



Aug. 30

Measurements of Quenching Factors for NaI(Tl) scintillating crystal

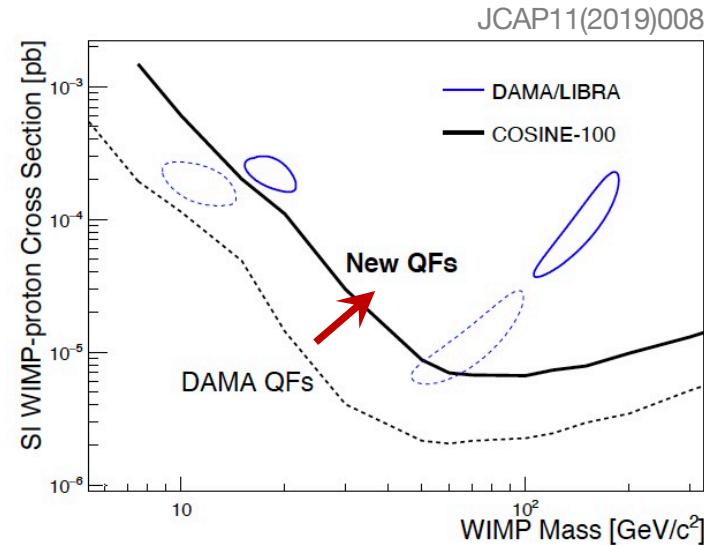
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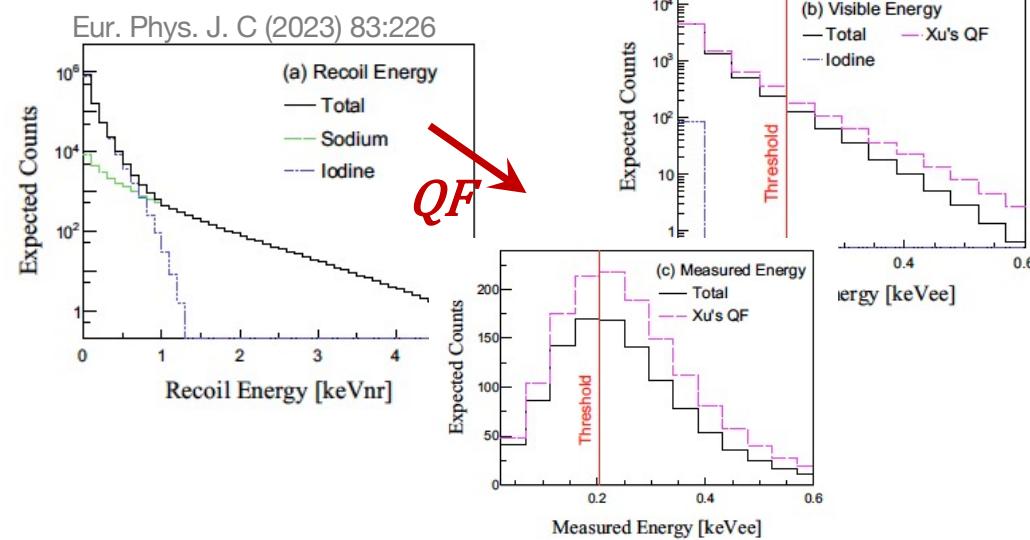
For the COSINE-100 & NEON experiments

Nuclear recoil for low energy studies

- Investigation of the interactions via nuclear recoil energy deposition
 - ← Detector calibrated with the X-ray or Gamma-ray
 - ← different scintillation responses for nuclear recoil and electron/gamma interactions
- essential to comprehend the ratio of visible and deposit energy, Quenching Factor (QF) =
$$\frac{E_{ee}}{E_{nr}} = \frac{E_{visible}}{E_{deposit}}$$



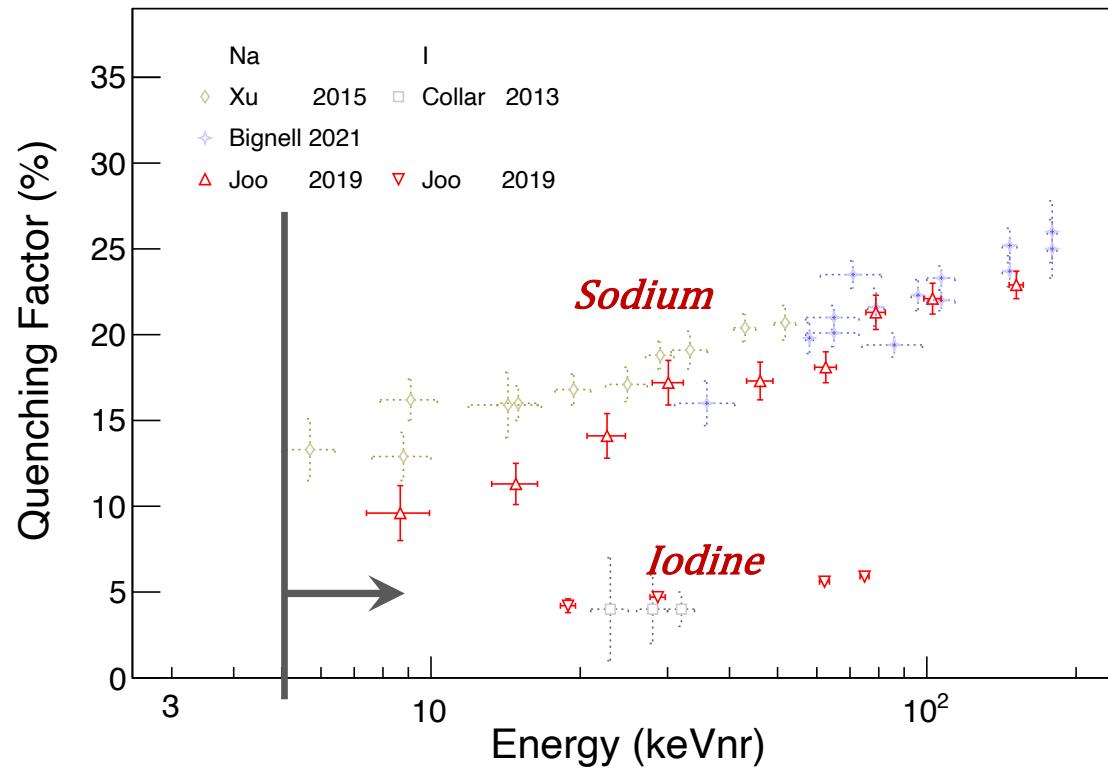
Effects of QF on WIMP mass-cross section



Expected CE ν NS signals

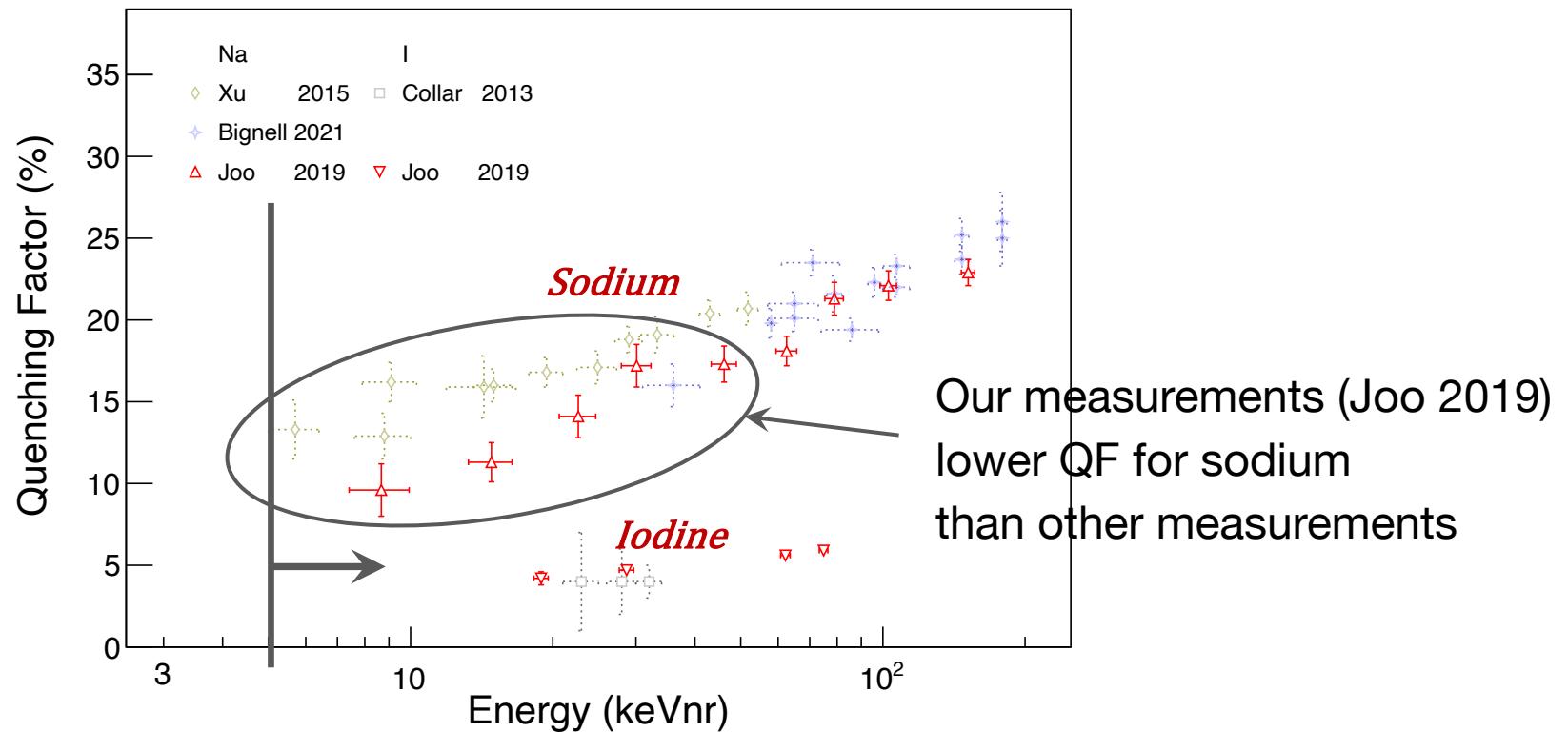
Current status of QF measurements

- No measurements below 5 keV for Sodium, 18 keV for Iodine



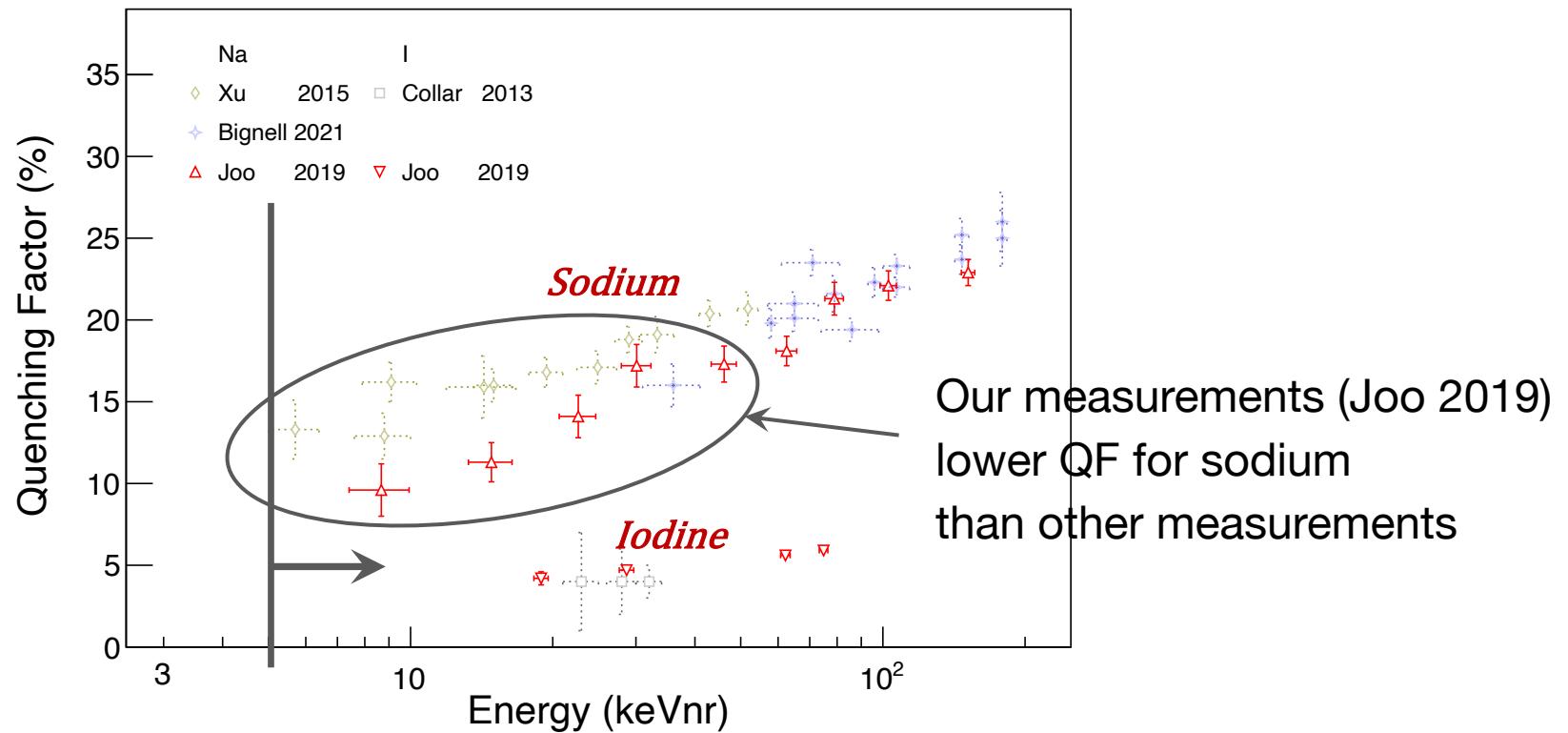
Current status of QF measurements

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Current status of QF measurements

- No measurements below 5 keV for Sodium, 18 keV for Iodine



We have measured QF at lower energies, and revisit previous measurements

Incident neutron energy

- Nuclear recoil energy: function of incident neutron energy

$$QF = \frac{E_{ee}}{E_{nr}}, \quad E_{nr} = \frac{2(1 + A - \cos^2\theta - \cos\theta\sqrt{(A^2 - 1 + \cos^2\theta)})}{(1 + A)^2} E_n$$

↑
incident neutron energy

- Neutron source: Deuteron-Deuteron based neutron generator

neutron energy differ by deuteron acceleration energy (E_d)

→ previous measurements:

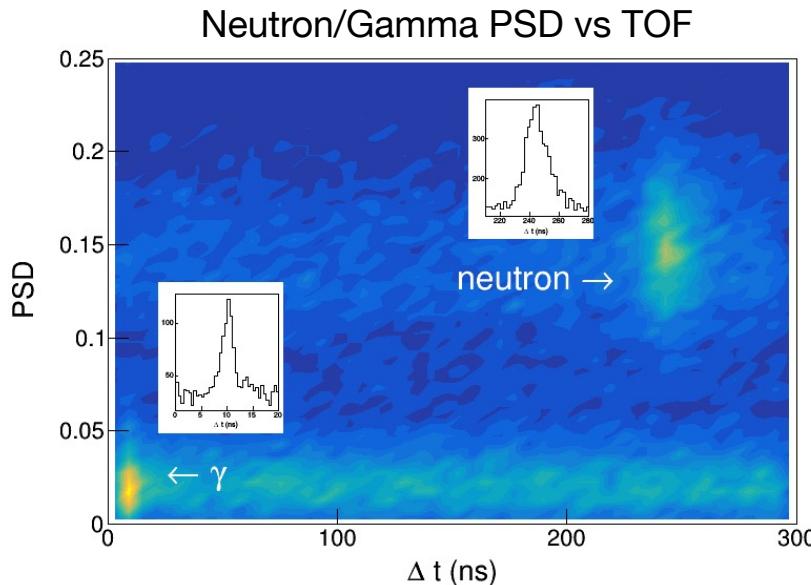
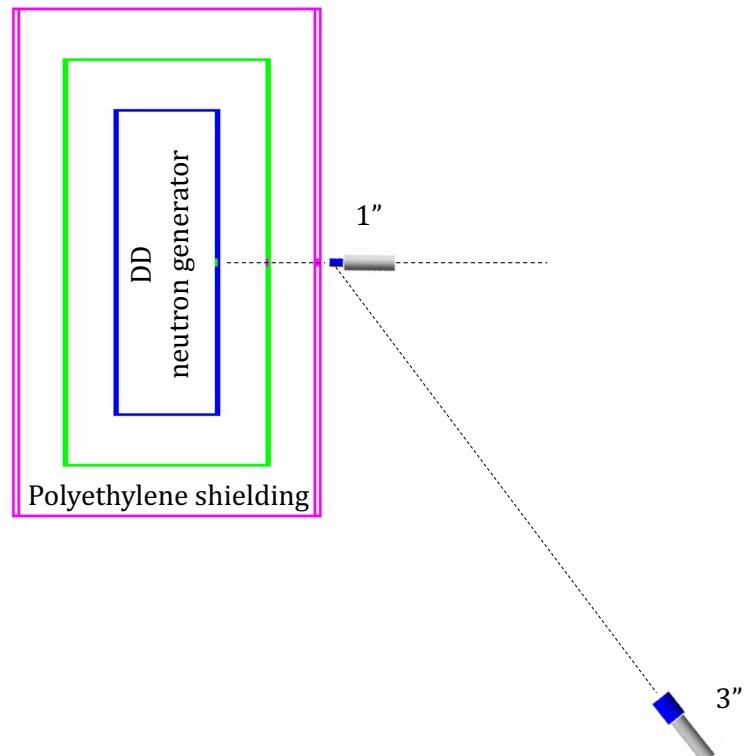
neutron energy: 2.43 ± 0.03 MeV (@ 60 keV deuteron energy)

lower QF, mis-estimation of neutron energy?

→ Revisit neutron energy measurements

Incident neutron energy

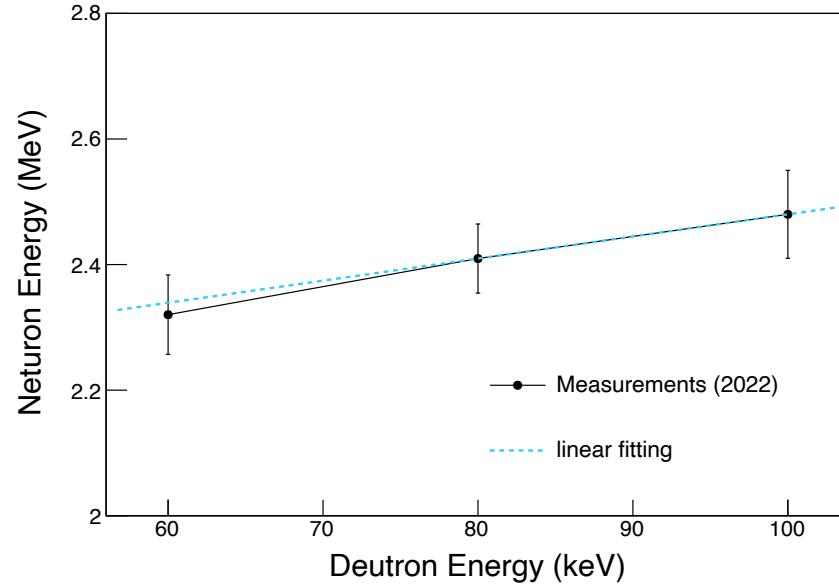
- Neutron energy measurements using Time-Of-Flight (TOF) of neutrons
 - two LS neutron detector - 1" (near), 3" (far)
 - measure TOF between two detectors



Measurements at $E_d = 100, 80, 60$ keV,
and estimate neutron energies

Incident neutron energy

- Neutron energy measurements using Time-Of-Flight (TOF) of neutrons
 - two LS neutron detector - 1" (near), 3" (far)
 - measure TOF between two detectors



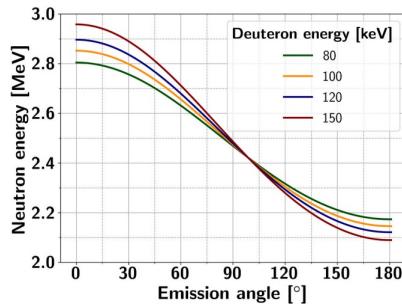
Incident neutron energy

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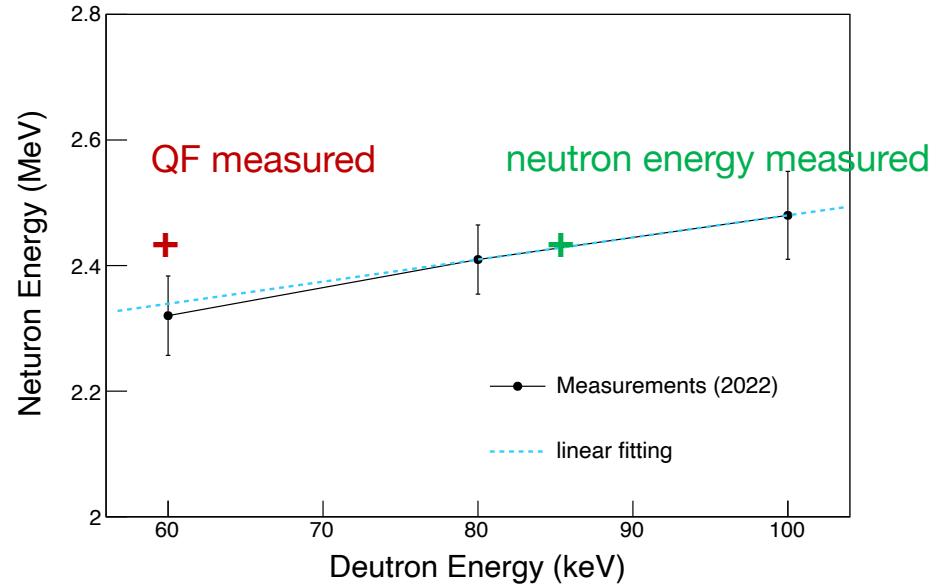
Previous measurements:

- QF measured under 60 keV setup
- but used 2.43 MeV neutron energy measured at 85 keV

(lower deuteron energy dependency at 90°)



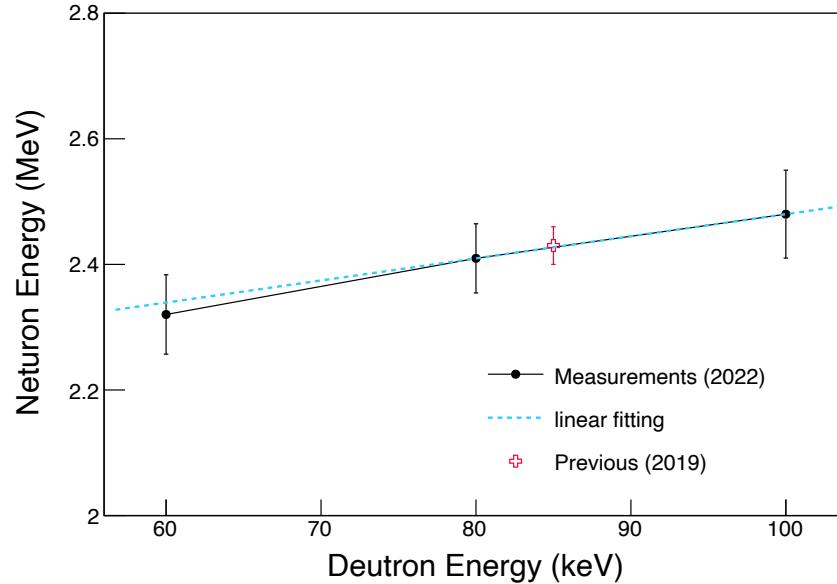
Appl.Radia.Isot.
174 (2021) 10975



Incident neutron energy

- Neutron energy measurements using Time-Of-Flight (TOF) of neutrons
 - two LS neutron detector - 1" (near), 3" (far)
 - measure TOF between two detectors

Neutron energy 2.43 MeV @ 85 keV
well agreed with our new measurements
 $\rightarrow 2.34 \pm 0.06$ MeV @ 60 keV



Revisit previous QF with 2.34 ± 0.06 MeV instead of 2.43 MeV
, and New measurements using 2.48 ± 0.07 MeV (100 keV)

New measurements

- Revisit previous measurements with correct neutron energy, and using newly updated analysis method
→ Let me introduce new measurements and analysis before revisit previous one

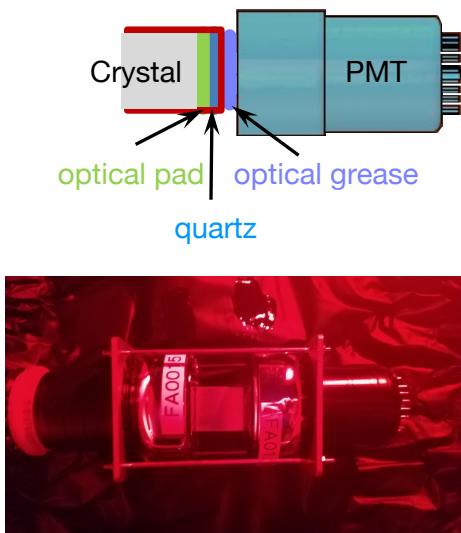
New measurements

- Revisit previous measurements with correct neutron energy, and using newly updated analysis method
 - Let me introduce new measurements and analysis before revisit previous one
- Different crystal with previous measurement
 - previous: same ingot to COSINE C2, C5, C8 crystal
 - new: same ingot to COSINE C6, C7
- New encapsulation having high light yield: used for NEON experiment
- Measure at low recoil energy (small recoil angle)
- Newly developed analysis method

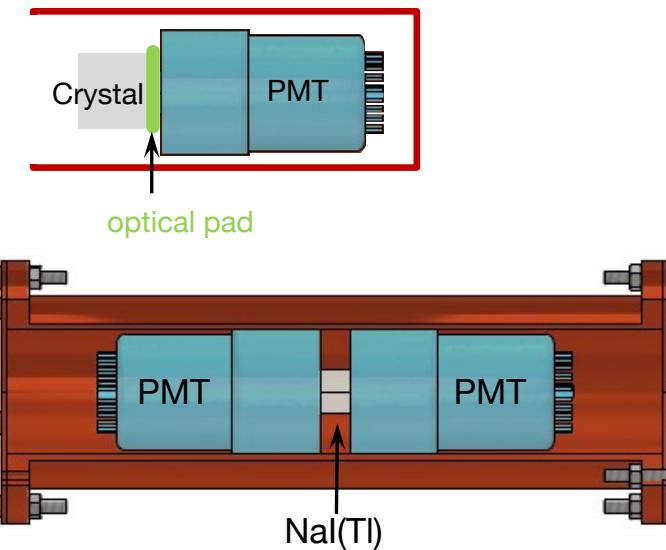
High light yield detector

- High light yield: 18 PE/keV (previous) → **26 PE/keV (new)**
 - KEY: direct couple to PMT without quartz to reduce light loss (small size of crystal: 14 mm x 14 mm x 14 mm)
 - proved by NEON experiment: avg ~22 PE/keV for large crystal (Eur. Phys. J. C (2023) 83:226)

Previous design



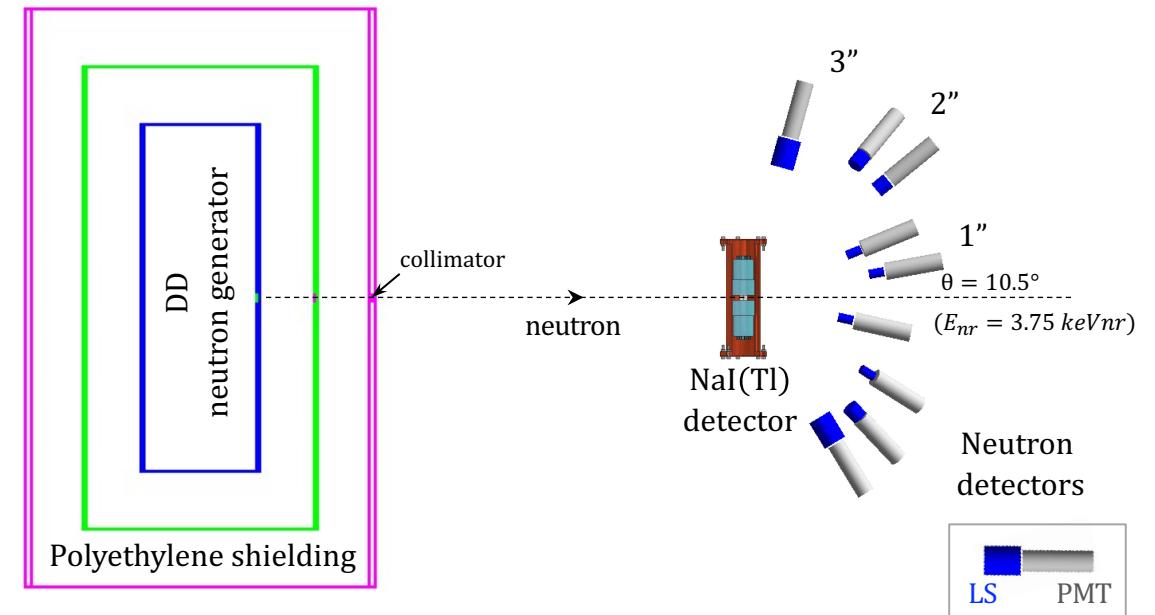
New design



enable lower energy thresholds

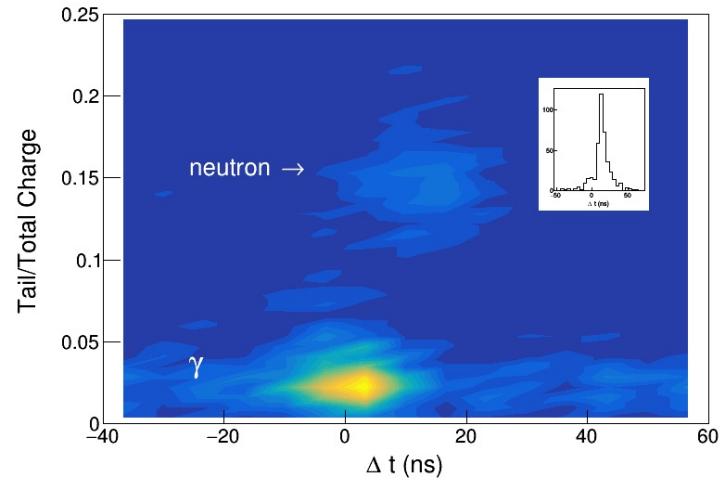
Experimental setup

- Neutron Generator
 - Deuteron-Deuteron based neutron generator (DD-109, Adelphi)
 - Estimated neutron energy = 2.48 ± 0.07 MeV
- Neutron detector
 - Liquid Scintillator (EJ301, Eljen Tech.)
good neutron/gamma PSD
 - installed at several angles,
especially at small angle **10.5°**
 - various size of neutron detectors,
1" diameter detectors at collinear angles
for enhanced angular resolution
- Electron-equivalent energy calibrated using 59.54 keV gamma from ^{241}Am

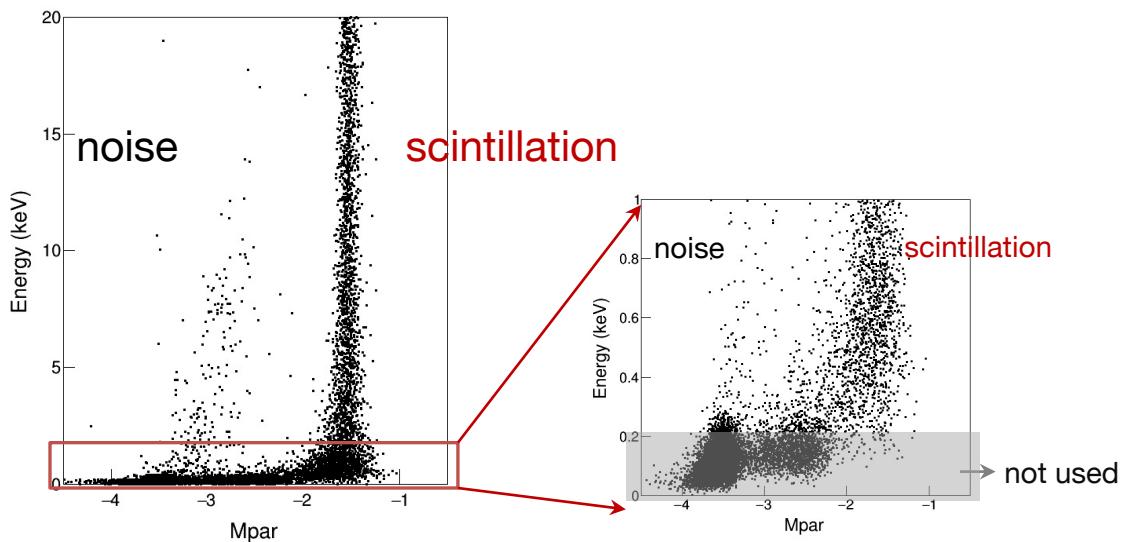


Event selections

- Neutron identification:
using different pulse shape of neutron and gamma and TOF
→ tail charge/total charge,
time difference (NaI-Neutron detector)

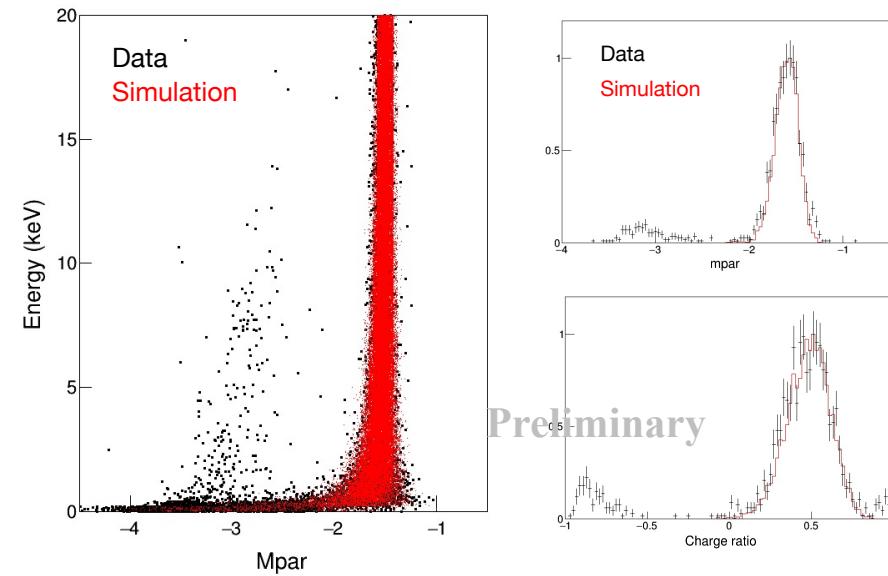
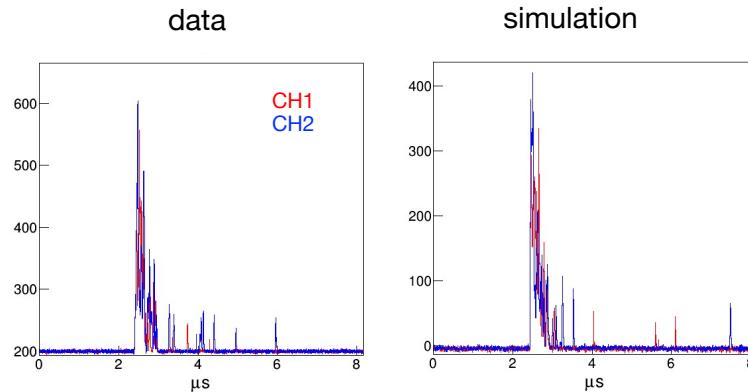


- Noise rejection cuts:
using mean decay time related parameter
 $MPar = \log(MT1 * MT2)$
($MT1$: mean decay time of PMT1)



Event selections

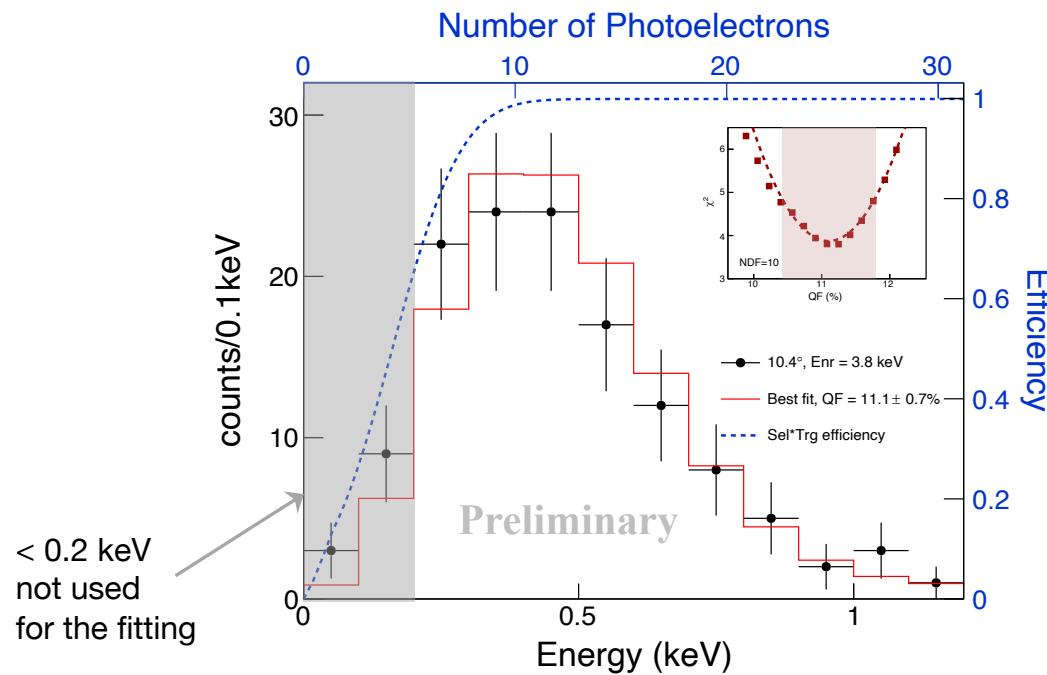
- Waveform simulation
 - developed to characterize low energy scintillation events
 - generates raw waveforms
 - Reconstructed variables from the waveform simulation are validated with calibration data.



Trigger and selection efficiencies are evaluated with the waveform simulation

Estimation of quenching factors

- Simulate nuclear recoil energy using GEANT4
- Deposited nuclear recoil energy processed to the waveform simulation
- Apply same event reconstruction and selection as the data
- χ^2 fit to the data with various simulated spectra from different QF values



High efficiency even below 1 keV

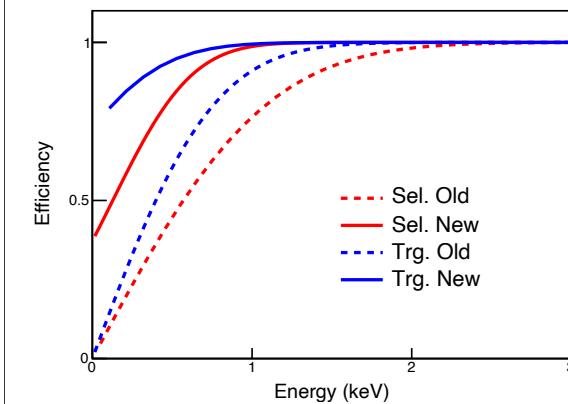
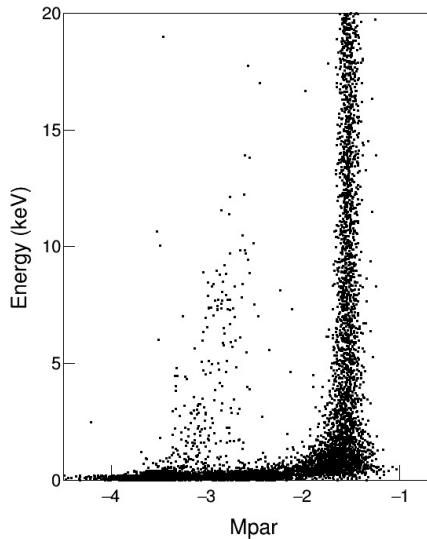
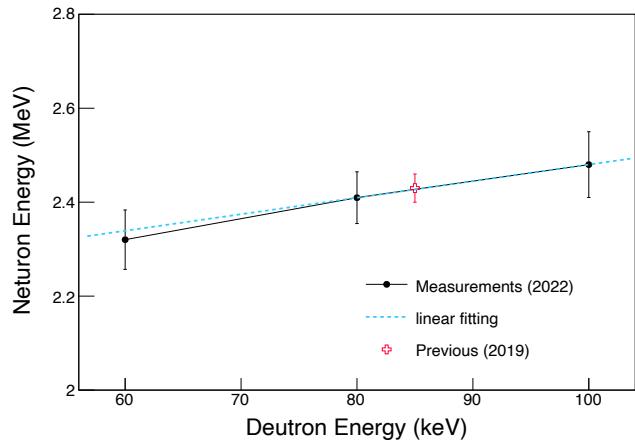
Na recoil energy distribution at 10.5°

$\text{Enr} = 3.75 \pm 0.02 \text{ keVnr}$

Best fitted QF = $11.10 \pm 0.69\%$

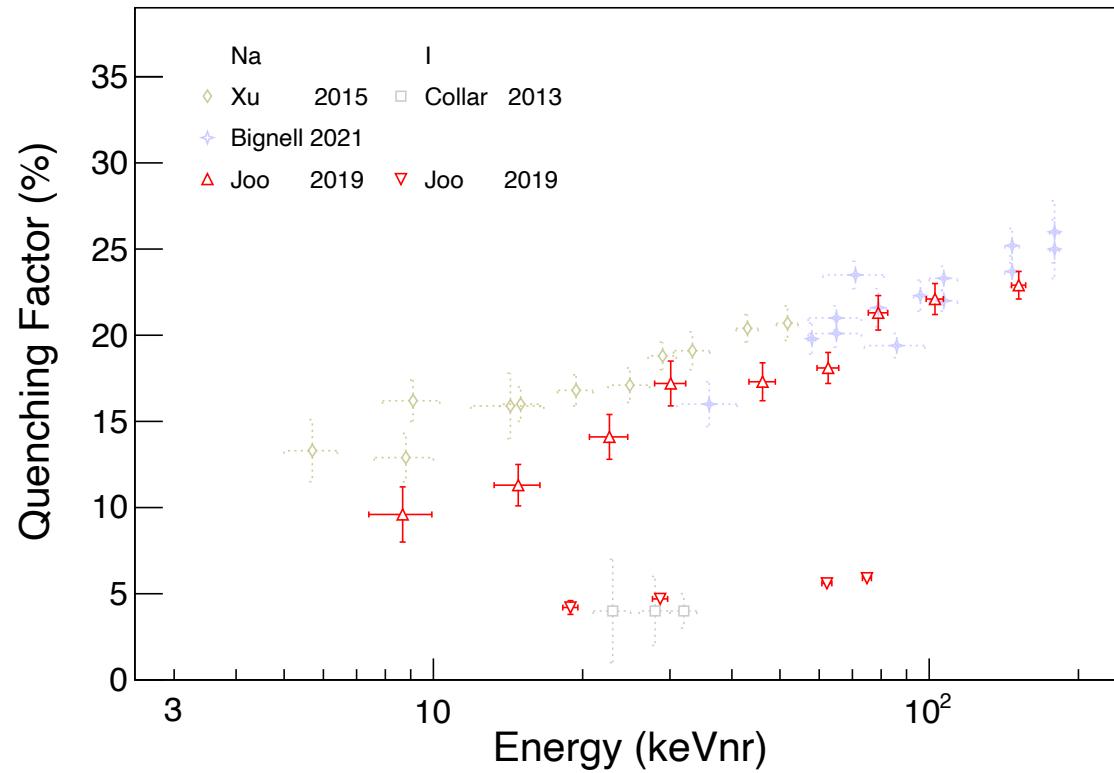
Revisit previous measurements

- Neutron energy update
 - 2.43 ± 0.03 MeV → 2.34 ± 0.06 MeV
 - Same event selection with the waveform simulation is applied
(Mean decay time parameter)
 - Selection, trigger efficiencies are also updated



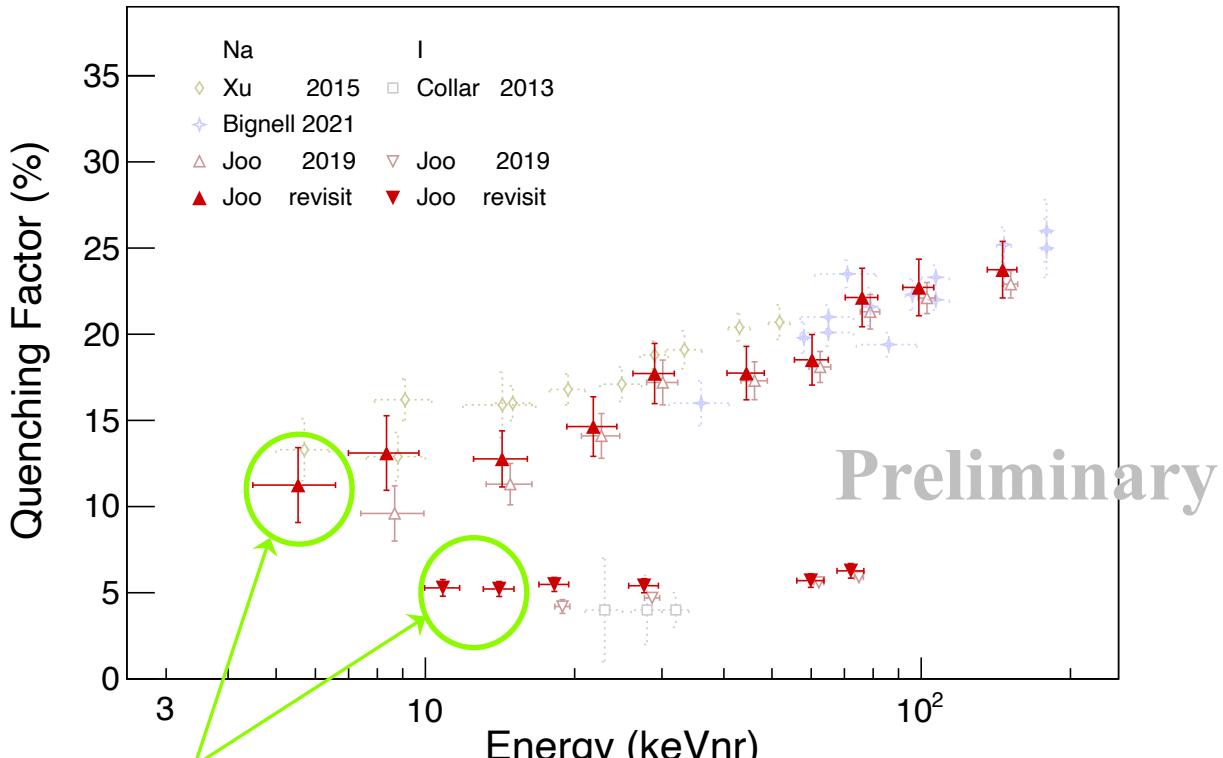
Quenching Factor for Na and I

- Previous results

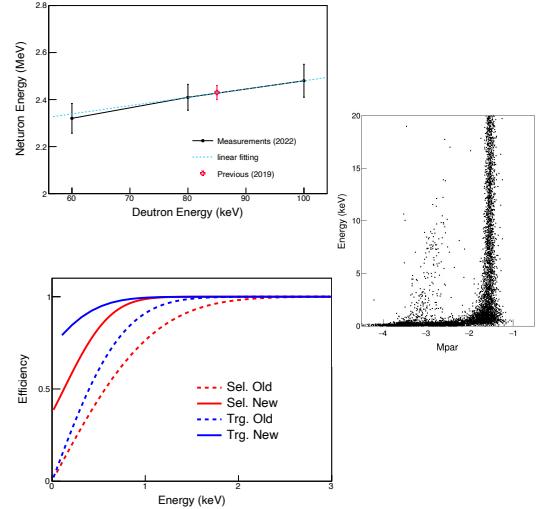


Quenching Factor for Na and I

- Revisit previous measurements:
(Neutron energy, event selections, efficiencies update)

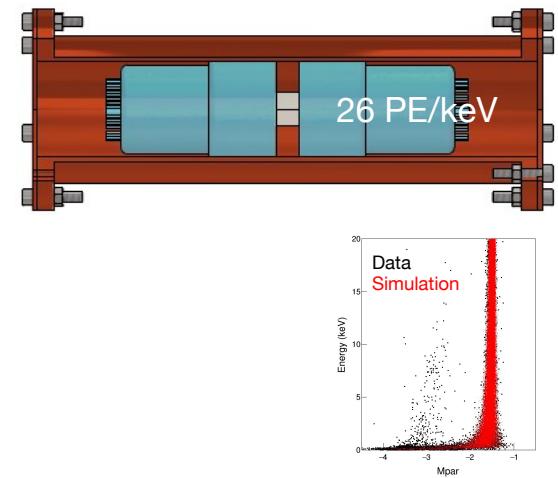
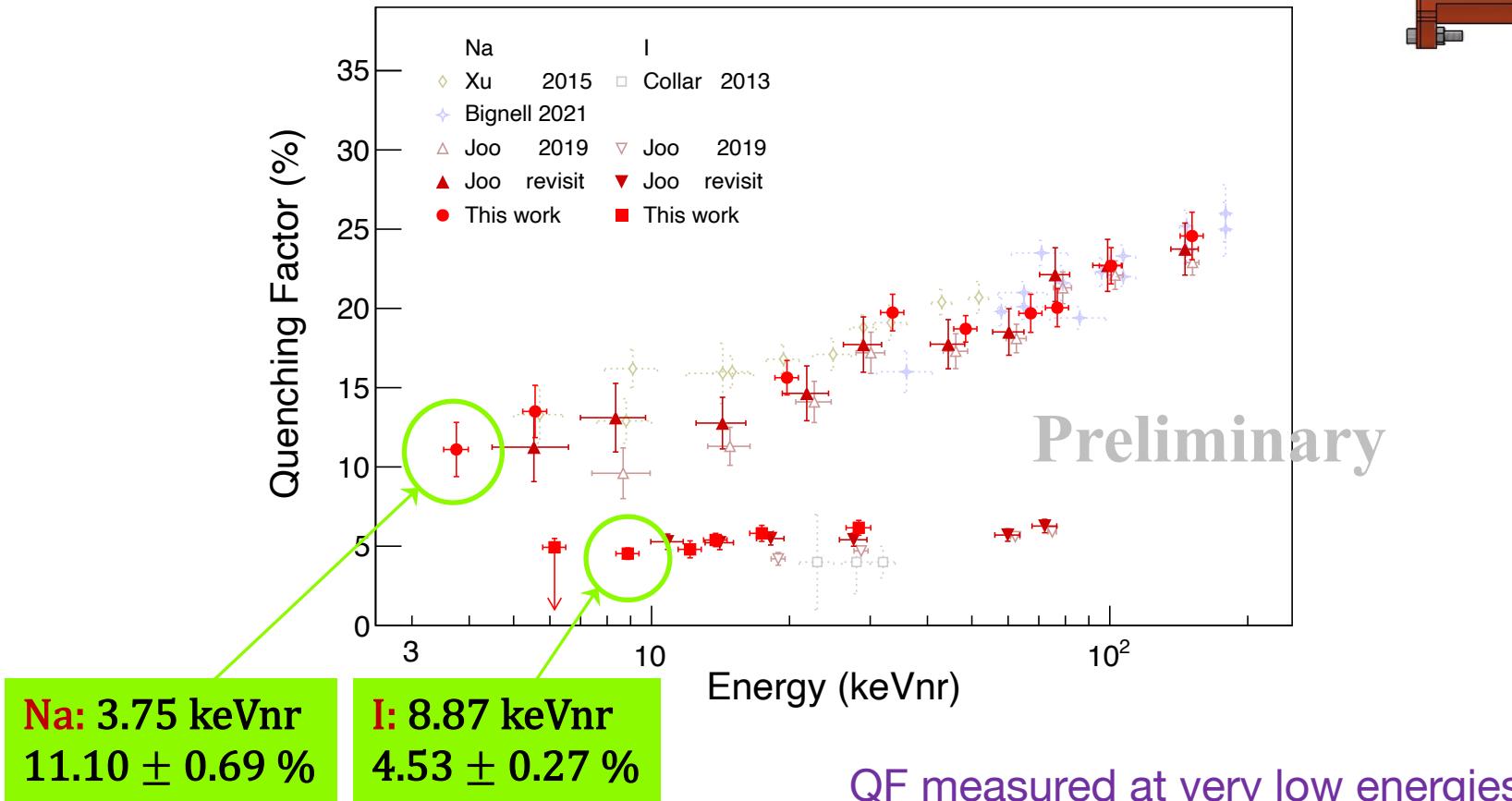


Exploring lower energies
through new event selections!



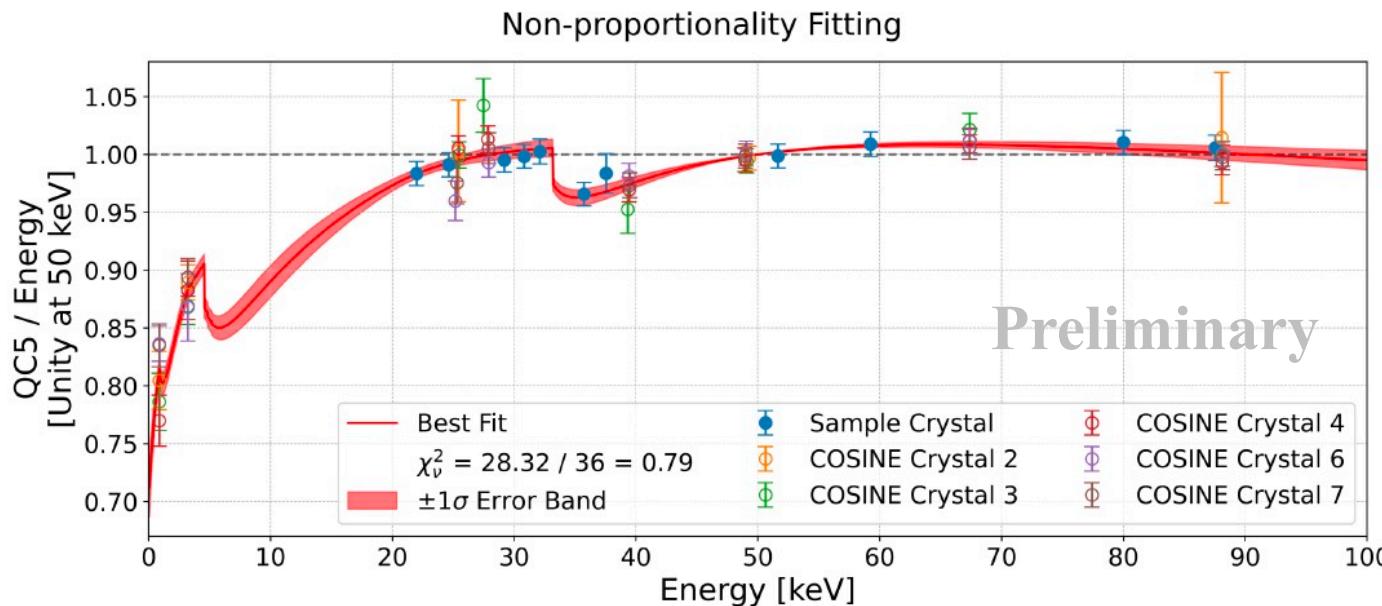
Quenching Factor for Na and I

- More measurement:
(High light yield detector, waveform simulation)



Non-proportionality (nPR) in the light output

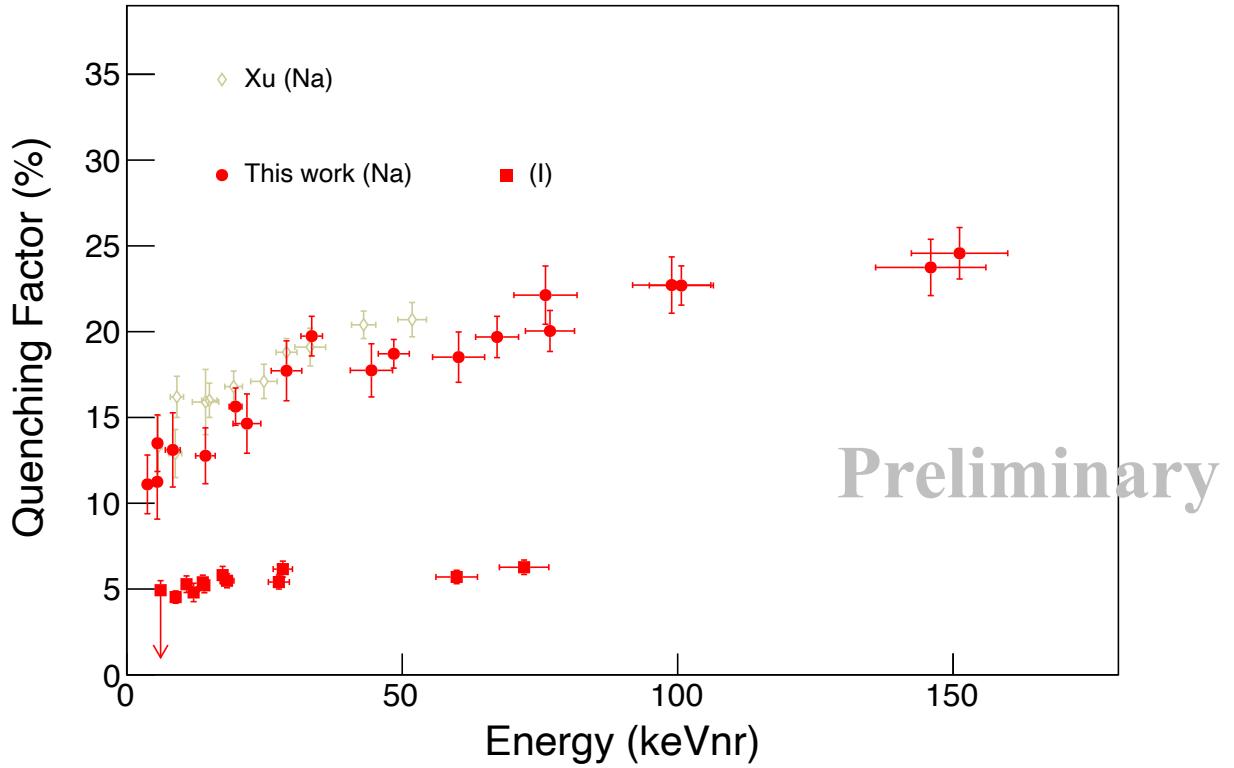
- Non-proportional behavior of scintillation detectors are well known phenomena
- Investigation of nPR in NaI(Tl): **X-ray and Gamma (not for electron)**
 - measurement using external radioactive source: ^{241}Am , ^{133}Ba , ^{109}Cd , and ^{137}Cs
 - internal radioactive in COSINE crystal: ^{210}Pb , ^{22}Na , and ^{40}K , cosmogenic: ^{125}I , ^{113}Sn , and ^{109}Cd



QF determined using Eee calibrated at 59.54 keV → Impact of nPR on the QFs?

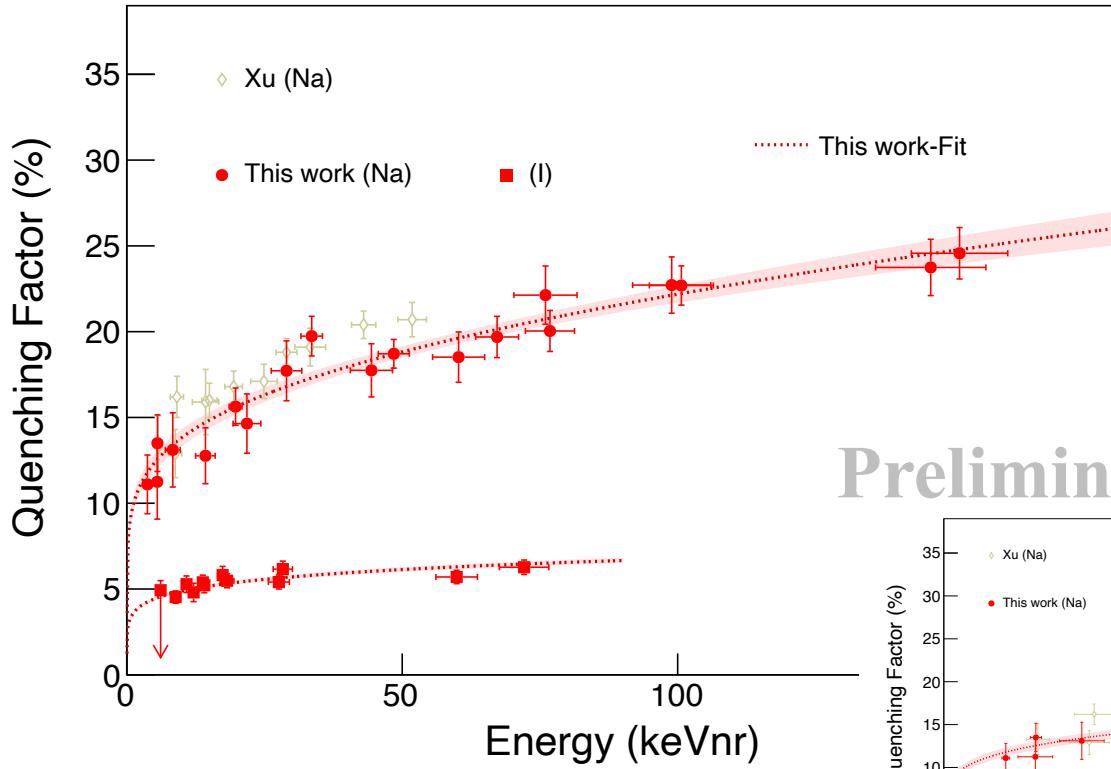
Impact of nPR on the QFs

- Our all measurements



Impact of nPR on the QFs

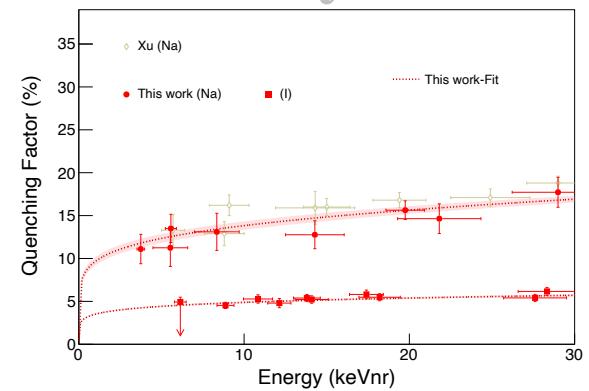
- Fitting with modified Lindhard model



$$f(E_R) = \frac{kg(\epsilon)}{1 + kg(\epsilon)}$$

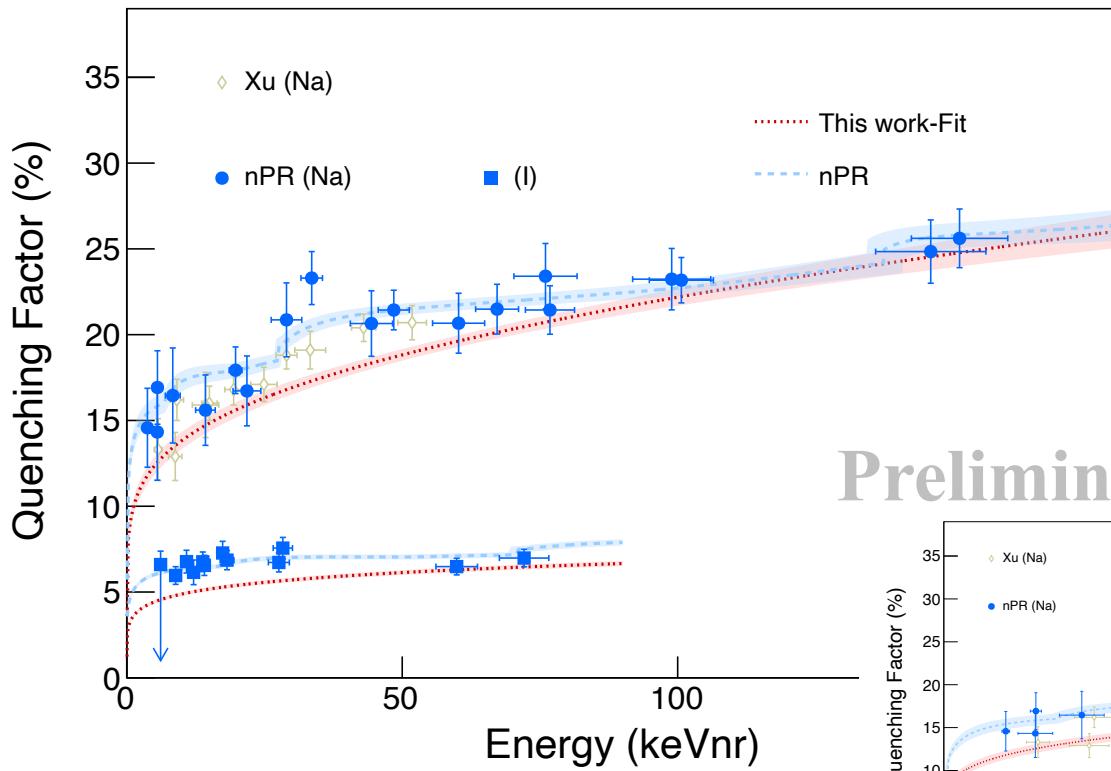
$$g(\epsilon) = 3\epsilon^{0.15} + 0.73\epsilon^{0.6} + \epsilon$$

modified Lindhard model
(JCAP11(2019)008)

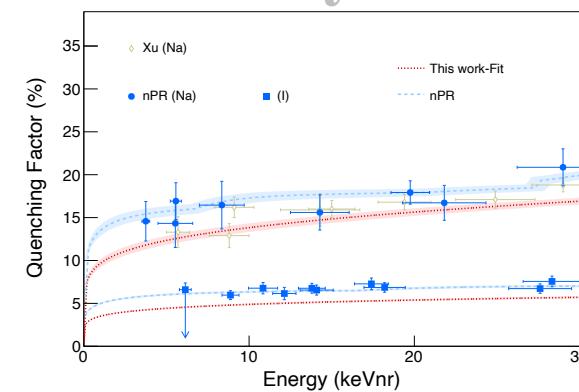
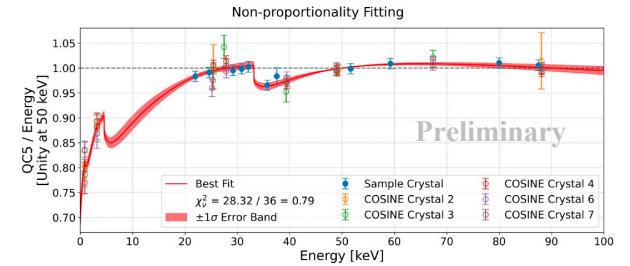


Impact of nPR on the QFs

- QF increases 30% at 5 keVnr (Na)



Preliminary



Summary

- QF is essential to understand nuclear recoil energies.
- Revisit previous measurements : Neutron energy calibration and event selection were updated.
- New measurements were conducted using high light yield detector 26 PE/keV.
- Develop the waveform simulation for event selection criteria and efficiency estimation
- For Na, $11.10 \pm 0.69\%$ at 3.75 keVnr, $4.53 \pm 0.27\%$ at 8.87 keVnr for I
- Impact of non-proportionality in light output investigated : An increase of about 30% QF at 5 keVnr for Na

