2022 Meeting of the Division of Particles & Fields of the KPS

NaI Experiments

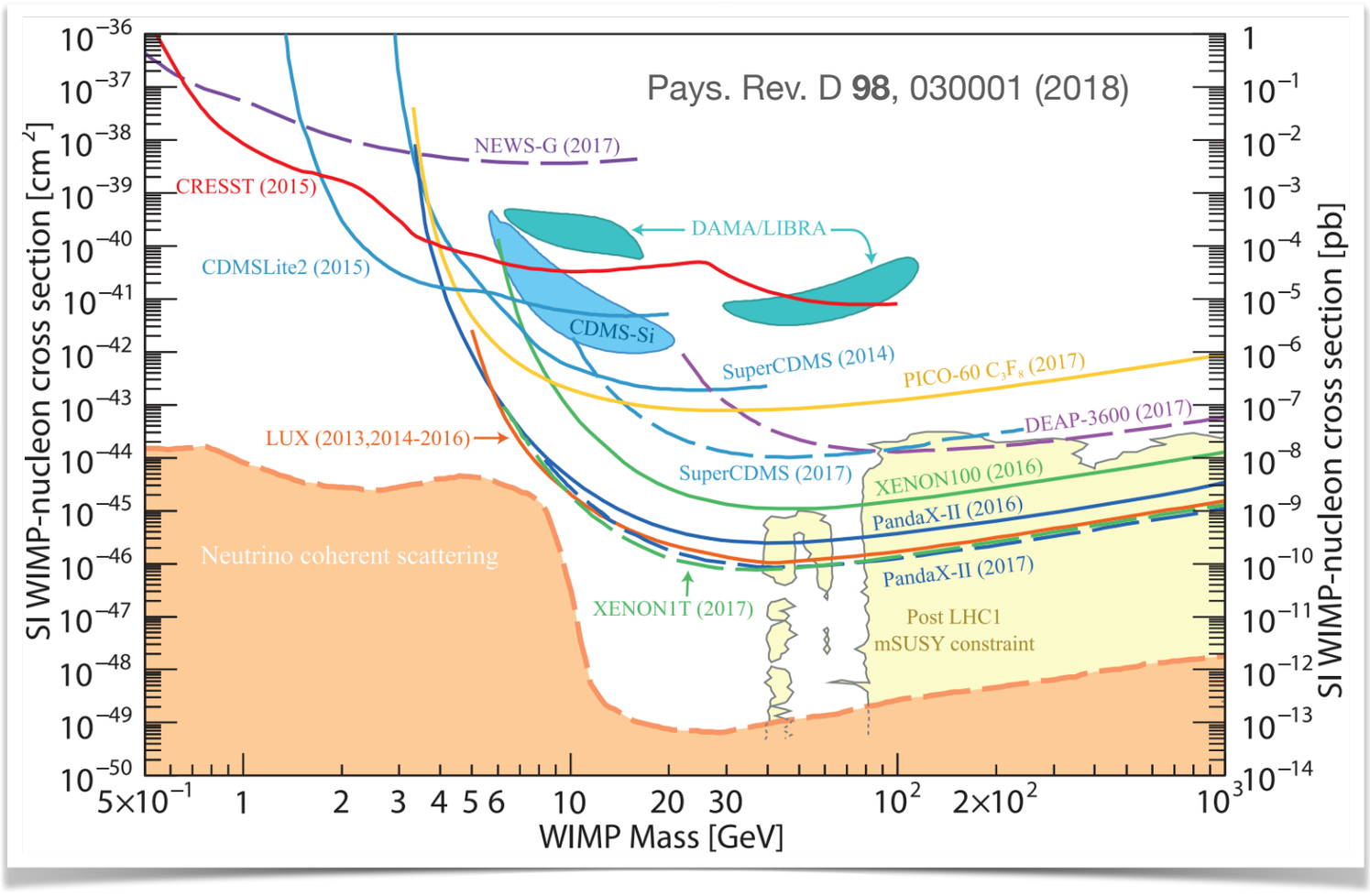
COSINE-100 & NEON

YoungJu Ko
CUP @ IBS
on behalf of the COSINE/NEON Collaboration
Dec. 17, 2022

Introduction to COSINE-100

DAMA/LIBRA Experiment

- No experiment to succeed the direct detection of DM, except DAMA/LIBRA



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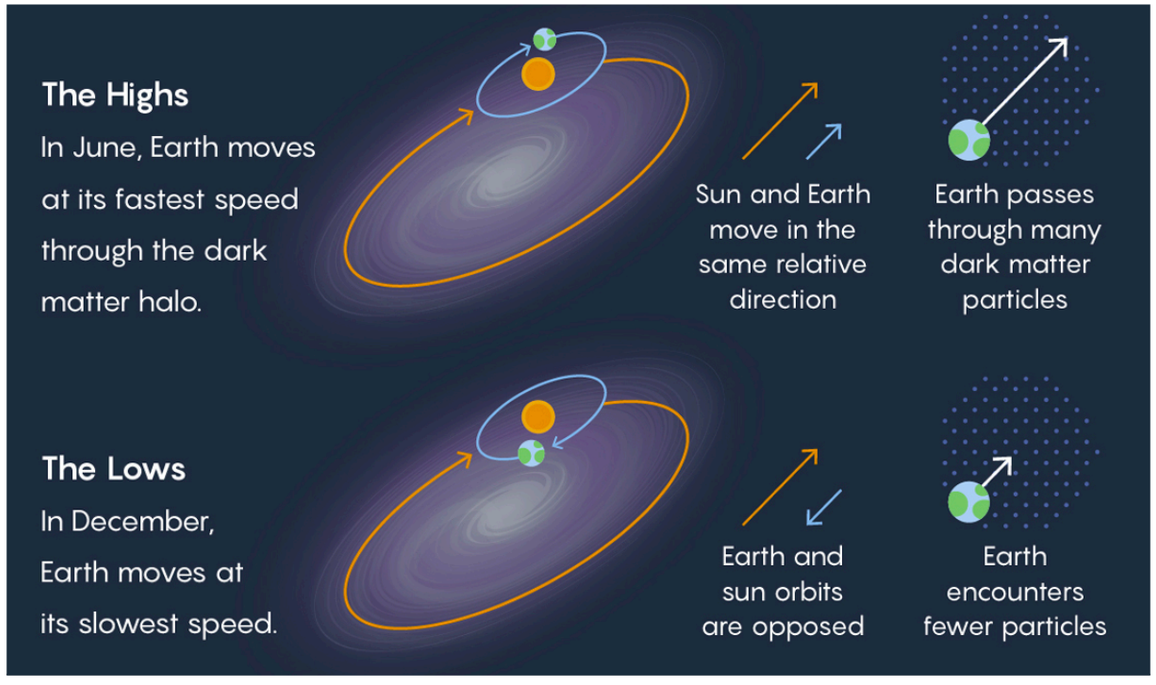
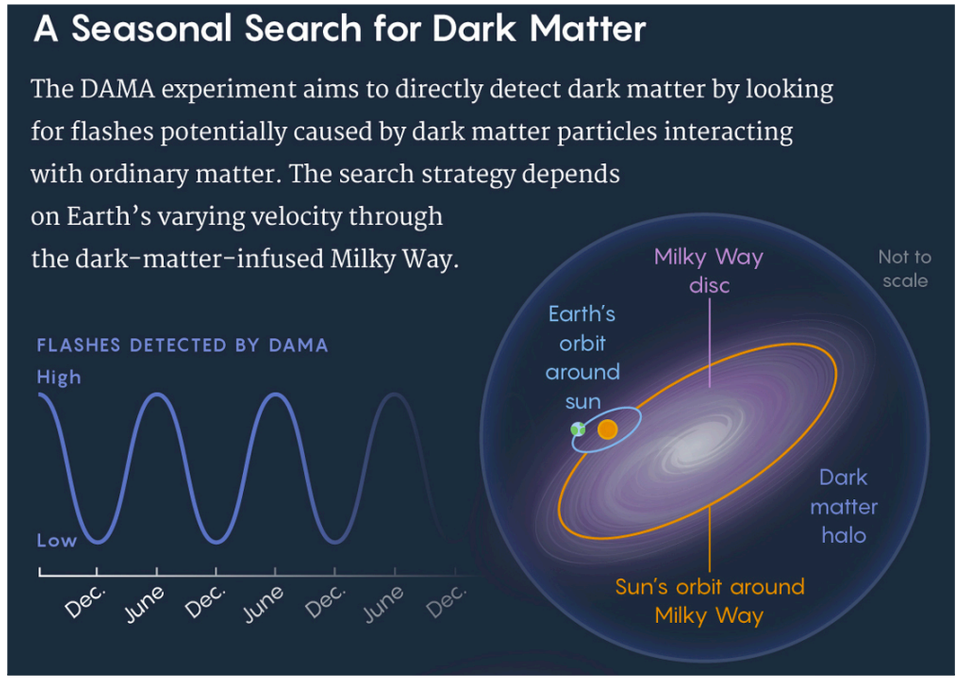


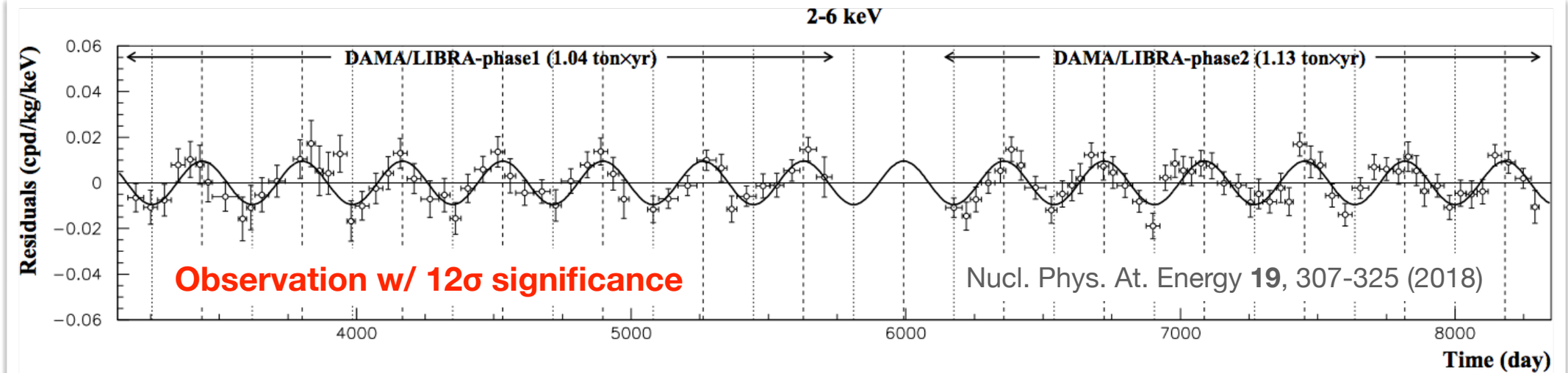


Introduction to COSINE-100

DAMA/LIBRA Experiment

- No experiment to succeed the direct detection of DM, except DAMA/LIBRA
- DAMA/LIBRA experiment
  - Search for annual modulation signature by DM
  - DM observation at 12σ C.L (2-6 keV, 2.17-ton·yr)
  - Compatible with the nature of DM candidates

    ($A = 0.0096 \pm 0.0008$ counts/day/kg/keV, $\varphi = 145 \pm 5$ days, $T = 0.9987 \pm 0.0008$ yr)

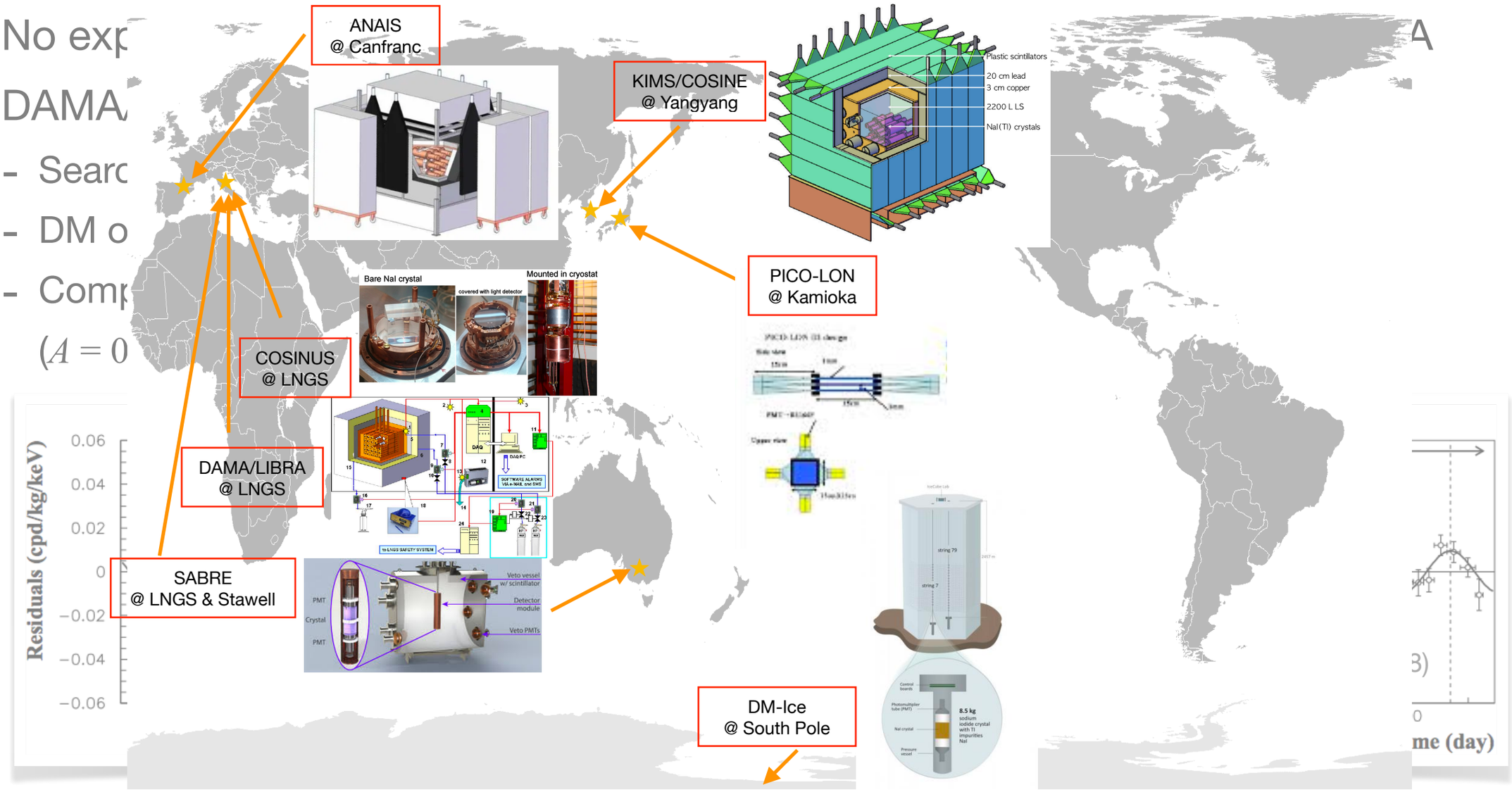


Introduction to COSINE-100

DAMA/LIBRA Experiment

- No exp
- DAMA
  - Searc
  - DM o
  - Comp

  $(A = 0$



- Only observed in DAMA/LIBRA
  - NaI(Tl) crystal is special for DM interaction?
  - Many efforts to test DAMA/LIBRA's signal, using NaI(Tl) crystal.

Introduction to COSINE-100

COSINE-100 Collaboration

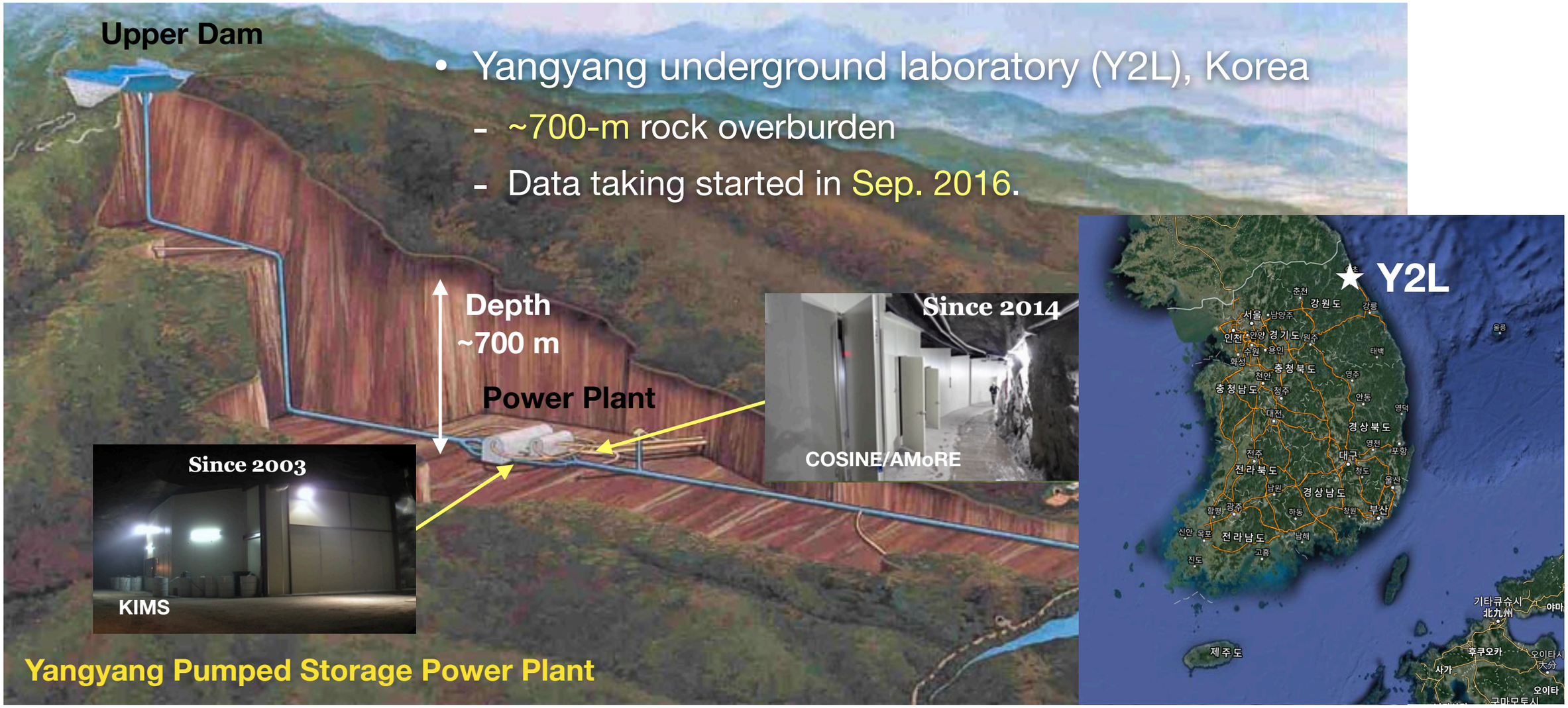
- DM-Ice and KIMS joint effort to search for DM interactions
  - ~50 collaborators in 17 institutes
  - To verify the DAMA/LIBRA's claim via the same target material

DM-ICE + KIMS Korea Invisible Mass Search Experiment = COSINE

Introduction to COSINE-100

COSINE-100 Collaboration & Experimental Site

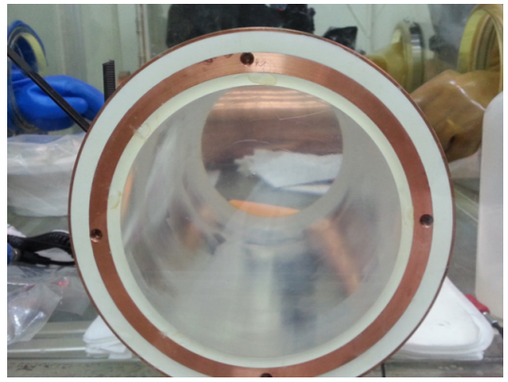
- DM-Ice and KIMS joint effort to search for DM interactions
  - ~50 collaborators in 17 institutes
  - To verify the DAMA/LIBRA's claim via the same target material

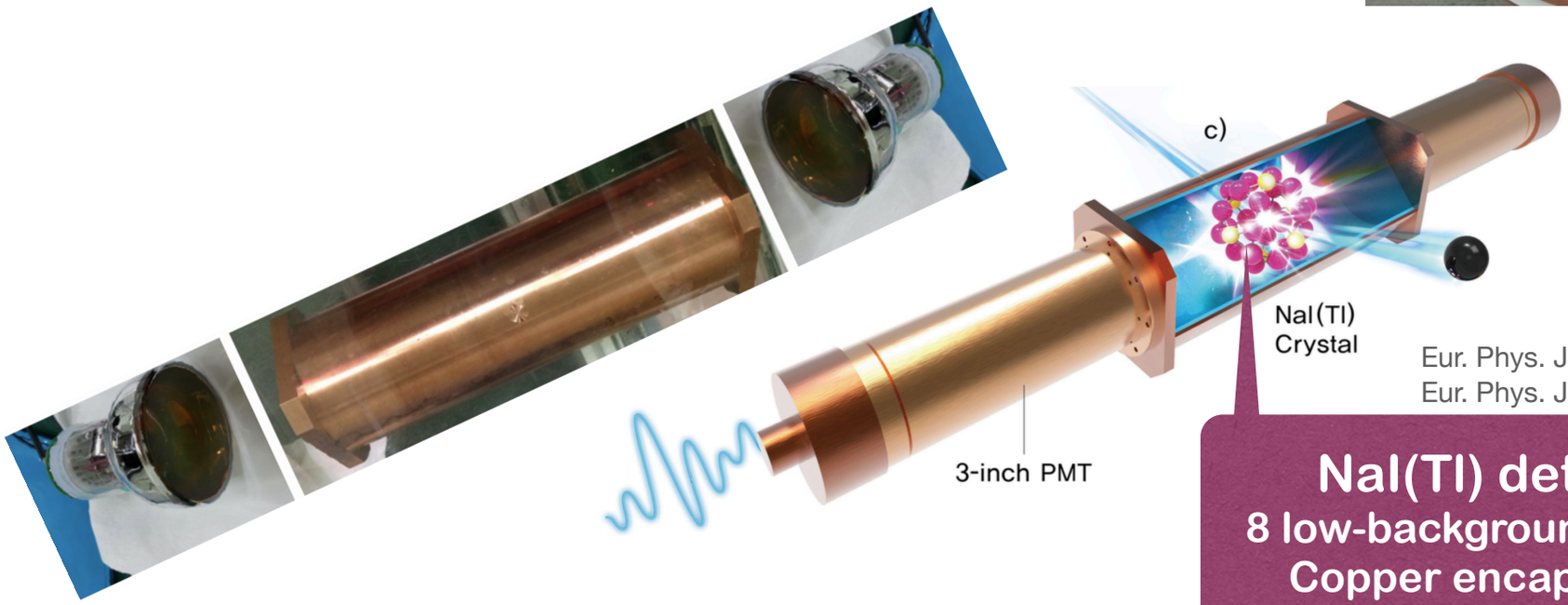


COSINE-100 Detector

Detector Configuration

- 8 low-background NaI(Tl) crystals w/ 106 kg in total
  - U/Th/K levels are less than DAMA, but total α (~^{210}Pb) are higher than DAMA
  - Total background: 2-3 times that of DAMA
  - Higher light yield (15 p.e/keV) than DAMA (5-10 p.e/keV)
- Crystal encapsulation (copper)
- Two 3” PMTs (R12669SEL) for each crystal





Eur. Phys. J. C **78**, 107 (2018)
Eur. Phys. J. C **78**, 490 (2018)

NaI(Tl) detector
8 low-background crystals
Copper encapsulation
Two 3” PMTs

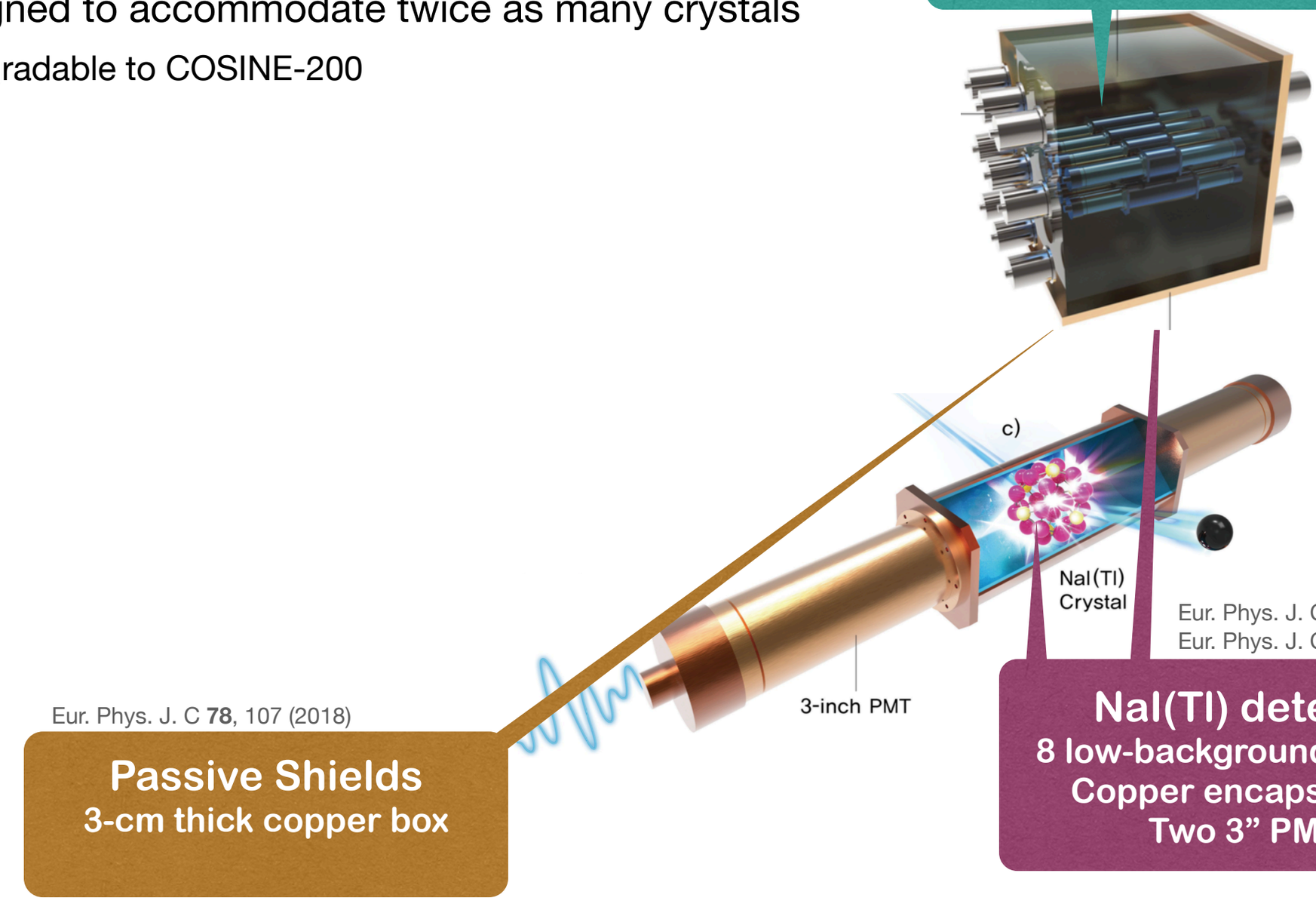
COSINE-100 Detector

Detector Configuration

- Liquid scintillator (LS) as an active veto
  - 2200-L LAB-based LS & 5” PMTs (R877)
  - Designed to accommodate twice as many crystals
    - Upgradable to COSINE-200

Nucl. Instrum. Meth. A **851**, 103 (2017)
Nucl. Instrum. Meth. A **106**, 165431 (2021)

Liquid Scintillator
2200-L LAB-based LS for veto
5” PMTs for LS detector



Eur. Phys. J. C **78**, 107 (2018)
Eur. Phys. J. C **78**, 490 (2018)

NaI(Tl) detector
8 low-background crystals
Copper encapsulation
Two 3” PMTs

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

Passive Shields
3-cm thick copper box

COSINE-100 Detector

Detector Configuration

JINST **13**, T02007 (2018), JCAP **02**, 013 (2021)

4π Muon Counter
37 plastic scintillator panels
2” PMTs (H7195) for muon counter

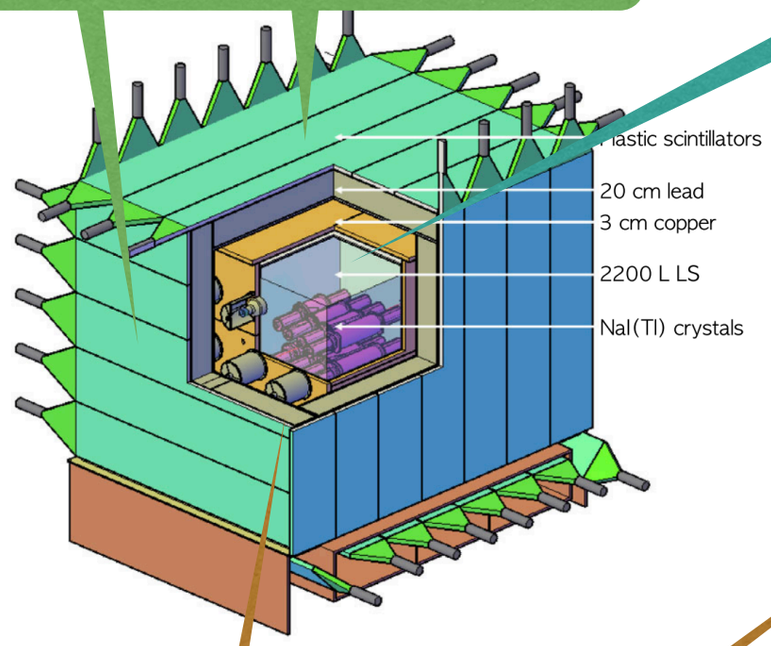
Nucl. Instrum. Meth. A **851**, 103 (2017)
Nucl. Instrum. Meth. A **106**, 165431 (2021)

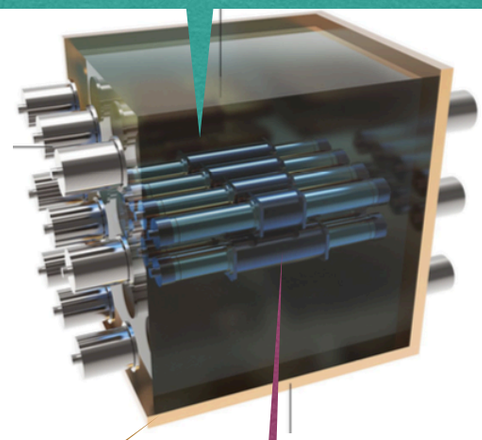
Liquid Scintillator
2200-L LAB-based LS for veto
5” PMTs for LS detector

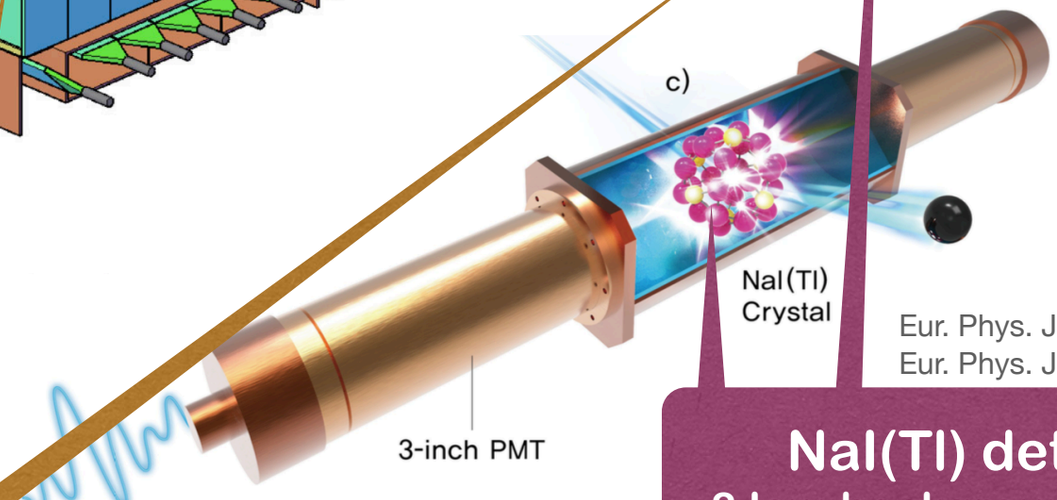
JINST **13**, T06005 (2018)

Neutron Monitoring
Fast neutron detector
(Liquid scintillator)

Thermal neutron detector
(^{3}He gas detector)







Eur. Phys. J. C **78**, 107 (2018)
Eur. Phys. J. C **78**, 490 (2018)

NaI(TI) detector
8 low-background crystals
Copper encapsulation
Two 3” PMTs

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

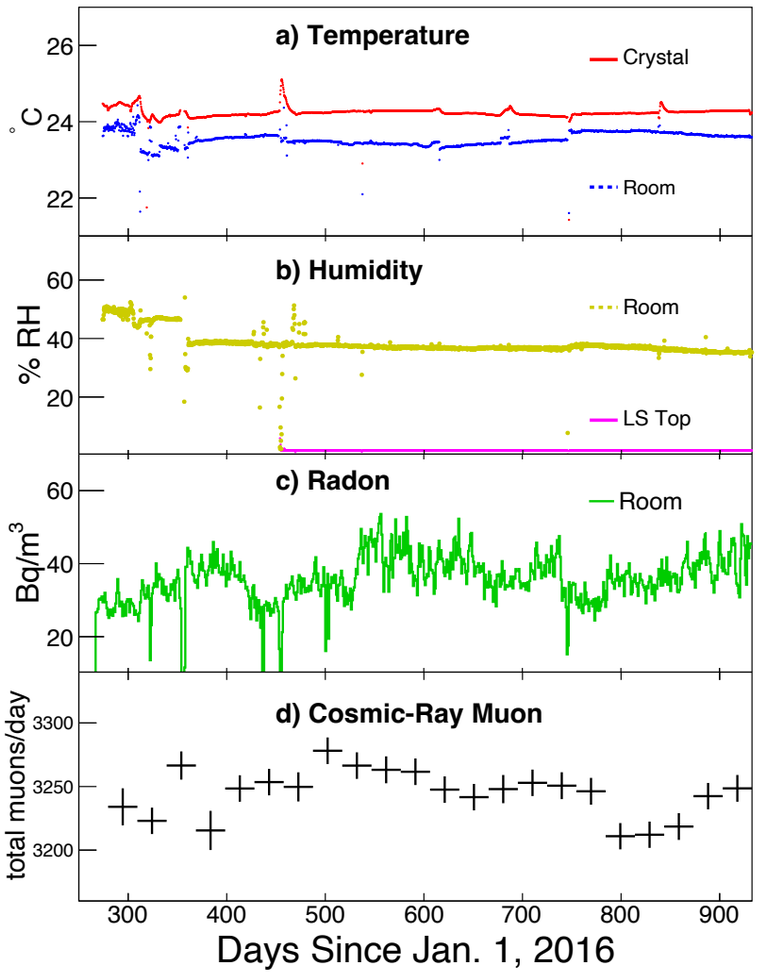
Passive Shields
3-cm thick copper box
20-cm thick lead shielding

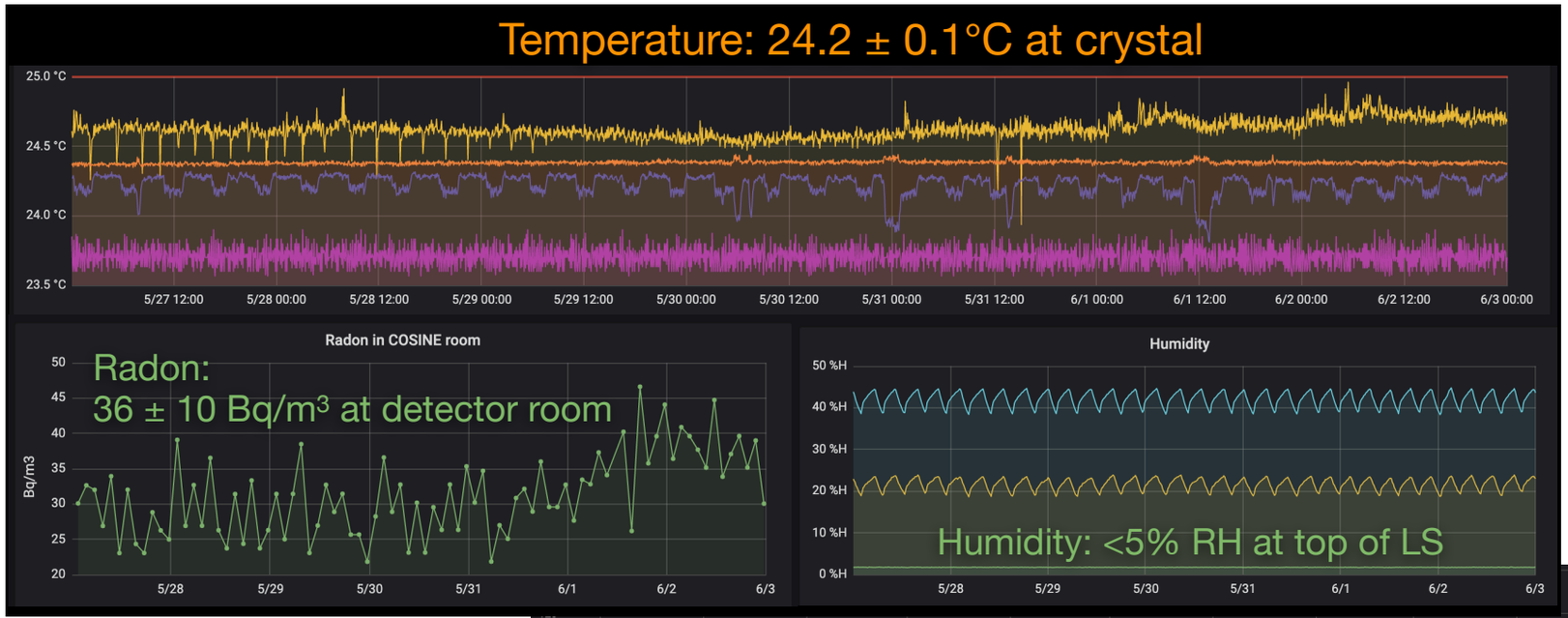
COSINE-100 Detector

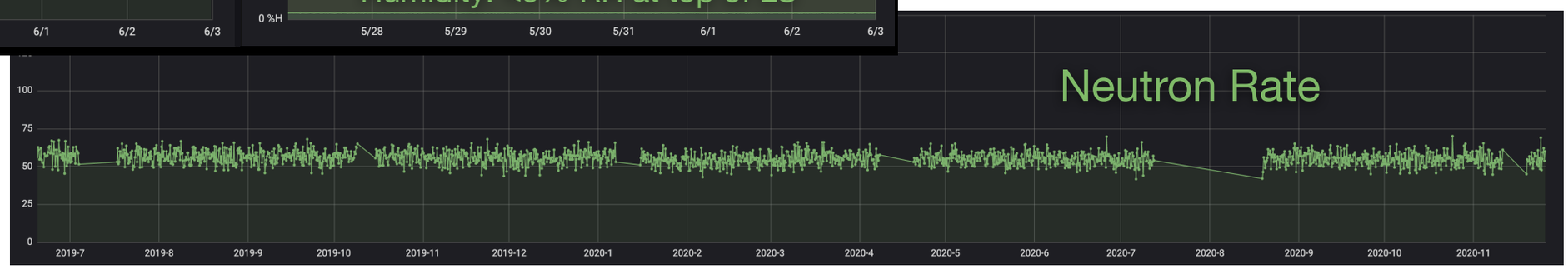
Monitoring

- Monitoring system (> 200 parameters)
  - DAQ system: trigger rate, electronics status
  - Stable environmental parameters
  - Monitoring for neutron rates

Phys. Rev. Lett. 123, 031302 (2019)



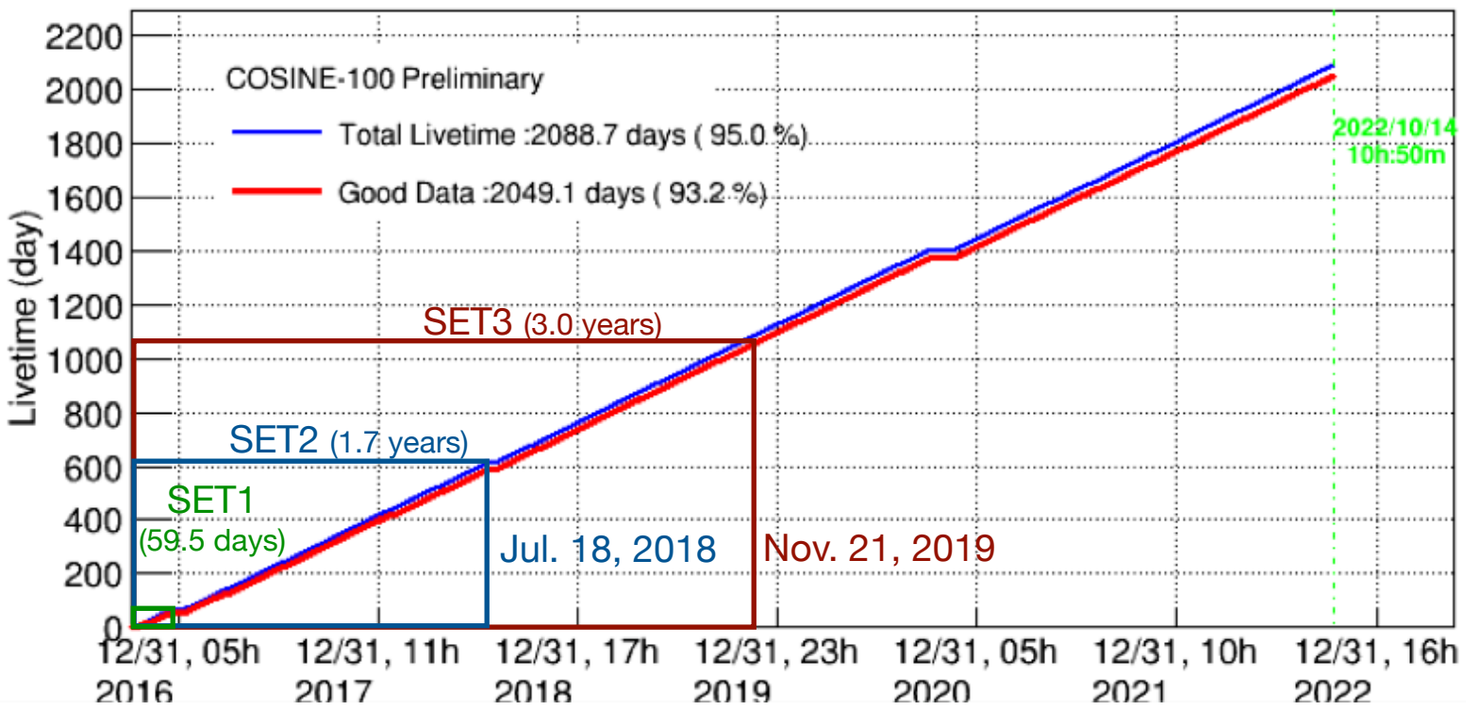




COSINE-100 Detector

Monitoring & Operation

- Monitoring system (> 200 parameters)
  - DAQ system: trigger rate, electronics status
  - Stable environmental parameters
  - Monitoring for neutron rates
- Stable running from Sep. 30, 2016 (5.6 years)
  - DAQ efficiency ~93% (calibration runs, power outage)
  - Exposure time: ~2100 days



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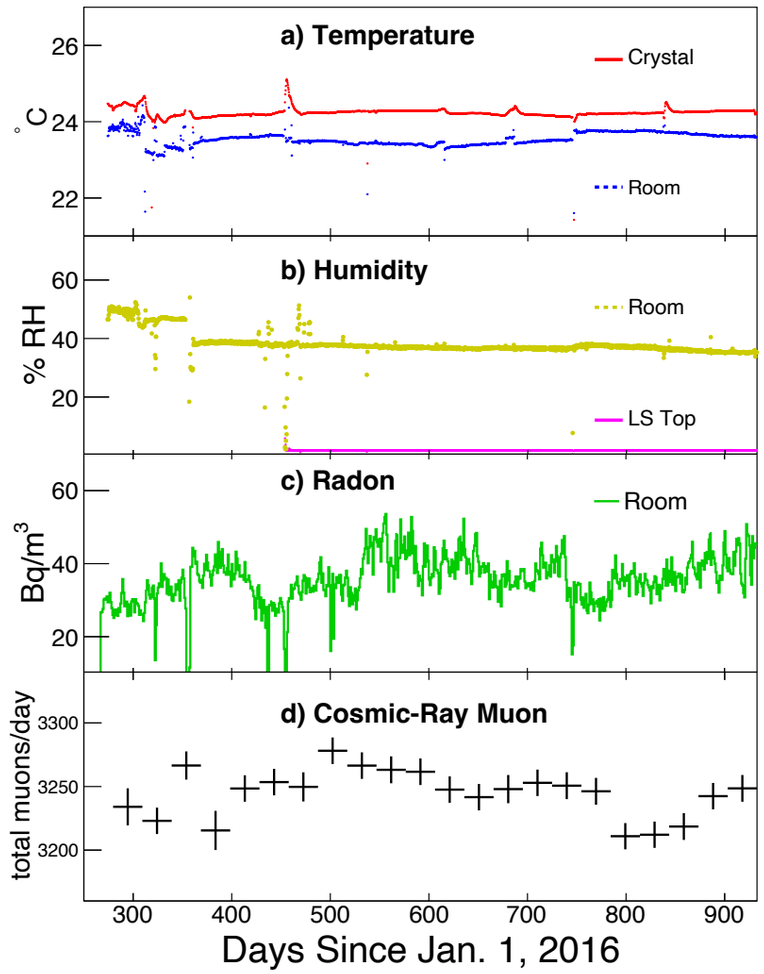
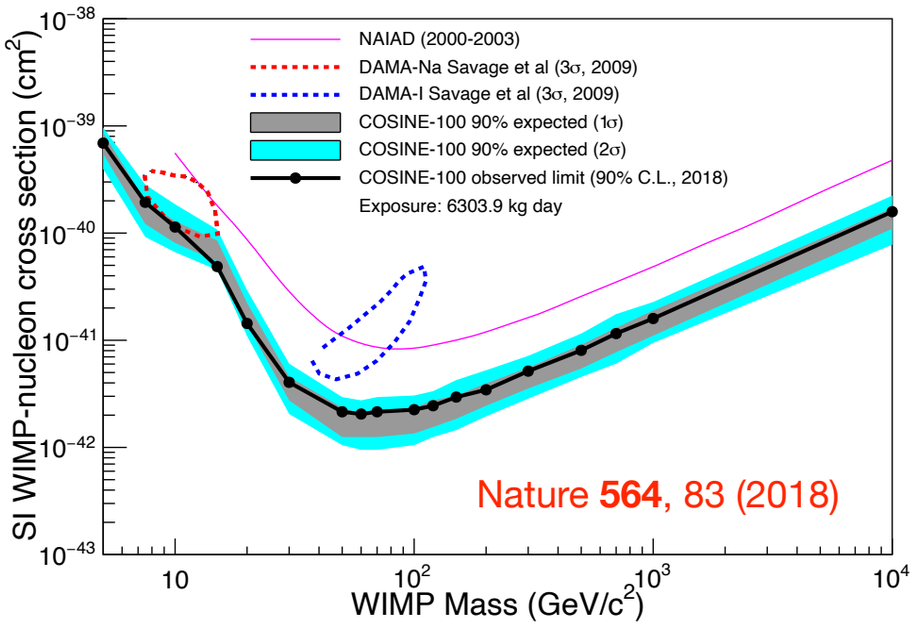


DM Search

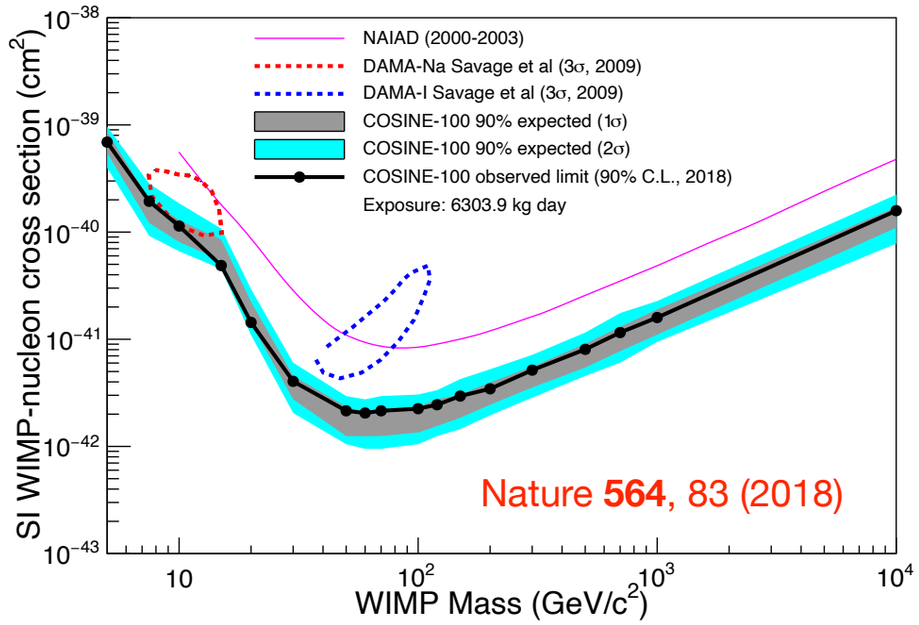
WIMP Extraction Analysis

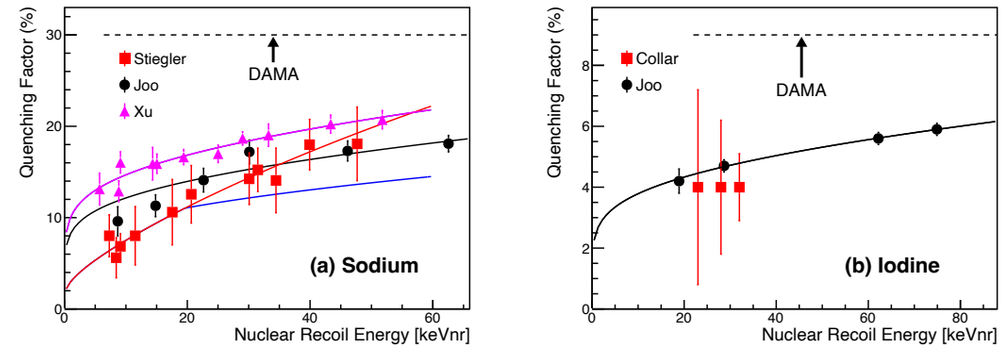


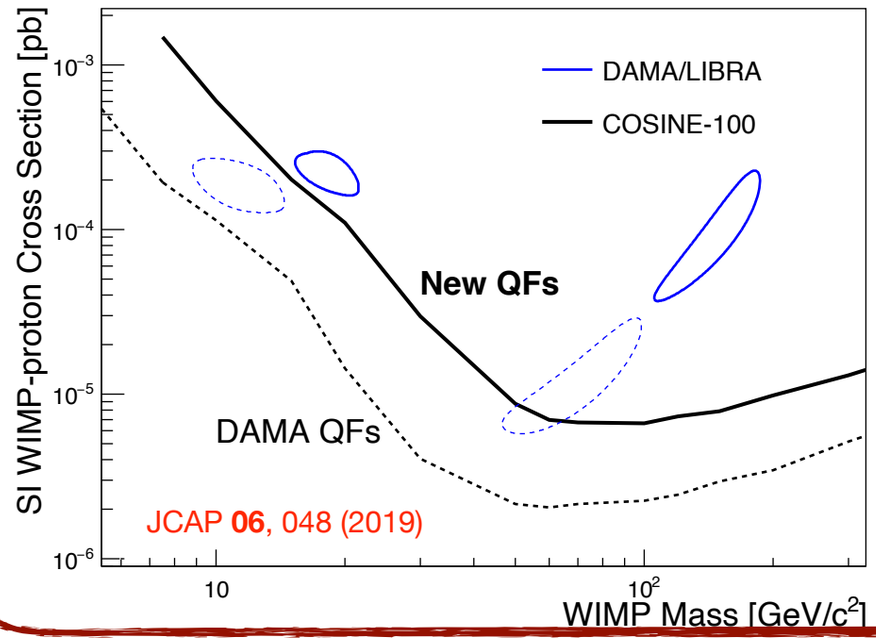
- SET1 data (59.5 days)
  - Spin Independent (SI) WIMP
  - Standard Halo Model (SHM)
  - Excluding region allowed by DAMA/LIBRA

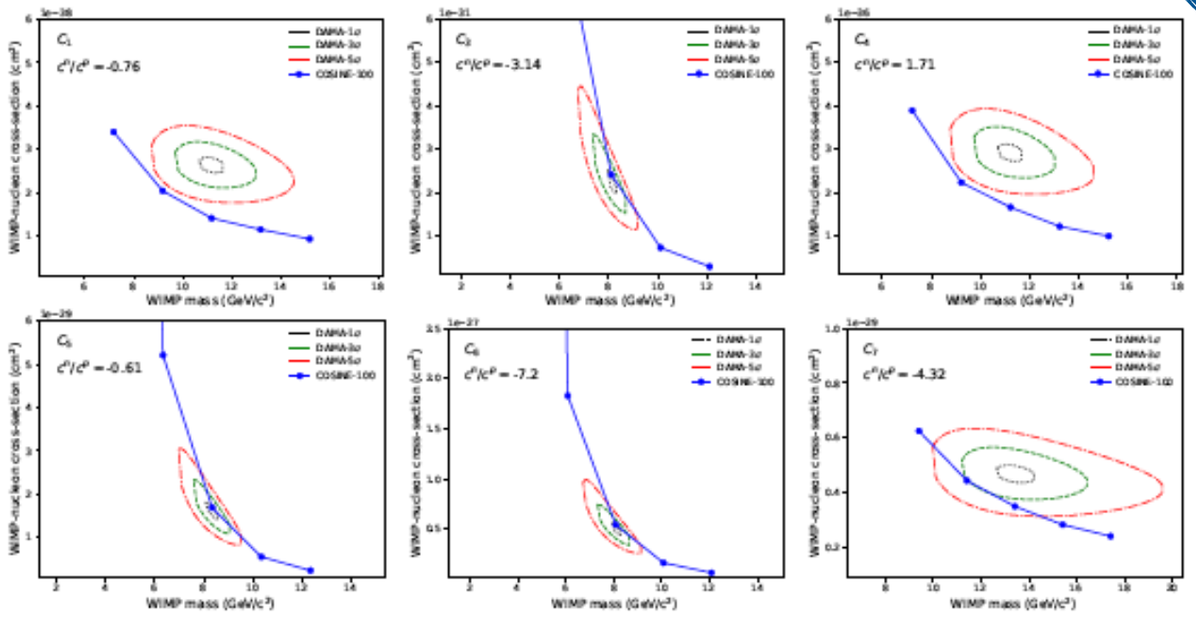
DM Search

WIMP Extraction Analysis







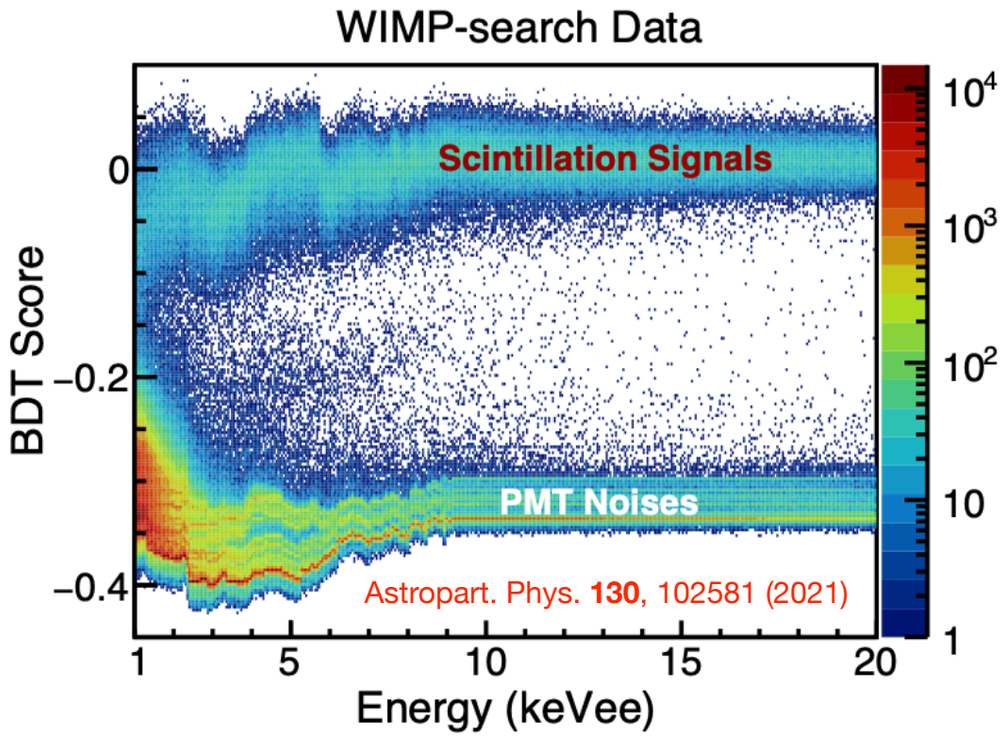


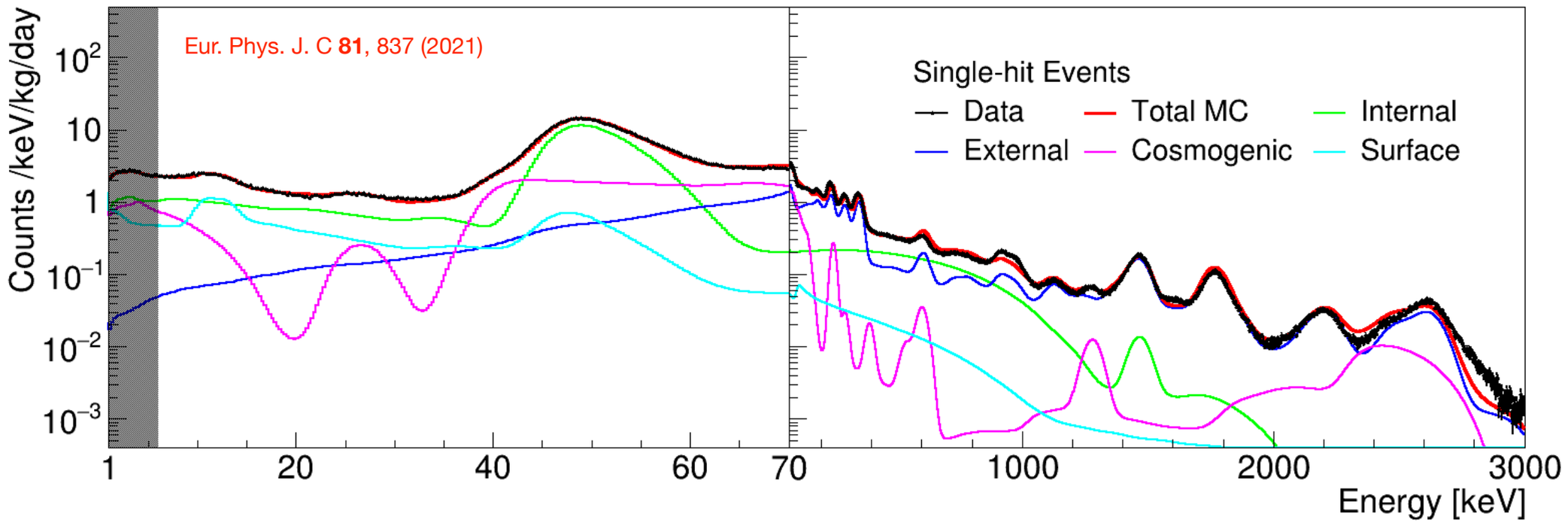
- Various models & quenching factor
  - SI & SD WIMP assuming different QF
  - Effective field theory (EFT) operators
    → Cannot exclude DAMA/LIBRA

DM Search

WIMP Extraction Analysis

- SET2 data (1.7 years)
  - Improvements
    - Analysis threshold (2 keV → 1 keV)
    - Background modeling



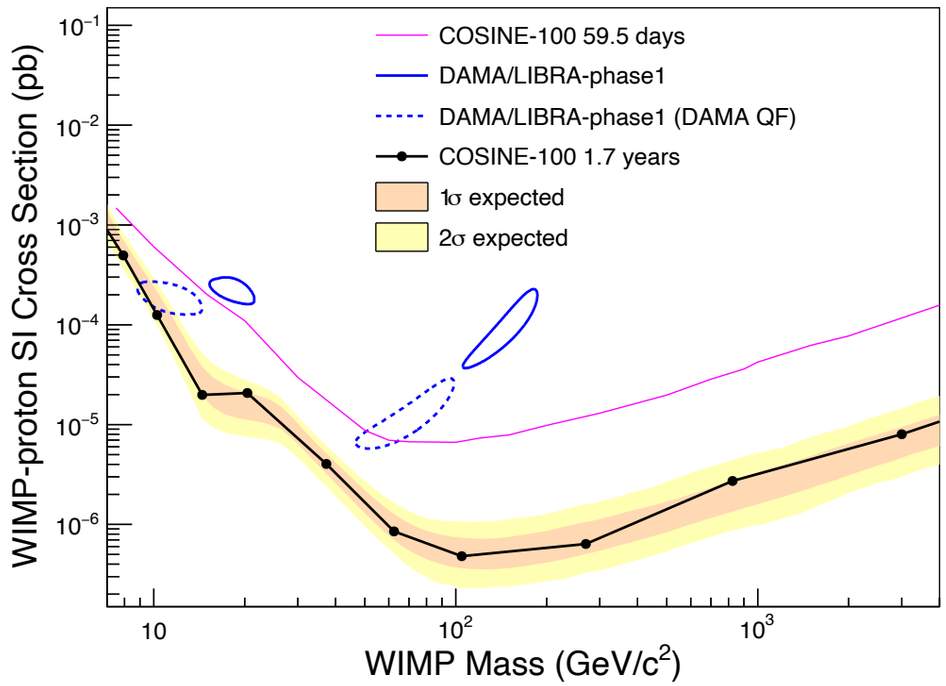


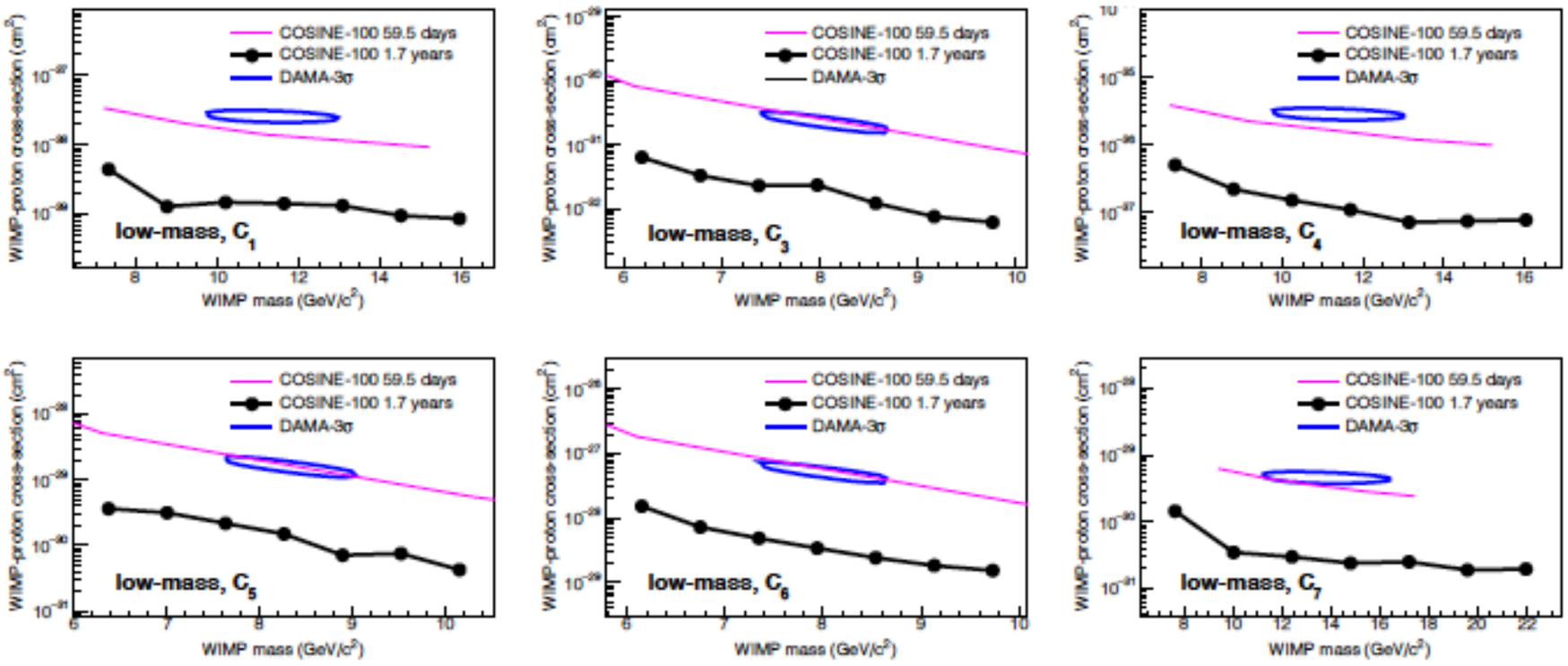
DM Search

WIMP Extraction Analysis

- SET2 data (1.7 years)
  - Improvements
    - Analysis threshold (2 keV → 1 keV)
    - Background modeling
  - Fully cover the alternative scenarios
    - Different QF & EFT operators

Sci. Adv. **7**, eabk2699 (2021)



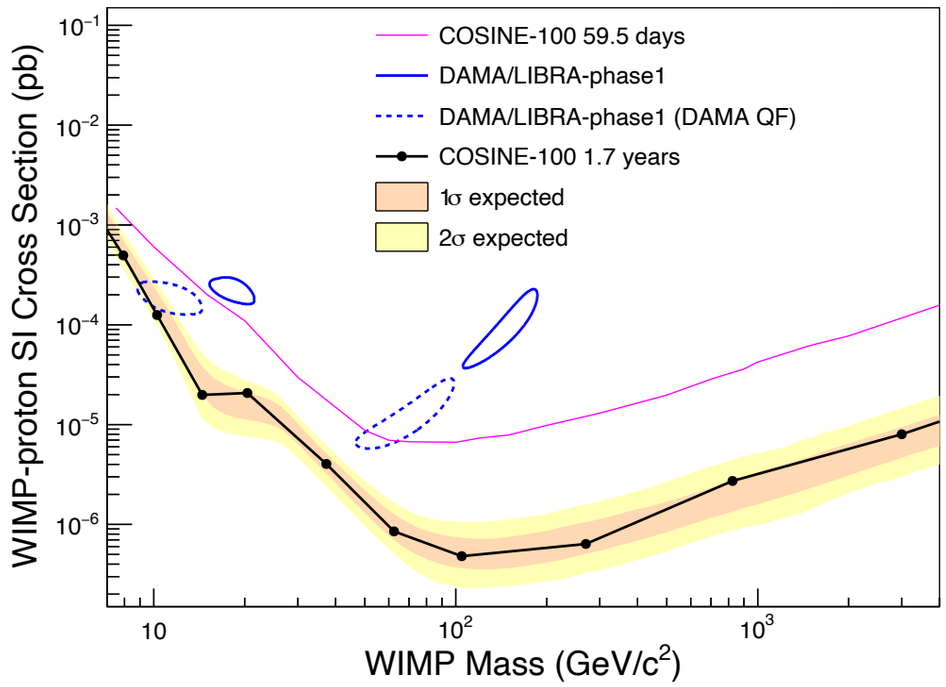


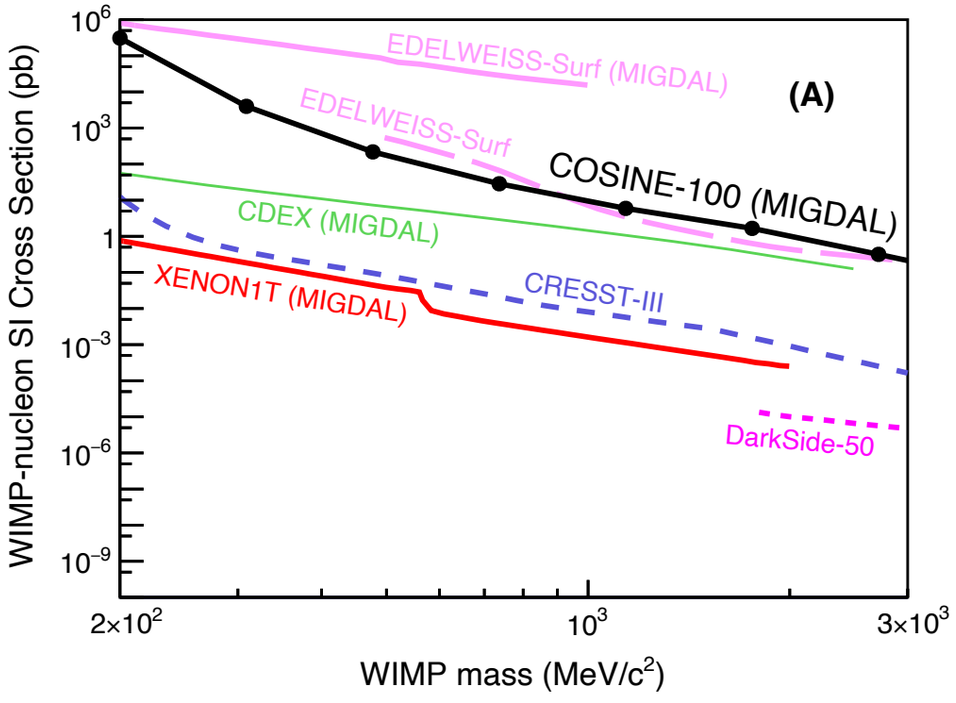
DM Search

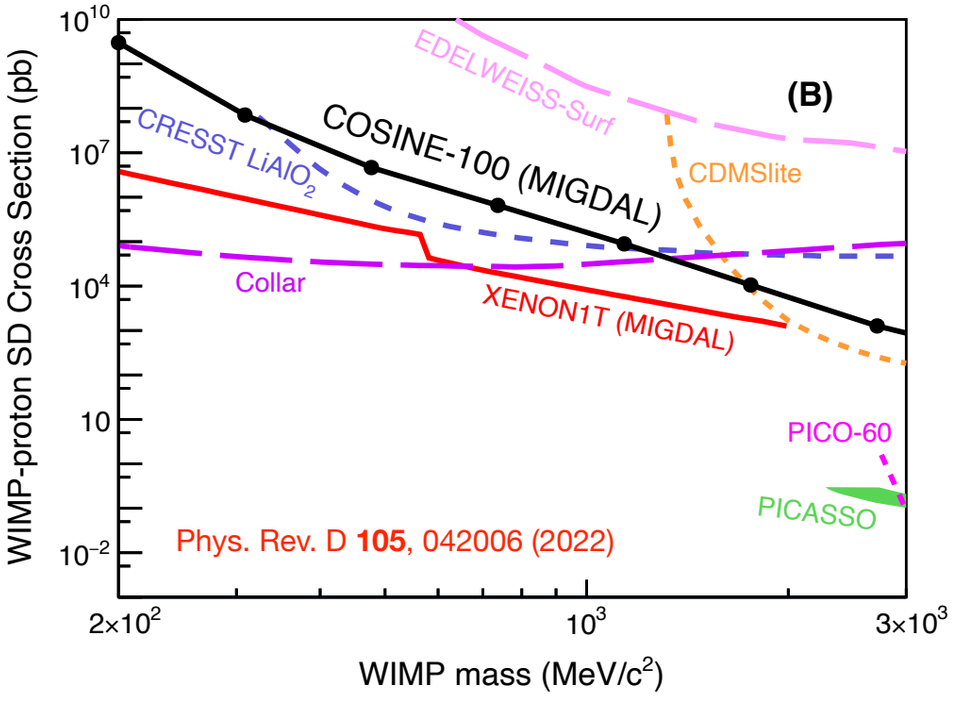
WIMP Extraction Analysis

- SET2 data (1.7 years)
  - Improvements
    - Analysis threshold (2 keV → 1 keV)
    - Background modeling
  - Fully cover the alternative scenarios
    - Different QF & EFT operators
  - Sub-GeV DM search via Migdal effect

Sci. Adv. **7**, eabk2699 (2021)







DM Search

Modulation Analysis

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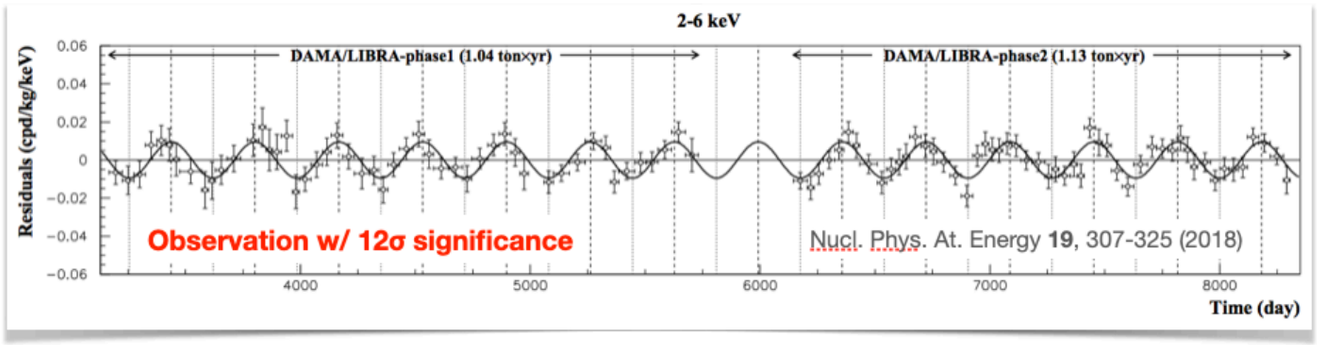

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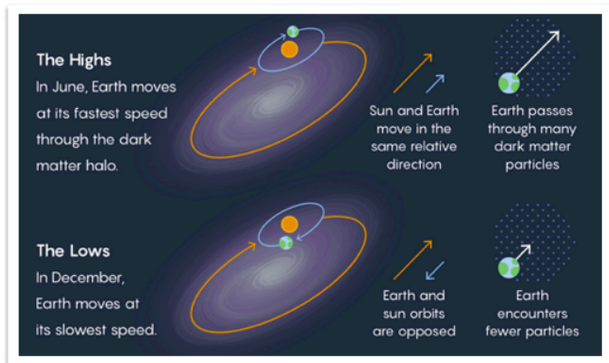
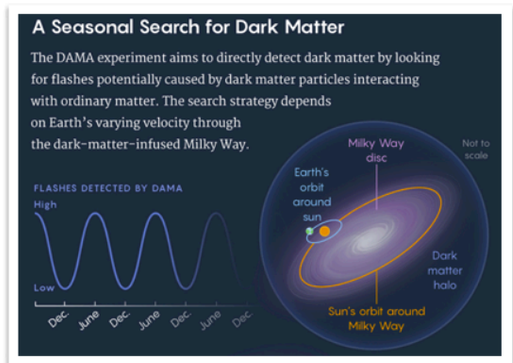


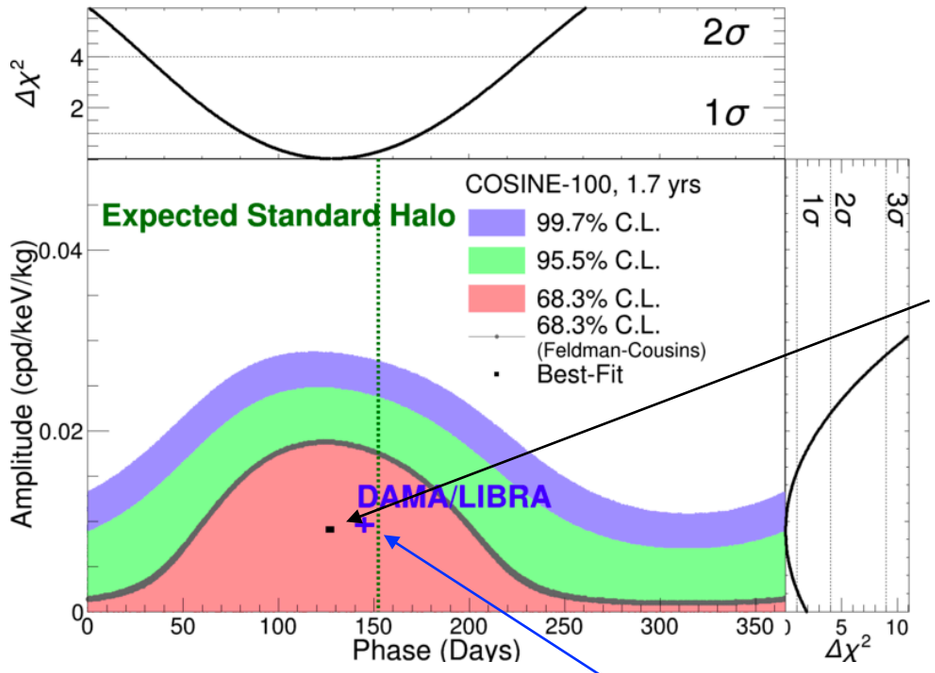


- Annual modulation analysis
  - DAMA/LIBRA observation
  - Model independent analysis

DM Search

Modulation Analysis

Phys. Rev. Lett. **123**, 031302 (2019)



COSINE-100 data-SET2
Amp. = 0.0092 ± 0.0067 cpd/keV/kg
Phase = 127.2 ± 45.9 days

DAMA/LIBRA-phase1+2
Amp. = 0.0096 ± 0.0008 cpd/keV/kg
Phase = 145 ± 5 days

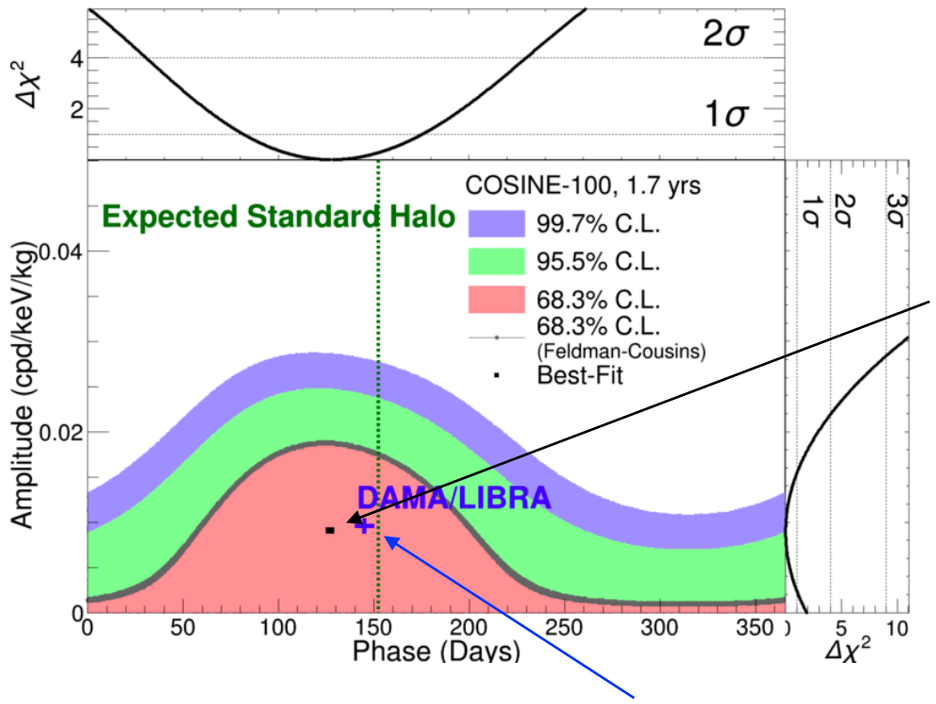
Configuration	Amplitude [cpd/kg/keV]	Phase (Days)
COSINE-100	0.0092 ± 0.0067	127.2 ± 45.9
DAMA/LIBRA (Phase1 + Phase2)	0.0096 ± 0.0008	145 ± 5
COSINE-100	0.0083 ± 0.0068	152.5 (fixed)
COSINE-100 (Without LS)	0.0024 ± 0.0071	152.5 (fixed)
ANAIS-112	-0.0044 ± 0.0058	152.5 (fixed)
DAMA/LIBRA (Phase1 + Phase2)	0.0095 ± 0.0008	152.5 (fixed)

- SET2 data (1.7 years)
  - 2-keV threshold
  - Agree w/ both null & DAMA hypothesis

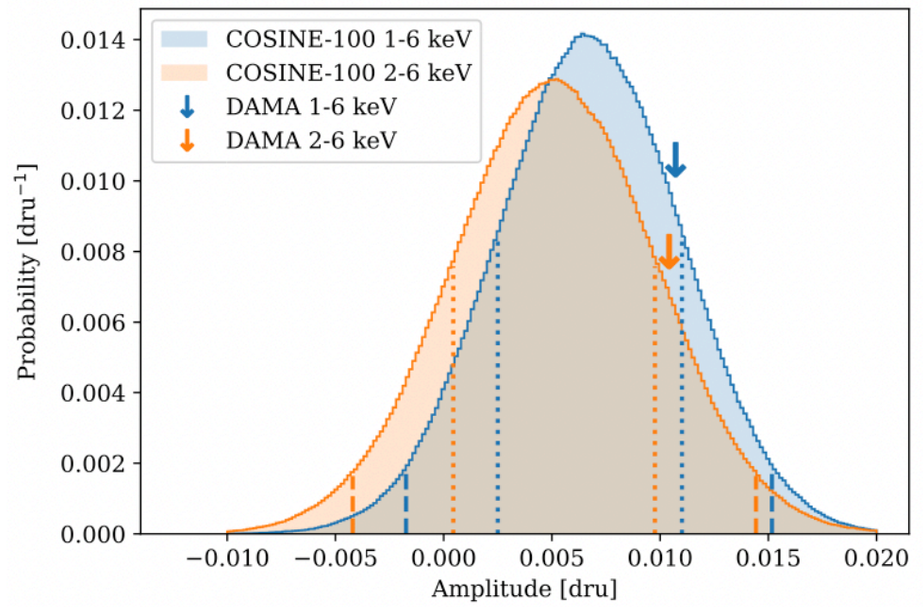
DM Search

Modulation Analysis

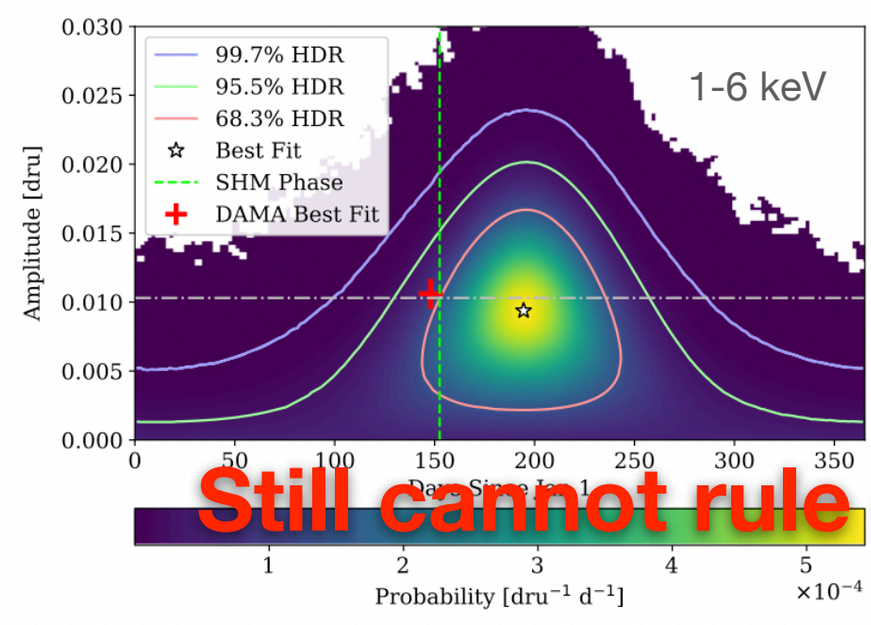
Phys. Rev. Lett. **123**, 031302 (2019)

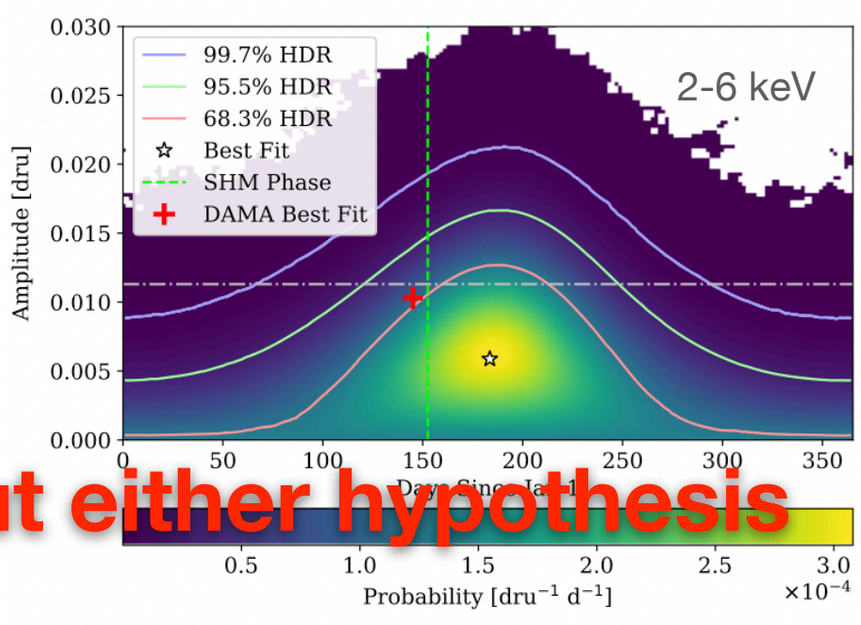


- SET3 data (3 years)
  - 1-keV threshold
  - Improvement in background model



Phys. Rev. D **106**, 052005 (2022)





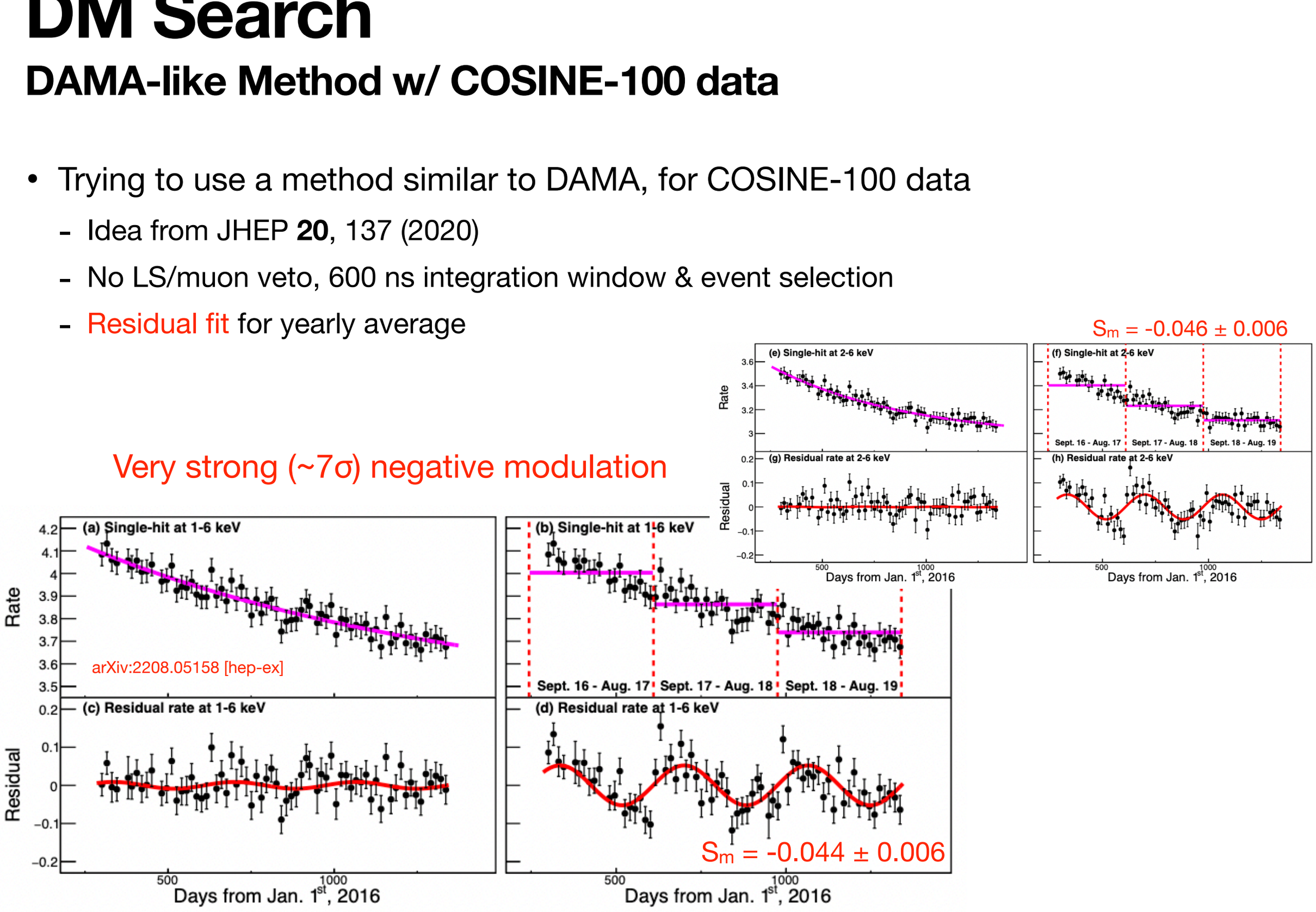
Still cannot rule out either hypothesis

DM Search

DAMA-like Method w/ COSINE-100 data

- Trying to use a method similar to DAMA, for COSINE-100 data
  - Idea from JHEP **20**, 137 (2020)
  - No LS/muon veto, 600 ns integration window & event selection
  - Residual fit for yearly average

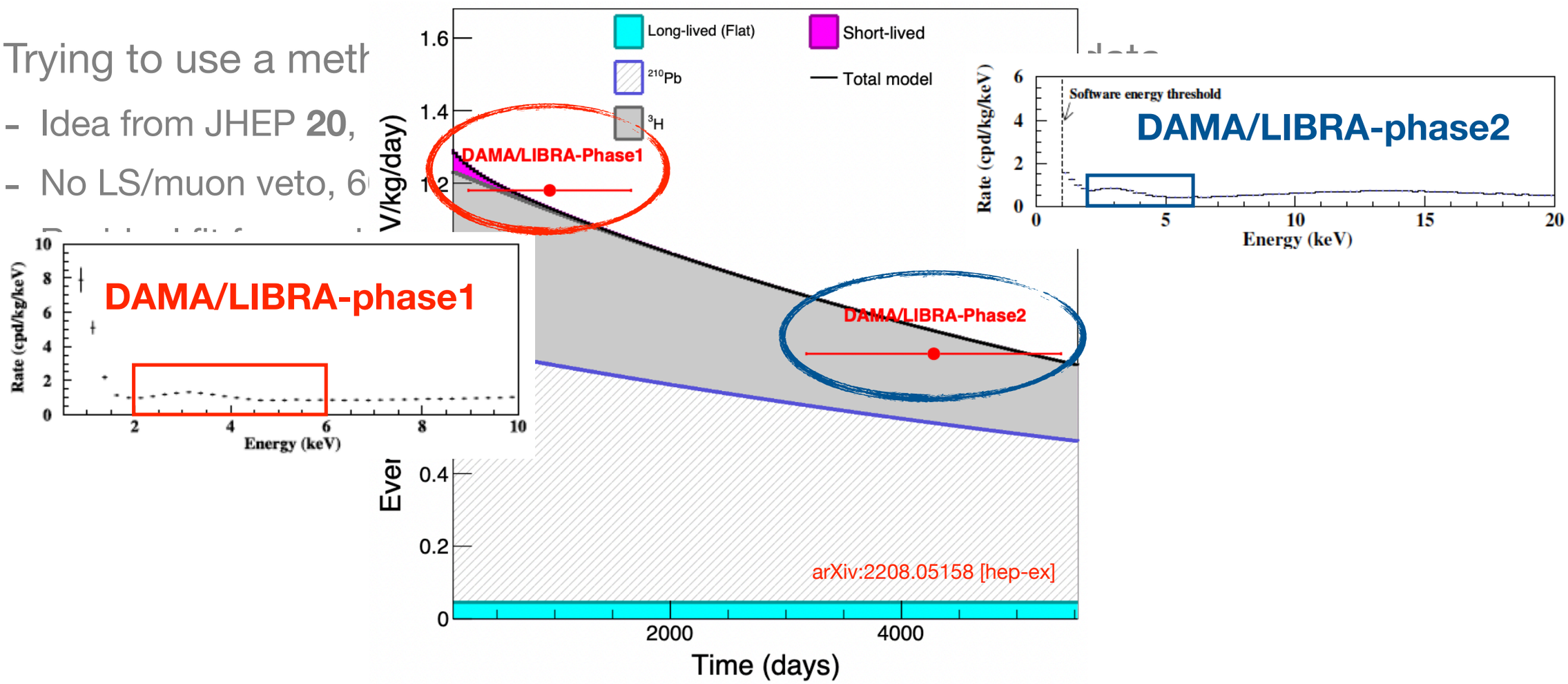
Very strong (~7σ) negative modulation



DM Search

Bias in DAMA's Method

- Trying to use a meth
  - Idea from JHEP **20**,
  - No LS/muon veto, 6

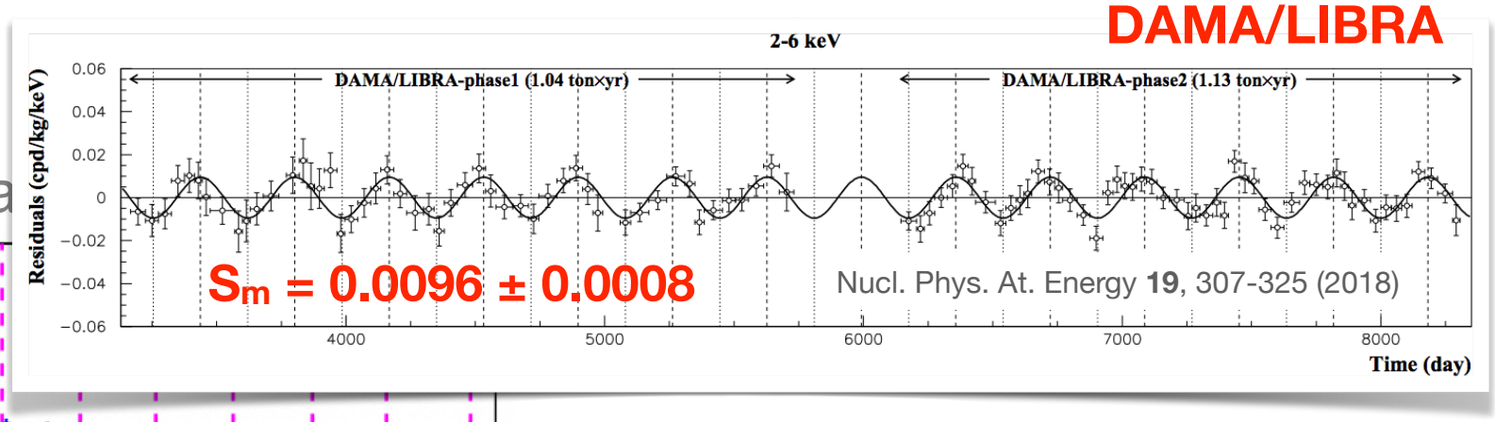


- DAMA background level + COSINE-100 background composition
  - Pseudo experiments based on null hypothesis

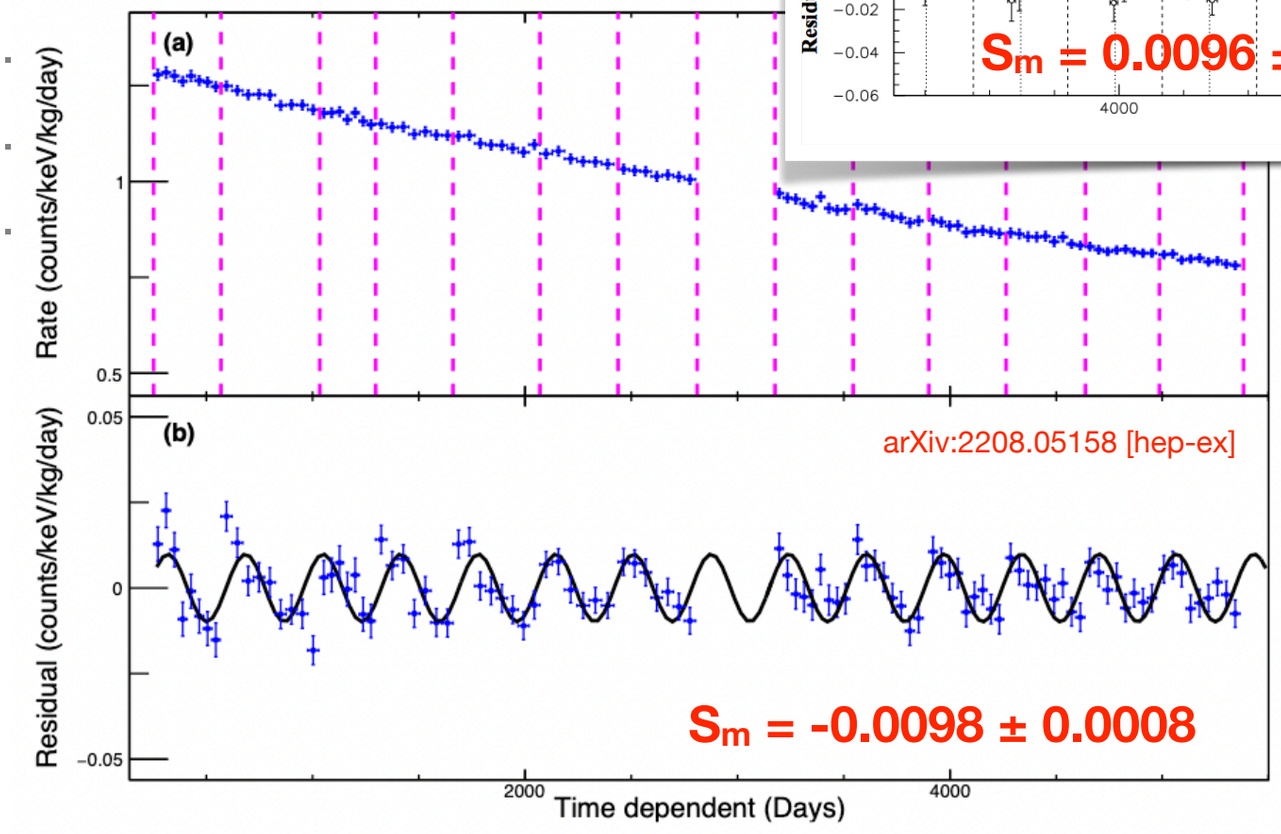
DM Search

Bias in DAMA's Method

DAMA/LIBRA



- Trying to use a method simila

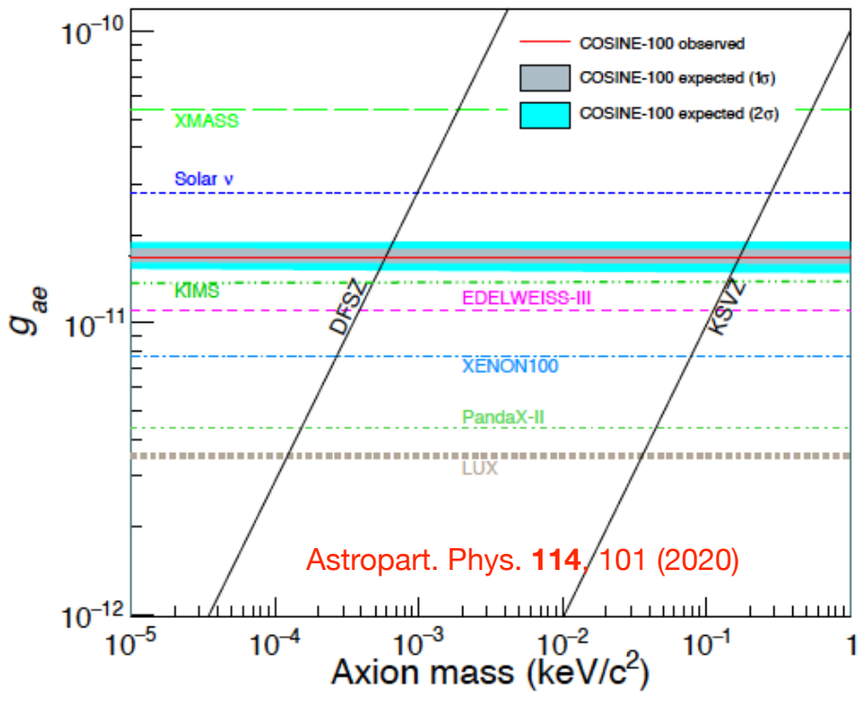


- DAMA background level + COSINE-100 background composition
  - Pseudo experiments based on null hypothesis
  - Residual fit for yearly average
  - Similar amplitude to DAMA, but opposite phase

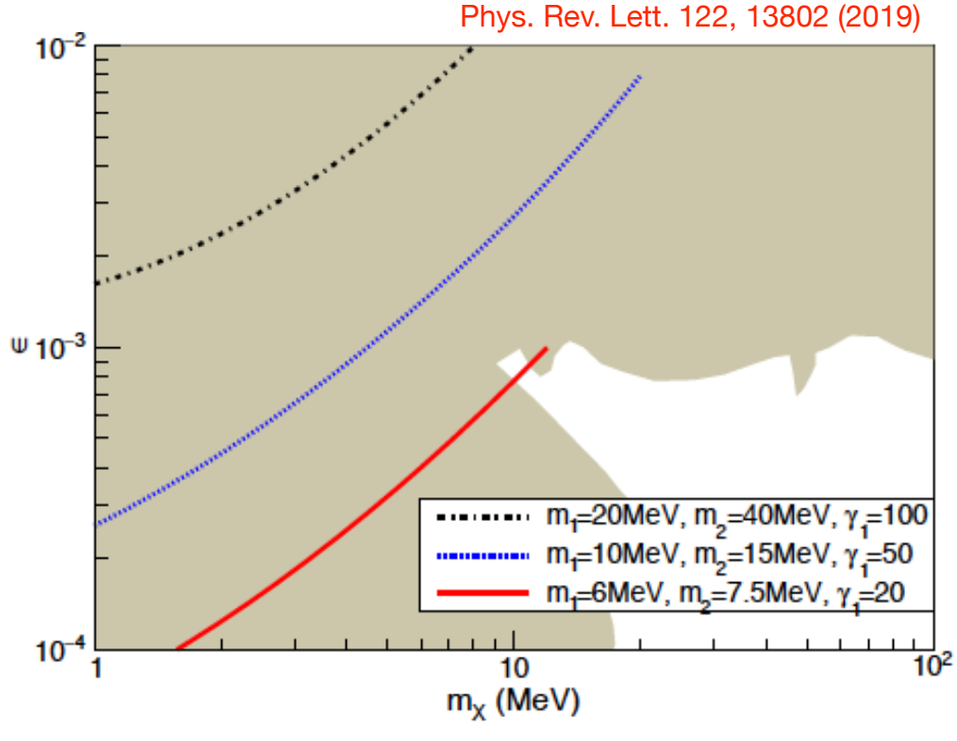
DM Search

Other Scenarios

- Other scenarios of DM
  - Solar axion
  - Inelastic boosted dark matter



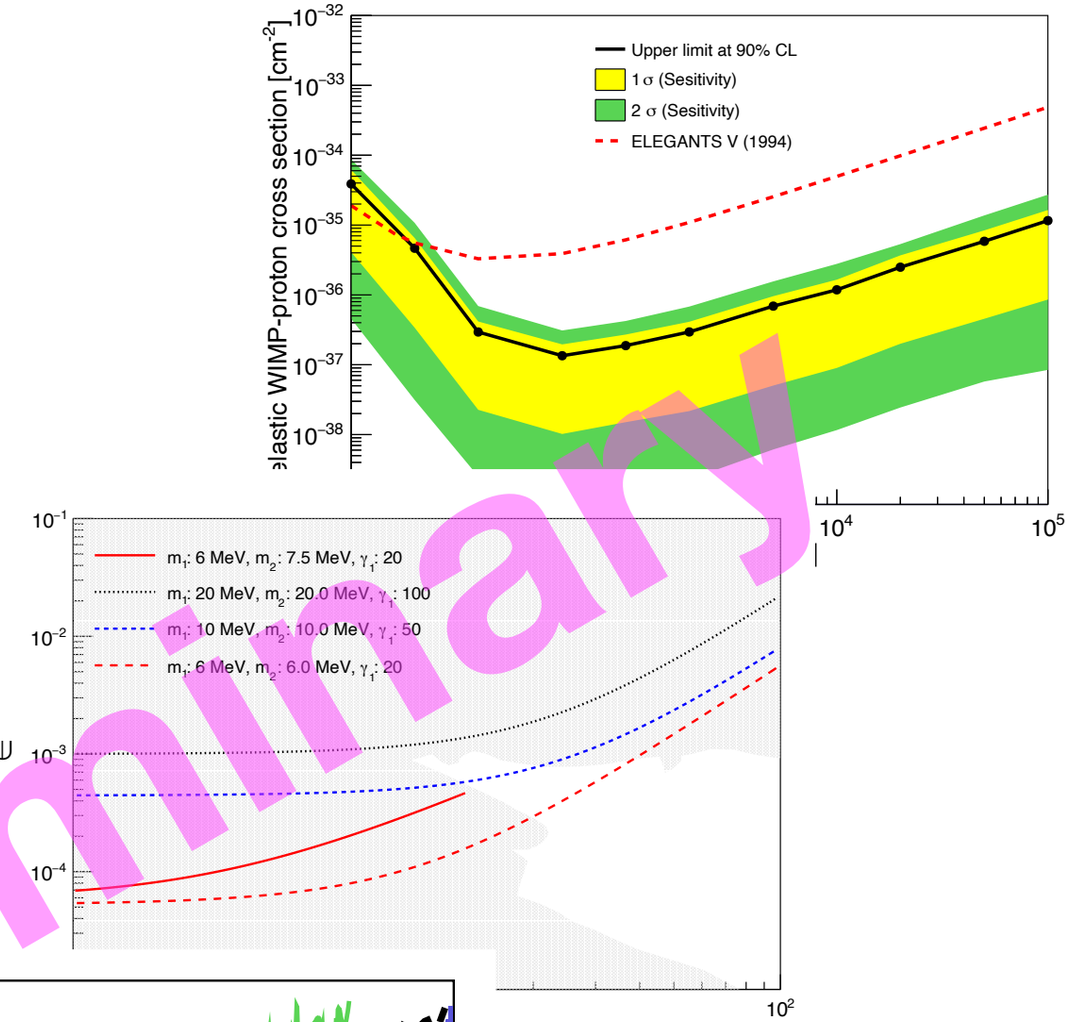
Phys. Rev. Lett. 122, 13802 (2019)

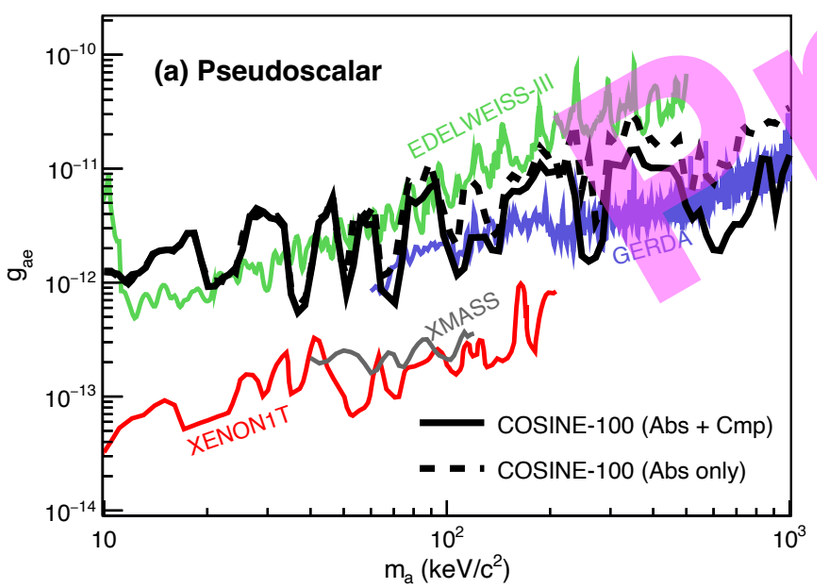


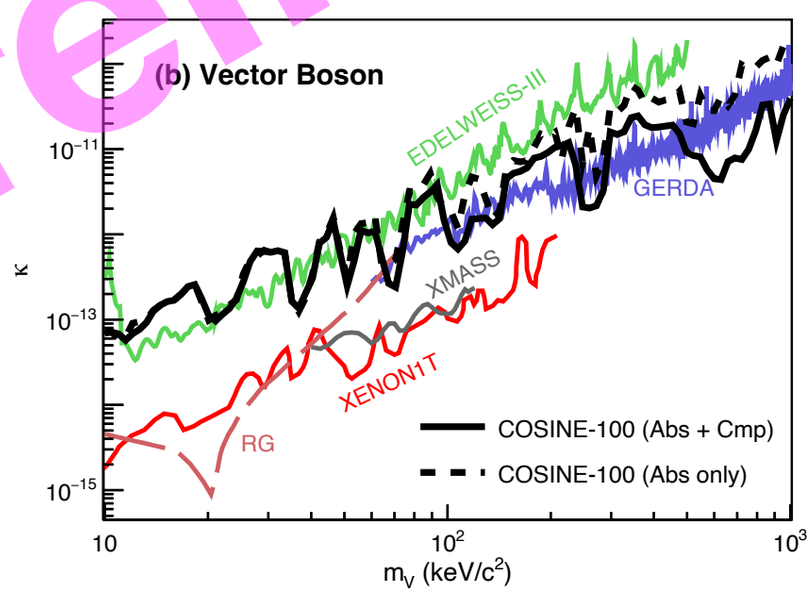
DM Search

Other Scenarios

- Other scenarios of DM
  - Solar axion
  - Inelastic boosted dark matter
- Ongoing analysis
  - WIMP-iodine inelastic scattering
  - Boosted dark matter
  - Bosonic super-WIMP





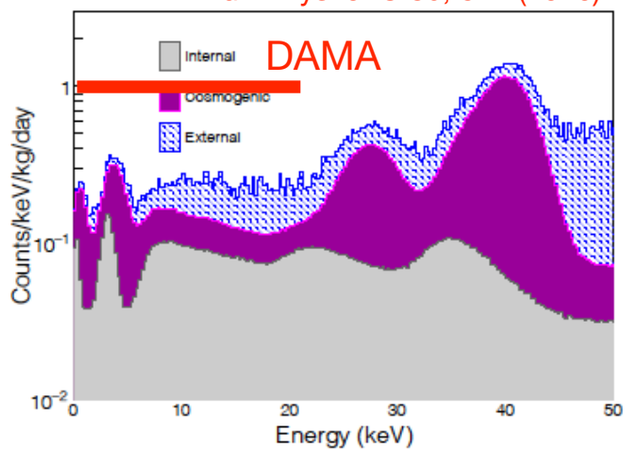


Plan for Next Phase

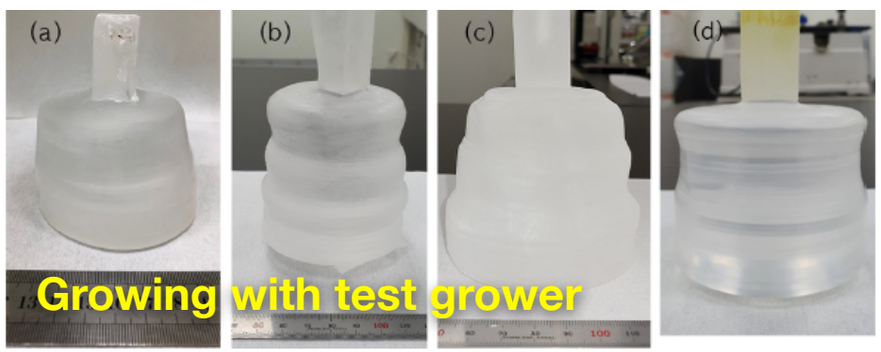
Crystal Development

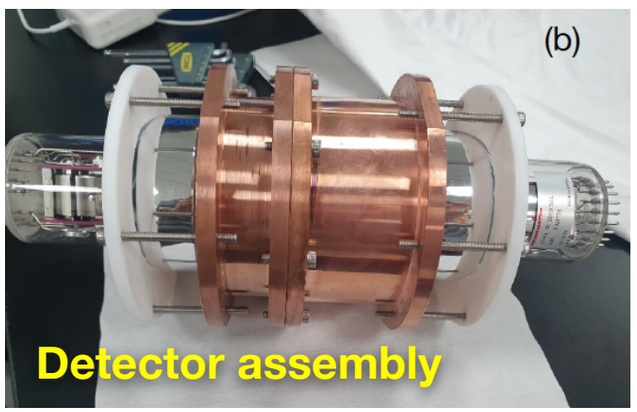
- Goal: lower background level than DAMA/LIBRA
  - COSINE-100: 2-3 times higher than DAMA/LIBRA
  - In-house development for the entire process
    - NaI powder purification
    - Crystal growing
    - Detector assembly

Eur. Phys. J. C **80**, 814 (2020)



	K [ppb]	210Pb [mBq/kg]	238U [Bq/kg]	232Th [Bq/kg]
Powder	5	-	< 20	< 20
Aug., 2018	684	3.8 ± 0.3	26 ± 7	< 6
Sep., 2019	**8**	**0.01 ± 0.02**	11 ± 4	7 ± 2
DAMA	< 20	0.01 ~ 0.03	8.7 ± 124	2 ~ 31

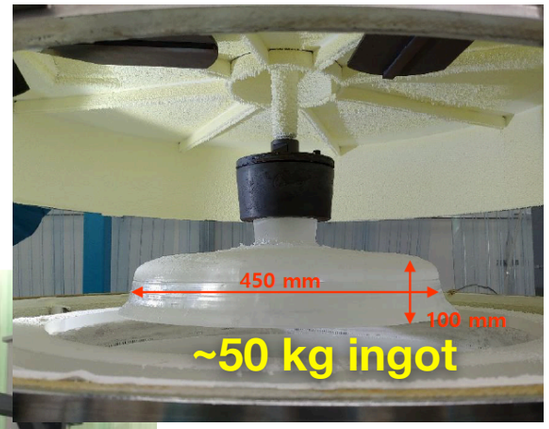


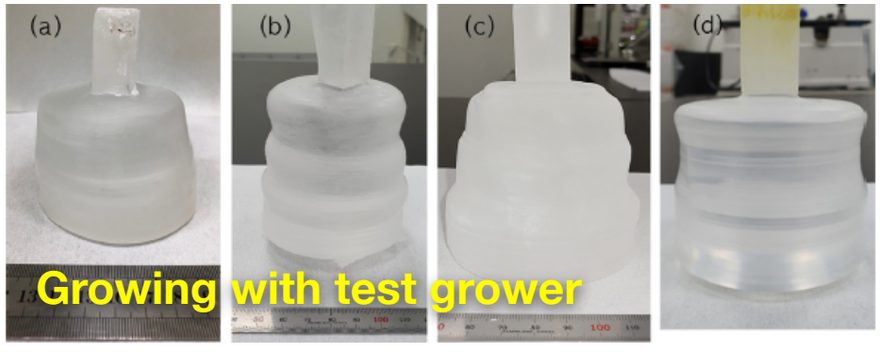


Plan for Next Phase

Crystal Development

- Goal: lower background level than DAMA/LIBRA
  - COSINE-100: 2-3 times higher than DAMA/LIBRA
  - In-house development for the entire process
    - NaI powder purification
    - Crystal growing
    - Detector assembly
  - Full size grower
    - Designed and built based on small test grower
    - Successful seeding and growing ~10-cm ingot

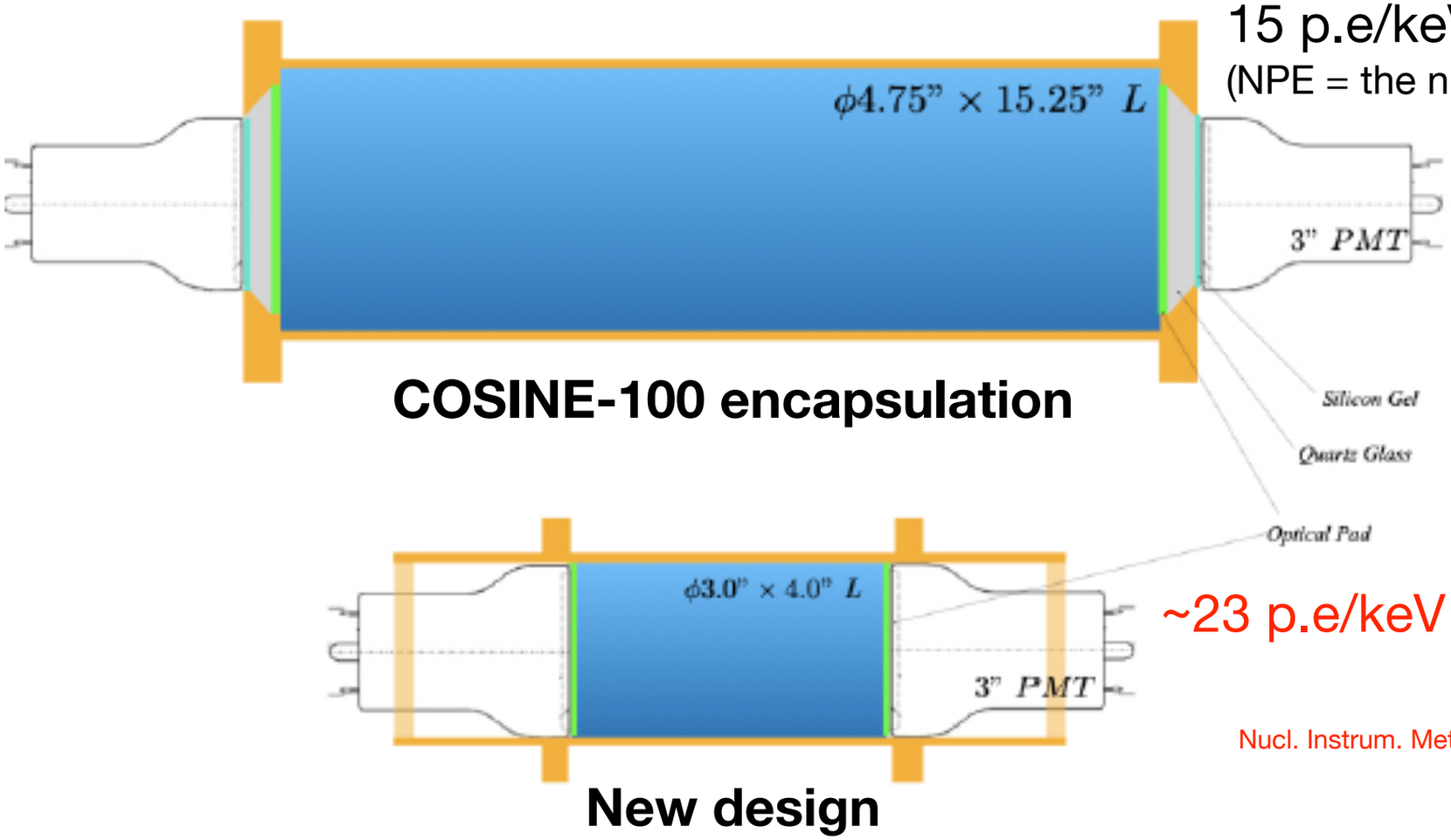




Plan for Next Phase

Lowering Threshold

- Novel technique of crystal encapsulation
  - Direct attachment of crystal to PMTs
  - ~50% increased light yield
  - It will be applied to COSINE-200 detector assembly



15 p.e/keV
(NPE = the number of photoelectrons)

COSINE-100 encapsulation

~23 p.e/keV

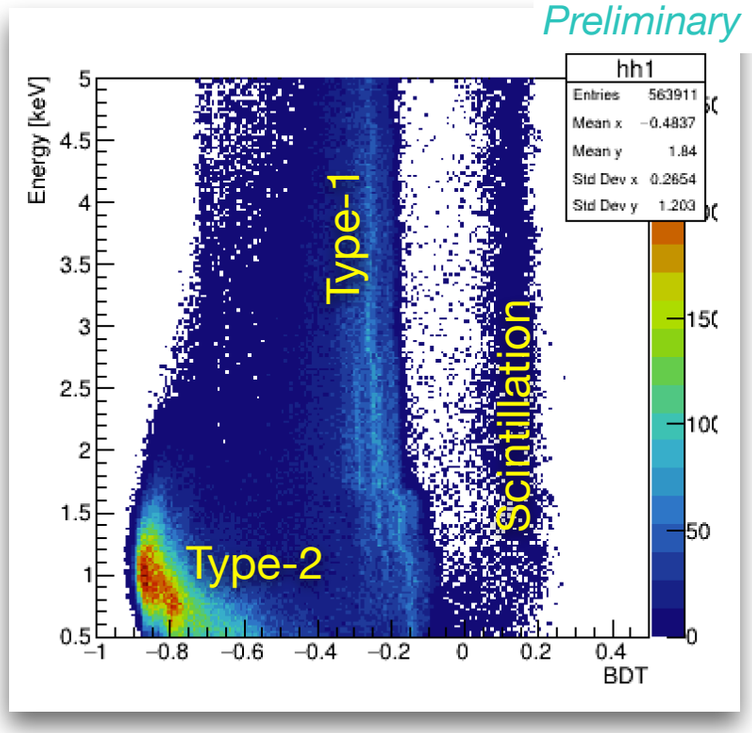
New design

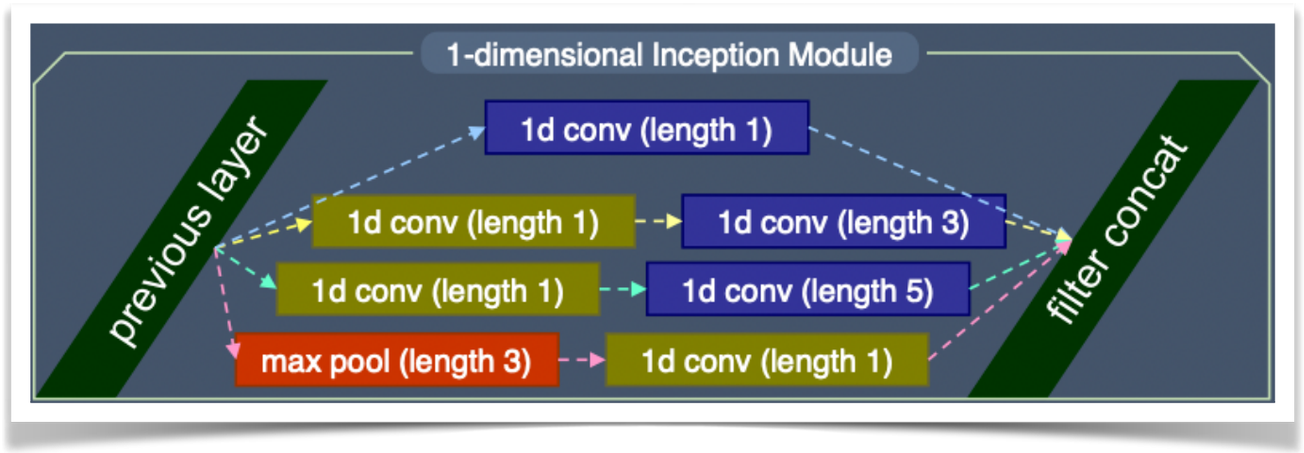
Nucl. Instrum. Meth. A **981**, 164556 (2020)

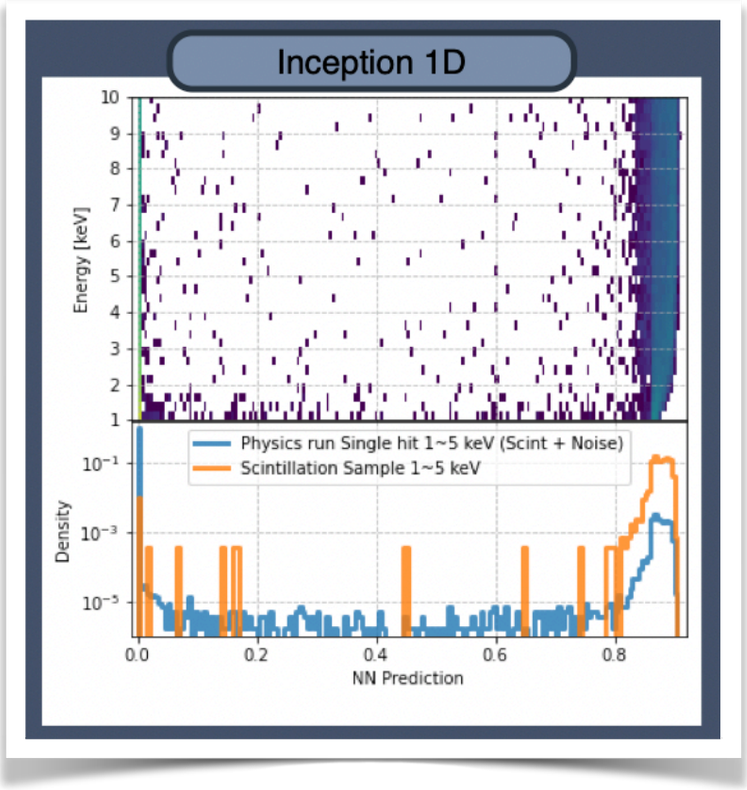
Plan for Next Phase

Lowering Threshold

- Novel technique of crystal encapsulation
  - Direct attachment of crystal to PMTs
  - ~50% increased light yield
  - It will be applied to COSINE-200 detector assembly
- Event selection
  - Improved multi-variable technique
    - ~0.5 keV (7 p.e) of energy threshold achievable
  - Deep learning



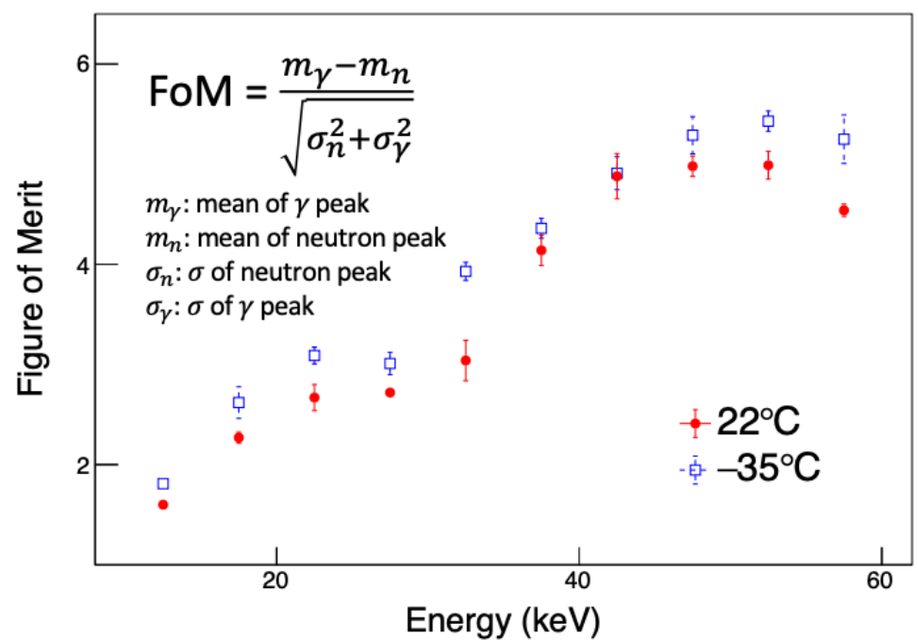


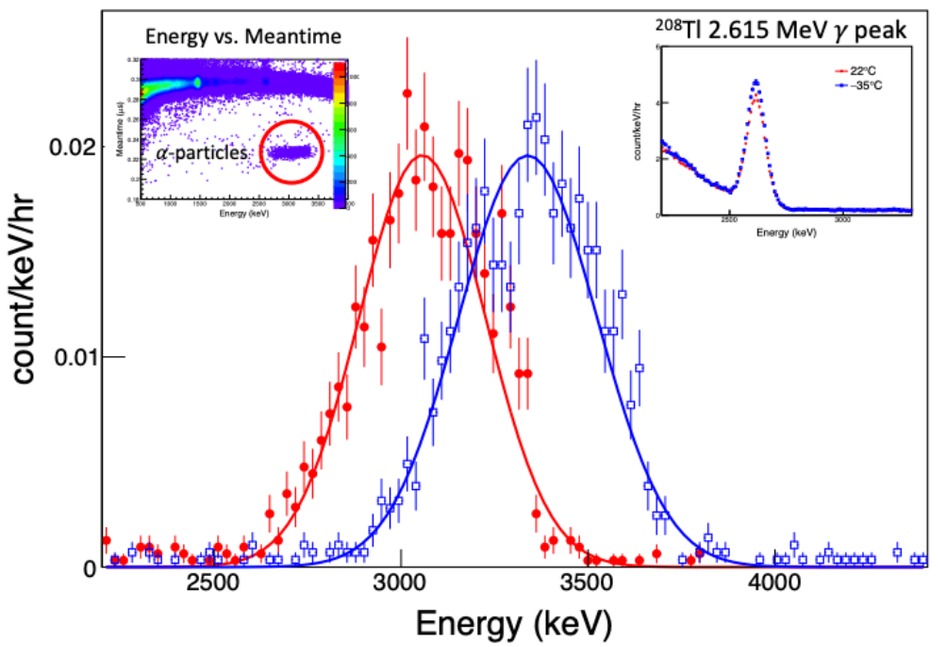


Plan for Next Phase

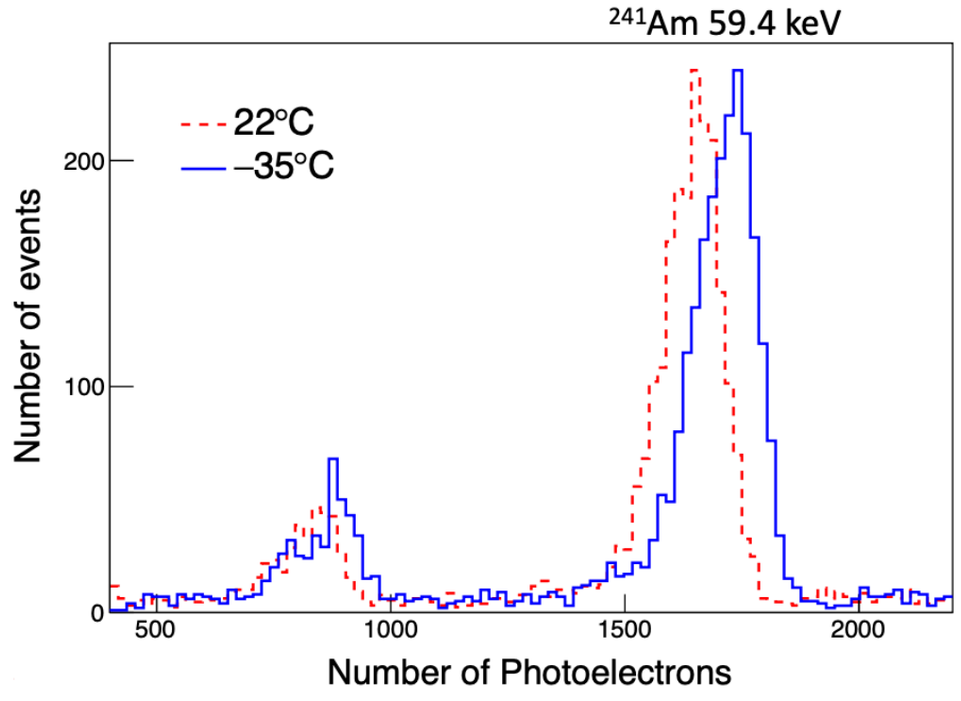
Lowering Threshold

- Nov … on
  - Di…
  - ~5…
  - It … assem
- Eve…
  - Im…
    - …
  - De…





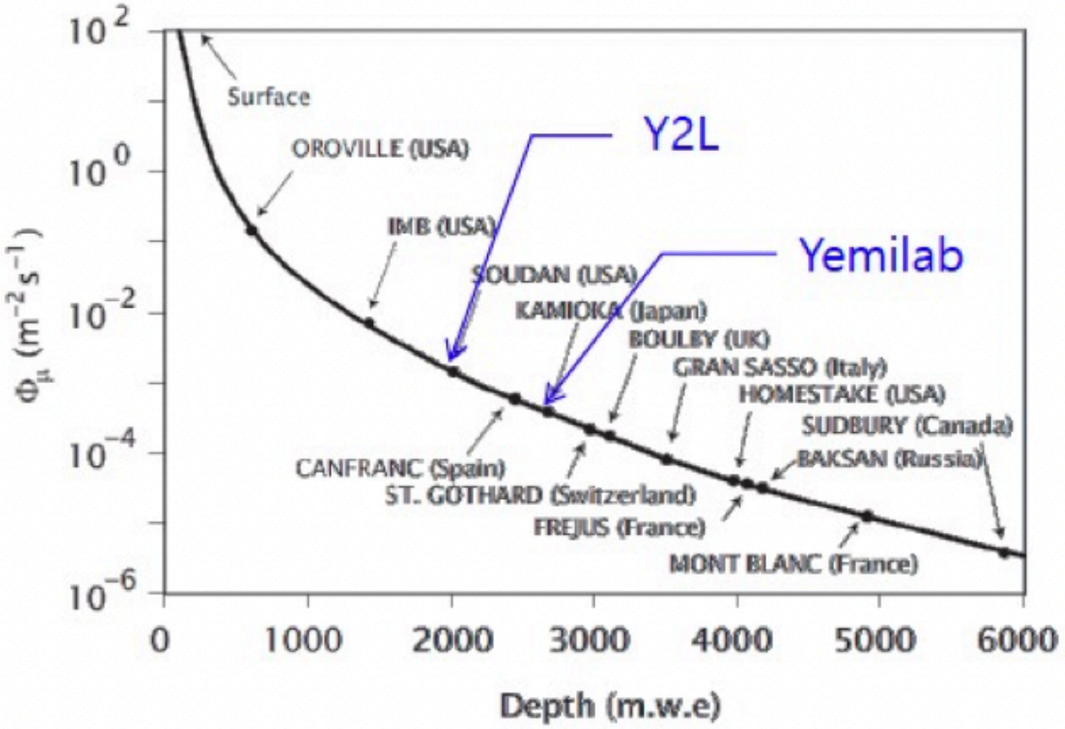
- Low temperature measurement
  - Improved PSD for γ & n
  - ~10% increased α quenching
  - Increased light yield
    - 27.6 ± 0.3 p.e/keV → 28.9 ± 0.2 p.e/keV

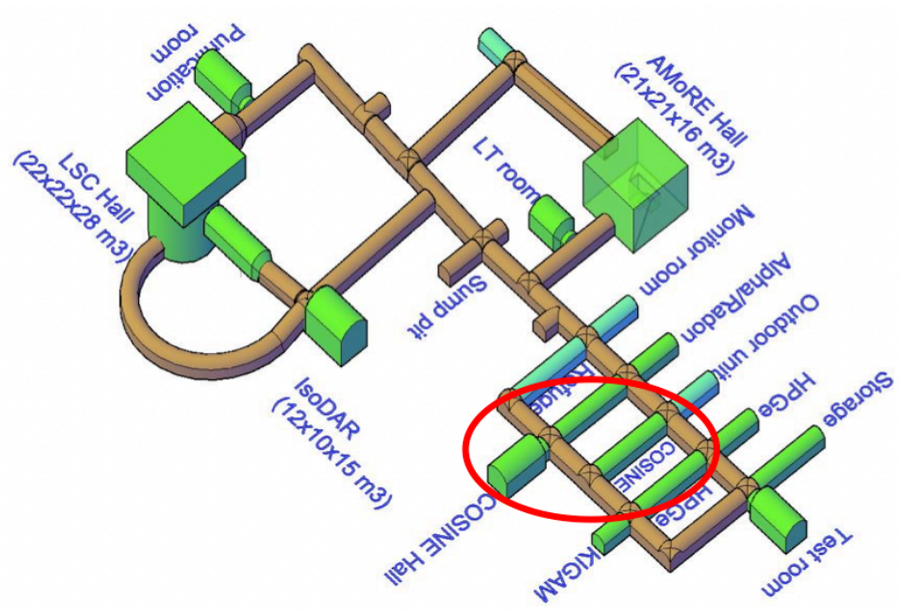


Plan for Next Phase

Upgrading COSINE-100

- Moving from Y2L to Yemilab
  - Late next year, 2023
  - Operation at -35°C

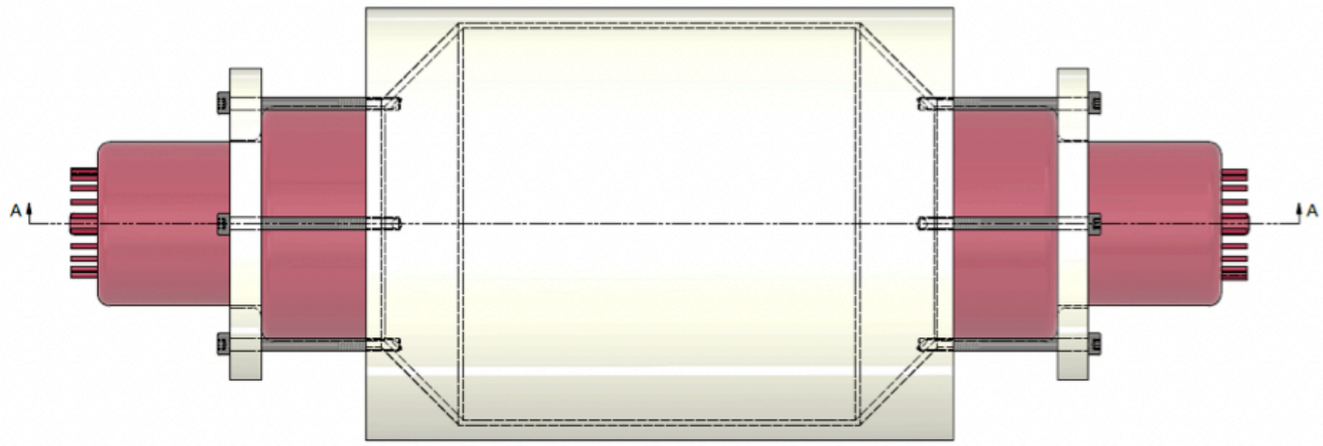


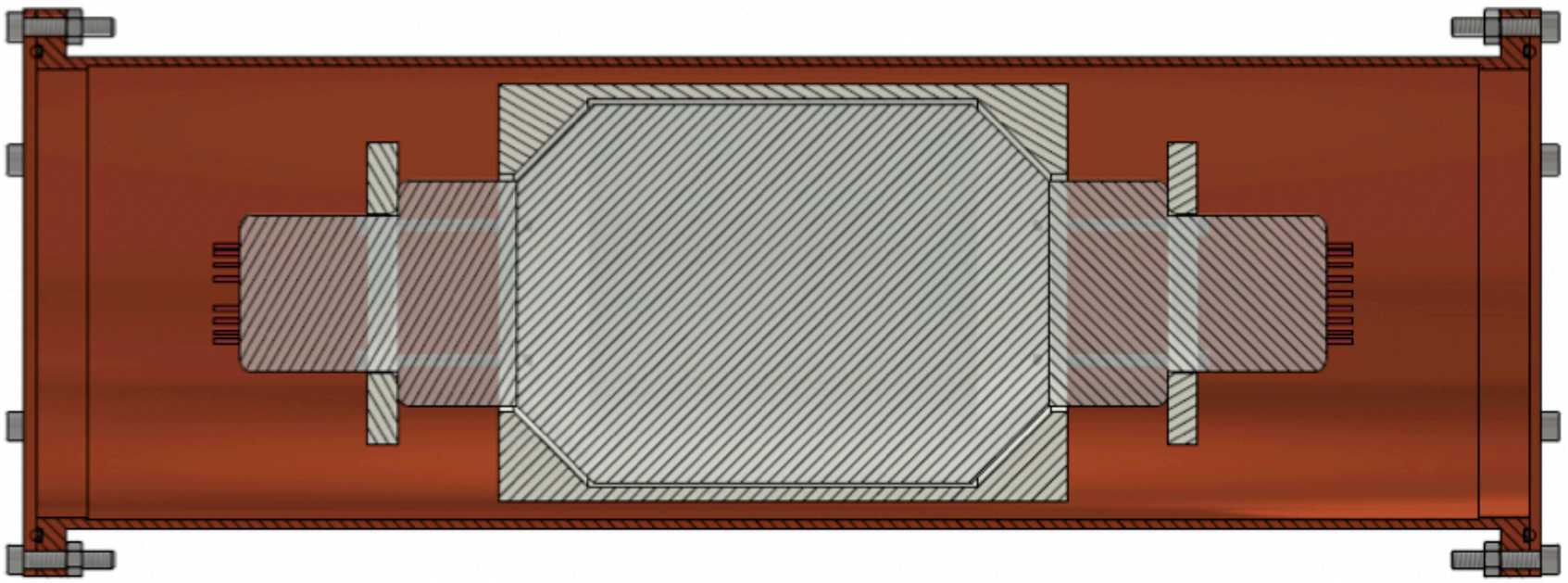


Plan for Next Phase

Upgrading COSINE-100

- Moving from Y2L to Yemilab
  - Late next year, 2023
  - Operation at -35°C
  - Recovering unused crystals
  - New technique of encapsulation

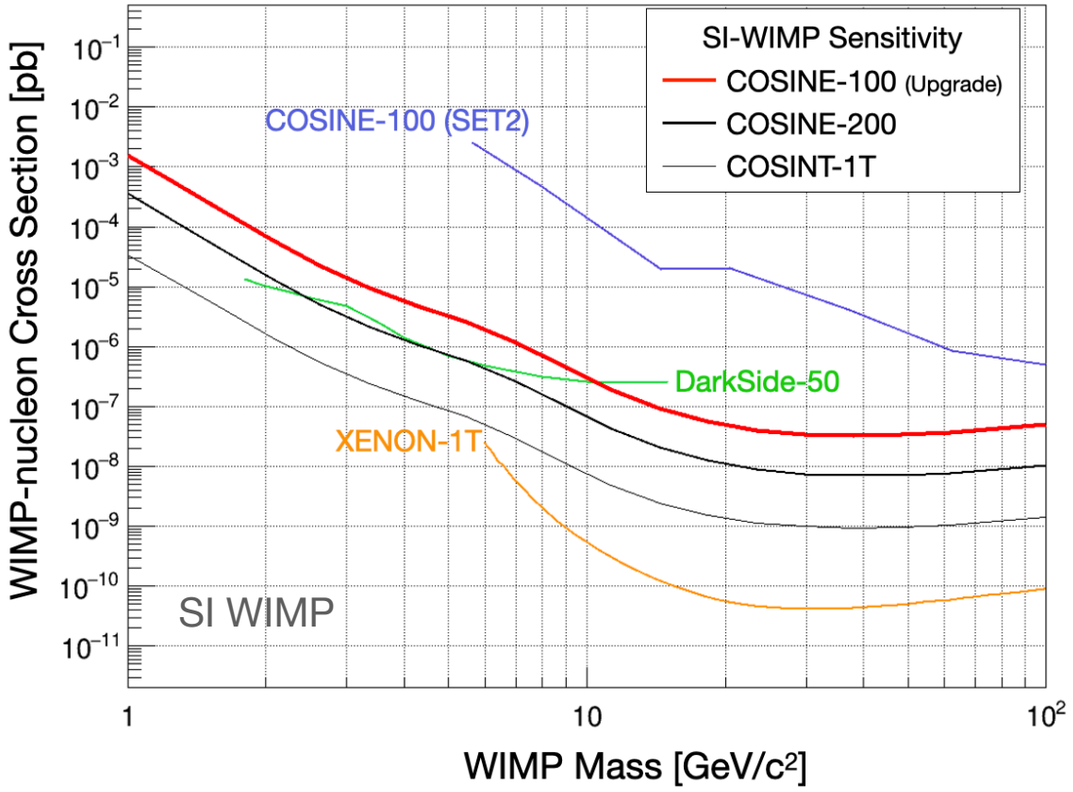


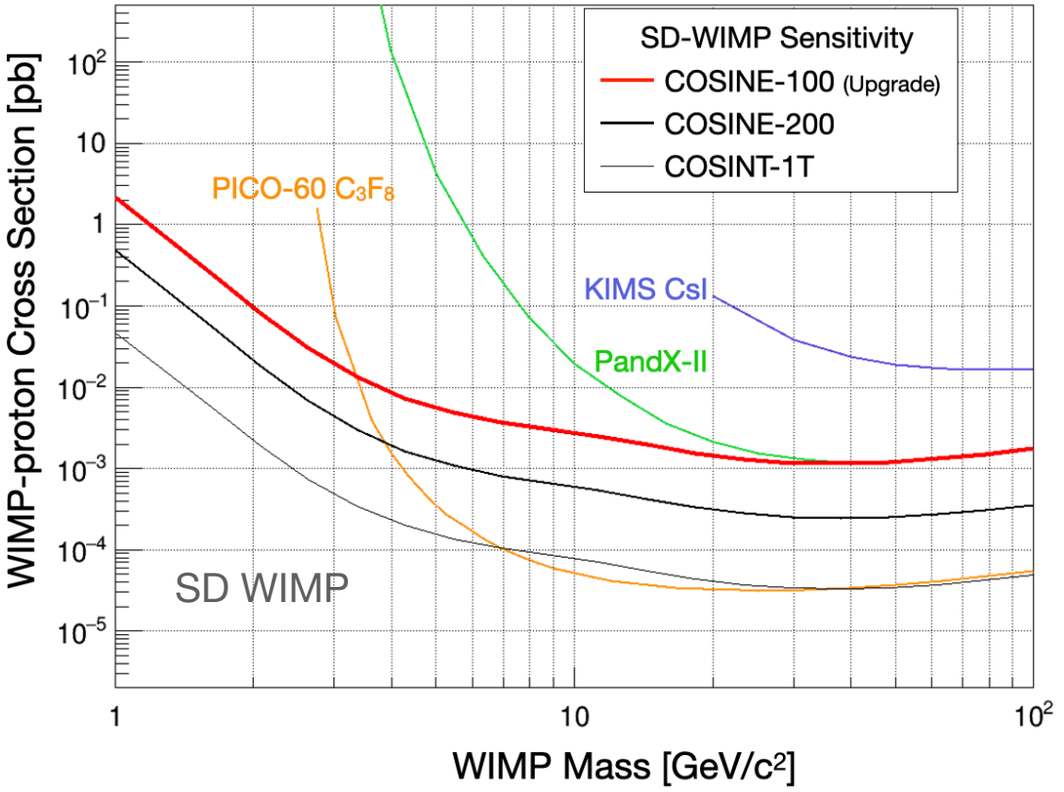


Plan for Next Phase

Sensitivity Study

22 PE/keV light yield
5 PE thrshold
No systematic uncertainty





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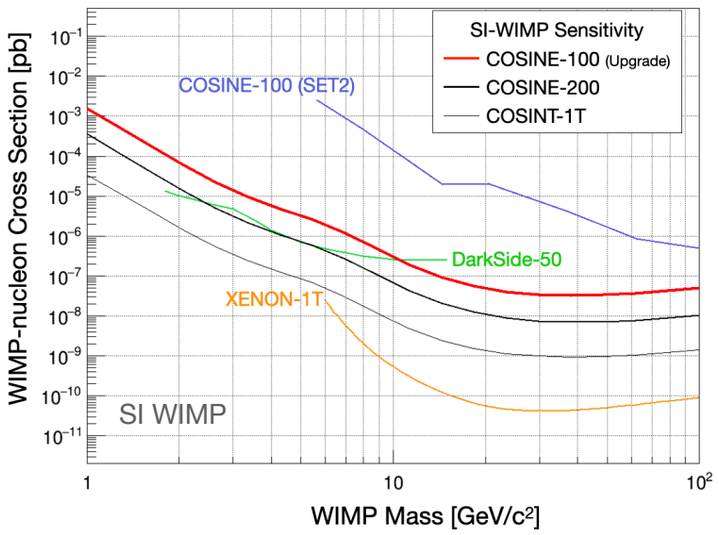
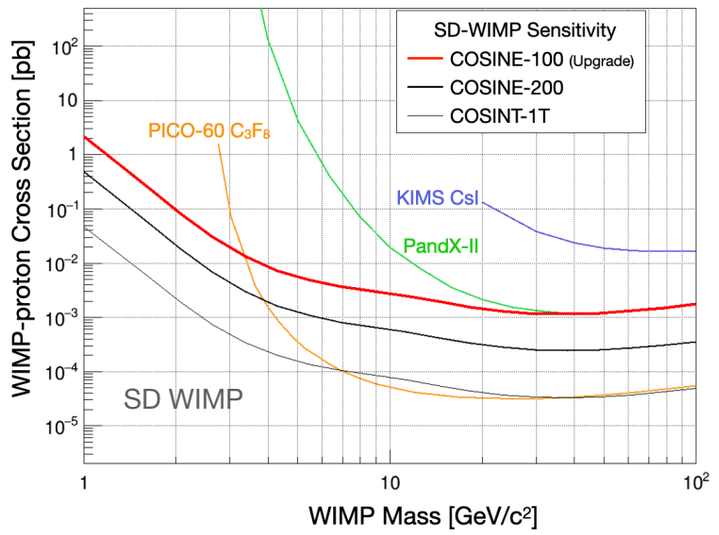
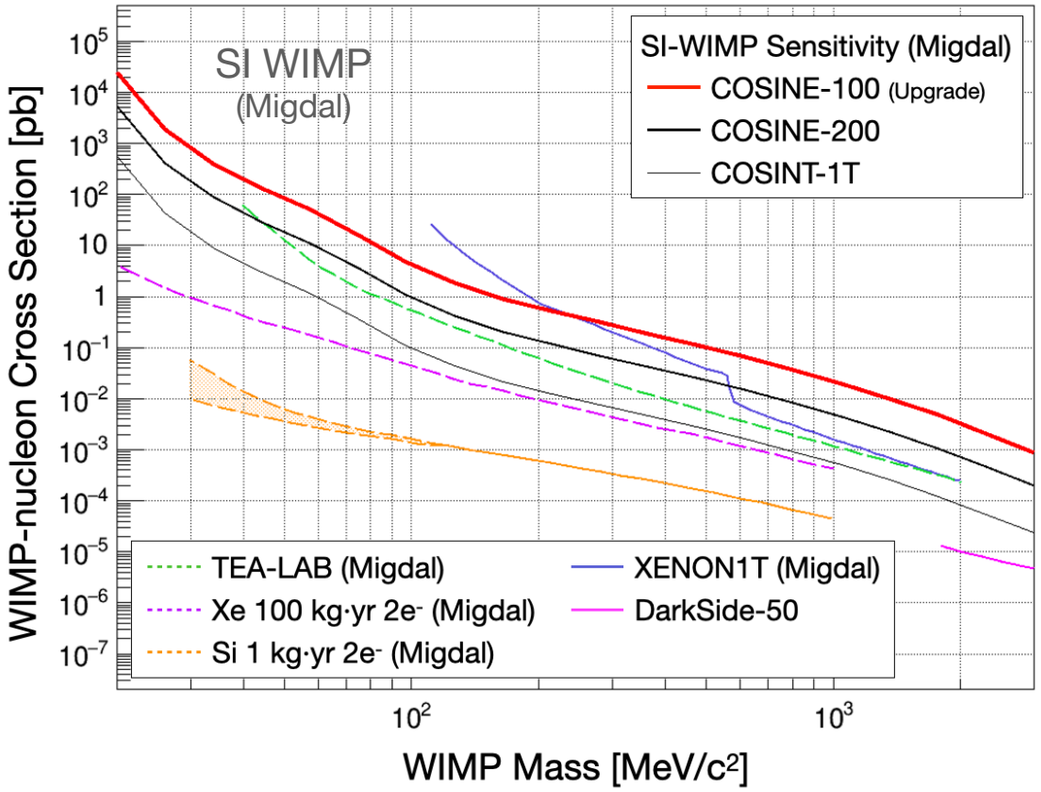
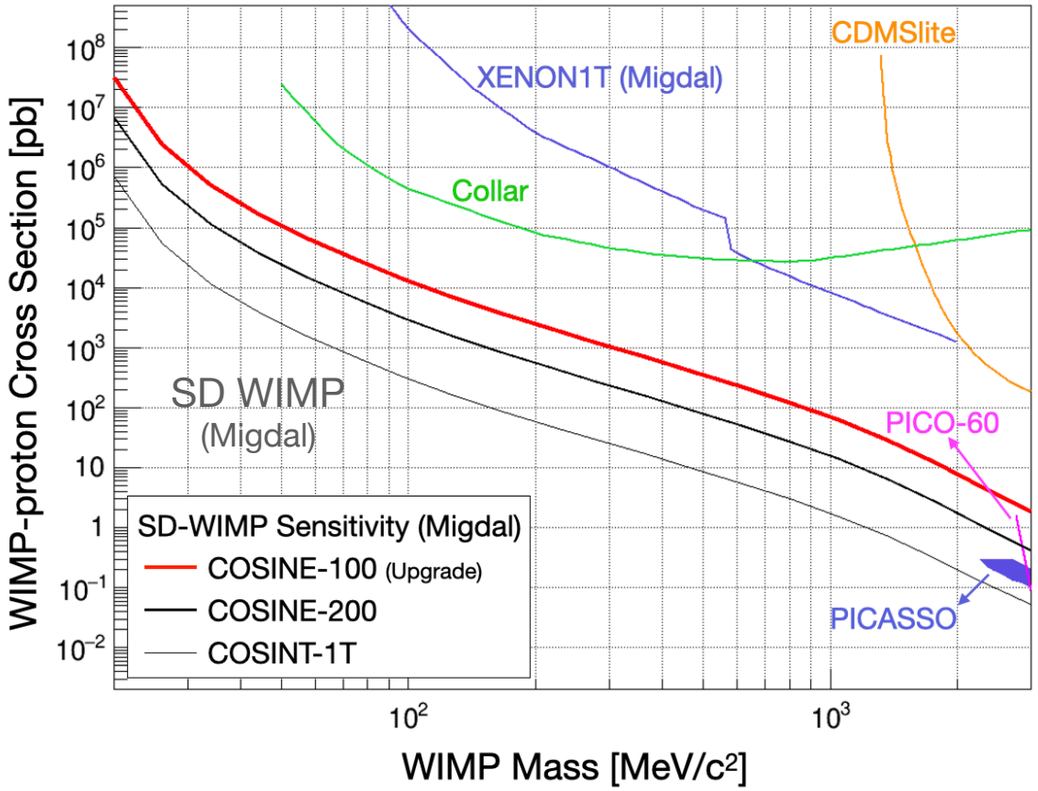




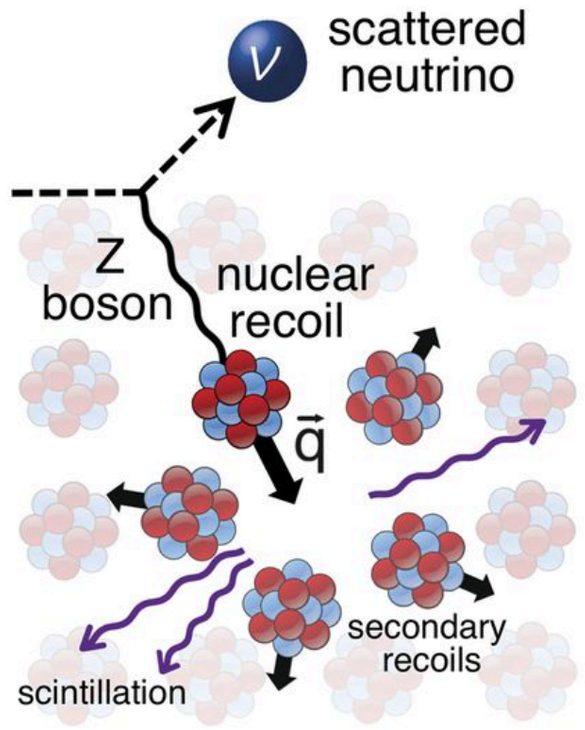


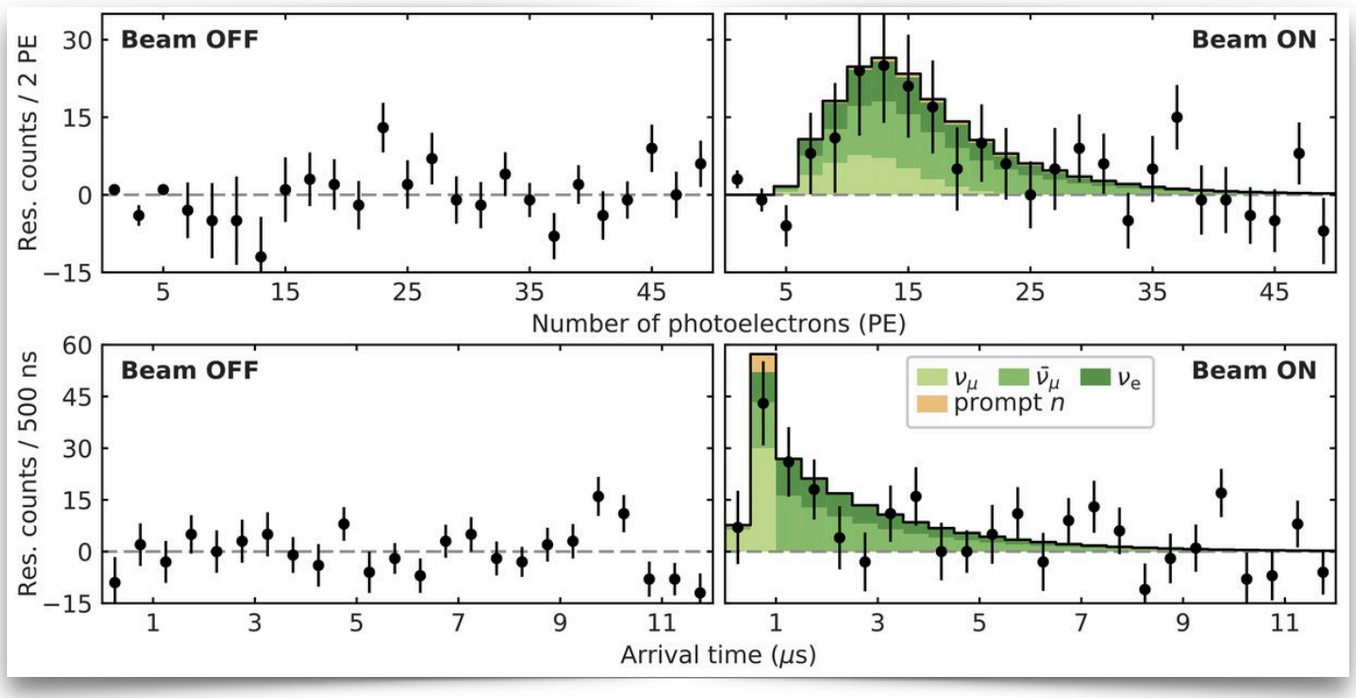


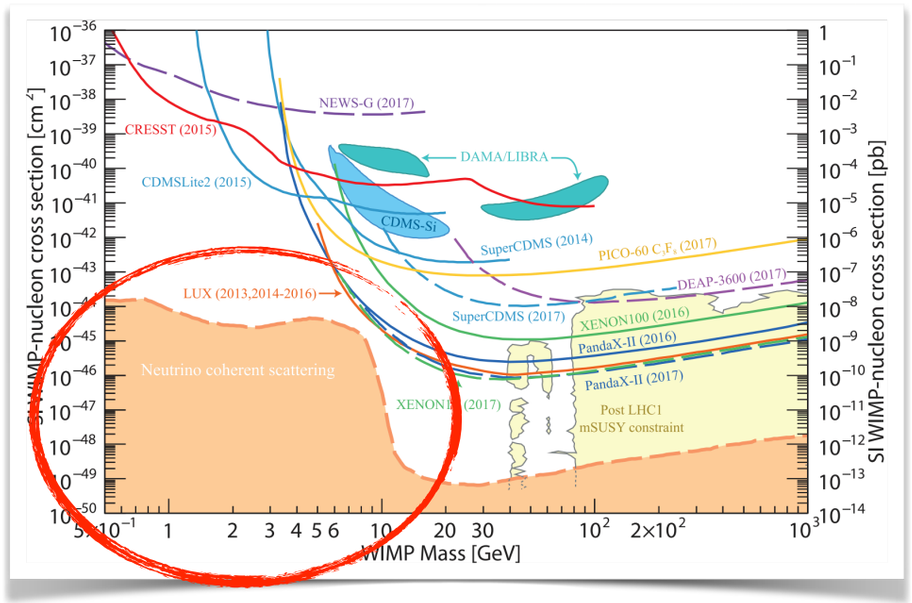
Introduction to NEON

Coherent Elastic Neutrino-Nucleus Scattering

- CEvNS
  - Predicted by D. Z. Freedman at 1974 (Phys. Rev. D **9**, 1389 (1974))
  - First measurement by COHERENT collaboration at 2017 (Science **357**, 1123-1126 (2017))
    (stopped pion source)
  - Sharing the same experimental signature w/ DM searches
    - Similar detection technique: cryogenic bolometers
    - The neutrino floor



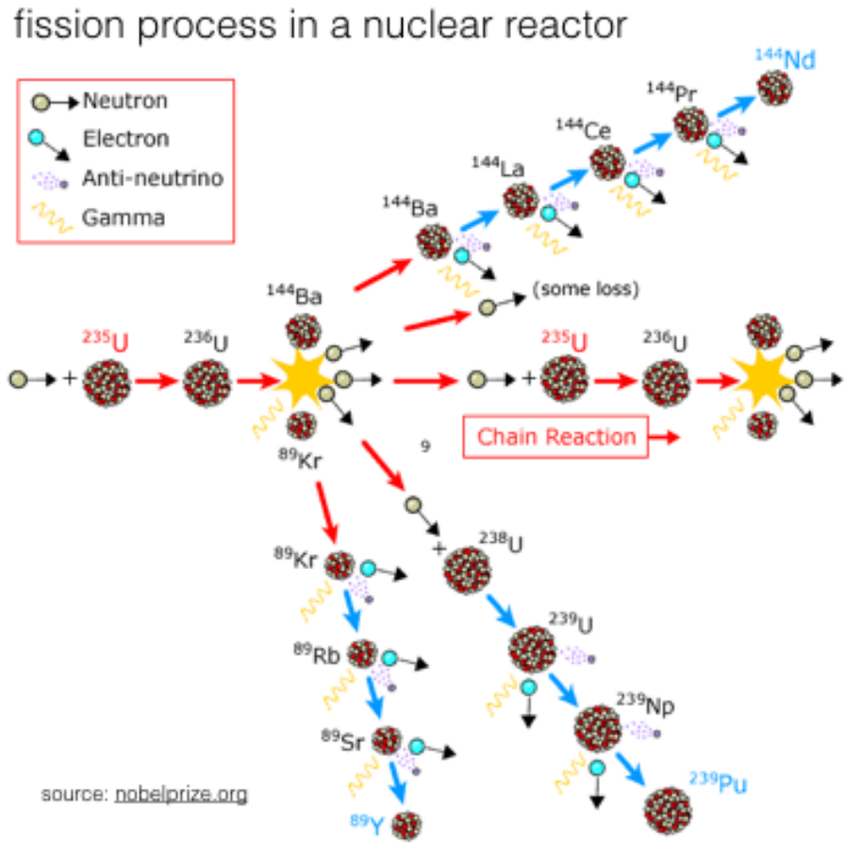


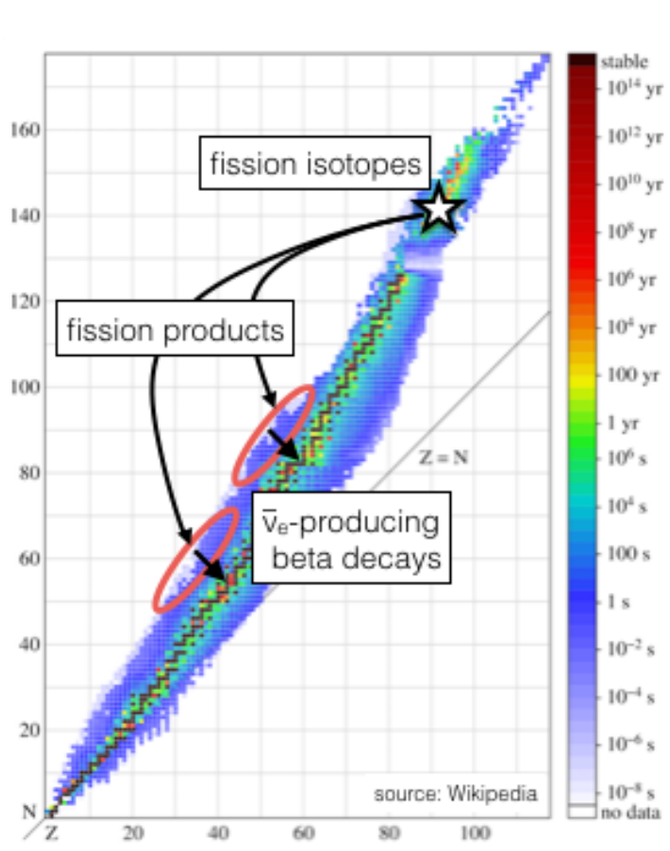


Introduction to NEON

Coherent Elastic Neutrino-Nucleus Scattering

- Neutrinos in reactor
  - Rich neutrino source
  - Low ν energy
    - Full coherency region
    - Complementary observation



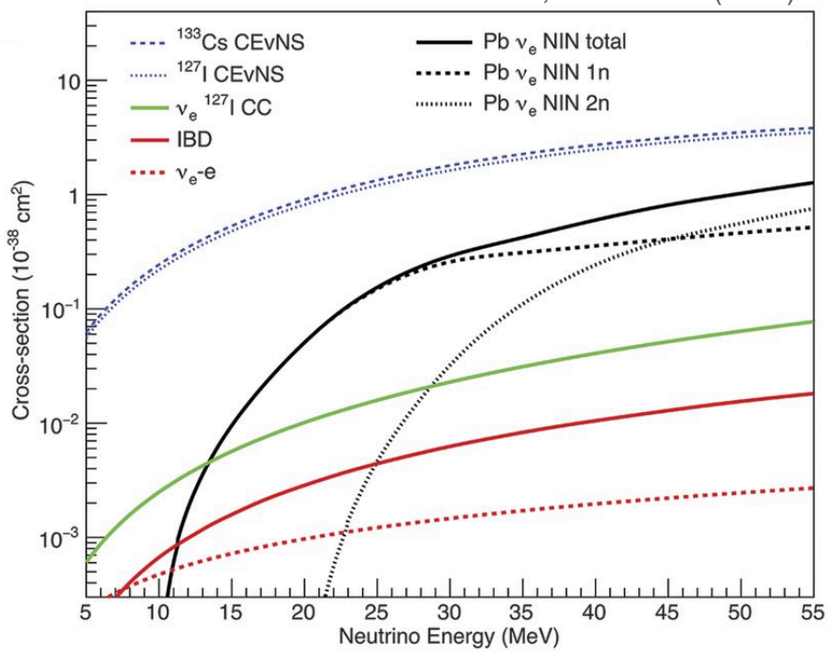


Introduction to NEON

Coherent Elastic Neutrino-Nucleus Scattering

- Neutrinos in reactor
  - Rich neutrino source
  - Low ν energy
    - Full coherency region
    - Complementary observation
  - CEvNS measurement
    - High cross section, but too low recoil energy
      (heavier target → higher cross section, lower recoil energy)
    - Shallow overburden → high background rate

Science **357**, 1123-1126 (2017)



- For…
  - Testing Standard model & searching new physics
  - MeV-scale Weinberg angle, non-standard interaction, neutrino magnetic moment, neutron form factor
  - Reactor antineutrino anomaly, anomalous spectra of reactor neutrinos

Introduction to NEON

Collaboration & Experimental Site

- To observe the CEvNS in reactor
  - NaI(Tl) crystal: technique from COSINE-100
  - ~20 collaborators in 5 institutes

Introduction to NEON

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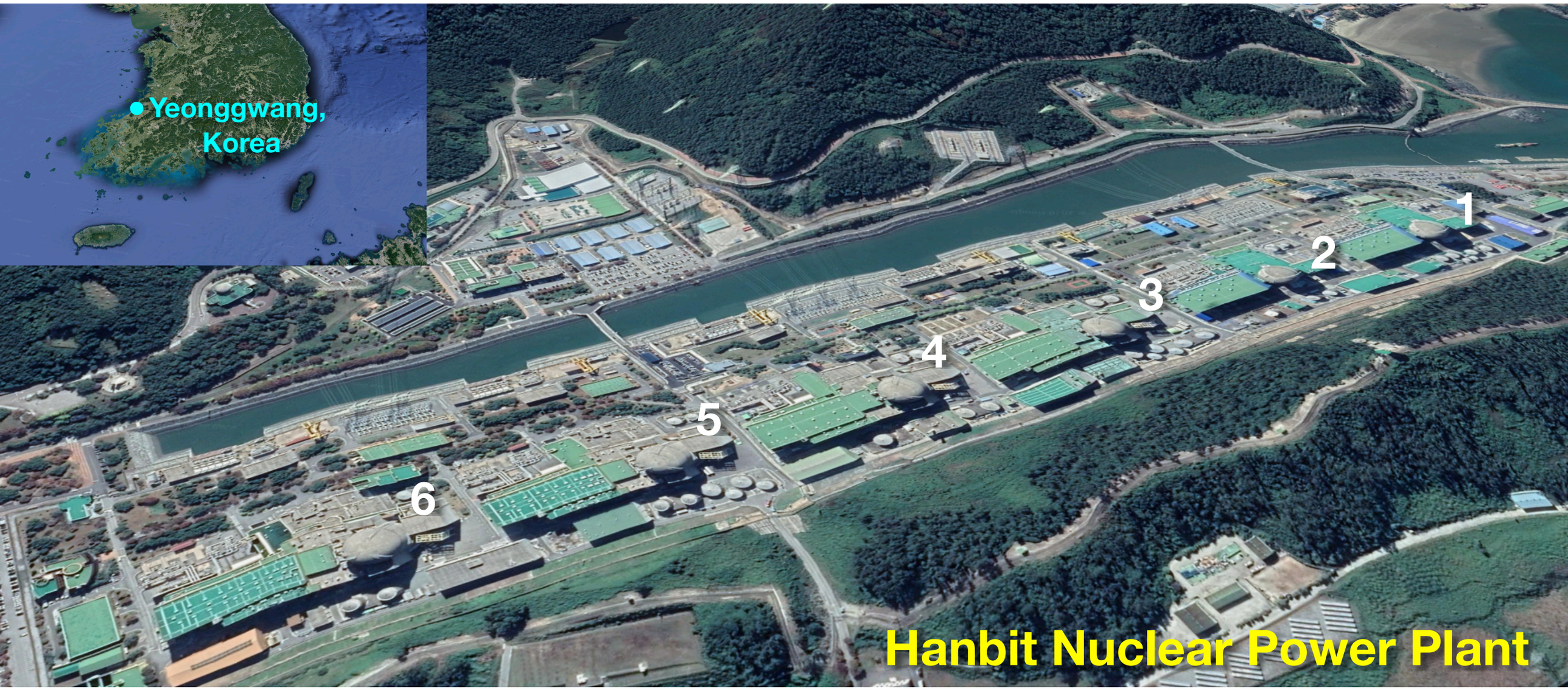

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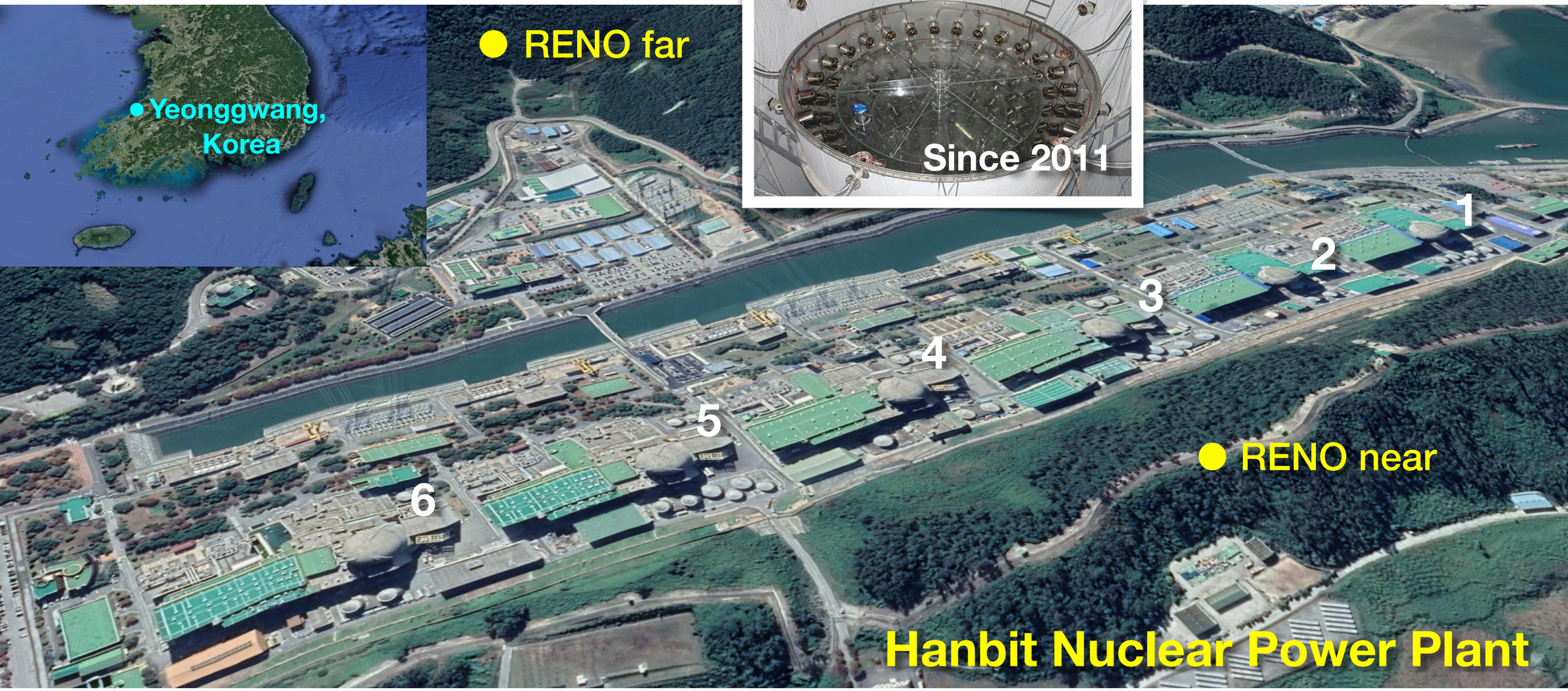

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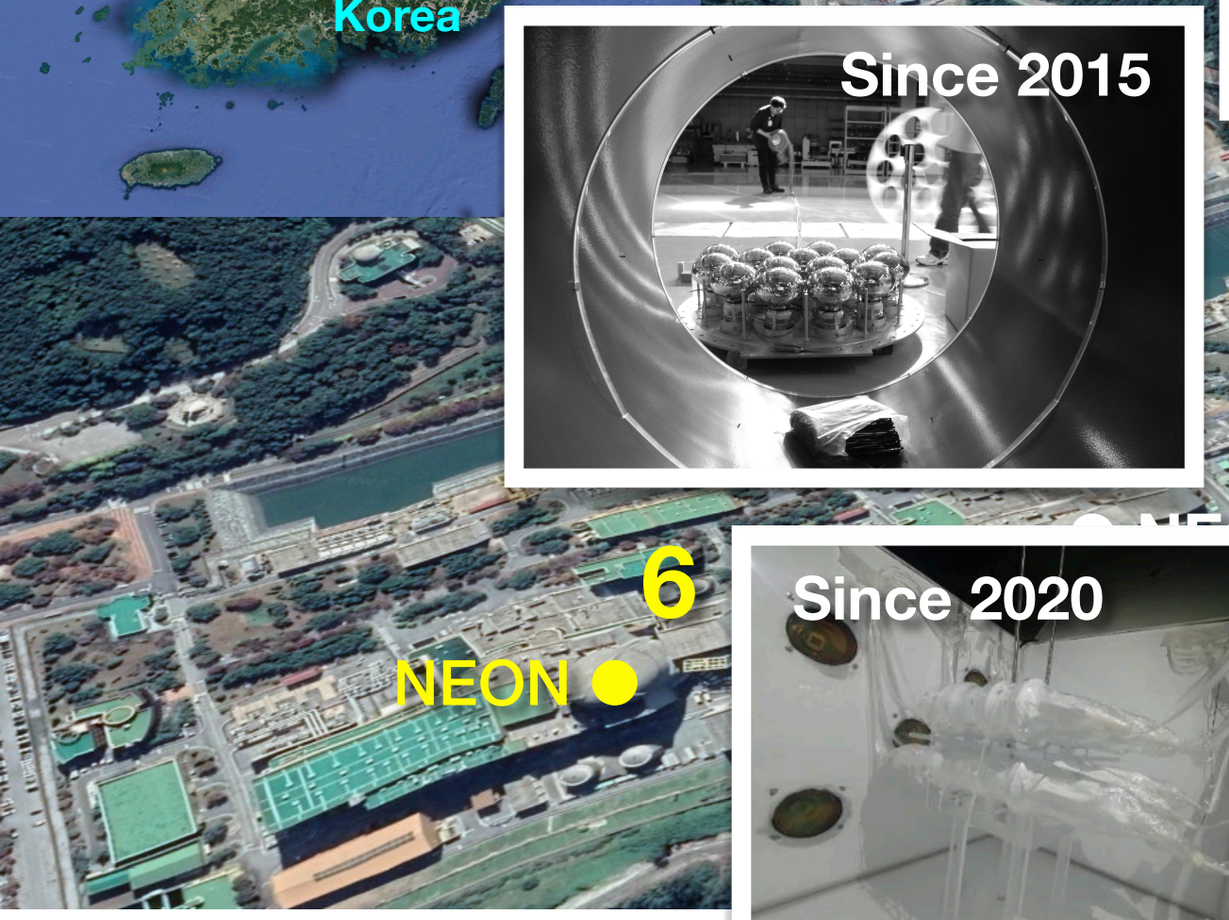

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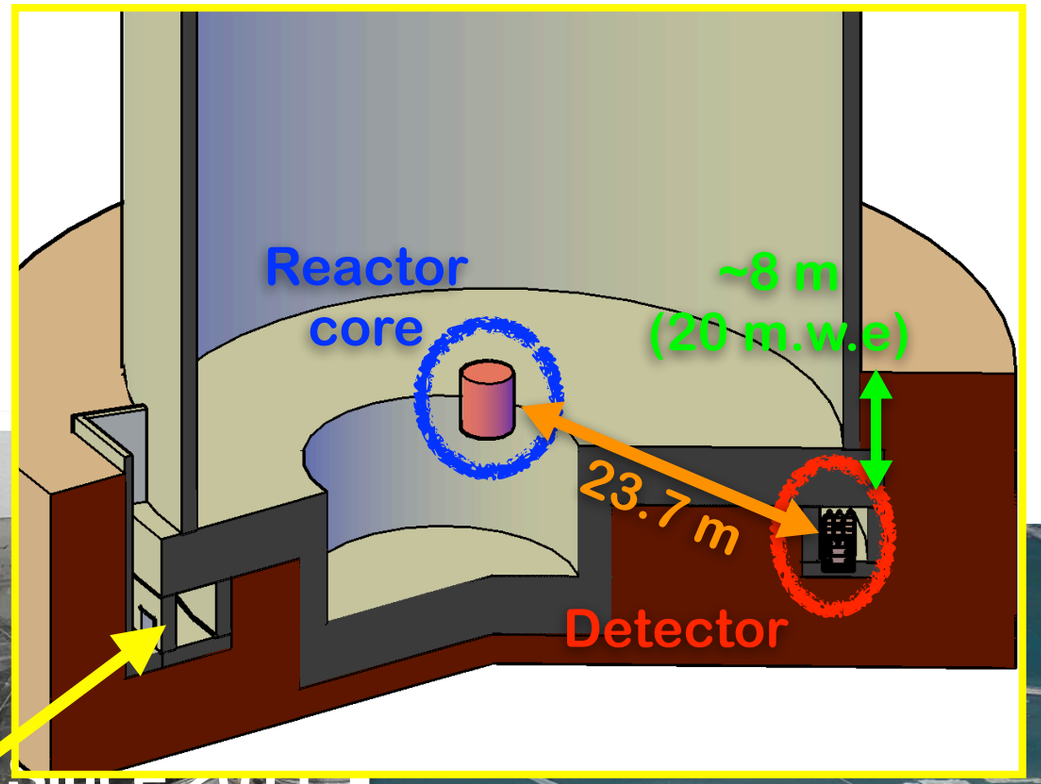
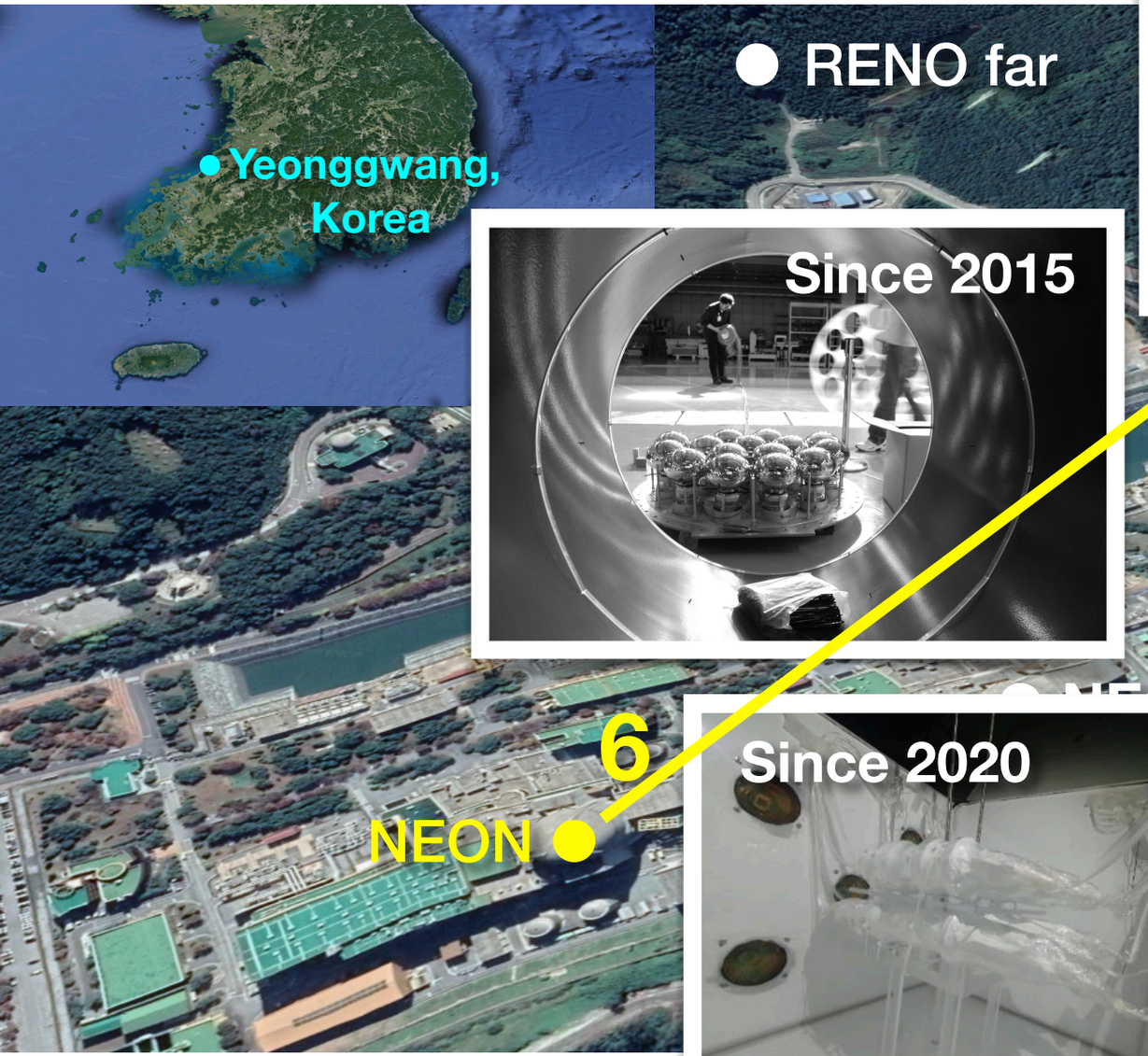
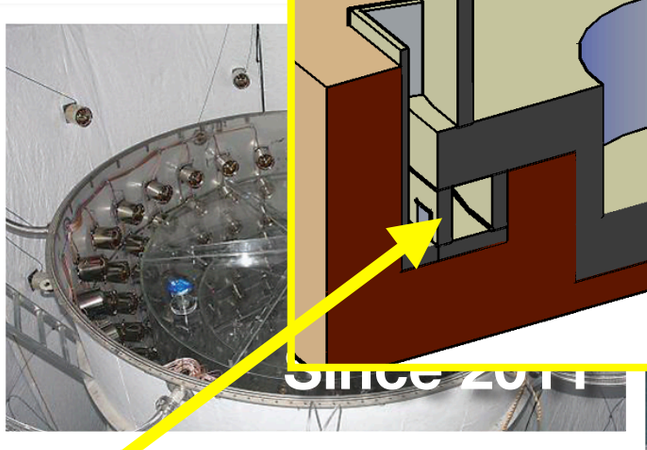




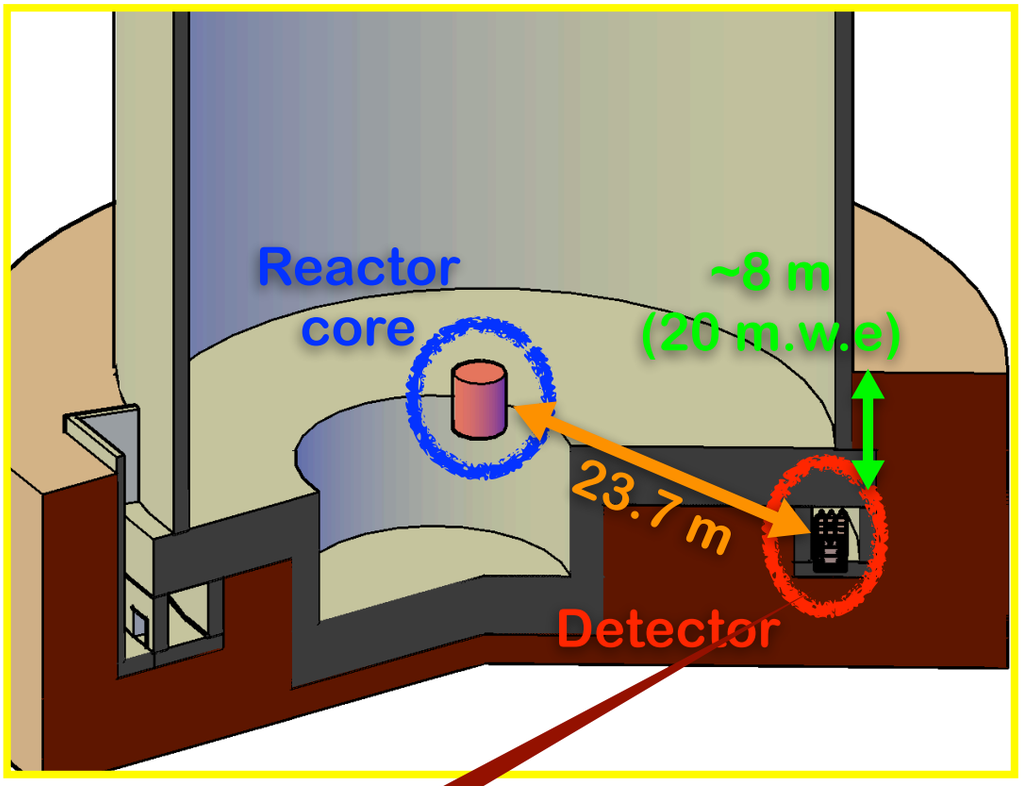


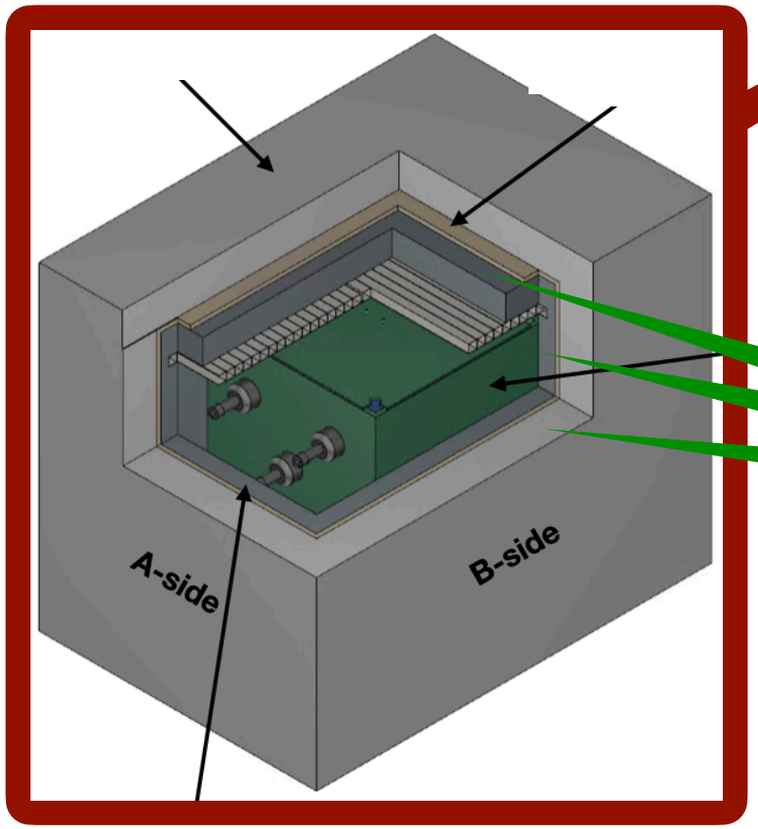
- Tendon gallery at reactor unit 5
  - 2.8-GW_{th} commercial reactor
  - Low enriched uranium fuel (4.6% ^{235}U)
  - 23.7-m baseline & 20-mwe overburden

Hanbit Nuclear Power Plant

Introduction to NEON

Detector Configuration



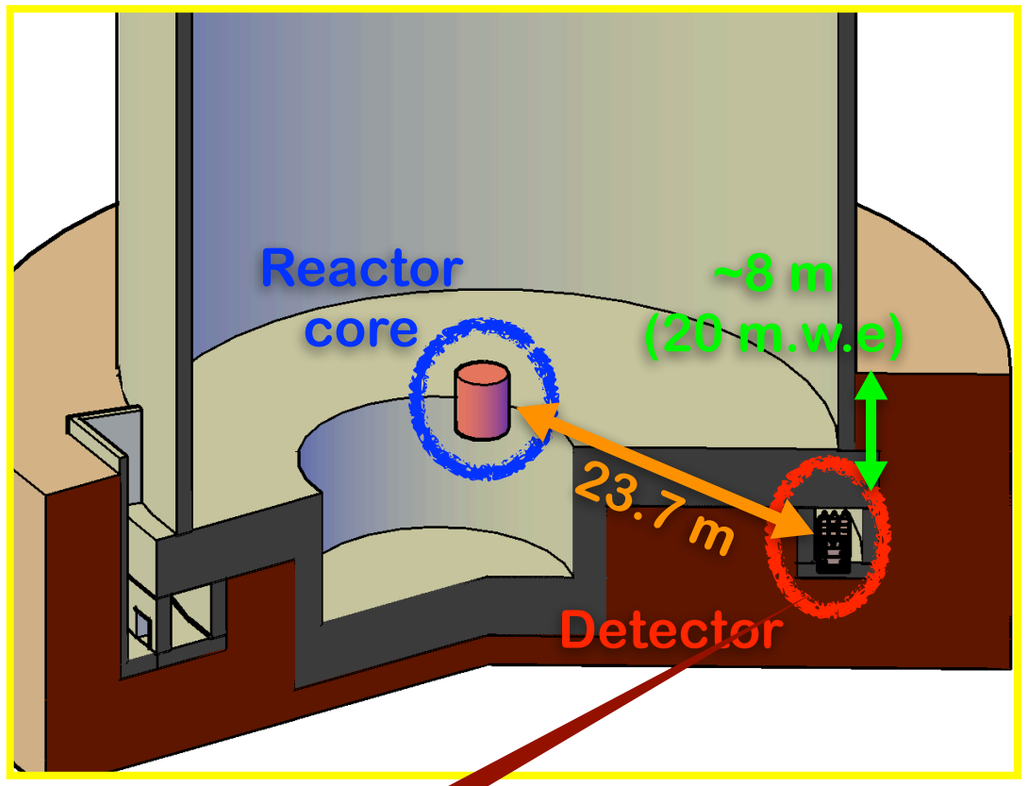


Shields

20/30-cm thick PE (n^0)
2.5-cm thick B-PE
10/15-cm thick lead shield (γ)

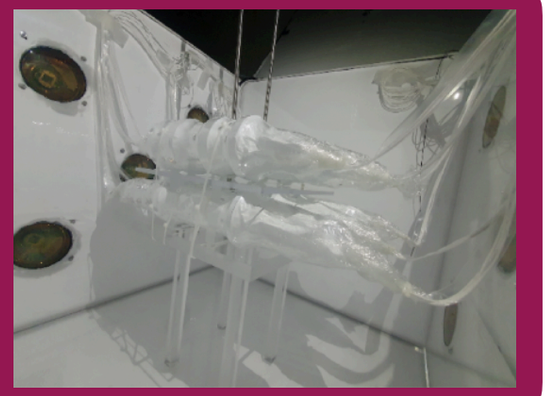
Introduction to NEON

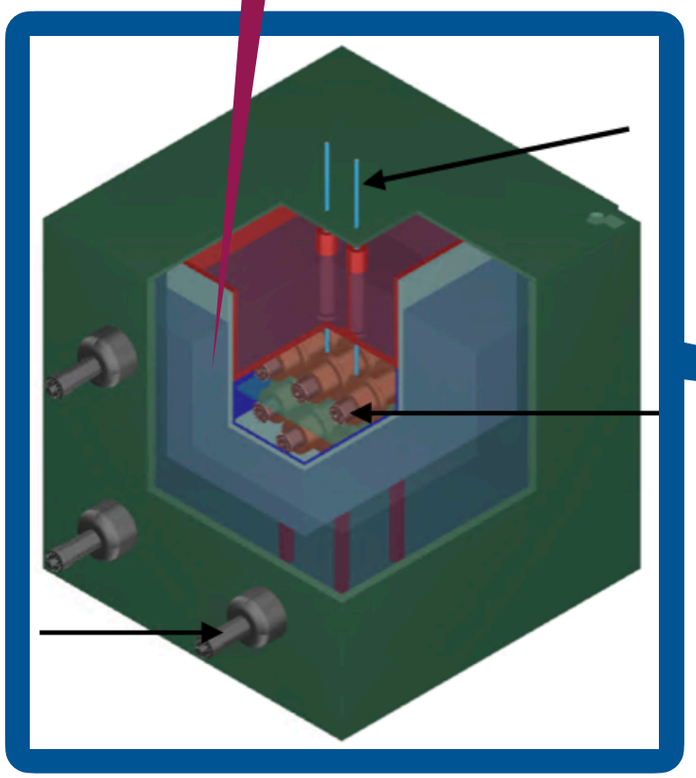
Detector Configuration

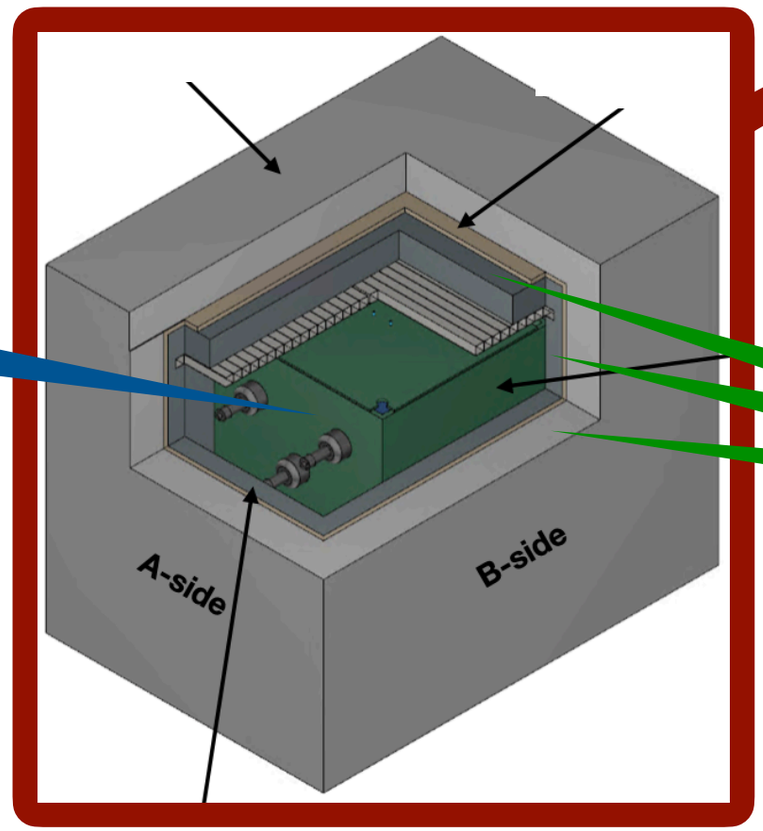


Liquid Scintillator

Passive shield
Tagging radiations
→ background reduction
10 5-inch PMTs







Shields

20/30-cm thick PE (n^0)
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10/15-cm thick lead shield (γ)

Introduction to NEON

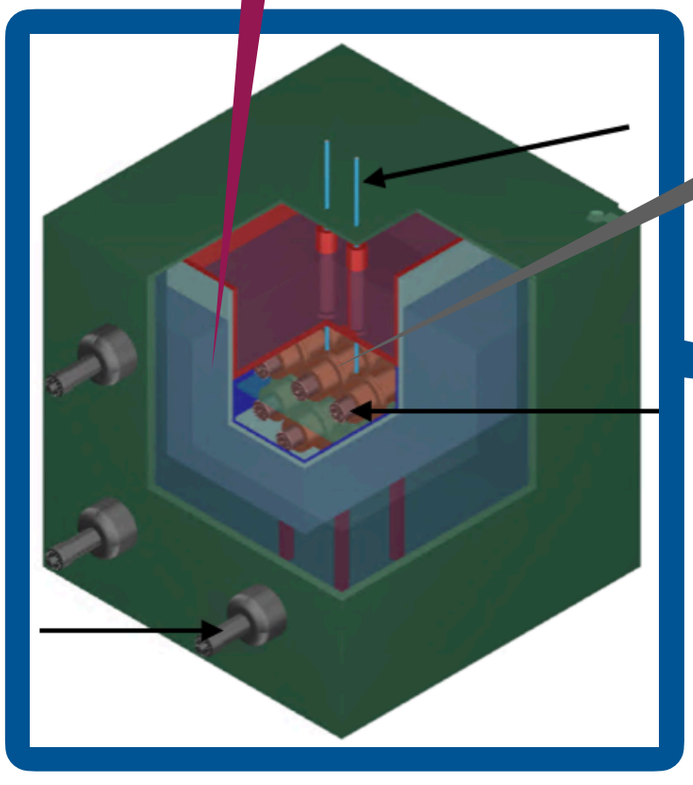
Detector Configuration

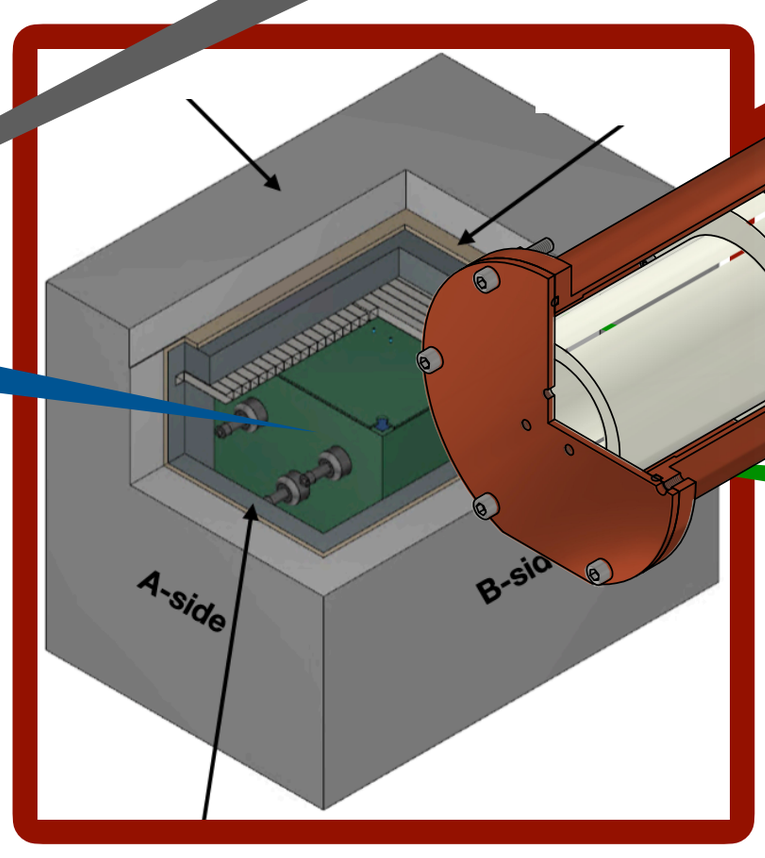
Liquid Scintillator

Passive shield
Tagging radiations
→ background reduction
10 5-inch PMTs

Active Target

6 NaI(Tl) crystals
16.8 kg of total mass
~24 NPE/keV light yield





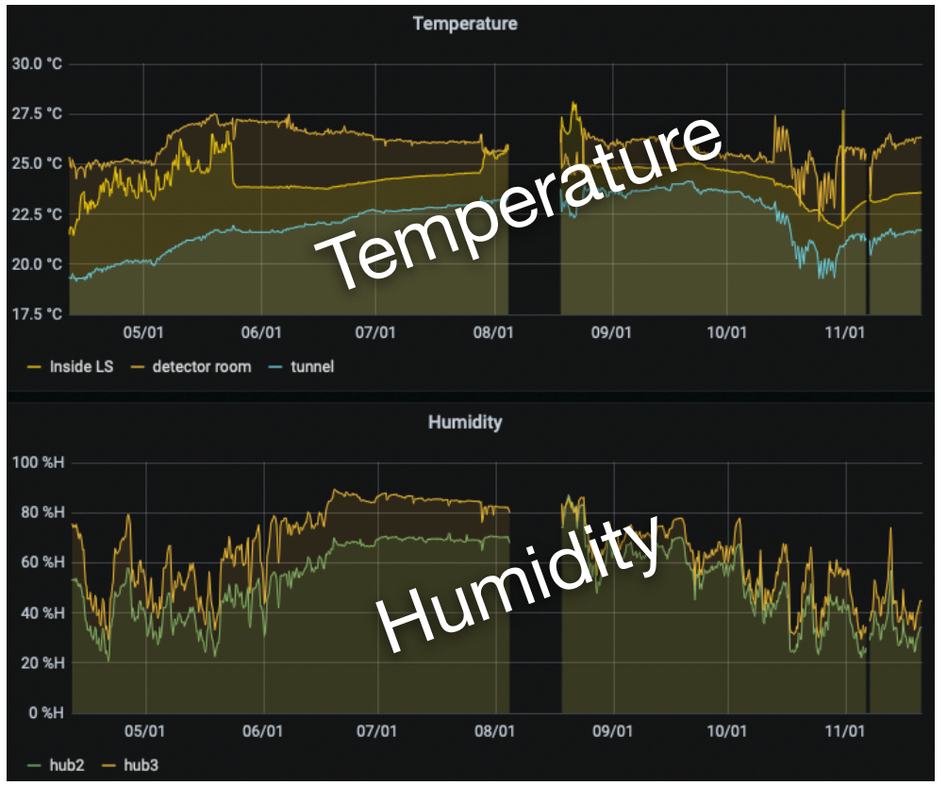
Shields

/30-cm thick PE (n^0)
2.5-cm thick B-PE
10/15-cm thick lead shield (γ)

Introduction to NEON

Operation

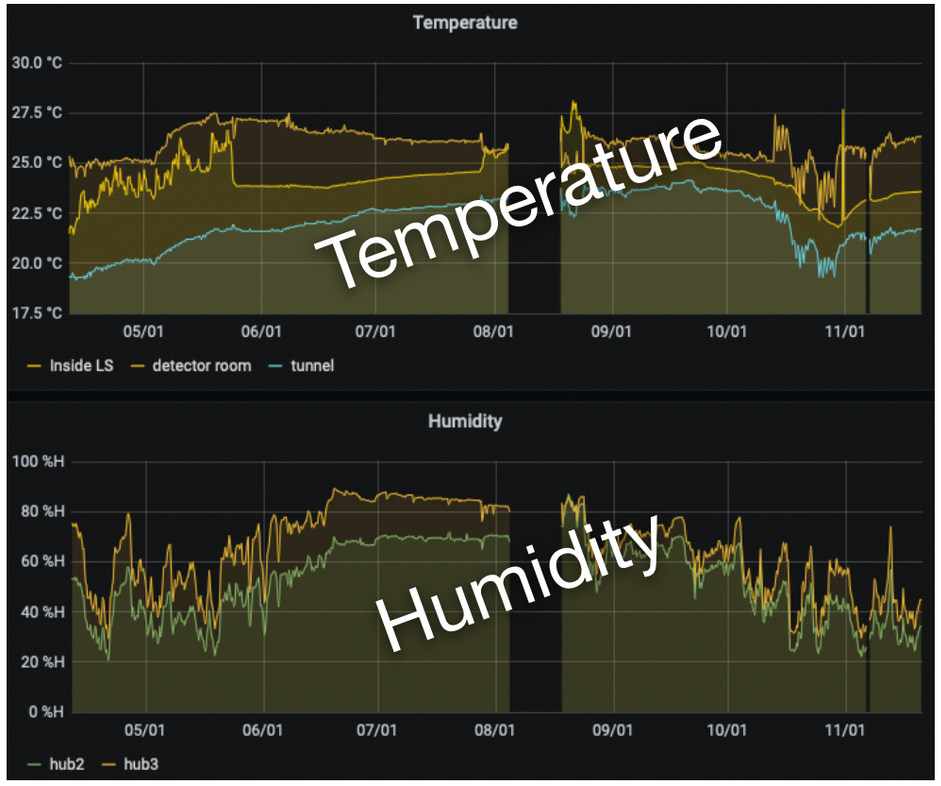
- Monitoring system
  - DAQ system: trigger rate, electronics status
  - Environmental parameter

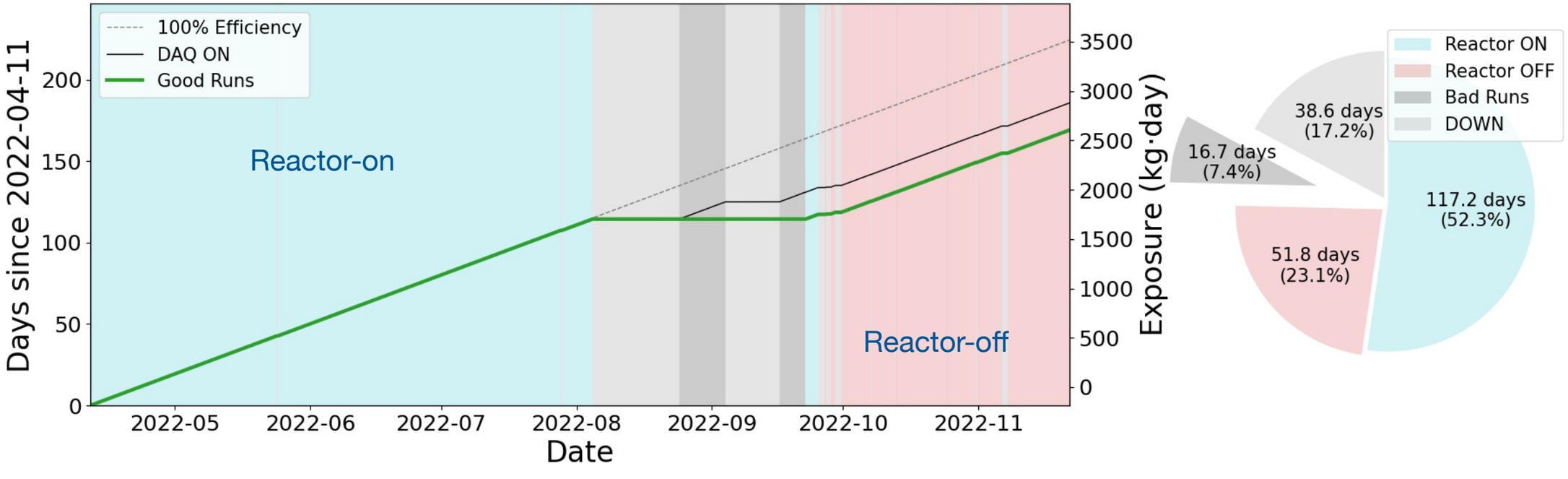


Introduction to NEON

Operation

- Monitoring system
  - DAQ system: trigger rate, electronics status
  - Environmental parameter
- Running from Apr, 2022
  - Upgrade for noise issue
  - ~83% DAQ efficiency (power outage)
  - 117-day reactor-on & 52-day reactor-off data



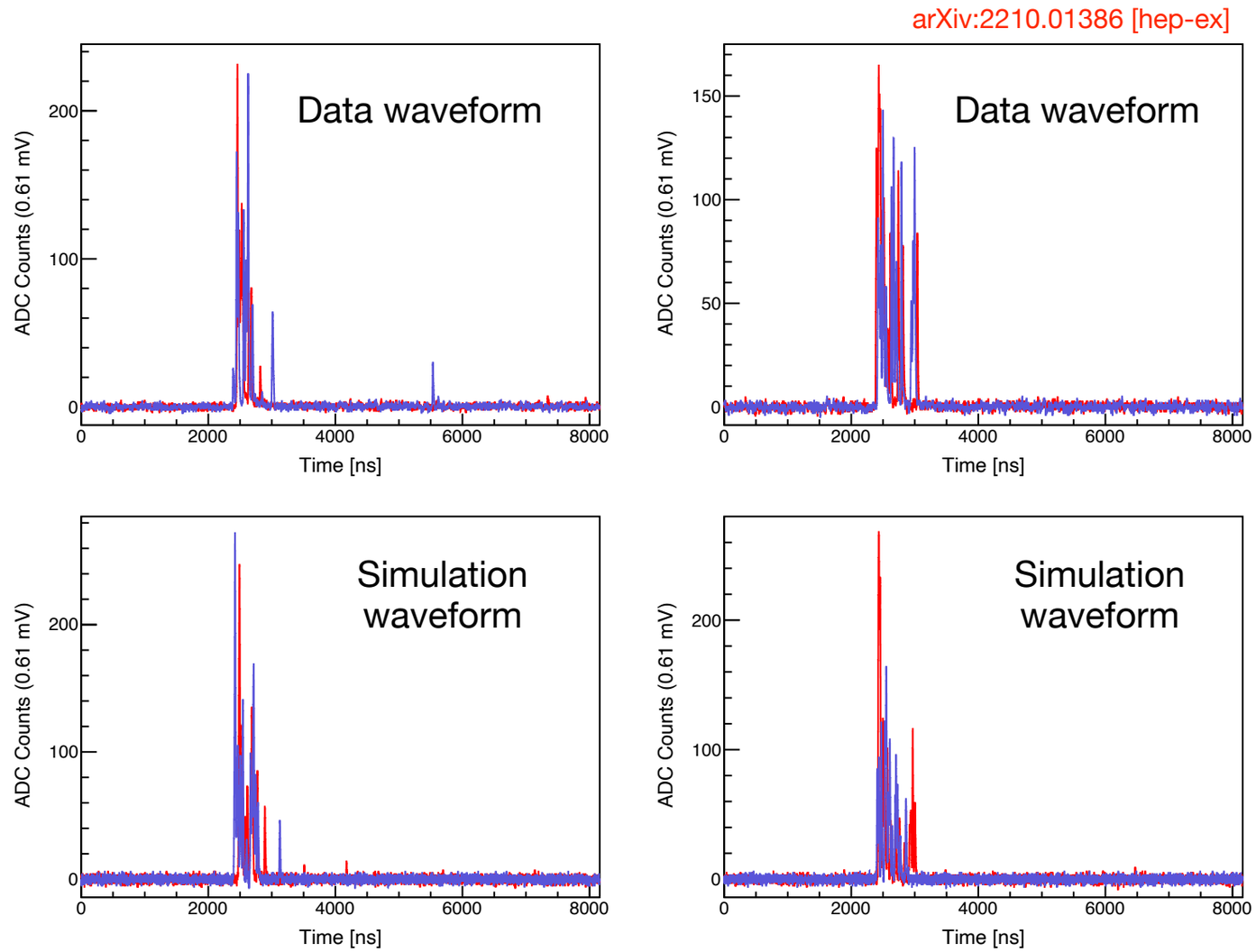


Introduction to NEON

Waveform Simulation for Event Selection

- Waveform simulation
  - Multiplier process (PMT), digitizing (ADC) & triggering (TCB)
  - Waveform generation
  - Parameter development for event selection
  - Training sample for ML/DL

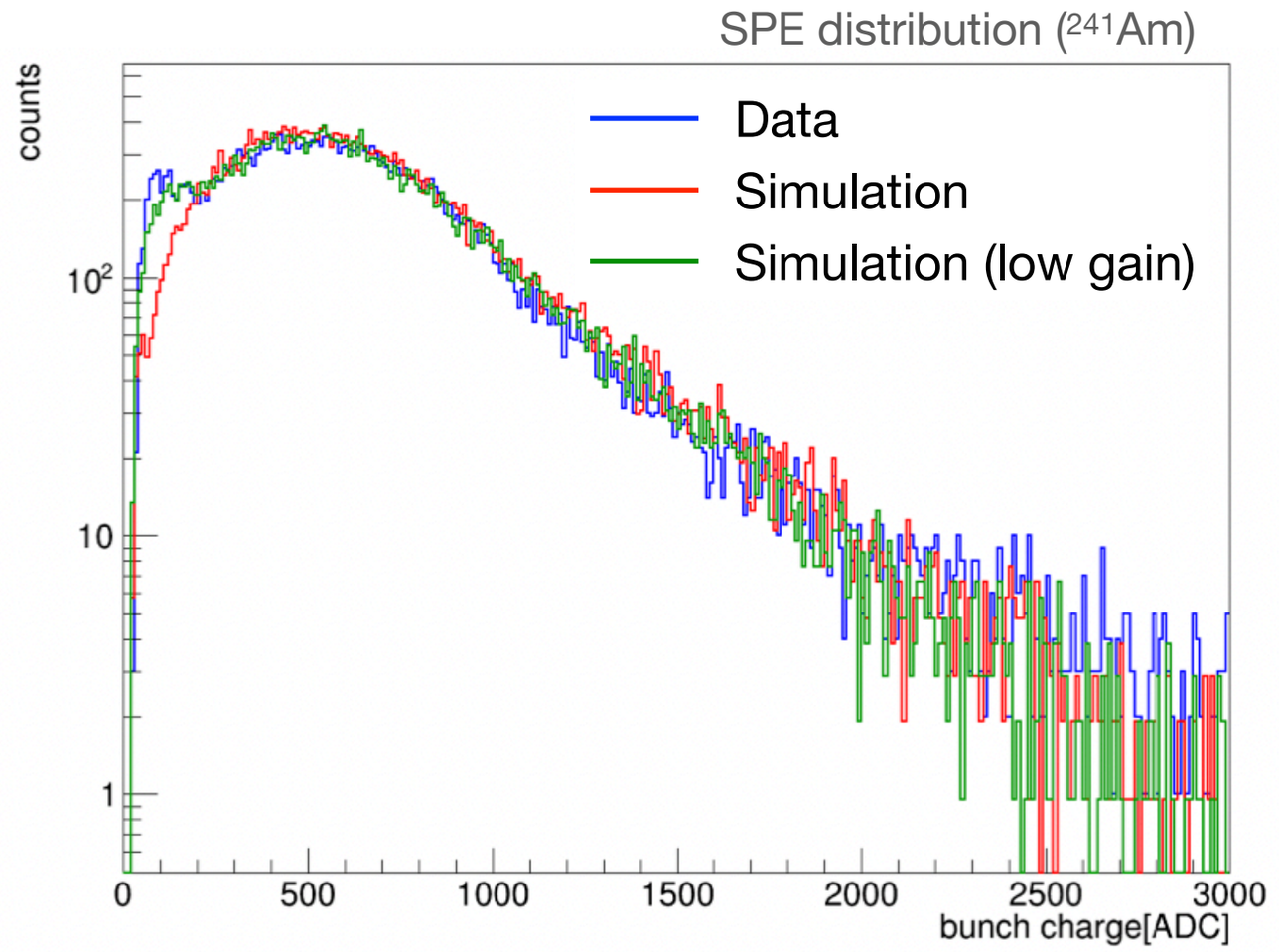
arXiv:2210.01386 [hep-ex]



Introduction to NEON

Waveform Simulation for Event Selection

- Waveform simulation
  - Multiplier process (PMT), digitizing (ADC) & triggering (TCB)
  - Waveform generation
  - Parameter development for event selection
  - Training sample for ML/DL
- Tuning simulation
  - Single photoelectron properties
    - Shape, height/width, low gain SPE



Introduction to NEON

Waveform Simulation for Event Selection

- Waveform simulation
  - Multiplier process (PMT), digitizing (AD
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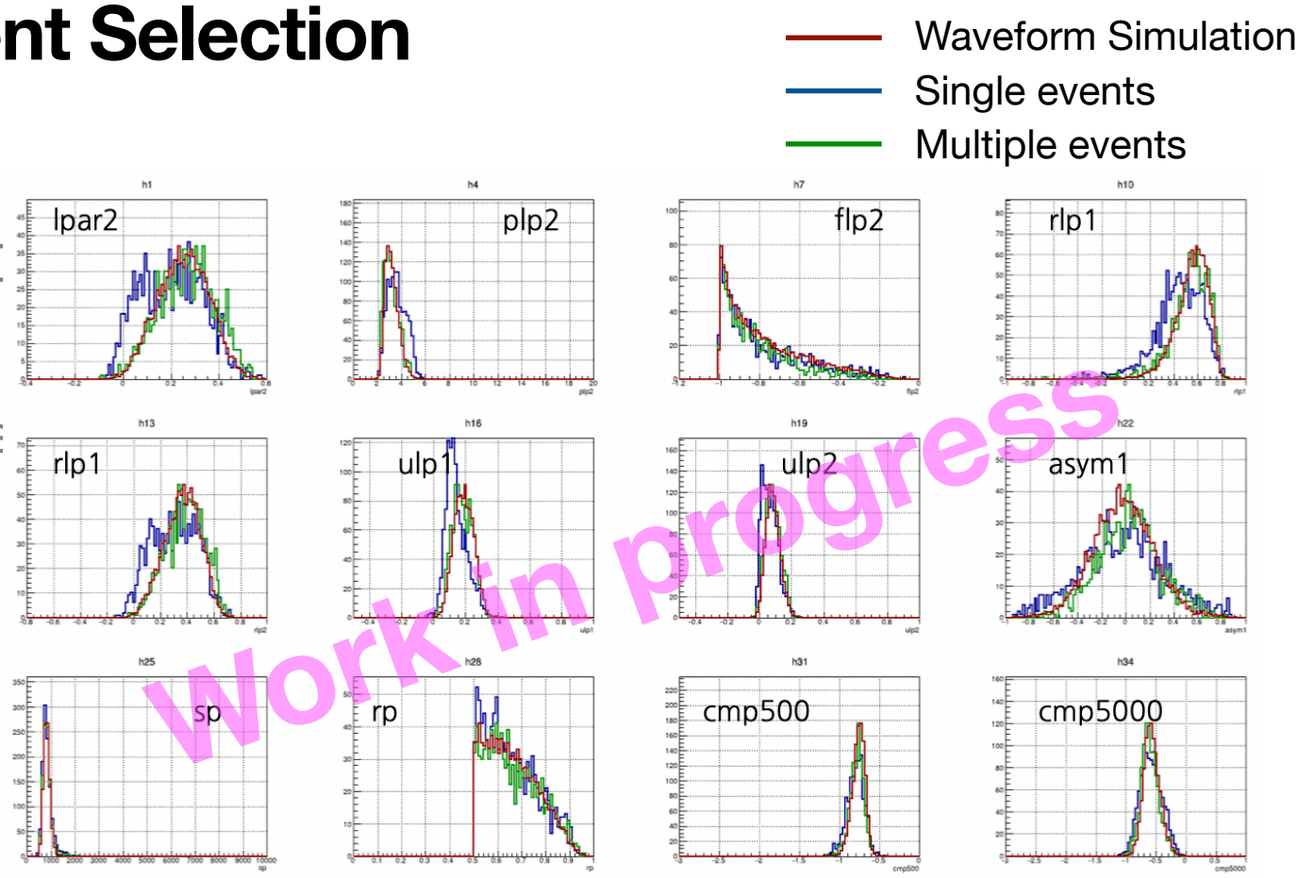
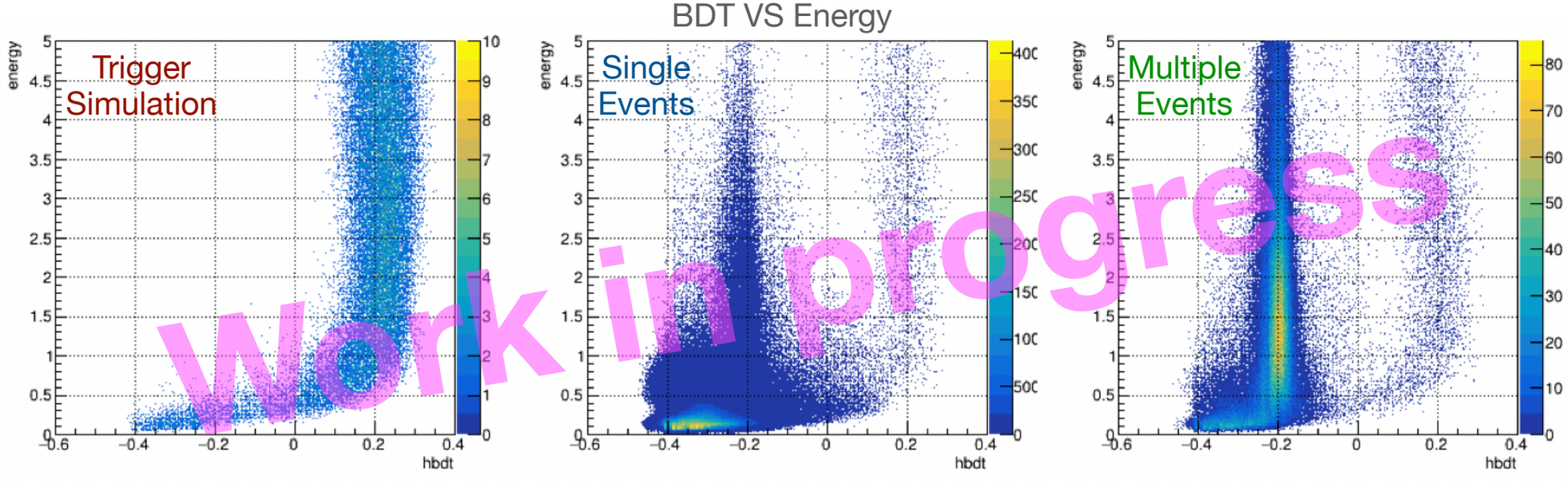
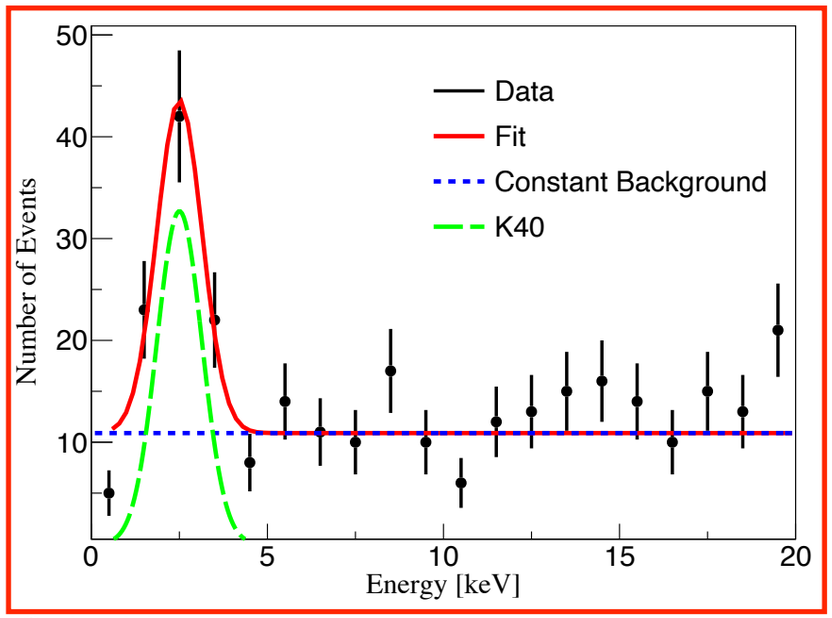
  - Parameter development for event sele
  - Training sample for ML/DL
- Tuning simulation
  - Single photoelectron properties
    - Shape, height/width, low gain SPE
  - Training via BDT





Introduction to NEON

Background Modeling



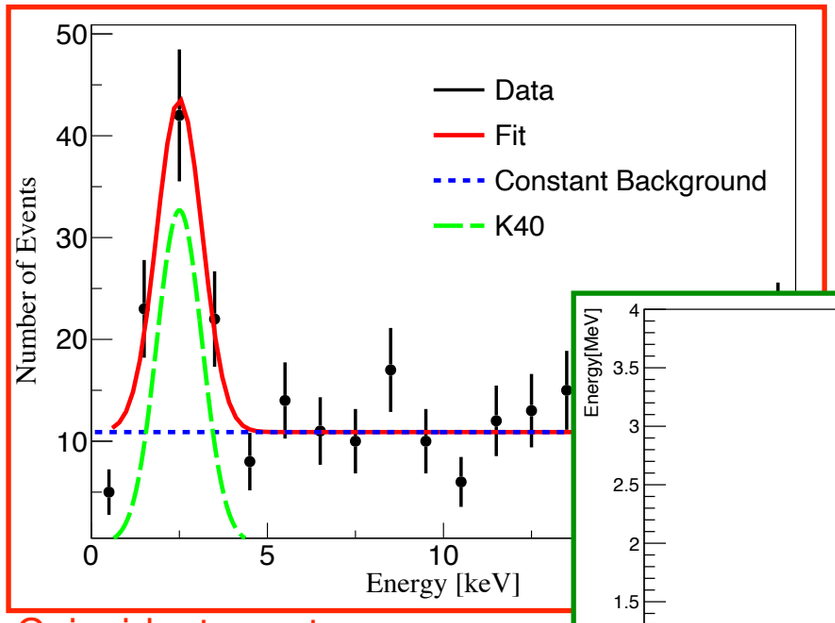
Coincident events

Crystal	Mass (kg)	Size (inch, D × L)	^{nat}K (ppb)	α Rate (mBq/kg)	^{210}Pb (mBq/kg)	^{216}Po(^{232}Th chain) (μBq/kg)	^{218}Po(^{238}U chain) (μBq/kg)
NEO-1	1.62	3 × 4	50±20	2.16±0.02	1.89±0.26	1.6±0.7	10.6±4.2
NEO-2	1.67	3 × 4	137±28	7.78±0.03	7.46±0.73	<59.8	<57.2
NEO-3	1.67	3 × 4	46±20	0.56±0.01	0.53±0.13	<3.6	<11.2
NEO-4	3.35	3 × 8	22±11	0.76±0.01	0.69±0.18	1.6±0.8	<3.3
NEO-5	3.35	3 × 8	<29	0.76±0.01	0.68±0.17	1.6±0.5	2.9±1.6
NEO-6	1.65	3 × 4	<38	0.94±0.01	0.88±0.21	5.8±1.3	11.0±3.3
COSINE-100(C6)	12.5	4.8 × 11.8	17±3	1.52±0.04	1.46±0.07	2.5±0.8	< 0.25

arXiv:2204.06318 [hep-ex]

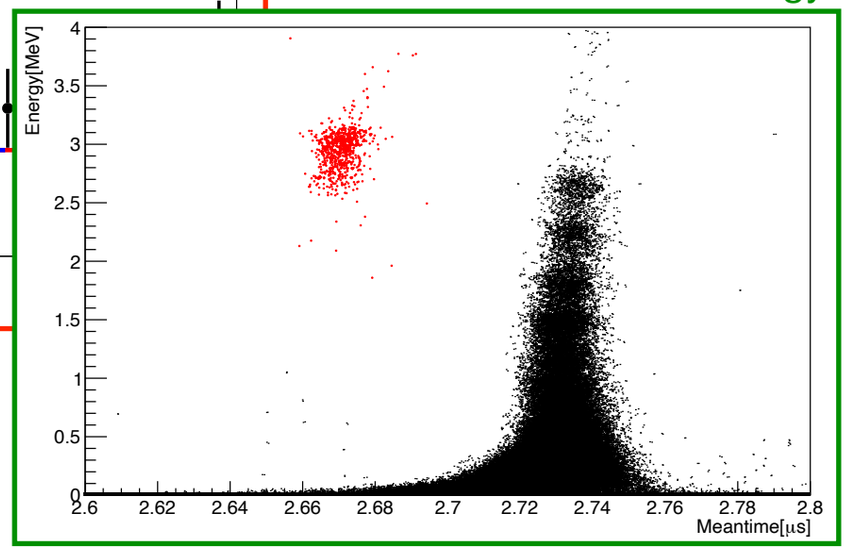
Introduction to NEON

Background Modeling



Coincident events

Meantime VS Energy



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Introduction to NEON

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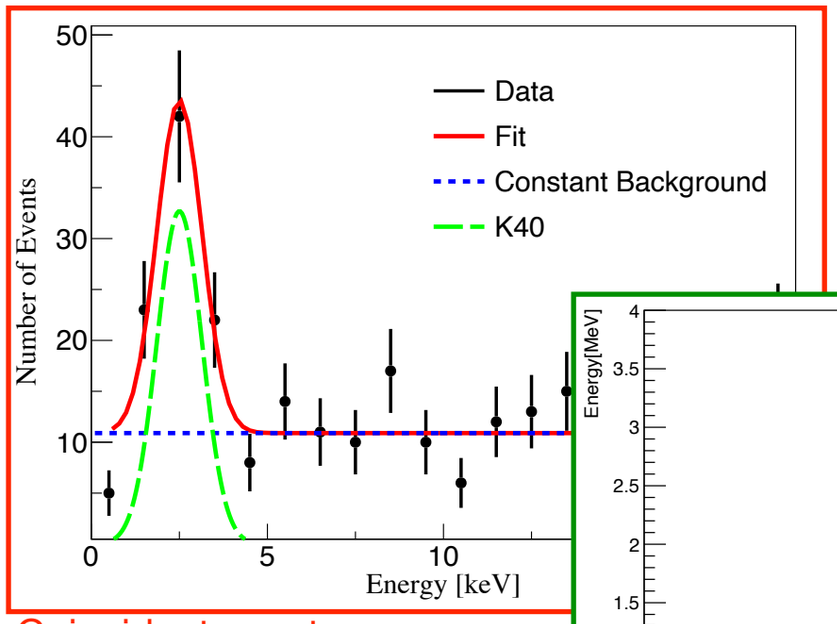

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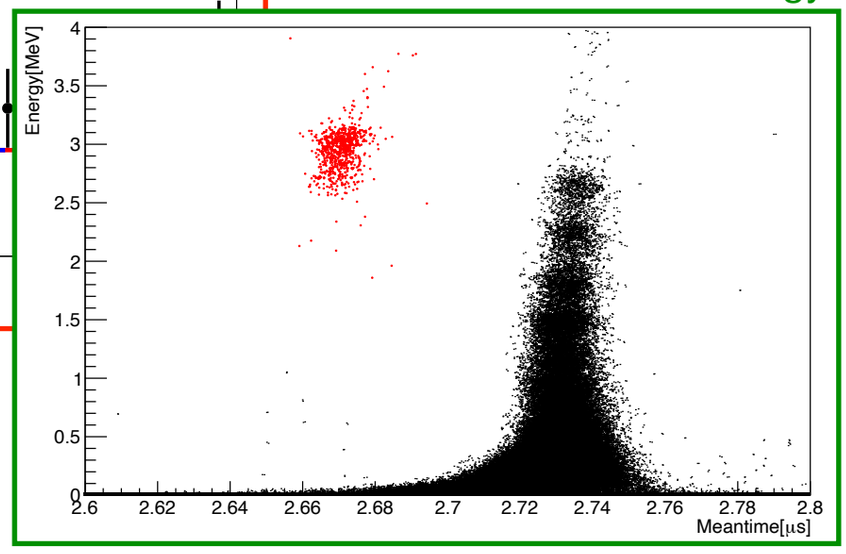
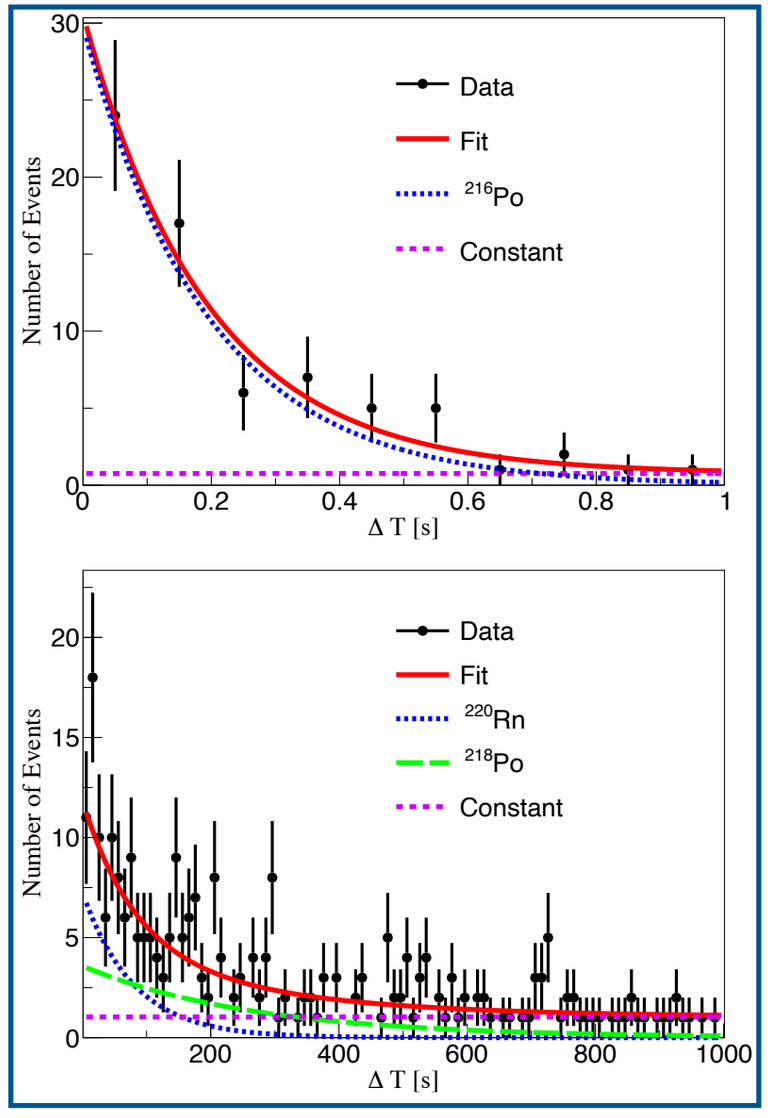


α-α coincidence



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Introduction to NEON

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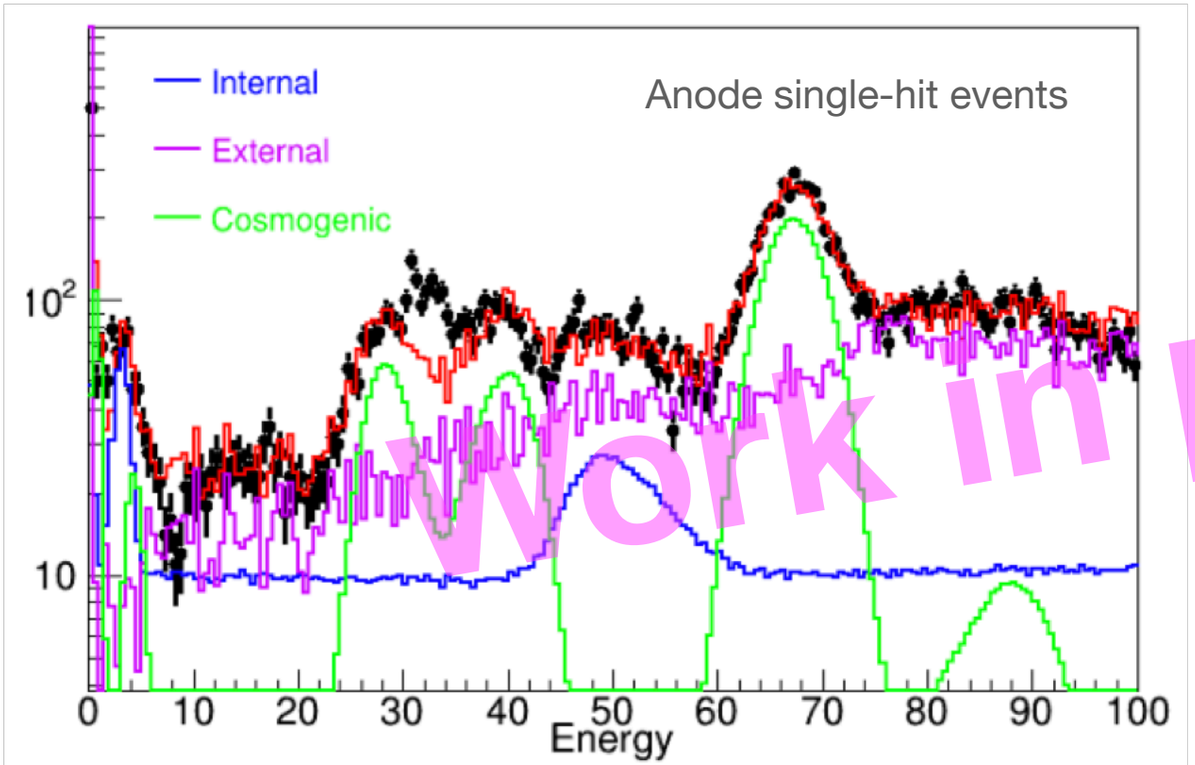

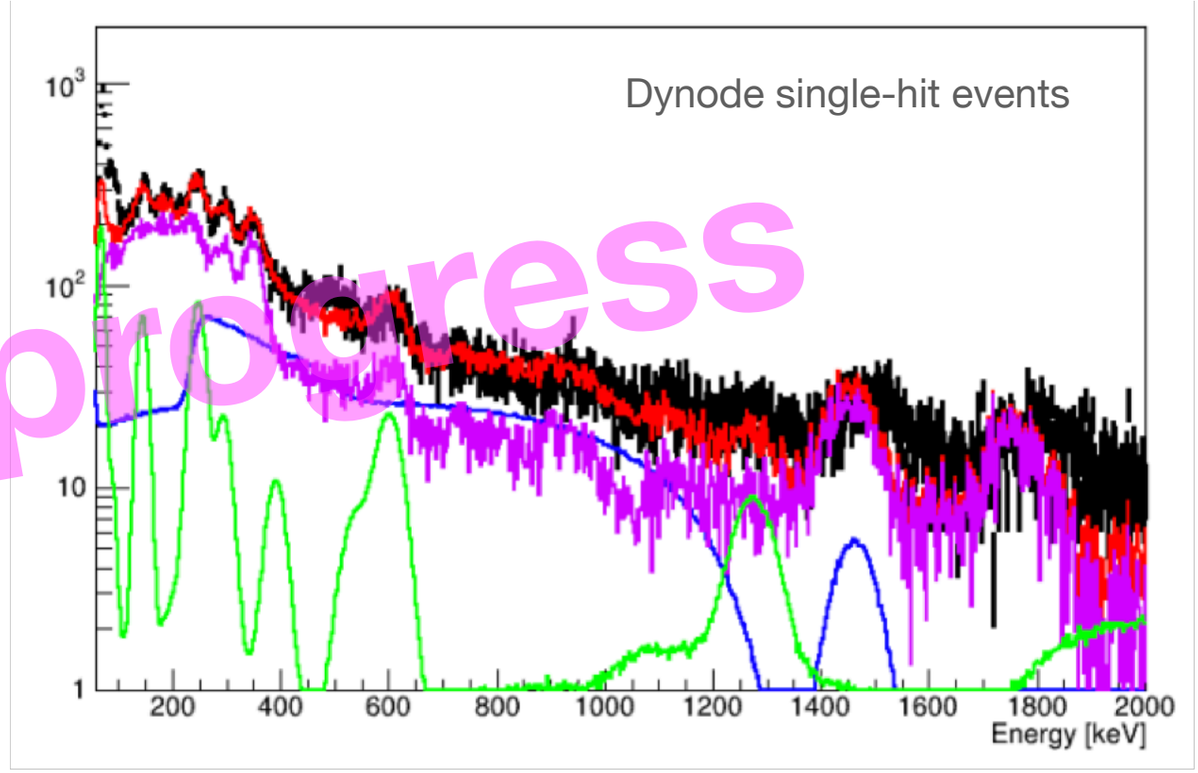

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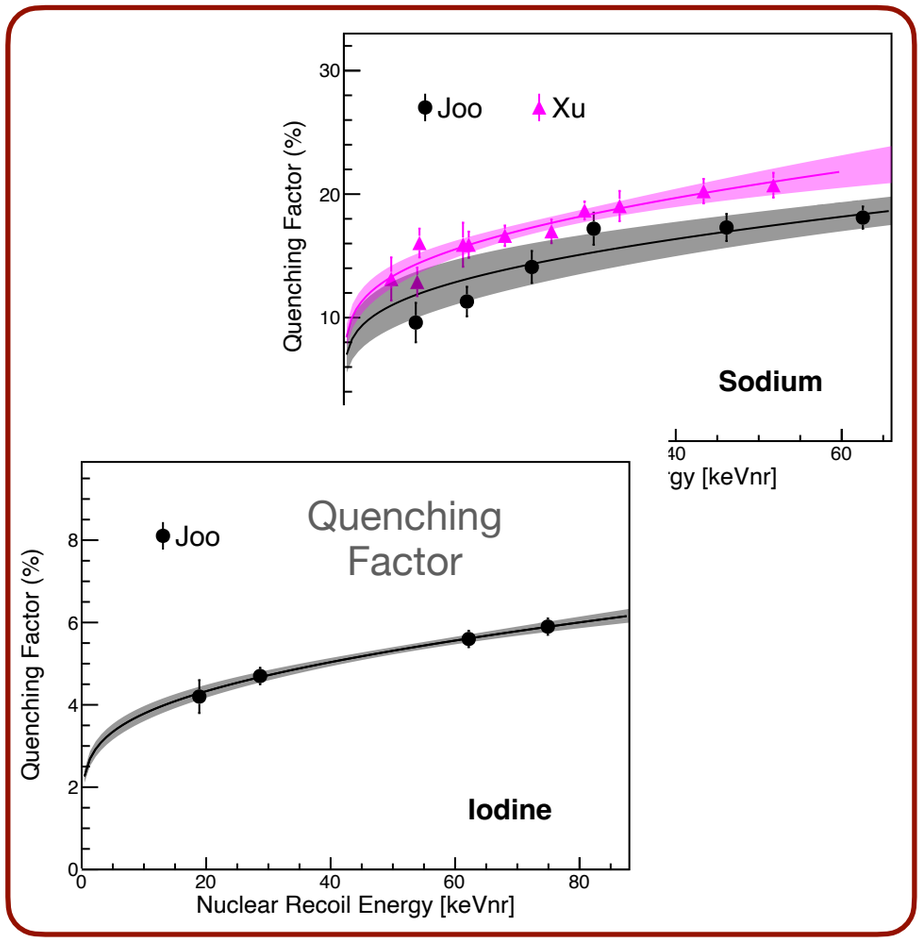
arXiv:2204.06318 [hep-ex]

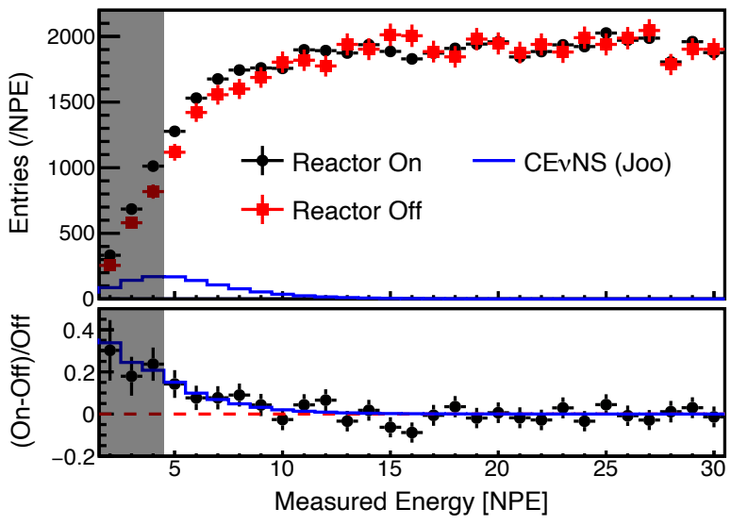
Introduction to NEON

Sensitivity

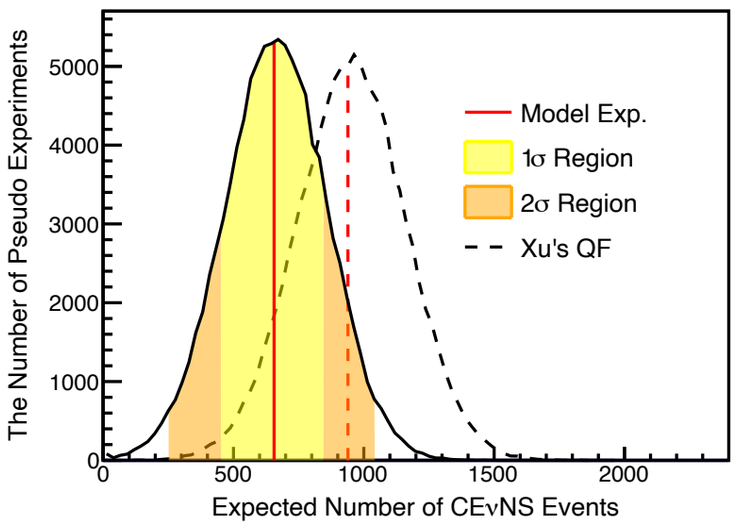
- Pseudo data
  - 7-counts/kg/keV/day background level
  - Quenching factor: Joo's & Xu's
  - 1-year-reactor-on & 100-day-reactor-off period



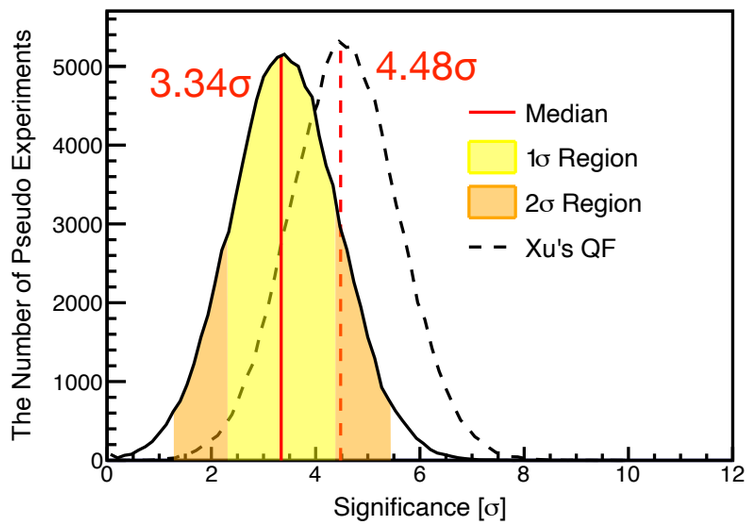
Pseudo Data



Expected # of CEvNS



Discovery Sensitivity

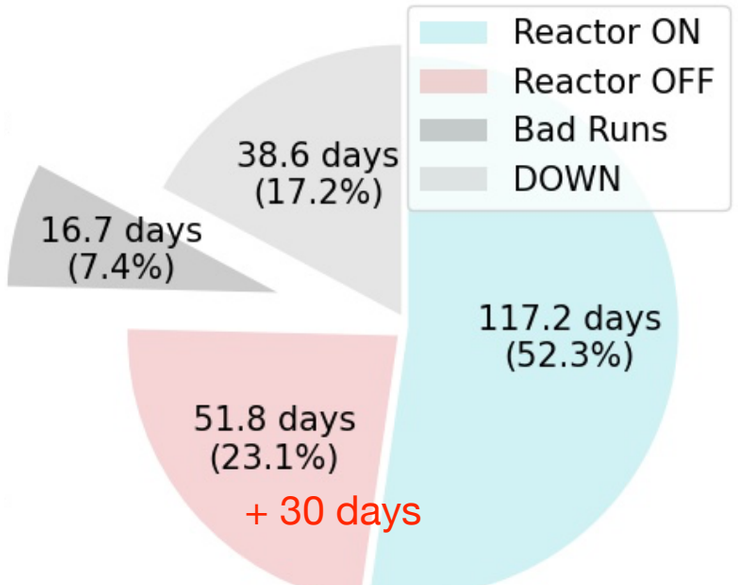


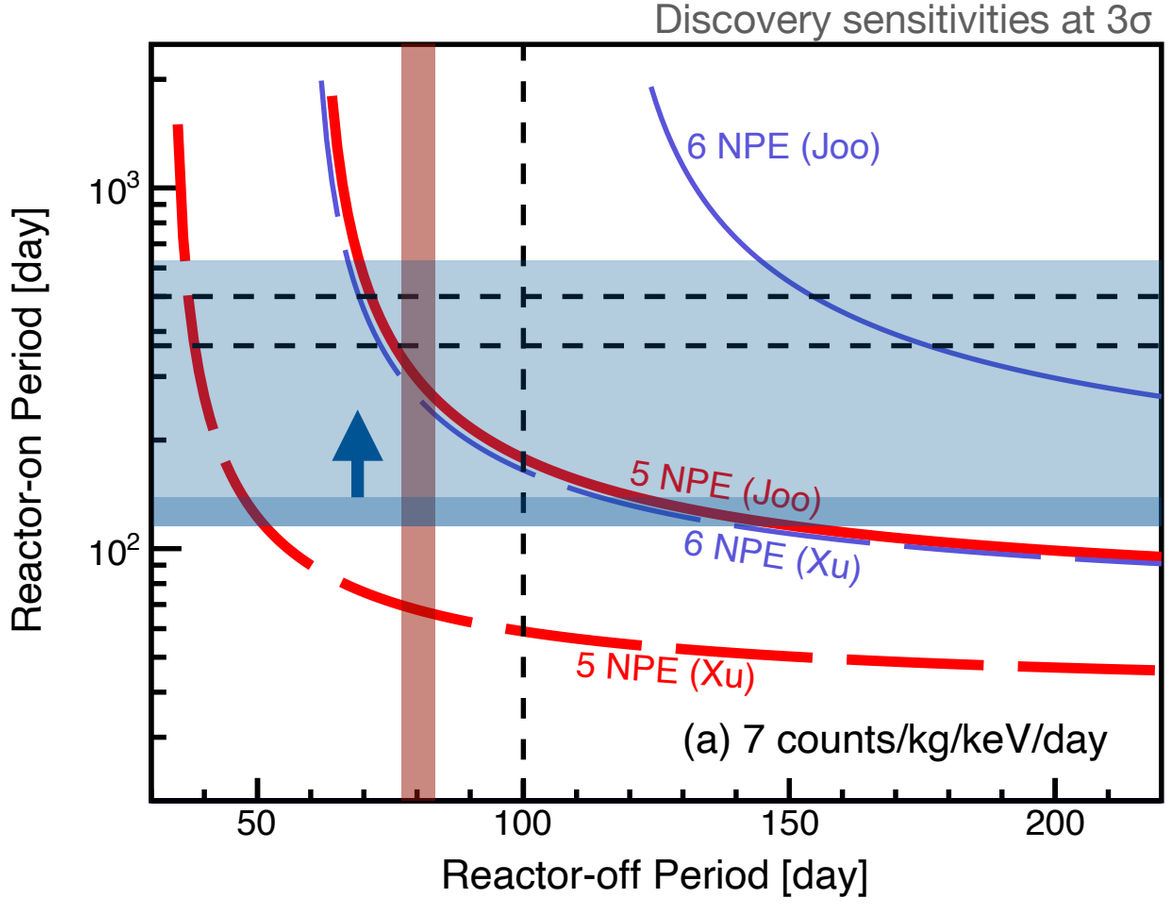
arXiv:2204.06318 [hep-ex]

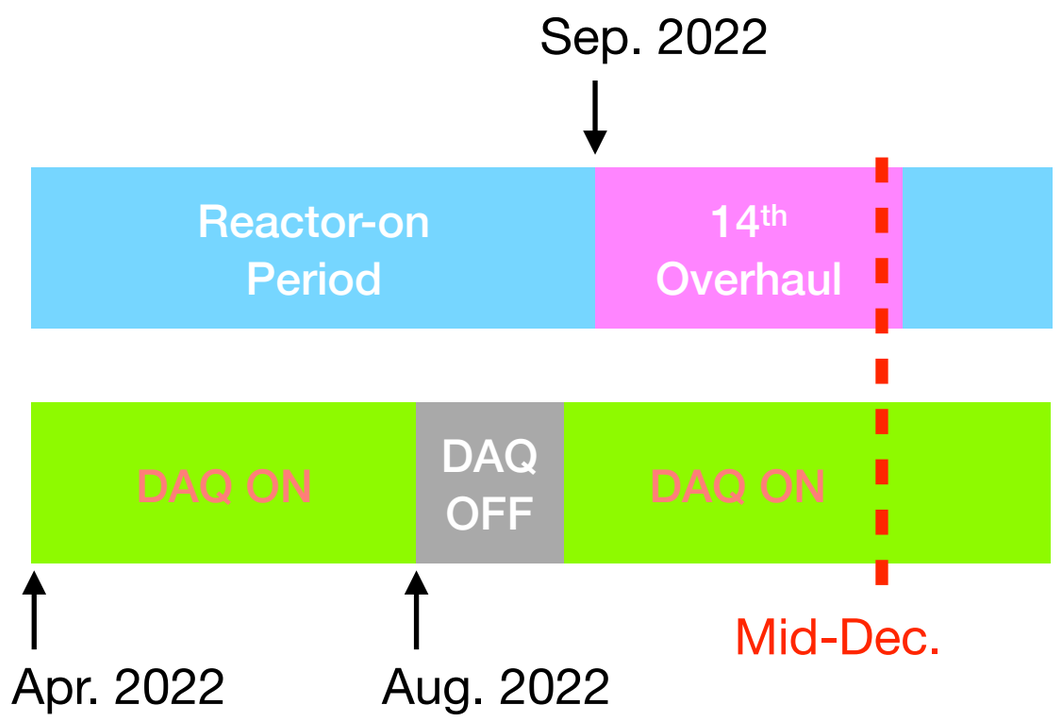
Introduction to NEON

Sensitivity

- Pseudo data
  - 7-counts/kg/keV/day background level
  - Quenching factor: Joo's & Xu's
  - 1-year-reactor-on & 100-day-reactor-off period
- ~80 days of reactor-off period & 120-day-on data







arXiv:2204.06318 [hep-ex]

Summary

- COSINE-100
  - To test the DAMA/LIBRA's signature w/ the same target, NaI(Tl)
  - WIMP extraction analysis
    - Excluding the region allowed by DAMA/LIBRA
    - Alternative scenarios are also covered, such as EFT & different QF
  - Modulation analysis
    - Model independent test
    - Cannot draw any conclusion yet
  - Plan for next phase
    - Lower background, lower threshold
    - COSINE-100 upgrade will start in the middle of next year.
    - Preparations for COSINE-200 are also underway.
- NEON
  - To observe CEvNS w/ reactor neutrinos
  - Detector has been running stably since last Apr.
  - Event selection & background modeling are ongoing.

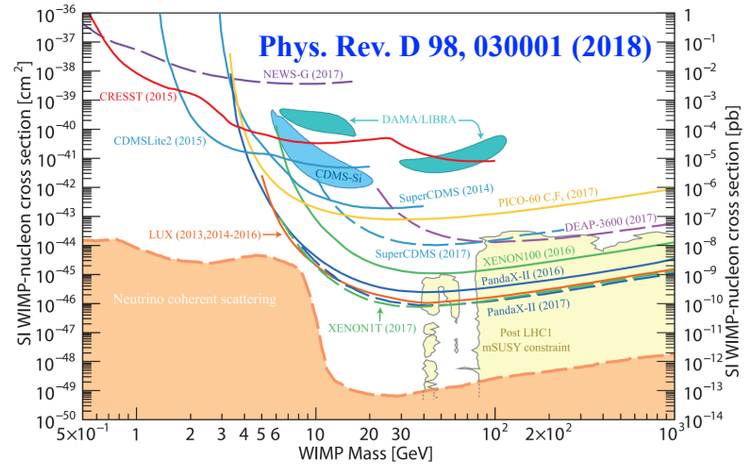
Thank You

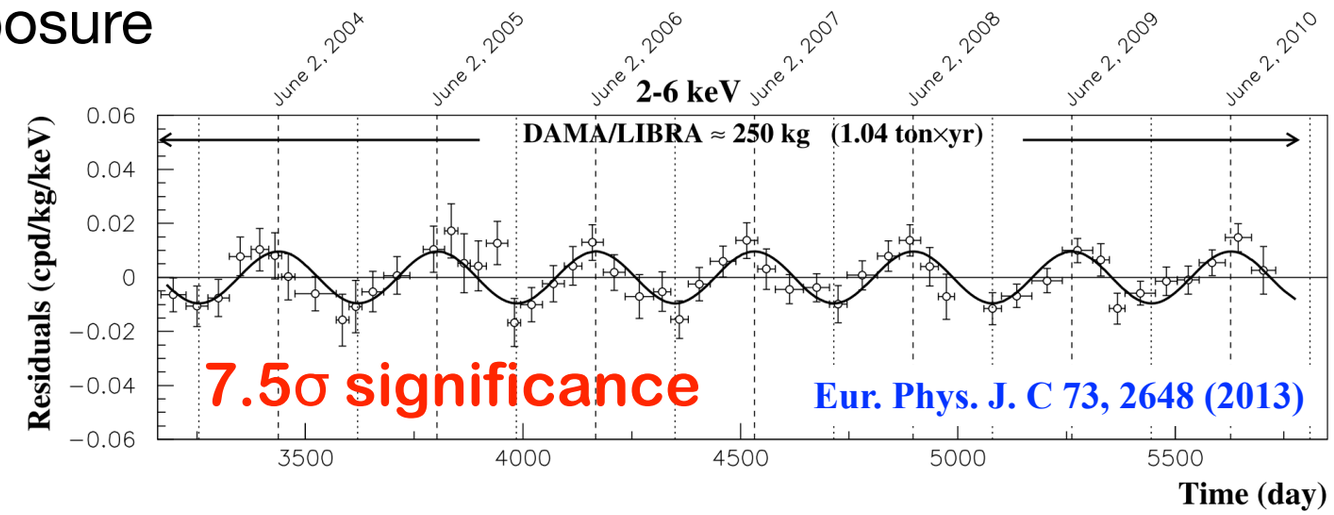
for Your Attention !!!

Backup

Phenomenological Condition

- There is no sign of SI WIMPs for > ~10^{-46} cm² at 30 GeV/c².
- Recent projects focus on the very low mass range below 10 GeV/c².
- DAMA/LIBRA experiment
  - Search for Dark matter (DM) annual modulation signature
  - 25×9.7-kg NaI(Tl) crystals @ LNGS, Italy
  - 1.04-ton×yr exposure

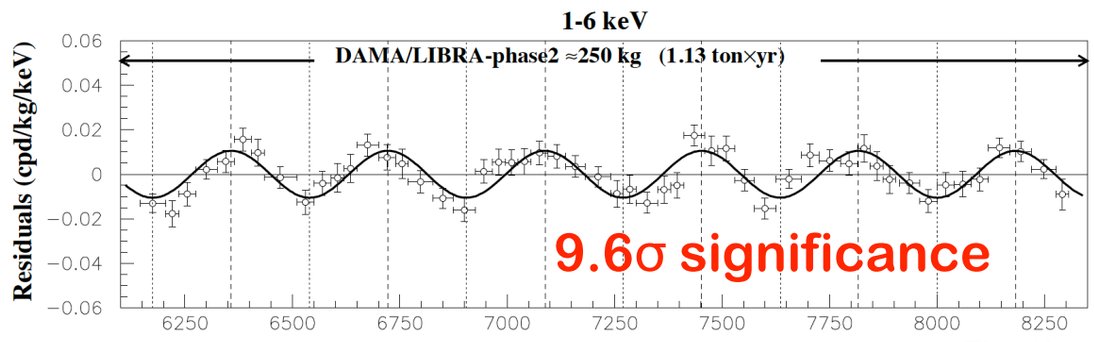


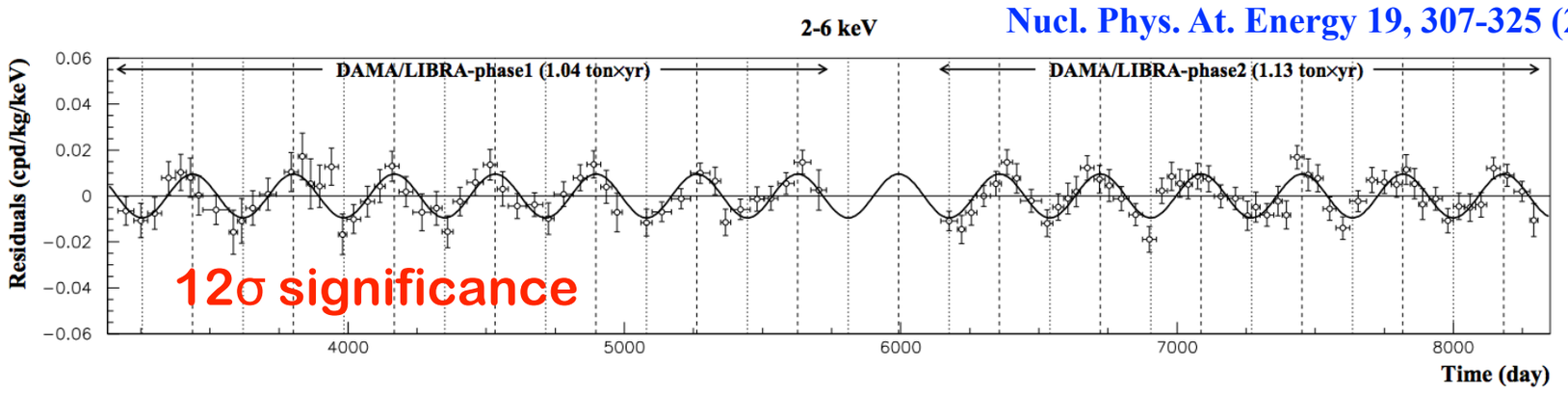


- DAMA/LIBRA claimed an **observation of the DM** at **7.5σ** C.L.
  - Using single-hit events in the 2-6 keV
  - Signal consistent with DM in terms of phase and period (phase = 144 ± 8 days & period = 0.998 ± 0.002 yr)

DAMA/LIBRA-phase2

- 1.13-ton×yr exposure
- The analysis threshold was lowered from 2 keV to 1 keV in phase2
- DM annual modulation signal is also observed in phase2.
  - Signal significance
    - **9.6σ** C.L. w/ phase2 only (1-6 keV, 1.13-ton×yt)
    - **12.0σ** C.L. w/ phase1+2 (2-6 keV, 2.17-ton×yt)

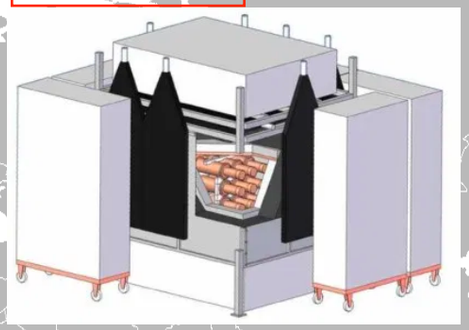




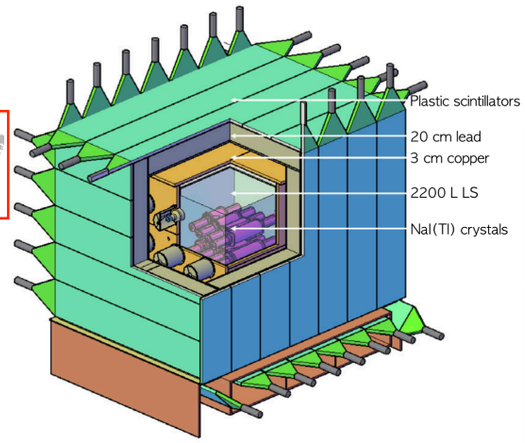
  - The results are still compatible with the nature of DM candidates.
    - phase = 145 ± 5 days & period = 0.9987 ± 0.0008 yr
    - Measured amplitude of annual modulation is 0.0096 ± 0.0008 counts/day/kg/keV.
- There are several experiments using the NaI(Tl) to test DAMA/LIBRA's signal.

Global Efforts using NaI(Tl)

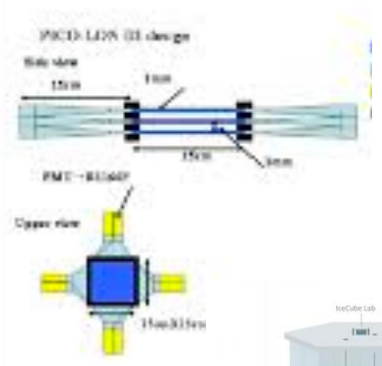
ANAIS
@ Canfranc



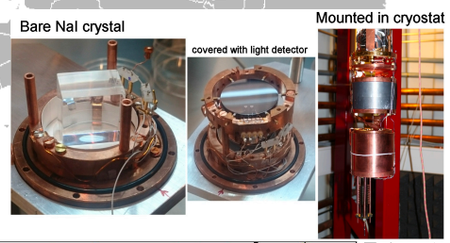
KIMS/COSINE
@ Yangyang



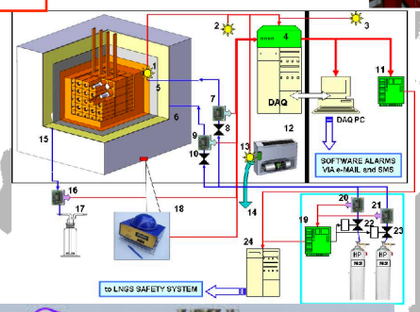
PICO-LON
@ Kamioka



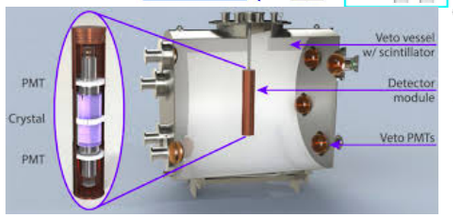
COSINUS
@ LNGS



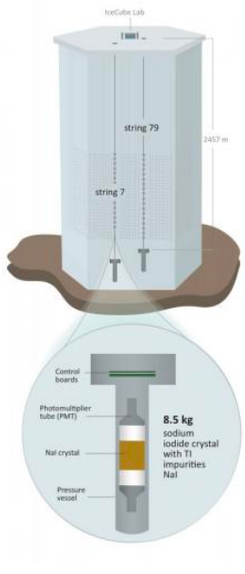
DAMA/LIBRA
@ LNGS



SABRE
@ LNGS & Stawell

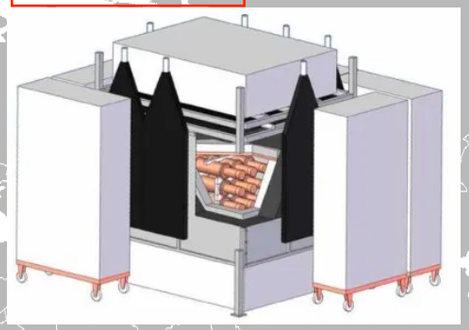


DM-Ice
@ South Pole



Global Efforts using NaI(Tl)

ANAIS
@ Canfranc



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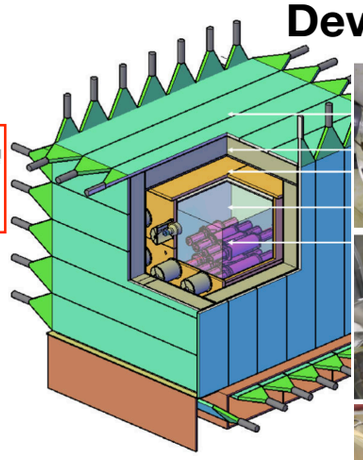

COSINUS
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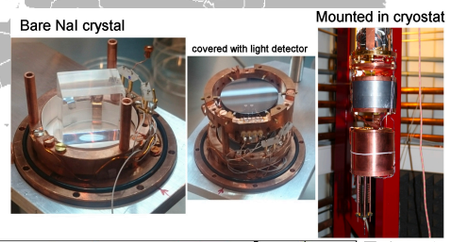

DAMA/LIBRA
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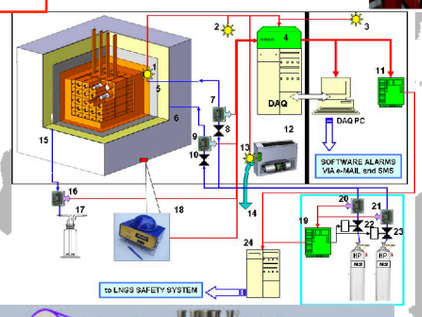
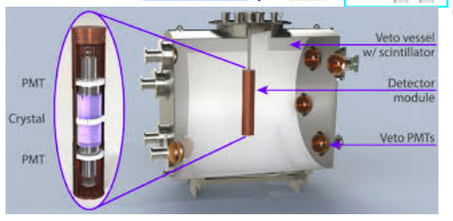


SABRE
@ LNGS & Stawell



PICO-LON
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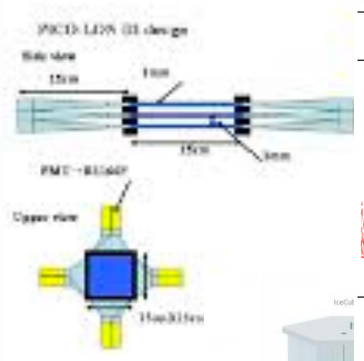
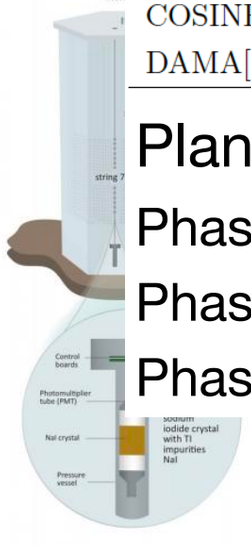
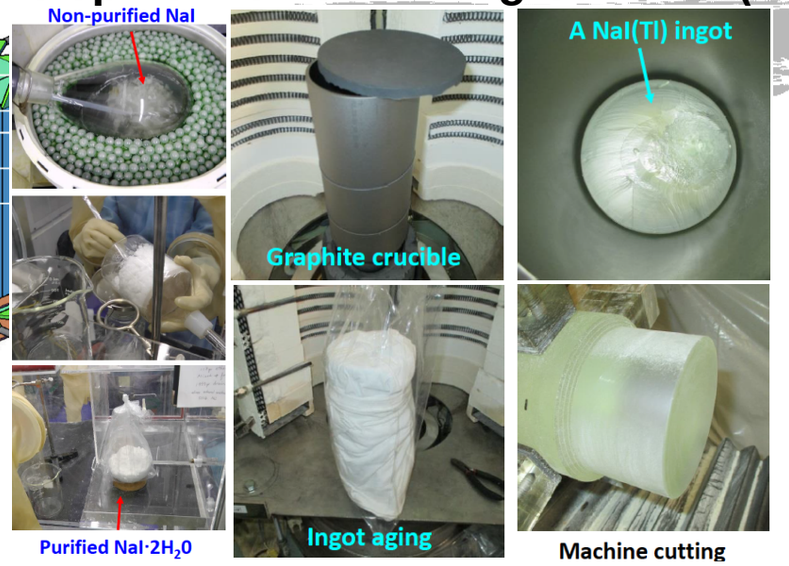


DM-Ice
@ South Pole



Development of low-background NaI(Tl)



ID of NaI/group	^{nat}K	^{226}Ra	^{210}Pb	^{232}Th
#68	120	57 ± 7	7500	8.4 ± 2.4
#71	< 20	120 ± 10	1500	6.8 ± 0.8
#73	< 30	44 ± 7	1300	7.2 ± 0.8
#85	–	13 ± 4	< 5.7	1.2 ± 1.4
Our goal	< 20	< 100	< 10	< 10
COSINE[10]	< 42	$8 \sim 60$	$10 \sim 420$	$7 \sim 35$
DAMA[18]	< 20	$8.7 \sim 124$	$10 \sim 30$	$2 \sim 31$

Plan

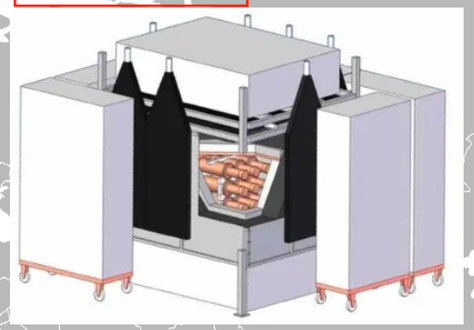
Phase1 @ 2021 spring w/ 23.4 kg

Phase2: 100 kg

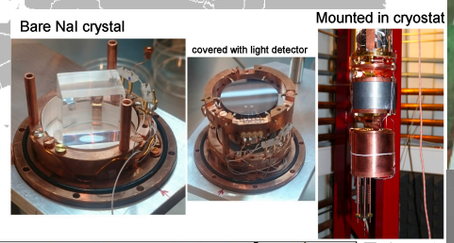
Phase3: 250 kg

Global Efforts using NaI(Tl)

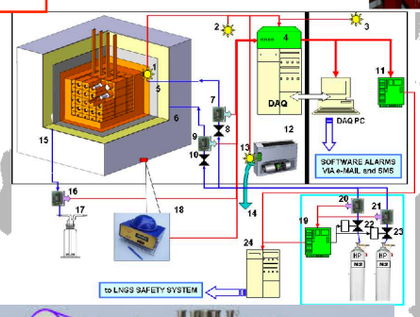
ANAIS
@ Canfranc



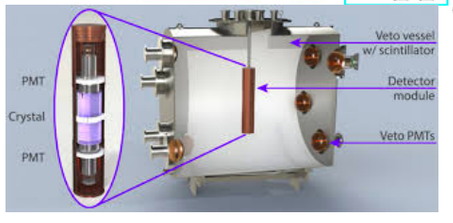
COSINUS
@ LNGS



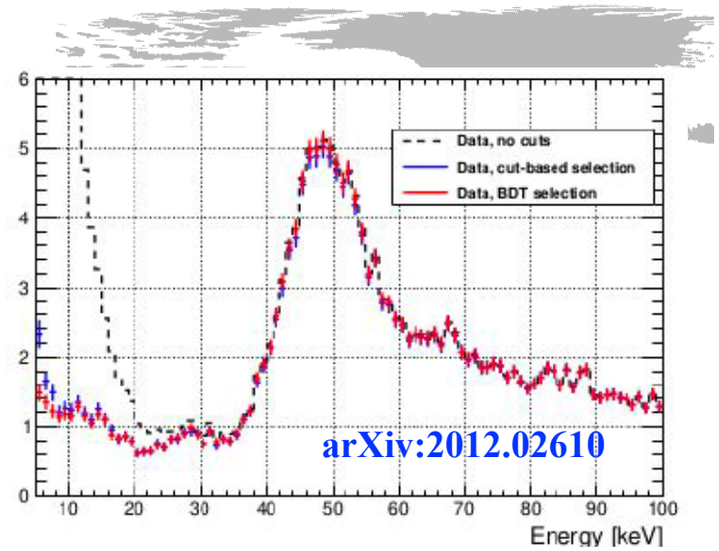
DAMA/LIBRA
@ LNGS



SABRE
@ LNGS & Stawell



Astropart. Phys. 106, 1 (2019)



^{40}K ~ 4.3 ppb (DAMA ~ 20 ppb)

^{210}Pb ~ 0.5 mBq/kg

(DAMA < 0.03 mBq/kg)

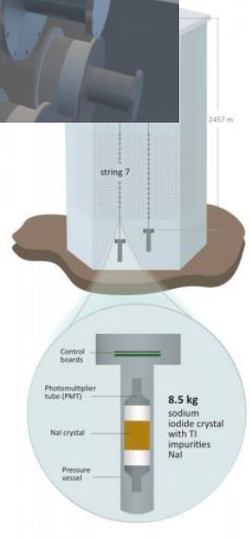
1 cpd/kg/keV @ 5-10 keV

SABRE-PoP starts measurements from Aug. 2020

Goal

0.1 cpd/kg/keV w/ 50 kg each Gran Ssaso & Stawell

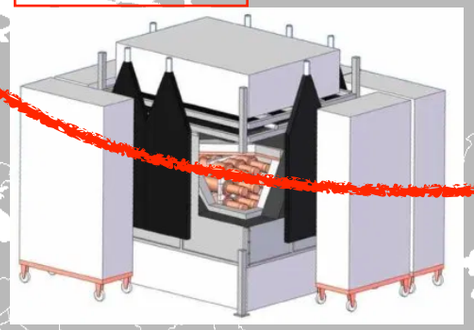
DM-Ice
@ South Pole



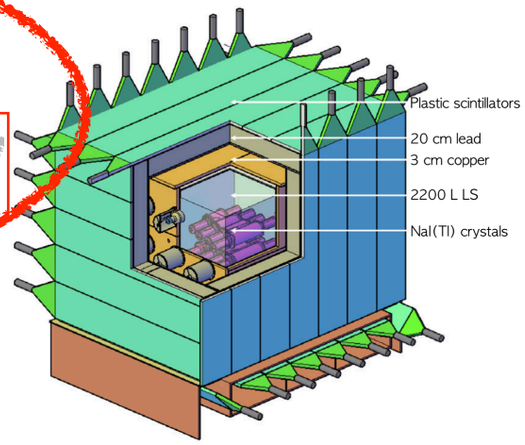
Global Efforts using NaI(Tl)

In data taking

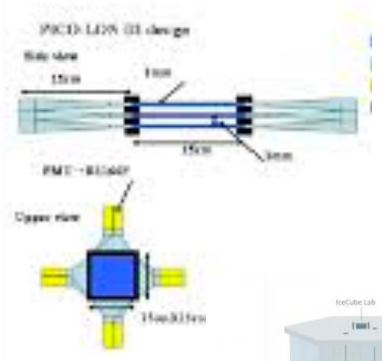
ANAIS
@ Canfranc



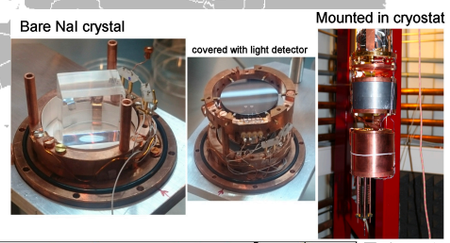
KIMS/COSINE
@ Yangyang



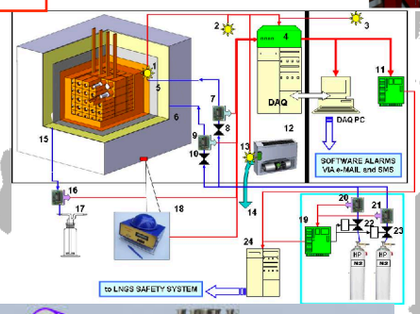
PICO-LON
@ Kamioka



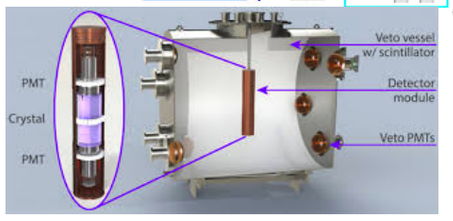
COSINUS
@ LNGS



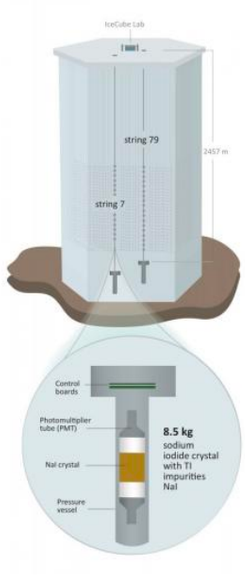
DAMA/LIBRA
@ LNGS



SABRE
@ LNGS & Stawell



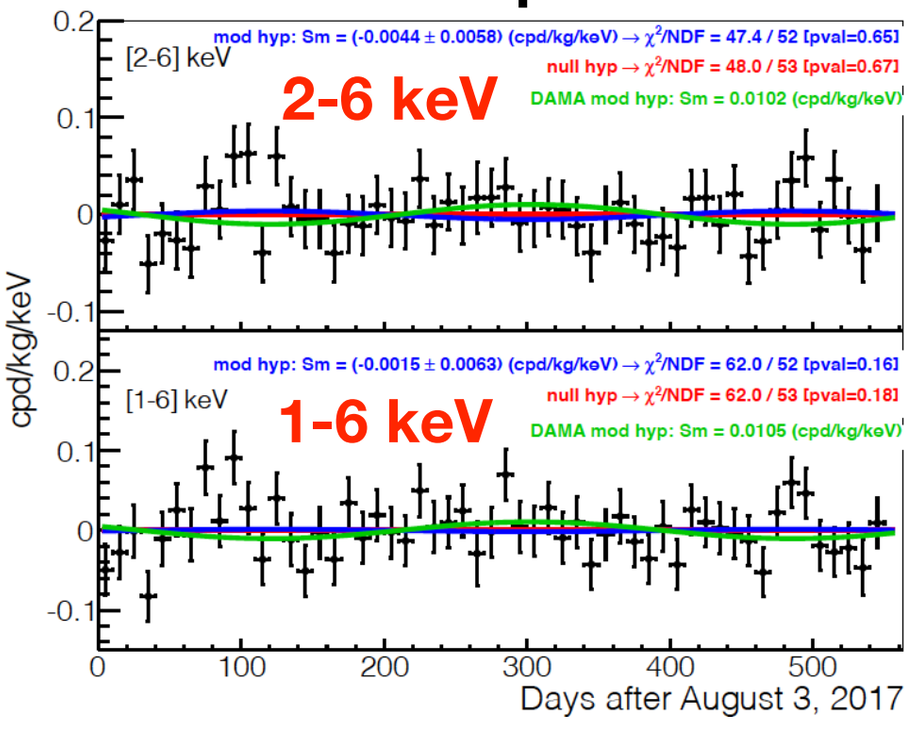
DM-Ice
@ South Pole



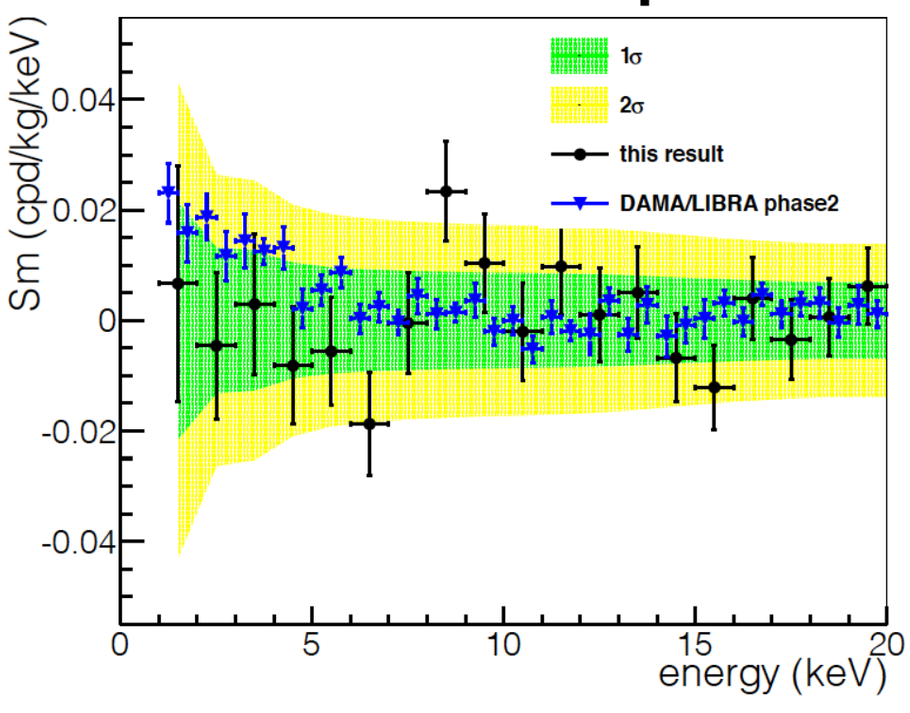
ANAIS-112

- Nine 12.5-kg NaI(Tl) modules (112 kg in total)
- Since Aug. 2017
- 1-keV threshold
- 2~5 cpd/kg/keV (dru) background at 2 keV (DAMA ~ 1 dru)
- First result w/ 1.5 years
  - There is no modulation observation, but uncertainties are not enough to rule out DAMA/LIBRA.

Residual spectrum



Modulation Amplitude



Phys. Rev. Lett 122, 131801 (2019)

ANAIS-112

- Recent results
  - Time dependent background modeling based on cosmogenic understanding
  - Three kinds of modeling for modulation fit

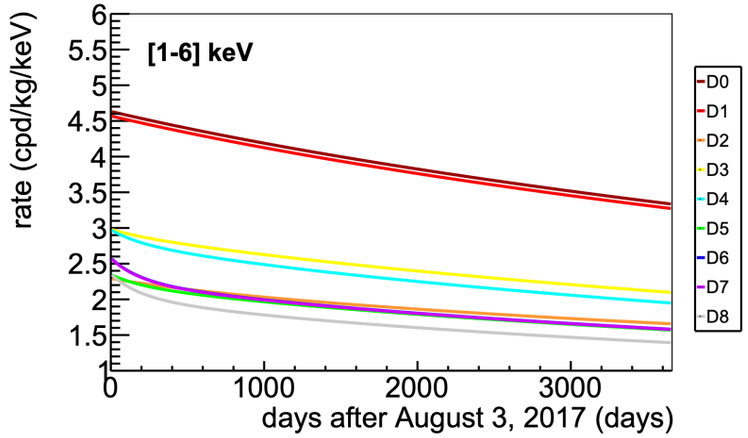
$$\mu_i = [R_0\phi_{bkg}(t_i) + S_m cos(\omega(t_i - t_0))]M\Delta E\Delta t.$$

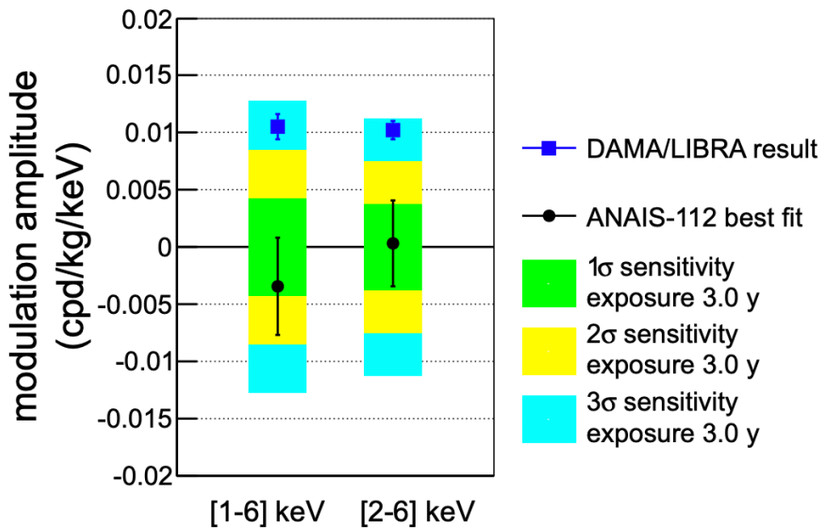
$$\phi_{bkg}(t_i) = 1 + fe^{-t_i/\tau}, \quad \text{— single exponential (eq.4)}$$

$$\phi_{bkg}(t_i) = 1 + f\phi^{MC}_{bkg}(t_i). \quad \text{— MC background model (eq.5)}$$

$$\mu_{i,d} = [R_{0,d}(1 + f_d\phi^{MC}_{bkg,d}(t_i)) + S_m cos(\omega(t_i - t_0))]M_d\Delta E\Delta t,$$

— MC background model for each module (eq.6)





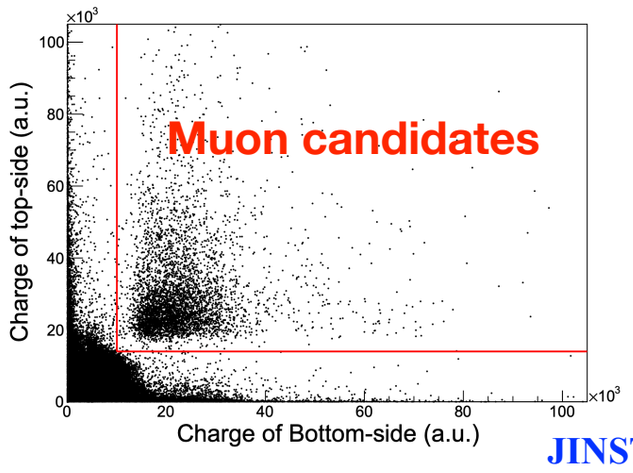
- Data supports the absence of modulation and incompatible with the DAMA/LIBRA at 3.3σ (2.6σ) for 1-6 keV (2-6 keV).

arXiv:2103.01175

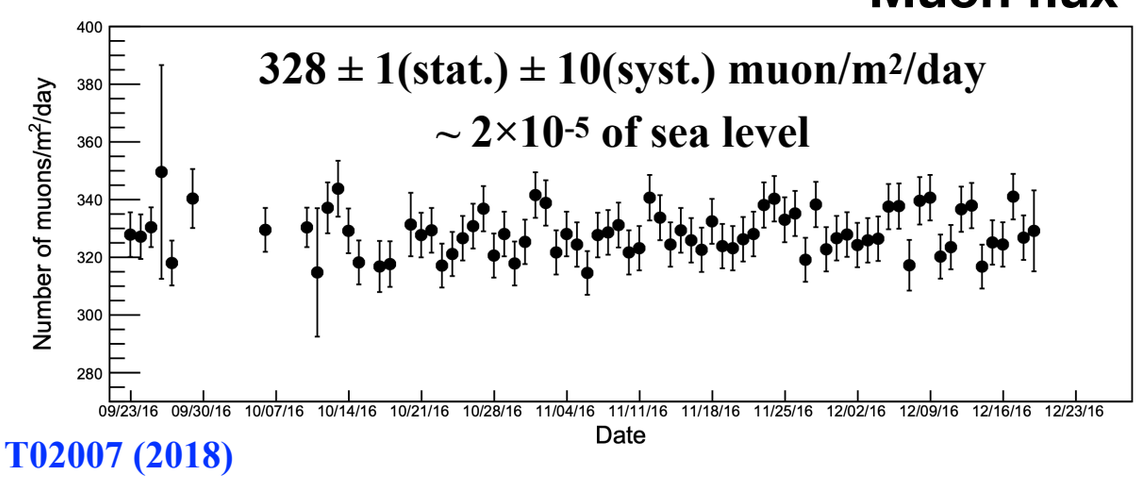
Energy region	Model	χ^2/NDF null hyp	Nuisance params.	S_m cpd/kg/keV	p value mod	p value null
[1–6] keV	eq. 4	132 / 107	3	-0.0045±0.0044	0.051	0.051
	eq. 5	143.1 / 108	2	-0.0036±0.0044	0.012	0.013
	eq. 6	1076 / 972	18	-0.0034±0.0042	0.011	0.011
[2–6] keV	eq. 4	115.7 / 107	3	-0.0008±0.0039	0.25	0.27
	eq. 5	120.8 / 108	2	0.0004±0.0039	0.17	0.19
	eq. 6	1018 / 972	18	0.0003±0.0037	0.14	0.15

Muon Detector

- 37 plastic scintillator panels surround the lead shield, at the outmost layer.
  - Muon rate has been monitored.
  - Muon correlated events in NaI(Tl) crystal are vetoed.



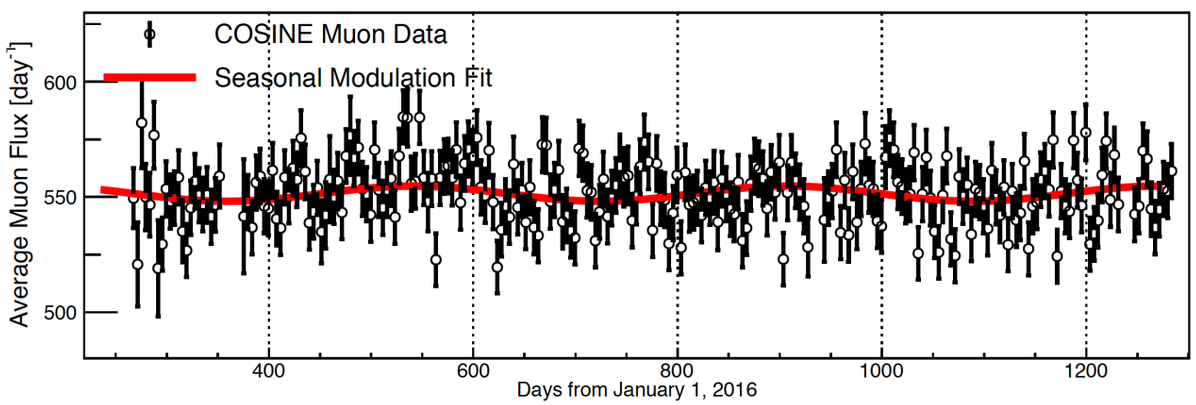
Muon flux



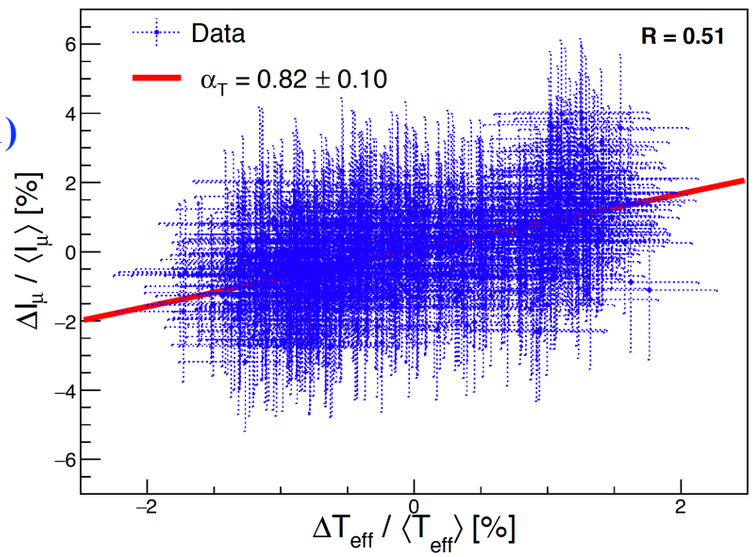
JINST 13, T02007 (2018)

- Study on muon annual modulation
  - Correlation w/ temperature

JCAP 02, 013 (2021)

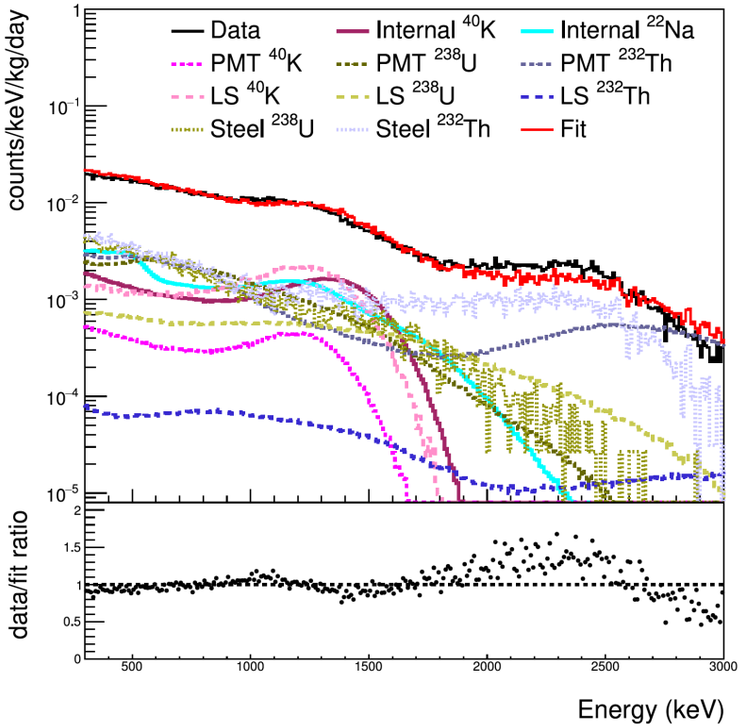


Muon flux & modulation fit

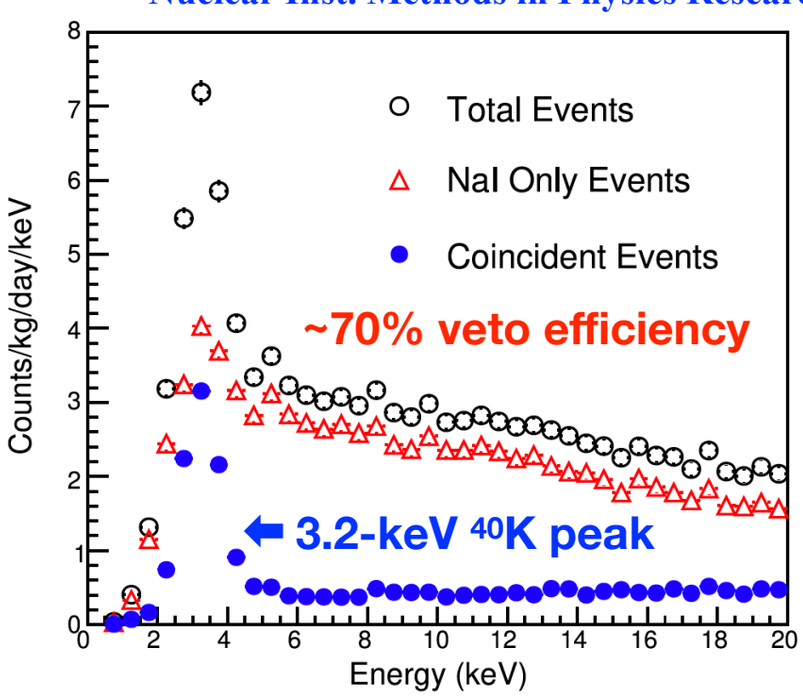


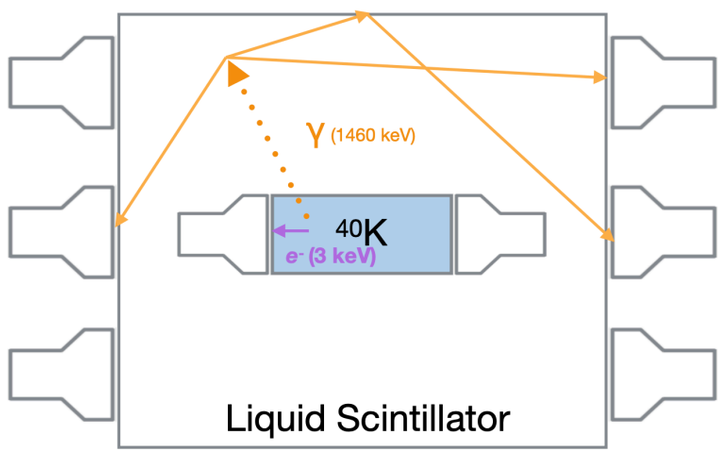
LS Veto System

- Detector response is well understood with a GEANT4-based simulation.
- Internal background of LS is low enough.
- Tagging multiple-hit events for vetoing
  - ~20% of tagging efficiency for 2-6 keV
  - ^{40}K events
    - One of the main background sources at low energies
    - Tagging efficiency of ^{40}K ~ 70%



Nuclear Inst. Methods in Physics Research, A 1006, 165431 (2021)

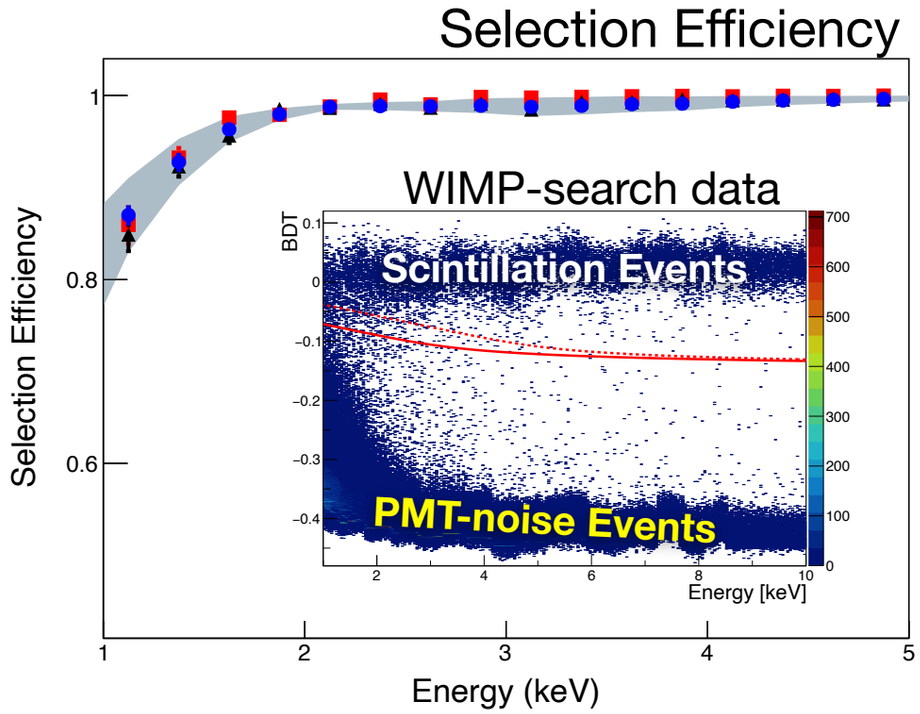




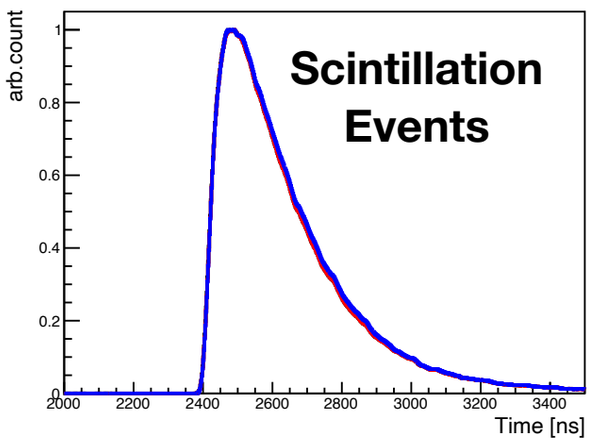
Event Selection

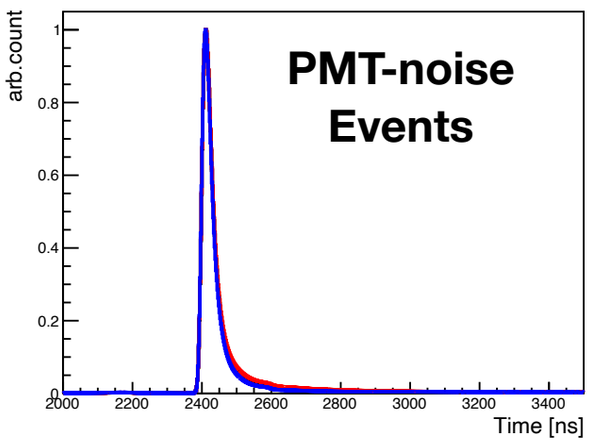
- Lowering threshold 2 → 1 keV
  - Development of a new likelihood parameter based on pulse shape
  - Boosted decision tree (BDT) is used to separate the signals from the noises.
  - Further studies are ongoing
    - Improved multi-variable technique
    - Deep learning

Astropart. Phys 130, 102581 (2021)

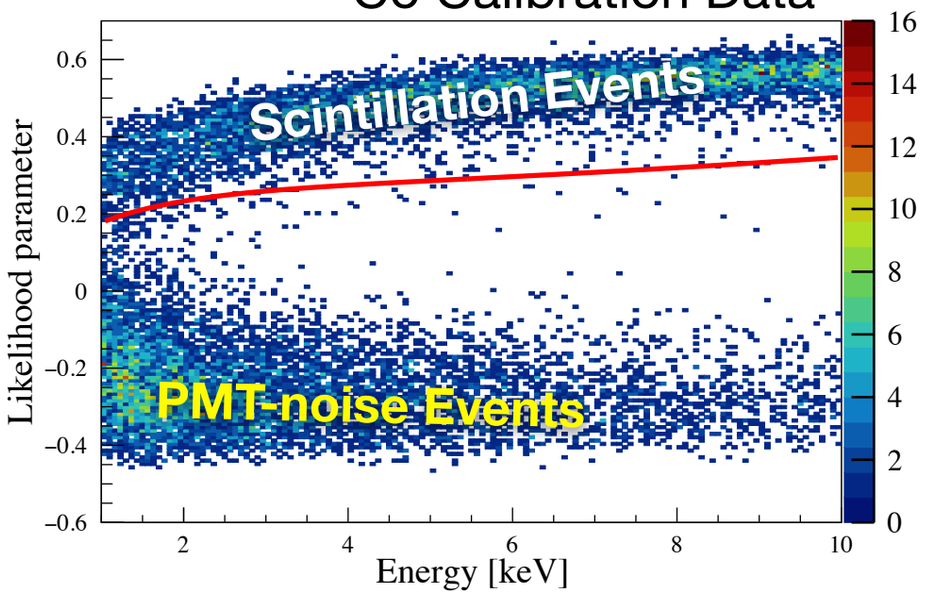


Pulse shape





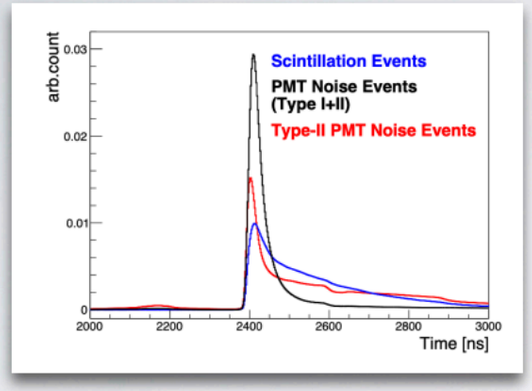
^{60}Co Calibration Data



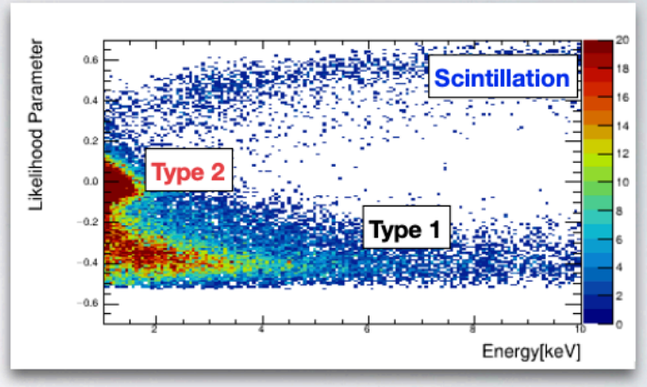
Improvements in Event Selection

Next update : Lowering threshold to 0.5keV

Waveform difference according to event types
Astropart. Phys. 130 (2021) 102581



Example of effective parameters : Likelihood parameter
Astropart. Phys. 130 (2021) 102581

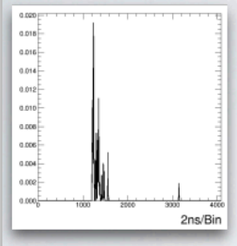


Lowering Threshold 1 keV → 0.5 keV

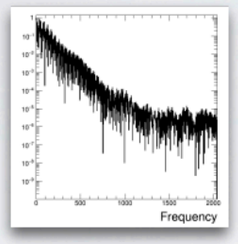
- Lowest limit on few GeV WIMP mass is expected.
- Type 2 Noise hard to be separated from scintillation in 0.5 ~ 1 keV region.

Next update : Lowering threshold to 0.5keV

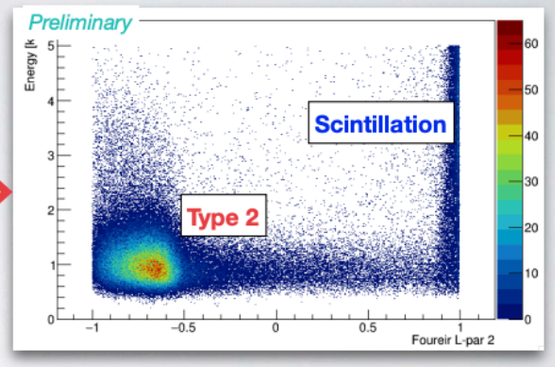
New parameter development example : Fourier Transformed Likelihood parameter



FFT

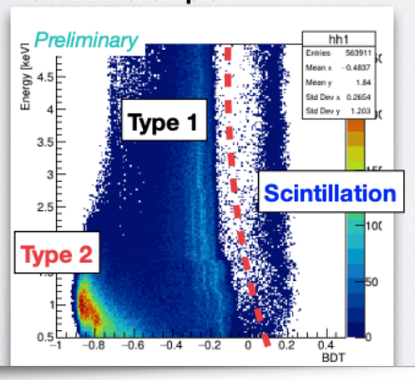


Parameterization



BDT Training

New BDT example



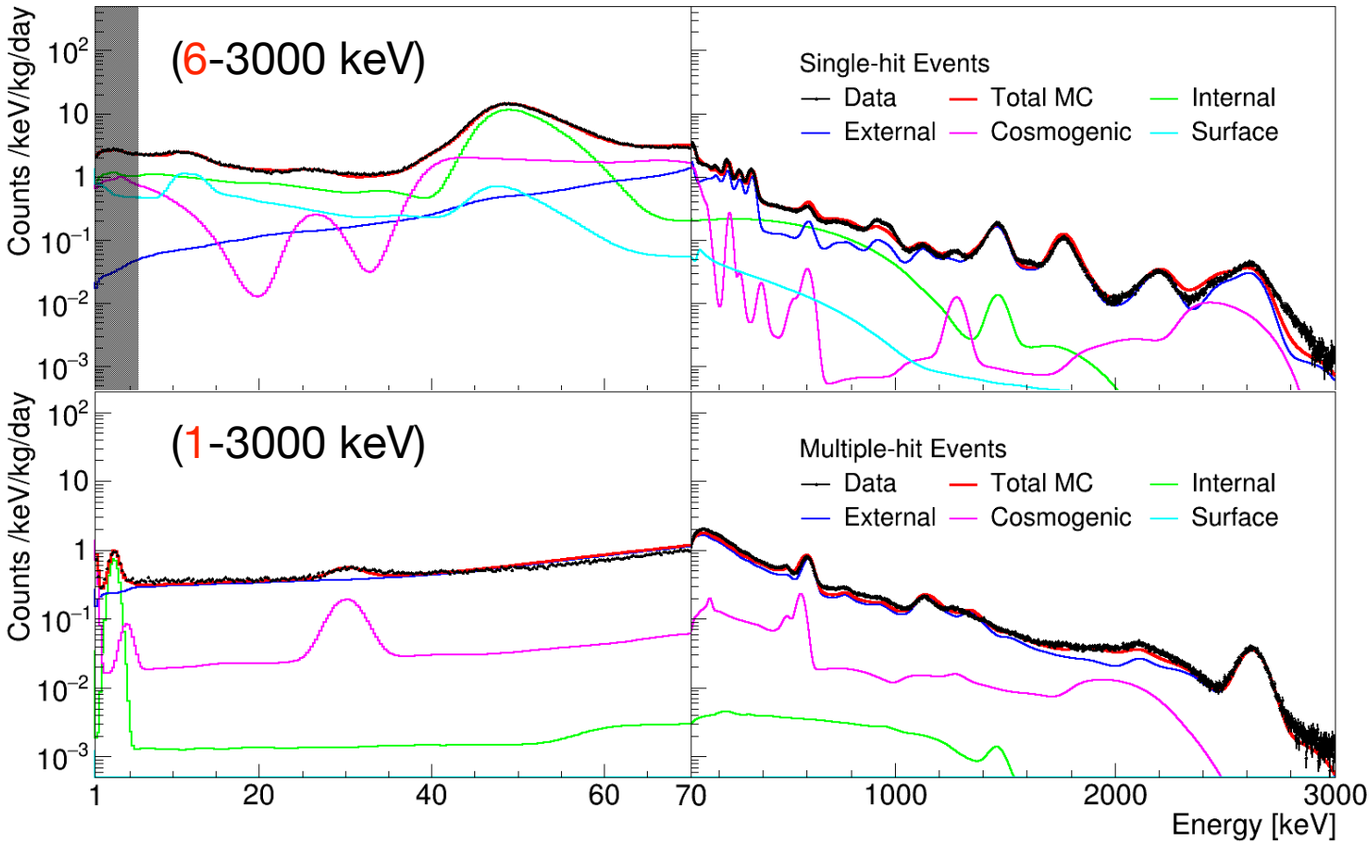
Lowering Threshold 1 keV → 0.5 keV

- Lowest limit on few GeV WIMP mass is expected.
- Type 2 Noise hard to be separated from scintillation in 0.5 ~ 1 keV region.
- New Parameters & BDT for Type2 Noise is being developed.

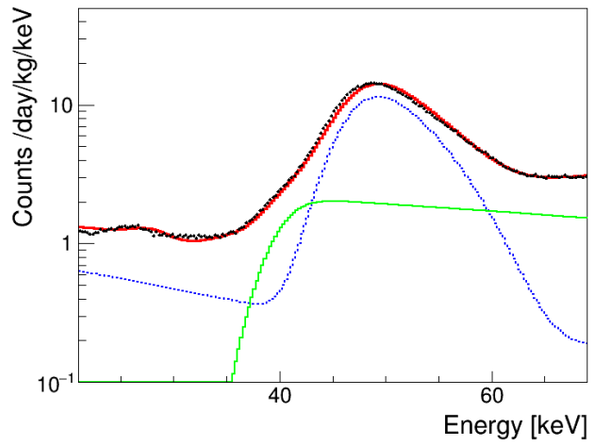
Background Modeling

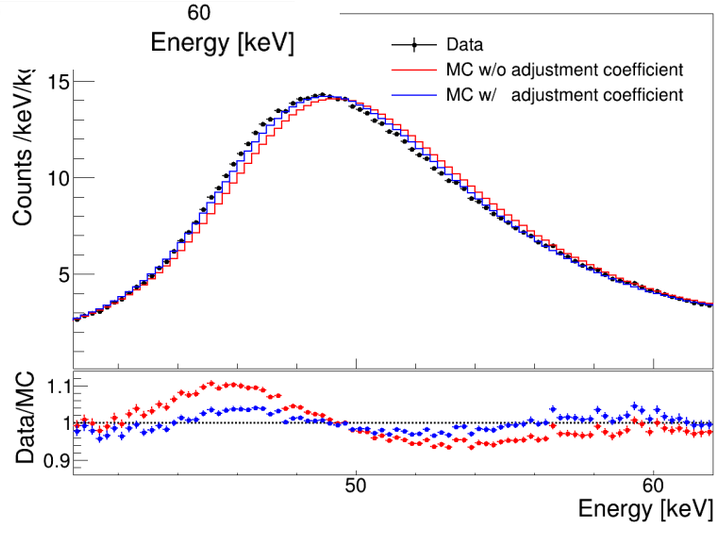
EPJC 81, 837 (2021)
Astropart. Phys. 126, 102528 (2021)

- Main background in low energy region
  - Contamination of crystals from K/U/Th
  - Cosmogenic activation (mostly ^{3}H)
  - ^{210}Pb on crystal surface



- Improvements
  - Better understanding of surface ^{210}Pb
  - Adding ^{129}I and rock γ (^{208}Tl)
  - Energy scale adjustment

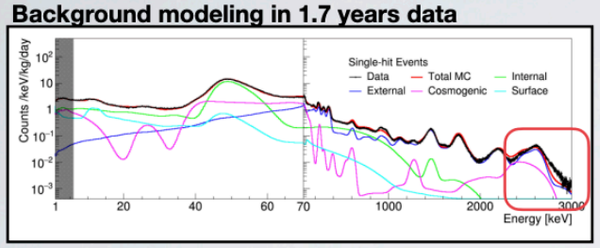




Improvements in Background Modeling

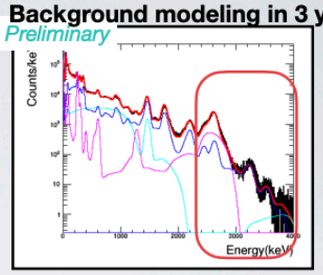
Next update : Improved background modeling

Background modeling in 1.7 years data



Proportionality correction →

Background modeling in 3 years data



Ex) Non-proportionality effect on ^{22}Na 3γ

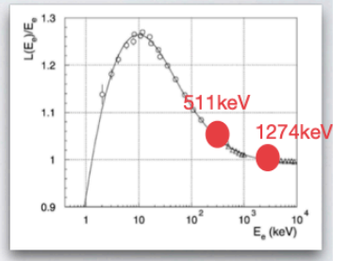
[True energy]

(511 + 511 + 1274) keV
= **2296** keV

[Considering non-proportionality]

$(511 \times f(511) + 511 \times f(511) + 1274 \times f(1274))$ keV
~ **2334** keV

→ **~40 keV Difference !**

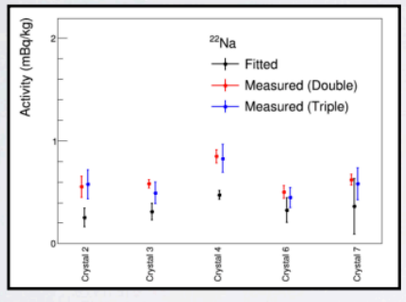


Nuclear Instruments and Methods in Physics Research Section A ,430, 2–3,(1999)
Reference energy nonlinearity of NaI(Tl) Crystal

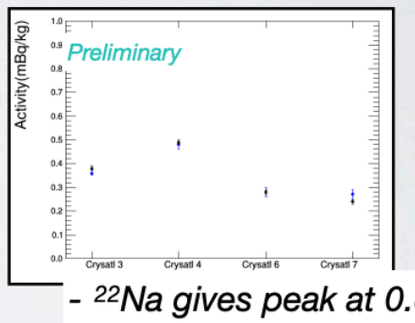
Modeling updates

- Solved not poor modeling in high-energy region(~2.8MeV) by fixing crystal energy proportionality problem
- Extended fitting region 3 MeV → 4 MeV

^{22}Na activity estimation



→



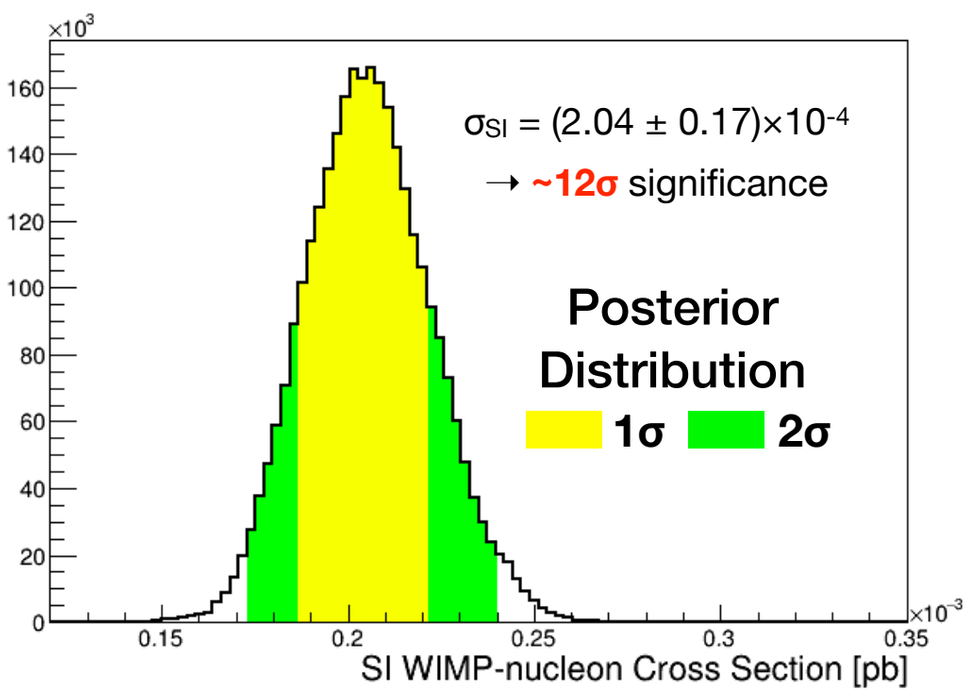
- *^{22}Na gives peak at 0.8 keV, with ~2.6 years half life!*

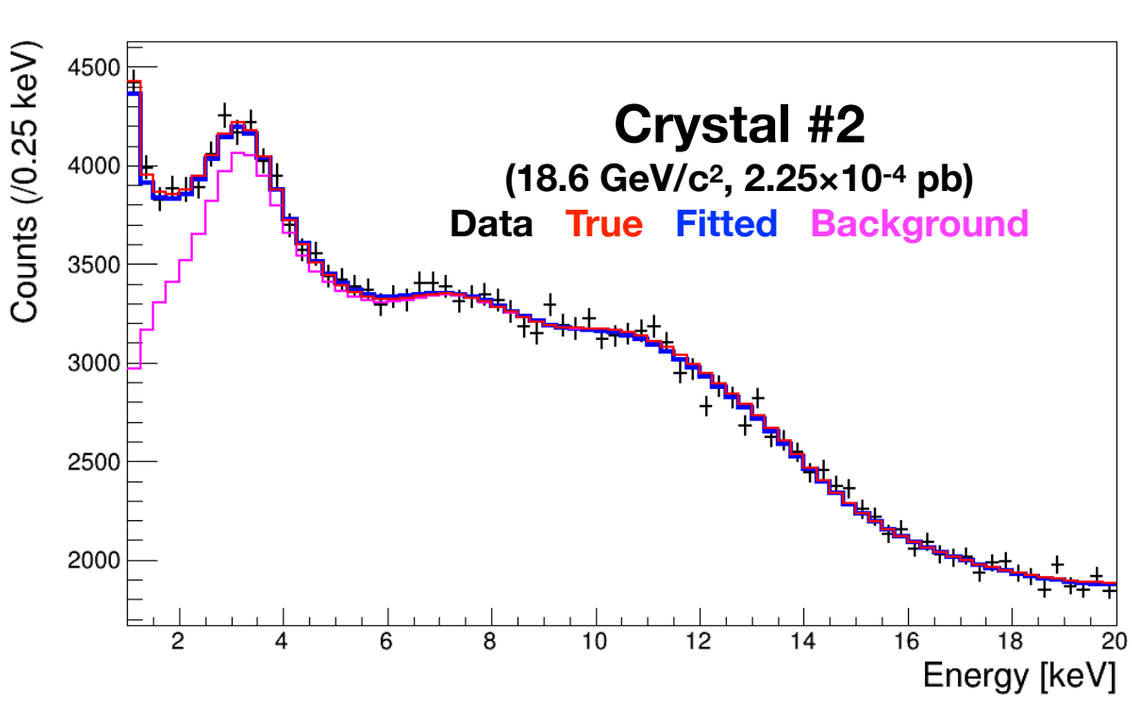
Modeling updates

- Solved not poor modeling in high-energy region(~2.8MeV) by fixing crystal energy proportionality problem
- Extended fitting region 3 MeV → 4 MeV
- Mismatch between Data and Modeling in ^{22}Na have been solved.

DAMA Signal Test

- Bayesian method
  - Markov chain monte carlo (MCMC) via Metropolis-Hastings
- Binned likelihood function
- Systematics
  - Background, Resolution, Efficiency, Surface ^{210}Pb, PMT activity & position





Bayesian Approach

- Posterior, marginalization

$$\mathcal{P}(\sigma|M) = \frac{P(M|\sigma)\,\pi(\sigma)}{\int d\sigma P(M|\sigma)\,\pi(\sigma)}$$

π: Prior for WIMP signal (flat)

Bayes' theorem

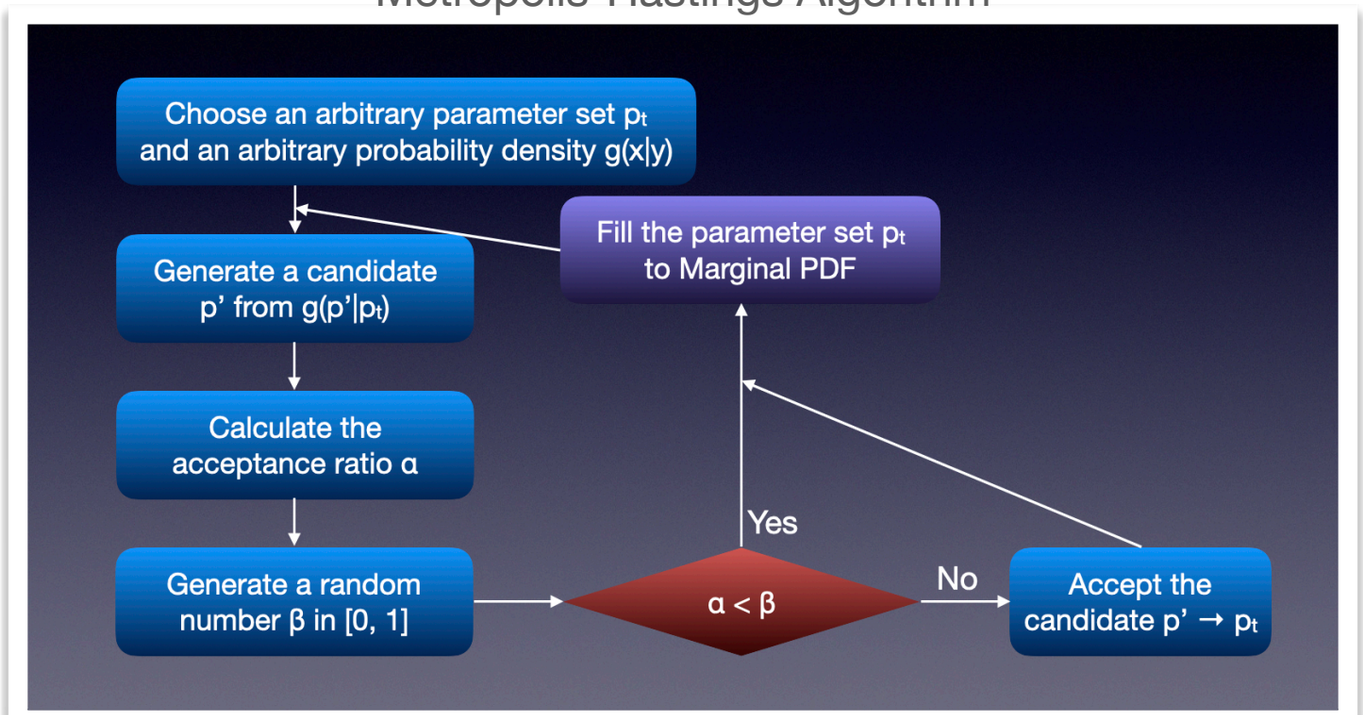
$$P(M|\sigma) = \mathcal{L}(\sigma|M) = \int d\alpha \int d\beta\, \mathcal{L}(\sigma|M,\ \alpha,\ \beta)\, \psi(\alpha,\ \beta)$$

ψ: Constraints for systematic uncertainties

Marginalization for α & β

Using Markov chain Monte Carlo via Metropolis-Hastings algorithm

Metropolis-Hastings Algorithm



Bayesian Approach

- Posterior, marginalization, and Poisson likelihood

$$\mathcal{P}(\sigma|M) = \frac{P(M|\sigma)\,\pi(\sigma)}{\int d\sigma P(M|\sigma)\,\pi(\sigma)}$$

π: Prior for WIMP signal (flat)

Bayes' theorem

$$P(M|\sigma) = \mathcal{L}(\sigma|M) = \int d\alpha \int d\beta\, \mathcal{L}(\sigma|M,\ \alpha,\ \beta)\, \psi(\alpha,\ \beta)$$

ψ: Constraints for systematic uncertainties

Marginalization for α & β

$$\mathcal{L}(\sigma|M,\ \alpha,\ \beta) = \prod_i^{N_{\rm crystal}} \prod_j^{N_{\rm bin}} \frac{(E_{ij})^{M_{ij}}}{M_{ij}} \exp(-E_{ij})$$

M_{ij}: Measured Number

E_{ij}: Expected Number

$$E_{ij}(\sigma,\ \alpha,\ \beta) = S_{ij}(\sigma,\ \alpha) + B_{ij}(\alpha,\ \beta)$$

$$S_{ij}(\sigma,\ \alpha) = \prod_k^{N_{\rm syst}} (1 + \alpha_{ik}\epsilon_{ijk})\, T_i\, M_i\, R_j(\sigma_{\rm WIMP}; m_\chi)$$

S_{ij}: WIMP signal

α_{ik}: Nuisance parameter

ε_{ik}: Relative uncertainty

$$B_{ij}(\alpha,\ \beta) = \prod_k^{N_{\rm syst}} (1 + \alpha_{ik}\epsilon_{ijk}) \sum_l (1 + \beta_{il}) B_{ijl}^{\rm MC}$$

B_{ij}: Background model

β_{il}: Nuisance parameter for fraction of background component

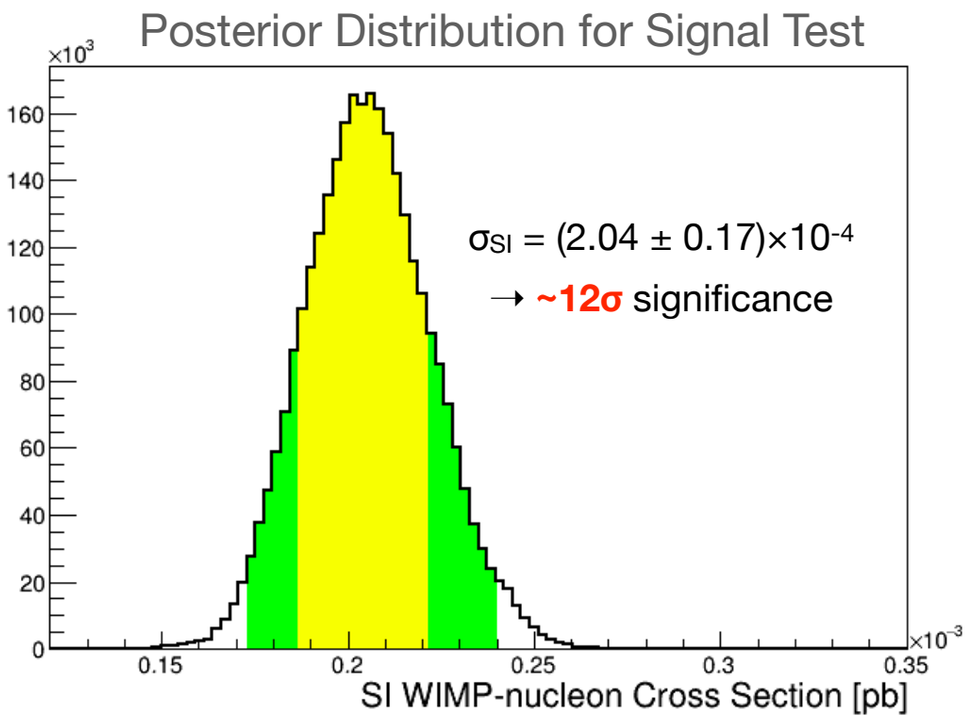
$$\psi(\alpha,\ \beta) = \prod_k^{N_{\rm syst}} \exp\left(-\frac{\alpha_{ik}^2}{2}\right) \prod_l^{N_{\rm bkgd}} \exp\left(-\frac{\beta_{il}^2}{2\delta B_{il}^2}\right)$$

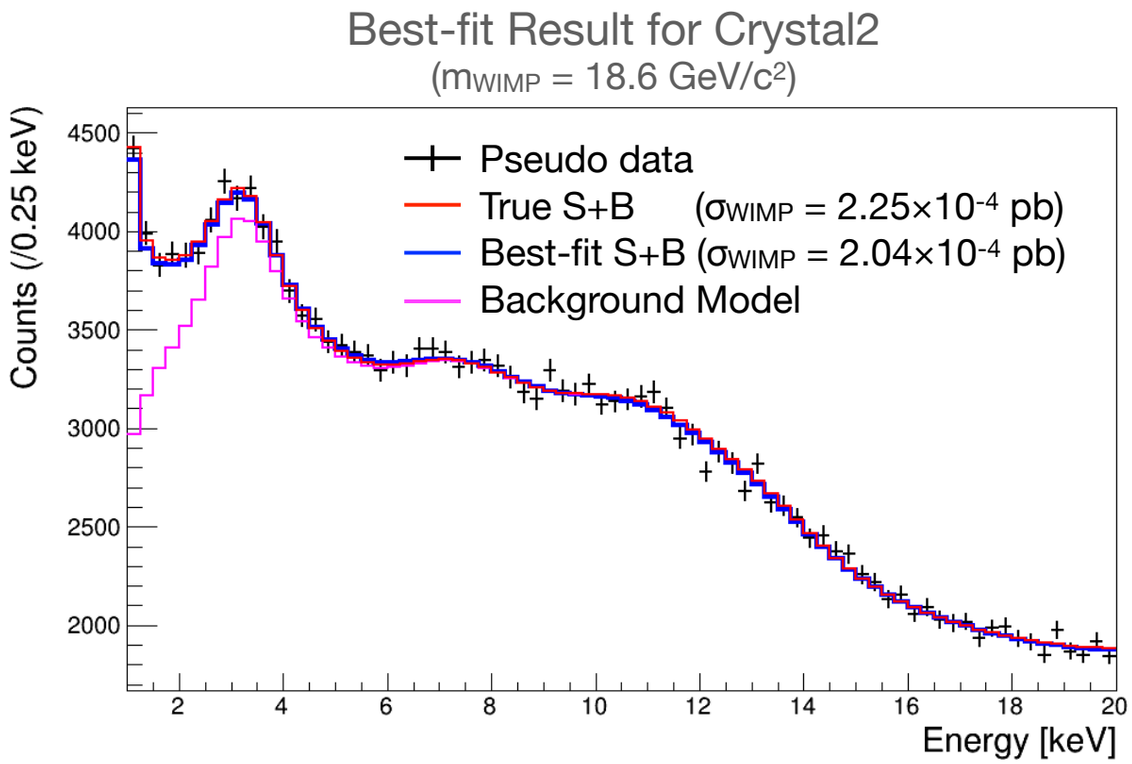
Gaussian constraints for nuisance parameters

δB_{ij}: Fraction uncertainties in background model

Signal Test & Sensitivity

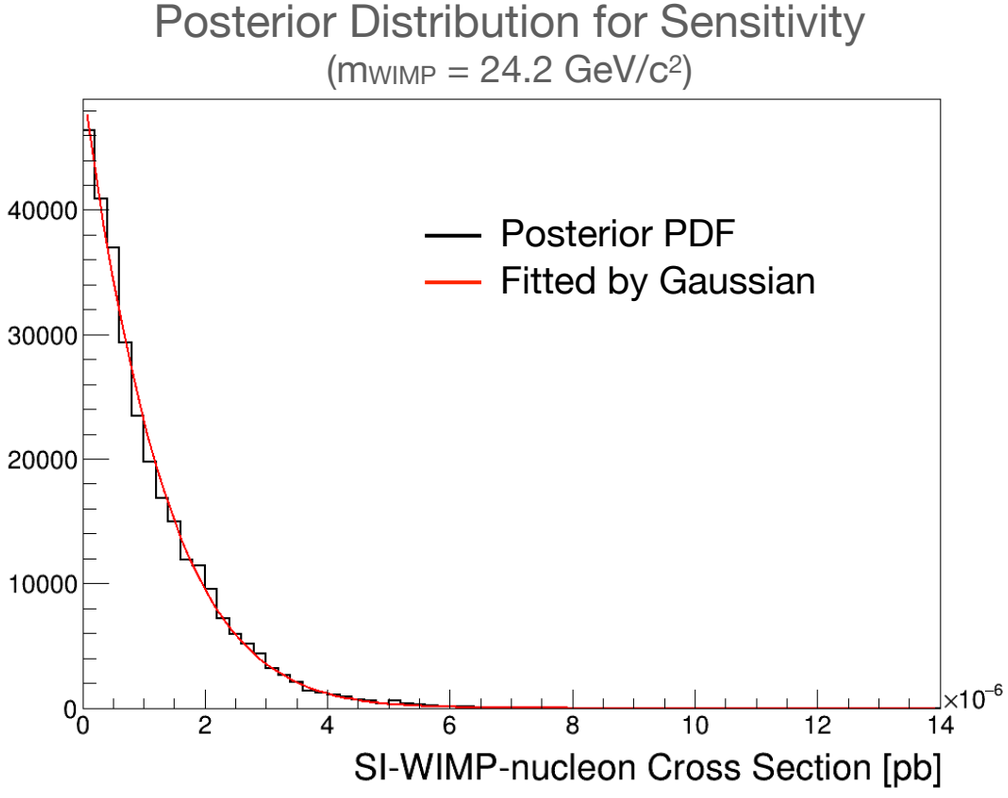
- Signal test for DAMA signal
  - Pseudo data based on hypothesis assuming DAMA
  - m_{WIMP} = 18.6 GeV/c^2, σ_{WIMP} = 2.25×10^{-4} pb

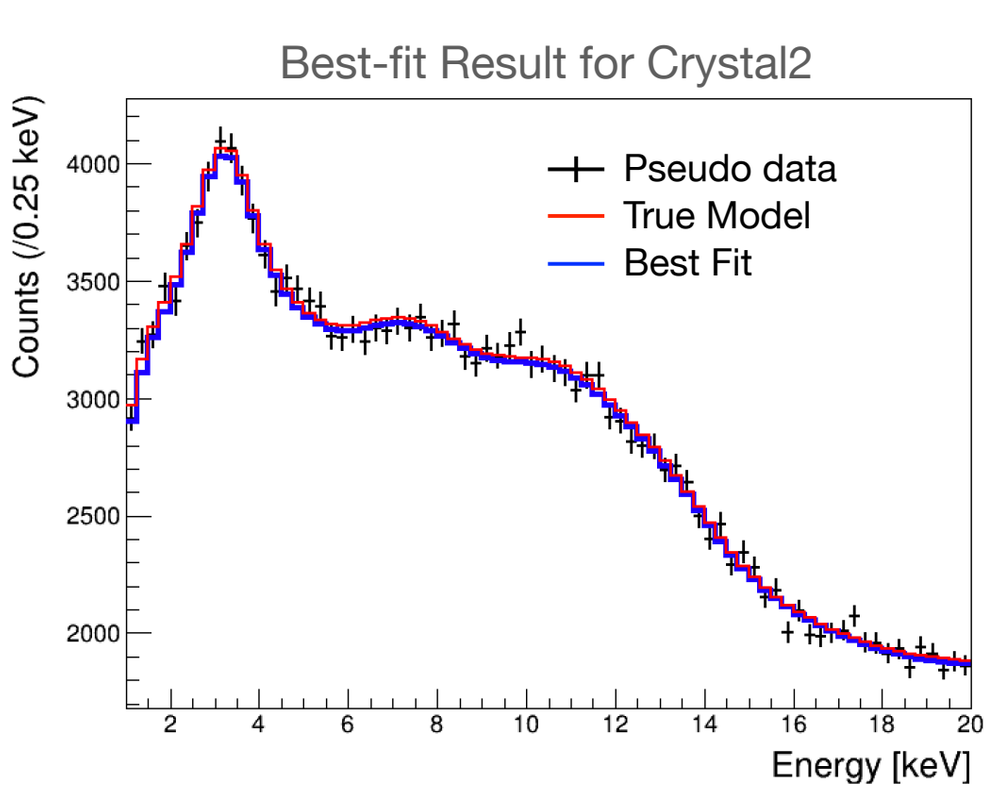




Signal Test & Sensitivity

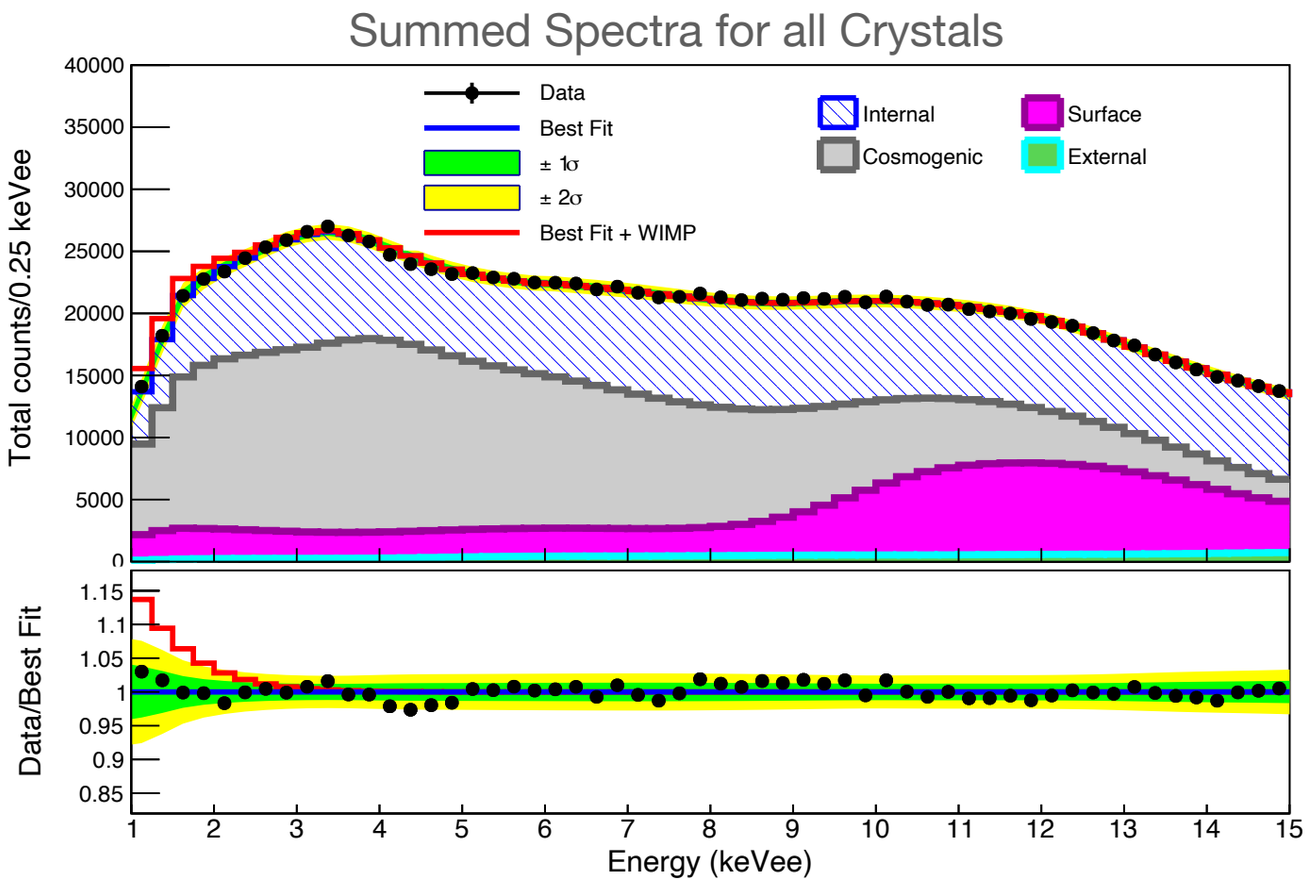
- Signal test for DAMA signal
  - Pseudo data based on hypothesis assuming DAMA
  - m_{WIMP} = 18.6 GeV/c^2, σ_{WIMP} = 2.25×10^{-4} pb
- Detector sensitivity
  - 1000 Pseudo-data sets based on null hypothesis
  - Sensitivity curve at 90% CL

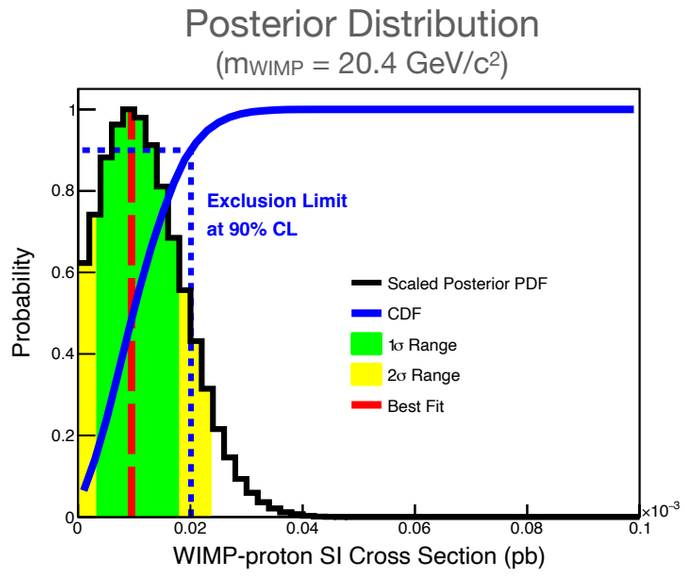


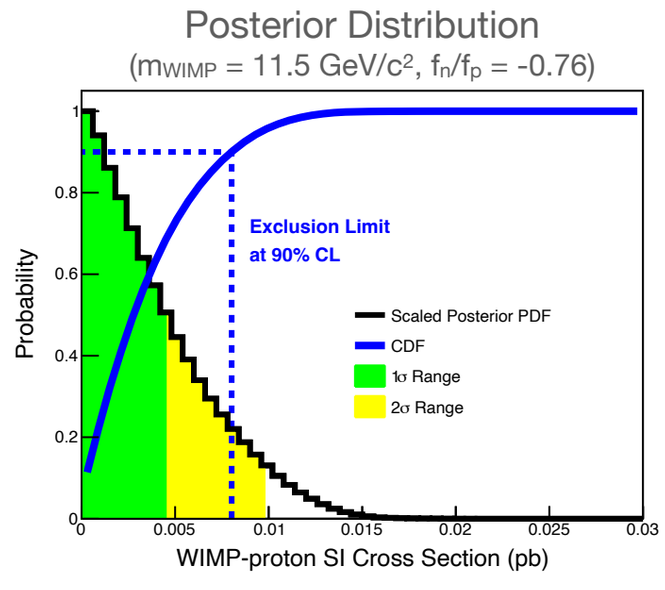


WIMP Extraction Analysis

- Trying to extract WIMP signal from data
- No significance for WIMP signal in data







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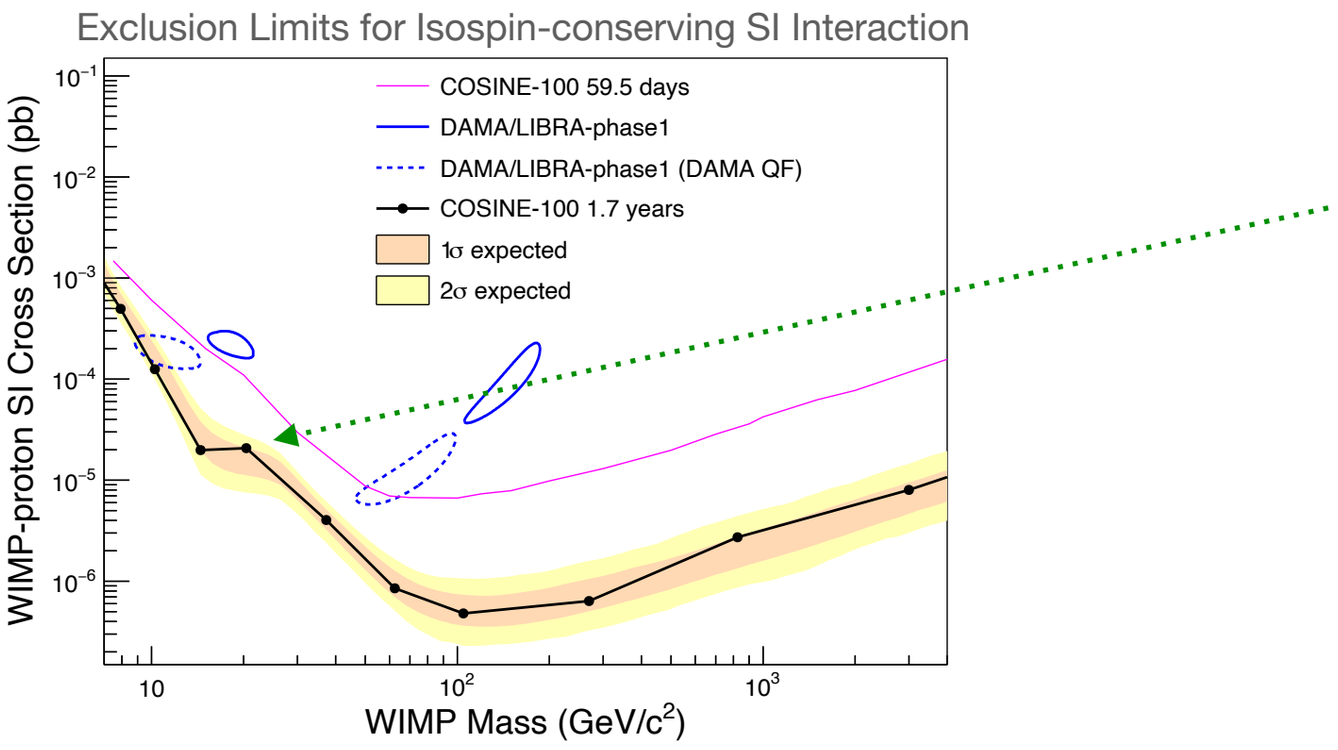

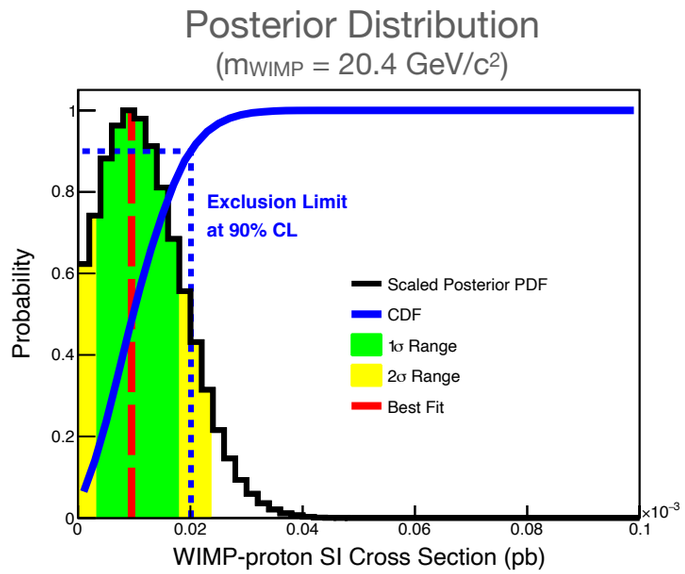

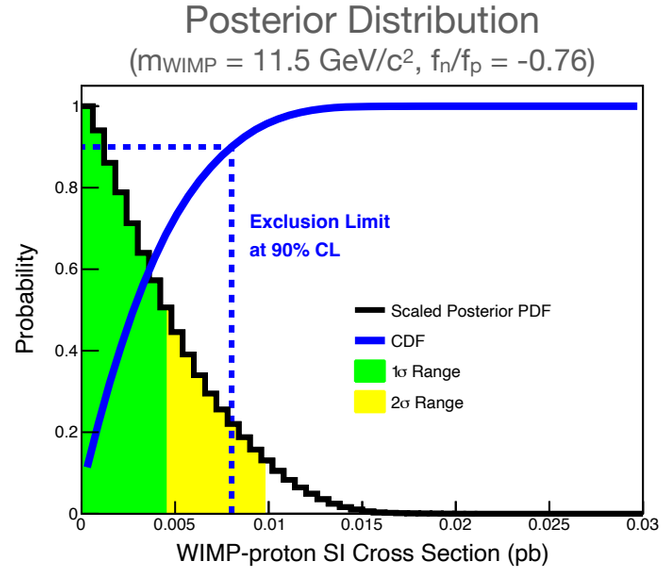

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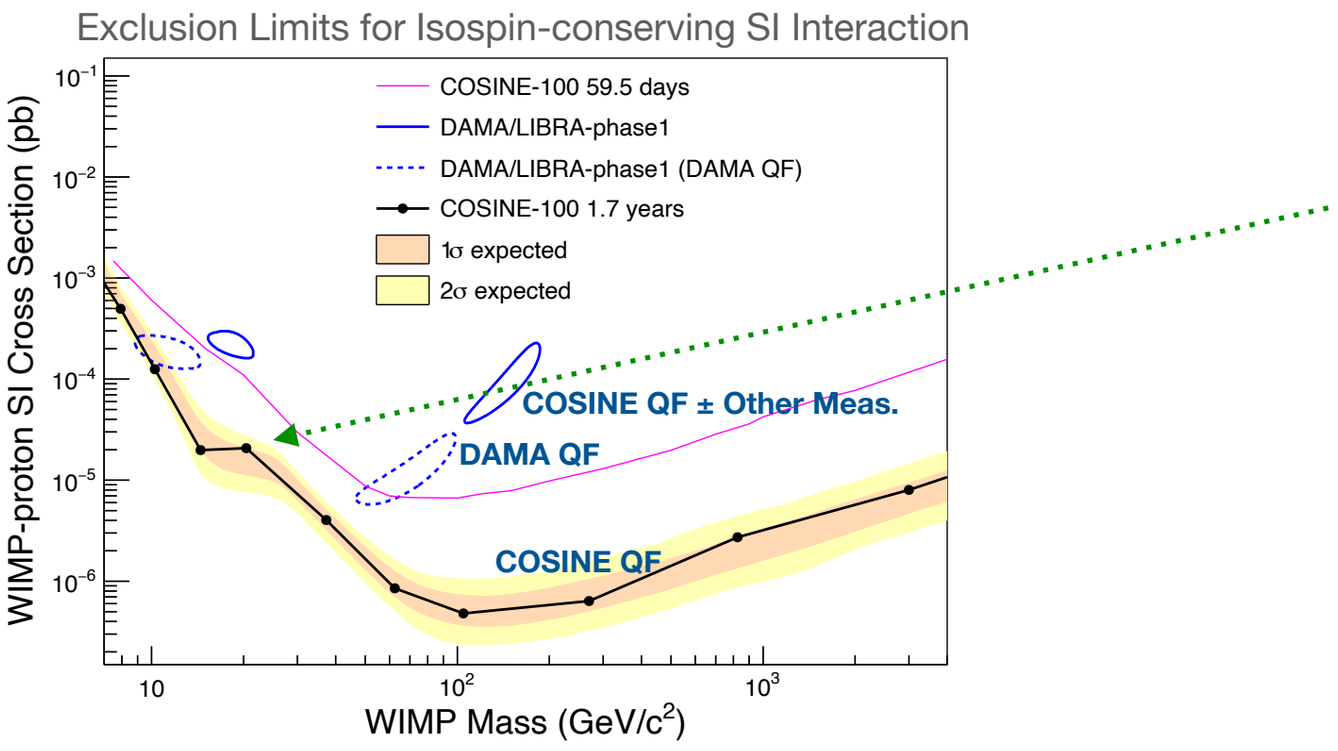

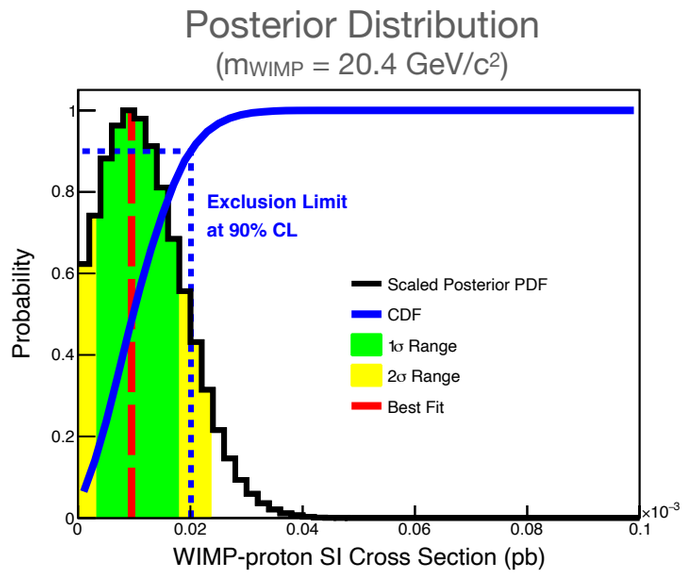

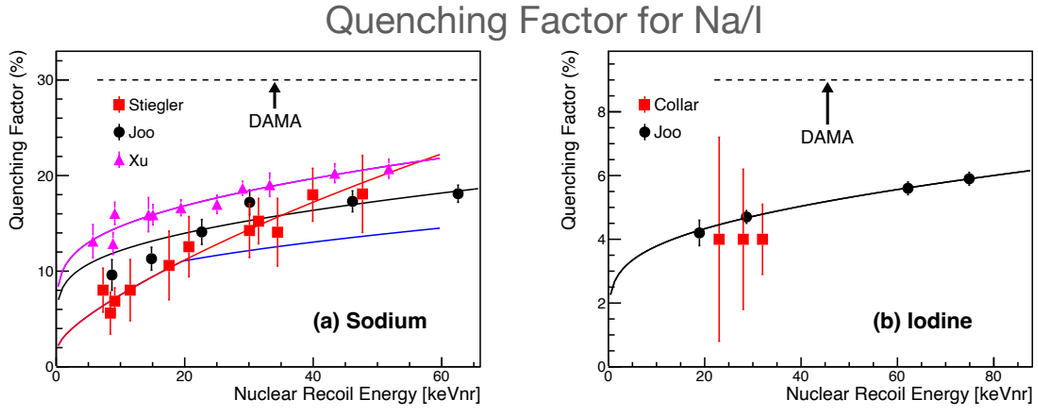

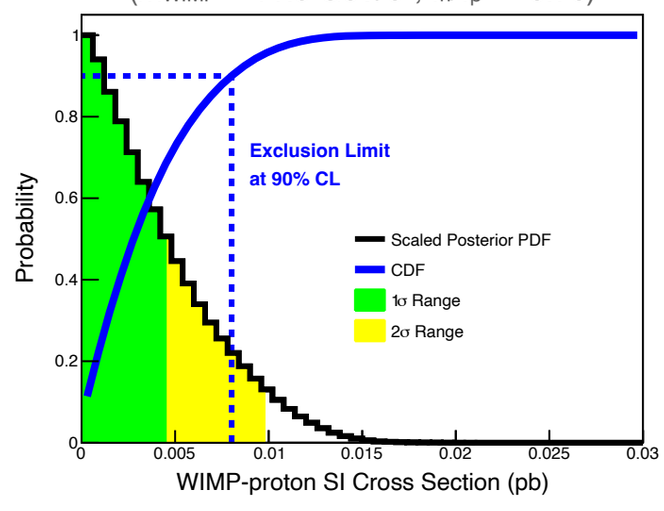

WIMP Extraction Analysis

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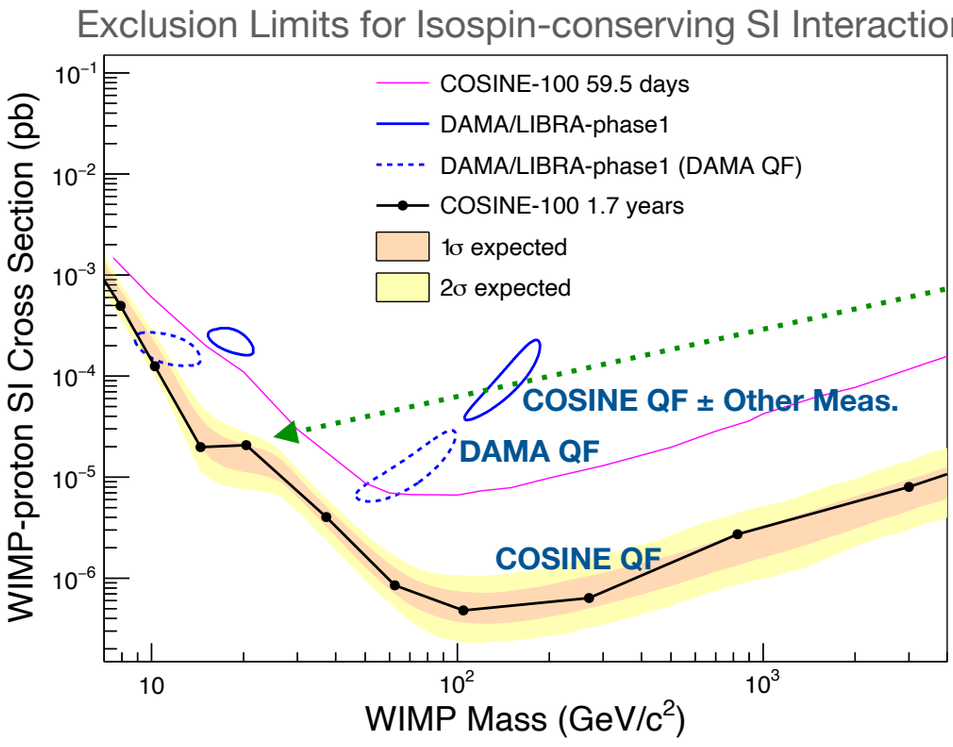
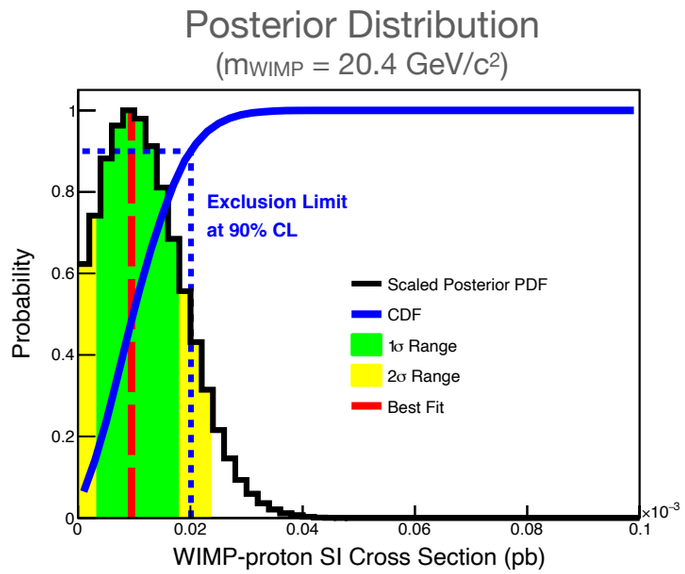
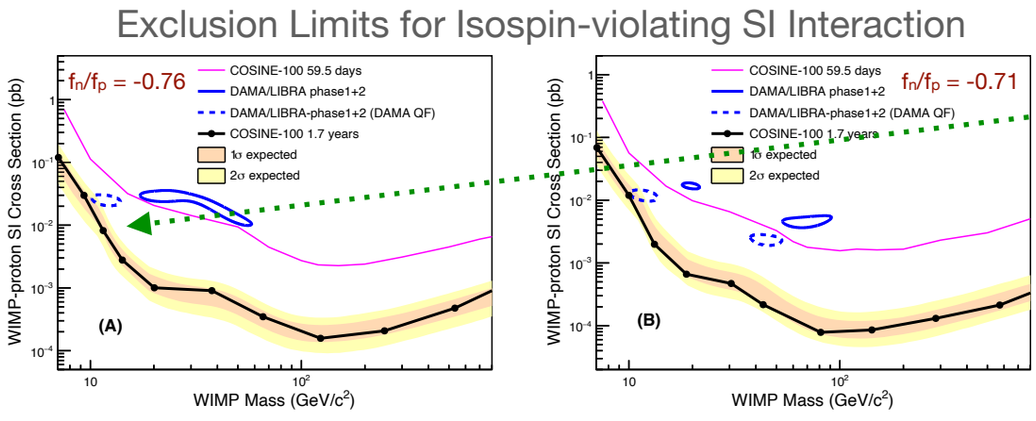
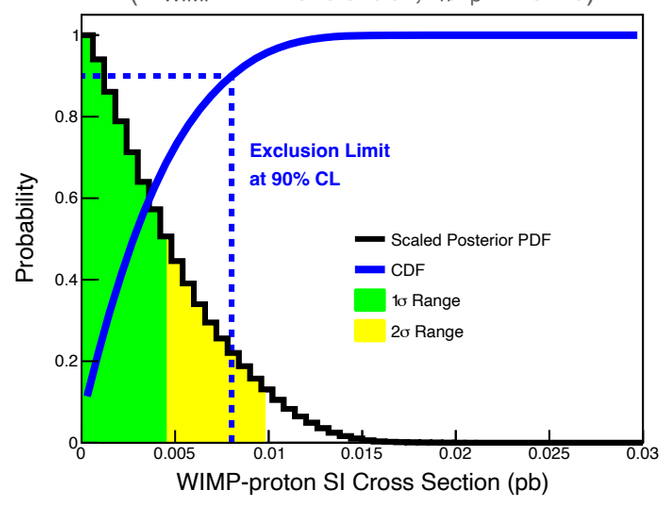




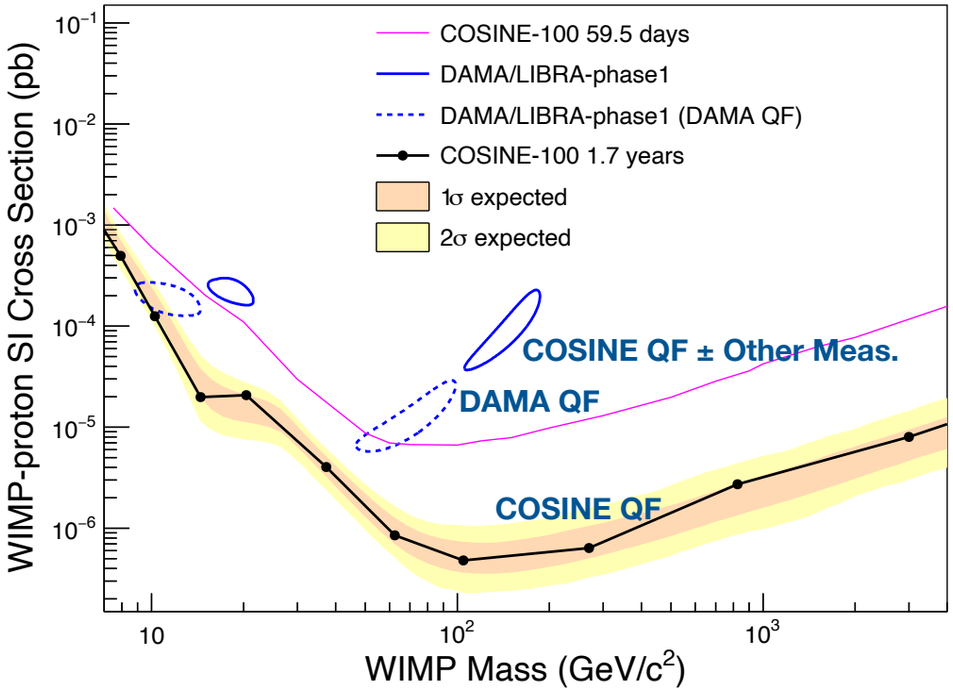




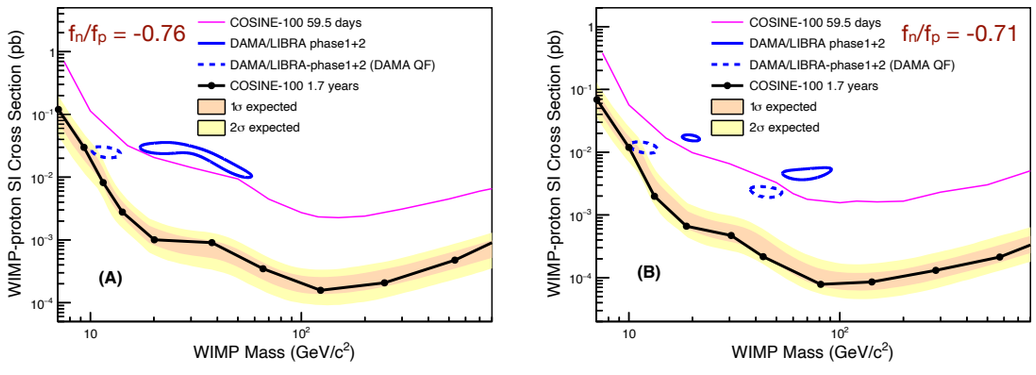
WIMP Extraction Analysis

- Trying to extract WIMP signal from data
- No significance for WIMP signal in data

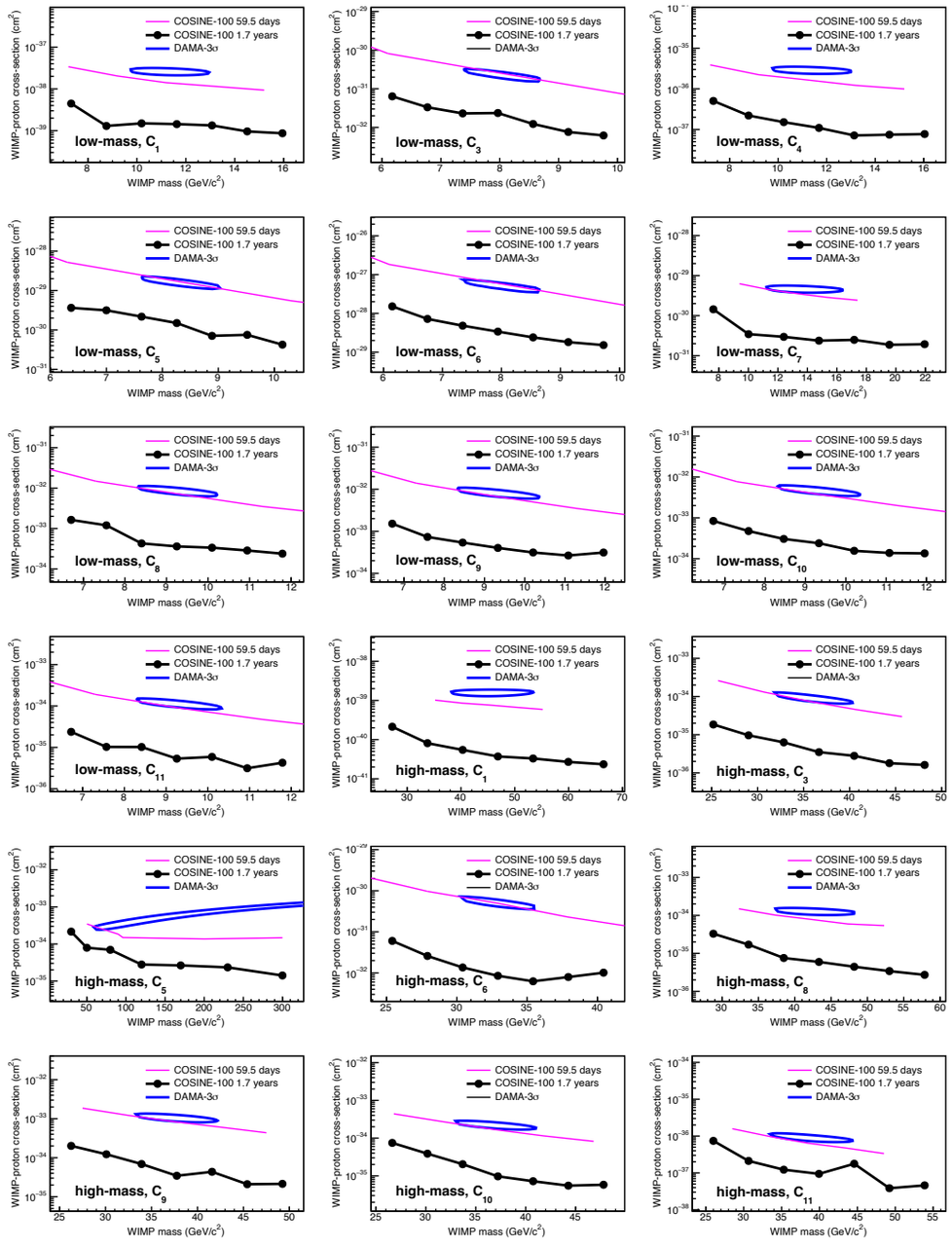
Exclusion Limits for Isospin-conserving SI Interaction



Exclusion Limits for Isospin-violating SI Interaction

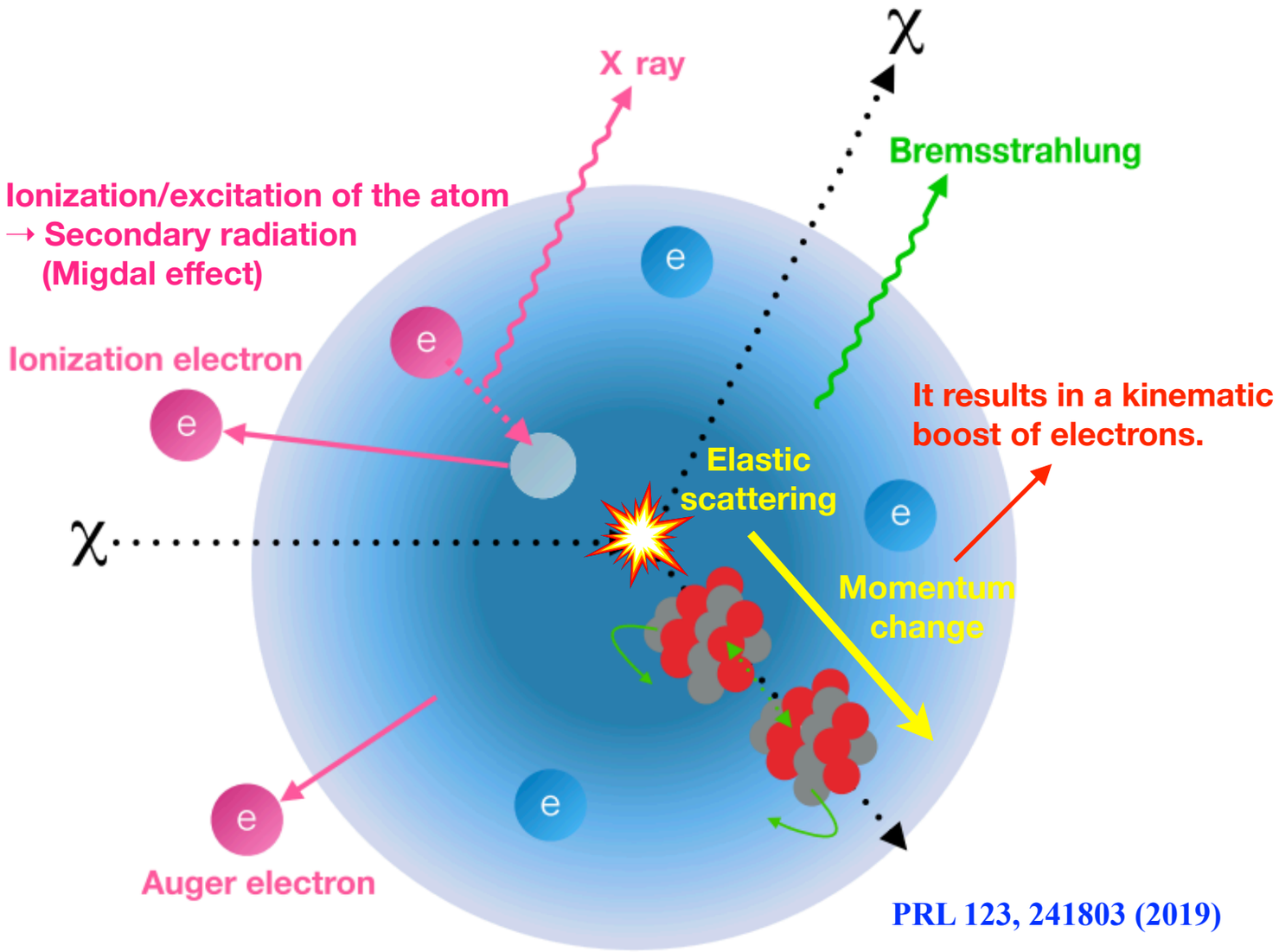


Exclusion Limits for EFT Operators



WIMP Signal via Migdal Effect

- Migdal Effect
  - Nuclear recoil → boost of electrons → secondary radiation



PRL 123, 241803 (2019)

WIMP Signal via Migdal Effect

- Migdal Effect
  - Nuclear recoil → boost of electrons → secondary radiation
  - Differential rate

Nuclear recoil energy

Quantum numbers

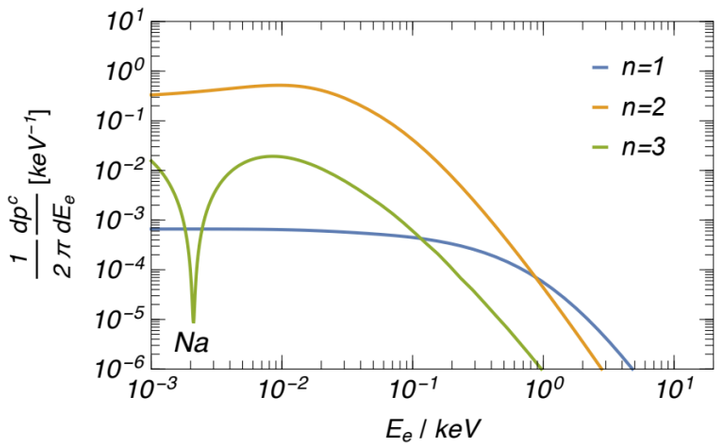
Binding energy

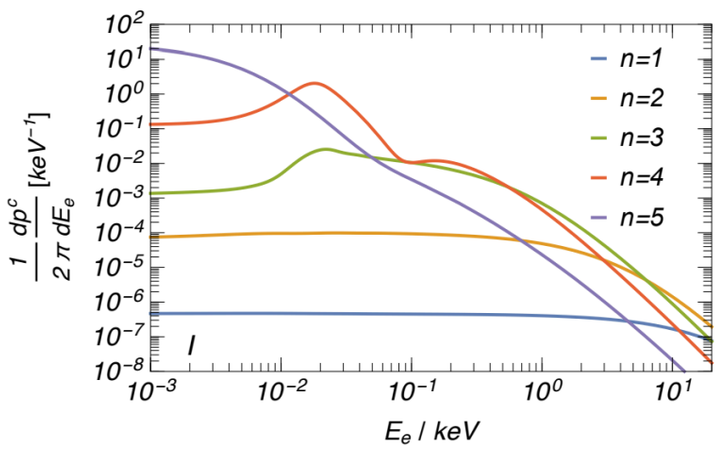
$$\frac{dR}{dE_{\rm ER}} \simeq \int dE_{\rm NR}\, dv\, \frac{d^2R}{dE_{\rm NR}dv} \frac{1}{2\pi} \sum_{n,l} \frac{d}{dE_{\rm ER}} p^c_{q_e}(n,l \to E_{\rm ER} - E_{nl})$$

Electron recoil energy

WIMP velocity

Probability for an atomic electron to be ionized and receive a kinetic energy E_{ER} - E_{nl}





JHEP **2018**, 194 (2018)

WIMP Signal via Migdal Effect

- Migdal Effect
  - Nuclear recoil → boost of electrons → secondary radiation
  - Differential rate & visible energy

Nuclear recoil energy

Quantum numbers

Binding energy

$$\frac{dR}{dE_{\rm ER}} \simeq \int dE_{\rm NR}\, dv\, \frac{d^2R}{dE_{\rm NR}dv}\frac{1}{2\pi}\sum_{n,l}\frac{d}{dE_{\rm ER}}p^c_{q_e}(n,l\rightarrow E_{\rm ER}-E_{nl})$$

Electron recoil energy

WIMP velocity

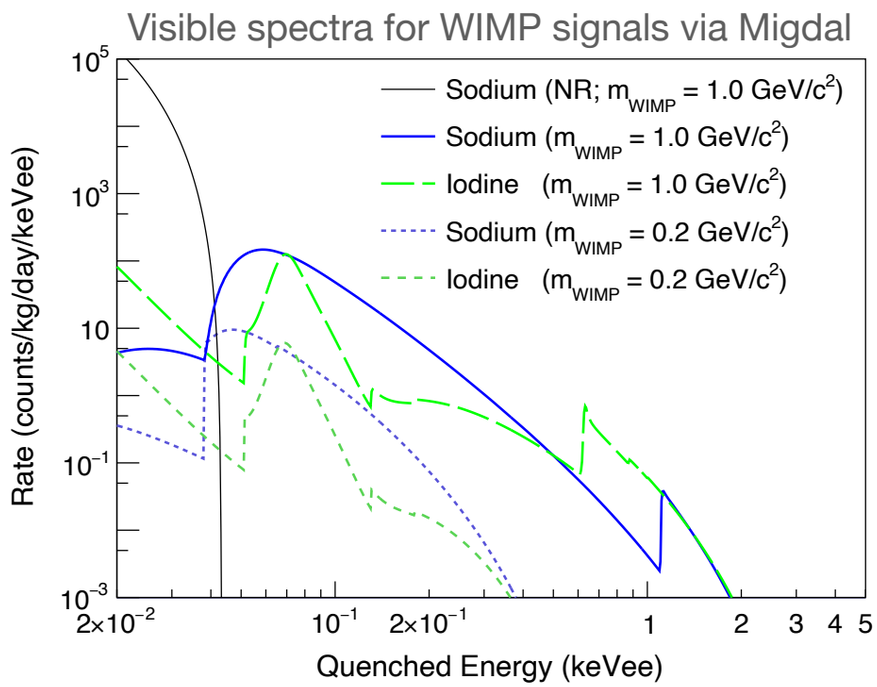
Probability for an atomic electron to be ionized and receive a kinetic energy E_{ER} - E_{nl}

$$E_{\rm vis} = q_{\rm NR}\cdot E_{\rm NR} + E_{\rm ER} + E_{nl}$$

Quenching factor for nuclear recoil energy to electron equivalent energy

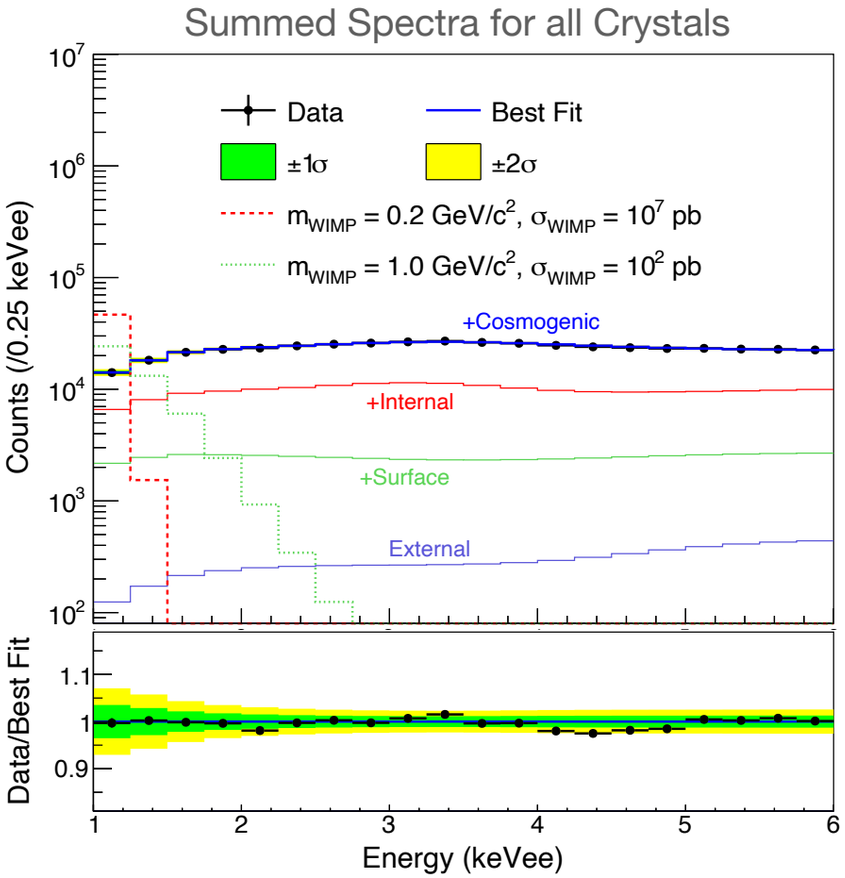
→ Advantage in quenching process

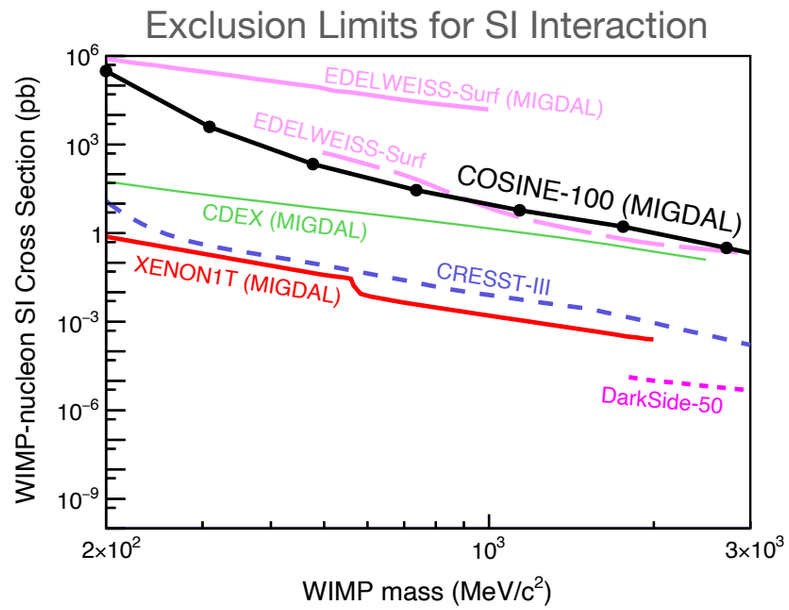
- $E_{\rm NR}$ is proportional to p_{qe}, not $E_{\rm ER}$.
- Lower mass region can be searched via migdal process.

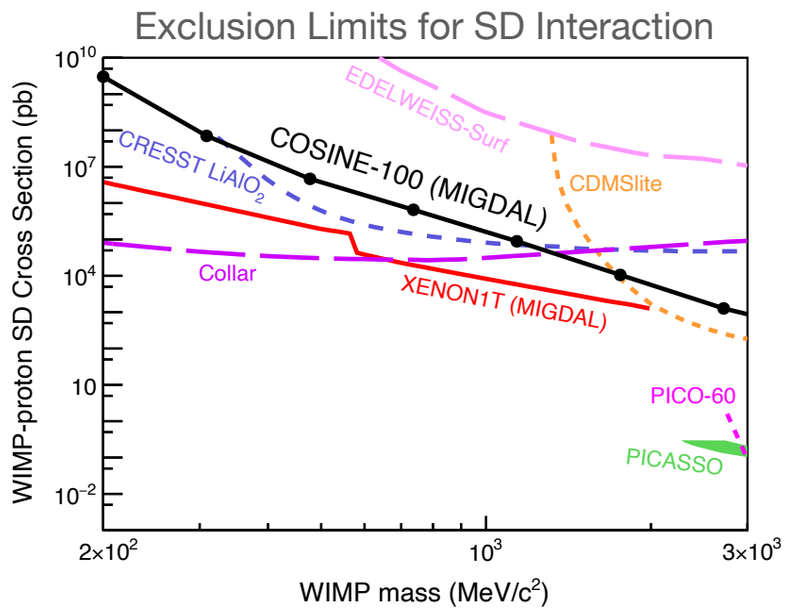


Low-Mass Search for WIMP

- The same method/data to SET2 extraction analysis
  - Data, background model, systematic uncertainties & bayesian approach
  - Only signal templates are different.
    - Using Migdal process
    - Nuclear recoil not considered
  - Search range extends down to 200 MeV/c².





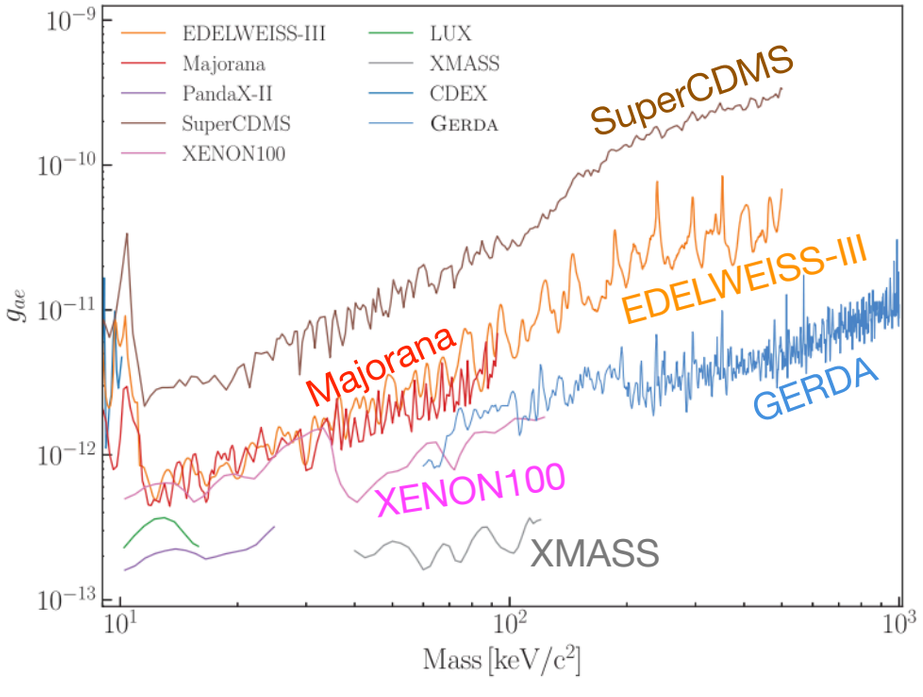


Bosonic Super-WIMP

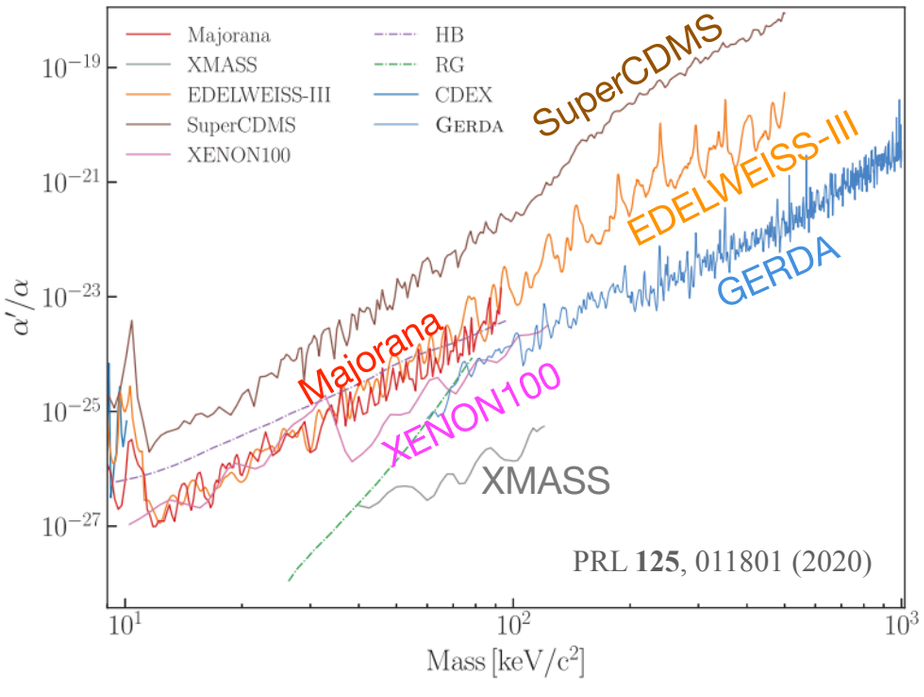
- A dark matter candidate
- Two types of BSW: pseudoscalar & vector boson
- XMASS, Majorana & XENON100
  - Below 100 keV/c^2
- Search area has been expanded by
  - SuperCDMS & EDELWEISS-III ~500 keV
  - GERDA ~1000 keV/c^2

$m_{a/V} > 2m_e \rightarrow$ can decay into (e^+, e^-)-pairs
(too short lifetime)

Exclusion Limits for Pseudoscalar



Exclusion Limits for Vector Boson



BSW Signal

- Absorption process can make signals in the detector

atom BSW (a: pseudoscalar, V: vector boson)

$$A + a/V \rightarrow A + e^-$$

$$\frac{\sigma_{\mathrm{abs,a}} v}{\sigma_{\mathrm{p.e}}(\omega = m_V)\, c} \approx g_{ae}^2 \frac{3 m_a^2}{16\pi\alpha m_e^2}, \quad \frac{\sigma_{\mathrm{abs,V}} v}{\sigma_{\mathrm{p.e}}(\omega = m_V)\, c} \approx \frac{\alpha'}{\alpha}$$

PRD **78**, 115012 (2008)

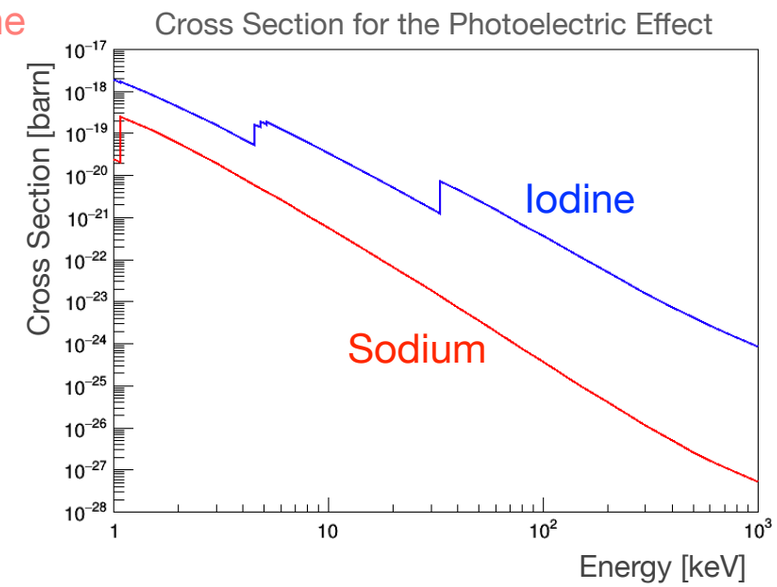
absorption cross section can be expressed w/ photoelectric cross section.

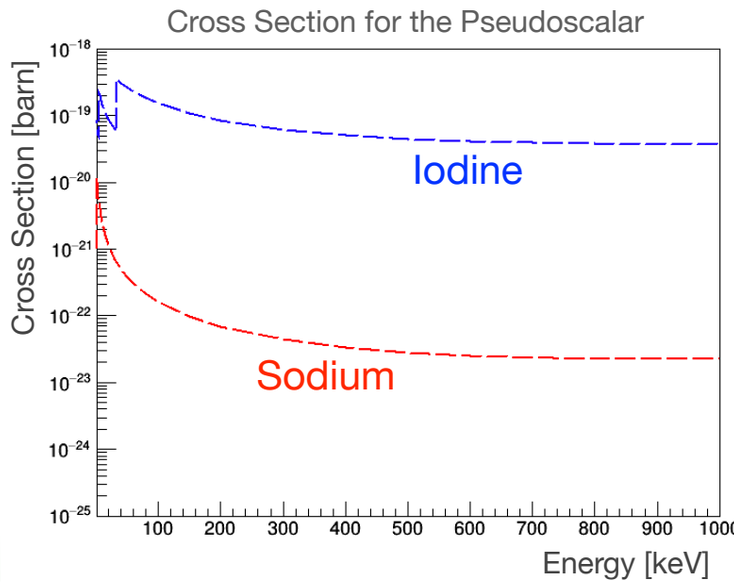
- Signal rate in the detector

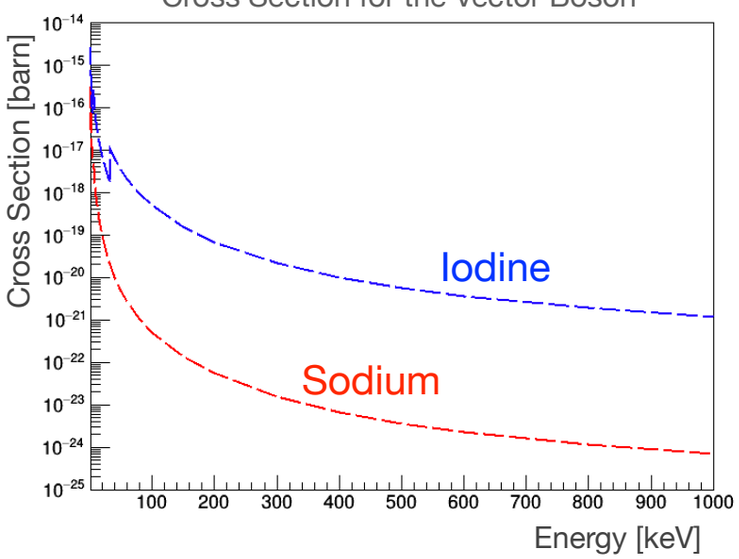
$$S_a \approx \frac{1.2 \times 10^{19}}{A} g_{ae}^2 \left(\frac{m_a}{\mathrm{keV}}\right) \left(\frac{\sigma_{\mathrm{p.e}}}{\mathrm{barn}}\right) \mathrm{kg}^{-1}\mathrm{day}^{-1}$$

$$S_V \approx \frac{4 \times 10^{23}}{A} \frac{\alpha'}{\alpha} \left(\frac{\mathrm{keV}}{m_V}\right) \left(\frac{\sigma_{\mathrm{p.e}}}{\mathrm{barn}}\right) \mathrm{kg}^{-1}\mathrm{day}^{-1}$$

All exclusion limits presented so far are based on the absorption process.







Compton-like Process

- In high-mass region, an additional process can be dominant.

$$e^- + a/V \to e^- + \gamma \quad \text{(Compton-like Process)}$$

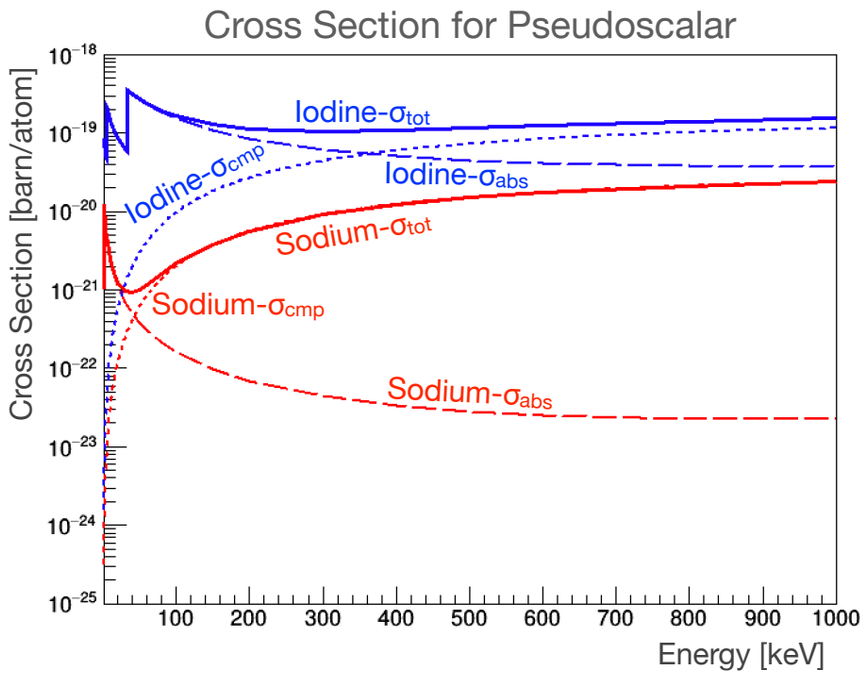
$$\sigma_{\mathrm{cmp},a} = g_{ae}^2 \frac{\alpha}{4m_e|\mathbf{k}|} \int_{-1}^{1} d\cos\theta_\gamma \frac{|\mathbf{q}|\mathcal{A}_P}{E_k + m_e - |\mathbf{k}|\cos\theta_\gamma}$$

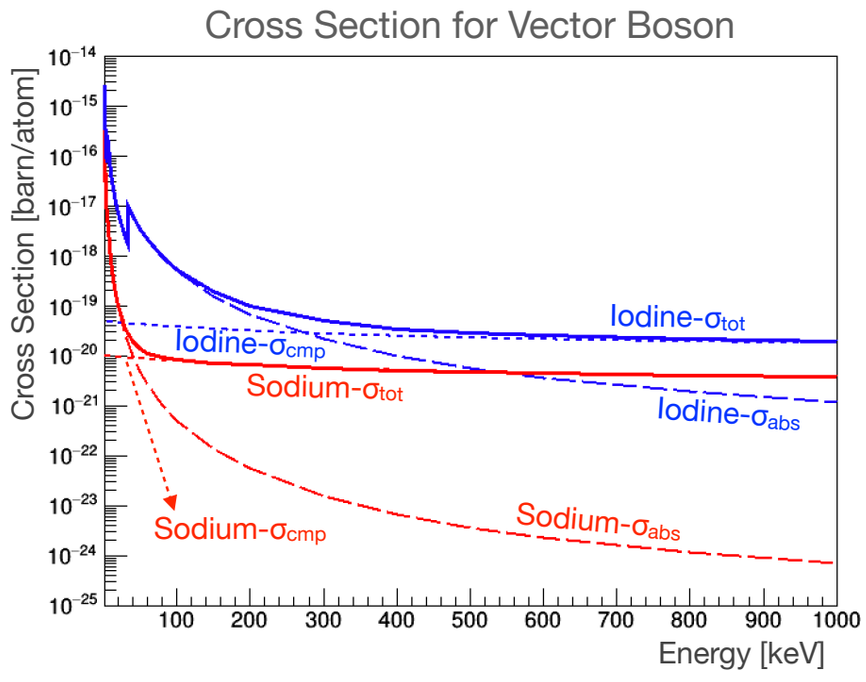
$$\sigma_{\mathrm{cmp},V} = \kappa^2 \frac{\pi\alpha^2}{3m_e|\mathbf{k}|} \int_{-1}^{1} d\cos\theta_\gamma \frac{|\mathbf{q}|\mathcal{A}_V}{E_k + m_e - |\mathbf{k}|\cos\theta_\gamma}$$

PRD **104**, 083030 (2021)

$$\text{where } |\mathbf{q}| = \frac{m_{a/V}^2 + 2E_k m_e}{2(m_e + E_k - |\mathbf{k}|\cos\theta_\gamma)}$$

- ✦ γ as well as e⁻ are also emitted.
- ✦ From ~150 keV, Compton-like process dominate over absorption process, for the Germanium case.





BSW Signal Generation

- Electron/gamma energy
  - Absorption process

$$A + a/V \rightarrow A + e^-$$

$$m_{a/V} \sim K_e$$ K_e: electron kinetic energy

  - Compton-like process

$$e^- + a/V \rightarrow e^- + \gamma$$

ω': gamma energy, ω: BSW energy

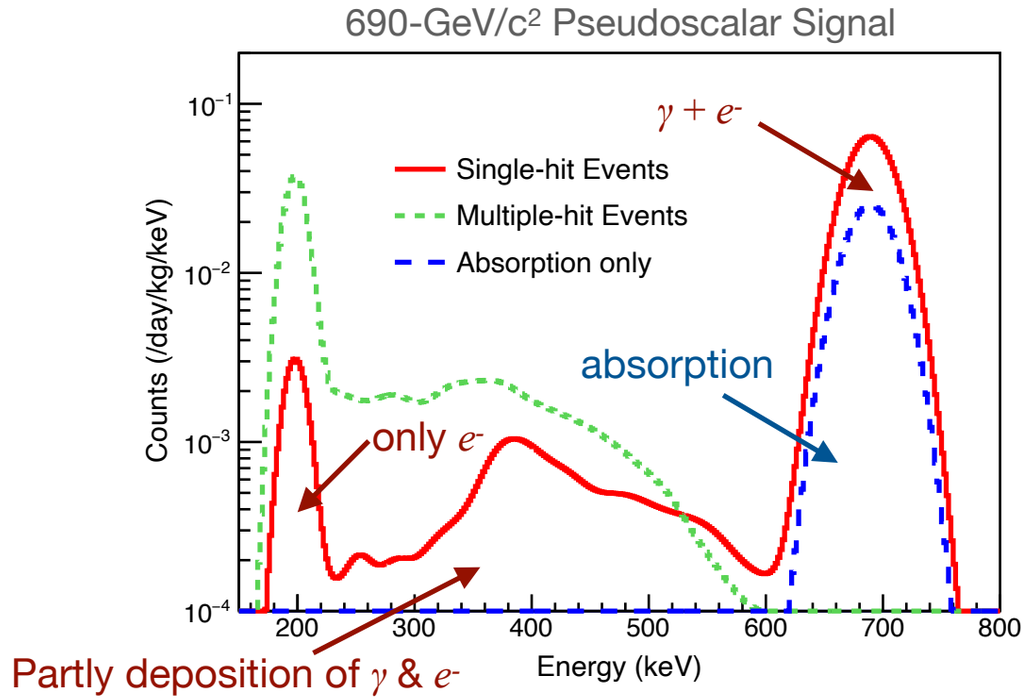
$$\omega' = \frac{m_{a/V}^2 + 2m_e\omega}{2\left(m_e + \omega - \sqrt{\omega^2 - m_{a/V}^2}\cos\theta\right)}$$

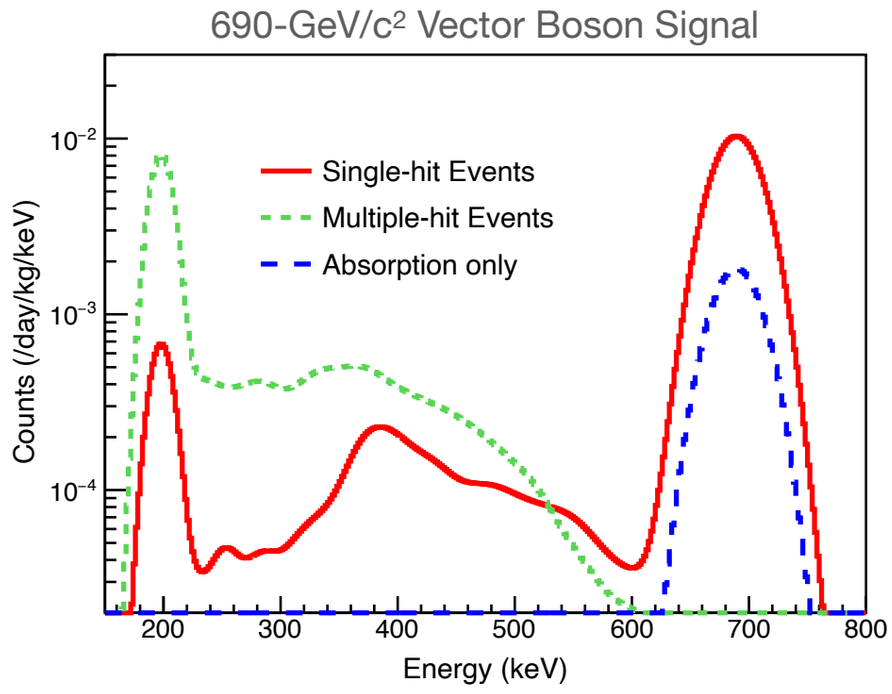
$m_{a/V}$: BSW mass

$$\sim \frac{m_{a/V}^2 + 2m_e m_{a/V}}{2(m_e + m_{a/V})} \quad (\omega \sim m_{a/V})$$

$$K_e = \omega - \omega' \sim \frac{m_{a/V}^2}{2(m_e + m_{a/V})}$$

  - Electron/gamma generation via COSINE-100 detector simulation



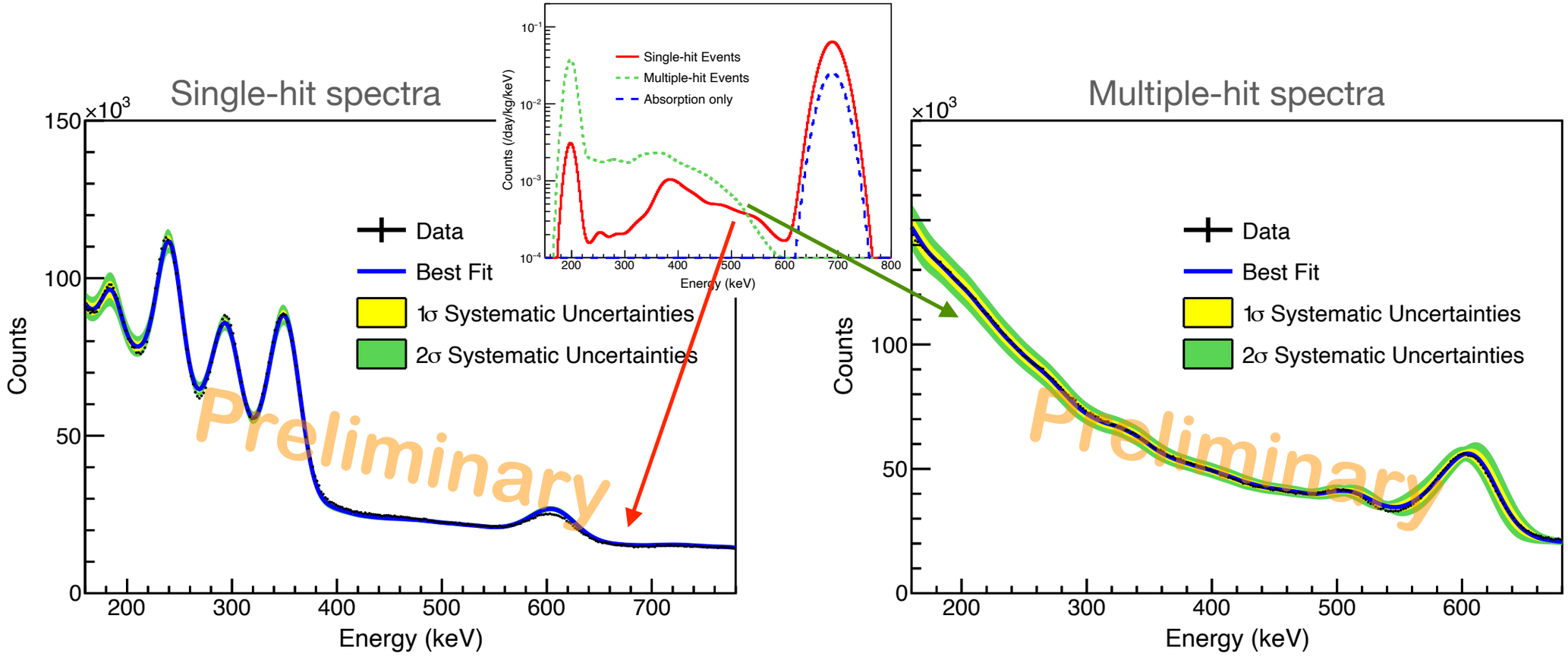


Extraction Analysis

- BSW extraction analysis
  - Bayesian approach

$$\mathcal{P}(\sigma|M) = \frac{P(M|\sigma)\,\pi(\sigma)}{\int d\sigma P(M|\sigma)\,\pi(\sigma)}$$

  - Simultaneous fitting for 5×2 channels: 5 crystals & single/multiple-hit channels



Extraction Analysis

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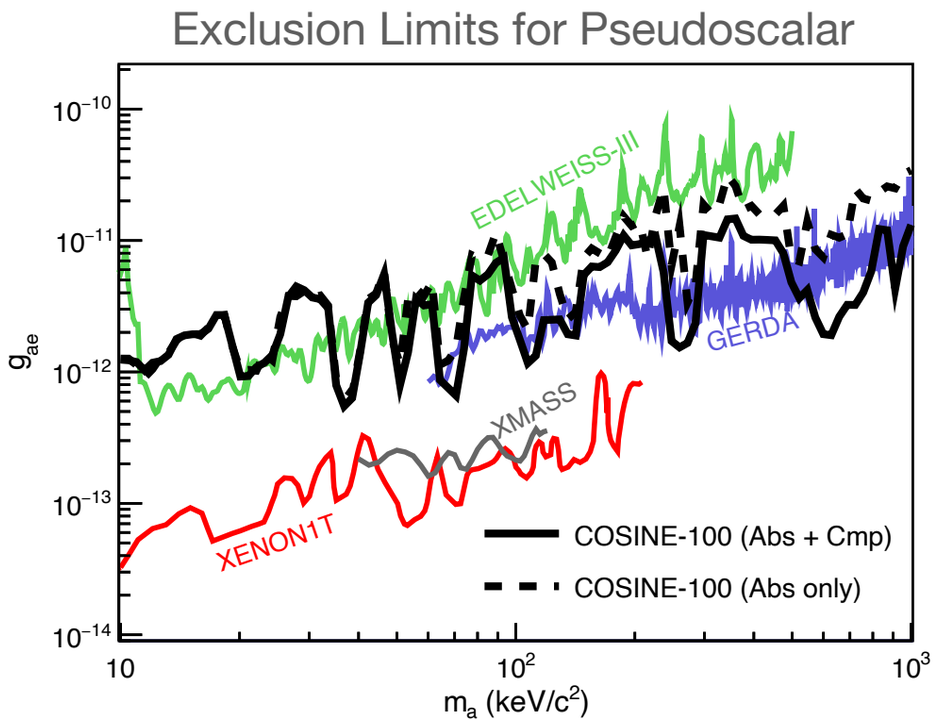
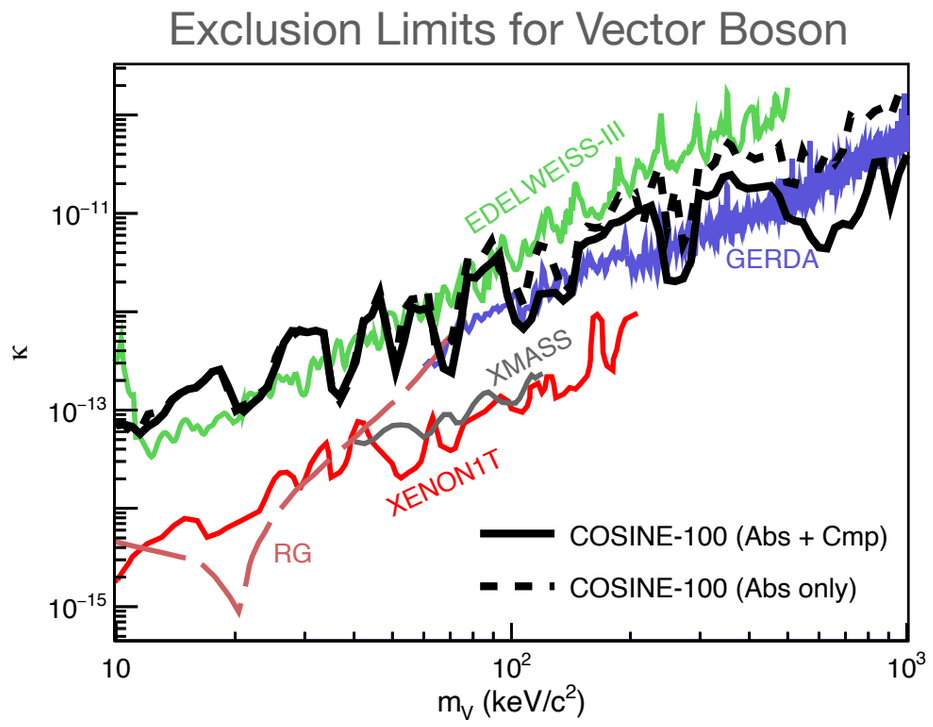
$$\mathcal{P}(\sigma|M) = \frac{P(M|\sigma)\,\pi(\sigma)}{\int d\sigma P(M|\sigma)\,\pi(\sigma)}$$

  - Simultaneous fitting for 5×2 channels: 5 crystals & single/multiple-hit channels
  - Search range: 100 mass points from 10 to 1000 keV/c^2
  - In the mass region greater than 200 keV/c^2, similar to GERDA
  - First result of using Compton-like process



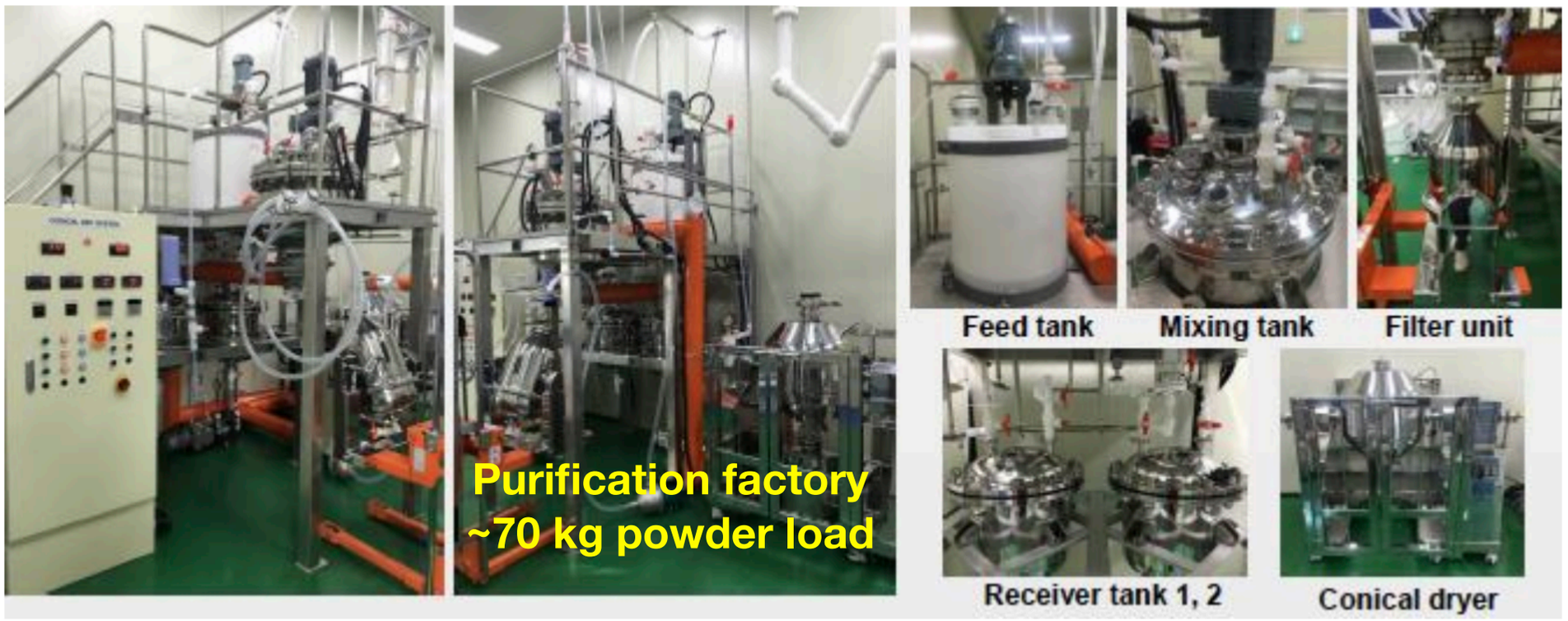


Crystal Development

- Goal: lower background level than DAMA/LIBRA
  - COSINE-100 has 2-3 times higher background than DAMA/LIBRA
  - In-house development for the entire process
    - **NaI powder purification**

J. Rad. Nucl. Chem. 317, 1329 (2018)
JINST 15, C07031 (2020)

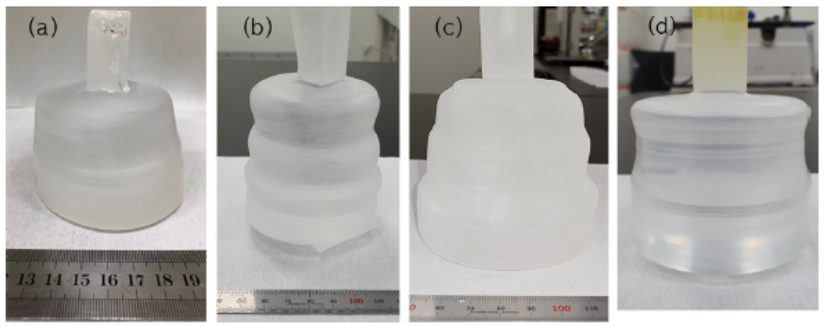
	K [ppb]	Pb [ppb]	U [ppb]	Th [ppb]
Initial	248	19.0	< 0.01	< 0.01
Purified	**< 16**	**0.4**	< 0.01	< 0.01

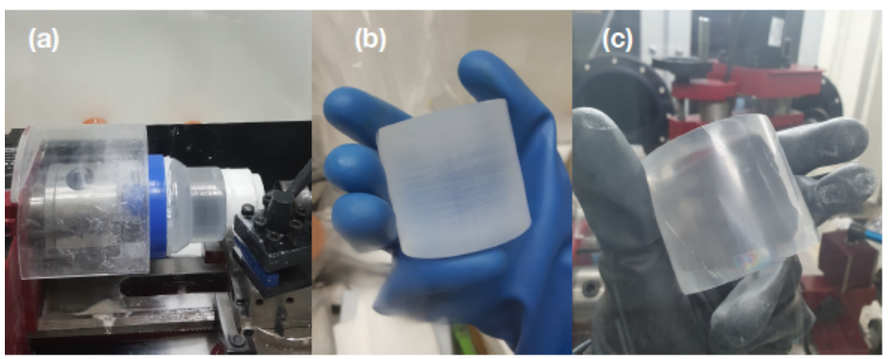


Crystal Development

- Goal: lower background level than DAMA/LIBRA
  - COSINE-100 has 2-3 times higher background than DAMA/LIBRA
  - In-house development for the entire process
    - NaI powder purification
    - **Crystal growing**
    - **Detector assembly**

Growing with test grower

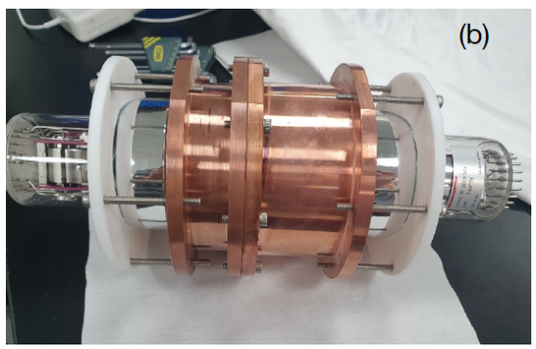


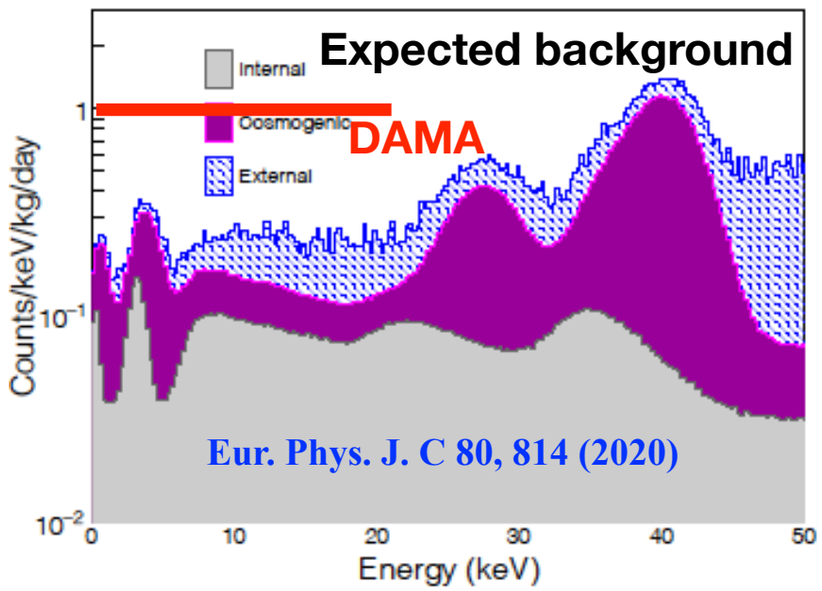


Crystal machining

	K [ppb]	210Pb [mBq/kg]	238U [Bq/kg]	232Th [Bq/kg]
Powder	5	-	< 20	< 20
Aug., 2018	684	3.8 ± 0.3	26 ± 7	< 6
Sep., 2019	**8**	**0.01 ± 0.02**	11 ± 4	7 ± 2
DAMA	< 20	0.01 ~ 0.03	8.7 ± 124	2 ~ 31

Detector assembly



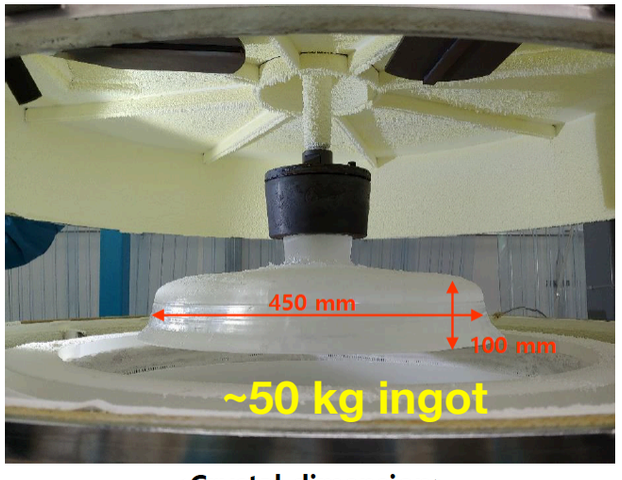


Crystal Development

- Goal: lower background level than DAMA/LIBRA
  - COSINE-100 has 2-3 times higher background than DAMA/LIBRA
  - In-house development for the entire process
    - NaI powder purification
    - Crystal growing
    - Detector assembly
  - Full size grower
    - Designed and built based on small test grower
    - Successful seeding and growing ~10 cm ingot

<Powder charging>

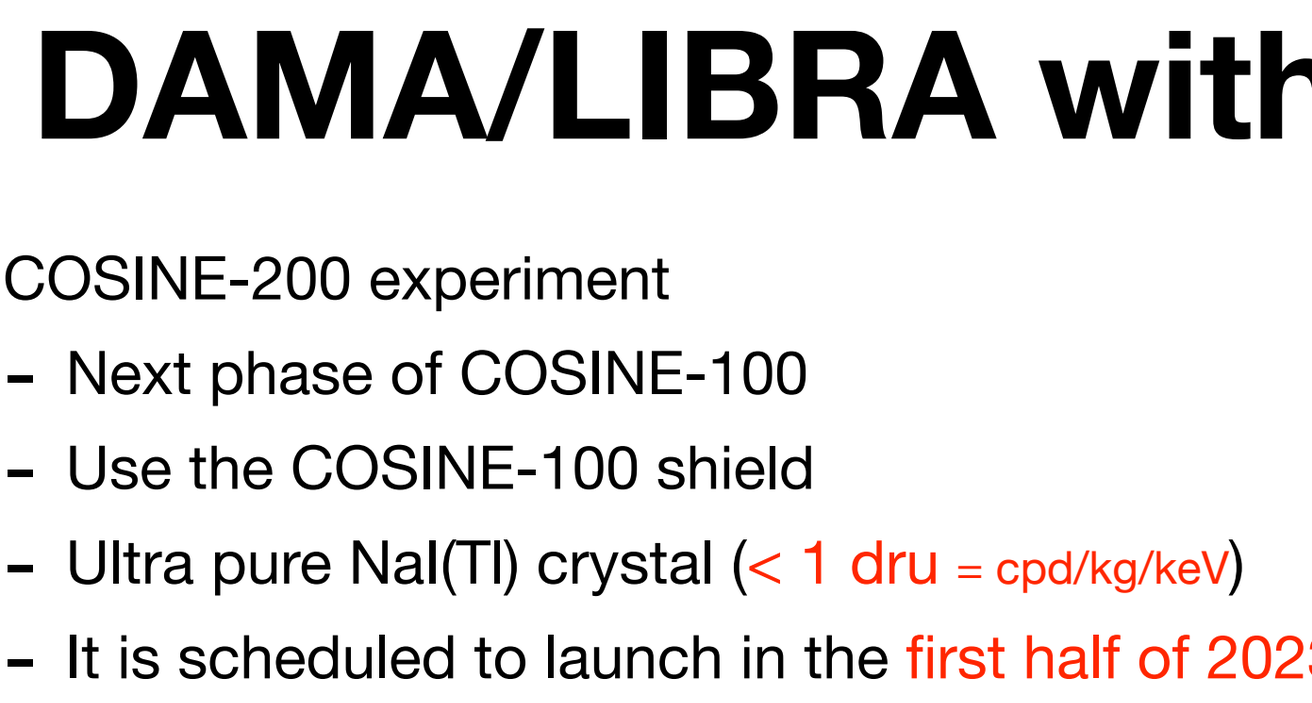
<Seed & holder>

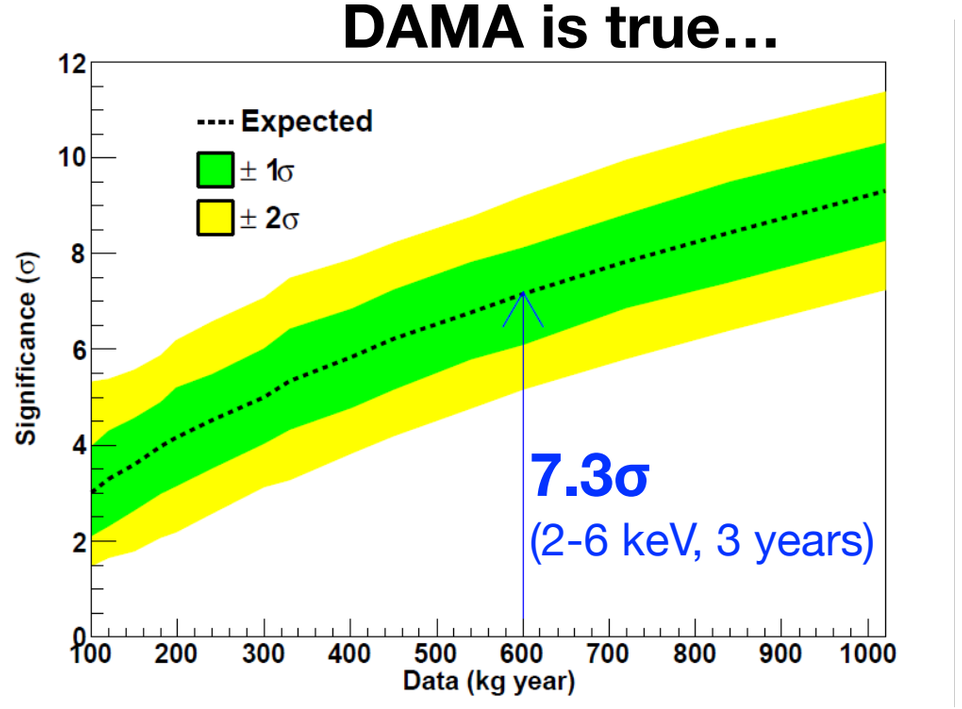


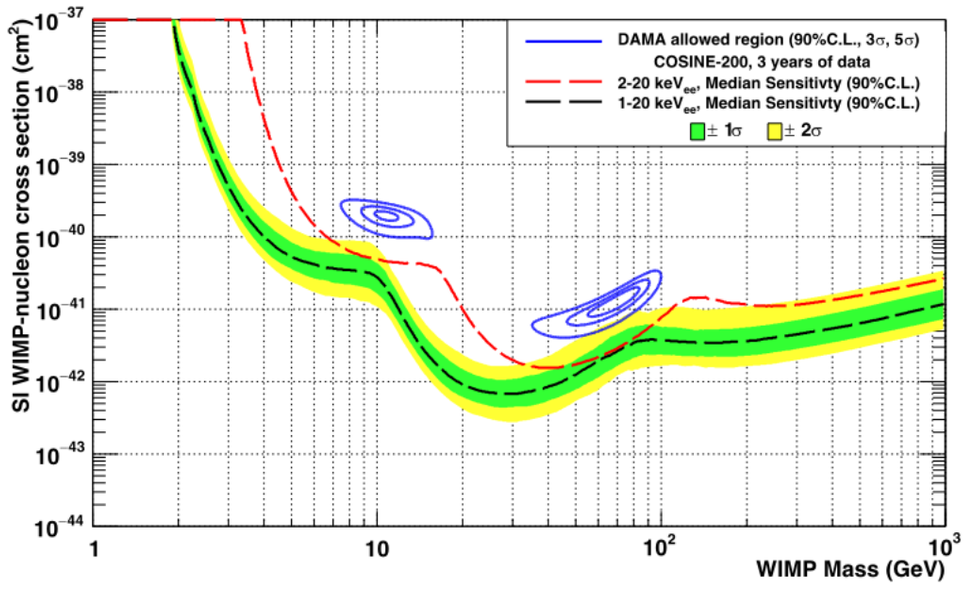
<Crystal dimension>

DAMA/LIBRA with COSINE-200

- COSINE-200 experiment
  - Next phase of COSINE-100
  - Use the COSINE-100 shield
  - Ultra pure NaI(Tl) crystal (< 1 dru = cpd/kg/keV)
  - It is scheduled to launch in the first half of 2023.
- Model-independent conclusion of DAMA/LIBRA is possible within **3 years**.

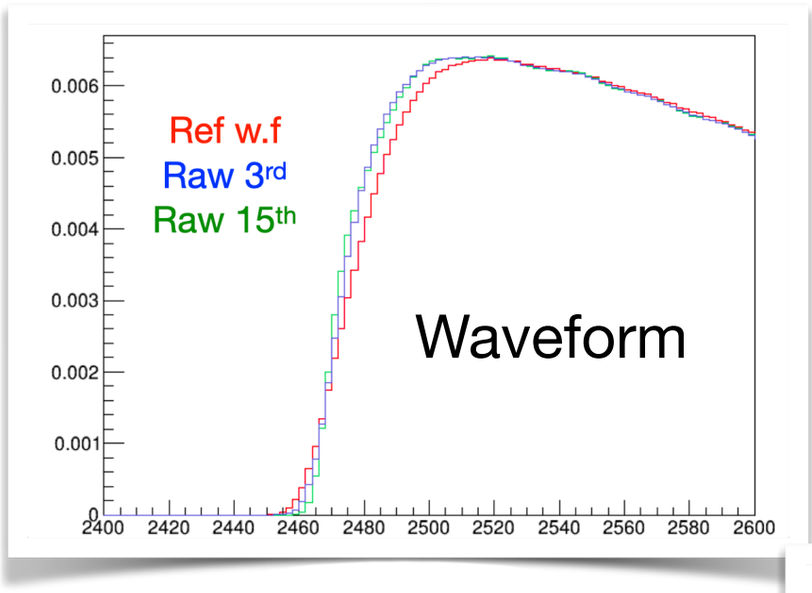


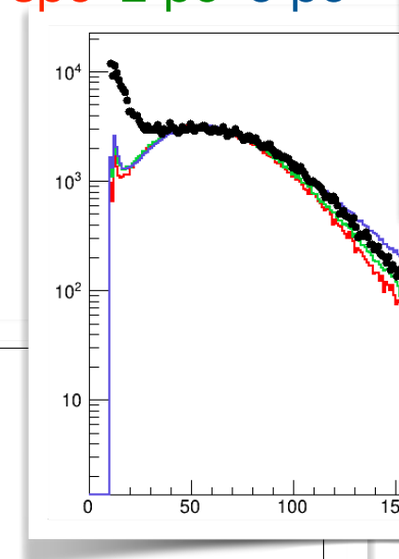


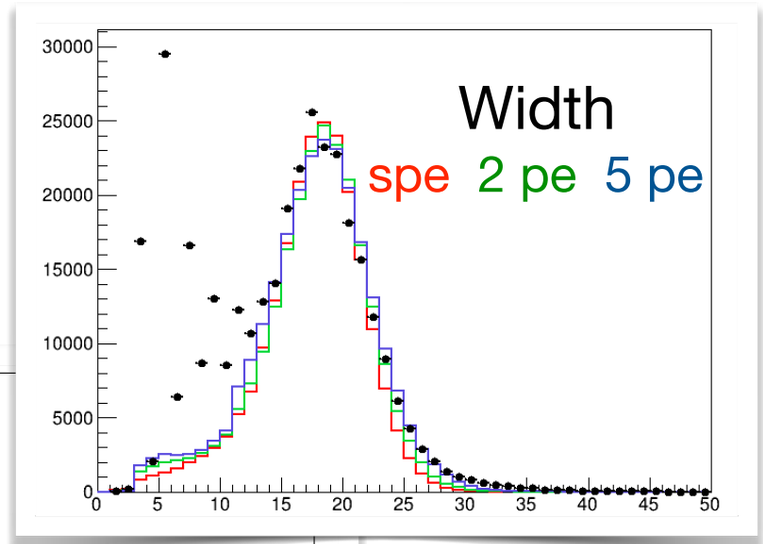


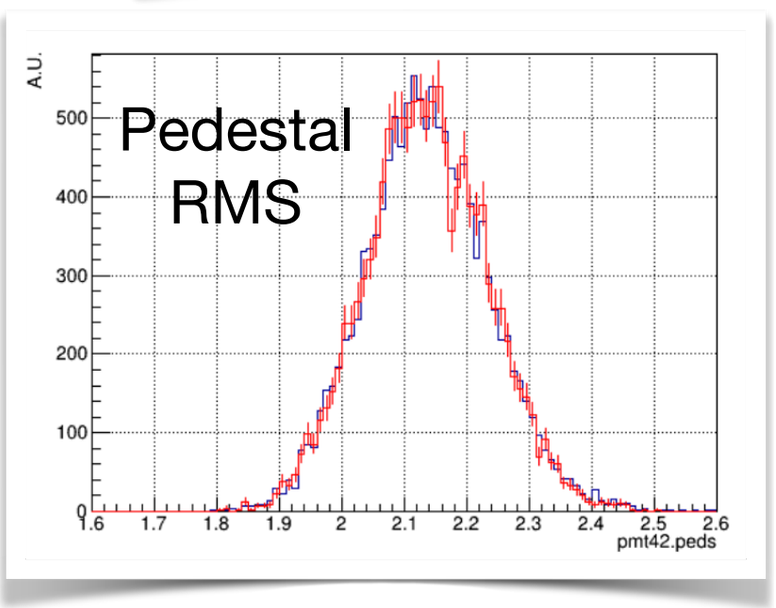
Trigger Simulation Tuning

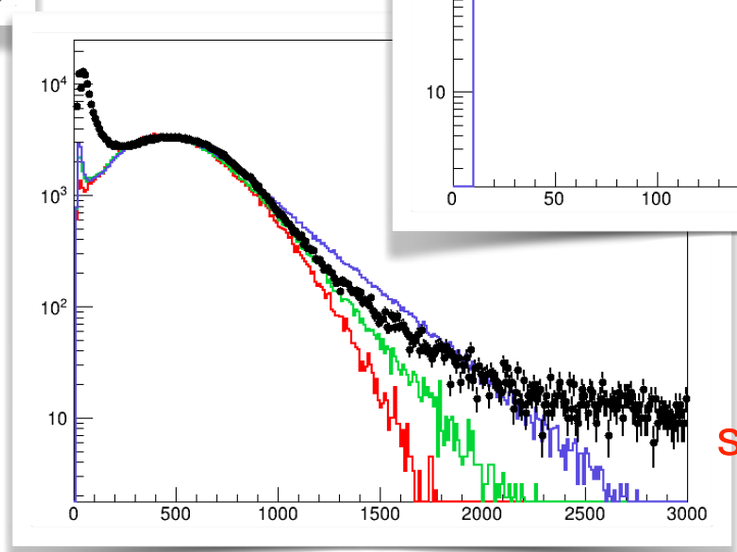
- Tuning parameters
  - SPE shape, height, width
  - Pedestal RMS, PMT gain, waveform shape





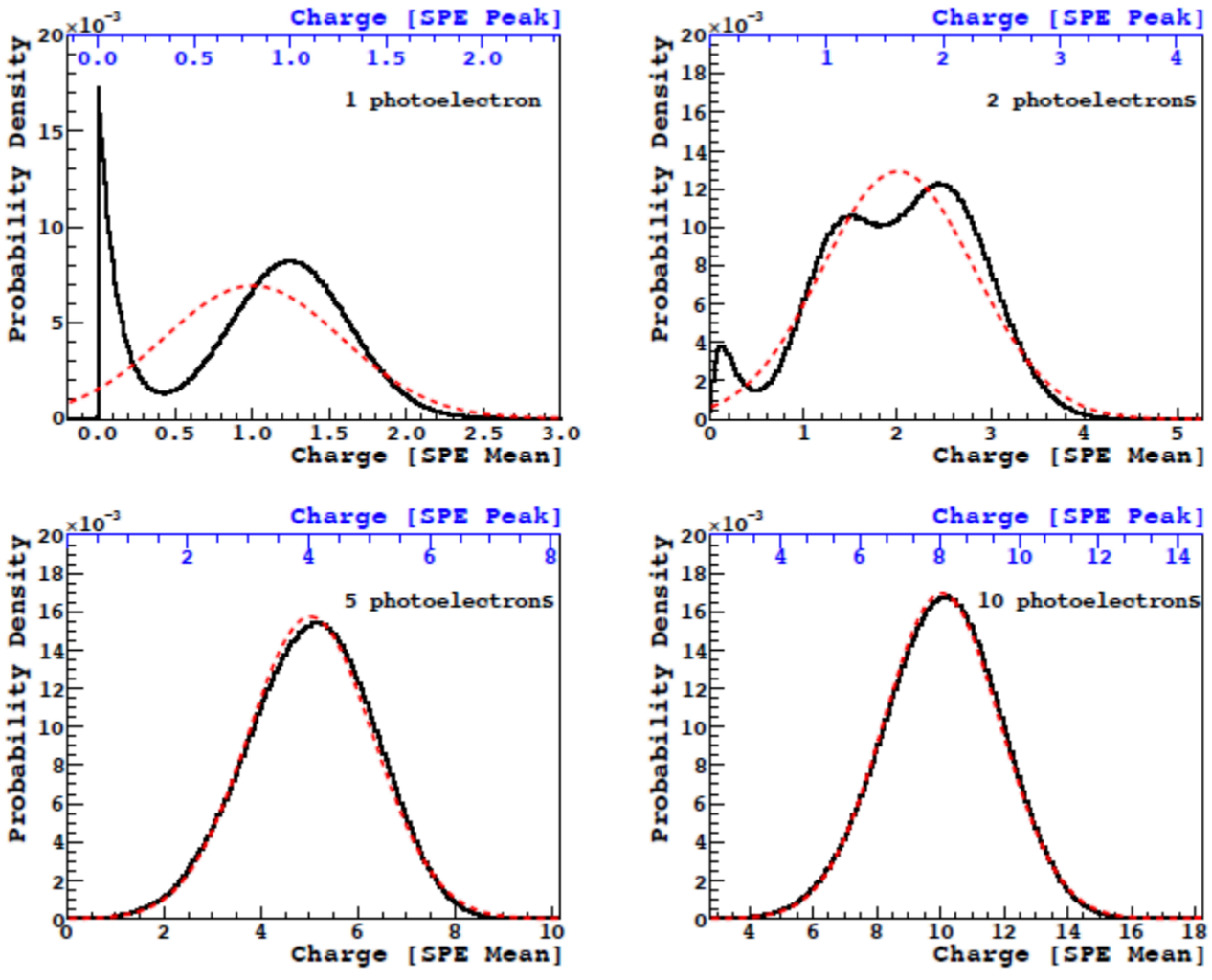






Trigger Simulation Tuning

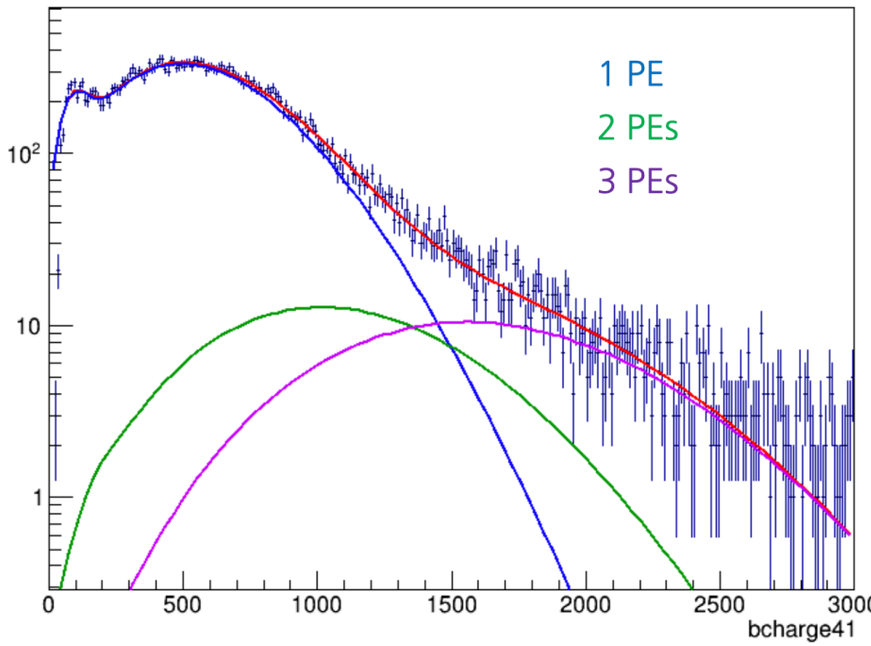
- Low-gain SPE
  - They can make some bias for few p.e analysis

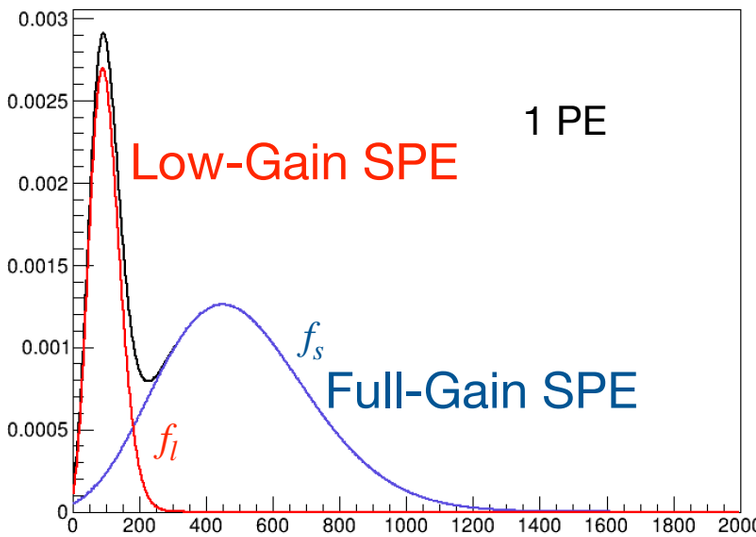


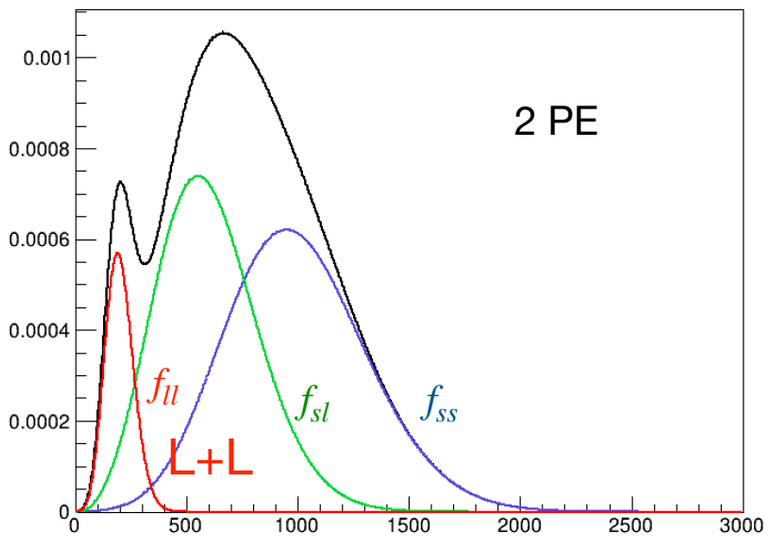
arXiv:1602.03150v2

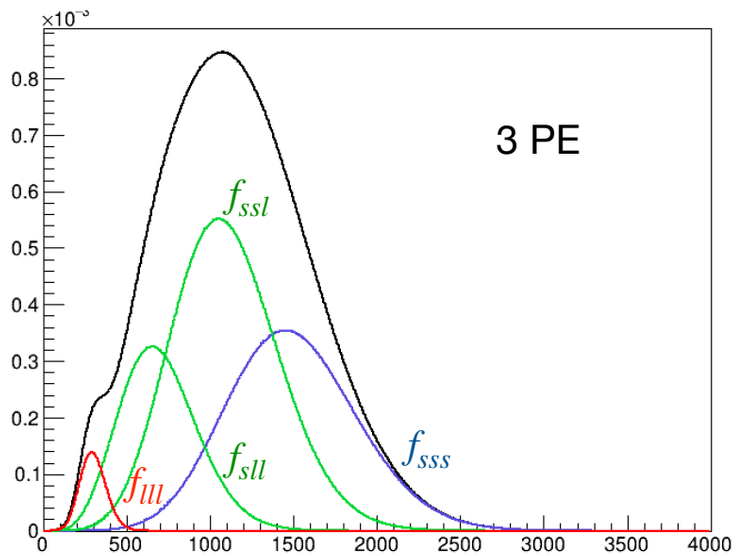
Trigger Simulation Tuning

- Low-gain SPE
  - They can make some bias for few p.e analysis
  - Trying to describe them via a model
    - Low-gain probability ~7%
    - Low-gain mean = 0.18 times SPE









Trigger Simulation Tuning

- Low-gain SPE
  - They can r
  - Trying to c
    - Low-gair
    - Low-gair