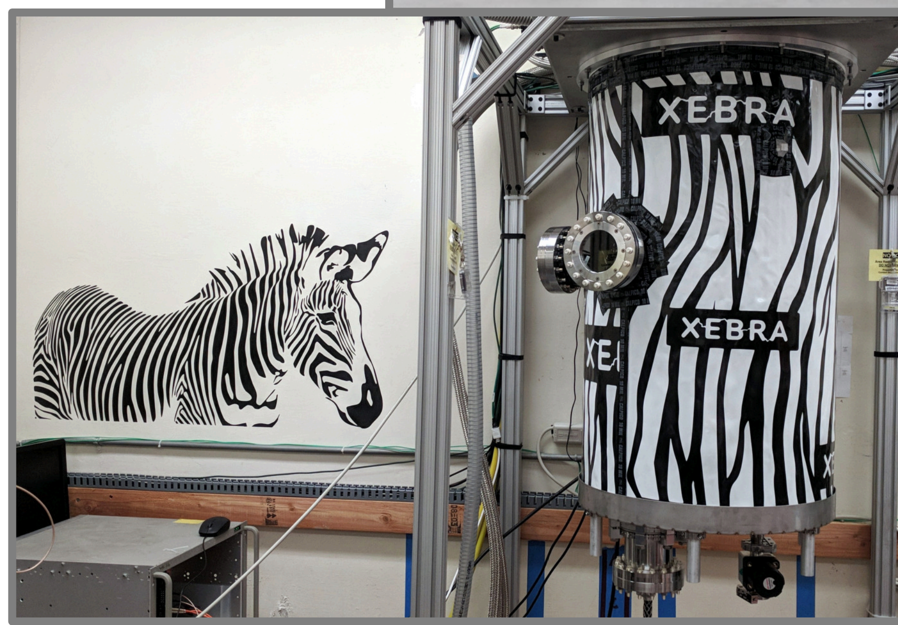
Results from sub-GeV dark matter searches & high voltage breakdown studies in liquid argon and xenon



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Yale
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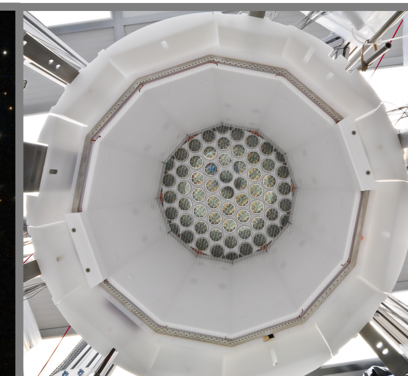
CENPA seminar at UW
February 7, 2019

Outline

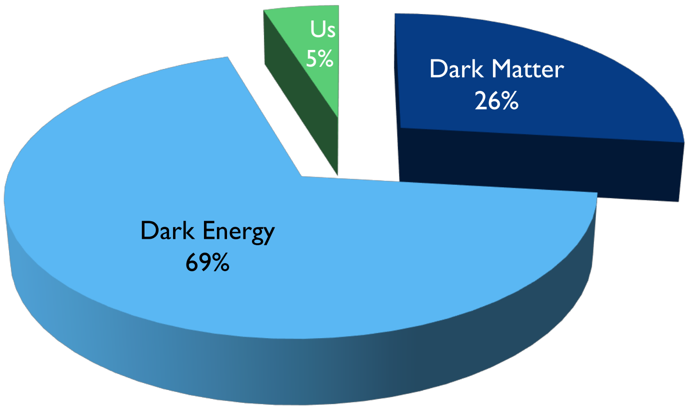
1. Introduction to the LUX detector

2. Sub-GeV dark matter searches using 2013 LUX data

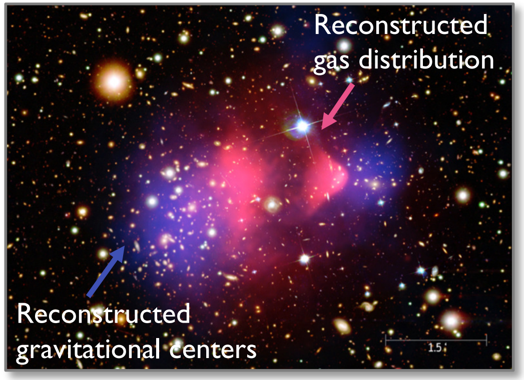
3. Dielectric breakdown studies in liquid argon & liquid xenon with XeBrA



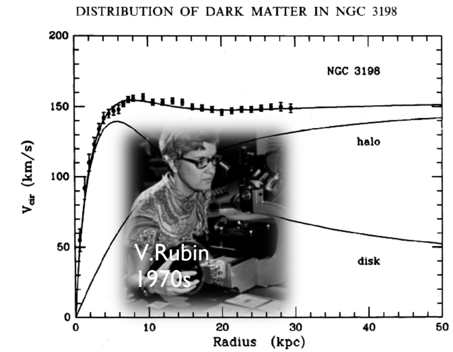
Evidence for DM comes from multiple sources



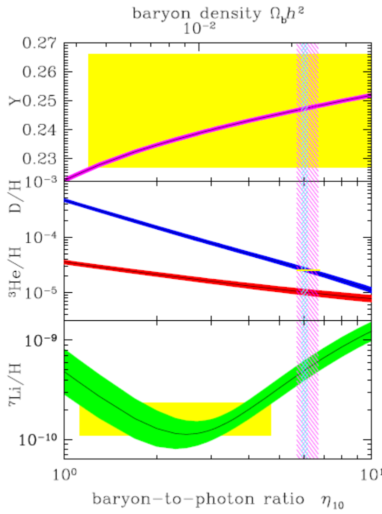
Gravitational lensing



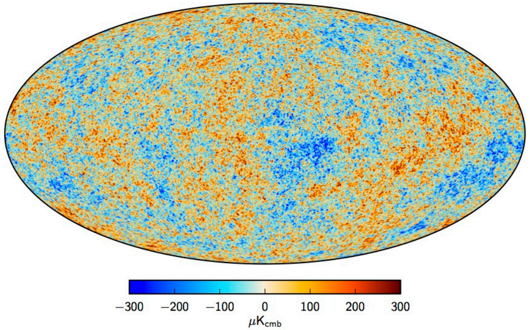
Galaxy rotation

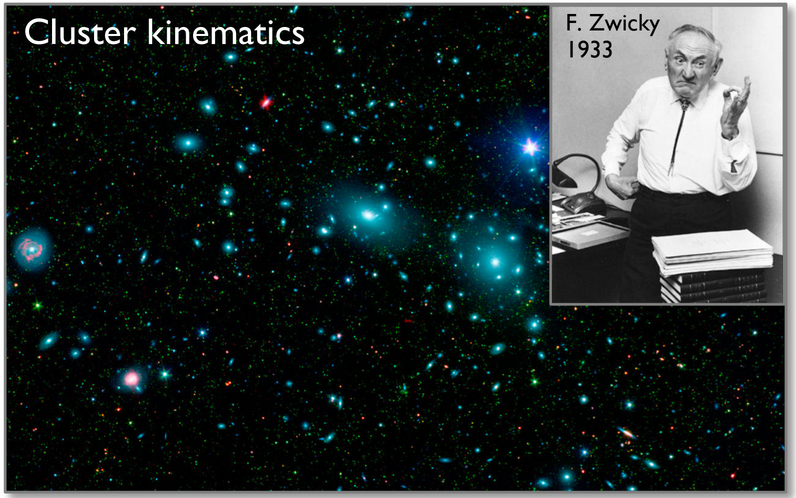


BBN



CMB



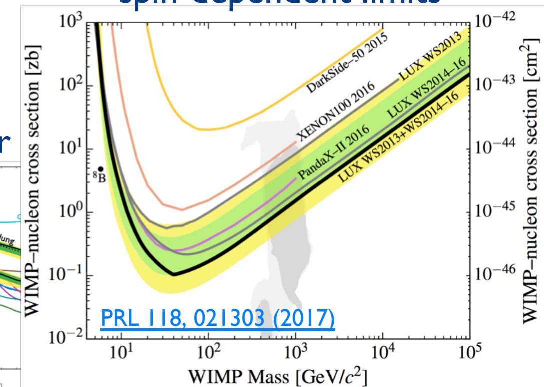


and more…

LUX searched for many types of dark matter

Limits on annual & diurnal rate modulation (various masses) PRD 98, 062005 (2018)

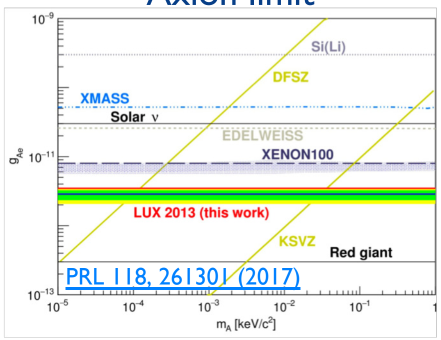
Spin-independent & spin-dependent limits



PRL 118, 021303 (2017)

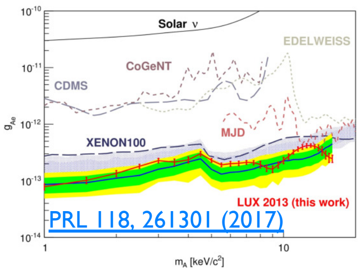
& PRL 118, 251302 (2017)

Axion limit



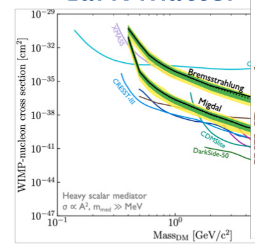
PRL 118, 261301 (2017)

Coupling between galactic ALPs and electrons

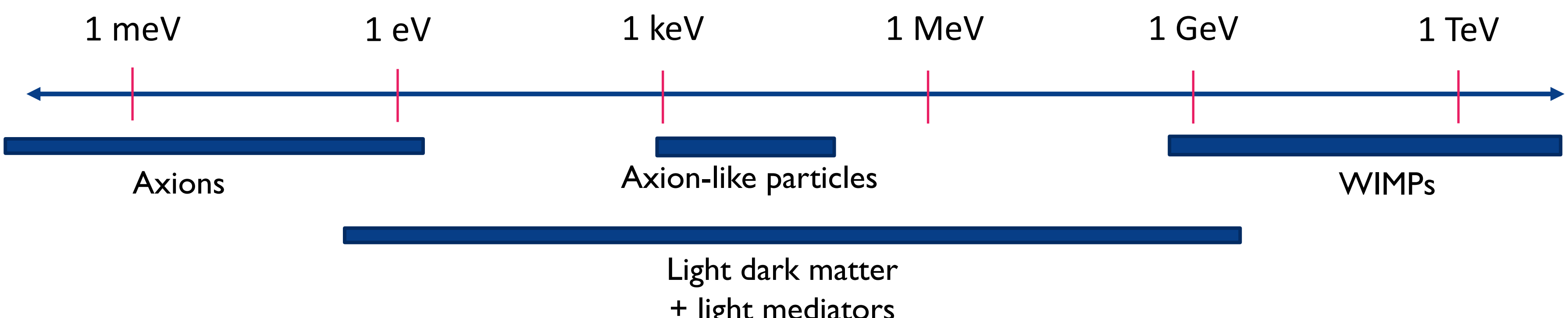


PRL 118, 261301 (2017)

Sub-GeV dark matter

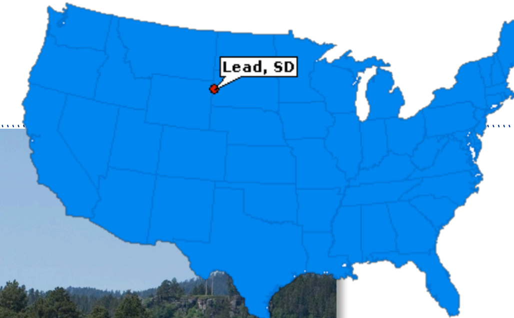


arXiv:1811.11241



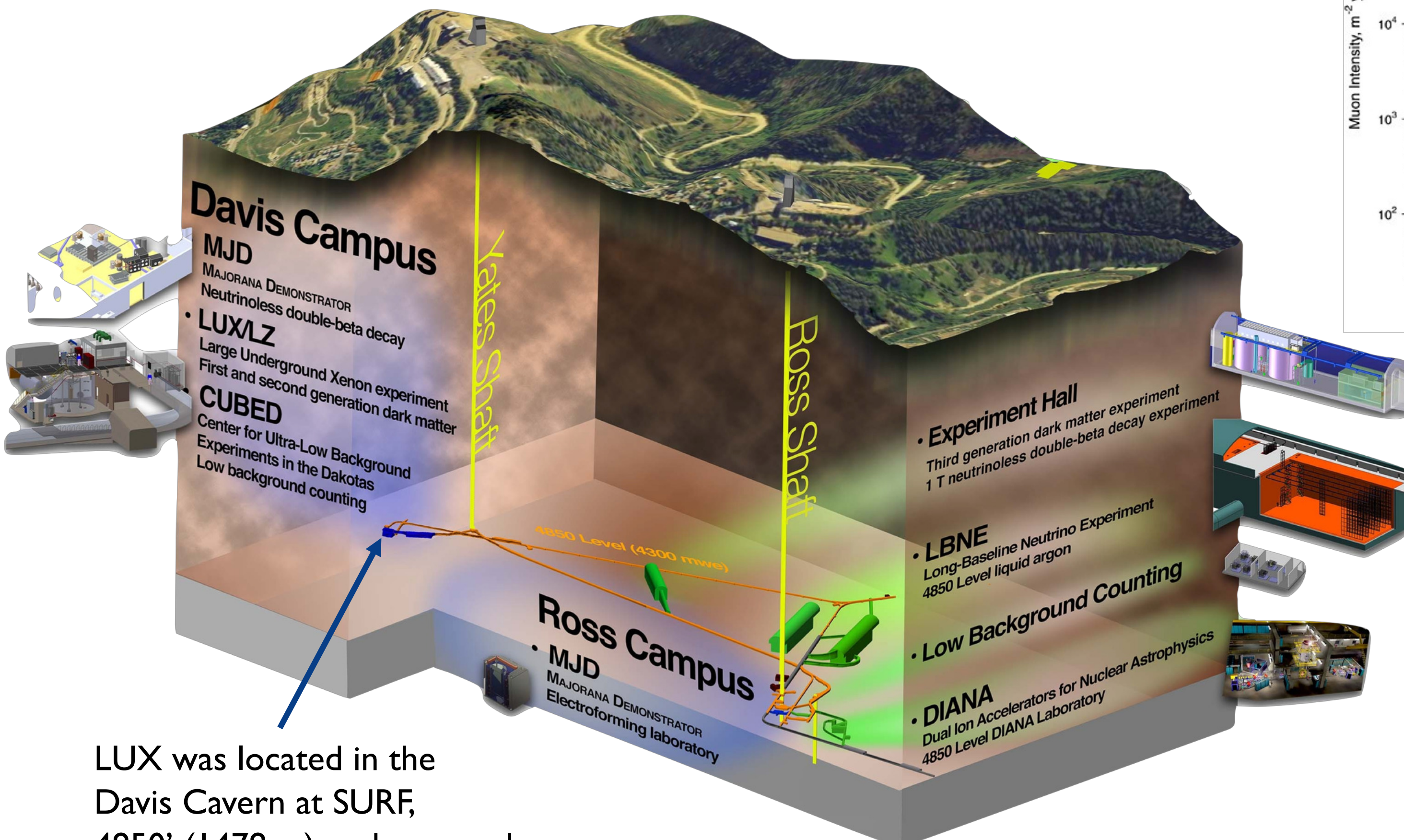
The Large Underground Xenon experiment

24 institutions
~100 people

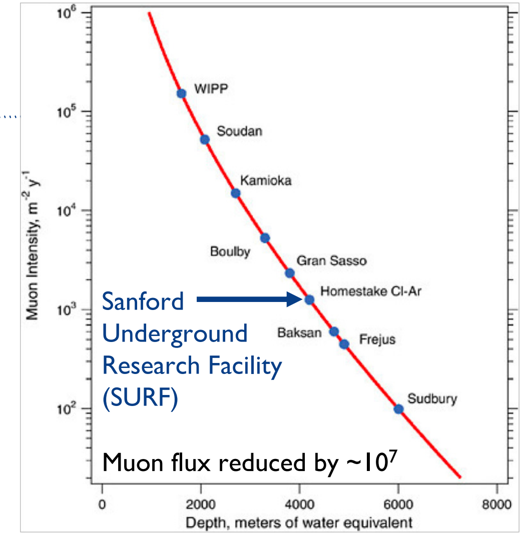


LUX collaboration meeting, June 2015
Sanford Underground Research Facility, Lead, SD

LUX lived 1 mile underground



LUX was located in the Davis Cavern at SURF, 4850' (1478 m) underground

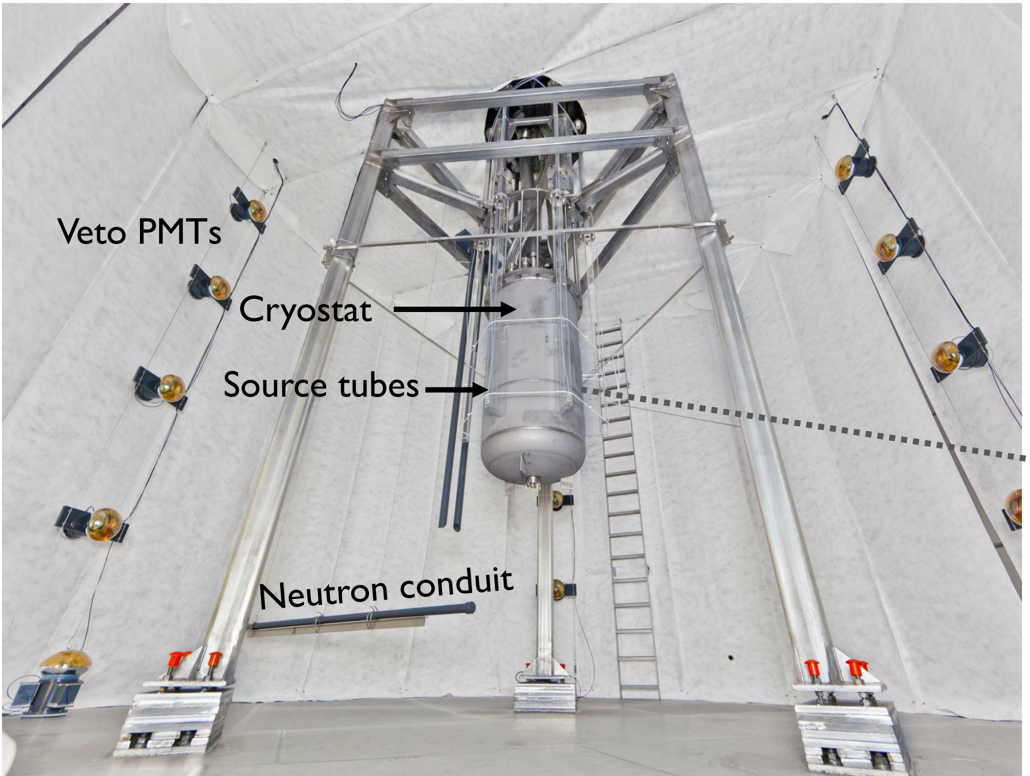


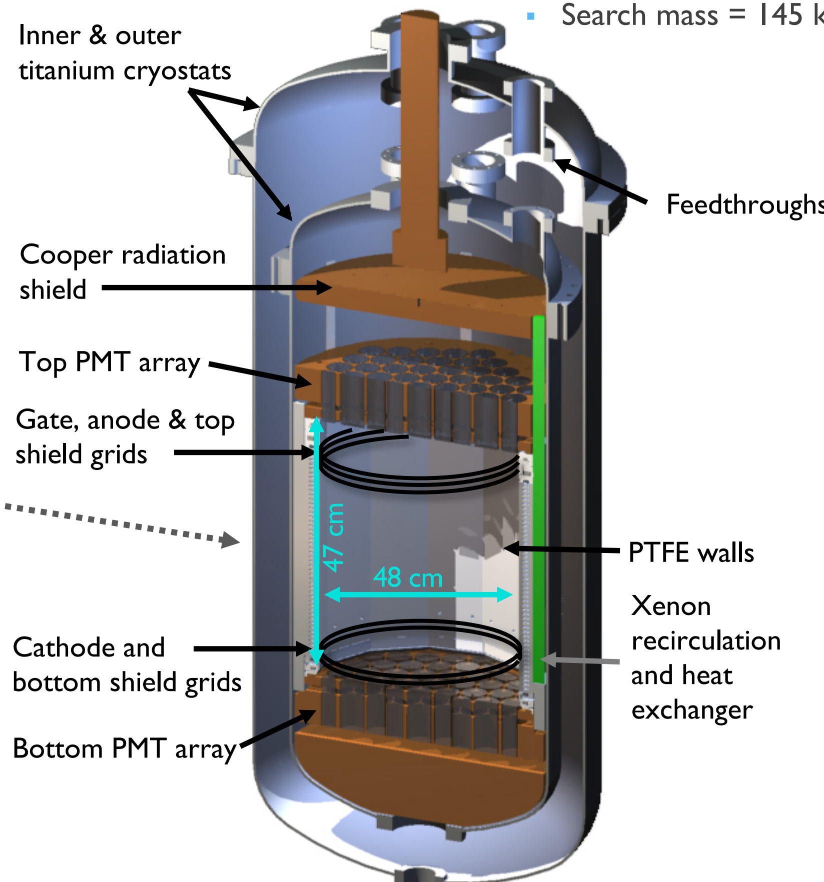
LUX detector was a two-phase TPC

NIM A 704, 111-126 (2013)

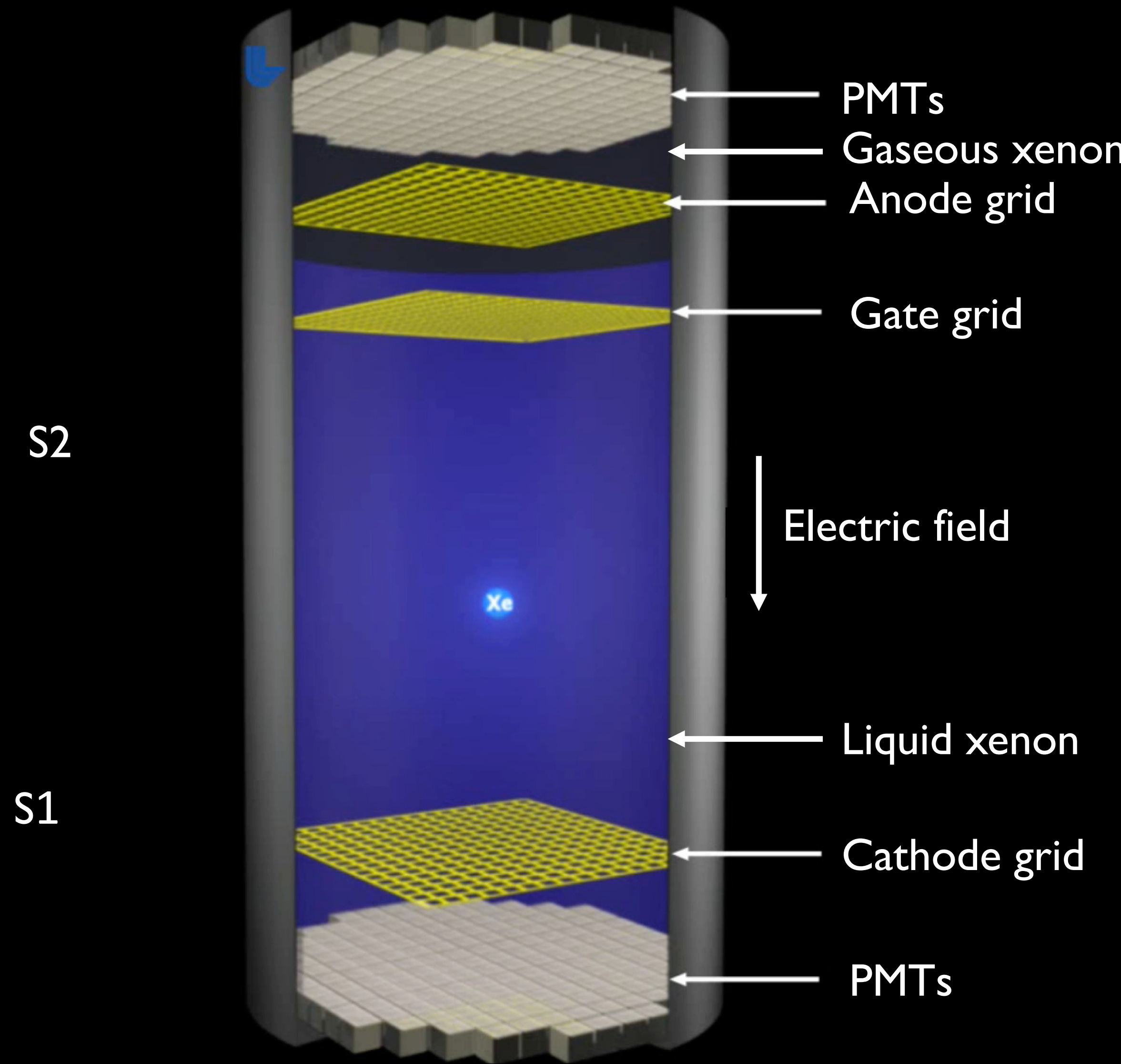
Liquid xenon target
- Active mass = 250 kg
- Search mass = 145 kg

Water tank

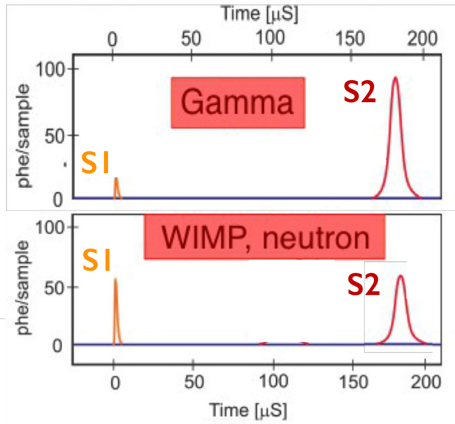




Particle interaction in a two phase time projection chamber



Distinguish between 2 types of particle recoil



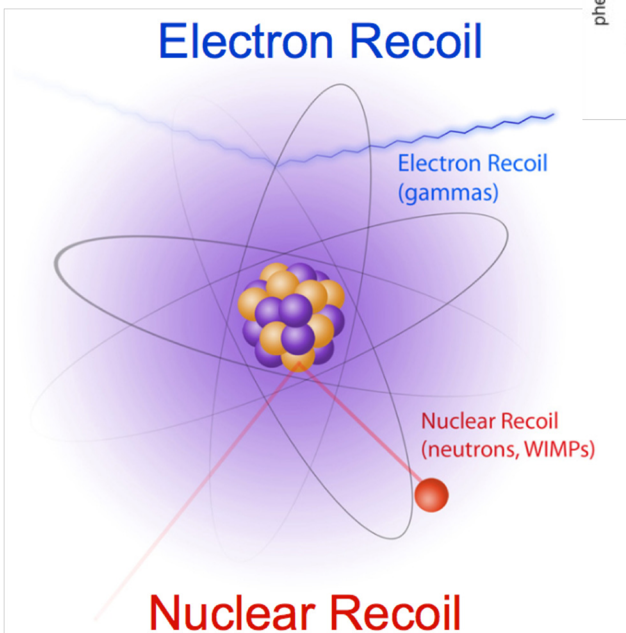
Electron recoil (ER)
- γ, B

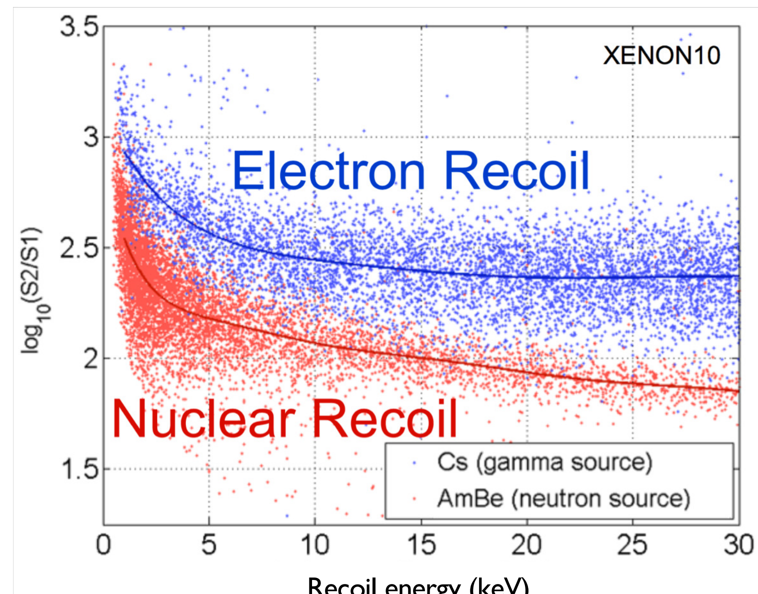
Nuclear recoil (NR)
- Neutrons, WIMPs

Discriminate electron & nuclear recoils using S2/S1 ratio

S1 – light signal (178 nm photons)

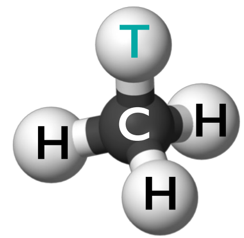
S2 – charge signal (electrons)

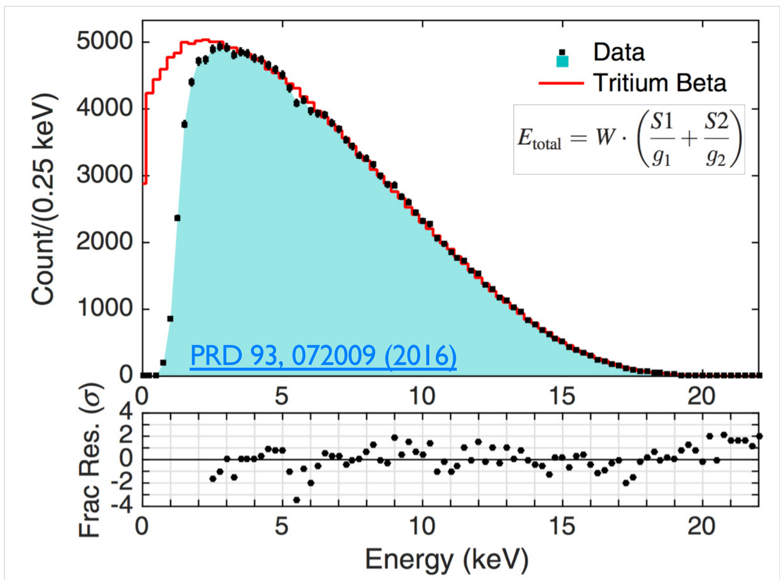


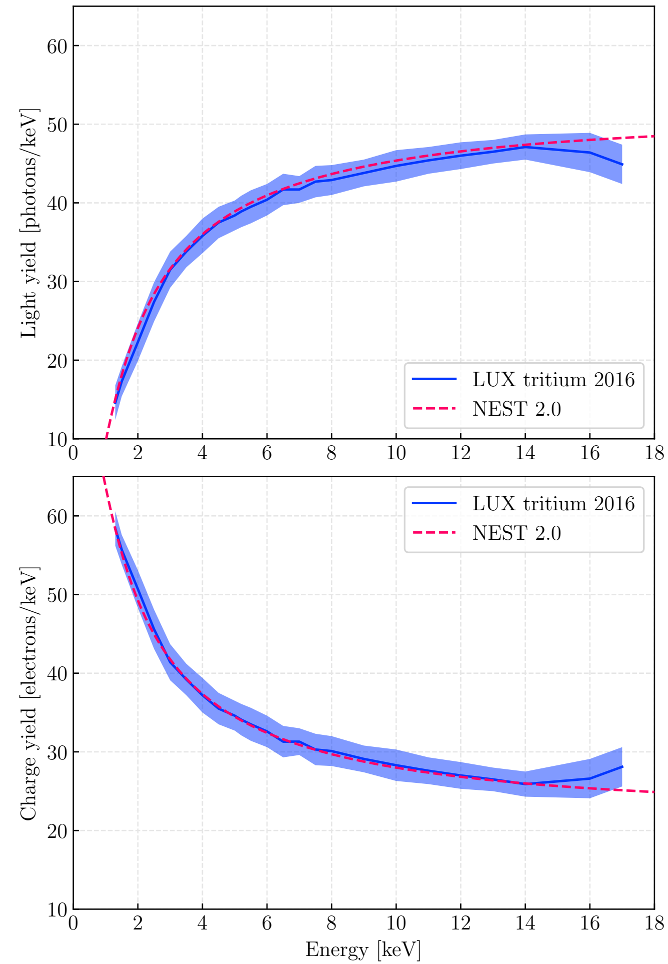


Tritium calibrates detector response to electron recoils

- Tritium β spectrum coincides with WIMP interaction energy
  - <E> = 5.9 keV, Q = 18.6 keV
- Study detector response to electron recoils (ER band determination)
- $T_{1/2}$ = 12.3 yr
  - Removed by purifying system ($T_{1/2}$ ~ 6 h)
- Injected quarterly as CH_3T

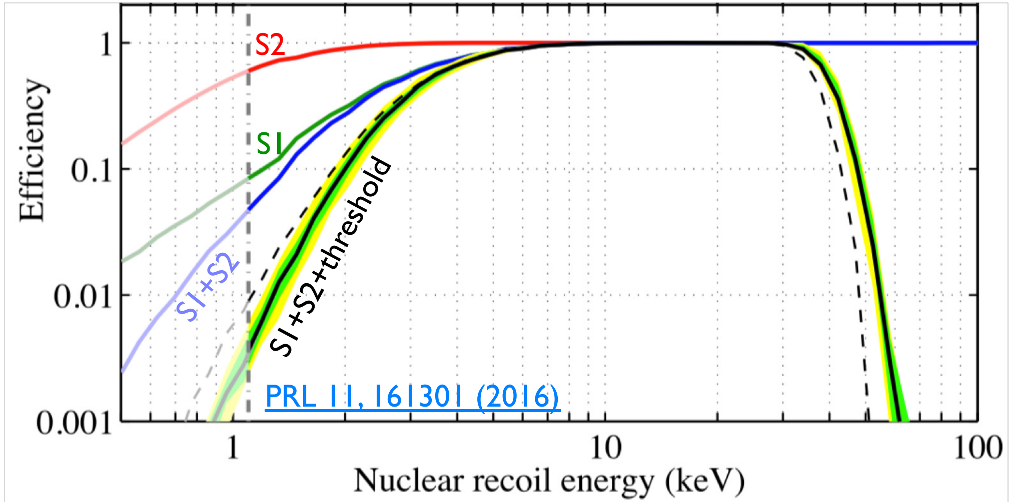




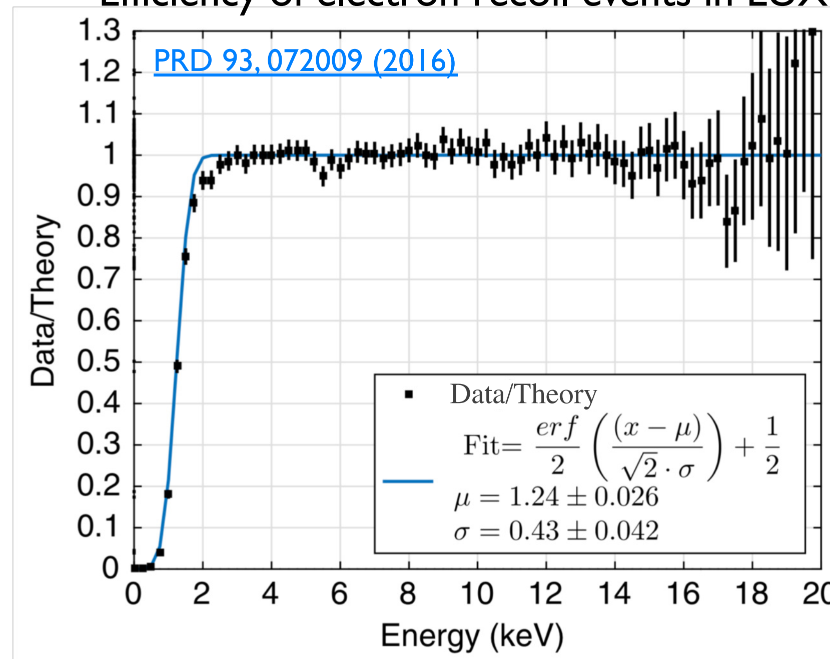


LUX is more sensitive to lower energies of electron recoils

Efficiency of nuclear recoil events in LUX in WS2013 reanalysis



Efficiency of electron recoil events in LUX



50% energy threshold:

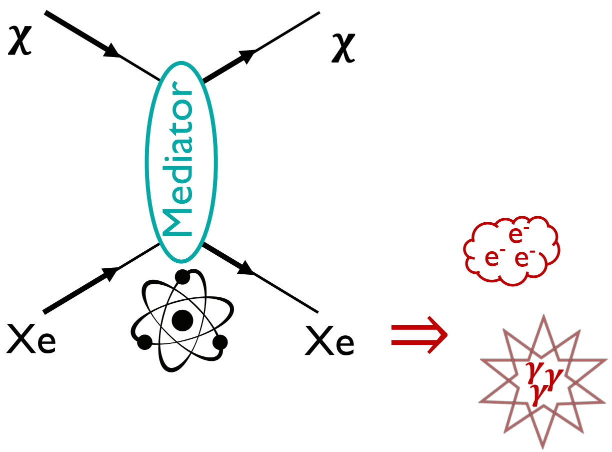
nuclear recoils = 3.3 keV

electron recoils = 1.2 keV

Direct detection experiments consider elastic scattering

Elastic scattering

- Nuclear recoil signal
- Assumed in the standard WIMP search
- LUX searches for $m_{DM} \gtrsim 5\text{GeV}$

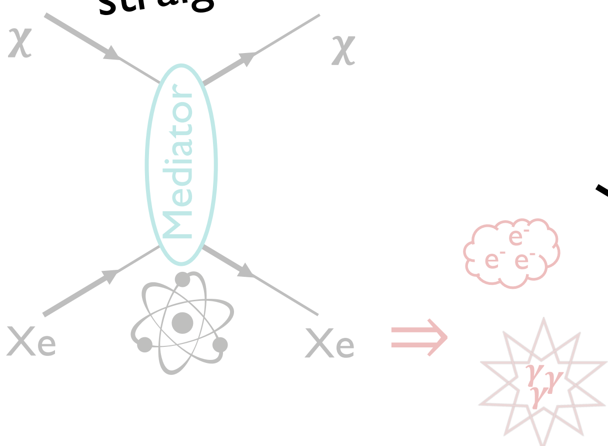


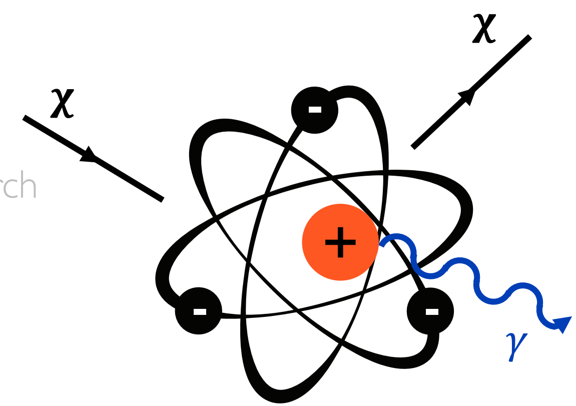
But irreducible signals are present in DM-nucleus interactions

Elastic scattering

- Nuclear recoil signal
- Assumed in the standard WIMP search
- LUX searches for $m_{DM} \gtrsim 5\text{GeV}$

Physics isn't this straightforward…

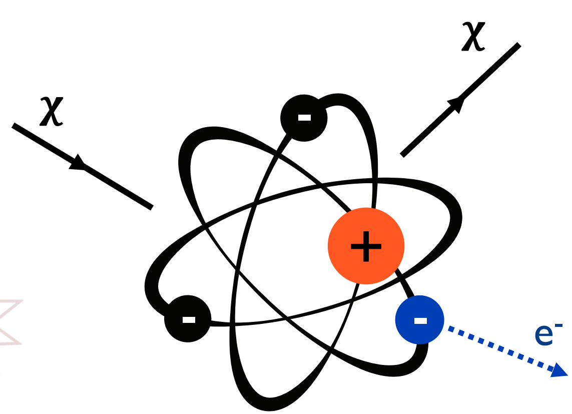




Bremsstrahlung photon emission from polarized atom

- C. Kouvaris & J. Pradler [PRL 118, 031803 (2017)]
- C. McCabe [PRD 96, 043010 (2017)]

LUX results from this work
arXiv: 1811.11241



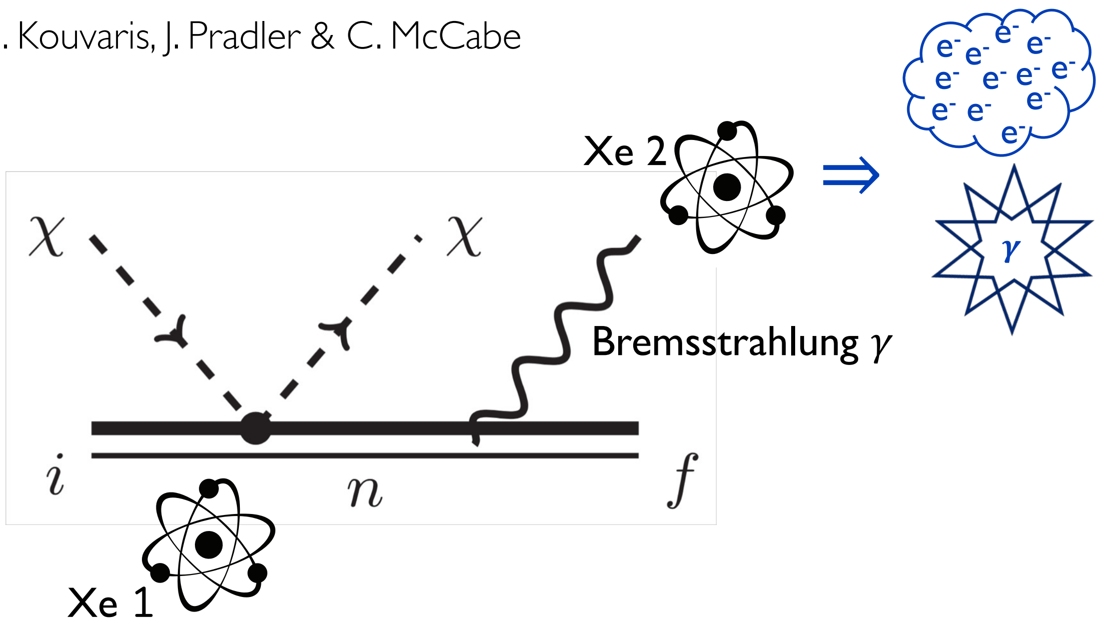
Electron emission caused by Migdal effect

- M. Ibe *et al.* [JHEP03 (2018) 194]
- M. J. Dolan *et al.* [PRL 121, 101801 (2018)]

LUX can detect sub-GeV DM via Bremsstrahlung

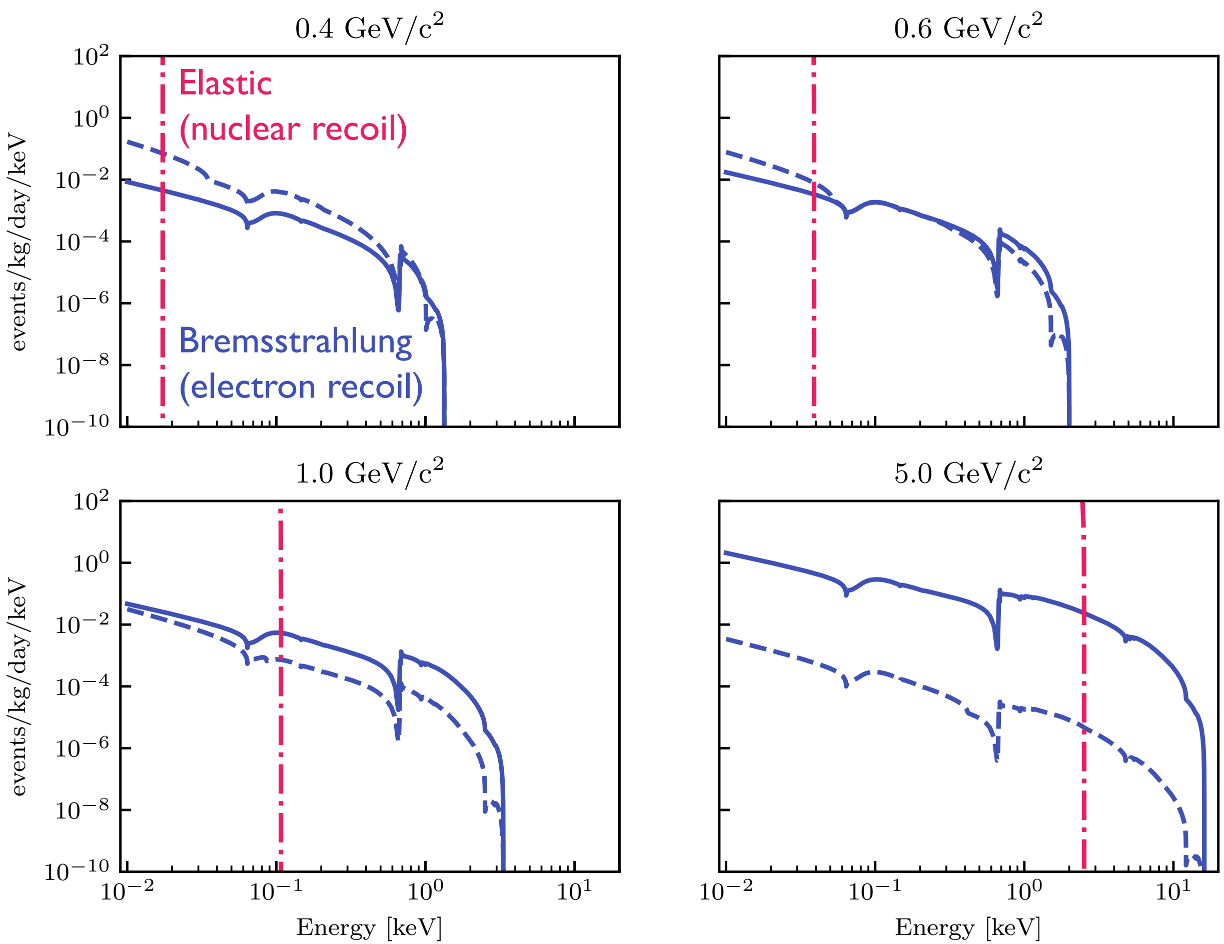
Bremsstrahlung

- Emission of a photon from a polarized xenon atom
- Nuclear interaction with electron recoil signal
- ER signal is much easier to detect at low energies!
- LUX can gain sensitivity to $\mathcal{O}$(MeV) DM
- Based on work by C. Kouvaris, J. Pradler & C. McCabe



Proposed by
C. Kouvaris & J. Pradler
PRL 118, 031803 (2017)

Expected scattering rates in xenon for Bremsstrahlung



— Heavy scalar mediator
$m_{MED} \gg q$

······ Light scalar mediator
$m_{MED} \ll q$

q = momentum transfer
$F_{med} = q^4_{ref} / q^4$
q_{ref} = 1 MeV

$\sigma = 10^{-35}$ cm^2

Photon emission rates in xenon were first calculated by C. Kouvaris & J. Pradler: [PRL 118, 031803 (2017)]

Light mediator calculated by C. McCabe: [PRD 96, 043010 (2017)]

LUX can detect sub-GeV DM via Migdal effect

Proposed by M. Ibe *et al.*
JHEP03(2018)194

- Nuclear interaction, with detectable ionization (electron recoil) signal for low mass DM
- Originally formulated in 1941 by A.B. Migdal assuming an impulsive force
- Reformulated this year by M. Ibe *et al.* using atomic energy eigenstates for their calculations instead, thereby avoiding the need to resolve the complex time evolution of the nucleus
- Based on work by M. Ibe *et al.* who have published the expected scattering rates & Dolan *et al.*

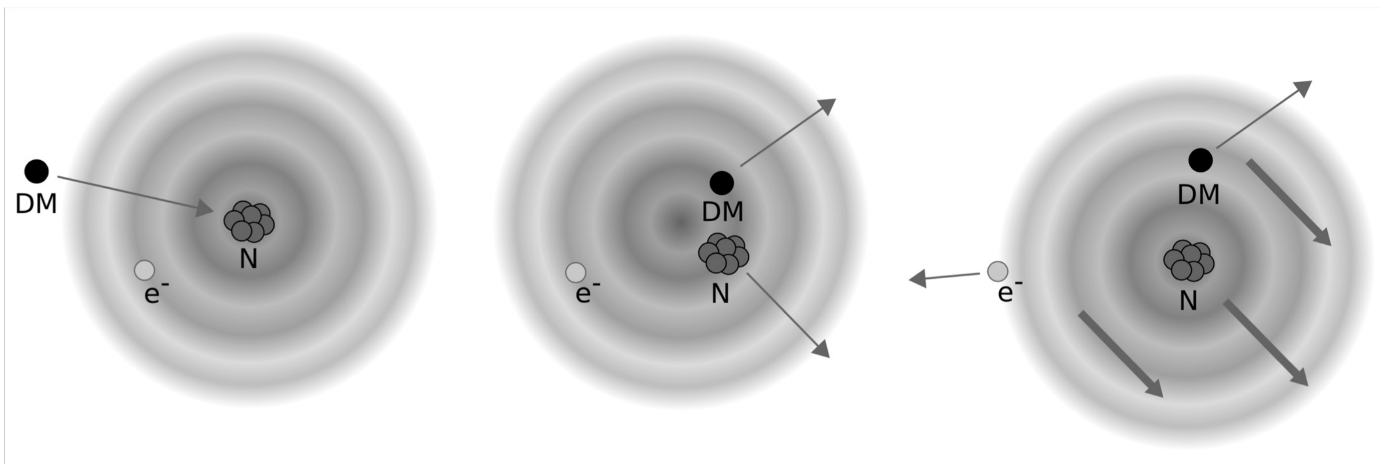
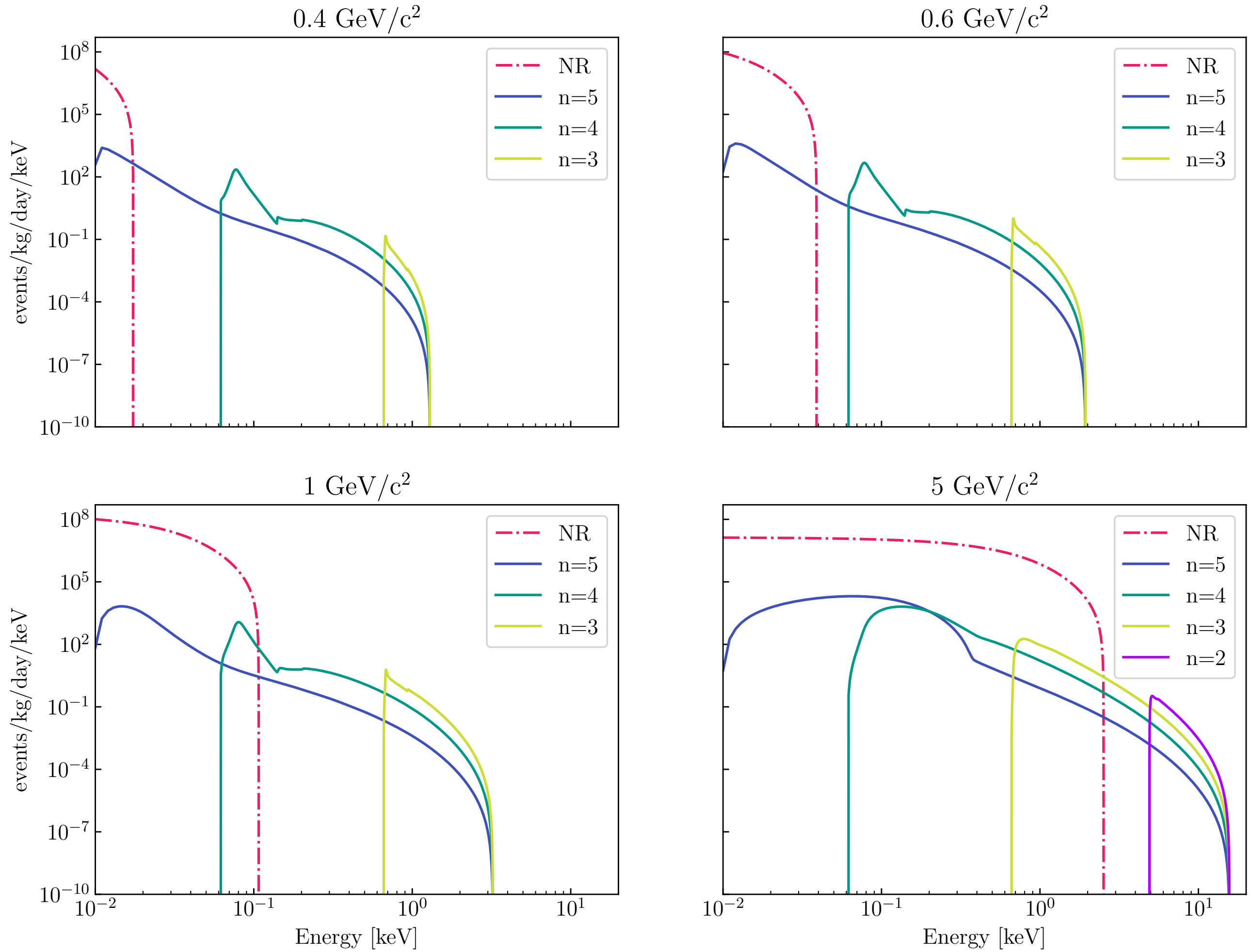


Figure from M. J. Dolan *et al.*
arXiv:1711.09906

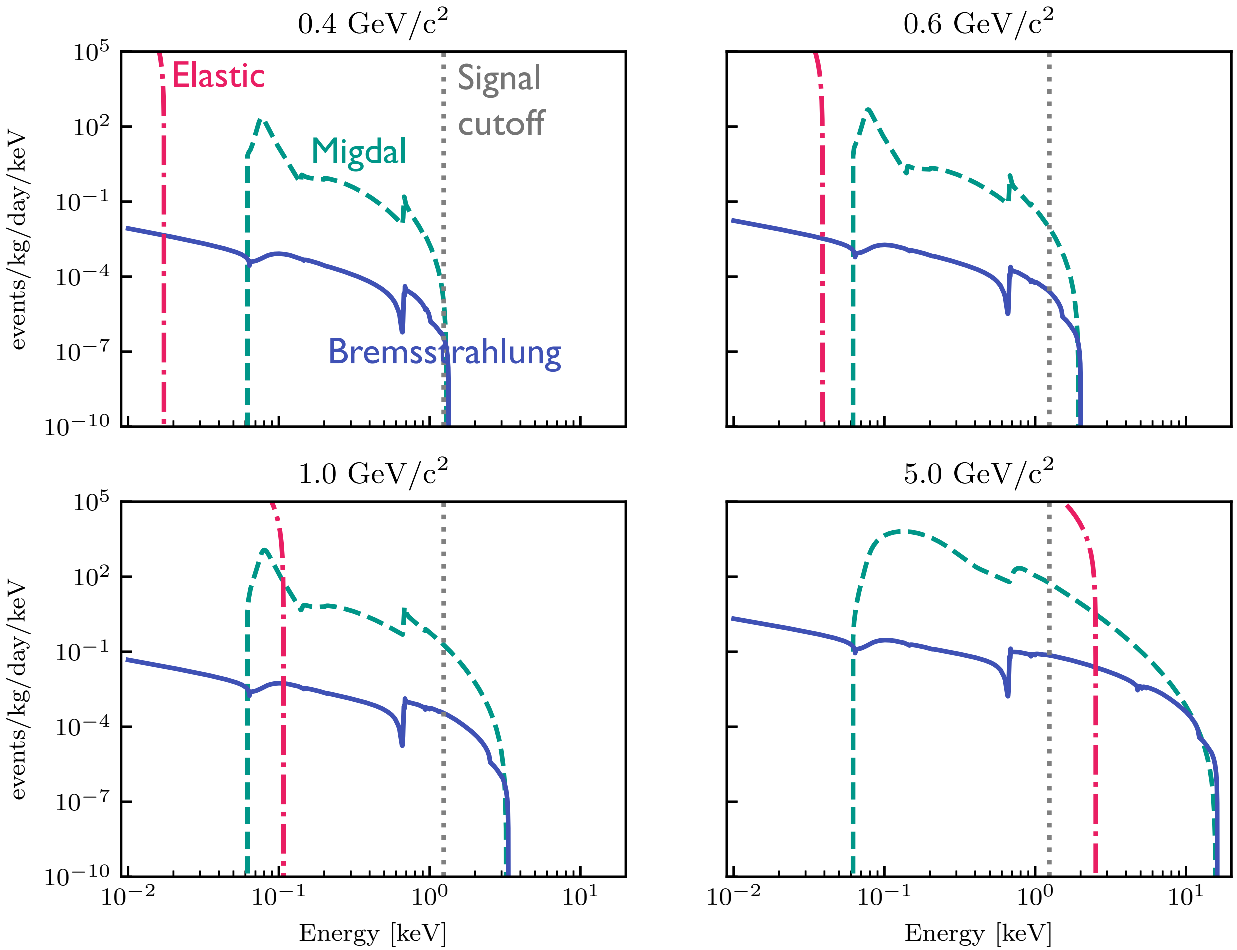
Expected scattering rates in xenon for Migdal effect

- Only n=3,4 considered in the analysis
- Assuming heavy scalar mediator
- σ = 10^{-35} cm^2



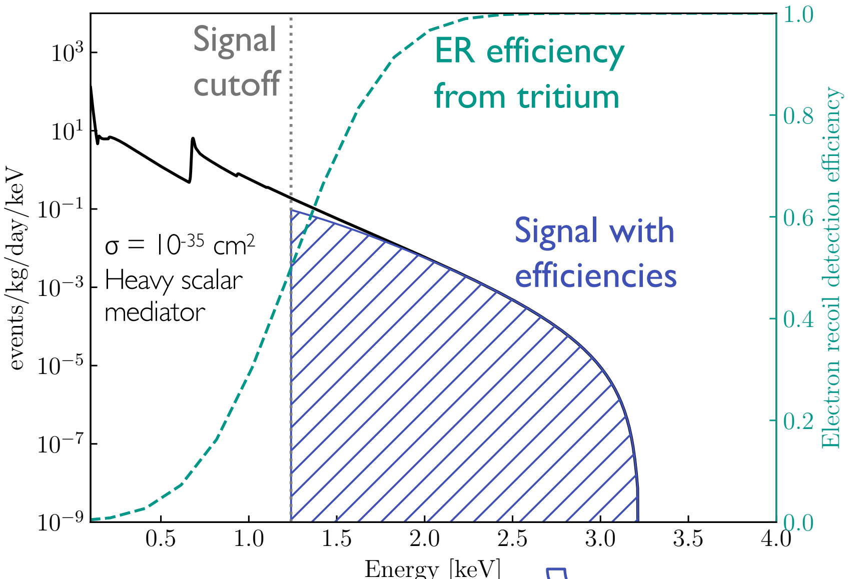
Expect higher event rates from Migdal compared to Brem

- Assuming heavy scalar mediator
- $\sigma = 10^{-35}$ cm^2

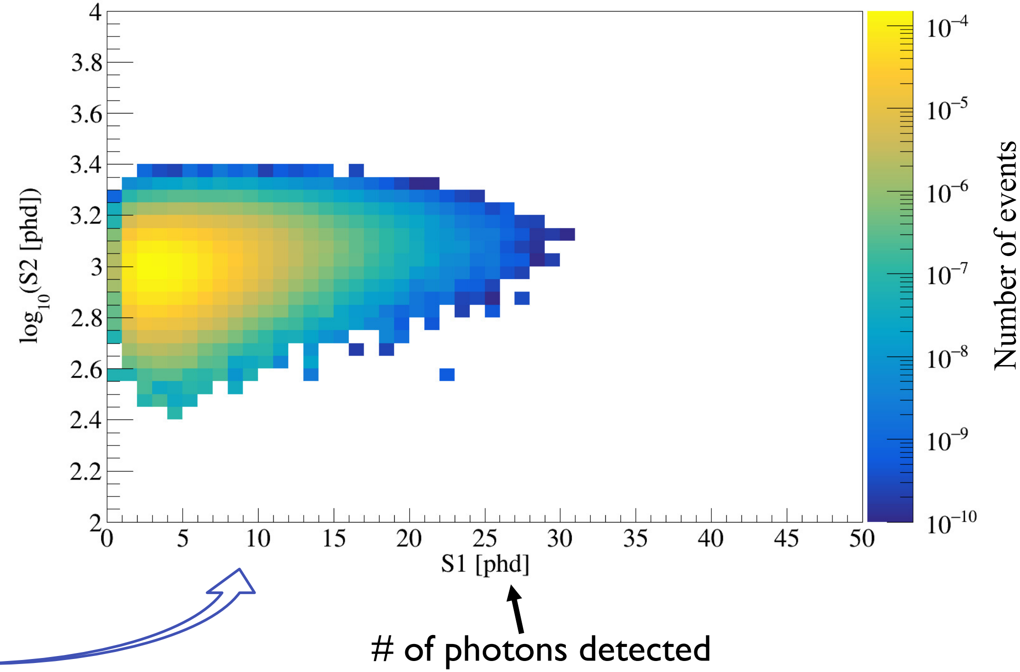


Example of a signal expected in LUX from m_χ = 1 GeV

Migdal scattering rates

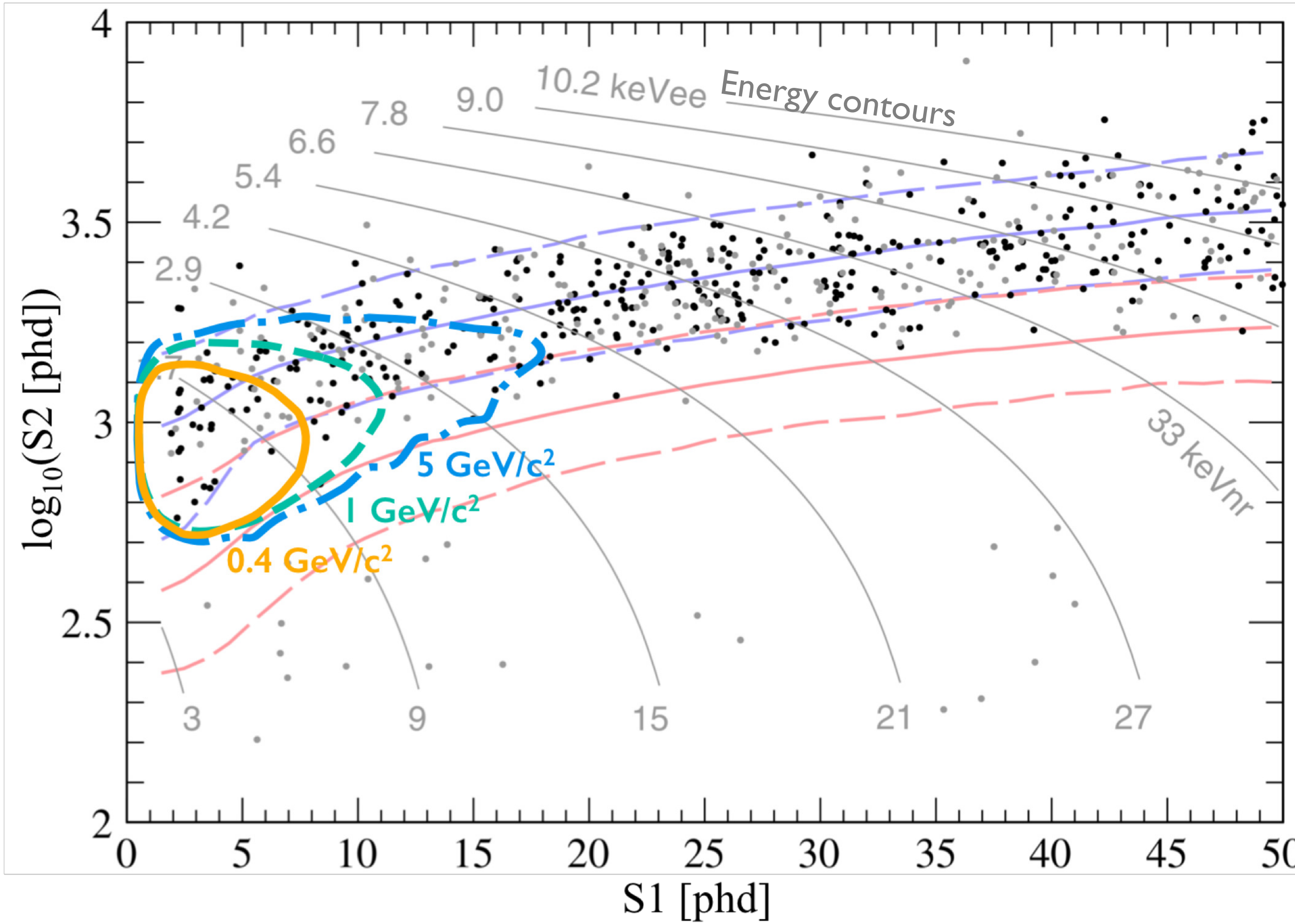


Expected signal in LUX



Simulate events for these scattering rates using NEST2.0 (Noble Element Simulation Technique package)
[JINST 8:C10003 (2013)]

Signal expected from Migdal effect in WS2013



Final WS2013 data after cuts

- 95 live-days
- 13,775 kg·day exposure
- 591 events

Electron recoil band

Nuclear recoil band for m_χ=50 GeV

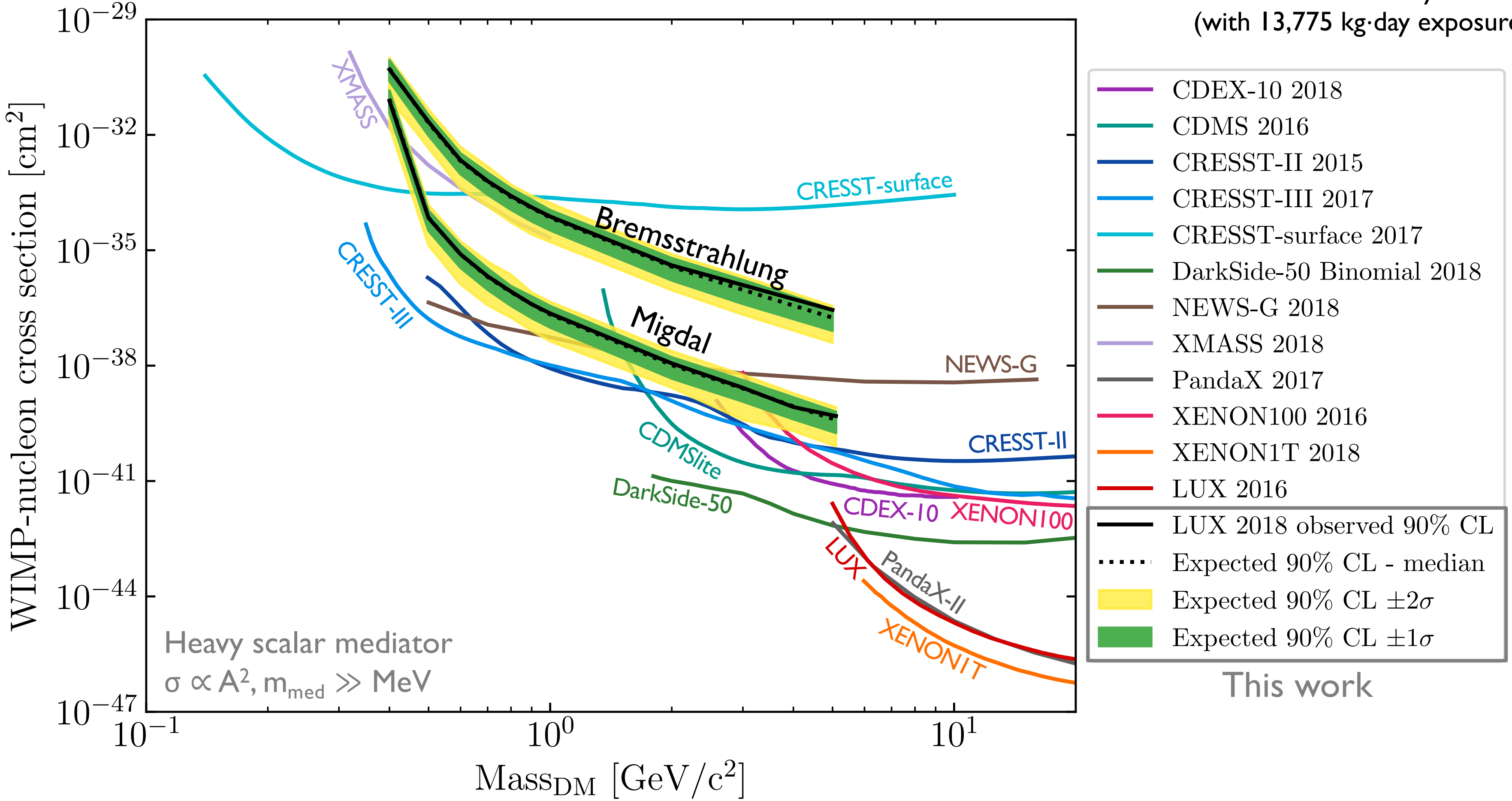
Black points: r ≤ 18 cm
Grey points: 18 < r < 20 cm
(edges of the fiducial volume boundary)

Brem heavy scalar mediator
Migdal heavy scalar mediator
Migdal light vector mediator

LUX limit calculated using profile likelihood ratio

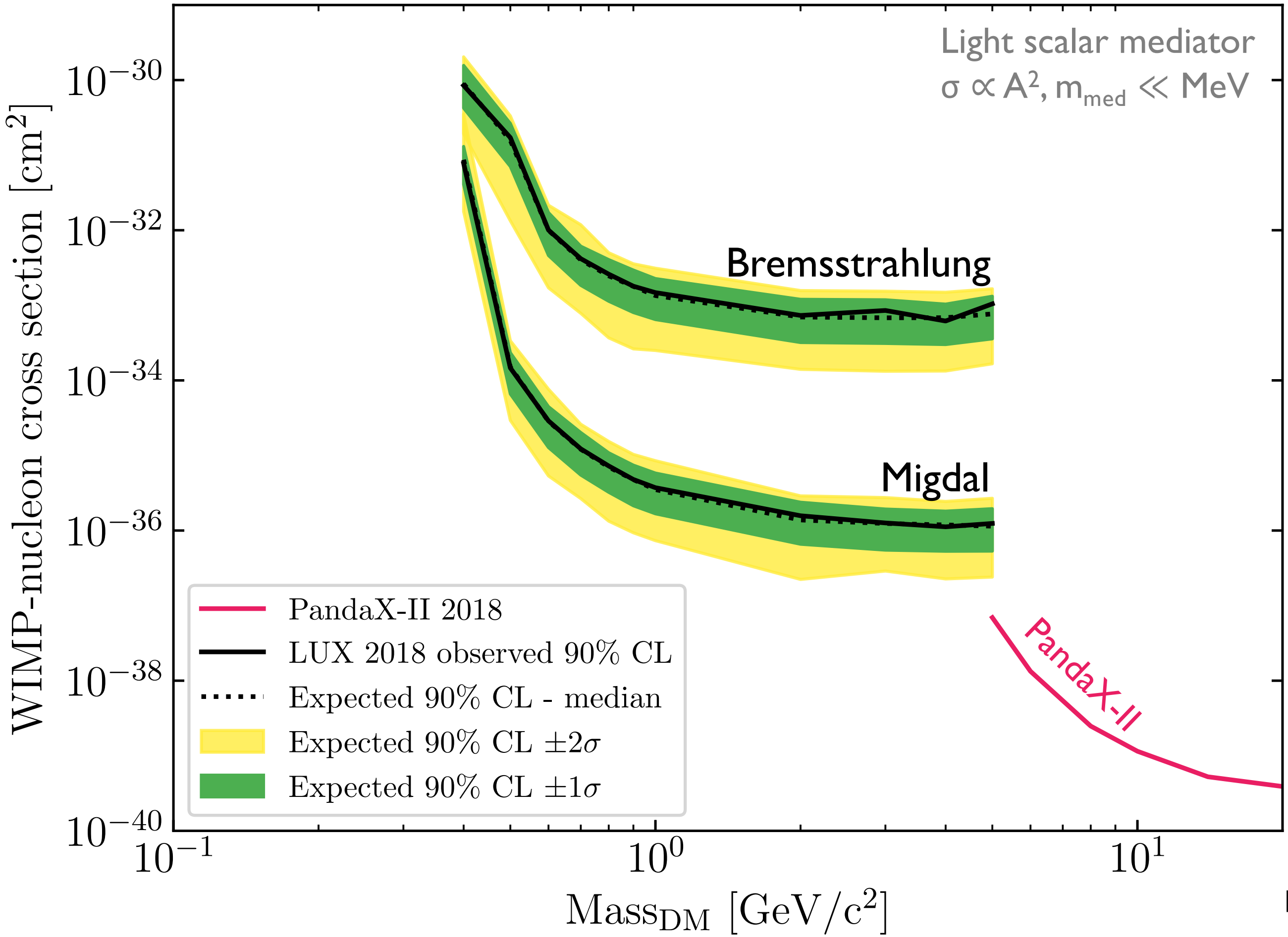
arXiv: 1811.11241

Limit is for 95 live-days of data
(with 13,775 kg·day exposure)



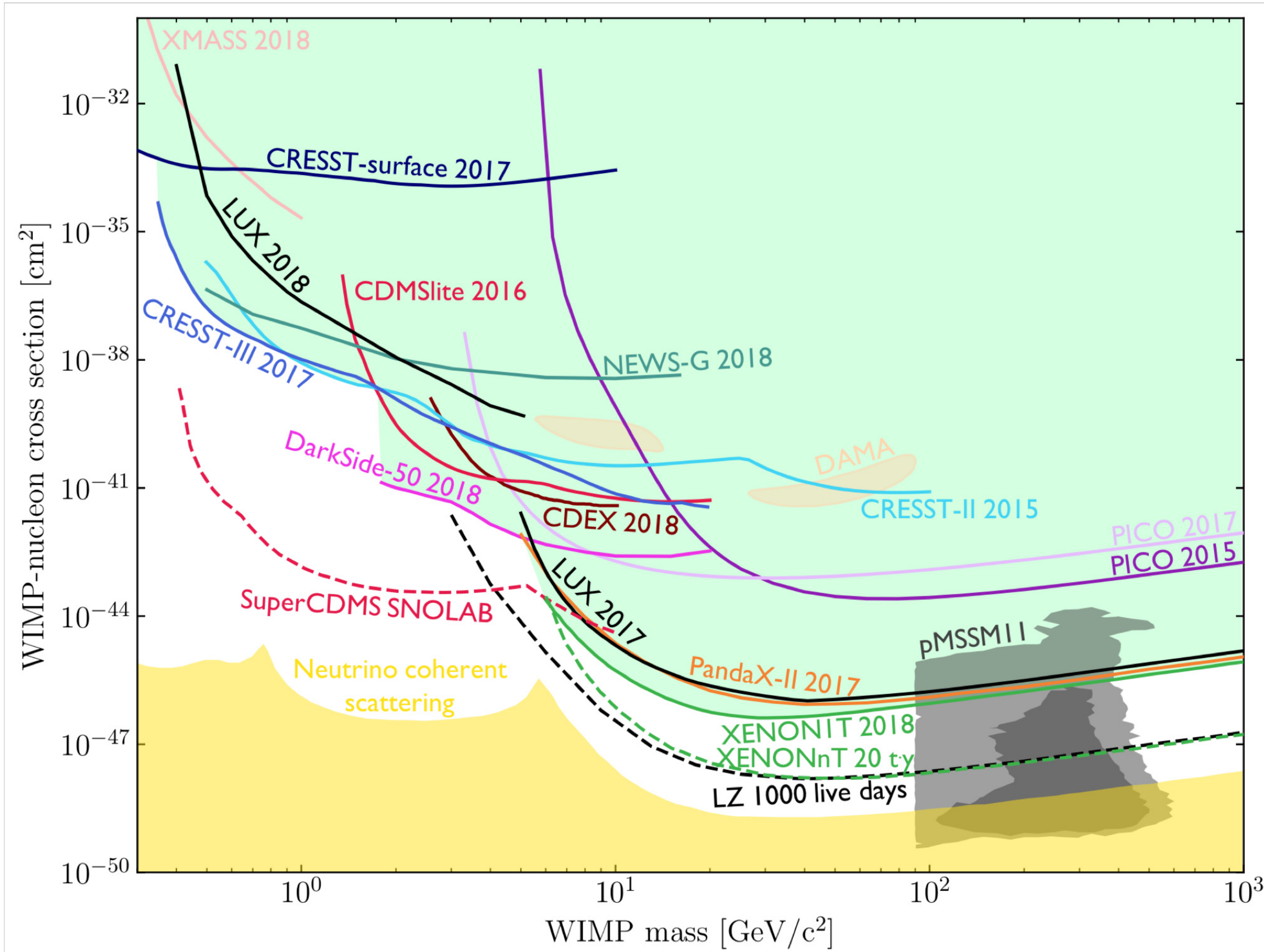
LUX limit assuming a light scalar mediator

arXiv: 1811.11241



Limit is for 95 live-days of data (with 13,775 kg·day exposure)

Current state of the field



Results
Projections

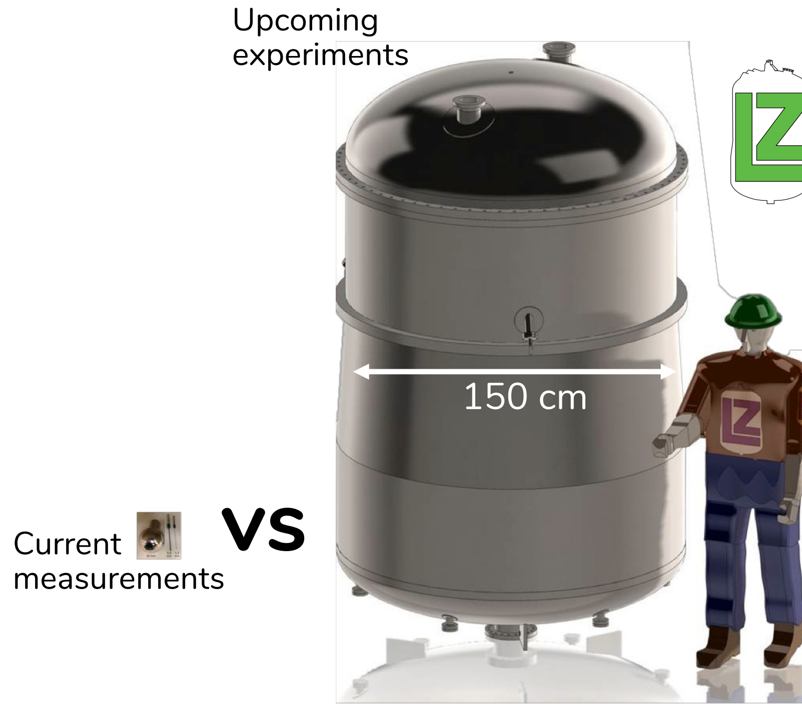
Motivation for XeBrA

Problem

- Lack of data characterizing high voltage (HV) behavior in noble liquids needed for dark matter detector design
  - Larger detectors need more HV – is there a threshold that will impede the scale up?

Solution

- I have acquired data characterizing HV in liquid argon (LAr) and liquid xenon (LXe)



XEBRA Xenon Breakdown Apparatus

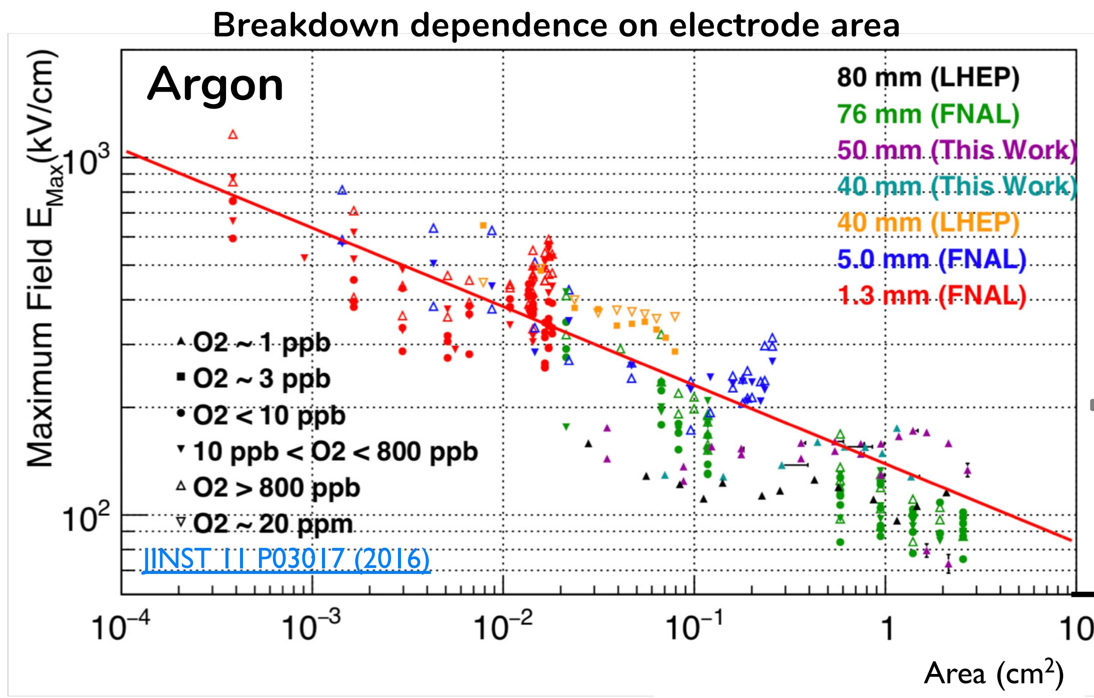
- Detector at LBNL developed by L. Tvrznikova, E. Bernard, K. O'Sullivan, W. Waldron, G. Richardson, S. Kravitz, Q. Riffard, J. Watson & D. McKinsey
  - Supported through the LBNL LDRD program

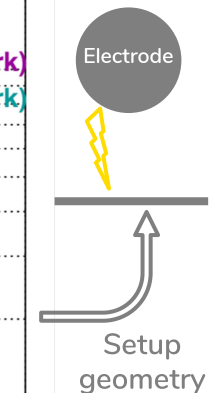
HV breakdown in LXe is not well understood

LAr & LHe data suggest breakdown depends on:

- Electrode stressed area
- Electrode volume
- Electrode material
- Surface finish
- Liquid purity
- Polarity
- Pressure & temperature
- And more …

But there is very little data in LXe!



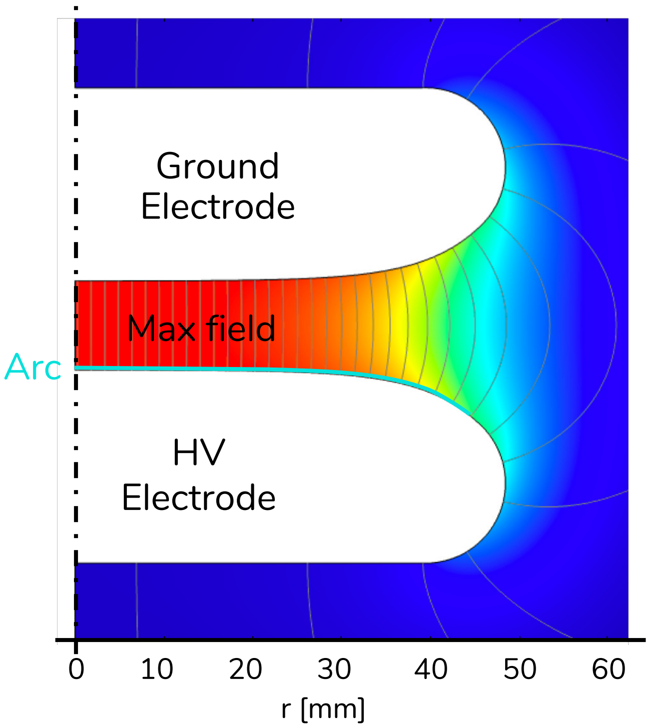


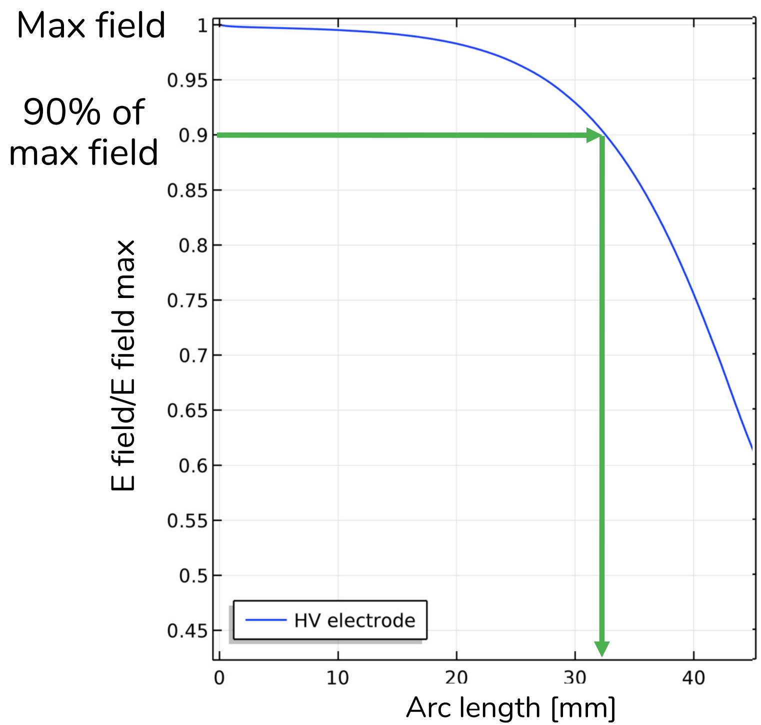
Design for the LZ cathode stressed area (500 cm^2)

Only consider area within 90% of max E-field

"Stressed area"

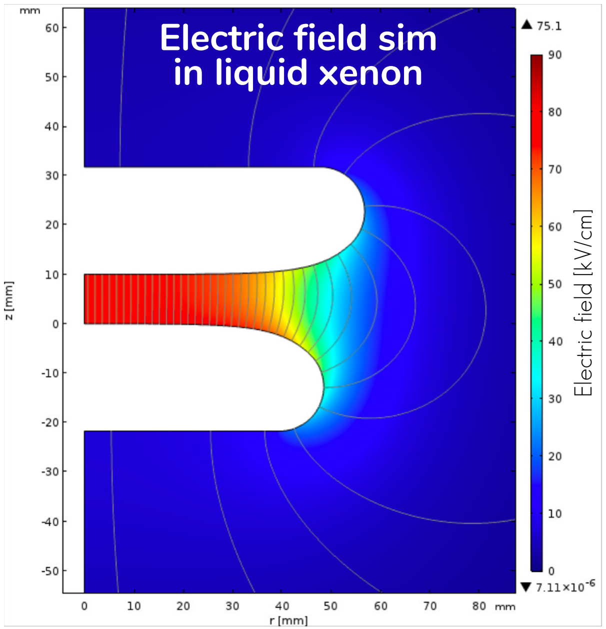
- Where sparks are most likely to happen

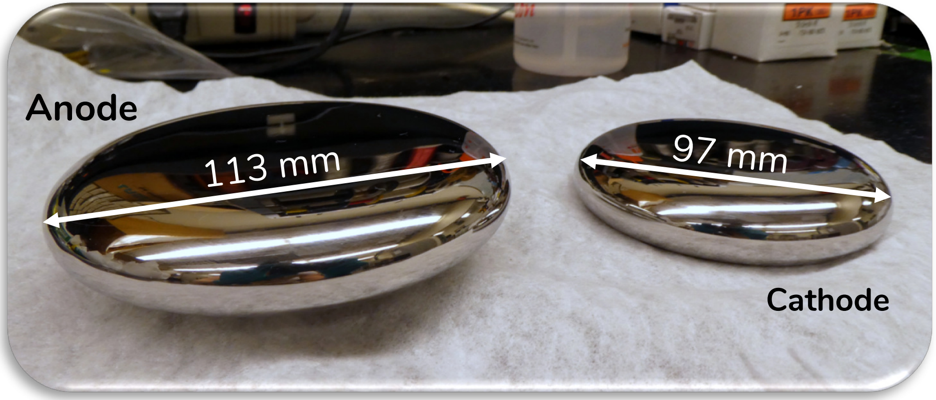




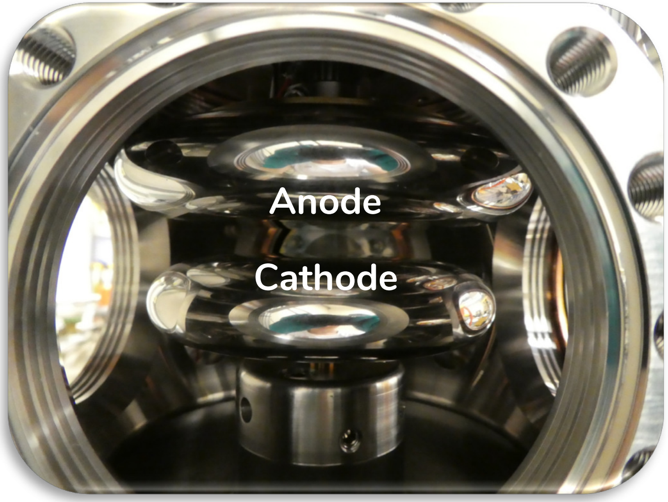
Rogowski electrodes provide large uniform area

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





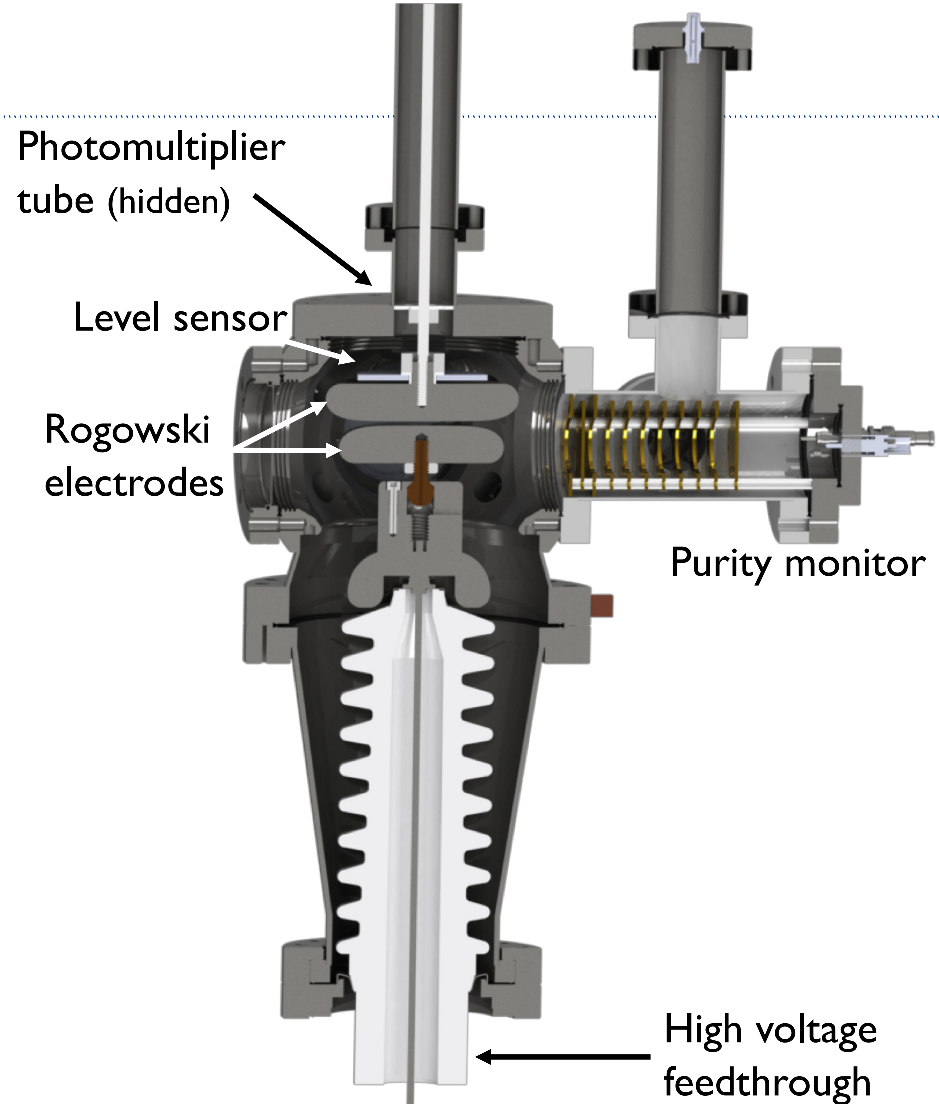
Location of electrodes in the detector



Cathode + HV feedthrough

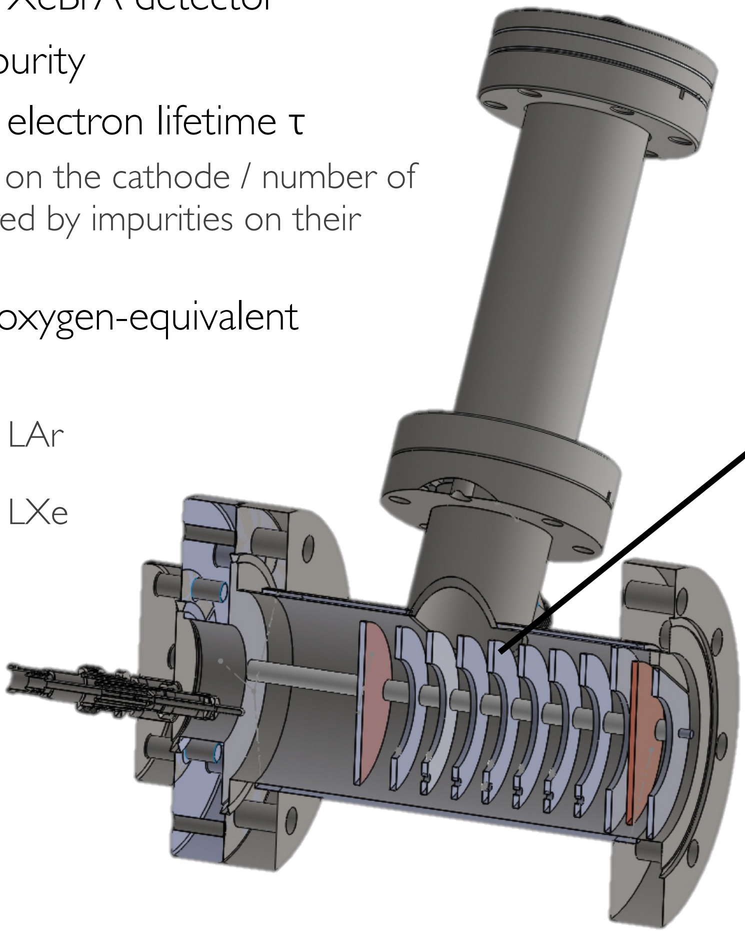
Apparatus details

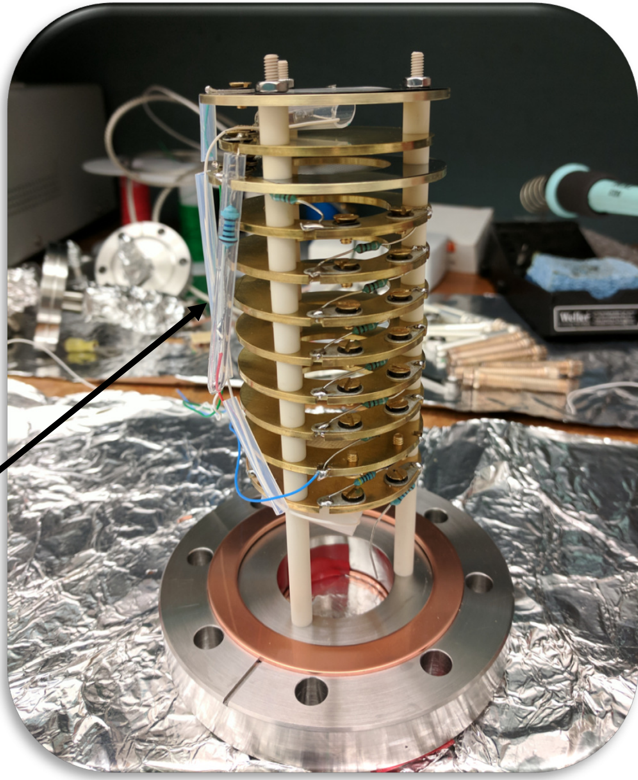
- Can be filled with either LXe or LAr with total experimental volume = 5.6 L
- Designed for HV up to -75 kV
- Max stressed electrode area = 58 cm^2
- Max electrode separation = 10 mm
- Ability to vary electrode separation remotely
- Continuous purification
- Monitoring of liquid purity
- Detection of both glow onset & breakdown
  - Current sensing, PMT & camera



XeBrA contains a purity monitor

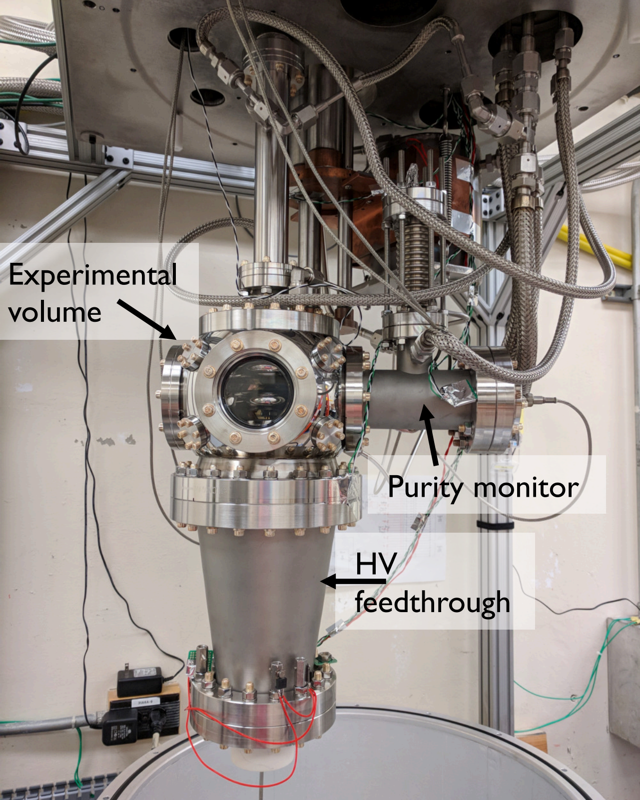
- Directly connected to XeBrA detector
- Monitors LXe & LAr purity
- Purity calculated from electron lifetime τ
  - Electrons generated on the cathode / number of electrons not captured by impurities on their way to the anode
- Can be converted to oxygen-equivalent concentration:
  - ρ[ppb]~408/τ[μs] in LAr
  - ρ[ppb]~455/τ[μs] in LXe

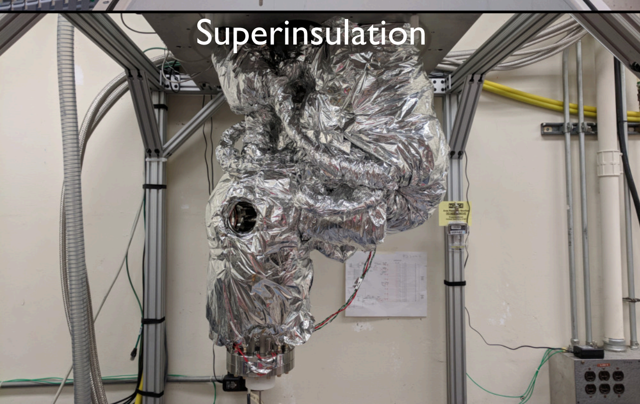


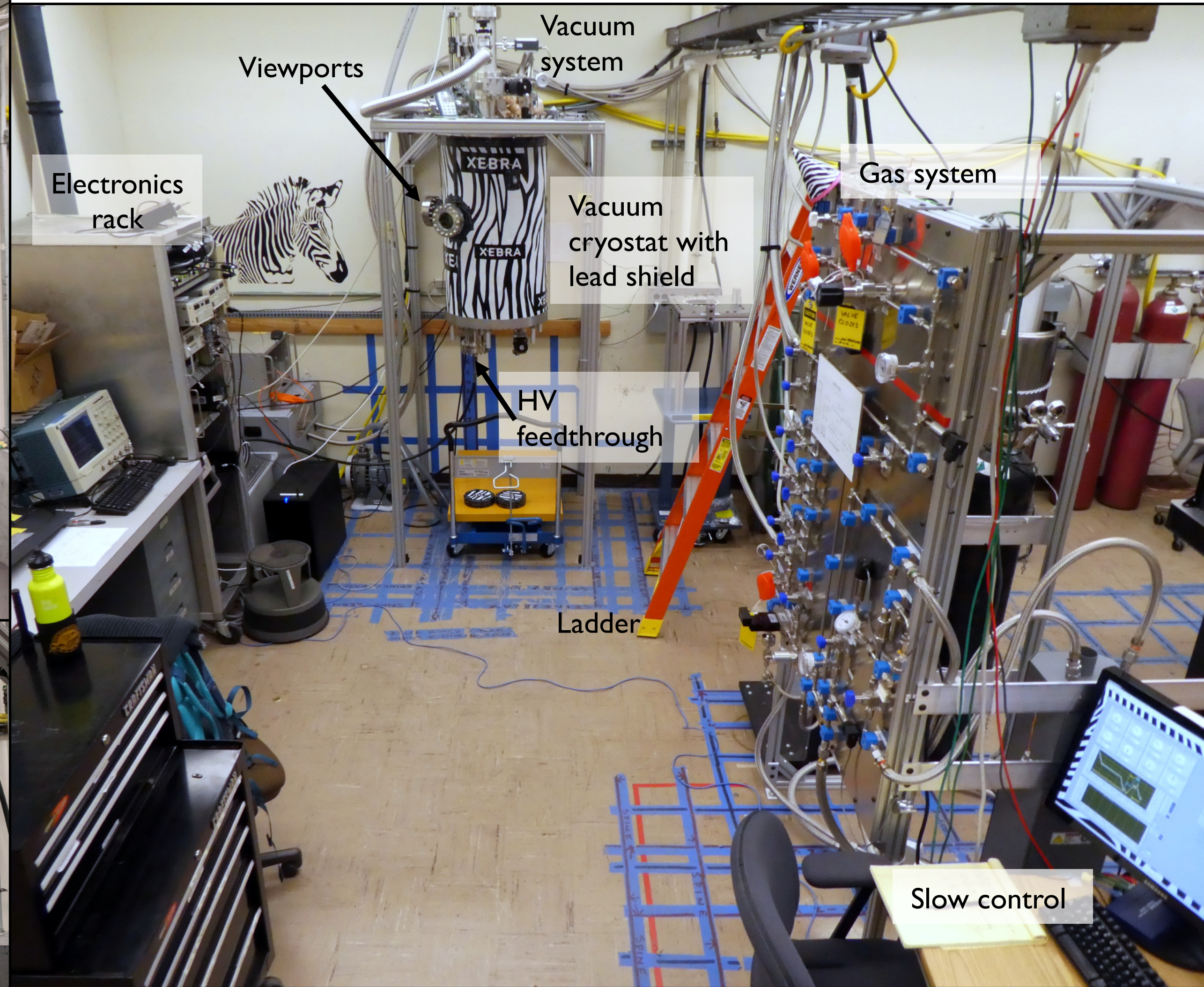


See, for example:
[A. Bettini, et al. NIM A 305.1 (1991)]()
[G. Carugno, et al. NIMA 292.3 (1990)]()
[Y. Li, et al. JINST 11 T06001 (2016)]()

XEBRA set up

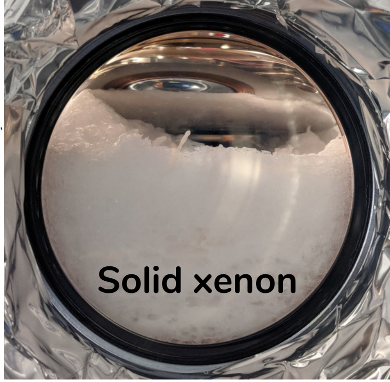

Experimental volume
Purity monitor
HV feedthrough


Superinsulation


Vacuum system
Viewports
Electronics rack
XEBRA
Vacuum cryostat with lead shield
Gas system
HV feedthrough
Ladder
Slow control

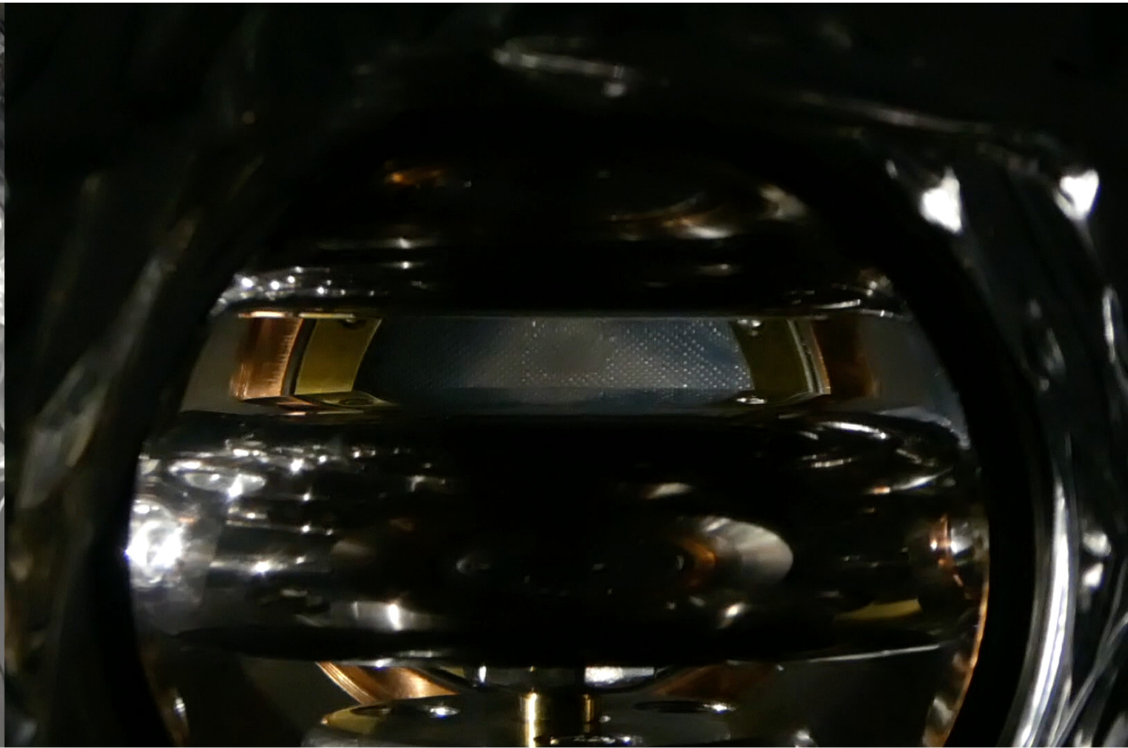
Viewports in action

- 3 hours of bubbles in LXe: https://www.youtube.com/watch?v=Zy9r8q1wmYc&t=179s
- Selection of sparks in LXe
- Selection of sparks in LAr
- Xenon phase changes: https://www.youtube.com/watch?v=vFYziAxh95w



Spark at 5mm in LXe

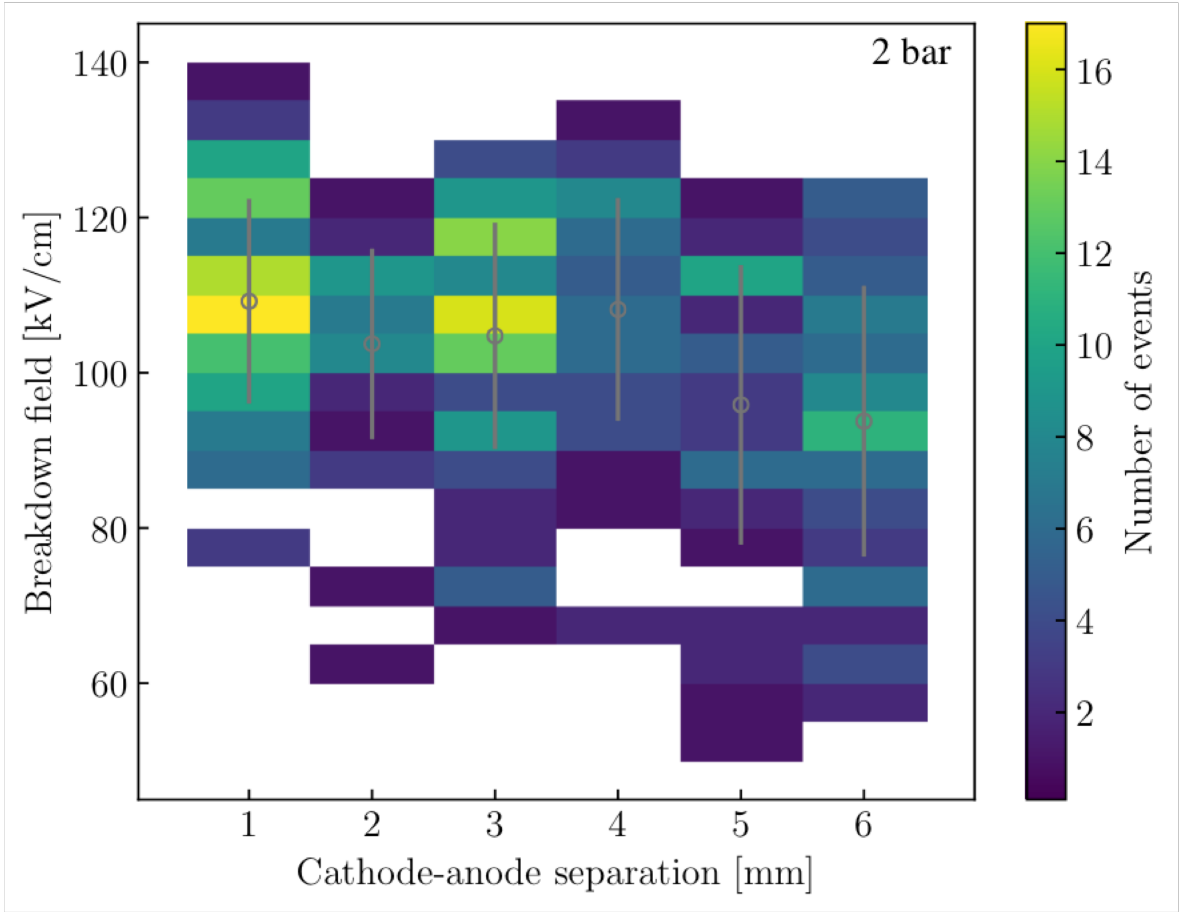
Spark at 7mm separation in LAr



Let’s look at data!

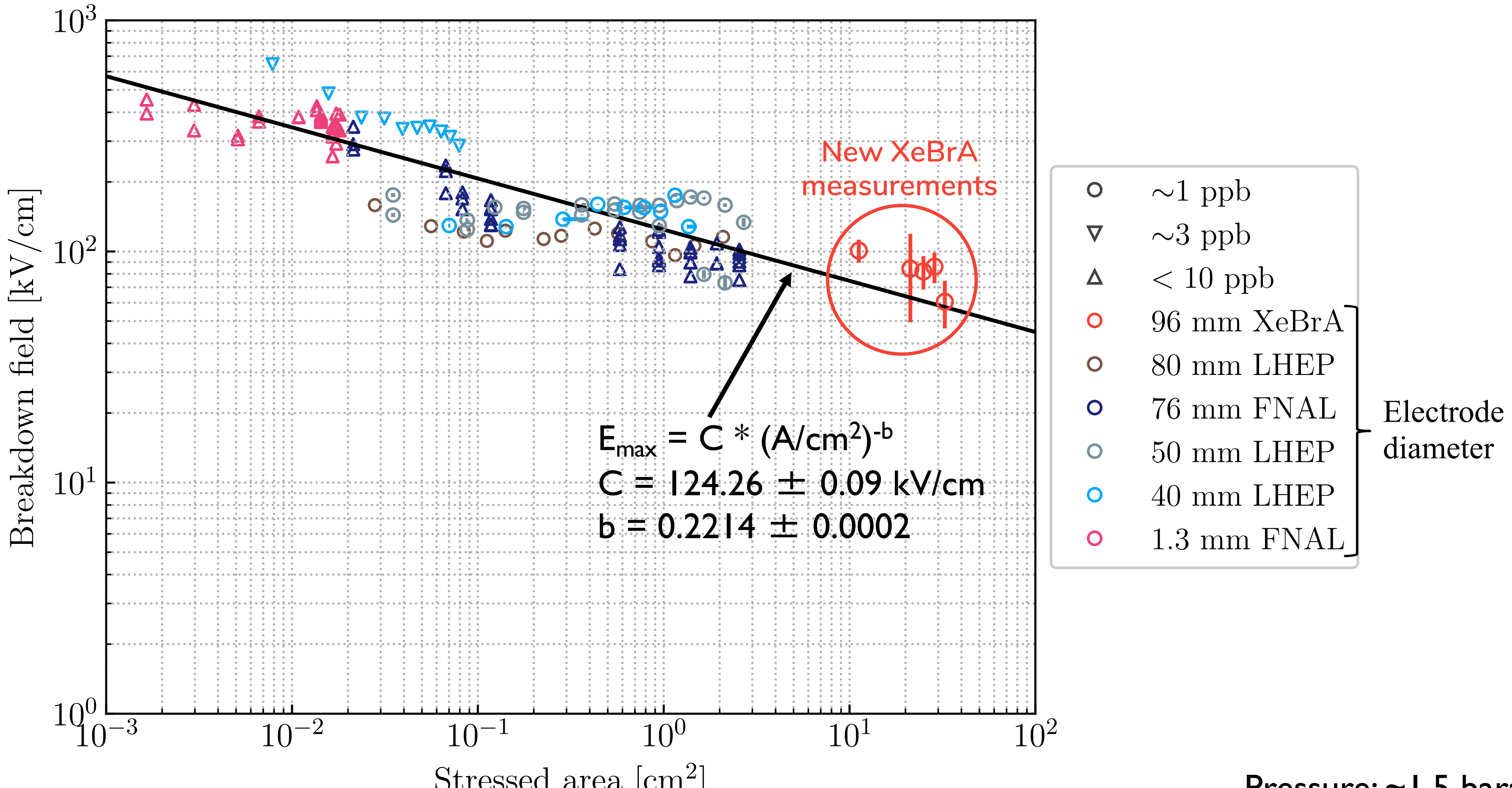
Breakdown field vs. electrode separation in LAr

- Pressure: 1.5 & 2 bara
- ~ 1 ppb (~300 μs) as measured by the purity monitor



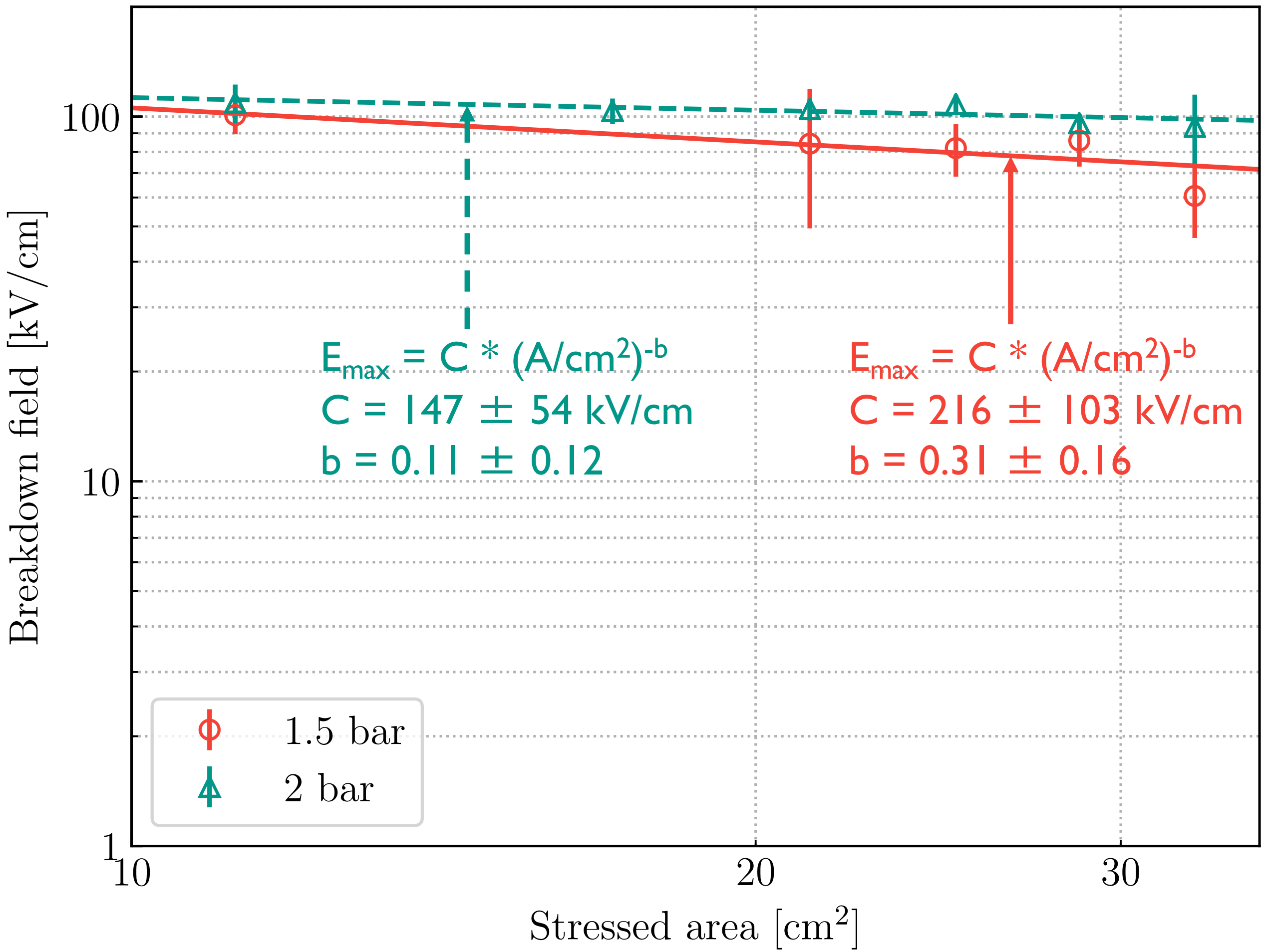
Note: circles represent the mean breakdown field and error bars the standard deviation

Breakdown field vs. stressed area in LAr

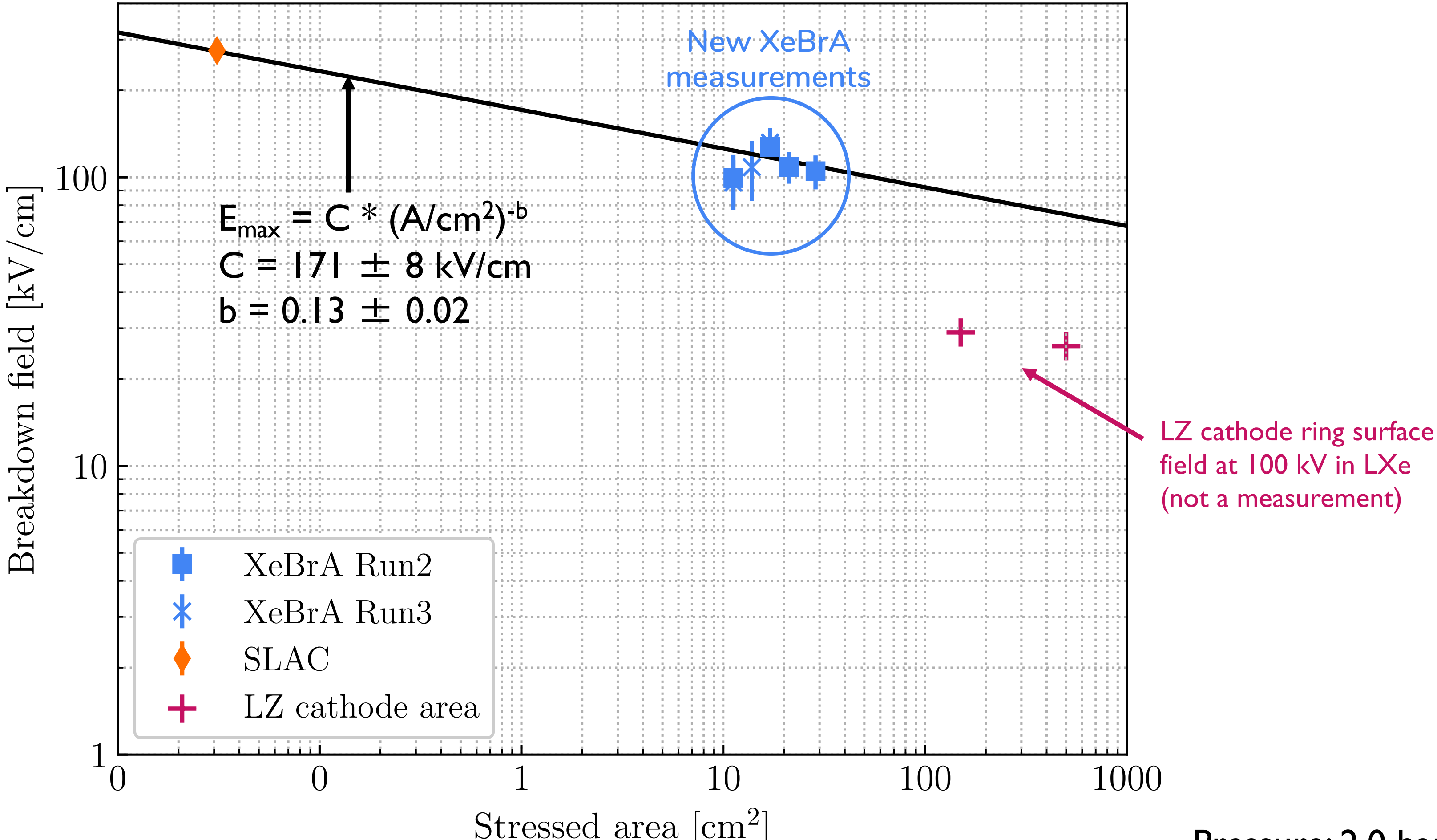


Pressure: ~1.5 bara

Breakdown field vs. stressed area and pressure in LAr

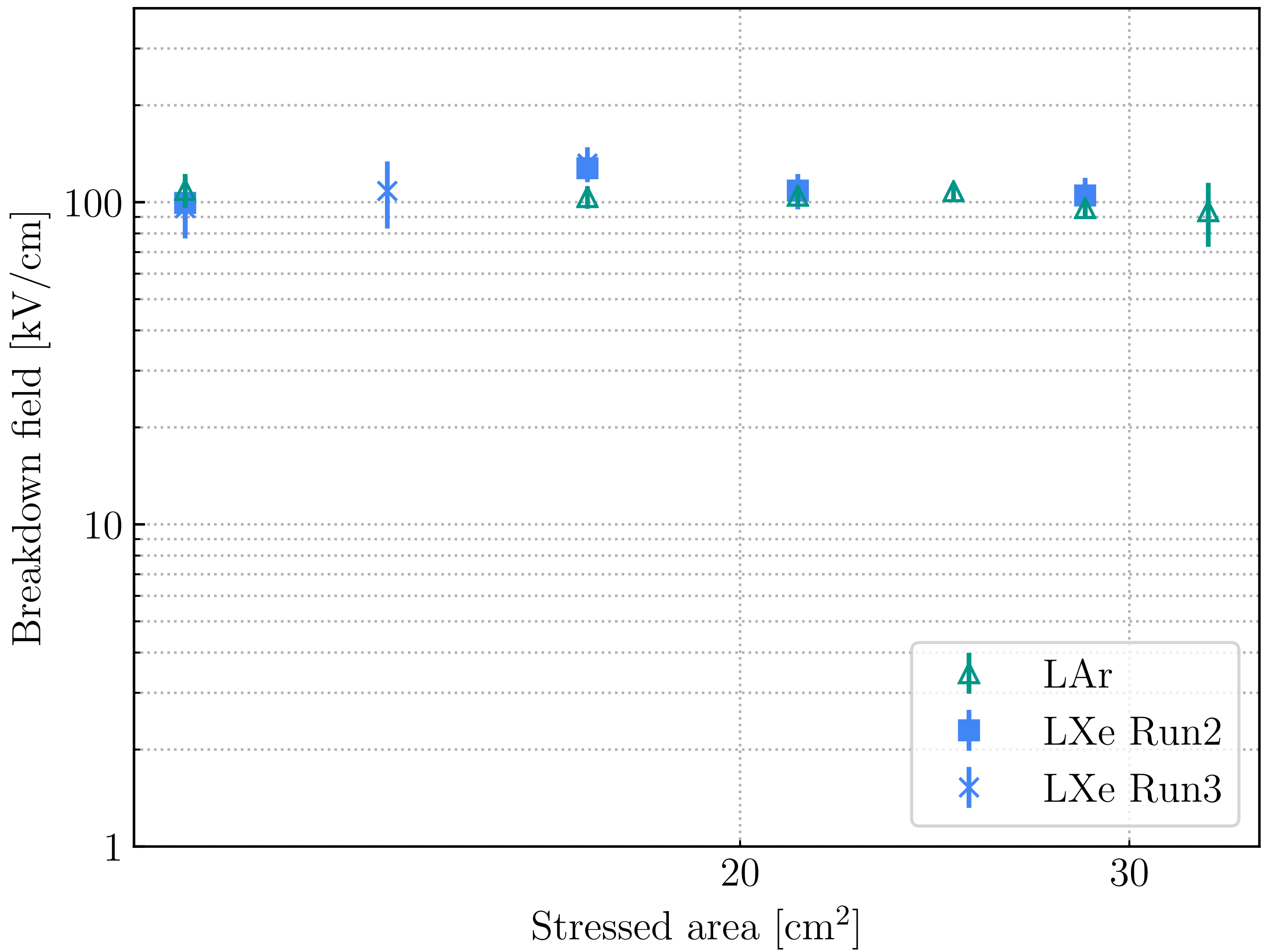


Breakdown field vs. stressed area in LXe



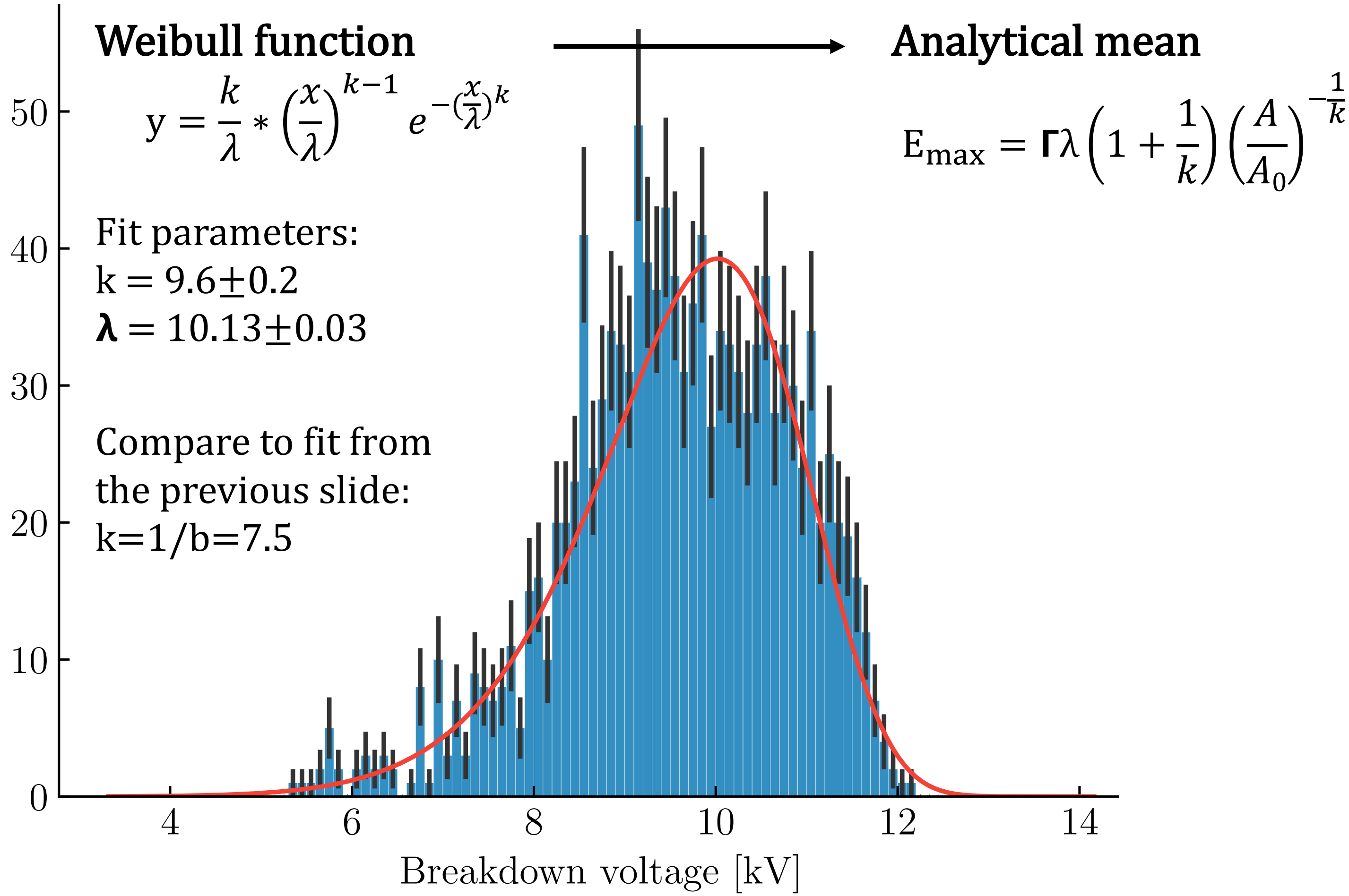
Pressure: 2.0 bara

Comparison of LAr and LXe data from XeBrA



Pressure: 2.0 bara

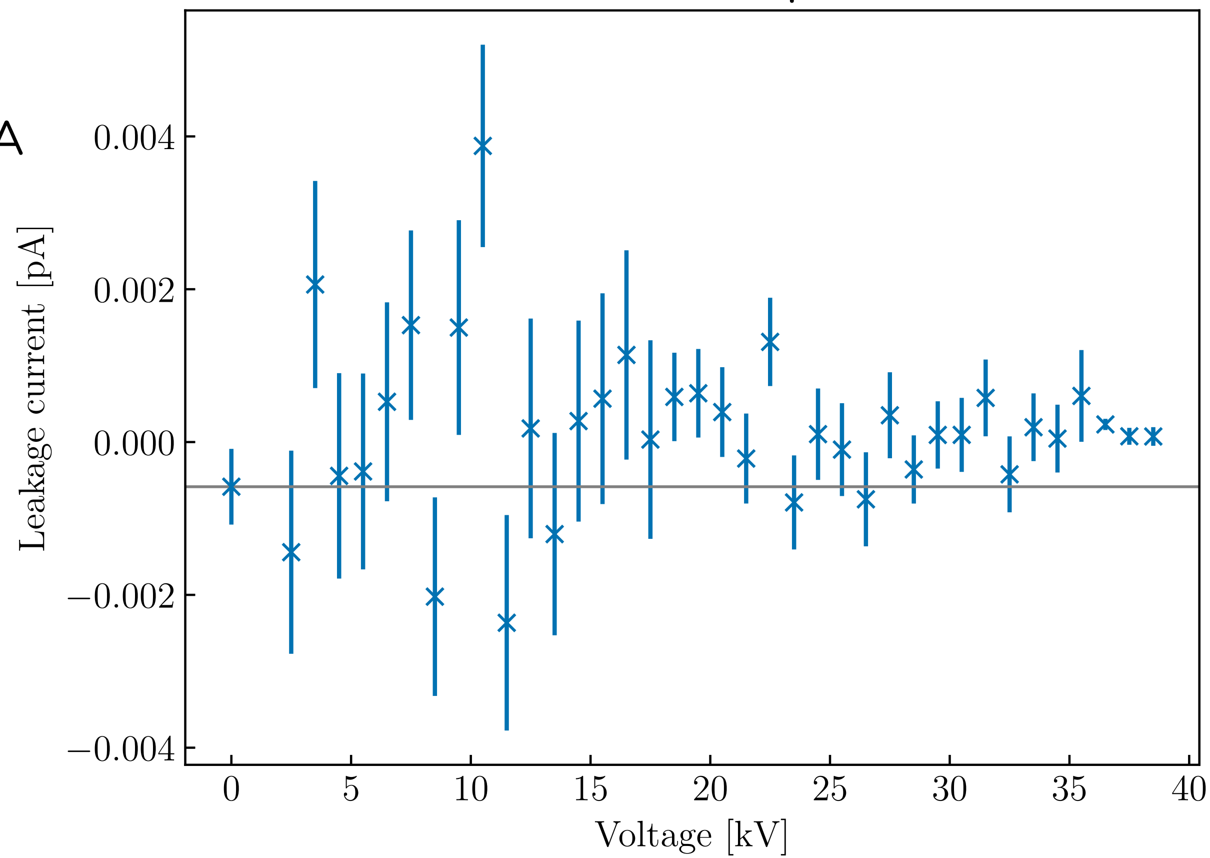
Fit of 1 mm electrode separation to Weibull function in LXe



Leakage current

- No obvious dependence of leakage current on voltage
- LXe: leakage current < 5 fA
- LAr: leakage current < 50 fA

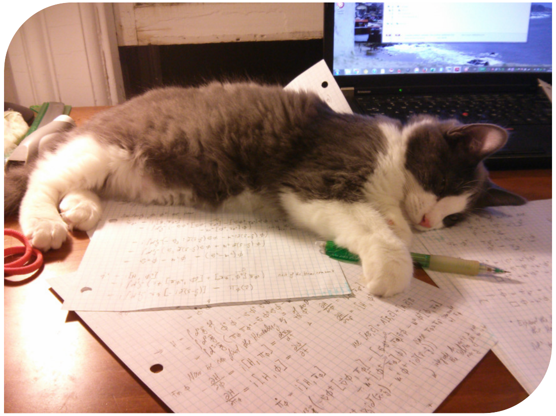
Leakage current in LXe
3 mm electrode separation

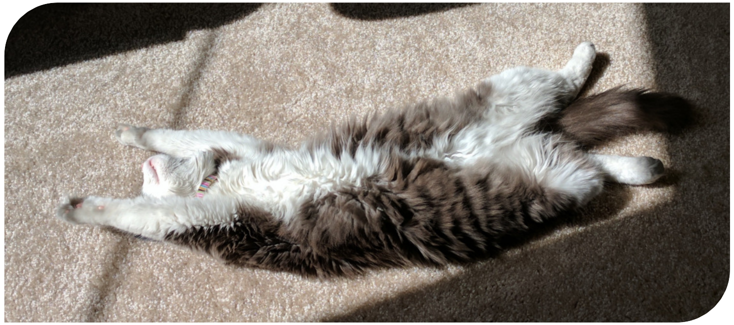


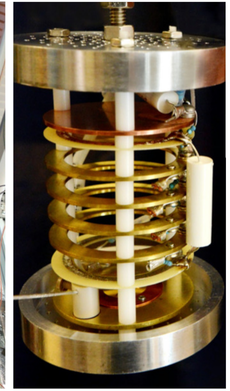
Conclusion

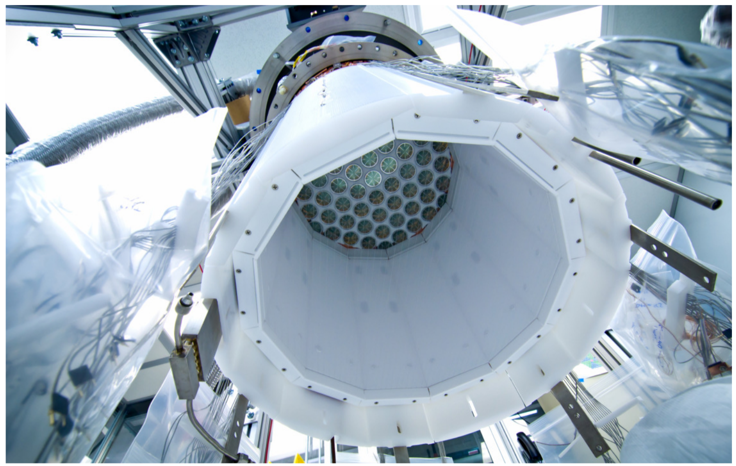
- Placed limits on sub-GeV DM using 2013 LUX data
  - This result extends the reach of liquid xenon detectors
  - Available at [arXiv: 1811.11241]
  - Recommended by reviewers for publication in the PRL

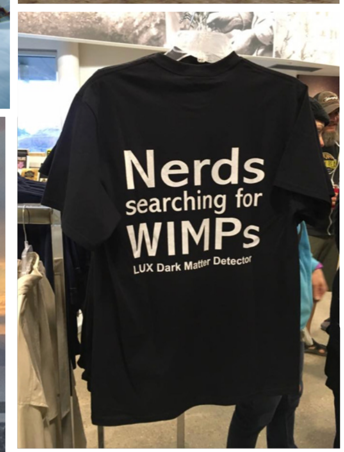
- Built & collected data with XeBrA at LBNL
  - Direct comparison of dielectric breakdown in liquid argon and xenon
  - Measurements with larger electrode areas than previously studied
  - Publication in preparation
  - Further data collection forthcoming
    - Study effects of varying electrode materials, finishes & coatings
    - Study effects of liquid purity & different impurities
    - …

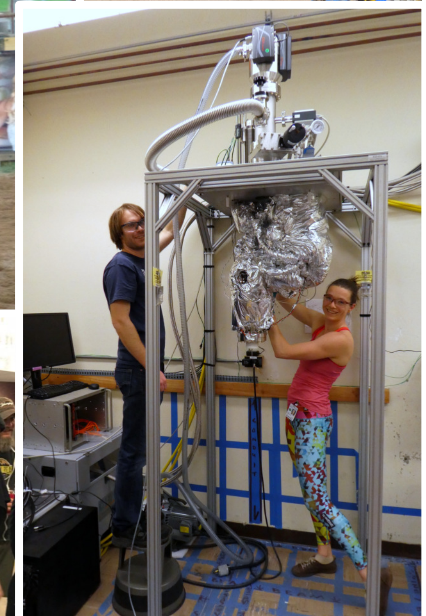


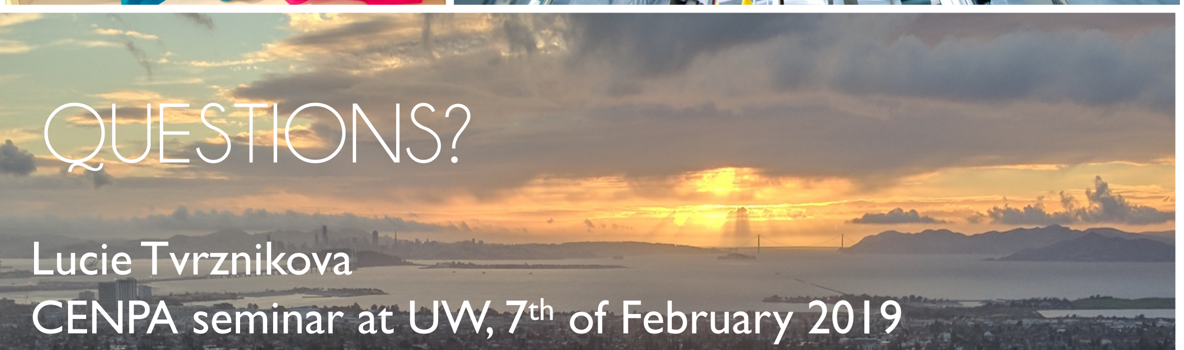












QUESTIONS?

Lucie Tvrznikova

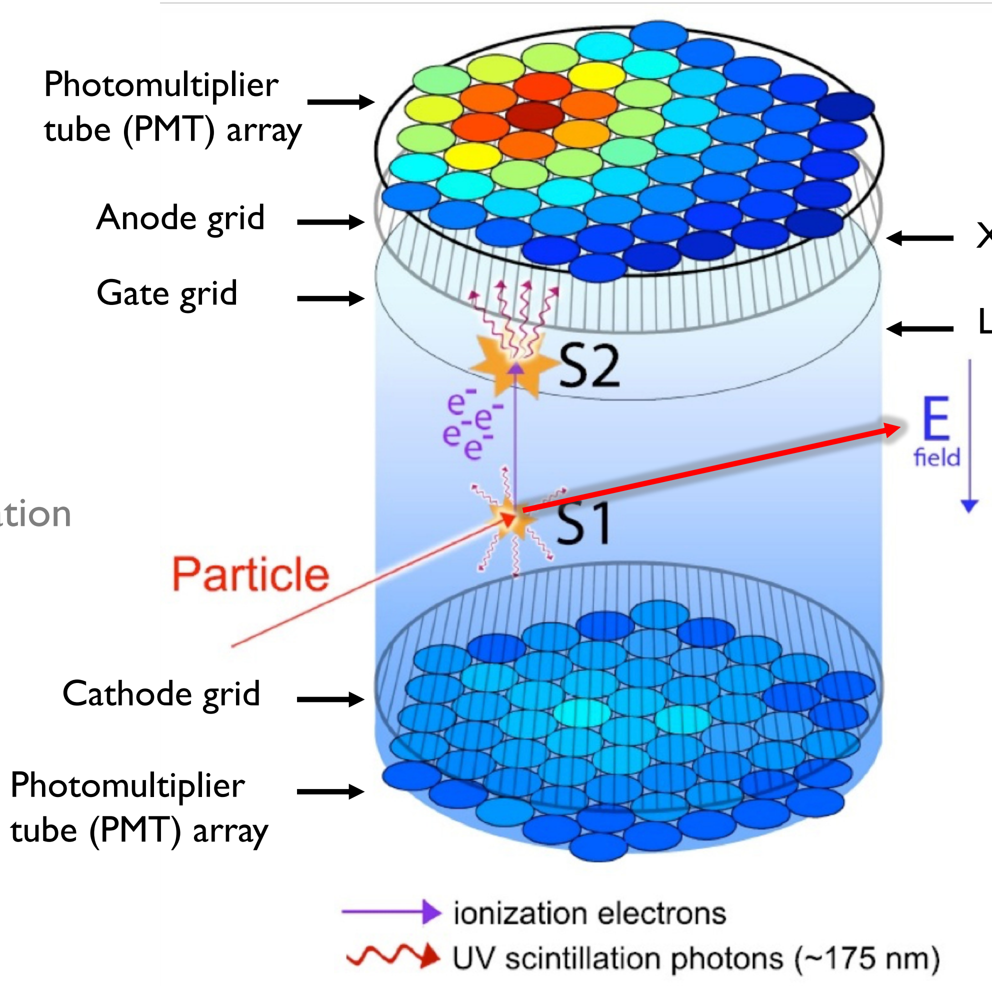
CENPA seminar at UW, 7th of February 2019

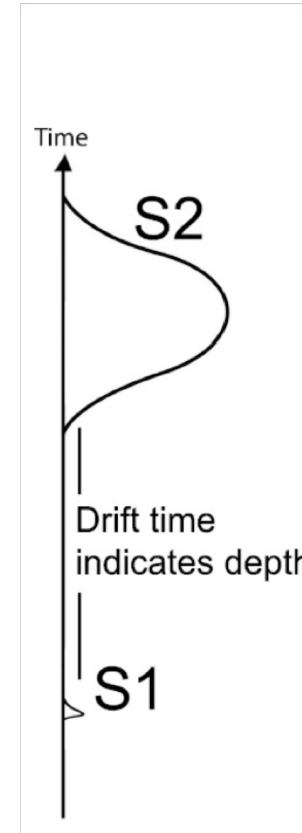
XEBRA

LUX is a xenon two phase TPC

TPC = Time Projection Chamber

- ✓ Full 3D position reconstruction
- ✓ S2/S1 discrimination





LUX collected data from 2013-2016

2006: LUX collaboration formed

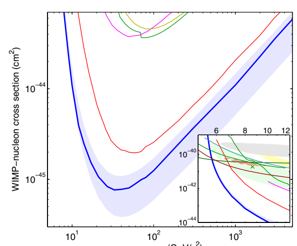
2008: LUX funded (DOE + NSF)

July 2012: LUX moves UG

April 2013: First science run starts

August 2013: Joined LUX

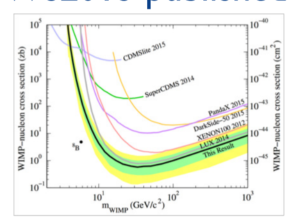
Nov 2013: First WS results reported (85.3 live-days)



PRL, 112, 091303 (2014)

Sept 2014: 332-day run start

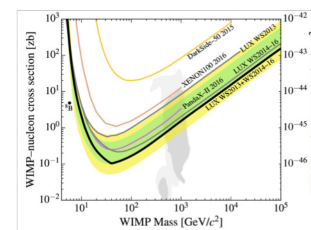
Dec 2015: Re-analysis of WS2013 published



PRL, 116, 161301 (2016)

May 2016: WS2014-16 finished

July 2016: 332-day WS result announced



PRL, 118, 021303 (2017)

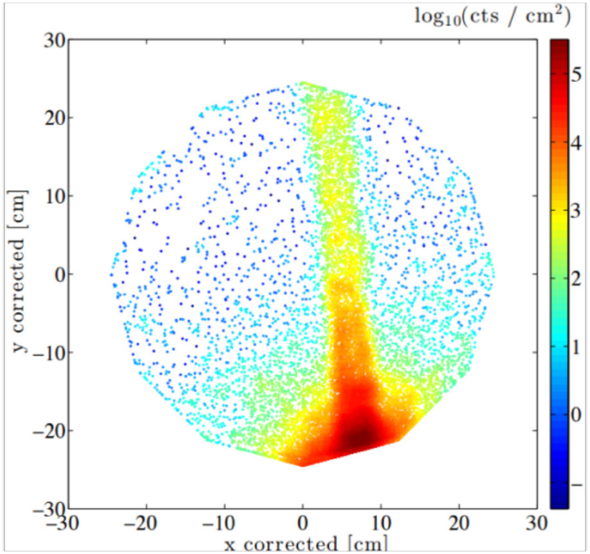
Sept 2016: decommissioning start

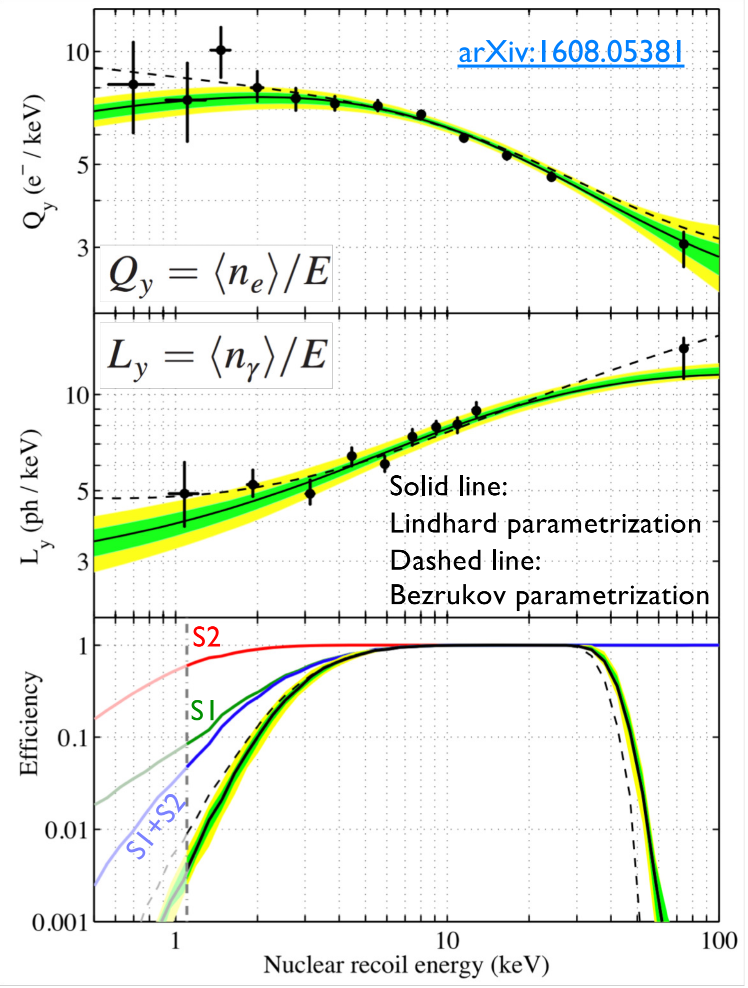
June 2017: LUX installed in a museum

Analyses still ongoing

DD neutrons calibrate nuclear recoils

- Deuterium-Deuterium neutron generator (2.45 MeV)
  - Located outside of the water tank
  - Quarterly at different z
  - Double scatters used for Q_y analysis
    - 0.7 – 74 keV
  - Single scatters used for L_y analysis and NR band
    - 1.1 – 74 keV





Calibrations help characterize detector response

PRD 97, 102008 (2018)

DD neutron generator arXiv:1608.05381

- Characterization of nuclear recoils

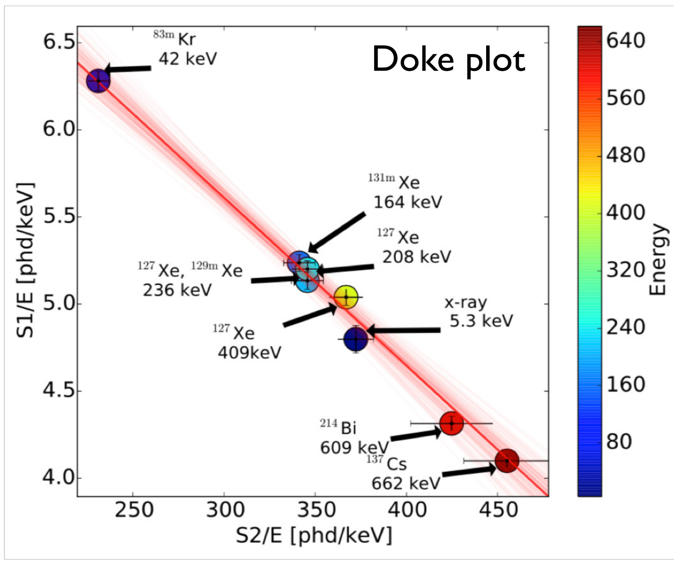
Tritium PRD 93, 072009 (2016)

- Characterization of electron recoils

^{83m}Kr PRD 11.112009 (2017)

- Detector performance monitoring

And more…



Energy deposition in the detector ∝ # of quanta produced by interaction

Work function
$W = (13.7 \pm 0.2)$ eV/quanta
$f \propto$ heat

$$E = fW(n_\gamma + ne)$$

Number of photons detected
$n_\gamma = S1/g_1$

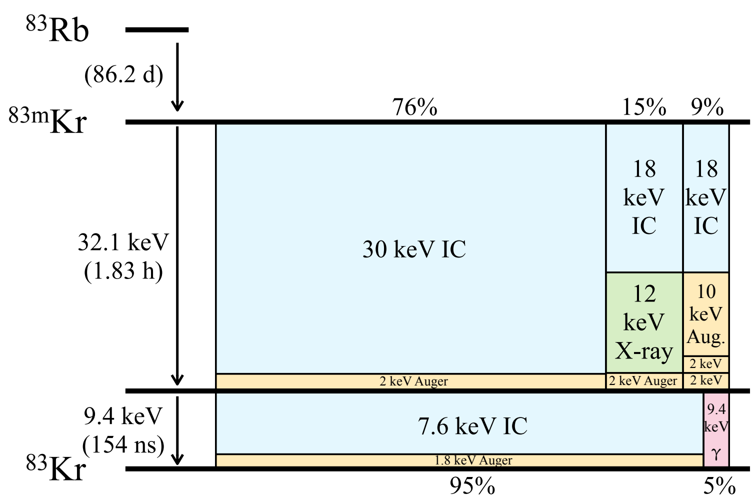
Number of electrons detected
$n_e = S2/g_2$

The detector specific gains g_1 and g_2 are obtained from calibrations

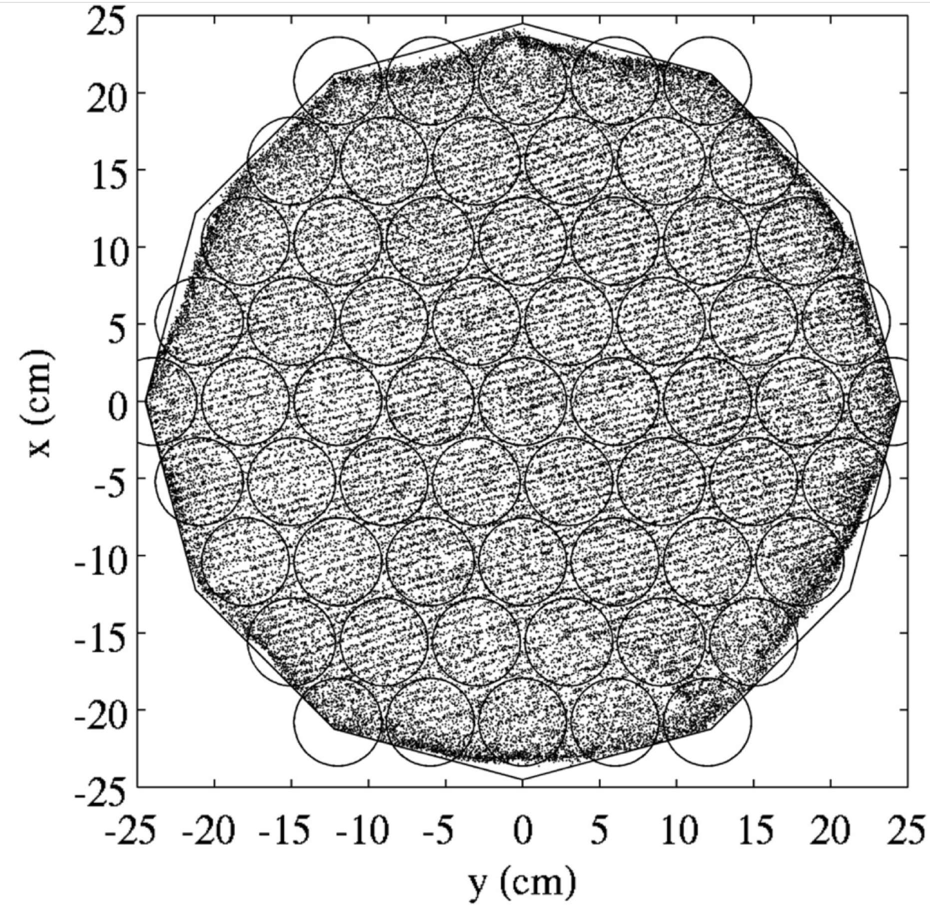
^{83m}Kr monitors detector performance

[PRD 11.112009 (2017)]

- ^{83m}Kr is injected regularly
- Mixes homogenously with LXe
- Used for:
  - Overall stability monitoring
  - Electron lifetime measurements
  - S1 & S2 position corrections
  - Electric field modeling
- Monoenergetic for our standard analysis

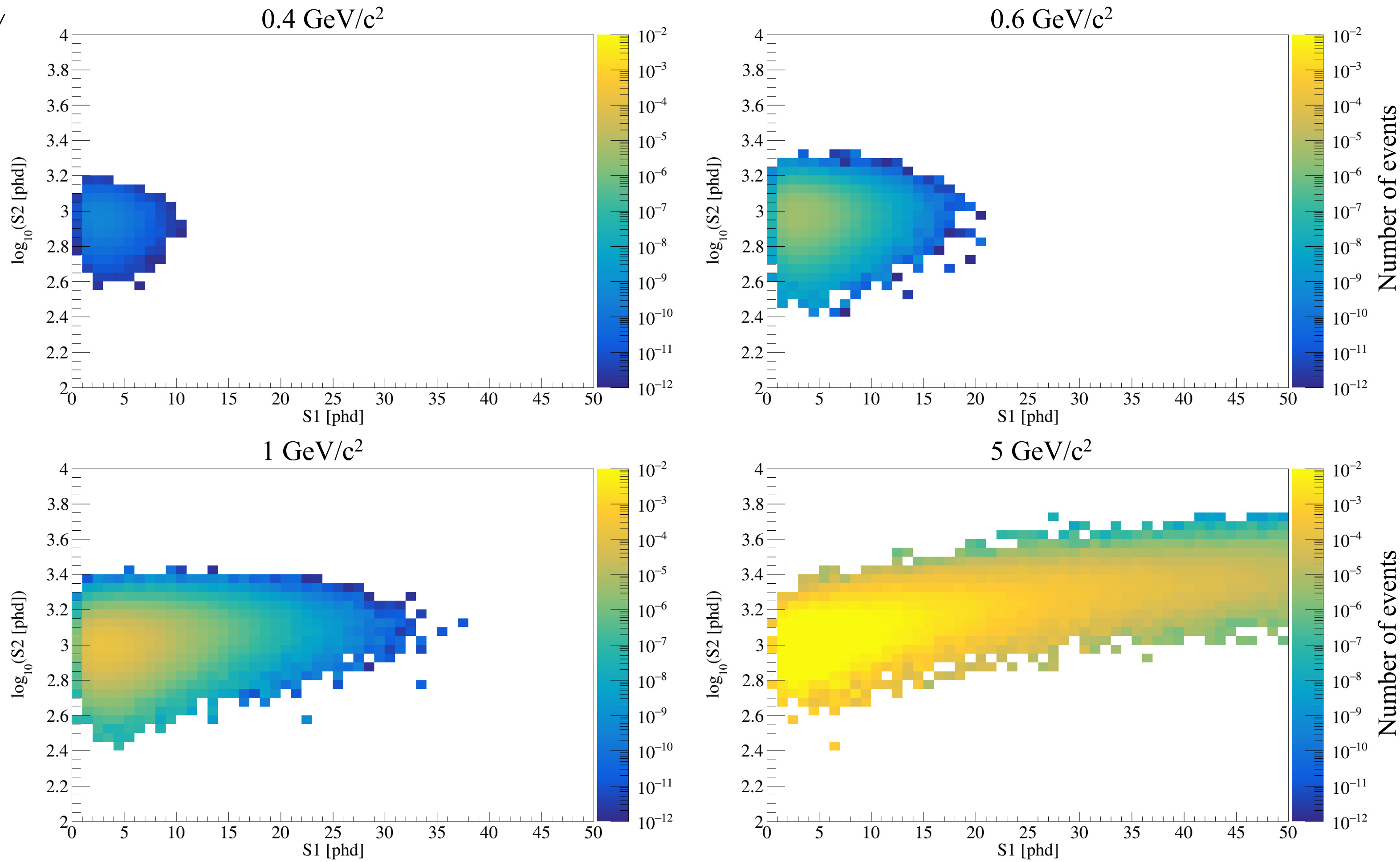


Drift time 4 - 8 µs



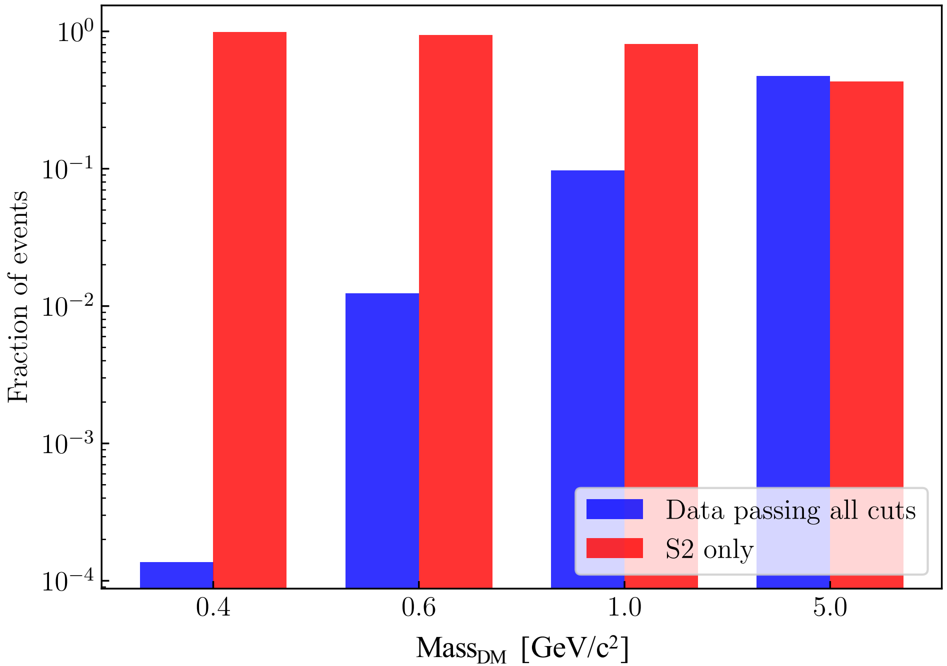
Expected signal spectra from Migdal simulated by NEST2.0

- Assuming heavy scalar mediator
- $\sigma = 10^{-35}$ cm^2

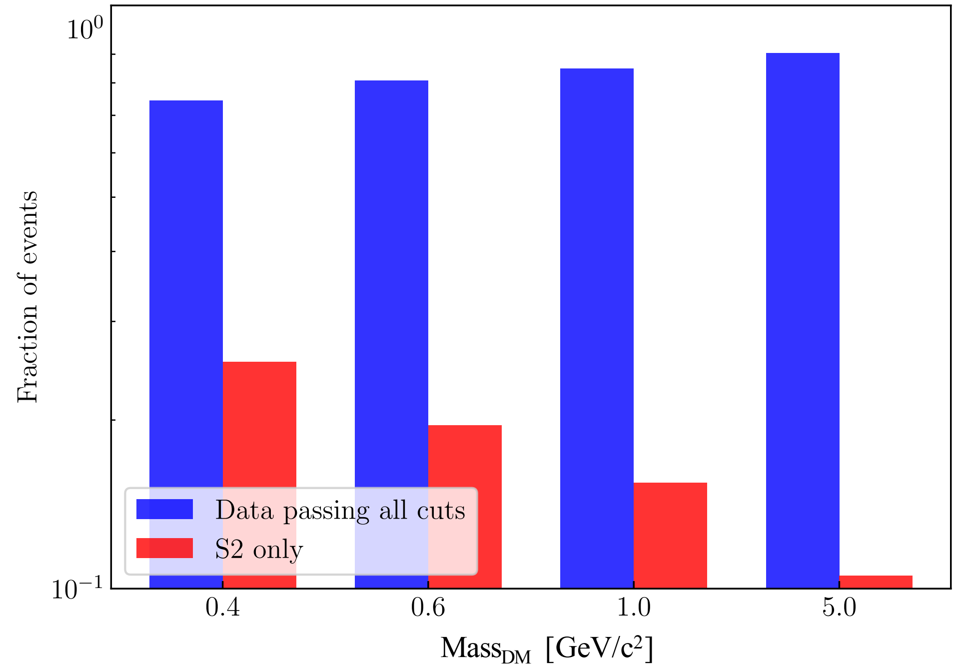


Only a fraction of events have both S1 & S2 signals

Bremsstrahlung



Migdal effect

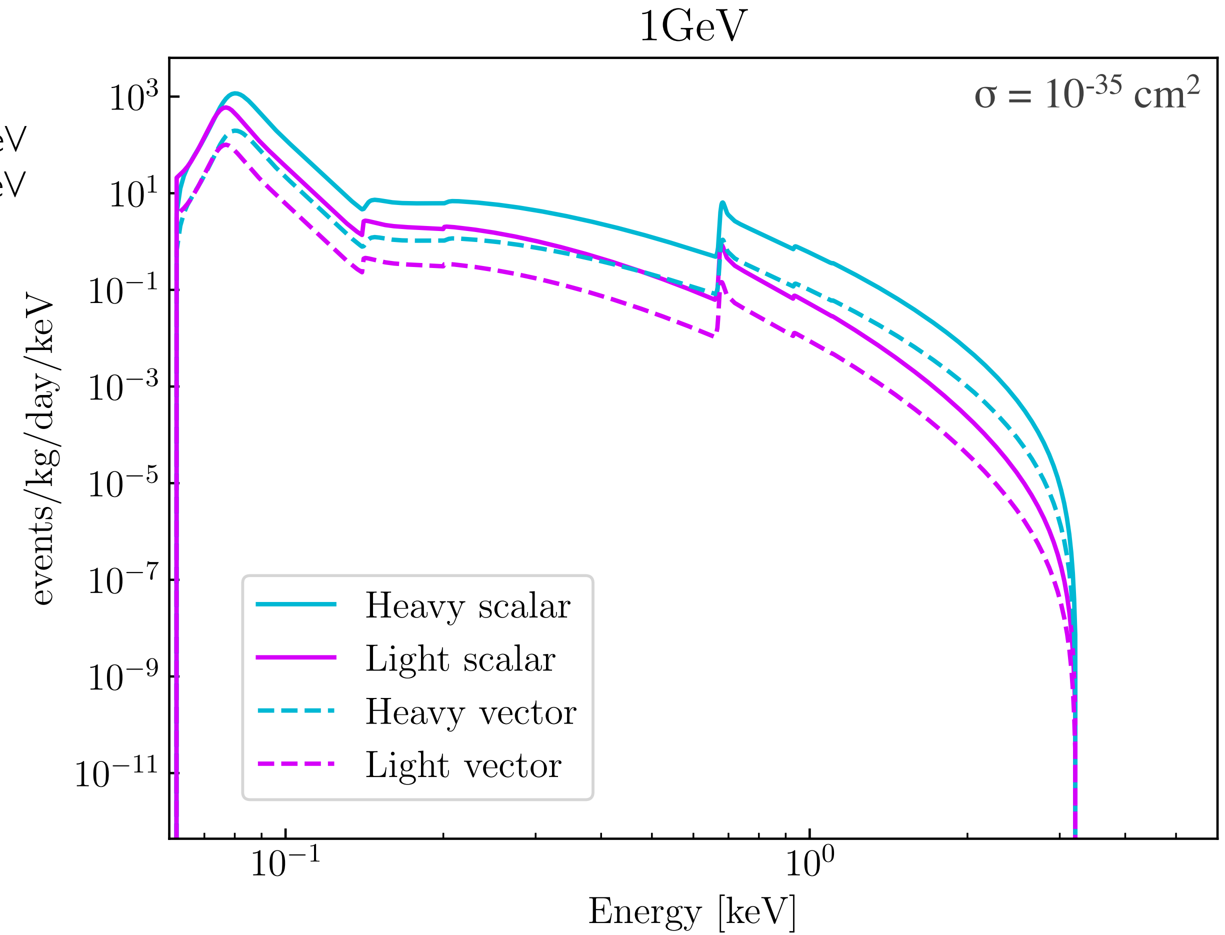


Heavy scalar mediator

Four different mediators were considered for Migdal effect

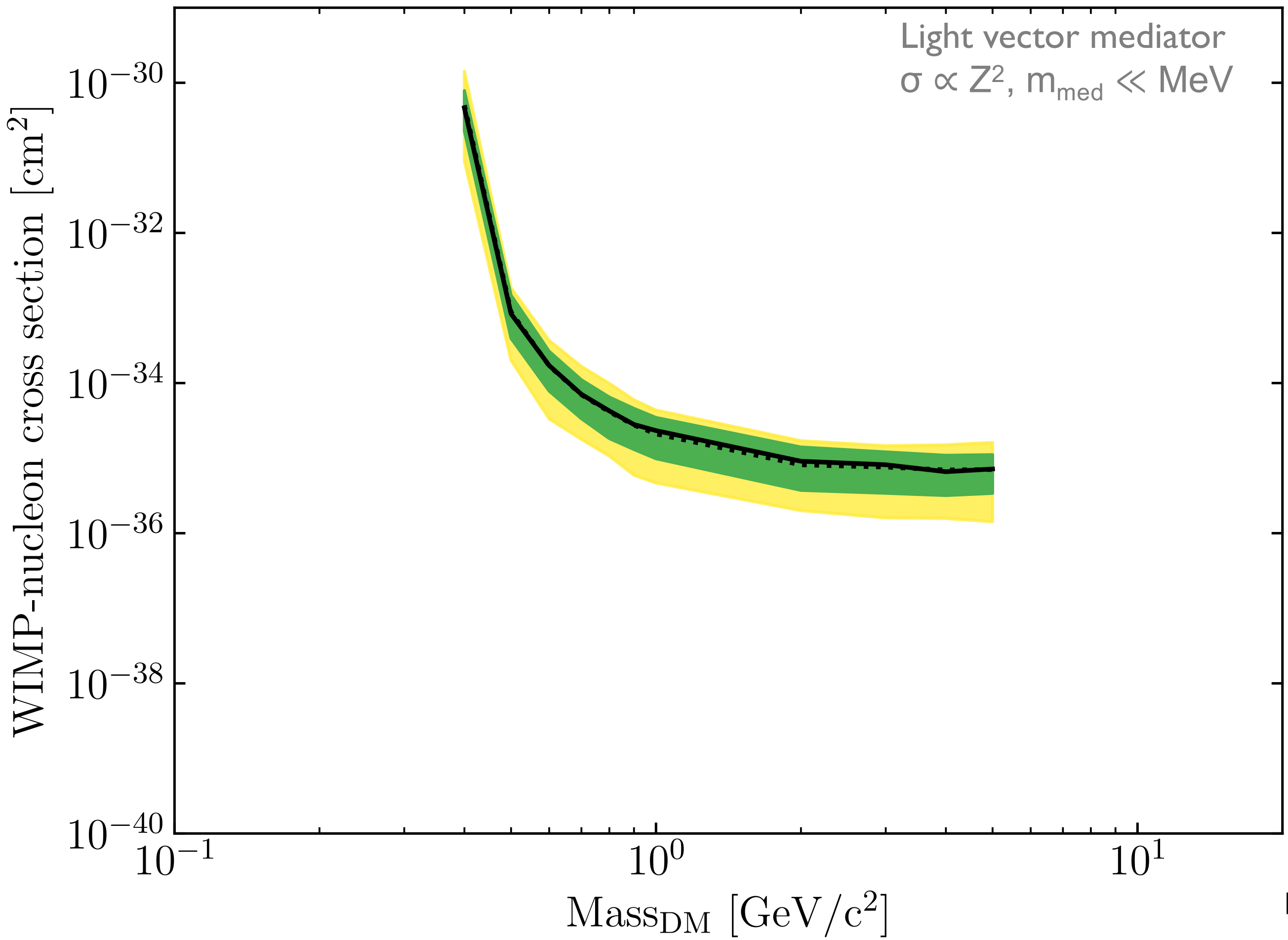
- Scalar mediator $\sigma \propto A^2$
- Vector mediator $\sigma \propto Z^2$

- Heavy mediator $m_{med} \gg$ MeV
- Light mediator $m_{med} \gg$ MeV
  q_{ref} = 1 MeV



LUX limit for the Migdal effect assuming vector mediator

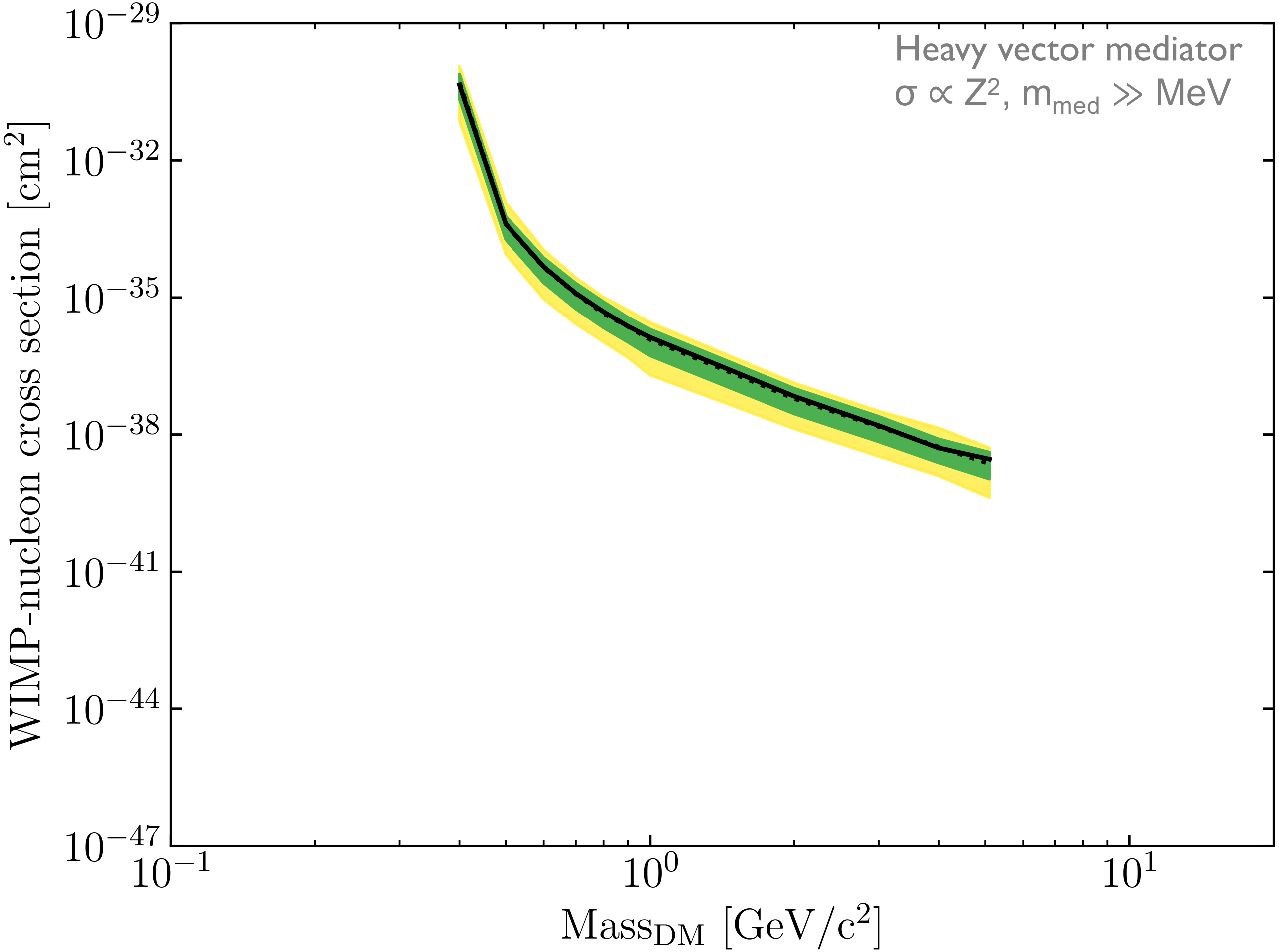
arXiv: 1811.11241



Limit is for 95 live-days of data
(with 13,775 kg·day exposure)

LUX limit for the Migdal effect assuming vector mediator

arXiv: 1811.11241

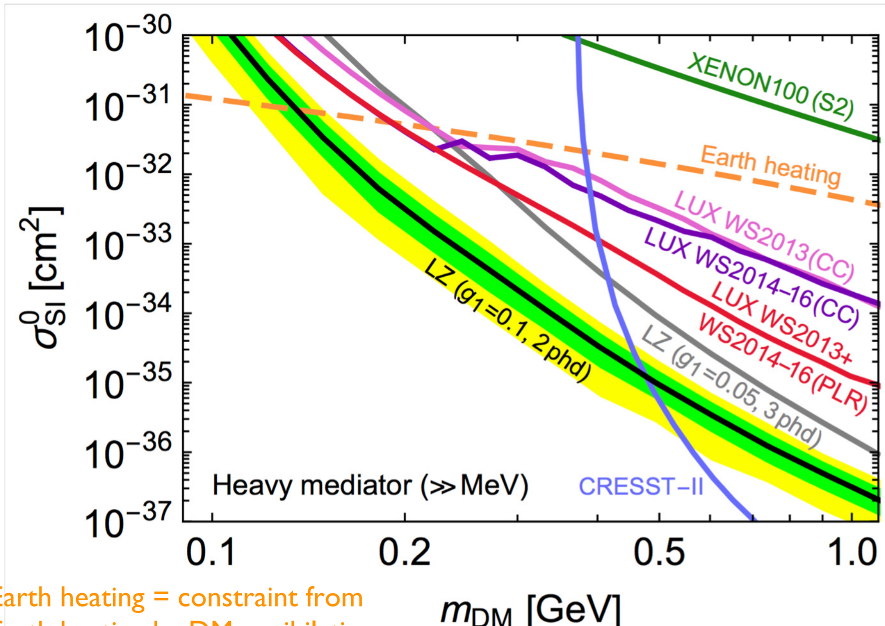


Limit is for 95 live-days of data (with 13,775 kg·day exposure)

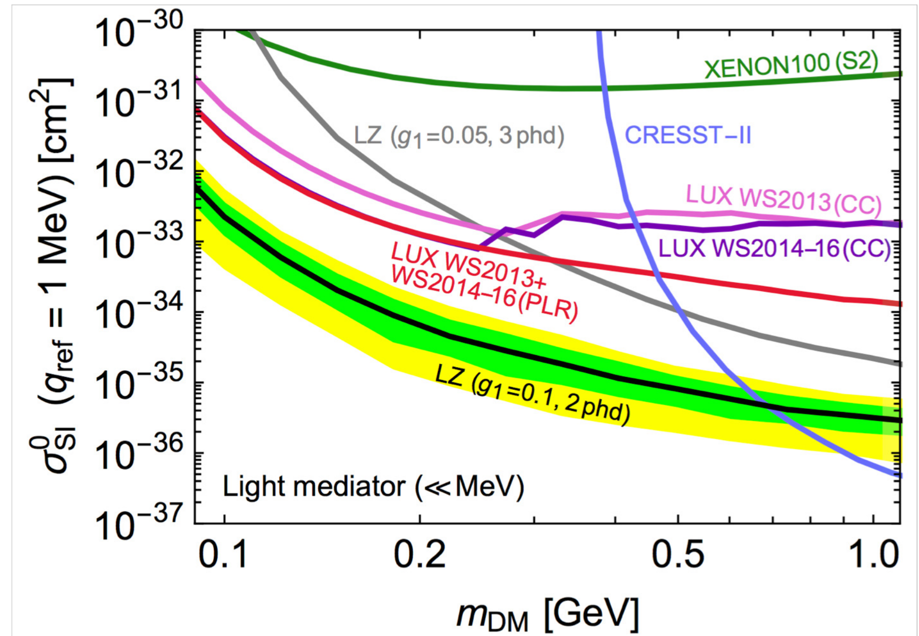
Limits from Bremsstrahlung – C. McCabe

PRD 96, 043010 (2017)

- C. McCabe published his work inferring LUX sensitivity to the sub-GeV signal and calculated limits for LUX & LZ



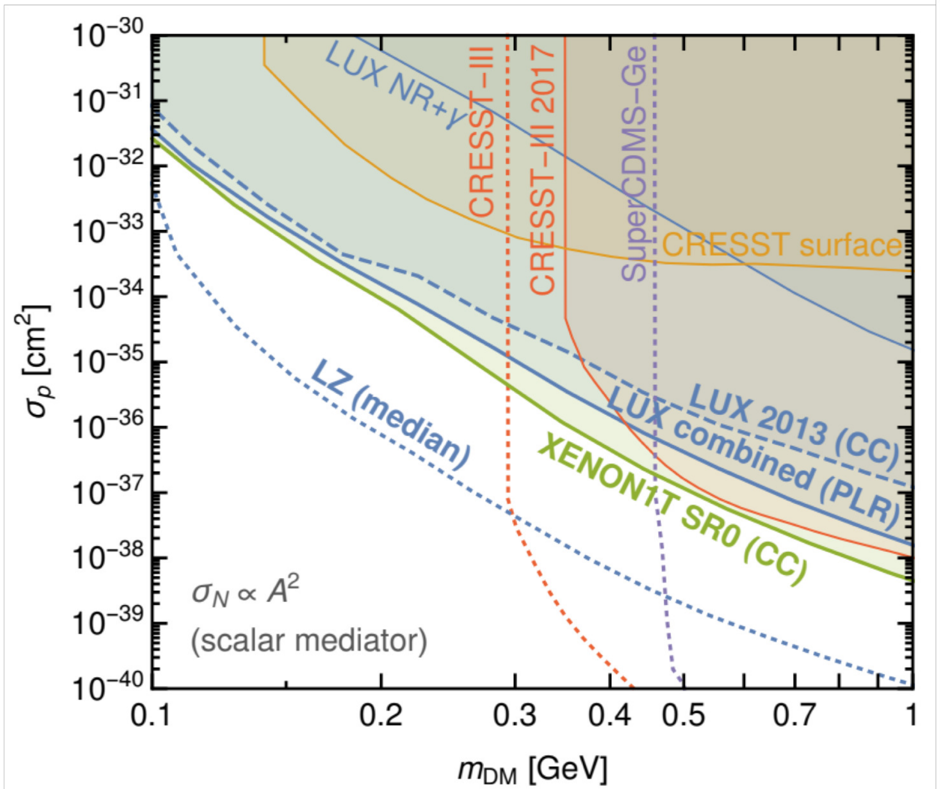
Earth heating = constraint from Earth heating by DM annihilation

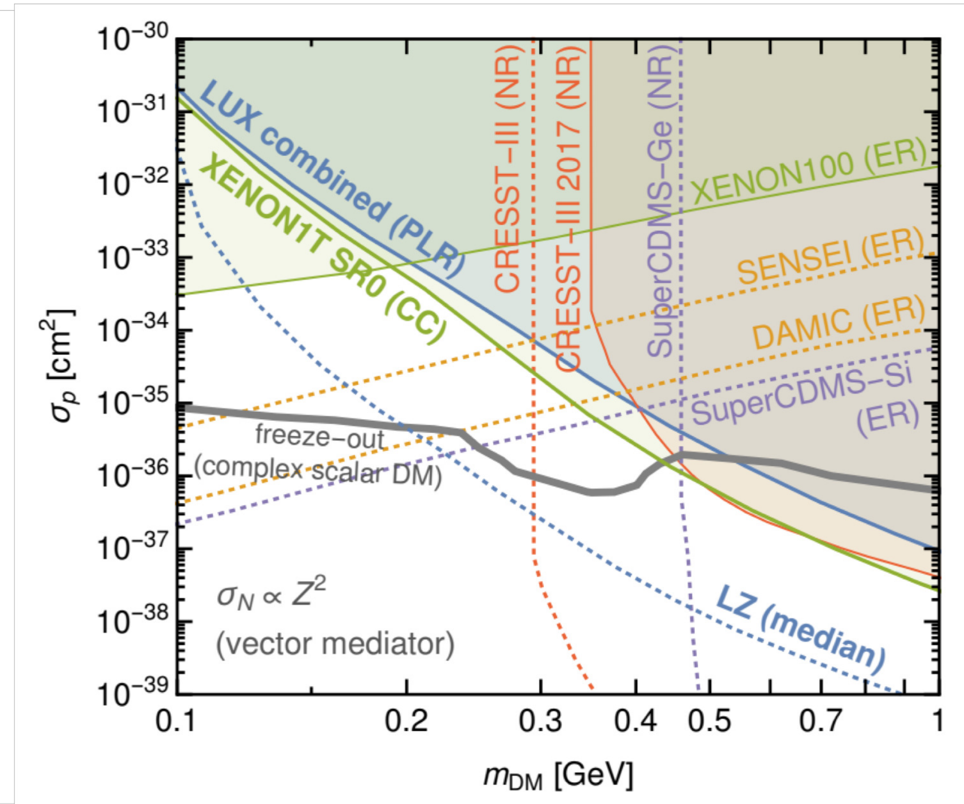


Limits from Migdal – Dolan *et al.*

arXiv:1700.09906

- M. J. Dolan, F. Kahlhoefer, and C. McCabe published limits for the Migdal effect assuming a heavy scalar mediator



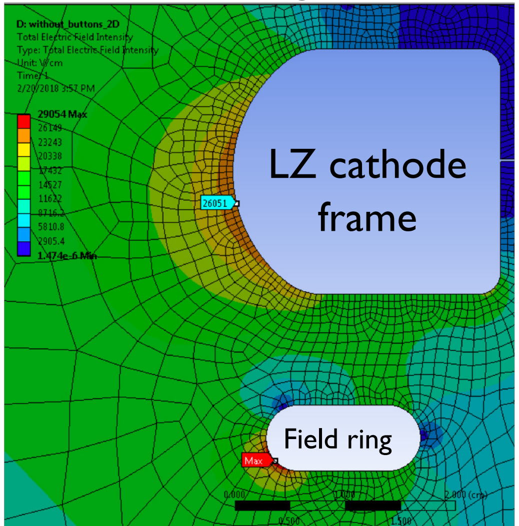


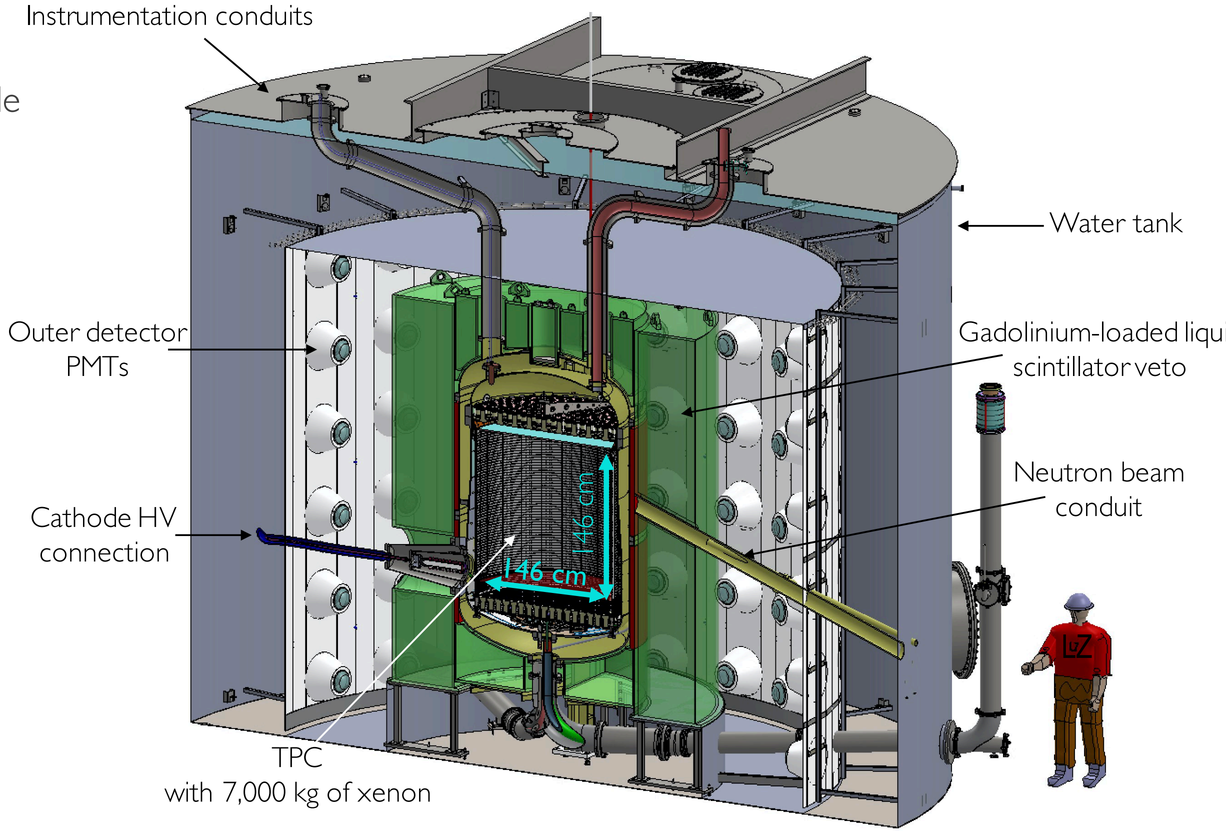
Larger detectors need higher cathode voltage

HV goal

- Deliver -100 kV to the LZ cathode
- Provide 685 V/cm drift field

LZ cathode ring field sim

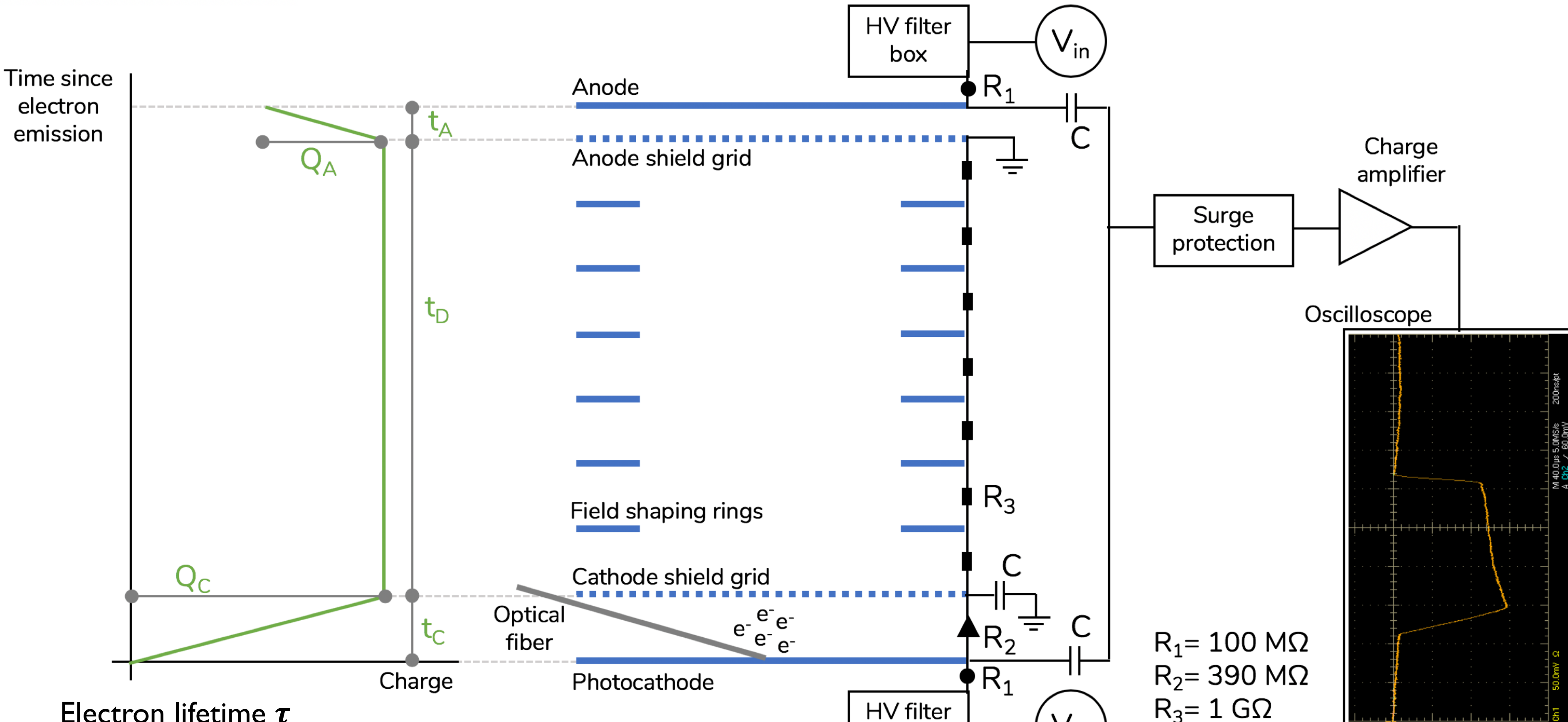




For technical details see LZ TDR, arXiv:1703.09144

For sensitivity see arXiv:1802.06039

Purity monitor measures electron lifetime



Electron lifetime τ

$\tau = -t_W / \ln(Q_A/Q_C)$

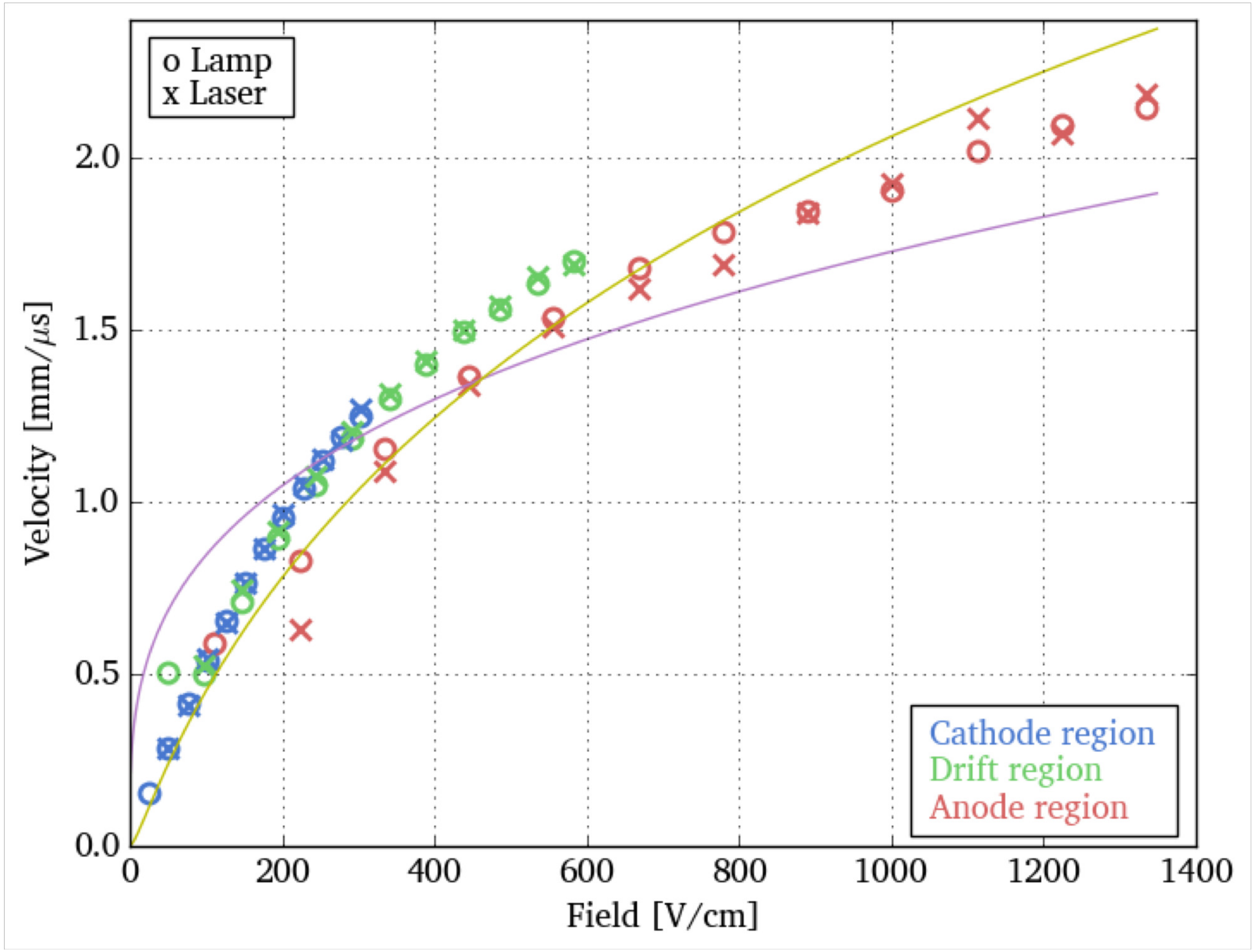
where $t_W = t_D+(t_A+t_C)/2$

Electron velocity in LAr measured by the purity monitor

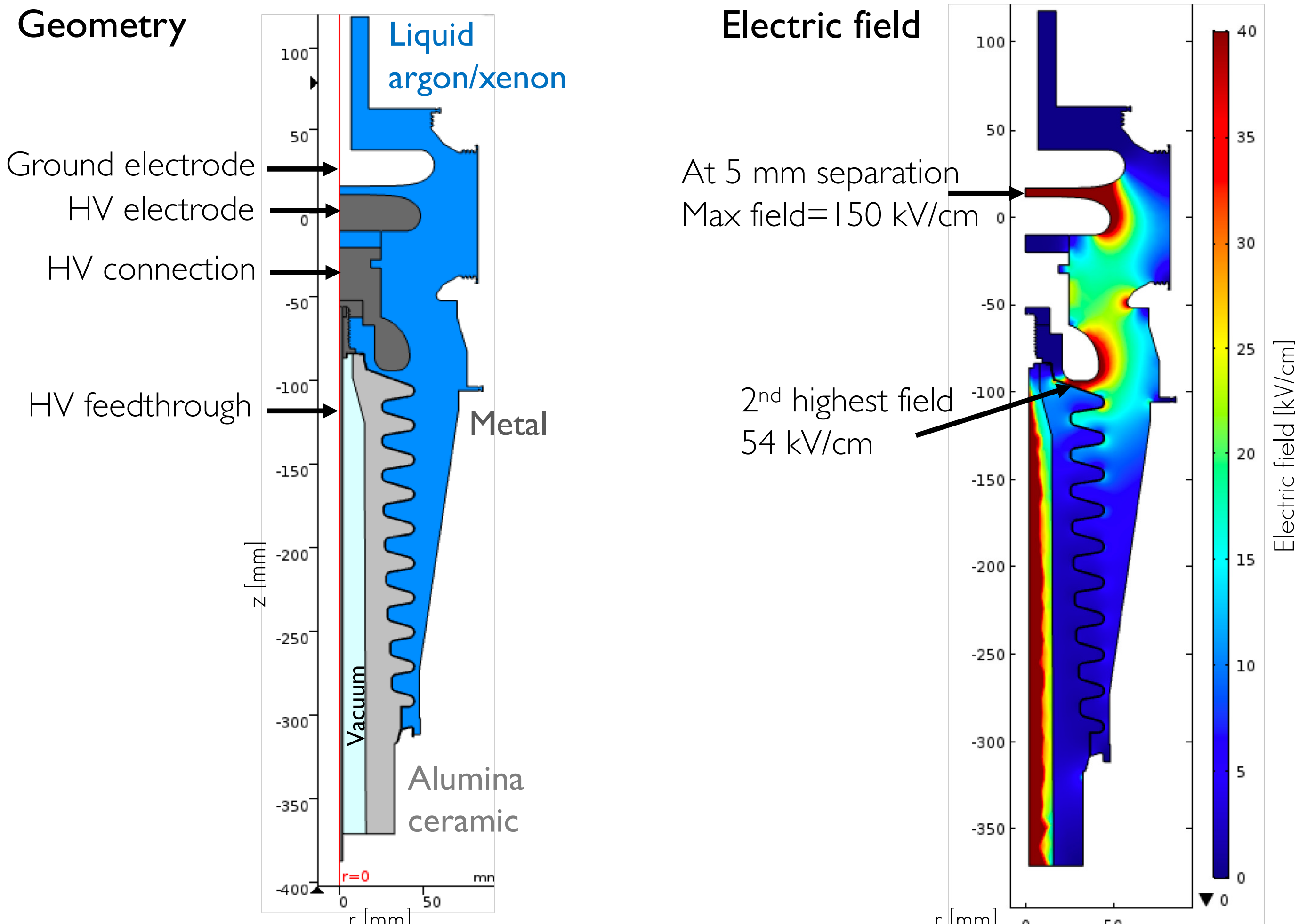
Purple line:
[Walkowiak, W., NIM A 449, p288-294 (2000)]
T = 87.3 K

Yellow line:
[He, Q. and McDonald, K. "Electron drift velocity in the uBooNE TPC." (2009)]
T = 85 K

The velocity also depends on temperature (~ linearly).
Measurements done at T = 87.3 K

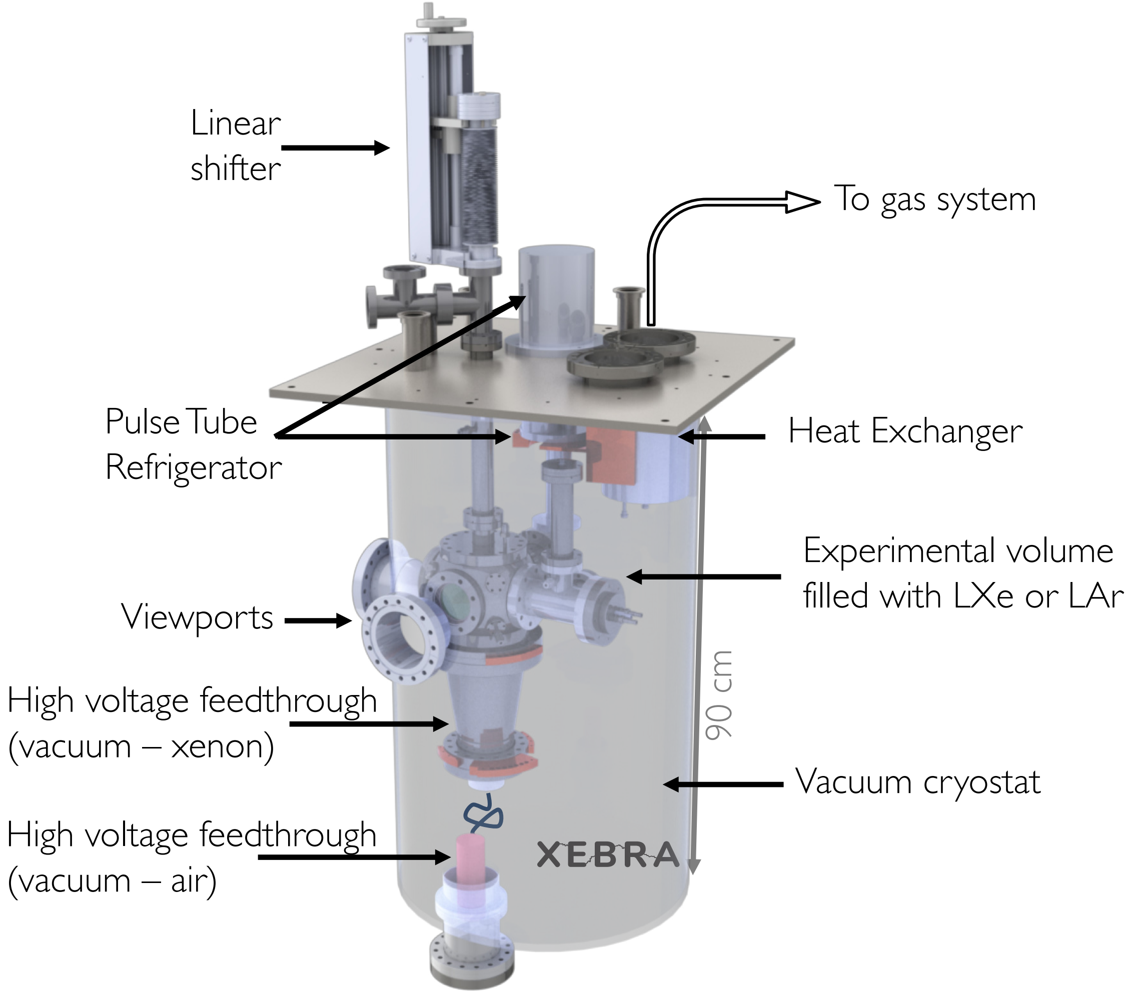


XeBrA design carefully considers E-field effects

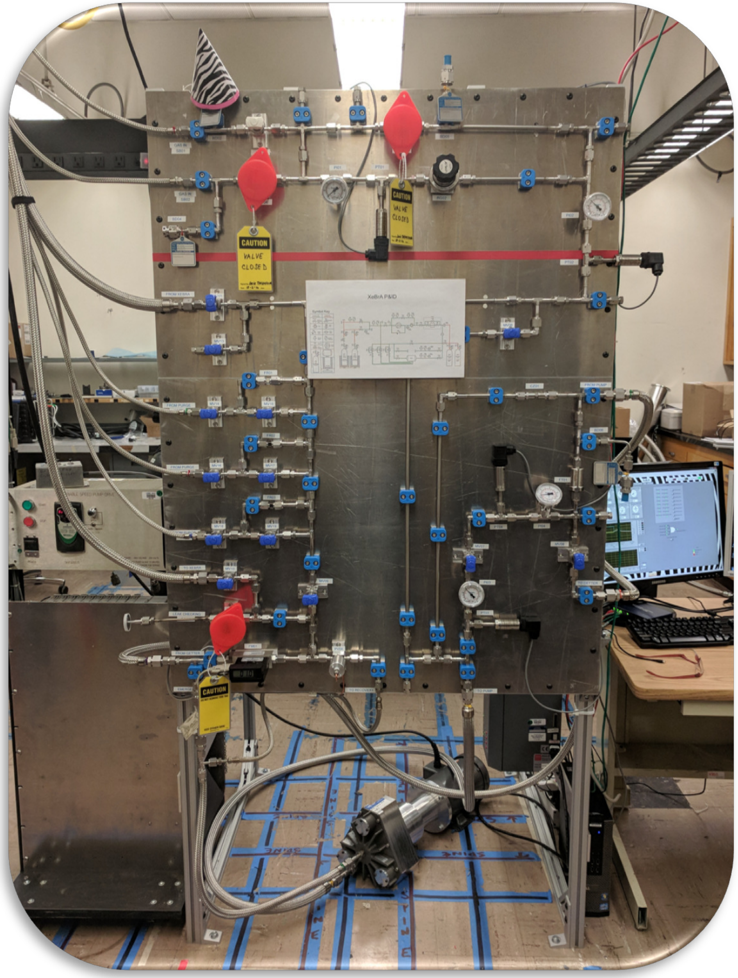


Axially-symmetric model built using COMSOL Multiphysics

XeBrA is designed to observe sparks in liquid nobles

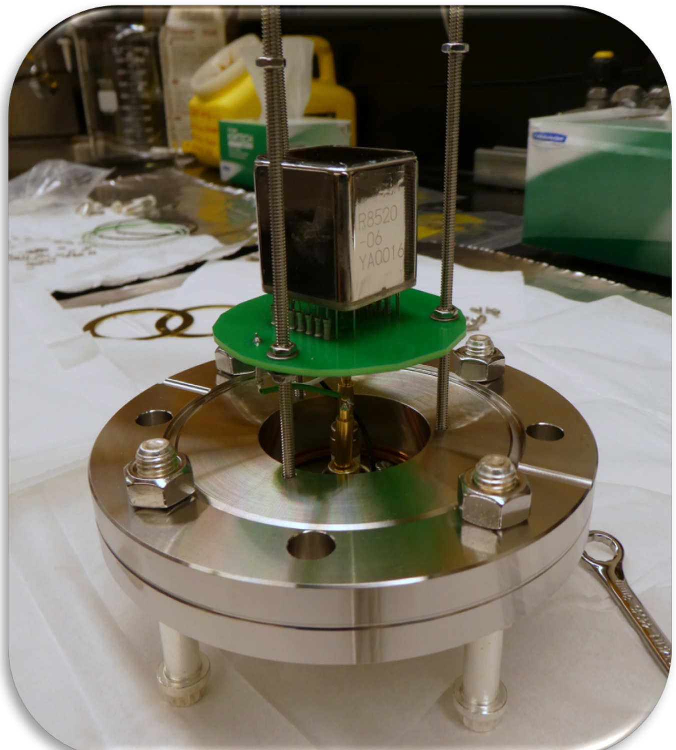


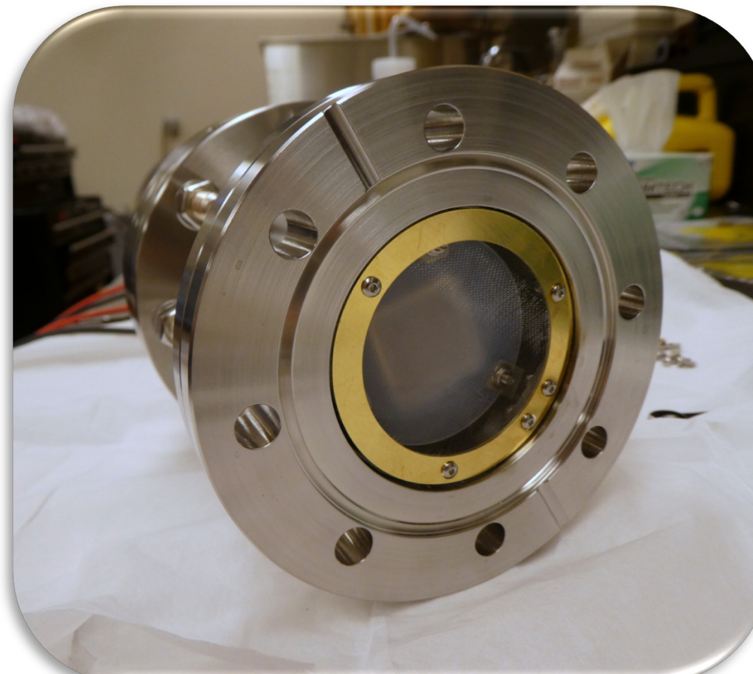
Gas system built for multiple detectors



PMT for electroluminescence studies

- Hamamatsu R8520-06 MOD with platinum underlay





Comparison of LAr and LXe for all available data