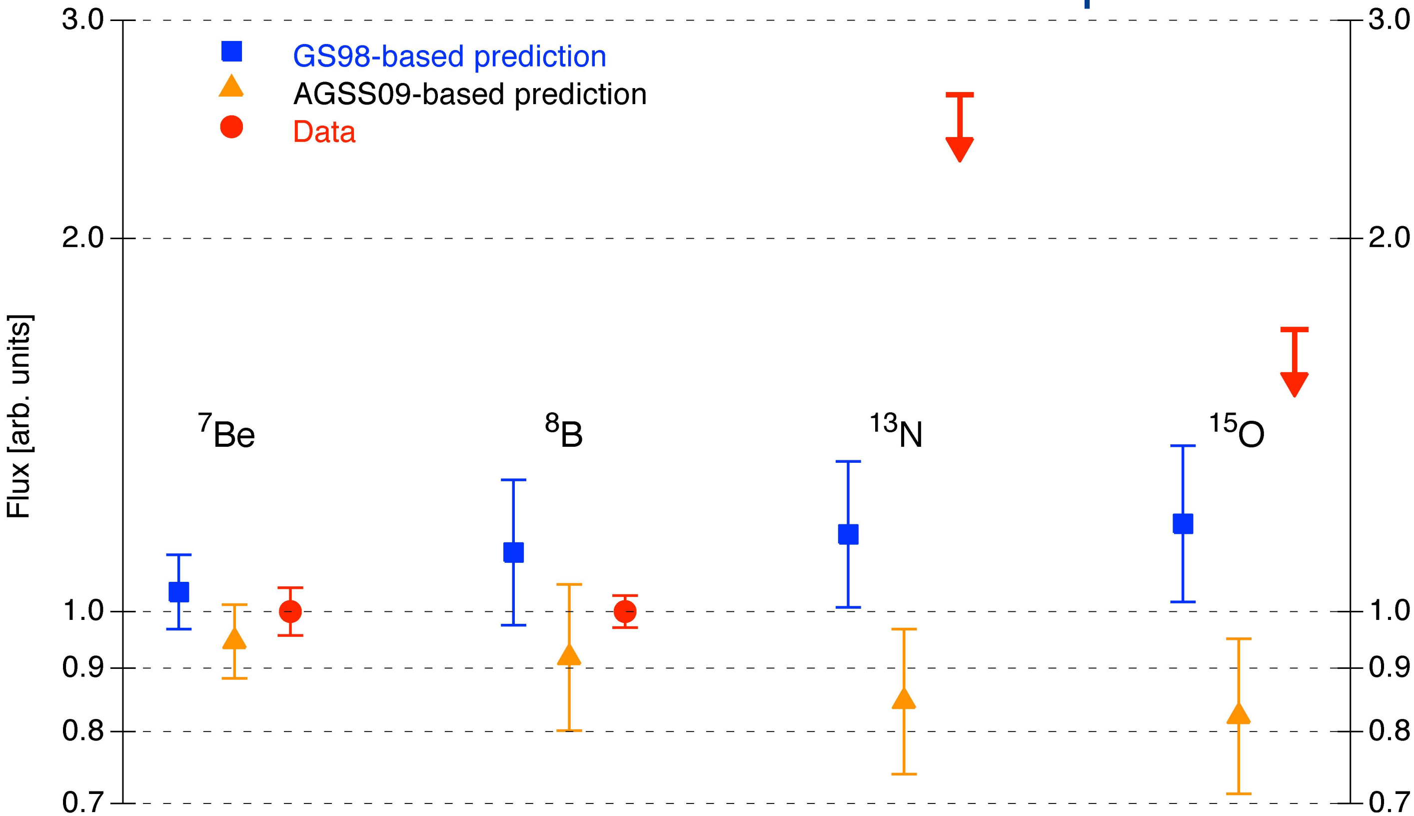
State of the art:

- LUNA cross section data (2006) led a breakthrough in precision.
- Big Bang energy range now covered with precision data (LUNA+others).
- Extrapolation to solar Gamow peak now much better constrained.

The way forward:

- Need one comprehensive data set connecting low-energy LUNA data with the many high-energy data sets!

Solar neutrino fluxes: Data and model predictions

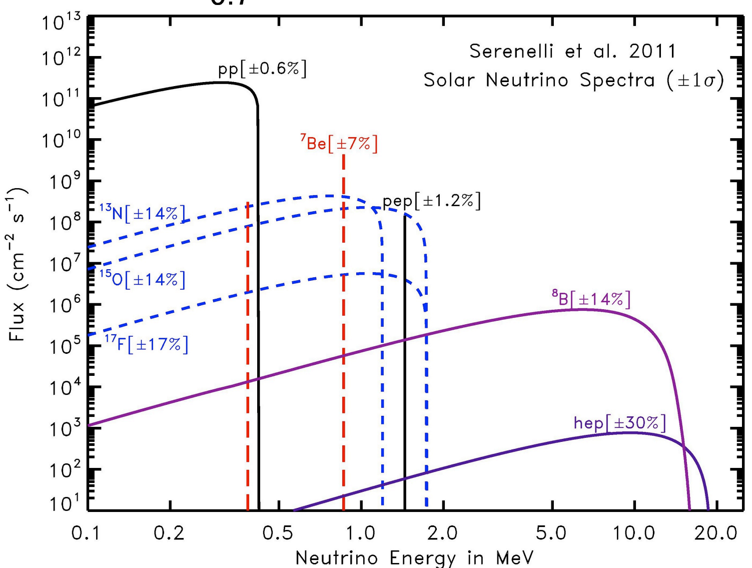


Neutrino fluxes:
Standard Solar Model;
Antonelli et al., 1208.1356

GS98 = Old, high CNO elemental abundances

AGSS09 = New, low CNO elemental abundances

- ^{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!**



What drives the uncertainties in the predicted solar neutrino fluxes?

Nuclear reaction rates (S_{11}, S_{33}, S_{34}, S_{17}, $S_{1,14}$)

	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
^{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

^{3}He(α,γ)^{7}Be

^{7}Be(p,γ)^{8}B

^{14}N(p,γ)^{15}O

- **Nuclear reaction rates are the largest contributor to the uncertainty!**

Pelletron, opened