LUX DARK MATTER SEARCH

NICK KINNAIRD

PY 897 SEMINAR

4/27/16

OUTLINE

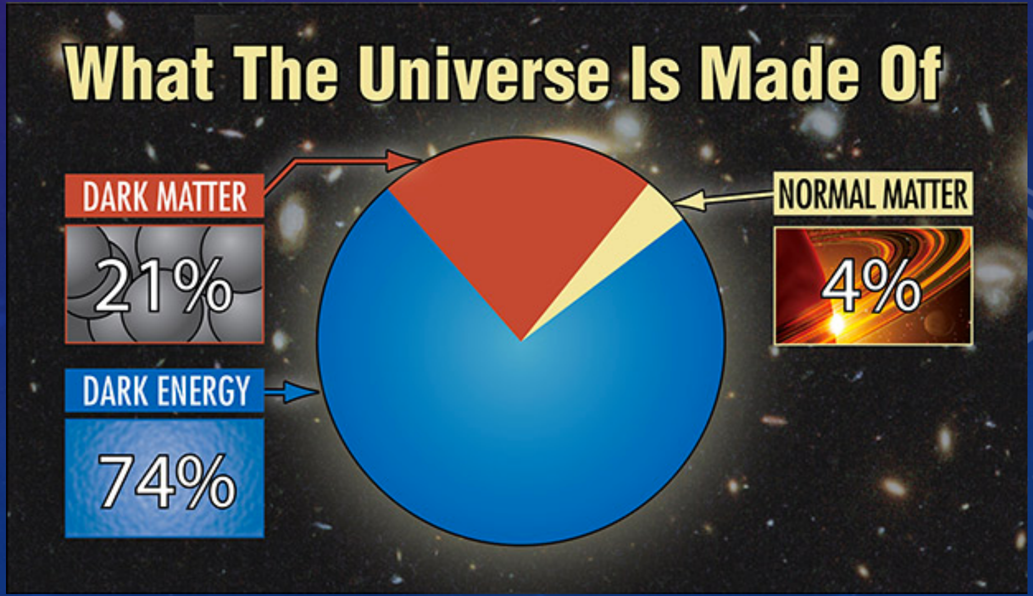
1. Introduction to dark matter
    1. WIMPs
    2. Detecting dark matter
2. LUX experimental overview
    1. Backgrounds – Sources/Calibration
3. Results
    1. Paper review – 1st Run
    2. More recent
4. The Future

OUTLINE

1. Introduction to dark matter
   1. WIMPs
   2. Detecting dark matter
2. LUX experimental overview
   1. Backgrounds – Sources/Calibration
3. Results
   1. Paper review – 1st Run
   2. More recent
4. The Future

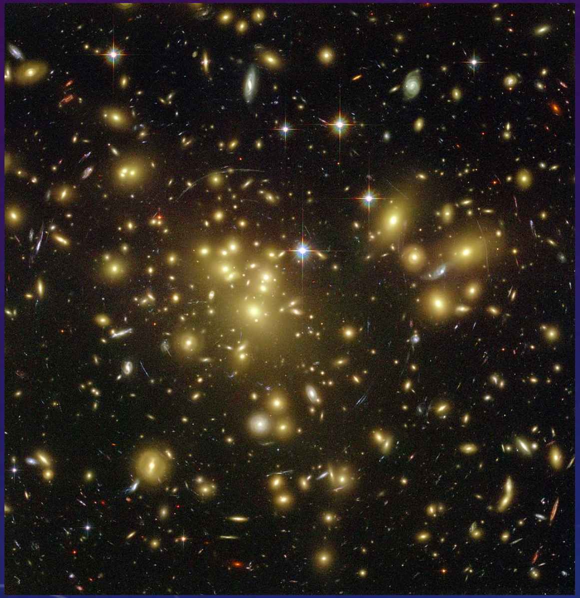
DARK MATTER

- Matter which seems to make up ~25% of the total mass energy of the universe
- Does not interact electromagnetically – hence the name
- Interacts gravitationally – all evidence for dark matter comes from gravitational observations
- Possibly (hopefully) interacts weakly – basis for direct detection experiments

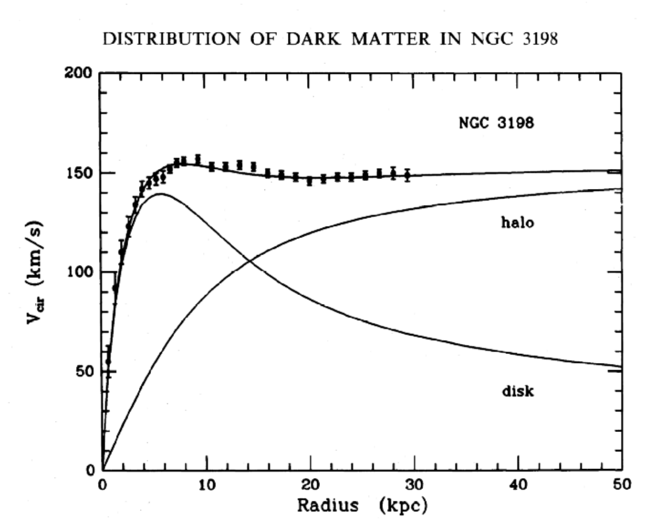


EVIDENCE FOR DARK MATTER

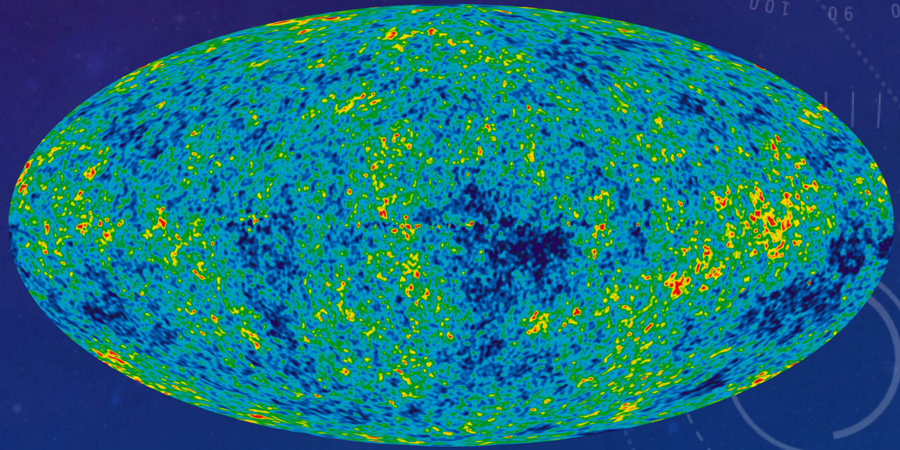
Gravitational lensing – larger effect than that expected from luminous matter



Galactic rotation curves – outer pieces move faster than expected



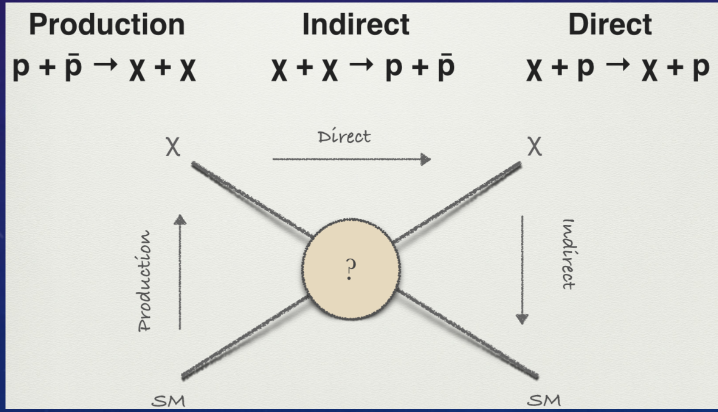
CMB anisotropies – early universe composition reflected in CMB power spectrum

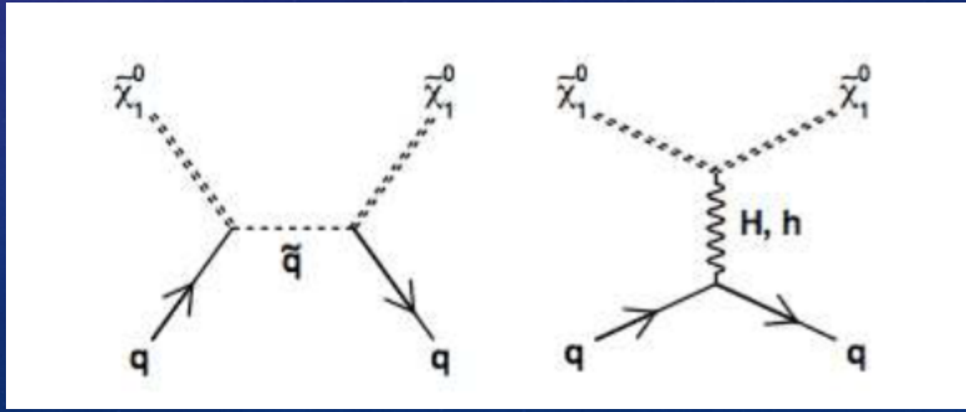


WIMPS

- Weakly Interacting Massive Particles are one of the proposed dark matter candidates - fits nicely into the Minimal Super Symmetric Model – possibly includes a lowest stable particle
- Spin independent and spin dependent interactions

$$L_{eff} = f_q(\bar{\chi}\chi)(q\bar{q}) + d_q(\bar{\chi}\gamma^{\mu}\gamma^{5}\chi)(\bar{q}\gamma^{\mu}\gamma^{5}q) + \ldots$$





DETECTING DARK MATTER

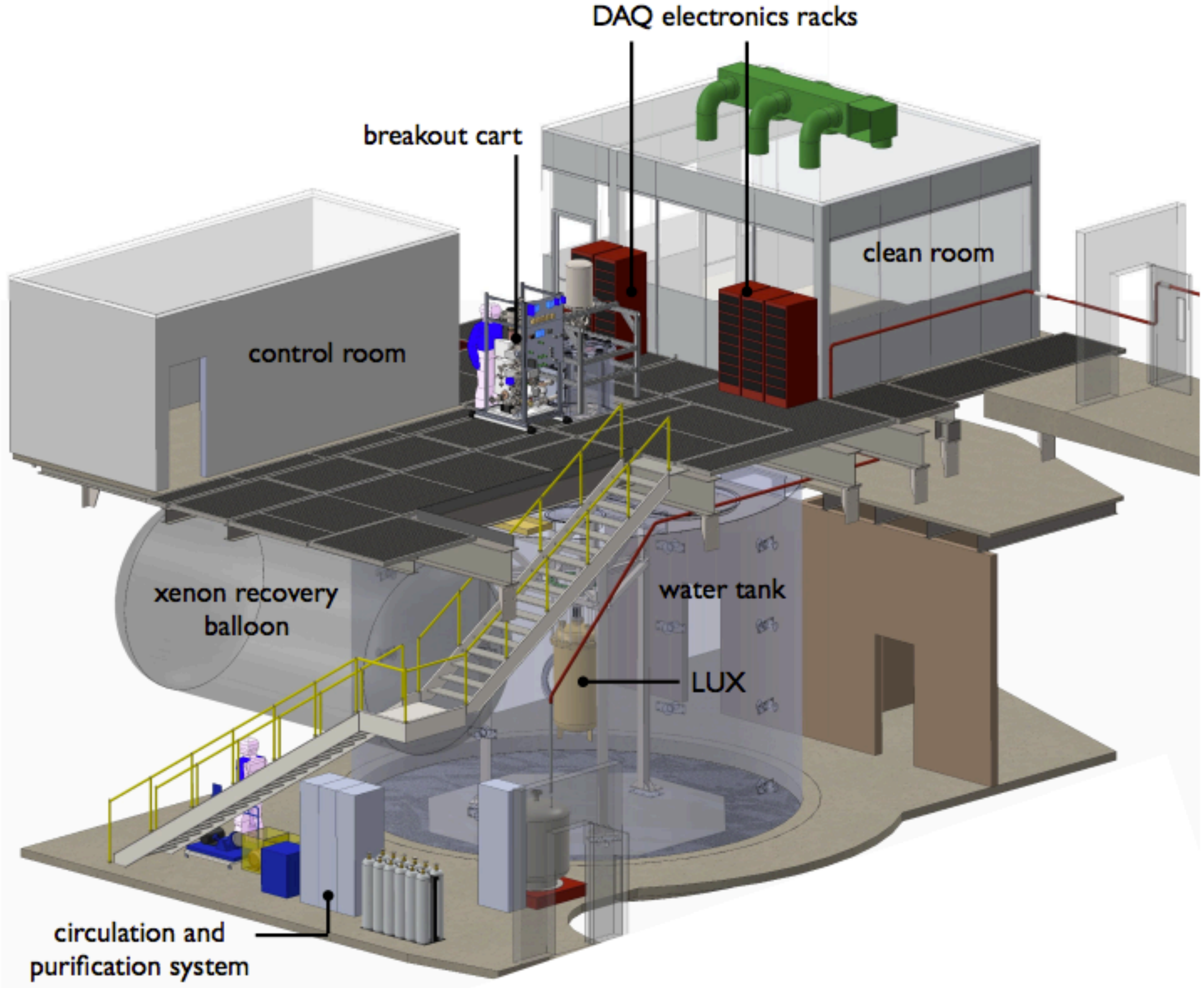
- WIMPs may scatter elastically with nucleons and cause recoils – expected energy deposition of 1-100 keV depending on the interaction type, WIMP mass, target mass – for direct detection experiments
- Main challenge is reducing backgrounds for such dark matter detection
- Electron recoils (ER) occur from particle backgrounds and must be distinguished from nuclear recoils (NR)
- Want some large, pure, low radioactive detector for high statistics and efficient background rejection – liquid xenon is an ideal choice
- Scintillation and ionization signals from the recoil can be used to determine the energy deposition and point of scattering

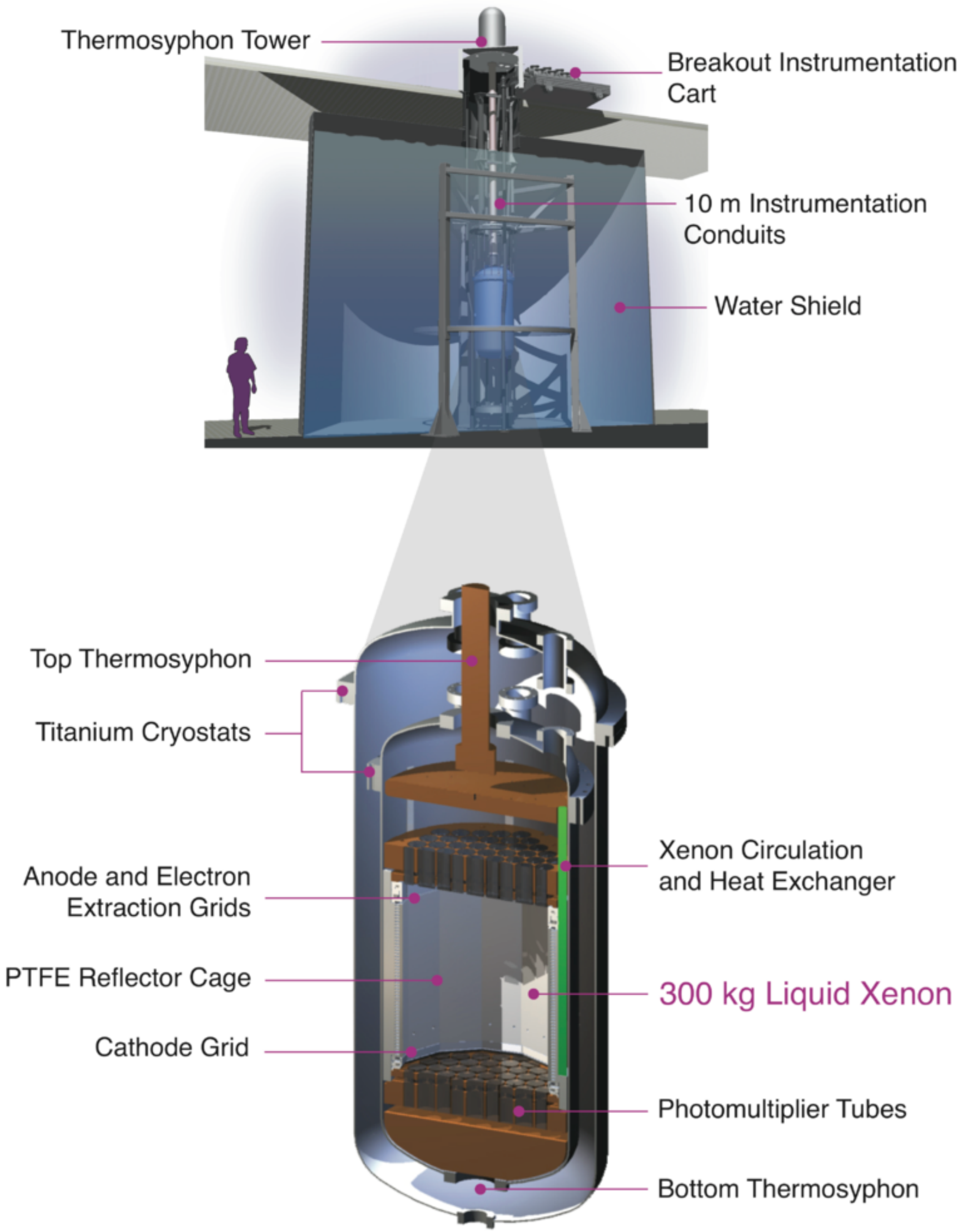
OUTLINE

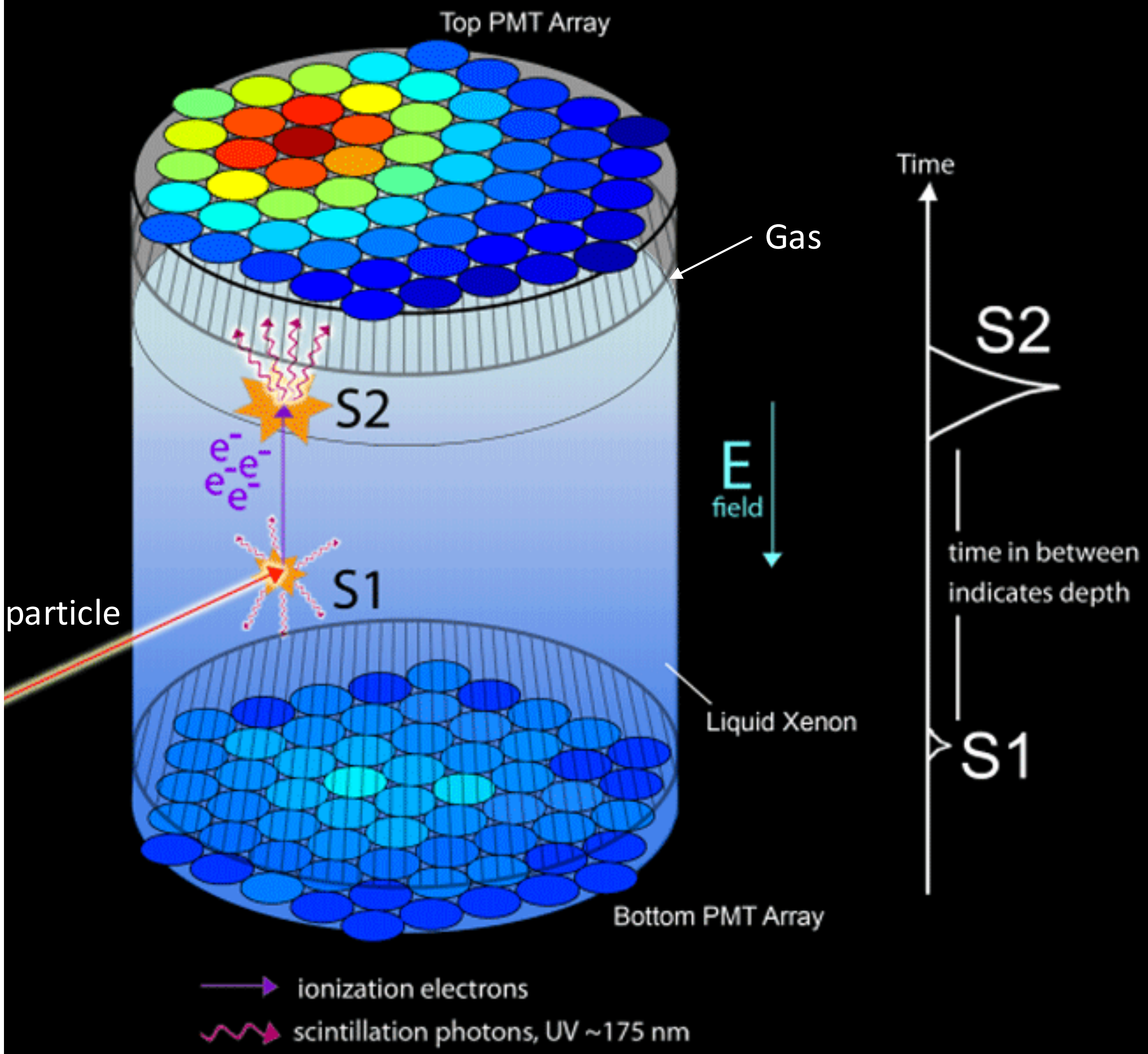
1. Introduction to dark matter
    1. WIMPs
    2. Detecting dark matter
2. LUX experimental overview
    1. Backgrounds – Sources/Calibration
3. Results
    1. Paper review – 1st Run
    2. More recent
4. The Future

LARGE UNDERGROUND XENON EXPERIMENT

- Located at the Sanford Underground Research Facility in Lead, South Dakota
- LUX is a dual-phase (liquid/gas) time projection chamber
- 4850 ft underground to shield from cosmic ray muons
- Surrounded by a 7.6 m diameter x 6.1 m tall water tank – more shielding
- Holds 370 kg of liquid xenon, TPC volume measures 47 cm diameter x 48 cm height
- Liquid xenon transparent to it's own scintillation light
- Uses PMTs to measure scintillation and electroluminescence light to reconstruct position and recoil energy

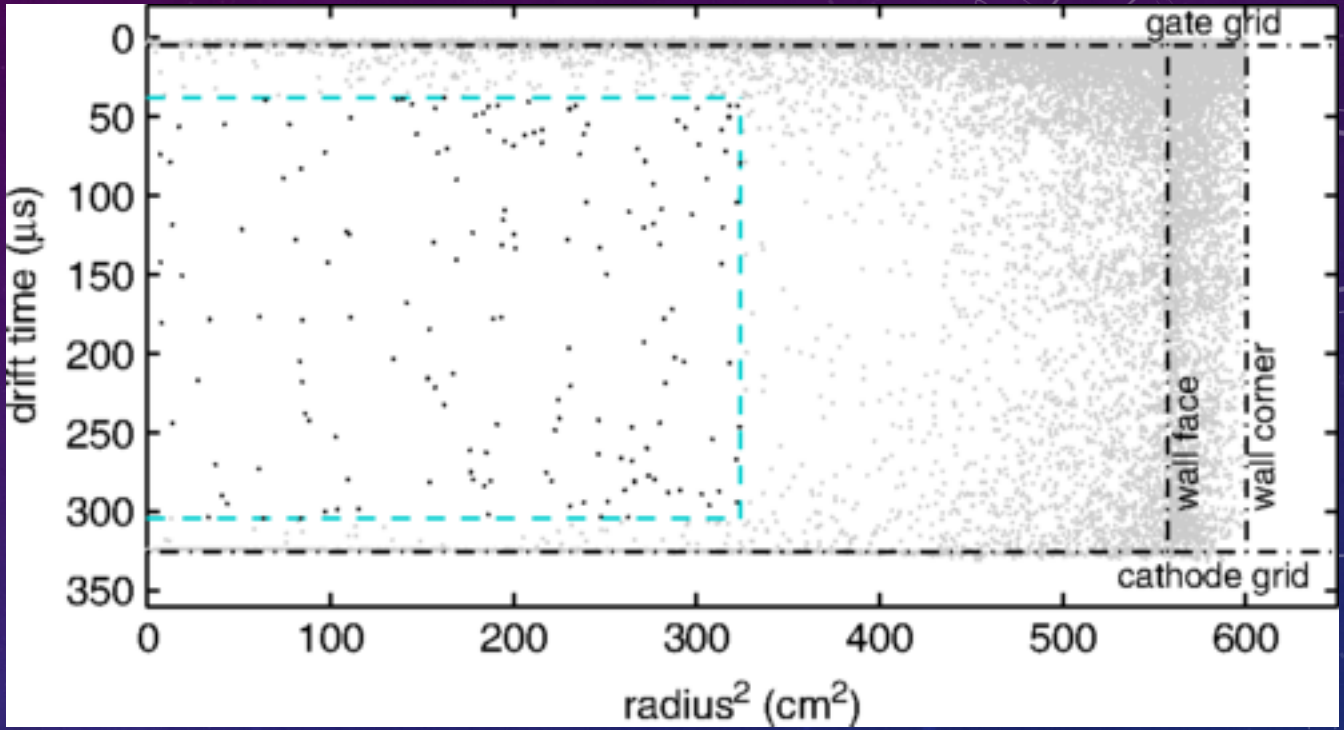

DAQ electronics racks
breakout cart
clean room
control room
xenon recovery
balloon
water tank
LUX
circulation and
purification system


Thermosyphon Tower
Breakout Instrumentation Cart
10 m Instrumentation Conduits
Water Shield
Top Thermosyphon
Titanium Cryostats
Anode and Electron Extraction Grids
PTFE Reflector Cage
Cathode Grid
Xenon Circulation and Heat Exchanger
300 kg Liquid Xenon
Photomultiplier Tubes
Bottom Thermosyphon


Top PMT Array
Gas
Time
S2
E field
particle
S1
time in between indicates depth
Liquid Xenon
Bottom PMT Array
ionization electrons
scintillation photons, UV ~175 nm

LUX EXPERIMENT

- Thermally isolated, stable to < 0.2 K
- Pressure stable to < 1%
- Liquid height stable to < 0.2 mm
- Xenon circulates through purifier – mean electron drift lengths of between ~87 cm and ~134 cm

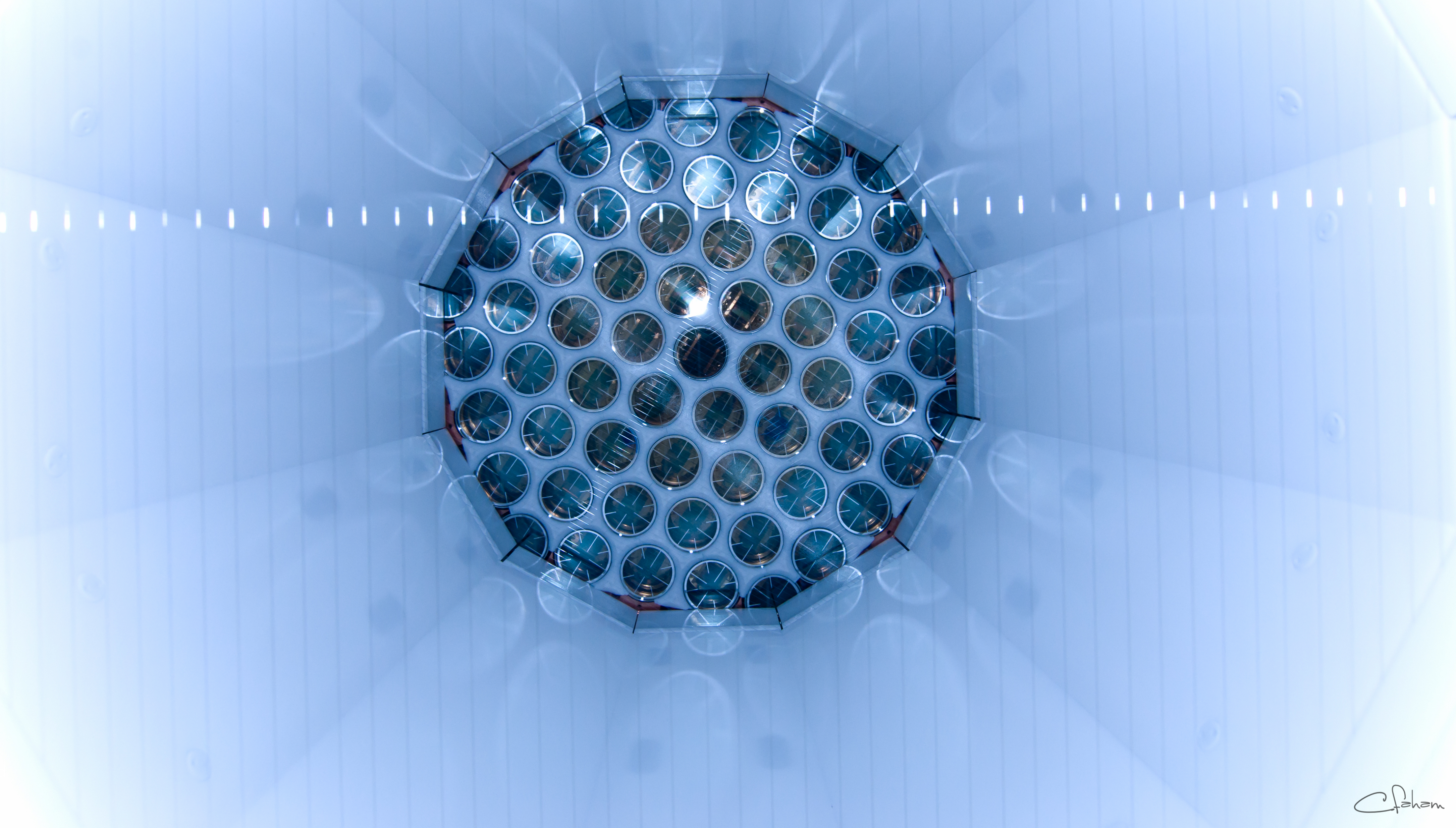


- Liquid xenon is self shielding - fiducial volume chosen and optimized to reduce backgrounds from detector walls, PMTs, and electrodes – fiducial mass = ~118 kg

LUX EXPERIMENT

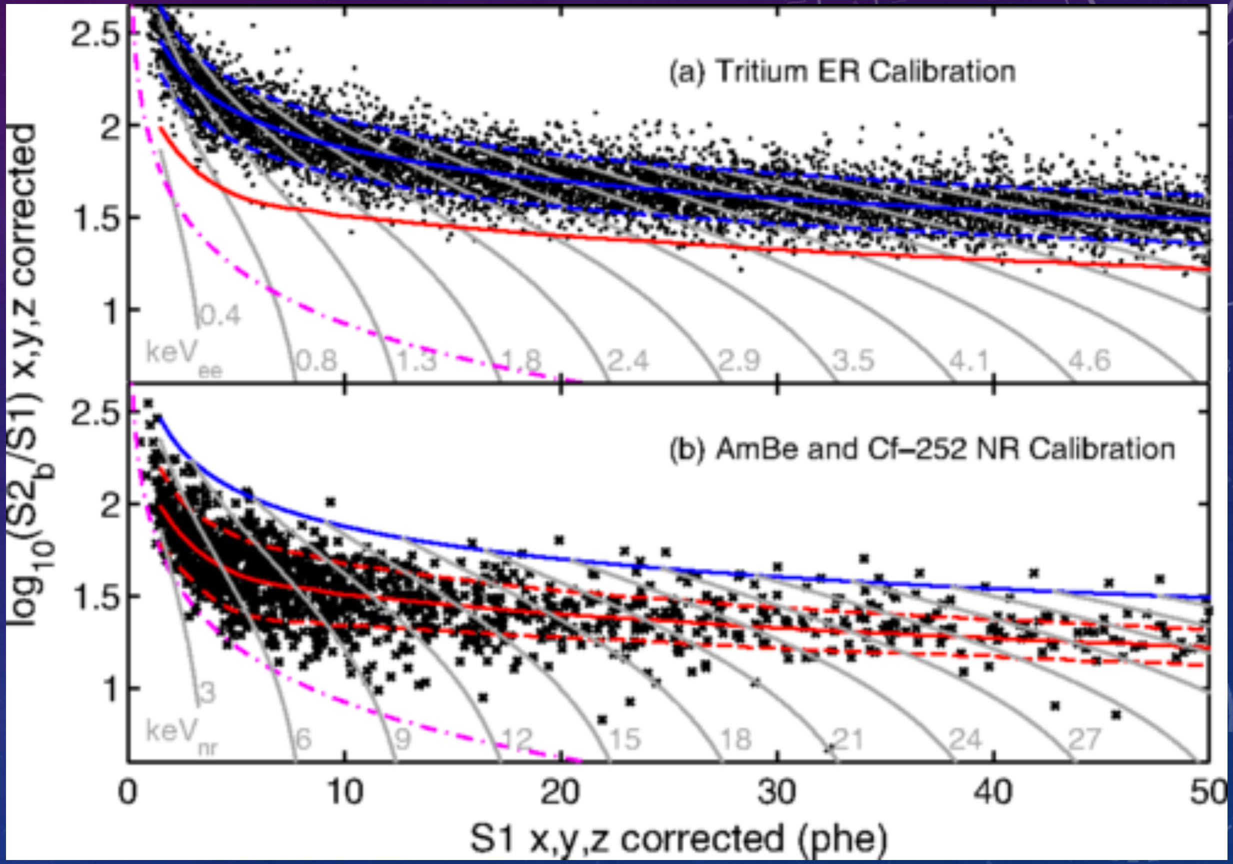
- 122 PMTs, half bottom and half top – immediately measure S1 and later S2 signals
- Horizontal position reconstruction resolution at ~4-6 mm for small S2 signals, with better for higher energies – vertical resolution is < 1 mm
- Gas electron extraction efficiency of ~ 0.65
- S2 photoelectrons observed per extracted electron is ~24.6
- Ratio of S2/S1 can be used to distinguish between electron and nuclear recoils – ER will have a higher S2 signal as more ionization electrons are produced - $\log_{10}(S2/S1)$ vs S1 is the standard parameter for displaying this

"The center of LUX, measured at low energies, is the radioactively quietest place in the world." – Rick Gaitskell/Dan McKinsey (LUX spokesmen)



CALIBRATION

- Internal electron recoil sources (tritiated methane, ^{83m}Kr) were injected into the system to calibrate acceptance – removed later by purifier
- The ^{83m}Kr was injected weekly to determine and verify stability of photon detection efficiency – modeled with NEST
- Nuclear recoil acceptance was calibrated with external neutron sources (AmBe, Cf-252) placed around the detector
- NR data results were crosschecked with events simulated in LUXSim



BACKGROUNDS

- Cosmic rays
- Gamma rays from PMT materials and detector walls
- Cosmogenically produced isotopes
- Krypton as a mass fraction of xenon – 4 ppt
- Radioactive xenon
- Neutron background too small and left out
- Backgrounds simulated with LUXSim (GEANT4 based)

Source	Background rate, $mDRU_{ee}$
γ-rays	$1.8 \pm 0.2_{stat} \pm 0.3_{sys}$
^{127}Xe	$0.5 \pm 0.02_{stat} \pm 0.1_{sys}$
^{214}Pb	0.11–0.22 (90% C. L.)
^{85}Kr	$0.13 \pm 0.07_{sys}$
Total predicted	$2.6 \pm 0.2_{stat} \pm 0.4_{sys}$
Total observed	$3.6 \pm 0.3_{stat}$

1 $mDRU_{ee} = 10^{-3}$ events/keV_{ee}/kg/day

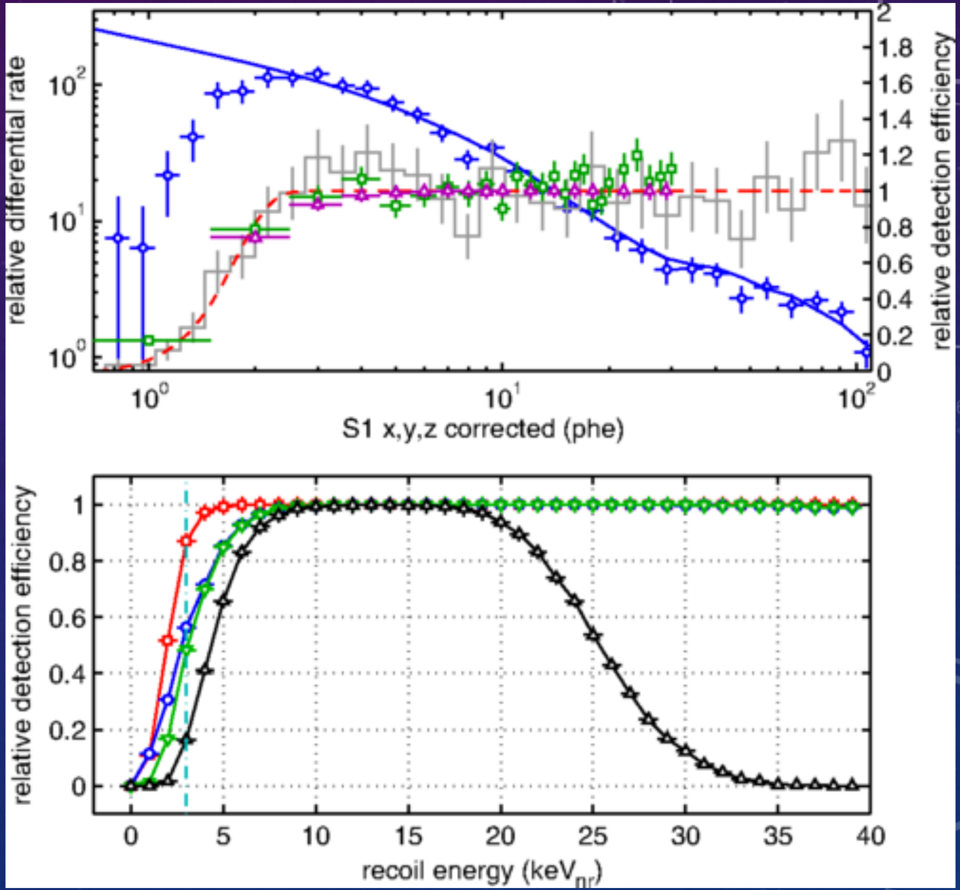
DAQ/TRIGGER

- DAQ threshold set to record > 95 % of all single pe pulses in each PMT
- Digital trigger used to identify events for further analysis – 16 trigger channels of non-adjacent PMTs
- 2 or more channels must have > 8 pe within 2 µs, results in > 99% efficiency for 200 pe analysis threshold in S2 (derived from calibration data)
- All pulses of light digitized from the DAQ within +- 500 µs of the trigger time were held for further analysis, to ensure S1 and S2 can always be associated
- Data between triggered events was kept to show whether the detector was quiet before and after the event

DETECTION EFFICIENCY

- Conservative artificial cutoff at 3 keV_{nr} assuming poor detection efficiency at those low energies
- Absolute efficiency estimated through visual inspection of NR calibration data waveforms ~98% within the region of interest
- Overall WIMP detection efficiency of 50% at 4.3 keV_{nr} (> 95% above 7.5 keV_{nr})

AmBe data/simulation (rate)
AmBe data NR (efficiency)
Tritium data ER (efficiency)
Full detector simulation NR (efficiency)



Individual S2
Individual S1
Both S1 and S2
WIMP efficiency for analysis thresholds (S2 and S1)

OUTLINE

1. Introduction to dark matter
    1. WIMPs
    2. Detecting dark matter
2. LUX experimental overview
    1. Backgrounds – Sources/Calibration
3. Results
    1. Paper review – 1st Run
    2. More recent
4. The Future

FIRST RUN

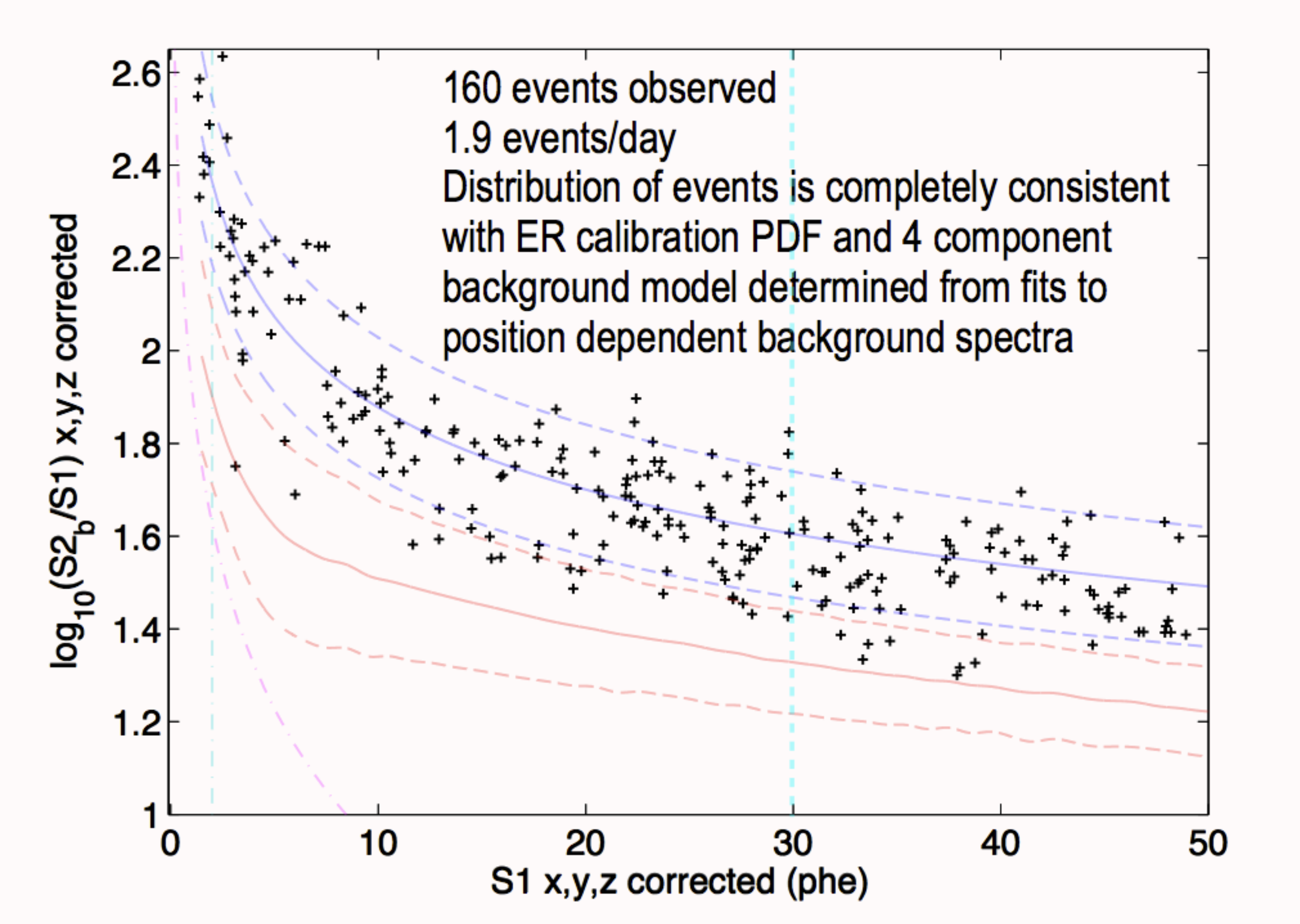
- 85.3 live days of WIMP search data in 2013
- A non-blind analysis was completed on said data, with minimal cuts and high acceptance to reduce bias
- 160 events that passed the cuts were observed for the run time – single scatter events with one S1 signal followed by one S2 signal – expected from elastic scattering of WIMPs

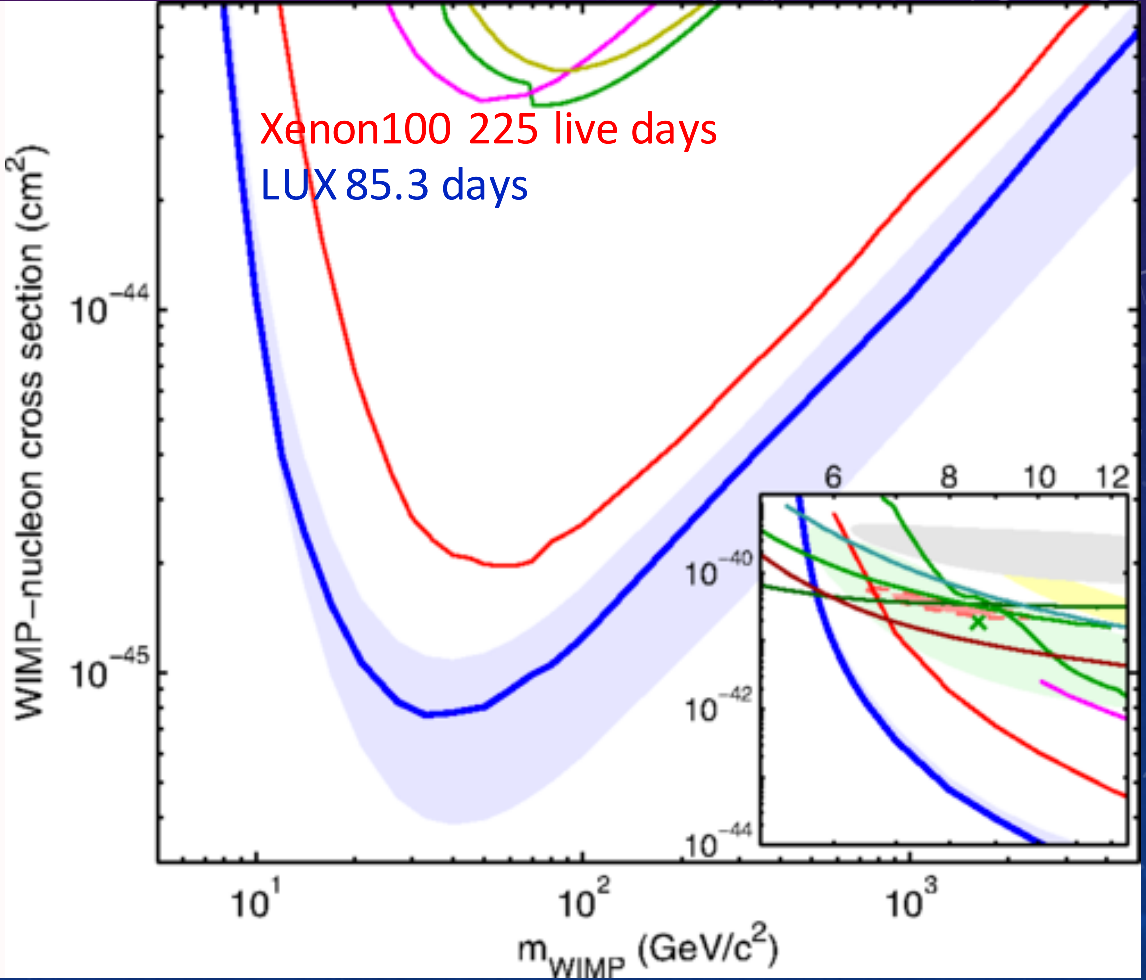
Cut	Explanation	Events Remaining
All Triggers	S2 Trigger >99% for $S2_{raw}$>200 phe	83,673,413
Detector Stability	Cut periods of excursion for Xe Gas Pressure, Xe Liquid Level, Grid Voltages	82,918,901
Single Scatter Events	Identification of S1 and S2. Single Scatter cut.	6,585,686
S1 energy	Accept 2-30 phe (energy ~ 0.9-5.3 keVee, ~3-18 keVnr)	26,824
S2 energy	Accept 200-3300 phe (>8 extracted electrons) Removes single electron / small S2 edge events	20,989
S2 Single Electron Quiet Cut	Cut if >100 phe outside S1+S2 identified +/-0.5 ms around trigger (0.8% drop in livetime)	19,796
Drift Time Cut away from grids	Cutting away from cathode and gate regions, 60 < drift time < 324 us	8731
Fiducial Volume radius and drift cut	Radius < 18 cm, 38 < drift time < 305 us, 118 kg fiducial	160

ANALYSIS AND 1ST RESULTS

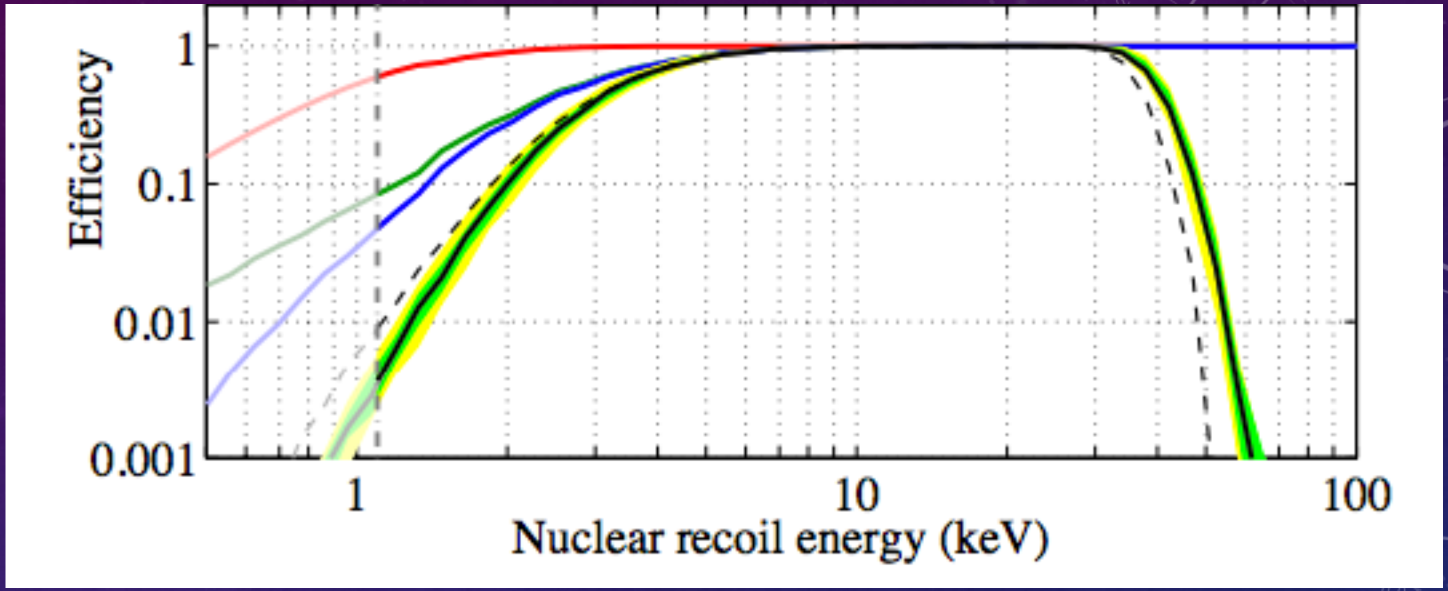
- A profile likelihood ratio was used to set confidence intervals for the spin independent WIMP-nucleon cross section
- Included physical parameters radius, depth, light (S1), and charge (S2) yields along with nuisance parameters from backgrounds
- All observed events were consistent with the predicted background of electron recoils – p-value of 35%
- Minimum upper limit of $\sigma = 7.6 \times 10^{-46}$ cm^2 at a WIMP mass of 33 GeV
- Review paper published March 4th, 2014

1ST RESULTS


160 events observed
1.9 events/day
Distribution of events is completely consistent with ER calibration PDF and 4 component background model determined from fits to position dependent background spectra
$\log_{10}(S2_b/S1)$ x,y,z corrected
S1 x,y,z corrected (phe)


Xenon100 225 live days
LUX 85.3 days
WIMP–nucleon cross section (cm^2)
m_{WIMP} (GeV/c^2)

MORE RECENT RESULTS



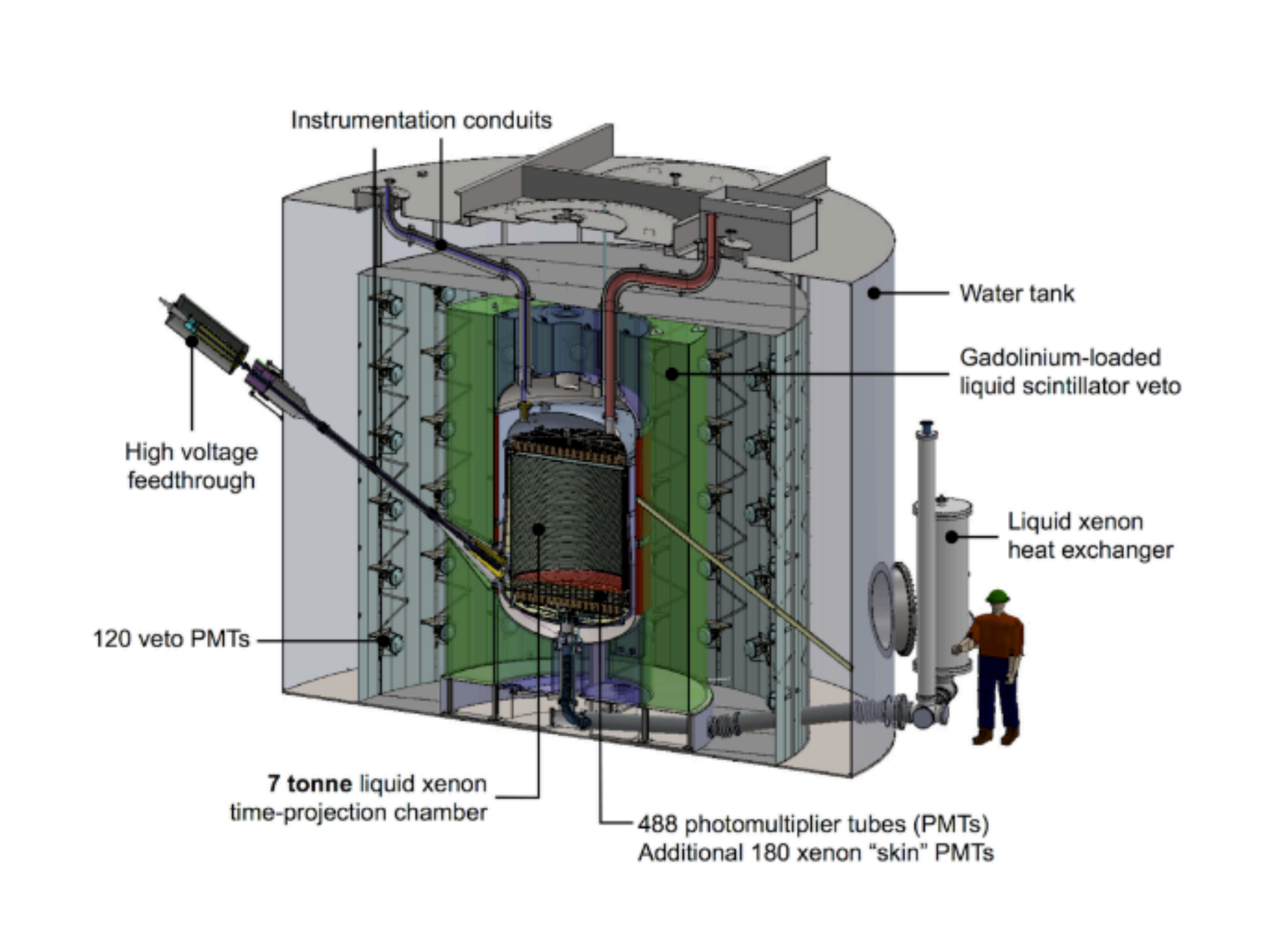
- Recent paper published (Jan. 27 2016) on the same data (with 10 more days) using advances in single photon calibration (lower cut to less than 3 keV_{nr}), event reconstruction algorithms, revised background model, new calibrations, larger fiducial volume
- Improved results from .76 zeptobarns to .6 zb at the same WIMP mass
- Currently the best experimental limit on this cross section
- Further developed techniques/simulations/algorithms for current 300 day run time – ending in mid 2016 with a blind analysis to follow

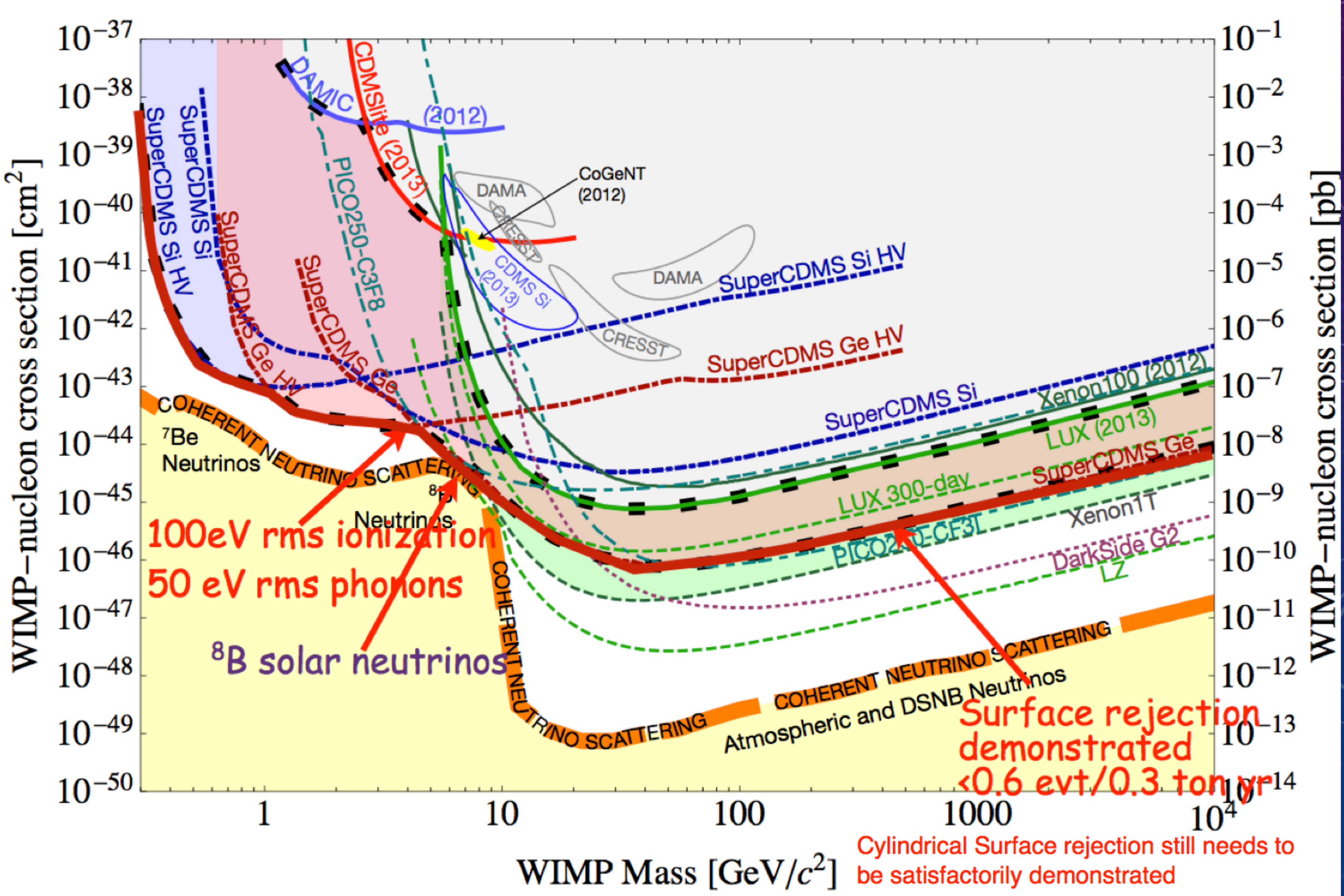
OUTLINE

1. Introduction to dark matter
    1. WIMPs
    2. Detecting dark matter
2. LUX experimental overview
    1. Backgrounds – Sources/Calibration
3. Results
    1. Paper review – 1st Run
    2. More recent
4. The Future

NEXT GENERATION – LZ – LUX ZEPLIN EXPERIMENT

- Same place
- More LXe (7 tons), more PMTs, more…
- Commissioning projected in early 2019
- Projected 3 year run to get close to fundamental limits from cosmic ray neutrino background





WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000
10^4
SuperCDMS Si HV
SuperCDMS Si
SuperCDMS Ge HV
SuperCDMS Ge
PICO250-C3F8
DAMIC
(2012)
CDMSlite (2013)
CoGeNT
(2012)
DAMA
CRESST
CDMS Si
(2013)
DAMA
CRESST
SuperCDMS Si HV
SuperCDMS Ge HV
SuperCDMS Si
Xenon100 (2012)
LUX (2013)
SuperCDMS Ge
LUX 300-day
Xenon1T
PICO250-CF3I
DarkSide G2
LZ
COHERENT NEUTRINO SCATTERING
^{7}Be
Neutrinos
^{8}B
Neutrinos
COHERENT NEUTRINO SCATTERING
COHERENT NEUTRINO SCATTERING
Atmospheric and DSNB Neutrinos
100eV rms ionization
50 eV rms phonons
^{8}B solar neutrinos
Surface rejection
demonstrated
<0.6 evt/0.3 ton yr
Cylindrical Surface rejection still needs to
be satisfactorily demonstrated

CONCLUSIONS

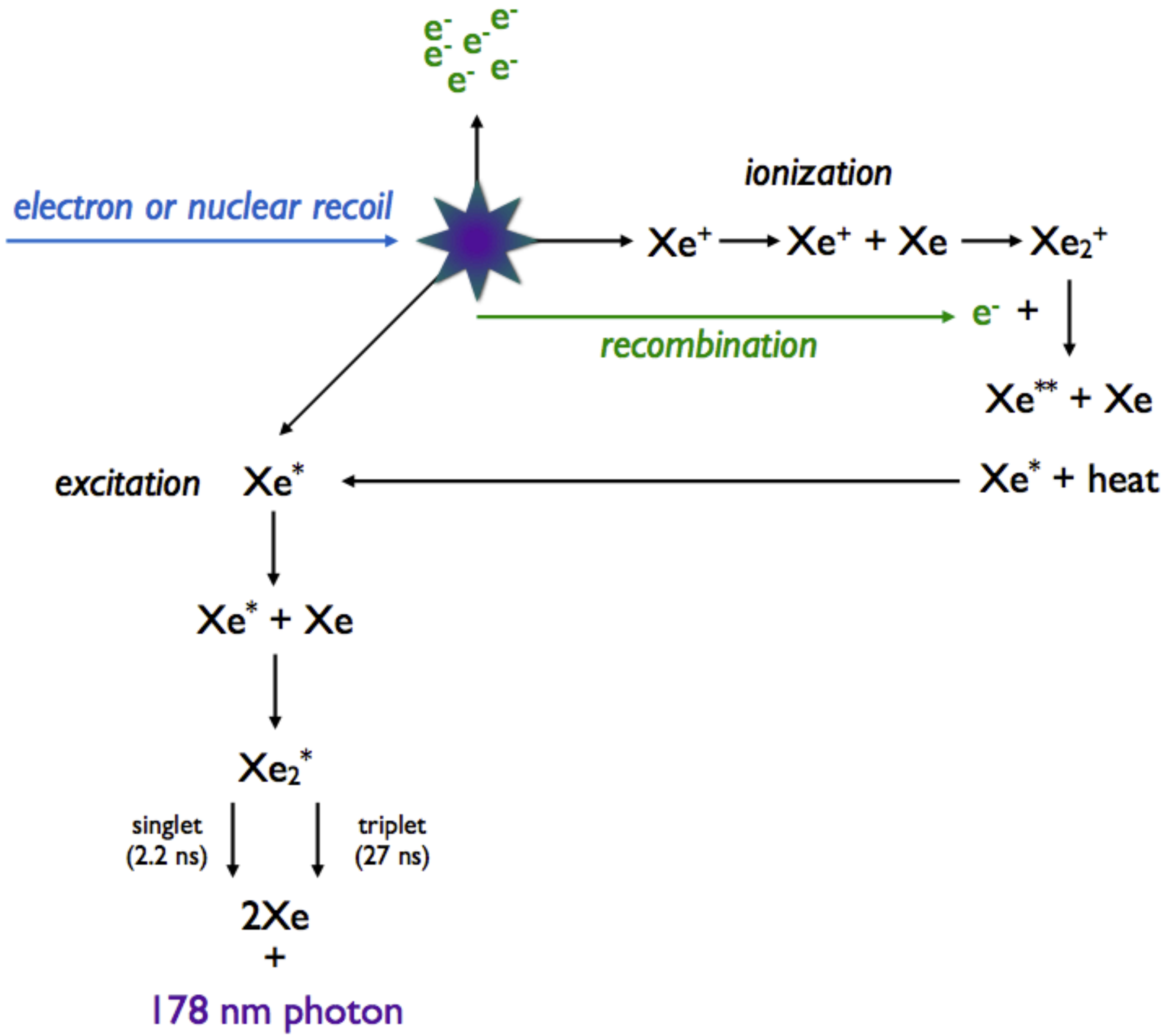
- A lot of sources point towards the existence of dark matter.
- There are some clever ways to build direct detection experiments, utilizing extremely low-radioactive detectors.
- The LUX experiment has produced the most stringent limits on the spin independent WIMP-nucleon elastic scattering cross section to date, and will have a new result either this year or early next year.
- There are next generation direct search dark matter experiments in the works, including LZ, which will push our ability to detect such dark matter about as far as it can go.
- Hopefully someone will discover something! Else models need to be revised or WIMPs are a bust.

END

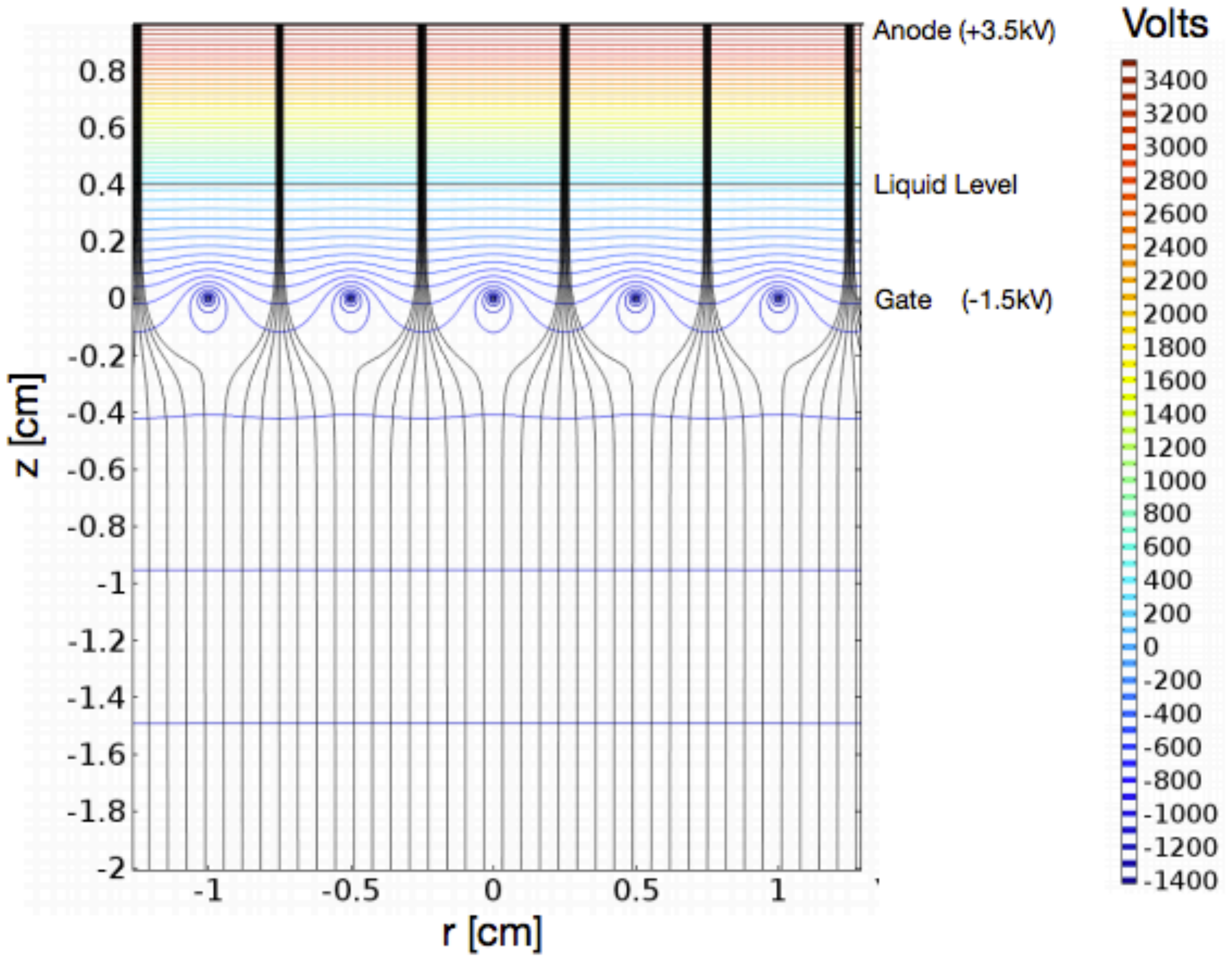
REFERENCES

- First Results from the LUX Dark Matter Experiment at the Sanford Underground Research Facility, D. S. Akerib *et al.* (LUX Collaboration), Phys. Rev. Lett. **112**, 091303, Published 4 March 2014
- **Barnes, Emma Jayne. *A Veto for the ZEPLIN-III Dark Matter Detector*. Thesis. University of Edinburgh, 2010.**
- Snowmass CF1 Summary: WIMP Dark Matter Direct Detection, P. Cushman et al., arXiv:1310.8327v2
- Improved WIMP scattering limits from the LUX experiment, D. S. Akerib et al. (LUX Collaboration), arXiv:151203506
- *"First results from the LUX dark matter search at SURF"*, R. Gaitskell and D. McKinsey, Oct 30, 2013
- *"LUX: A dual phase Xe TPC for direct dark matter detection"*, R. Ott, VCI 2013
- **Chapman, Jeremy J., *First WIMP Search Results From The LUX Dark Matter Experiment*. Thesis. Brown University, 2014.**
- LUX Dark Matter Collaboration, http://luxdarkmatter.org
- The LZ Dark Matter Experiment, http://lz.lbl.gov

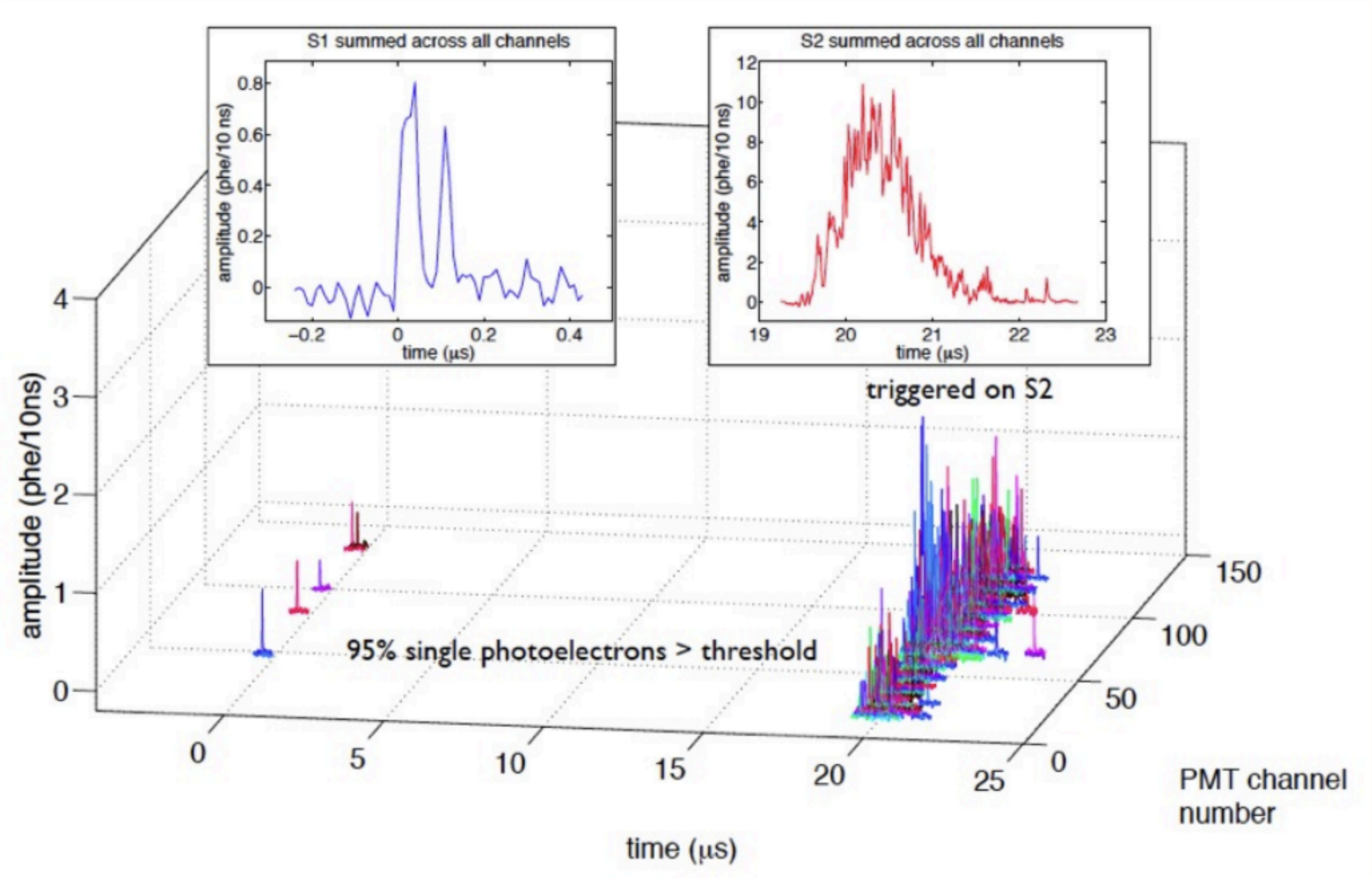
BACKUP


e- e- e- e- e- e-
electron or nuclear recoil
ionization
Xe+ → Xe+ + Xe → Xe2+
e- +
recombination
Xe** + Xe
excitation Xe*
Xe* + heat
Xe* + Xe
Xe2*
singlet (2.2 ns)
triplet (27 ns)
2Xe
+
178 nm photon

radio-isotope	strength (μCi)	strength (kBq)	half-life	yield
^{57}Co	1.0 (3)	37 (3)	271.8 d	**122**, 136 keV gamma-rays
^{60}Co	1.0	37	5.27 yr	**1173**, **1332** keV gamma-rays (simultaneous)
^{133}Ba	0.2 (3), 2.88	7.4 (3), 106.8	10.5 yr	80, 276, 302, **356**, 383 keV gamma-rays
^{137}Cs	0.25, 2.71, 1, 5, 10	9.25, 100.2, 37, 5, 370	30.07 yr	33, **662** keV gamma-rays
^{22}Na	0.93	34.4	2.6 yr	**1277** keV gamma-rays
^{228}Th	0.8	29.5	1.9 yr	238, 510, 583, 727, 860, **2614** keV gamma-rays
AmBe	90	3330	432 yr	$\sim$ 200 neutrons/second
^{252}Cf	0.083 (2), 0.078	3.07 (2), 2.88	2.65 yr	$\sim$ 300 neutrons/second


Anode (+3.5kV)
Liquid Level
Gate (-1.5kV)
Volts
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
-400
-600
-800
-1000
-1200
-1400
z [cm]
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
-1.4
-1.6
-1.8
-2
r [cm]
-1
-0.5
0
0.5
1

1.5 keV gamma ray scattering event



- Leakage fraction of ER events into NR events – great discrimination