Underground nuclear astrophysics from the Big Bang to astrophysical novae

International Workshop XLIII
on Gross Properties of Nuclei and Nuclear Excitations
„Nuclear Structure and Reactions: Weak, Strange and Exotic“

Hirschegg, 13.01.2015

Daniel Bemmerer

Laboratory Underground Nuclear Astrophysics

EuroGENESIS
Origin of the Elements and Nuclear History of the Universe

NAVI
Nuclear Astrophysics Virtual Institute

Partner von DRESDEN concept
exzellenz-dresden.de

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

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1. Motivation: The solar abundance problem and solar neutrinos
2. Technique: Experiments in underground laboratories
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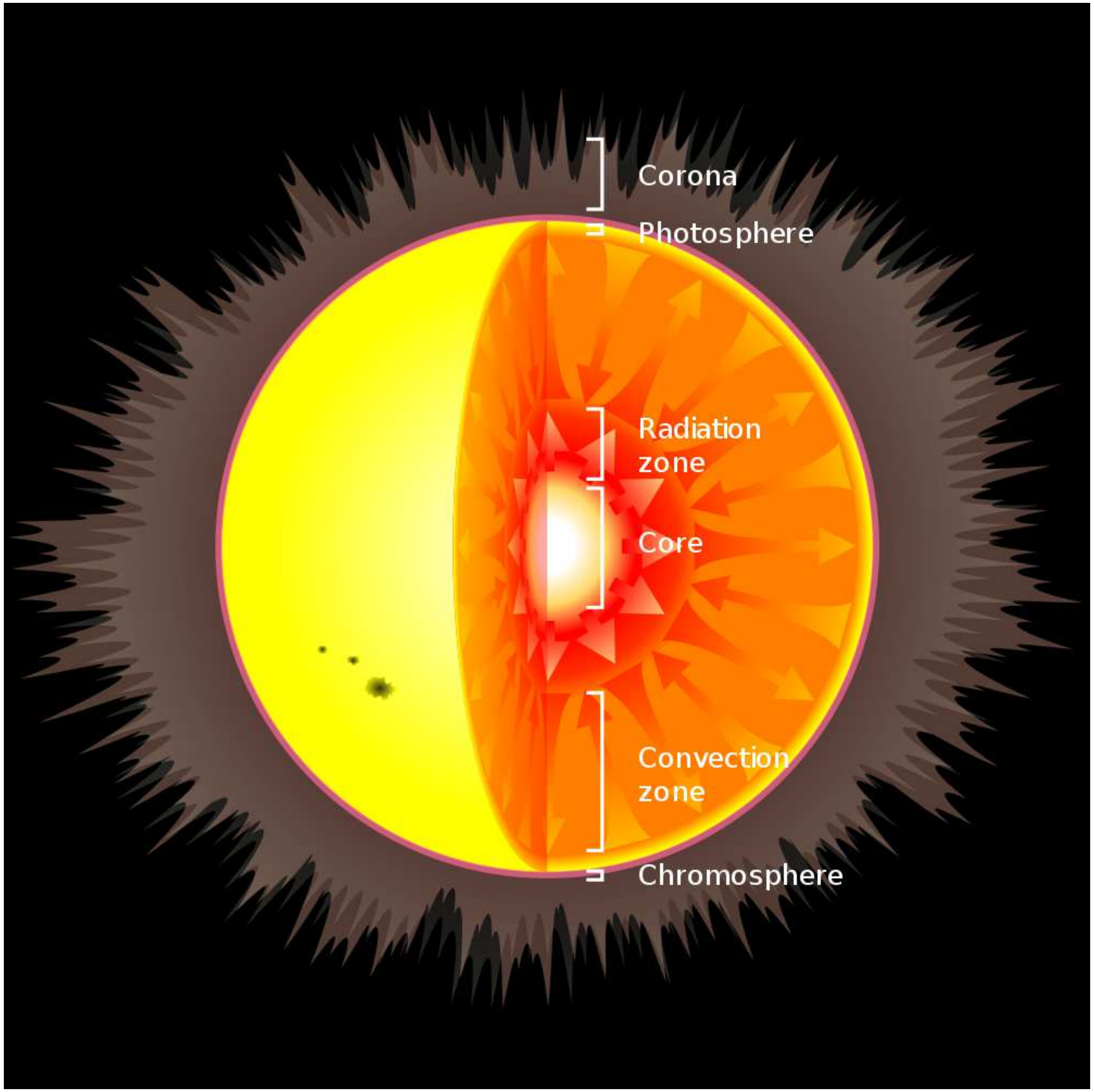
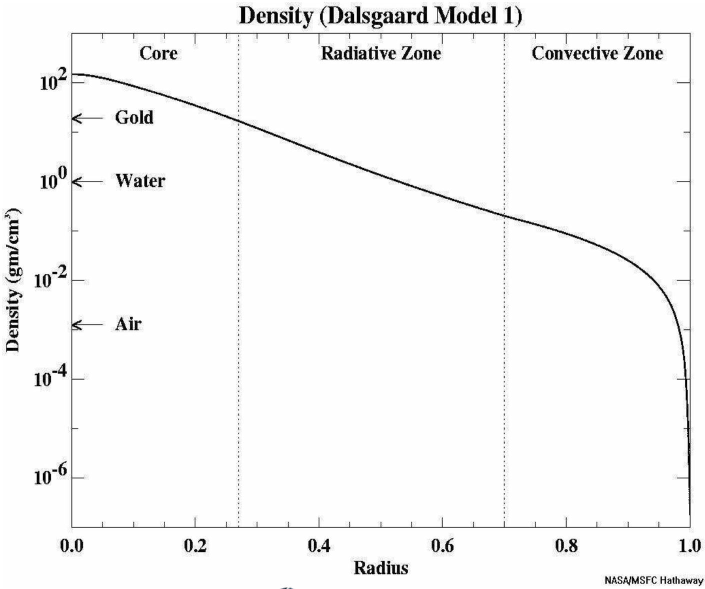
   Big Bang nucleosynthesis
4. The science case for new underground accelerators
5. Overground experiments for nuclear astrophysics

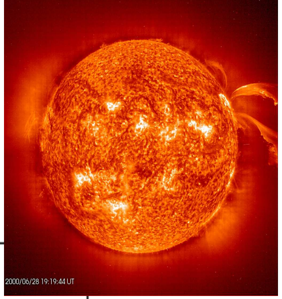
Structure of the Sun red: Observable

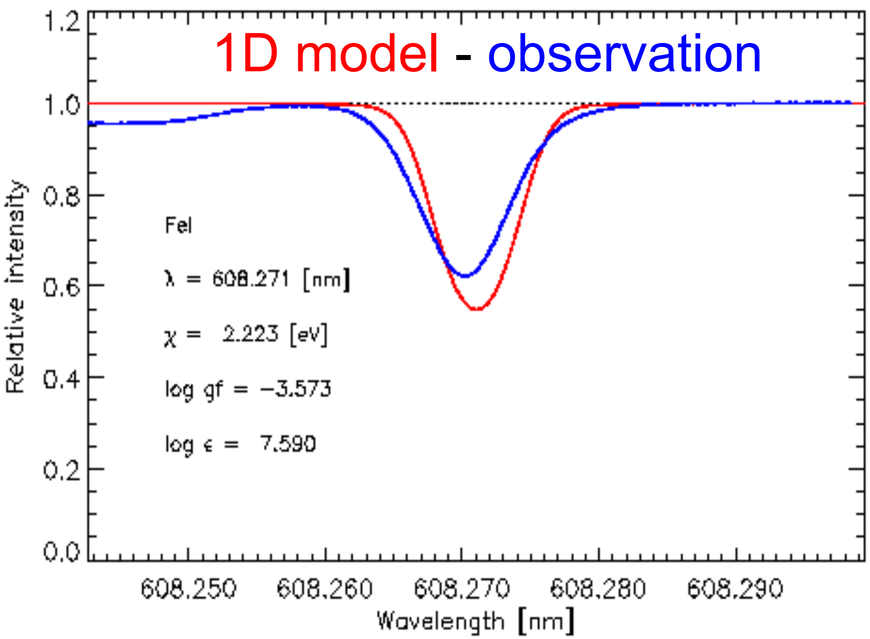


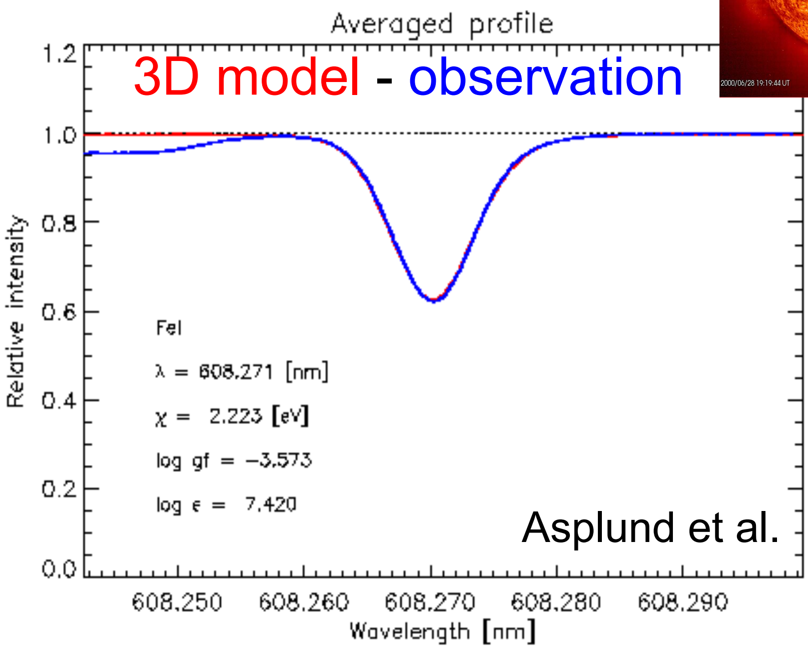
- Corona
- Chromosphere
- Photosphere
  Fraunhofer lines
- Convection zone
  p-modes (helioseismology)
- Radiation zone
- Core
  Neutrinos



Data on the Sun (1): Elemental abundances
from the model-based interpretation of the Fraunhofer lines







3-dimensional models of the photosphere lead to lower derived abundances:

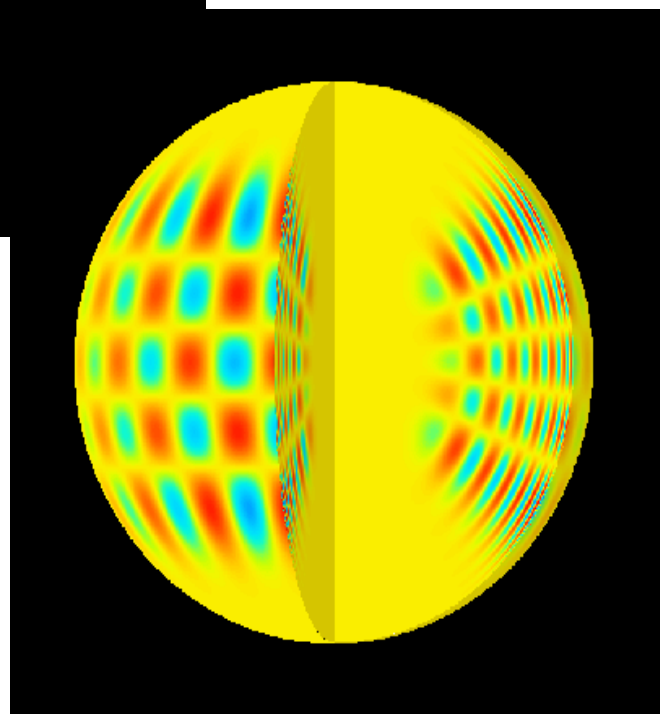
1D: 2.29% (by mass) of the Sun are “metals” (Li...U)

3D: 1.78% (by mass) of the Sun are “metals” (Li...U)

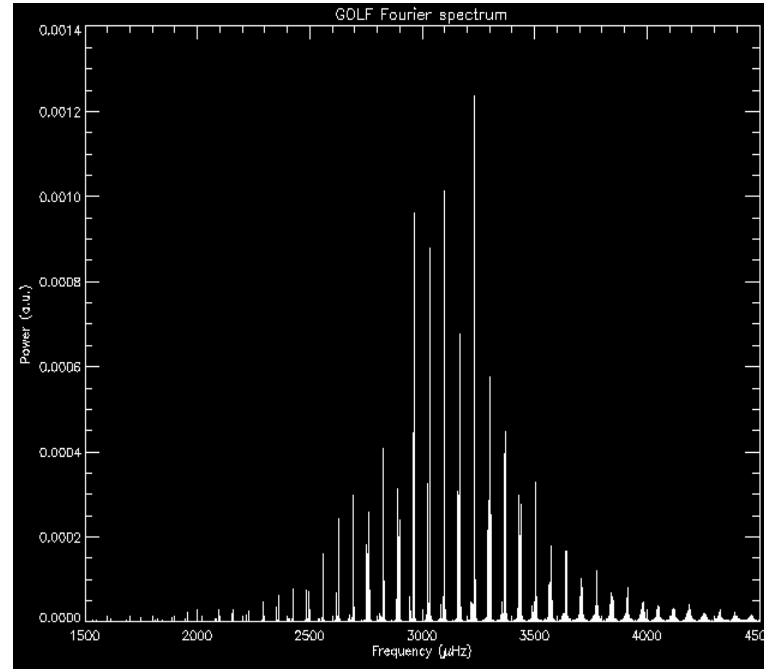
Data on the Sun (2): Helioseismology

Satellite “SoHo”

(Solar and Heliospheric Observatory)



Simulated standing waves, p-mode ~3 mHz



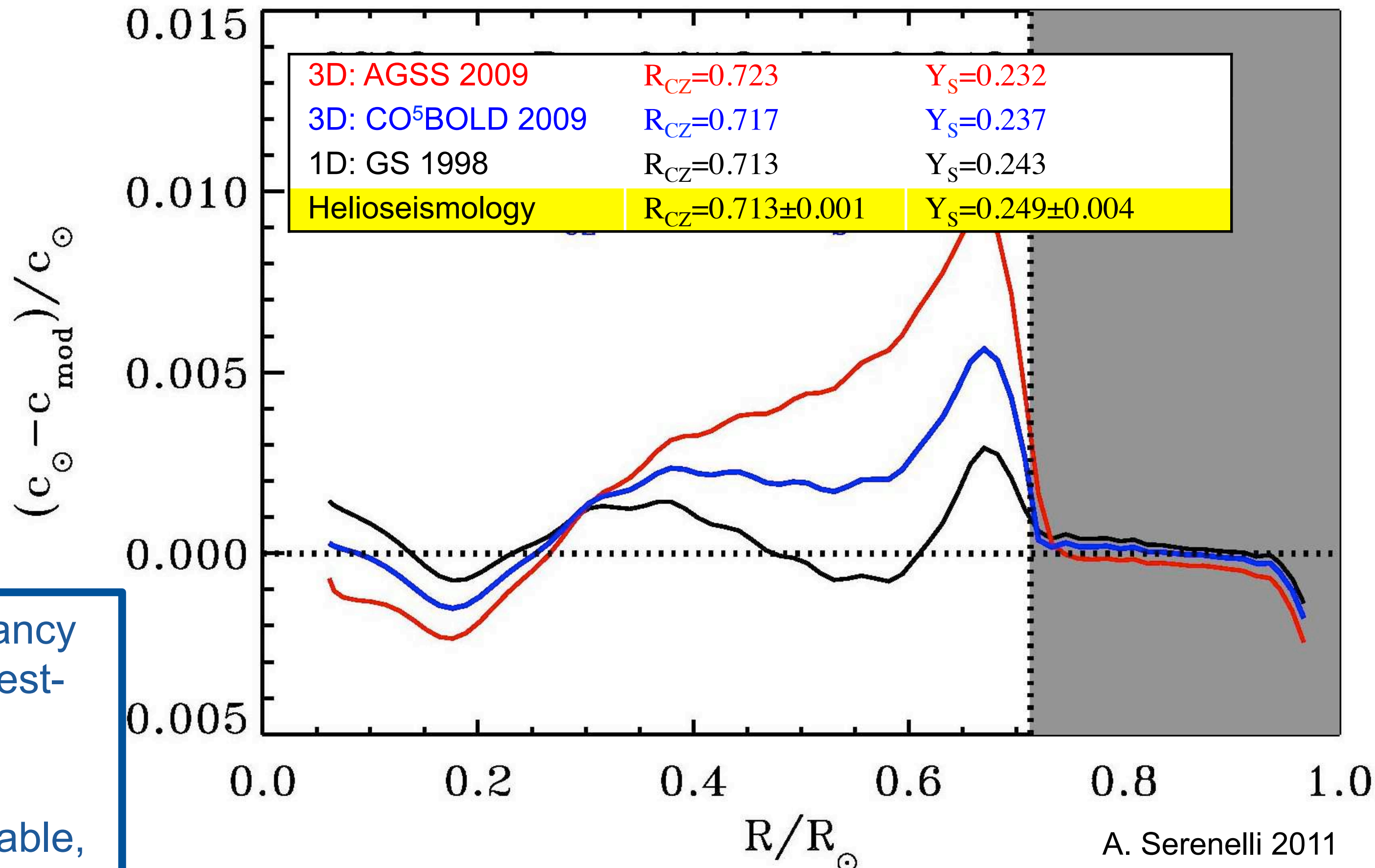
Fourier transformed spectrum from GOLF instrument on SoHo

The solar abundance problem:
Contradiction between elemental abundances and helioseismology

Solar models computed with different sets of elemental abundances:

1D: 2.29% (by mass) of the Sun are “metals” (Li...U)

3D: 1.78% (by mass) of the Sun are “metals” (Li...U)



A. Serenelli 2011

- A significant discrepancy for the closest and best-observed star in the universe!
- Can the third observable, solar neutrinos, address this problem?

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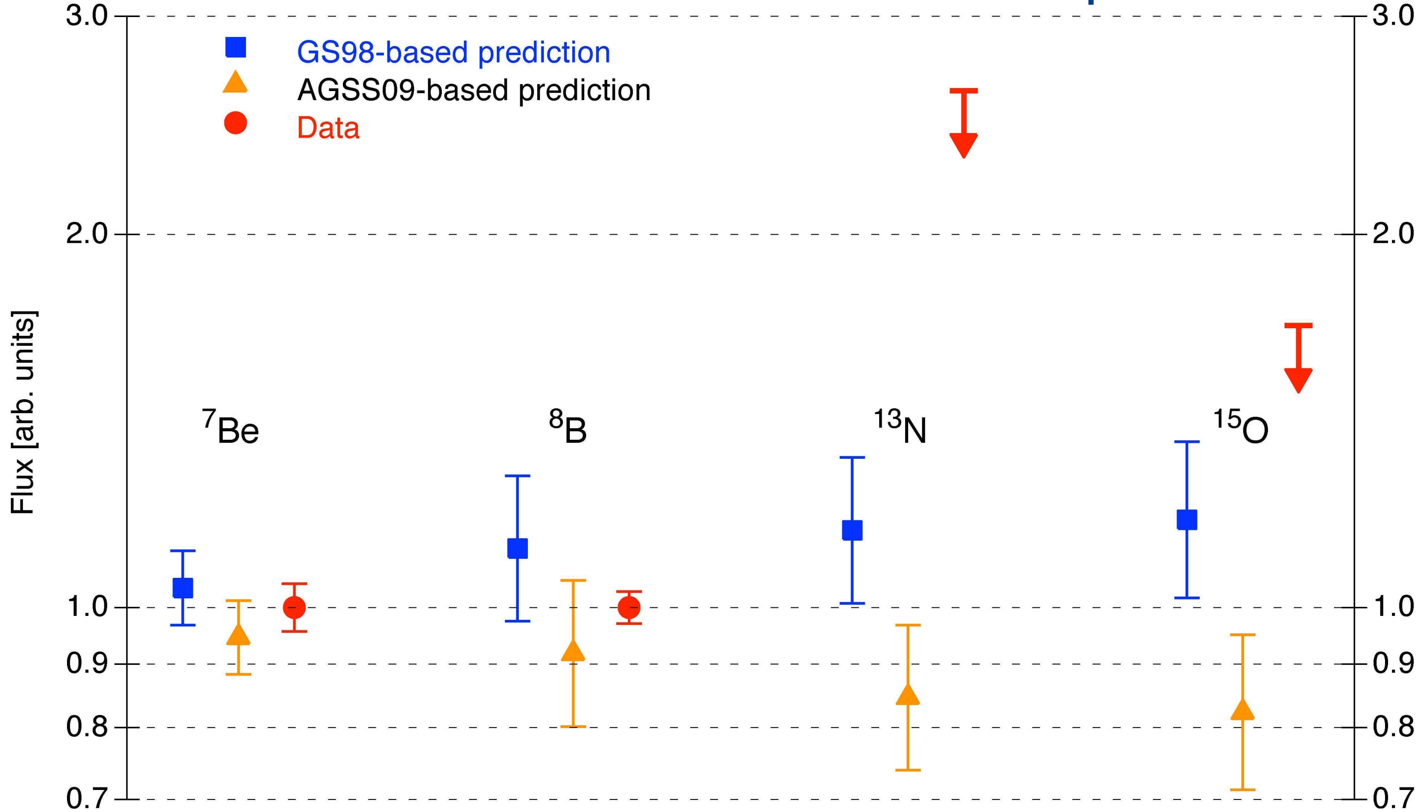
Solar neutrino fluxes: Data and model predictions

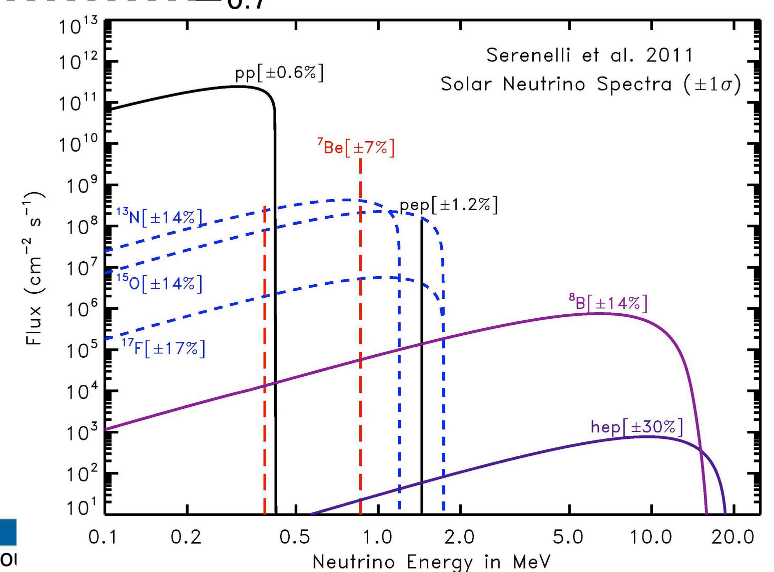


Neutrino fluxes:
Standard Solar Model;
Antonelli et al., 1208.1356

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

^{3}He(α,γ)^{7}Be

^{7}Be(p,γ)^{8}B

^{14}N(p,γ)^{15}O

Uncertainty contributed to neutrino flux, in percent

Antonelli et al., 1208.1356

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

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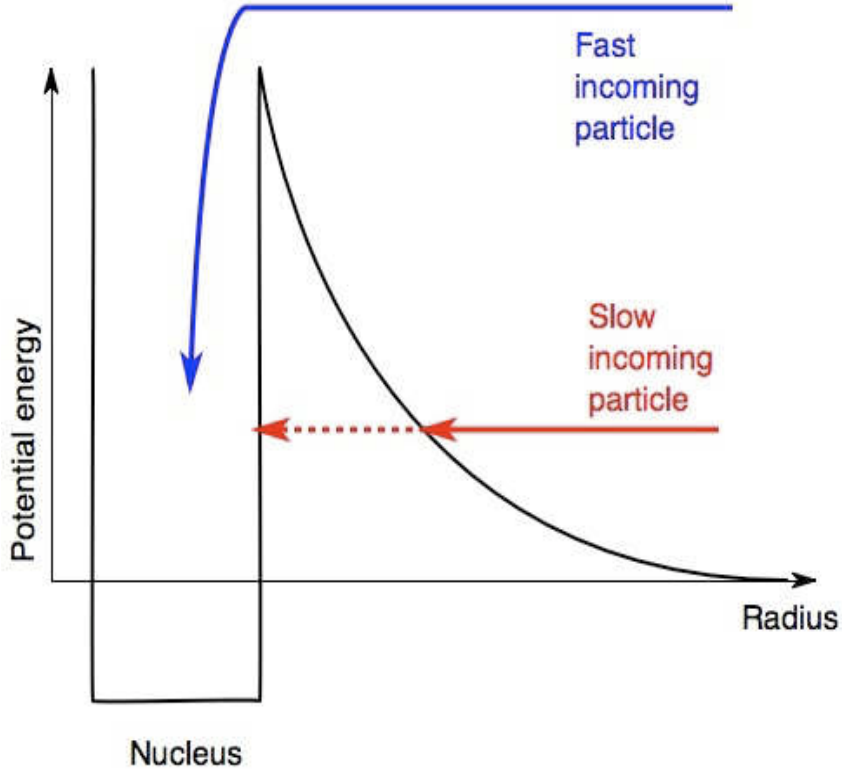
Nuclear reaction cross section σ for low-energy charged particles



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

↓

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

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

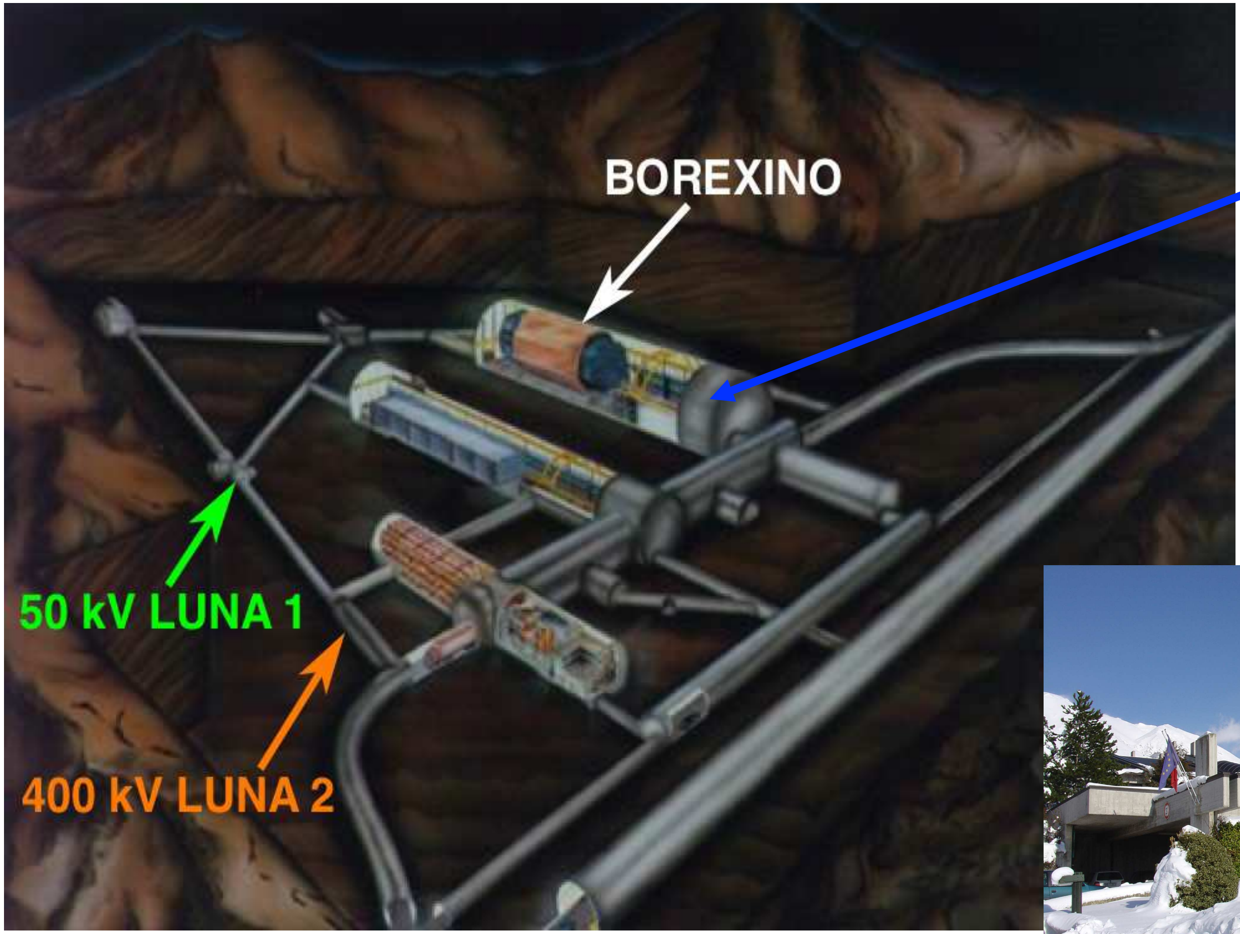
↓

Very low cross sections to be measured!

↓

Need low background.

LUNA laboratory at Gran Sasso / Italy today



LUNA-MV, planned

1992-2001

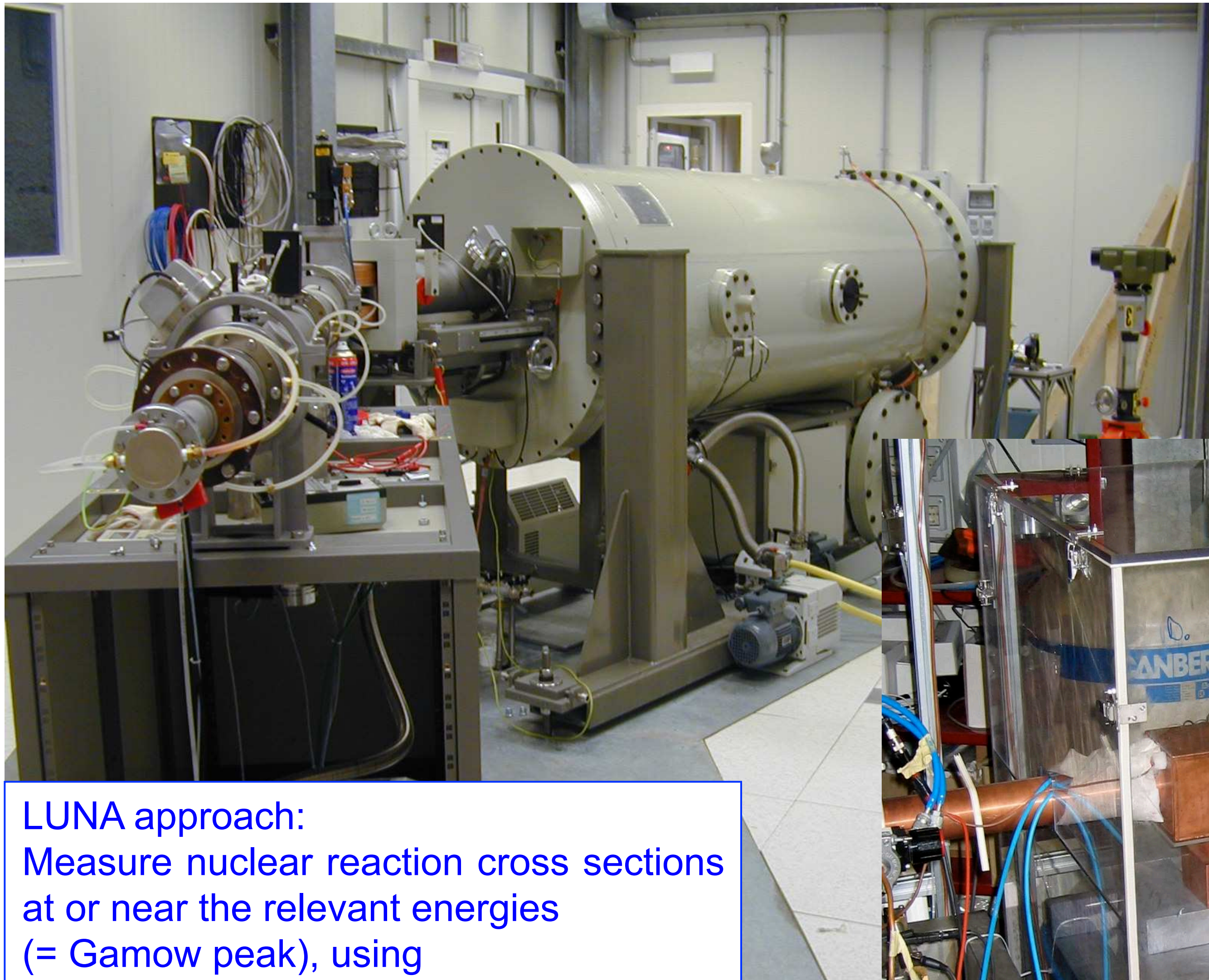
2000-2018

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

150 km from Rome

Access by motorway

The LUNA 0.4 MV accelerator deep underground



LUNA = Laboratory Underground for Nuclear Astrophysics

- Italy
- Germany
- 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

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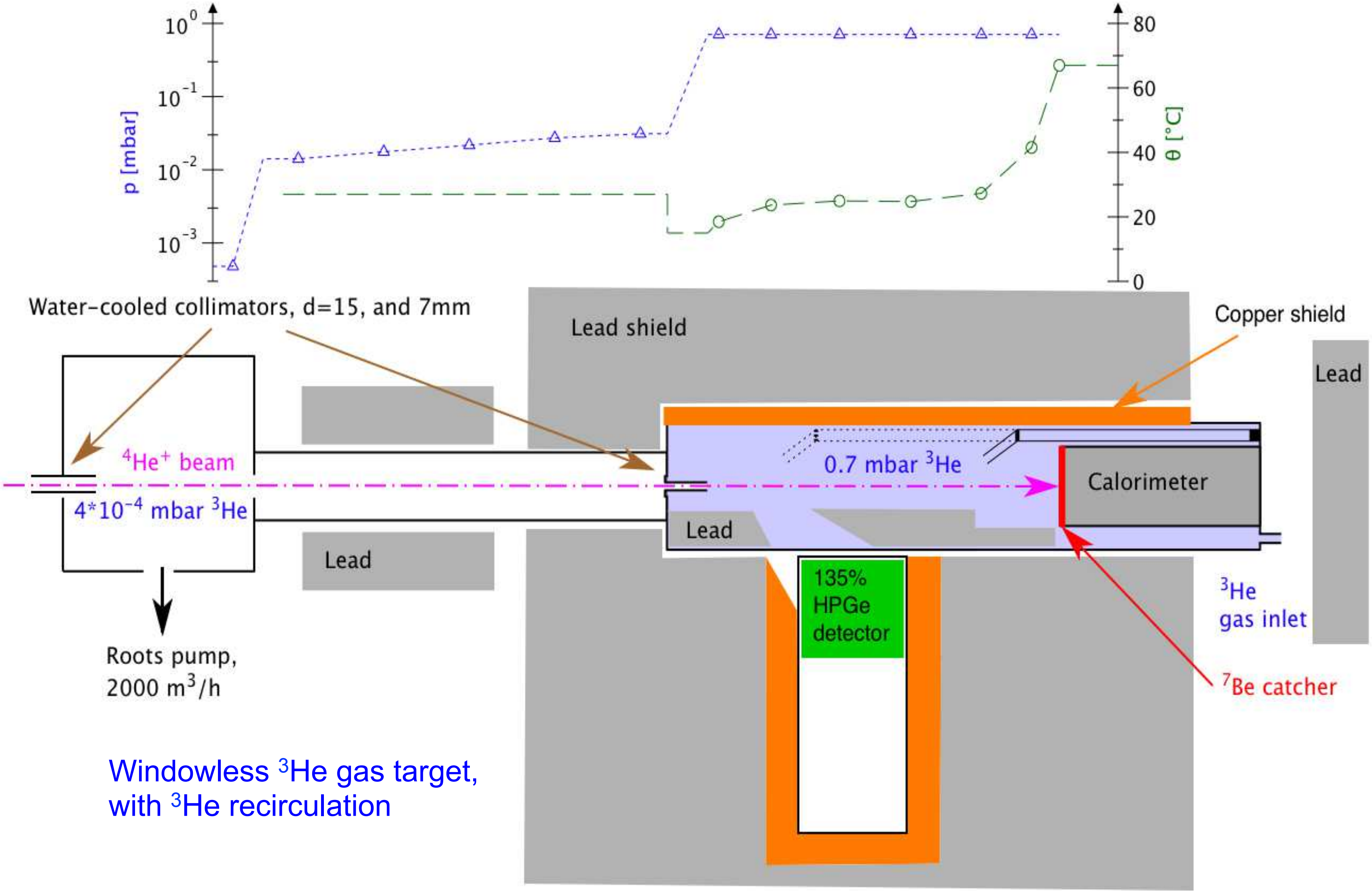
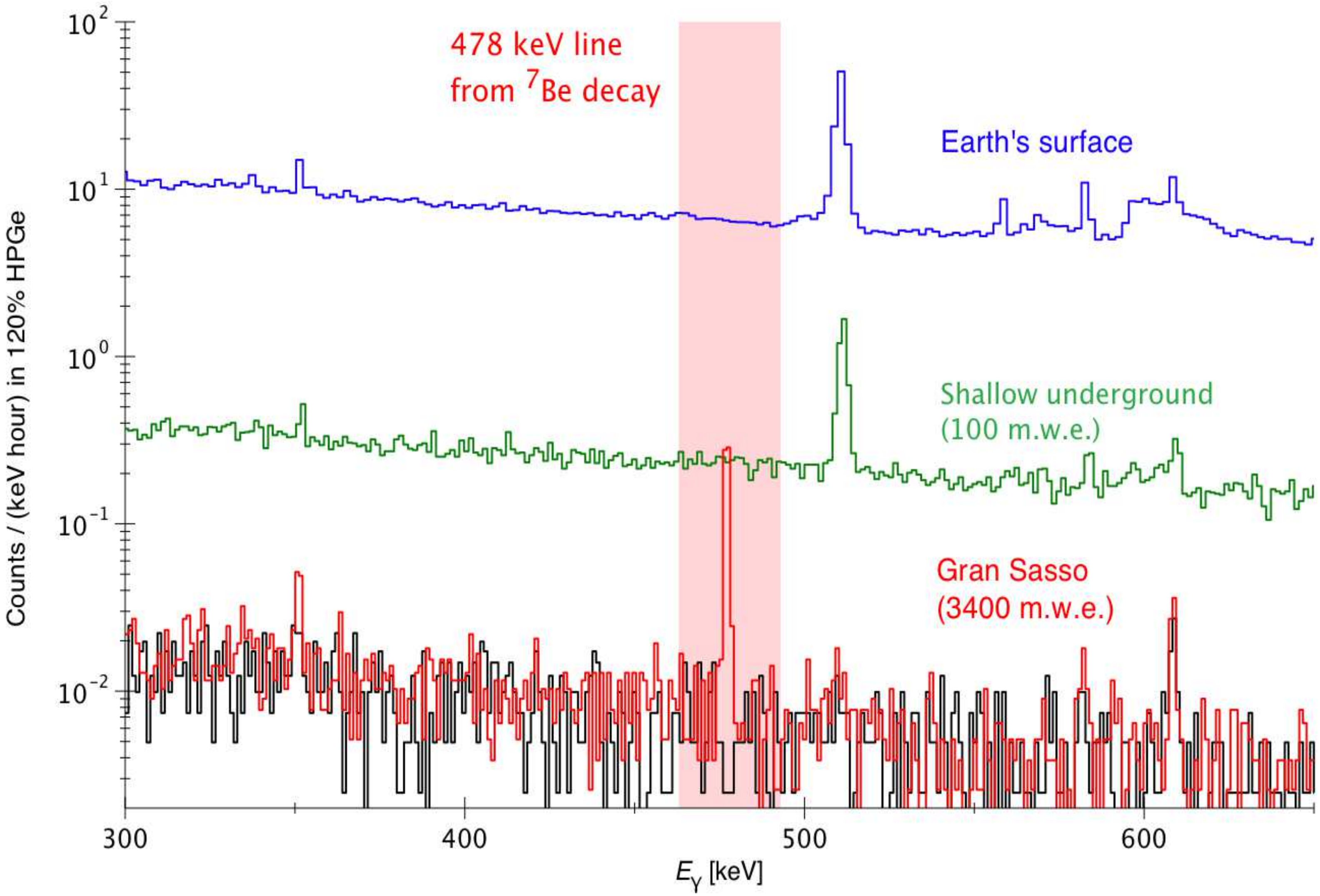
$^3He(\alpha,\gamma)^7Be$ experiment at LUNA (activation and prompt-γ technique)



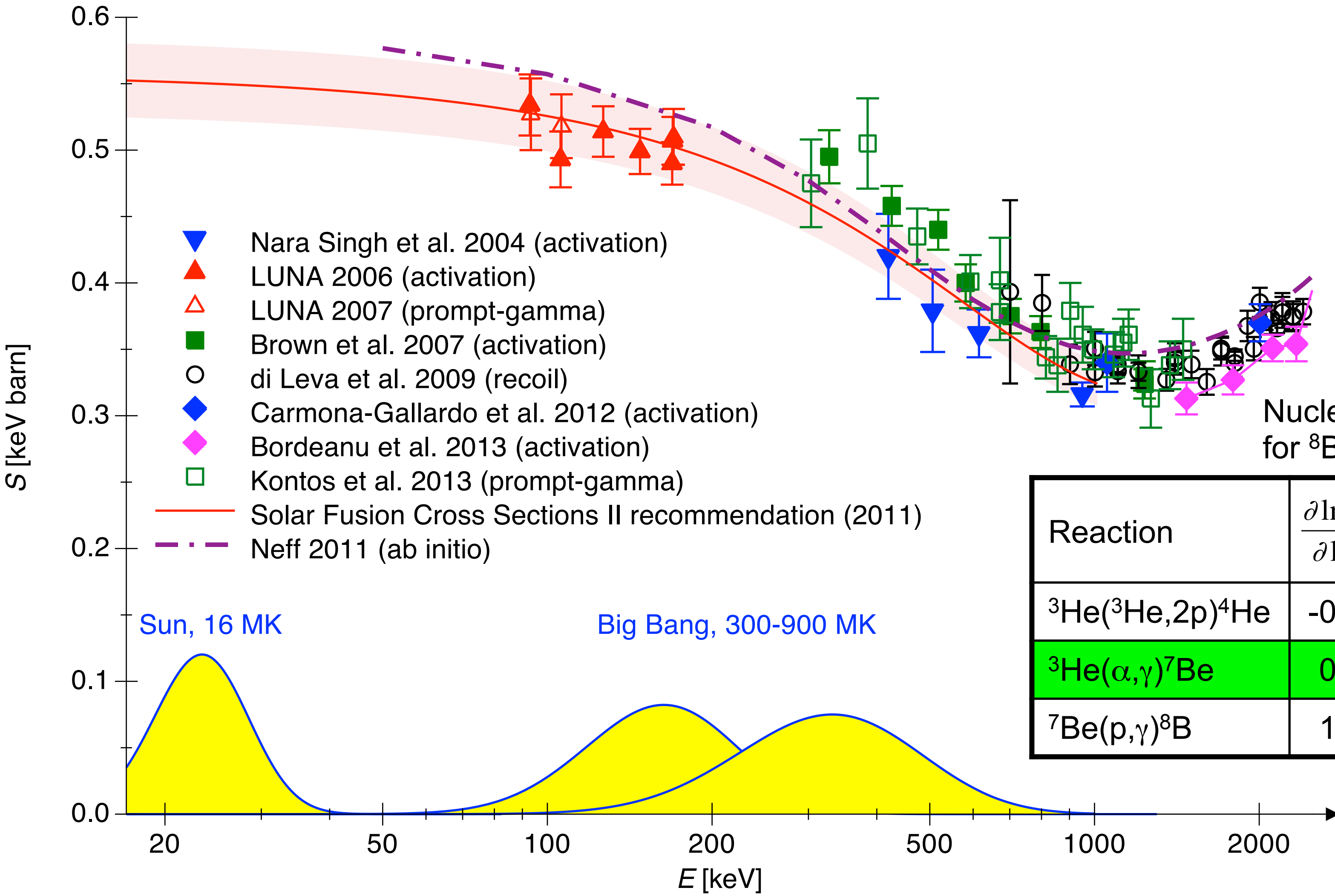
Windowless ^{3}He gas target, with ^{3}He recirculation

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



Detected ^7Be activities: 0.8 - 600 mBq

$^3He(\alpha,\gamma)^7Be$ reaction, S-factor results from LUNA and others



Nuclear physics input for ^8B neutrino flux Φ_B:

Reaction	$\frac{\partial \ln \Phi_B}{\partial \ln \sigma}$	$\Delta\Phi_B/\Phi_B$
$^3He(^3He,2p)^4He$	-0.43	1.8%
$^3He(\alpha,\gamma)^7Be$	0.85	~~7.5%~~ 4.5%
$^7Be(p,\gamma)^8B$	1.00	7.7%

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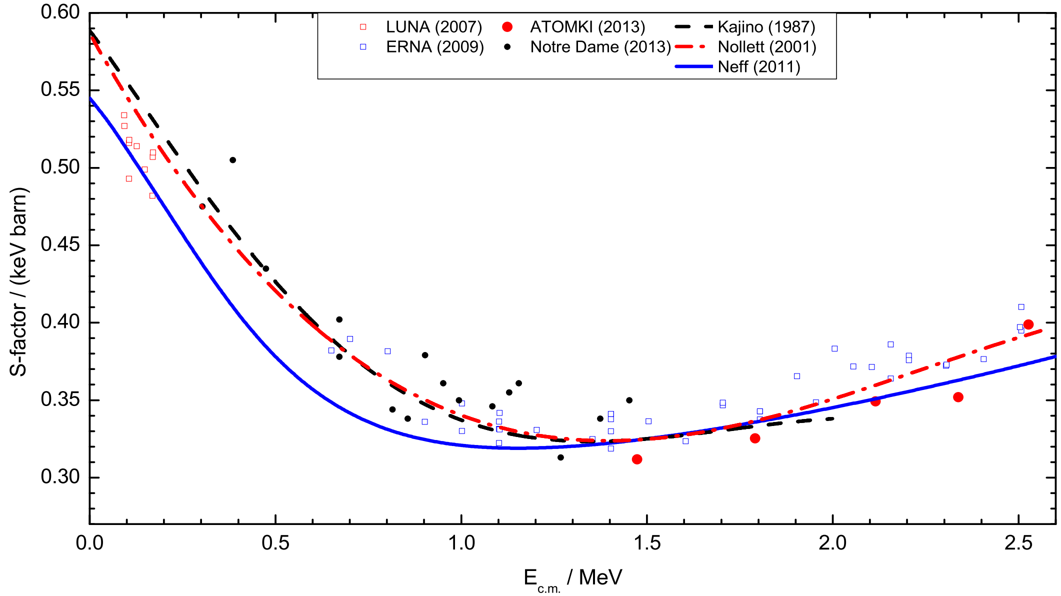
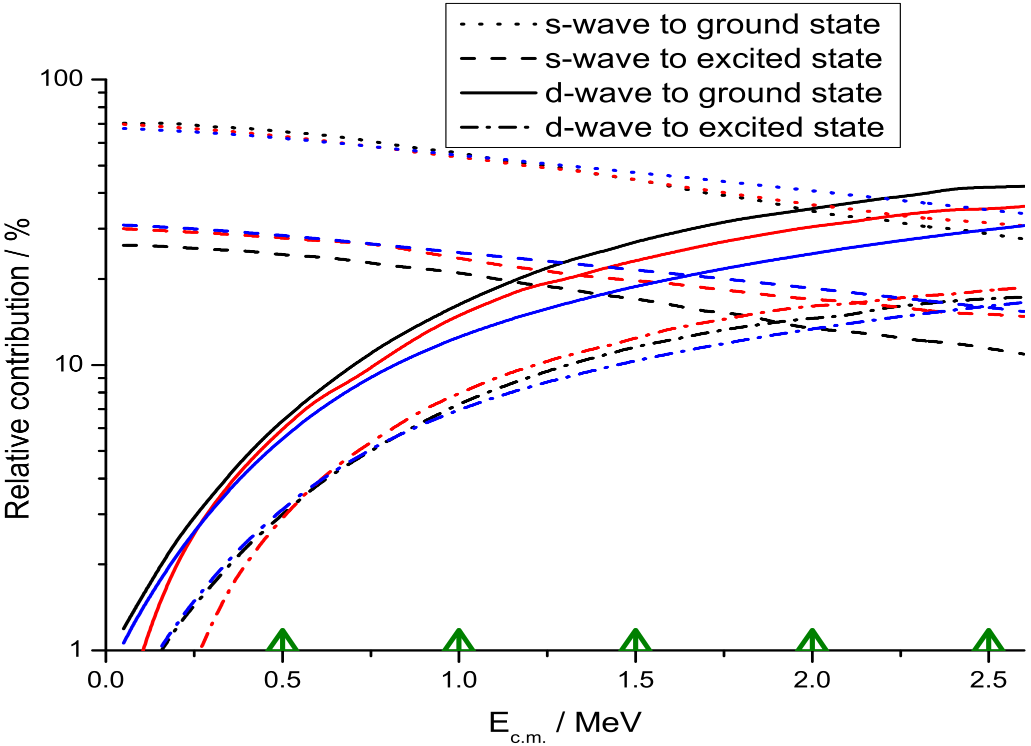
$^3He(\alpha,\gamma)^7Be$ reaction, what is needed for even better precision



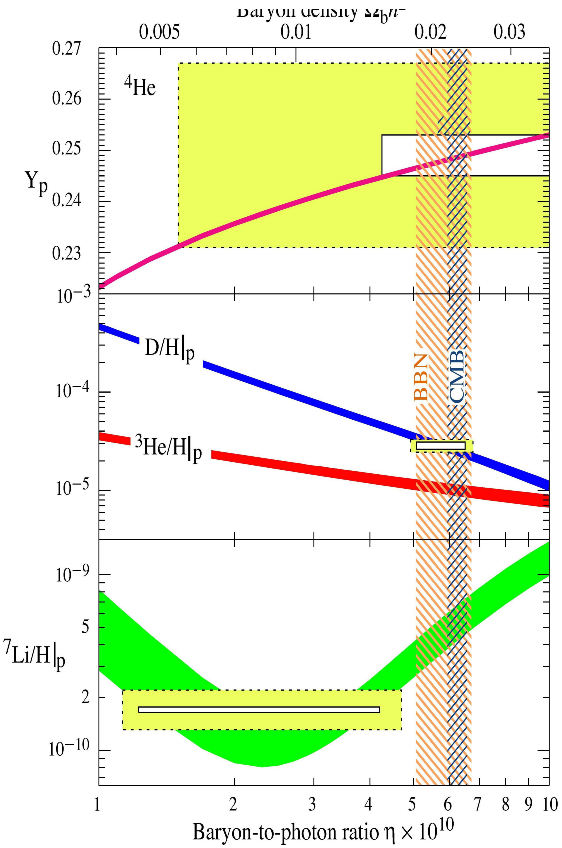


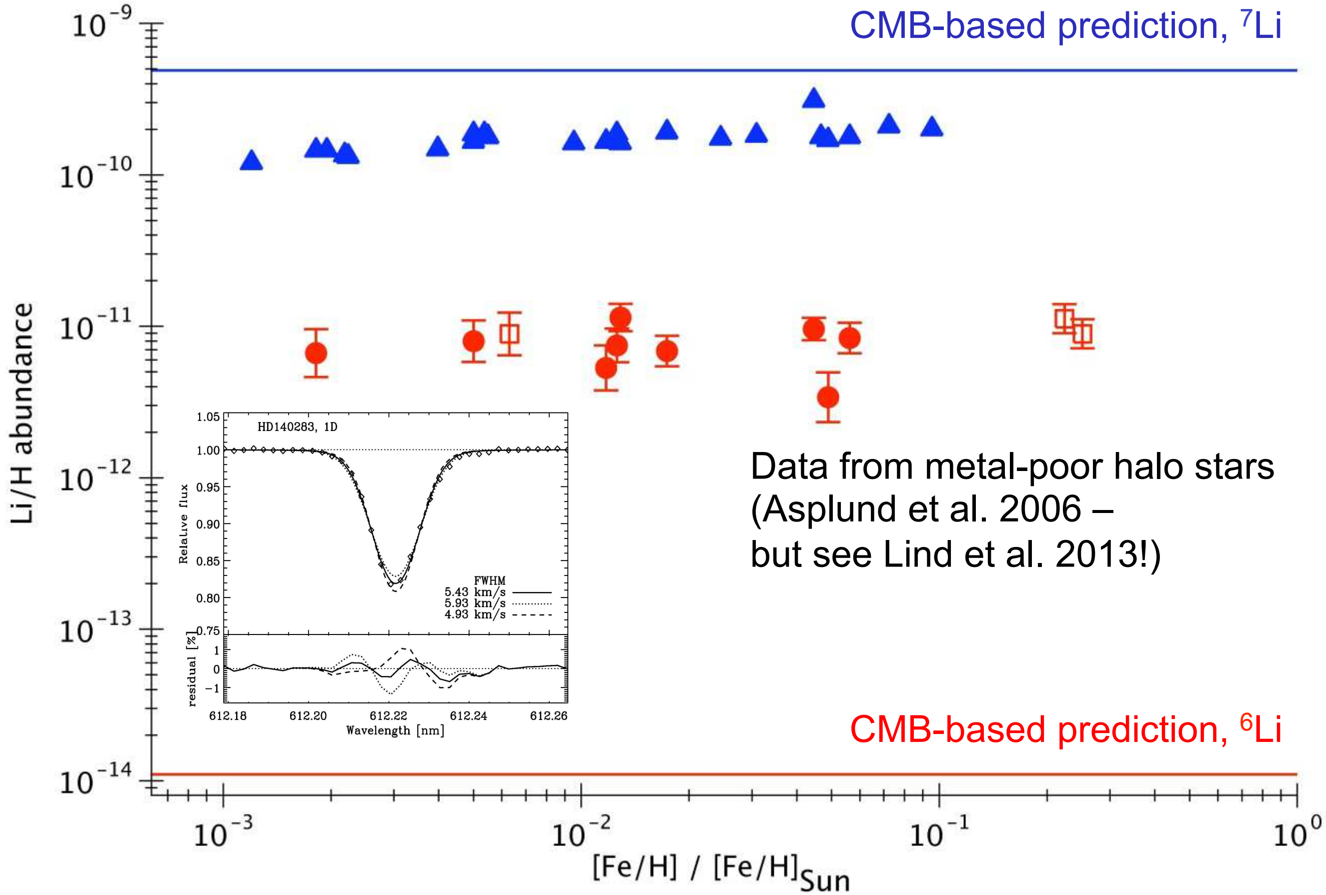
1. Comprehensive data set from 0.1 – 2.5 MeV.

2. Separation of s-wave from d-wave component at 1 – 2 MeV.

When this is given, the uncertainty of the evaluated reaction rate may decrease below 3%.

The Spite abundance plateau and the lithium problem(s)

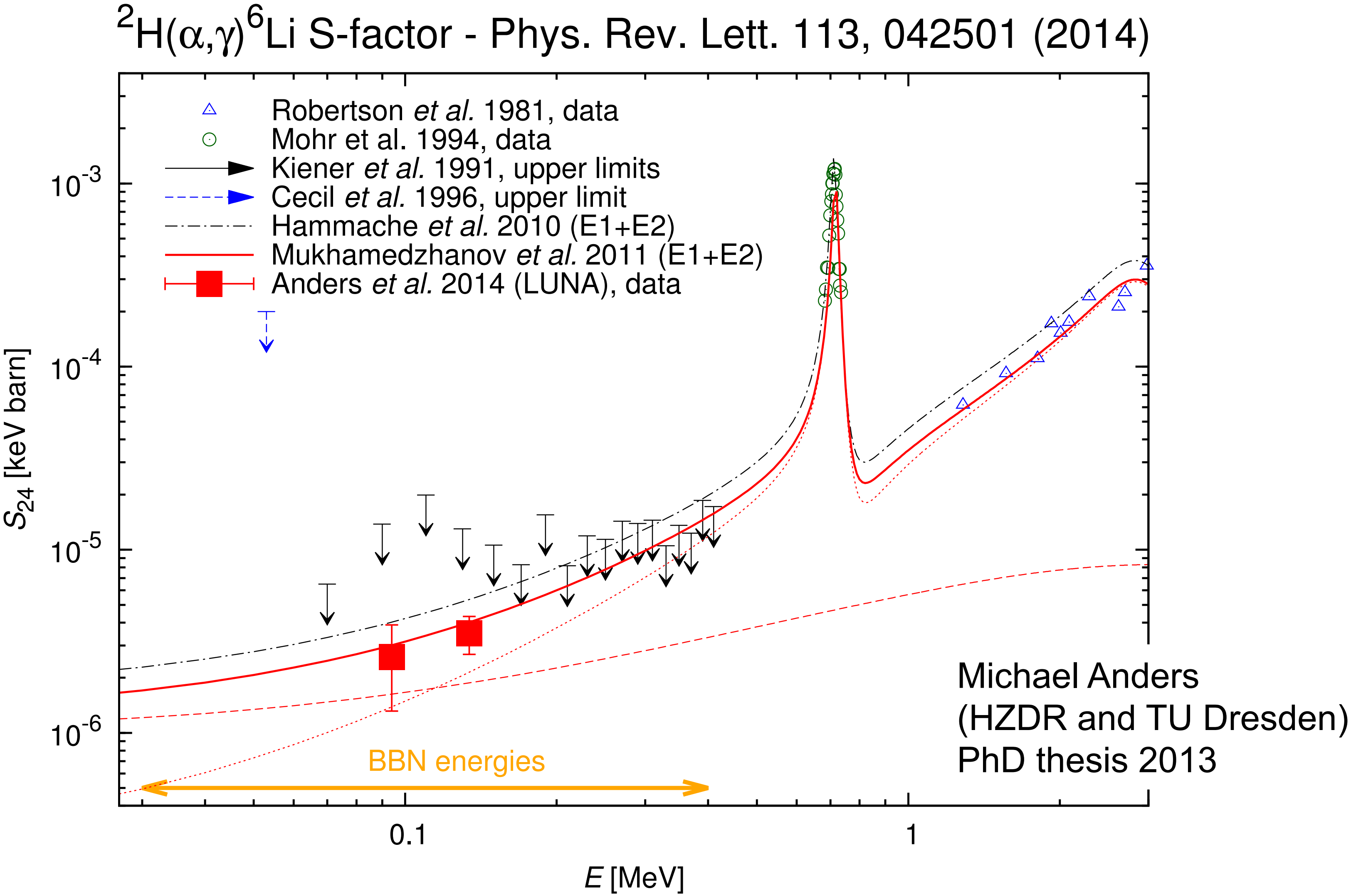




- Cosmic ^{7}Li problem: Less ^{7}Li in old stars than predicted.
  ^{7}Li production mainly by ^{3}He(α,γ)^{7}Be ➔ ^{7}Li
  LUNA data rules out a nuclear solution for the cosmic ^{7}Li problem.

- Reported cosmic ^{6}Li problem: Much more ^{6}Li in some old stars than predicted.
  ^{6}Li production mainly by the ^{2}H(α,γ)^{6}Li reaction.

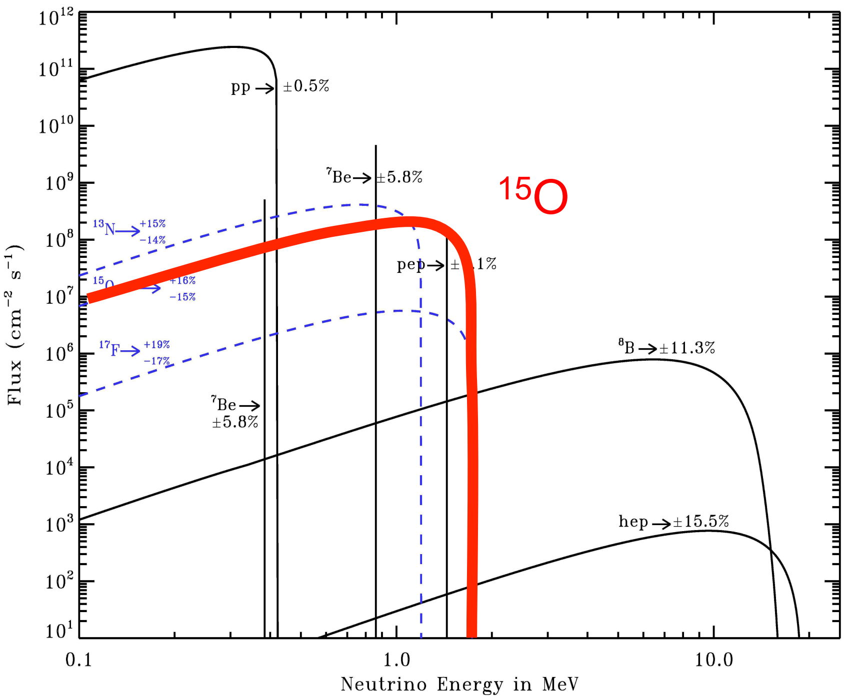
$^2H(\alpha,\gamma)^6Li$, LUNA results for the S factor and the ^6Li abundance

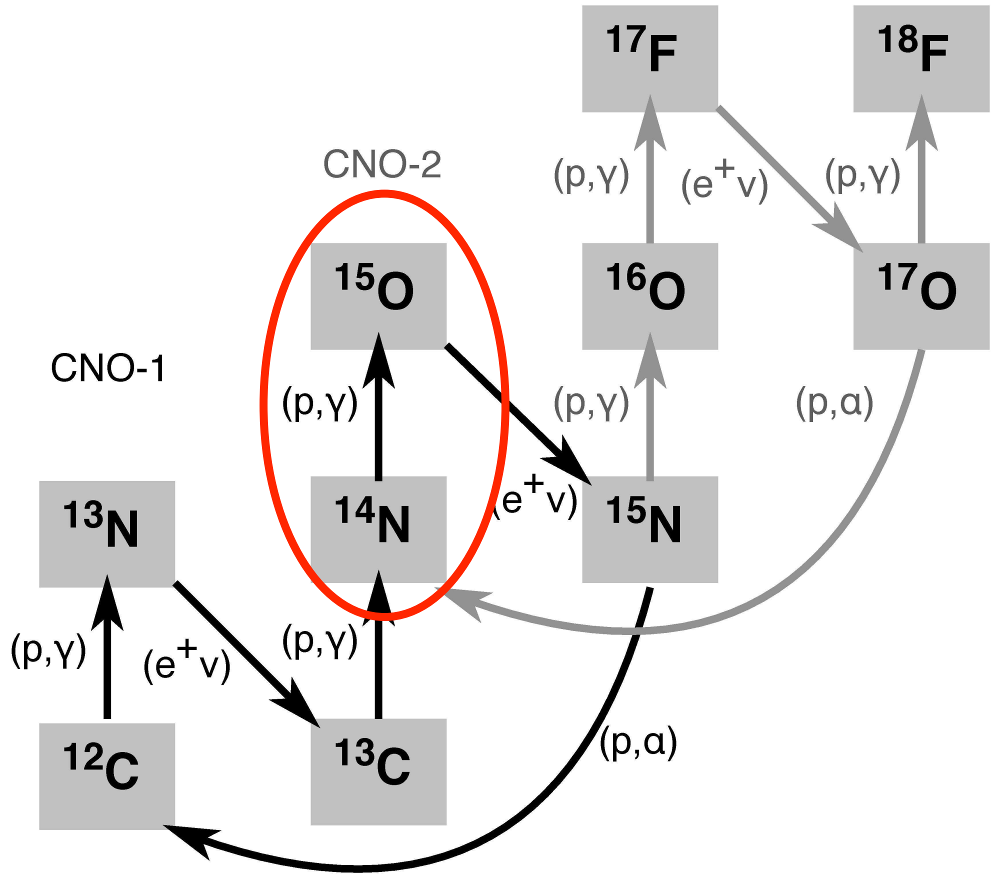


- First direct data point in the Big Bang energy window
- Determine primordial $^6Li/^7Li$ ratio = $(1.5 \pm 0.3) * 10^{-5}$ entirely from experimental data
- To be compared to reports of $^6Li/^7Li \sim 10^{-2}$

$^{14}N(p,\gamma)^{15}O$, bottleneck of the CNO cycle, and ^{15}O neutrinos

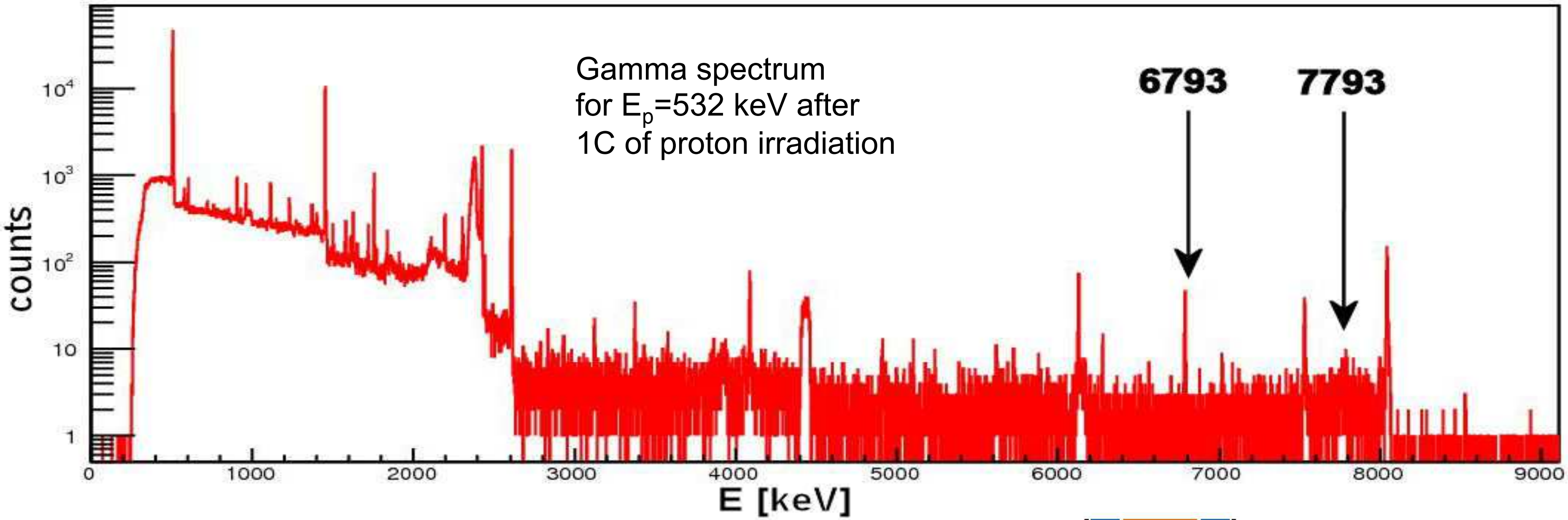
- $Q(\beta^+, {}^{15}O) = 2.754$ MeV
- Lifetime of ^{14}N in the solar center 10^8 a
- Bottleneck of the whole cycle: $^{14}N(p,\gamma)^{15}O$
- $$\frac{\partial \ln \Phi_{\nu(\text{O-15})}}{\partial \ln S[^{14}\text{N}(p,\gamma)^{15}\text{O}]} = 1$$

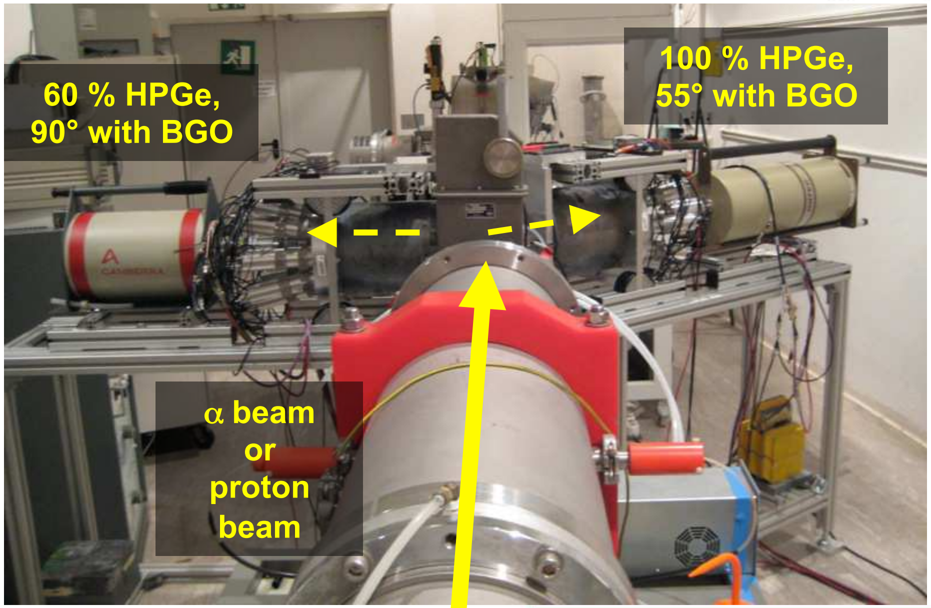


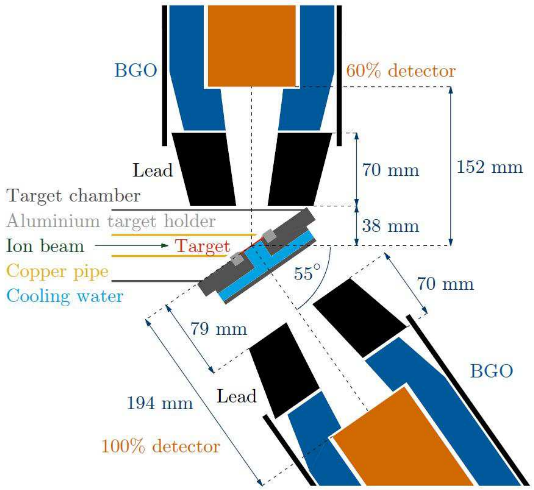


Work in progress: high-energy experimental data on $^{14}N(p,\gamma)^{15}O$

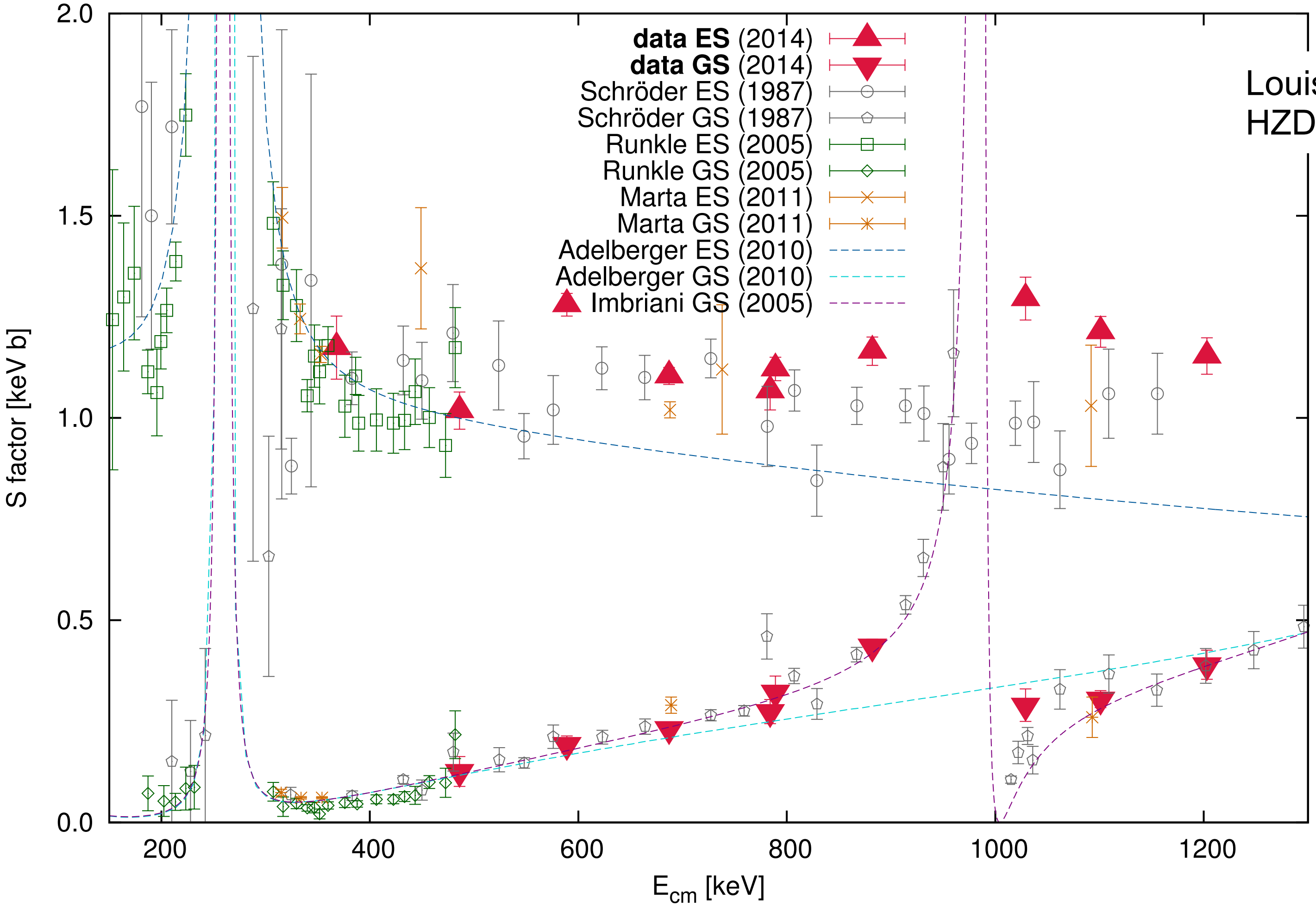
- Surface-based new data at 10 µA, 3 MV HZDR Tandem accelerator







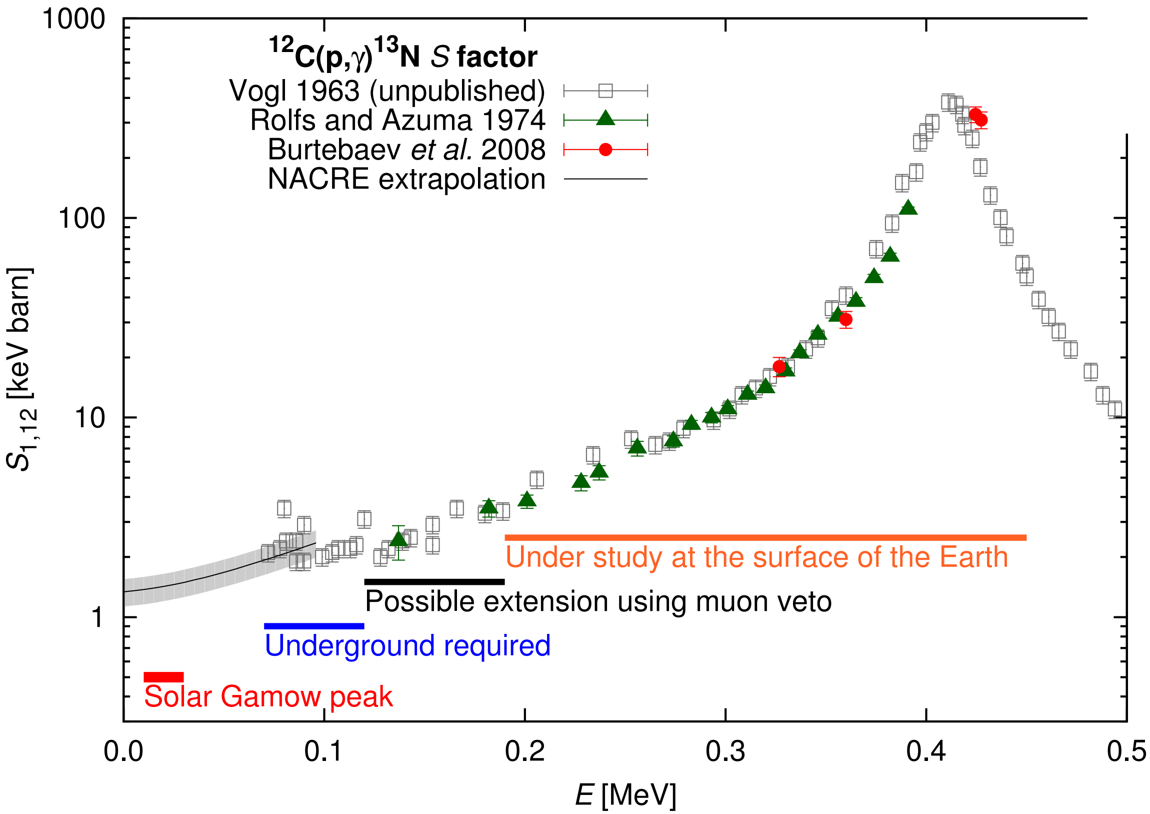
Preliminary high-energy experimental data on $^{14}N(p,\gamma)^{15}O$

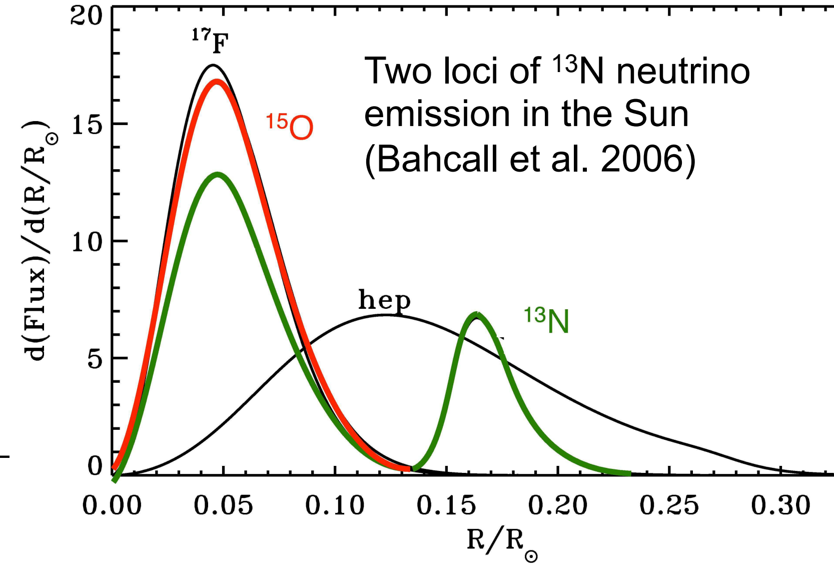


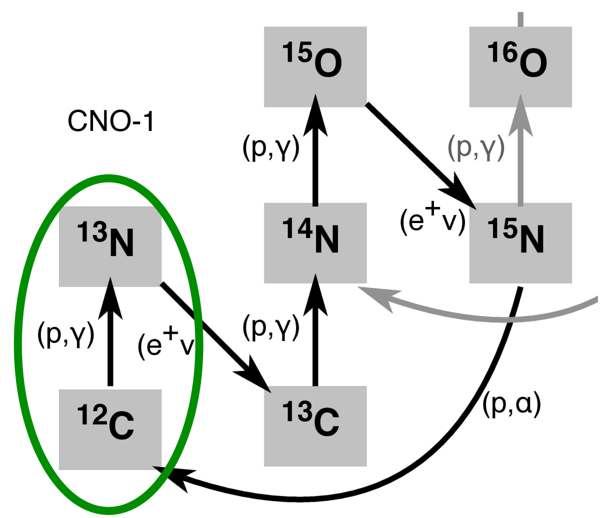
Louis Wagner et al.,
HZDR and TU Dresden

- Surface-based new data at 10 µA, 3 MV Tandem accelerator
- Link to low-energy LUNA data and study of weak branches still under construction: Greater beam intensity and long (~months) running times needed!

^{13}N neutrinos and the ^{12}C(p,γ)^{13}N reaction

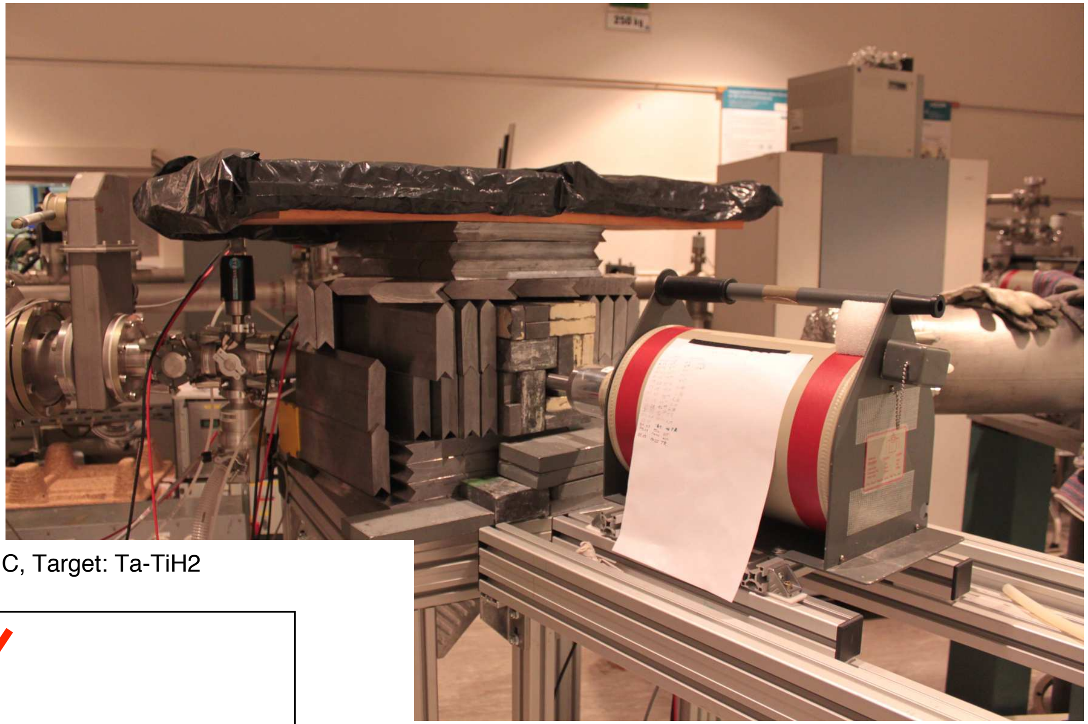




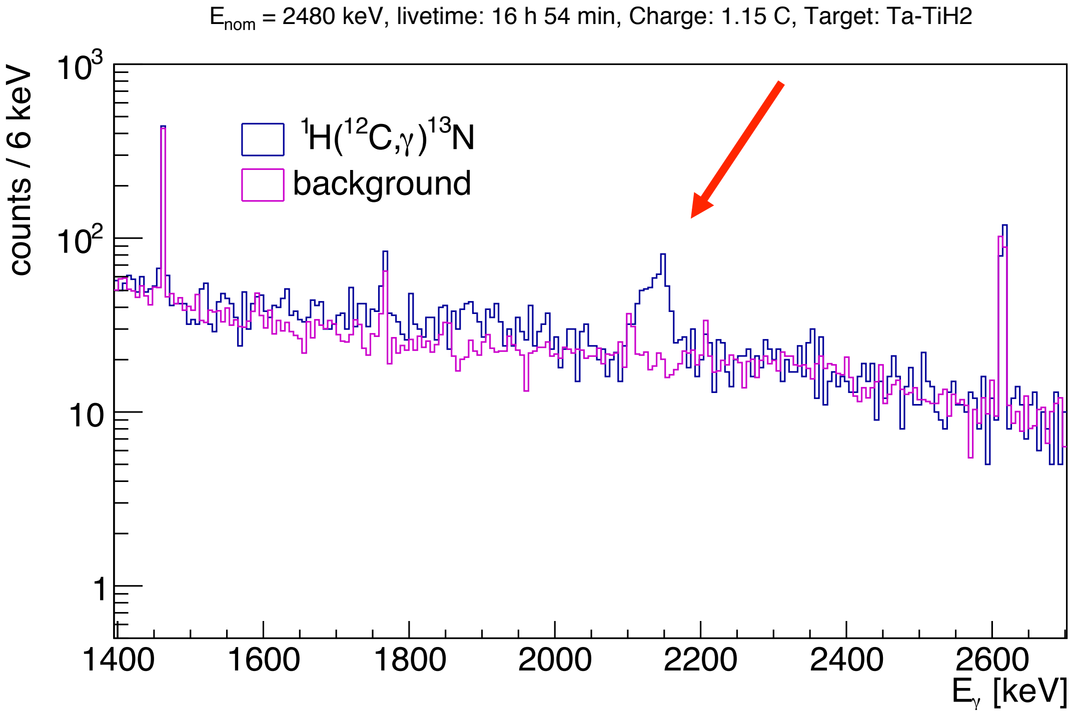


Mitglied der Helmholtz-Gemeinschaft
Daniel Bemmerer | Underground nuclear astrophysics | Hirschegg, 13.01.2015 | http://www.hzdr.de

^{13}N neutrinos and the ^{12}C(p,γ)^{13}N reaction



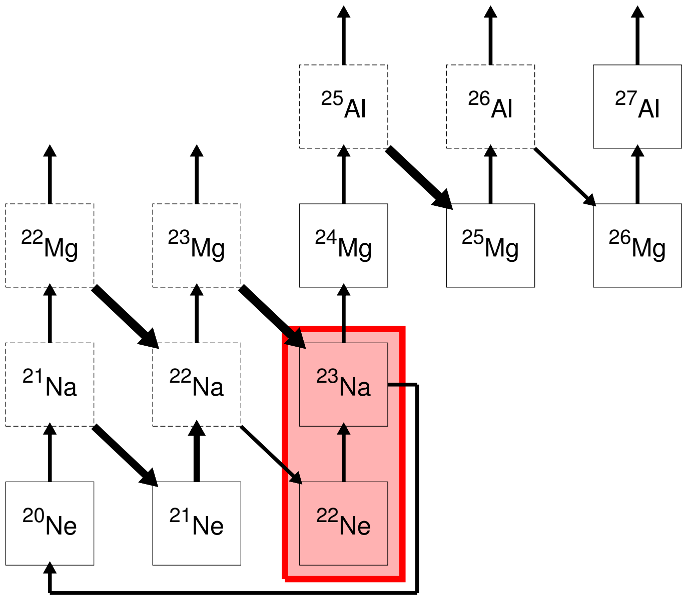
Run at E = 190 keV

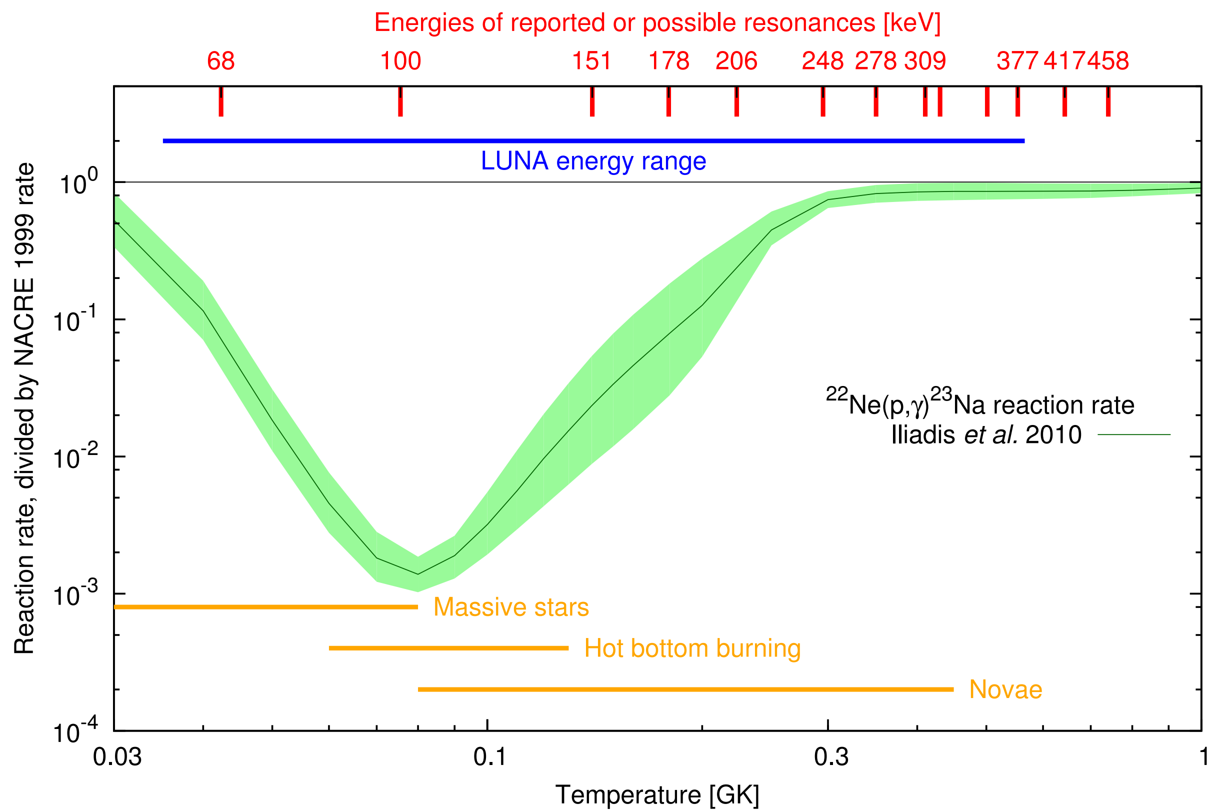


- Surface-based experiment in inverse kinematics shows no ion-beam induced background.
- Extension to even lower energies requires high ^{12}C beam intensity, gas target, and underground site.

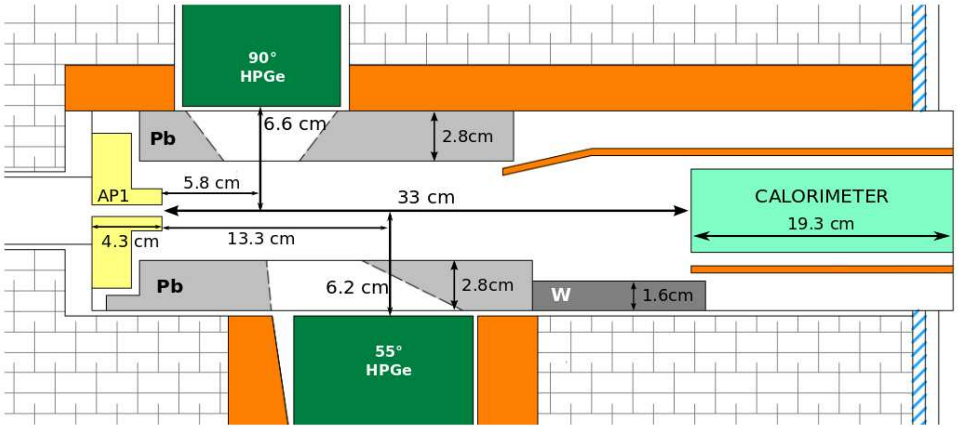
The neon-sodium cycle and the $^{22}Ne(p,\gamma)^{23}Na$ reaction

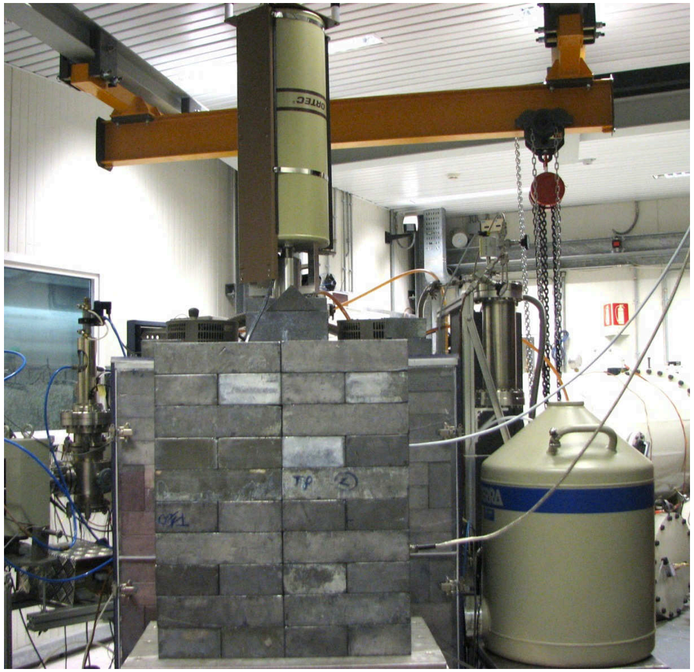
- Second to the slowest reaction in the Ne-Na cycle of hydrogen burning
- Strong effect on the abundances of ^{22}Ne and ^{23}Na
- Possible propagation to heavier nuclides

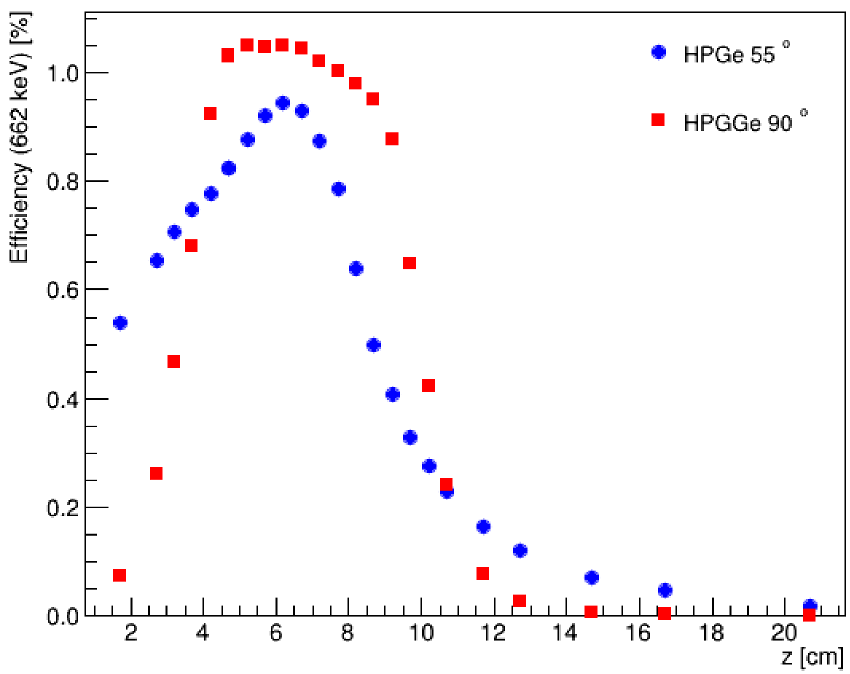




$^{22}Ne(p,\gamma)^{23}Na$ phase 1 setup at LUNA

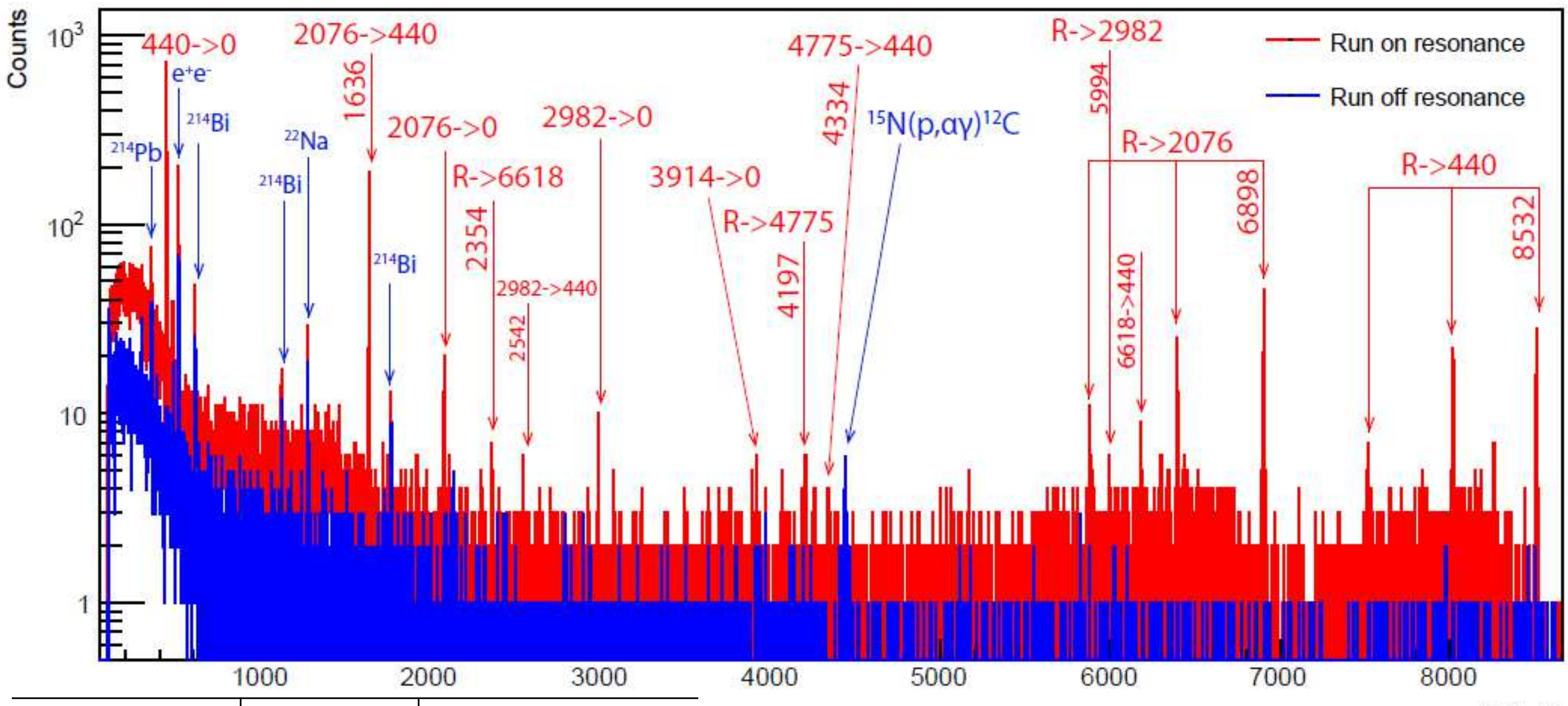






DRESDEN concept
HZDR
Mitglied der Helmholtz-Gemeinschaft

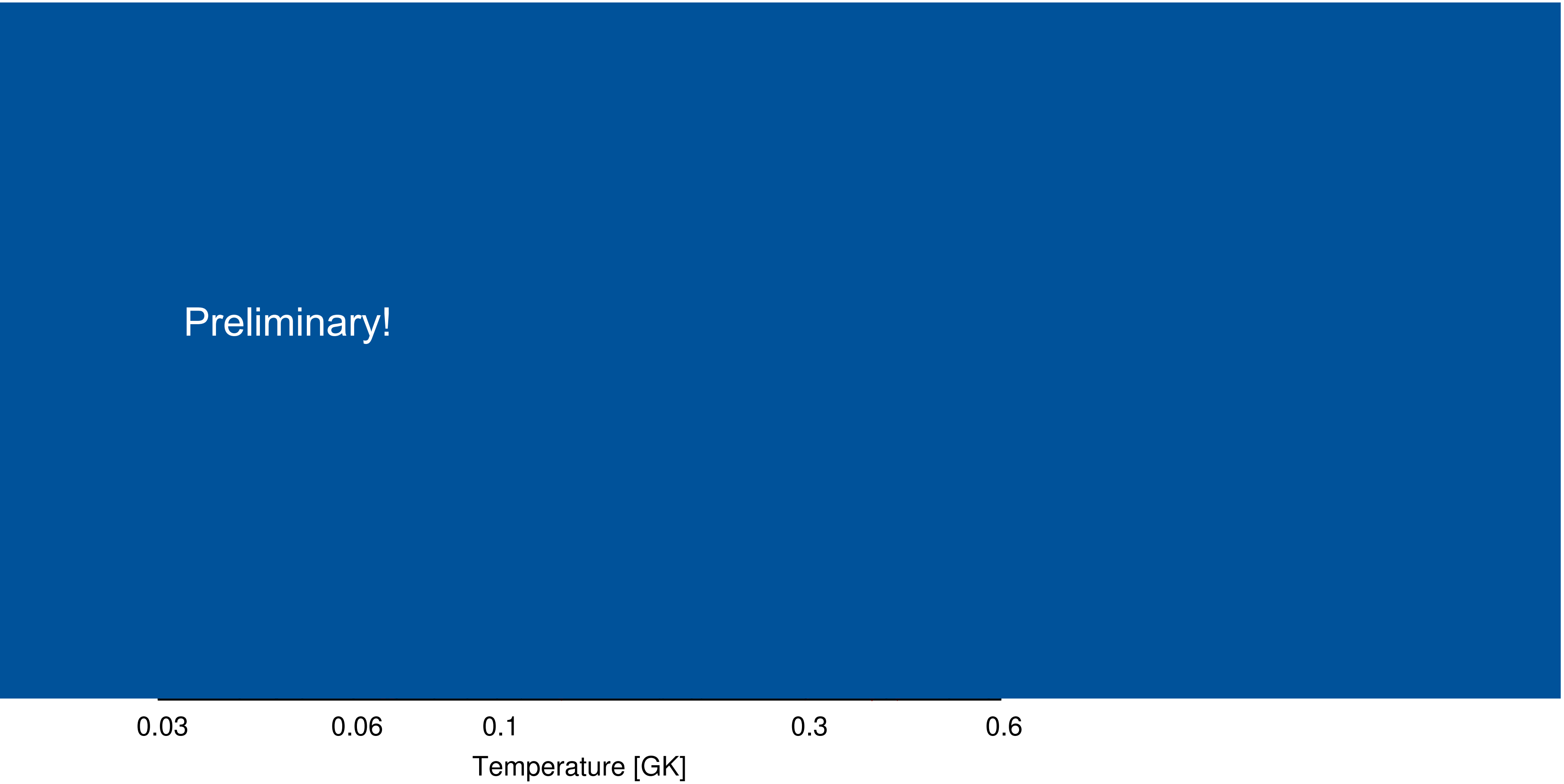
$^{22}Ne(p,\gamma)^{23}Na$ resonance at E_{res}^{lab} = 189.5 keV



Preliminary!

Mitglied der Helmholtz-Gemeinschaft

^{22}Ne(p,γ)^{23}Na, HPGe data and astrophysical reaction rate



LUNA phase 1 (preliminary data)

LUNA phase 2 (from March 2015)

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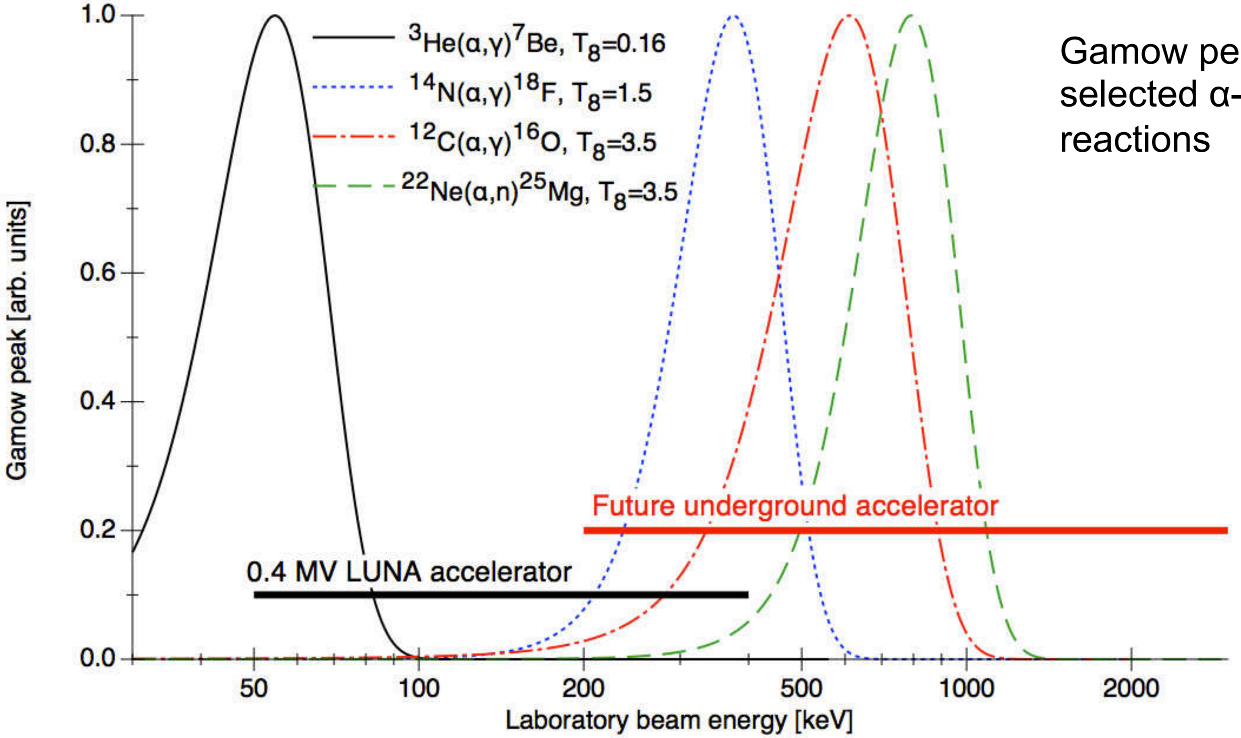
Limitations of the existing LUNA 0.4 MV accelerator

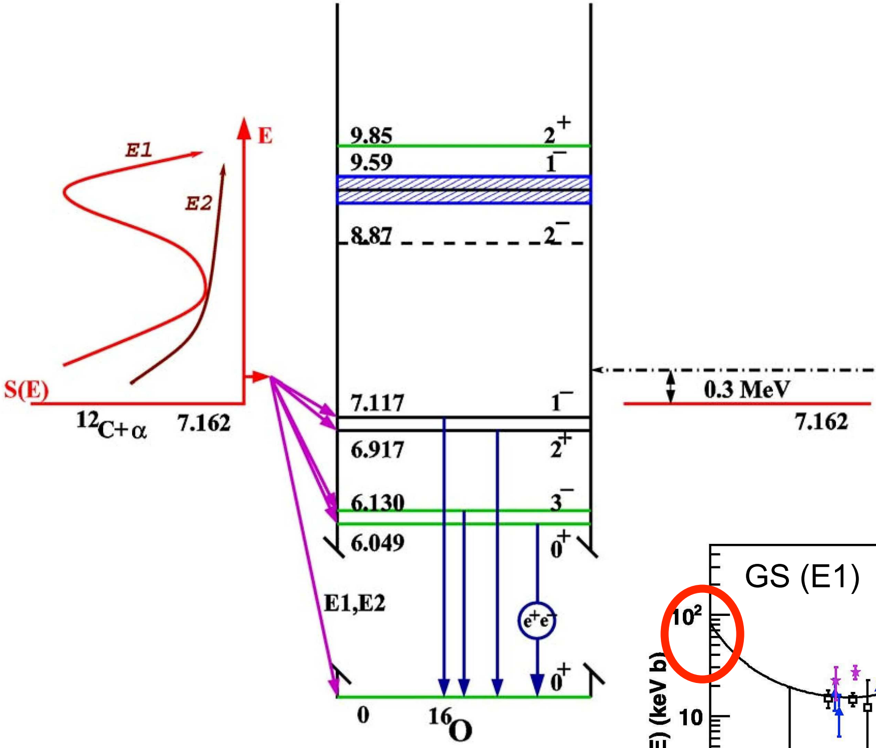


Gamow peak for selected α-induced reactions

> 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."

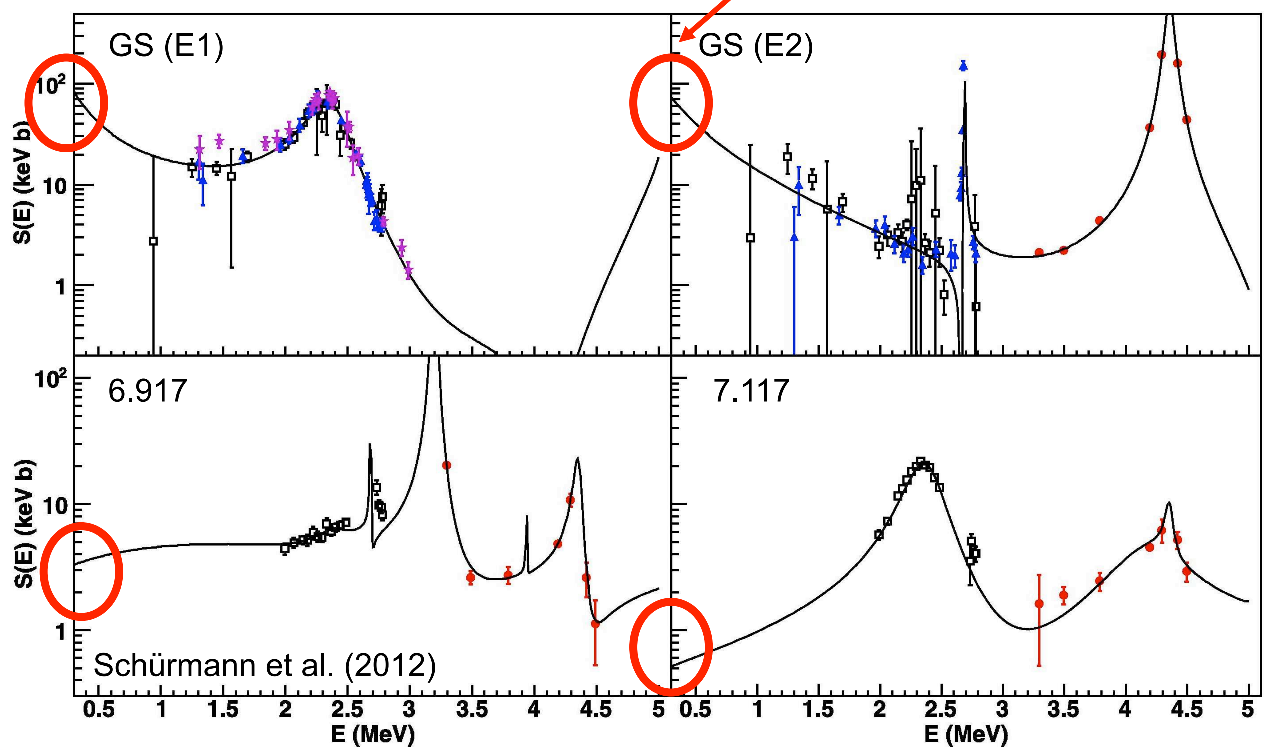
- Many reactions cannot be studied with a 0.4 MV accelerator alone.
  - Solar fusion reactions
  - Stellar helium and carbon burning
  - Neutron sources for the astrophysical s-process
- A new, higher-energy underground accelerator is needed!

The $^{12}C(\alpha,\gamma)^{16}O$ reaction, determining the $^{12}C/^{16}O$ ratio

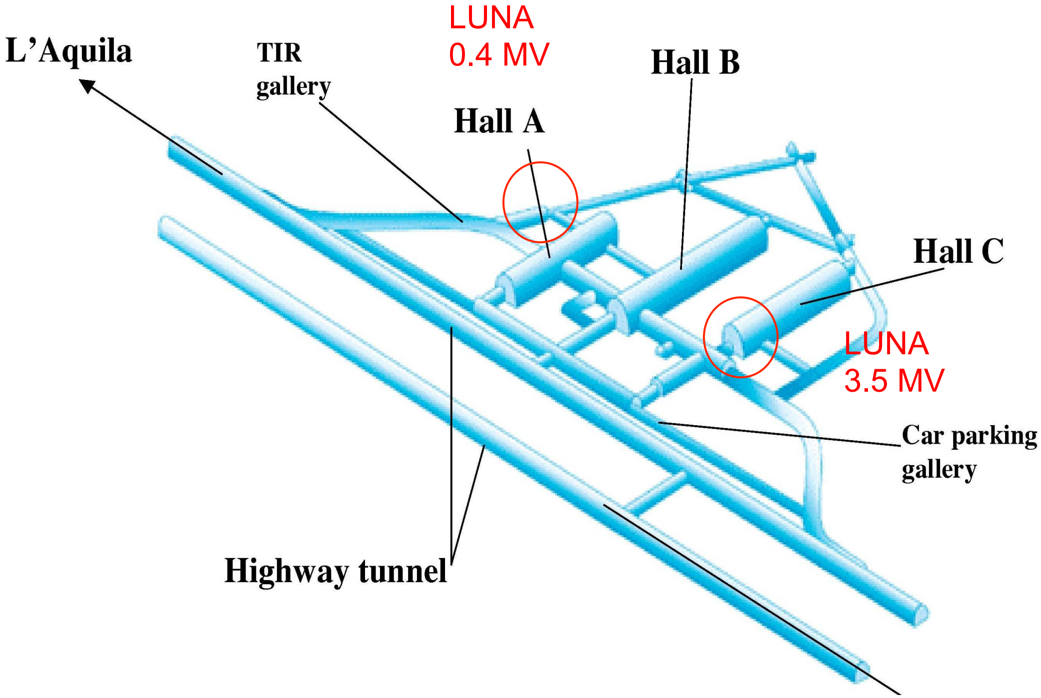


- The „Holy Grail of Nuclear Astrophysics“ (Willy Fowler, 1983 Nobel Laureate in Physics)
- Extrapolations to the Gamow energy still are only poorly constrained 30 years later
- New, low-energy cross section data may provide the needed breakthrough in precision!

Gamow energy
for core helium burning



Gran Sasso / Italy: LUNA-MV 3.5 MV accelerator



Italian research ministry approved funding in two parts:

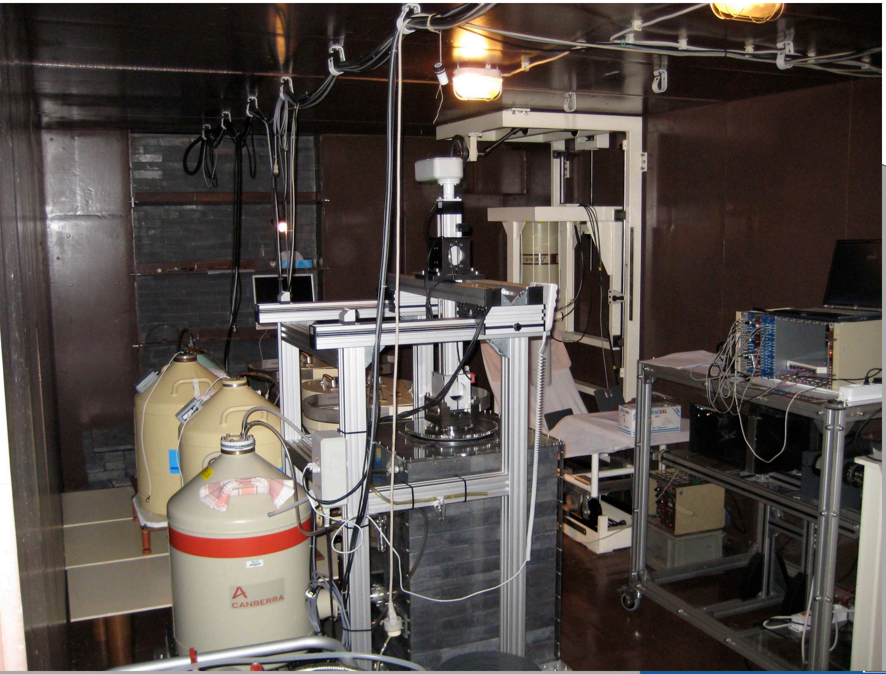
- 2.8 M€ for purchasing a 3.5 MV single-ended accelerator, with radio-frequency ion source (2012).
- 2.5 M€ for beam lines, magnets, instrumentation (2013).
- First beam expected 2018/2019

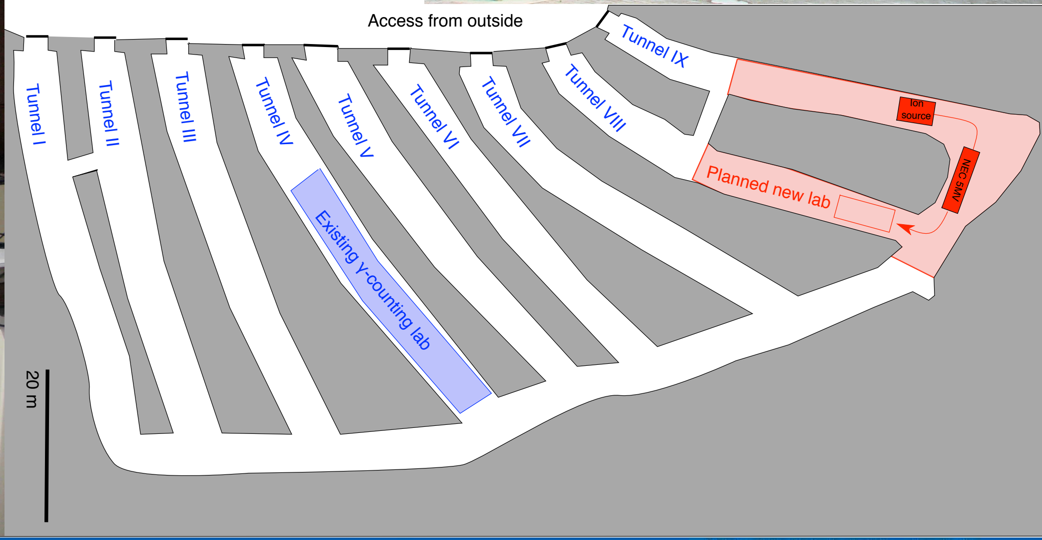
Scientific program:

- Stellar helium burning, including the „Holy Grail of Nuclear Astrophysics“ $^{12}C(\alpha,\gamma)^{16}O$
- $^{14}N(p,\gamma)^{15}O$ for solar fusion
- Neutron source reactions for the astrophysical s-process: $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$

Dresden Felsenkeller, below 47 m of rock: *Status quo*

- γ-counting facility for analytics, established 1982
- Deepest underground γ-counting lab in Germany
- 10 high-purity germanium detectors
- Scientific use 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
- Why not put an accelerator there?





Planned Felsenkeller accelerator, HZDR and TU Dresden

- 12-year old, working 5 MV accelerator
- 250 μA upcharge current (double pellet chains)
- External Cs sputter ion source: 100 μA H^- and C^-
- Work on internal RF ion source for 50 μA He^+

- Joint effort by TU Dresden (Kai Zuber et al.) and HZDR (Daniel Bemmerer et al.)
- Project is fully funded
- First beam expected early 2016

- Days 1+2: Solar fusion and carbon burning.
- Wide open for international users!

TECHNISCHE UNIVERSITÄT DRESDEN
DRESDEN concept
HZDR

Underground nuclear astrophysics, from the Big Bang to astrophysical novae

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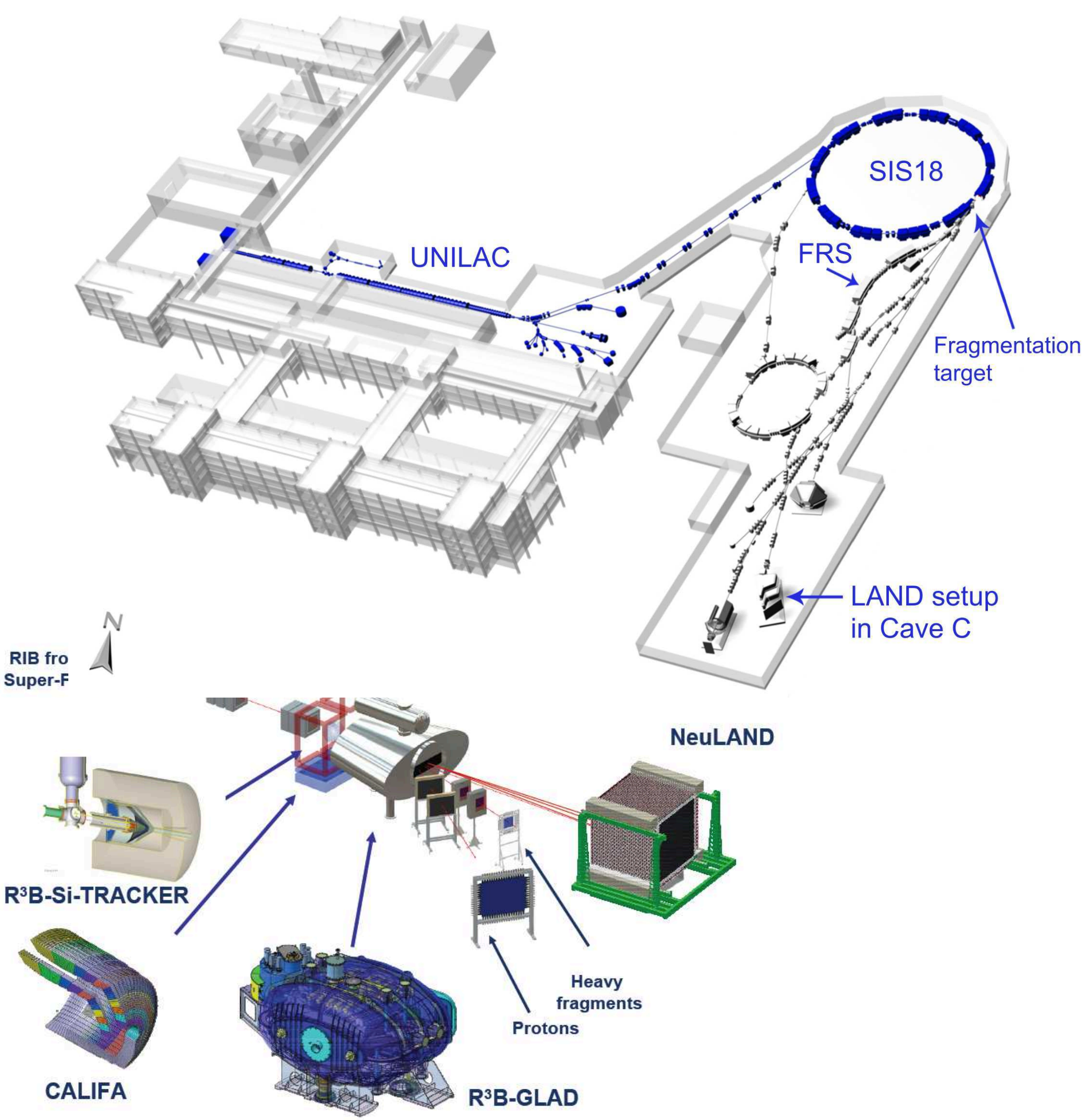
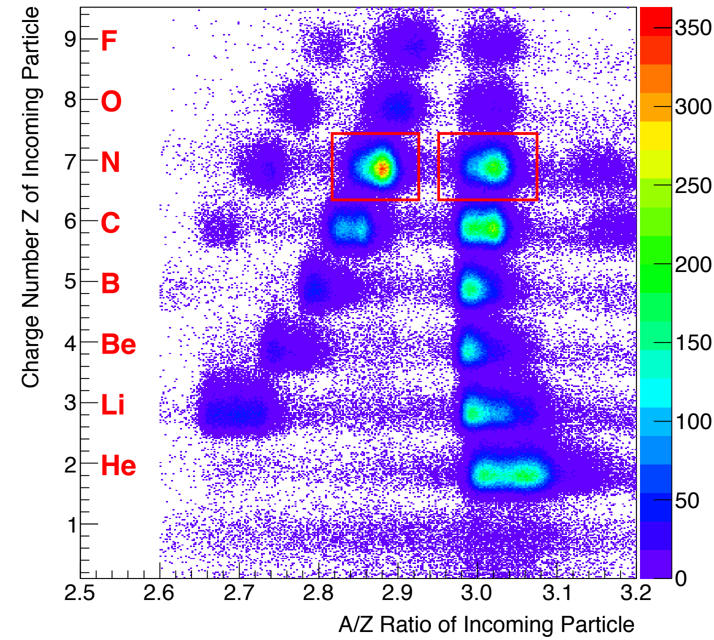
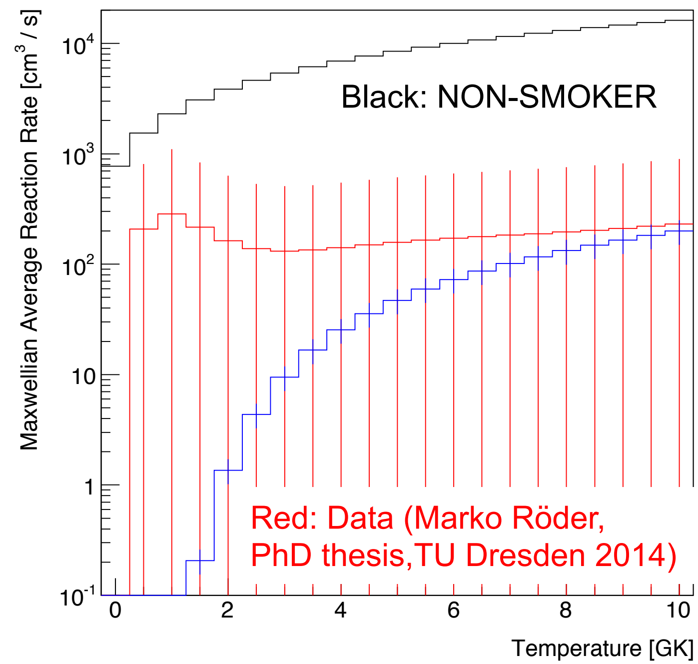
^{20,21}N Coulomb dissociation at GSI (S393)

Motivation

- r-process scenario including light nuclei

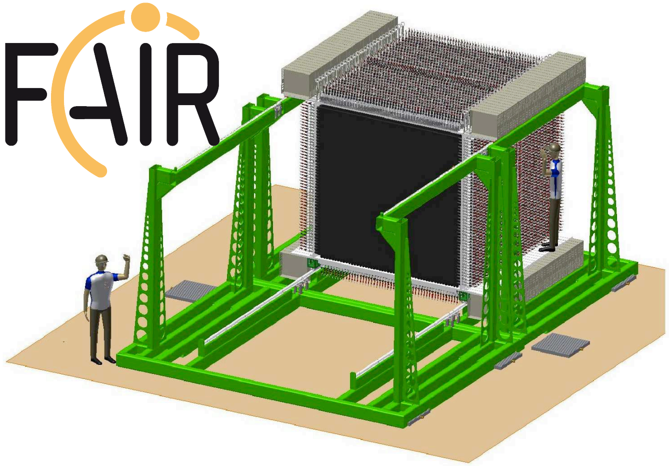




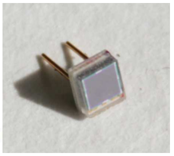


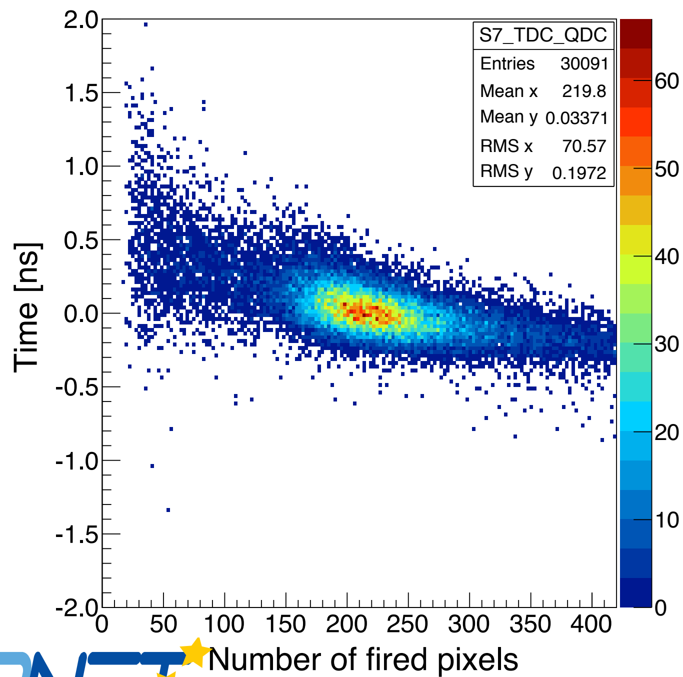
Re-instrument scintillator-based neutron detectors with SiPMs?

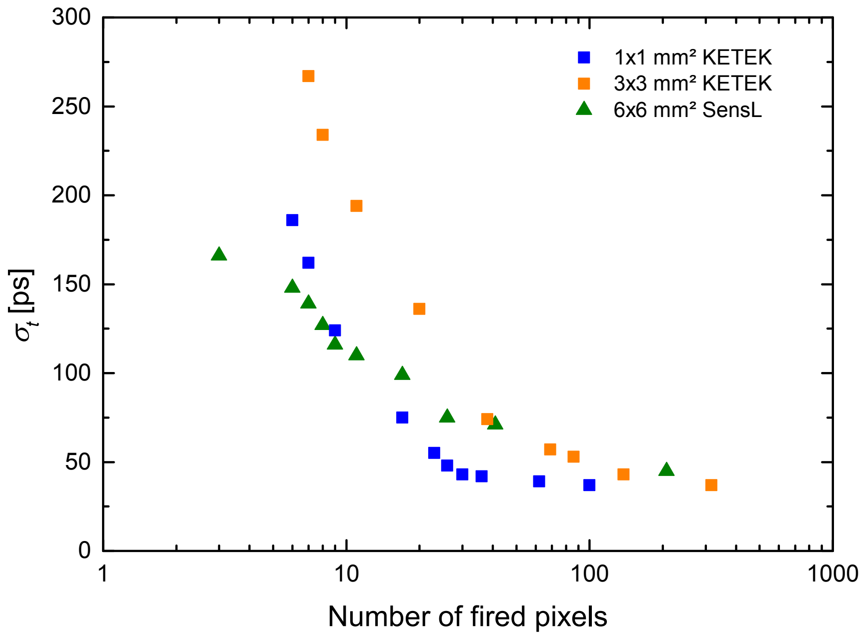
FAIR



- NeuLAND@R^{3}B, time-of-flight detector for 0.2-1.0 GeV neutrons
- Built from 3000 bars: 270 x 5 x 5 cm^3
- RP-408 (=EJ-200), peak emission at 420 nm
- Aim at very good momentum resolution near (γ,n) threshold
- Need 95% efficiency, σ < 0.15 ns time resolution
- Timing PMT's are a major cost driver







Photosensor work at HZDR:
- NeuLAND efficiency aim reached with two SiPM's / side
- Time resolution aim 0.15 ns reached with small scintillator
- Work in progress: time resolution with large NeuLAND bar

NUPNET ERA-NET for Nuclear Physics Infrastructures

DRESDEN concept HZDR

LUNA collaboration

Italy	Genova	F. Cavanna, F. Ferraro, P. Corvisiero, P. Prati
	Gran Sasso	A. Best, A. Boeltzig, A. Formicola, M. Junker
	Milano	A. Guglielmetti (LUNA spokeswoman), D. Trezzi
	Napoli	A. di Leva, G. Imbriani, V. Roca, F. Terrasi
	Padova	C. Broggini, A. Caciolli, R. Depalo, R. Menegazzo
	Roma	C. Gustavino
	Teramo	O. Straniero
	Torino	G. Gervino
Germany	Bochum	C. Rolfs, F. Strieder, H.-P. Trautvetter
	Dresden	M. Anders, D. Bemmerer, T. Szücs, M. Takács
Hungary	Debrecen	Zs. Fülöp, Gy. Gyürky, E. Somorjai, T. Szücs
UK	Edinburgh	M. Aliotta, C. Bruno, T. Davinson, D. Scott

HZDR Detector Technology and Systems group

Sun:	$^{14}N(p,\gamma)^{15}O$	Louis Wagner
	$^{12}C(p,\gamma)^{13}N$	Tobias Reinhardt (TU Dresden)
	$^{15}N(\gamma,\gamma)^{15}N$	Tamás Szücs
AGB, novae:	$^{22}Ne(p,\gamma)^{23}Na$ at LUNA	Marcell Takács
Supernovae:	$^{40}Ca(\alpha,\gamma)^{44}Ti$	Konrad Schmidt
GSI/FAIR work	SiPMs for NeuLAND	Stefan Reinicke
	$^{20,21}N(\gamma,n)^{20,19}N$	Marko Röder (TU Dresden)

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