Conceptual design of the COSINUS experiment using cryogenic NaI detectors for direct dark matter search

*A. **Fuss** for the COSINUS Collaboration*

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

TU WIEN

GSI

INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

SICCAS Since 1928

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

Outline

Motivation for COSINUS

Detectors, Crystals and Prototypes

Conceptual shielding design
+ Background Simulation

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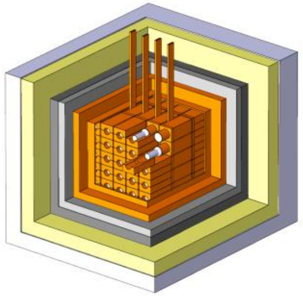
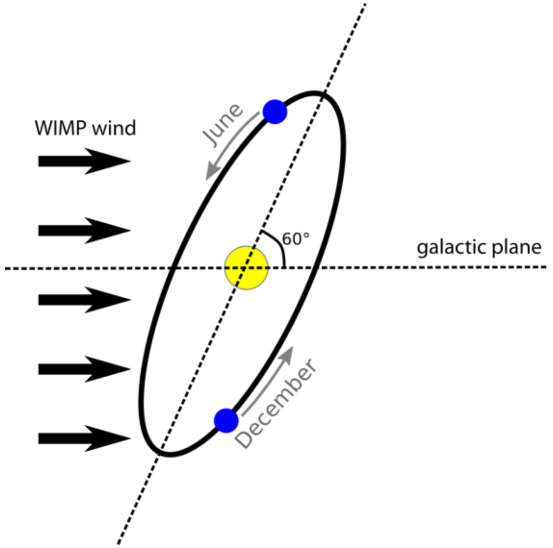
DAMA/LIBRA Results



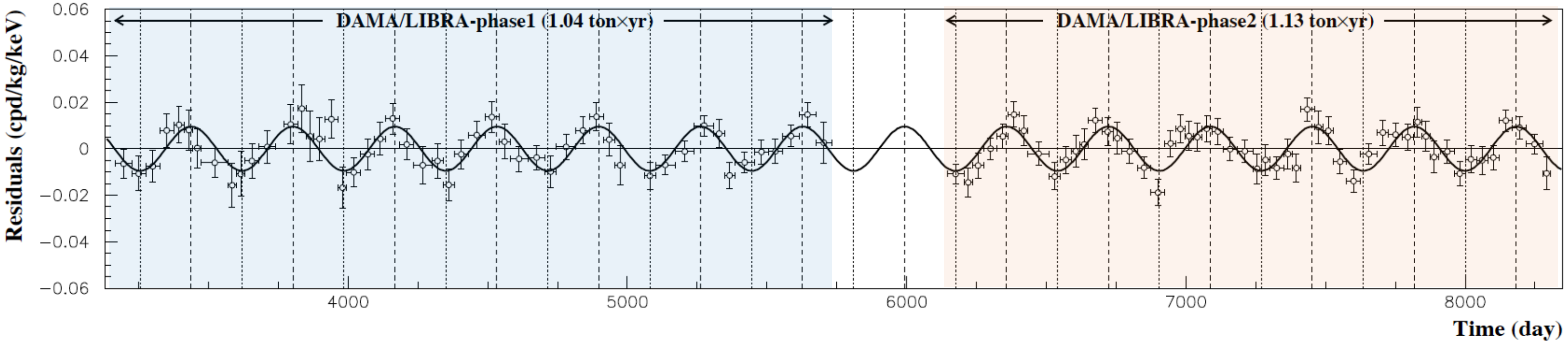



motion of the Earth causes relative modulation of velocity

→ **annual variation in the rate**

expected period: **1 year**
expected phase: **cosine peaking June 2nd**

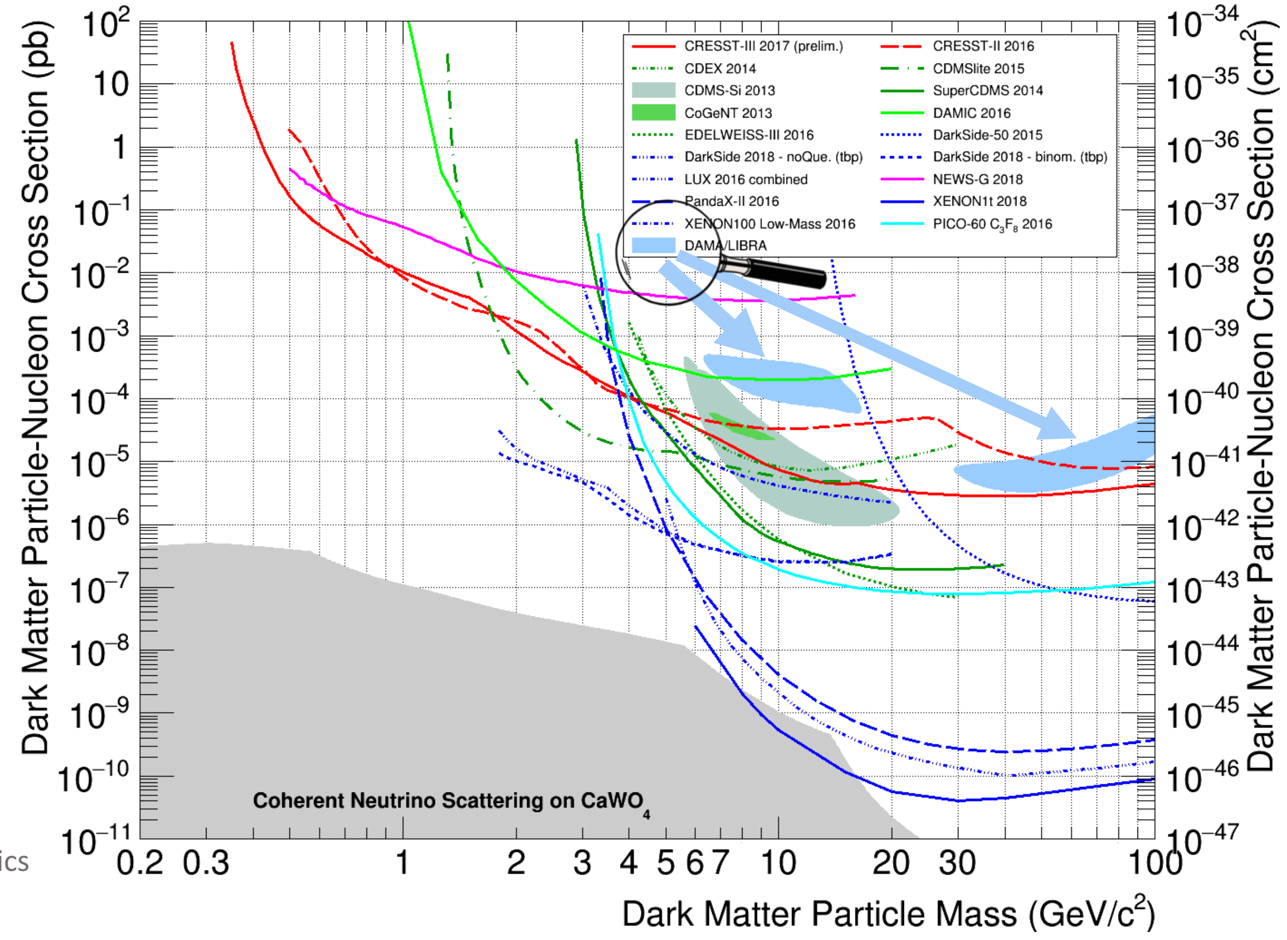
DAMA/LIBRA PHASE 1: 2003-2010 2-6 keV DAMA/LIBRA PHASE 2: 2011-2017



Total exposure:	2.17 tonne years (phase 1 + 2)
Statistics:	> 11.9 σ ✓
Period:	0.9987 ± 0.0008 years ✓
Phase:	25^{th} May +/- 5 days ✓
Modulation Amplitude:	0.0096 ± 0.0011 cpd/kg/keV
Convincing non-DM explanation	✗

Bernabei, R. et al. Universe 4 (2018) no.11, 116

DAMA/LIBRA Islands in the Dark Matter Landscape



Null results shown as:
90% C.L. upper limits on the spin-independent DM particle-nucleon cross section

DAMA/LIBRA:
3σ allowed parameter space

C. Savage et al., Journal of Cosmology and Astroparticle Physics 2009.04 (Apr. 2009), p. 010

- **Inconsistency with null-results** reported by most other direct dark matter experiments
- **<u>Question:</u> target dependency** of the cross-section?
- **<u>Idea</u>**: Use **same target material** with **low-temperature detection technology**

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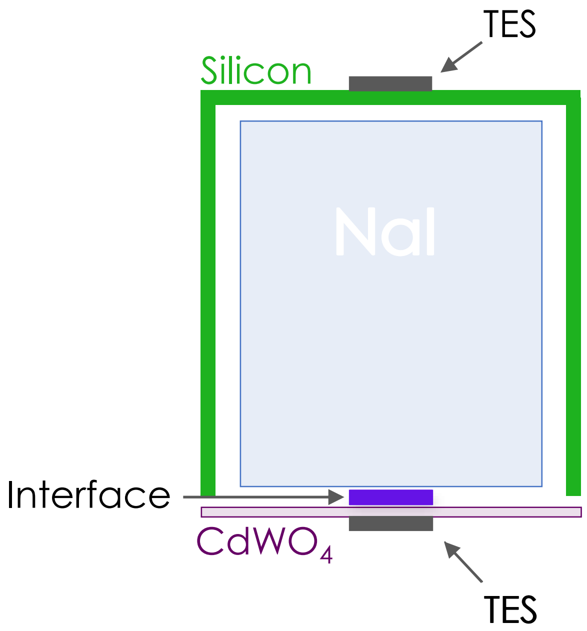
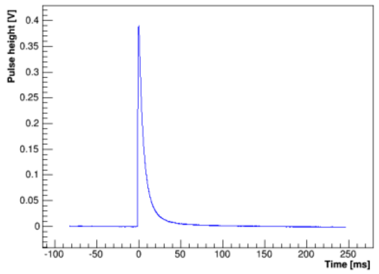
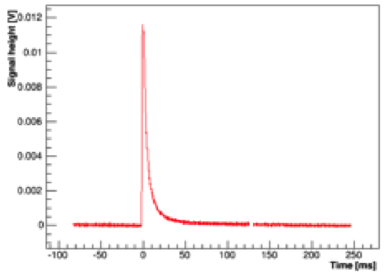
COSINUS Detector Design







NaI Target Crystal

- Scintillator
- Multi-element target
- Mass: ~ 30 – 200 g
- Hygroscopic

^{11}Na 53 I

Carrier Crystal

- Carries the thermometer (TES)
- Glue/oil as interface and link for phonons

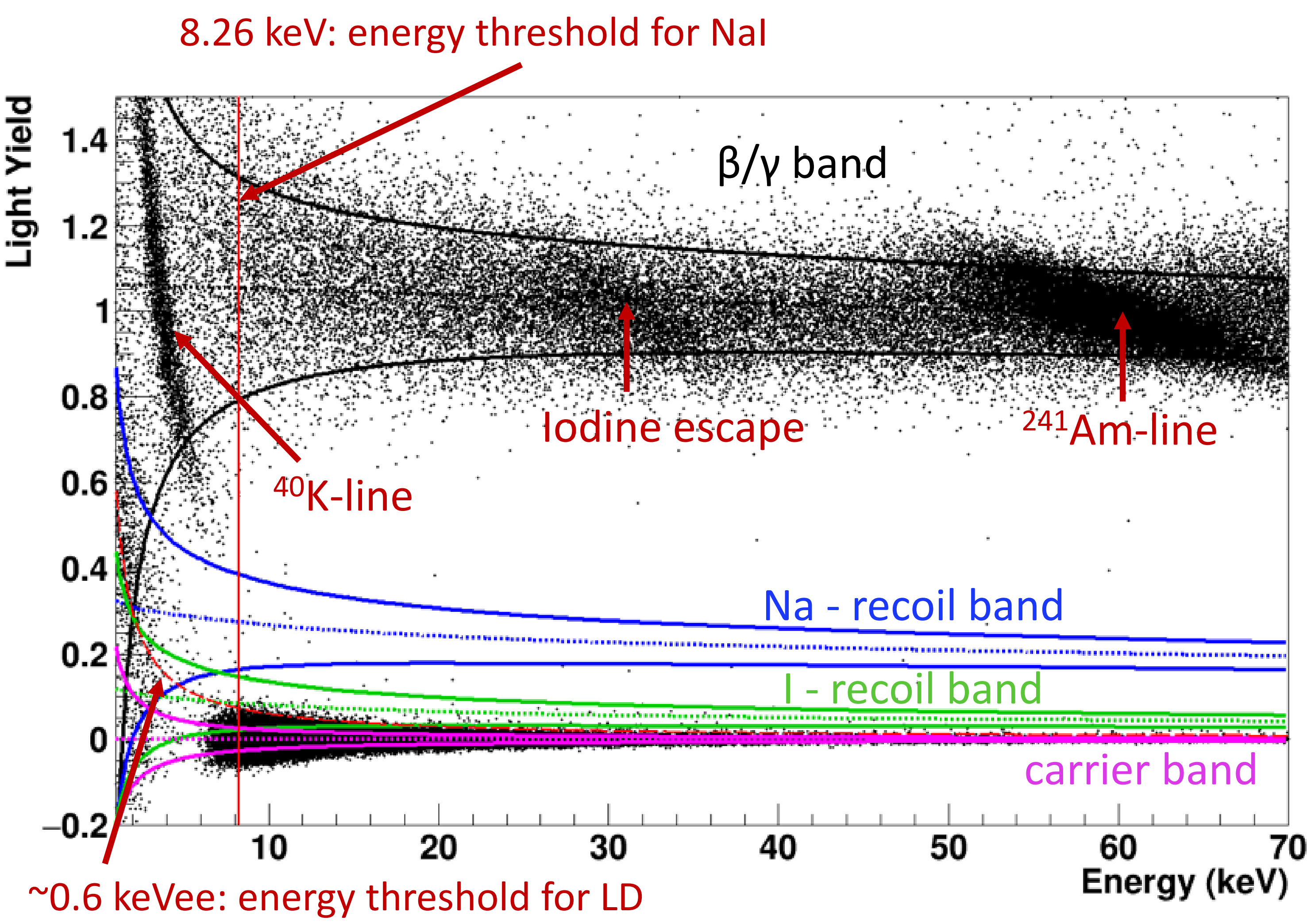
Light absorber

- Beaker-shaped HP silicon
- Fully active veto to reject surface backgrounds

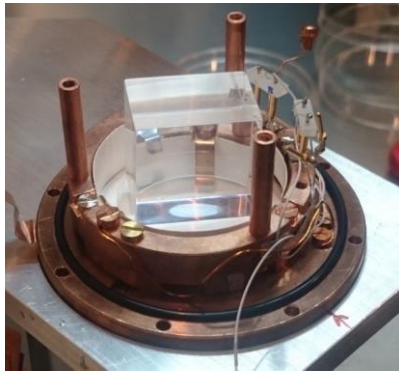
Two-channel readout

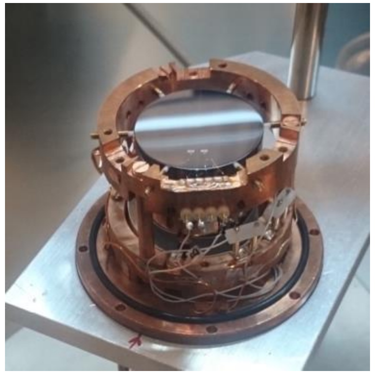
- Discrimination between nuclear recoils and β/γ-events

2nd Prototype Detector

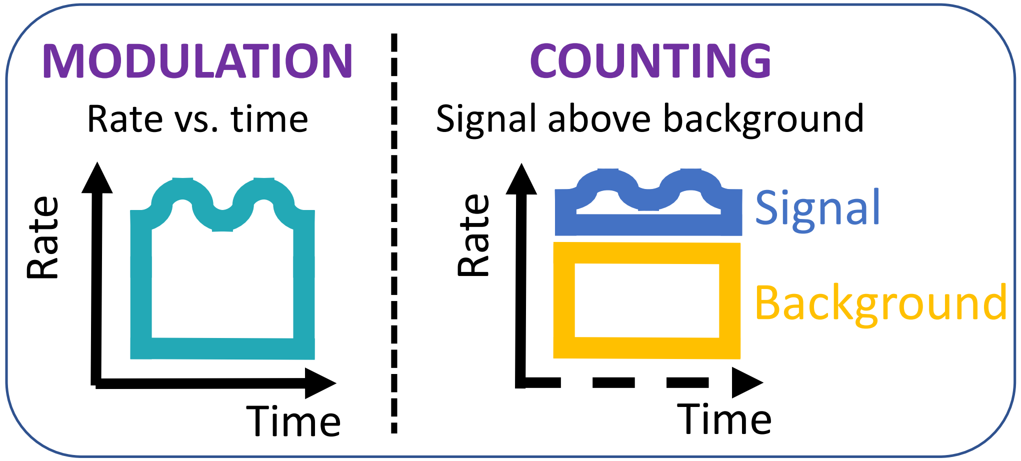


J Low Temp Phys 193 (2018) no.5-6, 1174-1181



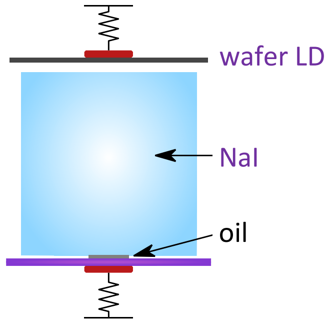


- First measurement of a NaI crystals at cryogenic temperature
- NaI energy threshold is (8.26 ± 0.02 (stat.))keV
- Carrier events identified by pulse shape



COSINUS R&D

1st PROTOTYPE (2016)



1st measurement of a NaI as cryogenic calorimeter

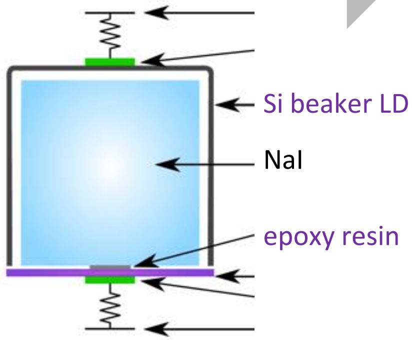
linear relation between light output and deposited energy

NaI threshold: 10 keV

3.7% detected in light

G. Angloher et al. JINST 12 P11007 (2017)

2nd PROTOTYPE (2016/17)



successful test of complete COSINUS detector design

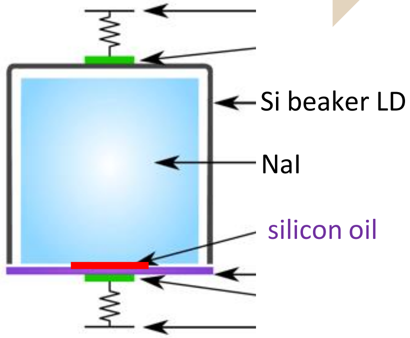
energy resolution at zero energy : 15 eV

NaI threshold: 8.3 keV

13 % detected in light

Schäffner, K. et al.
J Low Temp Phys 193 (2018) no.5-6, 1174-1181

3rd PROTOTYPE (2017)

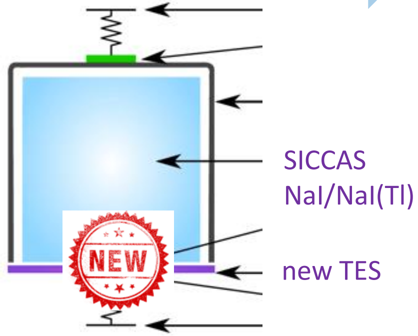


changed interface to thin layer of silicon oil

commissioning of:
in-house electronics
and DAQ from MIB

NaI threshold: 6.5 keV

4th → 12th PROTOTYPE (2017-19)



test of new batch of NaI/**NaI(Tl)** crystals from SICCAS

test of new TES-concept for the NaI crystal

Work ongoing!

Performance goal: 1 keV

Performance goal: 4 %

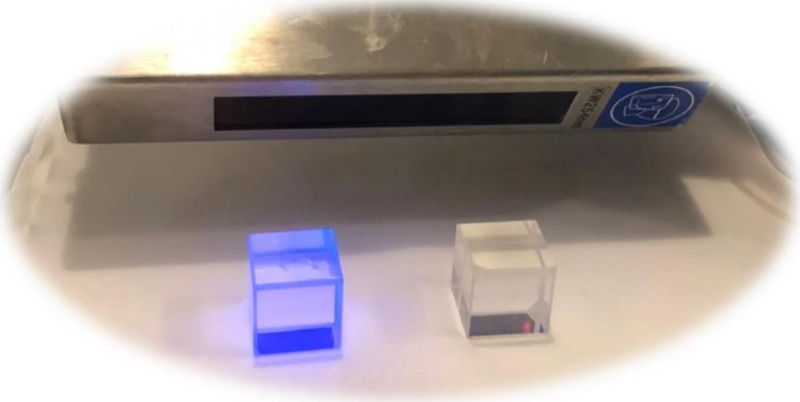
NaI Crystal Production

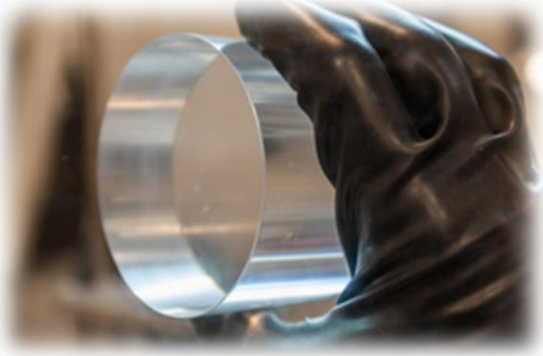
Since 1928
SICCAS

- Collaboration with I. Dafinei from INFN, Roma 1
- Yong Zhu from SICCAS joined the COSINUS collaboration
- Different batches of crystals tested:
  - NaI / NaI(Tl) grown from SICCAS powder (3 g – 30 g crystals)
  - Two 3-inch NaI crystals grown from Astrograde-powder at SICCAS
  - **Very promising radiopurity (ICP-MS analysis):**

    → 5-9 ppb of K at crystals' nose and 22-35 ppb at the tail

    → comparable or even higher purity than DAMA/LIBRA (~ 13 ppb)
  - NaI(Tl) with different amount of thallium dopant





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Conceptual shielding design
+ Background Simulation

Shielding Structure → Geant4 Simulations

- Initial Idea:

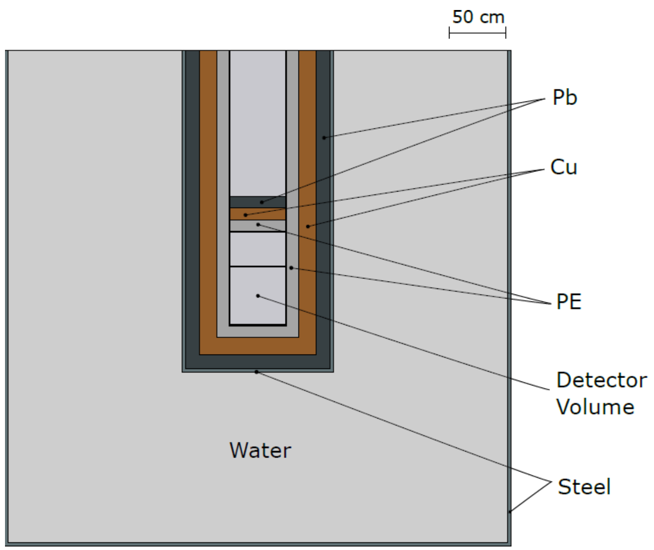
  → **Water tank + inner shielding** (made of Pb, Cu, PE)

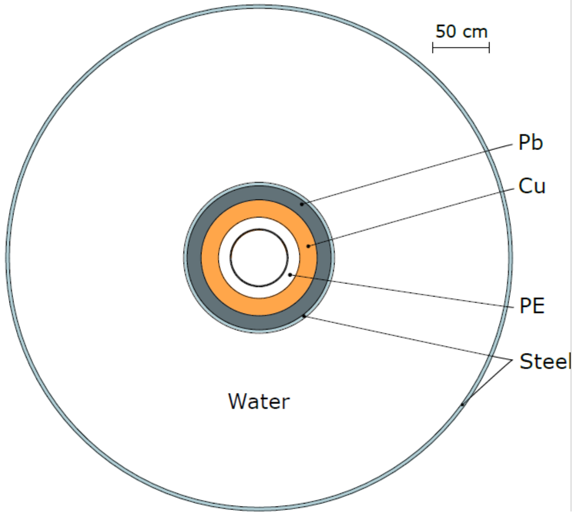
- Simple **Geant4** geometry implemented: concentric cylindrical volumes made of respective materials

- Background estimation with simulation

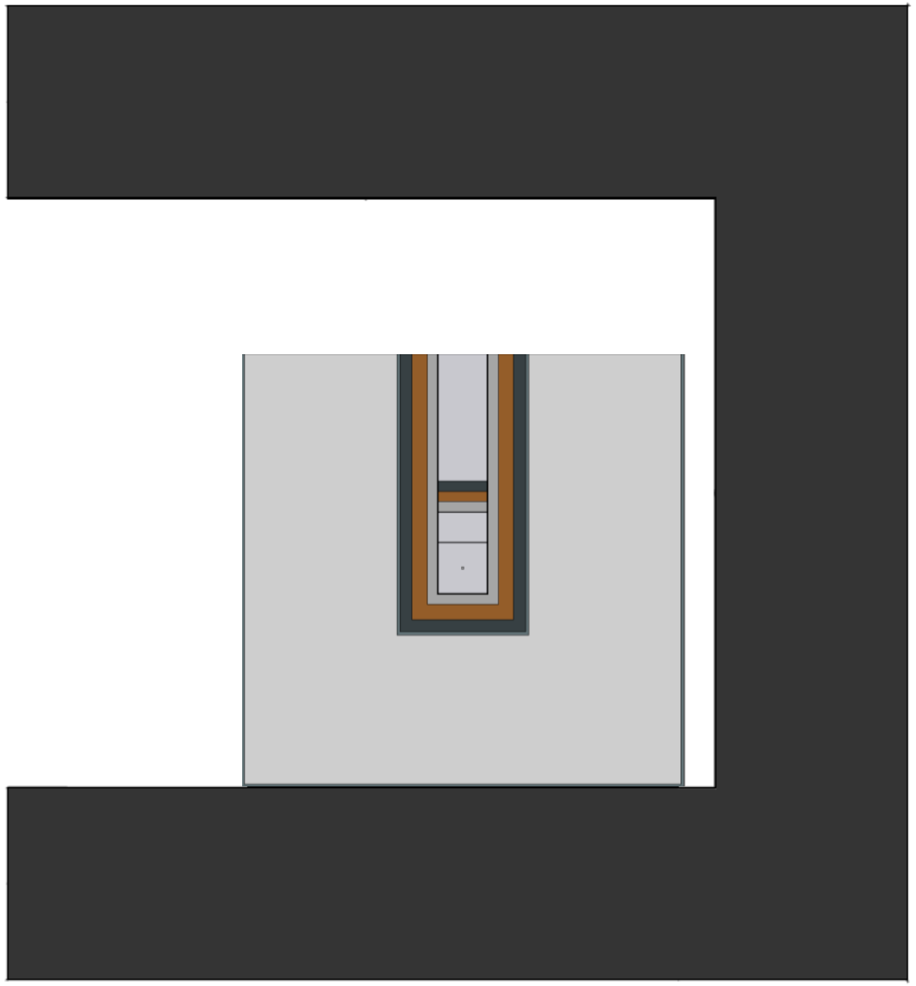
  → Testing different shielding thicknesses

  → No realistic detector design and arrangement was considered



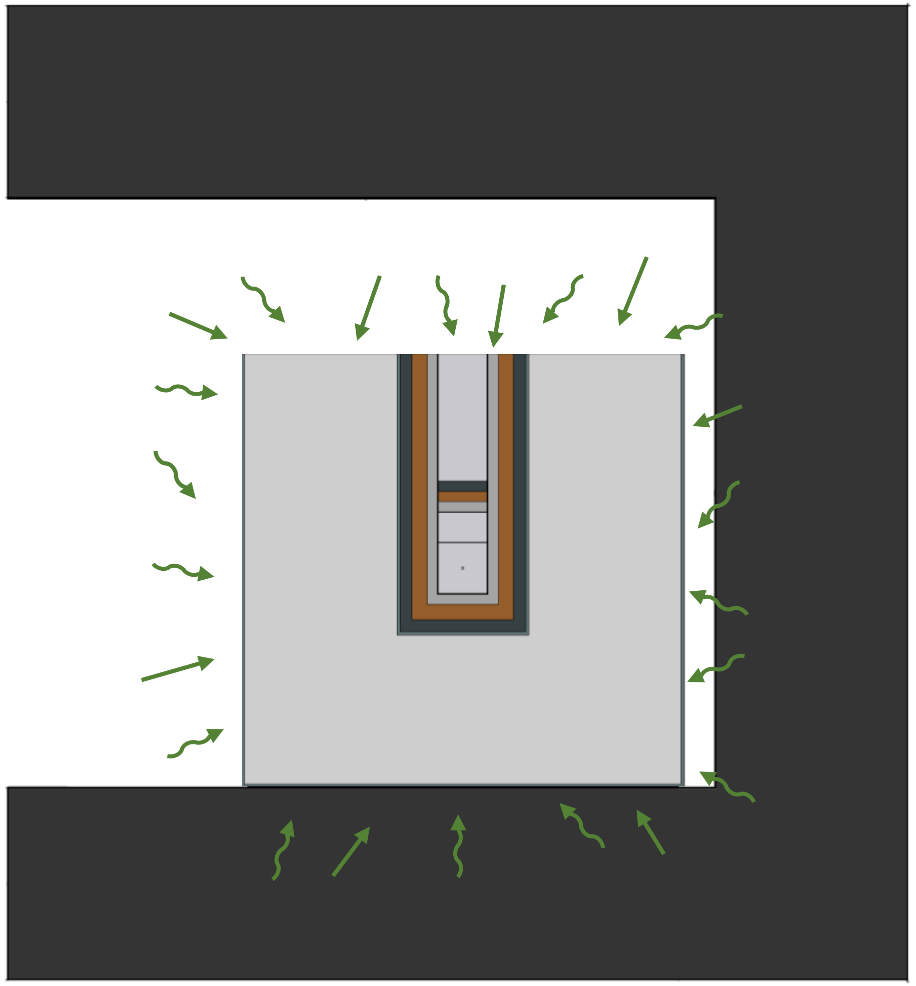


Background Components



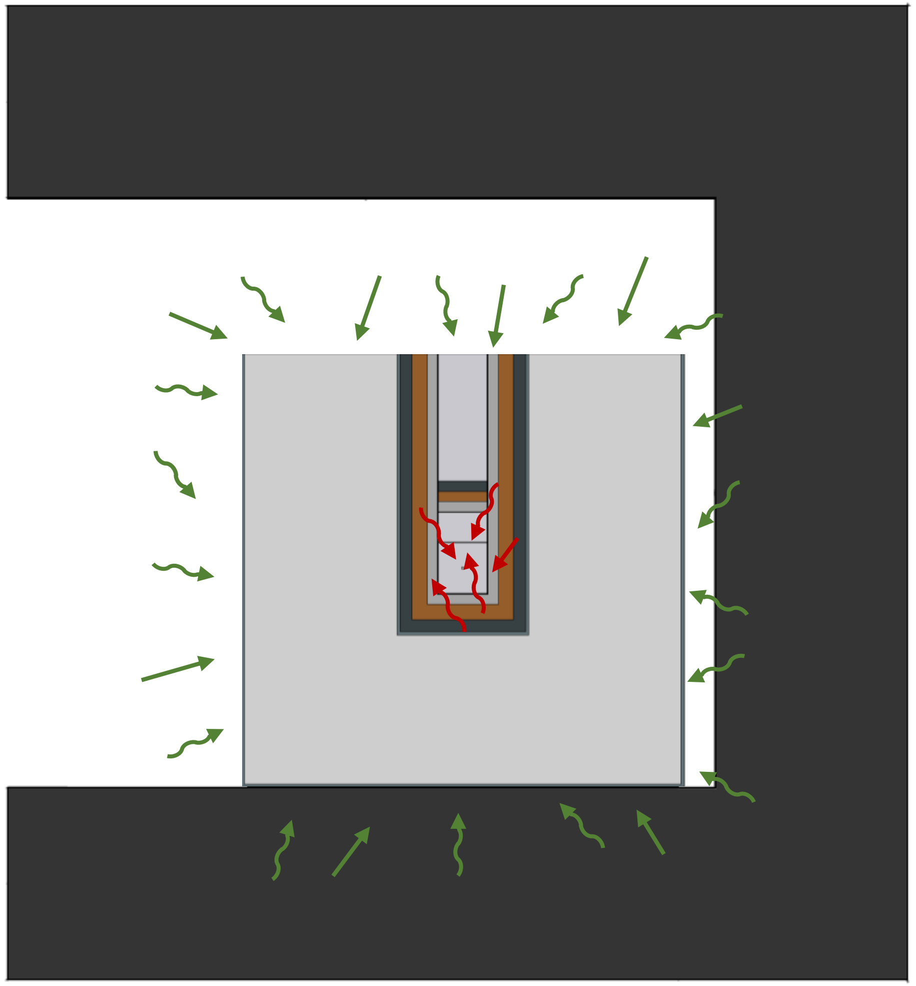
Background Components

- Ambient neutrons/gammas
  (origin: outside setup, mostly rock)



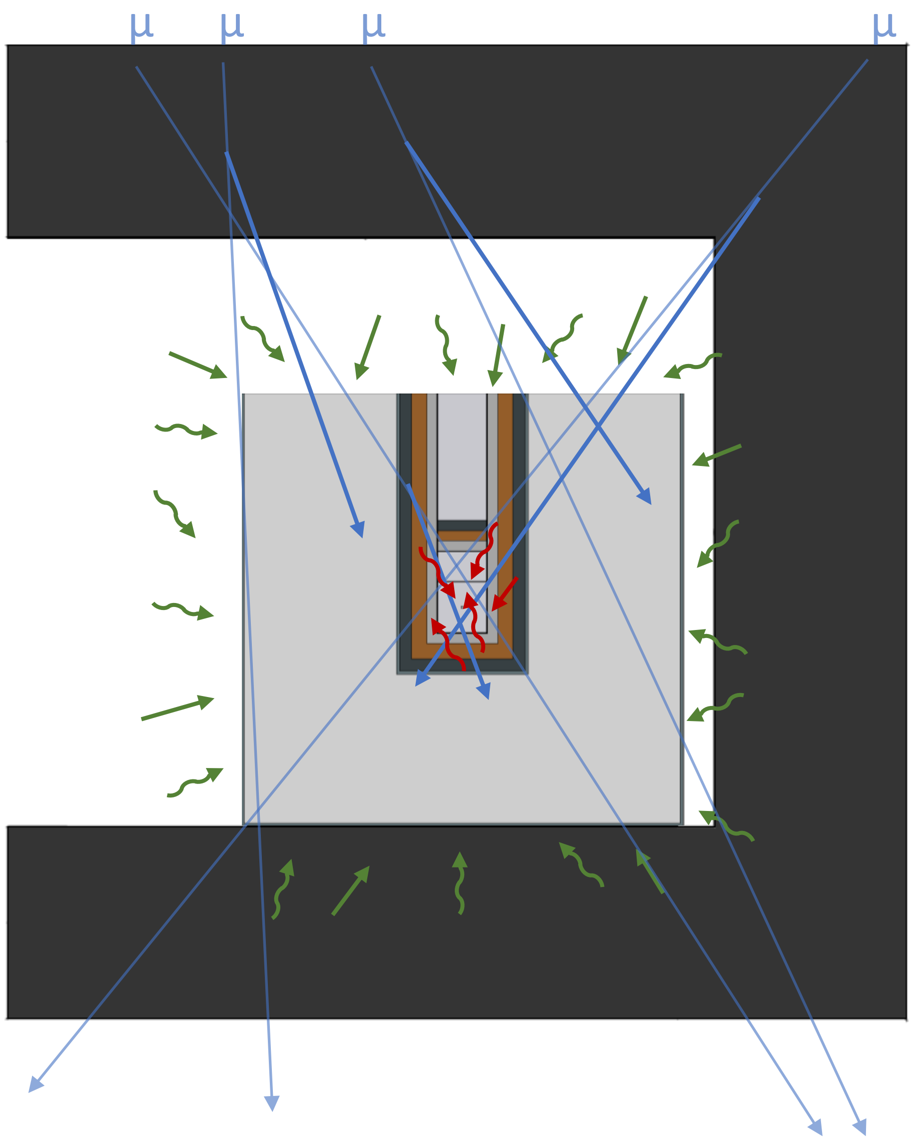
Background Components

- Ambient neutrons/gammas
  (origin: outside setup, mostly rock)
- "Radiogenic" neutrons/gammas
  (origin: materials in setup)



Background Components

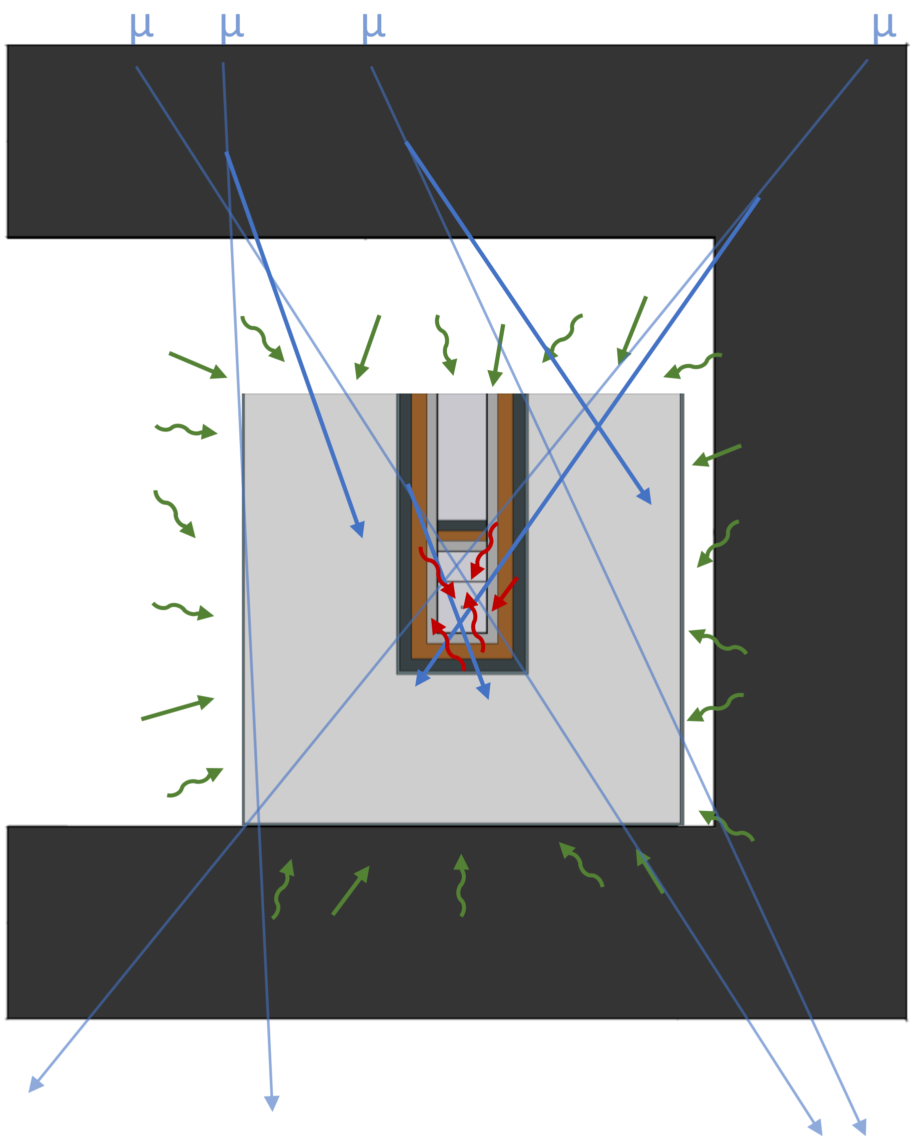
- Ambient neutrons/gammas (origin: outside setup, mostly rock)
- "Radiogenic" neutrons/gammas (origin: materials in setup)
- Cosmogenic neutrons (origin: muon interactions)



Estimating the Size of the Water Tank

Constraints:

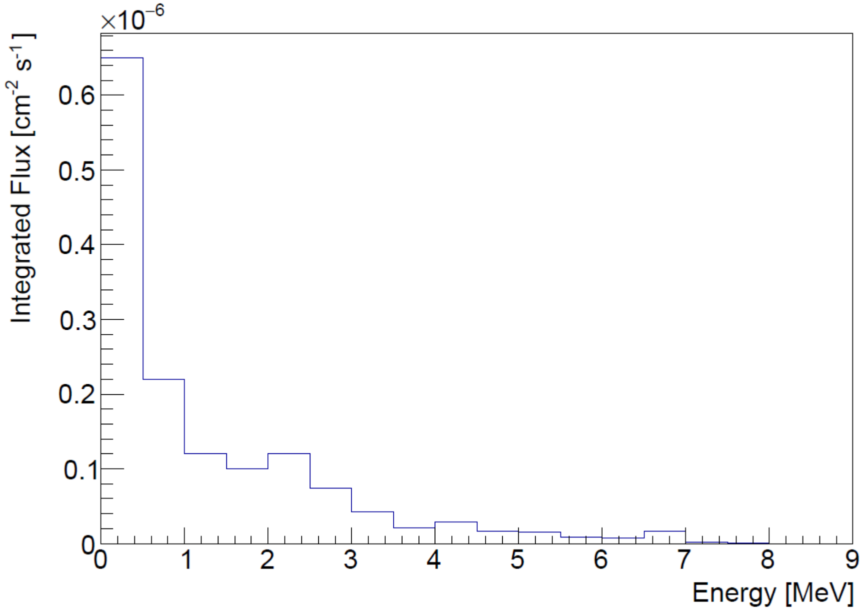
1. **Reduce ambient neutron/gamma flux** below the neutron/gamma flux due to inavoidable radioactive contaminations of the inner shielding materials (i.e. **below the ‘radiogenic‘ flux**)
2. **Muons** (and their secondaries) should on average travel far enough through the water to create **enough Cerenkov light to have an efficient veto**



Ambient Neutrons at LNGS through H_2O

- Spectrum by H. Wulandari

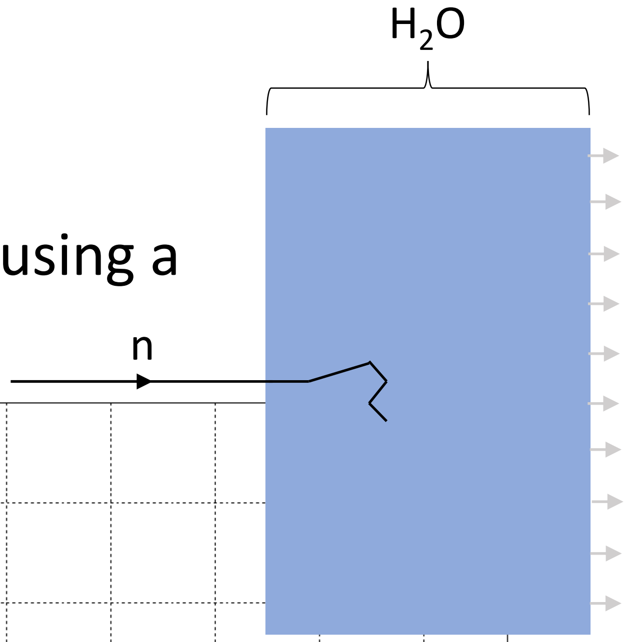
Adapted from **Wulandari**, H. et al. **Astropart.Phys.** **22** (**2004**)

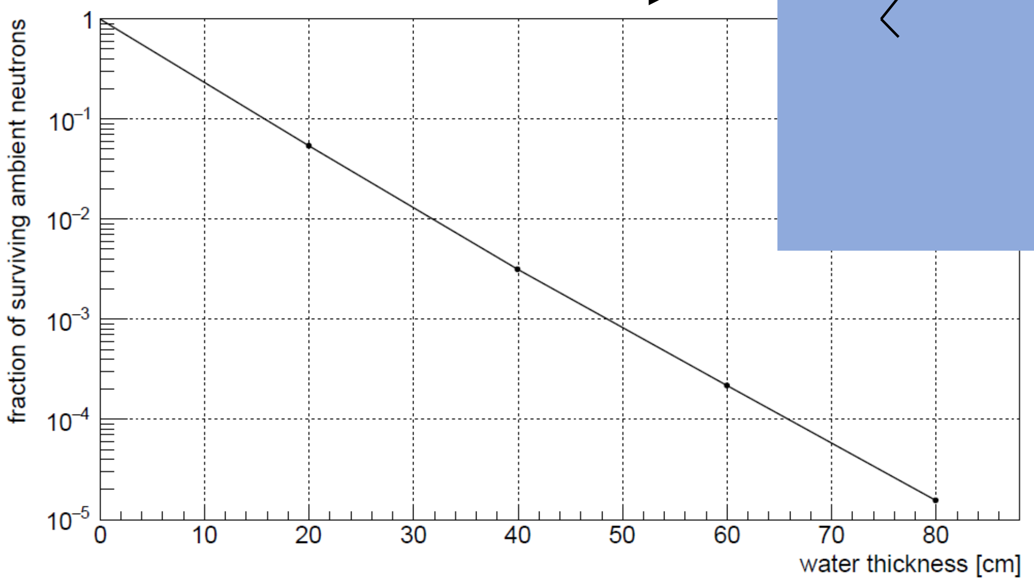


Integrated Flux above 500 keV: ~ $7.9 \cdot 10^{-7}$ n cm^{-2} s^{-1}

Flux in energy range 1 - 500 keV: ~ $6.5 \cdot 10^{-6}$ n cm^{-2} s^{-1}

- Simple simulation only using a 'box' made of H_20

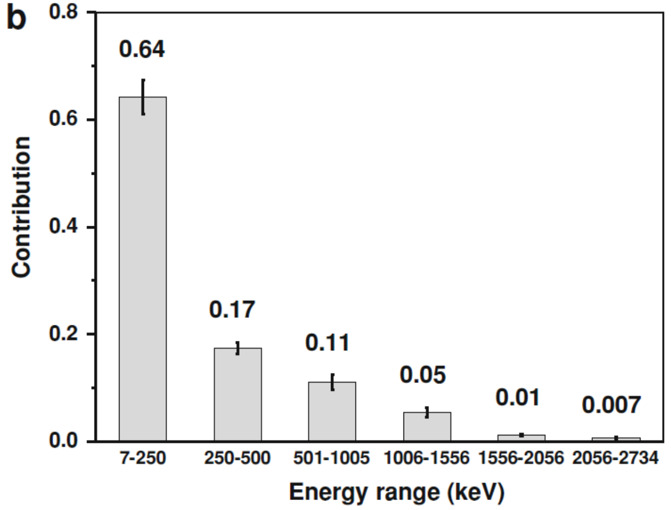




⇛ Ambient neutron background negligible!
No constraint for water tank thickness!

Ambient Gammas

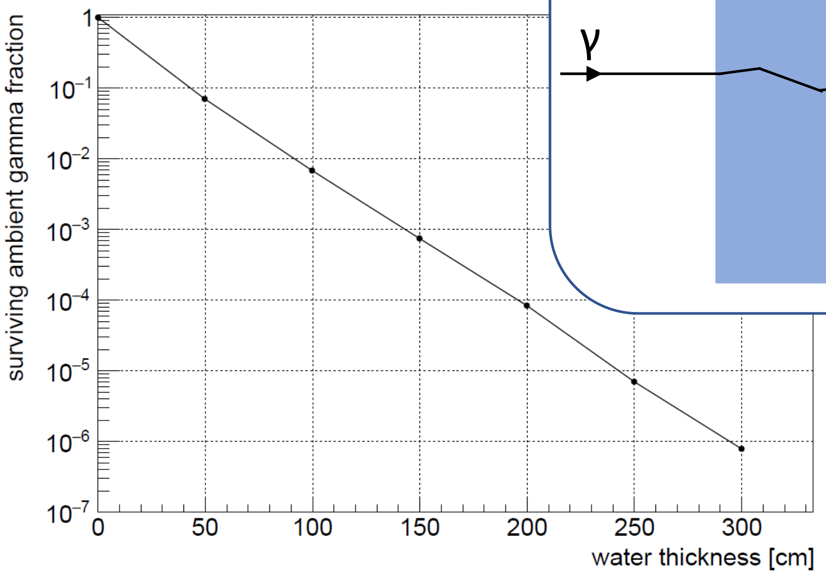
Malczewski, D. et al. J. Radioanal. Nucl. Chem. (2013) 295:749-754

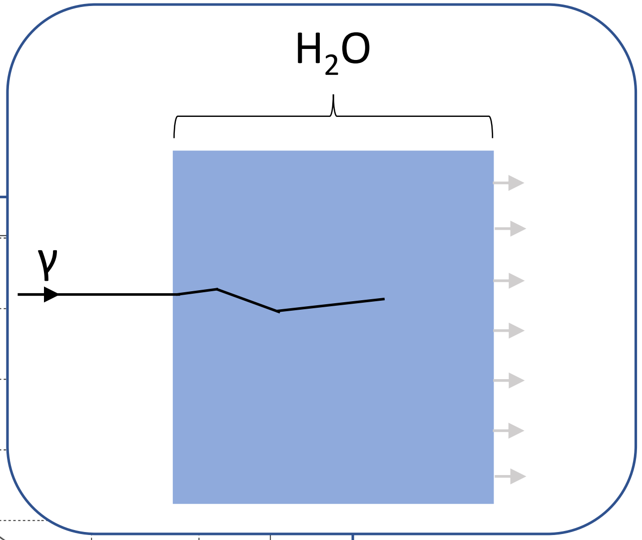


Total ambient flux
~0.23 cm^{-2} s^{-1}

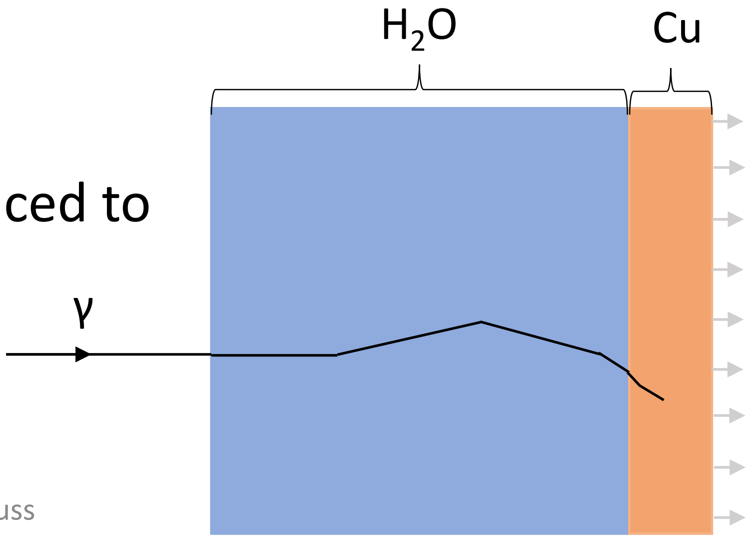
Ambient Gammas through water only:

Without inner shielding **O(10^{-6} cm^{-2} s^{-1})** reach the detector volume **after 3 m water**

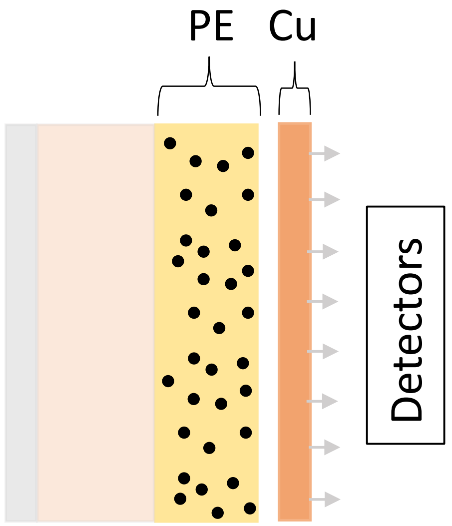




- e.g.: **3 m water + 8 cm Cu**: ambient gamma flux is reduced to **~ 2.2 · 10^{-8} cm^{-2} s^{-1}**



Radiogenic Gammas



Contamination levels assumed for Cu and PE:

C. Alduinoet al., JINST 11.07 (2016), P07009

U-238:	65	µBq/kg
Th-232:	2	µBq/kg
K-40:	23	µBq/kg
Co-60:	2	µBq/kg
Cs-137:	< 2	µBq/kg

U-238:	3800	µBq/kg
Th-232:	140	µBq/kg
K-40:	700	µBq/kg
Co-60:	< 100	µBq/kg
Cs-137:	60	µBq/kg

E. Aprile et al., Eur. Phys. J. C77.12 (2017), p. 890

Total gamma flux due to Cu contamination on inner surface: ~ 10^{-6} cm^{-2} s^{-1}
Total gamma flux due to PE contamination on inner surface: ~ 10^{-5} cm^{-2} s^{-1}

Conclusion of simulation:
The **gamma flux reaching the detector volume** is about **an order of magnitude higher when using PE** compared to not using PE as an innermost shield.

\+ **3 m of water → reduce the ambient gamma flux to (or below) the level of the intrinsic flux**. With a thin Cu shield, the ambient flux is definitely reduced below the intrinsic flux.

Radiogenic Neutrons

- Contamination levels used as input to SOURCES4A(C) code:
  (very radiopure reference materials have been selected)

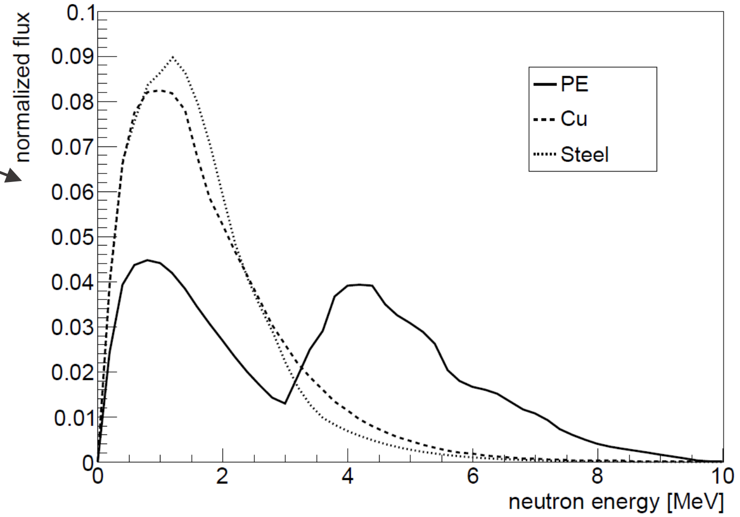
Material	^{238}U [mBq/kg]	^{235}U [mBq/kg]	^{232}Th [mBq/kg]	Reference	Neutron yield [cm^{-3} s^{-1}]
Steel	< 0.02	–	< 0.1	[42]	3.041×10^{-12}
Pb	< 0.01	–	< 0.07	[42]	1.249×10^{-13}
Cu	< 0.065	–	< 0.002	[43]	6.609×10^{-13}
PE	< 3.8	< 0.37	< 0.14	[44]	9.369×10^{-12}

[42] D. R. Artusa et al., Eur. Phys. J. C74 (2014), p. 3096

[43] C. Alduinoet al., JINST 11.07 (2016), P07009

[44] E. Aprile et al., Eur. Phys. J. C77.12 (2017), p. 890

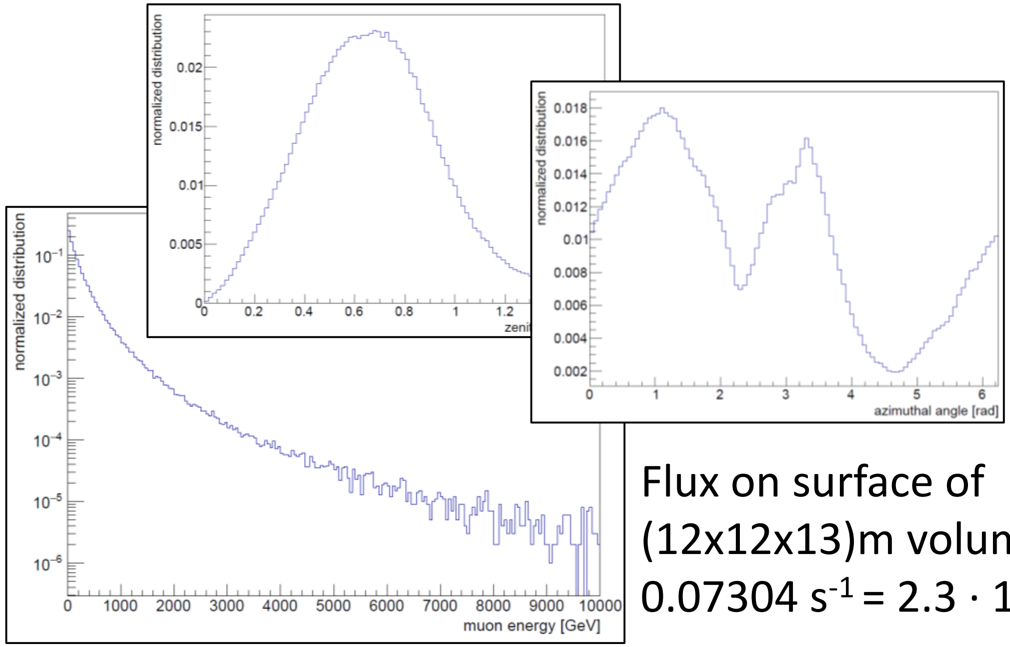
- SOURCES4A(C) output (neutron yield + spectrum)
  is used as input for Geant4 simualtion



Conclusion of simulation:
→ **Avoiding PE** as an innermost shield **reduces the radiogenic neutron background**
→ **Less material** (thin inner shield) leads to **less** sources for **radiogenic neutrons**

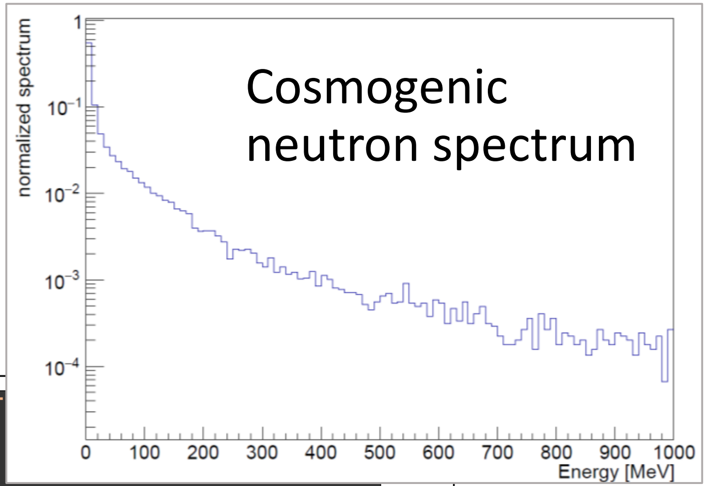
Cosmogenic Neutrons

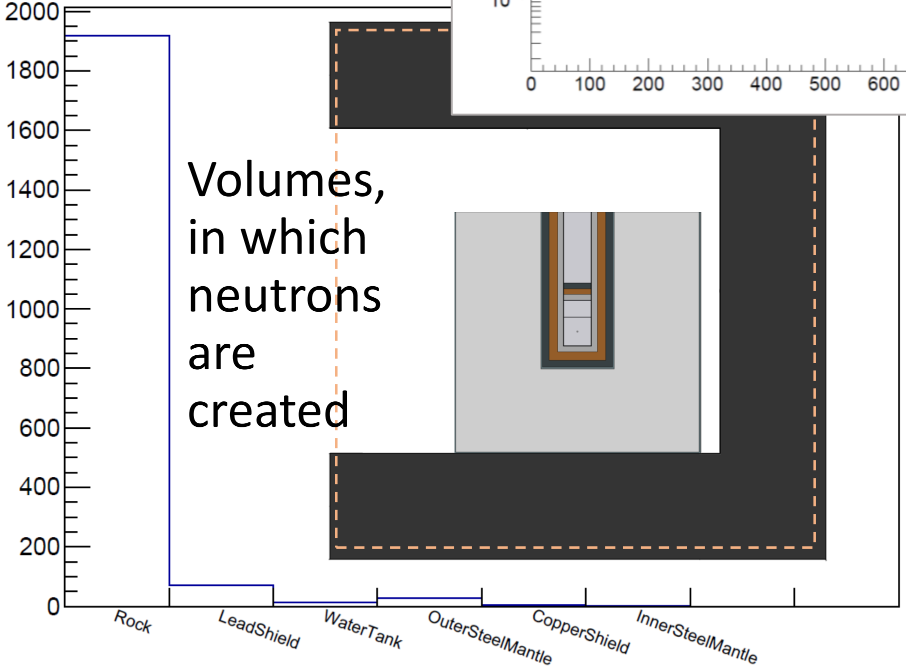
1) Muon propagation to LNGS laboratory using **MUSUN simulation**:



Flux on surface of (12x12x13)m volume:
$0.07304\ s^{-1} = 2.3 \cdot 10^{6}\ a^{-1}$

2) Interface to **Geant4 simulation**:





Conclusion of simulation:
If we avoid PE close to the detectors, we will also **omit using Pb to minimize neutron production**.

Background budget and goal

”less is more”

- Our **preferred optimal shielding design** omits using Pb and PE, and solely consists of a **water tank of 7 m diameter and height + 8 cm Cu** shielding
- Gamma-background can be discriminated via two-channel readout
- Dangerous Background: neutrons
- Goal: background-free experiment, i.e. < 1 count kg^{-1} yr^{-1} in signal region

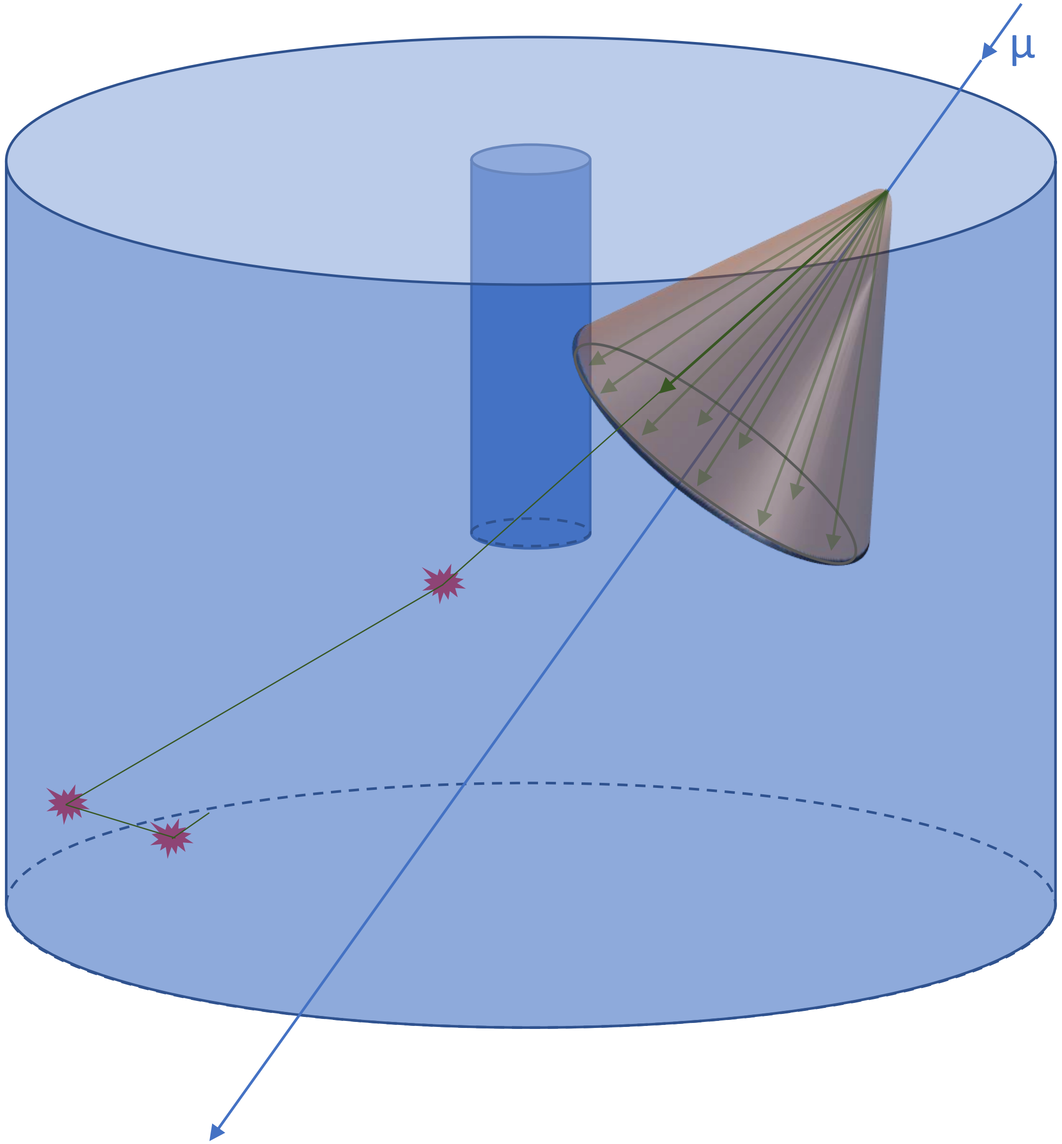
  → No exact count estimation possible with simple simulation setup

  → **Estimation** yields **O(1 count kg^{-1} yr^{-1}) for cosmogenic neutrons** and **O(10^{-2} count kg^{-1} yr^{-1}) for radiogenic neutrons**

  → Cosmogenic neutron background is ~ 2 orders higher than radiogenic neutron background without veto

  → **need for an active muon veto**

Geant4 Simulation – Tracking Cerenkov Light in the Water Tank



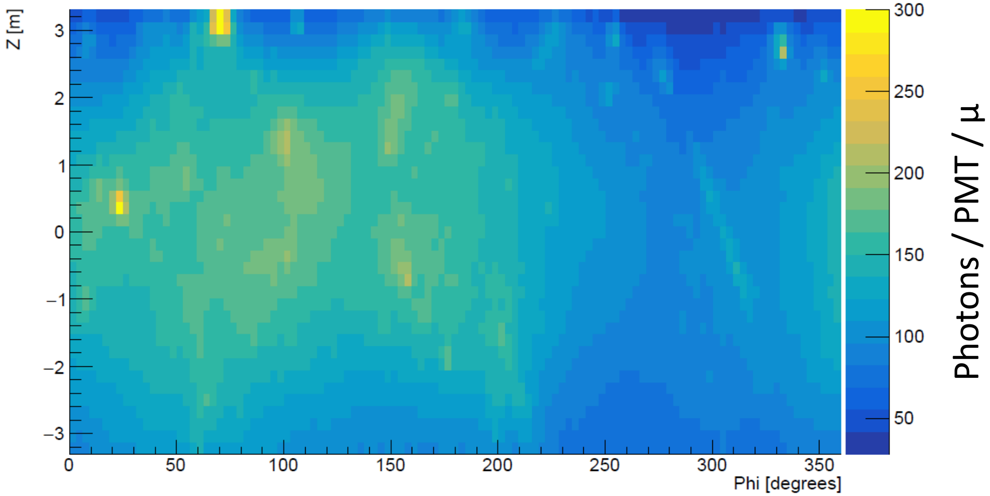
Cerenkov light cone created when e.g. a cosmic muon traverses the water

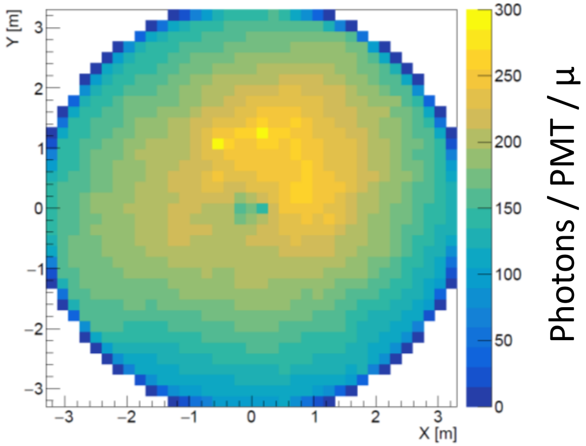
Storing the energy, hit positions and hit times of each photon

Hit Patterns on Tank Walls (Reflective Foil)

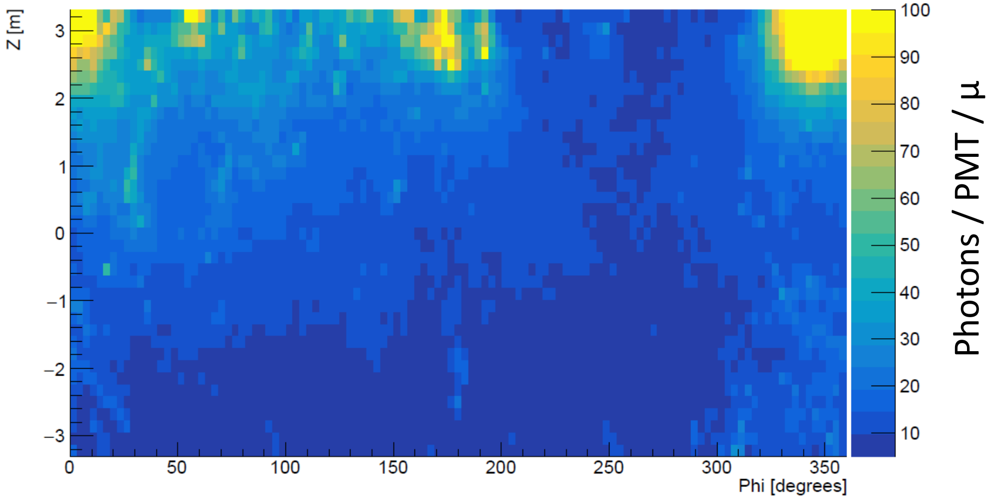
- Distinguish: - "**Muon Events**" (= muon (+ secondaries) travelling through water tank)
  - "**Shower Events**" (= only secondary particles travel through water tank)
- Only considering "dangerous" events, in which a neutron reaches the inner shielding

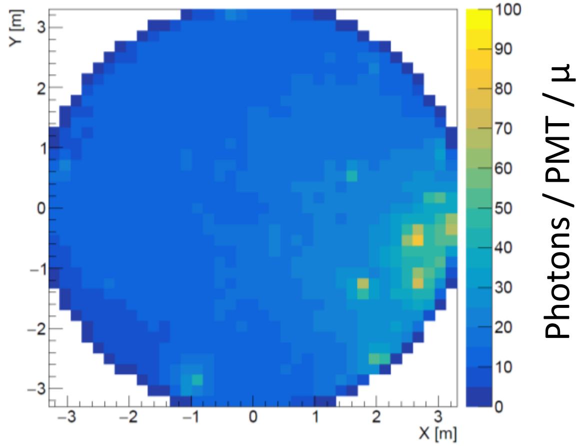
Muon Events





Shower Events



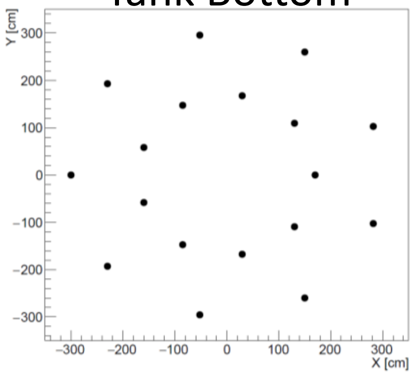


Tagging Efficiencies

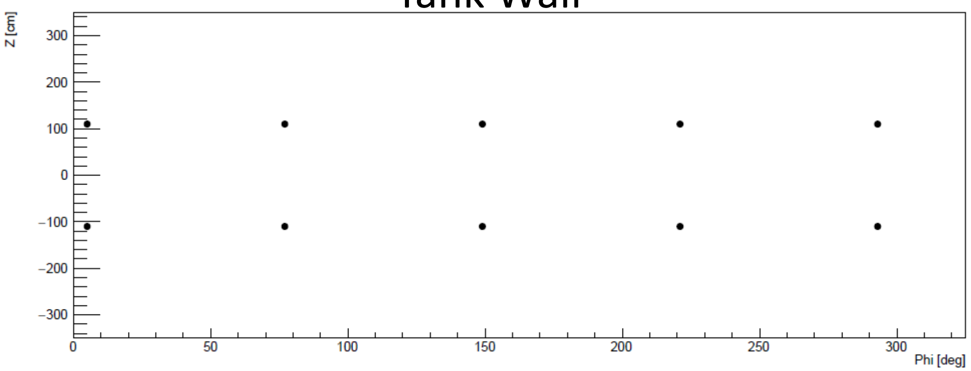
Characteristics(size, quantum efficiency, collection efficiency, etc.) **of Hamamatsu 8-inch PMTs were used**

Different **PMT arrangements** were tested, e.g.:

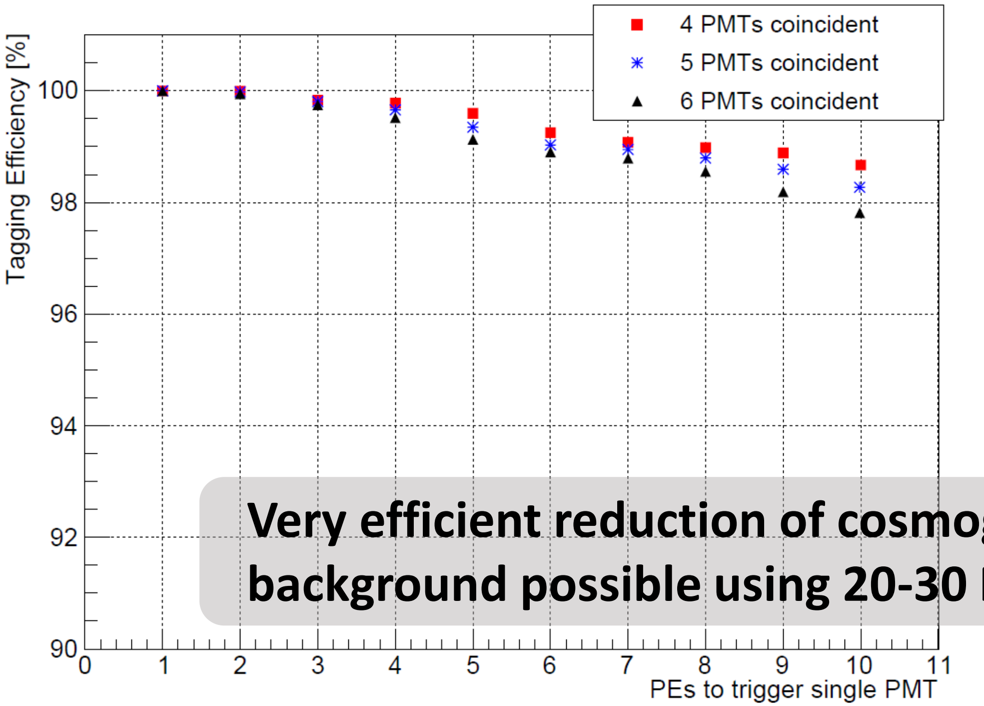
Tank Bottom



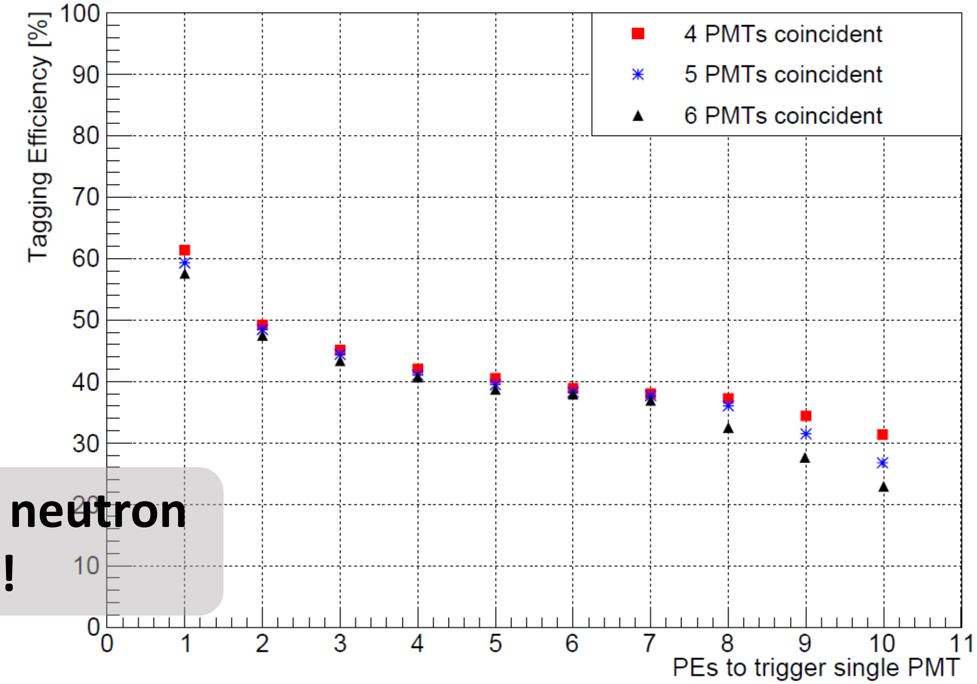
Tank Wall



Muon Events



Shower Events



Very efficient reduction of cosmogenic neutron background possible using 20-30 PMTs!

Conclusion

- COSINUS has access to **very radiopure NaI crystals (~ 10 ppb K)**
- Operating **NaI as a cryogenic detector** works and provides **particle discrimination via two-channel readout**
- **Background simulations** have been made in order to design a **dedicated shielding setup** for the experiment, **reaching the background goal**
  - ➢ The preferred optimal solution uses a **water tank of 7 m diameter and height** in combination with an inner shield solely made of **8 cm Cu**
  - ➢ The water tank will be used as an **active muon veto**

Thank you for your attention!

COSINUS

Additional Slides

(Extra Material)

Two Phases: COSINUS 1π and 2π

COSINUS 1π: Initial Phase

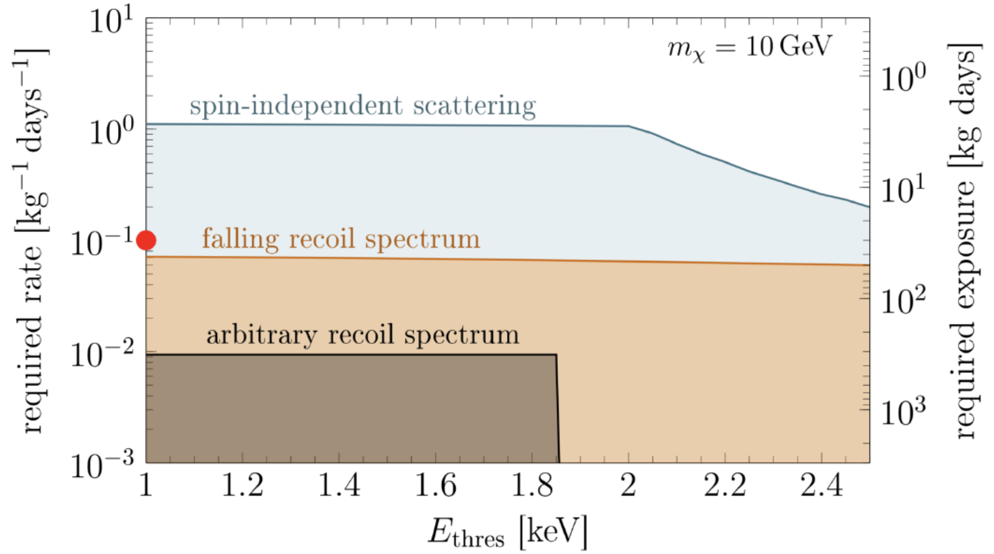
- 1st measurement with 10 modules for 100 kg days
- Setup planned for 25 modules for 1000 kg days

Goal: confirm or rule out nuclear origin of DAMA signal

COSINUS 2π

- Increased target mass, upgraded facility

Goal: modulation search



F. Kahlhöfer, K. Schmidt-Hoberg,K. Schäffner, F. Reindl and S. Wild, JCAP 1805 (2018) no.05, 074