Noble Liquid Detectors

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UC Berkeley and LBNL

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TRIUMF
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The Noble Liquid Revolution

Noble liquids are relatively inexpensive, easy to obtain, and dense.

Easily purified

- low reactivity
- impurities freeze out
- low surface binding
- purification easiest for lighter noble liquids

Ionization electrons may be drifted through the heavier noble liquids

Very high scintillation yields

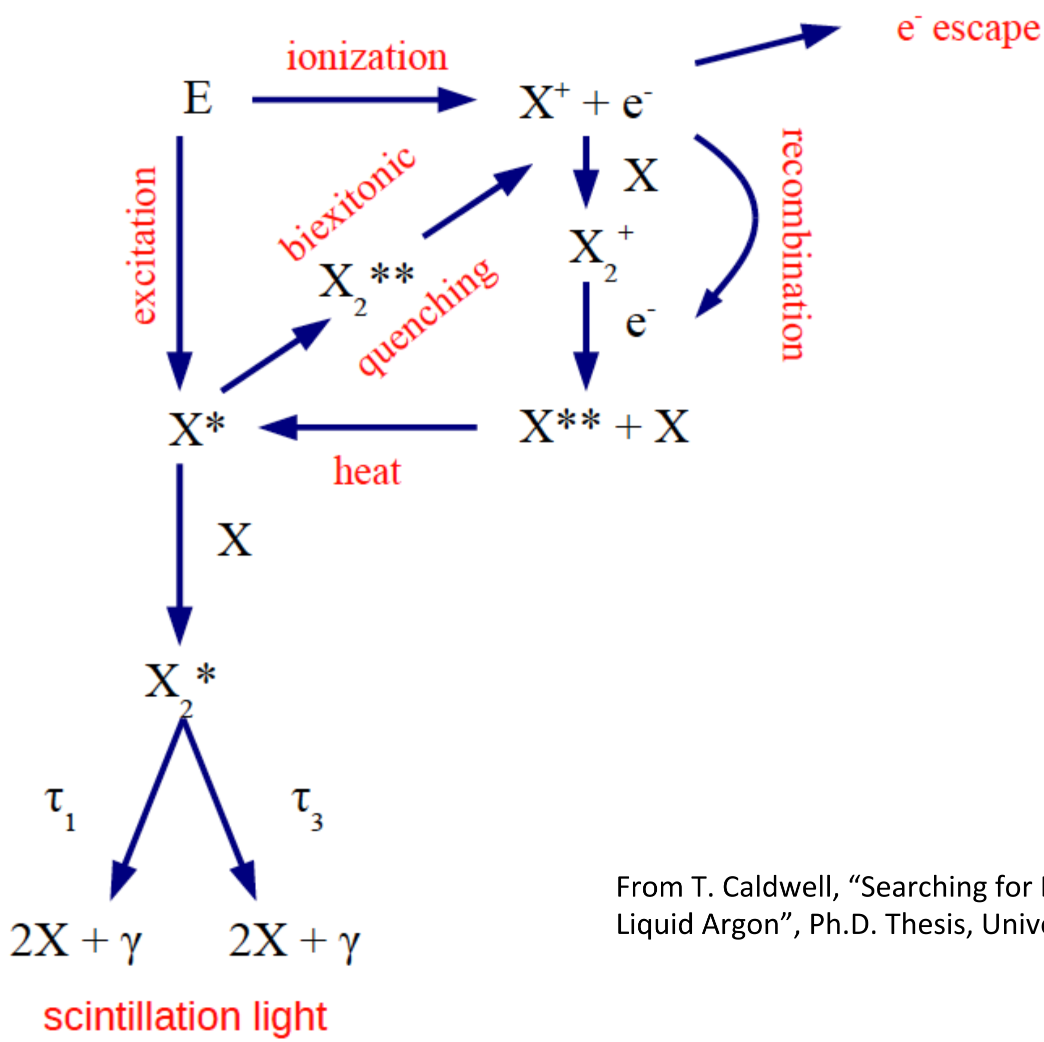
- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

Easy construction of large, homogeneous detectors

Noble Liquids: Basic Properties

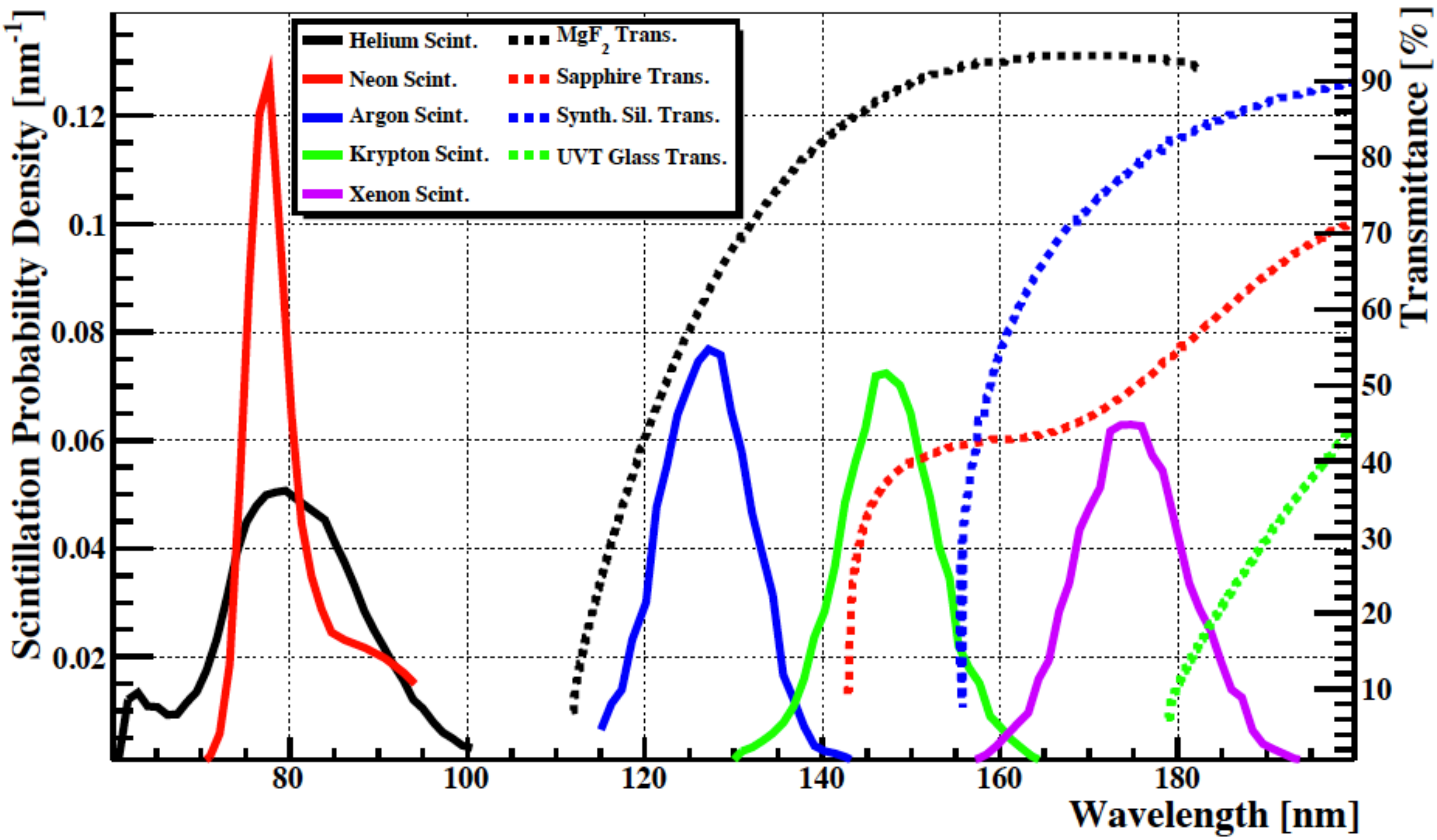
Element	Xenon	Krypton	Argon	Neon	Helium
Atomic number	54	36	18	10	2
Atomic mass	131.3	83.8	40.0	20.2	4.0
Boiling temperature (K)	165	120	87.3	27.1	4.2
Liquid density at 1 atm (g/cm^3)	2.94	2.4	1.40	1.21	0.125
Scintillation Yield (photons/keV)	60		40	30	19
Scintillation wavelength (nm)	178	150	128	78	80
Triplet time constant (us)	0.03	0.09	1.6	15	1.3×10^7
Long-lived isotopes	^{136}Xe	^{81}Kr, ^{85}Kr	^{39}Ar, ^{42}Ar	none	none

Noble Liquids: Charge and Light Production



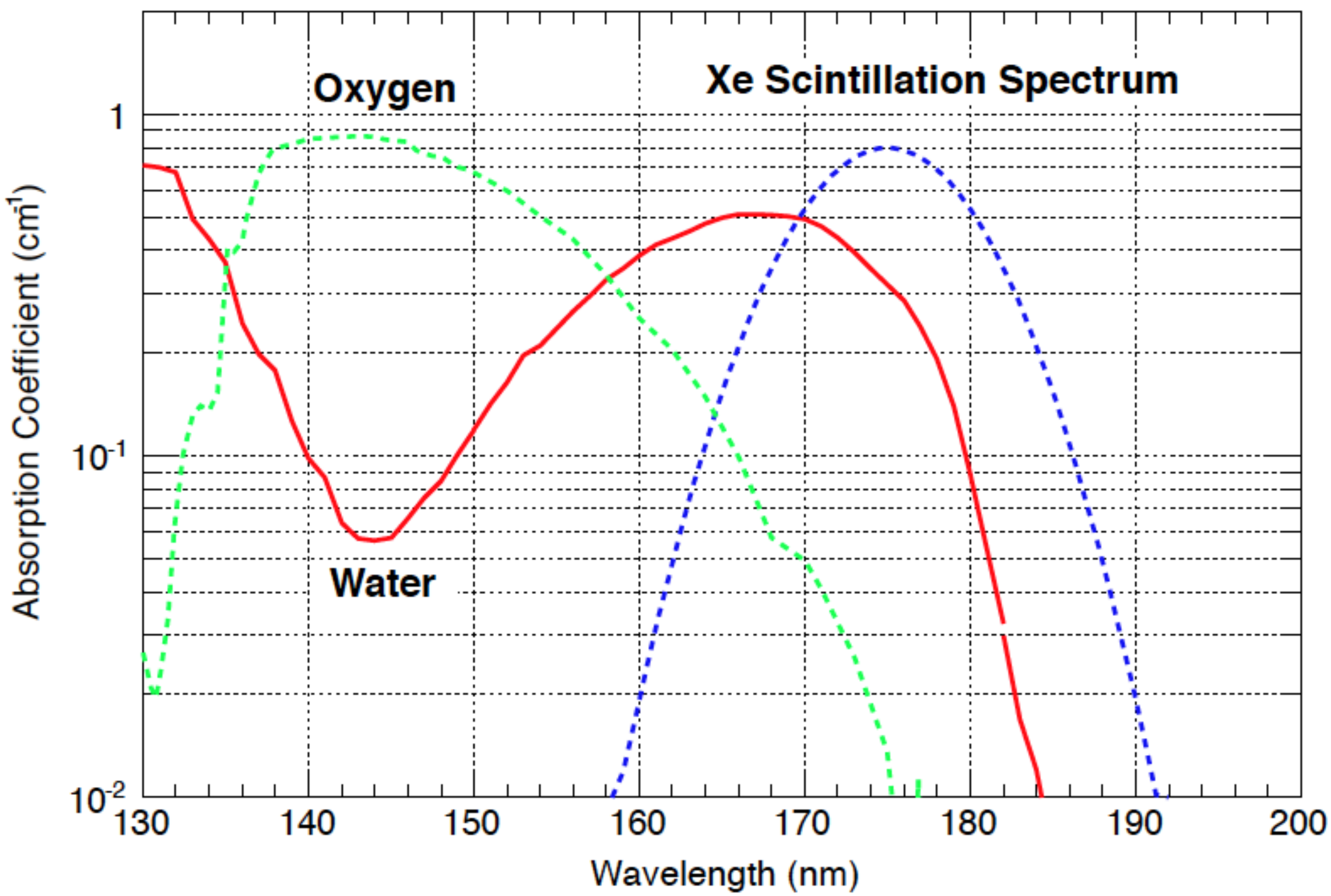
From T. Caldwell, "Searching for Dark Matter With Single Phase Liquid Argon", Ph.D. Thesis, University of Pennsylvania

Noble Liquids: Basic Properties



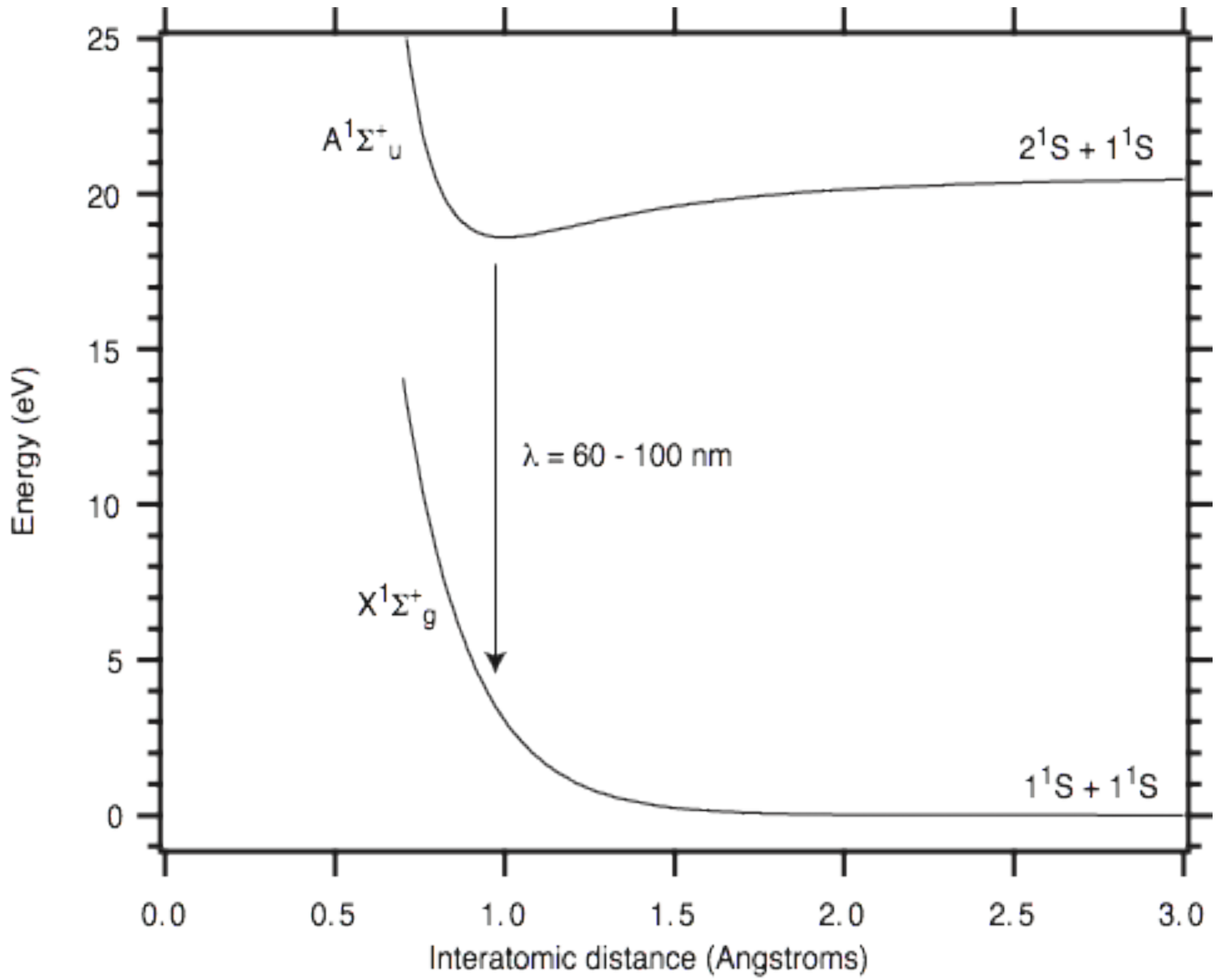
From V. Gehman et al., , "Fluorescence Efficiency and Visible Re-emission Spectrum of Tetraphenyl Butadiene Films at Extreme Ultraviolet Wavelengths", arXiv:1104.3259

Scintillation Absorption in Liquid Xenon



From V. Chepel and H. Araujo, "Liquid noble gas detectors for low energy particle physics", arXiv:1207.2292

Origin of the Broad Scintillation Peak



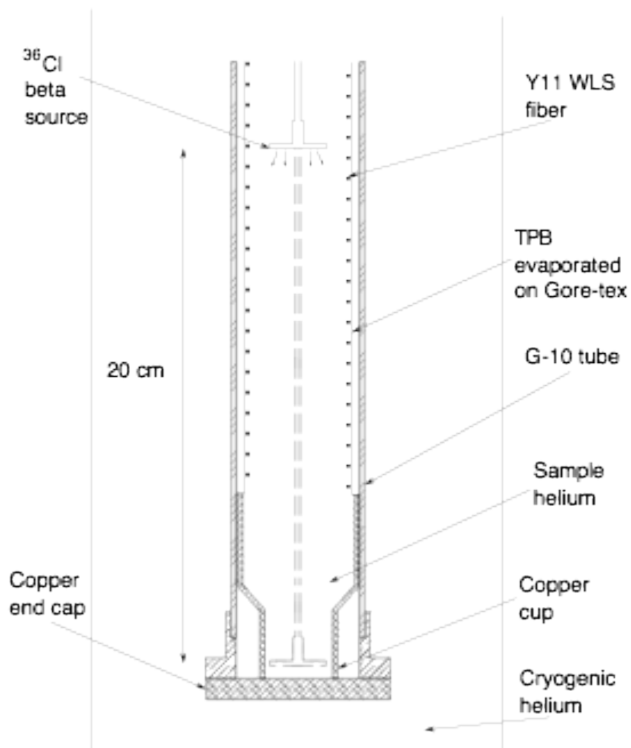
PHYSICAL REVIEW A VOLUME 59, NUMBER 1 JANUARY 1999

Radiative decay of the metastable $He_2(a\,^3\Sigma_u^+)$ molecule in liquid helium

D. N. McKinsey, C. R. Brome, J. S. Butterworth, S. N. Dzhosyuk, P. R. Huffman, C. E. H. Mattoni, and J. M. Doyle
Department of Physics, Harvard University, Cambridge, Massachusetts 02138

R. Golub and K. Habicht
Hahn-Meitner Institut, Berlin-Wannsee, Germany

(Received 27 July 1998)



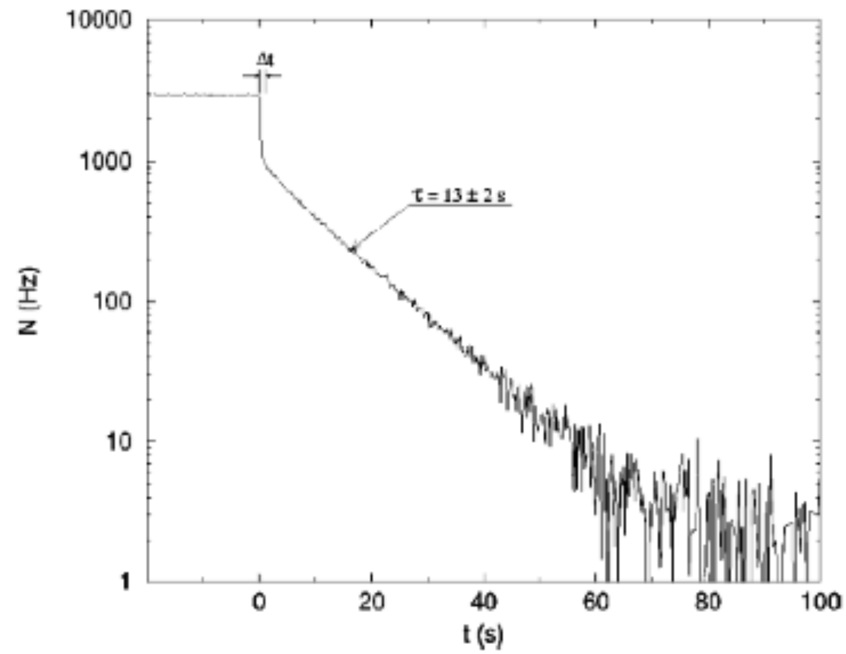


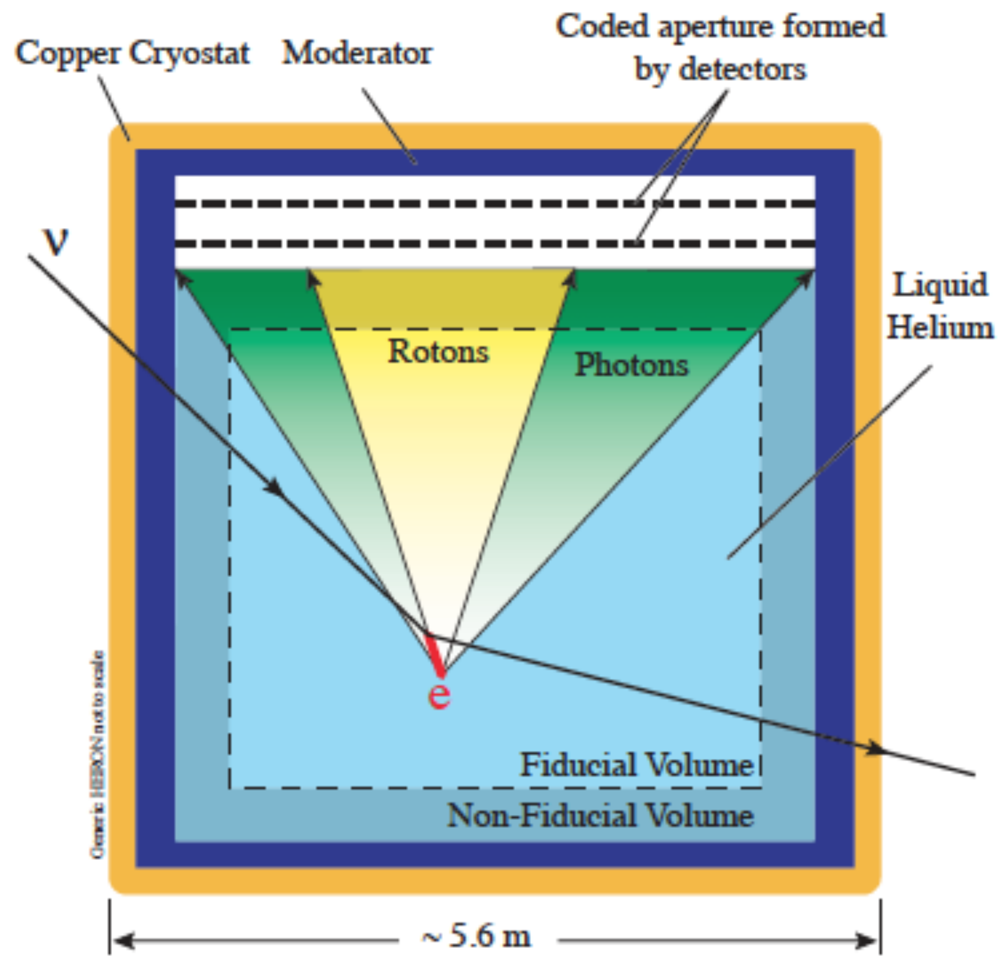
FIG. 2. Count rate N of detected $He_2(a\,^3\Sigma_u^+)$ decays versus time. A ^{36}Cl β source is placed in the center of the detection region and then removed in a time $\Delta t < 1$ s. This measurement was performed at a temperature of 1.8 K and resulted in a measured decay rate τ of 13 ± 2 s.

Superfluid helium-4 as a detector material

Proposed for measurement of pp solar neutrino flux using roton detection (HERON): R.E. Lanou, H.J. Maris, and G.M. Seidel, Phys. Rev. Lett. **58**, 2498 (1987).

Two signal channels, heat and light. Both measured with a bolometer array.

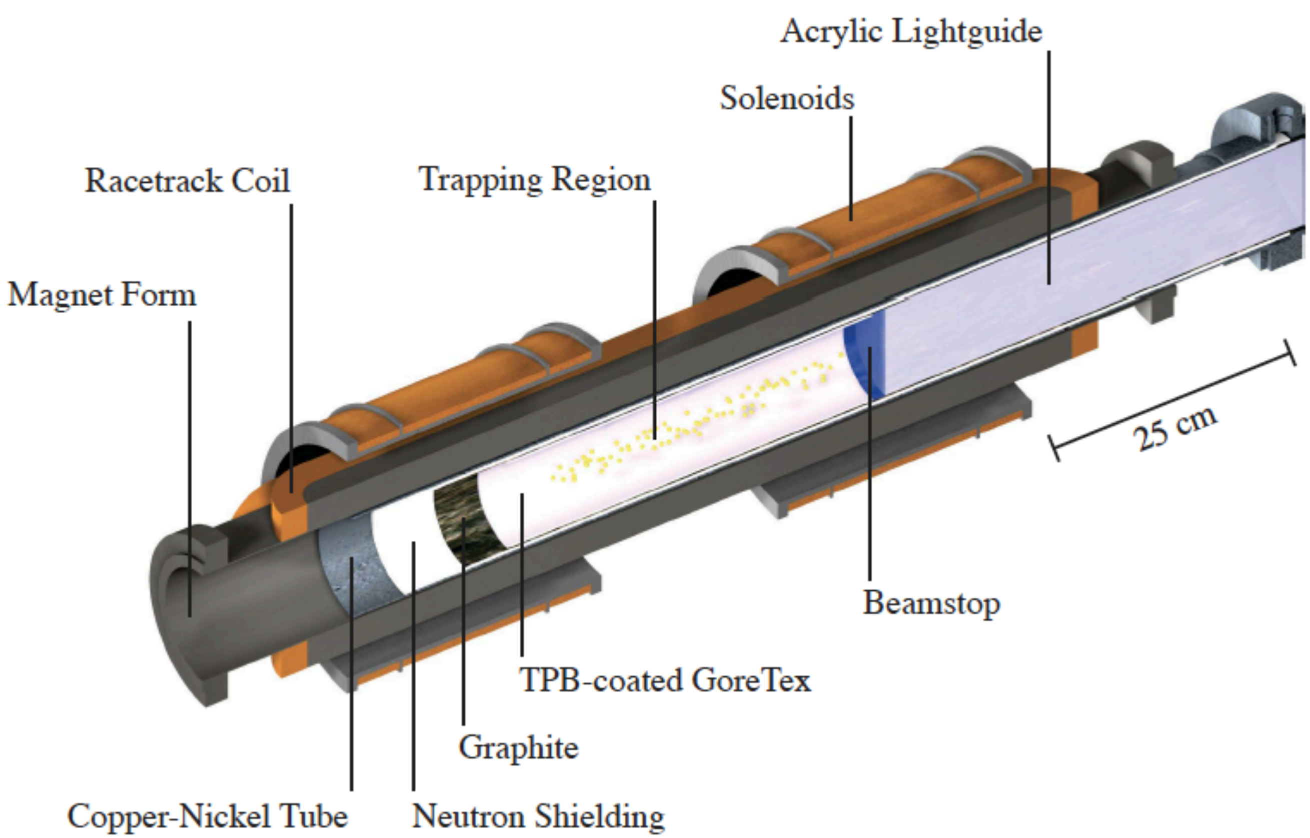
Also, “HERON as a dark matter detector?” in “Dark Matter, Quantum Measurement” ed Tran Thanh Van, Editions Frontieres, Gif-sur-Yvette (1996)



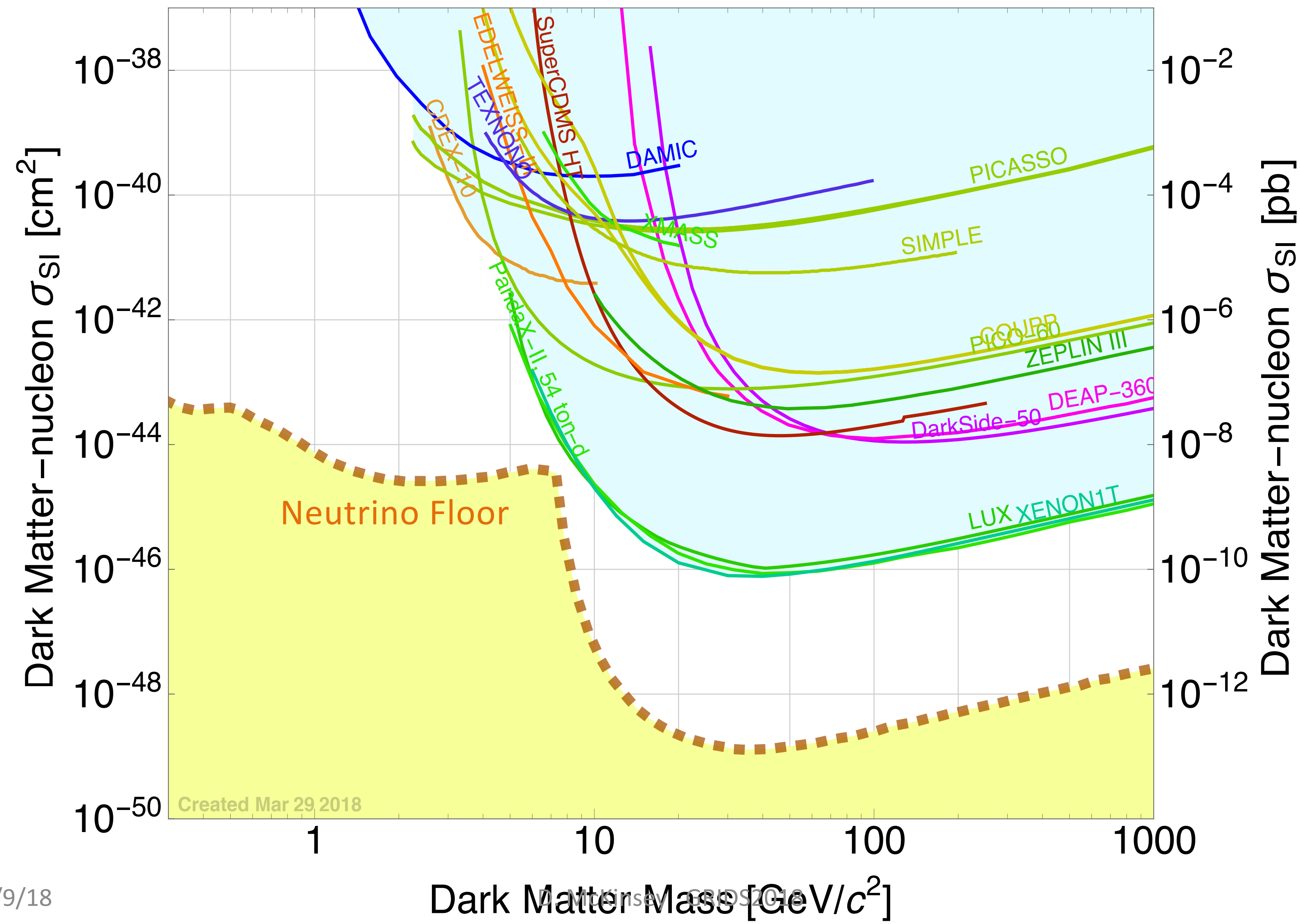
Superfluid helium-4 as a detector material

- Search for the neutron electric dipole moment: R. Golub and S.K. Lamoreaux, Phys. Rep. **237**, 1-62 (1994).

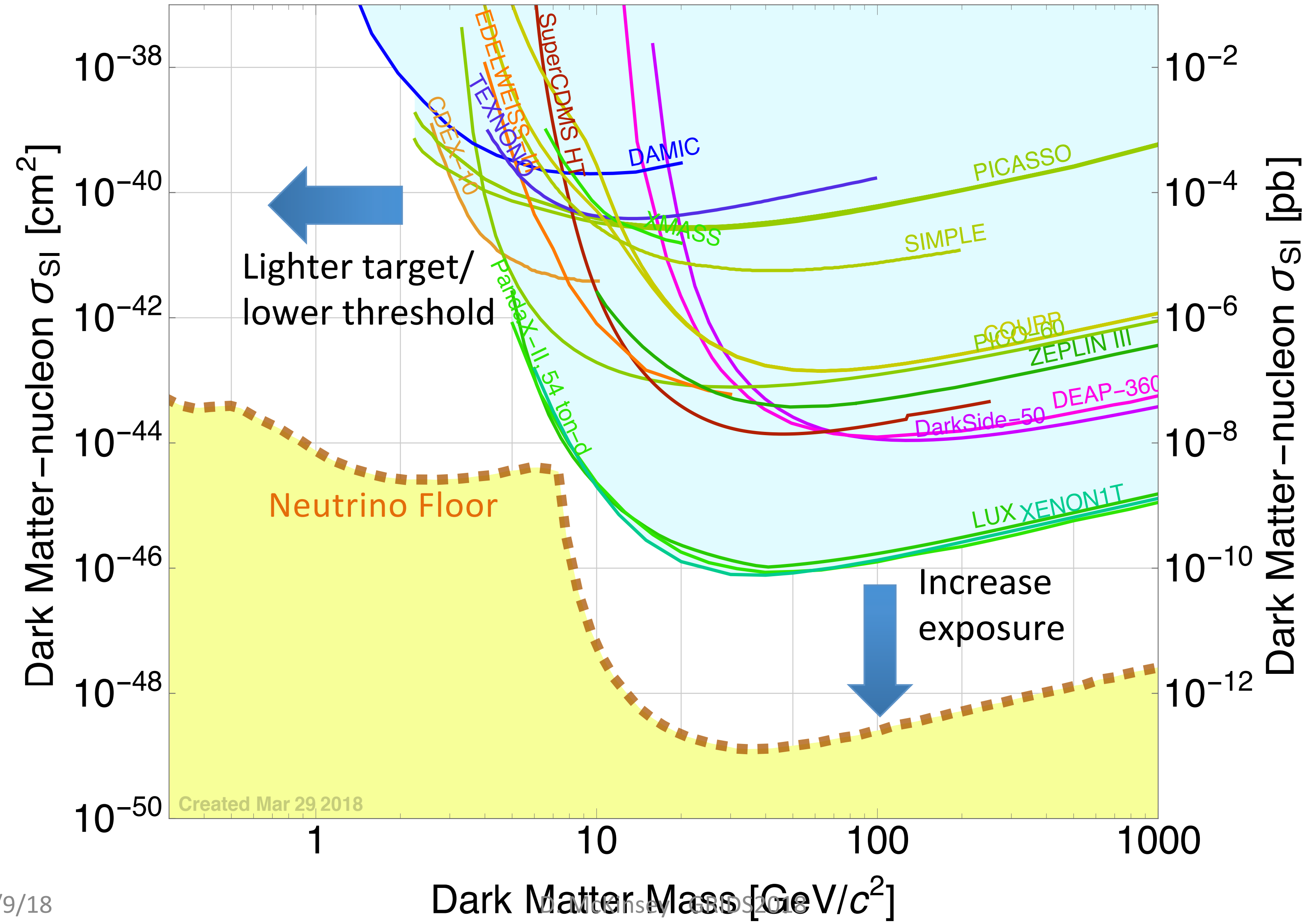
Measurement of neutron lifetime: P.R. Huffman et al, Nature **403**, 62-64 (2000).



Dark Matter Nuclear Recoils: Current Landscape

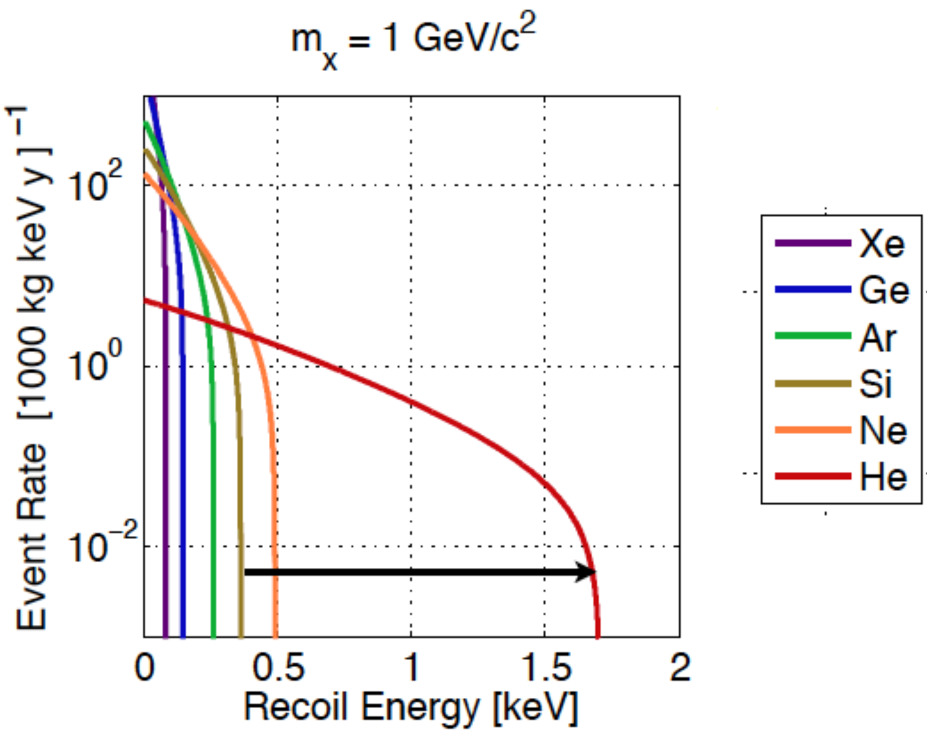


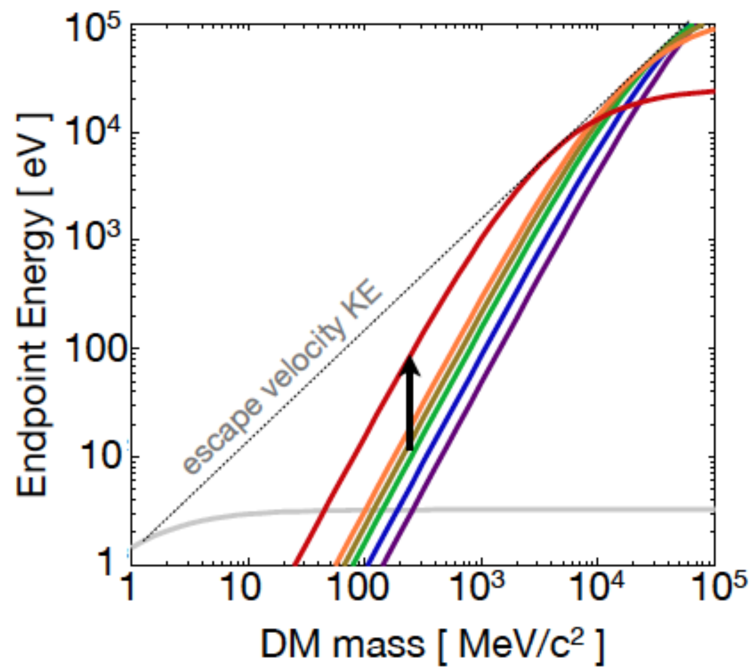
Dark Matter Nuclear Recoils: Future Directions



Helium for light dark matter detection

Light baryonic target with multiple signal channels, including light, charge, triplet excimers, phonons, and rotons.
(W. Guo and D. N. McKinsey, PRD 87, 115001 (2013).





Why Superfluid Helium-4?

- Liquid down to 0 K, allowing 10-100 mK-scale TES readout.
  - Take advantage of the great advances in TES technology
  - Take advantage of possible ~ 100% detection efficiency for photons, triplet excimers
  - Take advantage of the extremely low vapor pressure of superfluid helium at low temperatures, enabling quantum evaporation-based heat signal amplification.
- Helium is expected to have robust electronic excitation production efficiency, with a forgiving Lindhard factor, so nuclear recoil scintillation signals should be relatively large.
- Negligible target cost
- Low nuclear mass and charge -> low backgrounds from neutrino-nucleus scattering and gamma-nucleus scattering.
- Low vibration sensitivity: As a superfluid, small velocities don't generate excitations.
- Large ionization gap -> less signal quanta per keV than in super-, semiconductors. But no electron recoil background below 16 eV.
- Impurities easily removed from helium using cold traps and getters, and will literally fall out of the superfluid.

Superfluid Helium Detector Concept

(S. Hertel, U. Massachusetts, Amherst
Junsong Lin, Andreas Biekert, Vetri Velan, DNM, UC Berkeley)

Initial sensitivity studies, taking neutrino and gamma ray backgrounds into account:

Signal channels:

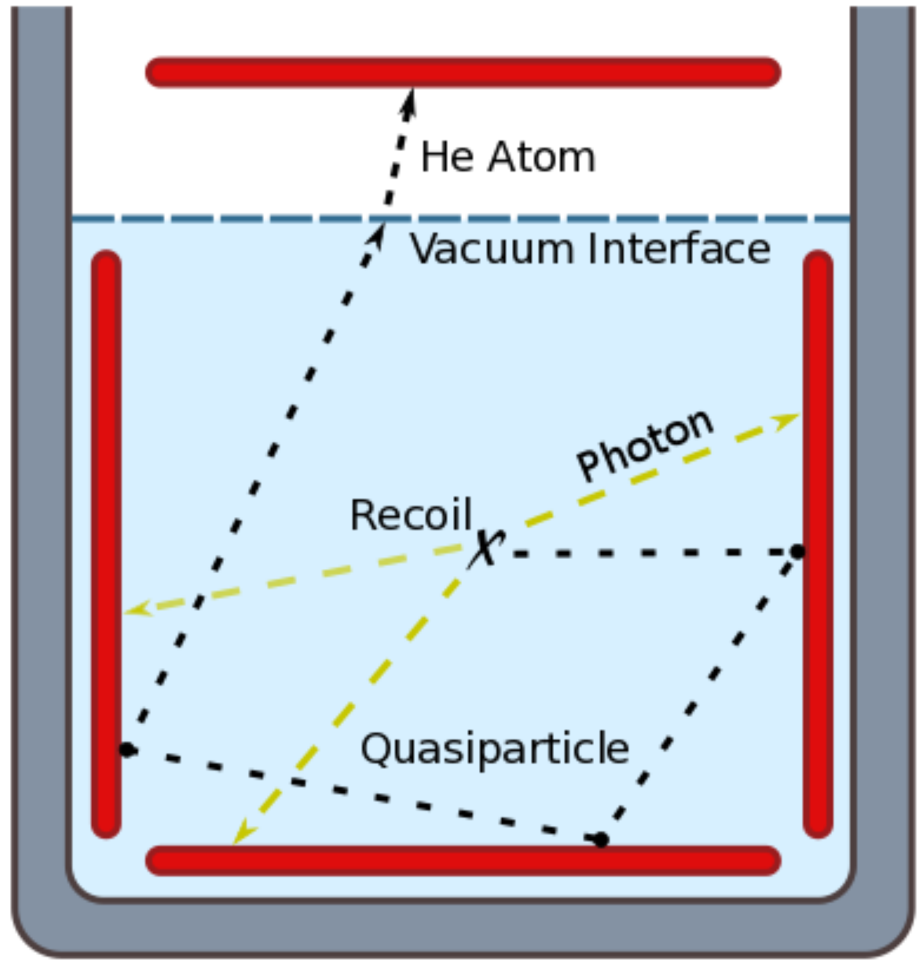
1) Scintillation
2) Ballistic Triplet Excimers
3) Phonons/Rotons

No drift field, and no S2 signal

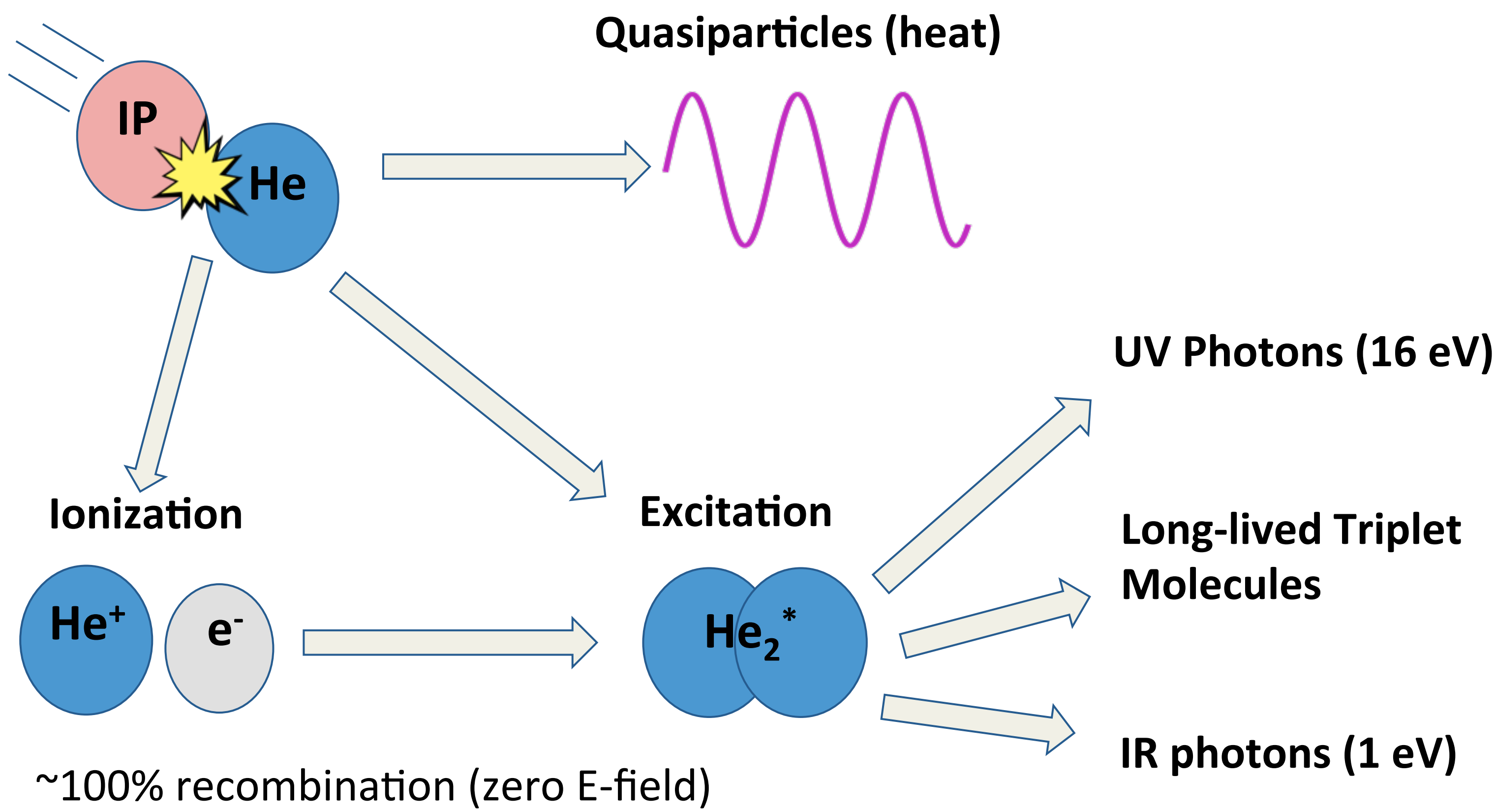
- No worry of few-electron background
- (Though could apply drift field to detect single electrons via roton/phonon production.)

Discrimination using signal ratios

Event position via signal hit patterns



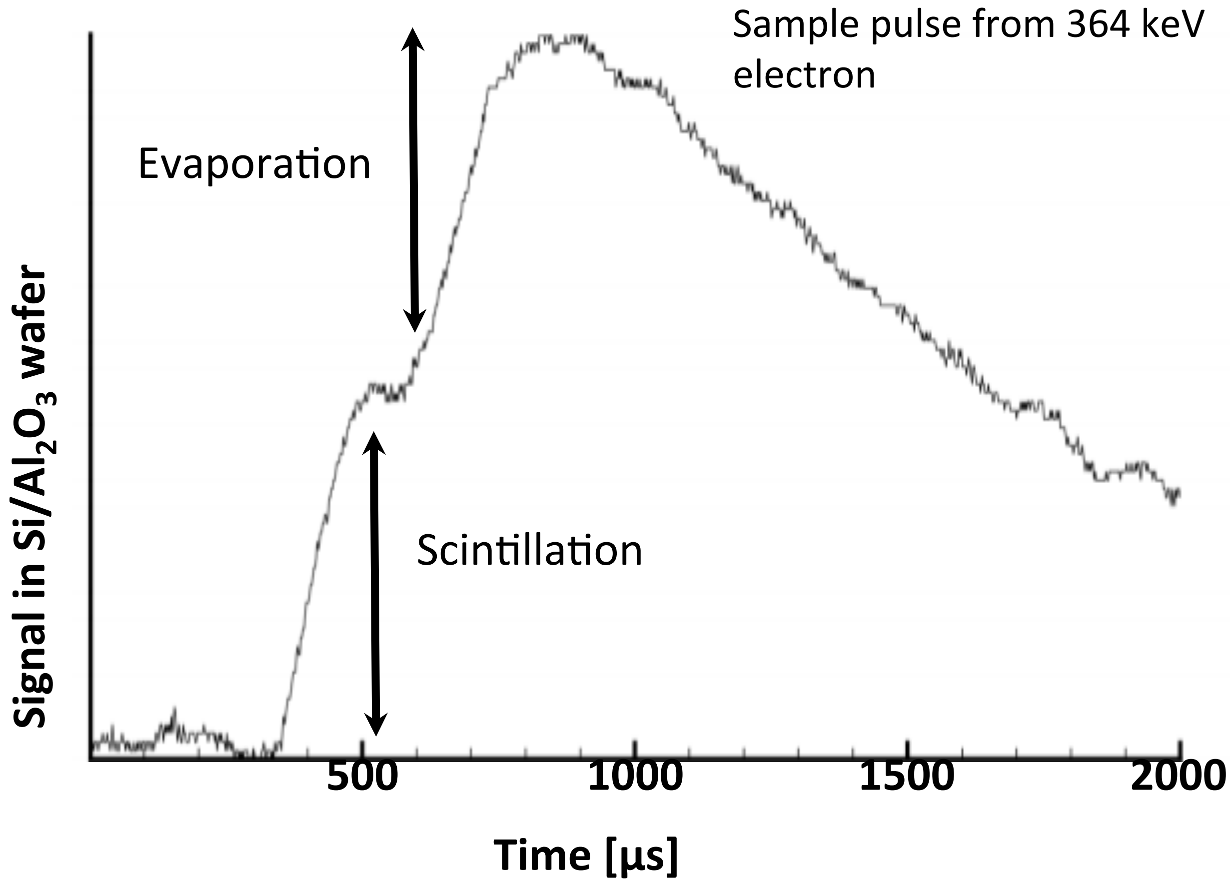
Anatomy of a Recoil



- UV and IR photons detectable as scintillation
- Triplet molecules directly detectable with TES
- Phonons and rotons can be detected with TESs, with some extra work

Concept Demonstrated

- HERON: proposed *pp* neutrino observatory
- Pulse at the right shows simultaneous detection of photons and rotons



J. S. Adams et al., AIP Conference Proceedings 533, 112 (2000).
Also see: J. S. Adams et al., Physics Letters B 341 (1995) 431-434.

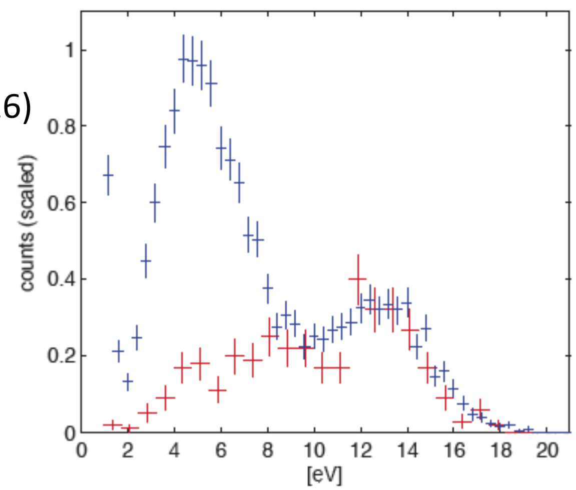
Reading Out Singlet Excitations (16 eV Photons)

Detecting photons is a simple calorimetry application. Operating calorimetry in LHe: less standard. Possible thanks to:

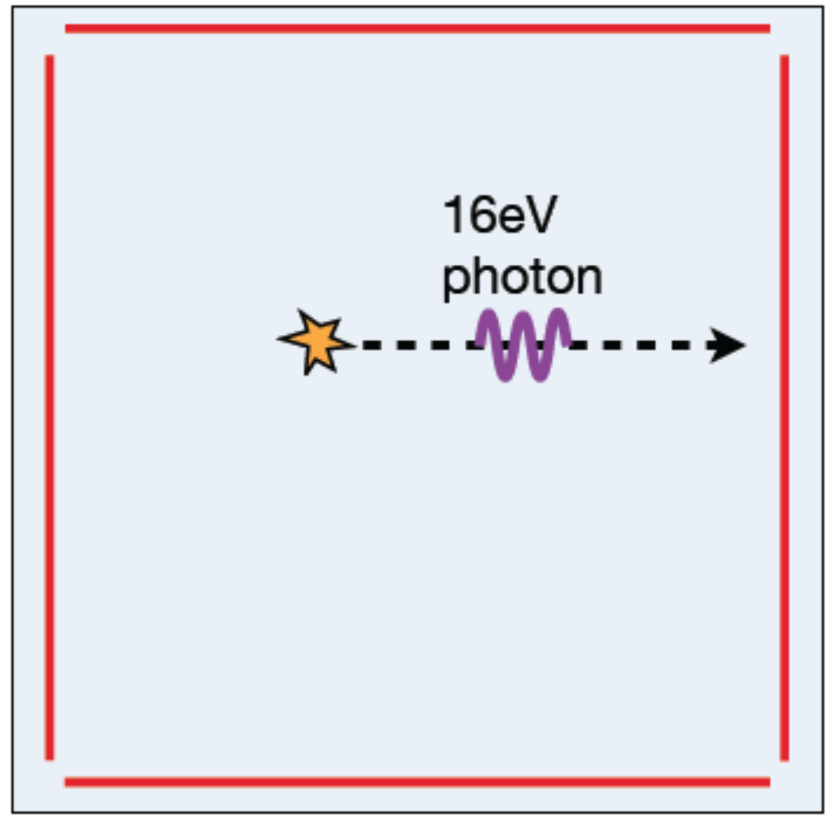
- Huge LHe-solid Kapitza resistance
- Fast conversion of photon energy to non-phonon excitations (e.g. Al quasiparticles)

Triplet excimers may also be read out using the same calorimetry!

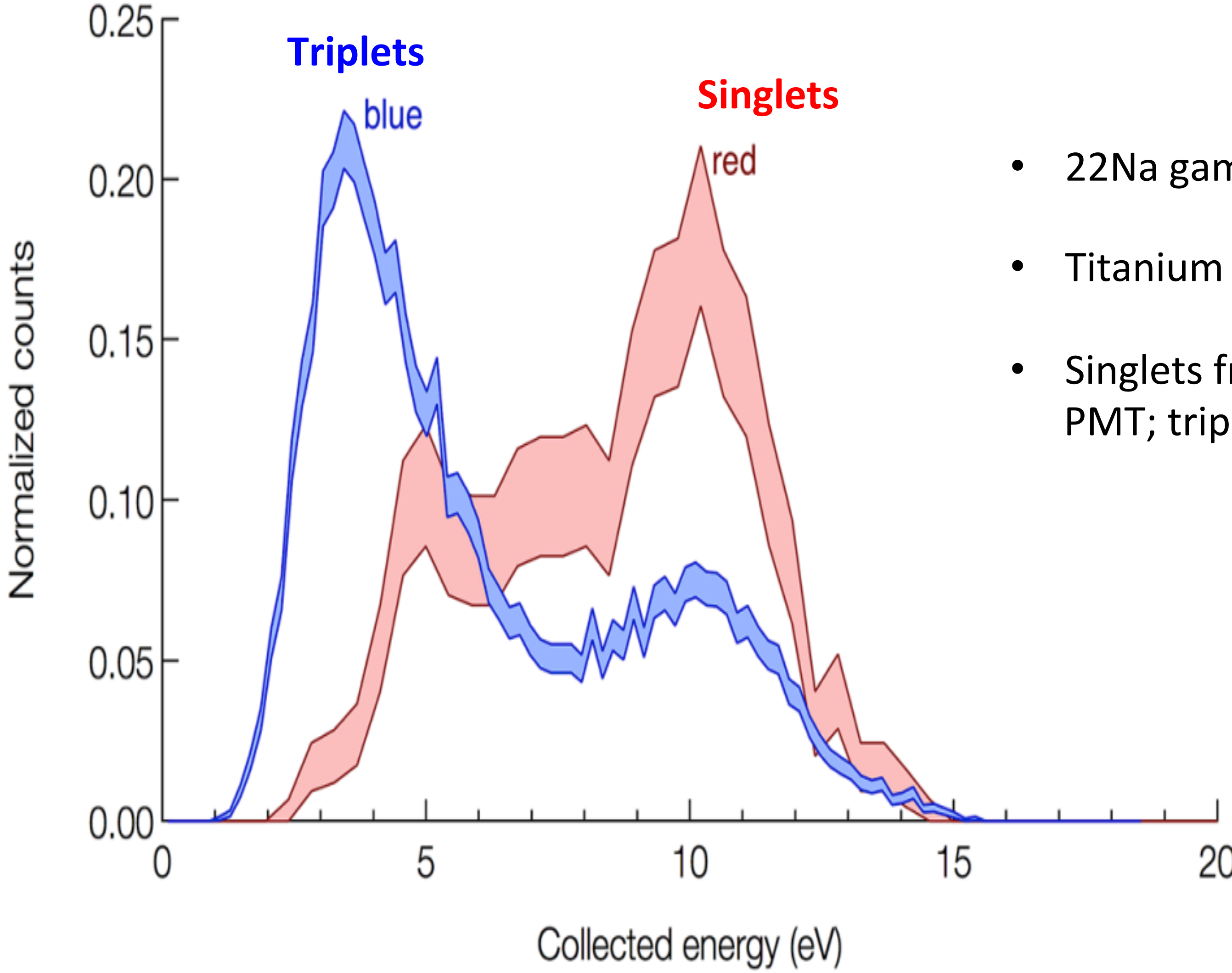
F. Carter et al,
J Low Temp Phys (2016)
arXiv:1605.00694



Simple detector: box with calorimetry inside



Ballistic Triplets



- 22Na gamma source
- Titanium TES in 100 mK 4He bath
- Singlets from TES coincident with PMT; triplets from only TES

Carter, et al., J. Low Temp. Phys. 186(3) 183-196 (2017)/arXiv:1605.00694

Phonons and Rotons

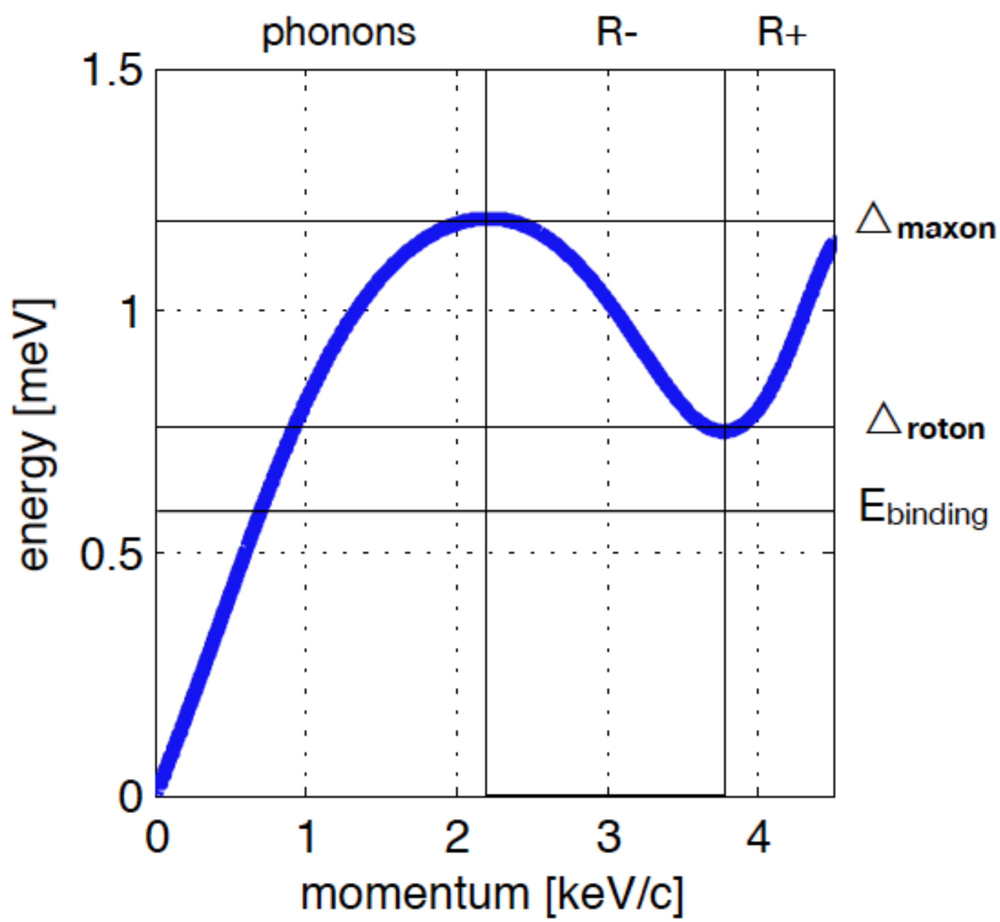
Superfluid supports vibrational modes (some non-intuitive).

Ballistic, ~150 m/s.

Enormous Kapitza resistance,
i.e. *tiny* probability of crossing into solid.

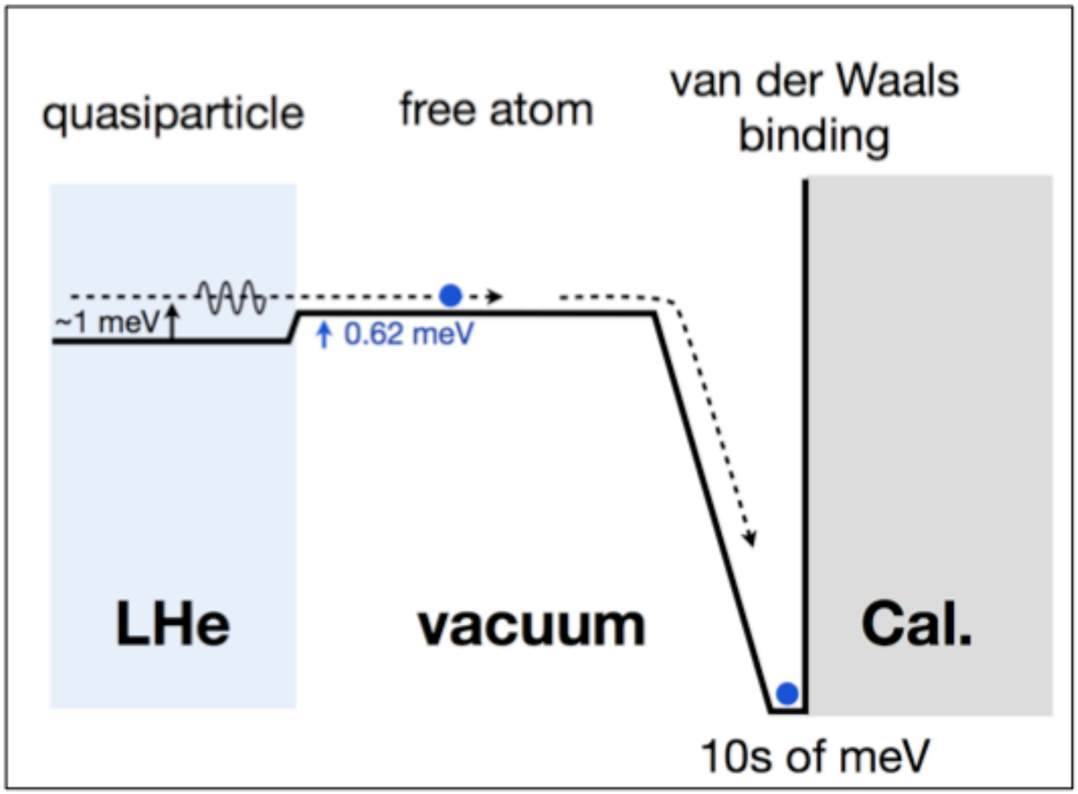
Few downconversion pathways.

Most signal expected in R- and R+ rotons, with absorption probability on walls measured to be 2.8 x 10^{-3}.
See Brown and Wyatt, J. Phys.: Condens. Matter 15, 4717 (2003).

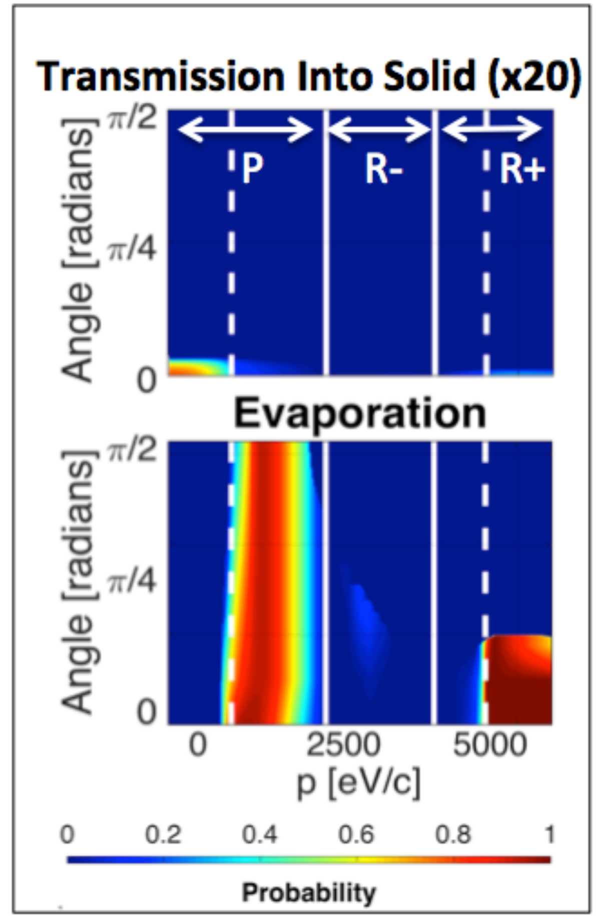


Quantum evaporation from superfluid helium – vacuum interface

Heat amplification from desorption – adsorption process
Adsorption gives 10-40 meV depending on surface



~10x signal energy enhancement!

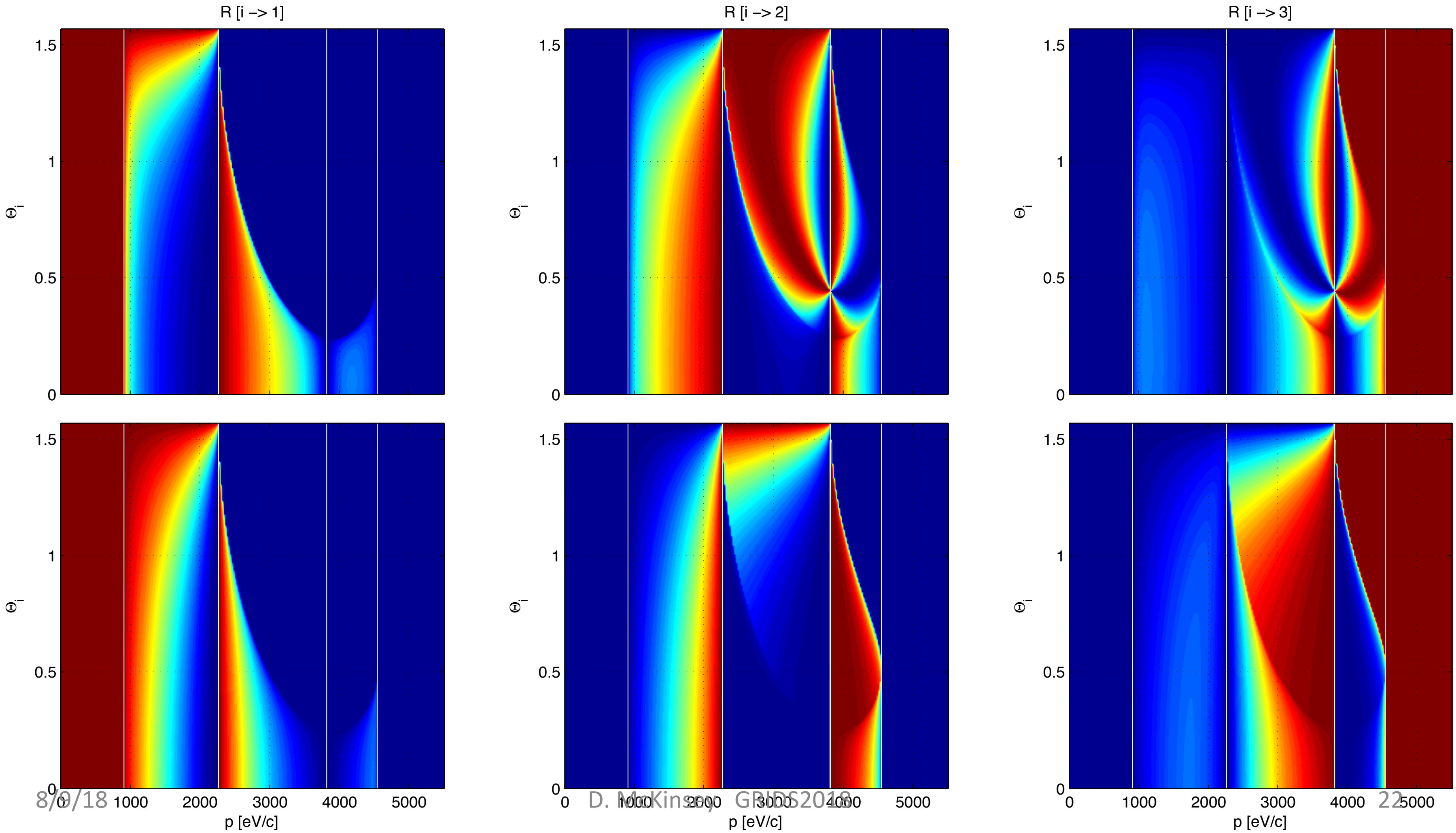


Phonons and rotons can change type when reflecting from surfaces

Calculations based on Tanatarov et al., arXiv:1004.3497

refection mode-change probabilities
(blue=0, red=1)

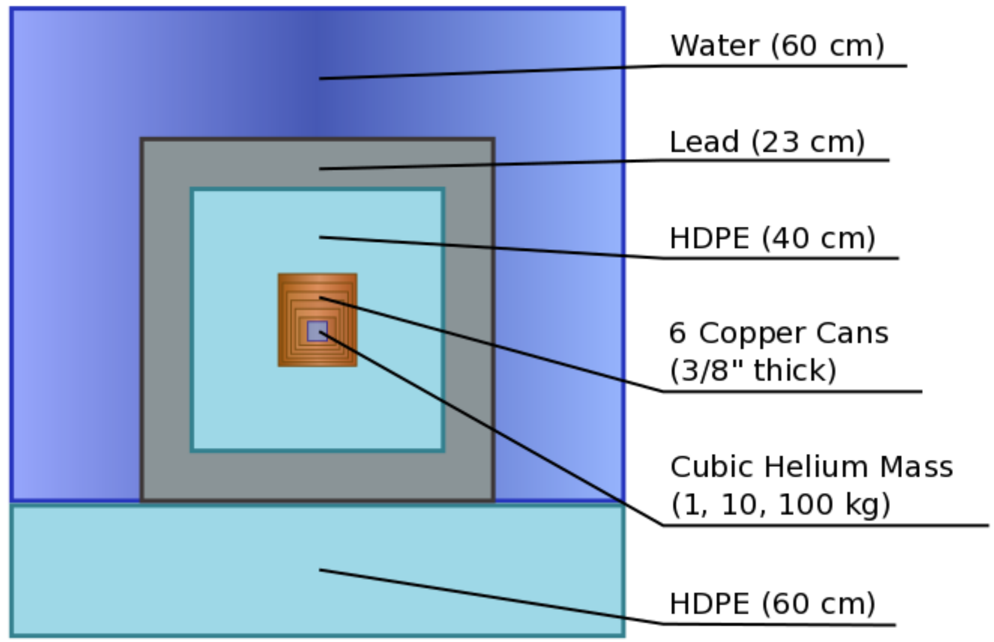
upper three: solid interface
lower three: vacuum interface



Expected Backgrounds

Backgrounds included:
- Neutrino nuclear coherent scattering
- Gamma-ray electron recoil backgrounds (similar to SuperCDMS)
- Note: Helium itself is naturally radiopure, and easily purified of contaminants
- Gamma-ray nuclear recoil backgrounds (see Robinson, PRD 95, 021301 (2017)

Arguments for low "detector" backgrounds:
- Low-mass calorimeter, easy to hold
- Target mass highly isolated from environment (superfluid: friction-free interfaces)

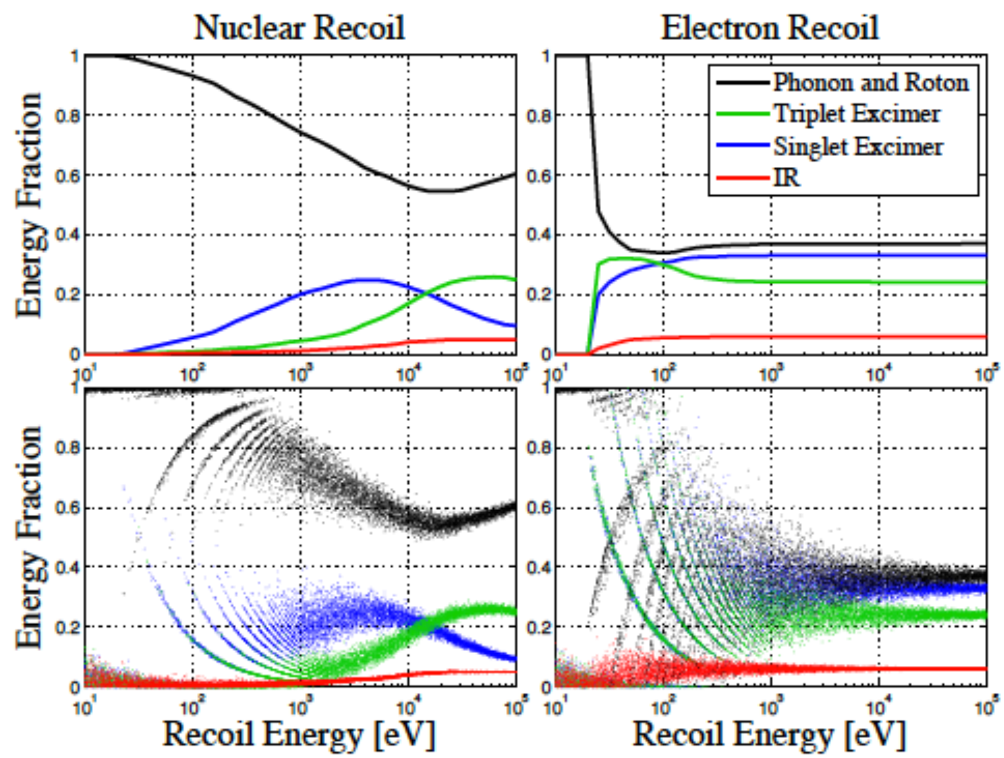


Electron recoil / nuclear recoil discrimination

Toy Monte Carlo detection efficiencies:

- singlet UV photons: 0.95 (4pi coverage by calorimetry)
- Triplet excimers: 5/6 (only solid surfaces)
- IR photons: 0.95 (similar to UV photons)

Excellent predicted discrimination at sub-keV energies



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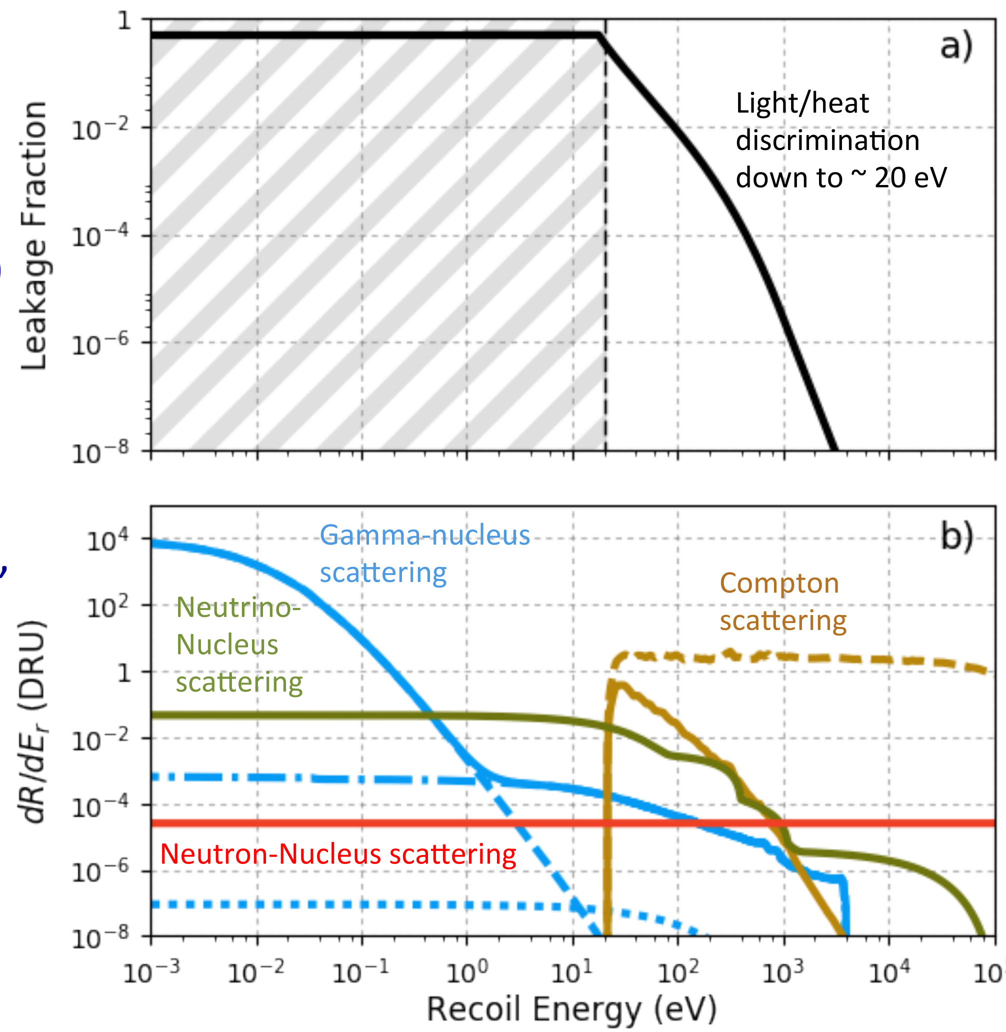
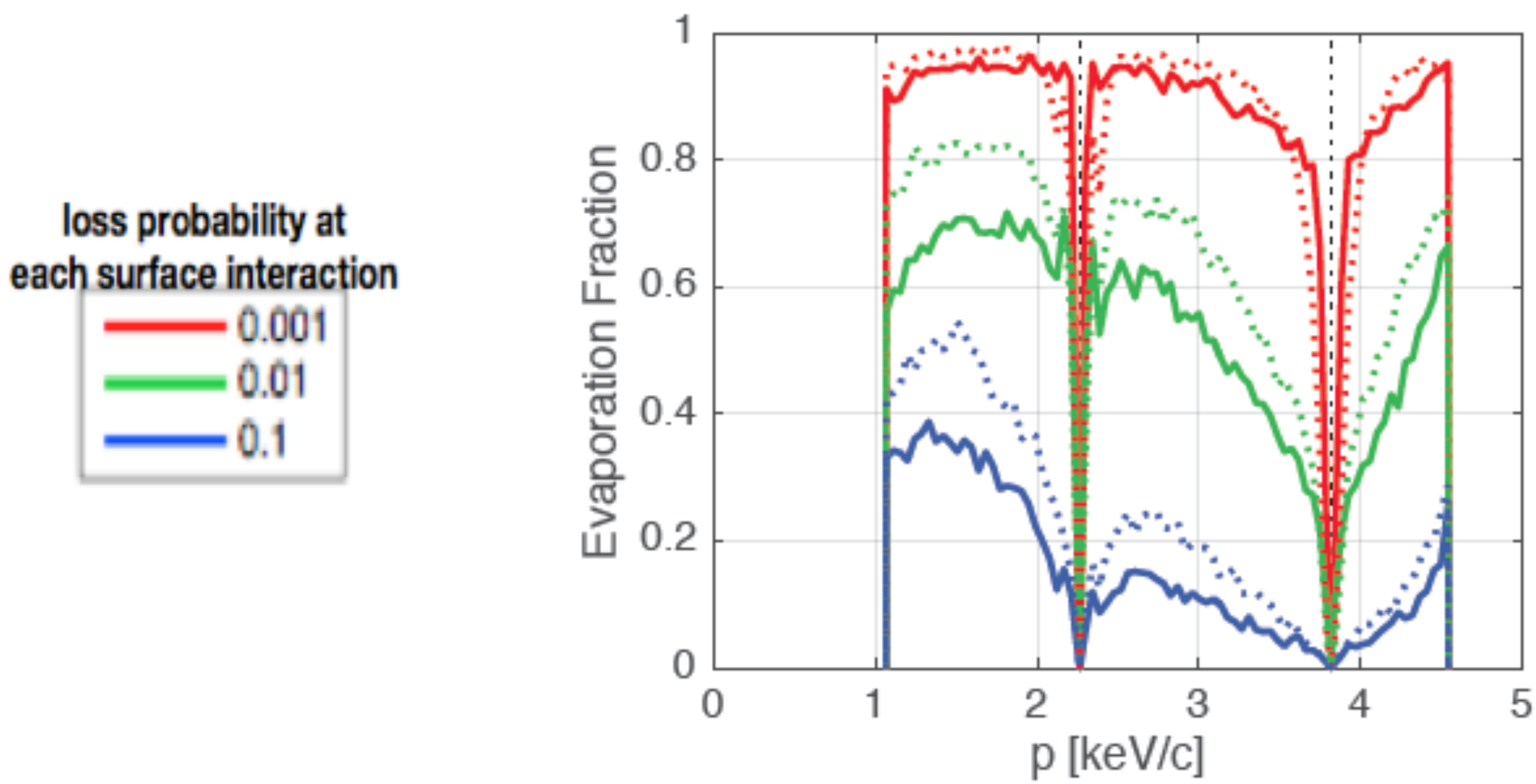


Phonon and Roton Monte Carlo Studies

Below are shown Monte-Carlo-determined efficiencies of detecting quasiparticles (phonons or rotons) as a function of quasiparticle momentum, for varying surface absorption probabilities (0.001 to 0.1)



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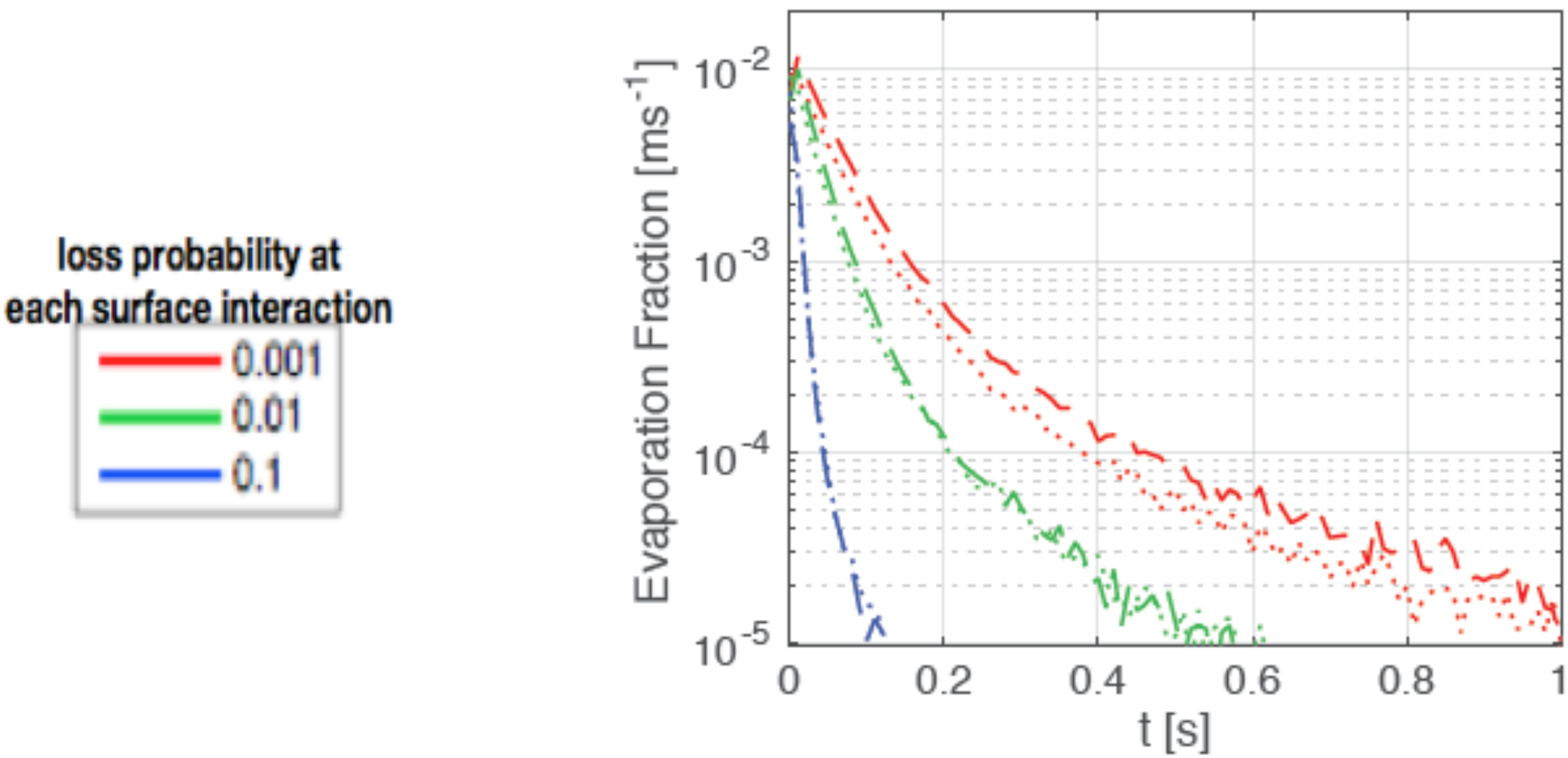


Heat-only Readout?

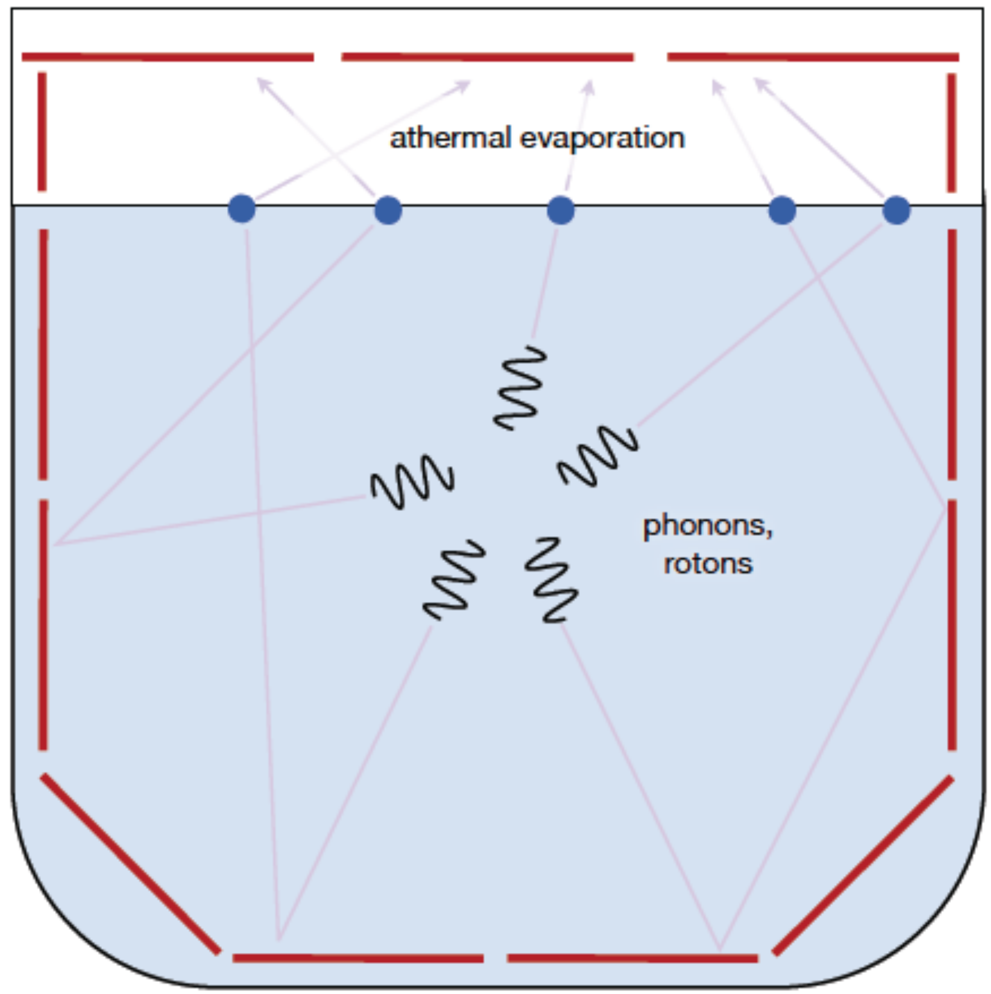
Signal channels:

- Phonons
- Rotons

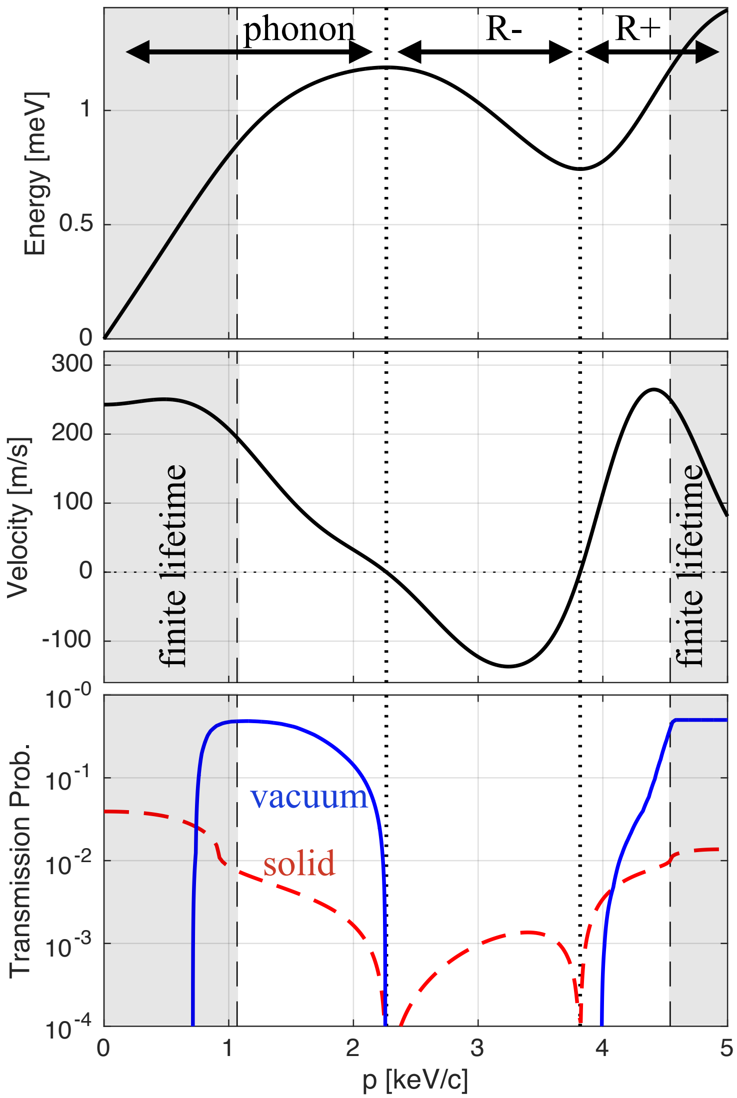
Energies in principle down to ~ 1 meV.

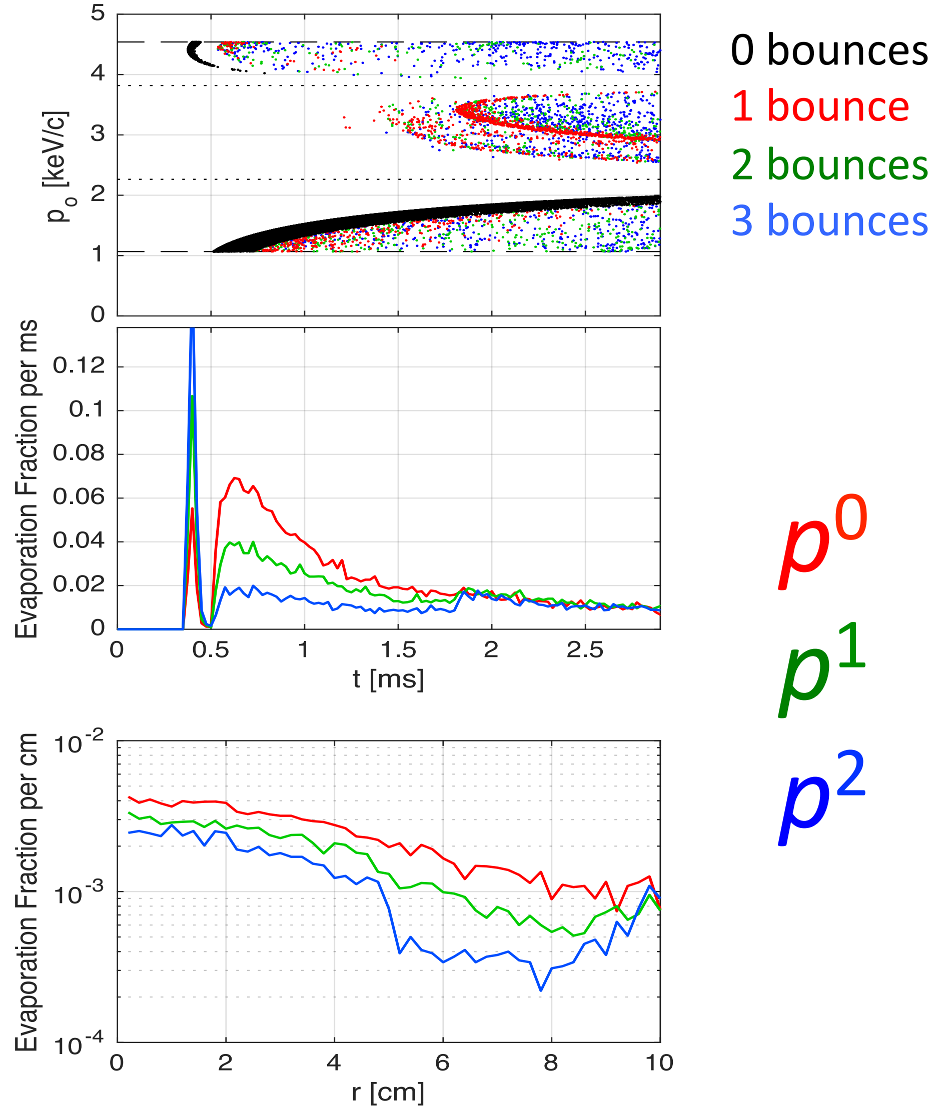
Discrimination using roton/phonon signal ratios likely. Electron recoils, detector effects, nuclear recoils likely create different roton/phonon distributions, with resulting differences in signal timing.

Position reconstruction using signal hit patterns



Background vs Signal Discrimination with Phonon/Roton Timing?





p^0

p^1

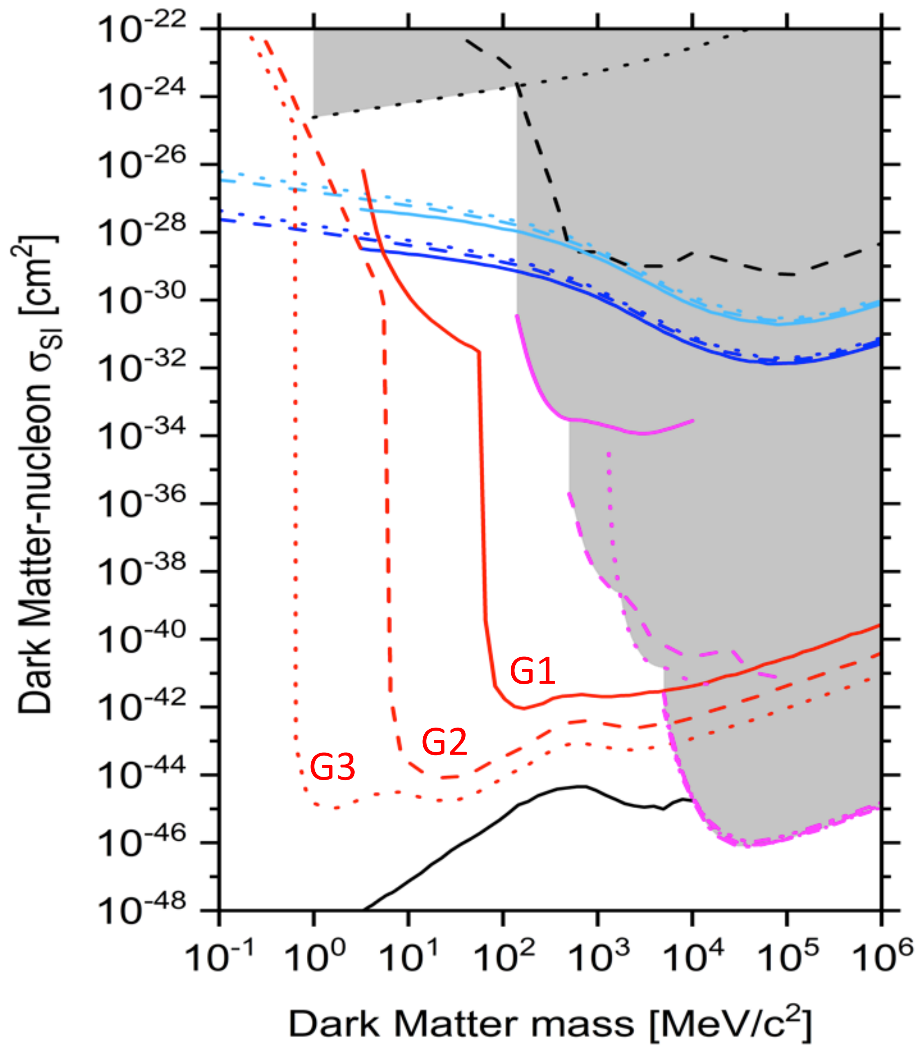
p^2

Possible stages of a superfluid helium program

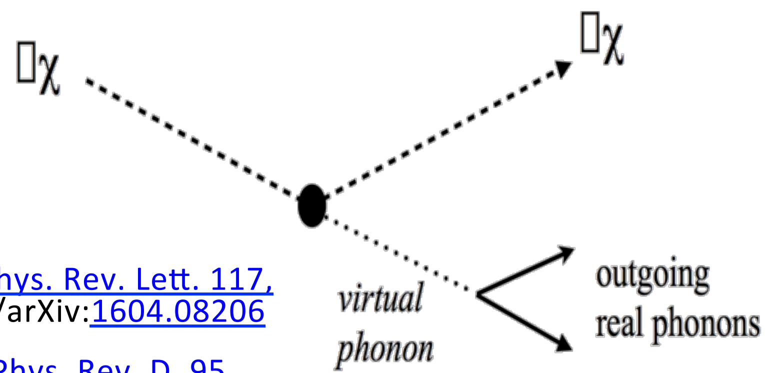
Generation 1: “shovel ready”
10 eVr threshold, 1 kg-y
Assuming 40 meV per He atom (graphene-fluorine)
20 eV calorimeter threshold w/ 5% evap. efficiency

Generation 2: “feasible after R&D”
100 meVr threshold, 10 kg-y
Assuming 40 meV per He atom (graphene-fluorine)
1 eV calorimeter threshold w/ 25% evap. Efficiency

Generation 3: “theoretically possible”
1 meVr threshold, 100 kg-y
Limit of single-atom counting
(~40 meV calorimeter threshold)



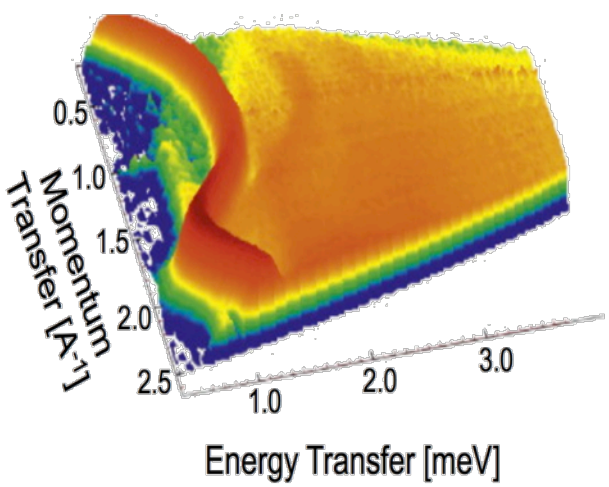
Higher Order Phonon Processes



Schutz et al., Phys. Rev. Lett. 117, 121302 (2016)/arXiv:1604.08206

Knapen et al., Phys. Rev. D. 95, 056019 (2017)/arXiv:1611.06228

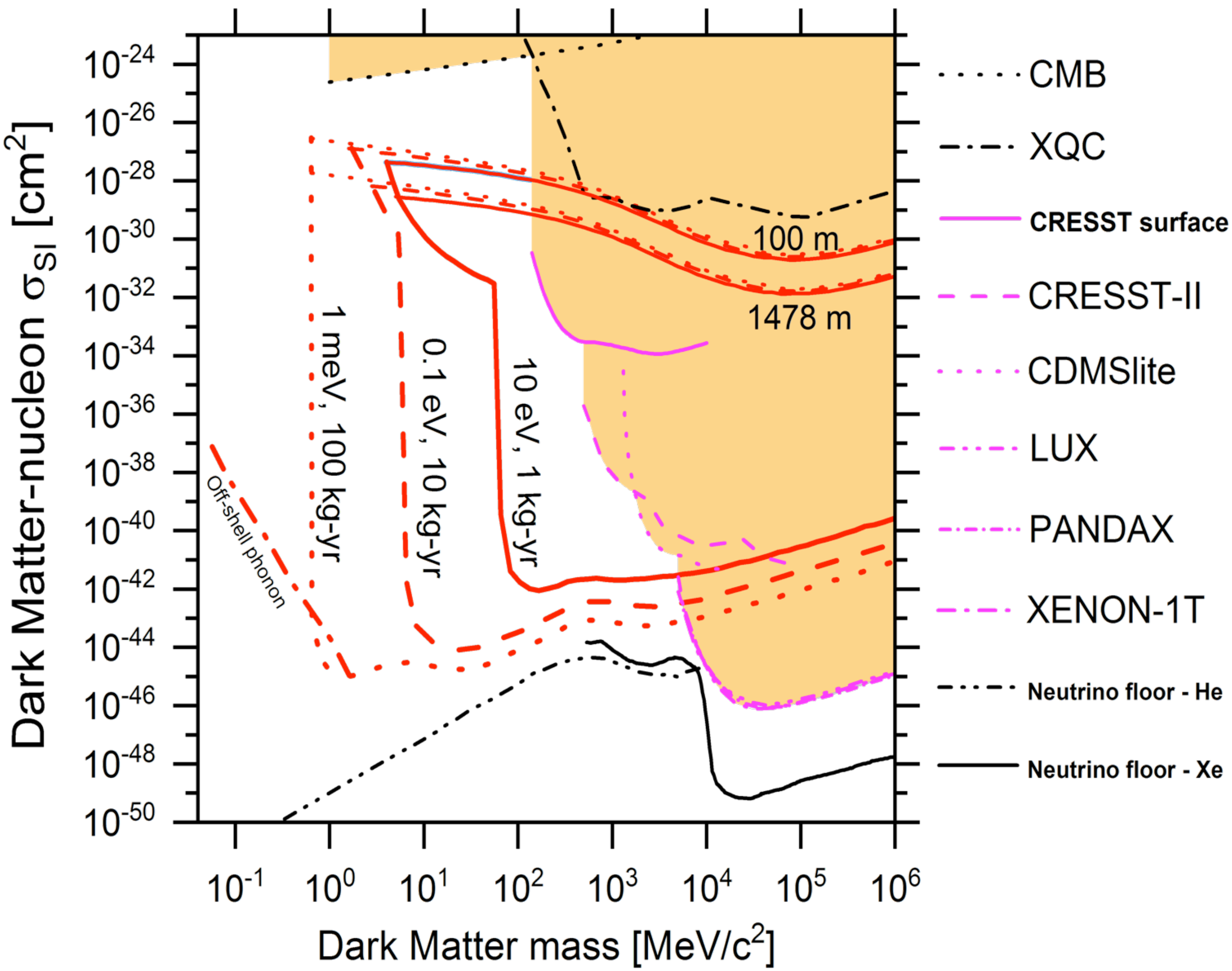
- Virtual phonons not limited to dispersion relation.
- Process allows sensitivity to keV-scale warm DM
- Two-phonon process experimentally observed in neutron scattering (below)



Visualization from: Nucl. Instr. Meth. Phys. Res. A 611, 259-262 (2009)/ arXiv:0811.4332

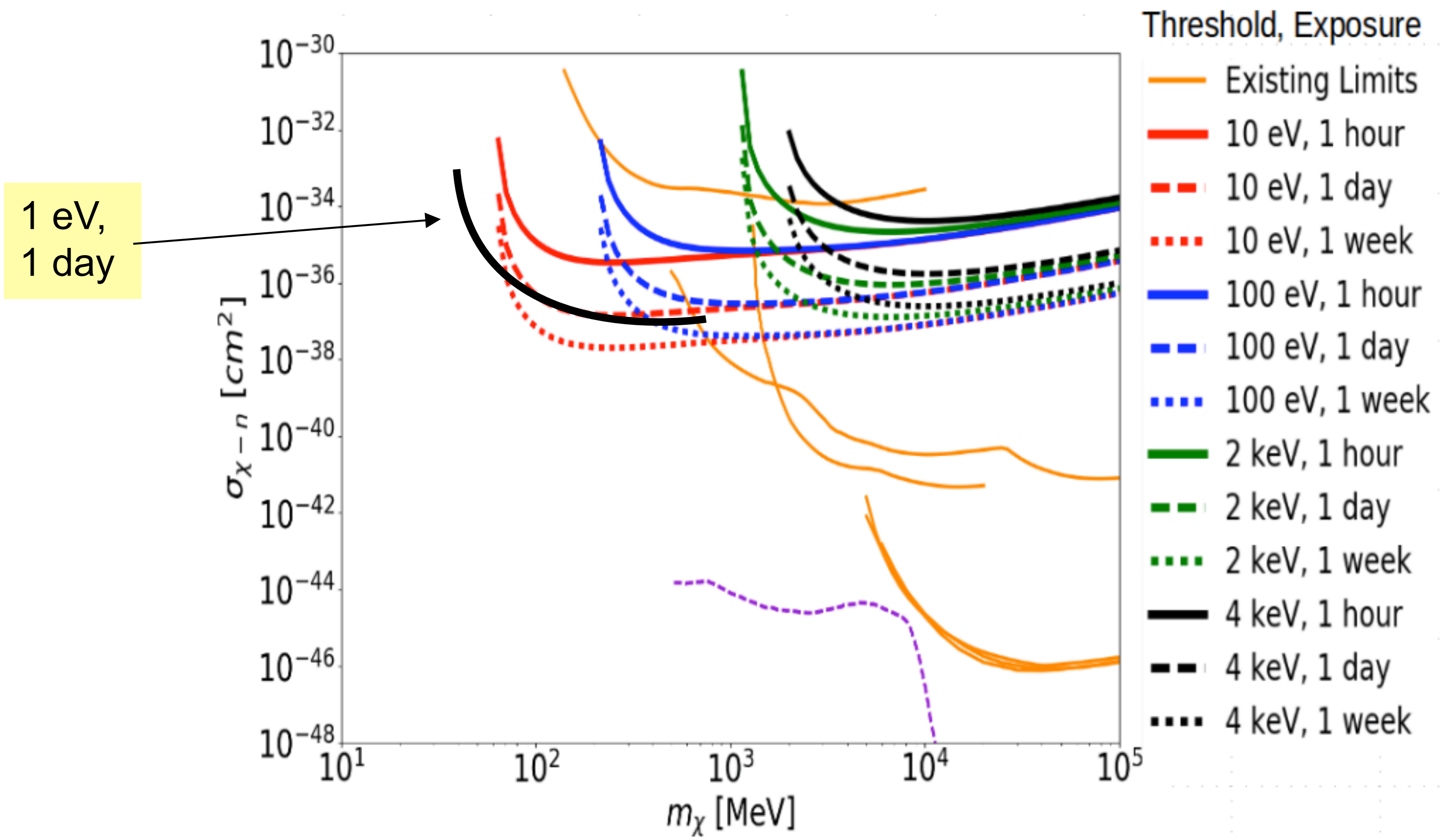
Measured in: Gibbs et al., J. Phys.: Condens. Matter 11, 603-628 (1999)

Projected Sensitivity – nuclear recoils

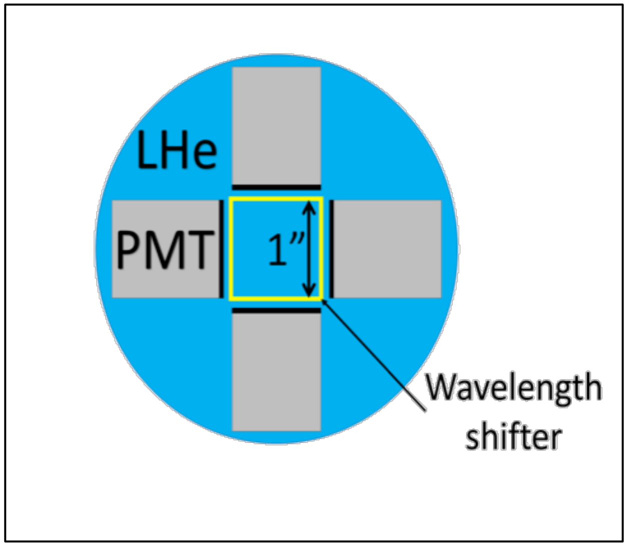


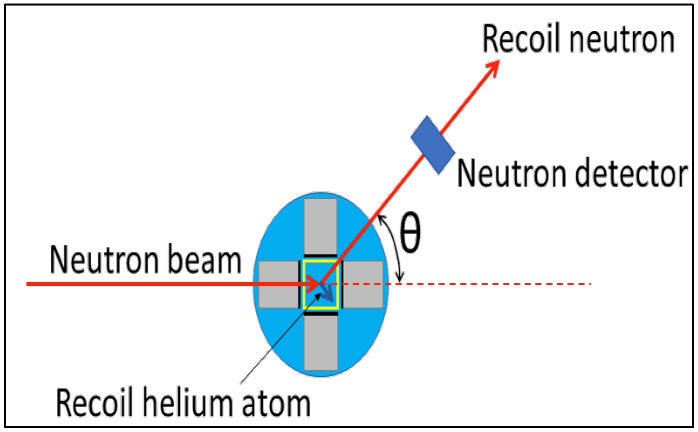
LHe reach at the surface

2g LHe on surface. Zero background



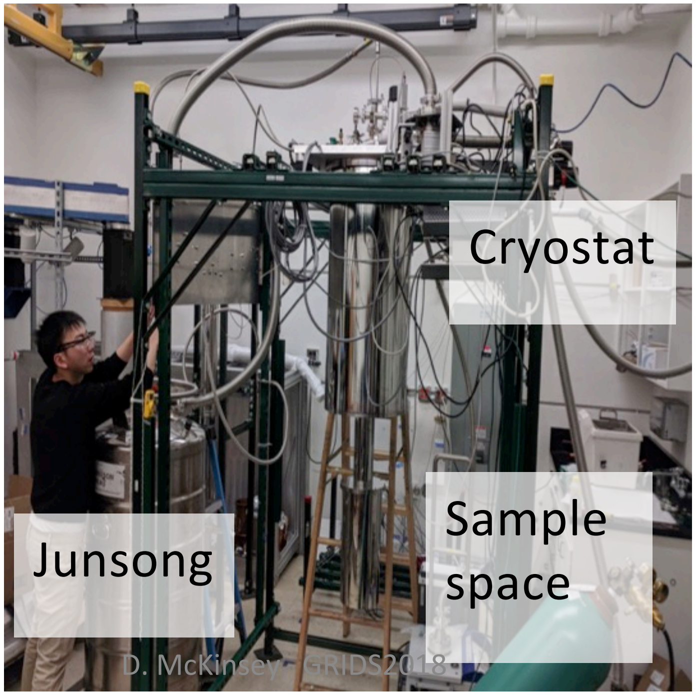
Next Steps





Now: Measure scintillation light yield from low energy nuclear recoils in superfluid helium

Also: Dilution refrigerator instrumentation studies (UCB + UMass)

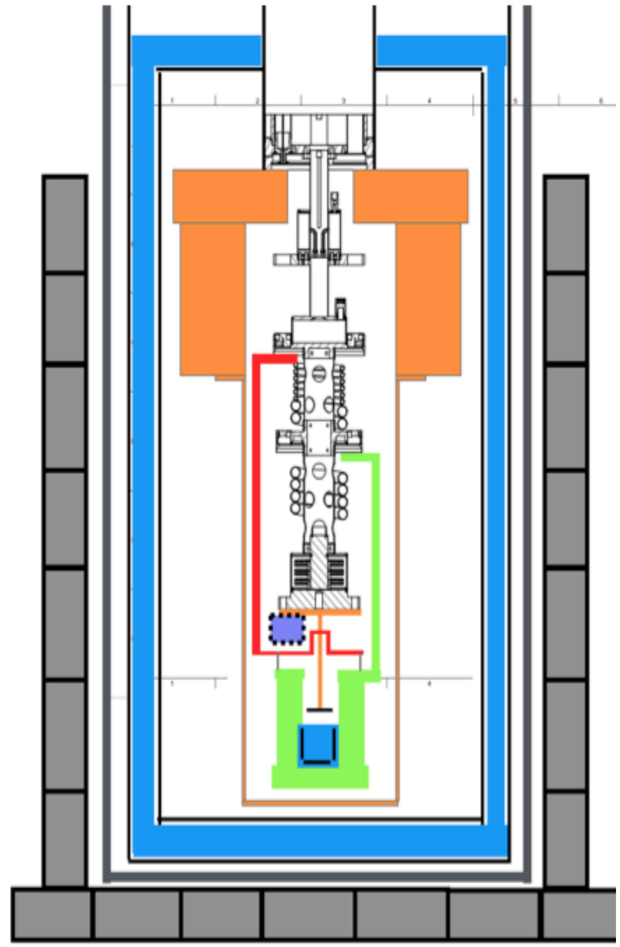


Right: Successful cool down to 1.5 K!

Superfluid Helium Detector

Leiden (wet, low-vibration) dilution refrigerator being set up in McKinsey lab at UCB

First tests being designed, with TES, SQUIDs, helium film burner, shielding



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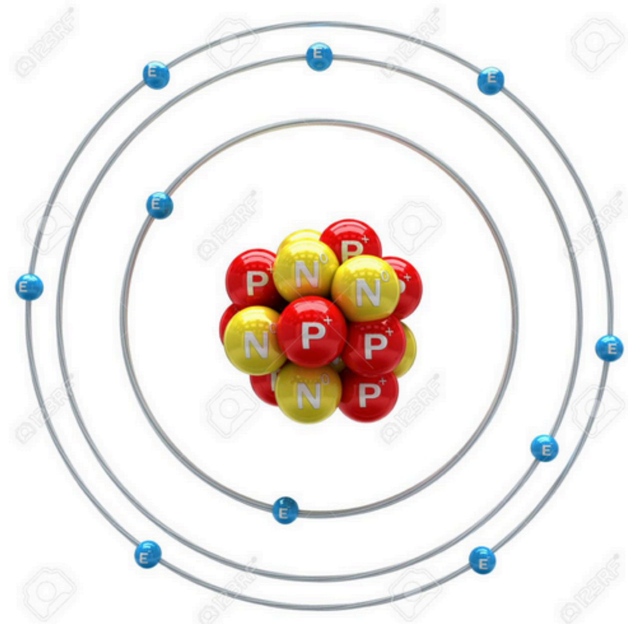
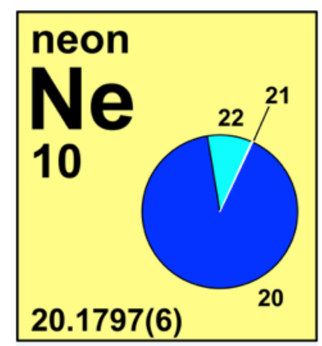
Scintillation Yield (photons/ keV)	60		40	30	19
Scintillation wavelength (nm)	178	150	128	78	80
Triplet time constant (us)	0.03	0.09	1.6	15	1.3×10^7
Long-lived isotopes	^{136}Xe	^{81}Kr, ^{85}Kr	^{39}Ar, ^{42}Ar	none	none

The Appeal of Liquid Neon (LNe)

- ✓ No long-lived isotopes!
- ✓ Density = 1.2 g/cc – efficient stopping of gamma rays, neutrons
- ✓ High scintillation yield
    - ~ 30 photons/keV
- ✓ Pulse shape discrimination (triplet lifetime 15 microseconds).
- ✓ High purity attainable
    - In addition to getters, can use charcoal to remove heavier nobles, hydrogen.
- ✓ 'Easy' cryogenics
    - Mechanical coolers readily available
- X However, electron drift is slow ~ mm/ms
    - Electrons form "bubble" states
    - Most suitable to "single-phase" configuration





The Appeal of Liquid Neon (LNe)

McKinsey and Doyle, arXiv:astro-ph/9907314,
J. Low Temp. Phys. **118**, 153 (2000).

Also see McKinsey and Coakley, astro-ph/0402007, Astroparticle Physics 22, 355 (2005) and Boulay, Hime, and Lidgard, nucl-ex/0410025.

CLEAN: <u>C</u>ryogenic <u>L</u>ow <u>E</u>nergy <u>A</u>strophysics with <u>N</u>oble gases.

First proposed use of self-shielding in a noble liquid detector (inspired by Super-Kamiokande, Borexino, SNO).

Goal: Measurement of pp-solar neutrino flux, via neutrino-electron scattering.

Main advantage over LXe is lower ER backgrounds (^{136}Xe double beta decay, Rn daughters in LXe).

This is arguably still the best way to do an accurate pp-solar neutrino flux measurement! (for the low, low price of a few hundred $M)

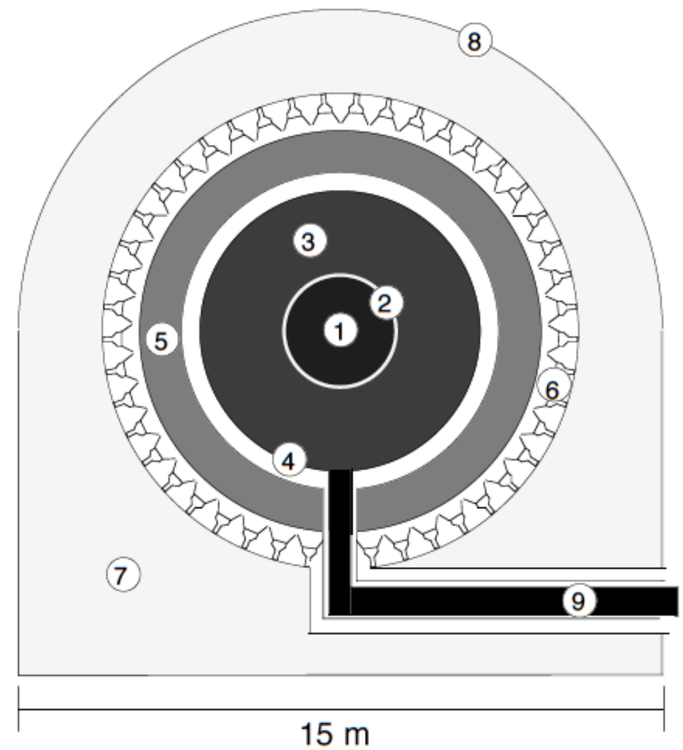
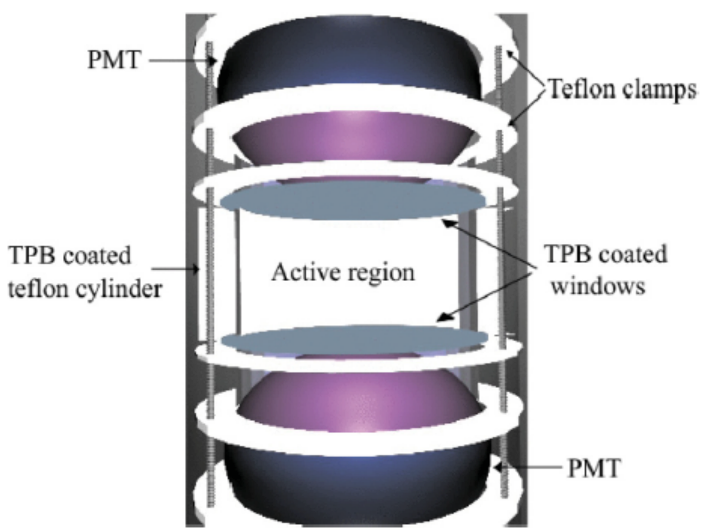


FIG. 1. Diagram of the proposed experiment: (1) Active region, containing 10 tons of ultrapure liquid helium or liquid neon. (2) Sheet of transparent material, coated on its inside surface with TPB waveshifter. In case B there would also be a vacuum region separating the active and shielding regions. (3) Shielding region, filled with ultrapure liquid neon or liquid helium.(4) Transparent copper grid composite or acrylic tank (5) Ultrapure liquid nitrogen (6) Photomultipliers (7) Ultrapure water (8) Stainless steel tank (9) Thermal link to refrigerator. Dimensions assume case A (liquid neon active region and liquid neon shielding region.)

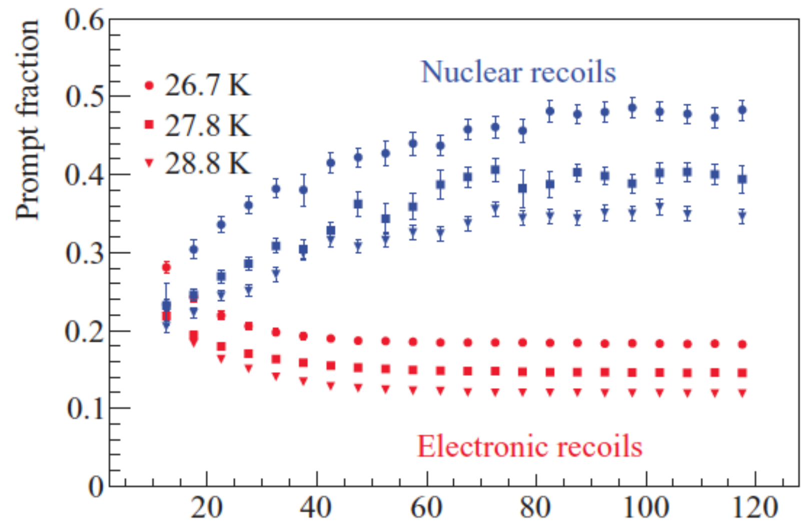
The Appeal of Liquid Neon (LNe)

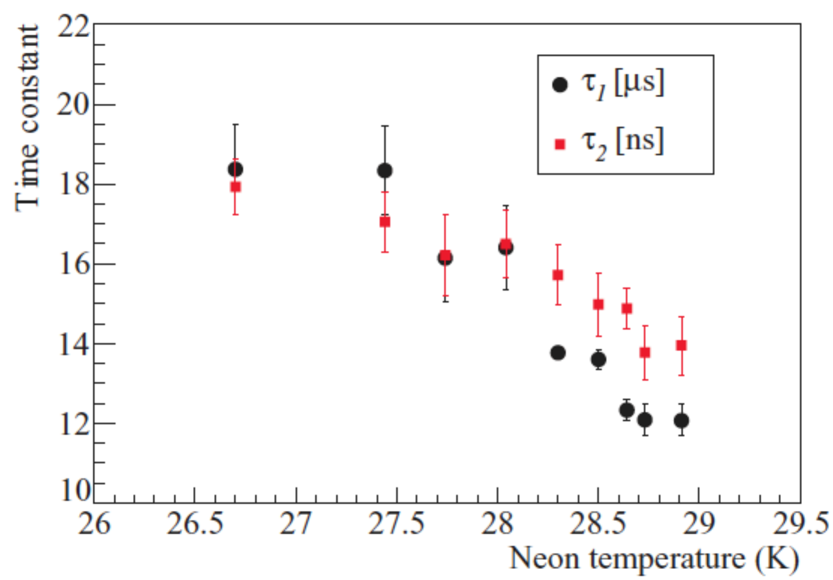
Signal yield: 3.5 photoelectrons/keV

Pulse shape discrimination measured;
Pressure/temperature dependence observed.



PHYSICAL REVIEW C **86**, 015807 (2012)

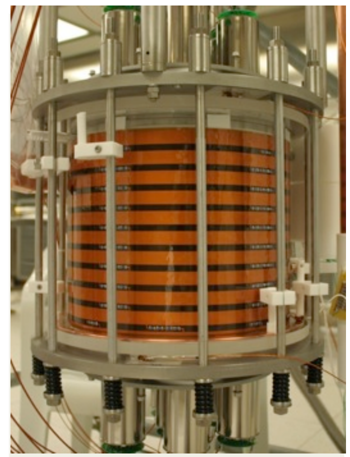
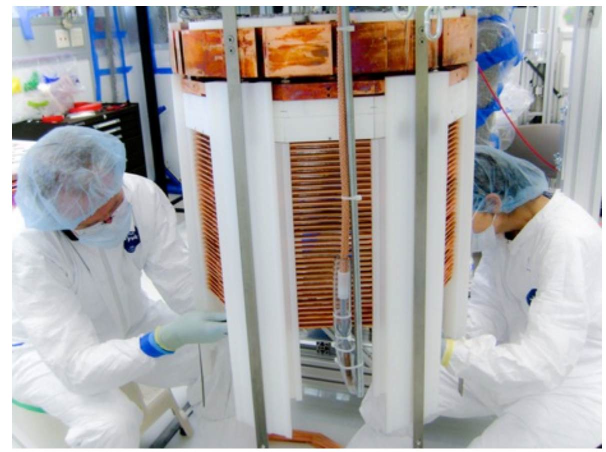




WIMP Direct Detection Technologies

- Dual-phase Ar (DarkSide, ArDM): Excellent electron recoil rejection, position resolution.

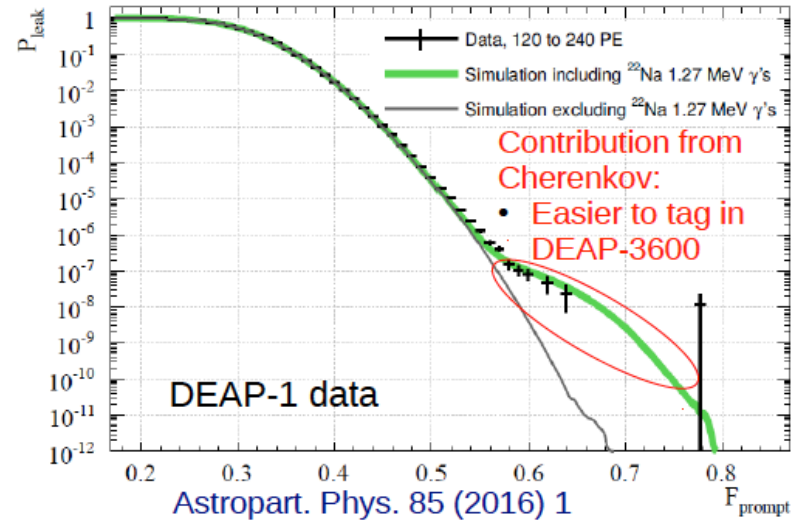
- Dual-phase Xe (XENON, LUX, Panda-X): Suitable target for both SI and SD, low energy threshold, excellent position resolution, self-shielding.
- Single-phase LAr, LXe (DEAP, CLEAN, XMASS): Simple and relatively inexpensive per tonne, pulse-shape discrimination and self-shielding.

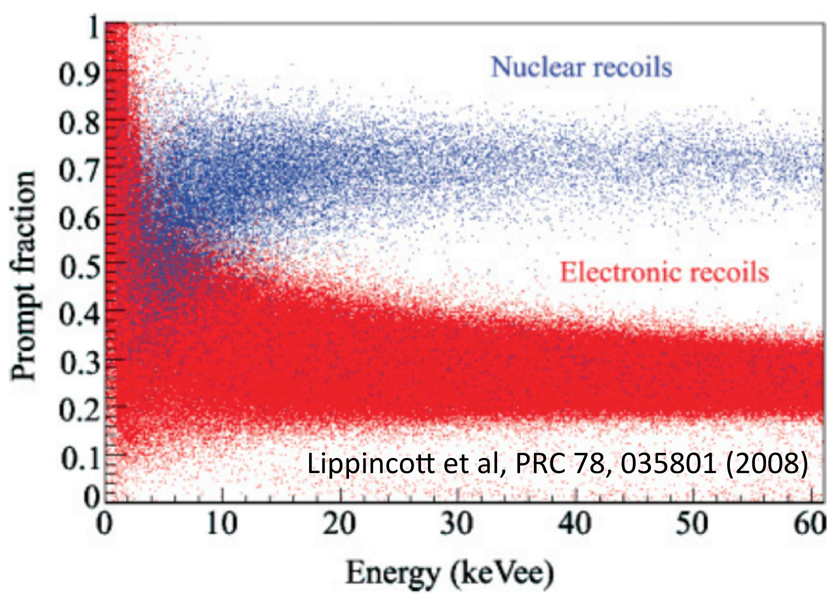
LAr Pulse Shape Discrimination

Discrimination based on the ratio of fast (singlet) scintillation light to the total.

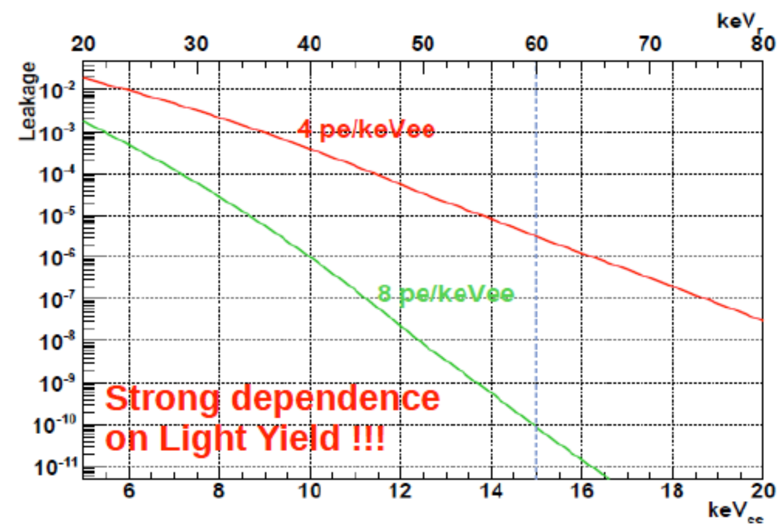
$$f_p = \frac{\int_{T_i}^{\xi} V(t)\,dt}{\int_{T_i}^{T_f} V(t)\,dt}$$



Astropart. Phys. 85 (2016) 1



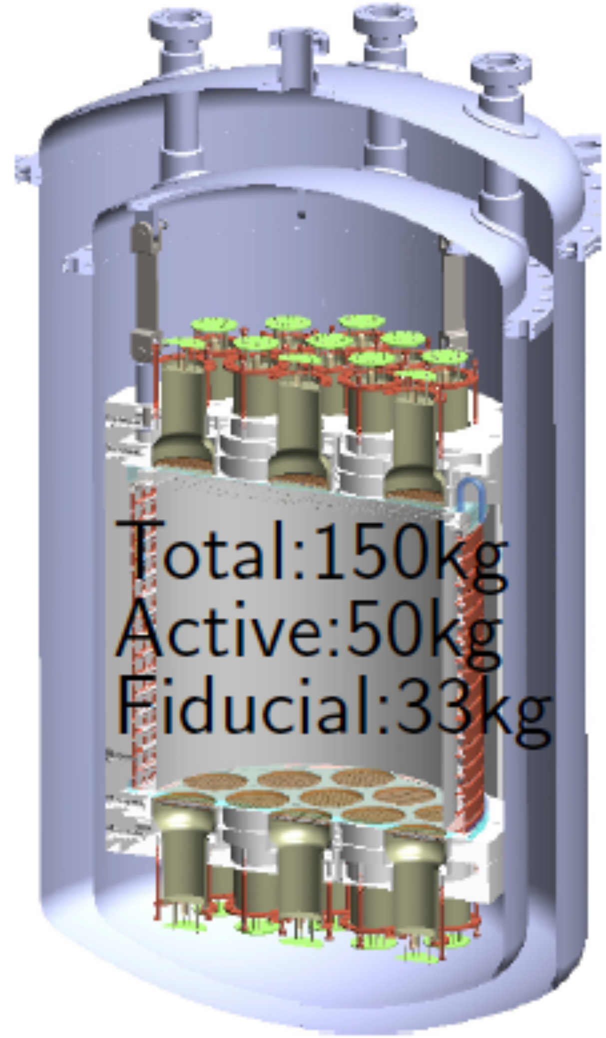
Lippincott et al, PRC 78, 035801 (2008)



M. Kuzniak, IDM 2018

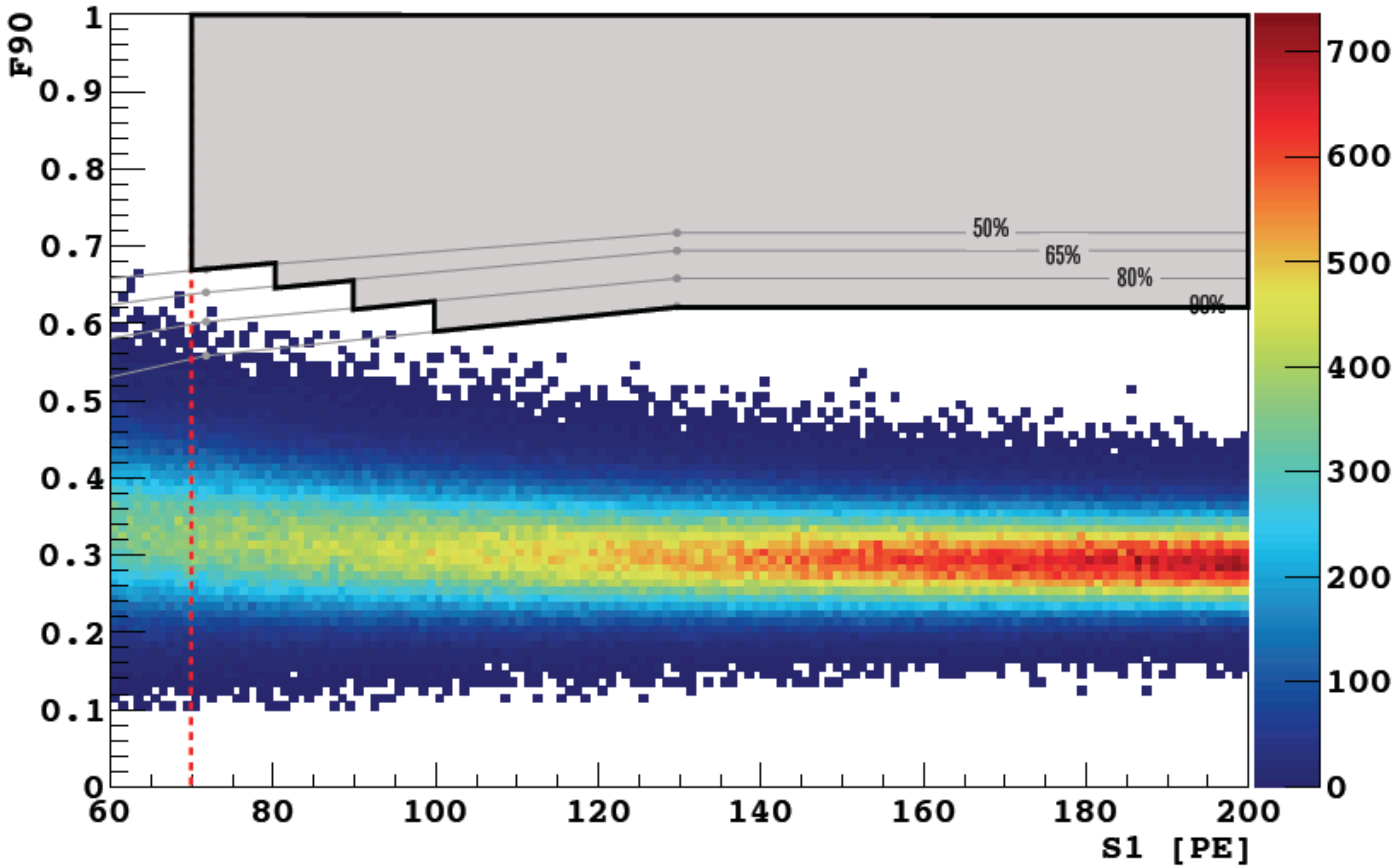
DarkSide-50

- A two-phase Argon detector.
- Funded by NSF, DOE, INFN.
- Uses both pulse shape and S2/S1 discrimination to reduce electron recoil backgrounds.
- Underground Ar, with ^{39}Ar reduced by factor > 100. Production at 0.5 kg/day.
- Located in Gran Sasso
- Projected sensitivity ~ 1 x 10^{-45} cm^2 at 100 GeV after 3 years live time.

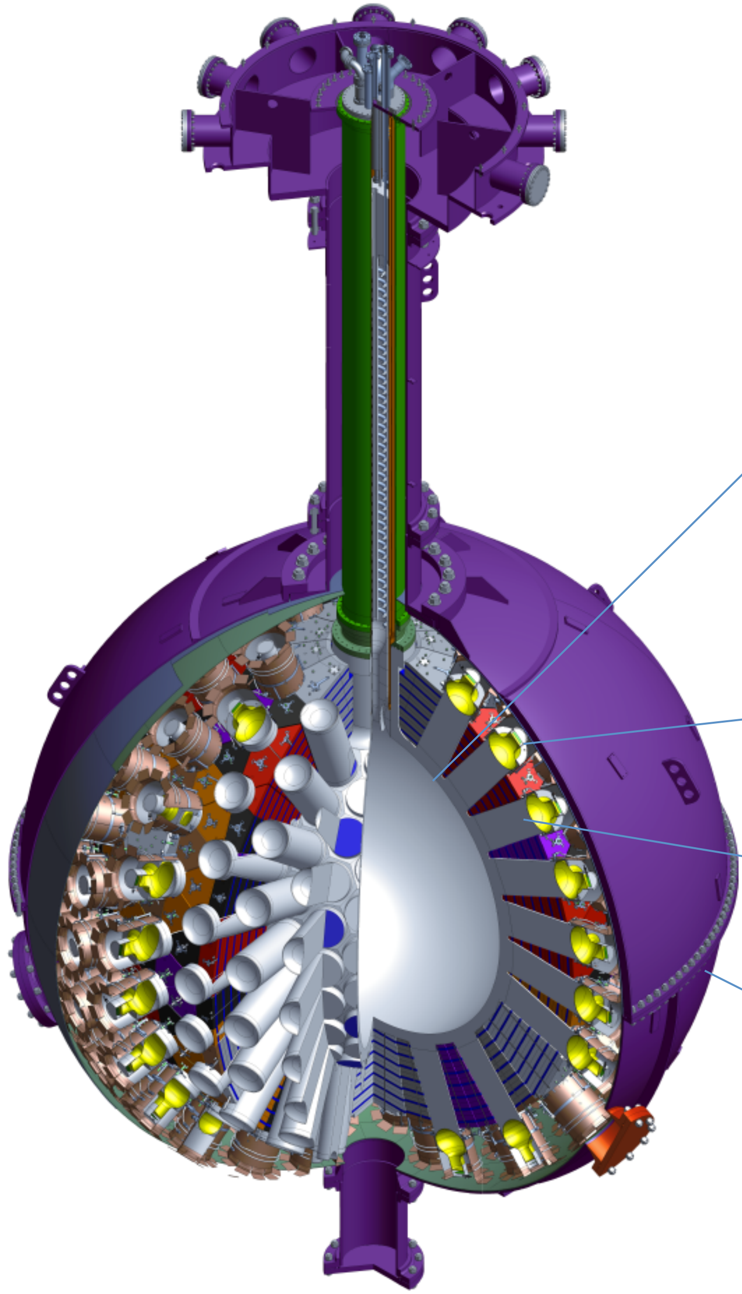


First Data from DarkSide-50 (280 kg days)

Slide from L. Grandi, UCLA Dark Matter 2014



DEAP-3600 Detector



3600 kg argon target
 (1000 kg fiducial)
in sealed ultraclean
Acrylic Vessel

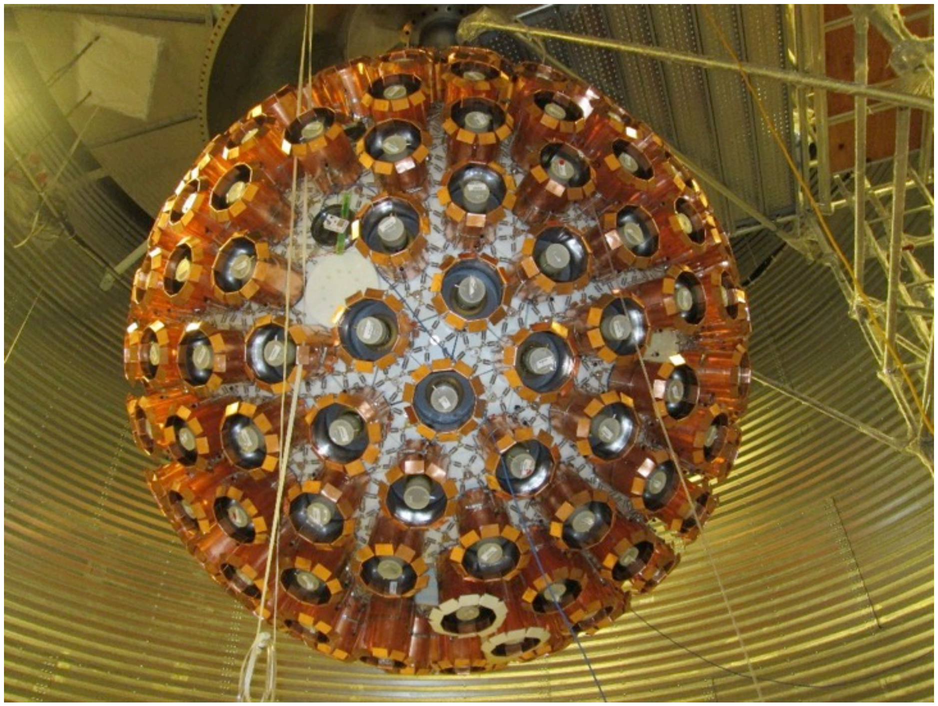
Vessel is “resurfaced”
in-situ to remove
deposited Rn daughters
after construction

255 Hamamatsu
 R5912 HQE PMTs 8-inch
 (32% QE, 75% coverage)

50 cm light guides +
 PE shielding provide neutron
moderation

Steel Shell immersed in 8 m
water shield at SNOLAB

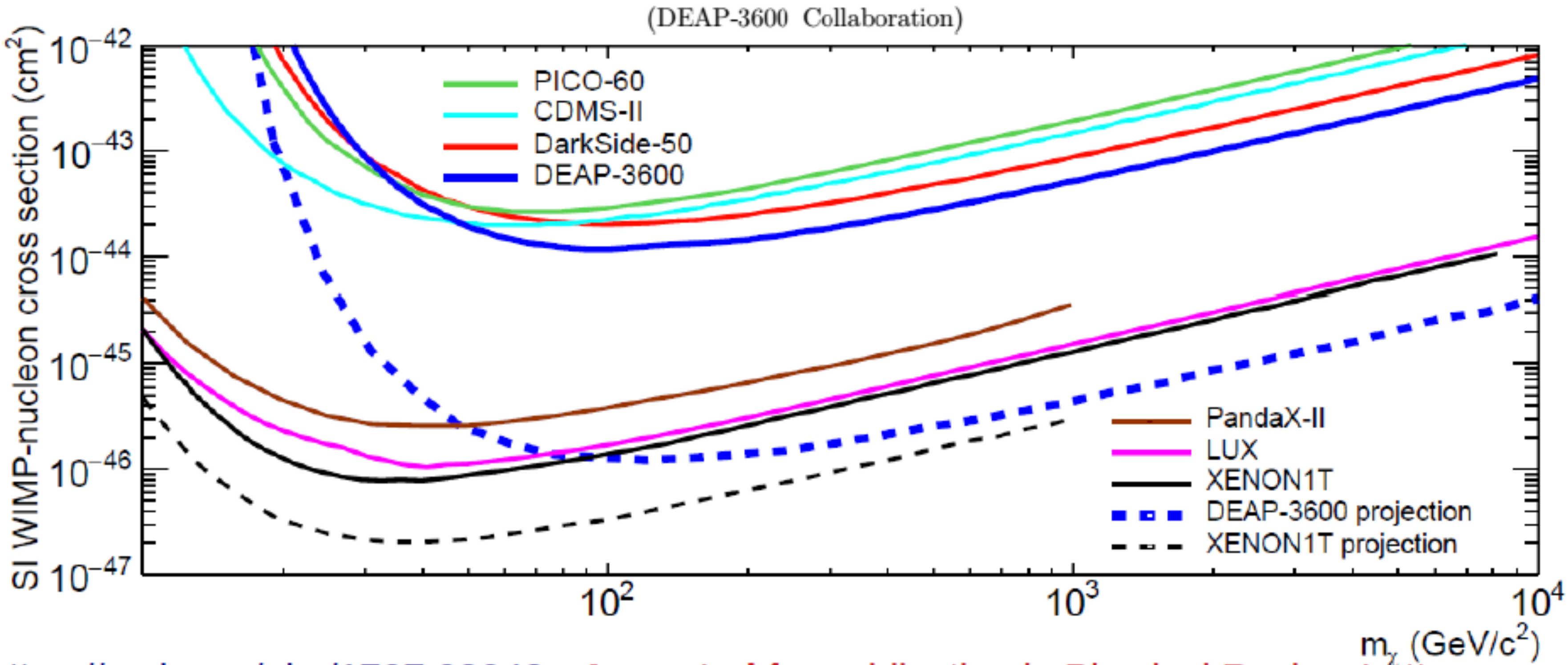
DEAP-3600 Detector at SNOLAB



Completed inner detector
255 8” R5912HQE PMTs
installed in shield tank

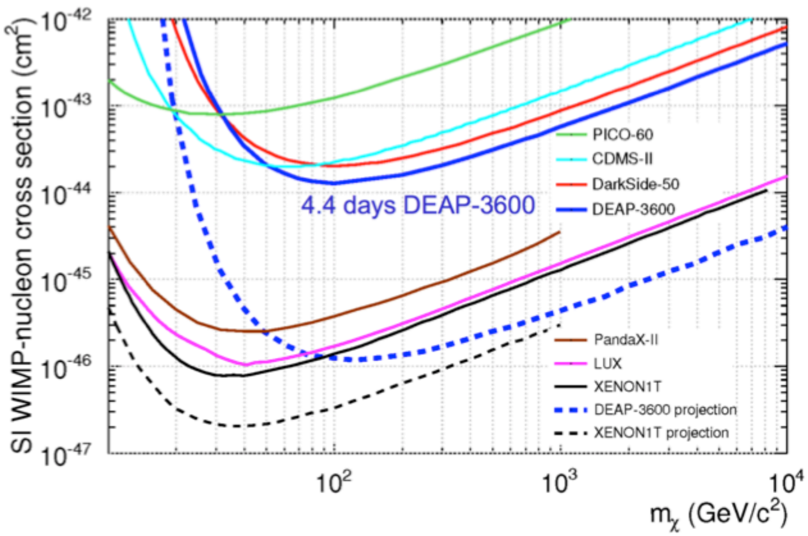
Steel Containment Sphere
in 8m diameter water shield tank

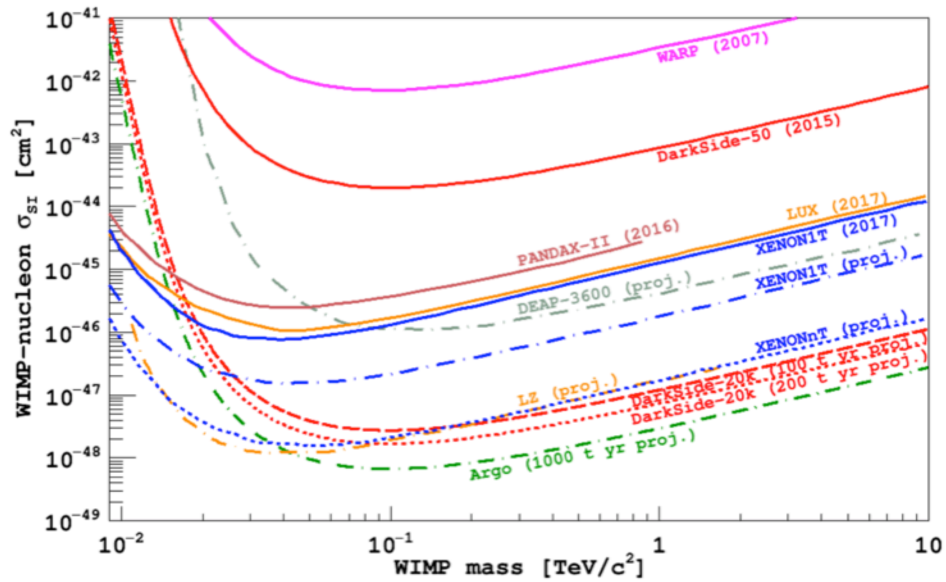
DEAP-3600 Detector at SNOLAB

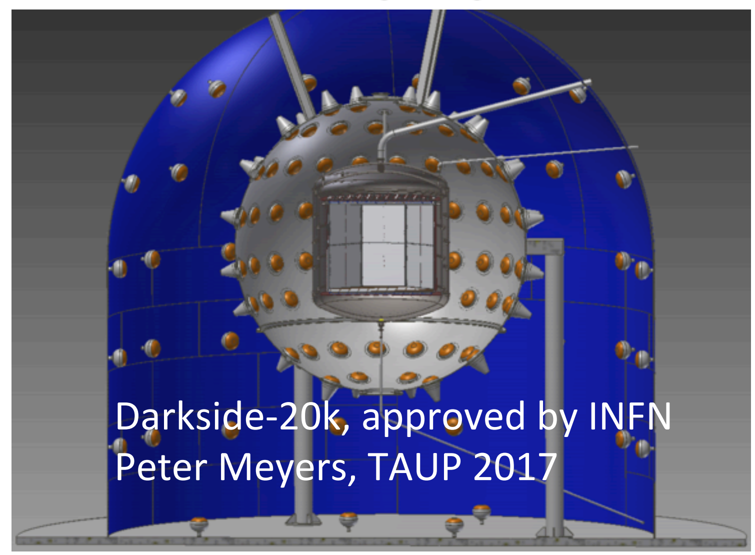


https://arxiv.org/abs/1707.08042 - **Accepted** for publication in Physical Review Letters

Liquid Argon:
DEAP-3600 & Darkside-20k





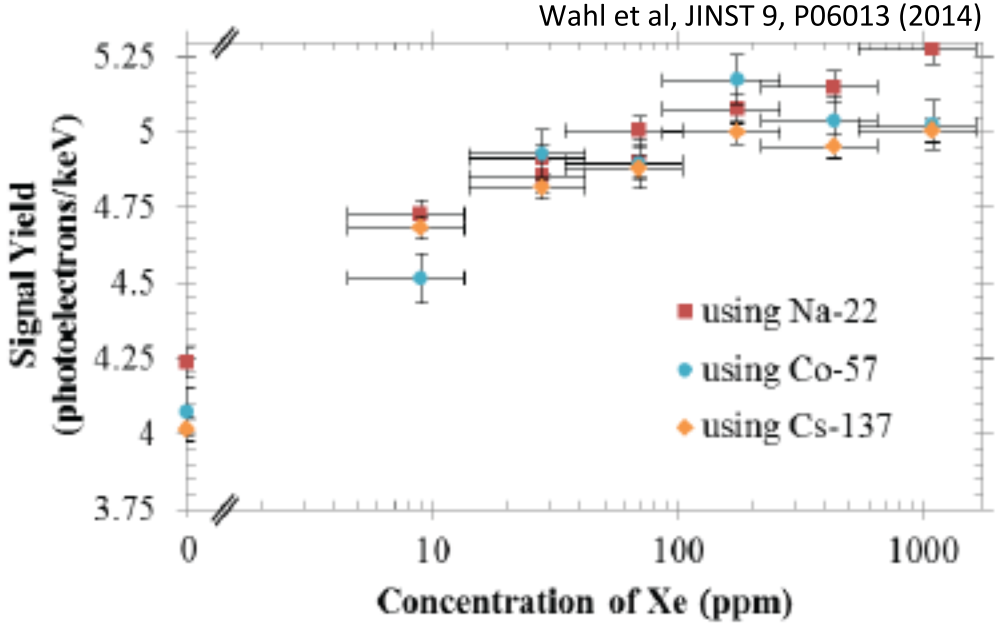


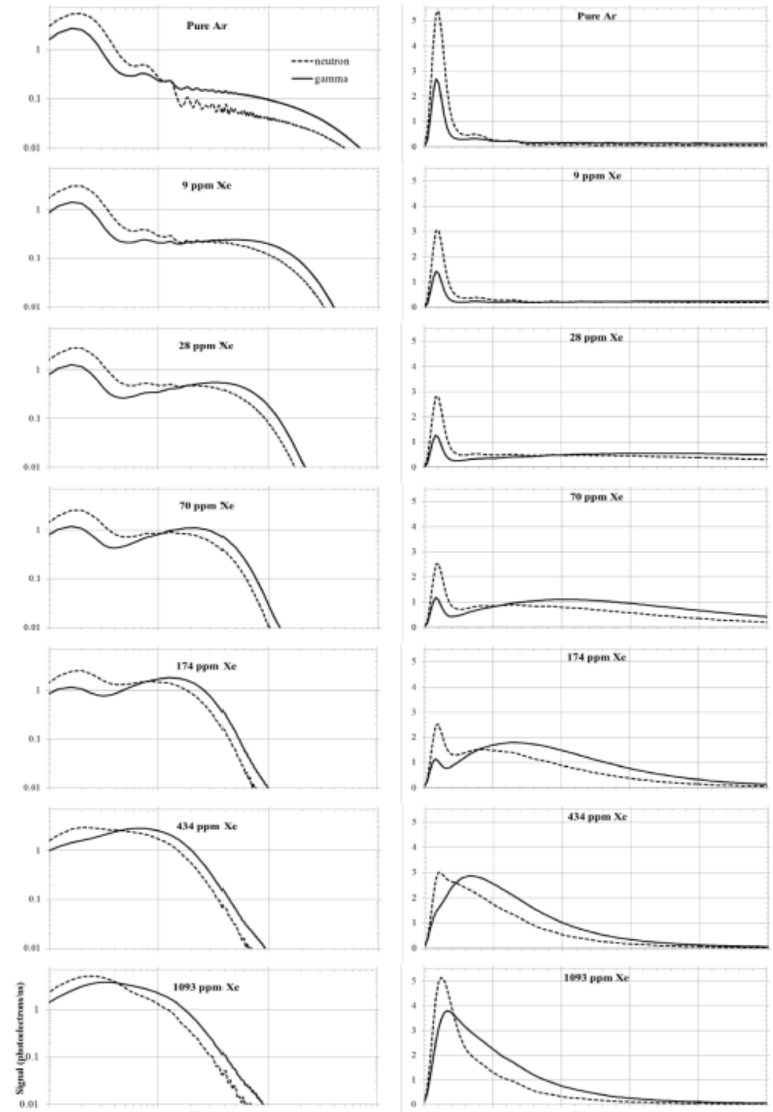
Doping LAr with Xe

Xe (up to ~ 0.1%) can be dissolved in LAr.
Advantages include:

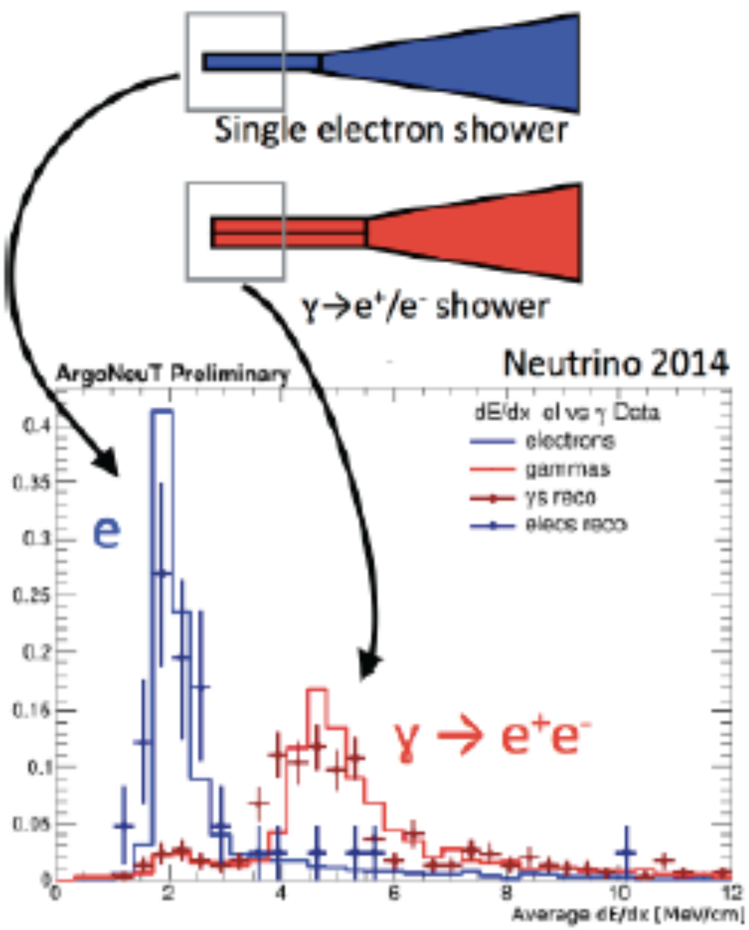
- Shifting scintillation to longer wavelengths (less scattering, direct PMT readout?)
- Larger signal yields
- Faster scintillation
- Better scintillation energy resolution

Wahl et al, JINST 9, P06013 (2014)



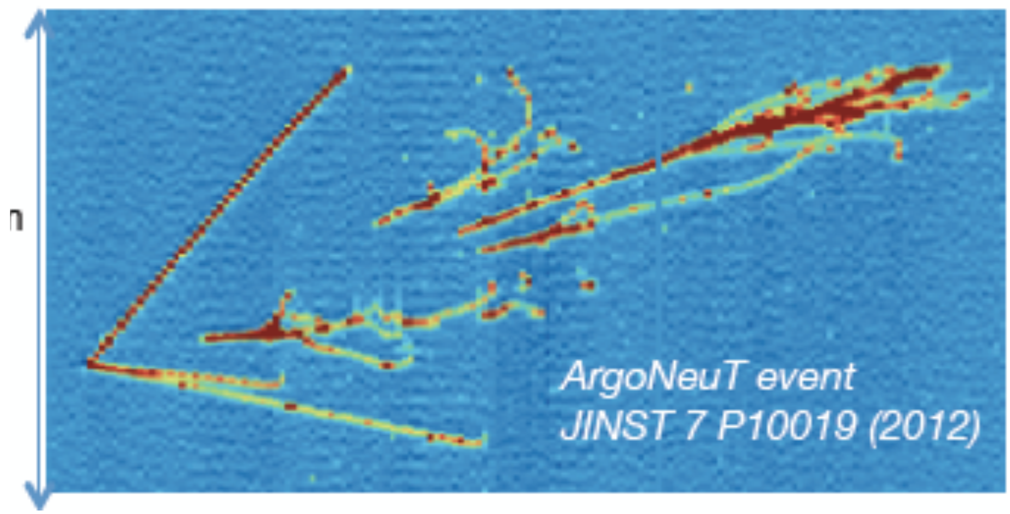


LAr-based Neutrino Detection



- Excellent 3-D imaging
- Excellent energy measurement
- Particle ID by dE/dx, event topology
- Scalable to large detectors

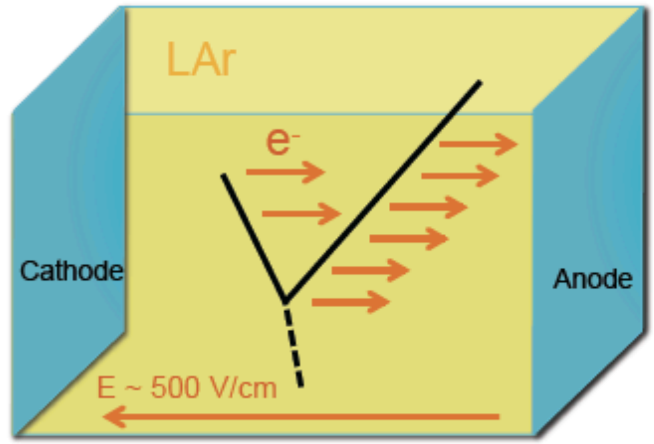
Challenges: large cryogenic vessels, liquid purification, high voltages, electronics, scintillation light collection.



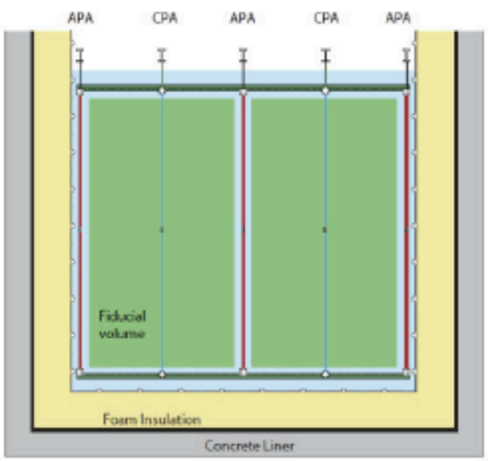
(E. Worcester, Neutrino 2018)

DUNE Far Detector

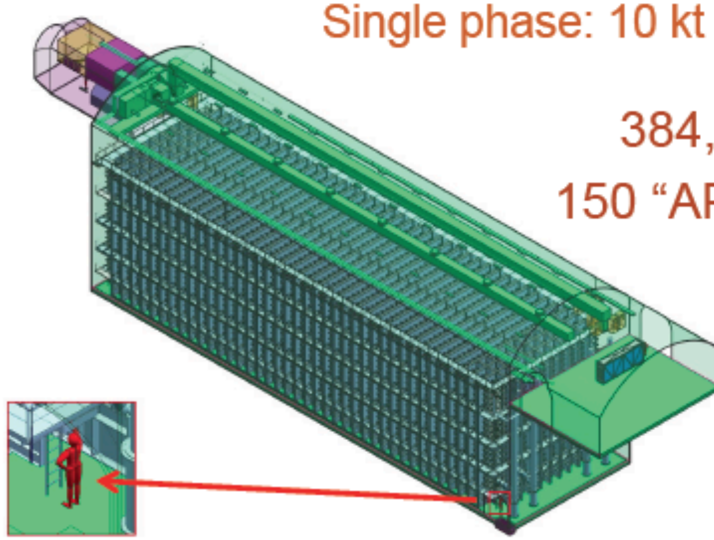
- 4 10-kt (fiducial) liquid argon TPC modules
- **Single-** and dual-phase detector designs (1st module will be single phase)
- Integrated photon detection
- Modules will not be identical



Single phase: modular wire-plane readout



Single phase: 10 kt module



384,000 readout wires

150 “APAs” (2.3 m x 6 m)

12 m high

15.5 m wide

58 m long

DUNE Far Detector

(E. Worcester, Neutrino 2018)

- 4 10-kt (fiducial) liquid argon TPC modules
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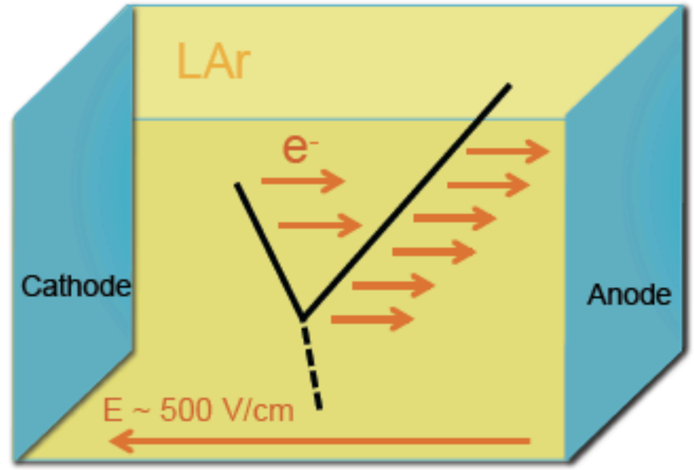
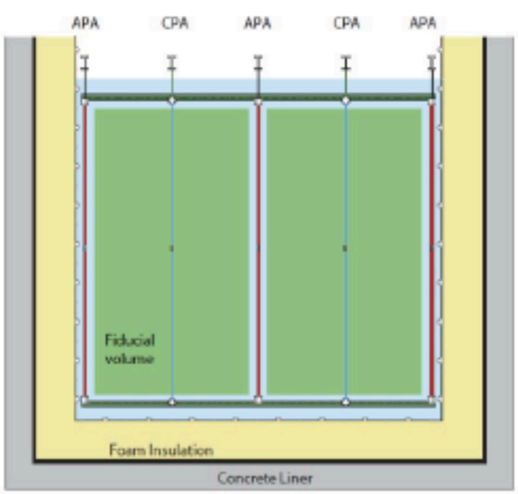
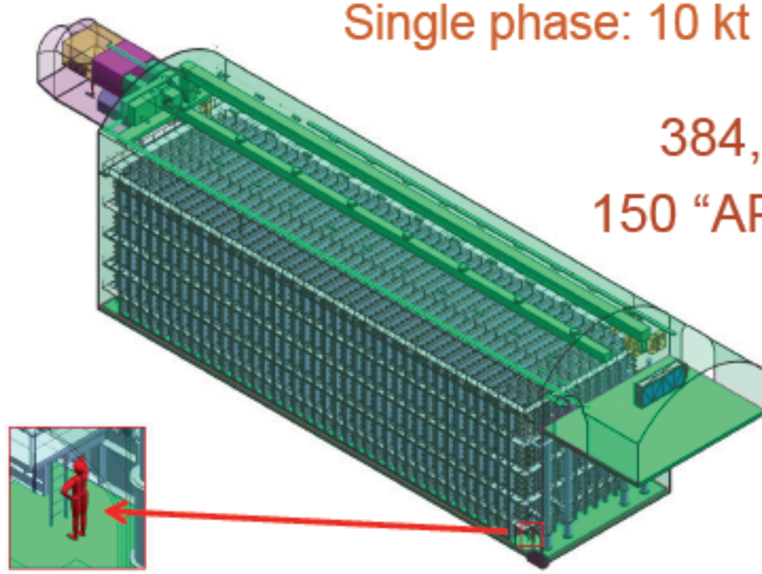


Single phase: modular wire-plane readout



Single phase: 10 kt module



384,000 readout wires

150 "APAs" (2.3 m x 6 m)

12 m high

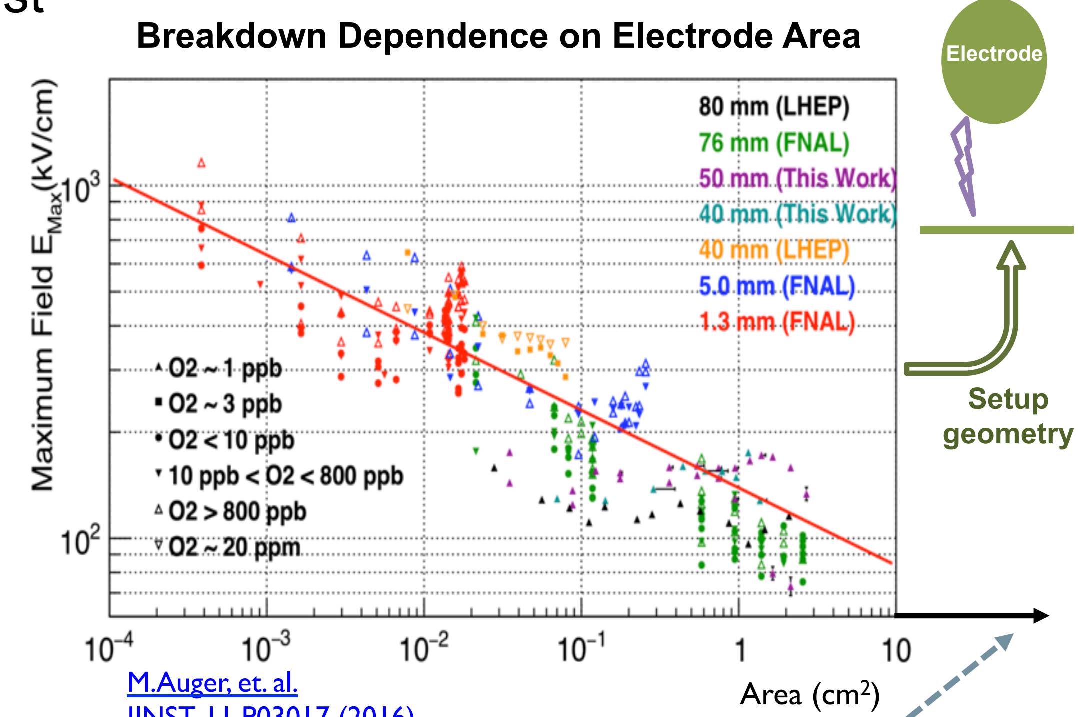
15.5 m wide

58 m long

State of the field for breakdown in LAr

Studies in LAr[1,2] & LHe[3] suggest breakdown depends on:

- Electrode spacing
- Electrode stressed area
- Electrode volume
- Liquid purity
- Electrode geometry
- Surface finish



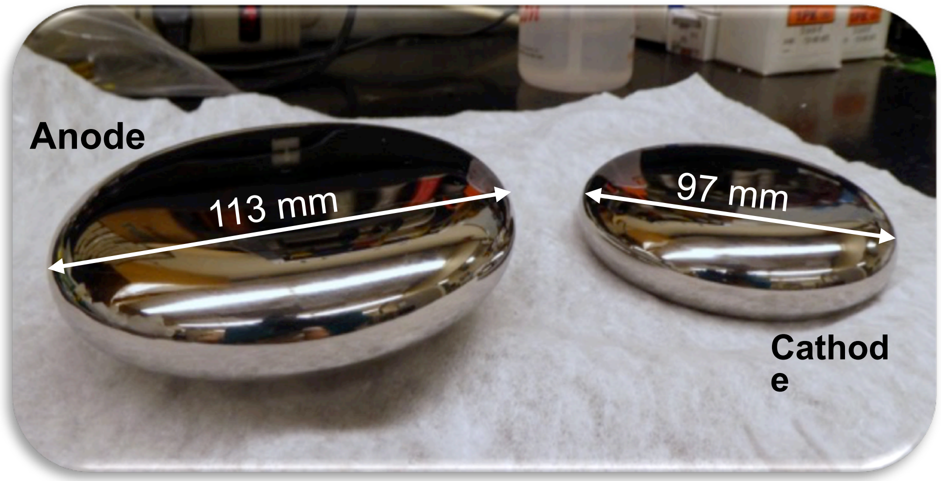
M.Auger, et. al. JINST 11 P03017 (2016)

Design for the LZ cathode stressed area (500 cm²)

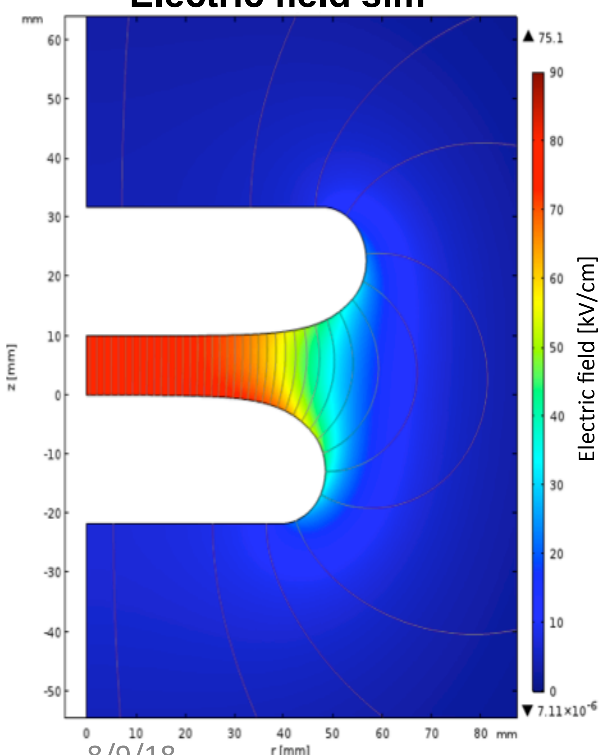
[1]S. Lockwitz, et al., arXiv:1408.0264v1
[2]M.Auger, et. al. JINST 11 P03017 (2016)
[3]J. Gerhold, et al., Cryogenics 34.7 (1994)

Rogowski electrodes

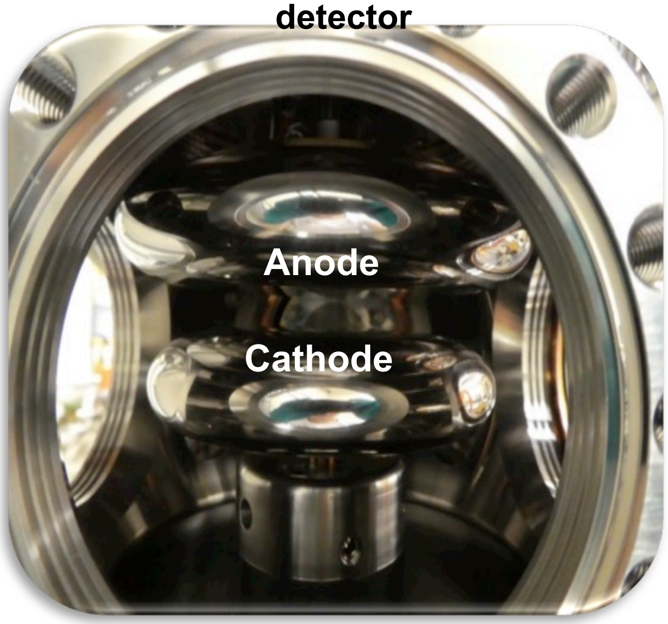
- Electrodes designed to have highest field near the center and maintain a nearly uniform field over a large area



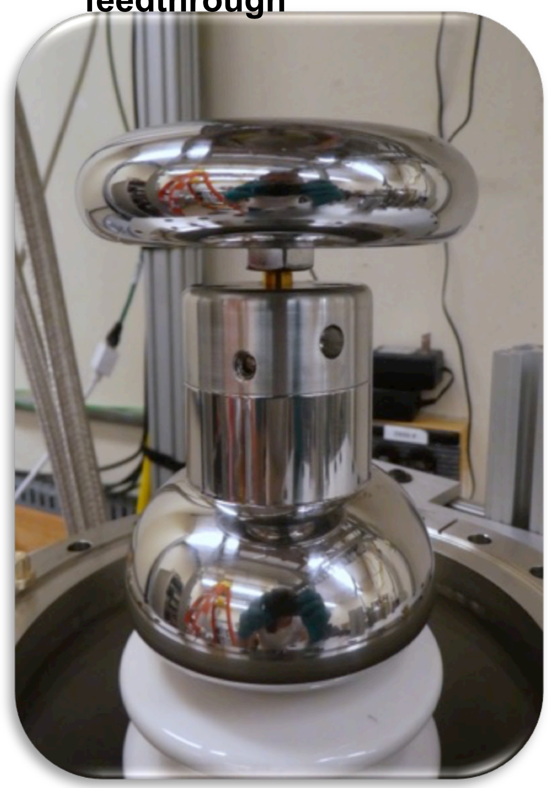
Electric field sim



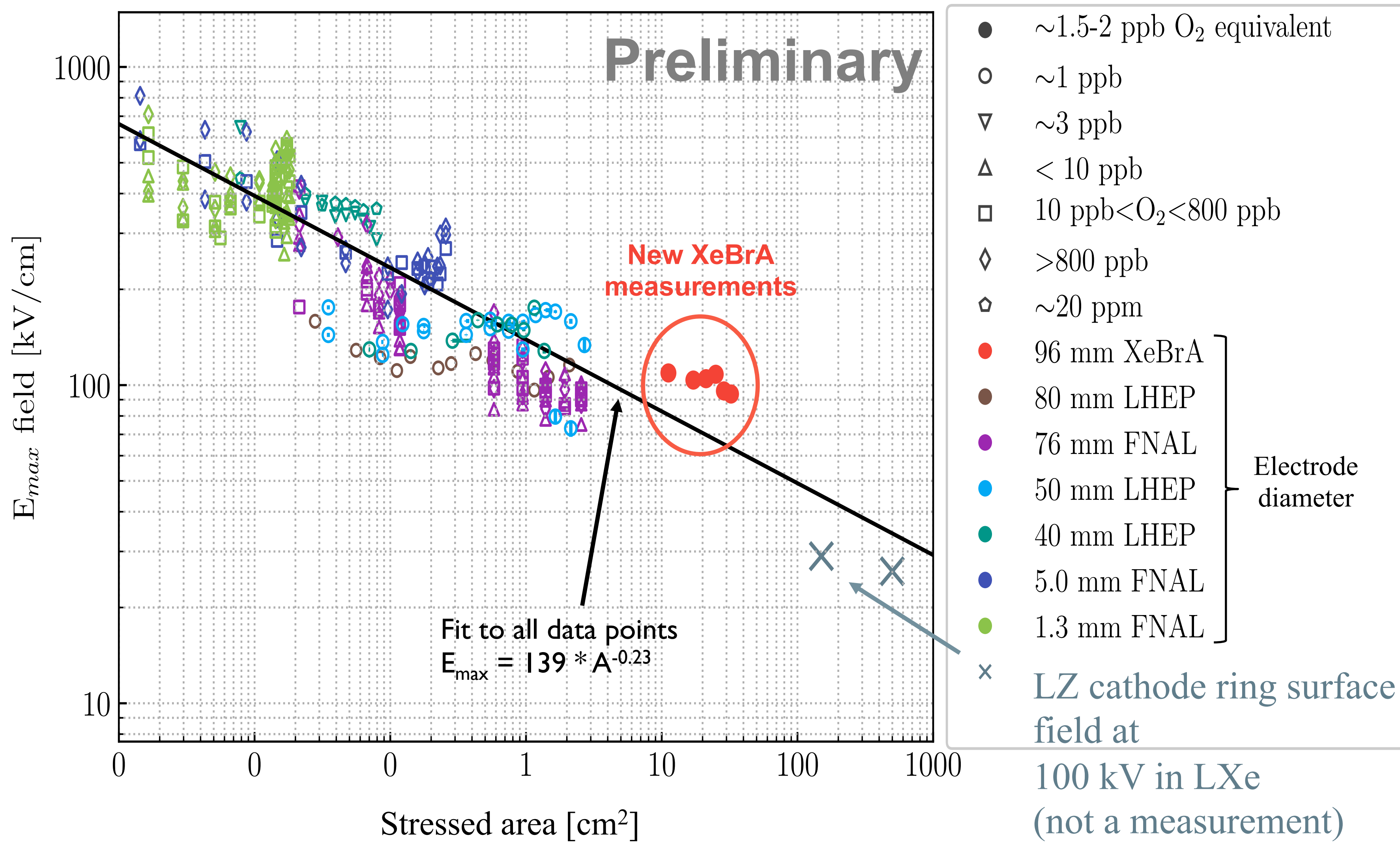
Location of electrodes in the detector



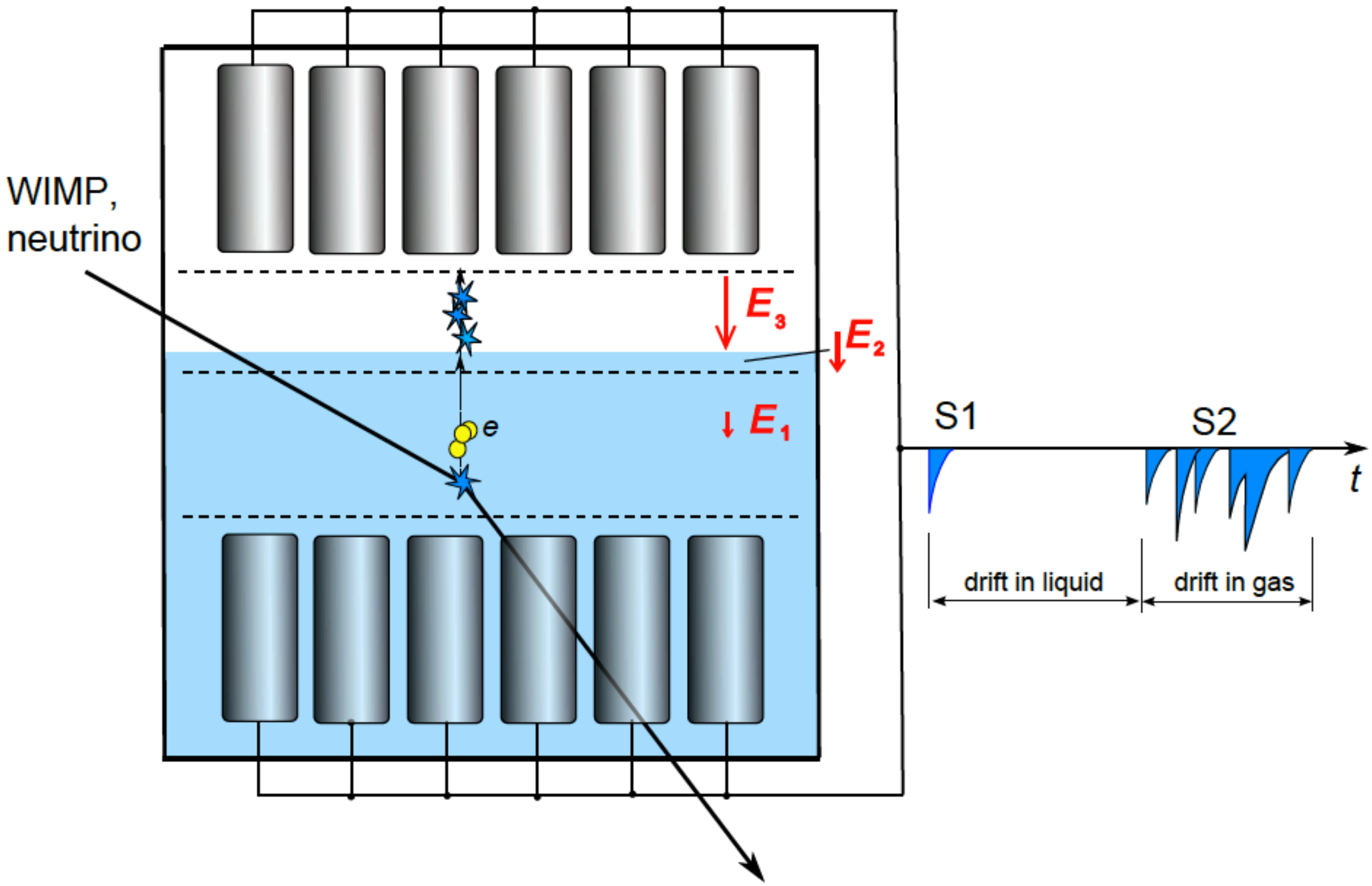
Cathode + HV feedthrough



Breakdown field vs area in argon run1

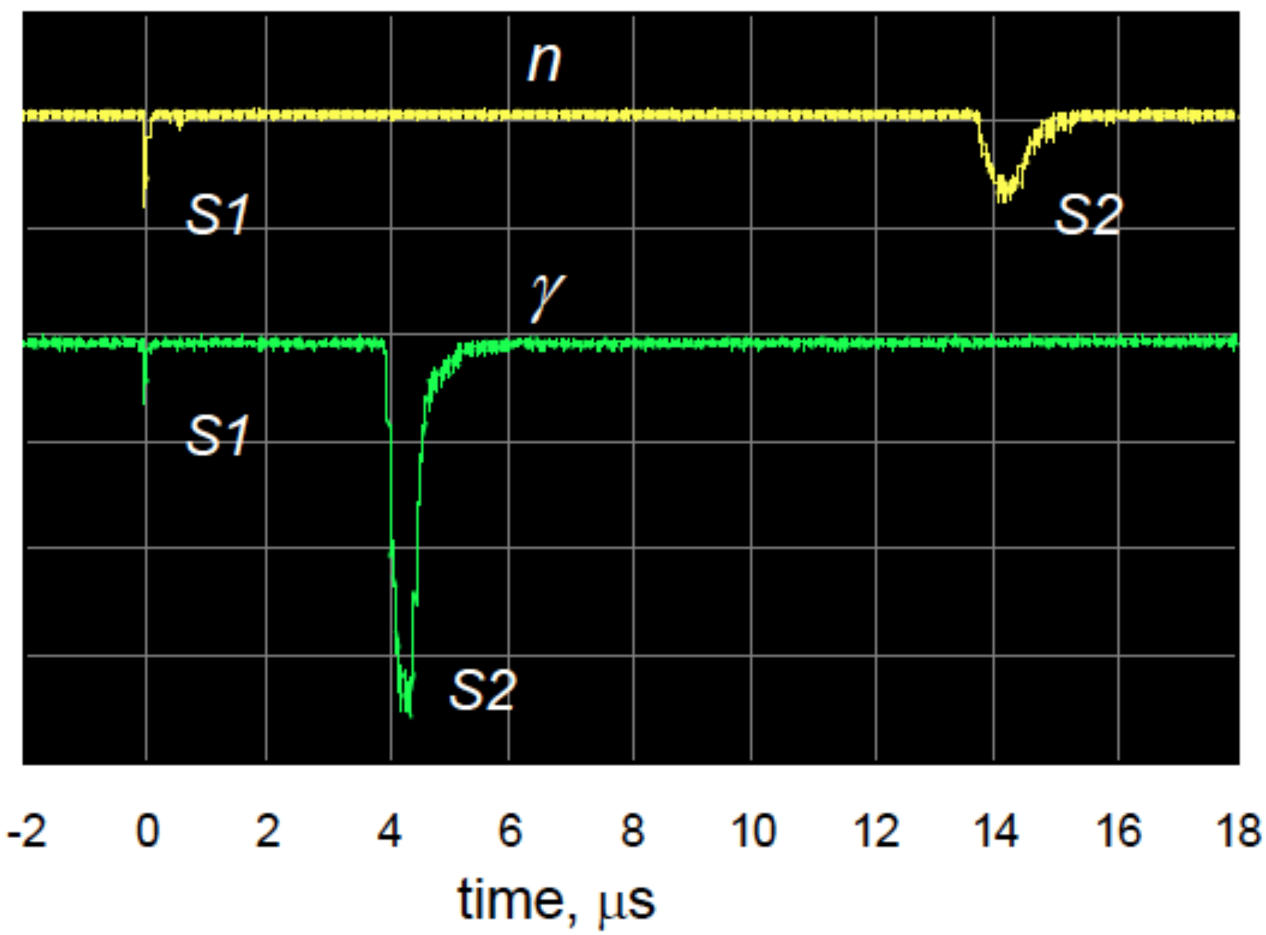


Operating Principle of a Two-Phase Detector



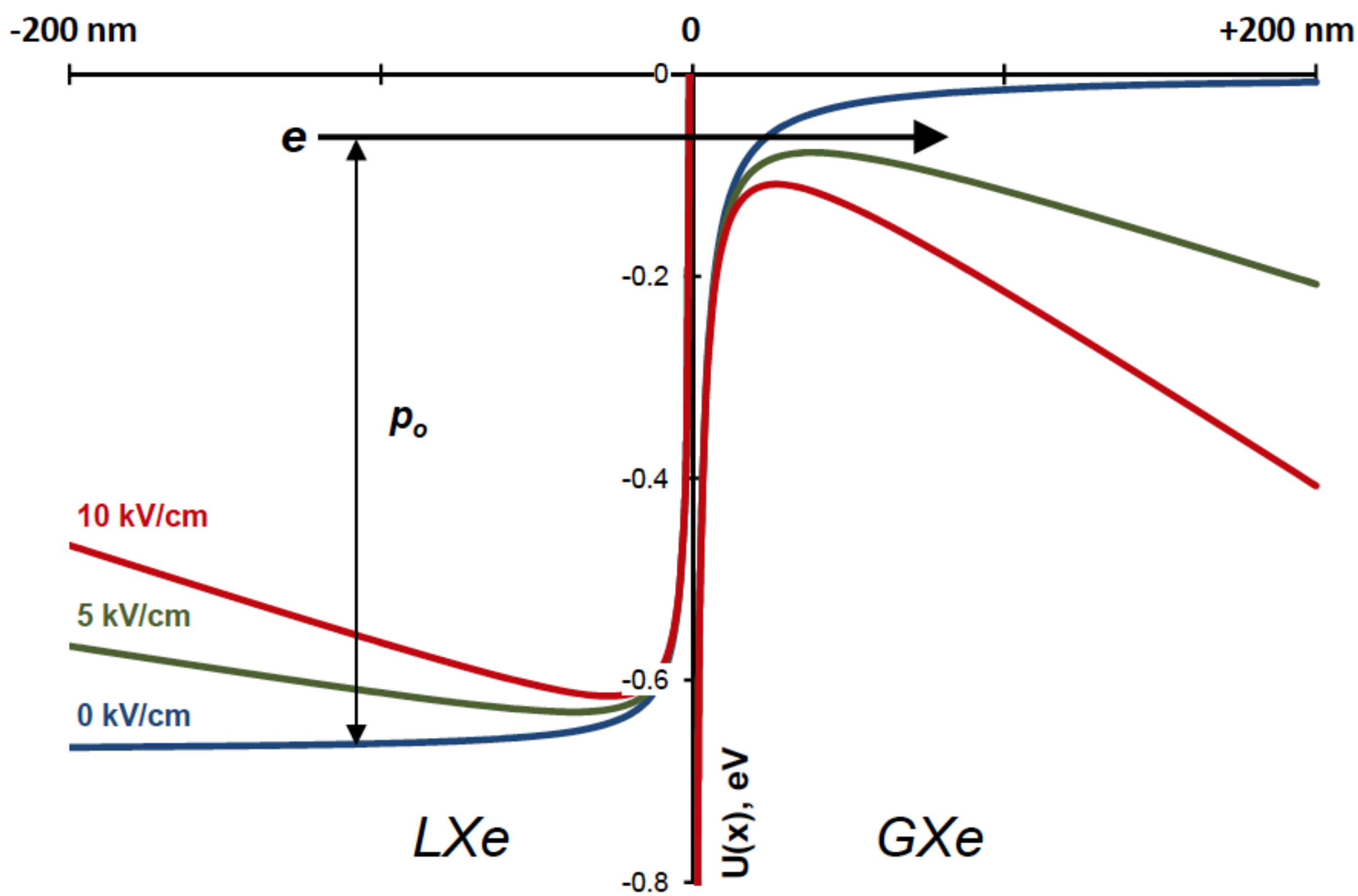
From V. Chepel and H. Araujo, "Liquid noble gas detectors for low energy particle physics", arXiv:1207.2292

Operating Principle of a Two-Phase Detector



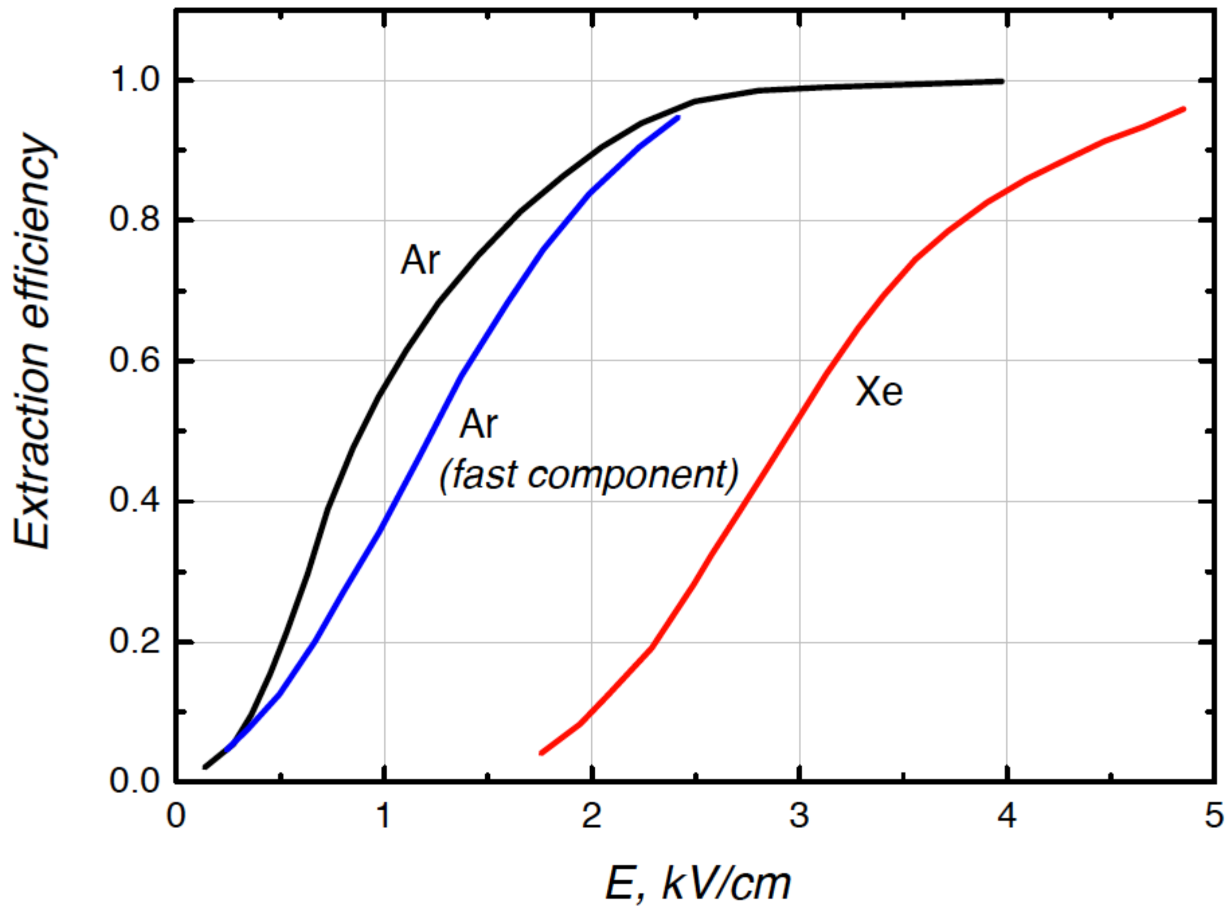
From ZEPLIN-III collaboration, D. Akimov et al., Astropart. Phys. 27, 46 (2007).

Electron Extraction from Liquid Xenon



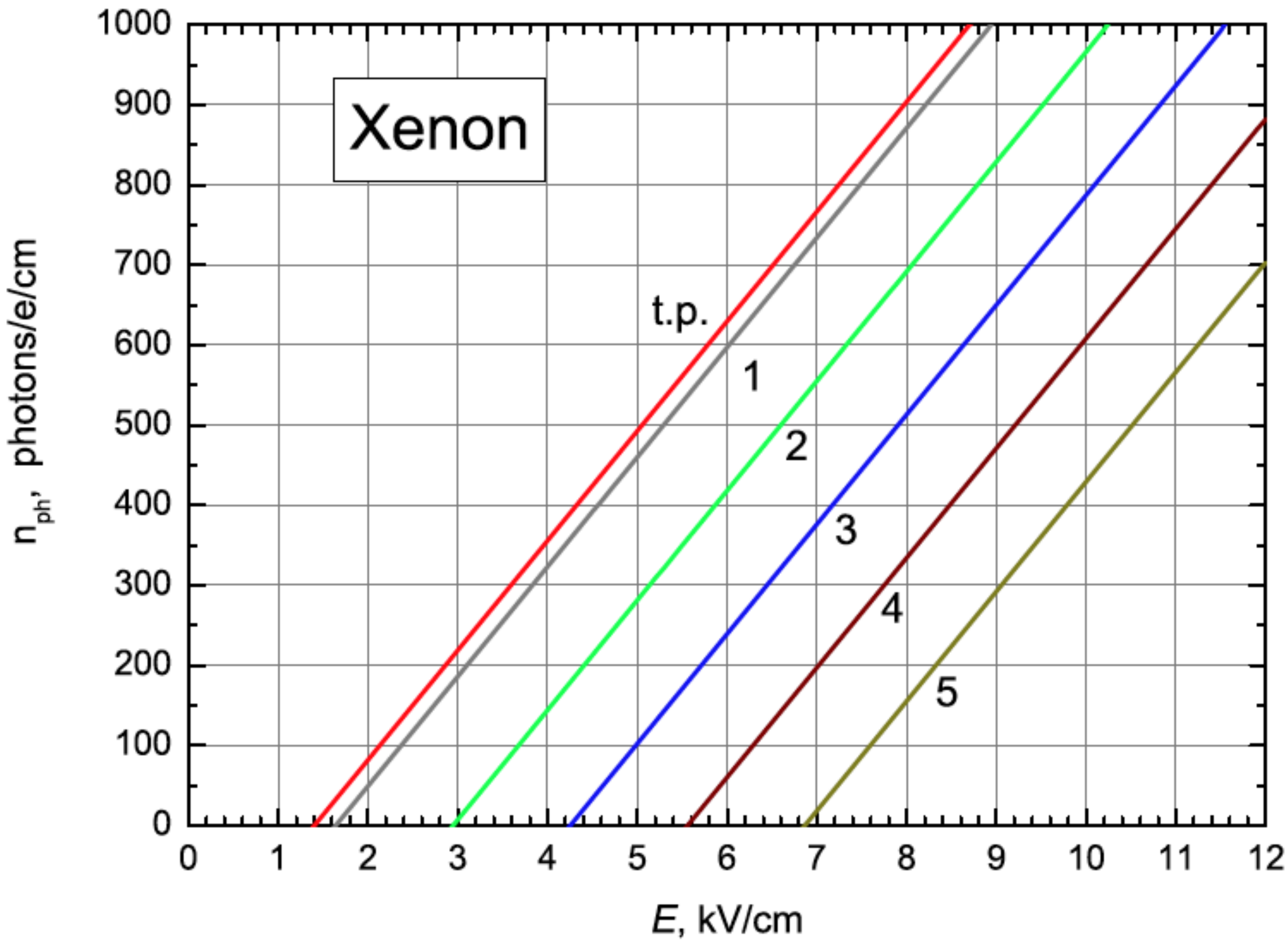
From V. Chepel and H. Araujo, "Liquid noble gas detectors for low energy particle physics", arXiv:1207.2292

Electron Extraction



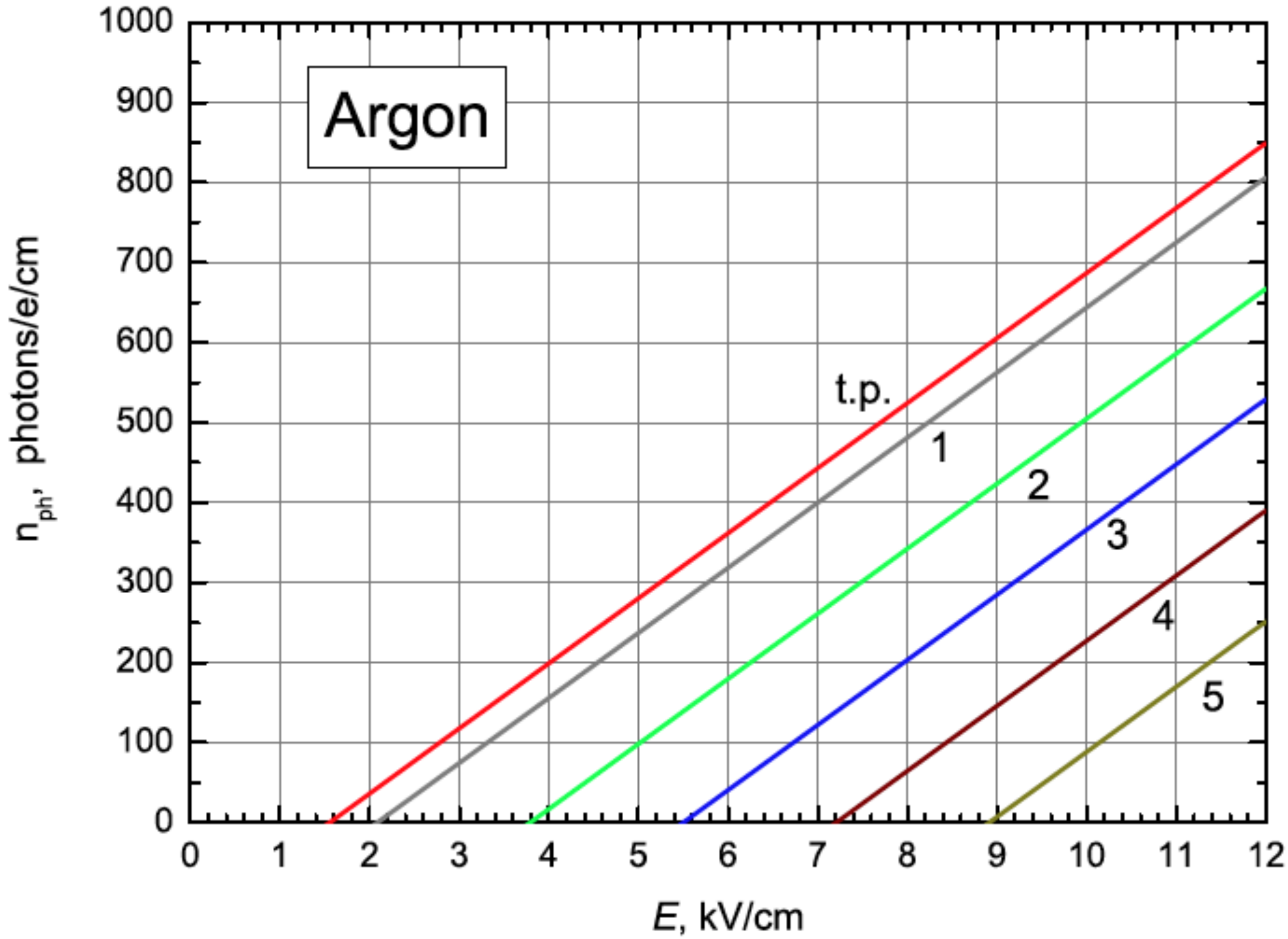
From V. Chepel and H. Araujo, "Liquid noble gas detectors for low energy particle physics", arXiv:1207.2292

Electroluminescence



From V. Chepel and H. Araujo, "Liquid noble gas detectors for low energy particle physics", arXiv:1207.2292

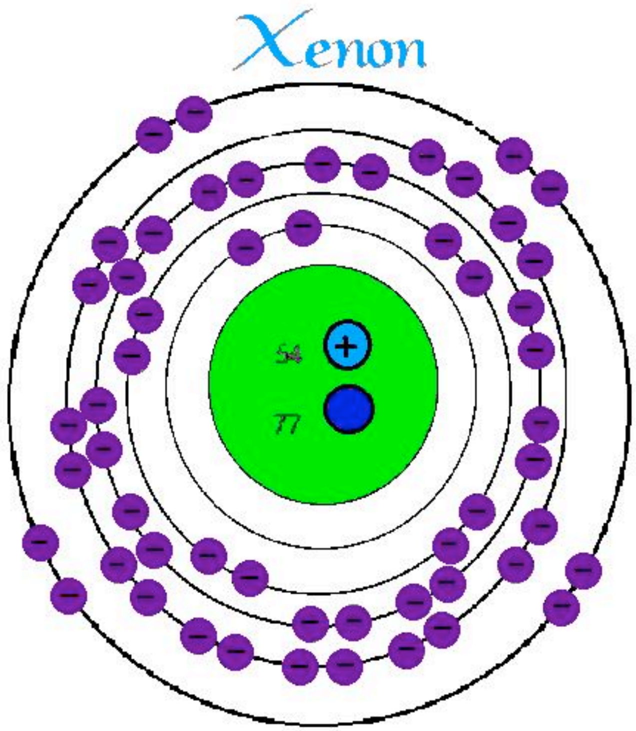
Electroluminescence



From V. Chepel and H. Araujo, "Liquid noble gas detectors for low energy particle physics", arXiv:1207.2292

The appeal of liquid xenon

- ✓ Density = 3 g/cc – efficient stopping and capture of gamma rays.
  - Photoabsorption dominates Compton scattering up to 300 keV (Z = 54)
  - Strong gamma stopping power: 6 cm attenuation length at 1 MeV
- ✓ High scintillation and ionization yields
  - Bright and fast scintillation yield from gammas: 42 photons / keV; 4 and 27 ns components.
- ✓ Ratio of scintillation and ionization is different for gamma rays versus neutrons
- ✓ High purity attainable
  - Long (> 1 m) electron drift lengths readily achievable
  - Electrons drift at 2 mm / microsecond under ~ 1 kV / cm drift fields
- ✓ 'Easy' cryogenics
  - Detectors typically operate at 178 K and 2 bar pressure.
  - Liquid nitrogen or mechanical coolers

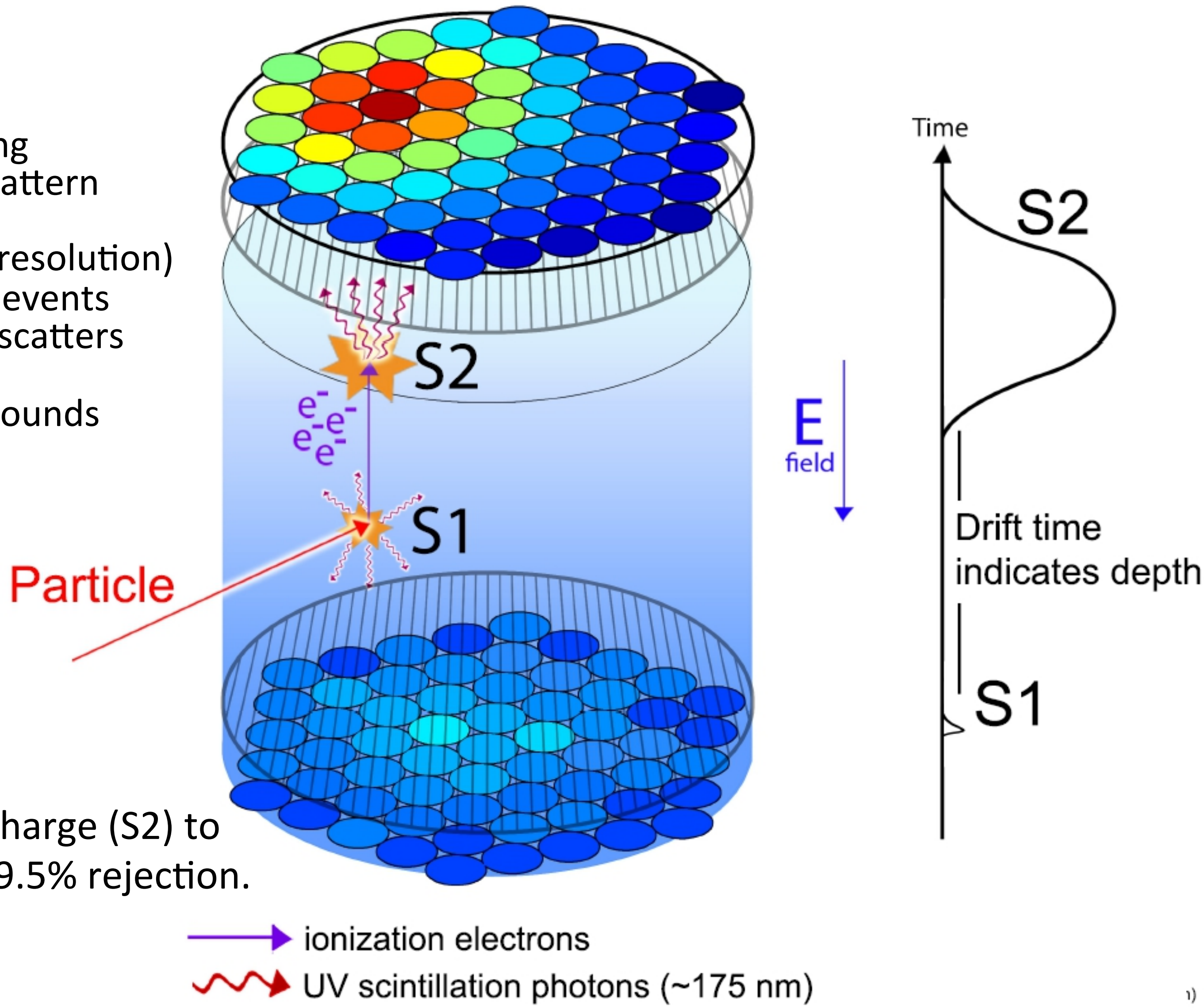


Two-phase Xenon WIMP Detectors

Z position from S1 – S2 timing
X-Y positions from S2 light pattern

Excellent 3D imaging (~mm resolution)
- eliminates edge events
- rejects multiple scatters

Gamma ray, neutron backgrounds reduced by self-shielding



Reject gammas, betas by charge (S2) to light (S1) ratio. Expect > 99.5% rejection.

Self-Shielding

In early 2000's, neutrino experiments (Super-K, SNO, KamLAND, Borexino) have demonstrated that extremely low background levels may be achieved by using an ultrapure liquid, surrounded by photomultipliers, with the outer part of the detector Shielding the inner part from radioactivity.

A realization: Liquefied noble gases may be used in the same way, with high light yields (like organic scintillator) but without the carbon-14. Such experiments may reach low enough energy thresholds to search for dark matter interactions. Noble liquids may be purified to an exceptional degree. Helium, neon, and xenon are radiopure.

First conceptions:
CLEAN (McKinsey and Doyle, arXiv:astro-ph/9907314,
McKinsey and Coakley, arXiv:astro-ph/0402007)
XMASS, Y. Suzuki, arXiv:hep-ph/0008296.

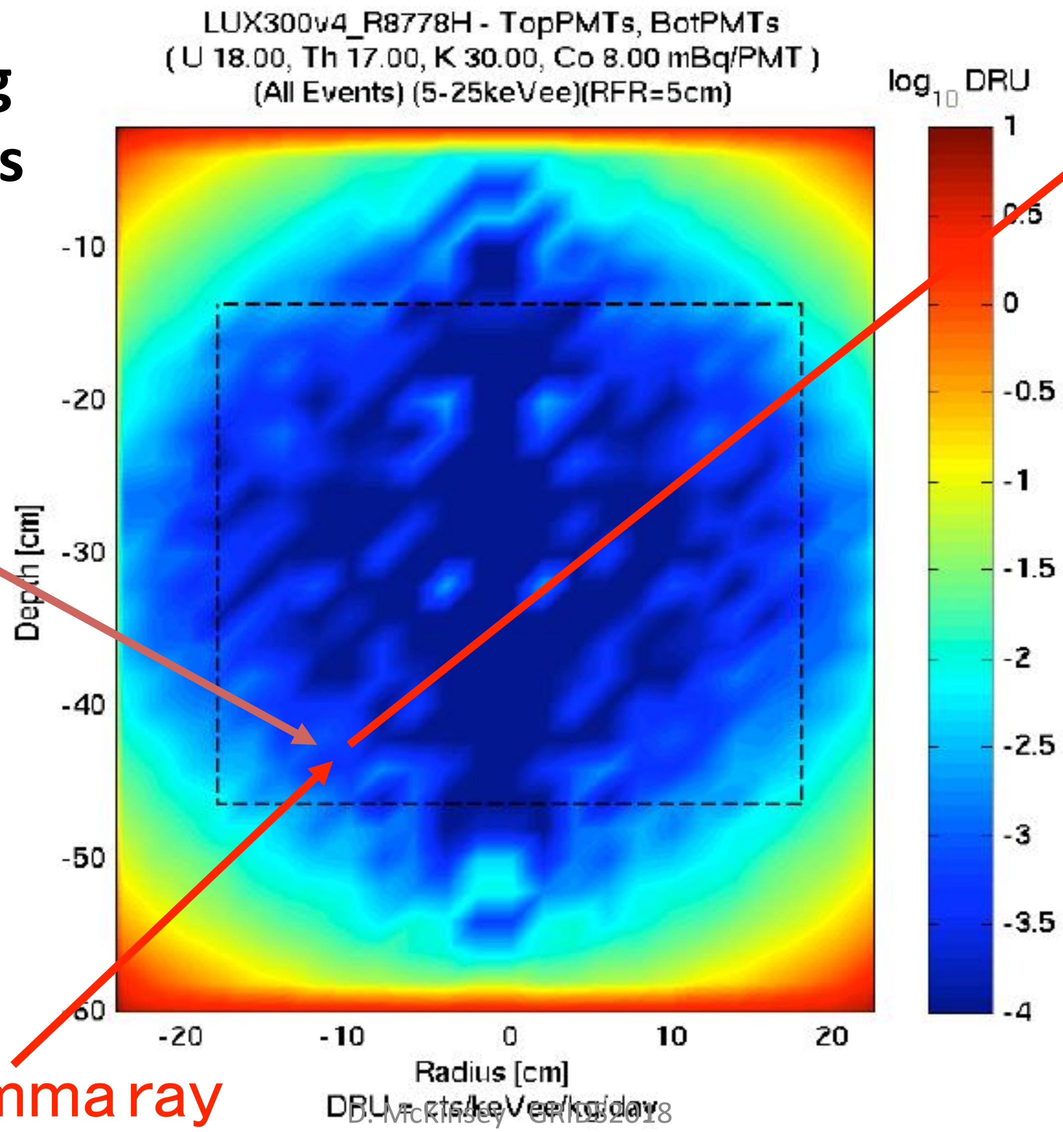
Much skepticism at the time: Can such detectors really have low enough internal backgrounds, low enough energy threshold, good enough position reconstruction?

In the years since, small, precise, clever detectors → Big, just smart enough detectors.

Kinematics alone provides strong rejection

Self-shielding is what makes LUX work

~ keV deposition



Must cross full volume without interacting again

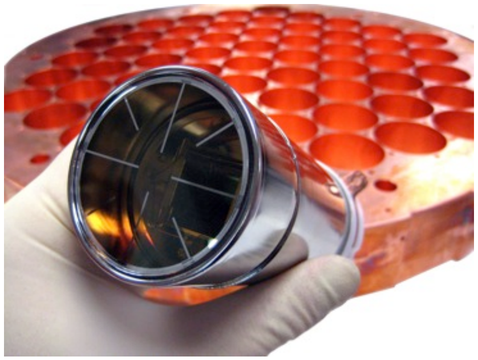
~ MeV gamma ray

Light Collection in Liquid Xenon

A key development: cryogenic PMTs with fused silica windows

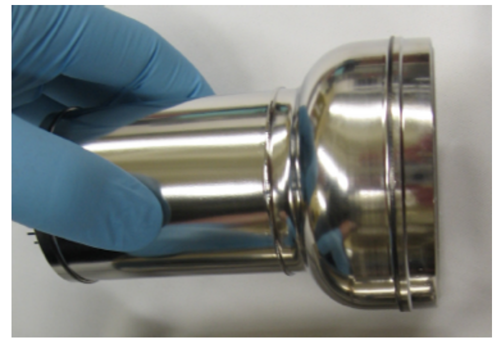
- PMT window passes 178 nm light
- No need for wavelength shifter
- 28-35% quantum efficiency
- Very low radioactivity

R8778 (5 cm round)



(5 cm hexagonal)

R11410 (8 cm round)

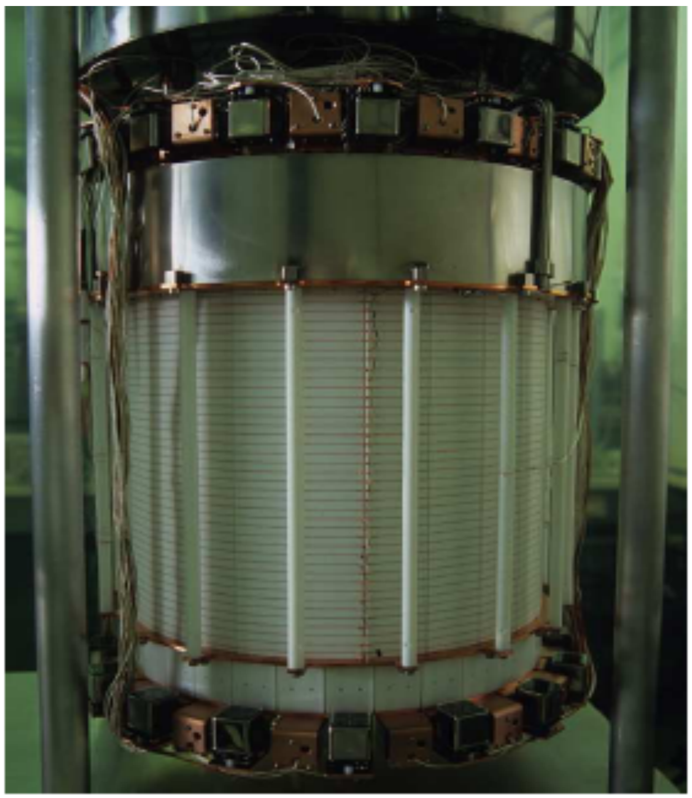


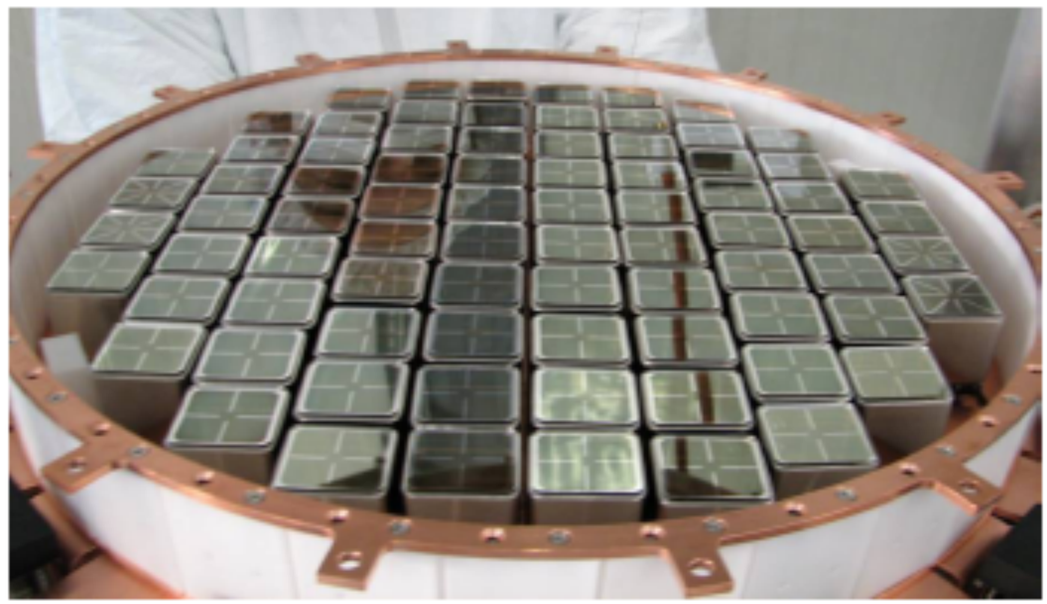
Another key development: Teflon (PTFE) is found to be extremely reflective (> 95%) to LXe scintillation

- Reflectivity in gaseous Xe is much lower ~ 50%, so this is mysterious
- Internal reflection at PTFE-LXe interface?
- Allows efficient light collection in two-phase Xe, without floating PMTs at high voltage

XENON100

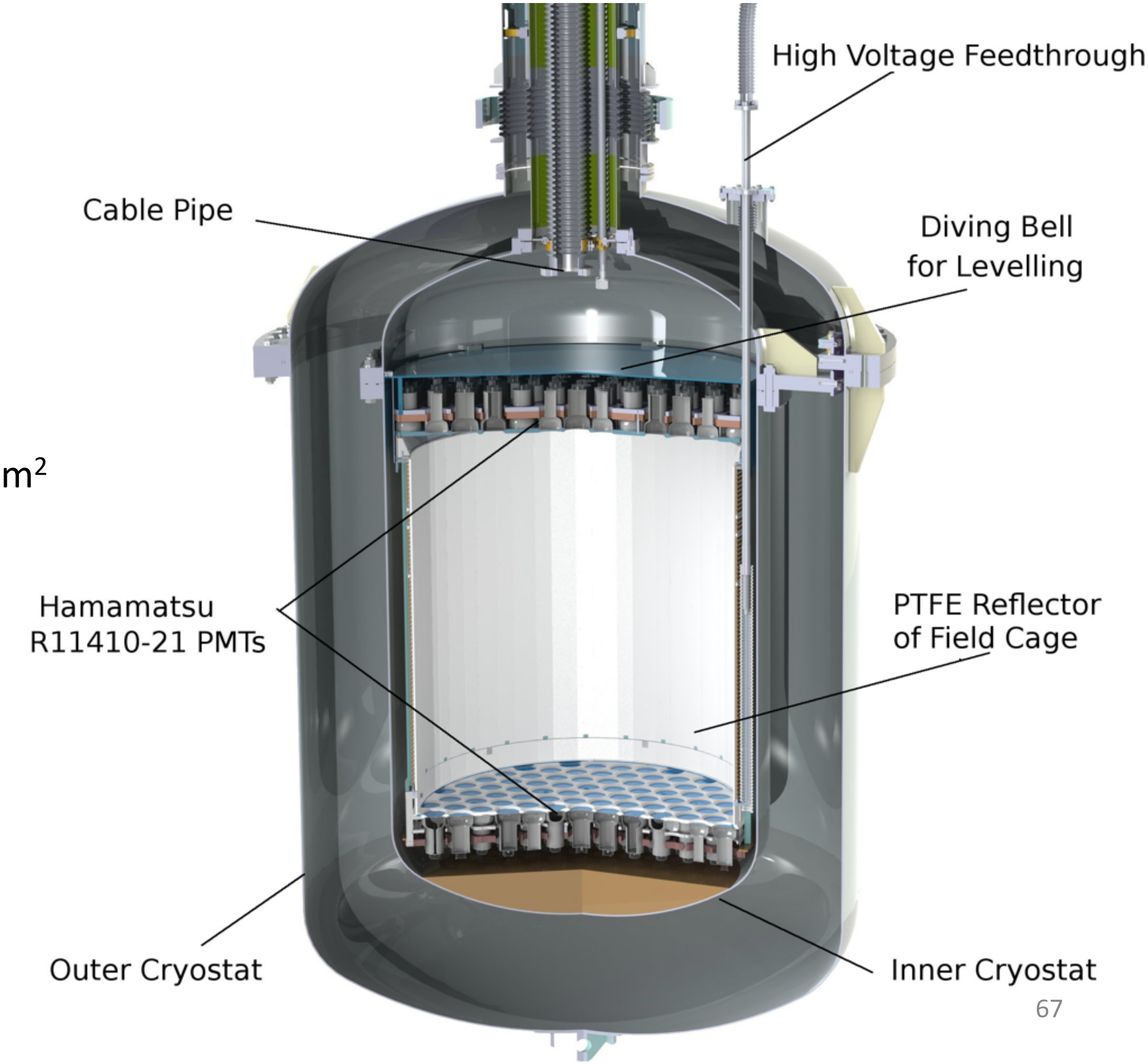
- Two-phase Xe detector with 62 kg active target, 34 kg fiducial mass
- 242 1-inch square PMTs: 1 mBq (U/Th) and ~30% QE
- Multilayer passive shield (Cu, Poly, Pb+Water)
- Background rate of 5.3e-3 events/keV/kg/day after veto cut, before discrimination
- 19 ppt of Kr contamination
- Next step: XENON1T, with sensitivity at 2e-47 cm^2 at 50 GeV in 2017.



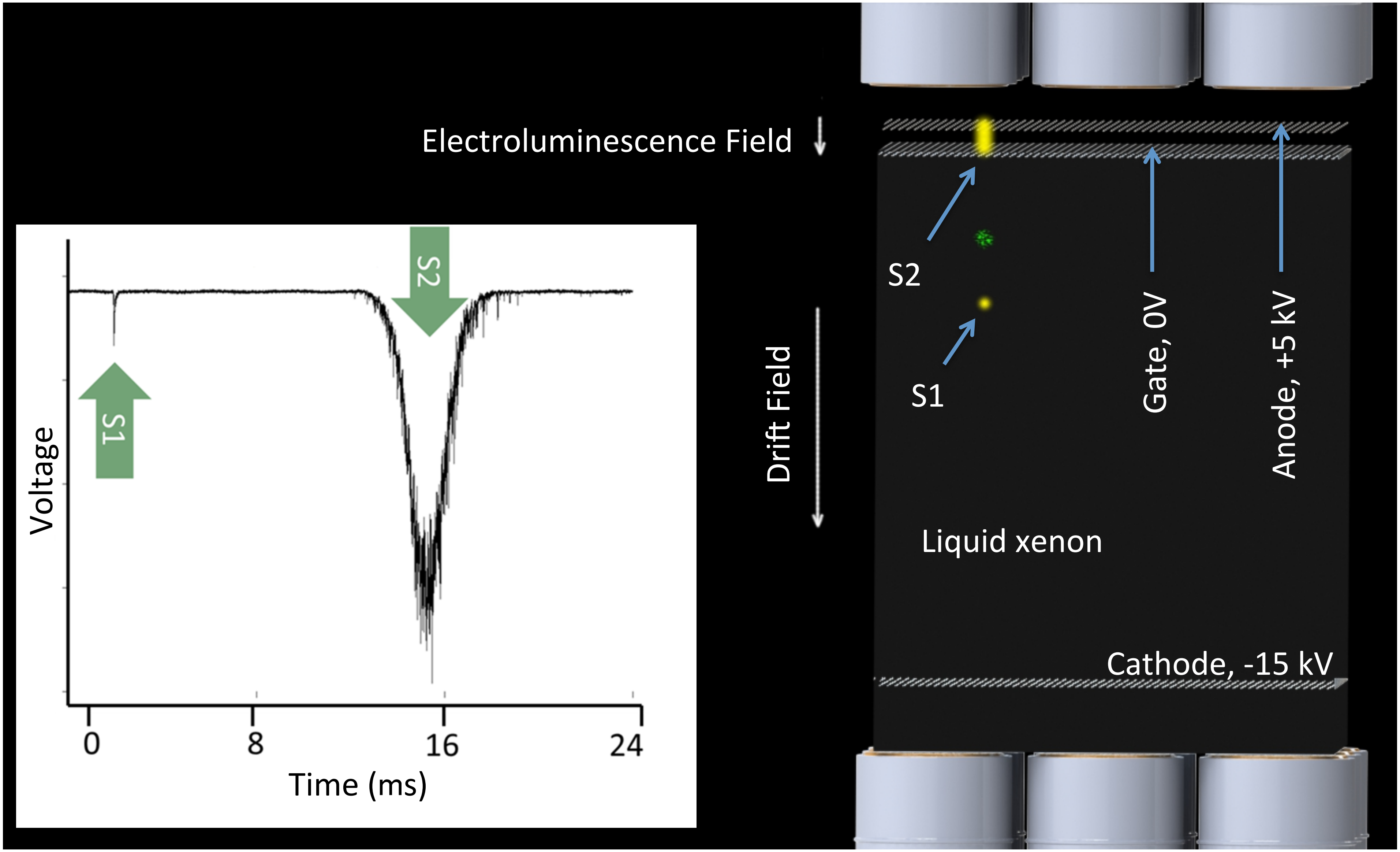


XENON1T

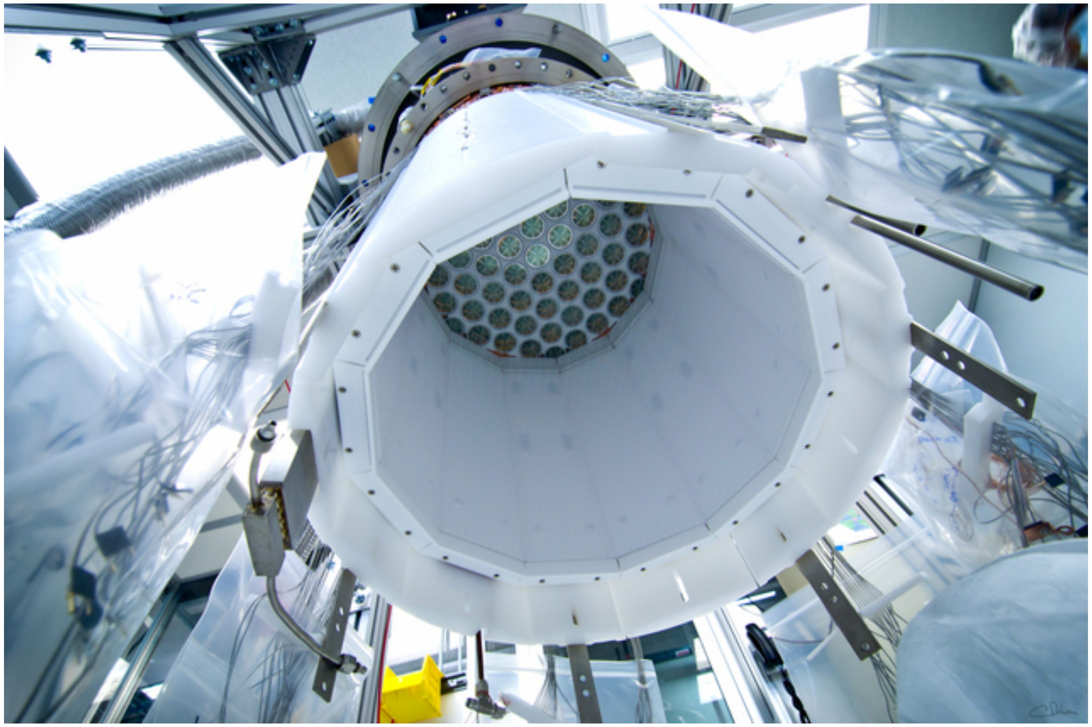
- 1 m-drift TPC
- 3.3 tonnes of LXe
- Water shielding
- Science goal: 2 x 10^{-47} cm^2
- Operational in 2015

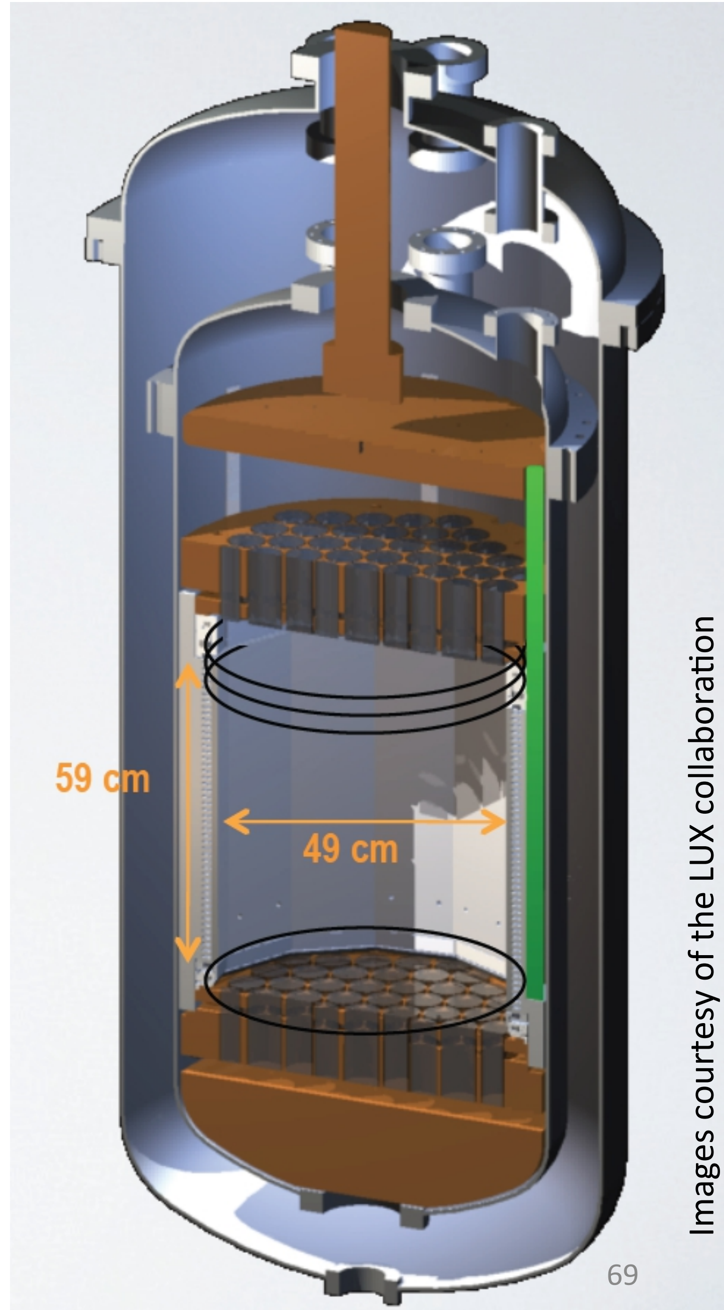


Two-Phase Xenon TPC Operation



Xenon for Physics – The LUX Detector





- Searches for extremely rare "WIMP" dark matter particle interactions.
- ~ 100 collaborators, 19 institutions.
- Co-Spokespersons are Dan McKinsey (UC Berkeley) and Rick Gaitskell (Brown)
- Deployed inside a large water tank at the Sanford Underground Laboratory, 4850 foot depth.
- The most sensitive WIMP detector, worldwide, 2013-2017.
- Energy threshold < 1 keV within 250 kg of active xenon.

LUX timeline

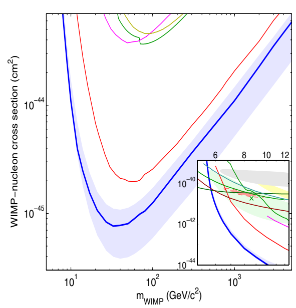
2006: LUX collaboration formed

2008: LUX funded (DOE + NSF)

July 2012: LUX moves UG

April 2013: First science run starts

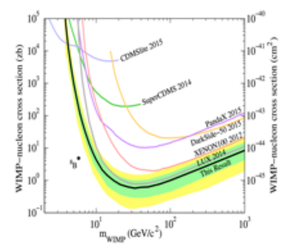
Nov 2013: First WS results reported (85.3 live-days)



PRL, 112, 091303 (2014)

Sept 2014: 332-day run start

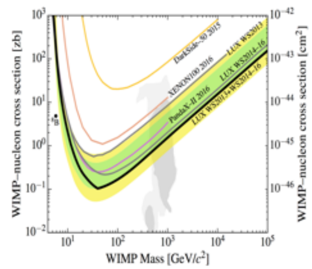
Dec 2015: Re-analysis of WS2013 published



PRL, 116, 161301 (2016)
PRL, 116, 161302 (2016)

May 2016: WS2014-16 finished

July 2016: 332-day WS result announced



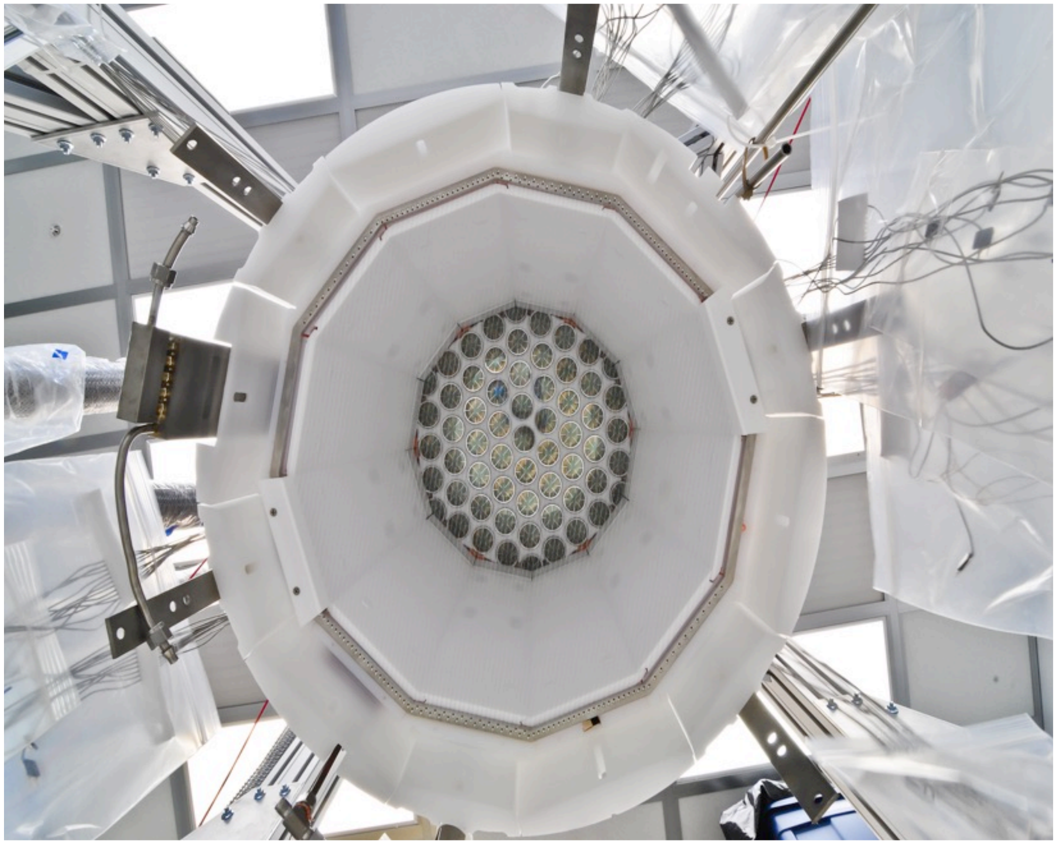
PRL, 118, 021303 (2017)

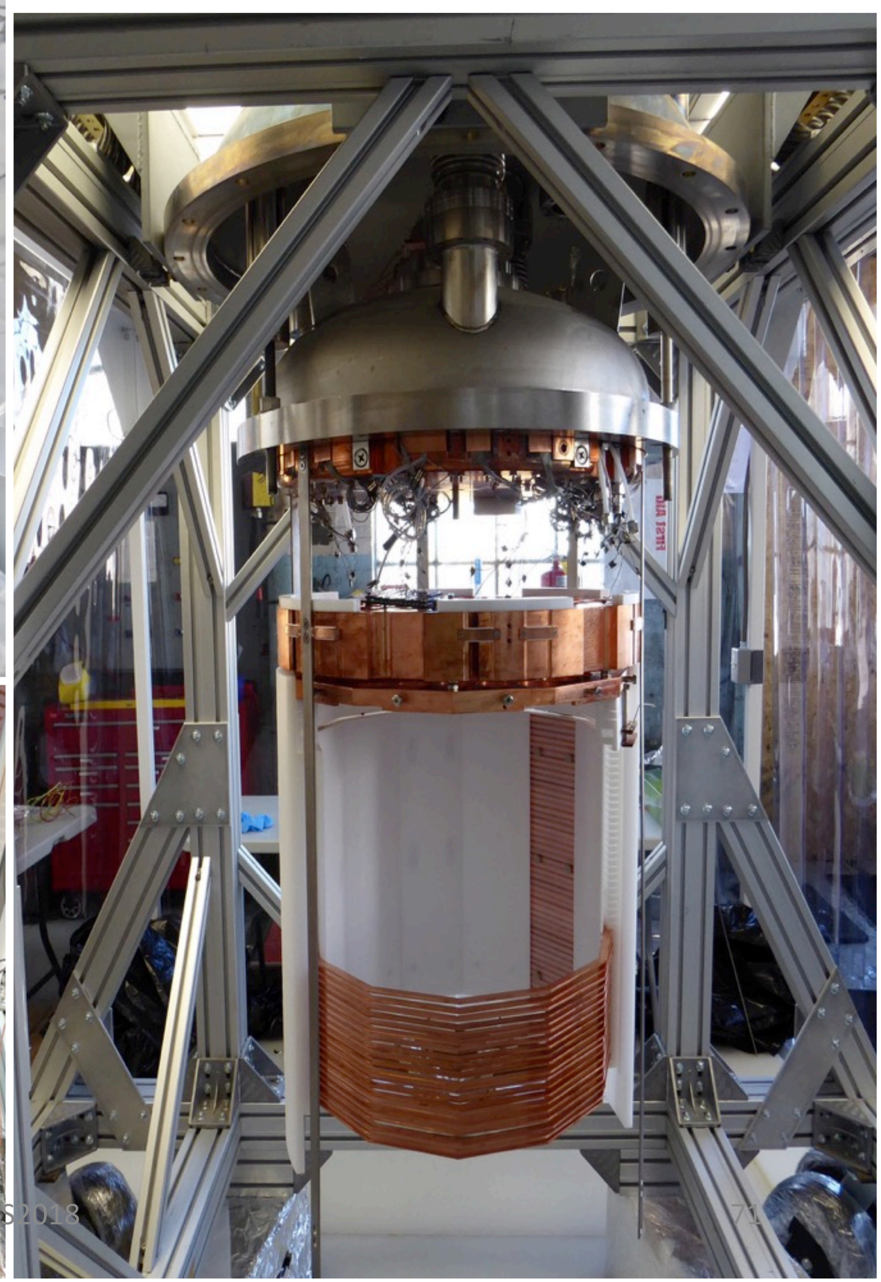
Sept 2016: decommissioning start

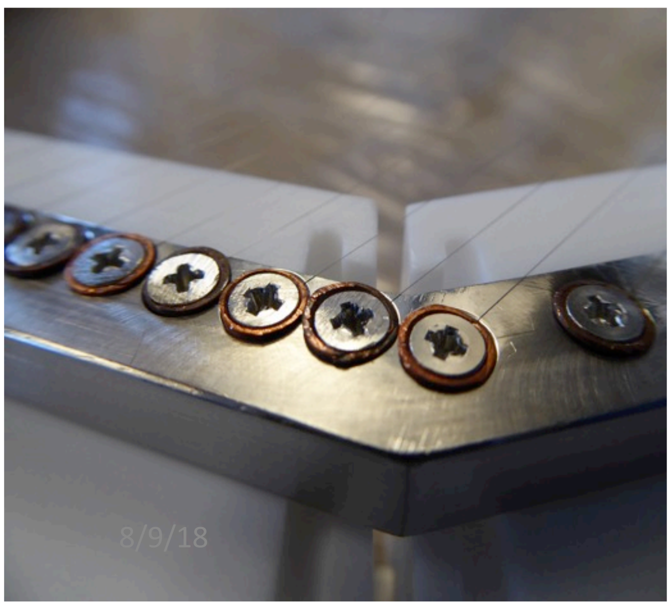
June 2017: LUX installed in a museum

Analysis still ongoing

INSIDE LUX

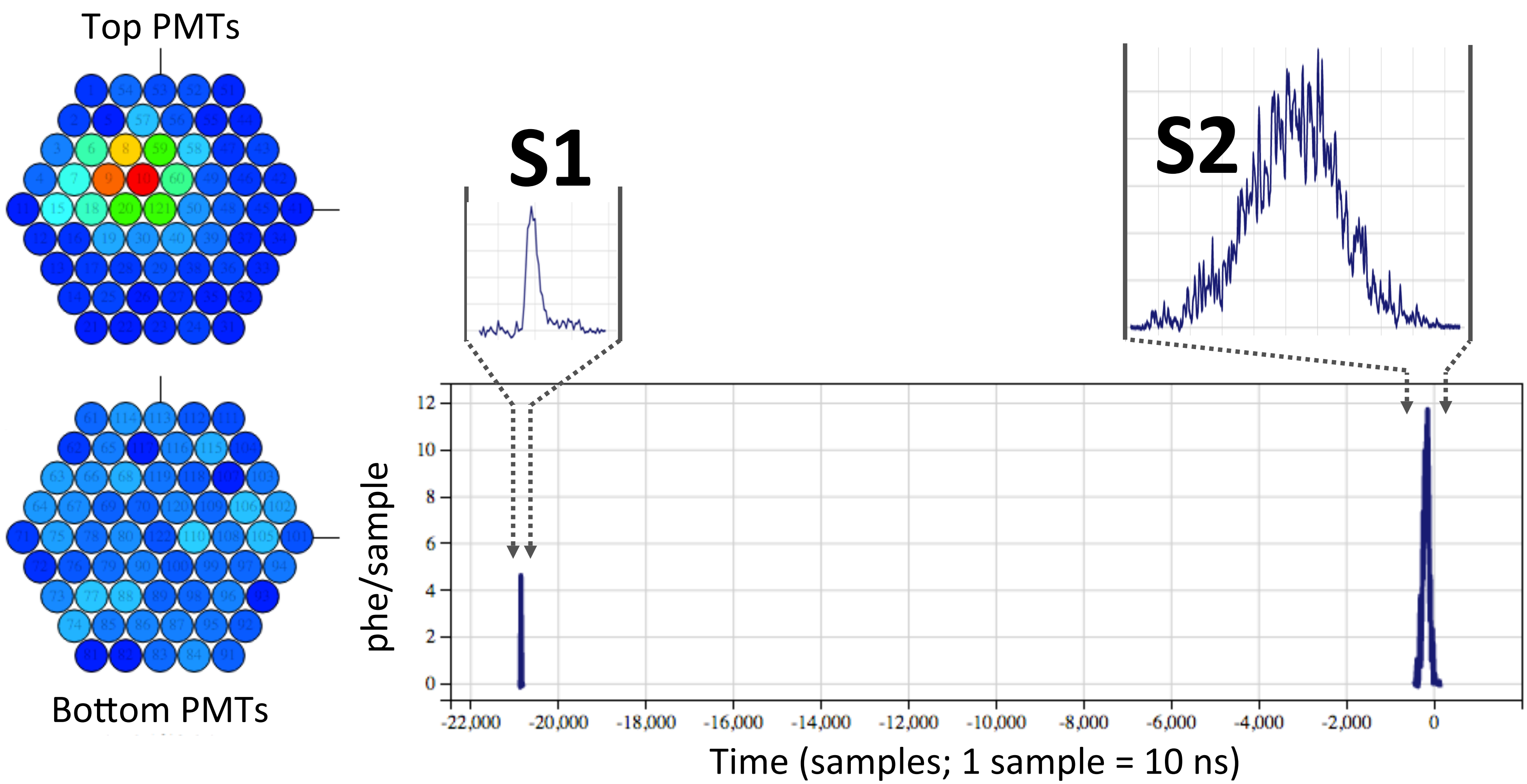






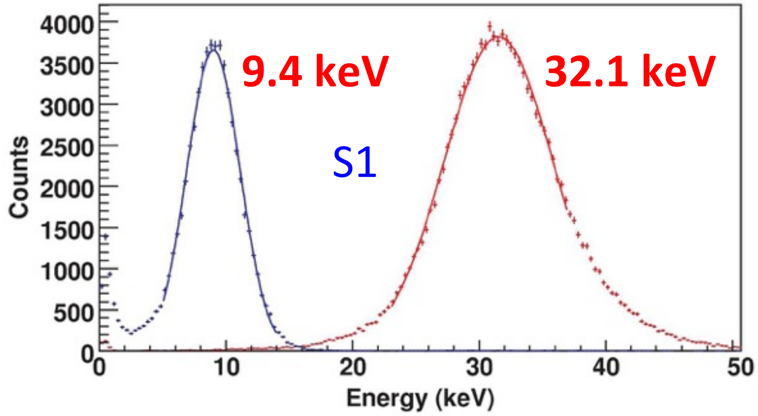
LUX events

We go to great lengths to shield and reduce backgrounds and at the end of the day (or 100's of days), we analyze data from single-site energy deposits that look like this:

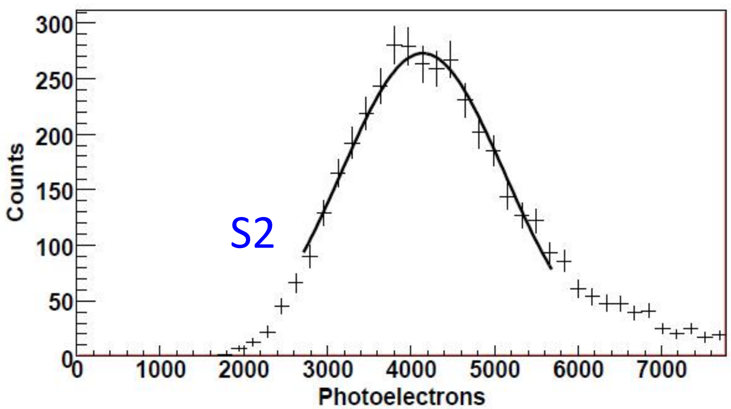


LUX Internal Sources

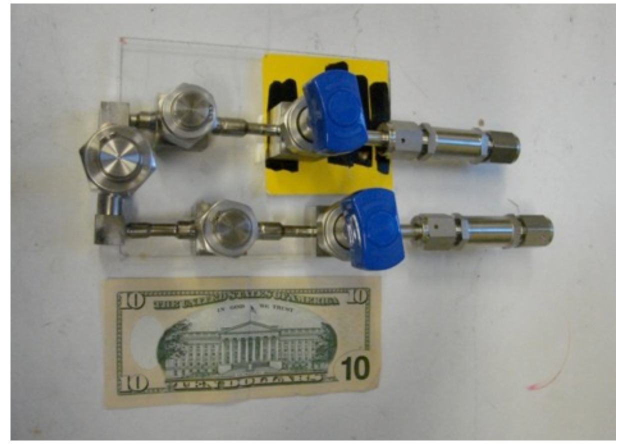
^{83m}Kr (half-life 1.86 hours)

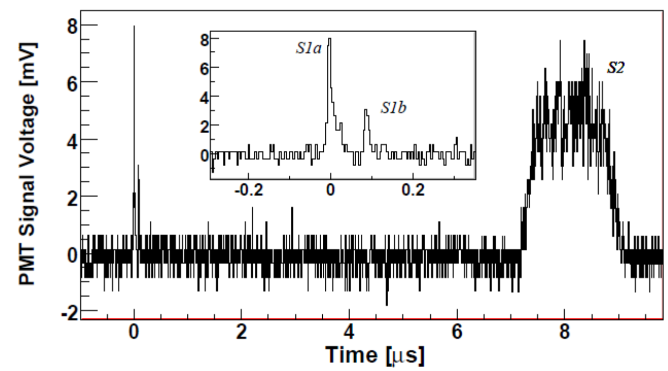


- **conversion electrons**
- **S1 LY and keVee, e^- lifetime**
- **Fills entire fiducial volume**



L. Kastens et al., Phys. Rev. C80: 045809 (2009).
A. Manalaysay et al., Rev. Sci. Instr. **81**, 073303 (2010)

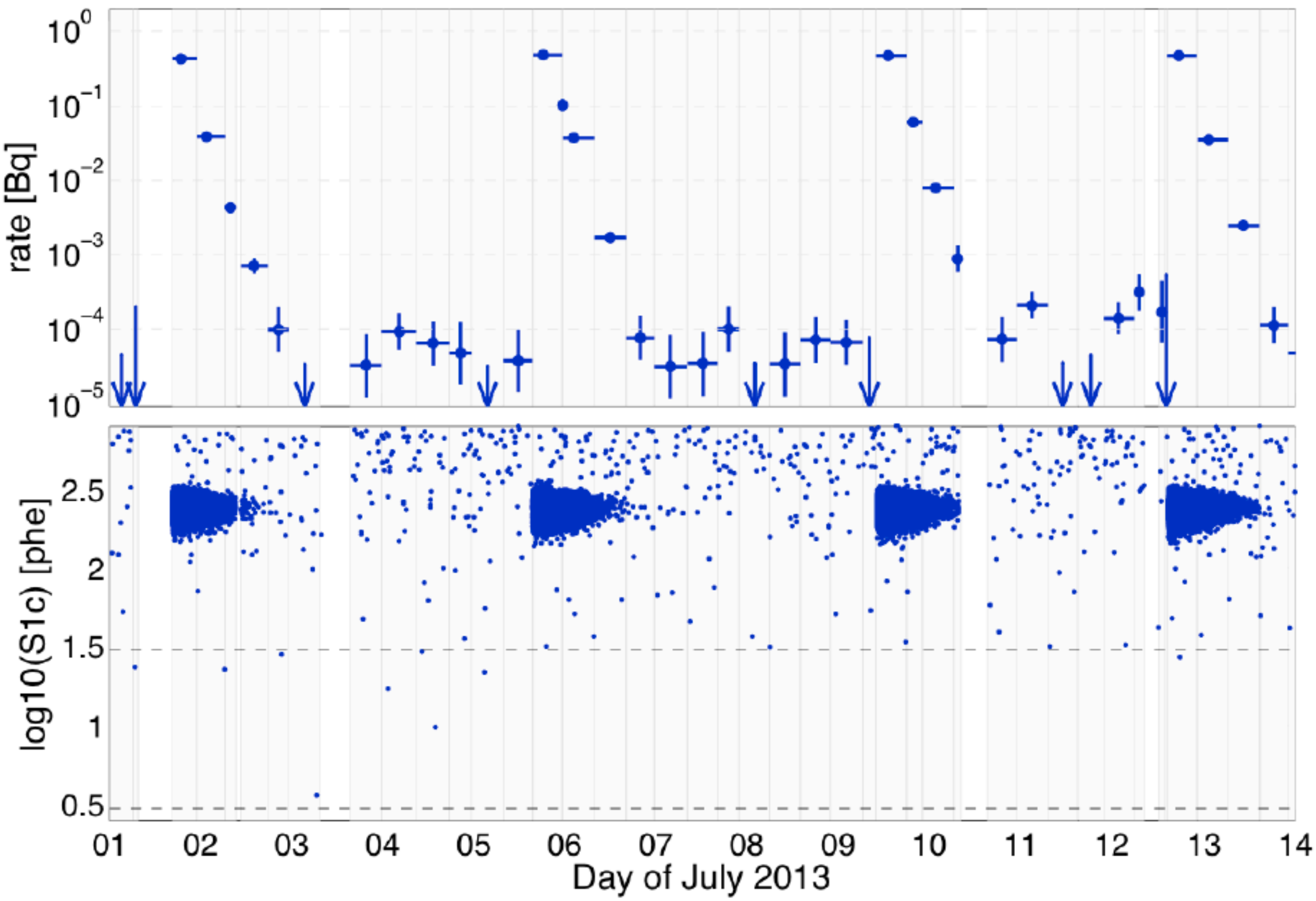




Tritium (half-life 12.3 yrs)

- **Injected as CH_3T**
- **Beta source, up to 18.6 keV**
- **Removed by purification system**
- **S2/S1 ER band**
- **Fills entire fiducial volume**

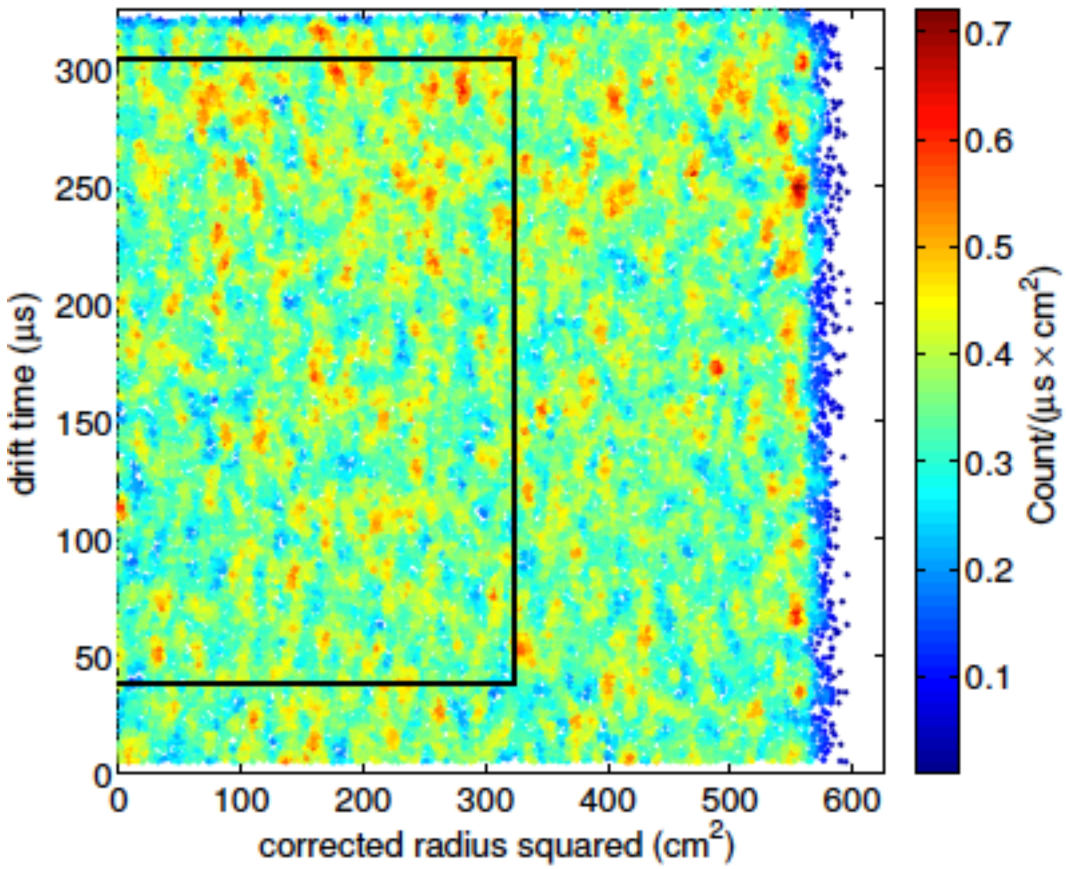
Repeated, frequent use of Kr-83m



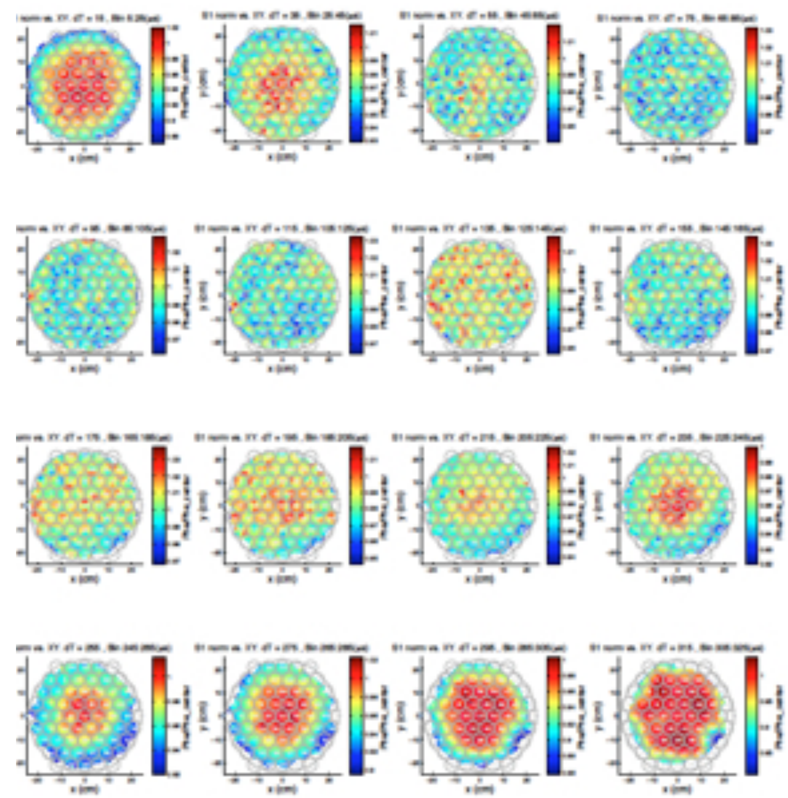
Kr-83m Calibration

- Over 1 million Kr-83m events, spread uniformly through the detector.

Fiducial volume determination

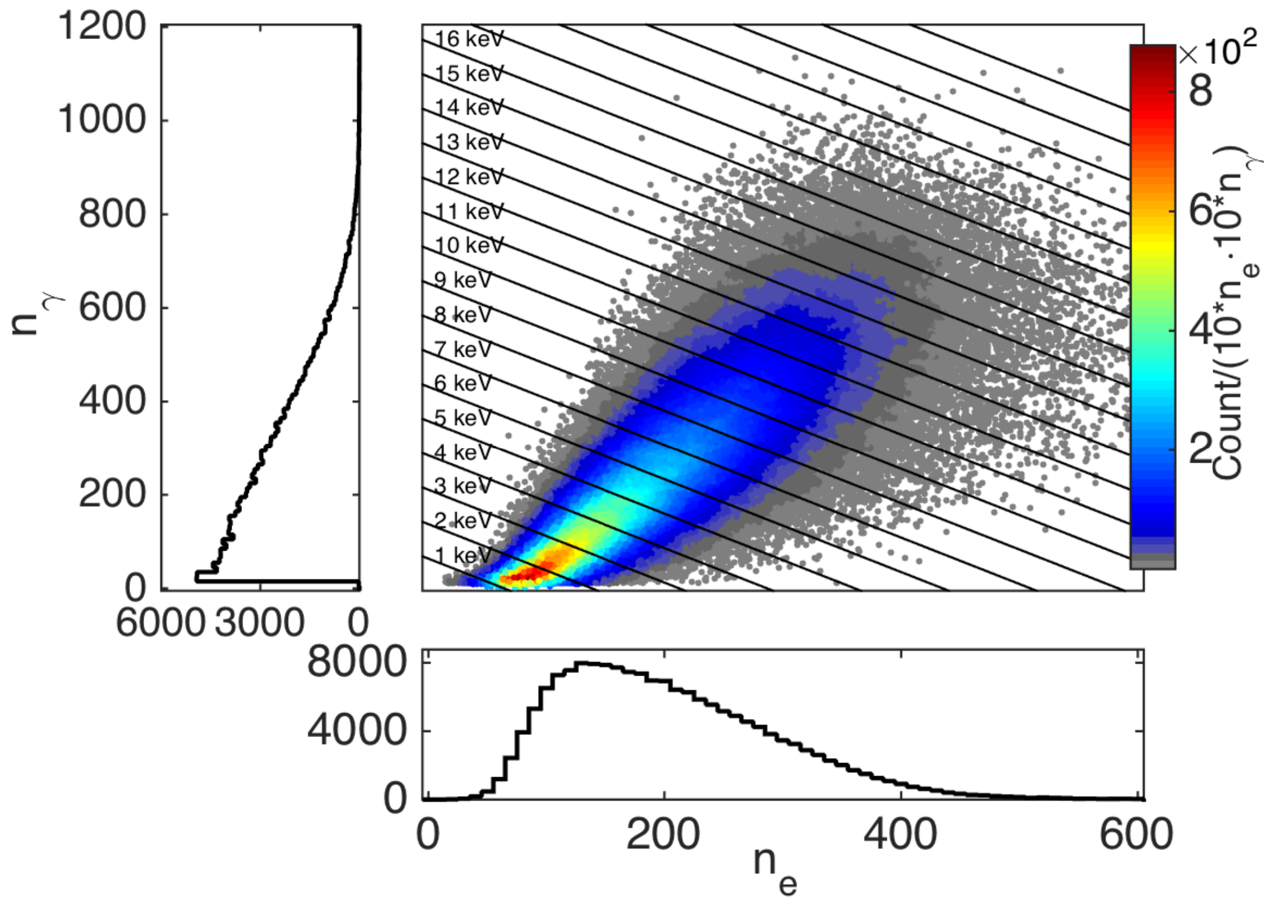


Position-based S1 corrections

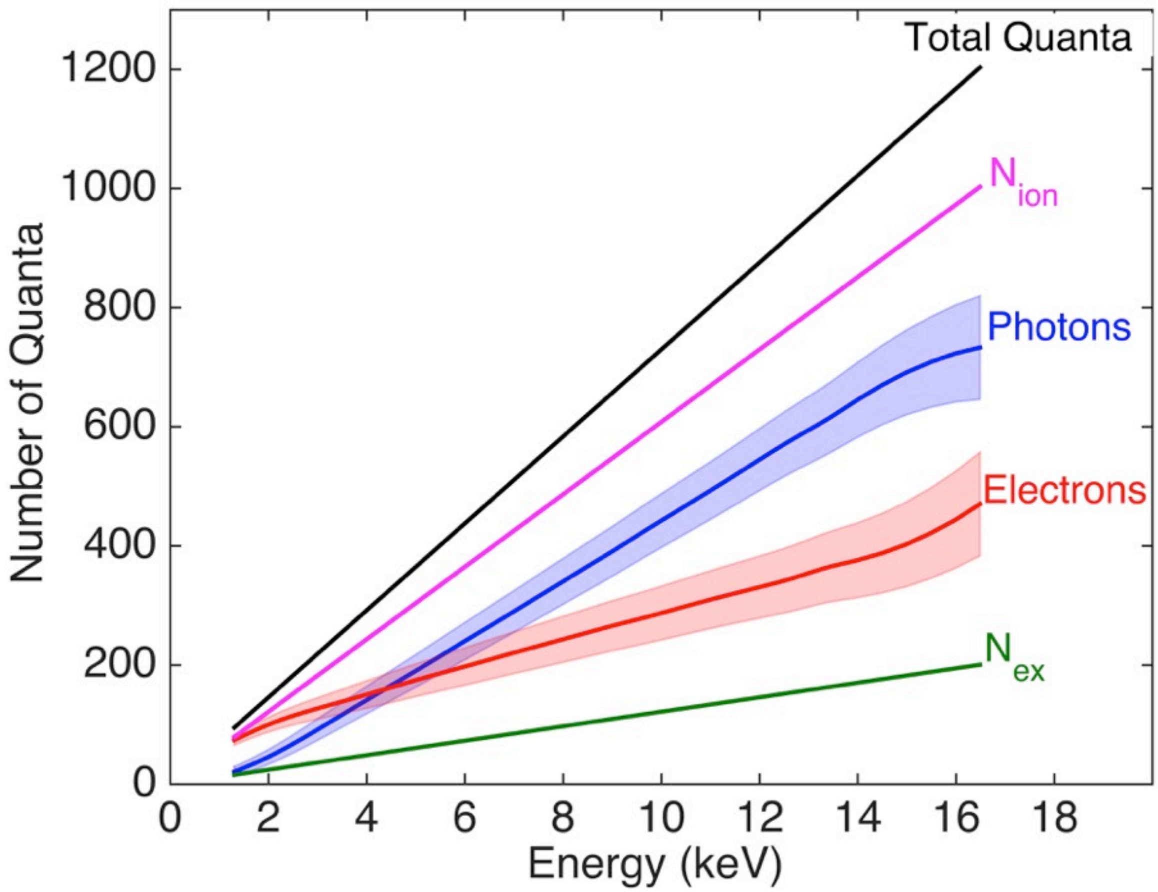


Tritium beta decay measured in both light and charge

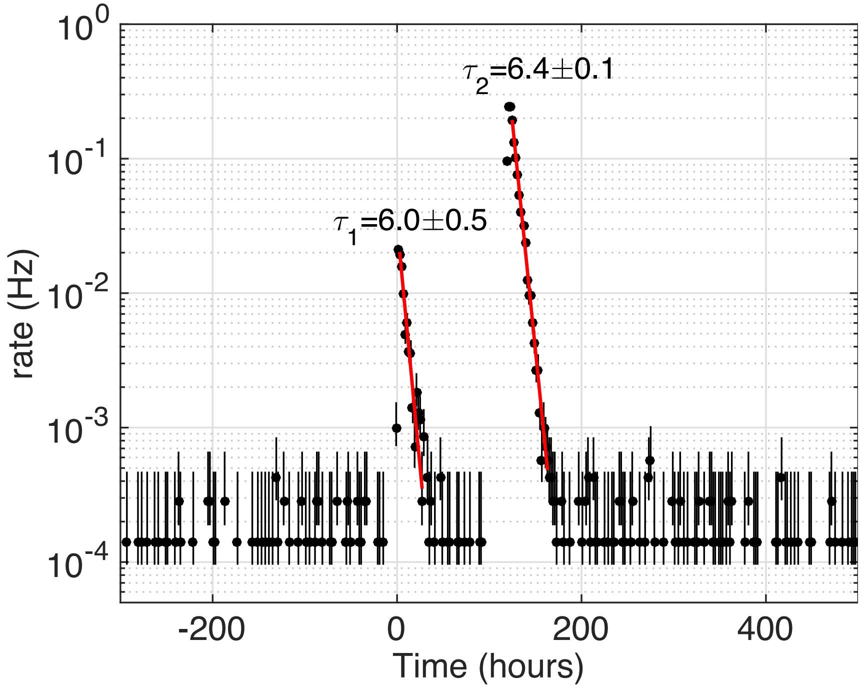
(Read more in Physical Review D 93, 2009 (2016))

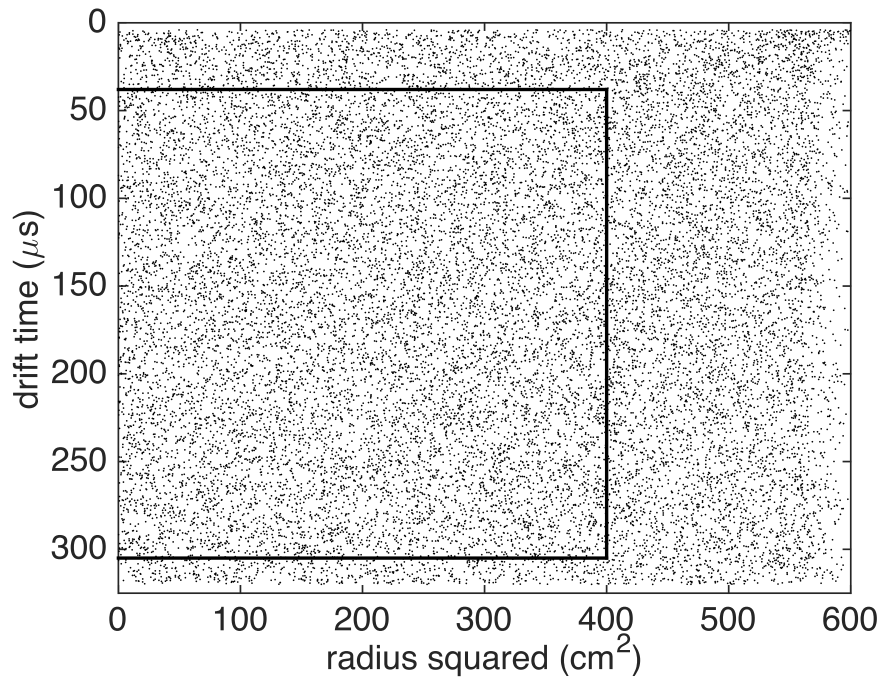


Total Quanta (electrons +photons) for electron recoils in LXe



Tritiated Methane injection



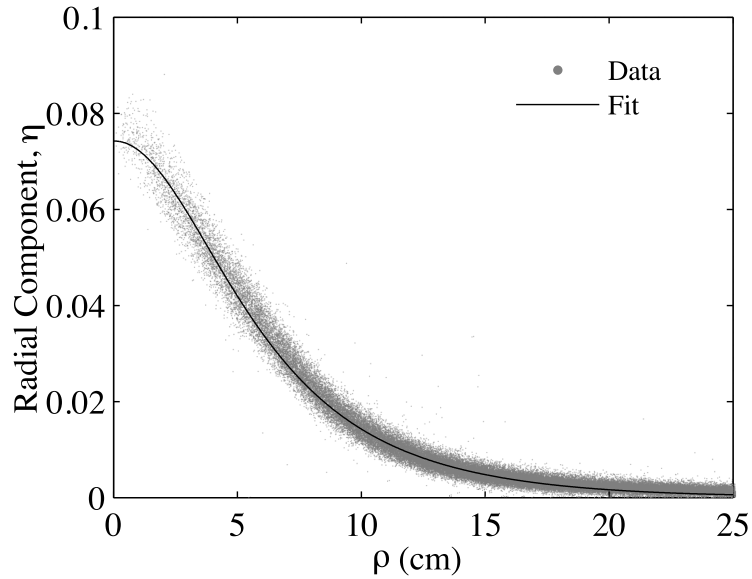


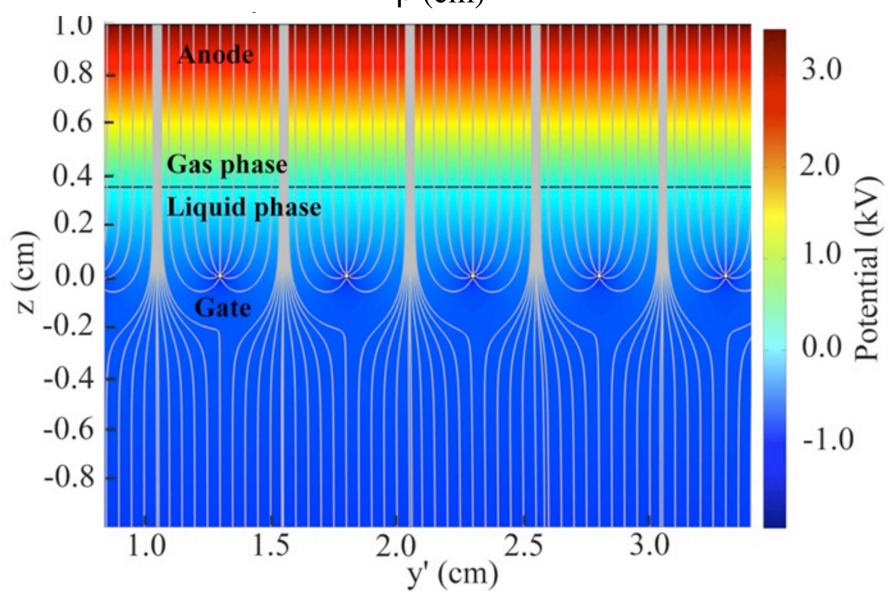
XYZ Position Reconstruction

Z coordinate is determined by the time between S1 and S2 (electron drift speed of 1.51 mm/microsecond)

Light Response Functions (LRFs) are found by iteratively fitting the distribution of S2 signal for each PMT. XY position is determined by fitting the S2 hit pattern relative to the LRFs.

Read more in:
J. Instrumentation 13, P02001 (2018).





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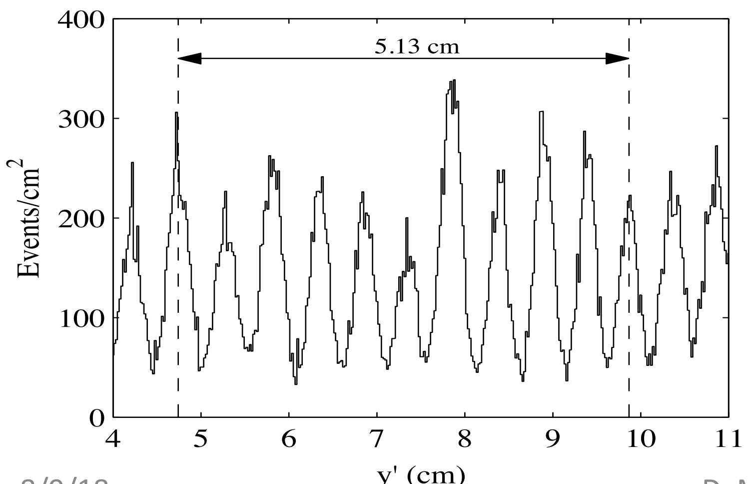
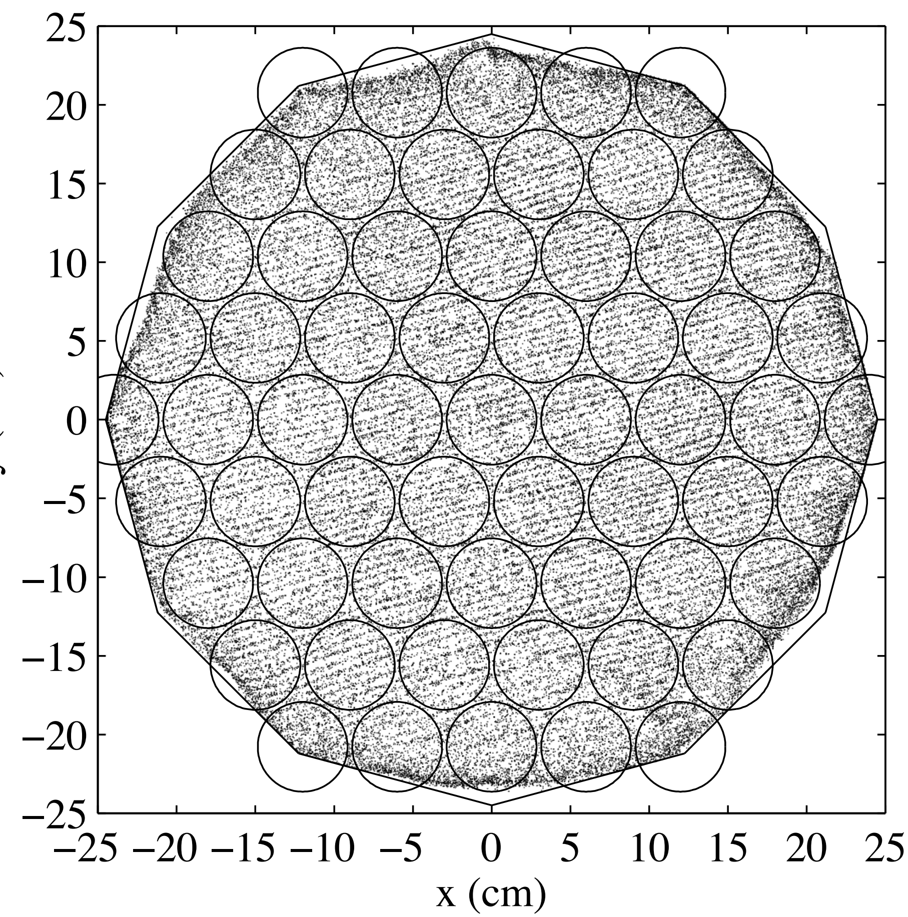
Reconstruction of XY from Kr-83m events resolves grid wires with 5 mm pitch.





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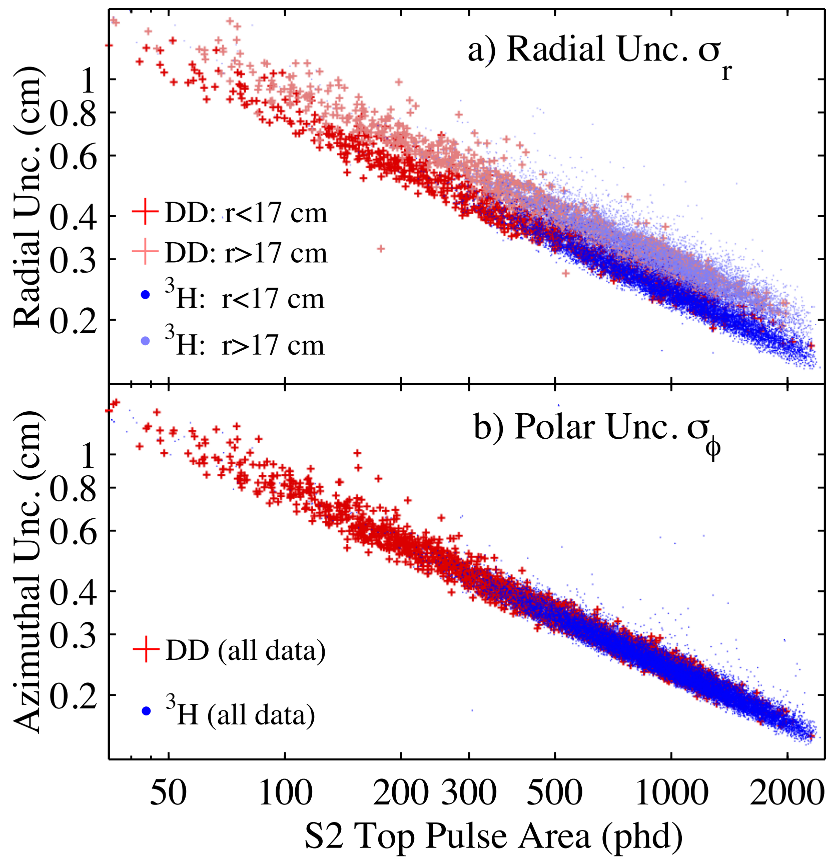
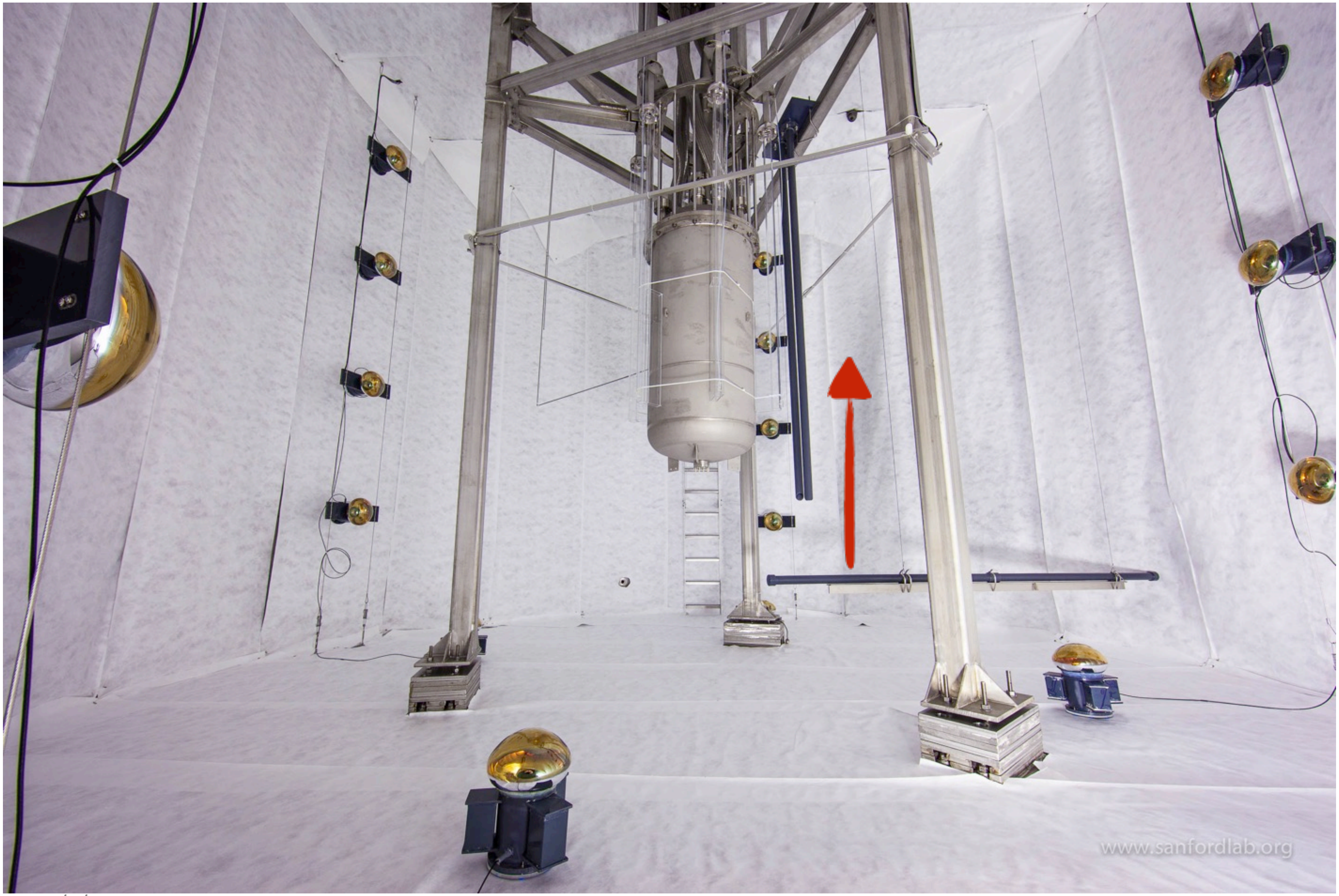
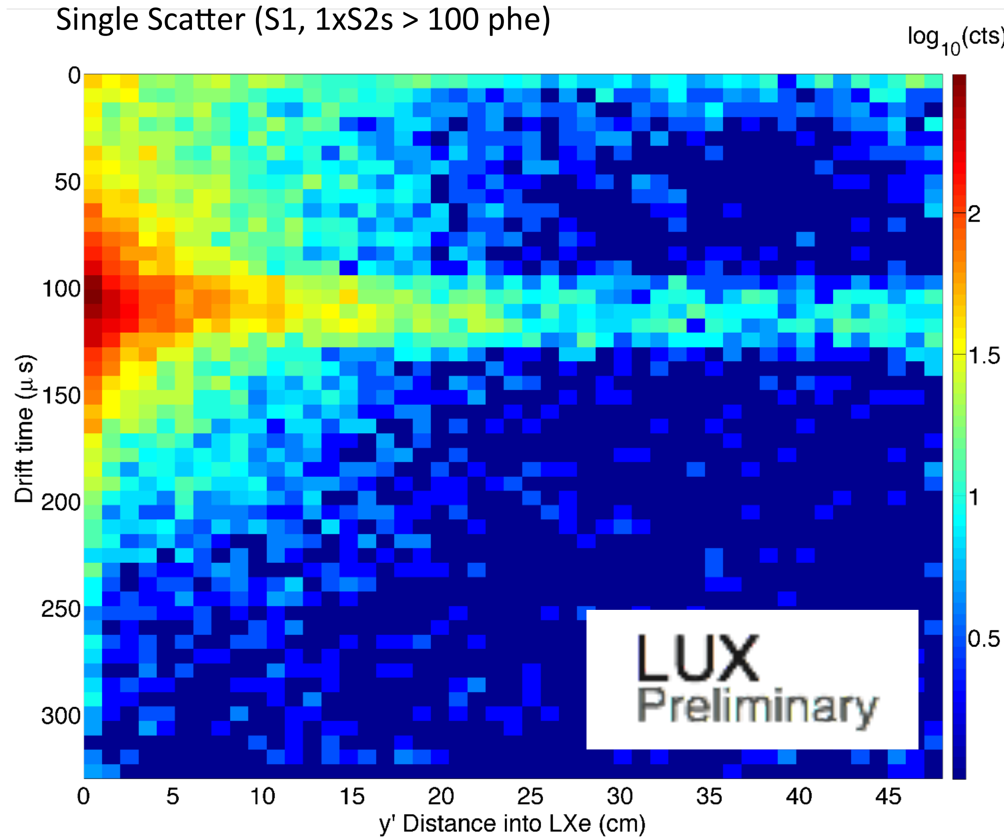


Neutron Conduit Installed in the LUX Water Tank - Fall 2012

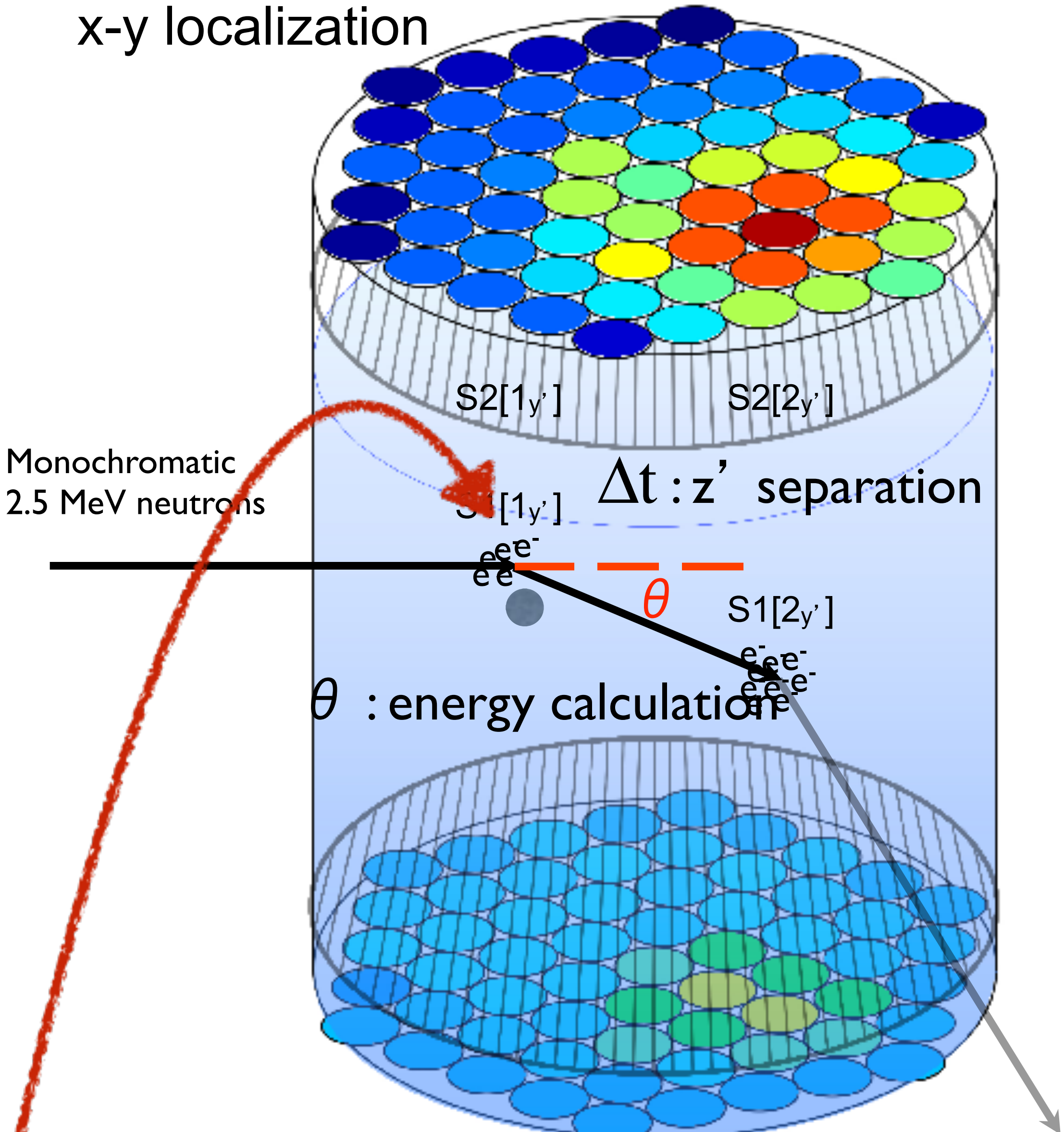


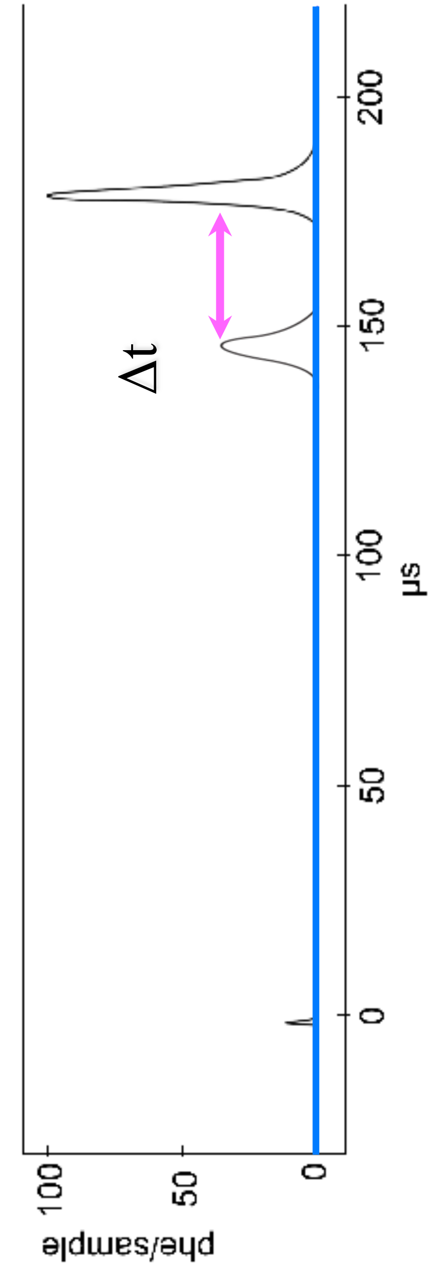
Neutron Generator Installed Outside LUX Water Tank - Fall 2013



- Neutron generator/beam pipe assembly aligned 15.5 cm below liquid level in LUX active region to maximize usable single / double scatters
- Beam leveled to ~1 degree
- 105.5 live hours of neutron tube data used for analysis

top hit pattern:
x-y localization





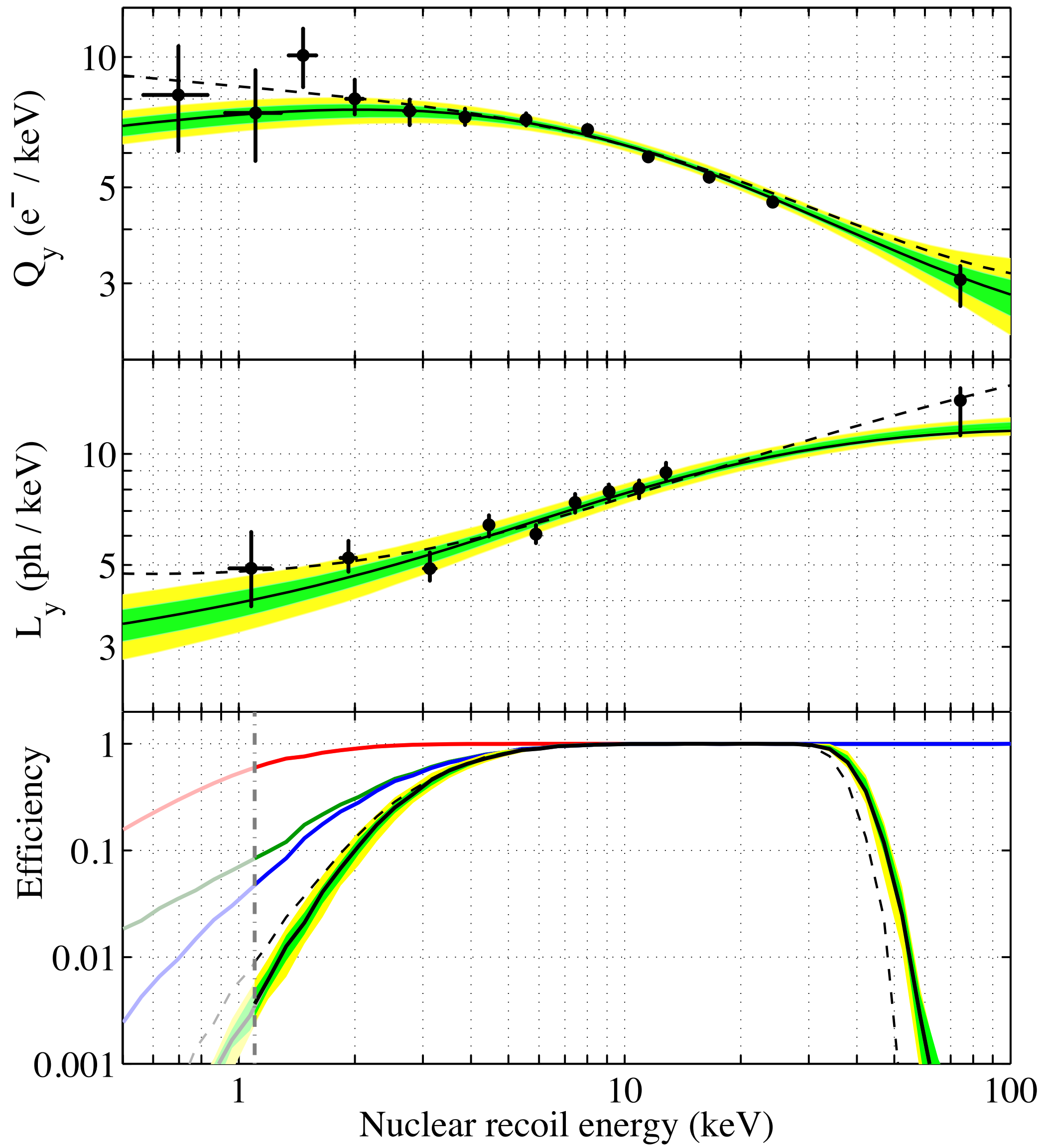
$$E_r = E_n \frac{4 m_n m_{Xe}}{(m_n + m_{Xe})^2} \frac{1 - \cos\theta}{2}$$

Charge and Light Yields for Nuclear Recoils,
Measured Using DD Neutron Calibration in LUX
LUX Collaboration, arXiv:1608.05381

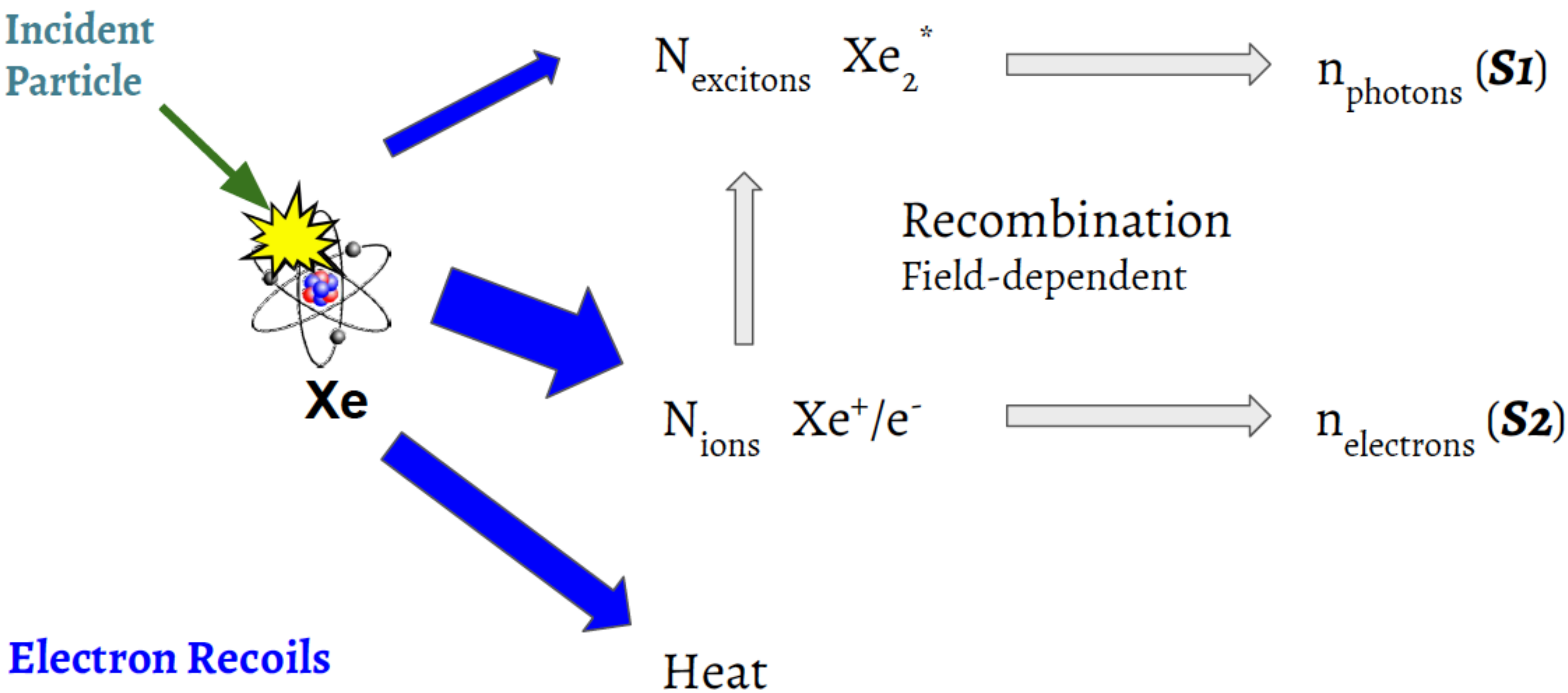
Charge Yield

Light Yield

WIMP signal efficiency



Energy Partitioning in LXe



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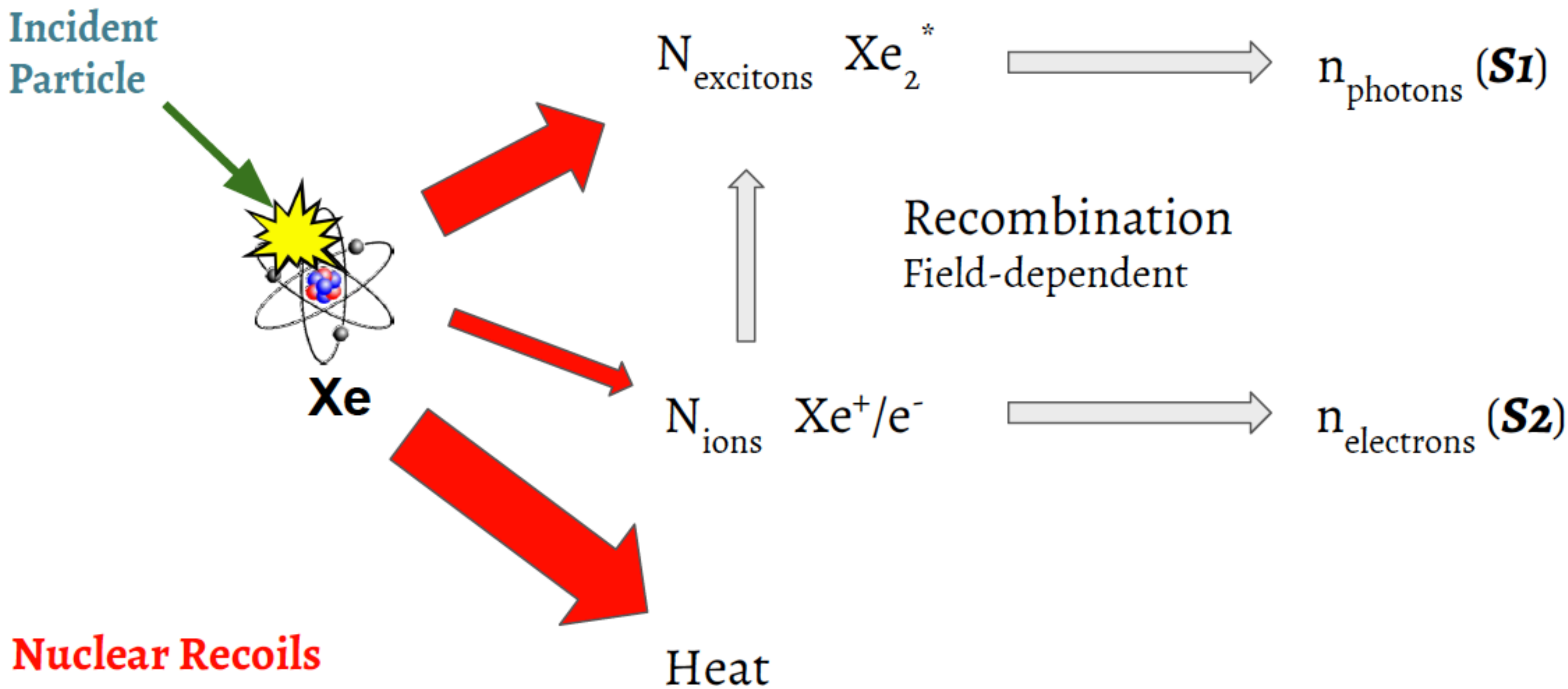
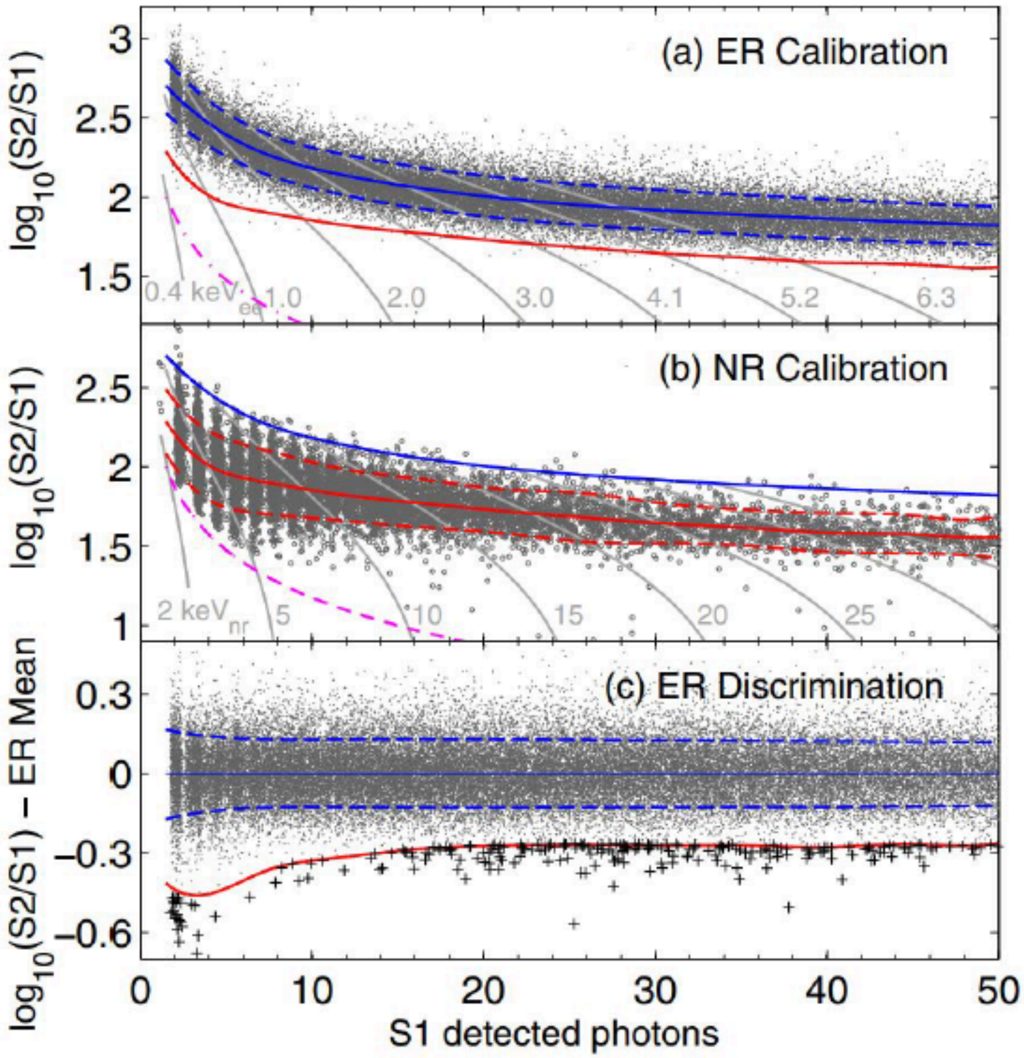


Charge/light discrimination in LXe



Phys. Rev. D 97, 102008 (2018)

Discrimination is based on $\log_{10}(S2/S1)$.

The ER and NR bands are roughly Gaussian in this quantity for moderate fields, indicating a recombination fraction that is Gaussian-distributed.

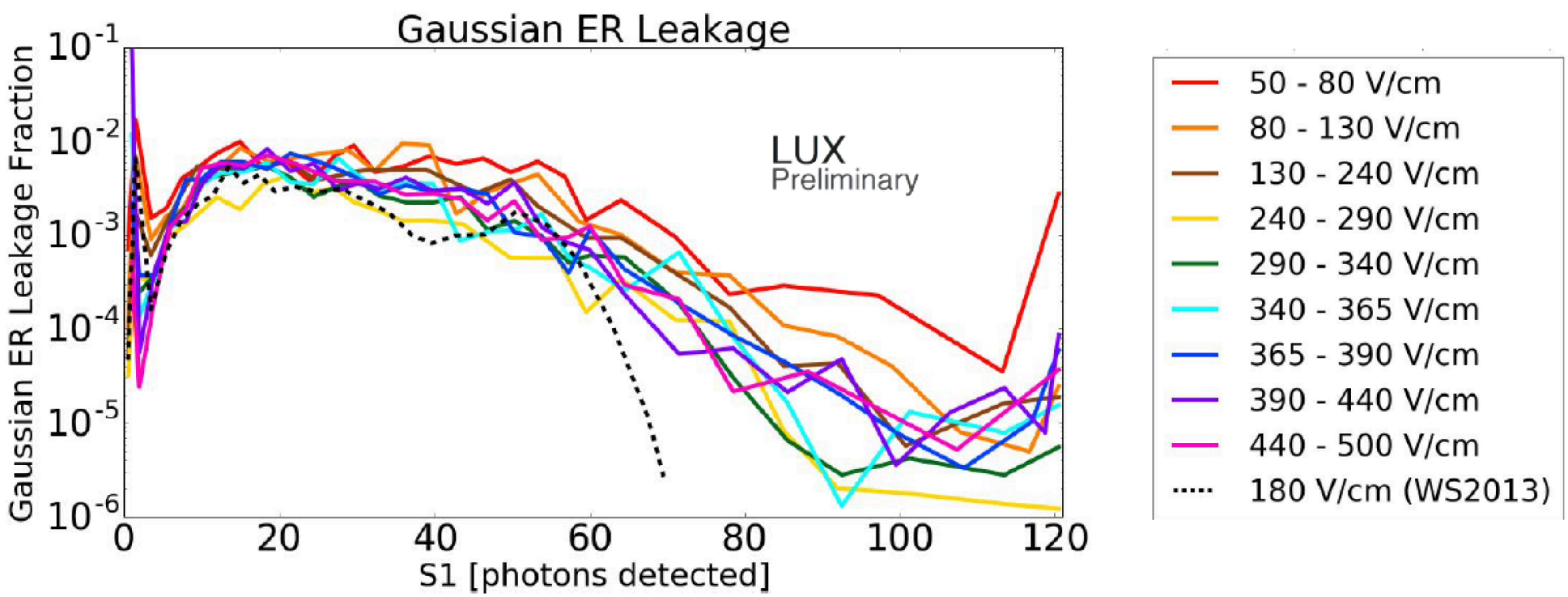
ER leakage typically reported at 50% NR acceptance.

ER leakage is typically between 99% and 99.9% in LXe, for S1 < 50 detected photons, but improves at higher energies.

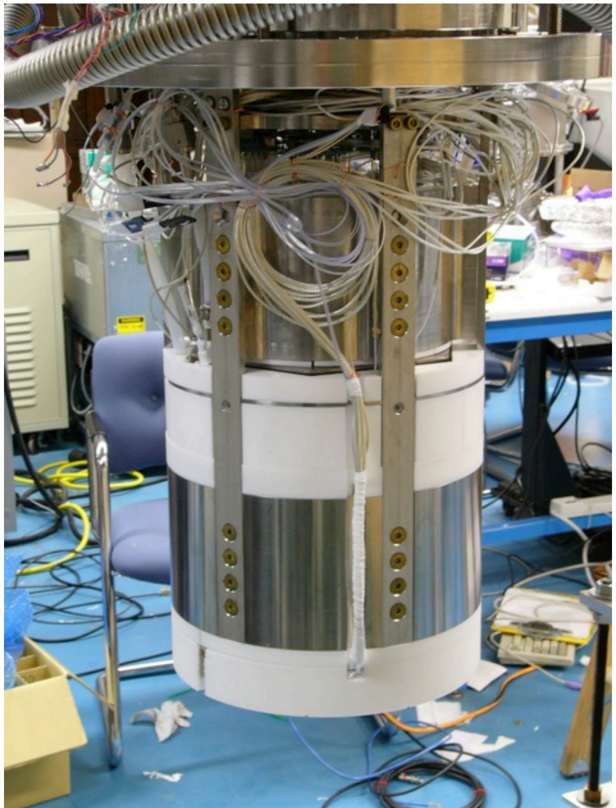
Charge/light discrimination in LXe

Estimation of leakage fraction, using ER and NR band medians, and ER band width.

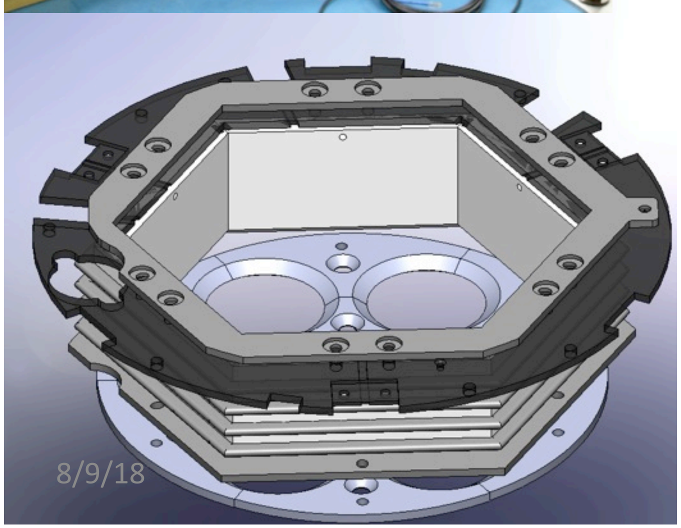
Leakage reported at 50% NR acceptance.

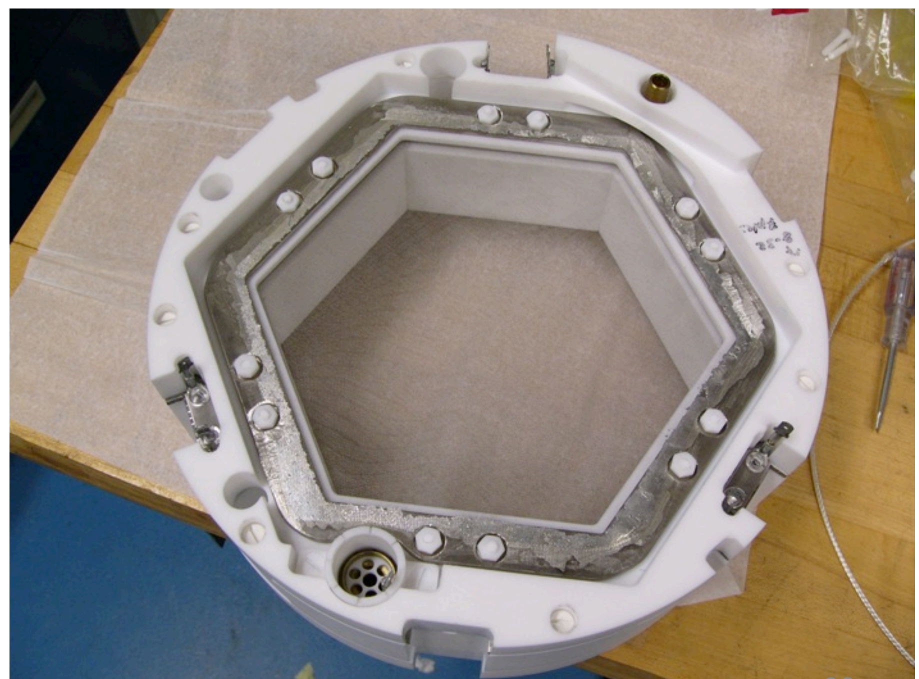


PIXeY – Particle Identification in Xenon at Yale



- Two-phase Xe detector; 4 kg active xenon volume.
- 5 cm tall by 18 cm across corners.
- Designed for optimal light collection and strong drift field.
- Ran at Yale from June 2014 through April 2015.
- Test platform for technologies supporting Compton imaging:
  - Uniform, transparent grids.
  - Cryogenic and xenon circulation platform.
  - PMT readout and data processing software.





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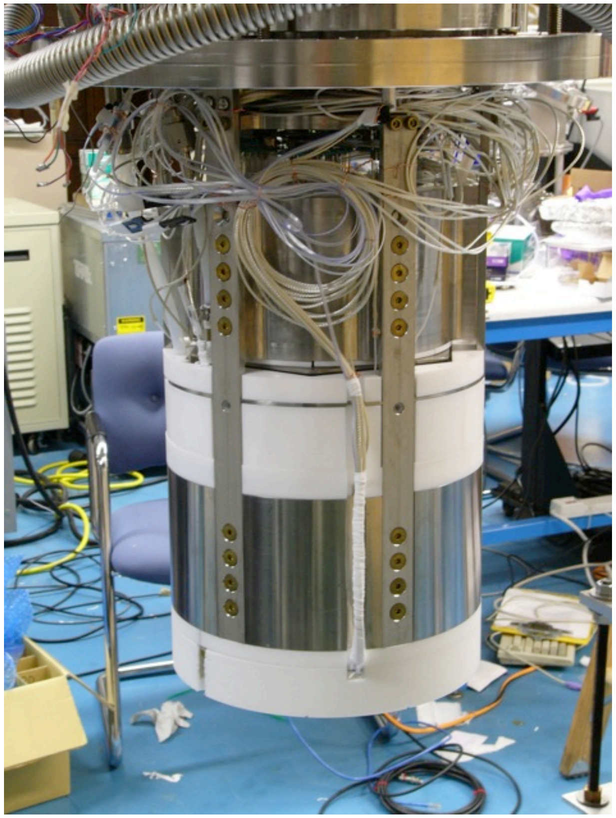

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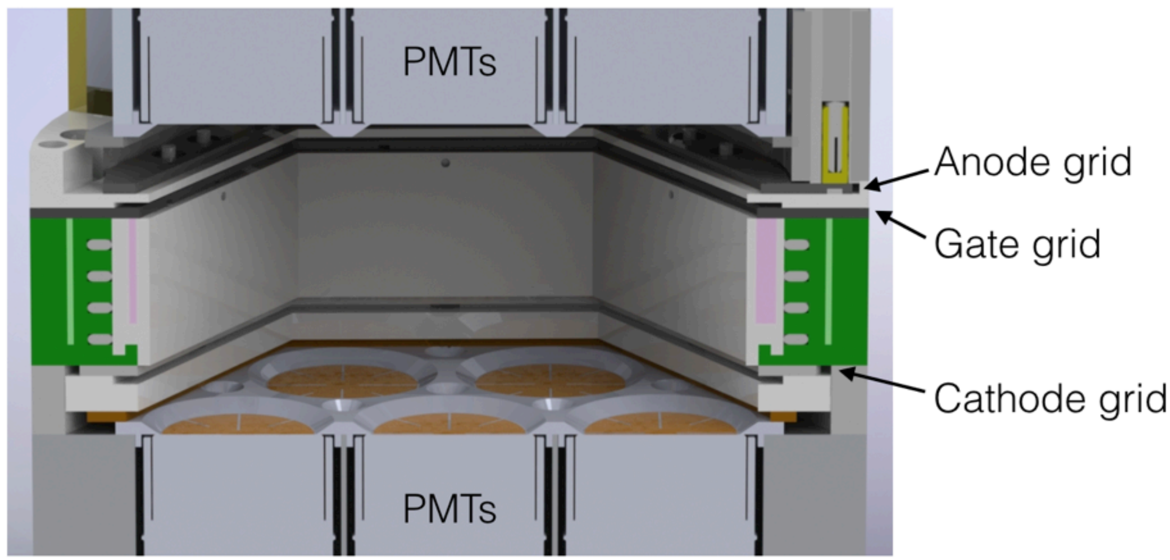
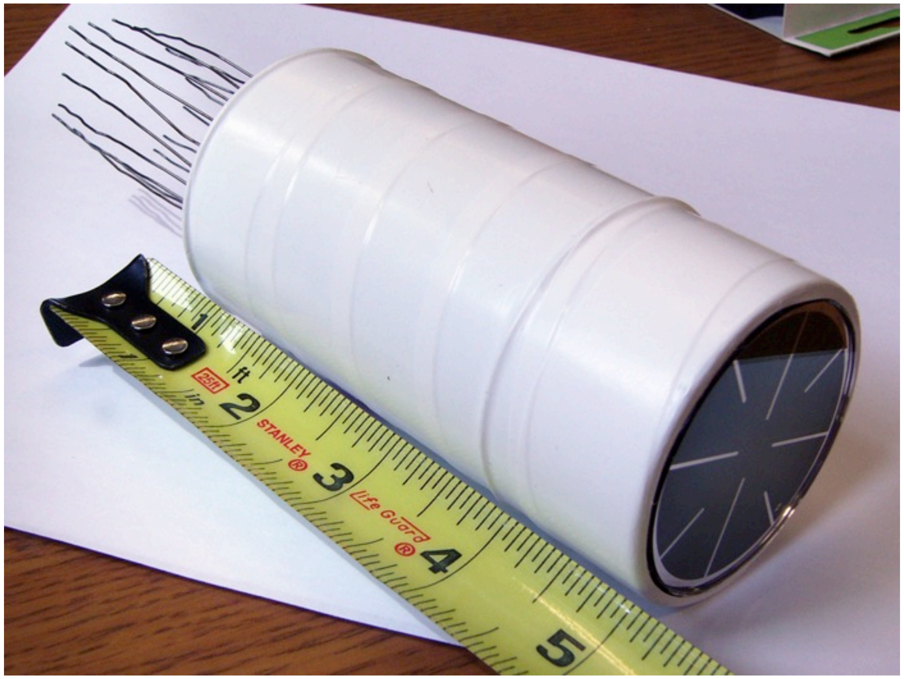
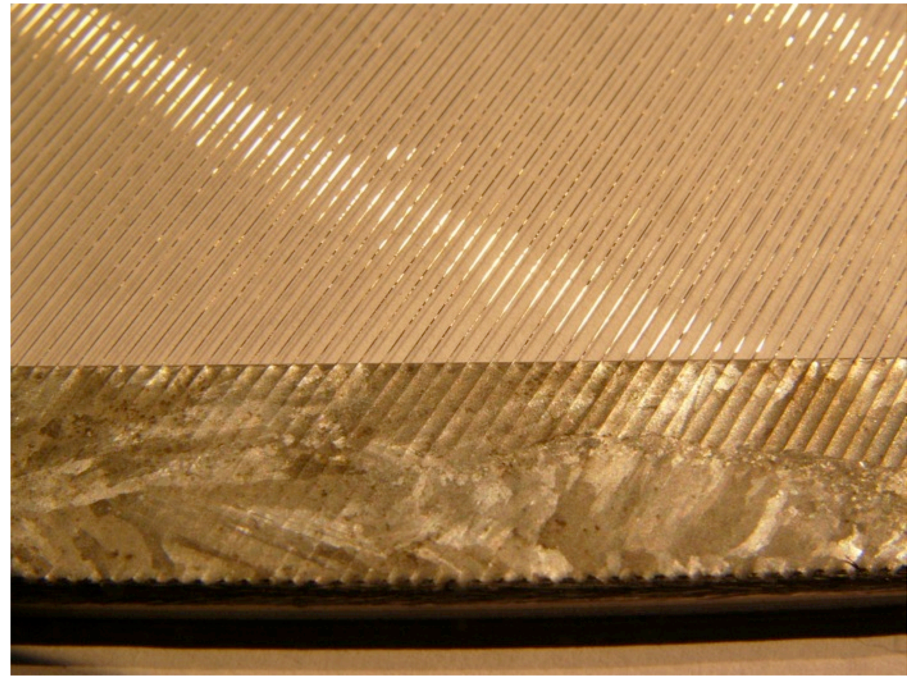


PIXeY Hardware: PMTs and Grids

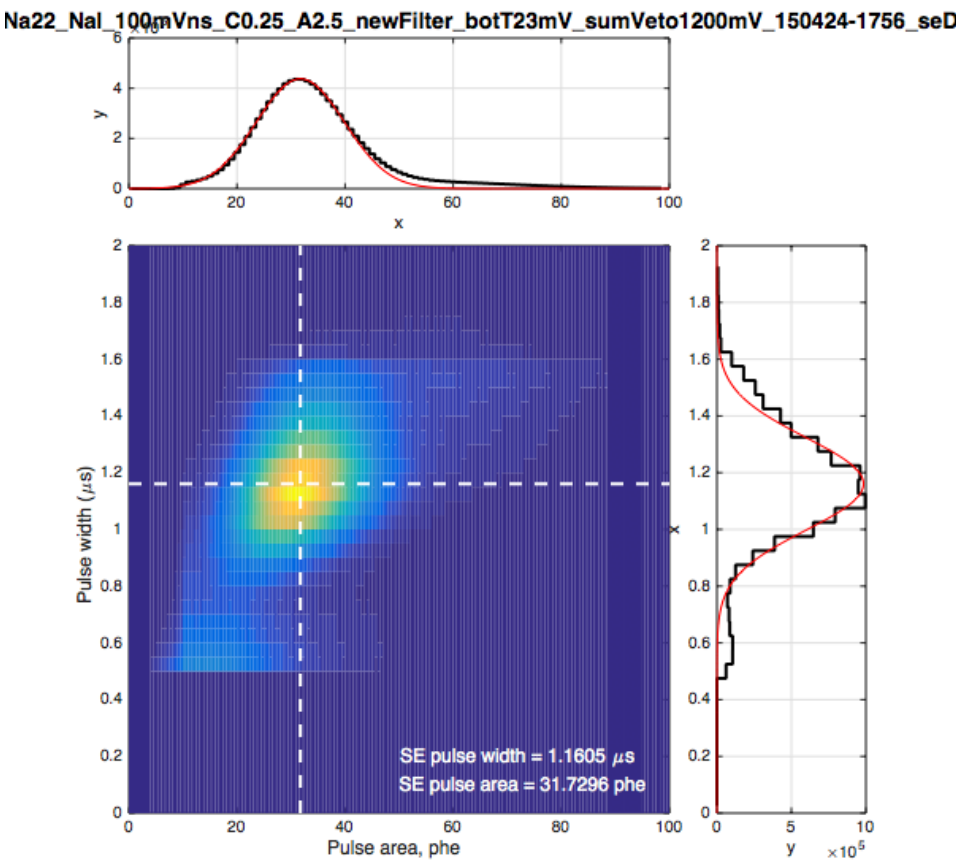


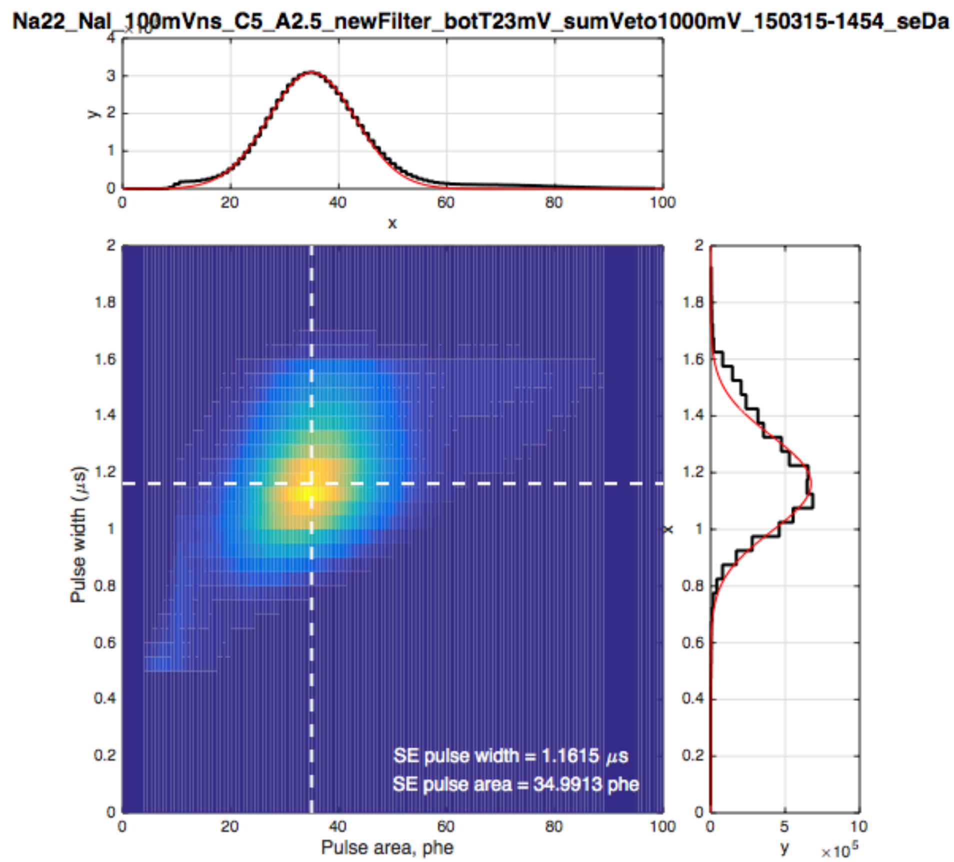


- Direct collection of 175 nm Xe scintillation light through quartz window.
- Bialkali Photocathode; 35% quantum efficiency; gain $10^5 – 10^7$
- Operate immersed in liquid xenon.
- Used in the LUX and XMASS LXe dark matter experiments.

- Wire and frame are monel alloy 400
  - 92% open field establishing grids
  - 80 μm wire, 1 mm pitch
  - 250 g/wire tension
  - Can fabricate to arbitrary pitch
- Maintain uniform tension while cold

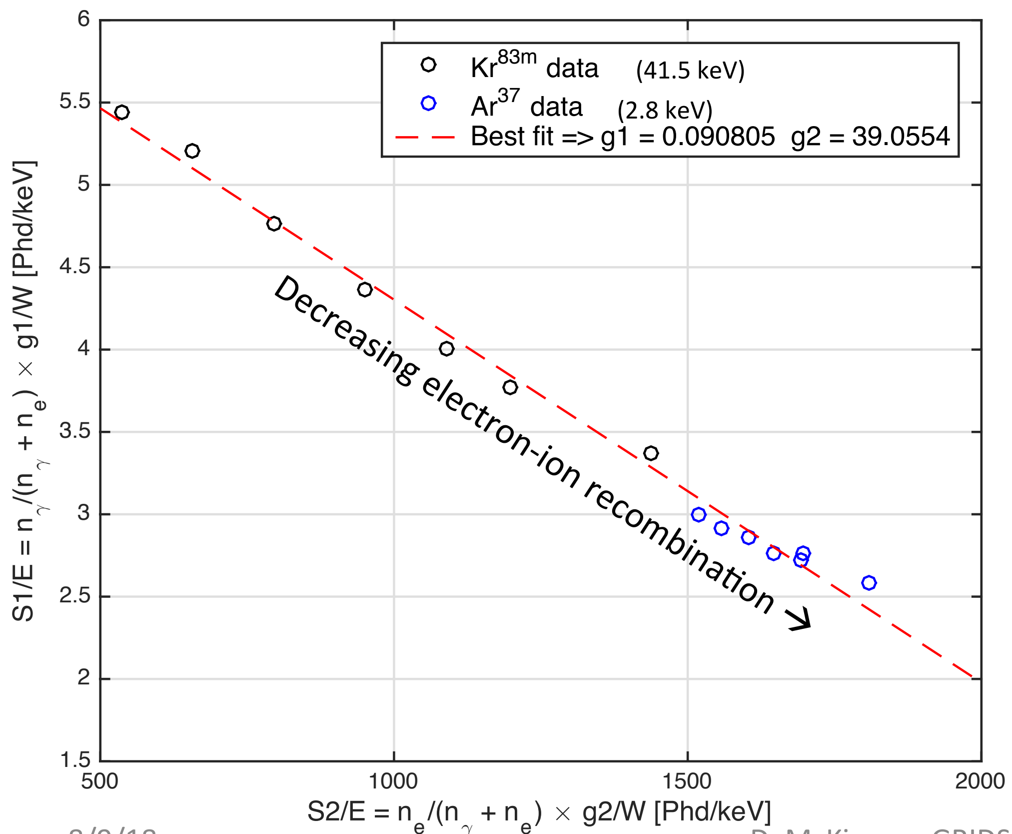
Single electrons

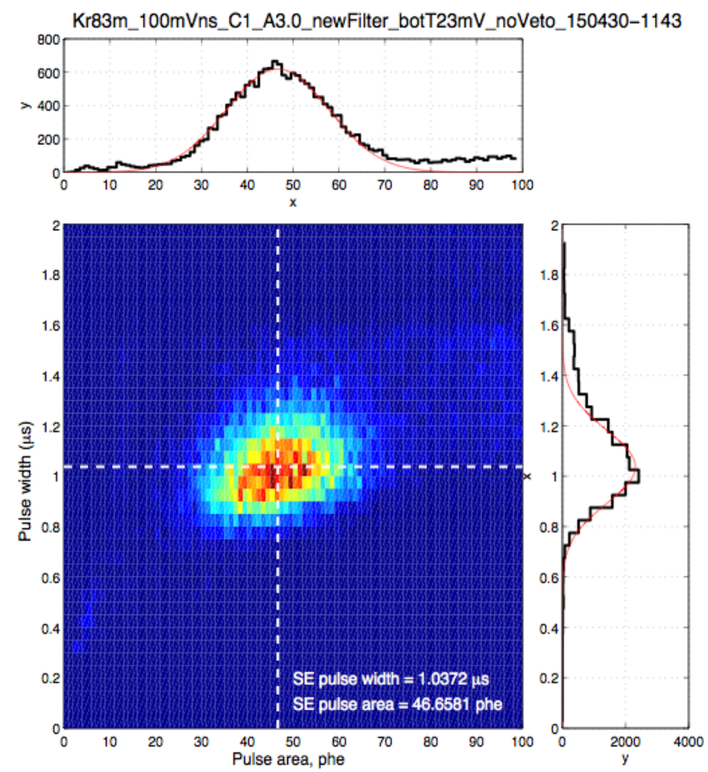




Detector Response

- S1 light collection – 9.1 ± 0.2$_{(stat)}$% - calculated from Doke plot method using ^{83m}Kr data at different fields*. Normalized to the center of the detector.
- Single electron response measured separately for every dataset - typically 34 ± 1.5$_{(sys)}$ phe.
- Corrections applied for depth-dependent corrections (electron lifetime and S1 light collection).
- Corrections not required for xy position dependent response within the inner 1/3 of the detector.





^{37}Ar Calibration Source

^{40}Ca + n → ^{37}Ar + alpha

^{37}Ar + e$^-$ → ^{37}Cl + n_e (35 day half-life)

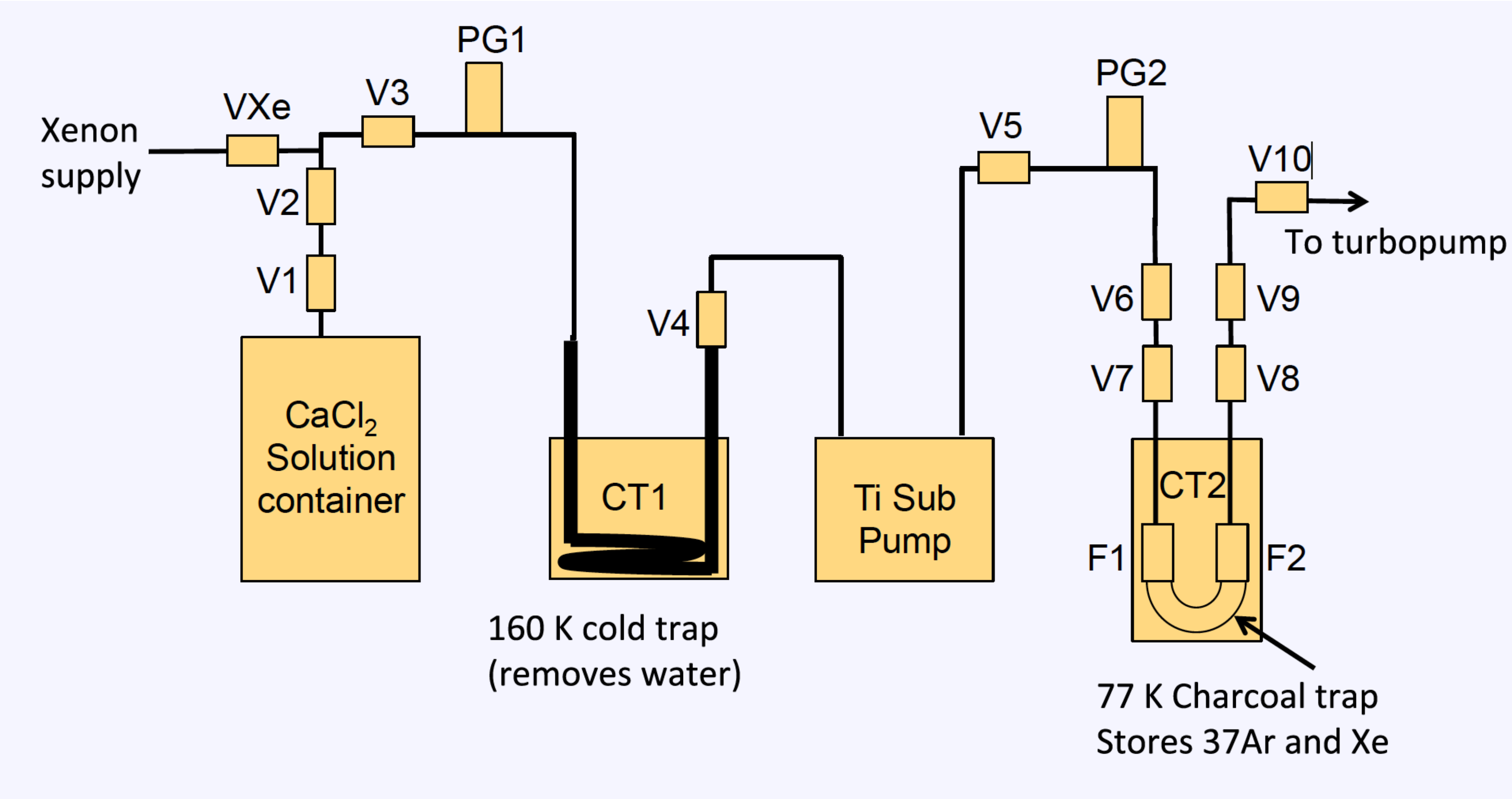
2.82 keV cascade from K shell capture

270 eV cascade from L shell capture

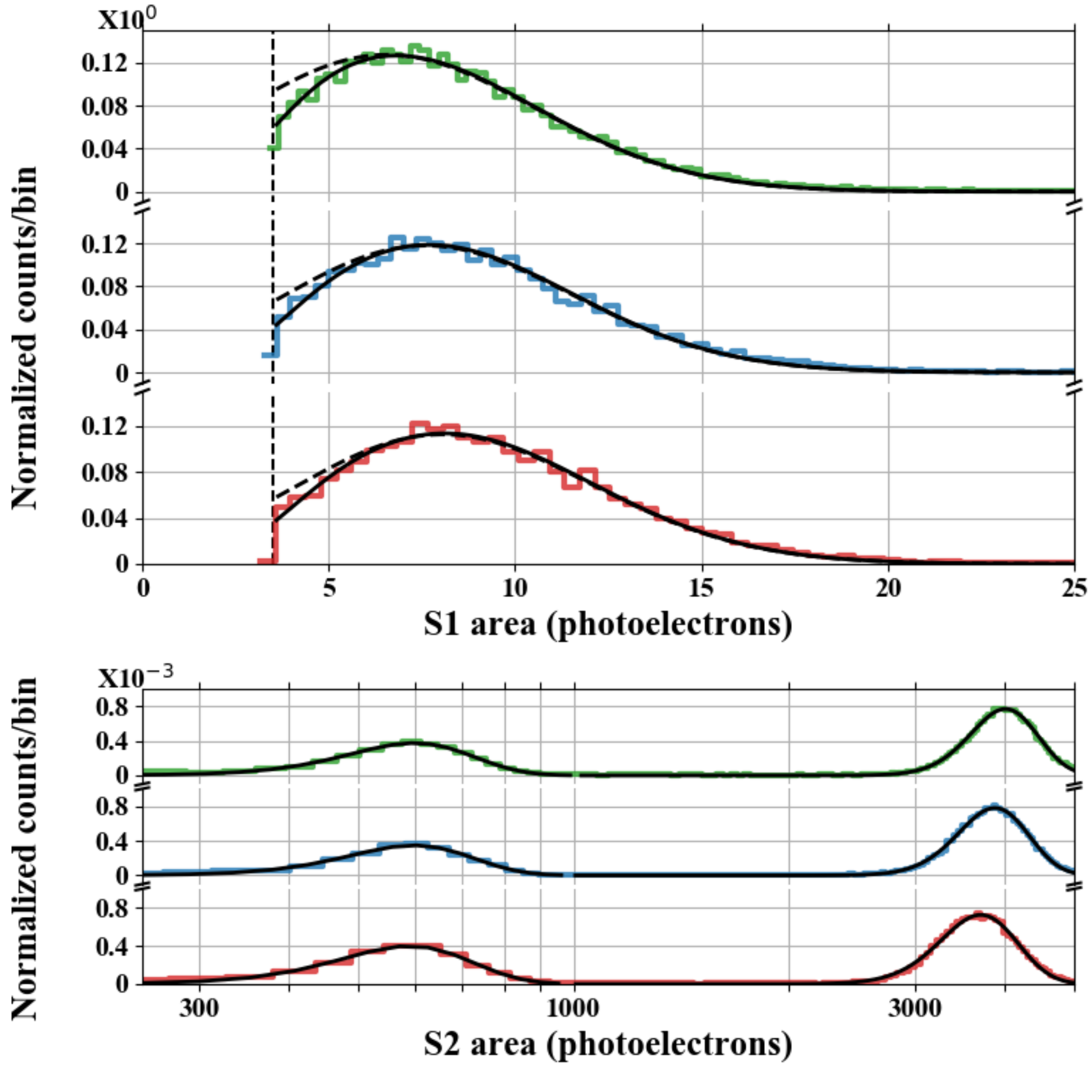
Observation of 2.82 keV capture cascade in LXe:
D.Yu. Akimov, et al., JINST, 9, 1104 (2014)

Observation of 2.82 keV and 0.27 keV cascades in LAr:
S. Sangiorgio, et al., Nucl. Inst. Meth A, 728, 69 (2013)

^{37}Ar Calibration Source

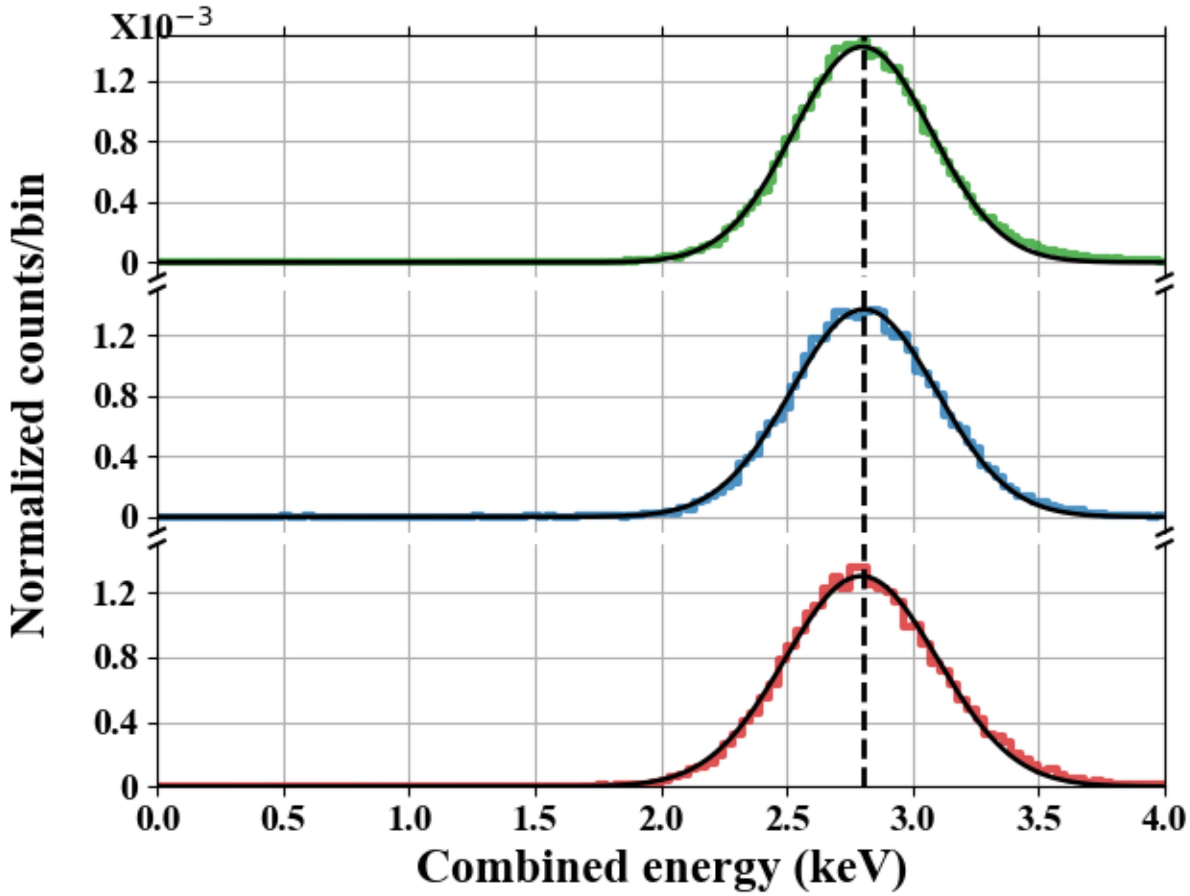


Detector Response Studied Down to Extremely Low Energies



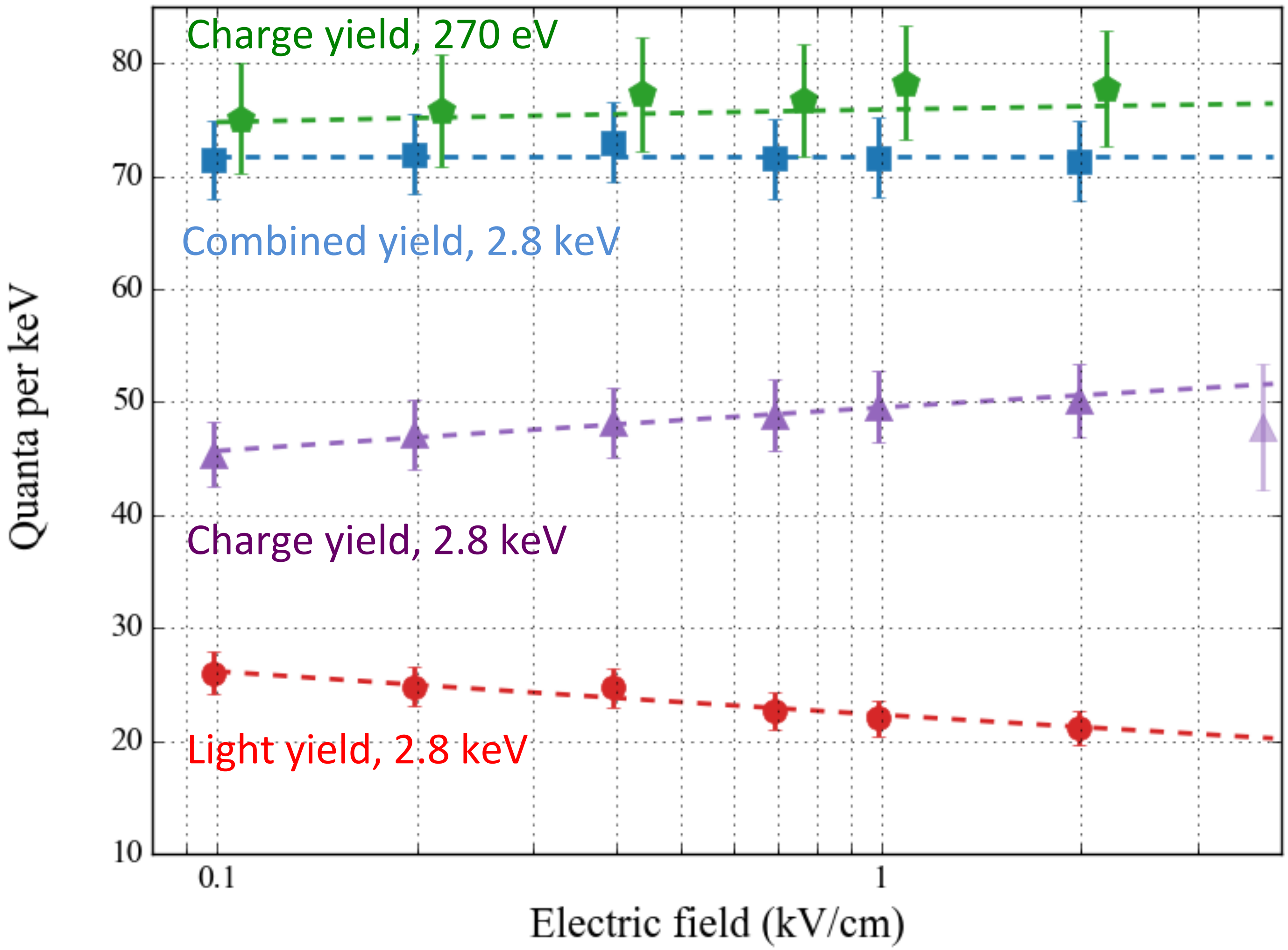
These calibrations use Ar-37, doped into the PIXeY detector

Detector Response Studied Down to Extremely Low Energies



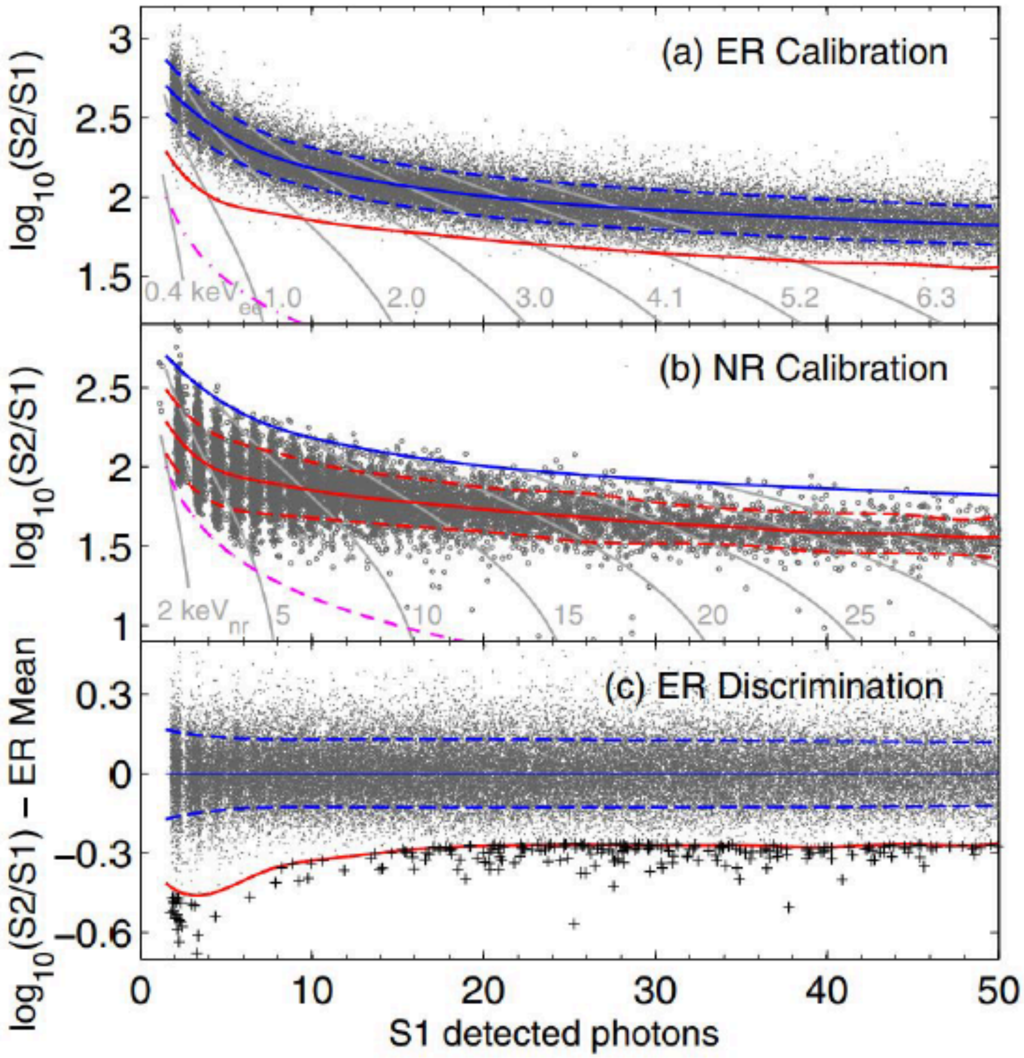
23% resolution (FWHM) at 2.8 keV

LXe Response Studied Down to Extremely Low Energies



E. M. Boulton et al., JINST 12, P08004 (2017).

Charge/light discrimination in LXe



Phys. Rev. D 97, 102008 (2018)

Discrimination is based on $\log_{10}$(S2/S1).

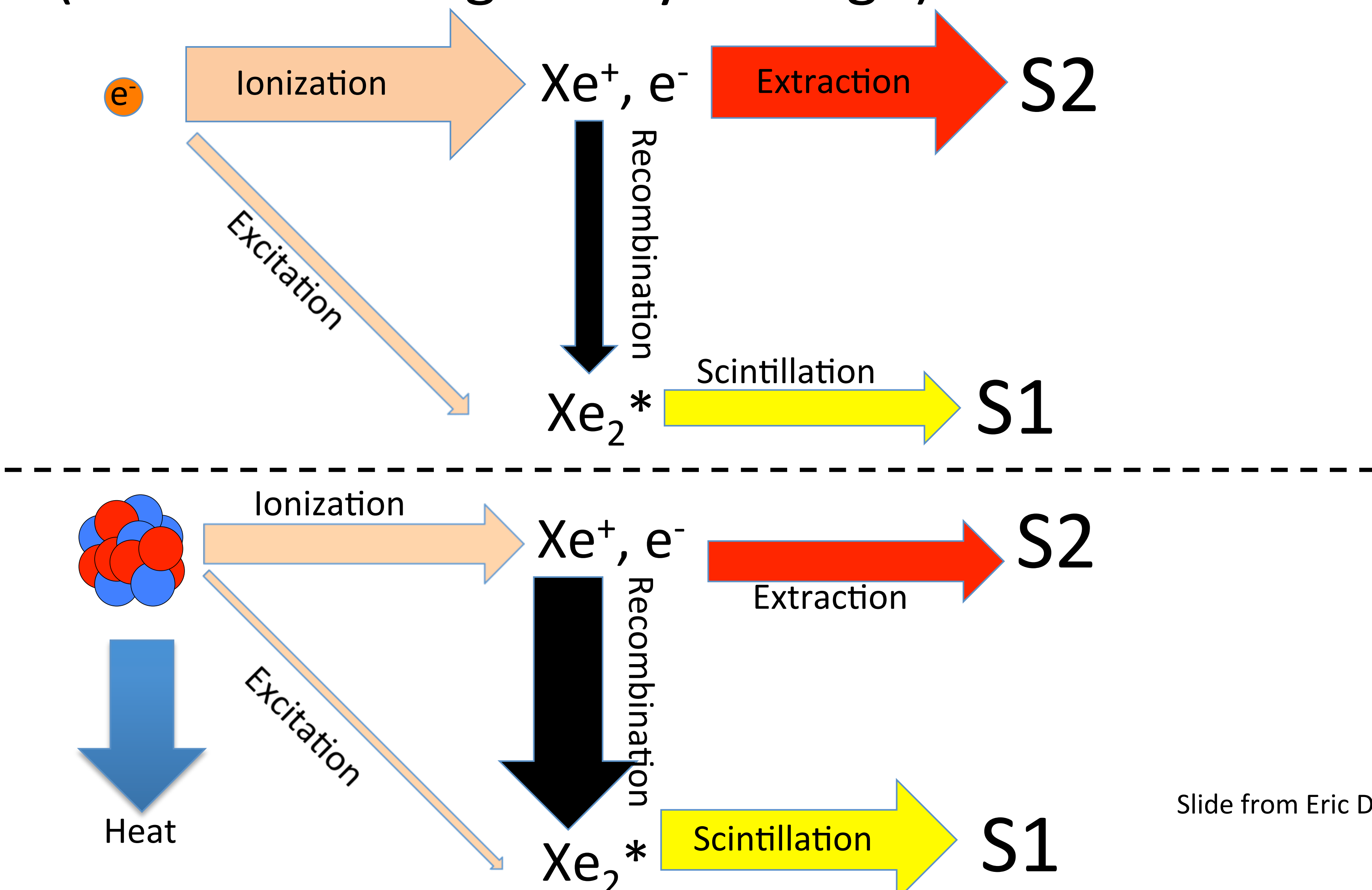
The ER and NR bands are roughly Gaussian in this quantity for moderate fields, indicating a recombination fraction that is Gaussian-distributed.

ER leakage typically reported at 50% NR acceptance.

ER leakage is typically between 99% and 99.9% in LXe, for S1 < 50 detected photons, but improves at higher energies.

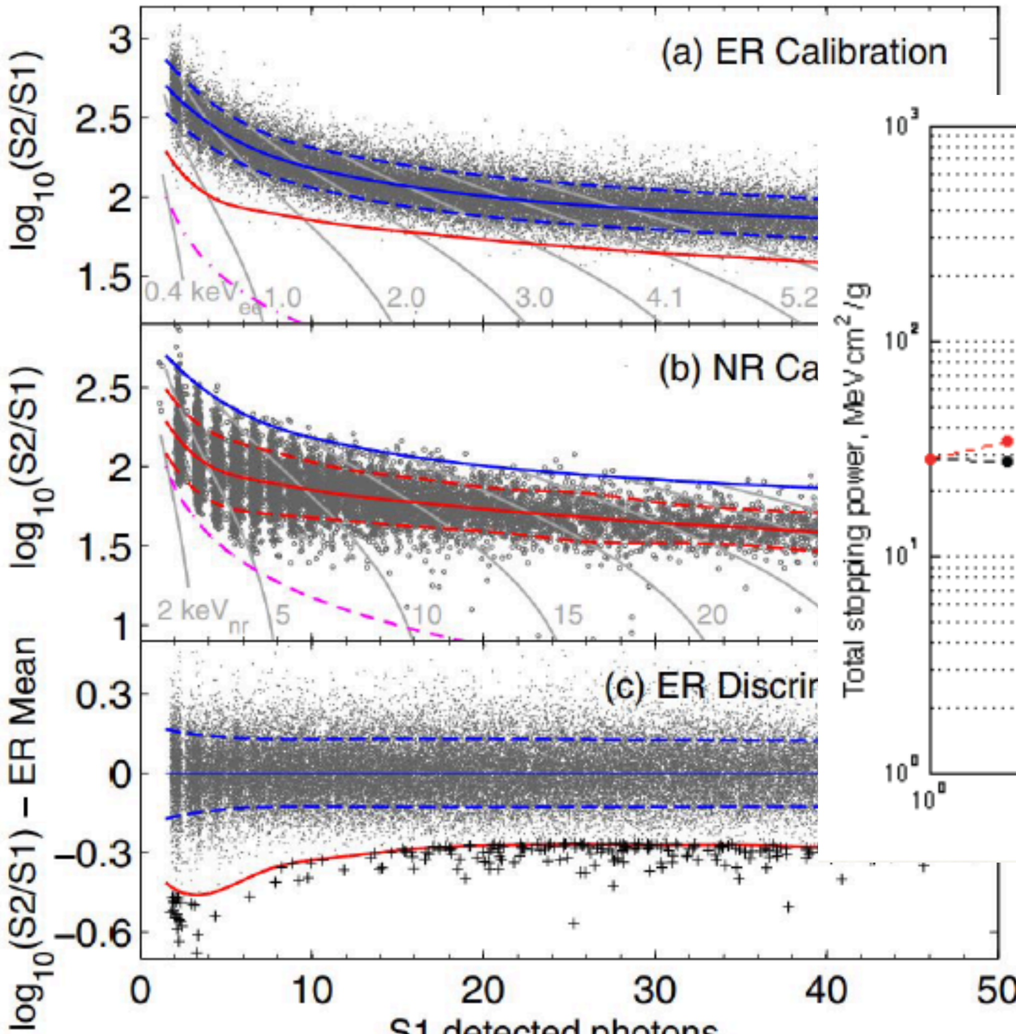
Discrimination in Liquid Xenon

(What we thought 10 years ago)



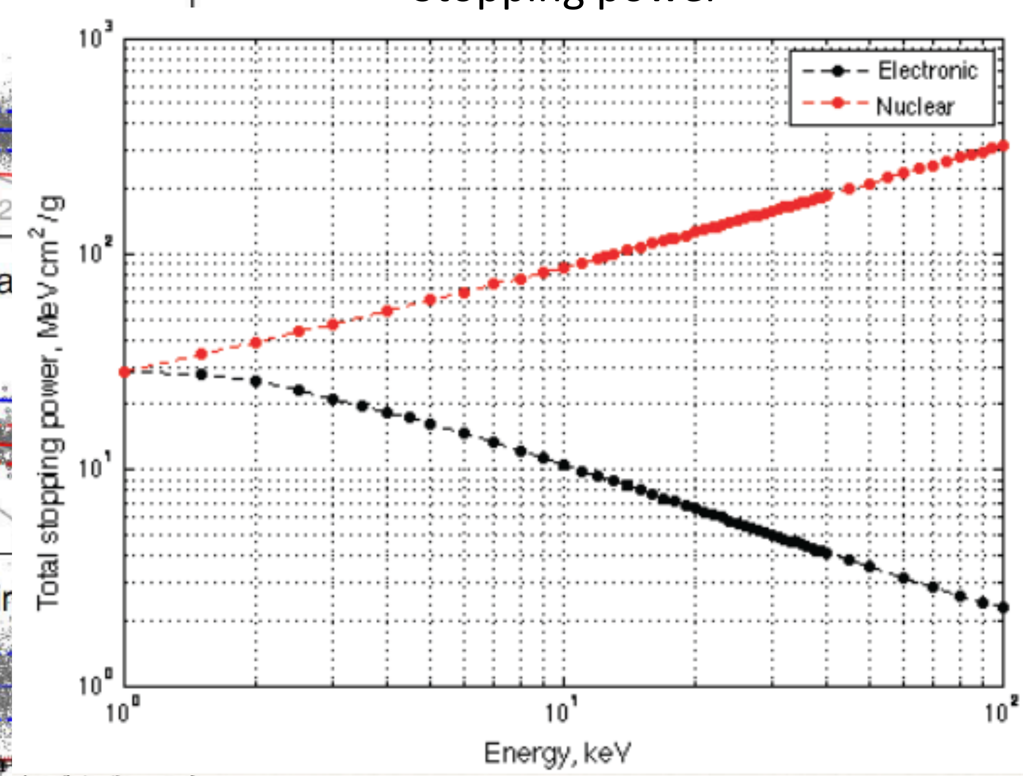
Slide from Eric Dahl

Charge/light discrimination in LXe



Phys. Rev. D 97, 102008 (2018)

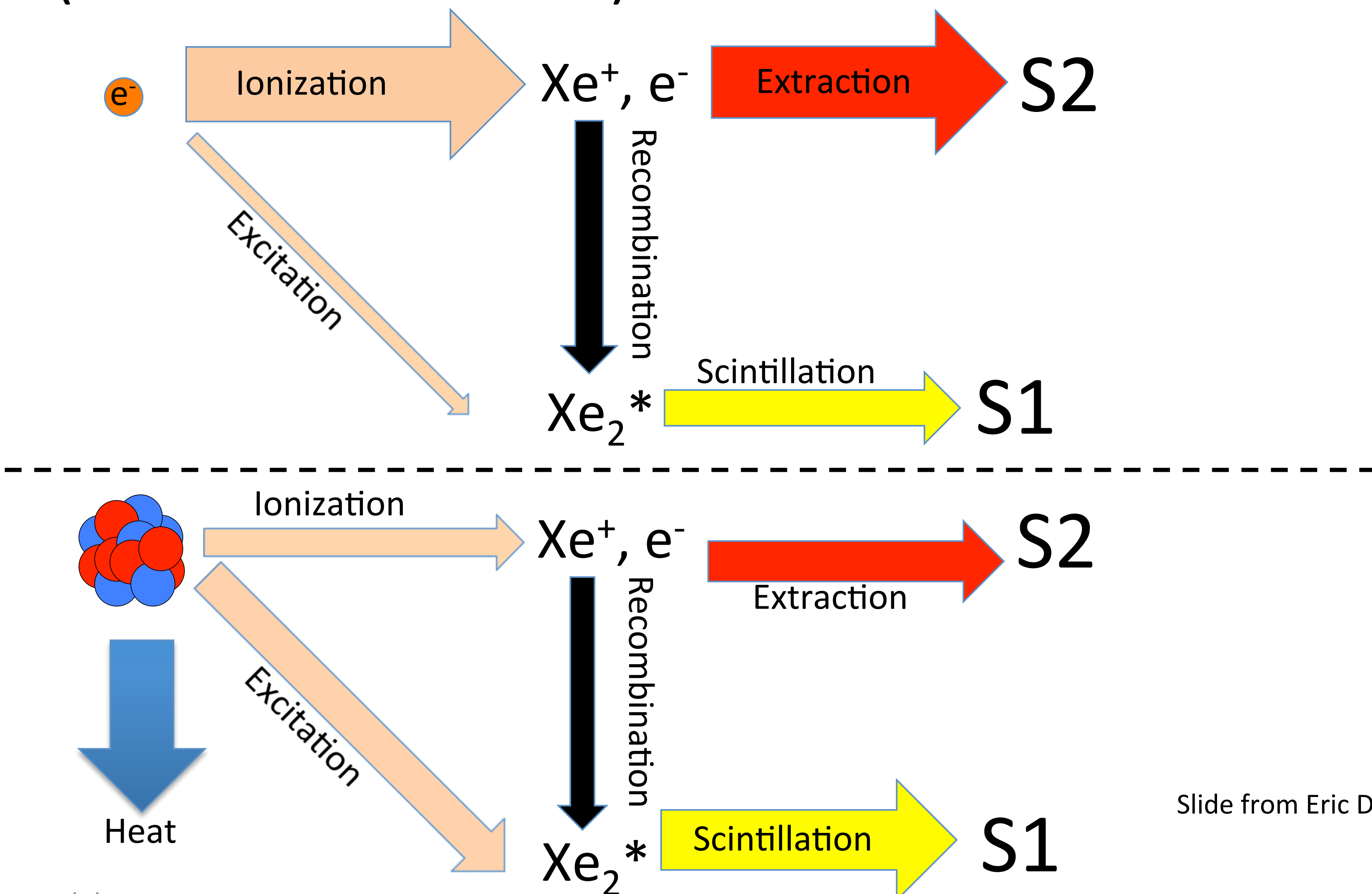
Stopping power



Stopping power variation with energy does **not** explain the ER and NR band shapes

Discrimination in Liquid Xenon

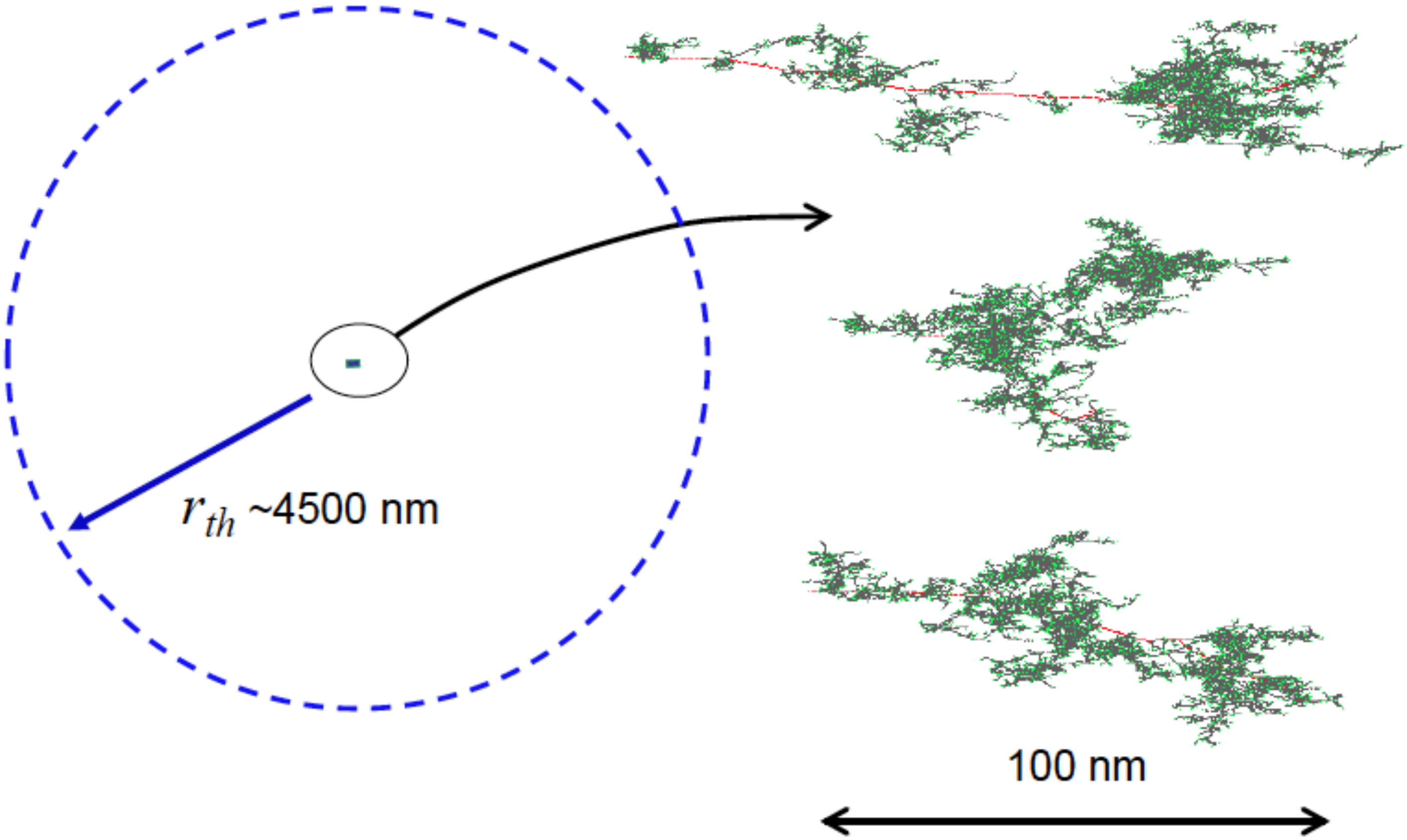
(What we think now)



Slide from Eric Dahl

Nuclear recoils in LXe

Electrons become spread over a sphere of radius r_{th}, roughly independent of energy.



From V. Chepel and H. Araujo, “Liquid noble gas detectors for low energy particle physics”, arXiv:1207.2292

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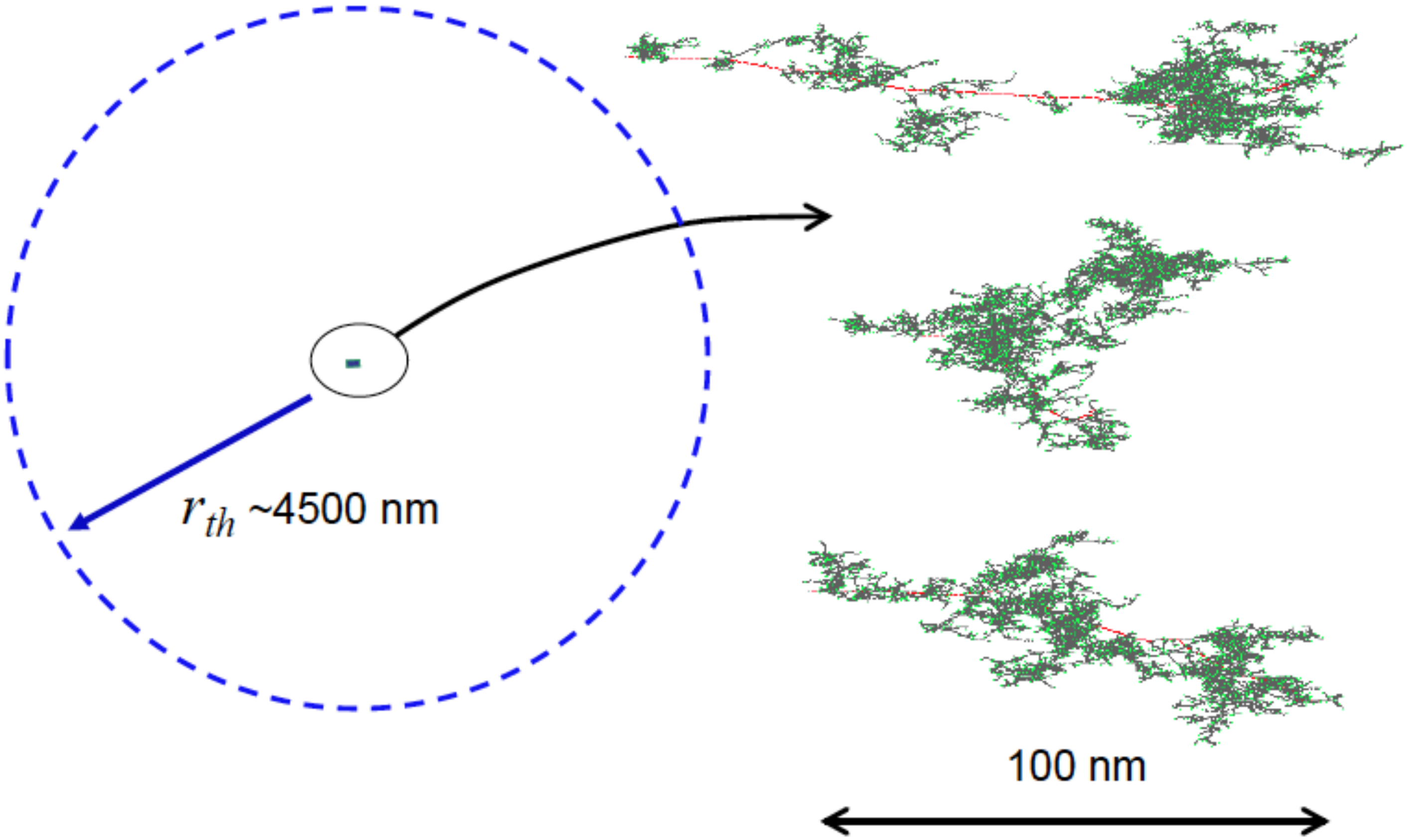


The chance that a given ion recombines decreases as the number of electrons in the sphere decreases! This causes the low-energy turn-up in the S2/S1 band, for both ER and NR.

Recombination

- The number of photons, n_γ, and number of electrons, n_e, are expressed as

$$n_\gamma = N_{ex} + rN_i$$
$$n_e = N_i\left(1 - r\right)$$

where N_{ex} and N_i are number of initial excitations and initial ionizations respectively. The ratio N_{ex} /N_i is different for ER and NR

- r is the fraction of ionized particles that recombine

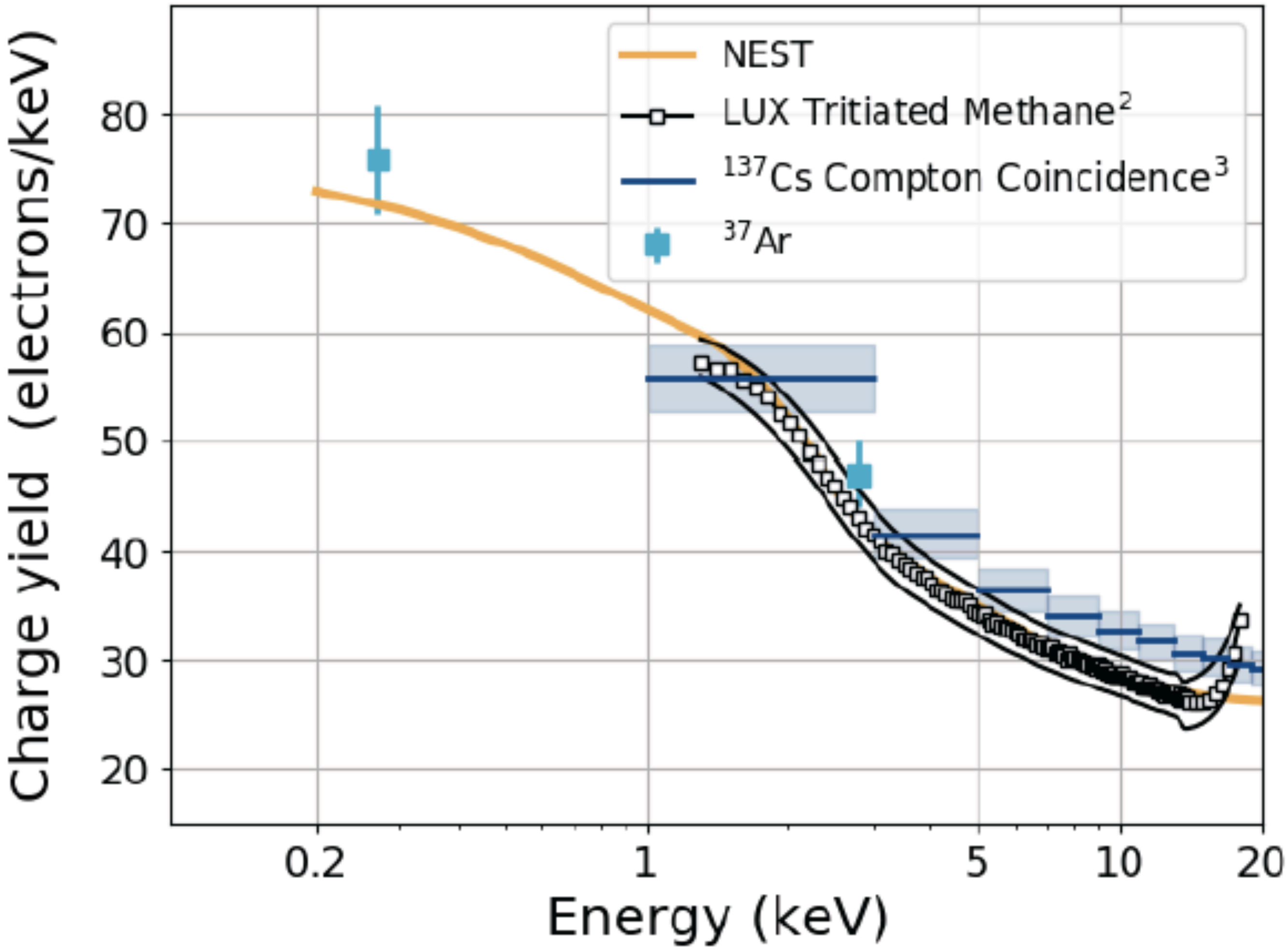
$$r = \frac{\frac{n_\lambda}{n_e} - \alpha}{\frac{n_\lambda}{n_e} + 1}$$

Thomas-Imel Box Model

$$\frac{\partial N_+}{\partial t} = -\alpha N_+ N_-$$
$$\frac{\partial N_-}{\partial t} = -v\frac{\partial N_-}{\partial z} - \alpha N_+ N_-$$

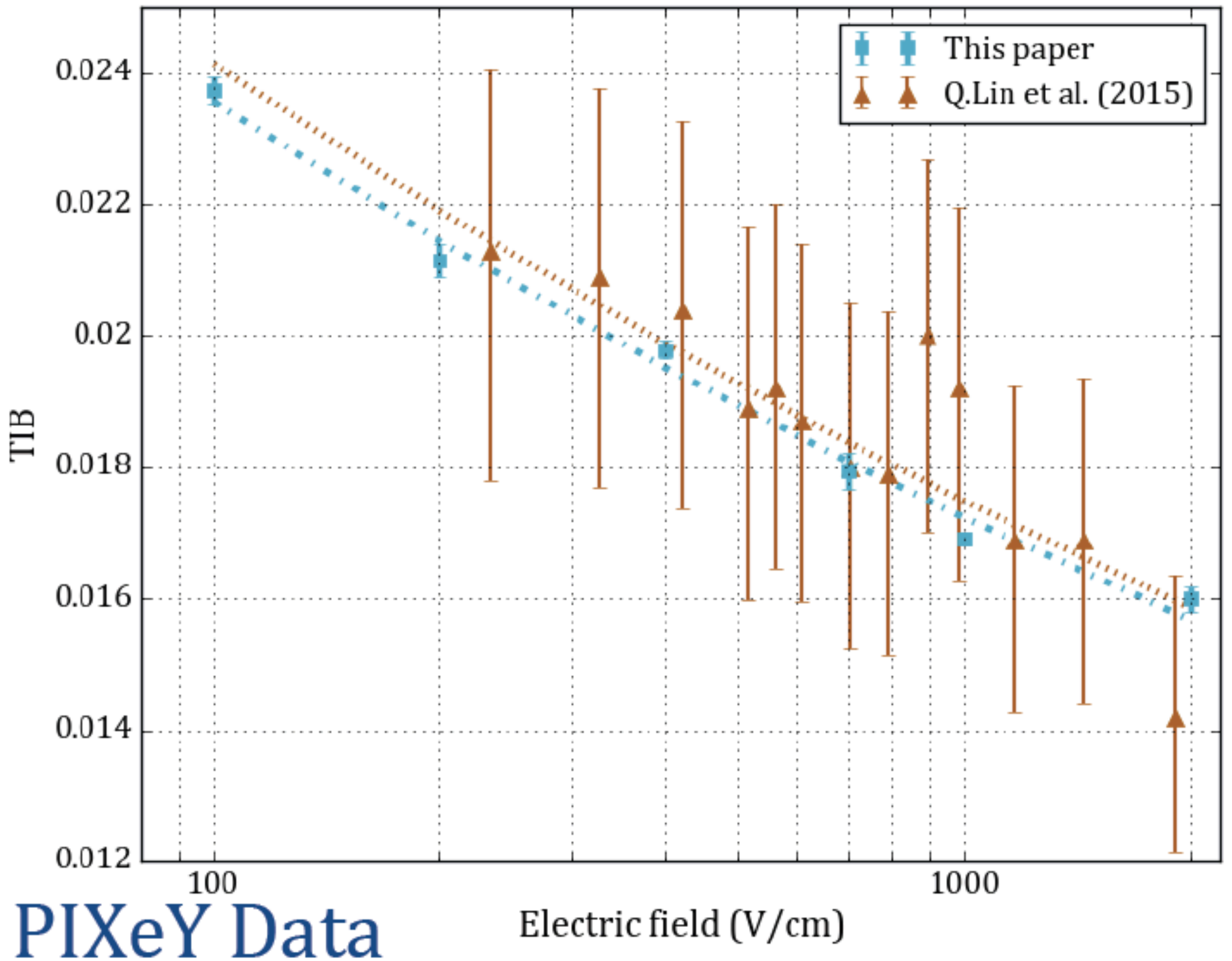
- Initial condition: N_+ and N_- uniform inside a square box, giving total ionization N_i
- As t→∞ : $\frac{n_e}{N_i} = \frac{1}{\xi}\ln(1+\xi)$, where $N_i \propto \xi$
- This "Thomas-Imel" box model is used to accurately predict yields in low-energy tracks

Electron Recoil Charge Yields



[2] L. W. Goetzke, E. Aprile, M. Anthony, G. Plante, and M. Weber, [arXiv:1611.10322].
[3] LUX Collaboration, D. S. Akerib et al. Phys. Rev. D **93**, 072009 (2016).

TIB Parameter at 2.8 keV

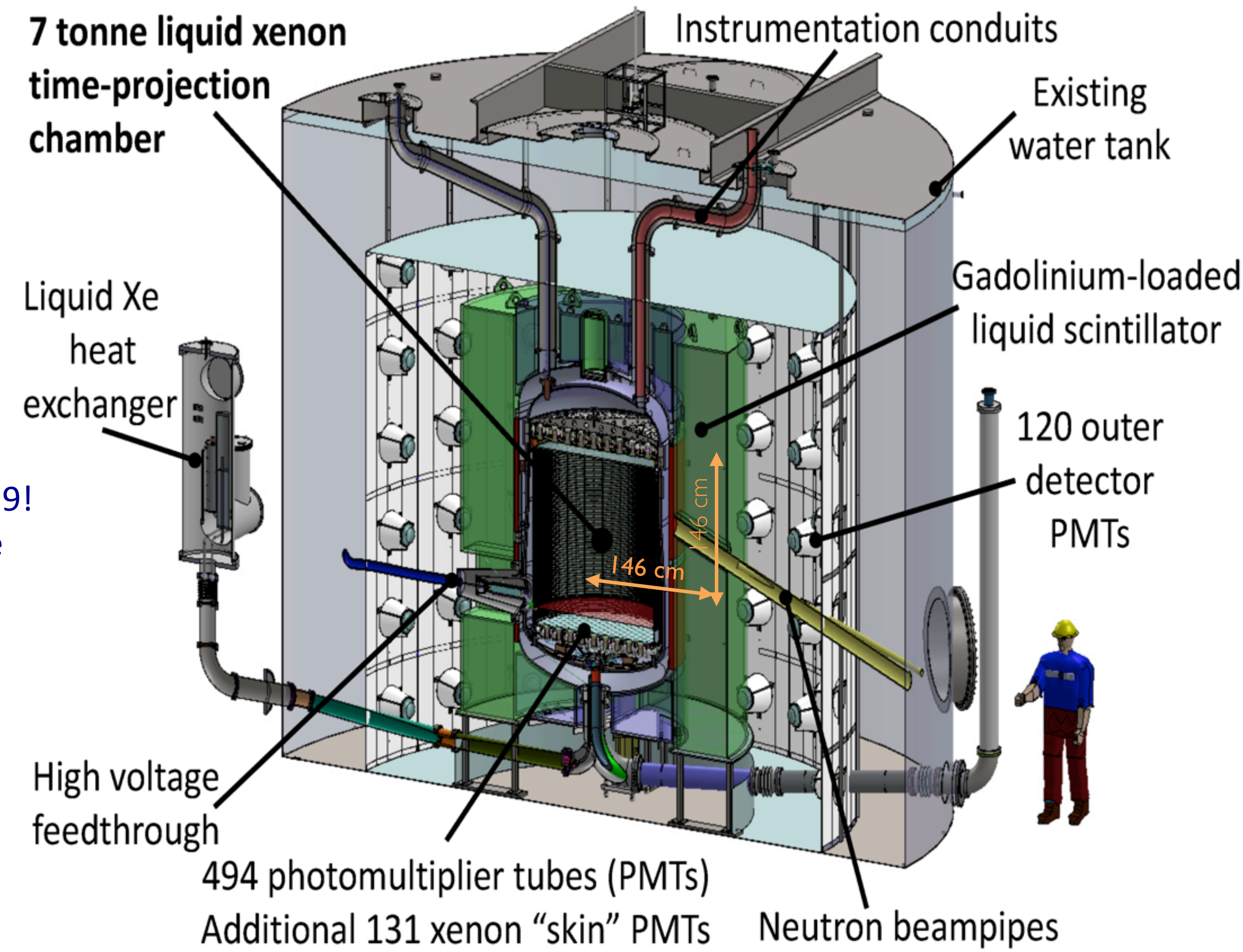


[3]Q. Lin, et al. pre-print arXiv:1505.00517v2 (2015)

From LUX to LUX-ZEPLIN (LZ)

LUX goes to a museum

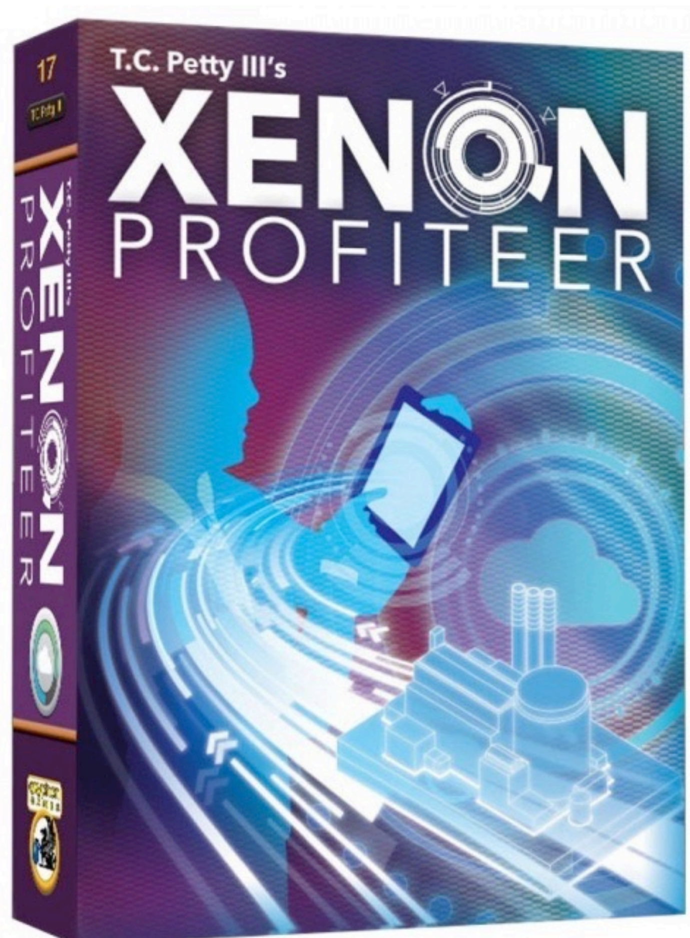
LZ design



Commissioning in 2019!
Will be 50 times more sensitive than LUX.

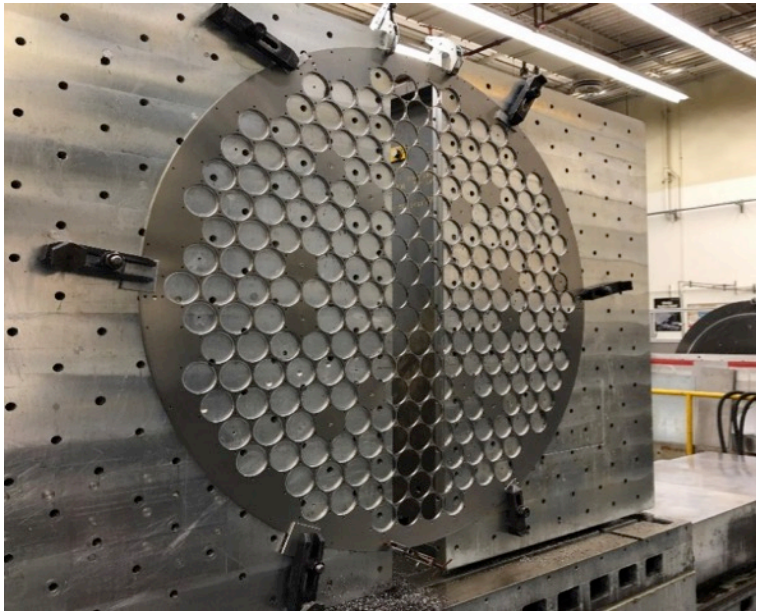
"In Xenon Profiteer, you use your entrepreneurial spirit and an Air Separation facility to isolate valuable Xenon and make a profit."

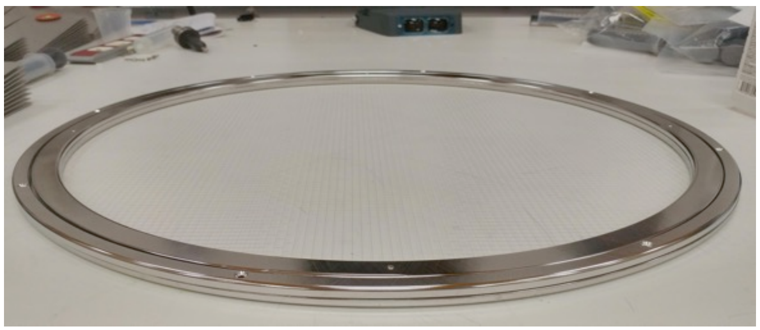
"***Xenon Profiteer*** is a highly thematic, deck-deconstruction, euro game for 2-4 entrepreneurs in which each player takes control of their own Air Separation
Facility and distills Xenon from their Systems to complete lucrative contracts. You will also physically expand your facility by building upgrades, pipelines, and acquiring new contracts and connecting them to your Center Console."



Gryphon and Eagle Games

LZ CONSTRUCTION





What will be the impact of LZ?

Baer, Barger, Serce: 'SUSY under siege from direct and indirect WIMP detection experiments'; arXiv: 1609.06735.

'Projections from ton-scale noble liquid detectors should discover or rule out WIMPs from the remaining parameter space of these surviving models.'

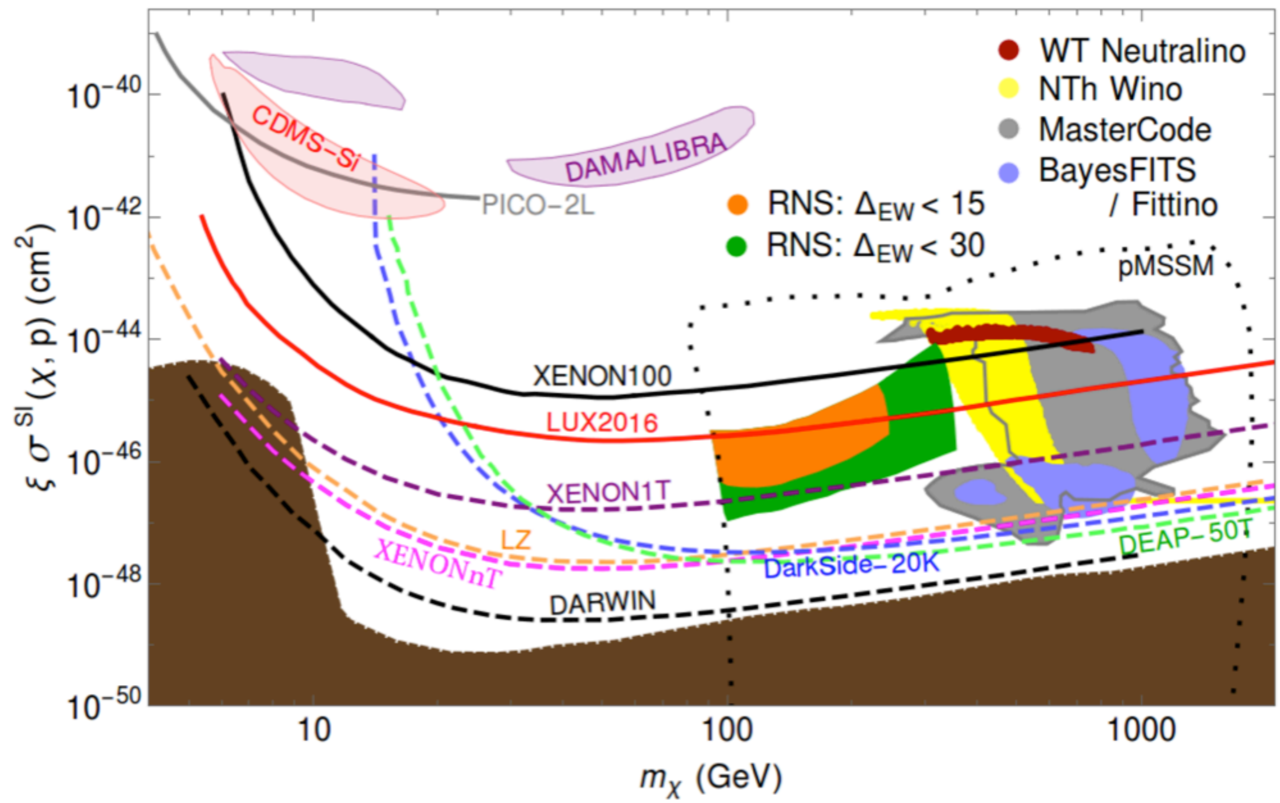
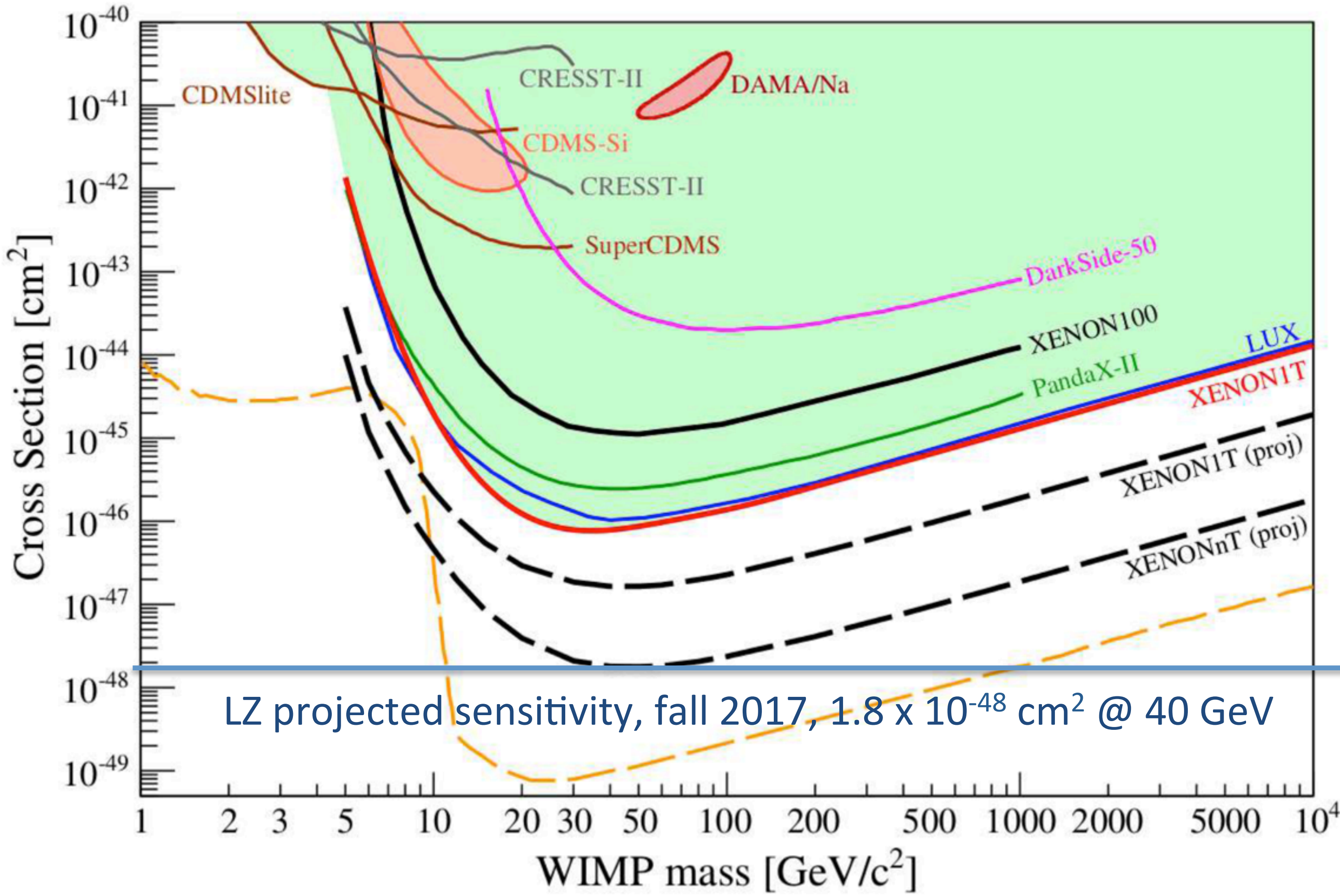


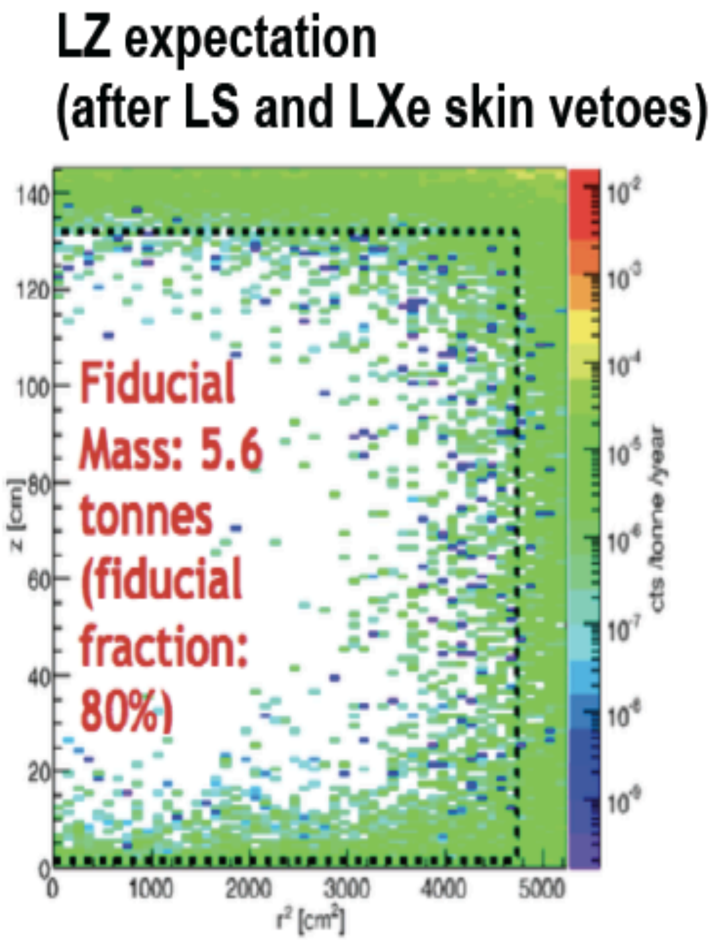
Figure 1: Plot of rescaled spin-independent WIMP detection rate $\xi\sigma^{SI}(\chi, p)$ versus m_χ from several published results versus current and future reach (dashed) of direct WIMP detection experiments. $\xi = 1$ (*i.e.* it is assumed WIMPs comprise the totality of DM) for the experimental projections and for all models *except* RNS and pMSSM.

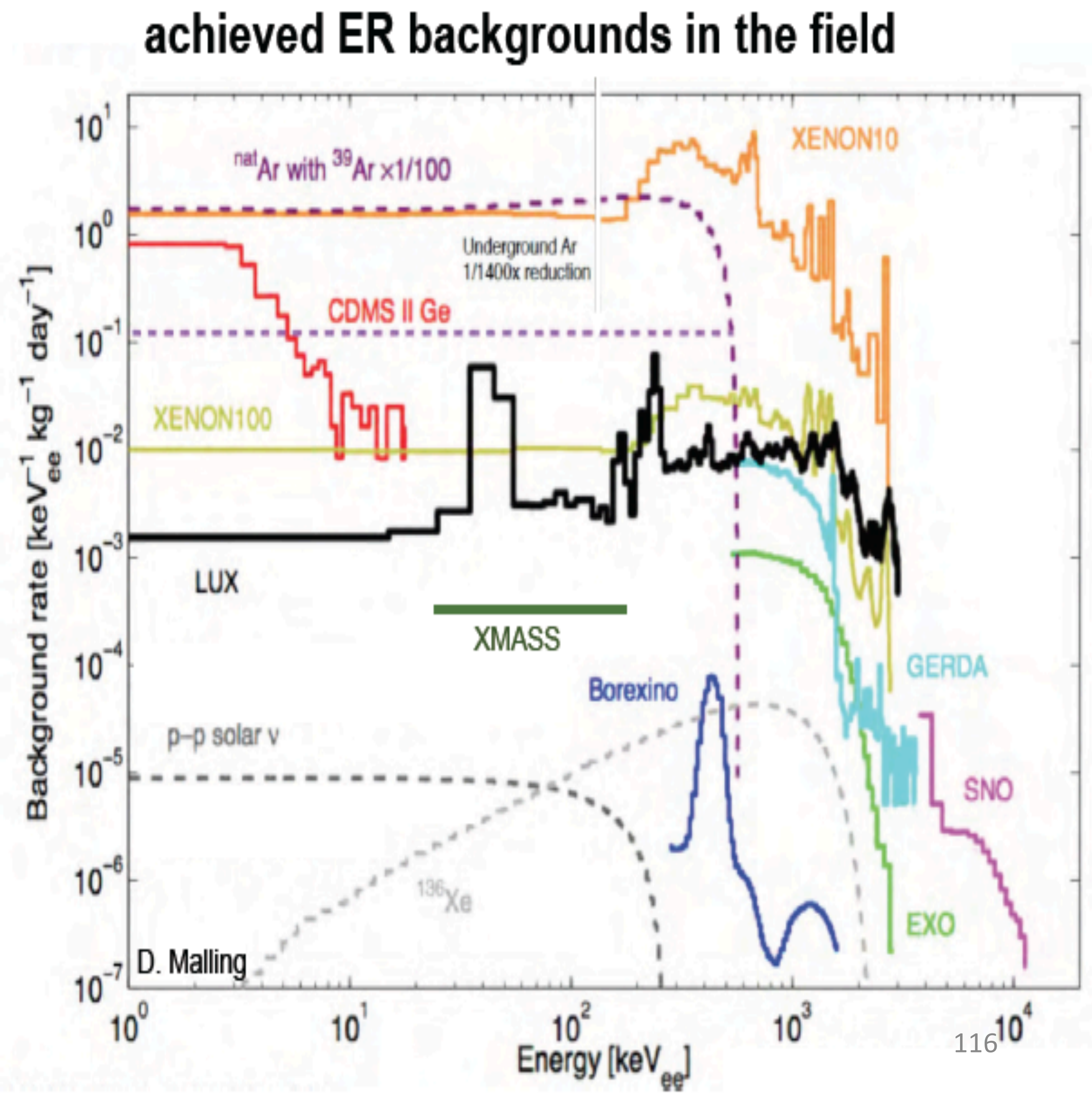
XENONnT sensitivity – PATRAS, May 2017



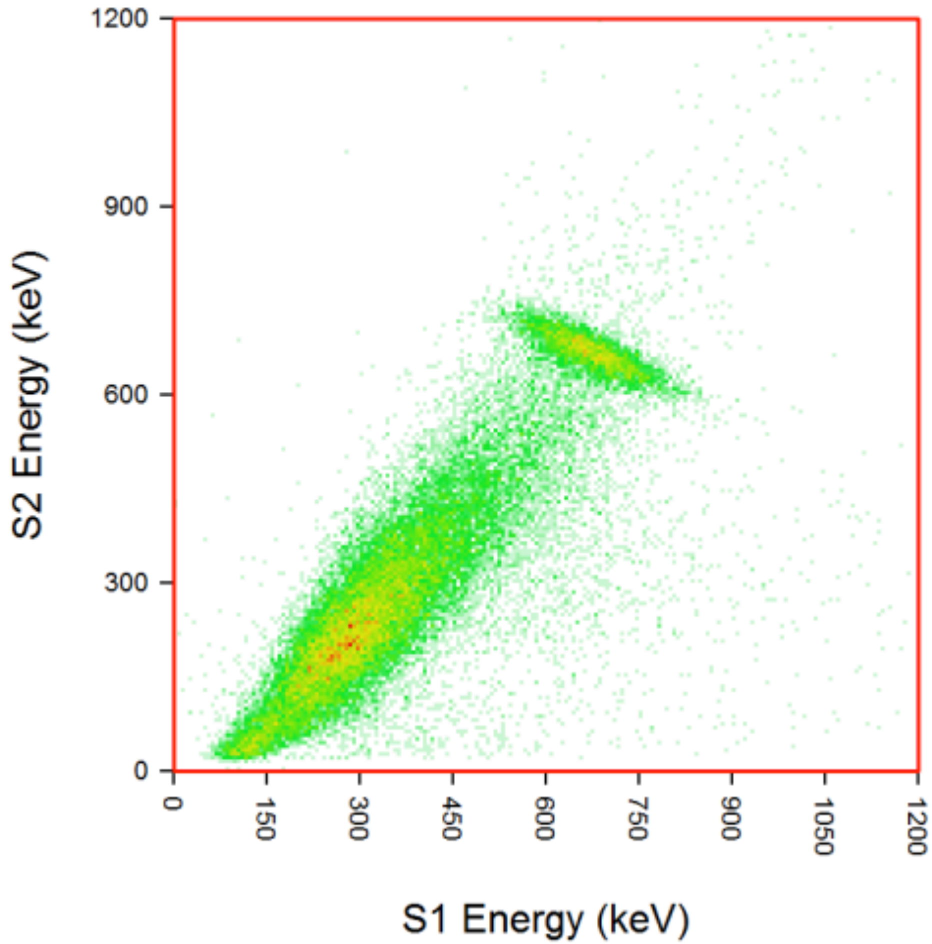
LZ projected sensitivity, fall 2017, 1.8×10^{-48} cm^2 @ 40 GeV

This technology excels at the combination of low background and low energy threshold



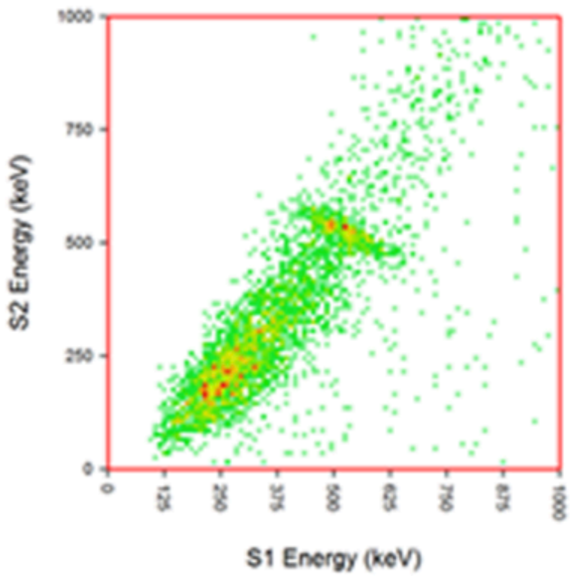


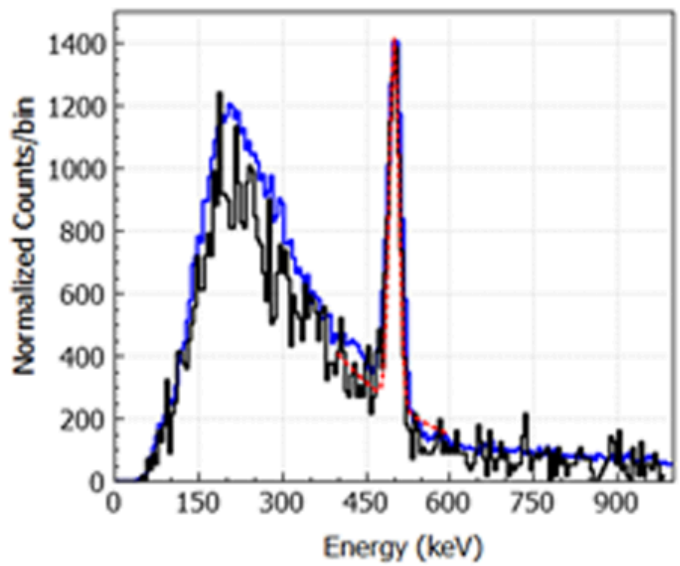
Anticorrelation in S1 and S2 Signals



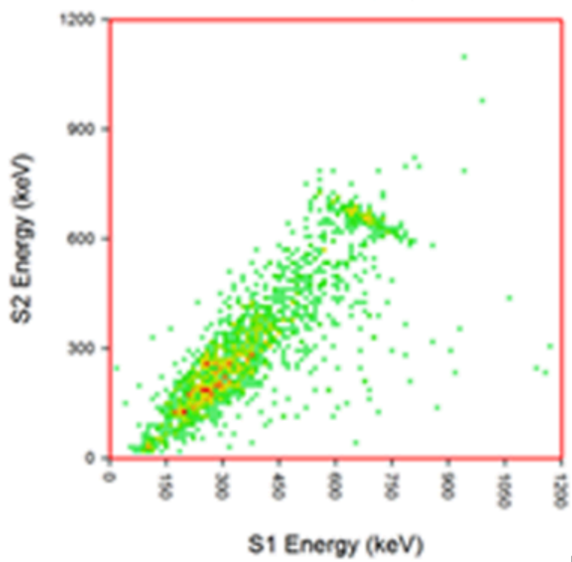
Gamma-ray data from Cs-137 as measured in the PIXeY detector. Monoenergetic gamma ray absorption events in LXe produce both light (S1) and charge (S2) signals, which are anticorrelated.

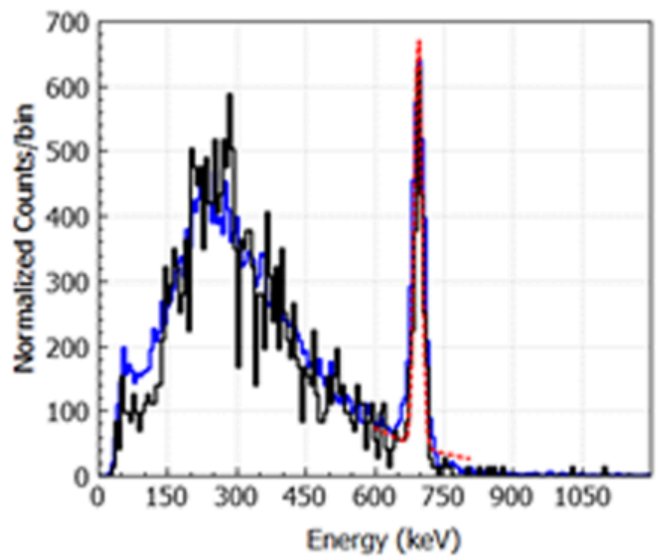
Energy resolution measurements in PIXeY, with 1 kV/cm drift field





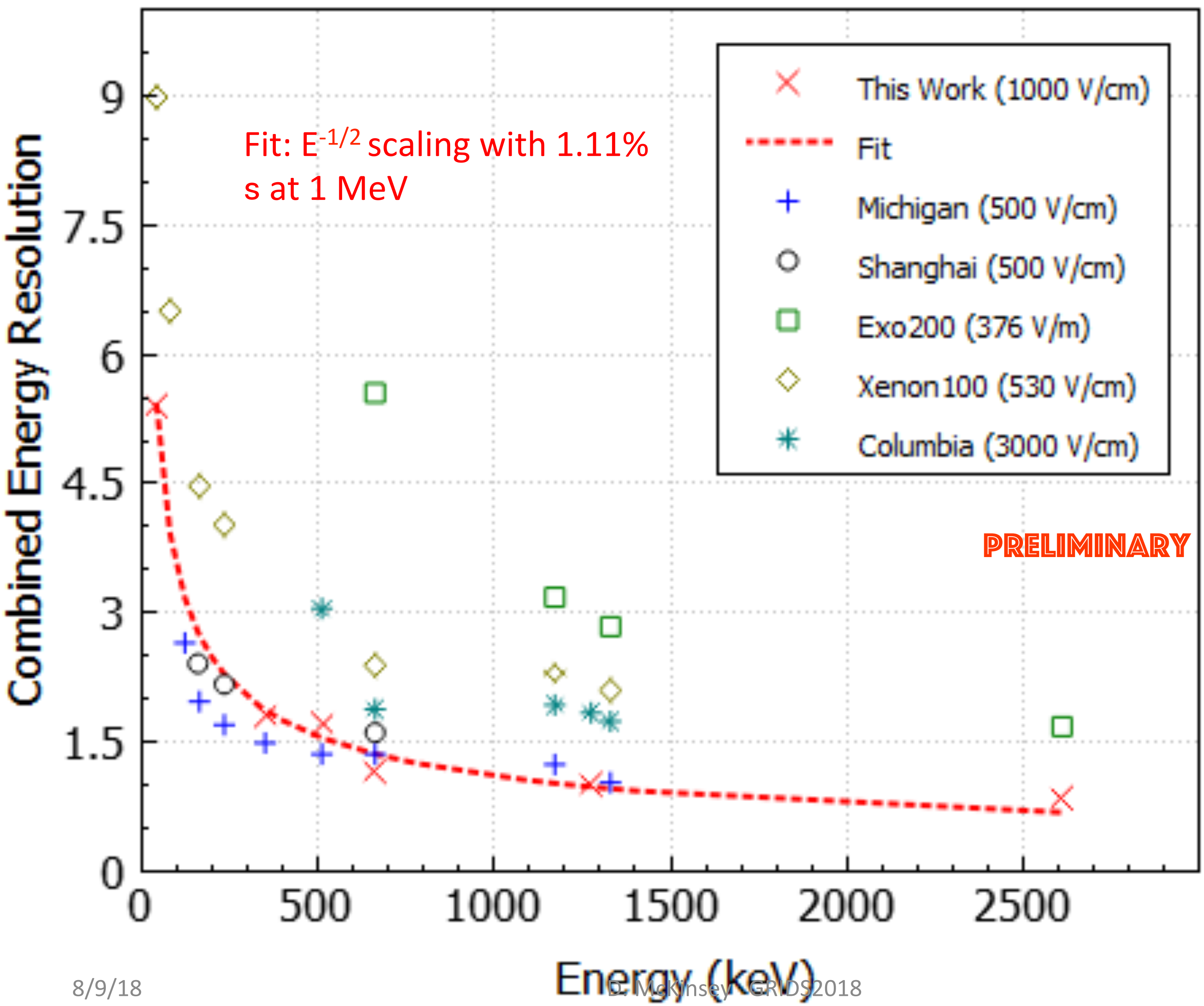
^{22}Na (511 keV)
3.9% FWHM





^{137}Cs (662 keV)
2.8% FWHM

Energy Resolution at 1 kV/cm Drift Field



Michigan-
S. Stephenson et al., J. Inst. 10 (2015) P10040

Shanghai-
Q. Lin et al., J. Inst. 9 (2013) P04014

Exo200-
Auger, M. et al. J. Inst. 7 (2012) P05010

XENON100-
E. Aprile et al., Astropart. Phys. 35 (2012), 573-590

Columbia-
Kaixuan Ni thesis, section 4.6.3 (2006)

LXe for Neutrinoless Double Beta Decay Searches

Advantages:

- Good energy resolution (~ 1% at Q-value)
- Excellent event multiplicity measurement
- Scalability -> self-shielding, measurement of position dependence of backgro
- Alpha particle identification
- Continuous purification to remove neutron activation backgrounds.

Existing experiments:

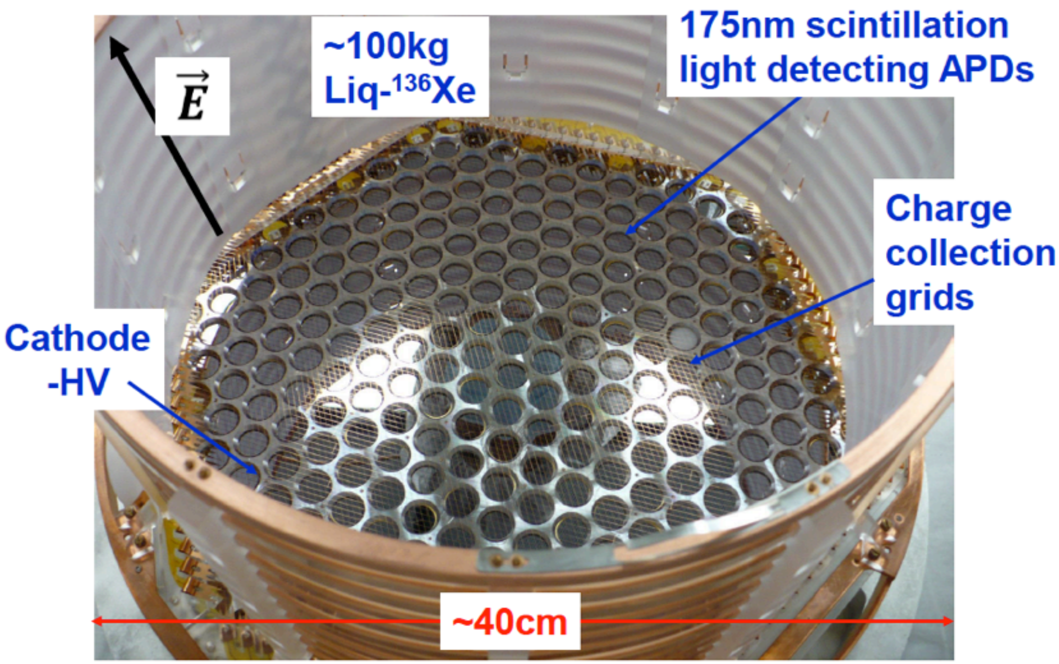
- EXO (running, current half-life limit of 3.8×10^{25} y)
- Xenon1T (2 tonnes natural Xe)

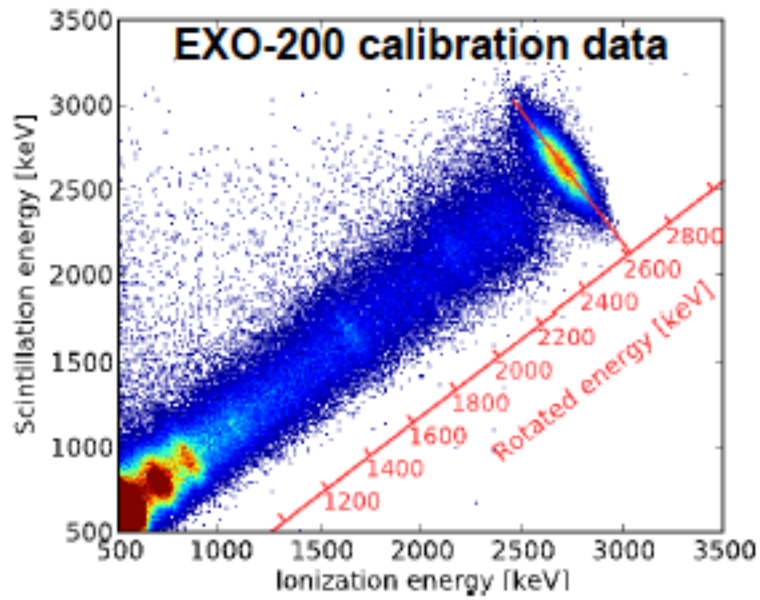
Future experiments:

- nEXO (5 tonnes of enriched ^{136}Xe, sensitivity 9×10^{27} y)
- LZ (7 tonnes natural Xe, sensitivity 1.2×10^{26} y, starts 2020)
- XENONnT (6 tonnes natural Xe)
- DARWIN ? (40 tonnes natural Xe)

LXe for Neutrinoless Double Beta Decay Searches

EXO-200 in progress, will end Dec. 2018. Currently sets a half-life limit of 3.8×10^{25} y .

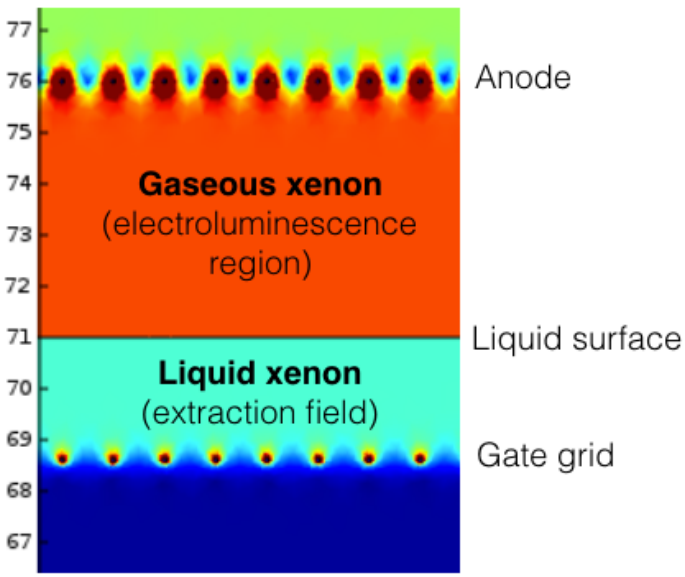


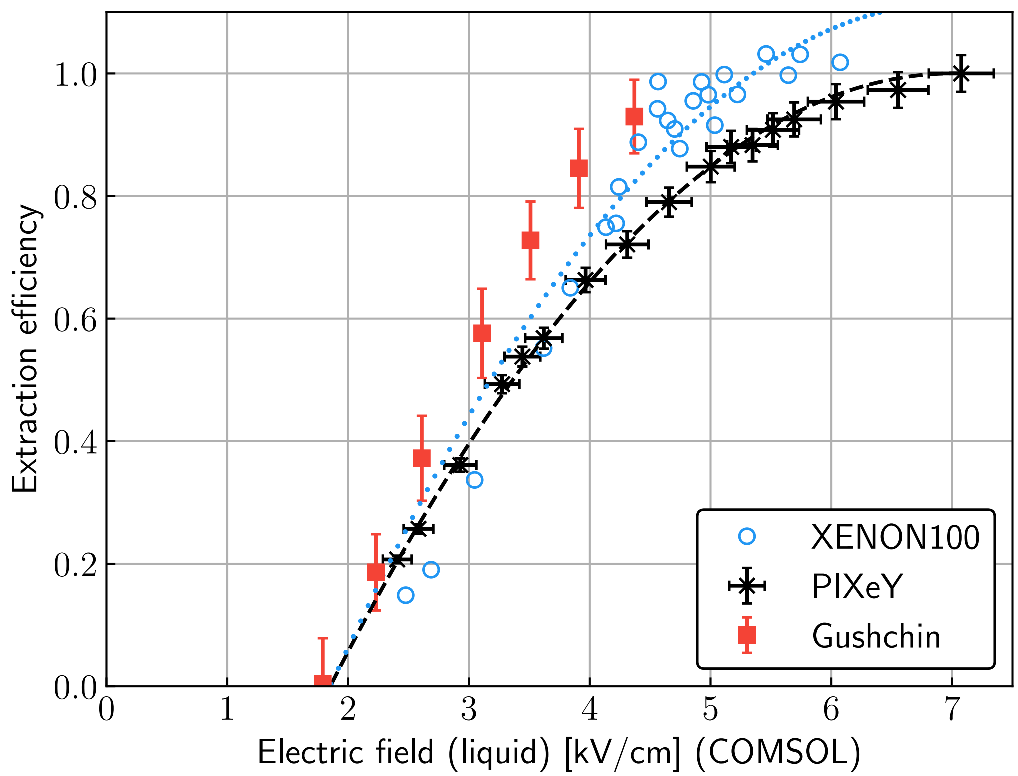


(G. Gratta, Neutrino 2018)

New measurement of electron extraction efficiency

B. N. Edwards et al., JINST 13, P01005 (2018)





This is the probability that an electron in liquid Xe is extracted into the gaseous Xe, for a given electric field applied across the liquid/gas interface.

Neutron vs Gamma-Ray Discrimination

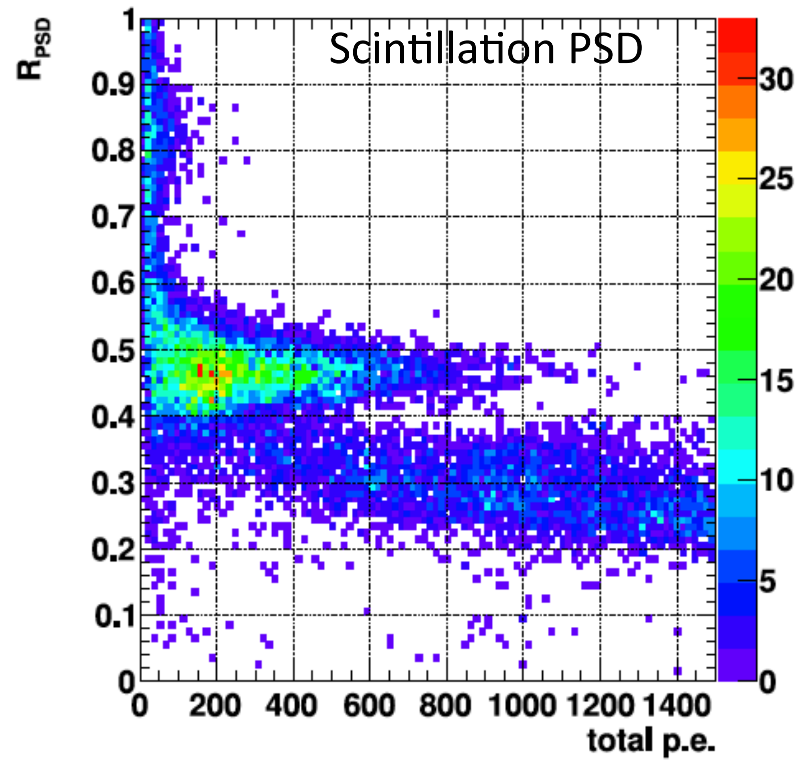
- Neutron energy deposition is suppressed by a factor of ~40 by simple kinematics:

$$E_{Xe} = 2E_n \frac{m_n m_{Xe}}{\left(m_n + m_{Xe}\right)^2}\left(1 - \cos\theta\right)$$

- Charge-to-light ratio is suppressed for neutrons
  Standard method for dark matter search

- Scintillation pulse-shapes are faster for neutrons, slower for gammas
  (K. Ueshima et al, arXiv:1106.2209)

  Also new LUX paper, arXiv:1802.06162 accepted to PRD

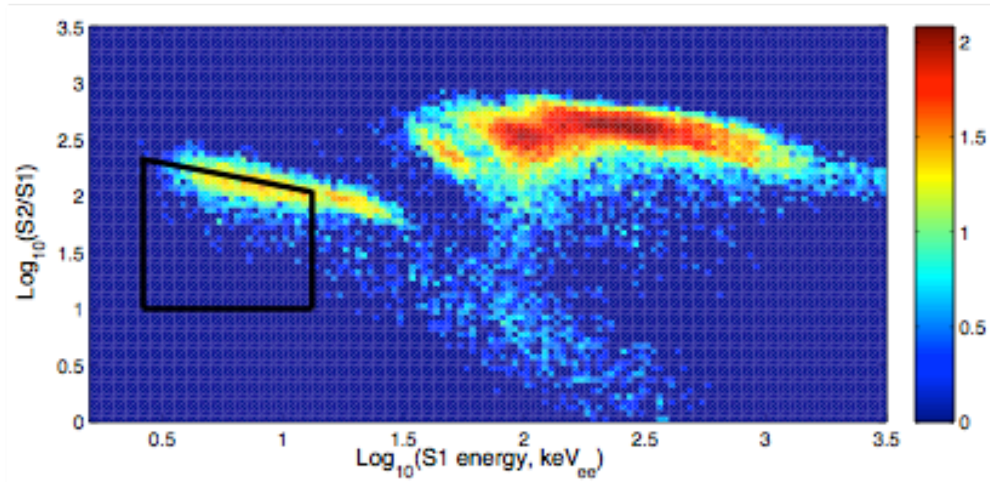


Neutron vs Gamma-Ray Discrimination in PIXeY

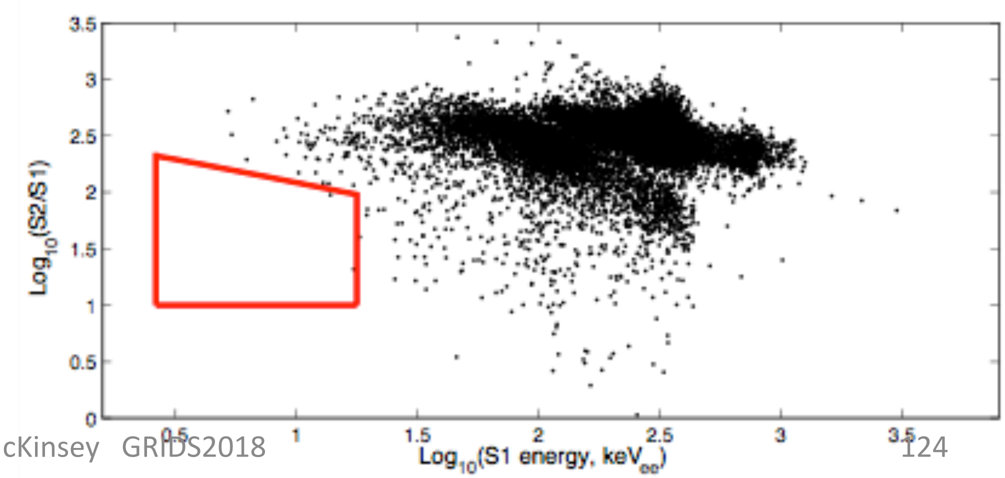
Overall factor of 40,000 gamma-ray rejection

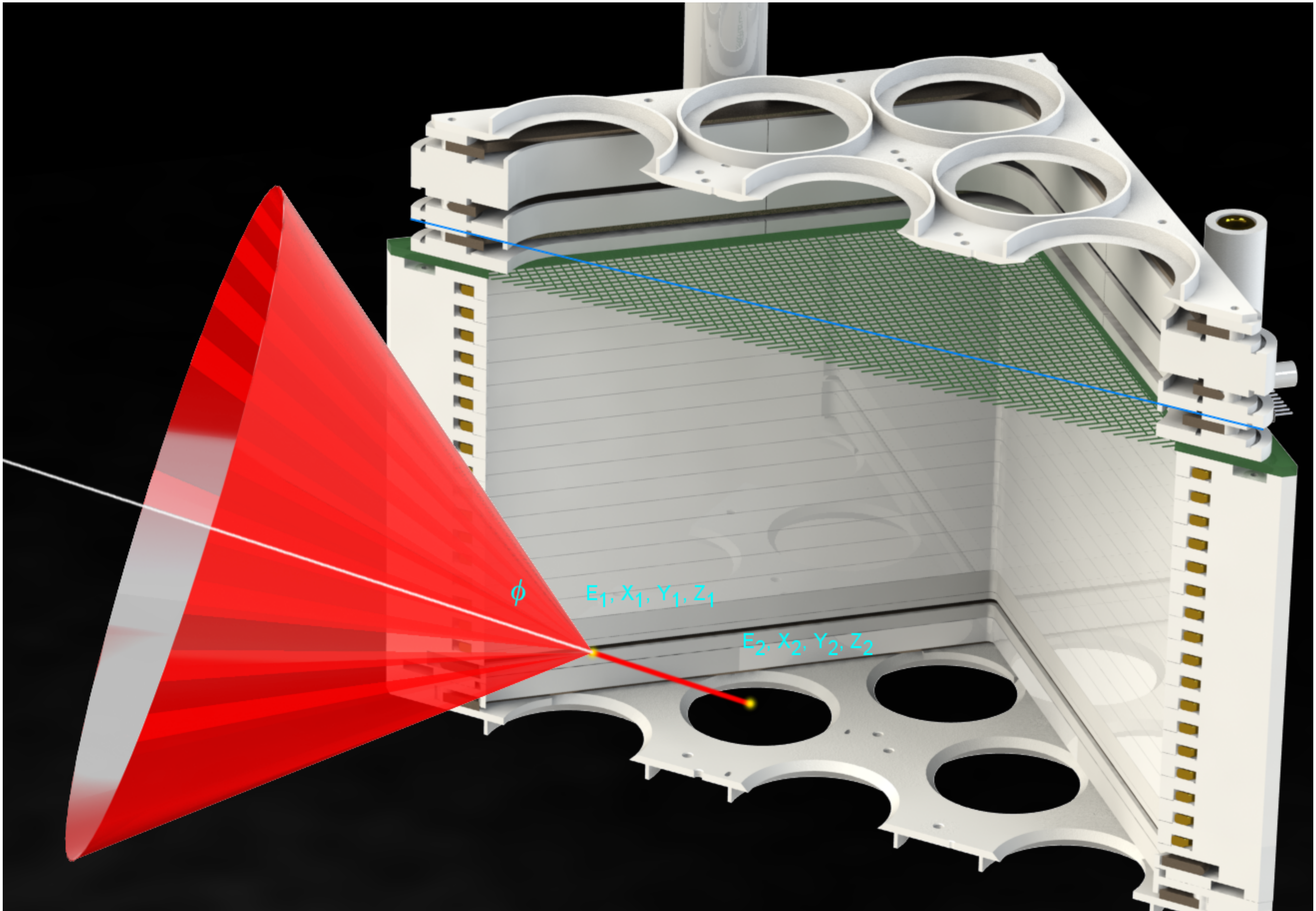
Factor of 40 from kinematics, > 1000 from charge/light ratio.

PIXeY neutron irradiation →

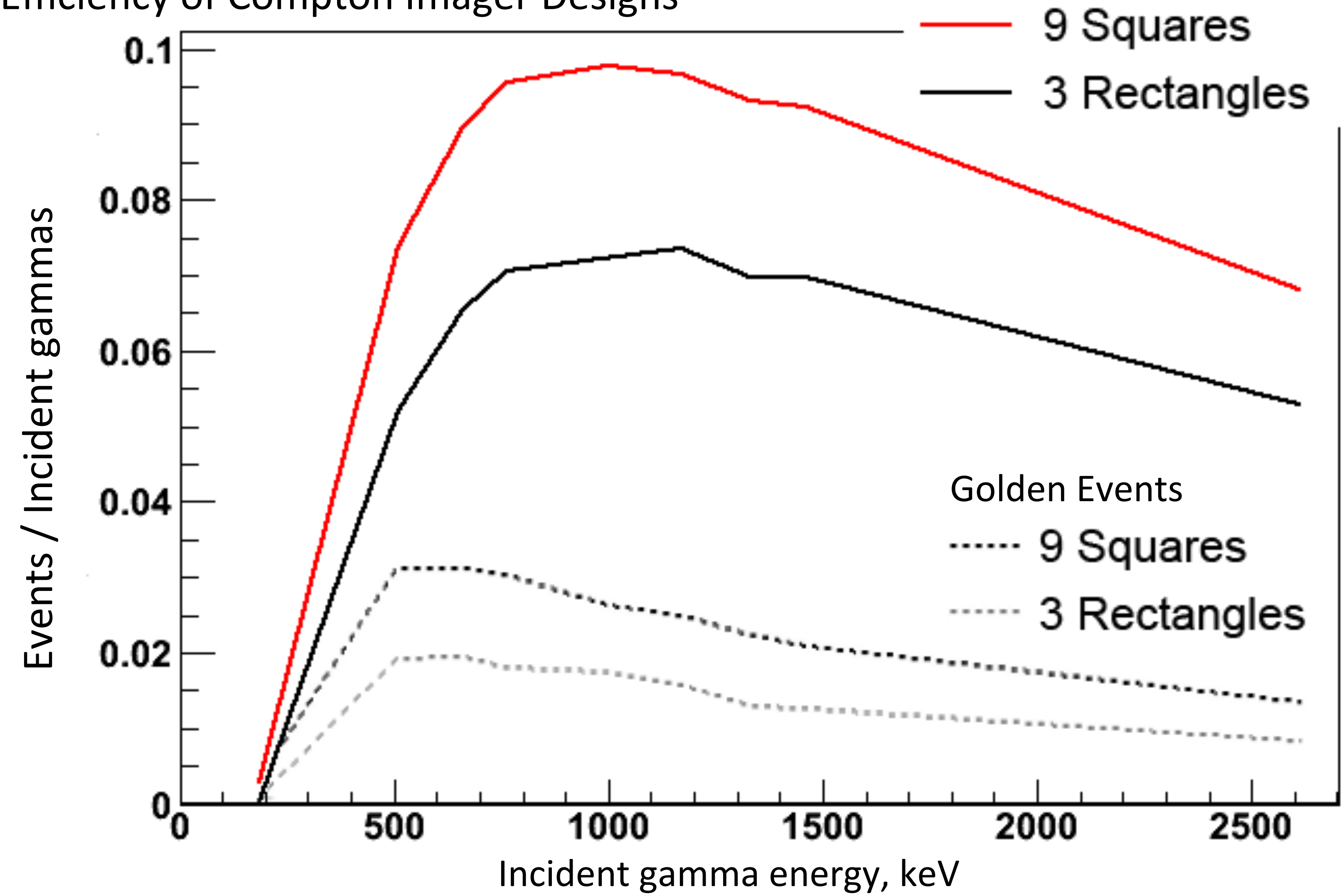


PIXeY gamma irradiation →




ϕ
E1, X1, Y1, Z1
E2, X2, Y2, Z2

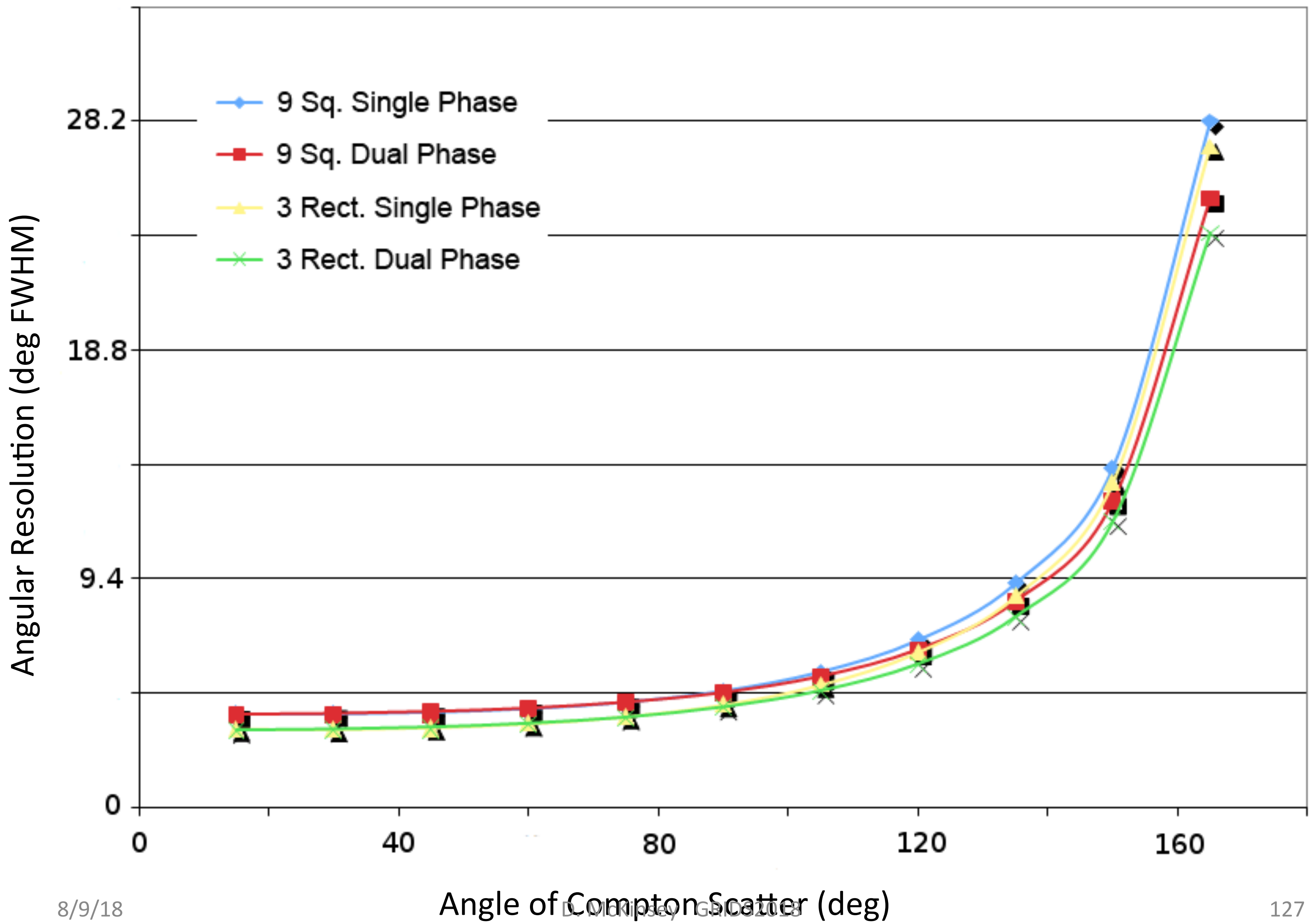
Early PIXeY Projection:
Efficiency of Compton Imager Designs



Golden events: Single isolated Compton scatter followed by photoabsorption.

Silver events: Single isolated Compton scatter followed by capture of the remaining energy within the active xenon.

Projected Angular Resolution of Golden Events from 1.001 MeV gamma

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