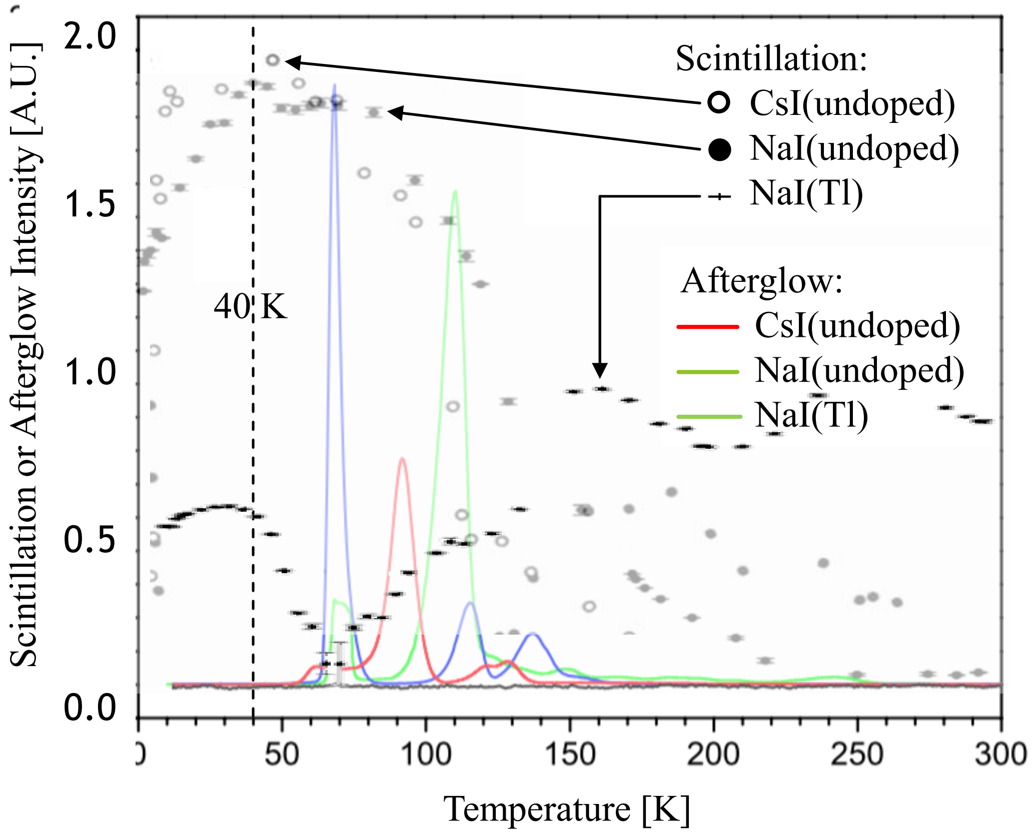
Potential of CEvNS measurements with cryogenic scintillators

Jing Liu, University of South Dakota

Magnificent CEvNS 2019, UNC

Undoped crystals



- NaI(undoped) & CsI(undoped) VS NaI(Tl) and CsI(Na)
- 40 K
  - Minimal after glow rate
  - Maximal light yield

Eur. Phys. J. C (2012) 72:2061

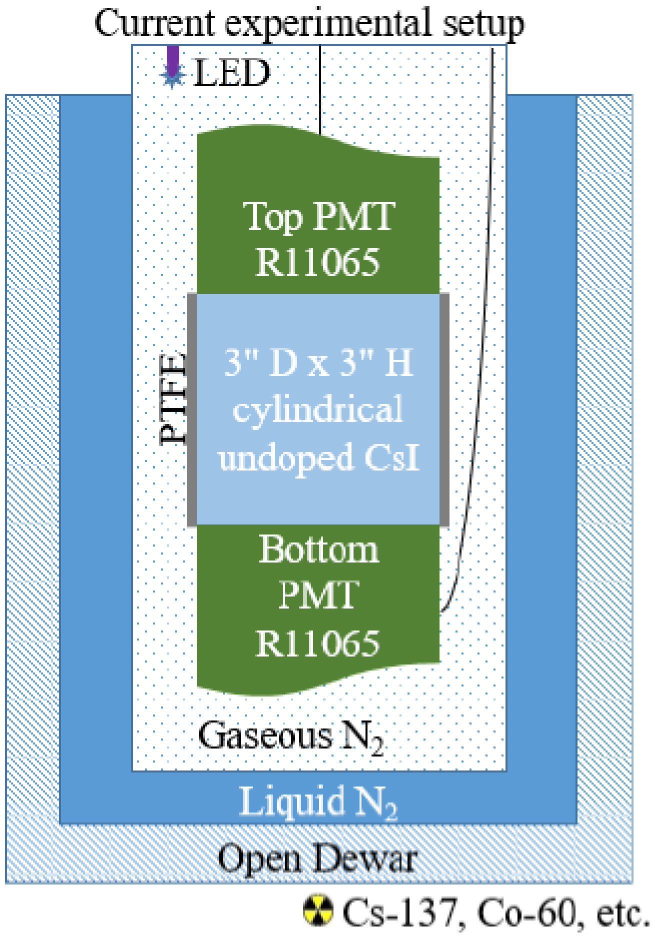
Phys. Rev. B 5 (1995) 2195

J. App. Phys., 123(11):114501, 2018

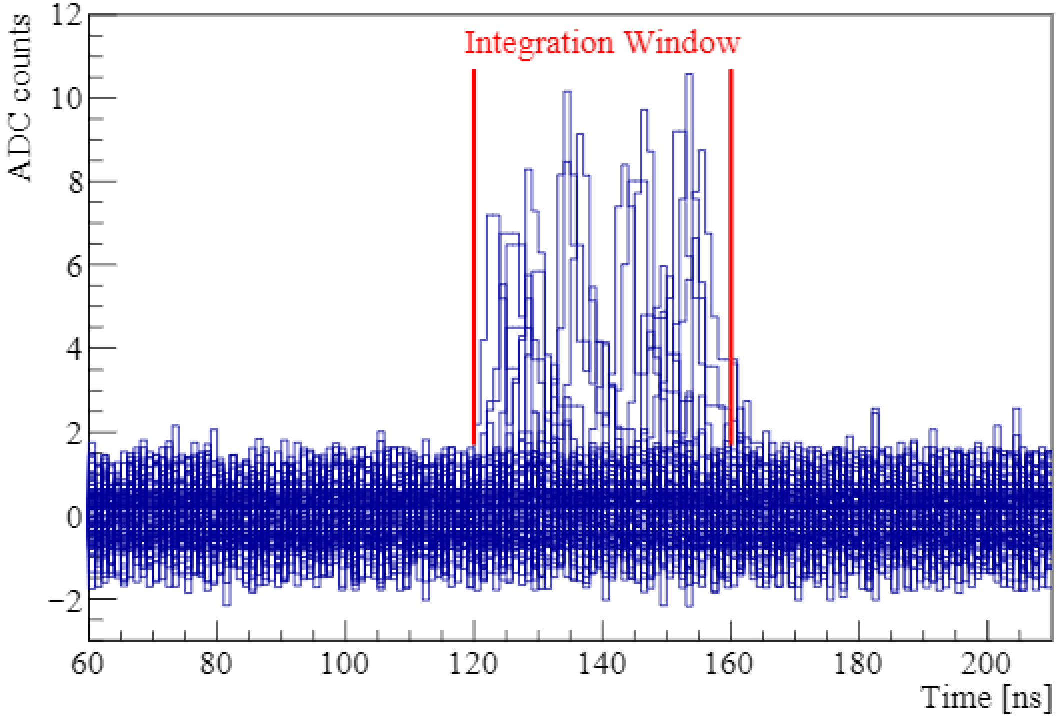
Light loss in complicated readout system cancels out the gain from light yield ☹

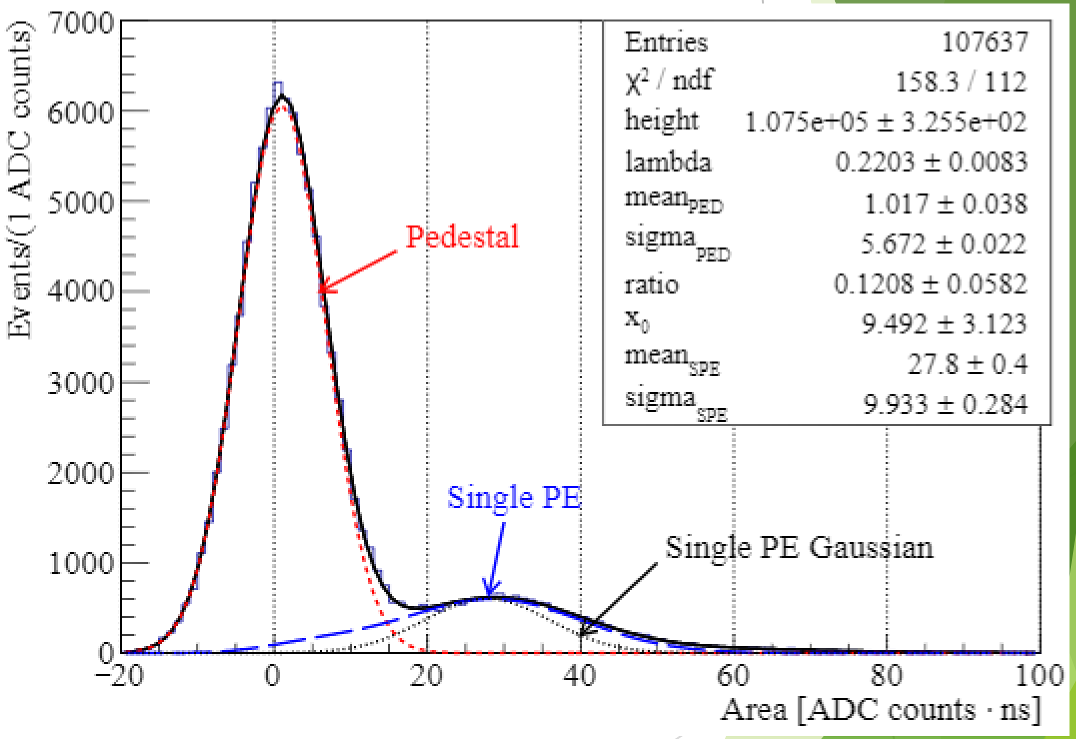

PMT at RT | Light guide | Crystal at LNT | Light guide | PMT at RT

Experimental setup



Single PE measurement





Single PE distribution

Poisson

Noise

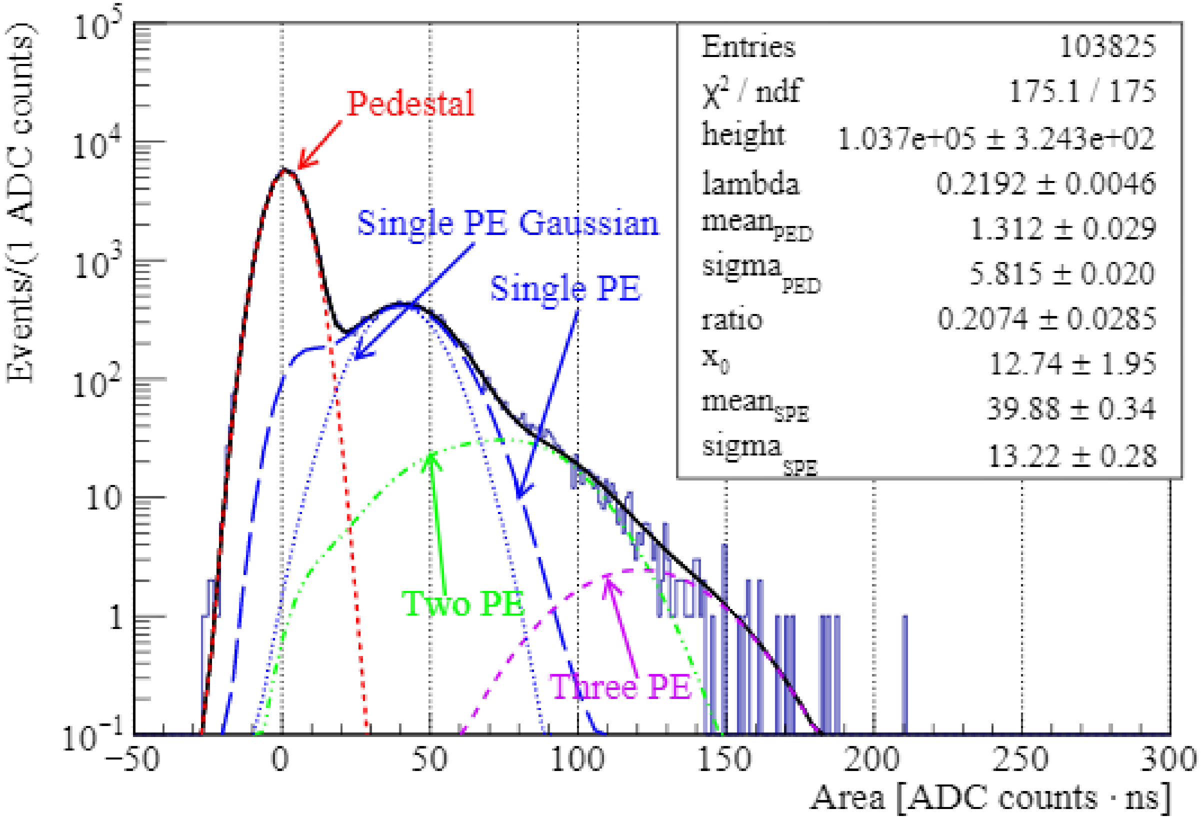
$$F(x) = \sum_{n=0} P(n;\lambda) f_n(x)$$

$$f_n(x) = \rho(x) * \psi_1^{n*}(x)$$

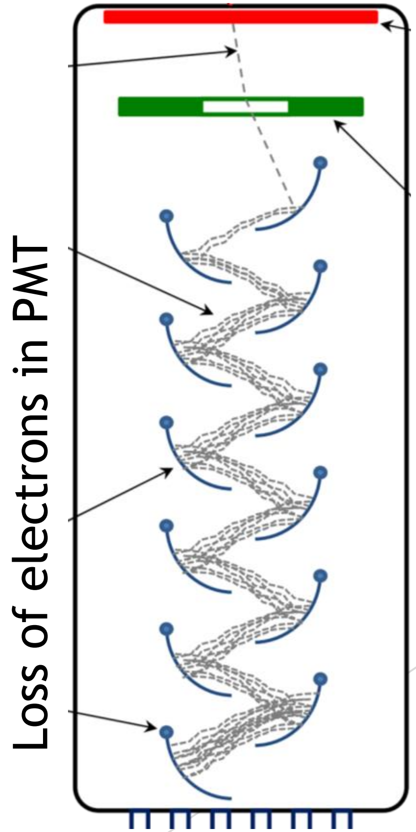
Electron loss

Gaussian

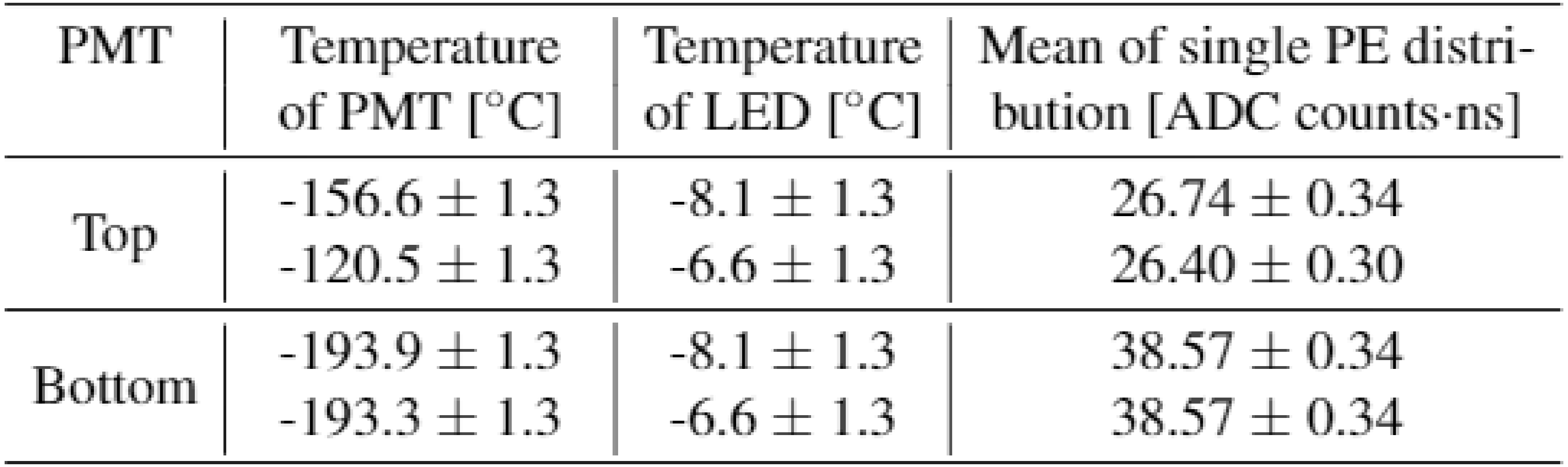
$$\psi_1(x) = \begin{cases} p_E\left(\frac{1}{x_0}e^{-x/x_0}\right) + (1-p_E)\mathrm{G}(x;x_m,\sigma) & x > 0; \\ 0 & x \le 0. \end{cases}$$



IEEE TRAN., VOL. 58, NO. 3, JUNE 2011



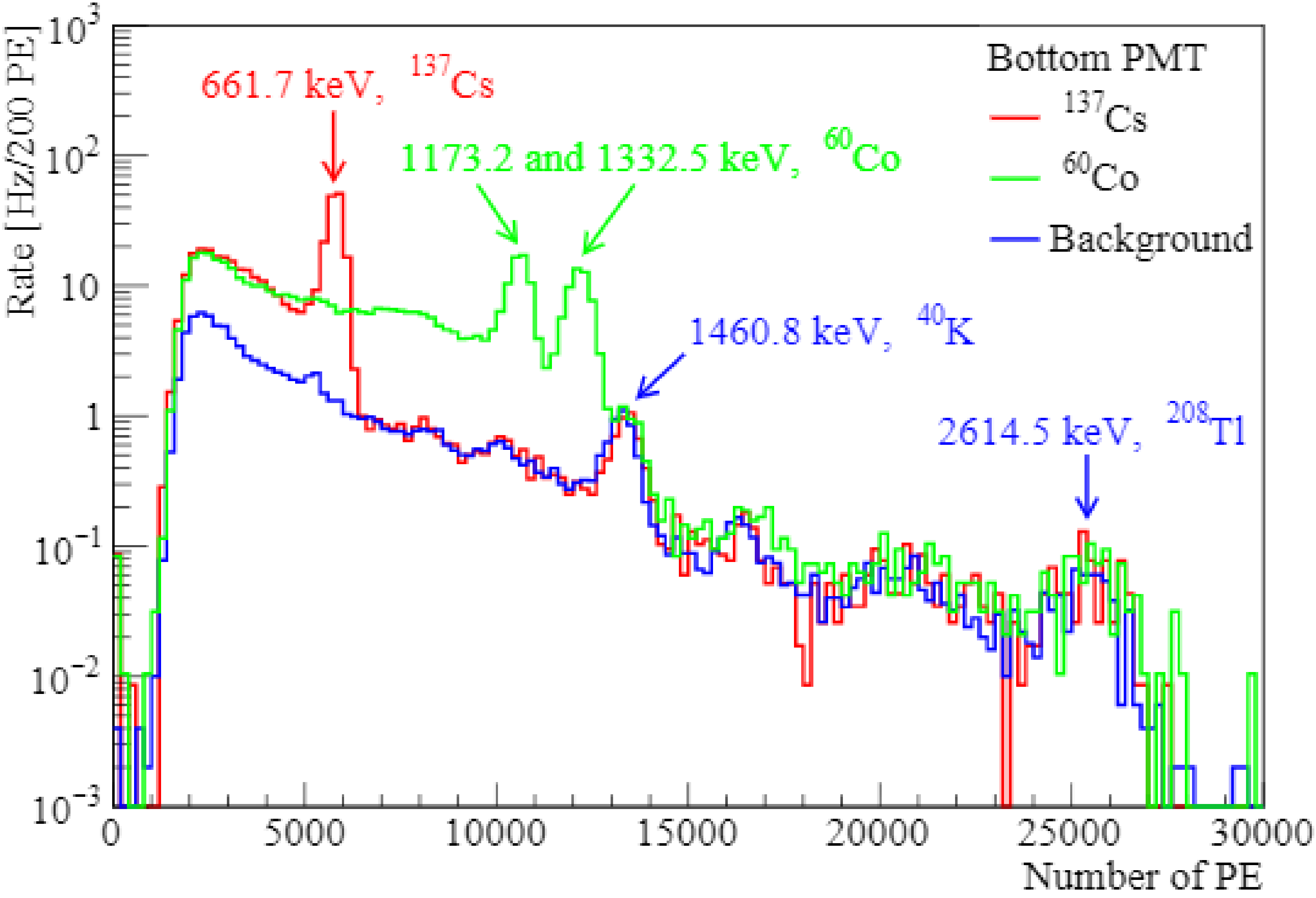
Uncertainty on gain



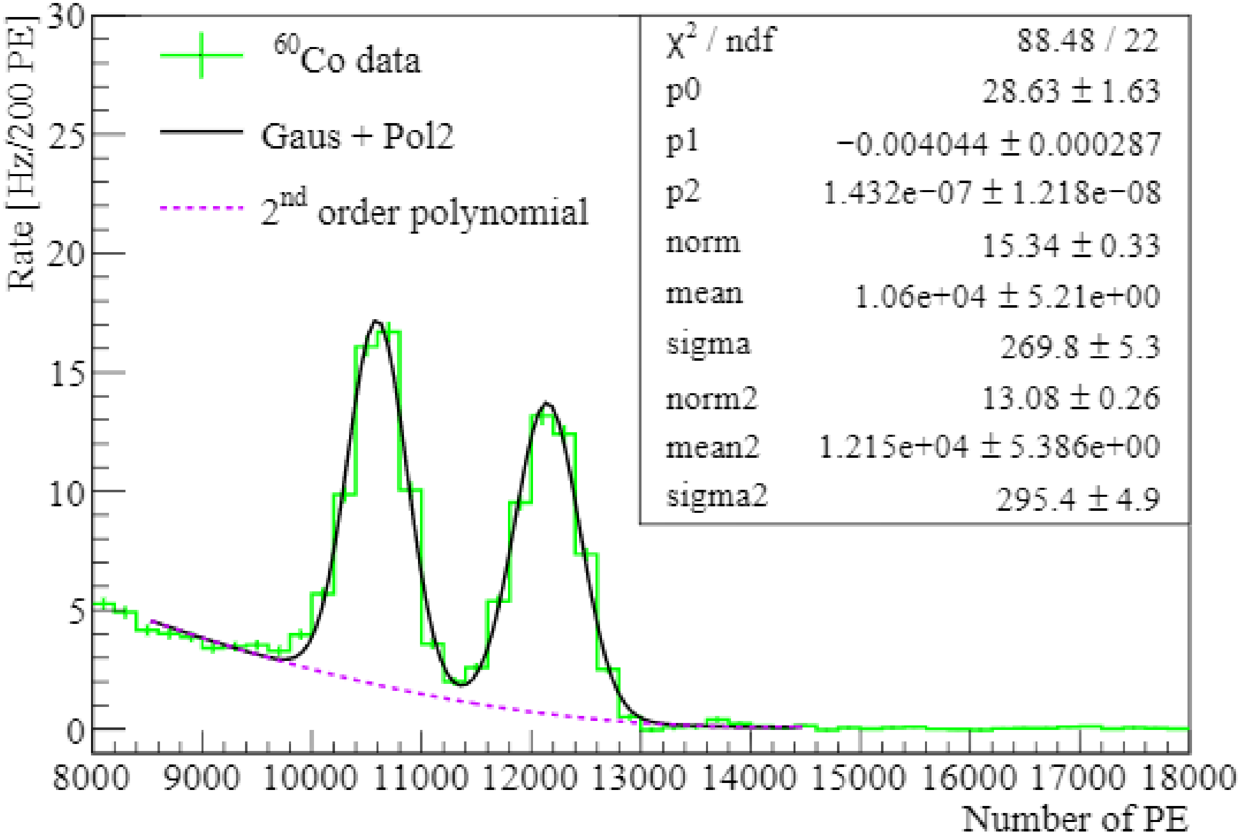
PMT	Temperature of PMT [°C]	Temperature of LED [°C]	Mean of single PE distribution [ADC counts·ns]
Top	-156.6 ± 1.3	-8.1 ± 1.3	26.74 ± 0.34
	-120.5 ± 1.3	-6.6 ± 1.3	26.40 ± 0.30
Bottom	-193.9 ± 1.3	-8.1 ± 1.3	38.57 ± 0.34
	-193.3 ± 1.3	-6.6 ± 1.3	38.57 ± 0.34

Amplification factor: 10

Energy calibration



Energy calibration



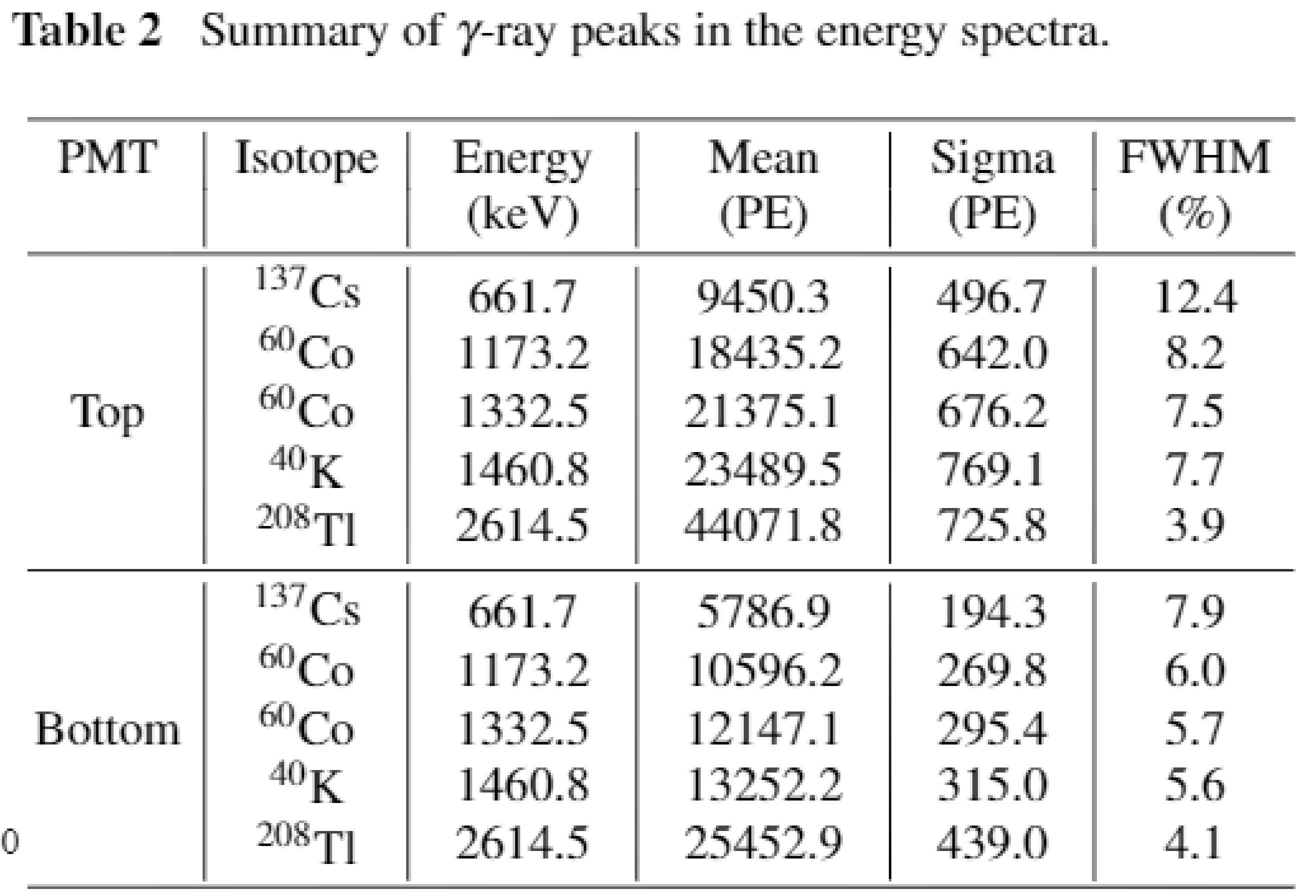
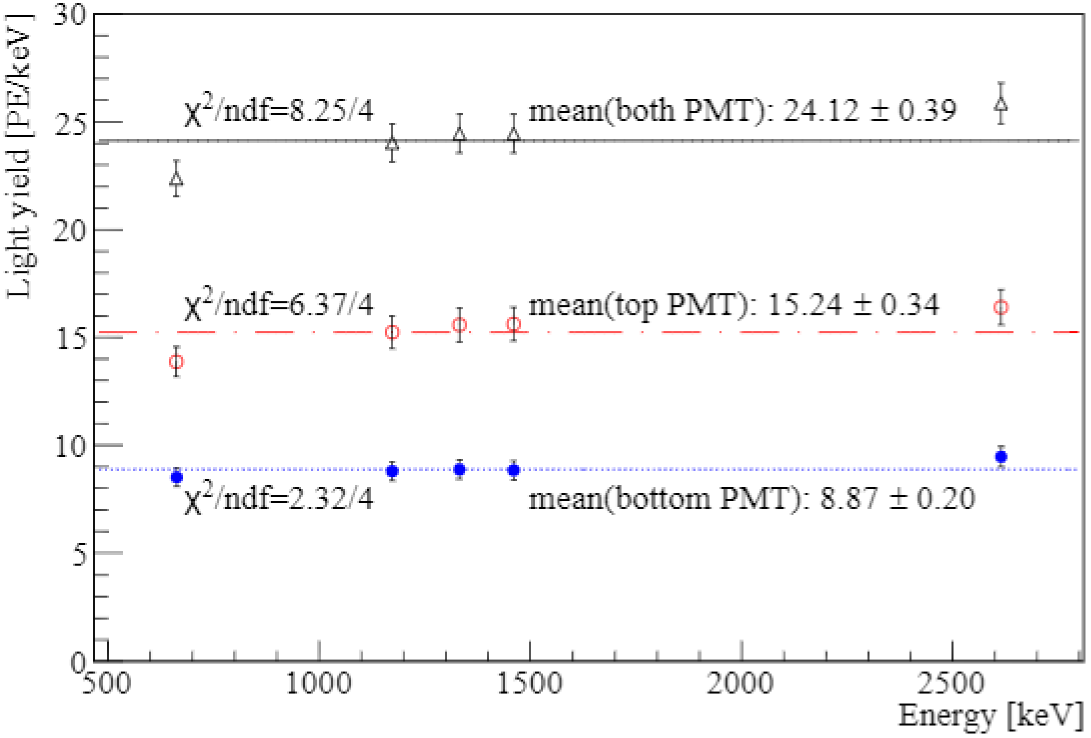


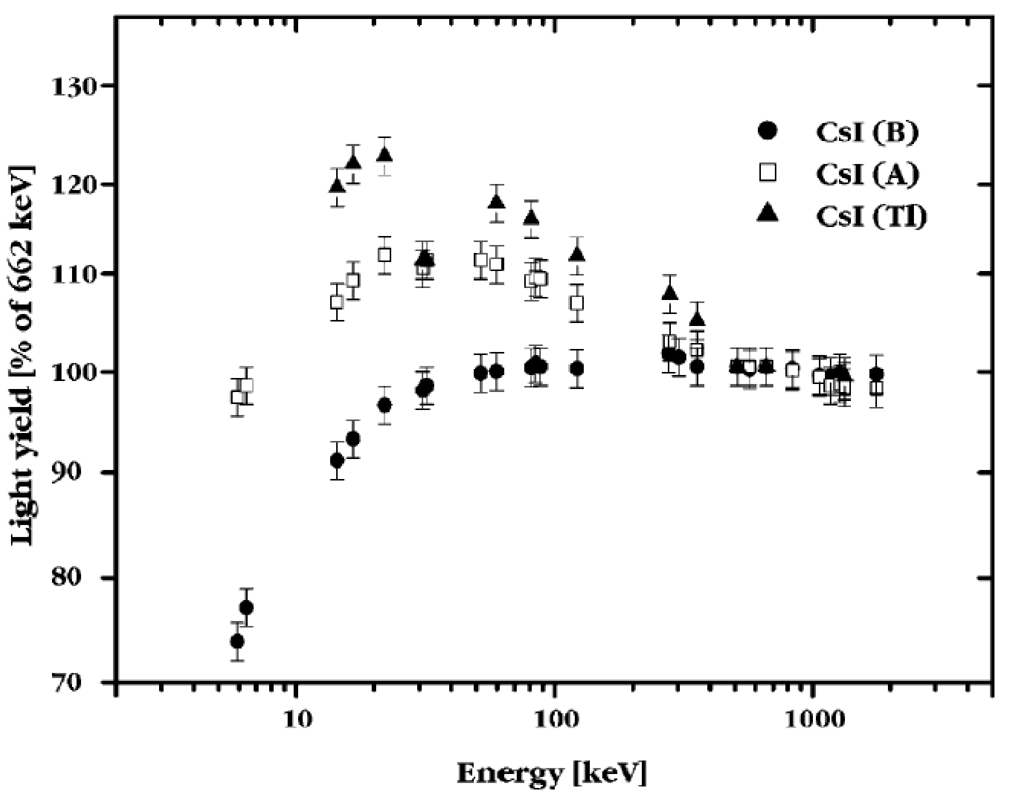
Table 2 Summary of γ-ray peaks in the energy spectra.

PMT	Isotope	Energy (keV)	Mean (PE)	Sigma (PE)	FWHM (%)
Top	^{137}Cs	661.7	9450.3	496.7	12.4
	^{60}Co	1173.2	18435.2	642.0	8.2
	^{60}Co	1332.5	21375.1	676.2	7.5
	^{40}K	1460.8	23489.5	769.1	7.7
	^{208}Tl	2614.5	44071.8	725.8	3.9
Bottom	^{137}Cs	661.7	5786.9	194.3	7.9
	^{60}Co	1173.2	10596.2	269.8	6.0
	^{60}Co	1332.5	12147.1	295.4	5.7
	^{40}K	1460.8	13252.2	315.0	5.6
	^{208}Tl	2614.5	25452.9	439.0	4.1

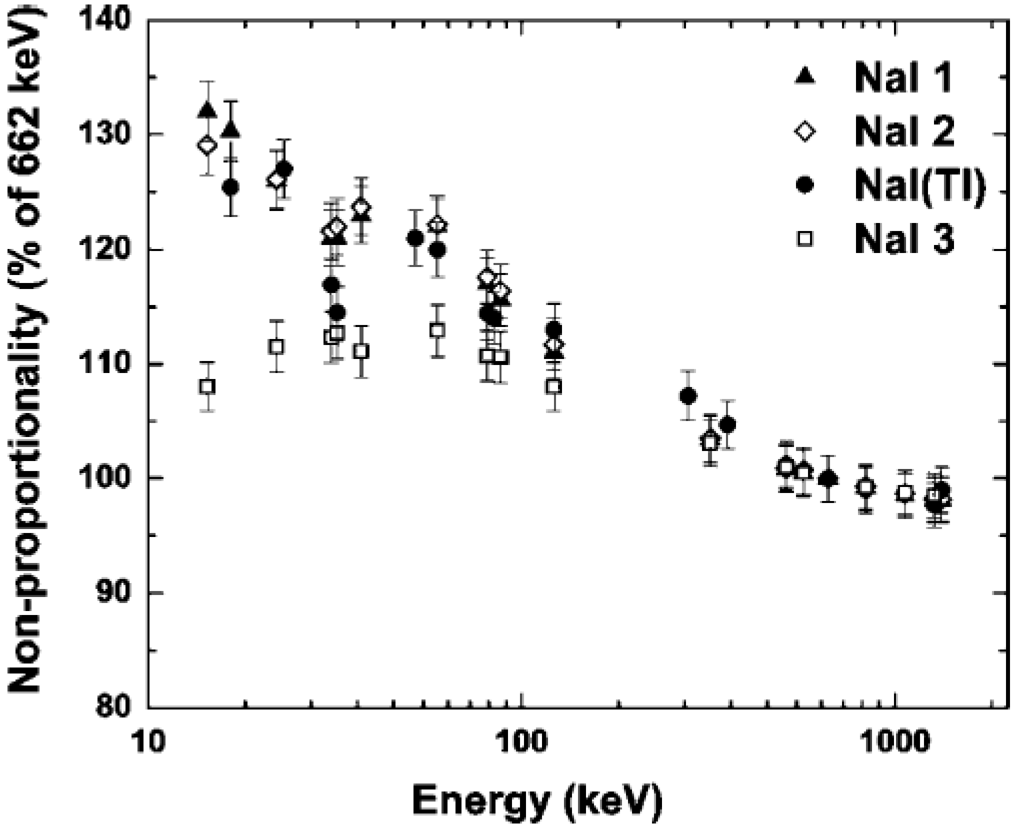
Light yield



M. Moszyński et al., NIMA, vol. 537, no. 1, pp. 357–362, Jan. 2005.



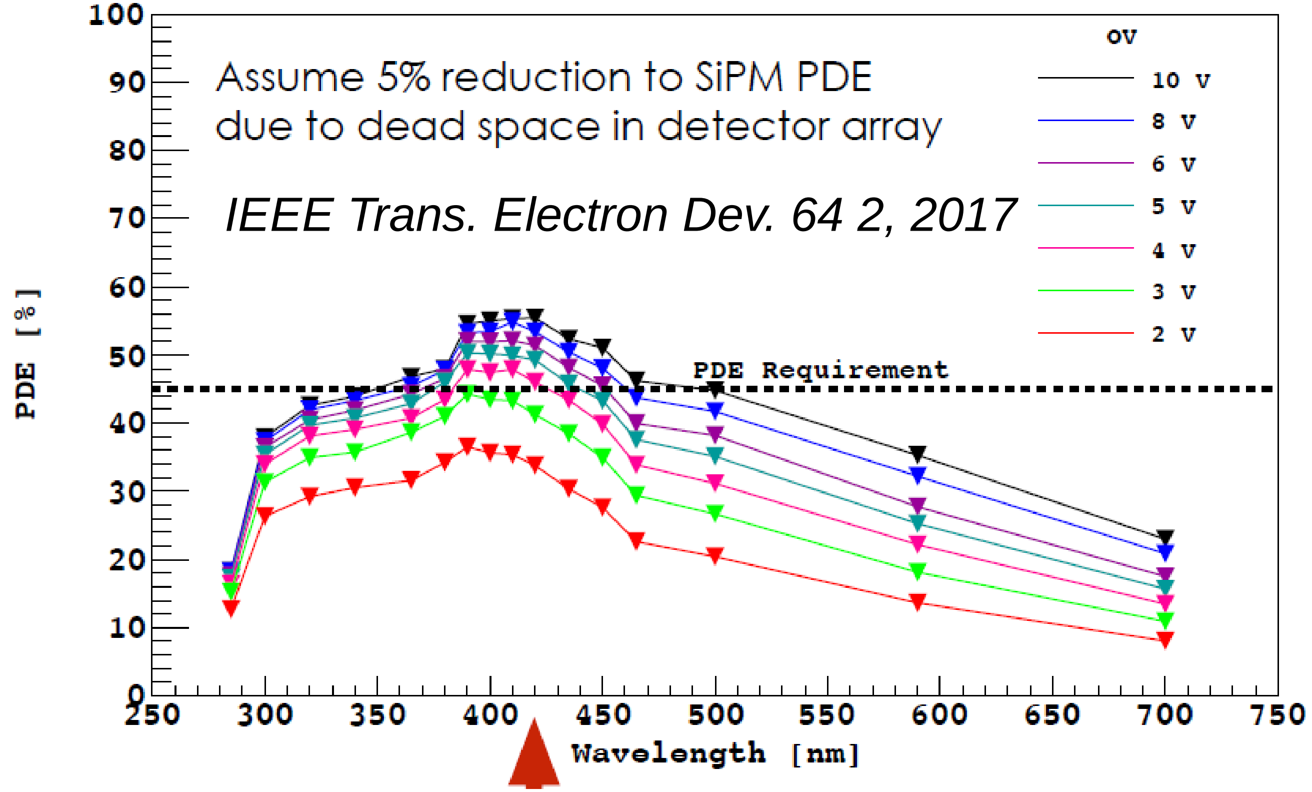
Nonlinearity of light yield



IEEE Trans., VOL. 56, NO. 3, JUNE 2009
A Comparative Study of Undoped NaI Scintillators With Different Purity
Marek Moszynski, et al.

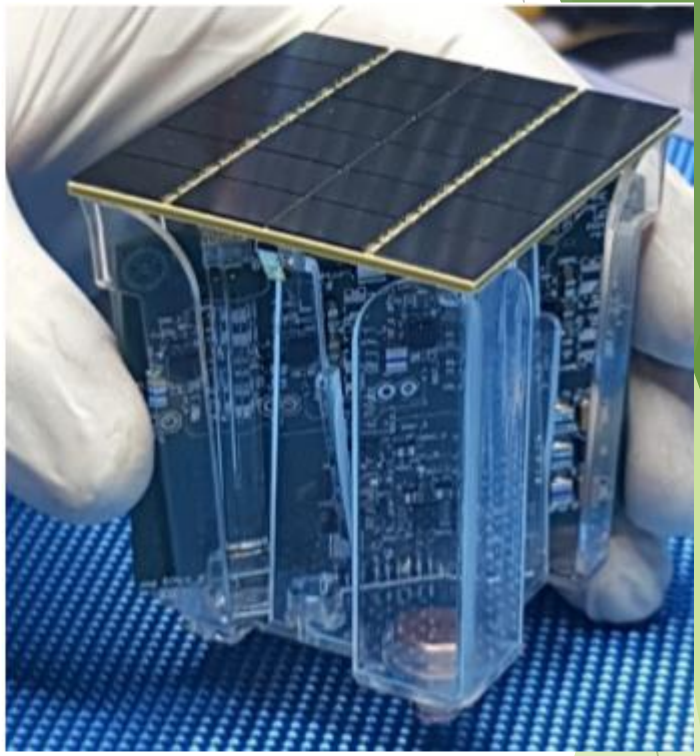
DarkSide SiPM Arrays

Progress and plans for DARKSIDE and QF measurements in LAr, Claudio Savarese



Assume 5% reduction to SiPM PDE due to dead space in detector array

IEEE Trans. Electron Dev. 64 2, 2017



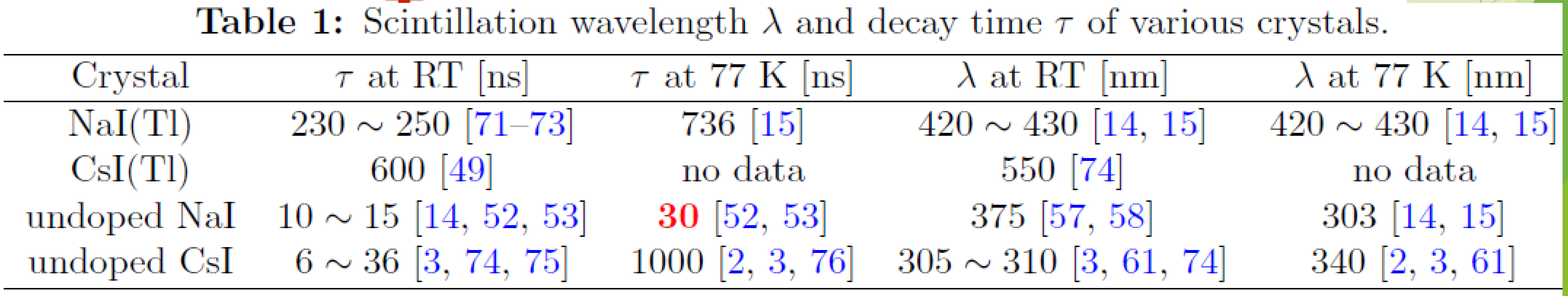
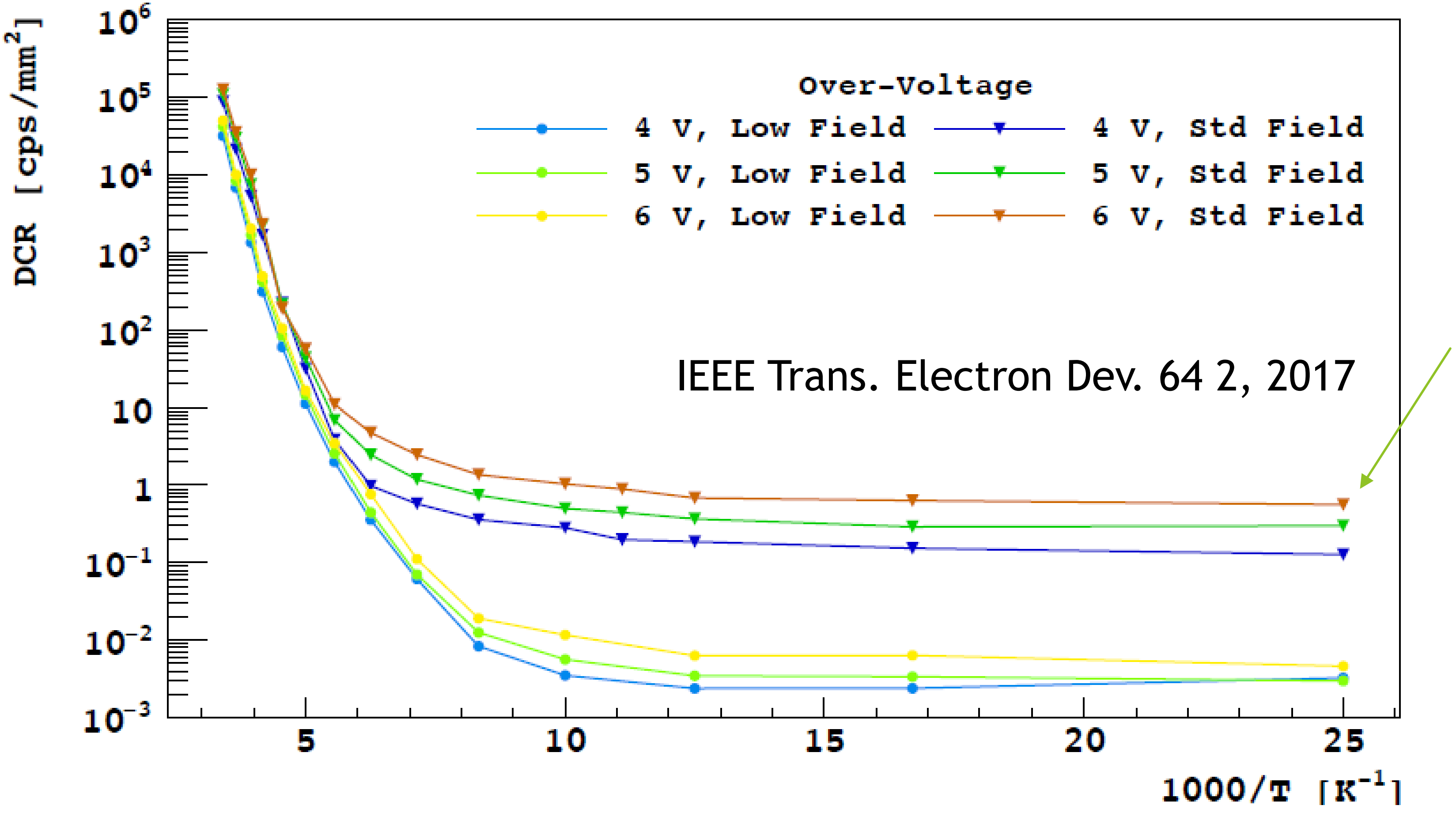


Table 1: Scintillation wavelength λ and decay time τ of various crystals.

Crystal	τ at RT [ns]	τ at 77 K [ns]	λ at RT [nm]	λ at 77 K [nm]
NaI(Tl)	230 ∼ 250 [71–73]	736 [15]	420 ∼ 430 [14, 15]	420 ∼ 430 [14, 15]
CsI(Tl)	600 [49]	no data	550 [74]	no data
undoped NaI	10 ∼ 15 [14, 52, 53]	**30** [52, 53]	375 [57, 58]	303 [14, 15]
undoped CsI	6 ∼ 36 [3, 74, 75]	1000 [2, 3, 76]	305 ∼ 310 [3, 61, 74]	340 [2, 3, 61]

Dark counts of large SiPM arrays

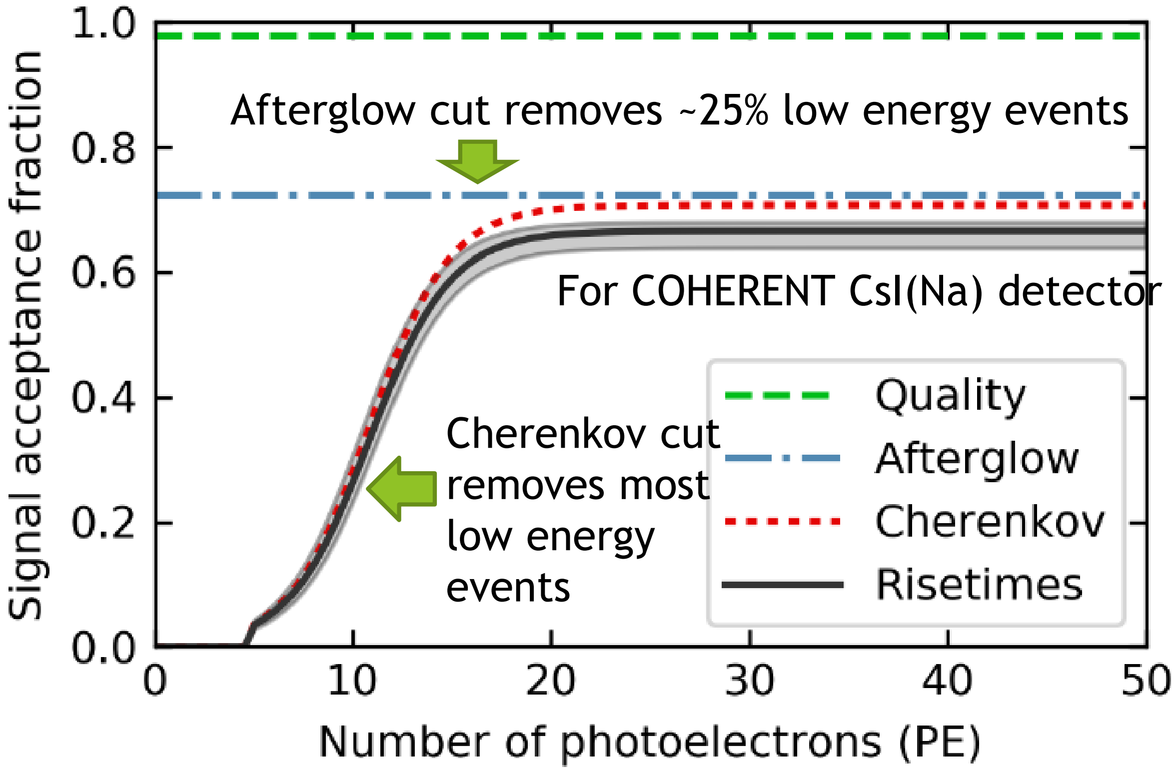


IEEE Trans. Electron Dev. 64 2, 2017

Suppressed by 10^6 after
2 PE coincidence

Another reason for SiPM

COHERENT Science paper



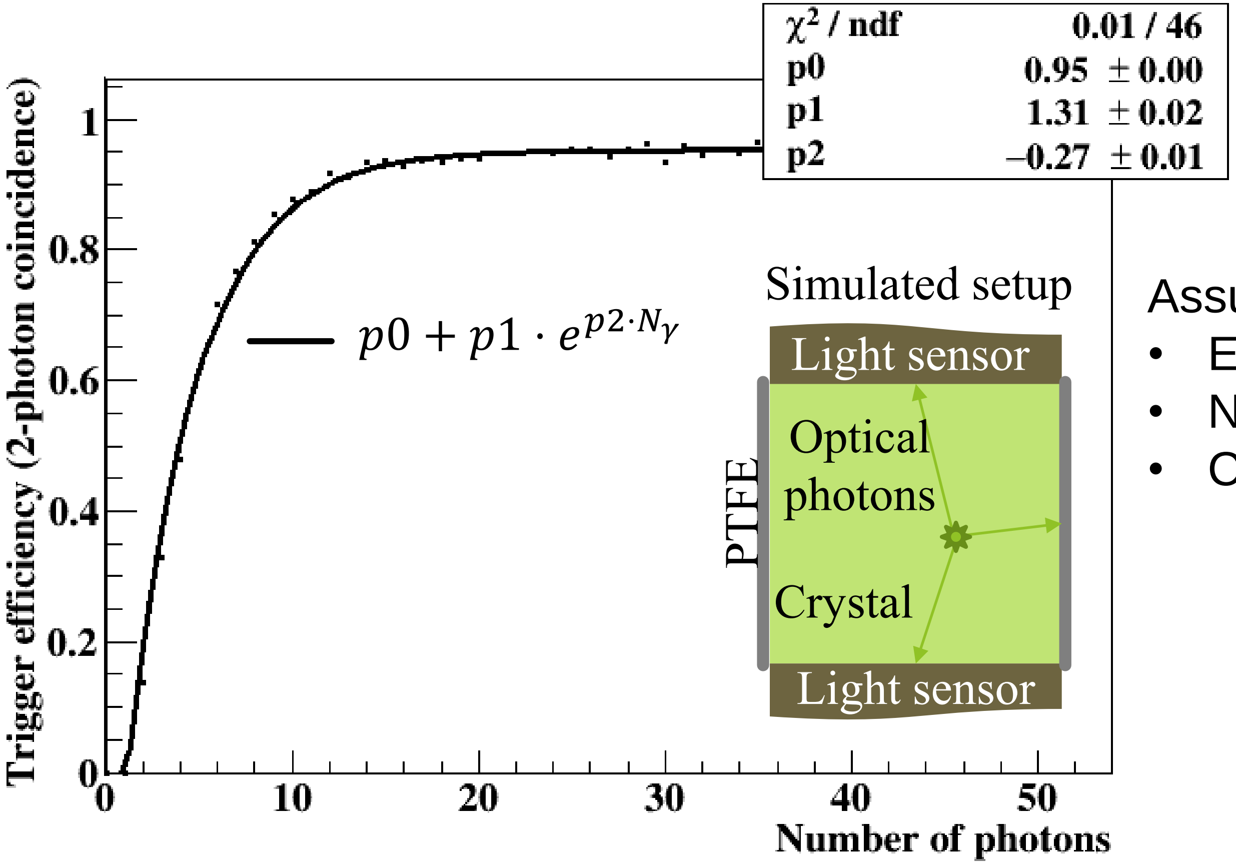
Afterglow cut removes ~25% low energy events

For COHERENT CsI(Na) detector

Cherenkov cut removes most low energy events

- Replace PMTs with SiPM
  - Eliminate Cherenkov light generated in PMT’s quartz window
  - PDE of SiPM > QE of PMT
  - Coincidence trigger to reduce SiPM dark count effect

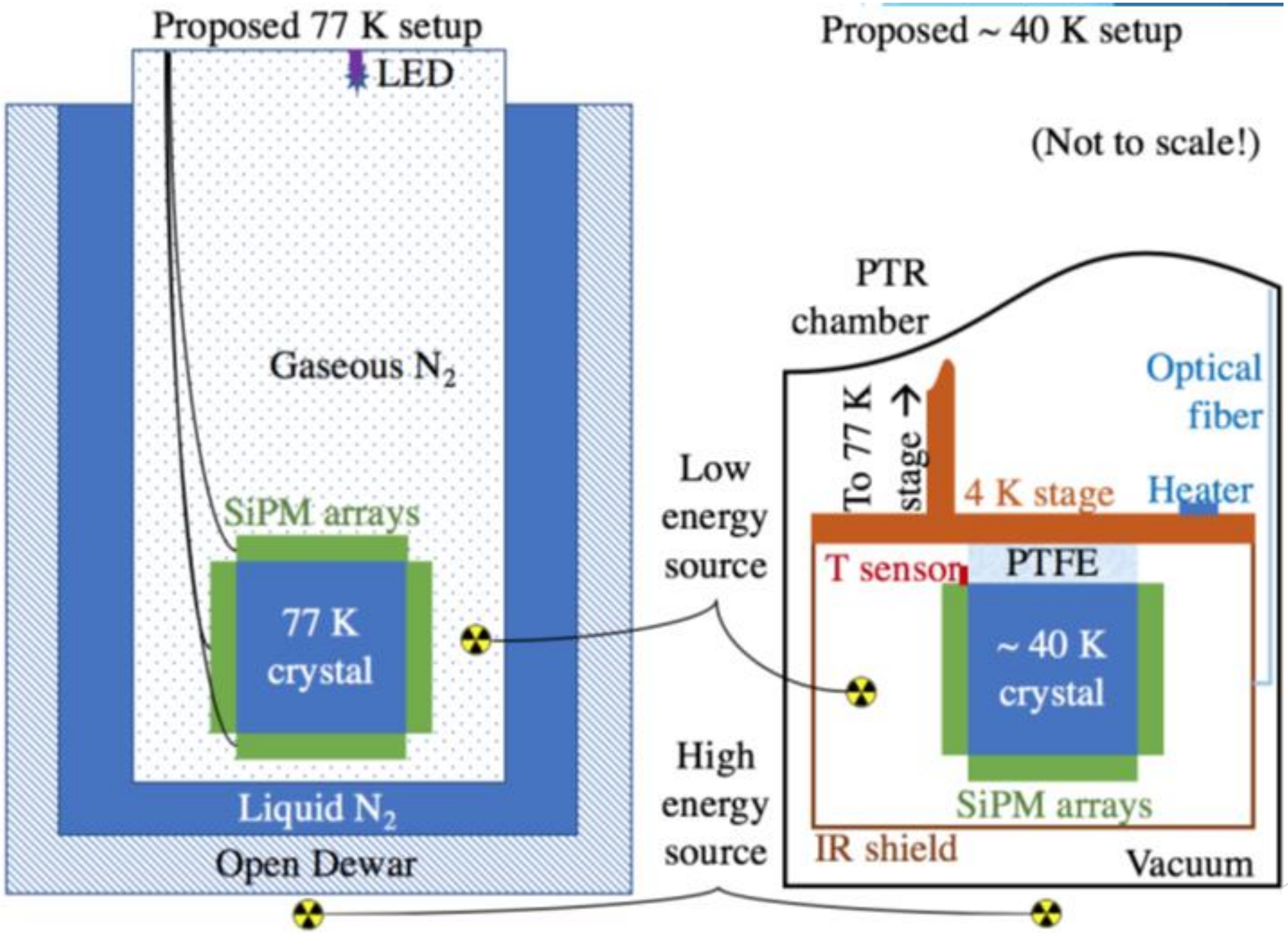
Thresholds



Assuming an 80% trigger efficiency

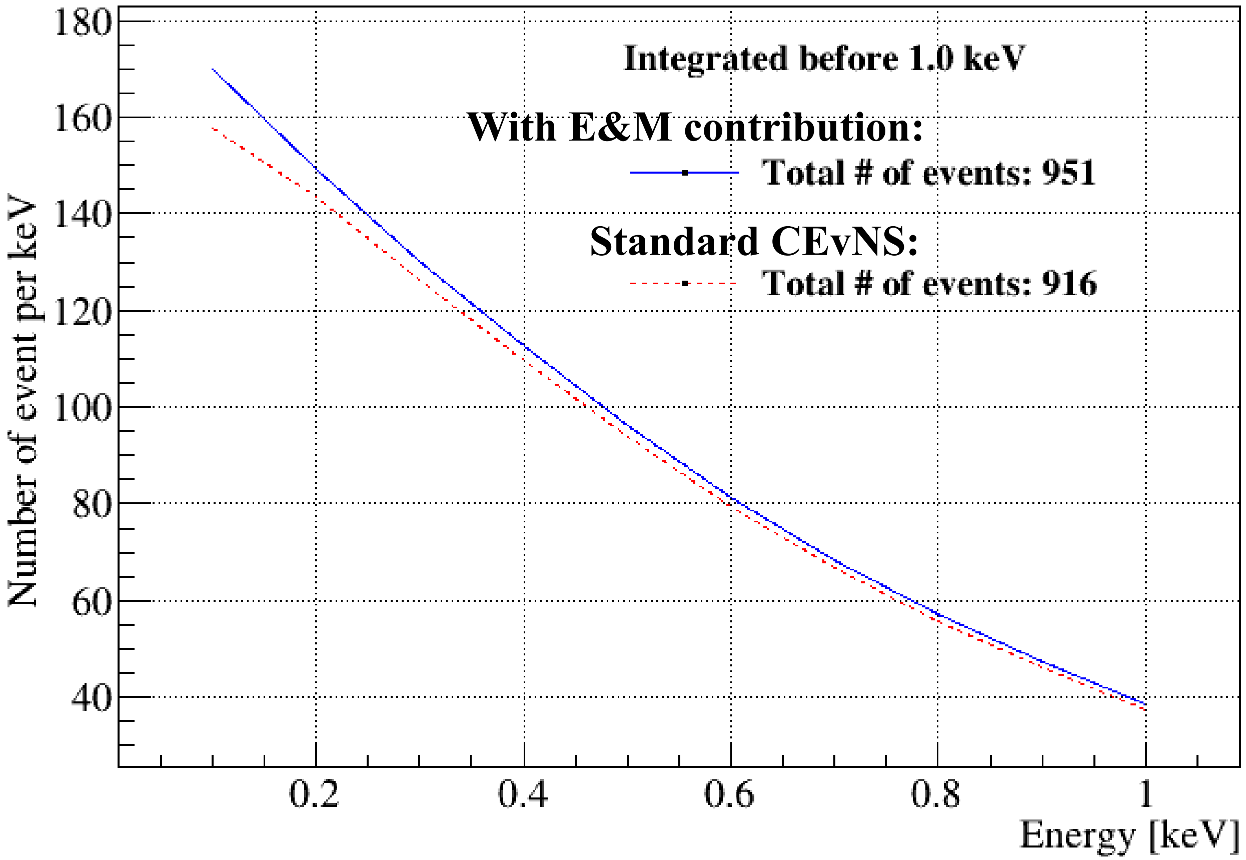
- ER threshold: 160 eVee
- Na recoil threshold: 2 keVnr (QF: 0.08)
- Cs recoil threshold: 3.2 keVnr (QF: 0.05)

Possible setup



CEvNS event rate

https://github.com/schol/dukecevns

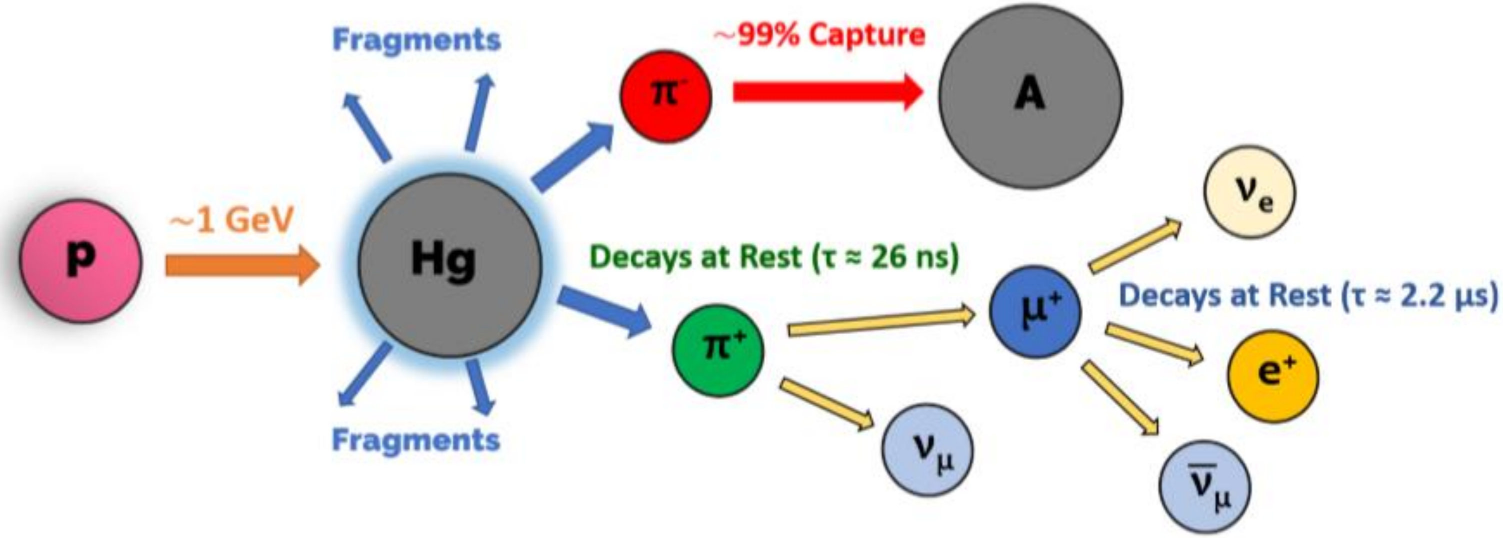


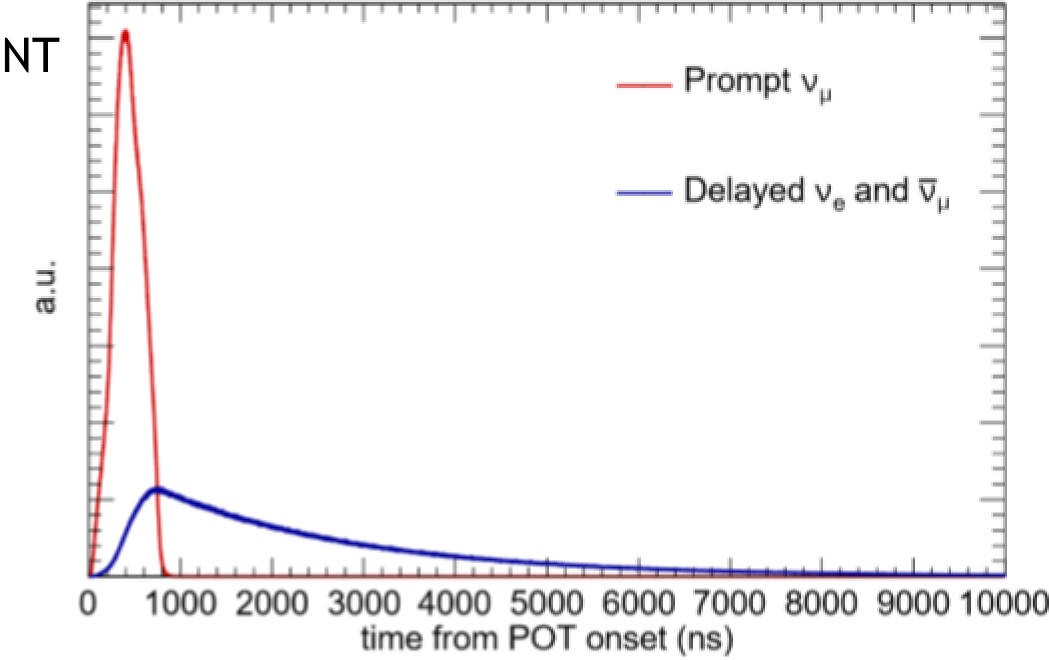
Assumptions:

- 50 PE/keVee
- 10 kg of undoped NaI
- 2 years of data taking
- NaI(Tl) quenching factor
- 2 PE coincident trigger

Light dark matter from SNS

M. Green on COHERENT

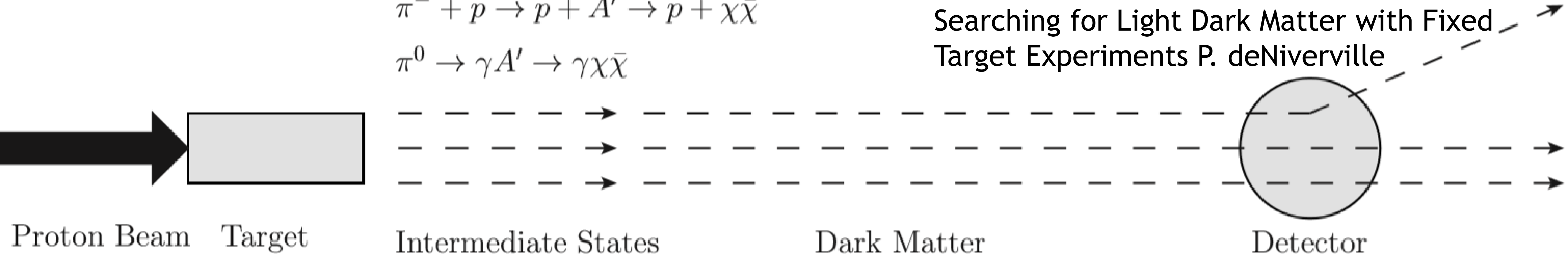




$$\pi^- + p \to p + A' \to p + \chi\bar{\chi}$$

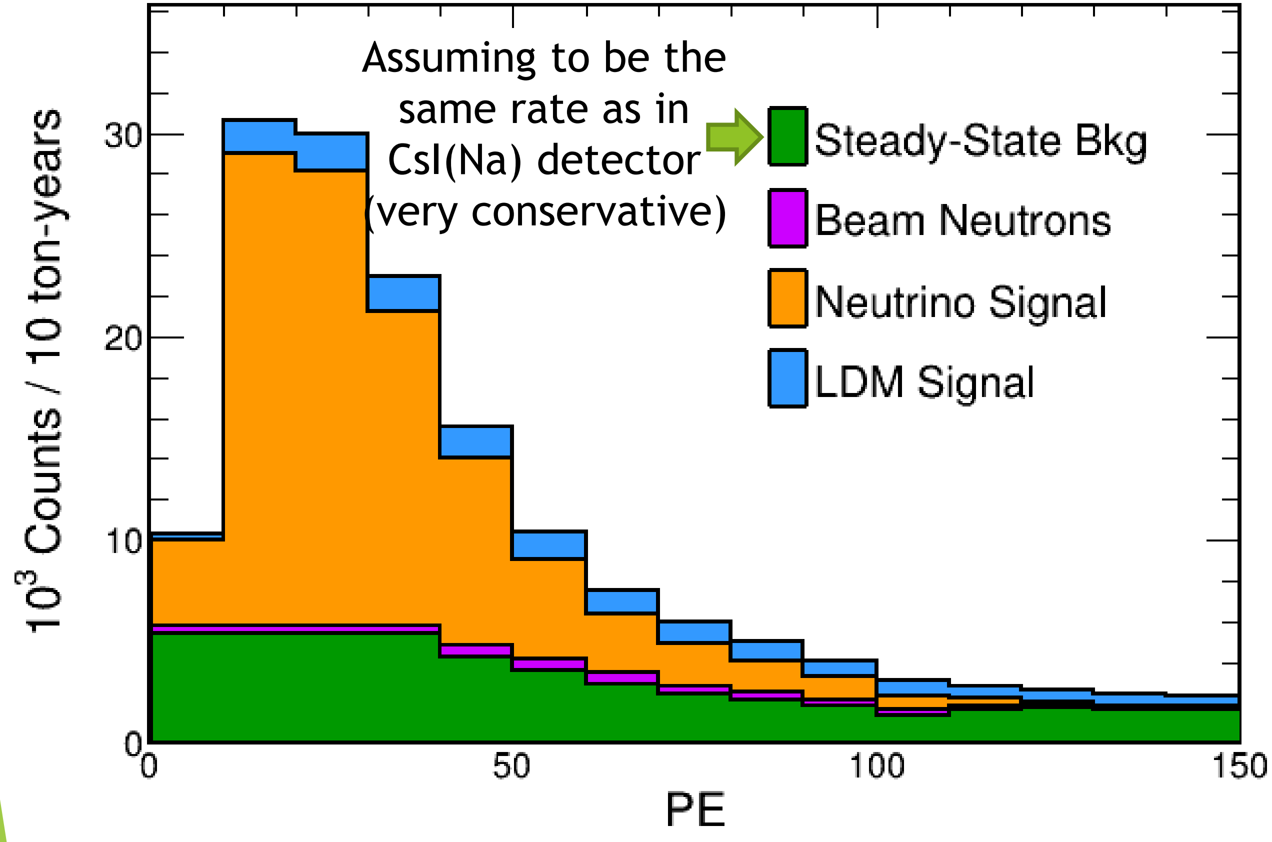
$$\pi^0 \to \gamma A' \to \gamma\chi\bar{\chi}$$

Searching for Light Dark Matter with Fixed Target Experiments P. deNiverville



Expectation

D. Pershey



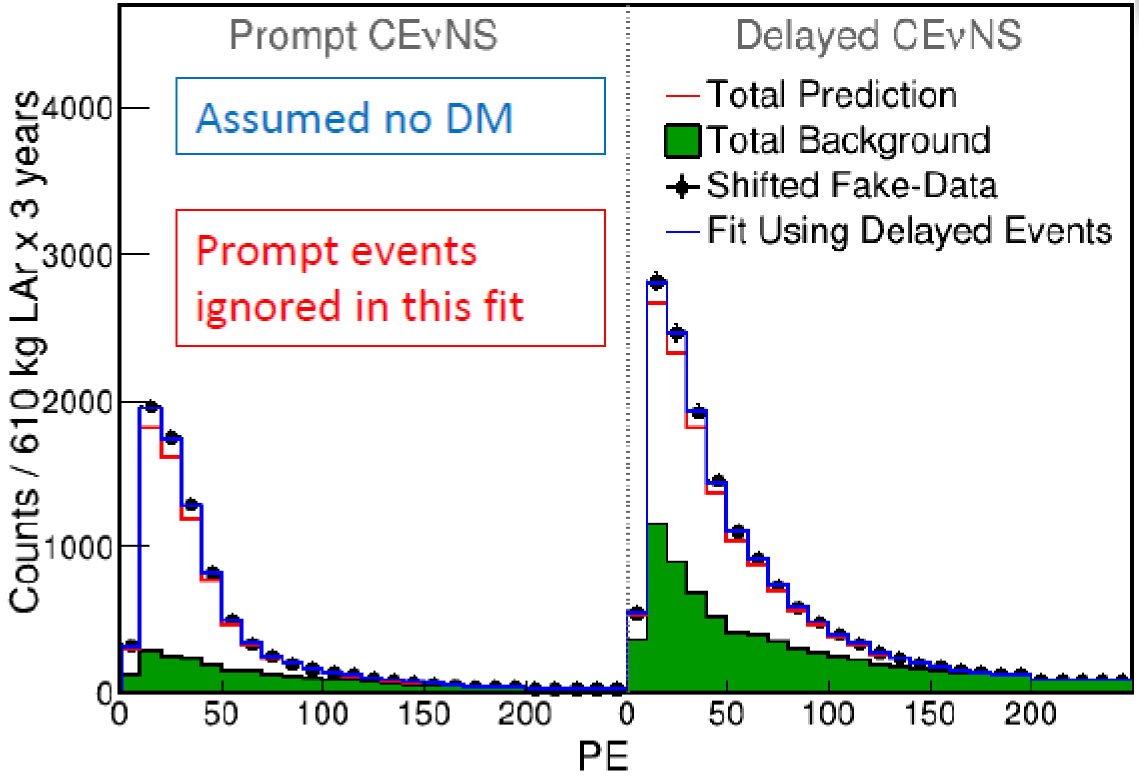
Assuming to be the same rate as in CsI(Na) detector (very conservative)

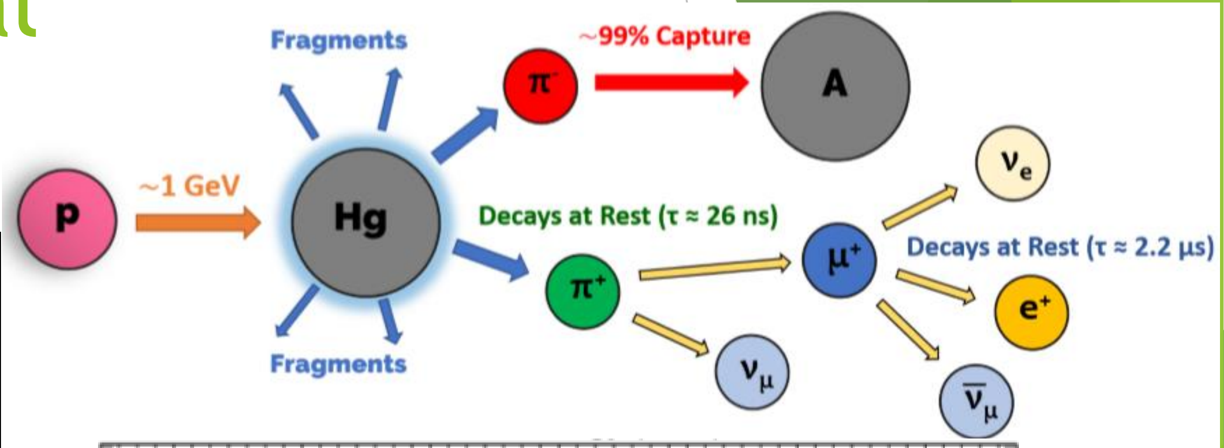
Assumptions:

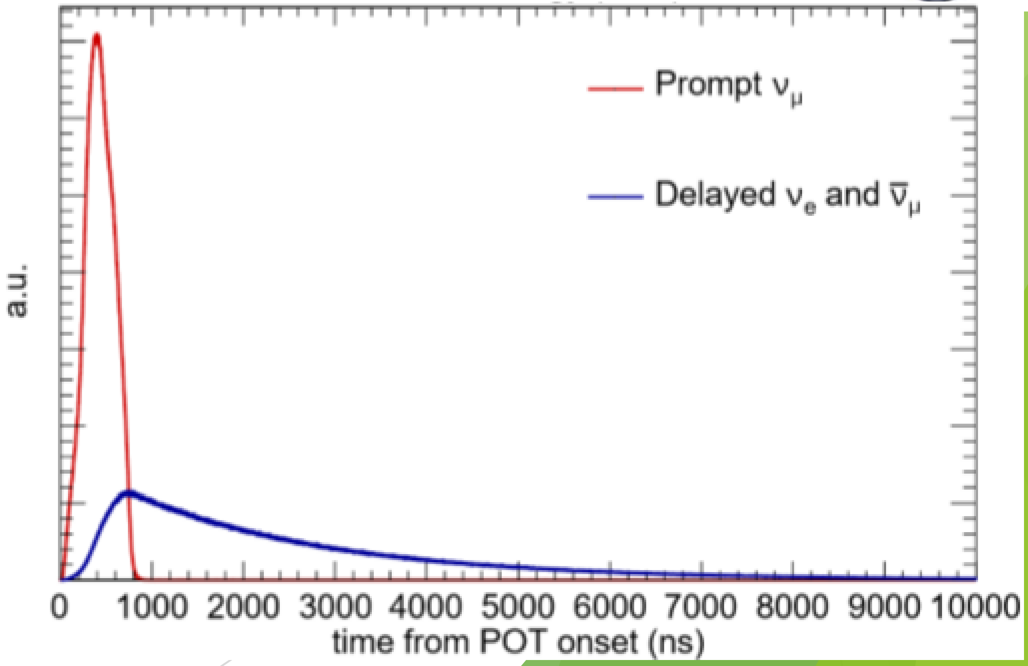
- 50 PE/keVee
- NaI(Tl) quenching factor
- 2 PE coincident trigger

Strategies to tackle background: using delay’s neutrino signal

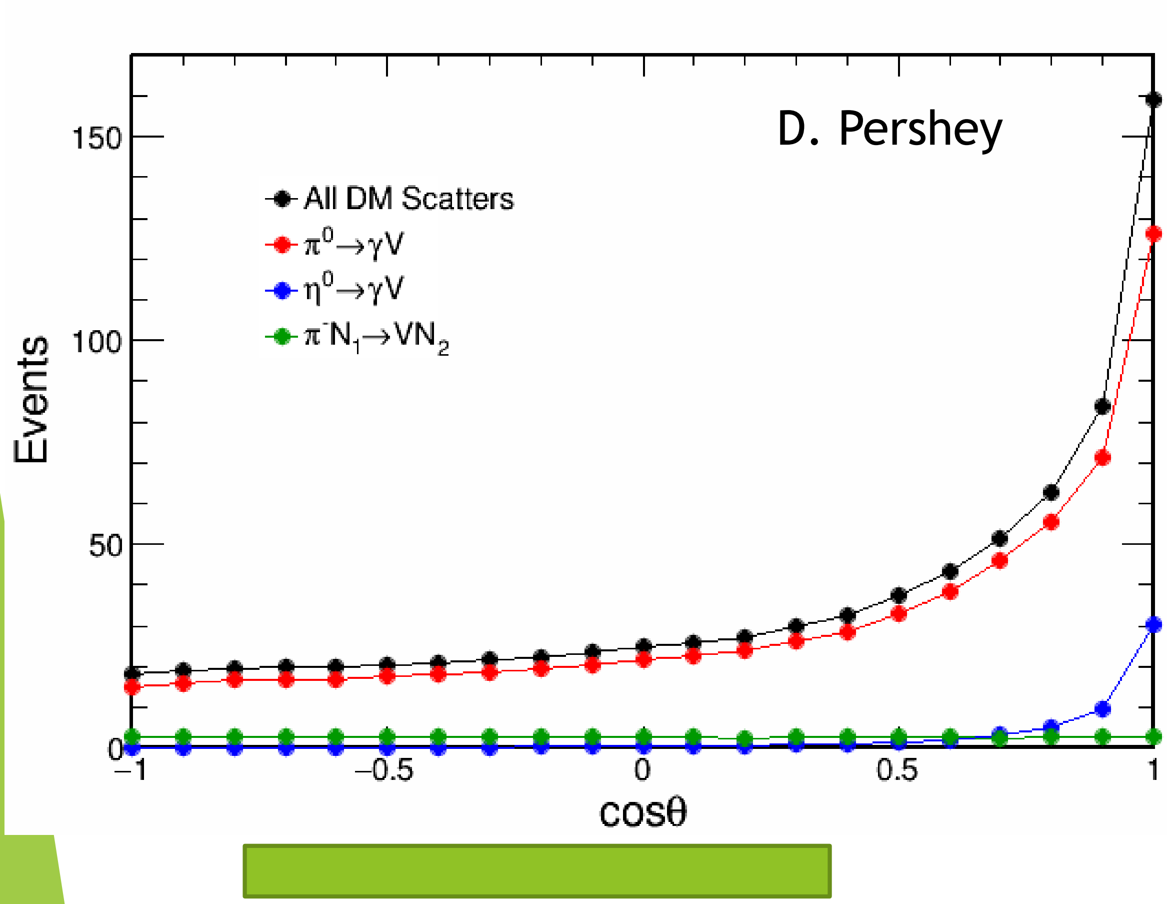
D. Pershey’s talk on LAr at SNS







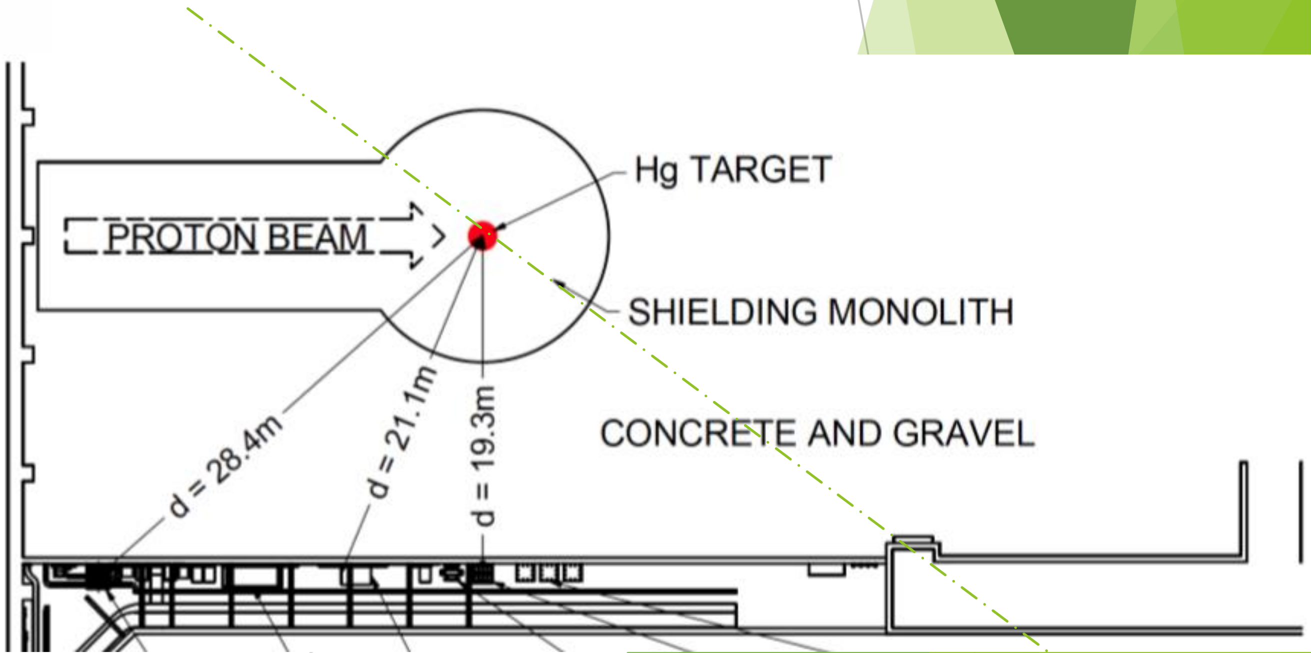
Strategies to deal with background: move the detector forward



Current Neutrino Alley Detectors

Evaluating the curve at these angle

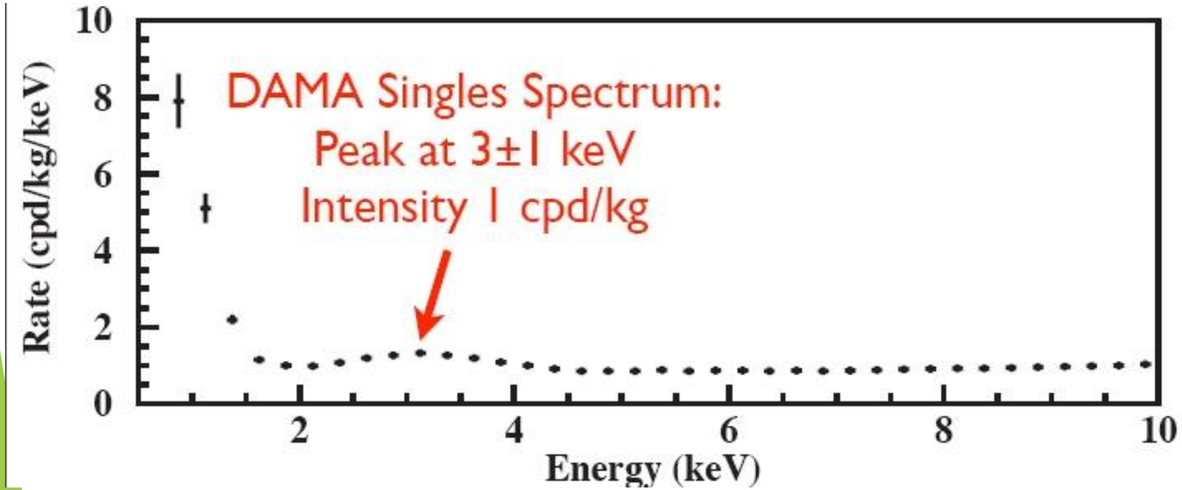
- DM(cosθ=0.3)/DM(cosθ=-0.7) = 1.41
- cosθ=0.3 also closer to the source (additional flux boost of 1.37)

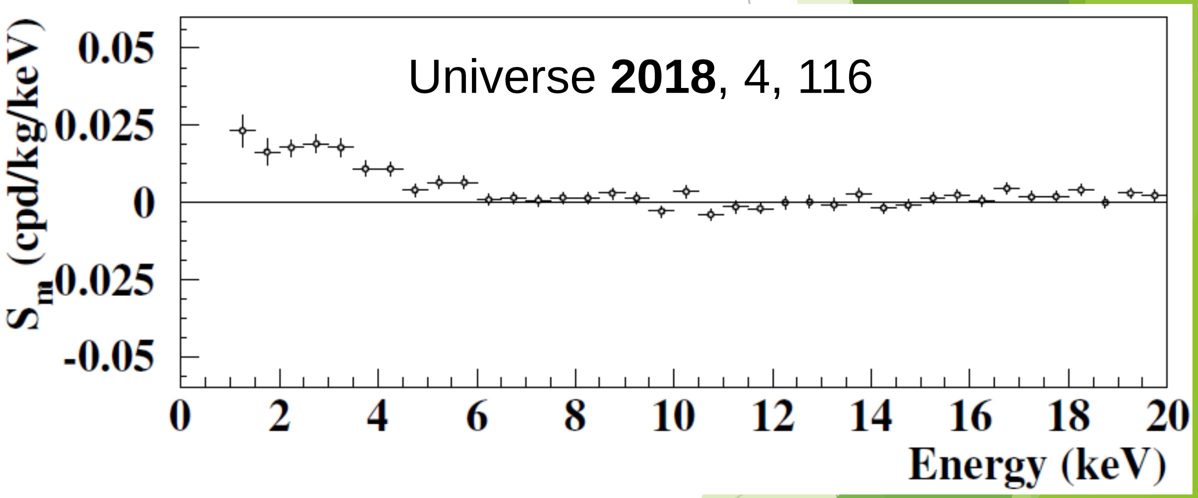


Strategies to tackle background: radiopurity of crystal

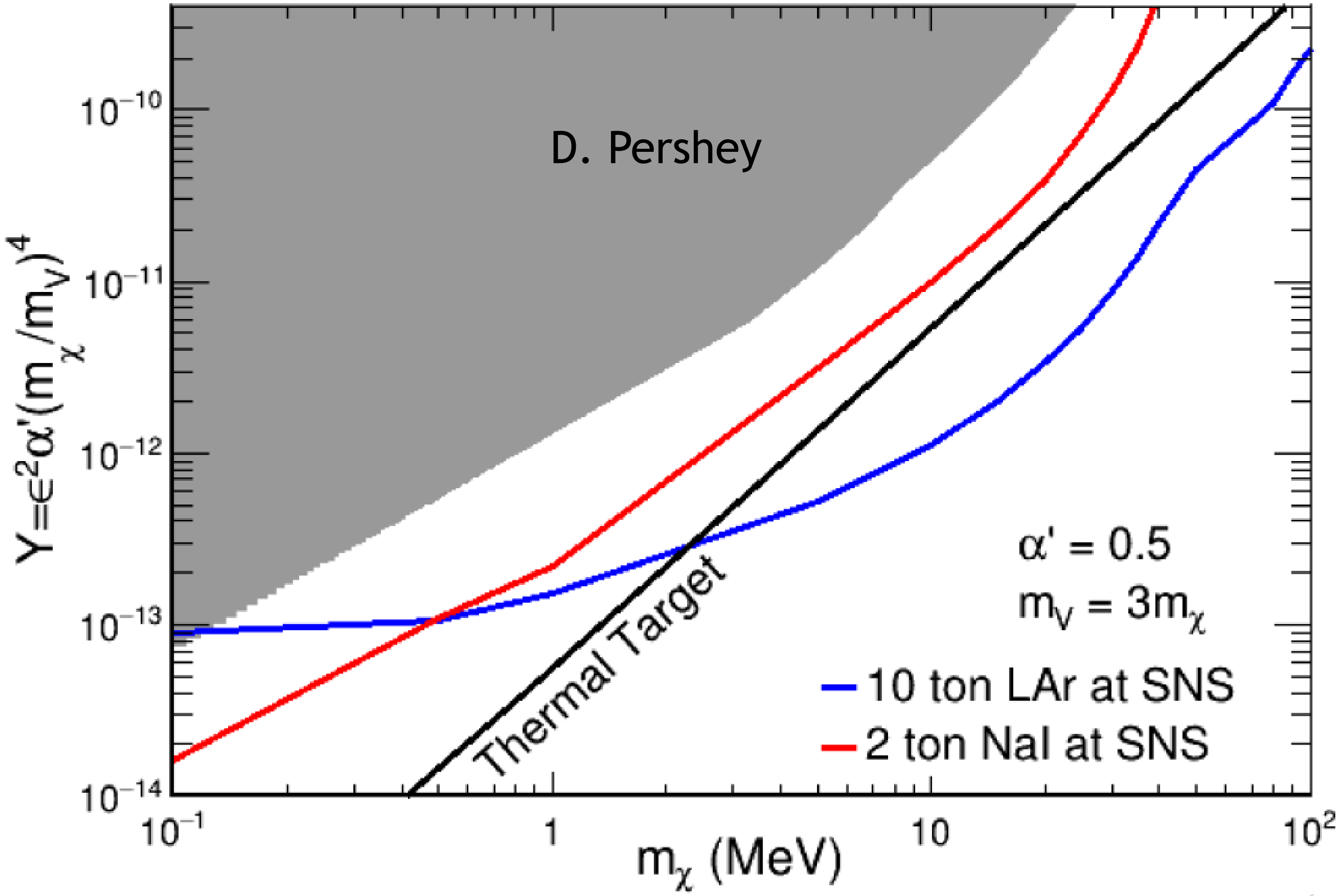
Possible sources of crystal:

- Alpha Spectra
- SICCAS
- AMCRYS
- Other experiments



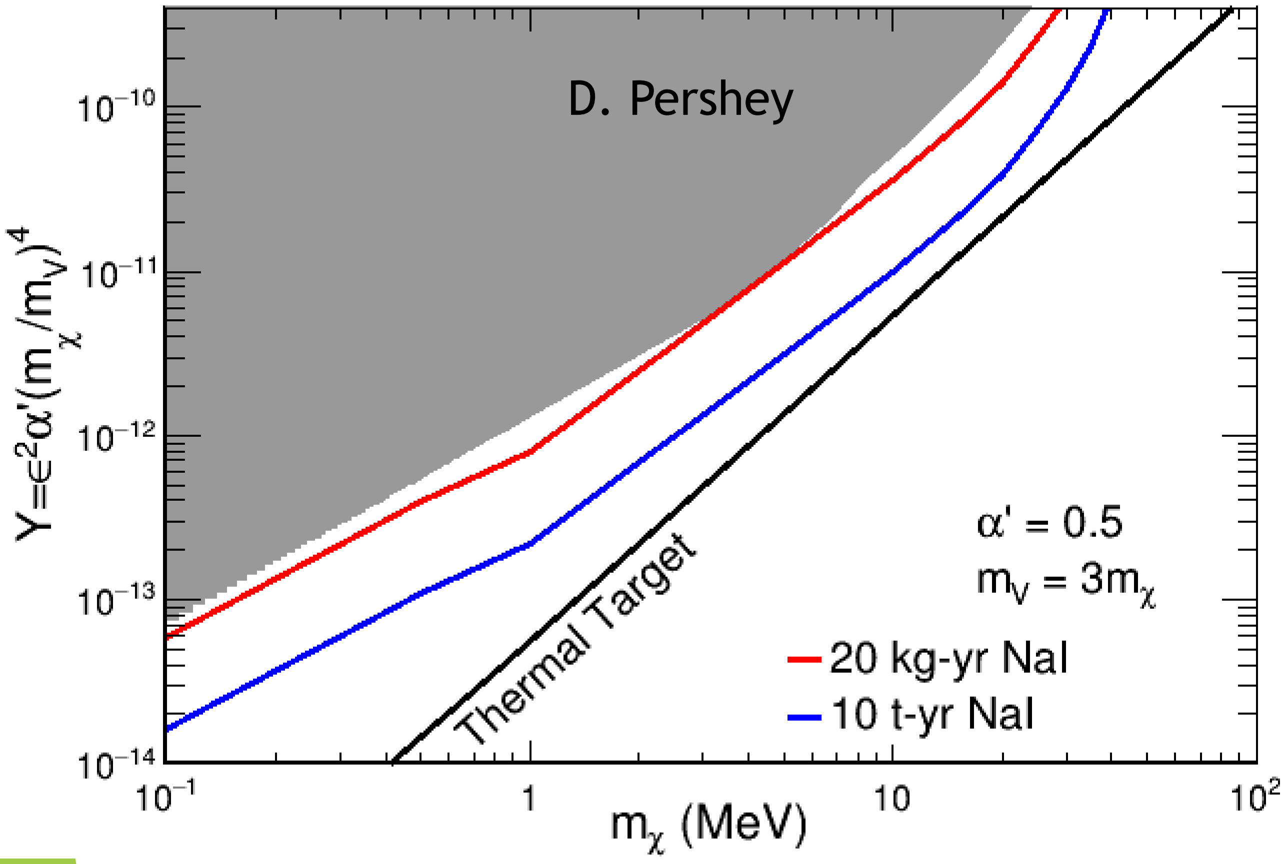

Universe **2018**, 4, 116

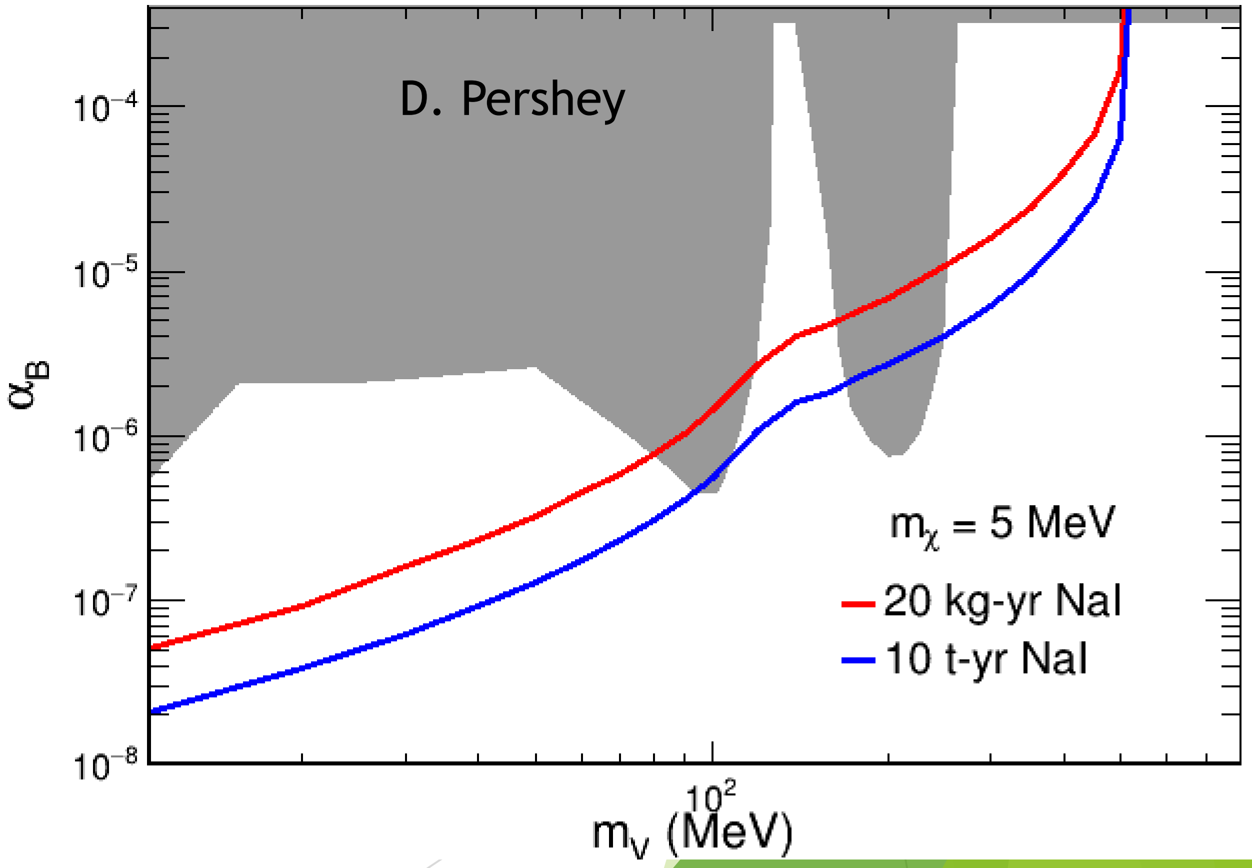
This approach + LAr



A prototype capable of delivering physics

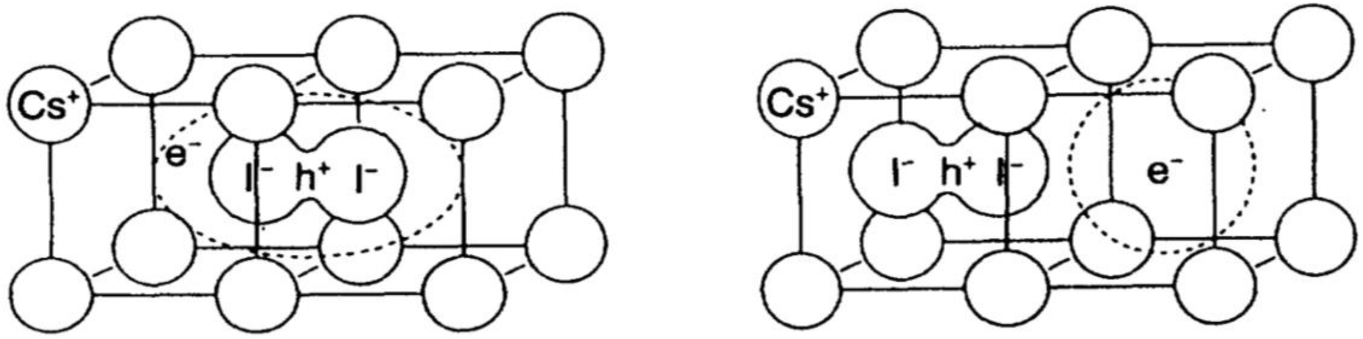
10 kg crystal + 2 years of data taking at SNS





Scintillation mechanism

Self trapped holes:

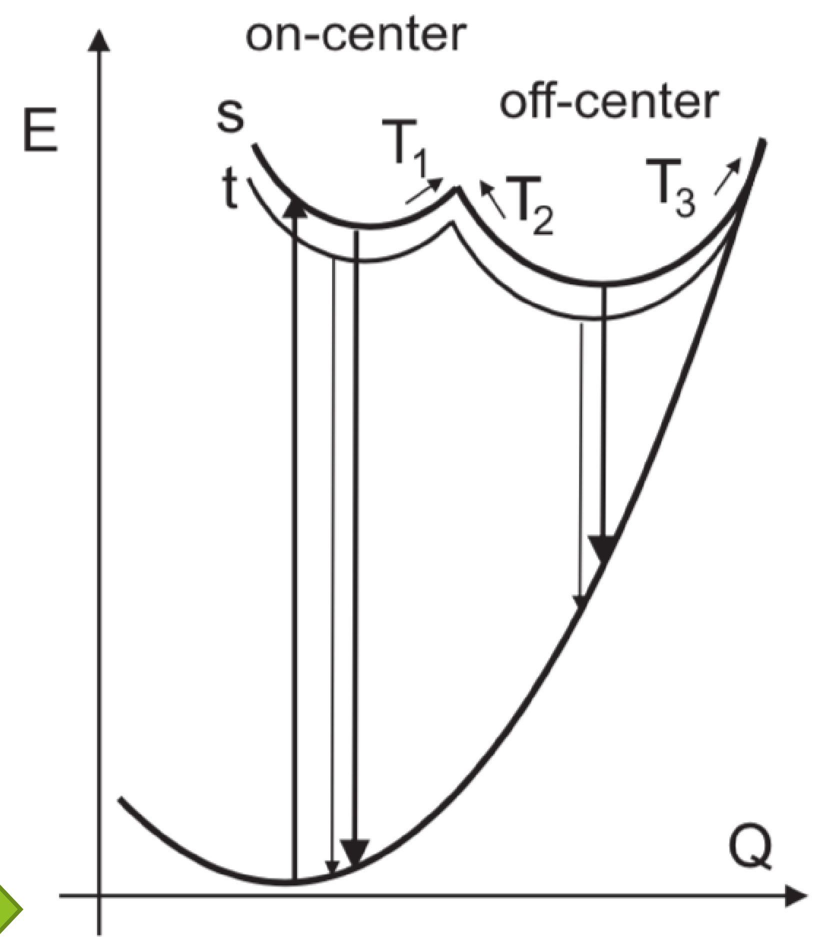


on–center configuration

off–center configuration

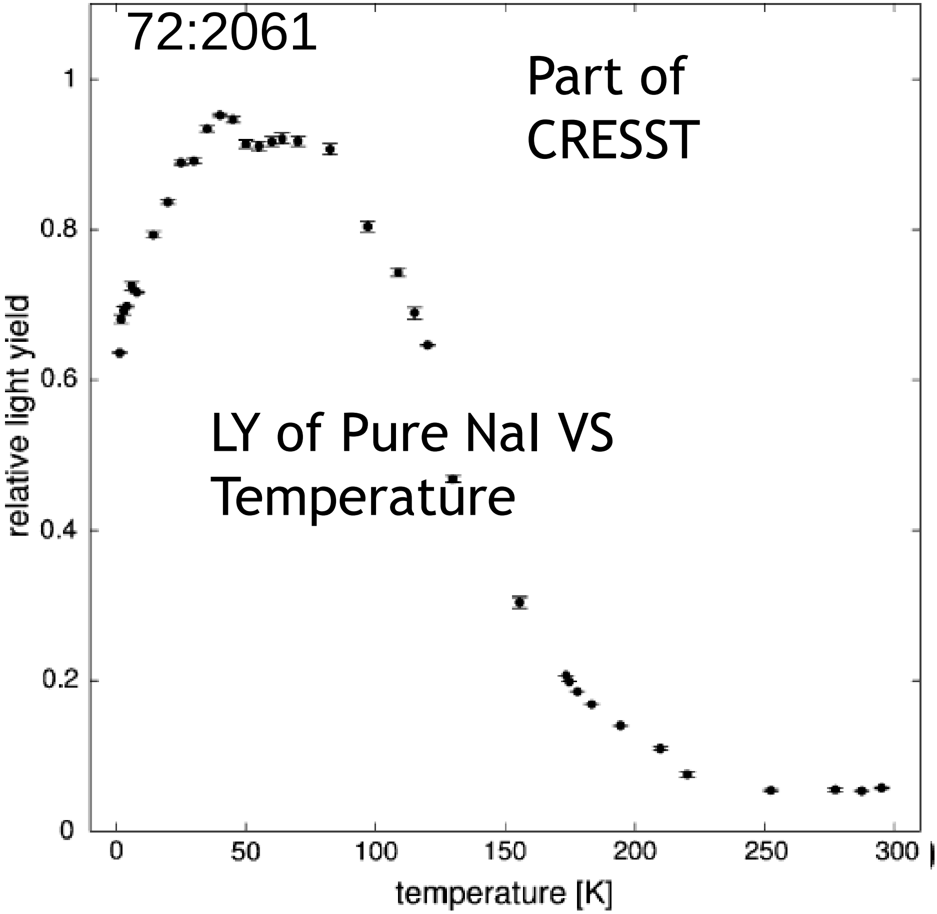
V. B. Mikhailik, V. Kapustyanyk, V. Tsybulskyi, V. Rudyk, and H. Kraus. Luminescence and scintillation properties of CsI: A potential cryogenic scintillator. physica status solidi (b), 252(4):804-810, 2015

H. Nishimura, M. Sakata, T. Tsujimoto, and M. Nakayama. Origin of the 4.1-eV luminescence in pure CsI scintillator. Phys. Rev. B, 51(4):2167{2172, 1995.



Scintillation mechanism

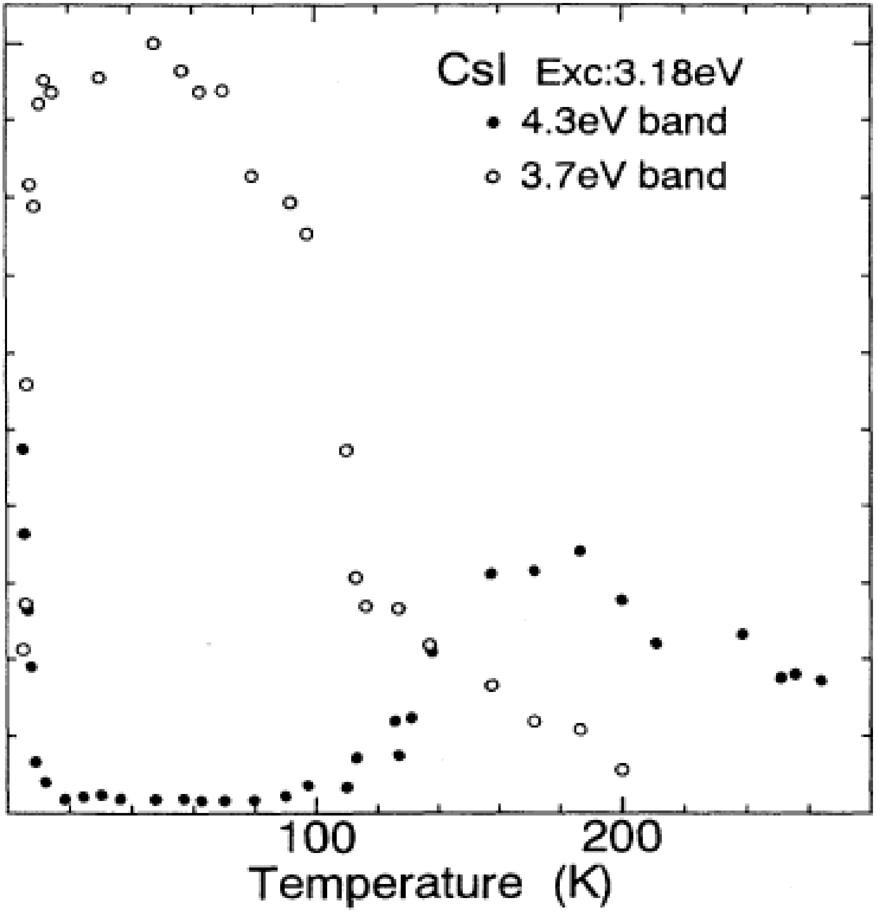
Eur. Phys. J. C (2012) 72:2061

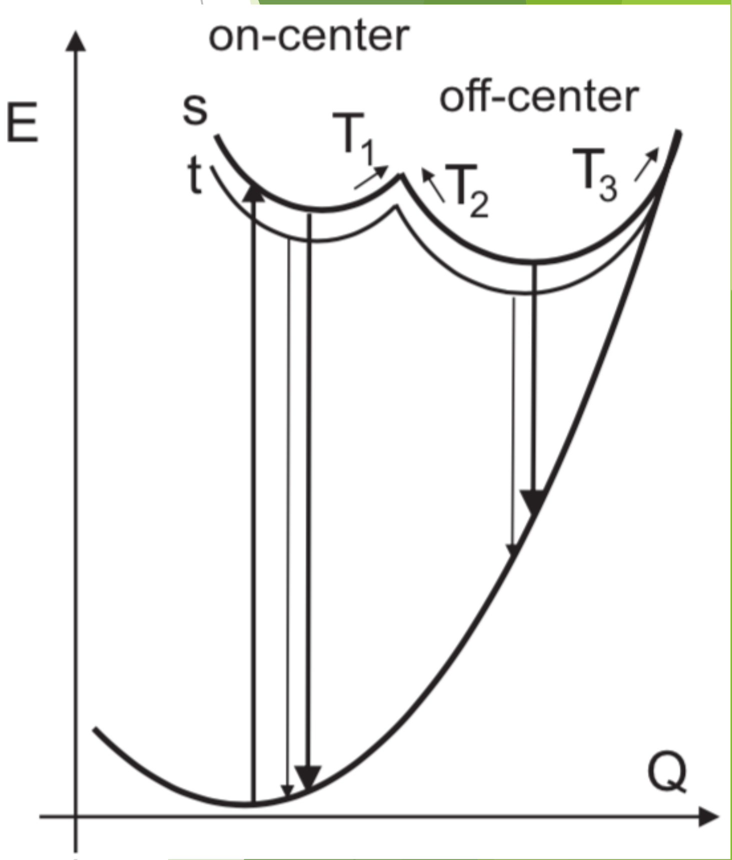


Part of CRESST

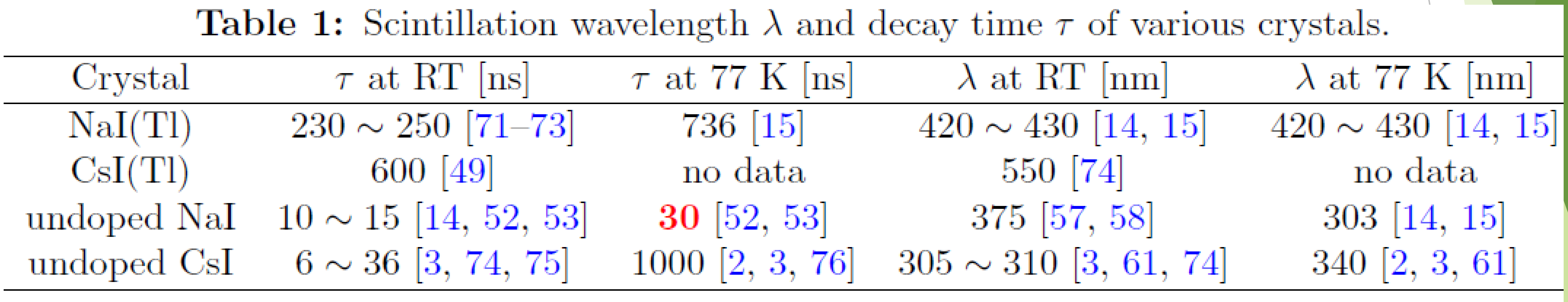
LY of Pure NaI VS Temperature

Phys. Rev. B 5 (1995) 2195





Decay times



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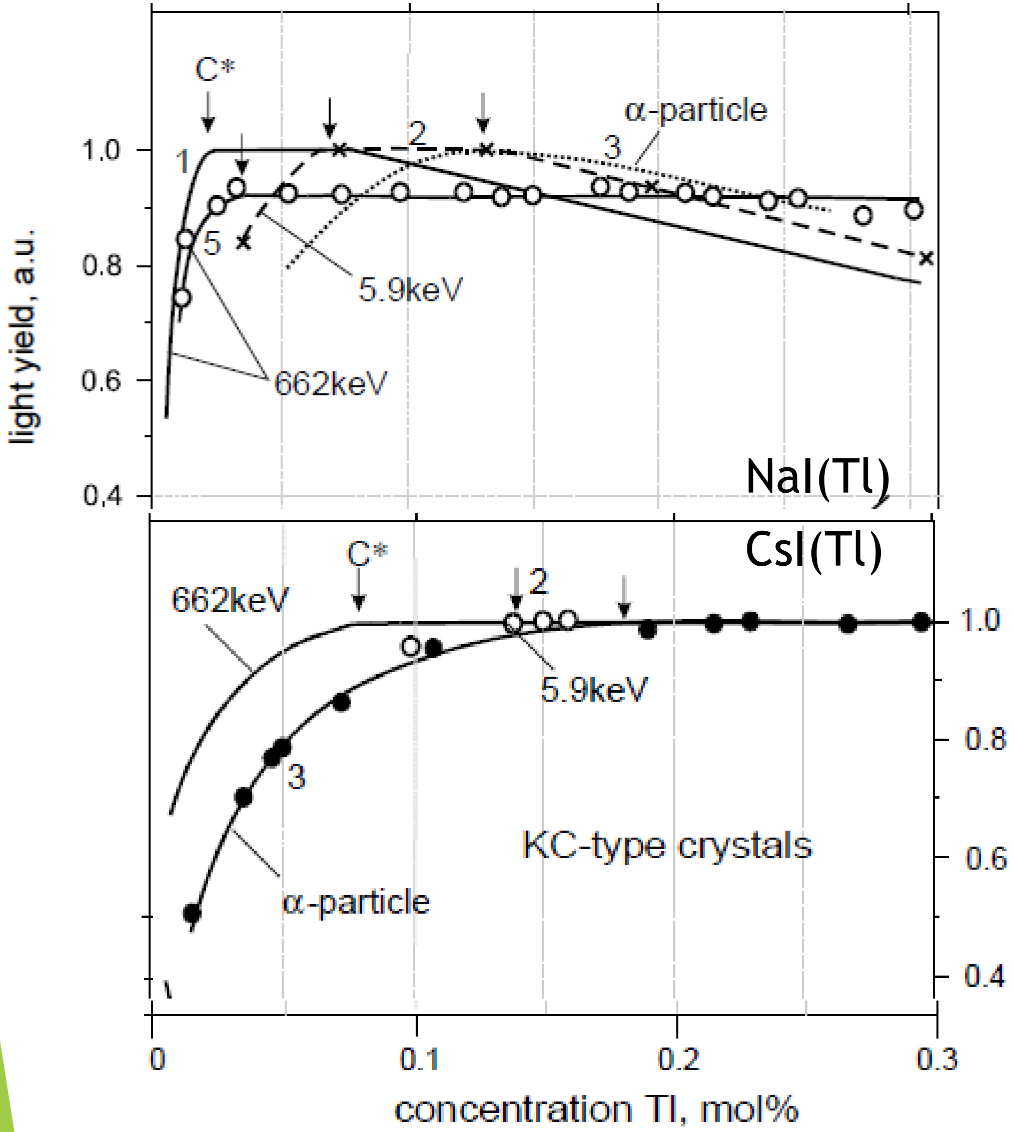
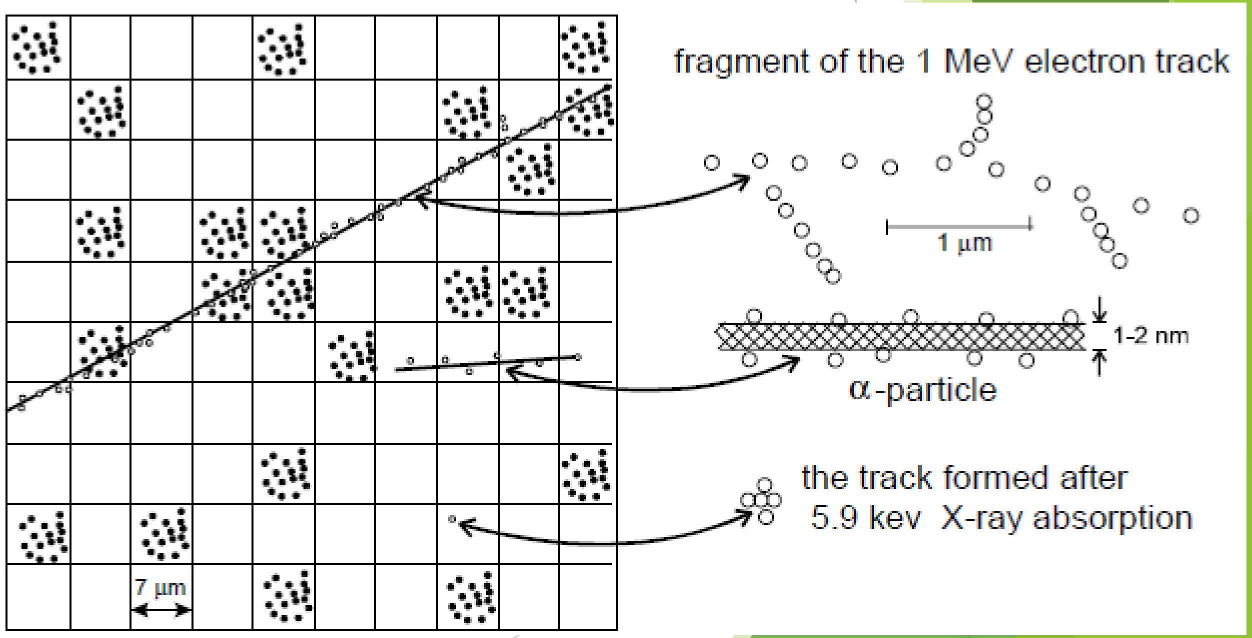
Quenching in Tl doped crystals



[1] L. N. Trefilova, et al., NIMA, vol. 486, no. 1, pp. 474–481, Jun. 2002.

[2] BRIT. J. APPL. PBYS., 1966, VOL. 17



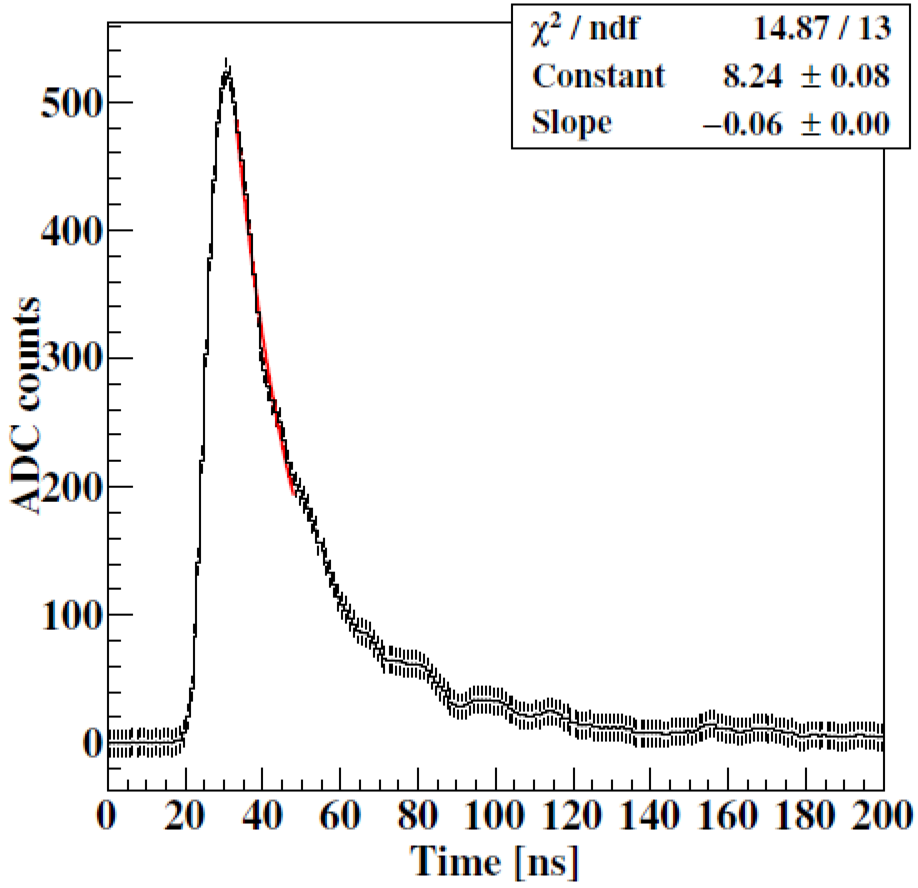
Quiz

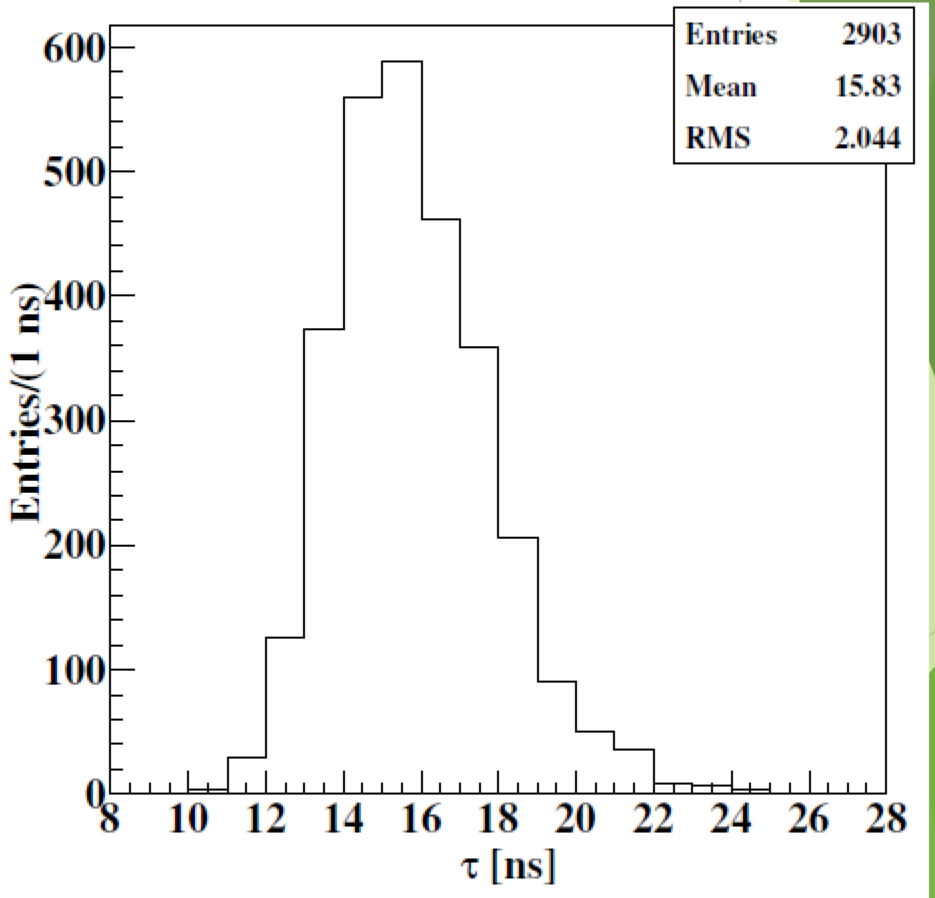
- What kind of crystals?
- Operation temperature?
- Light sensors?
- Threshold
  - Electron recoil?
  - Na recoil?
  - Cs recoil?
- Prototype
  - Mass?
  - Exposure?
- # of CEvNS?

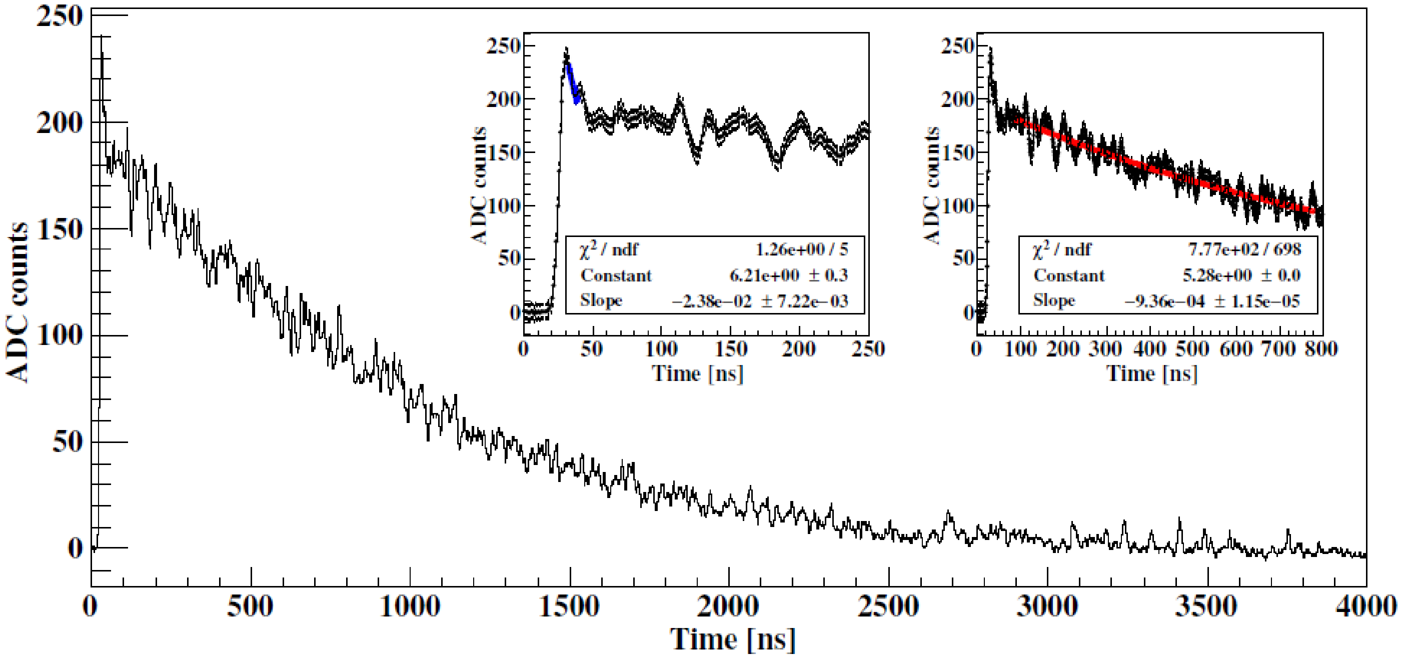
Answer

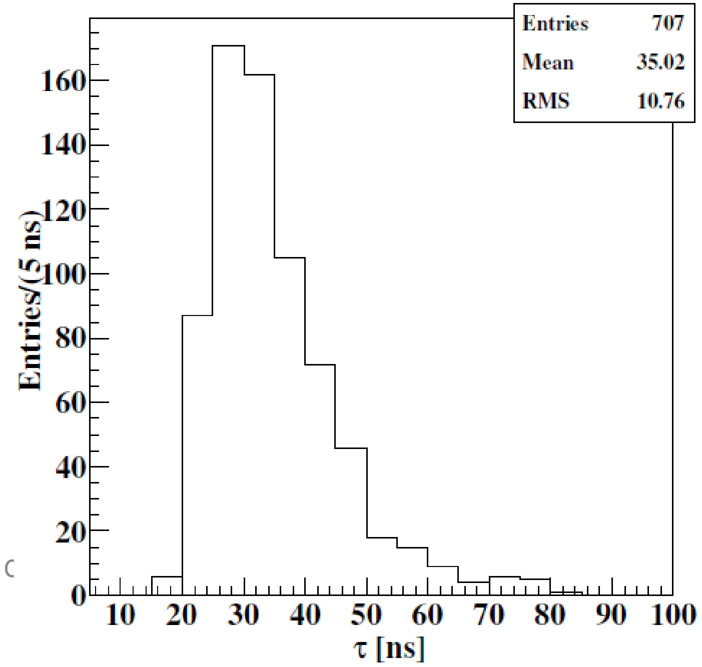
- What kind of crystals? Undoped NaI and/or CsI
- Operation temperature? 40 K (max LY, min after glow)
- Light sensors? SiPM arrays to avoid Cherenkov light
- Threshold
  - Electron recoil? ~180 eVee (80% trigger efficiency)
  - Na recoil? ~2 keVnr (80% trigger efficiency)
  - Cs recoil? ~3 keVnr (80% trigger efficiency)
- Prototype
  - Mass? 10 kg
  - Exposure? 2 years
- # of CEvNS? ~1000

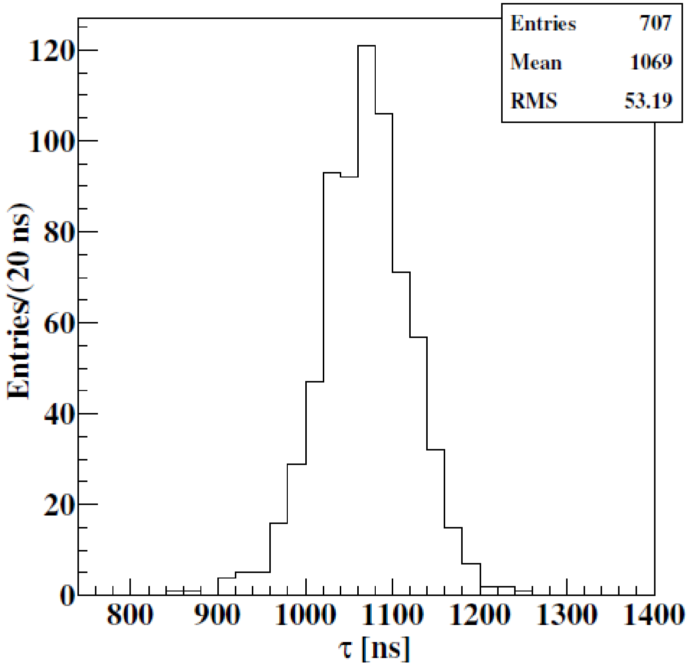
Crystal	Decay time at room temperature	Decay time at 77 K
NaI(Tl)	230 ~ 250 ns [31,32,33]	736 ns [26]
Undoped NaI	10 ns [3]	30 ns [3]
CsI(Tl)	600 ns [1]	
Undoped CsI	16 ns [34]	1 μs [1]

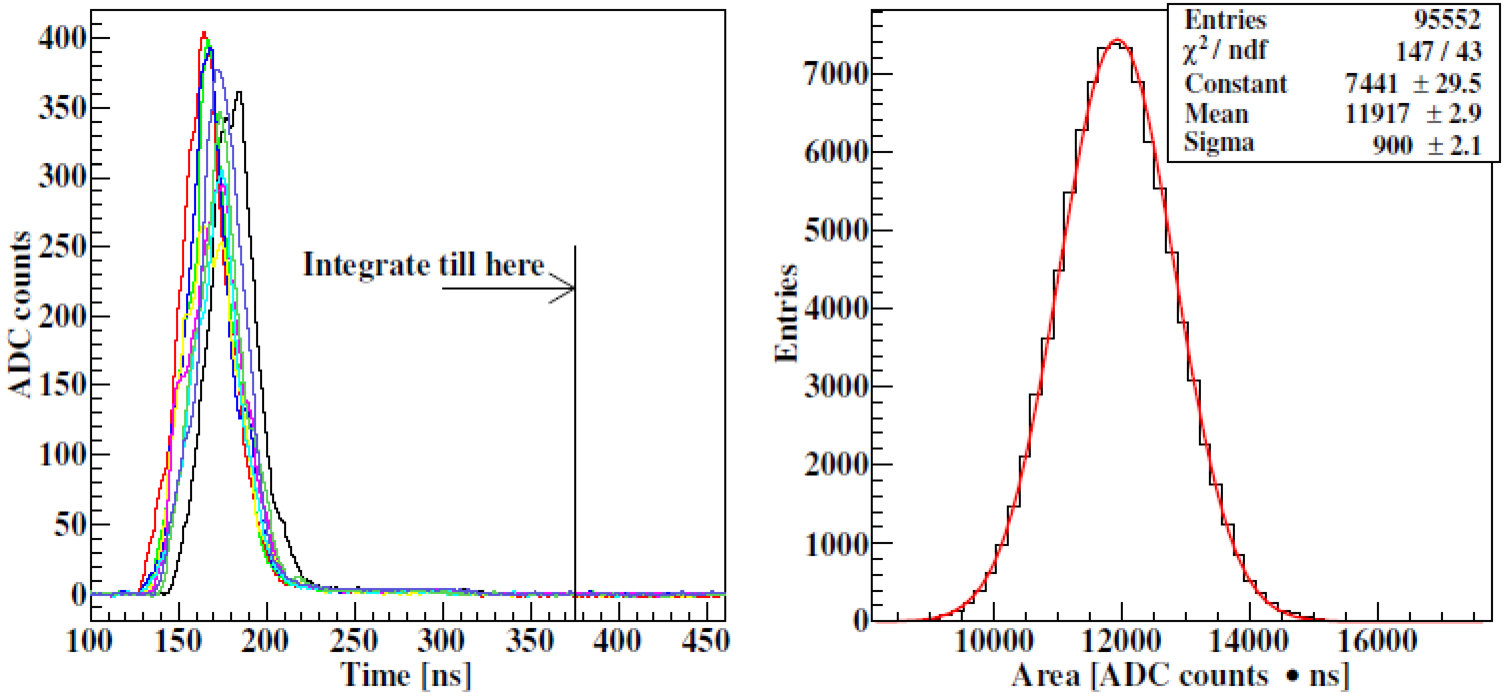


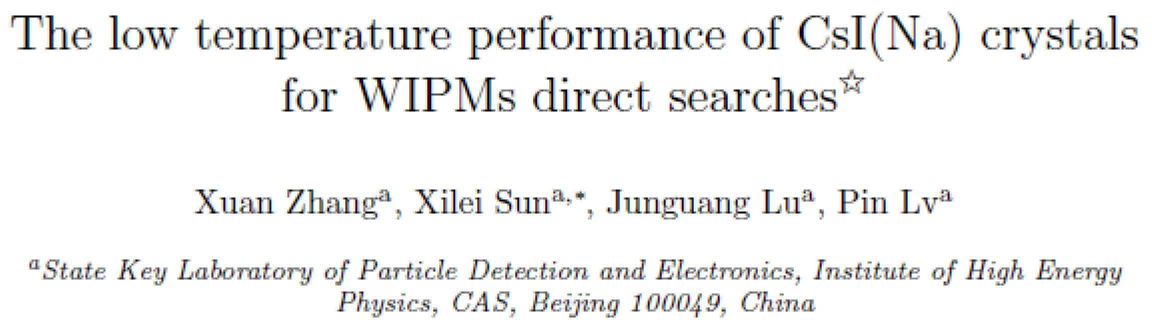



ADC counts
Time [ns]
0
50
100
150
200
250
0
500
1000
1500
2000
2500
3000
3500
4000
χ² / ndf 1.26e+00 / 5
Constant 6.21e+00 ± 0.3
Slope −2.38e−02 ± 7.22e−03
χ² / ndf 7.77e+02 / 698
Constant 5.28e+00 ± 0.0
Slope −9.36e−04 ± 1.15e−05


Entries 707
Mean 35.02
RMS 10.76
Entries/(5 ns)
τ [ns]
0
20
40
60
80
100
120
140
160
10
20
30
40
50
60
70
80
90
100


Entries 707
Mean 1069
RMS 53.19
Entries/(20 ns)
τ [ns]
0
20
40
60
80
100
120
800
900
1000
1100
1200
1300
1400


ADC counts
400
350
300
250
200
150
100
50
0
100
150
200
250
300
350
400
450
Time [ns]
Integrate till here
Entries
7000
6000
5000
4000
3000
2000
1000
0
10000
12000
14000
16000
Area [ADC counts • ns]
Entries 95552
χ^2 / ndf 147 / 43
Constant 7441 ± 29.5
Mean 11917 ± 2.9
Sigma 900 ± 2.1



The low temperature performance of CsI(Na) crystals for WIPMs direct searches☆

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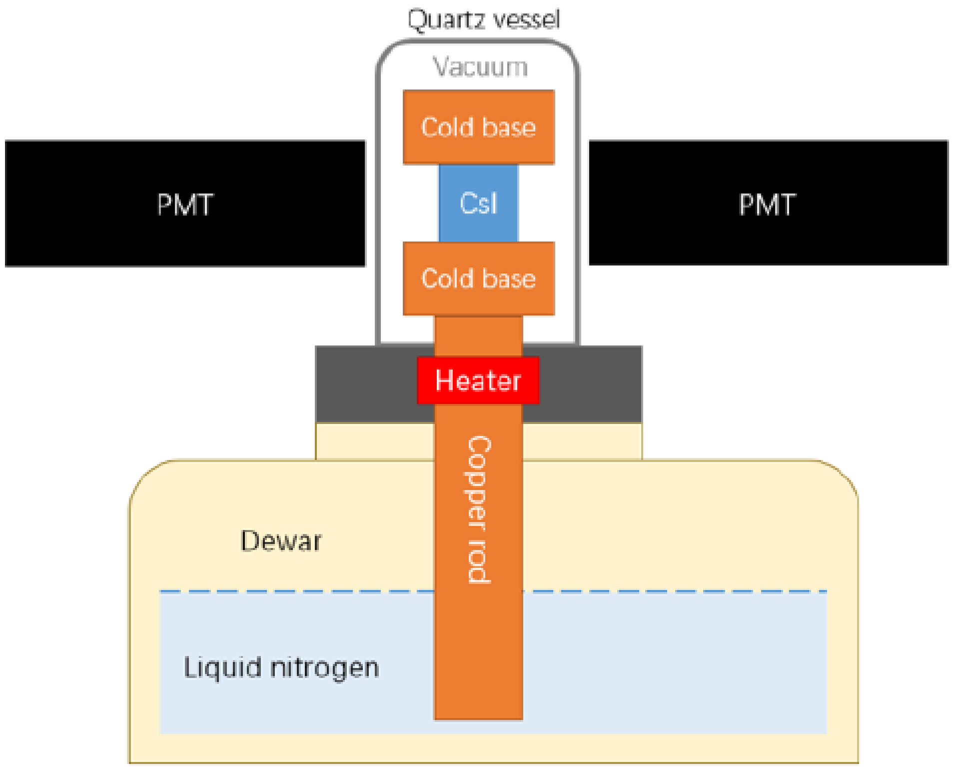
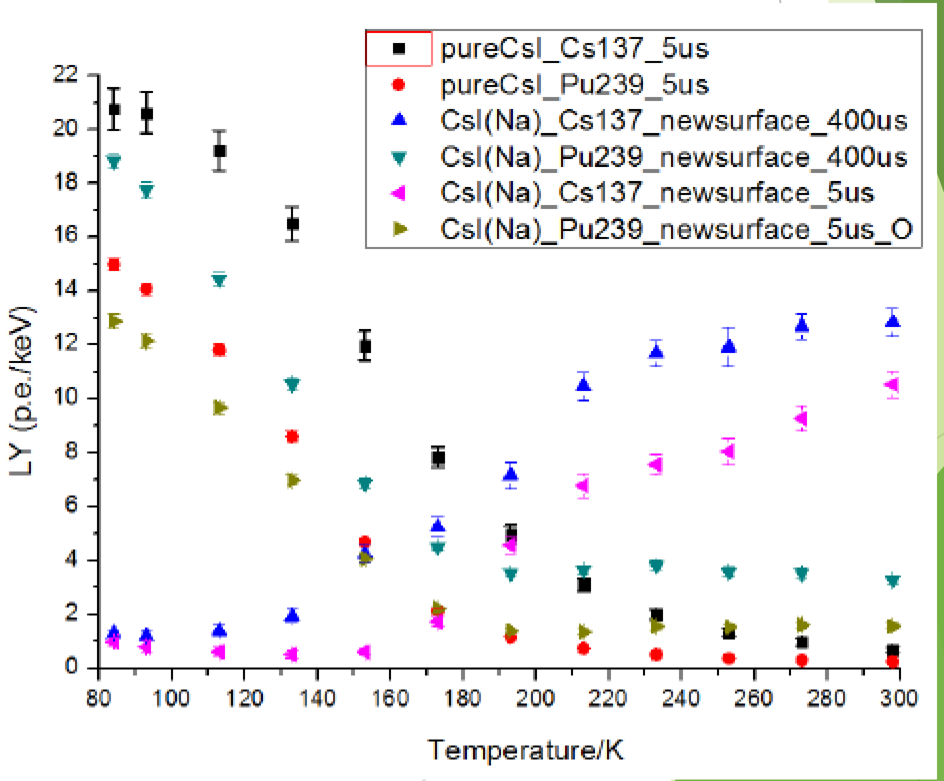
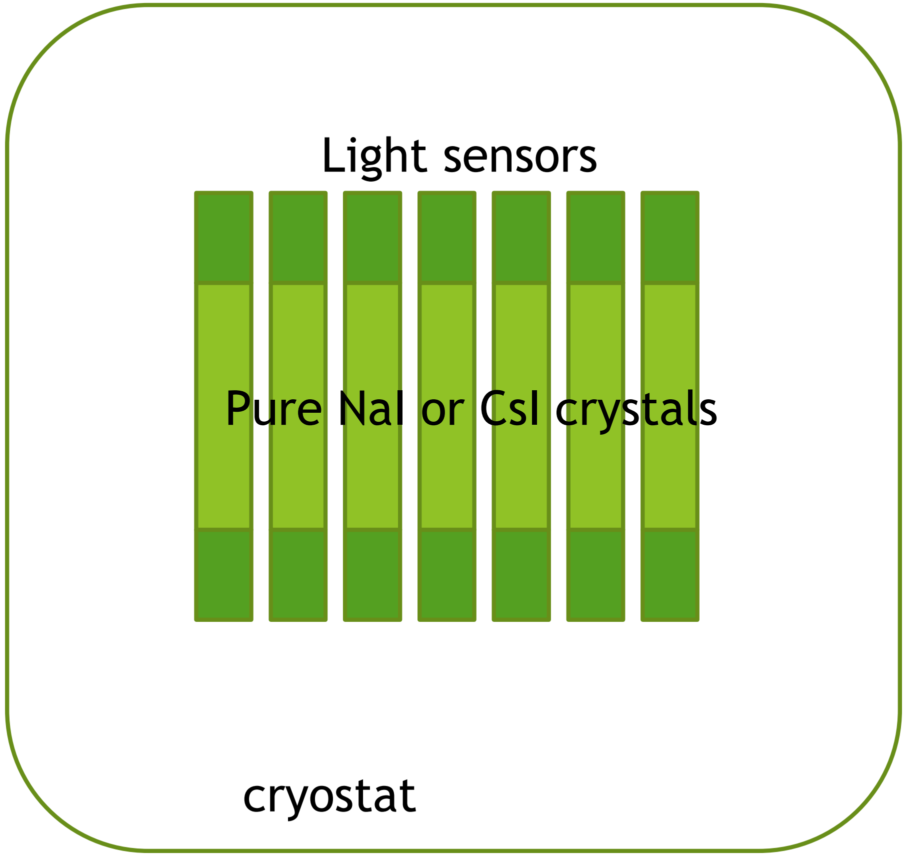
arXiv:1612.06071



APS April meeting, Light yield of pure CsI at 77 K




Light sensors
Pure NaI or CsI crystals
cryostat

Sole quenching measurement

alpha (5.3 MeV) counts only 85% of gamma (662 keV)

[1] E. Hahn and J. Rossel, “Scintillations des particules dans Csl,” Helv. Phys. Acta, vol. 26, p. 271, 1953.
[2] B. Hahn and J. Rossel, “Scintillations dans Csl et spectrométrie,” Helv. Phys. Acta, vol. 26, p. 803, 1953.