COSINE(NEON)/NEWSdm/SHiP/DAMSA

Dark Particles with (traditional) high resolution detector technologies

On behalf of the COSINE-100 collaboration and help (Yoon Chun Sil, Shin Seodong) from the SHiP, NEWSdm, and DAMSA collaborations

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December 17, 2021

중앙대학교

Dark Particle Detections in Korea

WIMP, iBDM, LDM, HNL, Dark Photon, Dark Axion, ALP

Weakly Interacting Massive Particle, inelastic Boosted Dark Matter, Light Dark Matter, Heavy Neutral Leptons, Axion Like Particle

Flux : Underground vs Beam dump

PID : Calorimetric vs Directional

Background : Neutron Background

Coherence : Z^2 dependence in detection and production

Resolutions : Energy and Position-Sensitive

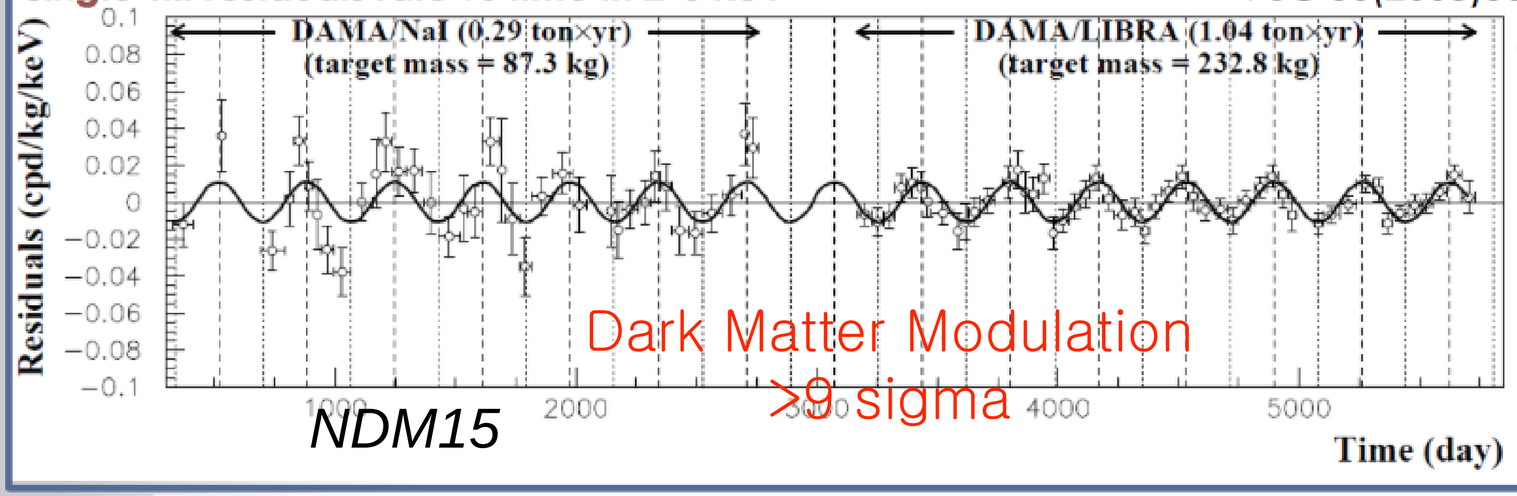
Energy Reach : Low-threshold detectors

The DAMA annual modulation signal, to be confirmed with independent measurements

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

Single-hit residuals rate *vs* time in 2-6 keV

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



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

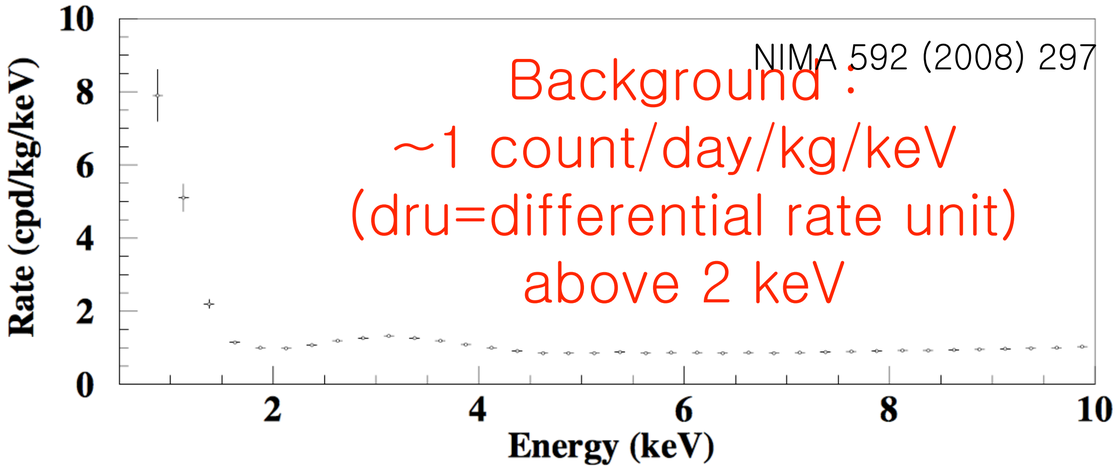
A=(0.0110±0.0012) cpd/kg/keV
χ^2/dof = 70.4/86 9.2 σ C.L.

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

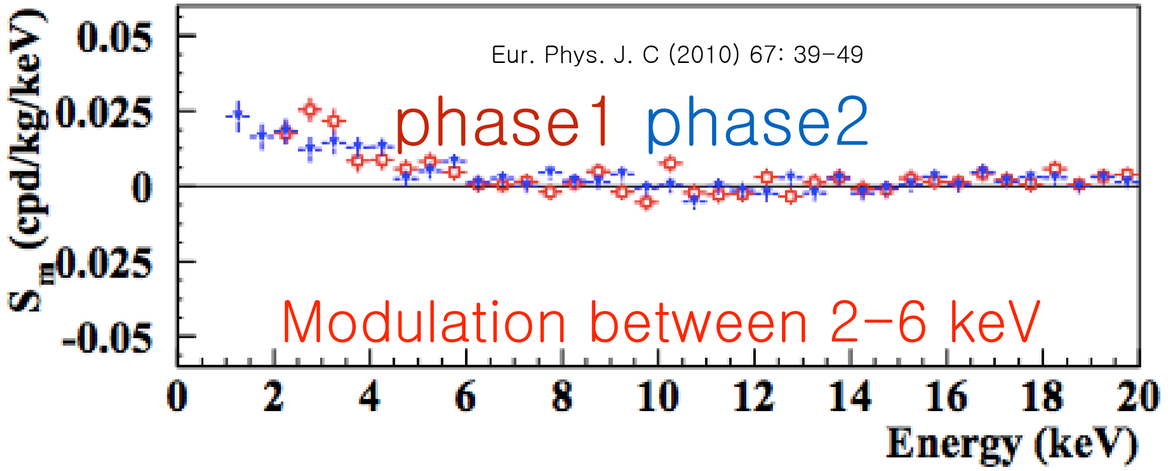
Dark Matter Modulation
>9 sigma

NDM15



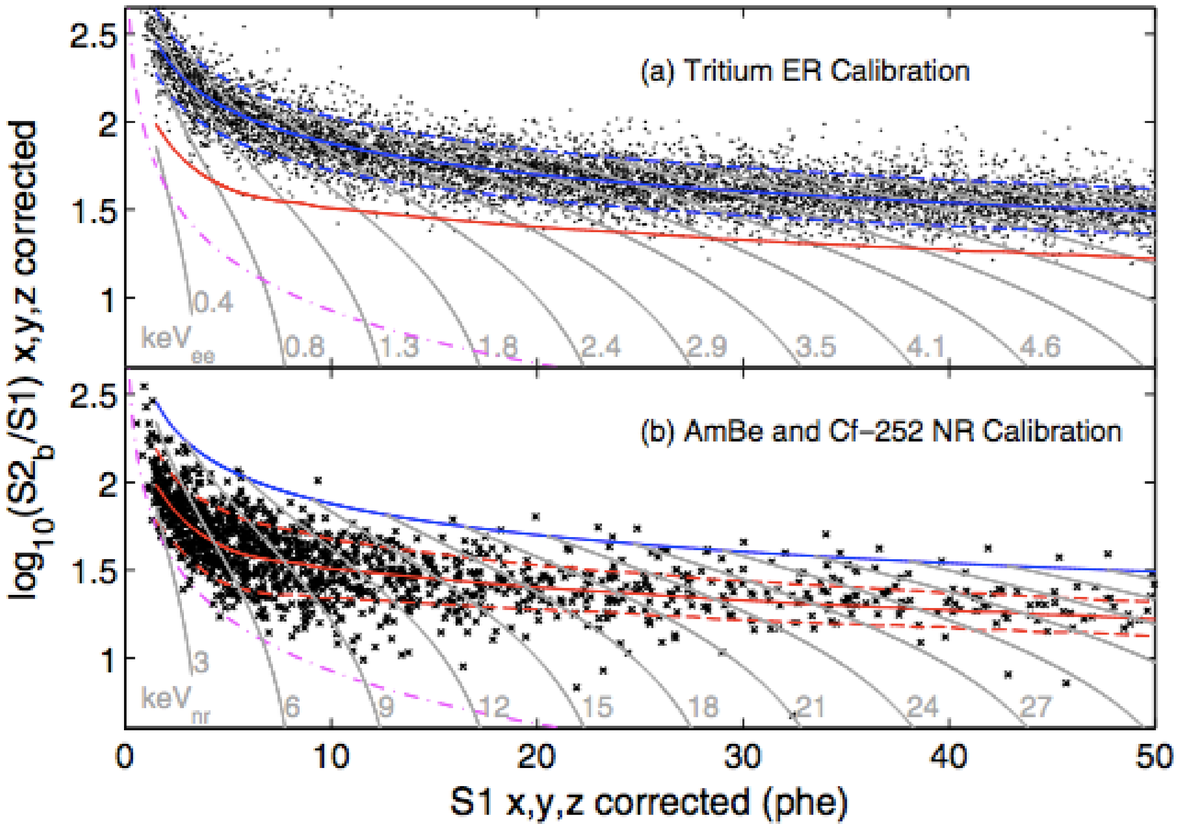
NIMA 592 (2008) 297

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

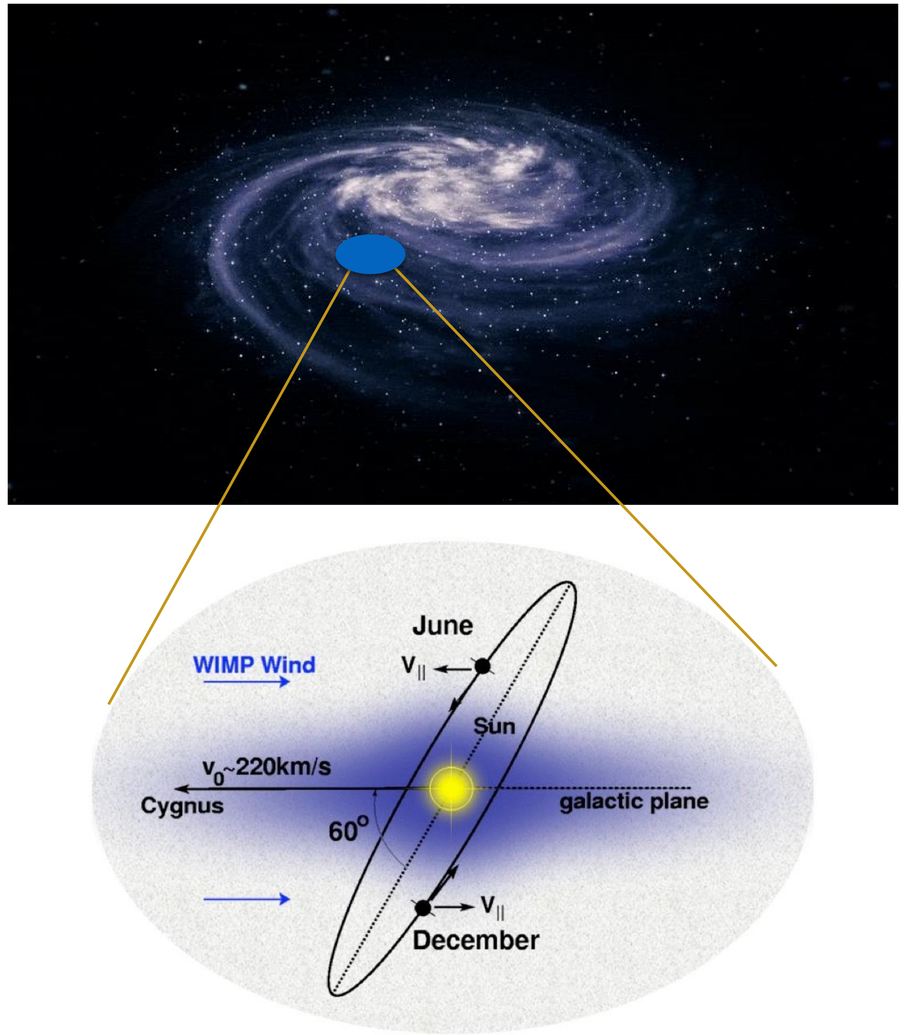


Dark Matter Direct Detection : WIMP Signals & Backgrounds

Discrimination of nuclear recoils (Signal) from electron/gamma recoils(Background)



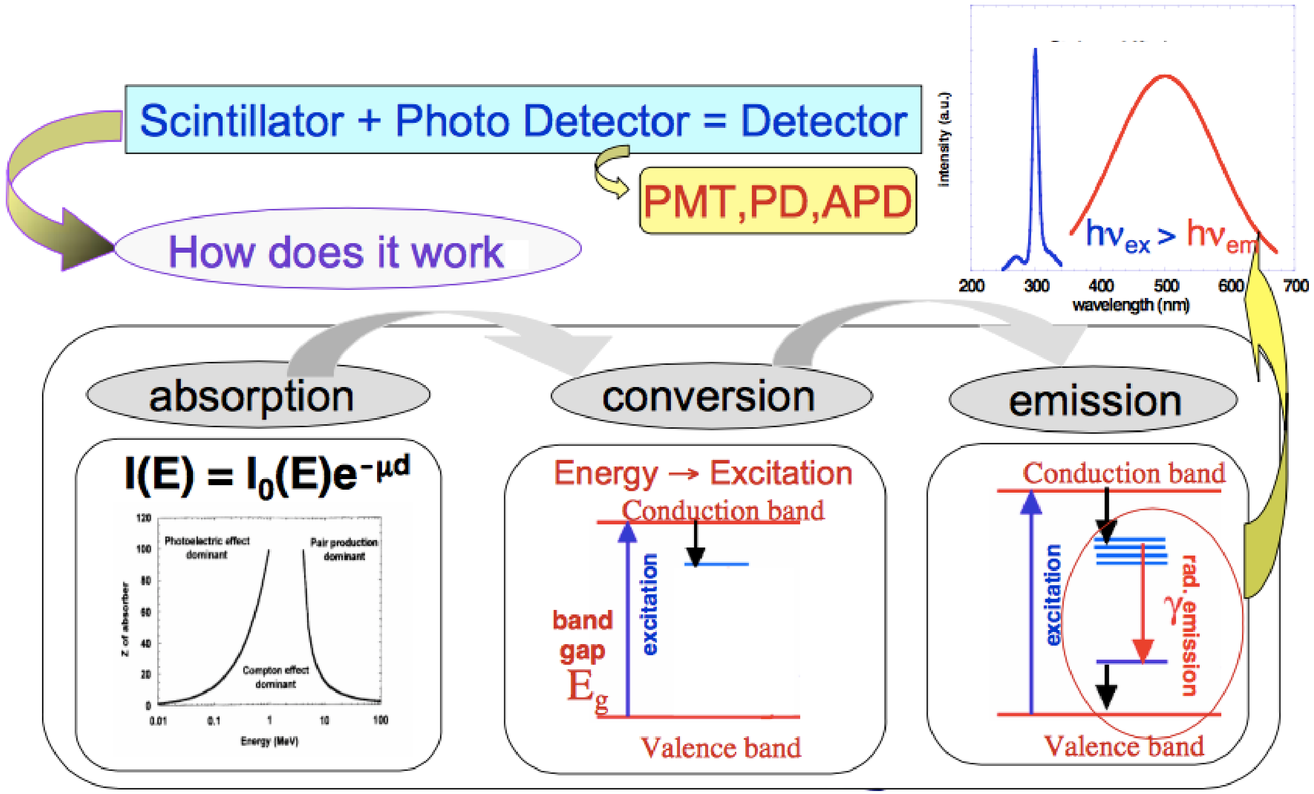
LUX Collaboration, Phys. Rev. Lett., (2014)



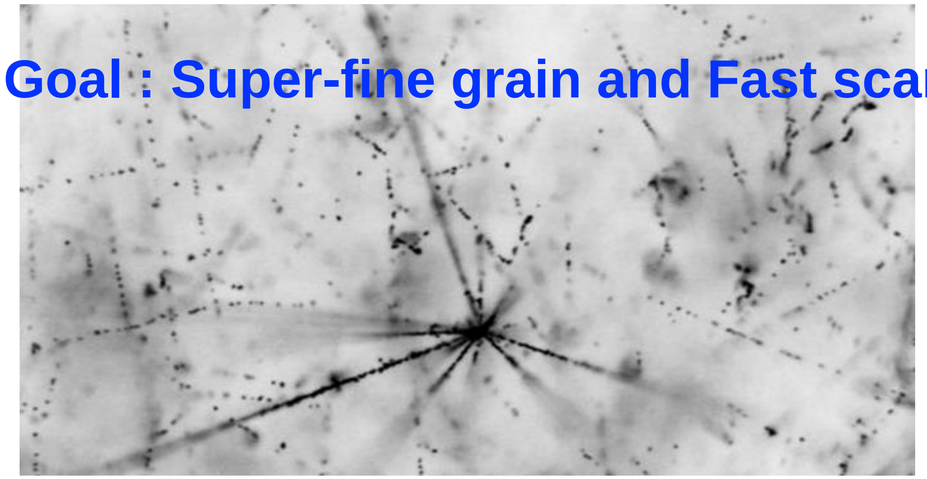
Annual modulation signal

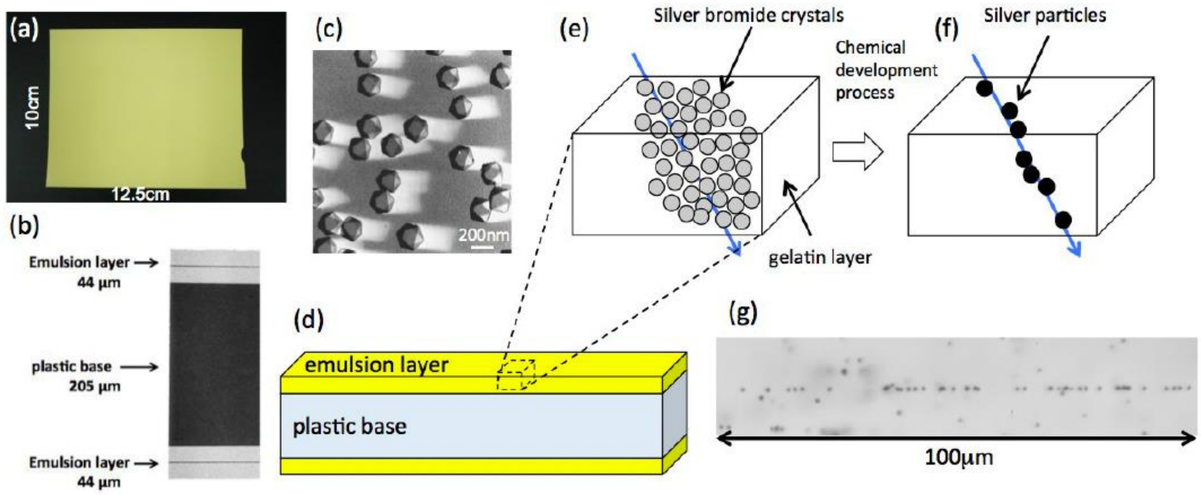
Crystal Scintillator and Nuclear Emulsion Technology

Goal : Collect as much visible light as possible



Goal : Super-fine grain and Fast scan



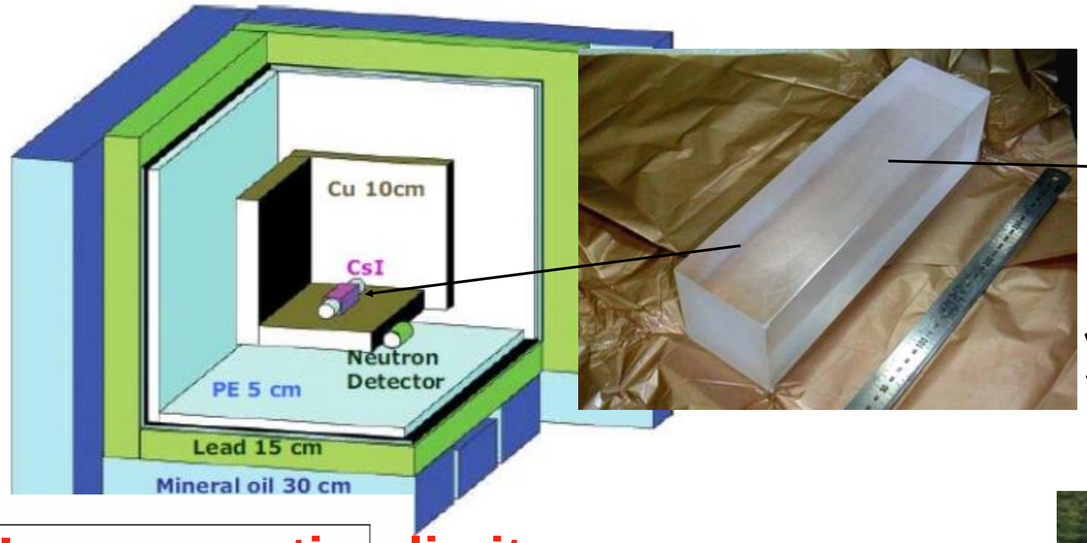


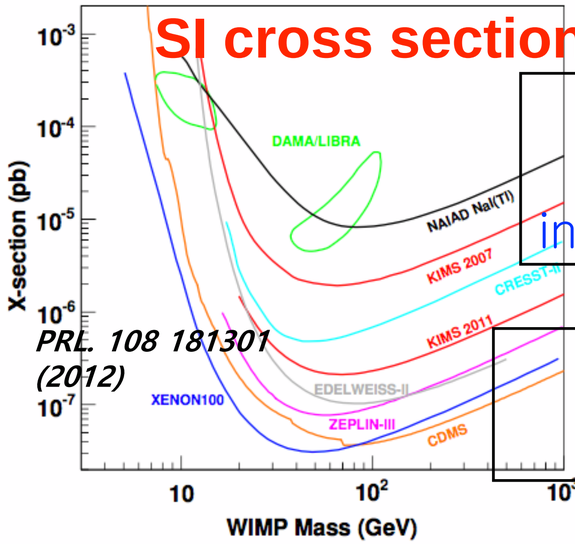
ΔE, Scalability, Slow turnaround, Hygroscopic

Δr, Grain-size, Scan speed, Various nuclei

Korea Invisible Mass Search (KIMS) since 2000

12 CsI(Tl) 8.7 kg crystals (103 kg total)
Background level achieved at ~3 dru (counts/keV/kg/day) at 3 keV

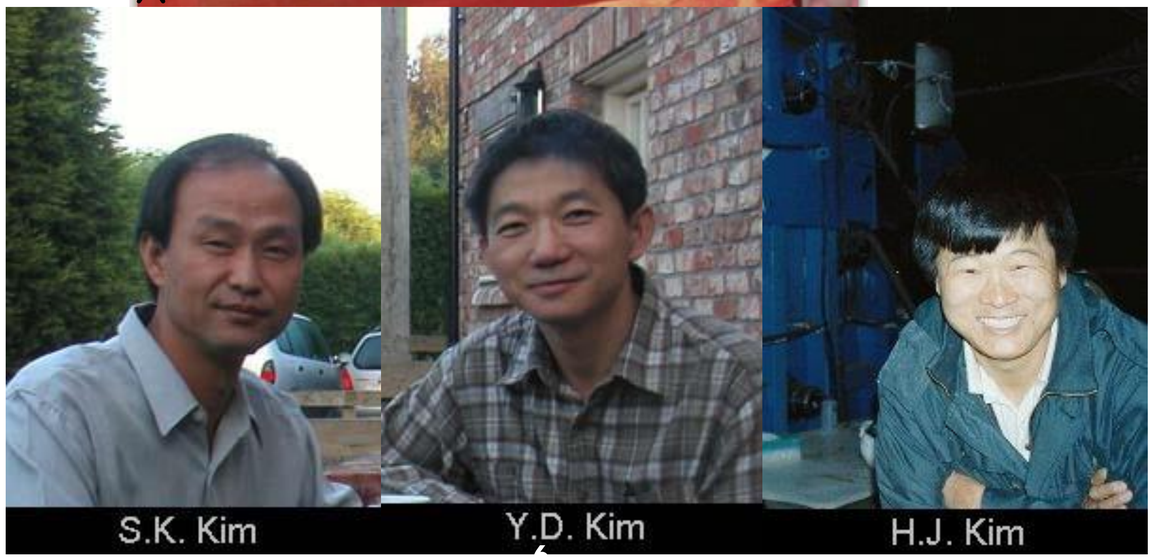




PRL. 108 181301 (2012)

KIMS-CsI results rejects DAMA signal in WIMP-Iodine interactions

Need to investigate WIMP-Sodium interactions



The COSINE-100 Experiment

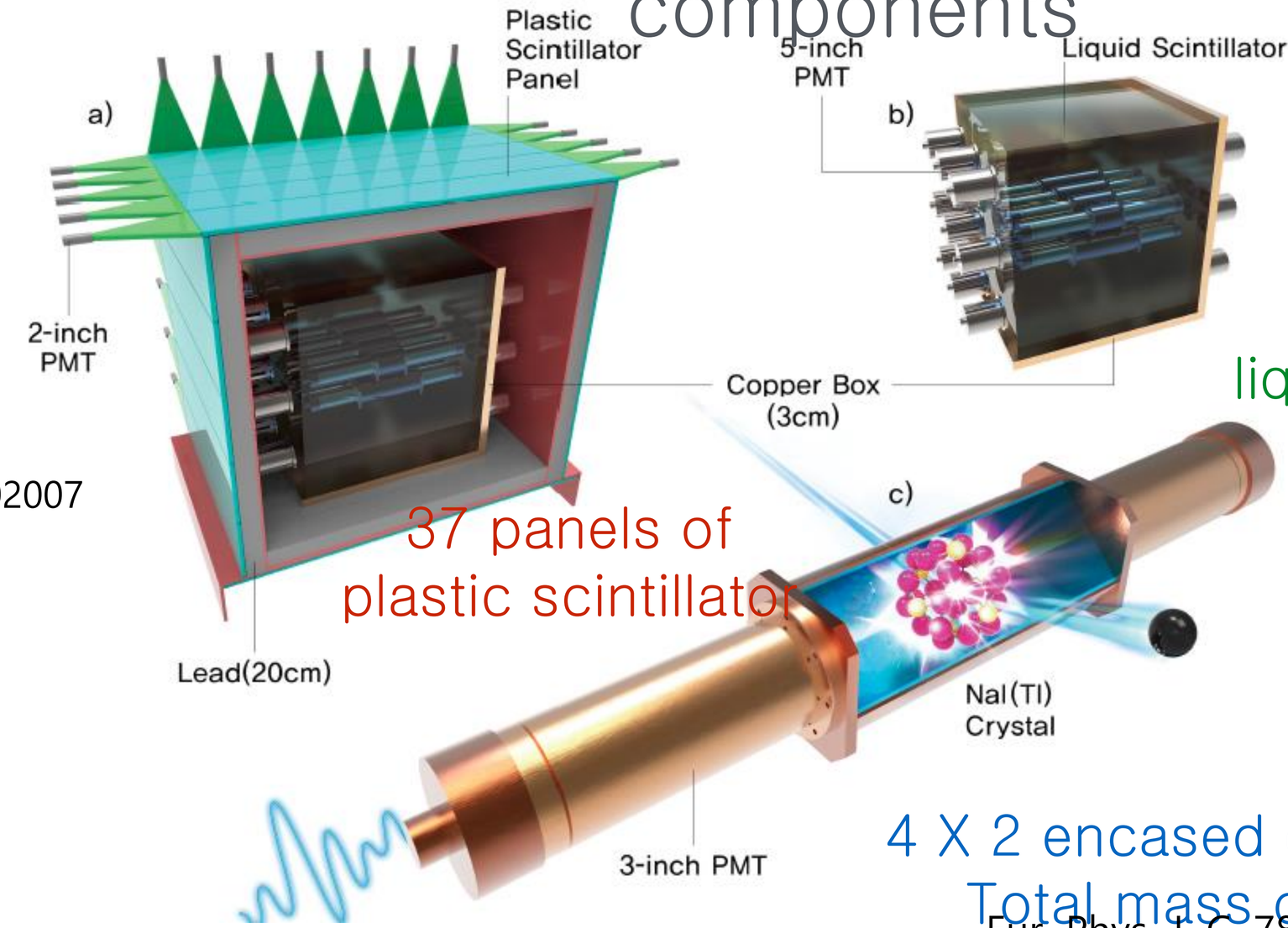
5 countries,
15 institutes
50 scientists

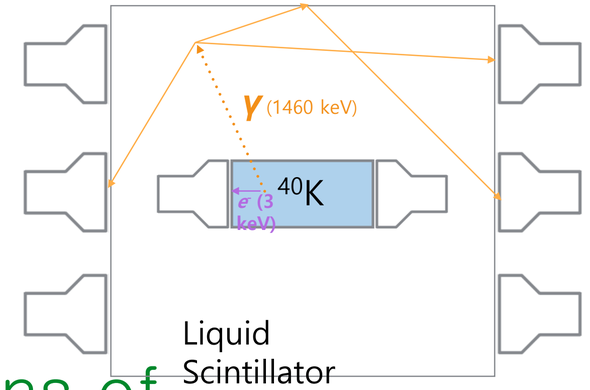
Joint collaboration between KIMS and DM-Ice to search for dark matter interactions in NaI(Tl) scintillating crystals.

KIMS
Korea Invisible Mass Search Experiment

DM-ICE

The COSINE-100 detector components





2 tons of liquid scintillator

Nucl. Instrum. Meth. A 851 102 (2017

JINST13 T02007 (2018)

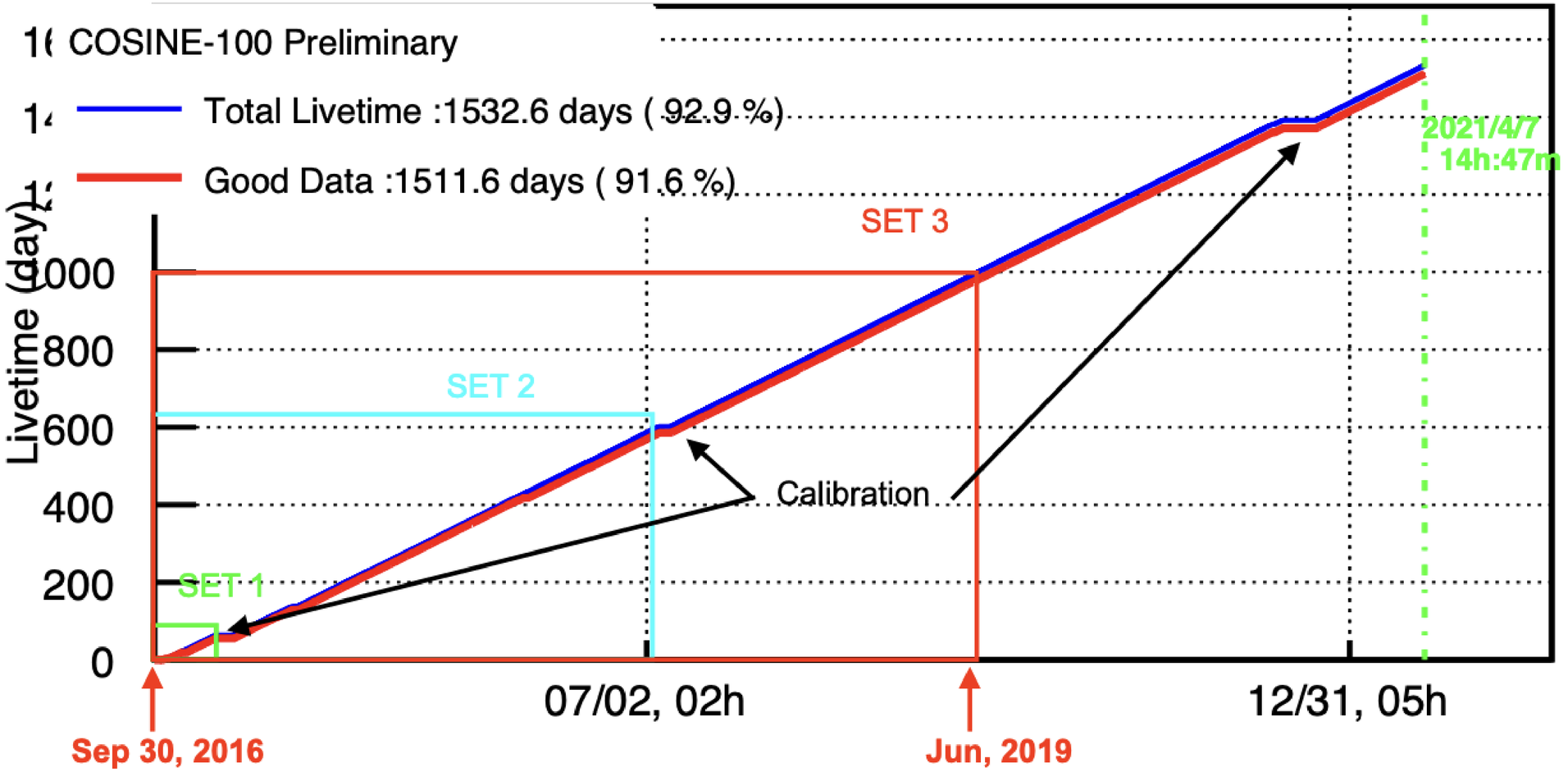
37 panels of plastic scintillator

4 X 2 encased crystal array

Total mass of 106 kg

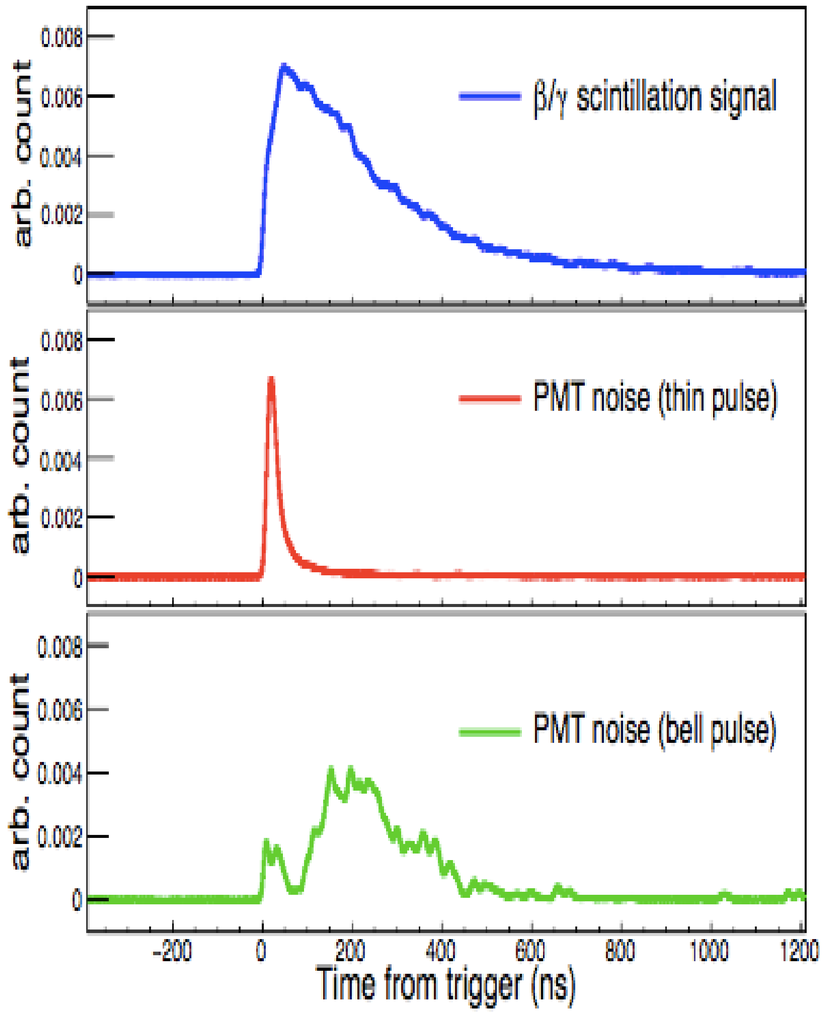
Eur. Phys. J. C. 78 107 (2018)

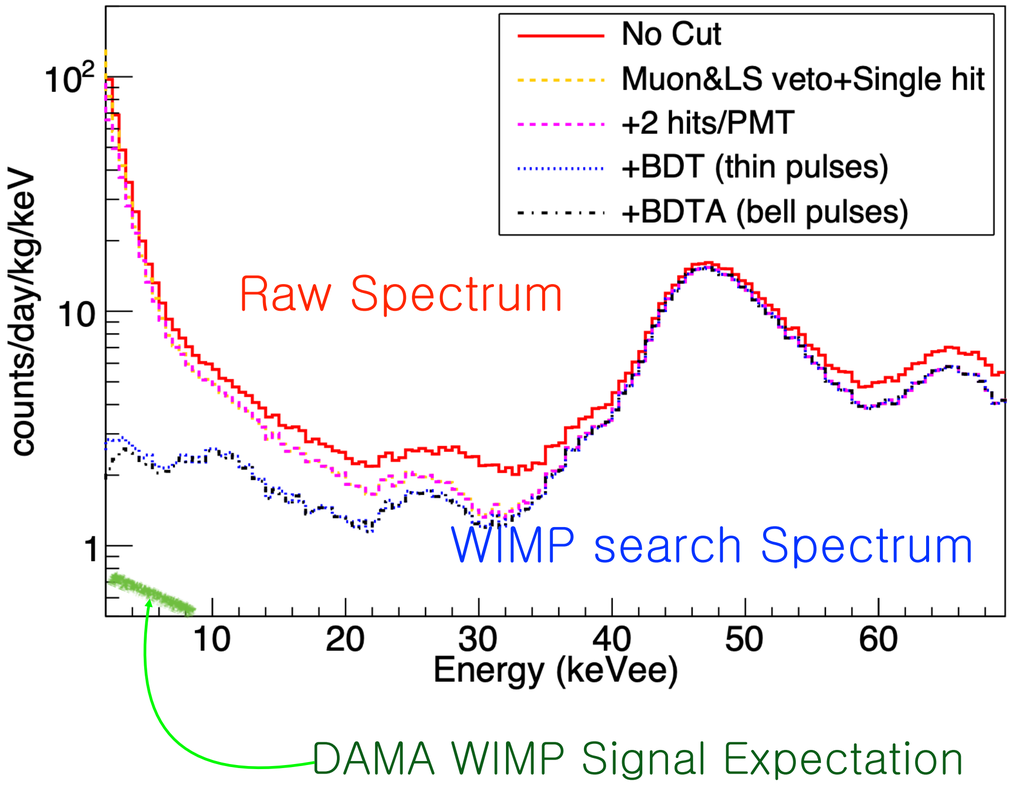
Exposure (Running for more than 5 years)



Stable running of the detector for 5 years. Good runs are more than 90%

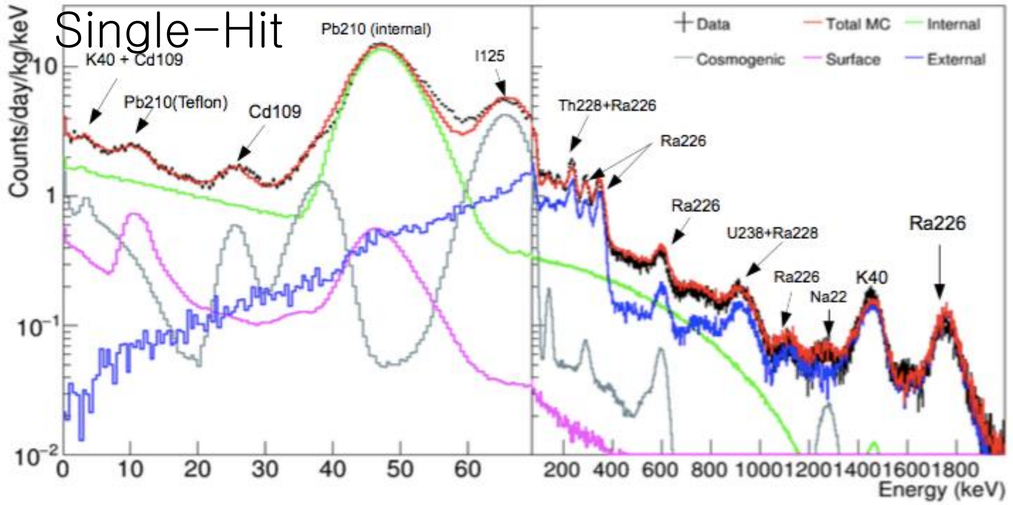
PMT noise reduction
Every experiment has noise and WIMP search=Noise Reduction

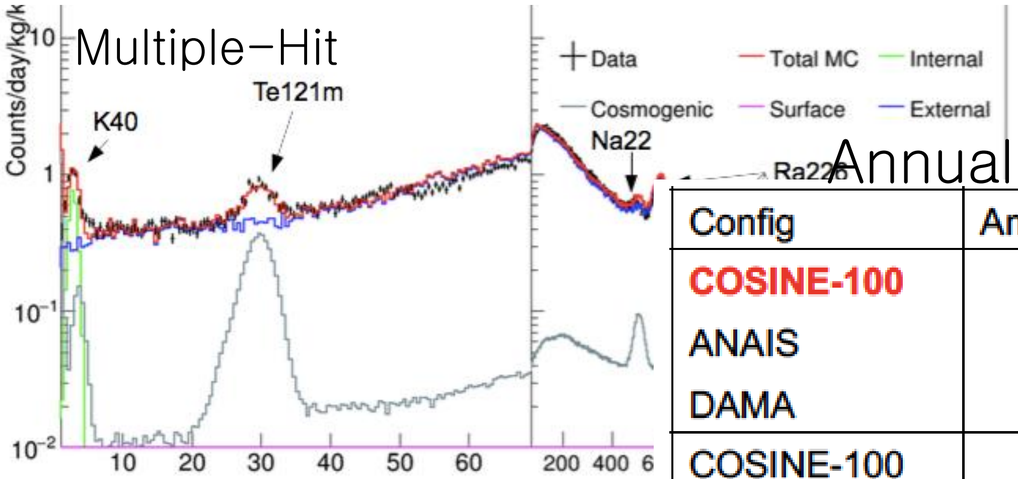




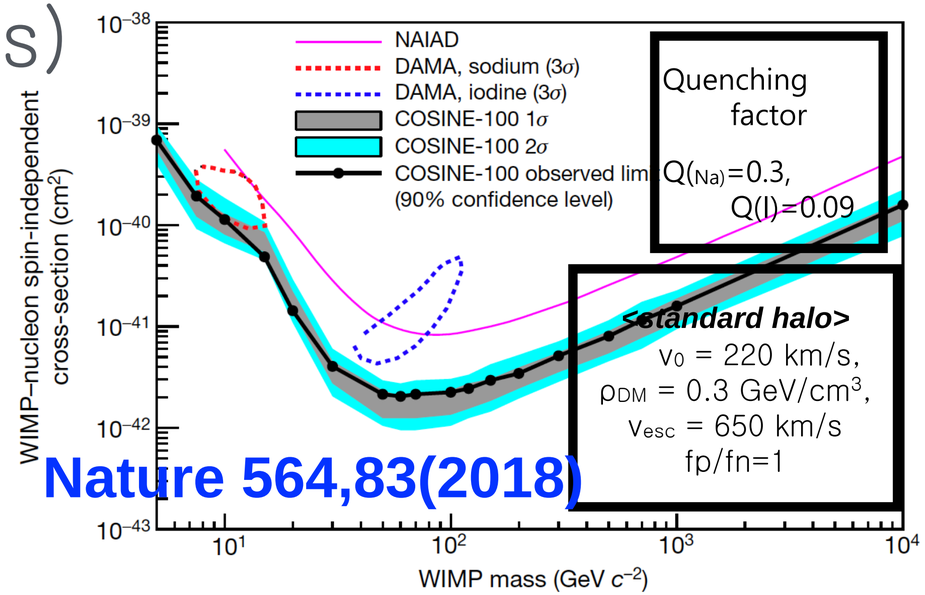
1. Constant Rate Analysis
2. Annual Modulation Analysis

COSINE-100 (2-keV Threshold Analyses)



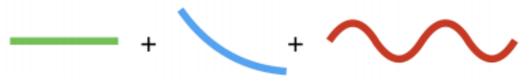


EPJC 78, 490 (2018)



Nature 564,83(2018)

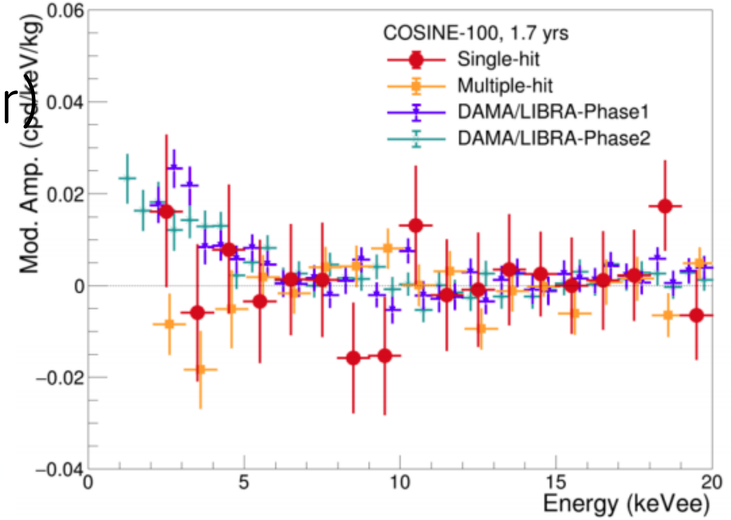
Offset + Exponential + Cosine is fit to data at 2-6 keV.



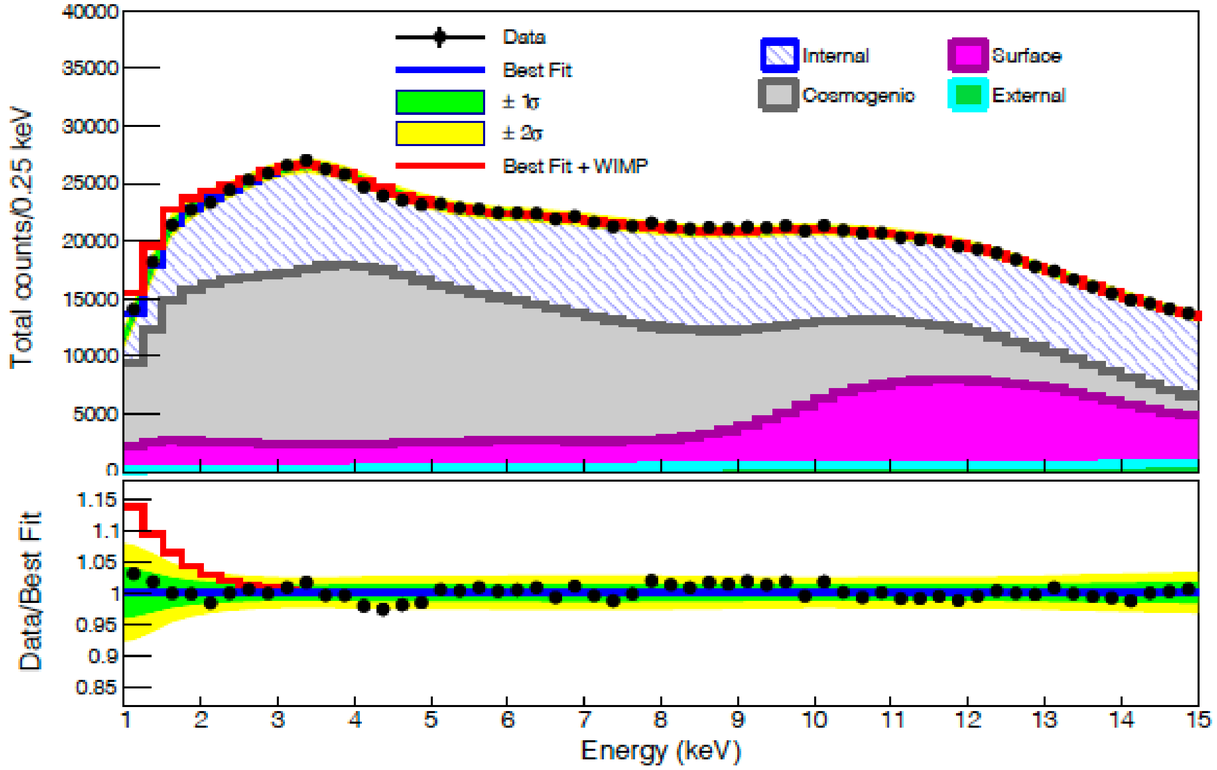
PRL 123,031302 (2019)

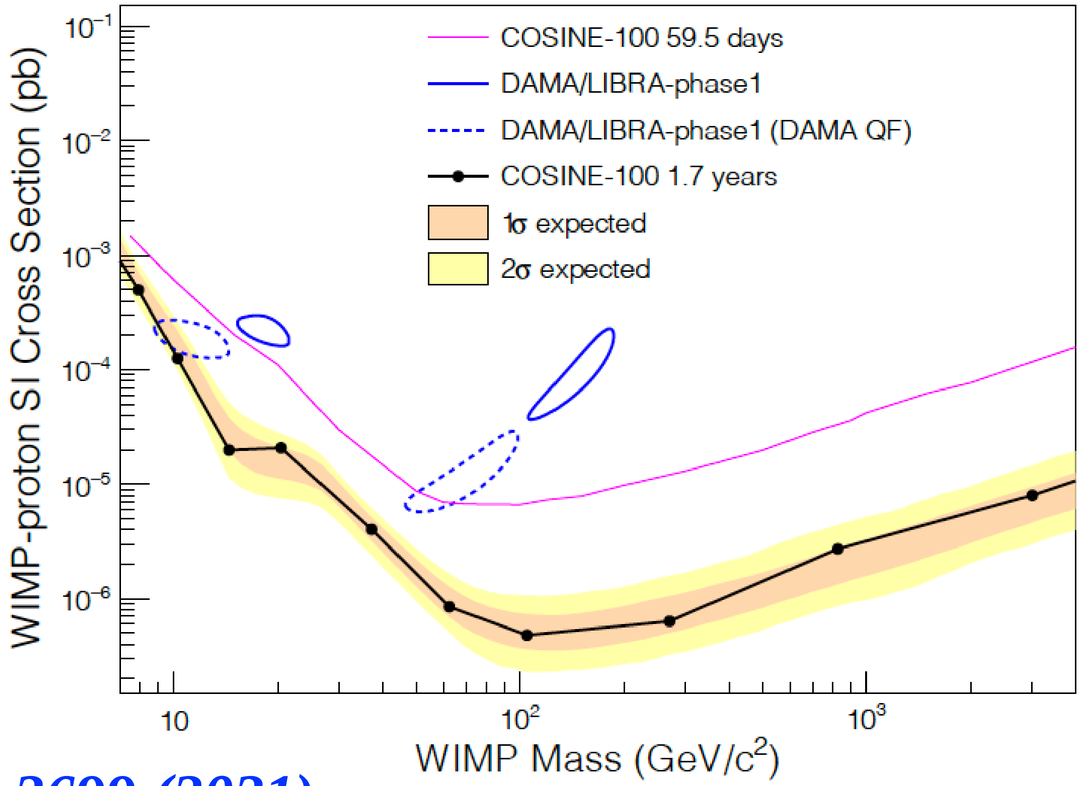
Annual Modulation Analysis(1.7 yr

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



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

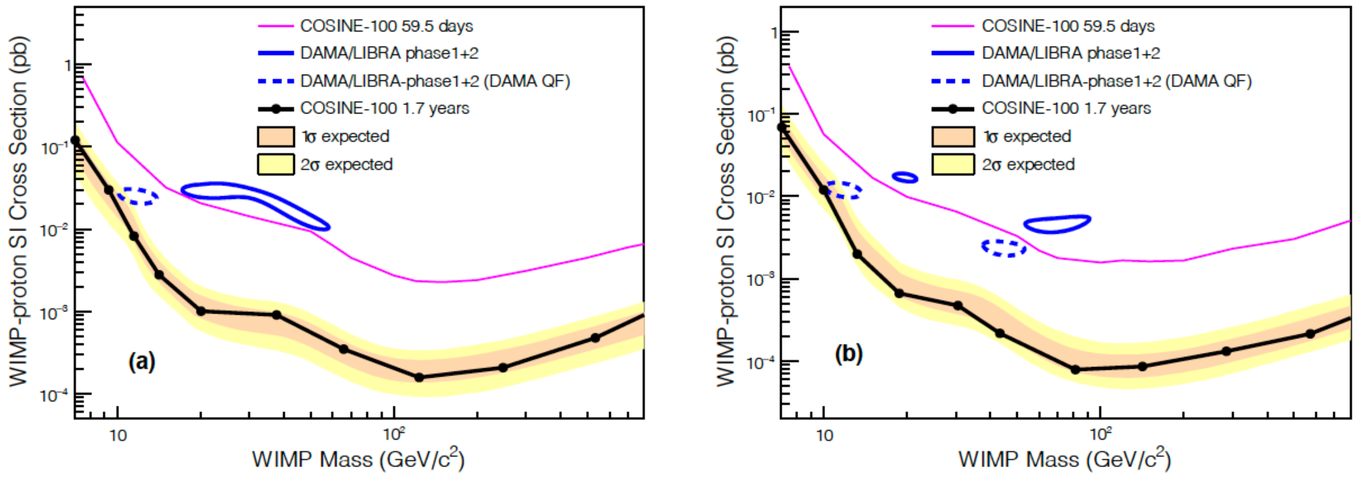




Sci. Adv. 7, eabk2699 (2021)

A factor of 10 improved result compared to the first result

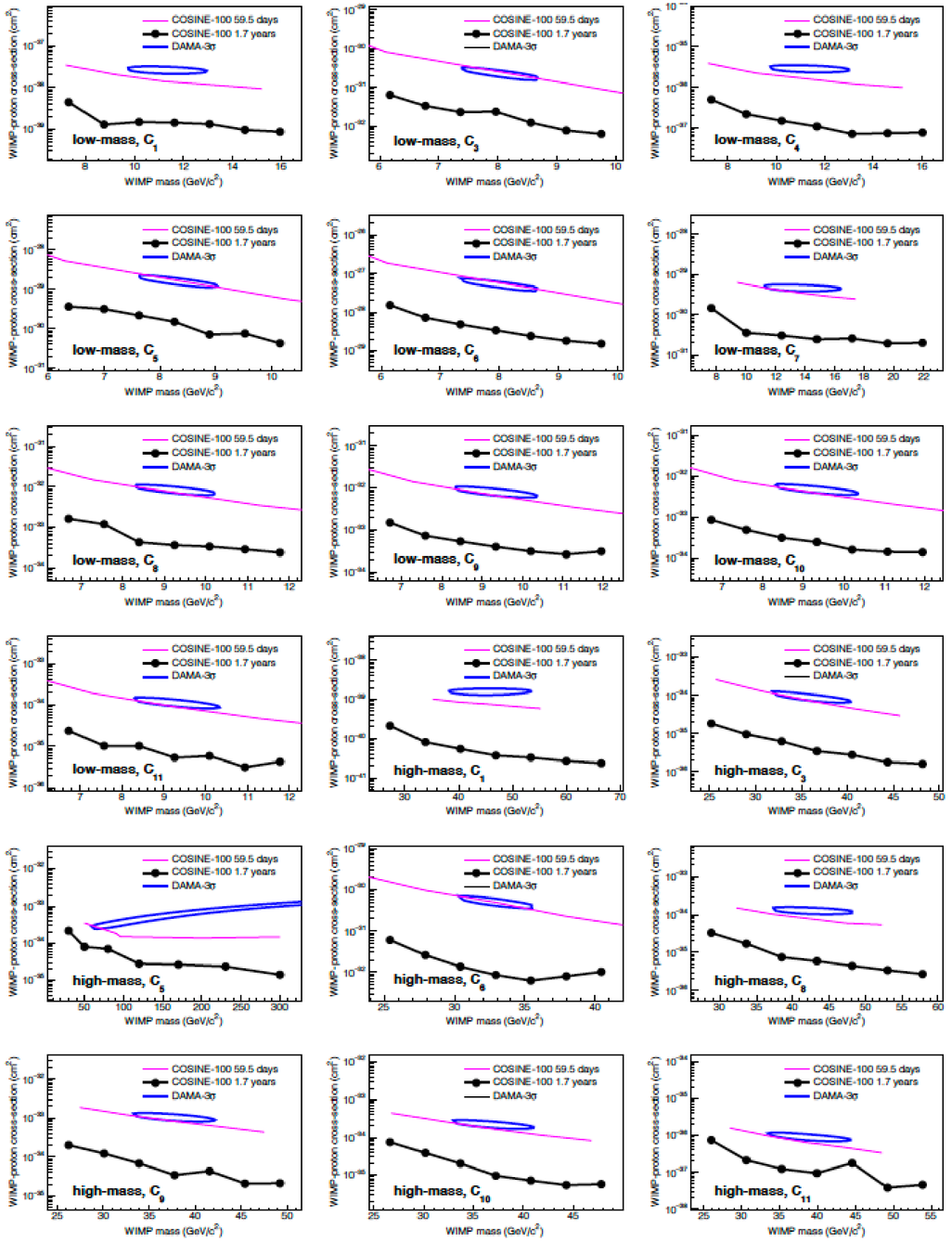
Constant Rate Analysis with 1-keV threshold (1.7 yr)



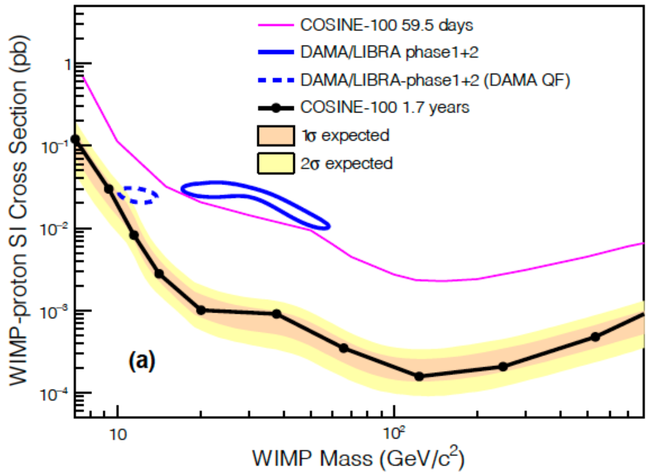
Sci. Adv. 7, eabk2699 (2021)

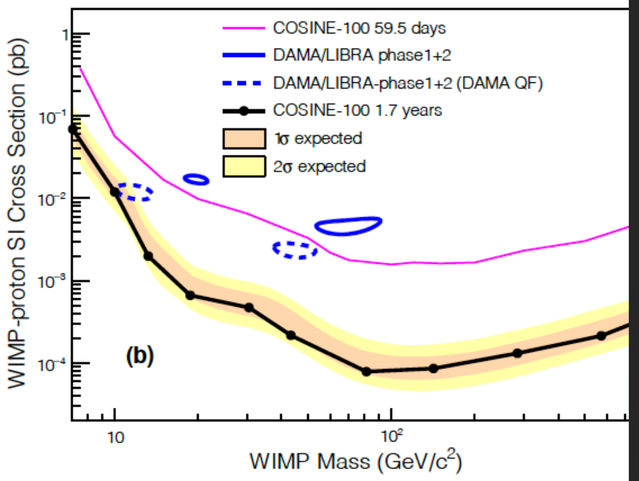
Additionally, we checked alternative hypotheses for isospin-violating cases and EFT operators with the same threshold and the updated quenching factors as DAMA/LIBRA.

We find, in general, those are incompatible with COSINE-100 data. There is no excess of events over the expected background, that can be interpreted as DAMA's annual modulation signal under the assumption of dark matter interactions based on the Standard Halo Model.



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





Sci. Adv. 7, eabk2699 (2021)

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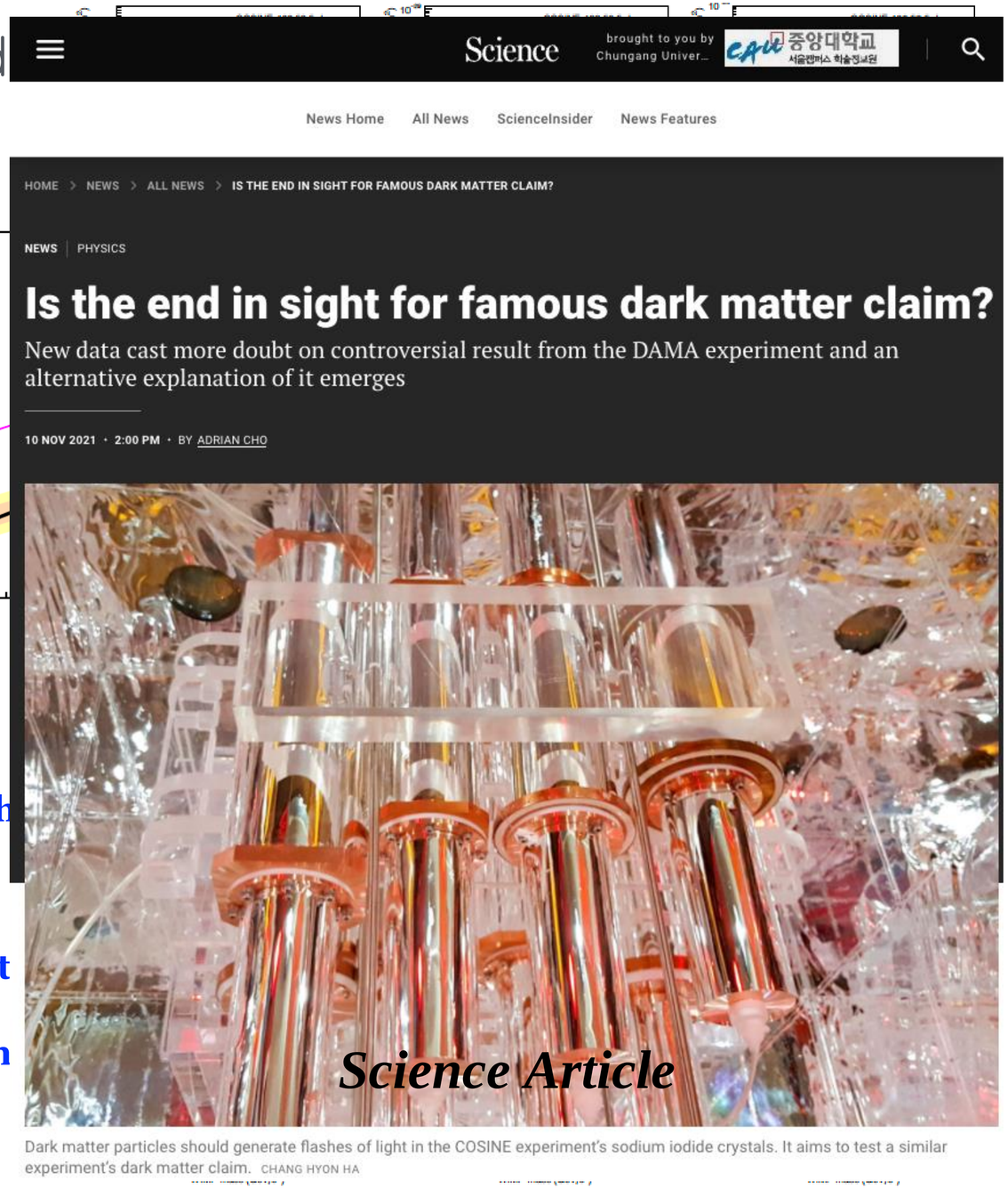
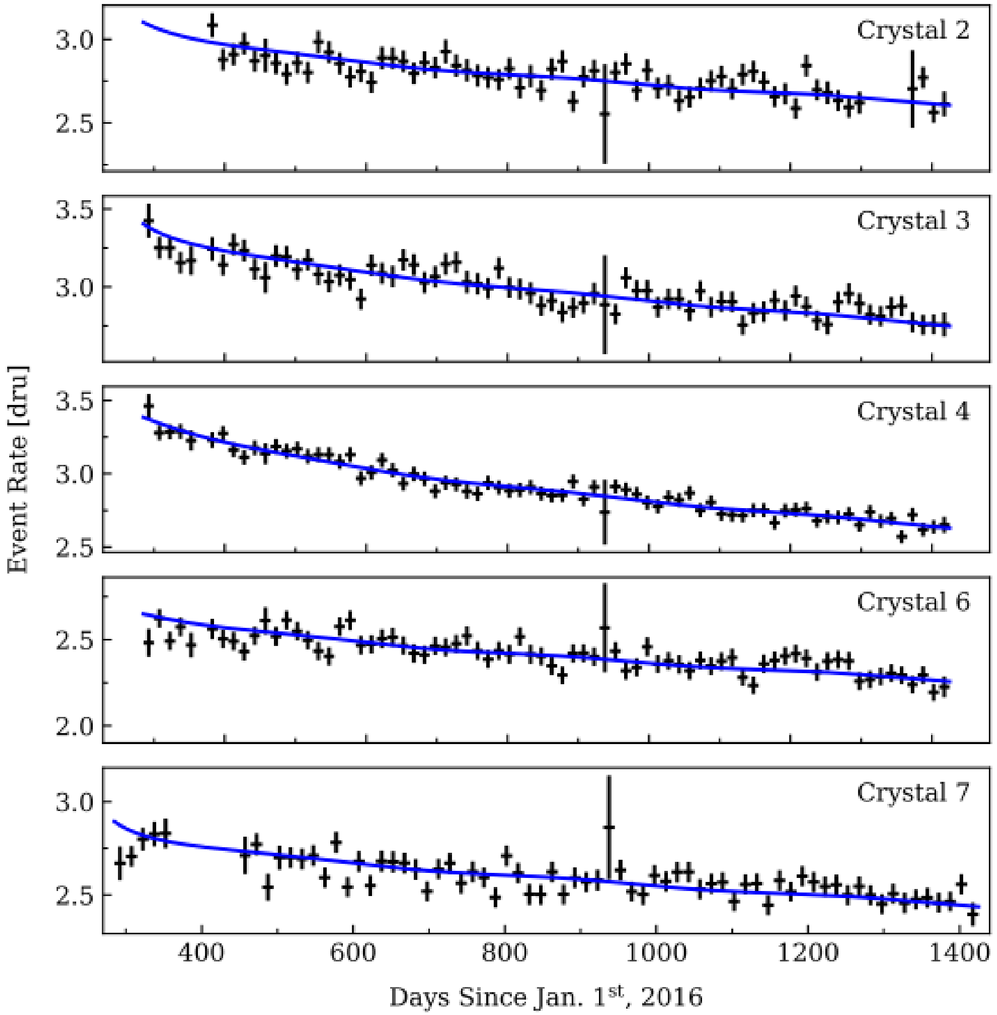
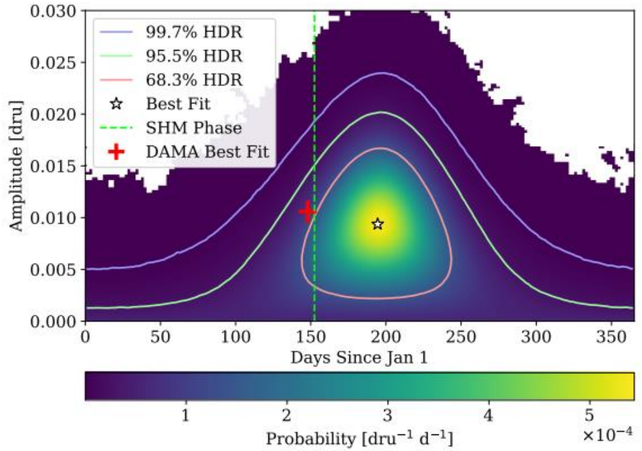


Annual Modulation Analysis with 1-keV threshold (2.82 yr)

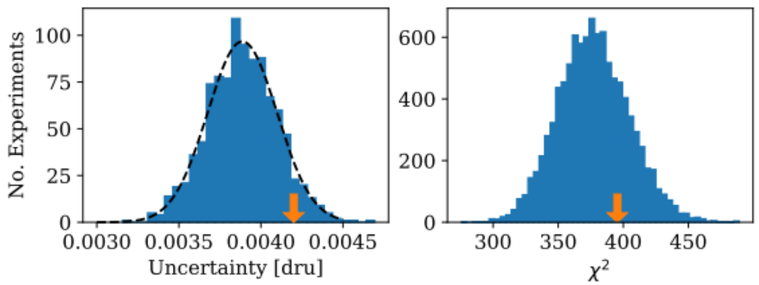


Better Modeling of Backgrounds
Better Pseudo experiments



Configuration	Amplitude [dru]	Phase [days]
COSINE-100 1–6 keV (This result)	0.0067±0.0042	152.5 (fixed)
COSINE-100 2–6 keV (This result)	0.0050±0.0047	152.5 (fixed)
COSINE-100 2–6 keV (2019 result [14])	0.0083±0.0068	152.5 (fixed)
ANAIS 1–6 keV (2021 result [16])	-0.0034±0.0042	152.5 (fixed)
ANAIS 2–6 keV (2021 result [16])	0.0003±0.0037	152.5 (fixed)
DAMA/LIBRA 1–6 keV (phase2 [7])	0.0105±0.0011	152.5 (fixed)
DAMA/NaI+LIBRA 2–6 keV [7]	0.0102±0.0008	152.5 (fixed)
COSINE-100 1–6 keV (This result)	$0.0094^{+0.0073}_{-0.0072}$	$194.5^{+49.0}_{-50.5}$
COSINE-100 2–6 keV (This result)	$0.0061^{+0.0064}_{-0.0061}$	Unconstrained
COSINE-100 2–6 keV (2019 result [14])	0.0092±0.0067	127.2±45.9
DAMA/LIBRA 1–6 keV (phase2 [7])	0.0106±0.0011	148±6
DAMA/NaI+LIBRA 2–6 keV [7]	0.0103±0.0008	145±5

PRD submitted (arXiv:2111.08863)



This Results (1–6 keV) : 0.0067 ± 0.0042 dru

DAMA/LIBRA : 0.0105 ± 0.0011 dru

Keep pounding! Need more data! Need better crystals!

COSINE-200 Preparations (much work done in Korea)

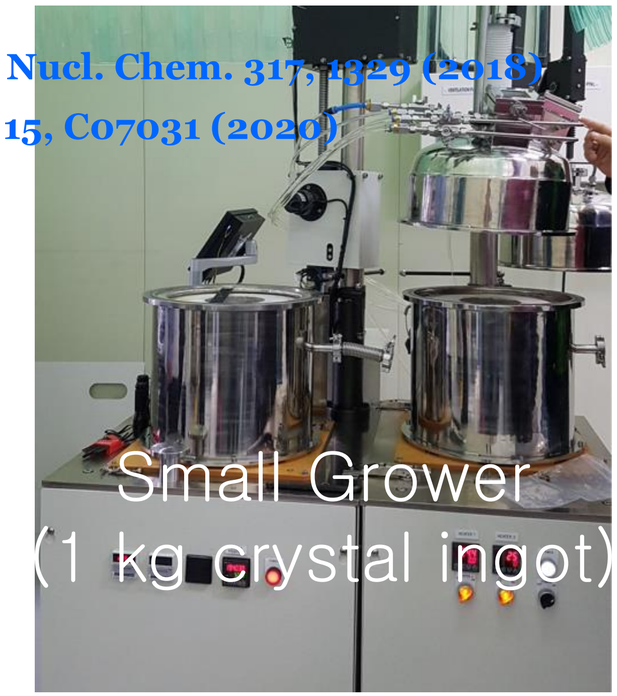
Powder Purification

	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)

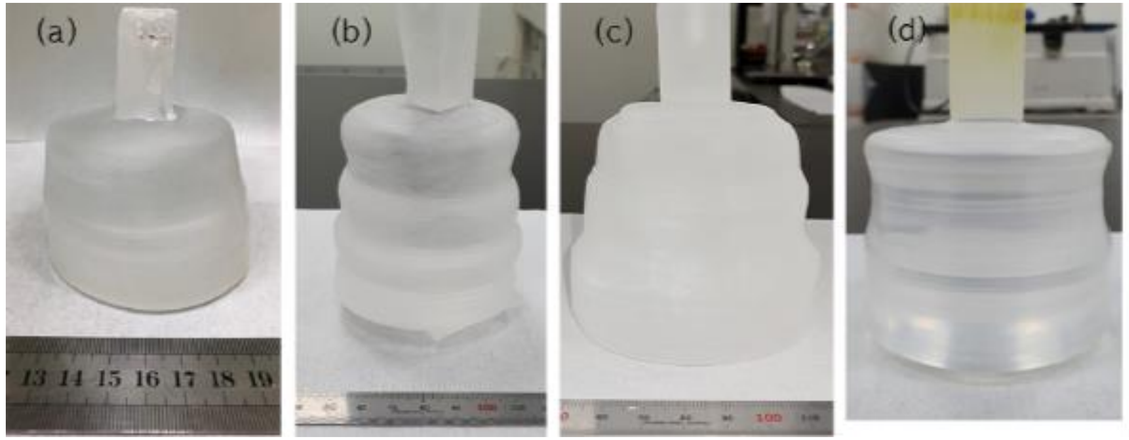


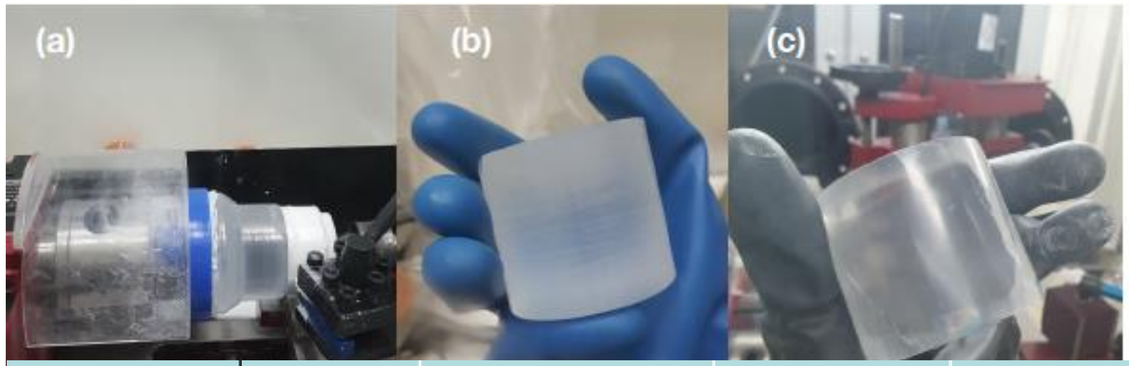
Small Grower
(1 kg crystal ingot)

Full-sized Grower
(100 kg crystal ingot)

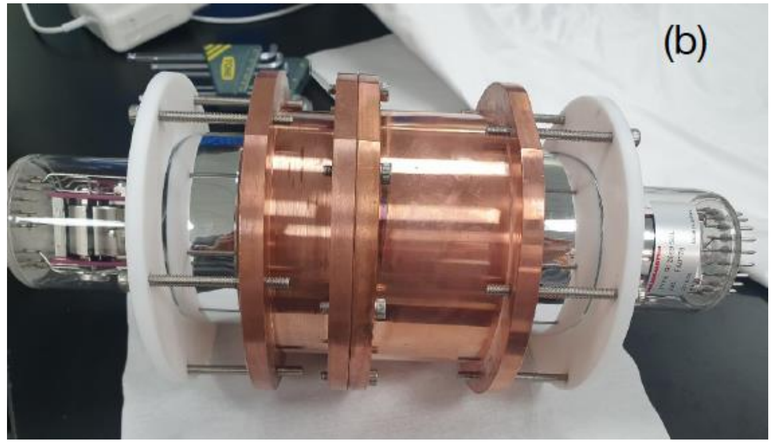
Background rate should be less than 1 dru (DAMA)

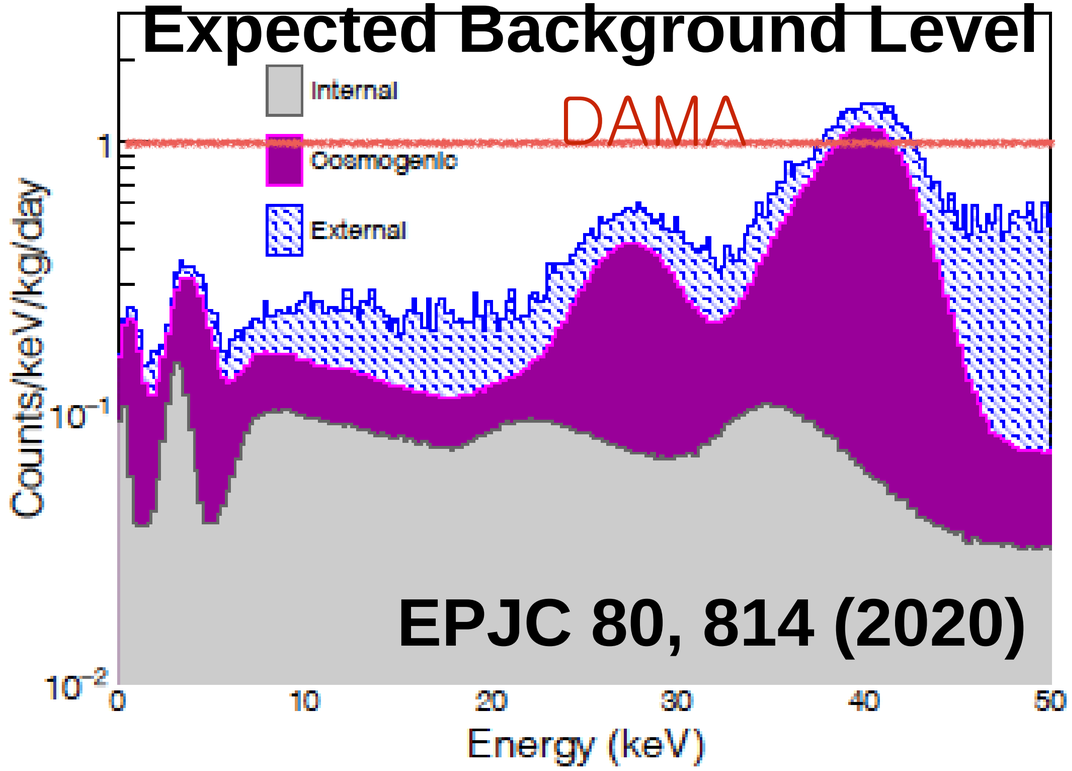
Prototype NaI(Tl) crystal detector





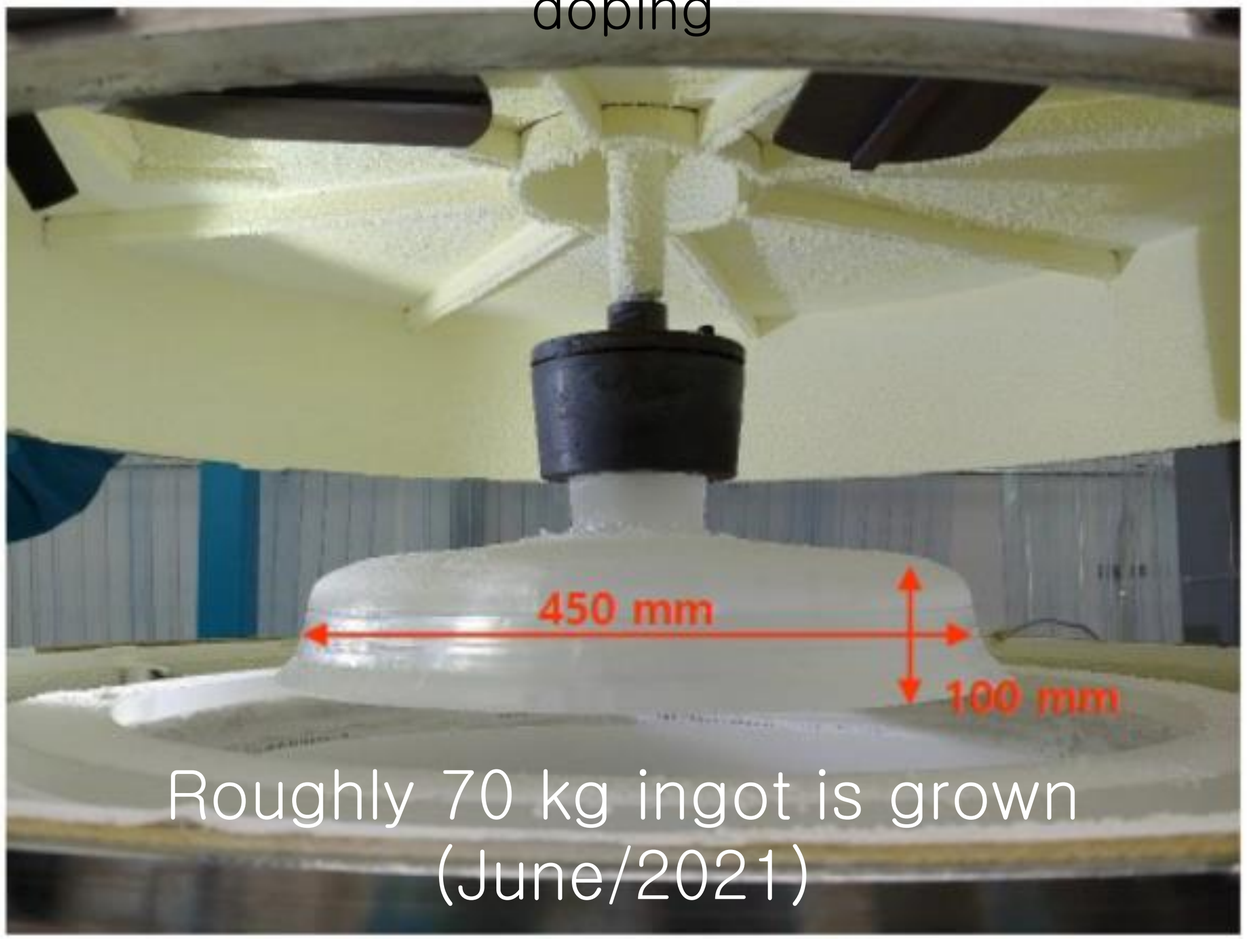
	K (ppb)	^{210}Pb (mBq/kg)	^{238}U (μBq/kg)	^{232}Th(μBq/
Powder	5	-	<20	<20
Aug/2018	684	3.8+/-0.3	26+/-7	<6
Sept/2019	**8**	**0.01+/-0.02**	**11+/-4**	**7+/-2**
DAMA	<20	0.01~0.03	8.7~124	2~31





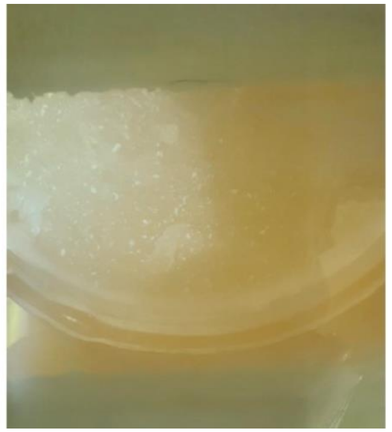
Large Size NaI(Tl) crystal growth at CUP

Test growing without Thallium doping



Roughly 70 kg ingot is grown (June/2021)

195 kg NaI Merck Powder loaded



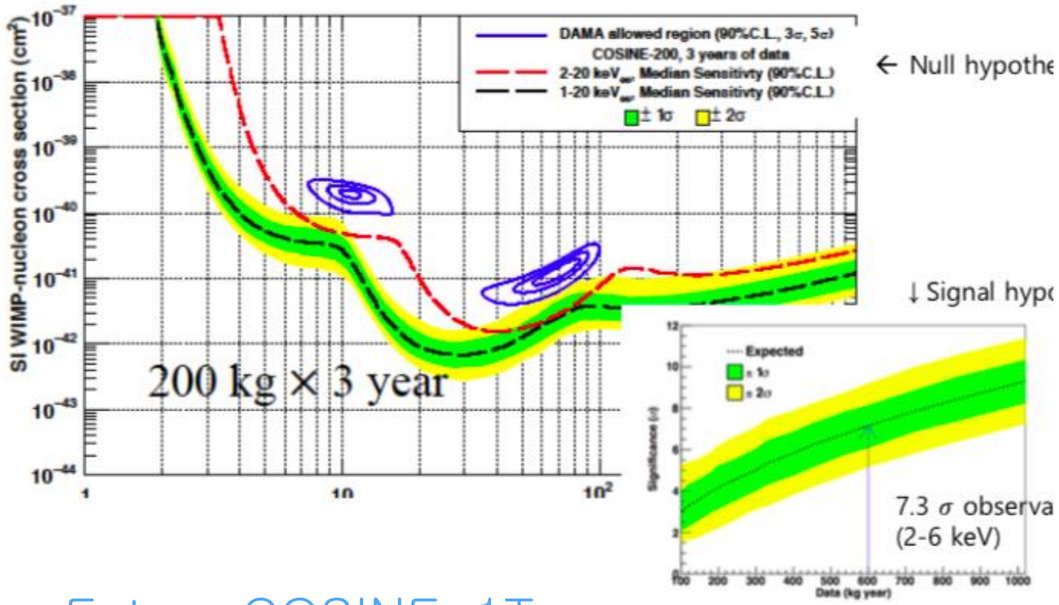
Sequence of crystallization

In-house Crystal growing starts working. Large-size Tl-doped and low-bkg crystal growth is the next step.

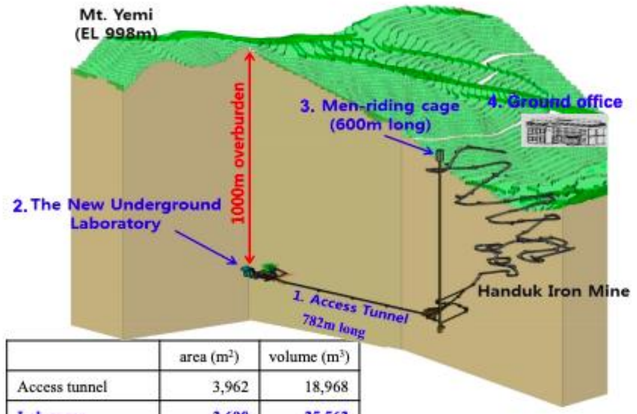
COSINE-200 (starting 2022-2023) @ Yemilab

Annual Modulation Analysis

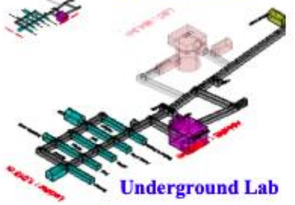
- 1 counts/day/kg/keV background assumed (same as DAMA/LIBRA)

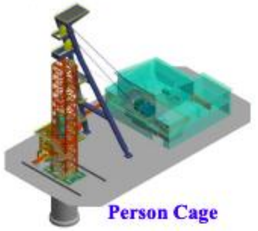


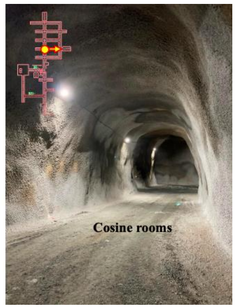
1. **Access Tunnel**, 782 m long with 12% down slope
2. **Underground Lab.** with 2600 m²
3. **Person Cage**, running vertical 587 m
4. **Ground Office** with 2500 m²



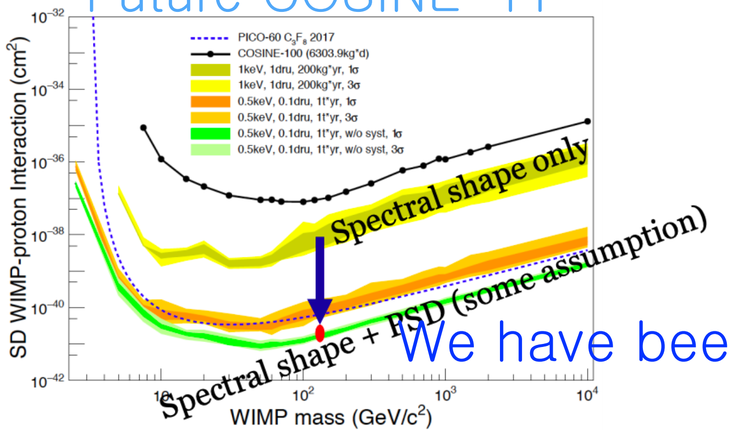
	area (m²)	volume (m³)
Access tunnel	3,962	18,968
Lab space	**2,600**	**25,562**
Connecting tunnel	4,847	14,161
amount	**11,525**	**58,691**







Future COSINE-1T



The ground office exterior

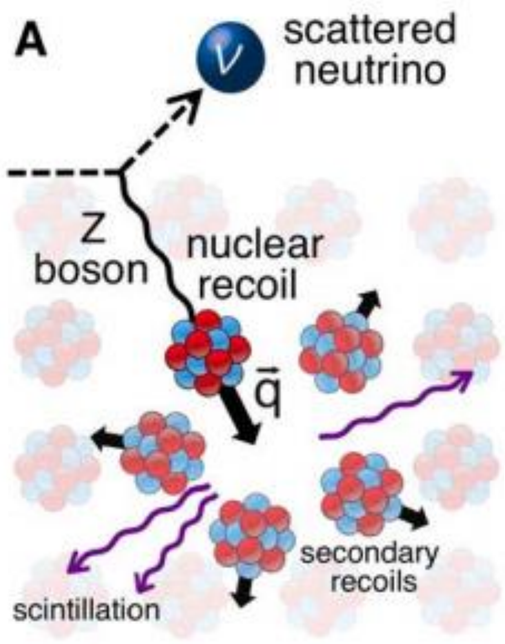
The reinforcement

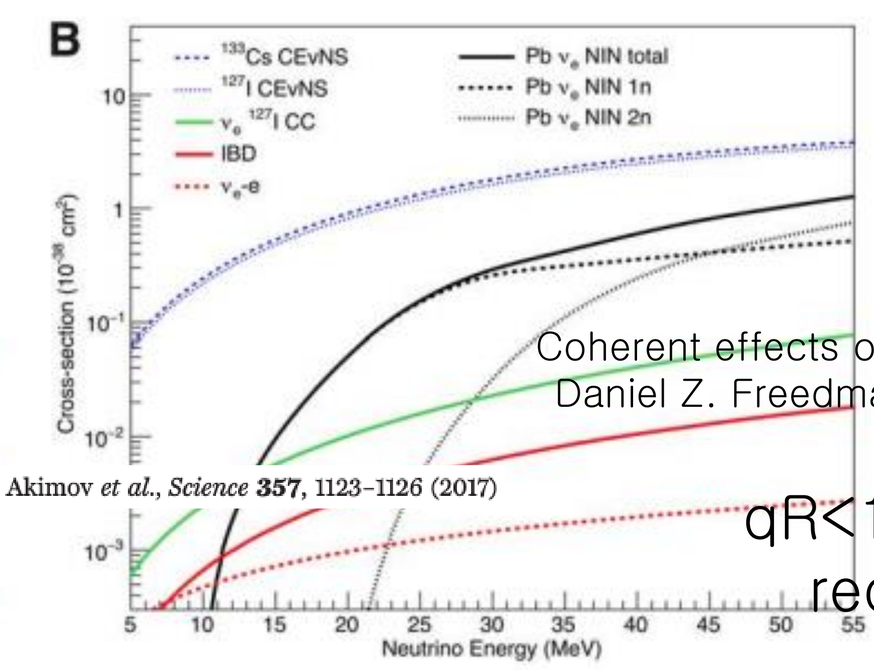
We have been preparing 200 kg experiment (COSINE-200) using better crystals with lower background

COSINE-100 Spinoff : NEON (Neutrino Elastic scattering Observation in NaI(Tl))

- 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) & N^2 dependence

- Dark Photon/Dark Axion Portal
- Neutrino Magnetic Moment
- Neutrino Non-Standard Interactions





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

$\overline{\nu}_e$

~MeV

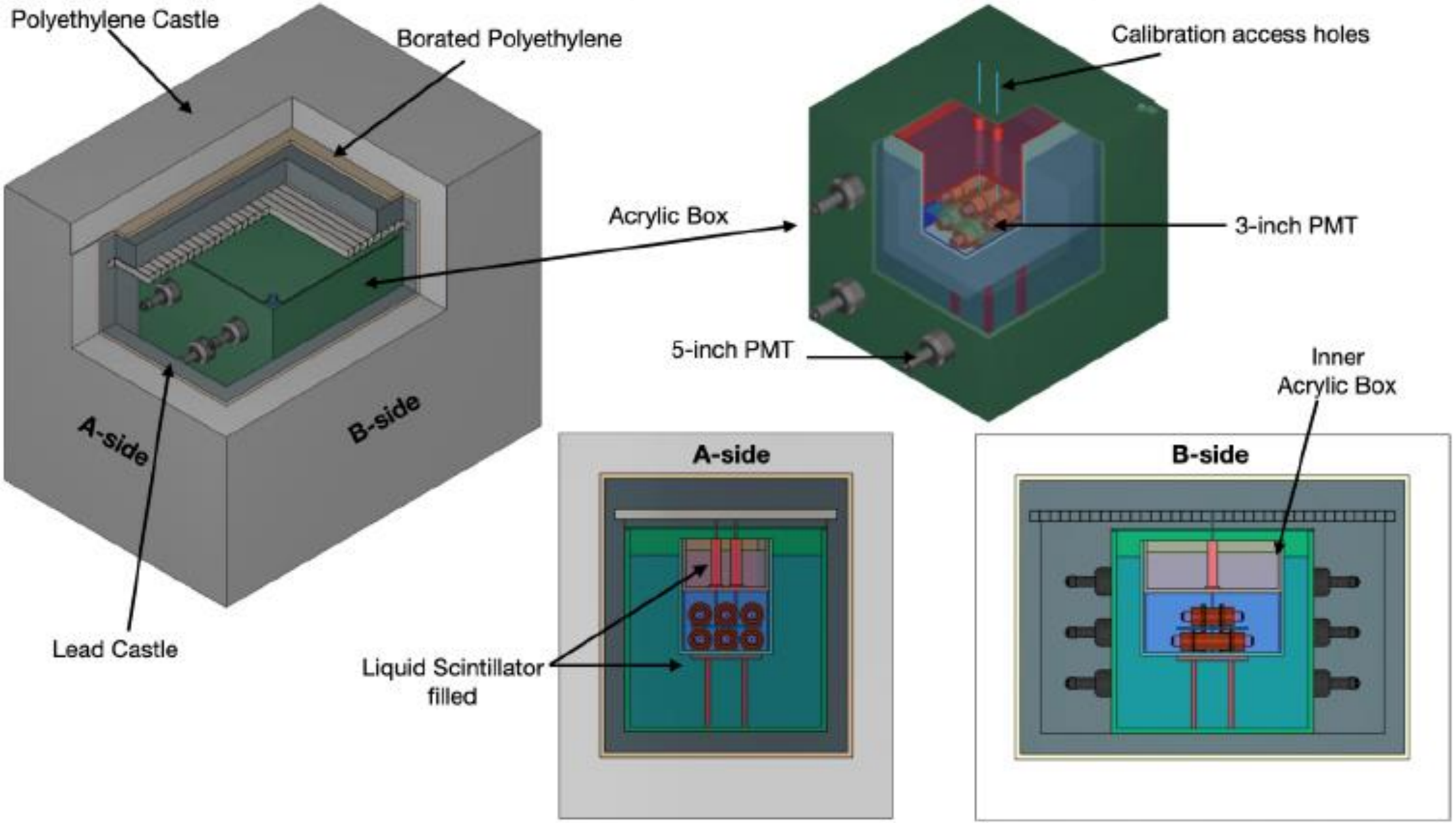
Coherent effects of a weak neutral curren
Daniel Z. Freedman (PRD 9,1389) 1974)

qR<1 : Coherent requirement

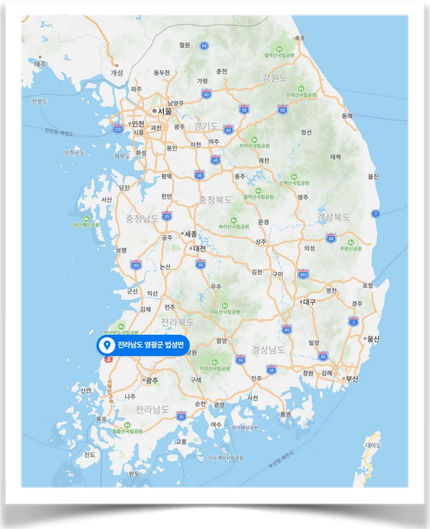
Na

~keV

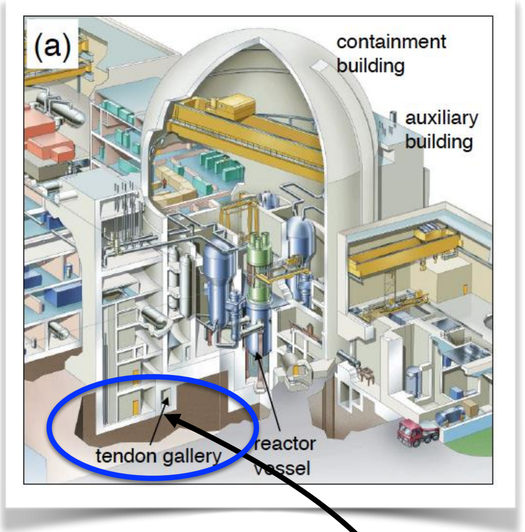
The NEON Experimental Setup



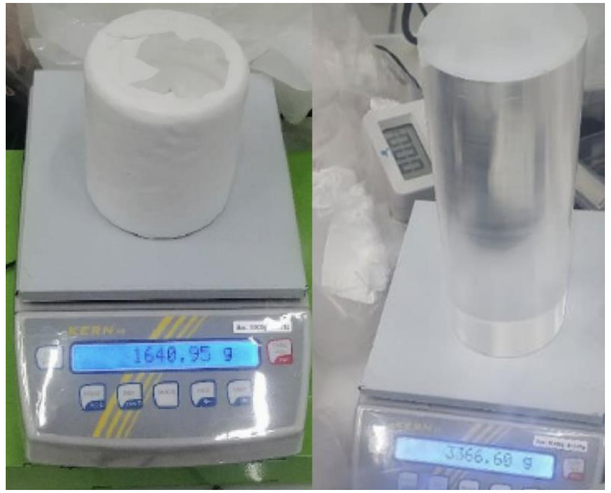
The NEON Experimental at Hanbit NPP

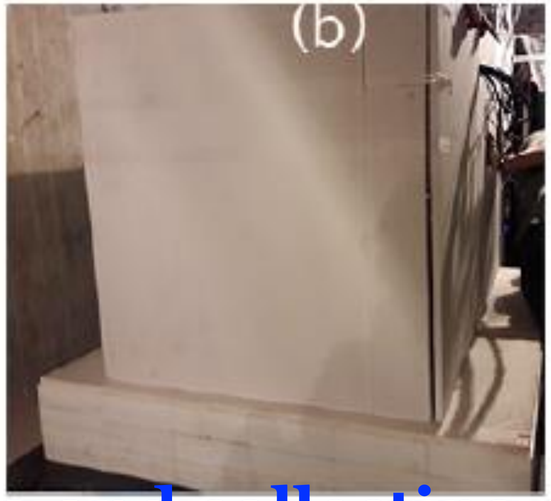


Hanbit Nuclear Power Plant (Yeonggwang)



No. 6 Reactor

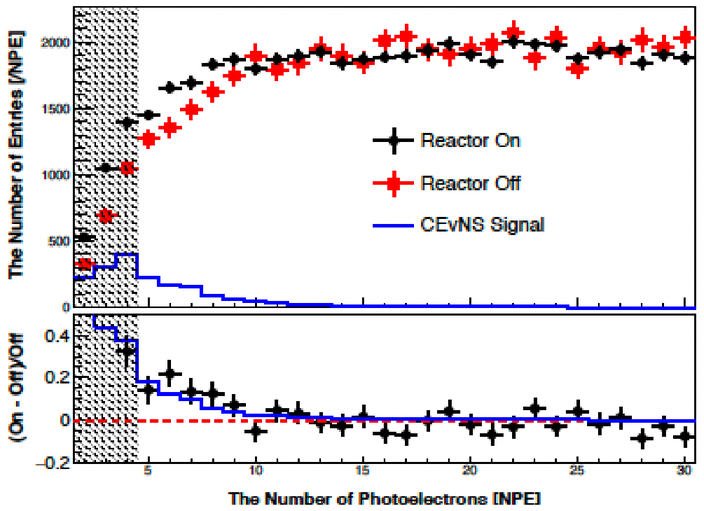




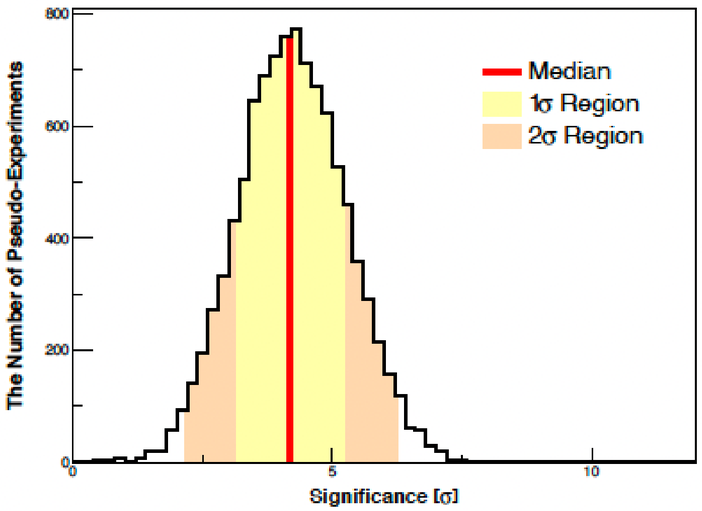
NEON is running and collecting data.

Expected Rate and Sensitivity for NaI(Tl) crystal detectors

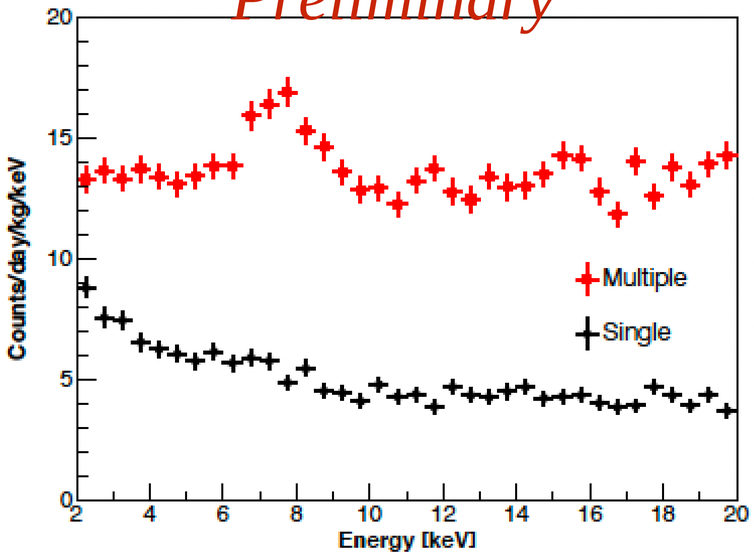
Preliminary



Preliminary

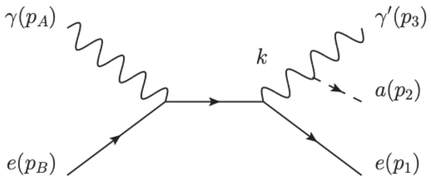


Preliminary

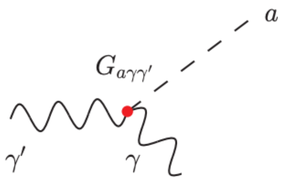


- Assumption for sensitivity study
  - ✓ 22-photoelectrons/keV(PEs/keV) light yield
  - ✓ 15-kg mass of detector
  - ✓ 5-counts/kg/day/keV flat background
  - ✓ 5-PEs threshold
  - ✓ 365/100-days reactor-on/-off data

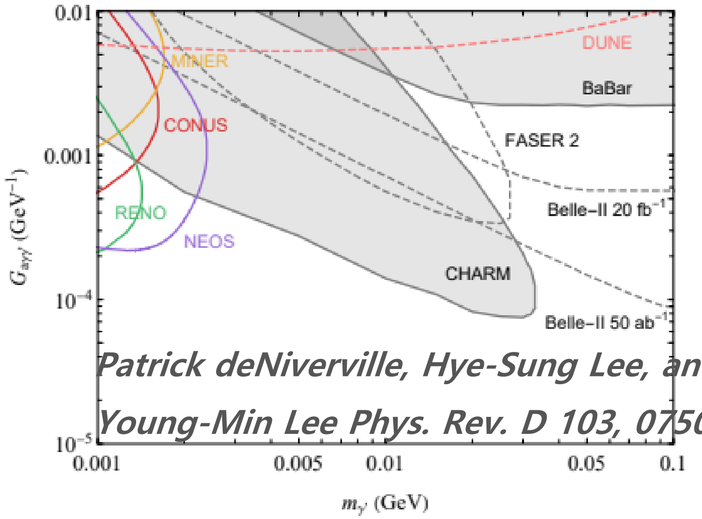
Possible Dark Axion Search similar to NEOS



Production



Detection



Patrick deNiverville, Hye-Sung Lee, and Young-Min Lee Phys. Rev. D 103, 075006

NEWSdm

Nuclear Emulsion for WIMP Search
– directional measurement

try to measure the "direction" of
WIMP-induced nuclear recoils

using Newly developed Nuclear emulsion
with Super-fine grain

- NIT (Nano Imaging Tracker)

NEWSdm Collaboration

70 physicists, 14 institutes

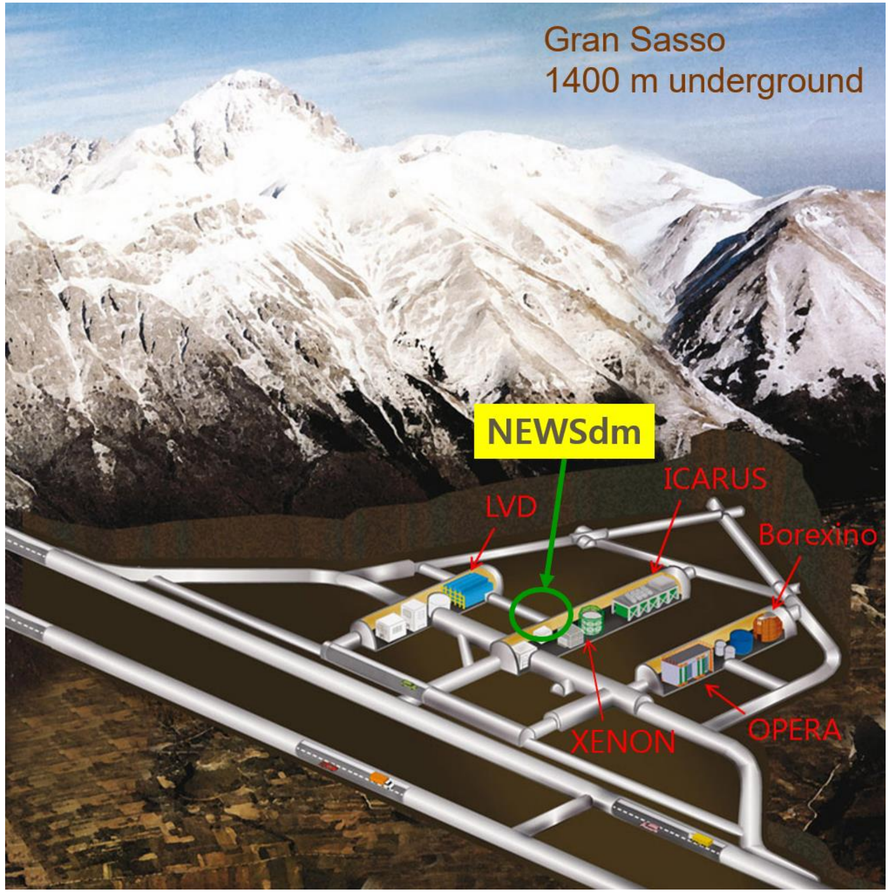
ITALY
INFN e Univ. Bari,
LNGS, INFN e Univ. Napoli,
INFN e Univ. Roma
GSSI Institute

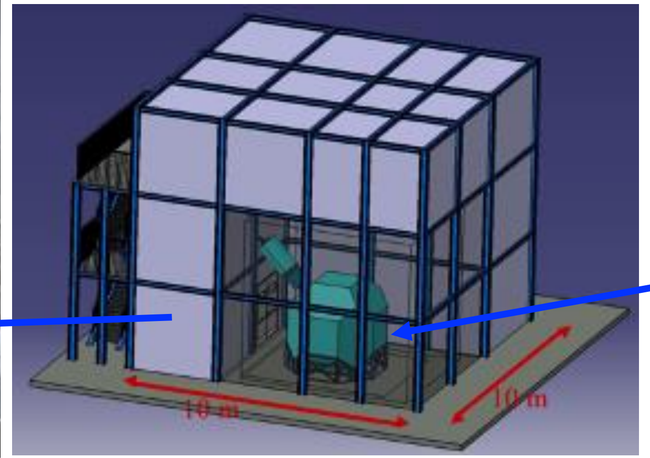
JAPAN
Chiba, Nagoya

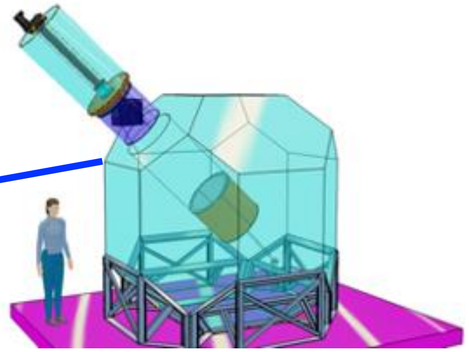
RUSSIA
LPI RAS Moscow, JINR Dubna
SINP MSU Moscow, INR Moscow
Yandex School of Data Analysis

KOREA
Gyeongsang

TURKEY
METU Ankara

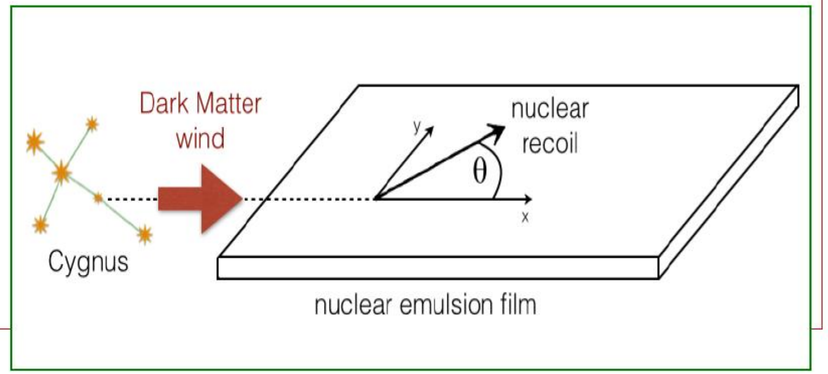


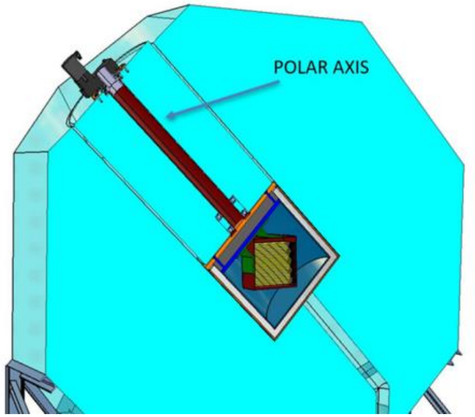




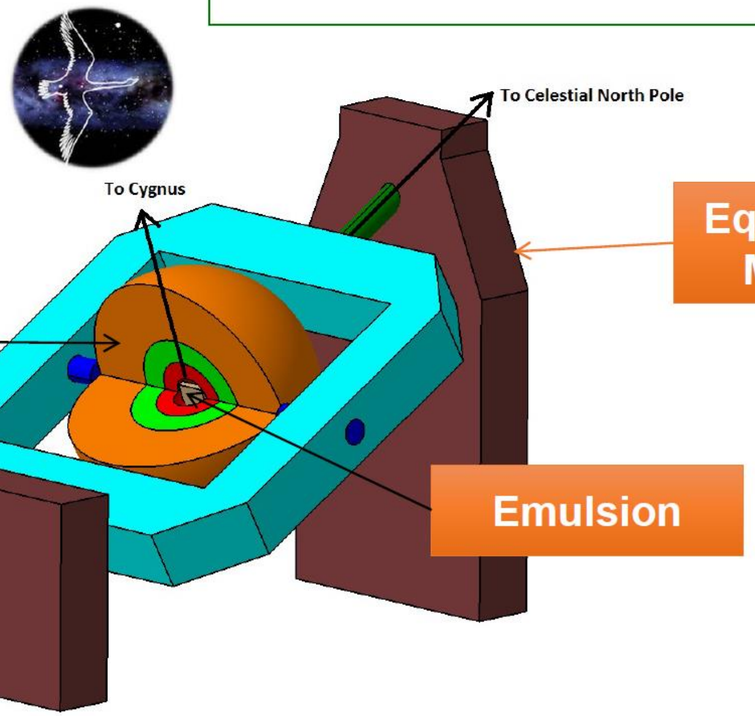
Directionality as a strong signature of the galactic WIMP

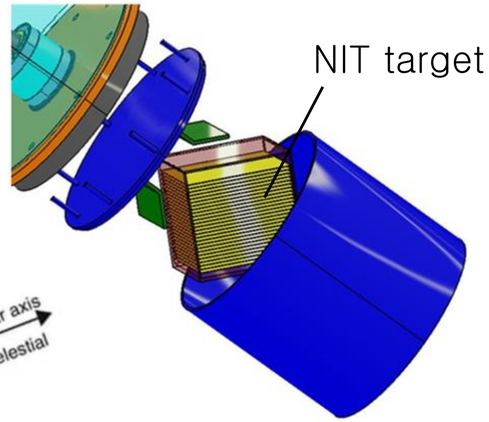
➔ **keep target pointed to DM wind (Cygnus)** by using the Equatorial telescope

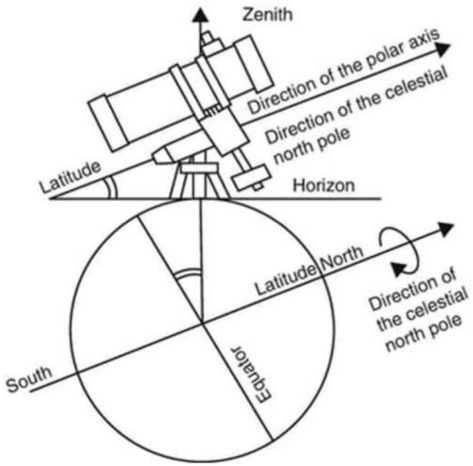




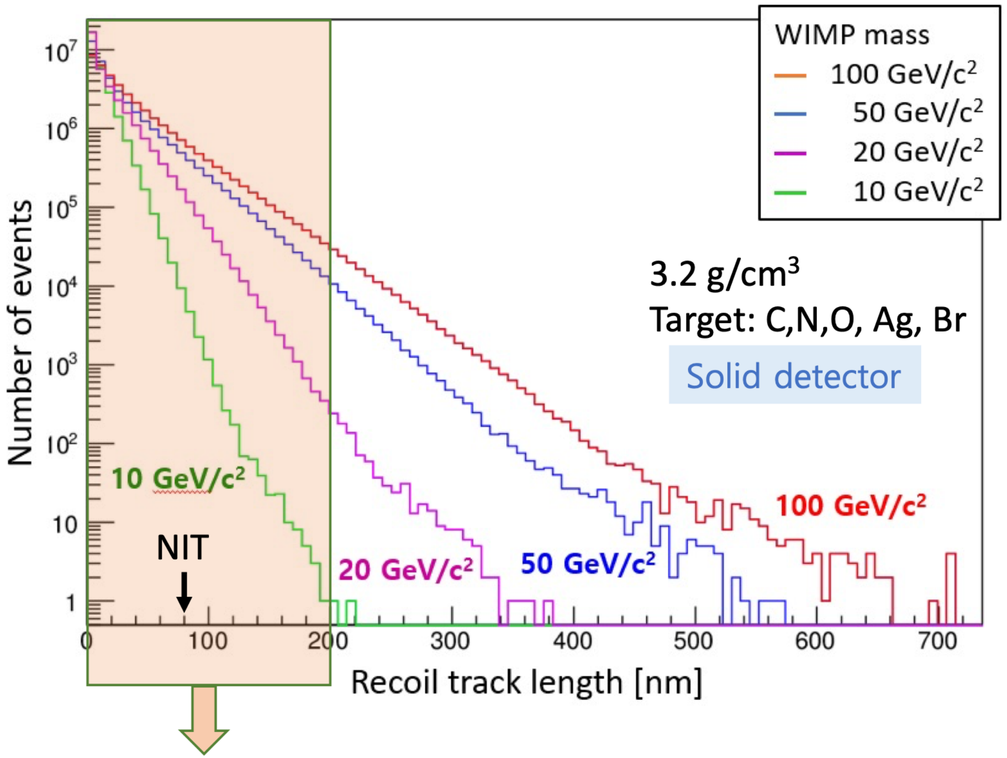
Cross-sectional view of NIT target with polyethylene shielding







Expected recoil lengths in the Nuclear emulsion for different WIMP masses

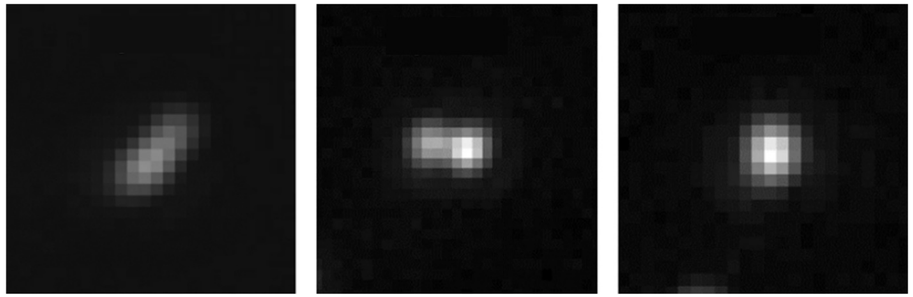


Inaccessible with standard optical techniques due to diffraction limit

Need super-resolution detector to measure tracks shorter than 200 nm ⇨ **Challenge #1**

The ranges of the signal tracks can be ~several 100 nm in the Nuclear emulsion.

Images of Optical microscope



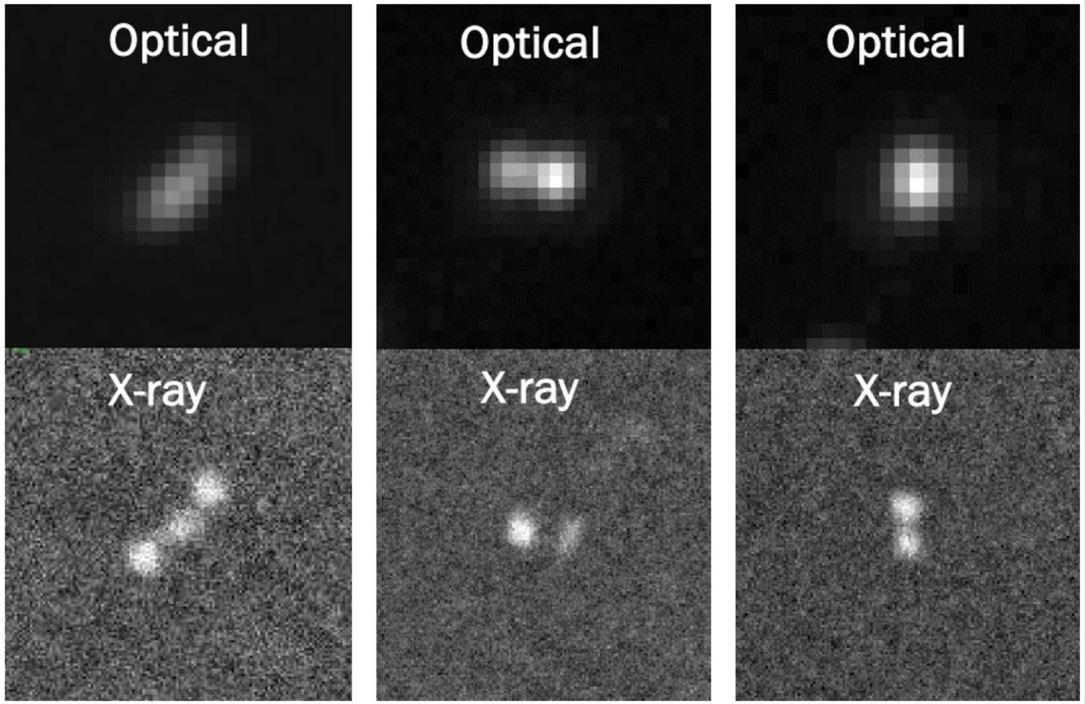
L = 380 nm L = 265 nm L = 160 nm

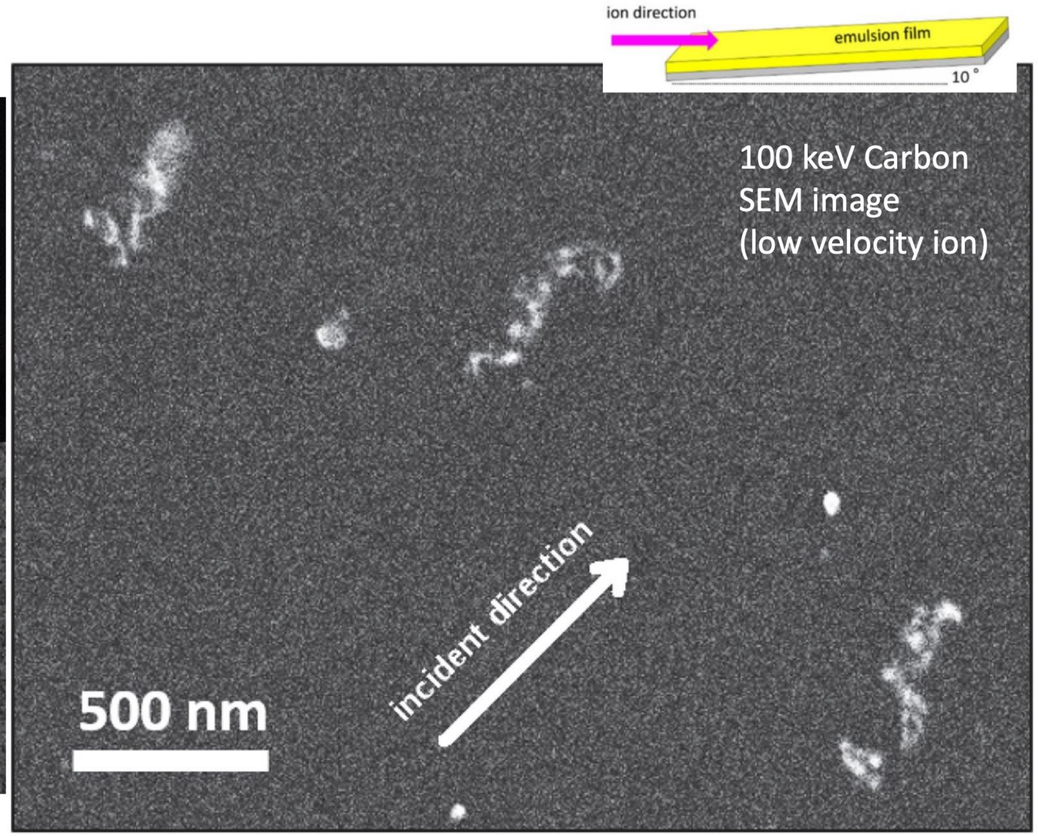
Recoil tracks due to 14 MeV neutron (D-T nuclear fission)

How can we see by the optical microscope?

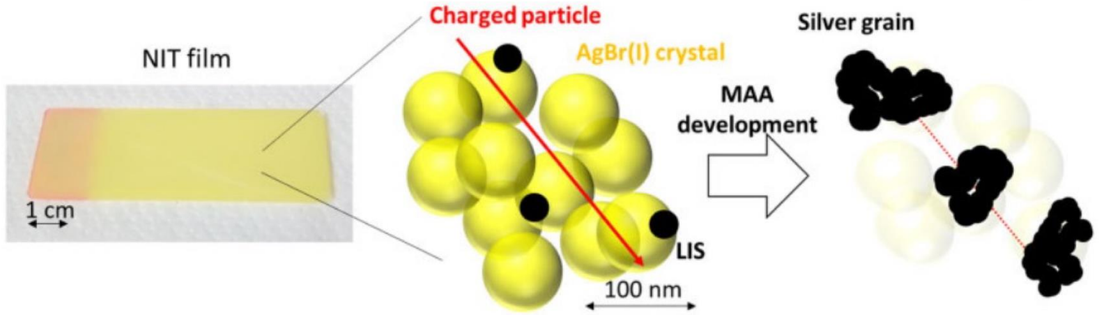
Challenge #2

Images by Optical, X-ray microscopes and SEM



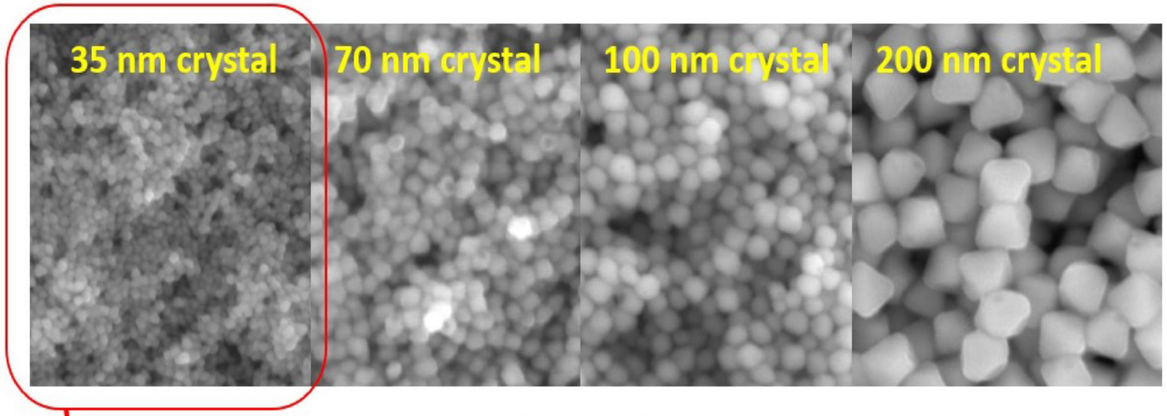


Filament structure of Ag grain



- Track formation by several grains
- Silver grains can visualize after development

Challange #1 NIT (Nano Imaging Tracker)

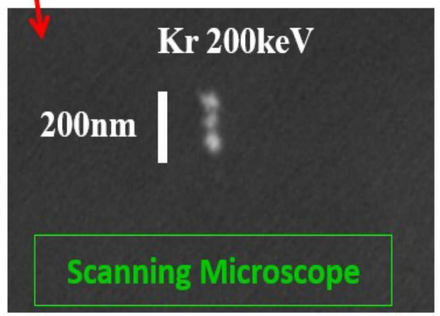


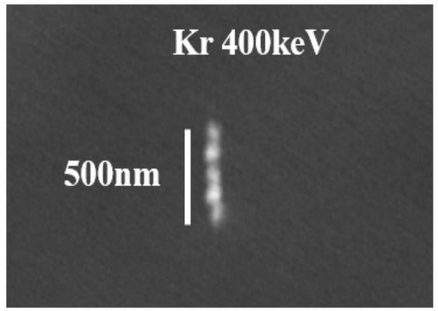
Newly developed emulsion with super-fine grain

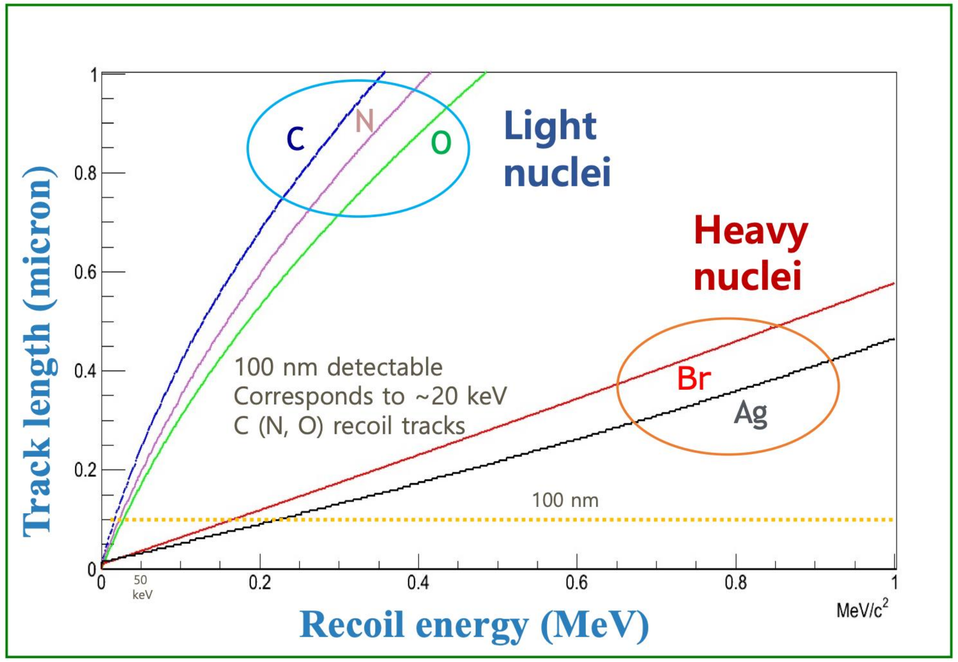
⇩

Intrinsic spatial resolution ~ 10 nm

500nm







NIT composition

Constituent	Mass Fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

(a) Constituents of nuclear emulsion

Element	Mass Fraction	Atomic Fraction
Ag	0.44	0.12
Br	0.32	0.12
I	0.019	0.003
C	0.101	0.172
O	0.074	0.129
N	0.027	0.057
H	0.016	0.396
S	0.003	0.003

(b) Elemental composition

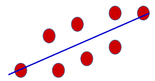
Challenge #2 Beyond optical resolution

LSPR (Localized Surface Plasmon Resonance) :
When the size of metallic grain is smaller than the wave length of the incident light,
*the **resonance** depends on the **polarization** of the light → Sensitive to the **shape** of the nano metallic grain*

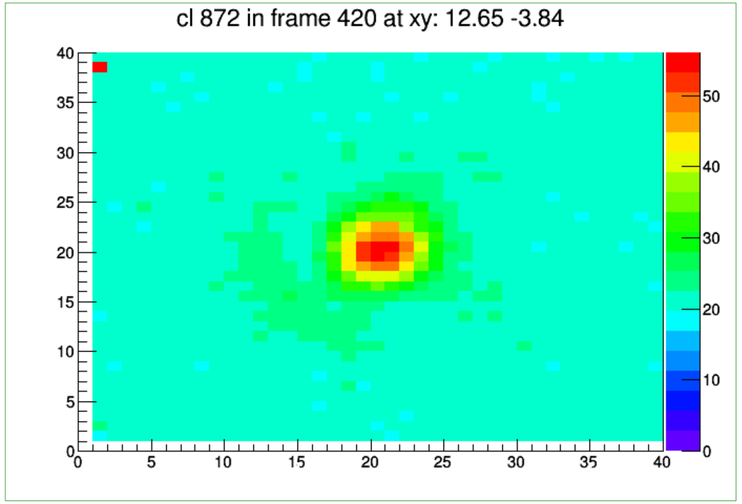
To detect tracks shorter than optical resolution
→ Taking multiple measurements over the whole polarization range
→ The shift of c.m. of the cluster gives information of nano-structure.

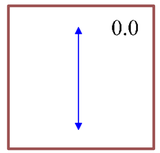
Background grain

c.m. of the cluster

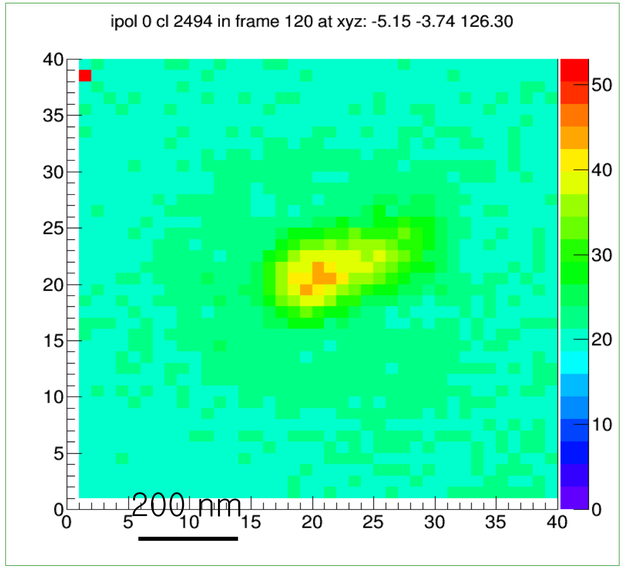


Signal-like event
(100keV C ion)
Max barshift





Polarization angle



Constructing a New Lab (#2) in GNU

Upgrade of the Scanning system for NEWSdm

Scanning Lab #2

Scanning Lab #1

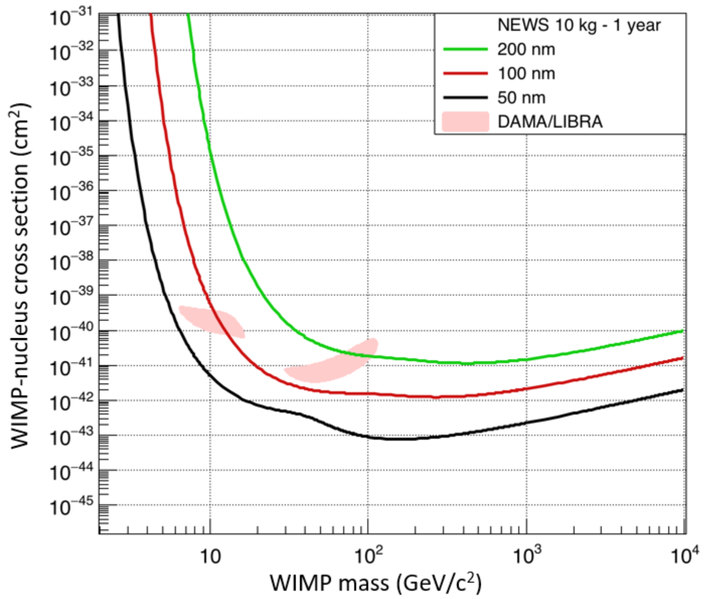
Also we will try to do the Emulsion treatments
(gel production, development …) at this Lab.

NEWSdm intermediate goal

10 kg pilot experiment

- submitted CDR to LNGSC (July 2021)

- First **directional** dark matter detector with 10 kg solid target
- Explore DAMA region with a completely different technique based on the **visual observation of recoil tracks** in the emulsion.
- Equatorial telescope with shielding & New emulsion facility construction



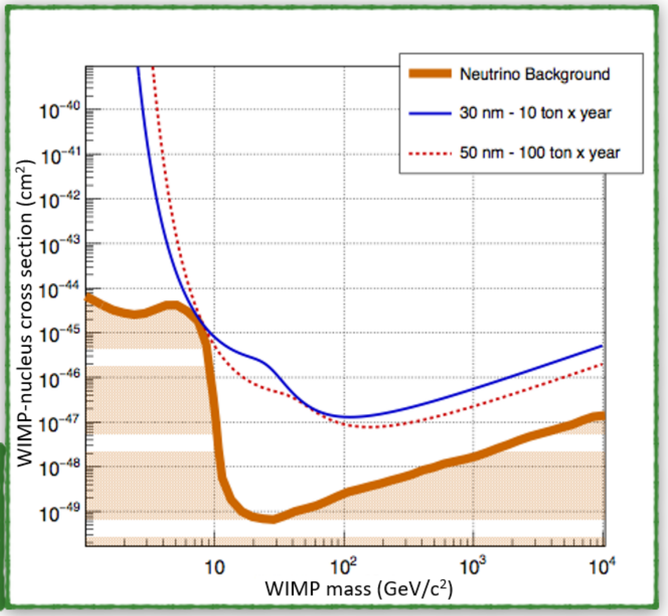
NEWSdm final goal

Overcome the Neutrino floor …

- Larger detector masses would be possible.
  - NIT is a **solid detector**.
- Other directional experiments use gaseous detectors.
  - difficult to make larger detector
  - difficult to make tracks due to diffusion effect

Requirements :

- **Reduction of NIT grain size**
  Ultra-NIT has 40 nm resolution (grain size 25 nm)
- **Larger mass scale detector**
- Further high speed scanning system

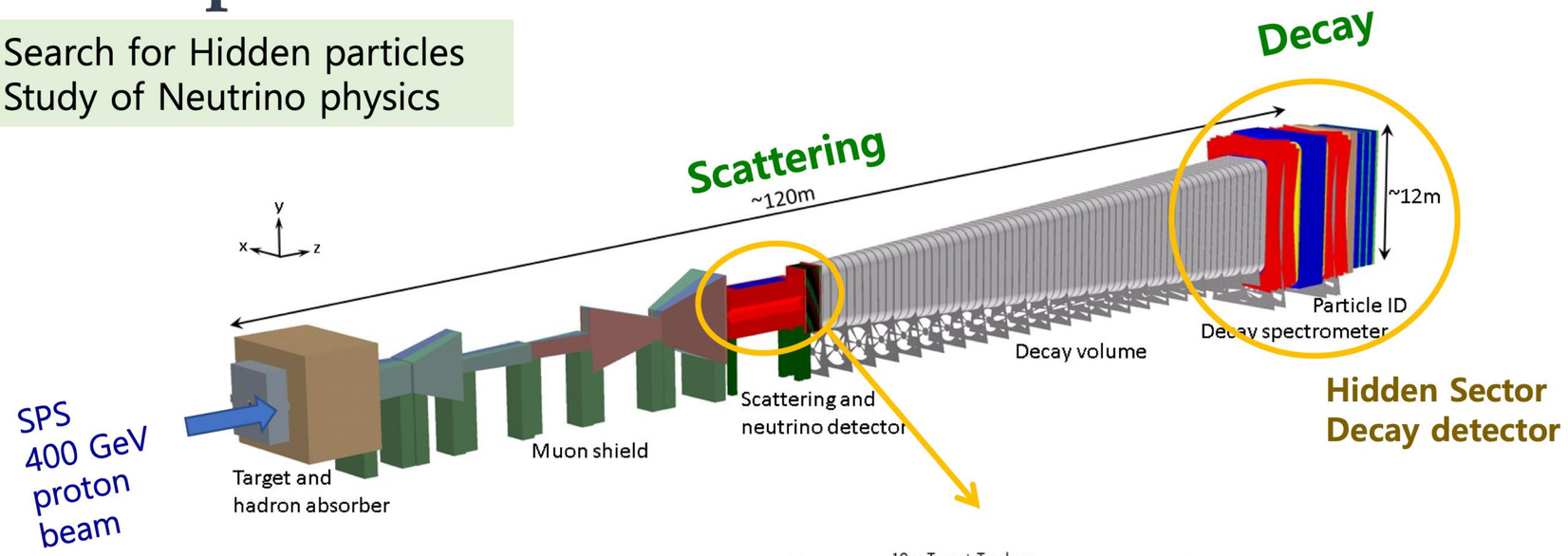


The neutrino bound is reached with:
10 ton x year exposure for **30 nm** grain NIT
100 ton x year exposure for **50 nm** grain NIT

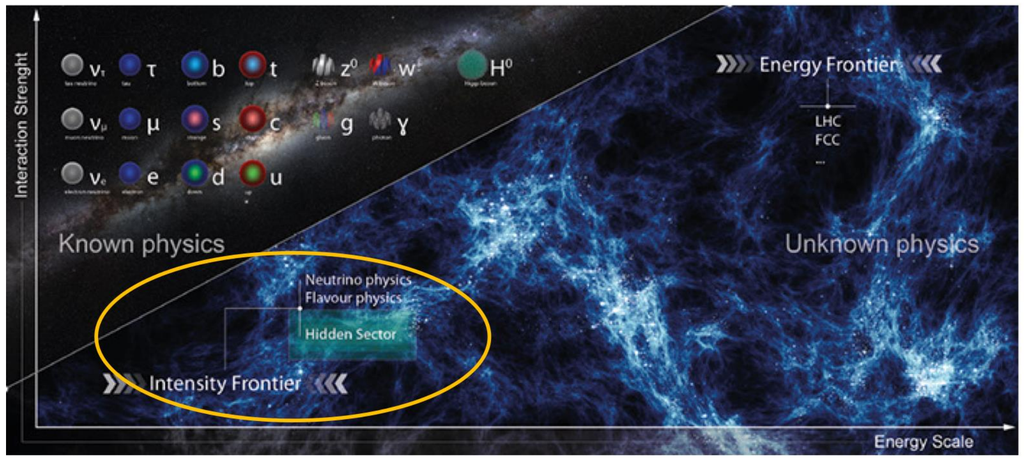
SHiP experiment

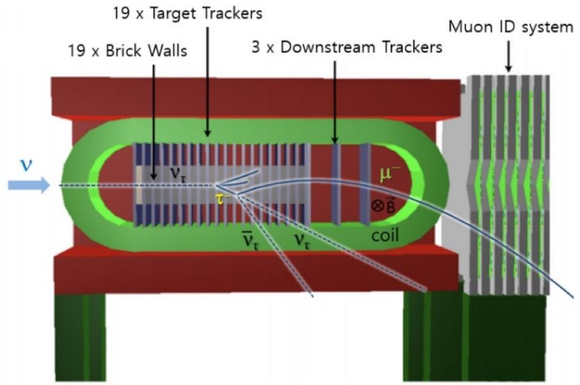
- Search for Hidden particles
- Study of Neutrino physics

HNL (Heavy Neutral Lepton),
Dark photon, Dark scalar, ALP etc.



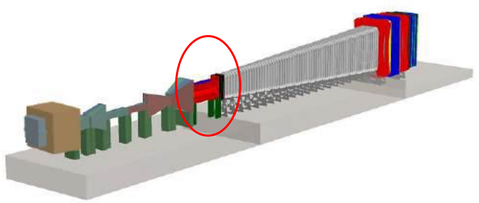
Hidden Sector
Decay detector





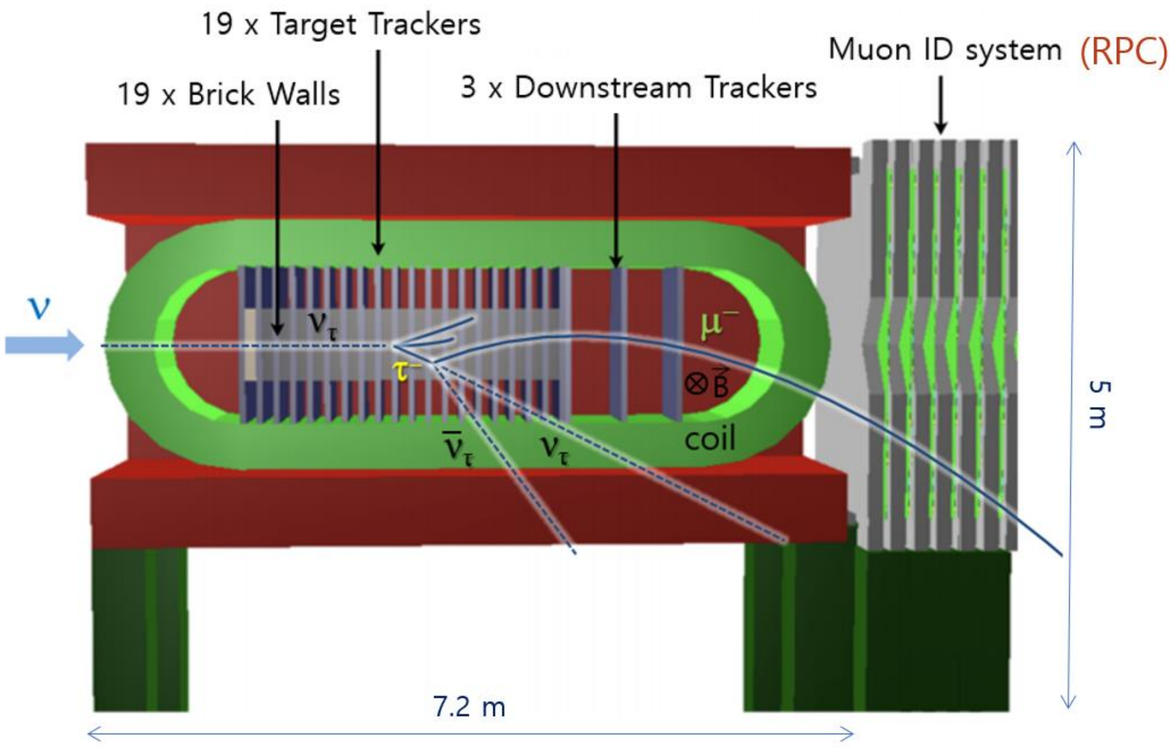
for detection
of Tau neutrinos
& LDM

Scattering and Neutrino Detector (SND)



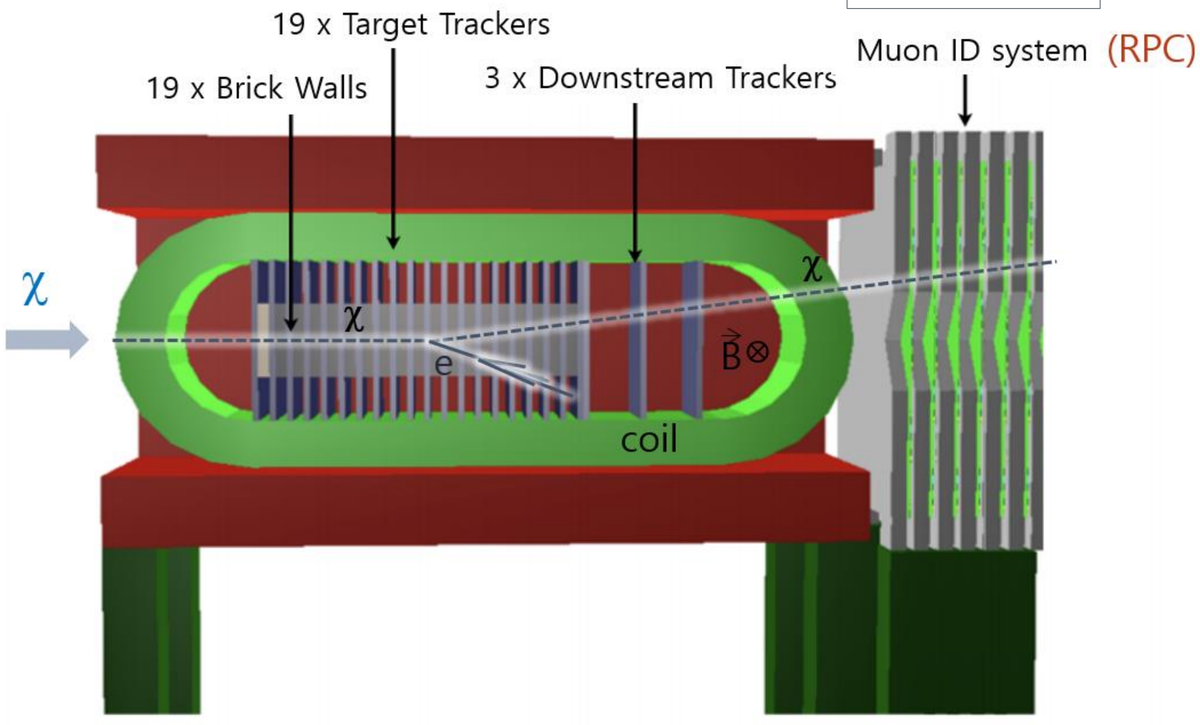
Scattering and Neutrino detector (SND) in SHiP

SHiP



Tau neutrino scattering at SND

SHiP RPC : KODEL



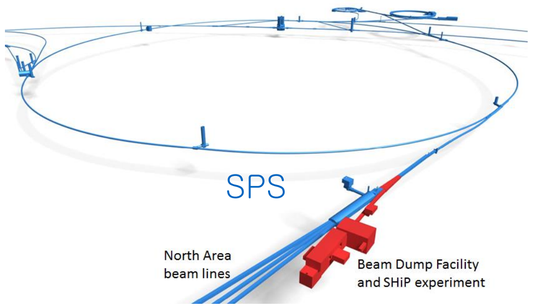
Light dark matter scattering at SND

- Electron recoil due to LDM scattering

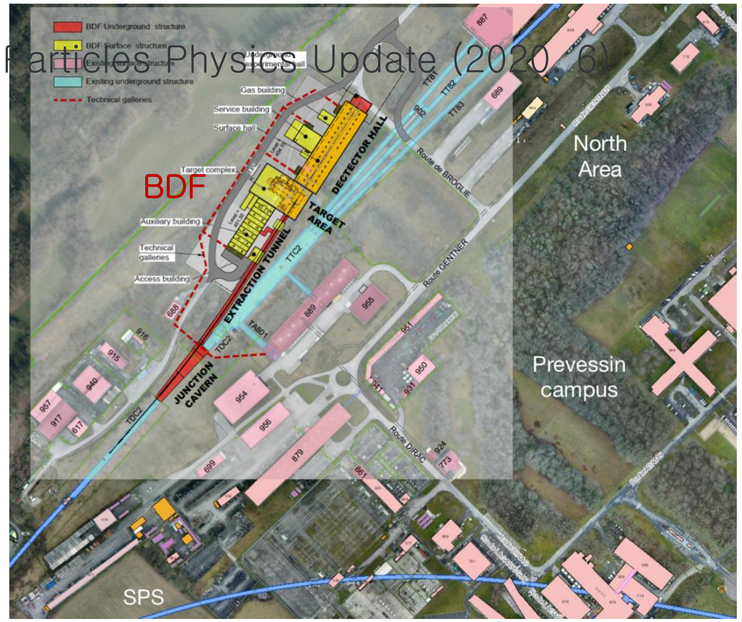
SHiP

Among the proposals for larger-scale new facilities investigated within the Physics Beyond Colliders study, the Beam Dump Facility at the SPS emerged as one of the frontrunners. However, such a project would be difficult to resource within the CERN budget, considering the other recommendations of this Strategy.

– European Strategy of Particles Physics Update (2020, 6)



BDF
(Beam Dump Facility)



SND@LHC

LHC

A precursor for SHiP
approved by CERN on 15 March 2021

Data taking from 2022 (LHC Run 3)

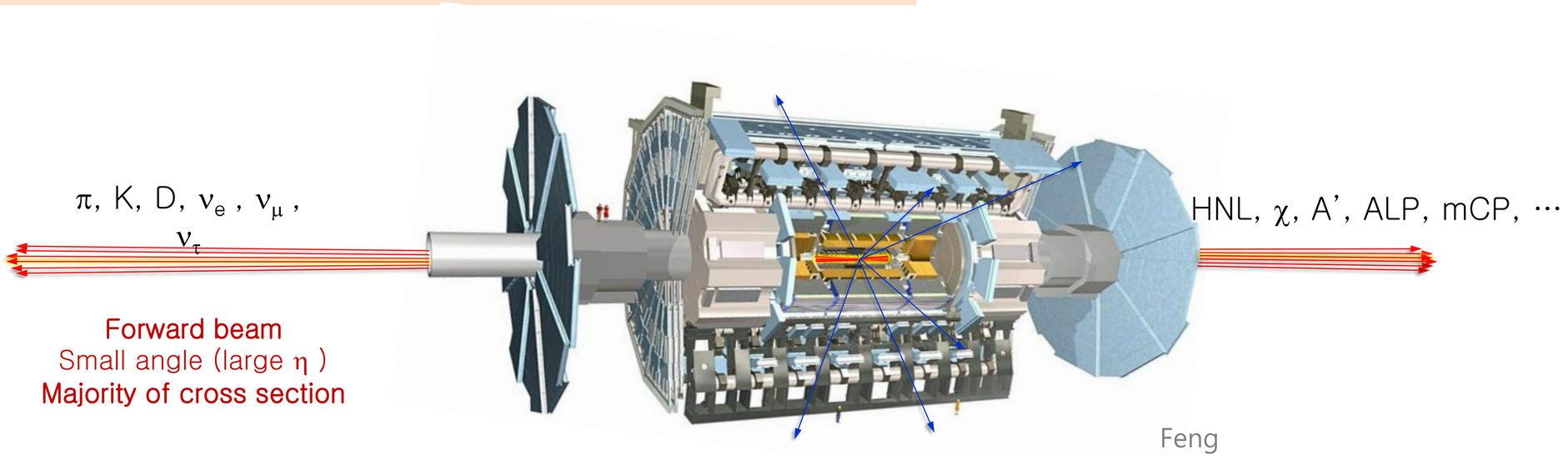
K-SHiP group will forcus the SND@LHC instead of the SHiP.

- They support the future collider (Higgs factory).
- We need to wait for the next ESPPU (more than 5 years).
- But SPSC approved BDF R&D

Physics goal of SND@LHC

- Study of **High energy neutrinos** in unexplored energy region
- Search for **FIPs (Feebly Interacting Particles)**

⇨ See K.Y. Lee's talk in Neutrino session



The LHC focused high P_T / low cross section events **(~ pb, fb)**
Total cross section is **~100 mb**, and most of highest energy are in the **forward region and low P_T.**
→ No detectors in the forward direction (hole in the beam axis)

SND@LHC Collaboration

Members from Asia and Europe

- Corea del Sud
- Giappone
- Turchia
- Bulgaria
- Germania
- Italia
- Portogallo
- Regno Unito, Inghilterra
- Russia, Mosca (Oblast)
- Svizzera
- CERN

20 Institutes
180 members

K-SND group

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Gwangju National University of Education

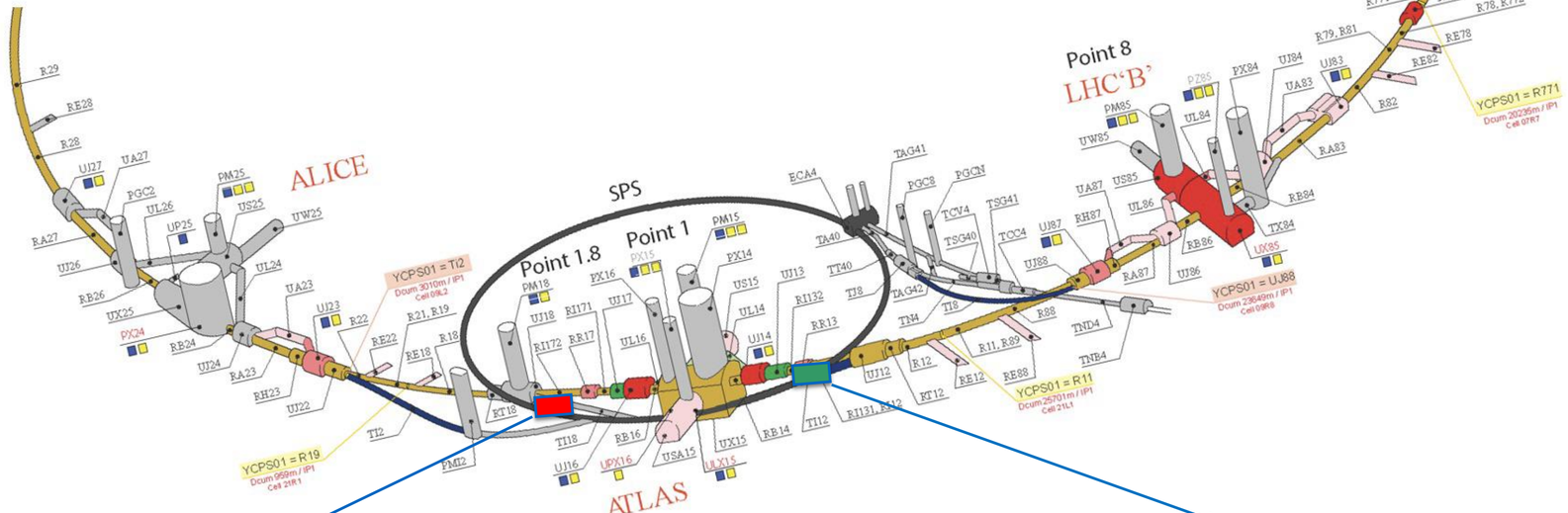
Y. G. Kim

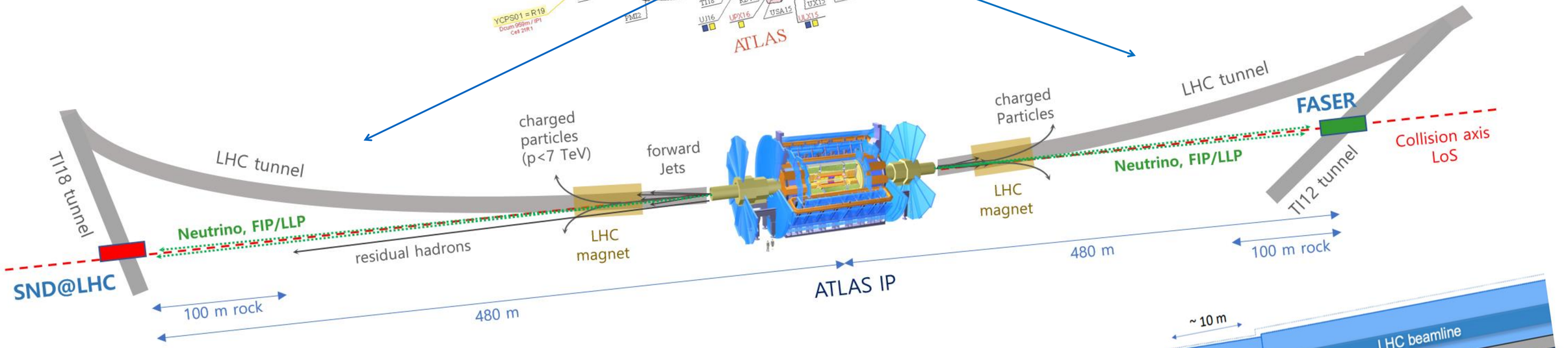
Sungkyunkwan University

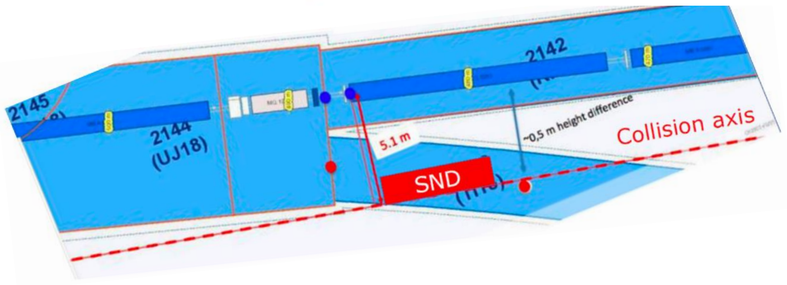
K.-Y. Choi

4 Institutes
8 members

Experimental site at LHC





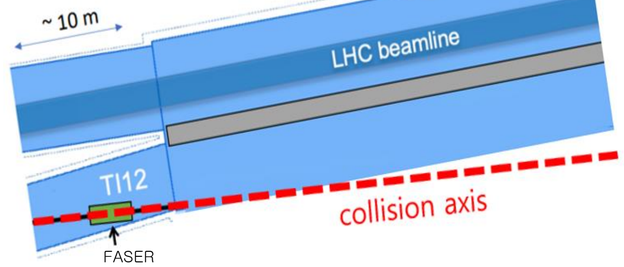


SND@LHC

$7.2 < \eta < 8.7$

FASER

$\eta > 9$



Search for FIPs at SND@LHC

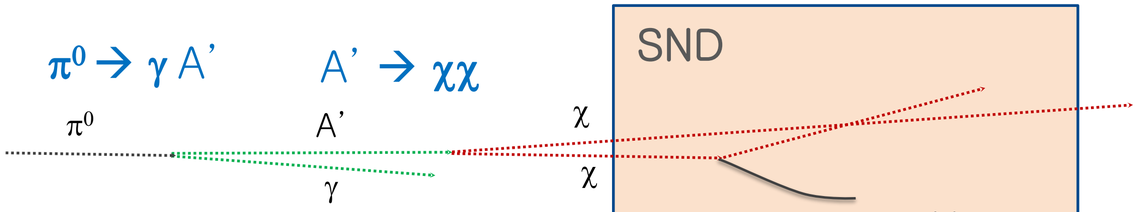
Light dark matter scattering

The LHC is an abundant source for mesons (π^0, η …)

→ Therefore, an abundant source for **dark photons** (A')

→ **Light dark matter** (LDM) can be produced from A' decay

→ We will detect the **recoils from LDM scattering** in the **SND**.



χ e → χ e e−recoil

χ p → χ p p−recoil

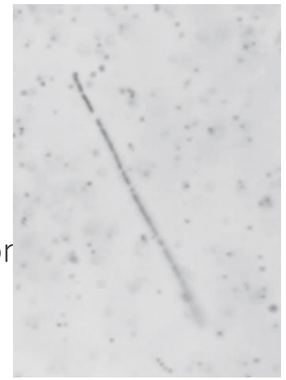
(Leptophobic)

χ N → χ N N−recoil

Samples of recoil tracks in emulsion

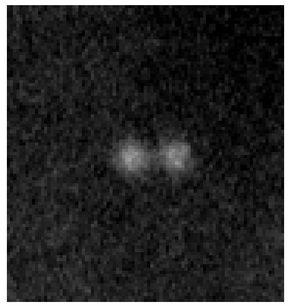
Proton recoil (~500 keV)

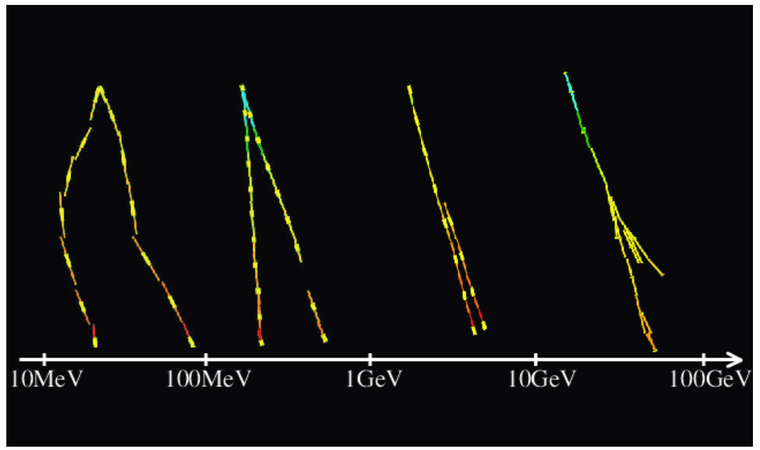
A proton track recoiled by a neutron ~ O(10) μm



Nuclear recoil (~100 keV)

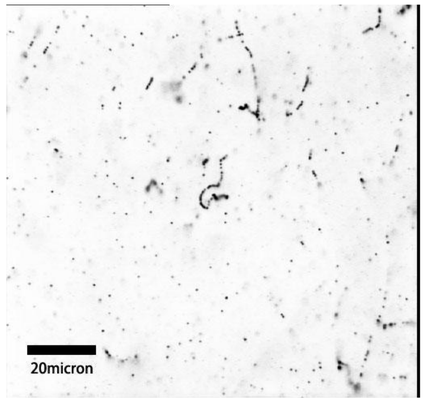
~ O(100) nm NIT (Special emulsion used in NEWSdm)



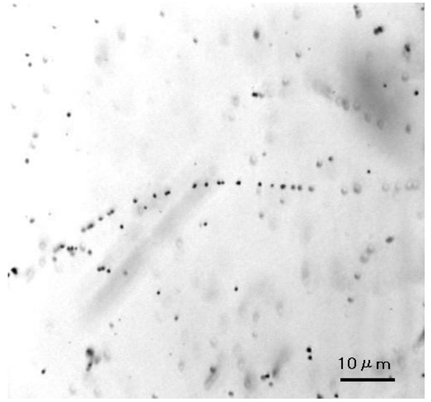


Reconstructed electron tracks in ECC

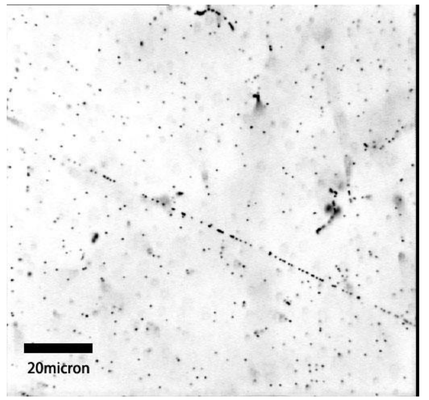
Electron tracks in Nuclear emulsion



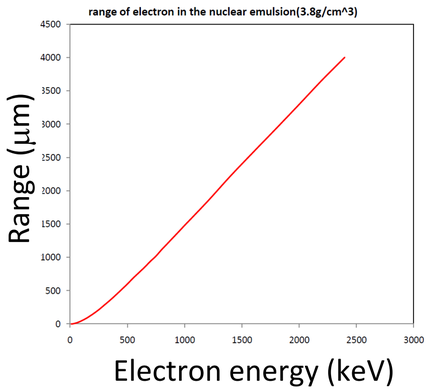
electron ~ 100 keV

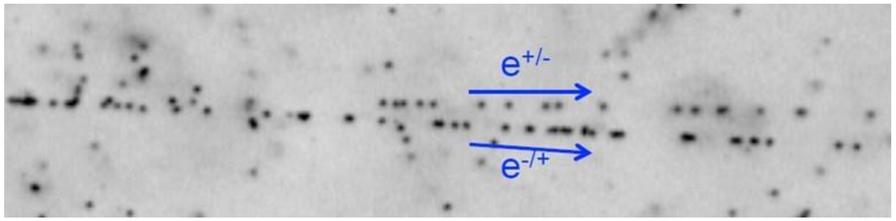


electron ~ 1 MeV



electron > 10MeV





Electron ~10 GeV

Backgrounds of LDM

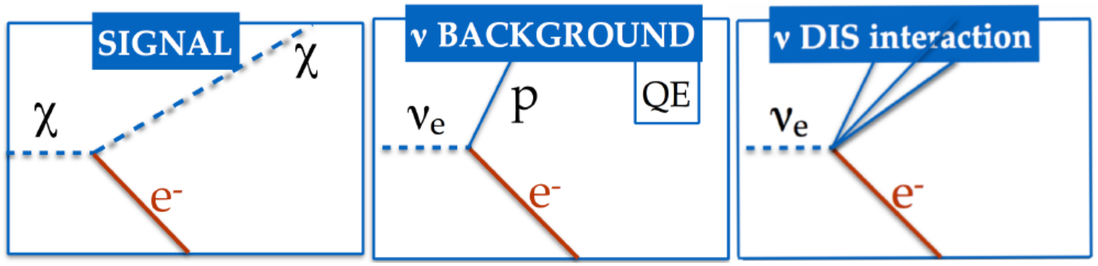
$\chi e \rightarrow \chi e$: Signal

It is difficult to identify the signals event by event.

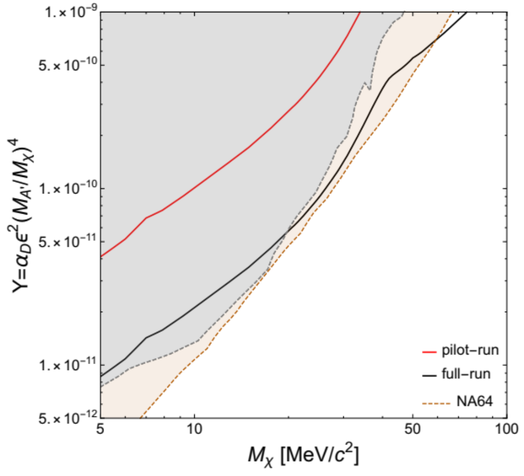
$\nu e \rightarrow \nu e$: Background

- E and θ cut provide effective discrimination.
- DM (ν) scattering events peaked at lower (higher) energy due to light (heavy) mediator.

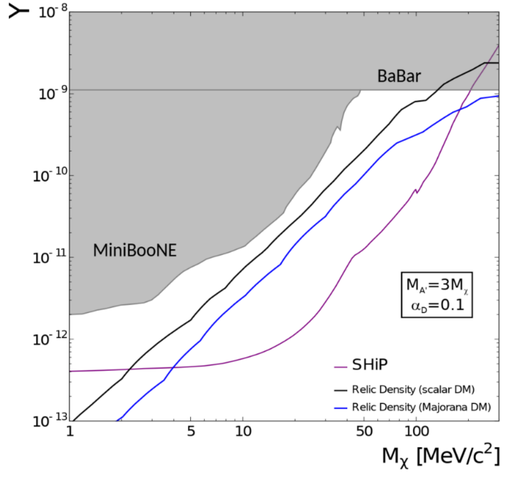
QE, RES, DIS: Cut on additional activity associate with the IP



SND@LHC



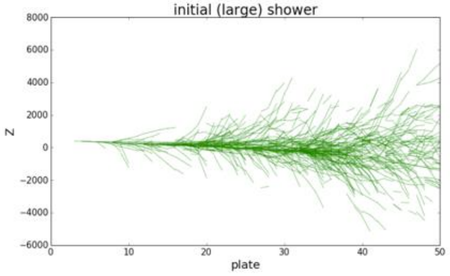
SHiP



SND@LHC exclusion limits for LDM from the decay of dark photon A' assuming $m_{A'}=3m_\chi$ and α_D= 0.1 (90 C.L.).

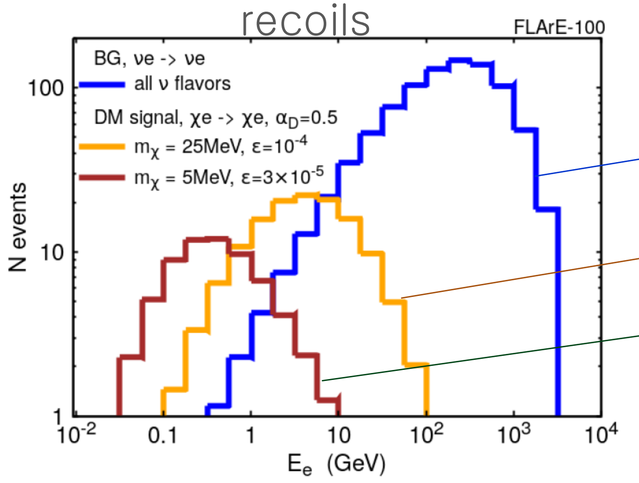
BG rejection

1) Energy–angle correlation
2) Presence of proton rejects Quasi-elastic scattering (QE)
3) Presence of hadron jets rejects Deep inelastic scattering (DIS)



Signal/bkg discrimination currently being studied using Machine Learning

Energies of Electron recoils



$\nu e \rightarrow \nu e$ BG

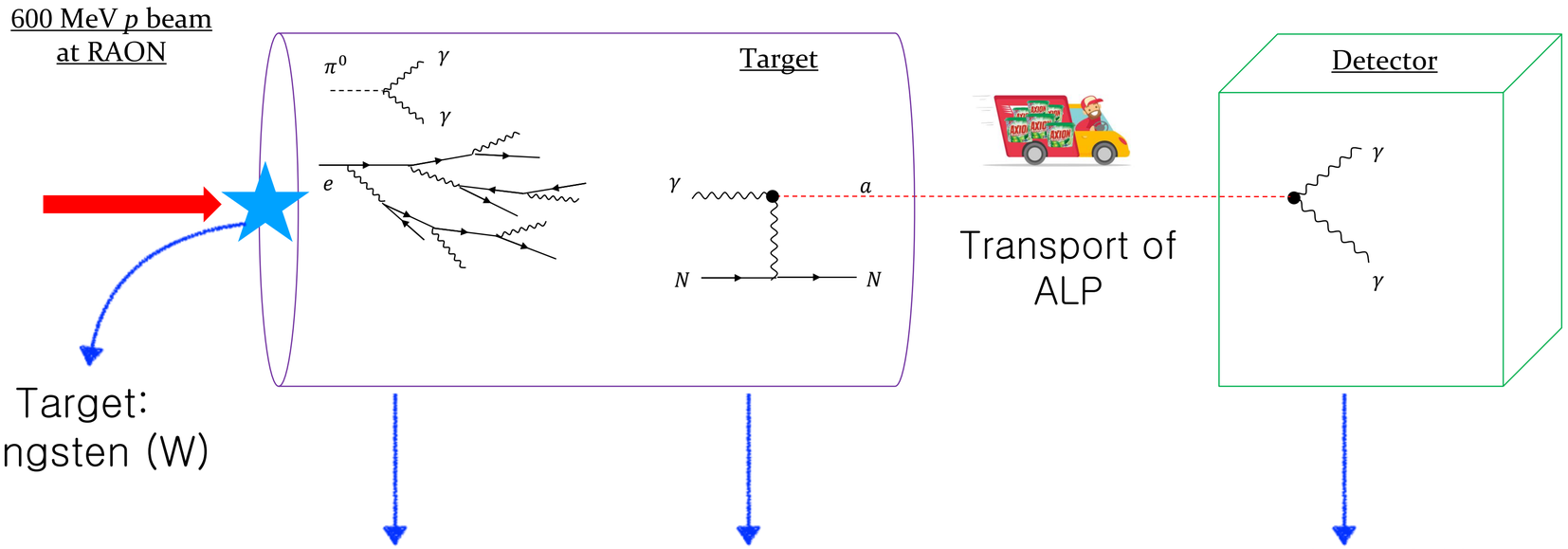
$\chi e \rightarrow \chi e$ (25 MeV)

$\chi e \rightarrow \chi e$ (5 MeV)

LDM

arXiv:2101.10338v2 FPF

DAMSA is a proposal to search for axion-like particles (ALPs) in the low-energy and high intensity proton beam facility at RAON



- Meson decays
- Electromagnetic showers
- etc

$$\frac{d\sigma_P^p}{d\cos\theta} = \frac{1}{4} g_{a\gamma\gamma}^2 \alpha Z^2 F^2(t) \frac{|\vec{p}_a|^4 \sin^2\theta}{t^2}$$

$$t = (p_1 - k_1)^2 = m_a^2 + E_\gamma (E_a - |\vec{p}_a| \cos\theta)$$

Dump produced Aboriginal Matter Searches at an Accelerator

담사: 깊은 생각 潭思

양운기Ex

권영준Ex

류민상Ex

유재훈Ex

공경철Th

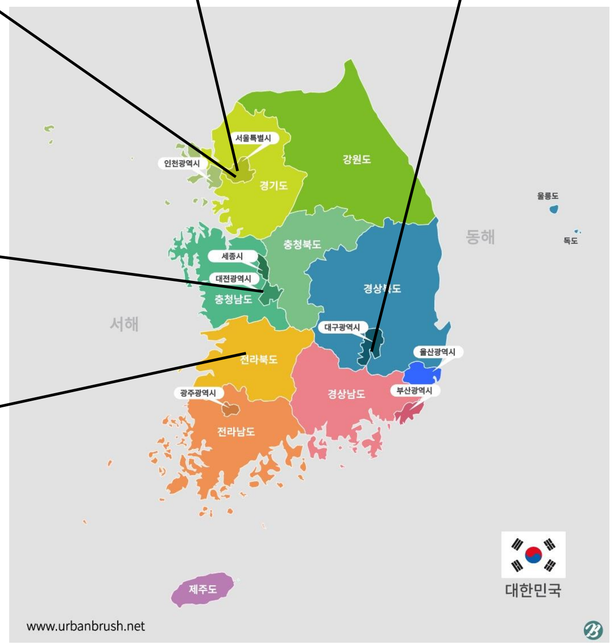
김두진Th

박종철Th

Th

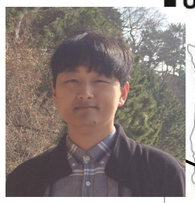
전북대학교 JEONBUK NATIONAL UNIVERSITY

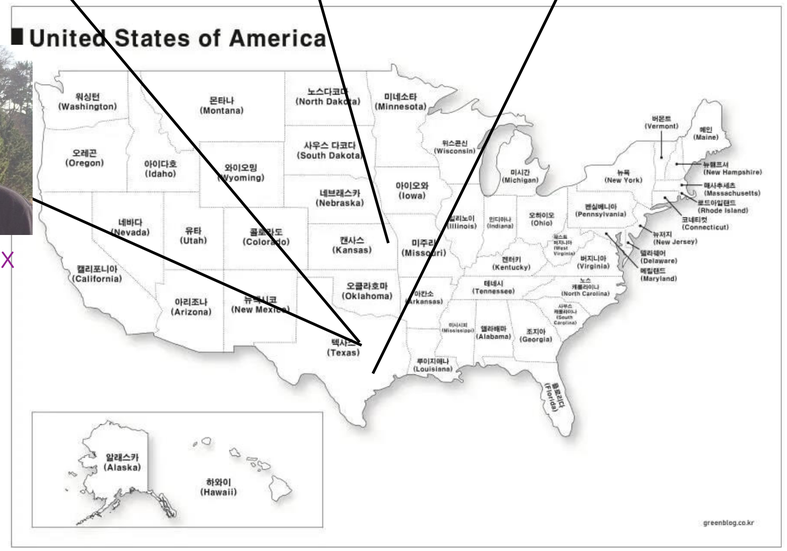
신서동



UNIVERSITY OF TEXAS ARLINGTON

장우영Ex



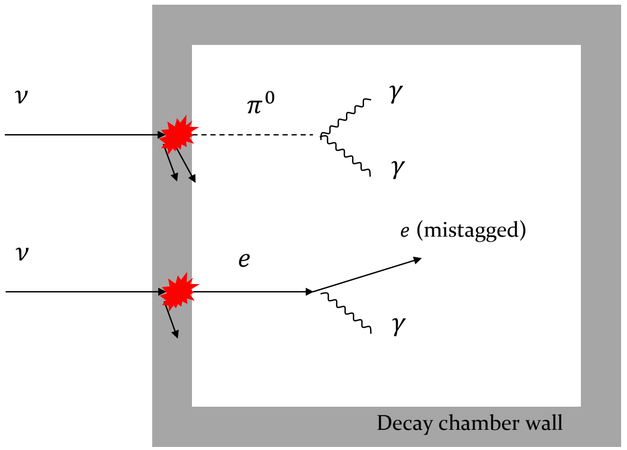


Th: Theorist Ex: Experimentalist

Strong collaboration between Experimenters and Theorists

Background consideration

Neutrino originating

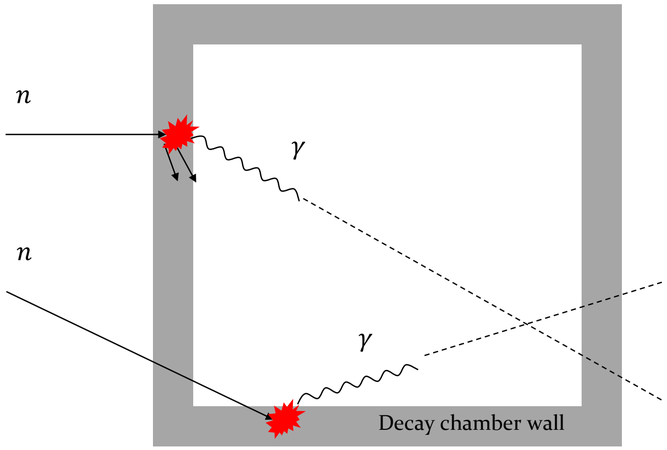


Beam energy is low (at most 600 MeV)

- Suppressed production of charged pions
- Neutrinos from stopped pions and muons, resulting in an isotropic, i.e., dispersed, neutrino flux

→ Negligible

Neutron originating



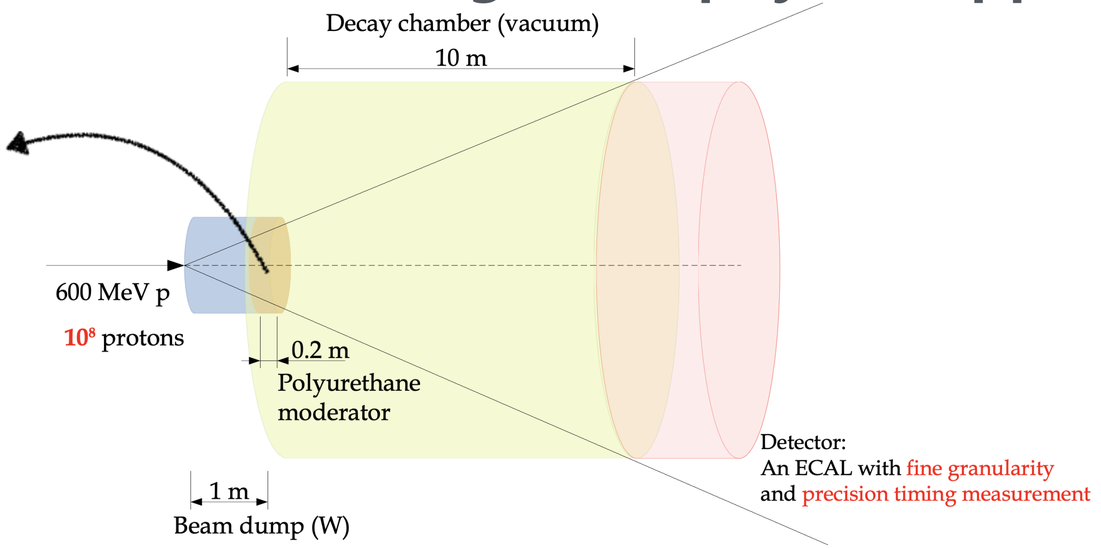
Any two photon tracks can mimic the signal

- Accidentally crossing each other at a point within position/timing resolutions
- Vector sum of their momenta traced back to the target, unlike the signal.
- Random invariant mass

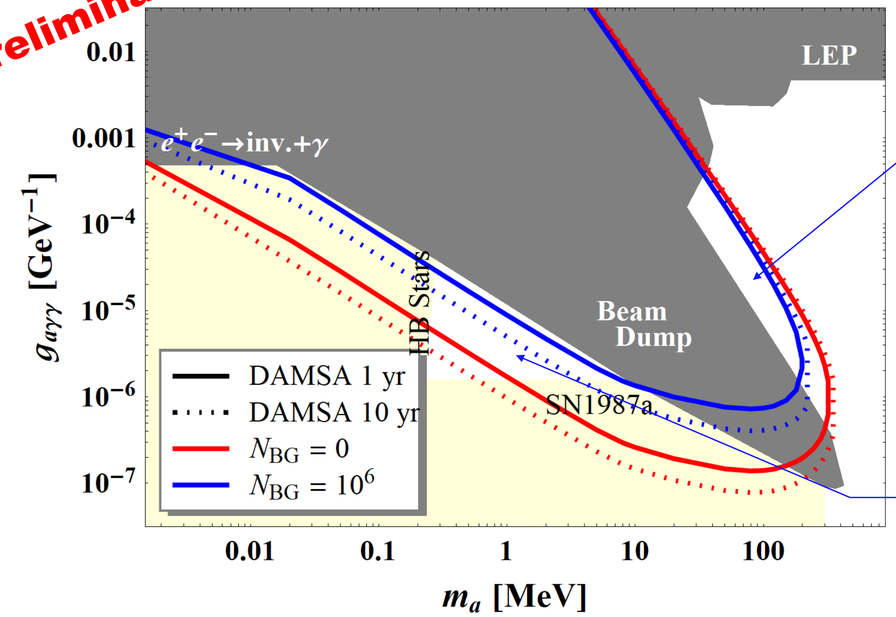
→ Reducible by more than $O(10^{11})$

Conceptual detector design and physics opportunities

Reduces neutron background



Preliminary



DAMSA can probe the ALP parameter region that has never been explored.

DAMSA will cover part of the so-called “cosmological triangle” where only (standard) cosmology would constrain.

Summary and Outlook

- Korean experimental effort in the dark sector has been growing.
- Traditional high resolution detectors are used to identify dark particles in the lab.
- Low threshold calorimetric detectors and position sensitive emulsion detectors are under further improvement.
- A staged approach from small-scale prototyping to a large detector is the key to a success.
- COSINE-200 (ann. modulation), SND@LHC (instead of SHiP, Light dark matter), NEWSdm (directional detection), and DAMSA (ALPs) are forthcoming in near future.
- Challenges include a quality crystal growth (COSINE-200), O(10 nm)-scale position resolution (NEWSdm), and neutron bkg. rejections (DAMSA)