



Low-level measuring techniques for neutrons: High accuracy neutron source strength determination and fluence rate measurement at an underground laboratory

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Physikalisch-Technische Bundesanstalt
... the National Metrology Institute of Germany

Fundamental
Constants



Federal Ministry
of Economics
and Technology



1887 Founding of the Physikalisch-Technische
Reichsanstalt (PTR) by Werner von Siemens and
Hermann von Helmholtz

... the first national metrology institute world-wide



- National Metrology Institute (NMI)
- Federal Ministry of Economics and Technology (BMWi)
- 150 Mio. € budget, plus third party funding
- Approx. 1260 permanent staff and 675 non-permanent staff including 125 PhD students
- 600 scientific papers per year

Braunschweig



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Metrology:

- Science and application of correct measurement
- Traceability of results to the SI through national standards
- Determination of results with verification of uncertainty



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PTB Ion Accelerator Facility (PIAF):

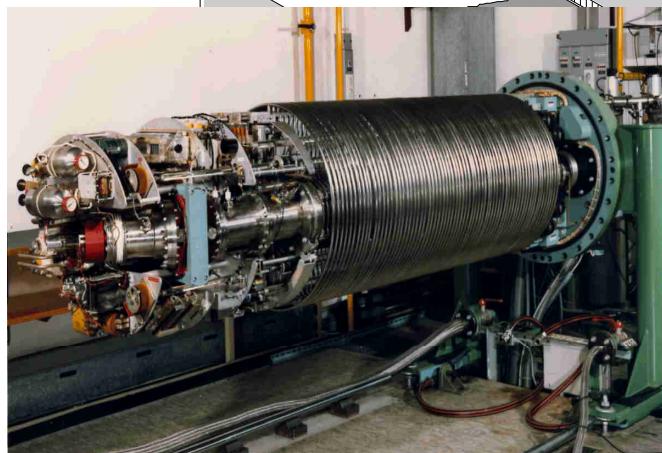
- 3.8 MV van de Graaff Accelerator
- Compact Cyclotron
- p, d, α : Energies up to $E_p < 20$ MeV, $E_d < 13$ MeV, $E_\alpha < 28$ MeV
- Used for the production of ions, neutrons, photons

Braunschweig

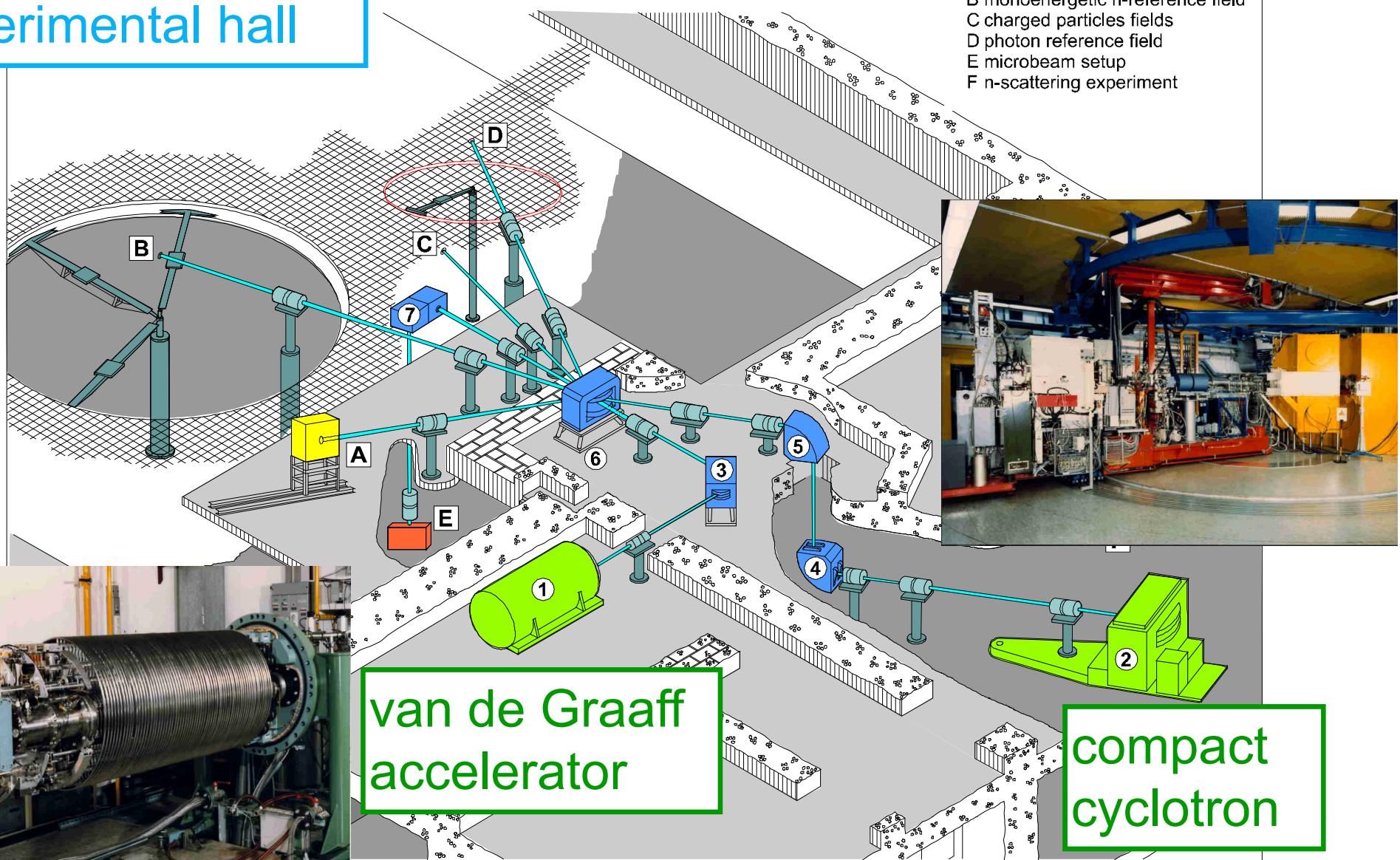
PTB Ion Accelerator Facility: overview

PTB

low-scatter experimental hall

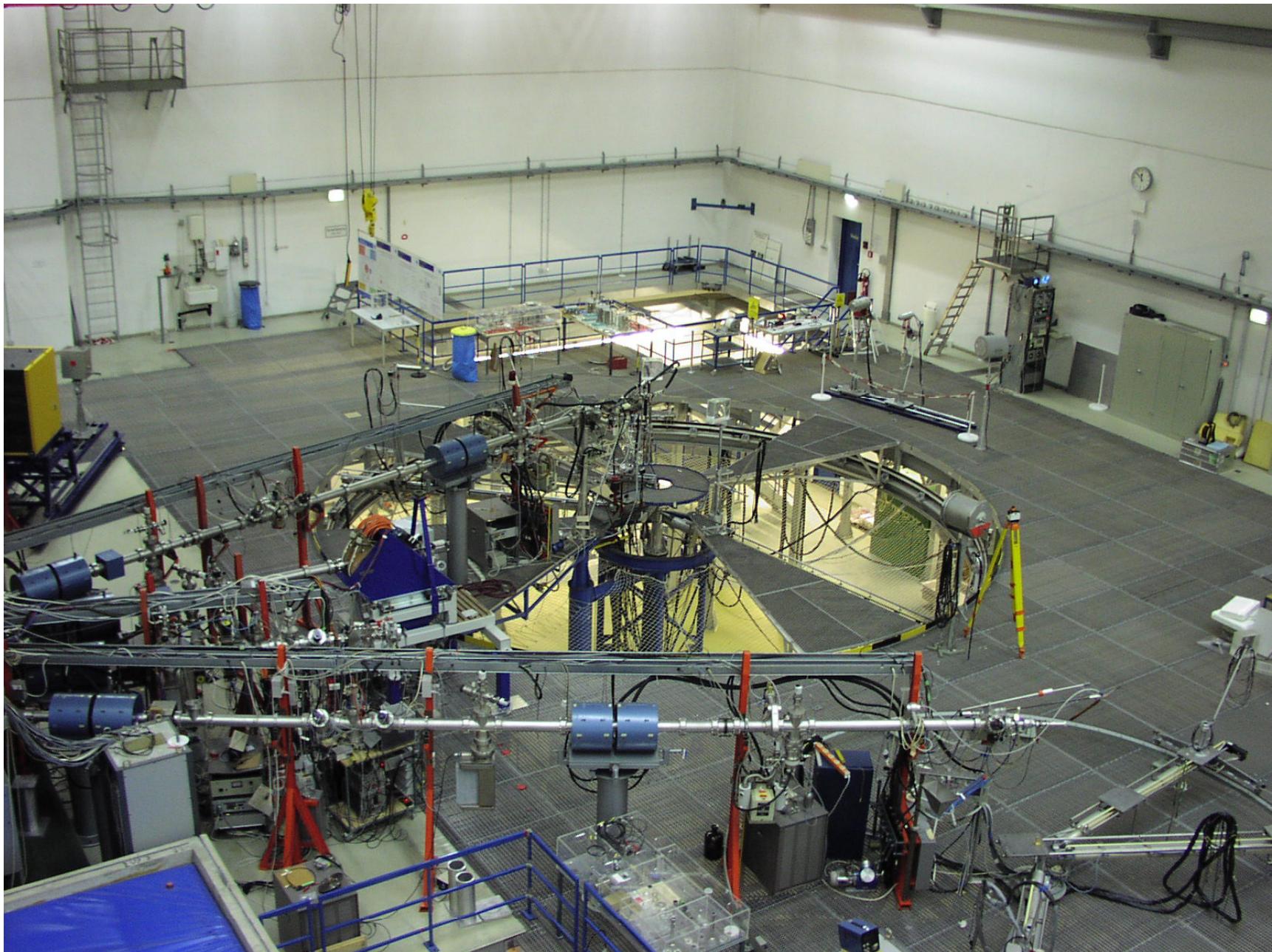


van de Graaff
accelerator



PTB Ion Accelerator Facility: low scatter hall

PTB

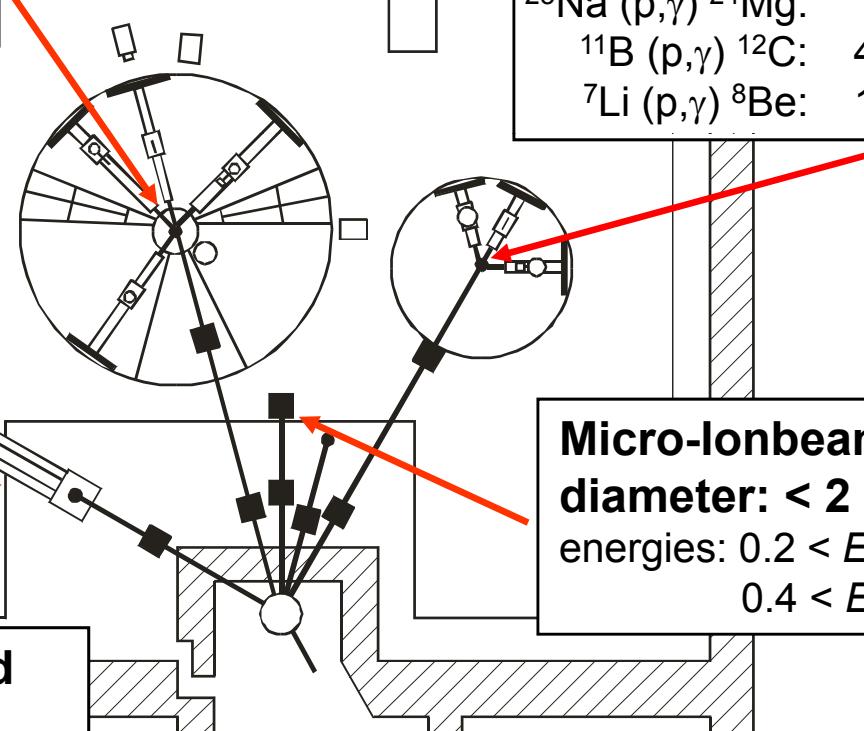


Mono-energetic Neutrons according to ISO 8529, 1-3	
^7Li (p,n) ^7Be :	144; 250; 565 keV
T (p,n) ^3He :	1.2; 2.5 MeV
D (d,n) ^3He :	5.0; 8.0 MeV
T (d,n) ^4He :	14.8; 19.0 MeV

Experimental Hall
25 m x 30 m x 14 m

High Energy Photons
according to ISO 4037

^{12}C (p,p'γ) ^{12}C :	4.44	MeV
^{19}F (p,αγ) ^{16}O :	6.13; 6.92; 7.12	MeV
optional:		
^{23}Na (p,γ) ^{24}Mg :	8.93	MeV
^{11}B (p,γ) ^{12}C :	4.44; 12.5; 16.49	MeV
^7Li (p,γ) ^8Be :	14.7; 17.64	MeV



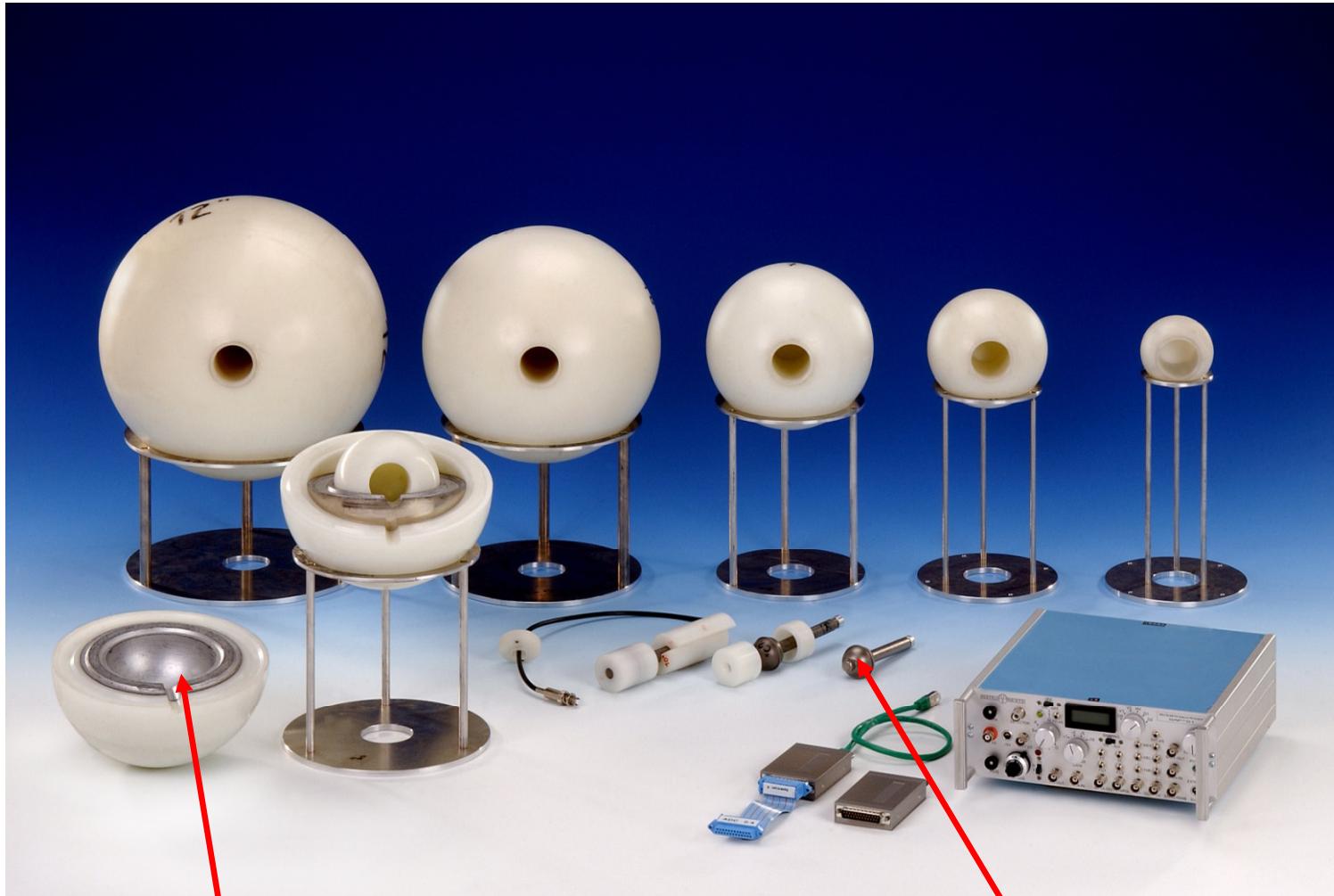
Micro-Ionbeam
diameter: < 2 μm FWHM
energies: $0.2 < E_p < 20$ MeV
 $0.4 < E_\alpha < 28$ MeV

**Intense Collimated Neutron Field
with Broad Energy Distributions**

$^9\text{Be} + \text{d}$ (13.5 MeV) : $\langle E_n \rangle \approx 5$ MeV
 $^9\text{Be} + \text{p}$ (22.0 MeV) : $\langle E_n \rangle \approx 10$ MeV

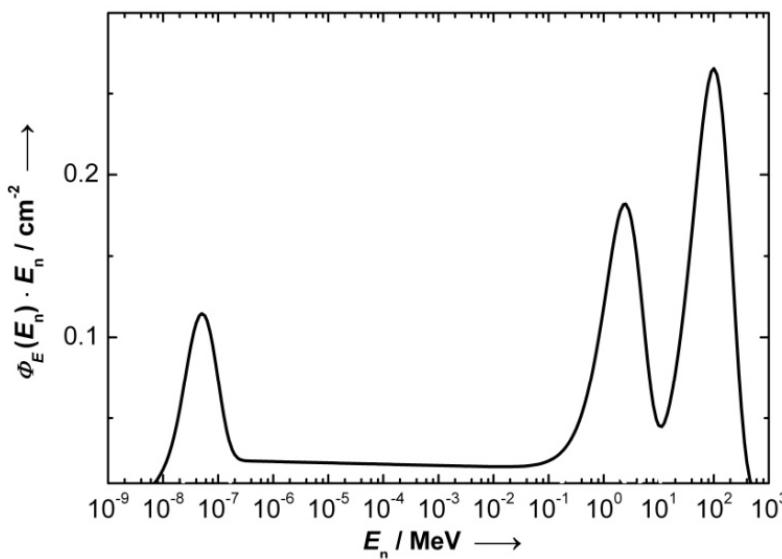
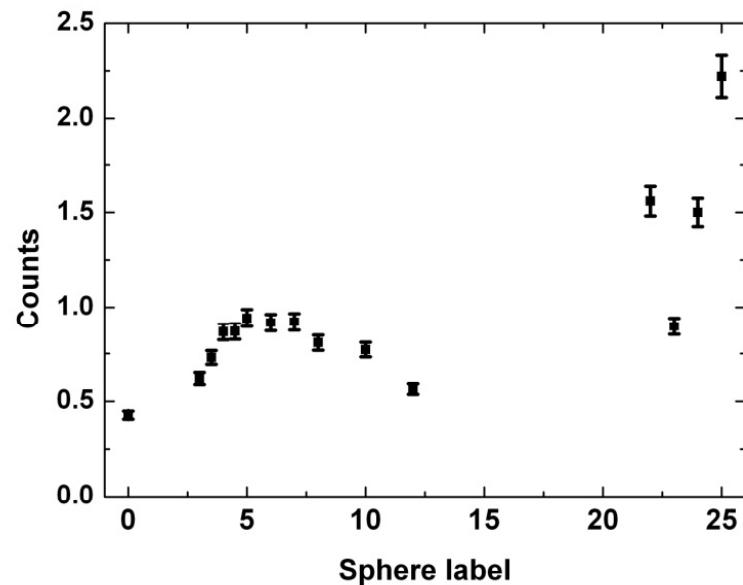
Compact Cyclotron
v.d.Graaff Accelerator

10 moderator spheres (PE), d : 7.62 cm to 30.48 cm



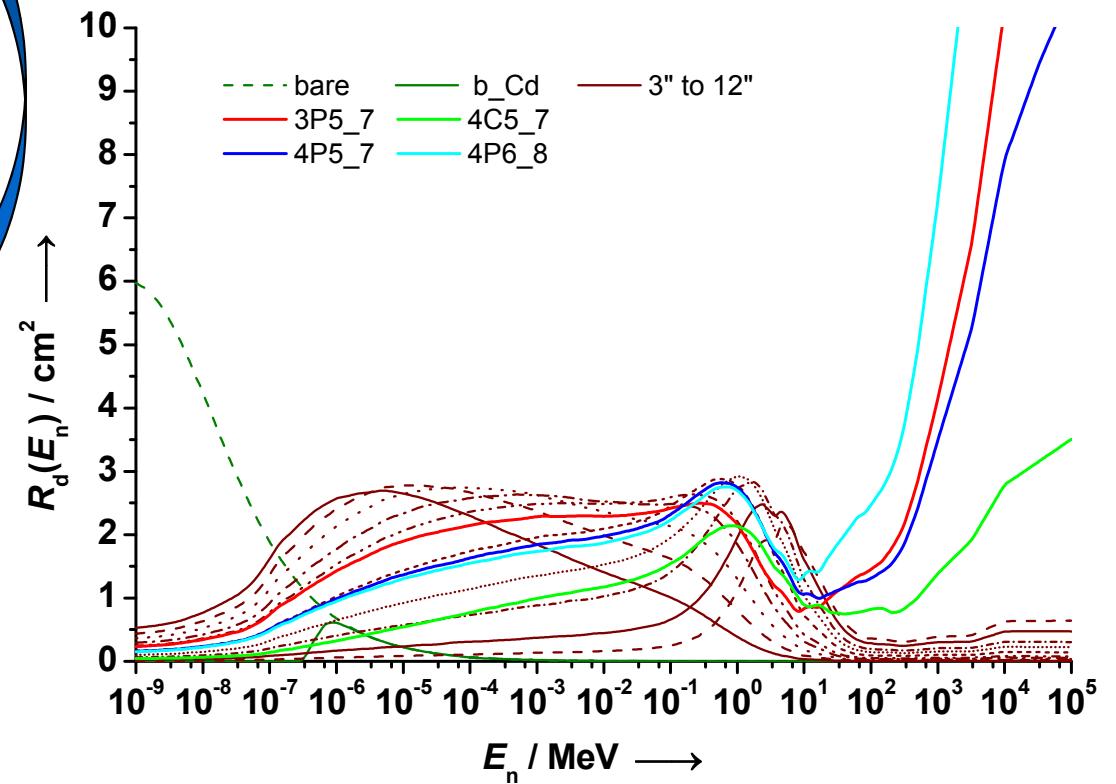
4 modified spheres with
copper and lead

^3He proportional counter as
thermal neutron sensor



$$N_d + \varepsilon_d = \int R_d(E) \Phi(E) dE$$

Few-channel unfolding using e.g.
maximum entropy unfolding or
Bayesian parameter estimation

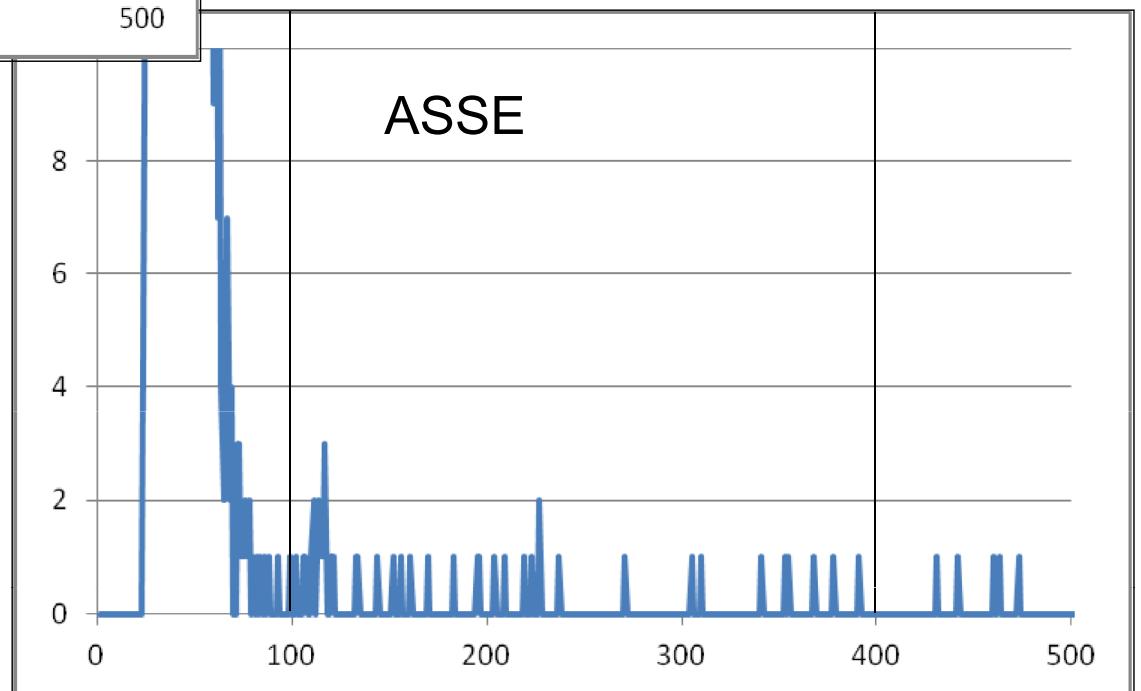
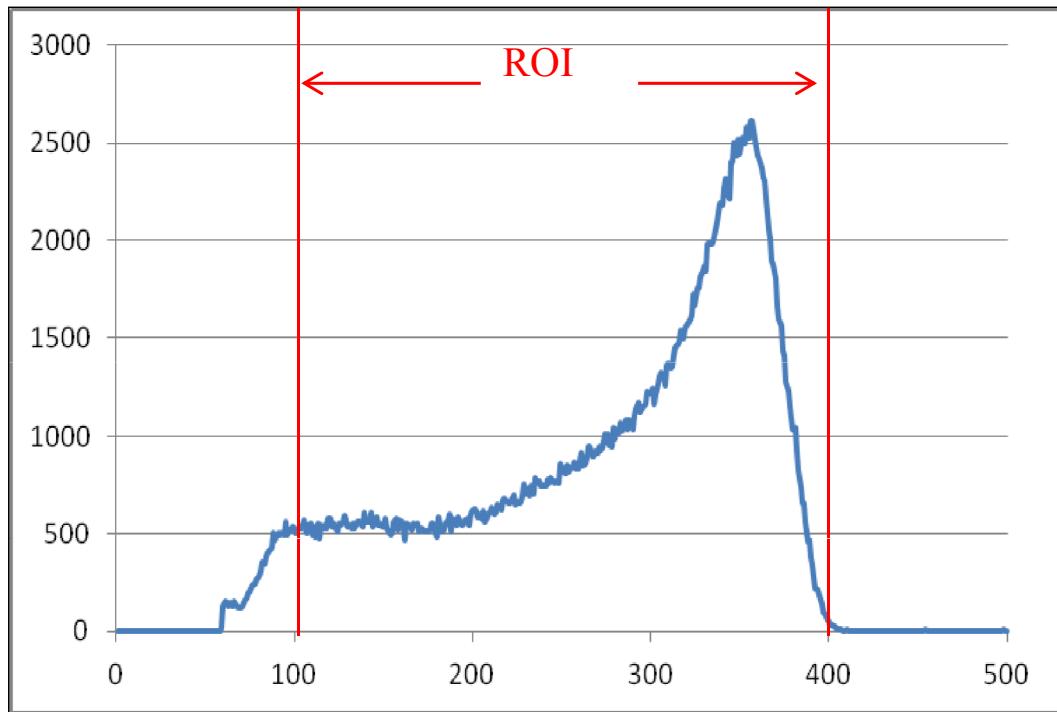


Measurements of ${}^3\text{He}$ counters in Asse salt mine

- Depth ~ 1100 m.w.e.
- Measurement time usually 3 to 10 days
- 17 ${}^3\text{He}$ counters, 8 electronic modules, in total 30 combinations (tried to find out optimal combinations for low noise)
- Longest measuring time 38 days (det. "A")
- Factor of > 50 between "good" and "bad" detectors



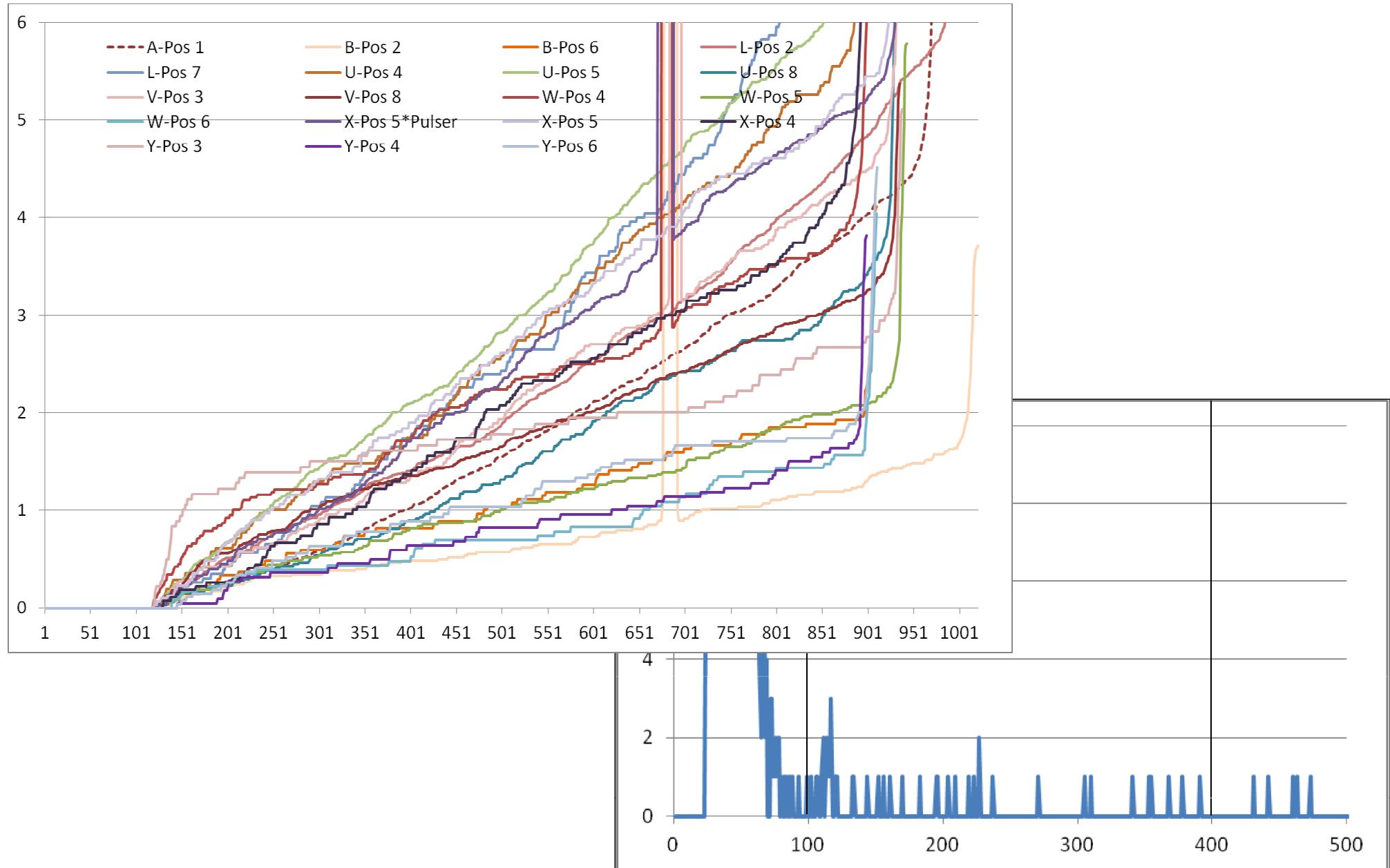
Measurements of ${}^3\text{He}$ counters in Asse salt mine



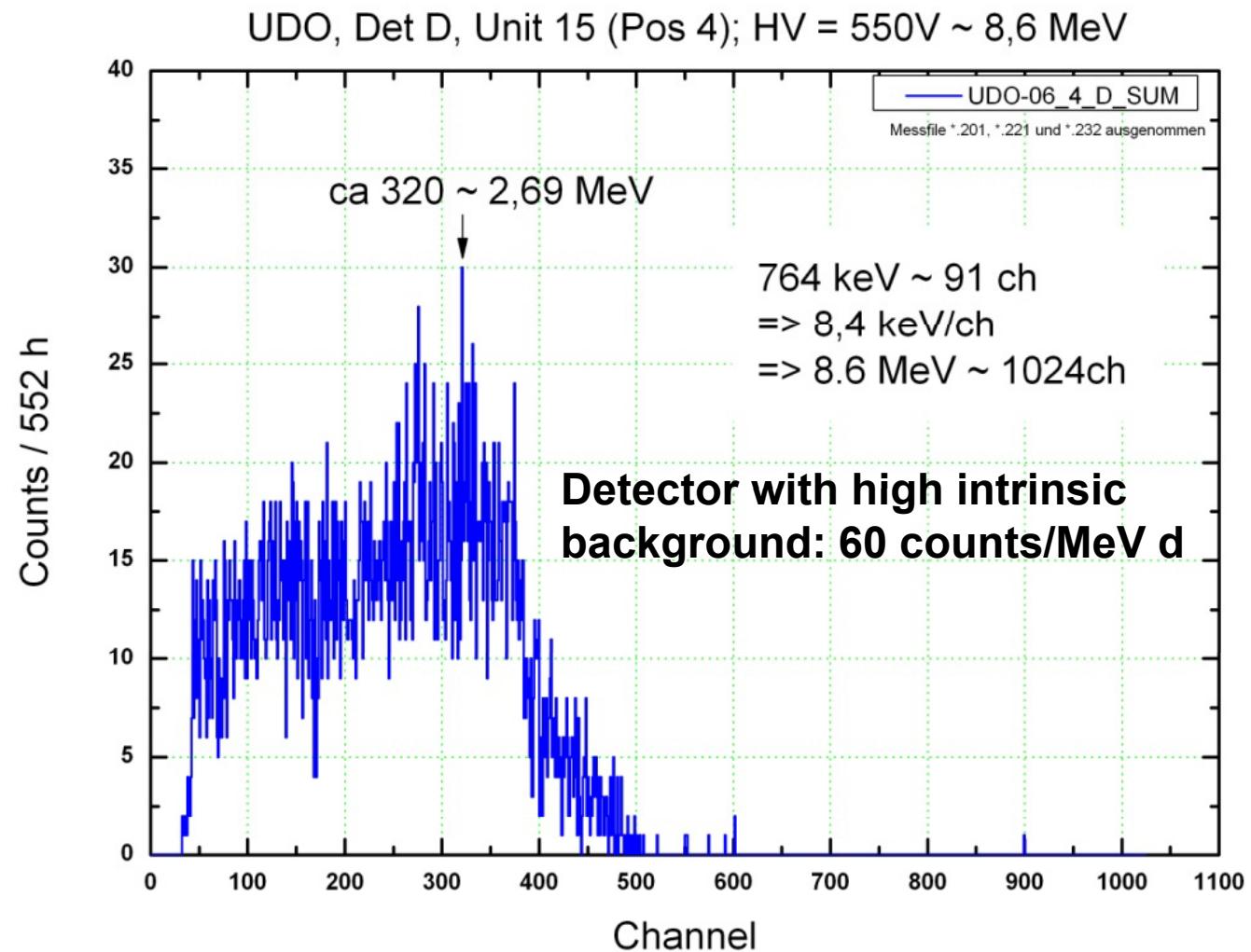
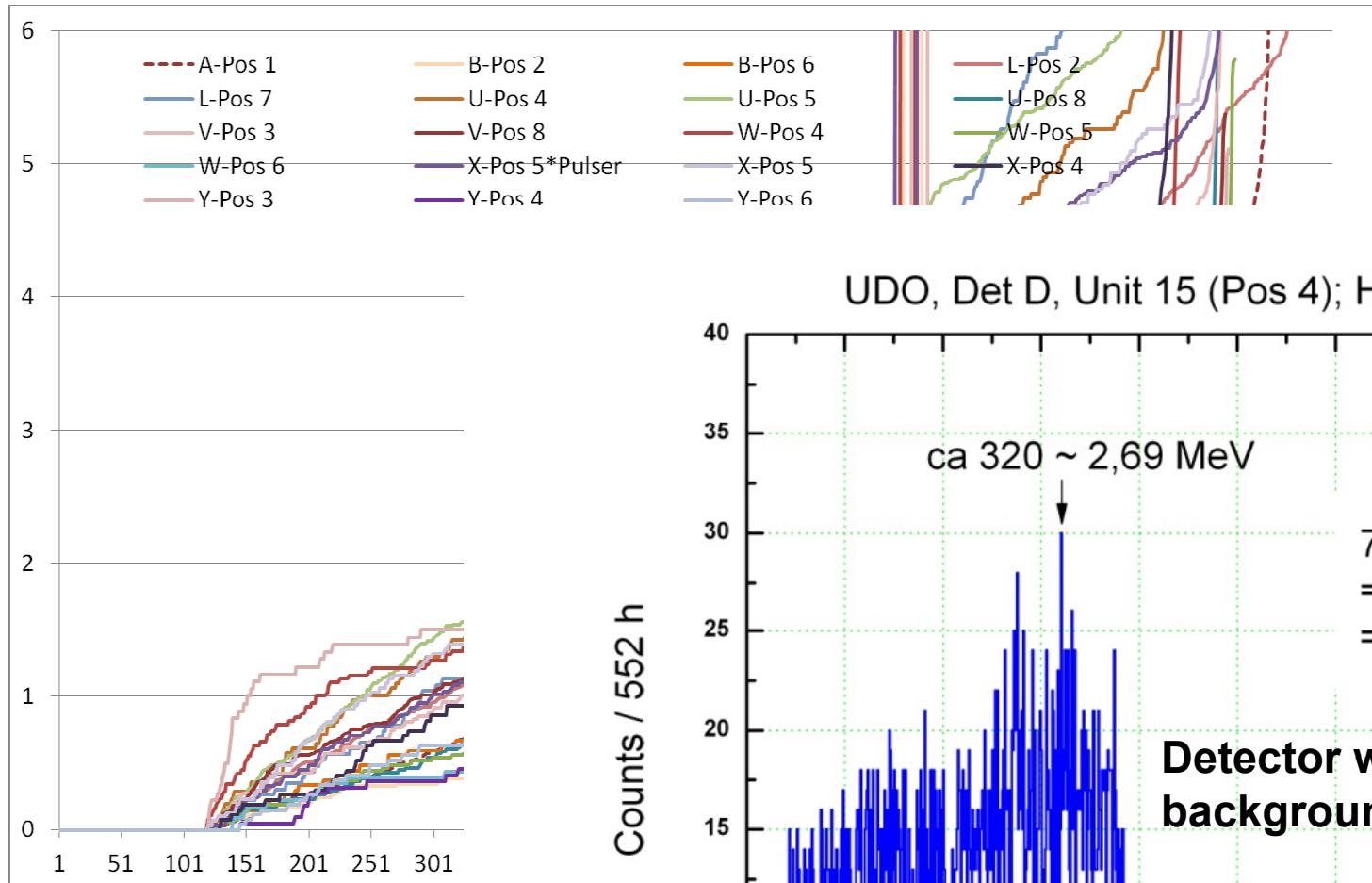
Measurements of ${}^3\text{He}$ counters in Asse salt mine

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Cumulative distributions



Cumulative distributions



Intrinsic background of ${}^3\text{He}$ counters

Det.	t / h	cts / 250ch	cts/d / 250ch	unc.	Pos 1 / Unit 20	Pos 2 / Unit 13	Pos 3 / Unit 14	Pos 4 / Unit 15	Pos 5 / Unit 16	Pos 6 / Unit 12	Pos 7 / Unit 18	Pos 8 / Unit 19		arith. mean	
A	978	145	3.6	8.3%	10.36										
A	978	145	3.6	8.3%	9.544										9.5
A	978	145	3.6	8.3%	8.804										
B	510	46	2.2	14.7%		3.765									
B	510	46	2.2	14.7%		2.539									
B	510	46	2.2	14.7%		1.101									
B															
B															
B															
D							69.01								
D							62.61								62.6
D							55.1								
I						52.94									
I						45.3									45.3
I						36.18									
L	462	113	5.9	9.4%		14.69									
L	462	113	5.9	9.4%		13.24									
L	462	113	5.9	9.4%		11.34									
M															
M															
M															
N															
N															
N															
O															
O															
O															
P															
P															
P															
R															
R															
R															
T															
T															
T															
U	318	95	7.2	10.3%			18.71	19.64							
U	318	95	7.2	10.3%			15.82	17.78							
U	318	95	7.2	10.3%			12.29	15.98							
V	438	62	3.4	12.7%		14.42									
V	438	62	3.4	12.7%		12.1									
V	438	62	3.4	12.7%		8.92									
W	660	87	3.2	10.7%			10	6.643	6.403						
W	660	87	3.2	10.7%			7.425	5.005	3.155						
W	660	87	3.2	10.7%			4.84	0.07897	0.1703						
X	678	158	5.6	8.0%			14.32	18.31							
X	678	158	5.6	8.0%			11.51	15.05							
X	678	158	5.6	8.0%			8.795	7.83							
Y	378	61	3.9	12.8%			4.707	5.995	9.662						
Y	378	61	3.9	12.8%			2.563	3.86	6.684						
Y	378	61	3.9	12.8%			1.002	0.2346	0.1692						
Z	588	145	5.9	8.3%			9.394		6.555						
Z	588	145	5.9	8.3%			6.244		5.459						
Z	588	145	5.9	8.3%			2.061		2.408						

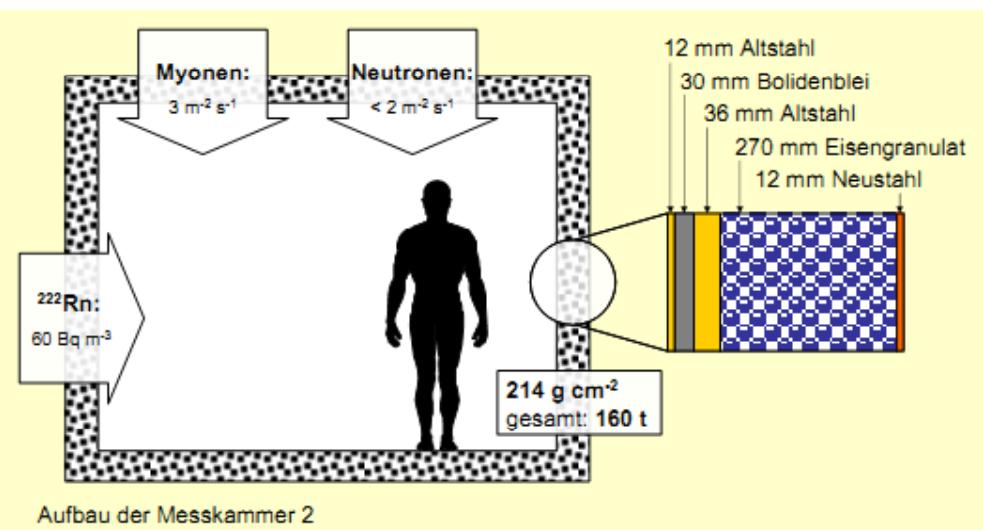
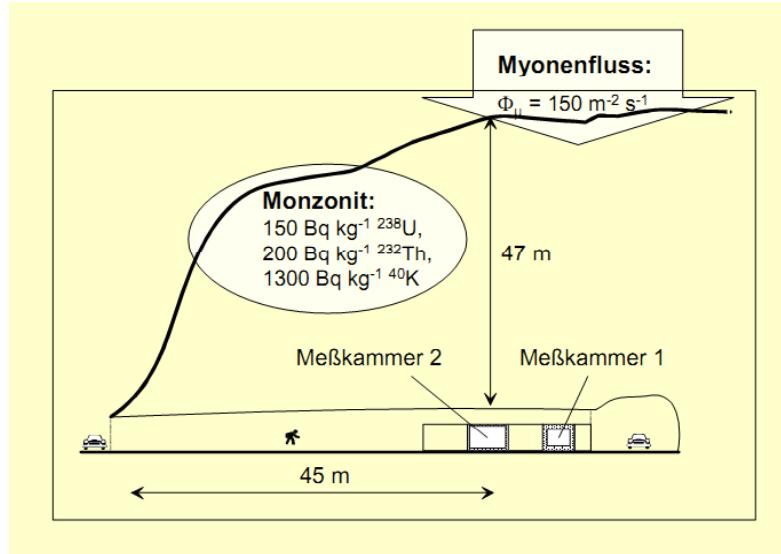
95 % credible intervals and medians
(counts day⁻¹ MeV⁻¹),
for channels 101 to 400:

“good” detectors: 2 to 10 counts day⁻¹ MeV⁻¹

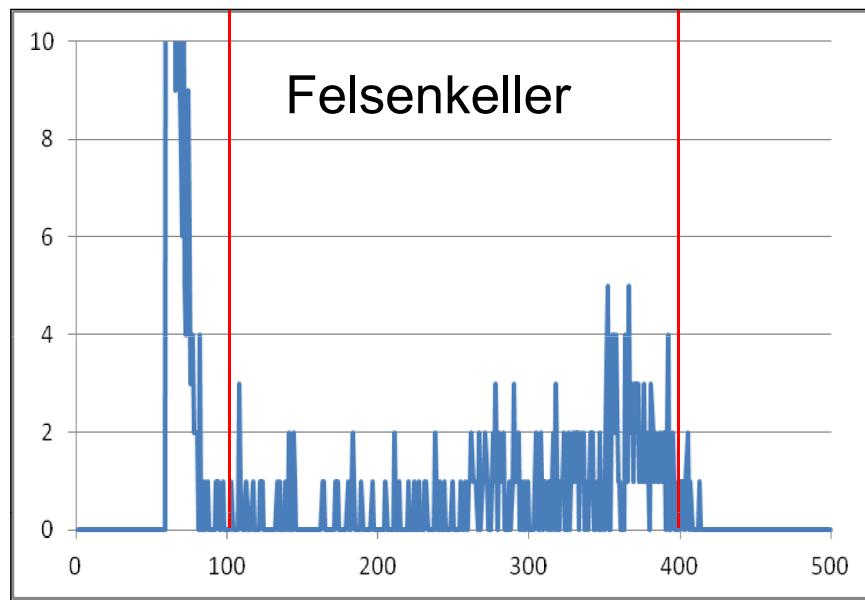
“bad” detectors: 50, 80, ...
135, 500 counts day⁻¹ MeV⁻¹

Low level measurements at Felsenkeller

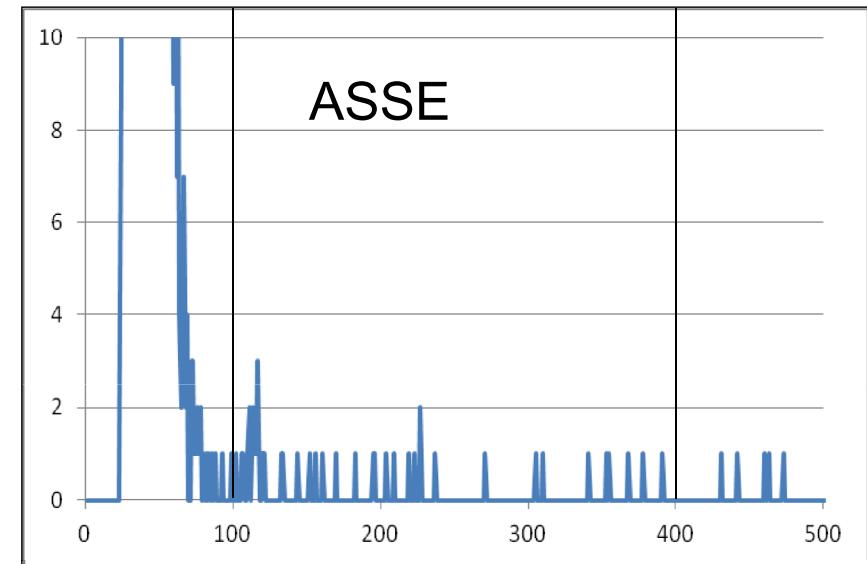
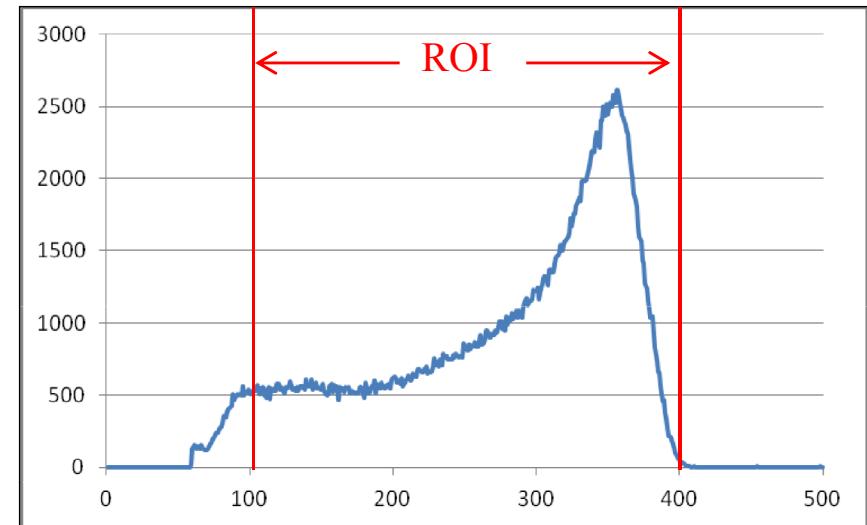
- Depth ~ 110 m.w.e.
- Measurements were made with 4 spheres:
the bare detector, 3" and 6" spheres, and a modified sphere
- The measurement time was ~ 3.5 days for each sphere



Low level measurements at Felsenkeller

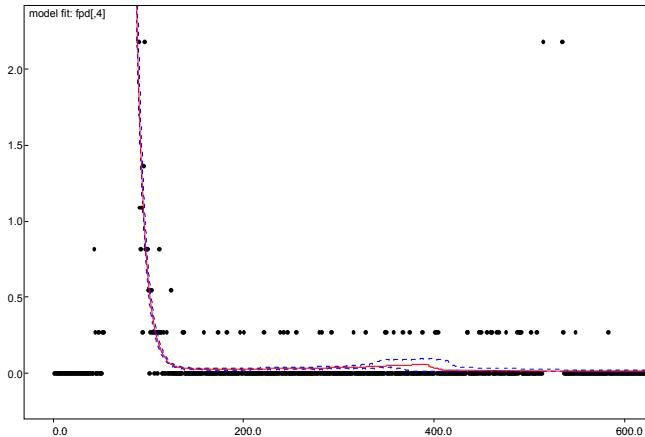


“Good” Measurement (laboratory conditions)

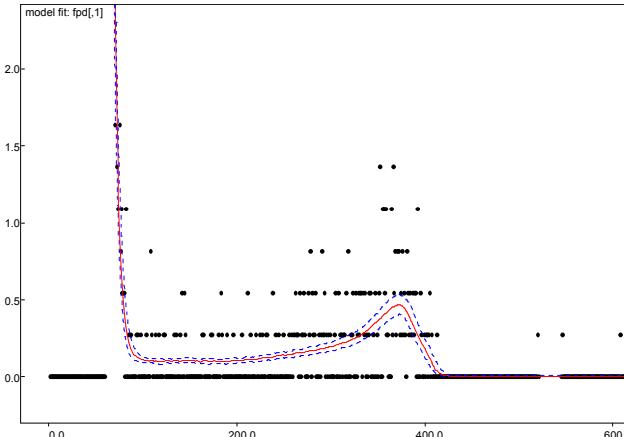


Data and Bayesian analysis

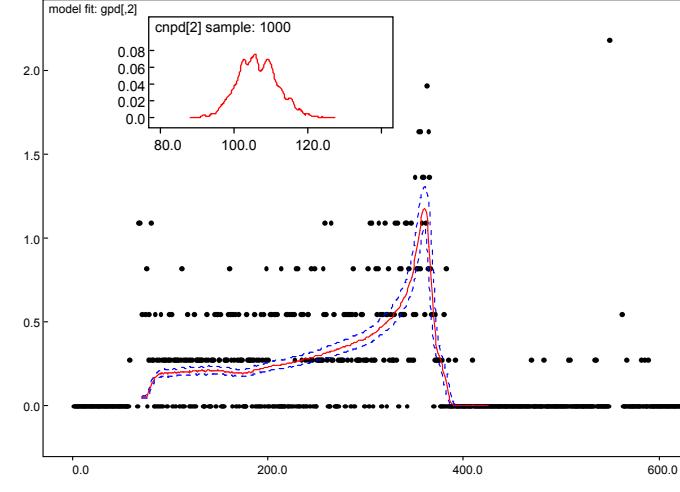
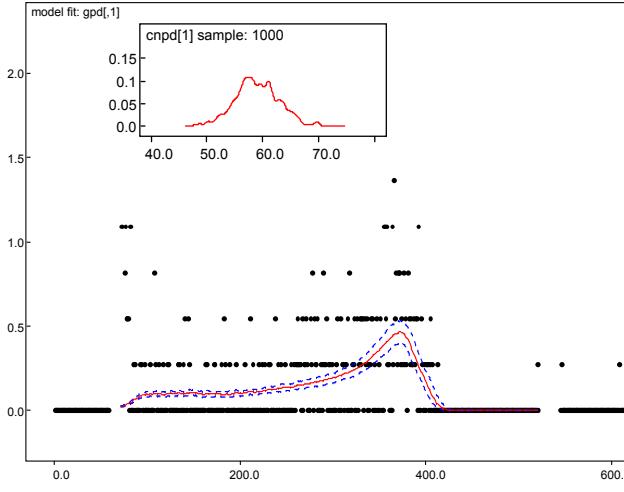
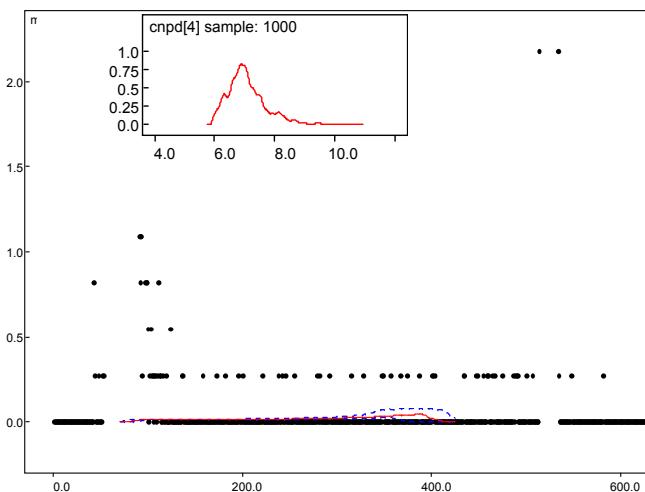
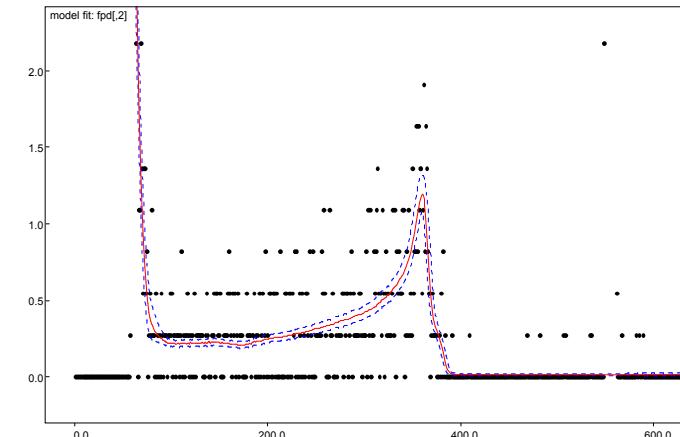
Bare detector



3" sphere



6" sphere

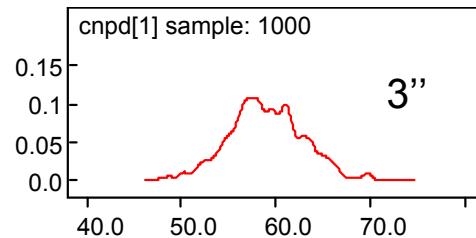
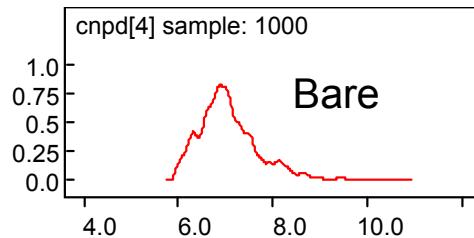


- Top figure: Data + fit of 3 components: Electronic noise, intrinsic background, and neutron signal

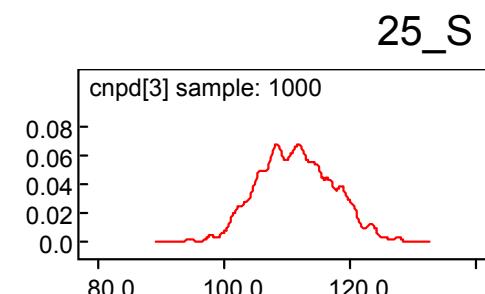
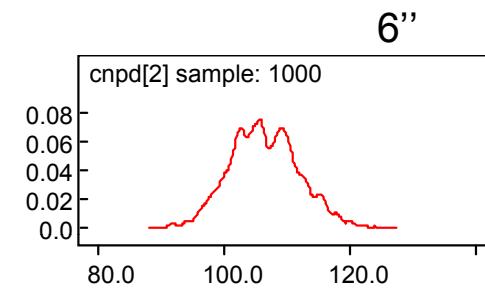
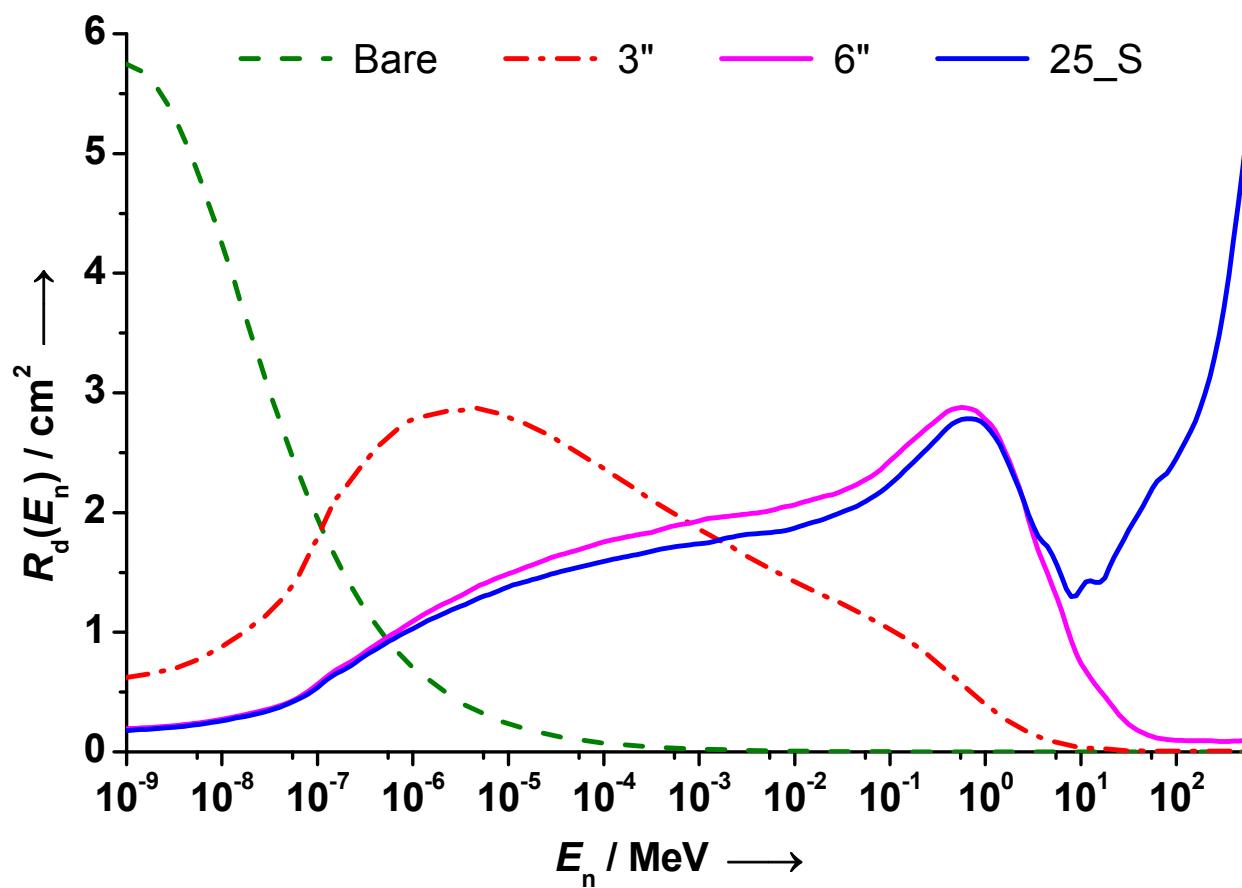
- Bottom figure: Data + neutron signal only

Insert : Probability densities for **counts per day due to neutrons only**

What does that data tell us?



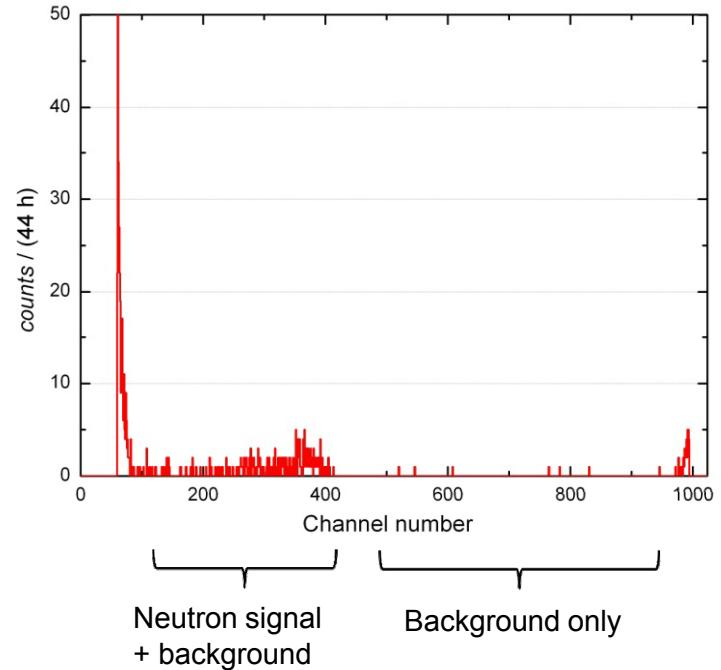
- Very few thermals neutrons
- No very high energy neutrons
- About 2 data points are left!!!



If we assume a simple form of the spectrum, **neutron flux $\sim (6 \pm 1) \text{ m}^{-2} \text{ s}^{-1}$**

Estimate of the lowest flux that can be measured

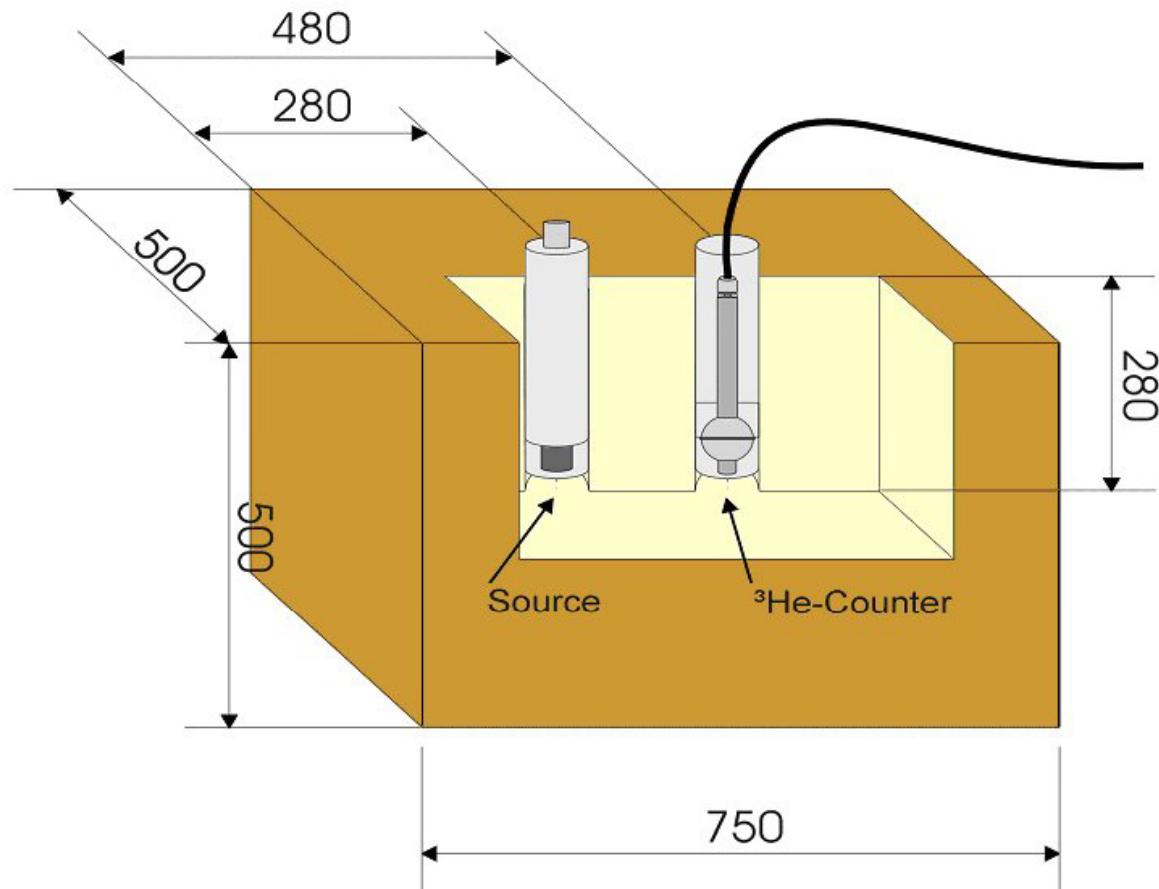
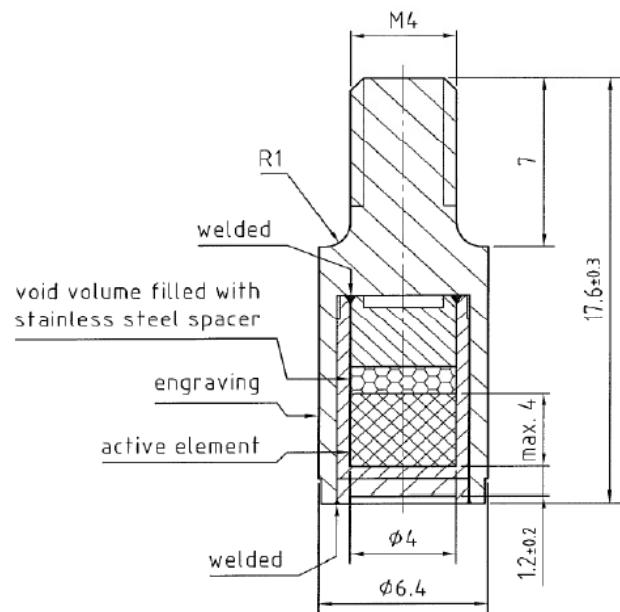
- Consider a “good” detector, with an intrinsic background of ~ 2 counts day $^{-1}$ MeV $^{-1}$
- The ROI covers $(0.764-0.192)$ MeV = 0.572 MeV
- Then, the signal due to the background is ~ 1 count day $^{-1}$
- In Felsenkeller, the 6” sphere measured ~ 110 neutron counts day $^{-1}$ in the ROI
- Assume that one can distinguish a neutron signal from the background when they are approximately equal.
- Then, it should be possible to measure neutron fluxes that are ~ 100 times smaller than the one at Felsenkeller; that is, fluxes $\sim 5 \times 10^{-2}$ m $^{-2}$ s $^{-1}$



n-emission rate of a 5.5 MBq ^{228}Th γ -source

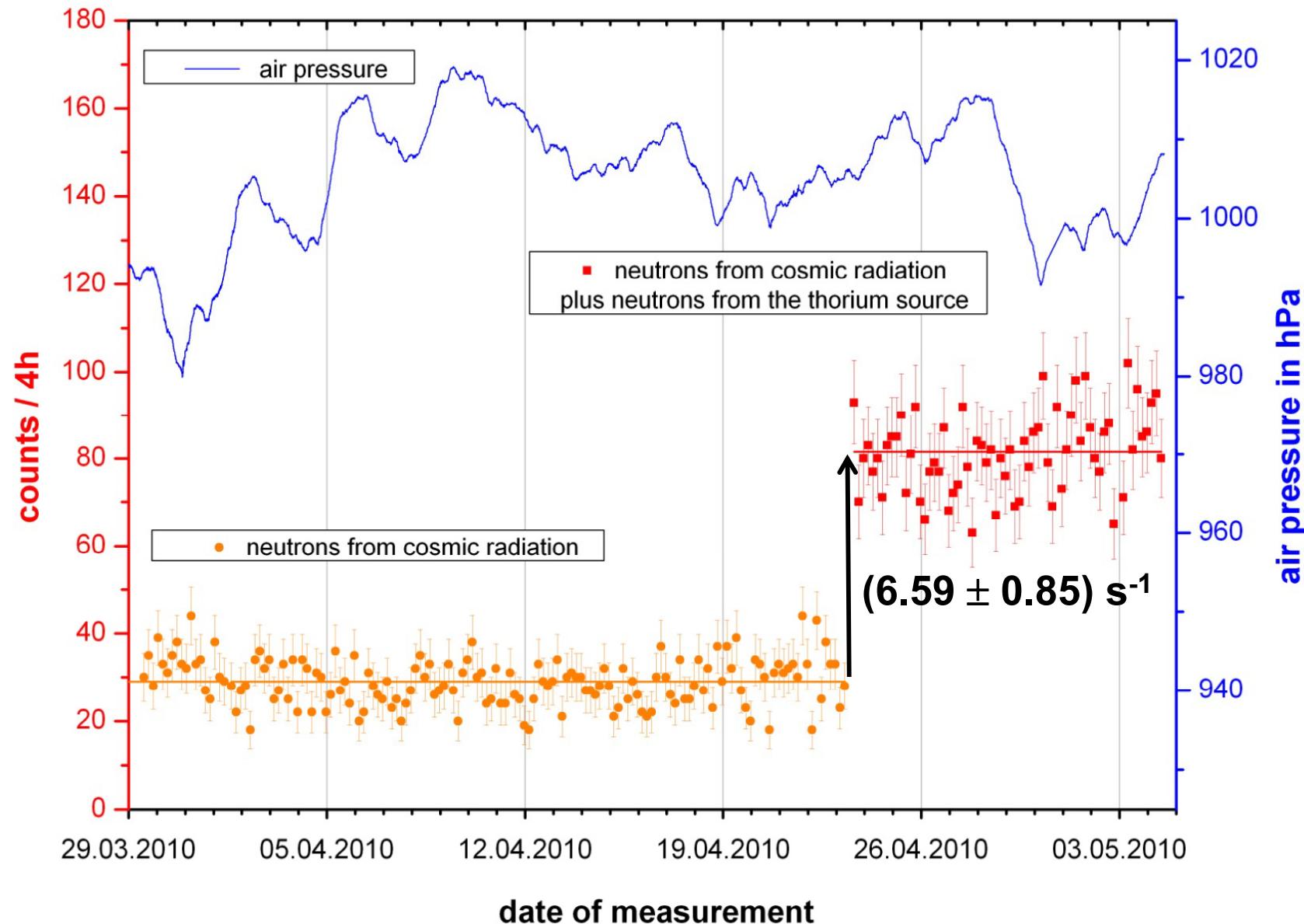


- γ calibration source for Borexino
- Source made of ThO_2
- Neutrons from (α, n) -reactions with O expected
- < 10 neutrons/s allowed for Gran Sasso
- γ/n ratio $\sim 10^6$



n-emission rate of a 5.5 MBq ^{228}Th γ -source

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n-emission rate of a 5.5 MBq ^{228}Th γ -source

- n-spectrum effects efficiency of moderating detector
- experimentally tested with three sources: ^{252}Cf , ^{241}AmB , $^{241}\text{AmBe}$
- dominates the uncertainty

reference source (rs)	mean energy $\langle E \rangle_{\text{rs}} / \text{MeV}$	source strength $B_{\text{rs}} / \text{s}^{-1}$	reference date	efficiency $c_{\text{rs}} = \dot{N}_{\text{rs}} / B_{\text{rs}}$
$^{241}\text{AmBe}$	4.05	72829 ± 1736	23.03.2010	1806 ± 43
^{241}AmB	2.61	149570 ± 1081	08.05.2010	1706 ± 12
^{252}Cf	2.13	1131906 ± 16979	06.05.2010	2064 ± 31

=> source strength : $B = (6.59 \pm 0.85) \text{ s}^{-1}$

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Production and characterization of a custom-made ^{228}Th source with reduced neutron source strength for the Borexino experiment

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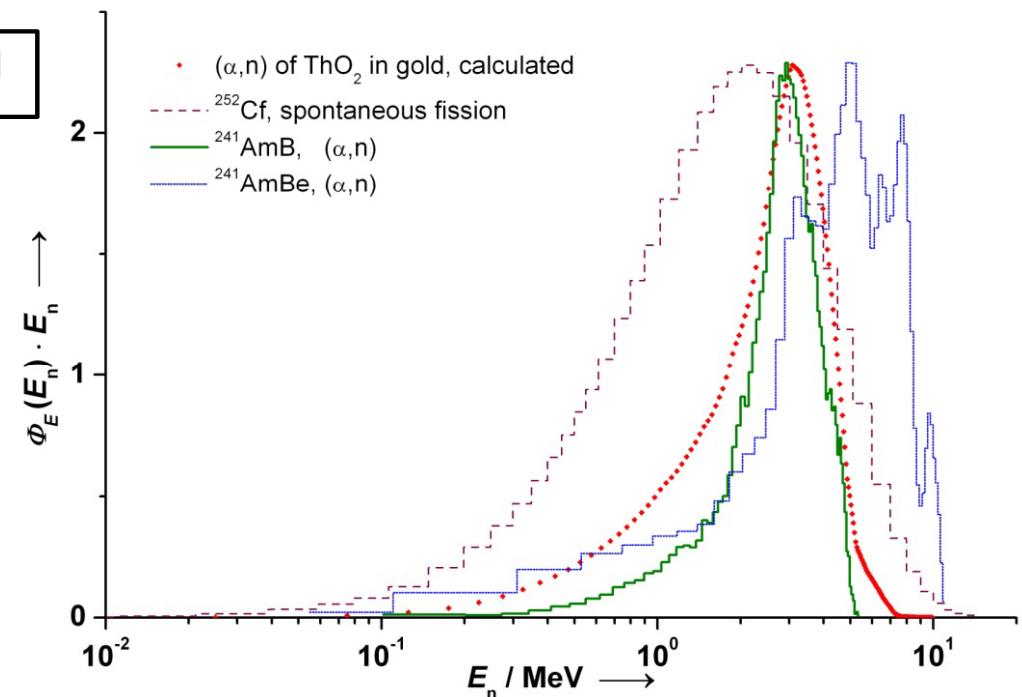
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- XENON100 Dark Matter Experiment uses $^{241}\text{AmBe}$ source for calibration
- New $^{241}\text{AmBe}$ ($3.7 \text{ MBq} \pm 15\%$) source from Eckart & Ziegler
- Estimated n-emission from manufacturer: $B = 240 \text{ s}^{-1}$

=> source strength : $B = (159.6 \pm 3.9) \text{ s}^{-1}$

Response of the XENON100 Dark Matter Detector to Nuclear Recoils

E. Aprile,¹ M. Alfonsi,² K. Arissaka,³ F. Arneodo,⁴ C. Balan,⁵ L. Bandis,⁶ B. Bauermeister,⁷ A. Behrens,⁶ P. Beltrame,^{8,9} K. Bokeloh,³ A. Brown,¹⁰ E. Brown,⁹ S. Bruenner,¹¹ G. Bruno,⁴ R. Budnik,¹ J. M. R. Cardoso,⁵ W.-T. Chen,¹² B. Choi,¹ A. P. Colijn,² H. Contreras,³ J. P. Cussomeau,¹² M. P. Decowski,² E. Duchovni,⁸ S. Fattori,⁷ A. D. Ferella,^{4,6} W. Fuljione,¹³ F. Gao,¹⁴ M. Garibini,¹⁵ C. Geiss,⁷ C. Glagut,³ K.-L. Ghioni,¹ L. W. Goetzke,¹ C. Grigioni,⁷ E. Gross,⁸ W. Hampel,¹¹ R. Iori,⁸ F. Kaether,¹¹ G. Kessler,⁶ A. Kish,⁶ H. Landsman,⁸ R. F. Lang,¹⁰ M. Le Calloch,¹² C. Levy,⁹ K. E. Lim,¹ Q. Lin,¹⁴ S. Lindemann,¹¹ M. Lindner,¹¹ J. A. M. Lopes,⁵ K. Lung,³ T. Marrodan Undagoitia,^{11,6} F. V. Massoli,¹⁵ A. J. Melgarjo Fernandez,¹ Y. Meng,³ M. Messina,¹ A. Molinario,¹³ K. Ni,¹⁴ U. Oberlack,⁷ S. E. A. Orrigo,⁵ E. Pantic,⁴ R. Persiani,¹³ G. Plante,⁶ N. Priel,⁸ A. Rizzo,¹ S. Rosendahl,⁹ J. M. F. dos Santos,⁶ G. Sartorelli,¹⁶ J. Schreiner,¹¹ M. Schumann,^{16,6} L. Scotti Lavina,¹² P. R. Scovell,^{3,*} M. Selvi,¹⁵ P. Shagin,¹⁷ H. Simen,¹³ A. Teymourian,³ D. Thers,¹³ O. Vitells,⁸ H. Wang,³ M. Weber,^{11,1} and C. Weinheimer⁹
(The XENON100 Collaboration)

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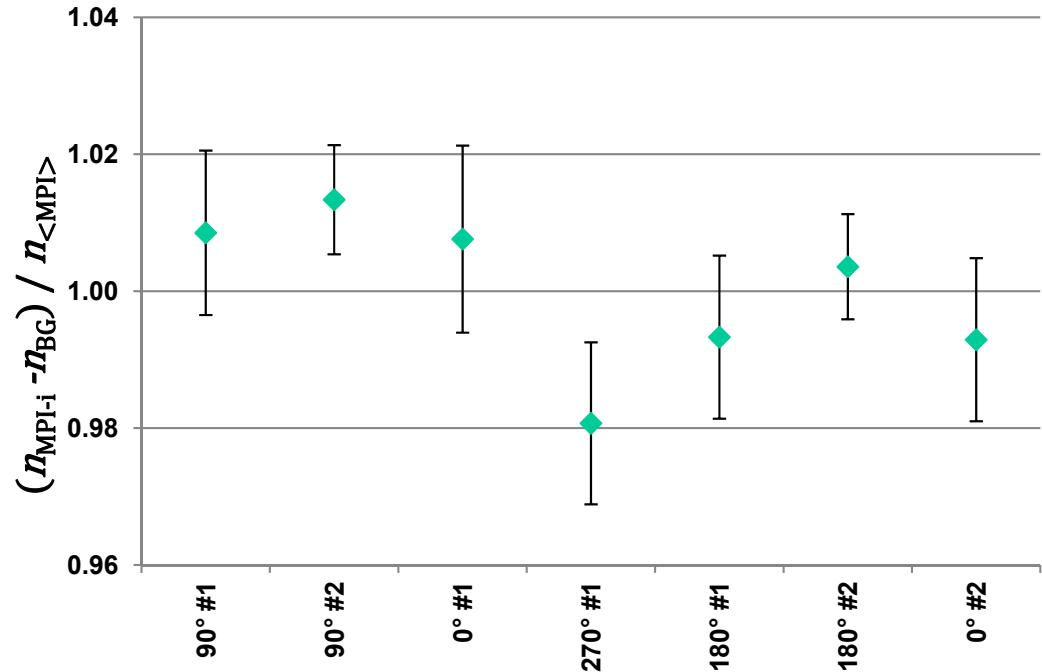
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(Dated: Wednesday 3rd April, 2013)

Results from the nuclear recoil calibration of the XENON100 dark matter detector installed underground at the Laboratori Nazionali del Gran Sasso (LNGS), Italy are presented. Data from measurements with an external AmBe neutron source are compared with detailed Monte Carlo simulation which is used to extract the energy dependent charge-yield Q_e and relative scintillation efficiency ϵ_{sc} . A very good level of absolute spectral matching is achieved in both observable signal channels – scintillation S1 and ionization S2 – along with agreement in the 2-dimensional particle discrimination space. The results confirm the validity of the derived signal acceptance in earlier reported dark matter searches of the XENON100 experiment.

PACS numbers: 95.35.+d, 14.80.Ly, 29.40.-n
Keywords: Dark Matter, XENON, Direct Detection, X-ray



“Response of the XENON100 Dark Matter Experiment to Nuclear Recoils“
The XENON100 Collaboration, will be submitted to Physical Review D

Thank you for your attention!