Discrimination between Electron and Nuclear Recoils in Dark Matter Detectors

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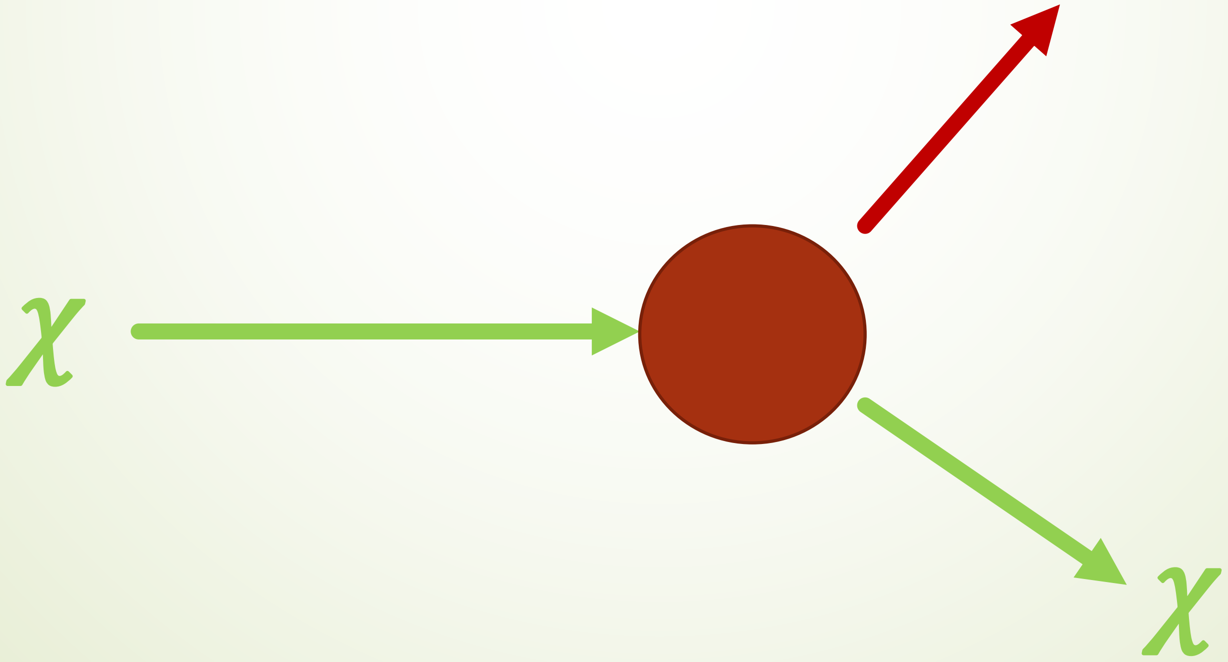
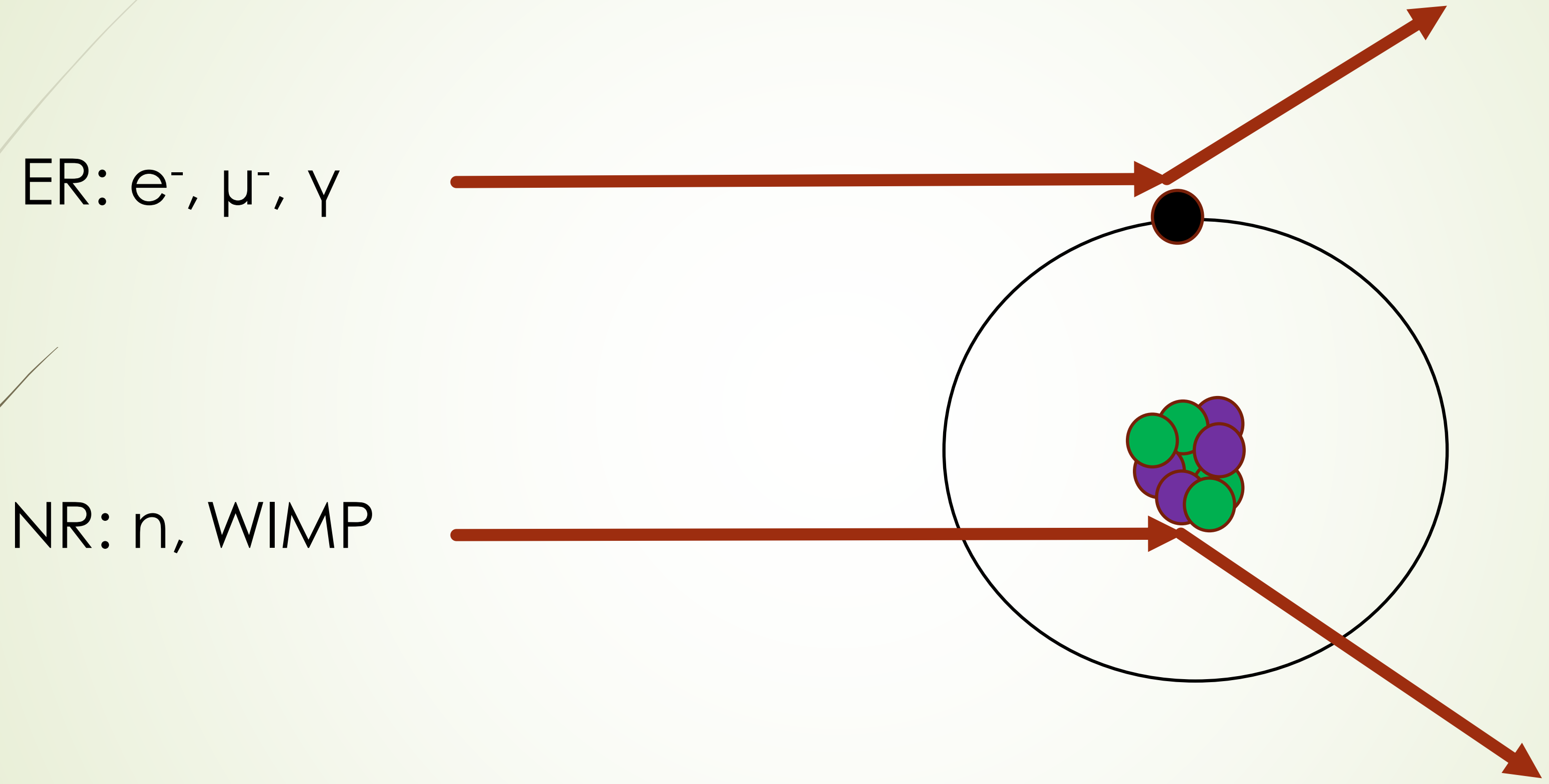
Dark Matter Direct Detection

- Basic principle of a DM search is to observe a dark matter particle (in this talk, WIMPs) interacting with a Standard Model particle
- Direct detection experiments search for recoils of a galactic WIMP with an atom



Dark Matter Direct Detection



ER: e^-, μ^-, γ

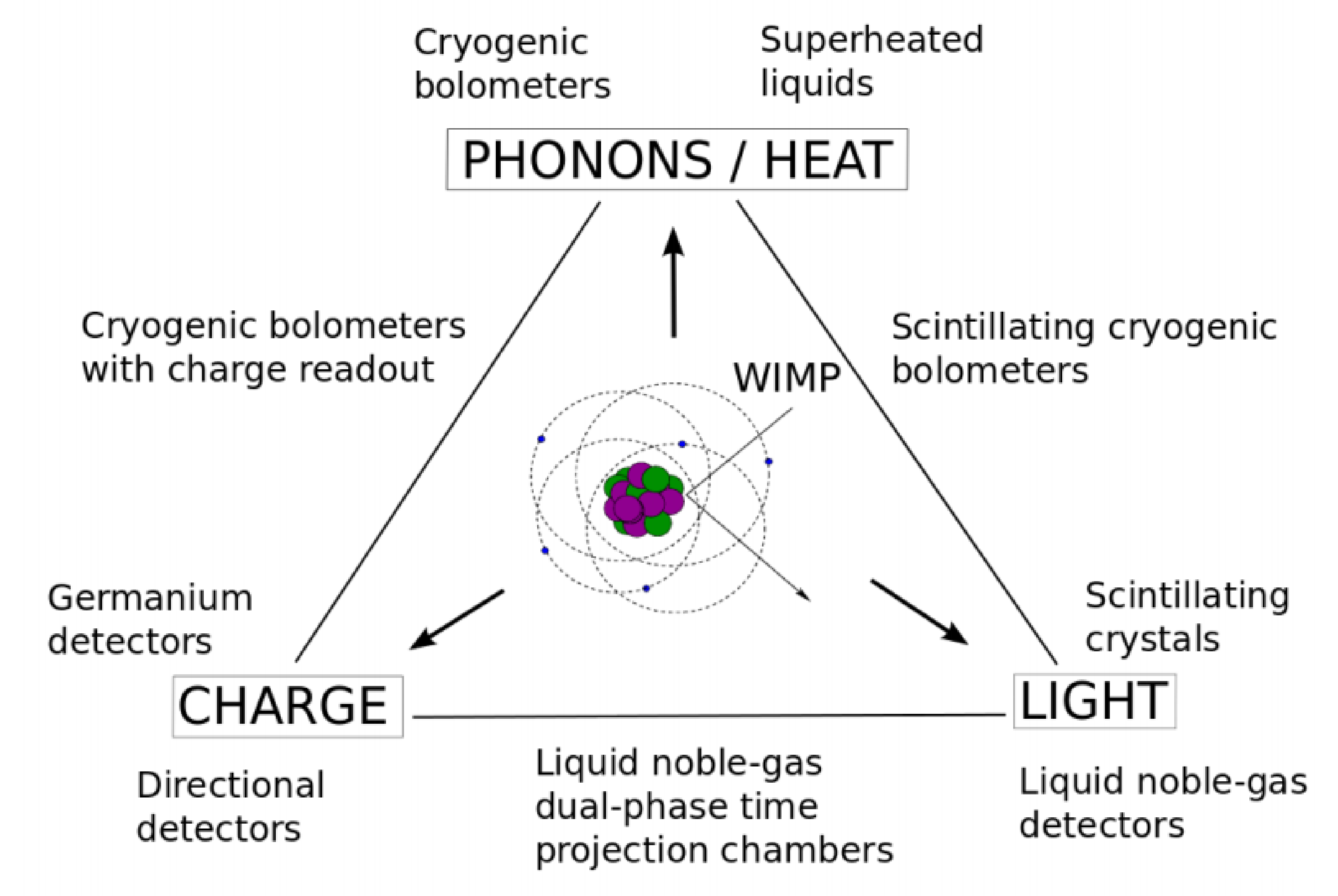
NR: n, WIMP

These two processes often produce similar signals, so it is necessary to “discriminate” between the two to reduce backgrounds

Energy deposits in material

- 3 primary channels through which energetic particles deposit their energy in matter:
  - Ionization (charge)
  - Scintillation (light)
  - Heat (phonons)
- Direct detection experiments attempt to detect 1 or 2 of these channels
- By detecting 2 channels, we are able to discriminate between nuclear recoils (NR) and electronic recoils (ER)

Energy deposits in material



Cryogenic bolometers

Superheated liquids

PHONONS / HEAT

Cryogenic bolometers with charge readout

WIMP

Scintillating cryogenic bolometers

Germanium detectors

Scintillating crystals

CHARGE

LIGHT

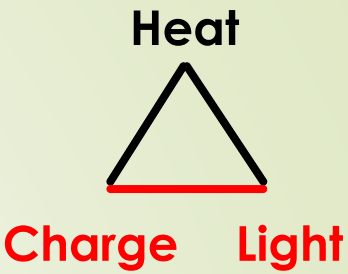
Directional detectors

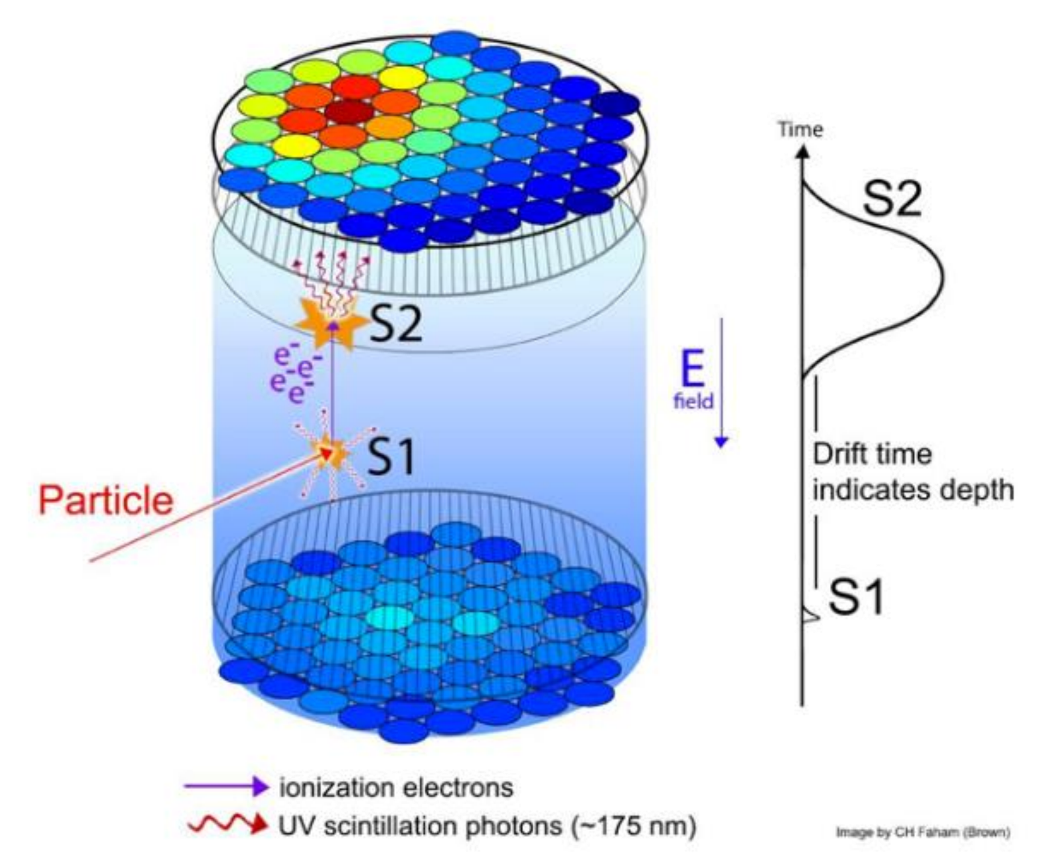
Liquid noble-gas dual-phase time projection chambers

Liquid noble-gas detectors

Source: Ref. [1]

Two-phase liquid noble element time projection chambers

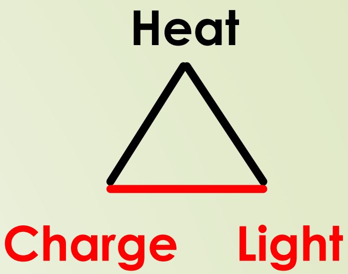




Source: Ref. [2]

- Capable of measuring both scintillation light and ionization electrons
- Detectors consist of:
  - A chamber of noble liquid (usually Xenon or Argon), with a gas phase region above the liquid
  - Photon detectors (typically photomultiplier tubes) surrounding the liquid region
  - An electric field (“drift field”) in the liquid, and a stronger “extraction field” in the gas
- At left: general schematic of interactions in LUX

Two-phase liquid noble element time projection chambers


Heat

Charge **Light**

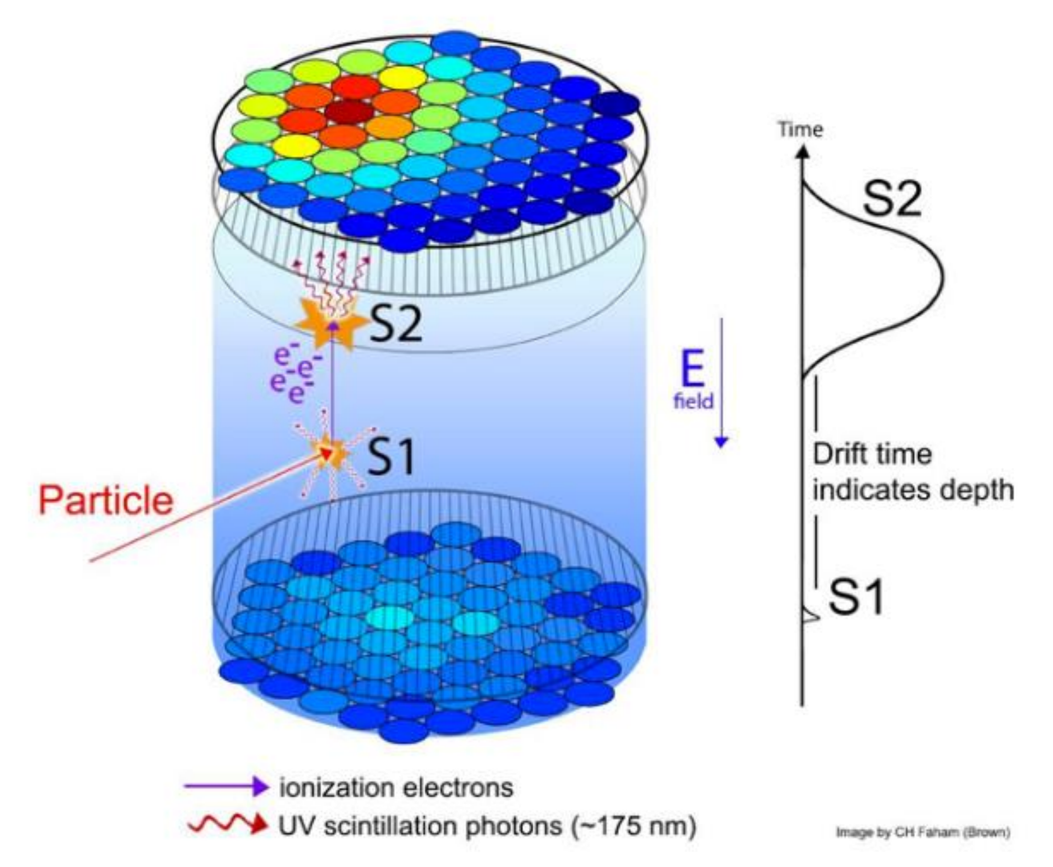
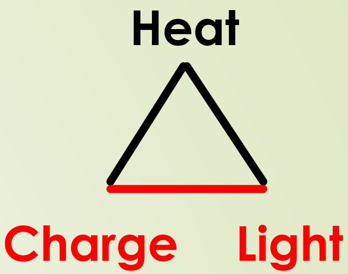


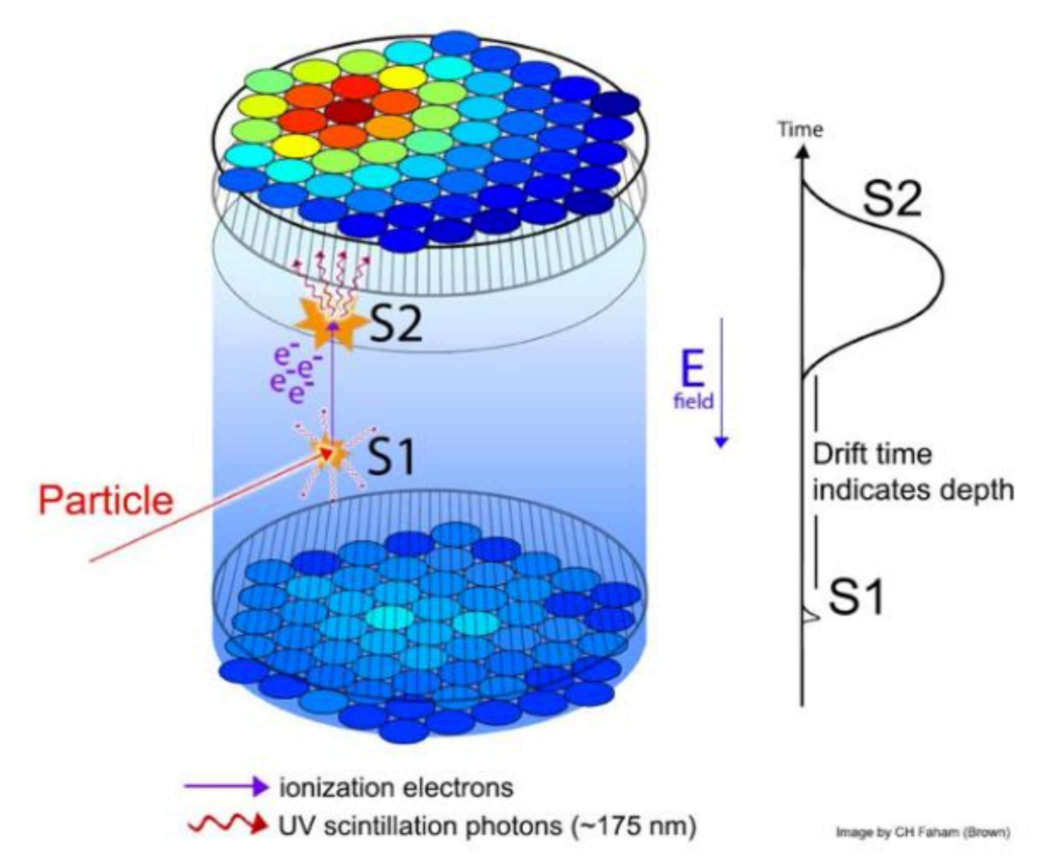
Image by CH Faham (Brown)

Source: Ref. [2]

- Primary scintillation light (S1) produced at the interaction site, detected by PMTs at the top and bottom of detector
- Ionization electrons drift up through the liquid xenon, in the drift field
  - Some recombine with positive ions, releasing more scintillation light (S1)
  - Others are extracted above the liquid surface, into gas phase region, where they form secondary proportional light (S2)
- Time between S1 and S2 gives us z-position of the recoil
- Pattern of S2 light on the PMTs gives us xy

Two-phase liquid noble element time projection chambers

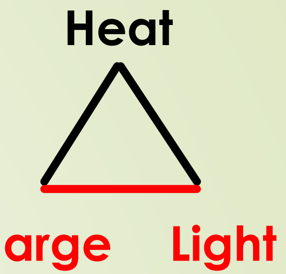




Source: Ref. [2]

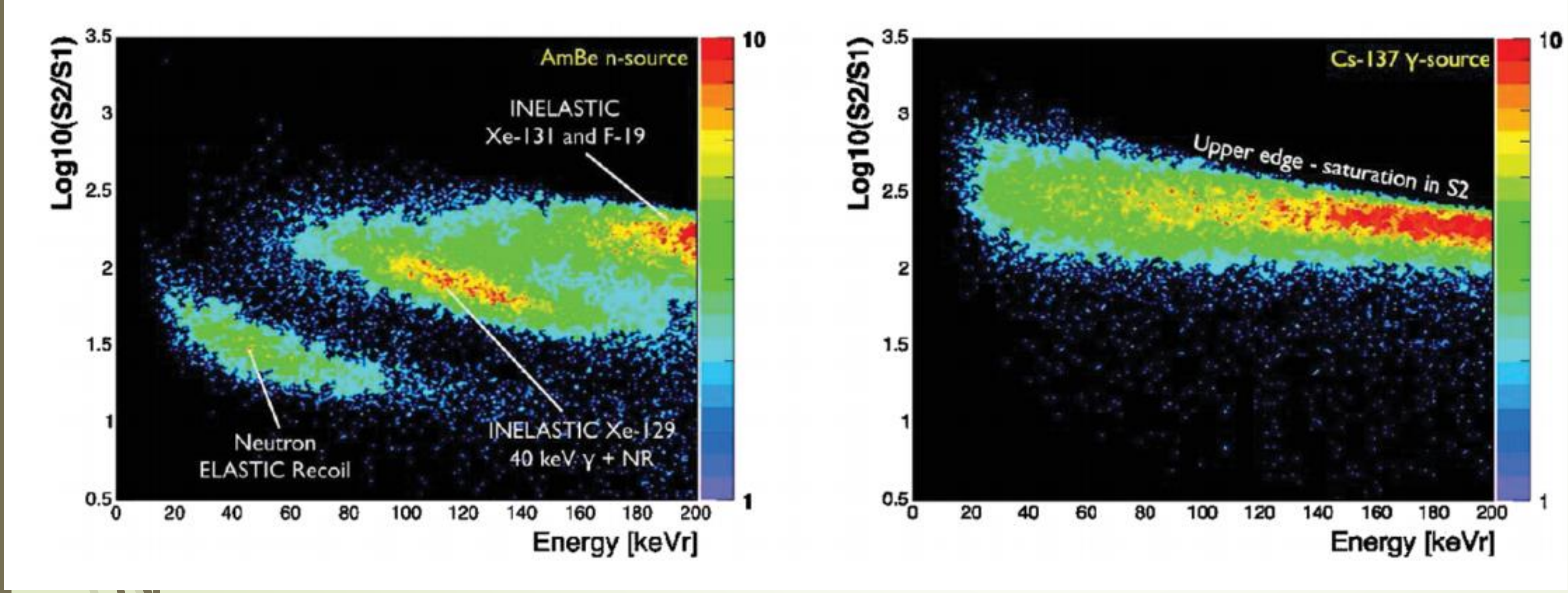
- Discrimination: the ratio of S2/S1 is different for electronic recoils and nuclear recoils
- Nuclear recoils have denser tracks, so they have more electron-ion recombination, and thus a lower S2/S1
- Crucially, this quantity is independent of particle ID—it depends on recoil type, energy, and detector properties

Two-phase liquid noble element time projection chambers



Heat

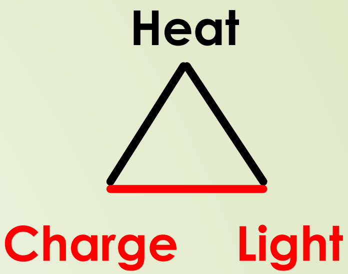
Charge **Light**

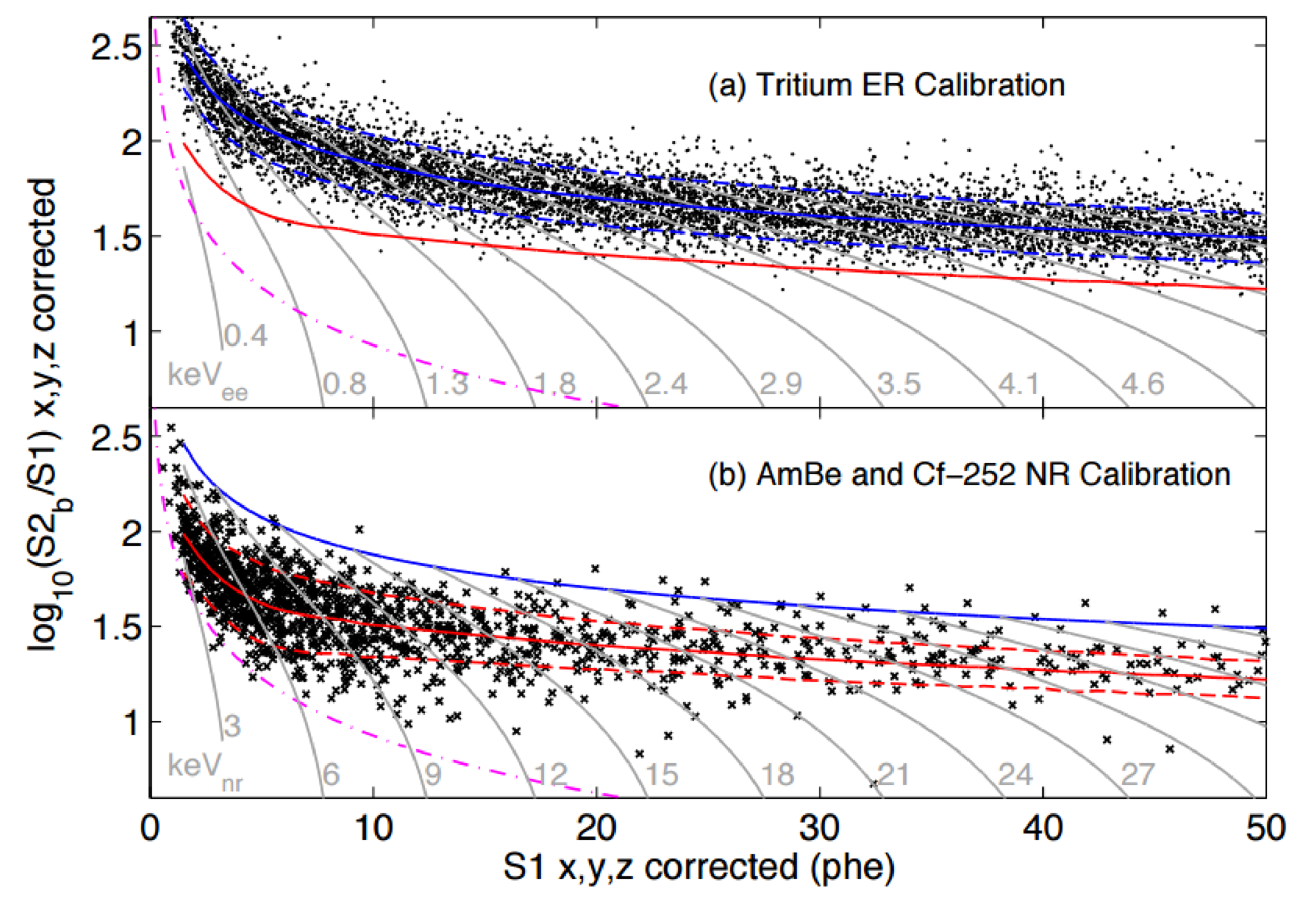


Source: Ref. [3]

- How do we actually discriminate (i.e. given a recoil, tell whether it is NR or ER)?
  - Answer: Calibration!
  - Use known sources of β and γ radiation to calibrate ER, and sources of neutrons to calibrate NR
- At left: Calibration results from a Columbia detector (AmBe for n, Cs-137 for γ)

Two-phase liquid noble element time projection chambers





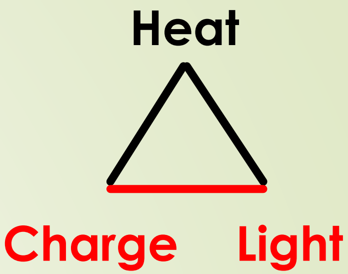
Source: Ref. [4]

How is this used in an analysis?

Lux 2013:

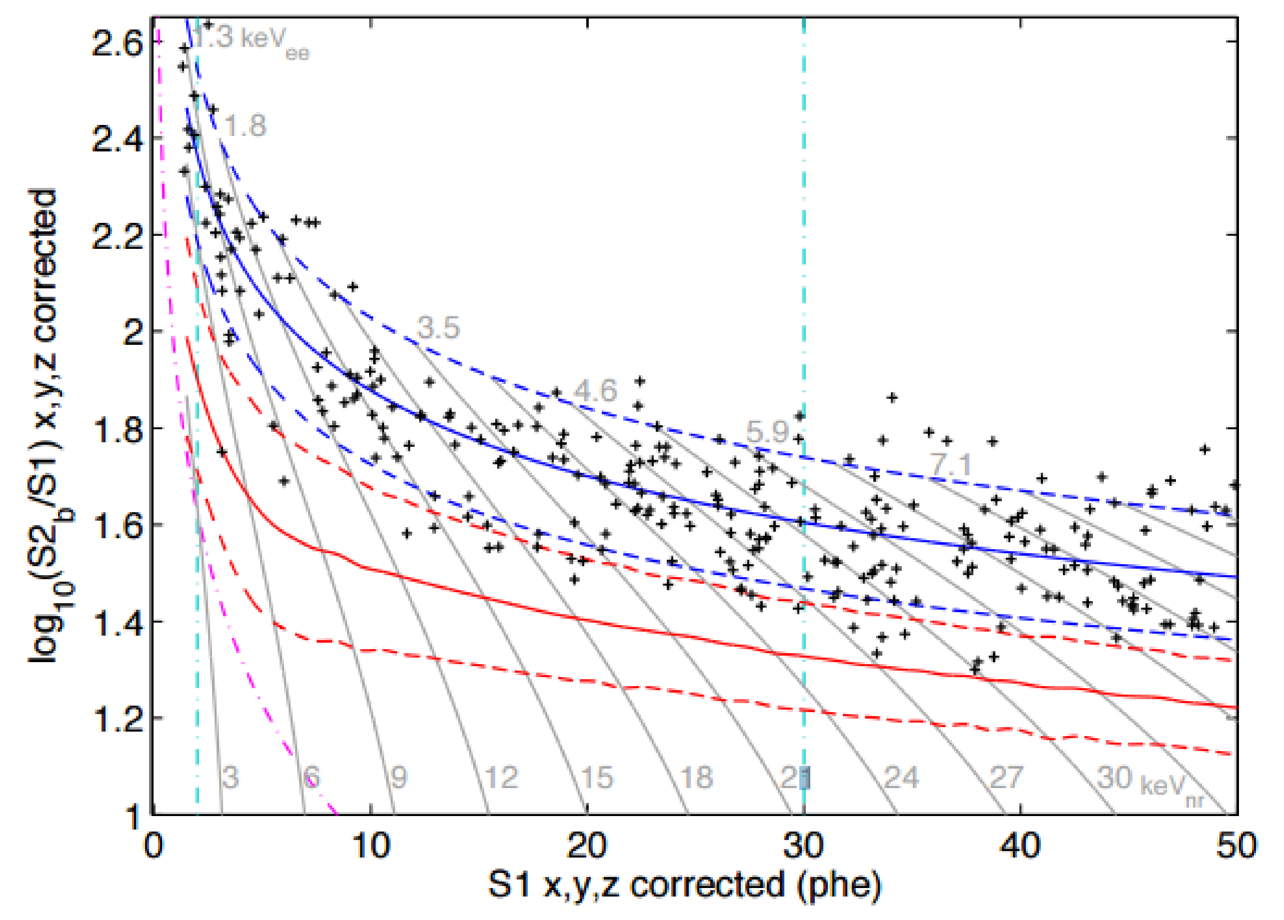
- ER calibrated with tritiated methane CH_3T, a β source
- NR calibrated with AmBe and Cf-252, neutron sources
- Discrimination power of 99.6%

Two-phase liquid noble element time projection chambers



Heat

Charge Light

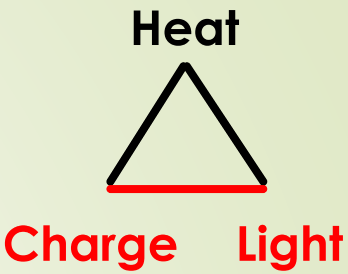


Source: Ref. [4]

Lux 2013:

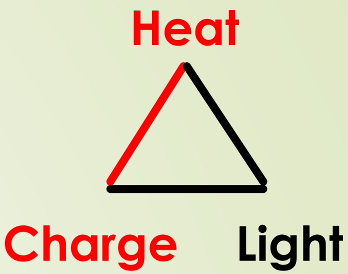
- WIMP search signal region, with 118 kg of fiducial mass and 85.3 live-day exposure
- Backgrounds include external γ, radio-isotopes in the detector, and neutrons
- Another background is leakage from ER events into the NR band—in this case, 0.64 ± 0.16 events
- Use these background expectations and results in a profile-likelihood-ratio to set limits on DM interactions

Two-phase liquid noble element time projection chambers



- The themes that were presented for discrimination in dual-phase TPCs are going to be valid in other detection techniques as well
- Identify the channels of energy deposit; analyze the apportionment of energy into the different channels
- Use calibration to separate NR signals from ER signals
- Use this discrimination to reject ER backgrounds, which are usually much more common than NR backgrounds

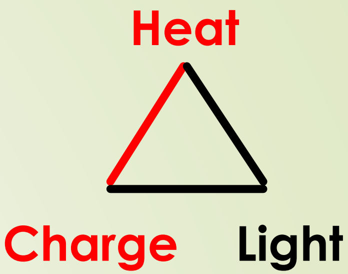
Cryogenic bolometers with charge readout



Source: Wikipedia

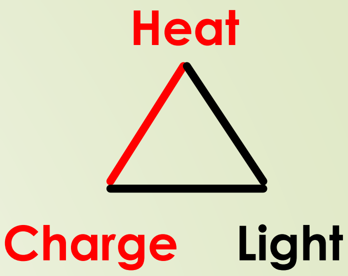
- To see how heat and charge channels in cryogenic bolometers can be used simultaneously to discriminate, we'll use CDMS-II as a case study
- The detector in CDMS-II is called a Z-Sensitive Ionization and Phonon (ZIP) detector (see left)
- Cryogenic crystal made of silicon or germanium

Cryogenic bolometers with charge readout



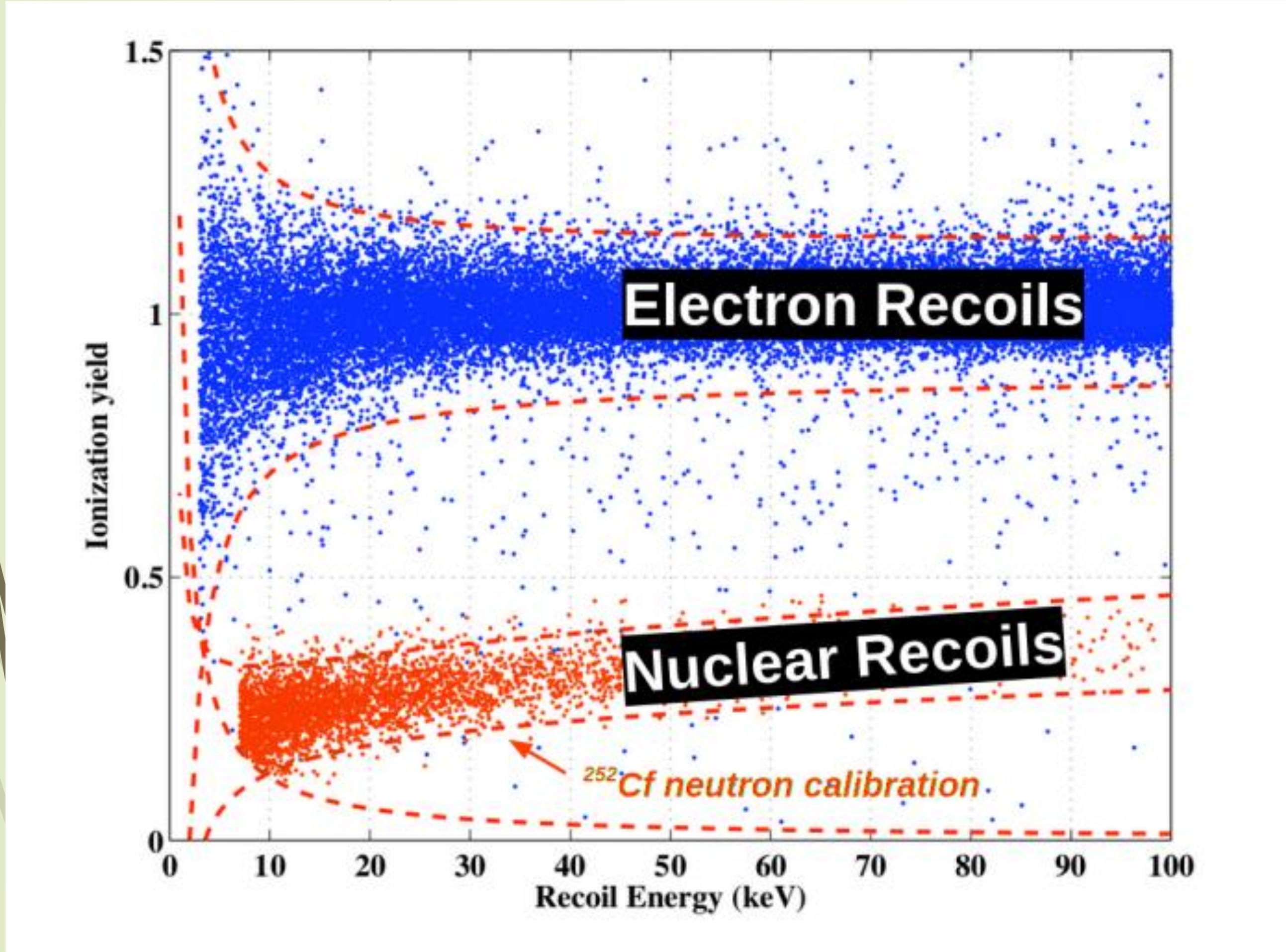
- Ionization signal:
  - Some portion of the recoil energy creates e-/h+ pairs in the crystal, which form a cascade of e-/h+ in the conduction band
  - Drift in an electric field towards electrodes
- Phonon signal:
  - Prompt phonons, generated from instantaneous displacement of nuclei and electrons
  - Recombination phonons from charge carriers reaching the electrodes (see above)
  - Luke phonons: energy dissipated in the crystal from the electric field doing work
  - Phonons measured by transition-edge sensors (TES), >4000 in each ZIP, connected to SQUIDs

Cryogenic bolometers with charge readout



Heat

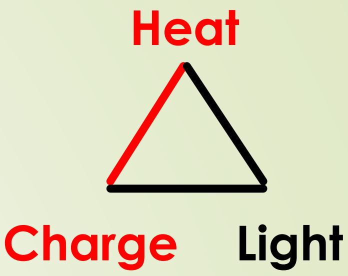
Charge **Light**

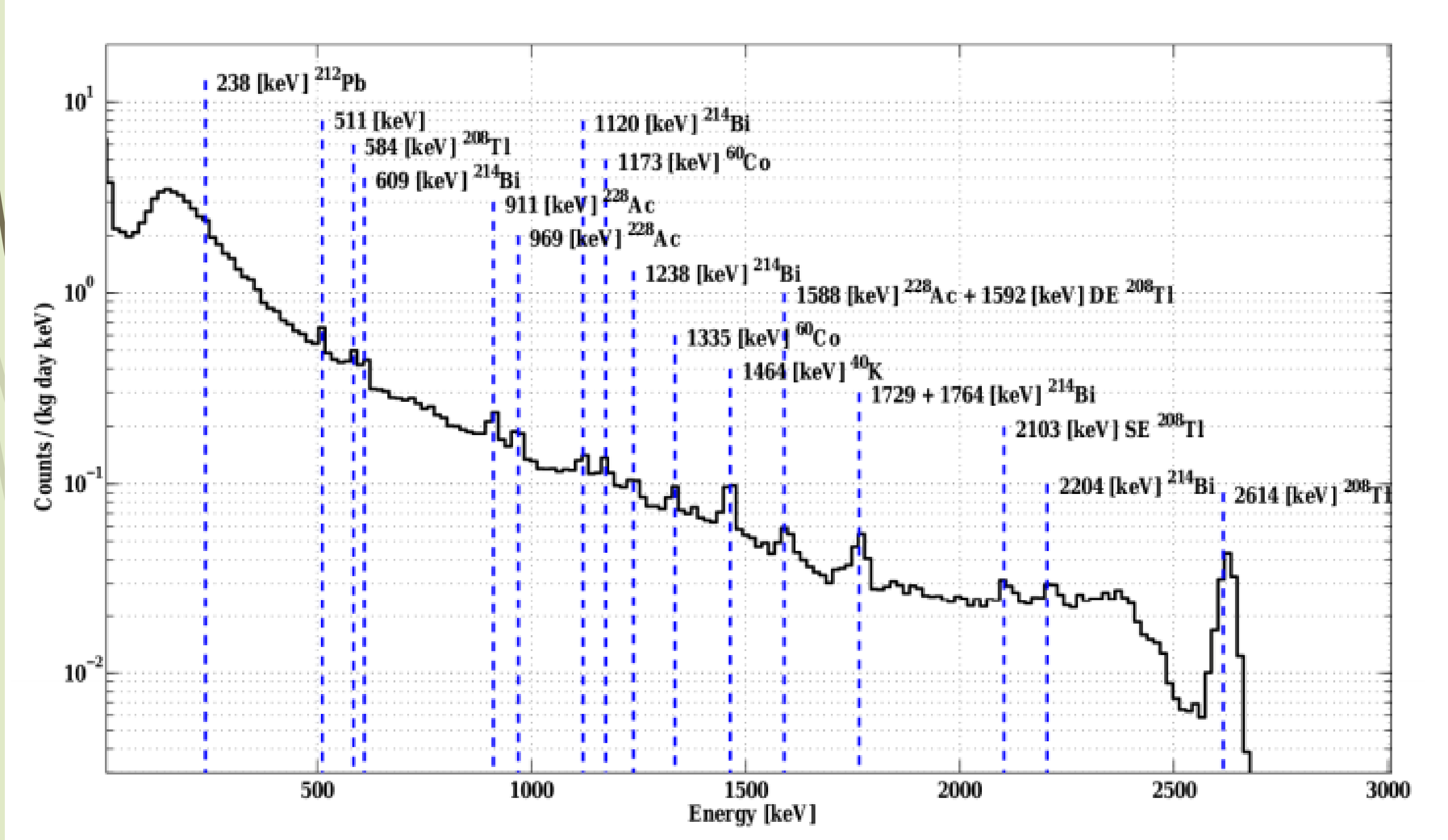


Source: Ref. [5]

- We expect ER to deposit more of their energy as ionization, compared to NR; this is exactly what we see
- Discriminating variable is ionization yield = E_Q/E_R
  - E_Q is the “electron-equivalent” ionization energy
  - E_R is the recoil energy
- ER calibration from ^{133}Ba (bands are ±3σ), NR calibration from ^{252}Cf (bands are ±2σ)

Cryogenic bolometers with charge readout

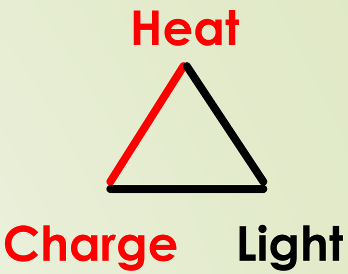


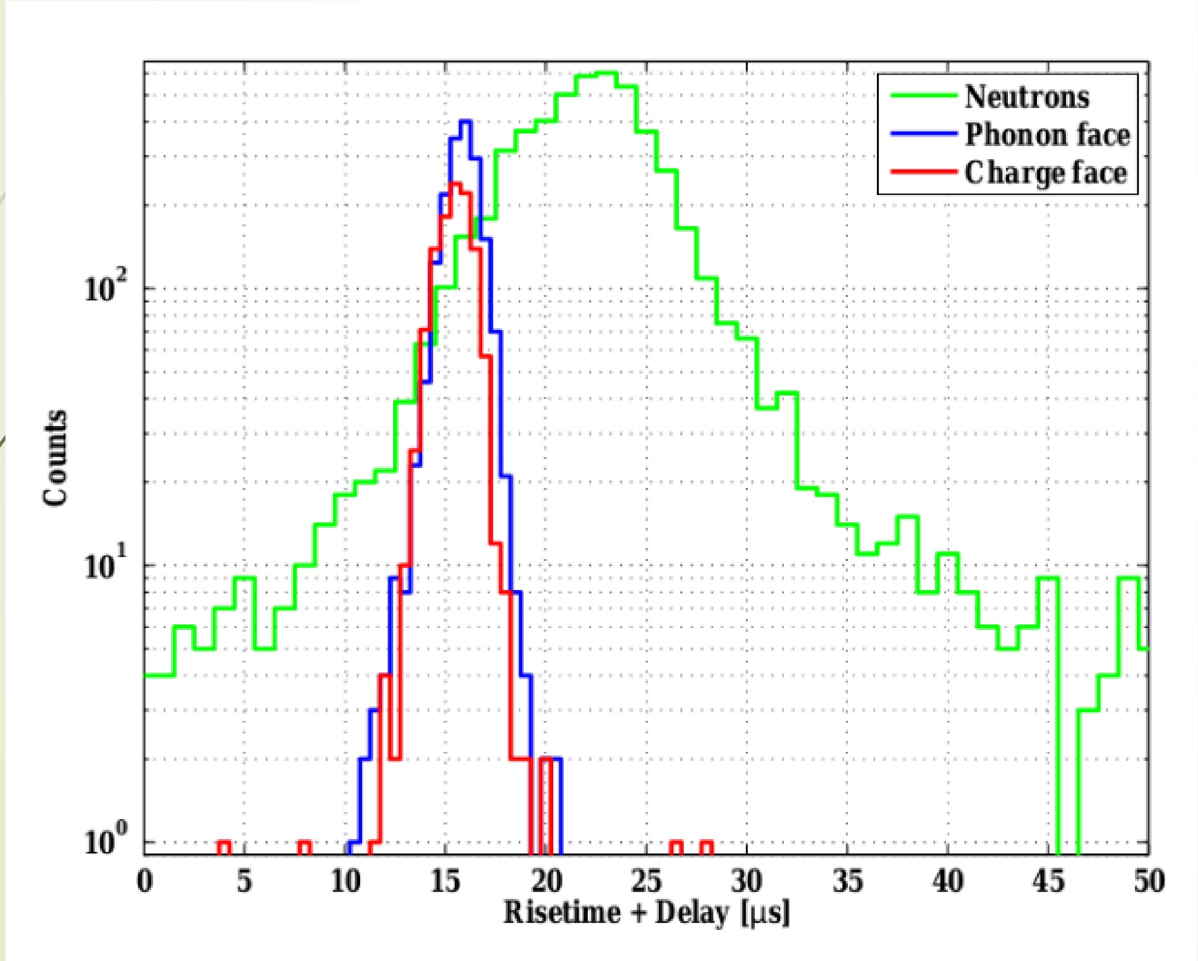


Source: Ref. [5]

- Backgrounds are:
  - Electron recoils in the bulk of the material, caused by radiogenic isotopes in the detector (see left), discriminated by ionization
  - Neutrons from internal sources or from cosmic ray-induced spallation, reduced by going underground and muon veto shield
  - (See next slide)

Cryogenic bolometers with charge readout

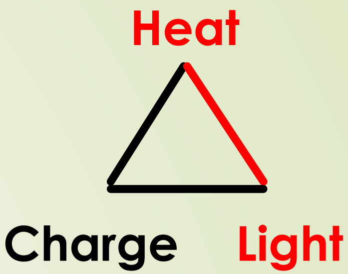


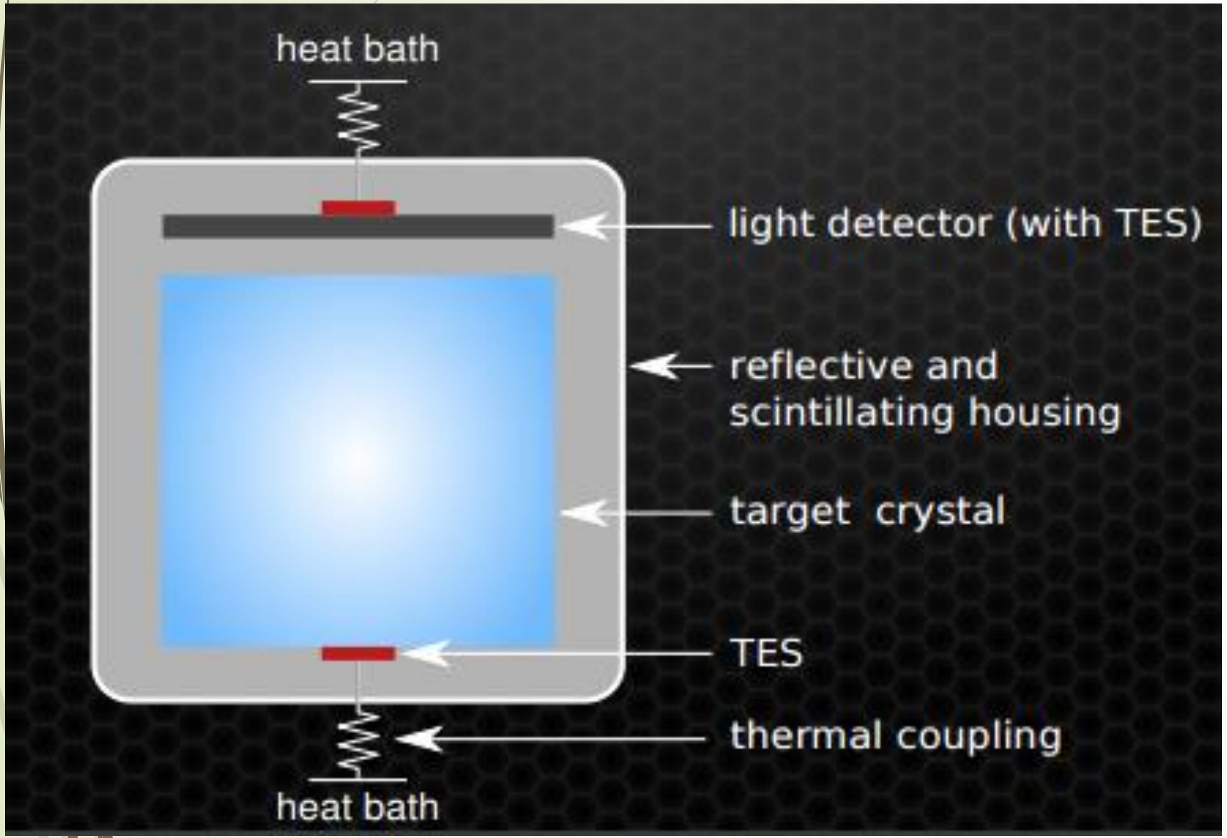


Source: Ref. [5]

- Backgrounds are:
  - ER at the edge of the detectors, discriminated by timing properties of the phonon signal (see left)

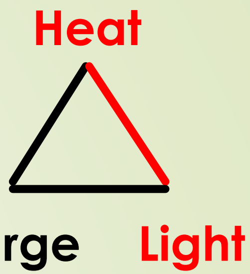
Scintillating cryogenic bolometers

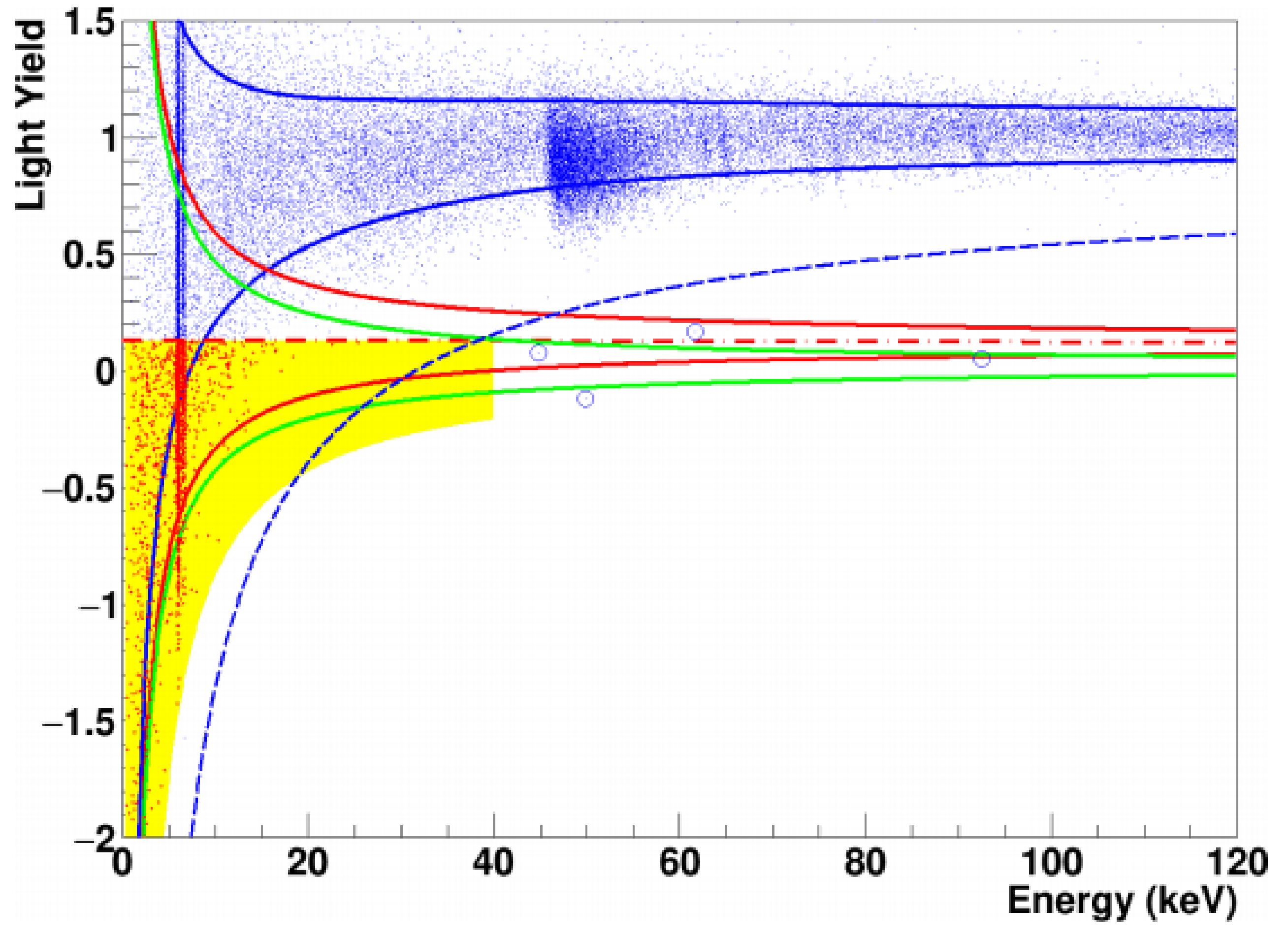




- Cryogenic Rare Event Search with Superconducting Thermometers (CRESST) is an example of a DM search that uses phonons and photons as signal channels
- As in other cryogenic bolometers, phonons propagate through crystal and are detected by TES
- CRESST uses scintillating $CaWO_4$ crystals, in conjunction with a silicon/sapphire wafer and TES, to measure photon signal

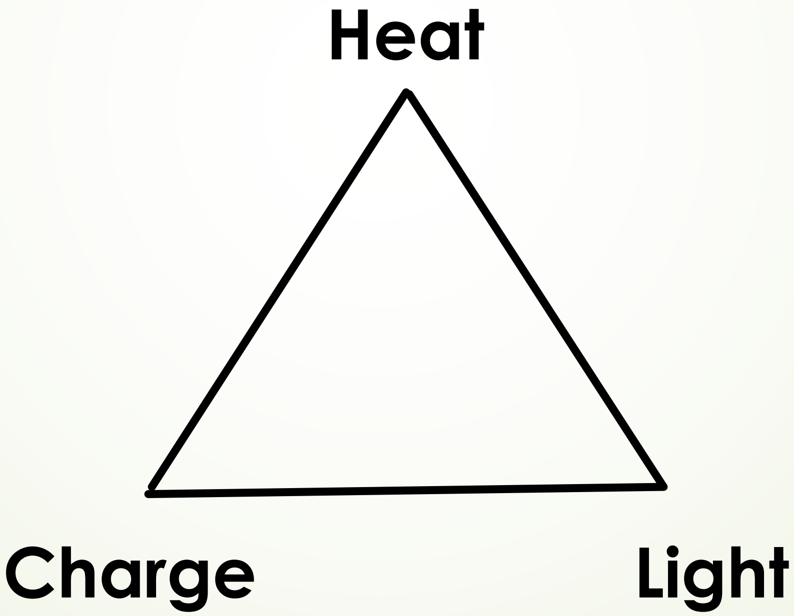
Scintillating cryogenic bolometers





- Light yield: ratio of light to phonon signal
- ^{57}Co for ER calibration (122 keV γ)
- NR calibration with neutron source
- Able to use quenching factors measured elsewhere, to determine NR bands for recoils of oxygen, tungsten, and calcium

We've finished all possible combinations of energy channels, so we're done, right…?



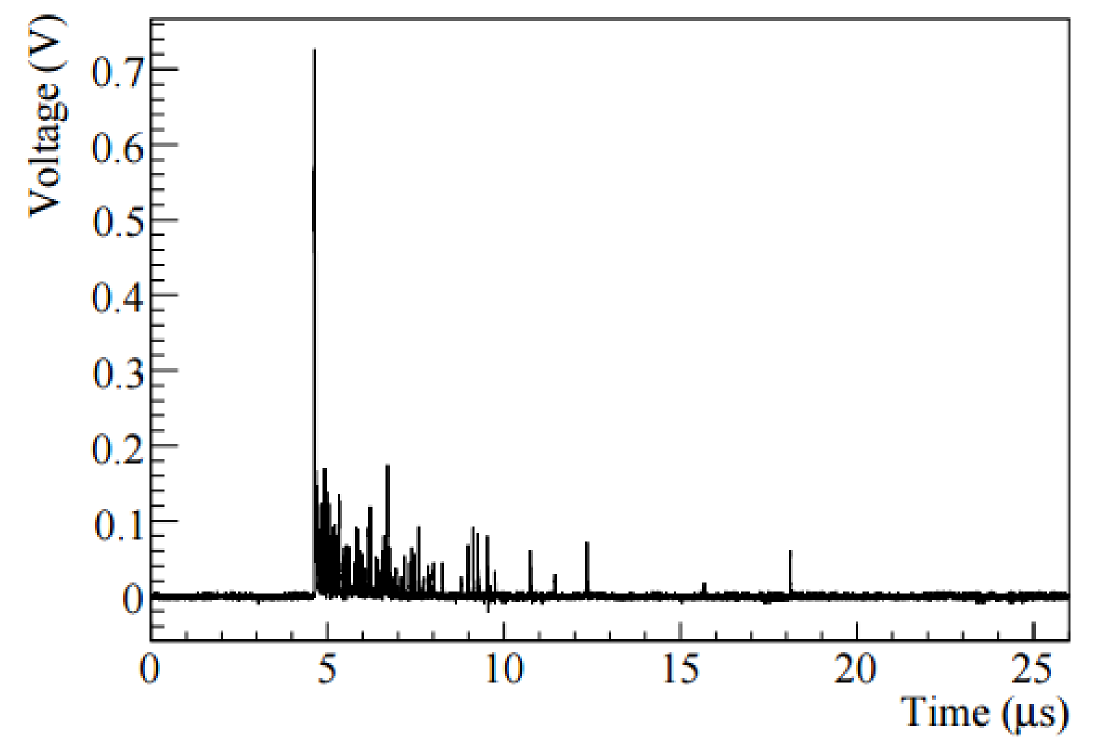
Heat

Charge

Light


BUT WAIT
Baking Soda
THERE'S MORE
quickmeme.com

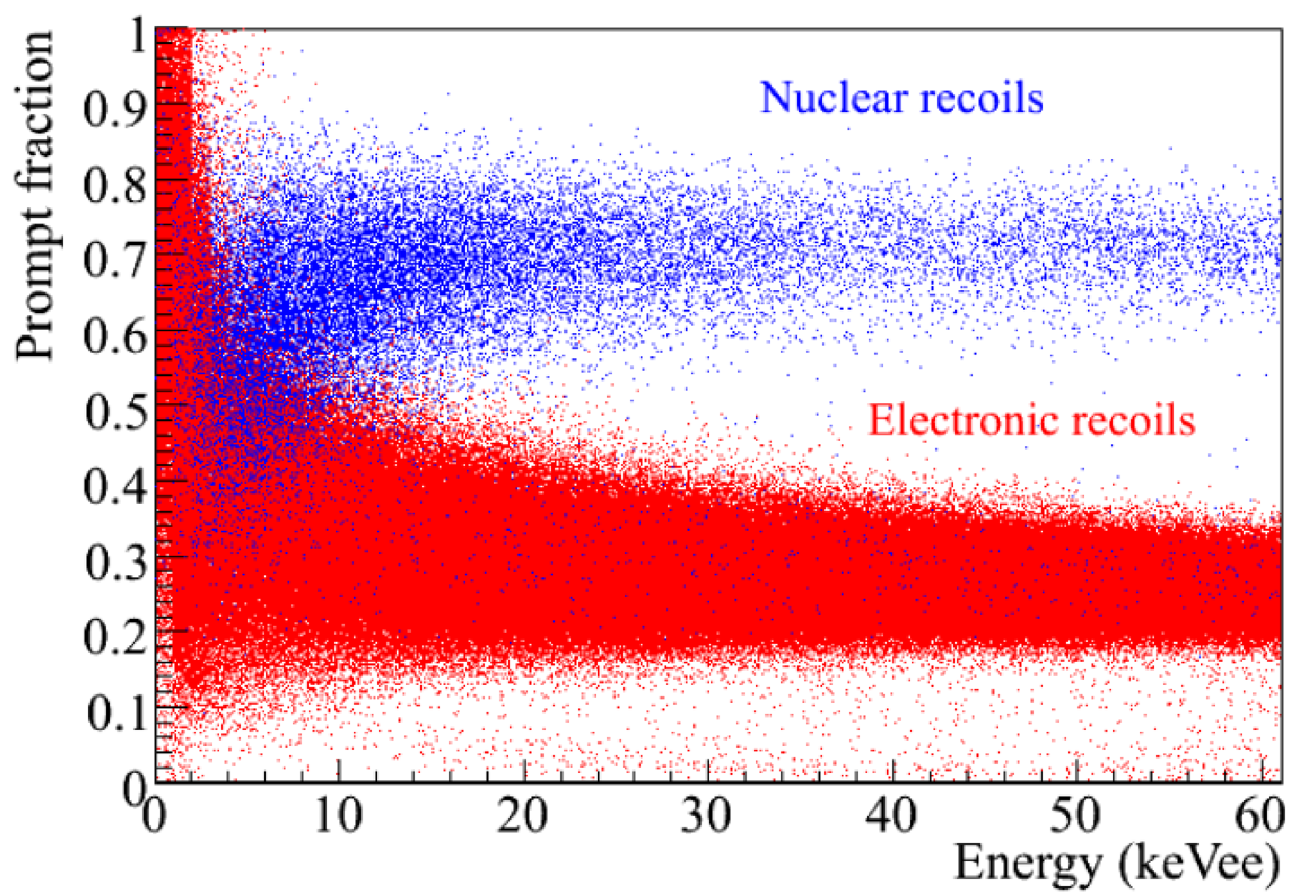
Pulse-Shape Discrimination



Source: Ref. [8]

- Liquid noble elements scintillate by forming excimers E_2^+ , which then de-excite with a characteristic timescale
- Singlet and triplet states have different time constants
- Triplet decays are suppressed in nuclear recoils, due to Penning ionization and spin exchange
- So this is a valid approach for discrimination, using only one channel of energy deposit
- Xe: $\tau_1 = 4\,ns, \quad \tau_3 = 22\,ns$
- Ar: $\tau_1 = 7\,ns, \quad \tau_3 = 1600\,ns$

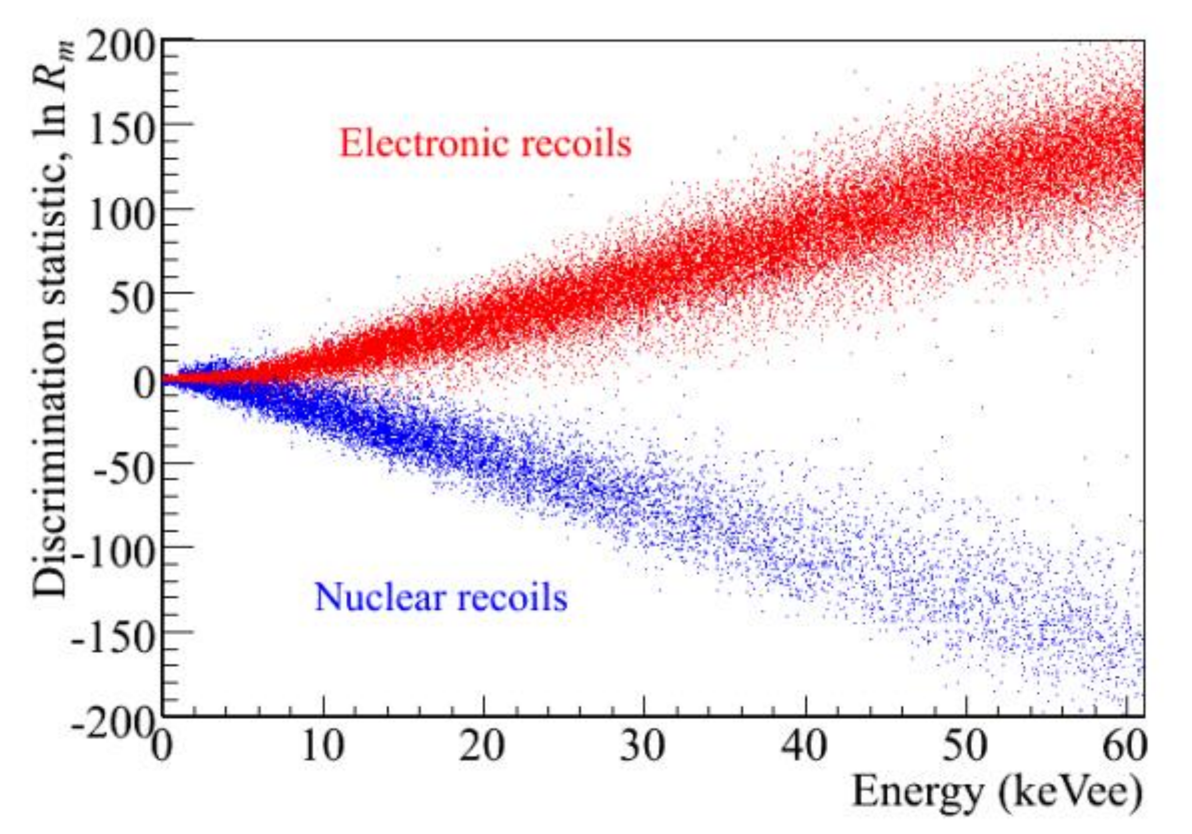
Methods of Pulse-Shape Discrimination



1. Prompt Fraction Method

- Define $f_p = \frac{\int_{T_i}^{\xi} V(t)dt}{\int_{T_i}^{T_f} V(t)dt}$
- Use this as discrimination variable
- At left, results from a single-phase LAr detector (3.14 L active volume).
- Here, $\xi = 90\ ns$ $T_i = t_0 - 50ns$, $T_f = t_0 + 9000\ ns$, and t_0 is the trigger time (empirically determined to give the best results).

Methods of Pulse-Shape Discrimination



2. Multibin method

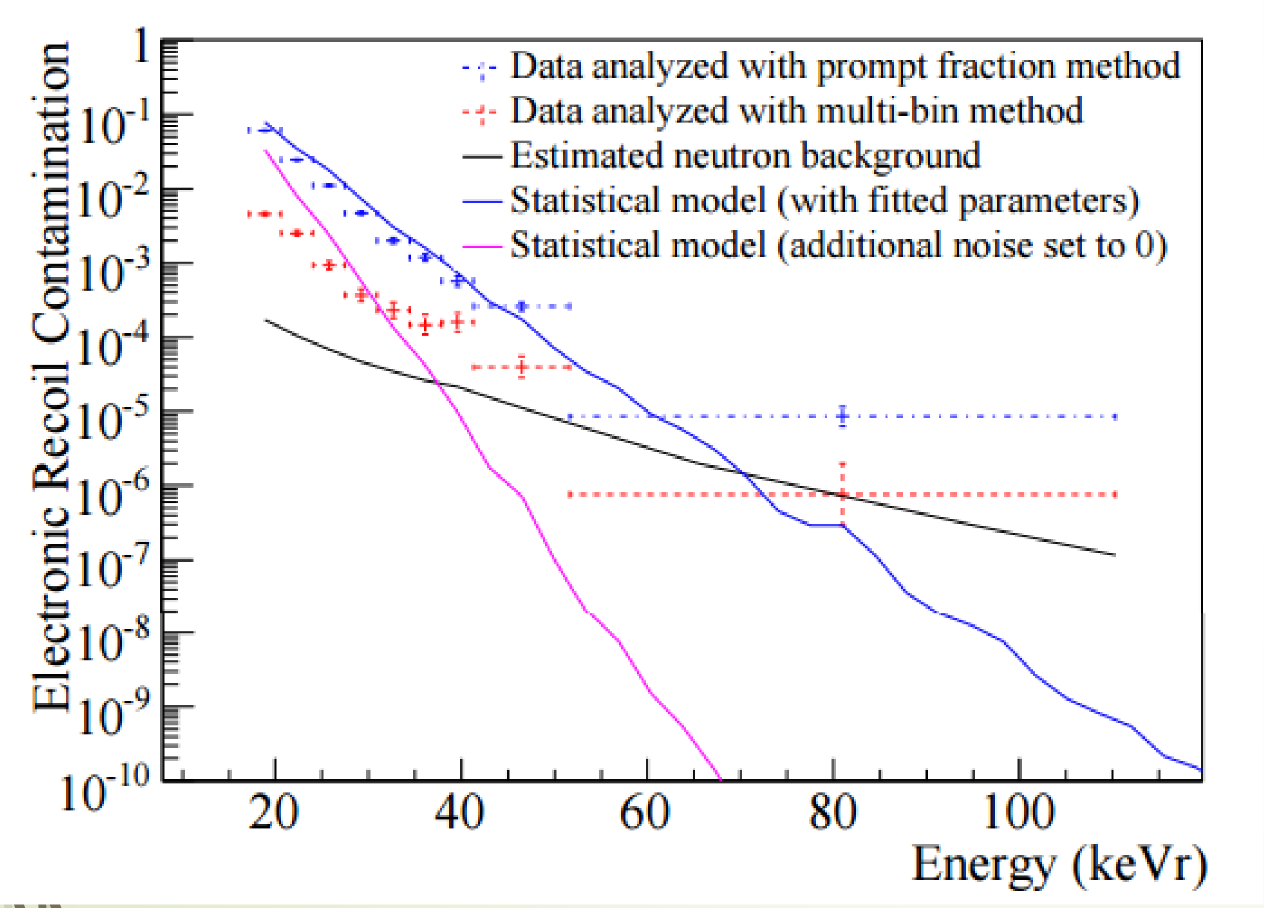
- Bin signal time and fraction of detected photoelectrons into K x L bins

$$\ln Y_e = N_{\mathrm{tot}} \sum_{k=1}^{K} \sum_{l=1}^{L} \delta_{ll'} p_m(k,l) \ln p_e(k,l') + \mathrm{const},$$

$$\ln Y_n = N_{\mathrm{tot}} \sum_{k=1}^{K} \sum_{l=1}^{L} \delta_{ll'} p_m(k,l) \ln p_n(k,l') + \mathrm{const}$$

$$\ln R_m = \ln Y_e - \ln Y_n .$$

Methods of Pulse-Shape Discrimination



- For given experiment, multibin method is better—there might be other algorithms
- Dark matter Experiment with liquid Argon and Pulse shape discrimination (DEAP-3600) aiming to use PSD in LAr, based on previous success in DEAP-1

Conclusions

- To reduce backgrounds (primarily from electrons and gamma rays), it is important to be able to discriminate between electron recoils and nuclear recoils in dark matter direct detection
- Noble liquid TPC's and cryogenic bolometers have been successful at this by looking at the ratios between two energy channels
- Other forms of discrimination exist that only use one channel of energy deposit, such as pulse-shape discrimination and annual modulation

Questions?

Sources

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