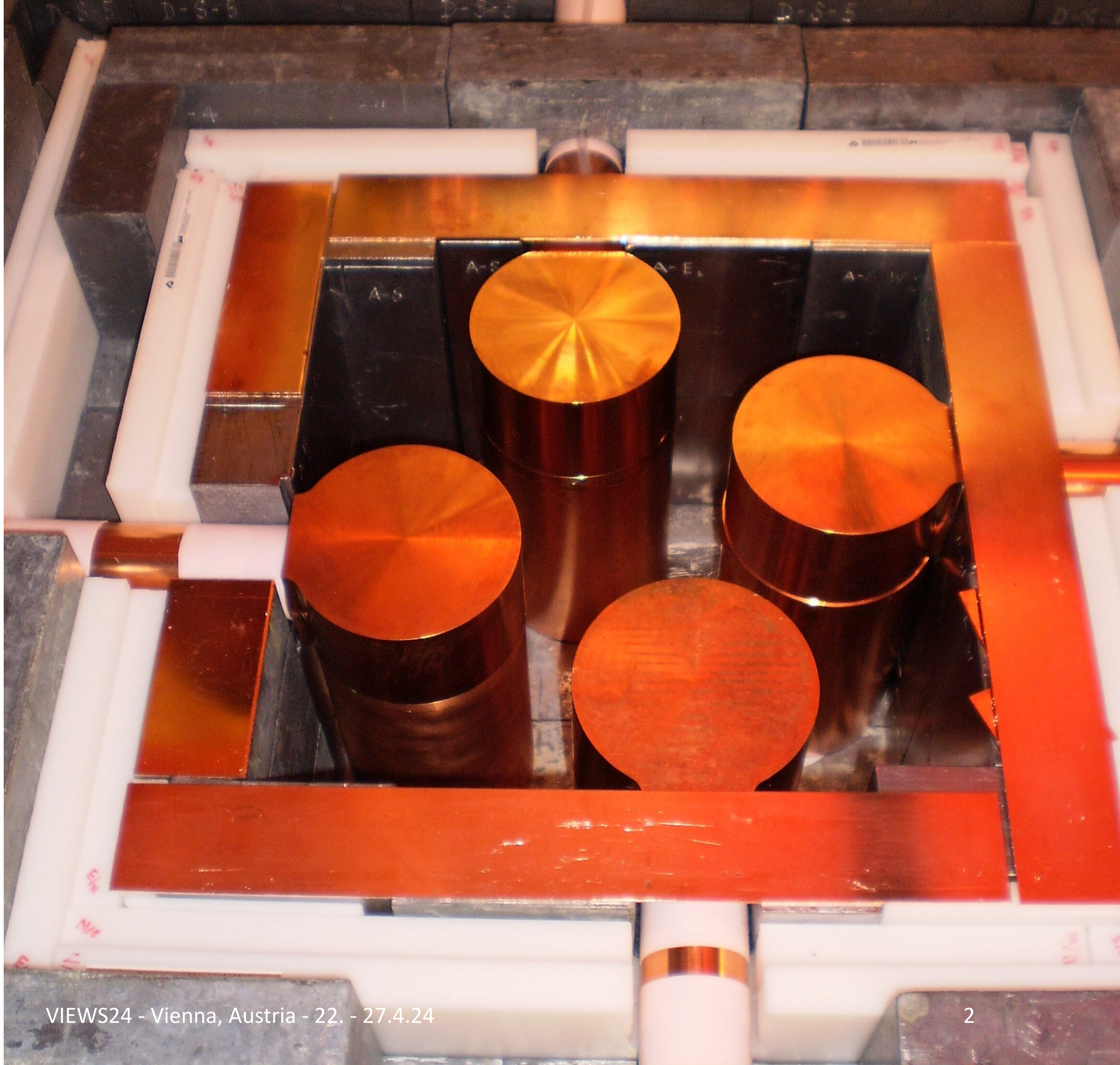
Geant4 simulations for CEvNS searches at nuclear power plants - the CONUS and CONUS+ experiments

Max-Planck-Institut für Kernphysik Heidelberg

Nicola Ackermann –
on behalf of the CONUS collaboration

An introduction to the CONUS experiment



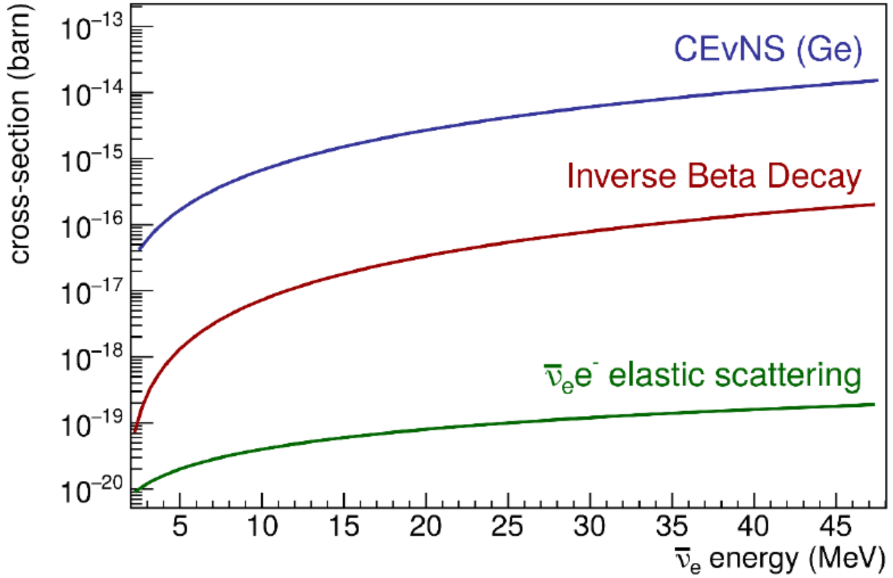
The CONUS experiment searches for CEvNS! But what is that?

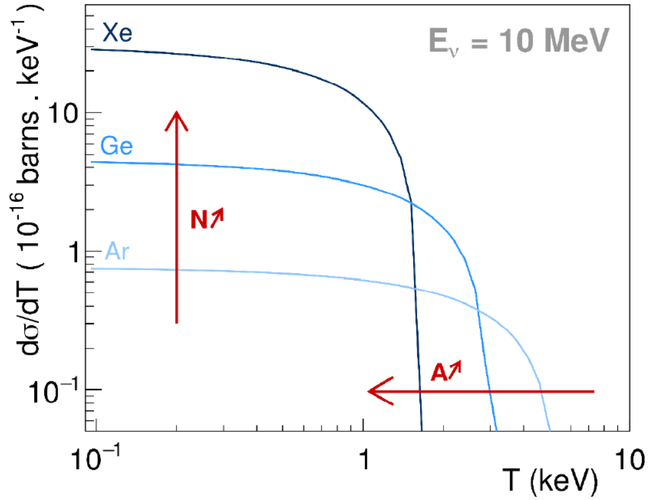
- CEvNS = Coherent Elastic Neutrino
  Nucleus Scattering

$$\frac{d\sigma(E_\nu,T)}{dT} \simeq \frac{G_F^2}{4\pi} \underbrace{[N-(1-4\sin^2(\theta_W))Z]^2}_{\approx N^2} \underbrace{F^2(q^2)}_{\to 1} M \underbrace{\left(1-\frac{MT}{2E_\nu^2}\right)}_{kinematics}$$

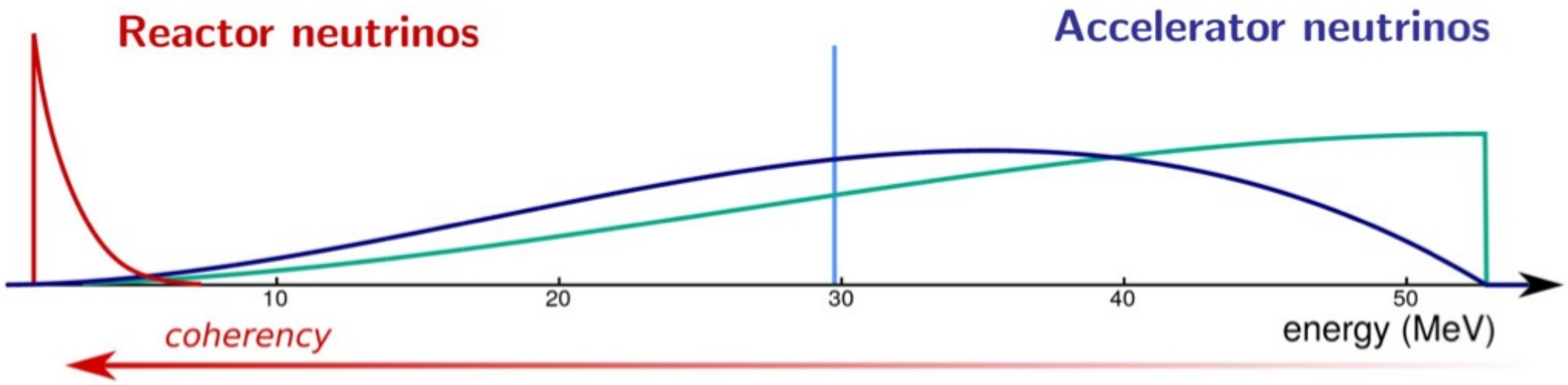
- Coherent interaction of neutrino with entire nucleus
  → enhanced cross section

- First predicted by Freedman in 1974





How can we detect CEvNS?



Reactors

- Neutrinos from fission products
- Only $\overline{\nu_e}$
- Energies of < 10 MeV (fully coherent)
- Still no observation
  Many experiments ongoing

Complementary experiments!

Accelerators

- Neutrinos from π-DAR
- Different flavors: ν_e, ν_μ and $\overline{\nu_\mu}$
- Energies of ~ 20 – 50 MeV
- First CEvNS observation:
  COHERENT in 2017 using CsI [Na]

Location and setup

CONUS was located at the nuclear power plant in Brokdorf, Germany (KBR)
KBR is permanently shut down since Dec 31st 2021

Distance to reactor core: 17.1 m

Neutrino flux: $2 * 10^{13}\ s^{-1}cm^{-2}$

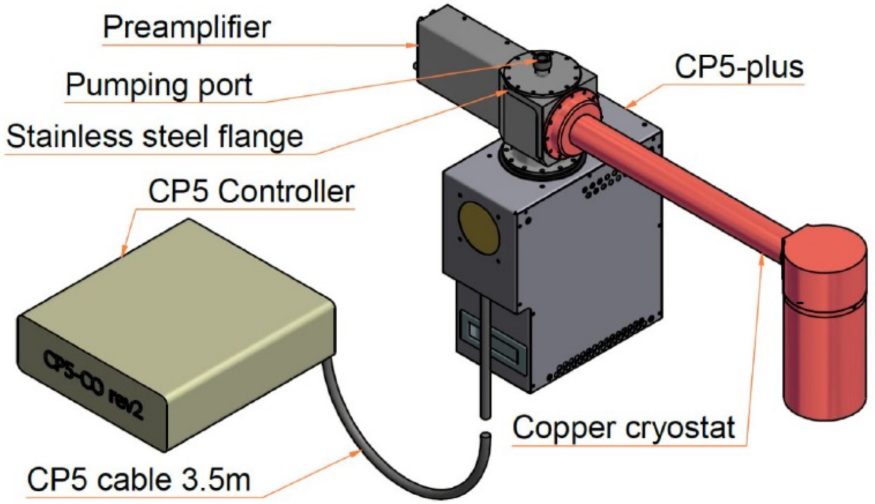
Operational from 2018 to 2022 with reactor OFF period in all of 2022

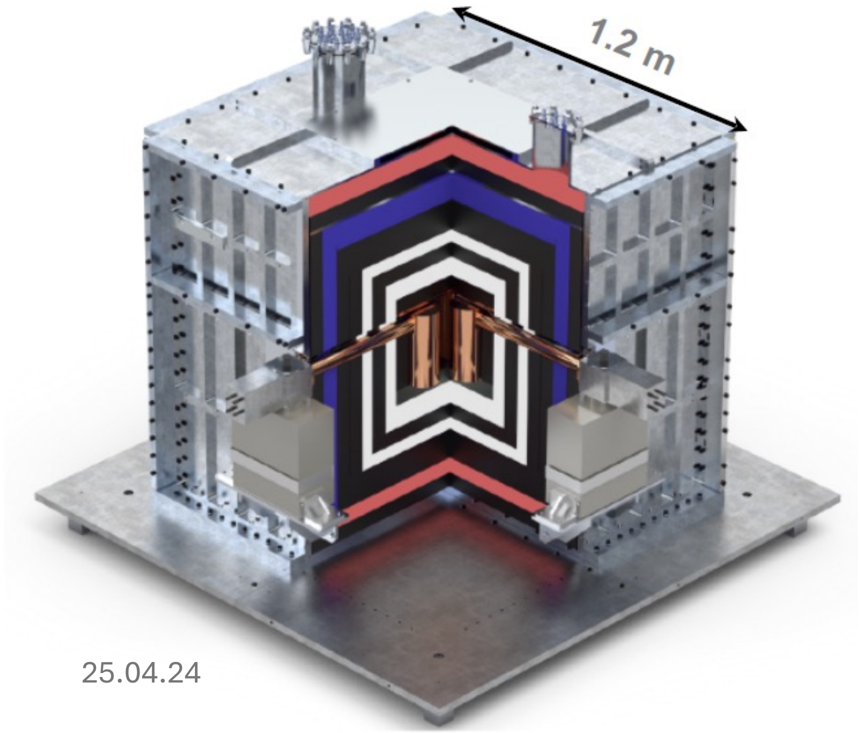
→ **Best Reactor limit for CEvNS searches from Run5:**
factor <2 above SM prediction

arXiv:2401.07684v2 [hep-ex]

4 p-type point contact HPGe detectors

- 1 kg each
- Ultra-low background materials
- Electrical cryocooling
- Energy resolution: 60 – 80 eV (Pulser, FWHM)
- Energy threshold: 210 eV (in Run 5)

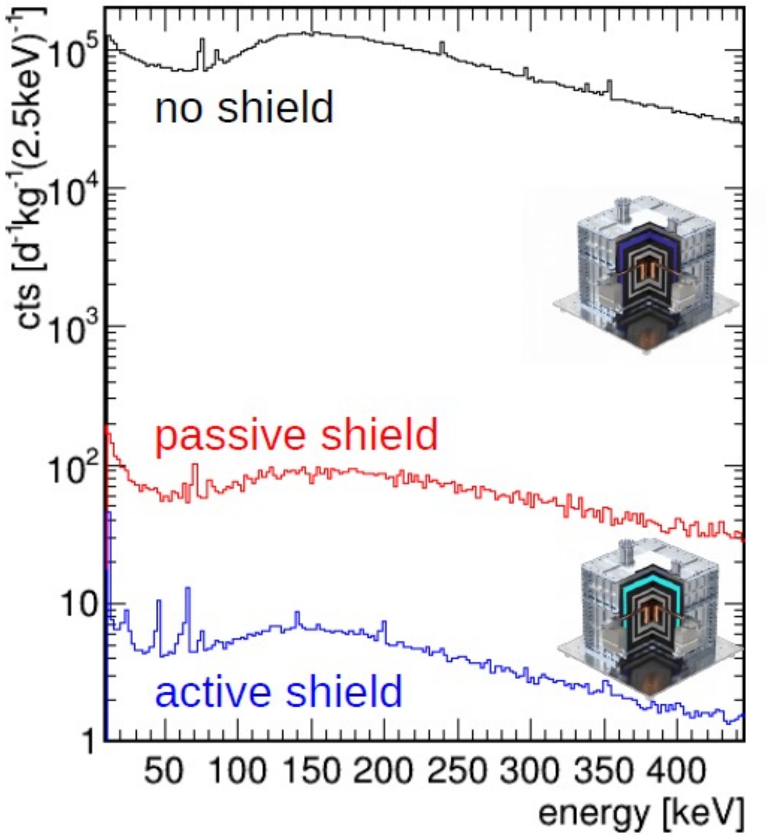


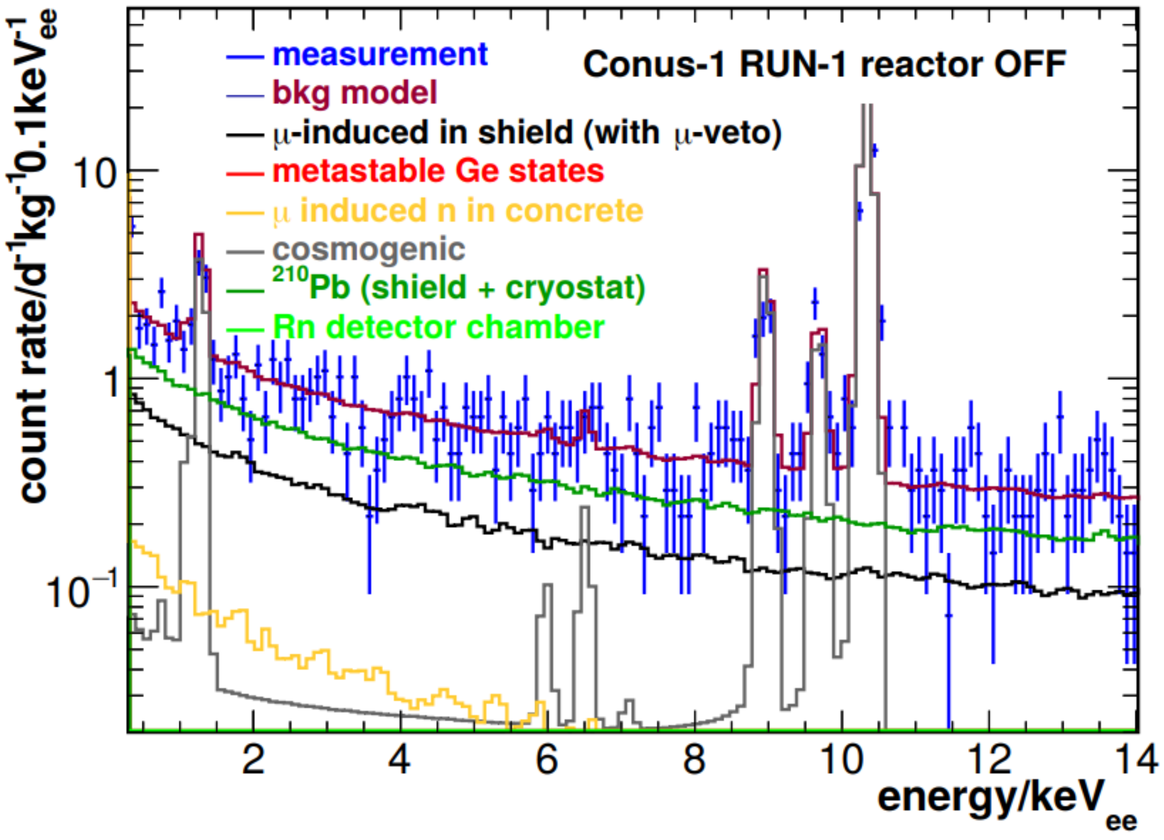


CONUS shielding:

- 11 tons in total
- Active + passive shielding
- Lead for gamma suppression
- (borated) PE for neutron suppression
- Active µ-veto system (plastic scintillator)
- Flushing of detector chamber against radon

Background suppression by the shield





Background is suppressed by four orders of magnitude!

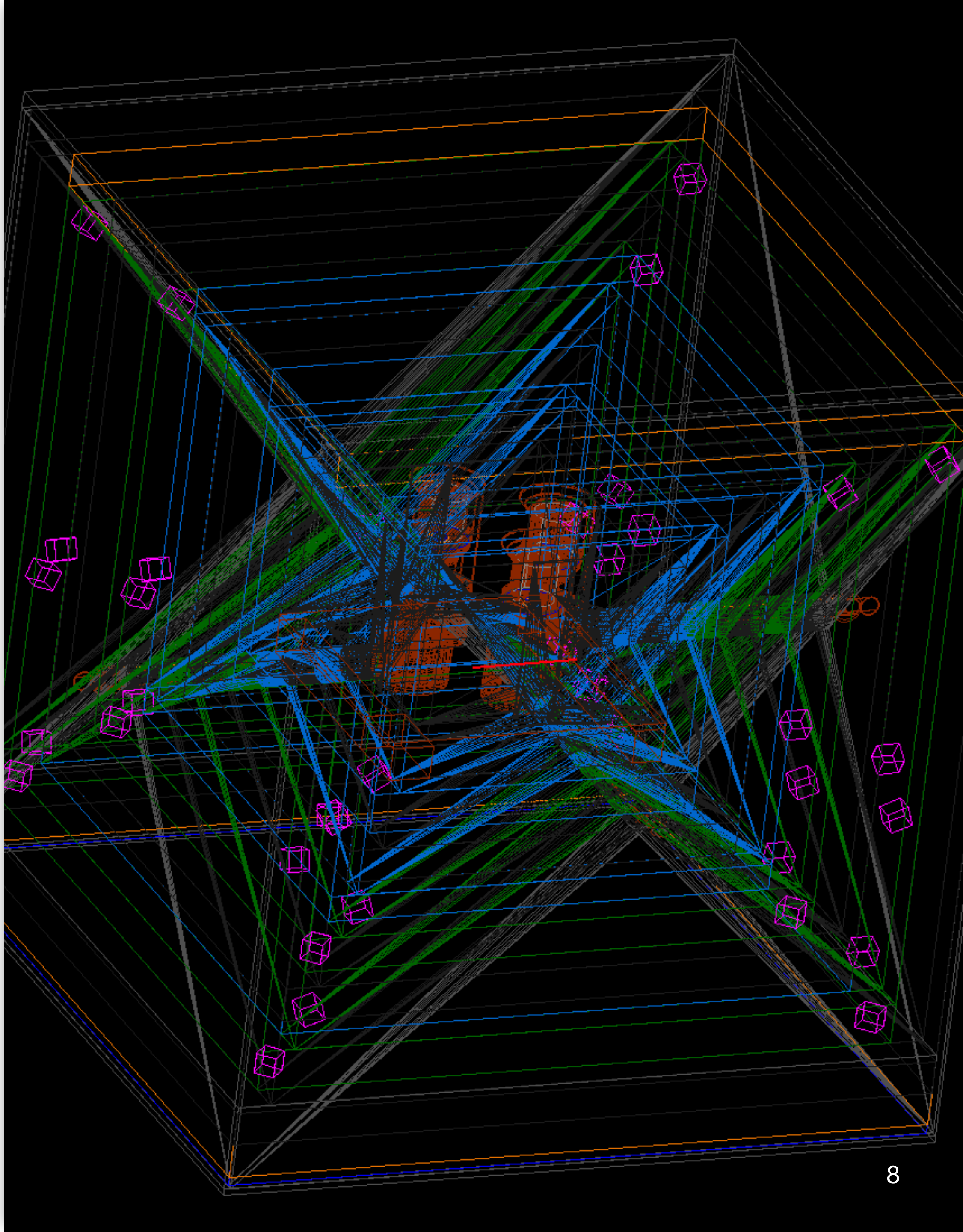
Stable level:~ 30 counts/kg/d in [0.21 - 1] keV (in Run 5)

→

Remaining Bkg. Needs to be fully understood!

Model with Geant4 Monte Carlo simulations!

Geant4 simulations for CONUS



Geant4 simulations for CONUS

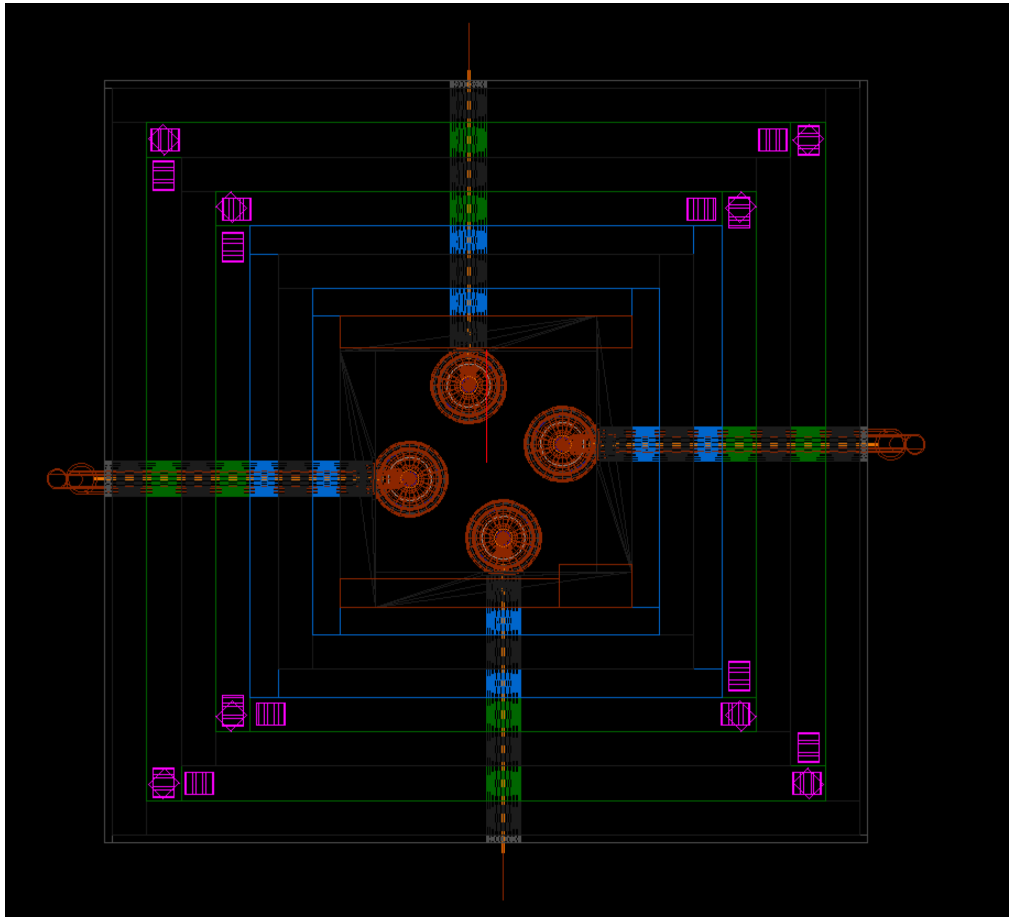
- CONUS collaboration uses MaGe
  - a Geant4-based MC framework for low-background experiments [arXiv:0802.0860 **[nucl-ex]**]

- MaGe was developed for the Majorana and Gerda experiments

- Physics lists optimized for low energy processes and underground applications (sub keV – MeV)

- Main goal of MaGe:
  Simulation of background sources in low background experiments like $0\nu\beta\beta$
  → ideal for CONUS

- We use:
  - production cut realm: DarkMatter
  - LowE electromagnetic processes
  - Bertini cascade model



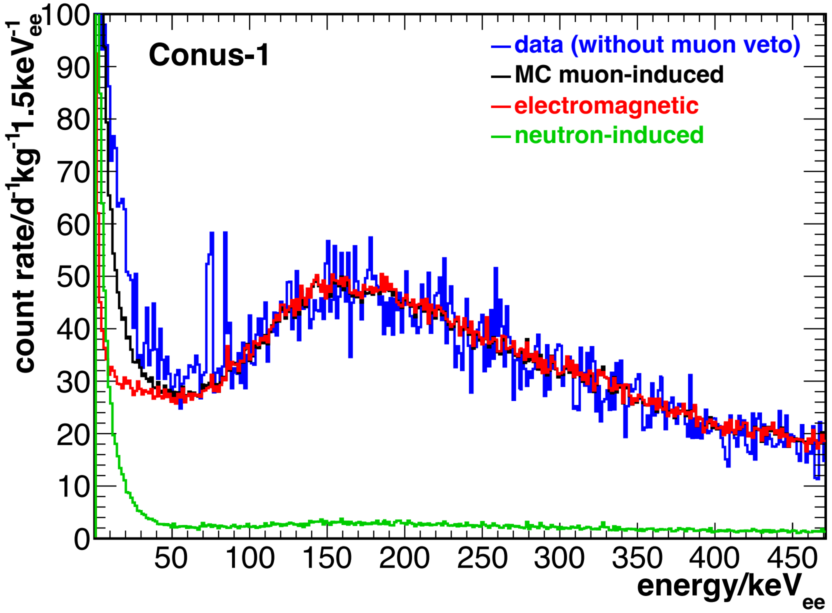
Complete detector geometry built in MaGe

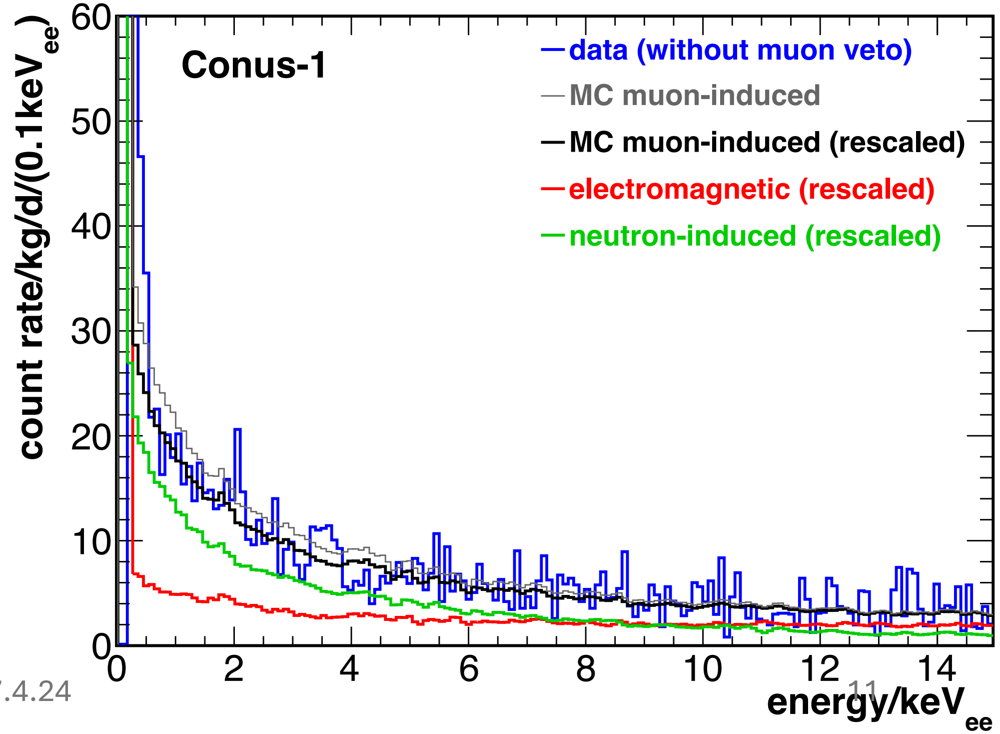
What are the main background contributions?

- Muon-induced background
- Reactor correlated background
- Cosmogenic induced background
- Pb210 inside the shield and cryostat

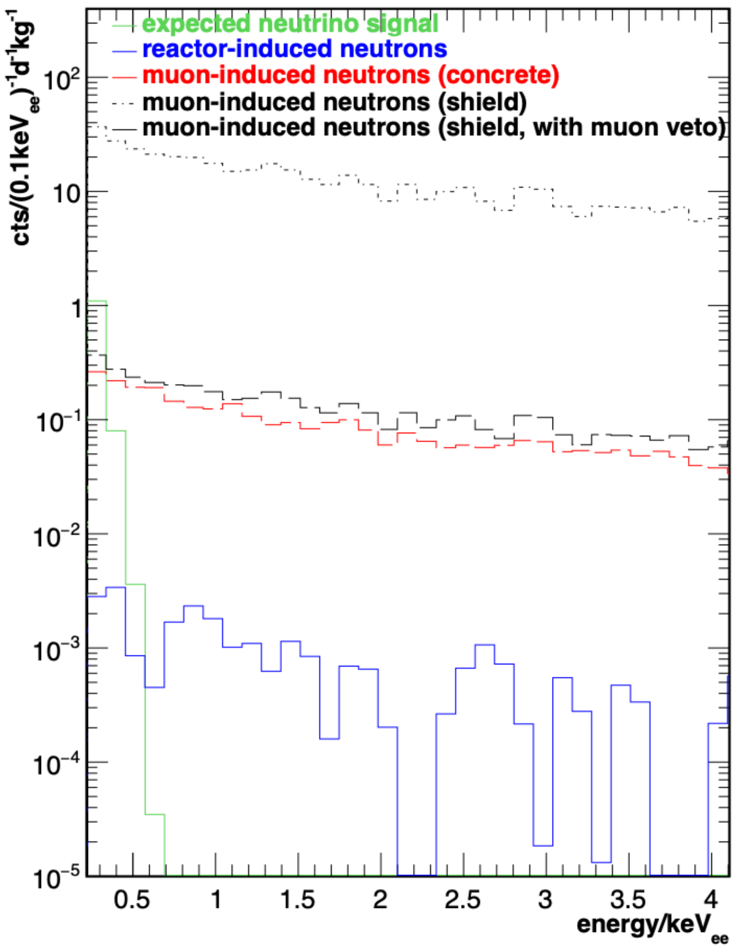
Muon-induced background

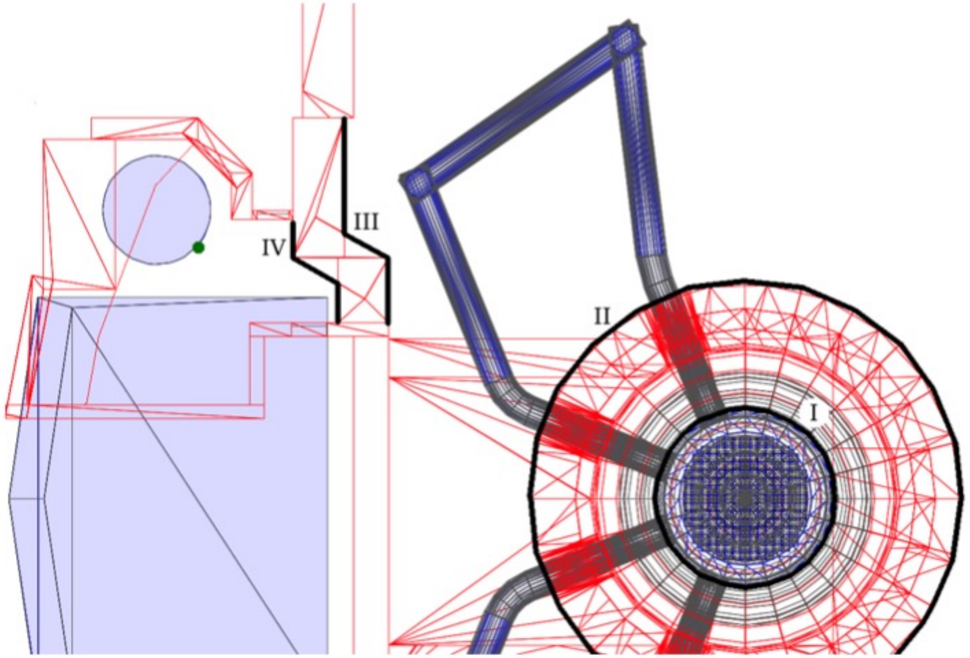
- Calculation of muon flux underground
- Propagation <u>through shield</u> in MC
    - Prompt electromagnetic: dominant above 50 keV
    - **muon-induced neutrons** (quenching applied): dominant in ROI (below 1 keV)
- validation of MC: excellent agreement, minor rescaling
    - Ge spectrometer at MPIK laboratory: *J.Phys.Conf.Ser. 718 (2016) 4, 042028*
    - Direct n measurement: Bonner sphere inside shield
    - Indirect n measurement: metastable Ge states





Reactor correlated background



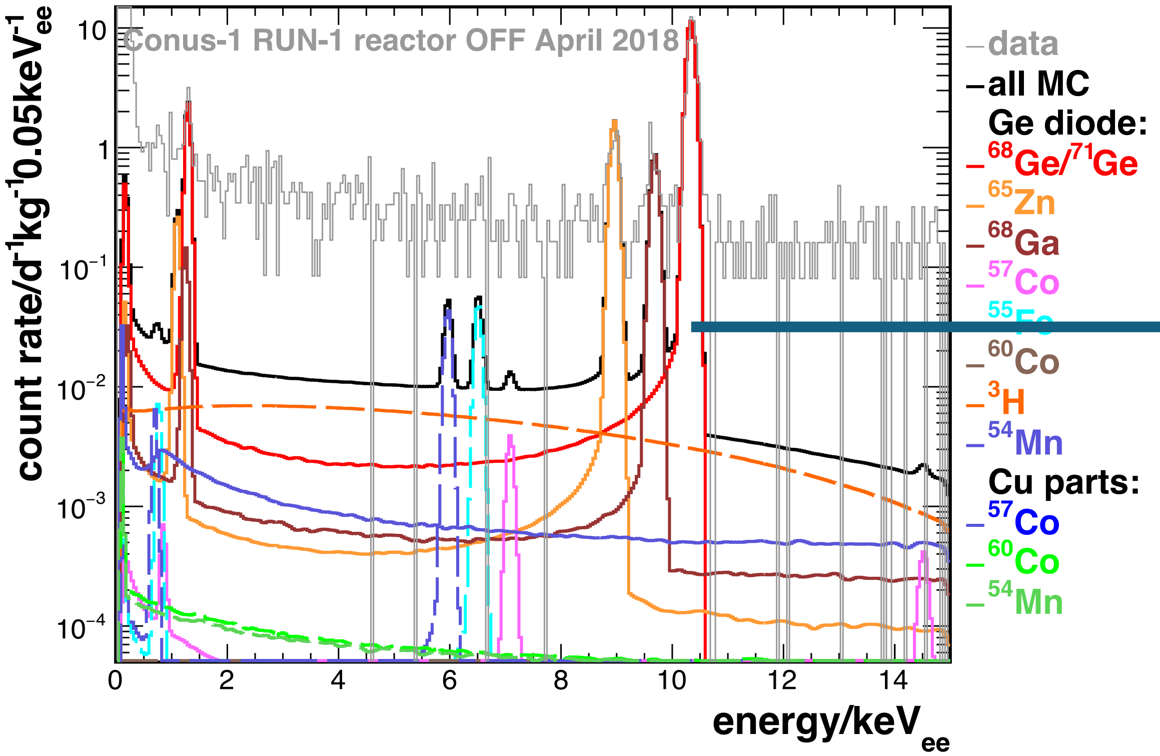


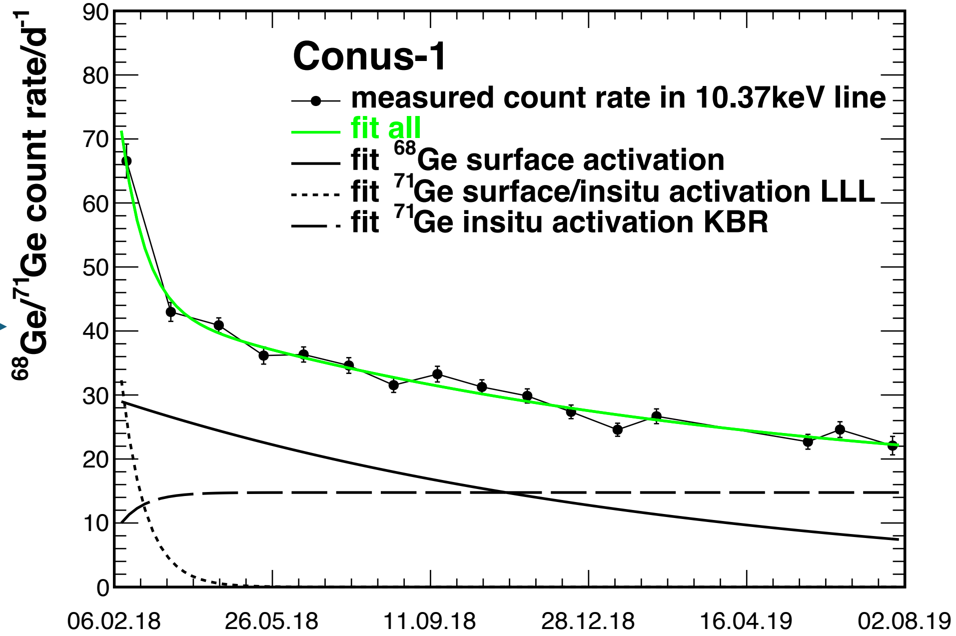
Reactor core and surrounding walls were implemented in MaGe

→ Neutrons from reactor were propagated through the walls to the CONUS room

Additionally, N16 in the cooling cycle of the power plant was simulated

Cosmogenic induced background





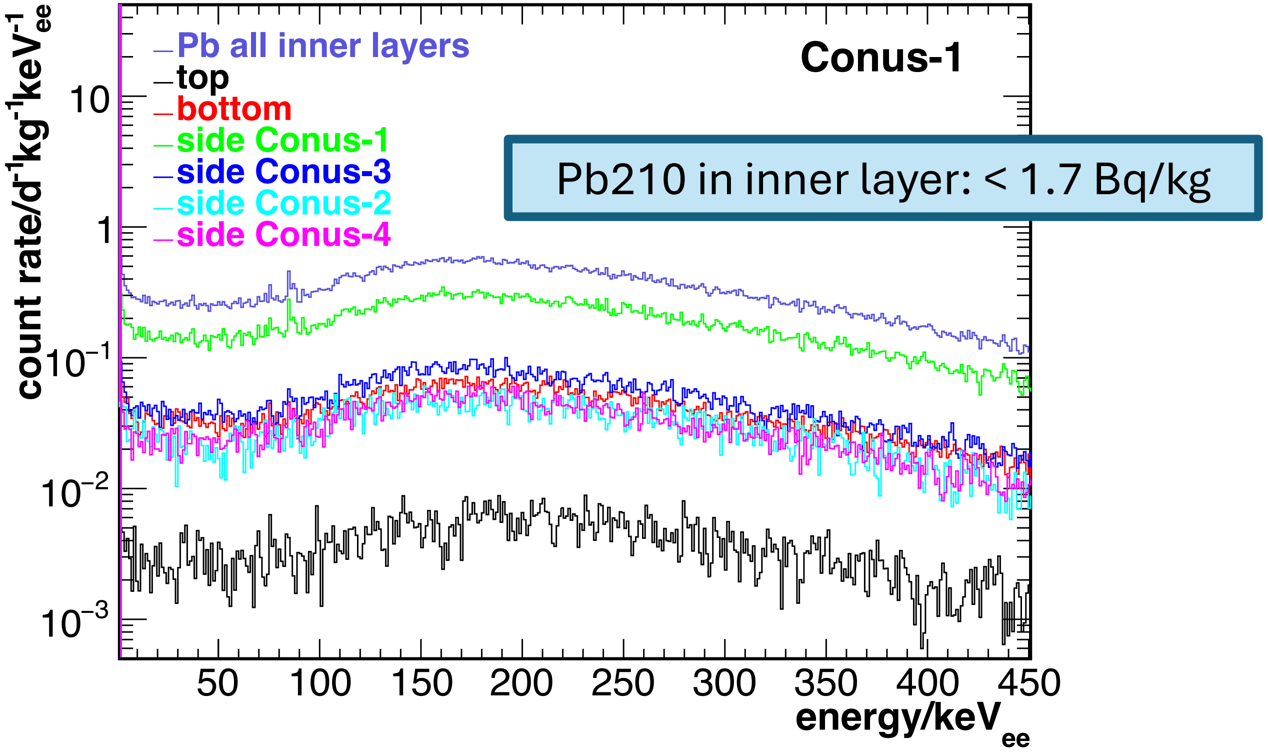
1) Ge and Cu activation at Earth's surface, e.g. Ge68 ($T_{1/2}$=271 d), Zn65 ($T_{1/2}$ =244 d), ...

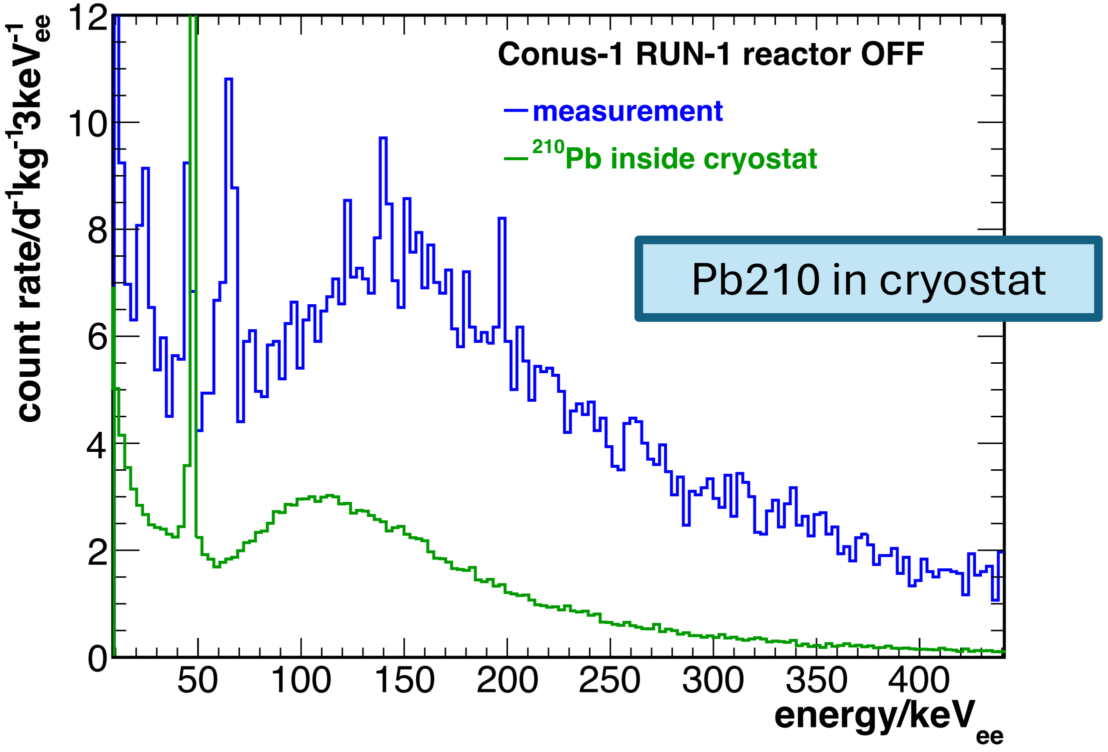
2) insitu by neutron capture: Ge71 ($T_{1/2}$ =11.4 d)

Contaminations are placed inside the Ge diodes and Cu parts inside the MC and scaled based on roadiopurity measurements and CONUS data

Pb210 inside shield and cryostat

- Pb210 contaminations very common in Pb → dedicated screening campaign
- Old Pb → Pb210 decayed away → Ancient Pb is free of Pb210 (half life 22 years)
- Surface contaminations of Cu parts and Ge diode are also possible (radon rich air, poor working conditions)





Full background model of CONUS

For the C1 detector in RUN-1

energy ranges	[0.4,1] keV_{ee}	[2,8] keV_{ee}	[40,48] keV_{ee}	[10,100] keV_{ee}	[100,440] keV_{ee}
C1	RUN-1 OFF	RUN-1 OFF	RUN-1 OFF	RUN-1 OFF	RUN-1 OFF
data [$d^{-1}kg^{-1}$]	11.5±0.9	40.5±1.8	22.1±0.9	262±3	529±4
bkg model [$d^{-1}kg^{-1}$]	11.9	40.2	29.0	264	529
prompt μ-induced	34%	33%	19%	27%	44%
metastable Ge states	0.4%	0.3%	0.3%	7%	1%
μ-induced n concrete	3%	2%	0.1%	0.3	0.1%
cosmogenic	3%	5%	0.5%	17%	2%
^{210}Pb shield	4%	6%	8%	11%	27%
^{210}Pb within cryostat	54%	52%	70%	35%	22%
other cont. within cryostat	1%	1%	2%	2%	3%
airborne Rn	0.2%	0.3%	0.4%	0.5%	1%

arXiv:2112.09585[physics.ins-det]

CONUS+ - The successor of CONUS

Running since October 2023!

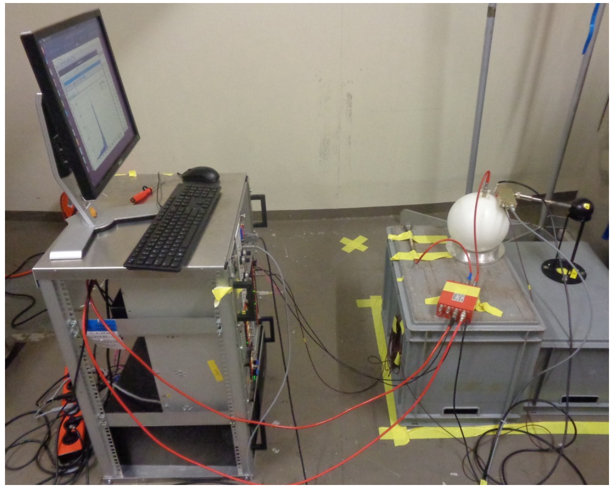
What changes need to be made to the Bkg. model?

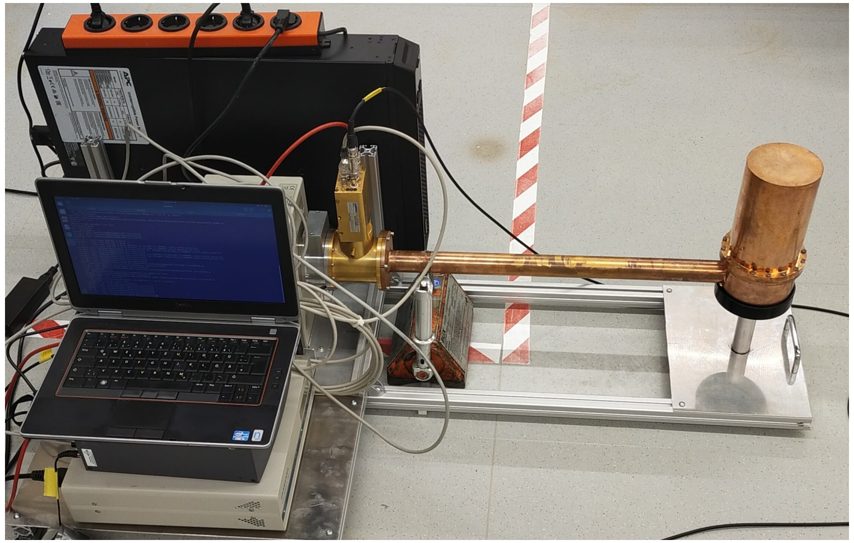
New Location!

- CONUS+ is located in the nuclear power plant in Leibstadt, Switzerland
- Distance of 20.7 m to reactor core
- Overburden of 7 – 8 m w.e. (compared to 24 m w.e. for CONUS in Brokdorf)

→ New and unknown muon and neutron fluxes

→ Extensive measuring campaign in summer of 2022





What changes need to be made to the Bkg. model?

Result of measuring campaign:

- muon flux 2.5 times higher than in KBR (expected from overburden)
- neutron flux 30 times larger than in KBR (still expected to be subdominant in ROI)
- high energy gamma bkg. 25 times lower than in KBR
- high Co60 contamination in room

Additionally: Change in shield setup!

- higher muon flux → need additional muon veto layer

→ one of the inner lead layers was replaced with additional plastic scintillator layer

Simulations for new background model are currently ongoing!

Same approach as for CONUS Bkg. Model but with updated detector geometry, new neutron / muon fluxes etc.

Summary

- The CONUS collaboration uses **MaGe** – a Geant4-based framework tuned and validated for simulations in the low energy regime
- CONUS background was fully understood and described by MC simulations
- **<u>Most prominent background sources:</u>**
  - muon-induced background
  - Pb210 within the cryostat

- Simulations for the background model of CONUS+ are currently ongoing
  → main differences: new location (i.e. new muon and neutron flux) and changes in detector geometry

- First CONUS+ results expected within the year!

Airborne radon in detector chamber

- From Rn222 decay chain:
  α decays of Rn222 and Po progenies are shielded by CU cryostat → only Bi214 and Pb214 are simulated (Pb210 has half-life of 22 years)

- Bi214 and Pb214 are simulated from the surface of the detector chamber

- Very good agreement with data