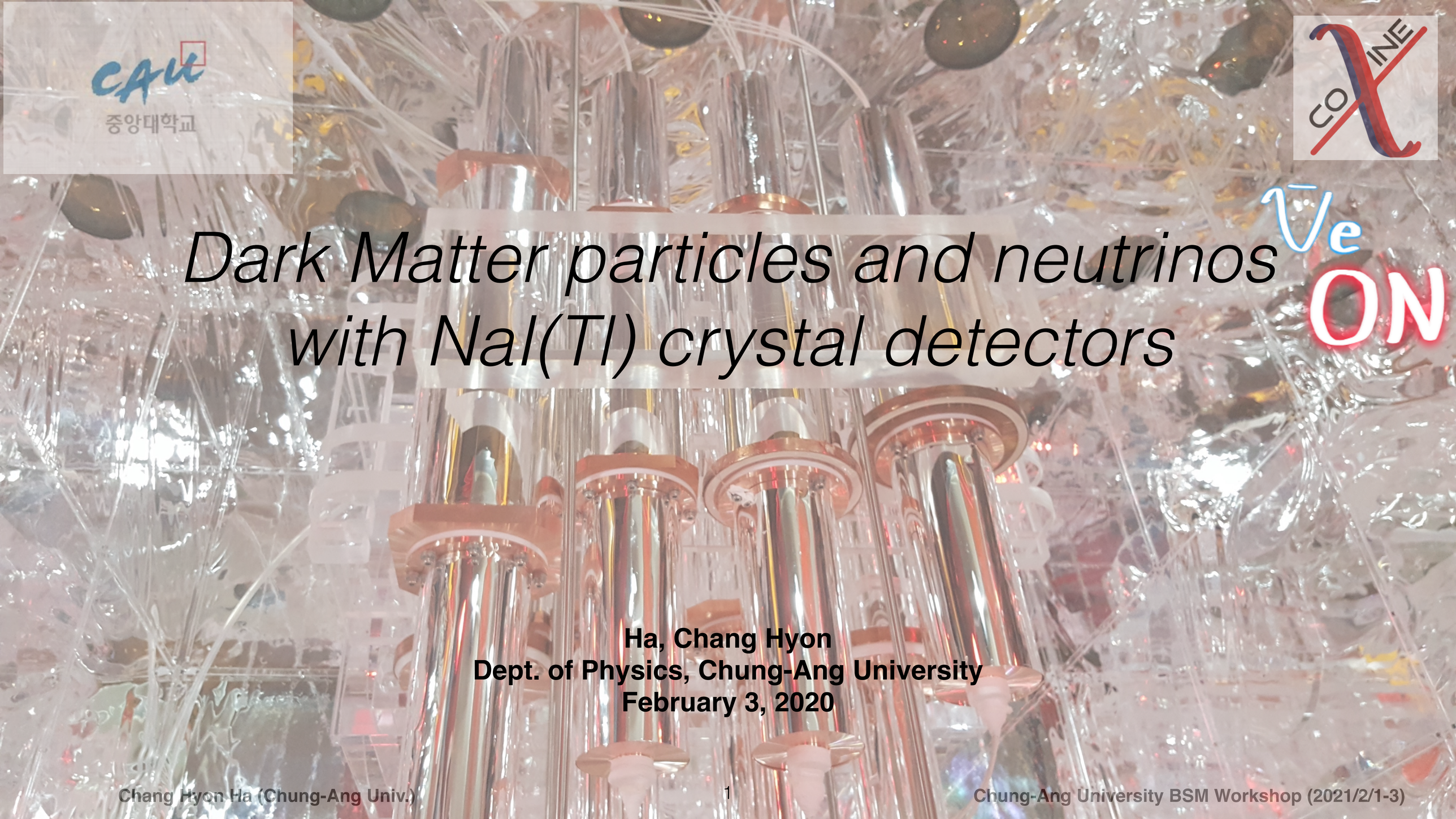
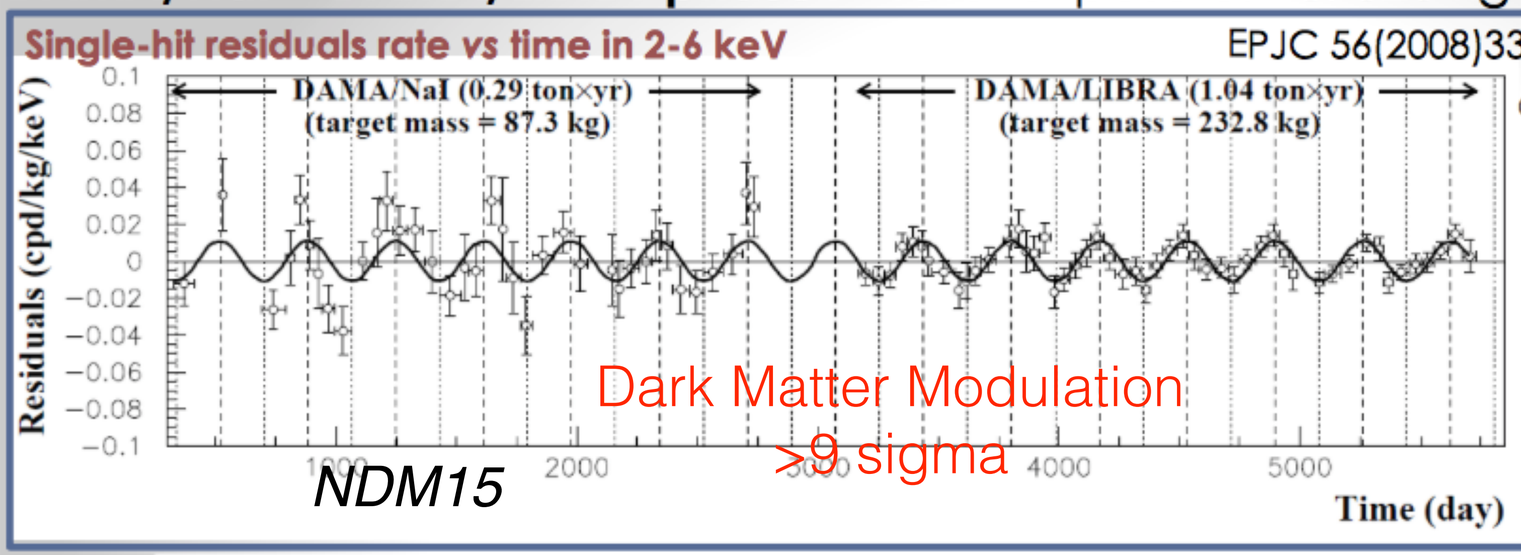


Dark Matter particles and neutrinos with NaI(Tl) crystal detectors

Ha, Chang Hyon
Dept. of Physics, Chung-Ang University
February 3, 2020

The DAMA annual modulation signal, to be confirmed with independent measurements by the same NaI(Tl) target material

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**



EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648

continuous line: t_0 = 152.5 d, T =1.0 y

A=(0.0110±0.0012) cpd/kg/keV

χ^2/dof = 70.4/86 9.2 σ C.L.

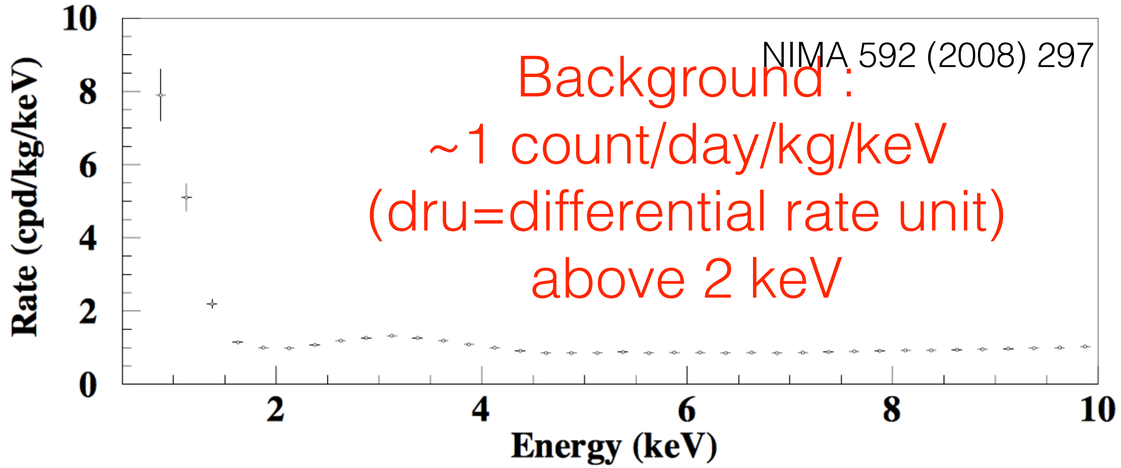
Absence of modulation? No

χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

Fit with all the parameters free:

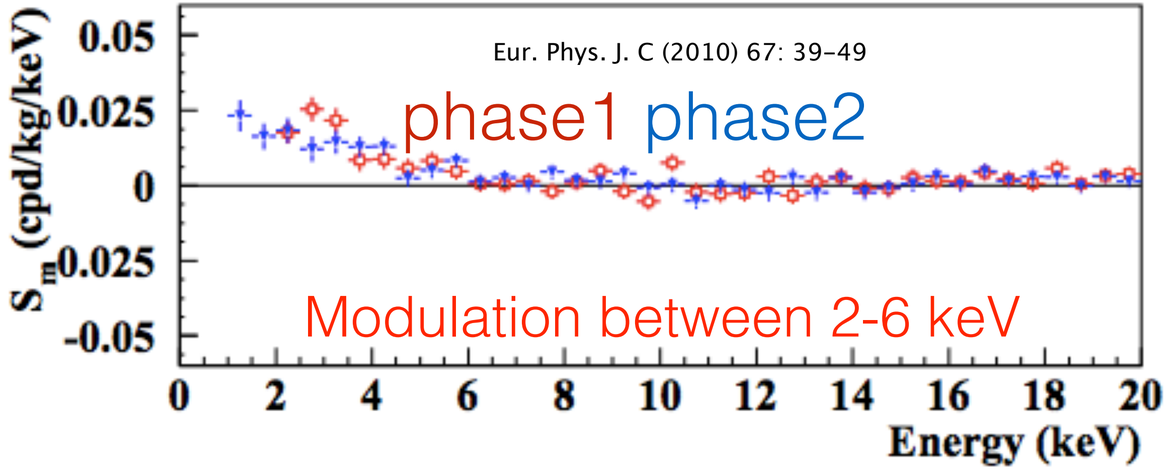
A = (0.0112 ± 0.0012) cpd/kg/keV

t_0 = (144±7) d - T = (0.998±0.002) y

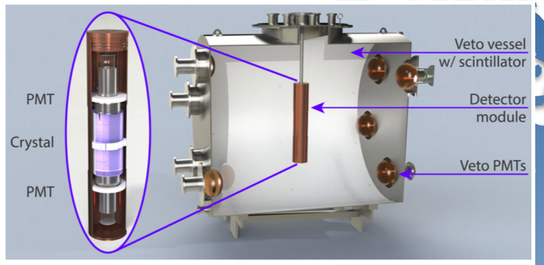


NIMA 592 (2008) 297

Background :
~1 count/day/kg/keV
(dru=differential rate unit)
above 2 keV

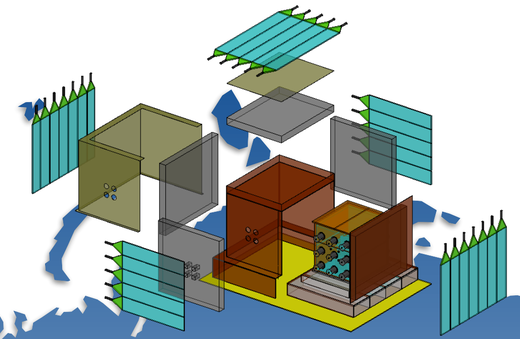


Global NaI(Tl) efforts

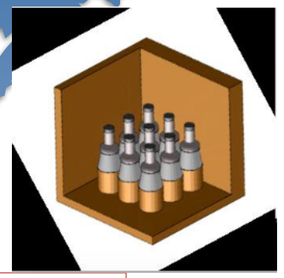


DAMA/LIBRA @ LNGS

SABRE @ LNGS

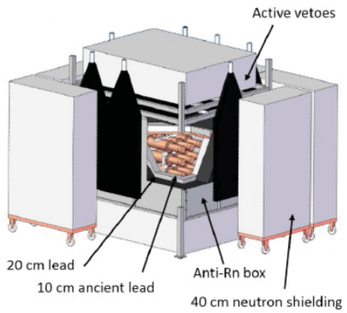


COSINE-100 @ Y2L

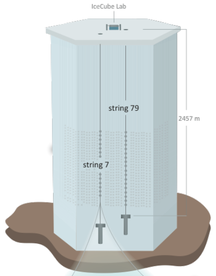


PICO-LON @ Kamioka

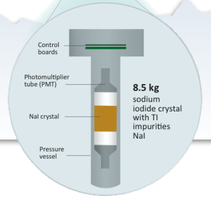
ANAIS @ Canfranc



SABRE @ Stawell



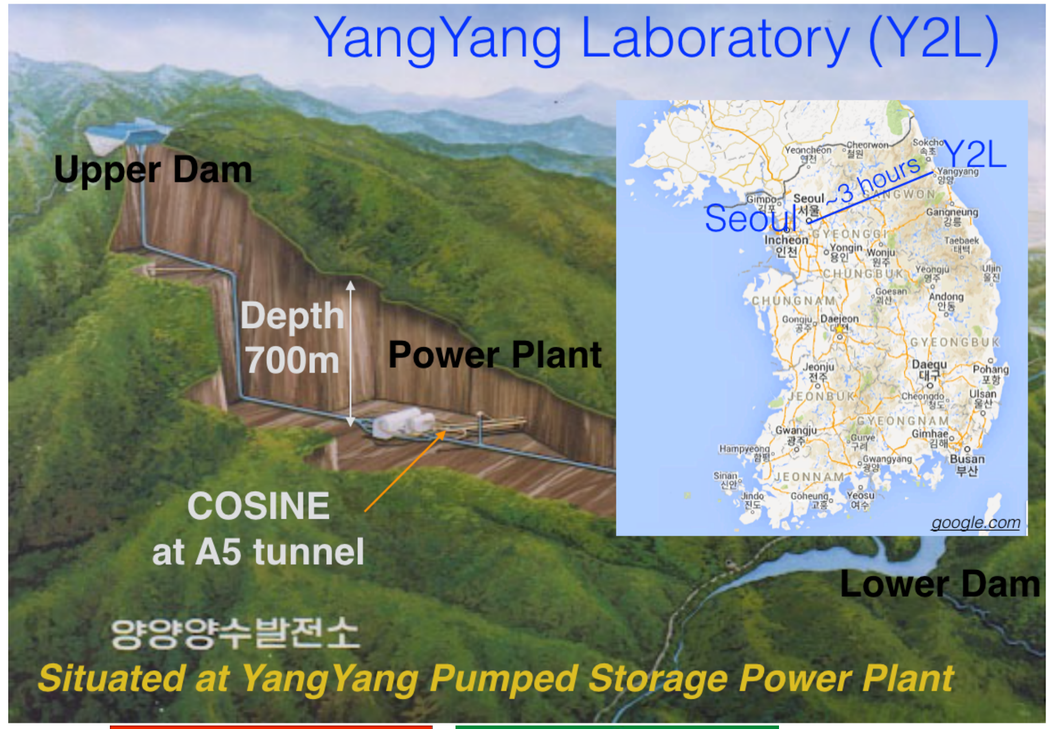
DM-Ice17 @ South Pole



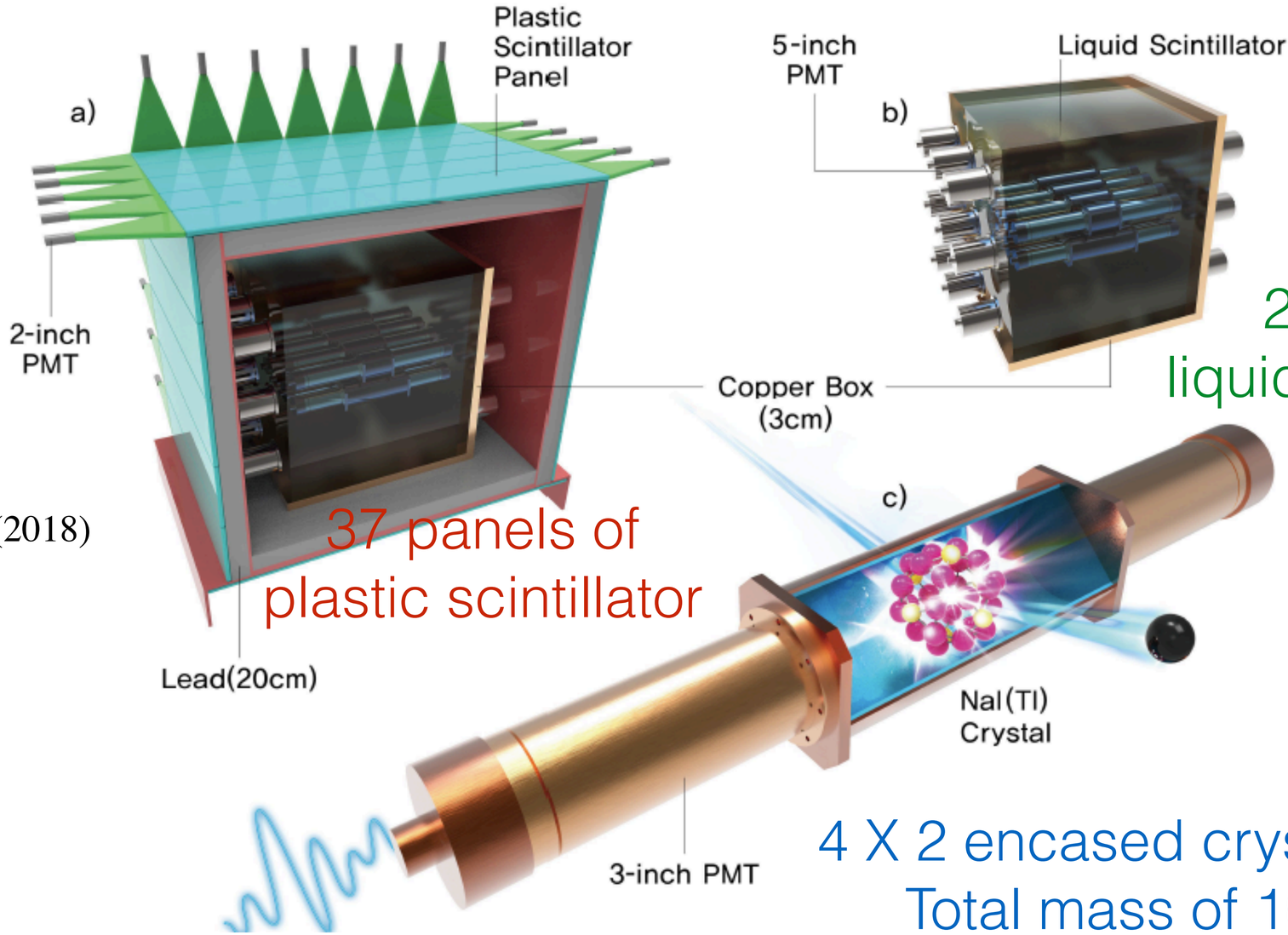
The COSINE-100 Experiment

5 countries,
15 institutes
50 scientists

Joint collaboration between KIMS and DM-Ice to search for dark matter interactions in NaI(Tl) scintillating crystals.



The COSINE-100 detector components



JINST13 T02007 (2018)

37 panels of
plastic scintillator

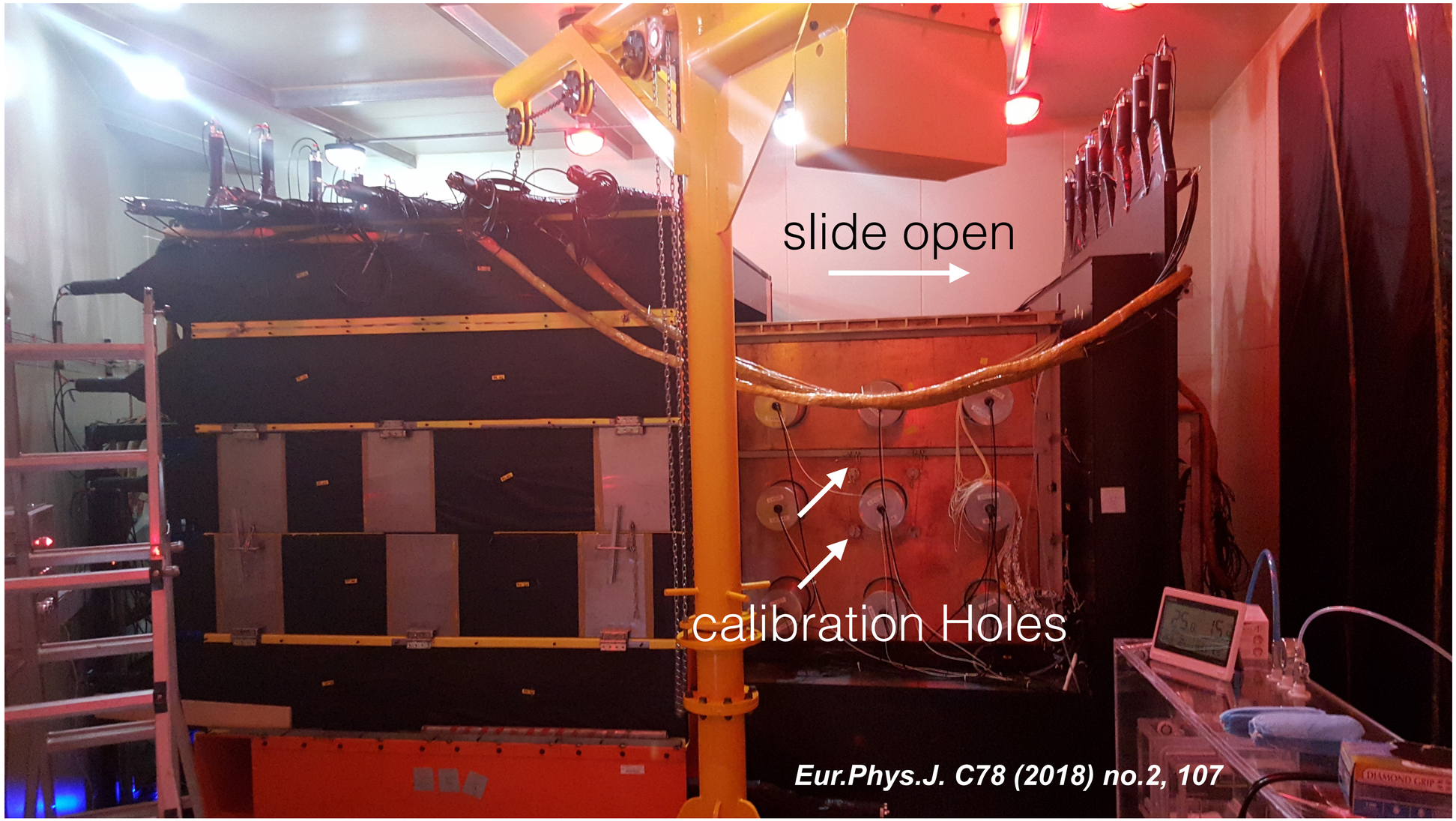
2 tons of
liquid scintillator

Nucl. Instrum. Meth. A 851 102 (2017)

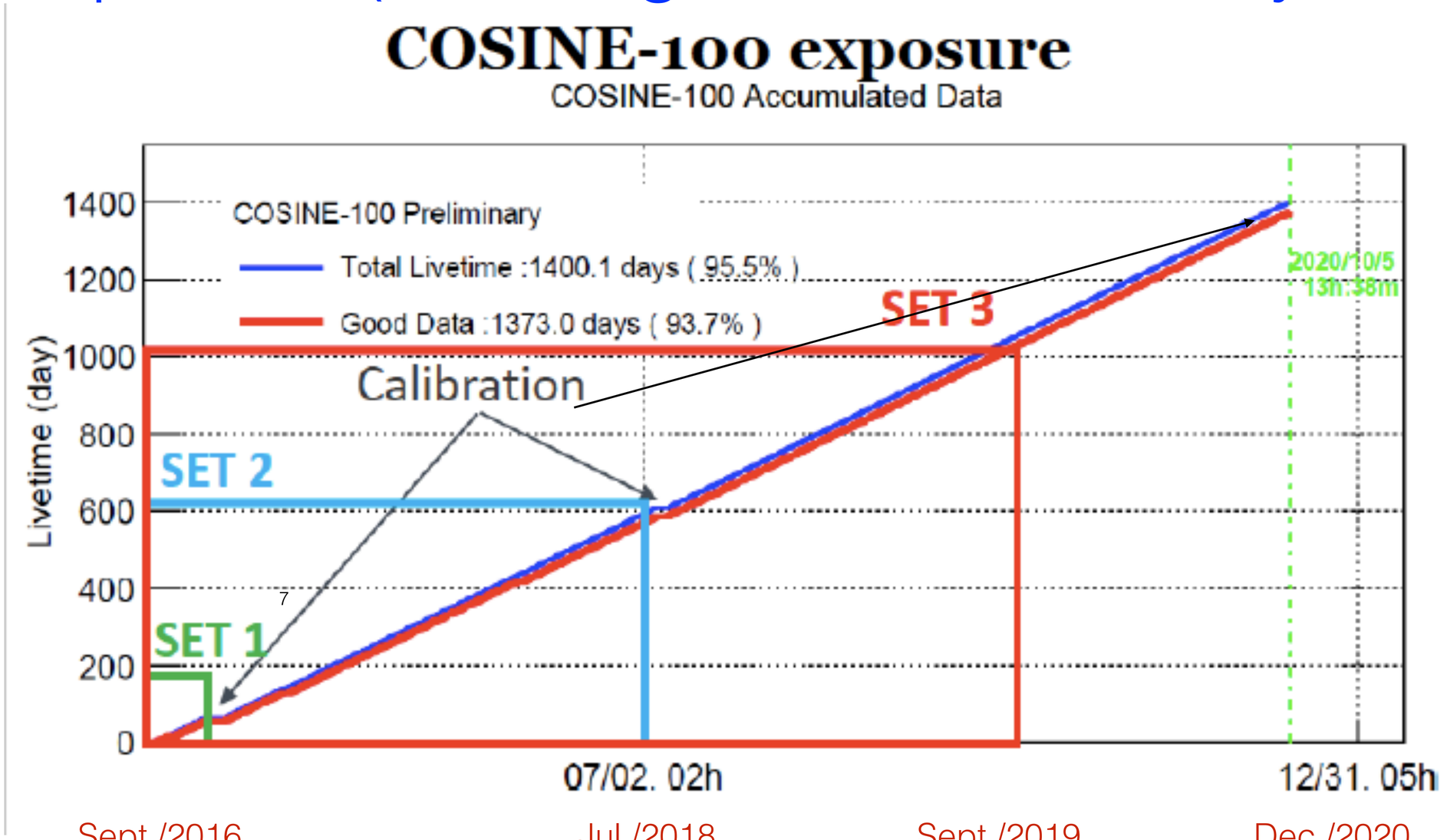
4 X 2 encased crystal array
Total mass of 106 kg

Eur. Phys. J. C. 78 107 (2018)

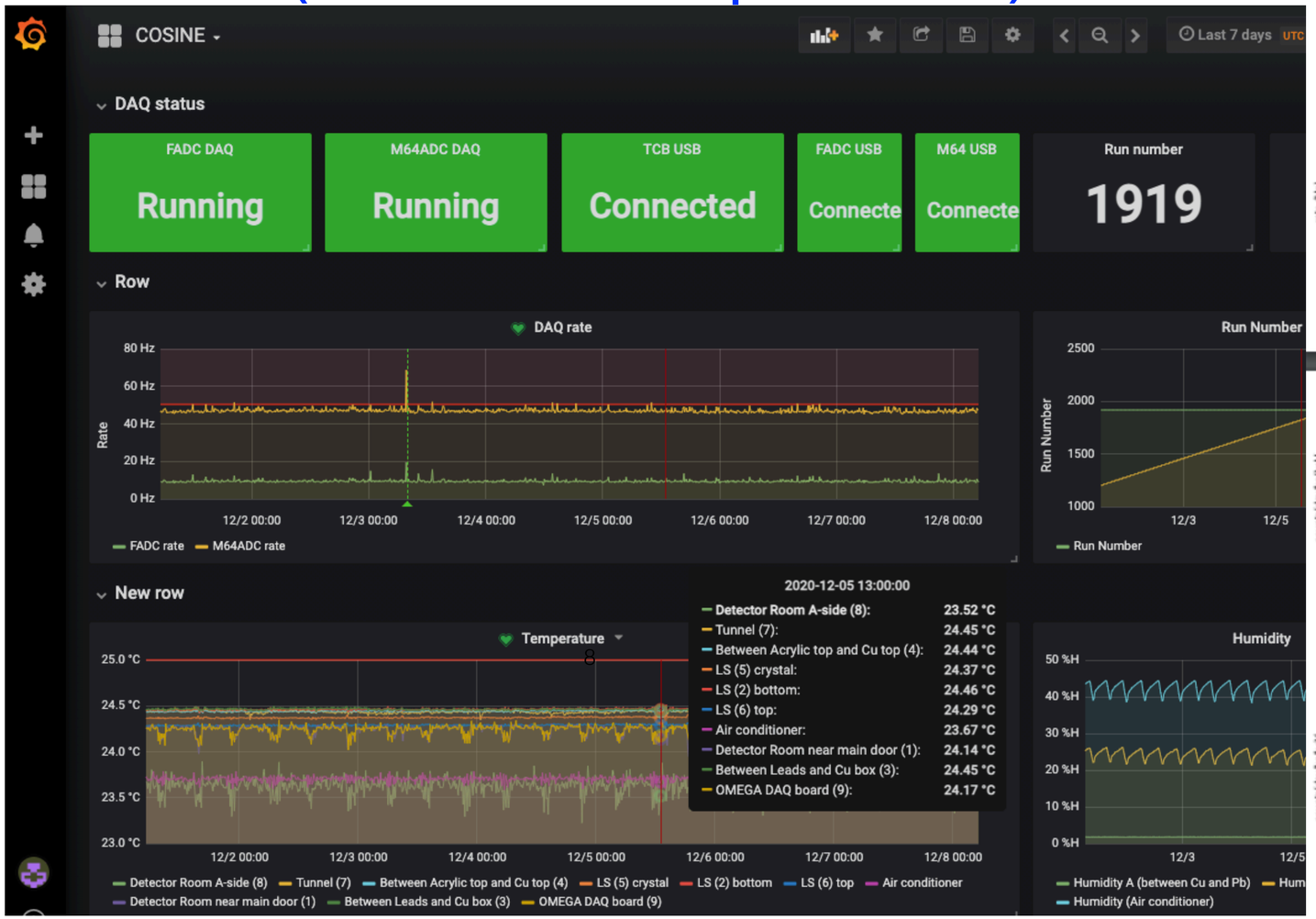
The COSINE-100 Detector

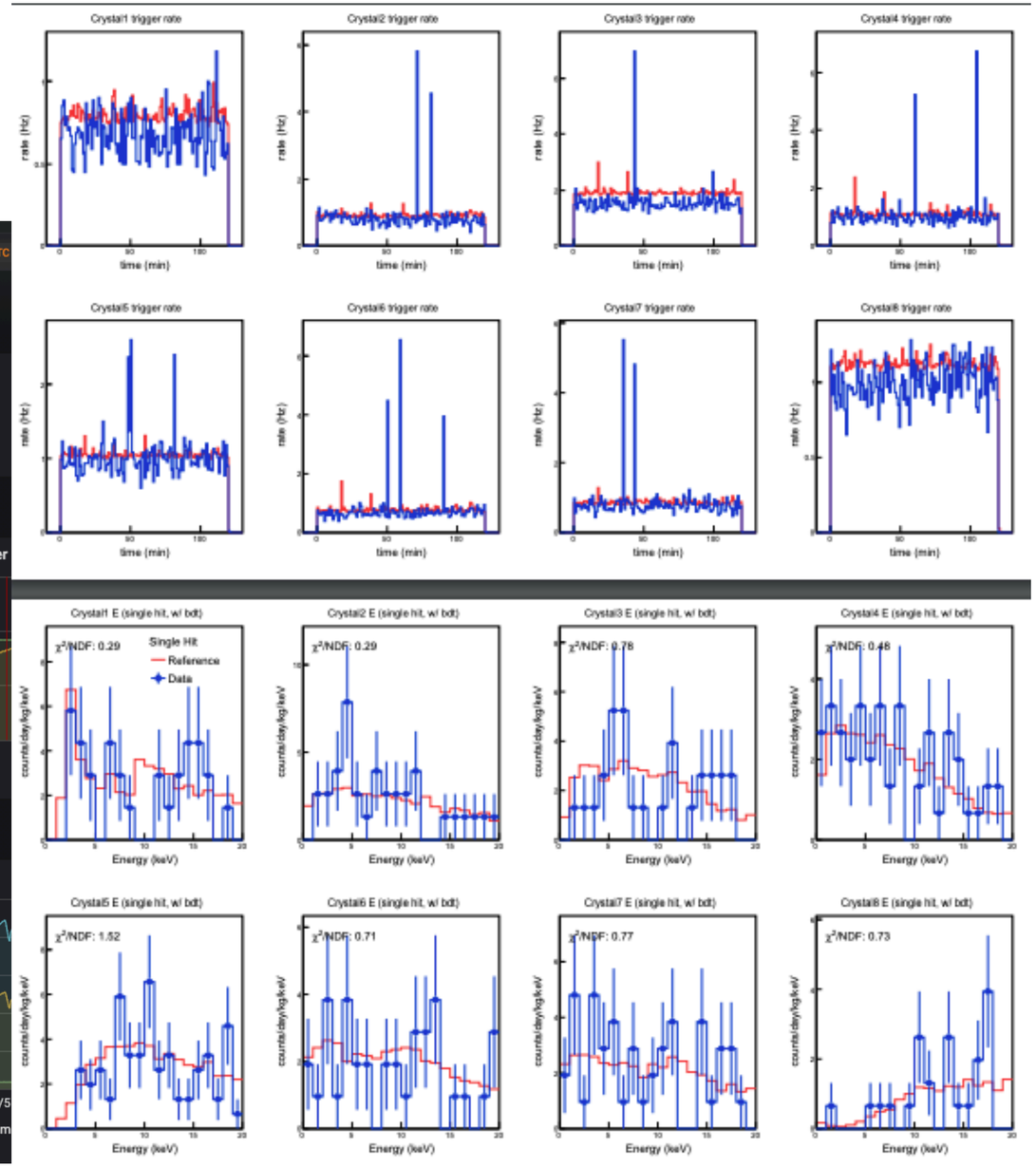


Exposure (Running for more than 4 years)



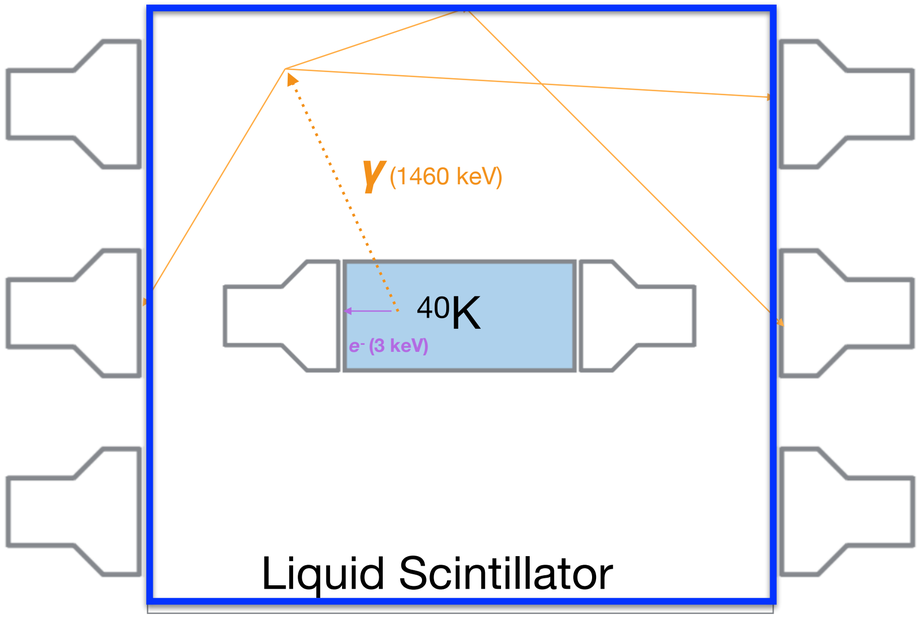
Data Monitoring (via Smartphone)

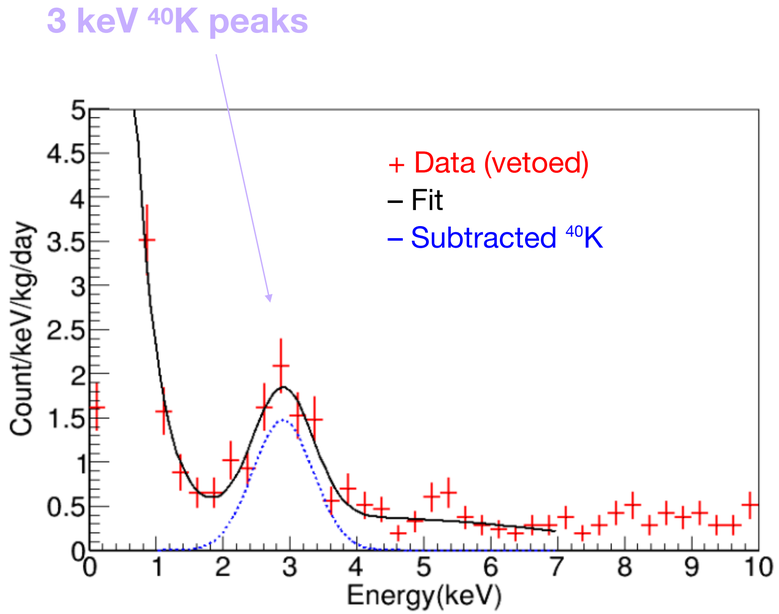


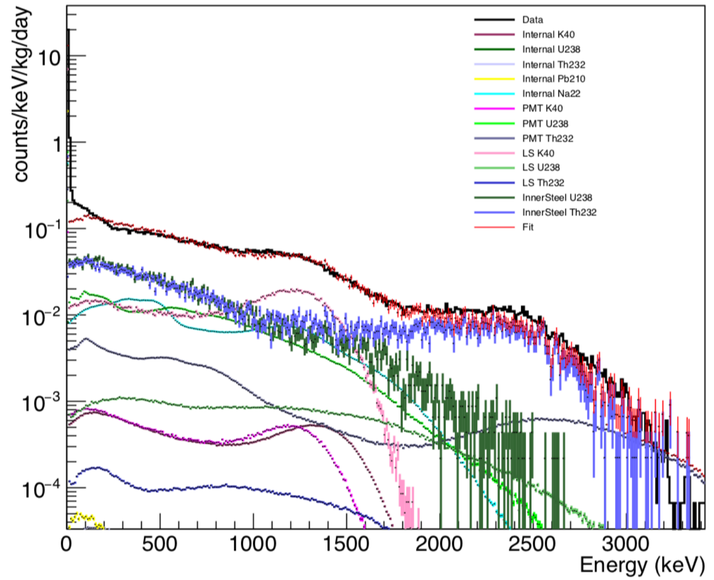


We monitor >100 parameters for the detector and Another 100 variables from data

Crystal-LS coincidence

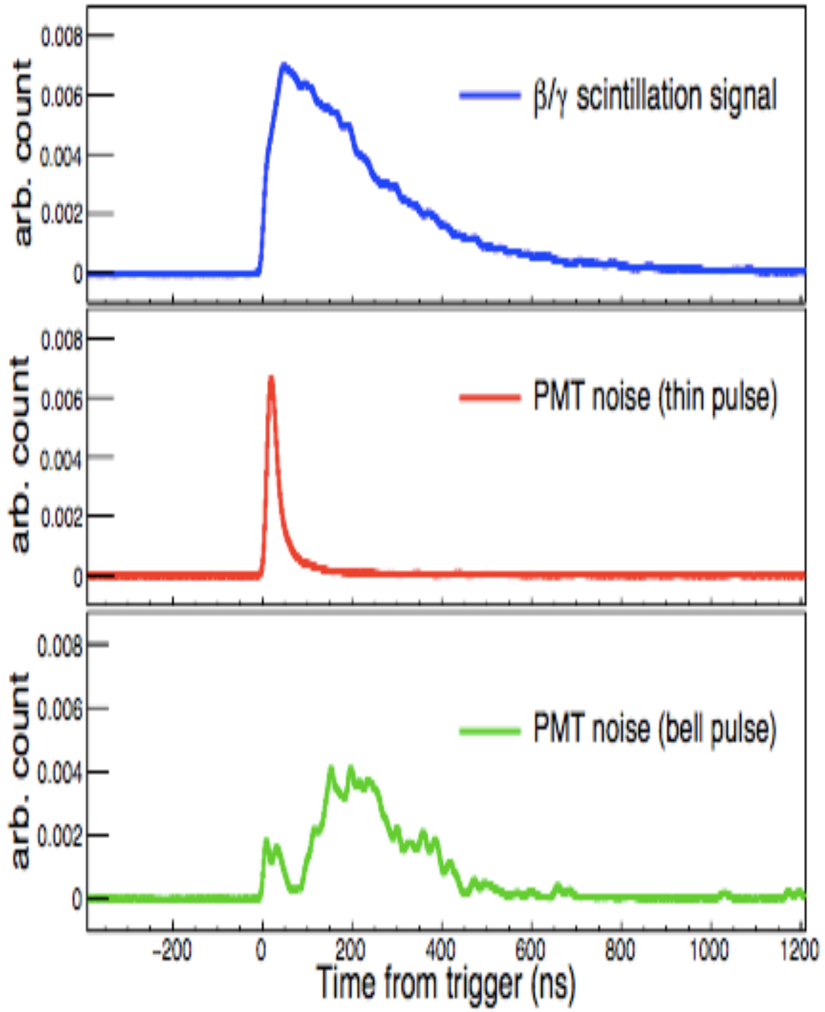


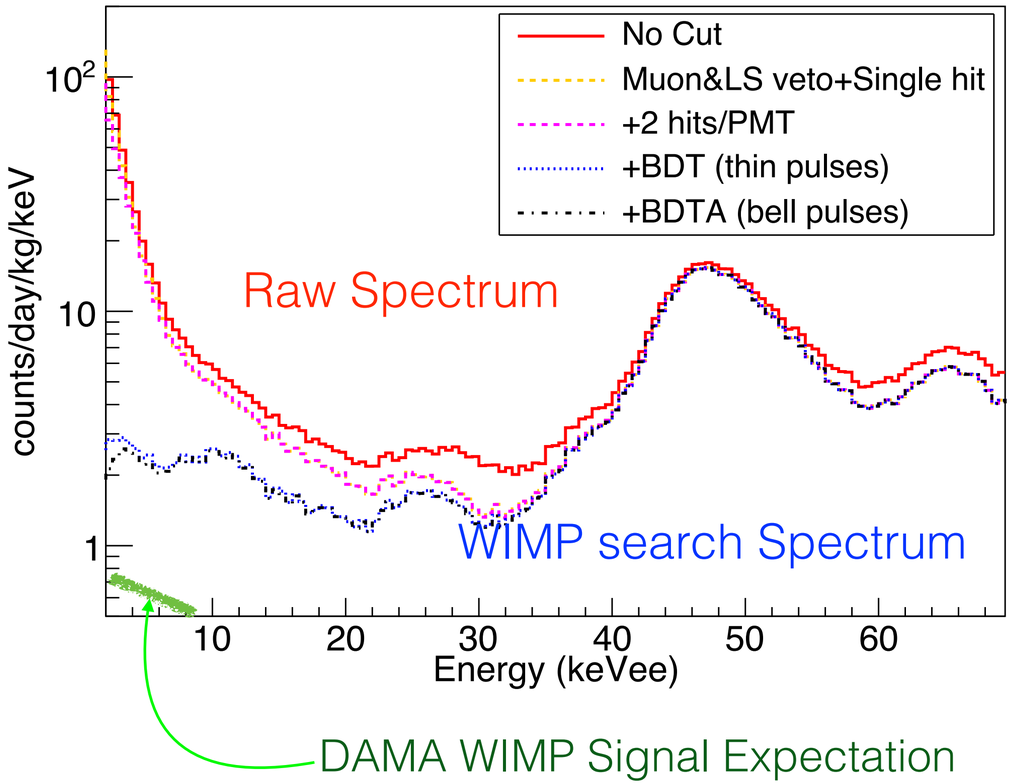




- Liquid scintillator light is passively read out when there is a trigger in a crystal.
- A crystal trigger with LS energy deposit larger than 80 keV is defined as multiple hit events.
- ^{40}K emits 1460 keV gamma with 3 keV Auger electron energy deposition in NaI crystal
- Tagging 1460 keV events with LS enables **vetoing of 3 keV background events (70-80%)**
- Liquid scintillator internal contamination well modeled with simulation

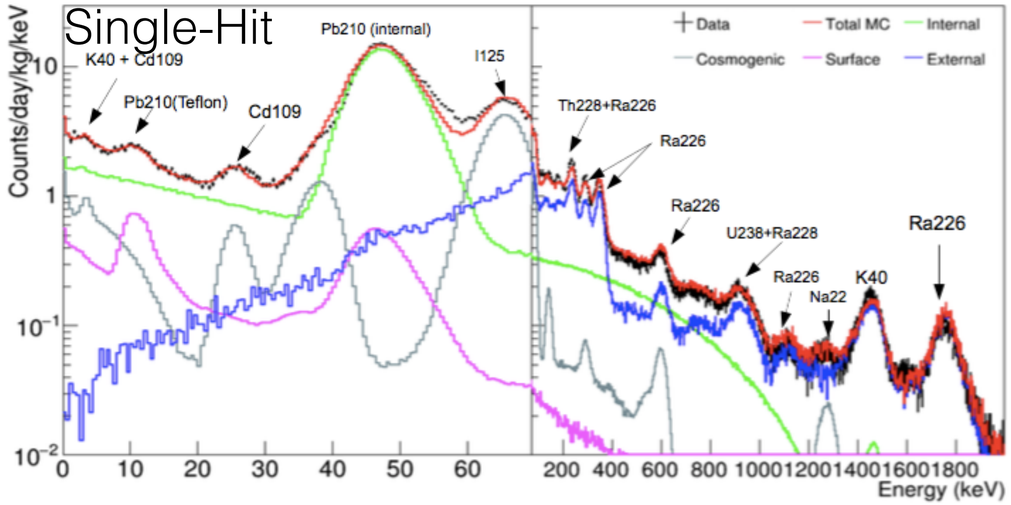
PMT noise reduction
Every experiment has noise and WIMP search=Noise Reduction

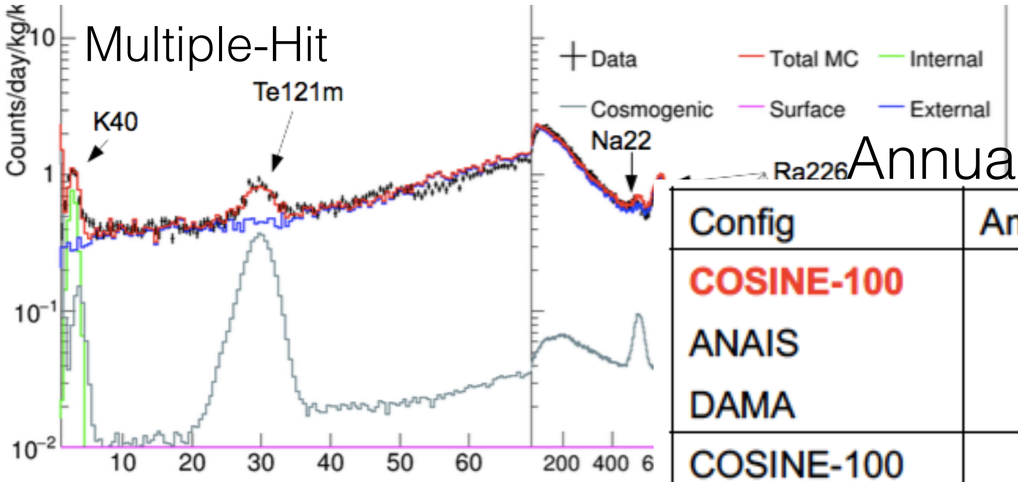




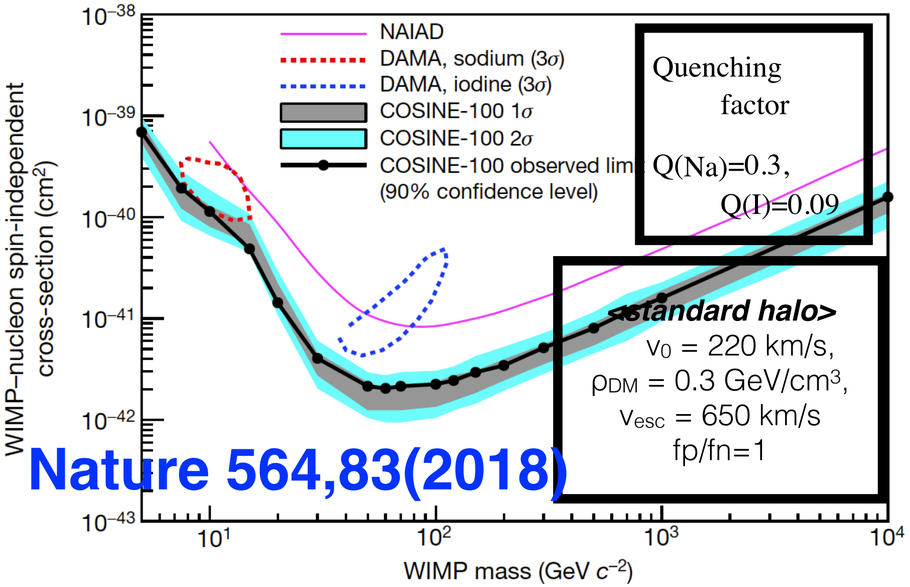
1. Constant Rate Analysis
2. Annual Modulation Analysis

COSINE-100
(2-keV Threshold Analyses)



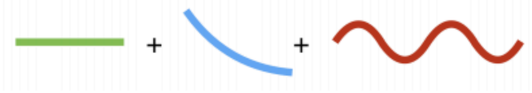


EPJC 78, 490 (2018)



Nature 564,83(2018)

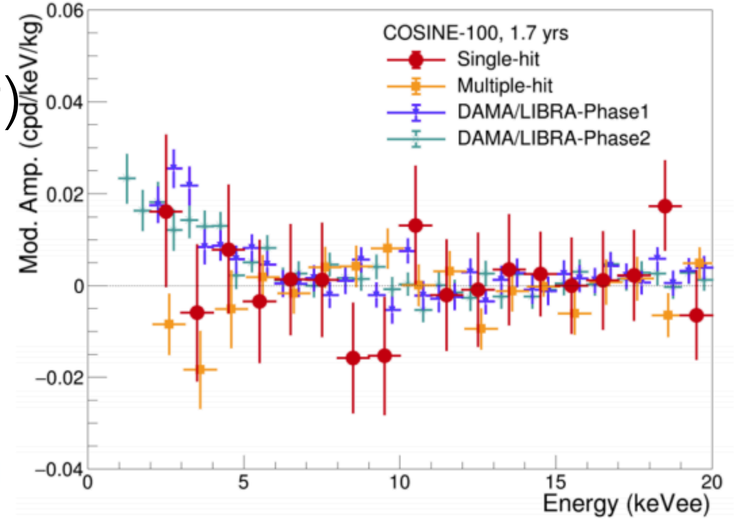
Offset + Exponential + Cosine is fit to data at 2-6 keV.



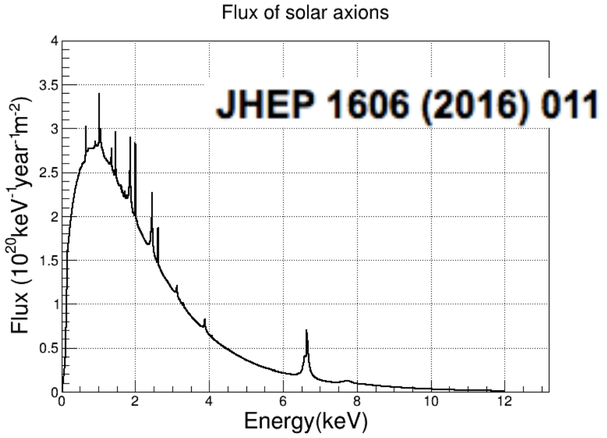
PRL 123,031302 (2019)

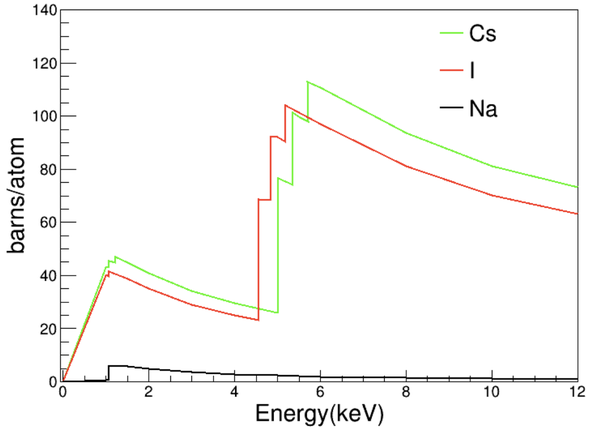
Annual Modulation Analysis(1.7 yr)

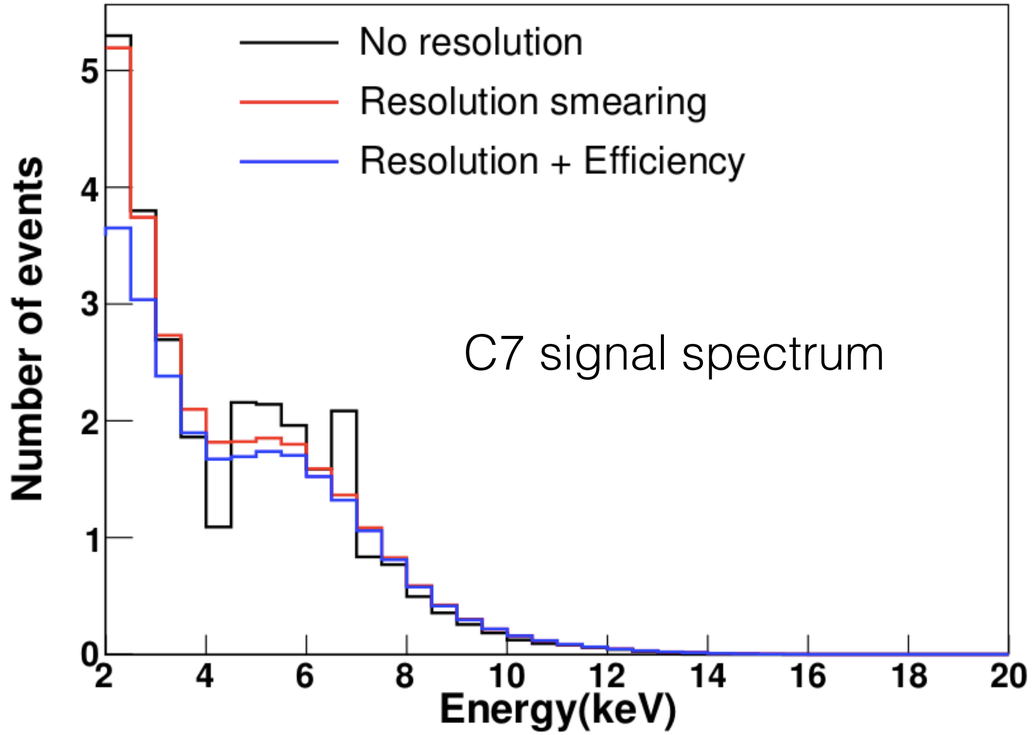
Config	Amplitude (2-6 keV)	Phase (days)
COSINE-100	0.0083 ± 0.0068	**152.5 (fixed)**
ANAIS	-0.0044 ± 0.0058	152.5 (fixed)
DAMA	0.0095 ± 0.0008	152.5 (fixed)
COSINE-100	0.0092 ± 0.0067	127 ± 46
DAMA	0.0096 ± 0.0008	145 ± 5

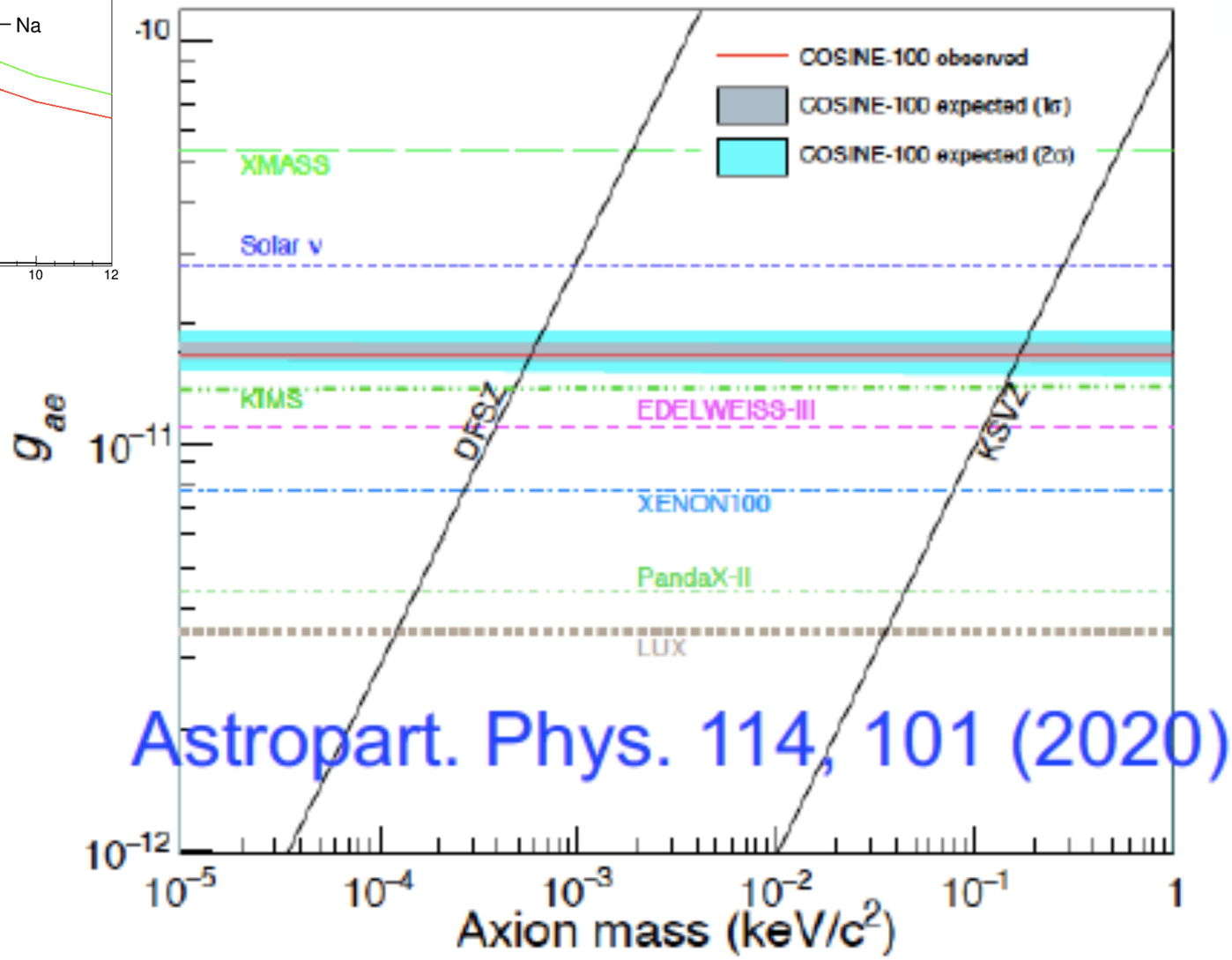


Solar Axion Search





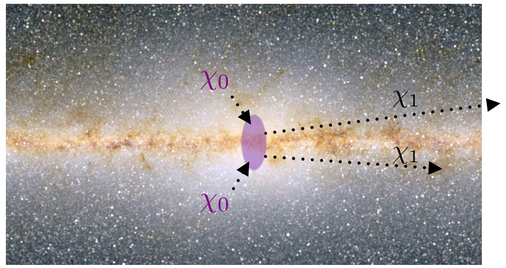


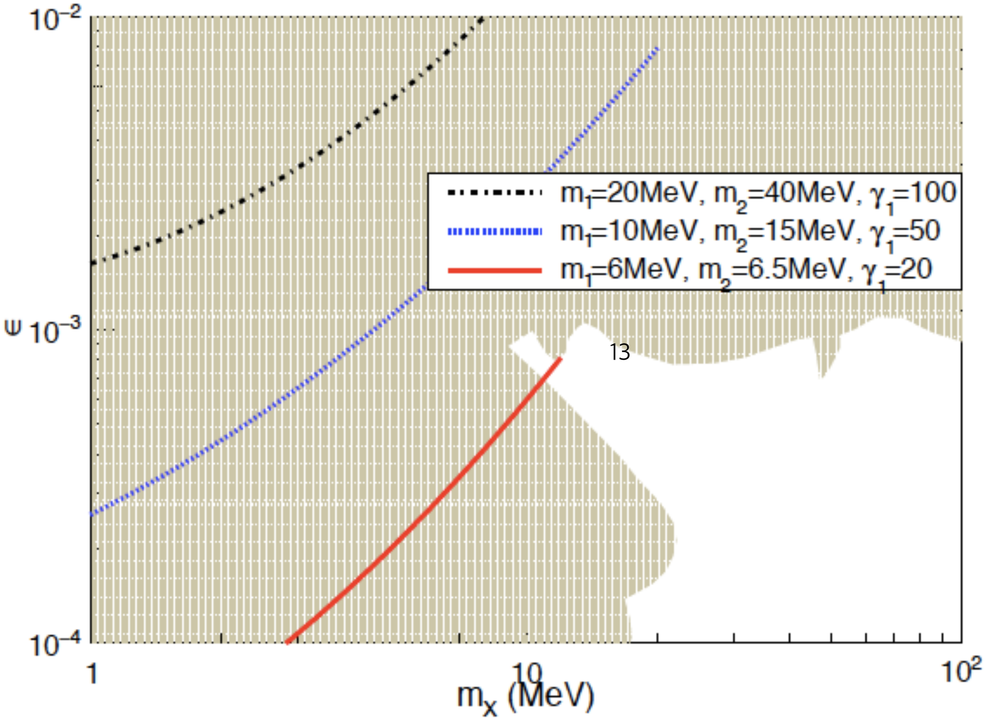


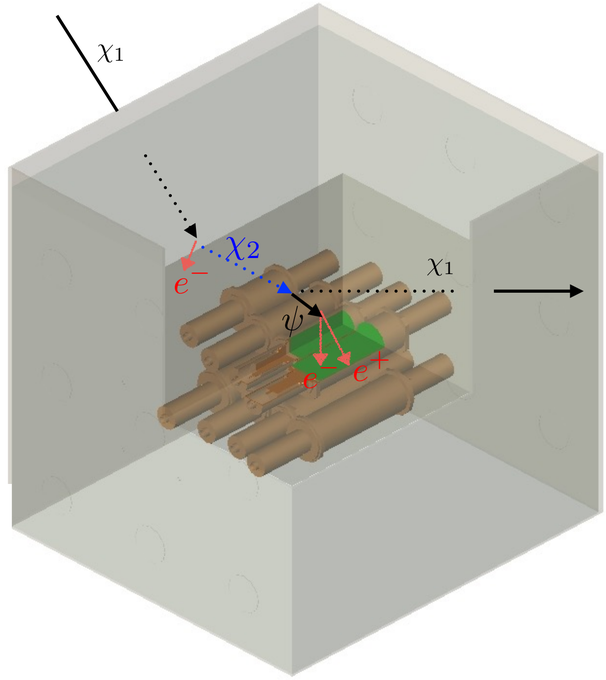
Astropart. Phys. 114, 101 (2020)

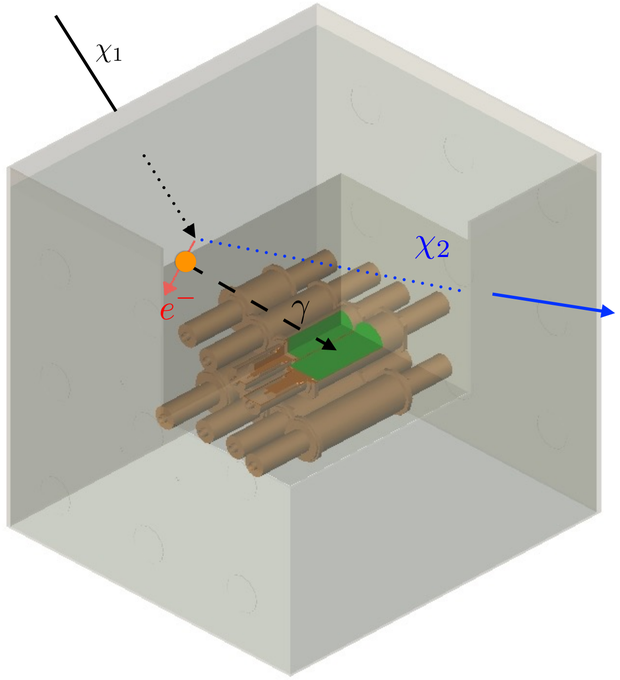
Inelastic Boosted Dark Matter

Physics Letters B 780 (2018) 543–552





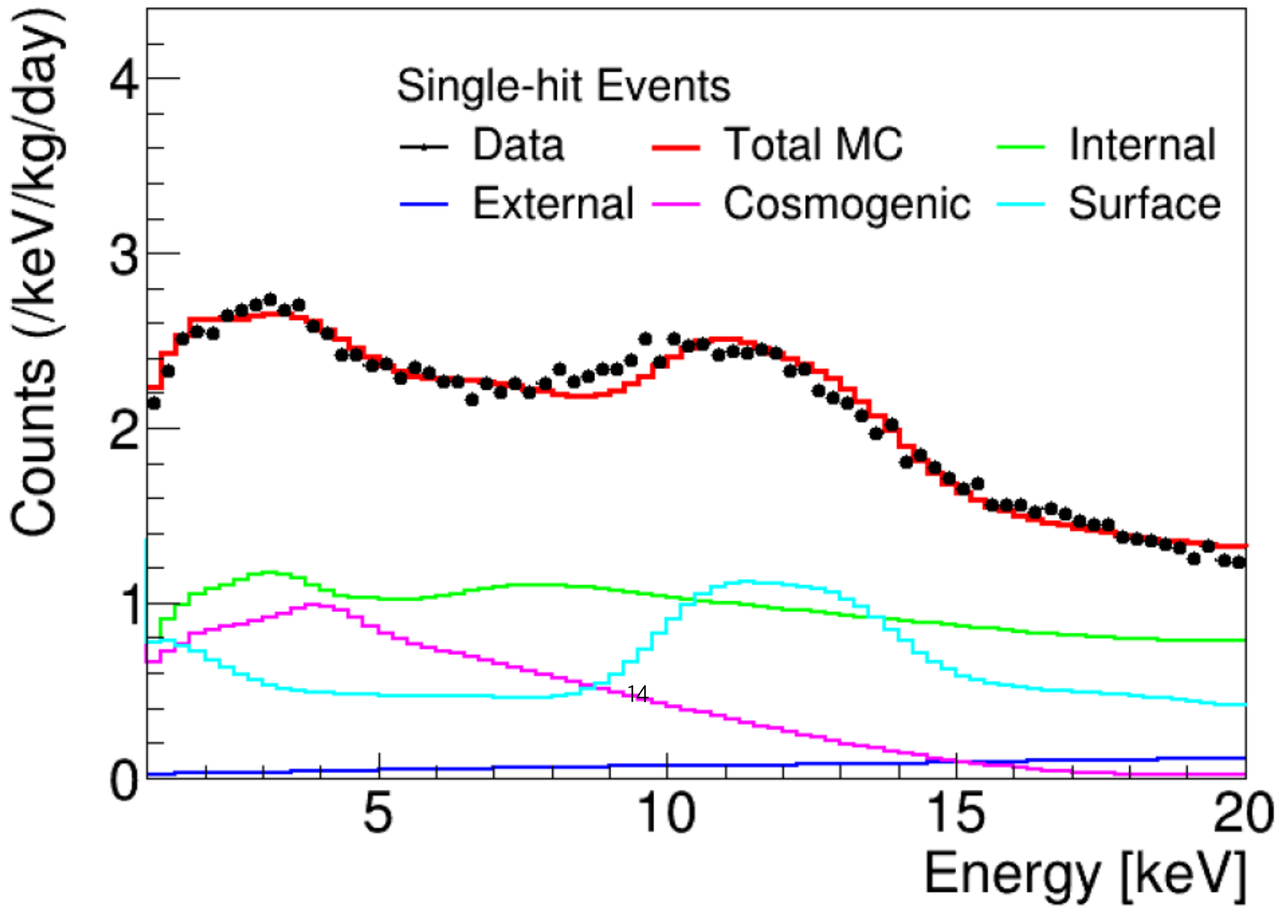


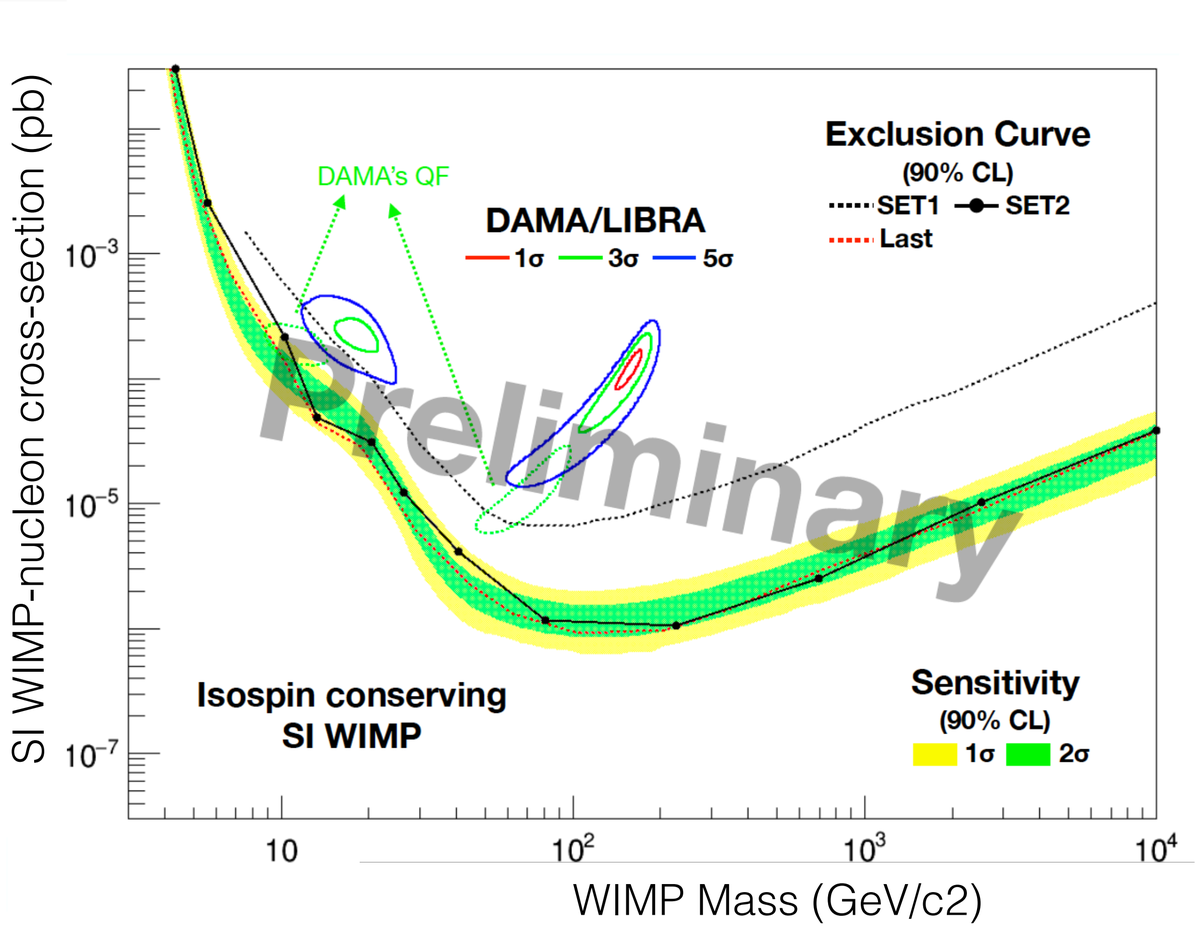


PRL 122,131802 (2019)

Using 2 tons of the LS volume as a crystal-LS combined target, we search for dark matter signals that could be displaced in a volume.

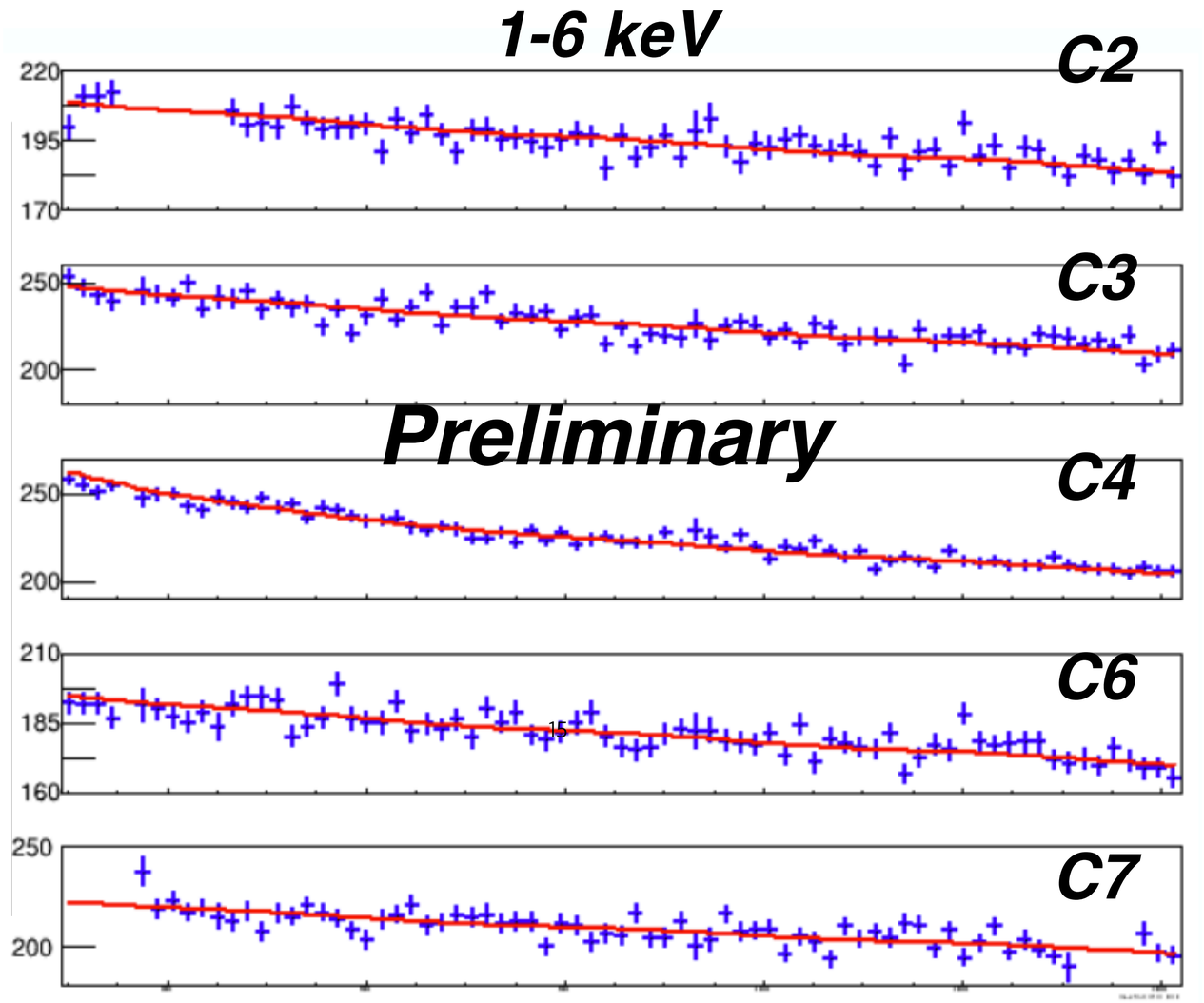
Constant Rate Analysis with 1-keV threshold (1.7 yr)



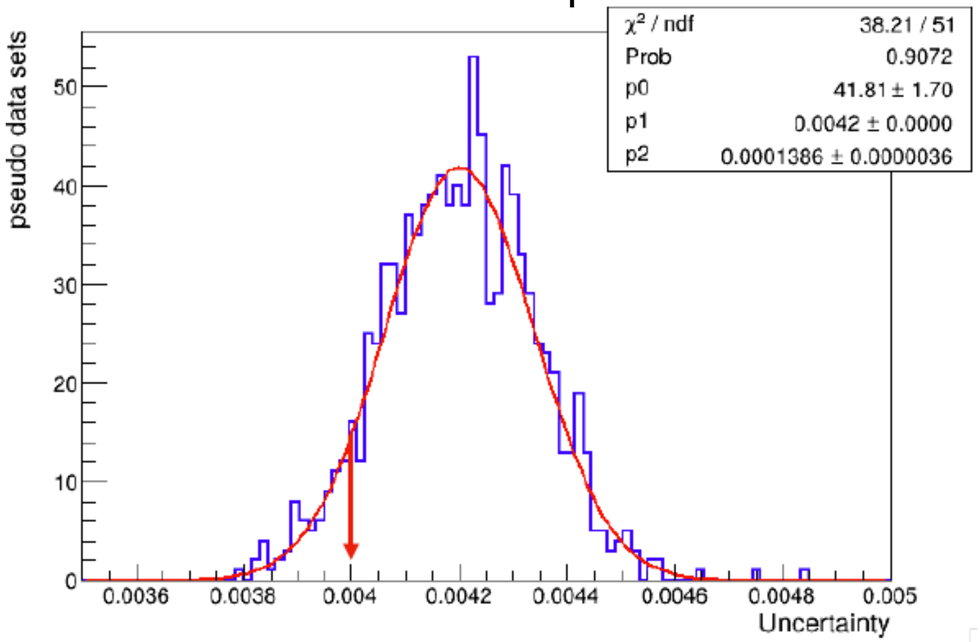


A factor of 10 improved result compared to the first result

Annual Modulation Analysis with 1-keV threshold (3 yr)



Better Modeling of Backgrounds
Better Pseudo experiments



Preliminary Results : 0.0061 ±0.0040 dru

DAMA/LIBRA : 0.0106 ±0.0011 dru

Keep pounding! Need more data! Need better crystals!

COSINE-200 Preparations (much work done in Korea)

Powder Purification

	K (ppb)	Pb (ppb)	U (ppb)	Th (ppb)
Initial NaI	248	19.0	<0.01	<0.01
Purified NaI	<16	0.4	<0.01	<0.01

K.A. Shin et al., J. Rad. Nucl. Chem. 317, 1329 (2018)
K.A. Shin et al., JINST 15, C07031 (2020)

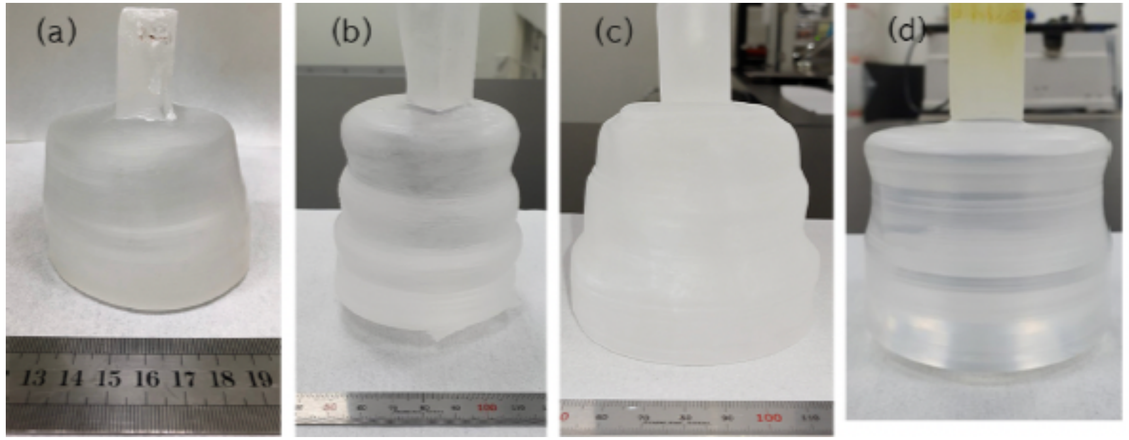
Purification
(70 kg powder load)

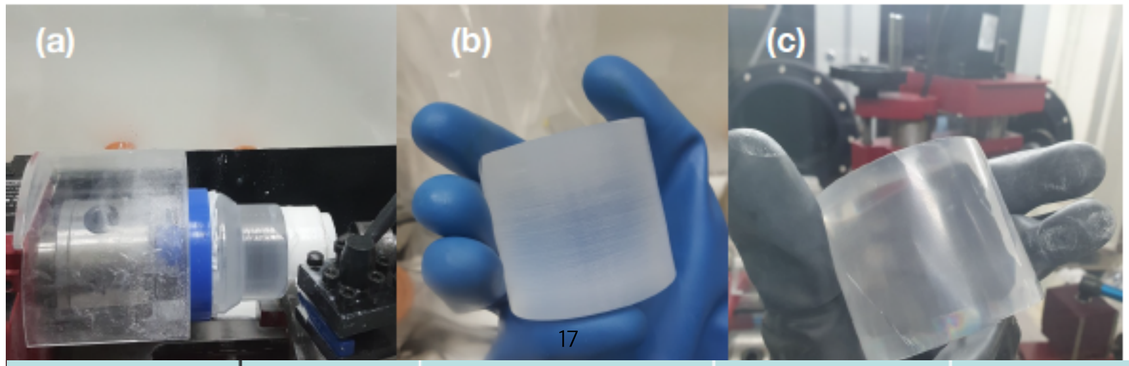

Small Grower
(1 kg crystal ingot)


Full-sized Grower
(100 kg crystal ingot)

Background rate should be less than 1 dru (DAMA)

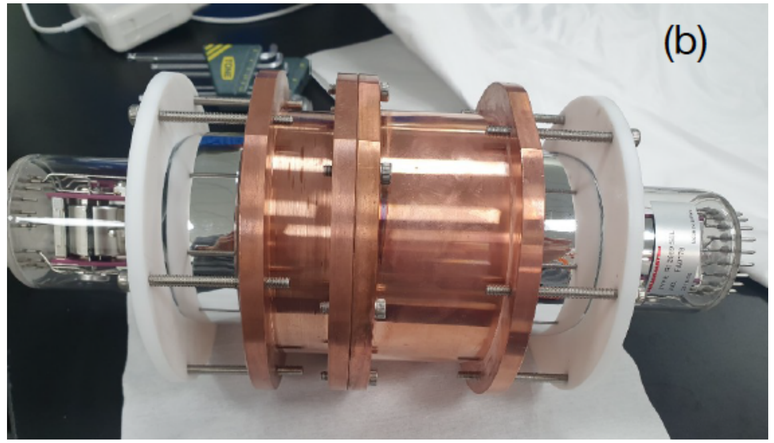
Prototype NaI(Tl) crystal detector

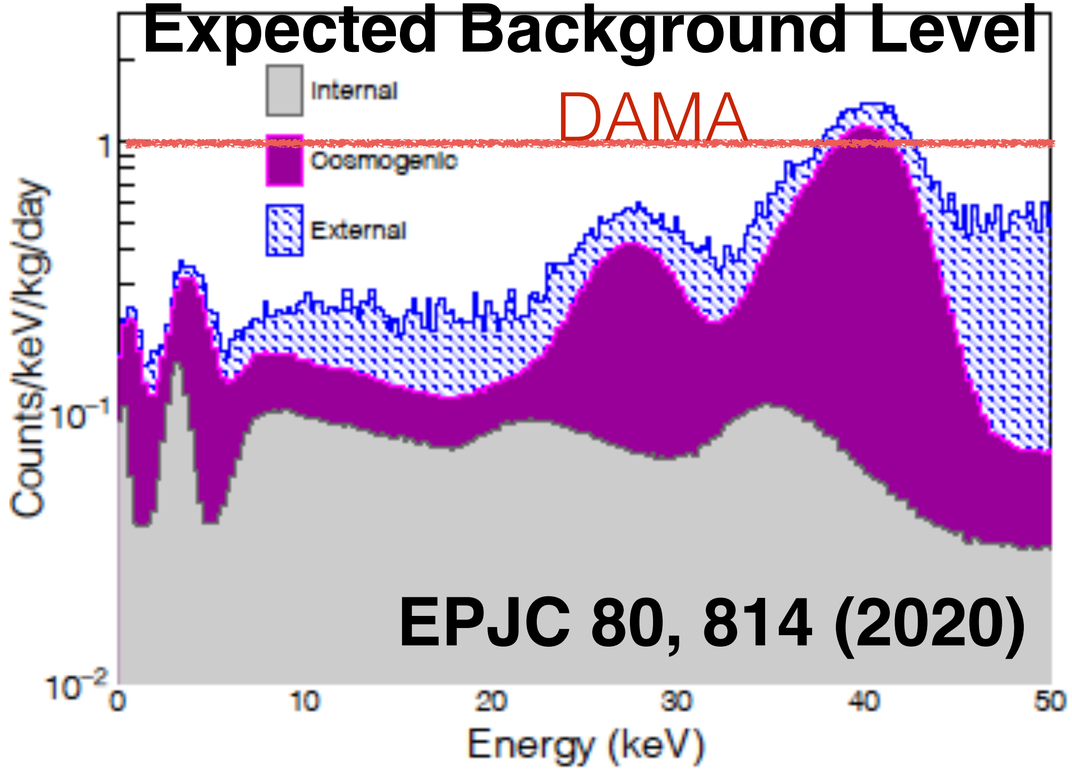




17

	K (ppb)	^{210}Pb (mBq/kg)	^{238}U (μBq/kg)	^{232}Th(μBq/
Powder	5	-	<20	<20
Aug/2018	684	3.8+/-0.3	26+/-7	<6
Sept/2019	**8**	**0.01+/-0.02**	**11+/-4**	**7+/-2**
DAMA	<20	0.01~0.03	8.7~124	2~31

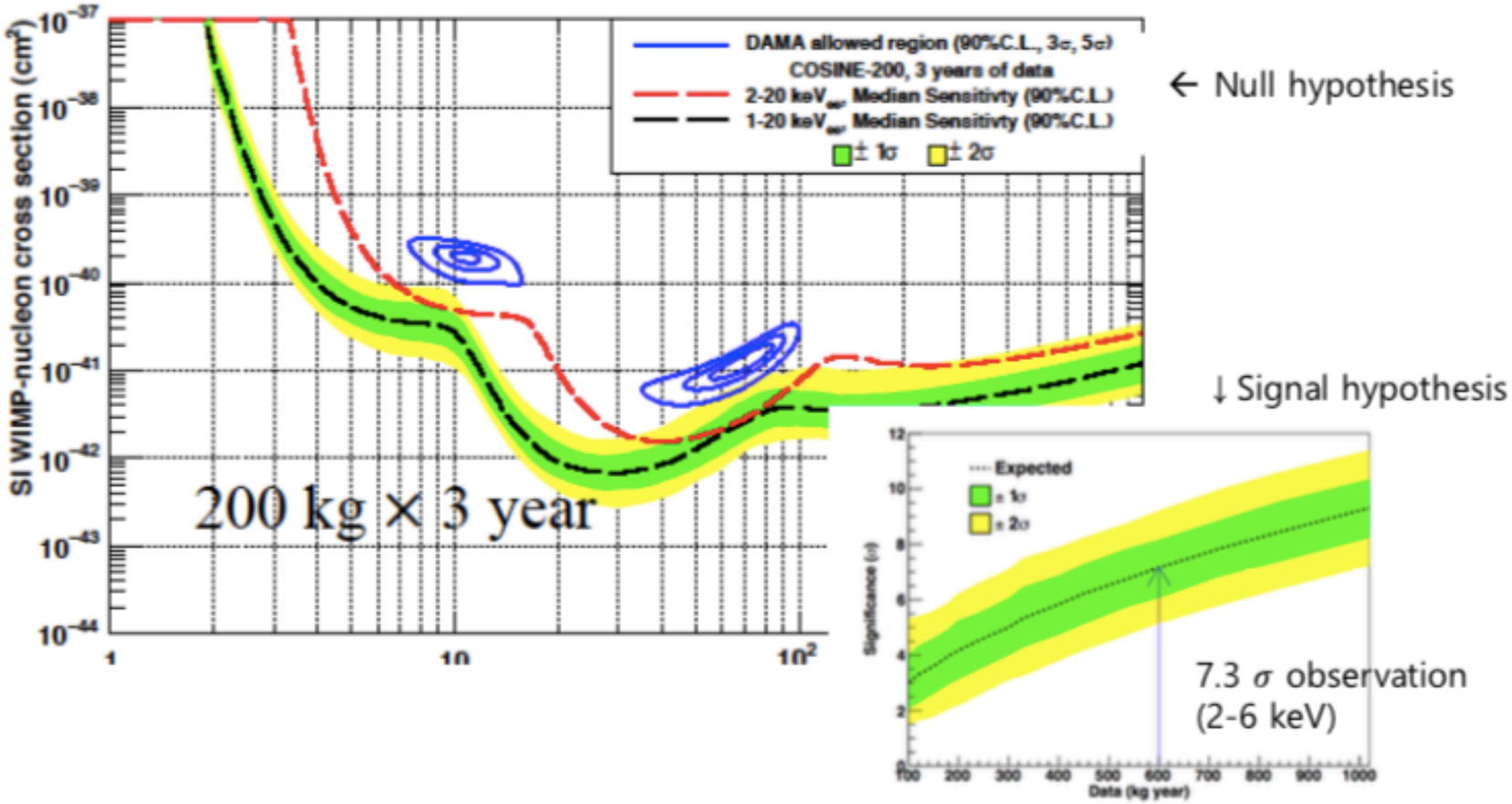




COSINE-200 (starting 2022)

- 1 counts/day/kg/keV background assumed (same as DAMA/LIBRA)

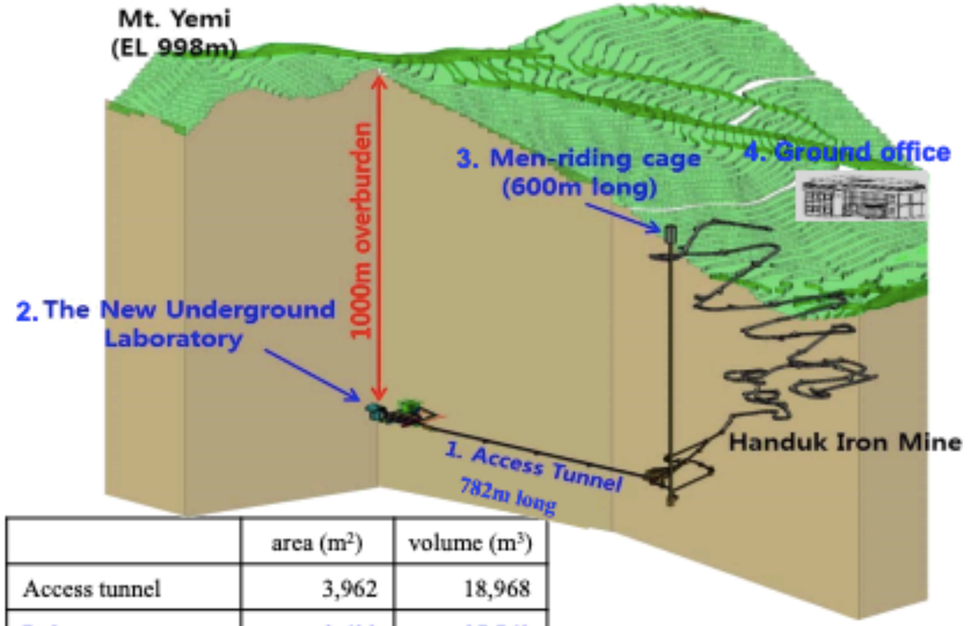
Annual Modulation Analysis



We have been preparing 200 kg experiment (COSINE-200) using better crystals with lower background

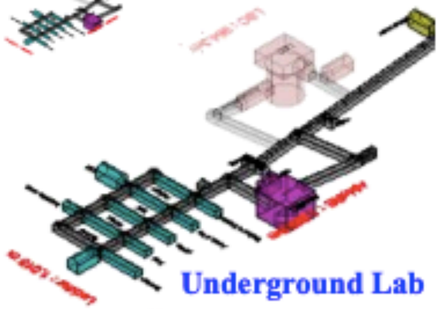
Yemilab Status

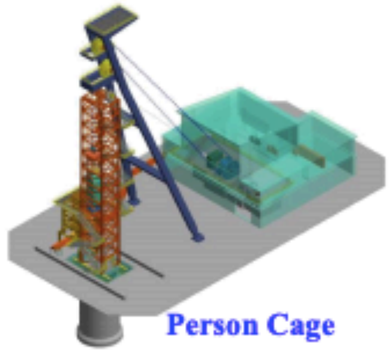
1. **Access Tunnel**, 782 m long with 12% down slope
2. **Underground Lab.** with 2600 m^2
3. **Person Cage**, running vertical 587 m
4. **Ground Office** with 2500 m^2



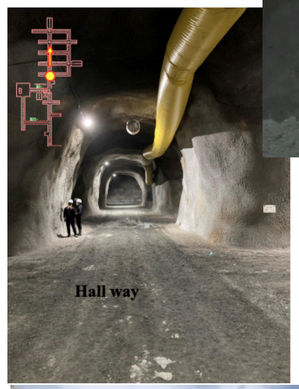
	area (m^2)	volume (m^3)
Access tunnel	3,962	18,968
Lab space	**2,600**	**25,562**
Connecting tunnel	4,847	14,161
amount	**11,525**	**58,691**


Access Tunnel


Underground Lab


Person Cage


Ground office



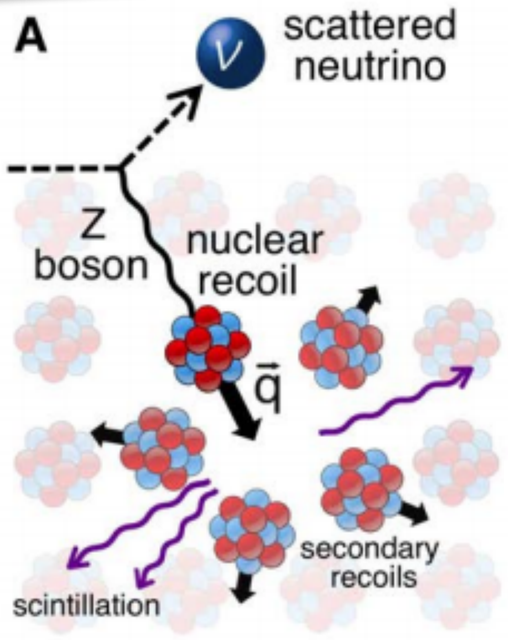

The ground office exterior

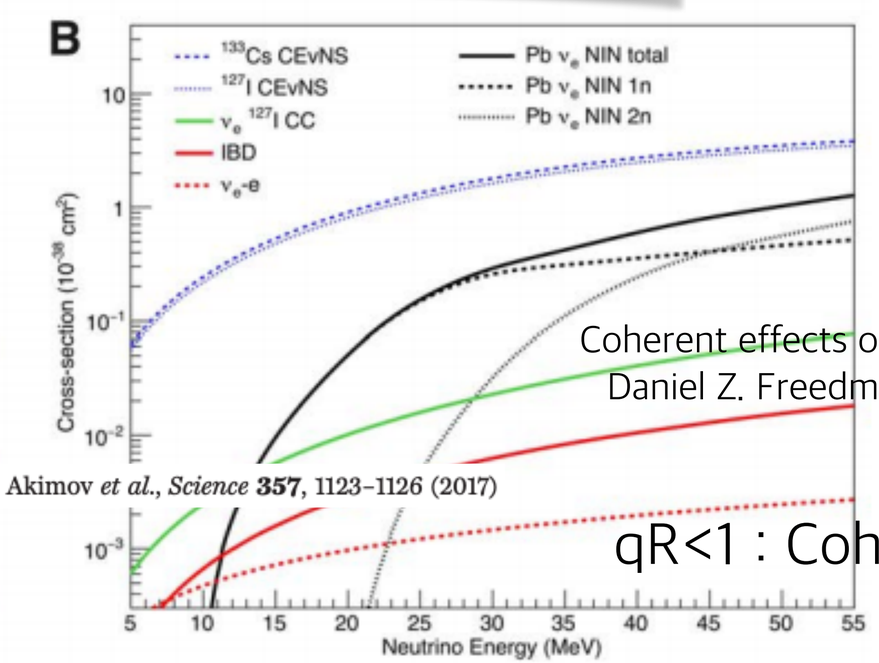

The reinforcement

Coherent Neutrino Nucleon Scattering (CNNS) Motivation

- The process predicted 46 years ago and the first measurement came just a few years ago (stopped pion) by the COHERENT collaboration.
- Aim at detection of Coherent scattering in reactors.
  - Single flavor (electron anti-neutrino) & A^2 dependence

- Neutrino Magnetic Moment
- Neutrino Non-Standard Interactions
- Neutrino-electron scattering.
- Sterile neutrinos (reactor anomaly)





Akimov *et al.*, *Science* **357**, 1123–1126 (2017)

Coherent effects of a weak neutral current
Daniel Z. Freedman (PRD 9,1389) 1974)

qR<1 : Coherent requirement

$\bar{\nu}_e$

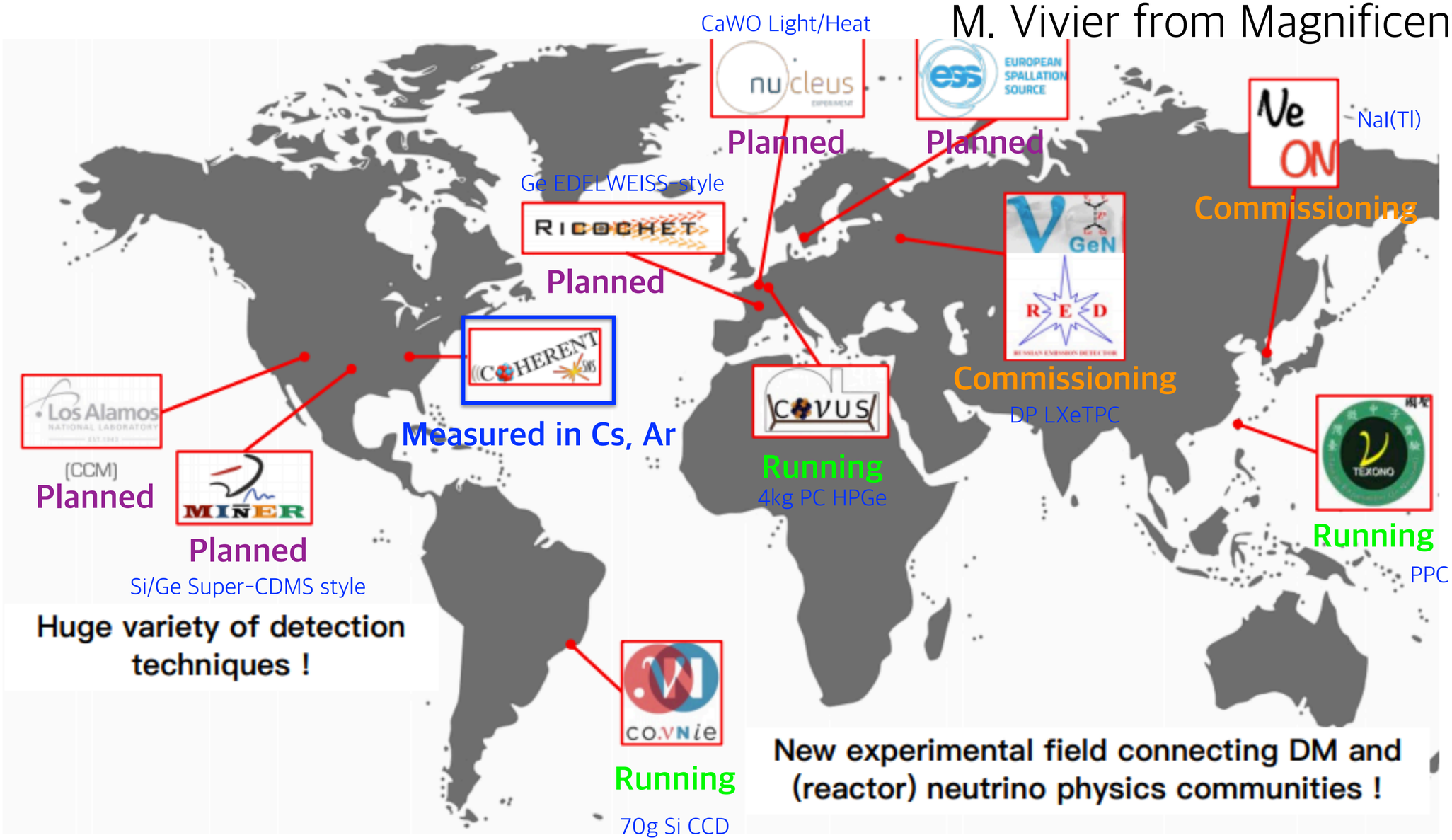
~MeV

~keV

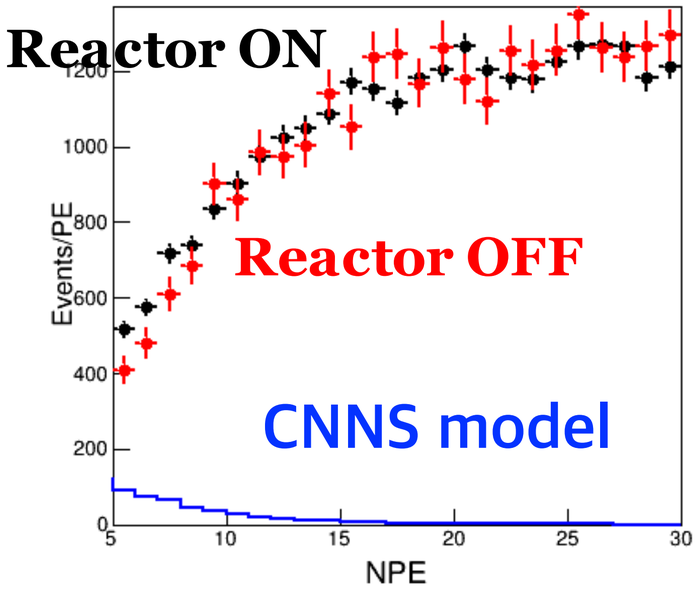
Na

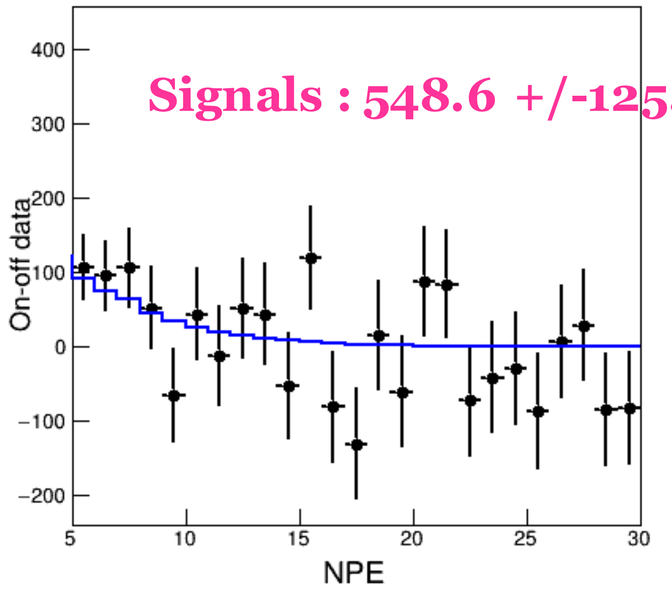
Worldwide efforts for CNNS

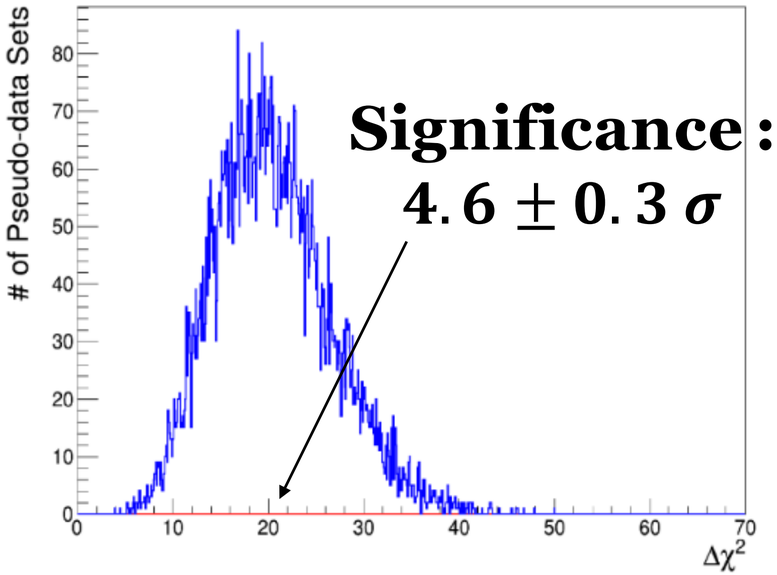
M. Vivier from Magnificent 2020



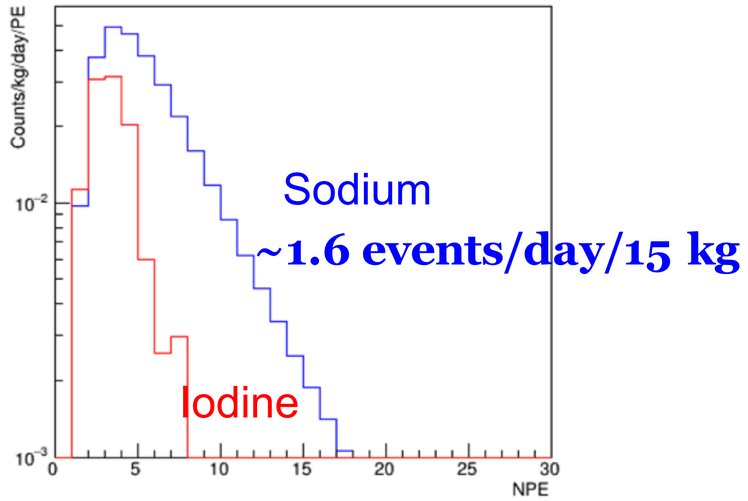
Expected Rate and Sensitivity for NaI(Tl) crystal detectors







- Assumption for sensitivity study
  - ✓ 22-photoelectrons/keV(PEs/keV) light yield
  - ✓ 15-kg mass of detector
  - ✓ 5-counts/kg/day/keV flat background
  - ✓ 5-PEs threshold
  - ✓ 365/100-days reactor-on/-off data



The NEON(Neutrino Elastic-scattering Observation on NaI(Tl)) Collaboration

15 members, 3 institutes

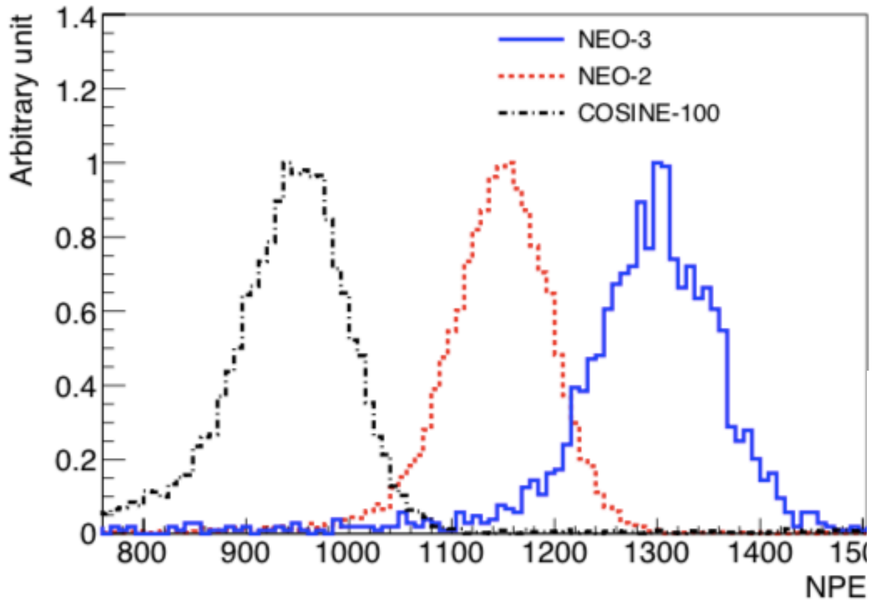
Active members of
the COSINE and NEOS experiments

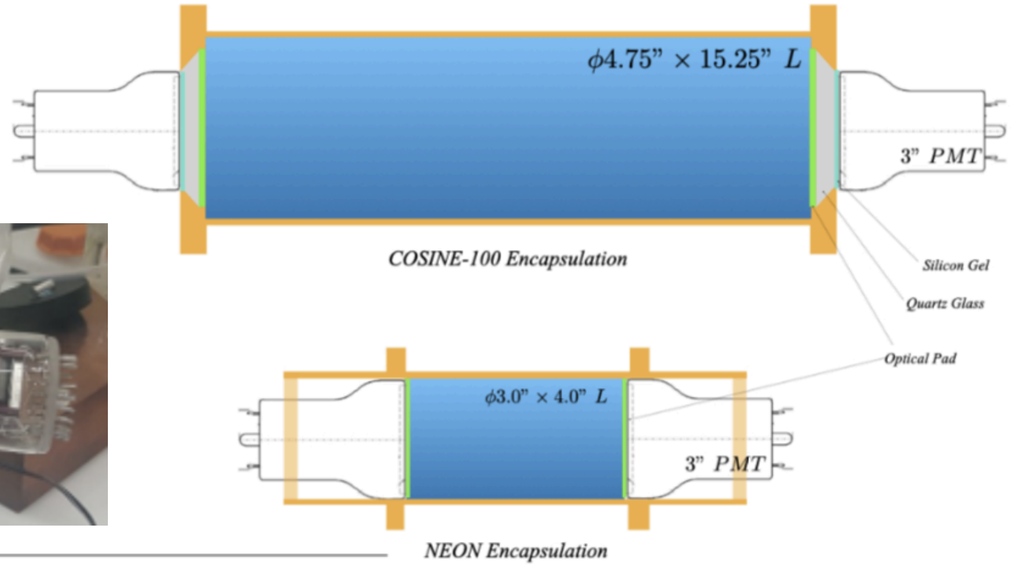
Goal : CNNS measurements in NaI(Tl) crystals from nuclear reactor.
(Low-background dark matter Crystal experts + Reactor neutrino experiment experts)

The Key Questions & Requirements for NEON

- Assumption for sensitivity study
  - ✓ 22-photoelectrons/keV(PEs/keV) **Light Yield** ✓
  - ✓ 15-kg mass of detector
  - ✓ 5-counts/kg/day/keV flat background
  - ✓ 5-PEs threshold
  - ✓ 365/100-days reactor-on/-off data

- High Light Yield ~ Low Threshold ~ More CNNS events
- COSINE-100 dark matter experiment NaI(Tl) ~ 15 P.E./keV
- NEO crystals show more than 20 P.E. / keV
- Direct PMT coupling to the crystal & Simpler Encapsulation and less materia'





NEO-1	NEO-2	NEO-3	COSINE-100
after(before)	after(before)	after(before)	C6
20.5±1 (10.7±0.7)	19.3±0.9(16.9±0.9)	21.8±0.9(17.7±0.9)	15.8±1

NIMA 981 (2020) 164556

The Key Questions & Requirements for NEON

- Assumption for sensitivity study
  - ✓ 22-photoelectrons/keV(PEs/keV) **Light Yield** ✓
  - ✓ 15-kg mass of detector ✓
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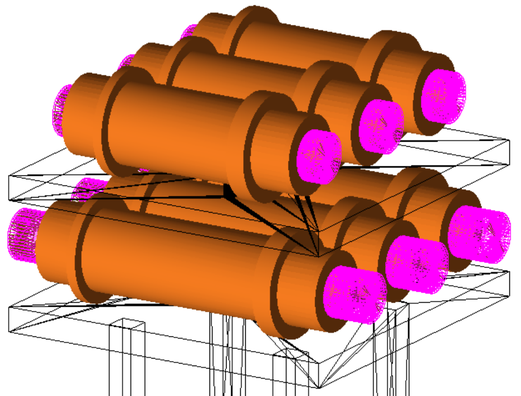
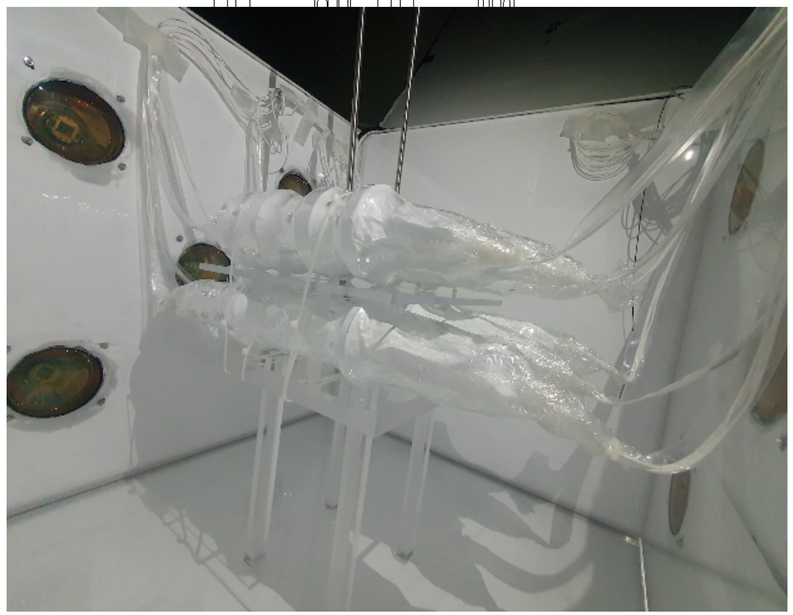
NEO-1, 2, 3
(1.64 kg)

NEO-4, 5, 6
(3.37 kg)



15 kg Crystal Mass



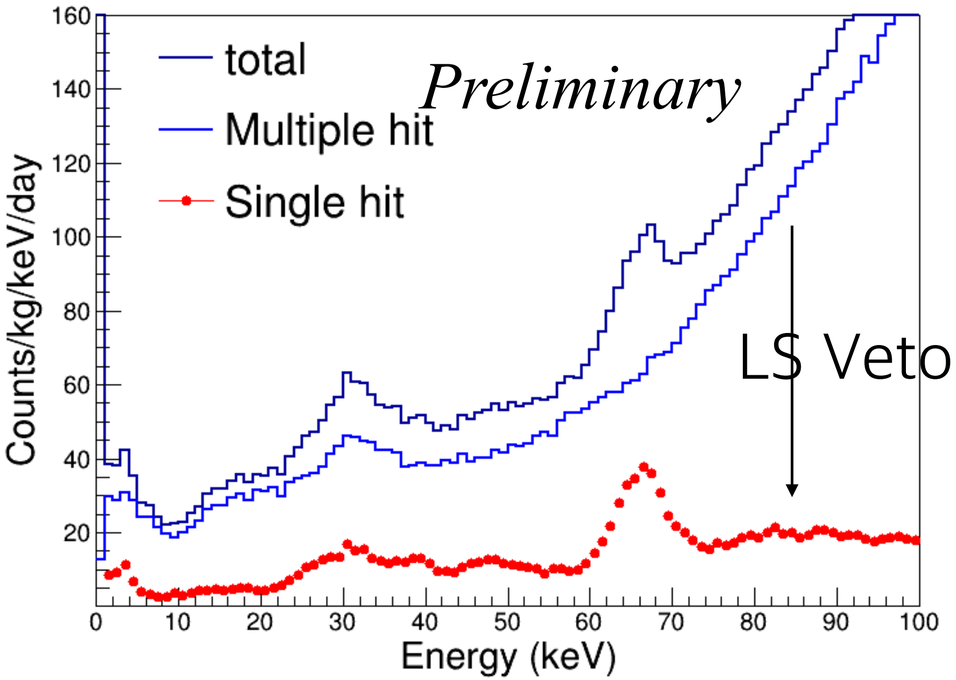
The Key Questions & Requirements for NEON

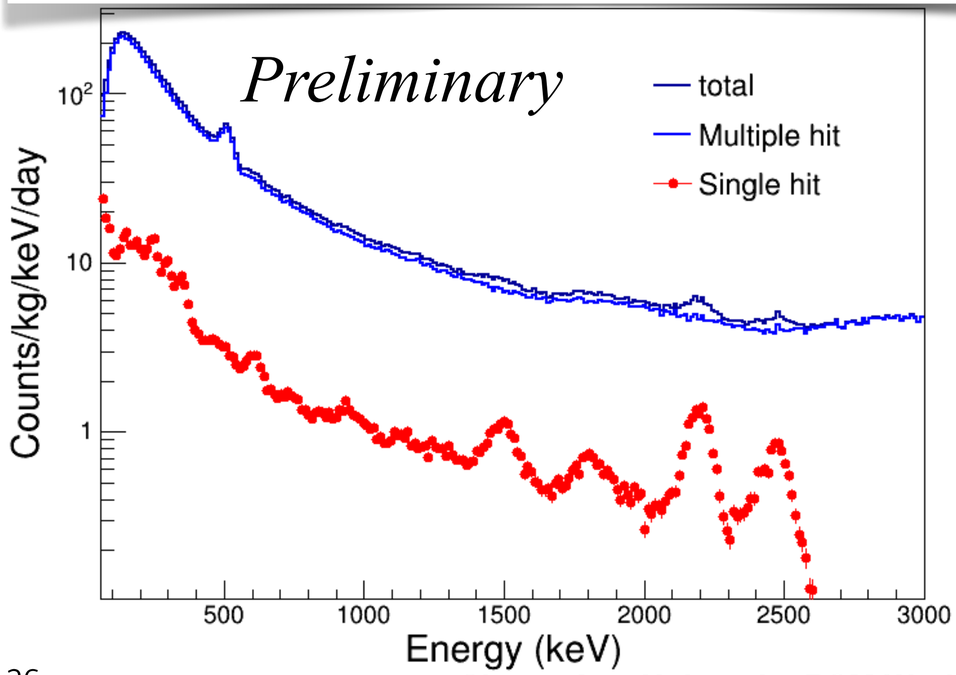
•Assumption for sensitivity study

- ✓ 22-photoelectrons/keV(PEs/keV) **Light Yield** ✓
- ✓ 15-kg mass of detector ✓
- ✓ 5-counts/kg/day/keV flat background ✓
- ✓ 5-PEs threshold
- ✓ 365/100-days reactor-on/-off data

- Can you reach 5 dru at the threshold region?

- Current : 3 counts/kg/day/keV at 5 keV (Single)
- Higher at the threshold region (~7 dru)
- This means crystals are pure enough and LS veto is working.
- To do : Analysis needs to be further developed to characterize the lowest energy events.





The Key Questions & Requirements for NEON

- Assumption for sensitivity study
  - ✓ 22-photoelectrons/keV(PEs/keV) **Light Yield** ✓
  - ✓ 15-kg mass of detector ✓
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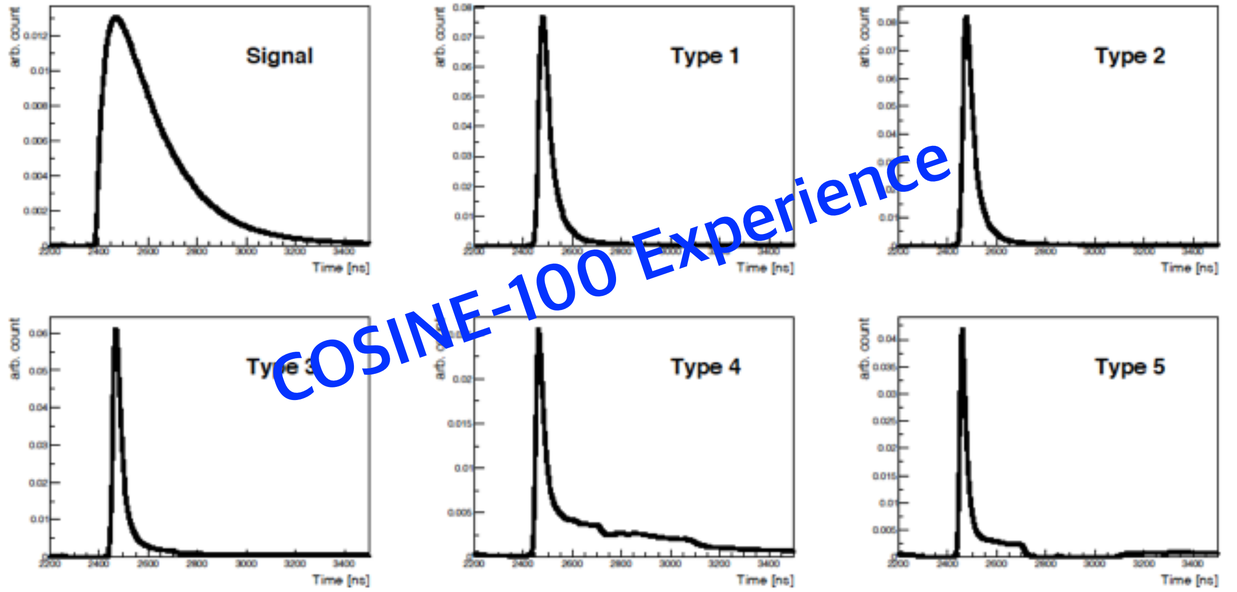
  - ✓ 5-PEs threshold
  - ✓ 365/100-days reactor-on/-off data

- Can you reach 5-PE (0.2 keV) threshold?

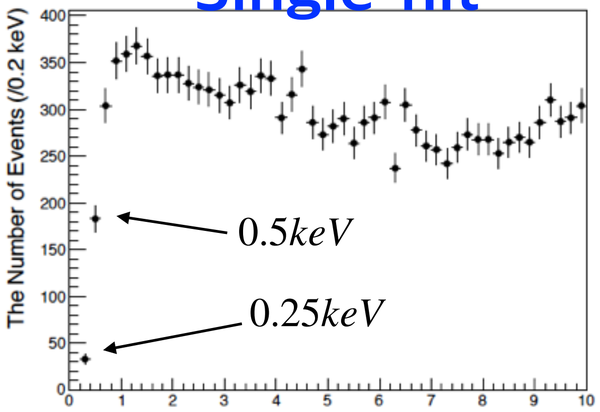
- Current : 1 keV (= 22 NPE) threshold in NEON
- Previously, we have developed BDT/ DeepLearning in COSINE crystals (0.4 keV = 6 NPE)
- To do : Multivariate analysis needs to be developed to reject PMT noise background. Dedicated calibration is on-going. We are confident!

characterize types of noise in COSINE crystals



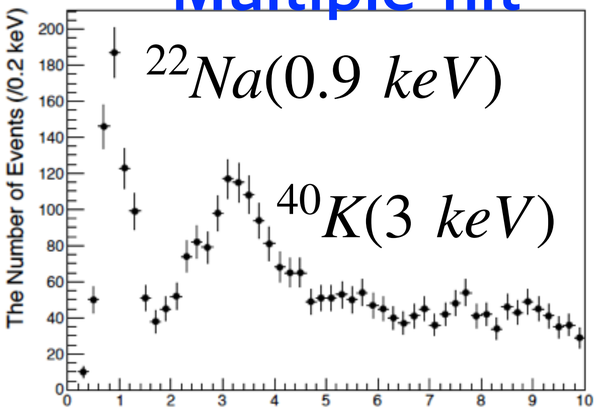
COSINE-100 Experience

Single-hit



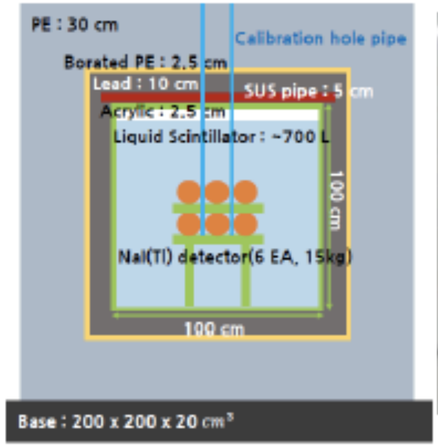
0.4 keV

Multiple-hit

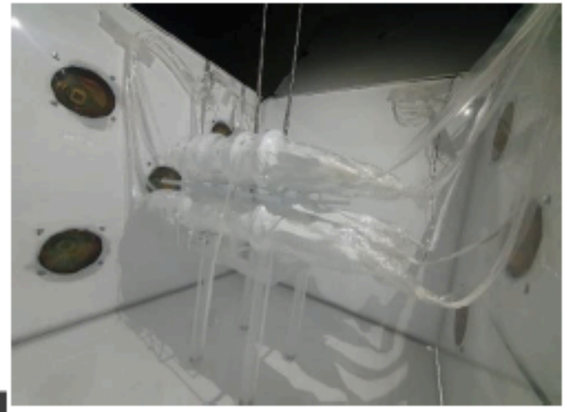


Readiness of the NEON Experiment

Shield design and Installation in Institute of Basic Science(IBS) Laboratory

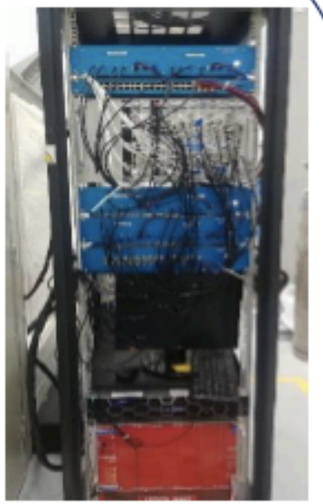


NEON shield design

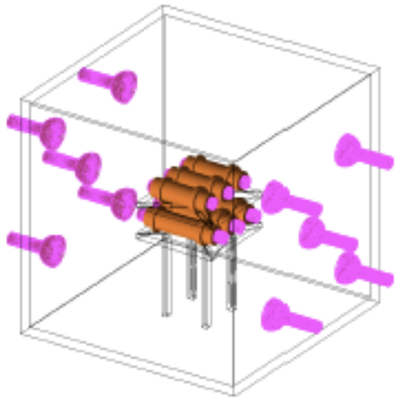


NaI(Tl) detectors in the acrylic box

NEON in IBS HQ basement



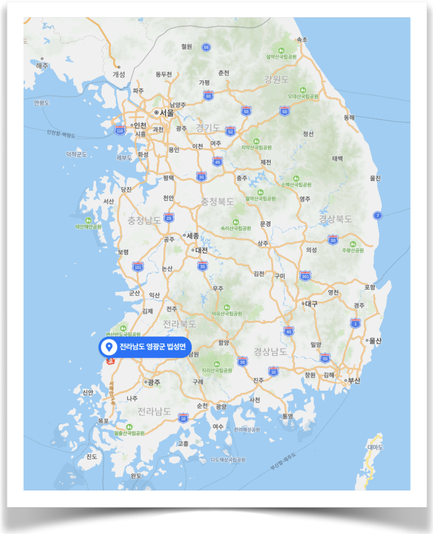
Data acquisition system



Simulation geometry

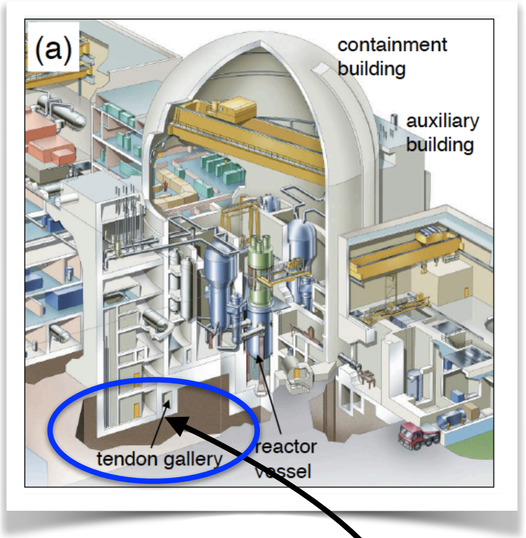
- Array of the NaI(Tl) detector(total 15 kg):
  - ✓first floor: three crystals(dimension: 3" × 8", mass: 3.36 kg)
  - ✓second floor: three crystals(dimension: 3" × 4", mass: 1.68 kg)
- Shielding material:
  - ✓ 700-L liquid scintillator(tagging multiple events with ten 5" PMTs)
  - ✓ 10 cm leads, 2.5 cm borated PE, 30 cm HDPE
- The data acquisition(DAQ) system is similar to the COSINE-100 experiment DAQ
- Dry run has begun at IBS Laboratory!
- Simulation study is ongoing

Construction of the NEON Experiment



November 2020

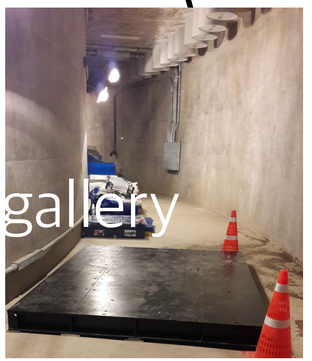
Hanbit Nuclear Power Plant (Yeonggwang)



No. 6 Reactor

NEON prototype @IBS

Transfer



Installation and construction

Schedule for the NEON Experiment

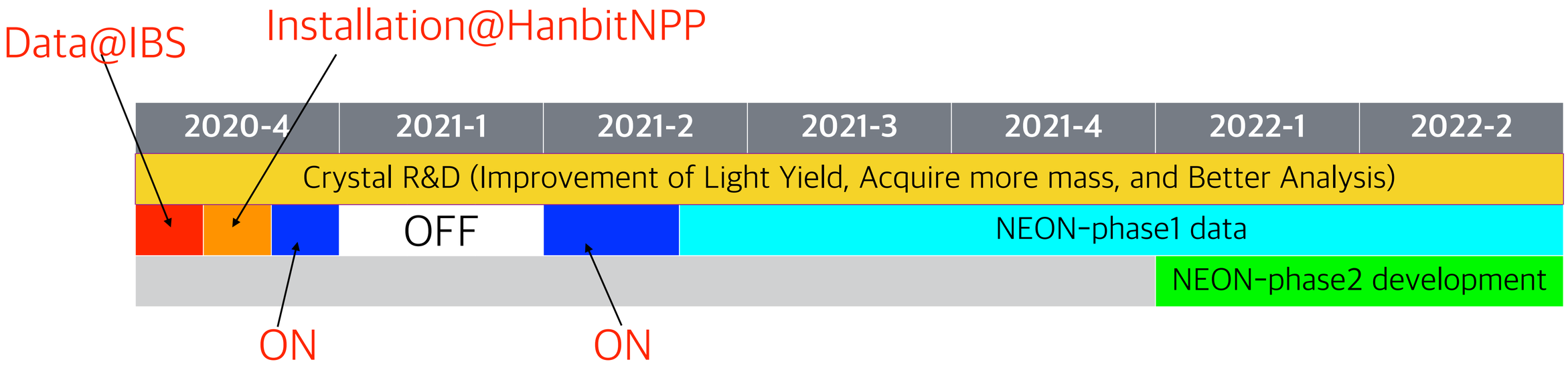
- Assumption for sensitivity study
  - ✓ 22-photoelectrons/keV(PEs/keV) **Light Yield** ✓
  - ✓ 15-kg mass of detector ✓
  - ✓ 5-counts/kg/day/keV flat background ✓
  - ✓ 5-PEs threshold ▲
  - ✓ 365/100-days reactor-on/-off data ✓

Can you actually do this?

—We started data-taking December of 2020

—Currently the reactor is off for maintenance.

—We take off-data for 3-months and the reactor will be back on.



Summary and Outlook

- Dark Matter direction detection aims at detecting nuclear recoils by WIMP.
- There is one claimed detection of WIMP from the DAMA experiment that uses annual variation phenomenon.
- Among various efforts, Korea is specialized in using the crystal scintillator target with the same material as DAMA. So, the reproduction of the experiment is possible.
- We have ruled out a theory that explains the DAMA signal as a dark matter particle but we, then, need to figure out where the modulation comes from with better detection sensitivity. Coming soon.
- We also search for other dark matter candidates such as solar Axion and iBDM, and other interaction signatures.
- Development of low-radioactivity, high-light yield NaI(Tl) opens a new opportunity not only for the dark matter particles but also for reactor neutrinos through the CNNS detection. Of course for various BSM candidates!
- Stay tune!