UNIVERSITY OF
SOUTH DAKOTA

Xenon Detectors Response to Low Energy Recoils for Dark Matter Searches

Acknowledgment

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Outline

❖ **Energy response to low energy recoils**

- Absolute calibration
- Comparison of relative and absolute calibration
- Reconstruct recoil energy using absolute calibration

❖ **Impact of energy resolution on discrimination of nuclear recoils from electronic recoils**

- Fano factor for electronic recoils and nuclear recoils
- Discrimination of nuclear recoils and electronic recoils based on Fano factor

Question in the Relative Calibration

Relative Calibration:

Electronic Recoils: $E_{eff} = \alpha E_R$ $\alpha = 1$

Nuclear Recoils: $E_{eff} = L_{eff} \times E_R$ $L_{eff} = \frac{\#N_{pe}^{NR}/E_{NR}}{\#N_{pe}^{ER}/E_{ER}}$

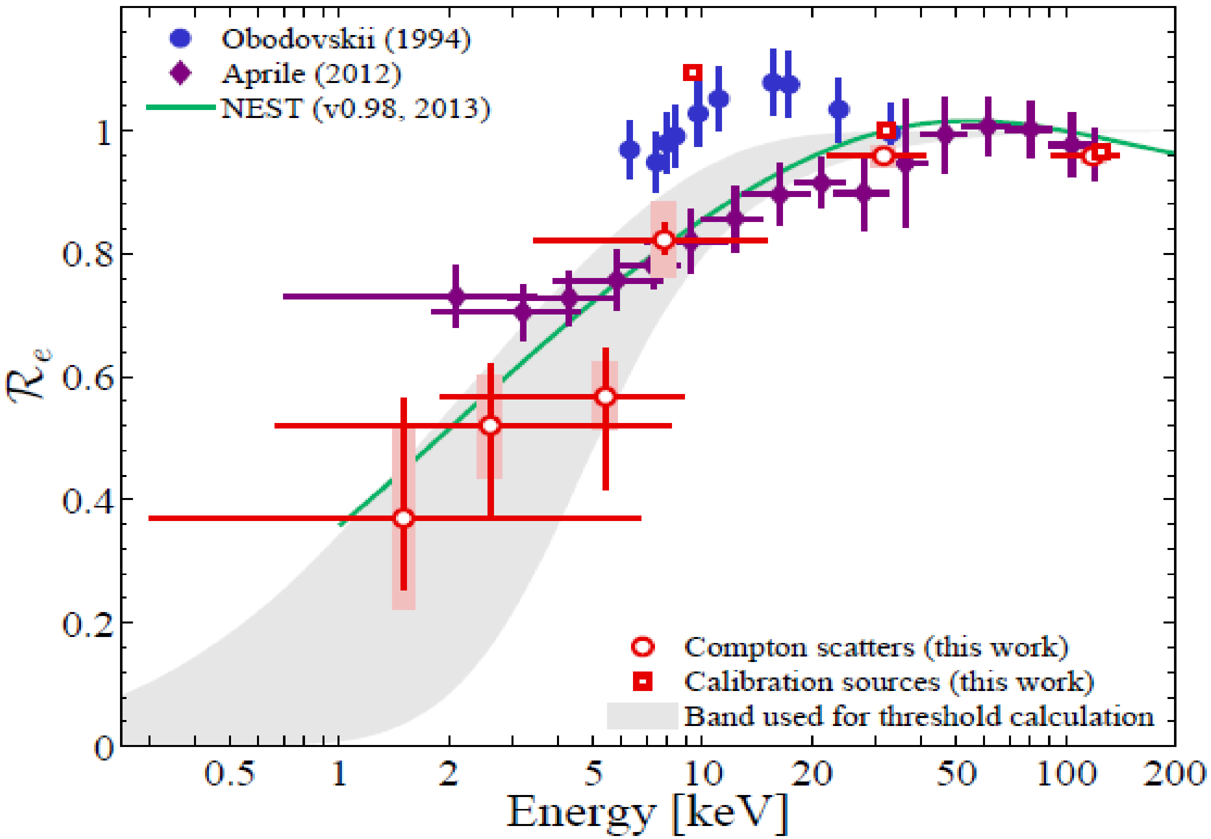
$L_{eff} = \eta \times \mu$

η: Lindhard quenching

μ:Hitachi quenching

This assumes the detector response to electronic recoils is linear below energy 10 or 122 keV, which is not true from a measurement by L. Baudis et al, Phys.Rev.D87:115015,2013

ER: Relative Scintillation Efficiency



L. Baudis et al, Phys.Rev.D87:115015,2013

This behavior can be described by Birks' Law:

$$R_e = \frac{\alpha_r}{1 + kB_r \frac{dE_R}{dx}}$$

α_r and kB_r can be determined using the experimental data shown in the plot.

NR: Energy Response Function

- **Lindhard quenching:** $E_{eff} = E_R \times \eta$, $\eta = \frac{kg(E_R)}{1+kg(E_R)}$
- **Birks' Law:** $E_{vis} = E_{eff} \times \mathrm{v}$, $v = \frac{\alpha}{1+kB\frac{dE_{eff}}{dx}}$

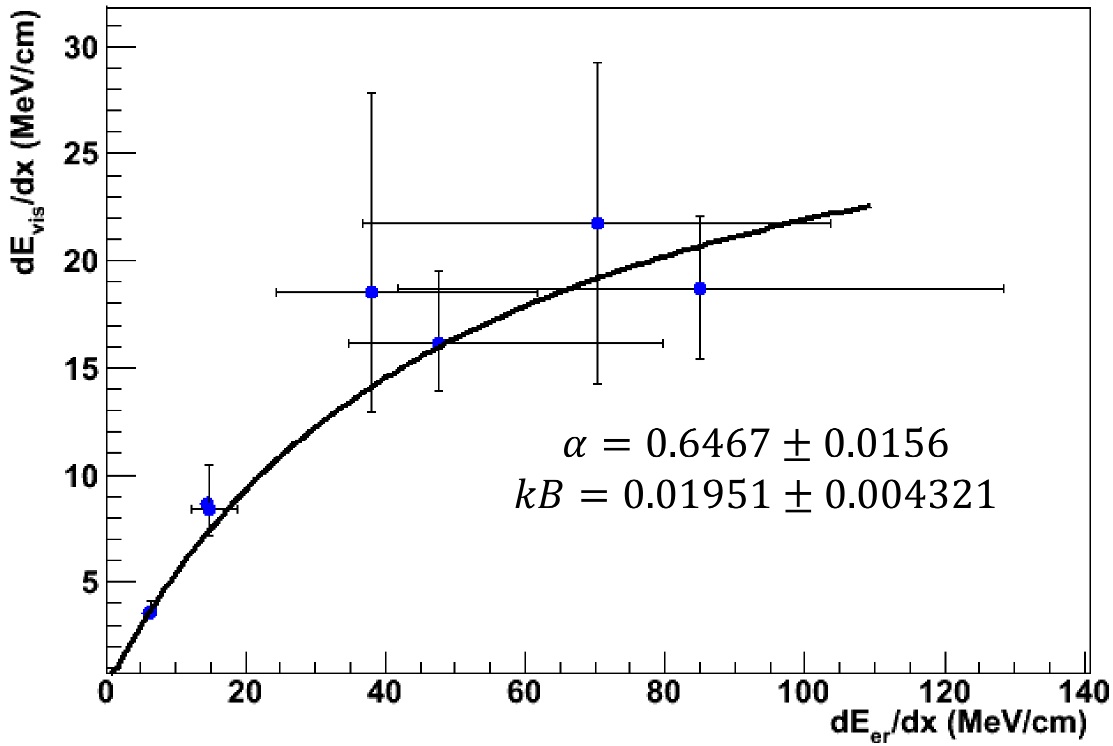
total scintillation efficiency: $\eta \times v$

↓

An absolute energy calibration

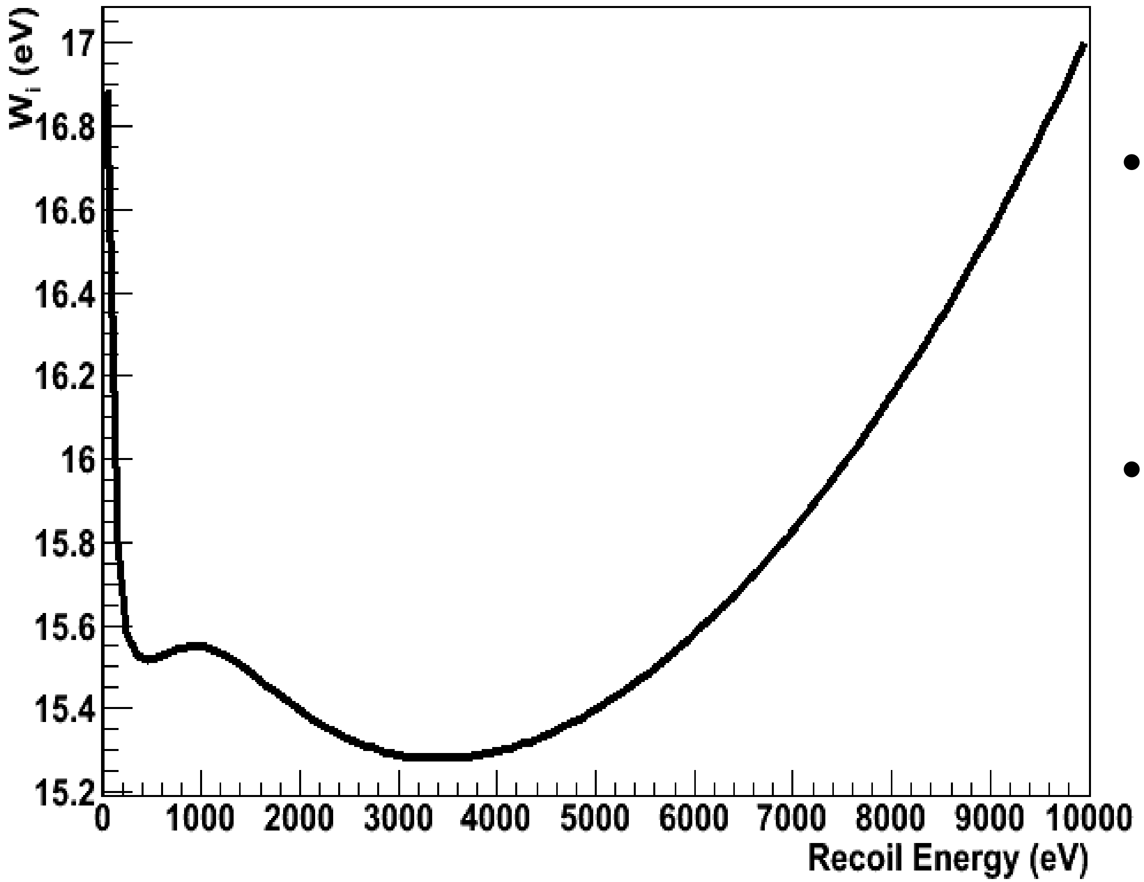
Determine α and *kB*

Data points are from L. Baudis et al, Phys.Rev.D87:115015,2013



$$\frac{dE_{vis}}{dx} = \frac{E_g}{W_i} R_e \frac{dE_R}{dx} = \frac{\alpha \frac{dE_R}{dx}}{1 + kB \frac{dE_R}{dx}}$$

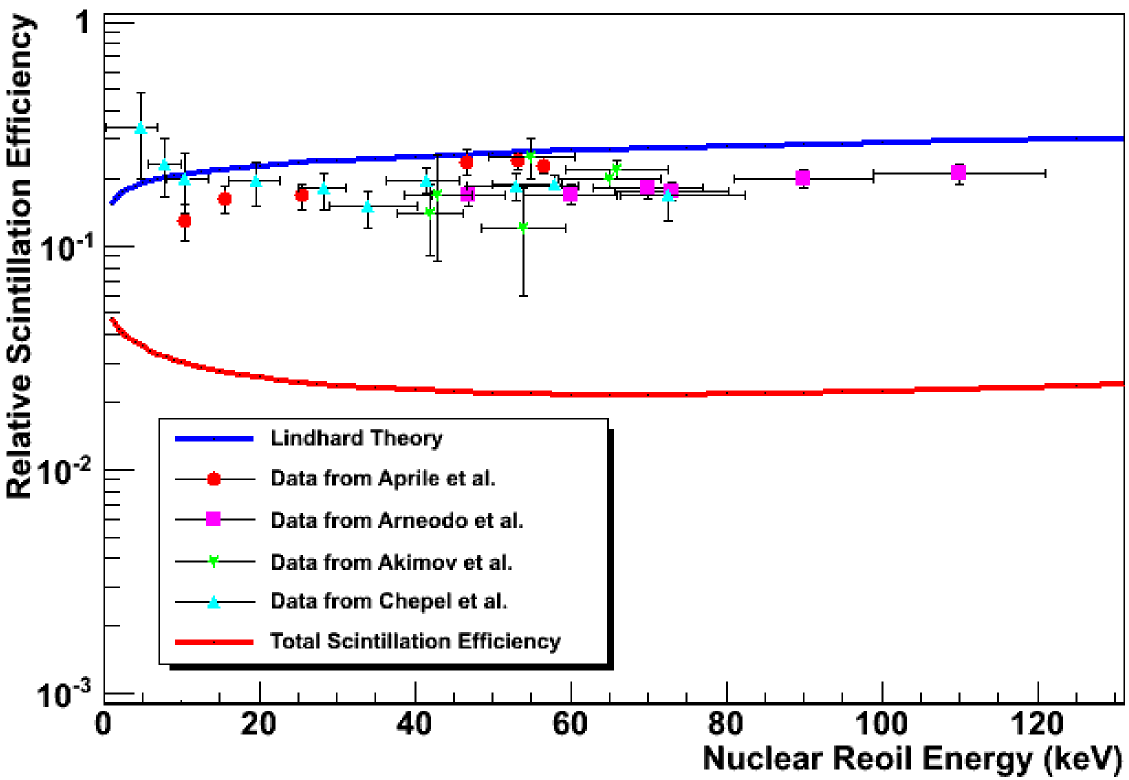
W_i as a Function of Energy



- W_i increases as energy decreasing below 1keV.
- Above 4keV, W_i increases as energy increasing.

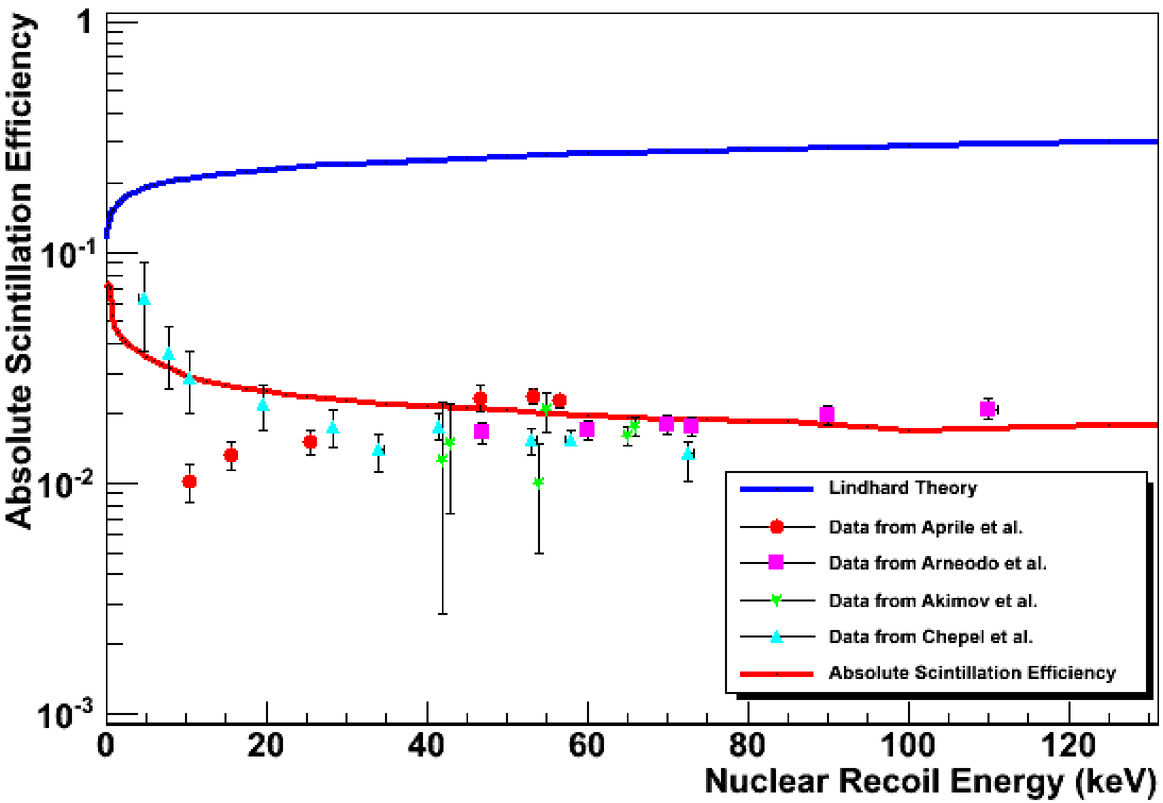
NR Relative Scintillation Efficiency in Comparison with Absolute Efficiency

$$\frac{E_{vis}}{E_R} = L_{eff} \qquad \frac{E_{vis}}{E_R} = \frac{\alpha}{1 + kB\frac{dE_{eff}}{dx}} \times \eta$$



- Lindhard quenching predicts scintillation efficiency decreases as energy decreasing.
- At low energies, scintillation efficiency increases as energy decreasing.

NR Absolute Scintillation Efficiency Comparison



- Normalize the data to absolute energy scale, the agreement between the data and our model is reasonable.

NR Energy Reconstruction

- **Relative calibration:**

$$E_{NR} = \frac{\#N_{pe}^{nr}}{L_{eff}\#N_{pe}^{er}/E_{ER}}$$

If $\#N_{pe}^{nr} = 3, \#N_{pe}^{er}/E_{ER} = 8.8/keV, E_{NR} =$ **3keV**

- **Absolute calibration:**

$$E_{NR} = \frac{E_g}{\eta\nu}\left(\frac{S_1}{\varepsilon_1} + \frac{S_2}{M_f\varepsilon_{ext}}\right)$$

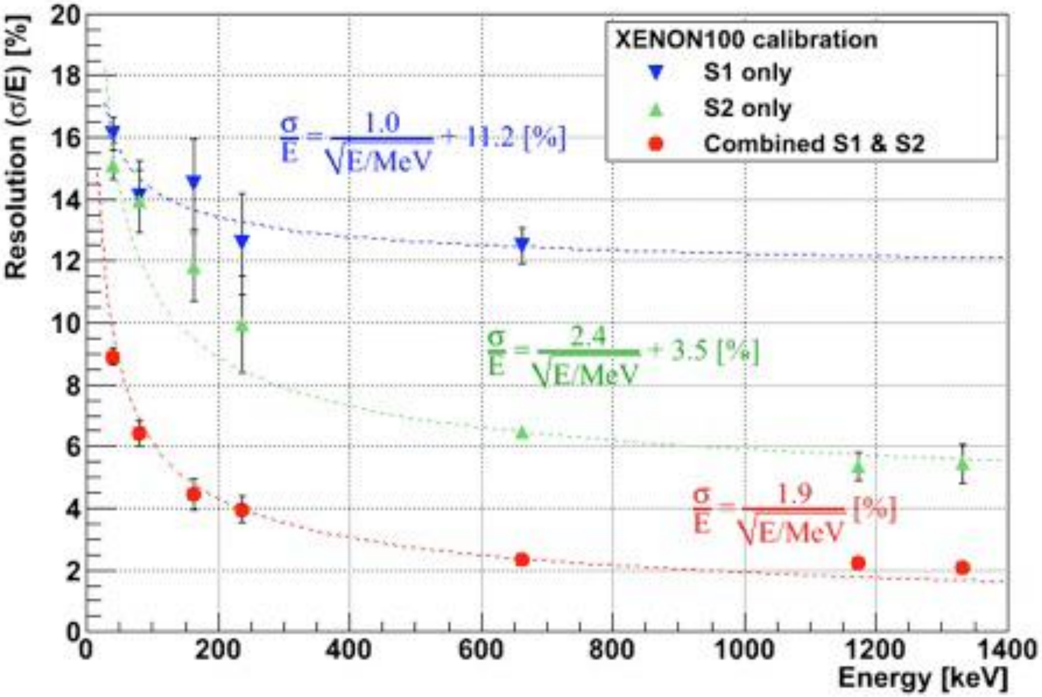
If $\#N_{pe}^{nr} = 3, S_2 = 50, \varepsilon_1$=0.14, $M_f = 24.55, \varepsilon_{ext} = 0.65$, $E_{NR} =$ **6.8keV**

ε_1: the product of photon detection efficiency and photoelectron quantum efficiency

ε_{ext}: electron extraction efficiency

M_f: photon multiplication factor

Energy Resolution and Fano factor



http://xenon.astro.columbia.edu/talks/Aprile_WONDER_2010.pdf

- Different sources of fluctuation in the signal chain contributing to the overall energy resolution
- Energy dependence of resolution: $\frac{\sigma(E)}{E} = \frac{c_1}{E} + c_2$

Statistical variation

Noise level

$$\sigma_{stat} = \sqrt{W_i(E)F(E)E}$$

T.Papp et al, Wiley Science, DOI:10.1002/xrs.754

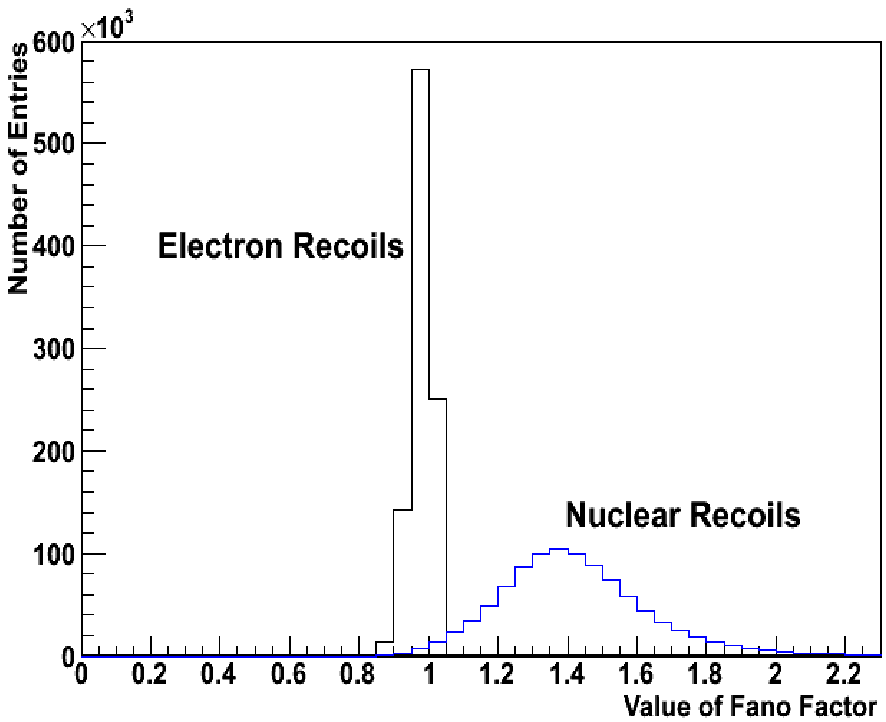
$$F_n = \frac{1.9\%^2}{15.6\times10^{-6}} \approx 23$$

Formulism for Fano factor

$$F_N = \sqrt{\frac{E_x}{E_g}\left(\frac{W_i}{E_g} - 1\right)}$$

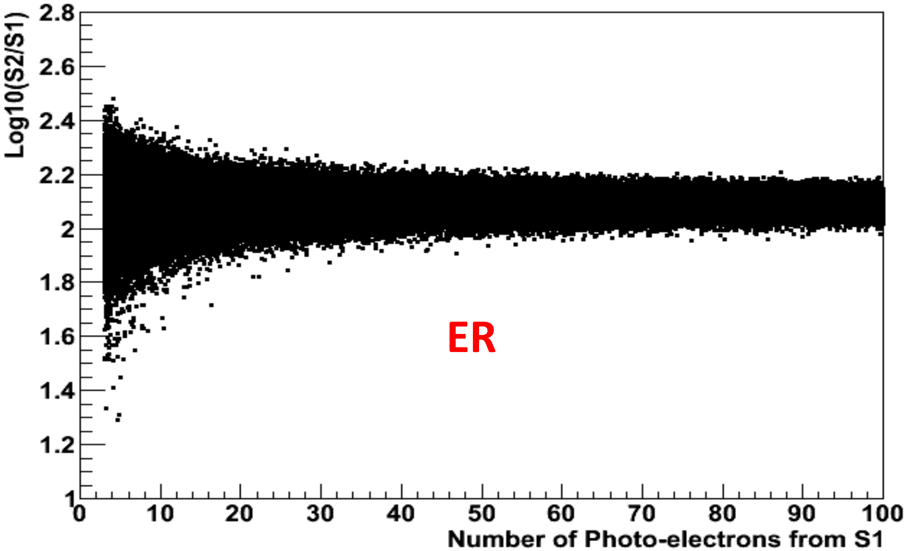
$$F_n = \sum_{i=1}^{m}\left(1 + \epsilon(F_N - 1)\right)$$

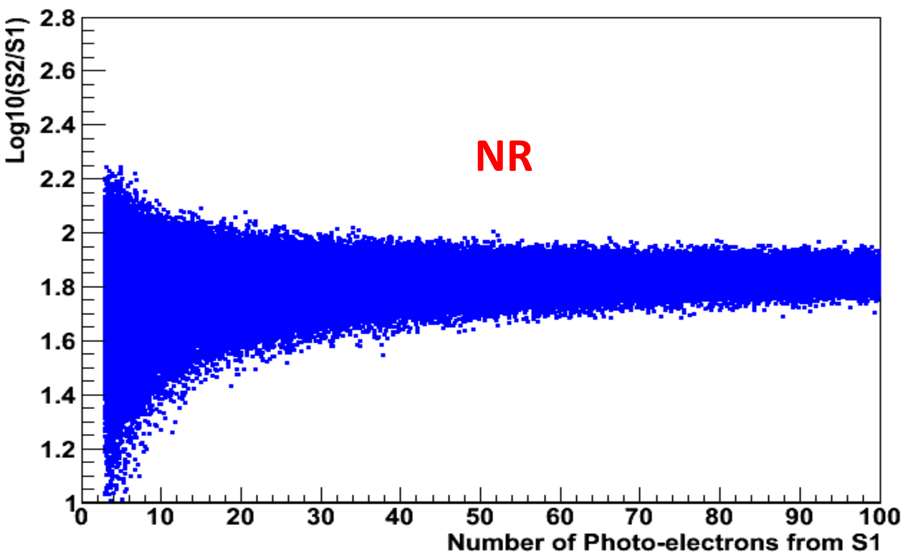
- If $F_n = 23$, with one PMT, $\overline{F_n} = 0.95$, Then, about 24 PMTs are triggered.
- If $F_N = 0.059$, $\epsilon = 9\%$, $F_n = 0.91$ for one PMT.



- Nuclear recoils Fano factor is always greater than that for electronic recoils.

Discrimination on ER and NR





❖ At low energies, statistical variation dominates energy resolution.

- Number of electron-hole pairs decreases as energy decreasing, Fano factor becomes larger, subsequently, statistical variation becomes larger.
- W_i increases as energy decreasing.

Conclusions

- Energy response to both electronic recoils and nuclear recoils are non linear.
- Due to high ionization density at low energies, additional quenching is involved.
- Absolute energy calibration requires low energy electronic recoil calibration.
- Fano factor dominates the energy resolution in the low energy region.
- Average energy per electron-hole pair leads to the difference of Fano factor between NR and ER.
- The difference in Fano factor impact on the nuclear band width and electronic recoil band width.

Thanks