Status of Neutrino Elastic-scattering Observation with NaI(Tl)

In-Soo Lee

Center for Underground Physics (CUP)

Institute for Basic Science

On behalf of the NEON collaboration

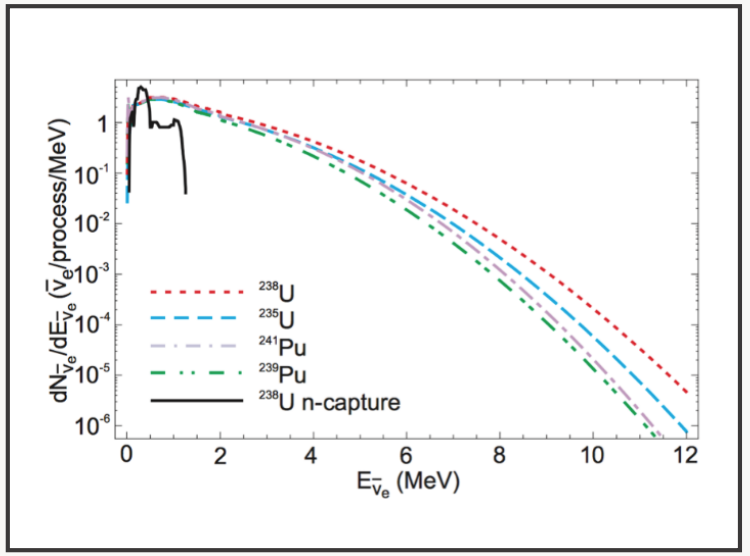
Institute for Basic Science

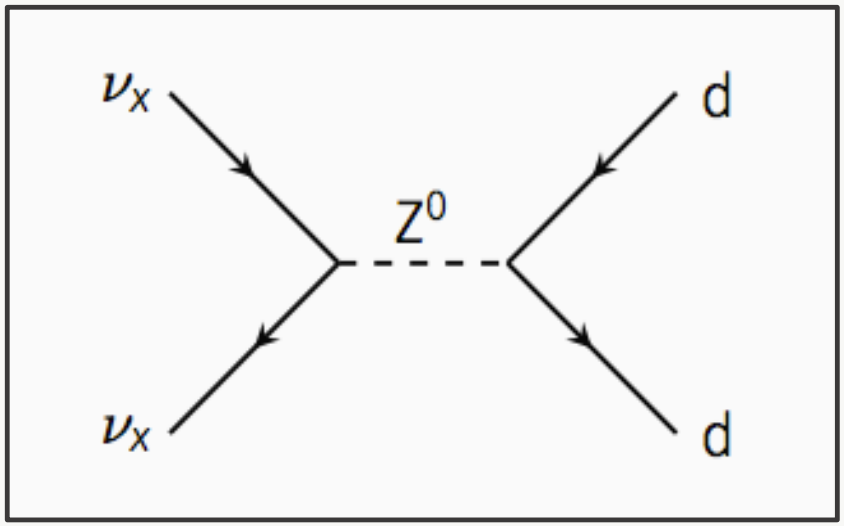
CENTER FOR UNDERGROUND PHYSICS

Coherent Elastic ν-Nucleus Scattering (CEνNS) @ Reactor

- **Neutrinos** are produced in **beta decays** of fission fragments.
  - **Single flavor** (electron anti-neutrino)
  - High flux : $10^{12}\sim10^{13}\ \nu/\mathrm{cm}^2 s$
  - $E_\nu < 10$ MeV → **fully coherent** regime
  - Clean in background, active and passive shielding
  - **Recoil energy** is less than **few keV.**
  - **Signal quenched**

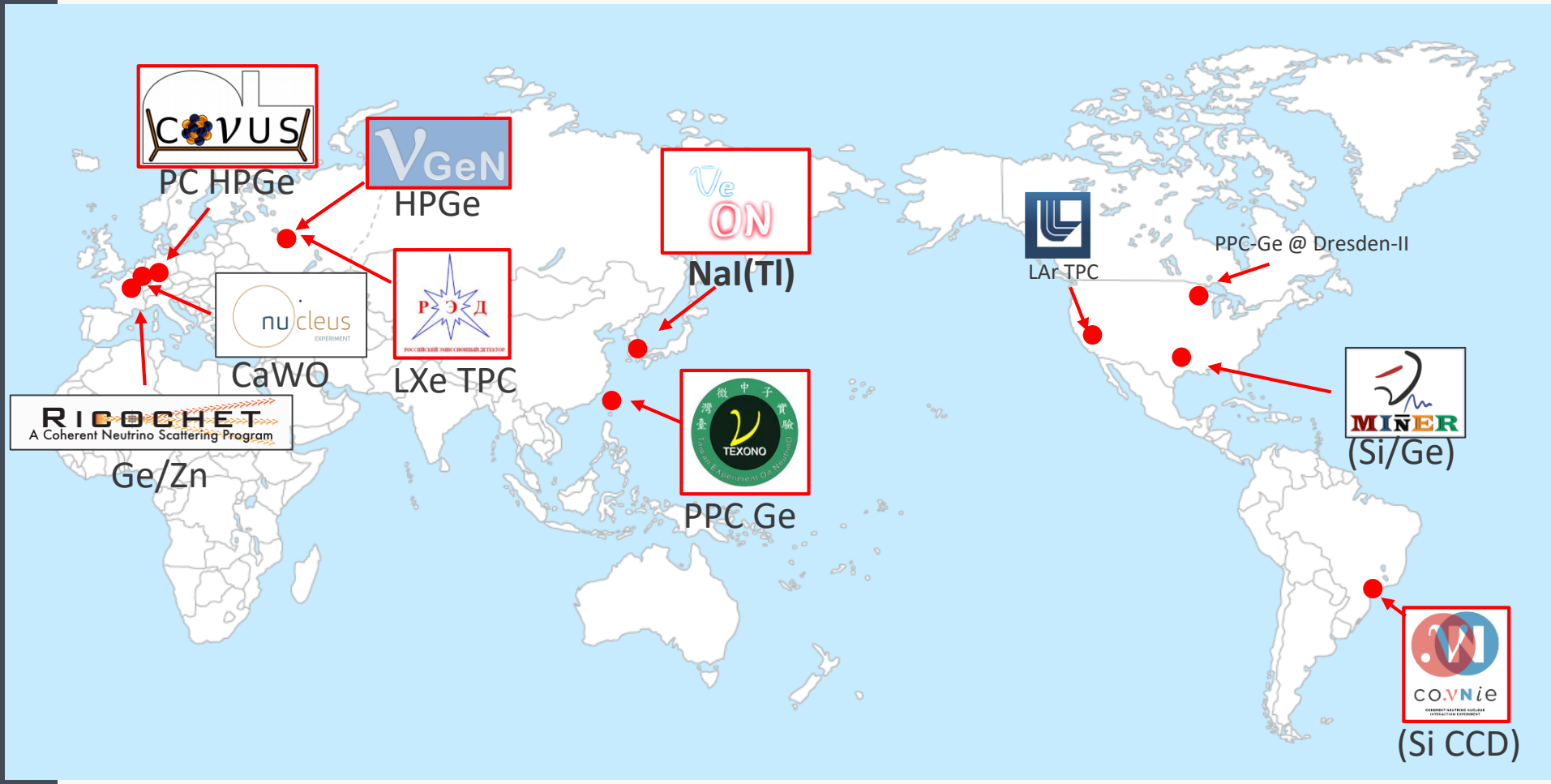
    → Require **very low threshold**





- **Physics?**
  - **Confirm SM**
  - **Beyond SM**
  - **Dark photon/Axion**
  - **Reactor monitoring**

World CEνNS @ Reactor



NEON collaboration

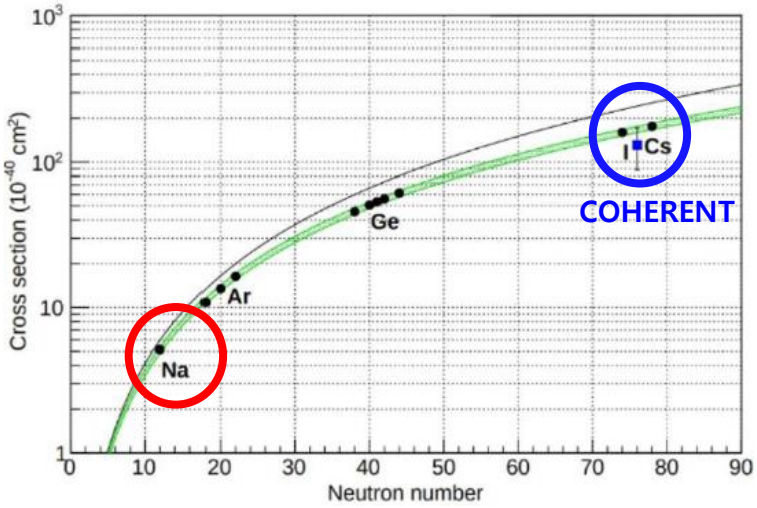
- **N**eutrino **E**lastic-scattering **O**bservation with **N**aI(Tl)
- 16 members, 3 institutes
  - Active members of the **COSINE-100** and **NEOS** experiments

- Aim to observe **CEνNS** from **reactor** $\overline{\nu}_e$ using **NaI(Tl)** detector
  - Low-background dark matter crystal experts (**COSINE-100**)
    + Reactor neutrino experiment experts (**NEOS**)

NaI(Tl) for CEνNS

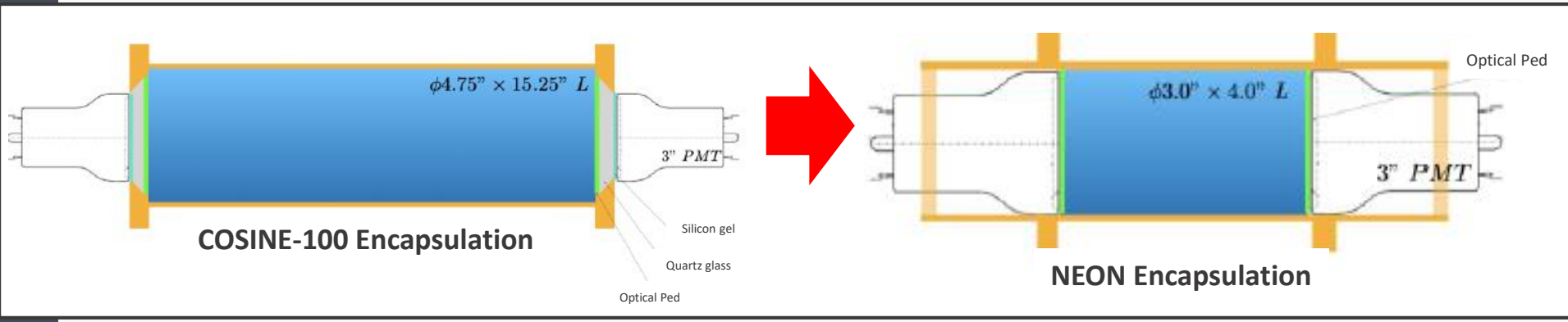
- High measured **light yield** (15 photo-electrons(PE)/keV in COSINE-100)
- Larger recoil energy from **Na** (N^2 dependence testable.)
- Easy to make **large size** detector O(10 kg)
- **Low background** detector available (<10 counts/kg/day/keV (DRU))

Properties	
Density [g/cm³]	3.67
Melting point [K]	924
Thermal expansion coefficient [C⁻¹]	47.4 x 10⁻⁶
Cleavage plane	<100>
Hardness (Mho)	2
Hygroscopic	yes
Wavelength of emission max [nm]	415
Refractive index @ emission max.	1.85
Primary decay time [ns]	250
Light yield [photons/keVγ]	38
Temperature coefficient of light yield	-0.3%C⁻¹



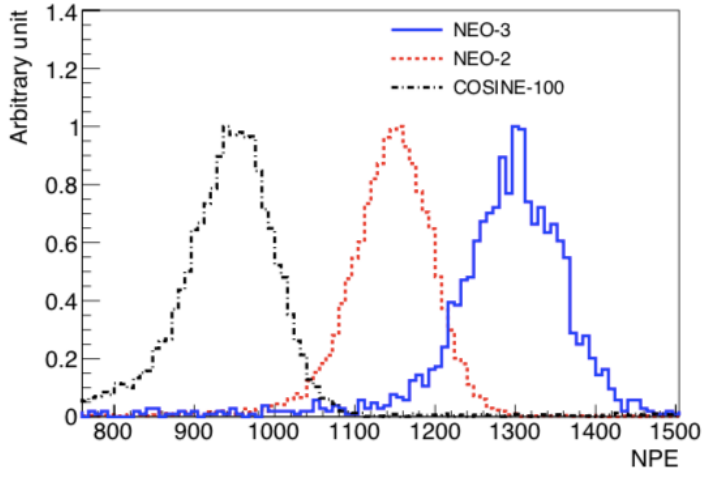
NEON detector

- **Optimizing** detector assembly for high light yield



- **Direct contact** between crystal and PMT
  - No quartz window

Am241 calibration@ Y2L underground Lab.

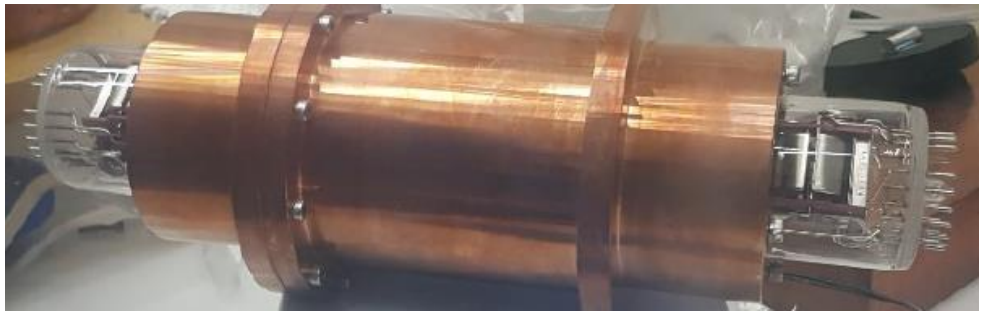


- Achieve light yield ~22 PE/keV !!
  - 5 PE ~ 0.22 keV

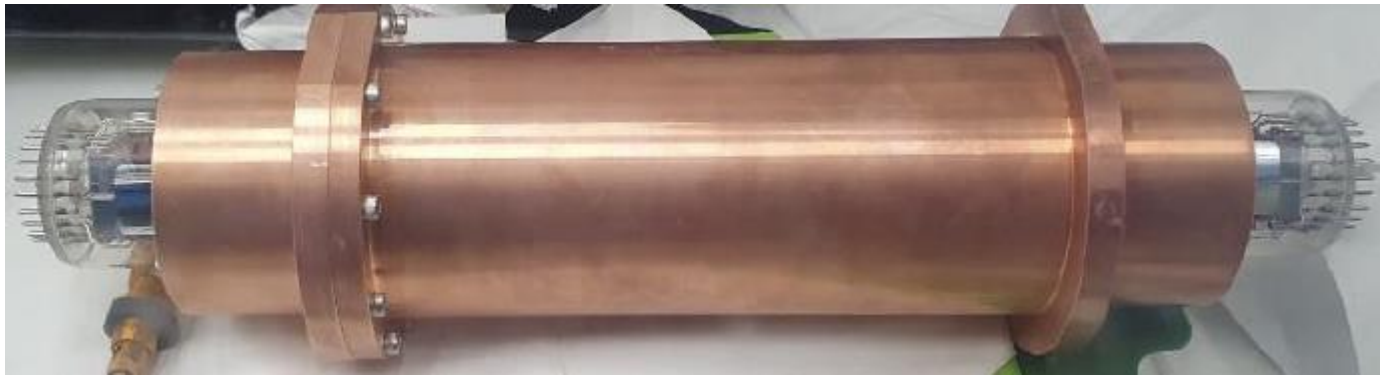
Nucl. Instrum. Meth. A 981 (2020) 164556

NEON detector cont'd

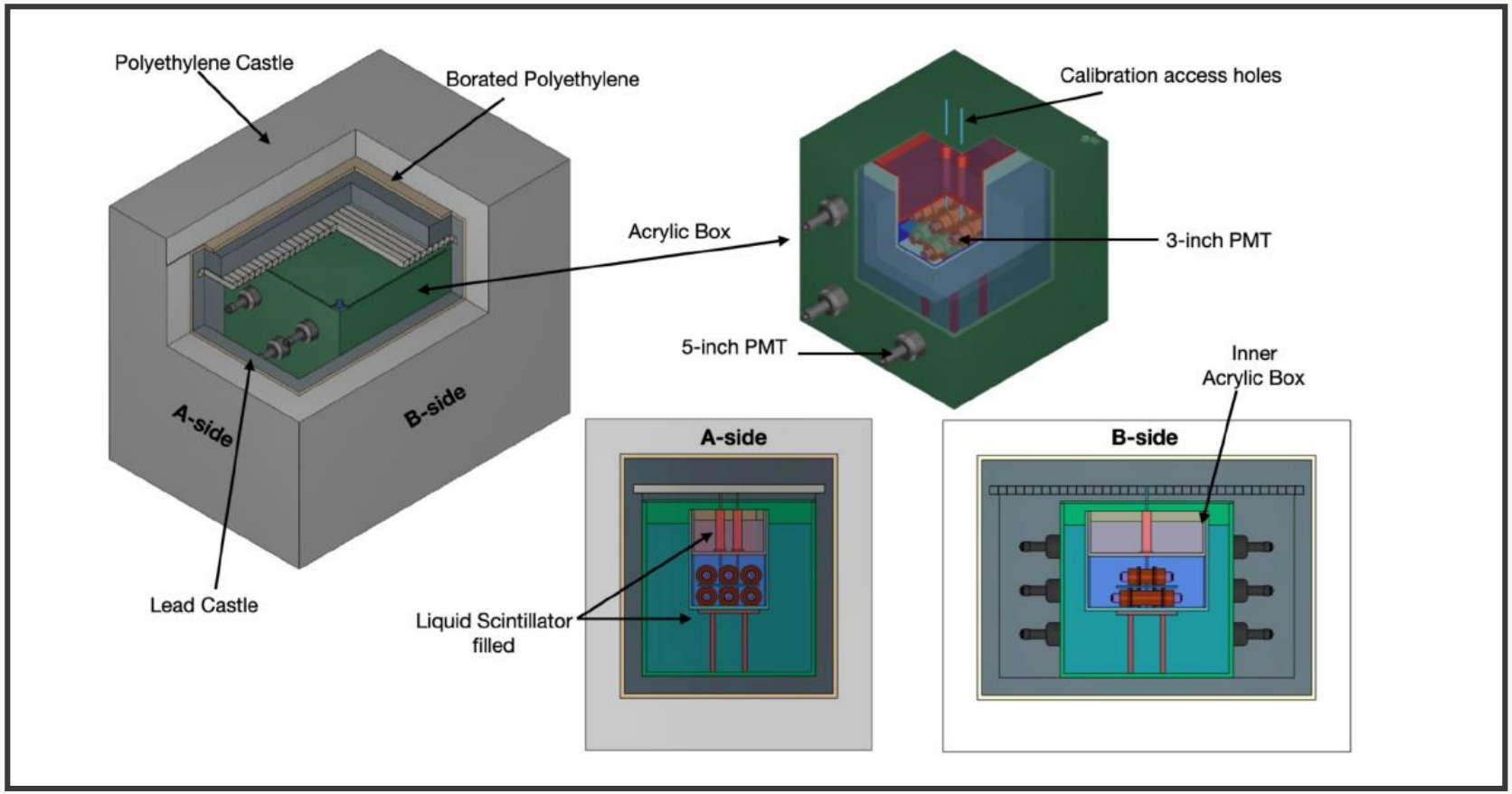
- **Total 13.3 kg** 6 Commercial Crystals
  - Light yield : 20~24 PE/keV
- 1.64 kg x 4 crystals



- 3.37 kg x 2 crystals



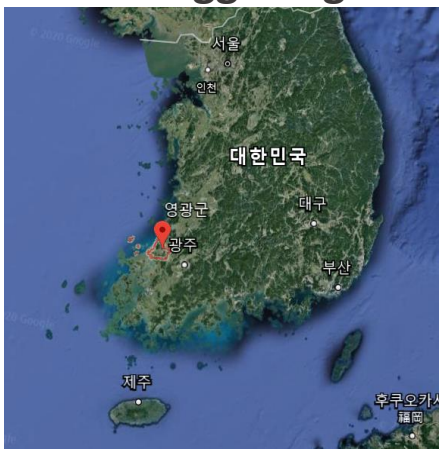
Shielding design



- 20 cm Poly-Ethylene + 5 cm Borated-Poly-Ethylene + 10 cm Lead for radiation shield
- ~ 700L Liquid scintillator (LS) in 1 m x 1 m x 1 m box for active veto
- 2 Calibration pipes

Hanbit Nuclear Power plant

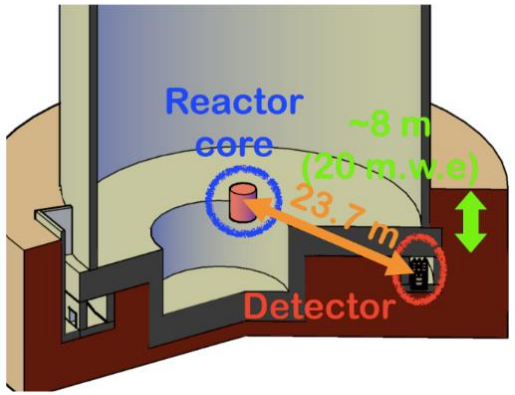
Yeonggwang



Hanbit Nuclear Power plant (Reactor 6)

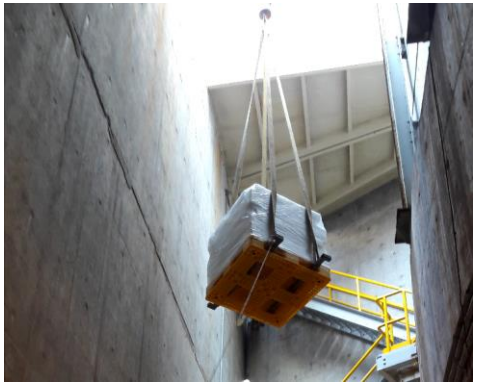
- **2.8 GW** thermal power
- Tendon gallery is ~24 m from reactor core
  - Well known environmental conditions from **NEOS** experiment
  - **Neutrino flux** $\Phi_0 = 7.1 \times 10^{12}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Tendon gallery

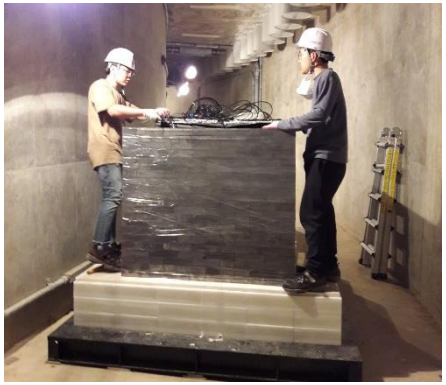


On-site installation

Nov 12 2020

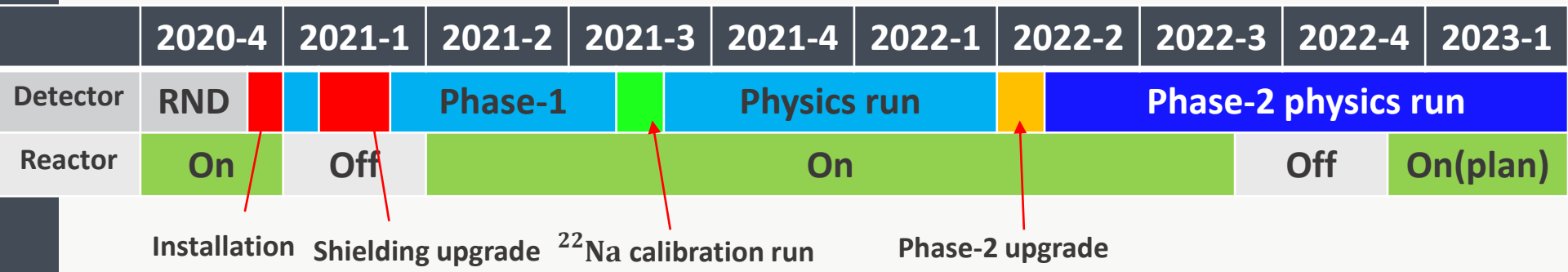



Nov 26 2020




- NEON detector and DAQ were installed at Nov. 26 in 2020
- Start **physics run** (**Phase 1 run**) from Dec. 2020

Operation status



- **^{22}Na calibration** run July~ Aug 2021
- **Phase 1 Operation (Dec. 2020~Mar. 2022)**
  - Reactor on : 11 months
  - Reactor off : 1 weak
- **Phase-2 Operation (Apr.2022~)**
  - Reactor on : 5 months +
  - Reactor off : 2 months (plan) +

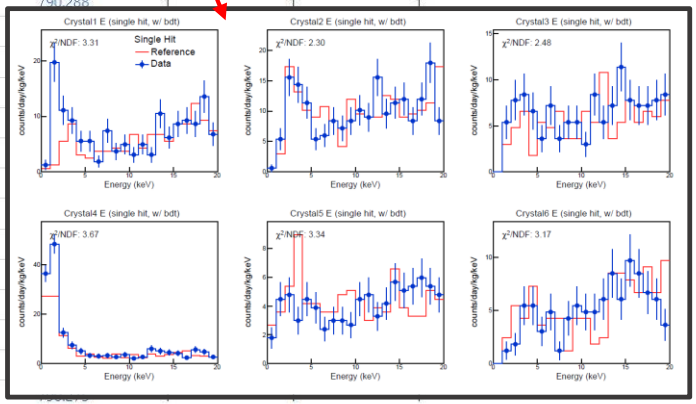
Monitoring

Data Quality Monitoring

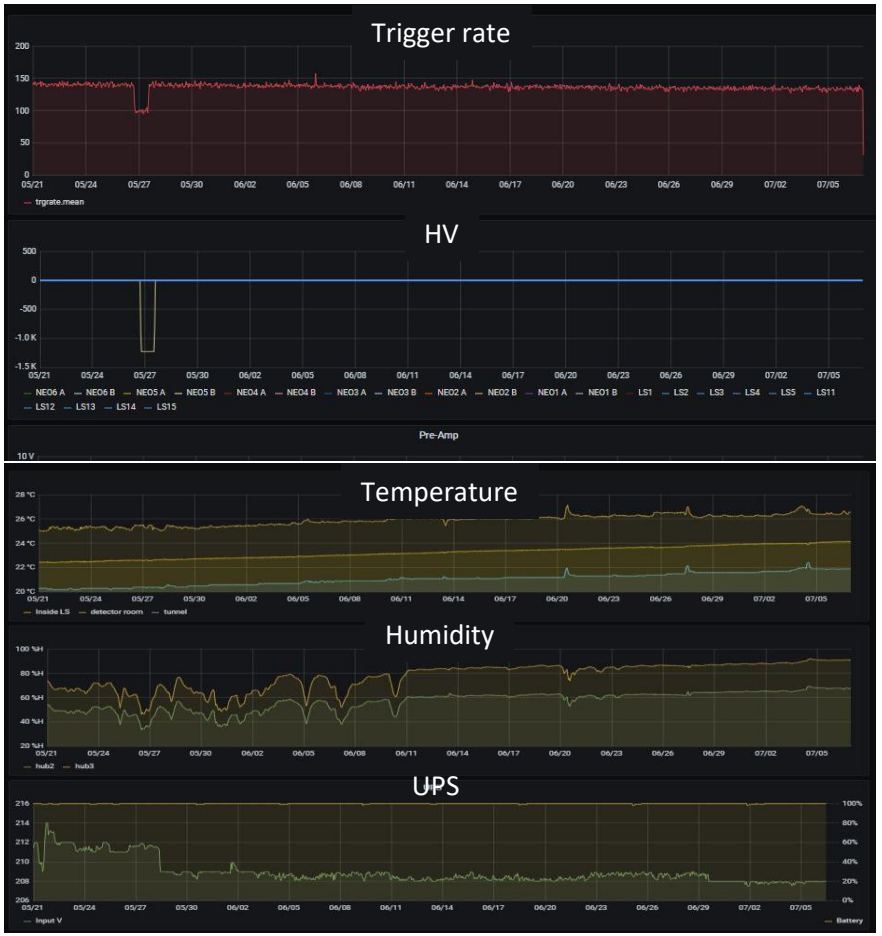
NEON Runlist DAQRun Dashboard Elog Instructions

Show Runlist

Date	Run number	Env bit	FADC bit	SADC bit
20210705	790.298	1	1	1
20210705	790.297	1	1	1
20210705	790.296	1	1	1
20210705	790.295	1	1	1
20210705	790.294	1	1	1
20210705	790.293	1	1	1
20210705	790.292	1	1	1
20210705	790.291	1	1	1
20210705	790.290	1	1	1
20210705	790.289	1	1	1
20210705	790.288	1	1	1
20210705				
20210705				
20210705				
20210705				
20210705				
20210705				
20210705				
20210705				
20210705				
20210705				
20210705				
20210705				
20210705				
20210705				

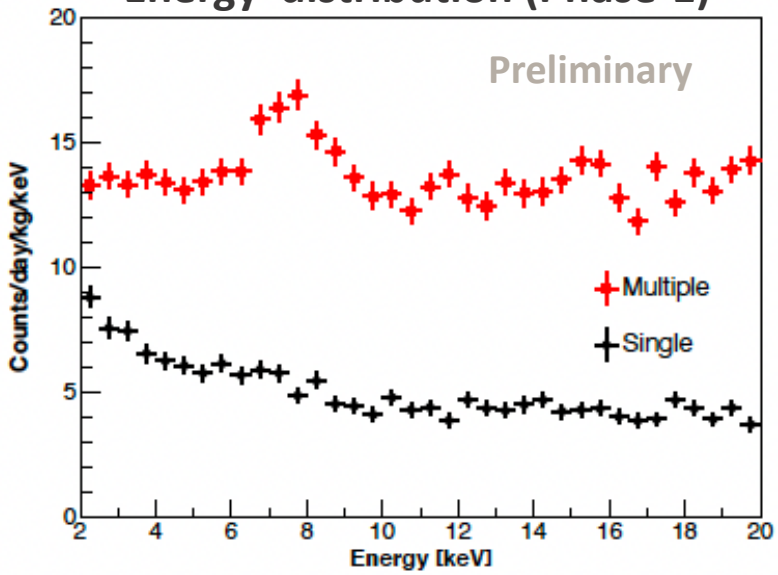


Environment Monitoring

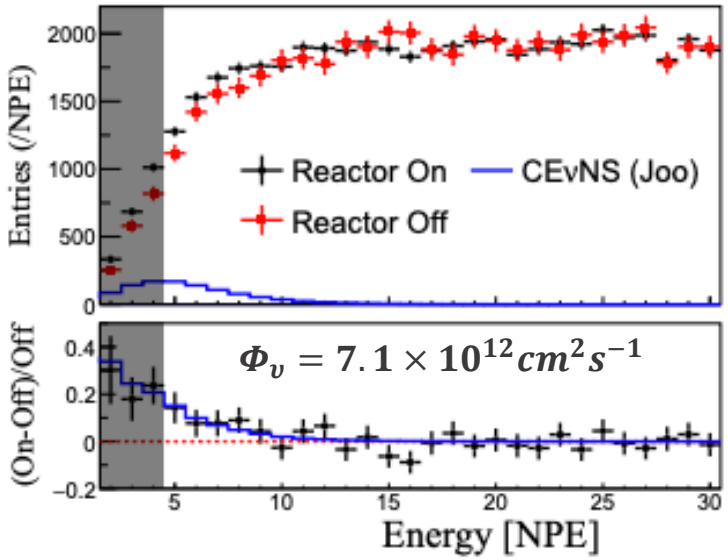


Sensitivity estimation

Energy distribution (Phase-1)



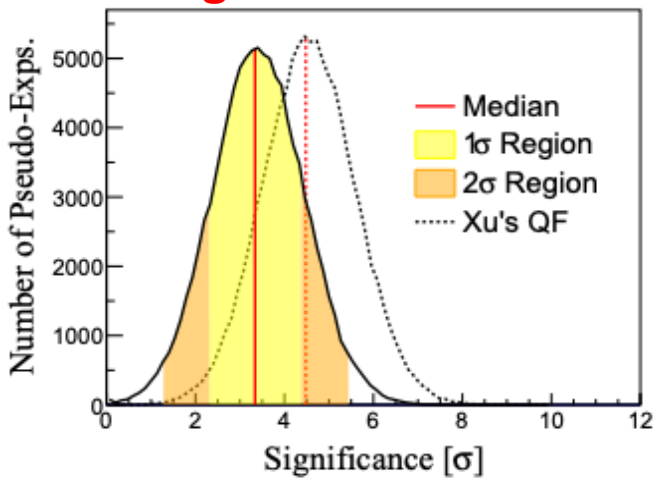
Single pseudo experiment



Assumption (Phase-1 detector condition)

- 7 counts/kg/day/keV flat background
- 13.3-kg mass of detector
- 365/100 days reactor on/off data
- 22 PE/keV light yield
- 5 PE threshold
- Quenching factor
  - Joo : Astropart. Phys. **108** (2019) 50
  - Xu : Phys. Rev. C **92** (2015) 015807

Significance > 3 σ

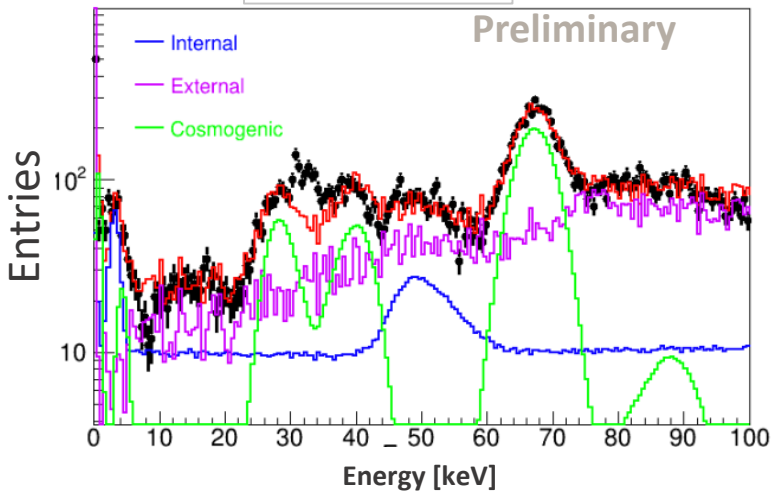


arXiv:2204.06318v1 [hep-ex] 8 Apr 2022

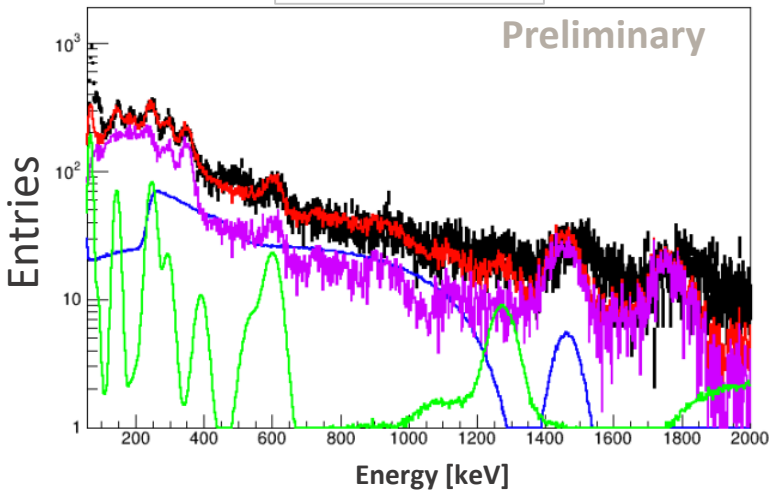
Studies in progress

Background modeling(w/ GEANT4)

Low energy

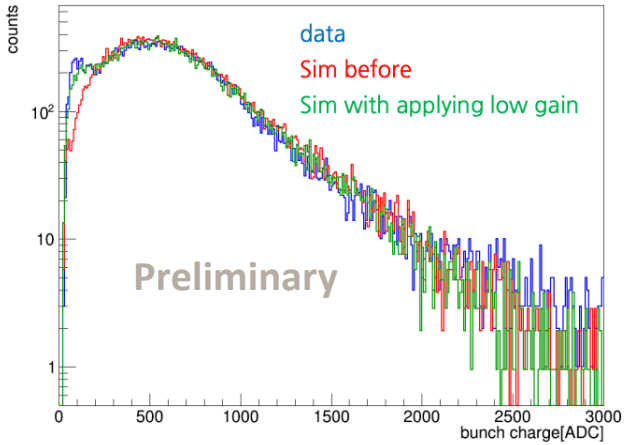


High energy



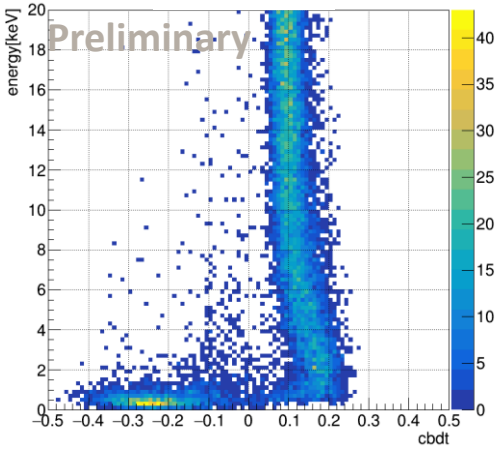
Event selection using photon simulation

Single photo-electron charge

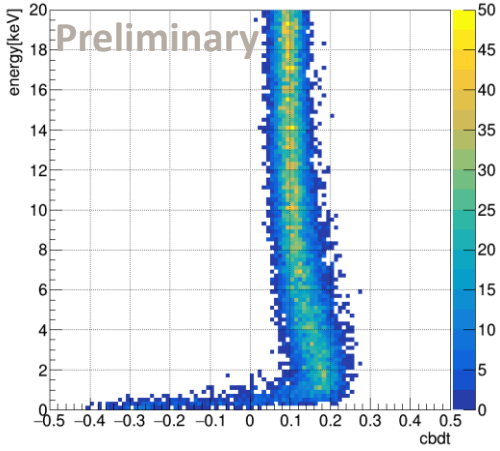


Boosted decision tree

Data

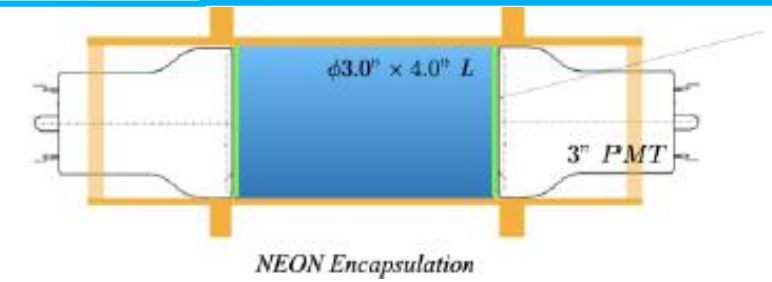


Simulation

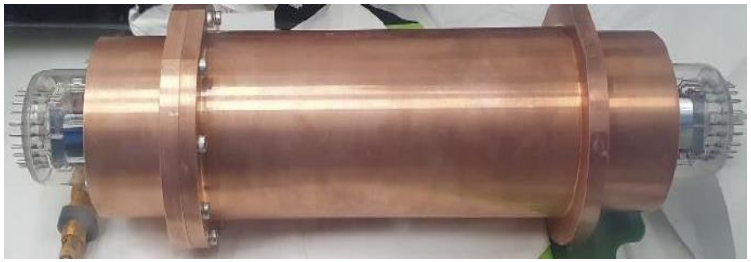


NEON-Phase 2 upgrade

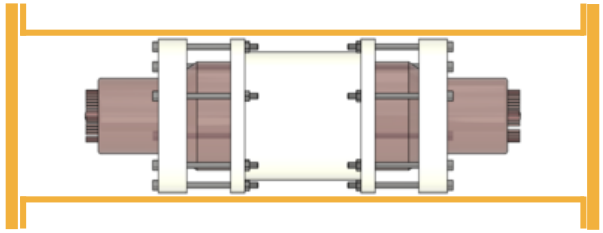
Phase 1

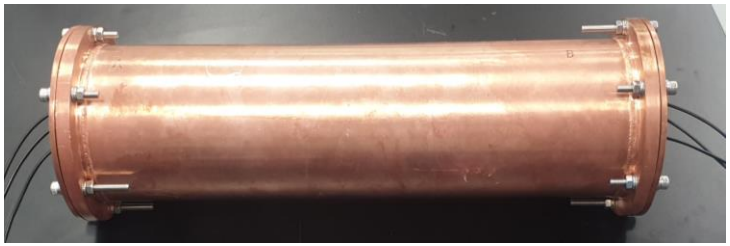


NEON Encapsulation



Phase 2

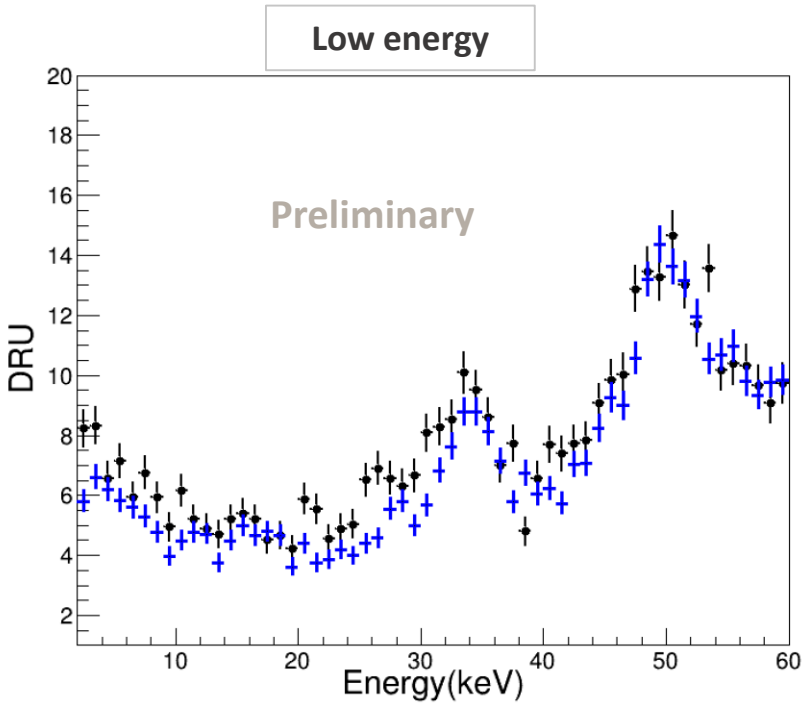


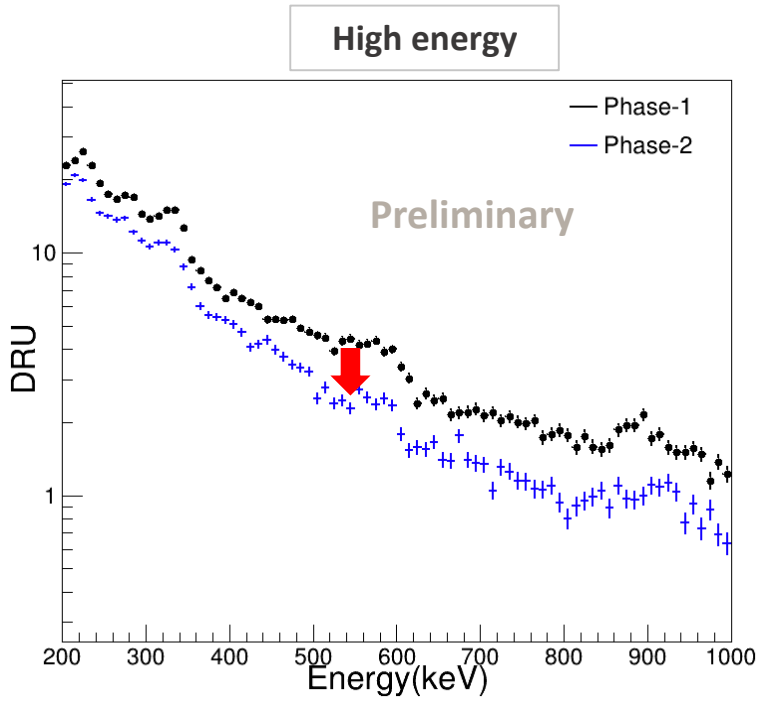


- Upgrade encapsulation (**Apr. 2022**)
  - Fix mechanical instability (Air or LS leak)
  - Achieve **higher light yields**
  - Add more mass : **13.6→ 16.3 kg**
- Exclude two high background crystals
- Include two **8" length crystals**

Crystal #	Size (dia x length)	Light yields(PE/keV)	
		Phase 1	Phase 2
1	3" x 4"	20.5 ± 0.9	Excluded
2	3" x 4"	19.3 ± 0.9	Excluded
3	3" x 4"	21.8 ± 0.9	23.9 ± 0.8
4	3" x 8"	22.4 ± 1.0	24.5 ± 0.7
5	3" x 8"	21.8 ± 0.9	22.9 ± 0.4
6	3" x 4"	21.7 ± 1.0	20.2 ± 0.4
7	3" x 8"	-	22.0 ± 0.5
8	3" x 8"	-	26.7 ± 0.8

NEON-Phase 2 upgrade cont'd





- Phase 1→ Phase 2
  - Improved Light yield & resolution
  - Reduced background.

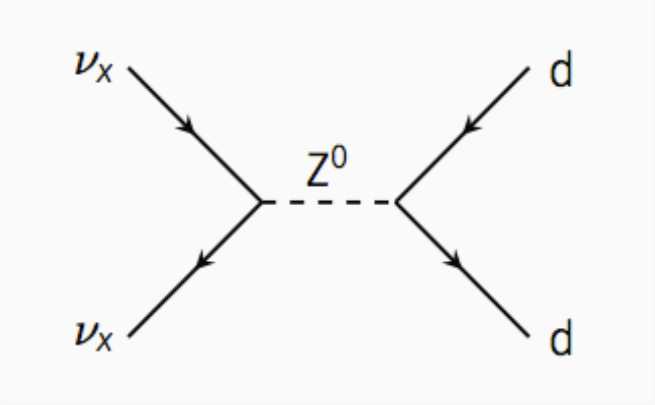
Summary

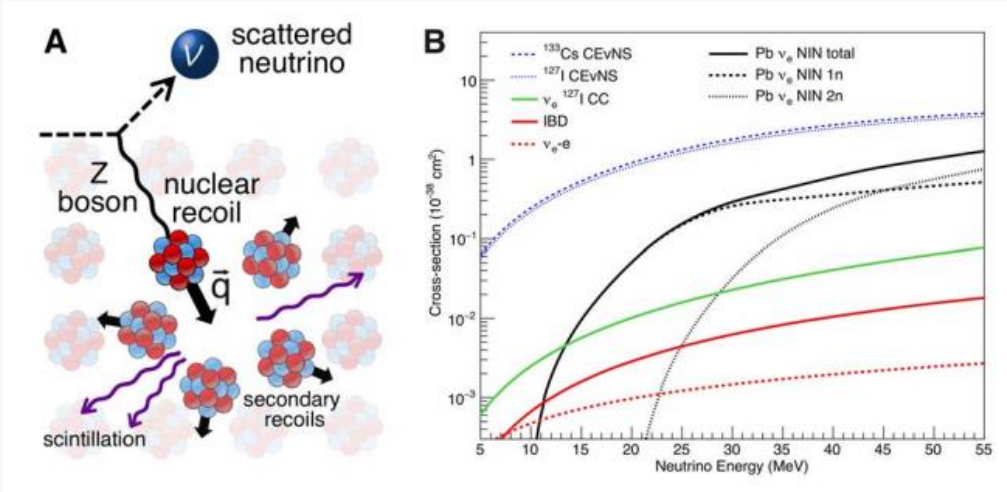
- **NEON** experiment aims to detect **CEνNS** using **NaI(Tl)** from reactor electron–antineutrino.
- Operation started from 2020
  - Phase 1 (Dec. 2020 ~ Mar. 2022)
    - Reactor on : ~11 months
    - Reactor off : 1 week
  - Phase 2 (Apr. 2022 ~ current)
    - Detector upgrade
      - 13.3 kg -> 16.3 kg
      - Higher light yields
    - Reactor on : 5 months +
    - Reactor off : 2months + (plan)
- Background modeling and events selection are in process.
- We expected sensitivity > 3 σ in NEON experiment.

Back up

Motivation-CEνNS

- Coherent Elastic Neutrino Nucleus Scattering (**CEνNS**)
  - Predicted at 1974 **PRD 9, 1389 (1974)**
  - First measurement by the COHERENT collaboration **Science 357, 1123-1126 (2017)**





- Precision test of SM
  - Cross section measurements
  - Weinberg angle
- Beyond SM physics
  - Neutrino non-standard interaction
  - Neutrino electromagnetic properties
  - ..
- Nuclear structure, reactor investigations
- Supernova neutrino

Motivation-CEνNS

- Coherent Elastic Neutrino Nucleus Scattering (**CEνNS**)
  - Predicted at 1974 **PRD 9, 1389 (1974)**
  - First measurement by the COHERENT collaboration **Science 357, 1123-1126 (2017)**

$$\frac{\mathrm{d}\sigma}{\mathrm{dT}} = \frac{G_F^2}{4\pi}\underbrace{[N-(1-4\sin^2\theta_w)Z]}^{\sim N^2}\,{}^2F^2(q^2)\mathrm{M}(1-\frac{MT}{2E_\nu^2})$$

G_F : Fermi coupling constant
Z : Atomic number of the nucleus
N : Neutron number of the nucleus
E_ν : Neutrino energy

θ_w : Weak mixing angle
$F(q)$: form factor
M : Mass of the nucleus

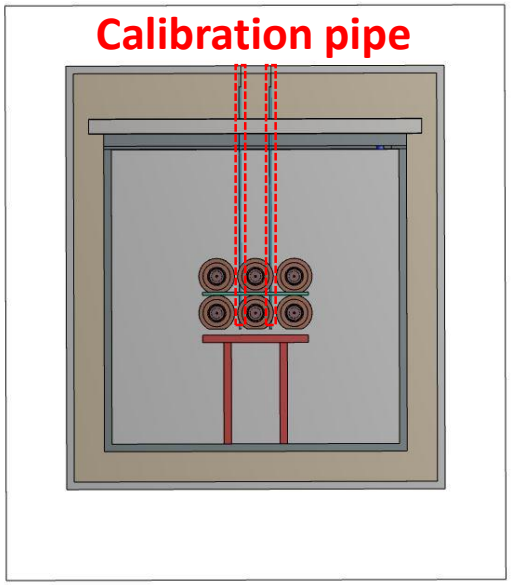
- Low momentum transfer
- Full coherency feature : $\sigma \propto N^2$
- Only experimentally accessible observable
  - Low energy recoil of the nucleus! $\mathrm{T_{max}} \propto {}^1/_{\mathrm{A}}$
  - Signal quenched

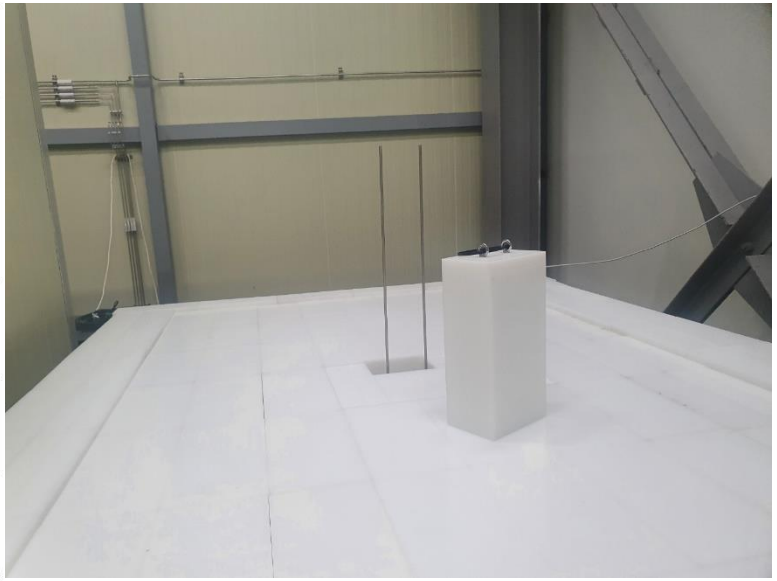
  → High light yield & very low energy threshold required!

CEνNS experiments @ reactor

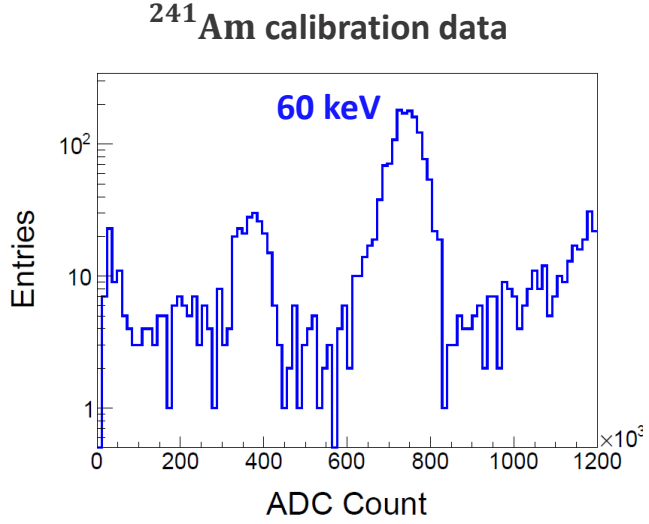
Experiment	Location	Flux ($cm^{-2}s^{-1}$)	Overburden (m. w. e.)	Detector
NEON	**Hanbit, Korea**	$\mathbf{7.1 \times 10^{12}}$	**~20**	**NaI(Tl)**
νGen	KNPP, Russia	$>5.1 \times 10^{13}$	~50	HPGe
CONUS	Brokdorf, Germany	2.4×10^{13}	24	HPGe
TEXONO	Kuo-Sheng NPP,Taiwan	6.4×10^{12}	~30	PC Ge
RED-100	KNPP, Russia	1.7×10^{13}	>50	LXe
CONNIE	Angra2,Brazil	6.8×10^{12}	0	Si CCD
RICOCHET	ILL, France	2.0×10^{12}	15	Ge
MINER	Texas A&M,USA	2.0×10^{12}	5	Si/Ge
NUCLEUS	Chooz,France	2.0×10^{12}	3	CaWO

Calibration

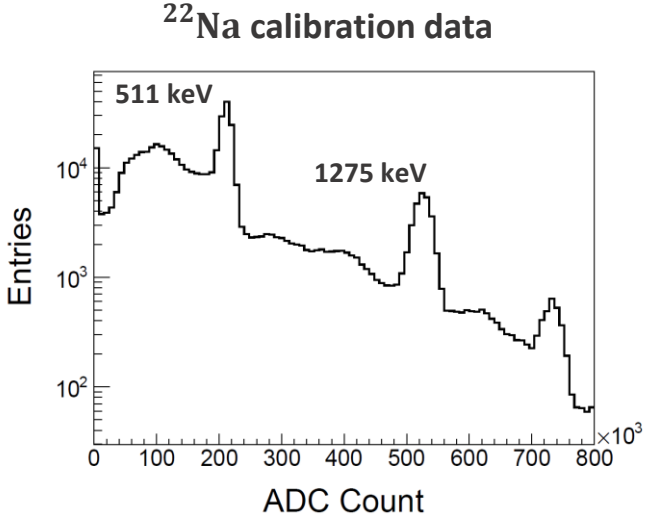




^{241}Am and ^{22}Na sources



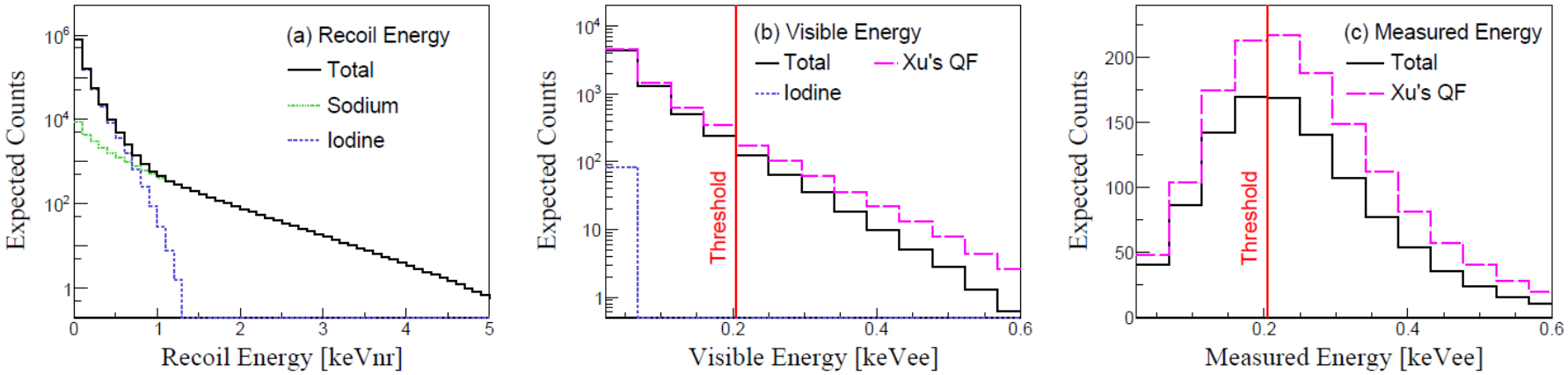
^{241}Am calibration data



^{22}Na calibration data

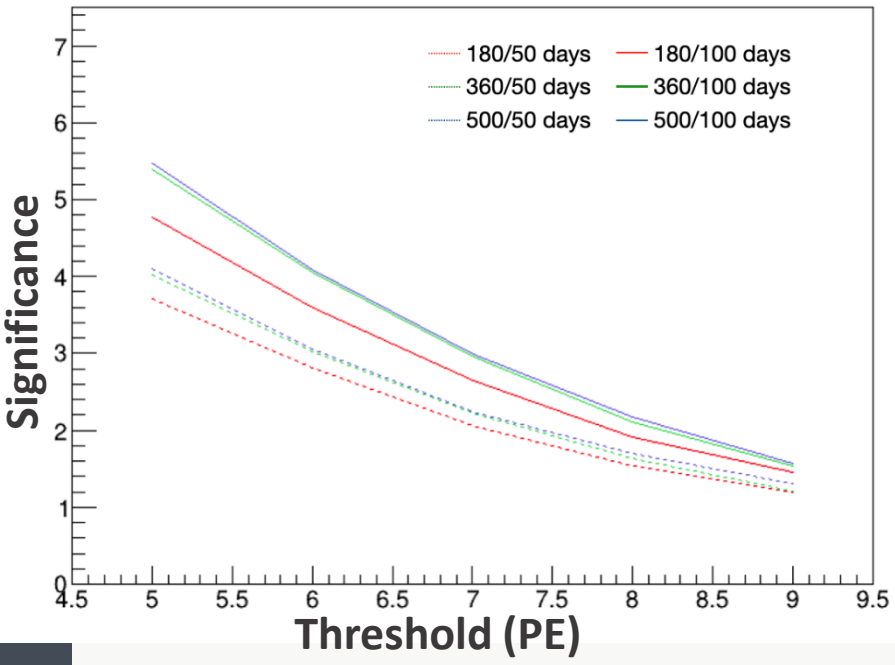
- Energy calibration with ^{241}Am
- Low-energy scintillation samples with ^{22}Na

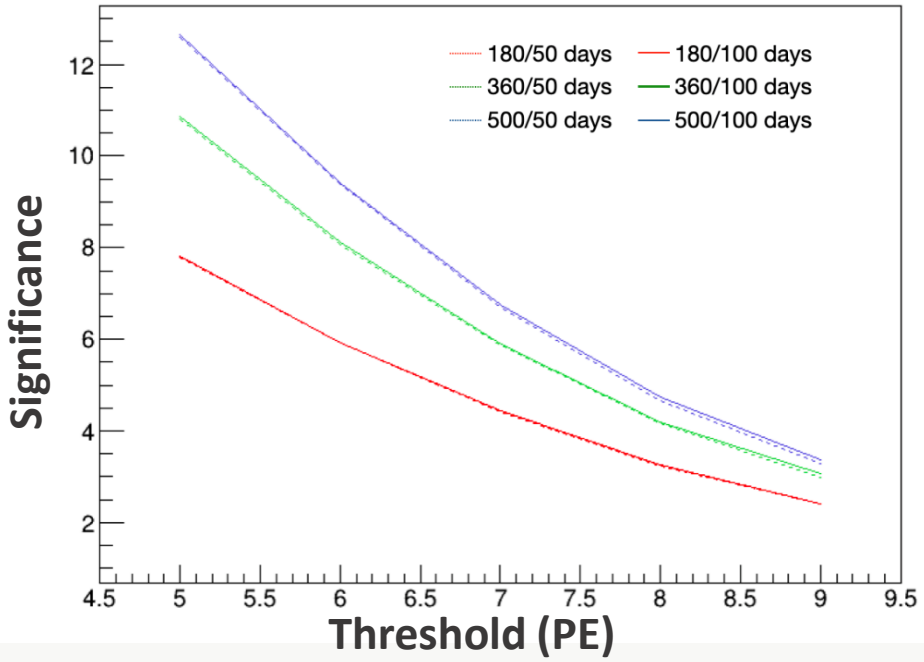
Reactor Neutrino CEνNS rate on NaI(Tl) target



- Assume the neutrino flux at NEOS site ($\Phi_\upsilon = 7.1 \times 10^{12}\mathrm{cm}^2\mathrm{s}^{-1}$)
- **Light yield** & **Threshold** are key factor!

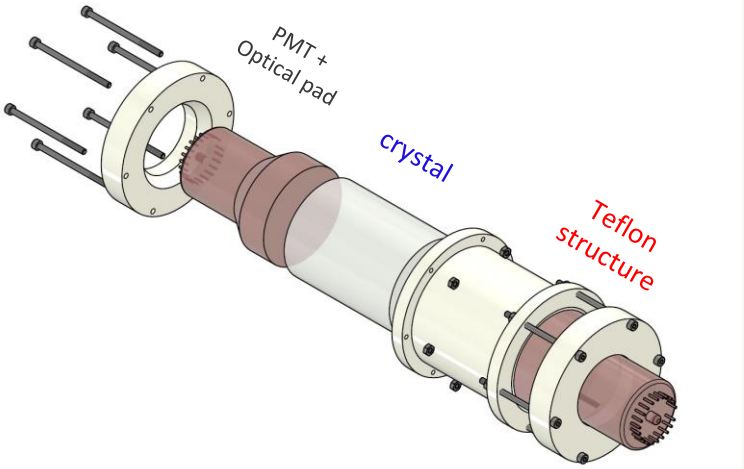
Required data size for 3 sigma ?

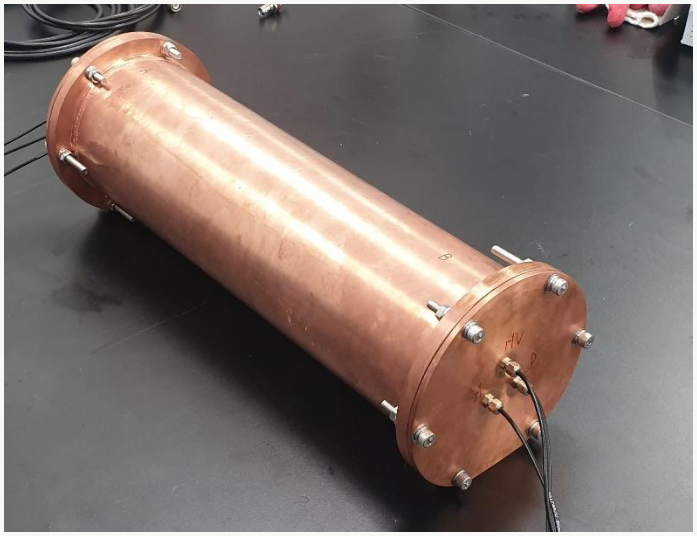


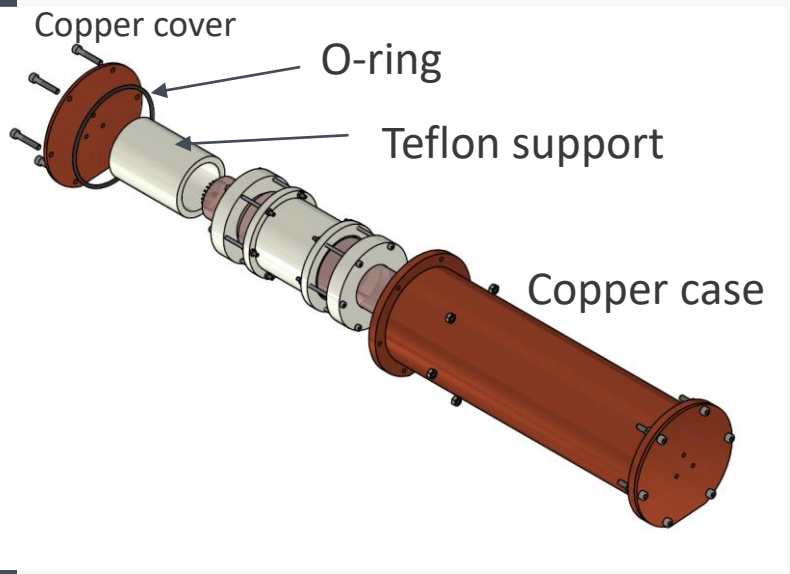


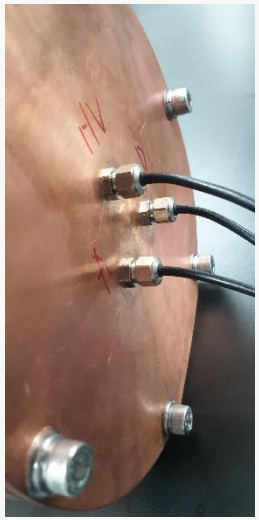
- Using pseudo-data based on phase-1 background data.
- Left : Analysis using **On-Off**
- Right : Analysis using **background modeling**
  - Use COSINE-100 systematics.

Phase 2 encapsulation

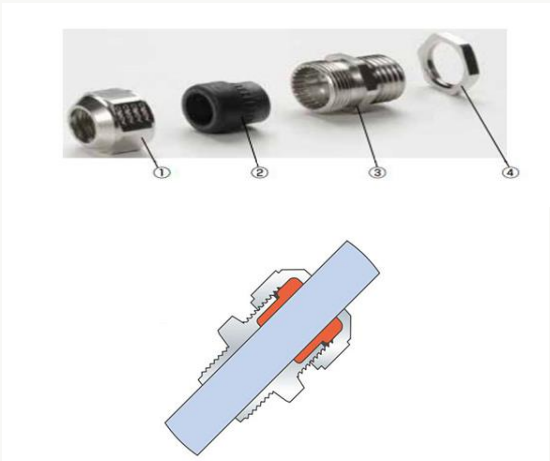






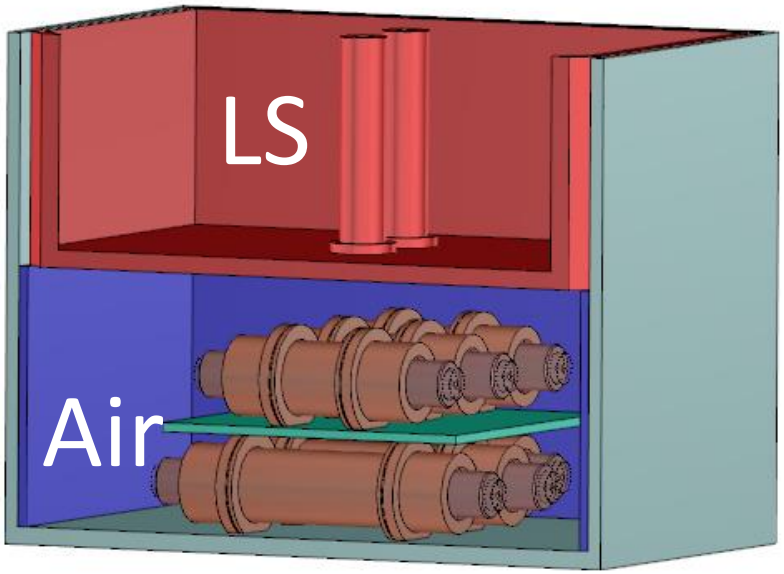


Cable gland



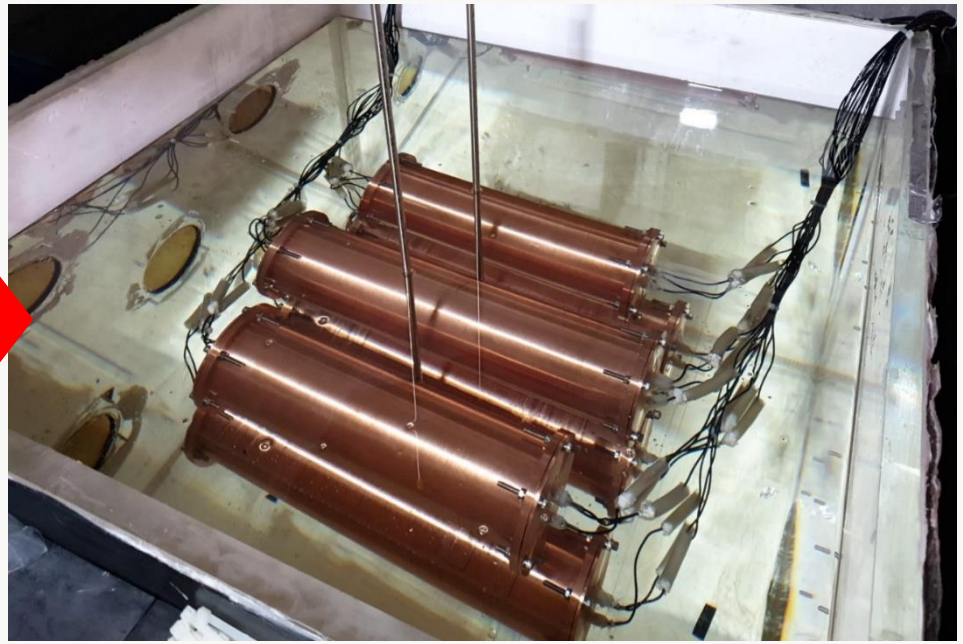
Phase 2 upgrade

Phase-1



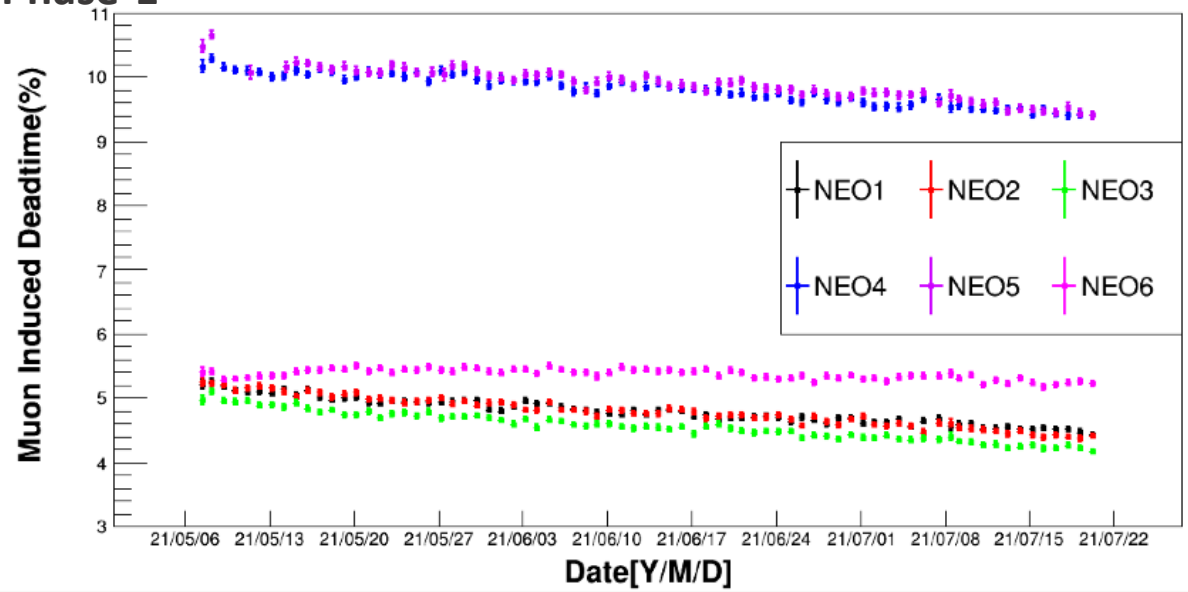
Inner acrylic box

Phase-2

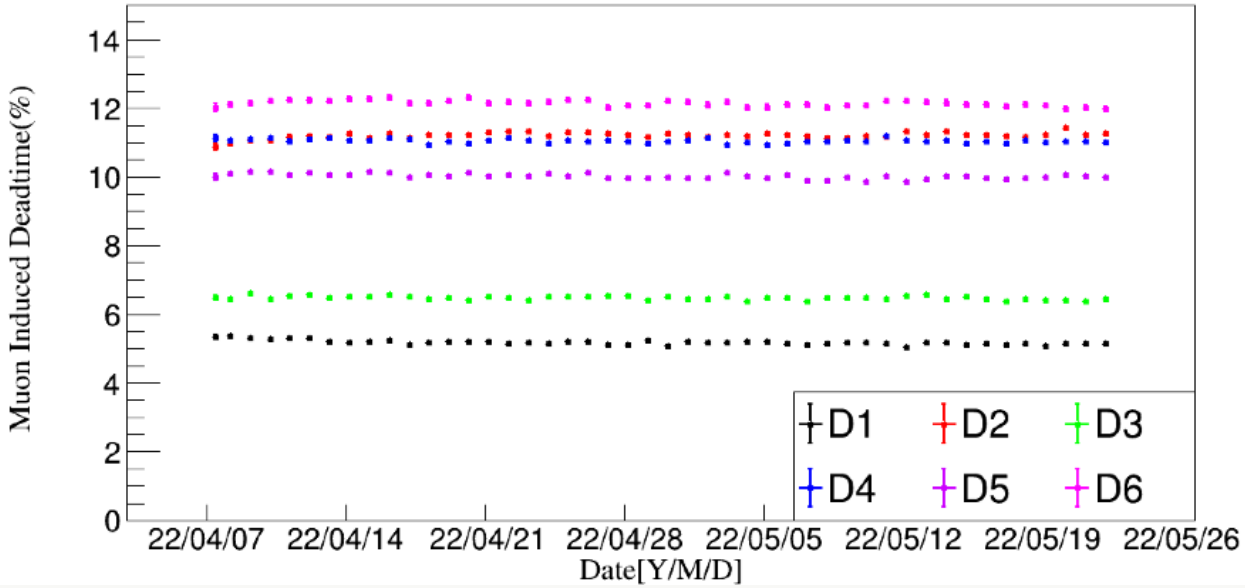


Gain stability

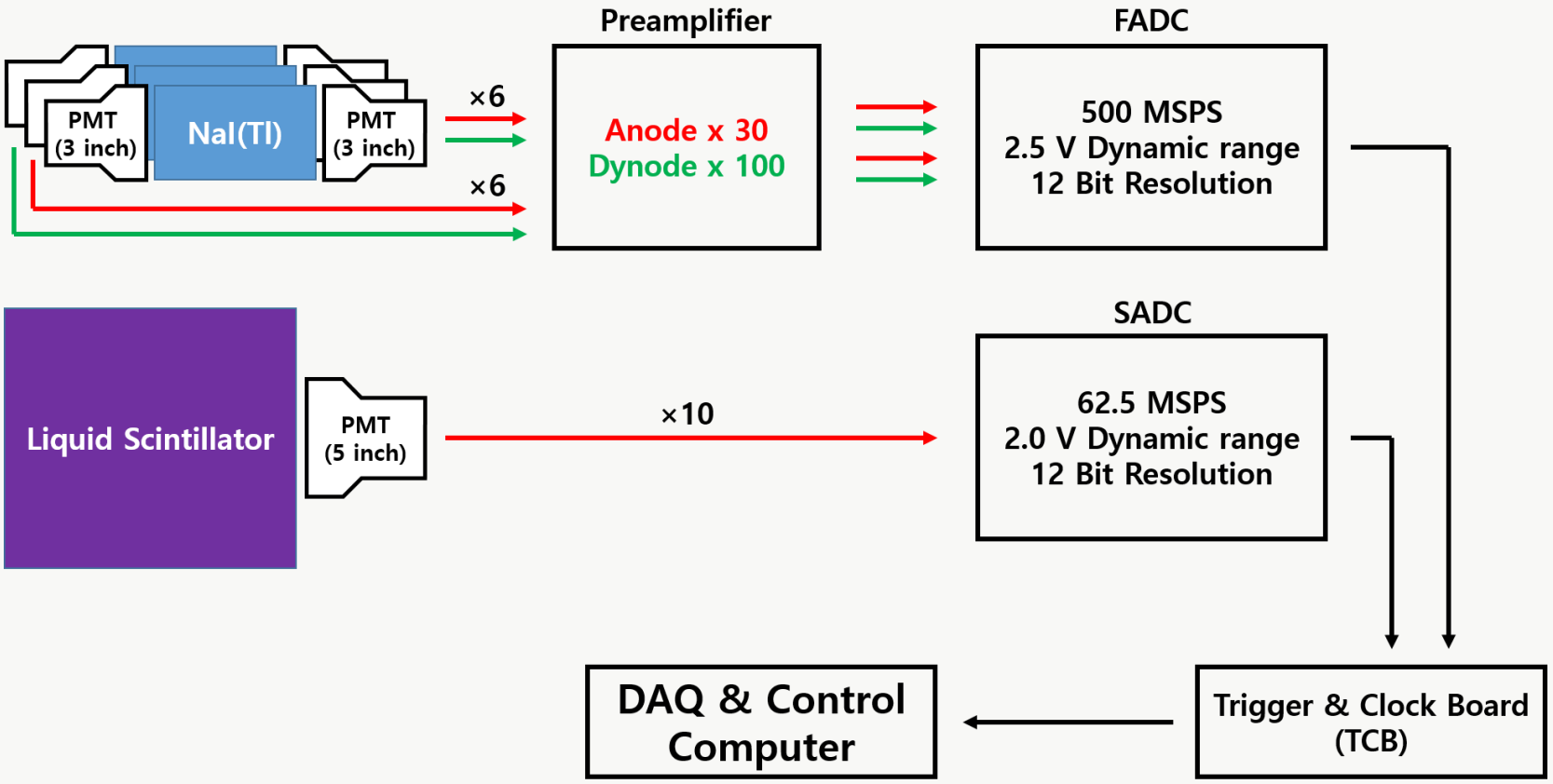
Phase-1



Phase-2



NEON DAQ


Preamplifier
FADC
PMT
(3 inch)
NaI(Tl)
PMT
(3 inch)
×6
×6
Anode x 30
Dynode x 100
500 MSPS
2.5 V Dynamic range
12 Bit Resolution
SADC
Liquid Scintillator
PMT
(5 inch)
×10
62.5 MSPS
2.0 V Dynamic range
12 Bit Resolution
DAQ & Control
Computer
Trigger & Clock Board
(TCB)