Solid Xenon Bolometers for Neutrinoless Double Beta Decay

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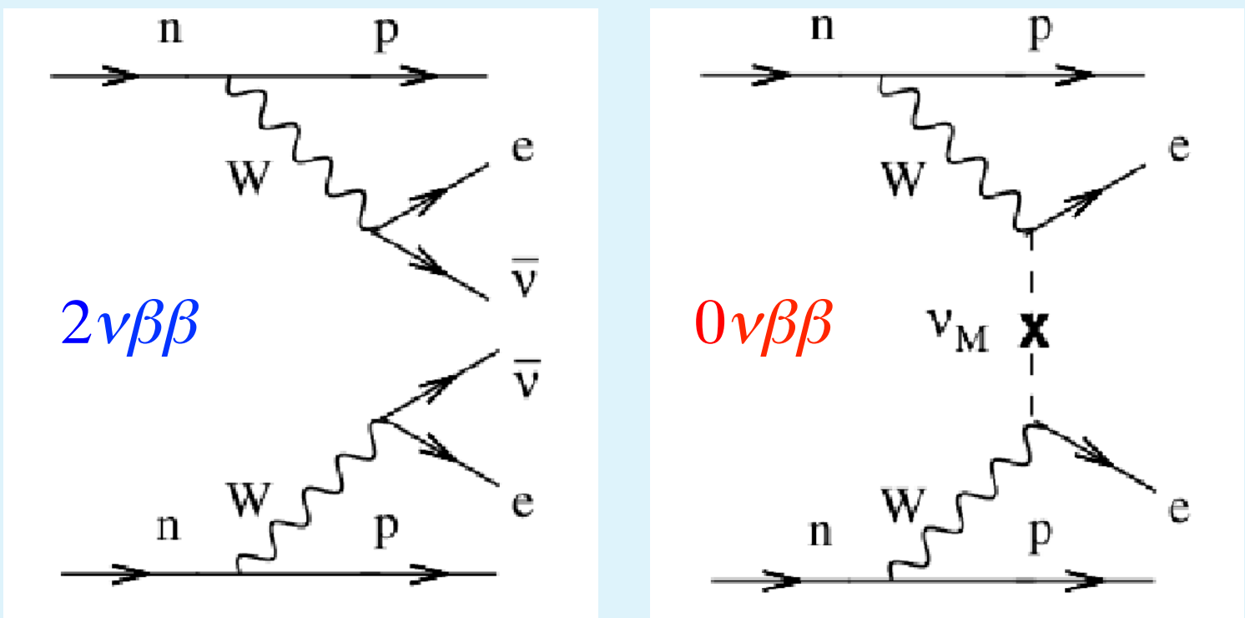
Cryogenic liquid xenon detectors have become a popular technology in the search for rare events, such as neutrinoless double beta decay and dark matter interactions. The power of the liquid xenon detector technology is in the combination of the ionization and scintillation signals, resulting in particle discrimination and improved energy resolution over the ionization-only signal. In comparison macrobolometers, which can be made from a variety of materials, have been shown to have an order of magnitude better energy resolution in the phonon channel. Solid xenon bolometers, under development at Drexel University, offer an opportunity to combine excellent energy resolution in the phonon channel with a scintillation or ionization signal for background rejection. This would be a powerful future detector technology in the search for neutrinoless double beta decay of Xe-136.

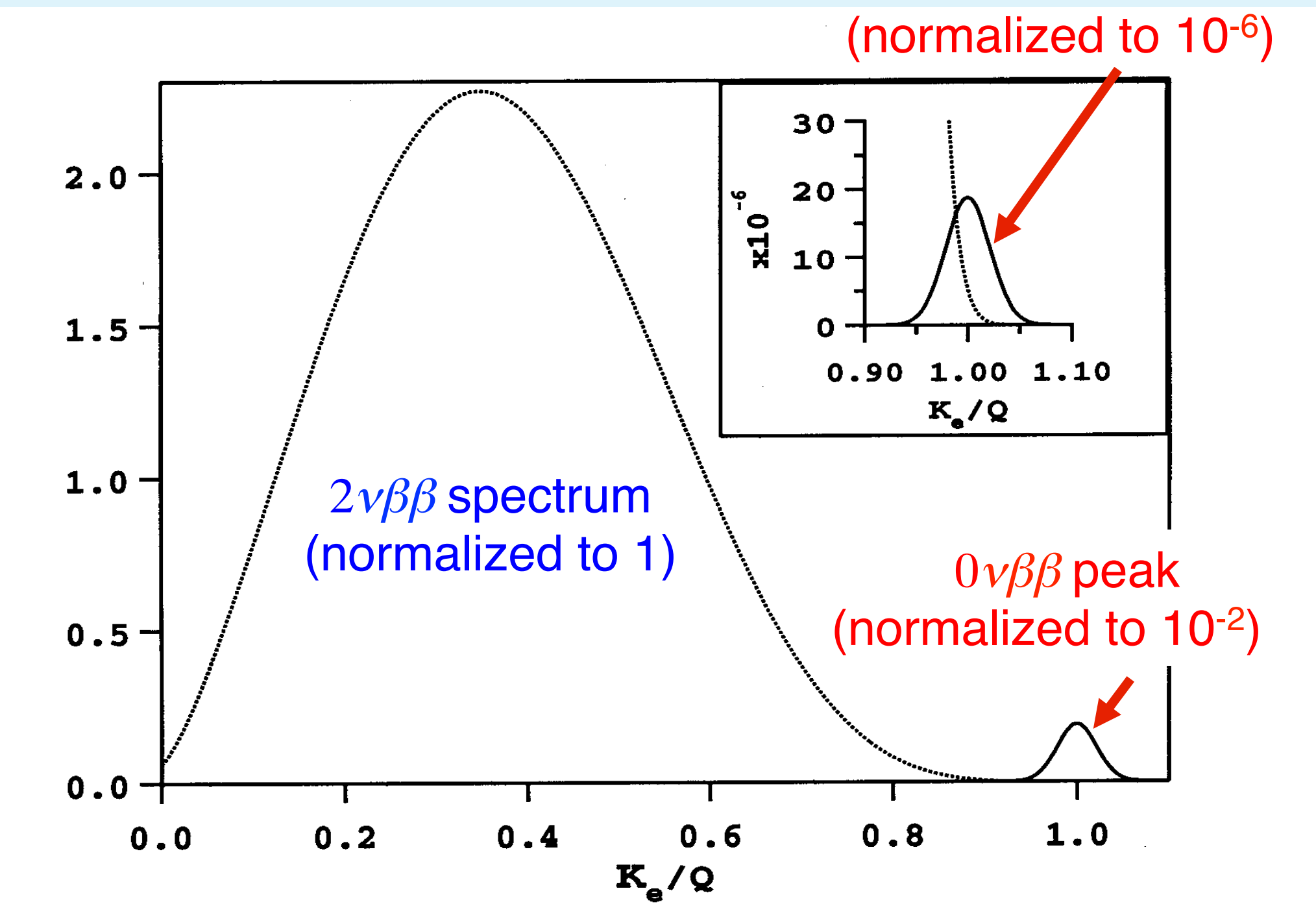


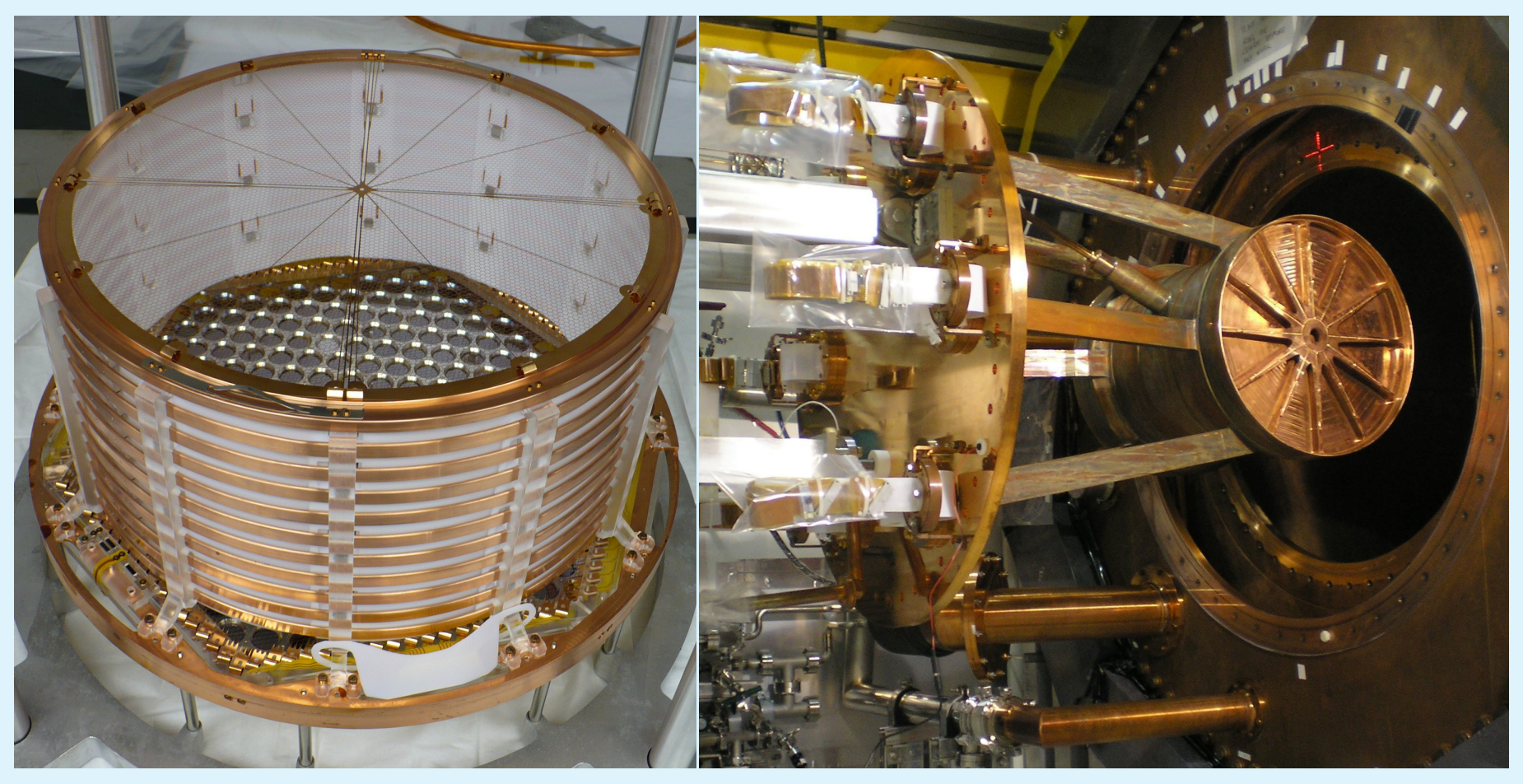
Double beta decay is a second order weak process allowed by the standard model. This is the dominant decay mode for certain even-even nuclei for which the single beta decay is energetically forbidden. In the case that neutrinos are Majorana particles, which means that the neutrino is its own antiparticle, a second process called neutrinoless double beta decay ($0\nu\beta\beta$) can occur. The rate for this process is given by

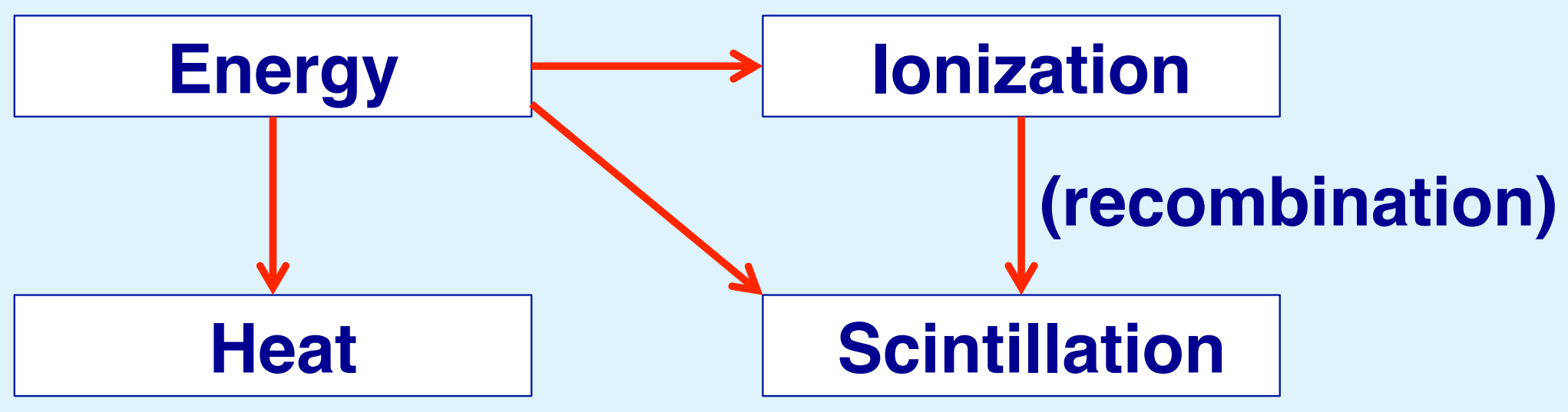
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}\left|M^{0\nu}\right|^2\left\langle m_\nu\right\rangle^2$$

where $G^{0\nu}$ is a phase space factor proportional to the *Q*-value[5], $M^{0\nu}$ is the nuclear matrix element, and m_ν is the effective Majorana mass. The observation of $0\nu\beta\beta$ would prove that neutrinos are Majorana particles.

$0\nu\beta\beta$ is detected by searching for a peak in the two-electron summed energy spectrum located precisely at the decay Q-value. $0\nu\beta\beta$ searches require detectors with large mass, excellent energy resolution, and low backgrounds. The next generation of $0\nu\beta\beta$ searches will require tonnes of source material. ^{136}Xe is an excellent candidate isotope for $0\nu\beta\beta$ searches for several reasons, including economical enrichment from the natural isotopic abundance of 8.9%.





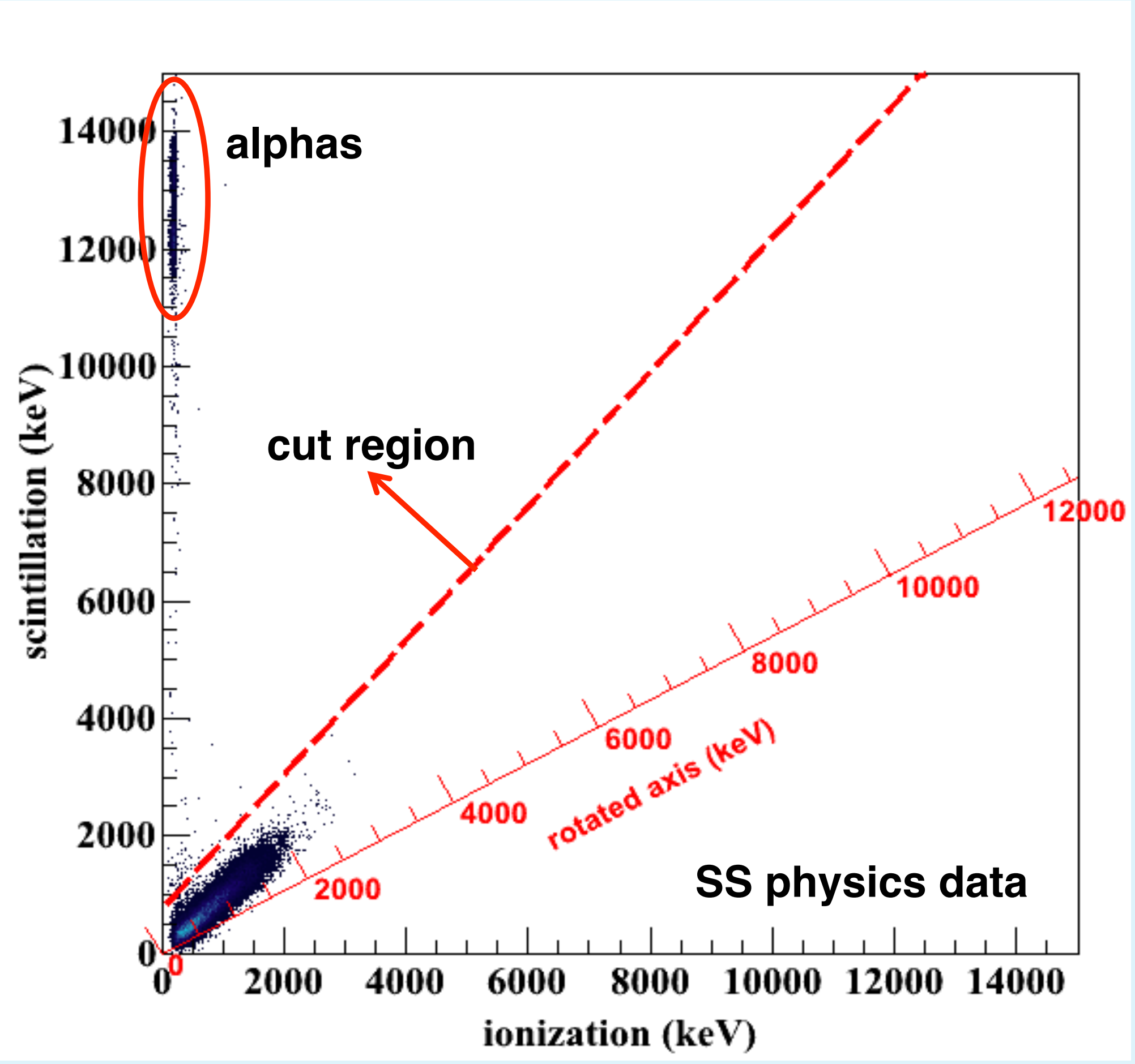


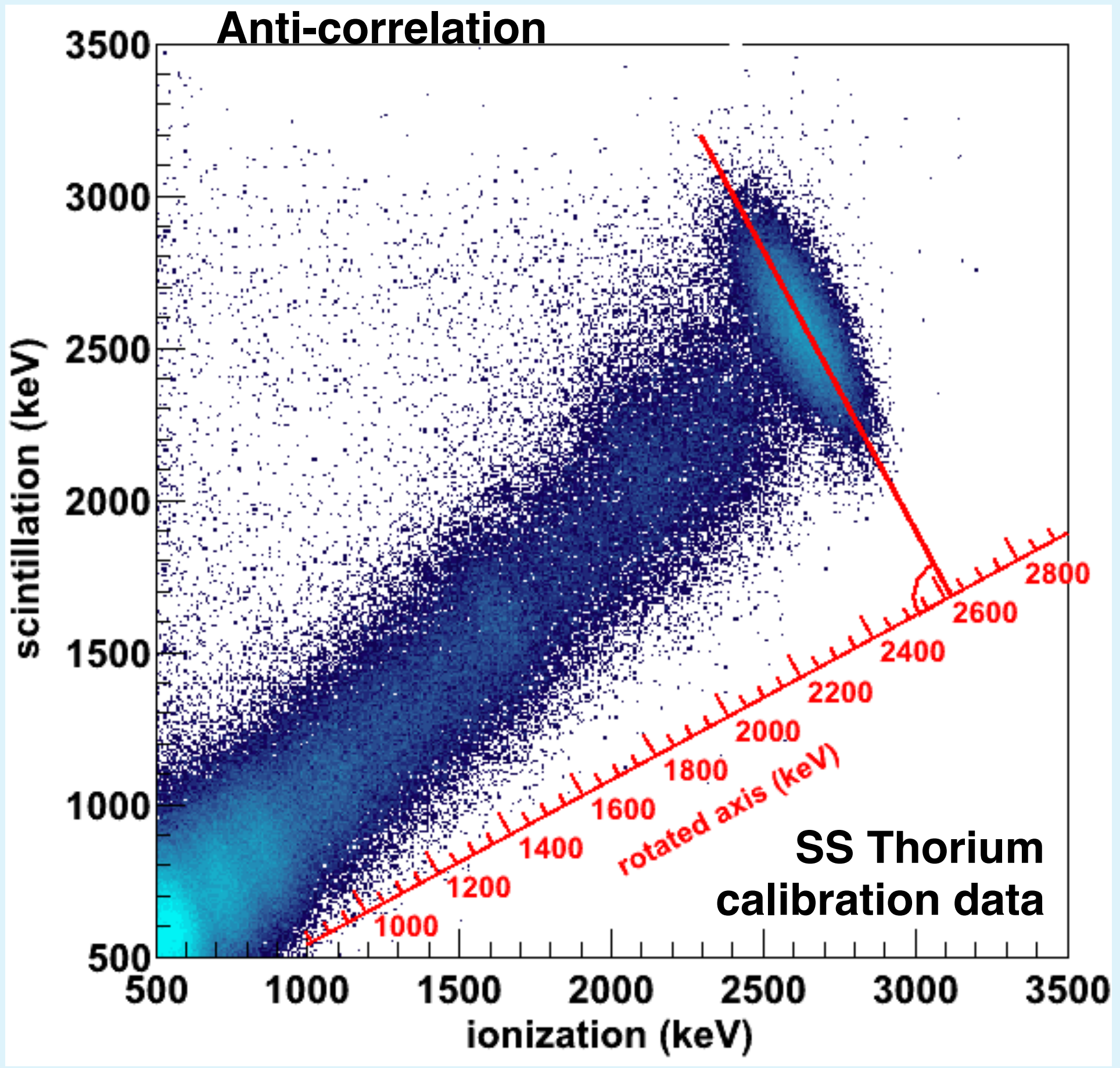
Energy → **Ionization**, **Heat**, **Scintillation**

Ionization → **Scintillation** **(recombination)**

EXO-200 is a liquid xenon time projection chamber searching for $0\nu\beta\beta$ of ^{136}Xe [1]. The EXO-200 detector has demonstrated an energy resolution of 1.6% at the Q-value and set a strong limit of $T_{1/2} > 1.1\times10^{25}$ years at 90% confidence level for $0\nu\beta\beta$ of ^{136}Xe [2]. The next generation experiment nEXO is planned to build on the success of EXO-200.

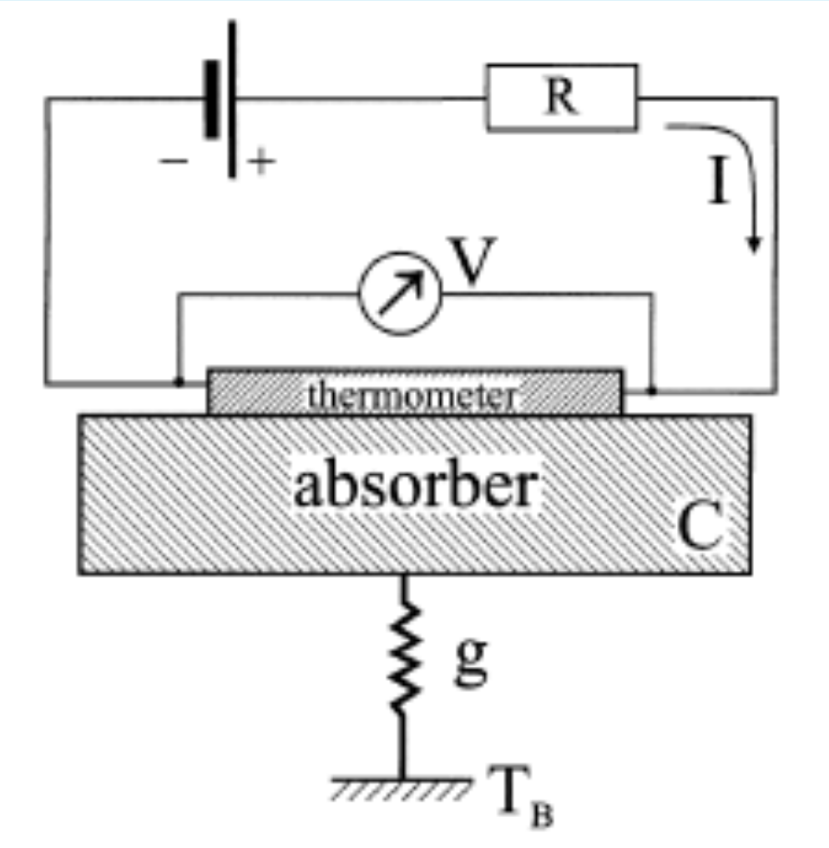
When radiation interacts with a noble gas detection medium such as xenon, energy is deposited in three signal channels: heat, ionization, and scintillation. The heat signal is not detectable in a liquid xenon detector, but the power of the liquid xenon detector technology is in the detection and combination of the ionization and scintillation signals. Because different kinds of particle interactions result in different ratios of scintillation to ionization, liquid xenon detectors have an excellent particle discrimination capability for background rejection.

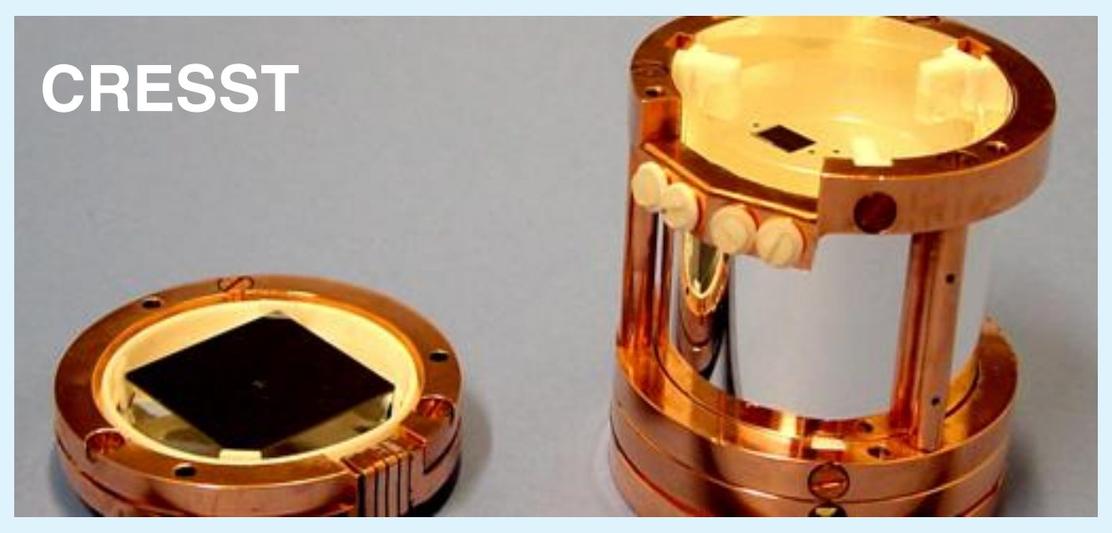


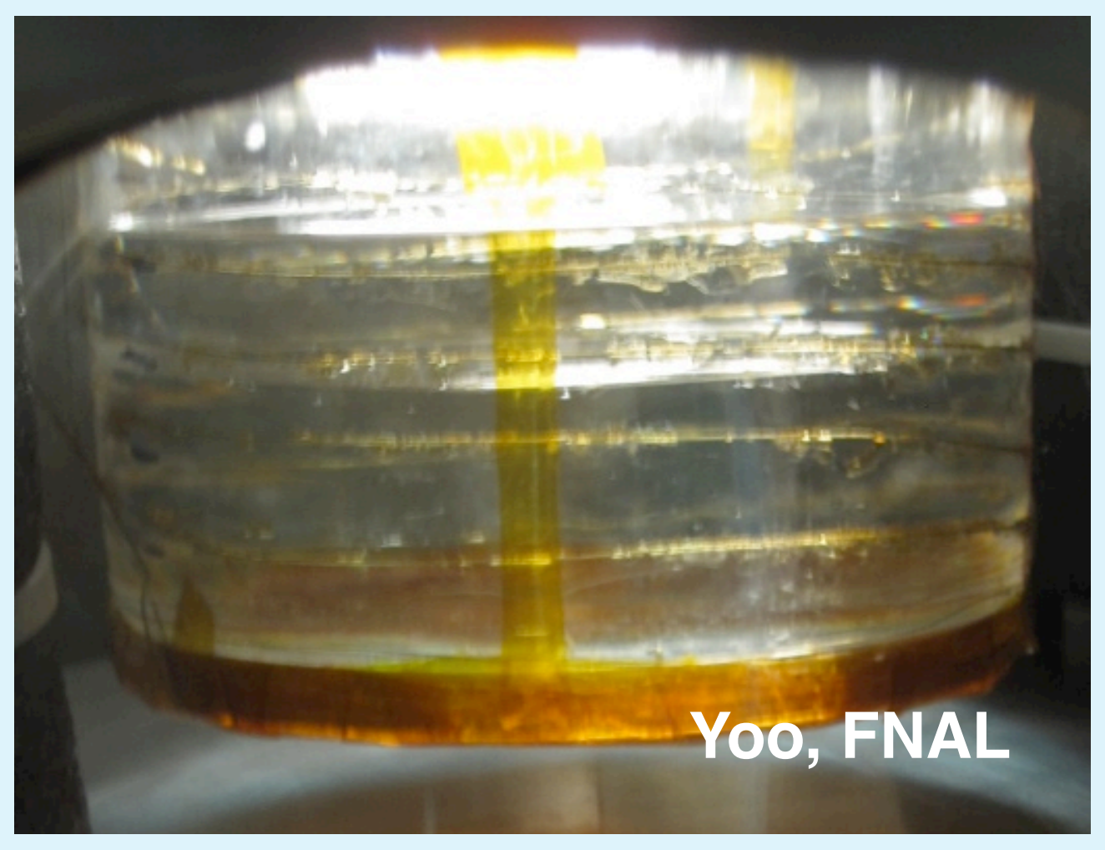


In addition, the combination of ionization and scintillation signals results in improved energy resolution over the ionization-only signal. Liquid xenon displays a microscopic anti-correlation behavior caused by large correlated fluctuations between the ionization and scintillation channels [4]. This phenomenon allows for improved energy resolution through a linear combination of scintillation and ionization signals. It is only in this rotated energy frame that EXO-200 achieves 1.6% energy resolution [4]. While this effect is an important component of the detector response that has been modeled empirically [5], it has not been described from first principles. Because they can detect the normally unusable heat signal directly, solid xenon bolometers may offer the final piece of the puzzle in understanding xenon detector energy response.

The bolometric detector technique and liquid xenon detectors have both been applied to rare event searches in basic nuclear physics, but they have never before been combined. Solid xenon detectors offer the possibility to combine the best aspects of ^{136}Xe as a $0\nu\beta\beta$ candidate isotope with the excellent energy resolution and background rejection of a scintillating bolometer. Because of the excellent counting statistics in the phonon channel, bolometers are demonstrated to have energy resolution an order of magnitude better than the energy resolution of a liquid xenon detector. In addition, an interaction with a xenon bolometer would now produce three potentially detectable signal channels -- heat, ionization, and scintillation.



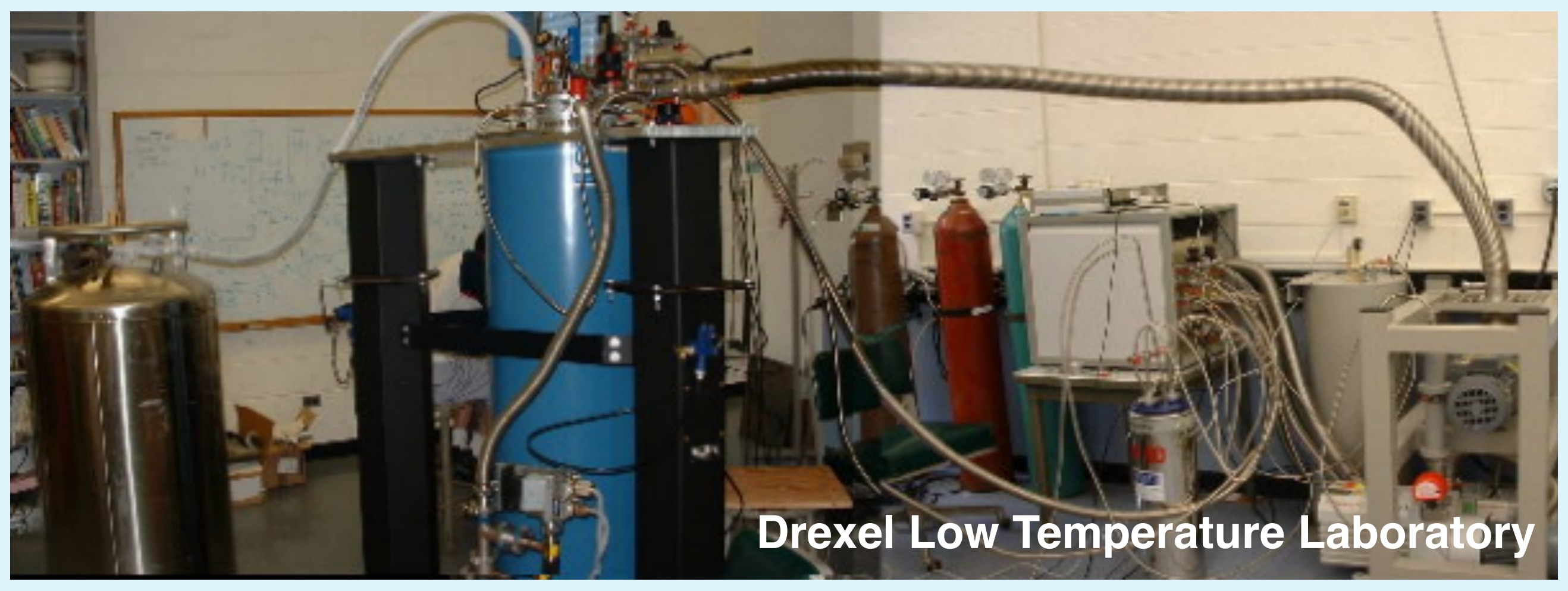




The combined measurement of any two energy channels can provide particle discrimination, and the combination of all three could be extremely powerful for both detector physics and fundamental physics applications. The LUCIFER collaboration is developing scintillating bolometers for $0\nu\beta\beta$ [6], and the CRESST experiment uses scintillating bolometers to search for dark matter [7].

A group at Fermi Lab has built on work done at Syracuse University using a cryobath method to produced large (~1 kg) solid xenon crystals at a temperature of ~160 K [8]. This work demonstrates the feasibility of growing large, transparent solid xenon crystals, although it is not well-suited for bolometer growth.

The Drexel group is developing a technique to grow the Xe absorbers *in situ* in a dilution refrigerator, with an ultimate goal of instrumenting scintillating Xe bolometers. The dilution refrigerator laboratory and experimental growth plate are shown below.



The search for $0\nu\beta\beta$ is the search for Physics Beyond the Standard Model, and improved detector technologies can have a profound impact on this field. While liquid xenon detectors have proven a promising technology for $0\nu\beta\beta$, solid xenon bolometers have the potential to improve the search even further through their superior energy resolution. Xe bolometers are expected to scintillate, which could also lead to powerful background rejection through particle discrimination.

Powerful liquid Xe detector technology, scintillating bolometer technology, and the growth of large transparent Xe crystals have all been demonstrated. The Drexel group is working toward the synthesis of these technologies in order to develop and characterize scintillating bolometers based on solid Xe.

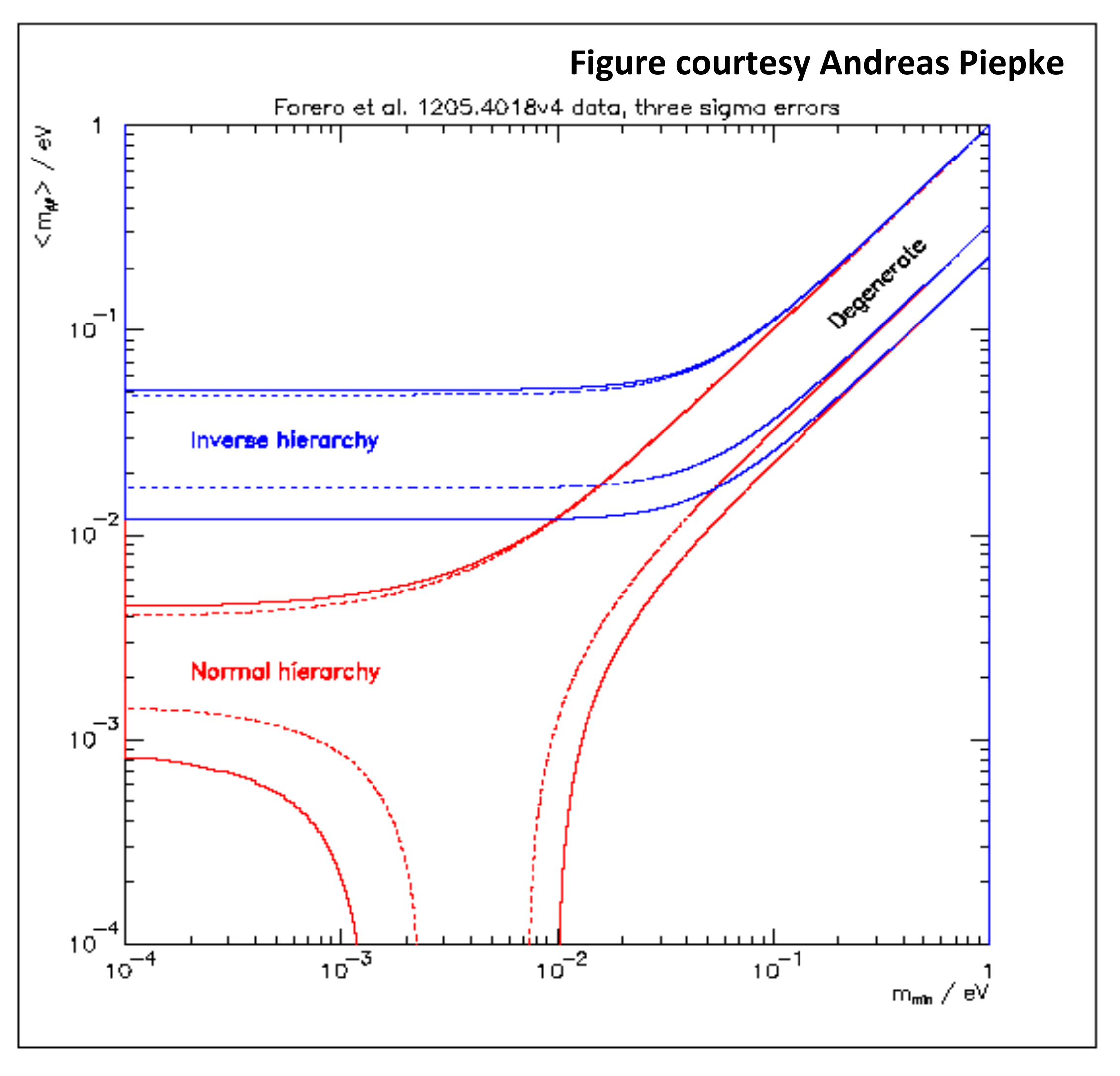


Figure courtesy Andreas Piepke

References

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