# R&D and physics potential of Mini neutrino detectors

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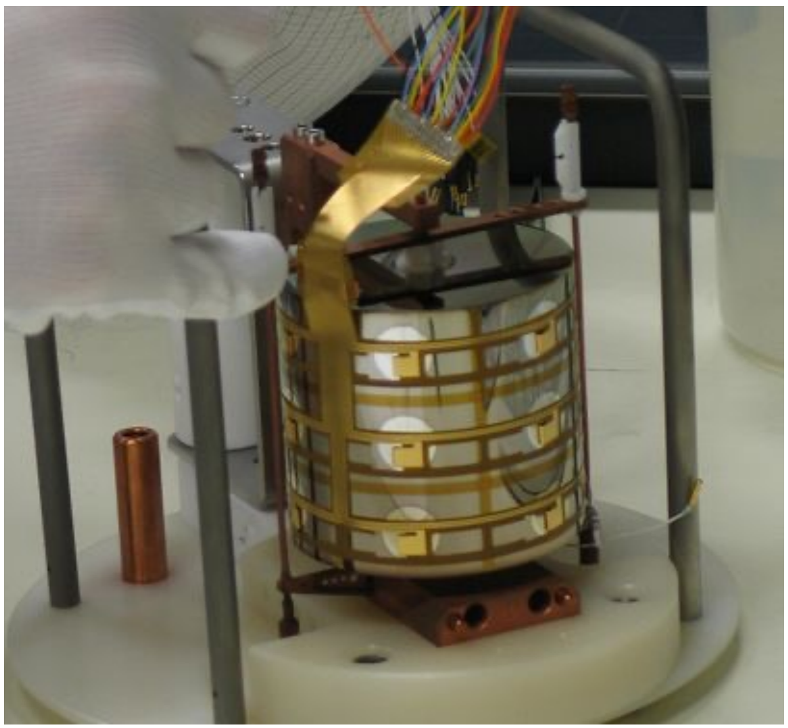
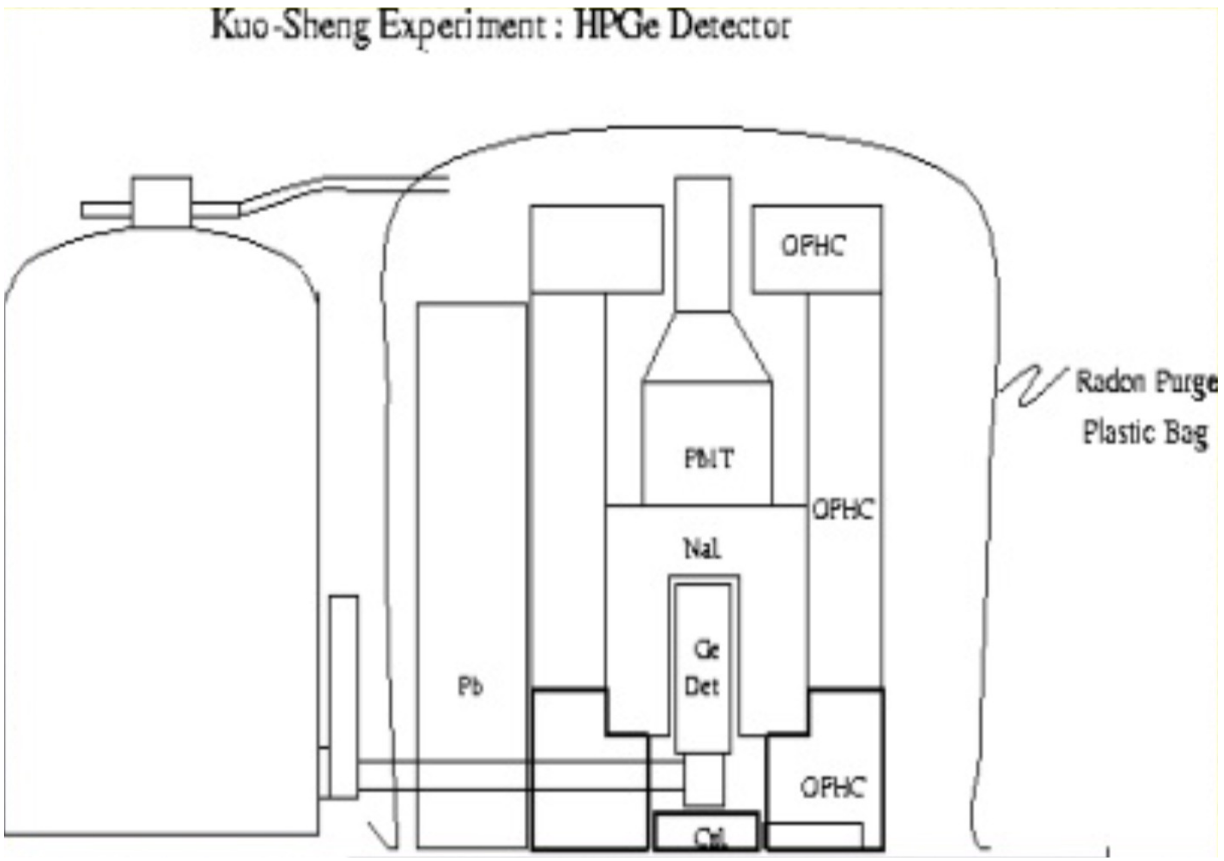
June 28, 2023

# Germanium detector




Cryogenic PMTs

# Texono



Kuo-Sheng Experiment : HPGe Detector
OFHC
PMT
OFHC
NaI
Ge
Det
Pb
OFHC
Radon Purge
Plastic Bag

member.ipmu.jp/masaki.yamashita/index.html

**Masaki Yamashita / 山下 雅樹** About Publications Talks Blog Posts

## Masaki Yamashita

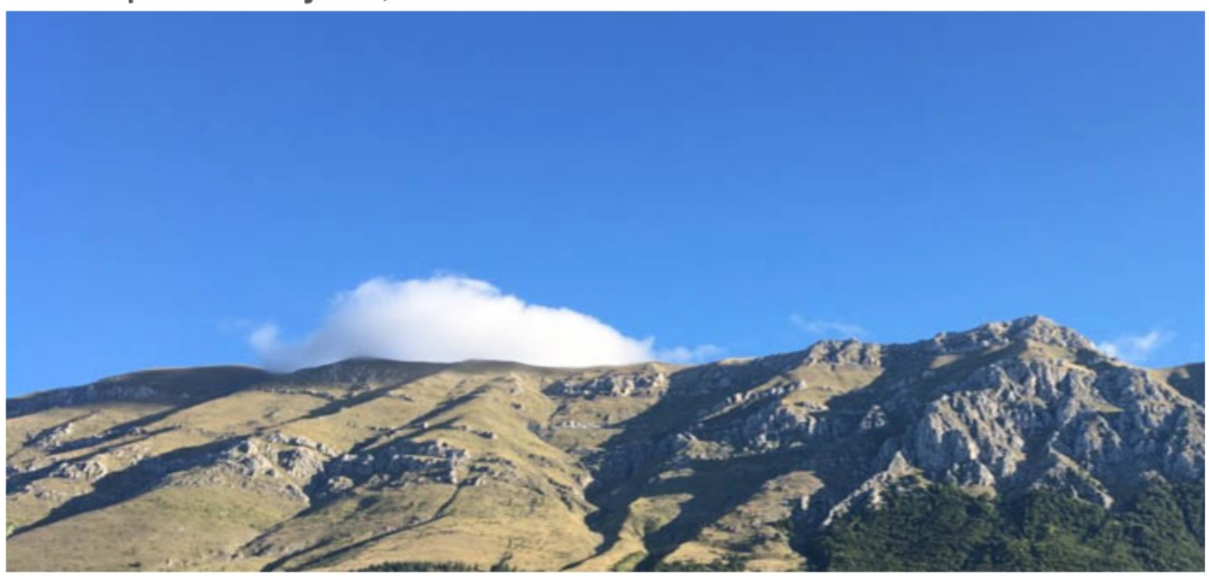
Project Associate Professor(特任准教授)

Kavli IPMU

The University of Tokyo

# Welcome to Masaki Yamashita's Page

Last Update May 10, 2023



(Gran Sasso, Italy)

# History of studies of pure NaI/CsI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… *ation*

… *liquid nitrogen temperatures*, Nucl. Instrum. Meth. **A 537** (2005) 357.

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J. Bonanomi and J. R
Acta 25 (1952) 725.

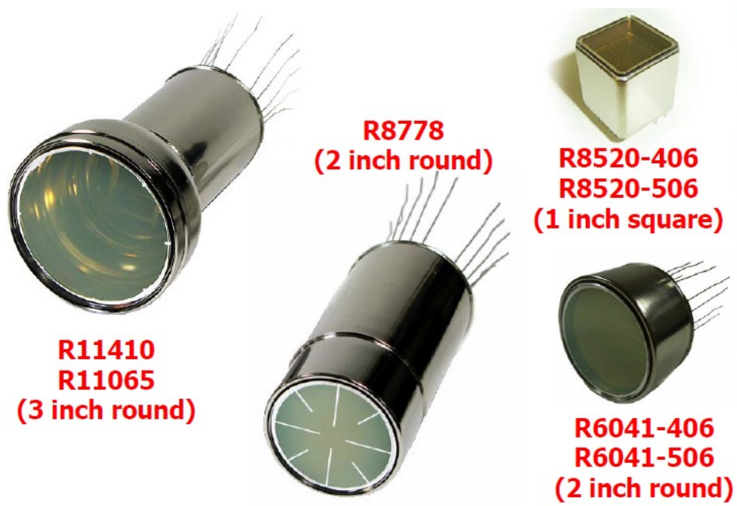

Inconsistent results on absolute light yield,
the best are about twice higher than those of doped ones at RT

# Light readout devices

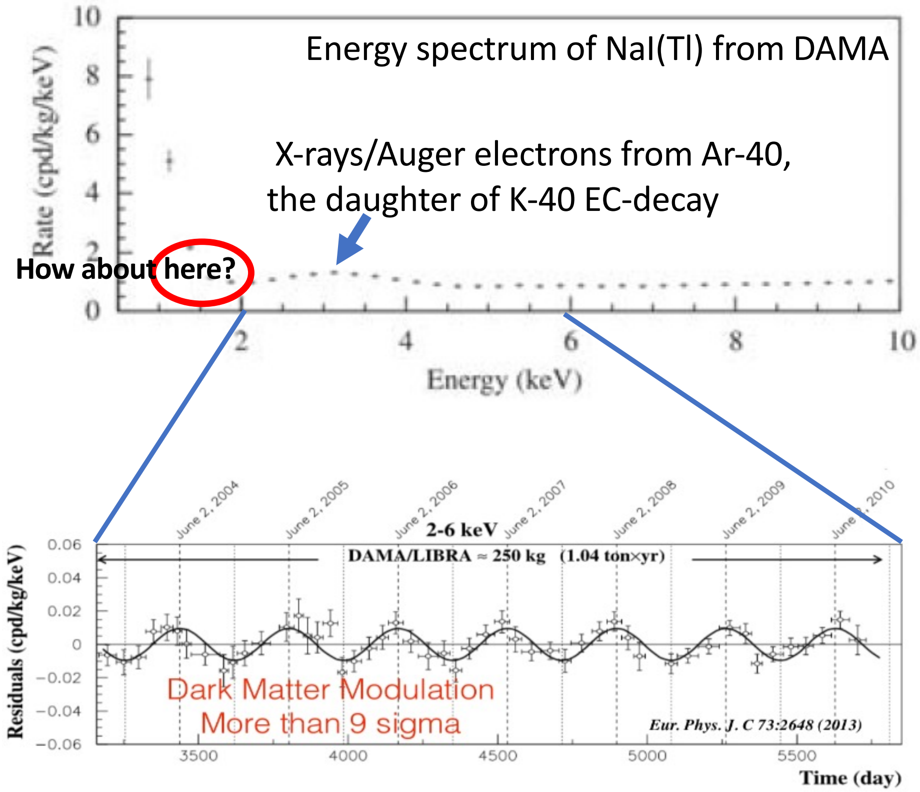
Light loss in complicated readout system cancels out the gain from light yield ☹

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

PMTs working at 77 K (Hotta, DM2014)




# DAMA




NaI/CsI based effort:

- COSINE
  - DM-ICE
  - KIMS
- ANAIS
- SABRE
- etc.

Focus:

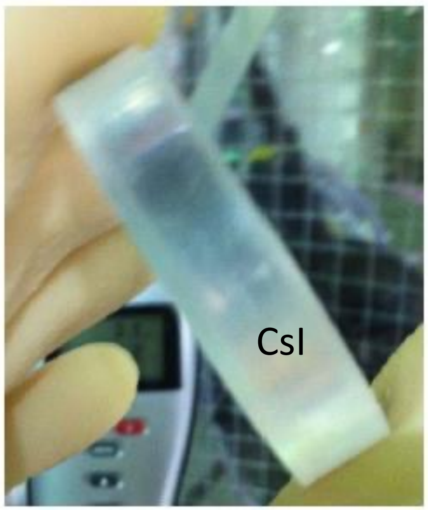
- Location
- Purification
- Active shield
- PMT
- Light collection

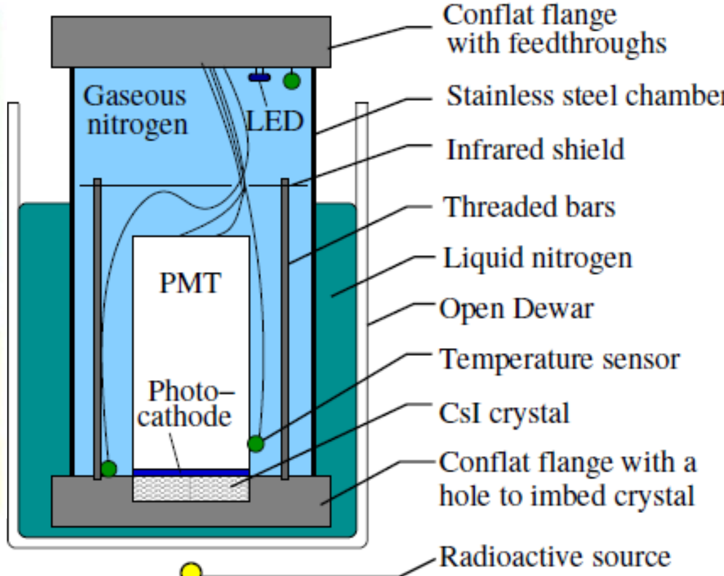
**Table 1:** Scintillation wavelength $\lambda$ and decay time $\tau$ of various crystals.

| Crystal | $\tau$ at RT [ns] | $\tau$ at 77 K [ns] | $\lambda$ at RT [nm] | $\lambda$ 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] |

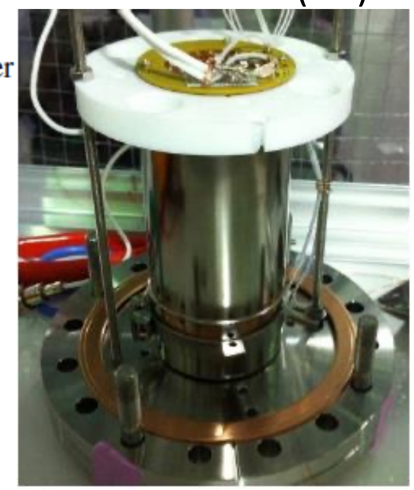
NaI is highly hygroscopic and mechanically fragile due to the existence of cleavage planes in the crystal, and it can crack given a sudden mechanical or thermal shock. This demands a sophisticated

# Proof-of-concept measurement

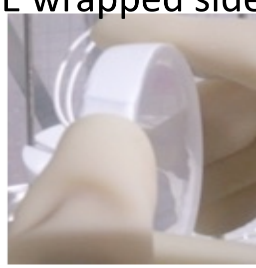


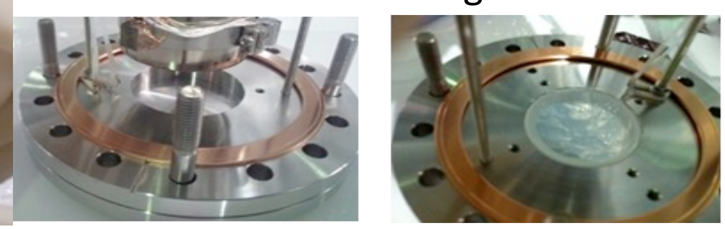

R8778MODAY (AR)



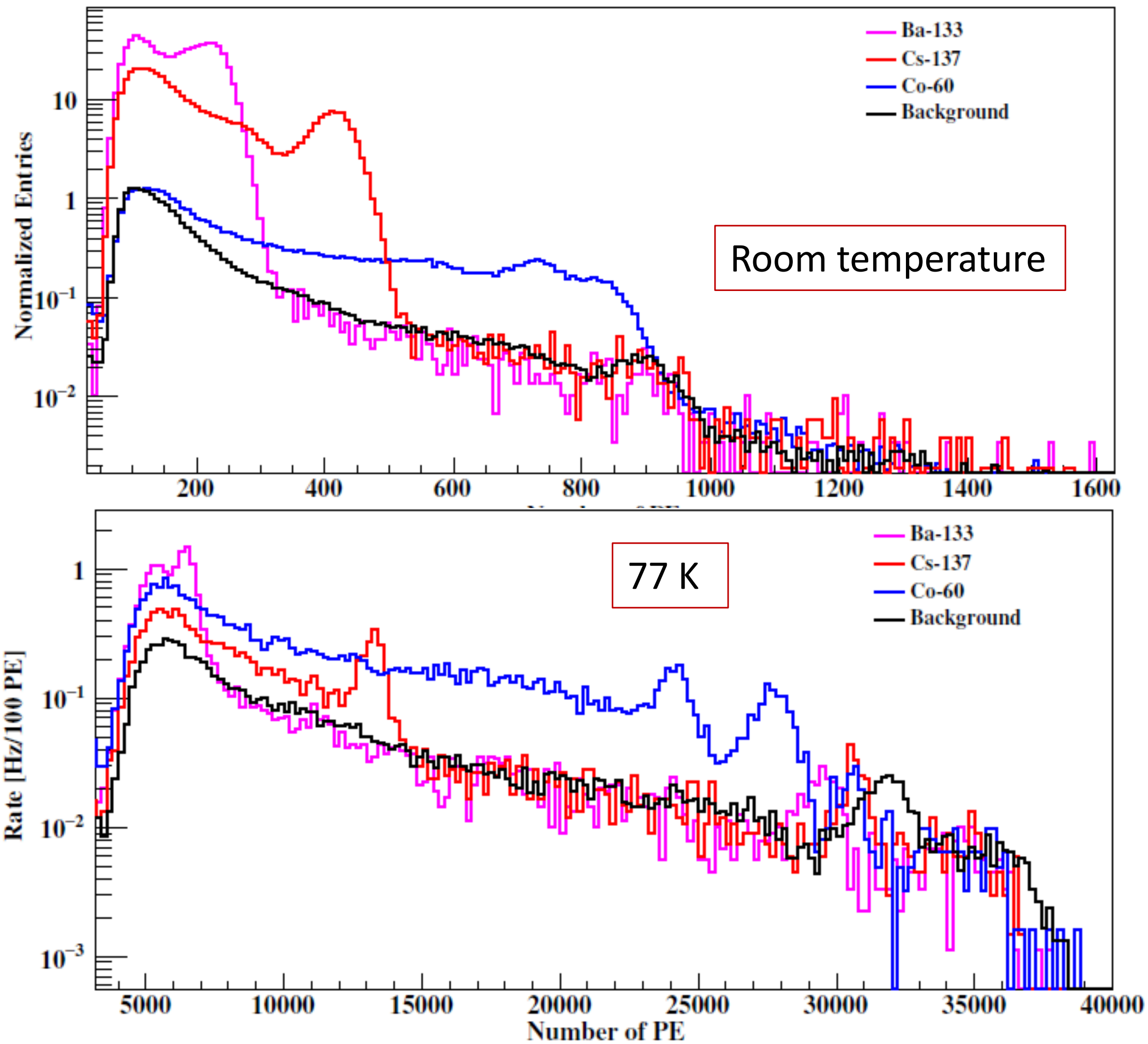

PTFE wrapped side surface



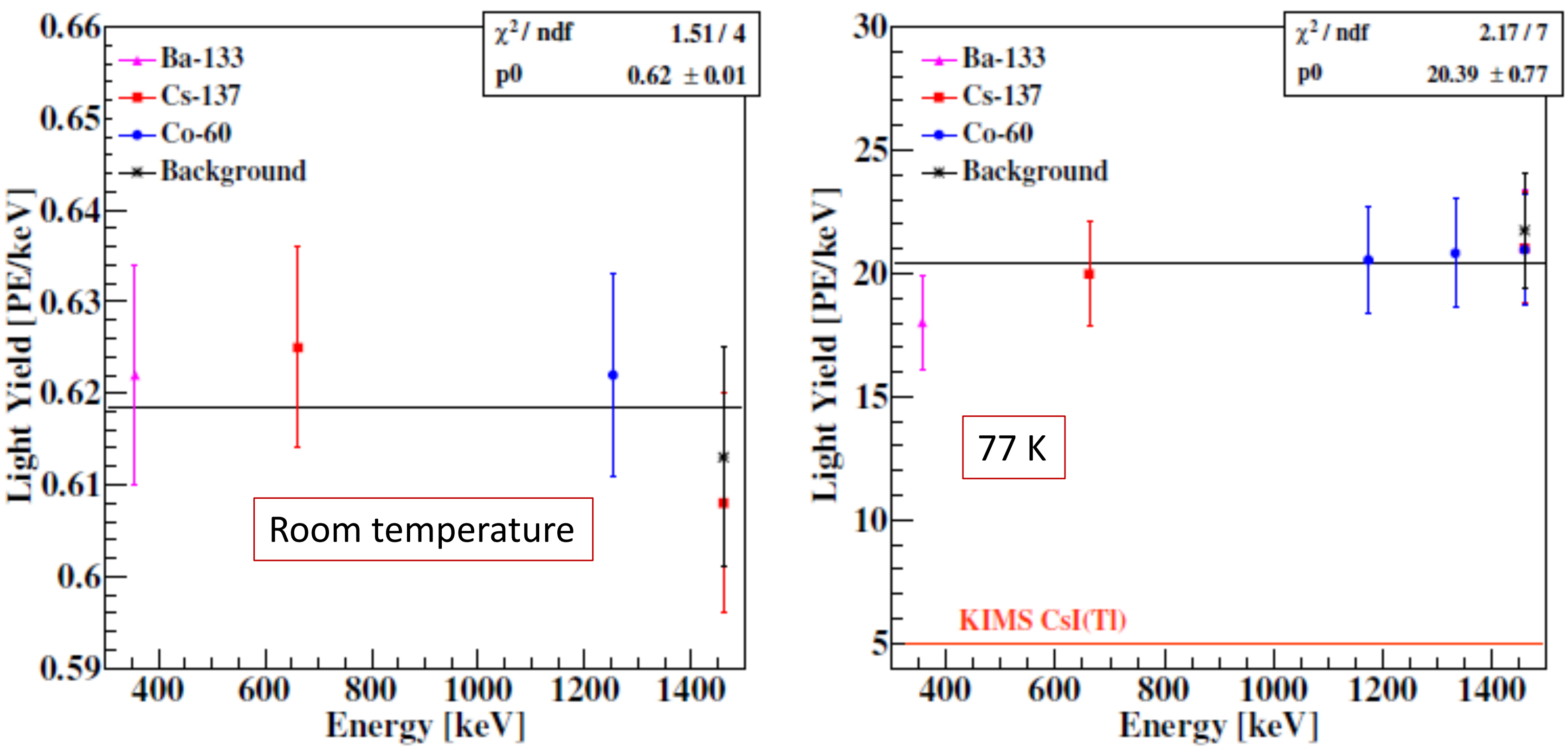
Bottom CF flange



# Energy calibration of a pure CsI crystal



Light yield [PE/keV] = Peak position [number of PE]/Peak energy [keV]

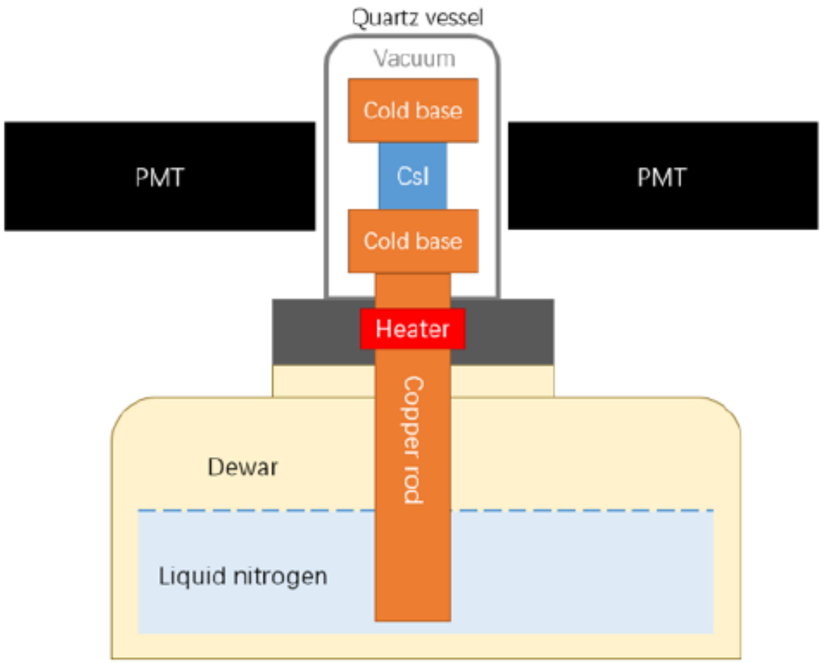


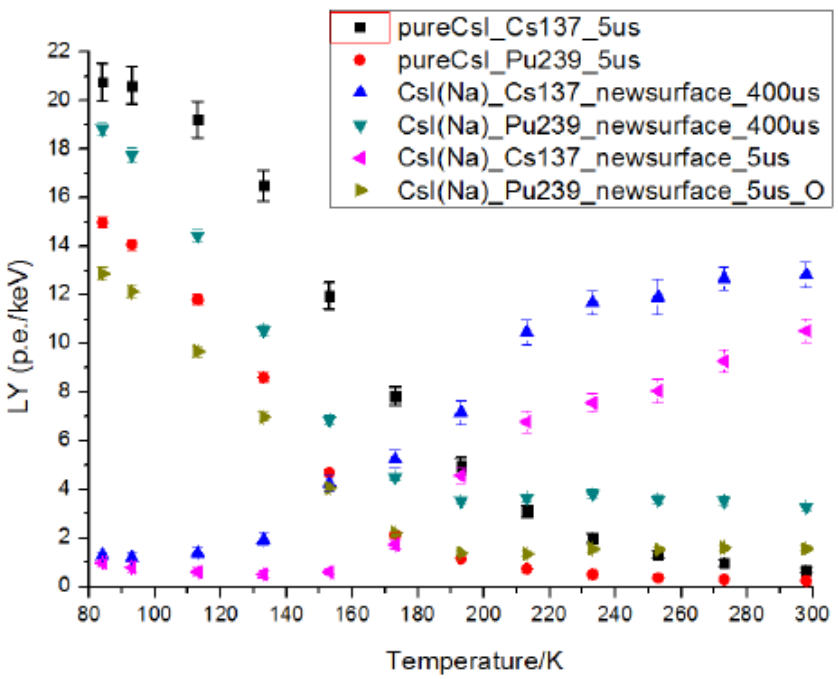
The low temperature performance of CsI(Na) crystals for WIPMs direct searches☆

Xuan Zhang[a], Xilei Sun[a,*], Junguang Lu[a], Pin Lv[a]

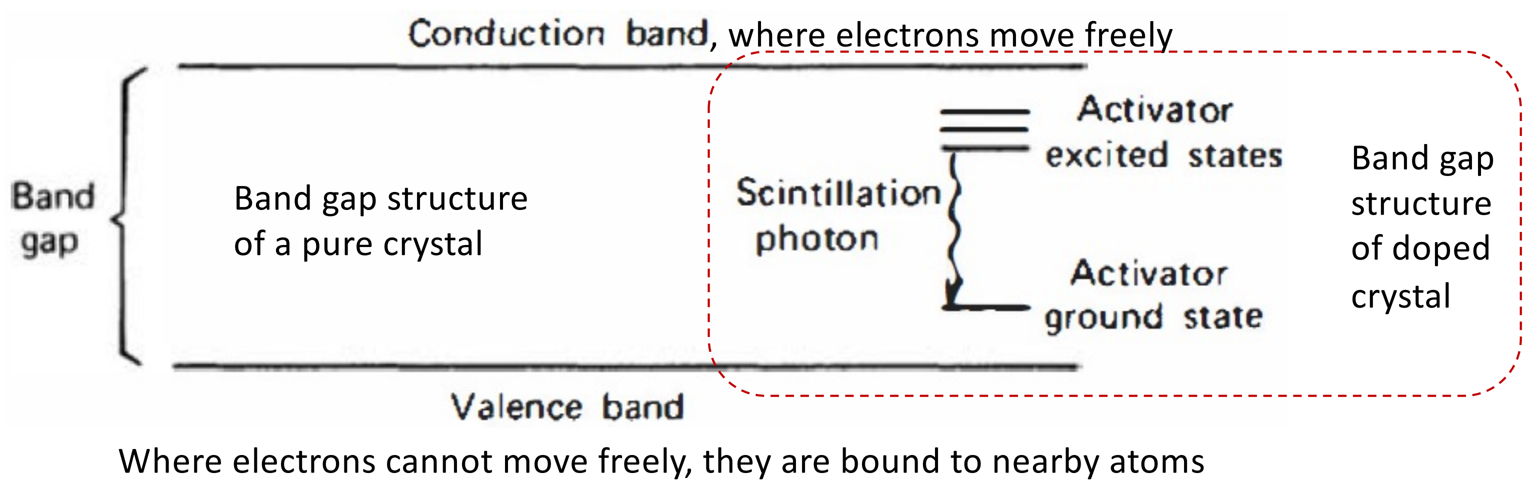
[a] State Key Laboratory of Particle Detection and Electronics, Institute of High Energy Physics, CAS, Beijing 100049, China

arXiv:1612.06071

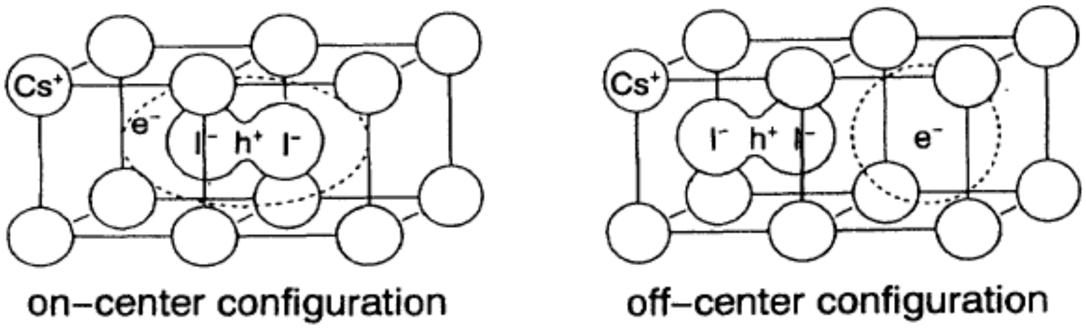


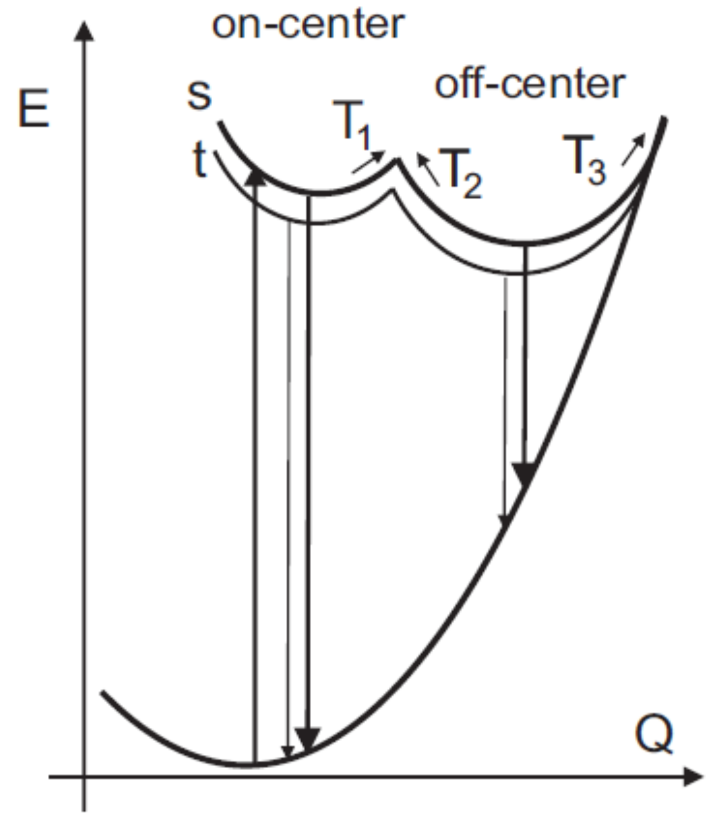



# Scintillation mechanism in inorganic crystals



# Self-trapped excitons



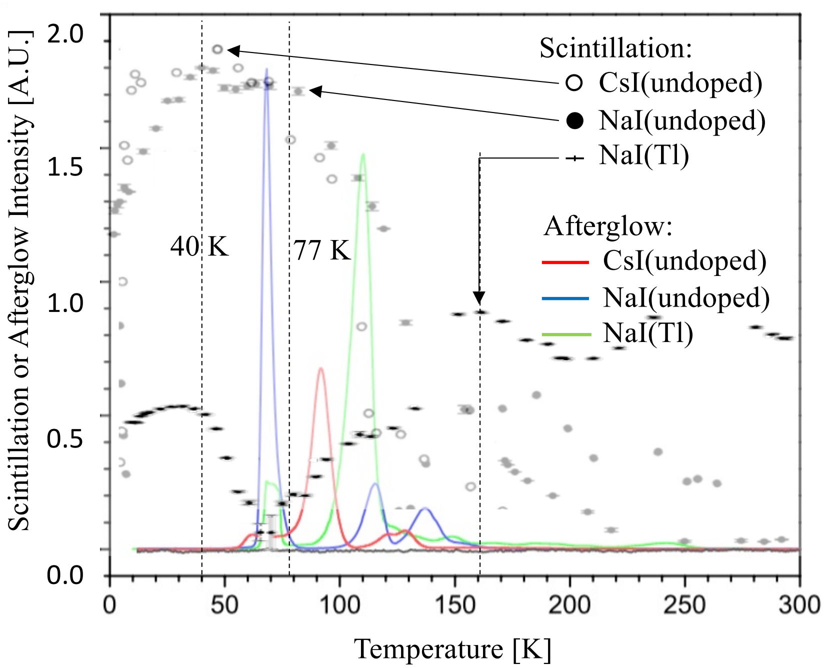




Doi:10.1103/PhysRevB.51.2167

Doi: 10.1002/pssb.201451464

# Operation temperature

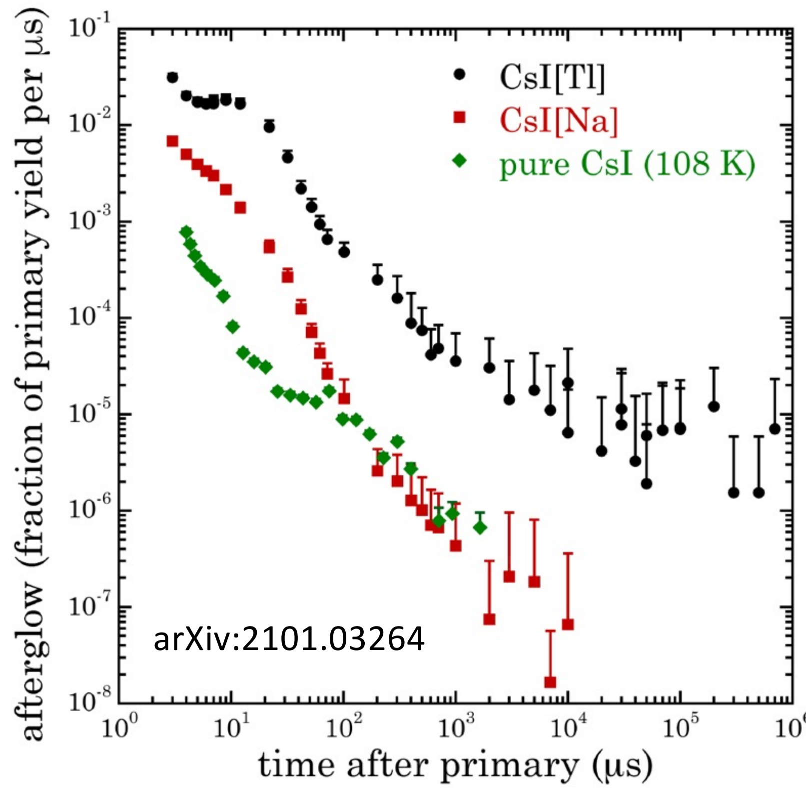
- NaI(undoped) & CsI(undoped) VS NaI(Tl) and CsI(Na)
- 40 K
  - Minimal after glow rate
  - Maximal light yield

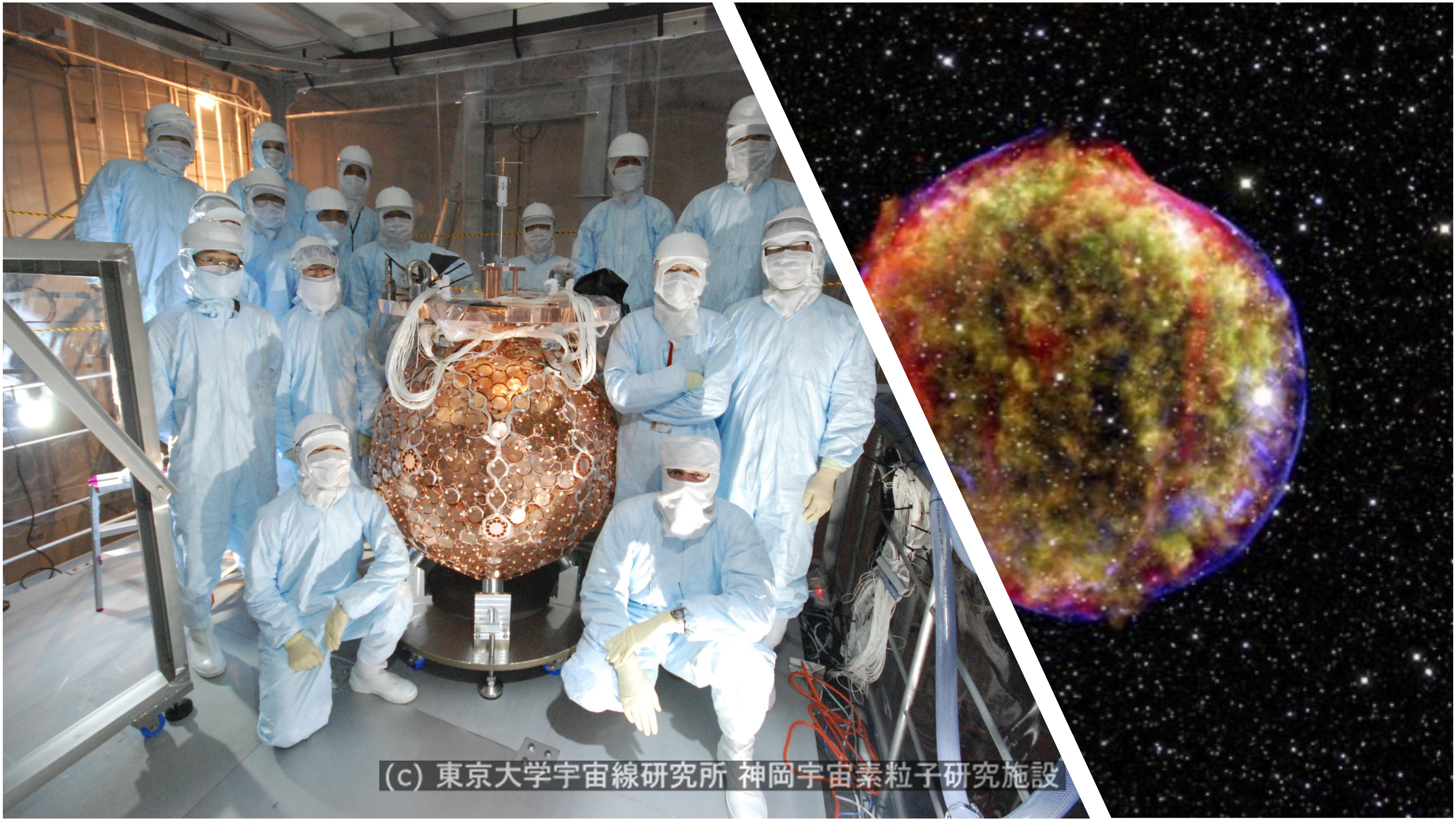



Eur. Phys. J. C (2012) 72:2061

Phys. Rev. B 5 (1995) 2167

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




(c) 東京大学宇宙線研究所 神岡宇宙素粒子研究施設

https://cds.cern.ch/record/248487/files/ppe-93-065.pdf

# $\nu e$ scatterings

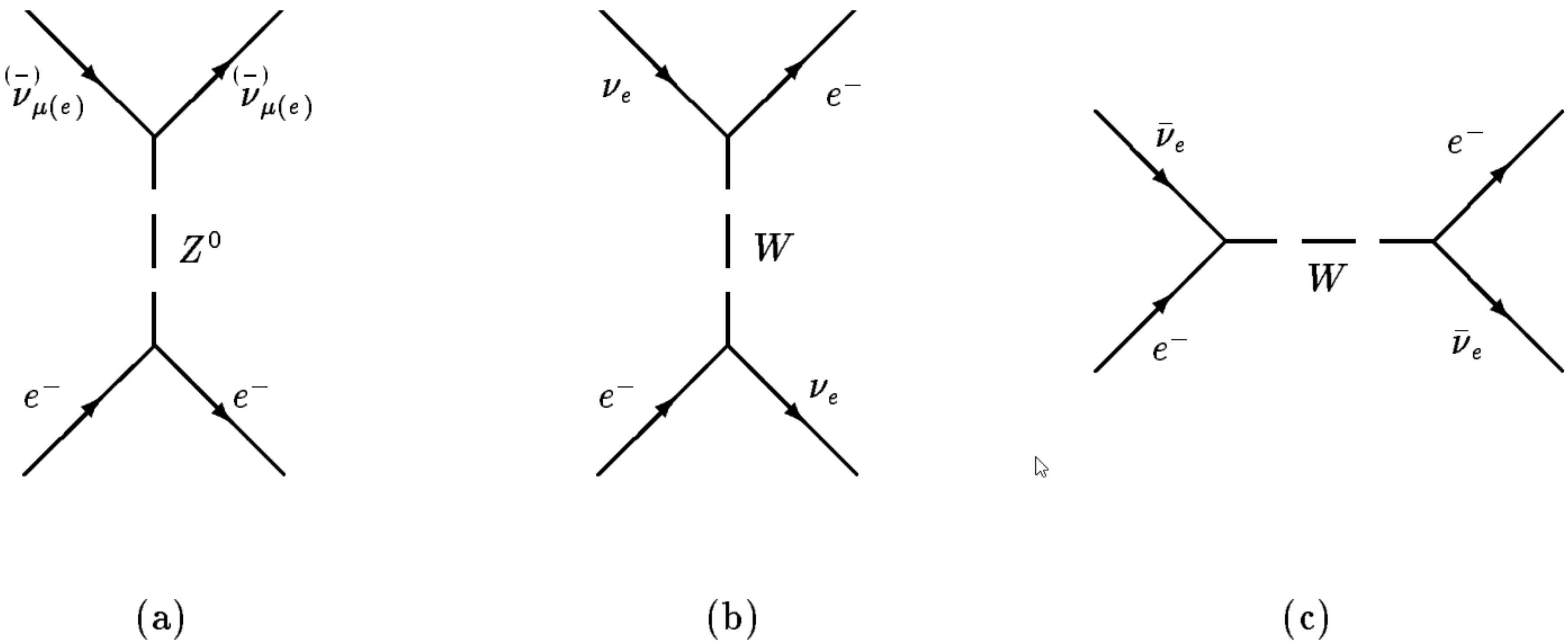
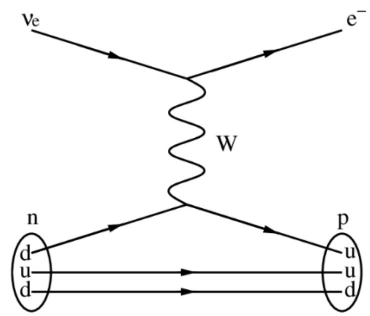



Figure 1: *Feynman diagrams for the processes of neutral current (NC) $\nu e$-scattering (a), and charged current (CC) $\nu_e e$-scattering via the exchange of a W-Boson (b,c).*

# $\nu N$ scatterings

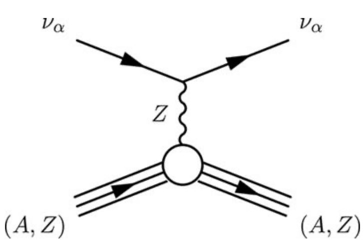
$\nu_e + {}^A_Z X \rightarrow e^- + {}^{\;A}_{Z+1}X^*$



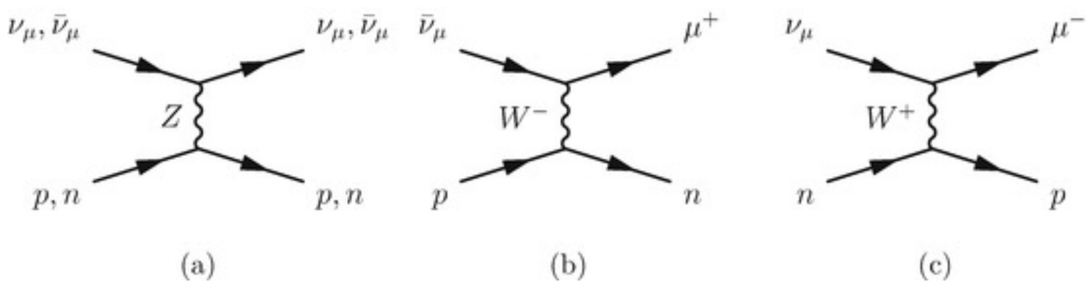

De-excitation after scattering: $X^* \rightarrow$

- ${}_{Z-1}X_N$ + **p**
- ${}_{Z}X_{N-1}$ + $x$**n**
- ${}_{Z}X_N$ + $\gamma$
- ${}_{Z-2}X_{N-2}$ + $\alpha$
- **Fission**

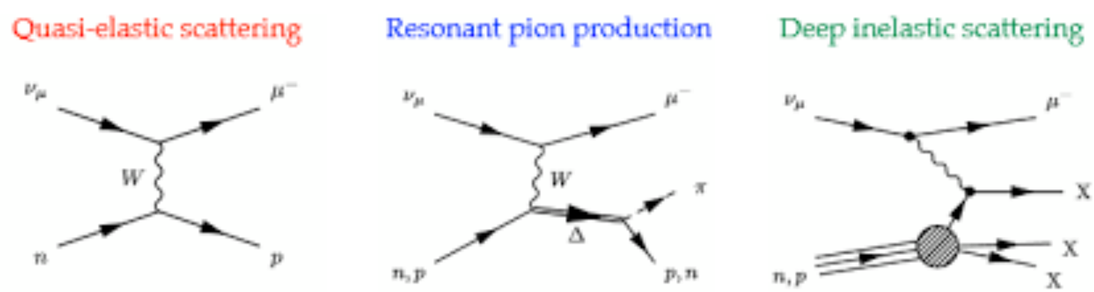
http://mtv.engin.umich.edu/wp-content/uploads/sites/431/2020/06/VRS-0609-1320-Johnson.pdf



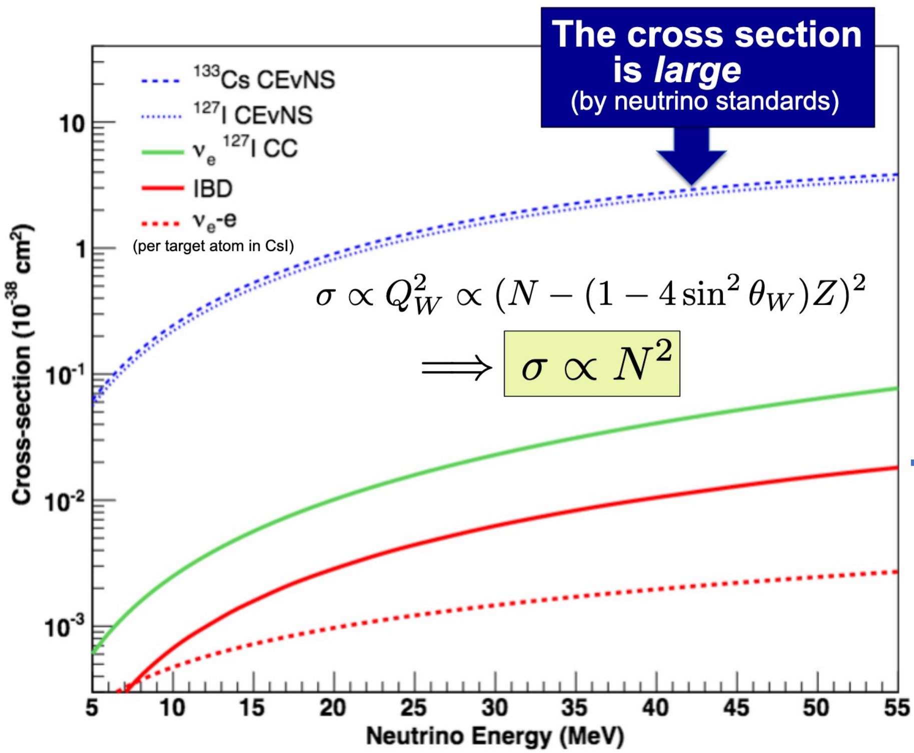

Elastic scattering at low energy (<~10 MeV)




Quasi-elastic or inelastic scatterings at higher energies

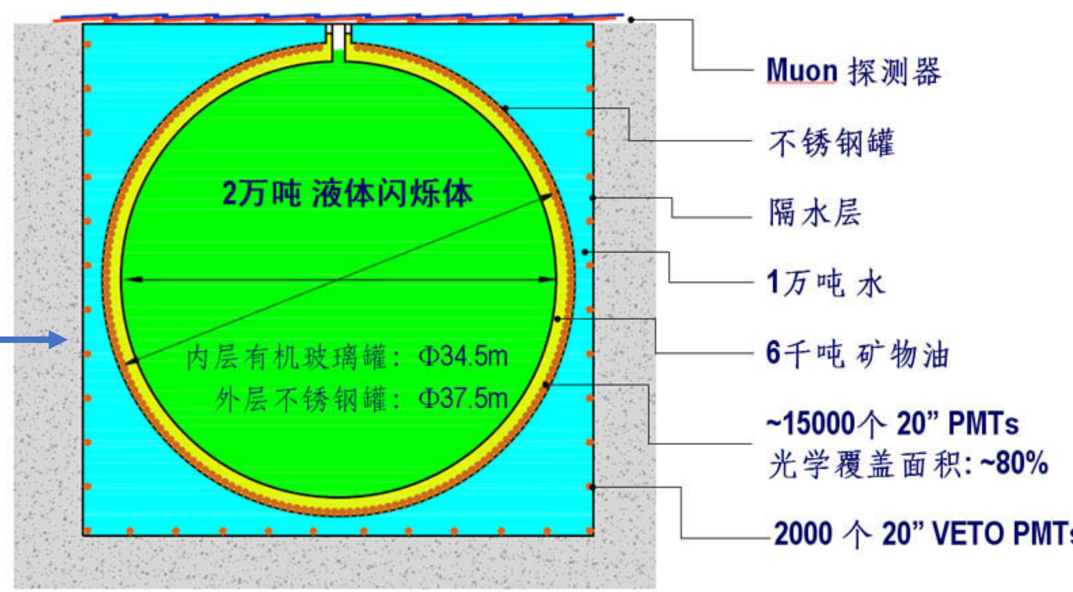


# Cross section of CEvNS




K. Scholberg, Lomonosov, 2021

江门中微子实验

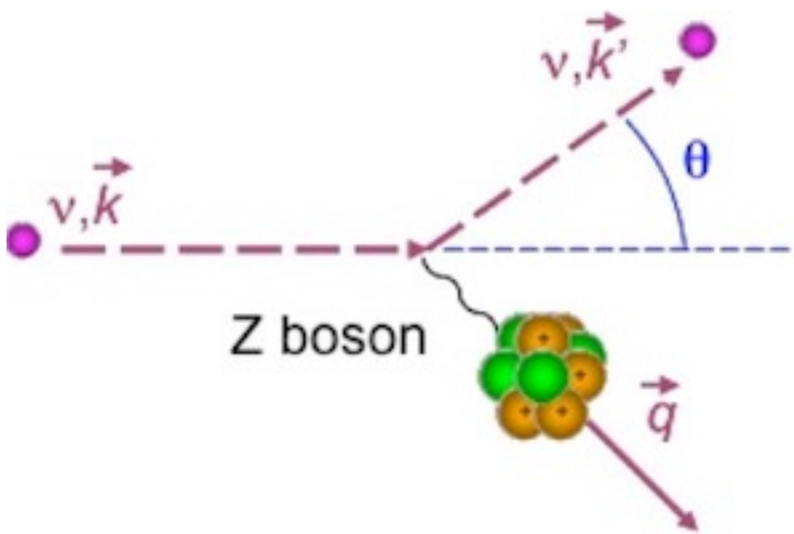


PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

# Coherent effects of a weak neutral current

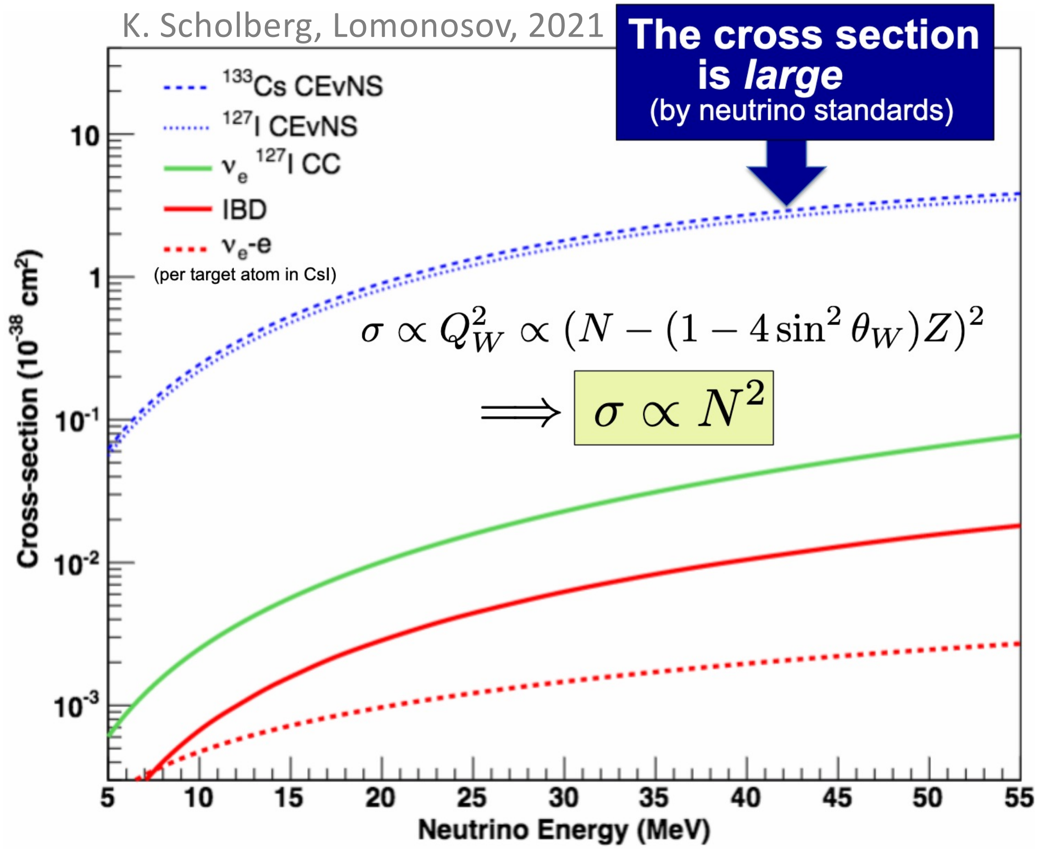
Daniel Z. Freedman†
*National Accelerator Laboratory, Batavia, Illinois 60510*
*and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790*

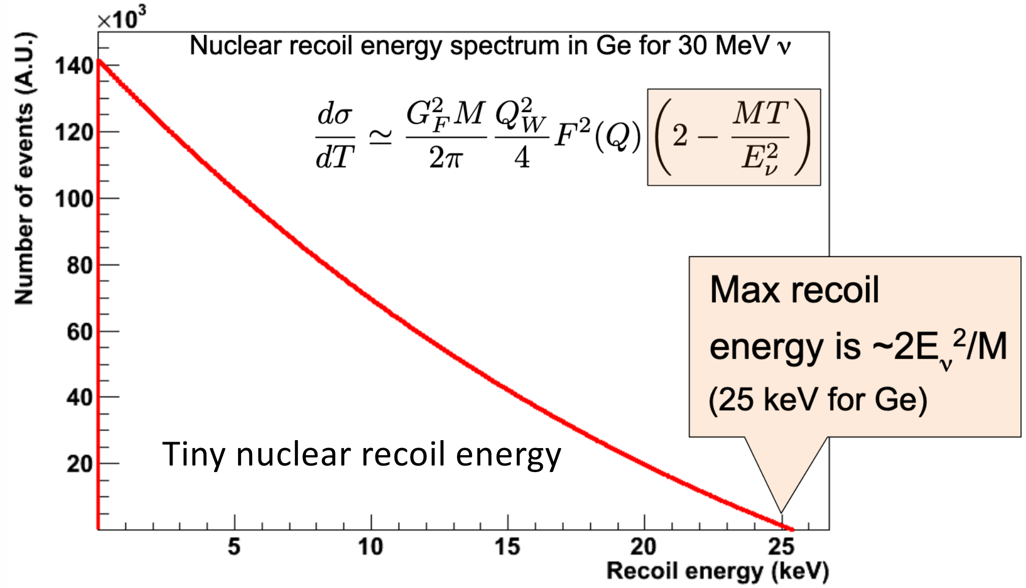
(Received 15 October 1973; revised manuscript received 19 November 1973)




# Good and bad

K. Scholberg, Lomonosov, 2021



# Detectability of galactic supernova neutrinos coherently scattered on xenon nuclei in XMASS

K. Abe[a,d], K. Hiraide[a,d], K. Ichimura[a,d], Y. Kishimoto[a,d], K. Kobayashi[a,d], M. Kobayashi[a], S. Moriyama[a,d], K. Nakagawa[a], M. Nakahata[a,d], T. Norita[a], H. Ogawa[a,d], H. Sekiya[a,d], O. Takachio[a], A. Takeda[a,d], M. Yamashita[a,d], B.S. Yang[a,d], N.Y. Kim[b], Y.D. Kim[b], S. Tasaka[c,1], J. Liu[d,2], K. Martens[d], Y. Suzuki[d], R. Fujita[f], K. Hosokawa[f], K. Miuchi[f], N. Oka[f], Y. Onishi[f], Y. Takeuchi[f,d], Y.H. Kim[g,b], J.S. Lee[g], K.B. Lee[g], M.K. Lee[g], Y. Fukuda[h], Y. Itow[i,e], R. Kegasa[i], K. Kobayashi[i], K. Masuda[i], H. Takiya[i], H. Uchida[i], K. Nishijima[j], K. Fujii[k], I. Murayama[k], S. Nakamura[k], XMASS Collaboration[2,*]

Astroparticle Physics 89 (2017) 51–56

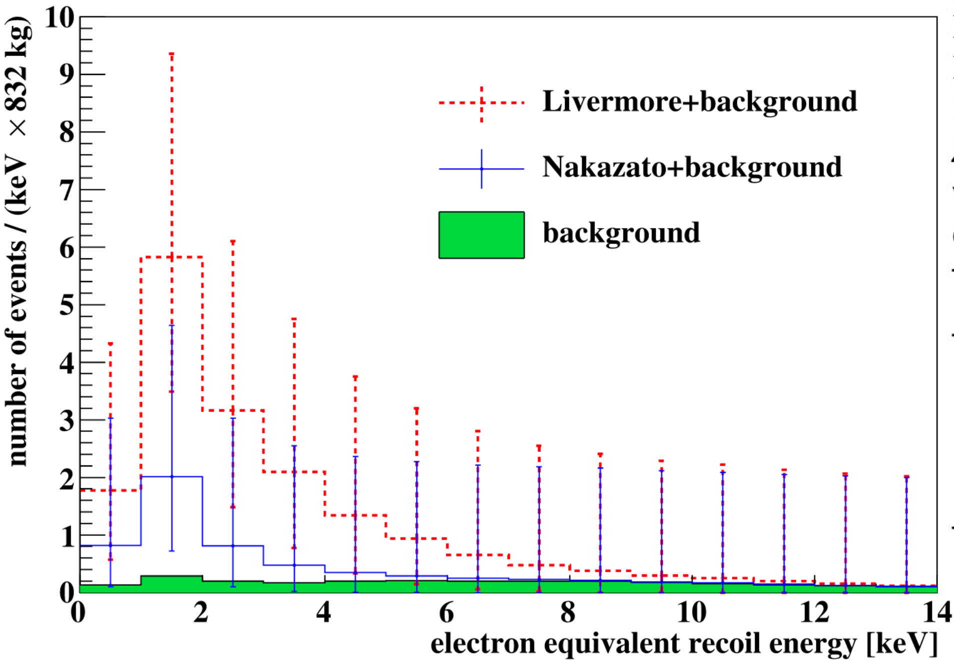



**Table 2**
Number of observable supernova events in XMASS. The weakest Nakazato model is the one with $M_p = 20$ $M_\odot$, $Z = 0.02$ and $t_{rev} = 100$ ms. The brightest Nakazato model is the one with $M_p = 30$ $M_\odot$, $Z = 0.02$ and $t_{rev} = 300$ ms. The black-hole-forming model is the one with $M_p = 30$ $M_\odot$, $Z = 0.004$. Neutrino energy spectra used in the calculation are all integrated from core collapse till about 18 s later.

| Supernova model | $d = 10$ kpc | $d = 196$ pc |
|---|---|---|
| Livermore | 15.2 | $3.9 \times 10^4$ |
| Nakazato (weakest) | 3.5 | $0.9 \times 10^4$ |
| Nakazato (brightest) | 8.7 | $2.3 \times 10^4$ |
| Nakazato (black hole) | 21.1 | $5.5 \times 10^4$ |


Science
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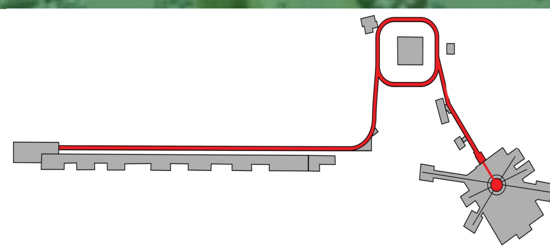
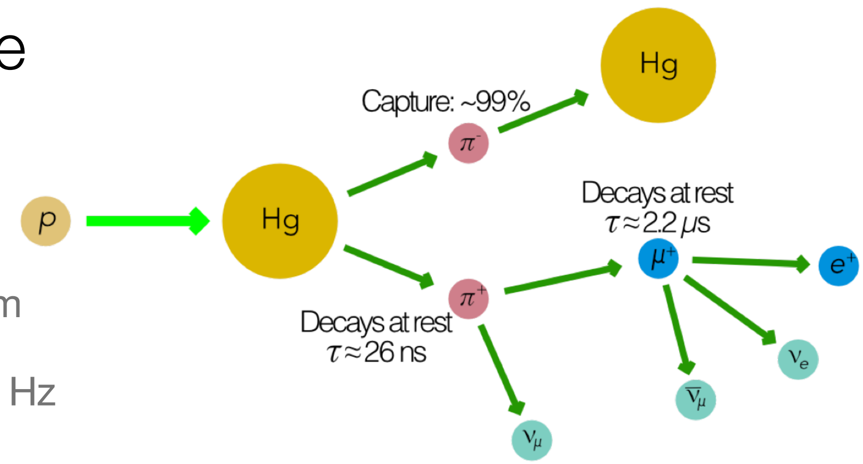
A compact detector spies
neutrinos scattering from nuclei
pp. 1098 & 1123


Proton beam energy: 0.9-1.3 GeV
Total power: 0.9-1.4 MW
Pulse duration: 380 ns FWHM
Repetition rate: 60 Hz

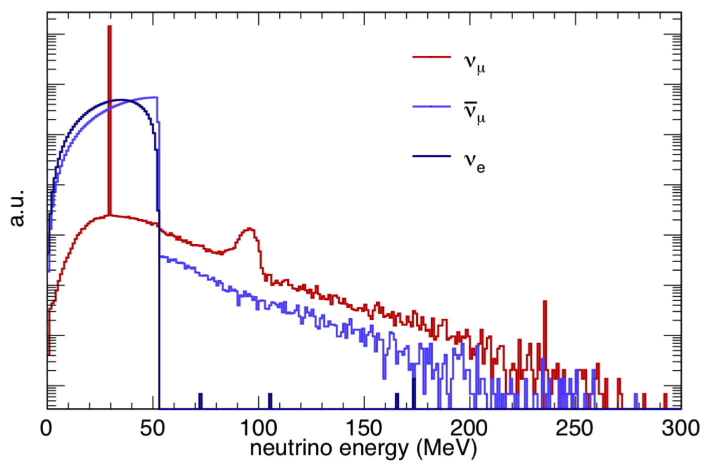


# The Spallation Neutron Source

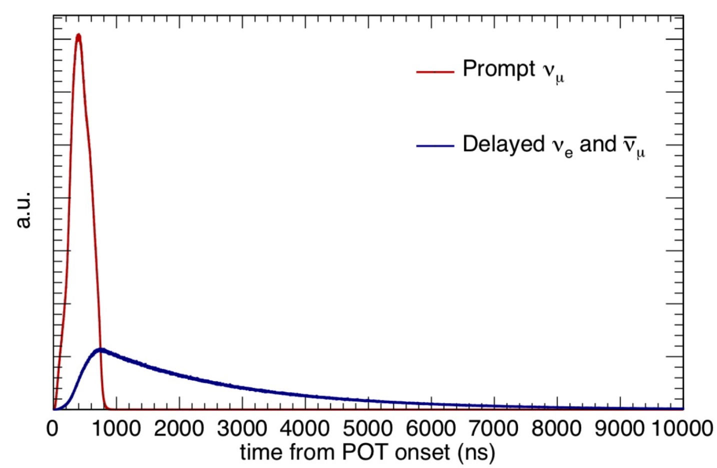
- Pion Decay-at-Rest Neutrino Source
- $\nu$ flux $4.3 \times 10^{7}$ $\nu$ cm$^{-2}$ s$^{-1}$ at 20 m
- Pulsed: 800 ns full-width at 60 Hz



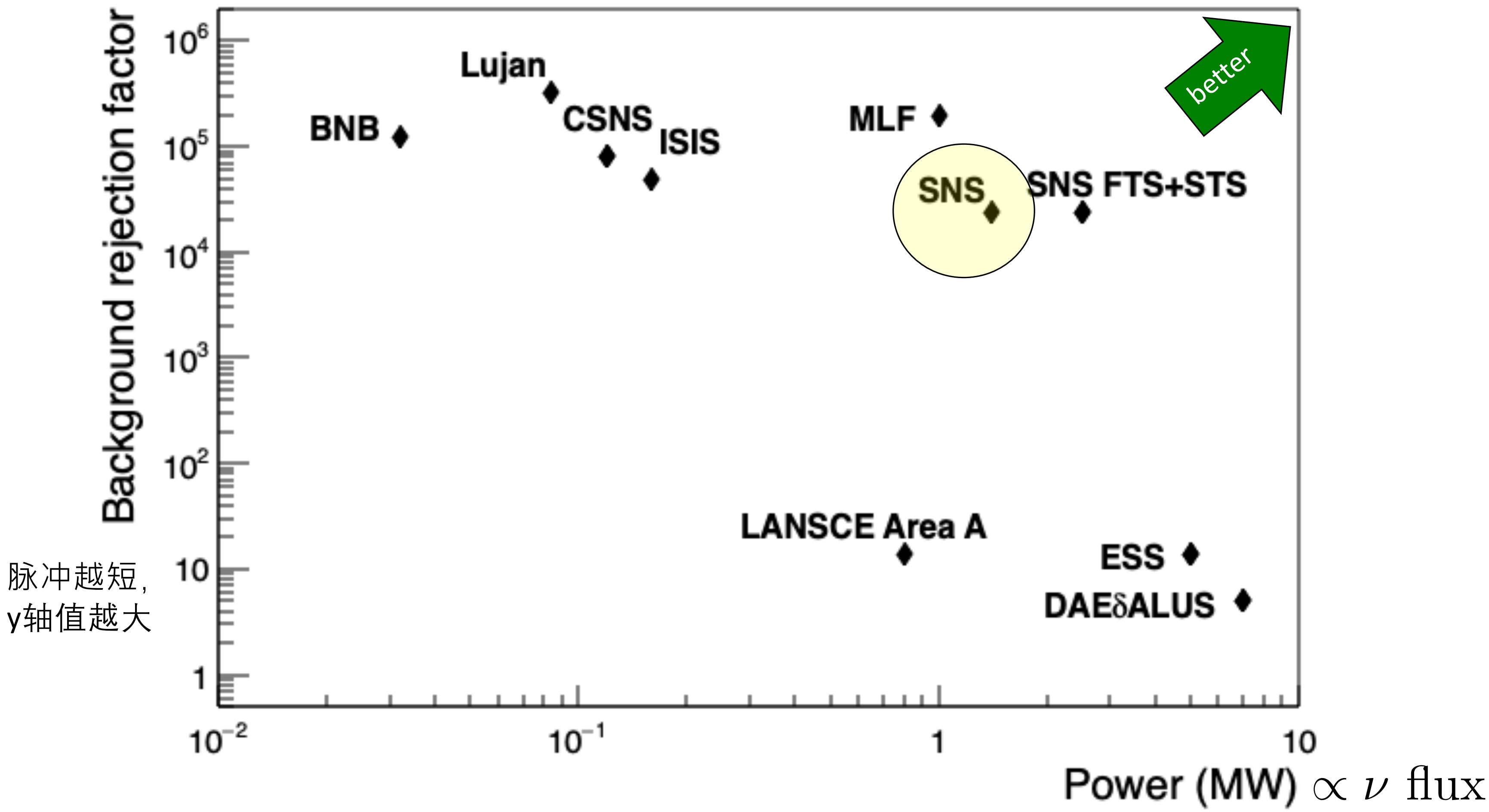

**<1% contamination from non-CEvNS scatters**



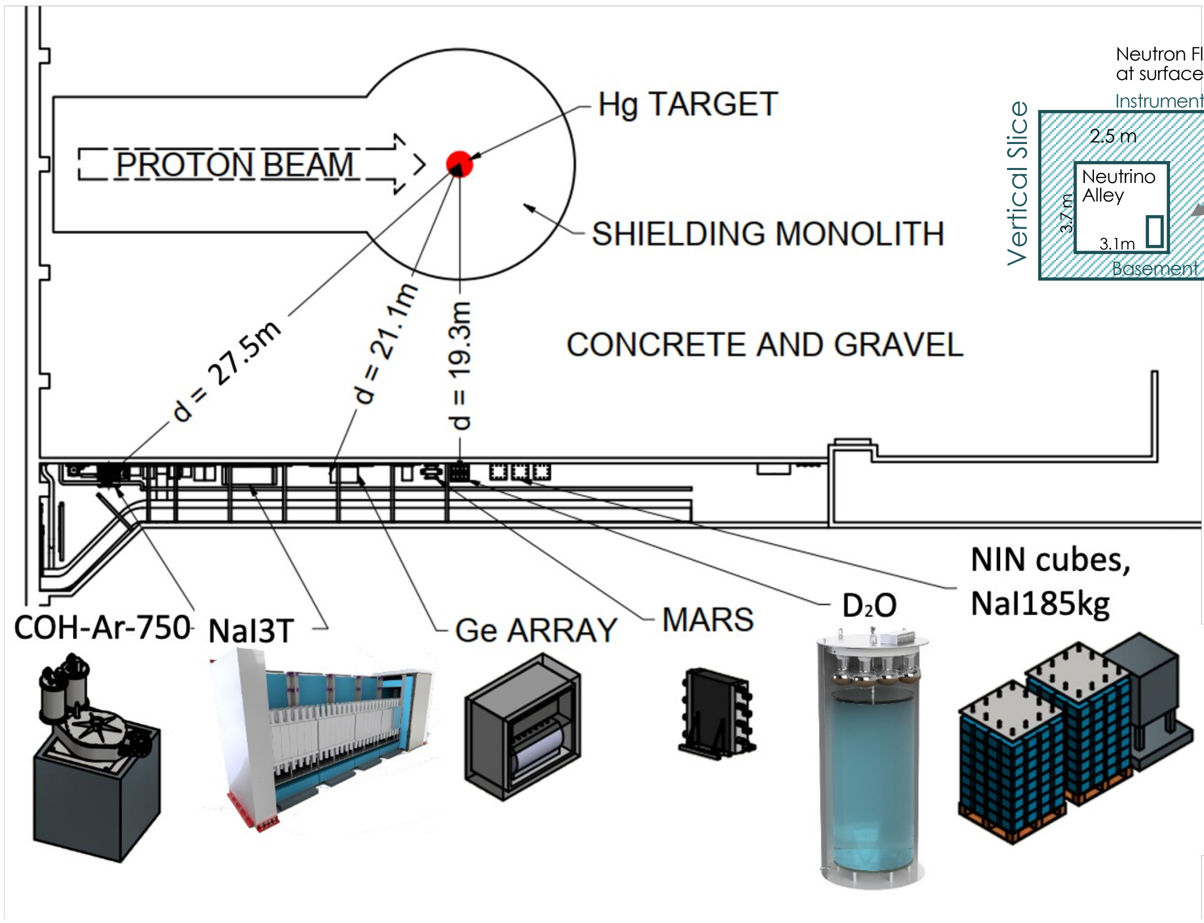

**~4x10$^{-5}$ background reduction**

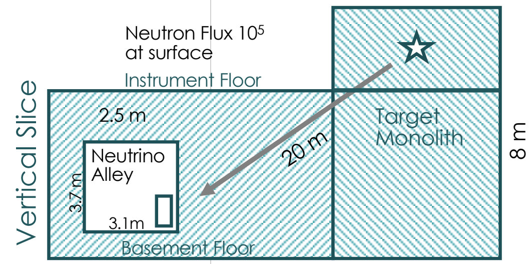


# Comparison of pion decay-at-rest ν sources



# The COHERENT Detectors at the SNS



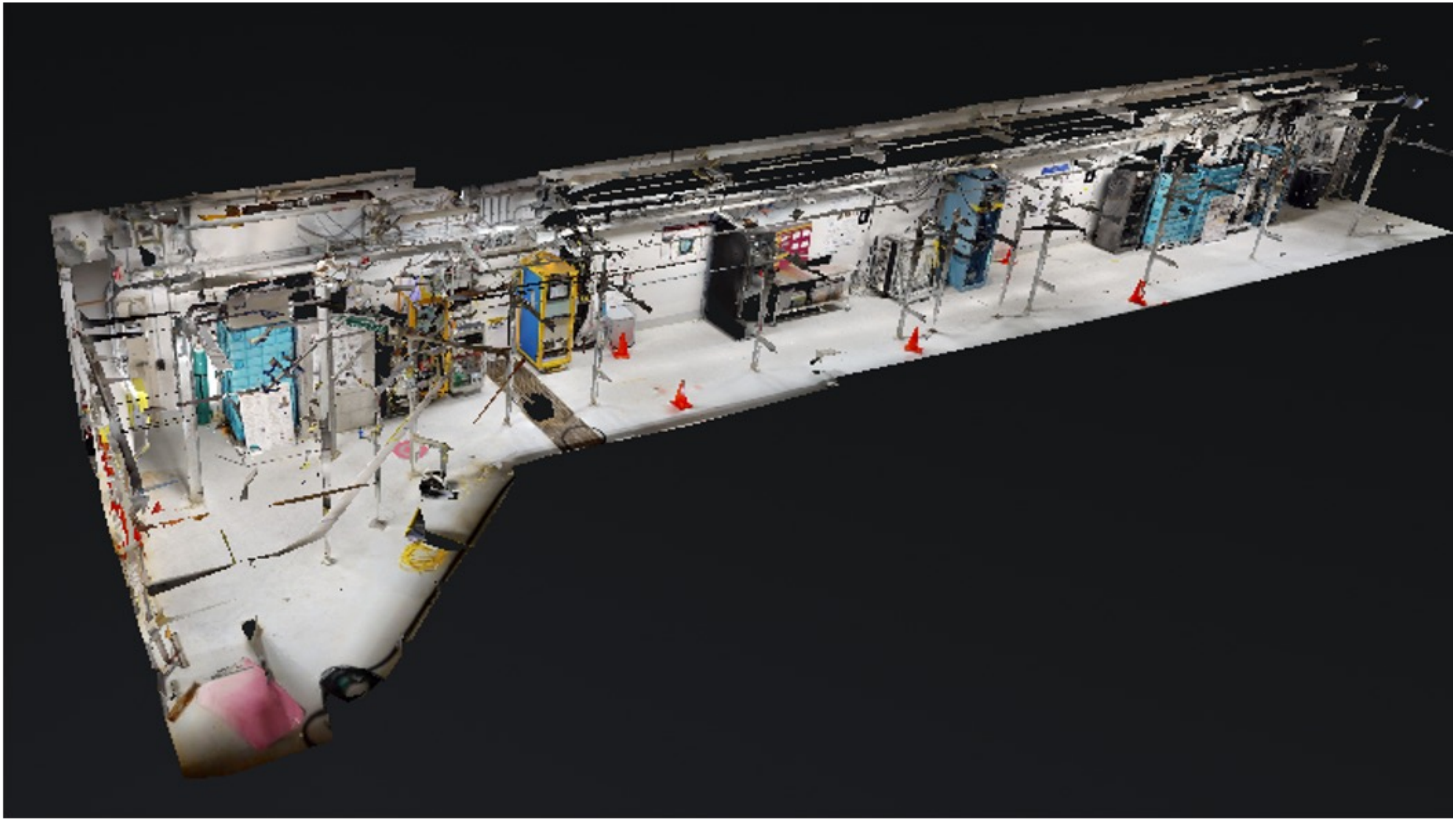



**Fig. 4:** Neutrino alley virtual tour at https://my.matterport.com/show/?m=XYA19MBVdQS.

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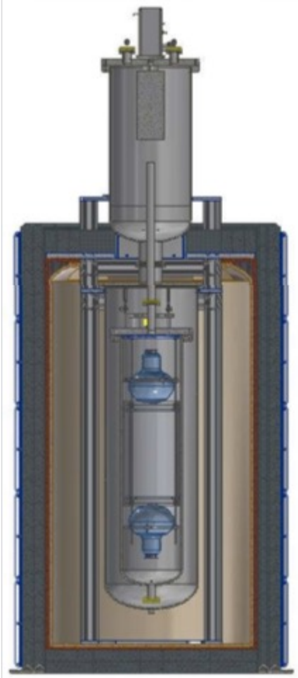
## First Measurement of Coherent Elastic Neutrino-Nucleus Scattering on Argon

D. Akimov *et al.* (COHERENT Collaboration)

Phys. Rev. Lett. **126**, 012002 – Published 7 January 2021



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REPORT

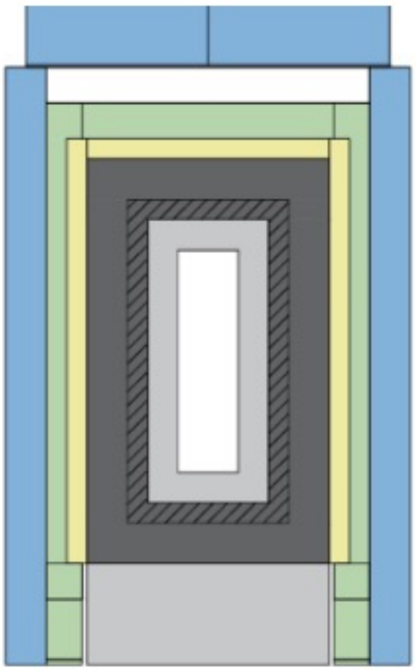
## Observation of coherent elastic neutrino-nucleus scattering

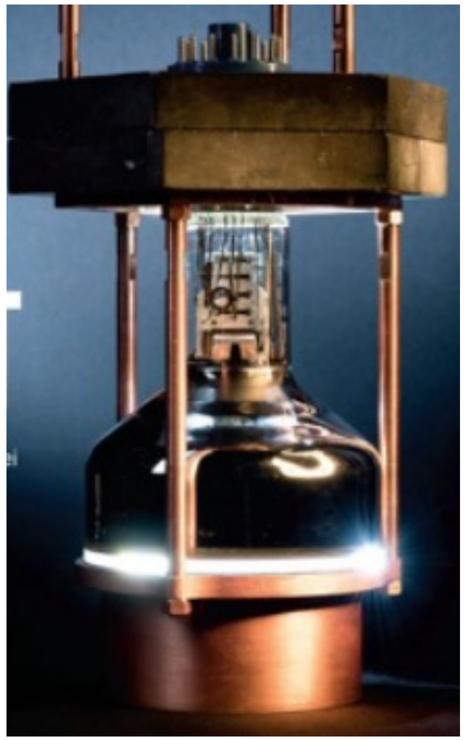
D. AKIMOV, J. B. ALBERT, P. AN, C. AWE, P. S. BARBEAU, B. BECKER, V. BELOV, A. BROWN, A. BOLOZDYNYA, [...], AND COHERENT COLLABORATION +72 authors

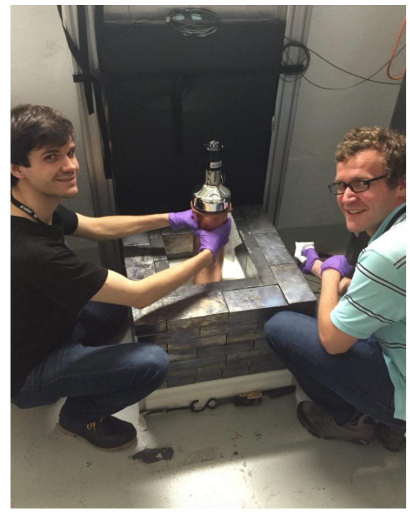
Authors Info & Affiliations

SCIENCE • 3 Aug 2017 • Vol 357, Issue 6356 •

## The CsI Detector in Shielding in Neutrino Alley at the SNS





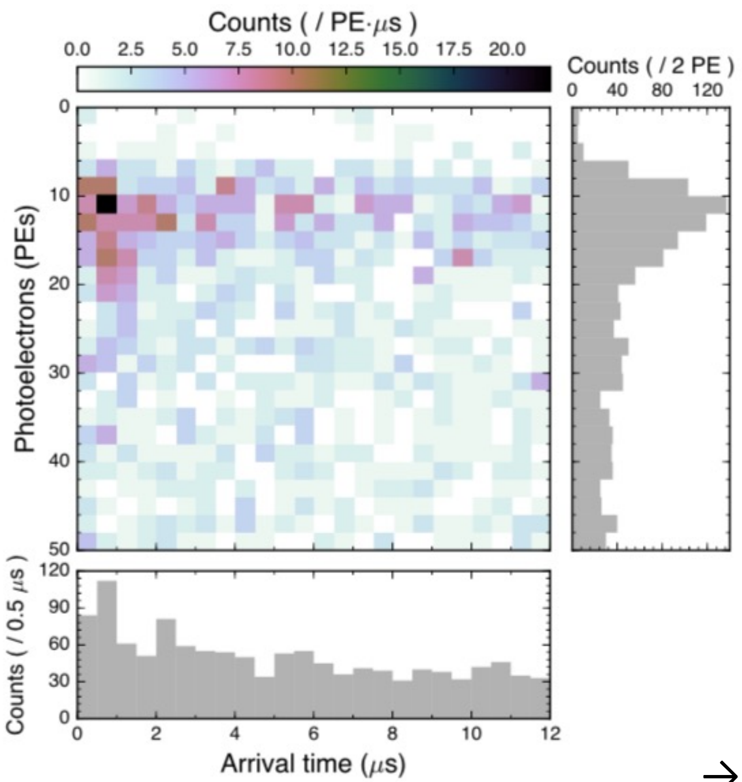


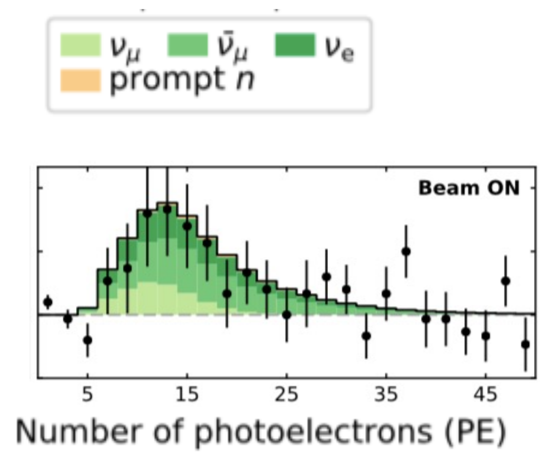
A hand-held detector!

Almost wrapped up...

| Layer | HDPE* | Low backg. lead | Lead | Muon veto | Water |
|---|---|---|---|---|---|
| Thickness | 3" | 2" | 4" | 2" | 4" |
| Colour | (light grey) | (hatched dark grey) | (dark grey) | (yellow) | (blue) |

First light at the SNS (stopped-pion neutrinos)
with 14.6-kg CsI[Na] detector




Background-subtracted and integrated over time

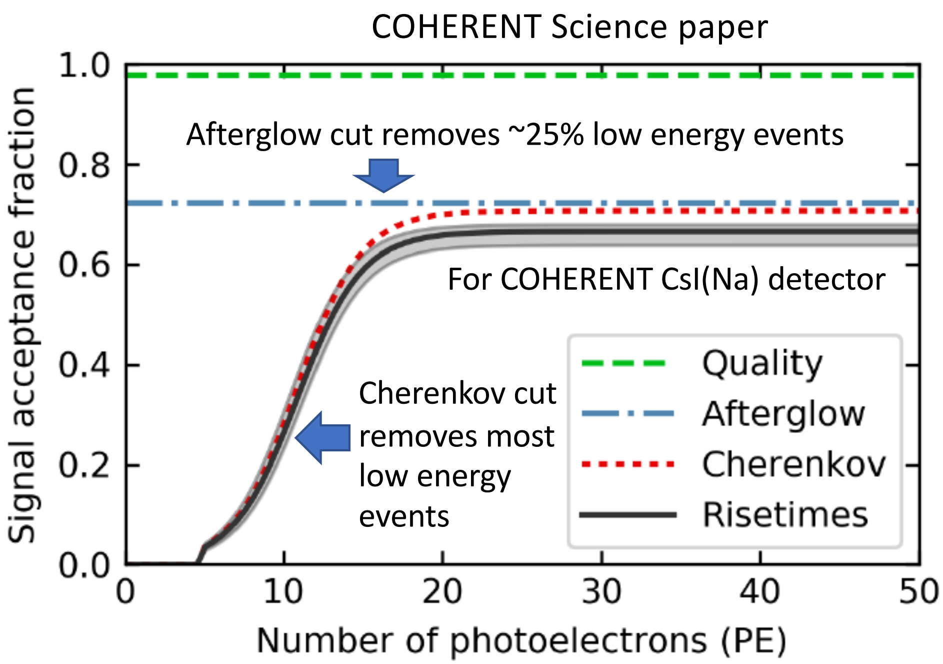
$$\mathrm{PE} \propto T \propto Q^2$$

→ measure of the Q spectrum

DOI: 10.5281/zenodo.1228631

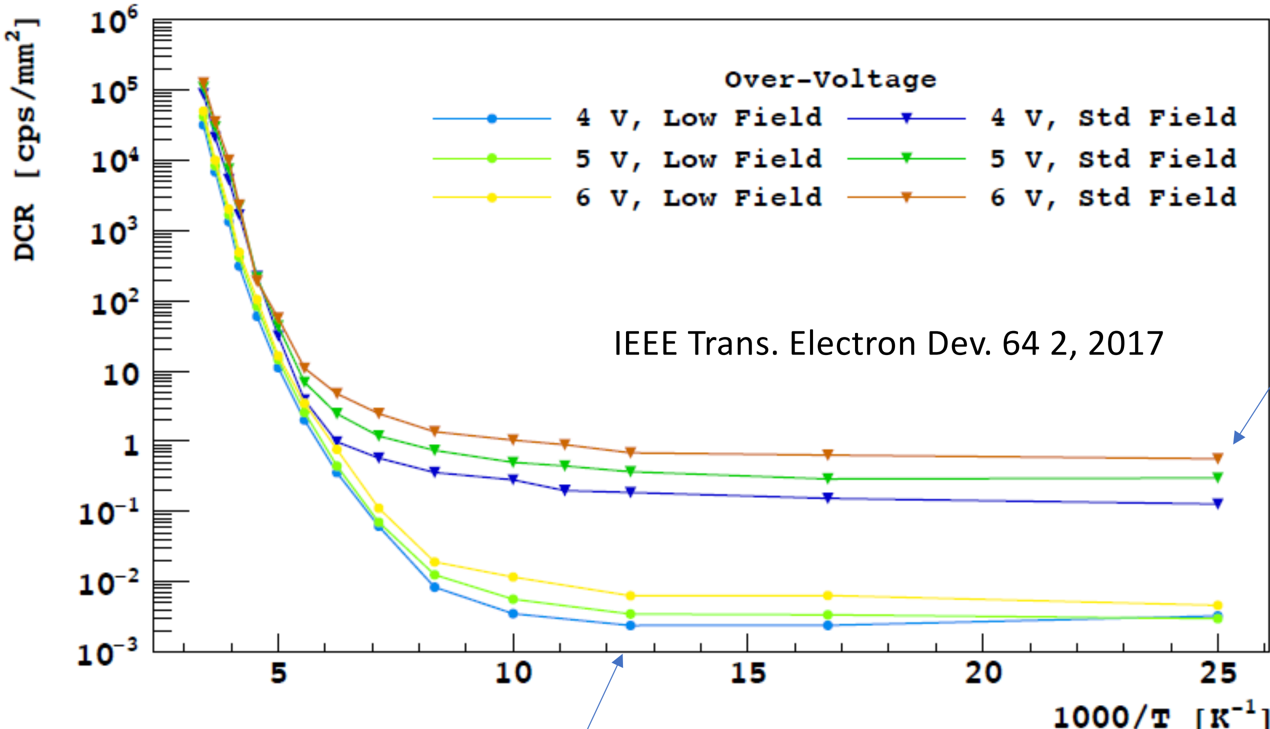
D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

# Reason for SiPM




- Replace PMTs with SiPM
  - Eliminate Cherenkov light☺ generated in PMT's quartz window
  - PDE of SiPM > QE of PMT ☺
  - high dark count rate ☹

# Dark counts of large SiPM arrays

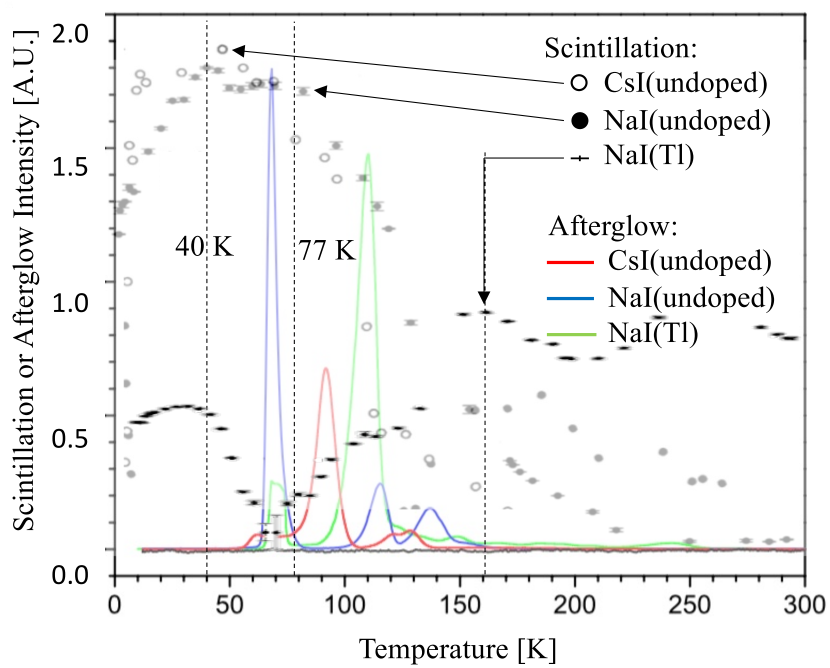



Suppressed by $10^6$ after 2 PE coincidence

Must be cooled down to at least 77 K

# Operation temperature

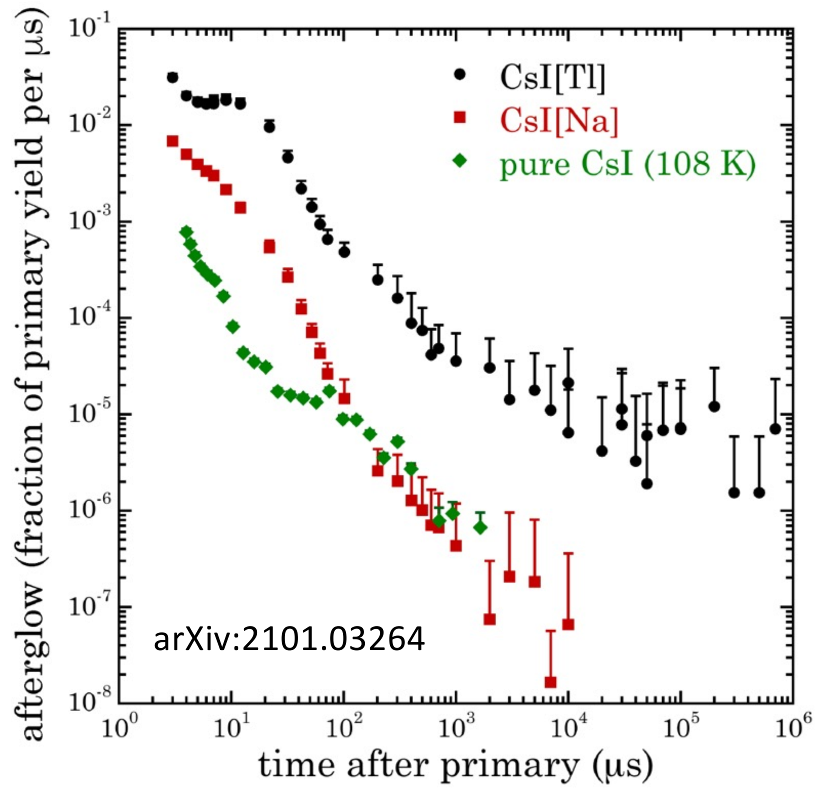
- NaI(undoped) & CsI(undoped) VS NaI(Tl) and CsI(Na)
- 40 K
  - Minimal after glow rate
  - Maximal light yield




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

Phys. Rev. B 5 (1995) 2167

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




arXiv:2101.03264

Eur. Phys. J. C (2022) 82:344
https://doi.org/10.1140/epjc/s10052-022-10289-x

THE EUROPEAN PHYSICAL JOURNAL C

Special Article - Tools for Experiment and Theory

# First operation of undoped CsI directly coupled with SiPMs at 77 K

**Keyu Ding**[1,a], **Jing Liu**[1,b], **Yongjin Yang**[1], **Dmitry Chernyak**[1,2]

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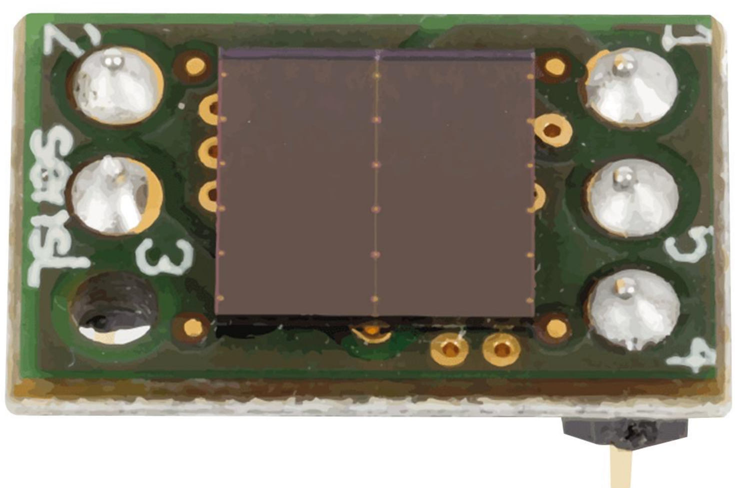
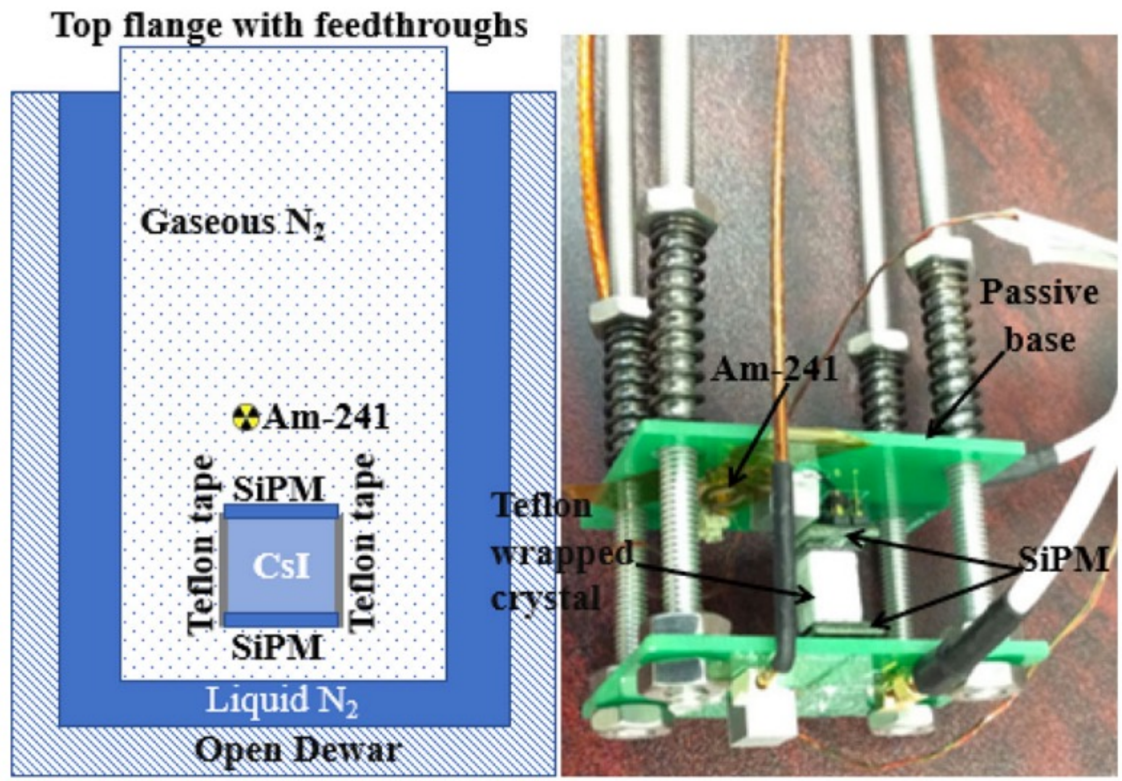
[2] *Present Address:* University of Alabama, Tuscaloosa, USA

The light yield of an undoped CsI crystal coupled to two SiPMs at 77 K was measured to be 43.0 ± 1.1 PE/keV$_{ee}$ using $X$ and $\gamma$-ray peaks from an $^{241}$Am radioactive source.

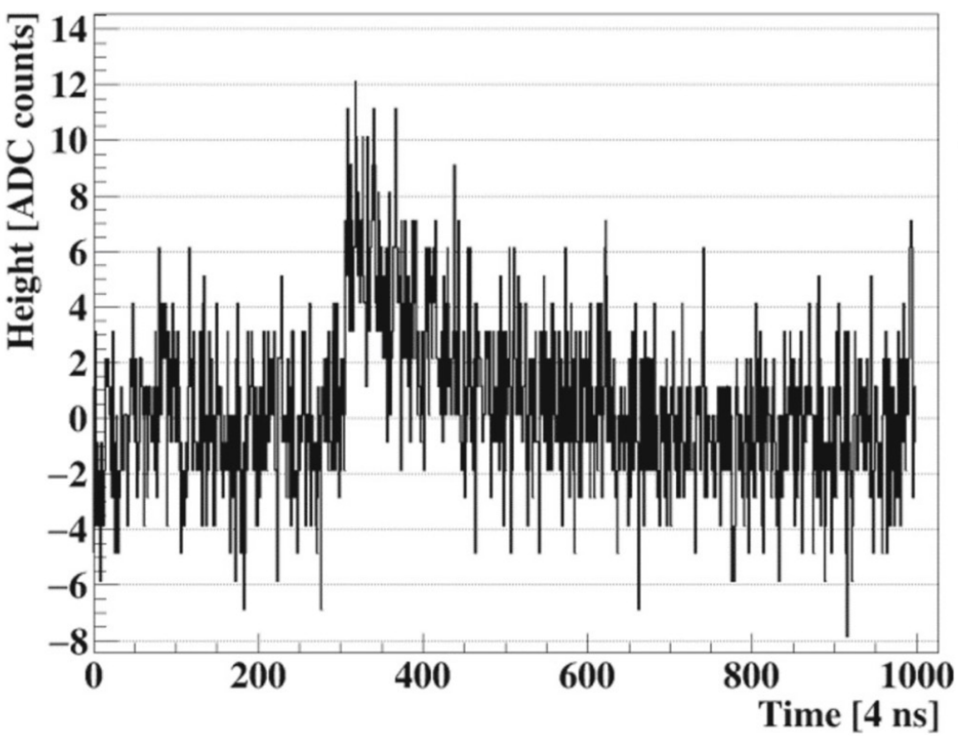
2 MicroFJ-SMTPA-60035

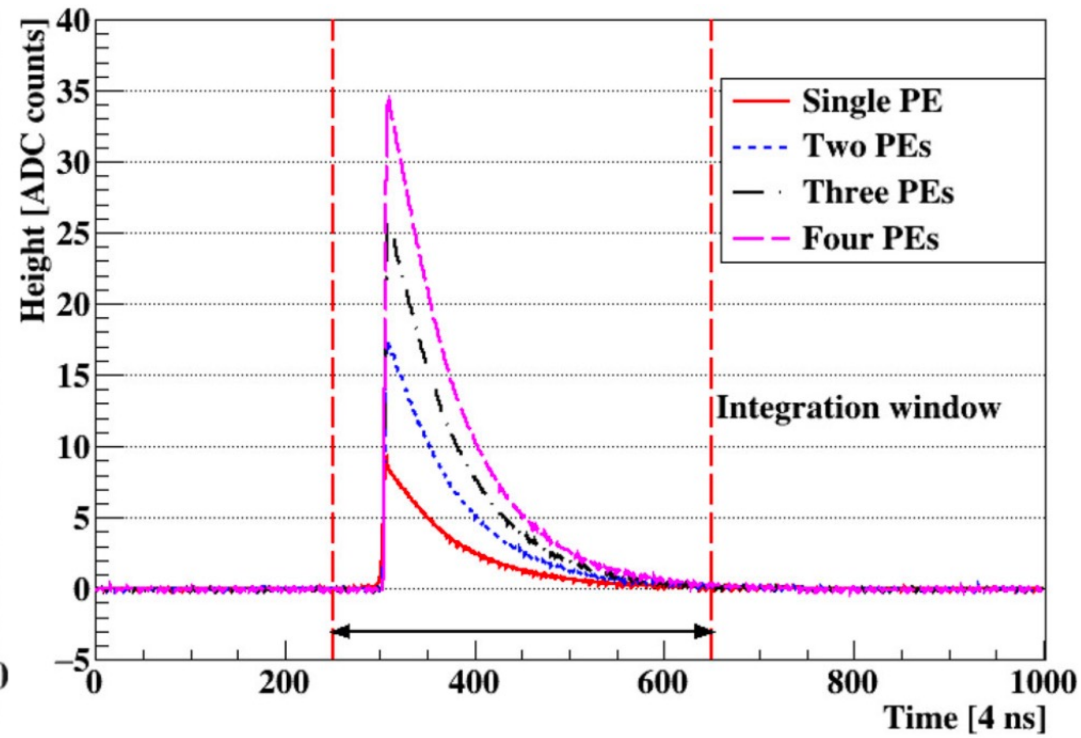
- sensor size: 6×6 mm$^2$
- pixel size: 35 × 35 μm
- total number of pixels: 18980





# Single PE response



# Energy calibration

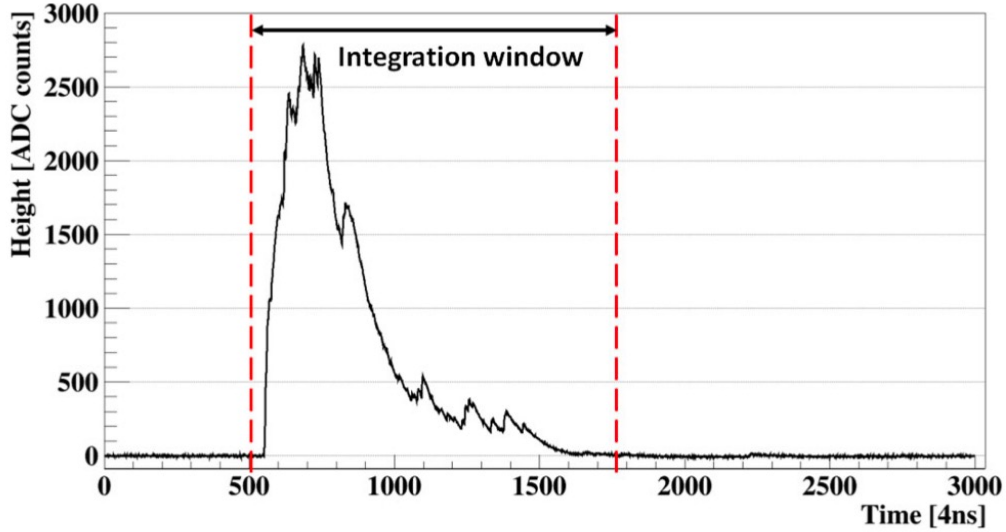
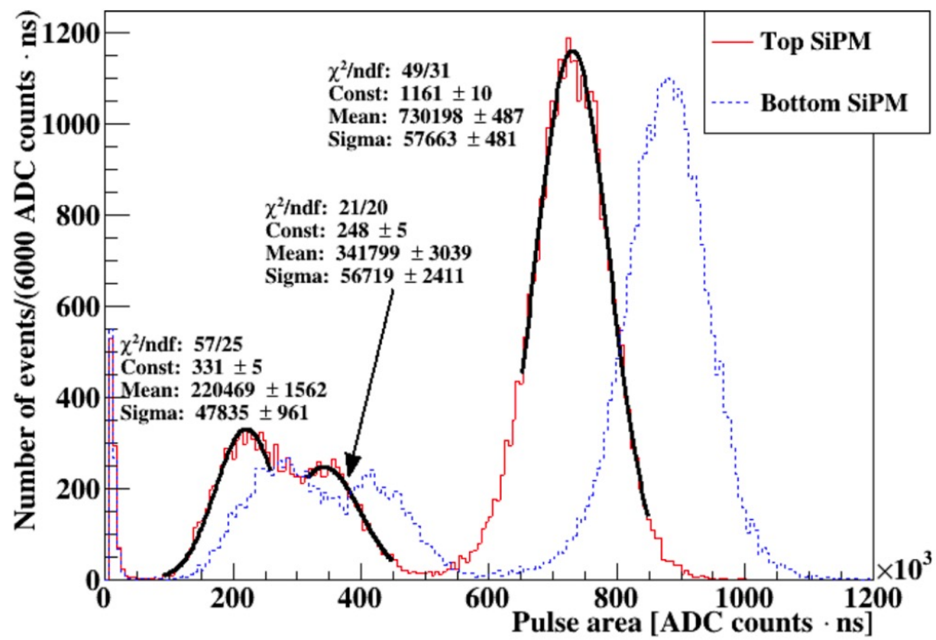
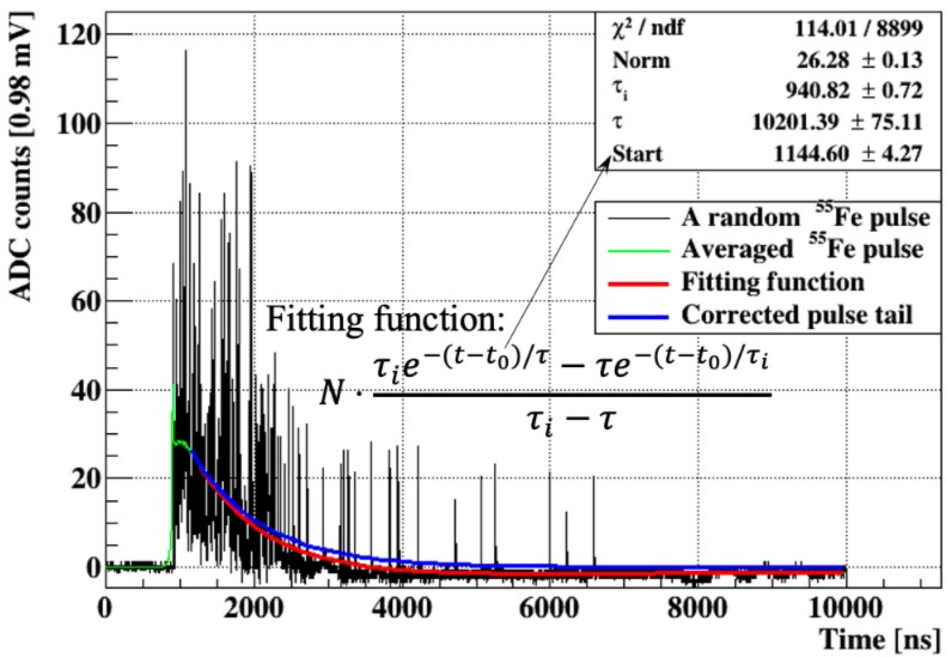
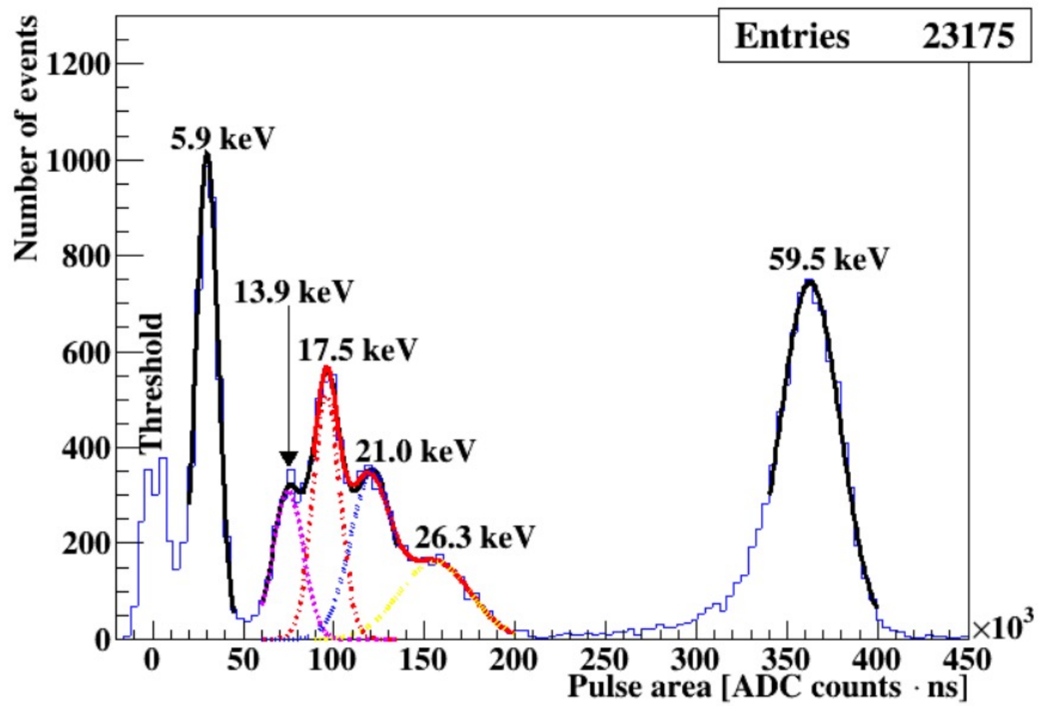



**Fig. 9** A randomly selected light pulse within the 59.5 keV peak from the top SiPM. The ones from the bottom SiPM are very similar

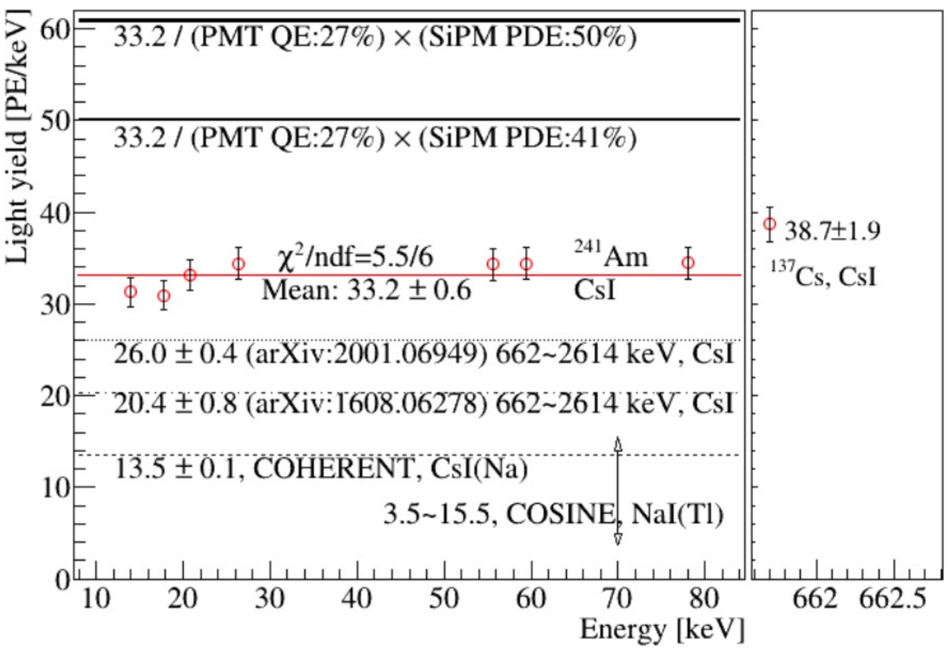


# Down to 5.9 keV



# Light yields




| Experiments | Type of crystal | Light yield [PE/keVee] |
|---|---|---|
| COHERENT 2017 | CsI(Na) | 13.5 ± 0.1 [3] |
| PMT+small crystal | CsI | 20.4 ± 0.8 [51] |
| PMTs+large crystal | CsI | 26.0 ± 0.4 [35] |
| Improved light collection | CsI | 33.5 ± 0.7 [52] |
| PMT → SiPMs | CsI | 40.1 ± 1.1 [53] |
| WLS coating on SiPMs | CsI | 50.0 ± 1.0 † |
| 77 → 40 K, 50% PDE* | CsI | 60 (projected) |

# Reactor neutrino physics potentials of cryogenic pure-CsI crystal


Lei Wang,[1,2] Guanda Li,[3,1] Zeyuan Yu,[1] Xiaohua Liang,[4] Tian'an Wang,[5] Fang Liu,[6] Xilei Sun,[1,2,7,*] Cong Guo,[1,2,7,†] and Xin Zhang[1,2]

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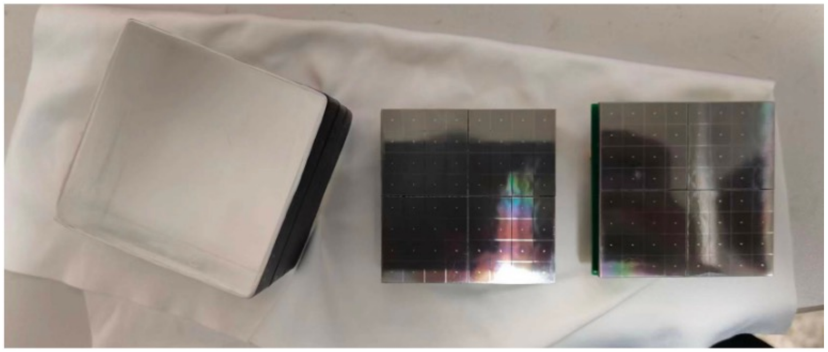
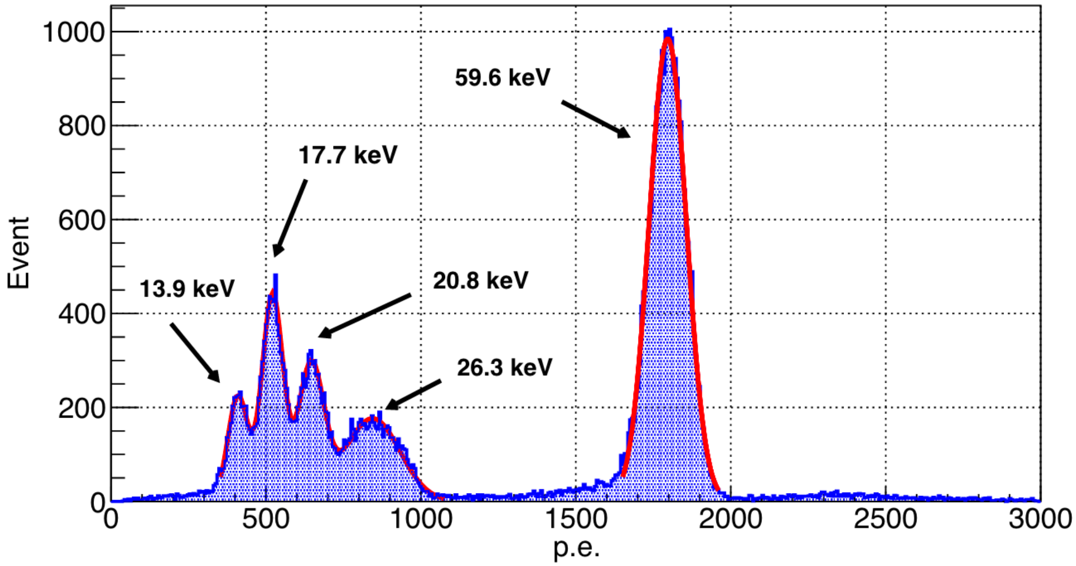
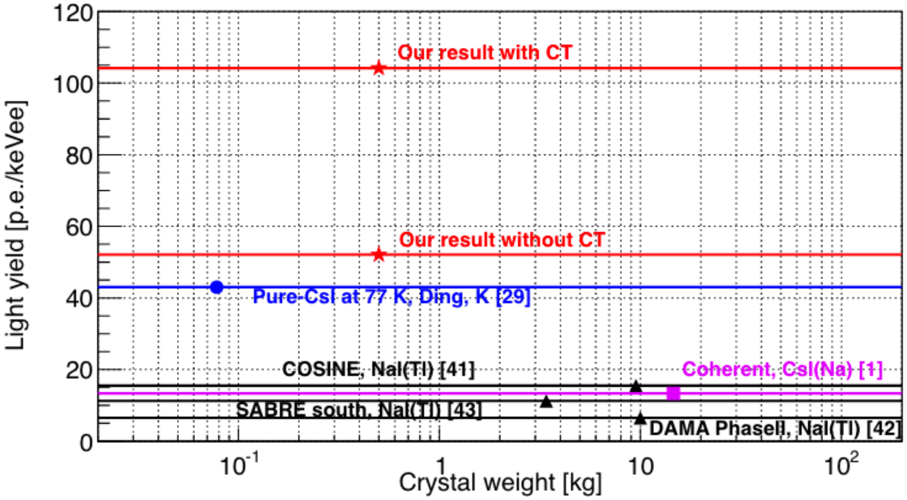
[7] *State Key Laboratory of Particle Detection and Electronics, Beijing 100049, China*



(Dated: December 29, 2022)



# 100 → 1000 neutrinos/year

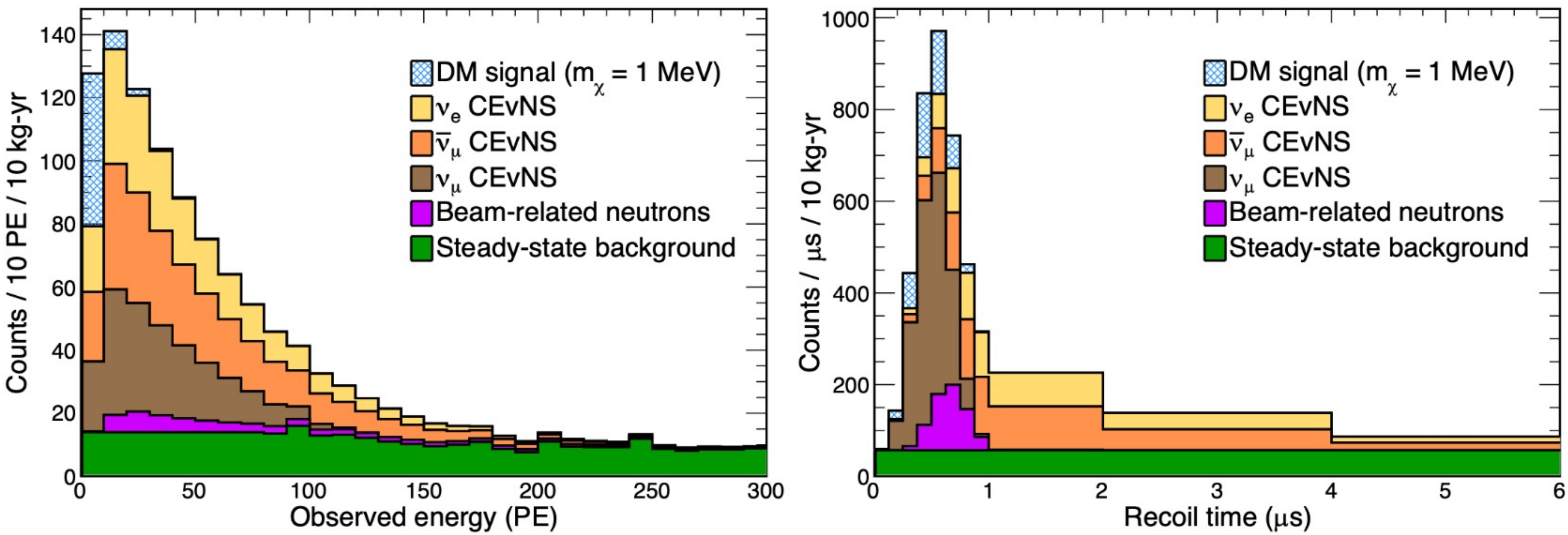
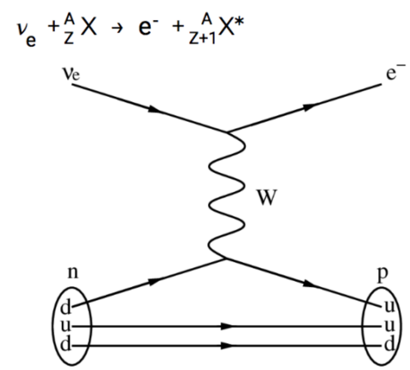



**Fig. 12:** Energy (left) and time (right) distributions of CEvNS and DM signals in a 10 kg undoped CsI detector at the SNS.

# Non-standard neutrino interactions (NSI)




$$\mathcal{L}^{NSI}_{\nu H} = -\frac{G_F}{\sqrt{2}} \sum_{\substack{q=u,d \\ \alpha,\beta=e,\mu,\tau}} [\bar{\nu}_\alpha \gamma^\mu (1-\gamma^5)\nu_\beta] \times (\varepsilon^{qL}_{\alpha\beta}[\bar{q}\gamma_\mu(1-\gamma^5)q] + \varepsilon^{qR}_{\alpha\beta}[\bar{q}\gamma_\mu(1+\gamma^5)q])$$

"Model-independent" parameterization

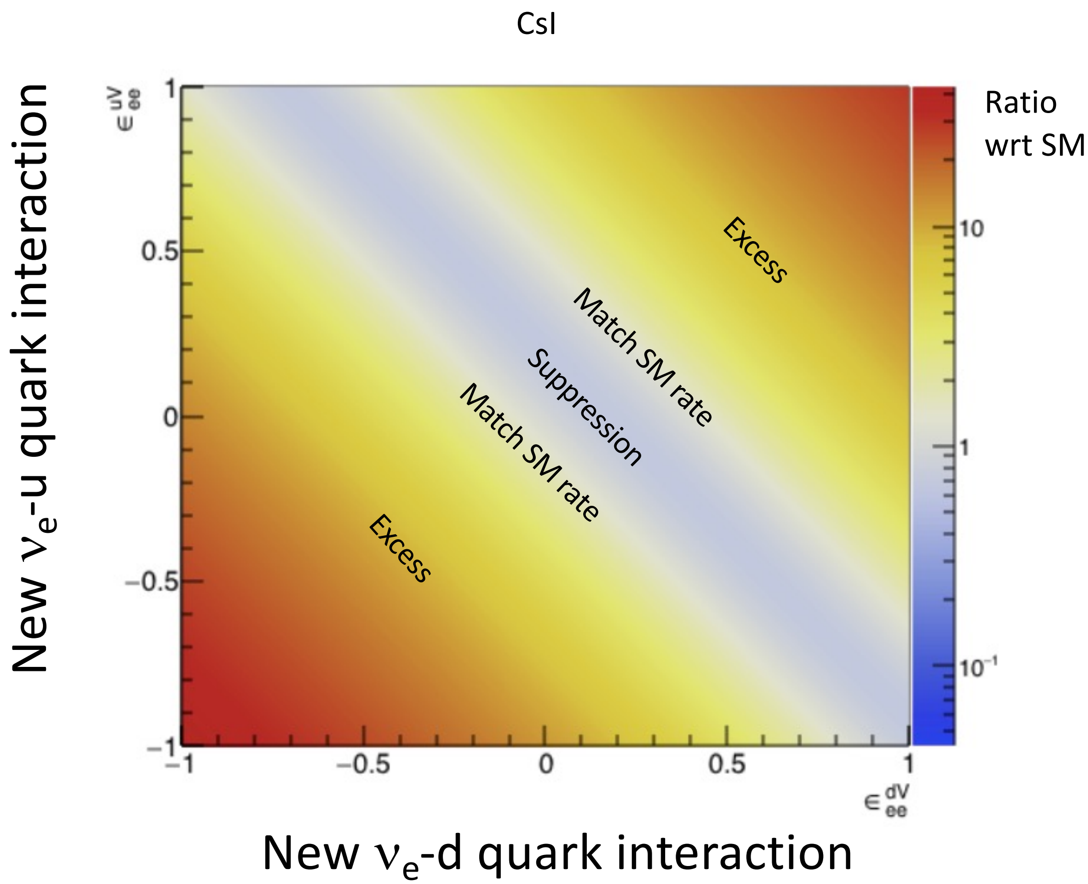
"Non-Universal": $\varepsilon_{ee}$, $\varepsilon_{\mu\mu}$, $\varepsilon_{\tau\tau}$

Flavor-changing: $\varepsilon_{\alpha\beta}$, where $\alpha \neq \beta$

Davidson et al., JHEP 0303:011 (2004)
Barranco et al., JHEP 0512:021 (2005)

Signatures of Beyond-the-Standard-Model Physics

Look for a CEvNS excess or deficit wrt SM expectation



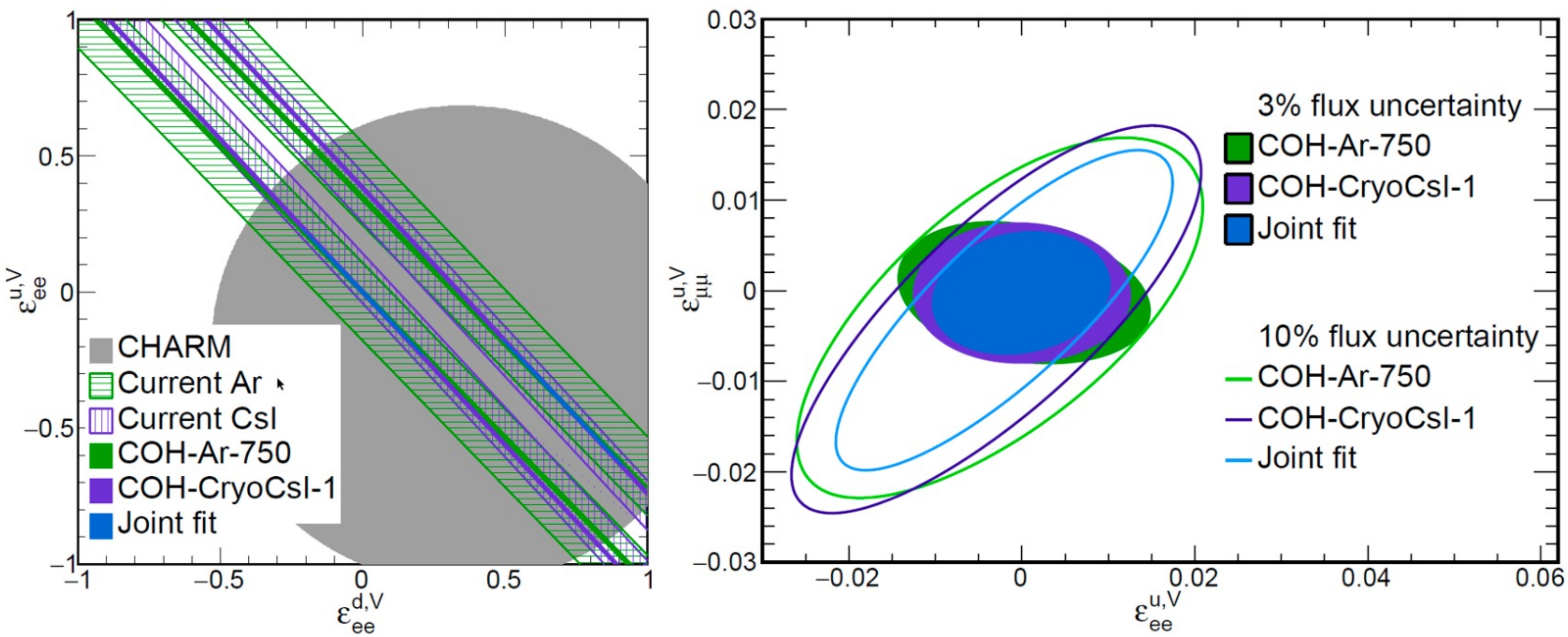



**Fig. 1:** Allowed regions in the non-universal NSI parameter spaces at 90% C.L. constrained by a 10 kg cryogenic CsI after two years of operation [26] compared to existing constraints [3, 15].

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https://doi.org/10.1140/epjc/s10052-020-8111-7

THE EUROPEAN PHYSICAL JOURNAL C

Check for updates

Regular Article - Experimental Physics

# Prospect of undoped inorganic crystals at 77 Kelvin for low-mass dark matter search at Spallation Neutron Source

**Dmitry Chernyak**[1], **Daniel Pershey**[2], **Jing Liu**[1,a], **Keyu Ding**[1], **Nathan Saunders**[1], **Tupendra Oli**[1]

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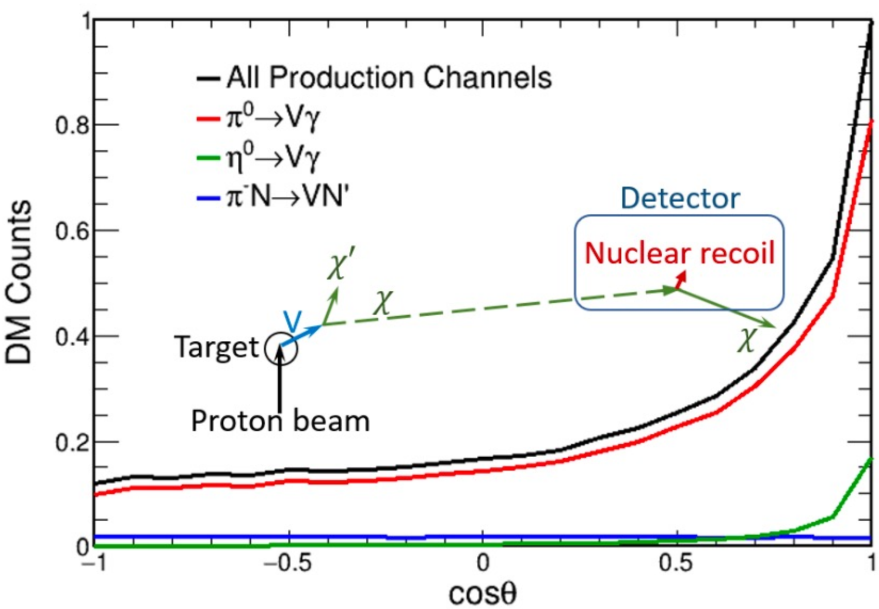


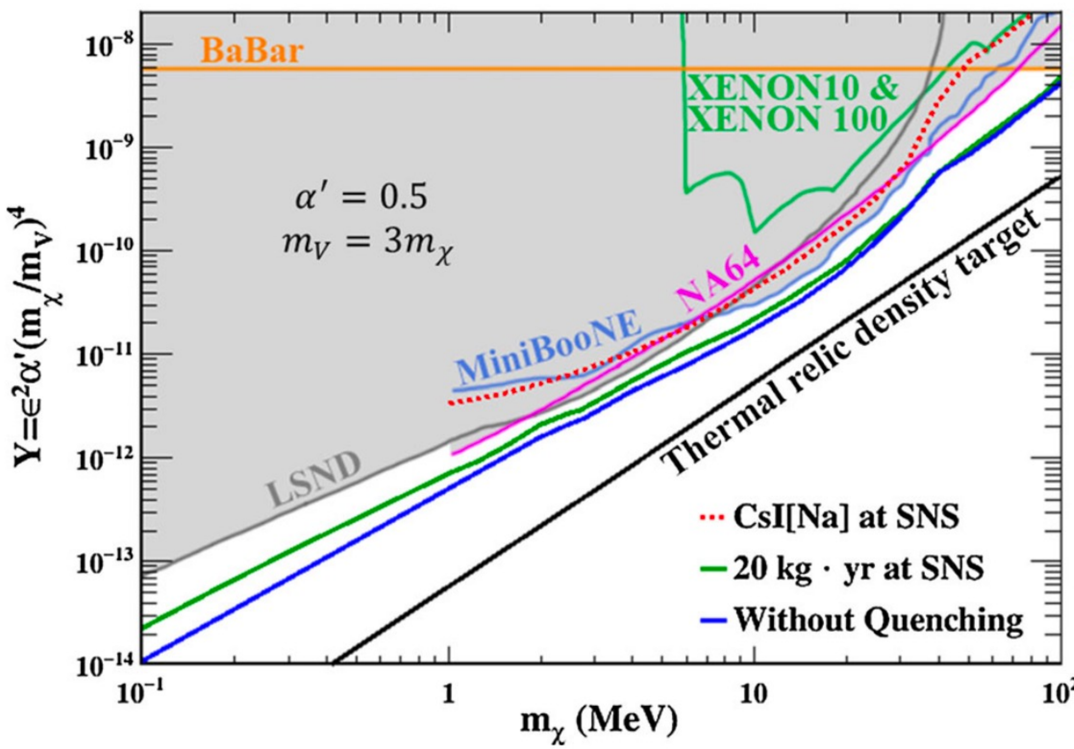

Astroparticle Physics 84 (2016) 70–77

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# A CsI low-temperature detector for dark matter search

G. Angloher[a], I. Dafinei[b], A. Gektin[c], L. Gironi[d,e], C. Gotti[d], A. Gütlein[f,g], D
M. Maino[d], S.S. Nagorny[h], S. Nisi[i], L. Pagnanini[h], L. Pattavina[i], G. Pessina
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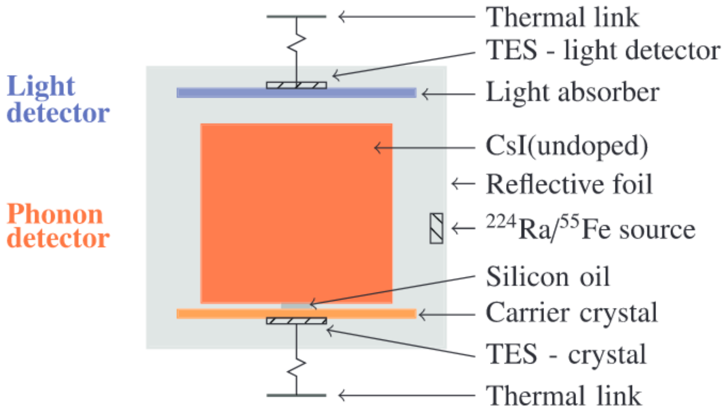


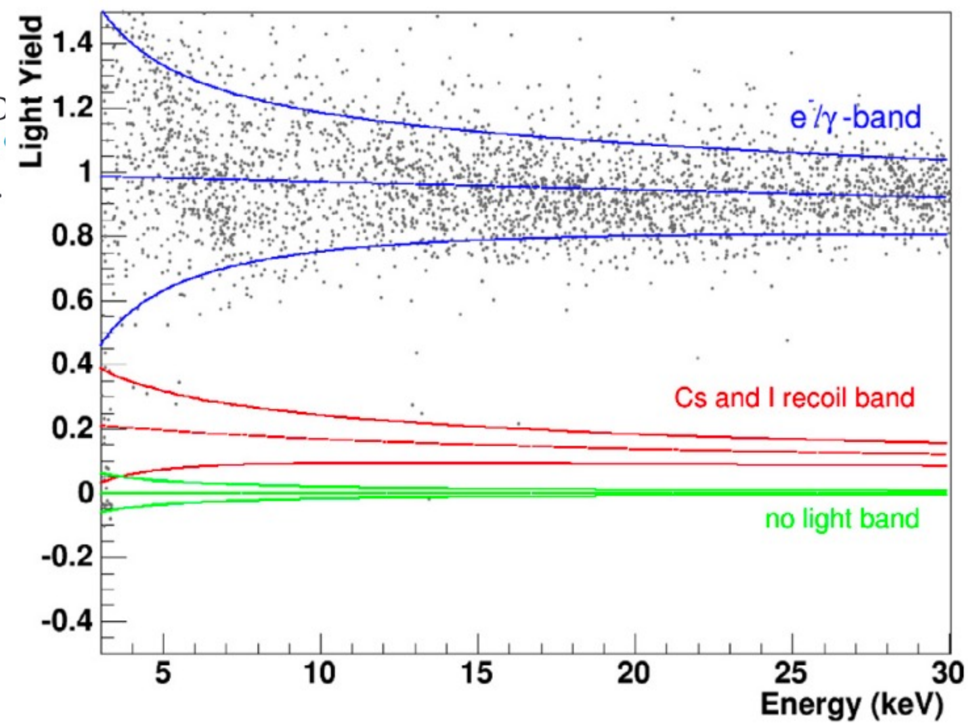

# Road map and resources

- Resources:
  - IHEP: detector development
  - UCAS: CEvNS detection at CSNS
  - SIC CAS: crystal growth with the help of
    - Suerfu Burkhant (NaI)
    - Soo-Bong Kim (CsI)
  - Tsinghua: dark matter search in underground lab
- Road map:
  - IHEP + SICCAS (KEK & SYSU) @ SNS
  - IHEP + SICCAS (KEK & SYSU) + UCAS @ CSNS
  - IHEP + SICCAS (KEK & SYSU) + UCAS + Tsinghua @ CJPL
    - 77 K
    - mili K