Progress of CryoCsI R&D from COHERENT

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On behalf of COHERNT Collaboration

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Outline

- About COHERENT
- Why CryoCsI?
- Detector System and characterization
  - Light yield and uniformity
  - Long term stability
- Background
  - Radioactive background of crystal
  - Steady-State background
- Quenching Factor
- Sensitivity Estimation

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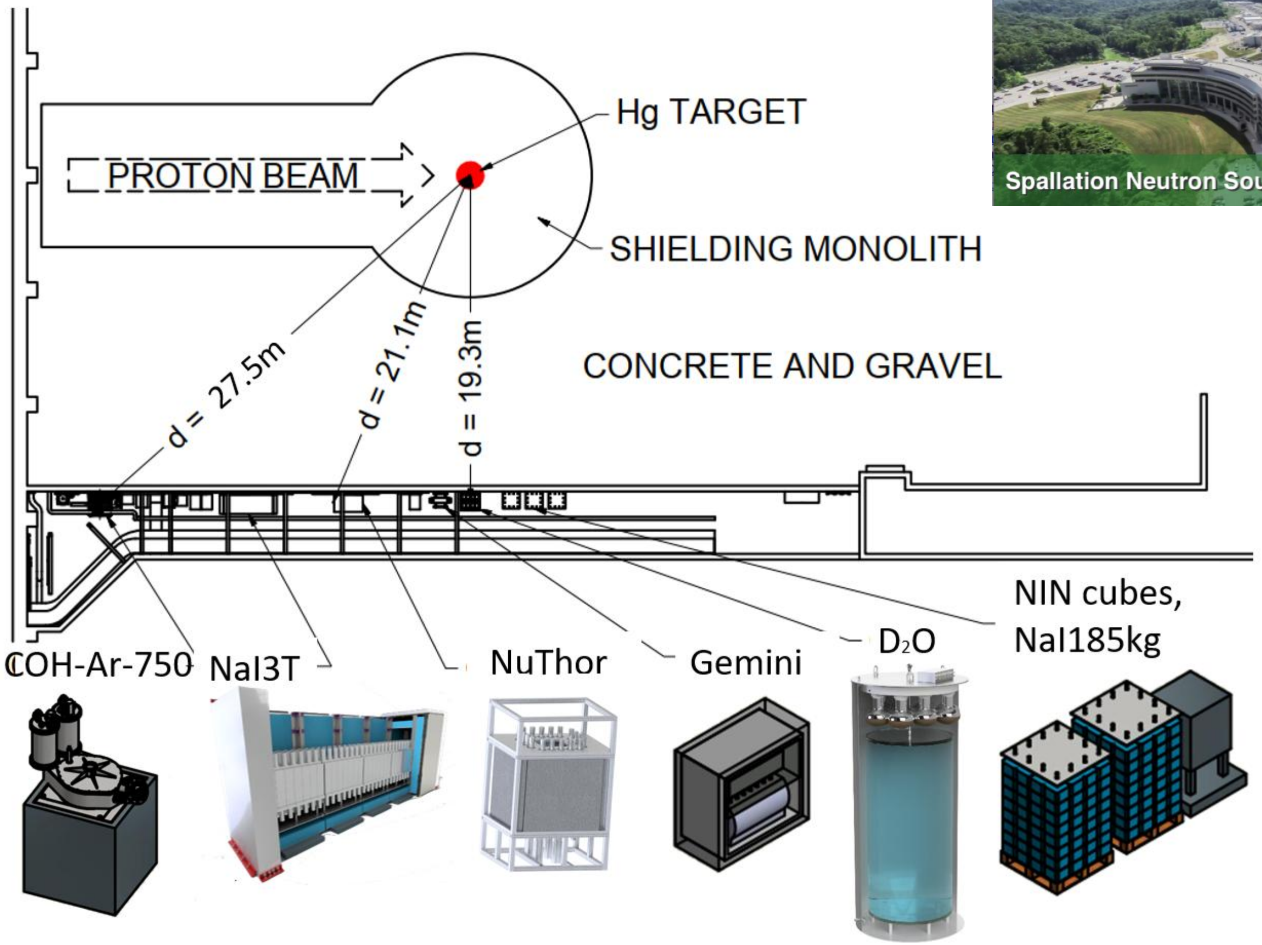

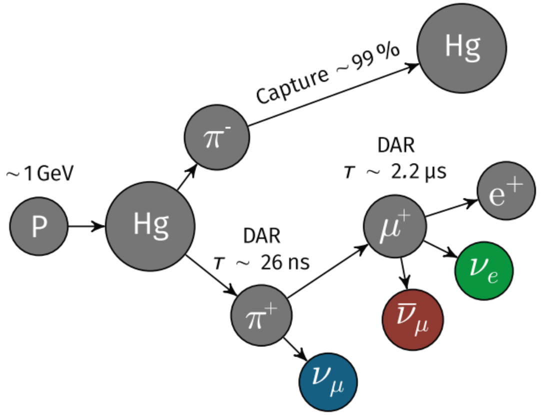

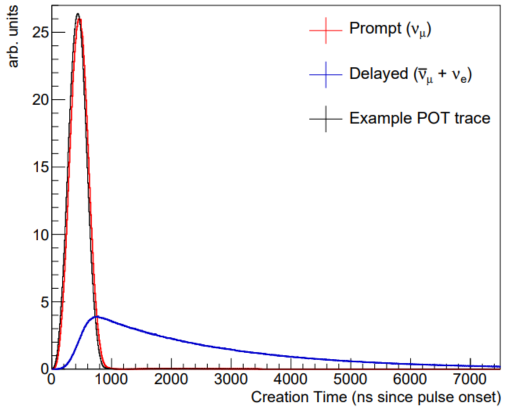

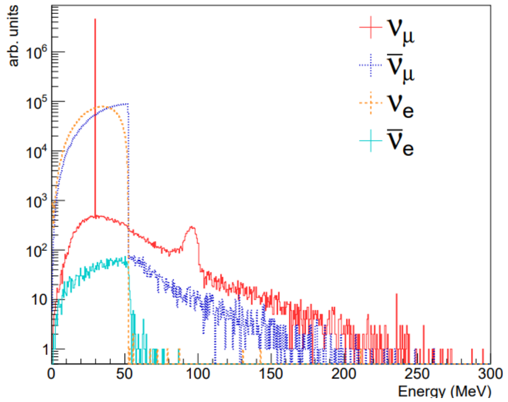

Beam Energy: 1.3GeV
Beam Power: 1.8MW soon to 2MW
60Hz and 380ns FWHM

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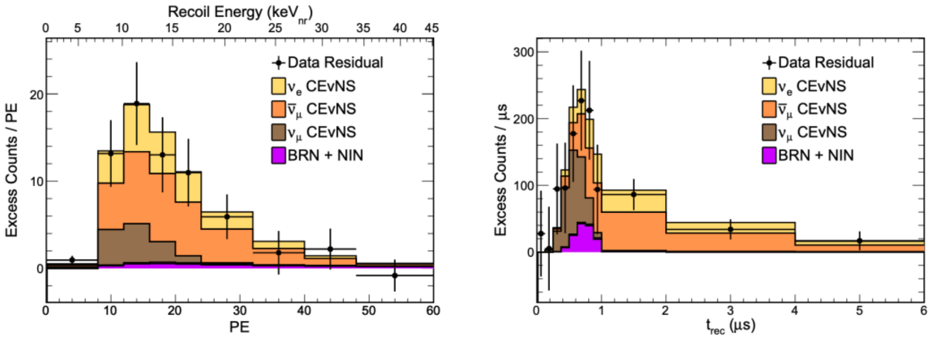
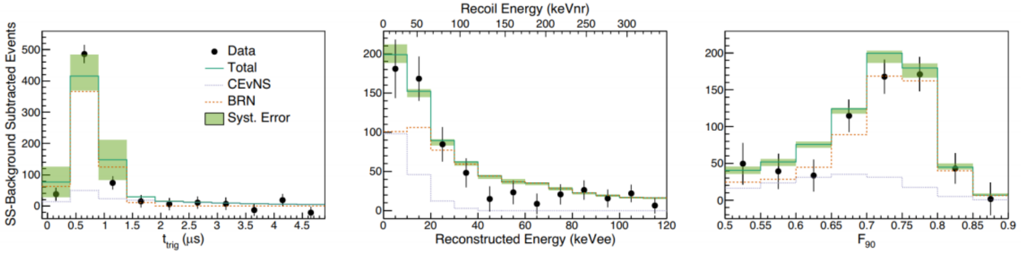
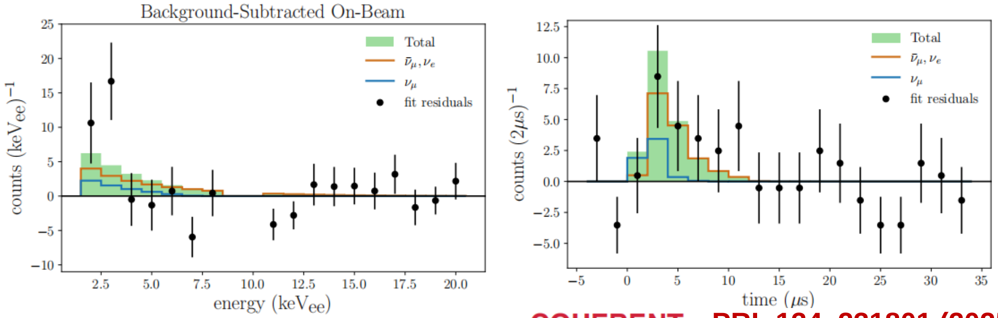
Results from COHERENT



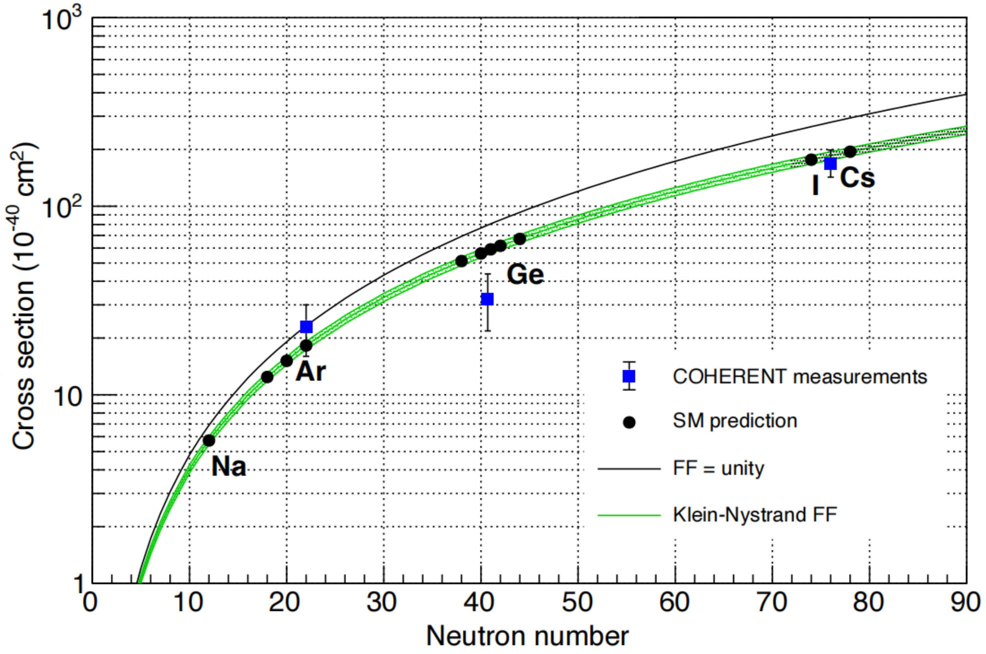
COHERENT, PRL 129 081801 (2022)



COHERENT, PRL 126 012002 (2021)



COHERENT, PRL 134, 231801 (2025)



More data on the way!

Moving to precision measurement!

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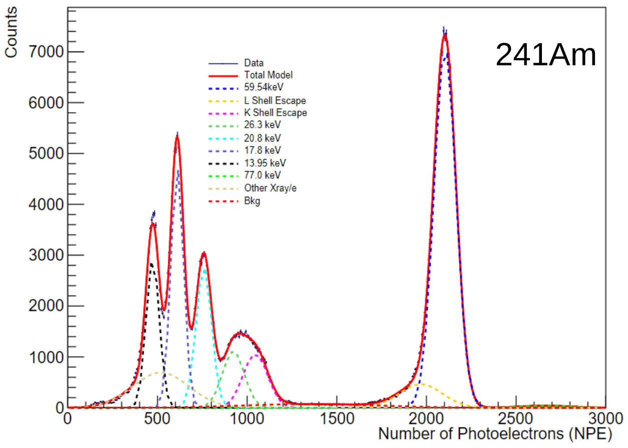
Why CryoCsI?

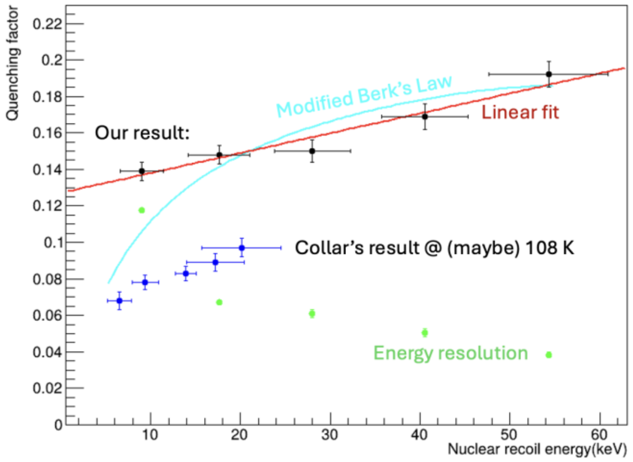
High light yield and good resolution



$LY \geq 35.2 \pm 0.6\text{PE/keVee}$

$FWHM = 6.9\%@60\text{keV}$

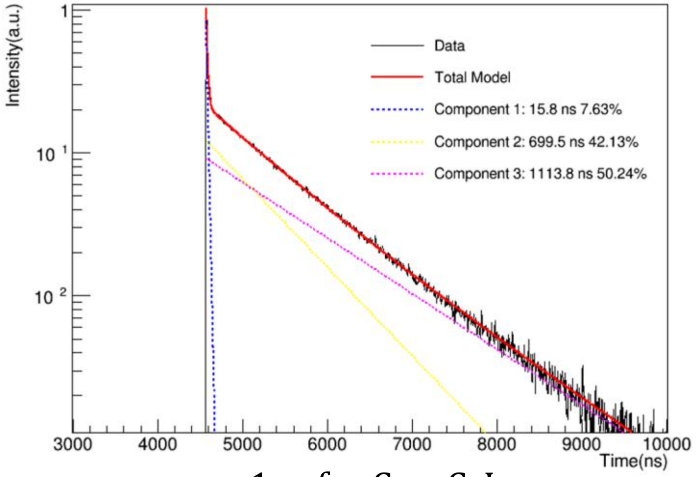
High quenching factor



$\sim 15\%@77K$

$\sim 8\%@293K$

Low afterglow



$1\mu s$ for CryoCsI

$17\mu s$ for CsI(Na)

A Lower threshold down to 1keV_{nr}

Higher statistics and better sensitivity to physics

Important to precision CEvNS!

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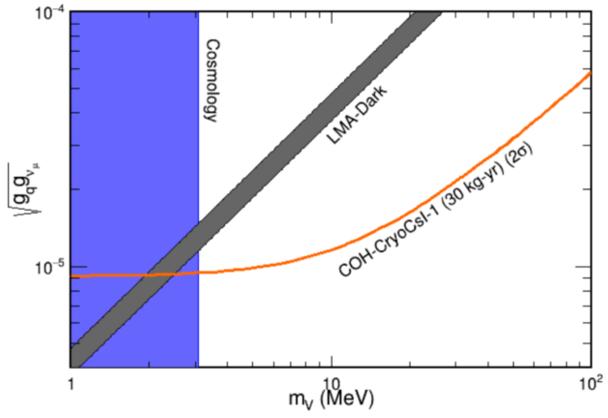
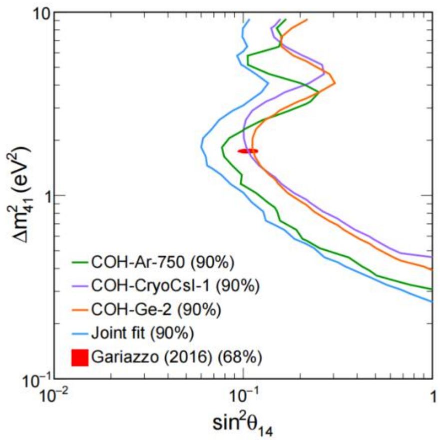
Physics to explore

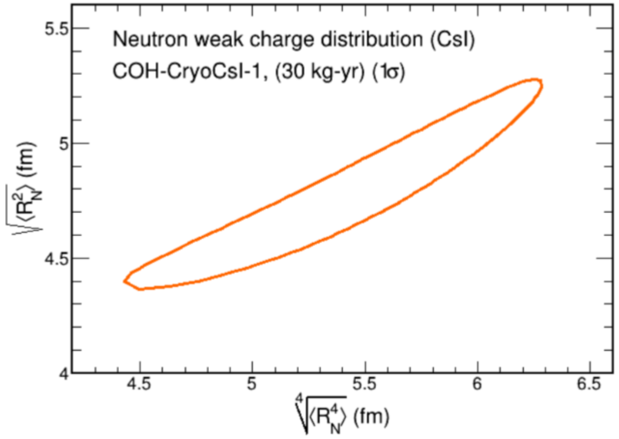
•COHERENT: 10.1103/PhysRevD.109.092005



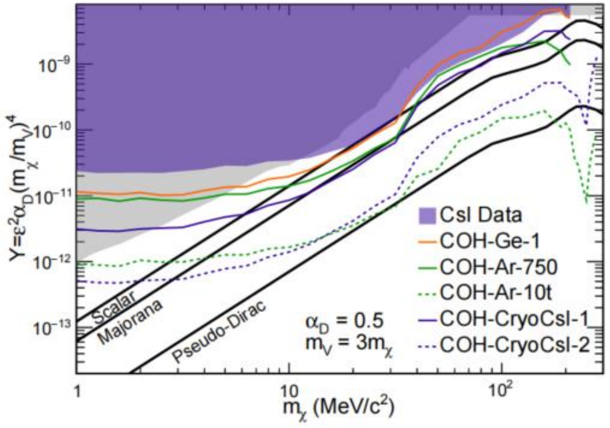
NSI



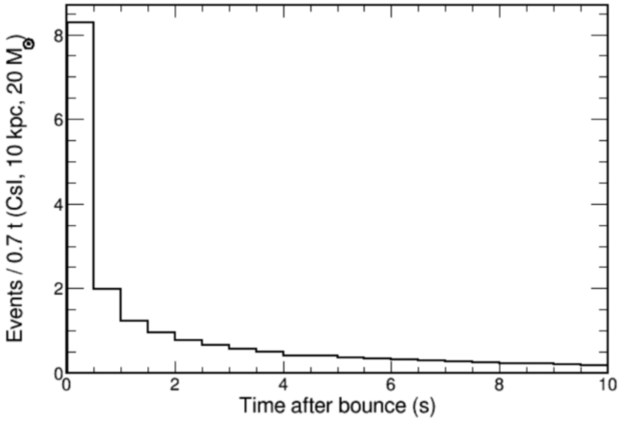
Sterile neutrino



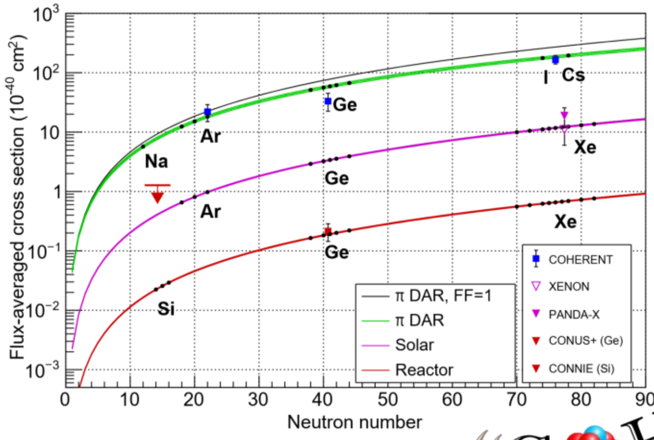
Neutron weak charge



Dark matter



Supernova



SM CX

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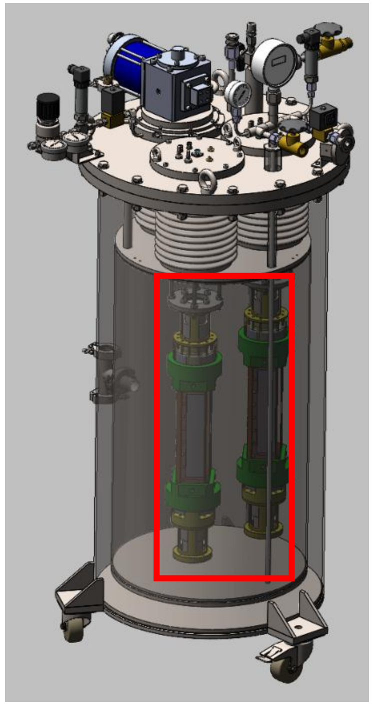
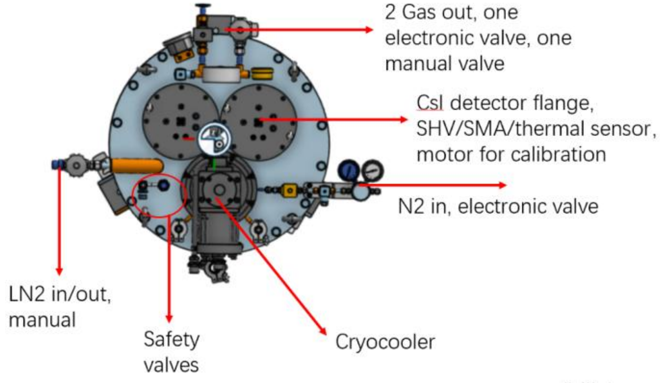
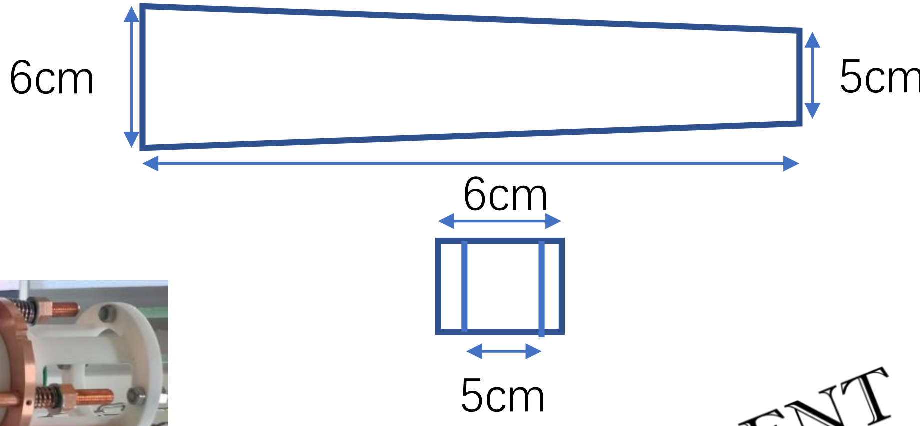
Detector system

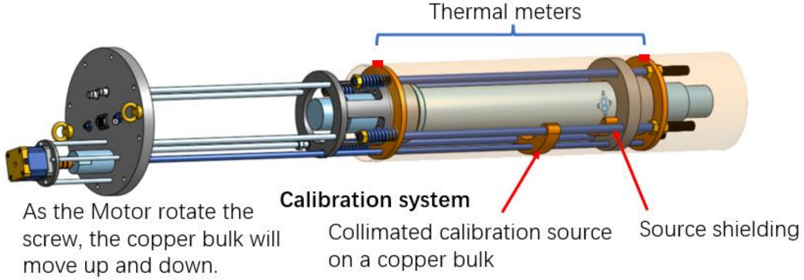
Two detector modules inside





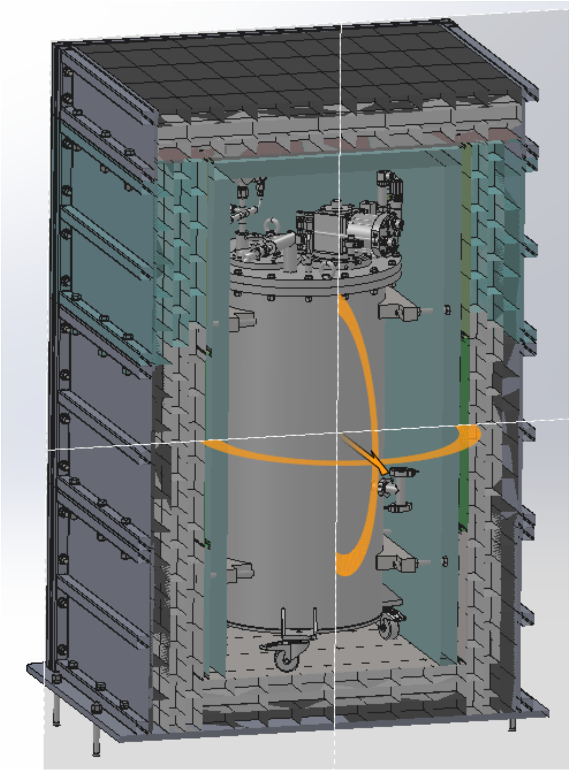
3.3kg each from SICCAS



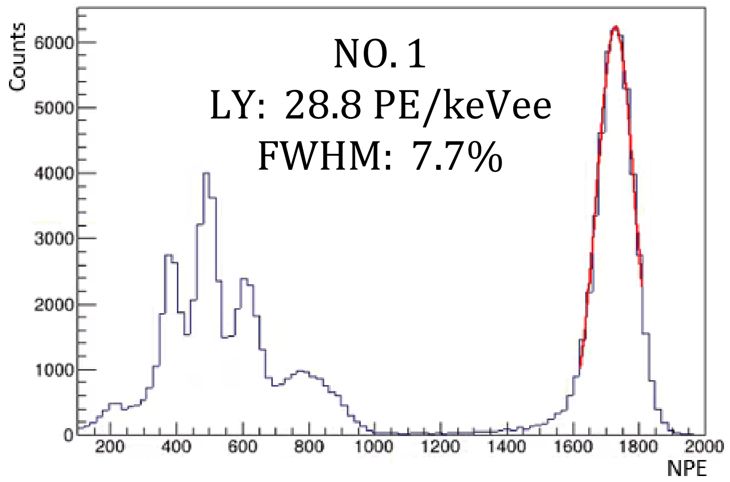


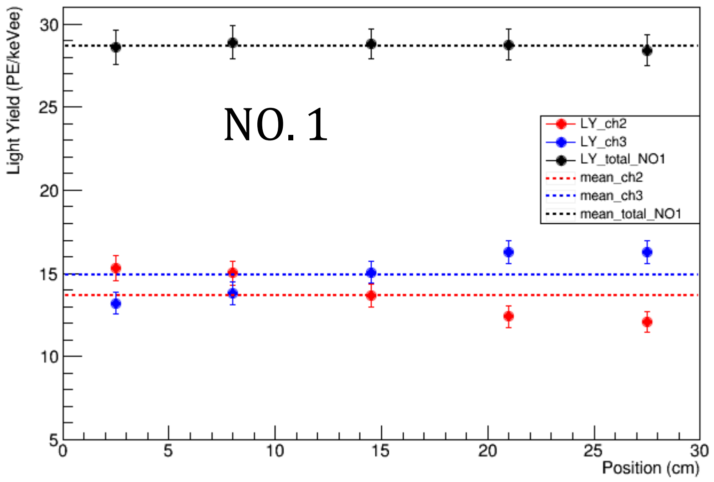
Shielding structure

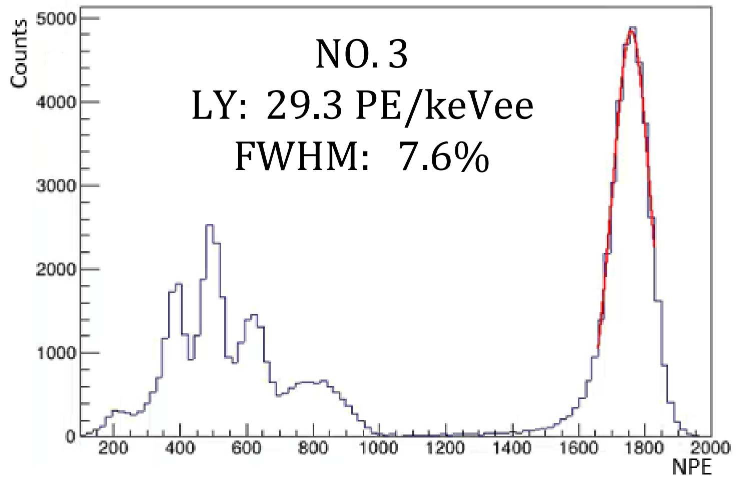
- Shielding (inner to outer): 10cm HDPE + 5cm Lead + steel frame
- Size: $\mathbf{120 \times 120 \times 188\ cm}$
- Mass: $\mathbf{7.3ton}$ $\approx$ 0.4ton dewar + 5.1ton lead + 0.8ton HDPE + 1ton steel frame, no Cu inside yet
- 3 wiring holes for cables and gas tubes, could be optimized to 2

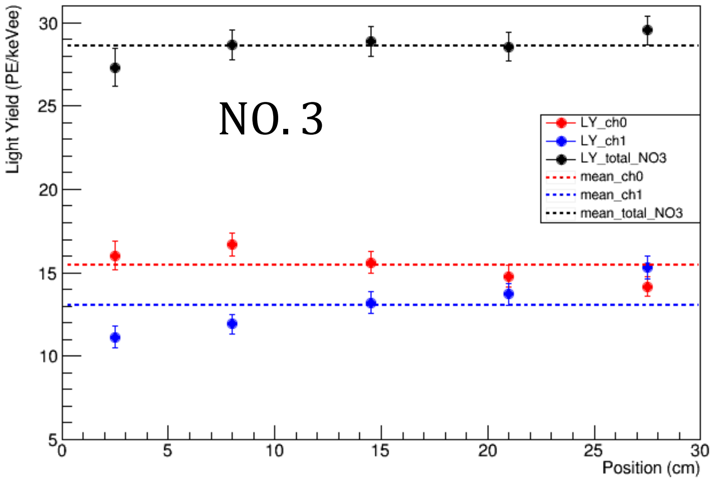


Light Yield and Uniformity



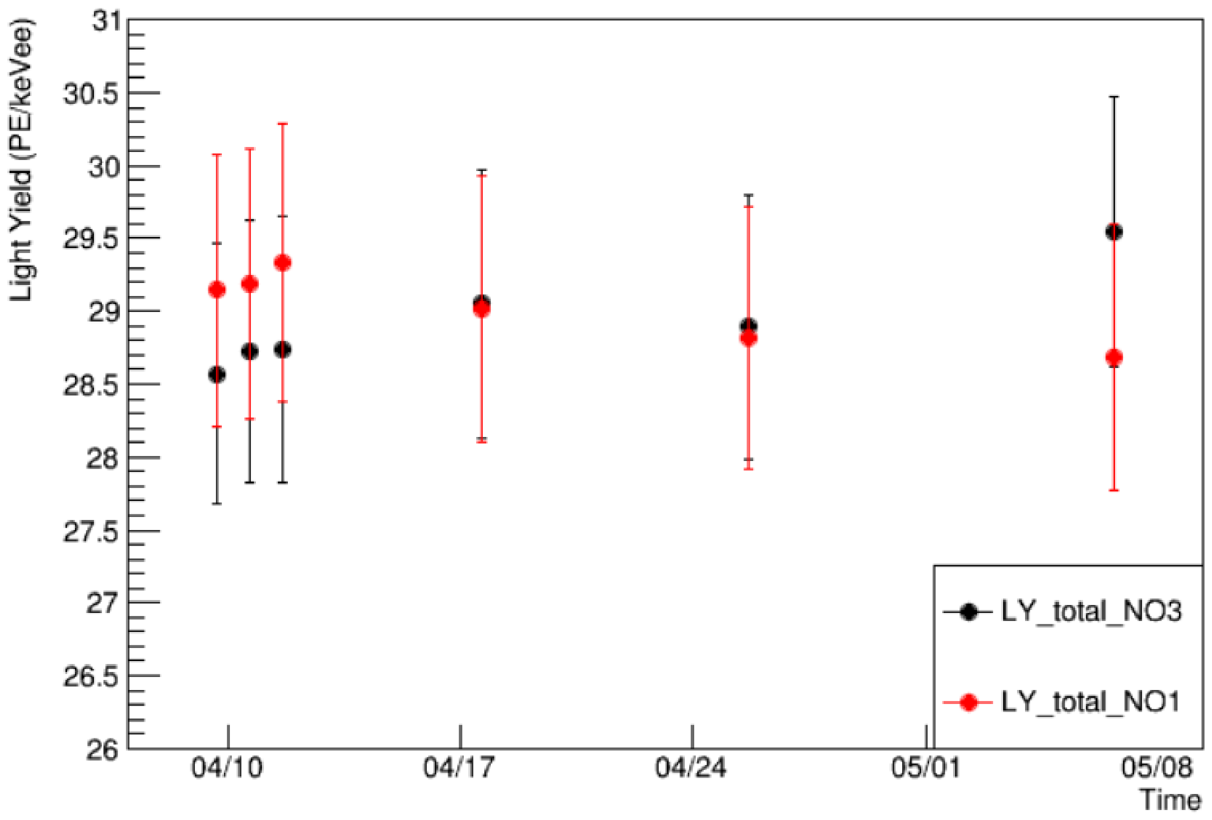




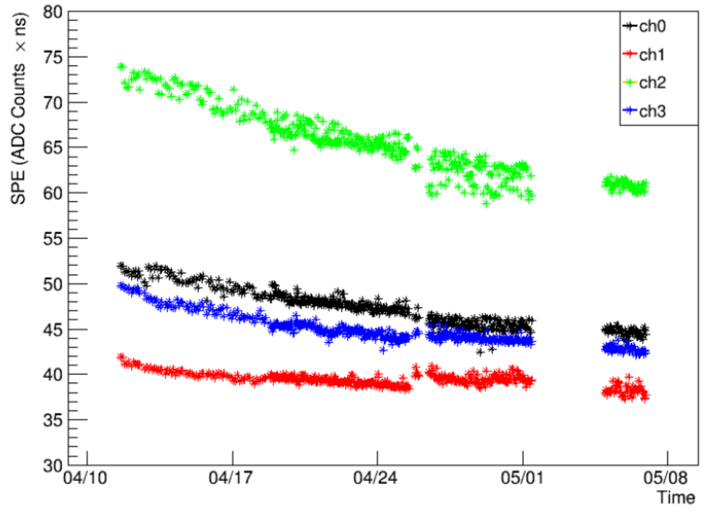


- Calibrated by Am241 60 keV gamma ray
- Excellent light yield and spatial uniformity

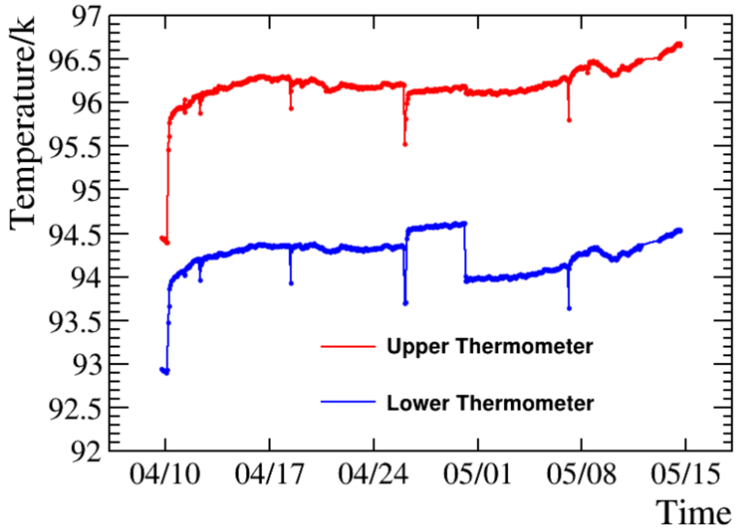
Stability of 1 month run



Light Yield



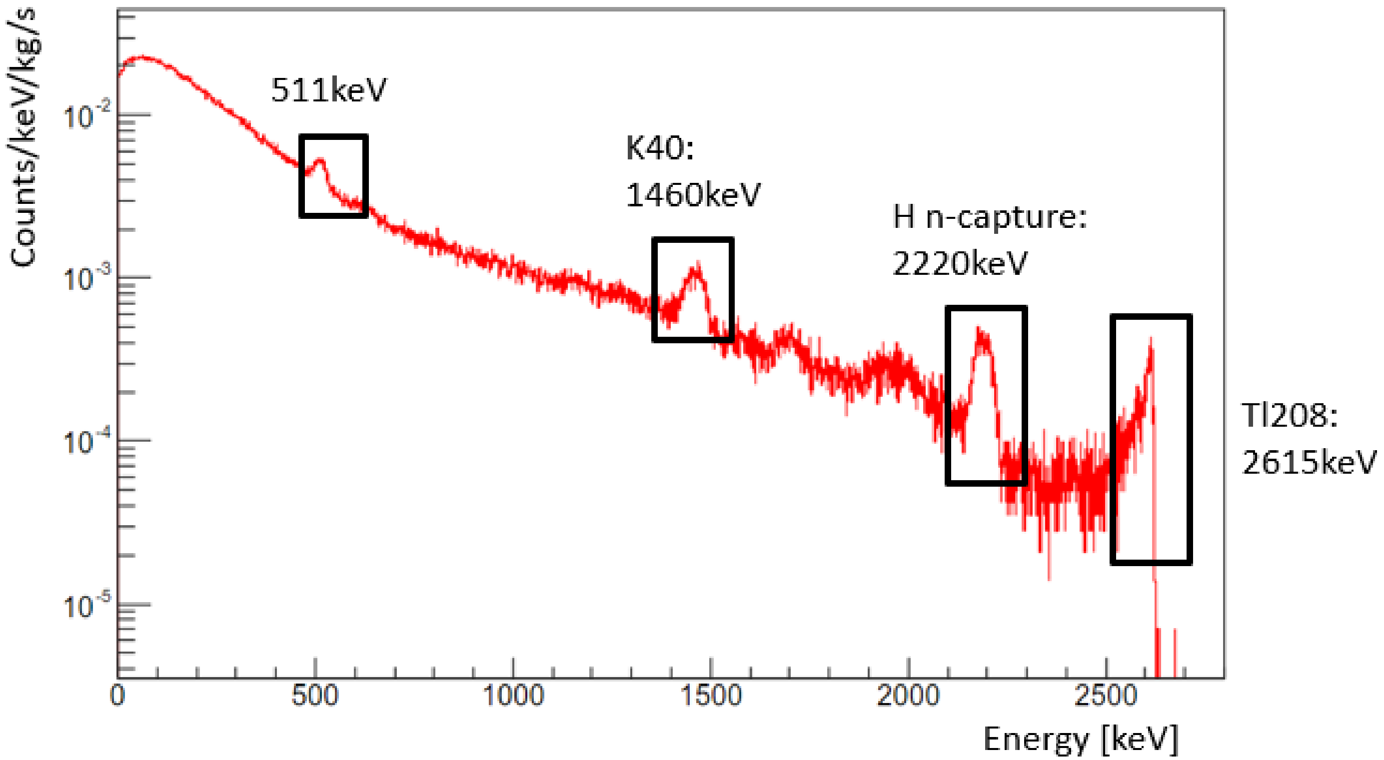
PMT Gain



Temperature

Radioactive background of crystal (SICCAS)

Self Trigger Data of 24h



Background peaks for energy and resolution calibration

Unit: mBq/kg

Crystal	Cs134 (796 keV)	Cs137 (662 keV)
NO. 1	<4.45	4.8 ± 1.5
NO. 3	4.6 ± 1.4	<1.31

Much better than CsI(Na) from AMCRY

Material	Date Screened	Sample Mass (kg)	Activity (mBq/kg)
Amcrys-H CsI(Na) boule slice	April 2014	0.366	2.38 ± 2.17 ^{238}U <0.53 ^{232}Th 16.67 ± 15.85 ^{40}K 27.87 ± 3.28 ^{137}Cs 25.87 ± 1.96 ^{134}Cs 6.59 ± 3.47 ^{126}I

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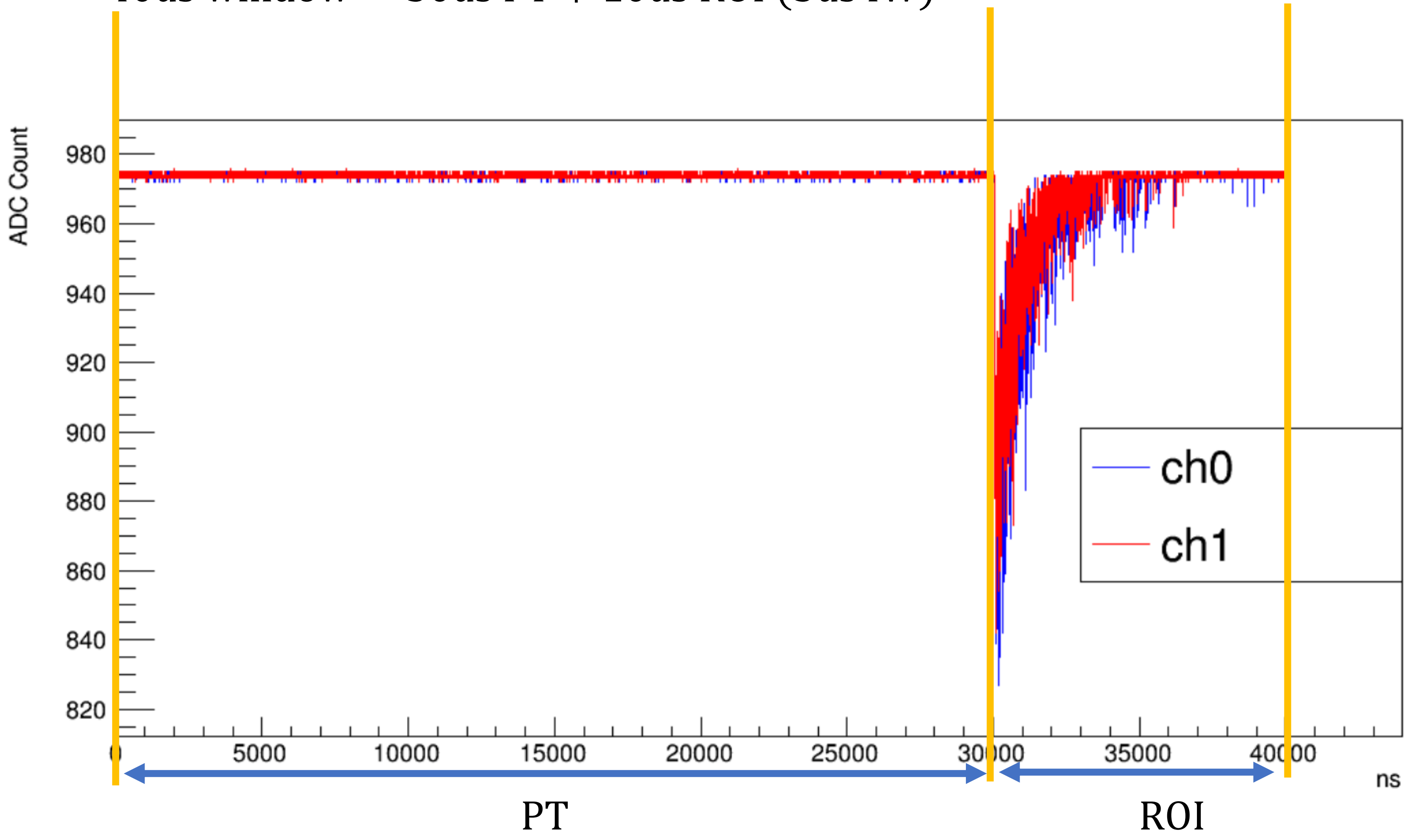
The External trigger run in UCAS:

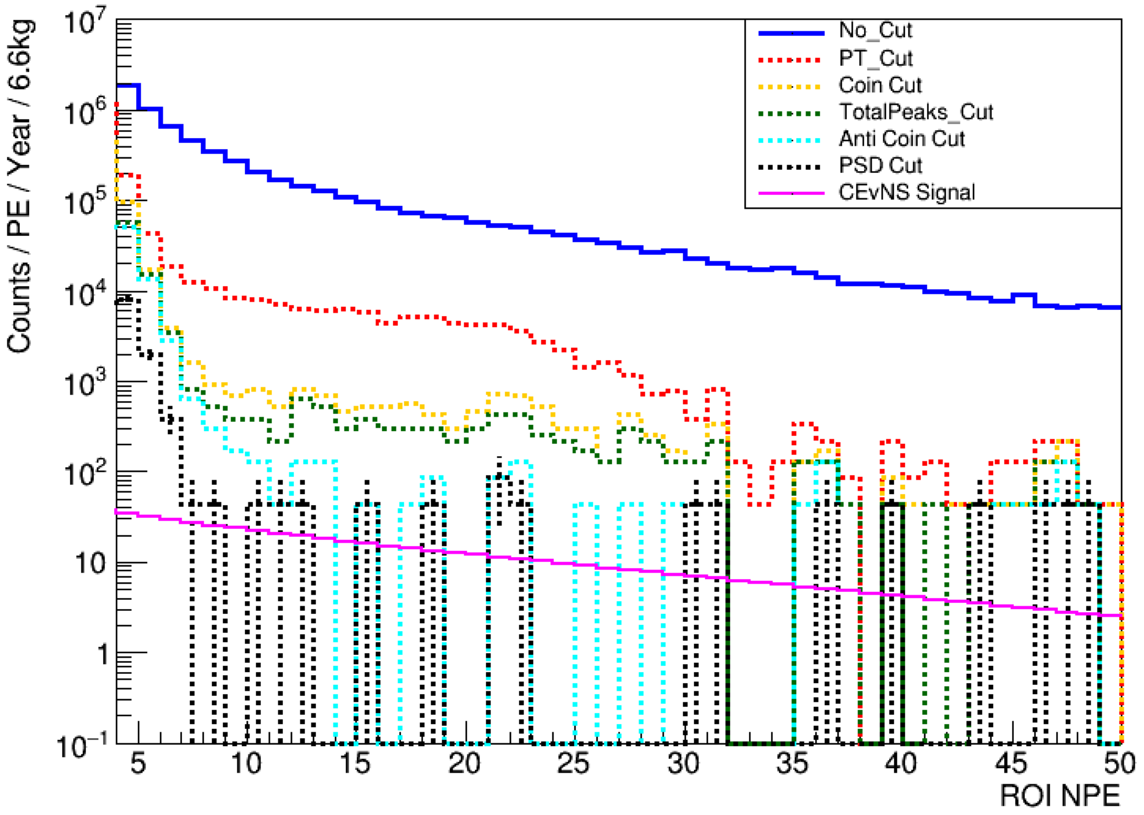
Forced Trigger Run 60Hz, 3 weeks:
40us window = 30us PT + 10us ROI (5us IW)

All Bkg are Steady – State Background
Cosmogenic background is higher in UCAS
No Muon Veto Applied
A convervative estimation

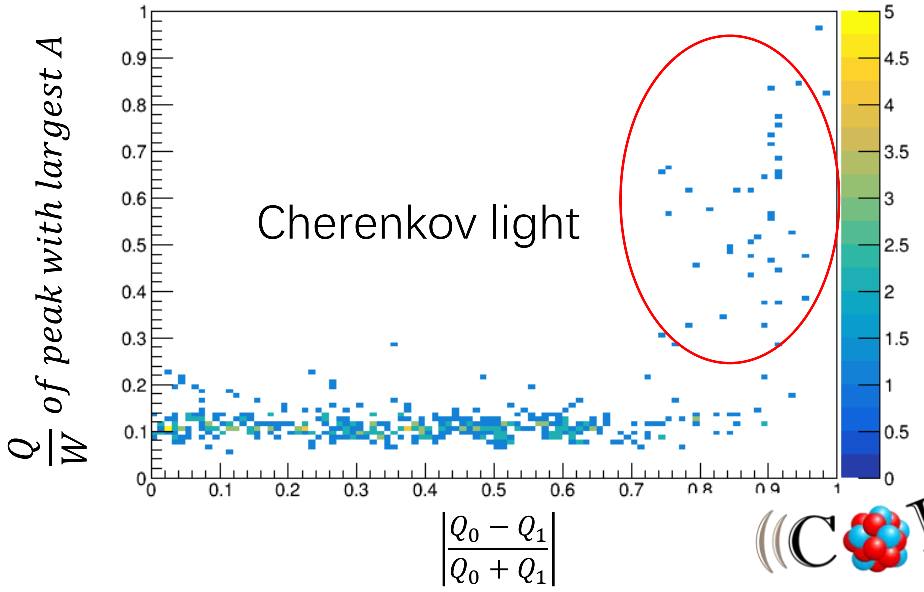


Cuts to suppress background

Cut Name	Condition
PT Cut	$N_{pt} \leq 1$
Coin Cut	$N_{iw}^{0} \geq 1$ && $N_{iw}^{1} \geq 1$
Total Peaks Cut	$N_{iw}^{total} \geq 4$
Cherenkov Cut	See picture below
Anti Coin Cut	Only one crystal pass cuts above
PSD Cut	PSD ∈ [600,1000]

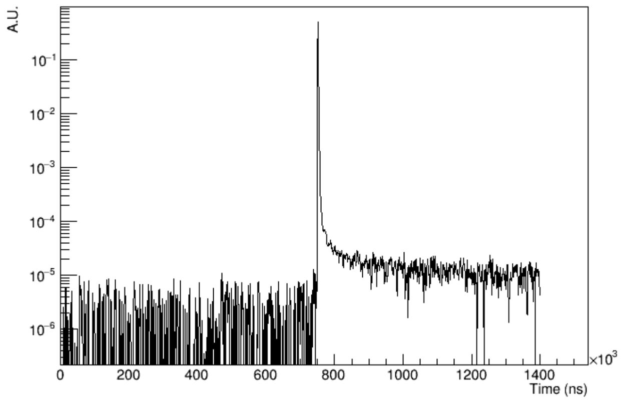


$S/B \sim 1$ for NPE ≥ 7



PSD method to suppress afterglow

$$\mathrm{PSD} = \frac{\sum_i^N A_i \times (T_i - T_0)}{\sum_i^N A_i}$$, The mean arrivle time of PEs

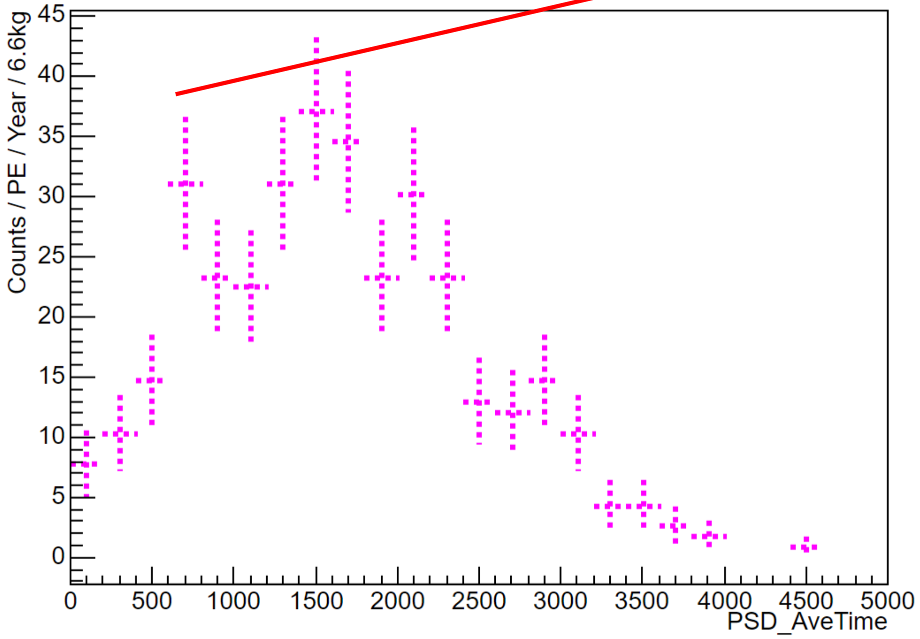


Physical signal ~ 1us

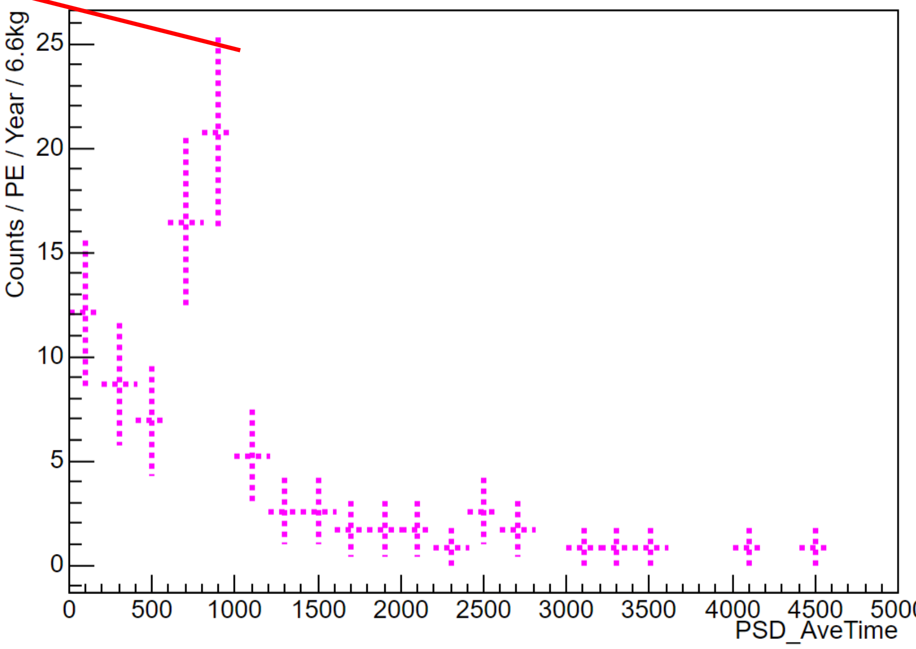
Afterglow ~ 1.3ms

Actual Physical signal

NPE 5-7

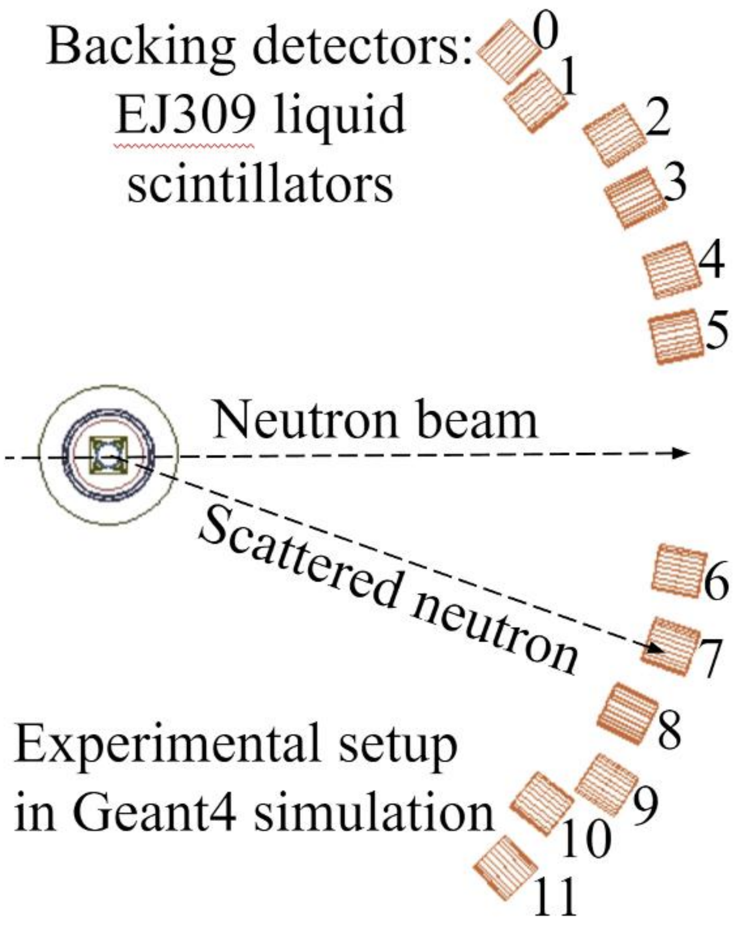


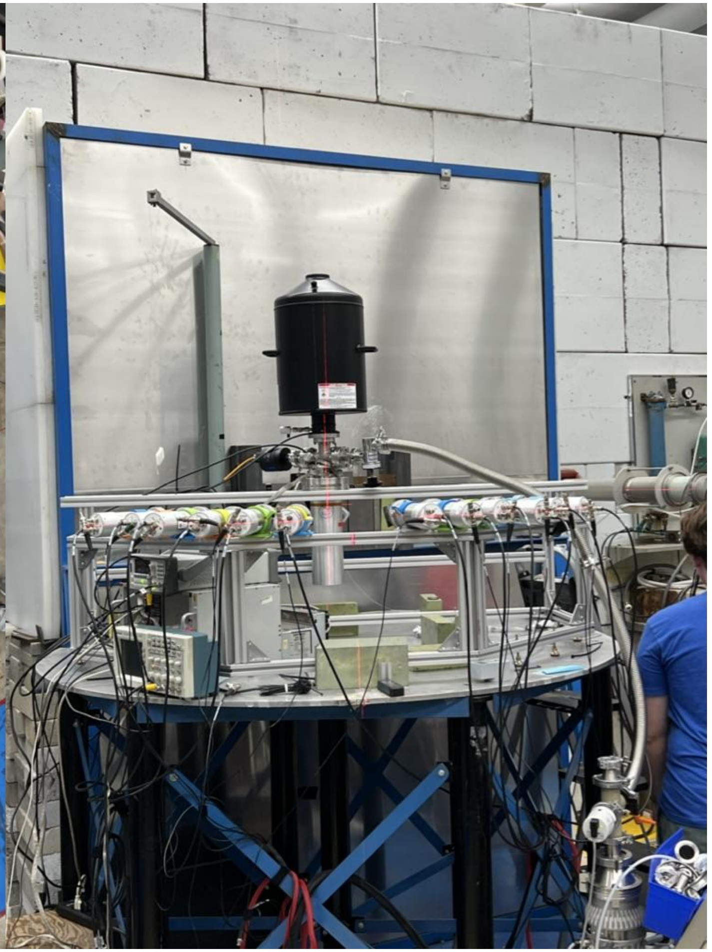
NPE 7-100



Quenching factor measurement

$$\mathrm{QF} = \frac{LY_{nr}}{LY_{er}}$$





$$E_R = \frac{2(1 + A - \cos^2\theta - \cos\theta\sqrt{A^2 - 1 + \cos^2\theta})}{(1+A)^2} E_n$$

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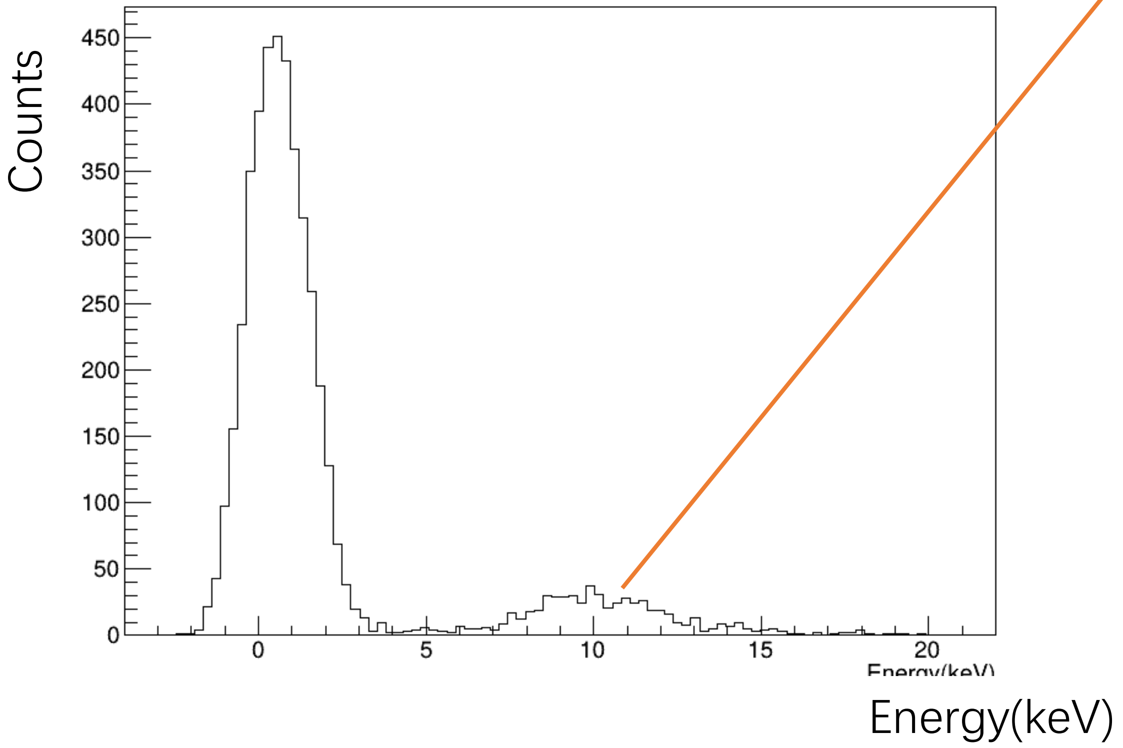
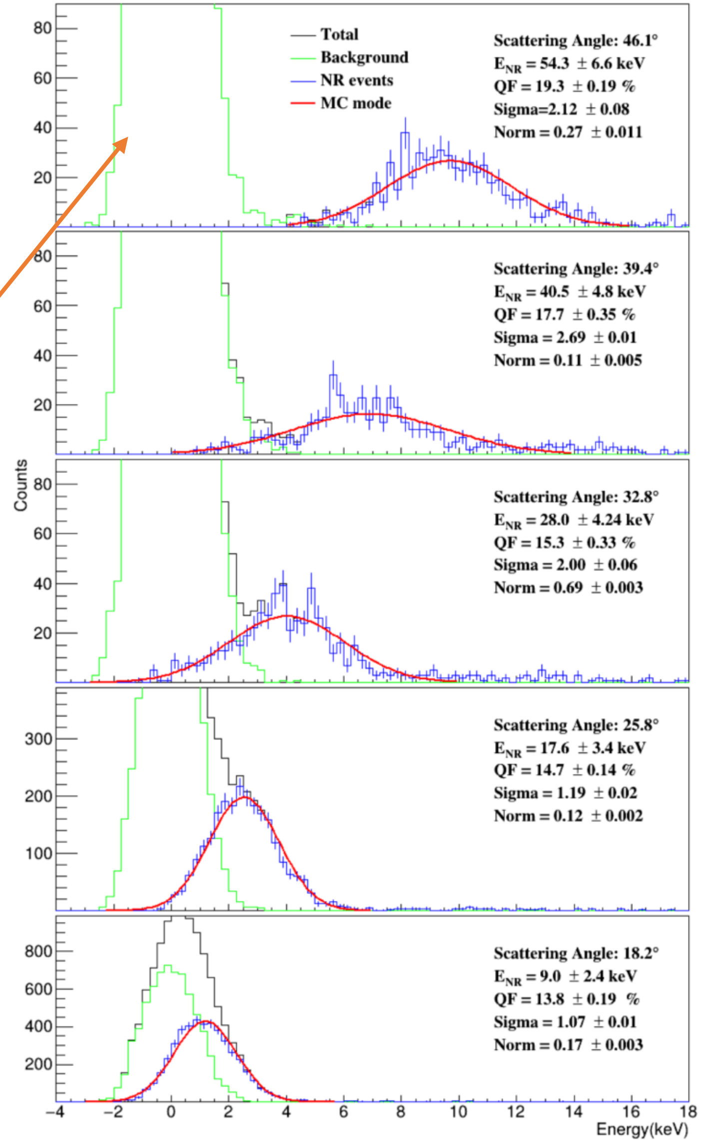
Quenching factor Fitting

QF: adjust position of the model
Sigma: width of the model
Norm: height of model





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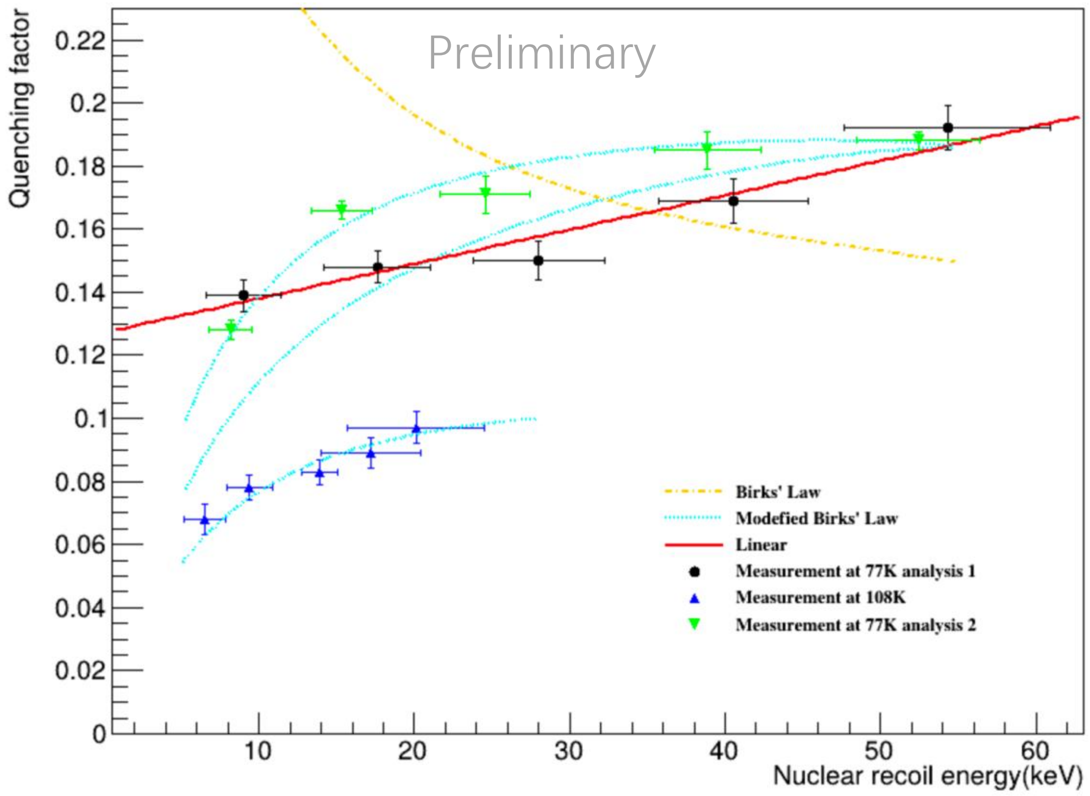
QF Result



- Black and Green
  - Our results @ 77K, two independent analysis
  - Discrepencies, subtle things like:
    - Neutron energy;
    - Integration window;
    - Afterglow;
  - Difficult and need to be very carful
  - More experiments on the way
  - Publish after complete understanding
- Blue:
  - Past measurement: @ 108K arXiv: 2101.03264
- ~15% @ 77K
- Around twice as 108K or Room Temperature (293K)
- Help to lower the threshold

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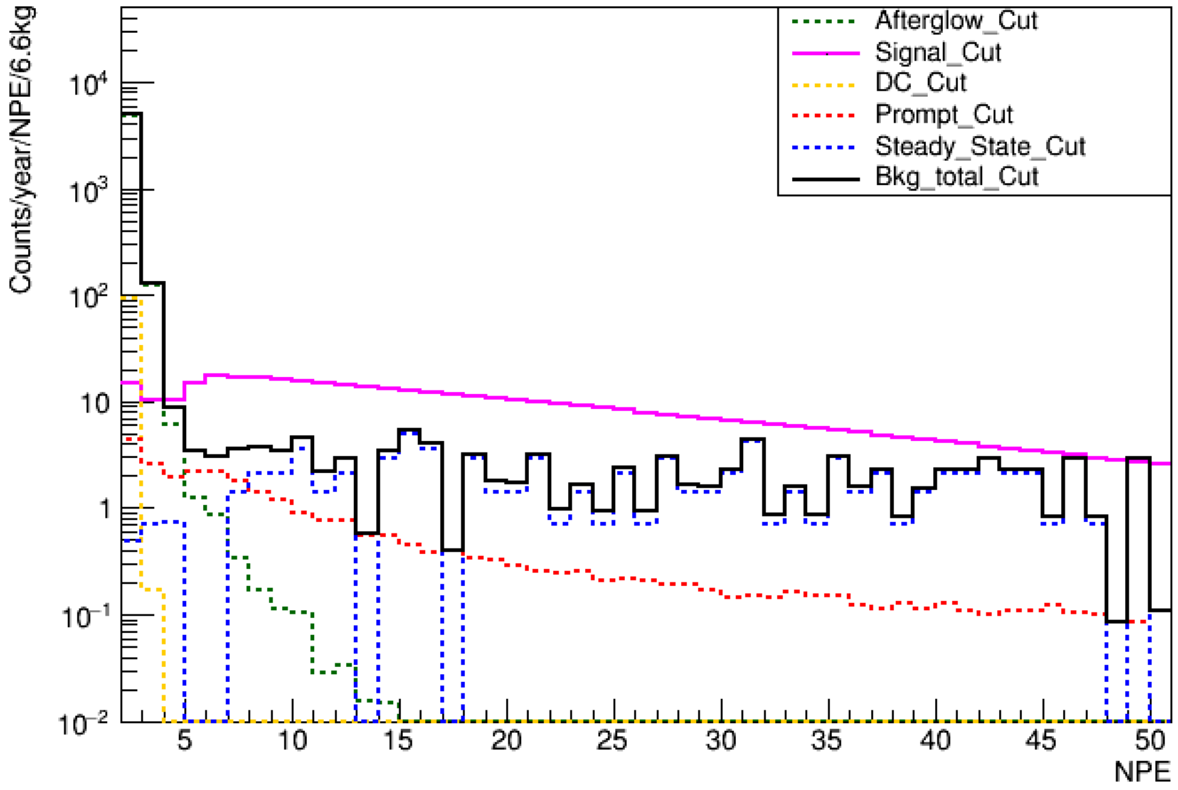
Sensitivity and Statistical Uncertainty

+Muon Veto + 5cm Cu + optimized PSD cut



Threshold: 4PE; S/B > 4
0.8keVnr for 15% QF
(1.4MeV assumed)

$$SN = \frac{N_{sig}}{\sqrt{N_{bkg} + N_{sig}}}$$

5σ detection for 1month beam time, better when arrival time information considered.

Observable events in 1.4MW

- 6.6kg CryoCsI: ~370/year
- RT QF: ~330/year
- 15kg CsI(Na): ~200/year

Soon to 2MW, 530/year

Summary

- *A* 6.6*kg* CryoCsI detector working very well
  - LY: 29PE/keVee, FWHM: <8% @ 60keV
  - Radioactivity is very low
  - Stable in one month Run
  - PSD Method used to suppress afterglow
- Quenching Factor measurement
  - ~15% @ 77K
  - Higher than the 8% @ RT and 108K
- Sensitivity:
  - Threshold down to 0.8keVnr with 15% QF
  - Expected detected event rate: 530/year in 2MW
- Moving to deploy procedure: seismic study etc.

- Future Upgrades:
  - Larger mass -> 100kg
  - SiPM readout -> Higher QE
  - Crystal shape improvement -> Better light collection
  - TPB/NOL coating -> Better spectrum matching
  - Aiming at 50PE/keVee (Maybe 100?)

COHERENT Collaboration

Consortium for Monitoring Technology and Verification
NSF
NRF 한국연구재단 National Research Foundation of Korea
NNSA National Nuclear Security Administration
U.S. DEPARTMENT OF ENERGY | Office of Science

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Duke University
TUNL Triangle Universities Nuclear Laboratory
서울대학교 SEOUL NATIONAL UNIVERSITY
Los Alamos National Laboratory EST. 1943
Laurentian University Université Laurentienne
岡山大学 OKAYAMA UNIVERSITY
NC STATE UNIVERSITY
The University of Tennessee Knoxville
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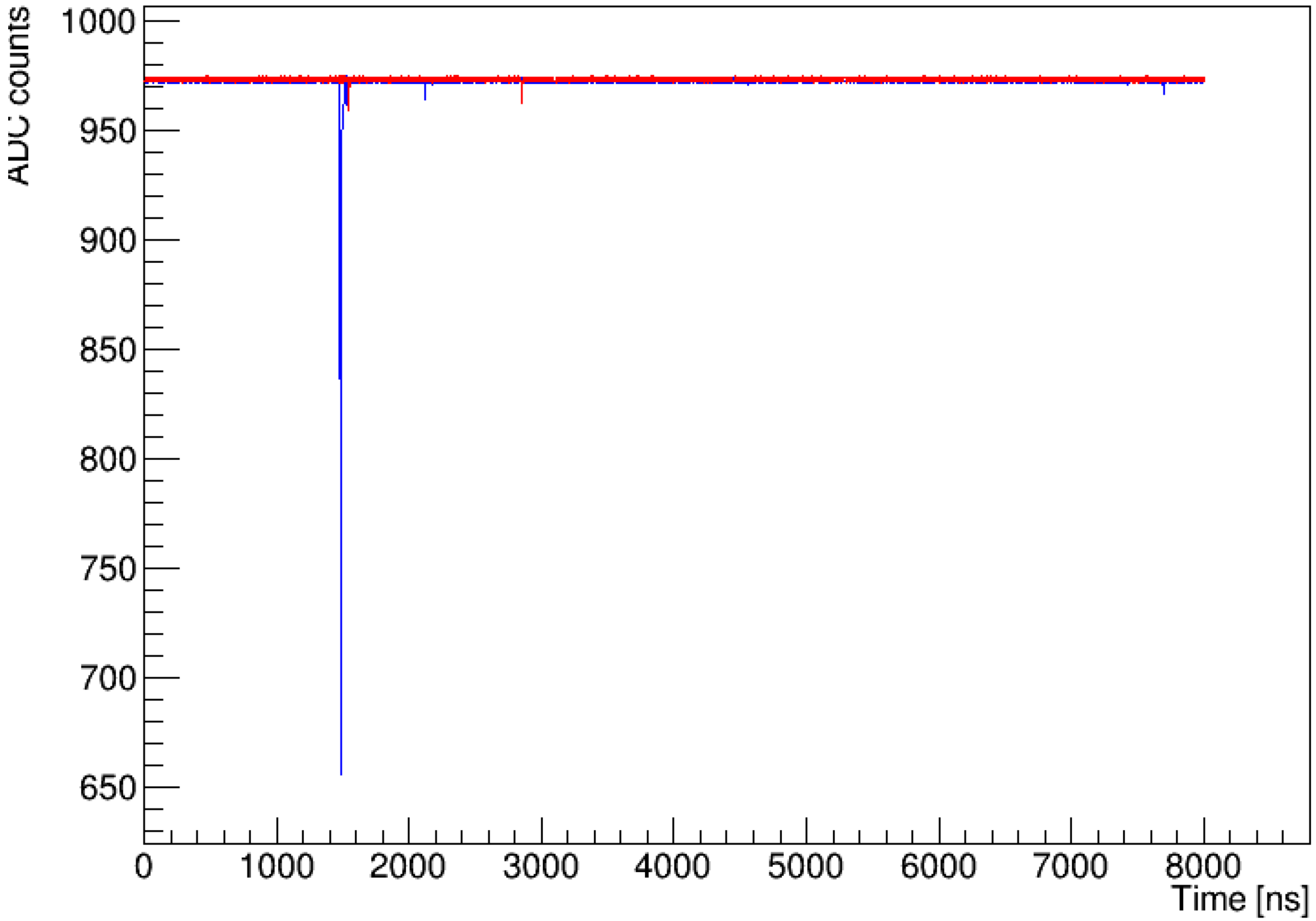
UF University of Florida
Kyoto University Founded 1897
University of Hawai'i
Concord U
SLAC National Accelerator Laboratory
Virginia Tech
Washington & Jefferson College
Florida State University 1851
MEPhI

Cherenkov event



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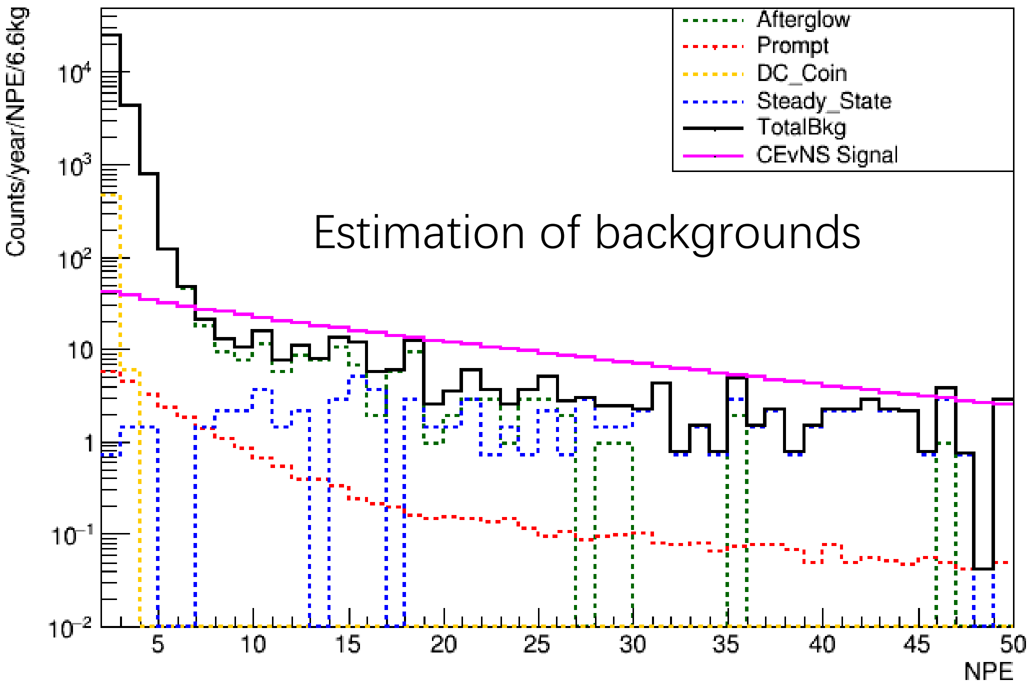
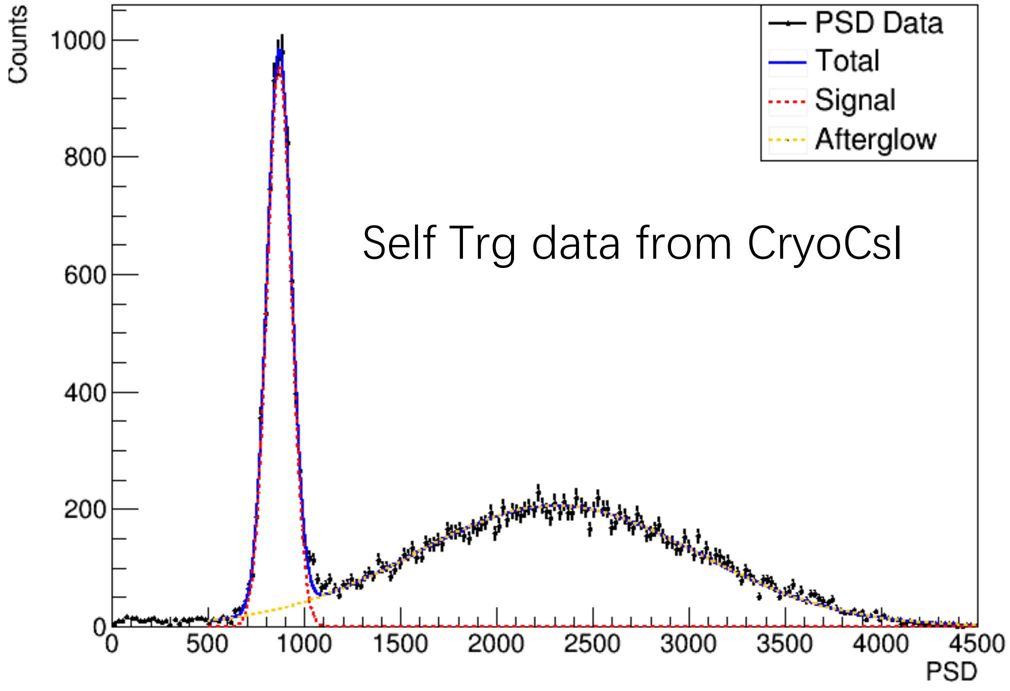
1. Afterglow will dominate the background for CryoCsI
2. Afterglow can be distinguished from real physical signal by PSD method (Proposed by Dan Pershey)

$$PSD = \frac{\sum_i^N A_i \times (T_i - T_0)}{\sum_i^N A_i}$$





3. We want to test PSD method on CsI(Na) to validate it and we can get better statistics

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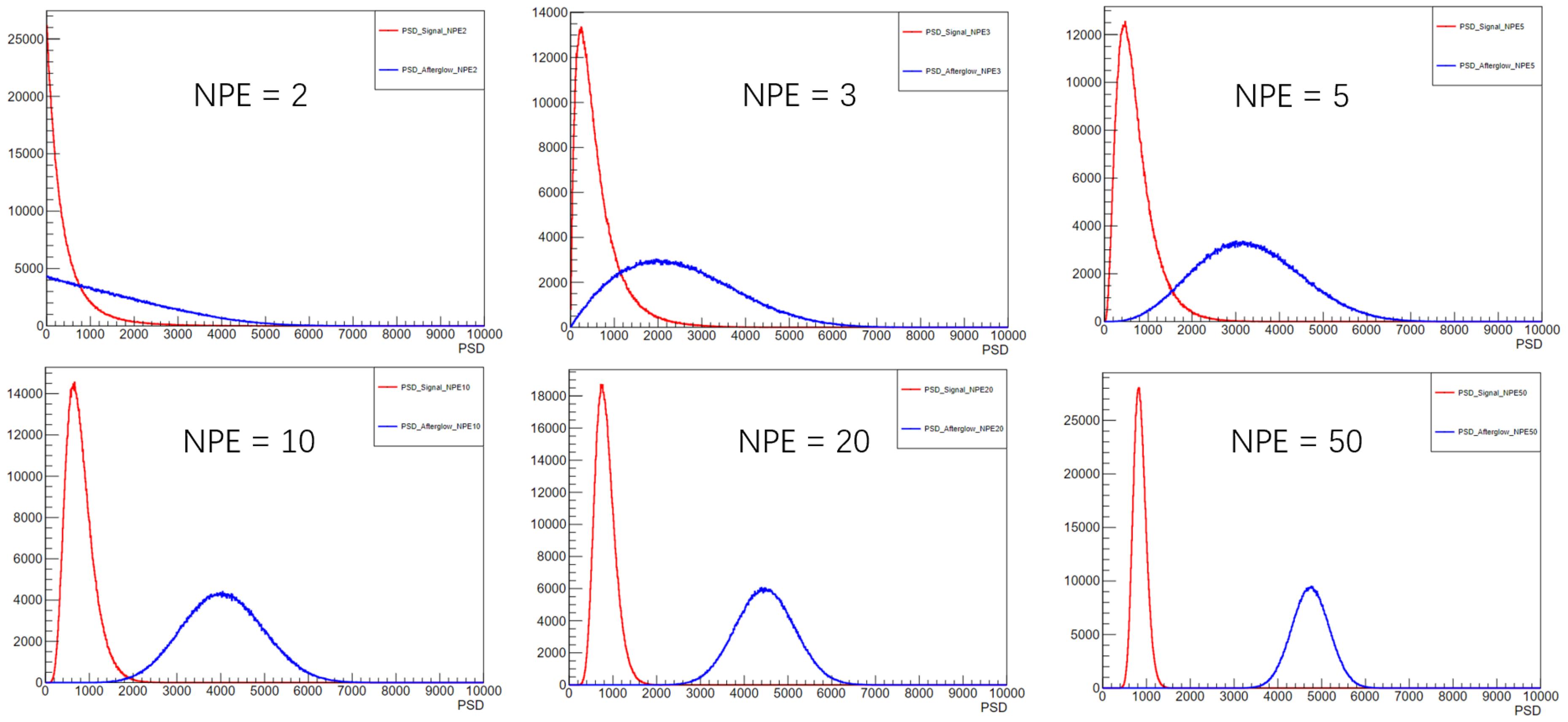
MC of PSD for afterglow and physical events



Red: Physical Events
Blue: Afterglow

Very distinguishable for NPE >= 10

Would be beneficial

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Self-trigger data

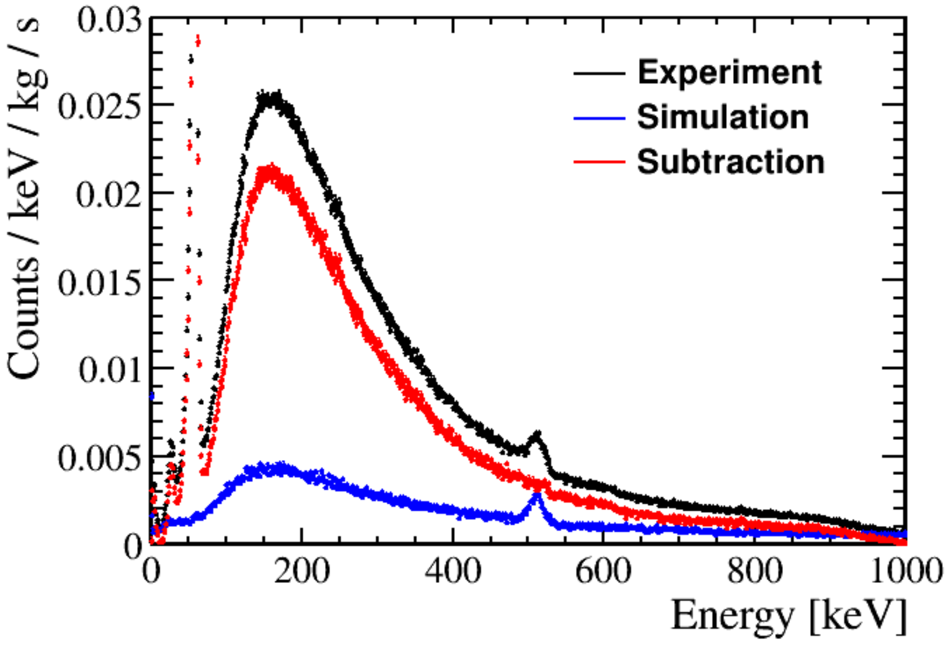
- CsI radioactivity much lower than initial guess: **~0.3Hz**
- Self-trigger rate: no shielding : with shielding = 1000 : **30 Hz**
- Other trigger sources: cosmic muon, env gamma, dewar radioactivity…

Hint: 511 peak mainly from cosmic muon

- Cosmic muon simulation:
- Using 511keV peak to normalize
- Using event ratio that both crystal have signal to normalize
- Cosmic muon can contribute 20~35% of bkg

- Env gamma simulation:
- Shielding can reduce env gamma by a factor of ~1300
- Env gamma cannot be the main bkg

Cosmic Muon Simulation Result

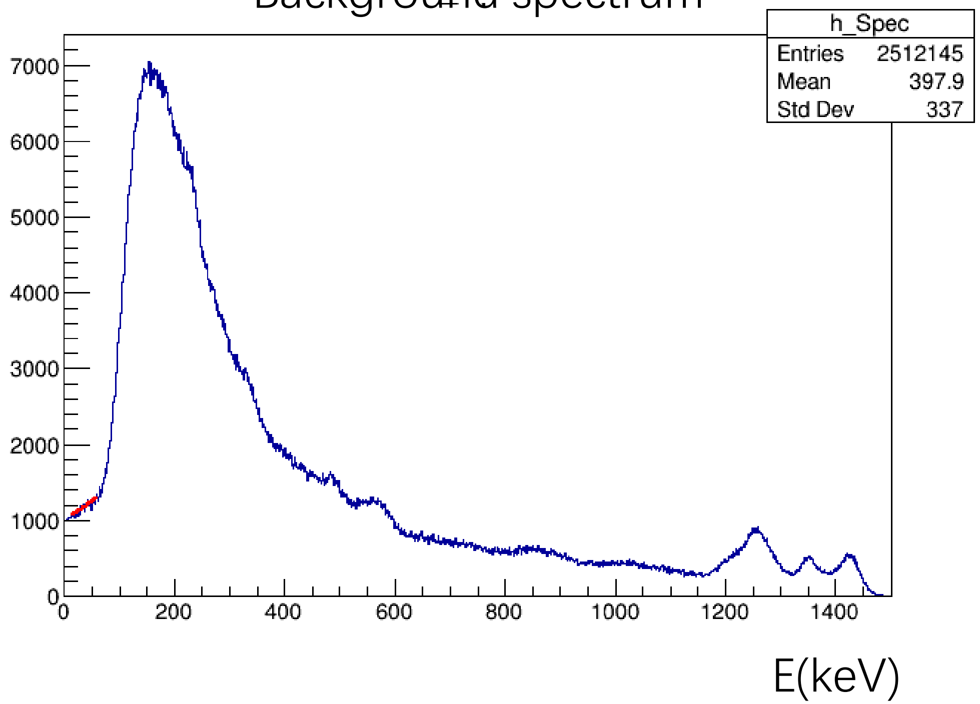


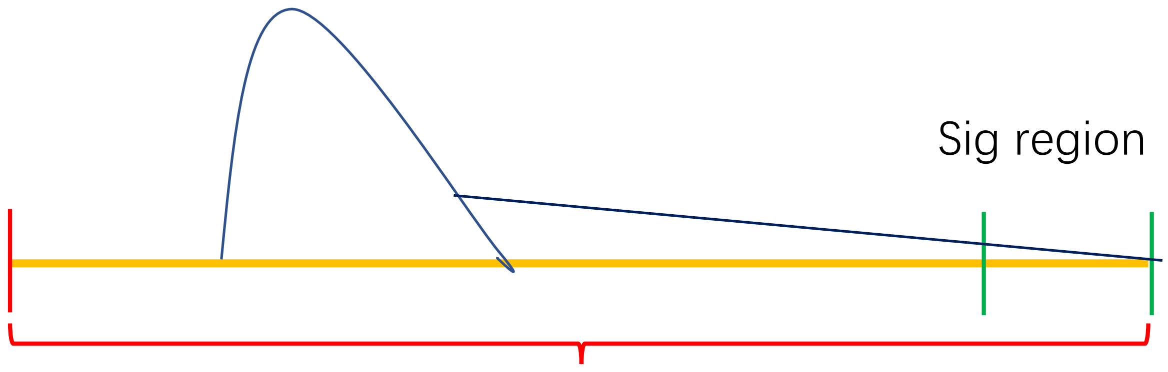
Afterglow MC Simulation

Self Trigger Run:

Background Event rate: 500Hz

Background spectrum





1. Randomly generate physical signal with Poisson distribution (Mean: 6.3Events) in this time window
2. Sampling PE time according to the decay time, PE number according to Energy and LY
3. One afterglow event is generated

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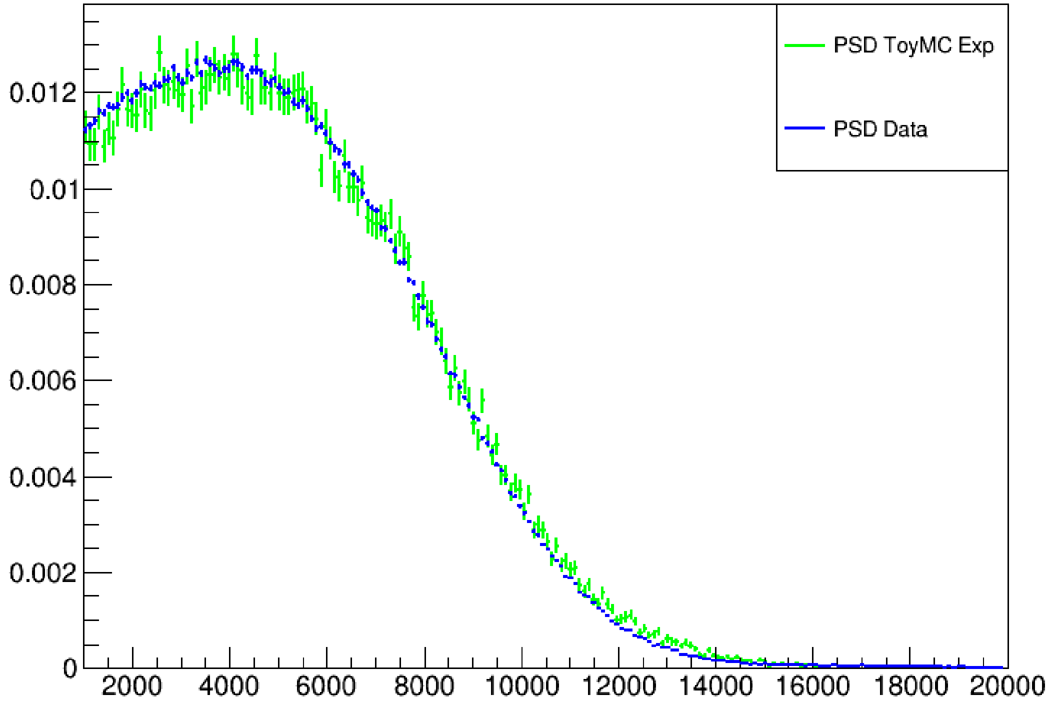
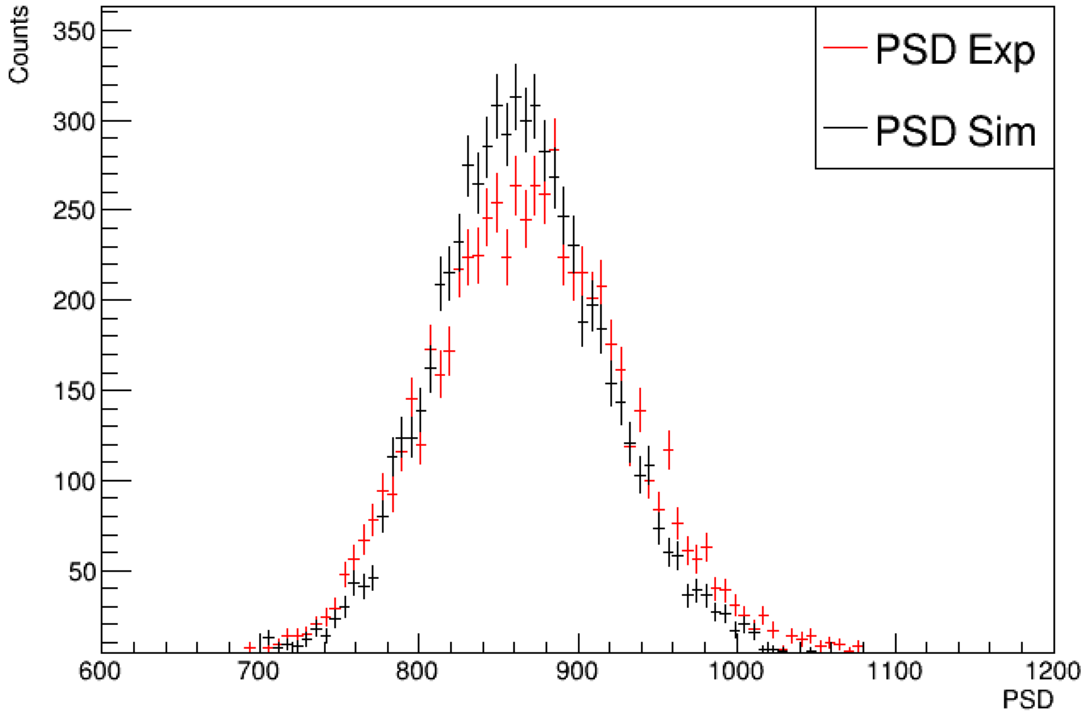
Validation of MC Simulation

External Trigger Data NPE: 2-10



Afterglow events

Self Trigger data: 3-20keV



Physical events

The MC modeling is reliable

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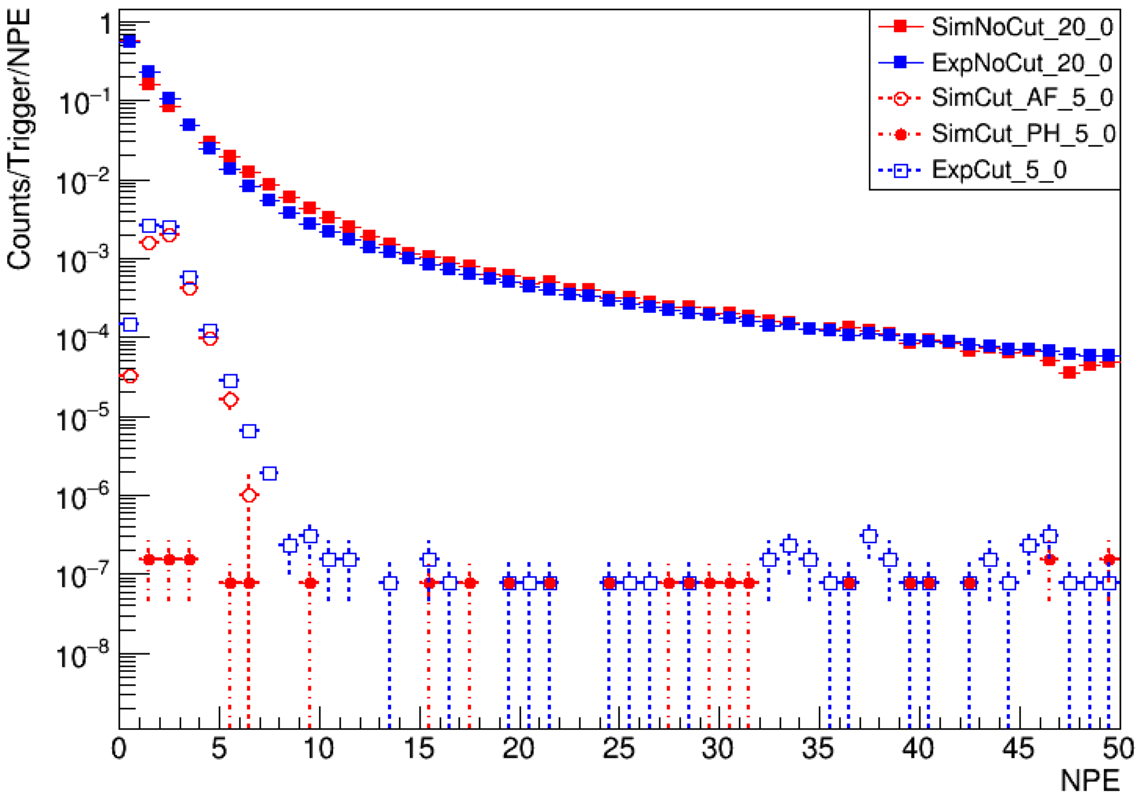
Compare between Exp and Sim



Sim Results = Physical events + Afterglow Events

Cuts Applied

1. PMT Coincidence
2. Cherenkov cut (data)
3. Pre-trace No-PE cut
4. For sim data, additionally require the Signal time is 60us away from sig region to veto the strong light from the main part which not considered in simulation.

Simulation and experiment agrees very well.
The method has been proven reliable.

COHERENT SNS

Radioactivity Estimation

Total peak area method: standard method for peak area estimation for single un-interfered peak

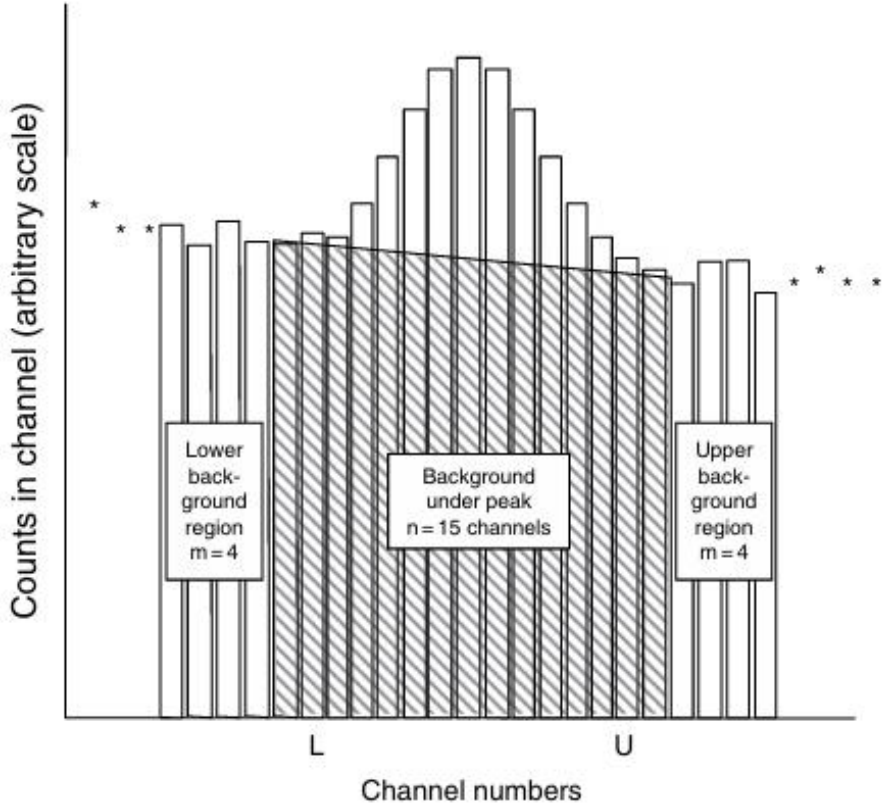
- Background: Compton continuum
- Assumption: continuum is linear

$$A = \sum_{i=\mathrm{L}}^{\mathrm{U}} C_i - n\left(\sum_{i=\mathrm{L}-m}^{\mathrm{L}-1} C_i + \sum_{i=\mathrm{U}+1}^{\mathrm{U}+m} C_i\right)/2m$$

Total counts: G

Background counts: B

- Small peak and large bkg: bkg estimation uncertainty dominates total uncertainty of peak area measurement

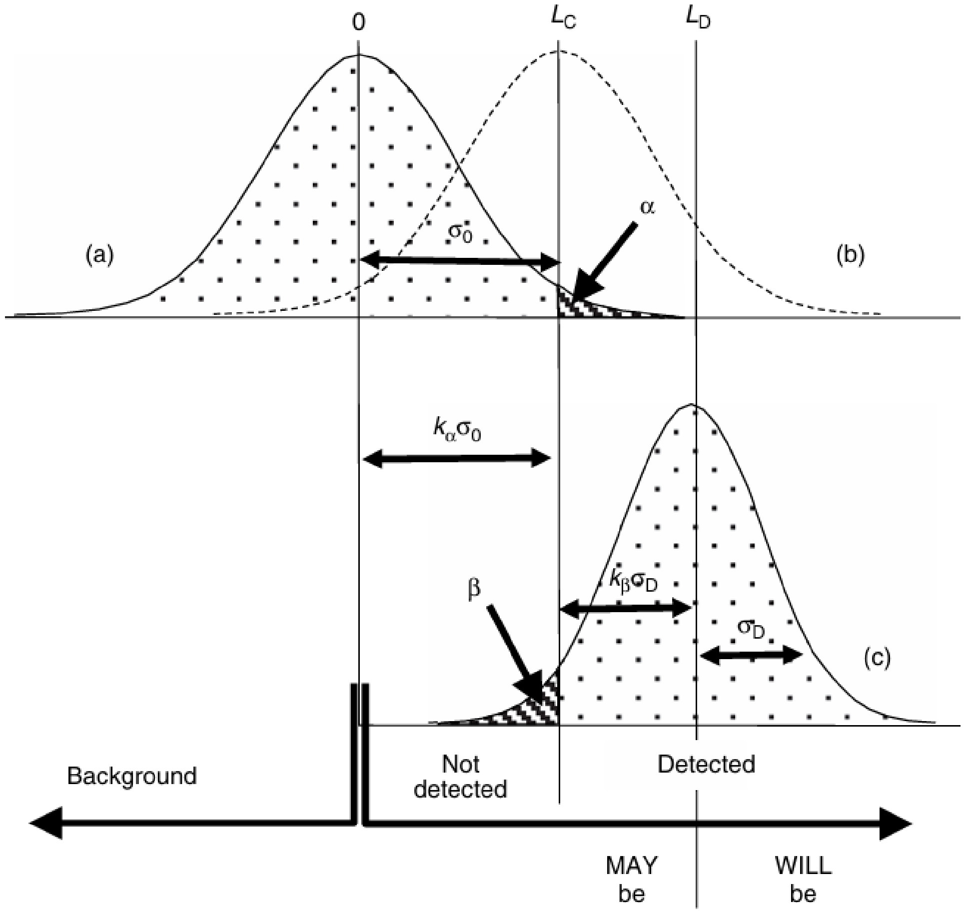


Gilmore, Gordon, and David Joss. *Practical gamma-ray spectrometry*. John Wiley & Sons, 2024.

Radioactivity Estimation

Some statistically determined levels:

- Critical limit (L_C)– a decision level: 'Is the net count significant?'
- Detection limit (L_D)–'**What is** the minimum number of counts I can be confident of detecting?'
- Upper limit (L_U)–'Given that this count is not statistically significant, **what is** the maximum statistically reasonable count?'
- Minimum detectable activity (MDA)– 'What is the least amount of activity I can be confident of detecting?'



Radioactivity Estimation

- Critical limit:

$$L_C = 1.645\sigma_0 = 1.645\sqrt{B(1+\frac{n}{2m})}$$

- Detection limit:

$$L_D = 2.71 + 3.29\sqrt{B(1+\frac{n}{2m})}$$

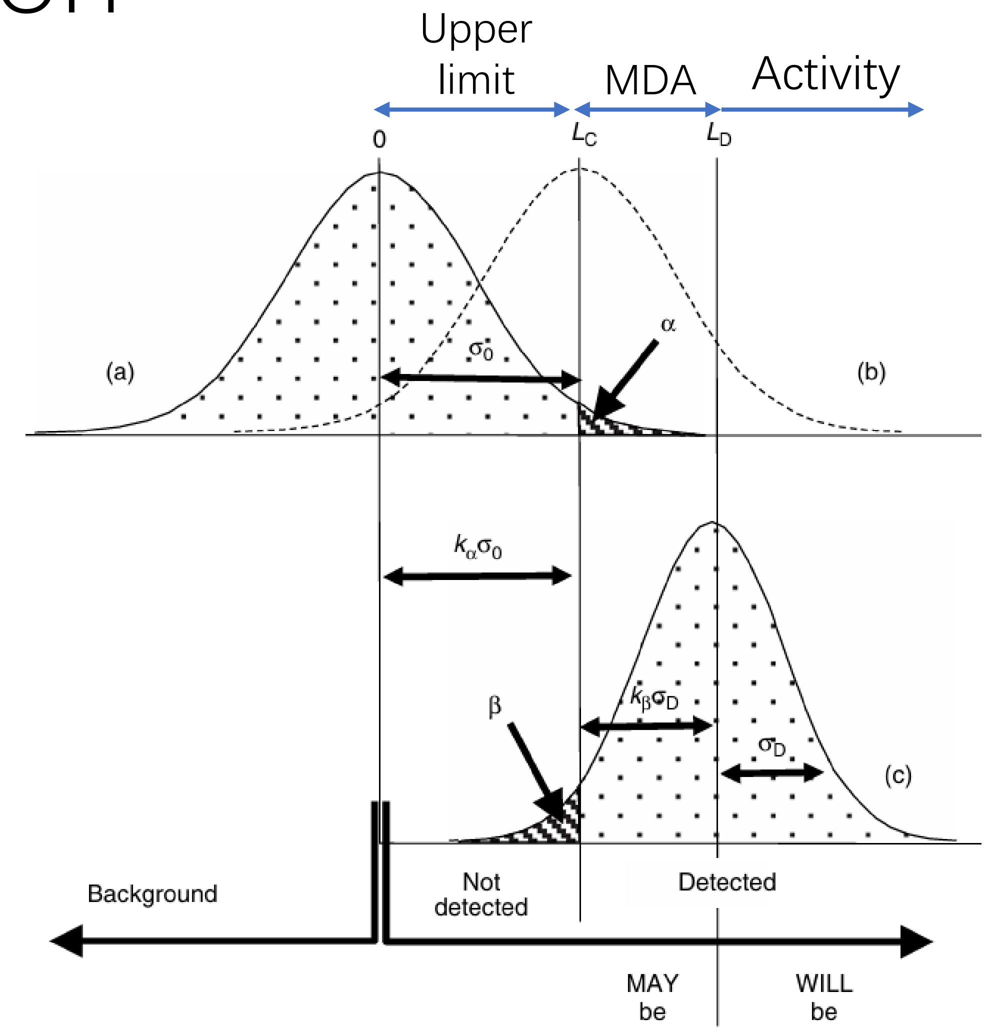
- Upper limit:

$$L_U = A + 1.645\sqrt{A + B(1+\frac{n}{2m})}$$

- MDA: minimum detectable activity

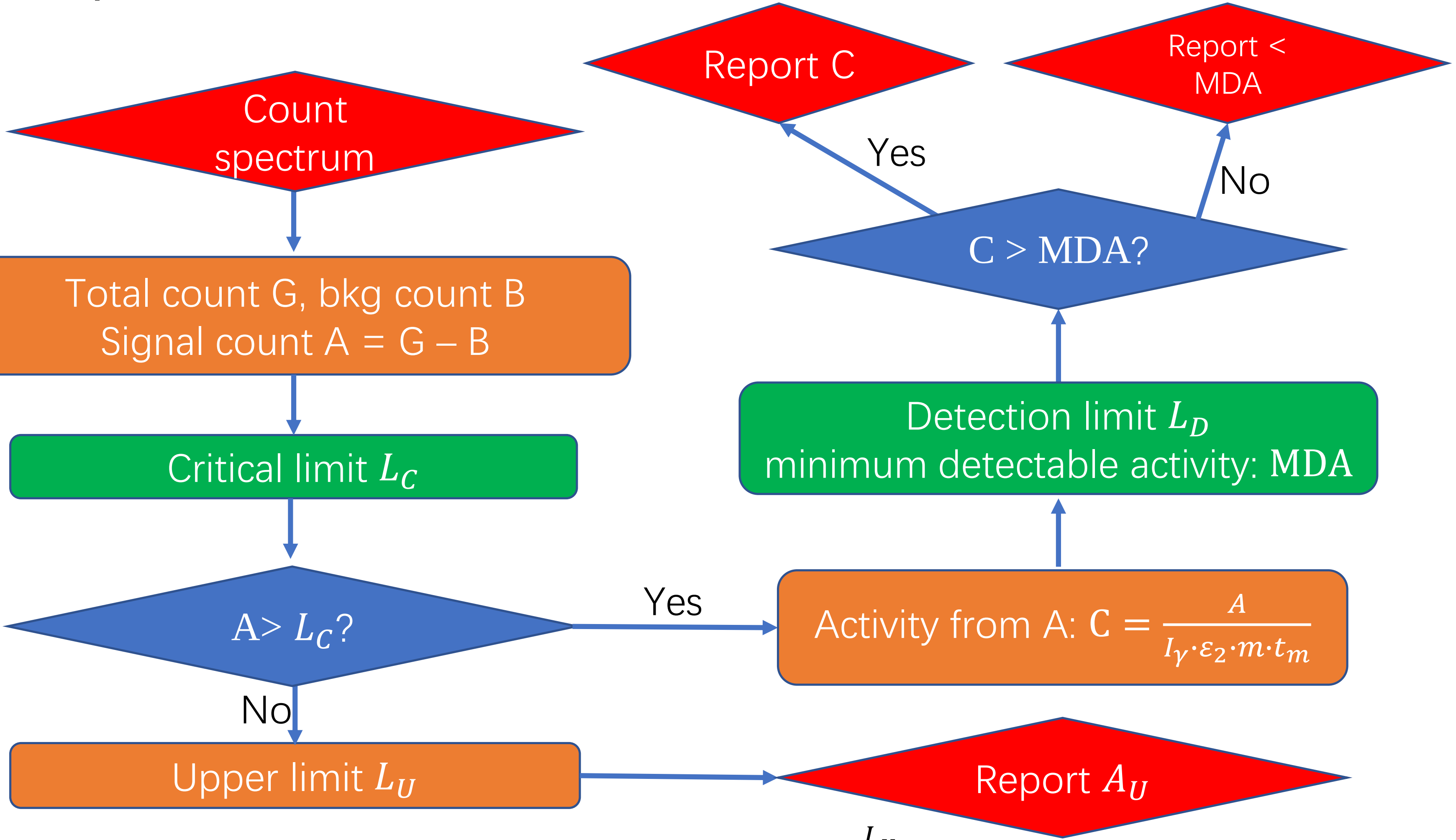
$$\mathrm{MDA} = \frac{L_D}{I_\gamma \cdot \varepsilon \cdot m \cdot t_m}$$

- Uncertainty: $u_A^2 = \mathrm{A} + \mathrm{B}\ \ (1 + \mathrm{n}/2\,\mathrm{m})$ $\quad u_C = \sqrt{u_A^2 + u_\varepsilon^2}$



Radioactivity Estimation

- **Total peak area method:**



$$A_U = \frac{L_U}{I_\gamma \cdot \varepsilon \cdot m \cdot t_m}$$