Calibrating nuclear recoil detectors for rare event searches

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Publication related to this talk

- Review of common calibration techniques
- Analysis of common biases
- Recommendation on data presentation

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ANNUAL REVIEWS

Annual Review of Nuclear and Particle Science

Detection and Calibration of Low-Energy Nuclear Recoils for Dark Matter and Neutrino Scattering Experiments

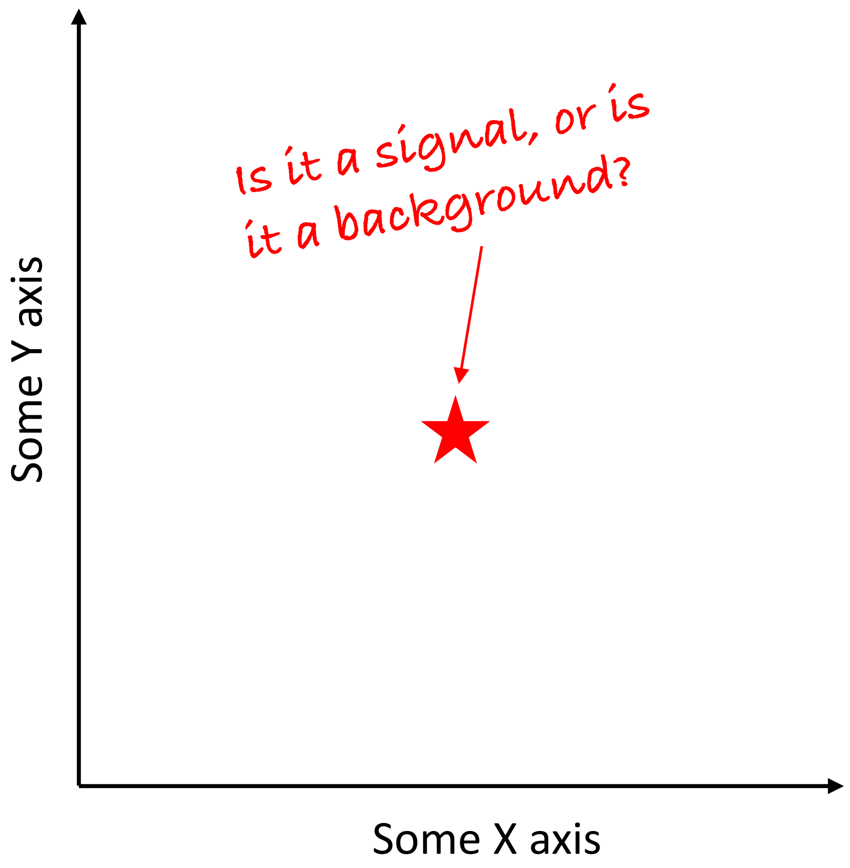
Jingke Xu,[1] P.S. Barbeau,[2] and Ziqing Hong[3]

The importance of calibrations

An uncalibrated instrument is not much different from a toy

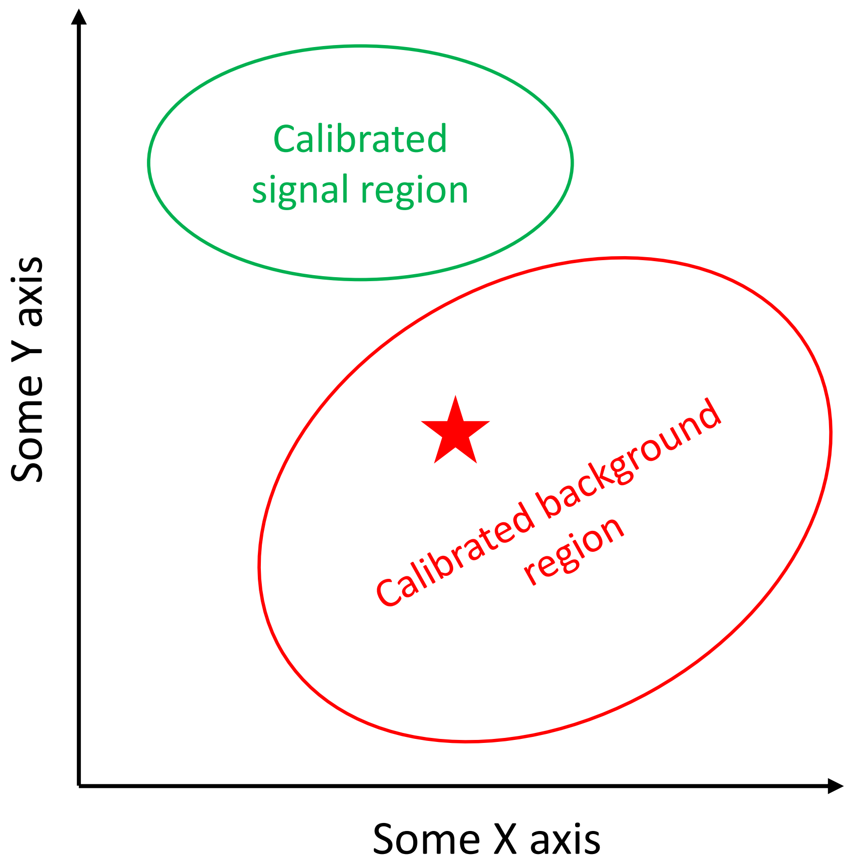
Calibration in rare event searches

- Rare event searches anticipate few events and each observation counts
- How to decide if an event is a signal or a background?
- If signal, what does it tell us: Energy, position, type of interaction, etc?



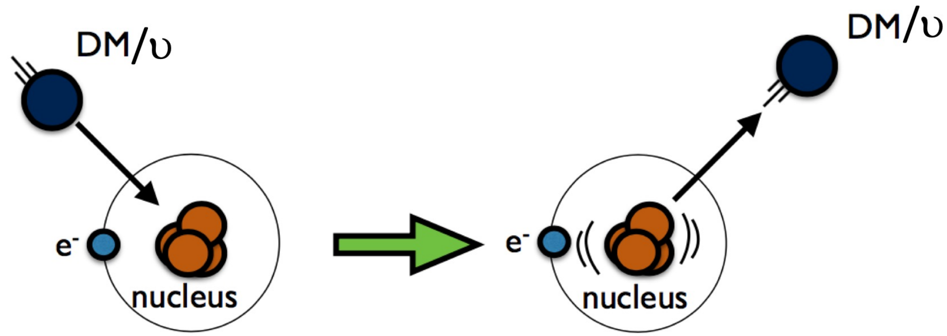
Calibration in rare event searches

- Rare event searches anticipate few events and each observation counts
- How to decide if an event is a signal or a background?
- If signal, what does it tell us: Energy, position, type of interaction, etc?
- Questions may be answered with robust calibrations



Nuclear recoil signals

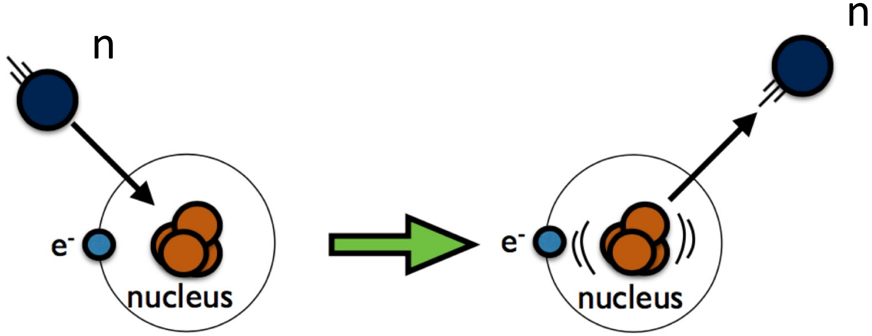
- WIMP dark matter searches center on the detection of nuclear recoils (NRs)
  - Identification of dark matter is a high priority of particle physics
  - Even electrophilic dark matter can produce significant NRs
- Coherent Elastic Neutrino-Nuclear Scatters (CEvNS) produce NRs
  - Recently observed
  - Possible pathway to BSM physics
- NRs offer possible discrimination from ambient electron recoil (ER) backgrounds



Production of desired NR signals

NR detectors are usually calibrated with neutron scatters

- Single neutron scatter with an at-rest nucleus has simple kinematics
- Incoming neutron energy and outgoing neutron angle constrains NR energy
- Scattered neutrons can be tagged with detectors with n/γ discrimination
- Neutron timing from source and/or tagging reduces backgrounds
- Elastic scatter of mono-energetic neutrons has driven the improvement of calibration precision



$$E_T = \frac{2E_n m_n^2}{(m_T + m_n)^2}\left(\frac{m_T}{m_n} + \sin^2\theta - \cos\theta\sqrt{\left(\frac{m_T}{m_n}\right)^2 - \sin^2\theta}\right)$$

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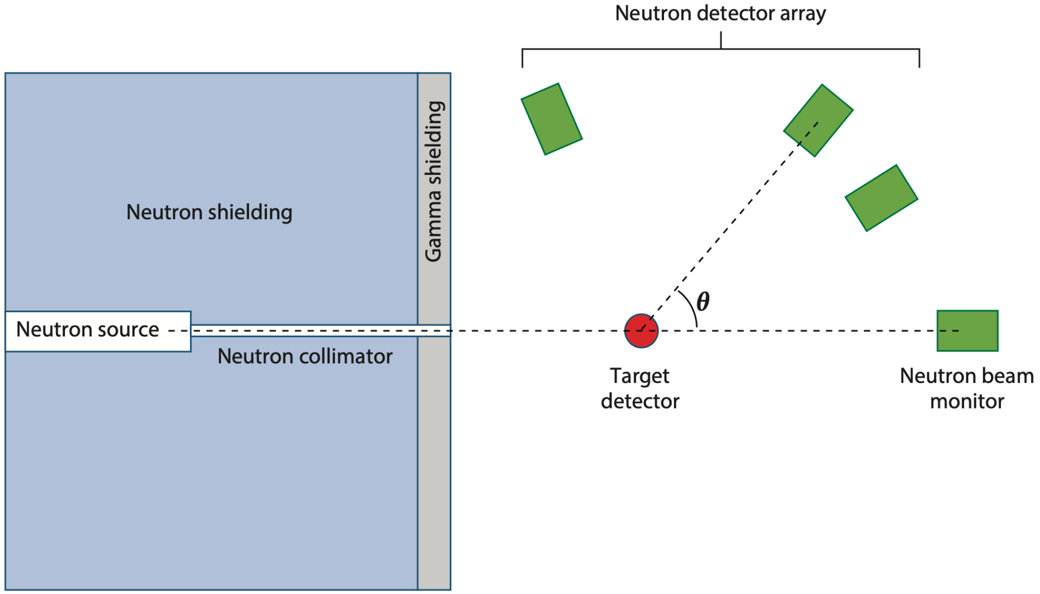

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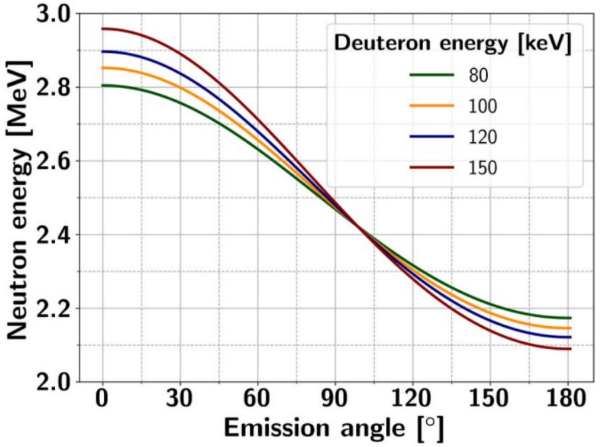
Selection of neutron sources

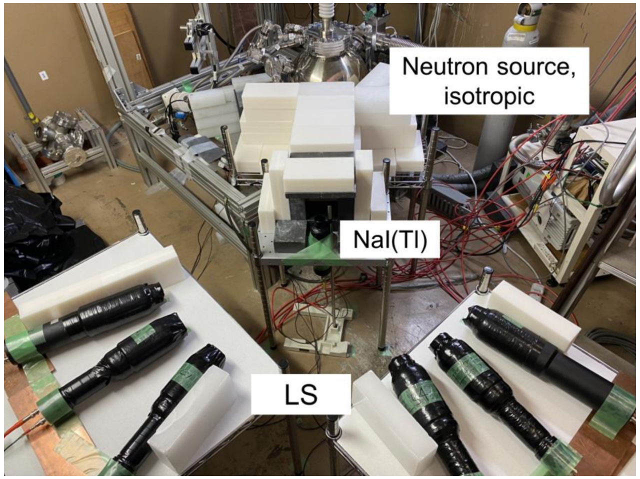
- What neutron flux is needed?
- Is the neutron source mono-energetic or continuous?
- How well is the neutron energy measured?
- Does the neutron energy vary with operation conditions?
- Can you measure the neutron energy in situ/event-by-event?
- Do you know the neutron production time?



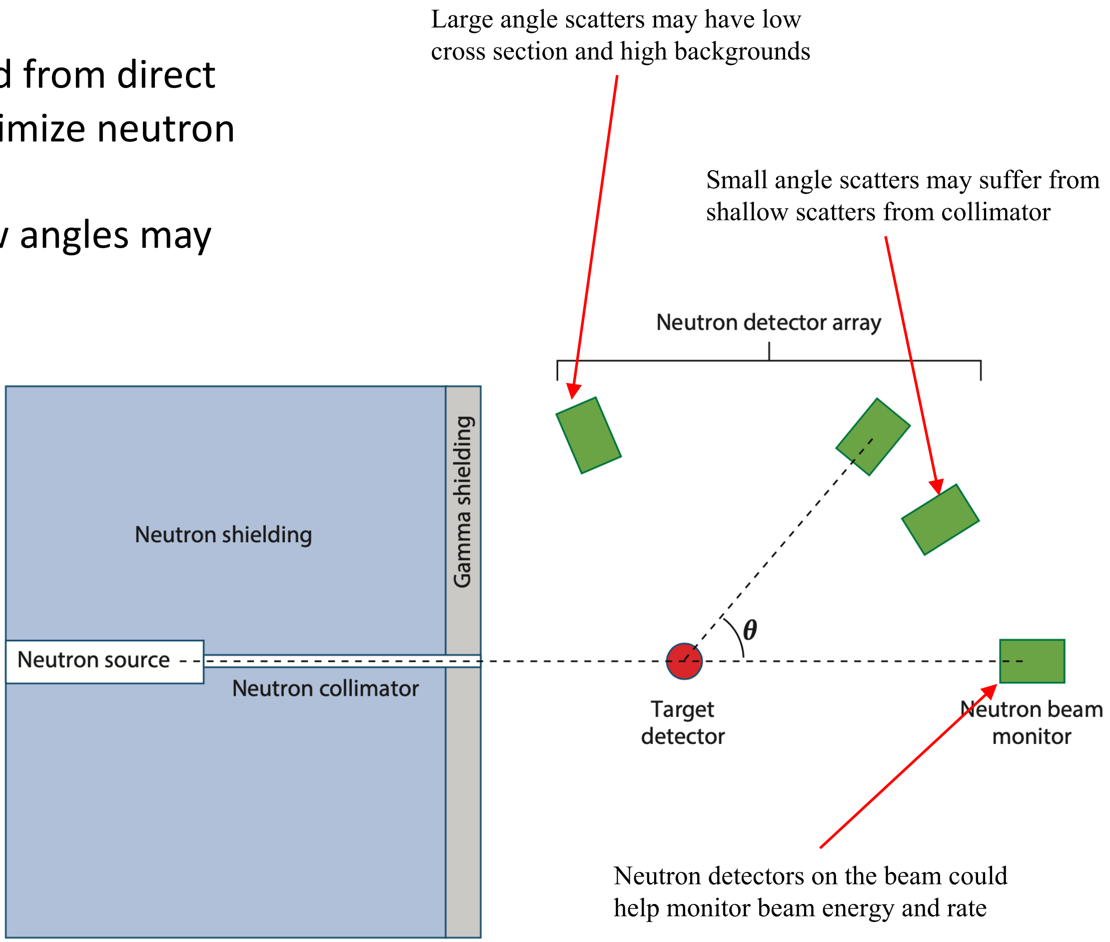
Source	Energy: Range (MeV)	Energy: Distribution	Yield	Timing
^{252}Cf	0–10 (average of 2)	Continuous	10^3 n/s/μCi	γ-Tagging[a]
Fission reactors	0–10 (average of 2)	Continuous	10^{12}–10^{16} n/s/MW$_{th}$	NA
AmBe	0–10	Continuous	$\sim 5 \times 10^{-5}$ n/α	γ-Tagging[a]
PuBe	0–10	Continuous	$\sim 5 \times 10^{-5}$ n/α	γ-Tagging[a]
AmLi	0–1.5 (average of 0.45)	Continuous	$\sim 10^{-6}$ n/α	ND
SbBe	0.023	Monoenergetic	$\sim 10^{-5}$ n/γ	NA
YBe	0.152	Monoenergetic	$\sim 10^{-5}$ n/γ	NA
D-D	2–3	Monoenergetic	$\lesssim 10^9$ n/s	$\lesssim 10$ μs
D-T	13–15	Monoenergetic	$\lesssim 10^{10}$ n/s	$\lesssim 10$ μs
p-Li	0–2	Monoenergetic	Varies[b]	$\gtrsim 1$ ns
p-V	0–0.2	Monoenergetic	Varies[b]	$\gtrsim 1$ ns

Configuration for neutron detectors

- Ideal neutron detector should be fast, and have n/γ discrimination capabilities
- Neutron detectors should be shielded from direct neutrons, and placement should minimize neutron multi-scatter backgrounds
- Neutron scatters of very high and low angles may suffer low signal to noise ratios



A neutron detector setup that may lead to significant multi-scatter backgrounds



Bias from measurement efficiencies

- Detectors often have a low signal acceptance for small signals
- Near-threshold measurements may see a higher apparent signal distribution if signal acceptance is unaccounted for
- Similar bias may rise in high energy region from cuts (dynamic range/saturation, etc)

Mitigation strategies:

- Rigorously evaluate signal acceptance
- Check rate with expectation
  - How accurate is the expectation?
- Adopt a triggerless scheme?
  - Trigger on coinciding signals from neutron production/detection

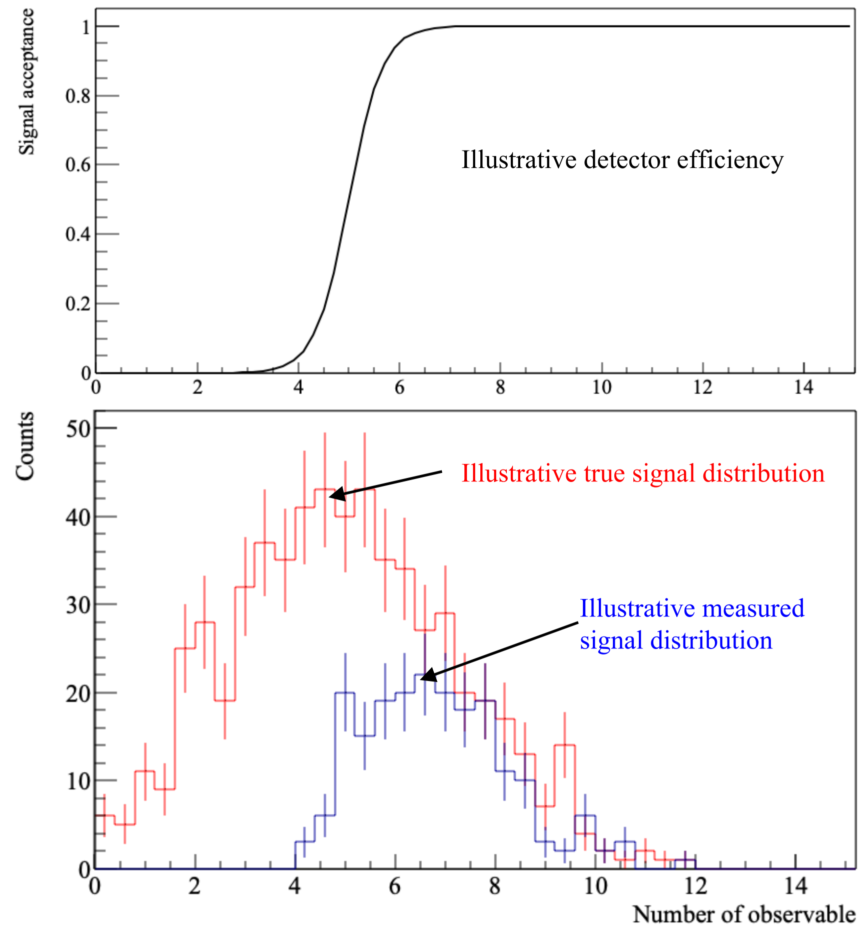
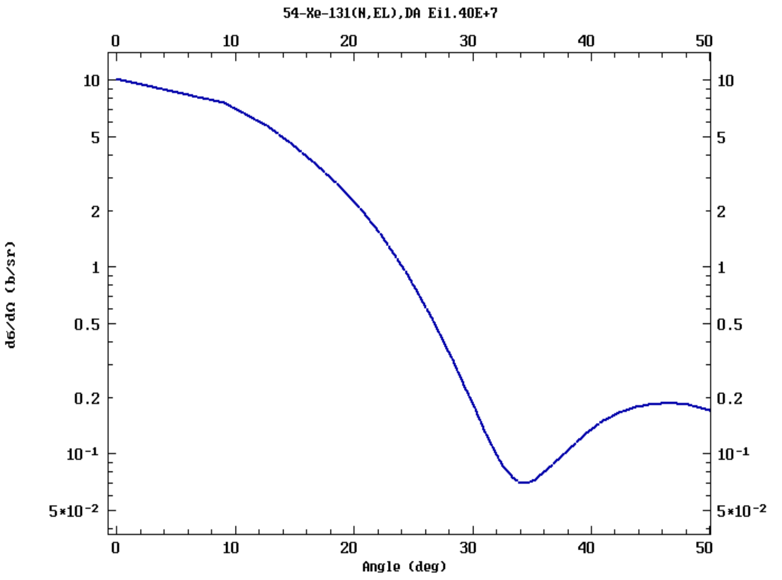


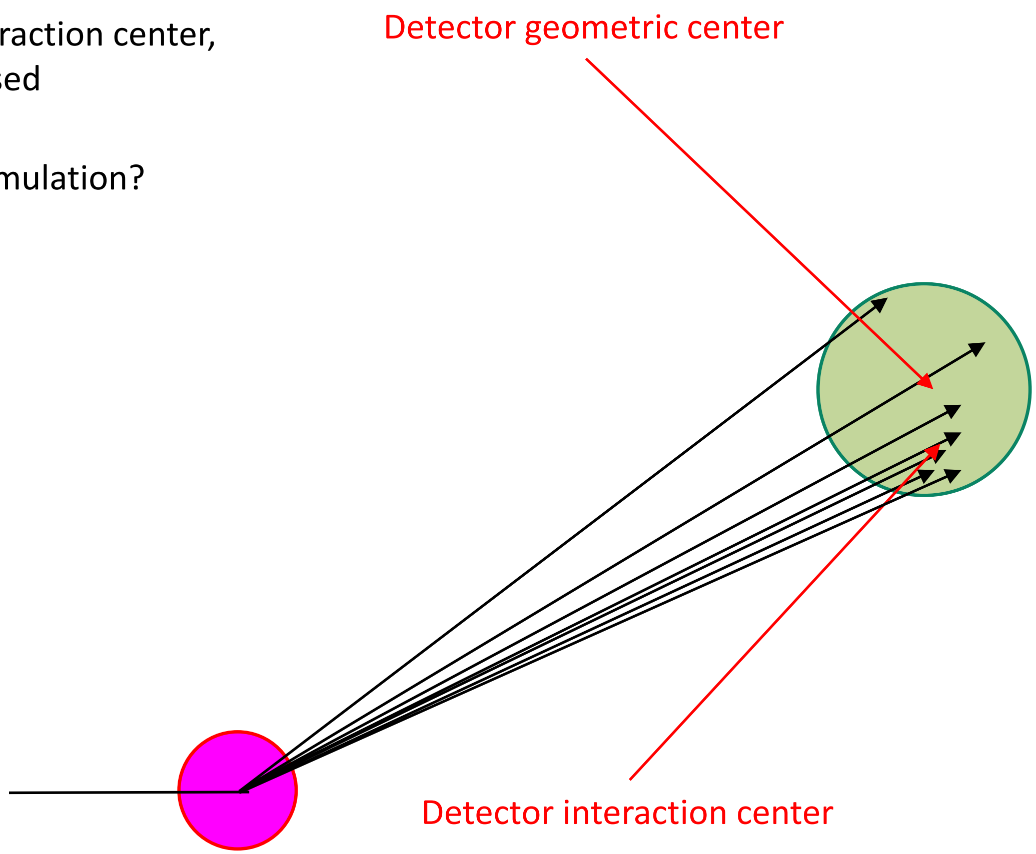
Illustration of measurement bias due to low detector efficiencies for small signals

Bias from neutron scatter cross section

- Elastic neutron scatters are often forward-peaked, and may have resonances at certain angles
- Detector geometric center may not be the interaction center, and estimate of mean scatter angle can be biased
- May be mitigated with event-level simulations
  - What is the cross section uncertainty in simulation?



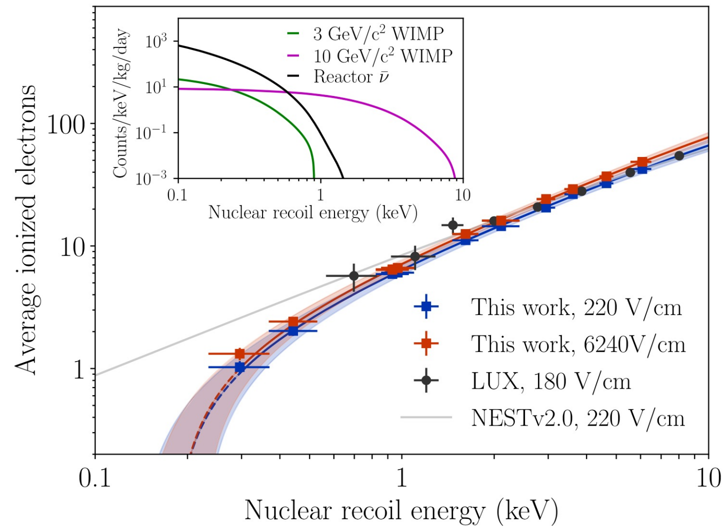
Example: angular cross section of 14MeV n scatters with ^{131}Xe

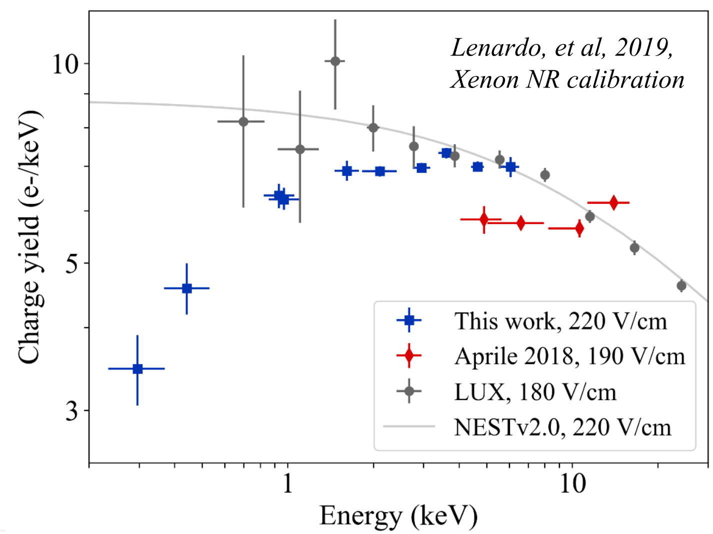


Presentation of calibration result

If total number of quanta can be measured

- Reporting number of quanta vs energy
  - Most useful for modeling and comparison
  - Graph may be dominated by energy scaling
  - Good for tabulated presentation
- Reporting yield vs energy
  - Good for studying microphysics
  - May cause energy uncertainties to be redundantly reflected in both X and Y axis
  - Good for graphical presentation
- Underlying assumption: signal efficiency in the measurement is subdominant





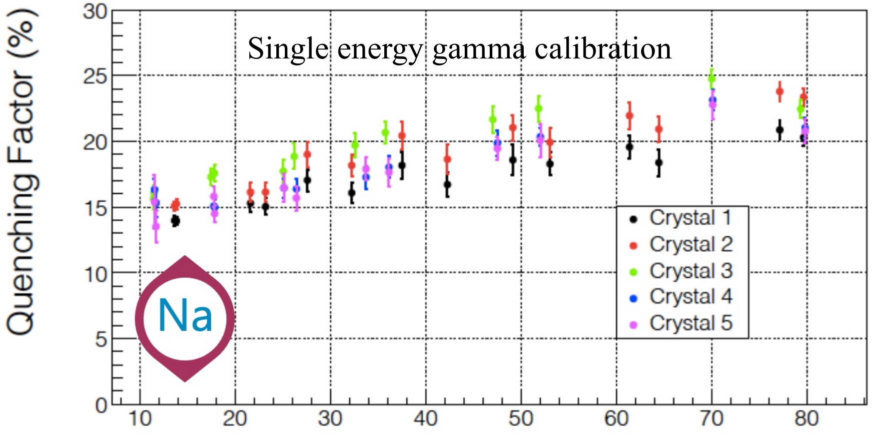
Presentation of calibration result

Quenching factor is often reported when total number of quanta can not be obtained

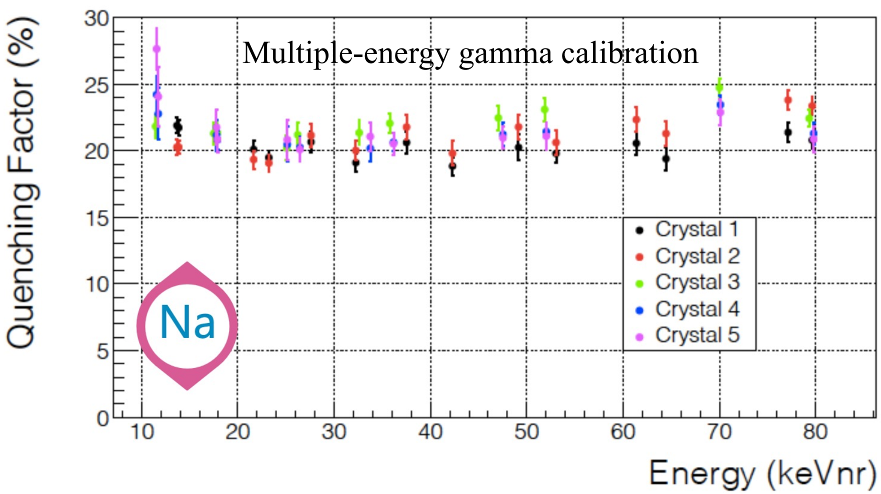
- Use yield values relevant to a reference measurement to cancel efficiencies
- Choosing different reference calibrations can lead to apparent discrepancies

Recommendations on reference choice

- Similar characteristics with NR signals
- Correct any residual efficiency difference
- Easily obtainable calibration in large and small experiments
- Report what reference you choose

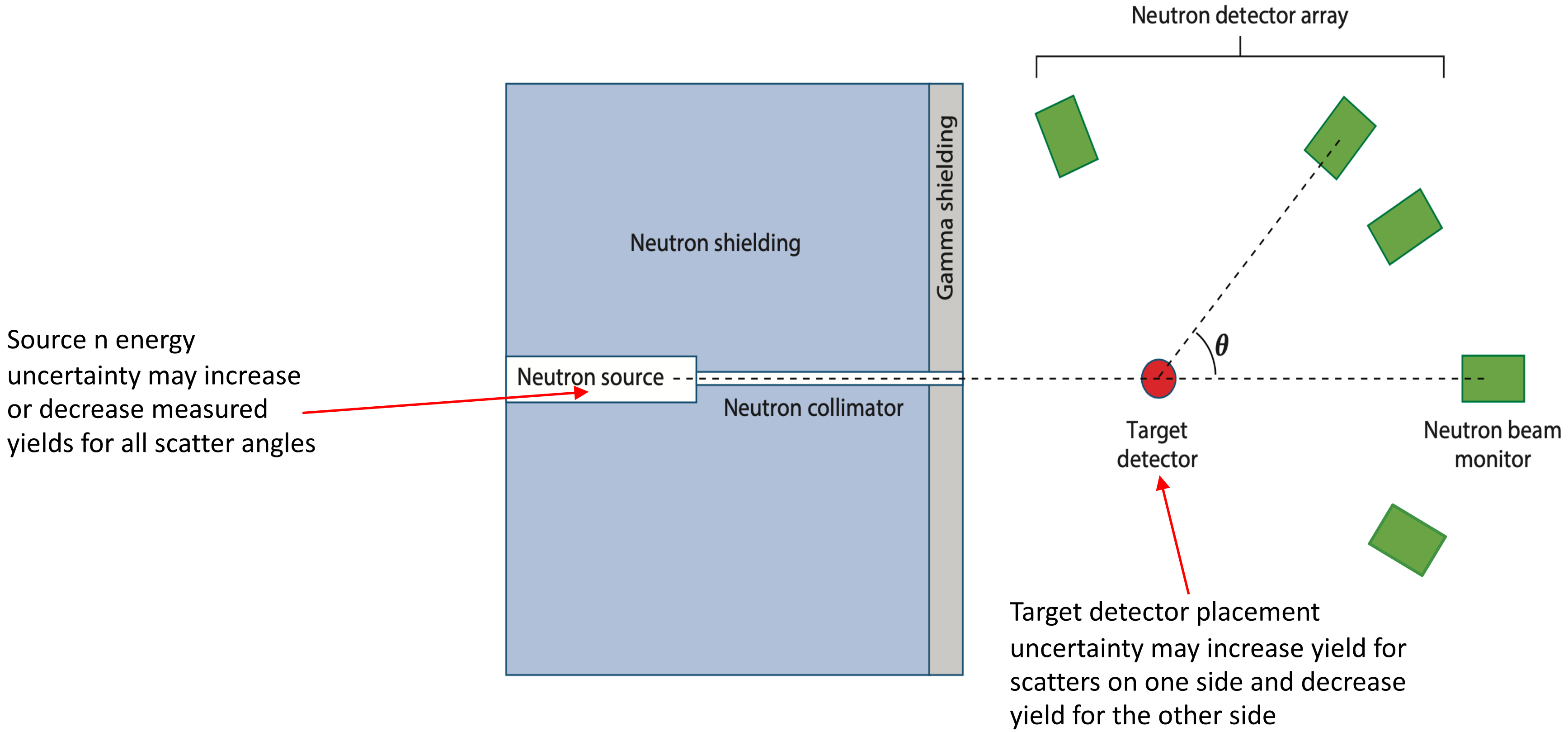


Cintas et al, 2022



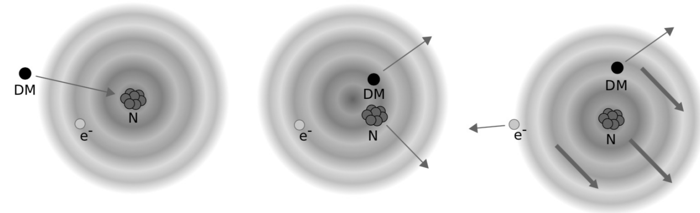
Presentation of calibration result

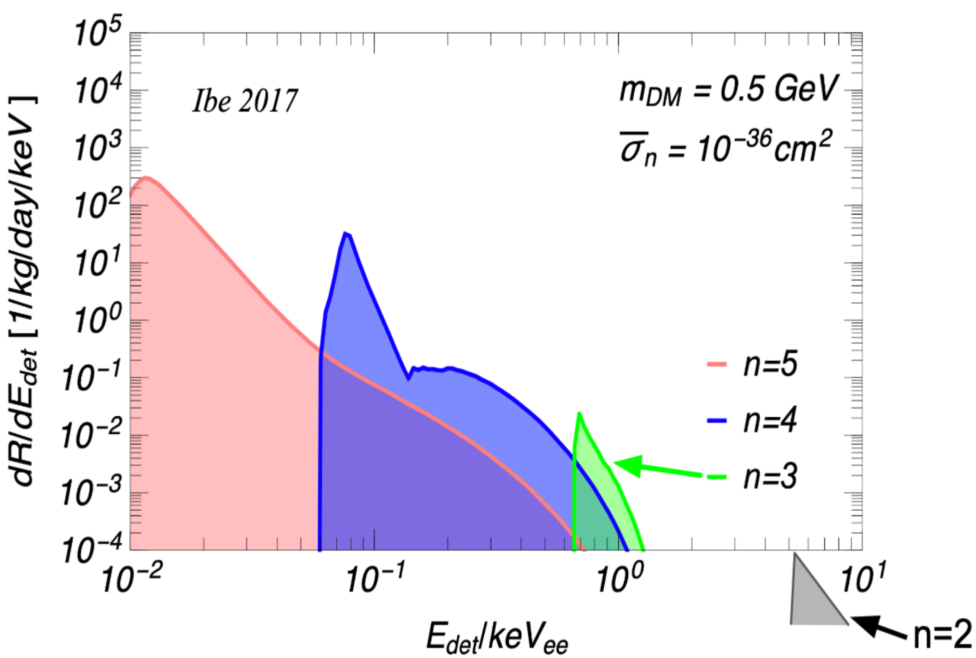
- Separate systematic and statistical uncertainties
- Break down different types of systematic uncertainties when possible
- Consider uncertainties from indirect sources



More than calibration…

- NR calibrations measure the elastic and inelastic neutron interaction cross sections
- NR calibrations can be a pathway to measure new physics processes
  - Migdal effect (*Lenardo, 11/7*)
  - Directional/Channeling effect





LLNL setup for LXe Migdal measurement, arXiv:2307.12952

Summary

- Detection of nuclear recoils (NRs) is central to WIMP dark matter searches and coherent elastic neutrino-nucleus scatter studies
- NR calibration enables an experiment to characterize signal responses and possible signal-background discrimination
- Good progress has been reported in NR calibrations, both in improving accuracy and in lowering energy thresholds
- Biases may rise from calibration and can be mitigated
- We made recommendations on how to report experimental results to facilitate comparison of different results
- Refer to *Annu. Rev. Nucl. Part. Sci. 2023. 73:95–121* for more information

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