Dark Matter Direct Detection with LUX and LZ

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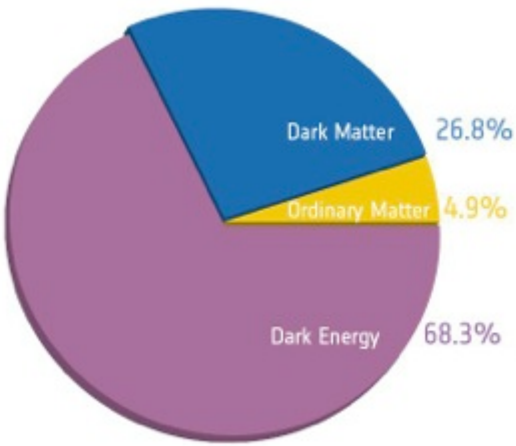
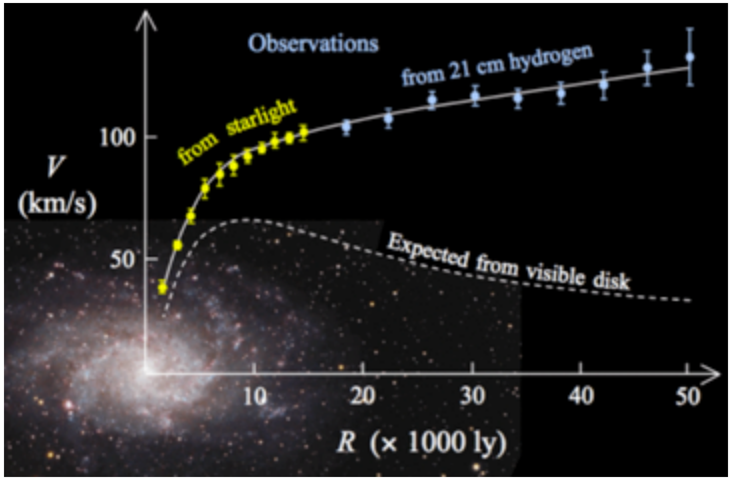
Dark Matter Direct Detection Motivation

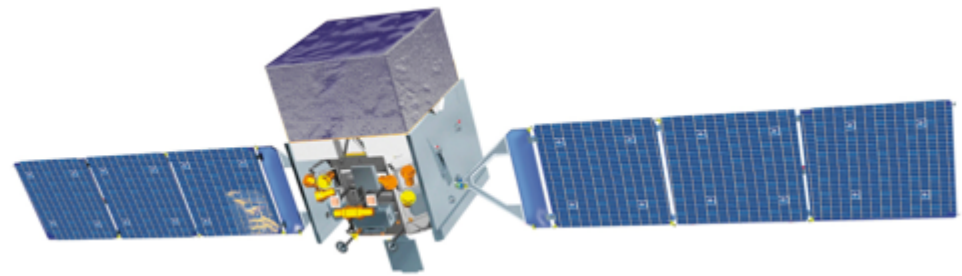
- Overwhelming gravitational Evidence
- Best guess: WIMPS
  - WIMP Miracle: Relic density in the early universe matches cross-section expected from weak force
  - Consistent with BBN & CMB models





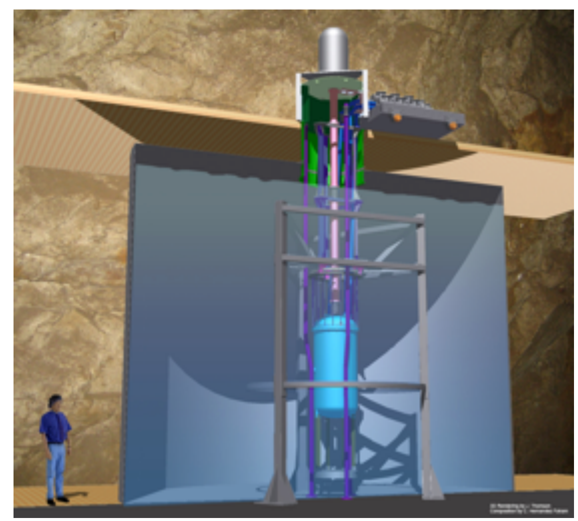
Three Approaches

- Indirect Detection
  - Example: Fermi-LAT
  - Looks for signs of dark matter annihilation



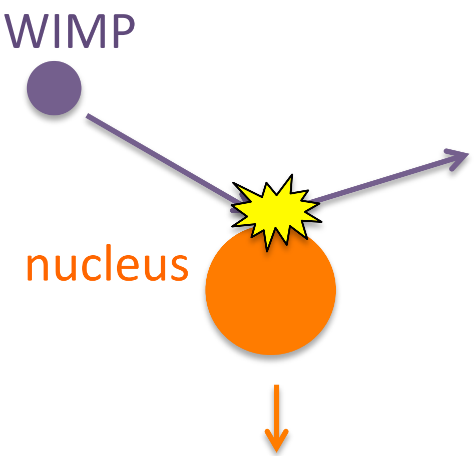
- Production at Colliders
  - Missing E_T signature (no direct interaction with detector)

- Direct Detection
  - This talk



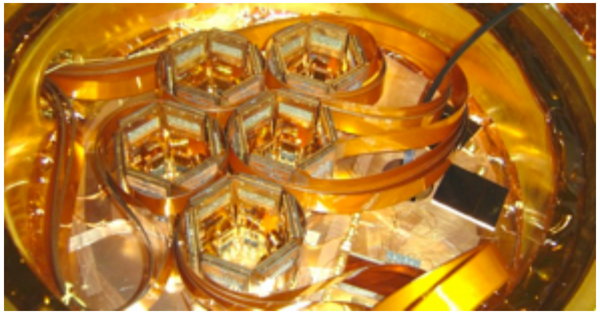
WIMP Direct Detection

- WIMP-nucleus elastic scattering
- Nuclear recoil is detected
- What makes a good detector?
  - Large mass atom
  - Low-radioactivity
  - Low-energy threshold (Recoil energy is a falling exponential)
  - Signal/Background Discrimination



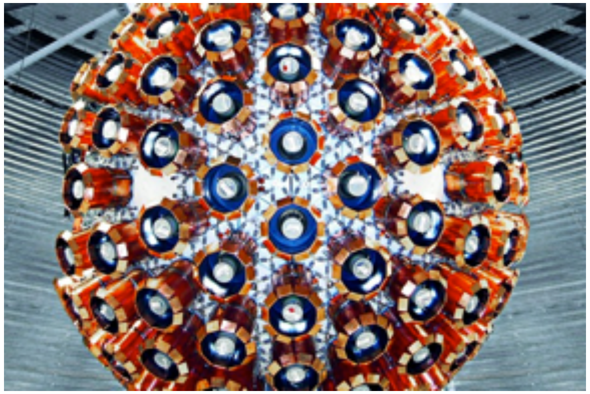
Types of detectors

- Germanium
  - Example: CDMS



- NaI
  - Example: DAMA, DM-ICE

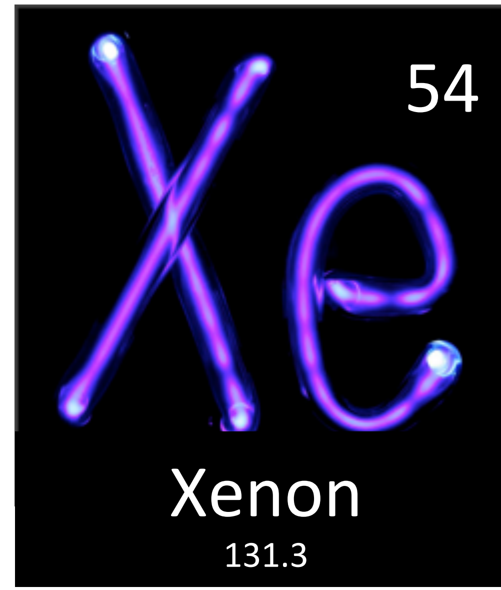
- Liquid Argon
  - Example: DEAP, MiniCLEAN



- Liquid Xenon (this talk)
  - Example: LUX, XENON100

Liquid Xenon as a Target

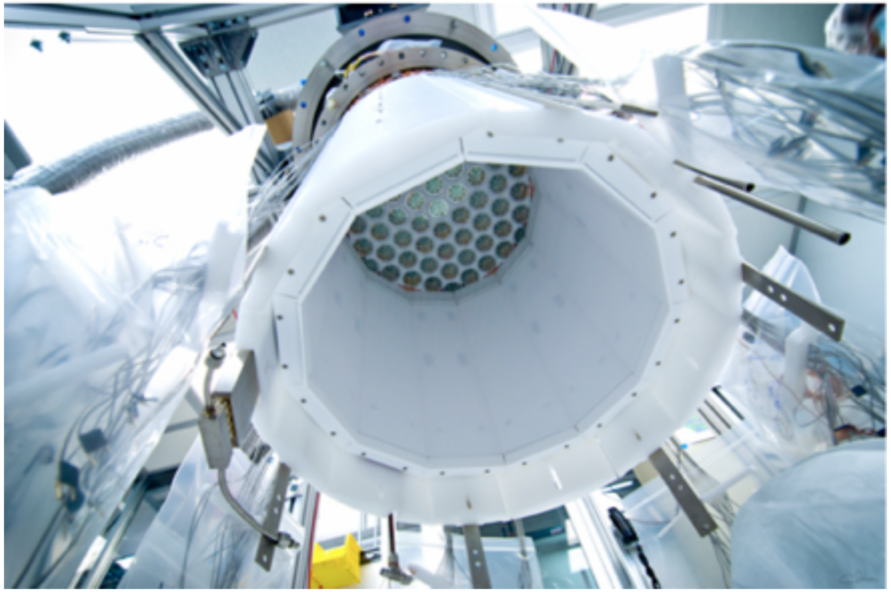
- Relatively easy to obtain
- Large atom
  - Large target
  - Self-shielding
- Easily purified, no long lived unstable isotopes
- Noble element
  - ionization electrons won't get recaptured
  - Transparent to own scintillation light
- Scalable technology



LUX @ The Sanford Underground Research Facility

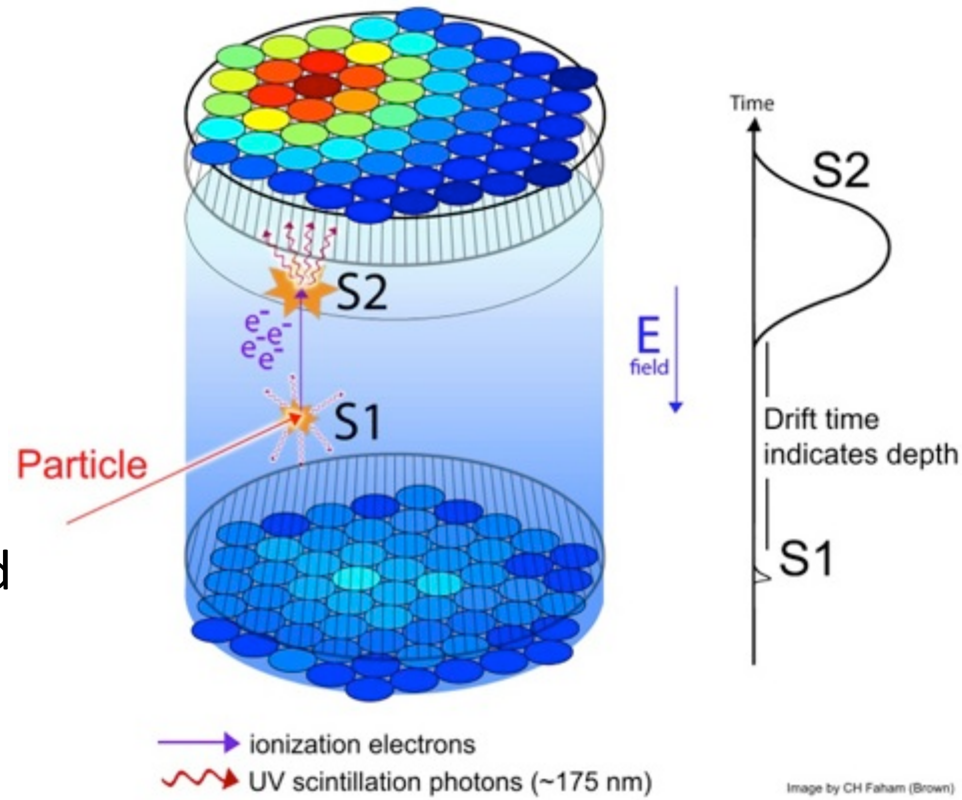
The LUX Detector

- Dual-phase Xe Time Projection Chamber
- 370 kg LXe (250 kg active)
- Outer water tank for gamma&neutron shielding
- 122 PMTs split between top and bottom arrays
- Dimensions:
  - Height: 48 cm
  - Diameter: 47cm
  - Water tank diameter: 7.6m



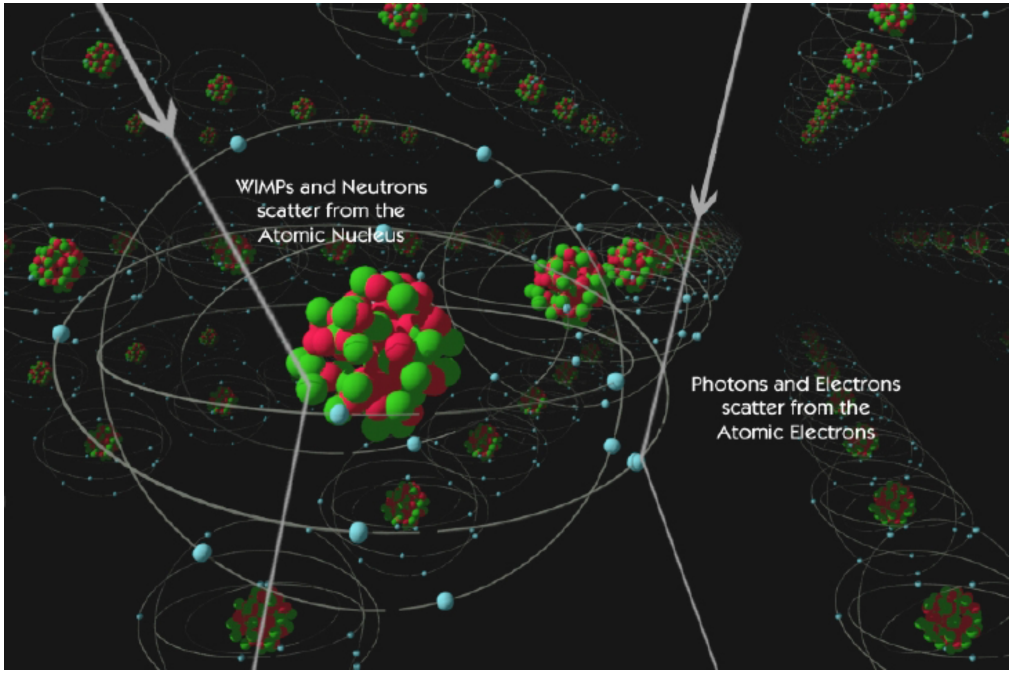
Events in Liquid Xenon TPCs

- Two scintillation signals for each event:
  - S1: de-excitation of short-lived Xenon dimers
  - S2: ionization electrons liberated at the event site extracted into the gas phase and electroluminesce.
- Time difference between S1 and S2 gives depth
- S2 hit pattern gives lateral position information



Event Discrimination

- Detect WIMPs via Nuclear Recoils (NR)
- Most of our background events are Electron Recoils (ER)
- These two types of events produce different amounts of light and charge in the detector
  - Characterize charge-to-light ratios (S2 vs S1) and amounts as a function of energy



Signal Production – Signal Events

- Nuclear Recoils
- Lower charge-to-light ratio

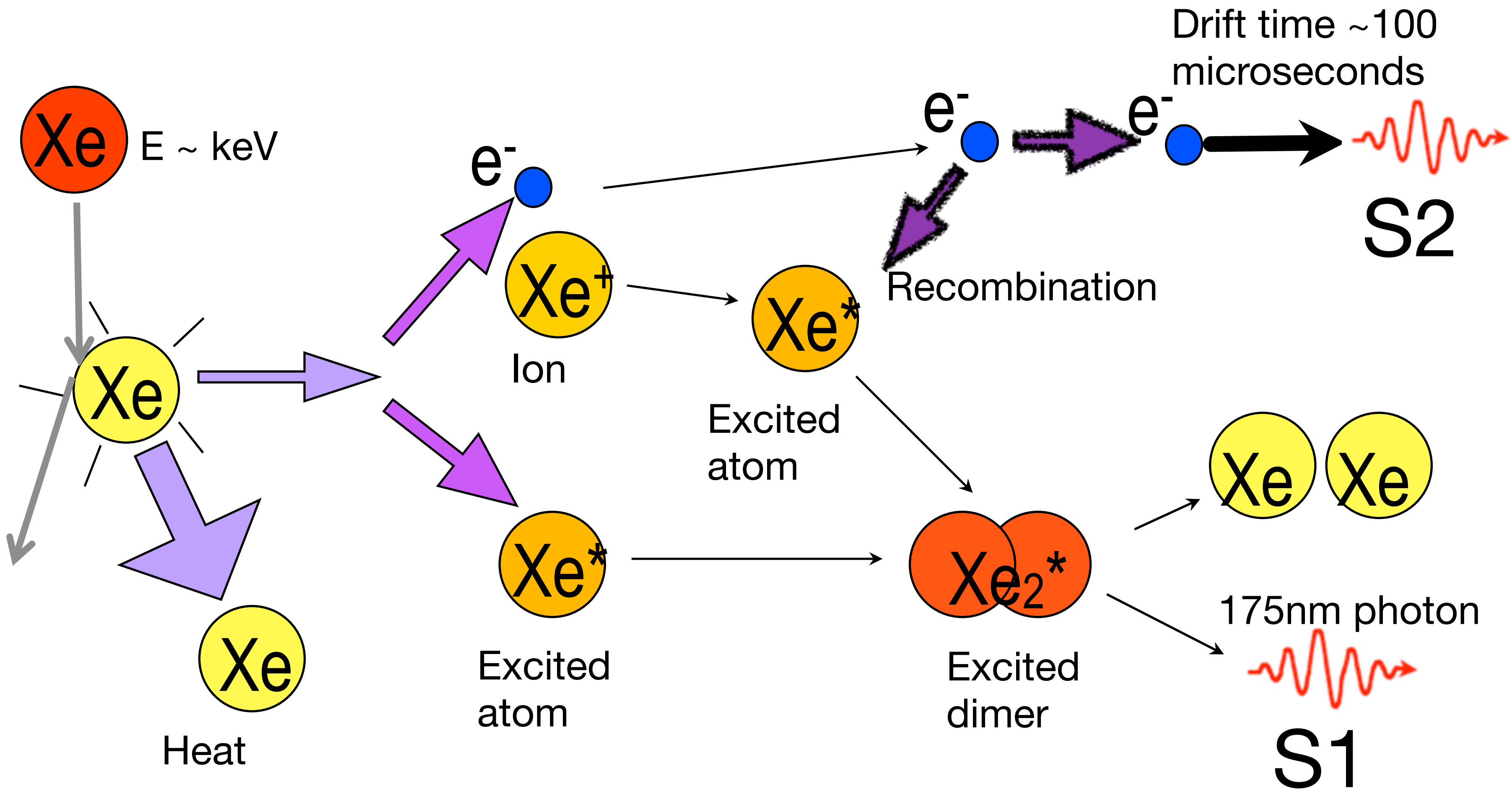


Figure: Gibson/Shutt

Signal Production – Background Events

- Electron Recoils
- Higher charge-to-light ratio

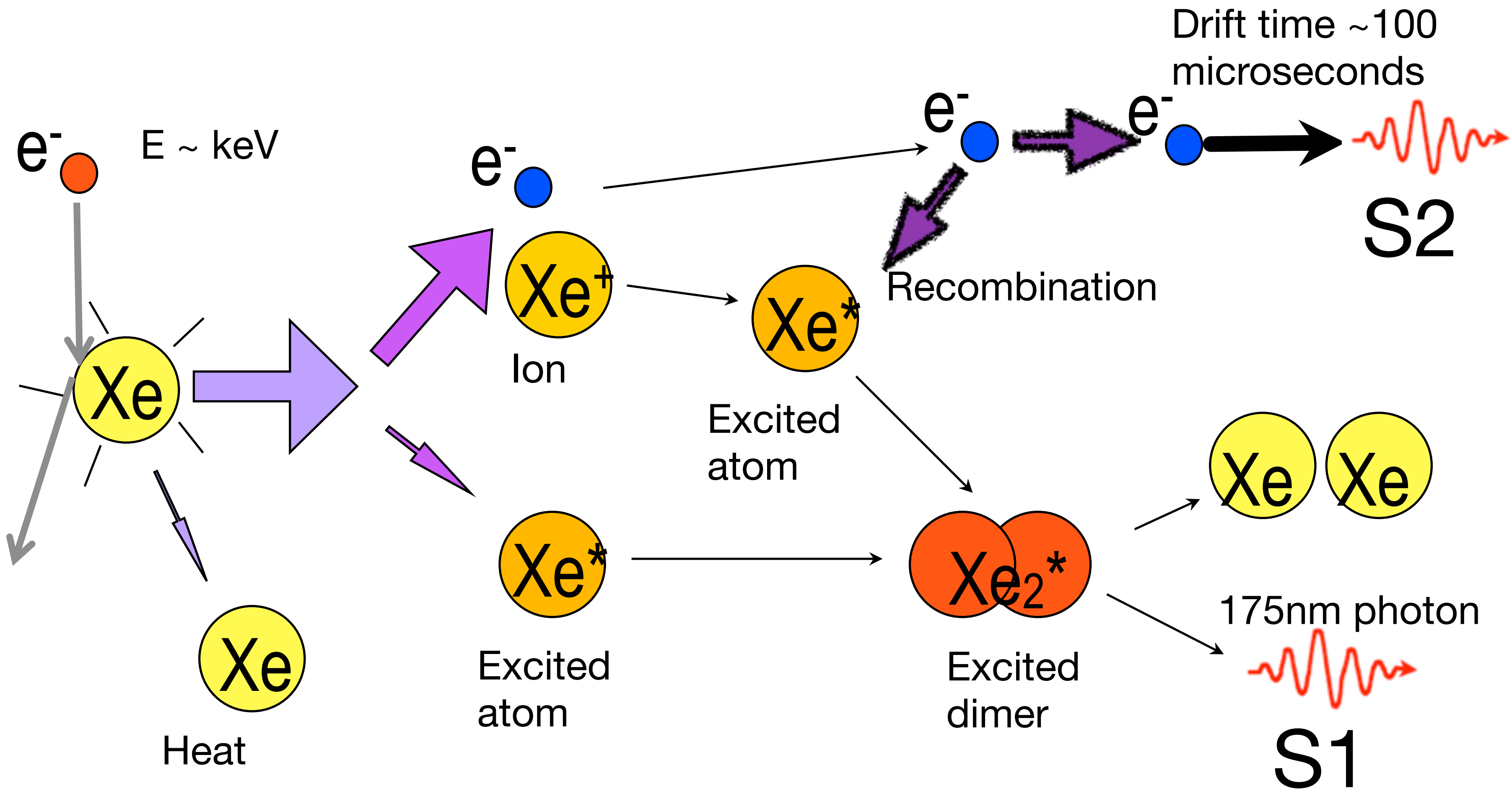


Figure: Gibson/Shutt

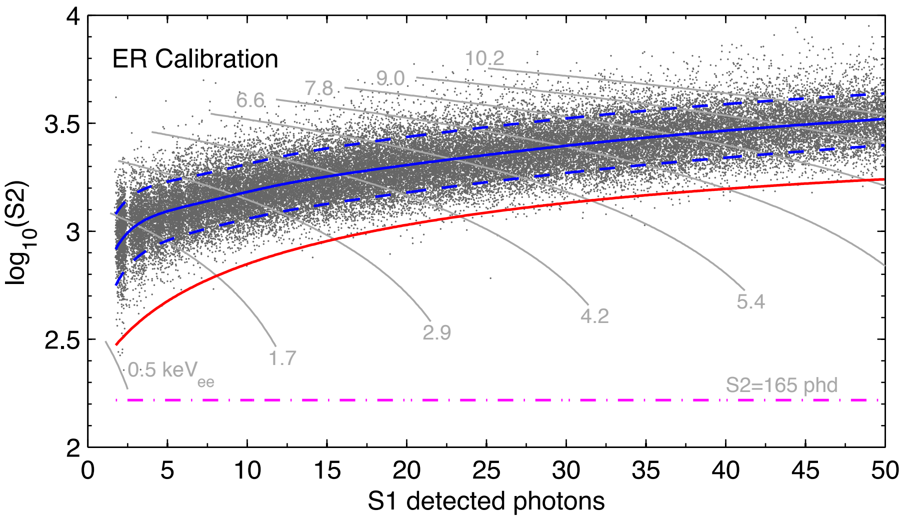
Background and Signal Calibrations

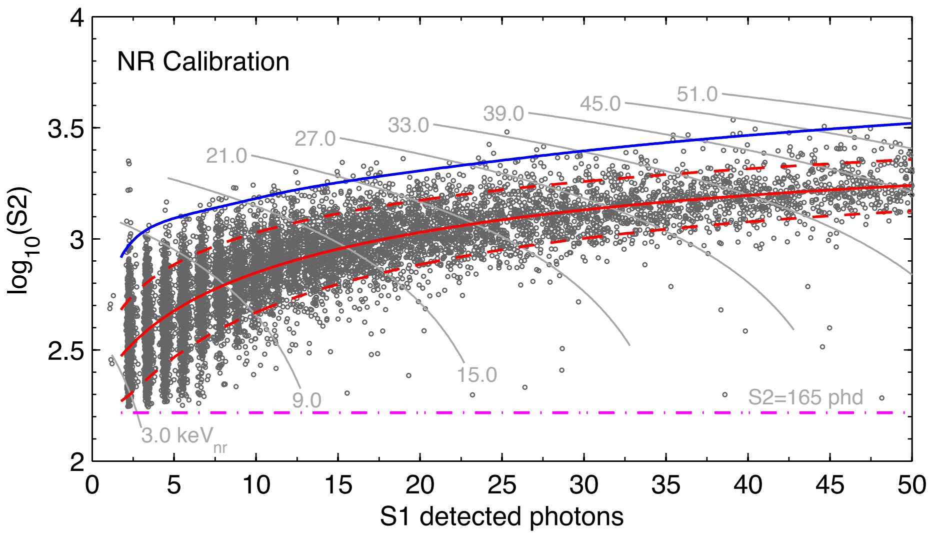
Background Events

- Electron Recoil (ER)
- Higher charge-to-light ratio
- Calibrate using high-statistics tritium dataset (165,863 events)

Signal Events (WIMP-like)

- Nuclear Recoils (NR)
- Lower charge-to-light ratio
- Calibrate using D-D neutrons
  - *In-situ* nuclear recoil (NR) calibration

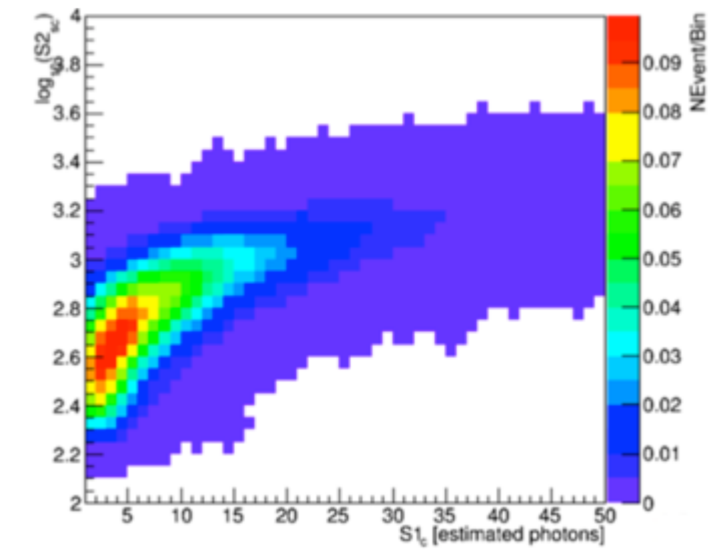




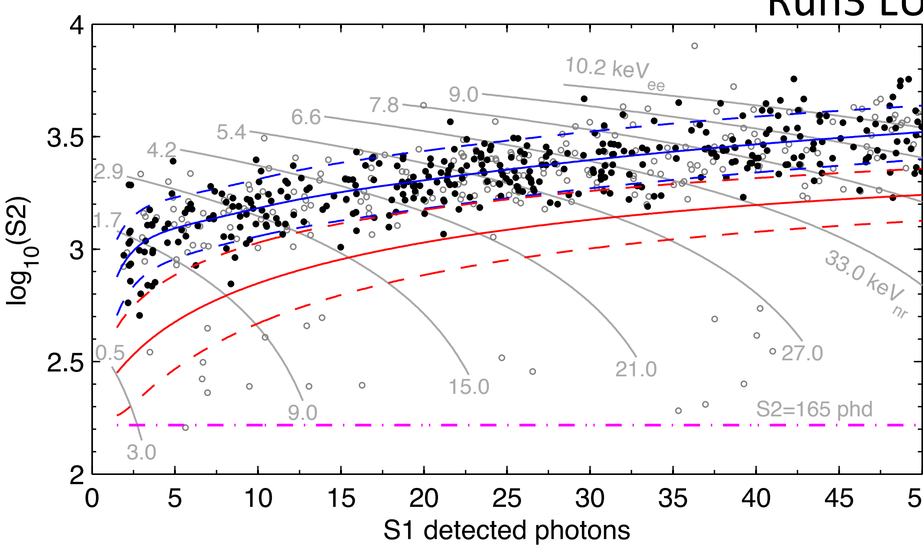
Profile Likelihood Ratio (PLR)

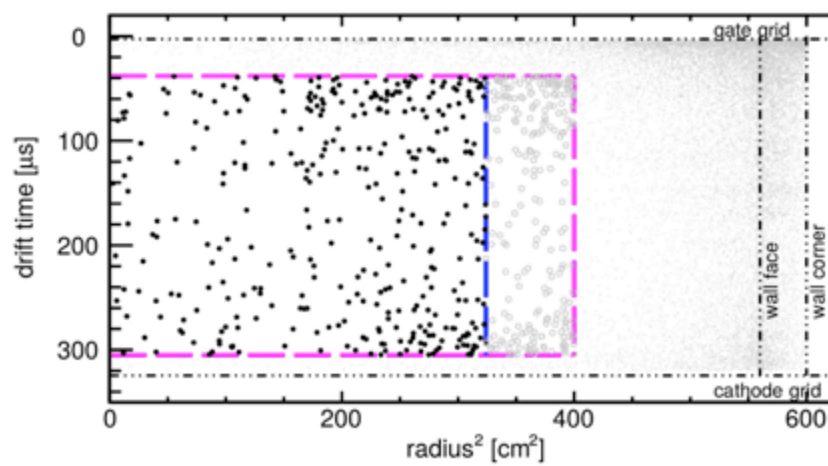
- Compares data to background distribution and signal distributions for different mass models
- Function of S1, S2, radius, and depth
- Fit for systematic parameters (derived from DD data)
- More powerful after calibrations

i.e. Expected signal distribution for a 33 GeV WIMP



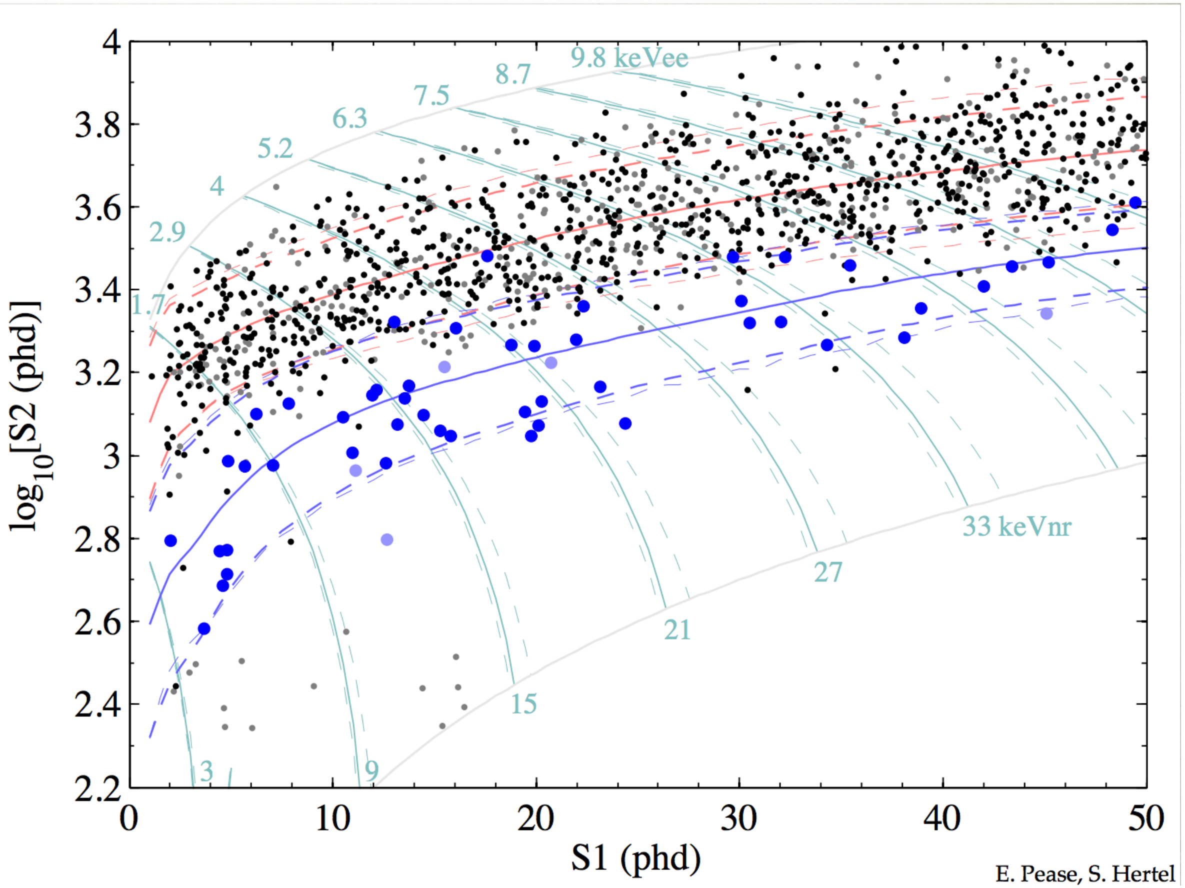
Run3 LUX data





LUX Run 4 Data

- Exposure: 332 live days, increased by a factor of >3
- Blinded via "Salting": inject fake signal events into data
  - Allows scrutiny of individual events without bias
- Electric field non-uniformities: Split detector into 16 bins, each with field-specific ER and NR response model



E. Pease, S. Hertel

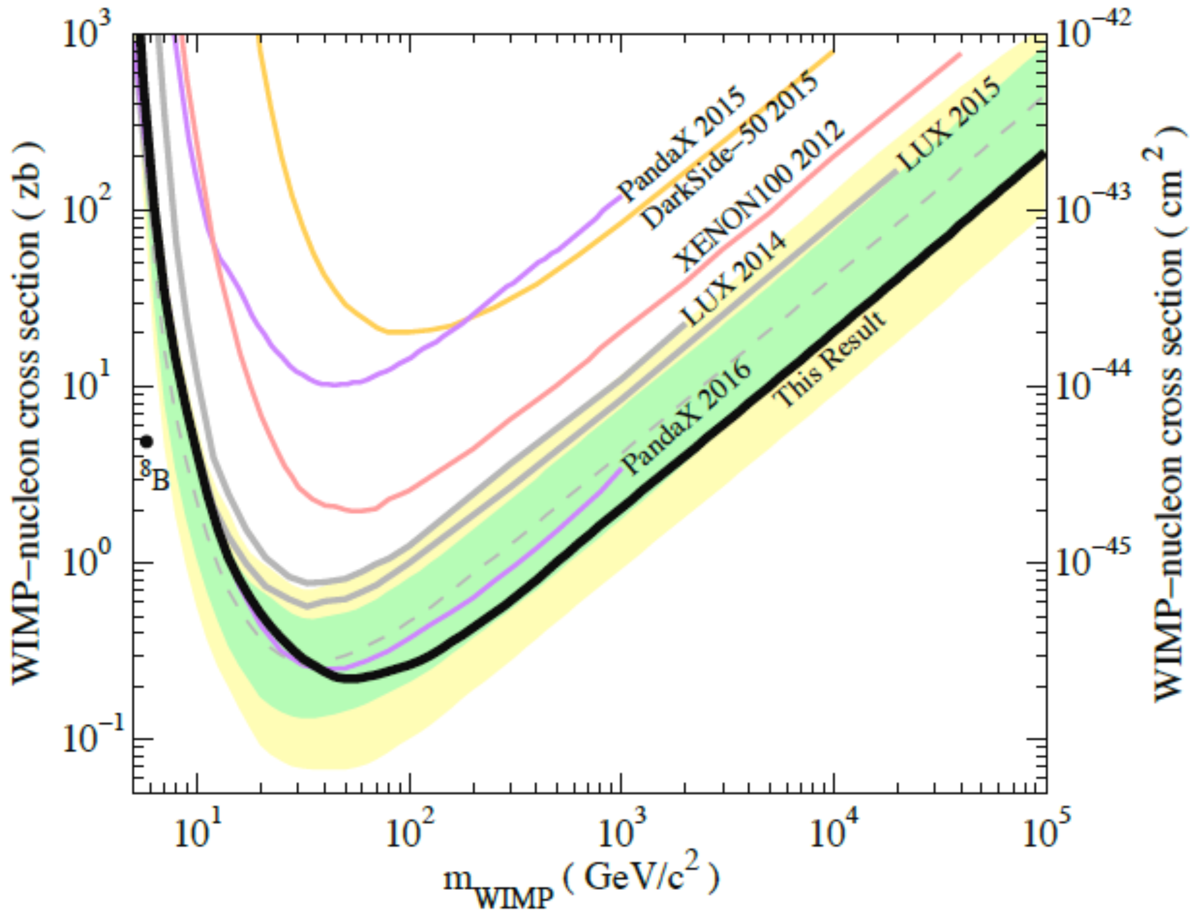
Black: Bulk Events

Grey: within 1 cm of boundary

Blue: salt events (unknown during analysis)

Red and blue curves are ER and NR bands respectively

LUX Run4 Limits



- Black: Observed Limit
- Green and yellow bands represent 1 and 2 sigma ranges (background only trials)

Upgrading to LUX-Zeplin

Led Zeppelin cover

Alternative LZ Logo

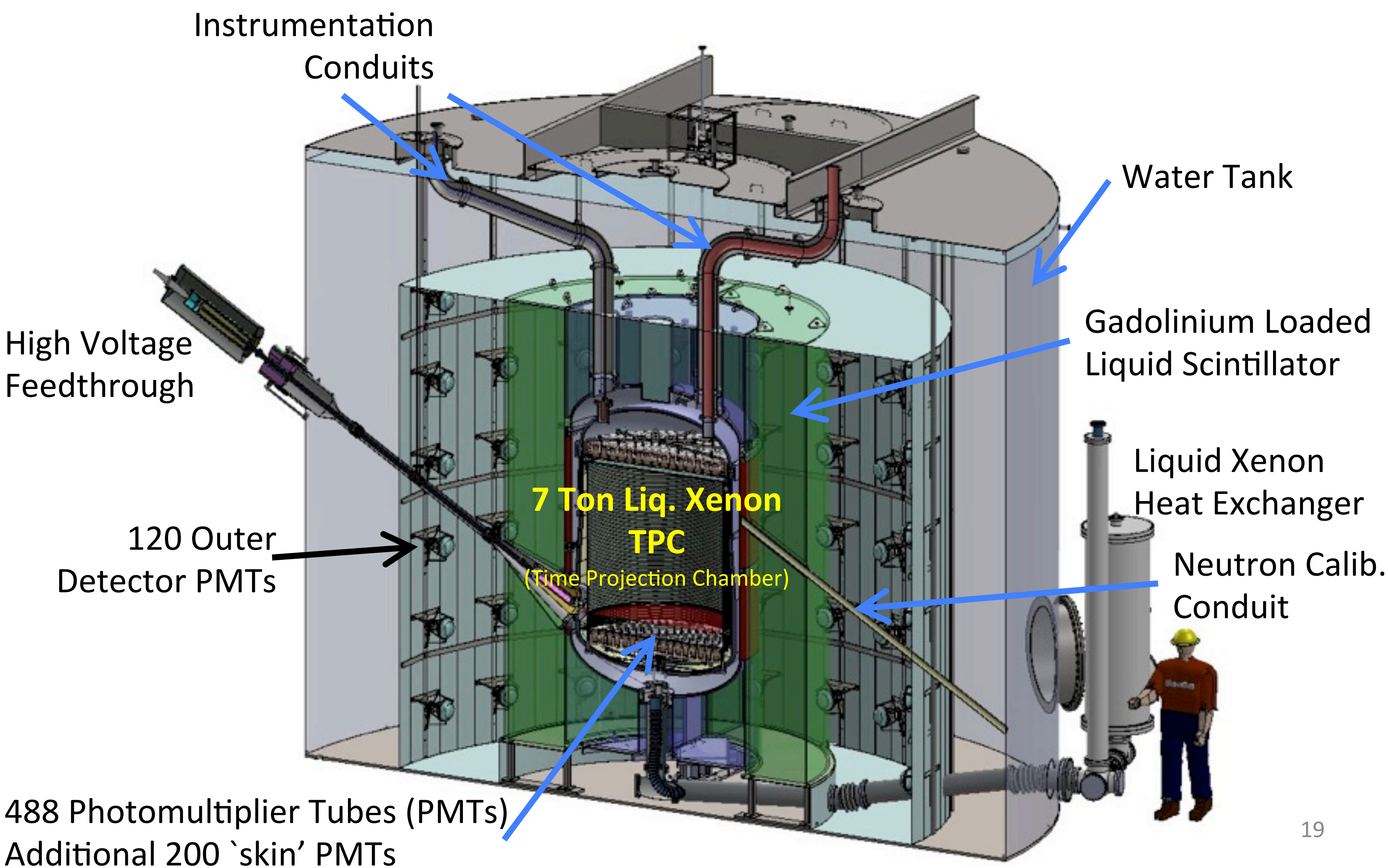
Credit: Matt Gifford

LZ Overview

- Combining technology from LUX and ZEPLIN
- Scale Up: Factor of 50
- Turn on in early 2020

Total Xe mass – 10 T
WIMP Search Mass – 5.6 T

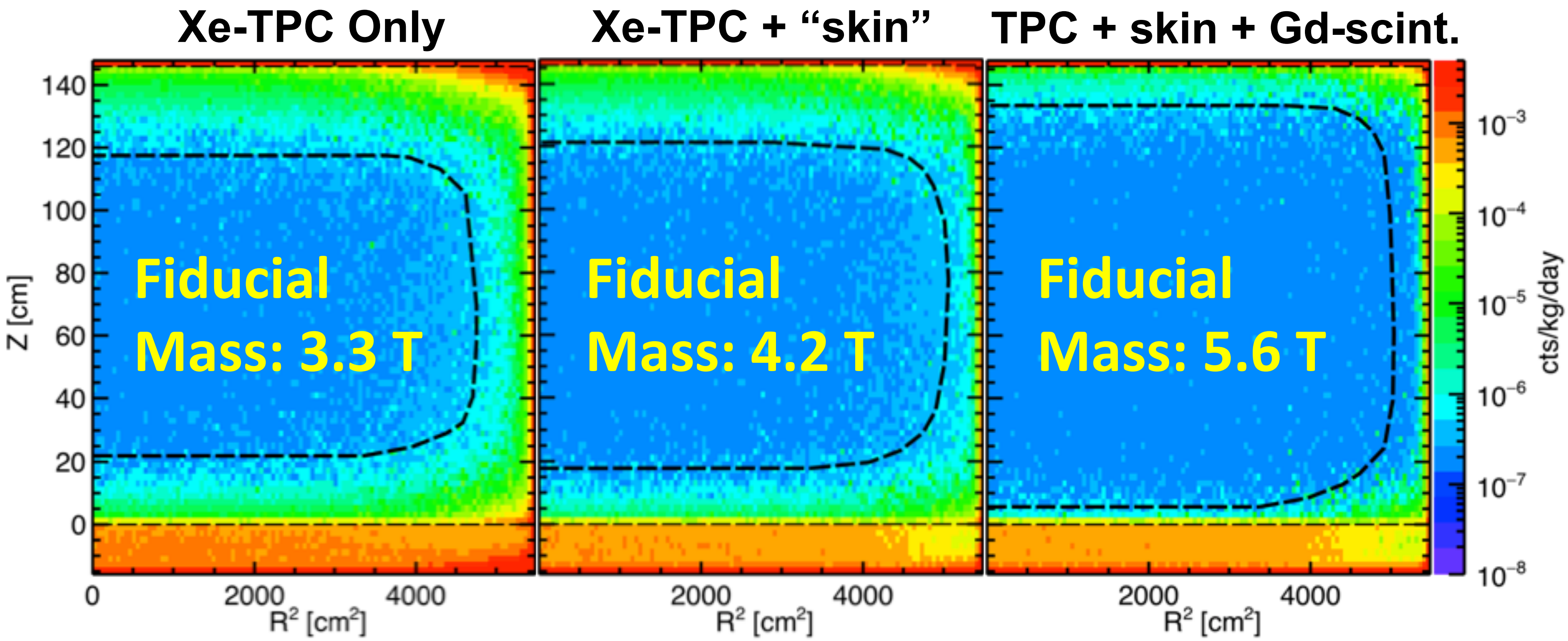
LZ Detector


Instrumentation
Conduits
Water Tank
High Voltage
Feedthrough
Gadolinium Loaded
Liquid Scintillator
Liquid Xenon
Heat Exchanger
7 Ton Liq. Xenon
TPC
(Time Projection Chamber)
120 Outer
Detector PMTs
Neutron Calib.
Conduit
488 Photomultiplier Tubes (PMTs)
Additional 200 `skin' PMTs

How to Maximize the WIMP target mass?

- Two-component outer detector:
  - Gd-loaded scintillator
  - instrumented Xenon "skin"
  - tag neutrons and gammas

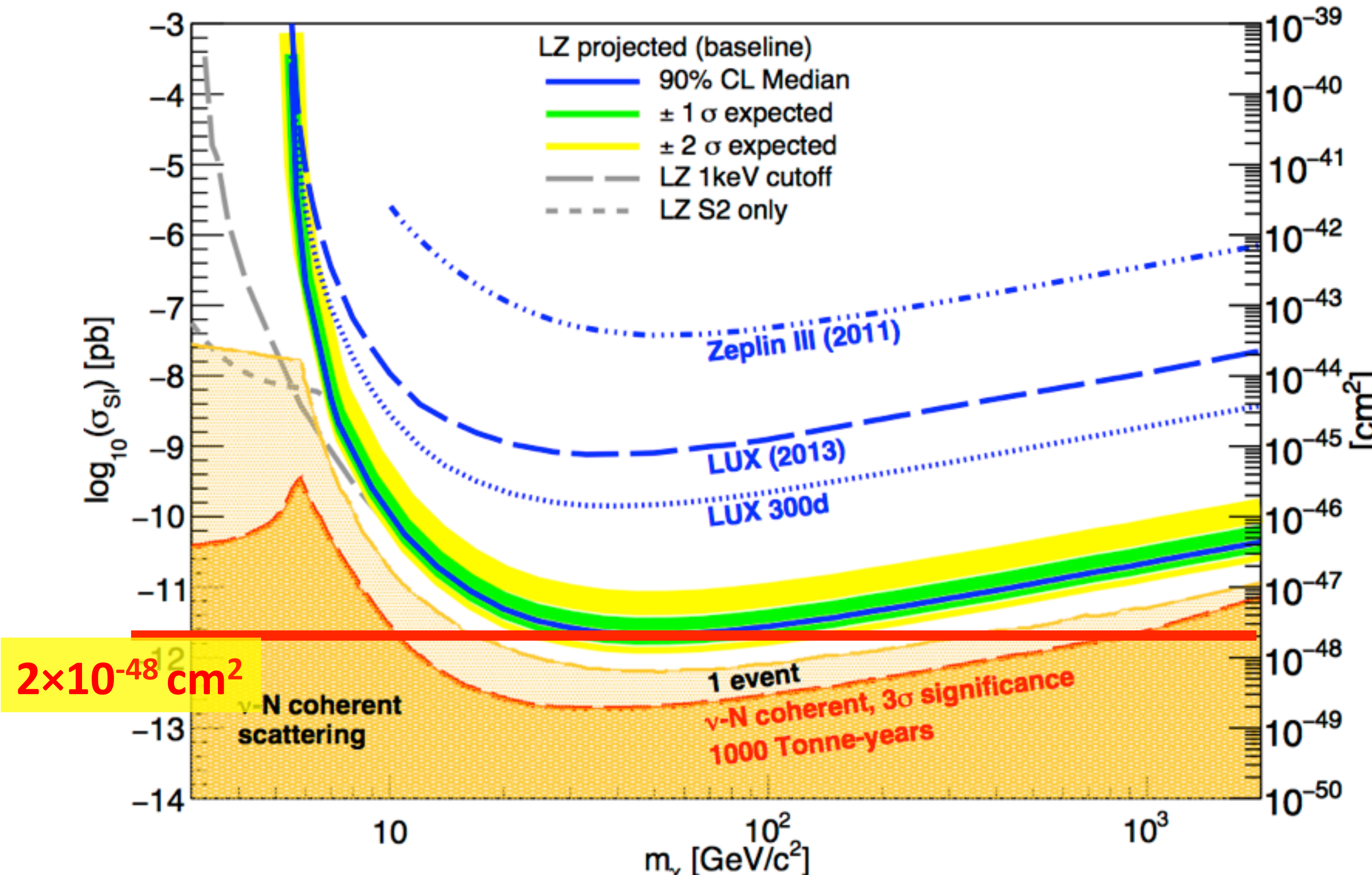
Powerful independent measure of backgrounds
→ discovery potential!



Turn on in early 2020

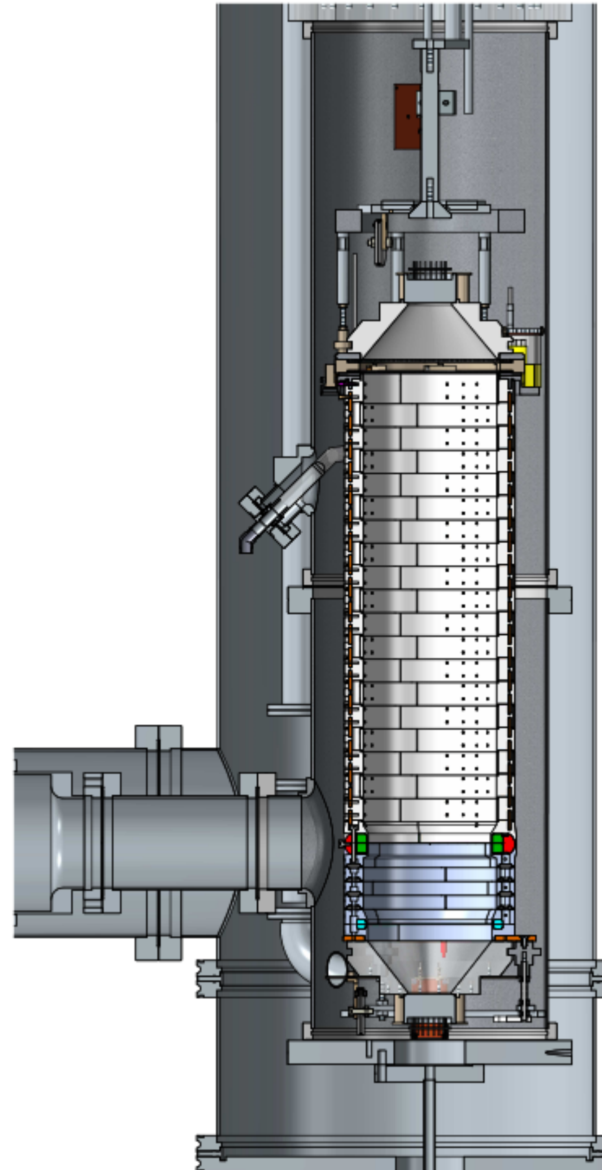
Projected Sensitivity – Spin Independent

(LZ 5.6 Tons, 1000 live days)



LZ R&D at SLAC

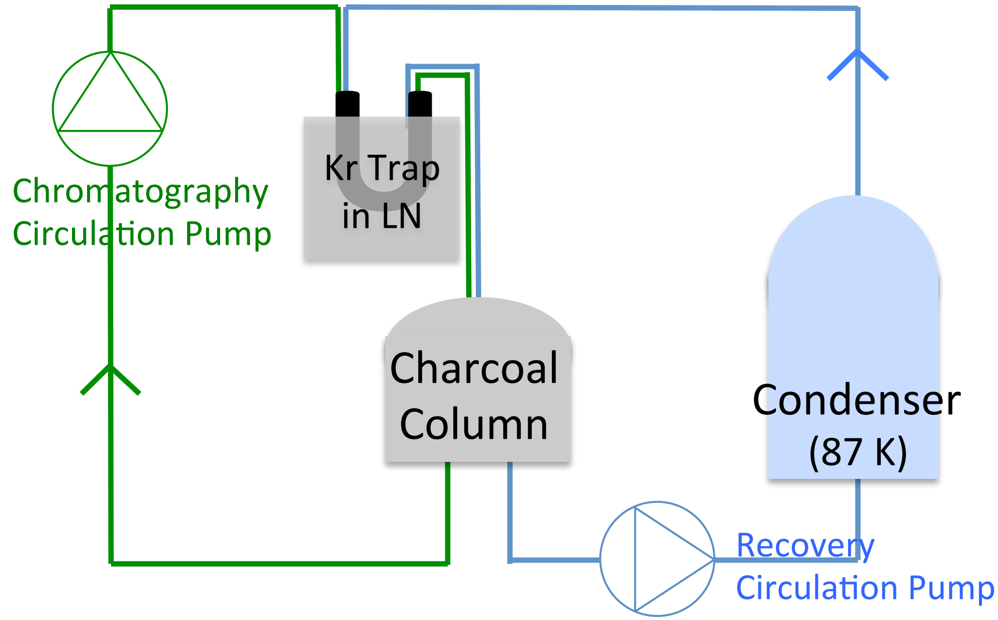
- 120 kg LXe
- Main goals:
  - HV tests
  - Gas handling and purification
  - Vessel for heat exchangers
  - Testing other LZ subsystems

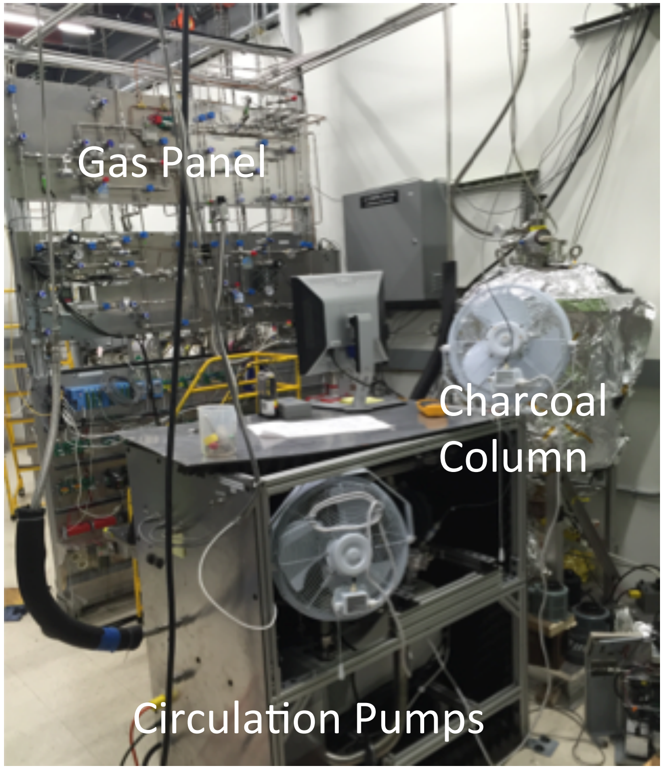


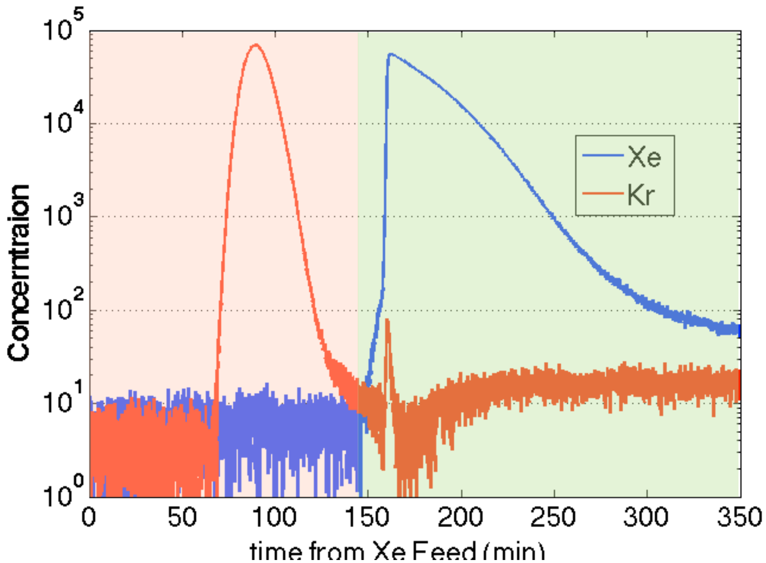
Kr85 background and removal

>1000 ppt → 3 ppt → 0.015 ppt

(Commercial Xe) (LUX) (LZ Goal)

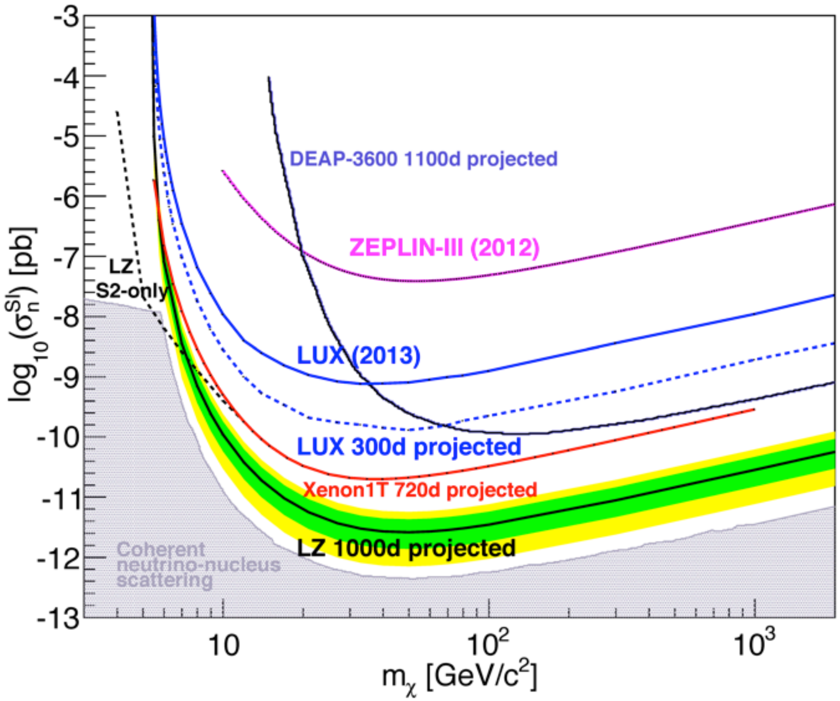






Conclusions

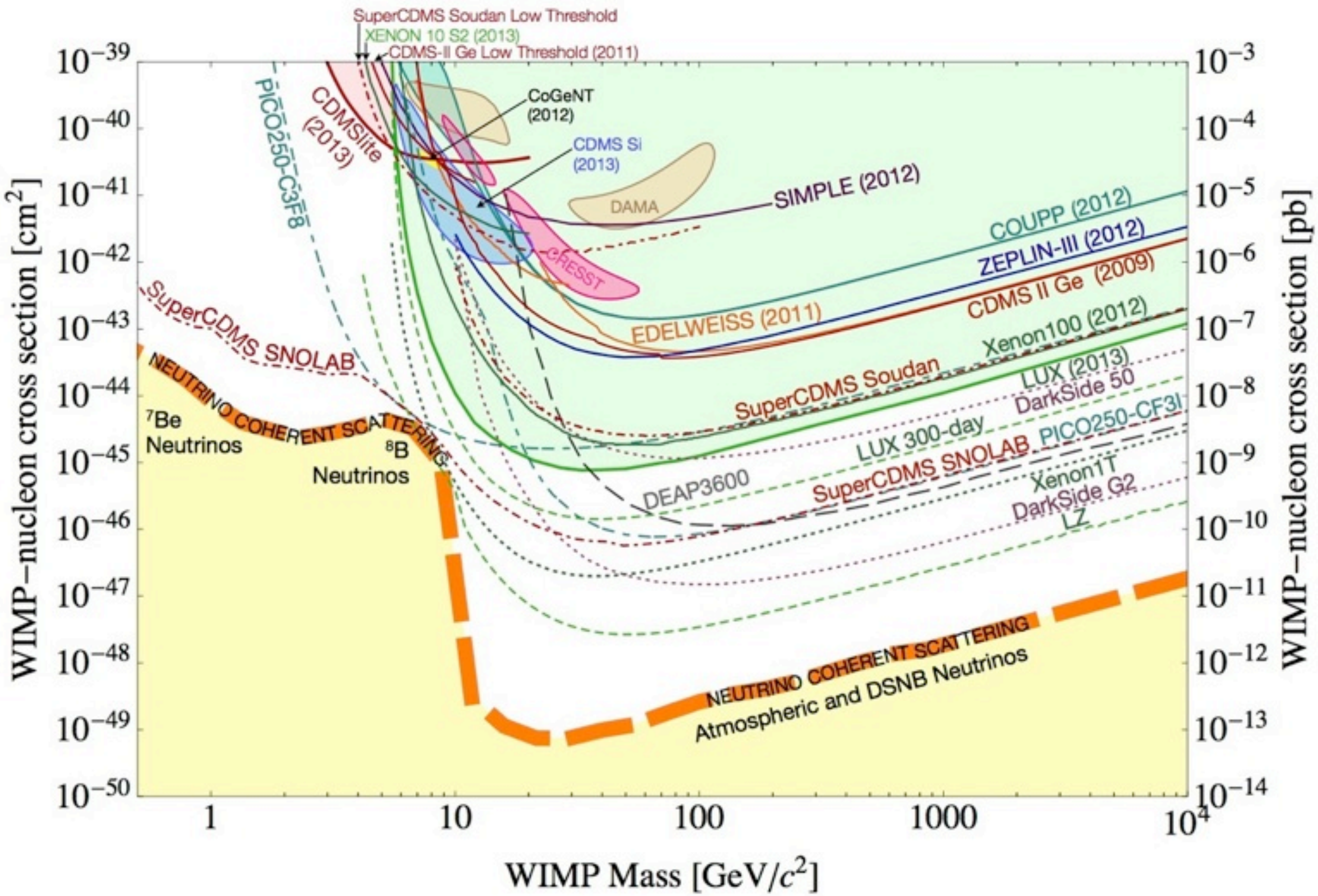
- New limits from LUX just announced a few weeks ago!
- LZ benefits from excellent LUX calibration & techniques
- Extensive prototyping underway here at SLAC
- Exciting time for Dark matter direct detection, real discovery potential!
  - Xenon1T, DEAP-3600 coming soon!



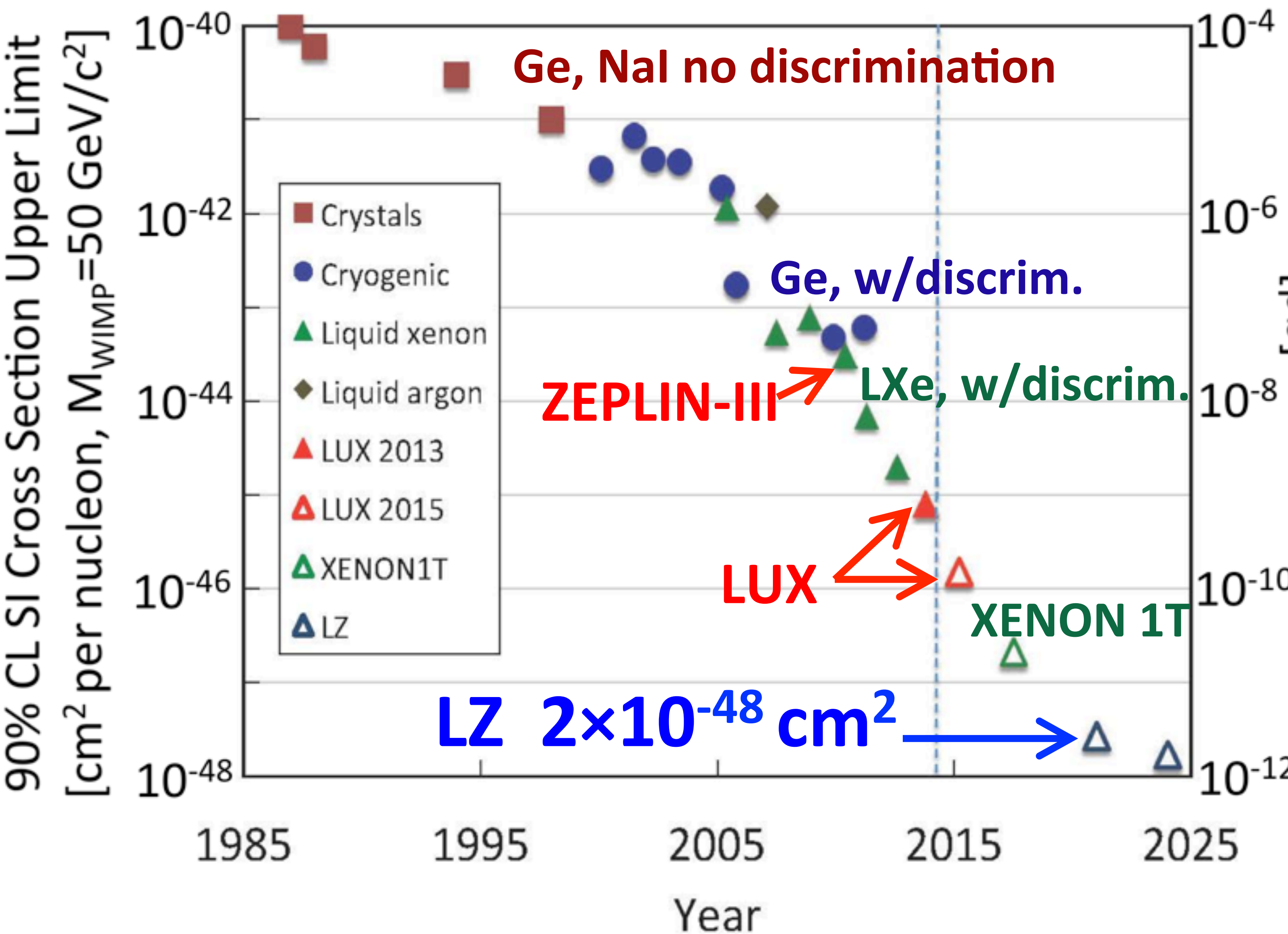
Backup

All limits – from snowmass

(out of date)



Time Evolution of Direct Detection Sensitivities



WIMP Miracle

A happy coincidence implied that new physics at the TeV scale with appropriately weak cross section leads to a dark matter relic

$$\Omega_x h^2 = \frac{3\cdot 10^{-27} cm^3/s}{\langle \sigma_A v \rangle} \approx 0.12$$

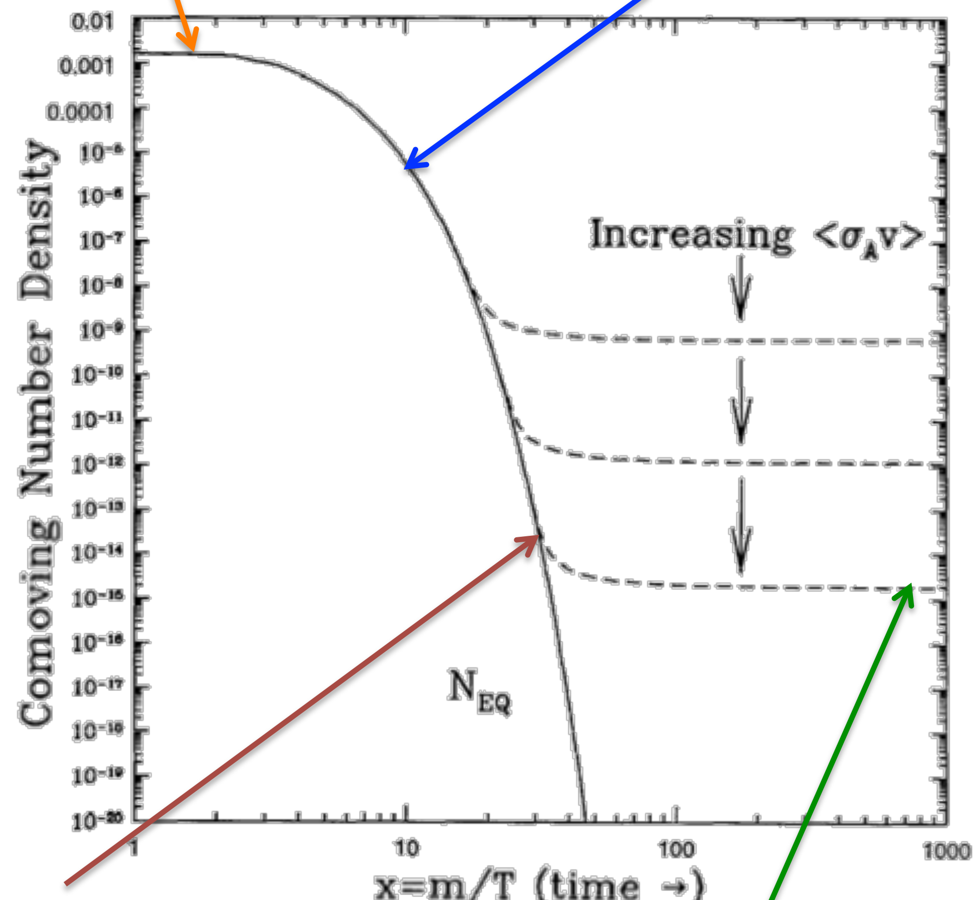
$$\Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}$$

1. Flat region. Constant density. Equal production and annihilation.

$n_{eq} \sim T^3$

2. Exponential suppression as temperature falls below mass of dark matter particle.

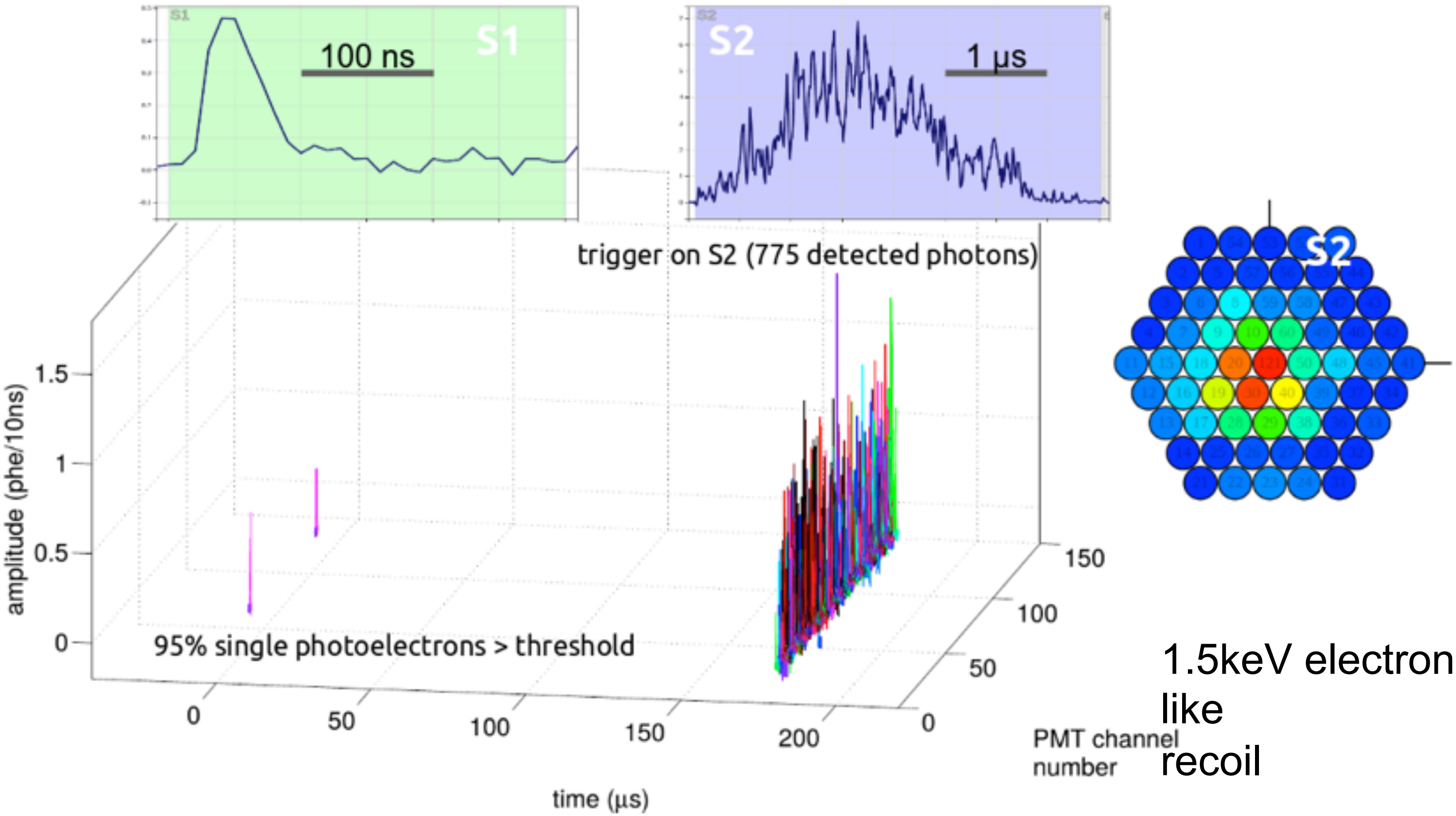
$n_{eq} \sim (m/T)^{3/2} e^{-m/T}$



3. Turn over as annihilation rate decreases, becoming smaller than the expansion rate.

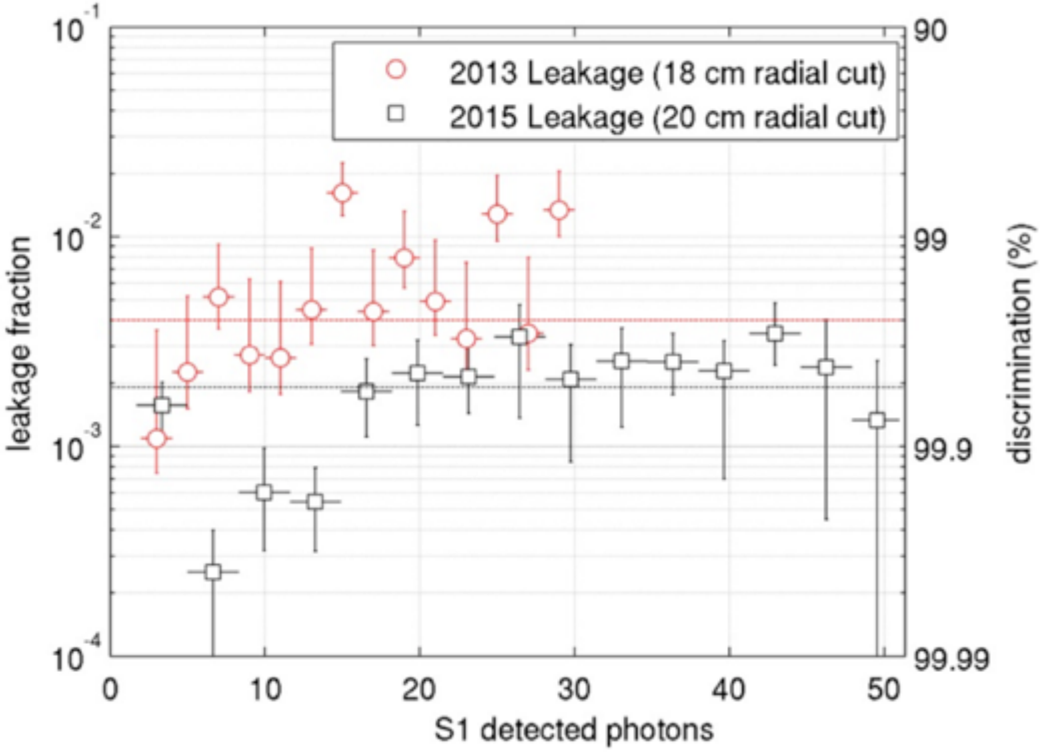
4. Relic abundance remains. Larger cross-sections keep annihilations occurring for longer.

Waveform Example in LUX



1.5keV electron-like recoil

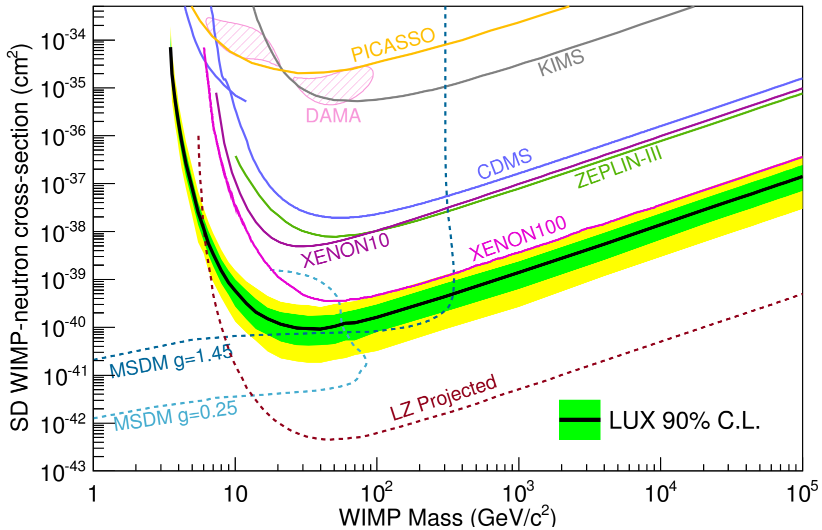
LUX ER leakage into NR



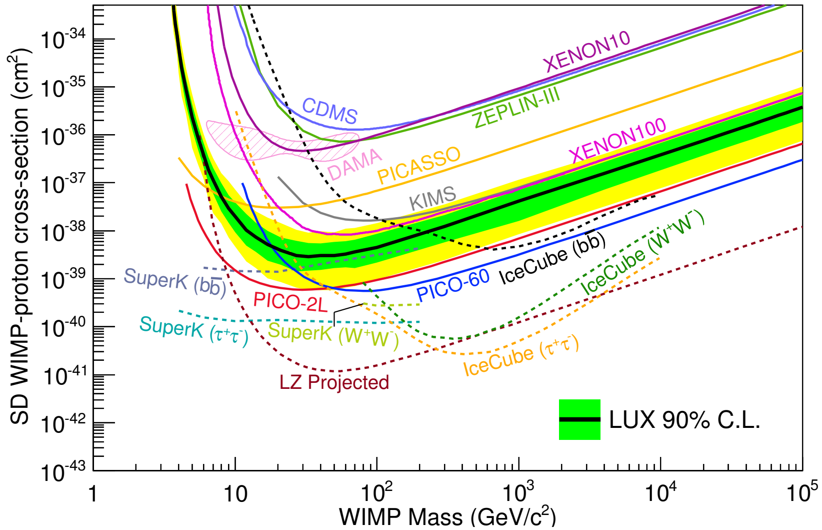
(arXiv:1602.03489)

Spin Dependent Limits (run3)

- More sensitive to neutron than proton coupling
  - Odd-neutron Xenon isotopes dominant, meaning spin carried by unpaired neutron



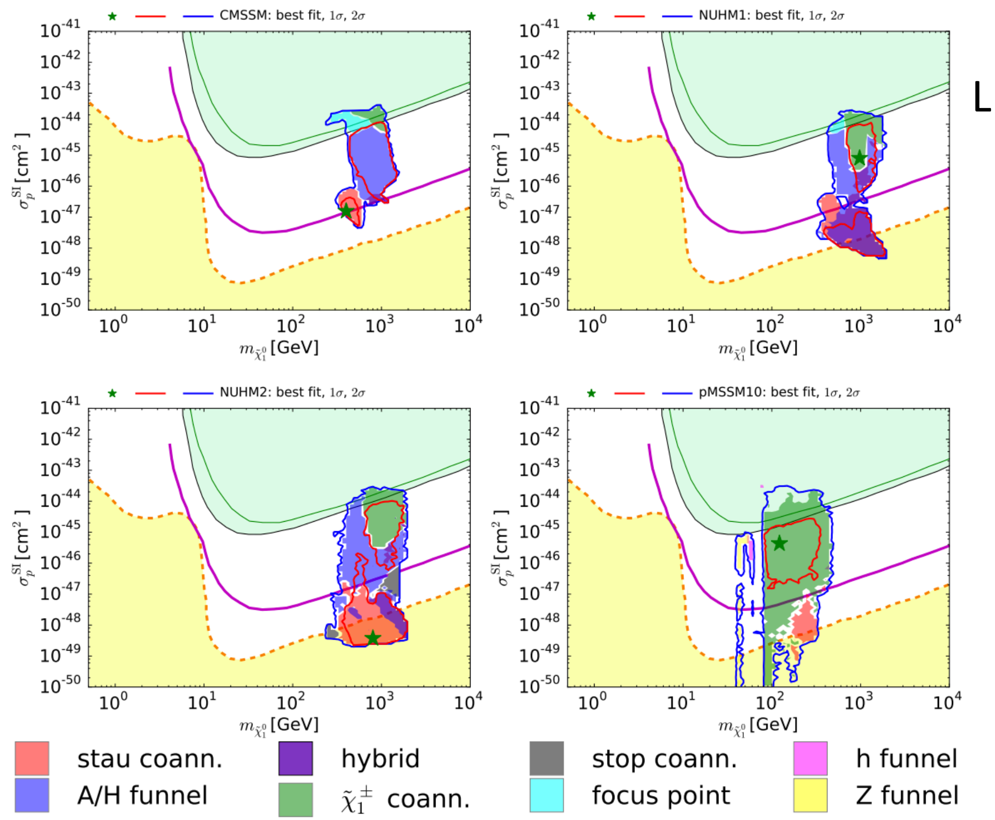
WIMP-neutron Cross-section



WIMP-proton Cross-section

Direct Detection + LHC predictions

- From arxiv:1508.01173



LUX2013

LZ

Figure 8. *The $(m_{\tilde{\chi}_1^0}, \sigma_p^{SI})$ planes in the CMSSM (upper left), the NUHM1 (upper right), the NUHM2 (lower left) and the pMSSM10 (lower right). The red and blue solid lines are the $\Delta\chi^2 = 2.30$ and 5.99 contours, and the solid purple lines show the projected 95% exclusion sensitivity of the LUX-Zepelin (LZ) experiment [35]. The green and black lines show the current sensitivities of the XENON100 [33] and LUX [34] experiments, respectively, and the dashed orange line shows the astrophysical neutrino 'floor' [37], below which astrophysical neutrino backgrounds dominate (yellow region).*