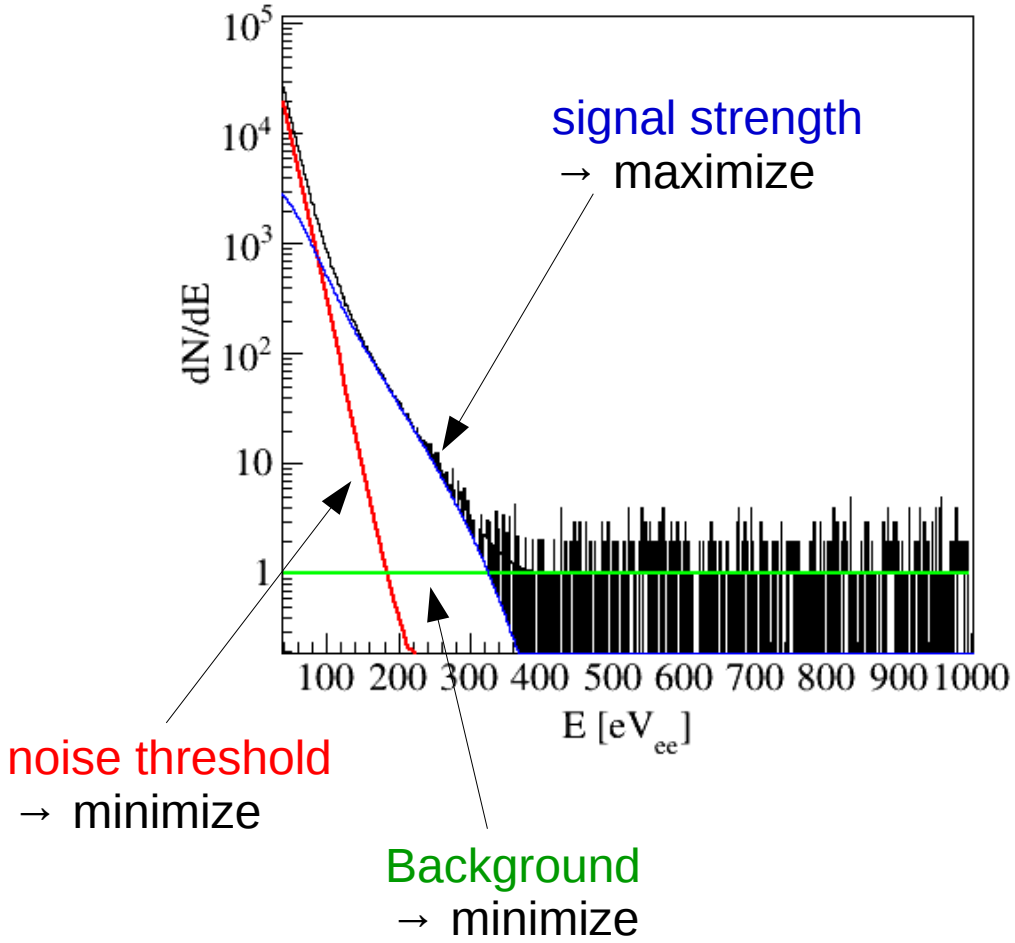
The CONUS Coherent Reactor Neutrino Scattering Experiment

Janina Hakenmüller
Max-Planck-Institut für Kernphysik, Heidelberg, Germany

on behalf of the CONUS collaboration

Applied Antineutrino Physics 2018 Workshop, 11.10.2018, Livermore

Coherent elastic neutrino nucleus scattering



signal strength:

$$\sigma_{\nu A}^{tot} \approx \frac{G_F^2}{4\pi^2} \cdot N^2 \cdot E_\nu^2$$

Maximize E_ν, but: Coherency condition

$$E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}} \text{ [MeV]}$$

Maximize N, but: recoil energy

$$E_{rec}^{max} = \frac{2 \cdot E_\nu^2}{m_n \cdot A + 2 \cdot E_\nu} \approx \frac{2 \cdot E_\nu^2}{m_n \cdot A}$$

CONUS: Coherent Neutrino nUcleus Scattering

Collaboration:

C. Buck, J. Hakenmüller, G. Heusser, M. Lindner, W. Maneschg,
T. Rink, T. Schierhuber, H. Strecker
- *Max Planck Institut für Kernphysik (MPIK), Heidelberg*

K. Fülber, R. Wink
- *Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf*

Scientific cooperation:

M. Reginatto, M. Zboril, A. Zimbal
- *Physikalisch-Technische Bundesanstalt (PTB), Braunschweig*

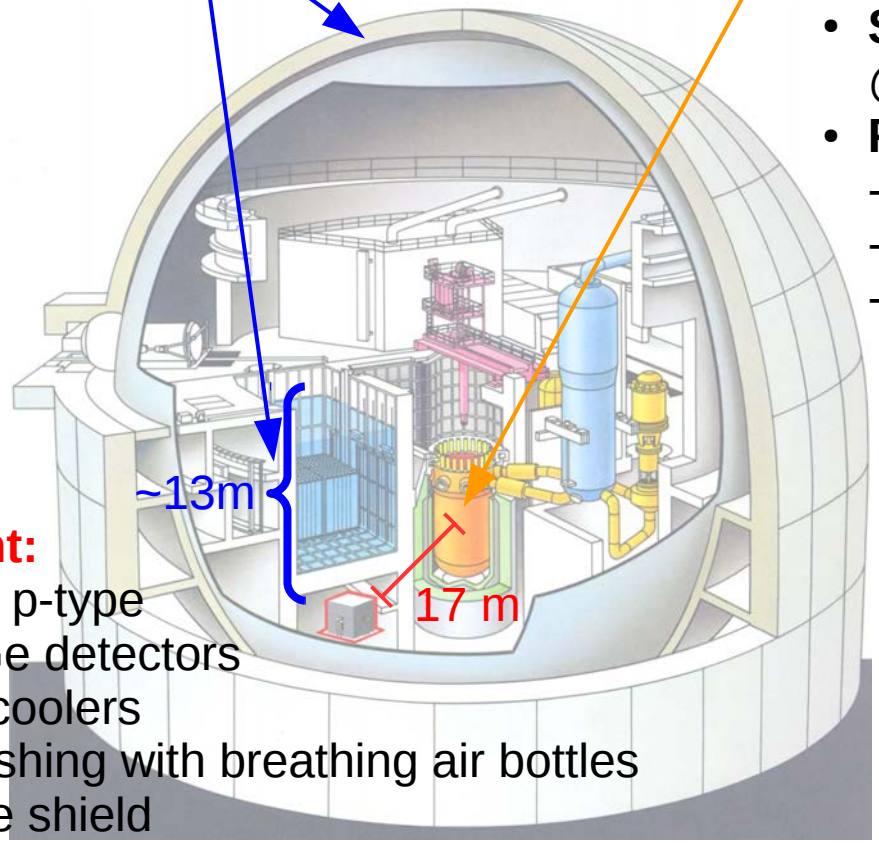
Reactor site

Nuclear power plant at Brokdorf (GER)
- pressurized light water reactor

Overburden at <u>shallow</u> depth:
10-45 m w.e. (angular dep.)
=> muon-induced background

Reactor core:
thermal power 3.9 GW
high duty cycle (1 month/yr off)

- **Signal:** Anti neutrinos @17m: **2.4×10^{13} $\bar{\nu}$/s/cm^2**
- **Potential background:** Neutrons
  -Bonner Sphere measurement
  -MC simulation
  -HPGe measurement

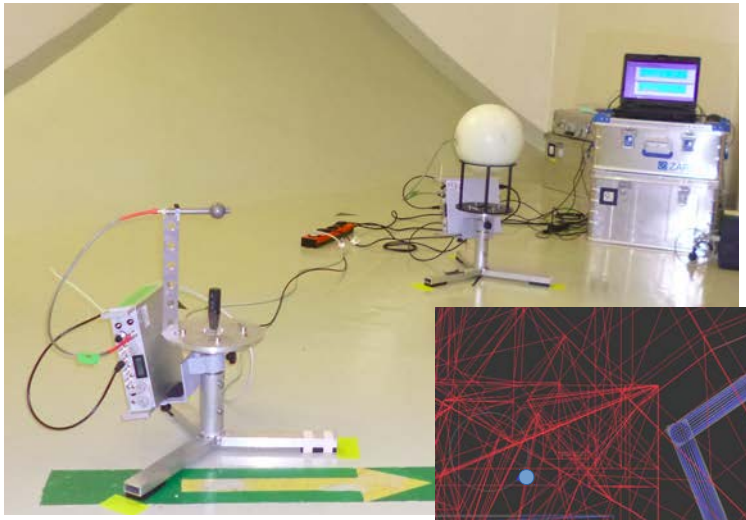


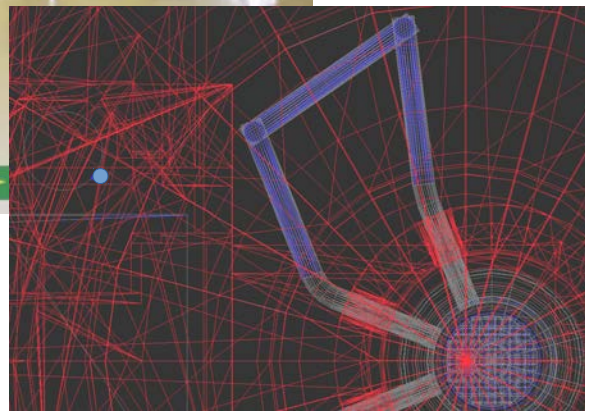
Fast neutron classes	Corr. with therm. power
μ-ind. in Pb inside shield	No
μ-ind. above ceiling	No
(α,n)-reactions from walls	No
fission n from spent fuel rods	No
fission n from reactor core	Yes

CONUS Experiment:

- **4kg** low threshold p-type point contact HPGe detectors
- electrical PT cryocoolers
- Rn removal by flushing with breathing air bottles
- active and passive shield

Neutrons at reactor site



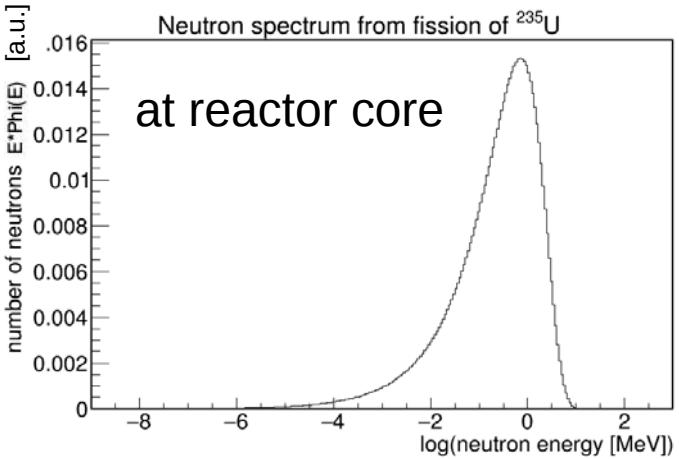


NEMUS by PTB

https://www.ptb.de/cms/ptb/fachabteilungen/abt6/fb-64/643-neutronenspektrometrie/nemus.html

1. **Neutron field** highly thermalized (>80%), correlated with thermal power
   → fully absorbed by B-PE layers (MC)
2. Residual fluence from reactor:
   - if at all: up to O(1MeV)
     => shield highly effective
   - cosmic 100 MeV n: negligible
   → **reactor-correlated fast n**
   inside shield nearly **negligible**

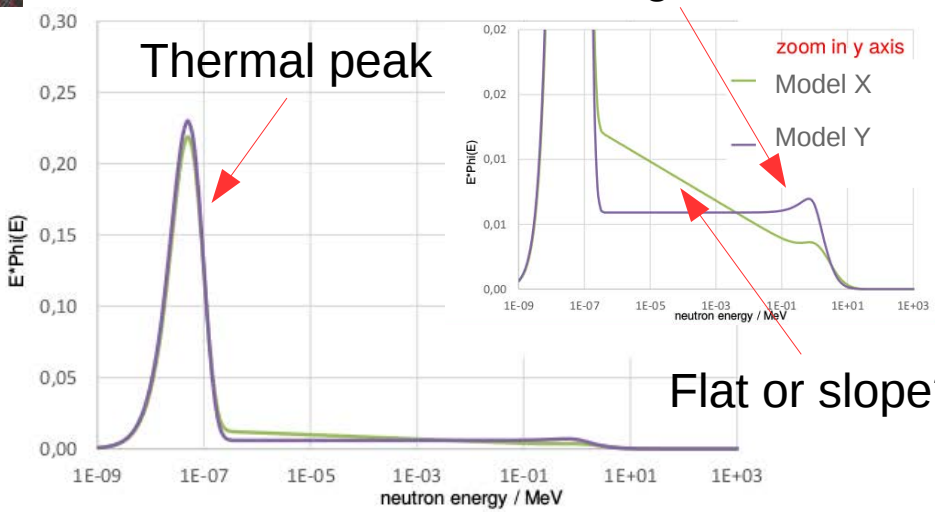
Publication coming soon!



propagation

water
steel
concrete
...

Remaining fast neutrons?

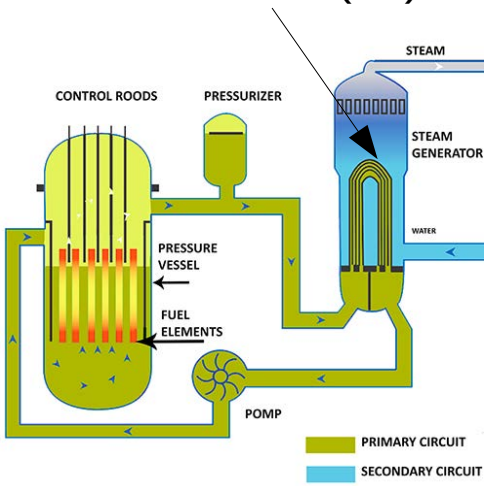


Flat or slope?

Main fission isotopes: ^{235}U (>50%), ^{239}Pu, ^{241}Pu

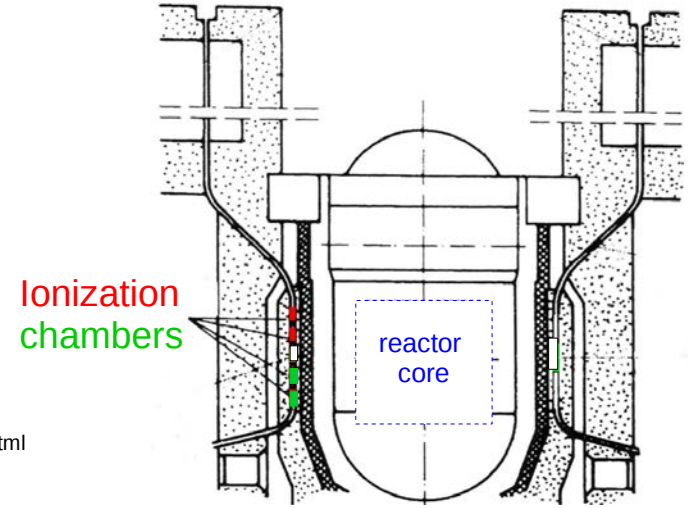
Correlation to thermal power

Thermal balance
in secondary circuit:
time resolution (1h)

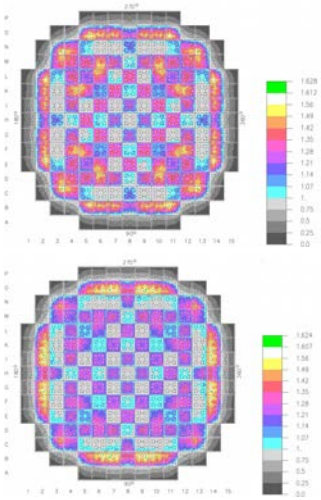


http://www.i15.p.lodz.pl/strony/EIC/ne/technology_3.html

Ionization chambers
around reactor core:
time resolution (1h)
rough spatial resolution

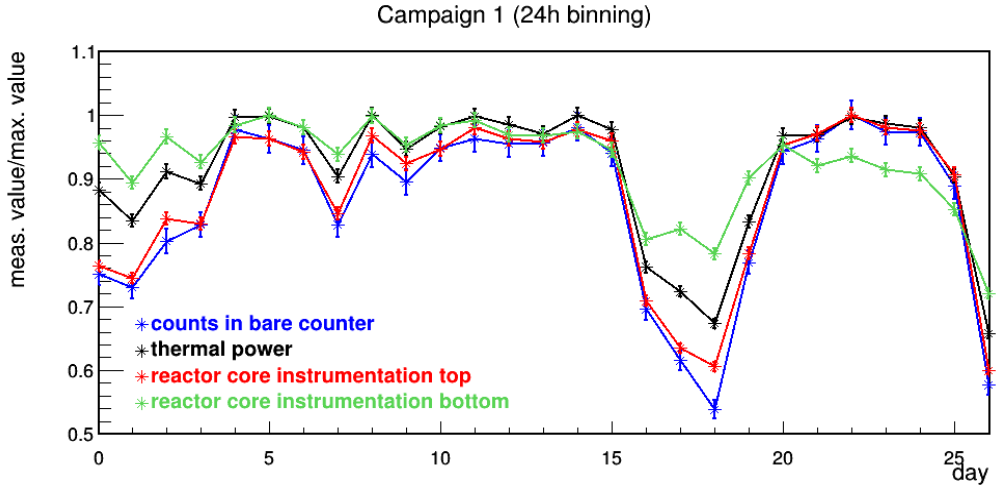


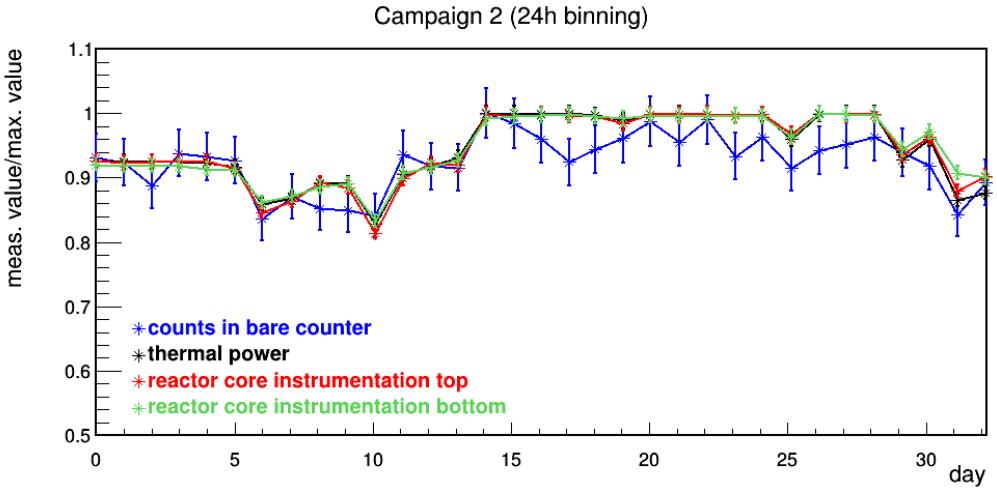
Core simulation:
CASCADE 3D
time resolution (=< 2h)
spatial resolution (10-20cm)



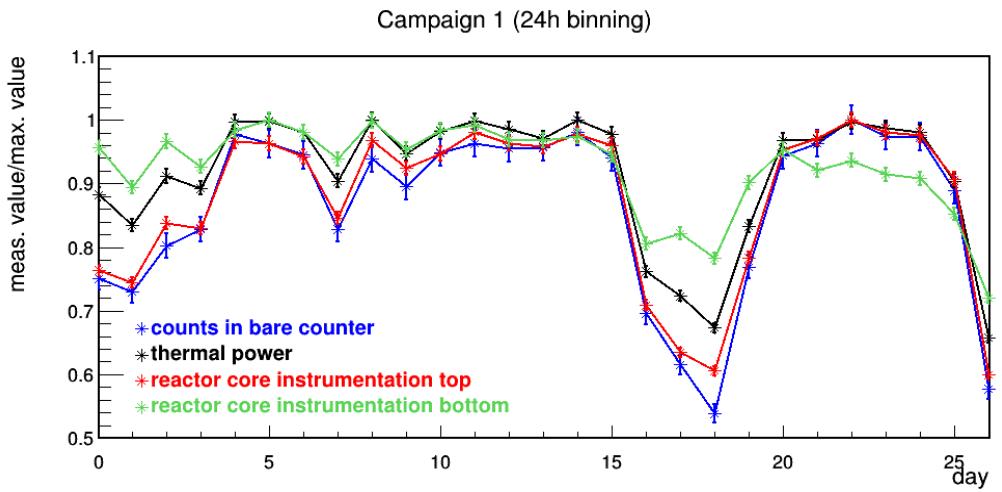
begin of cycle

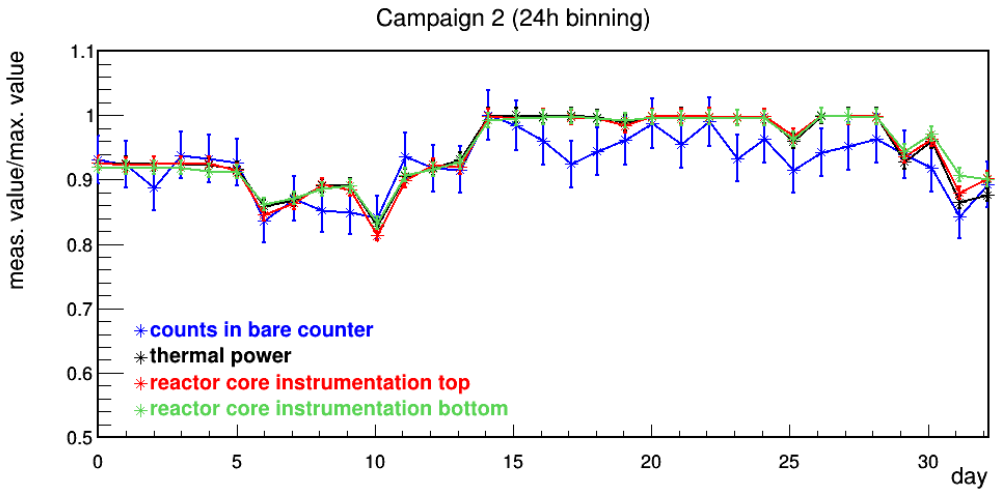
end of cycle

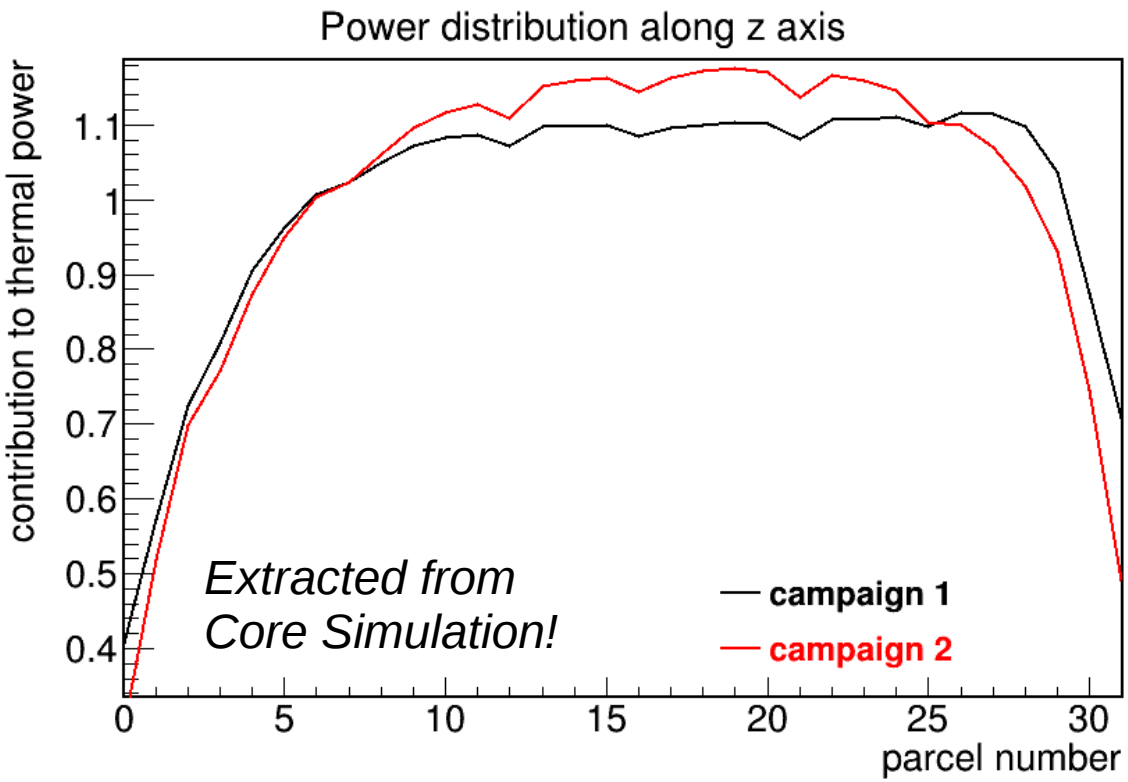




Correlation to thermal power



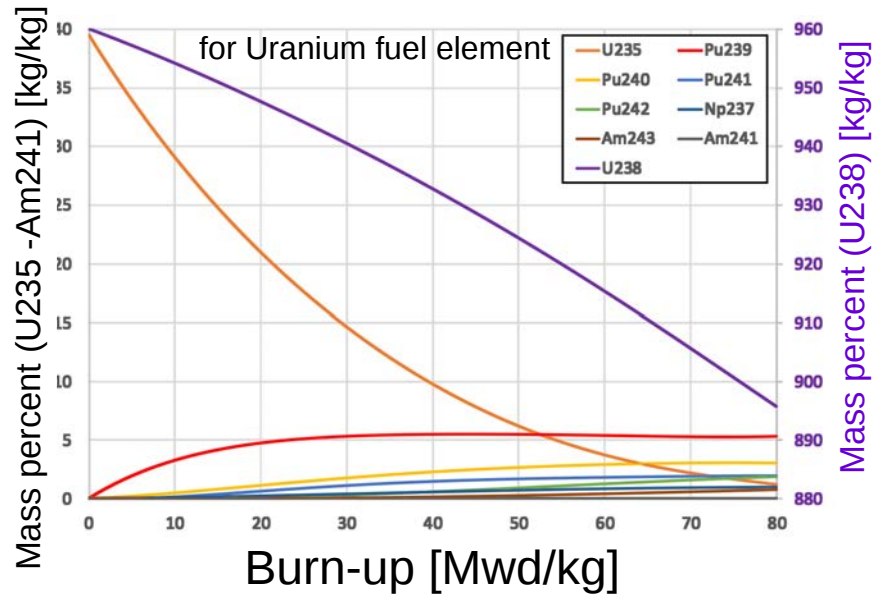




Neutrino spectrum and flux

Uncertainty estimation

- **Reactor power:** ≤4%
  - temperature of water and steam
  - mass flow water
  - steam moistness
- **Distance to reactor core:** ≤2%
- **Fuel composition:**
  - new: (^{235}U: 3.95%, 4.4%) well-known
  - burn-up



Isotope contributions to fission

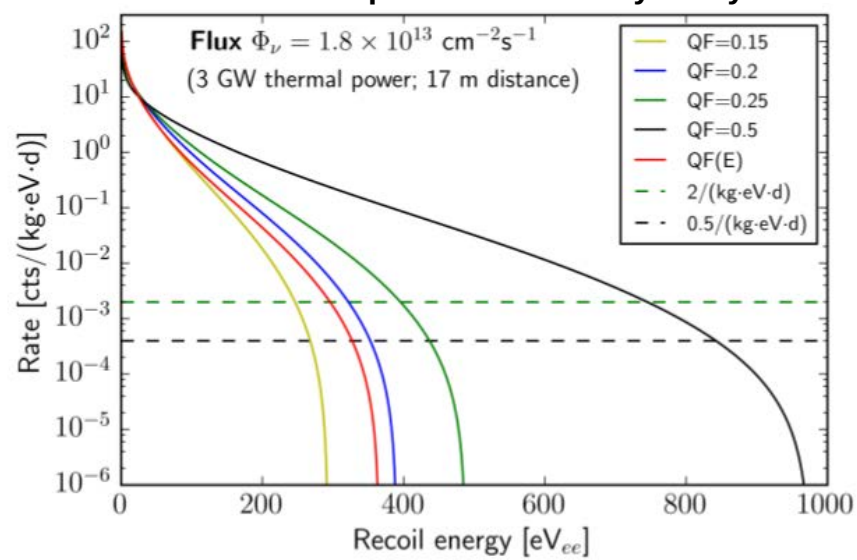
Model assumptions/Simulations
(Huber 2011, Haag 2014,...)

Neutrino flux and spectrum

- **Quenching:** **25%!**
- **Energy resolution:** well known
- **Detector efficiency:** well known

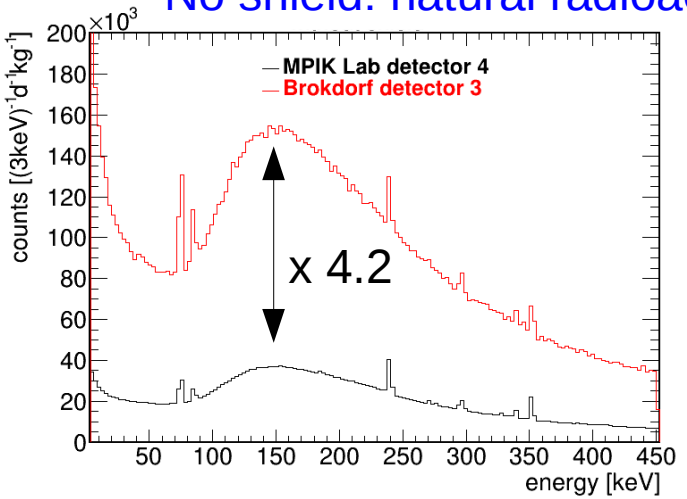
CEνNS rate and spectrum

CEνNS spectrum feasibility study



Background reduction

No shield: natural radioactivity



MPIK lab: low radioactive concrete

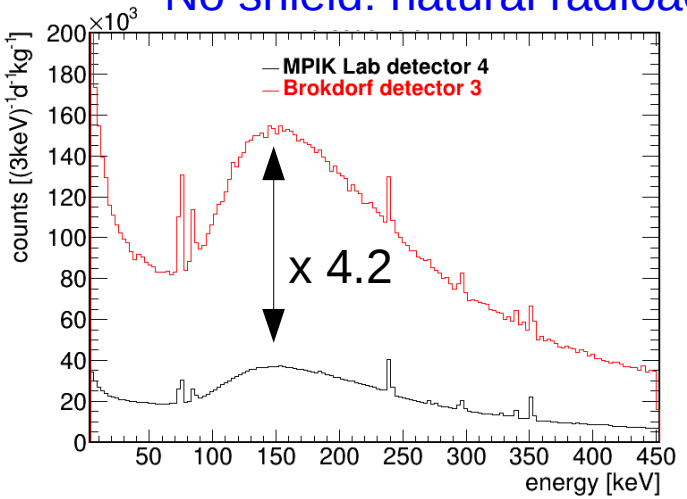
NPP Brokdorf: standard concrete, containing ^{137}Cs

^{60}Co in dust

gammas from reactor (neutron capture)

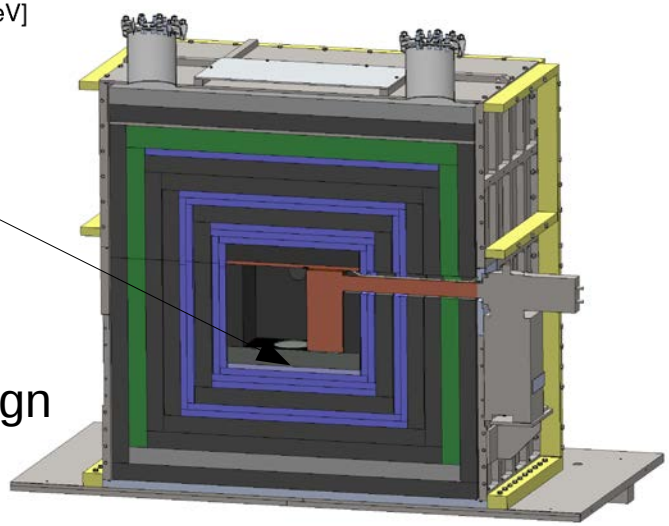
Background reduction

No shield: natural radioactivity



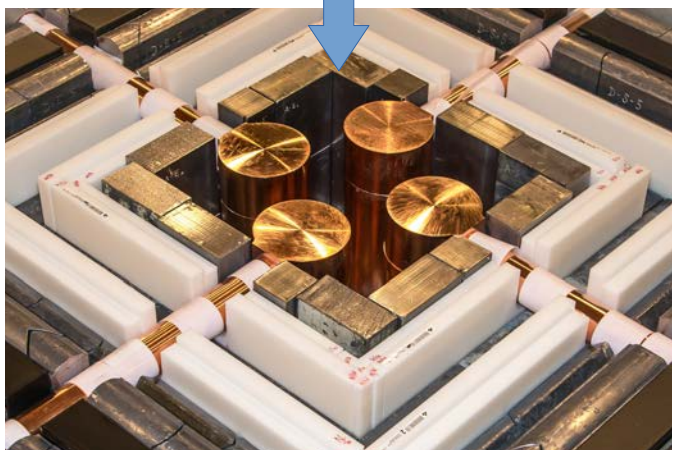
MPIK lab: low radioactive concrete
NPP Brokdorf: additonal background contributions

Innermost layer Pb:
Bremstrahlung ~ Z^2
self-shielding ~ Z^5
=> lower continuum for Pb
^{210}Pb activity:
dedicated screening campaign
=> select suitable bricks
=> mean < 2Bq/kg



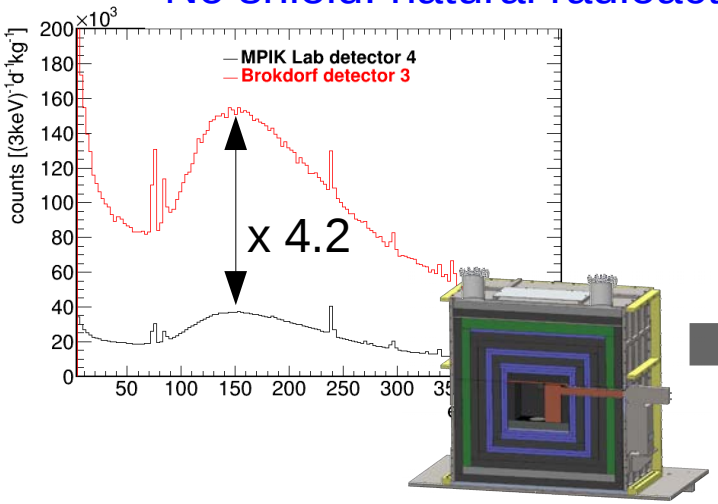
25 cm Pb

Freiburg cathedral lead



Background reduction

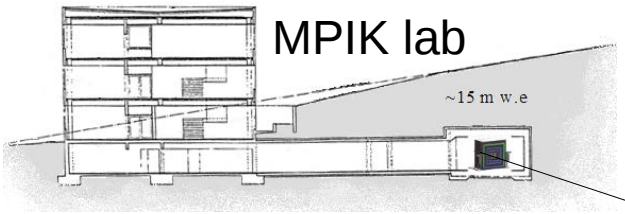
No shield: natural radioactivity

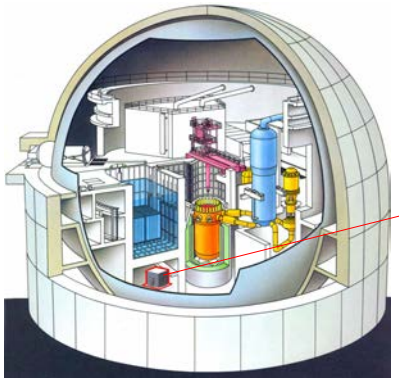


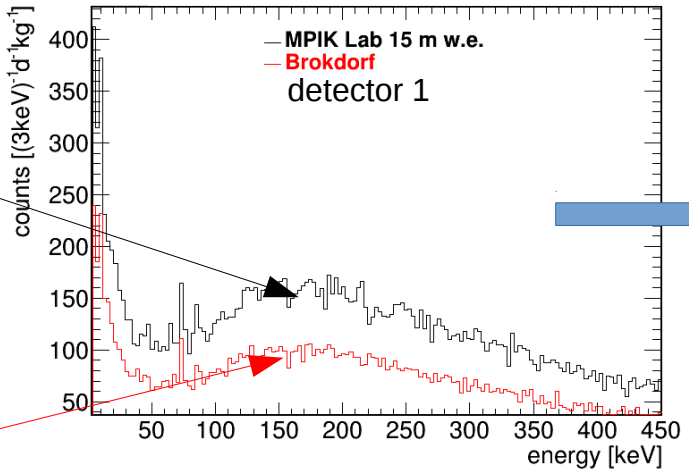
MPIK lab: low radioactive concrete
NPP Brokdorf: additonal background contributions

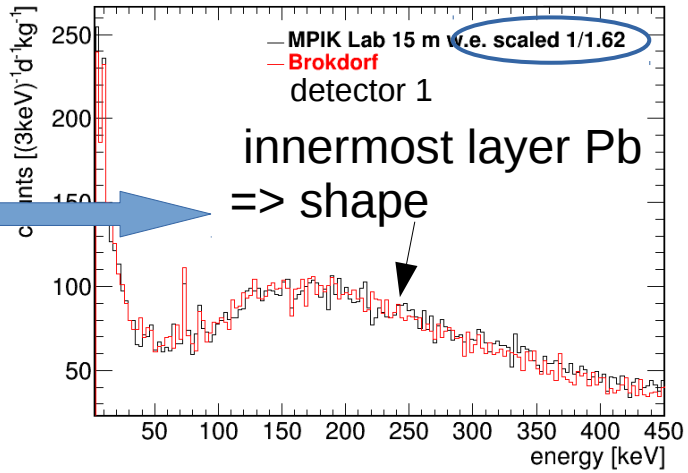
25 cm Pb

Passive shield: muon-induced continuum



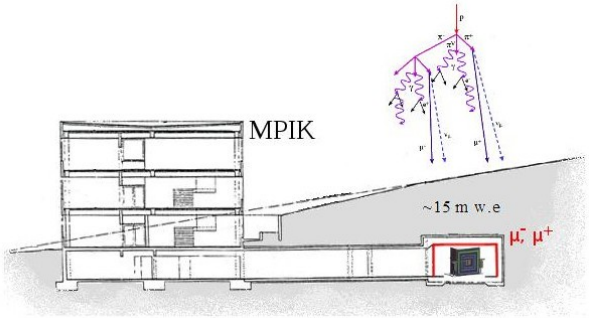




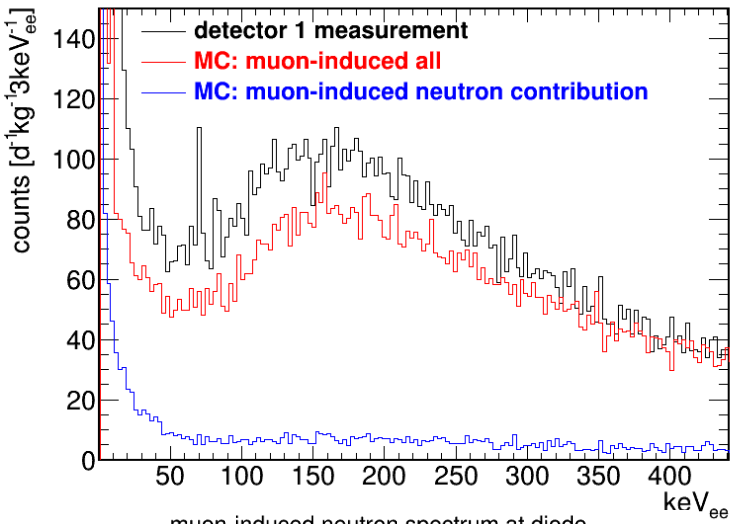


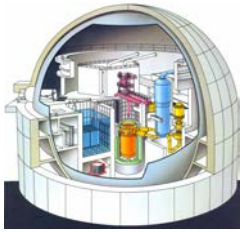
MPIK lab: reduction by 1000
NPP Brokdorf: additional background successfully suppressed
same shape as in MPIK lab
R(NPP Brokdorf) = R(MPIK lab)/1.62
=> effective depth: **24 m w.e.**

MC Simulation of muon-induced bkg



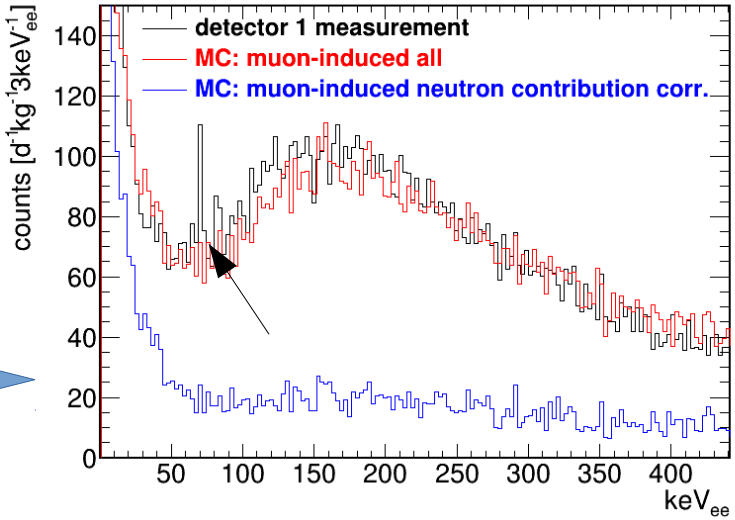
Validated technique up to O(100keV) inside similar shield
- calculation of muon-flux in MPIK laboratory
- propagate muons through shield
  with Geant4 based framework MaGe
- **excellent agreement** for prompt **muon-induced continuum**
- **lack of neutrons** (40-70%)

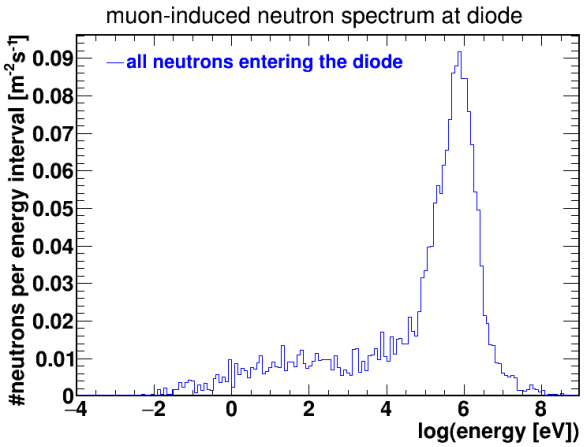




1. scale MC by 1.62

2. correct for missing neutrons



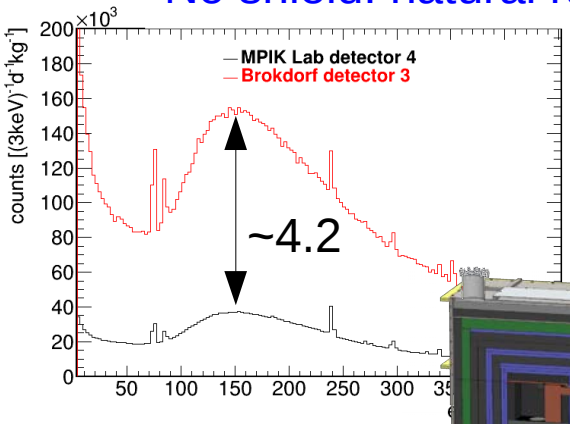


Validation of neutron correction factor (2013-ongoing):
- similar shield with coax HPGe (GIOVE 40-70%)
  (Taup proceeding 2015)
- consistency of all 4 detectors
- count rate of neutron-induced germanium lines
- Bonner Sphere measurement inside shield

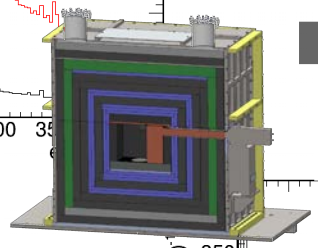
ongoing

Background reduction

No shield: natural radioactivity

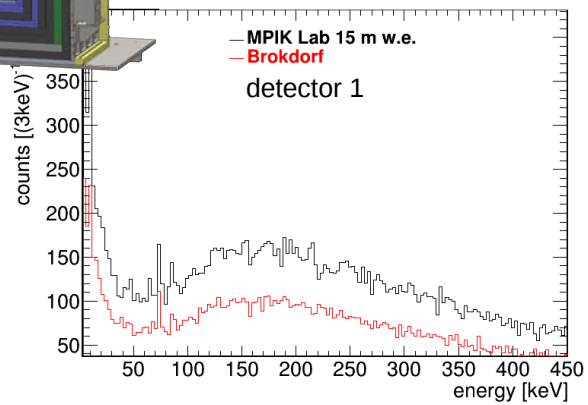


MPIK lab: low radioactive concrete
NPP Brokdorf: additonal background contributions



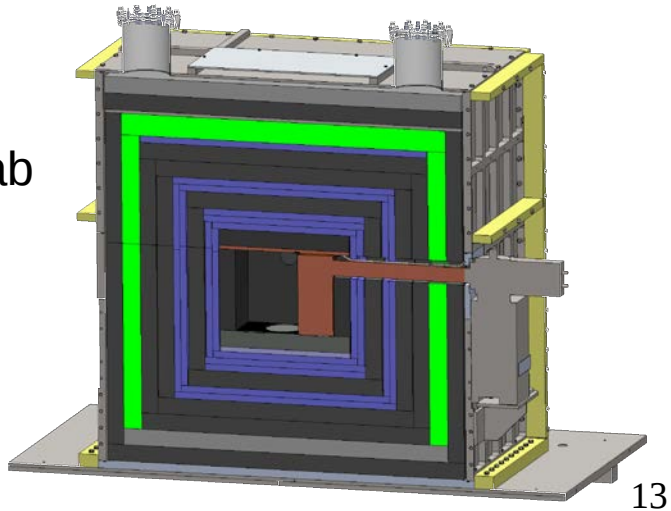
25 cm Pb

Passive shield: muon-induced continuum



MPIK lab: 15 m w.e.
NPP Brokdorf: 24 m w.e.

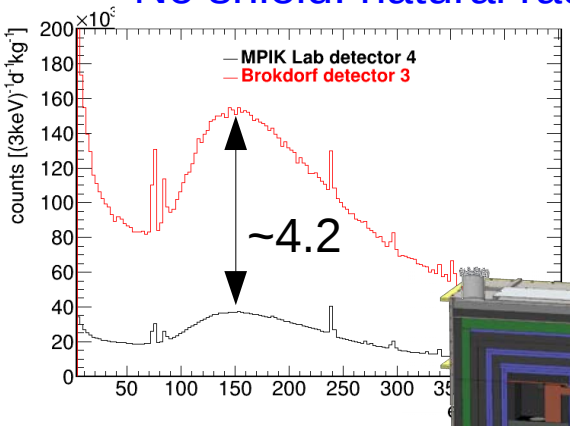
Muonveto
B-doped PE



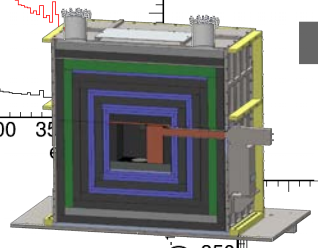
Basis for shield design: GIOVE at MPIK lab
(**G**ermanium **I**nner and **O**uter **Ve**to)
(G. Heusser et al., Eur. Phys. J. C 75 531, 2015)
-shell-like passive shield
-borated PE against neutron bkg
-active veto plates (99% efficiency)
=> virtual depth of several 100 m w.e.

Background reduction

No shield: natural radioactivity



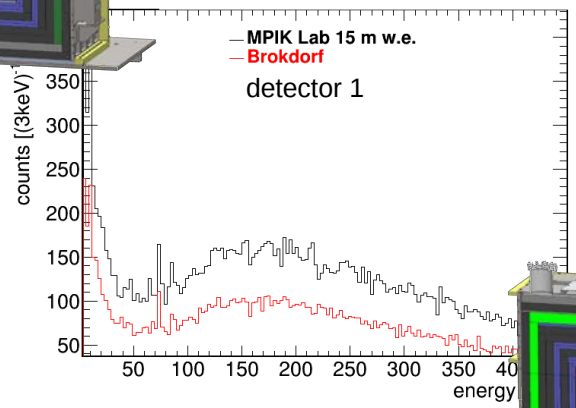
MPIK lab: low radioactive concrete
NPP Brokdorf: additional background contributions



25 cm Pb

Passive shield: muon-induced continuum

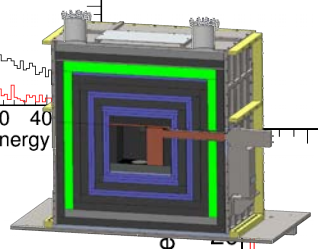
MPIK lab: 15 m w.e.
NPP Brokdorf: 24 m w.e.

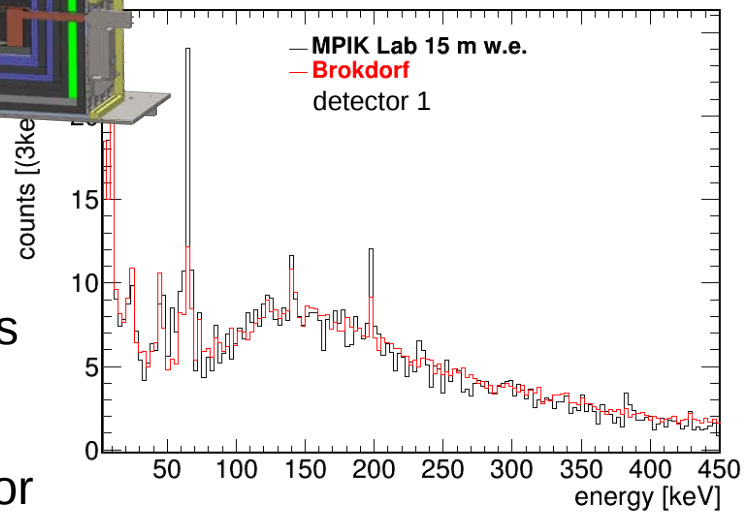


Muonveto

B-doped PE

active shield

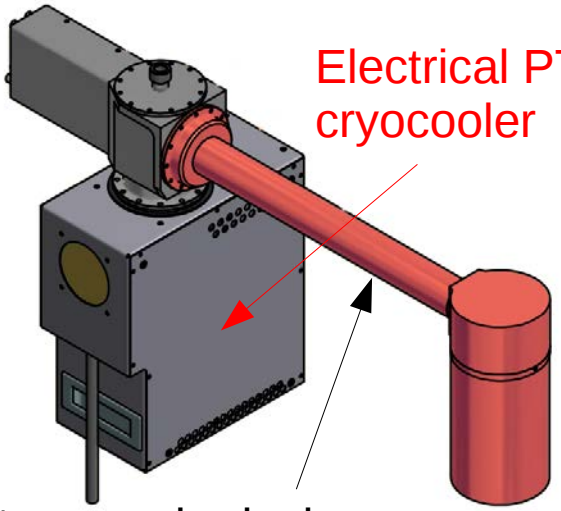




Reduction by factor 10
-Neutron-induced Ge isotopes:
NPP Brokdorf=MPIK lab/1.62
-Continuum: identical
-background modelling in progress

MPIK lab: shallow depth
NPP Brokdorf: shallow depth + reactor

CONUS detectors



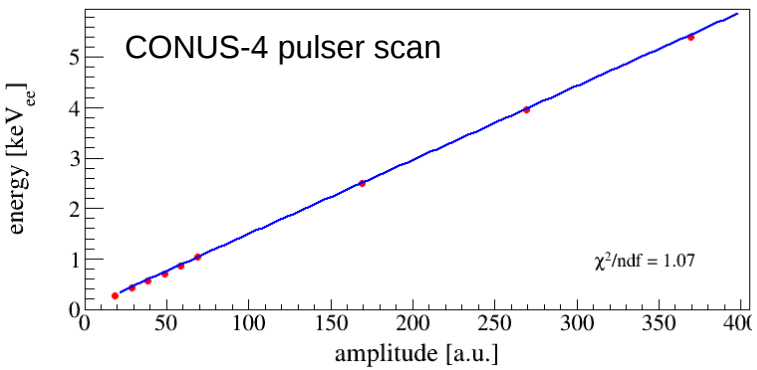
custom-made design

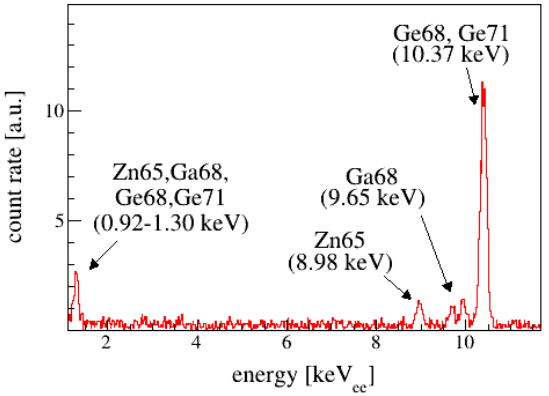
CONUS 1-4:

- p-type point contact HPGe
- crystal / active mass: **4.0 kg / 3.85 kg**
- spec for pulser res. (FWHM): ≤85 eV
  → detector noise threshold of ≤300 eV
- very low bg components (material screening)
- prod. in close coop. with Canberra France

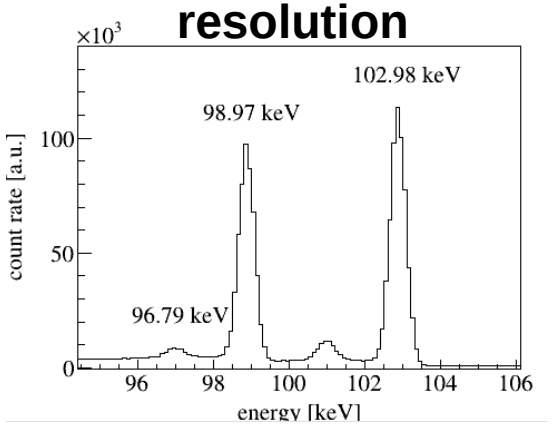
Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	69±1
CONUS-2	77±1
CONUS-3	64±1
CONUS-4	68±1

Linearity of energy scale





resolution

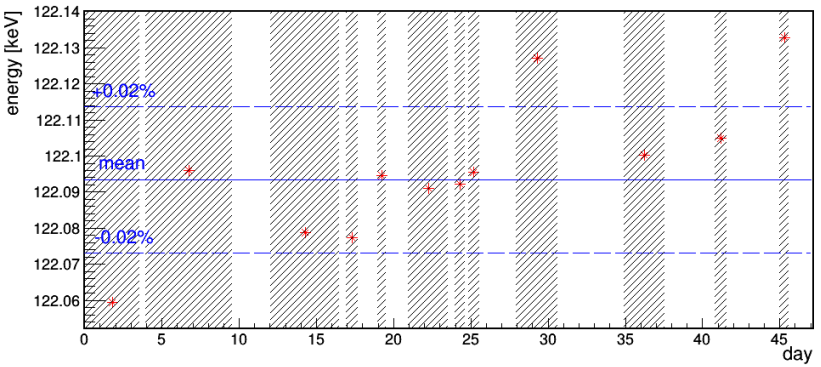


^{241}Am source measurement

Long term stability

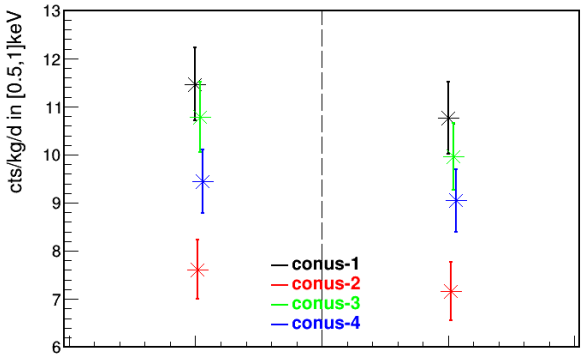
under lab. conditions:
std. dev. of peak position:
+-15eV (+-0.02%)
(within 45 days)

CONUS-2 ^{57}Co 122keV line position



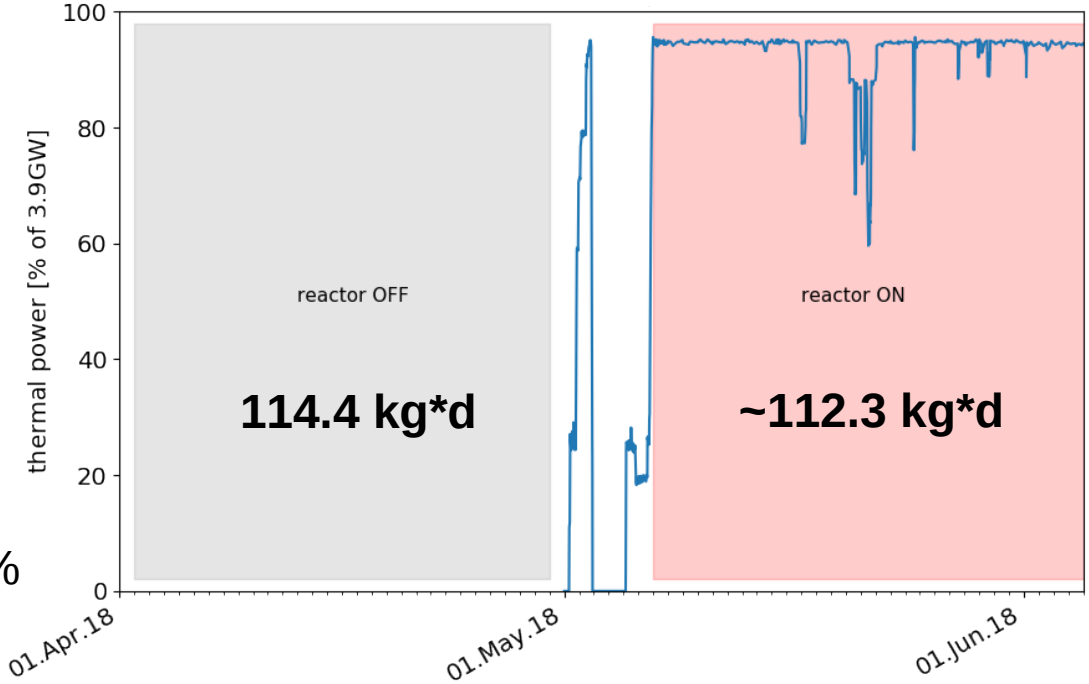
First rate analysis

Bg stability in interval (0.5,1.0) keV



reactor OFF reactor ON

Reactor thermal power:



Definition of efficiencies:

- active volume: (96+-2)%
- muon AC ind. trg. Efficiency: (97.9+-0.1)%
- trg. efficiency in ROI: ~80% (individual)
- (not yet included: bg red. due to slightly reduced x-ray bg contribution in ROI → 'slow pulses')

Data release June 2018	counts	counts/d/kg (*)
Reactor OFF (114 kg*d)	582	--
Reactor ON (112 kg*d)	653	--
ON-OFF (exposure corr.)	84	0.94
Significance	**2.4 sigma (stat.)**	2.3 sigma

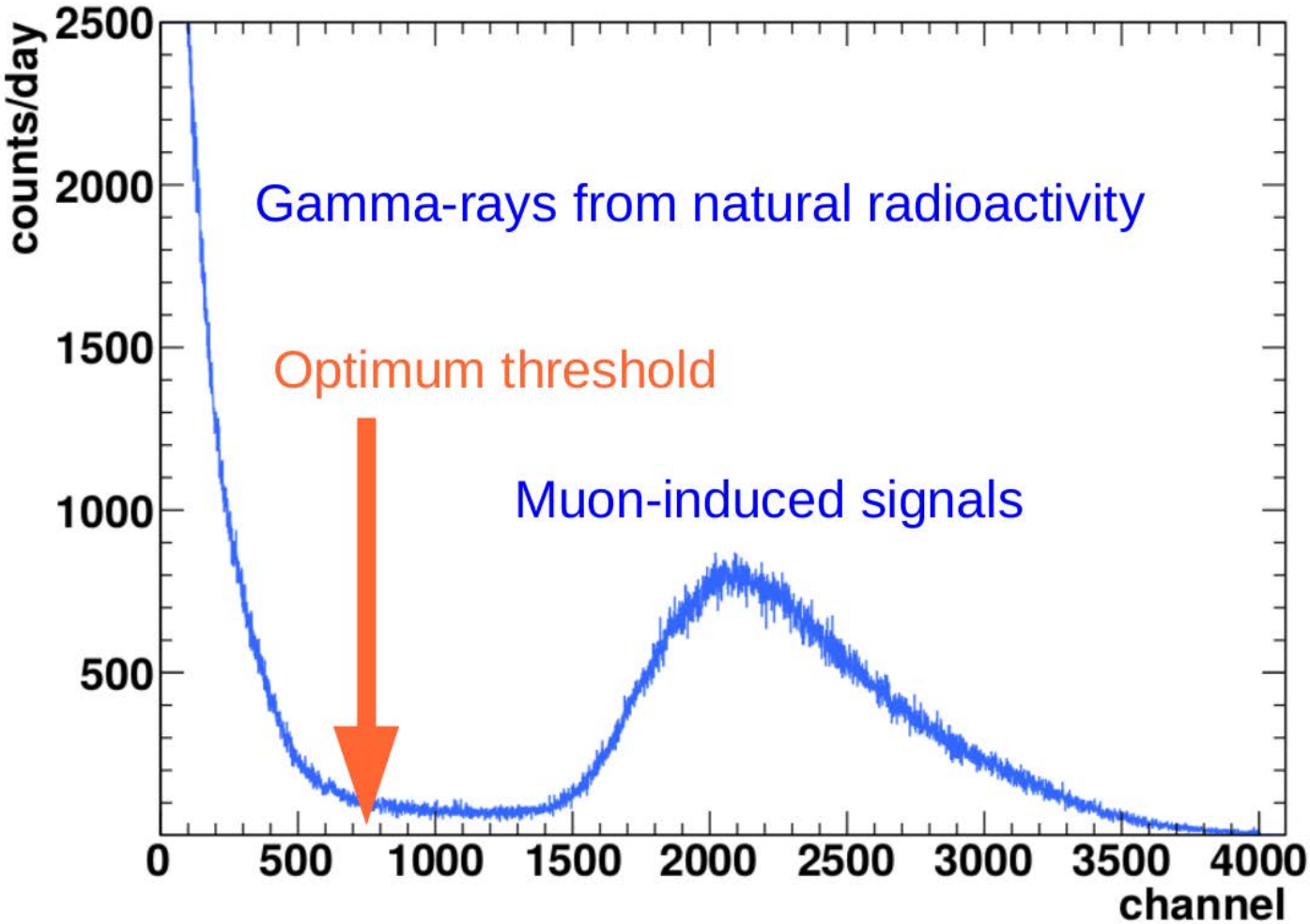
→ **NEUTRINO2018: Observed excess of events is within expected CEvNS signal range**

Conclusions

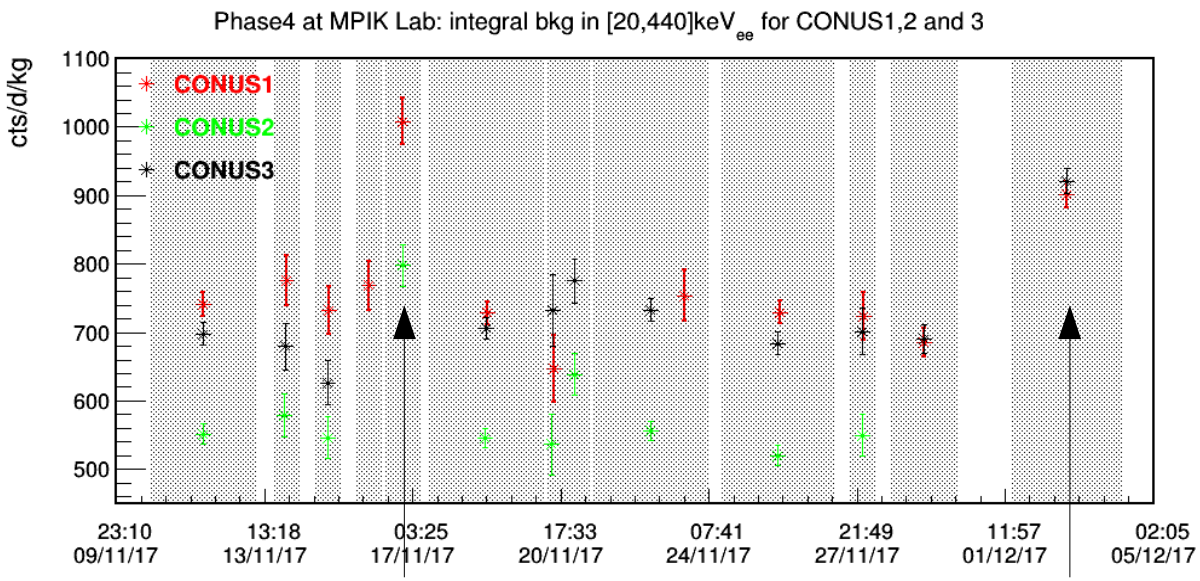
- Neutron measurement at reactor site: → highly thermalized field, shielded well
- Successful background suppression by active and passive shield, background modelling ongoing
- Detailed information on anti neutrino source = reactor available
- First data release in June 2018: 114 kg*d / 112 kg*d of reactor OFF/ON data
  Observation of an excess in the ROI at a statistical significance of **2.4 sigma**
  → First hint for CEvNS observation at a nuclear reactor
- Ongoing data collection and refined analysis → **more detailed analysis and publication soon!**

Acknowledgement:
PTB: T. Klages, A. Lücke; KBR: D. Solasse, A. Klischies, M. Alpers, T. Schröder, H. Rathjen; LNGS: M. Laubenstein; JKR: M. Wojcek; MPIK: M. Reissfelder, R. Hofacker, J. Westermann, B. Gramlich, A. Schwarz, S. Form, B. Mörk, T. Spranz, T. Apfel, N. Winkler, R. Heldner, M. Chardon, K. Zink, F. Köck; J. Schreiner, R. Lackner; C. Lüders; Canberra: V. Marian, M.O. Lampert, Q. Pascal

Plastic scintillator muon spectrum



Radon mitigation

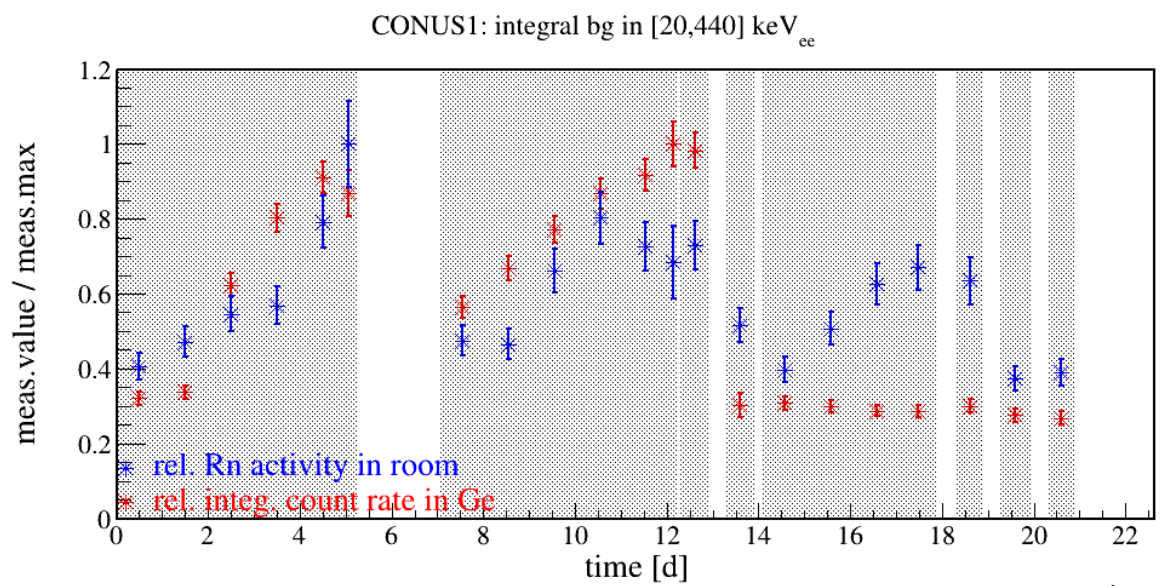


Shield opened
for source insertion

Test of Rn density of shield

MPIK laboratory:
~50Bq/m^3
Flush with boil-off nitrogen

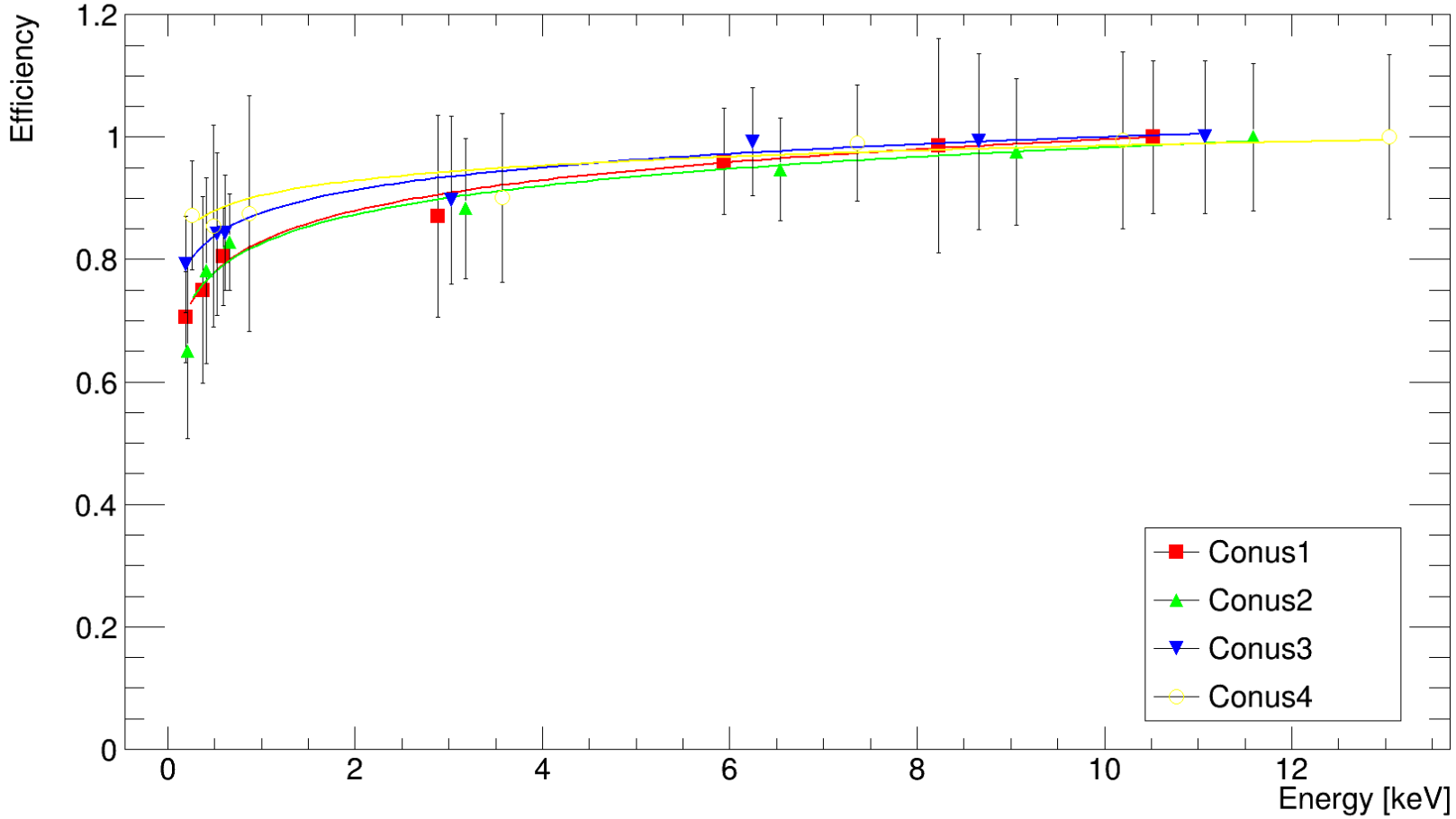
NPP Brokdorf:
~100 Bq/m³ (max. 300 Bq/m³)
Flush with breathing air bottles



no flushing

flushing with
breathing air bottles

Detector trigger efficiency



DAQ/Electronics

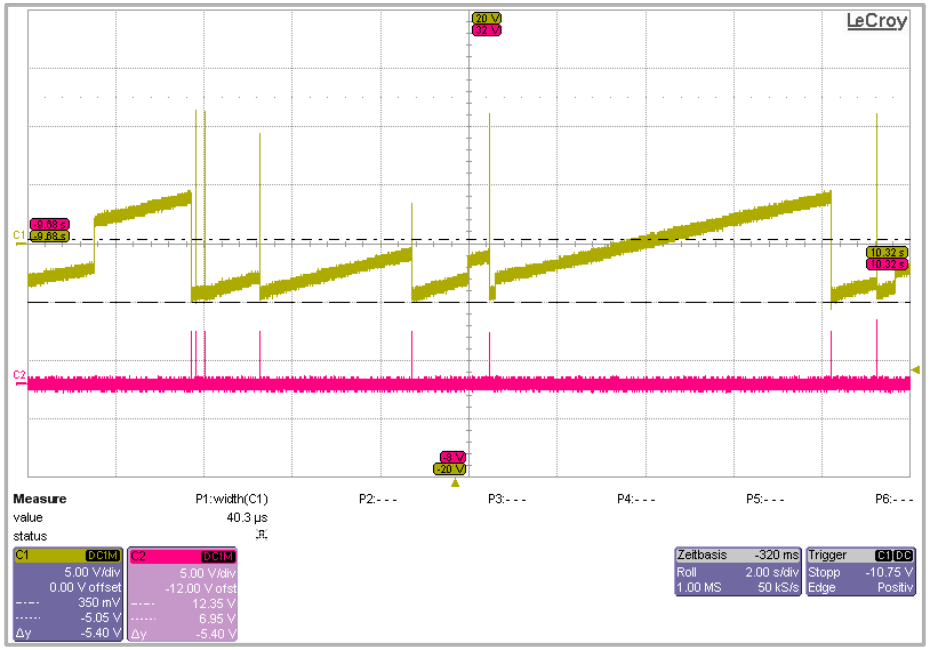
Signal processing:

1. JFET, custom-build by Canberra France

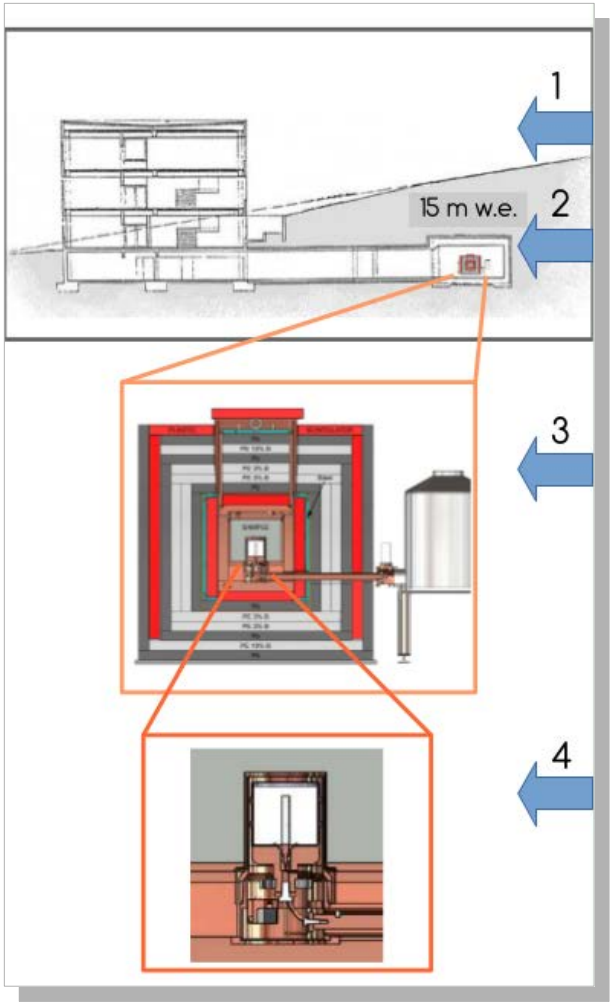
2. Reset preamplifier Model PSC 954-P
   - dynamic range:[-6,+4]V
   - reset time: 20 mus
   - Inhibit logic pulse: 160-200 mus

3. DAQ: Lynx Digital Signal Analyzer (Canberra)
   - shaping amplifier
   - fast digitized analogue-to-digital converter (80 MHz sampling rate)
   - energy reconstruction via trapezoidal filter: typical risetime: 15 mus typical flat top: 0.8 mus
   - store: energy/timestemp information

4. Custom-created acquisition software
   → Python framework (Lynx SDK)



MC: prompt muonic bg in GIOVE/CONUS



Analytic calculations:

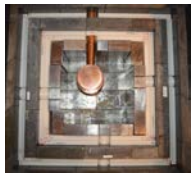
1. Muon flux above ground:
   - Extrapolation formulas by Bogdanova [9] & Bugaev/Reyna [10,11]
   - Altitude effect corrected (305 m a.s.l.)
2. Muon and neutron flux at ~15 m w.e.:
   - Muons energy loss: $dE_\mu/dX = a + bE_\mu$
   - Primary neutron flux: exponential decrease with λ=165-200 g/cm^2

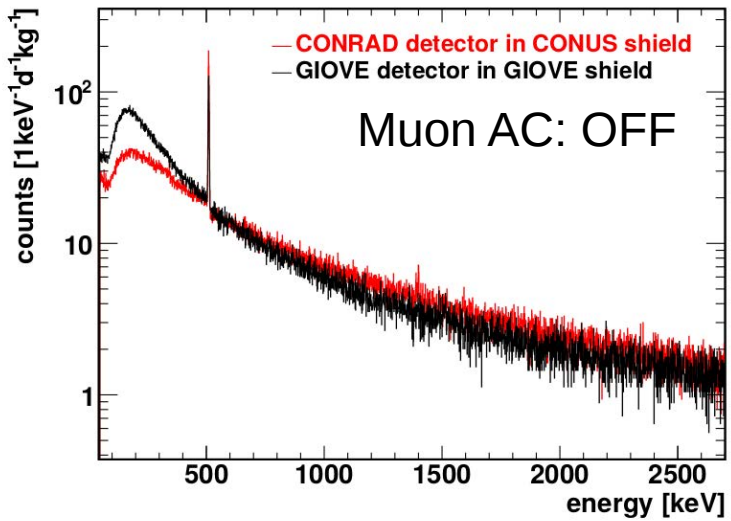
MC simulations with MaGe:

3. Simulation of muons through shield:
   - Muon starting positions: on lab walls
   - μ^+/μ^- ratio≈1.3, similar to sea level
4. Simulation of muon-induced neutrons through shield and Ge diode:
   - Propagation in different shield layers
   - Backscatter effects considered

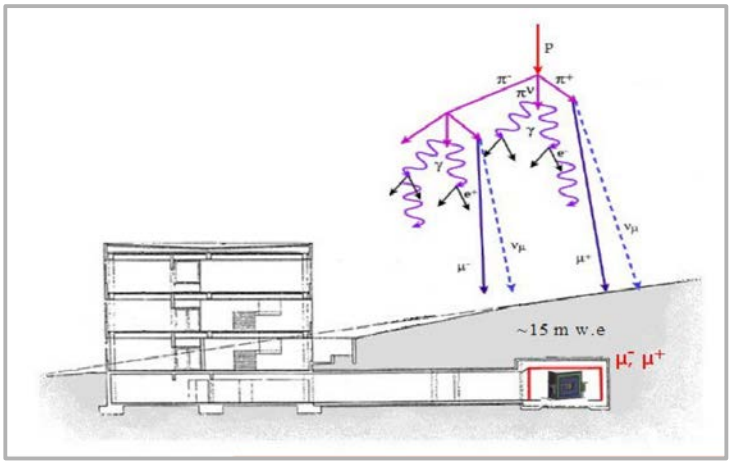
Muonic background at shallow depth

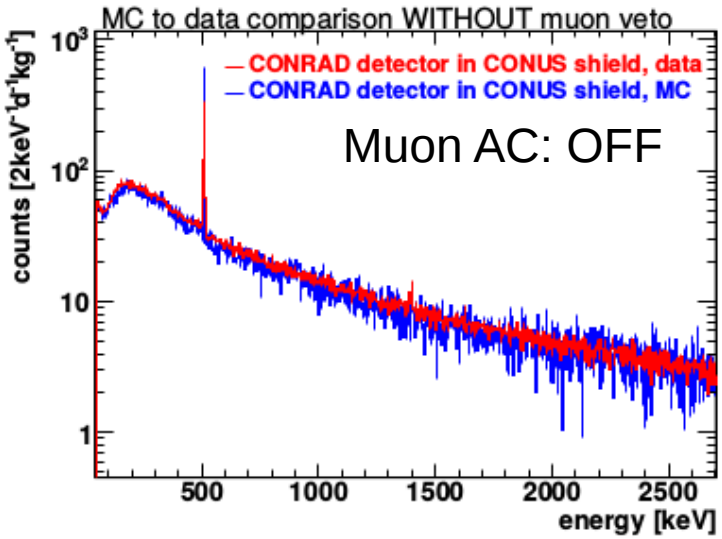
Commissioning at MPIK-based lab:
- only CONRAD inside shield
- muon anticoincidence (AC):



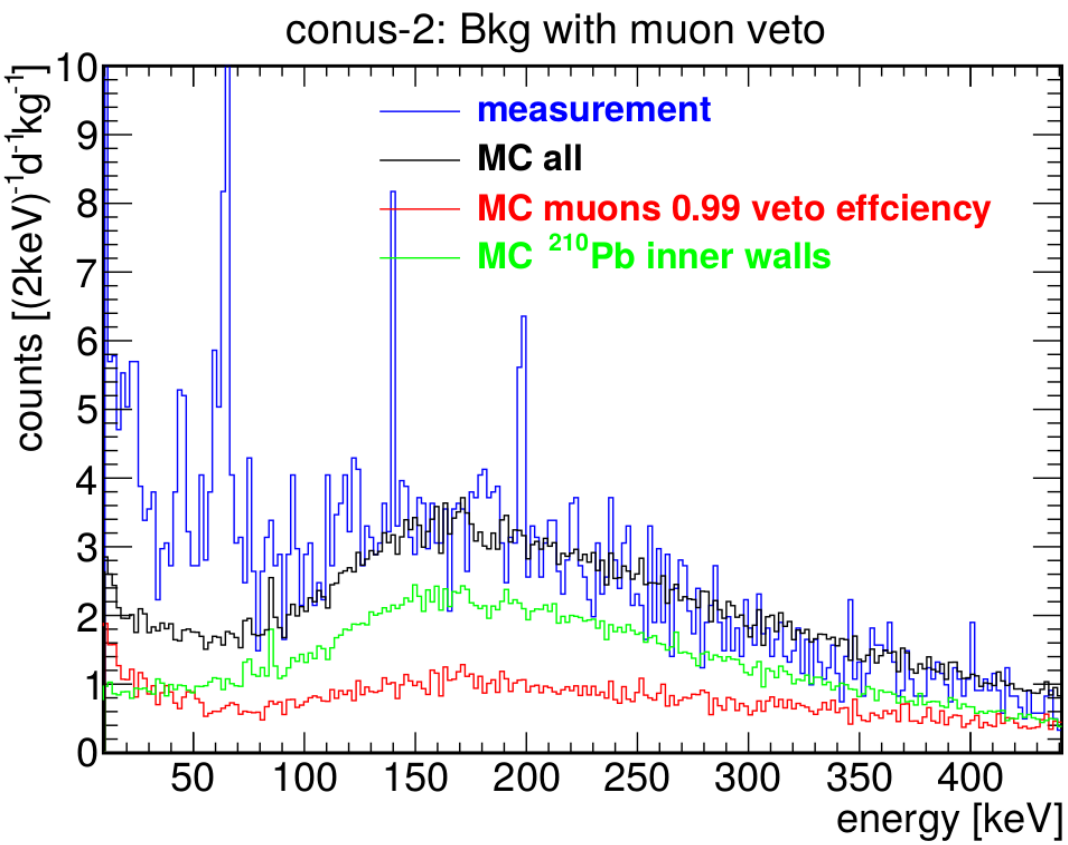


- spectrum dominated by prompt muonic bg
- innermost layer made of Pb instead of Cu: ~40% better bg suppression below 200 keV
- MC of prompt muonic bg based on Geant4-toolkit MaGe agrees with data at few % level !





Spectral Decomposition for MPIK laboratory



Bkg decomposition in [20,440] keV

det	prompt muon	^{210}Pb	others
1	~20%	~50%	~30%
2	~30%	~50%	~20%
3	~20%	~50%	~30%

Determine Pb210 activity:

1. low bg alpha/beta counting (M. Woycek)
2. beta spectrum: comparison data vs. MC with GIOVE detector

(+ some from previous measurements)