Calibration of SuperCDMS Dark Matter Detectors for Low-Mass WIMPs

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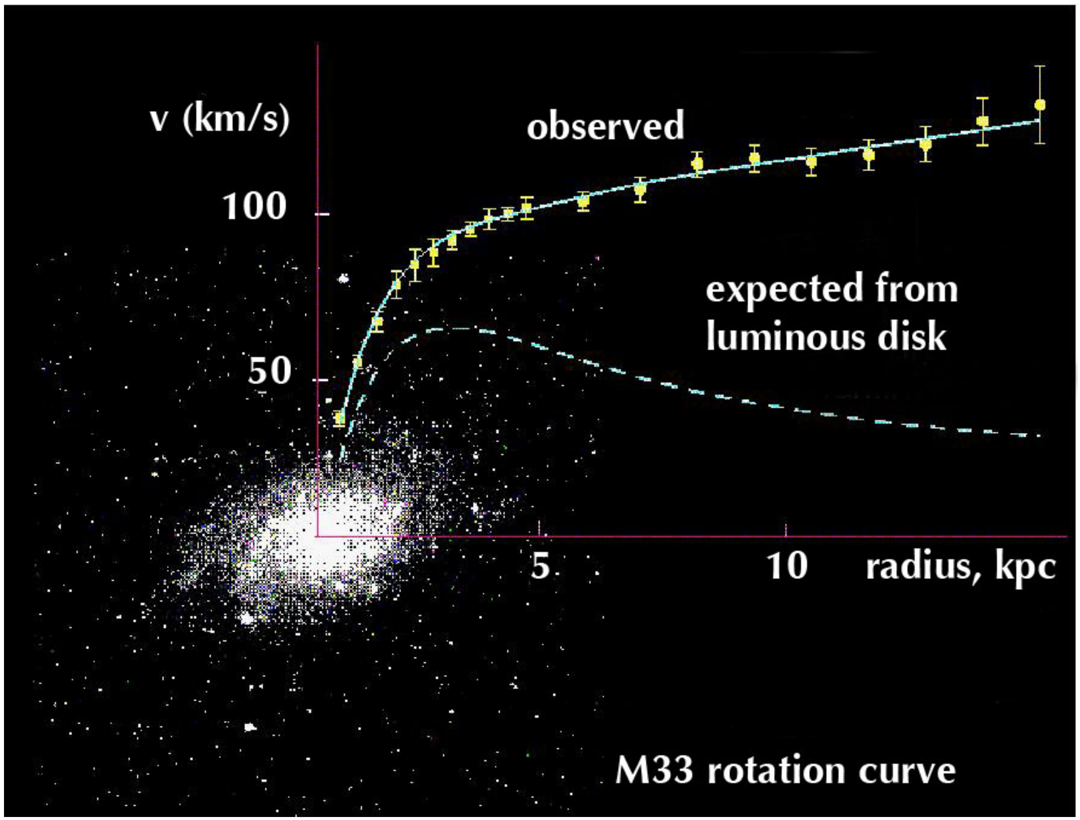
Evidence for Dark Matter
Galaxy Rotation Curves



- 1978: Rubin et al. measured rotation speeds of spiral galaxies.
- Disagreement with expectation from luminous disk.

➡ Early evidence of dark matter in galaxies.

Present data suggests that dark matter comprises ~85% of mass in the universe.

Direct Detection of Dark Matter

- Astrophysical evidence: Majority of dark matter **cannot** be normal baryonic.
- Non-baryonic particles postulated as dark matter constituents.
  - Interactions with normal matter at or below weak scale.
- Goal of “direct detection”:
  - Search for particle dark matter candidates.
  - Sensitive to predicted interactions with normal matter.

Hypothesized WIMP Particle

WIMP: Weakly Interacting Massive Particle

- Massive non-baryonic particle (~GeV/c^2-TeV/c^2).
- Predicted to interact with normal atoms via nuclear recoils.
- **Primary SuperCDMS search candidate.**

1 SuperCDMS intro & detector operating modes

2 Why calibrate our low-energy nuclear recoil energy scale?

3 How the nuclear recoil energy scale relates to “ionization yield”

4 How we aim to calibrate the nuclear recoil energy scale

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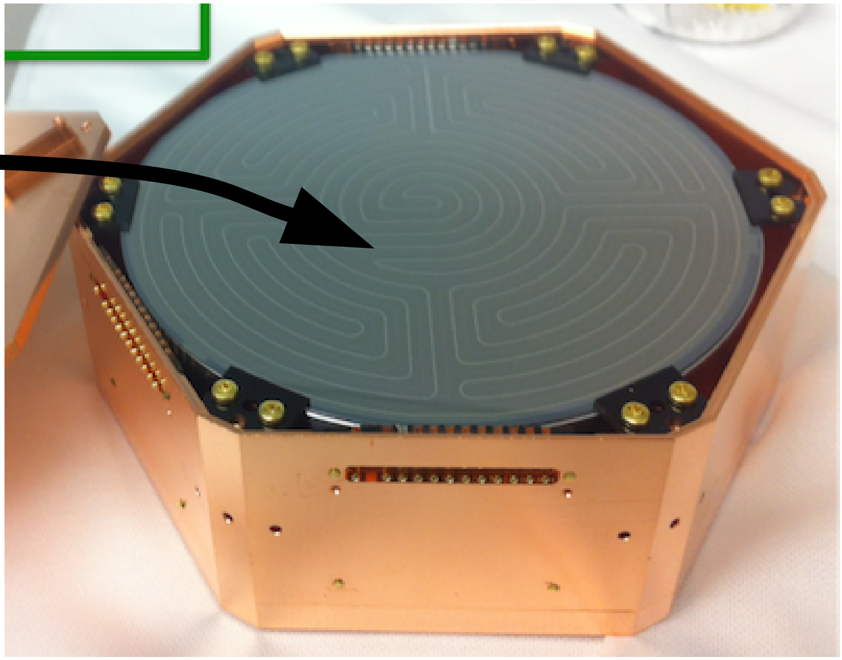
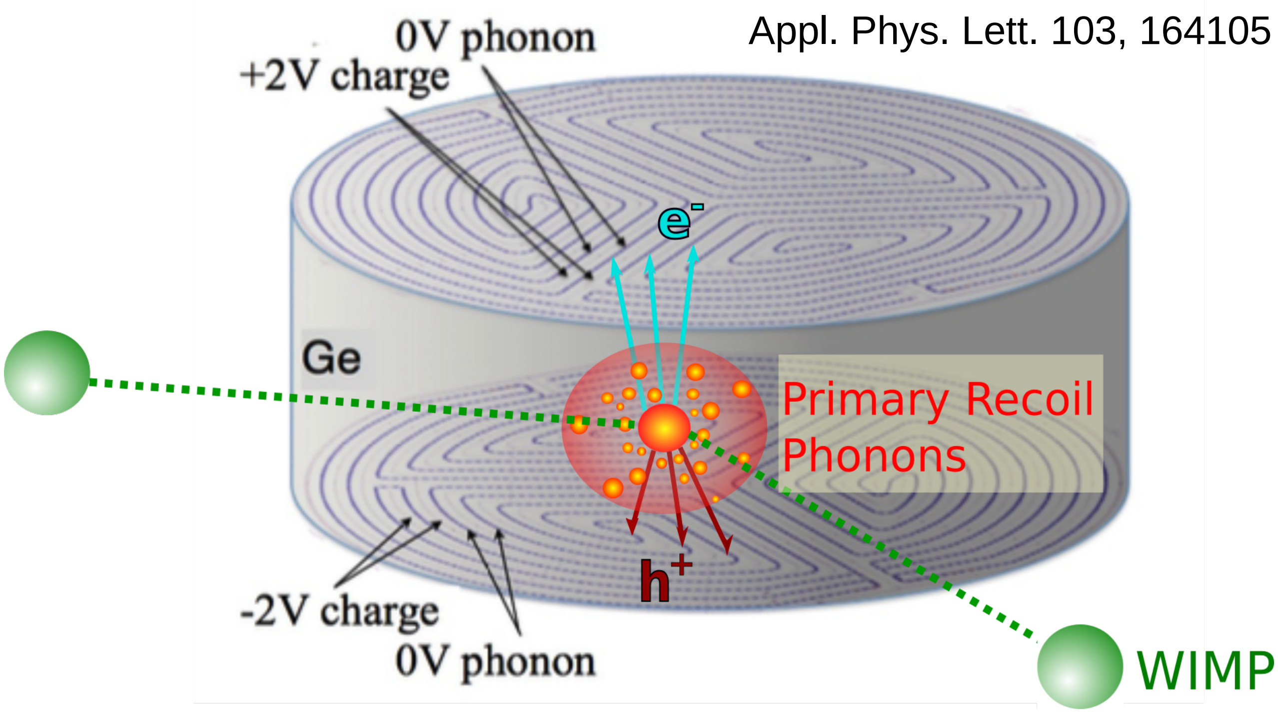
SuperCDMS Experiment

- Direct-detection WIMP search.
- Cryogenic semiconductor detectors.
- Measure WIMP-nucleon recoils via:
  - ionization
  - phonons
- World-leading sensitivity to low-mass WIMPs (1.6-5.5 GeV/c^2)



- Two detector operating modes: **iZIP** and **CDMSlite**

iZIP Operation

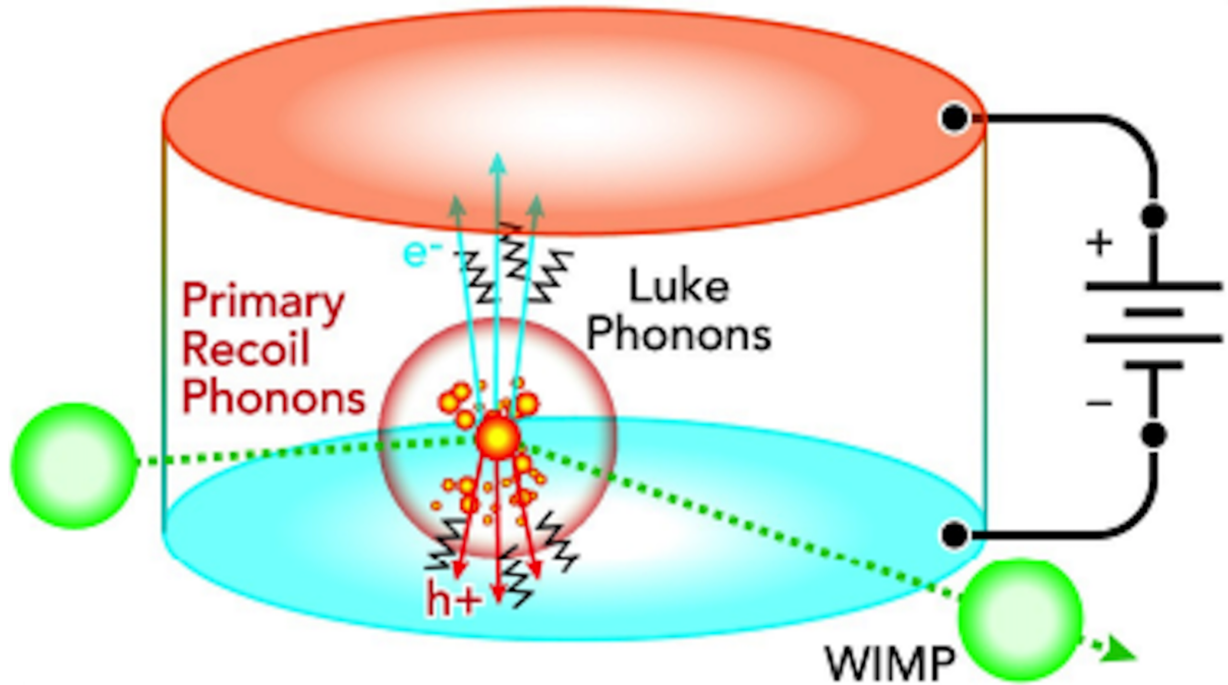


- 4V bias
- **Electron-hole (e-h) pairs** drift to electrodes.
- **Phonons** also produced.

- Measure **primary** ionization (e-h) and phonon energy.
- Compare primary phonon and ionization energies to discriminate **nuclear recoils (NR**) vs. **electron recoils (ER)**.

CDMSlite Operation

- 25-75V Bias.
- Primary e-h pairs pick up energy.
- Goes into producing "Luke phonons".



- Primary e-h signal **magnified** by Luke phonons.
  → sensitive to lower-energy recoil events than iZIP mode.
- Tradeoff: Luke phonons prevent ER/NR discrimination.

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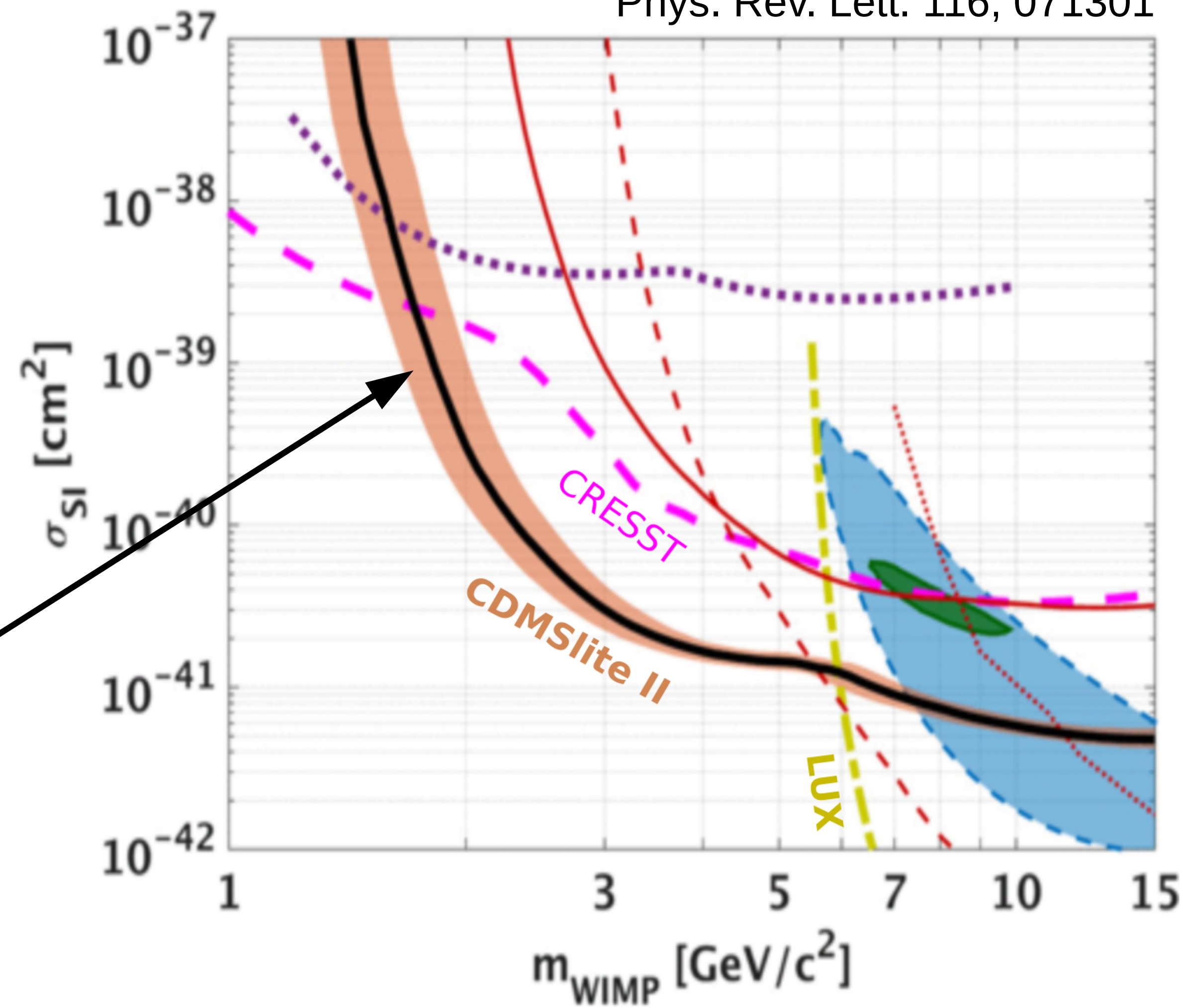
Latest SuperCDMS WIMP Sensitivity
Detectors in CDMSlite Mode

Phys. Rev. Lett. 116, 071301



Uncertainty band dominated by uncertainty in NR energy scale of detectors.

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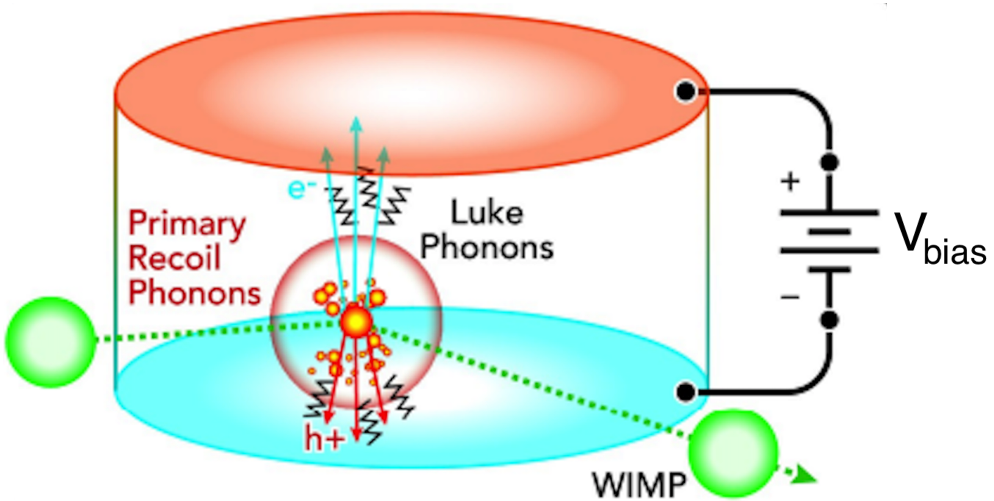
2 Why calibrate our low-energy nuclear recoil energy scale?

3 **How the nuclear recoil energy scale relates to "ionization yield"**

4 How we aim to calibrate the nuclear recoil energy scale

Ionization Yield

$$E_{\text{measured}} = E_{\text{recoil}} \left(1 + Y_{\text{ionization}} \frac{eV_{\text{bias}}}{\epsilon} \right)$$



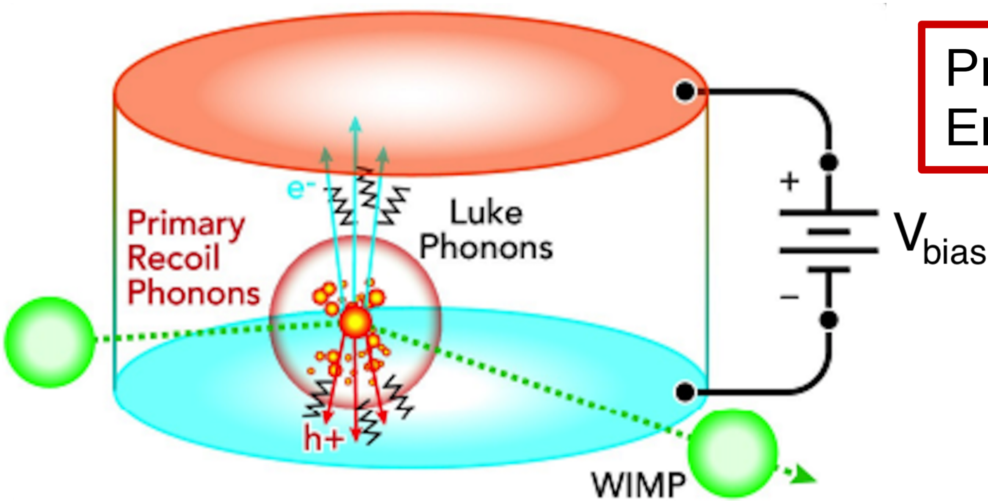
Ionization Yield

Measured Phonon energy

$$E_{\text{measured}} = E_{\text{recoil}}\left(1 + Y_{\text{ionization}}\frac{eV_{\text{bias}}}{\epsilon}\right)$$

Primary Recoil Energy

Ionization Yield



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Primary Recoil Energy

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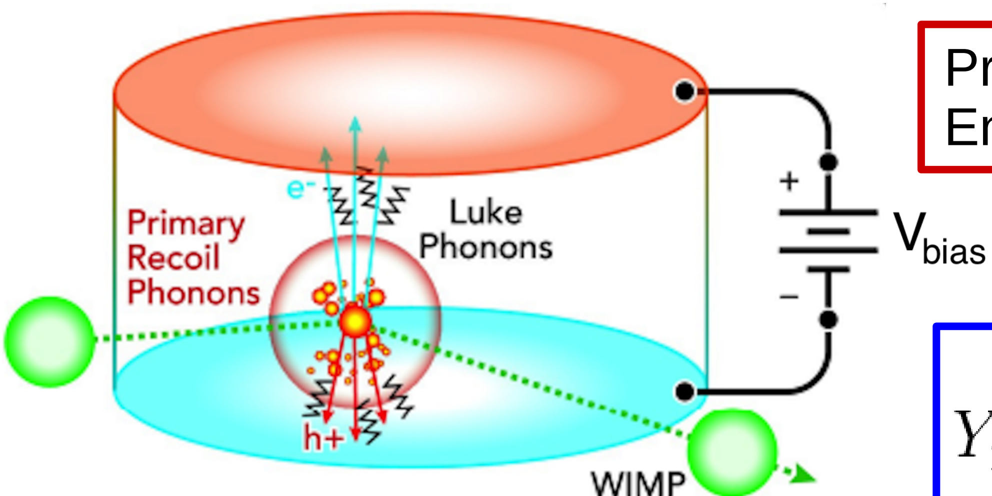

$$Y_{\mathrm{ionization}} = \frac{(E_{\mathrm{e/h}})_{\mathrm{primary}}}{E_{\mathrm{recoil}}} \begin{cases} \equiv 1 \text{ for ER} \\ < 1 \text{ for NR} \end{cases}$$

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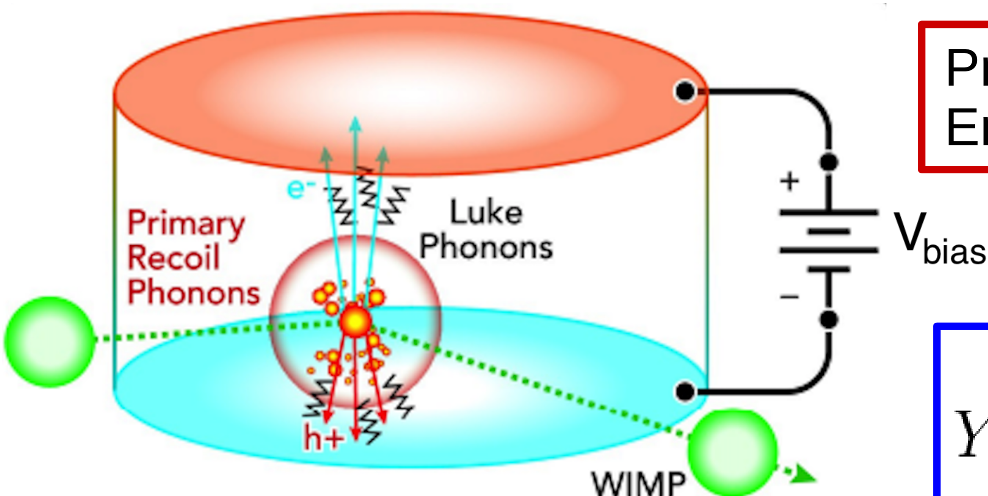

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- iZIP: Measures yield, but low accuracy at low recoil energy.
- CDMSlite: Cannot measure yield.

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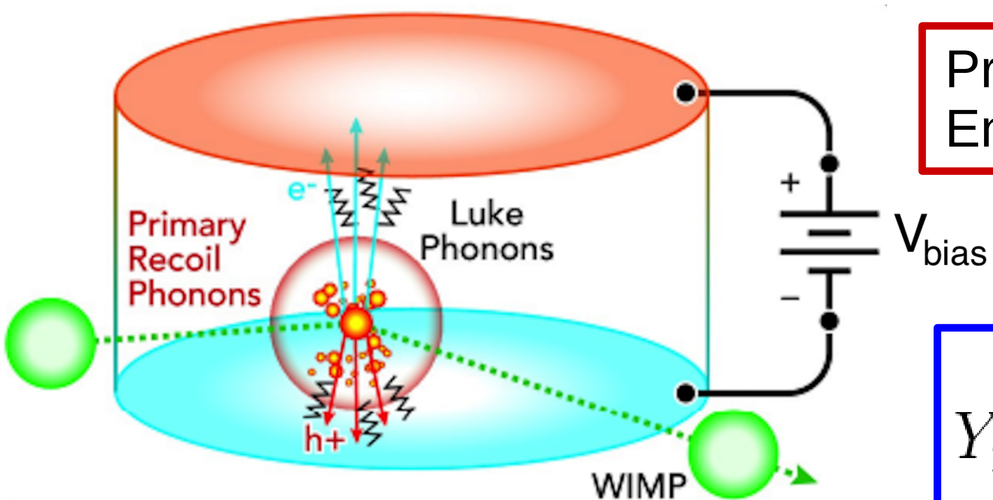
Primary Recoil Energy

Ionization Yield



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- iZIP: Measures yield, but low accuracy at low recoil energy.
- CDMSlite: Cannot measure yield.

Require ionization yield info

Lindhard Model for Ionization Yield

$$Y_{\text{ionization}}(E_r) = k\frac{g(E_r)}{1 + k \cdot g(E_r)}$$

- Good agreement with experiment for ~MeV recoils.
- Deviations seen in keV range.
- $g(E_r)$, k: theoretically specified for Ge, but
  - $\mathbf{k} \rightarrow \mathbf{k}(\mathbf{E_r})$ at low energy

- CDMSlite-mode analysis assumes Lindhard with:

  $0.1 < k < 0.2$

  ➔ **Large energy scale uncertainty**

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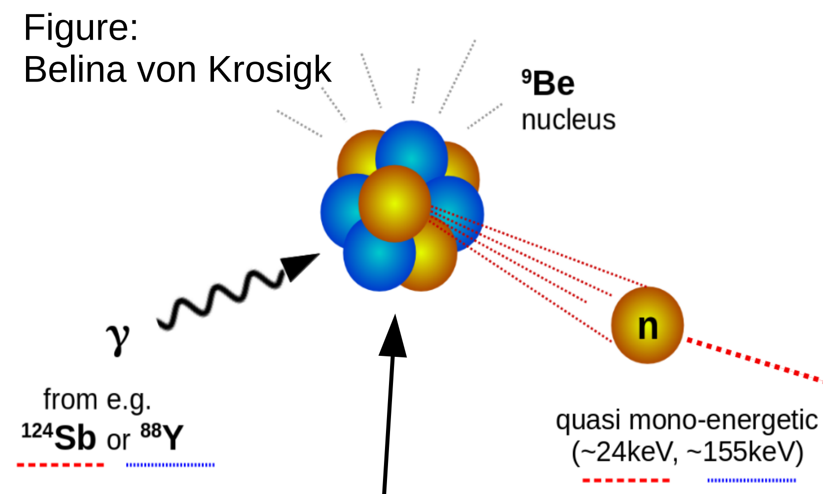
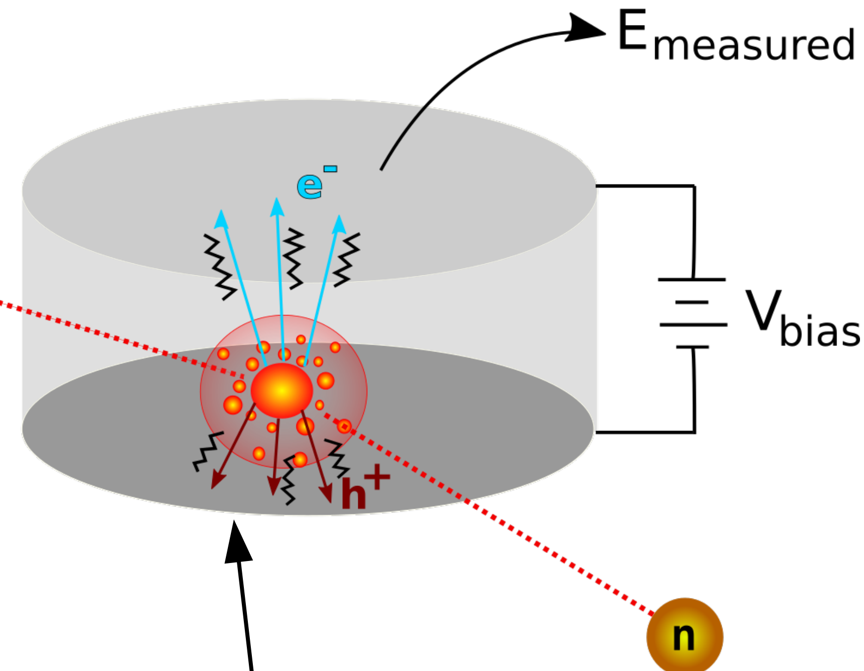
Photo-neutron Calibration Concept



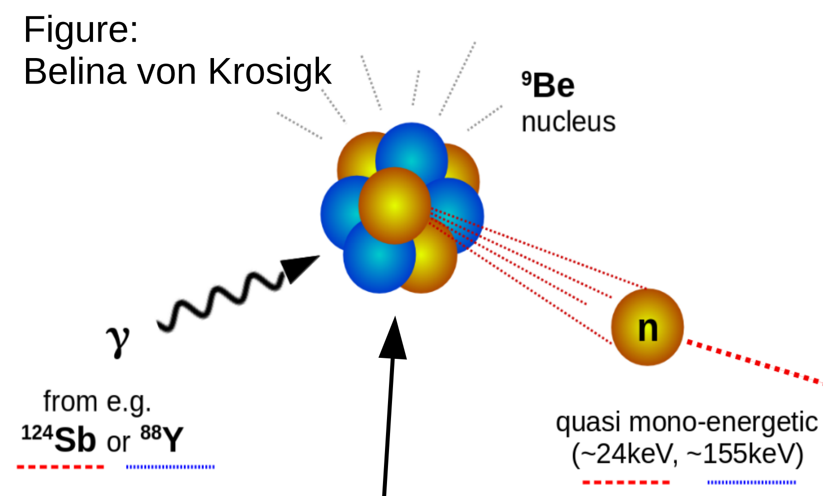
Pass gammas through Be wafer



Measure NR spectrum.

Compare with Geant4 simulation to calibrate energy scale.

Photo-neutron Calibration Concept



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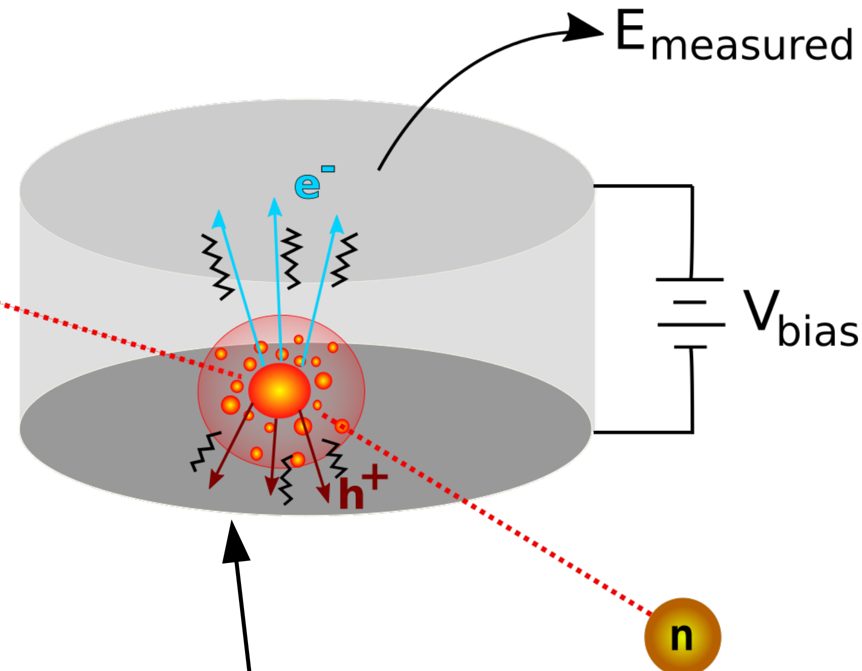


Measure NR spectrum.

Compare with Geant4 simulation to calibrate energy scale.

- Large gamma background.
  - Also take data without Be wafer
  - Subtract off this background.

Experimental Setup

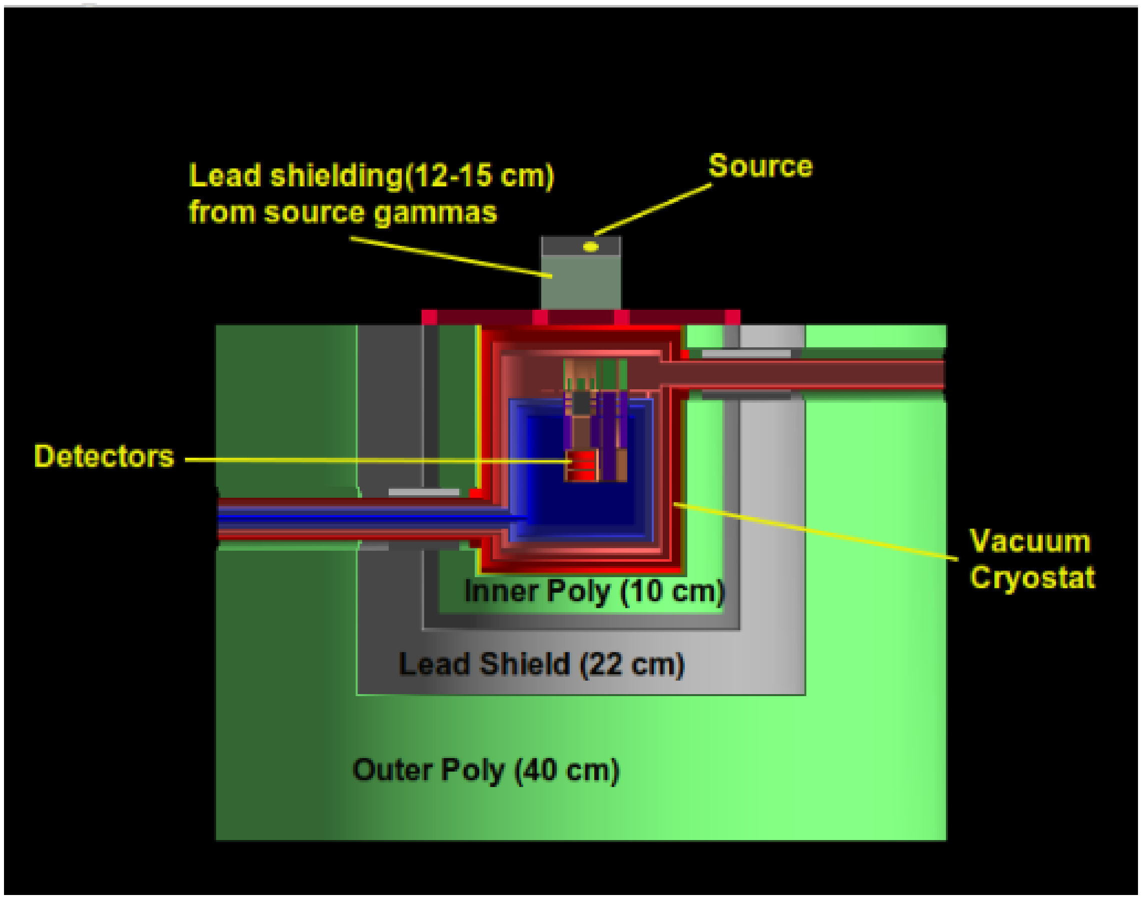
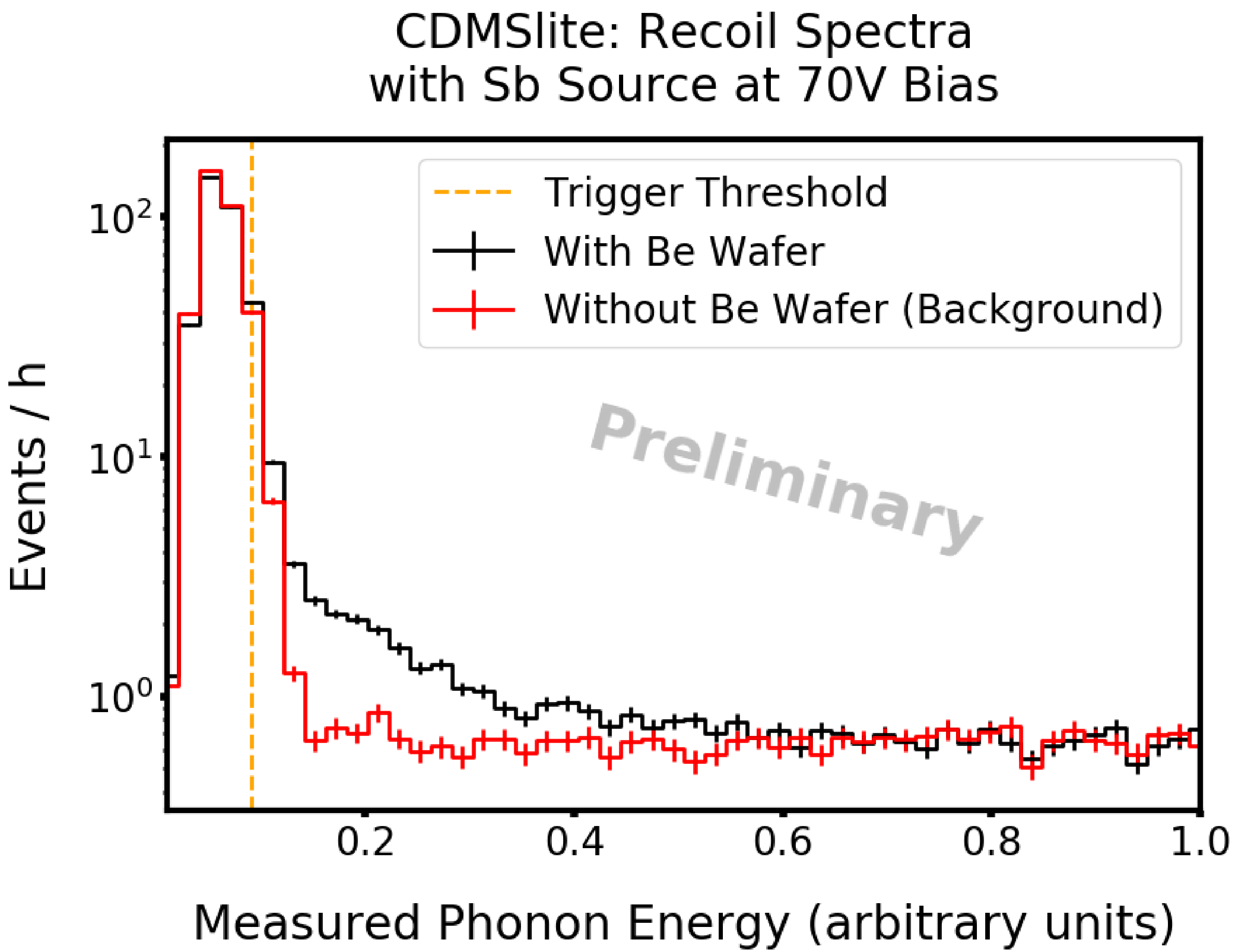


Figure: Anthony Villano

- 5 months of data-taking.
- One detector in iZIP mode, the other in CDMSlite mode.
- Alternated weekly between:
  - Be wafer in place
  - No Be wafer (measure gamma background)

Preliminary Spectra
(Sb source, detector in CDMSlite mode)



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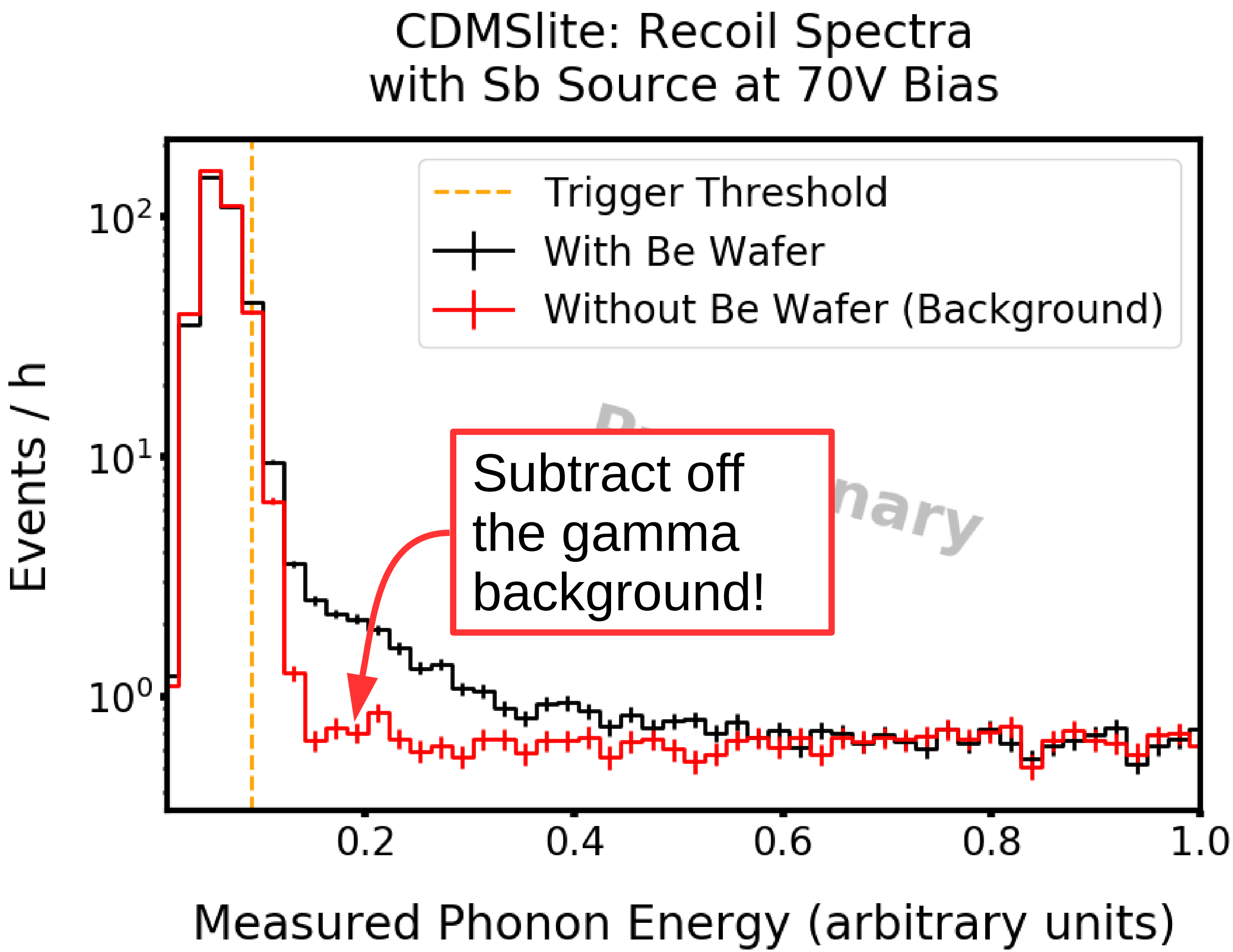

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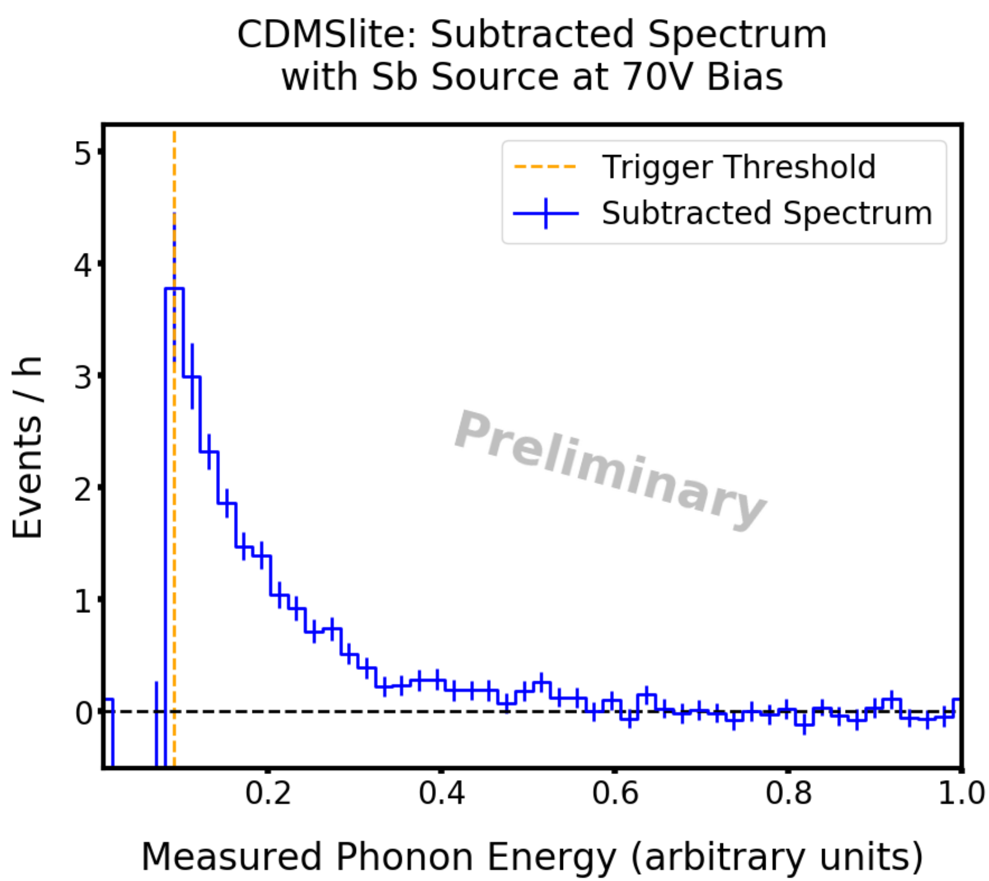
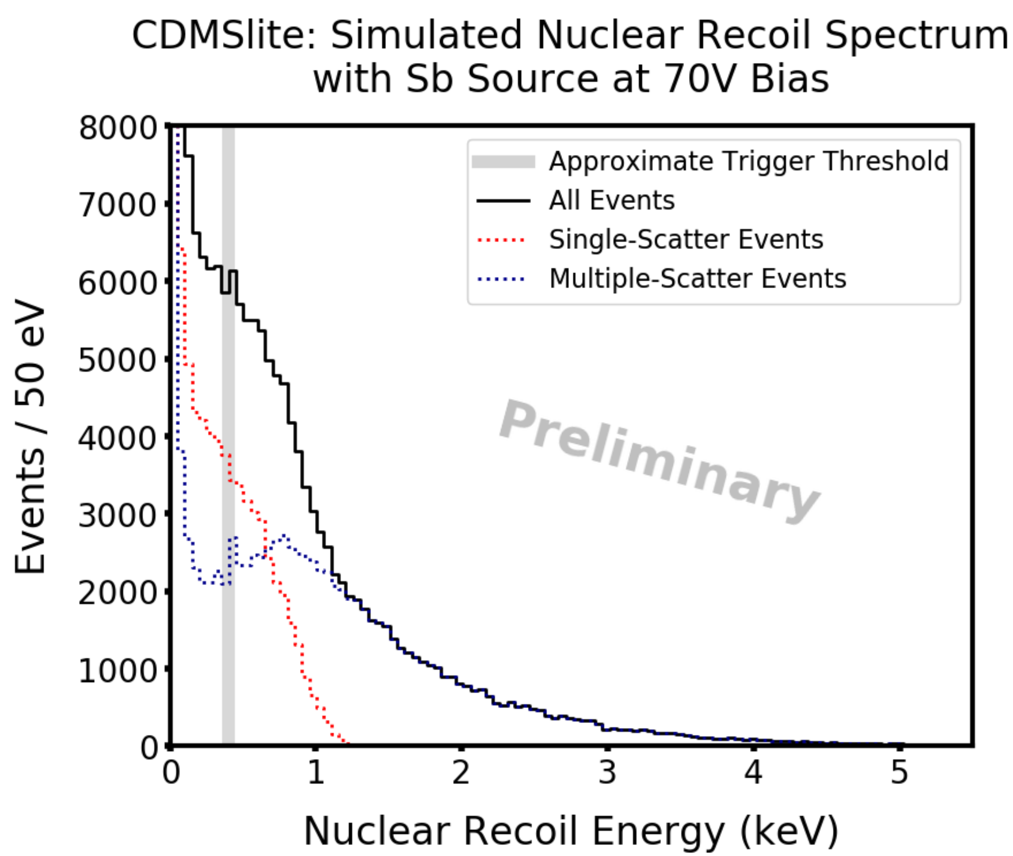


Geant4 Simulated

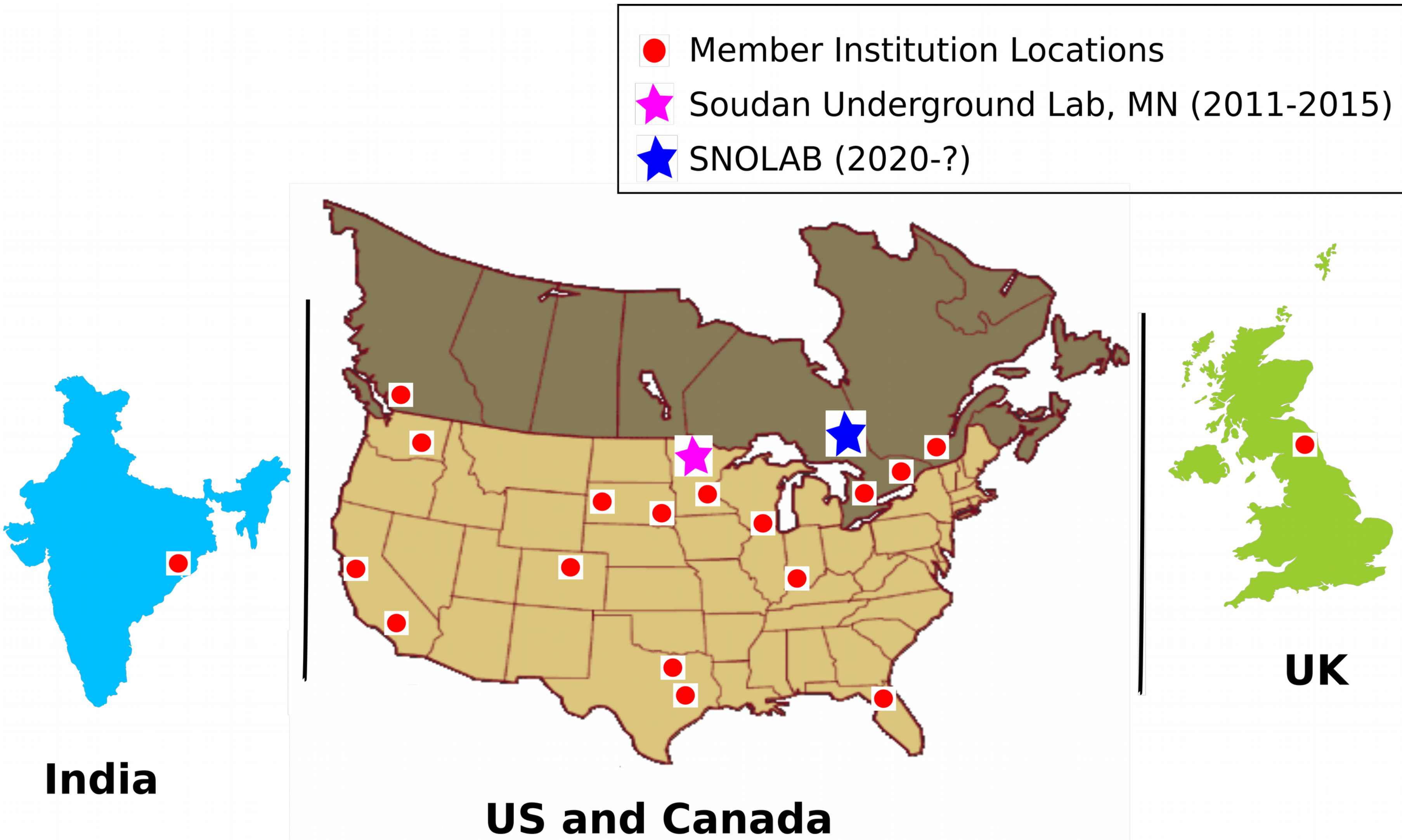


Simulation: Anthony Villano

Summary

- **Goal:** Calibrate NR energy scale of Ge crystal detectors.
  - ~1-8 keV range
- Important for precision of low-mass WIMP searches with Ge detectors.
- Analysis of photo-neutron data is ongoing.
- Will apply negative log-likelihood fit to Lindhard variants to:
  - Model ionization yield.
  - Calibrate the NR energy scale.

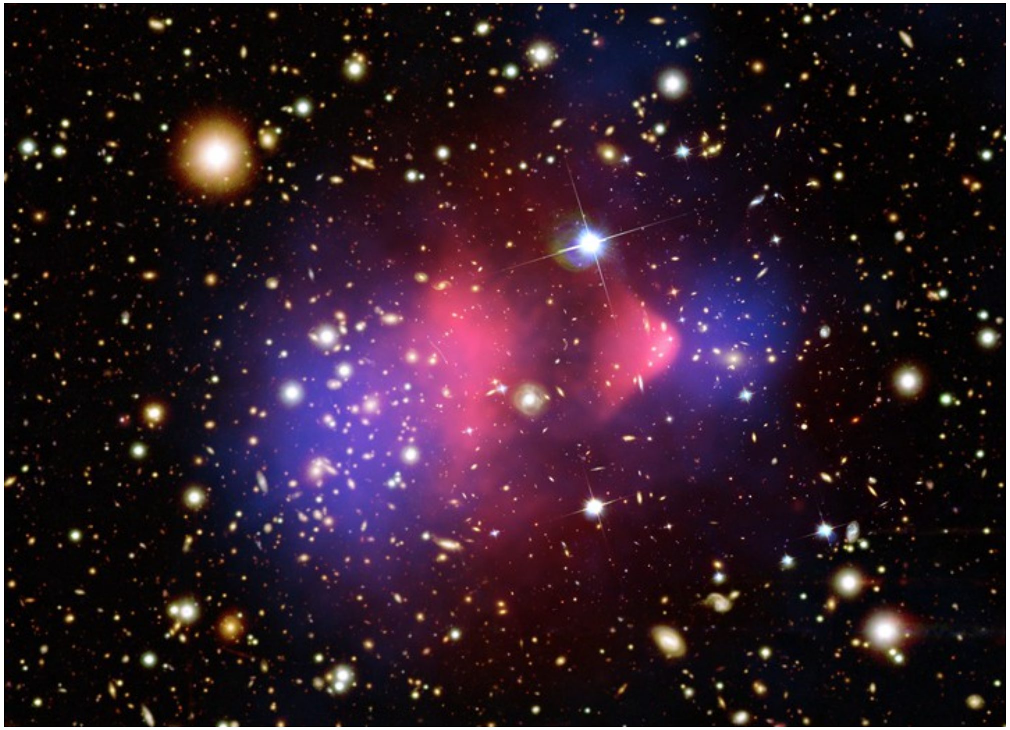
SuperCDMS Experiment



Backup Slides

Evidence for Dark Matter
Bullet Cluster

- Observed distributions formed after two galaxy clusters collided.
- Blue: mass distribution
- Pink: distribution of light-emitting matter
- Luminous matter lags behind non-luminous matter due to interactions.

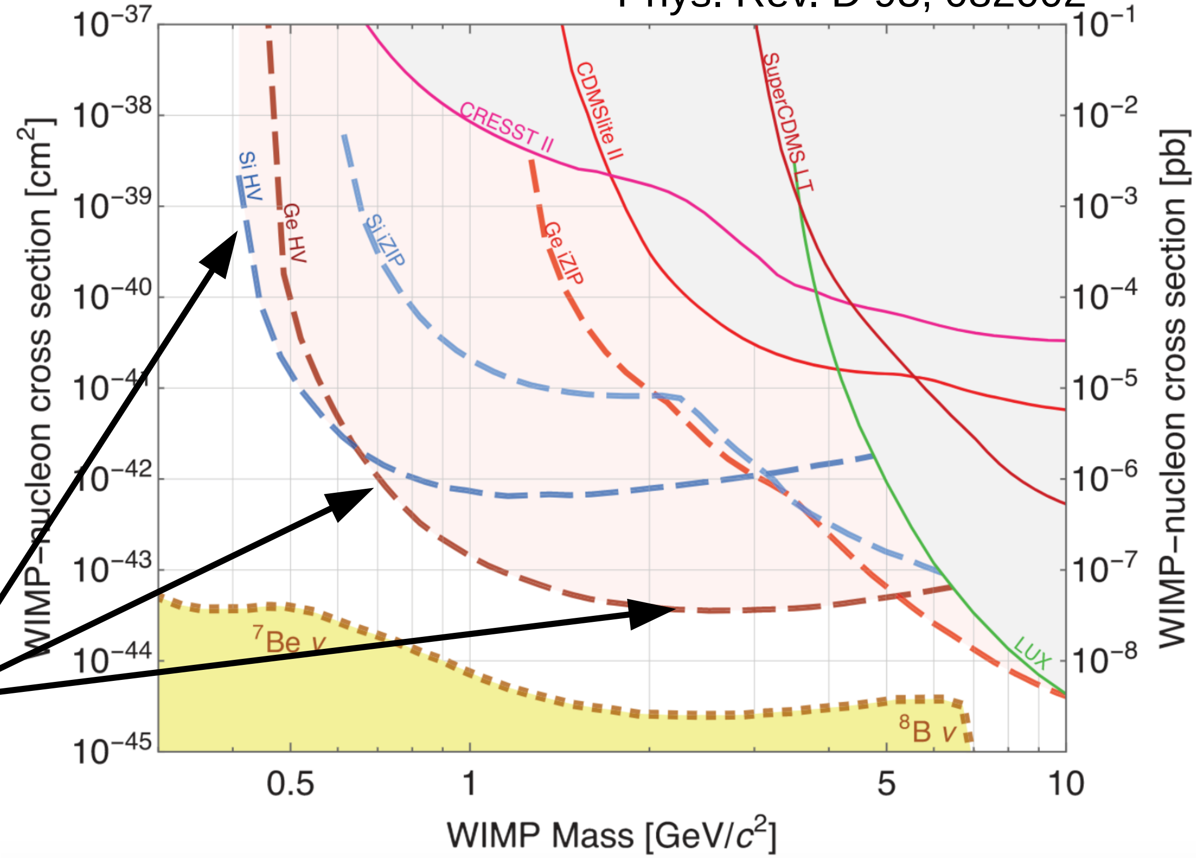


WIMPs

- **WIMP:** Weakly Interacting Massive Particle
  - Originally motivated by supersymmetry.
  - Mass expected in GeV-TeV range.
  - Interaction cross-section predicted at the weak force scale.
  - Expected to interact with normal atoms via nuclear recoils.

SuperCDMS SNOLAB Projections

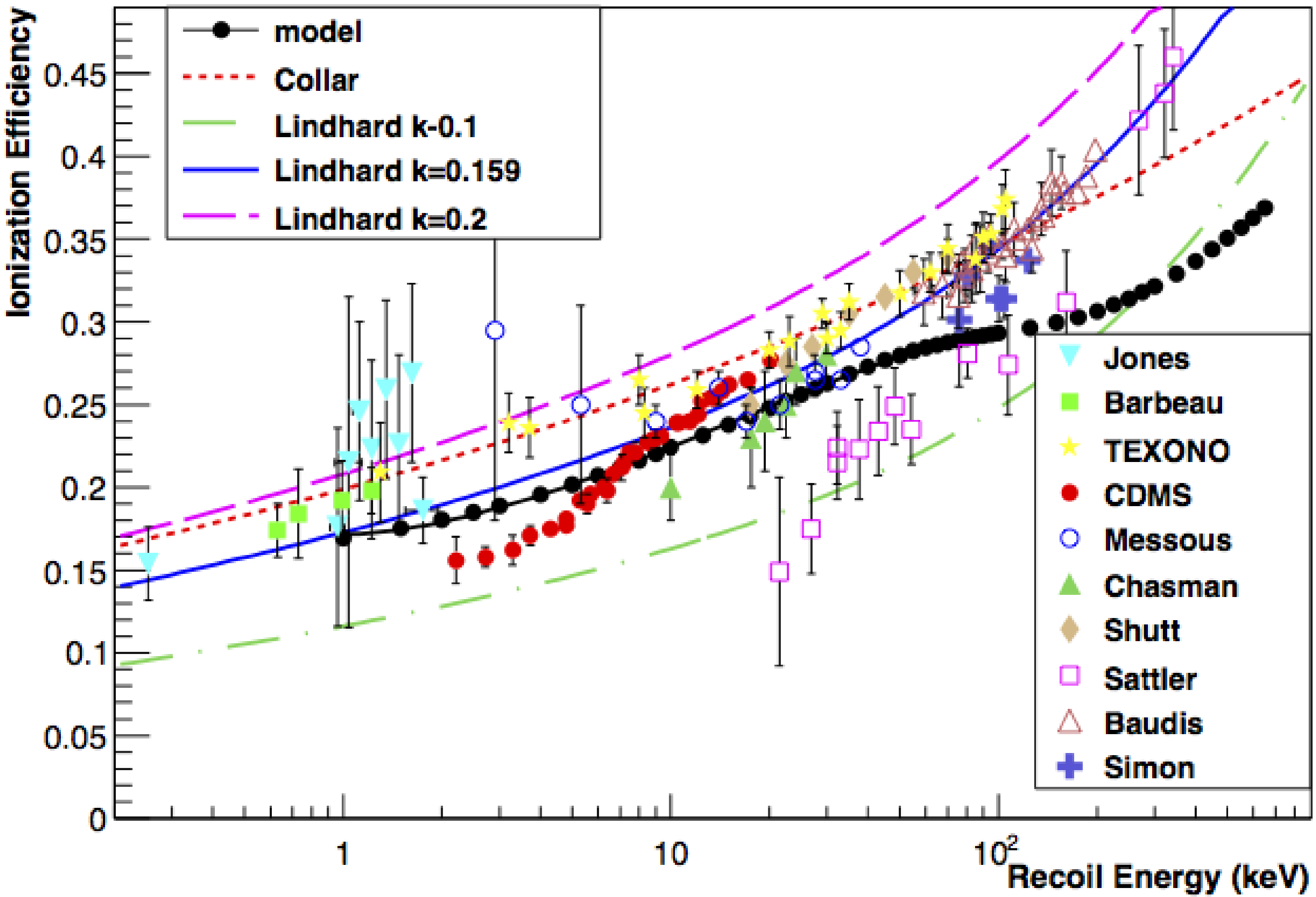
Phys. Rev. D 95, 082002



Expect to probe WIMP masses down to 0.4 GeV/c^2 at SNOLAB.

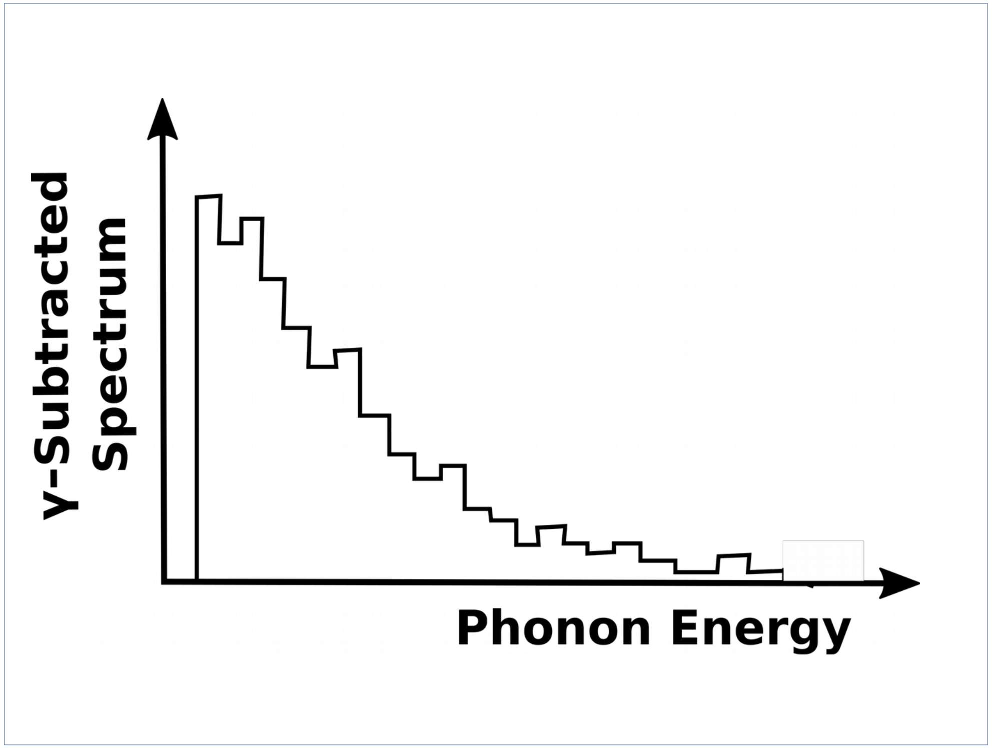
- Need a good understanding of NR energy scale in this region.

Existing Ionization Yield Measurements

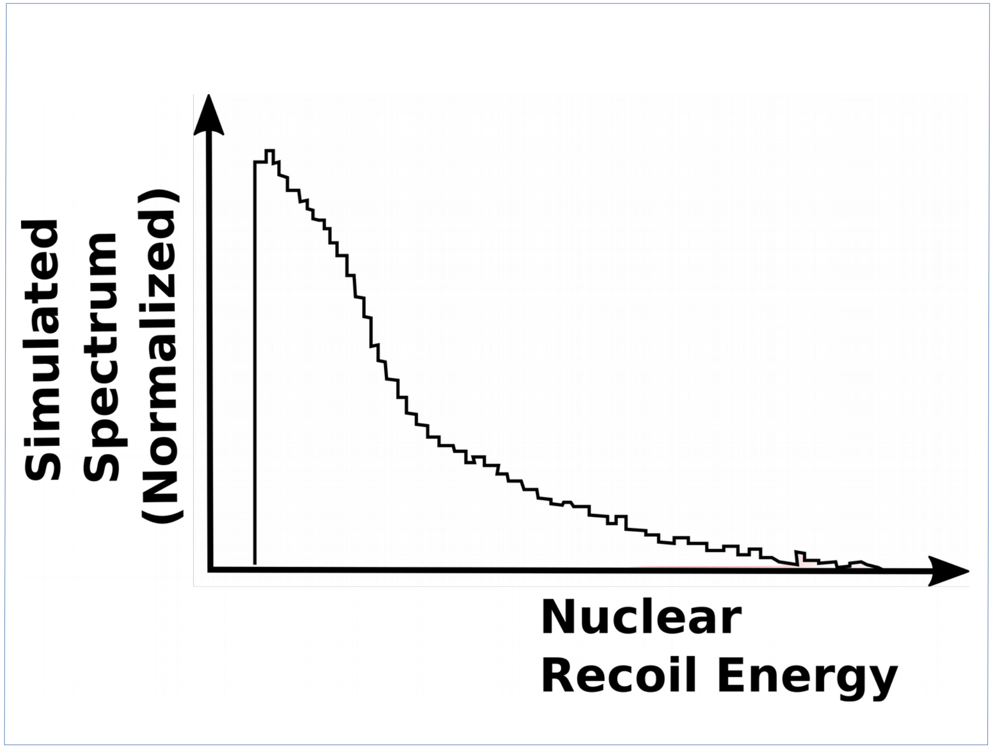


Energy Scale Calibration
Integral Test

Experimental



Geant4 Simulated



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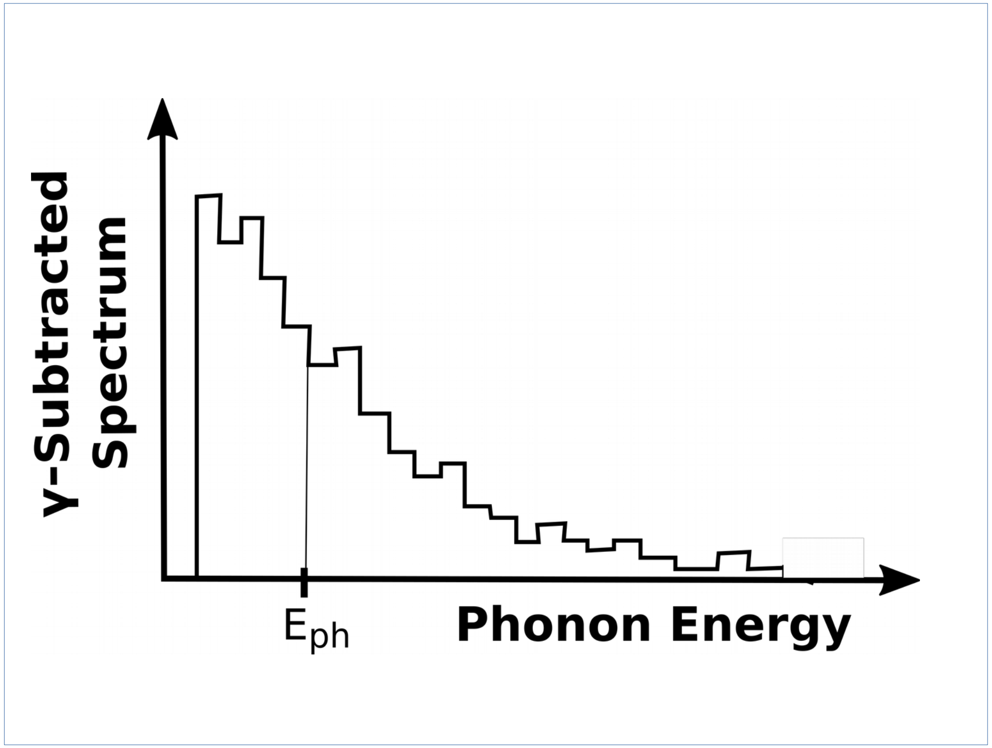

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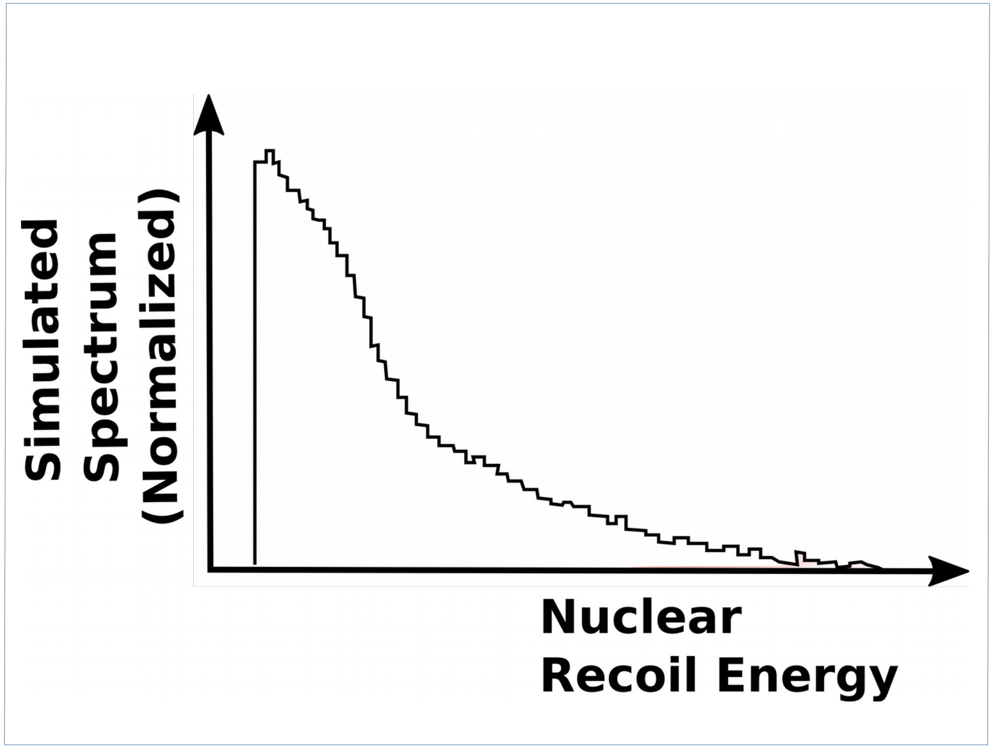

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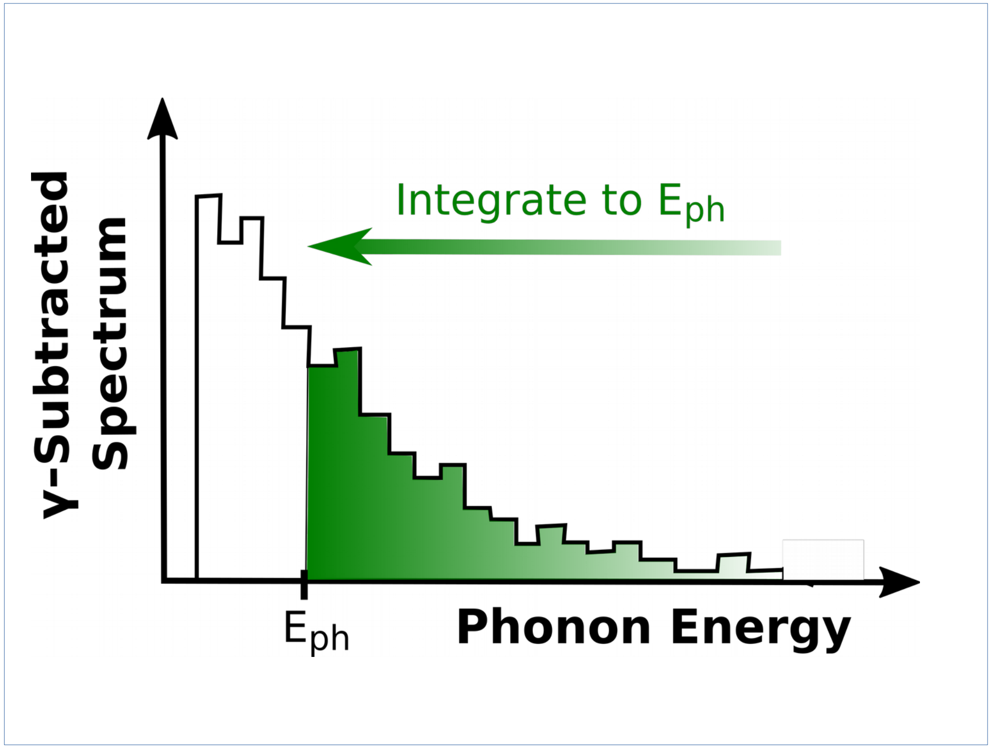

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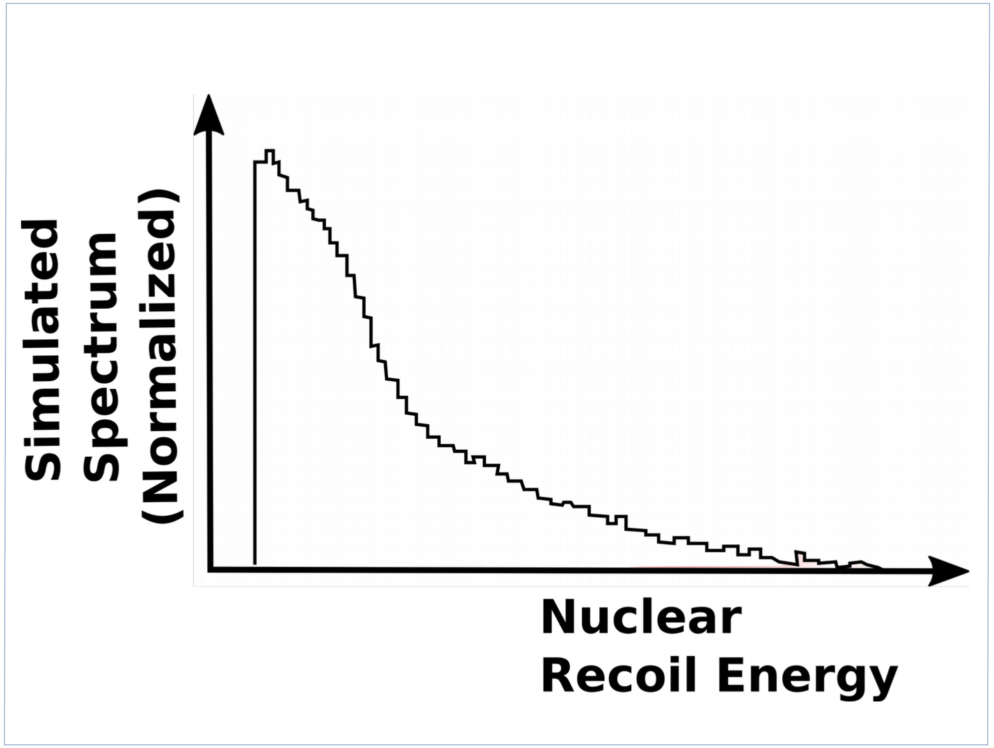

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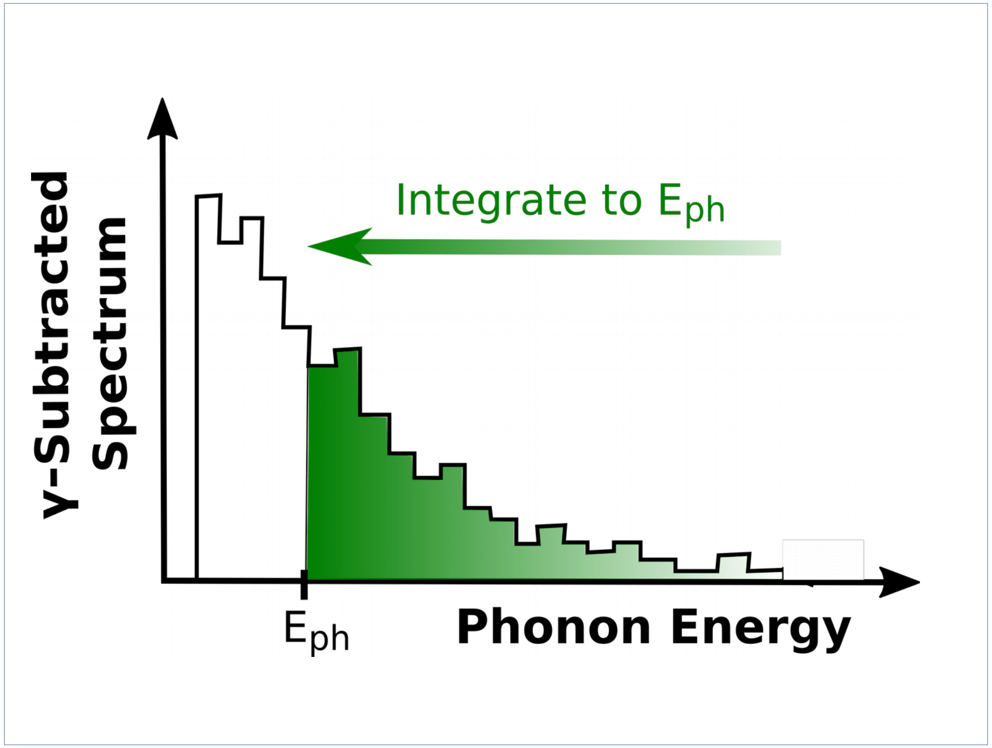

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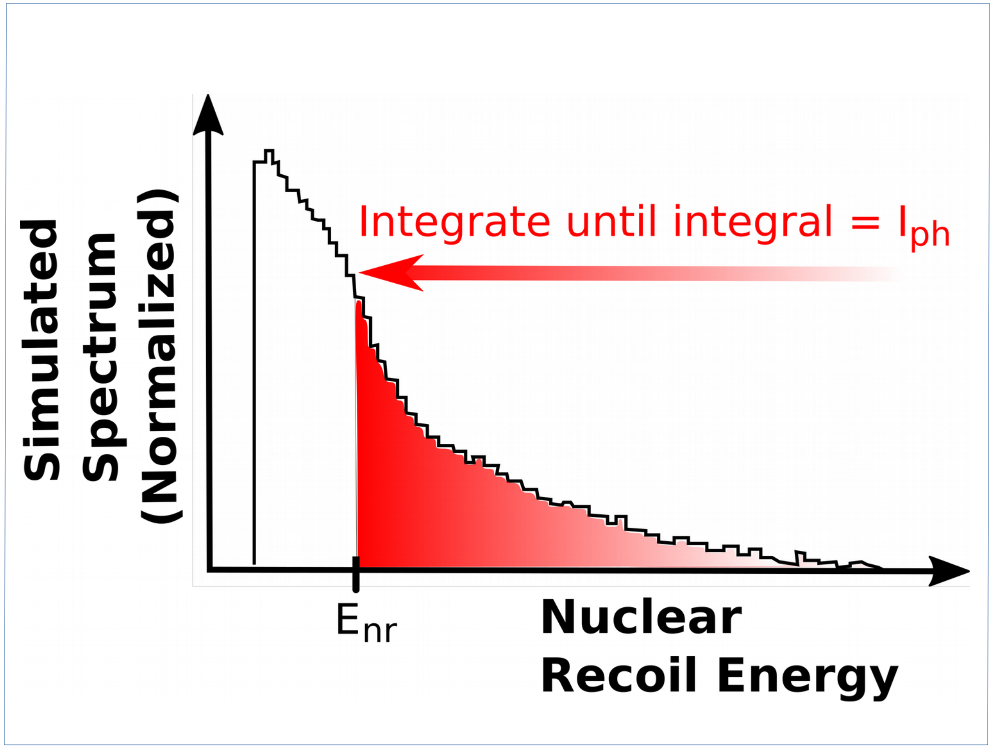

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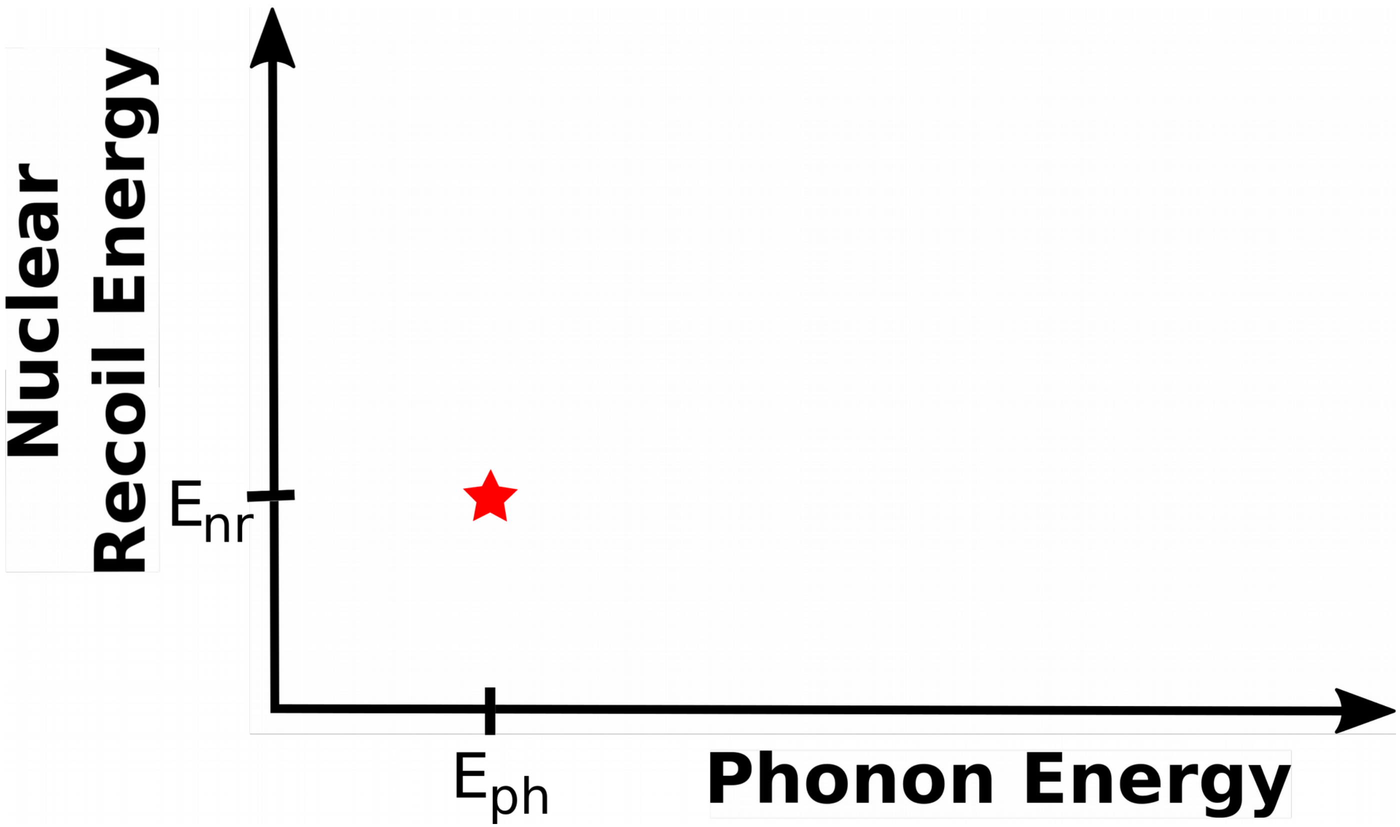
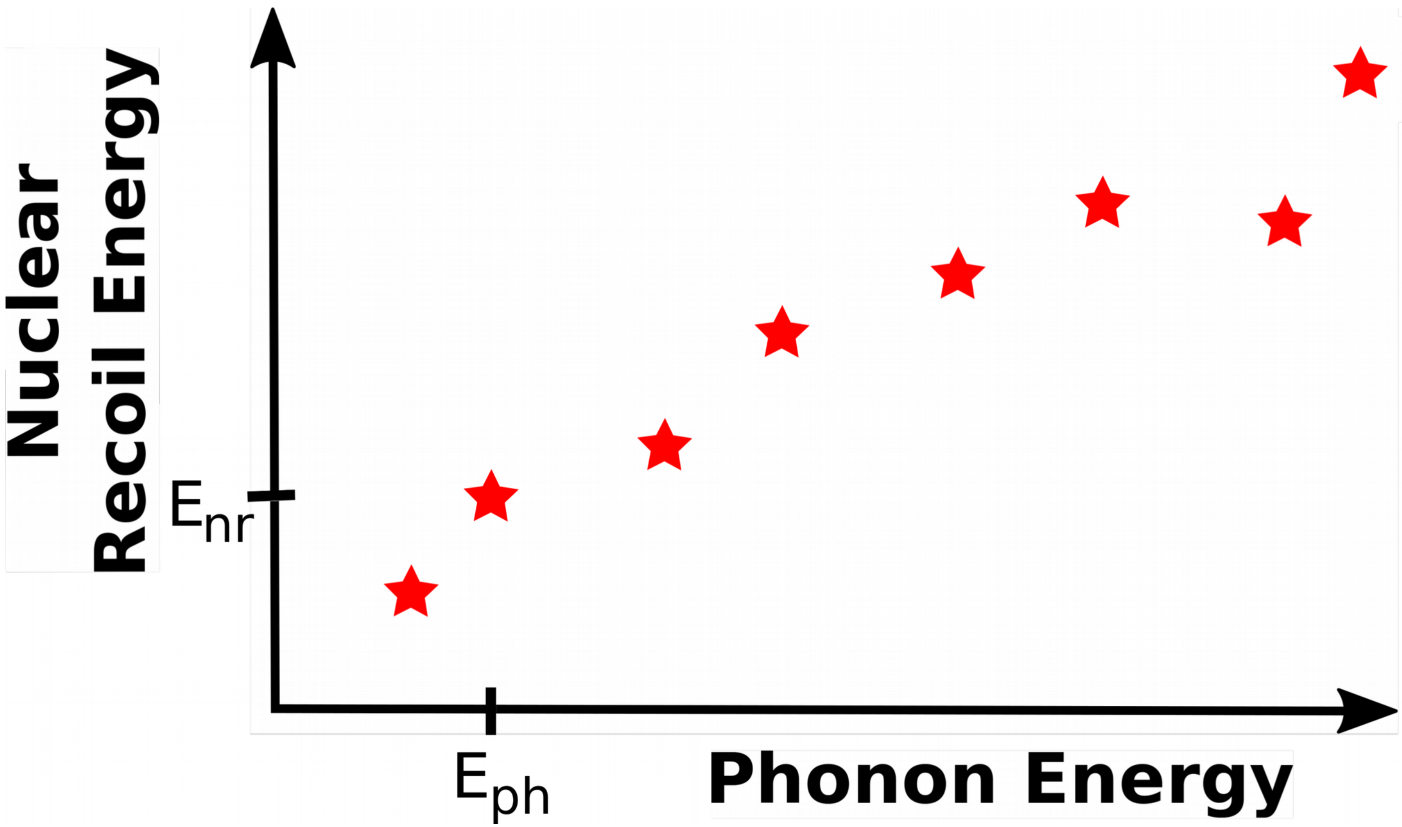


Energy Scale Calibration
Integral Test

Repeat for different phonon energies...



Energy Scale Calibration

Integral Test

Evaluate agreement with
Lindhard or other yield models