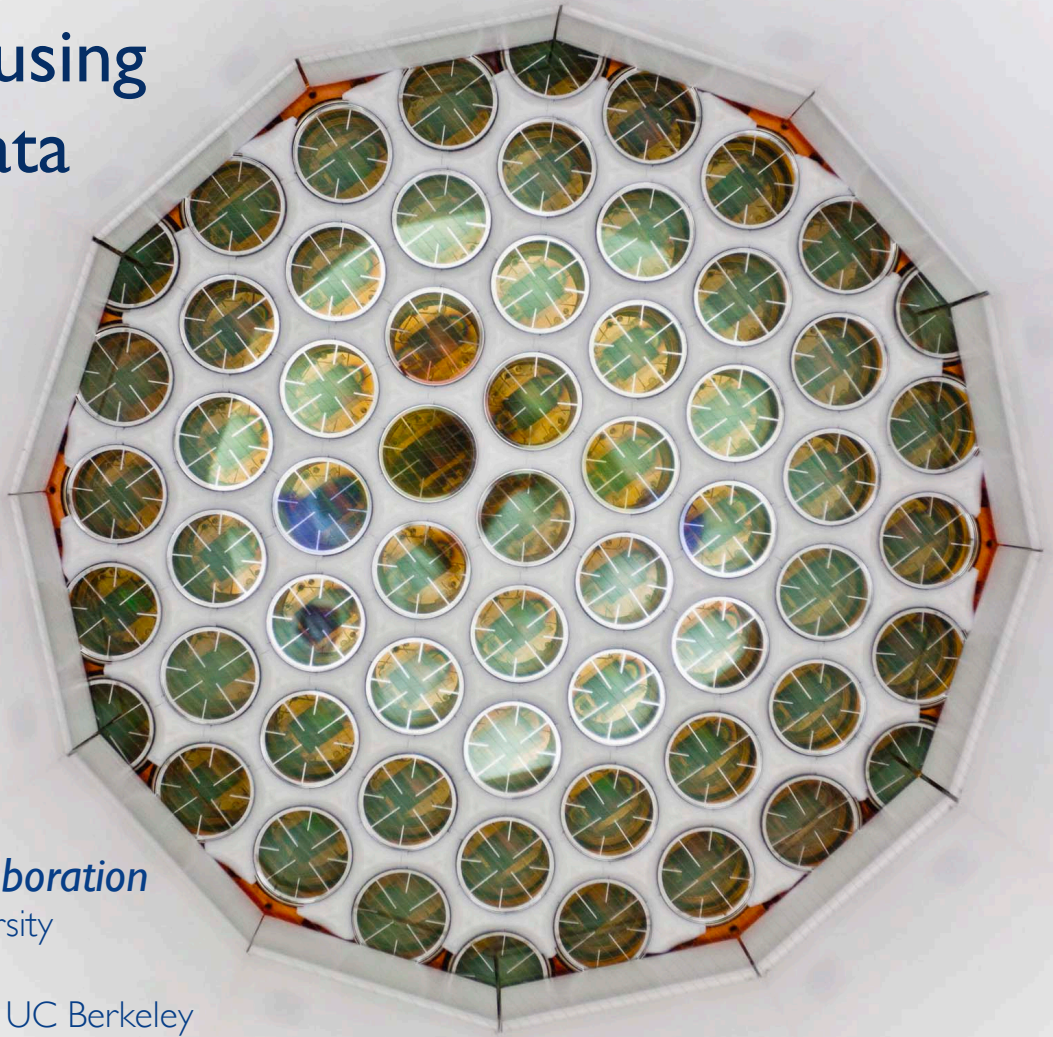
# Results of a search for sub-GeV dark matter using 2013 LUX data




Lucie Tvrznikova

*on behalf of LUX collaboration*

Ph.D. Candidate, Yale University

Research Assistant, LBNL

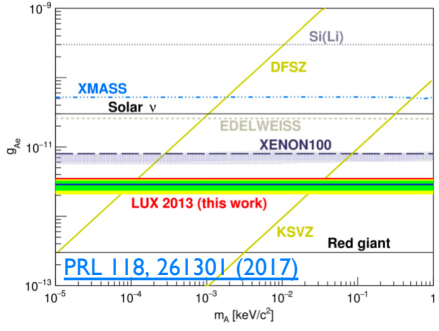
Visiting Student Researcher, UC Berkeley


Dark Interactions workshop at BNL. October 5, 2018

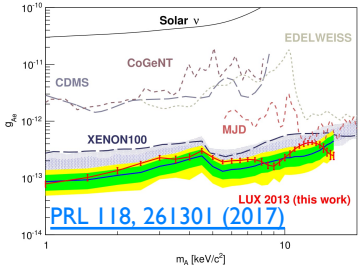
# LUX data improved experimental boundaries

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

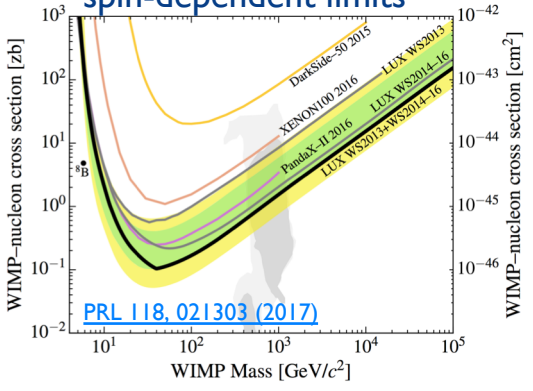
Axion limit




Coupling between galactic ALPs and electrons




Spin-independent & spin-dependent limits




& [PRL 118, 251302 (2017)]

1 meV — 1 eV — 1 keV — 1 MeV — 1 GeV — 1 TeV

Axions

Axion-like particles

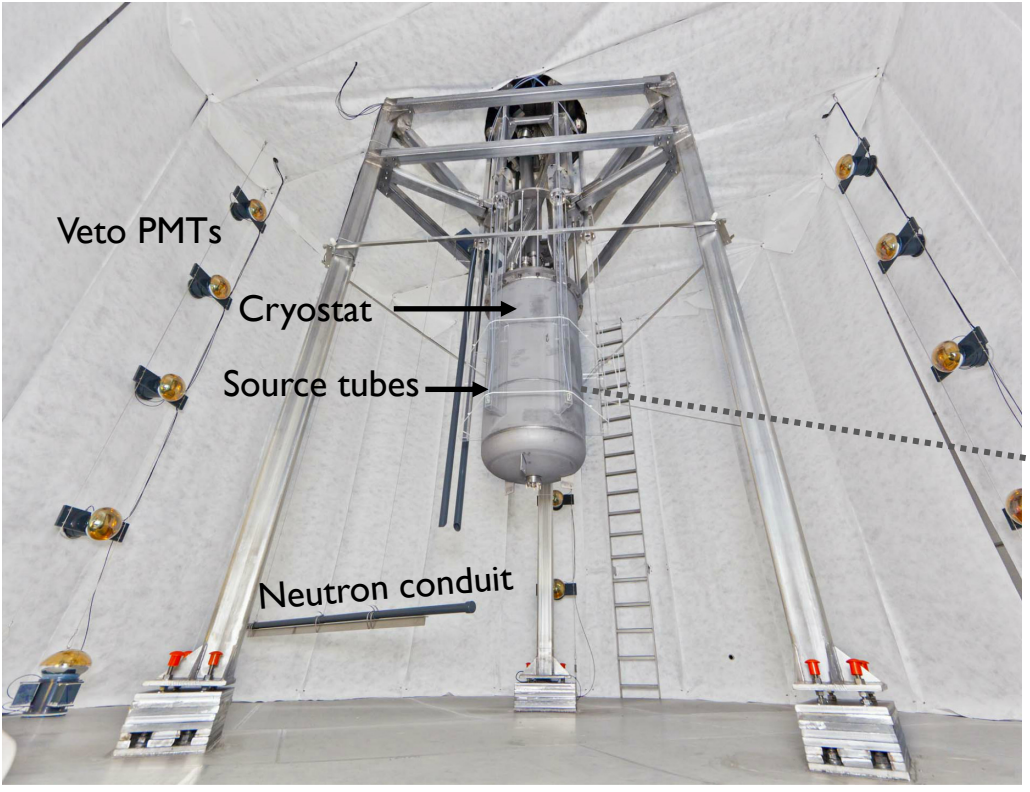
Light dark matter + light mediators

WIMPs

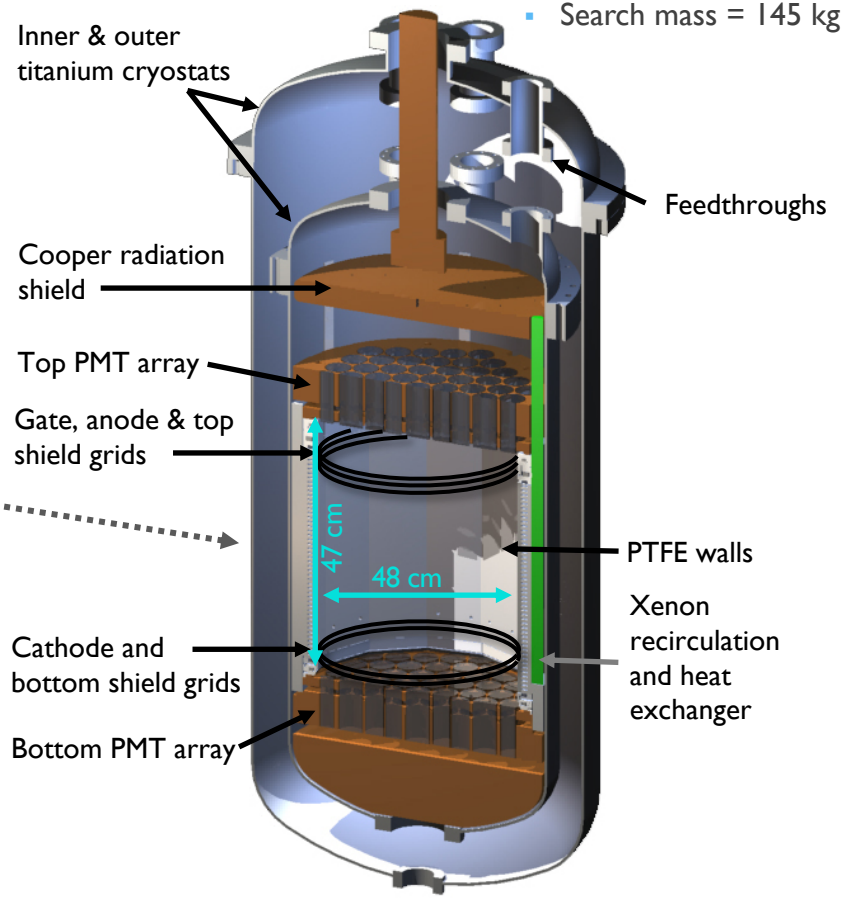
SIMPs

# LUX detector operated 4850 ft (1478 m) underground

Water tank



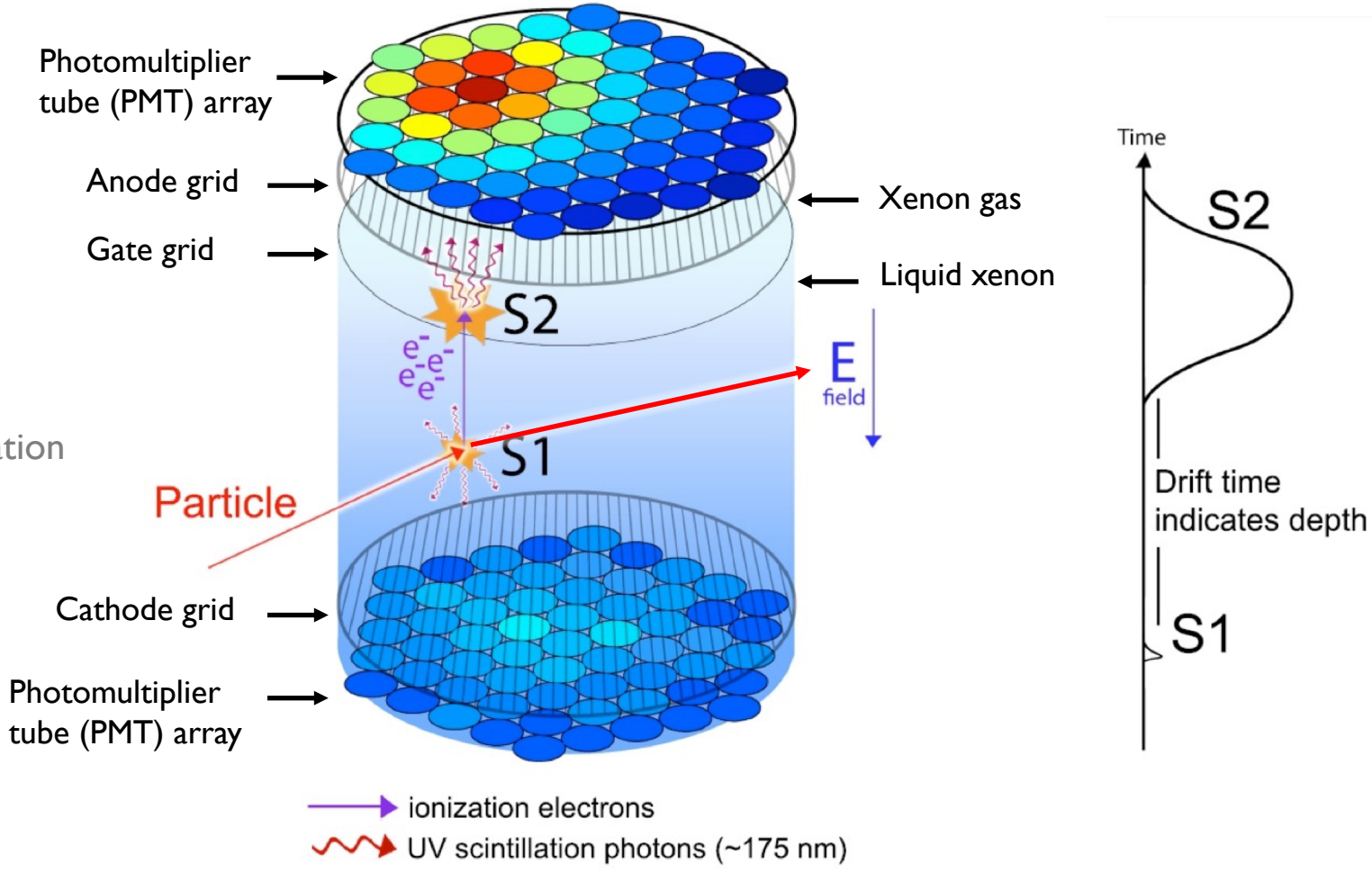

Liquid xenon target
- Active mass = 250 kg
- Search mass = 145 kg



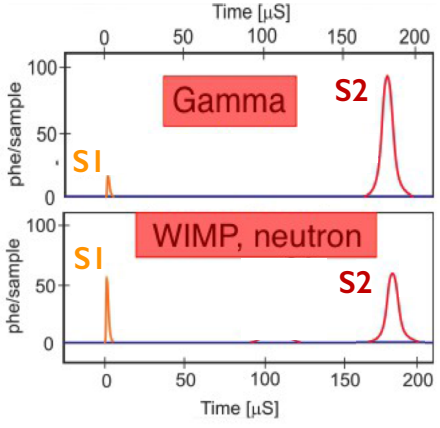
# LUX is a xenon two phase TPC

TPC = Time Projection Chamber

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



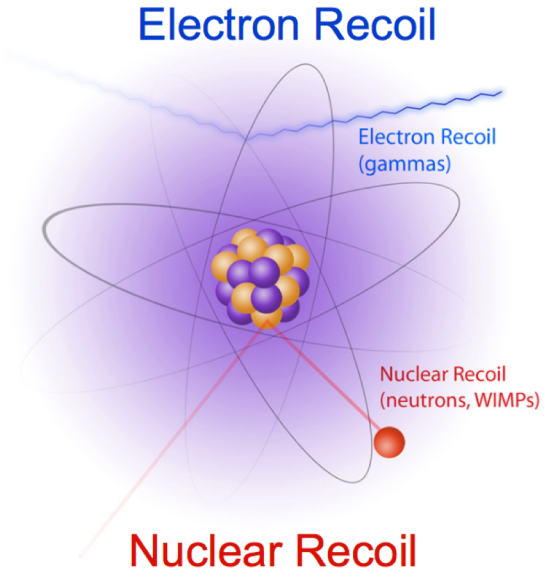
# Distinguish between 2 types of particle recoil

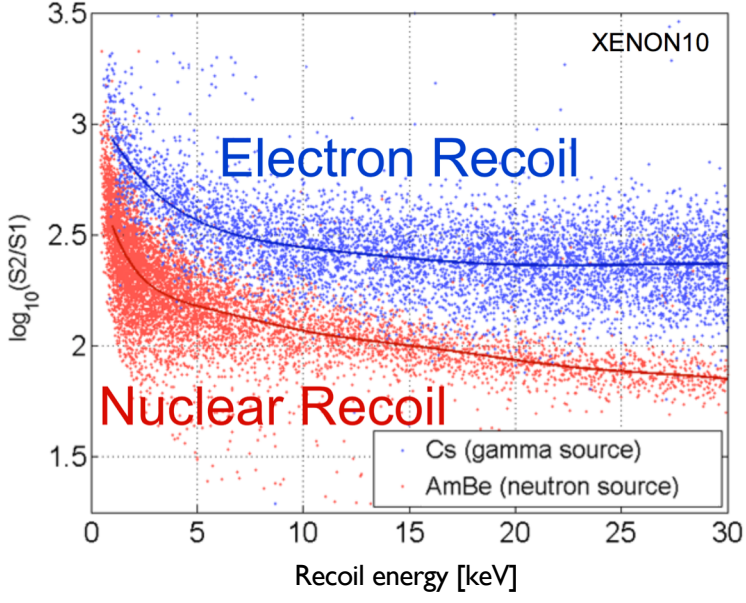



Electron recoil (ER)
- γ, B

Nuclear recoil (NR)
- Neutrons, WIMPs

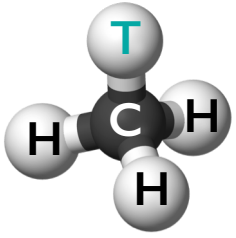
Discriminate electron & nuclear recoils using S2/S1 ratio
S1 – light signal (178 nm photons)
S2 – charge signal (electrons)

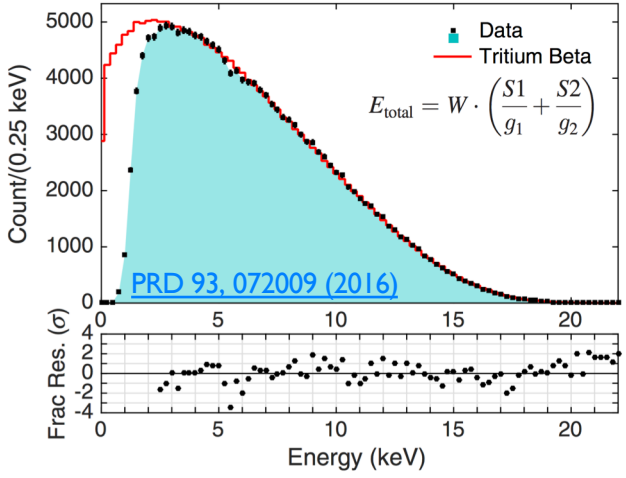


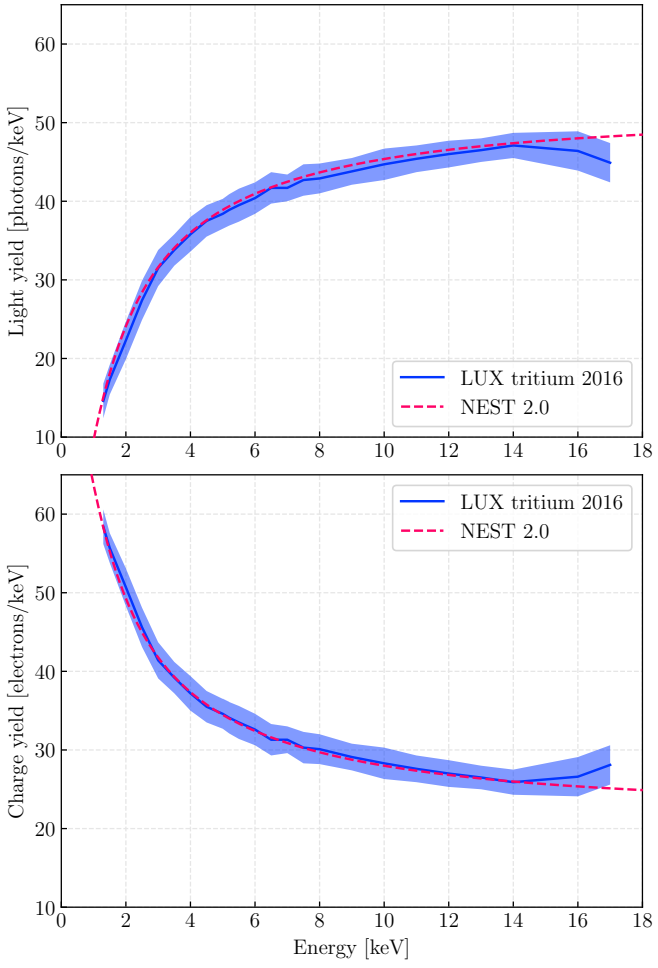



# Tritium calibrates detector response to electronic recoils

- 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 $CH_3T$

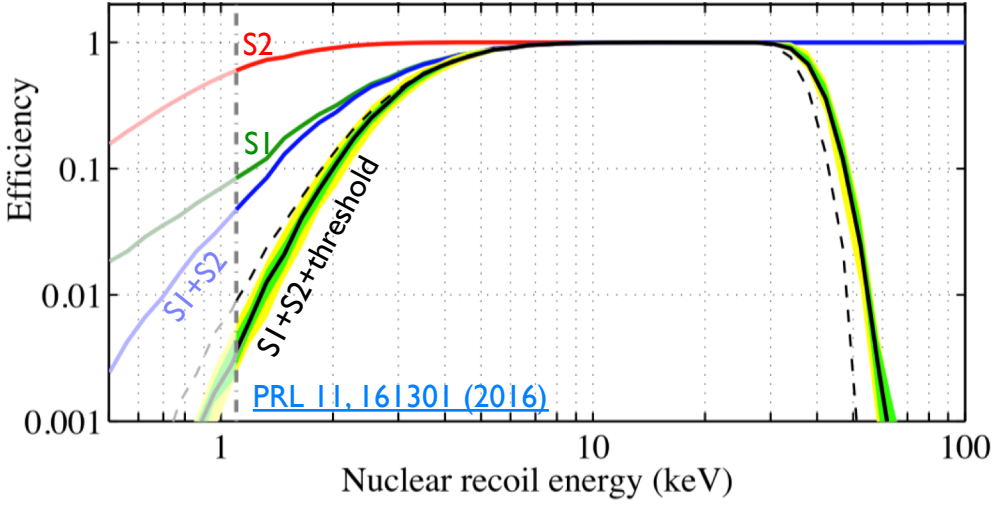


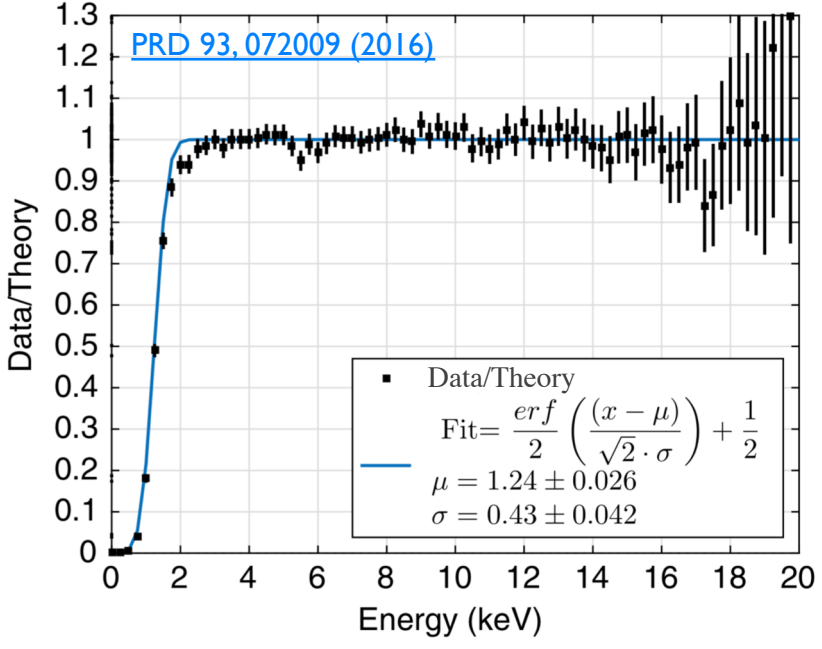



# LUX is more sensitive to lower energies of electronic recoils

Efficiency of nuclear recoil events in LUX in WS2013 reanalysis




Efficiency of electron recoil events in LUX

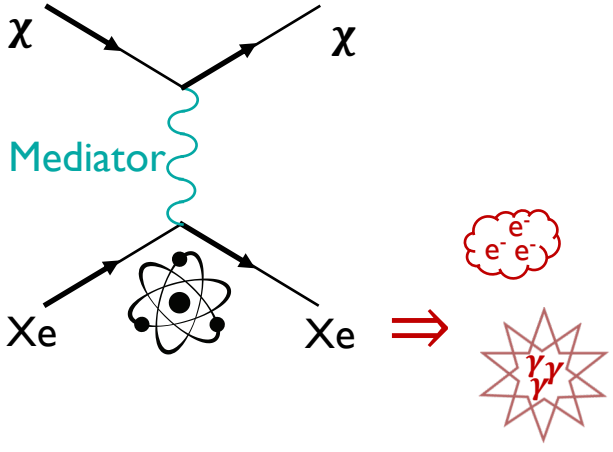



50% energy threshold:
nuclear recoils = 3.3 keV
electronic recoils = 1.2 keV

# Direct detection experiments consider elastic scattering

## Elastic scattering

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

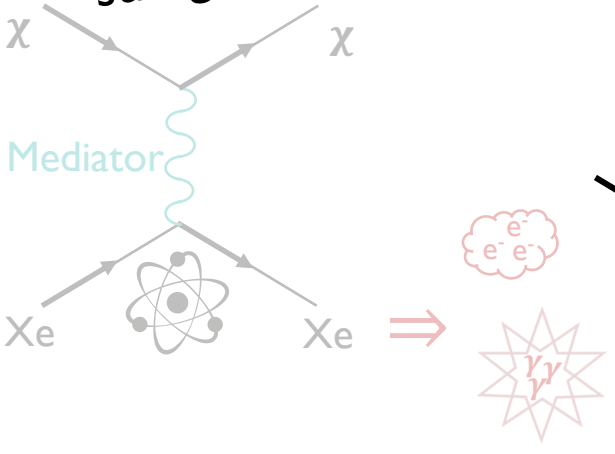


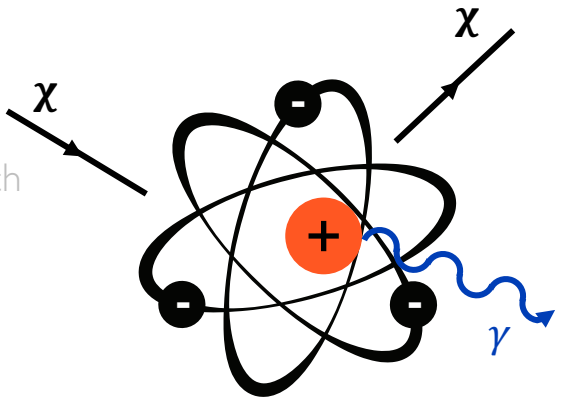
# But irreducible signals are present in DM-nucleus interactions

Elastic scattering

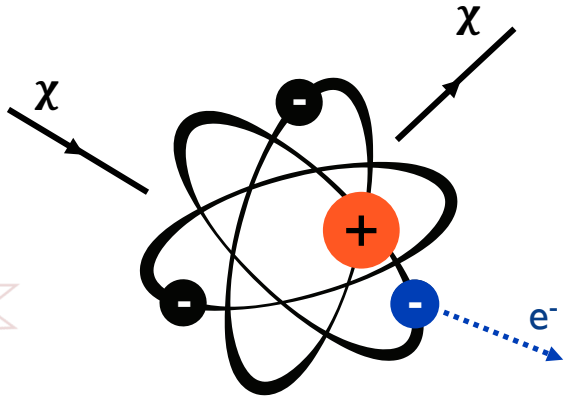
- Nuclear recoil signal
- Assumed in the standard WIMP search
- LUX searches for $m_{DM} \gtrsim 5$GeV

Physics isn't this straightforward…




$E_{recoil} \lesssim 0.1$ keV




**Bremsstrahlung photon emission from polarized atom**

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

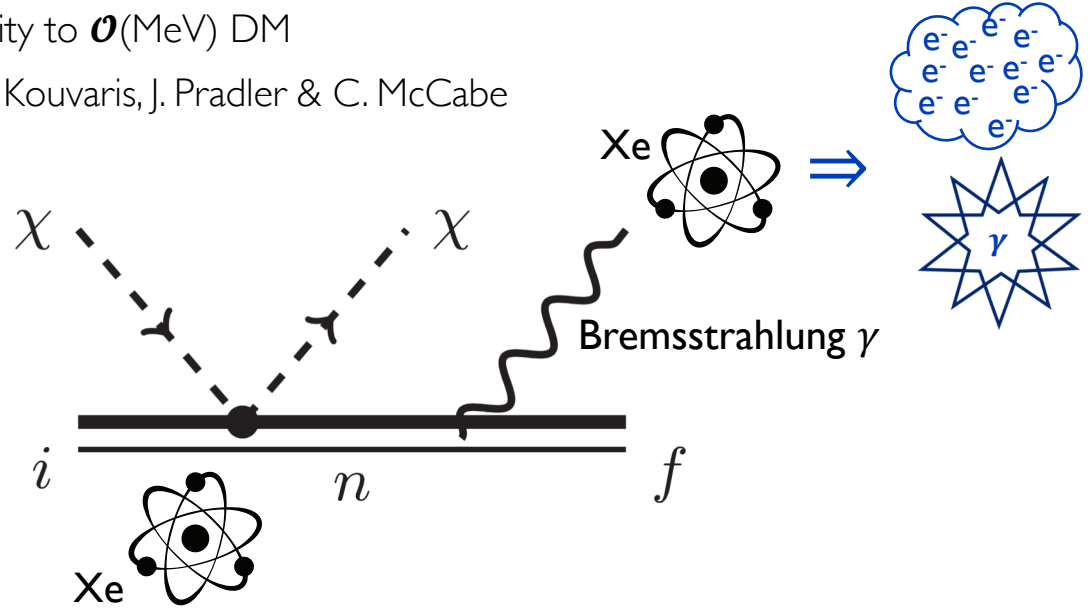
**Electron emission caused by Migdal effect**

- M. Ibe *et al.* JHEP03(2018)194
- M. J. Dolan *et al.* arXiv:1711.09906

# LUX can detect sub-GeV DM via Bremsstrahlung

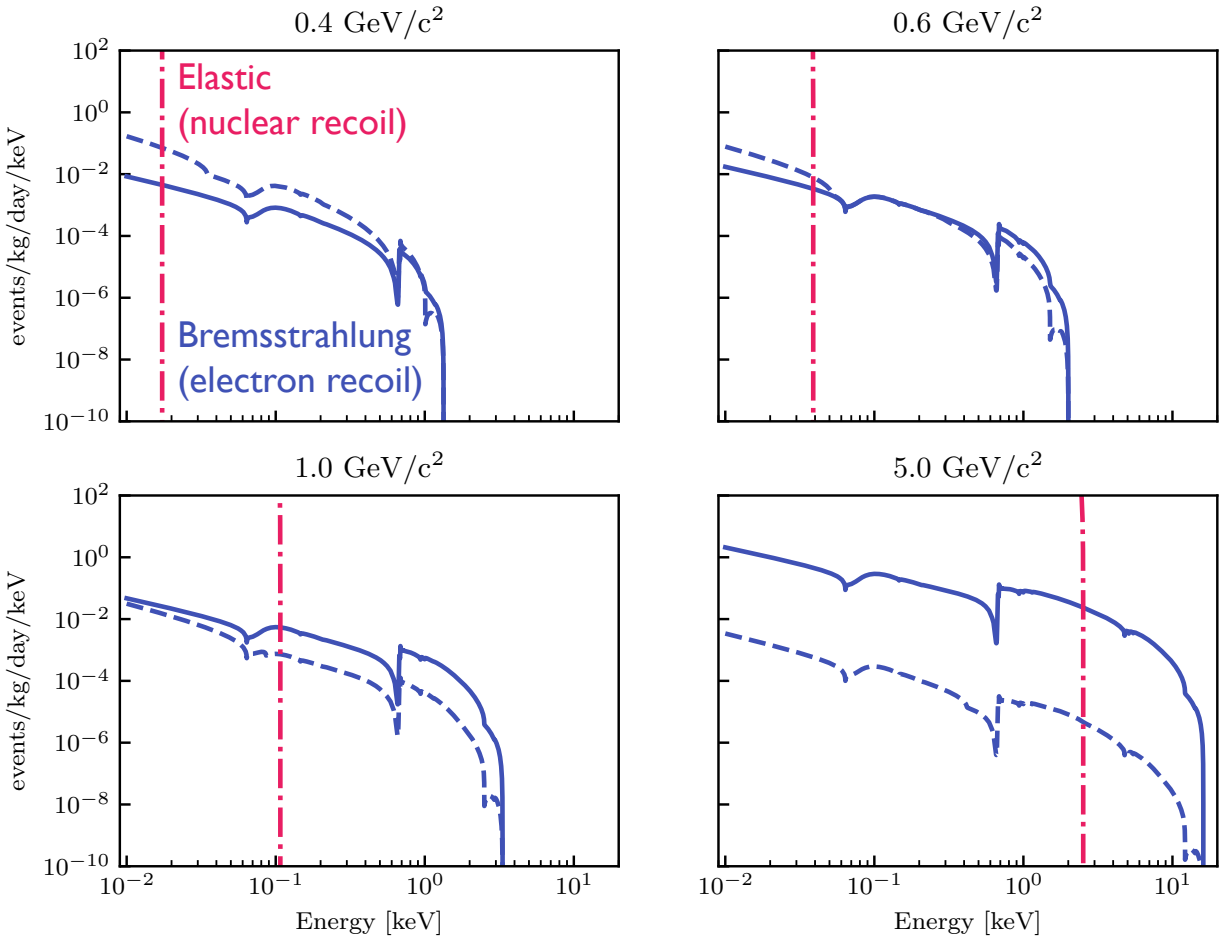
## Bremsstrahlung

- Irreducible dark matter – nucleus inelastic scattering
- Emission of a photon from a polarized xenon atom
- Nuclear interaction with electronic 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

$\sigma = 10^{-35}$ cm²

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

- Irreducible dark matter – nucleus inelastic scattering
- Nuclear interaction, with detectable ionization (electronic 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.*

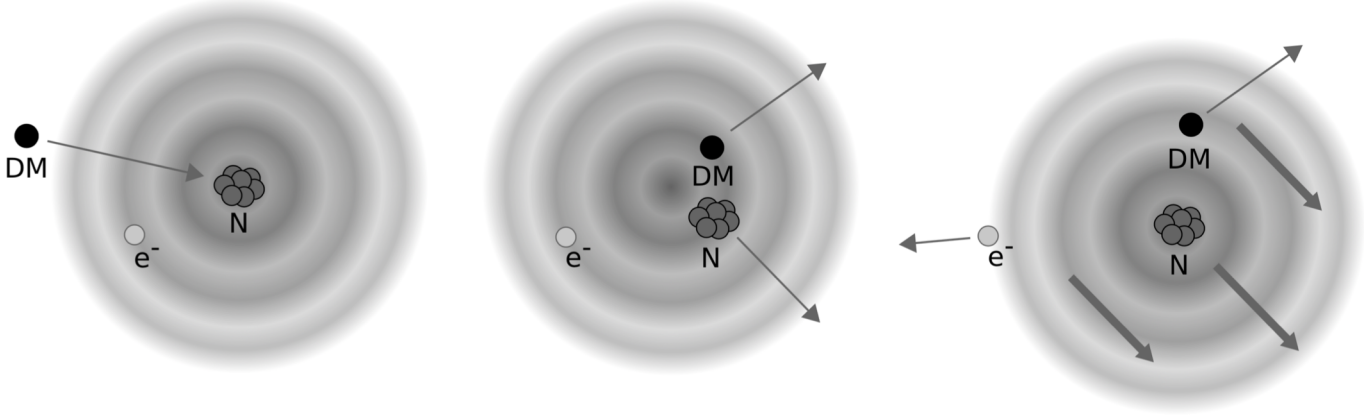
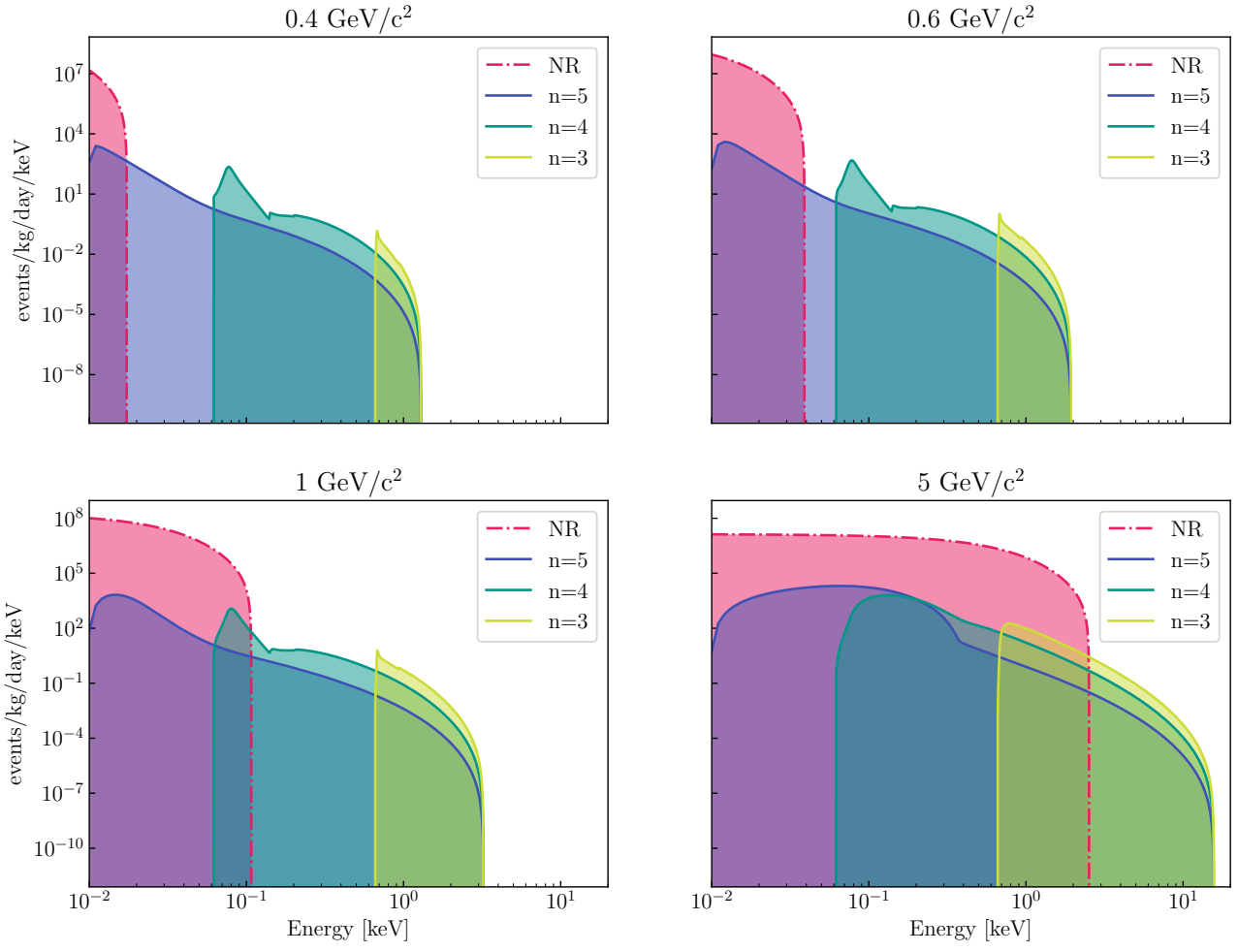



Figure from M. J. Dolan *et al.*
arXiv:1711.09906

# Expected scattering rates in xenon for Migdal effect

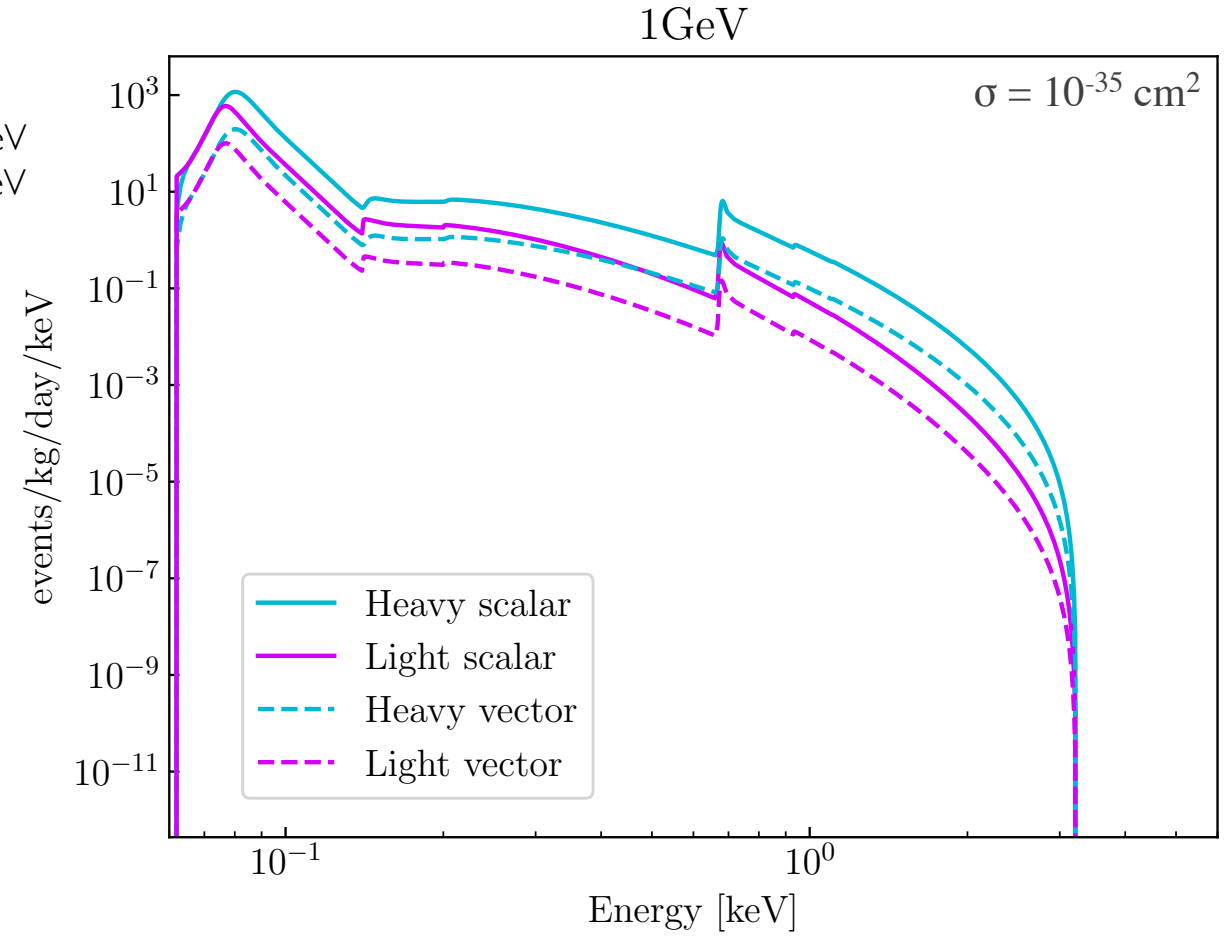
- Only n=3,4 considered in the analysis
- Assuming heavy scalar mediator
- $\sigma = 10^{-35}$ cm$^2$



# Four different mediators were considered for Migdal effect

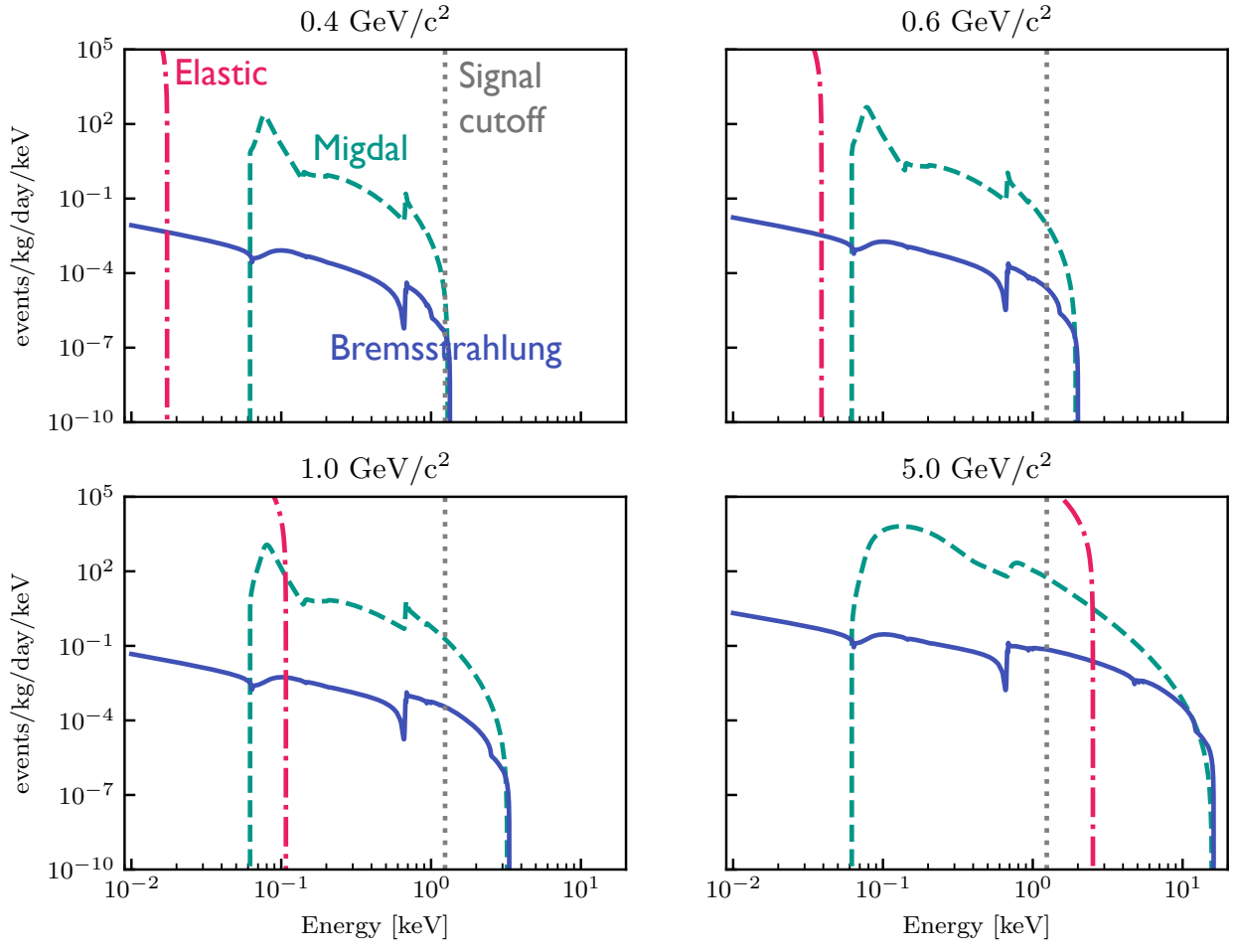
- Scalar mediator $\sigma \propto A^2$
- Vector mediator $\sigma \propto Z^2$

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



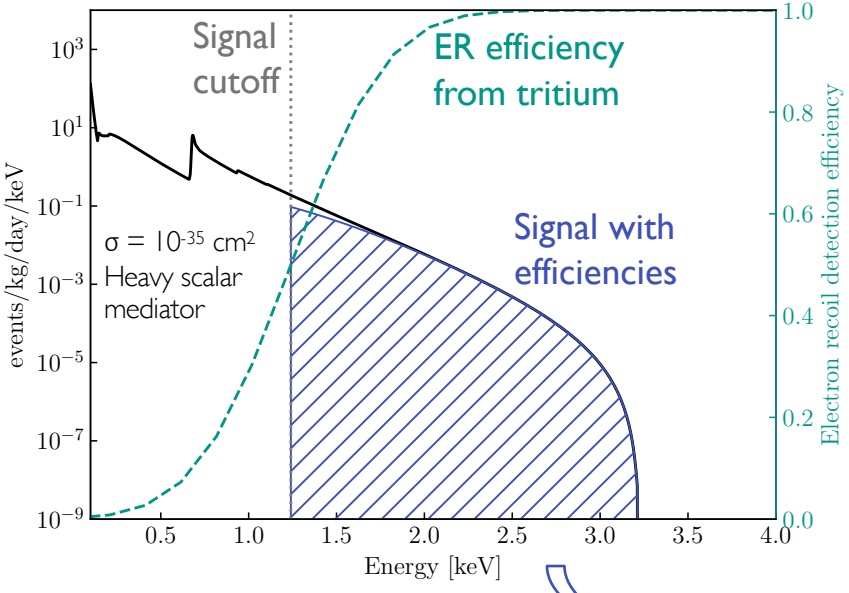
# Expect higher event rates from Migdal compared to Brem

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

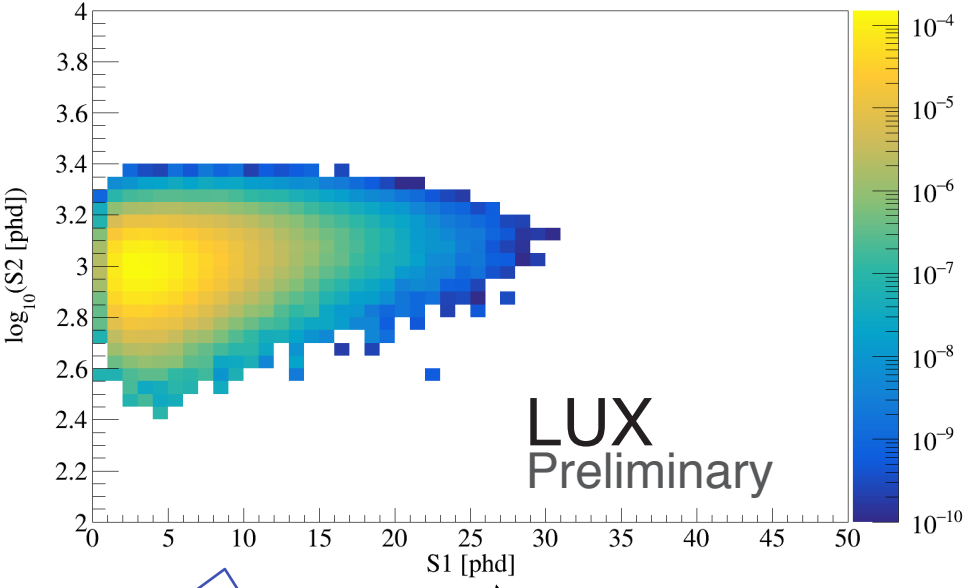


# Example of a signal expected in LUX from $m_\chi$ = 1 GeV

## Migdal scattering rates



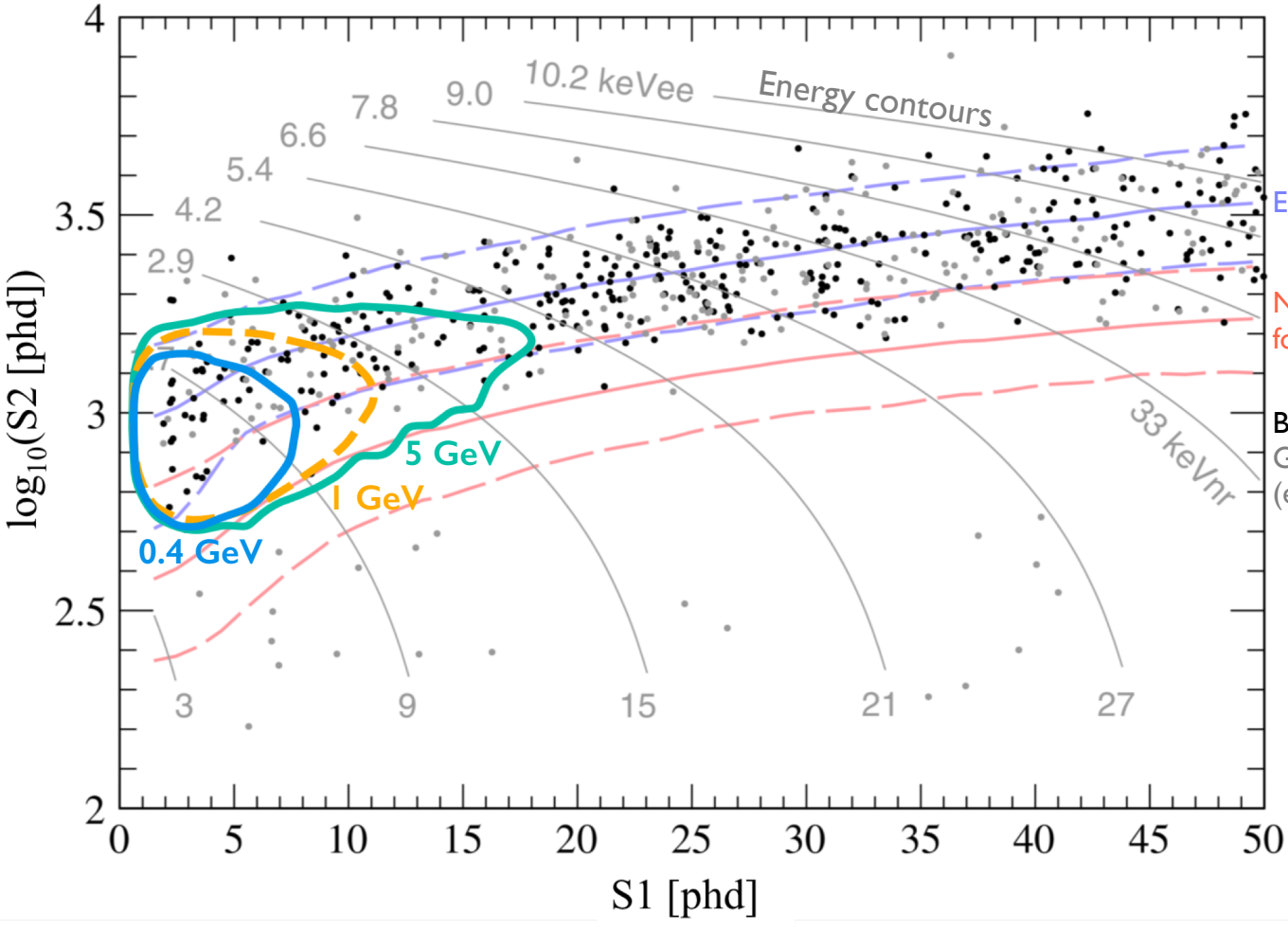

## Expected signal in LUX




# of photons detected

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
- cf. Fig. 2 in PRL 116, 161301 (2016)

Electron recoil band

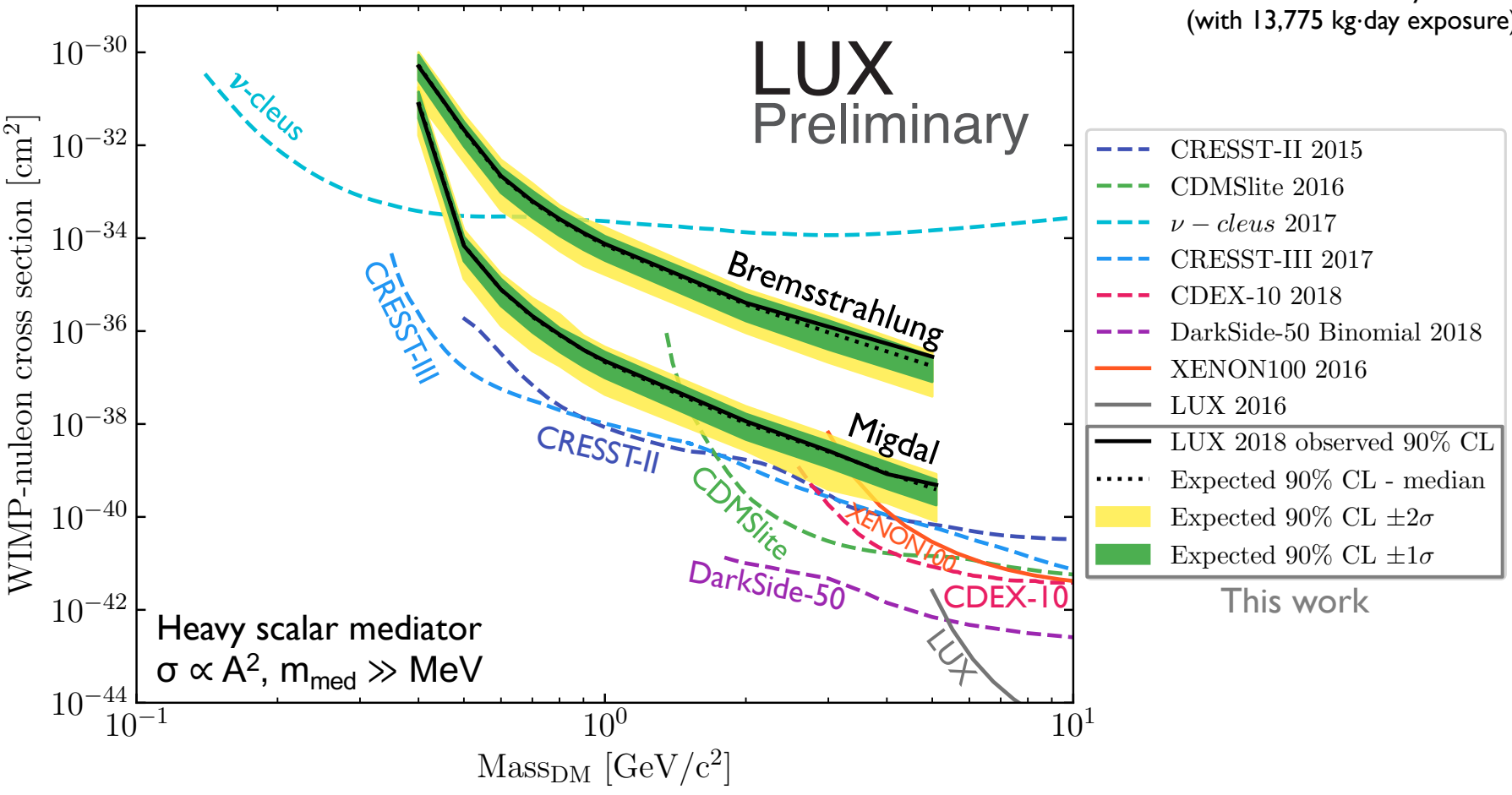
Nuclear recoil band for $m_\chi$=50 GeV

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

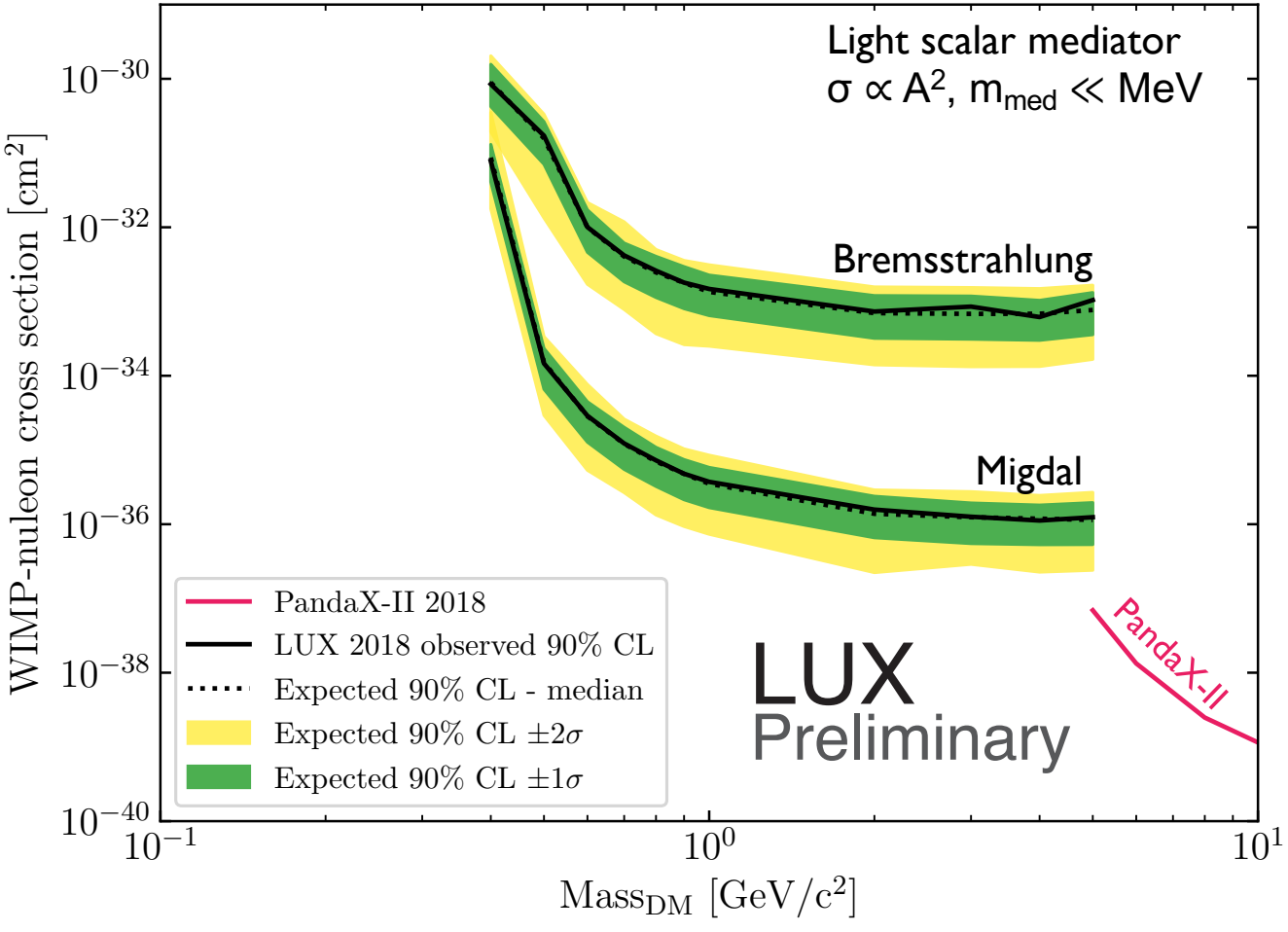
Migdal effect contours
Solid: light vector mediator
Dashed: heavy scalar mediator

# LUX limit calculated using profile likelihood ratio

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

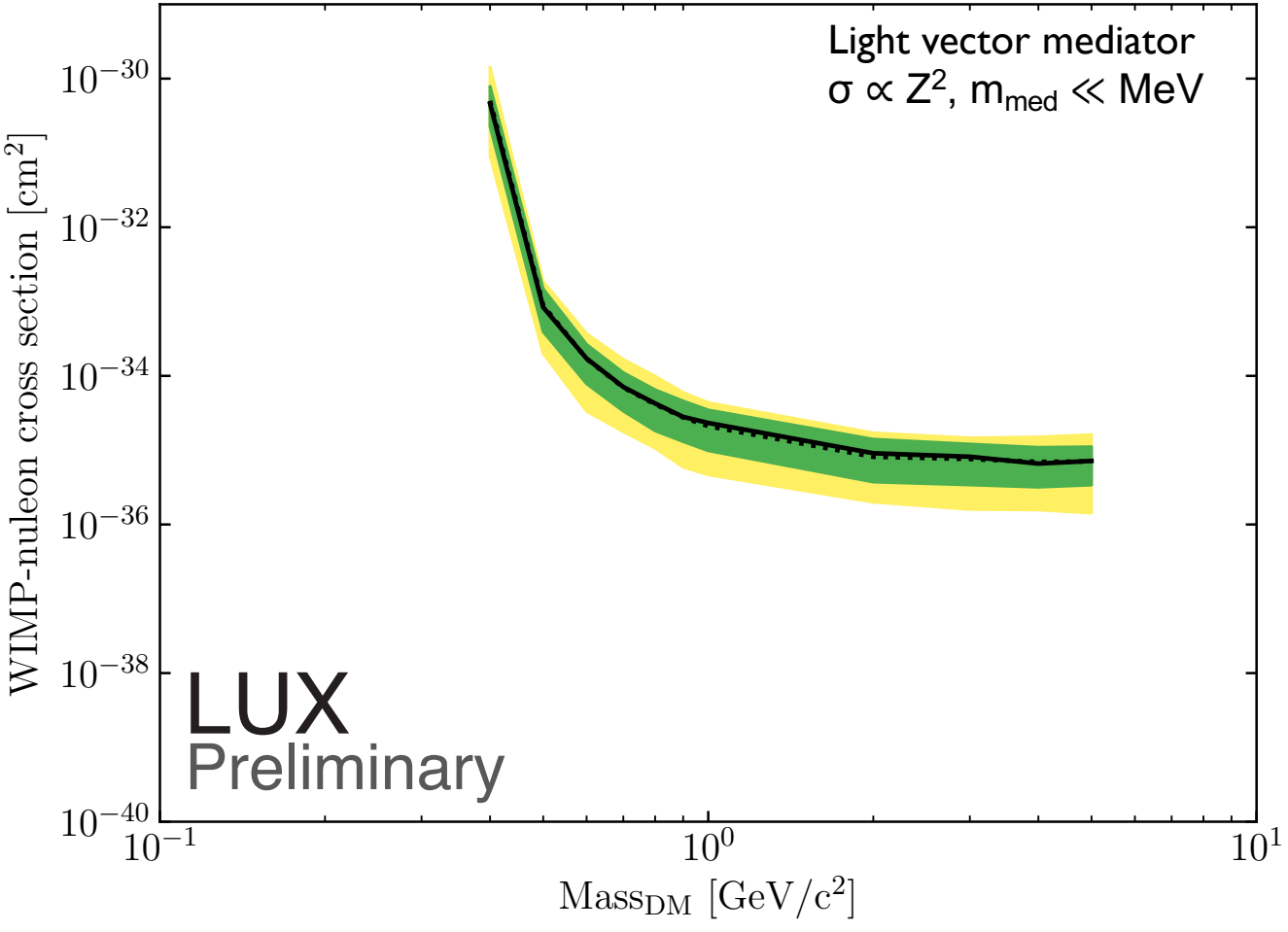


# LUX limit assuming a light scalar mediator



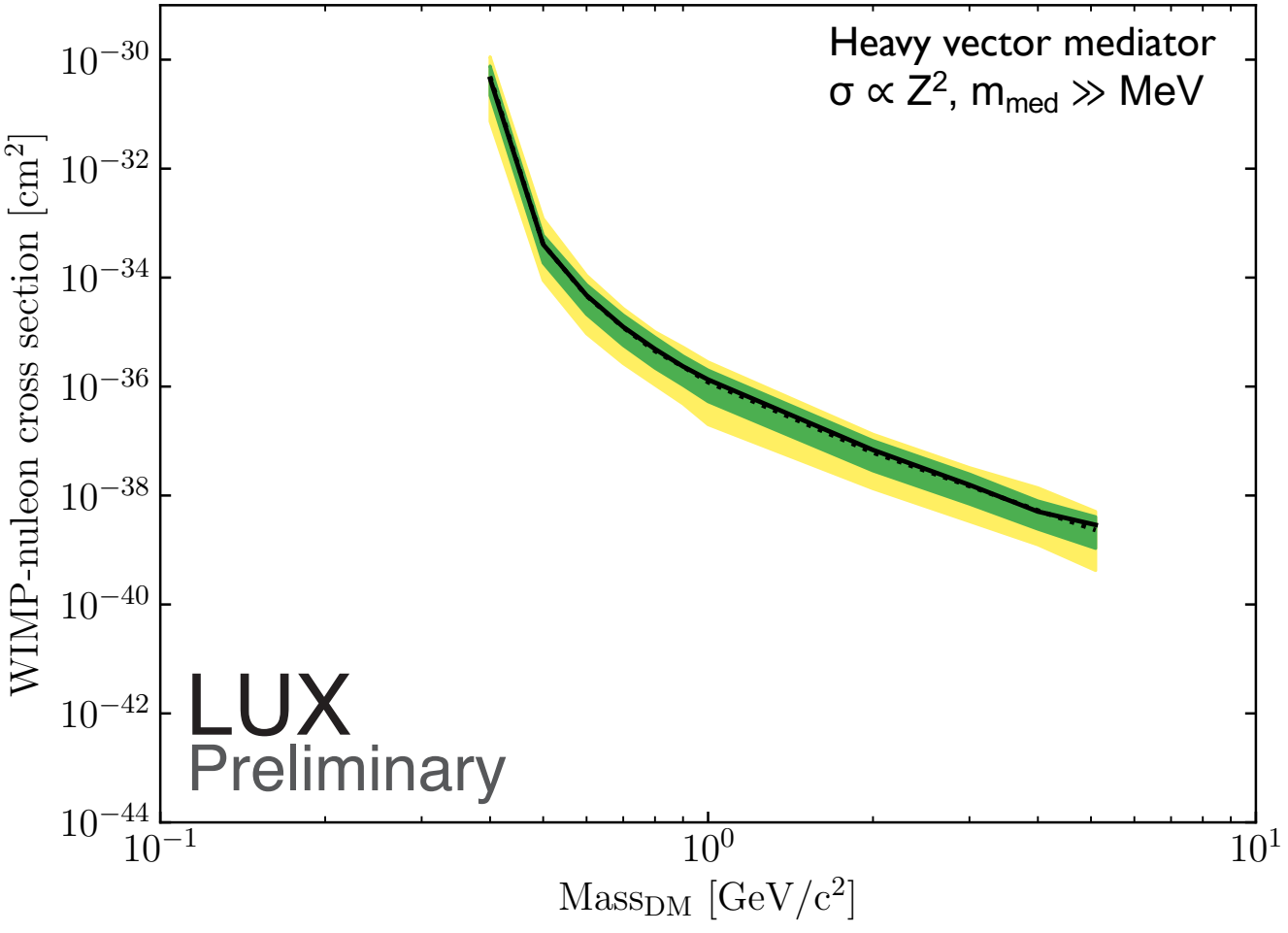

Limit is for 95 live-days of data (with 13,775 kg·day exposure)

# LUX limit for the Migdal effect assuming vector mediator




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

# LUX limit for the Migdal effect assuming vector mediator



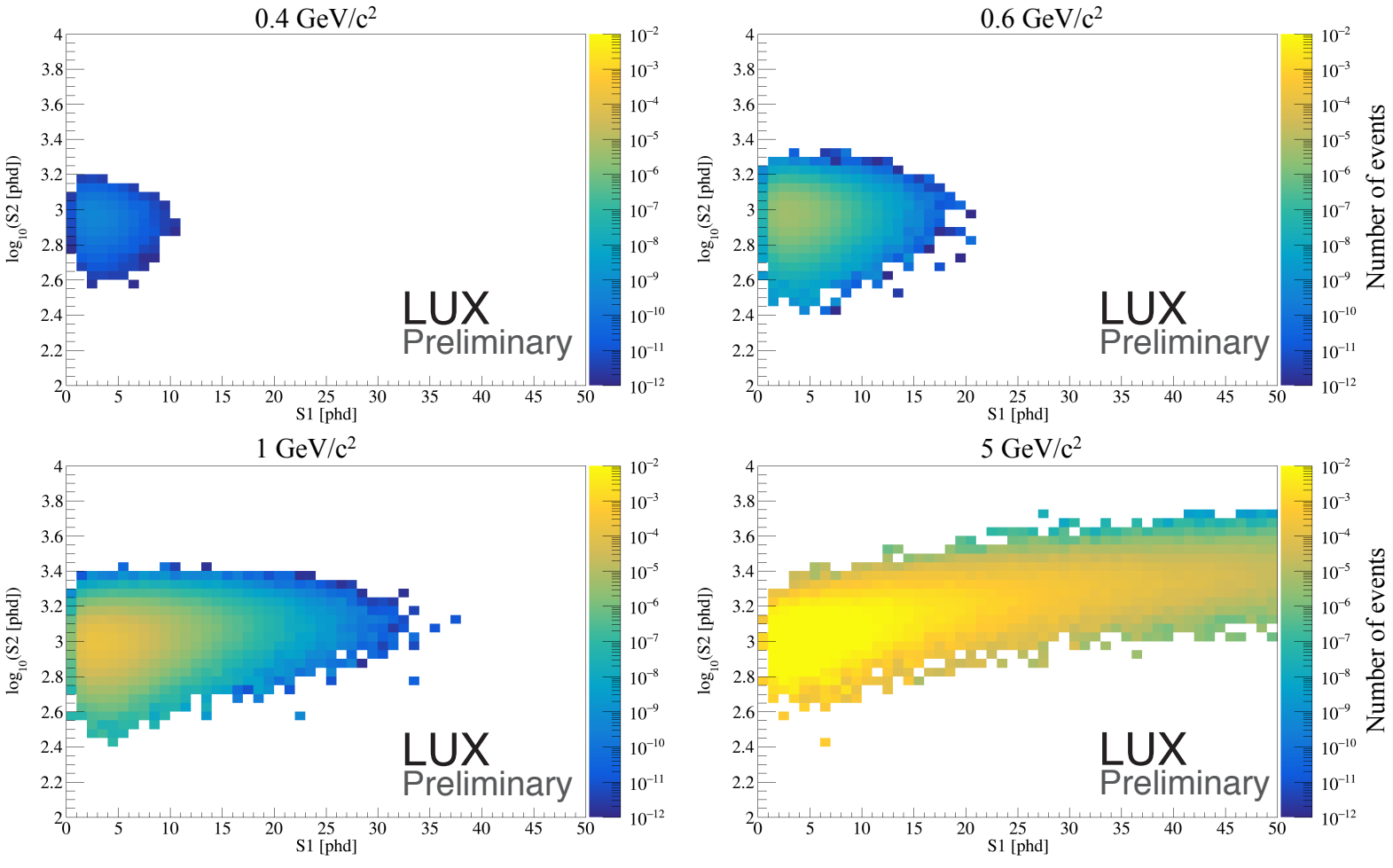

Limit is for 95 live-days of data (with 13,775 kg·day exposure)

# Conclusion

- Bremsstrahlung and Migdal effects allow LUX to search for sub-GeV DM
- LUX sensitivity extends down to DM with masses of 0.4 GeV, providing the most stringent limits from LXe detectors to light DM
- Tritium provides direct calibration for the signal model used in these analyses
- Work is based on scattering rates calculated and published by
  – C. Kouvaris & J. Pradler for Bremsstrahlung (PRL 118, 031803 (2017))
  – M. Ibe *et al.* for Migdal effect (JHEP03(2018)194)
  - Also limits from M. J. Dolan *et al.* (arXiv:1711.09906) & C. McCabe (PRD 96, 043010 (2017))
- Publication in preparation
  - Expected to be on arXiv very soon!
- Analysis of sub-GeV DM using the entire LUX exposure is ongoing

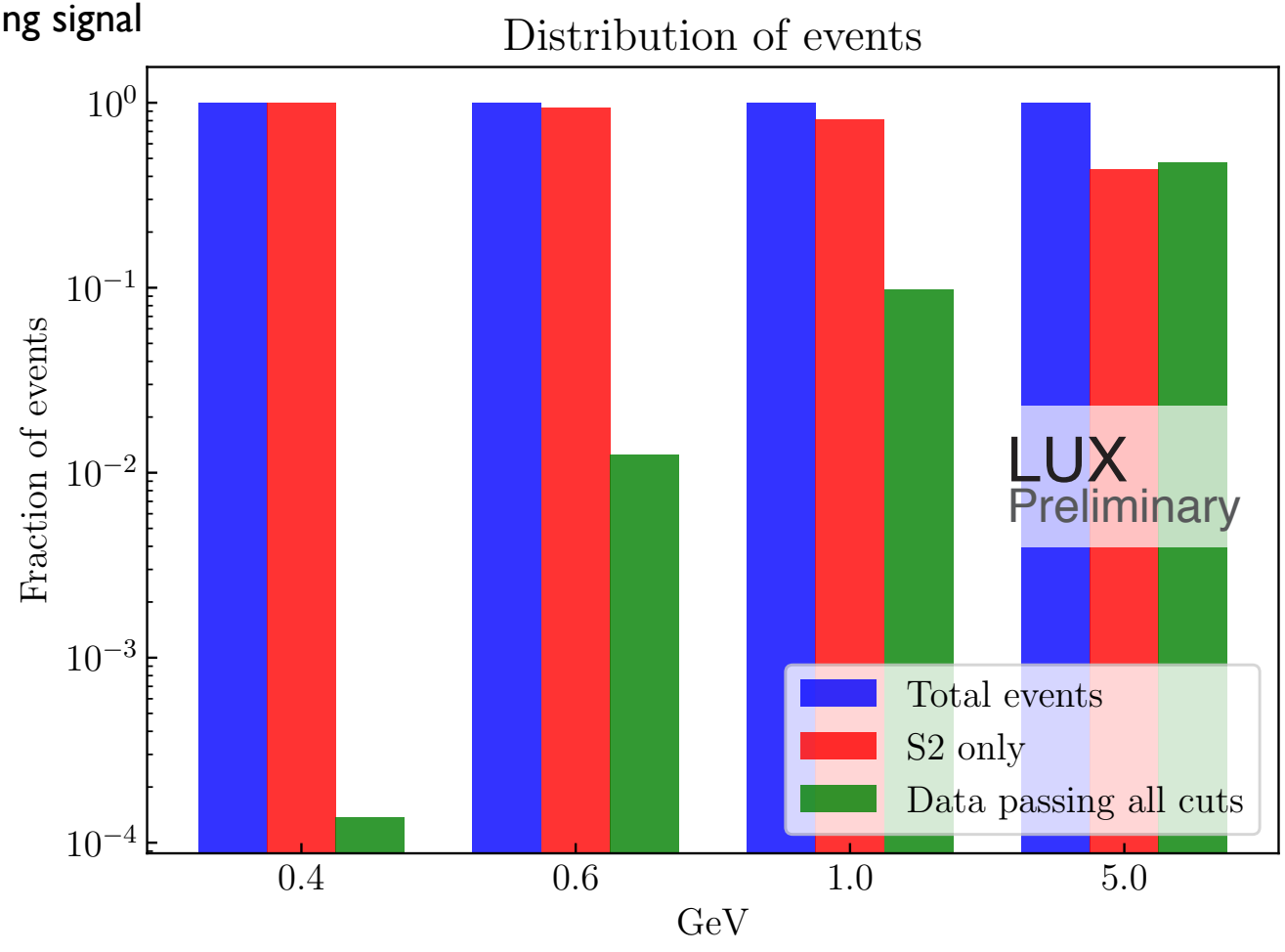
# Expected signal spectra from Migdal simulated by NEST2.0

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



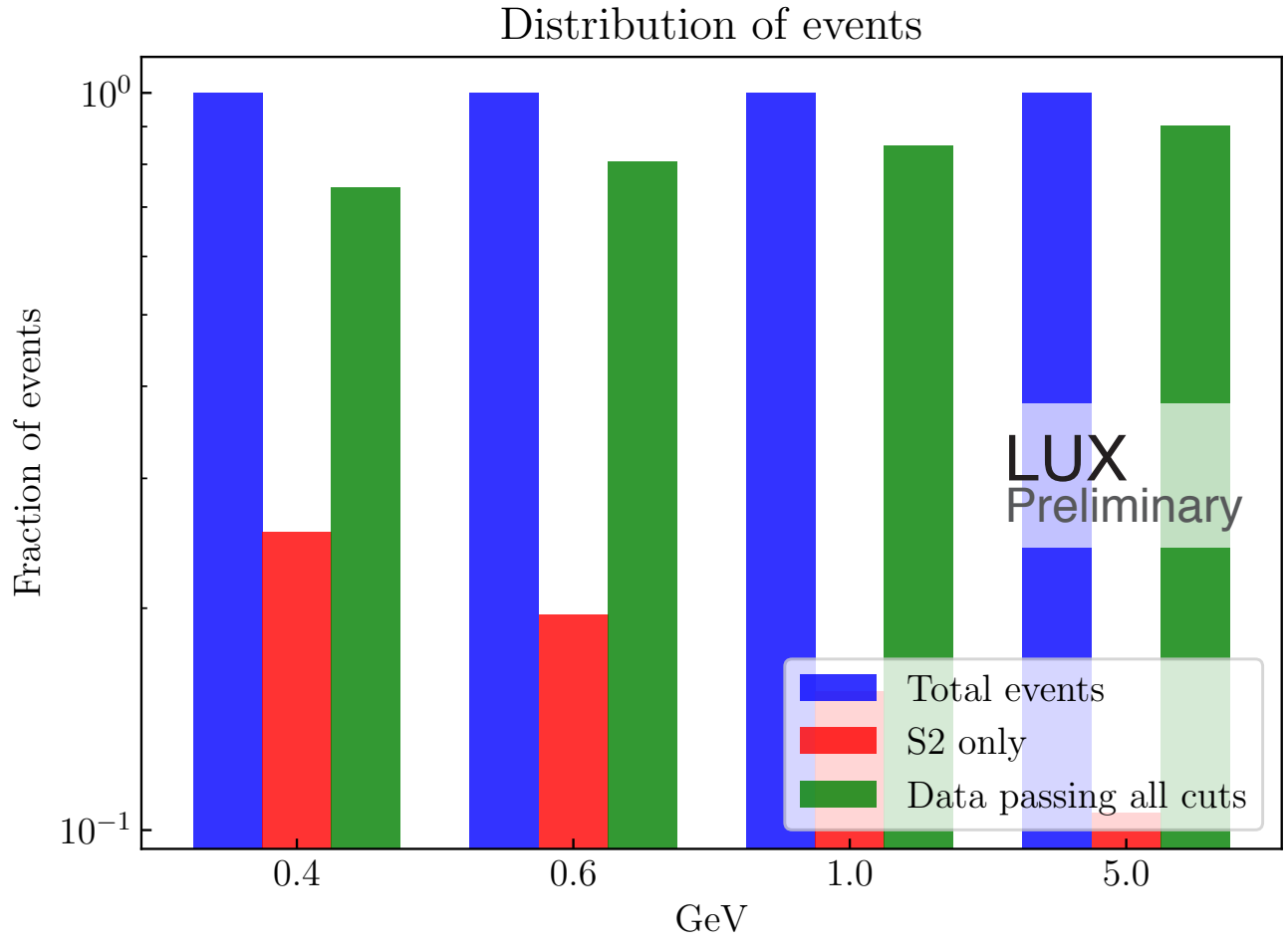
# Only a fraction of events have both S1 & S2 signals

Bremsstrahlung signal
Heavy scalar mediator



# Only a fraction of events have both S1 & S2 signals

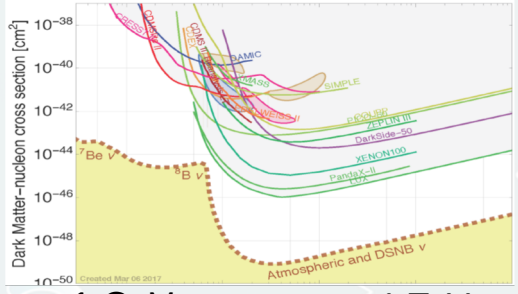
Migdal signal
Heavy scalar mediator



# LUX collaboration

LUX =
Large
Underground
Xenon
Experiment

# LUX detector is searching for dark matter




1 meV | 1 eV | 1 keV | 1 MeV | 1 GeV | 1 TeV

Axions

Axion-like particles

Light dark matter
+ light mediators

WIMPs

SIMPs

~meV energy detection

~eV energy detection

~keV energy detection

Absorption

Scattering

Illustration by Sandbox Studio, Chicago with Ana Kova

# LUX collected data from 2013-2016

2006: LUX collaboration formed

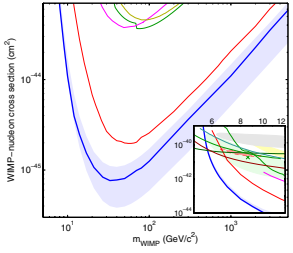
2008: LUX funded (DOE + NSF)

July 2012: LUX moves UG

April 2013: First science run starts

August 2013: Joined LUX

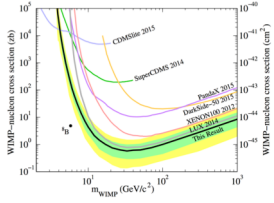
Nov 2013: First WS results reported (85.3 live-days)




PRL, 112, 091303 (2014)

Sept 2014: 332-day run start

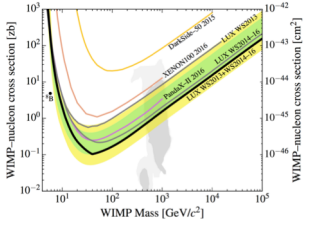
Dec 2015: Re-analysis of WS2013 published




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

May 2016: WS2014-16 finished

July 2016: 332-day WS result announced




PRL, 118, 021303 (2017)

Sept 2016: decommissioning start

Analyses still ongoing

June 2017: LUX installed in a museum

# Calibrations help characterize detector response

PRD 97, 102008 (2018)

## Energy deposition in the detector

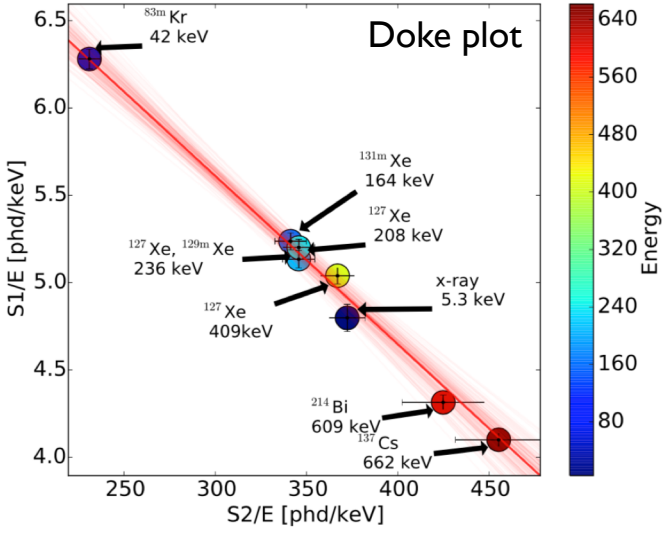
- Proportional to number of quanta produced by interaction

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

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
- $W = (13.7 \pm 0.2)$ eV/quanta




## DD neutron generator

arXiv:1608.05381

- Characterization of nuclear recoils

## Tritium

PRD 93, 072009 (2016)

- Characterization of electronic recoils

## $^{83m}$Kr

PRD 11.112009 (2017)

- Detector performance monitoring

# LUX collaboration

## Berkeley Lab / UC Berkeley

| | |
|---|---|
| Bob Jacobsen | PI, Professor |
| Murdock Gilcrease | Senior Scientist |
| Kevin Lesko | Senior Scientist |
| Michael Witherell | Lab Director |
| Peter Sorensen | Divisional Fellow |
| Simon Fiorucci | Project Scientist |
| Evan Pease | Postdoc |
| Daniel Hogan | Graduate Student |
| Kelsey Oliver-Mallory | Graduate Student |
| Kate Kamdin | Graduate Student |

## Brown University

| | |
|---|---|
| Richard Gaitskell | PI, Professor |
| Junhui Liao | Postdoc |
| Samuel Chan | Graduate Student |
| Dongqing Huang | Graduate Student |
| Casey Rhyne | Graduate Student |
| Will Taylor | Graduate Student |
| James Verbus | Ex-Postdoc |

## University of Edinburgh

| | |
|---|---|
| Alexander Murphy | PI, Professor |
| Paolo Beltrame | Ex-Research Fellow |
| Maria F. Marzioni | Graduate Student |
| Tom Davison | Graduate Student |

## Lawrence Livermore National Laboratory

| | |
|---|---|
| Adam Bernstein | PI, RED group leader |
| Kareem Kazkaz | Physicist |
| Jingke Xu | Postdoc |
| Brian Lenardo | Graduate Student |

## Stanislaus State

| | |
|---|---|
| Wing To | PI, Assistant Professor |

## Imperial College London

| | |
|---|---|
| Henrique Araujo | PI, Professor |
| Tim Sumner | Professor |
| Alastair Currie | Ex-Postdoc |
| Adam Bailey | Ex-Graduate Student |
| Khadeeja Yazdani | Ex-Graduate Student |
| Nellie Marangou | Graduate Student |

## SLAC NATIONAL ACCELERATOR LABORATORY

| | |
|---|---|
| Dan Akerib | PI, Professor |
| Thomas Shutt | PI, Professor |
| Tomasz Biesiadzinski | Research Associate |
| Christina Ignarra | Research Associate |
| Alden Fan | Research Associate |
| Wei Ji | Graduate Student |
| TJ Whitis | Graduate Student |

## LIP Coimbra

| | |
|---|---|
| Isabel Lopes | PI, Professor |
| José Pinto de Cunha | Assistant Professor |
| Vladimir Solovov | Senior Researcher |
| Alexandre Lindote | Postdoc |
| Francisco Neves | Auxiliary Researcher |
| Claudio Silva | Research Fellow |
| Paulo Bras | Graduate Student |

## PennState

| | |
|---|---|
| Carmen Carmona | PI, Assistant Professor |
| Emily Grace | Postdoc |

## SD Mines

| | |
|---|---|
| Xinhua Bai | PI, Professor |
| Douglas Tiedt | Graduate Student |

## SDSTA / Sanford Lab

| | |
|---|---|
| David Taylor | Senior Engineer |
| Markus Horn | Research Scientist |

## UNIVERSITY AT ALBANY State University of New York

| | |
|---|---|
| Matthew Szydagis | PI, Assistant Professor |
| Cecilia Levy | Postdoc |
| Jack Genovesi | Research Assistant |

## TEXAS A&M UNIVERSITY

| | |
|---|---|
| Robert Webb | PI, Professor |
| Paul Terman | Graduate Student |

## Berkeley

| | |
|---|---|
| Daniel Mckinsey | PI, Professor |
| Ethan Bernard | Project Scientist |
| Elizabeth Boulton | Graduate Student |
| Junsong Lin | Postdoc |
| Brian Tennyson | Graduate Student |
| Lucie Tvrznikova | Graduate Student |
| Vetri Velan | Graduate Student |

## UC DAVIS UNIVERSITY OF CALIFORNIA

| | |
|---|---|
| Mani Tripathi | PI, Professor |
| Aaron Manalaysay | Project Scientist |
| James Morad | Ex-Graduate Student |
| Sergey Uvarov | Ex-Graduate Student |
| Jacob Cutter | Graduate Student |
| Dave Hemer | Senior Machinist |

## WISCONSIN UNIVERSITY OF WISCONSIN-MADISON

| | |
|---|---|
| Kimberly Palladino | PI, Assistant Professor |
| Shaun Alsum | Graduate Student |
| Rachel Mannino | Postdoc |

## UC SANTA BARBARA

| | |
|---|---|
| Harry Nelson | PI, Professor |
| Sally Shaw | Postdoc |
| Scott Haselschwardt | Graduate Student |
| Curt Nehrkorn | Graduate Student |
| Melih Solmaz | Graduate Student |
| Dean White | Engineer |
| Susanne Kyre | Engineer |

## UCL University College London

| | |
|---|---|
| Chamkaur Ghag | PI, Professor |
| Jim Dobson | Postdoc |
| Umit Utku | Graduate Student |

## UNIVERSITY OF MARYLAND

| | |
|---|---|
| Carter Hall | PI, Professor |
| Jon Balajthy | Graduate Student |

## UMassAmherst

| | |
|---|---|
| Scott Hertel | PI, Assistant Professor |
| Christopher Nedlik | Graduate Student |

## UNIVERSITY of ROCHESTER

| | |
|---|---|
| Frank Wolfs | PI, Professor |
| Wojtek Skulski | Senior Scientist |
| Eryk Druszkiewicz | Electrical Engineer |
| Dev Aashish Khaitan | Graduate Student |
| Mongkol Moongweluwan | Graduate Student |

## University of Sheffield

| | |
|---|---|
| Vitaly Kudryavtsev | Reader, Particle Physics |
| Elena Korolkova | Research Associate |
| David Woodward | Research Associate |
| Peter Rossiter | Graduate Student |

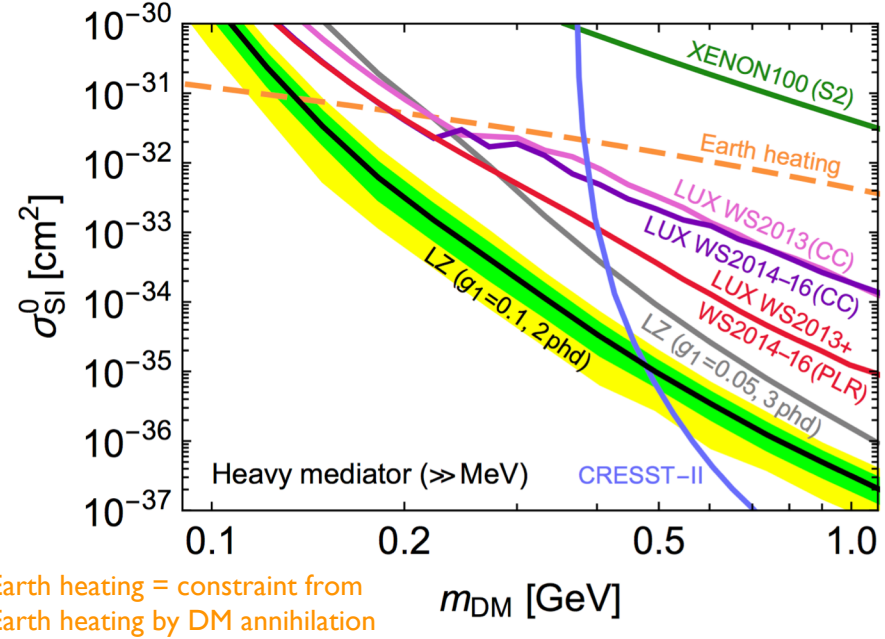
## UNIVERSITY OF SOUTH DAKOTA

| | |
|---|---|
| Dongming Mei | PI, Professor |

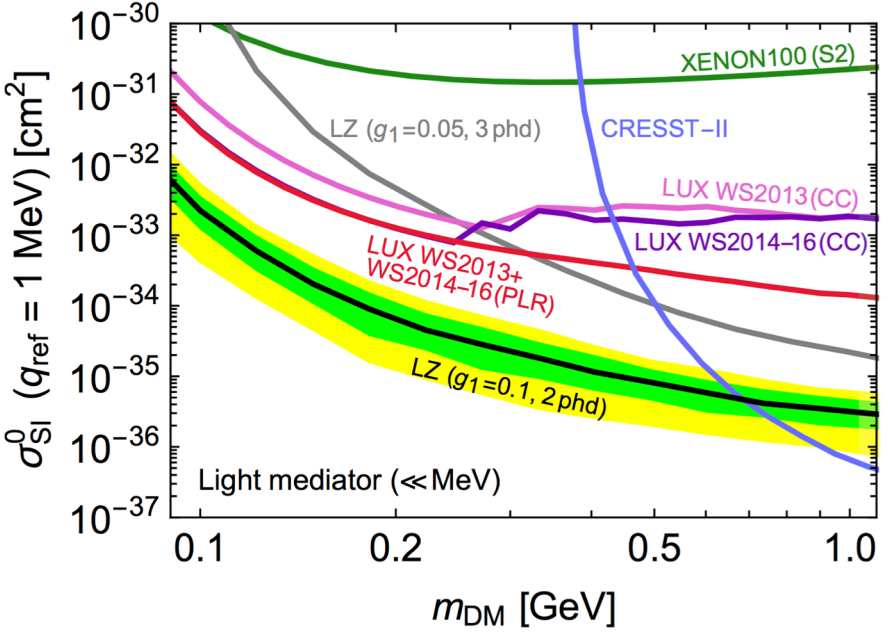
# Limits from Bremsstrahlung – C. McCabe

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