Underground nuclear astrophysics at the Dresden Felsenkeller: status report

NAVI Annual Meeting, 16.12.2013

Daniel Bemmerer

Nuclear Astrophysics Virtual Institute

EuroGENESIS
Origin of the Elements and Nuclear History of the Universe

TECHNISCHE UNIVERSITÄT DRESDEN

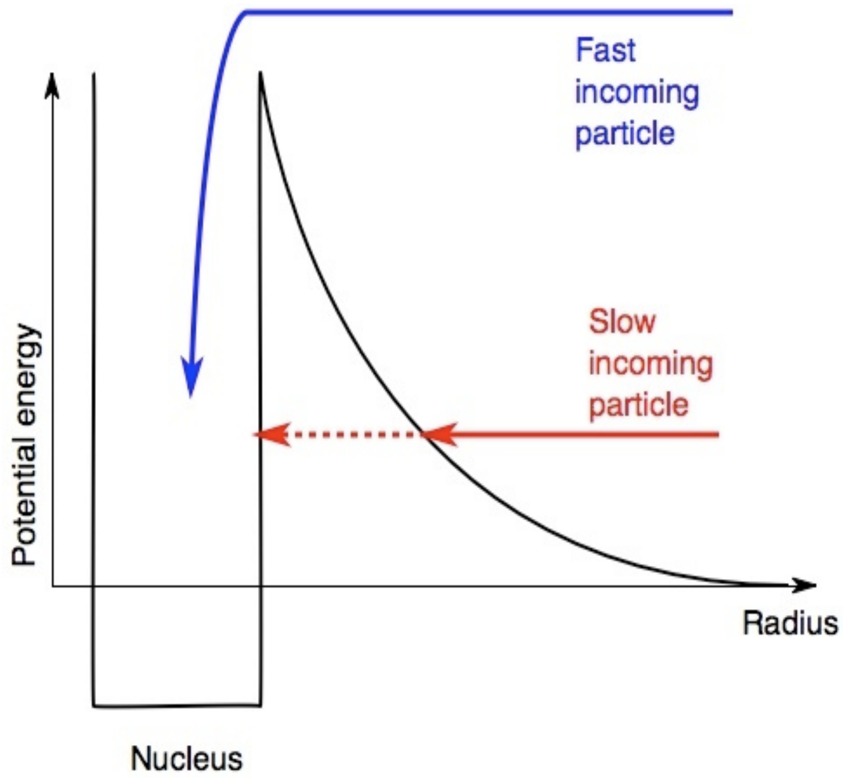
Partner von DRESDEN concept
exzellenz-dresden.de

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Underground nuclear astrophysics at the Dresden Felsenkeller: status report

- Motivation, scope, and methods
- Status quo at Felsenkeller
- Activation study using Felsenkeller: ^{40}Ca(α,γ)^{44}Ti
- Feasibility study and background intercomparison
- Accelerator purchase and upgrades
- Funding, people, outlook

Nuclear reaction cross section σ for low-energy charged particles



- Typical Coulomb barrier height : ~ MeV
- Typical stellar temperature k_B * T ~ keV

→ The energy dependence of the cross section is dominated by the tunneling probability.

Definition of the astrophysical S-factor *S(E)*:

$$\sigma(E) = \frac{S(E)}{E} \exp\left[-2\pi Z_1 Z_2 \alpha \left(\frac{\mu c^2}{2E}\right)^{0.5}\right]$$

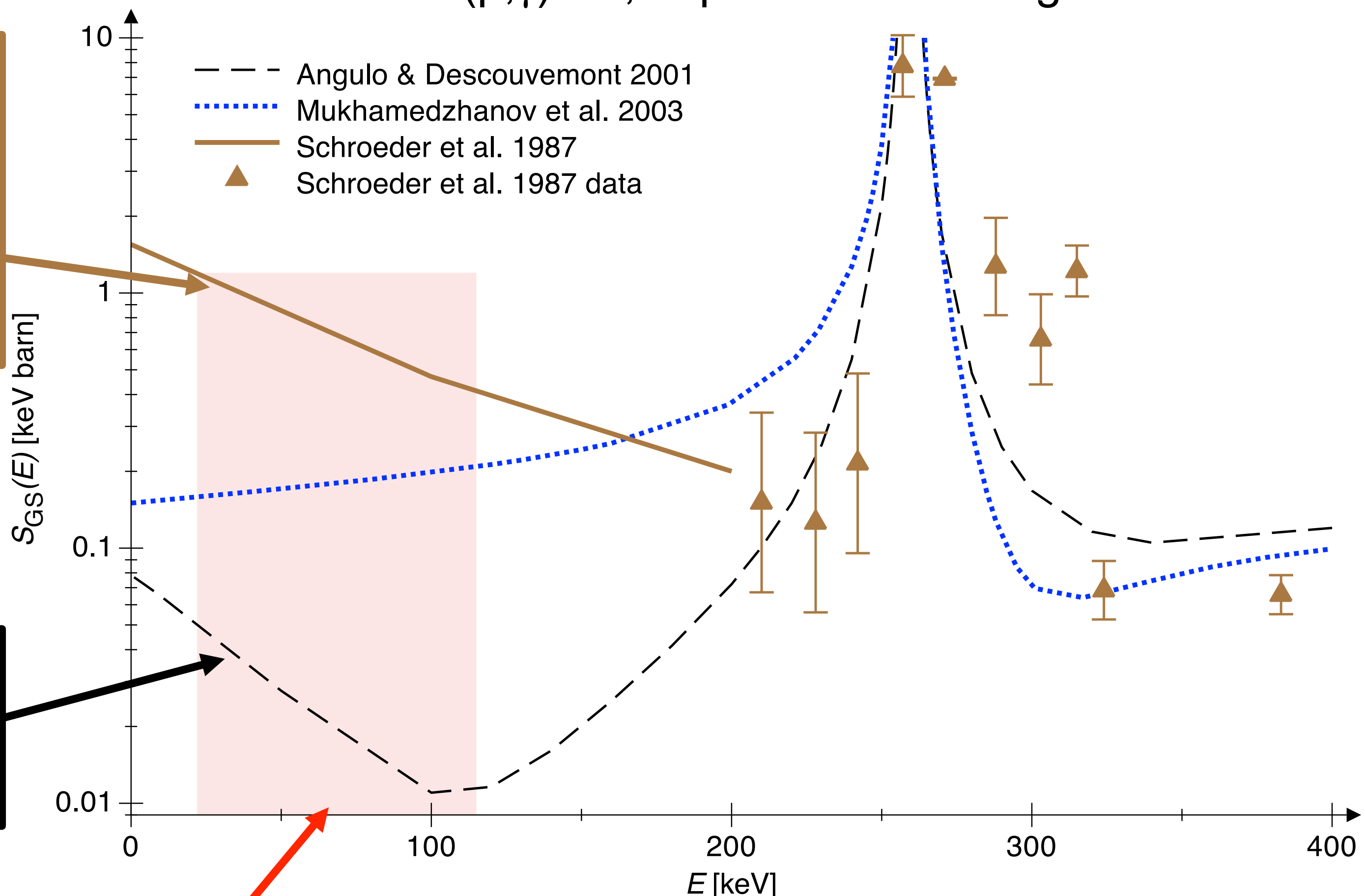
Either extrapolate –

or measure at very low counting rates, underground!

Extrapolations can be ambiguous: Example CNO cycle

State of the art, 2004
$^{14}N(p,\gamma)^{15}O$, capture to the ^{15}O ground state

Schröder et al. 1987:
Ground state capture contributes 50% of total S factor.
Adopted in astrophysical reaction rate compilations!



Angulo et al. 2001:
Ground state capture contributes 5% of total S factor.

Astrophysically relevant energy range

LUNA laboratory at Gran Sasso / Italy

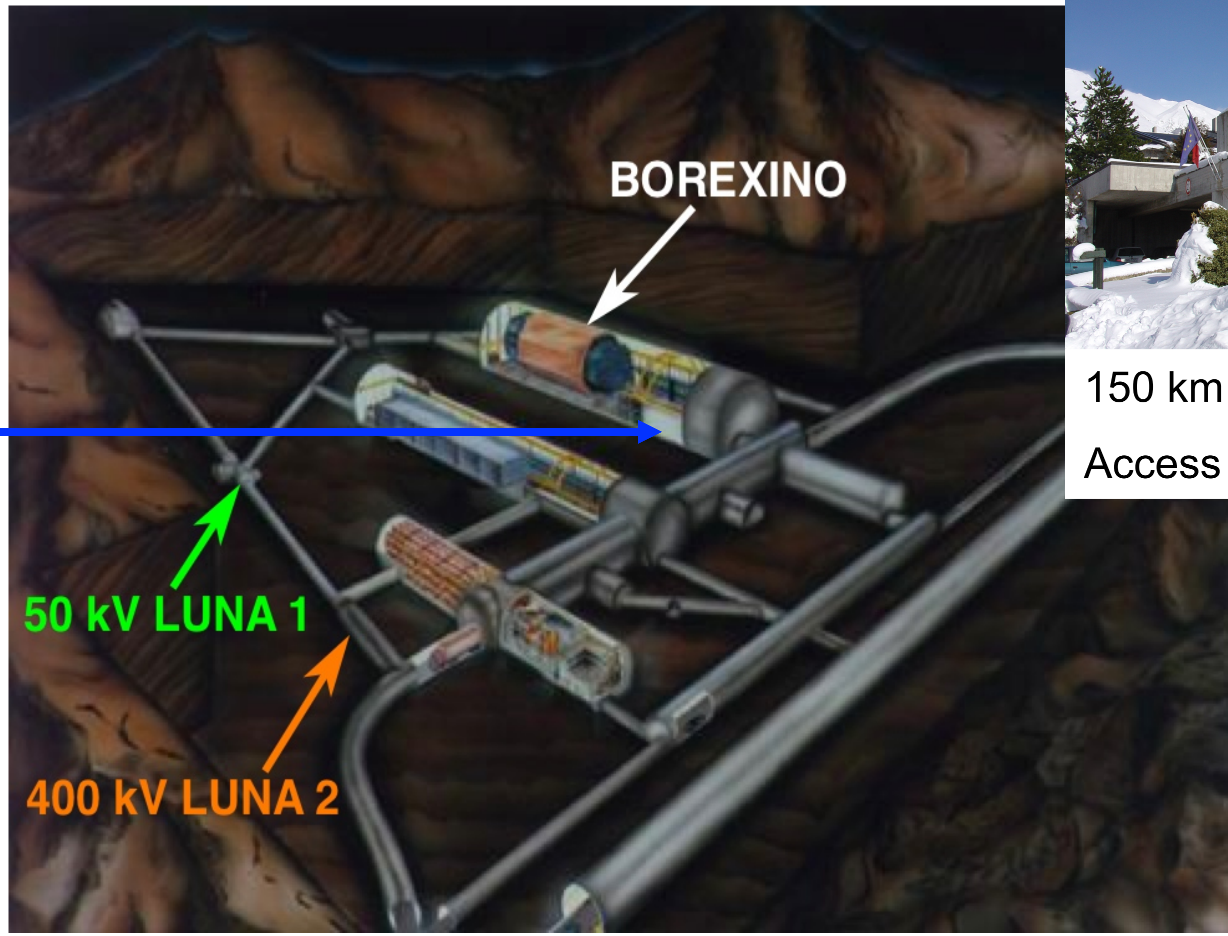
150 km from Rome

Access by motorway

LUNA-MV, planned

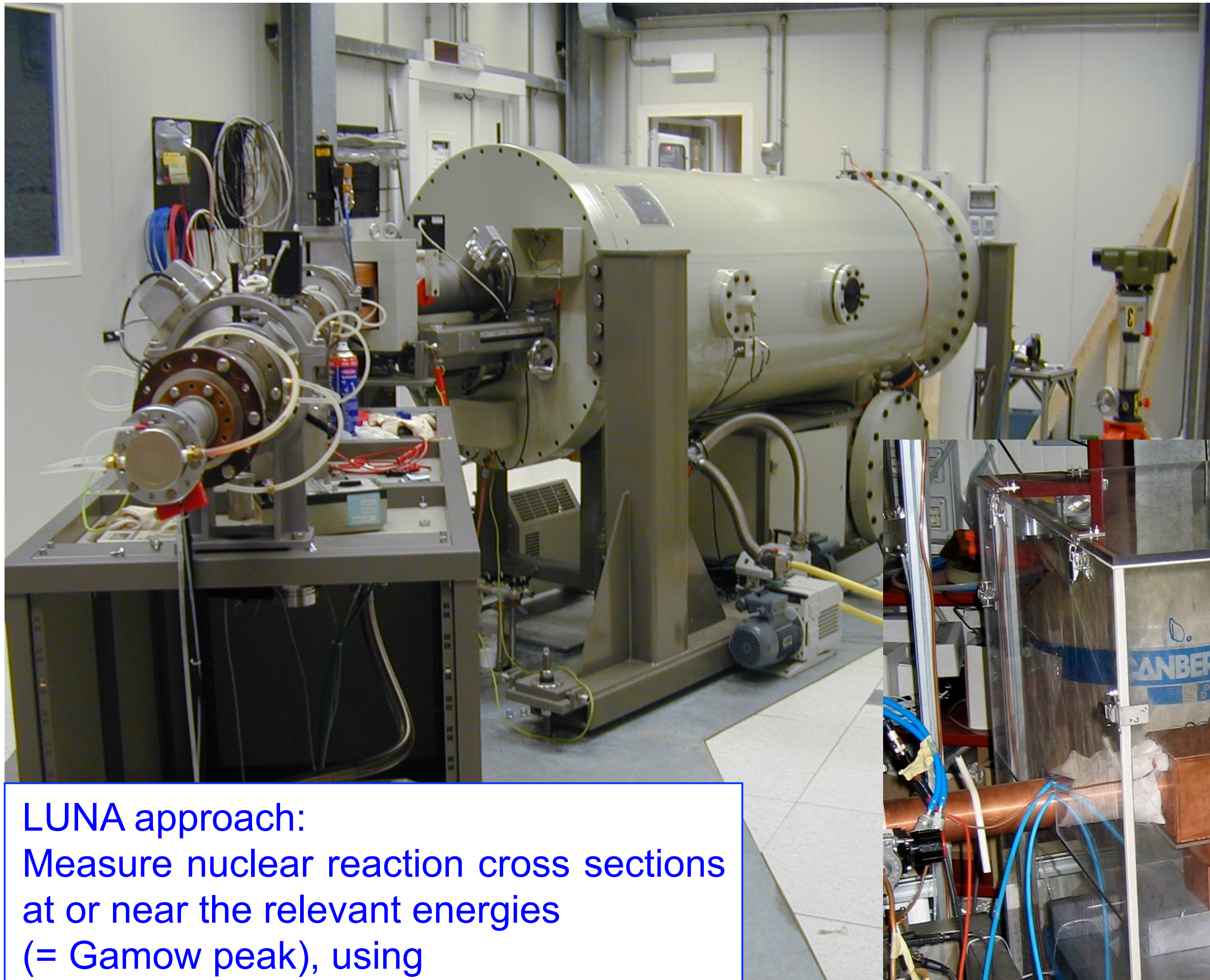
1992-2001

2000-2014



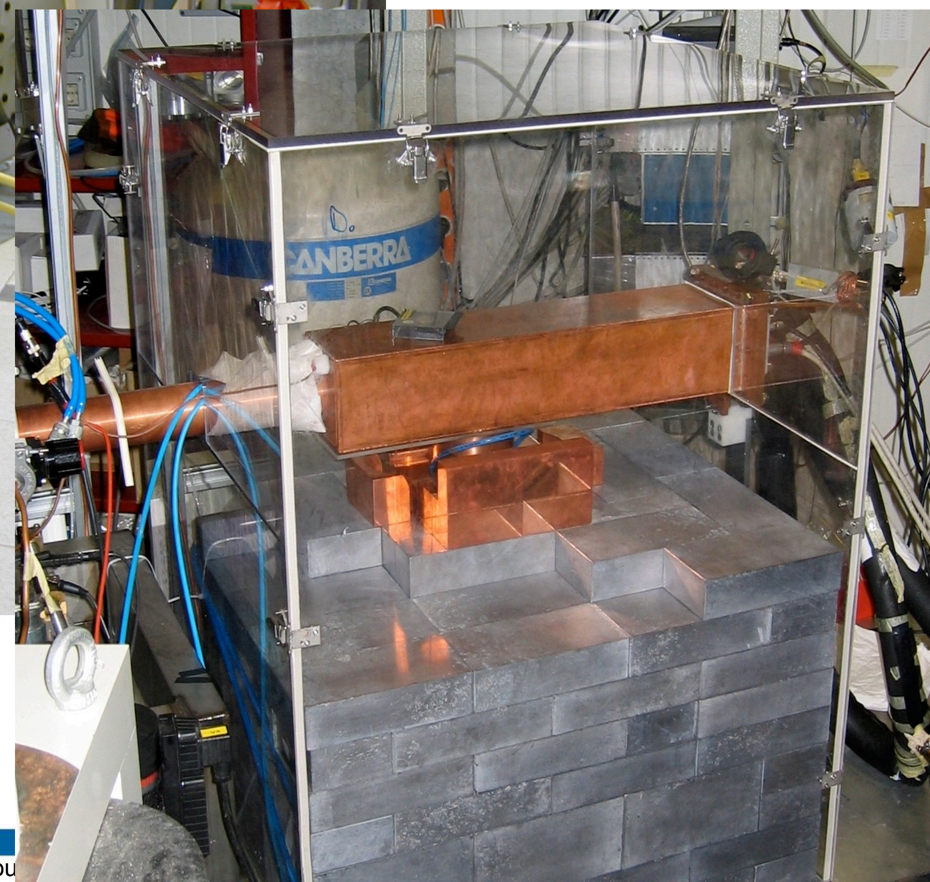
~1400 m rock 10^6 μ-reduction 10^3 n-reduction

The LUNA 0.4 MV accelerator deep underground



LUNA = Laboratory Underground for Nuclear Astrophysics

- Italy
- Germany (Dresden, Bochum)
- Hungary
- UK

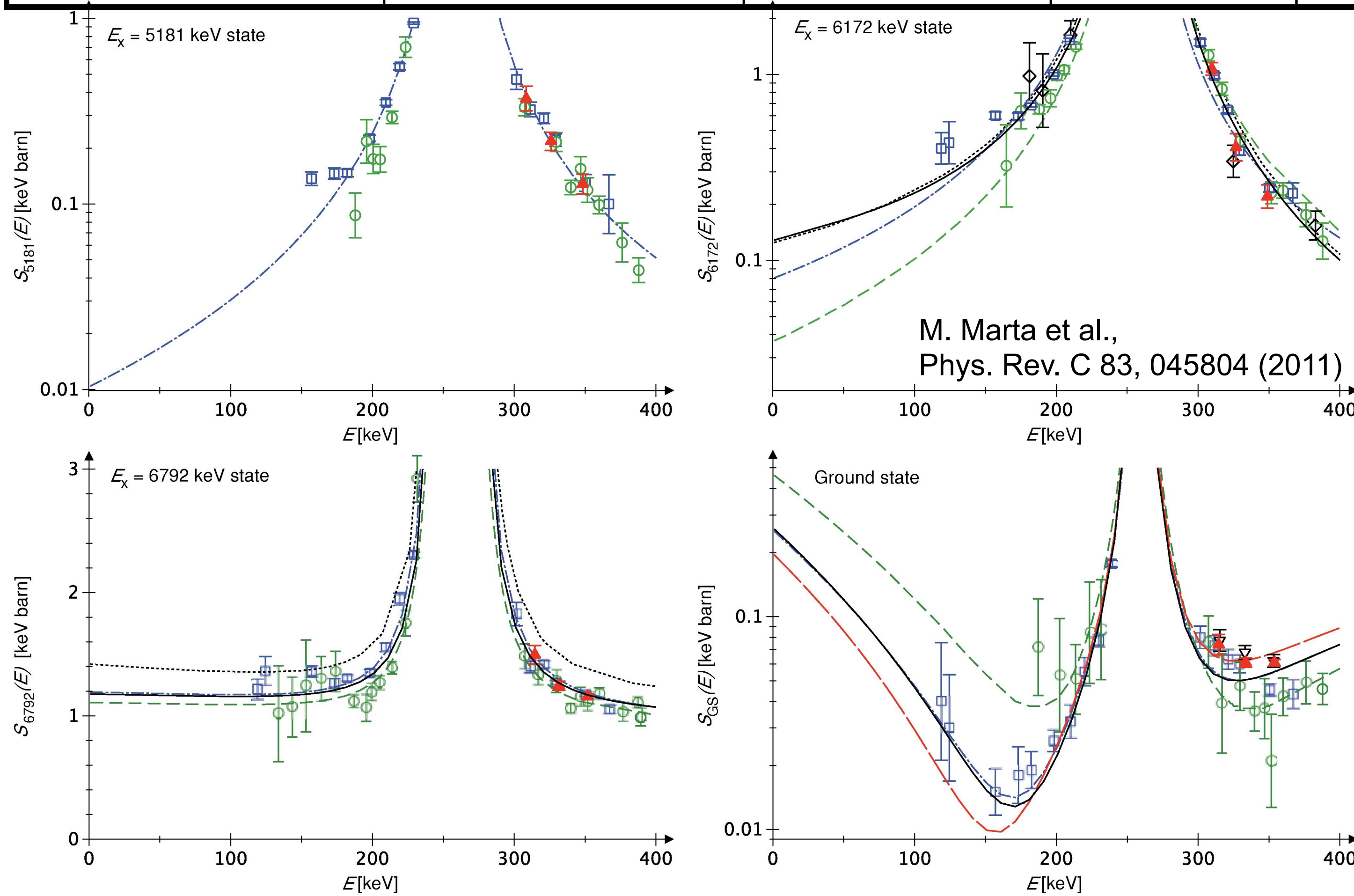


LUNA approach:
Measure nuclear reaction cross sections at or near the relevant energies (= Gamow peak), using

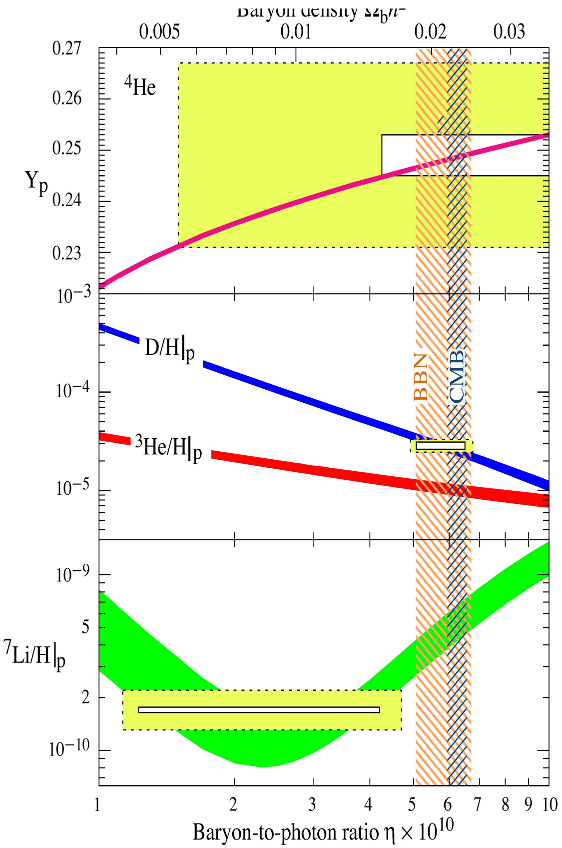
- high beam intensity
- low background
- great patience

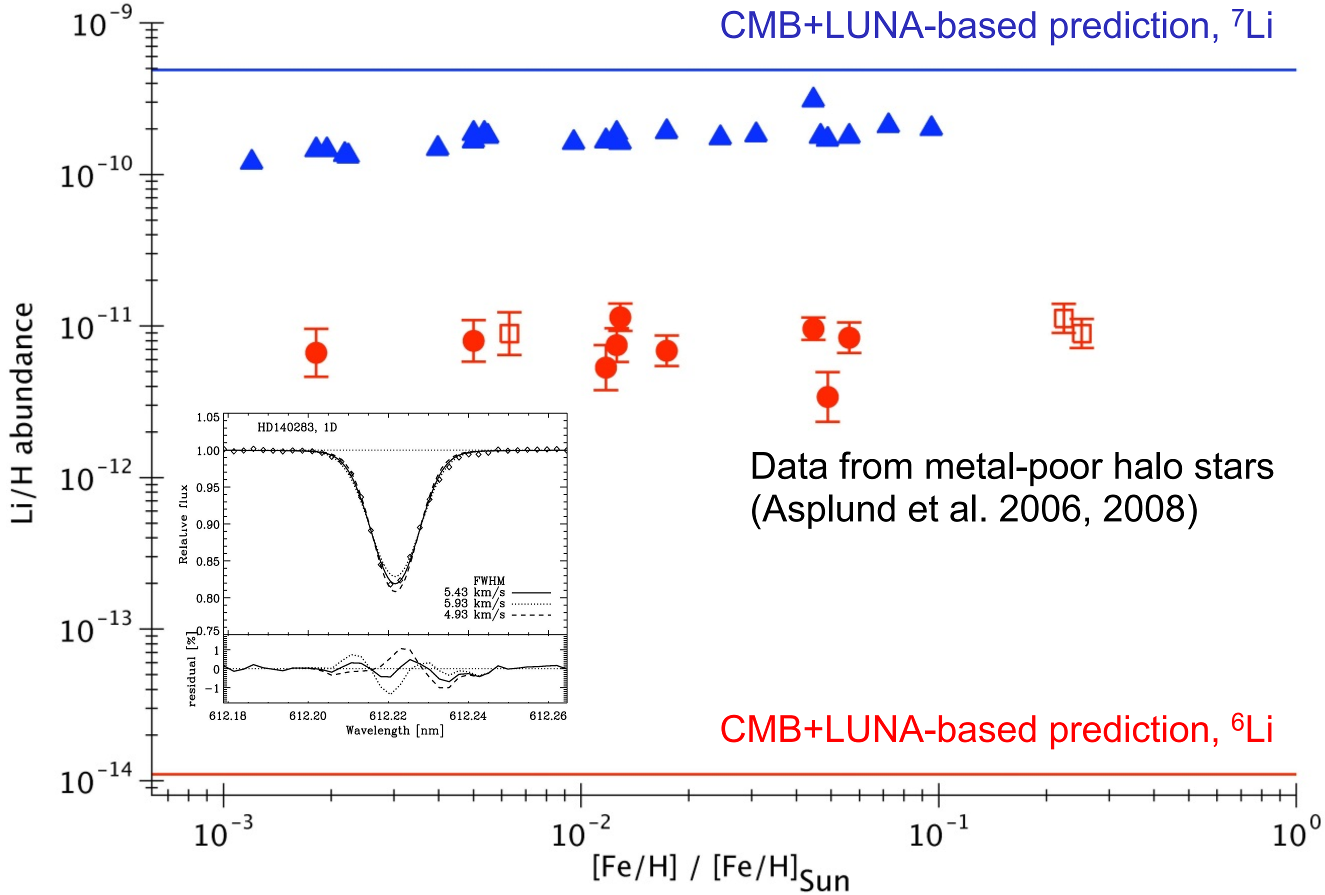
LUNA divided the $^{14}N(p,\gamma)^{15}O$ cross section by 2!

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)



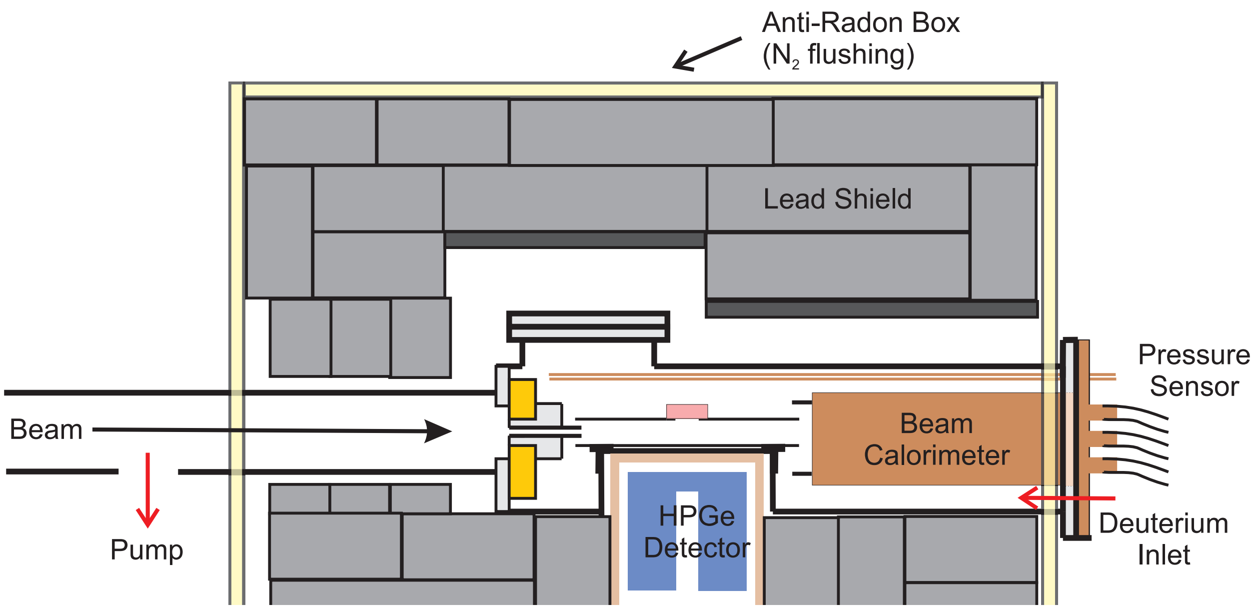
The Spite abundance plateau and Big-Bang lithium



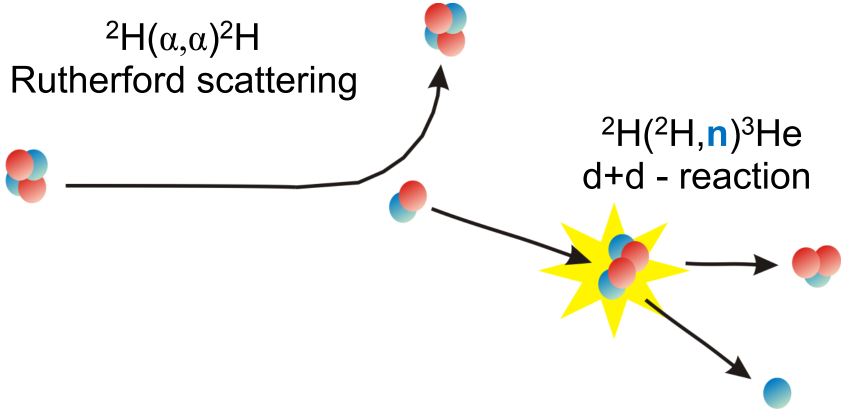


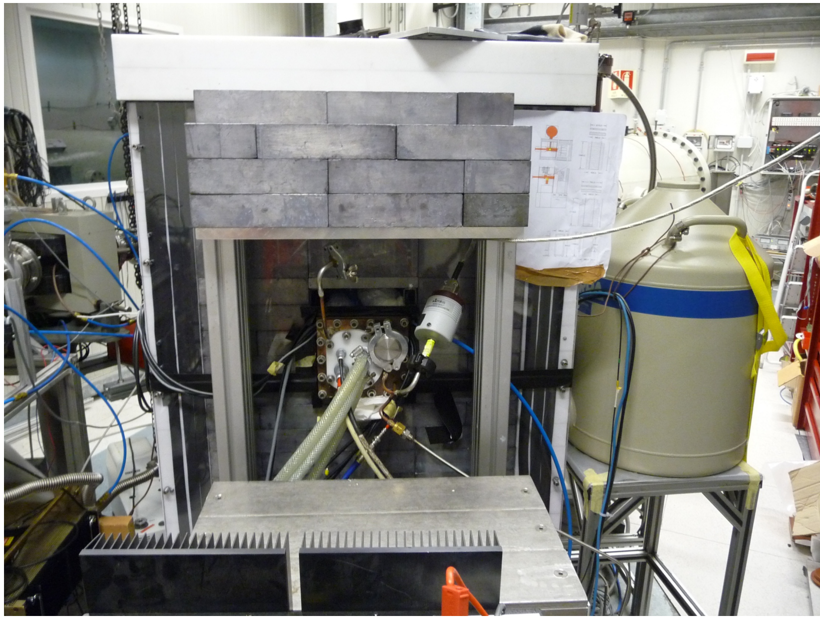
- Cosmic ^{7}Li problem: Less ^{7}Li in old stars than predicted.
  Big-Bang ^{7}Li production mainly by ^{3}He$(\alpha,\gamma)^7$Be ➔ ^{7}Li
- Possible cosmic ^{6}Li problem: Reports of ^{6}Li in old stars.
  Big-Bang ^{6}Li production mainly by the ^{2}H$(\alpha,\gamma)^6$Li reaction.
- **LUNA addresses both ^{7}Li and ^{6}Li!**

$^{2}H(\alpha,\gamma)^{6}Li$ experiment at LUNA, setup

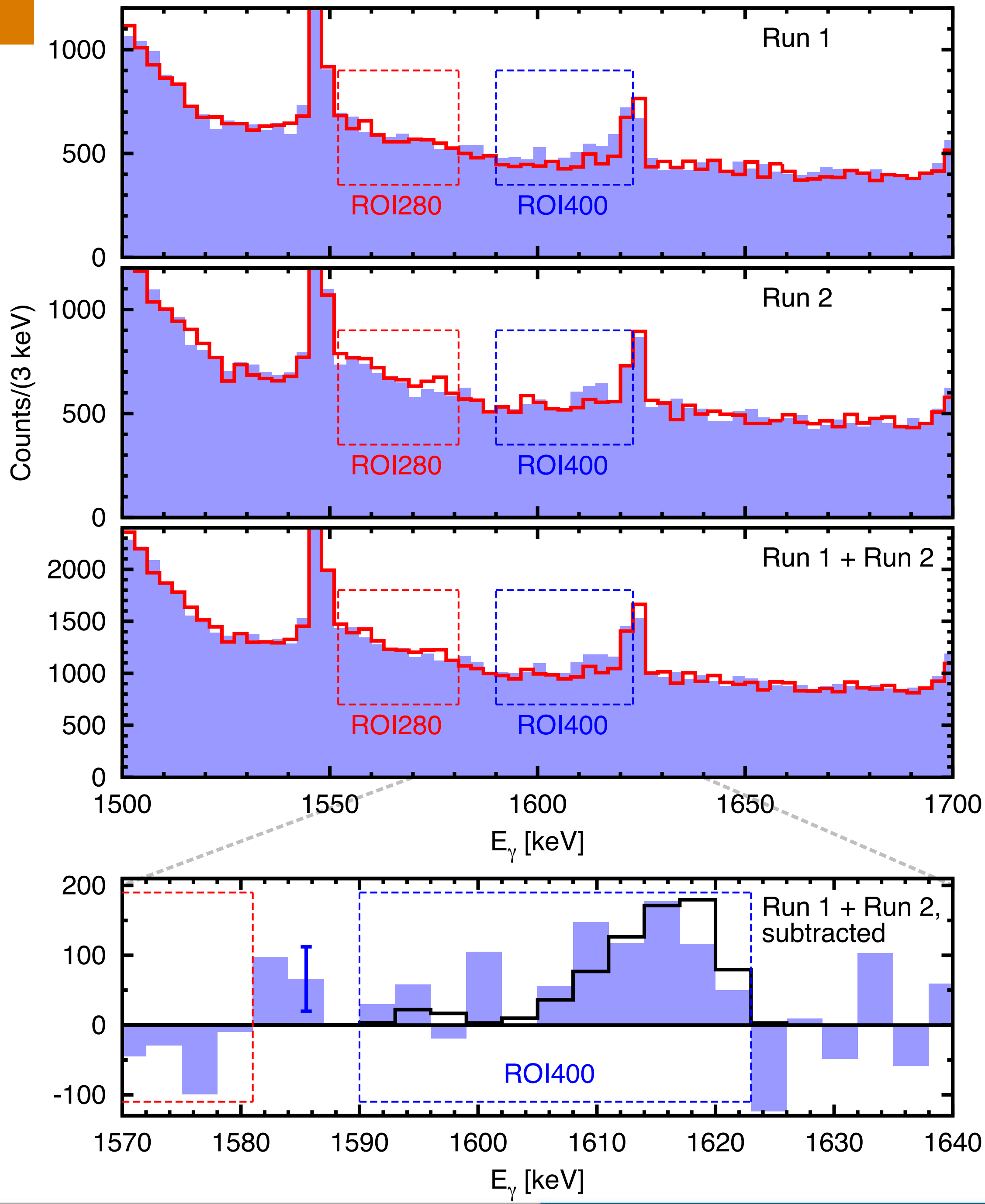


Main background from a two-step process:

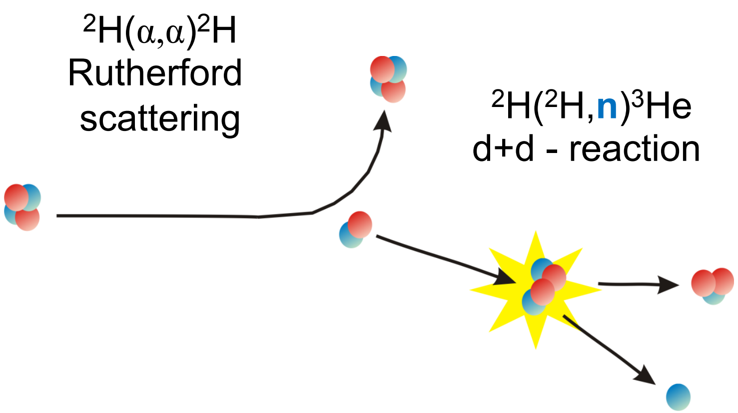




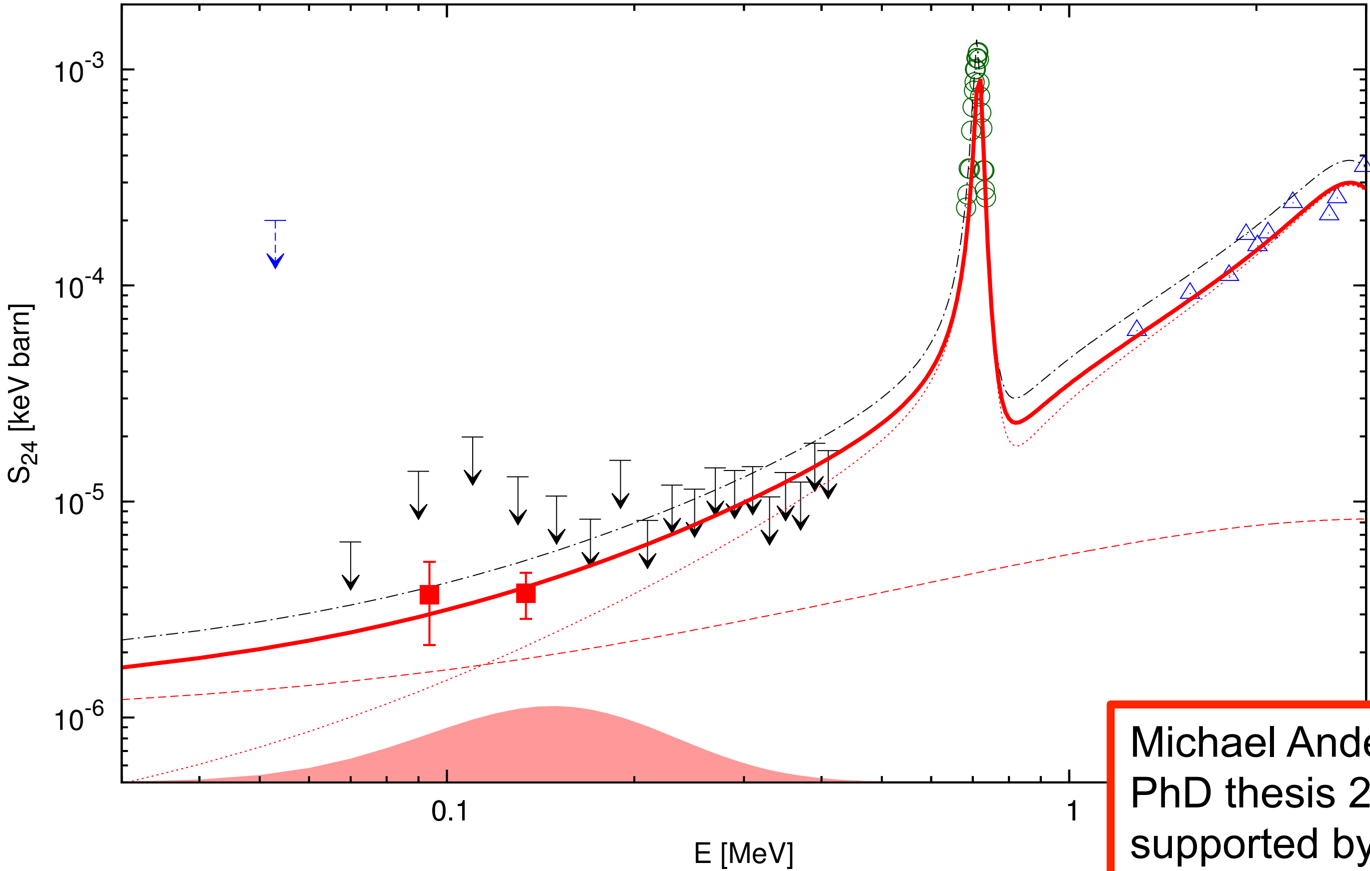
$^2H(\alpha,\gamma)^6Li$ spectra



Main background from a two-step process:



$^{2}H(\alpha,\gamma)^{6}Li$, LUNA results for the S factor and the ^{6}Li abundance



Michael Anders (HZDR), PhD thesis 2013, supported by DFG

- First direct data point in the Big Bang energy window
- Determine primordial $^{6}Li/^{7}Li$ ratio = $(1.7 \pm 0.4) * 10^{-5}$ entirely from experimental data
- To be compared to reports of $^{6}Li/^{7}Li \sim 10^{-2}$

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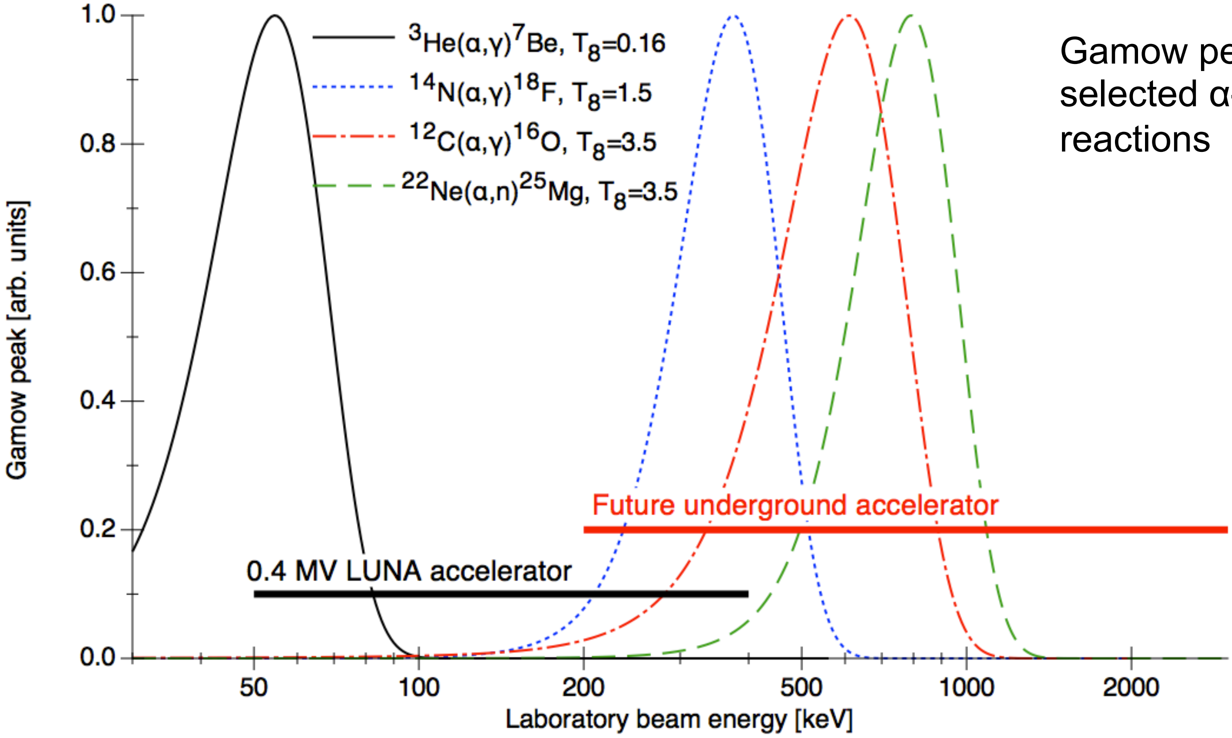
Limitations of the existing LUNA 0.4 MV accelerator



Gamow peak for selected α-induced reactions

NuPECC
Long Range Plan 2010:

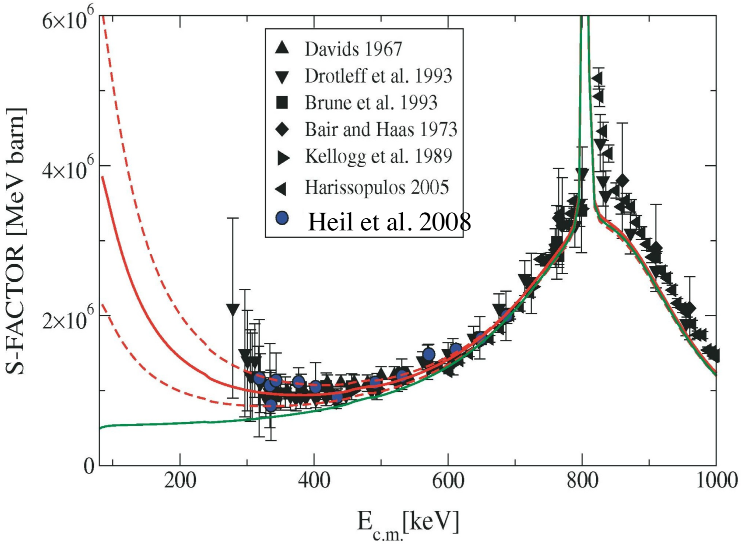
"An immediate, pressing issue is to select and construct the next generation of underground accelerator facilities. (…)
There are a number of proposals being developed in Europe and it is vital that construction of one or more facilities starts as soon as possible."

- Many reactions cannot be studied with a 0.4 MV accelerator alone.
  - Solar fusion reactions
  - Stellar helium and carbon burning
  - Neutron sources for the astrophysical s-process

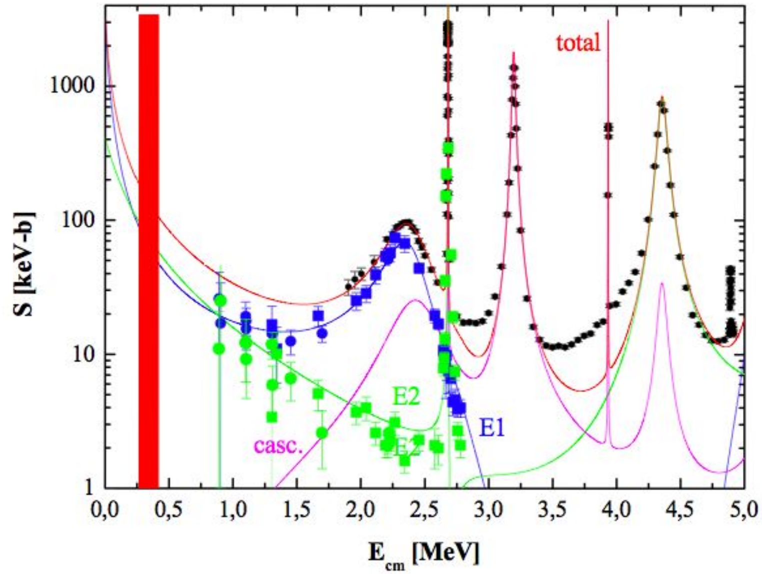
➔ **A new, higher-energy underground accelerator is needed!**

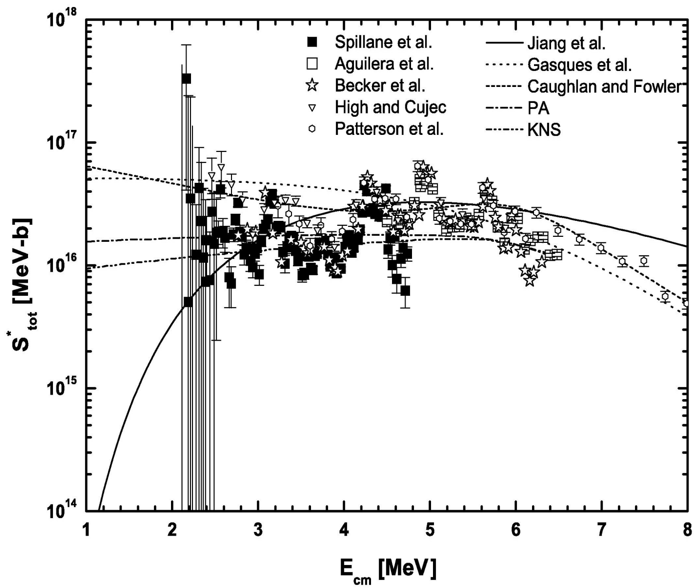
A new, higher-energy accelerator underground: Science case (1)

Neutron sources for the s-process
- $^{13}C(\alpha,n)^{16}O$
- $^{22}Ne(\alpha,n)^{25}Mg$



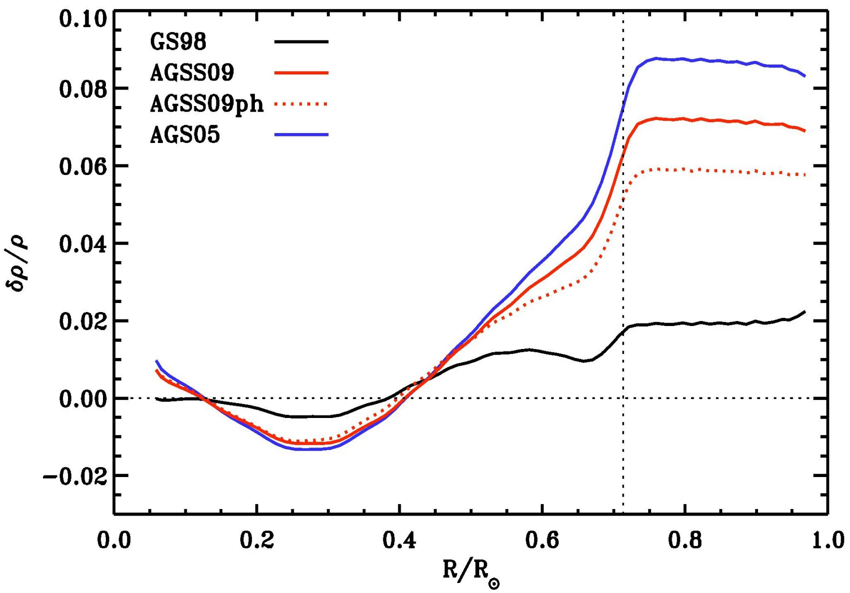
Helium burning
- $^{12}C(\alpha,\gamma)^{16}O$
- $^{14}N(\alpha,\gamma)^{18}F$
- $^{15}N(\alpha,\gamma)^{19}F$
- $^{18}O(\alpha,\gamma)^{22}Ne$





Carbon burning
- $^{12}C(^{12}C,\alpha)^{20}Ne$

A new, higher-energy accelerator underground: Science case (2)

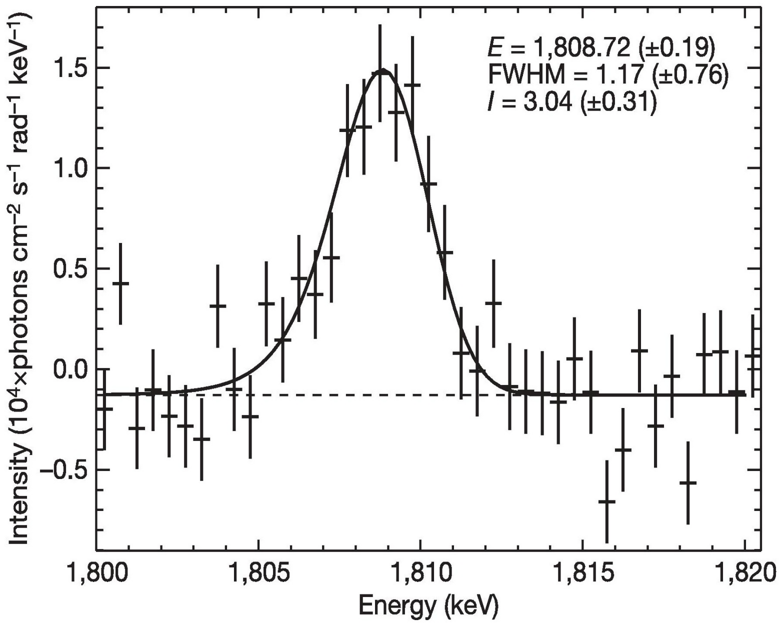


Solar composition problem

- $^{3}He(\alpha,\gamma)^{7}Be$, E>0.4 MeV
- $^{14}N(p,\gamma)^{15}O$, E>0.4 MeV

Radionuclides seen in space based observatories

- ^{26}Al, ^{44}Ti, ^{60}Fe



Applied physics

- $^{1}H(^{15}N,\alpha\gamma)^{12}C$, hydrogen depth profiling

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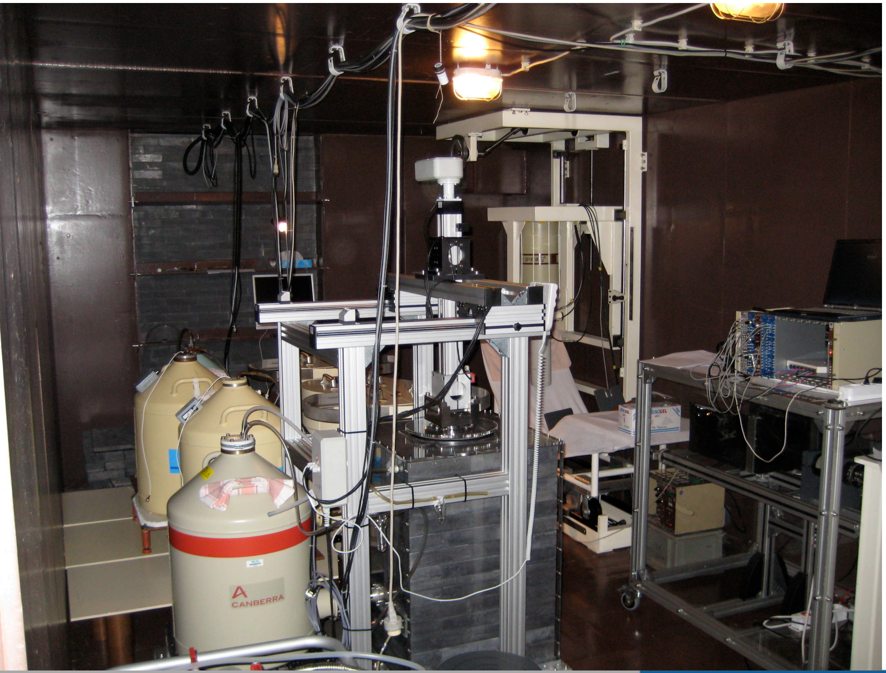
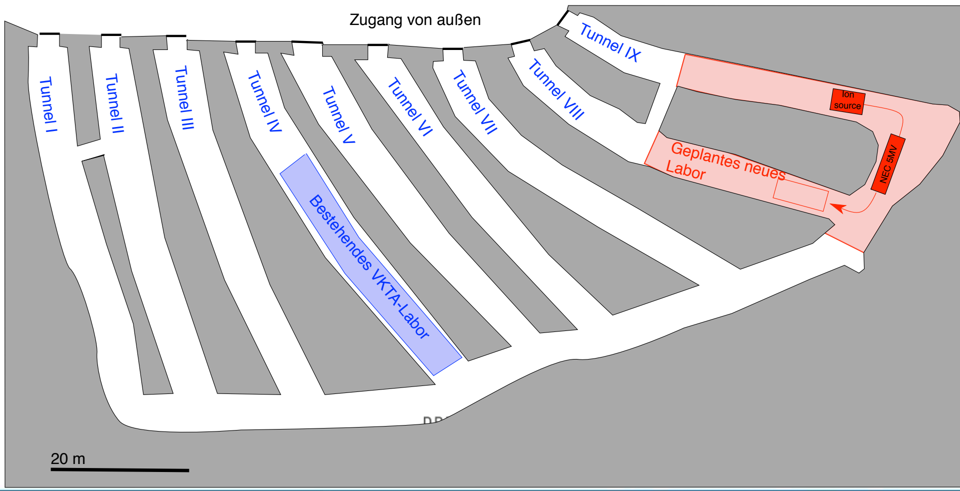
Status quo, Dresden Felsenkeller, below 47 m of rock

- γ-counting facility for analytics, established 1982
- Deepest underground γ-counting lab in Germany
- 10 high-purity germanium detectors
- Since 2009, contract enabling scientific use of Felsenkeller by HZDR (Daniel Bemmerer et al.) and by TU Dresden (Kai Zuber et al.)
- Several active Bachelor + Master + PhD theses using Felsenkeller
- 4 km from TU Dresden, 25 km from HZDR campus
- Underground space available





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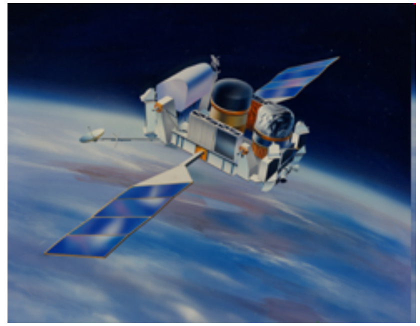
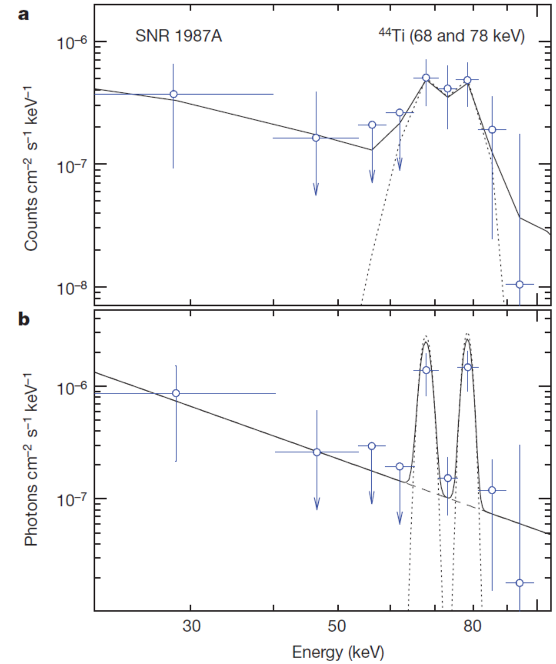
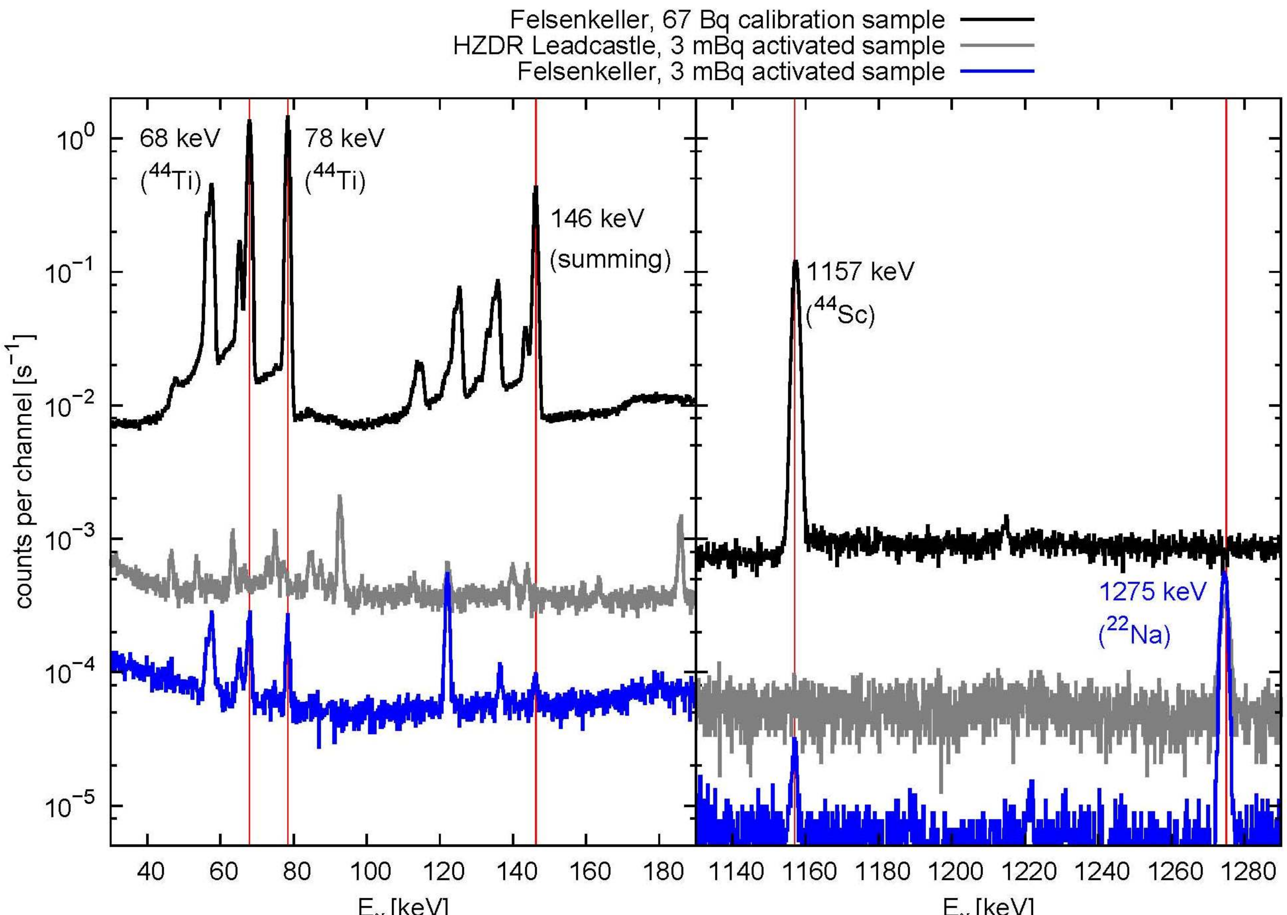
^{44}Ti from SN 1987A and ^{40}Ca(α,γ)^{44}Ti, studied by activation

- ^{44}Ti half-life is 60 years
- Energy source for late light curve of SN1987A



INTEGRAL data: Grebenev et al., Nature (2012)





New, precise data on $^{40}Ca(\alpha,\gamma)^{44}Ti$

K. Schmidt et al.,
Phys. Rev. C 88, 025803 (2013):

- Precise determination of strength of 4.5 MeV resonance triplet
- Activation and in-beam γ-spectrometry methods applied
- Activation sample is planned to be used for AMS in the future

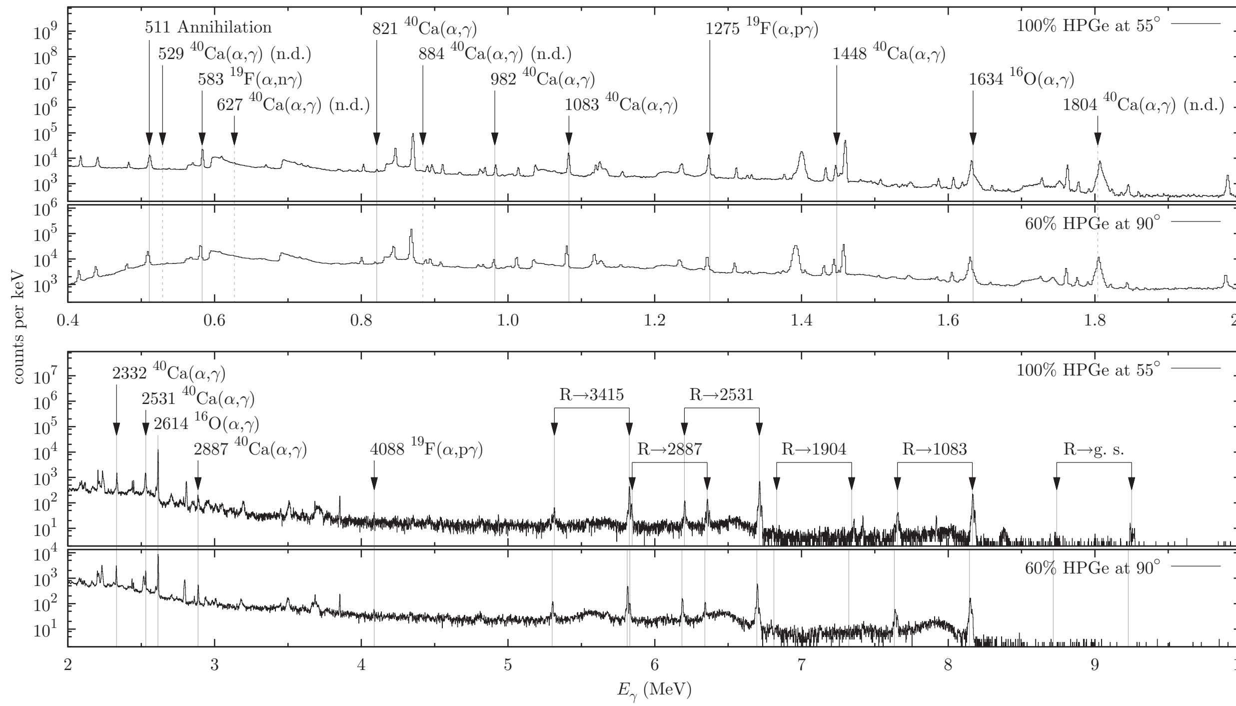


TABLE I. Summed resonance strength of the triplet at $E_\alpha =$ 4.5 MeV, from this work and from the literature.

$\omega\gamma$ (eV)	Reference	Technique
8.3 ± 1.7	Dixon *et al.* [16]	in-beam γ spectroscopy
8.8 ± 3.0	Nassar *et al.* [17]	AMS
7.6 ± 1.1	Vockenhuber *et al.* [18]	recoil detection
9.0 ± 1.2	Robertson *et al.* [20]	in-beam γ spectroscopy
8.4 ± 0.6	present work	activation and in-beam γ spectroscopy

- First paper of planned several papers now published
- PhD project of Konrad Schmidt (HZDR), 2011-2014, supported by DFG

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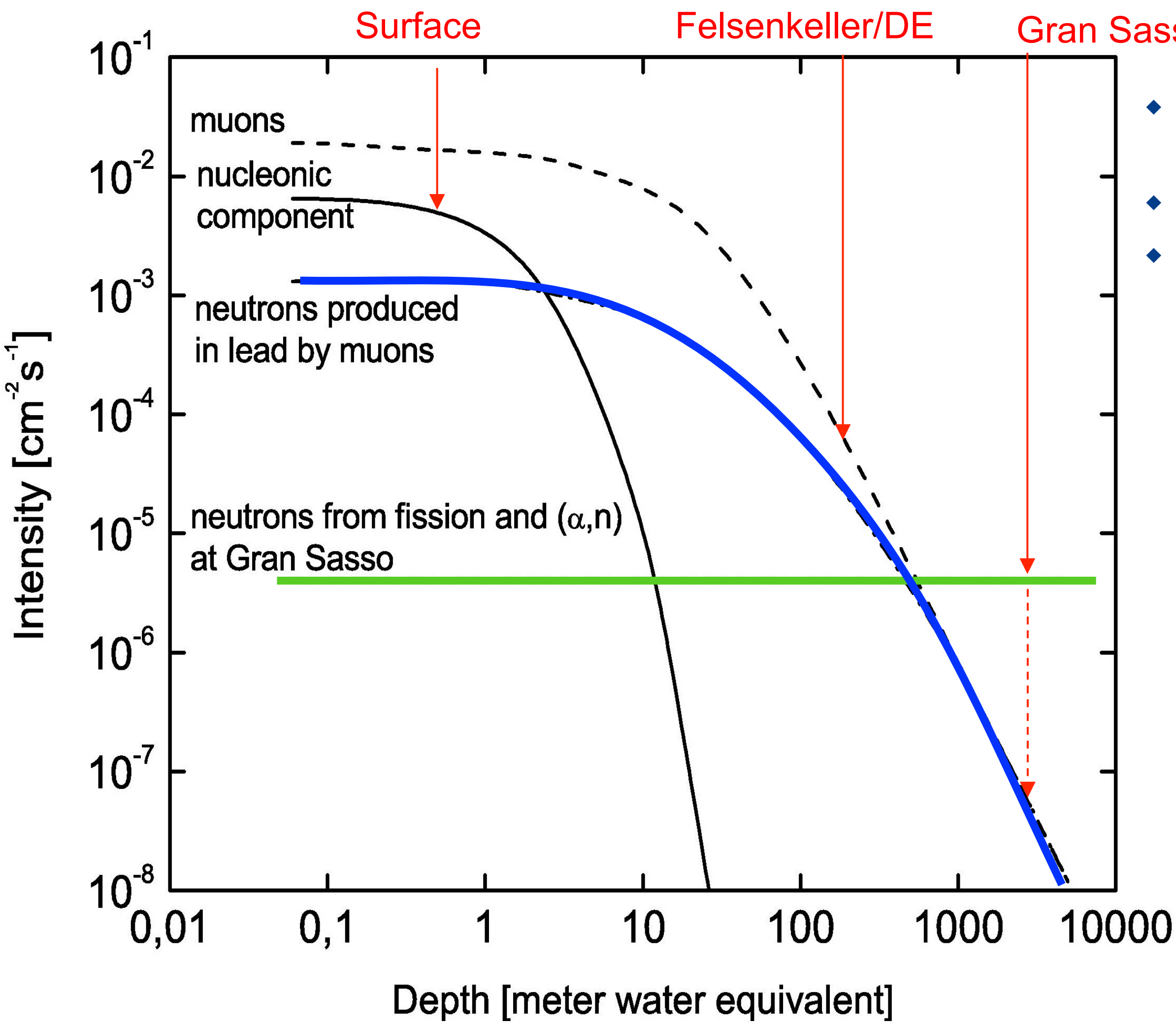
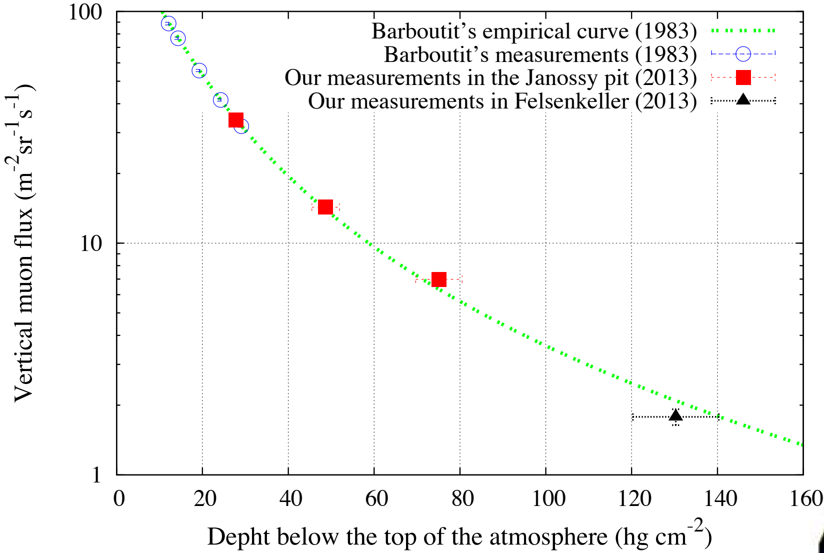
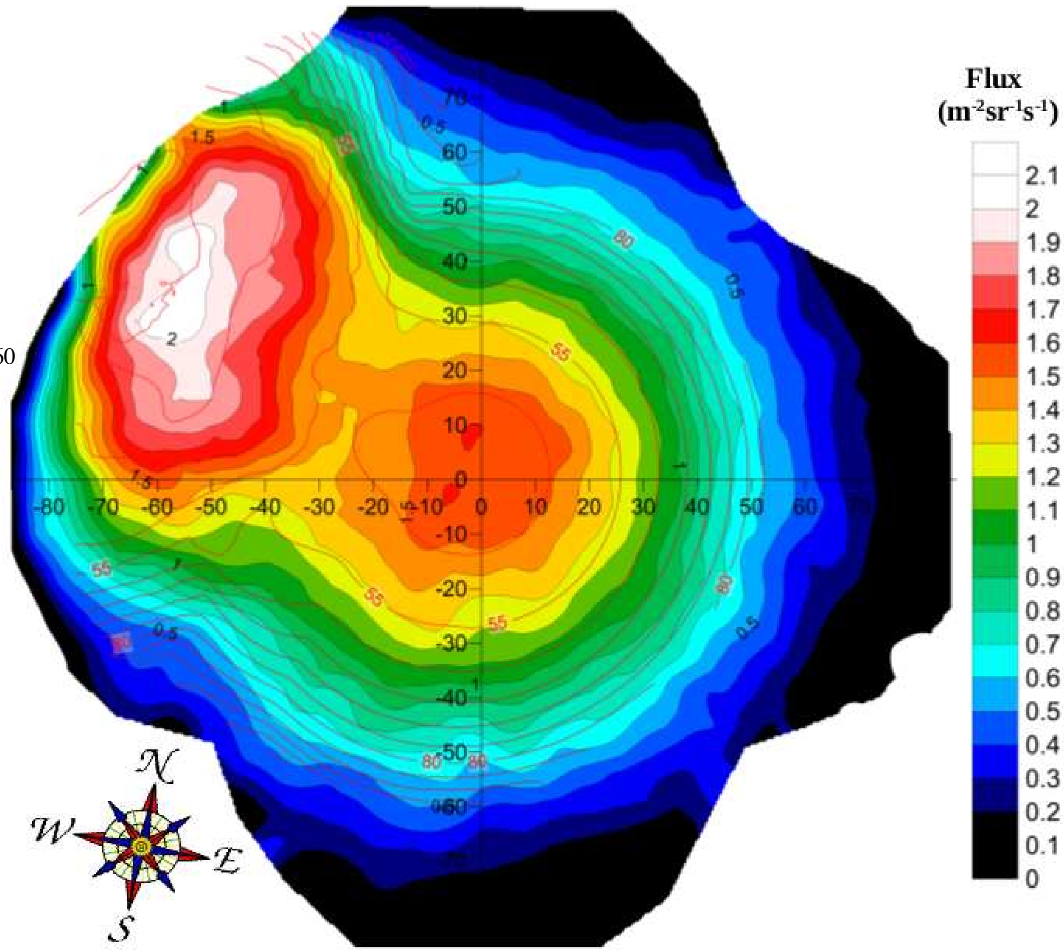
Felsenkeller: Rock overburden, and muon flux reduction



- Muon flux measured and mapped by Budapest group
- Optical mapping of terrain profile
- Overall factor of 30 flux reduction

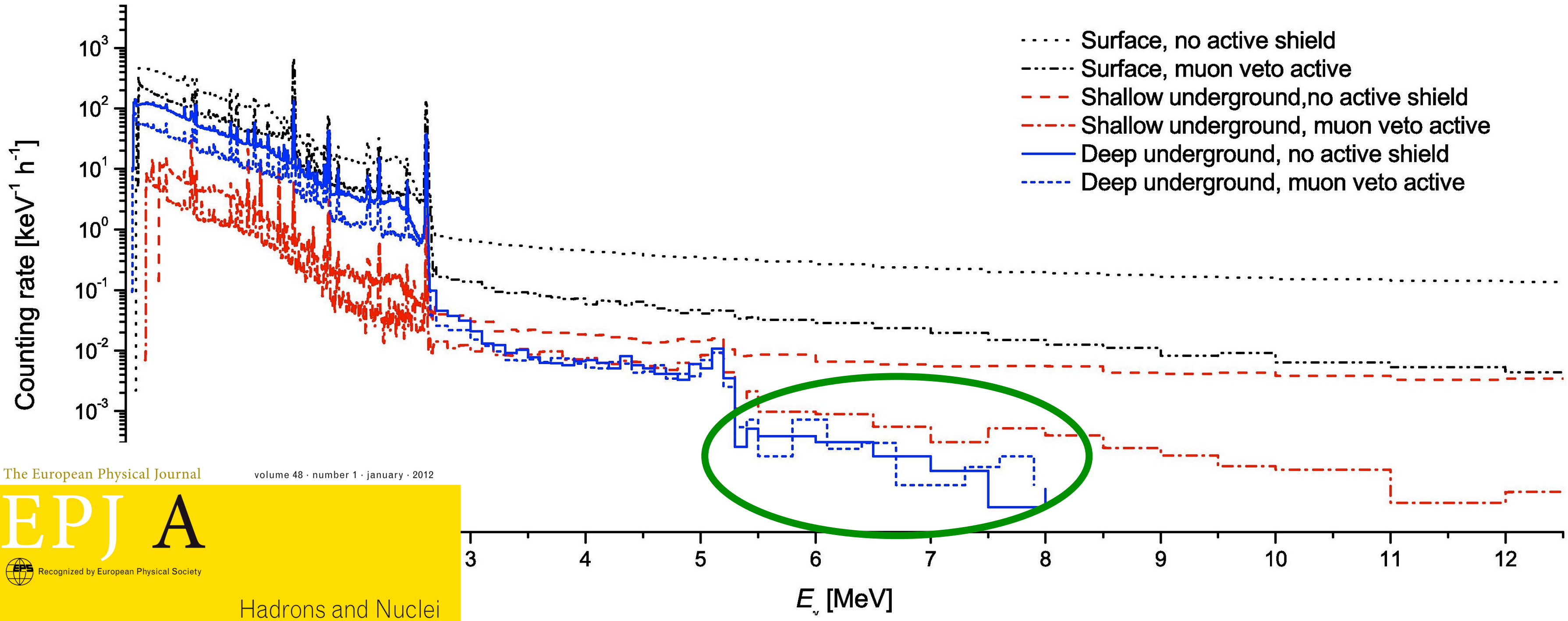
Felsenkeller, muon flux data

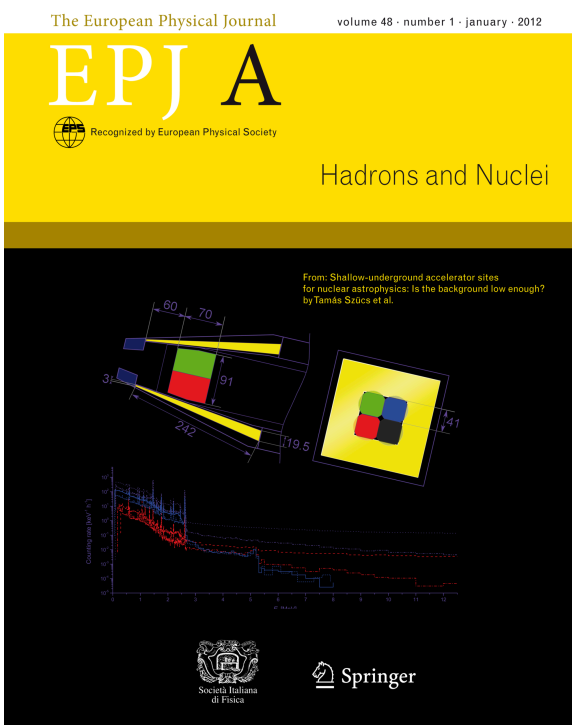




- Measurement with REGARD muon tomograph (Budapest U.)
- Rock overburden equivalent to 130 meter water, slightly higher than in the low-activity lab (110 m.w.e.)
- Precise angular distribution allows to plan active veto accordingly.

Background, in a typical HPGe detector for nuclear astrophysics





→ Felsenkeller: Combination of active veto and 47m rock gives a background close to the deep-underground background at 6-8 MeV.

→ Explanation: Environmental (α,n) neutrons dominate the deep-underground background.

Tamás Szücs et al.,
Eur. Phys. J. A 48, 8 (2012)

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Purchase of 5MV Pelletron accelerator (2012)

- 12-year old, working 5 MV accelerator
- Bought off an insolvent spin-off of York Univ.
- 250 µA upcharge current (double pellet chains)
- Well-suited for low-energy nuclear astrophysics

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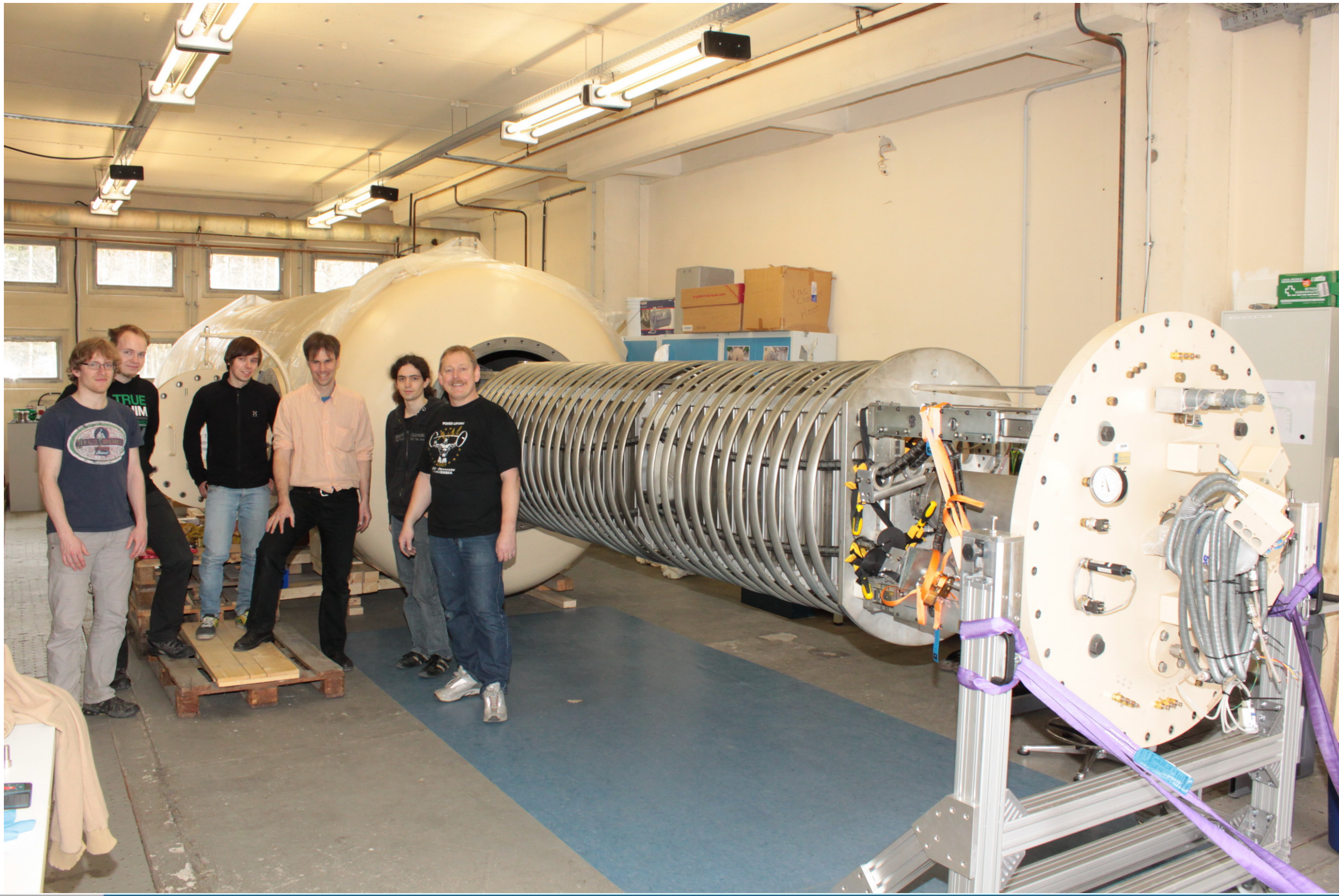
Work at HZDR on upgrading 5MV Pelletron

- All accelerator and beam line components stored at HZDR since July 2012
- Two MC-SNICS cesium sputter ion sources came with the purchase
  $^{12}C^{-}$ beam (designed for ^{14}C): 100 μA
  $^{1}H^{-}$ beam: 100 μA
  but no good intensity for noble gases (He^{-}, Ne^{-}, Ar^{-})

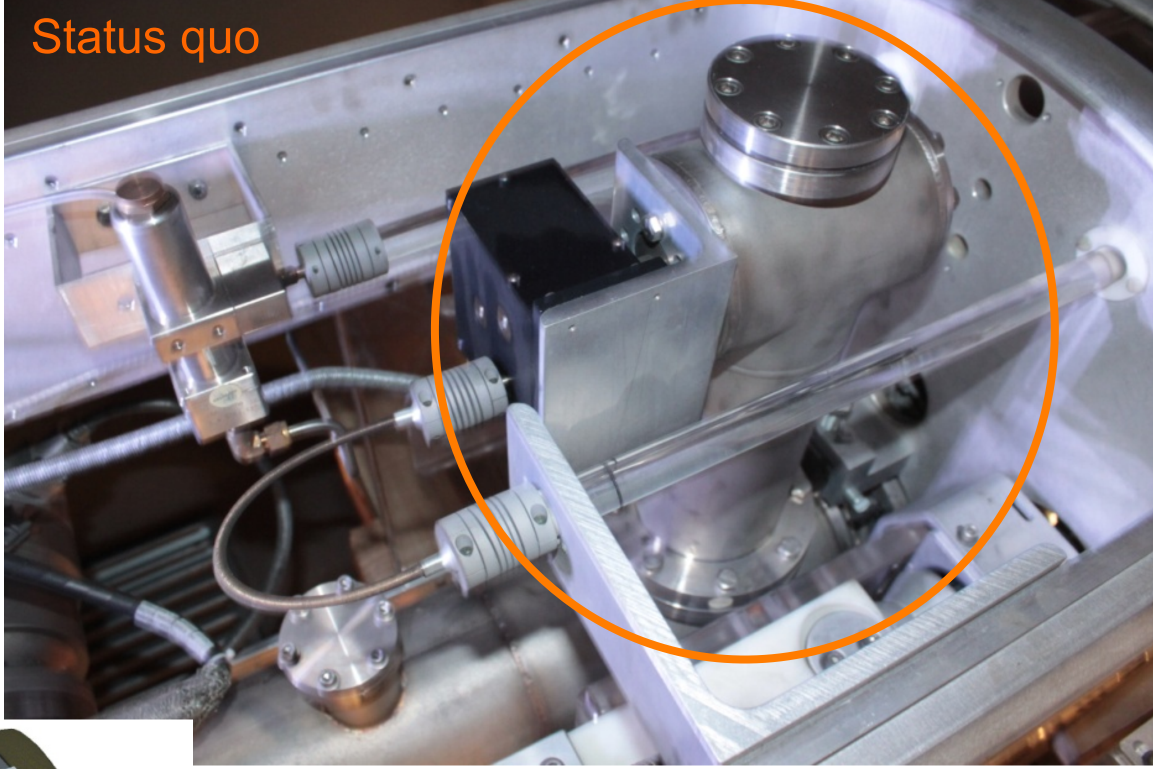
Ongoing projects:

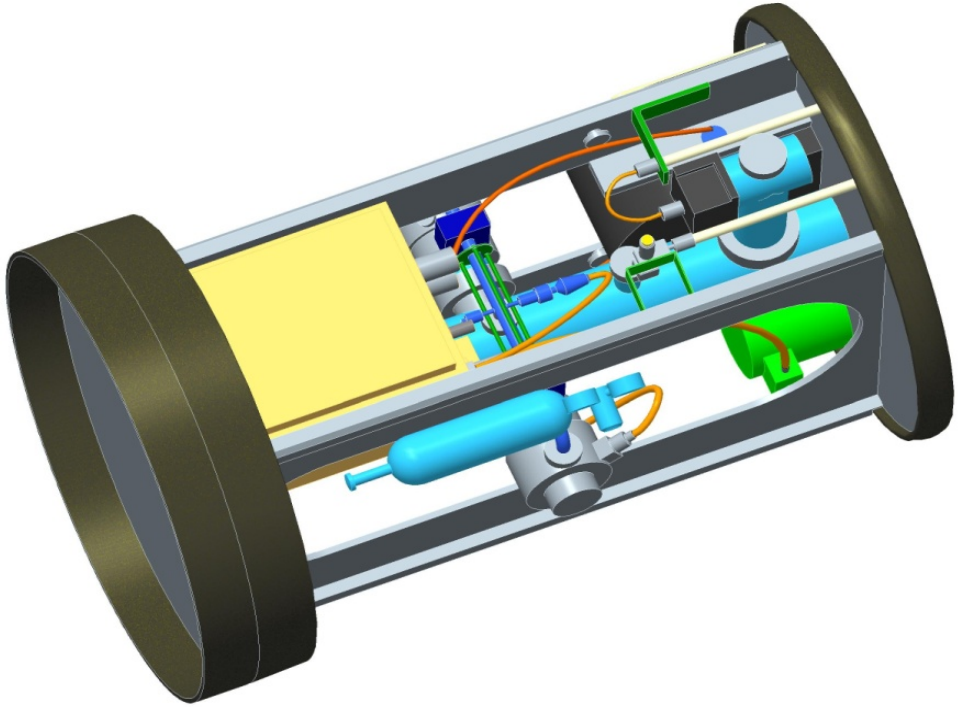
- Terminal ion source for better He^{-}, Ar^{-} beam intensities
- CAMAC control software
- Windowless gas target



High voltage terminal

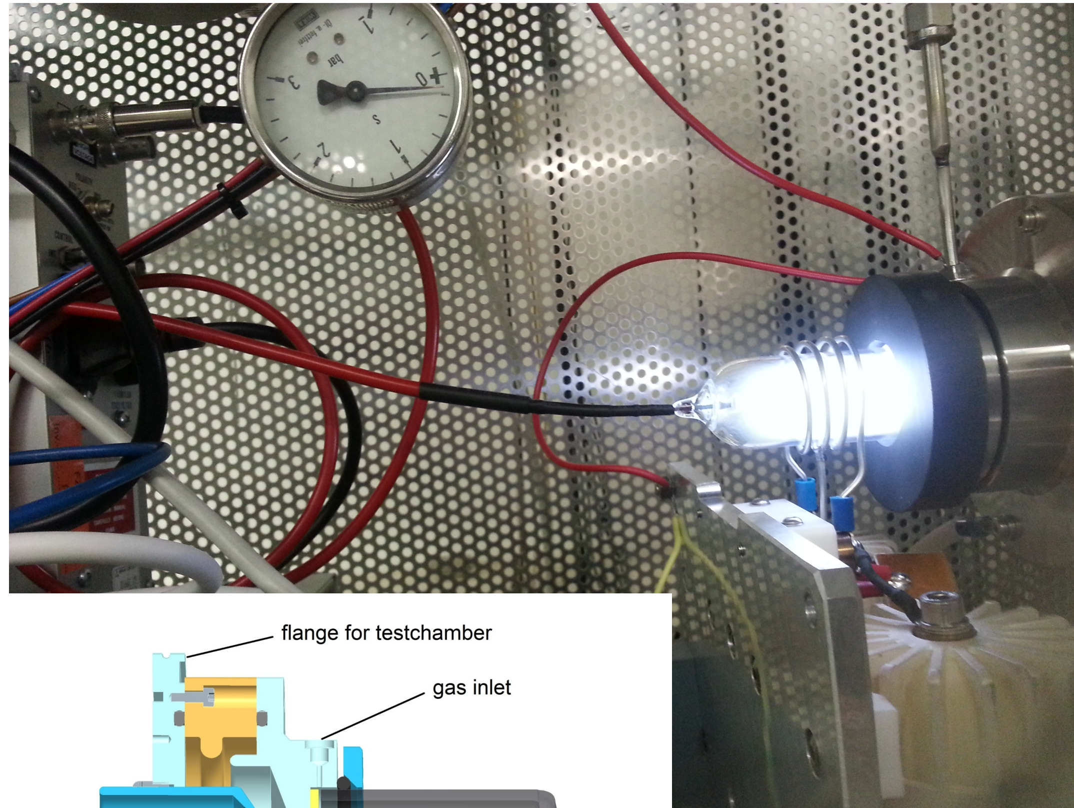
- 500 W of electrical power available on high voltage terminal (rotating shaft system)
- Gas stripper system will remain on terminal, including two 360 l/s turbomolecular pumps
- Carbon foil stripper system not necessary any more, has been removed

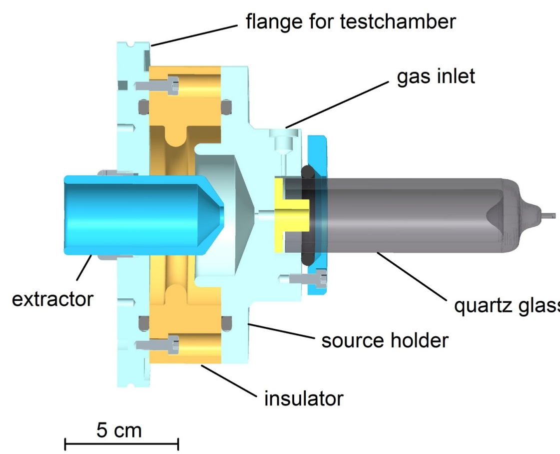




Radio frequency ion source, to be installed on high voltage terminal

- Home-made model,
  based on RF ion source on terminal of HZDR 2 MV van de Graaf accelerator, in operation since late 1970s (!)
- RF emitter based on Russian high power valves
- Electrostatic deflector in order to send the beam to the beam line still to be developed
- Working plasma discharge, first tests show successful extraction of 60 μA He^+ current
- Aimed for intensity 100 μA H^+, He^+
- Diploma thesis work under way (Stefan Reinicke)





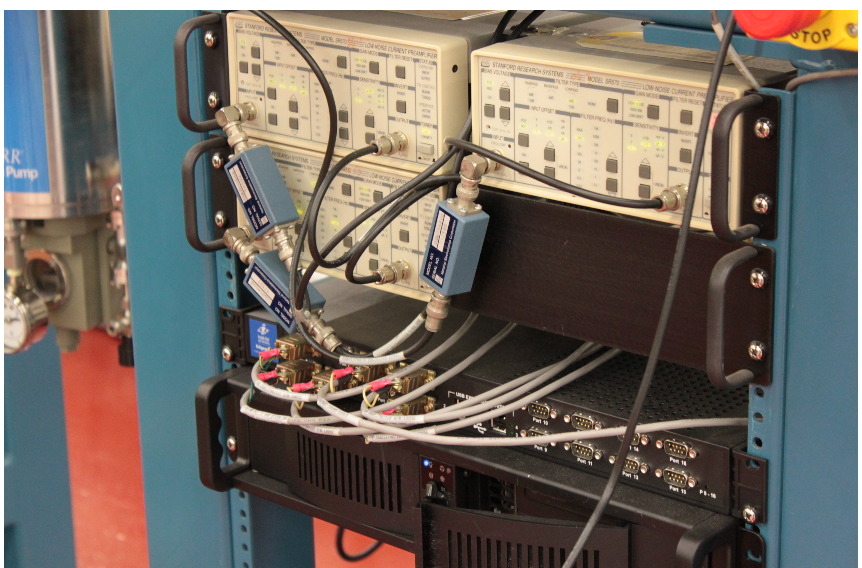
CAMAC and RS232 control

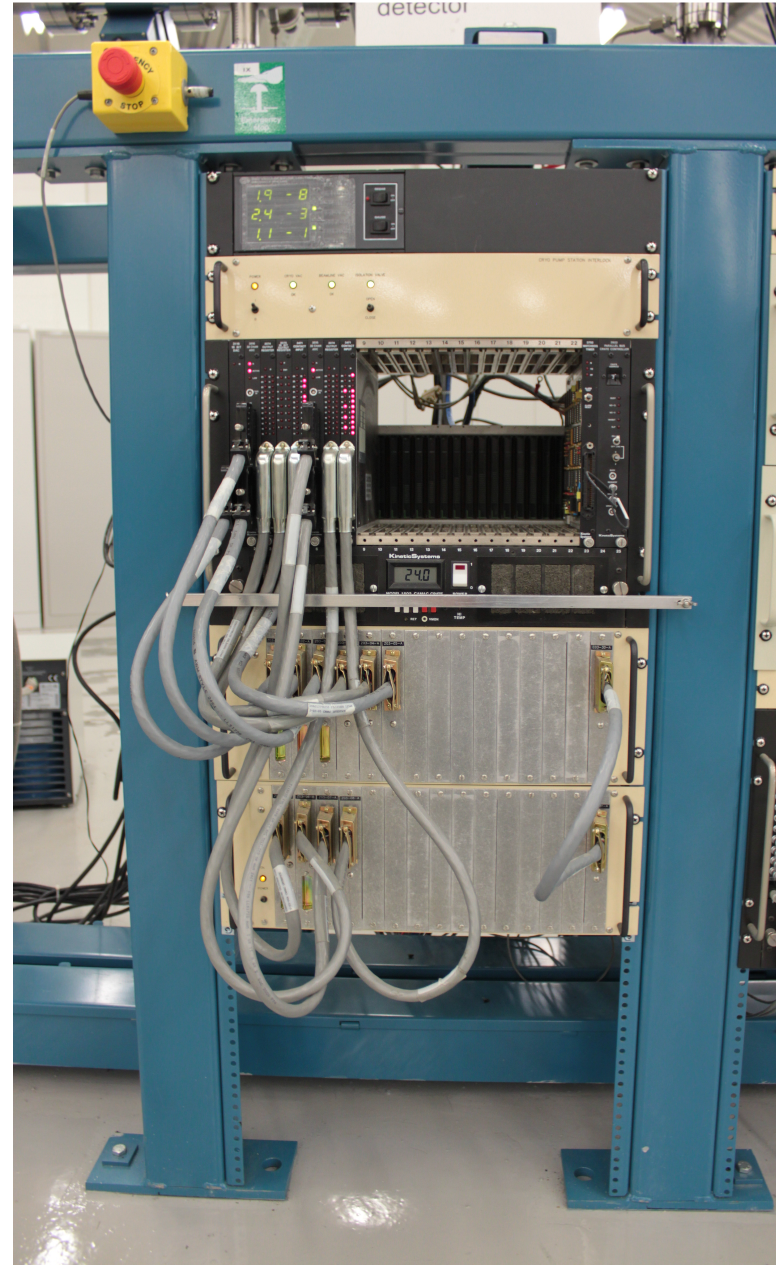
Status quo:

- CAMAC crate controllers with CAMAC DACs+ADCs, accessed via ethernet by NEC proprietary control software
- RS232 controlled devices accessed via industrial PCs and ethernet, also by NEC proprietary control software
- No access to source codes provided

Ongoing work

- B.Sc. thesis on additional slow control of CAMAC units (Jonas Wielicki)
- Aim to have an alternative way of controlling beam transmission relevant devices





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Civil construction

Permissions needed:

- Construction permit
- Operation of an ion accelerator

Main safety issues:

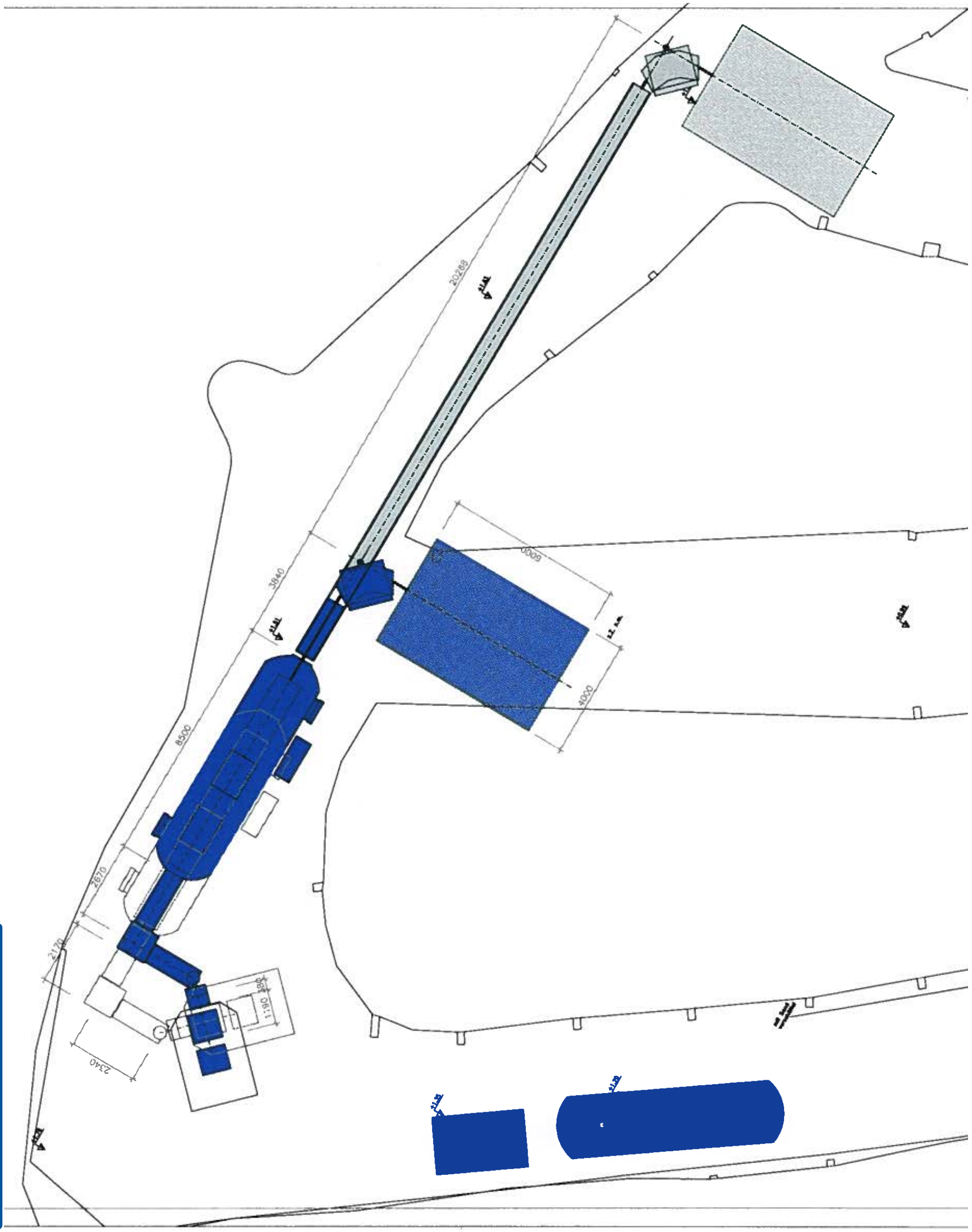
- Radioprotection and access
- Fire and evacuation
- Suffocating gas (SF_6)

Status

- Draft project by two private engineering firms (civil and laboratory engineering) completed, January-March 2013
- Cost estimates, including planning and contingency, for 0.6 M€

Total investment needed: 1.0 M€

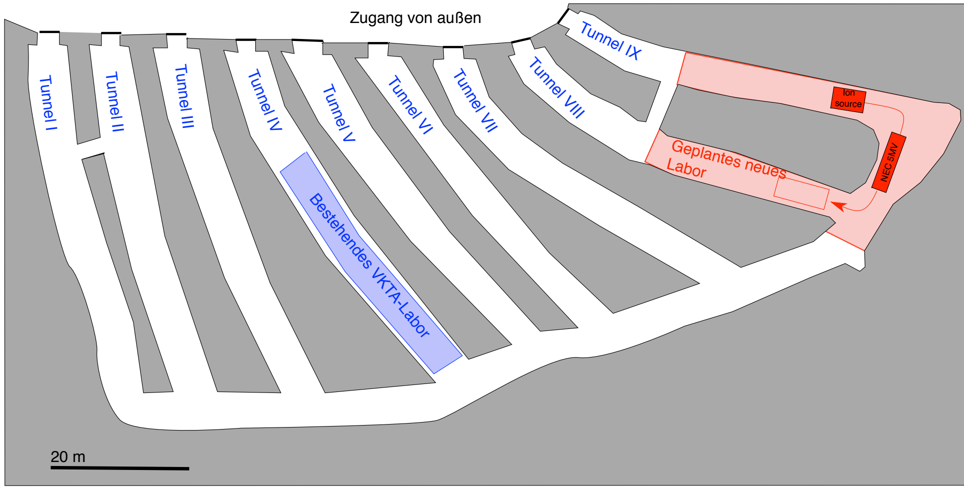
- 0.4 M€ spent (accelerator, transport)
- 0.2 M€ pledged (HZDR, Vienna)
- 0.4 M€ applied for (Kai Zuber, TU Dresden excellence initiative fund)



NAVI-Felsenkeller group

Name	Role	Funding
Daniel Bemmerer	PI	HZDR
Bernd Rimarzig	Engineer	HZDR
Michael Anders	PhD student (2009-2013) LUNA	DFG
Konrad Schmidt	PhD student (2011-2014) ^{44}Ti Felsenkeller	DFG
Tamás Szücs	Postdoc (2013-2015) H-burning	NAVI
Marcell Takács	PhD student (2013-2016) H-burning	NAVI
Louis Wagner	PhD student (2013-2016) H-burning	NAVI
Stefan Reinicke	Diploma student RF ion source	NAVI/HZDR
Johannes Krause	Student worker gas target	NAVI/HZDR
Jonas Wielicki	Student worker Pelletron CAMAC control	NAVI/HZDR

Approach for 2013-2016



Work on investment funding (0.4 M€ still needed)

- TU Dresden application (Kai Zuber)
- ...

Work on improvements of 5MV accelerator

- Radio-frequency ion source
- Computer control of all components
- Gas target design and tests

Surface-based experiments at HZDR ion accelerators

- CNO cycle, $^{14}N(p,\gamma)^{15}O$ (talk by Louis Wagner)
- CNO cycle, γ-widths in ^{15}N (mirror of ^{15}O)
- CNO cycle, $^{12}C(p,\gamma)^{13}N$ and $^{16}O(p,\gamma)^{17}F$ in inverse kinematics
- pp-chain and Big Bang: $^{3}He(\alpha,\gamma)^{7}Be$ angular distribution
- ...

Collaboration with LUNA-0.4 MV (DFG)

- $^{2}H(\alpha,\gamma)^{6}Li$ (concluded)
- $^{22}Ne(p,\gamma)^{23}Na$ (to be applied for)

Background intercomparisons between underground labs

- Canfranc/Spain, Freiberg/Germany

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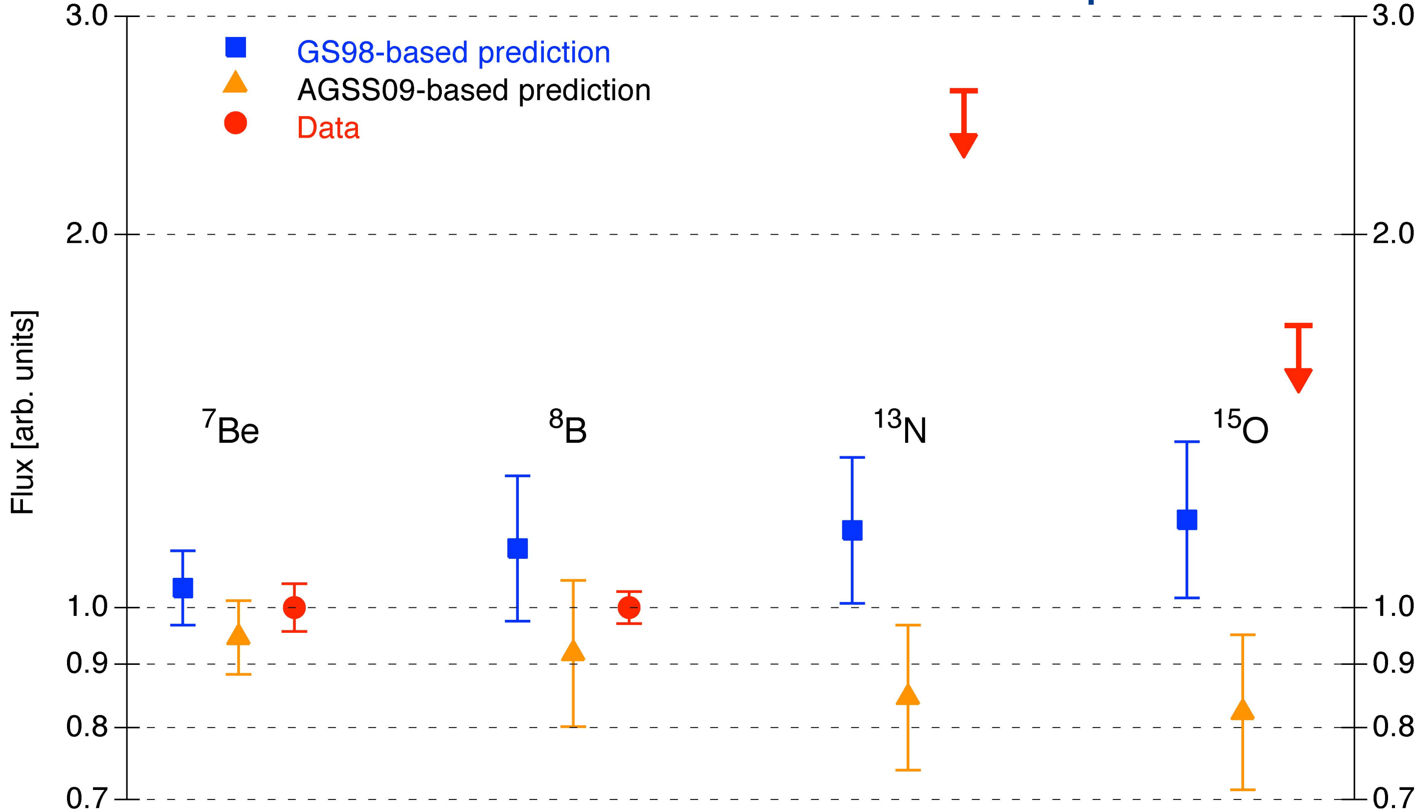
Solar neutrino fluxes: Data and model predictions

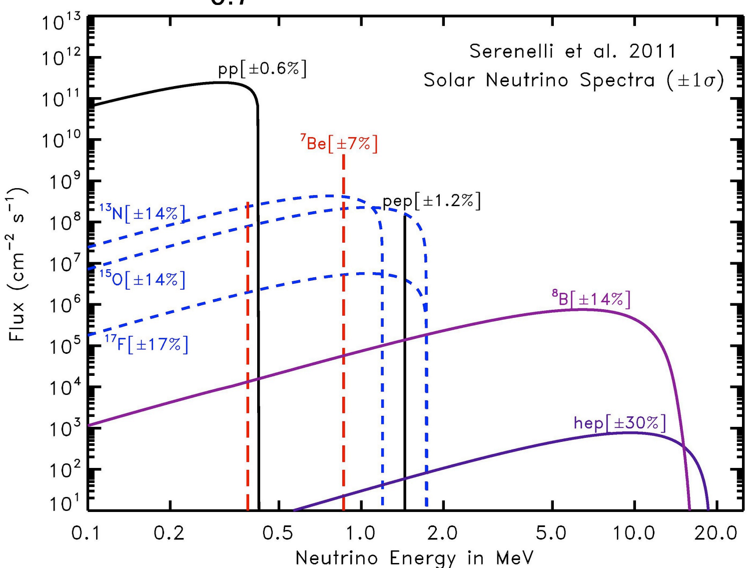


Neutrino fluxes:
Standard Solar Model;
Antonelli et al., 1208.1356

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}	$S_{1,14}$	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

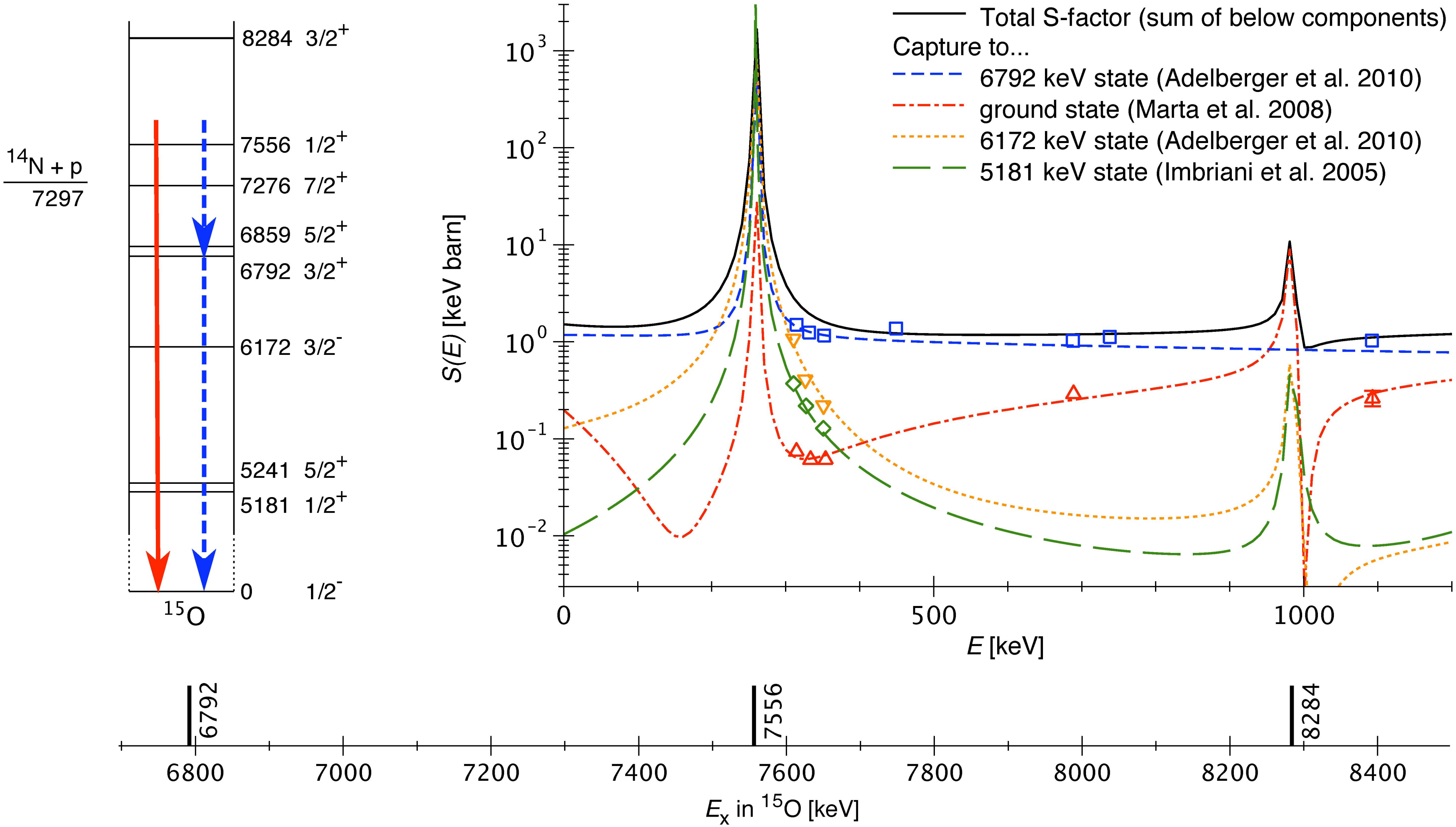
^{3}He(α,γ)^{7}Be

^{7}Be(p,γ)^{8}B

^{14}N(p,γ)^{15}O

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

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



- Need new direct data between 0.3 and 2.0 MeV
- Need new indirect data on subthreshold resonance
- Talk by Louis Wagner this morning!

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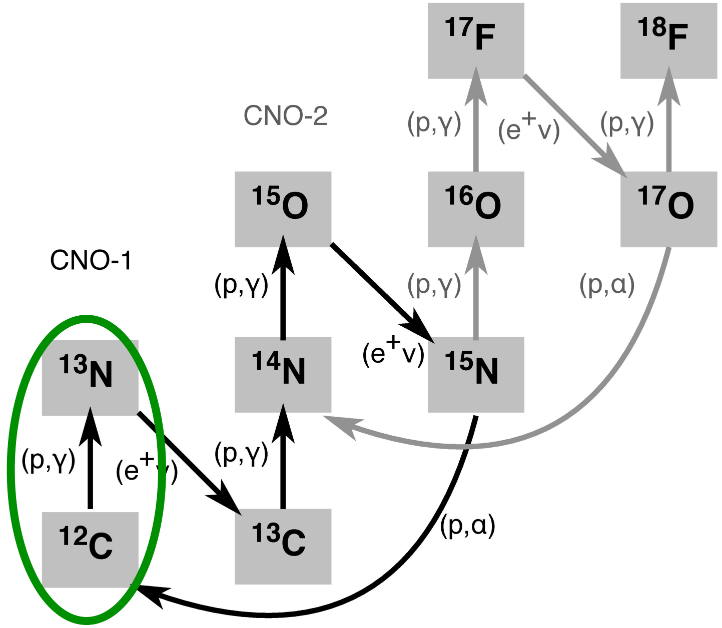
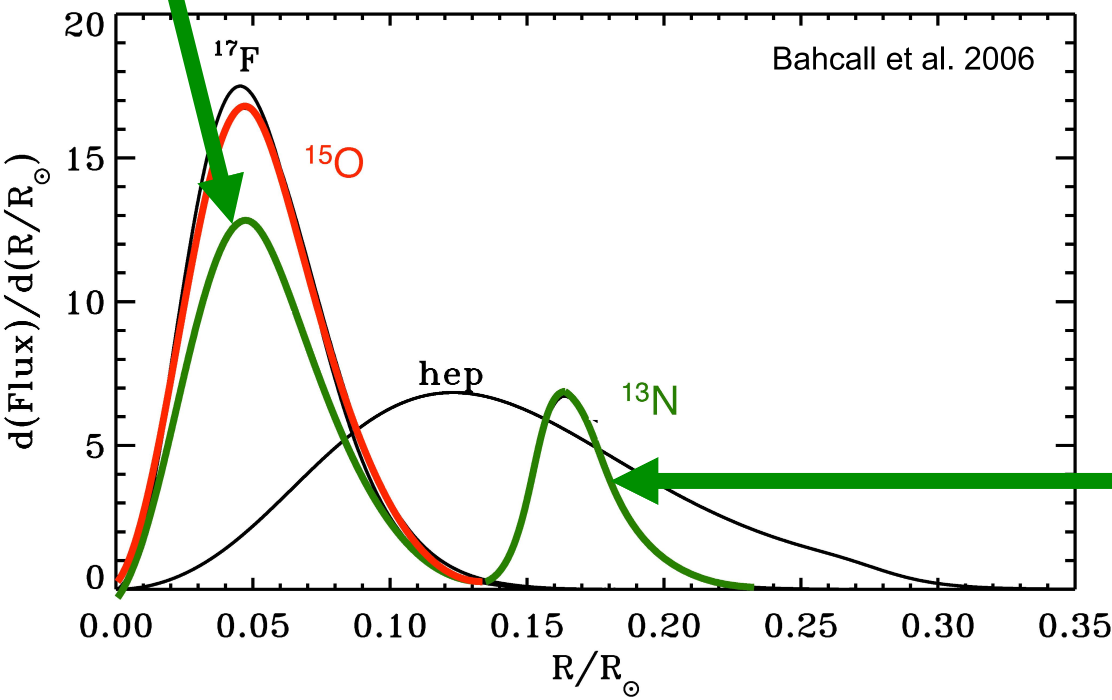
Double-peaked source distribution for ^{13}N neutrinos

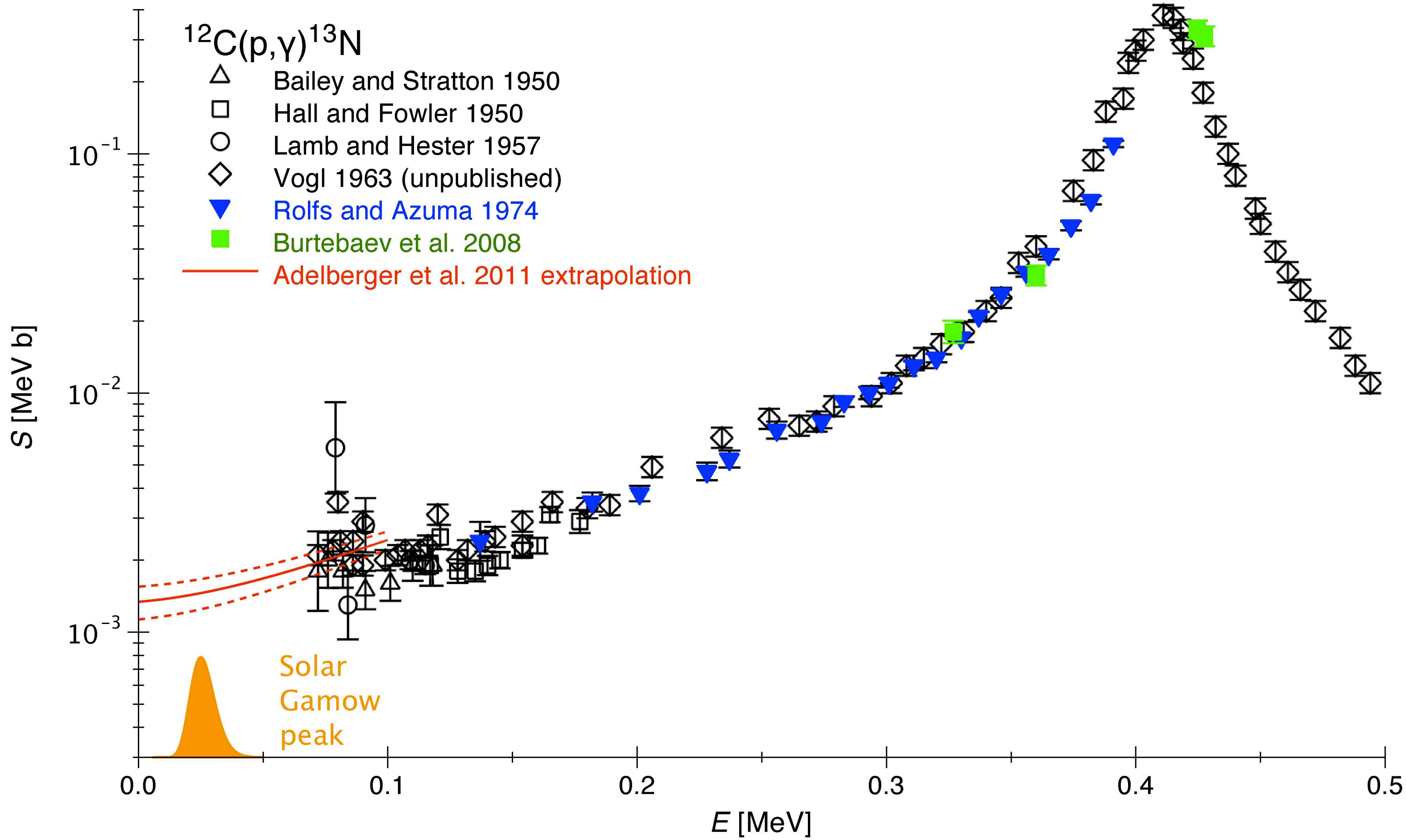
- Center of the Sun, T = 16 MK
- Lifetime $\tau(^{12}C) = 7 * 10^5$ a << $2 * 10^8$ a = $\tau(^{14}N)$
- ^{12}C in the solar center is quickly converted to ^{14}N, and CNO cycle reaches equilibrium
- ^{13}N neutrino emission at the center of the Sun is determined by the $^{14}N(p,\gamma)^{15}O$ rate





- $R/R_\odot \sim 0.16$, T = 12 MK
- $\tau(^{12}C) = 2 * 10^8$ a
- $\tau(^{14}N) = 10^{11}$ a >> age of the Sun
- CNO cycle never reaches equilibrium
- Size of ^{12}C-depleted zone depends on $^{12}C(p,\gamma)^{13}N$ rate

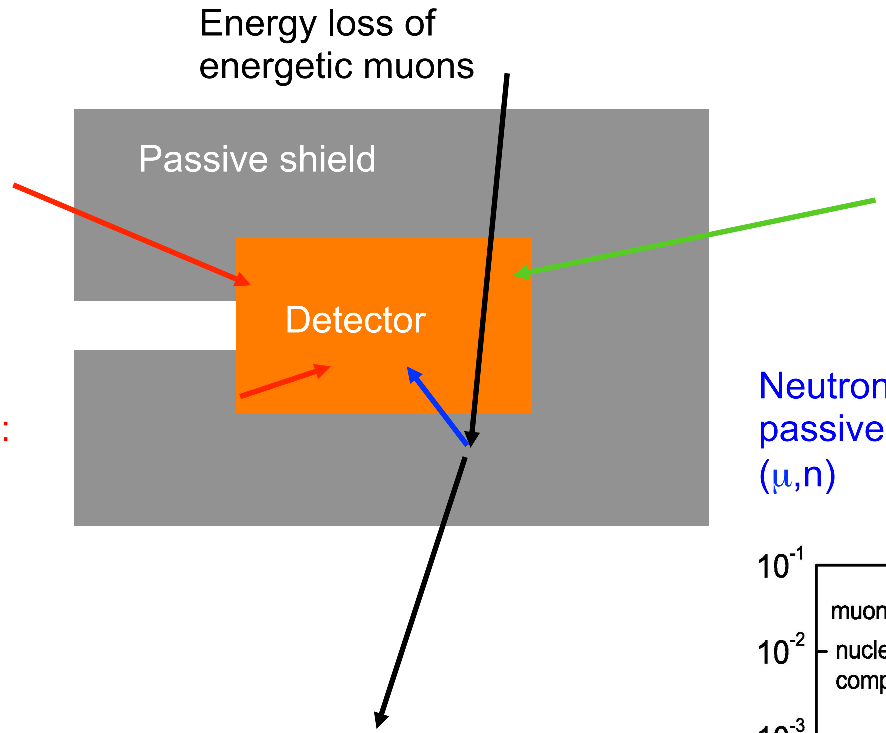
^{13}N neutrinos and the $^{12}C(p,\gamma)^{13}N$ reaction



- No experimental data at or near the solar Gamow peak
- Existing data near E = 0.1 MeV are from the 1950's
- Adelberger *et al.* 2011 cites 17% uncertainty
- New data at low and high energy are needed!

What drives the laboratory background in γ-ray detectors?

Radioisotopes in the laboratory:
^{238}U - daughters
^{232}Th - daughters
^{40}K

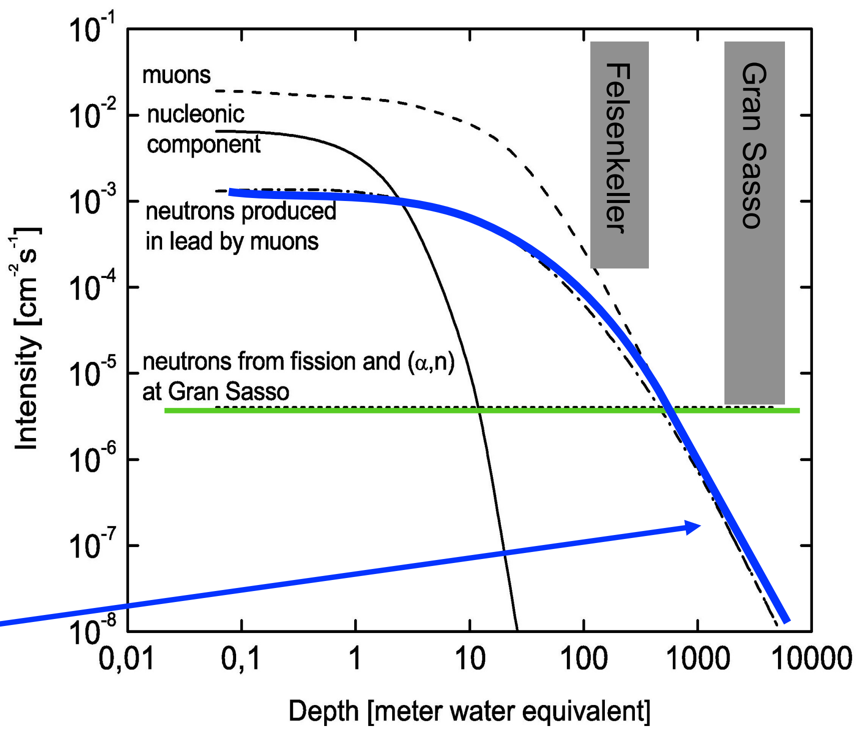


Neutrons from outside the shield:
- cosmic ray
- (α,n) in rock

Radioisotopes in detector and shield:
^{238}U - daughters
^{232}Th - daughters
^{60}Co, ^{138}La

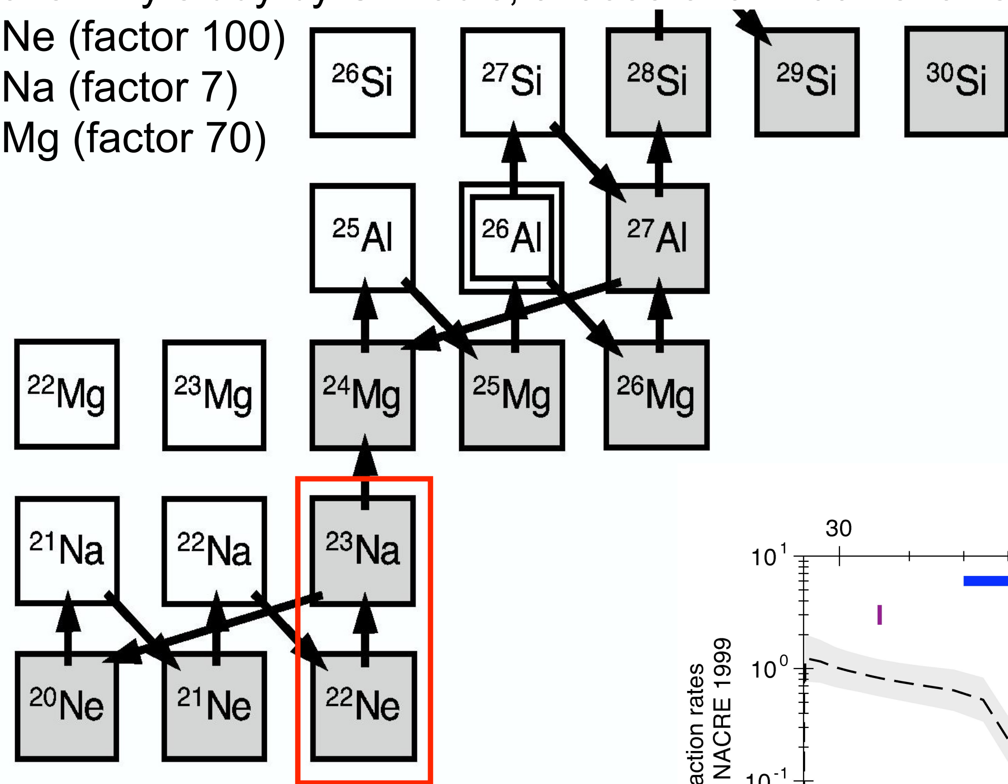
Neutrons created in the passive shield by muons (μ,n)

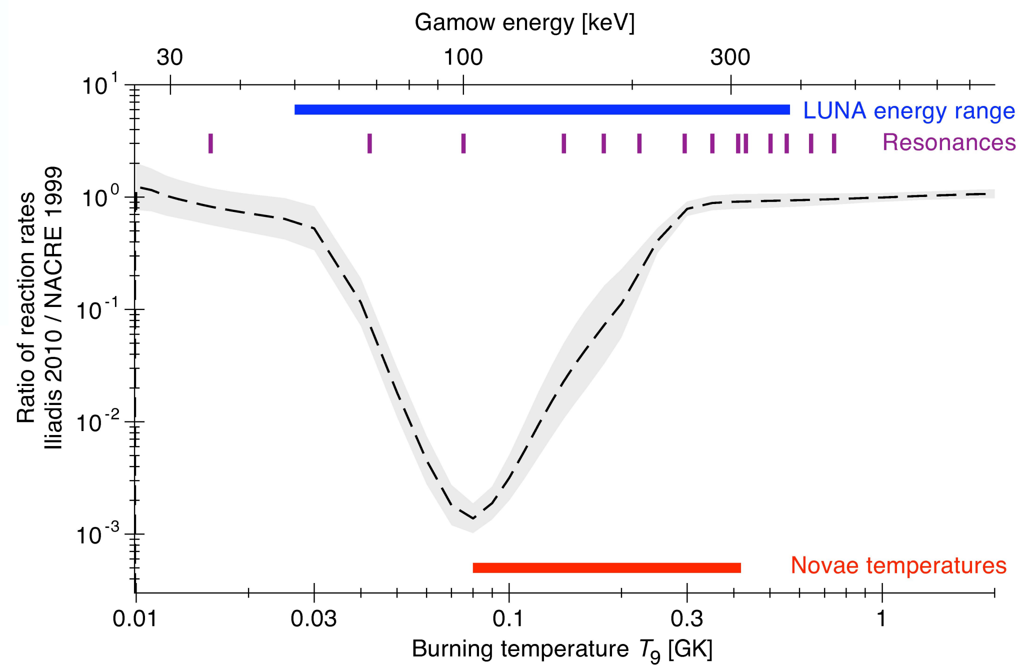
	Affects energies…	Address by..
Red	$E_\gamma < 2.7$ MeV	shielding or purification
Green	$E_\gamma < 12$ MeV	shielding
Black	$E_\gamma < 70$ MeV	active veto
Blue	$E_\gamma < 12$ MeV	**1000 m rock**



Next experiment at LUNA: Hydrogen burning and $^{22}Ne(p,\gamma)^{23}Na$

- NeNa cycle of hydrogen burning in astrophysical novae
- Sensitivity study by C. Iliadis, J. José et al. 2002 shows impact on the abundances of
  ^{22}Ne (factor 100)
  ^{23}Na (factor 7)
  ^{24}Mg (factor 70)





Is there also an effect on the ^{22}Ne abundance in SN Ia precursors?