COSINUS

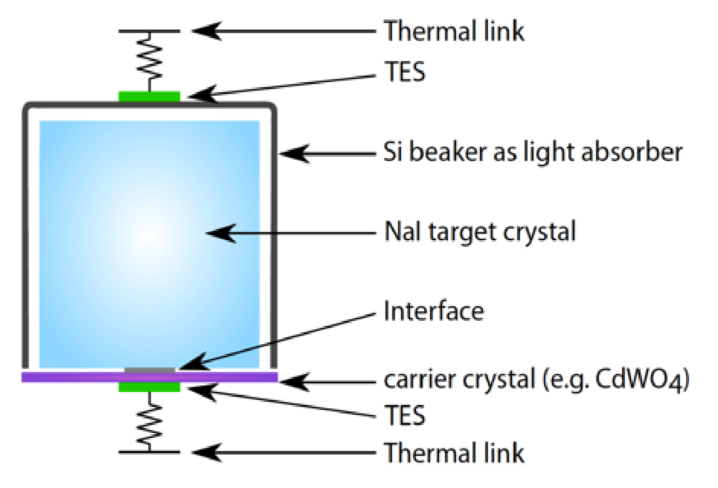
…a NaI*ce* experiment

Natalia Di Marco

GSSI & INFN

Method

Eur. Phys. J. C (2016) 76:441



LIGHT YIELD = $\frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$

Performance goal

- E_{th} = 1 keV (5 σ_{Phonon})
- σ_{Phonon} = 0.2 keV
- σ_{Light} = 0.11 keV_{ee}
- 4% of deposited energy measured as light

Gross exposure: 100 kg-days

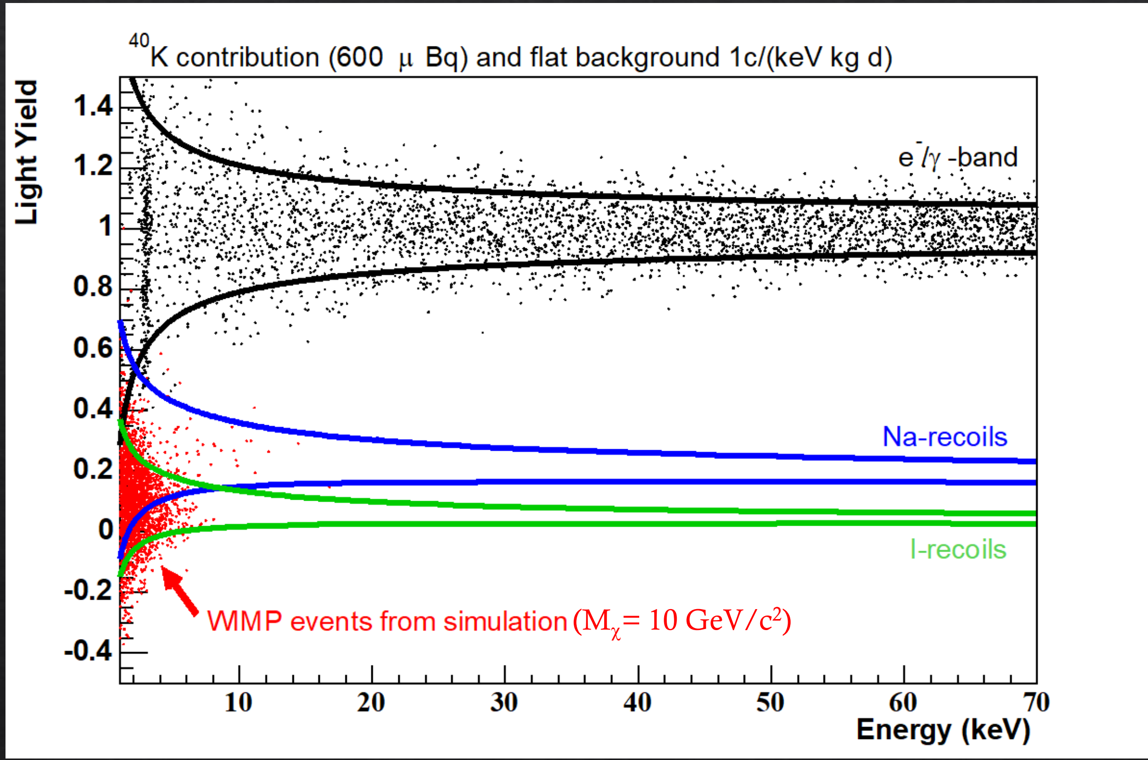
Background:

- 1 cts/keV/kg/yr
- 600 μBq ^{40}K

Light quenching factor

(from Tretyak, Astropart. Phys. 33, 40 (2010))

- Na → 0.3
- I → 0.1



Motivation

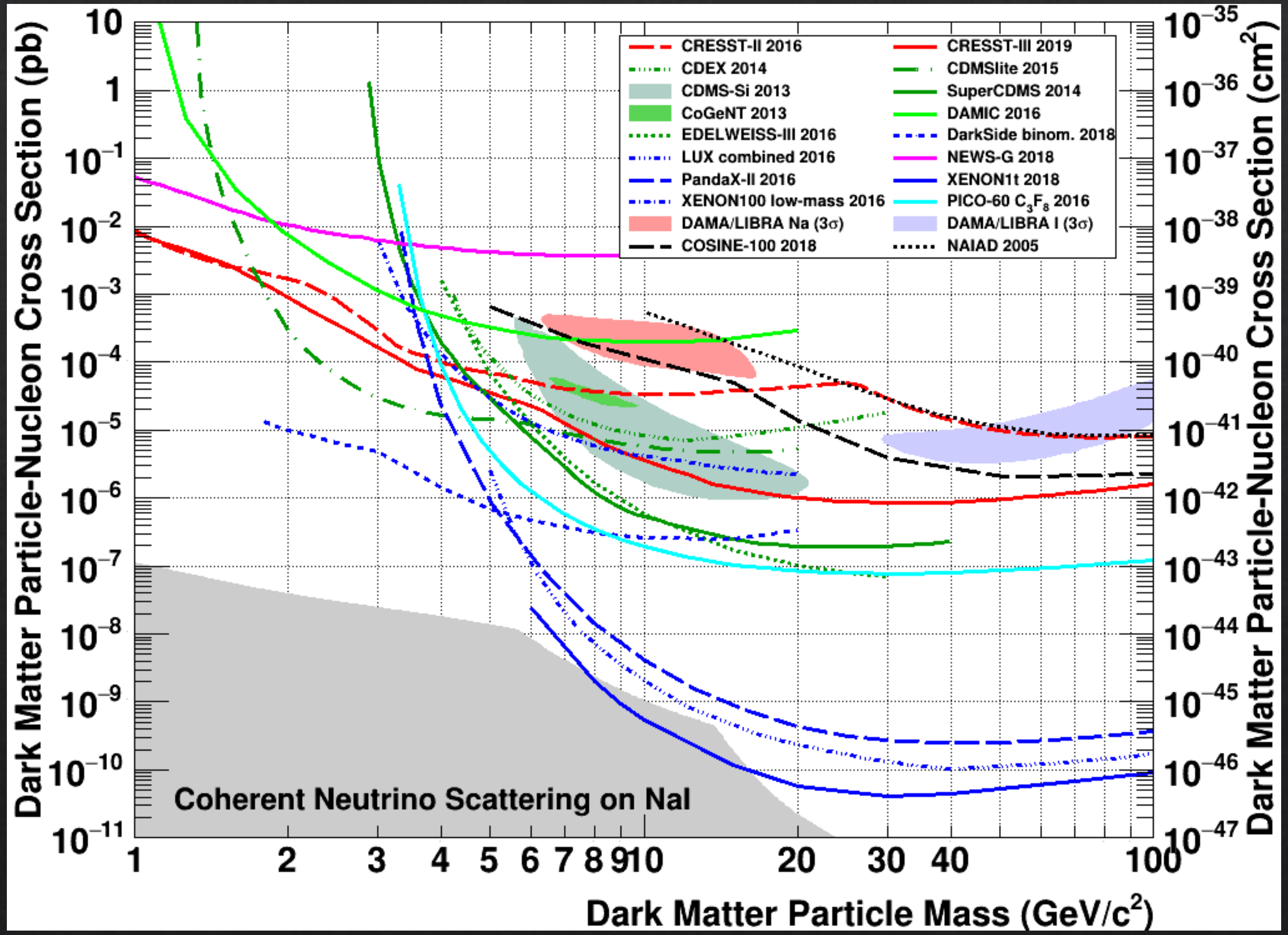
$$\frac{dR}{dE_r} = N_N \frac{\rho_0}{m_\chi} \int_{v_{min}}^{v_{max}} d\vec{v}\, f(\vec{v}) v \,\frac{d\sigma}{dE_r}$$

UNKNOWNS:

Astrophysics

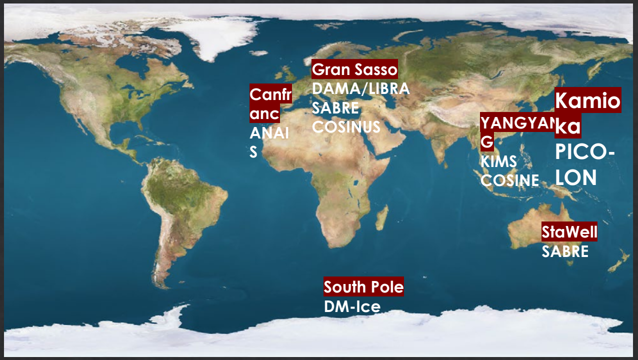
Particle/Nuclear Physics

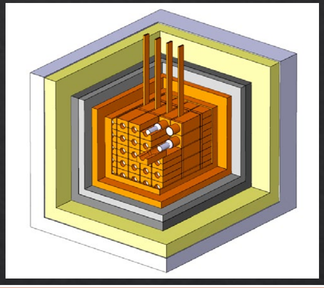
Detector Properties

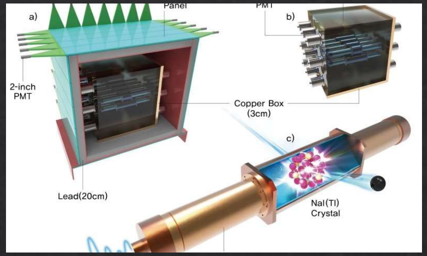


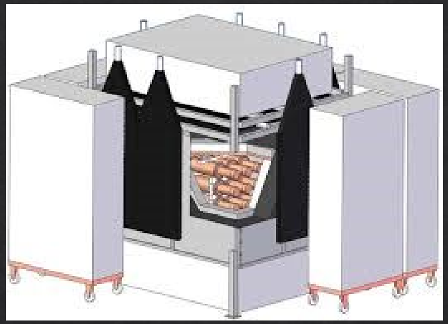
Target material dependence:
test DAMA with NaI experiment(s)

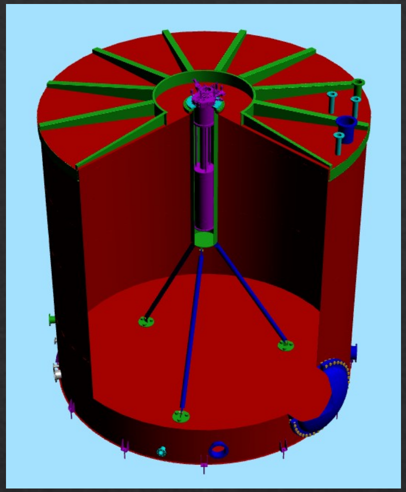
NaI exp. comparison









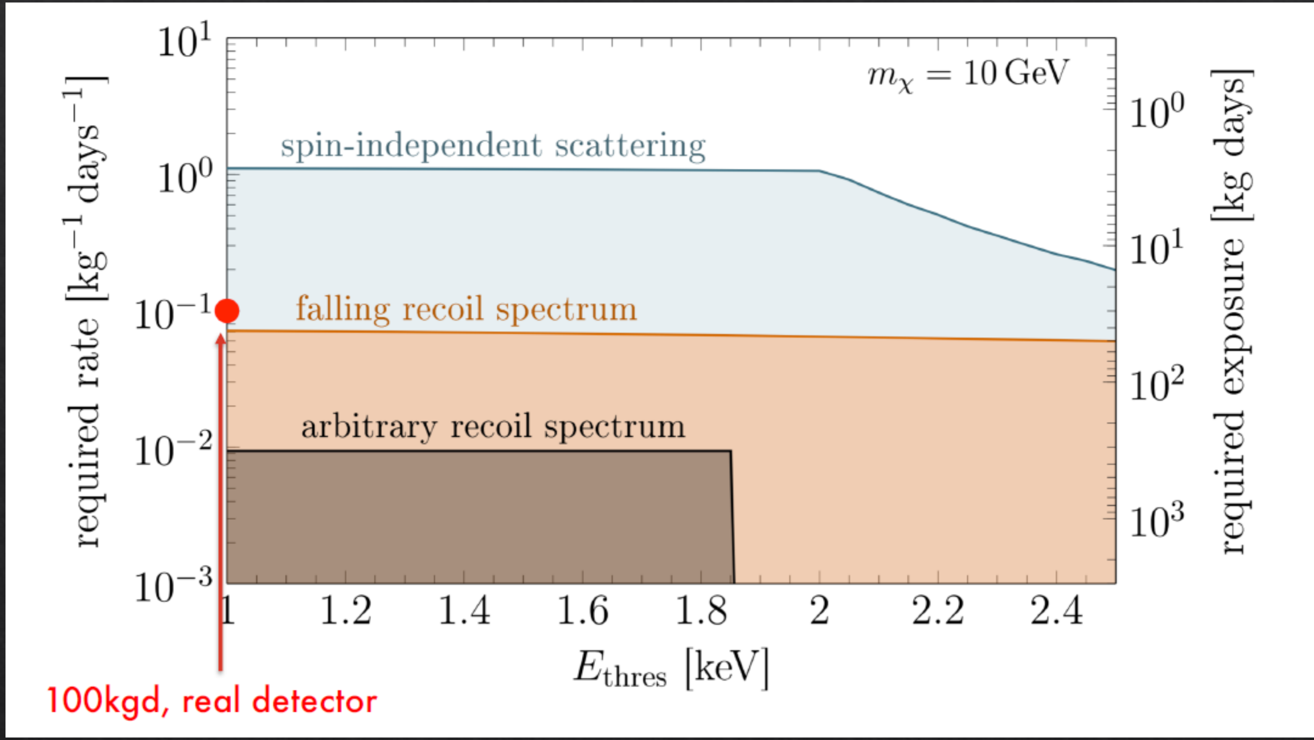


	DAMA	COSINE	ANAIS	COSINUS
Threshold	1 keV_{ee}	2 keV_{ee}	1 keV_{ee}	Phonon det. 1 keV Light det. : 600 eV_{ee}
Mass	250 kg	106 kg	112 kg	11 kg (COSINUS-2π)
LY	6.0 -10.0 ph.e./keV (phase2)	15 ph.e./keV	15 ph.e./keV	32 ph.e./keV
Particle ID	NO	NO	NO	✓ YES

COSINUS advantages:

- **particle identification capability**
- **reliable energy scale** (independent from the uncertainties on the QFs)
- **better energy resolution**
- **lower threshold for nuclear recoils**

Physics Reach



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

Halo-independent constraints

- Blue → spin-independent scattering
- Light brown → any recoil spectrum falling with energy
- Dark brown → exclusion (95% C.L.) without presuming any model on the dark matter halo or interaction properties except for the assumption that dark matter induces nuclear recoils.

COSINUS-1π → 100 kg days: exclude the DAMA region by about two orders of magnitude under standard assumption
10 crystals, 50 gr each → 1 year of data taking
1000 kg days: 95% C.L. exclusion in a model independent way
20 crystals, 50 gr each → 3 year of data taking,
20 crystals, 150 gr each → 1 year of data taking

COSINUS-2π → search for **modulation**

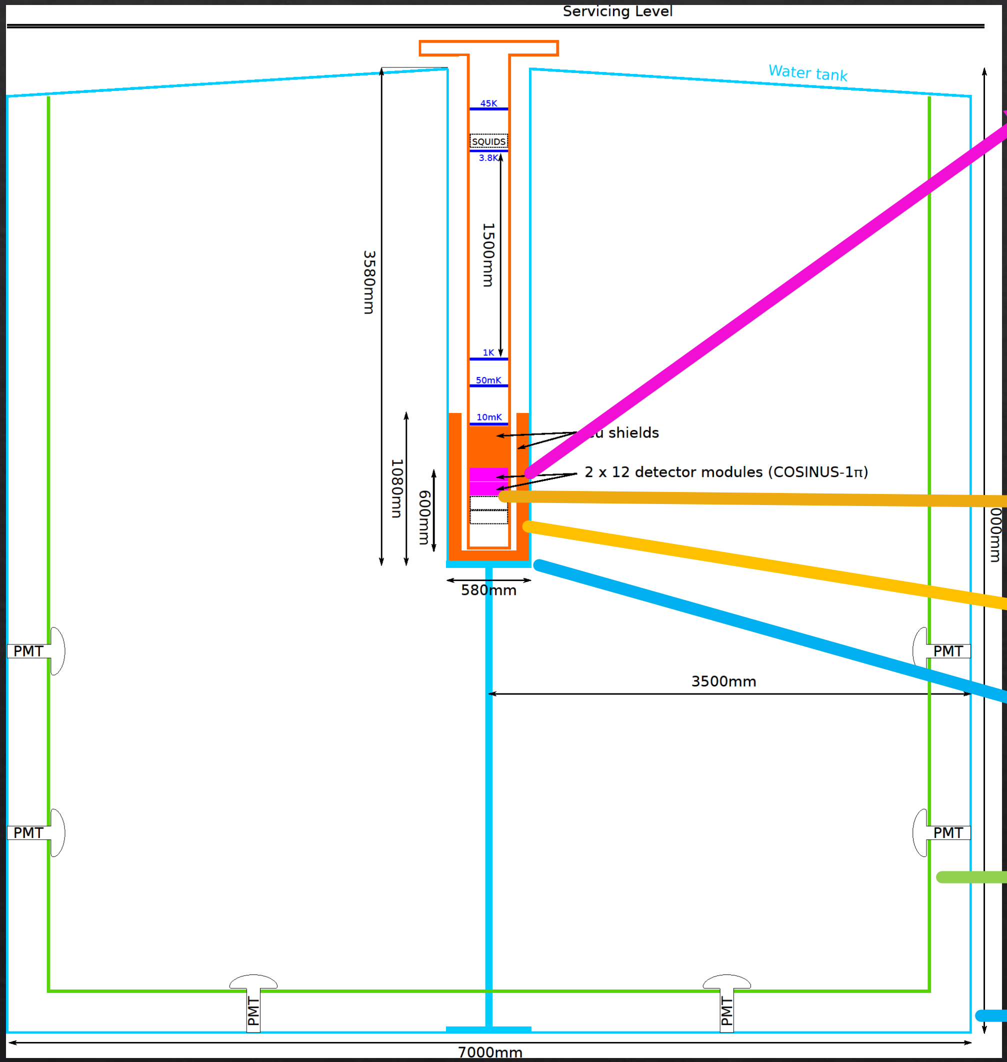
R&D summary

STATUS:

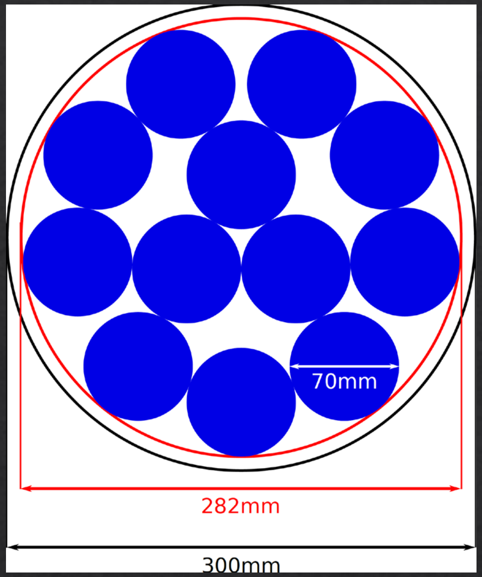
- NaI threshold about 5 keV (design goal –> 1 keV)
- LD resolution 15 eV (goal achieved)
- 13% measured in light in pure NaI (design goal was 4%)
  10% measured in Tl-doped NaI
- Good radiopurity (goal achieved)

…Ready to start!

The experiment



Detector
COSINUS-1π: up to 24 detectors (50 - 150 gr each)
COSINUS-2π: up to 72 detectors (50 - 150 gr each)



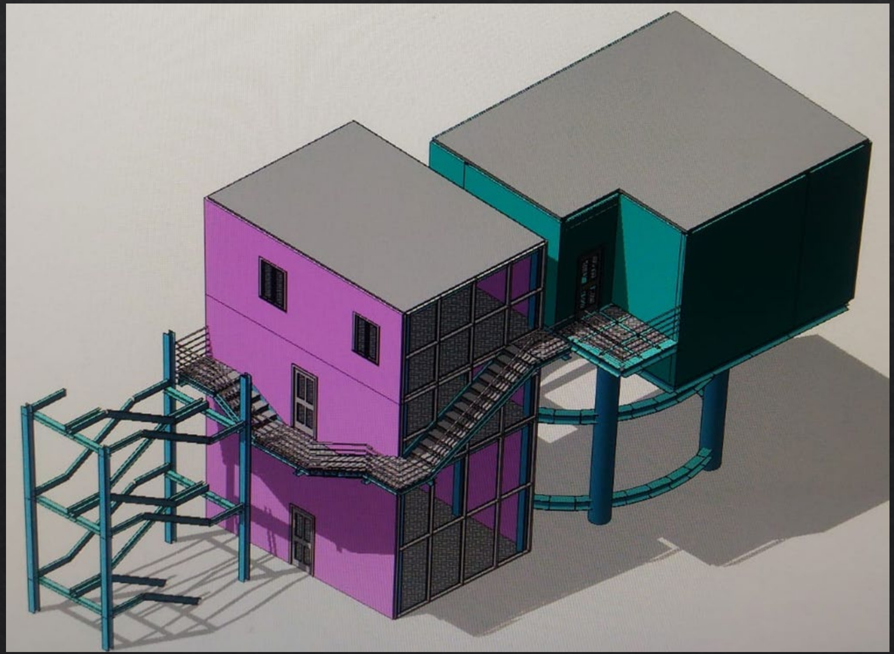
Cryostat

Shielding

Dry well

Cherenkov Muon Veto System

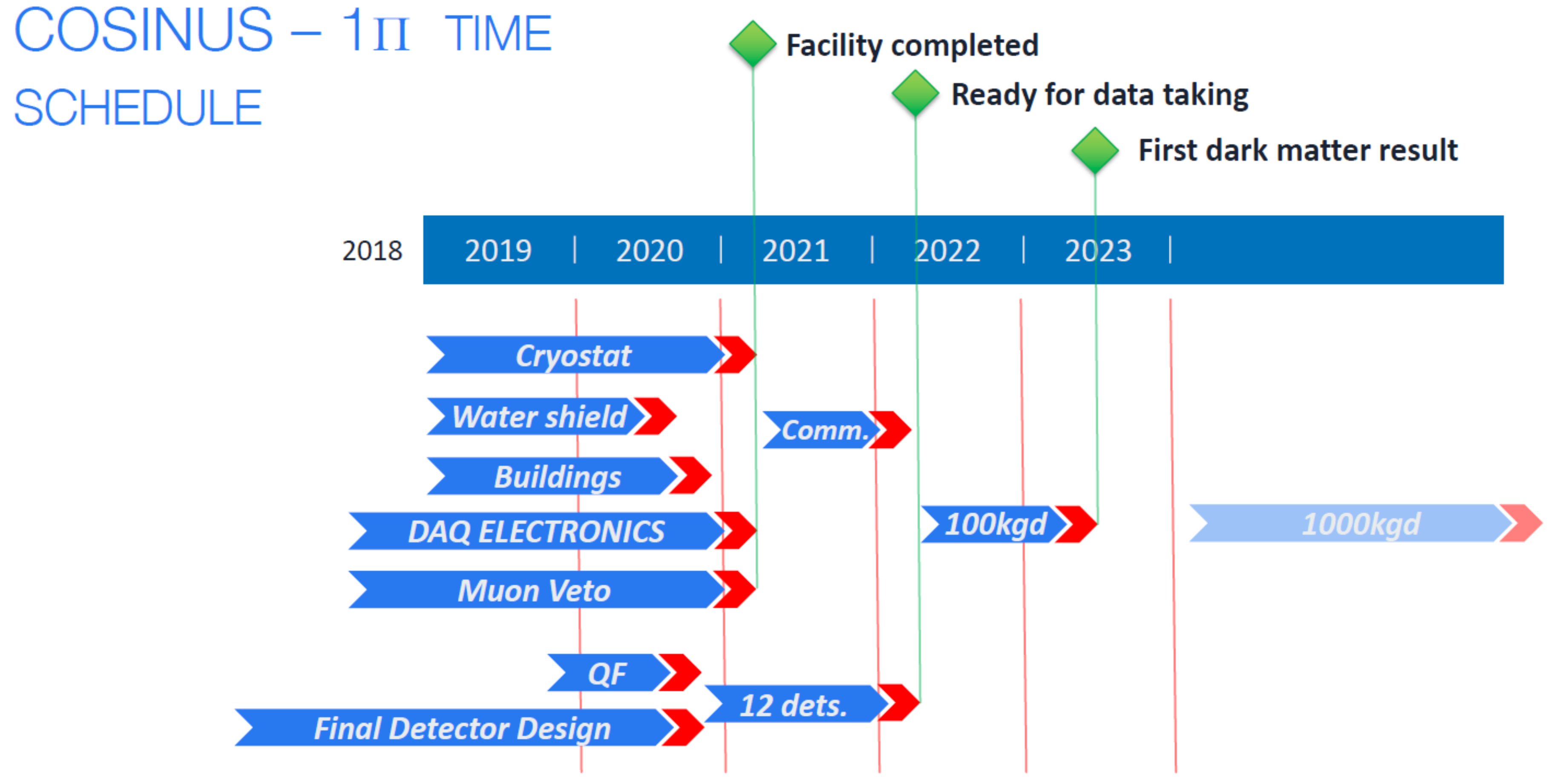
Water Tank



Paper ready to be submitted to EPJC

Time schedule

Proposal submitted to LNGS Scientific Committee in March 2019
Letter of Intent submitted to CSNII in June 2019
LNGS TDR → October 2019 LNGS Scientific Committee



Plan for 2020

- Phonon pulse formation and propagation: study in cooperation with Physics Dep. L'Aquila University
- EXFAS spectroscopy measurements (@Diamond Facility - Cambridge) vs Tl %: beamtime 3 – 7 July 2020

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- TES optimization:

  New TES in production @ Max Planck, meaurement @LNGS (underground facility) in March2020
- Light Yield vs Tl concentration, Light Yield vs Temperature @LNGS (above ground setup) in Spring2020

  Measurement of the LY on different NaI samples doped with different Tl percantage as a function of temperature from room temperature to 15K
- QFs measurement vs Tl concentration

  1) @RoomTemperature: meaurement @ TUNL (Triangle Universities Nuclear Laboartory) in April 2020

  2) @Cryogenic temperature: meaurement @LNGS (underground facility)) in March2020

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  2) @Cryogenic temperature: meaurement @LNGS (underground facility)) in March2020
- Test of read-out electronics prototype
- Finalization of water cherenkov veto design studies
- Start the construction of the apparatus

The Collaboration

GSSI
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V. Zema

INFN - LNGS
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M. Balata
P. Martella

INFN - Sezione Roma 1
I.Dafinei

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F. Petricca
F. Pröbst
R. Stadler
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2 x PhD student (funding secured)
Technician (funding secured)

Institute for High Energy Physics Austrian Academy of Sciences and Technical University Vienna, Vienna
F. Reind (Spokesperson)
J. Schieck
S. Fichtinger
M. Friedl
A. Fuss
D. Schmiedmayer
C. Schwertner
M. Stahlberg
PhD Student

SICCAS - Shanghai Institute of Ceramics, Shanghai
Y. Zhu

Helsinki Institute for Physics
Agreement on participation (@ July 2019)
Concrete discussion on cryogenic expertise (@September 2019)

BACKUP

COSINUS-1π in the International Scientific Panorama

What happens if COSINE/ANAIS in 2022/2023

confirm DAMA

do not confirm DAMA

More attractive scenario (obviously):

Then we definitively need an other technique (but same target material) to cross check the signal, the energy scale and discover if the signal is in the electron or nuclear recoil band (= study the interaction properties).

OK. Still DAMA is there. Still DM to discover.
And what about energy scale?

- What is DAMA «signal»? Systematic? New background? Being in the same location is an advantage

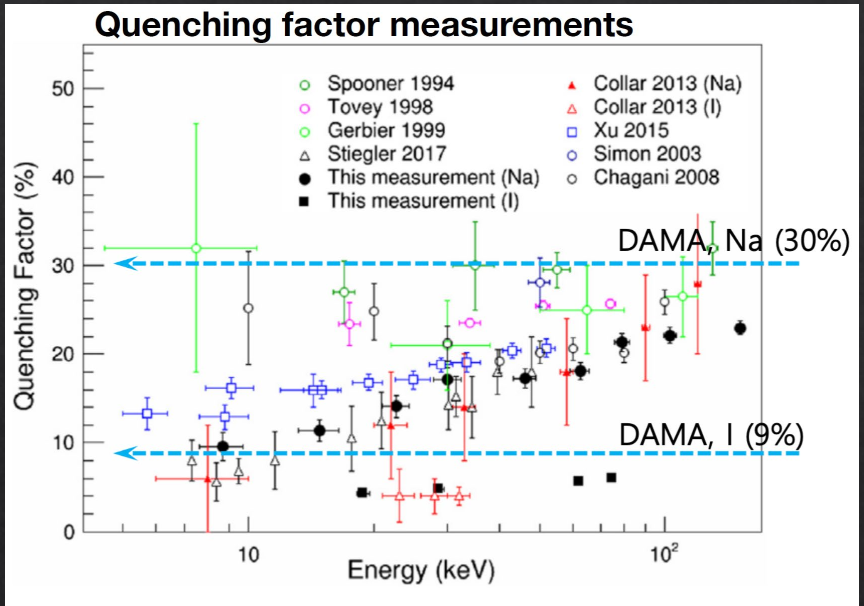
- Systematic in ANAIN/COSINE? Energy scale for DAMA, COSINE and ANAIS indeed depends on QFs, which in turn could depend on Tl concentration.

In contrast, COSINUS measures the energy scale with the phonon signal, which is independent from light quenching. Thus, the COSINUS goal threshold (1 keV) is always lower than that of competitors even for the unrealistic assumption of no quenching (QF=1)

- We can definitively increase the mass and do DM modulation search

The QFs problem

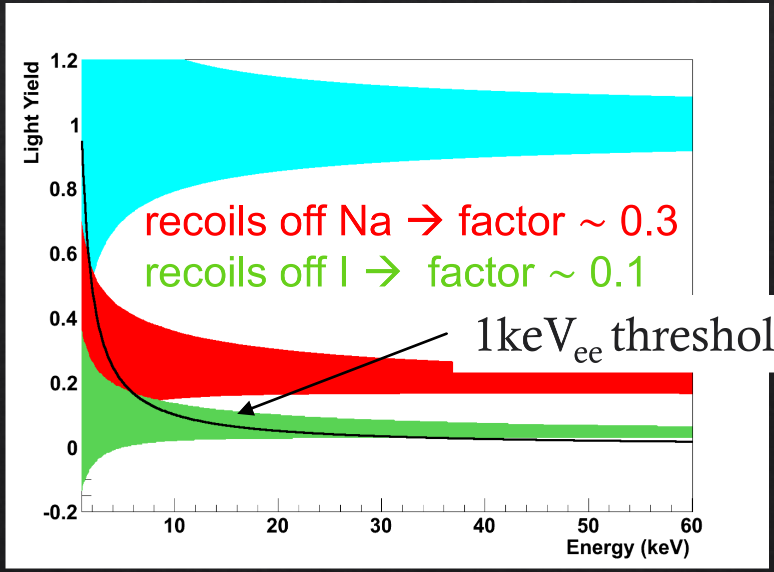
Astropart. Phys. 108 50-56 (2019)



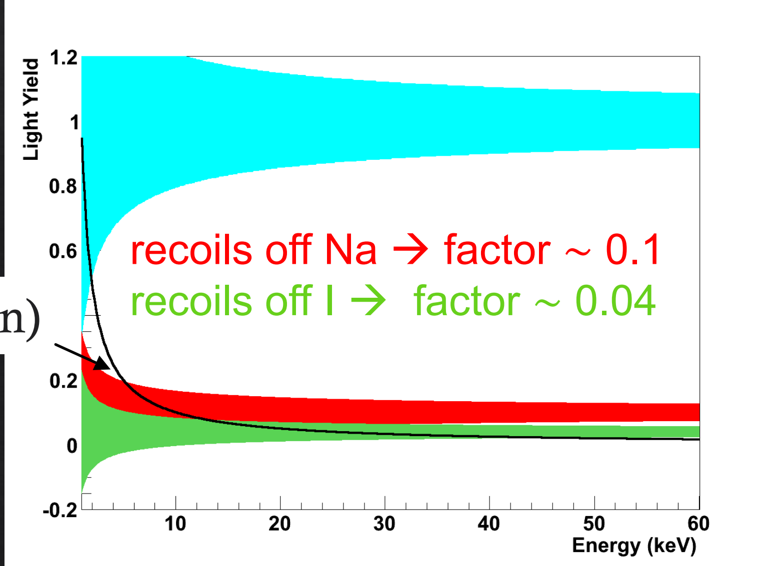
Quenching factors are uncertain

→

Uncertainty on nuclear recoil energy scale



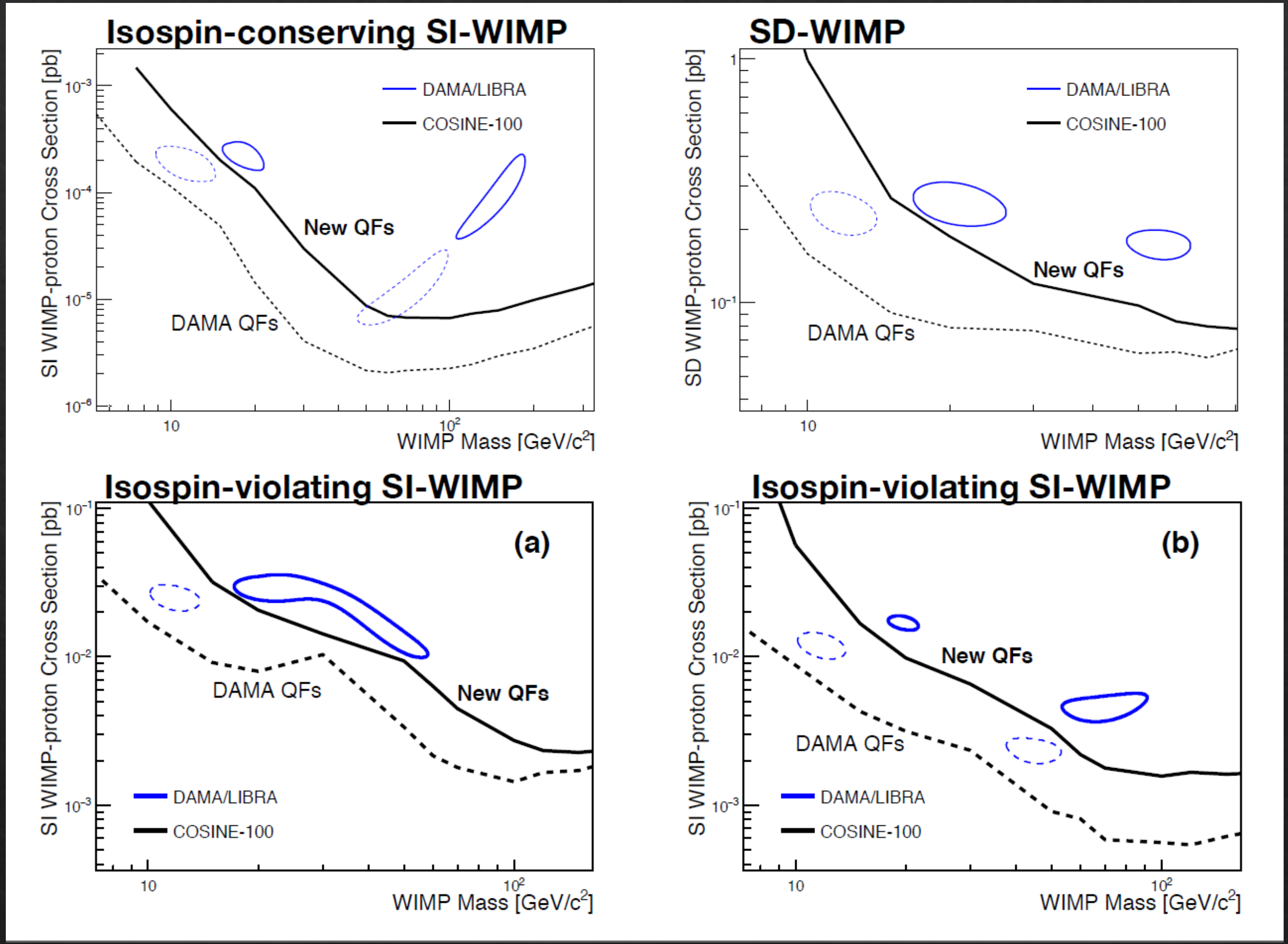
$1keV_{ee}$ threshold (light detection)



The QFs problem

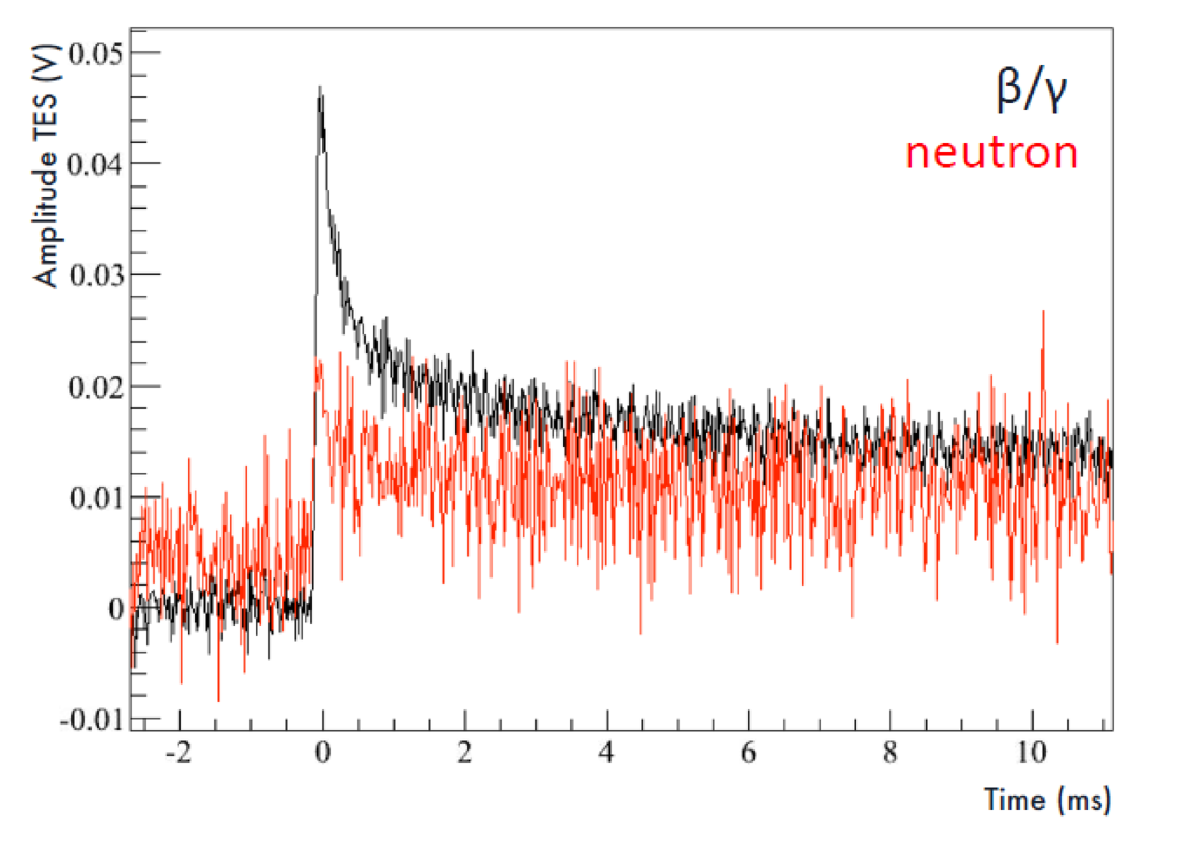
arXiv:1907.04963v2 [hep-ex]

Y. J. Ko (COSINE-100) @ TAUP 2019



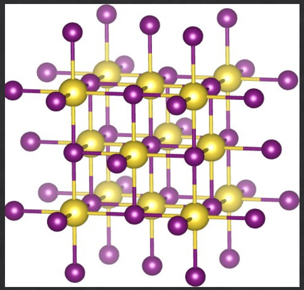
R&D results

Na6 – particle discrimination



- Different pulse-shapes for neutron and β/γ-events, NOT observed for other materials (CRESST, CaWO4)
- TES not yet well adapted to slow phonon signals of NaI
- TES Optimization
- Simulation/study of phonon signal pulse formation (solid state physics, L'Aquila university)

Vibrational Properties of Sodium Iodine crystal
First-Principles Density Functional Theory



G. Profeta, A. Filipponi and M. Nardone

PHYSICAL REVIEW VOLUME 119, NUMBER 3 AUGUST 1, 1960

Lattice Dynamics of Alkali Halide Crystals*

A. D. B. WOODS, W. COCHRAN,† AND B. N. BROCKHOUSE
Physics Division, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada
(Received March 11, 1960)

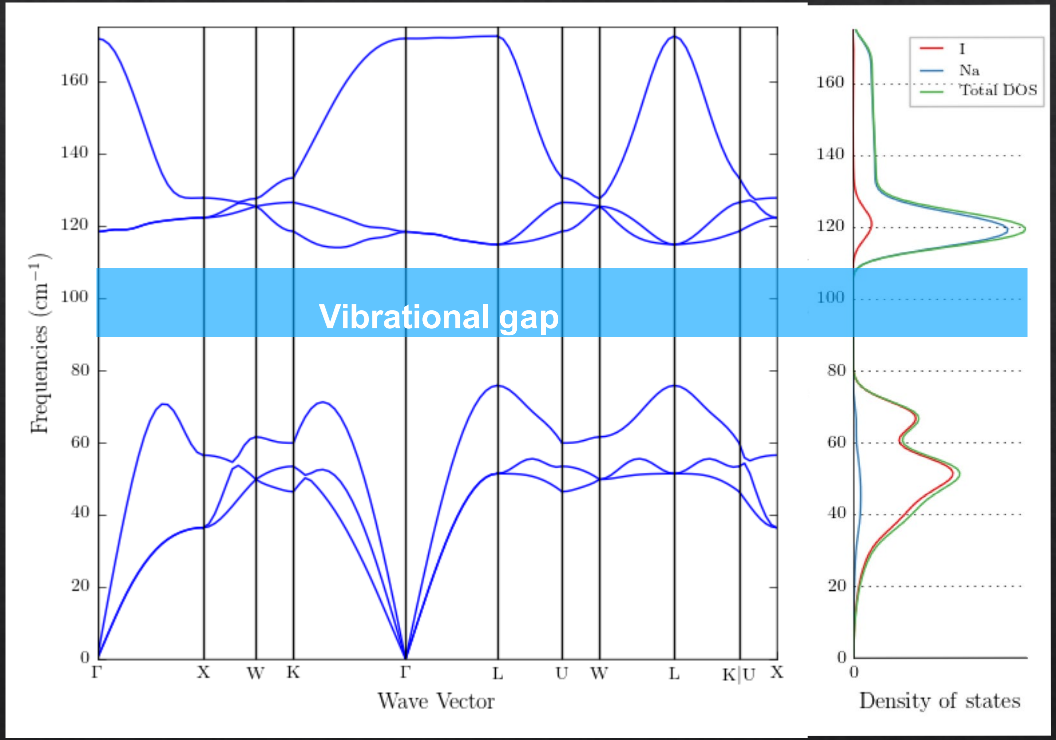
The paper comprises theoretical and experimental studies of the lattice dynamics of alkali halides. A theory of the lattice dynamics of ionic crystals is given based on replacement of a polarizable ion by a model in which a rigid shell of electrons (taken to have zero mass) can move with respect to the massive ionic core. The dipolar approximation then makes the model exactly equivalent to a Born-von Kármán crystal in which there are two "atoms" of differing charge at each lattice point, one of the "atoms" having zero mass. The model has been specialized to the case of an alkali halide in which only one atom is polarizable, and computations of dispersion curves have been carried out for sodium iodide. We have determined the dispersion $\nu(\mathbf{q})$ relation of the lattice vibrations in the symmetric [001], [110], and [111] directions of sodium iodide at 110°K by the methods of neutron spectrometry. The transverse acoustic, longitudinal acoustic, and transverse optic branches were determined completely with a probable error of about 3%. The dispersion relation for the longitudinal optic (LO) branch was determined for the [001] directions with less accuracy. Frequencies of some important phonons with their errors (units 10^{12} cps) are: TA[0,0,1]1.22±0.04, LA[0,0,1]1.82±0.06, TA[$\frac{1}{2}$,$\frac{1}{2}$,$\frac{1}{2}$]1.52±0.05, LA[$\frac{1}{2}$,$\frac{1}{2}$,$\frac{1}{2}$]2.32±0.06, TO[0,0,0]3.6$_0$±0.1, TO[0,0,1]3.8$_0$±0.1, TO[$\frac{1}{2}$,$\frac{1}{2}$,$\frac{1}{2}$]3.5$_0$±0.1. The agreement between the experimental results and the calculations based on the shell model, while not complete, is quite satisfactory. The neutron groups corresponding to phonons of the LO branch were anomalously energy broadened, especially for phonons of long wavelength, suggesting a remarkably short lifetime for the phonons of this branch.

NaI: Phonon dispersion

Longitudinal Optical (LO)

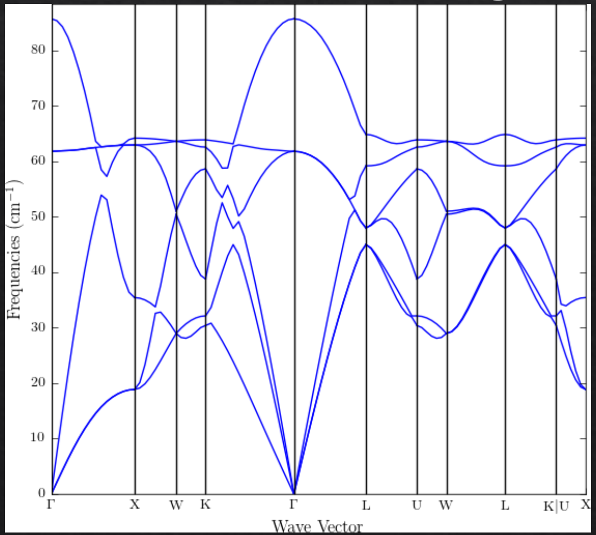
Transversal Optical (TO)

Acoustic Phonons (TO)



M_{Na}=23 amu M_I=127 amu M_{Na} / M_I =0.18

CsI: No Vibrational gap



M_{Cs}=133 amu M_I=127 amu M_{Cs} / M_I =1.04

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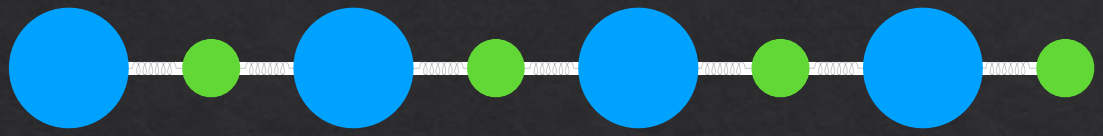
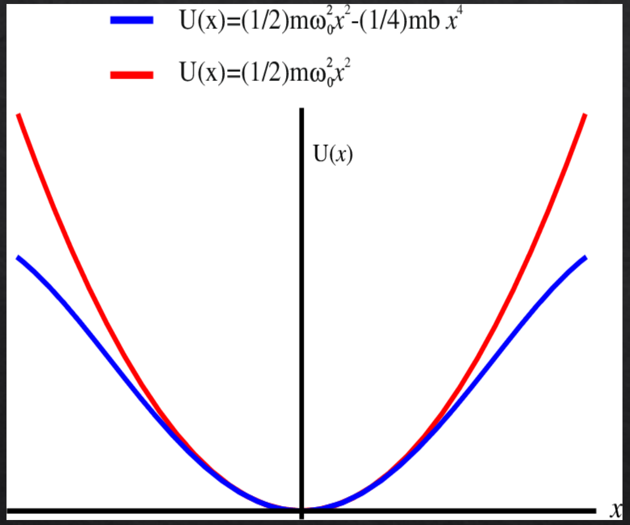
Sodium Iodine Thermal Detectors:
A Toy-model one-dimensional chain with 100 atoms

G. Profeta, A. Filipponi and M. Nardone

Intrinsic localized modes observed in the high-temperature vibrational spectrum of NaI., *Phys. Rv. B* **79**, 134304 (2009).

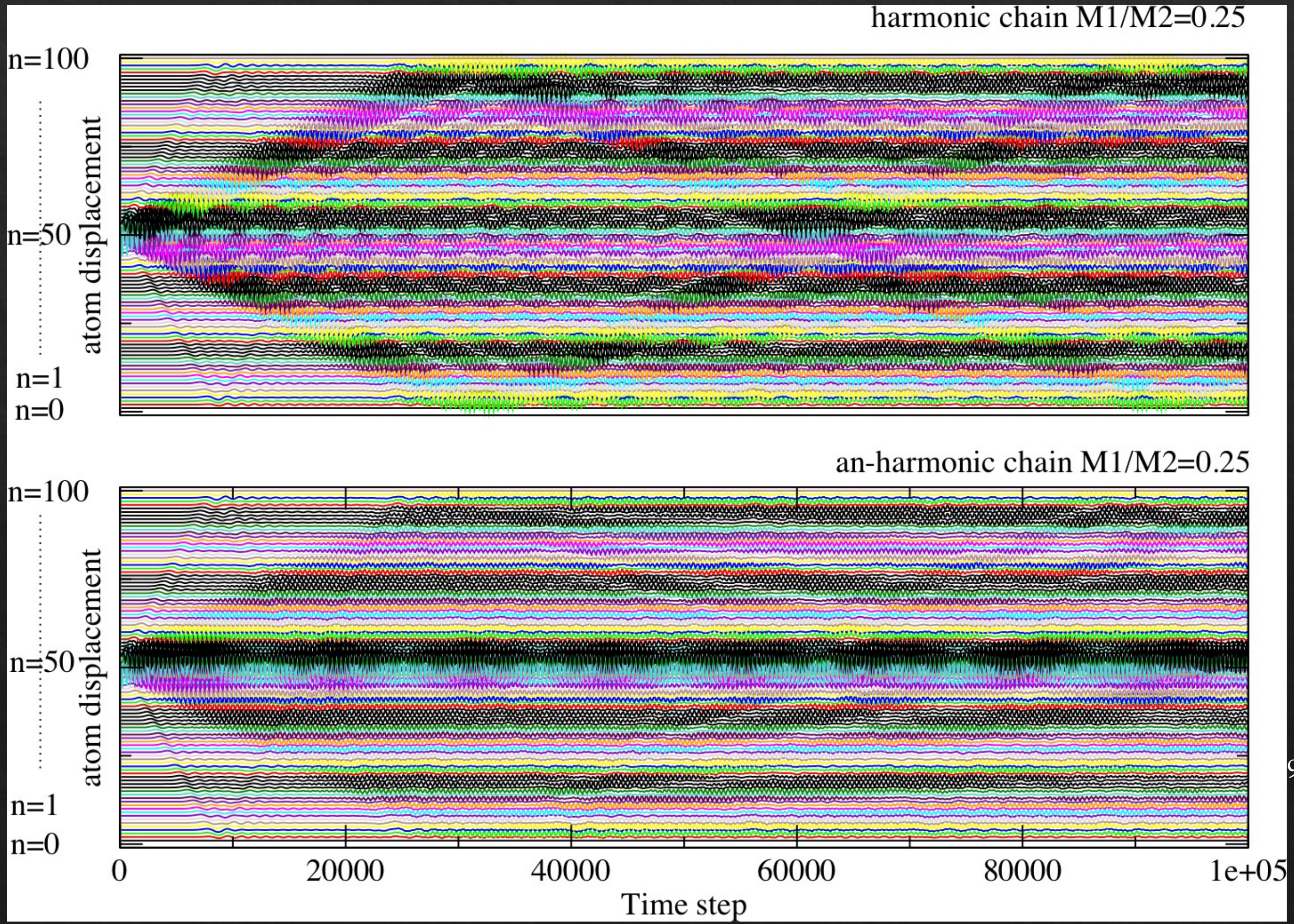
$U(x)=K_2\,x^2 + K_4\,x^4$





Event in the Central atom: Large displacement

Event in the Central atom: Large displacement

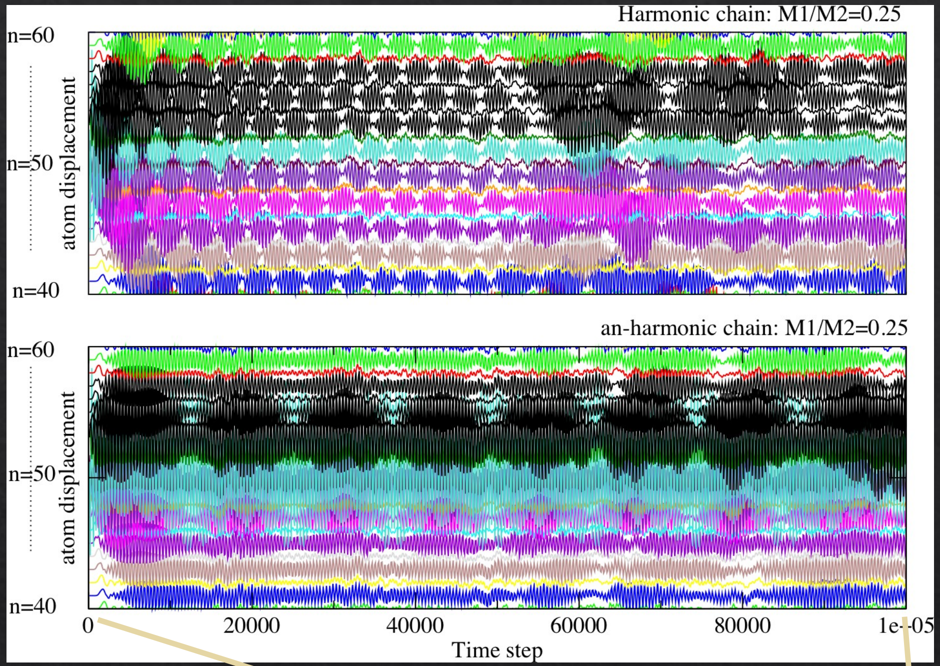


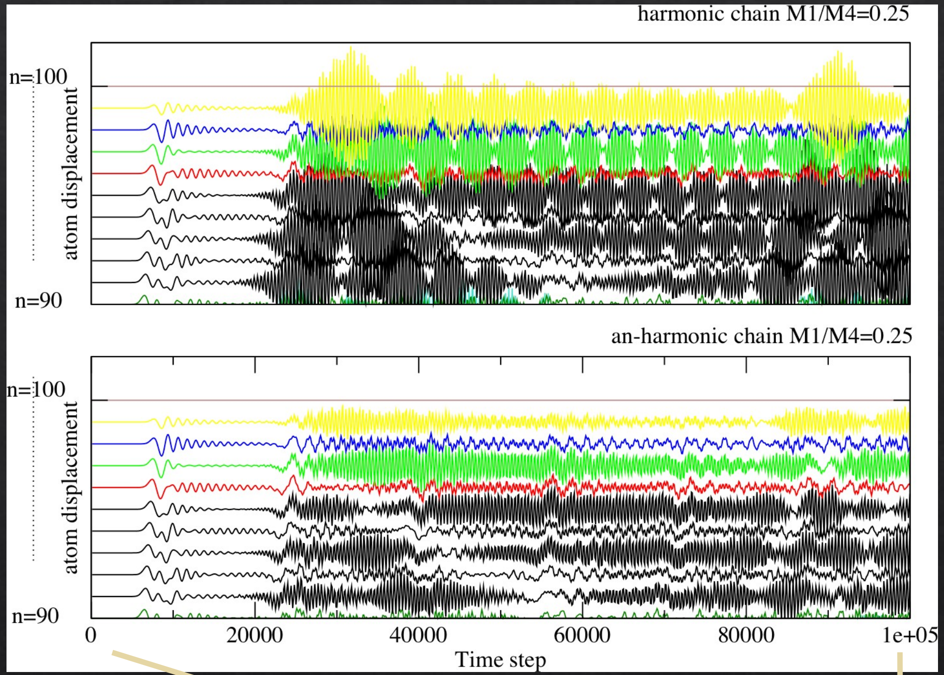
Localized vibrations

Sodium Iodine Thermal Detectors:
A one-dimensional model (100 atoms)

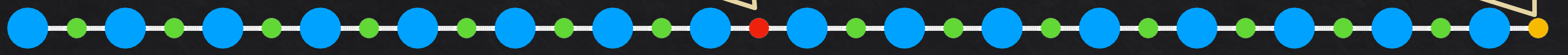
G. Profeta, A. Filipponi and M. Nardone

De-localized





Localized



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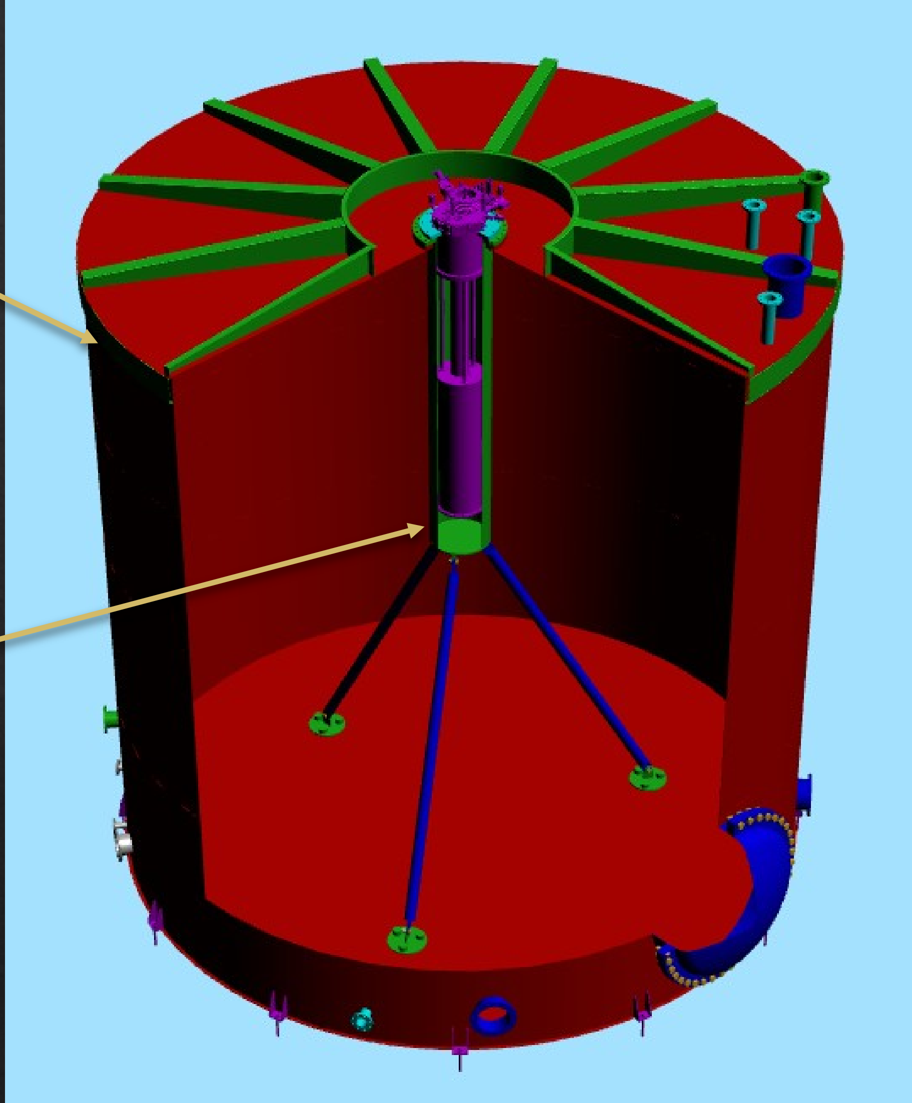
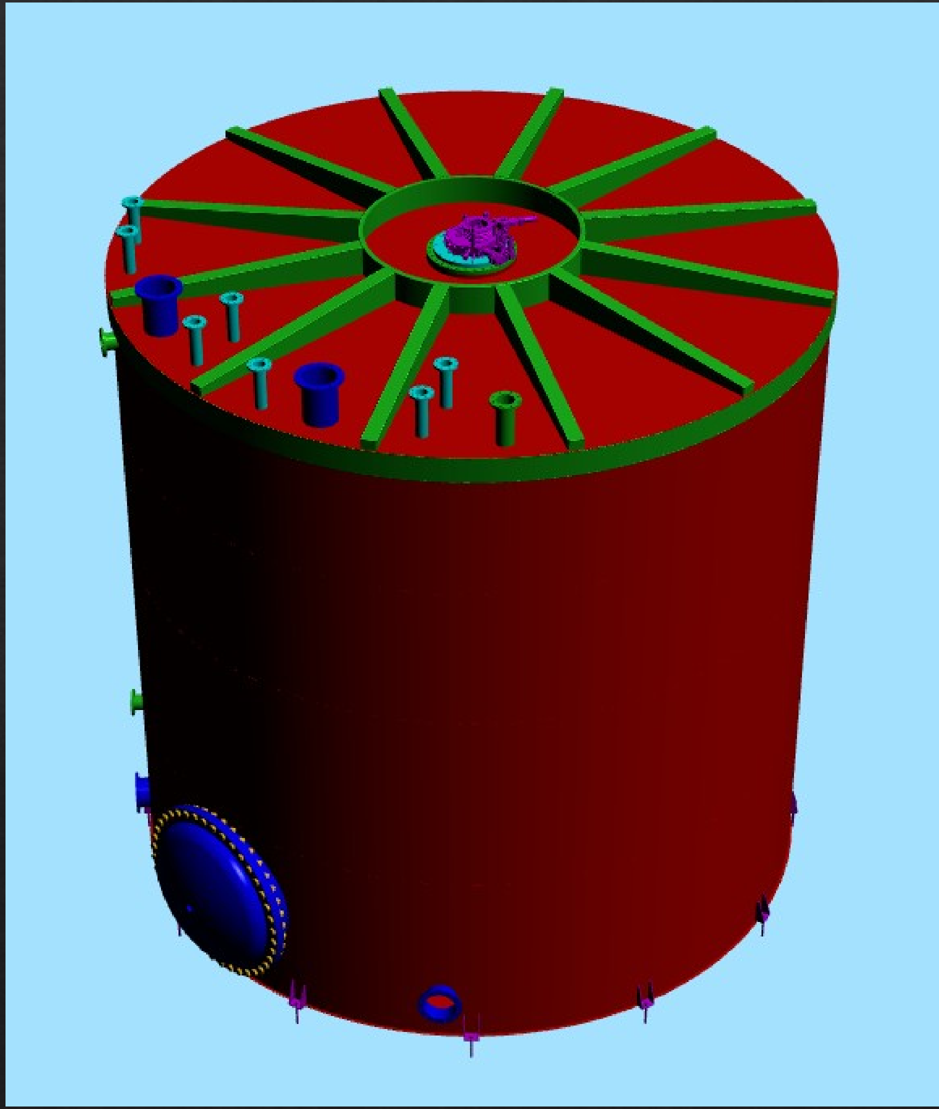
The experiment

Stainless steel water tank
- Height = 7 m
- Diameter = 7 m
- Thickness = O(8 mm)



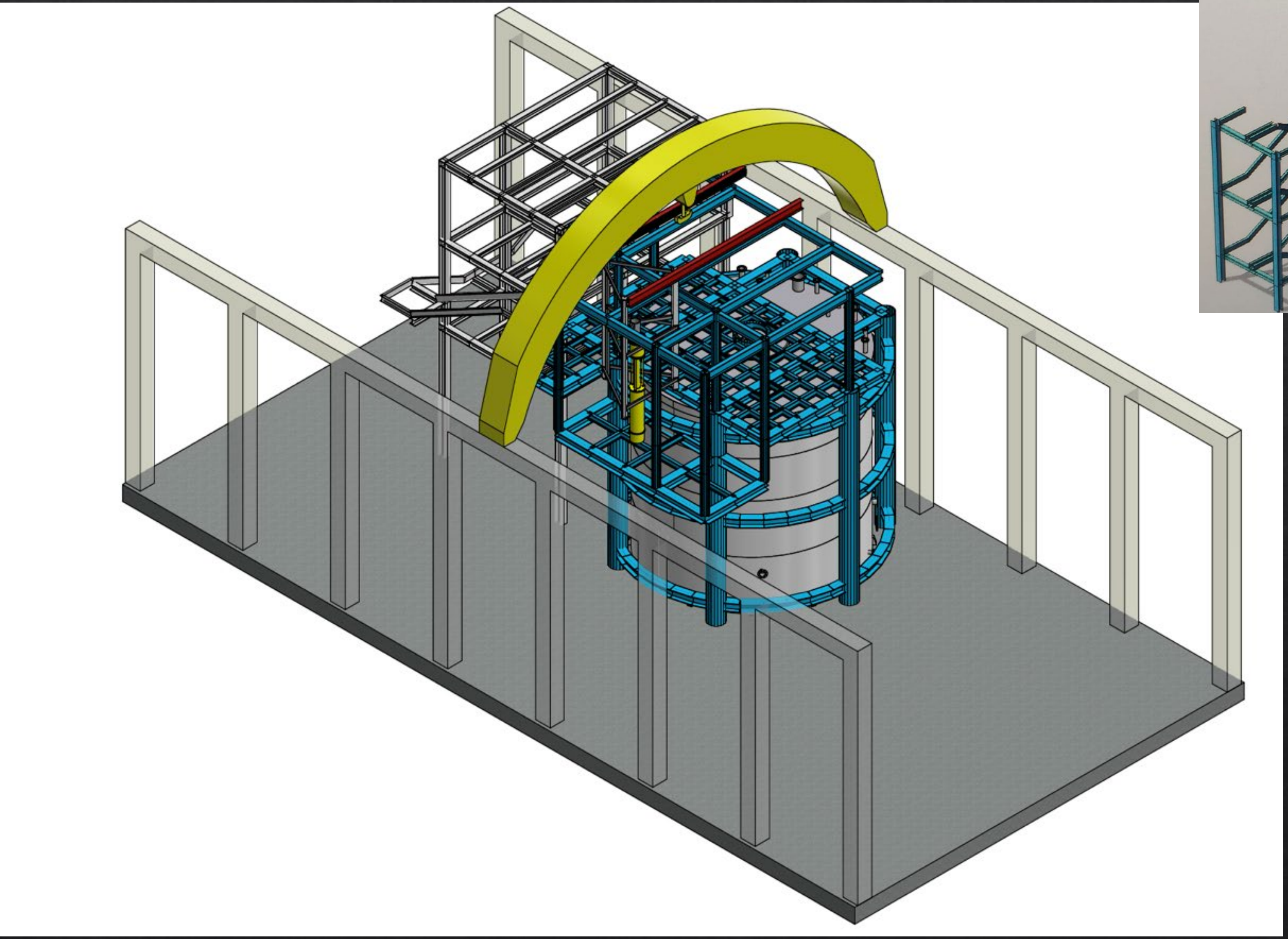


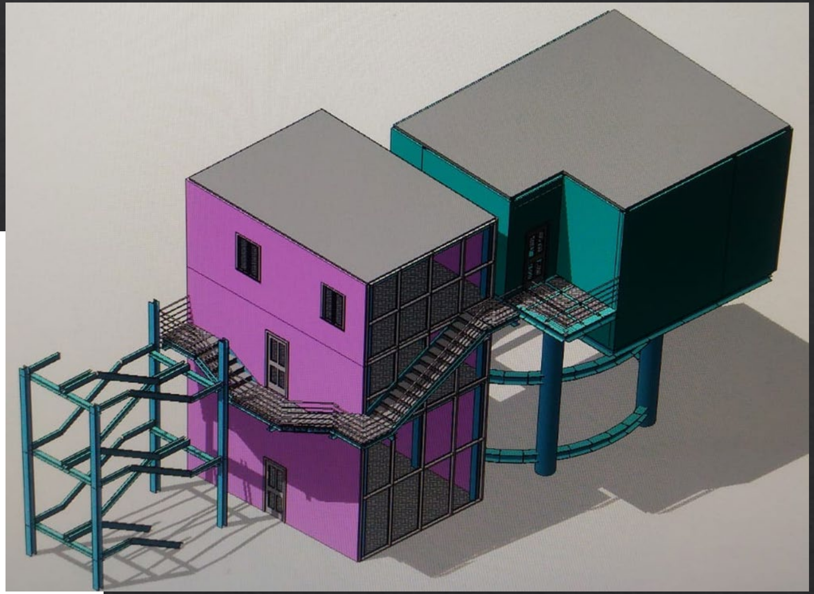
Radiopure stainless steel dry well
- Diameter = 580 mm
- Height = 3580 mm

- Holding dilution refrigerator (350 kg) and Cu shielding (1350 kg)

The experiment

Facilities

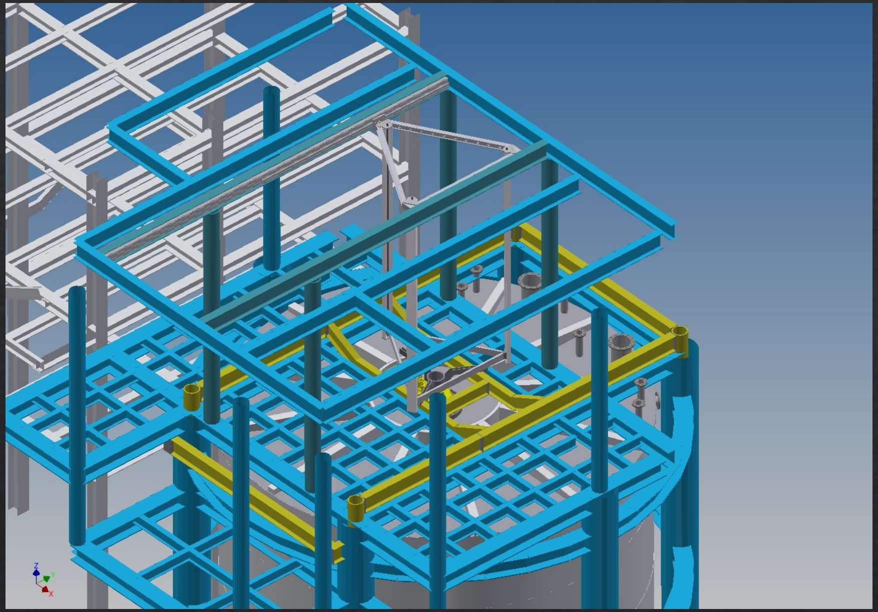


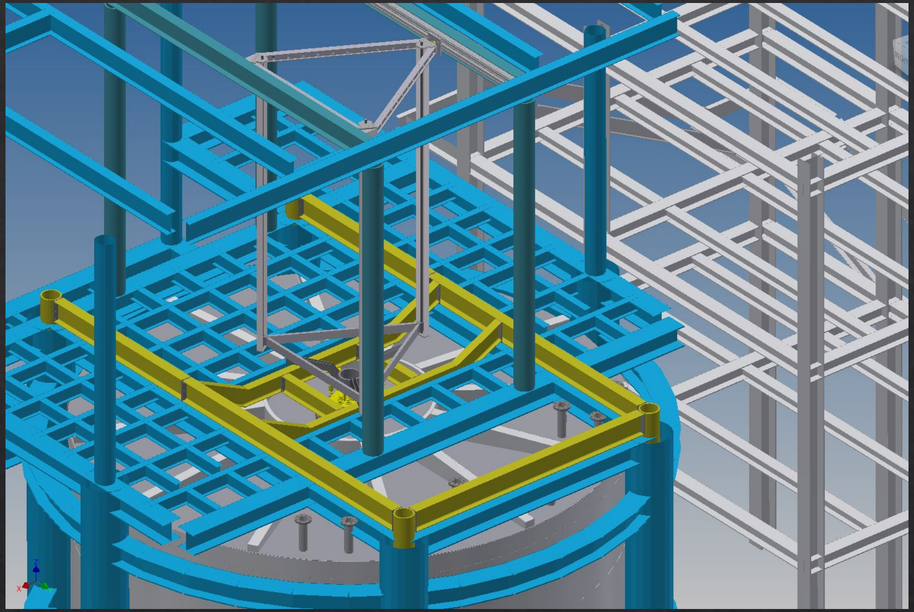


Platform:
- Faraday cage
- Clean Room (ISO7)

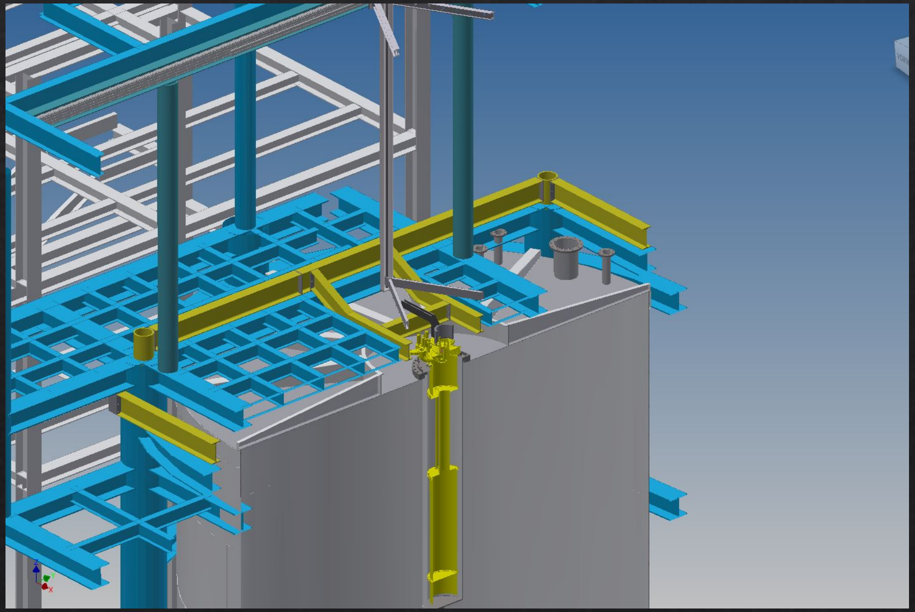
Building:
- Infrastructure for refrigerator
- Working area
- DAQ electronics
- IT infrastructure

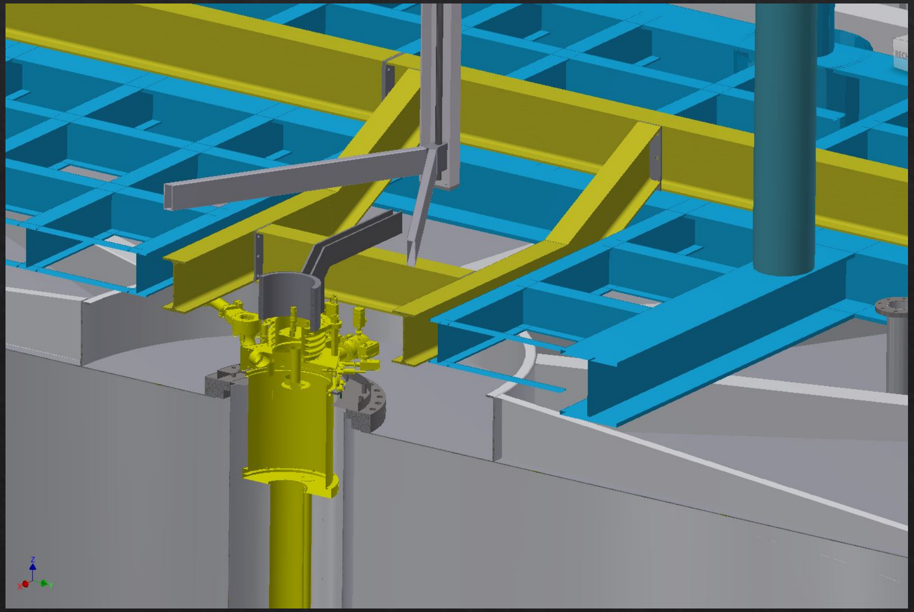
The experiment





Lifting system



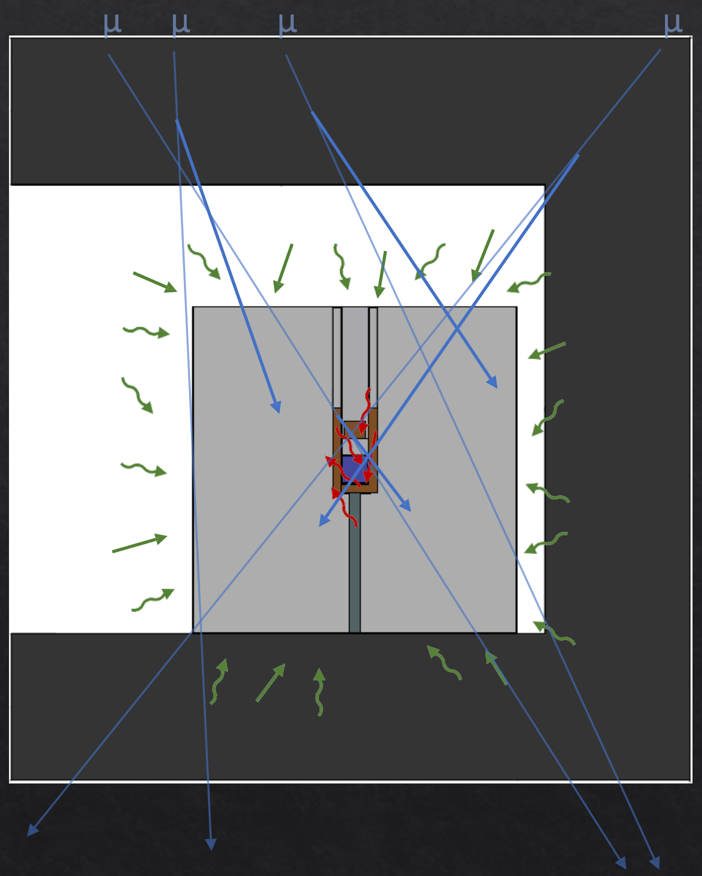


The simulation

Simulation of individual **background sources**:

- **Neutrons**: - Cosmogenic (muon-induced)
  - Radiogenic (radioactive contaminations in shielding materials)
  - Ambient (flux at laboratory due to rock radioactivity)

- **Gammas**: - Ambient (flux at laboratory due to rock radioactivity)
  - Intrinsic/Radiogenic (radioactive contaminations in shielding materials)



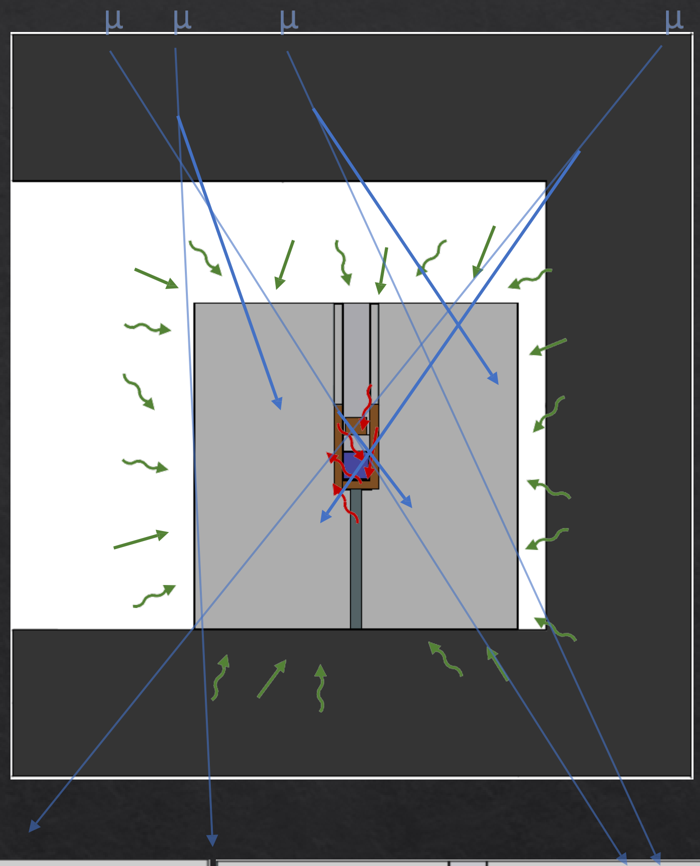
LNGS ambient neutron and gamma fluxes from literature
Intrinsic material contamination levels (steel, H_2O, Cu, Pb, PE) from GERDA, Xenon and CUORE experience

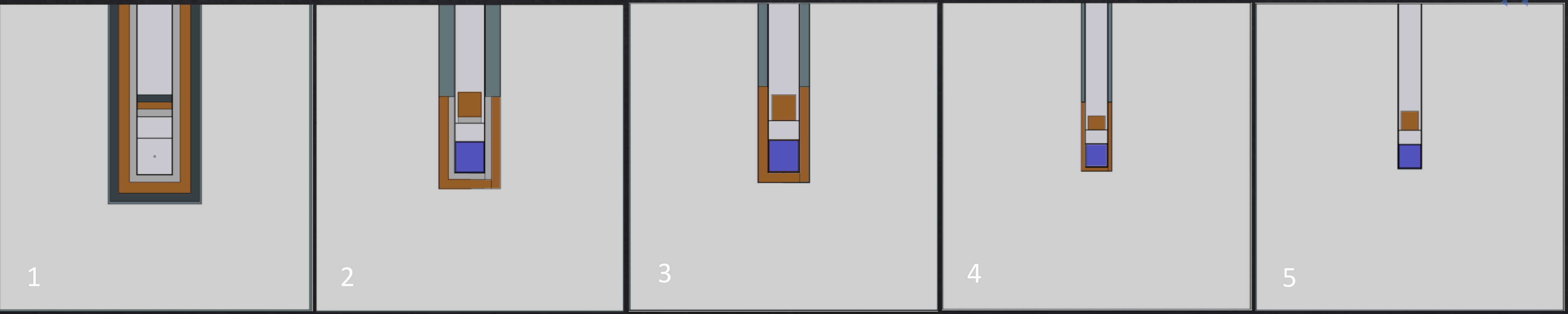
MUSUN + GEANT4 codes
SOURCES4C code

The simulation

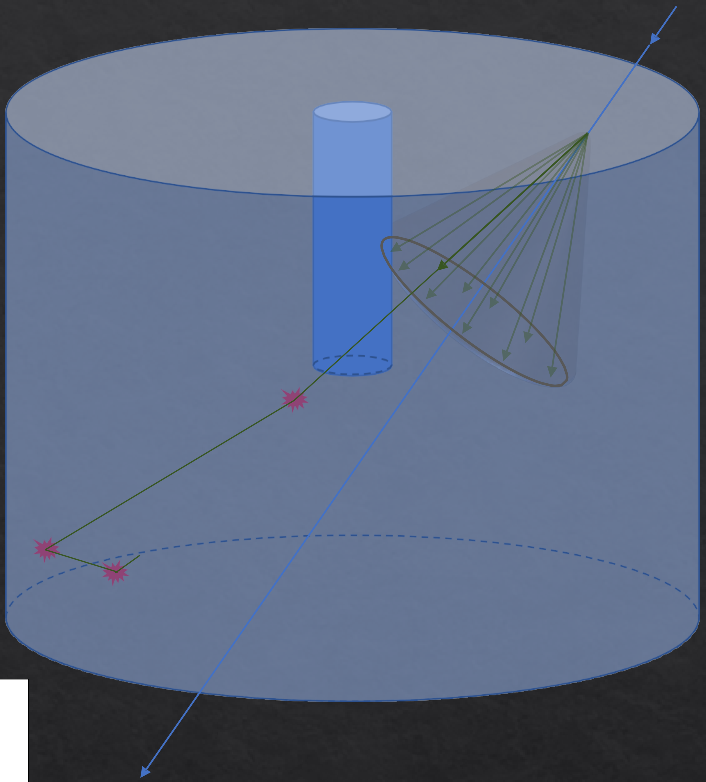
- 5 different shielding options considered

Option	Tank stainless [cm]	Water radius [cm]	Dry-well stainless [cm]	Pb [cm]	Cu [cm]	PE [cm]	Cryostat Cu [cm]	Top shield Pb+Cu+PE [cm]
1	1.5	150	0.4	10	15	10	0.8	10+15+10
2	1.5	200	0.4	0	15	10	0.8	0+40+10
3	1.5	200	0.4	0	15	0	0.8	0+40+0
4	1.5	300	0.4	0	8	0	0.8	0+30+0
5	1.5	300	0.4	0	0	0	0.8	0+40+0





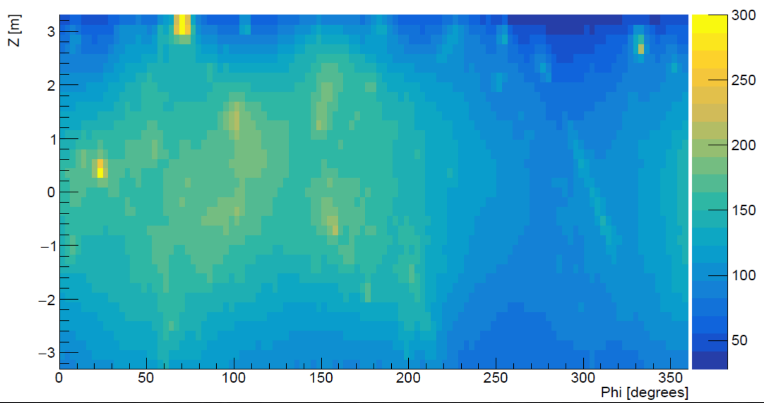
The simulation



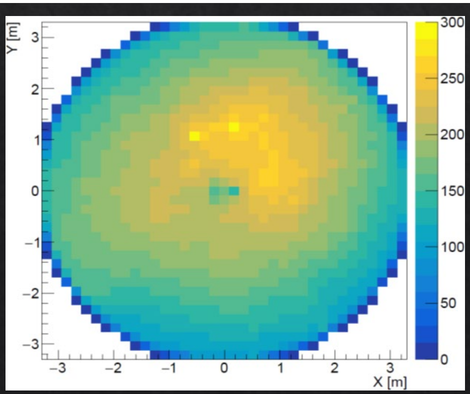
Estimate an **“optimum“ number and arrangement of PMTs** in the water tank

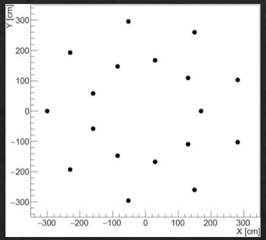
- Create **photon hit pattern** on wall and bottom of water tank
- **Estimate tagging efficiency** for different PMT arrangements and trigger conditions

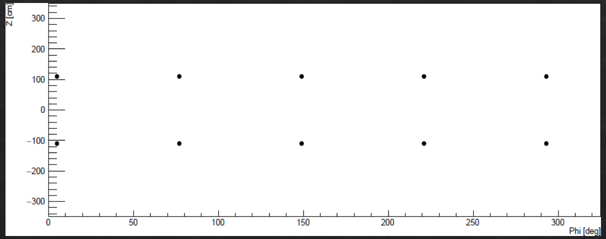
Photons / PMT / μ

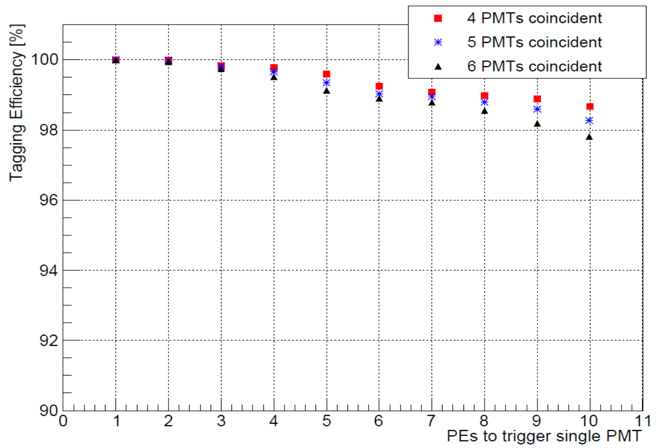


Photons / PMT / μ









Preliminary

18 – 28 PMTs
5-fold PMT coincidence with a trigger on the single photoelectron within a time window of a few 100 ns.