Photo: Matt Kapust (SURF)

Noble liquid radiation detectors: science and applications

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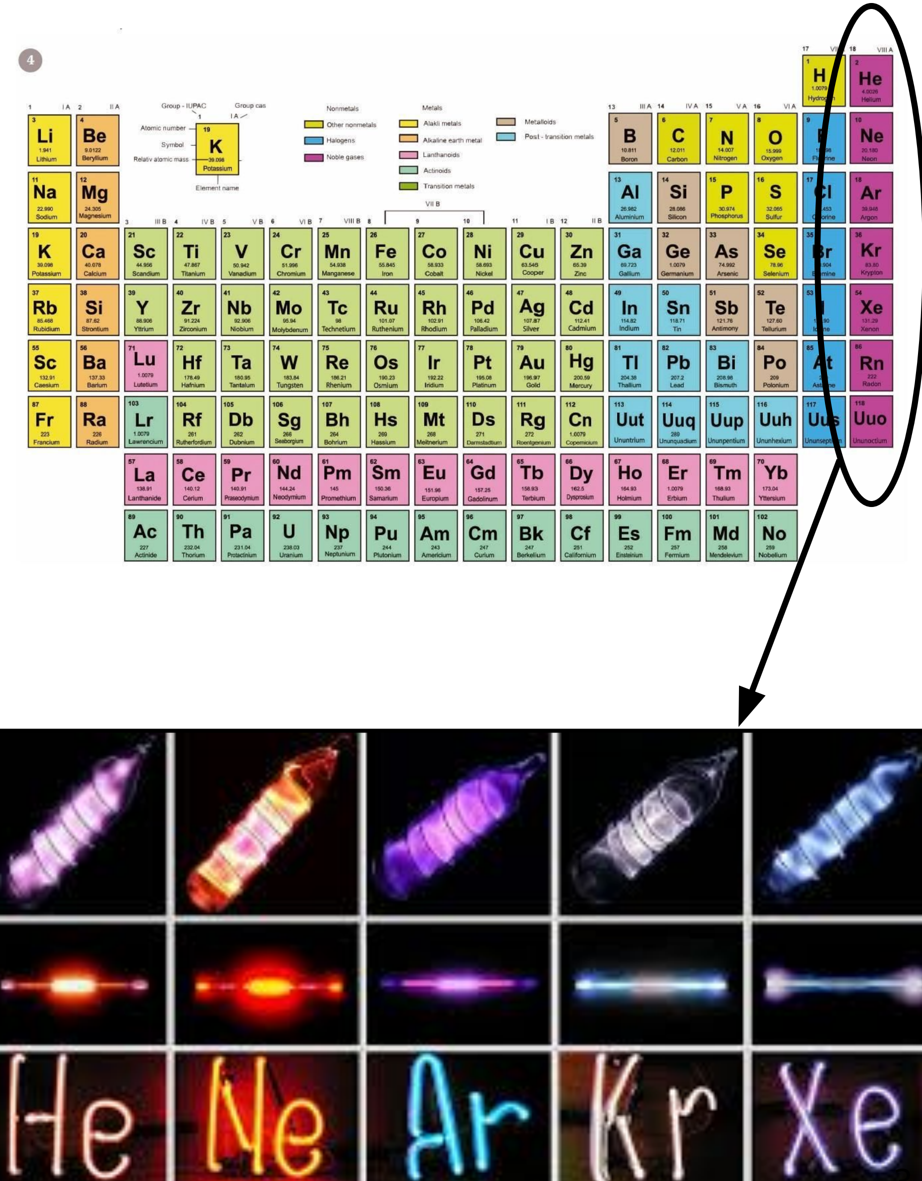
Outline

- Radiation detection with noble liquids
- Application: dark matter detection
- Application: low energy neutrino detection
- Application: neutrinoless double-beta decay

The noble elements

Radiation can generate signals via:

- **Scintillation**
  - Dimer formation → VUV photons
- **Ionization**
  - Negative electron affinity important
- **Vibrational excitations (superfluid He)**
  - Phonons + rotons



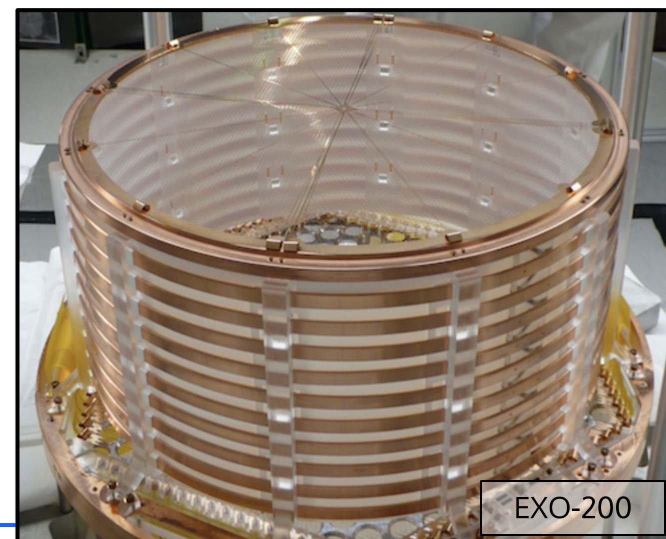
Two classes of detectors

Single channel (ionization or scintillation):

- Scintillation-only detectors easier to build/operate, can have good particle ID
- Ionization-only detectors can have extremely low energy thresholds

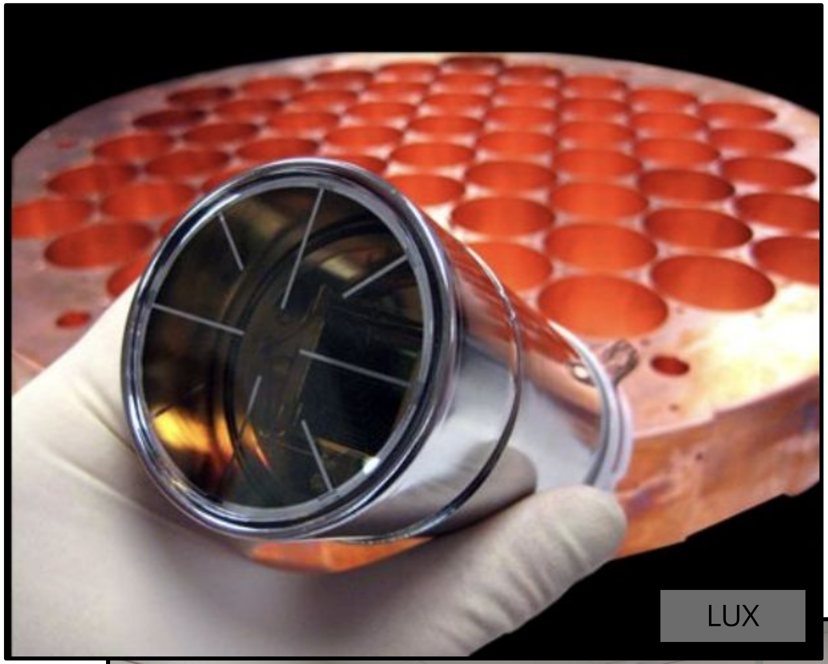
Dual-channel detectors (ionization *and* scintillation:

- Good particle ID *and* low thresholds
- Superior energy resolution at MeV scales



Design challenges

- **VUV-sensitive photodetectors**
  - PMTs, SiPMs
- **Fluid/gas system engineering**
  - Circulation/purification
  - Cryogenics
  - Evaporation/condensation
  - Pressure control
- **High voltage engineering**
  - Modern detectors need O(100kV)



What makes them interesting detectors?

- **Dense, monolithic, high-Z target**
- **Scalable to large detector sizes (tons)**
- **Low-background capabilities for rare-event physics**
- **By choosing the right kind of readout we can variously (or simultaneously) achieve:**
  - Extremely low energy thresholds
  - mm-scale position resolution
  - Strong particle ID (i.e. neutron/gamma)
  - Good energy resolution (~1% at 2.6 MeV)

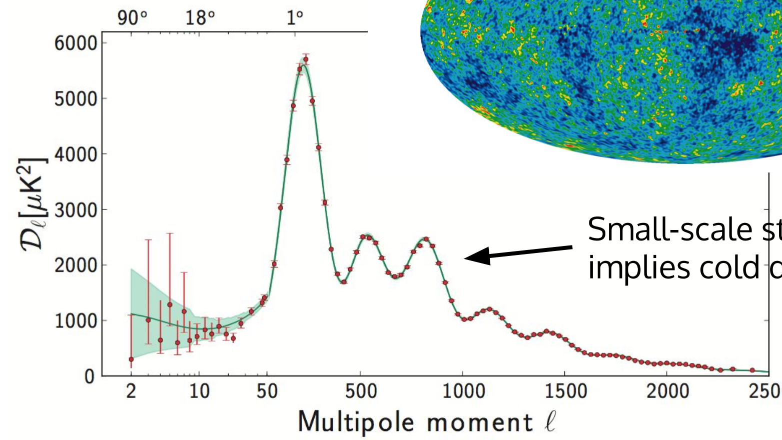
Current applications

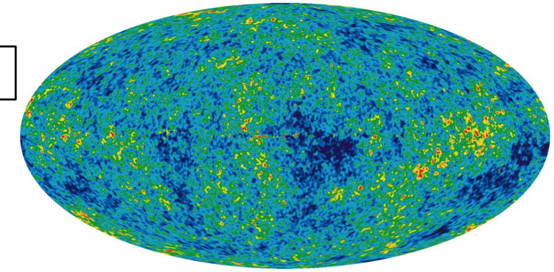
- **Dark matter searches**
  - LUX/LZ, PandaX, XENONnT collaborations all use liquid xenon detetors
  - DEAP-3600, DarkSide use liquid argon
  - Liquid He R&D ongoing here at Berkeley
- **Neutrino detection**
  - R&D ongoing for low-energy neutrino detection (reactors, solar neutrinos)
  - High energy neutrino tracking detectors (DUNE prototypes)
- **Compton/medical imaging**
  - CoDeX at Yale/Berkeley
  - Others that I'm not aware of

Application: dark matter searches

Dark matter

Cosmic microwave background

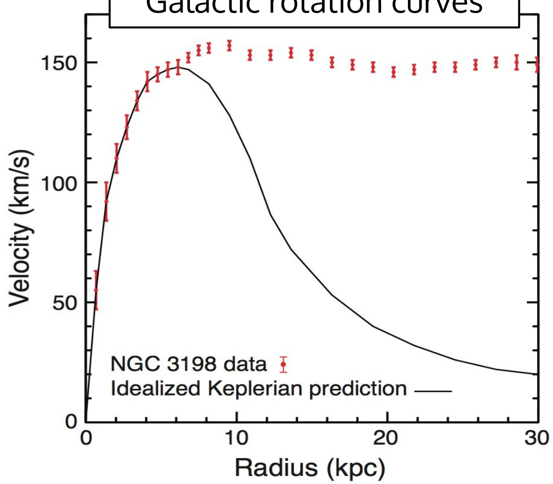


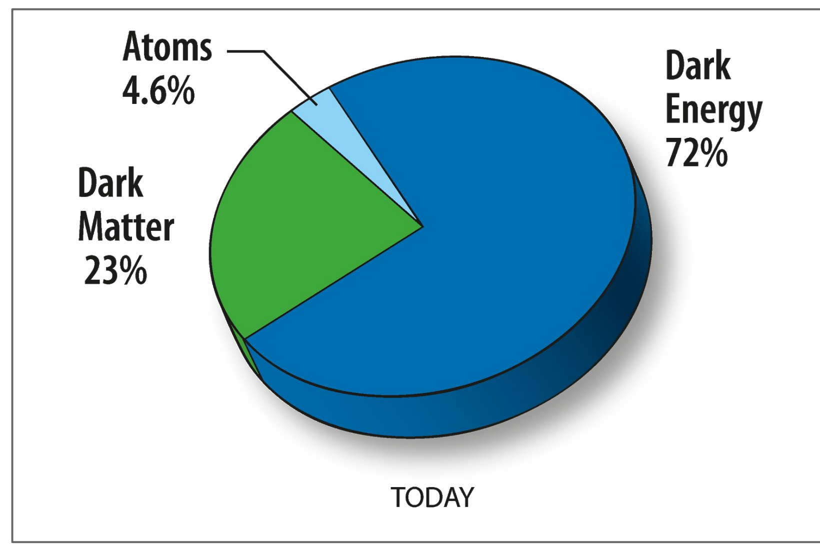


Small-scale structure implies cold dark matter

Merging galaxy clusters

Galactic rotation curves

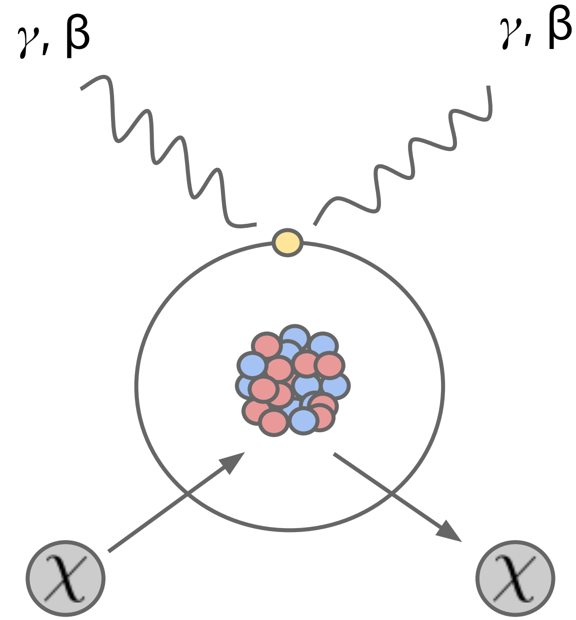




WIMP dark matter

Weakly **I**nteracting **M**assive **P**articles

- **New neutral particle, beyond the standard model**
- **Weak-scale annihilation cross-section** gives us the right amount of dark matter
- Would exist in a sort of non-interacting gas throughout the galaxy, bound by gravity
- Predicted to produce **NUCLEAR RECOILS**
- Most backgrounds (γ's and β's from radioactive decay) produce **ELECTRON RECOILS**



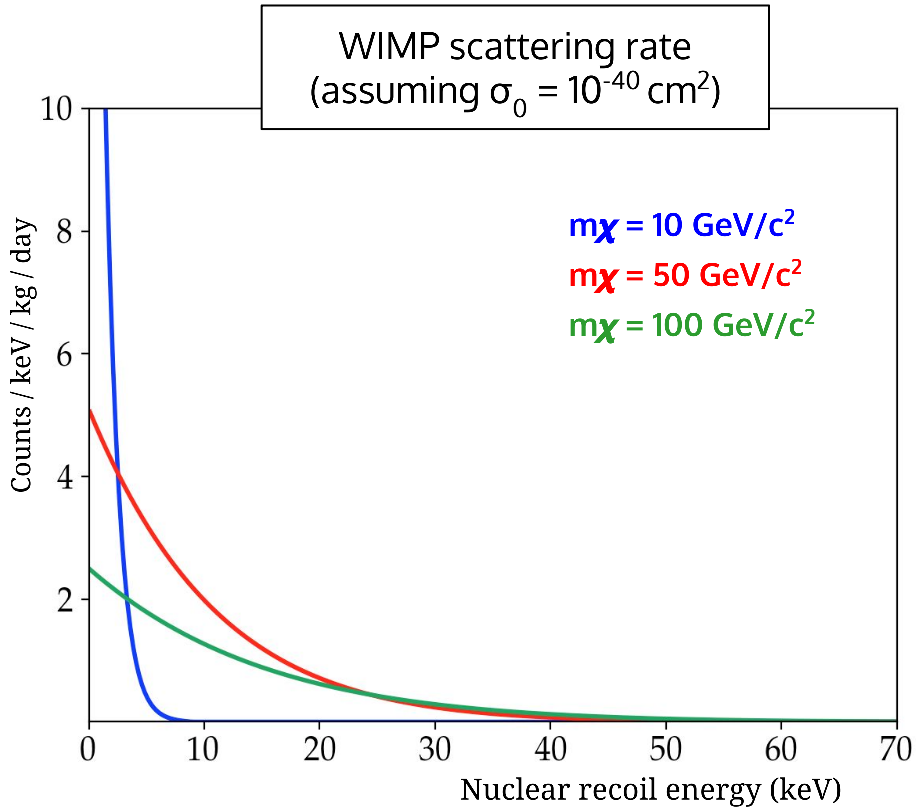
WIMP scattering spectrum

Assumptions

- Weak scale scattering cross section with nuclei
- Mass density ~ 0.3 $GeV/c^2/cm^3$
- Maxwellian velocity distribution with v_0 = 220 km/s
- Velocity distribution truncated at galactic escape velocity

Detection requires:

- Sensitivity to low energy recoils
- Low backgrounds (cosmic rays/ambient radioactivity)
- Large targets
- Nuclear recoil /electron recoil discrimination
- Good position resolution



Dual-phase xenon/argon TPC detectors

Ionized electrons

Primary scintillation light

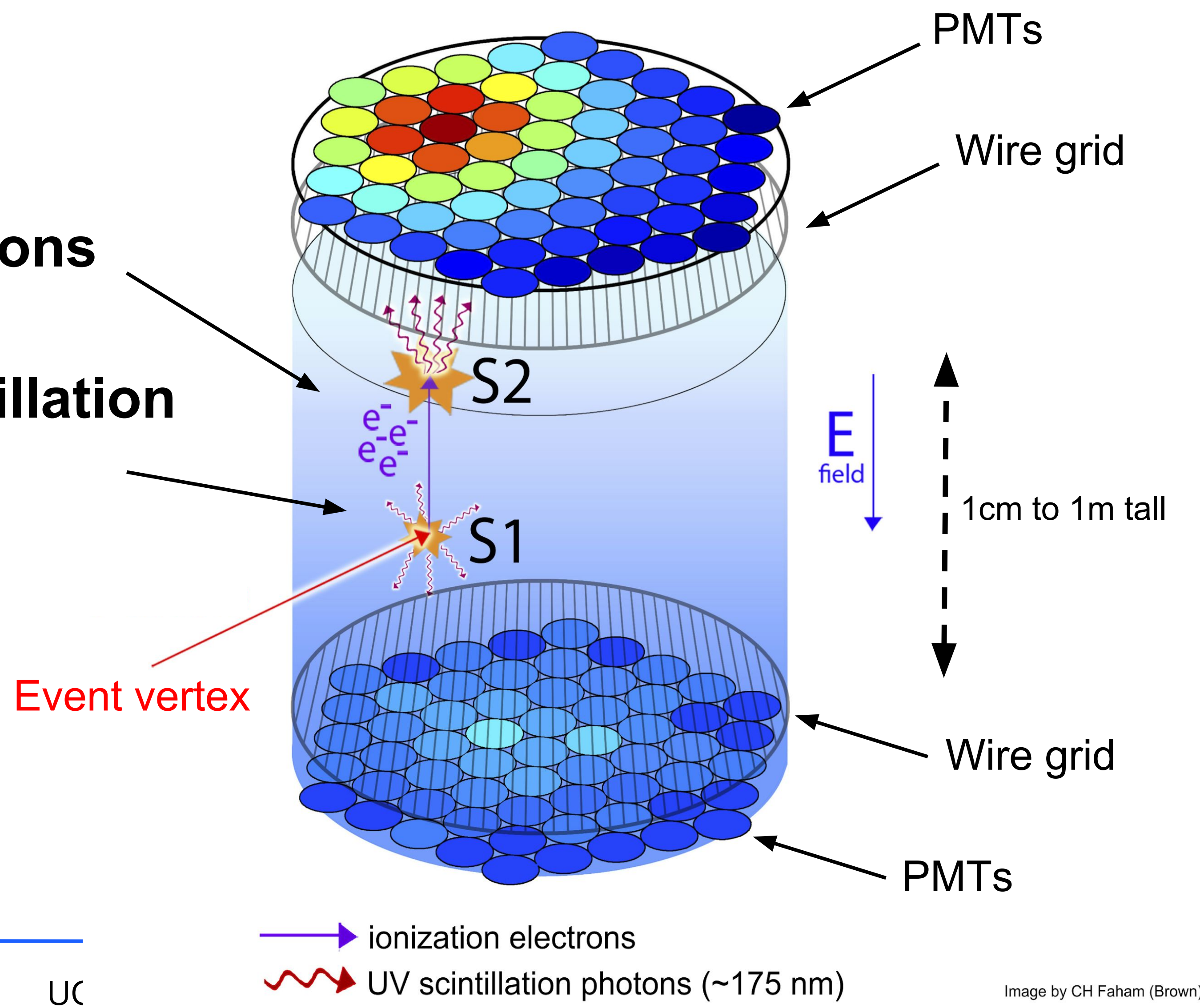


Image by CH Faham (Brown)

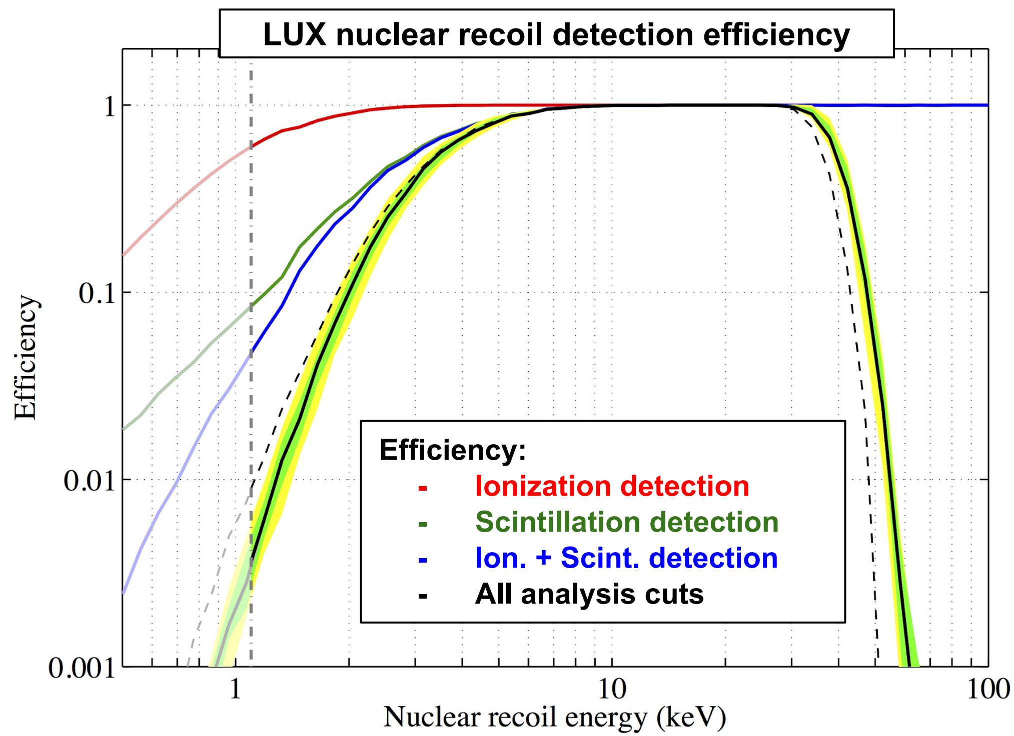
Low energy thresholds

Detection efficiencies:

- O(100% for ionization electrons)
- O(10% for scintillation photons)

This translates to:

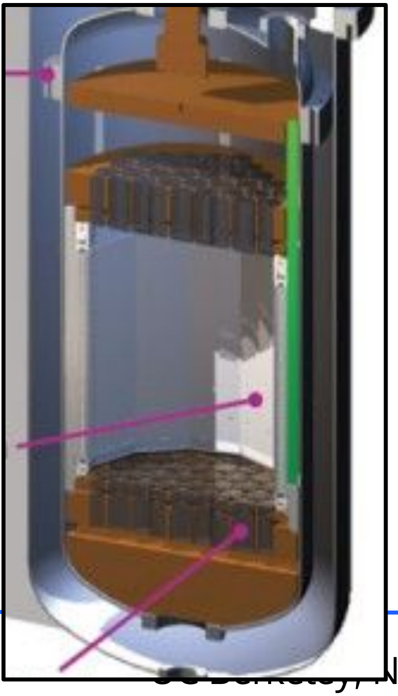
- Thresholds at 1's of keV



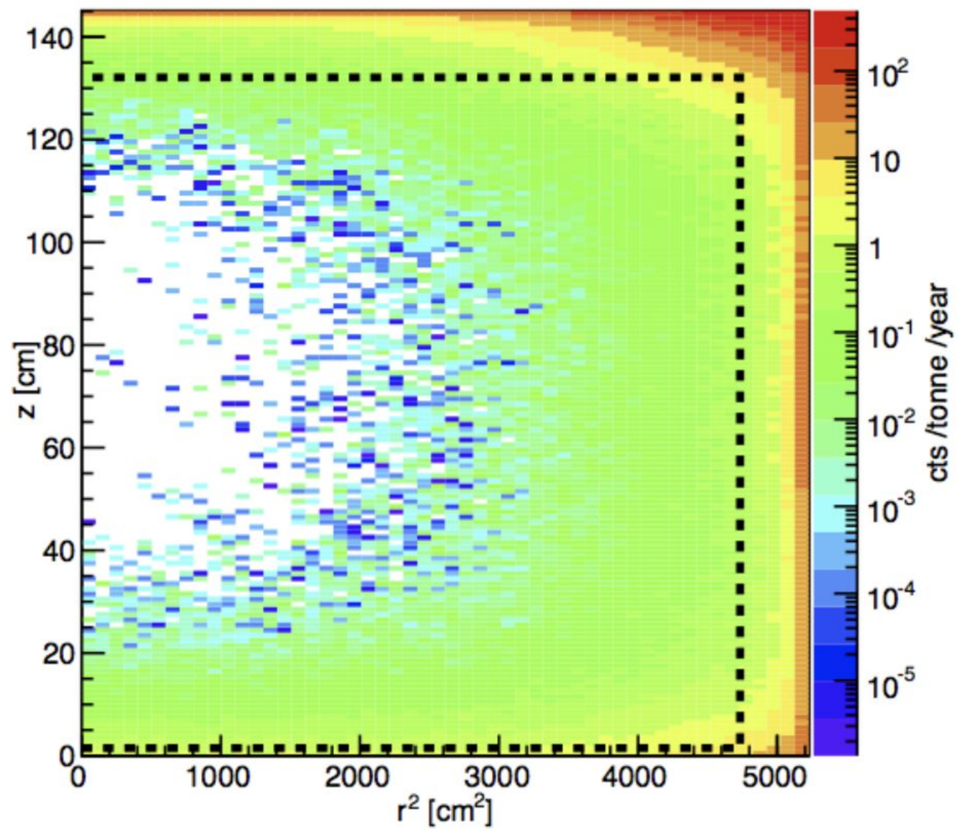
Position reconstruction

Most backgrounds come from outside the target

- Radioactivity in detector construction materials
- Radioactivity in PMTs
- etc.

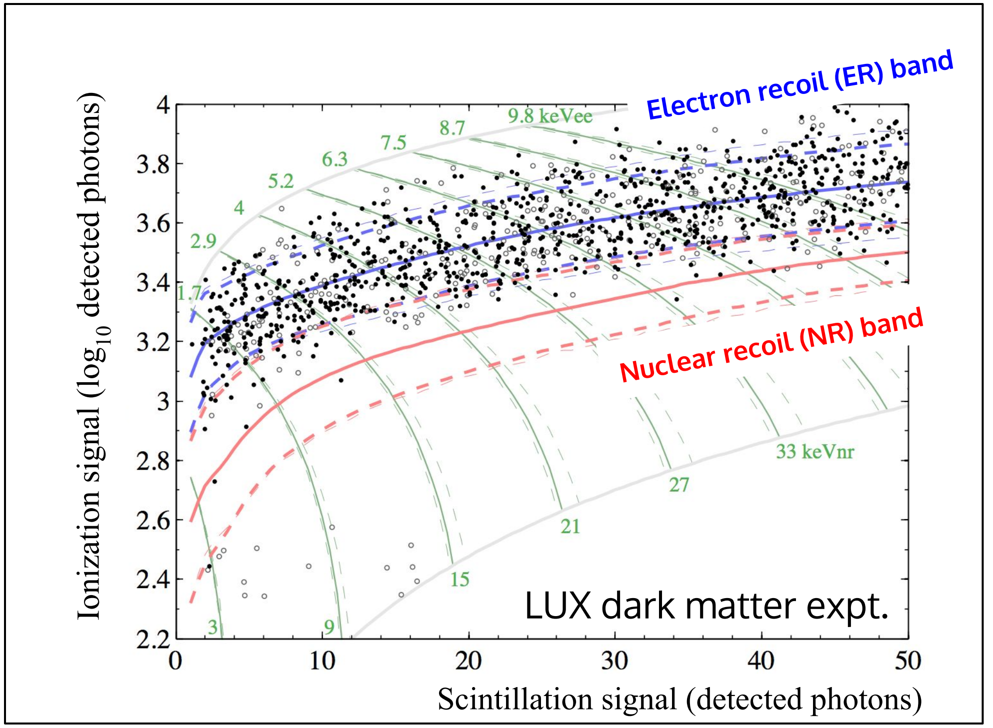


Radioactive backgrounds simulation in LZ



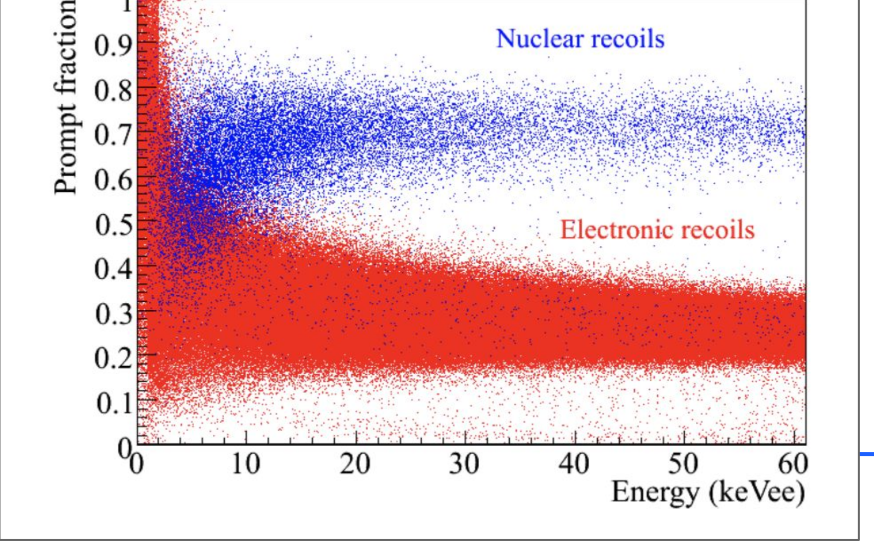
Particle ID

- **Charge/light ratio differs between different particle types**
  - Used in liquid xenon experiments



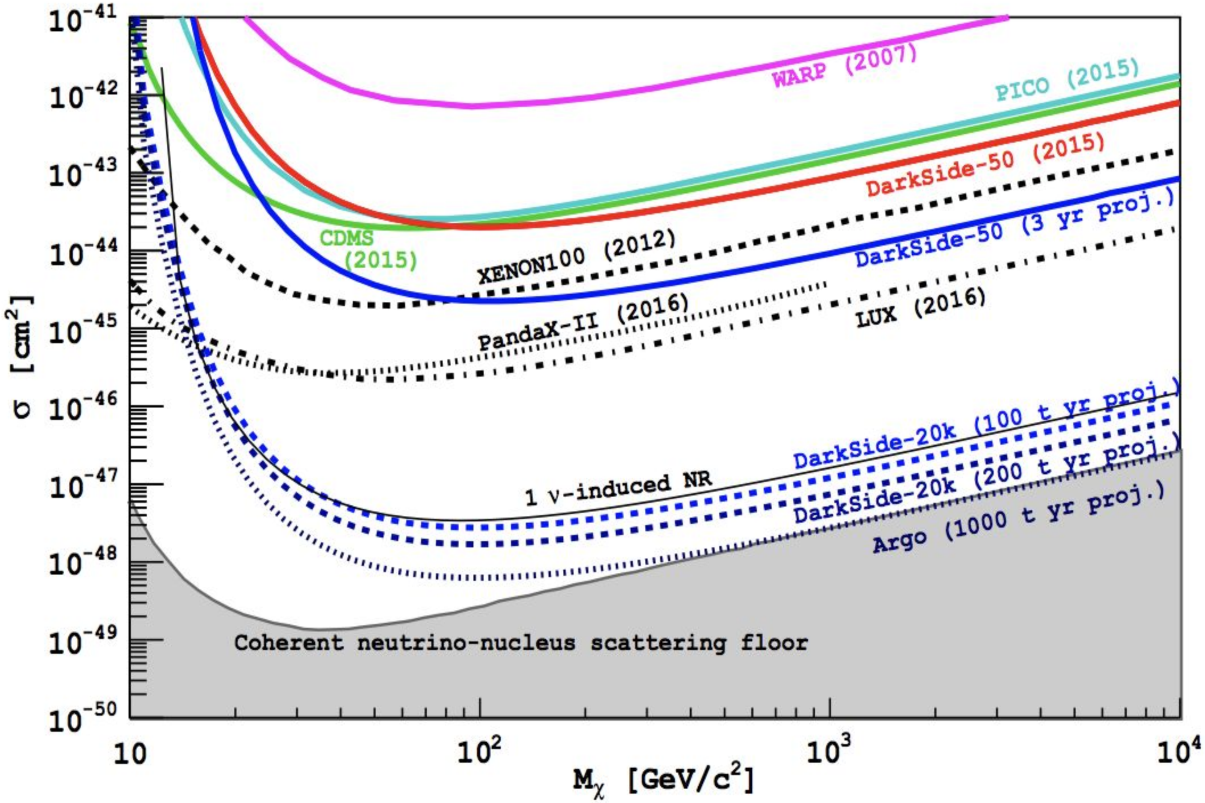
- **Pulse shape discrimination very good in lighter elements**
  - Used in liquid argon experiments

PSD in liquid argon



Scalability

World leading sensitivities



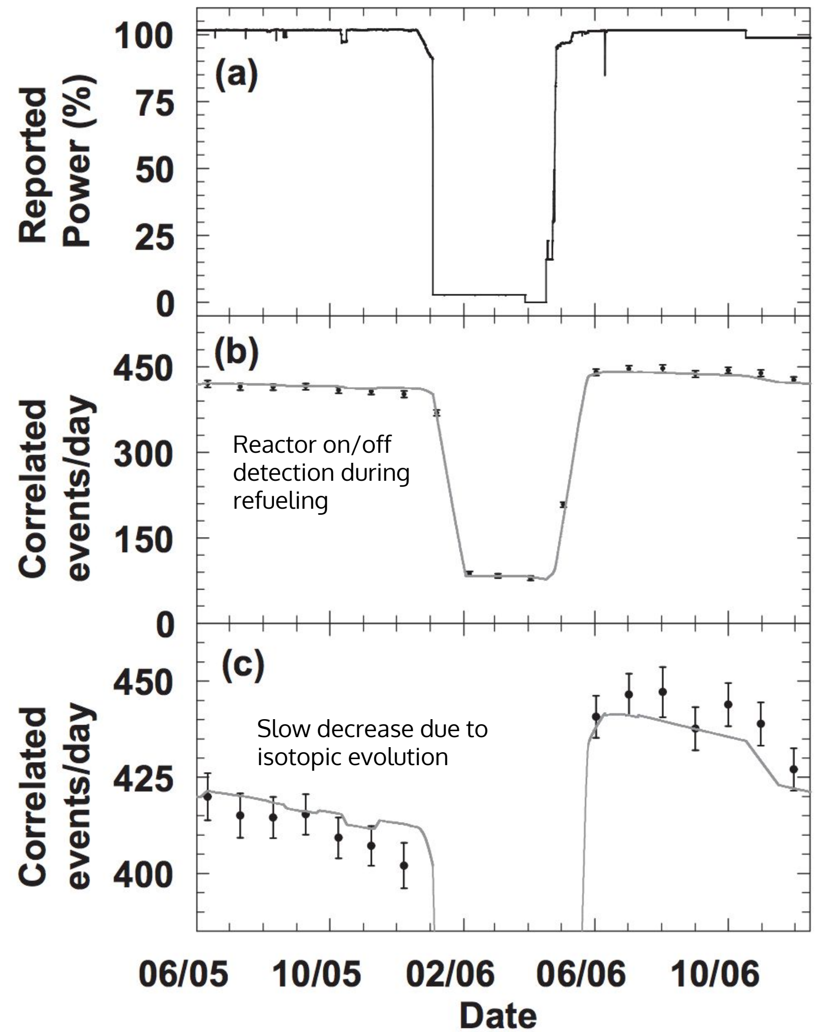
Xenon-based experiments have been leaders since 2012

Xe- and Ar-based experiments will continue to lead in the future

Application: low-energy neutrino detection

Low energy neutrinos from reactors

Bowden et al. J. Appl. Phys. (2009)



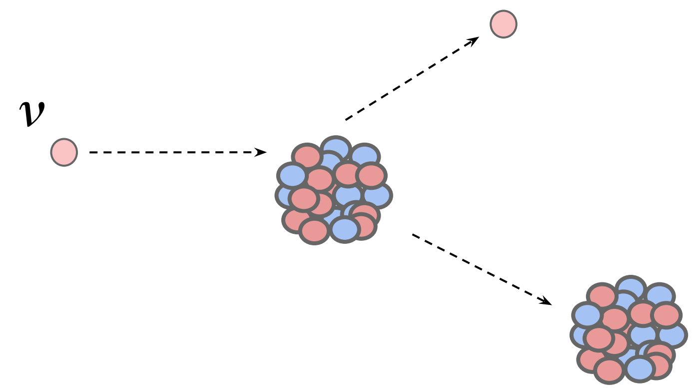
Nonproliferation applications particularly interesting for this group

- Online, direct measurements of nuclear reactions inside reactor
  - Short-term changes in rate → changes in reactor power
  - Long-term changes in rate / spectrum → evolution of isotopic content in core
- Non-intrusive, no disruption to reactor operations
- Very difficult to shield or spoof

CENNS as a new tool for detection

Coherent **E**lastic **N**eutrino-**N**ucleus **S**cattering

$\sigma \sim$ (# of neutrons)^2 x 10^{-43} cm^2
$\sim$ 10^{-39} cm^2 (compared to 10^{-43} for IBD)



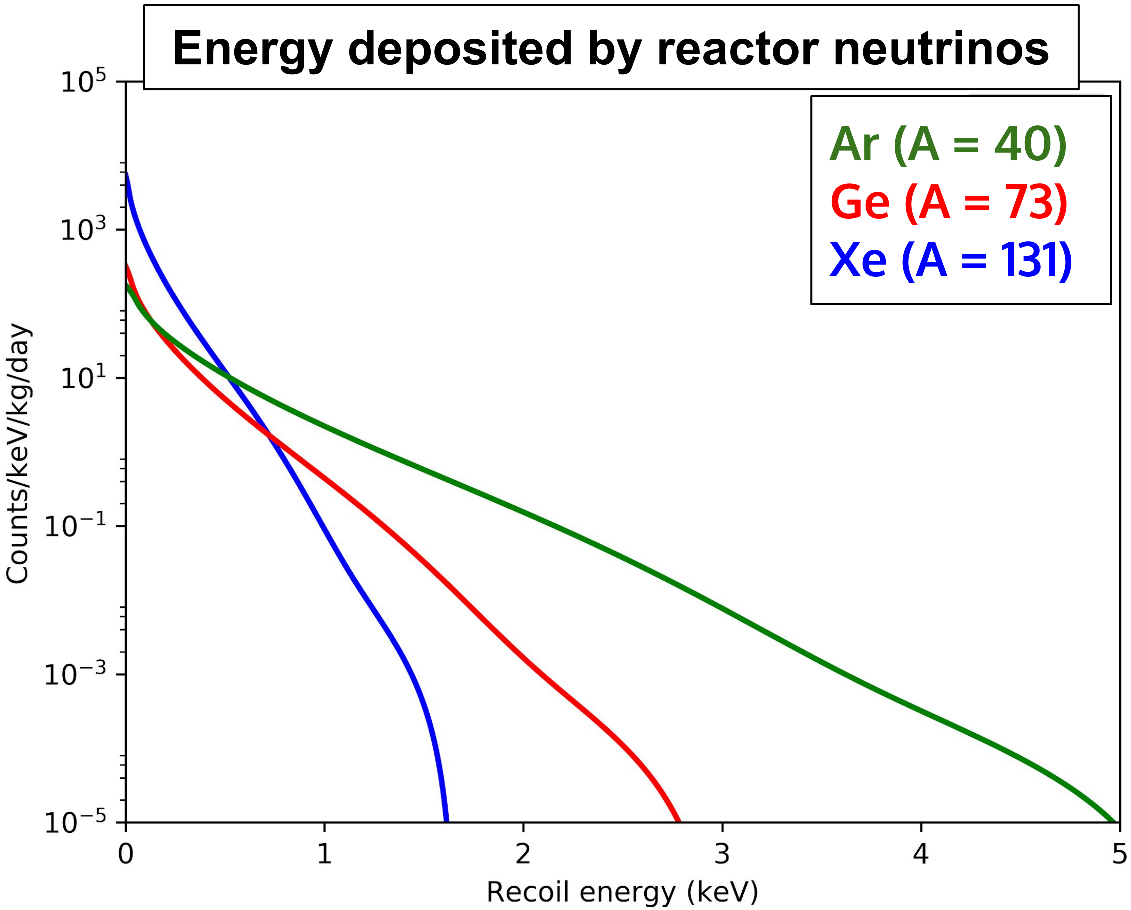
First measured by COHERENT collaboration at Spallation Neutron Source (ORNL)

- Akimov et al., Science **357** (2017)

Multiple interesting applications:

- Tests of SM with different detector targets
- Supernova detection / solar astrophysics in dark matter experiments
- Reactor monitoring for nonproliferation

Coherent scattering on different targets



Different targets → different spectra

- Lighter nuclei produce higher energy recoils, easier to detect

Ionization-only mode in liquid TPCs

Scintillation detection efficiency limits sensitivity at low energies

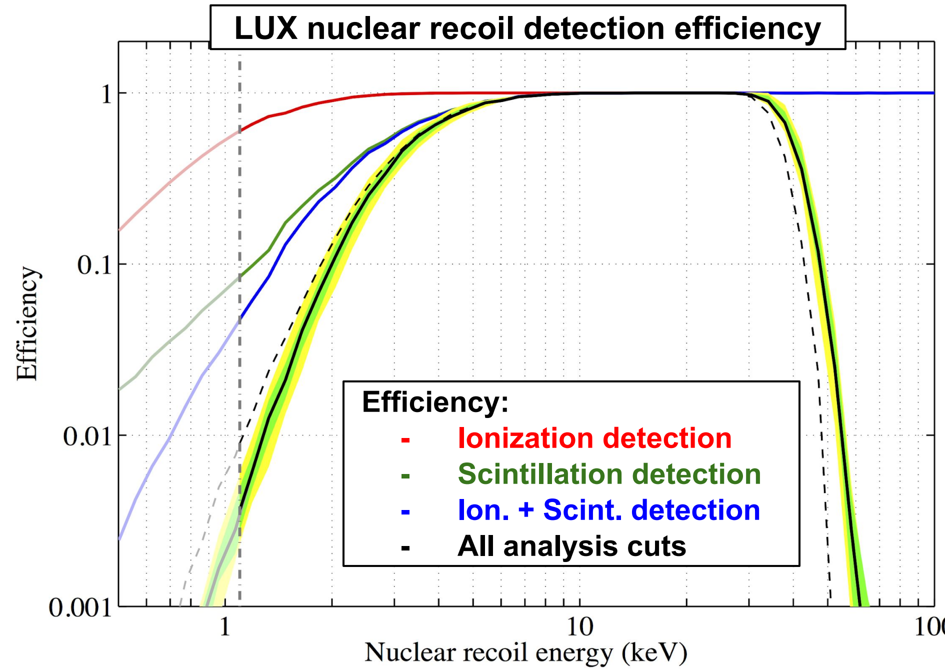
To go further, we can look at only the ionization signal.

New backgrounds:

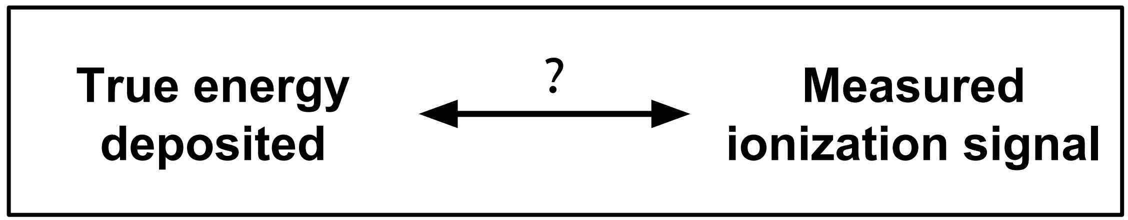
- Identify/mitigate sources of few-electron emission noise

Signal:

- Need sub-keV data on ionization response of target

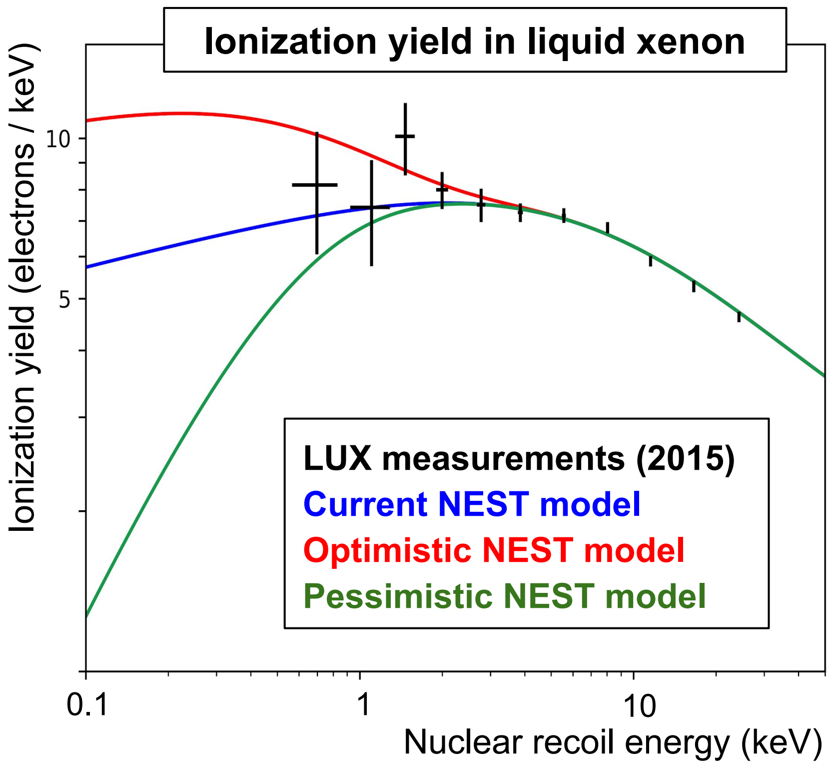


Reactor CENNS in xenon (for example)



Reactor CENNS in xenon (for example)

True energy deposited ⟷ ? ⟷ **Measured ionization signal**



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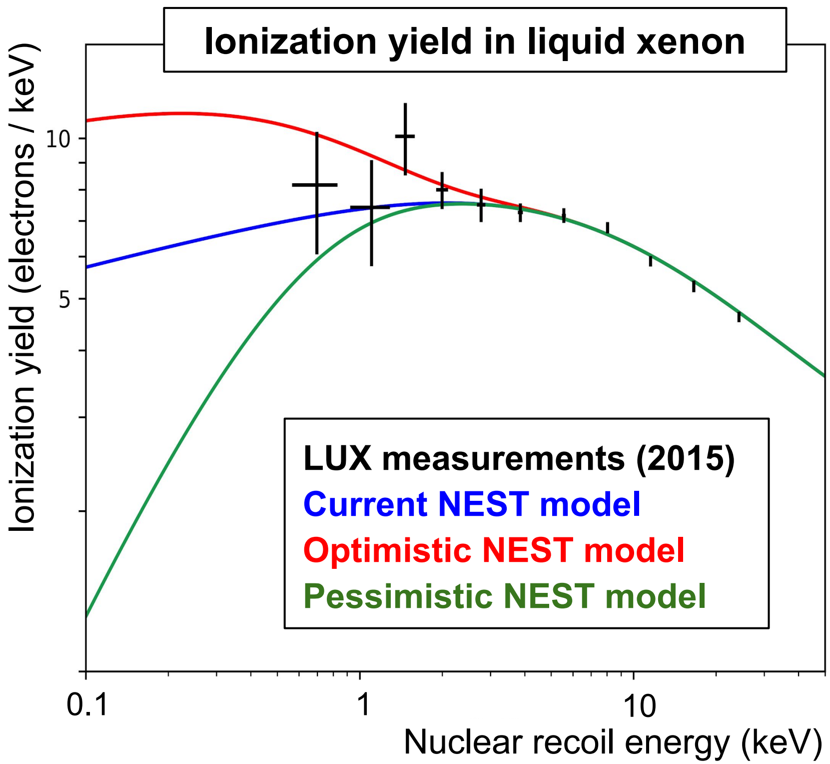
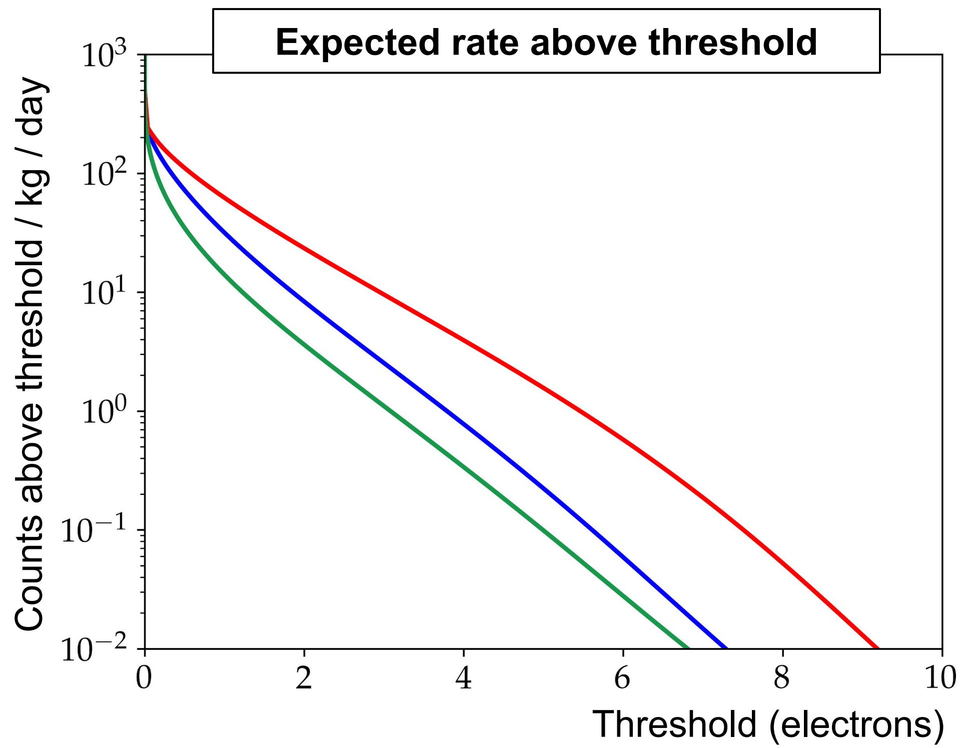


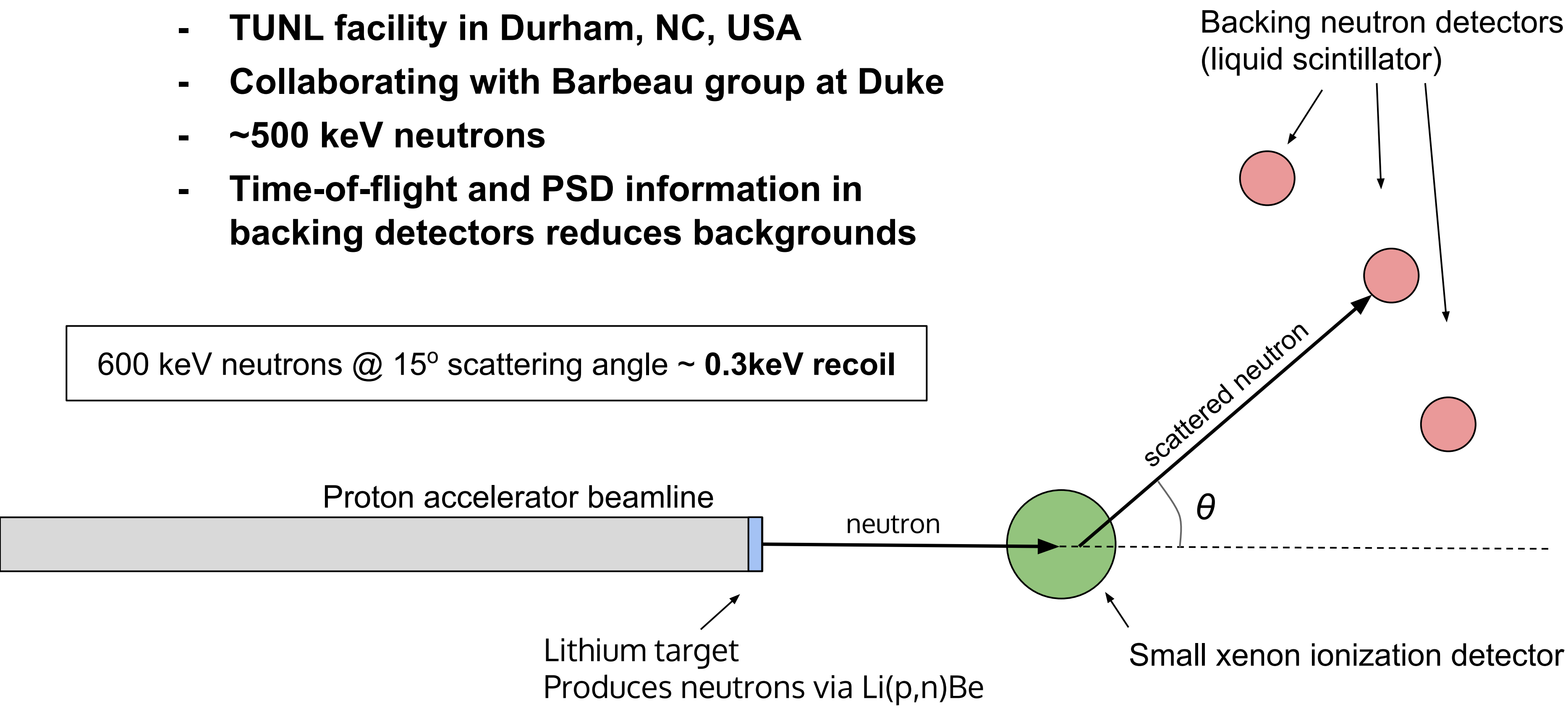


Signal yields measurements

Scattering of monoenergetic neutrons using pulsed proton accelerator

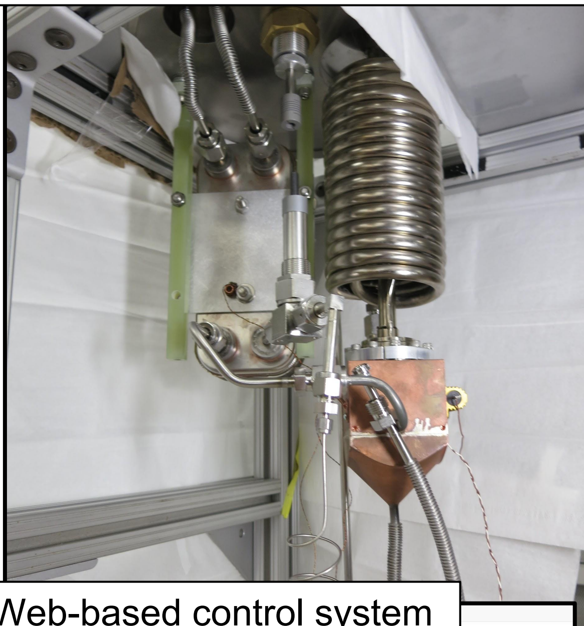
- **TUNL facility in Durham, NC, USA**
- **Collaborating with Barbeau group at Duke**
- **~500 keV neutrons**
- **Time-of-flight and PSD information in backing detectors reduces backgrounds**

600 keV neutrons @ 15° scattering angle ~ **0.3keV recoil**

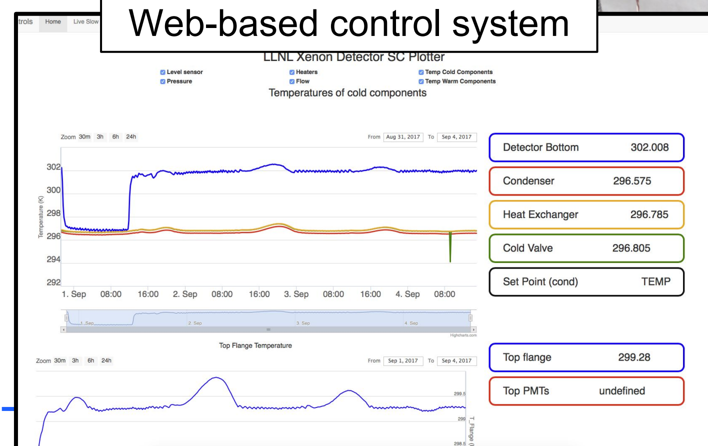


The XeNeu Detector at LLNL

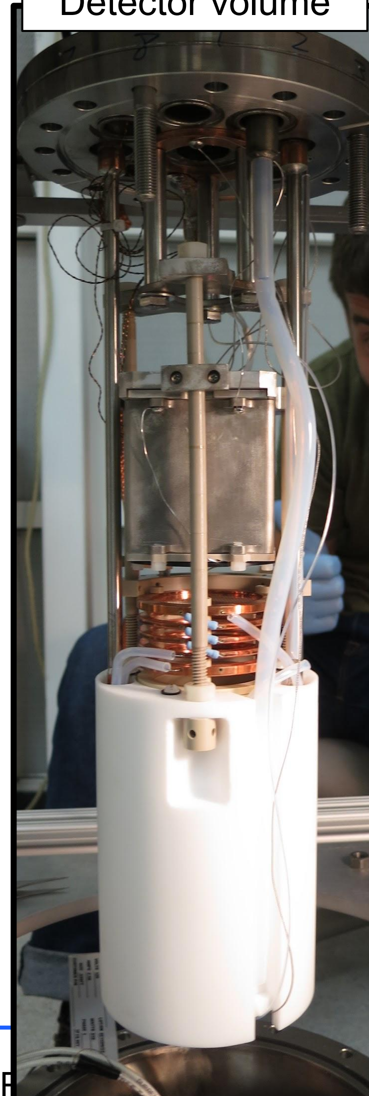
Cooling system / heat exchanger



Web-based control system

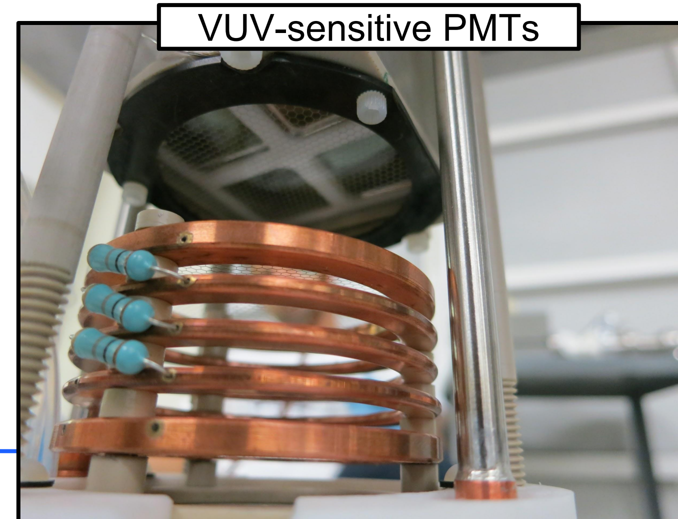


Detector volume

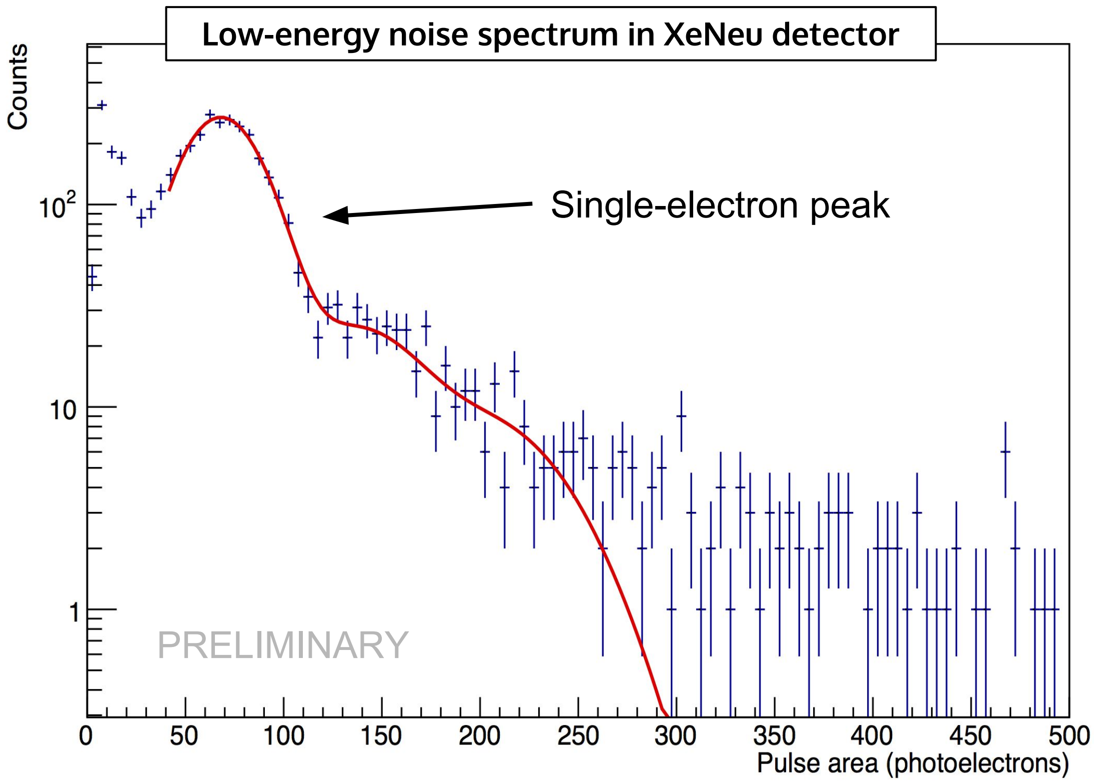


Portable gas handling/purification system

VUV-sensitive PMTs



Excellent low-energy sensitivity!



Good low-energy resolution

- 70 phe for single extracted electrons (compared to ~25 phe in LUX)

Good high voltage performance

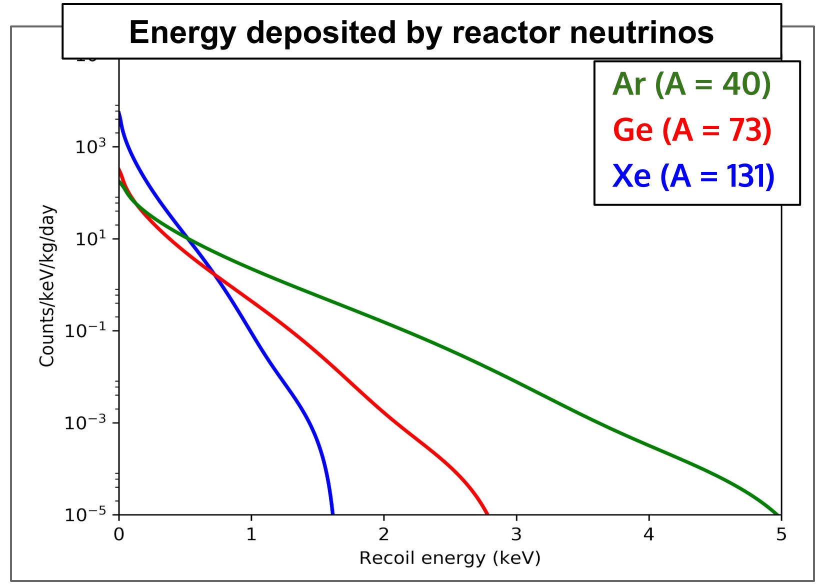
- >95% electron extraction into gas (compared to ~60% in LUX measurement)

First results

(Preliminary plots)

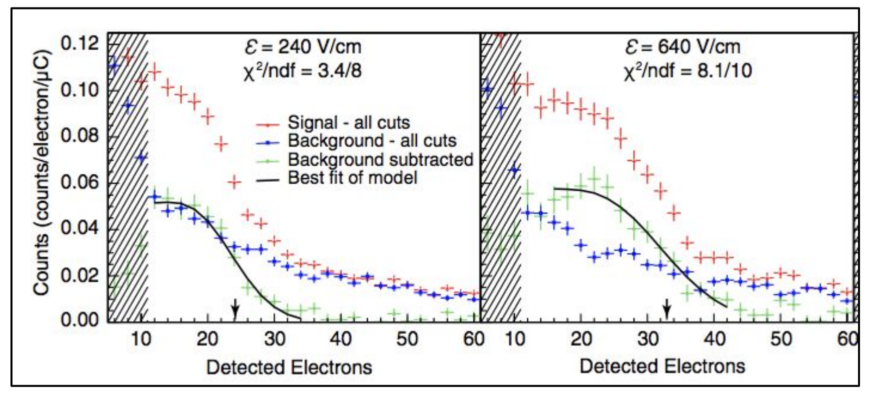
Liquid argon is also extremely interesting!

- **Significantly lower backgrounds than existing xenon detectors**
  - DarkSide collaboration, *PRL* 2018
- **Higher recoil energies for, e.g., reactor neutrinos**



However, **backgrounds and signal are even less well understood than in xenon!**

- LLNL/UCB efforts still at the cutting edge (five years later)



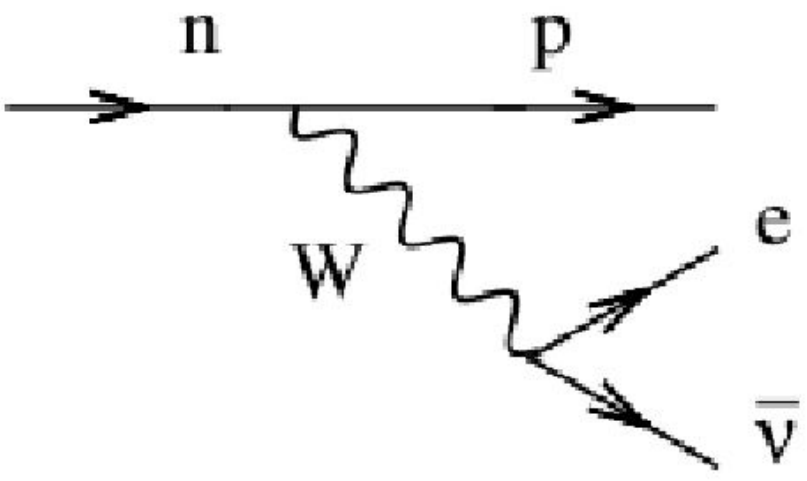
Joshi et al., *PRL* 2013

Takeaways

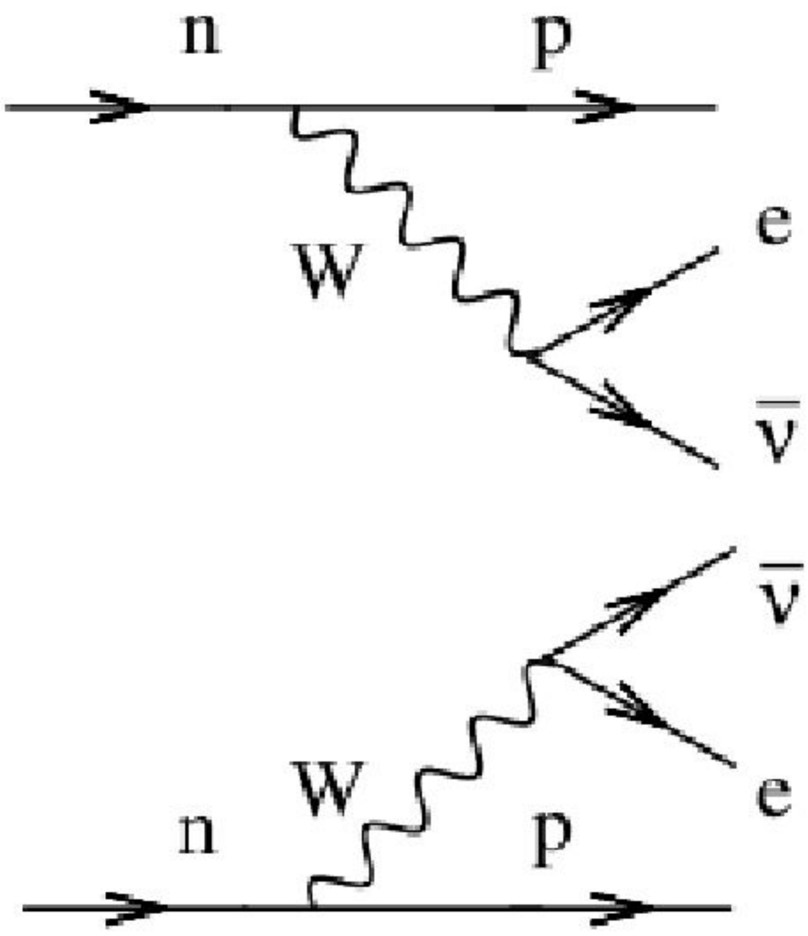
- **Noble liquid detectors are pushing down to few-electron ionization sensitivities with kg-scale detectors**
    - Sub-keV signal sensitivity
- **This is a highly active field of research at present**
- **Applications in dark matter research, neutrino detection, and non-proliferation**

A final application: neutrinoless double beta decay

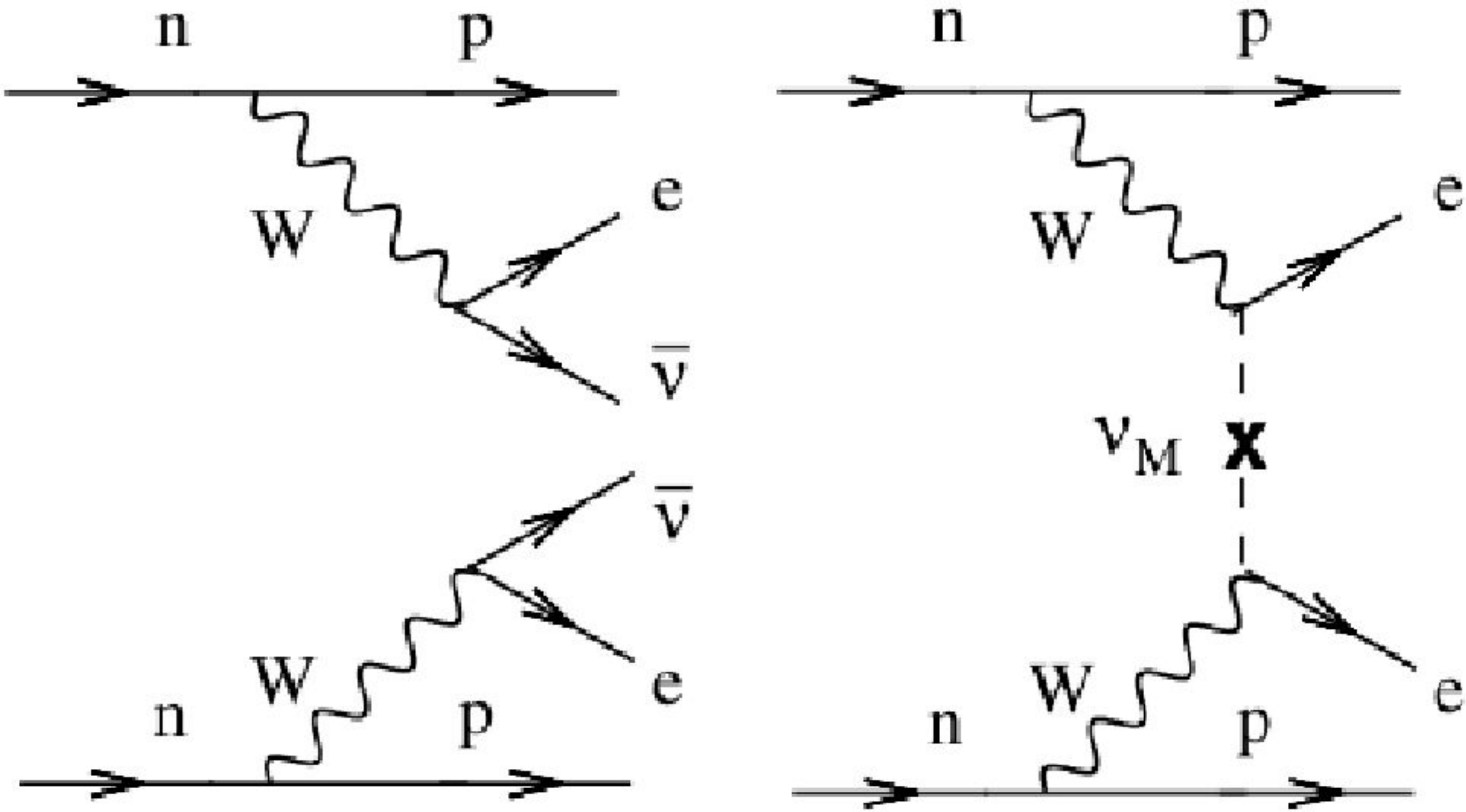
Beta decay



Double beta decay



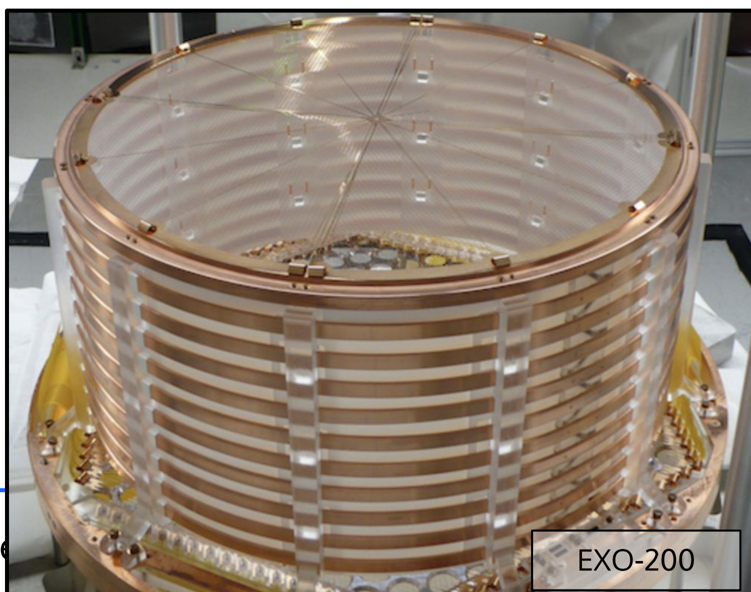
Neutrinoless double beta decay

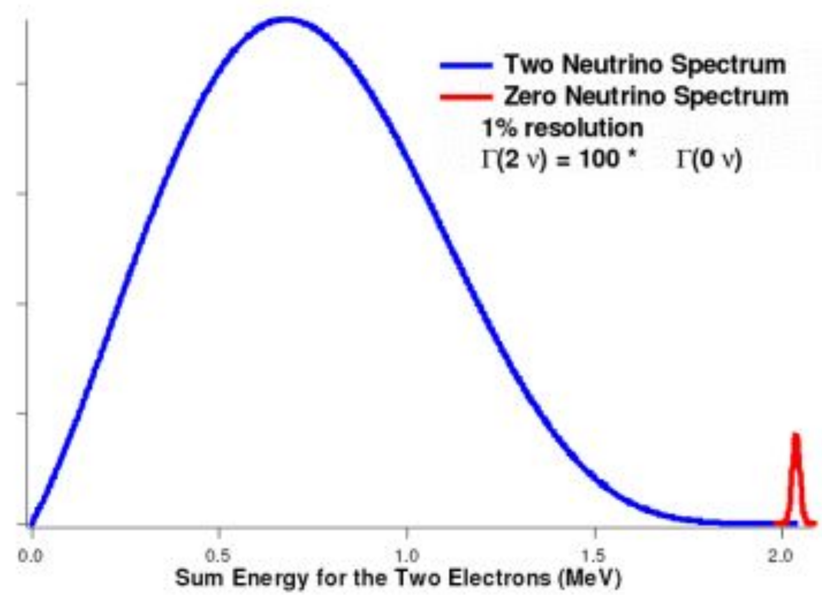


Searches with ^{136}Xe

Dual-channel Xe detector with enriched target

- Factor of 10 enrichment in ^{136}Xe (80-90%)
- Q-value at 2.4 MeV
- Read out both scintillation and ionization, as in DM searches

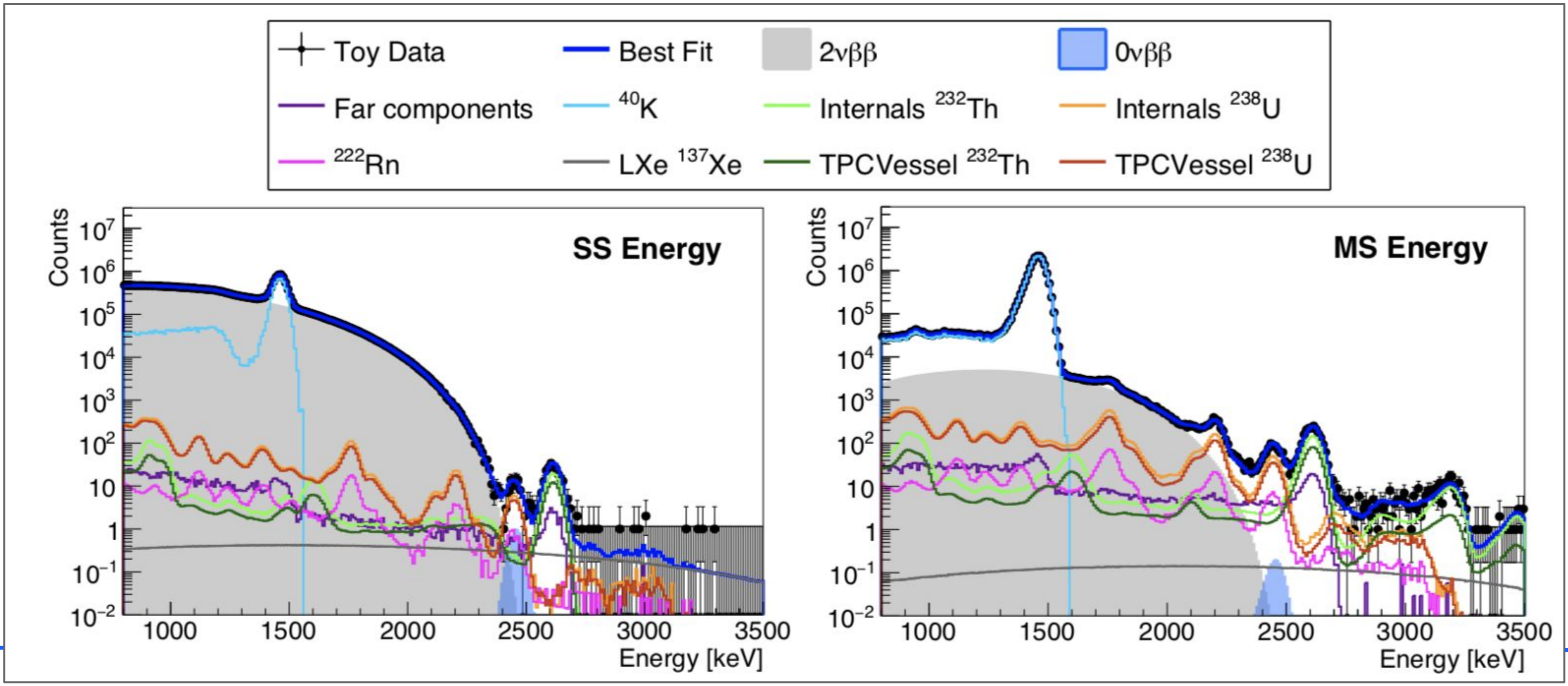




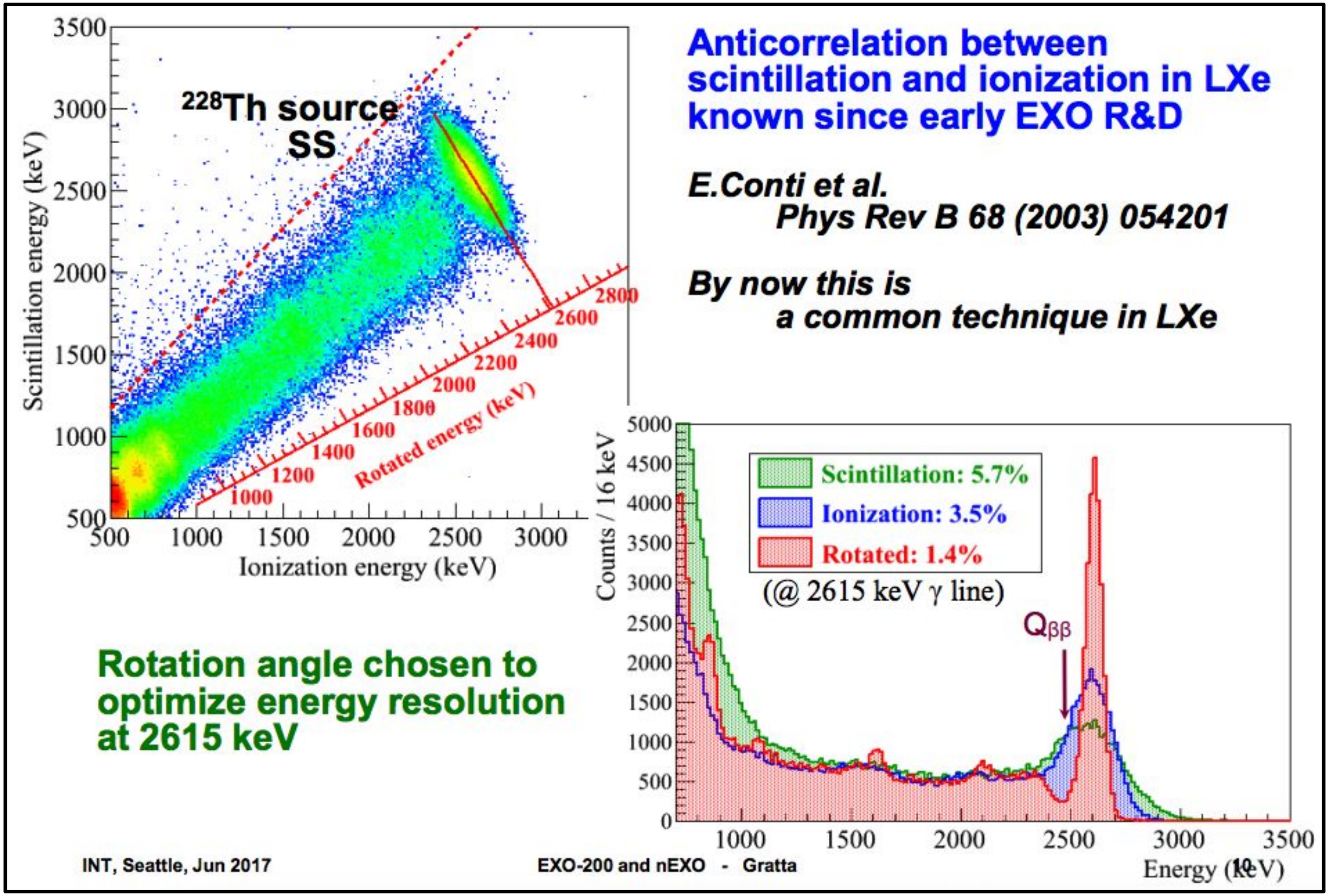
Searching with ^{136}Xe: nEXO

Success requires:

- Low radioactivity detector (U and Th are primary concerns)
- Large target (up to 5 tons)
- Good position resolution (separate single/multiple scatters)
- Good energy resolution (~1% at 2.4 MeV)



Energy resolution in LXe



Slide by G Gratta

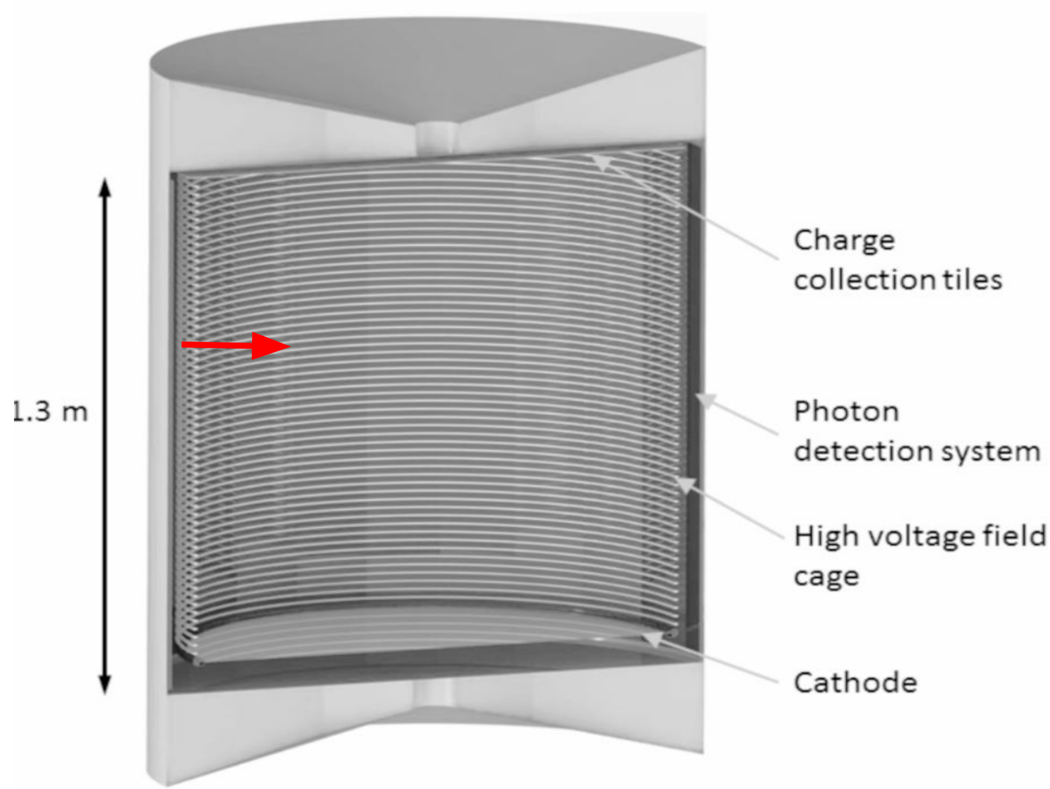
An interesting challenge...

How do you calibrate a 1.5m x 1.5m Xe detector at ~2 MeV?

- Stopping length of gammas is ~8 cm

Current ideas: internal sources

- ^{220}Rn injection
  - Long chain of alphas, betas that mixes into Xe volume
- Neutron activation of ^{136}Xe target
  - ^{137}Xe is beta with endpoint at 4 MeV



Conclusions

- **Noble liquid detectors are extremely powerful**
- **Xe and Ar are widely used in particle physics**
- **Interesting combination of detector characteristics:**
  - High stopping power
  - Scalability
  - Low backgrounds
  - Dual-channel detection
- **Fast-paced, exciting field of research today and looking forward**

Shameless plug

LLNL group has opportunities for talented students!

- World-class detector development
- Hardware and software

Feel free to get in touch:

- blenardo@stanford.edu

Questions?