Towards the detection of coherent elastic neutrino nucleus scattering

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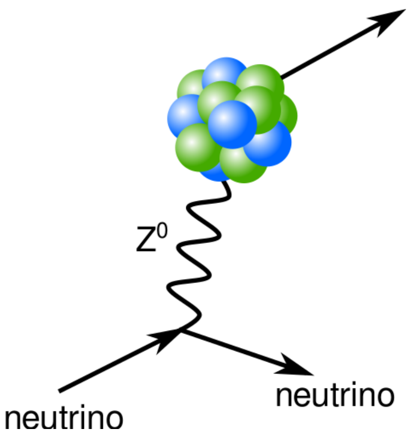
IMPRS Seminar, MPIK, 22.01.2019

Neutrino interactions in standard model



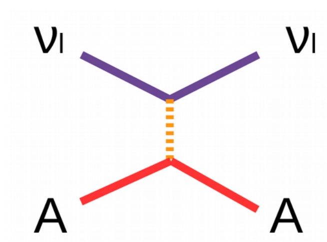
coherent elastic neutrino nucleus scattering (CEνNS)

1974 predicted (D.Z.Freedmann, Phys. Rev. 9 (1974) 5)

2017 first detection by COHERENT experiment: partially coherent 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 $\bar{\nu}_e$



Maximizes E, but coherency condition

nuclear form factor

$$\frac{d\sigma}{d\Omega}=\frac{G_f^2}{16\pi^2}\left(N-(1-4\sin^2\theta_W)Z\right)^2 E_\nu^2(1+\cos\theta)F^2(Q^2)$$

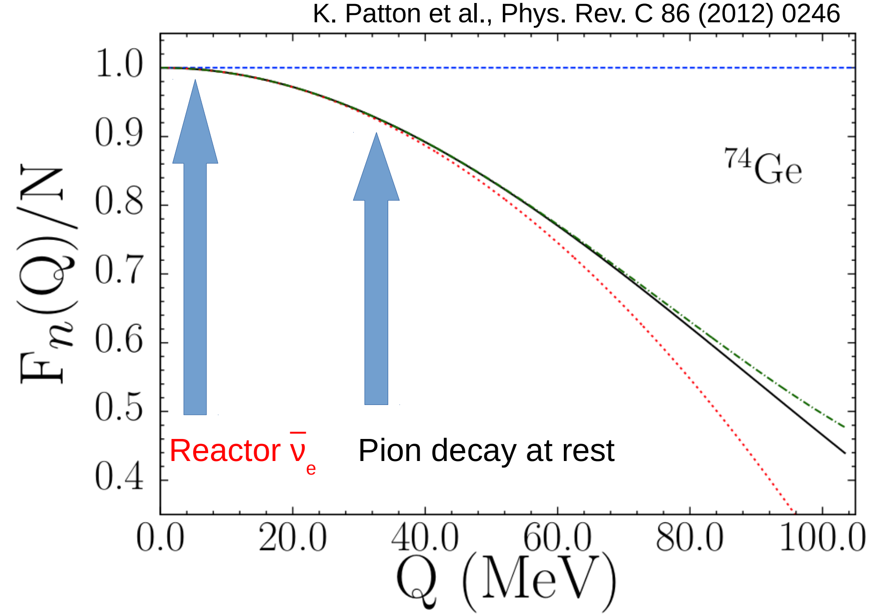
- flavor blind
- coherency condition: λ(mom. Transfer) > size of atom

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

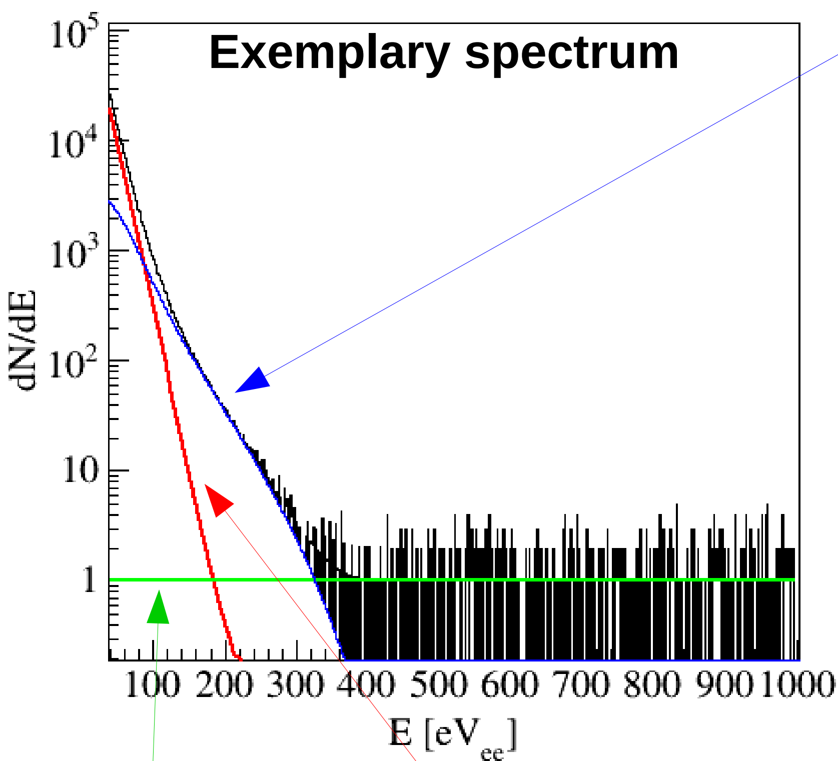
=> for Ge: E_{max} <50MeV

fully coherent <30MeV

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



Experimental challenges



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

- Detector material: mean mass number
  → Ge, Ar, Na

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

- Neutrino source:
  - Nuclear reactor → fully coherent
  - Pion decay at rest → partially coherent

noise threshold → minimize
new development for Ge!

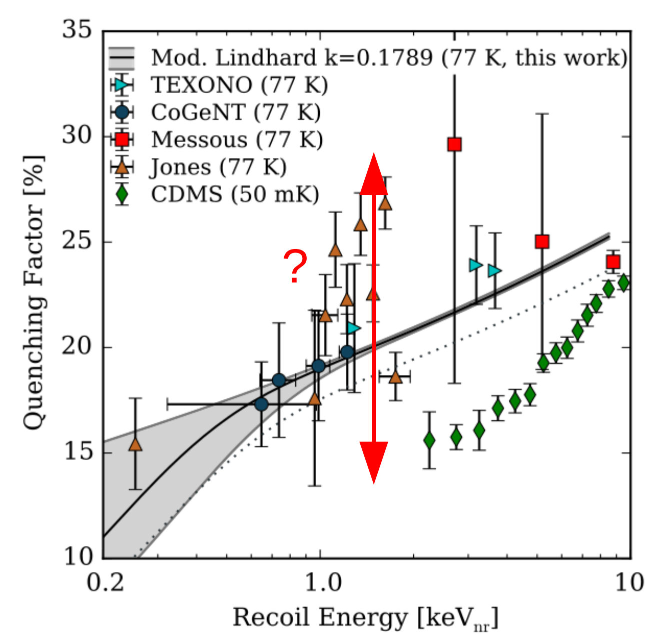
Background → minimize
- time correlation:
  - reactor on/off
  - beam on/off
- shield, „clean" materials

Quenching:

E_ν: 10MeV

max E_{Recoil}: 3keV

Max E_{ion}: ~600eV

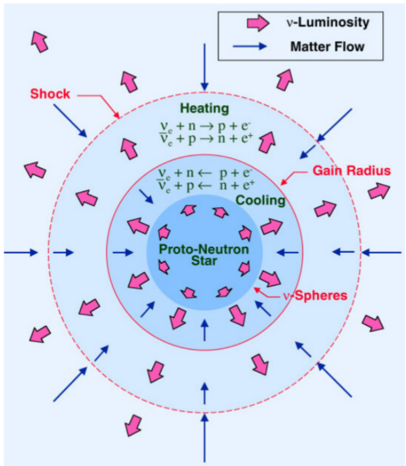


A. E. Chavarria et al, Phys. Review D 94, 082007 (2016)

Relevance of CEνNS

SM

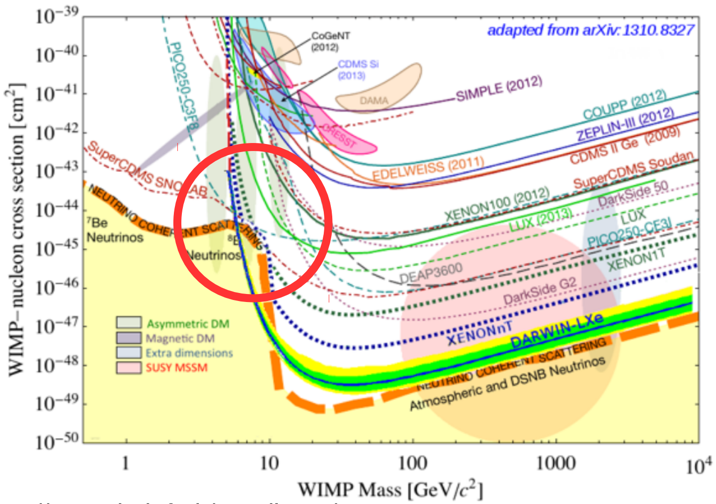
- Stellar collapse:
  99% energy
  release in ν
  → CENNS
  moving outwards



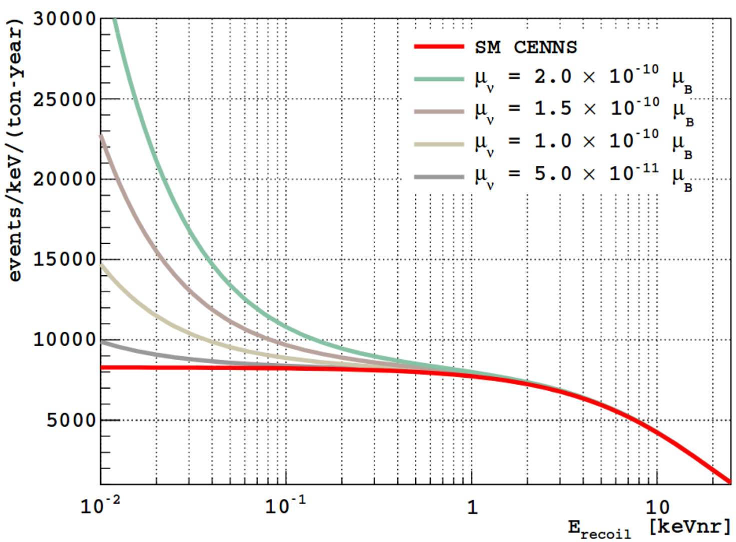
Credit: TeraScale Supernova Initiative

- 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“



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



BSM

- Neutrino magnetic moment
  minimal extention SM: $10^{-19}\mu_B$
  models exist with $\leq 10^{-14}\mu_B$
  current limit: $<2.8 \cdot 10^{-11}\mu_B$ [Borexino PhaseII]
  → precision experiment required

For muon neutrino flux ($2.5 \cdot 10^7$ ν/cm²/s from pion decay at rest)
Brice et al, arXiv:1311.5958v1 [physics.ins-det] 23 Nov 2013

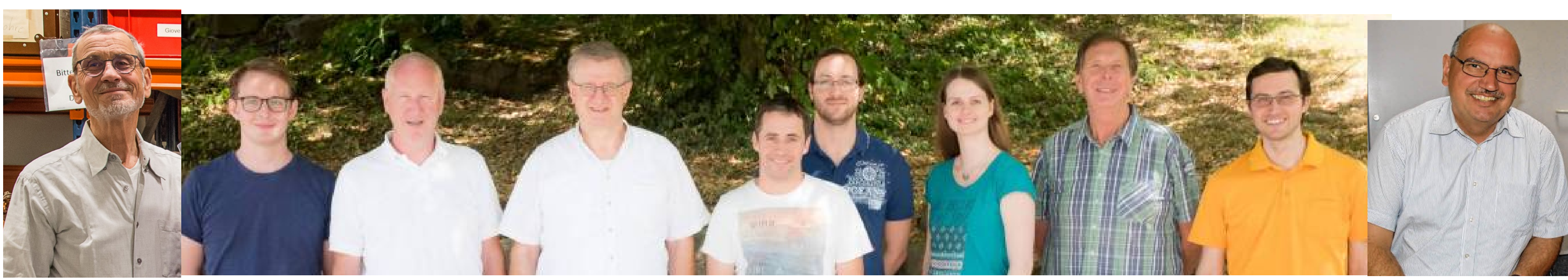
- Non-standard interactions
  If ε~0.01 sensitive to TeV scales! → competitive to much larger neutrino experiments

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:

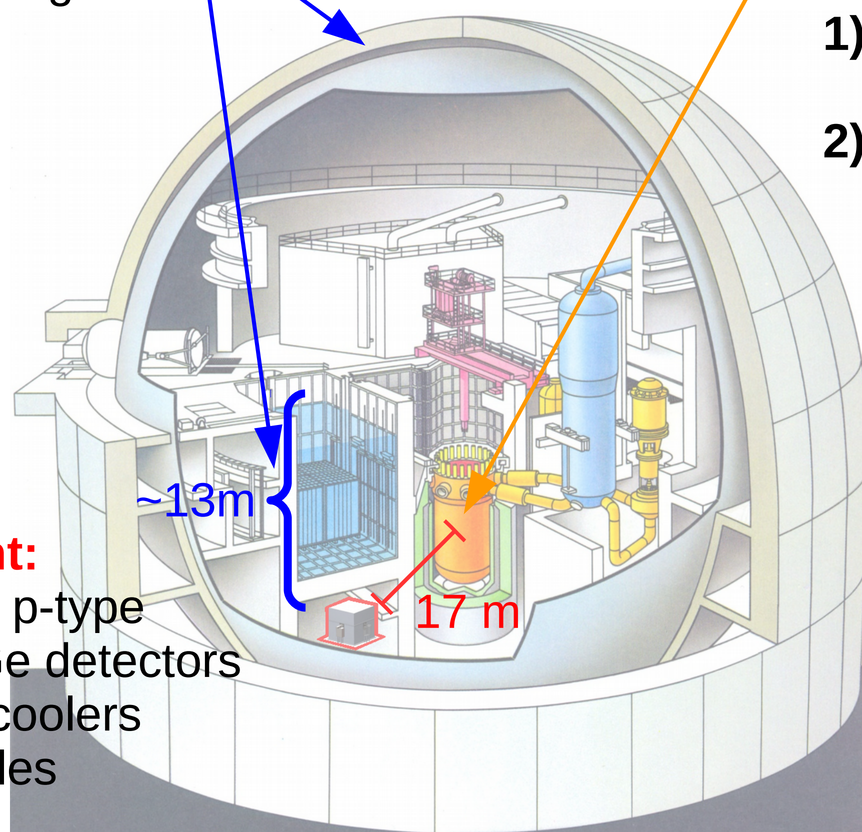
M. Reginatto, M. Zboril, A. Zimbal
- *Physikalisch-Technische Bundesanstalt (PTB), Braunschweig*

Reactor site

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

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

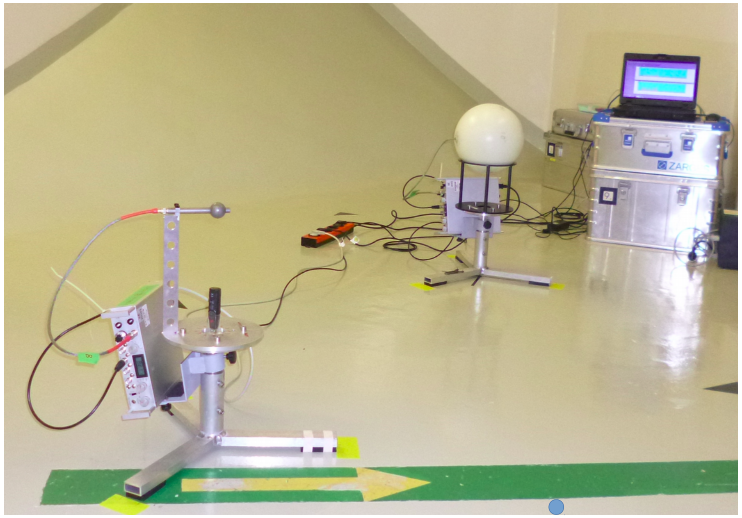
Reactor core:
thermal power 3.9 GW
high duty cycle (1 month/yr off)
1) **Signal:** Anti neutrinos @17m
~10^{13}/(cm² s)
2) **Potential background:** Neutrons



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

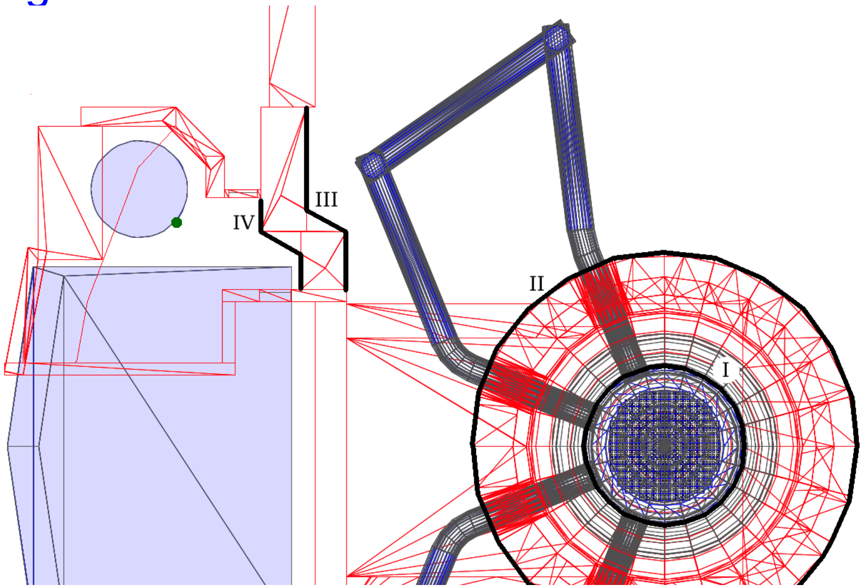
Neutrons at reactor site



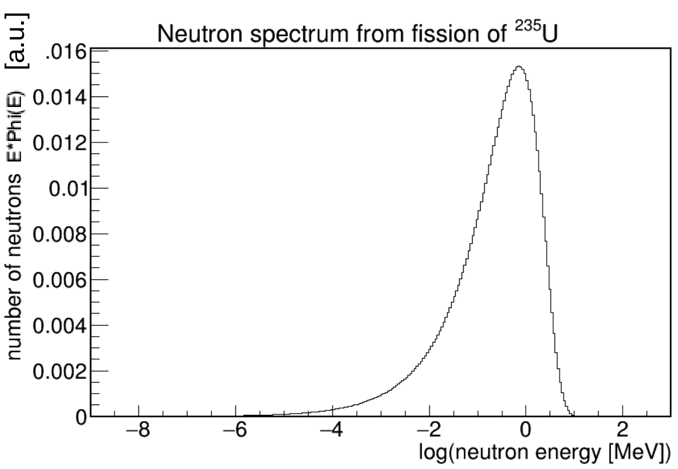
NEMUS by PTB: spectral resolution possible!

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

Propagation of reactor neutrons to A408 in Geant4



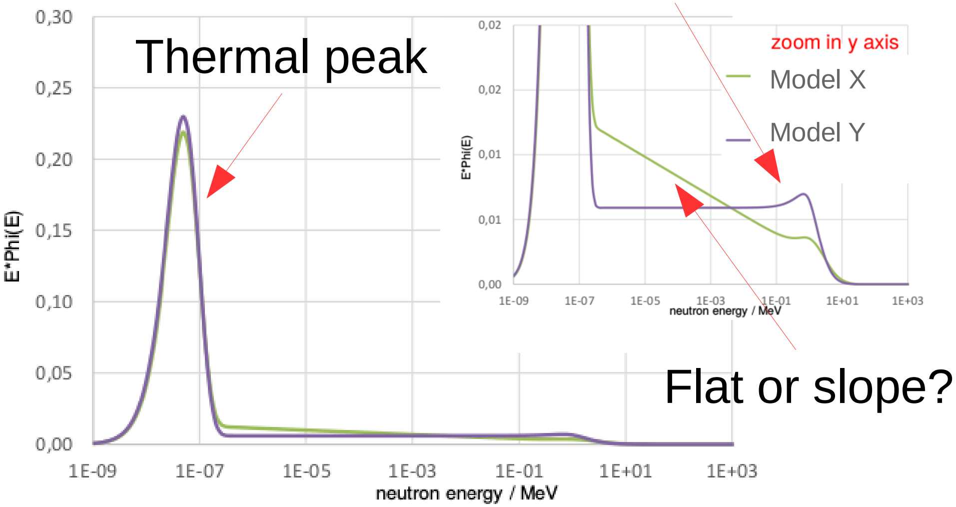
at reactor core



propagation

water
steel
concrete
...

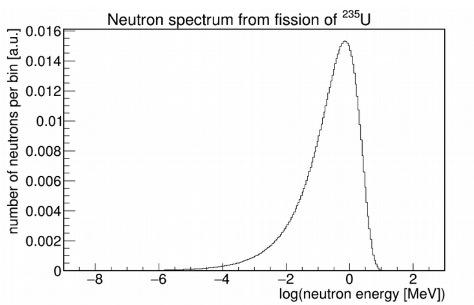
Remaining fast neutrons?



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

Neutrons at reactor site

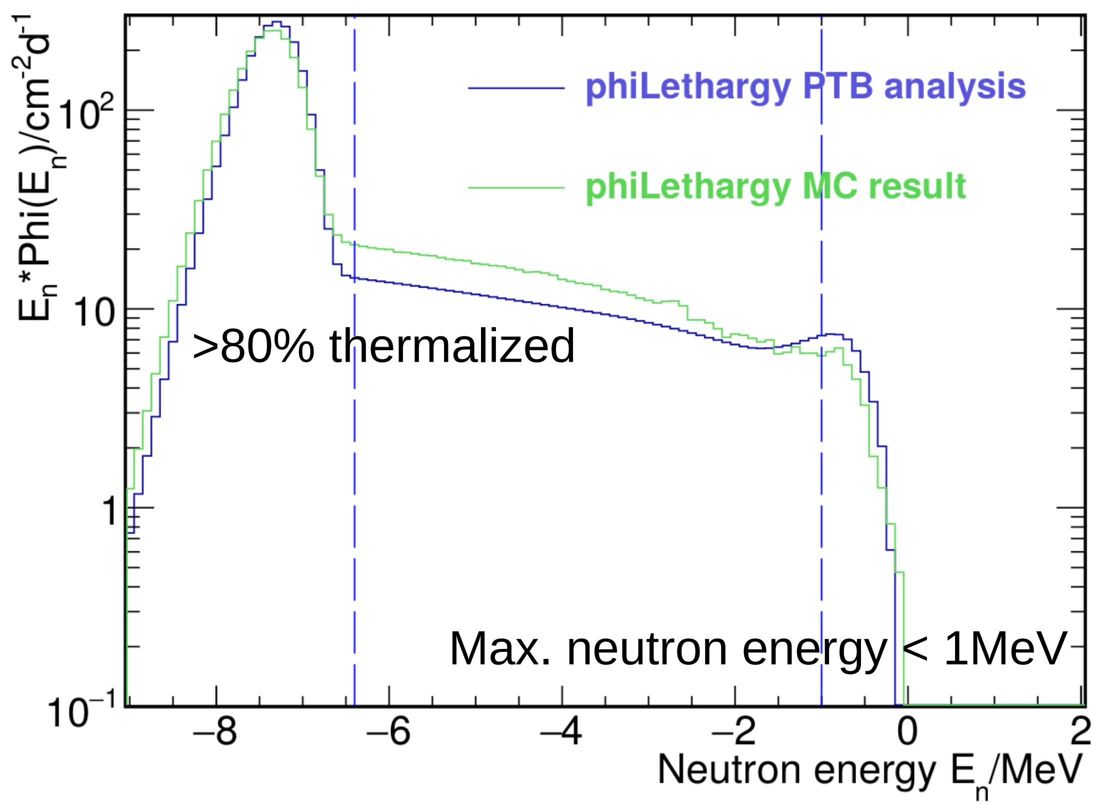
at reactor core



propagation

water
steel
concrete
...

ON – OFF = reactor correlated



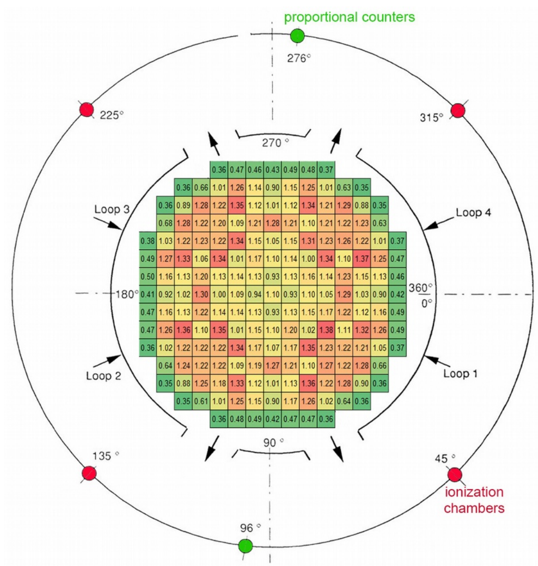
Main results:

1. Neutron fluence 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 of ~20%
   => in depth understanding of neutron background **on site**
4. MC result in front of room similar, same maximum energy

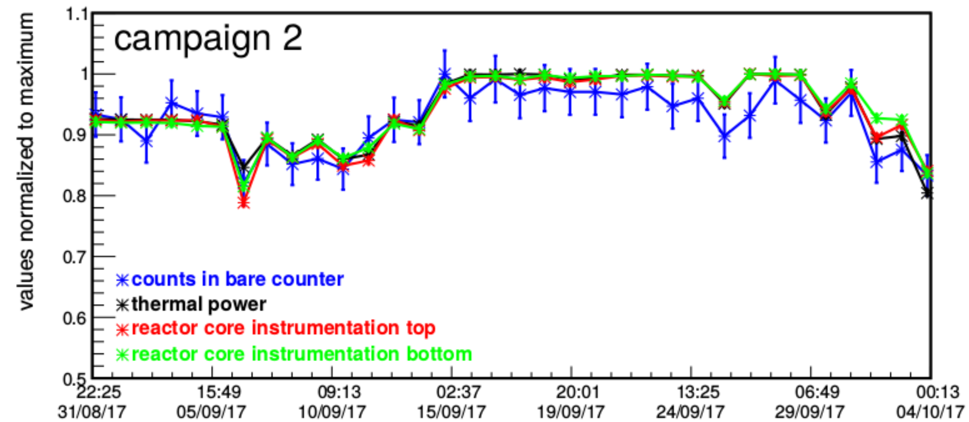
Reactor power vs neutron fluence

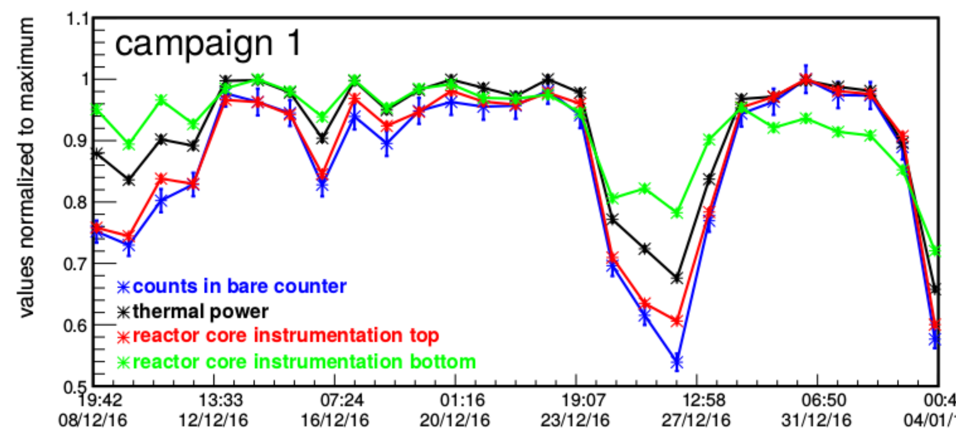
Data available on reactor

- Thermal power from heat in secondary circuit
- Reactor incore and excore instrumentation

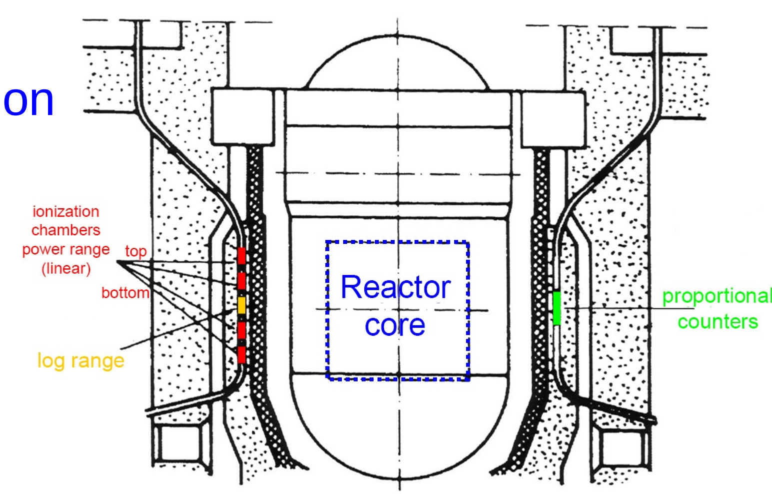


Incore instrumentation





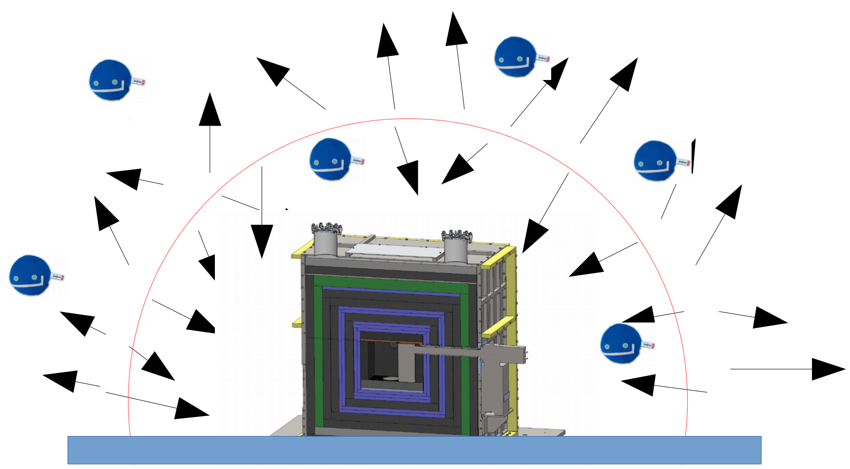
Excore instrumentation



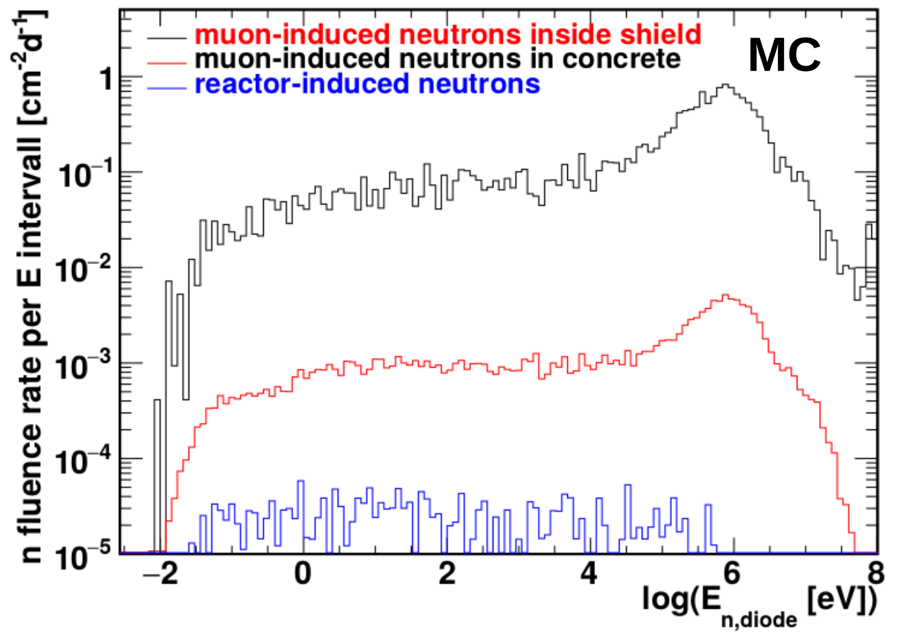
Correlation: between neutron flux at CONUS site and thermal power – in particular for instrumentation at top

Reactor neutrons

Neutrons outside CONUS shield in A408



Neutrons at CONUS diodes



MC result:

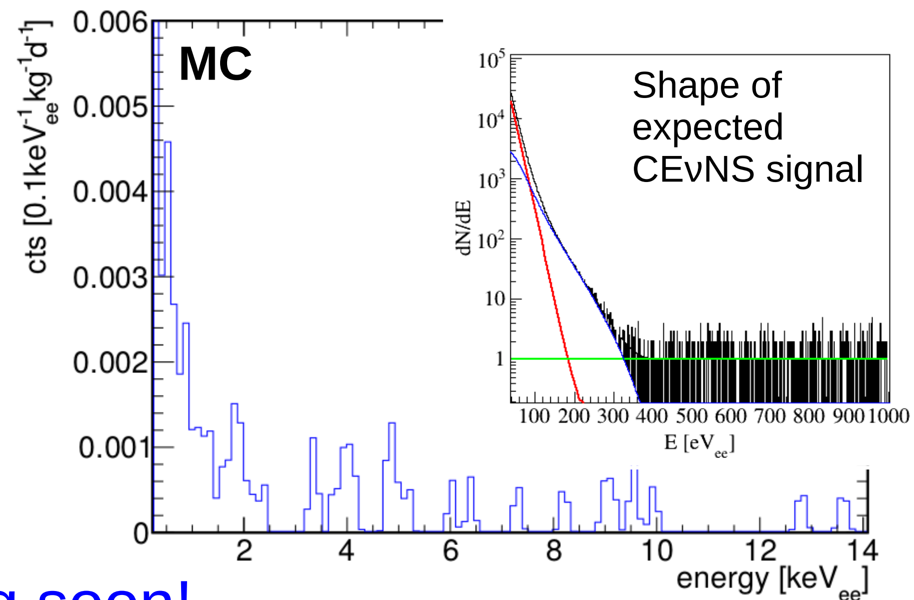
Muon-induced neutrons shield: O(10 $cm^{-2}d^{-1}$)

Muon-induced neutrons concrete: O(0.1 $cm^{-2}d^{-1}$)

Reactor-correlated neutrons: O(0.001 $cm^{-2}d^{-1}$)

Reactor neutron-correlated count rate in region of interest: 0.01 cts/kg/d

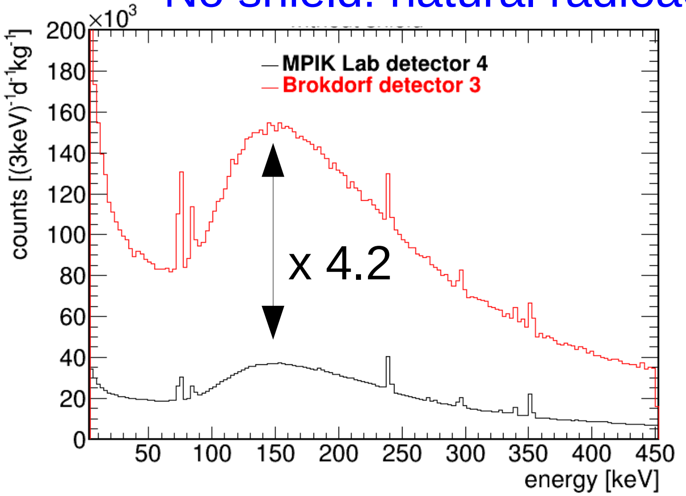
→ background inside CONUS shield is negligible!



Publication coming soon!

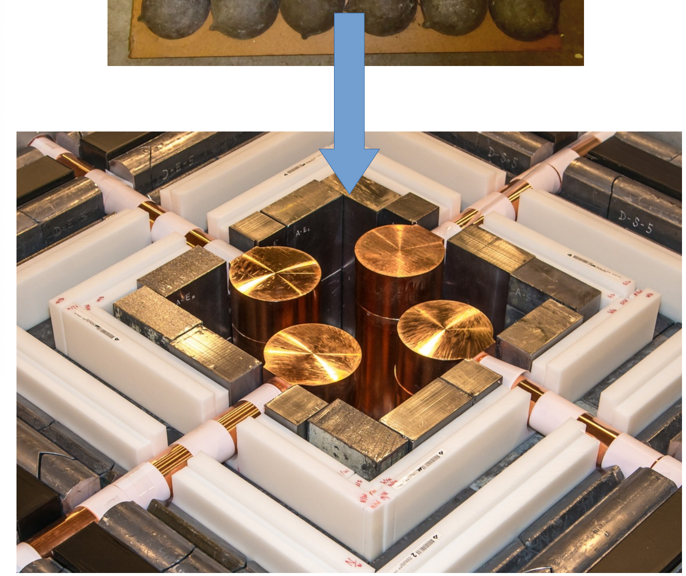
Background reduction

No shield: natural radioactivity

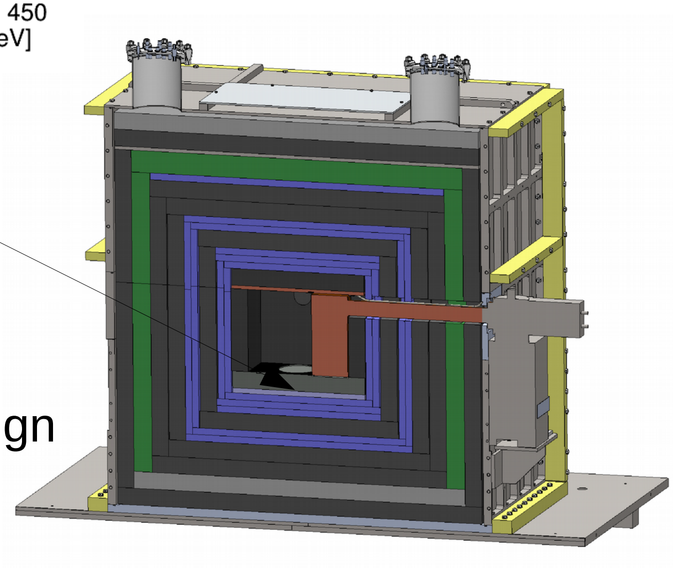


MPIK lab: low radioactive concrete
NPP Brokdorf: additonal background contributions

Freiburg cathedral lead



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

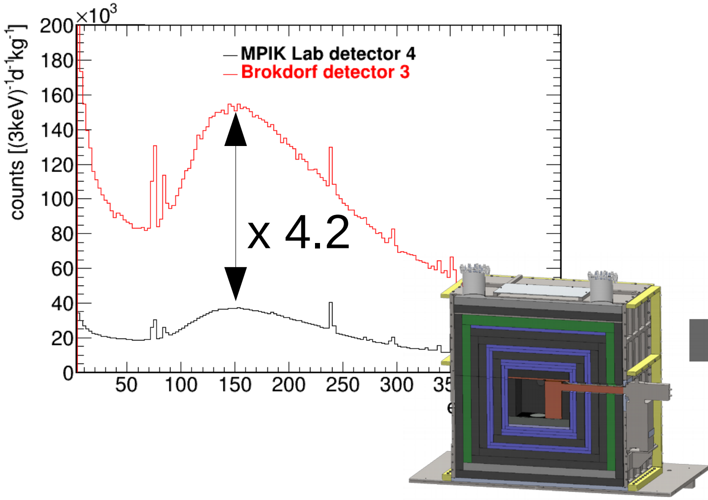


25 cm Pb

Inspired by GIOVE design
(R&D in Heidelberg: 2017-2013)

Background reduction

No shield: natural radioactivity



MPIK lab: low radioactive concrete
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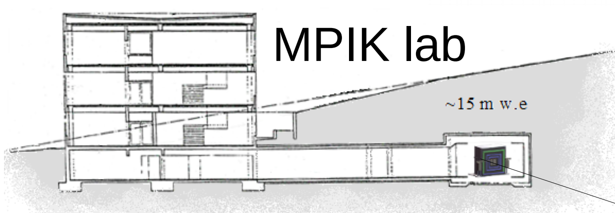
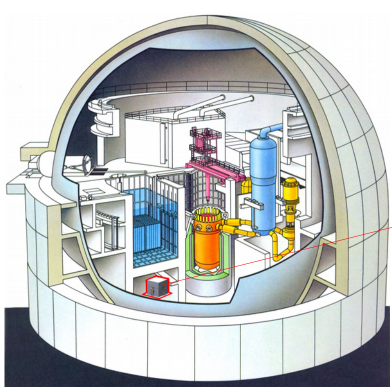
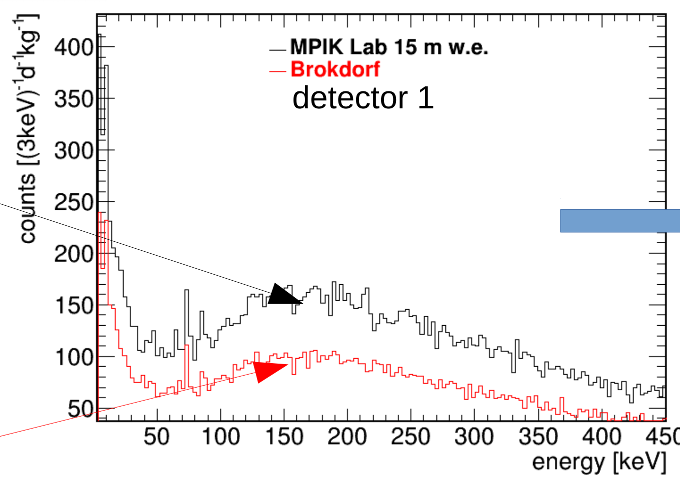
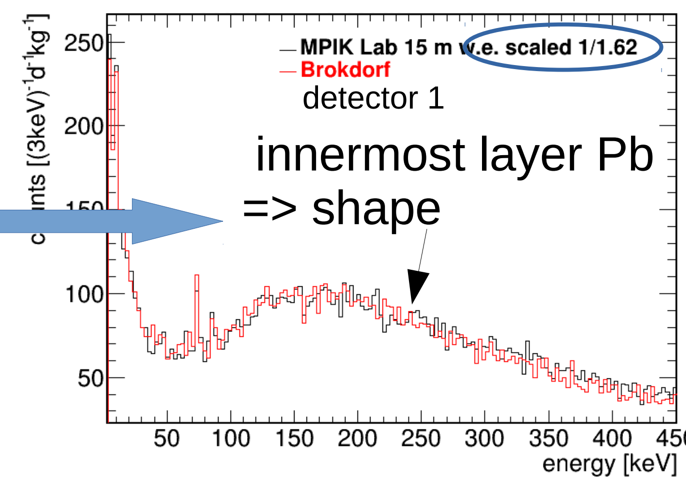
25 cm Pb





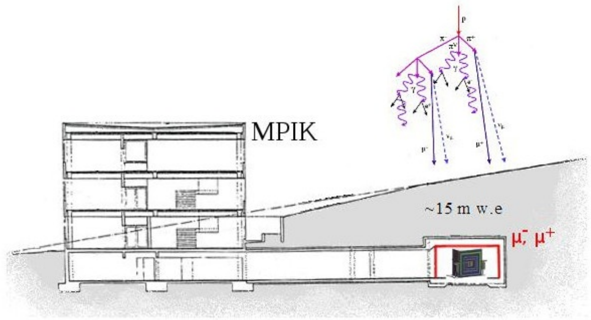
Passive shield: muon-induced continuum





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.**

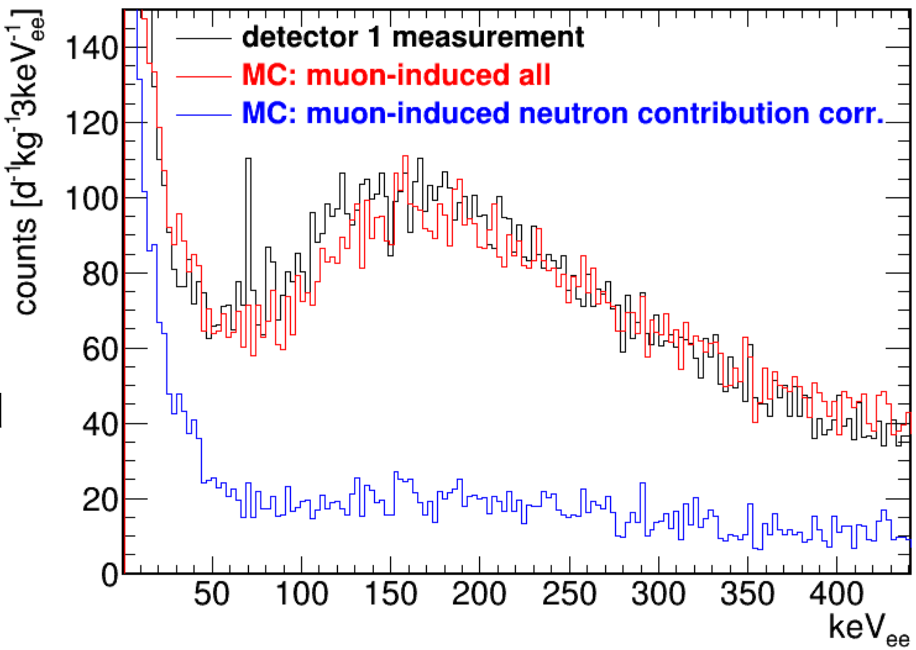
MC Simulation of muon-induced bkg



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%) → correct for missing neutrons

Validation of neutron correction factor:
(2013-ongoing)

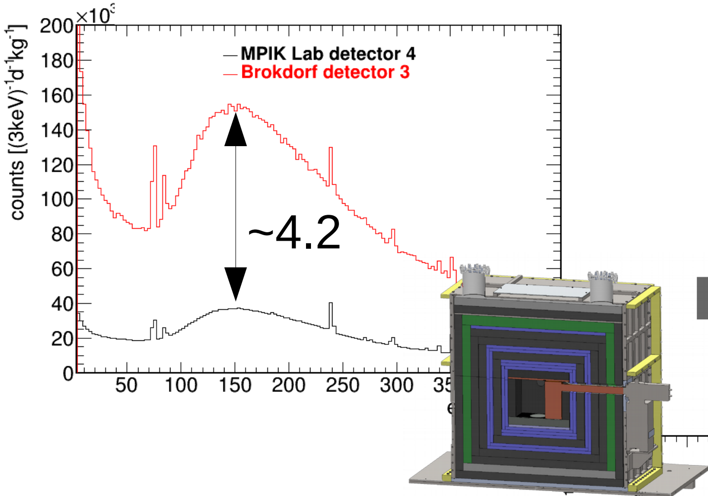
- similar shield with coax HPGe
  (Taup proceeding 2015)
- consistency of all 4 detectors
- count rate of neutron-induced Ge lines
- Bonner Sphere measurement inside shield



ongoing

Background reduction

No shield: natural radioactivity

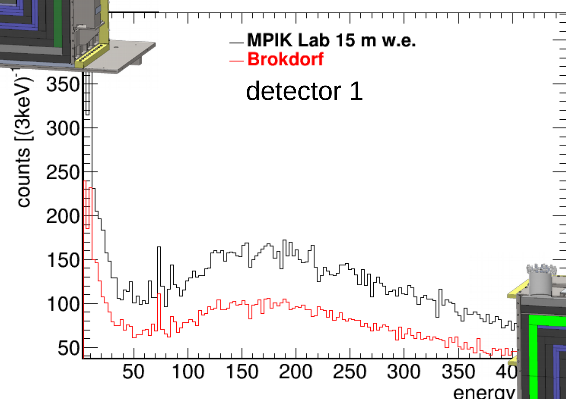


MPIK lab: low radioactive concrete
NPP Brokdorf: additional background contributions

25 cm Pb

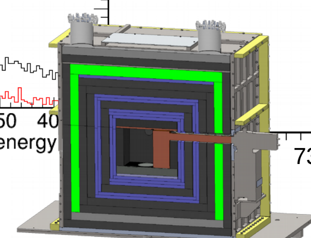
Passive shield: muon-induced continuum

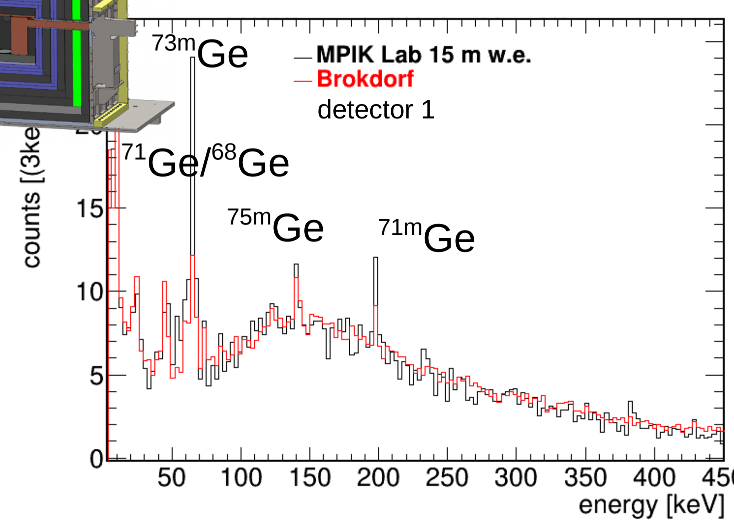
MPIK lab: 15 m w.e.
NPP Brokdorf: 24 m w.e.



Muonveto
B-doped PE

active shield





Reduction by factor 10
-Neutron-induced Ge isotopes:
NPP Brokdorf=MPIK lab/1.62
-Continuum: identical
Remaining: metastable Ge isotopes
muon-induced continuum
^{210}Pb

} Bkg model

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

CONUS: first data set

1. Collect data
- reactor off: background
- reactor on: signal + background

↓

2. Check stability
- energy scale
- background
- energy threshold
- noise, time distribution
- correlations to environment

↓

3. Apply quality cuts

↓

DATA SET

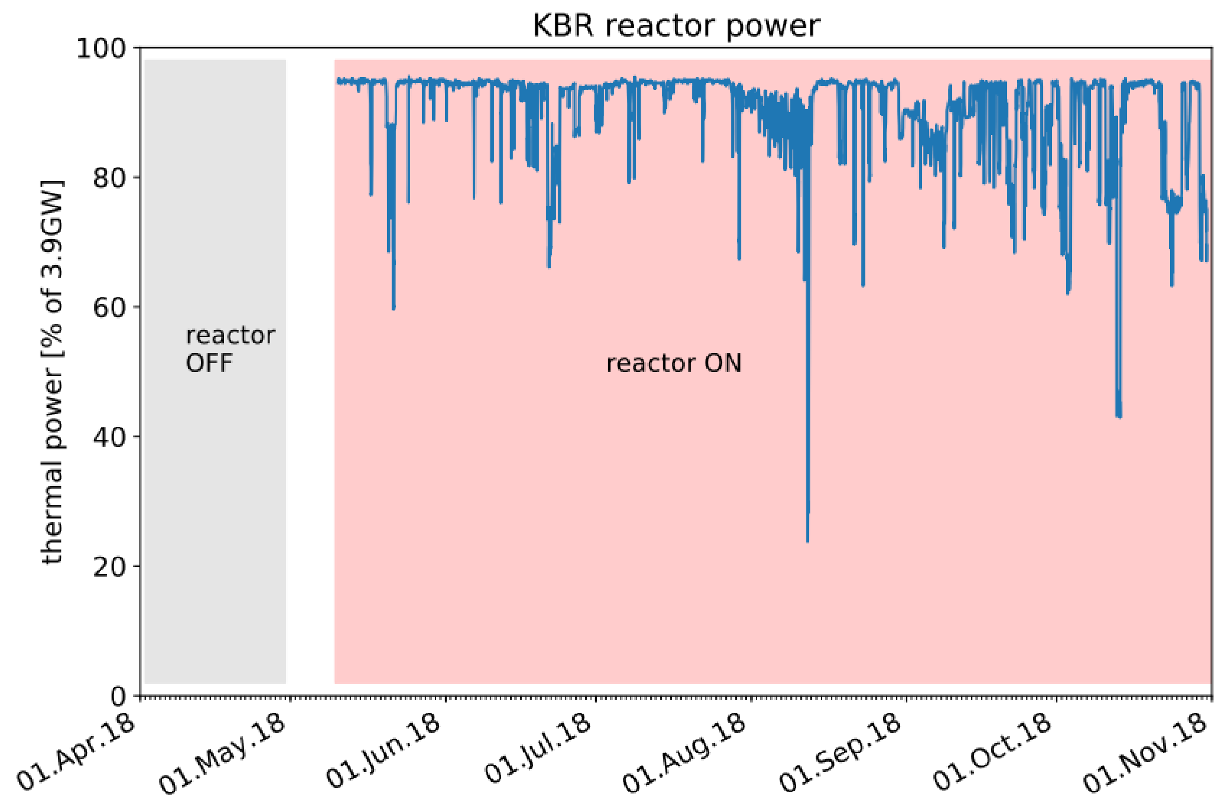
CONUS: first data set

1. Collect data
- reactor off: background
- reactor on: signal + background

2. Check stability
- energy scale
- background
- energy threshold
- noise, time distribution
- correlations to environment

3. Apply quality cuts

DATA SET



1 month reactor off, 6 month reactor on

CONUS: first data set

1. Collect data
- reactor off: background
- reactor on: signal + background

↓

2. Check stability
- energy scale
- background
- energy threshold
- noise, time distribution
- correlations to environment

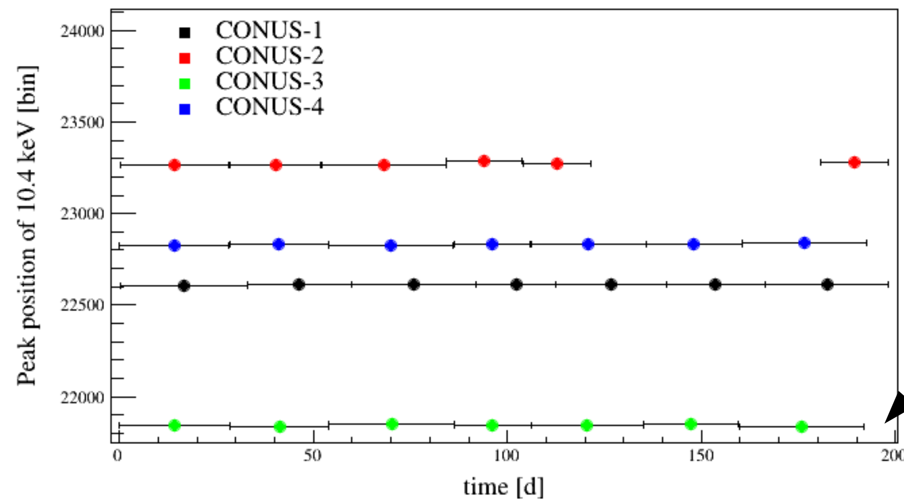
↓

3. Apply quality cuts

↓

DATA SET

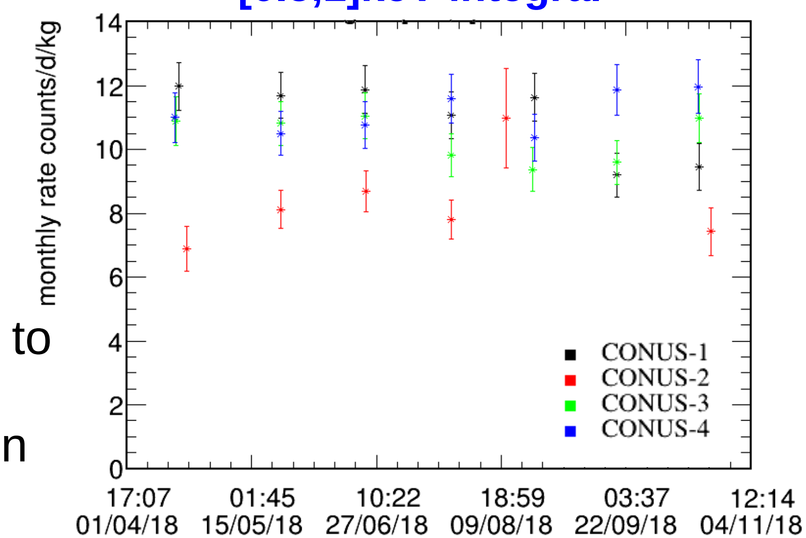
Peak position 10.4keV line in background:



7 month!

+-5eV => threshold very well known

[0.5,1]keV integral



stable:
- no data loss due to Rn background
- minor contribution of decaying bkg

CONUS: first data set

DATA SET

Final calibration
Determine energy thershold

Detector	Reactor OFF [d]	Reactor ON [d]
CONUS1	24.9	156.9
CONUS2	16.7	102.1
CONUS3	23.0	158.2
CONUS4	24.4	158.1
total	**89**	**575**

Rate analysis
excess in region of interest?

Systematics
compare to expected shape
- reactor: thermal power,...
- detectors: efficiency
- background: decay
- DAQ: dead time losses
- quenching

Shape analysis
compare to expected shape
Background model

CONUS: first data set

DATA SET

Final calibration
Determine energy thershold

Detector	Reactor OFF [d]	Reactor ON [d]
CONUS1	24.9	156.9
CONUS2	16.7	102.1
CONUS3	23.0	158.2
CONUS4	24.4	158.1
total	**89**	**575**

Rate analysis

Latest data release: **December 2018**
3 detectors (without CONUS-2 due to instabilities)

	Counts
Reactor OFF (72 d kg)	238+-18
Reactor ON (474 d kg)	1739+-47
ON-OFF	126+-128
Significance	**1 sigma**

reduced reactor off time → benificial for shape analysis
=> stay tuned!

Summary & Outlook

- **Characterization of Room A408** at nuclear power plant
  - Detailed understanding of **neutron background**:
    - Neutron spectrum from Bonner Sphere measurement
    - MC of neutrons from reactor
    - Contribution inside CONUS shield **negligible**

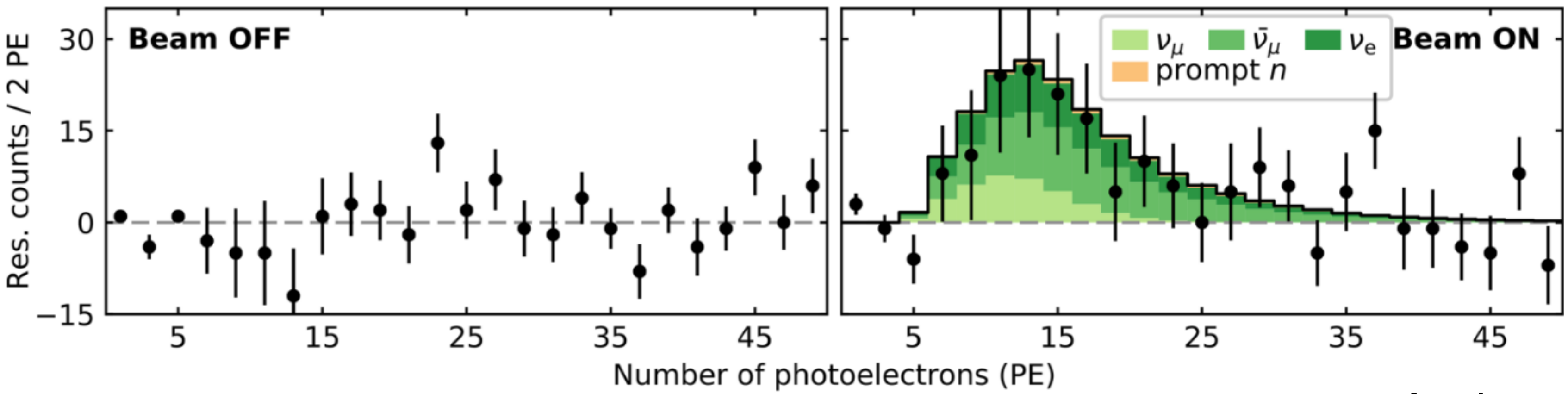
    } Characterization at exact location of experiment!
  - Detailed understanding of **gamma background** from outside shield
    - Succesfull suppression inside shield
- Stable detector operation since O(6months)

- **Rate only analysis december 2018**: 1sigma → shape analysis in progress
- Detailed study of systematics
  - Quenching
  - Detector efficiencies
  - Calibration
  - Reactor physics
- Ongoing data collection at 90% duty cycle
- Several **publications** in preparation (→ stay tuned!)
- Background modelling in progress

Thank you for your attention!

BACK UP

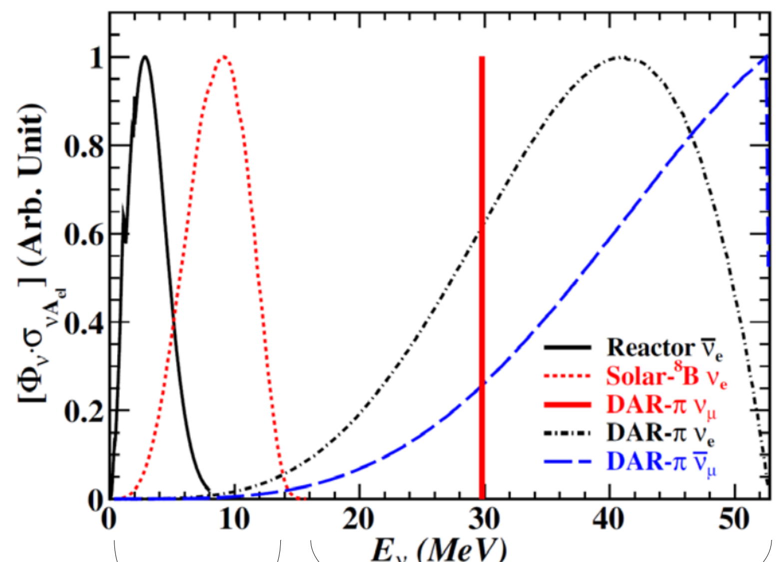
First detection: COHERENT



D. Akimov et al., Science 10.1126/science.aao0990, 2017

- 4 different targets (N^2 dependence):
  CsI scin. crystals (14.6 kg) + NaI (185 kg), single phase LAr (35 kg), HPGe (10 kg)
- neutrino source:
  Spallation Neutron Source (SNS) (USA)
  - multiple flavors of neutrinos ($\bar{\nu}_\mu$, ν_μ , ν_e)
  - neutrino energies within partially coherent regime
  - flux: $4.3 \cdot 10^7\ s^{-1}\ cm^{-2}$ in 20 m distance
  - pulsed-beam ⇒ strong time correlation of signal
- First result (August 2017) (D. Akimov et al.)[2]
  15 month of live-time accumulated with CsI[Na]
  6.7 σ significance for excess in events,
  1 σ consistency with SM prediction (black line)

Loss of coherency

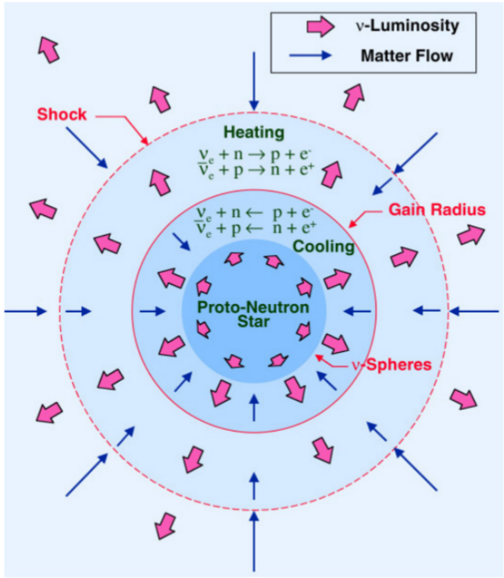


Reactor $\bar{\nu}_e$: fully coherent

Pion decay at rest

Relevance of CEνNS

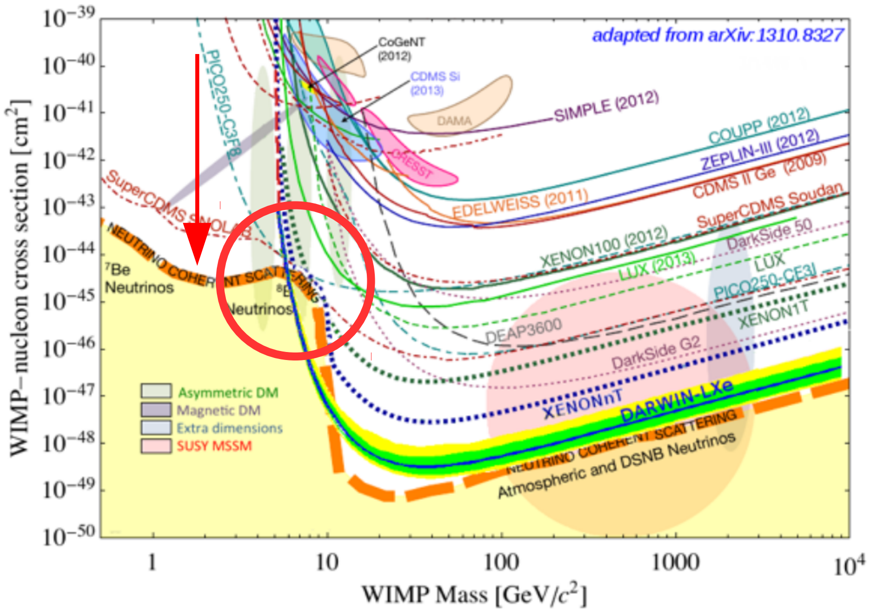
Stellar collapse:
99% energy release in ν
→ CENNS moving outwards



Credit: TeraScale Supernova Initiative

Neutrino floor in dark matter experiments

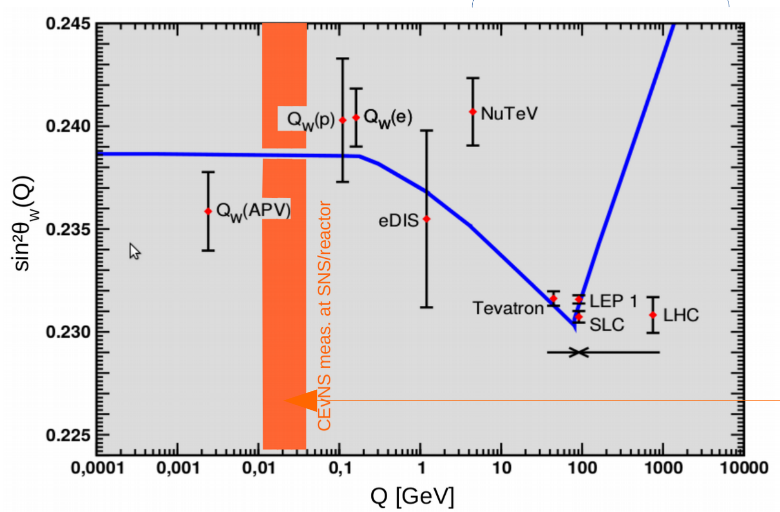
- Signature like dark matter
  → same detector response
- „today's signal, tomorrow's background"



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

collider experiments

J.Erler, A.Freitas, PDG, ch.10, 2016



$$\frac{d\sigma}{d\Omega}=\frac{G_f^2}{16\pi^2}(N-(1-4\sin^2\theta_W)Z)^2E_\nu^2(1+\cos\theta)F^2(Q^2)$$

Weinberg angle at low energies
Deviations → physics beyond standard model

Challenging reactor environment: 17m away from reactor core

- work under ‘unusual’ conditions: up to 35°C, transport by handcraft
- preservation of cleanliness (tested at MPIK-lab)

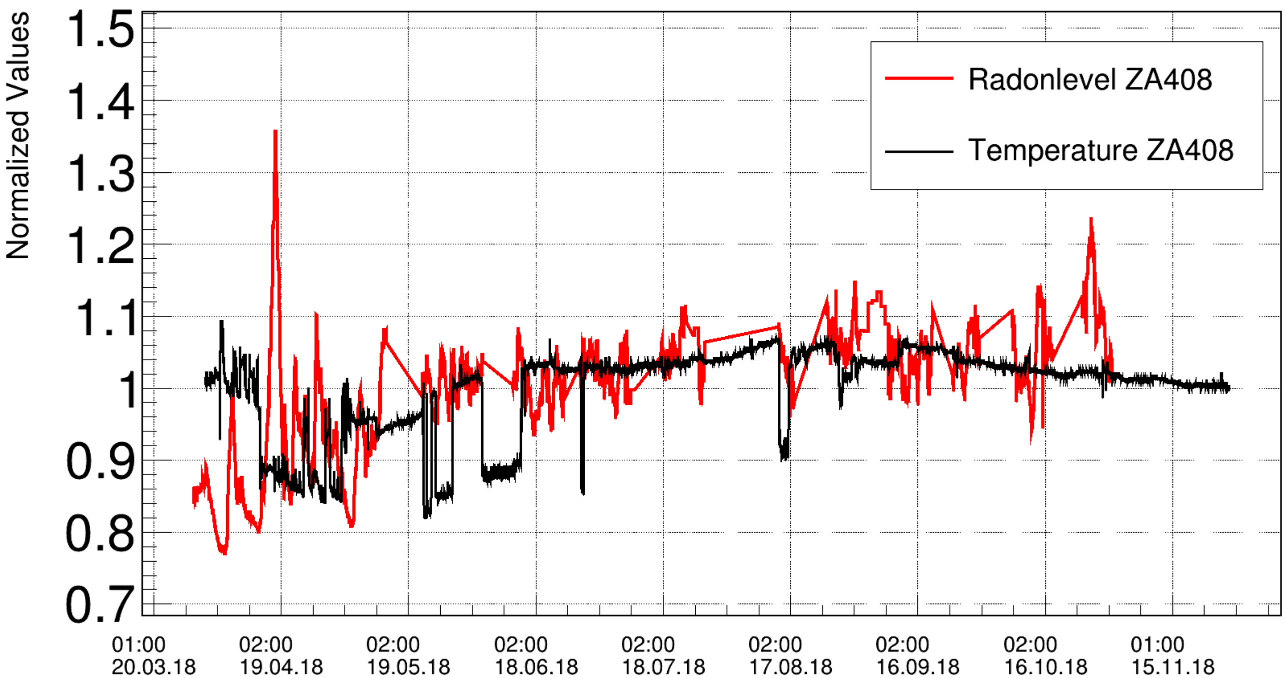
→ **Challenging** during assembly ✓ ; Challenging for detector cooling → close monitoring

- no intranet (due to safety regulations): → no remote control

→ **Challenging** during operation → data export only via shifter ✓

- radon in air (no easy ventilation possible), no liquid nitrogen allowed

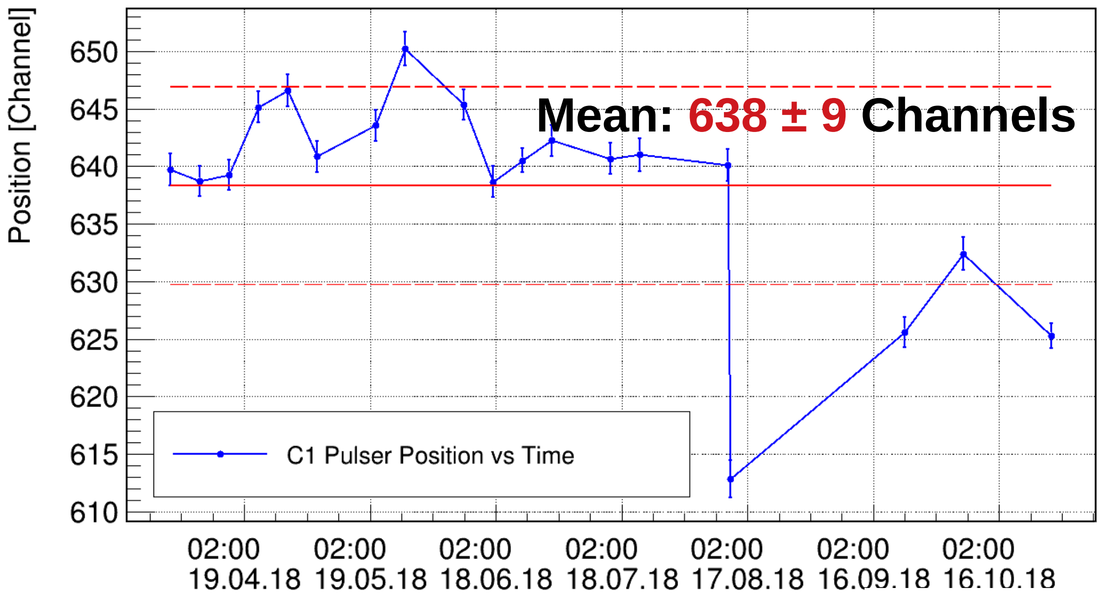
→ **Challenging** for background reduction → flush with breathing ari bottles ✓



Close monitoring of enviromental conditions
- temperature: logged every 15 min
- radon: logged every 30 min

Stability: Energy scale

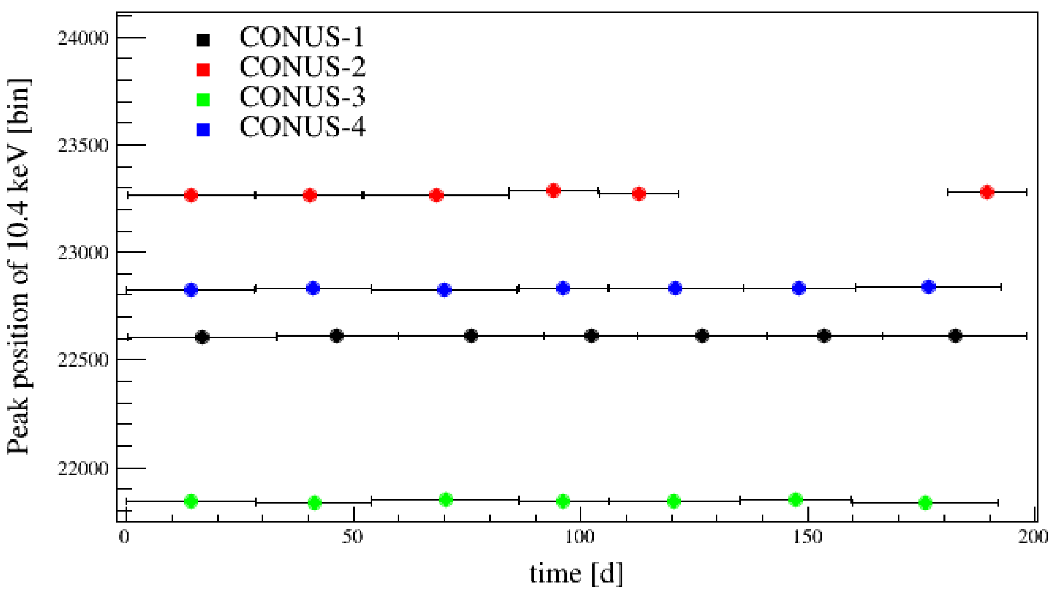
Pulser Position for C1:



Pulser position: **stable!**

→ variation of ~2eV

Peak position 10.4keV line in background:



Peak position in physics data: **stable!**

Standard deviation:

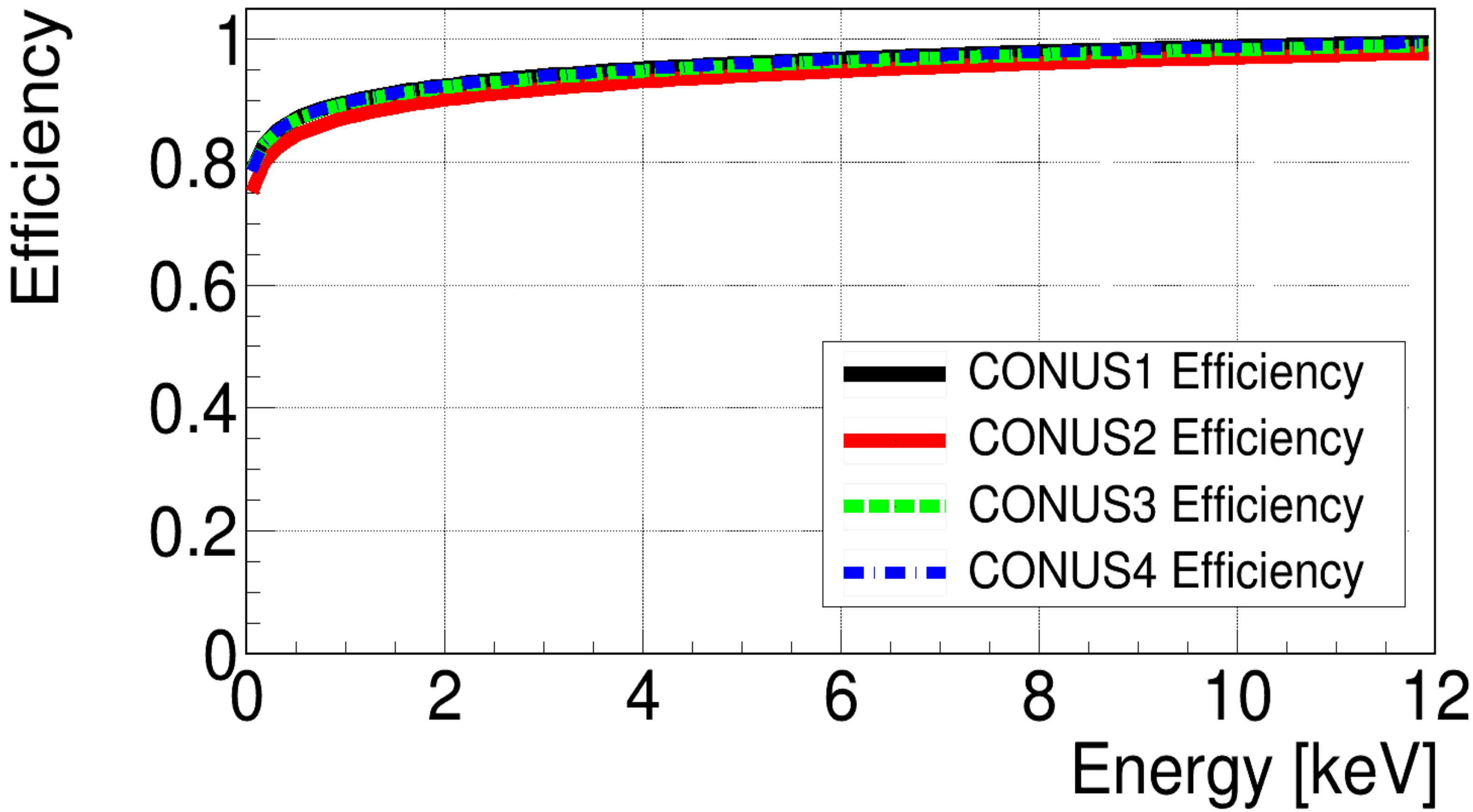
C1: +-1.4eV

C2: +-2.8eV

C3: +-2.2eV

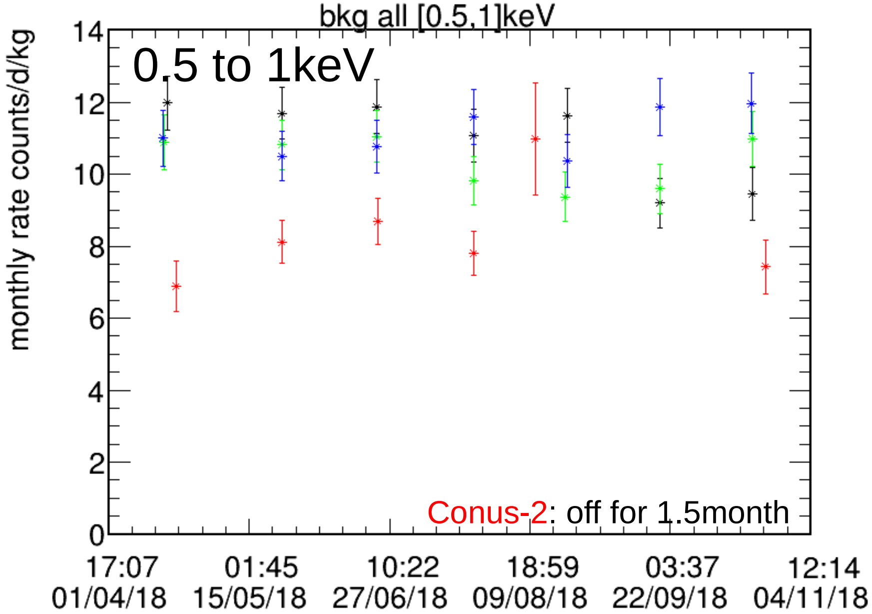
C4: +-1.3eV

Detector efficiencies at low energies

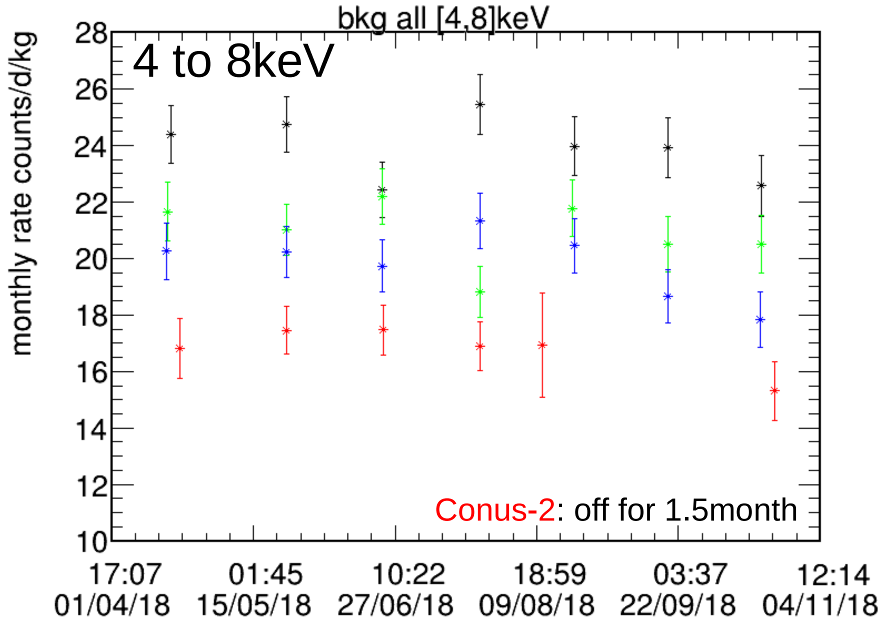


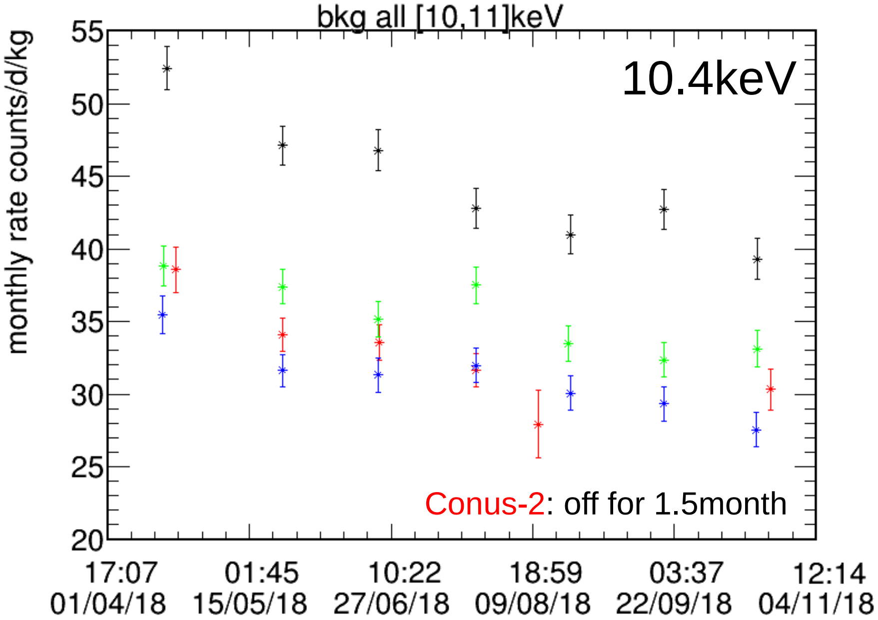
pulser measuremnts: combining multiple weeks
function: y = p0 + p1 * log(x)

Stability: Background



- no background contribution from radon
- minor contribution of decay of cosmogenic induced Ge isotopes
  → MC: smaller 5% effect





Conus-1
Conus-2
Conus-3
Conus-4