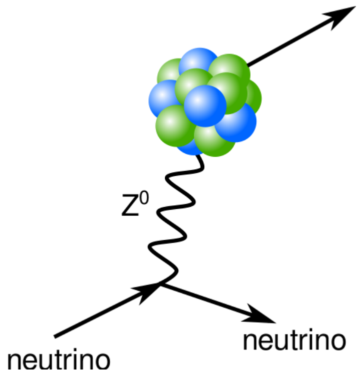
Coherent elastic neutrino nucleus scattering with the CONUS experiment

Janina Hakenmüller for the CONUS collaboration

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

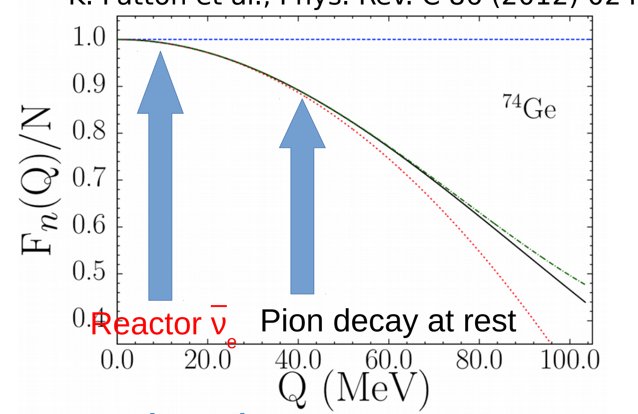
Low Radioactivity Techniques 2019, Jaca, 23.05.2019

Coherent elastic neutrino nucleus scattering (CEνNS)



1974 predicted (D.Z.Freedmann, Phys. Rev. 9 (1974) 5)
2017 first detection by COHERENT experiment:
pion decay at rest source
6.7 σ significance for excess in events, 1 σ consistency with SM
→ CONUS: looking at **fully** coherent regime with reactor $\bar{\nu}_e$

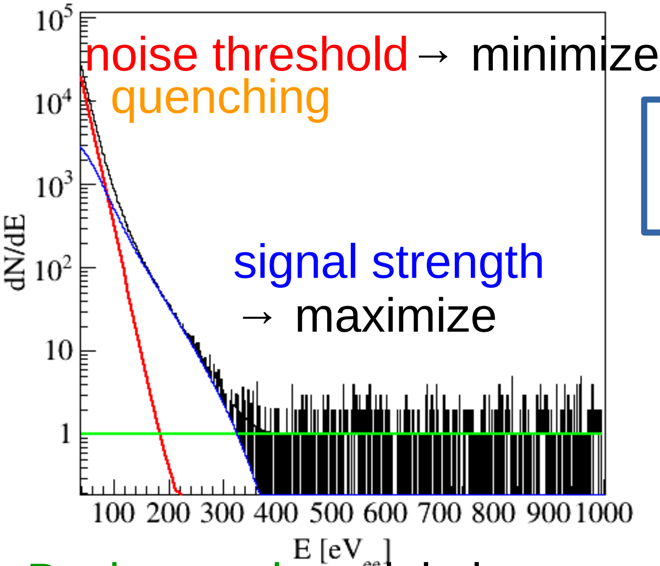
K. Patton et al., Phys. Rev. C 86 (2012) 0246



coherency condition:
λ(mom. Transfer) > size of atom
=> for Ge: E_{max}≤50 MeV
fully coherent ≤30 MeV

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

recoil energy
~ 1/mass nucleus



Background → minimize

physics motivation:
- Supernovea
- ν floor for dark matter exp.
- Weinberg angle at low energies
- ν magnetic moment
- Non-standard ν interactions
- ….

CONUS: Coherent Neutrino nUcleus Scattering

MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

CONUS

Preussen Elektra

Collaboration:
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- *Max Planck Institut für Kernphysik (MPIK), Heidelberg*

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- *Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf*

Scientific cooperation:
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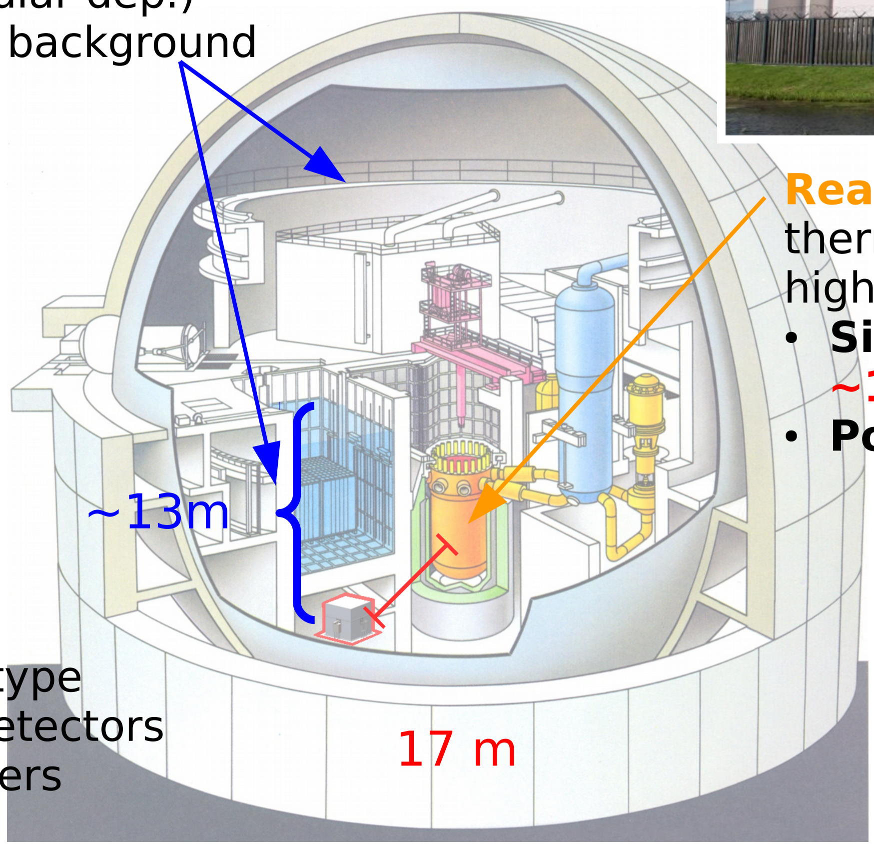
- *Physikalisch-Technische Bundesanstalt (PTB), Braunschweig*

PTB Messen ▪ Forschen ▪ Wissen

Antineutrino source:

Nuclear power plant at Brokdorf (GER)

Overburden at shallow 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)

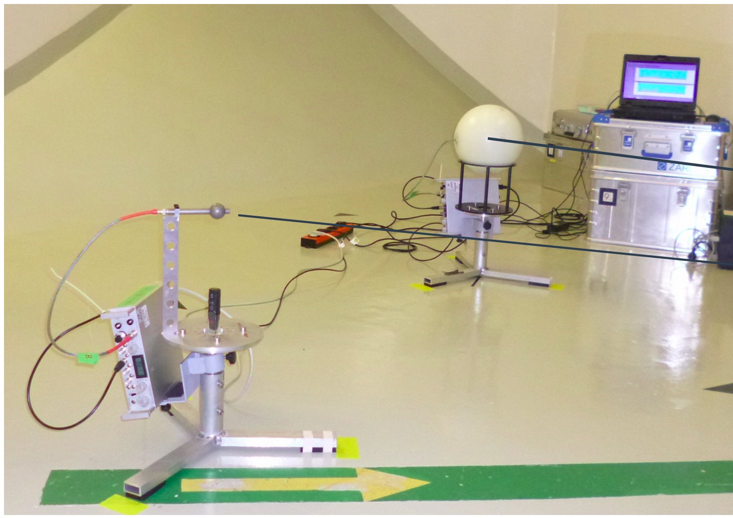
- **Signal:** antineutrinos @17m
  ~10^{13}/(cm² s)
- **Potential background:** Neutrons

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

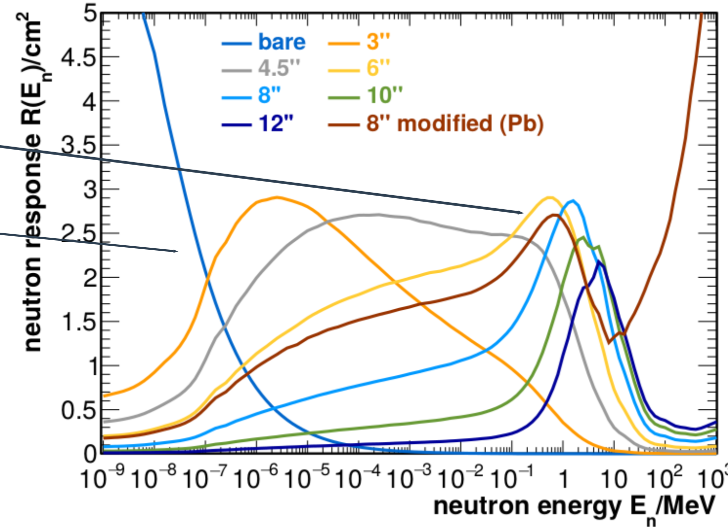
CONUS experiment:

- **4kg** low threshold p-type point contact HPGe detectors
- electrical PT cryocoolers
- Flush with air bottles

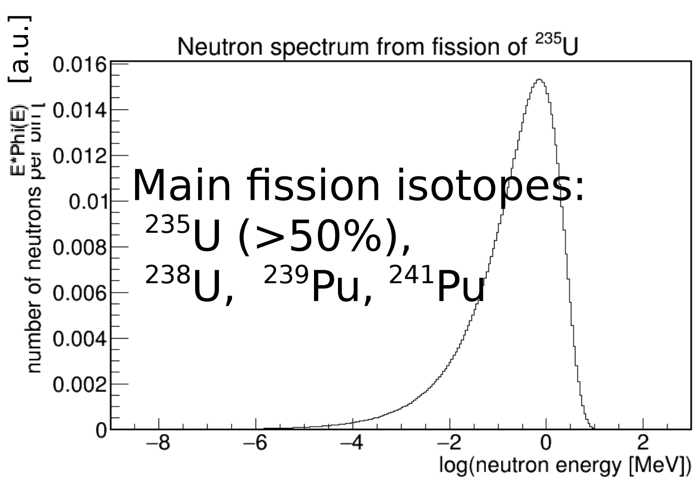
Reactor-correlated neutrons: on site measurement



Sphere diameter in inch ↔ Sensitivity to neutron energy



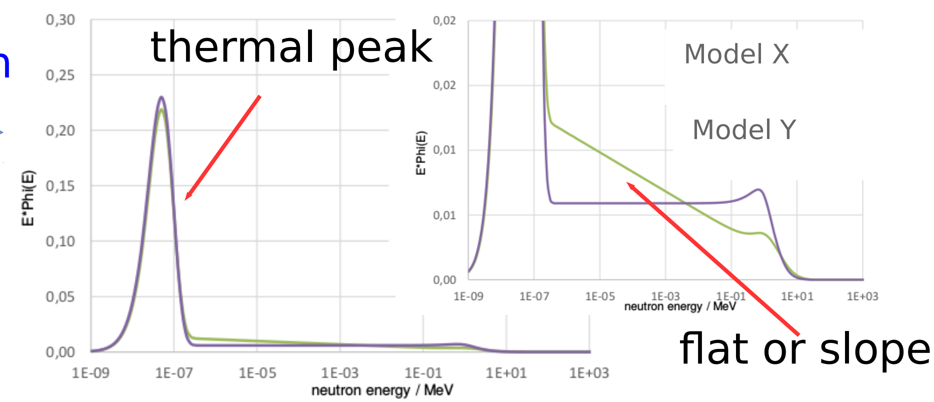
NEMUS by PTB: spectral resolution possible!



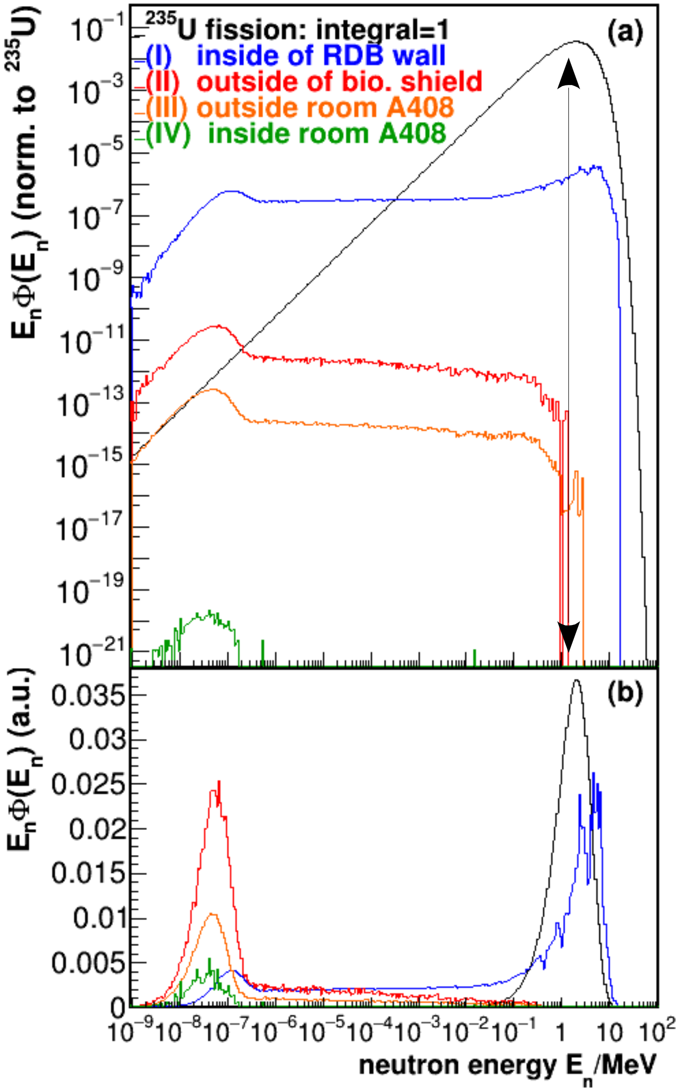
Main fission isotopes:
^{235}U (>50%),
^{238}U, ^{239}Pu, ^{241}Pu

propagation

water
steel
concrete
…

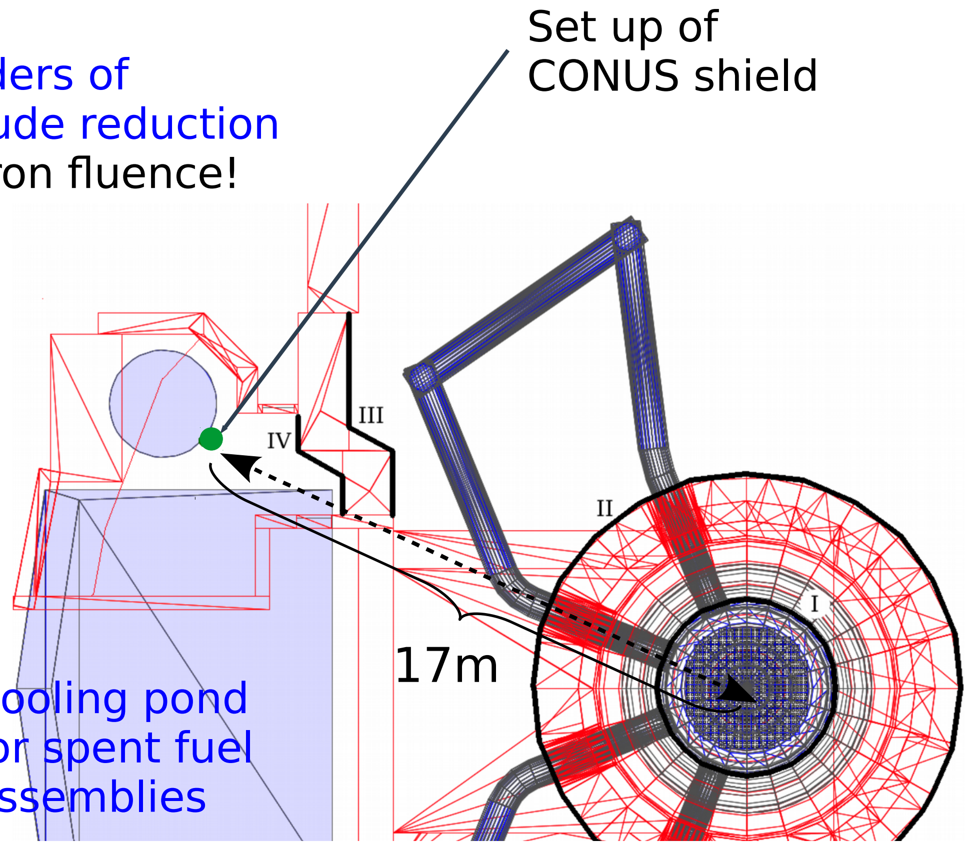


Reactor-correlated neutrons



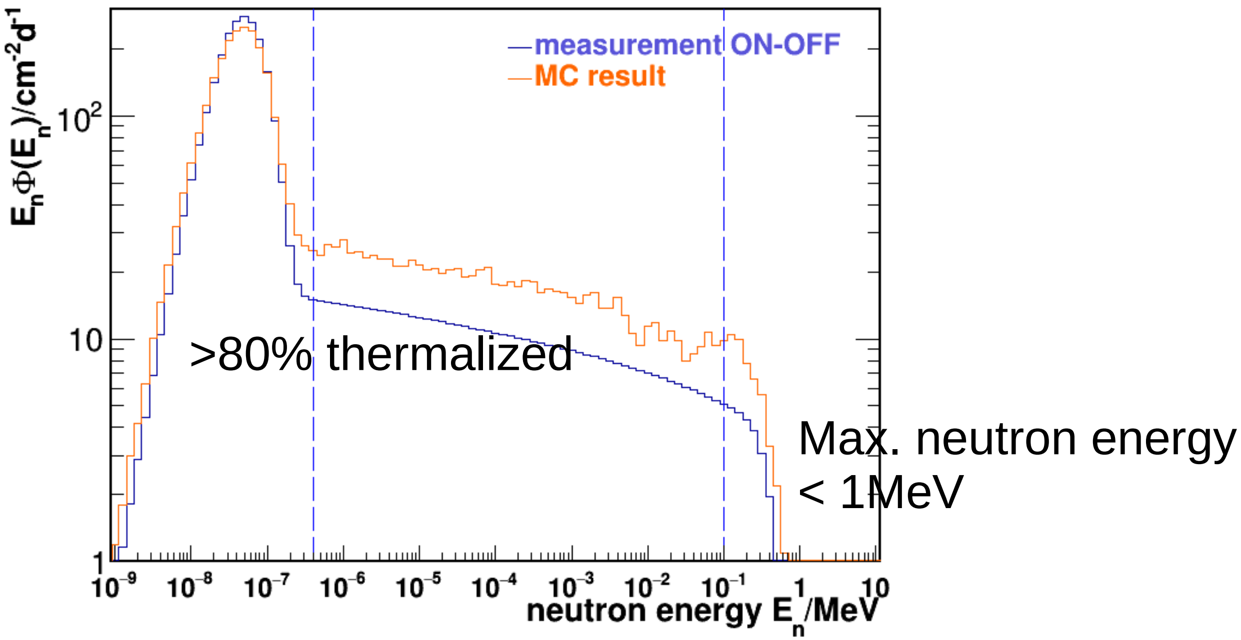
Propagation of reactor neutrons to A408
Geant4-based MC framework MaGe

~20 orders of magnitude reduction in neutron fluence!



Reactor-correlated neutrons

ON – OFF = reactor-correlated

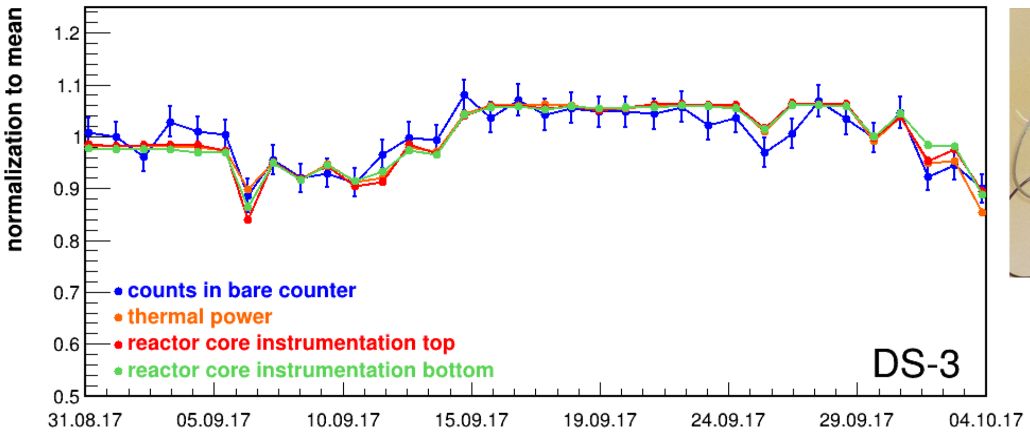


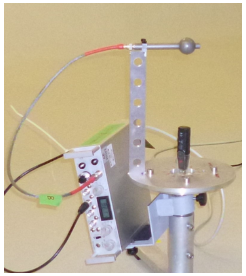
Main results:

1. Neutron fluence rate at distance of 17m to reactor core ~**factor 2 lower** than earth surface!
2. **highly thermalized** neutron field, correlated to reactor power
3. inhomogeneity in thermal neutron fluence rate of ~20% within a few meters inside A408
   => in-depth understanding of neutron background **on site**
4. MC spectrum of neutrons entering the outside of the wall of A408 similar,
   same maximum energy

Correlation to thermal power

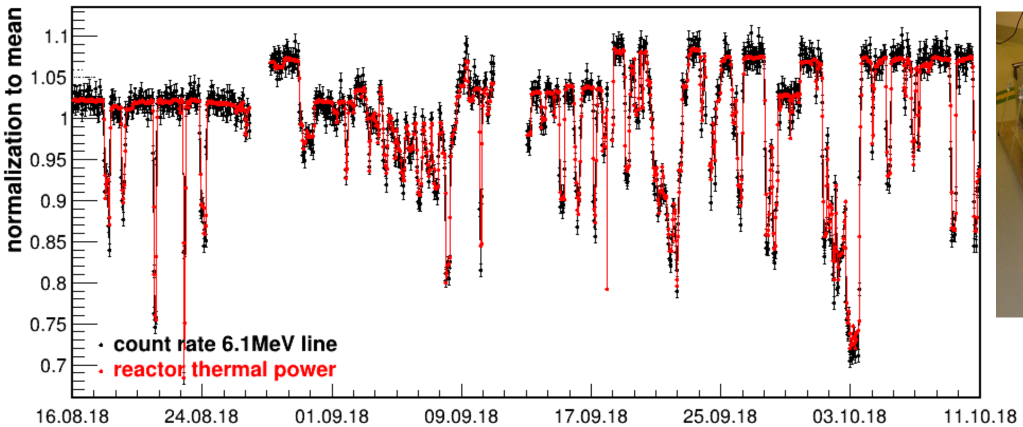
<u>Comparison:</u> measurements at CONUS experimental site with thermal power from energy balance of secondary cooling circuit (2.3% uncertainty)





Thermal neutron counter:

- Correlation to in-core and ex-core instrumenation observed as well



HPGe detector without shield:

- ^{16}N γ-rays (main line: 6.1MeV) from primary cooling cycle
- natural radioactivity (Th, U, K)

Highly correlated to thermal power → **potentially** dangerous background contribution!

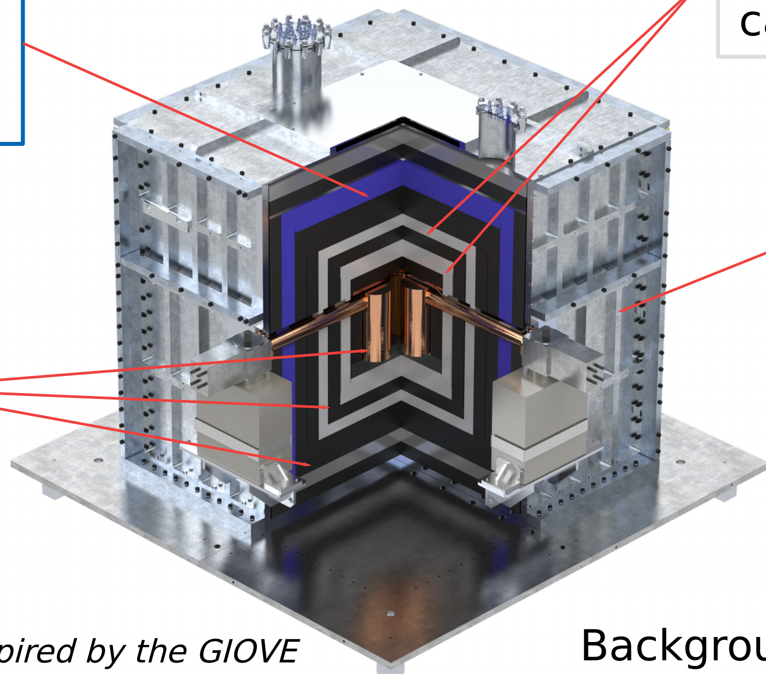
CONUS Shield

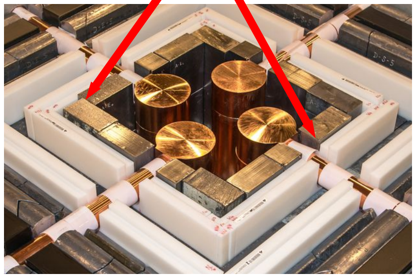
Active muon veto:
suppress cosmic ray muon induced background

Borated PE:
moderate and capture neutrons

Steel cage:
confinement of shield flushed with breathing air from bottles against Radon (up to 300Bq/m^3)

25cm Pb:
Shield radioactivity from environment low in ^{210}Pb





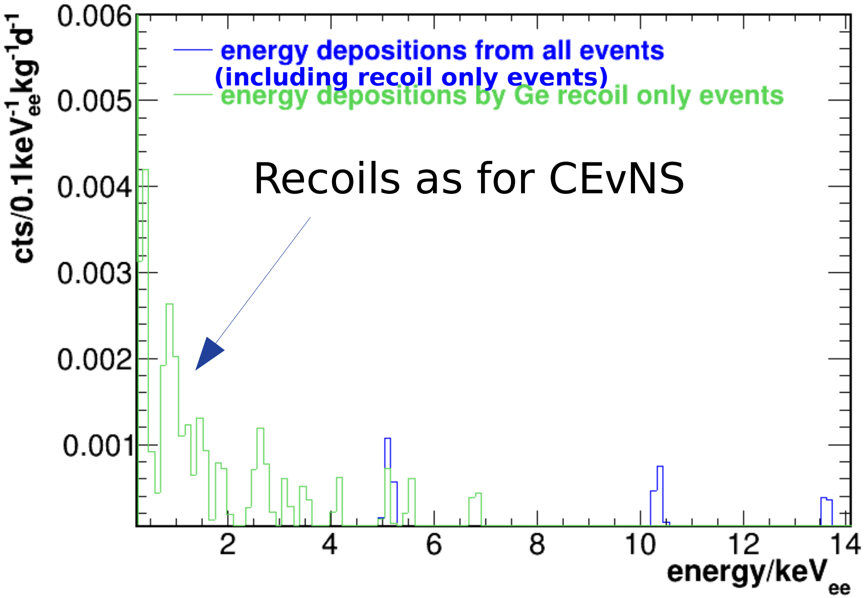
Inspired by the GIOVE spectrometer shield design (MPIK, Eur. Phys. J. C (2015) 75: 531)

Background rate:
order of 10cts/keV/kg/d in [0.5,1.0]keV

How efficient does the shield suppress the reactor-correlated neutrons and γ-radiation?
→ **propagation** of measured neutron spectrum and known γ-ray energies through shield in **MC**

Reactor-correlated background suppression

Expected spectrum in Ge diode:



Reactor neutrons

Energy range	Measured background [cts/kg/d]	MC generated **reactor-correlated** [cts/kg/d]
[0.3, 0.6]keV$_{ee}$	12±1	0.013±0.004
[0.6, 11]keV$_{ee}$	148±2	0.035±0.006
[11, 400]keV$_{ee}$	716±16	0.13±0.02

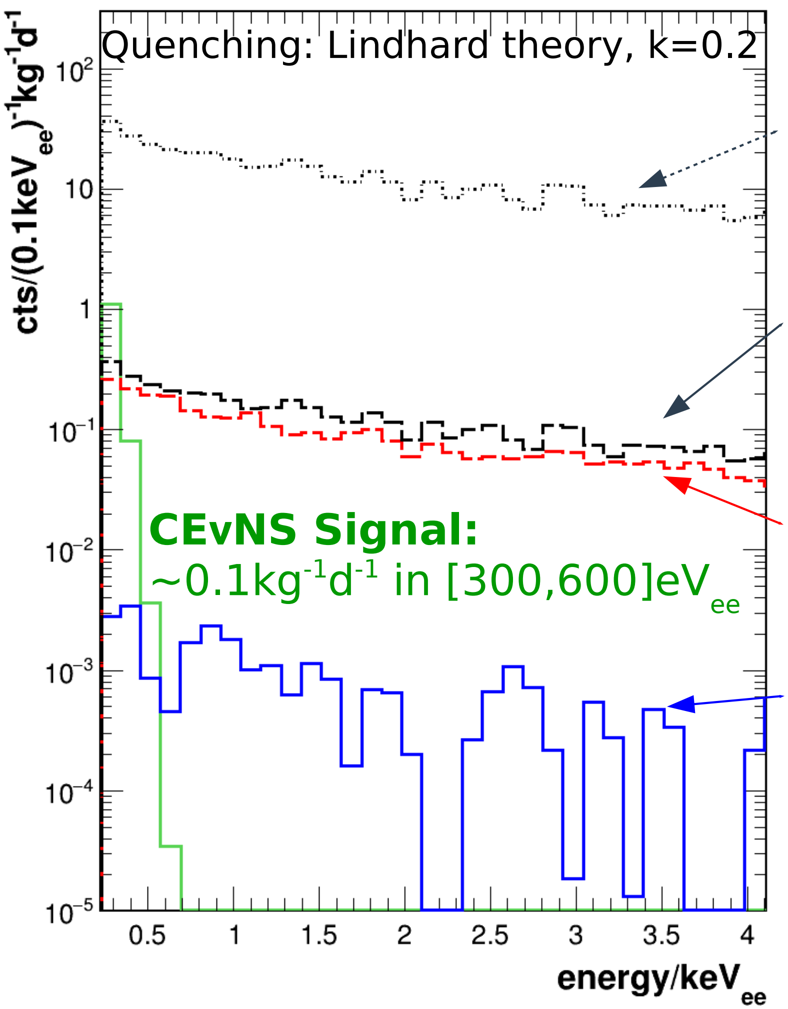
- at least **one order of magnitude smaller** than expected CEvNS signal for realistic quenching

→ Reactor-correlated contributions negligible <u>inside</u> shield!

Reactor-correlated high-energy γ radiation

- 25cm of Pb → nearly constant γ-ray attenuation from 2-10MeV
- dominant reactor-correlated contribution: ^{16}N
- $(11\pm2)\cdot10^{-5}$ cts/kg/d in [0,450]keV$_{ee}$ → negligible

All neutron contributions and CEvNS signal



J. Hakenmüller et al, arXiv:1903.09269 [physics.ins-det]), submitted to EPJ-C

μ-induced **neutrons** inside shield
→ metastable Ge states

μ-induced **neutrons** inside shield
with active μ veto
(veto efficiency ~99%)

μ-induced **neutrons** inside concrete

Steady state
- **Not** reactor-correlated
- constant in time to first order

reactor-induced **neutrons**

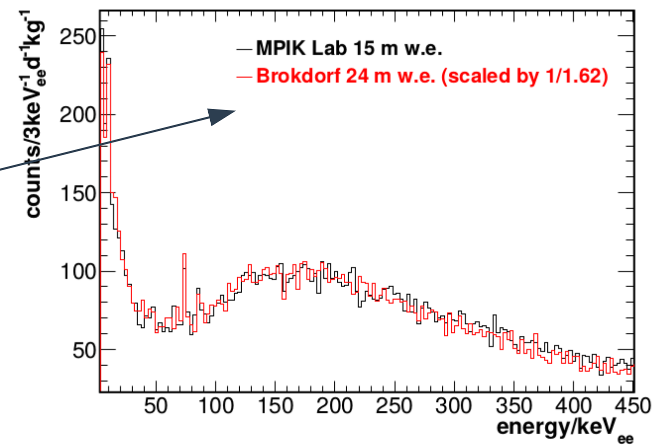
Reactor correlated,
BUT negligible

hadronic component of cosmic rays
→ fully suppressed by overburden of 10-45 m w.e.

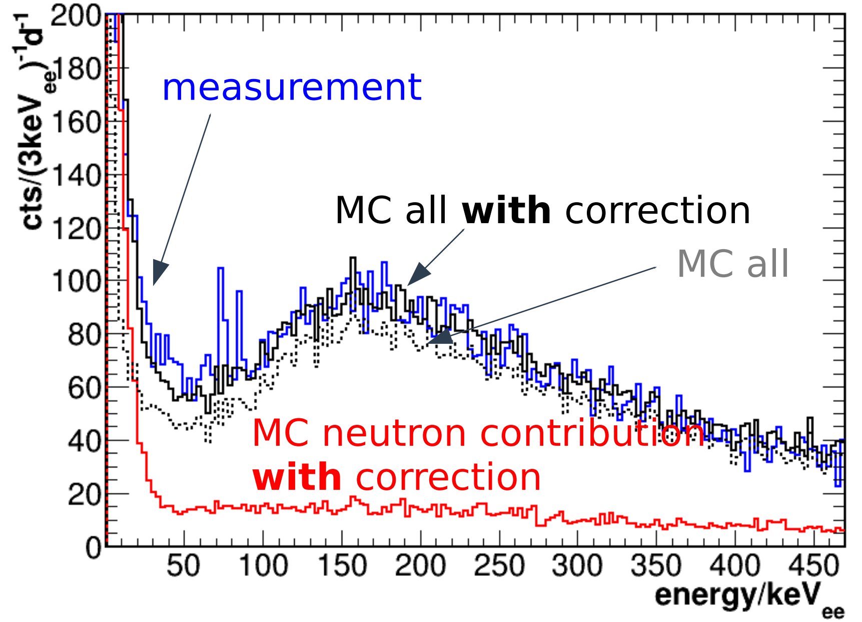
Muon-induced background inside shield

MC with MaGe, based on Geant4: muons through CONUS shield

- **Validation:** for similar shield at MPIK lab at 15m w.e. (>40keV) (TAUP proceeding 2017)
  → excellent agreement for prompt em. component
  → missing neutrons 40-70% (in Geant4.9.6)
- **Location:** from MPIK to KBR scaling factor 1.62 (measured spectra of passive shield at both locations)
- **Neutron correction factor:** for lack of neutrons (2013-**ongoing**)
  - consistency of all 4 detectors
  - count rate of neutron-induced germanium lines
  - Bonner sphere measurement inside shield



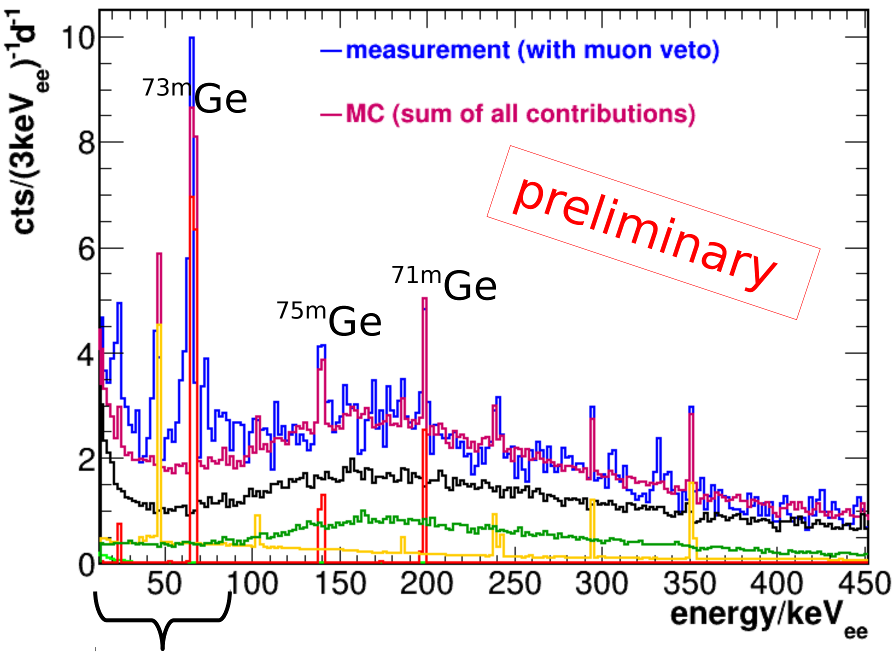
location	139.5keV ^{75m}Ge [$kg^{-1}d^{-1}$]	n flux at diode [$cm^{-2}d^{-1}$]	diff. to MC (data-MC)/data
MPIK lab 15 m w.e.	3.5+-1.0 →	24+-7	~60%
KBR 24 m w.e.	2.5+-0.2 →	17+-2	~65%



Background with applied muon veto

Total background suppression factor of active and passive shield: **10^4**

Exemplary remaining background:



Discrepancies due to interference of:
- life time of the metastable Ge states
- time constant of data acquisition

Conus-2	% of bkg [100,450]keV_{ee}
prompt μ-induced (with μ veto)	64%
metastable Ge	2%
^{210}Pb lead bricks	26%
within cryostat	9%

same for all detectors (prompt μ-induced, metastable Ge)

individual (^{210}Pb lead bricks, within cryostat)

Minimized by screening measurements beforehand! (at MPIK and LNGS, ^{210}Pb at Jagiellonen University)

Towards lower energies:
- Muon-induced neutrons inside concrete
- Cosmic activation: $^{68}Ge/^{71}Ge$, ^{65}Zn, ^{68}Ga,...

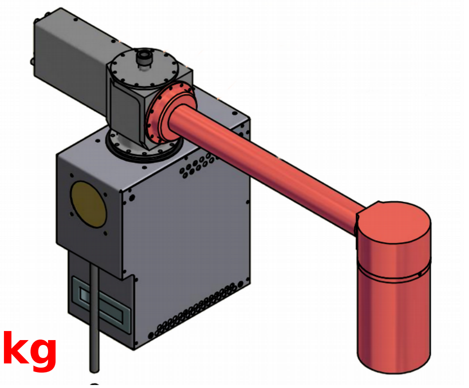
Latest results of CEvNS rate analysis

Preliminary! **3 detectors**

Counting analysis (~300-550eV)	**counts**
Reactor OFF (65 kg*d)	354±19
Reactor ON (417 kg*d)	2405±49
ON-OFF	133±130

Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	74±1
CONUS-2	75±1
CONUS-3	59±1
CONUS-4	74±1

crystal / active mass: **4.0kg/3.74kg**



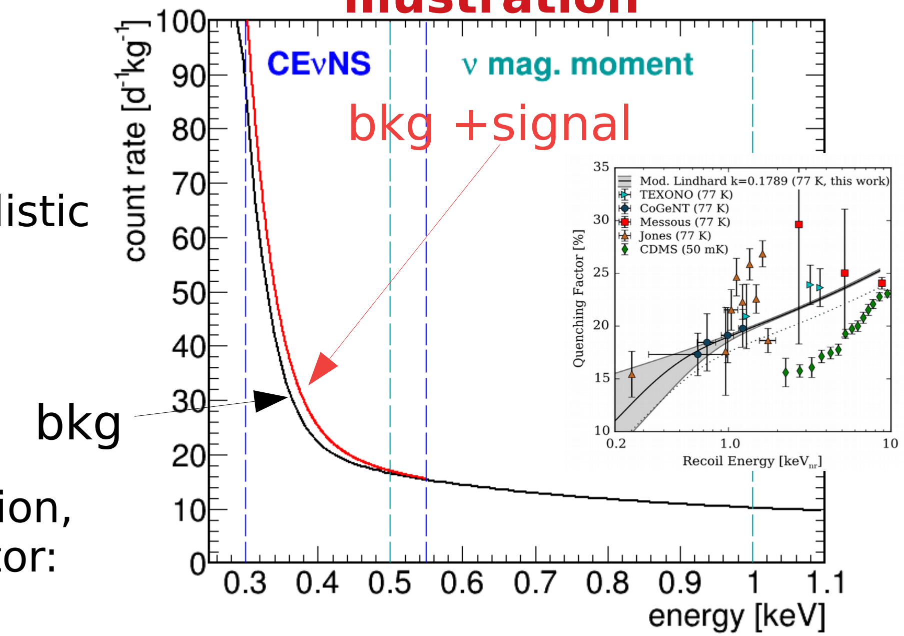
First full data set:

- rate only → shape analysis in progress
- statistically limited by reactor off period
  → next regular outage of one month soon
- order of magnitude as theory prediction for realistic quenching

Shape Analysis: on-going

- careful data selection for understanding of a few artifacts
- highly quenching-dependent
- systematics: energy scale and linearity calibration, detection efficiency, background stability, reactor: flux, shape neutrino spectrum,...

illustration



Summary

- **reactor antineutrino experiment at KBR Brokdorf** with ~4kg high-purity low threshold Ge spectrometers in an elaborate shield operational since April 2018

- detailed characterization of **reactor-correlated background** at **exact location** of the CONUS experiment
  - Bonner sphere measurement
  - non-shielded Ge spectrometer
  - dedicated MC simulations

  } **Reactor-correlated background negligible inside CONUS shield,** arXiv:1903.09269 [physics.ins-det])

- remaining background contributions studied in MC

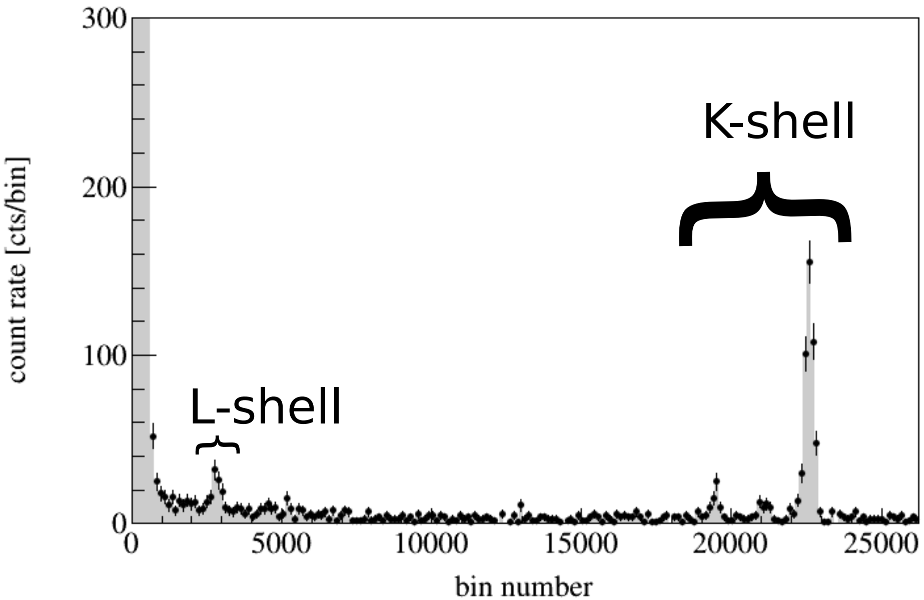
- **first full data set:** 1 month reactor OFF, 6 month reactor ON
  - rate analysis of preliminary data selection, limited by statistics
    1 sigma excess in the region of interest for CEvNS
  - Spectral shape analysis: ongoing
  - next reactor outage in June 2019 (one month)

- upgrades planned: detailed studies of systematics, shape information, more reactor OFF, PSD,…a lot more to come

Thank you for your attention!

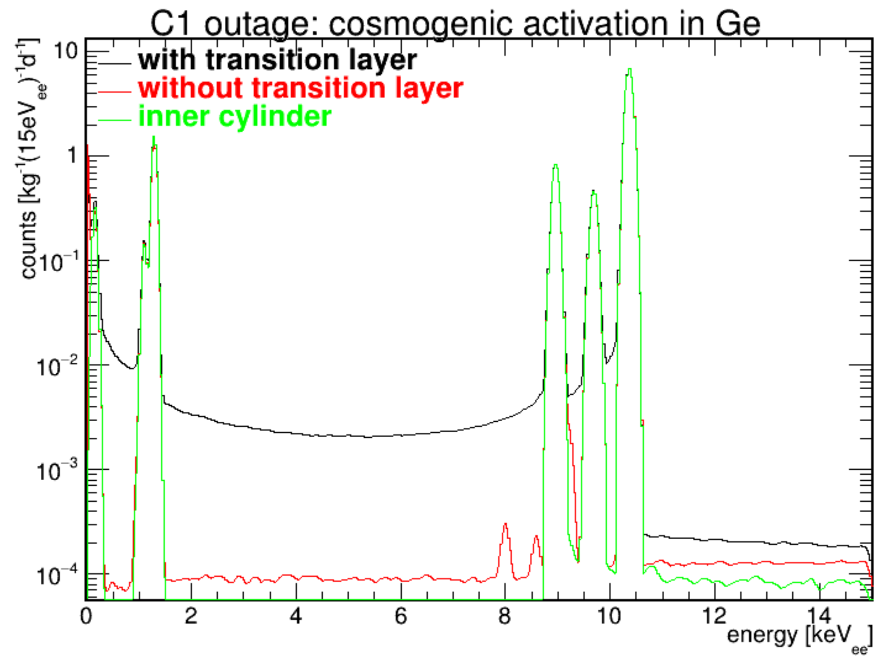
BACK UP

Cosmogenic activated lines



Useful for peak position determination:

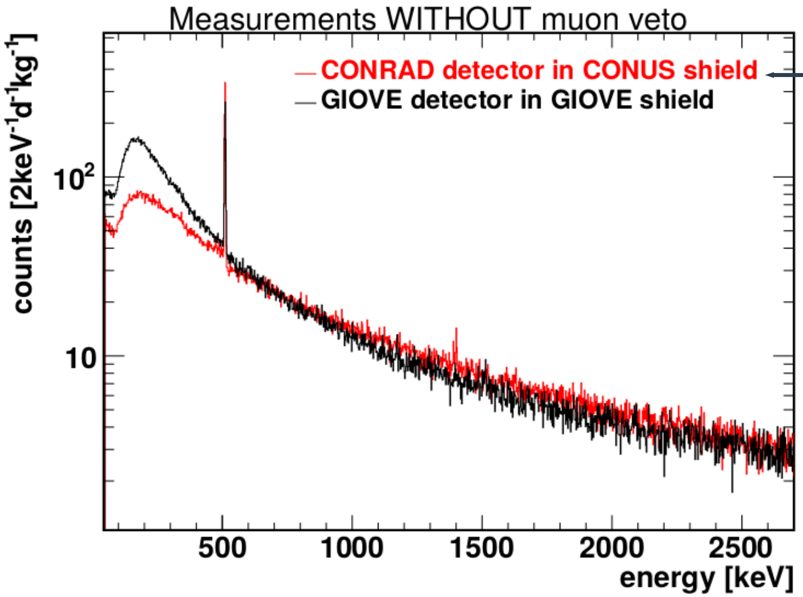
- rely on cosmogenic lines at 10.37keV and 1.3keV
- literature values (peaks and K/L ratios) well known
  → use to constrain the 1.1-1.3 keV peak structure
- linearity confirmed via pulse generator scans
- fit uncertainty (incl. full error prop.): **+- 5eV**
- time instabilities (syst.+stat.): **+-10 eV**



Main isotope	$T_{1/2}$ [d]	E_n [MeV]
Ge-71	11.4	10^{-6}-1
Ge-68	271.0	>20
Ga-68	0.046	←Ge-68
Zn-65	244.0	>60

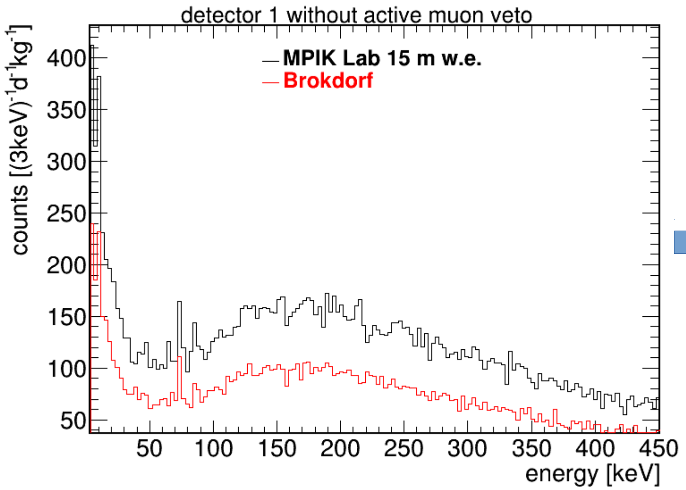
} decaying background

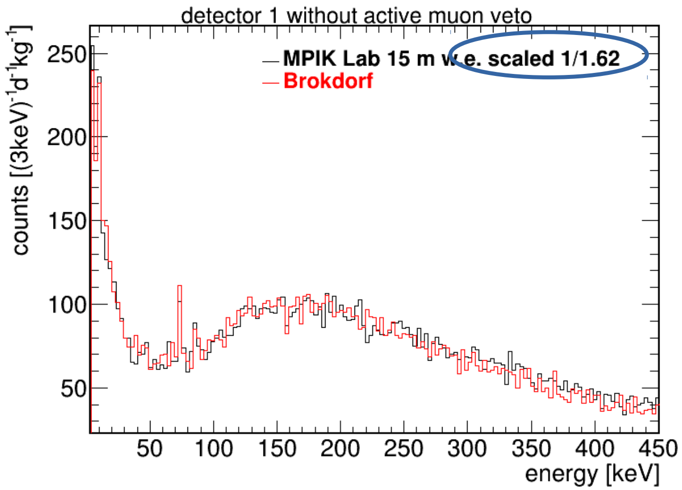
Shield design



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

Background KBR vs MPIK





Background without active muon veto:

- MPIK 15 m w.e. scaled to KBR by factor 1/1.62
  => **effective overburden KBR:** 24m w.e.
- same shape => same relevant physics processes

Radon mitigation at reactor site

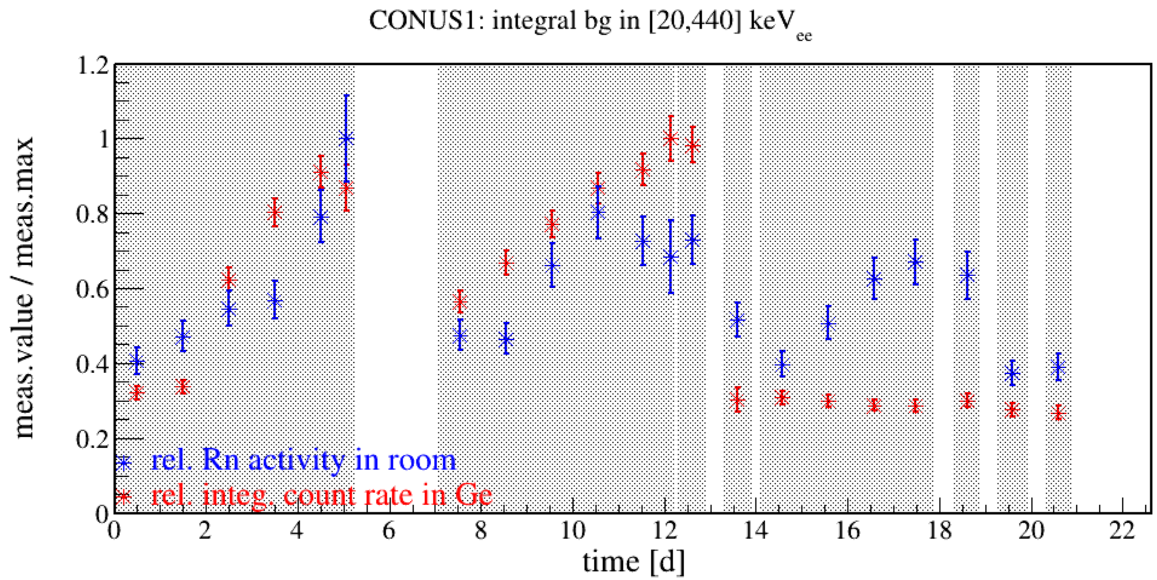
Radon in air at experimental site:

- closed environment, no fresh air, thick concrete walls:
  → Rn concentrations: ~100 Bq/m³ (max. 300 Bq/m³)

Counter measures:

Option	Consideration
hermetical sealing	not sufficient
boil-off N_2 dewar	not allowed
pressurized air	to be filtered, still Rn cont.
synthetic air bottle	import/export
breathing air bottle	refill in-house, cheap

→ for CONUS:
cartridge 4 x 6.8 l bottles (300bar)
flux: ~1 l/min



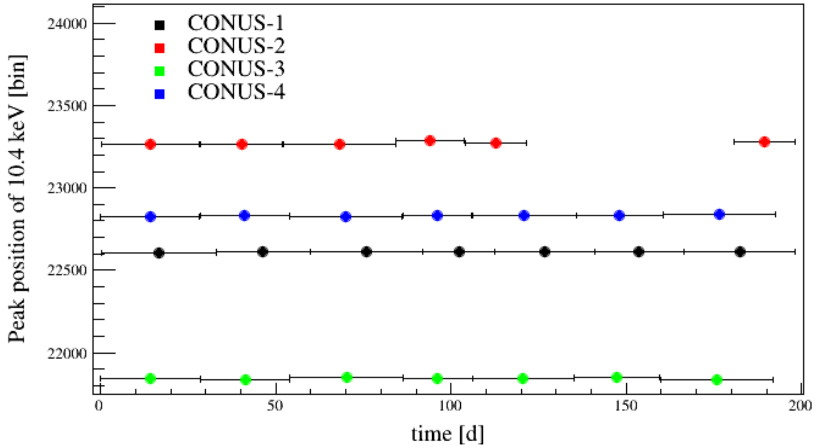
no flushing

flushing with
breathing air bottles

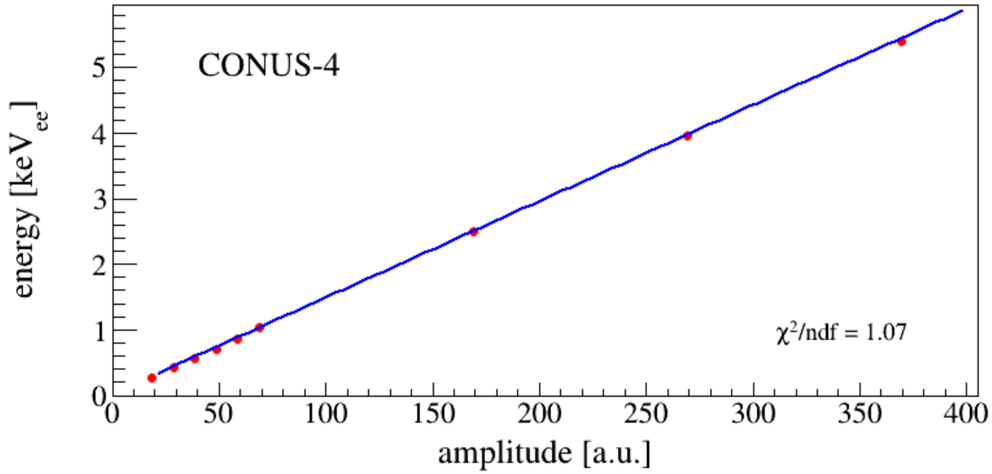
Stability and linearity

Peak position 10.4keV background line:

+-5eV => threshold very well known



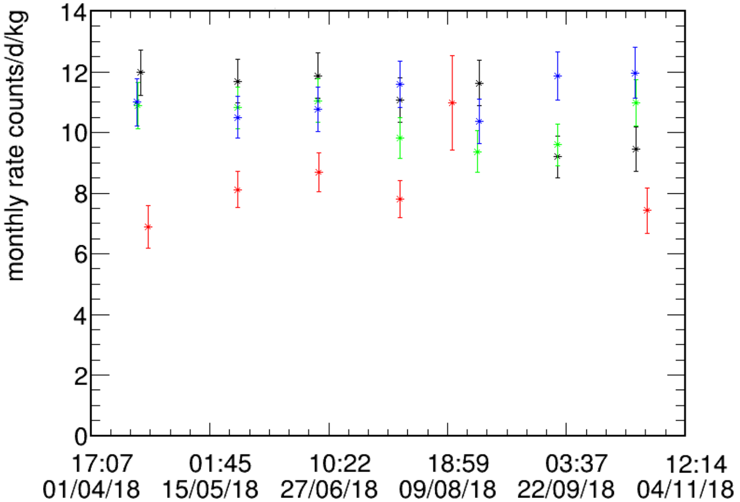
Linearity of energy scale:



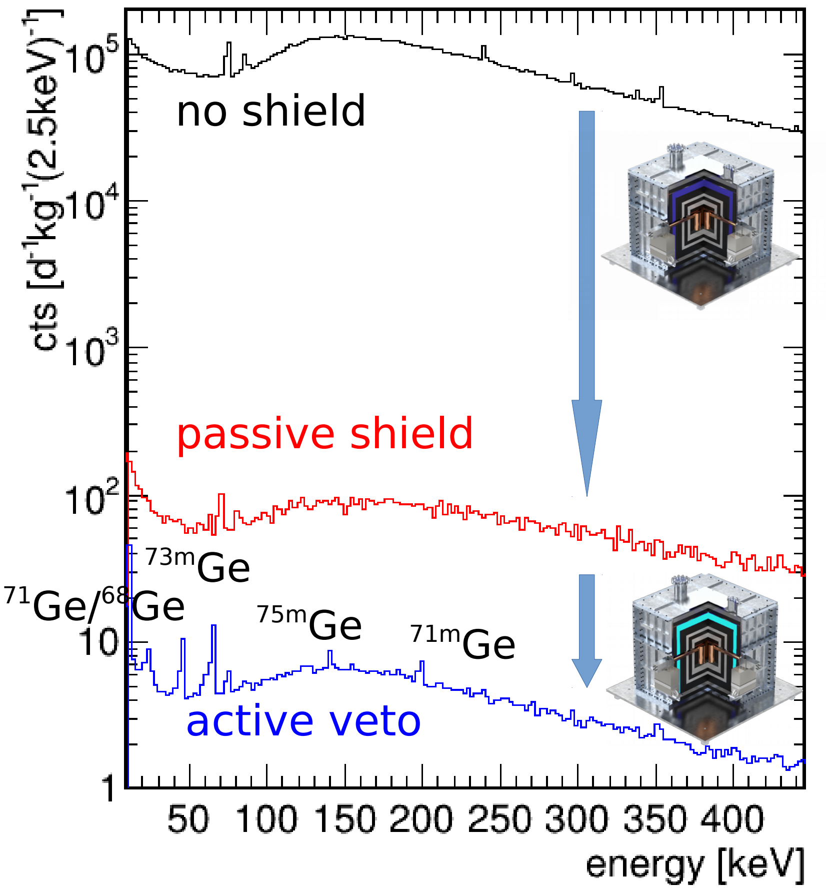
Background rate [0.5,1]keV$_{ee}$

stable:

- no data loss due to enhanced background by Randon
- minor contribution of decaying bkg



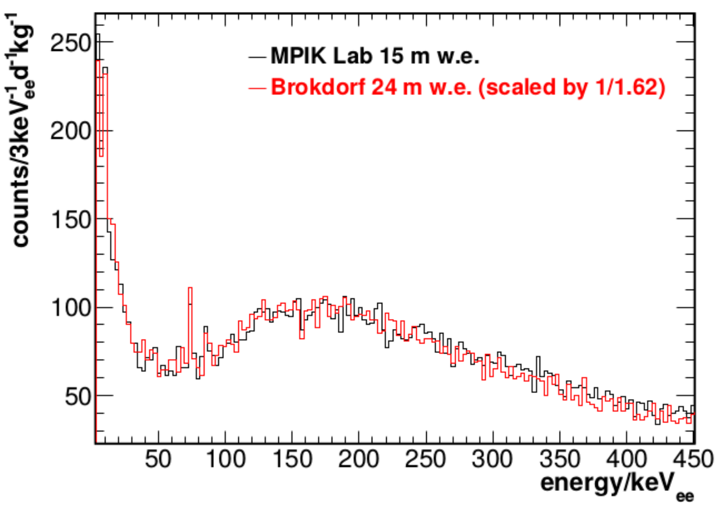
Non-reactor correlated background within CONUS shield



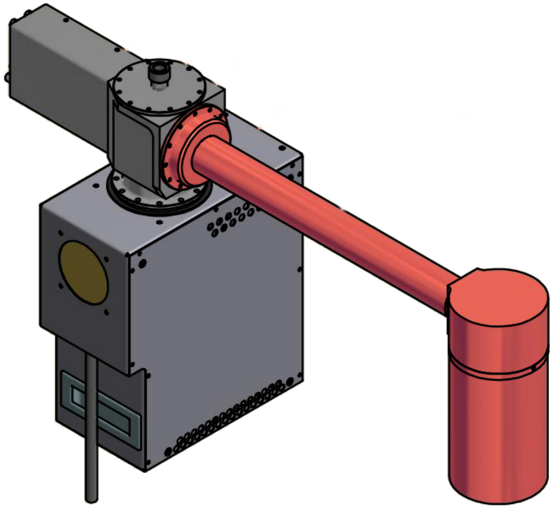
4 x bg in MPIK lab

- ^{16}N from cooling cycle
- neutron capture in conrete

muon-induced: 1/1.62 x bg in MPIK lab
→ effective depth of 24 m w.e.



CONUS low threshold HPGe Detectors



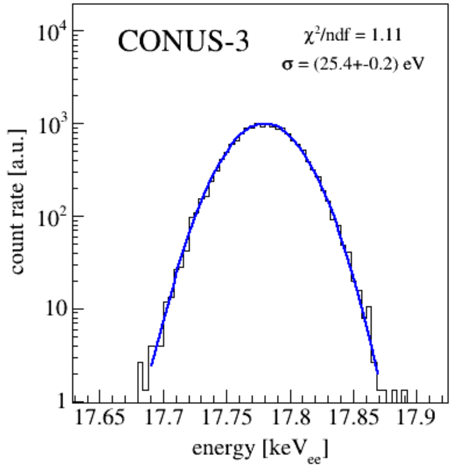
CONUS 1-4:
- p-type point contact HPGe
- crystal / active mass: **4.0 kg / 3.74 kg**
- spec for pulser res. (FWHM): ≤85 eV
  → Detector noise threshold of ≤300 eV
- electrical PT cryocoolers
- very low bg components
- design compatible with shield dim.
- prod. in close coop. with Canberra France

novel development

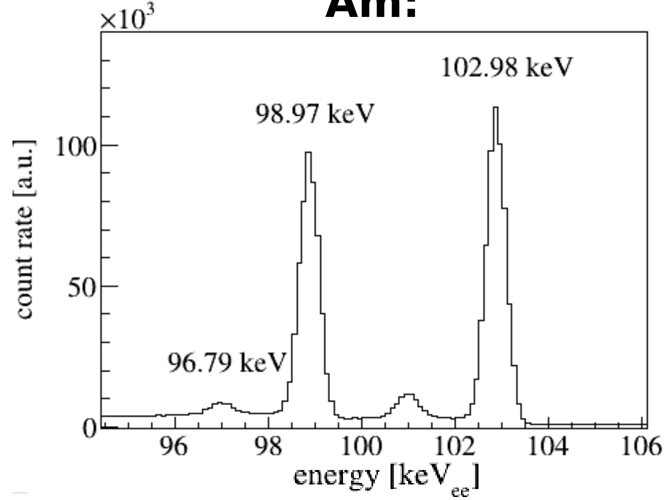
Detector	Pulser FWHM$_P$ [eV$_{ee}$]
CONUS-1	74±1
CONUS-2	75±1
CONUS-3	59±1
CONUS-4	74±1

Pulser resolution under laboratory conditions

Pulser:



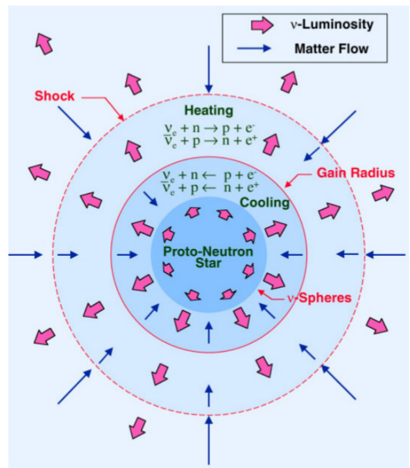
^{241}Am:



Physics motivation

SM

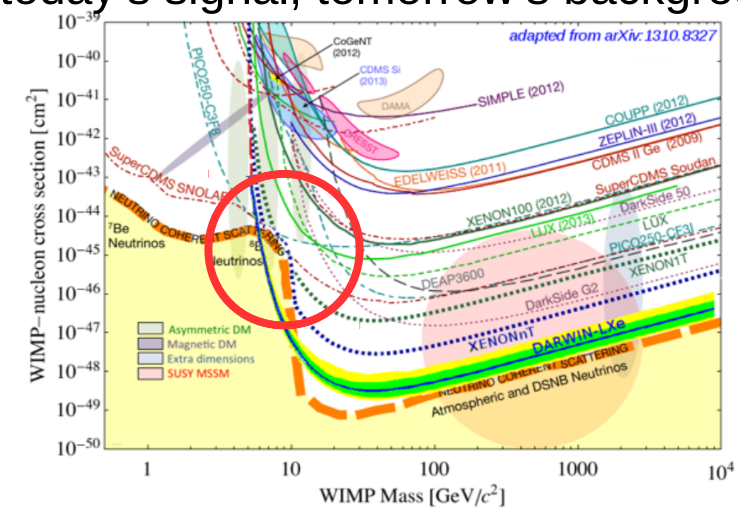
- Stellar collapse: 99% energy release in ν → CEνNS moving outwards



Credit: TeraScale Supernova Initiative

- Weinberg angle at low energies deviations → physics beyond SM

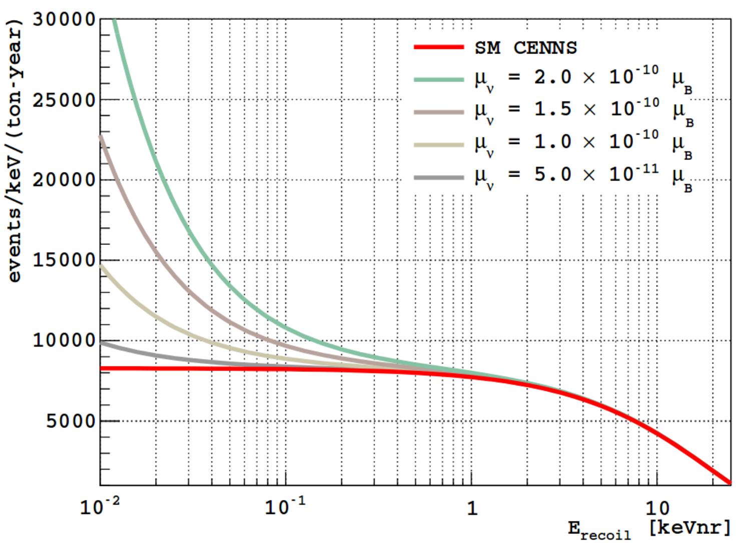
- Neutrino floor in dark matter experiments
  Signature like dark matter
  → same detector response
  „today‘s signal, tomorrow‘s background“



BSM

- Neutrino magnetic moment
  minimal extention SM: $10^{-19}\mu_B$
  current limit: $<2.8*10^{-11}\mu_B$ [Borexino PhaseII]
  Sensitivity current CONUS data: $<10^{-10}\mu_B$
- Non-standard neutrino interactions

https://agenda.infn.it/getFile.py/accesscontribId=11&sessionId=3&resId=1&materialId=slides&confId=9608



Brice et al, arXiv:1311.5958v1 [physics.ins-det] 23 Nov 2013