EFFECTIVE FIELD THEORY SEARCH RESULTS FROM THE LUX RUN 4 DATA SET, AND CONSTRUCTION OF THE LZ SYSTEM TEST PLATFORMS

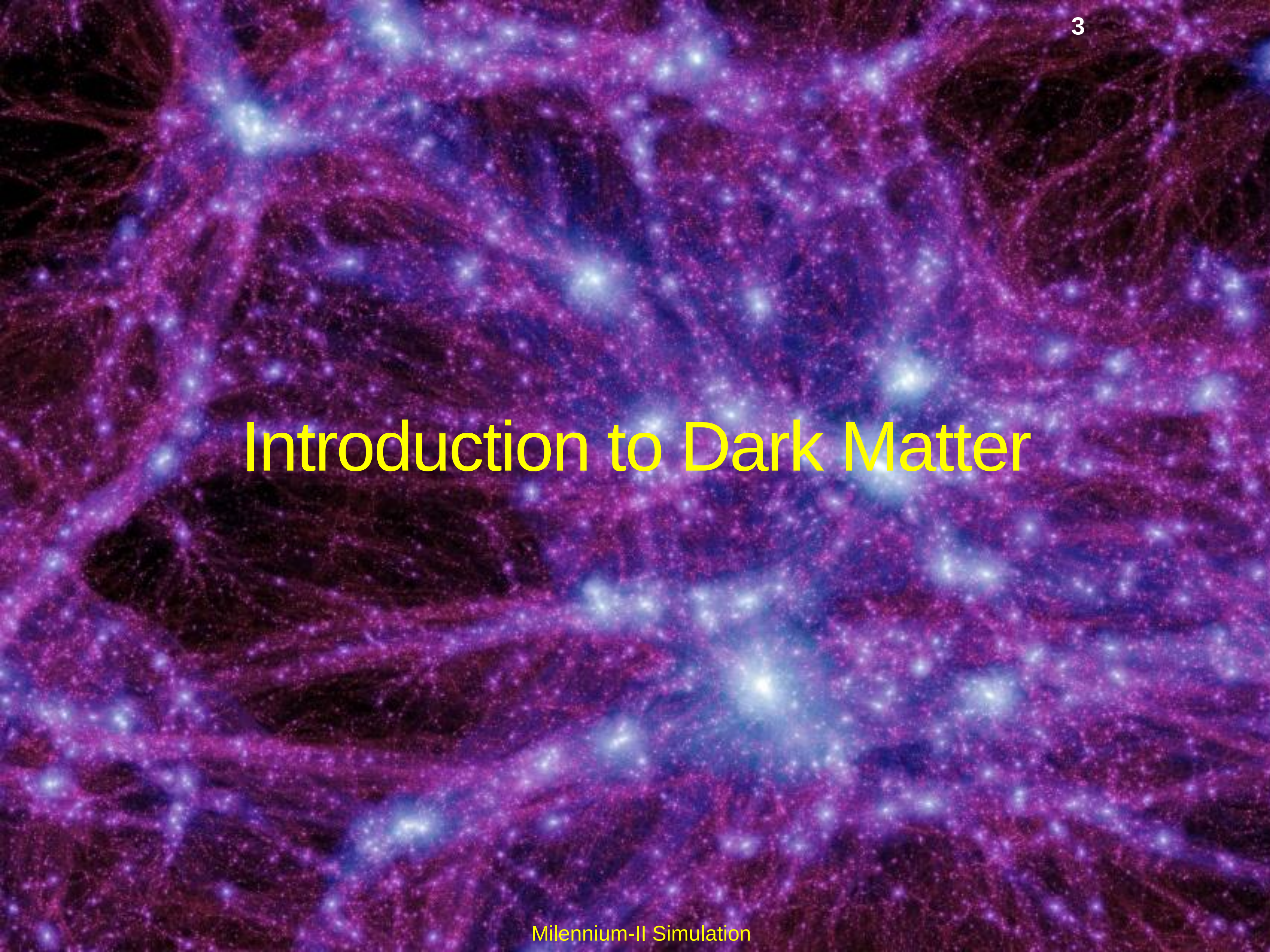
Shaun Alsum

Outline

- Intro to Dark Matter
- The LUX detector
- The LUX Run 4 Spin-Independent Search
- The LZ System Test at SLAC
- The LUX Run 4 Effective Field Theory Analysis

I will explain my specific role more clearly during each section.

Introduction to Dark Matter



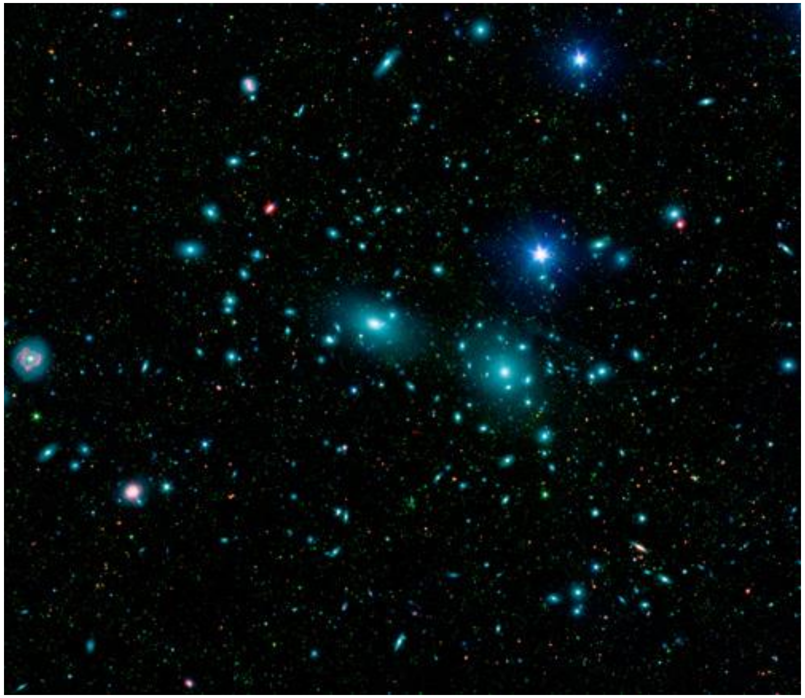
Milennium-II Simulation

Dark Matter – The Beginning (ish): The Coma Cluster

- Fritz Zwicky measured the doppler shifts of ~1000 galaxies in the Coma Cluster.
- Mass of the cluster can be determined via the virial theorem

$$2\langle T \rangle = \langle U \rangle \longrightarrow \langle T \rangle = \frac{1}{2} M \langle v^2 \rangle$$

- Not consistent with the mass determined via luminosity measurements.
- Large amount of missing mass



The Coma Cluster.

Dark Matter – Evidence: Rotation Curves

- Vera Rubin studied Rotation curves
- Galactic rotation curves plateau or increase as one passes beyond the edge of the visible matter.

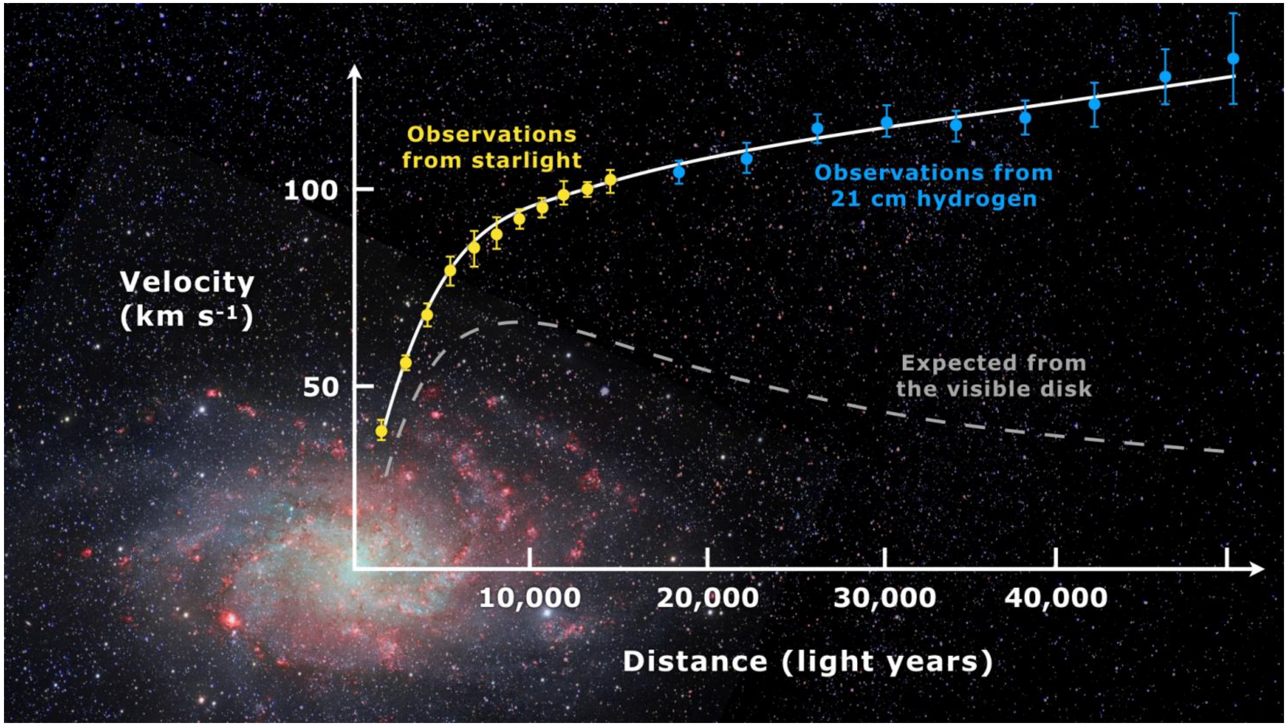
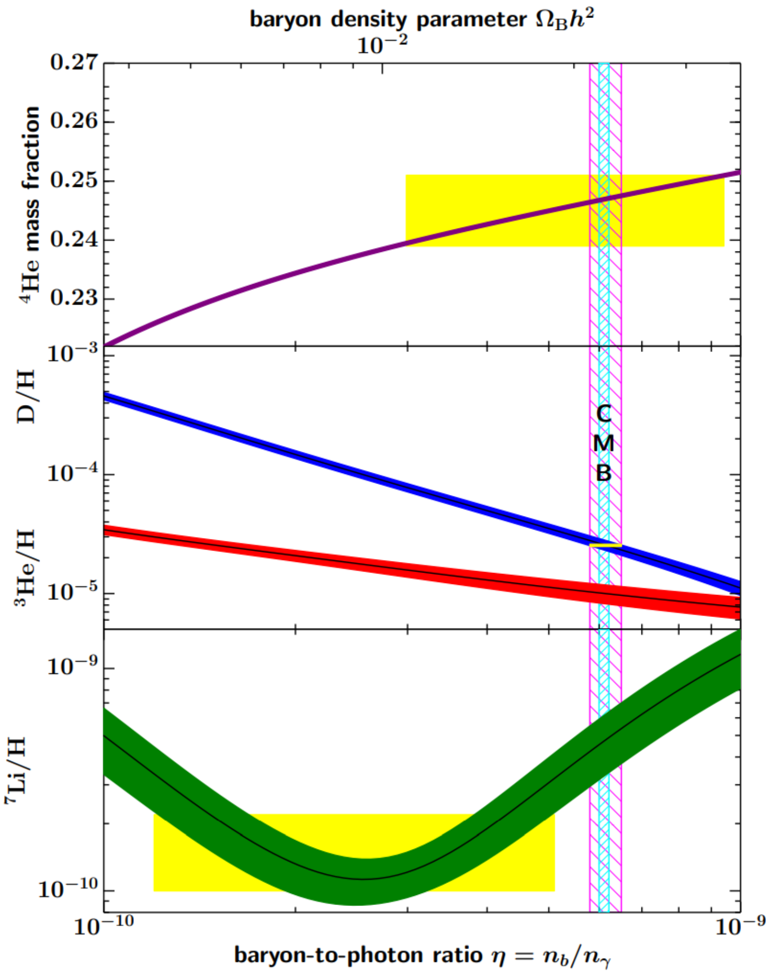


Figure by Mario De Leo - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=74398525

Observed and Predicted rotation curves of the galaxy M33.

Dark Matter – Evidence: BBN and CMB



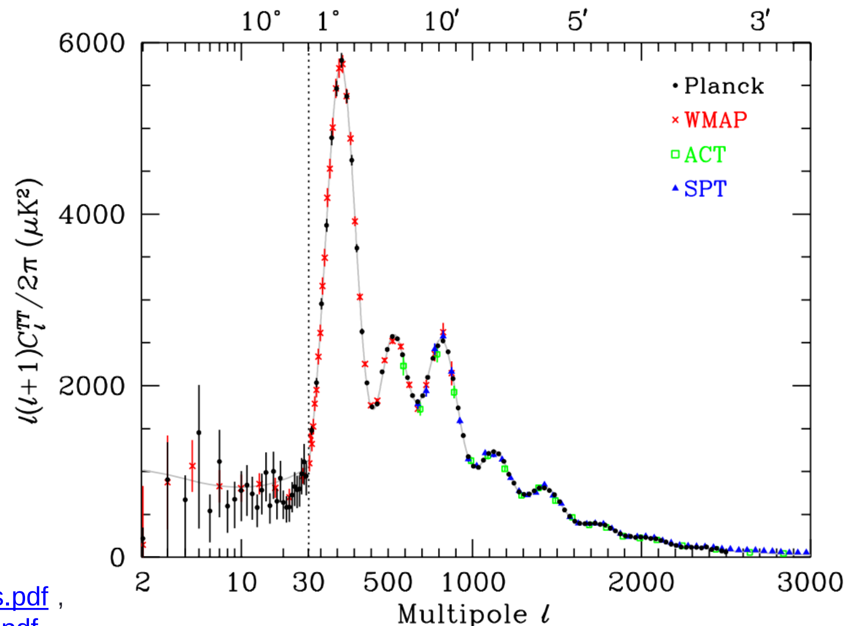
Matter density of the universe is measured at

$$\rho_m = .34 \times 10^{-30} \frac{g}{cm^3} \quad \rightarrow \Omega_m = 0.30$$

Relative density of light elements is sensitive to baryon density, measurements indicate

$$\rho_b \approx 0.05 \times 10^{-30} \frac{g}{cm^3} \rightarrow \Omega_b \approx 0.044$$

Shape of the CMB power spectrum also sensitive to the ratio of cold (non baryonic) dark matter



Figs from PDG BBN and CMB Reviews:https://pdg.lbl.gov/2020/reviews/rpp2020-rev-bbang-nucleosynthesis.pdf , https://pdg.lbl.gov/2020/reviews/rpp2020-rev-cosmic-microwave-background.pdf

Dark Matter - Properties Checklist

Dark matter requirement shortlist:

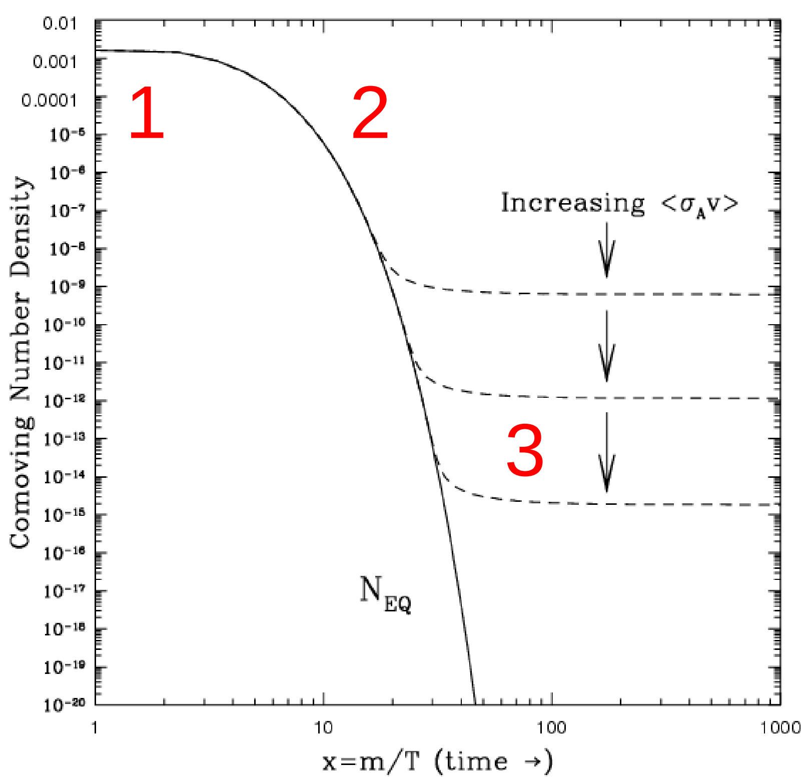
- Little electromagnetic interaction
- Stable over universal timescales
- Cold (slow moving/clumpy)
- Non-baryonic

Matching candidate: Weakly Interacting Massive Particle (WIMP)

- New (to us), Stable, Particle (non-baryonic)
- Interacts only via weak force and gravity
- ~ > few GeV, so slow moving

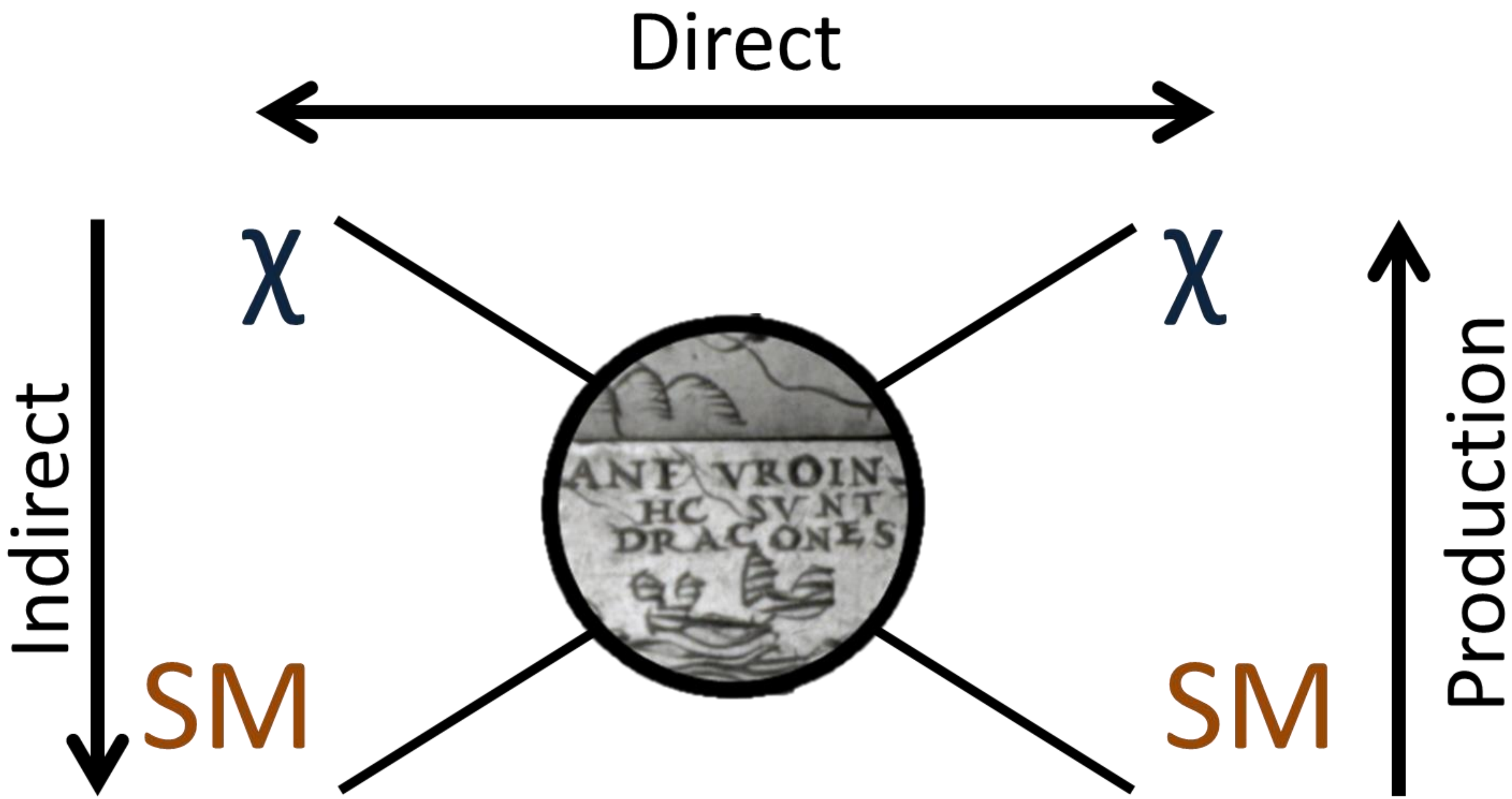
Dark Matter – WIMP Freeze Out

- Assume a DM particle (X) in thermal equilibrium in early universe
  $X + X \leftrightarrow SM + SM$ (1)
- Expansion occurs, no longer enough energy for SM particles to annihilate to X
  $X + X \rightarrow SM + SM$ (2)
- Expansion continues, dilute enough that X no longer find each other (3)
- $\Omega_X h^2 \approx \frac{3\times10^{-27}\frac{cm^3}{s}}{\langle\sigma v\rangle}$
- $\langle\sigma v\rangle \approx 3\times10^{-26}\frac{cm^3}{s}$
- $v = O(c)$ so $\sigma = O(10^{-34}\ cm^2)$



E. Kolb and M. Turner, The Early Universe. Westview Press, 1994.:

Dark Matter – Detection Methods



Dark Matter – Detection Methods

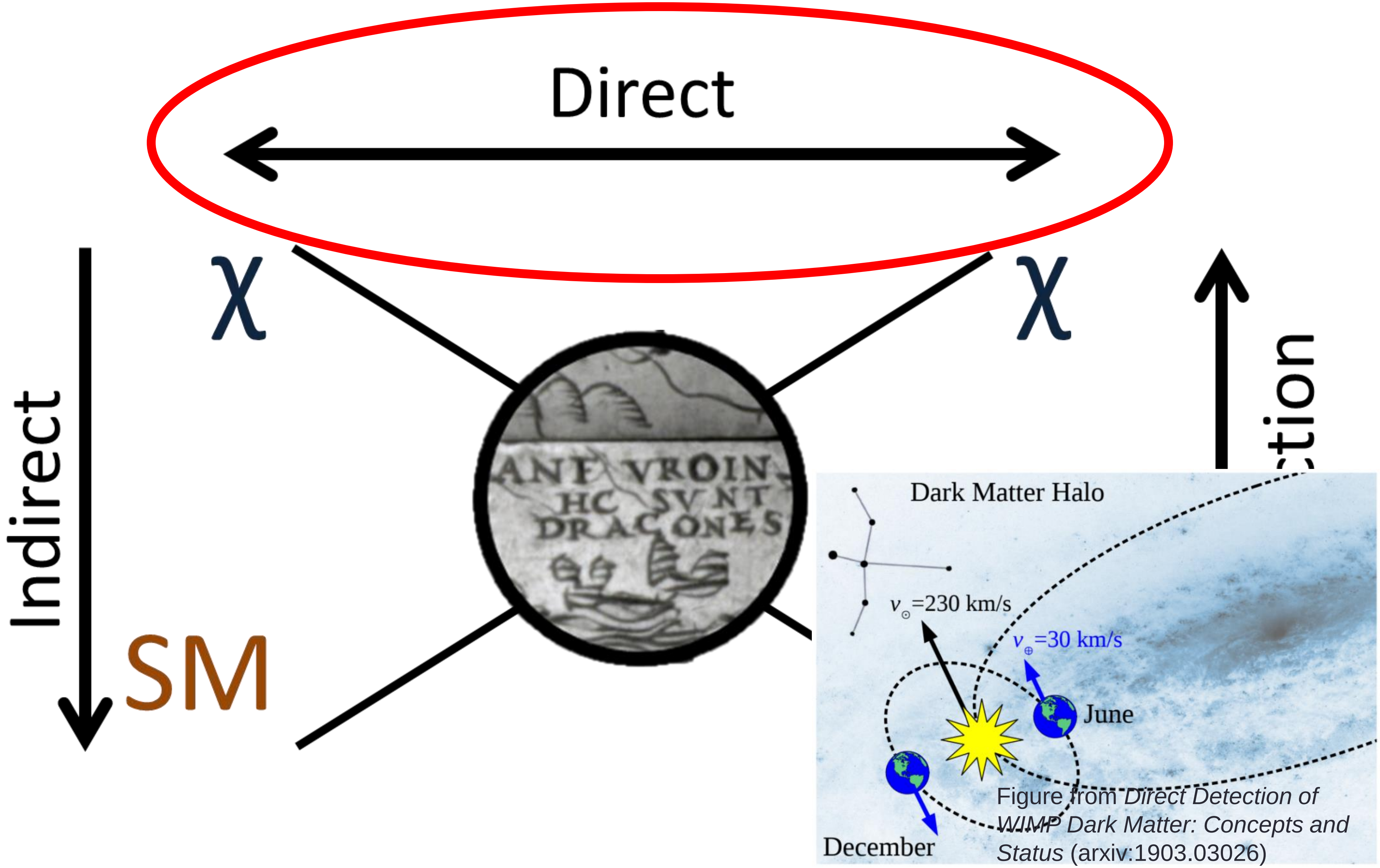


Figure from *Direct Detection of WIMP Dark Matter: Concepts and Status* (arxiv:1903.03026)

The LUX Detector

Projects

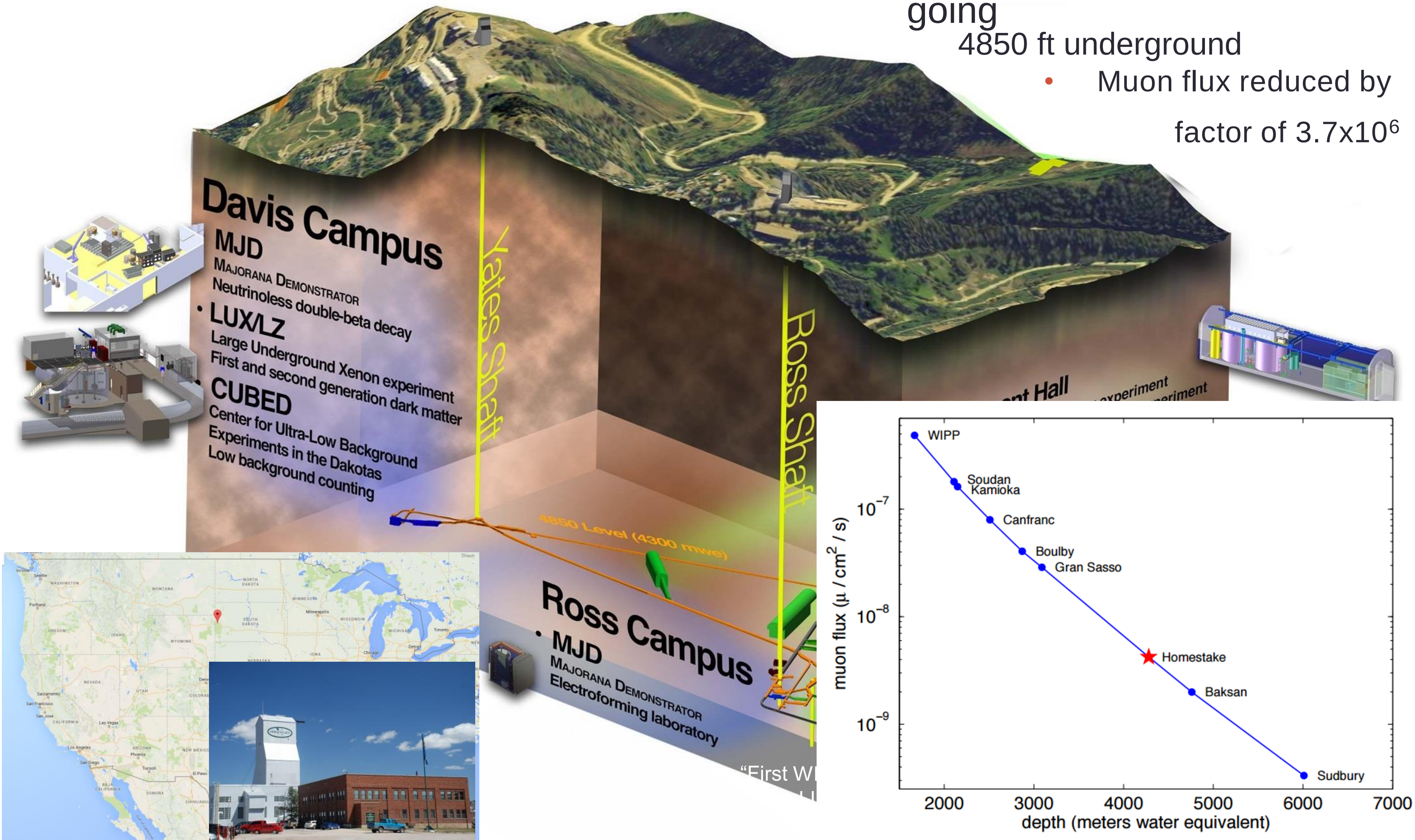
- The Large Underground Xenon (LUX) experiment
  - A dark matter direct detection experiment
- LZ - LUX-Zeplin
  - It's like LUX, but bigger…

Members of the LUX collaboration present at the Albany meeting. Oct, 2015

Members of the LZ collaboration present at the Livermore meeting. Jan, 2016

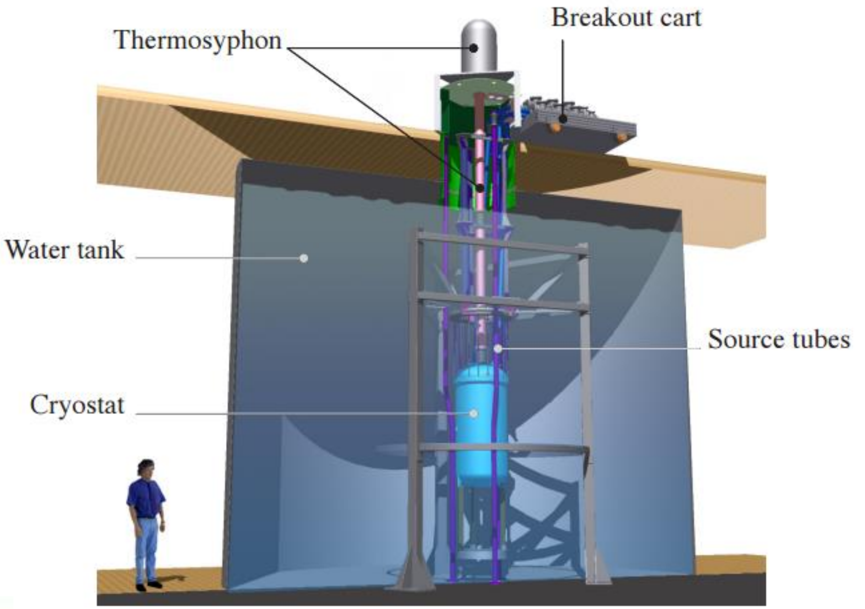
LUX - Shielding

- Escape Cosmic radiation by going
  - 4850 ft underground
    - Muon flux reduced by factor of 3.7×10^6



LUX - Shielding

- Water tank protects from:
  - muon-induced spallation
  - radioactivity from heavy metals in cavern walls
- Xe self-shielding protects from:
  - n from muon capture in water tank
  - Radiation from detector components



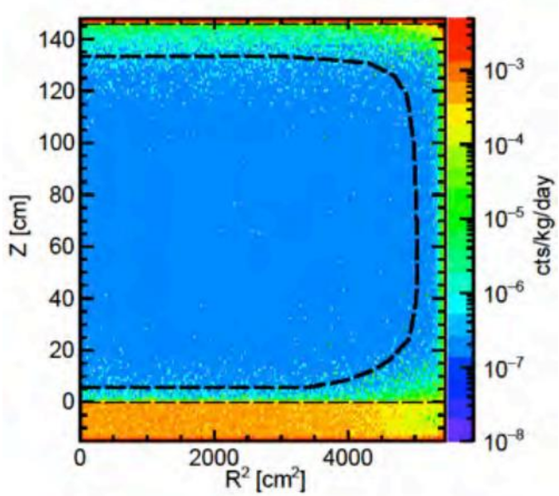
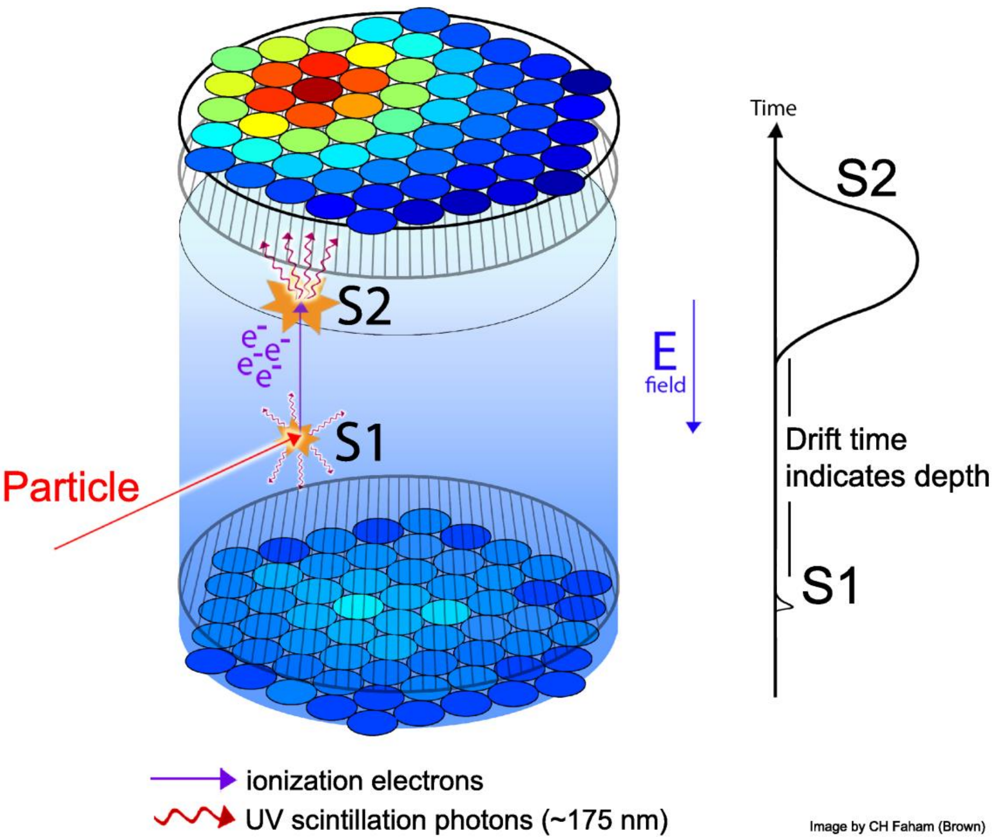


Figure from *The Large Underground Xenon (LUX) Experiment* (arxiv:1211.3788)

LUX – The Basics

- Cylindrical container with PMTs at the top and bottom
- Contains liquid scintillator target with gas layer
- Applied electric field to drift free electrons
- Particle interaction creates two signals:
  - Scintillation (S1) measured by PMTs
  - Charge (S2) caused by extraction of freed electrons measured by PMTs via electroluminescence
- XY position measured by S2 Pattern
- Z position measured by time delay between S1 and S2



LUX - Specific Design

- ~300 kg of Xe (100 active)
- 61 PMTs Top and Bottom
- 5 grids:
  - Bottom: Protects PMTs
  - Cathode: bottom of drift field
  - Gate: top of drift, bottom of extraction region
  - Anode: top of extraction region
  - Top: Protects PMTs
- Field shaping rings keep field uniform and vertical
- PTFE (Teflon) walls, liquid Xe-PTFE interface ~100% reflective at 175nm

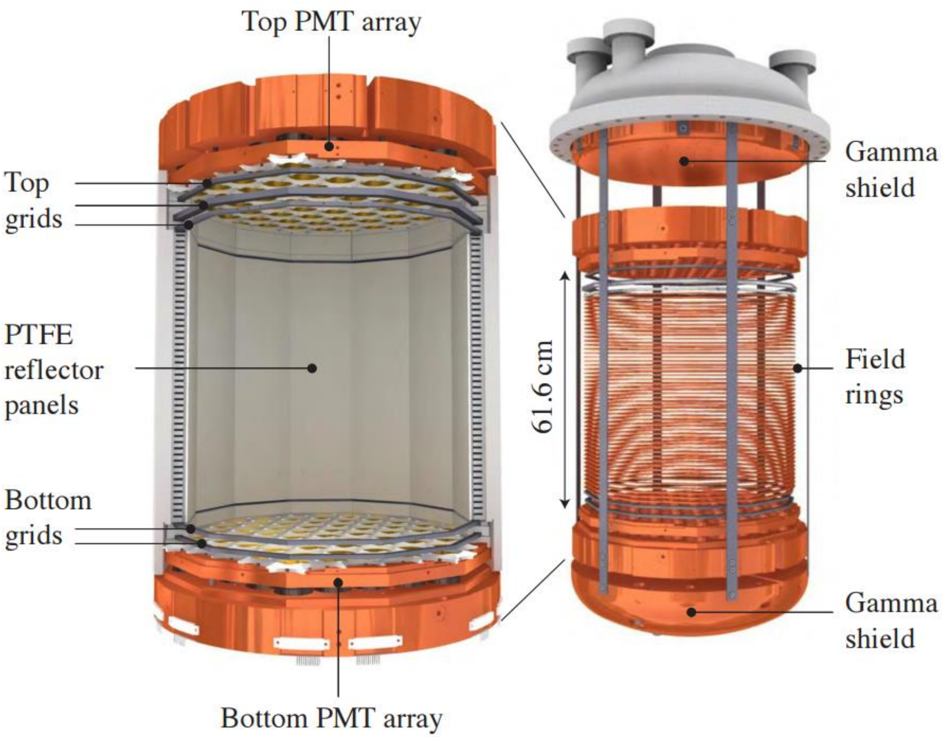


Figure from *The Large Underground Xenon (LUX) Experiment* (arXiv:1211.3788)

LUX – Xenon Scintillation

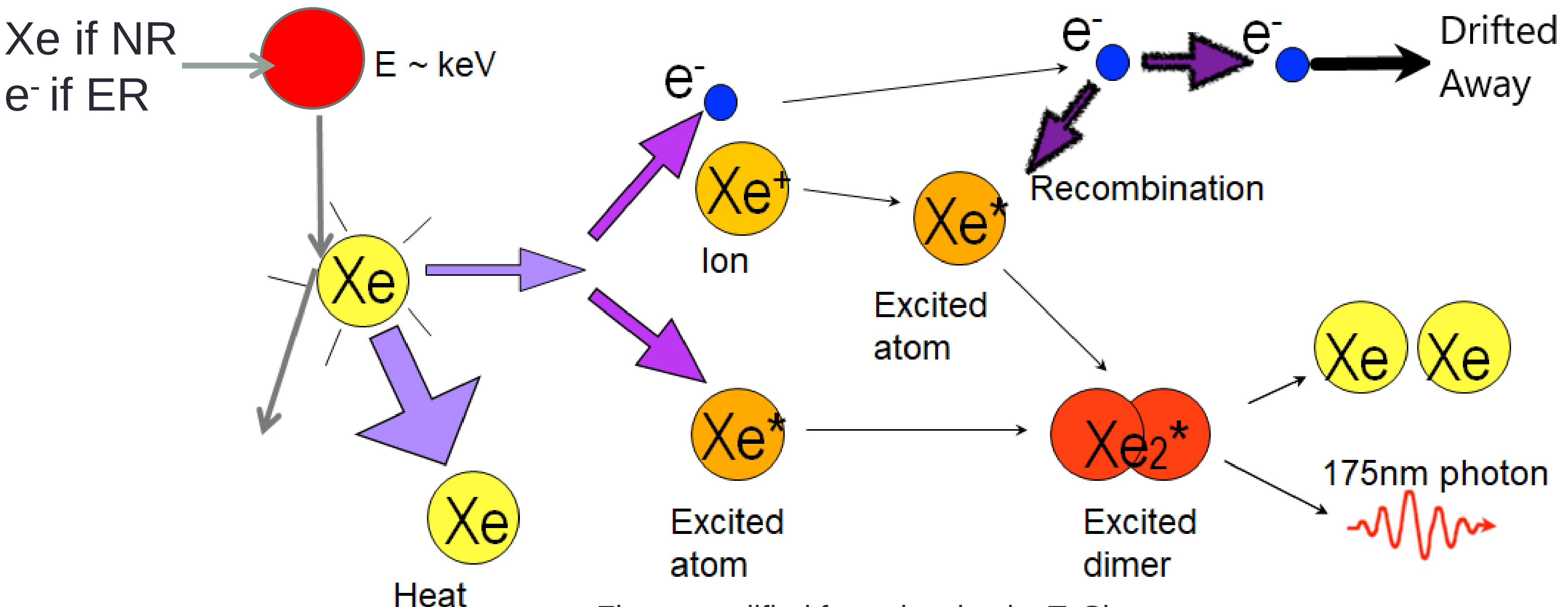
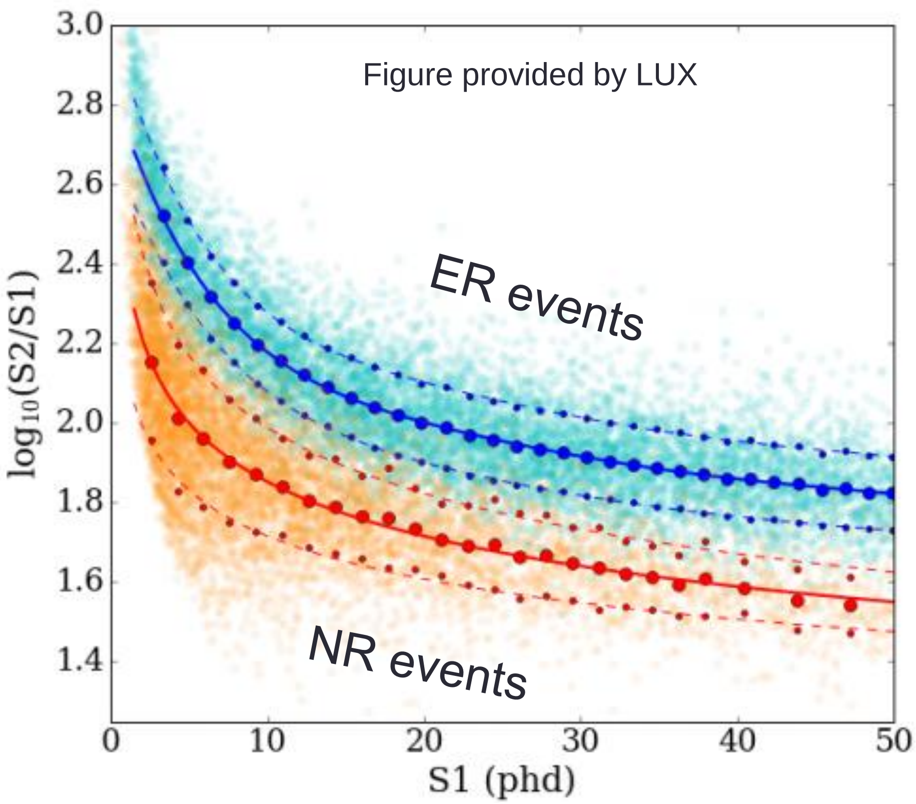


Figure modified from drawing by T. Shutt

$$
\begin{array}{ll}
\mathrm{Xe}^{+} + \mathrm{Xe} \rightarrow \mathrm{Xe_2}^{+} & \\
\mathrm{e}^{-} + \mathrm{Xe_2}^{+} \rightarrow \mathrm{Xe}^{*} + \mathrm{Xe} & \text{recombination} \\
\hdashline
\mathrm{Xe}^{*} + \mathrm{Xe} \rightarrow \mathrm{Xe_2}^{*v} & \text{excimer formation} \\
\mathrm{Xe_2}^{*v} + \mathrm{Xe} \rightarrow \mathrm{Xe_2}^{*} + \mathrm{Xe} & \text{relaxation} \\
\mathrm{Xe_2}^{*} \rightarrow \mathrm{Xe} + \mathrm{Xe} + \gamma & \text{photon emission}
\end{array}
$$

LUX - ER vs NR Discrimination

- Want to distinguish WIMPs from backgrounds…
- Events are separated into two categories:
  - Electron Recoil (ER): charged particles, photons
  - Nuclear Recoil (NR): neutral particles (like WIMPS)
- ERs produce more charge, NRs produce more light.
- S2/S1 ratio can distinguish.



LUX SI - Calibrations

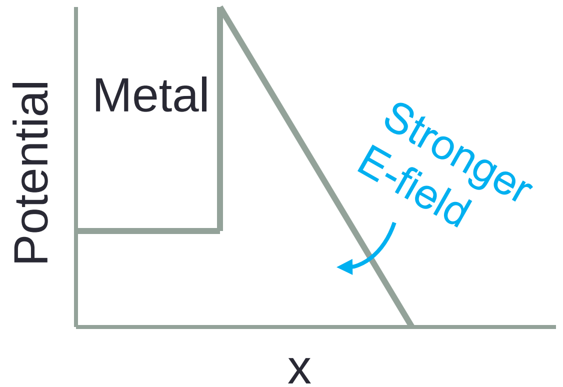
- Calibrate position dependent responses of the detector
  - ^{83m}Kr – internal conversion electrons
- Calibrate the ER recoil band
  - ^{3}H – low energy β decay
  - ^{14}C – higher energy β decay
- Calibrate the NR recoil band
  - neutrons from Deuterium-Deuterium (DD) fusion

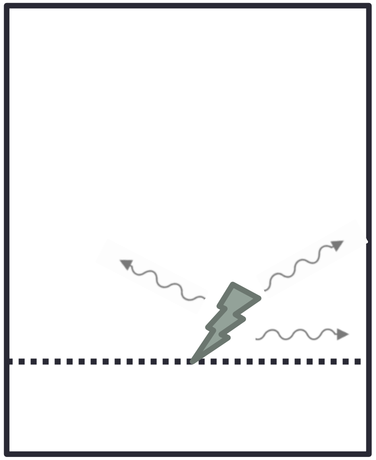
The LUX Run 4 Spin-Independent Search

Sep 11, 2014 – May 2, 2016
332 live days of WIMP Search data.

LUX – Electron Emission

- LUX operated at lower voltages than intended
- Excess field emission prevented voltage increases
- Attempt to solve via *Grid Conditioning*
  - Intentionally spark grids
  - Sparks occur preferentially near imperfections
  - Imperfections burn off
  - Process damaged PTFE making it susceptible to charge build-up





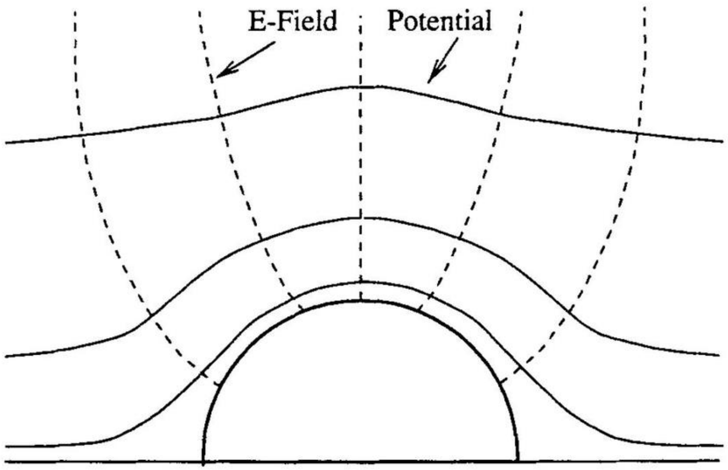
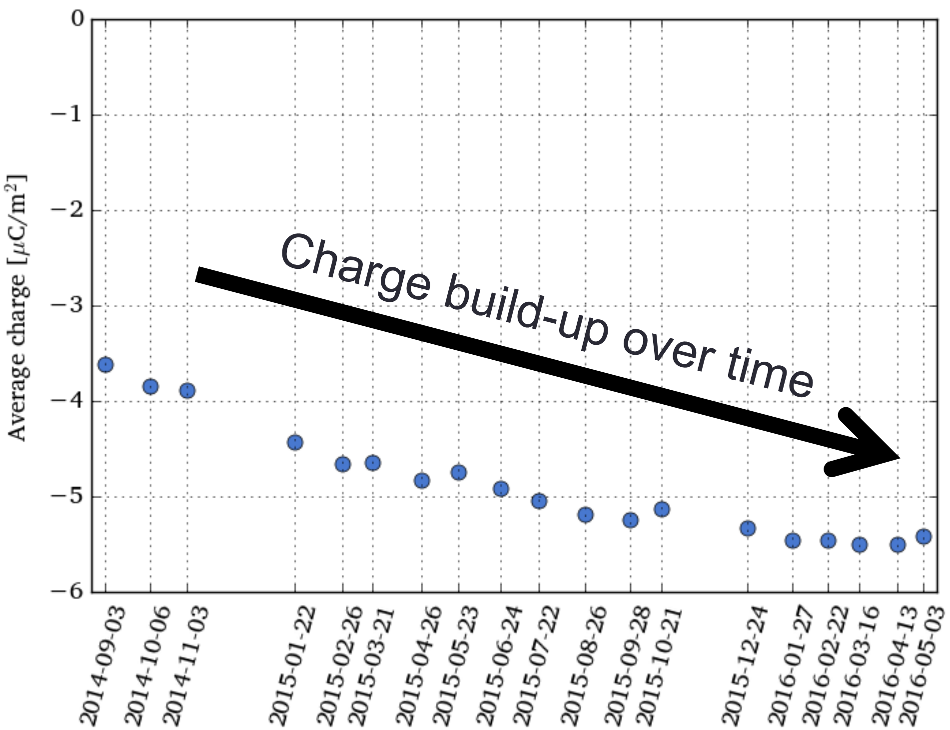
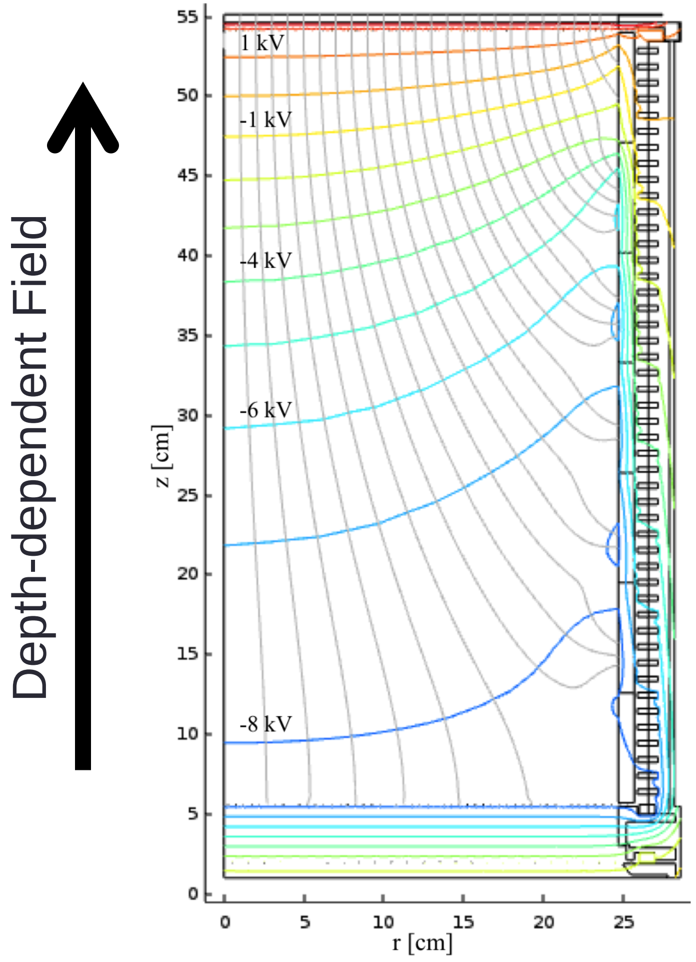


Figure from *Towards the Formulation of a Realistic 3D Model for Simulation of Magnetron Injection Guns for Gyrotrons (A Preliminary Study)*

LUX – Electric Field Distortion

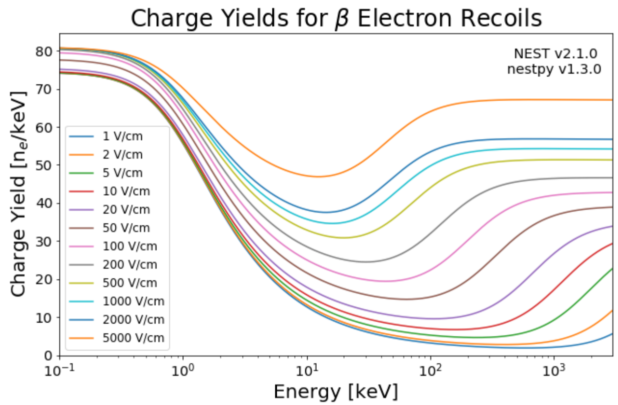


Figures provided by the LUX collaboration

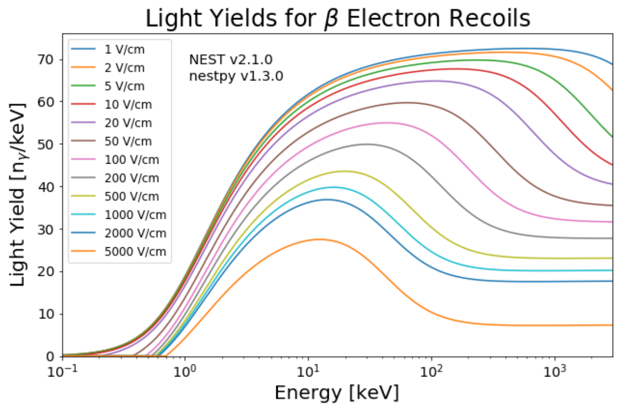


LUX – Splitting up the Detector

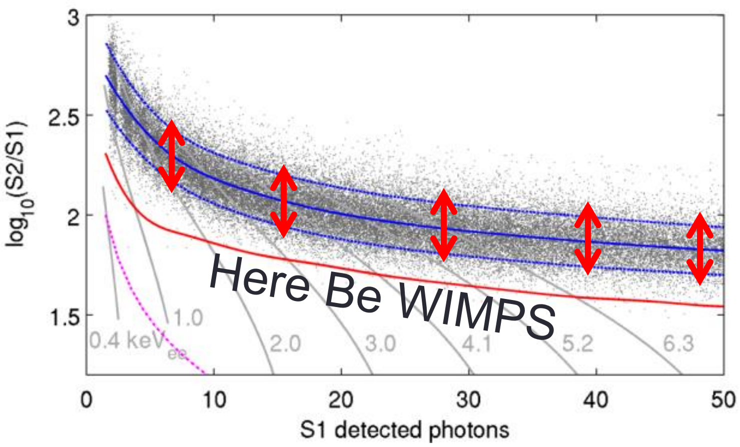
- Changing field affects ER signal.
- Split the detector into 16 pieces, 4 “time bins” and 4 “z-slices”



Field-dependent charge (S2) Response



Field-dependent Light (S1) Response



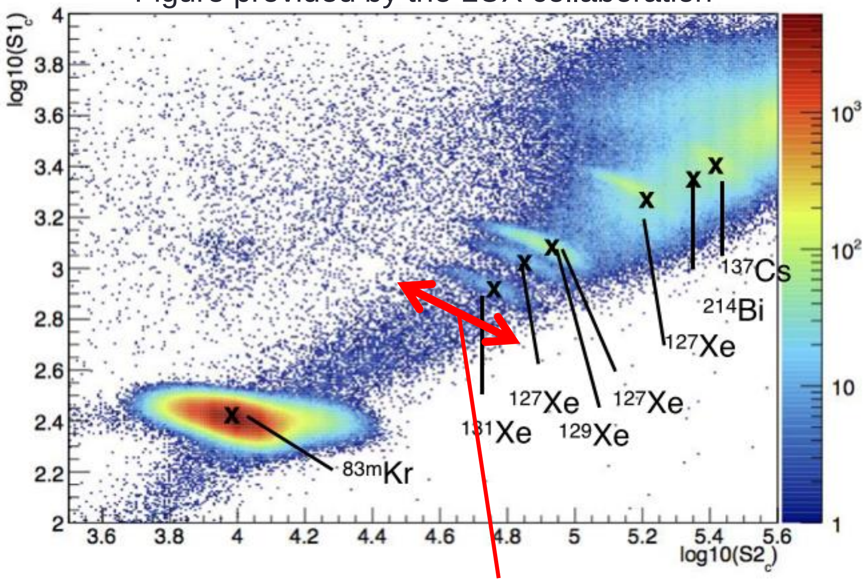
Including regions of differing field widens the ER band, increasing “leakage” into the signal region.

Benchmark Plots provided by NEST: http://nest.physics.ucdavis.edu/benchmark-plots

LUX – Fitting The ER Backgrounds

- Simulate backgrounds in LUXSim (Geant4)
- Use NEST (Xe response simulation) to get S1 and S2 response from energy depositions.
- Fit to each "sub-detector" letting NEST parameters float to fit Tritium calibrations
    - g1
    - g2
    - Mean E-field
    - Fano Factor

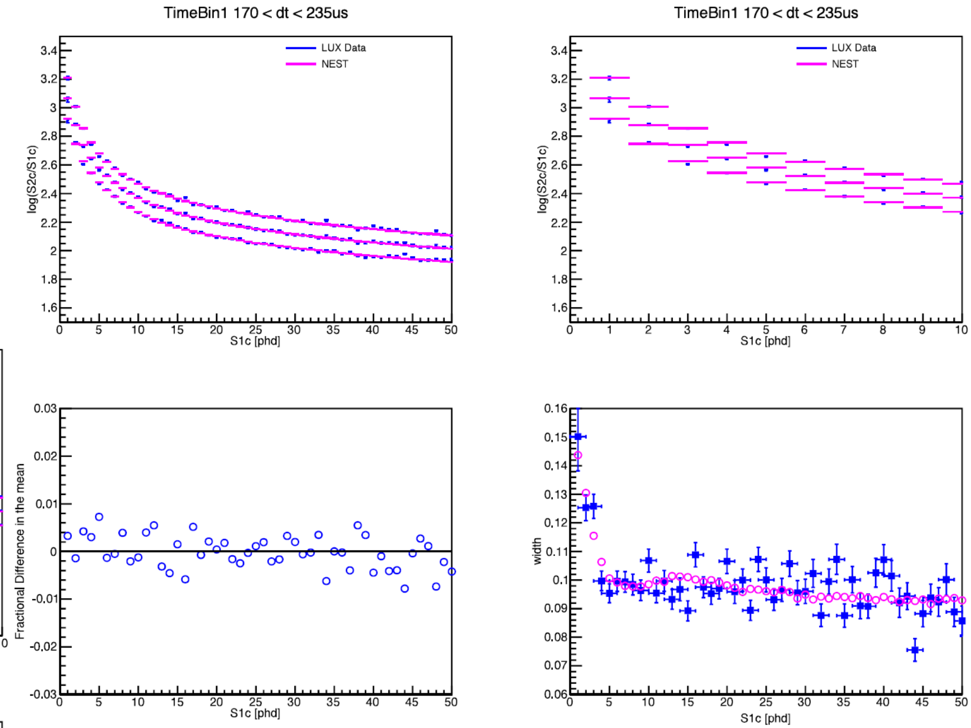
Figure provided by the LUX collaboration

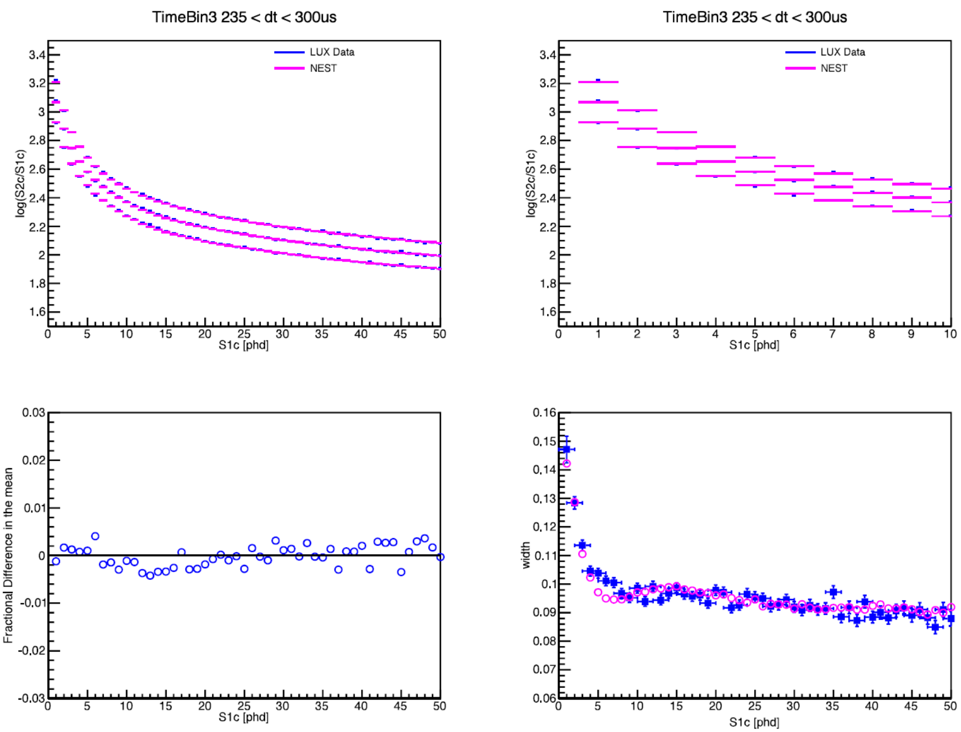


Anti-correlation determined by Fano Factor

LUX – Fitting The ER Backgrounds

- Example fits

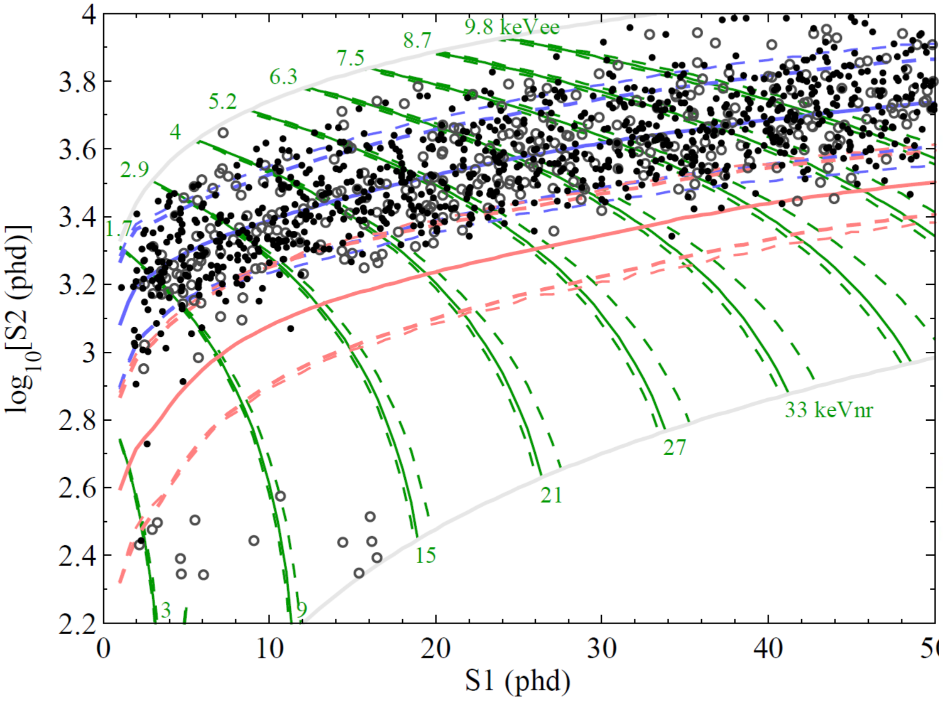


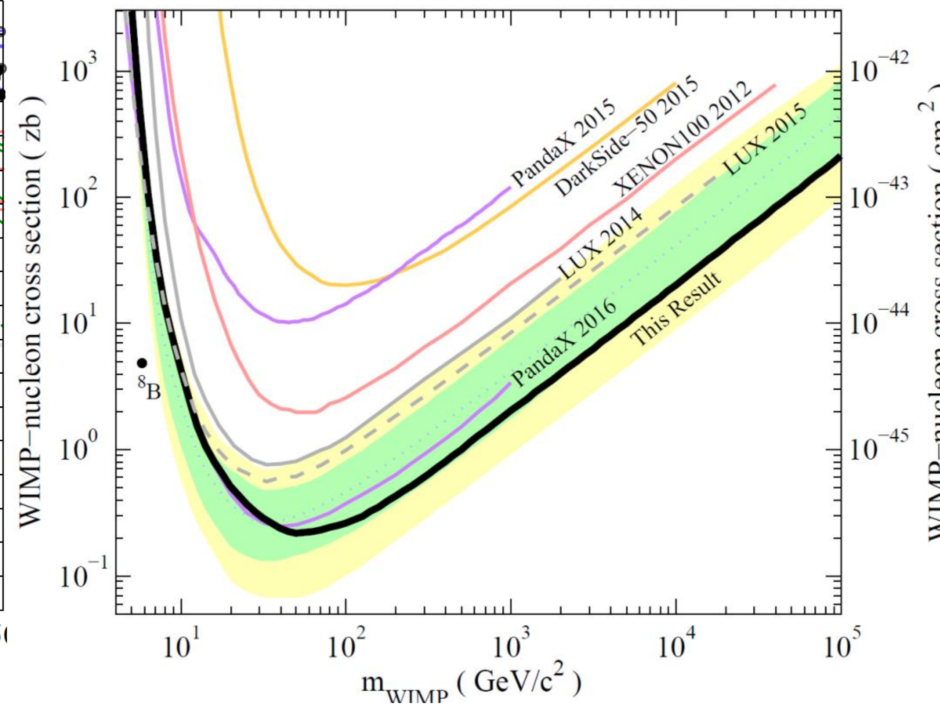


LUX – Additional Tasks

- Operating the detector on-site
- Remote monitoring of the detector
- Implementing electric field variation in LUXSim (LUX Geant4 implementation)
- Performing Deuterium-Deuterium (DD) neutron calibrations
- Estimating radiogenic neutron background rate

LUX – The Spin-independent Result





LUX SI WIMP-Search Data Set

Green = constant energy

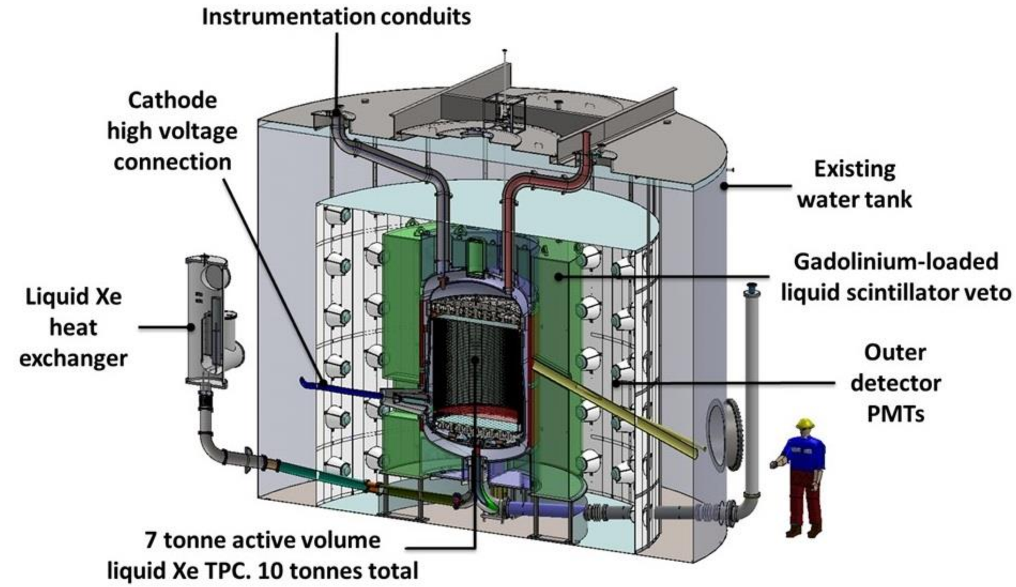
Red = NR Band

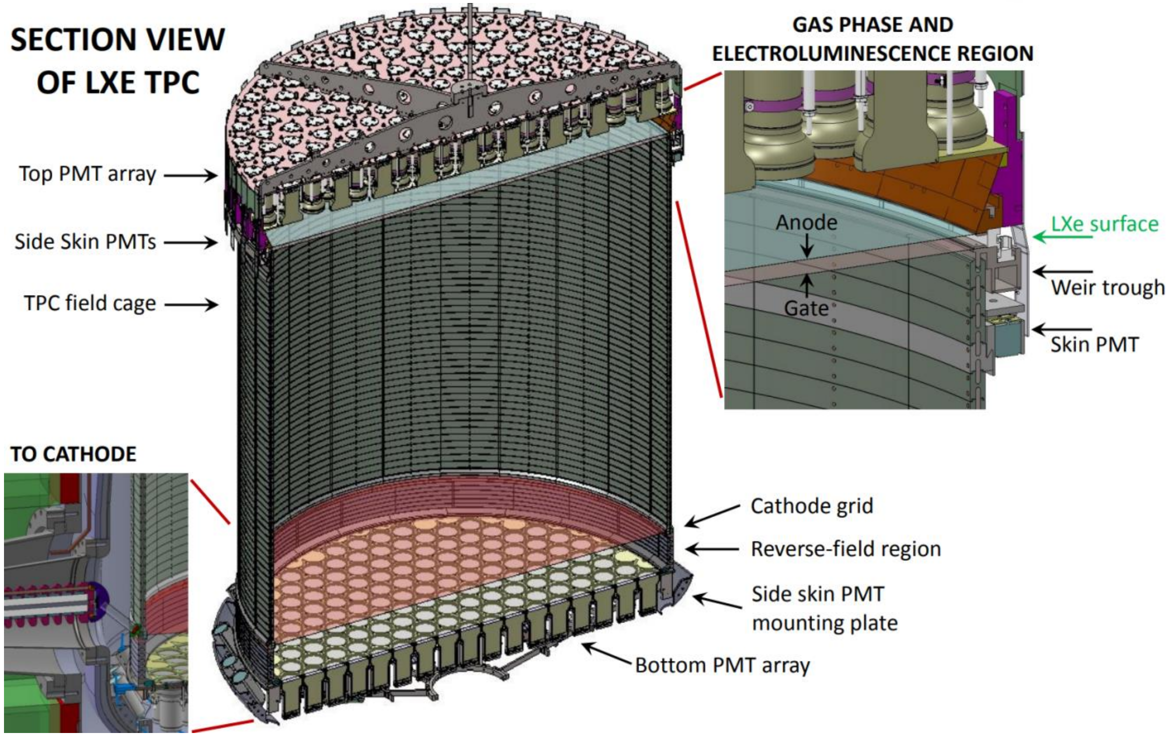
Blue = ER Band

The LZ System Test at SLAC

Hardware - LZ

- ~ 10,000 kg Xe
- Subsystem Upgrades



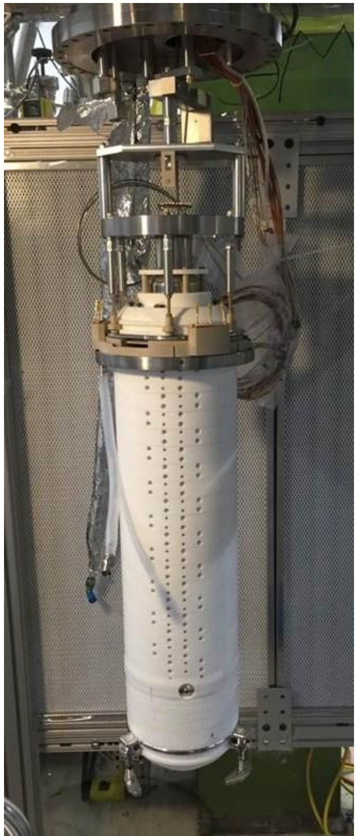


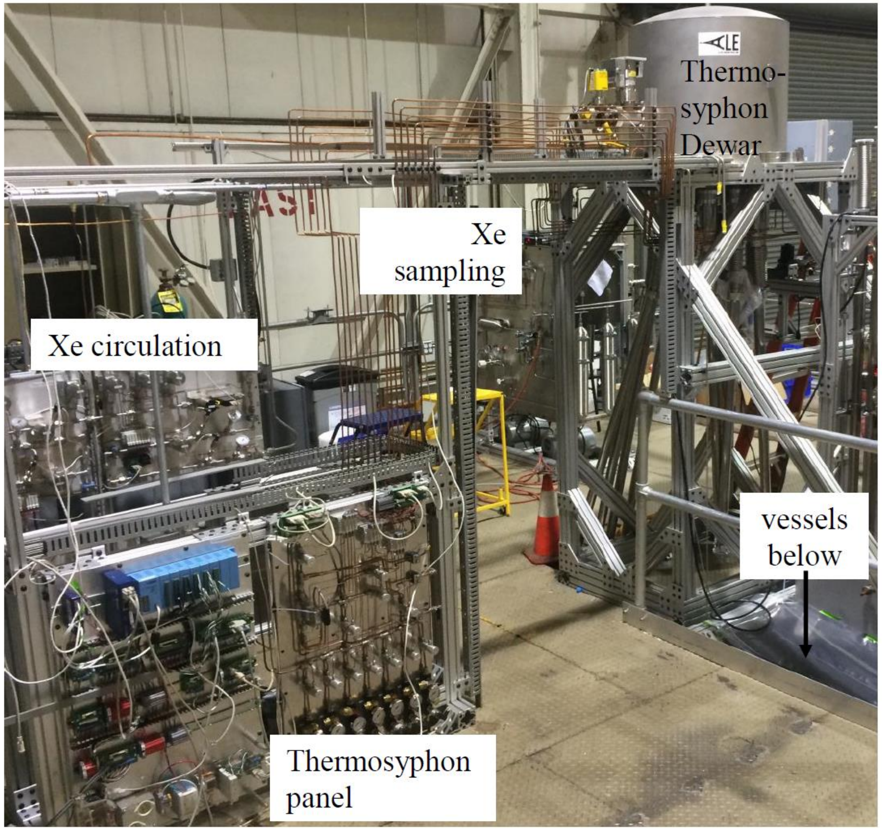
Figures from *LZ TDR* (arXiv:1703.09144)

Hardware - SLAC

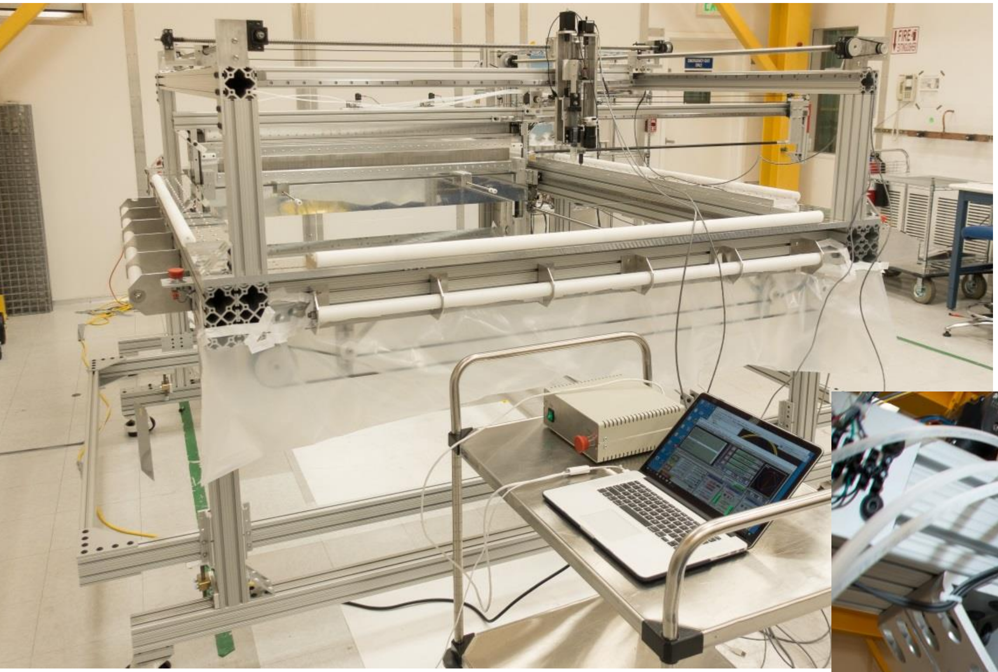
Hardware – Activities at SLAC

- Built and ran Phase I detector – scaled prototype of LZ
- Built xenon circulation, purification, and cooling infrastructure.
- Wove LZ grids.





Hardware – Grid Weaving



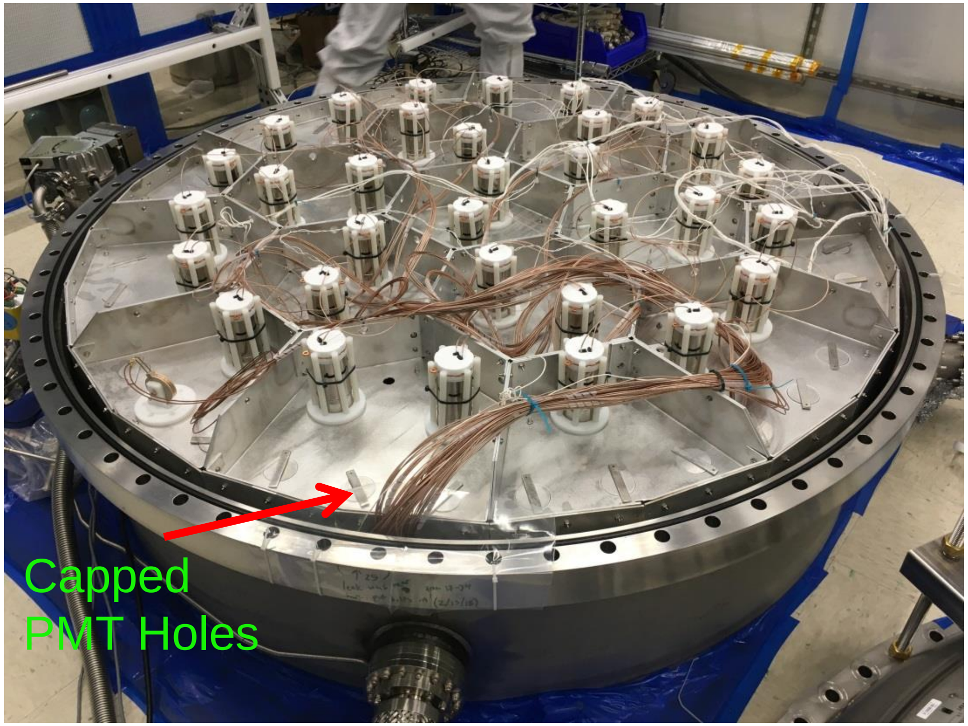
Just some cool pictures…

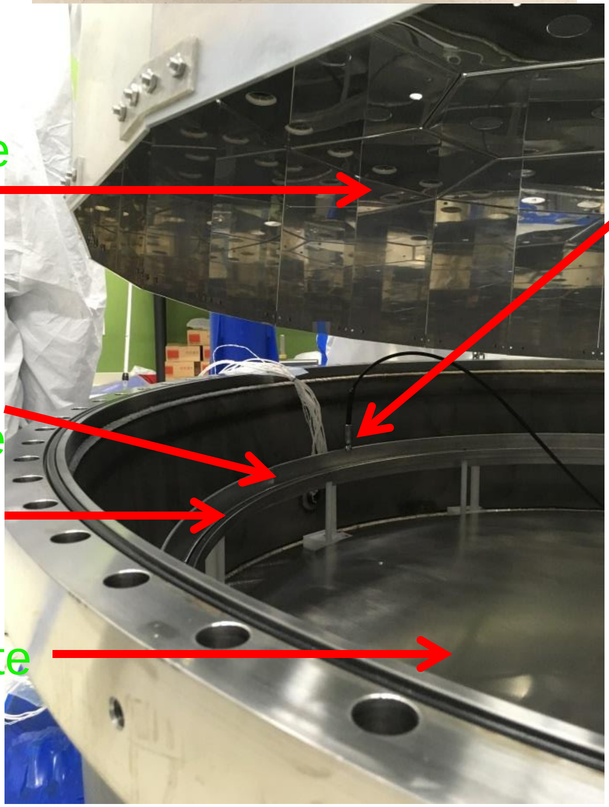
Photos courtesy of Steffen Luitz
https://www.luitzphotography.com/

Insert picture of
complete grid

Hardware - System Test Phase II

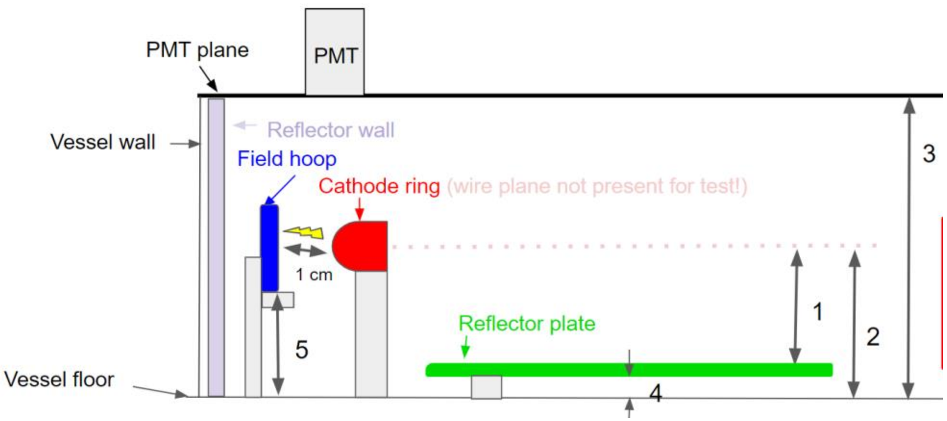
- Full LZ Grid Sized
- Gas only test
- MgF_2 Coated Aluminum for reflectivity

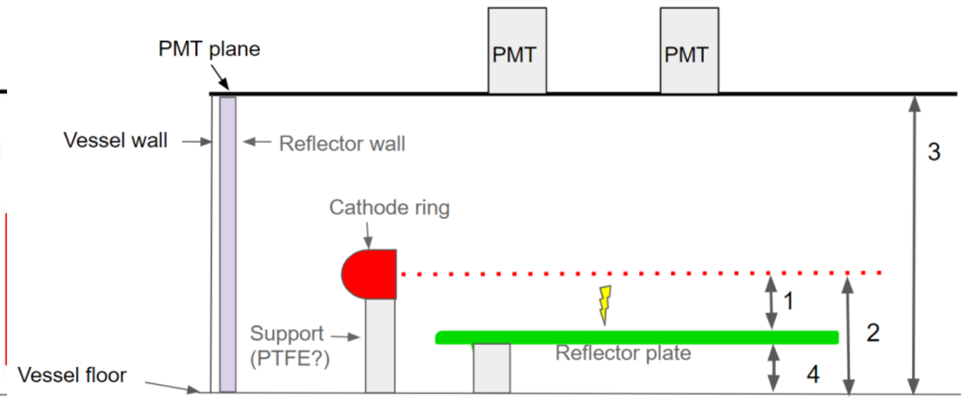


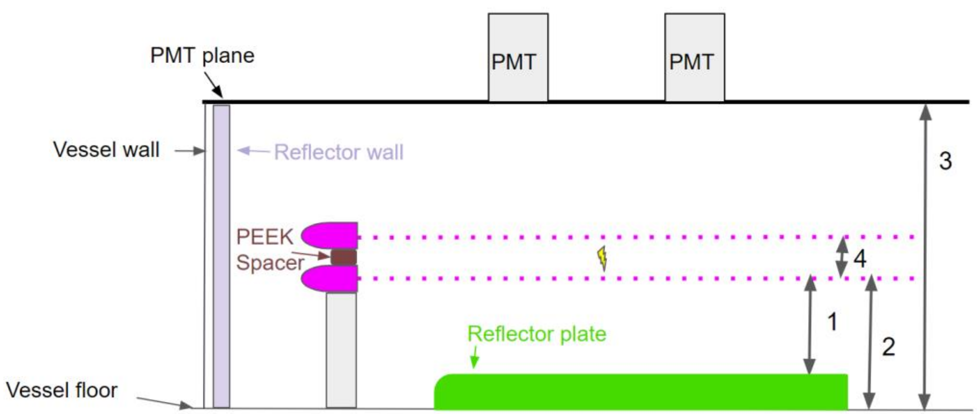


Hardware - System Test Phase II

- Tests performed on:
  - Cathode radial field
  - Cathode bulk field
  - Extraction field







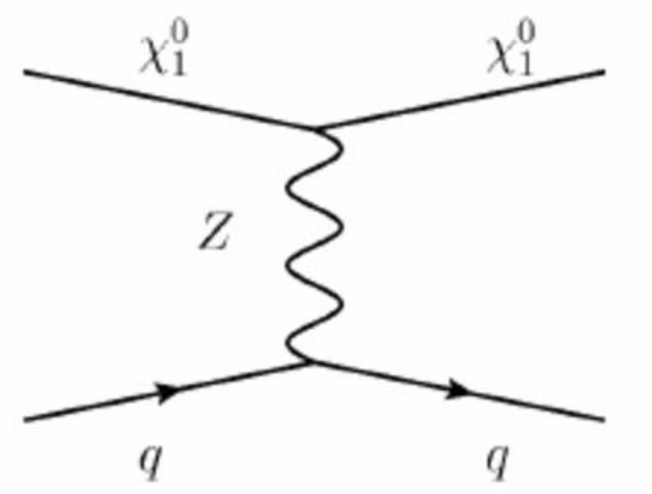
Tests confirmed acceptable levels of electron emission.

Grids now installed in LZ!

The Effective Field Theory

EFT – How It Works

- Known interaction? Just follow the rules...
  - For instance…

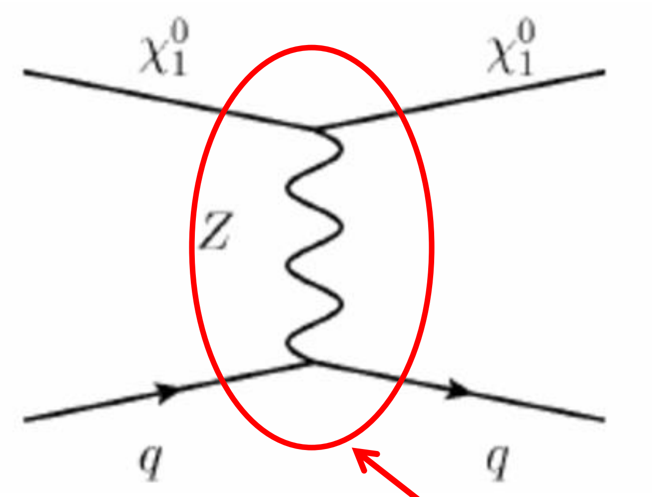


Get things like

$$\mathcal{M} = const * g^2 X\gamma^\mu(1-\gamma^5)X\frac{1}{{M_Z}^2}Q\gamma^\mu(1-\gamma^5)Q$$

EFT – How It Works

- Known interaction? Plug and chug.
  - For instance…



Get things like

$$\mathcal{M} = const * g^2 X\gamma^\mu(1-\gamma^5)X\frac{1}{{M_Z}^2}Q\gamma^\mu(1-\gamma^5)Q$$

But we don't actually know what's in here.

EFT – How it Works

So we write

$$M = XO_xXNO_NN$$

EFT – How it Works

- Just allow for all possible options that don't violate symmetries.
- Relevant quantities are then
  - Hermitian
  - Galilean Invariant

$$\boldsymbol{I},\quad i\boldsymbol{q},\quad \boldsymbol{v}^{\perp},\quad \boldsymbol{S}_{\chi},\quad \boldsymbol{S}_{N}$$

Identity

Transferred momentum

Relative velocity $\perp$ to **q**

WIMP spin

Nucleon spin

EFT – Allowed Operators

$$\mathcal{O}_1 = 1$$

$$\mathcal{O}_2 = \left(v^\perp\right)^2$$

$$\mathcal{O}_3 = i\vec{S}_N \cdot \left(\vec{q} \times \vec{v}^\perp\right)$$

$$\mathcal{O}_4 = \vec{S}_\chi \cdot \vec{S}_N$$

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot (\vec{q} \times \vec{v}^\perp)$$

$$\mathcal{O}_6 = \left(\vec{S}_\chi \cdot \vec{q}\right)\left(\vec{S}_N \cdot \vec{q}\right)$$

$$\mathcal{O}_7 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_8 = \vec{S}_\chi \cdot \vec{v}^\perp$$

$$\mathcal{O}_9 = i\vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{q}\right)$$

$$\mathcal{O}_{10} = i\vec{S}_N \cdot \vec{q}$$

$$\mathcal{O}_{11} = i\vec{S}_\chi \cdot \vec{q}$$

$$\mathcal{O}_{12} = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}^\perp\right)$$

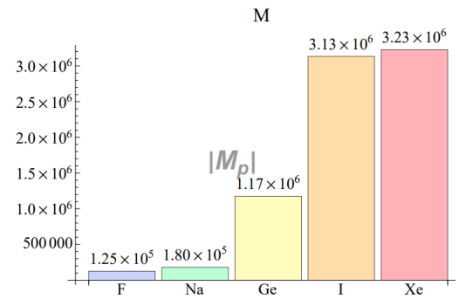
$$\mathcal{O}_{13} = i\left(\vec{S}_\chi \cdot \vec{v}^\perp\right)\left(\vec{S}_N \cdot \vec{q}\right)$$

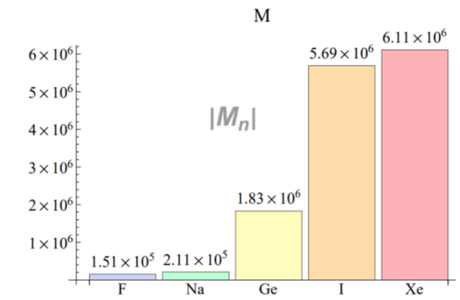
$$\mathcal{O}_{14} = i\left(\vec{S}_\chi \cdot \vec{q}\right)\left(\vec{S}_N \cdot \vec{v}^\perp\right)$$

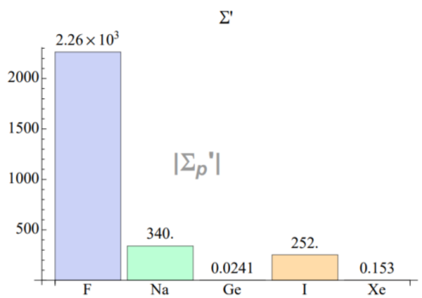
$$\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \vec{q}\right)\left(\left(\vec{S}_N \times \vec{v}^\perp\right) \cdot \vec{q}\right)$$

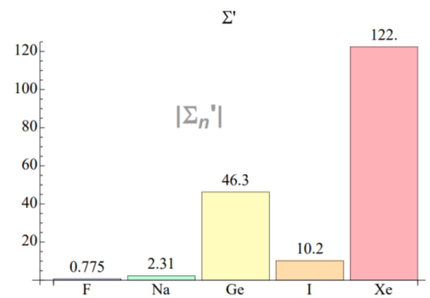
EFT – Nuclear Responses

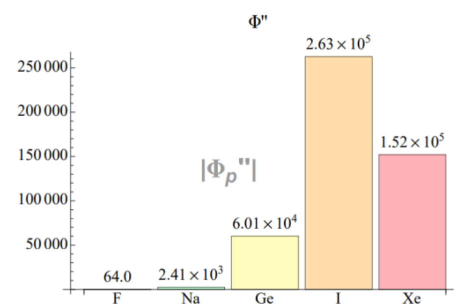
These operators can be expressed as combinations of 6 nuclear responses:











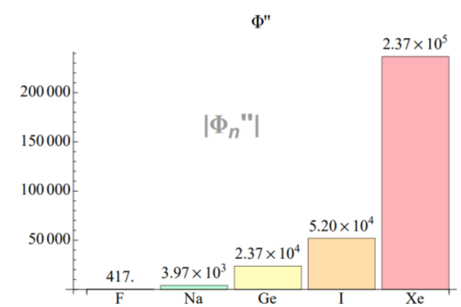


Figure from *The Effective Field Theory of Dark Matter Direct Detection* (arxiv:1203.3542)

EFT – The Rate

- In practical terms:
  - look up F_k in a table.
  - Look up a_{ijk} in a table as well.

$$\frac{1}{2j_\chi+1}\frac{1}{2j+1}\sum_{\text{spins}}|\mathcal{M}|^2 \equiv \frac{m_A^2}{m_N^2}\sum_{i,j=1}^{15}\sum_{N,N'=p,n} c_i^{(N)}c_j^{(N')}\sum_{k=M,\Sigma'',\Sigma',\Delta,\Phi'',\widetilde{\Phi}'} a_{ijk}\left(j_\chi, v^2, q^2\right) F_k^{(N,N')} \tag{7.37}$$

Coefficients assigning nuclear responses to operators

Nuclear response function

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = N_T \frac{\rho_0}{32\pi m_\chi^3 m_A}\int_{v>v_{\min}} \frac{1}{v} f(\vec{v})|\mathcal{M}|^2\,\mathrm{d}^3 v$$

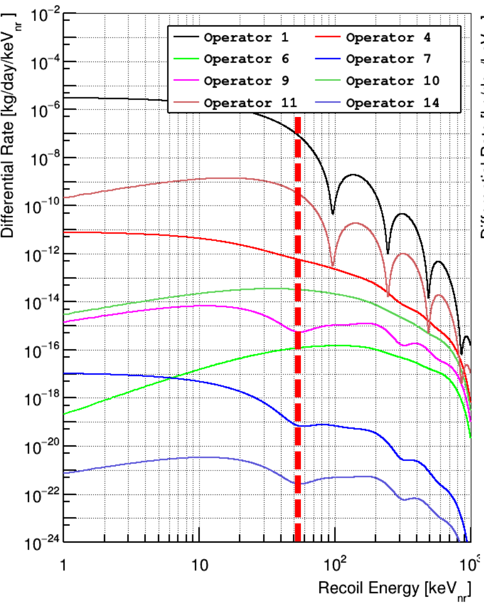
The EFT Analysis

- Signal Models
- Data Quality
- Background Models
- Statistical Inference
- The Result

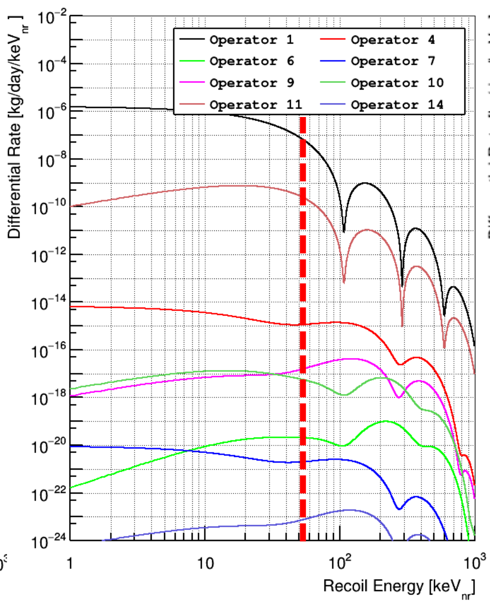
EFT Results – Signal Spectra

- Spectra created using Mathematica package from arxiv:1308.6288

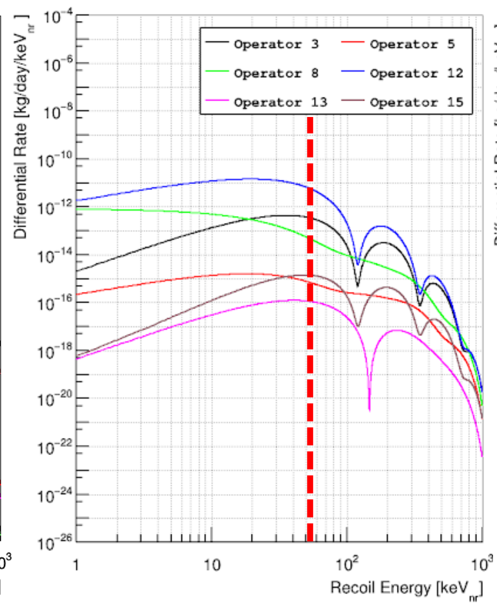
500 GeV WIMP



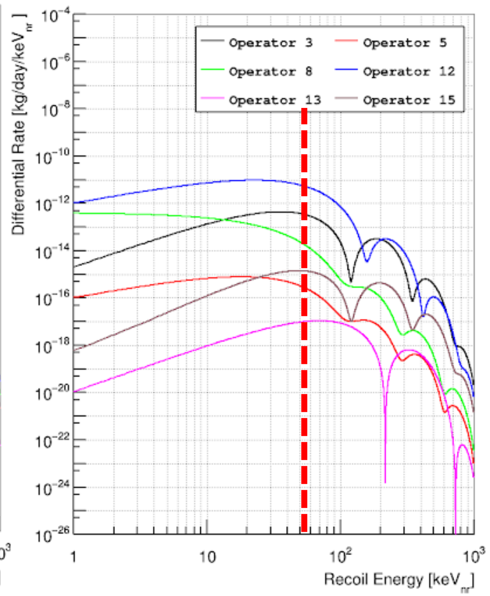
WIMP-neutron



WIMP-proton



WIMP-neutron



WIMP-proton

Many Operators peak at high energy.
Extend ROI for the operators that need it.

Re-do all aspects of the analysis to extend to high energy.

EFT Analysis – Data Quality Cuts

- Cut philosophy: remove an event unless it can…
  - Be confused for a WIMP
  - Constrain an event population whose other members may be confused for a WIMP
- Cuts
  - 1 S1 + 1 S2 – WIMPs never multiply scatter
  - S1: 2 PMT coincidence – reduce electronics noise
  - S1 & S2 Range – outside of signal range/ill-defined simulation regime
  - Fiducial – reduce background/signal ratio utilizing Xe self-shielding
  - S1 Prompt Fraction – eliminate gas events
  - S1 Max Peak Area – eliminate many categories – primarily coincident gas s1 + bulk s2
  - S2 Pulse Width – eliminate gas events
  - S2 Pulse Shape – eliminate multiple scatters too close in depth to resolve
  - S2 Position Reconstruction – eliminate multiple scatters too close in x-y to resolve
  - Bad Area – eliminate events contaminated by too much additional activity.
  - γ-x – eliminate events that multiply scatter once above and once below the cathode
  - ^{83m}Kr exclusion period – eliminate ^{83m}Kr events: only applied for high energy couplings
  - Far from model – eliminate events inconsistent with either signal or background models

EFT Analysis – Cuts - Fiducial

- Intended to eliminate the vast majority of backgrounds, which can't penetrate far into liquid Xe.
- Select Events only in the fiducial region (further than 3 cm from the reconstructed wall).

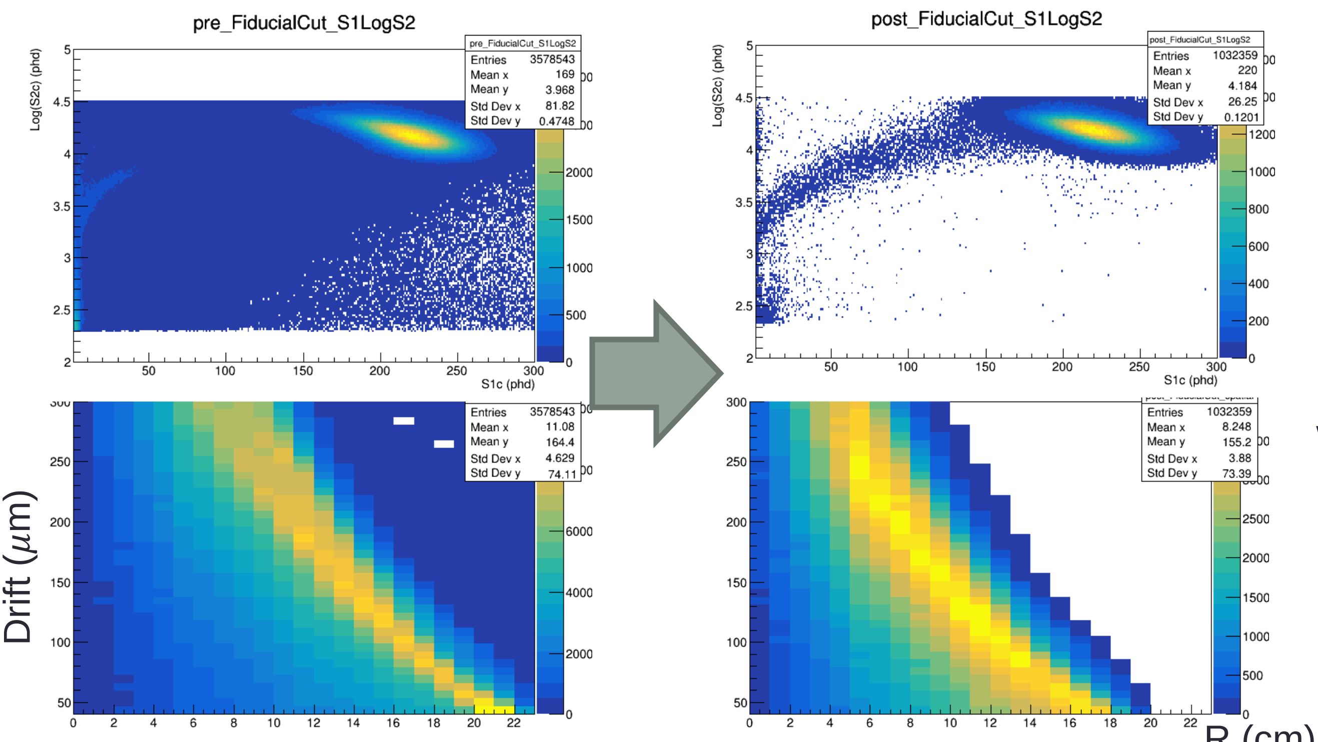
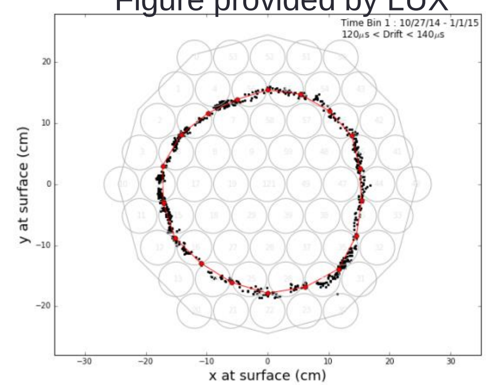


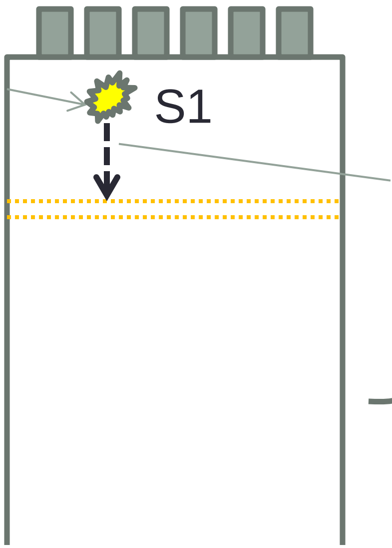
Figure provided by LUX



Wall found using ^{210}Po αs

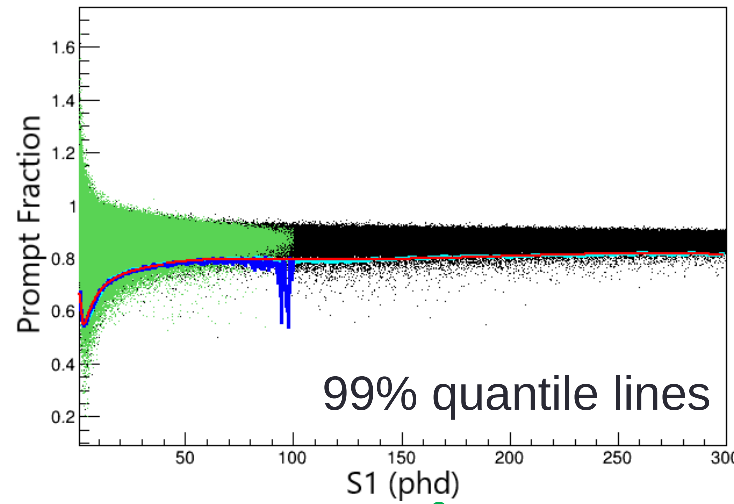
EFT Analysis – Cuts – Prompt Fraction

- Intended to eliminate gas events



Weak S2 begins immediately

Prompt Fraction = Fraction of S1 light arriving in first 120 ns



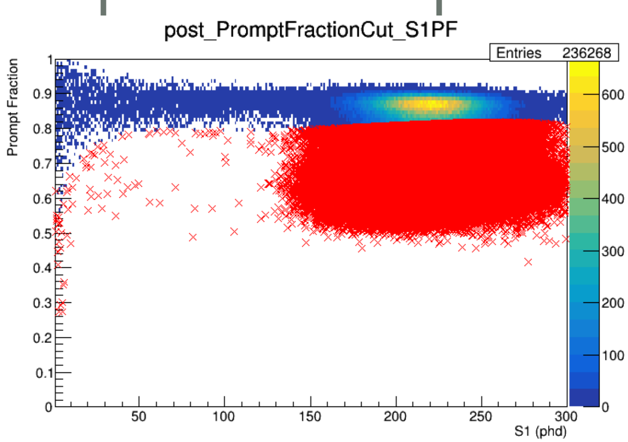
Green = ^{3}H Calibration

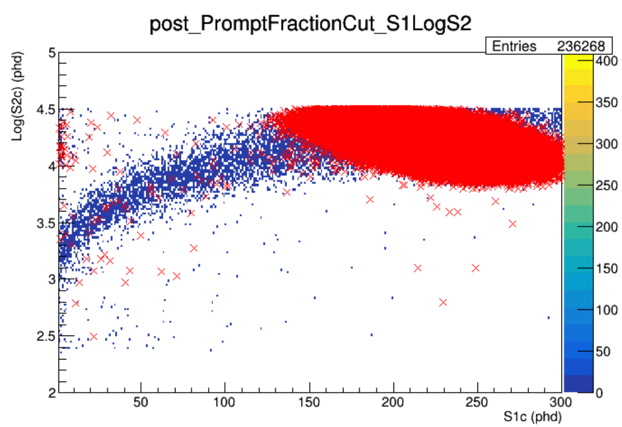
Black = ^{14}C Calibration

Dark Blue = 99% Tritium

Light Blue = 99% ^{14}C

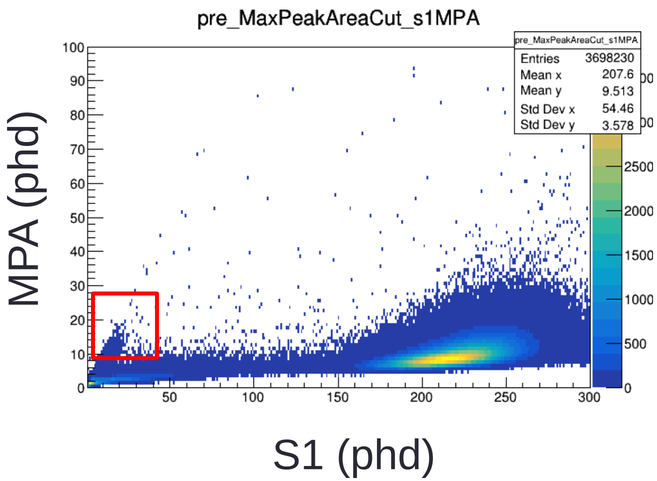
Red = Fit

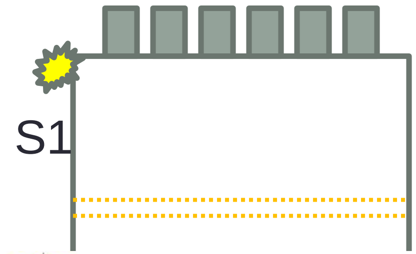


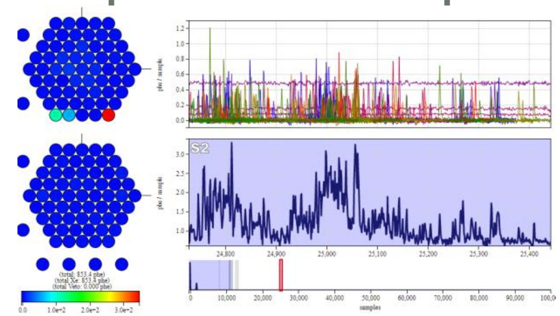


EFT Analysis – Cuts – Max Peak Area

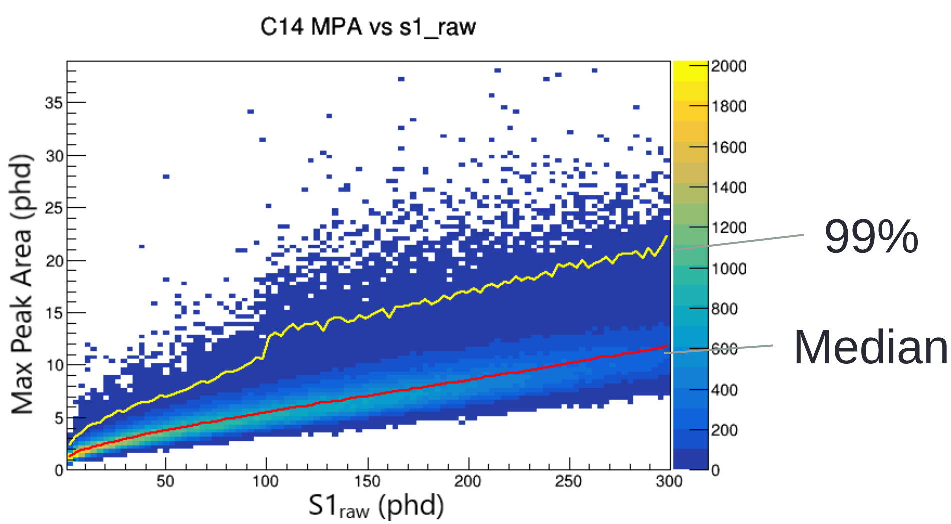
- Eliminate leakage from outside detector
- Eliminate other PMT related issues





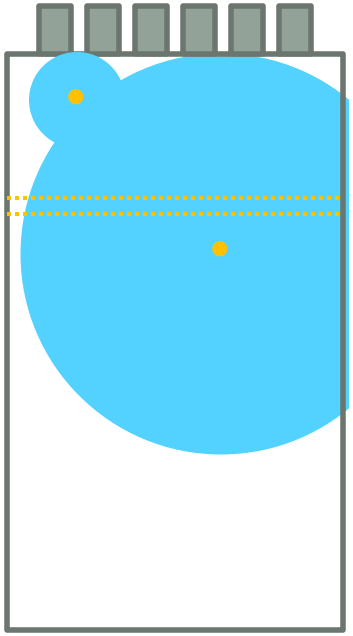


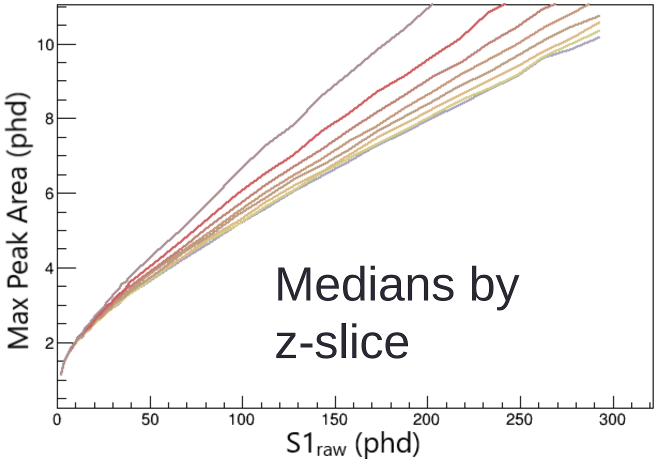
Look at this in ^{14}C calibration data

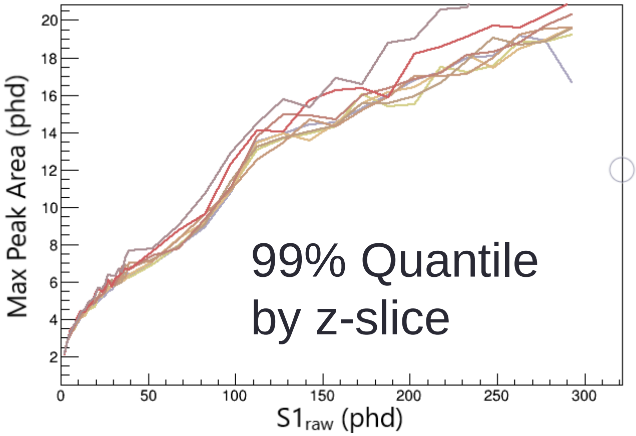


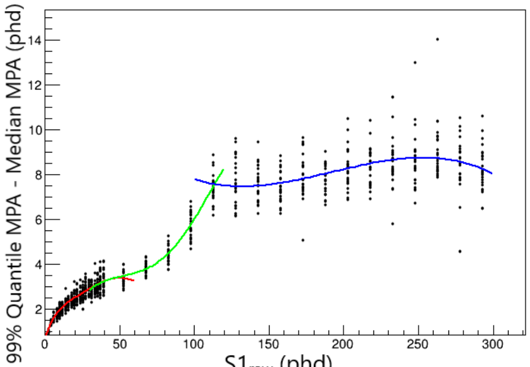
EFT Analysis – Cuts – Max Peak Area

- MPA depends on 2 major factors
  - Total S1 photons detected
  - Distance from the PMT array



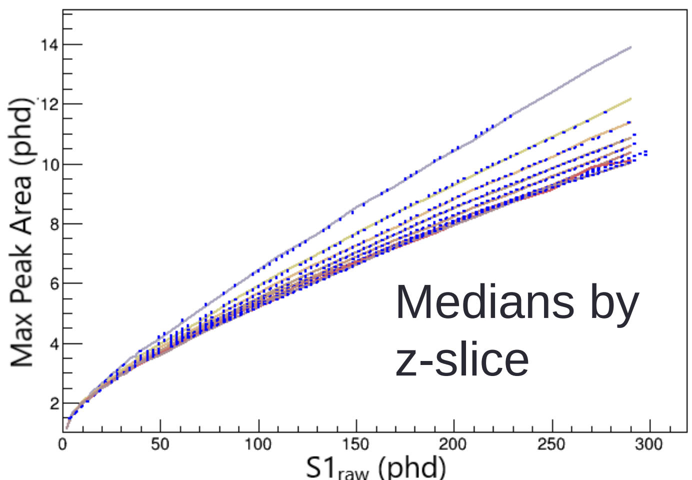




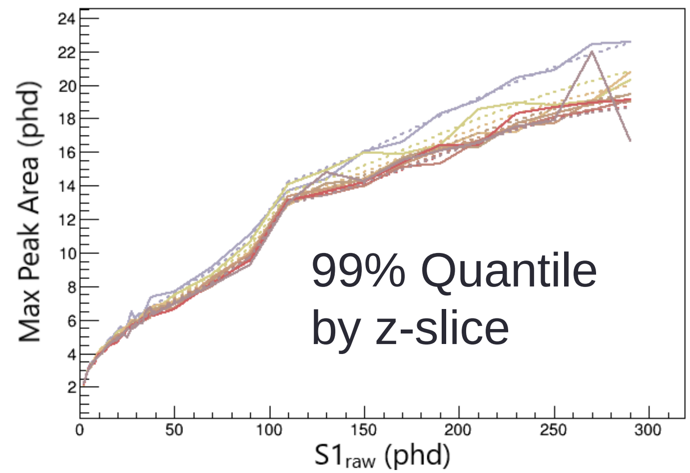


EFT Analysis – Cuts – Max Peak Area

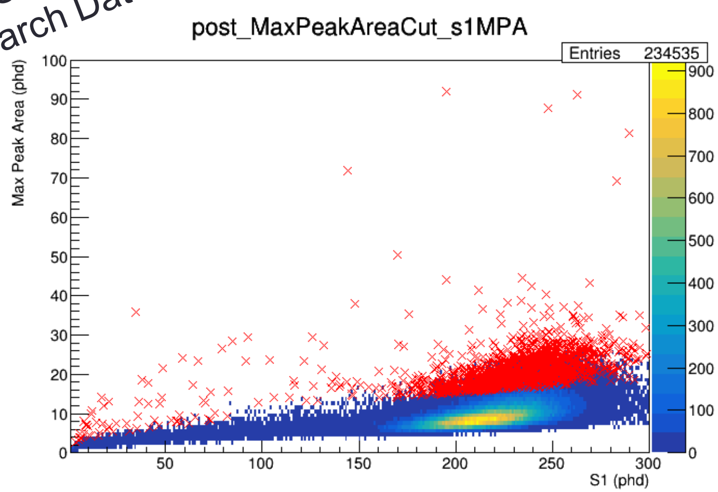
Fit Medians

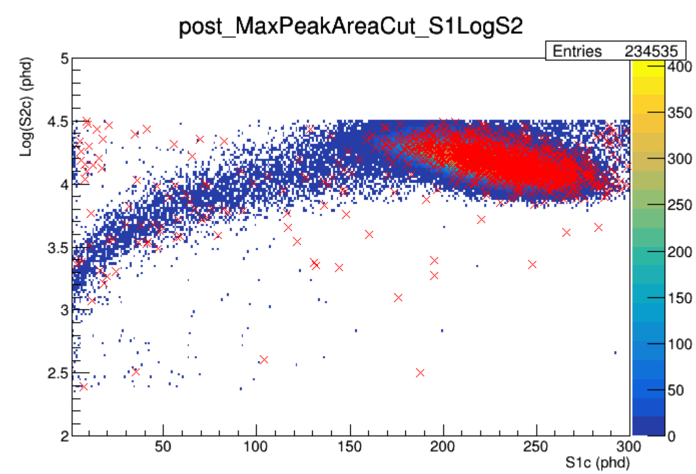


Add Universal Offset



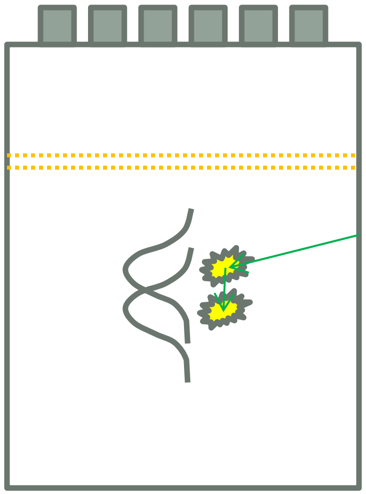
Apply the Cut to
WIMP Search Data



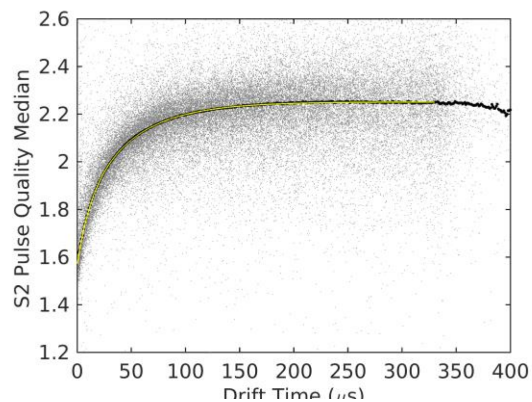


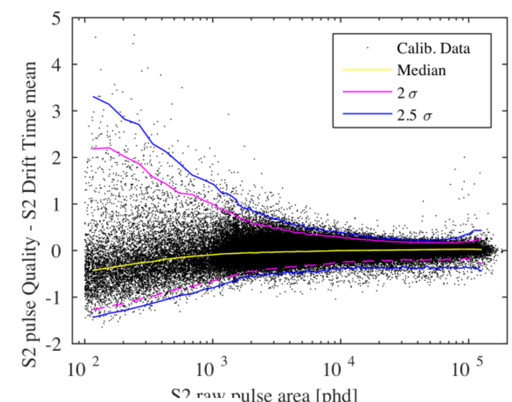
EFT Analysis – Cuts – S2 Shape

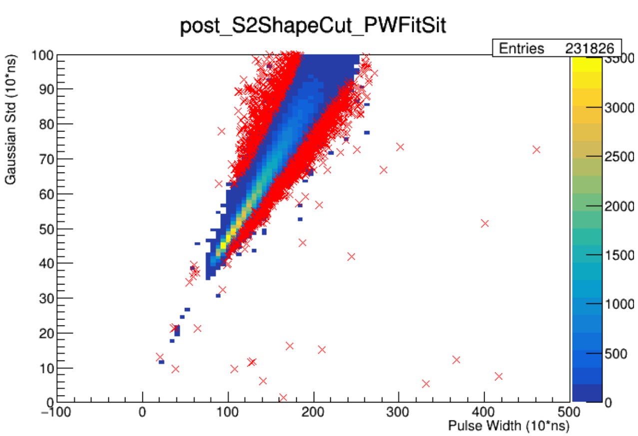
- Intended to eliminate multiple scatters close in z.

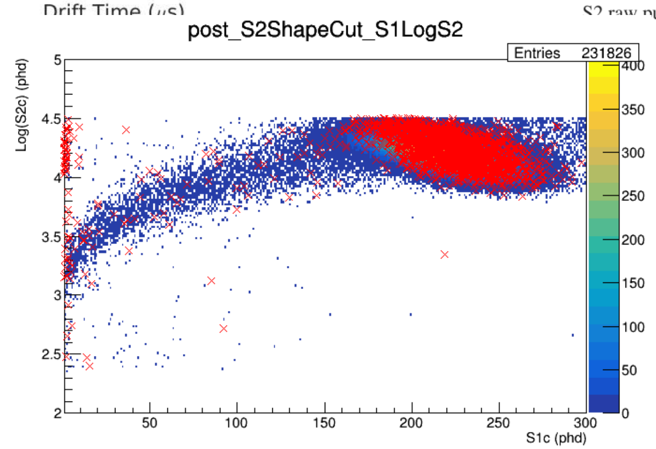


- Pulse Quality = Pulse Width / Gaussian Fit σ
- Depends on drift – electron clouds diffuse the longer they drift.
- Depends weakly on S2 Size



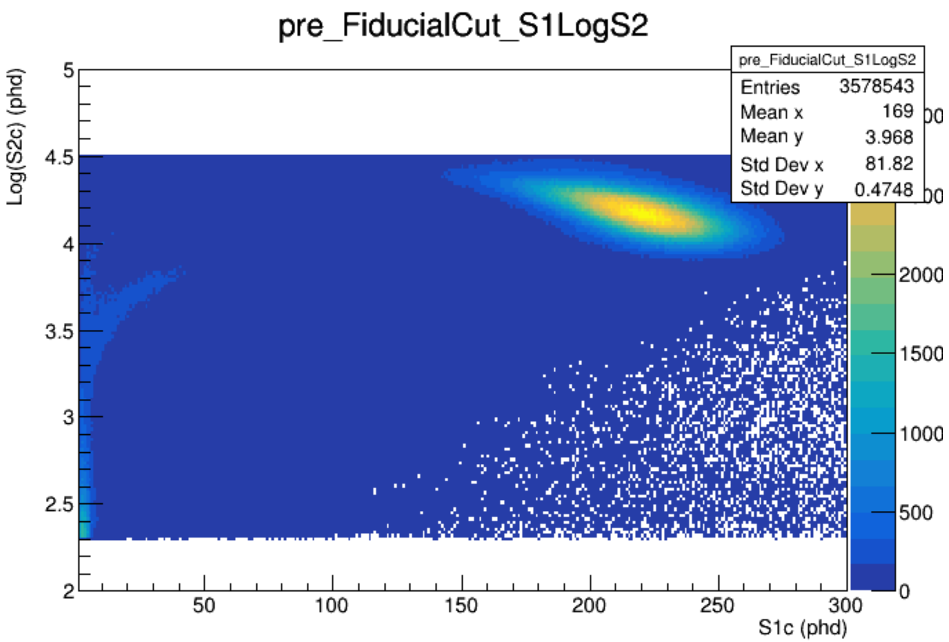


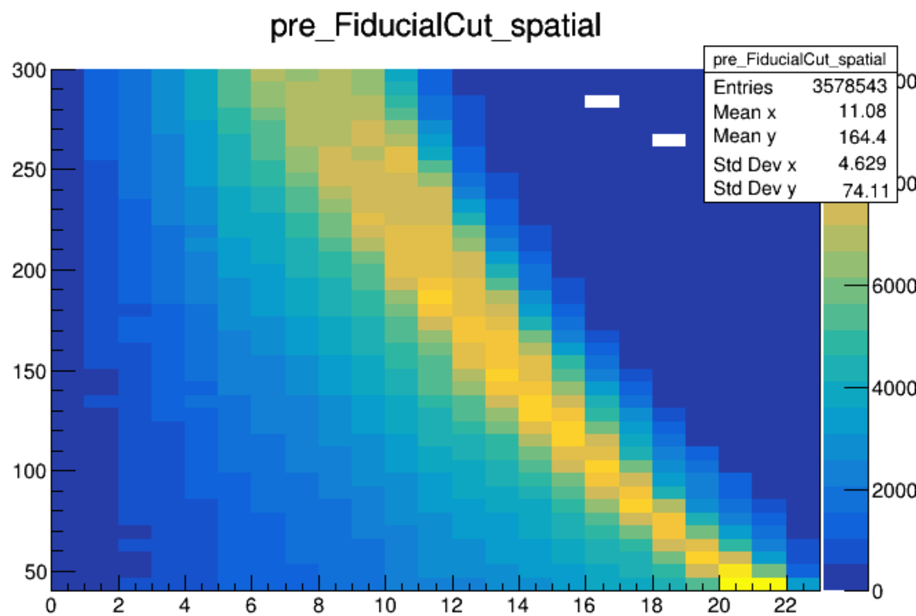




EFT Analysis - Cuts Montage

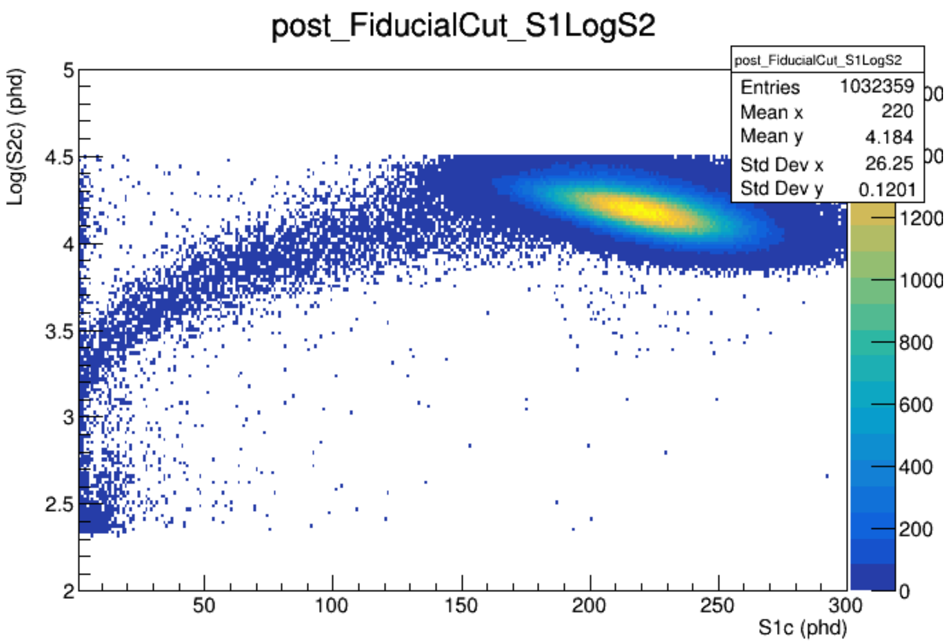
Initial 1S1 1S2 data

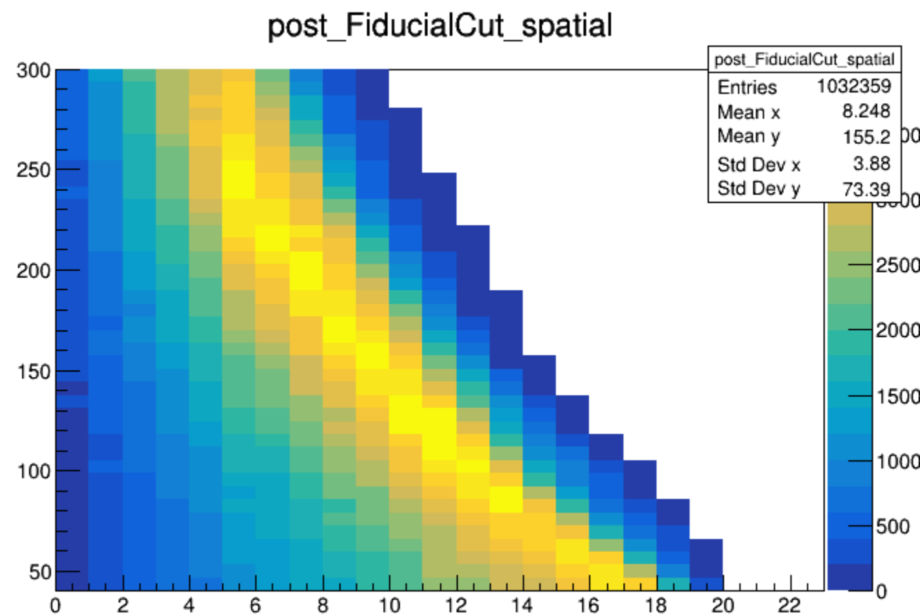




EFT Analysis - Cuts Montage

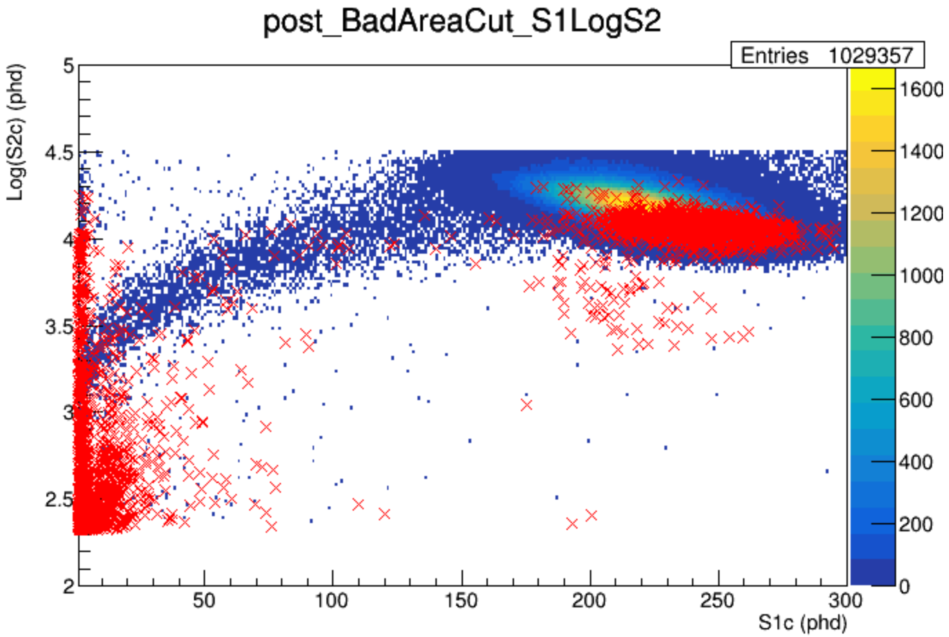
Fiducial

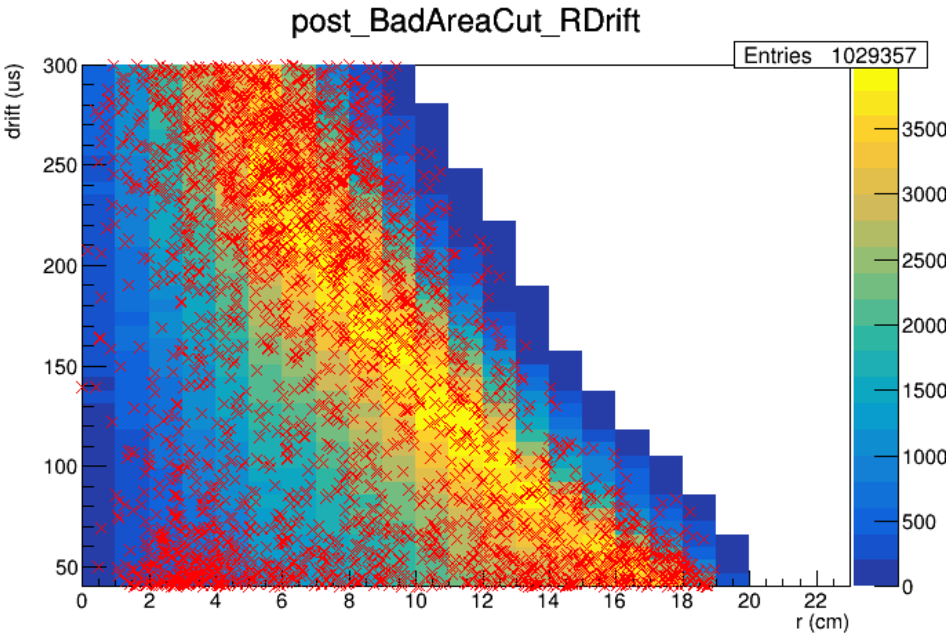




EFT Analysis - Cuts Montage

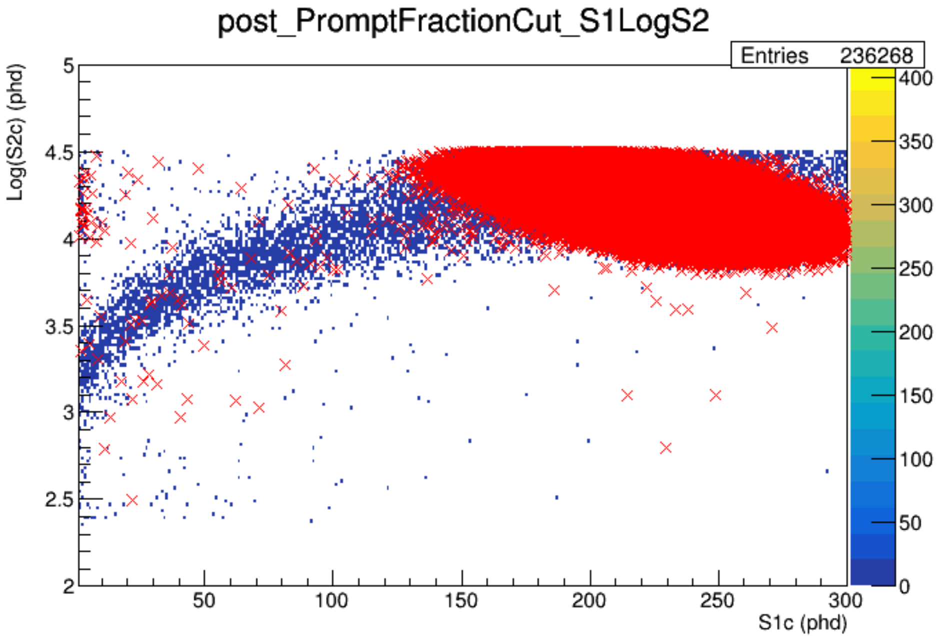
Bad Area

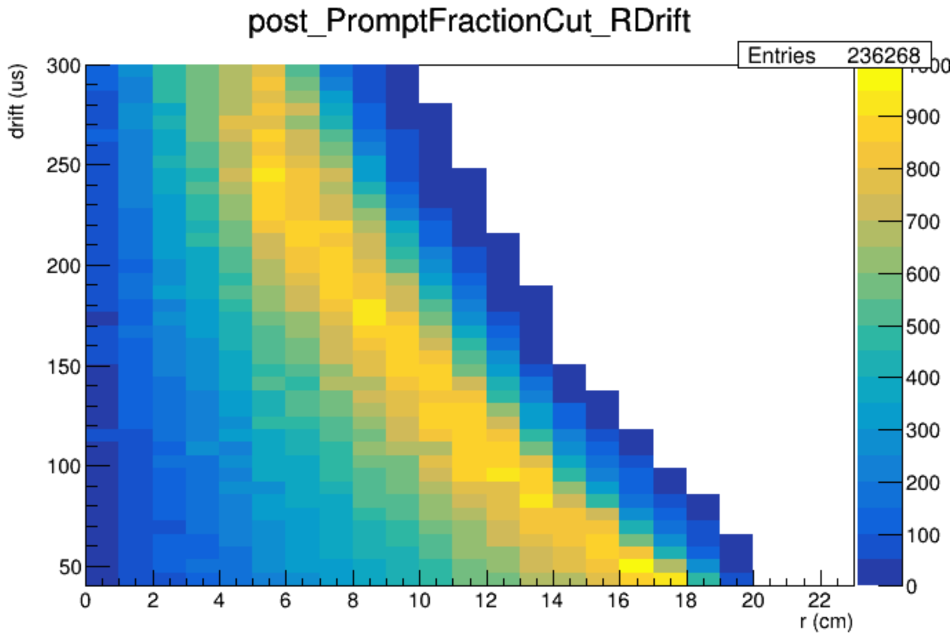




EFT Analysis - Cuts Montage

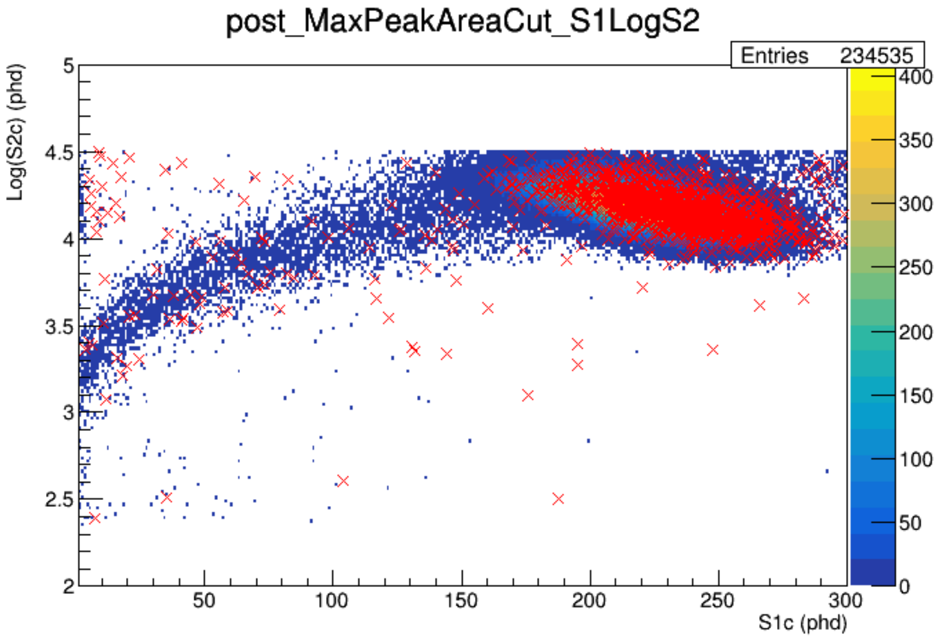
S1 Prompt Fraction

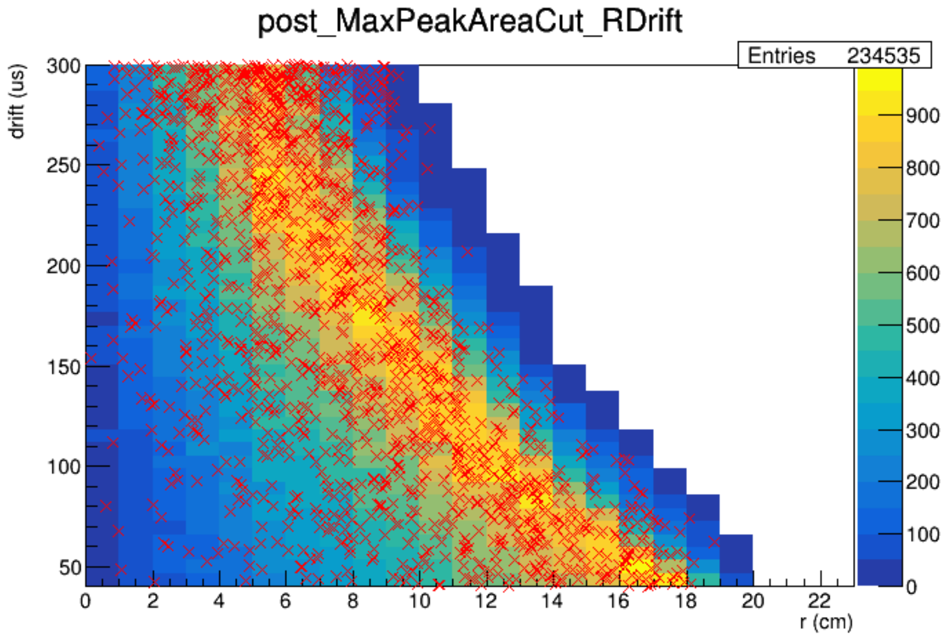




EFT Analysis - Cuts Montage

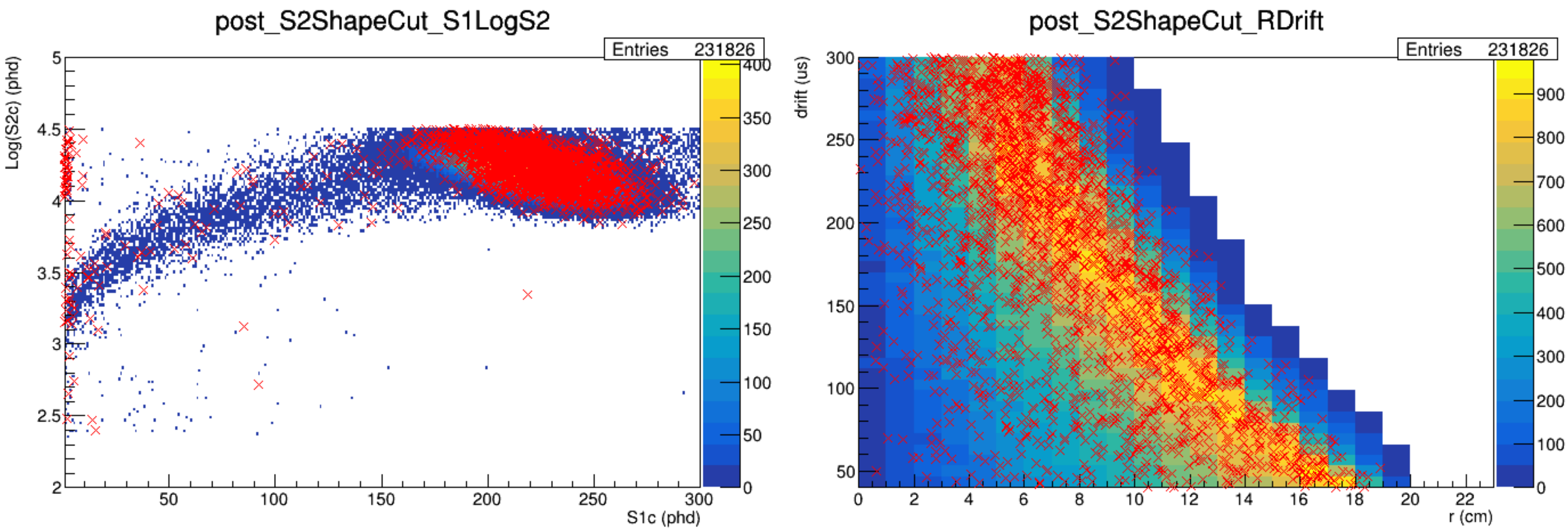
S1 Max Peak Area





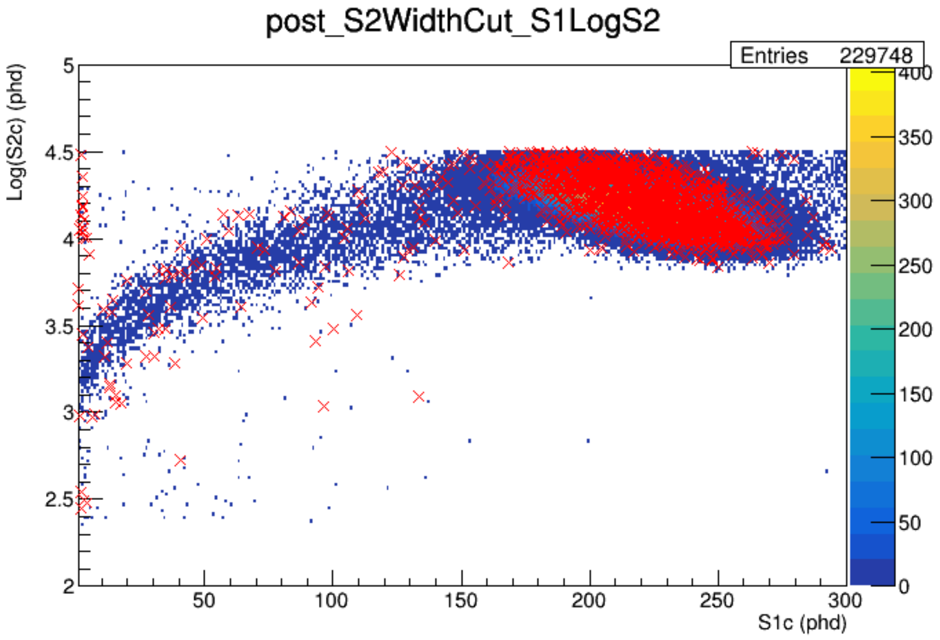
EFT Analysis - Cuts Montage

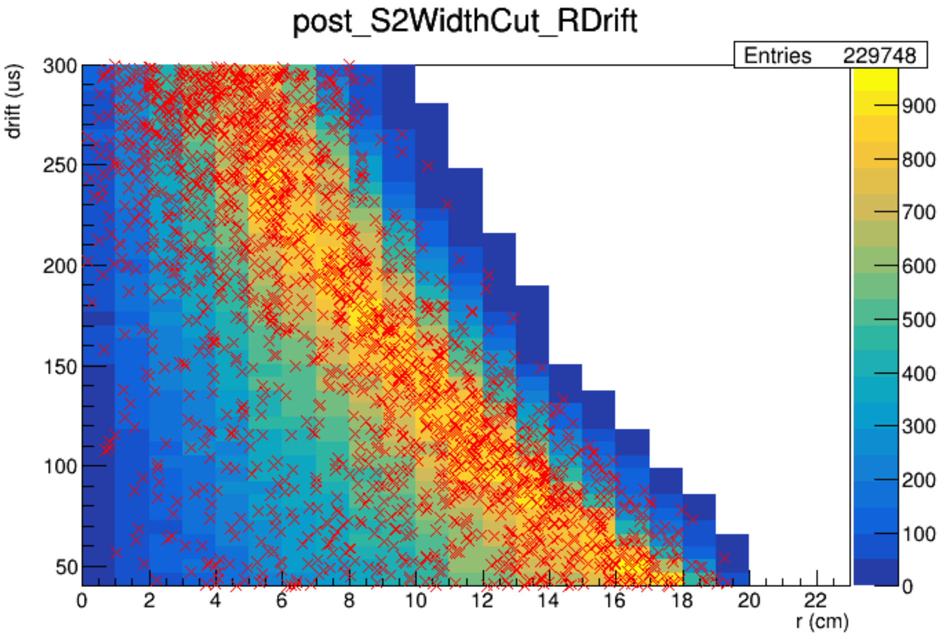
S2 Shape



EFT Analysis - Cuts Montage

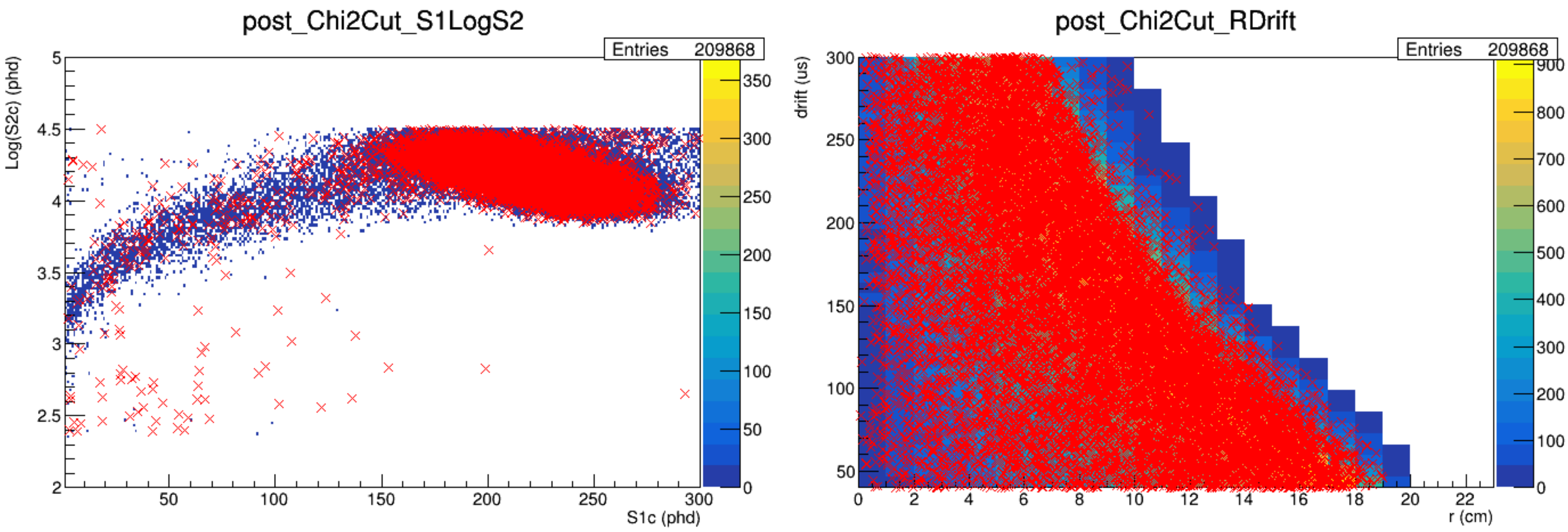
S2 Width





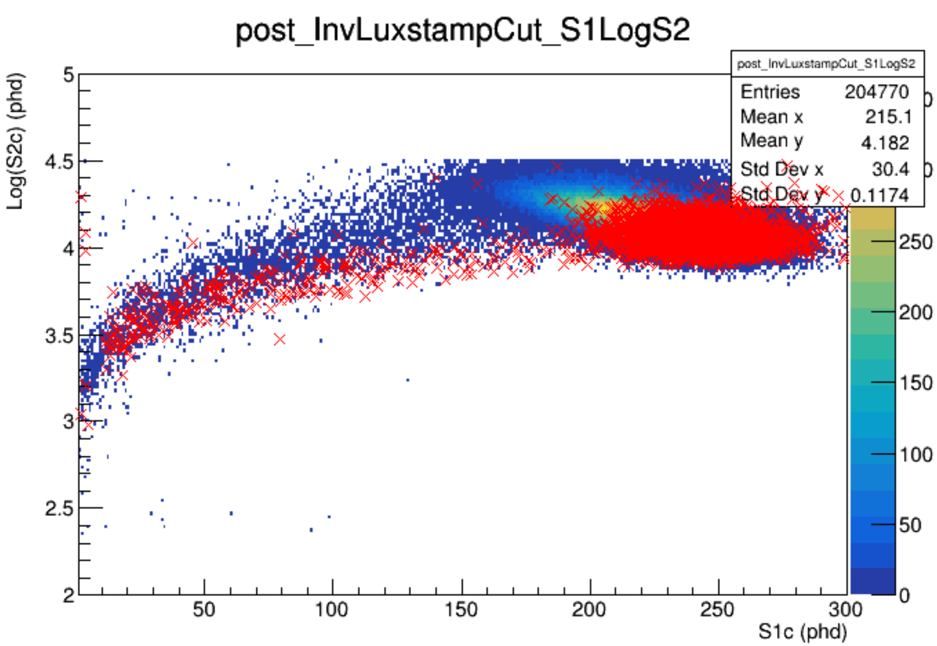
EFT Analysis - Cuts Montage

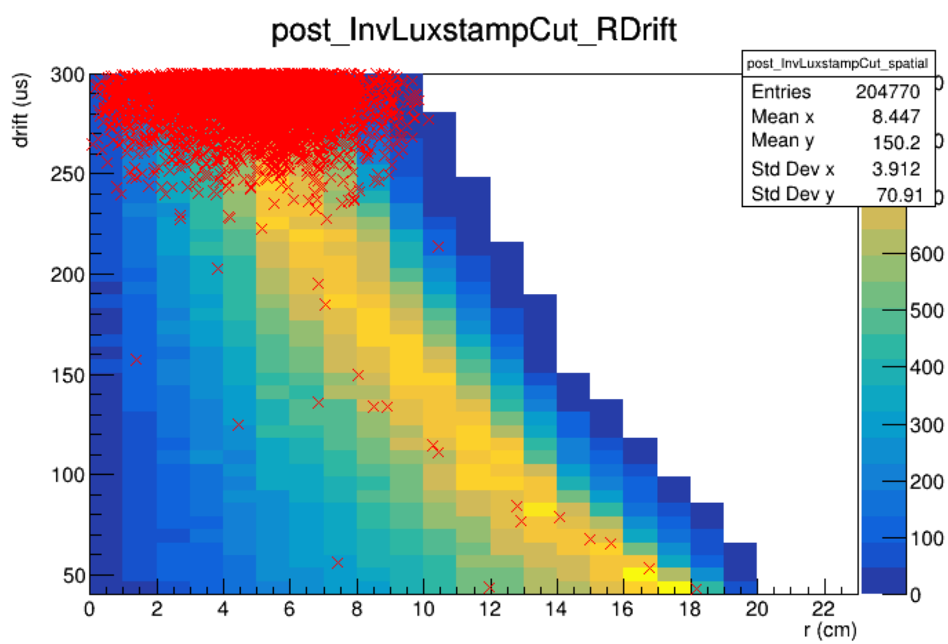
Position Reconstruction



EFT Analysis - Cuts Montage

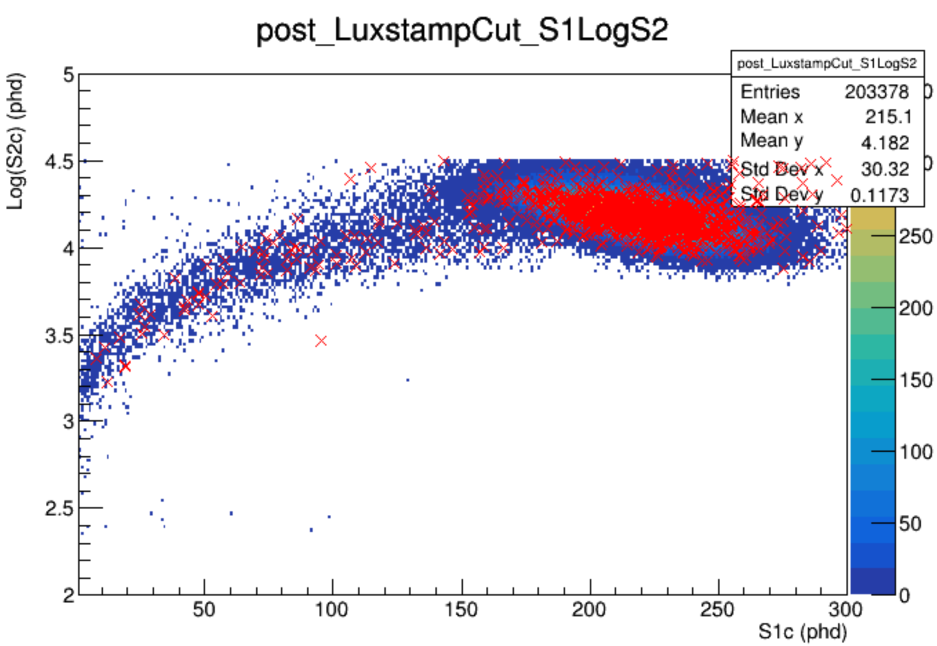
γ-X

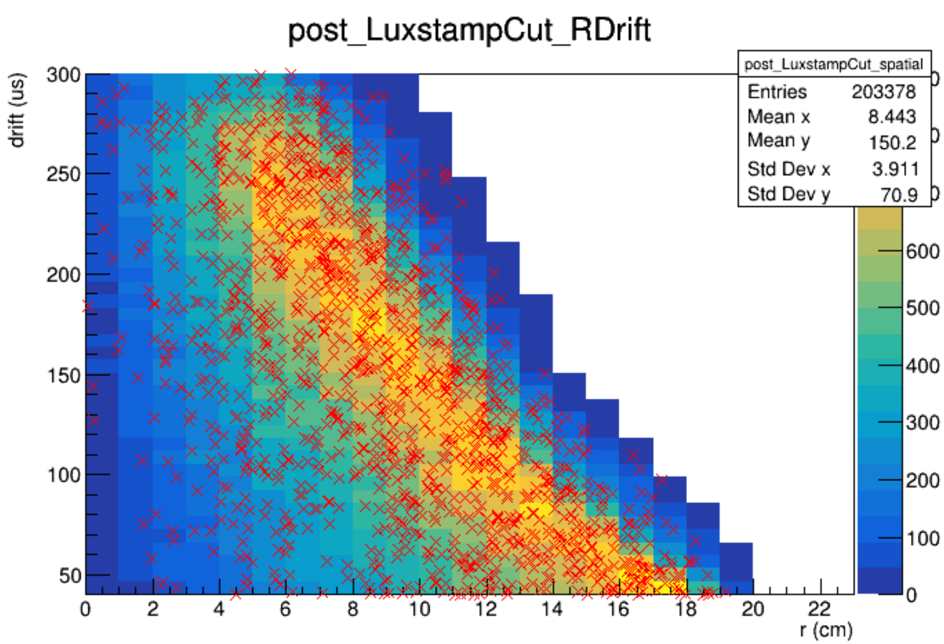




EFT Analysis - Cuts Montage

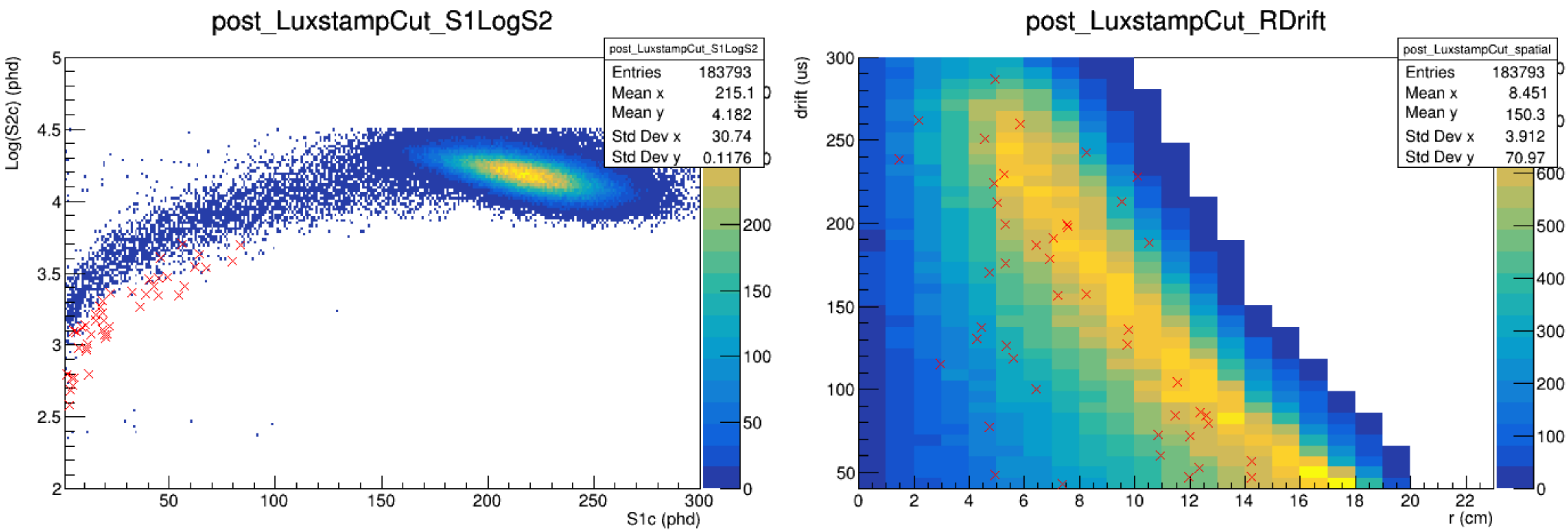
Corrupted Events





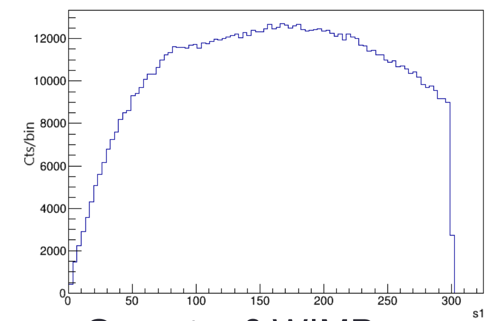
EFT Analysis - Cuts Montage

Salt: fake signal-like data injected into the data set to prevent bias.



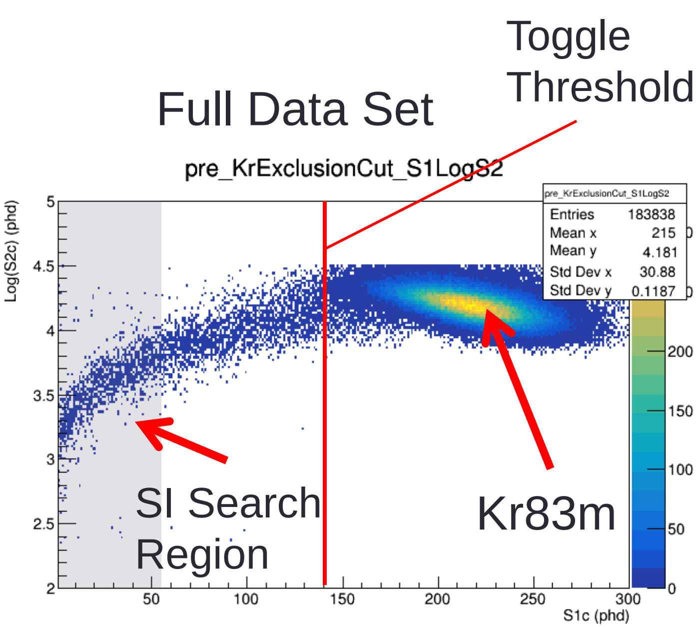
EFT Analysis – Krypton Exclusion Periods

- Unlike the low energy SI search, ^{83m}Kr is now a background.
- Exclude time surrounding ^{83m}Kr Calibrations if ROI extends above 140 phd S1.
- Exclusion window optimized by computing expected limit on Operator 6 WIMP-neutron coupling at m_x = 1000 GeV.
- Excludes additional 44.8 live days (~ 13%)

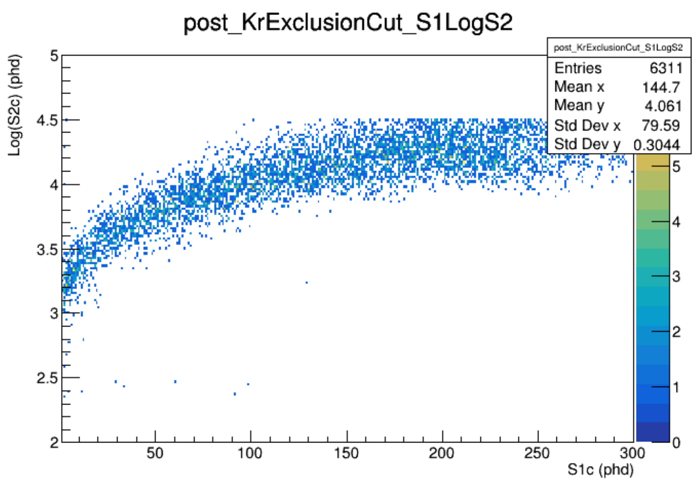


Operator 6 WIMP-n m_x = 1000 GeV Spectrum

Full Data Set

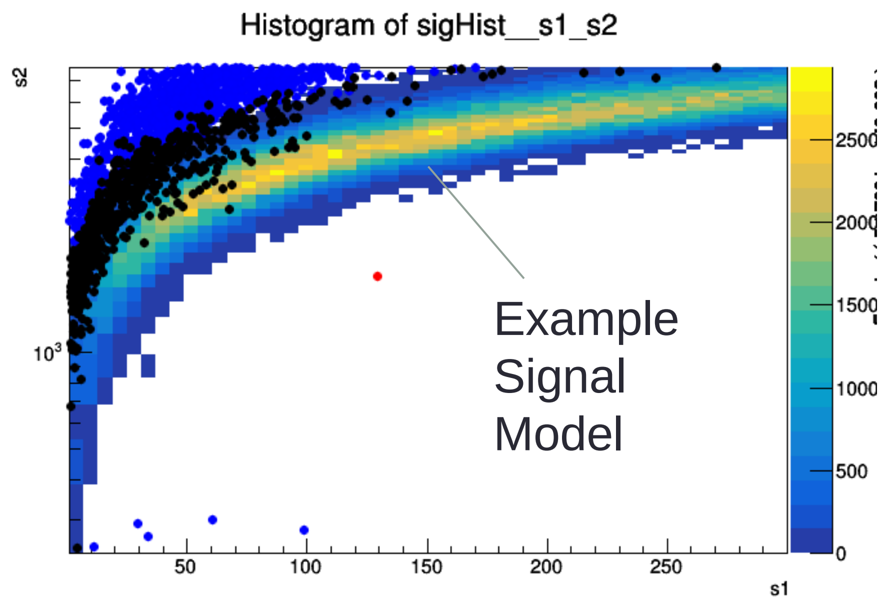


Kr Exclusion Period



EFT Analysis – Far From Model Cut

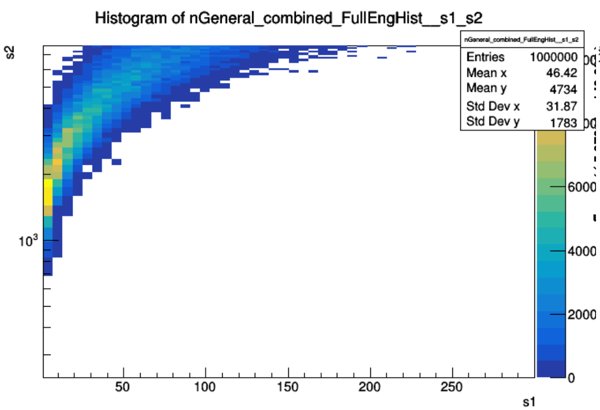
- Performed on a signal-by-signal basis
- Want to keep data consistent with signal, or that could constrain populations confused for signal.
- Cut events far from either:
  - Finely bin S2 vs S1 space
  - Evaluate probability of each bin
  - Sort bins from highest to lowest prob
  - Sum over lowest prob bins until p_{total} > 4σ tail
  - Eliminate events in these bins

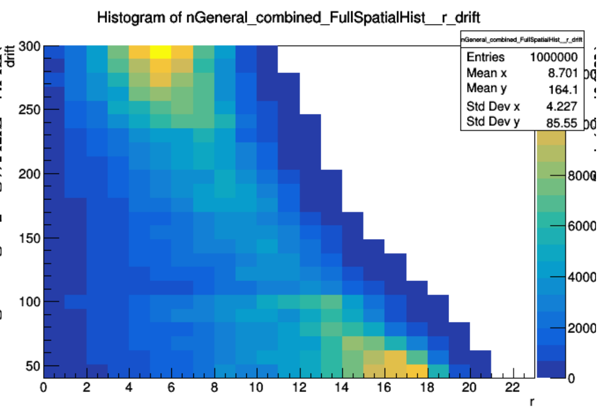


Black = Compatible with Signal
Blue = Compatible with Background
Red = Eliminated

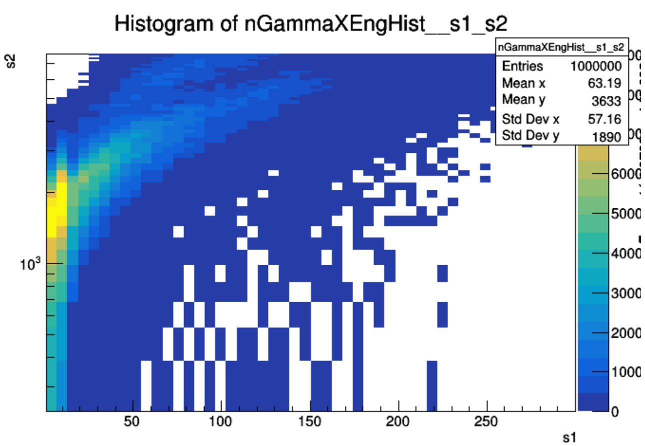
EFT Analysis – Background Models

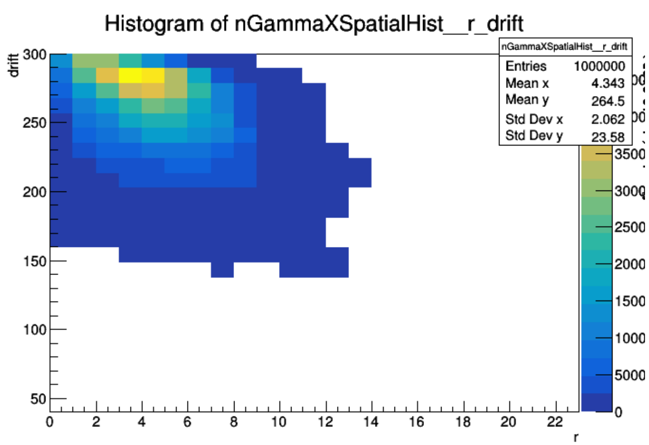
- ER





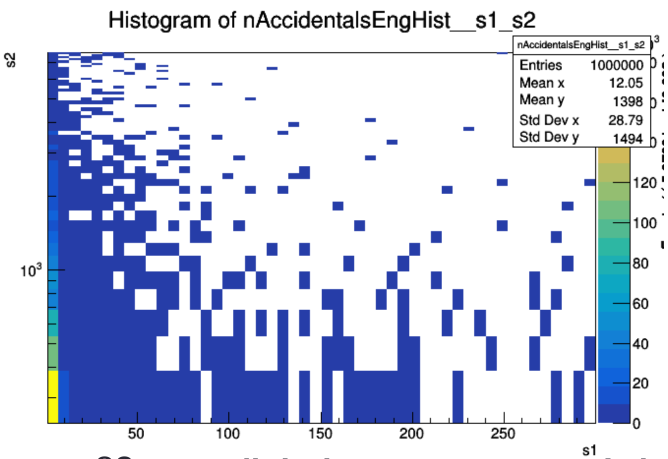
- γ-X

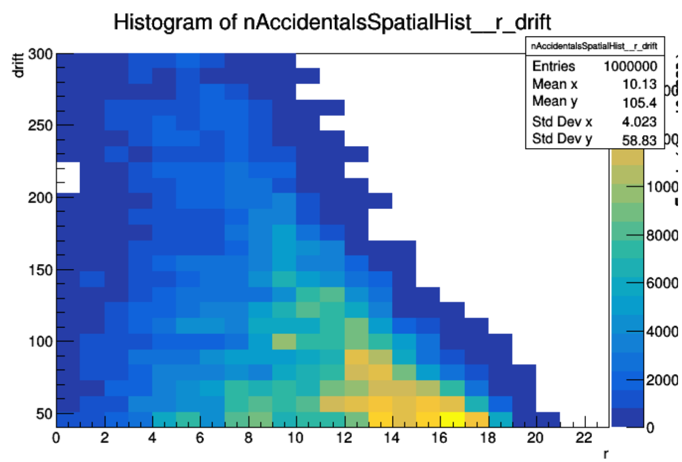




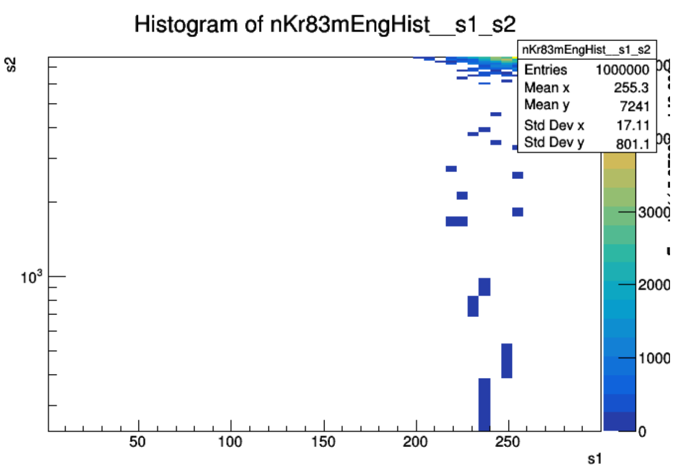
EFT Analysis – Background Models

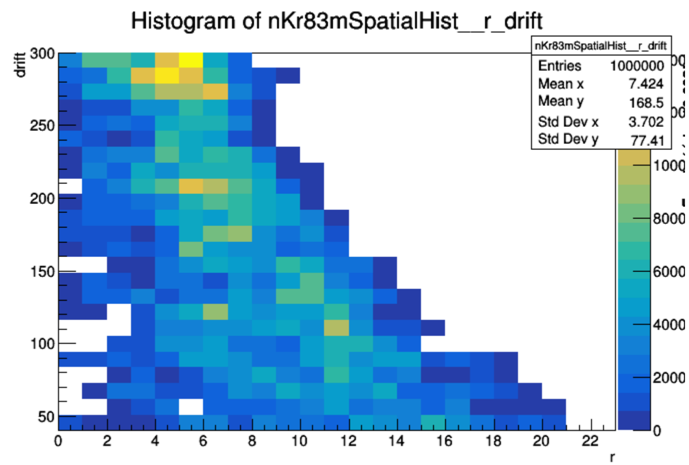
Coincidences





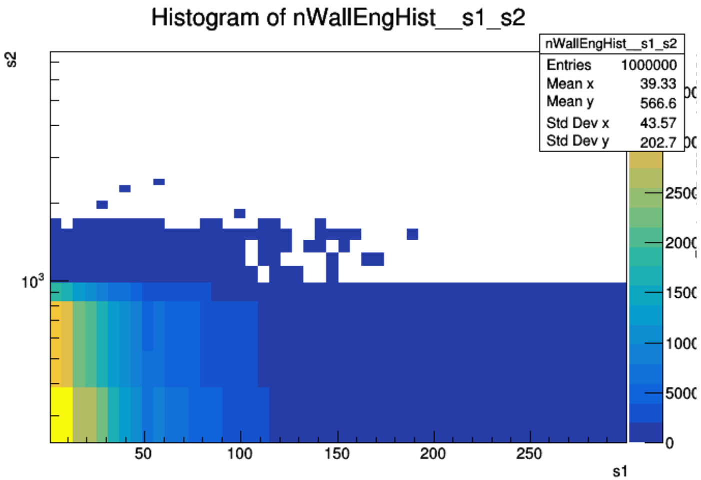
^{83m}Kr (high energy only)

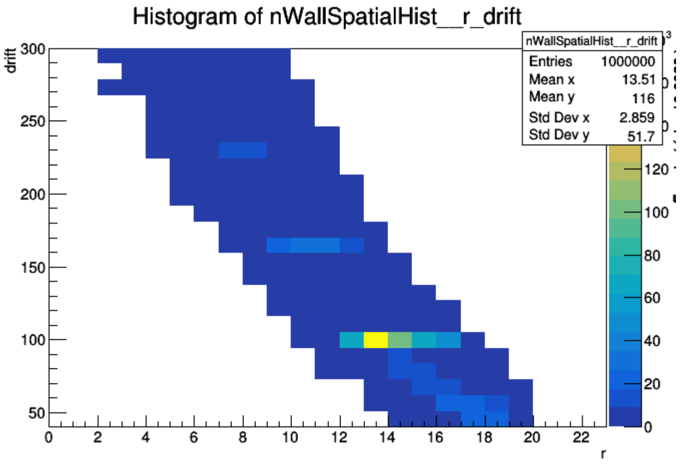




EFT Analysis – Background Models

Wall

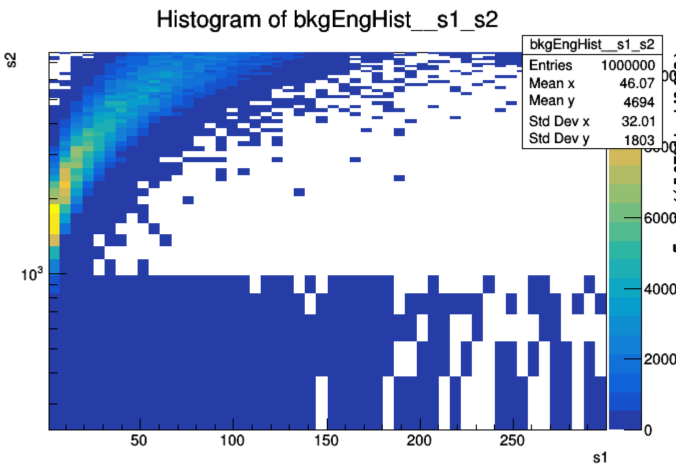


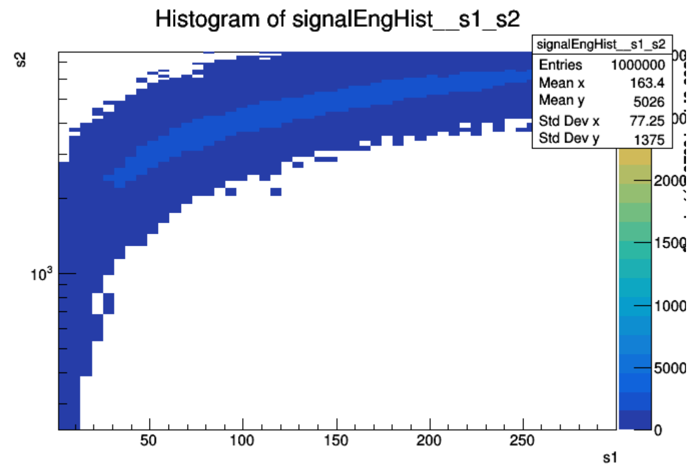


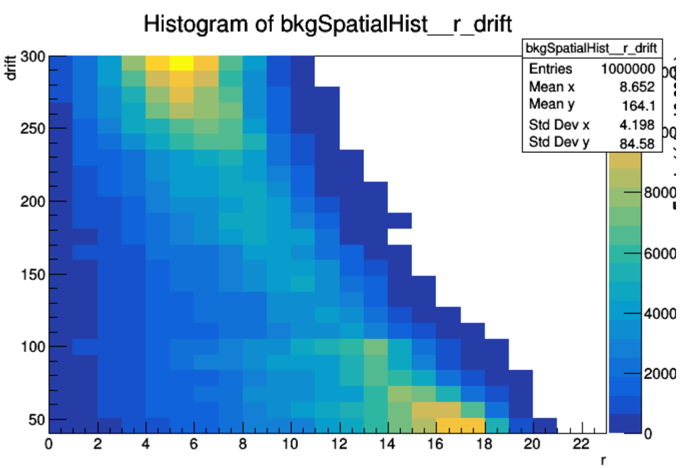
EFT Analysis - Models

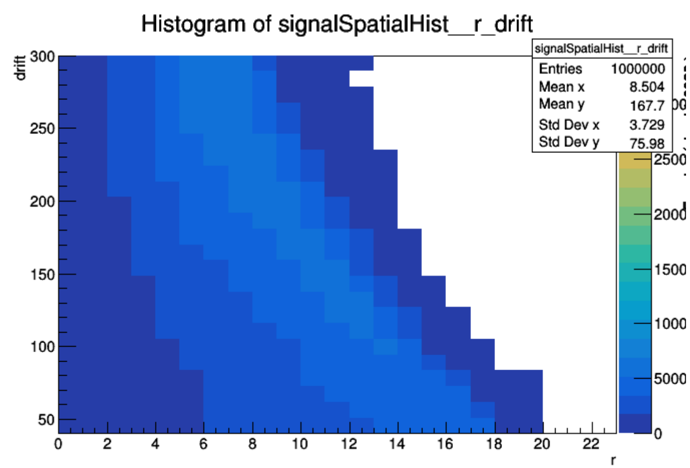
Backgrounds

Signal









EFT Analysis – Statistics – Hypothesis Tests

- Hypothesis Test: Establish consistency of a set of data with a stated hypothesis
  - Precisely state the *null hypothesis*
  - Choose a *test statistic*
  - Establish an acceptance/rejection region
  - Determine whether the test statistic lies in the acceptance region, or the rejection region.
- Hypothesis test with an *alternative hypothesis*: reject one hypothesis *in favor* of another
- Two possible errors:
  - Type I: True null hypothesis is rejected
  - Type II: False null hypothesis is accepted
- Two important quantities to measure a hypothesis test's effectiveness:
  - Significance: Fraction of the time a Type I error is made
  - Power: 1 – Fraction of the time a Type II error is made

EFT Analysis – Statistics – Profile Likelihood Ratio

- Neyman Pearson Lemma:
  - If H_0 and H_1 *simple* best choice is $$T(\vec{X}) = \lambda(\vec{X}) = \frac{\mathcal{L}_M\left(\vec{\theta_0}\middle|\vec{X}\right)}{\mathcal{L}_M\left(\vec{\theta_1}\middle|\vec{X}\right)}$$
  - With acceptance region $A = \{\lambda | p(\lambda) > 1 - \alpha\}$
  - Where $p(\lambda)$ is the *p-value* of the result.
    - The p-value is the fraction of the time one would get a more extreme result assuming H_0 is true.

- Our hypotheses are **not** simple: use the model that best fits the data for each hypothesis, weighted by auxiliary measurements or priors:

$$H_0 : \mu = \mu_0$$
$$H_1 : \mu \neq \mu_0$$

$$\lambda(\vec{X}) = \frac{\mathcal{L}_{M+P}\left((\mu_0, \hat{\hat{\theta}})\middle|\vec{X}\right)}{\mathcal{L}_{M+P}\left((\hat{\mu}, \hat{\theta})\middle|\vec{X}\right)}$$

$$\mathcal{L}_{M+P}\left((\mu, \vec{\theta})\middle|\vec{X}\right) = \mathcal{L}_M\left((\mu, \vec{\theta})\middle|\vec{X}\right)\mathcal{P}_\theta(\vec{\theta})$$

  - $\hat{\mu}$, $\hat{\theta}$, and $\hat{\hat{\theta}}$ are the values of parameters that maximize their respective likelihoods (are the best fit to the data)

EFT Analysis – Statistics – LUX Likelihood

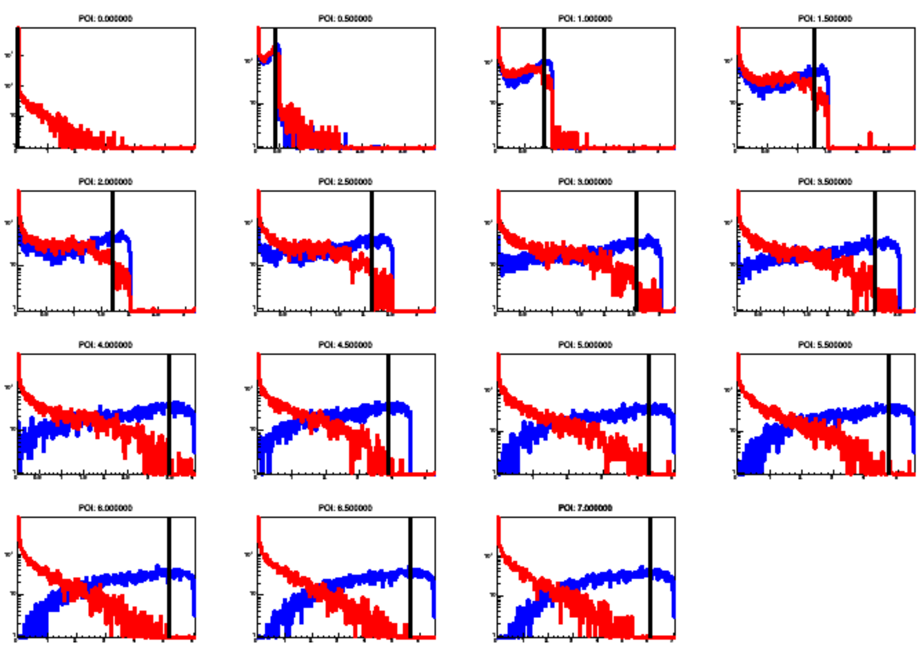
$$\mathcal{L}\left(\left(\mu,\vec{\theta}\right)\middle|\vec{X}\right) = \mathrm{Pois}\left(n_{\mathrm{obs}};n_{\mathrm{exp}}\right) \cdot \prod_{\vec{x}_i\in\vec{X}}\left[n_{\mathrm{sig}}R_{\mathrm{sig},t_i,z_i}\mathcal{P}_{\mathrm{sig},t_i,z_i}\left(\vec{\mathcal{O}}_i\right) + \sum_{b_j} n_{b_j}R_{b_j,t_i,z_i}\mathcal{P}_{b_j,t_i,z_i}\left(\vec{\mathcal{O}}_i\right) + n_{\mathrm{wall}}R_{\mathrm{wall},t_i,z_i}\mathcal{P}_{\mathrm{wall},t_i,z_i}\left(\vec{\mathcal{O}}_i\right)\right] \cdot \prod_{\theta_i\in\vec{\theta}}\mathcal{P}_i\left(\theta_i\right)$$

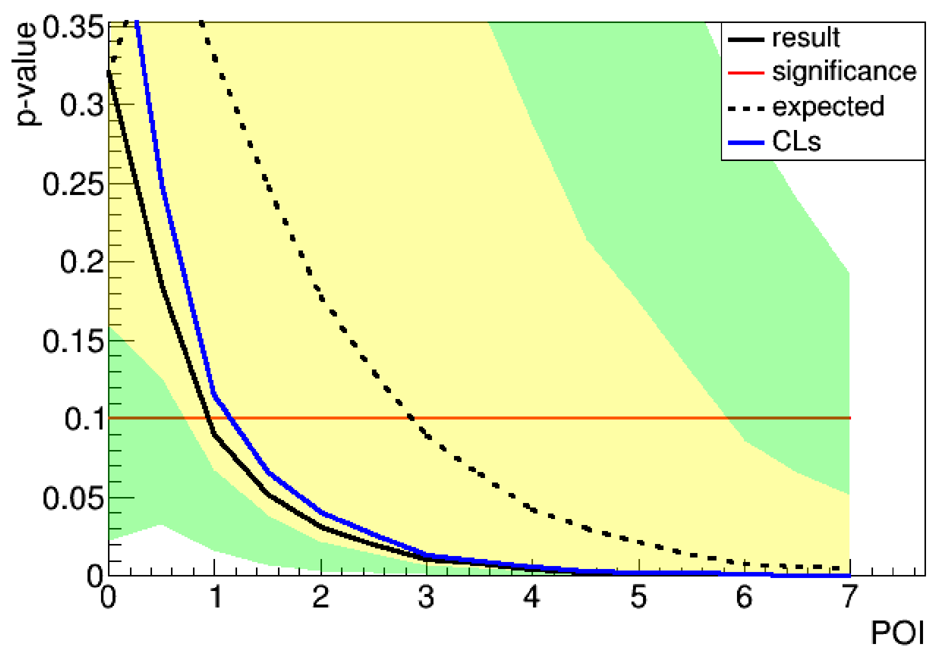
- POI: n_{sig}
- n = number of events we expect from that source
- R = Fraction of those events we expect from that sub-detector (time bin/z-slice)
- $\mathcal{P}$ = the PDF describing that source (or np)
- θ = a parameter describing the model (nuisance parameter)
- The wall model is special, it isn't split like the others shown below.

$$\mathcal{P}_{\mathrm{source},t_i,z_i}\left(\vec{\mathcal{O}}_i\right) \equiv \mathcal{P}_{\mathrm{source},t_i,z_i}\left(r_i,\mathrm{drift}_i,\phi_i\right)\mathcal{P}_{\mathrm{source},t_i,z_i}\left(\mathrm{S1c}_i,\mathrm{S2c}_i\right)$$

EFT Analysis – Statistics - Hypothesis Test Inversion

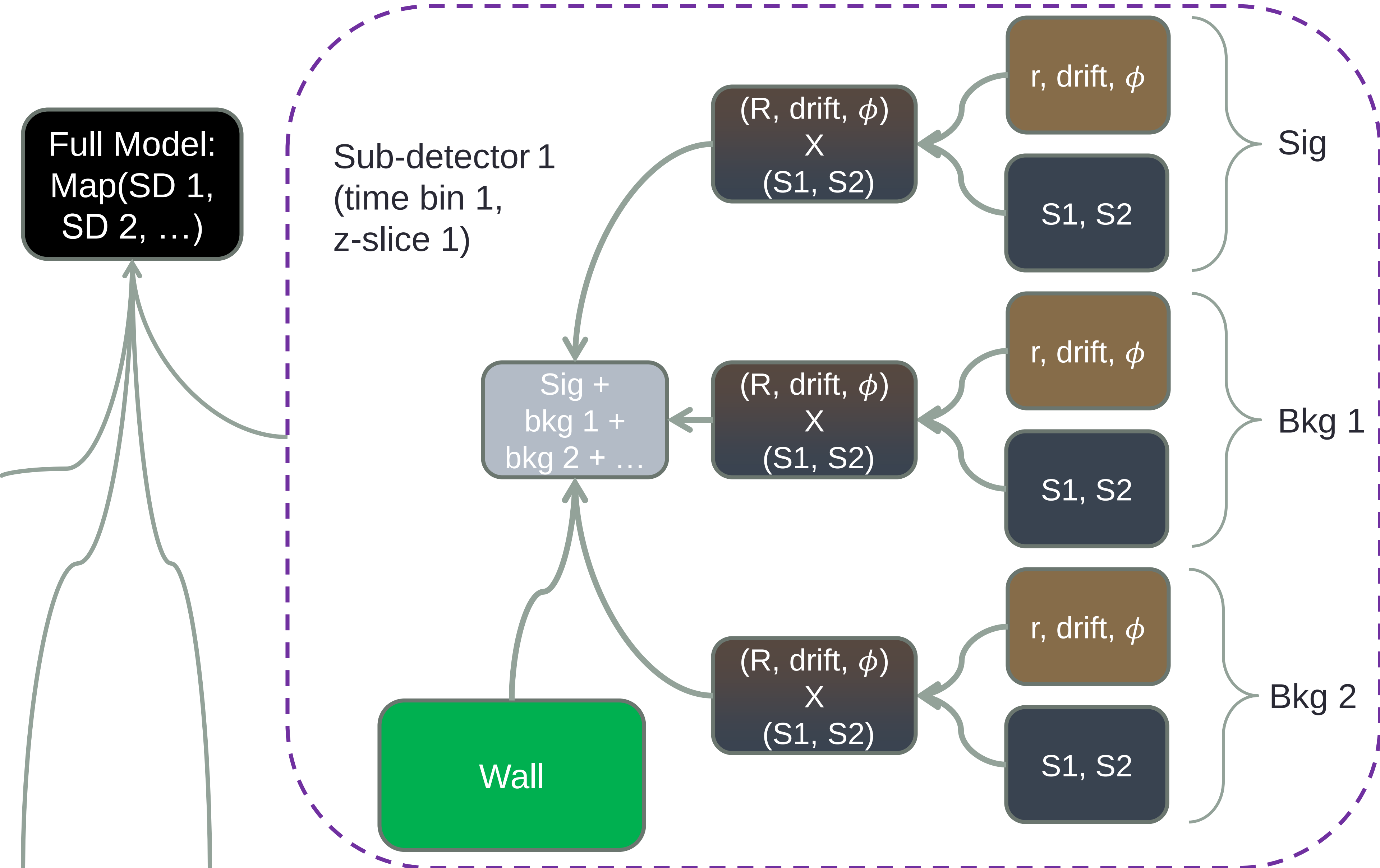
- perform a series of hypothesis tests with varying, but related hypotheses:
  - H_0: $\mu = \mu_0$
  - H_1: $\mu \neq \mu_0$ ($\mu < \mu_0$ for one-sided)
- values of μ_0 whose hypothesis tests yield a p-value greater than 0.1 form the 90% confidence interval.





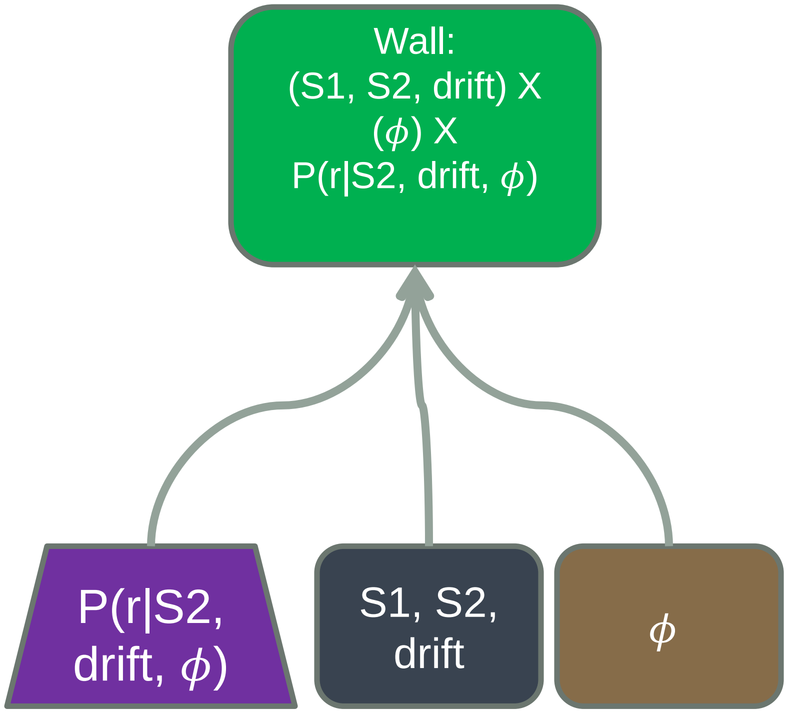
EFT Analysis – PLR Implementation

- Re-wrote PLR
  - Flexibility
  - Efficiency
  - Ease of understanding
  - Parallel processing


Full Model: Map(SD 1, SD 2, …)
Sub-detector 1 (time bin 1, z-slice 1)
Sig + bkg 1 + bkg 2 + …
(R, drift, ϕ) X (S1, S2)
r, drift, ϕ
S1, S2
Sig
(R, drift, ϕ) X (S1, S2)
r, drift, ϕ
S1, S2
Bkg 1
(R, drift, ϕ) X (S1, S2)
r, drift, ϕ
S1, S2
Bkg 2
Wall

EFT Analysis –PLR Implementation Wall Model

- Full 5D model
  - Wall position depends on depth, ϕ
  - Wall σ depends on S2
  - Radial distribution depends on wall position and σ



Wall Radial distribution modeled by
$M*Gaus(r|\ R_{wall}, \sigma_1)$ +
$(1 – M)*Gaus(r|\ R_{wall}, \sigma_2)$

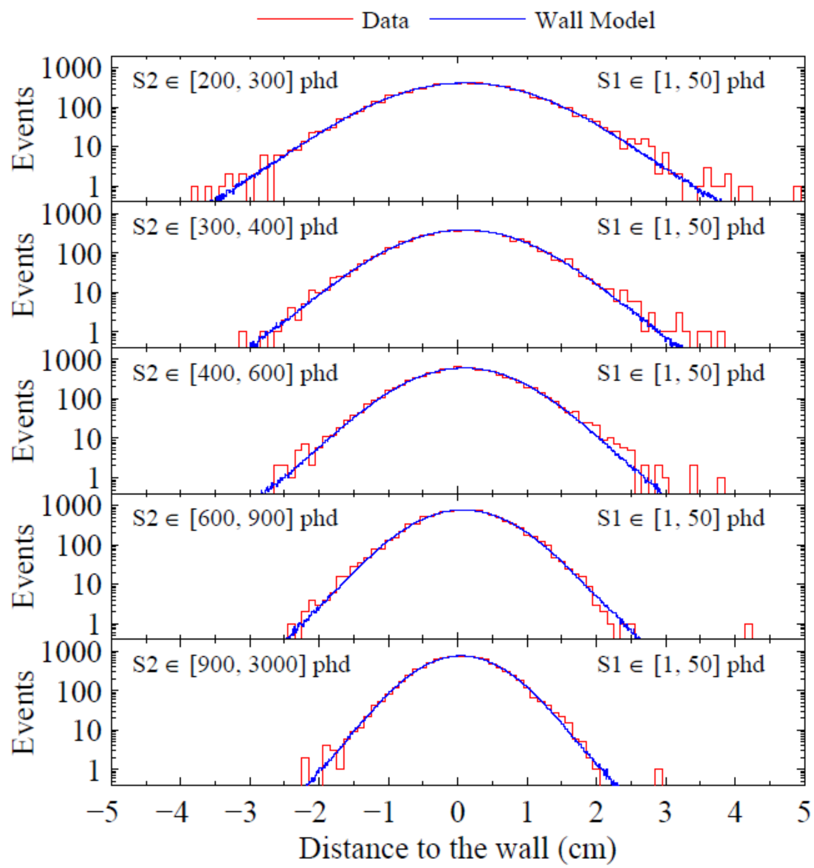
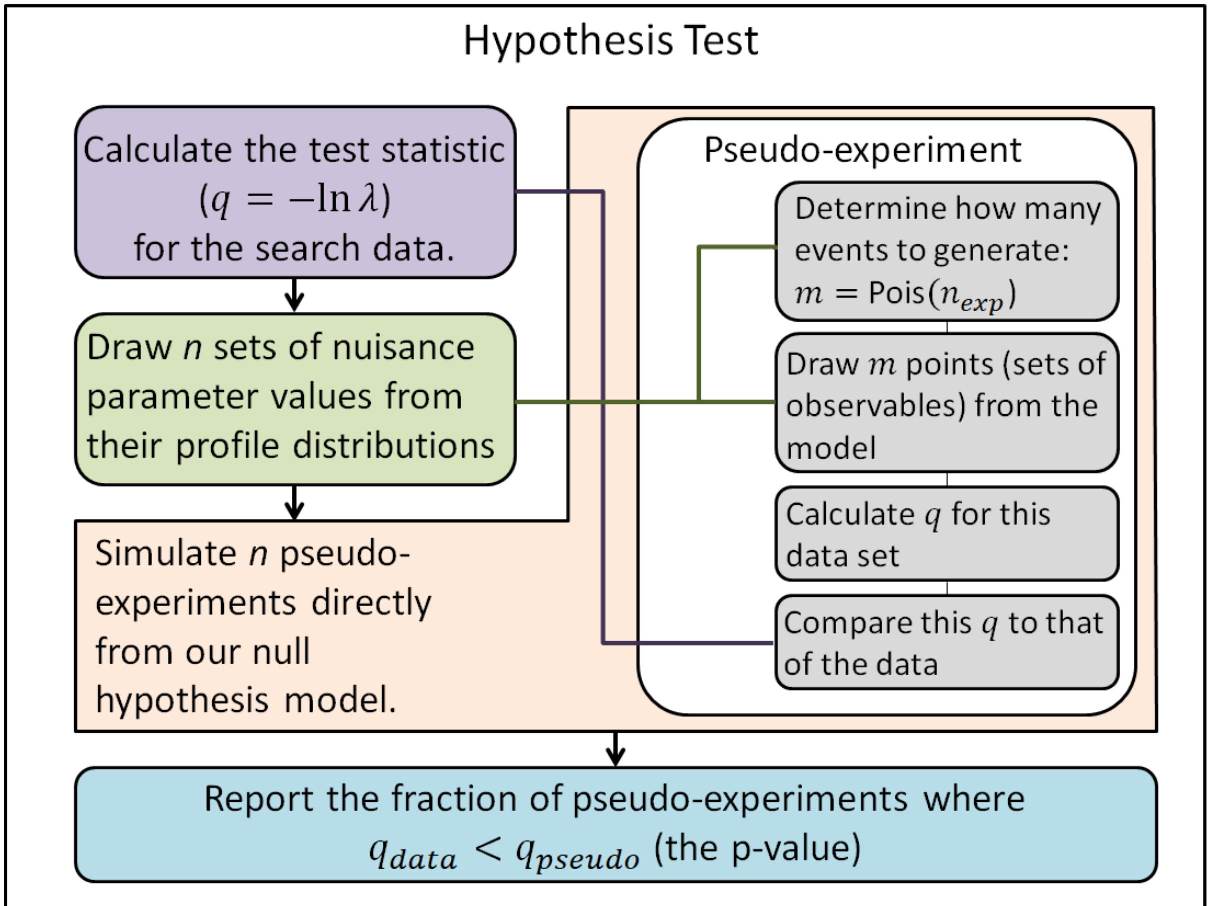
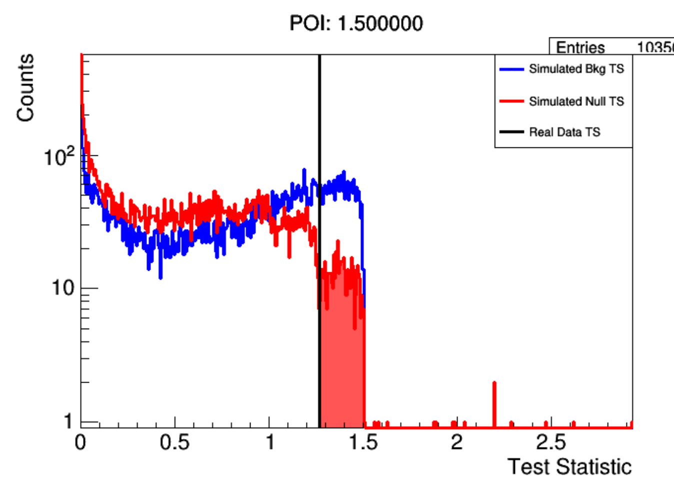


Figure from Claudio in LUX

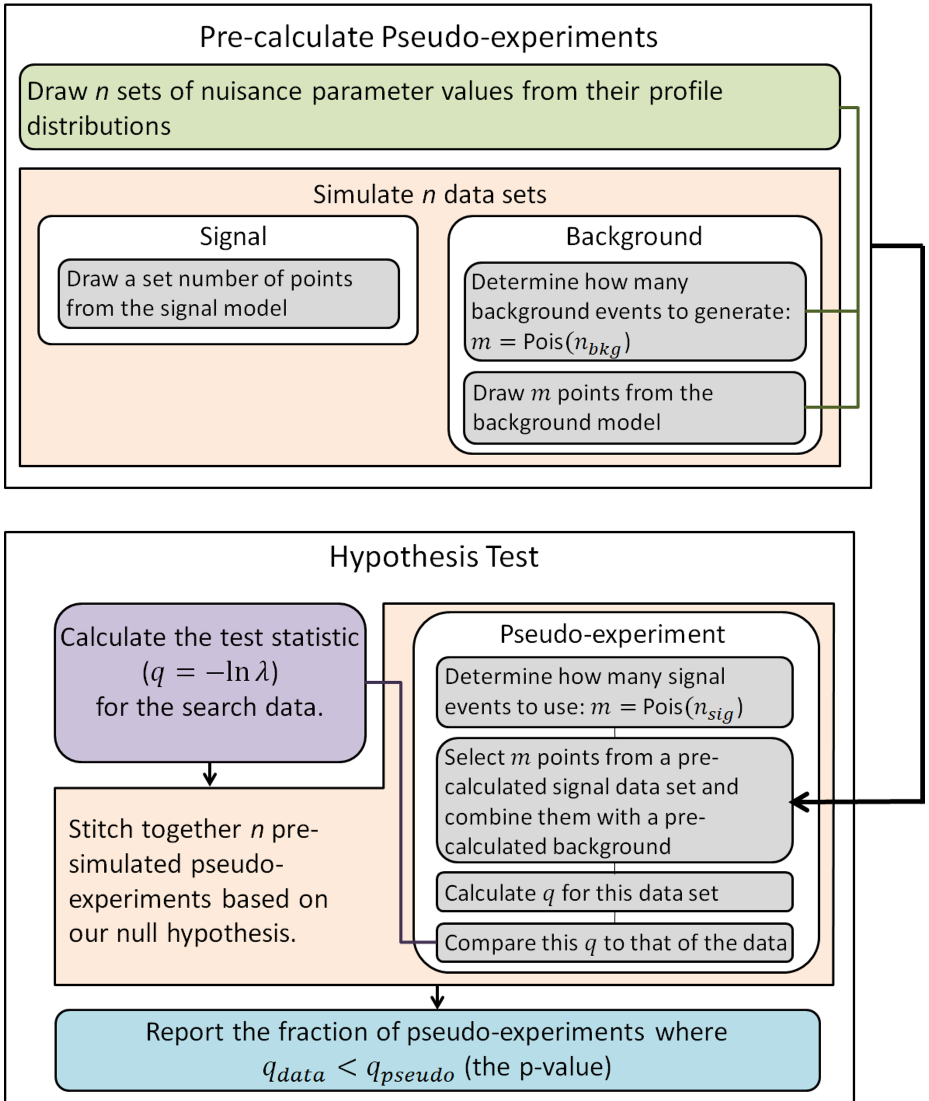
EFT Analysis – PLR Implementation – Hypothesis Test





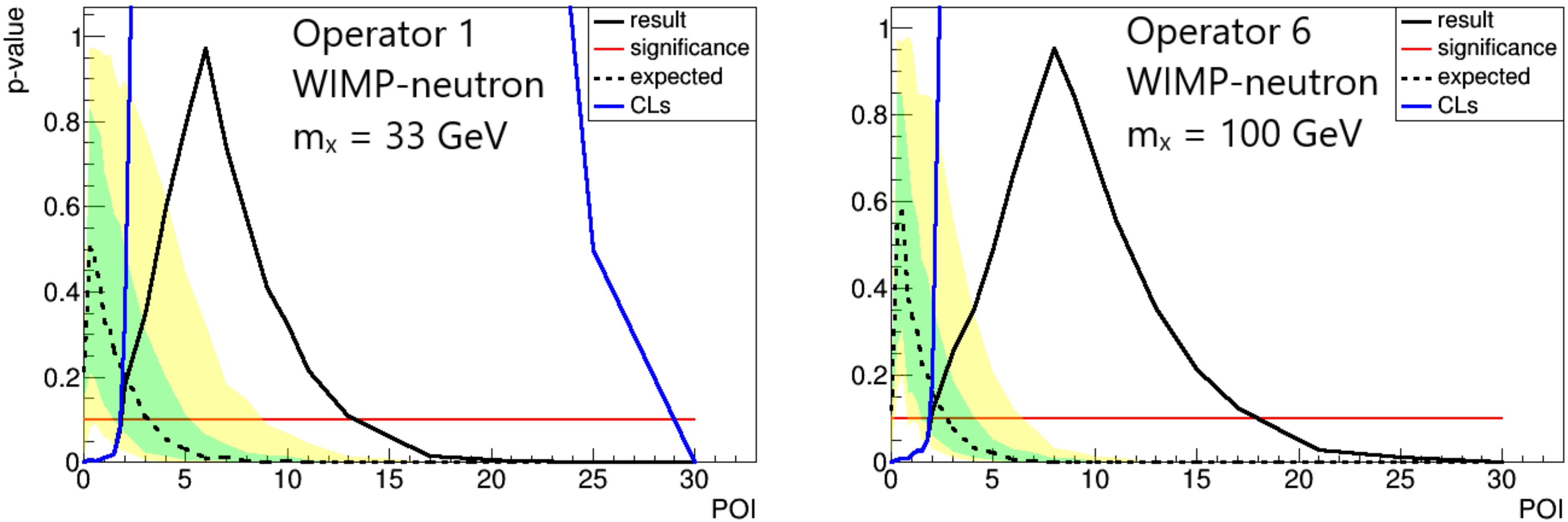
EFT Analysis – PLR Implementation – Toy Pre-generation

As long as POI only changes the ratio of PDFs, not their fundamental shape, can re-use psuedoexperiments.



EFT Analysis - Limits

- Inconsistent with n_{sig} = 0 for many operators
- Believed to be because of mis-modeled leakage from the ER background model
  - A lot of effort put into addressing this, but not fully there yet.

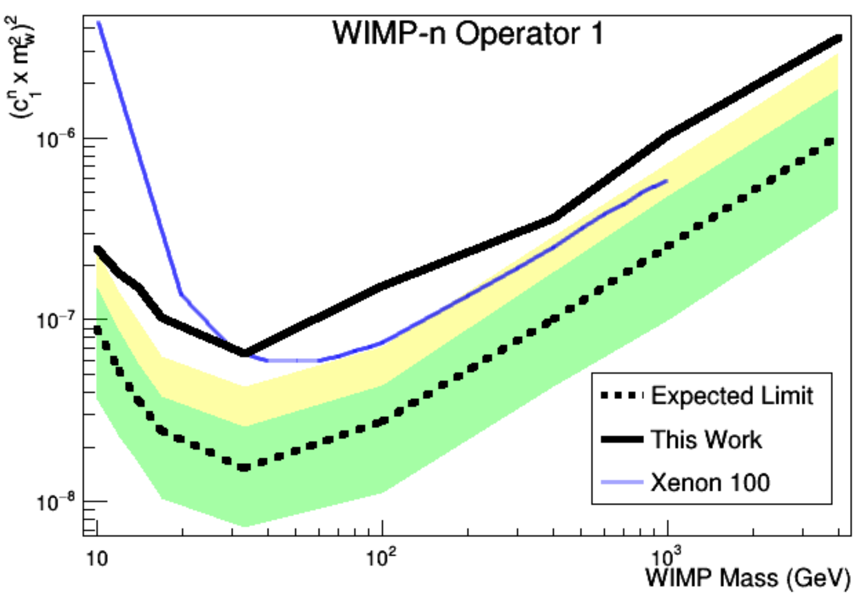


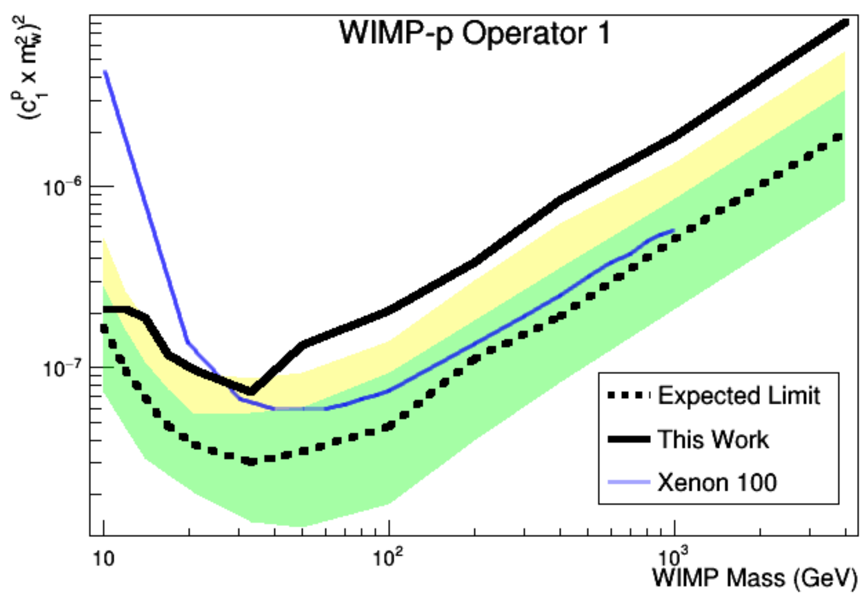
$$\frac{dR}{dE_R} = \frac{c_i^{(N)^2} \rho_0}{32\pi m_\chi^3 m_N^2} \int_{v>v_{min}} \frac{f(\vec{v})}{v} F_{i,i}^{(N,N)}\left(v^2, q^2\right) \mathrm{d}v$$

EFT Analysis - Limits

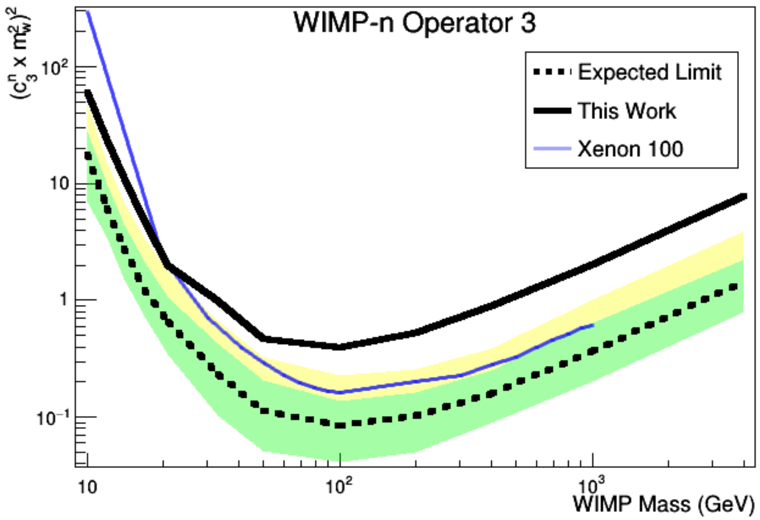
Limits plotted against Xenon 100 results for comparison

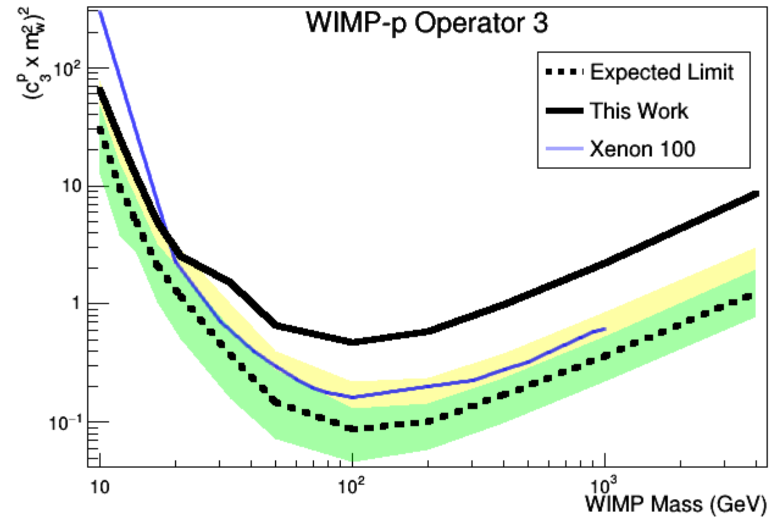
Caveat: not true comparison – their result uses the WIMP-isoscalar ($c^0 = c^n + c^p$) coupling.

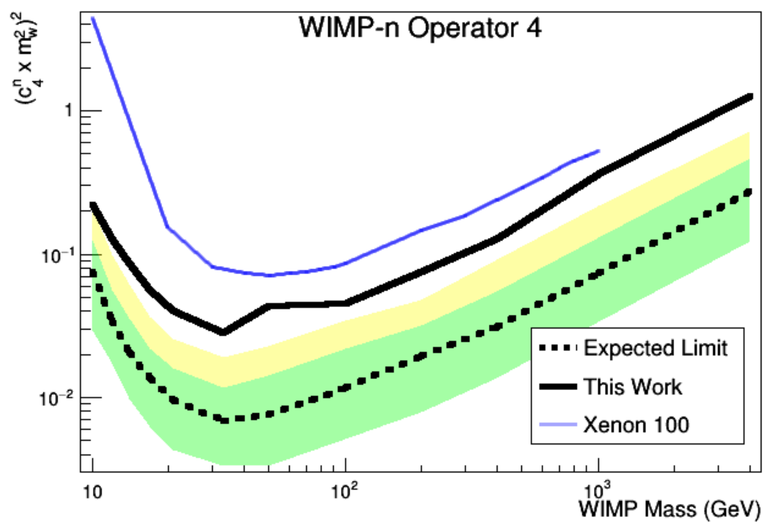


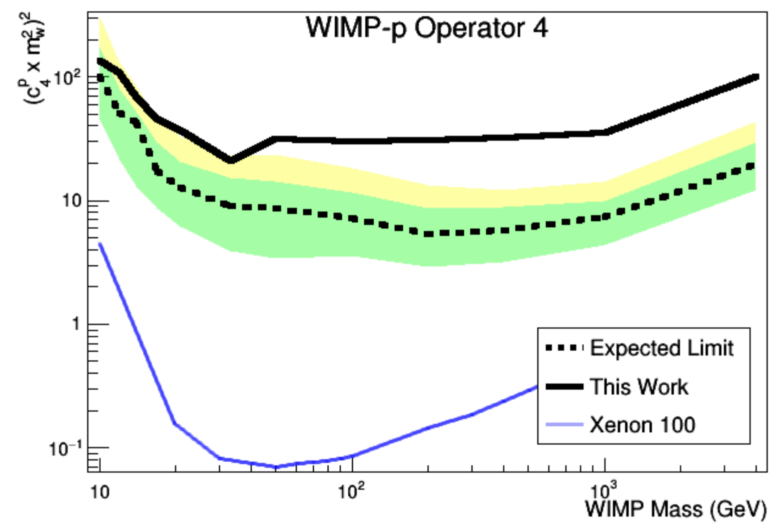


EFT Analysis - Limits

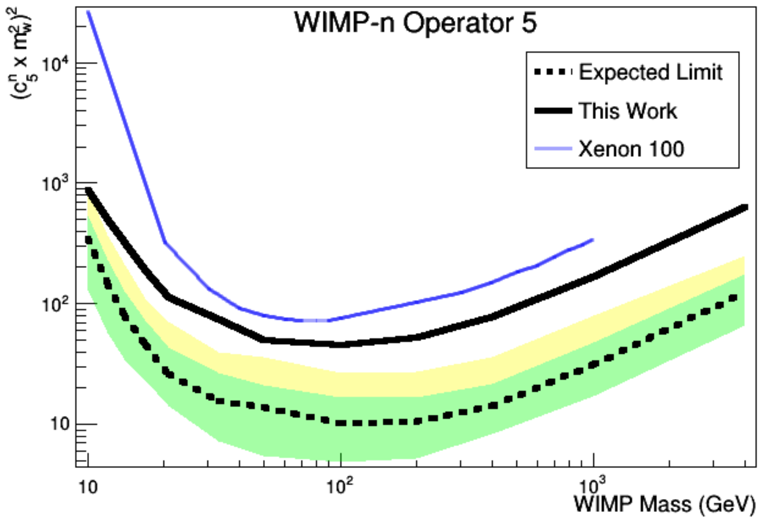


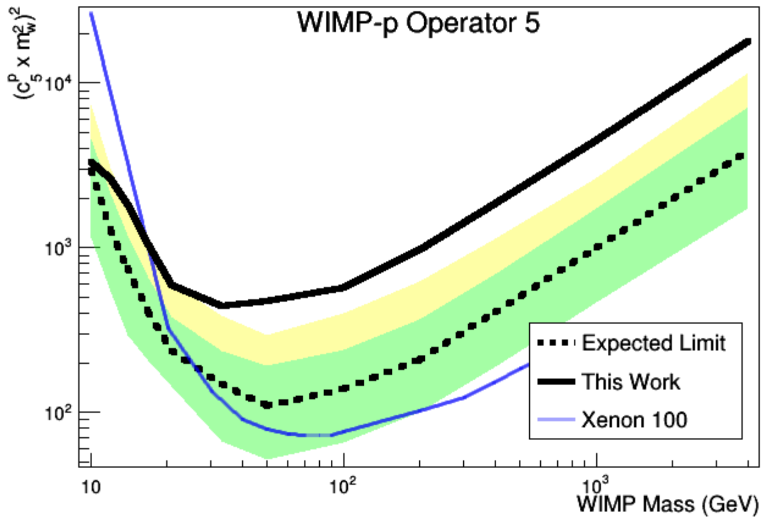


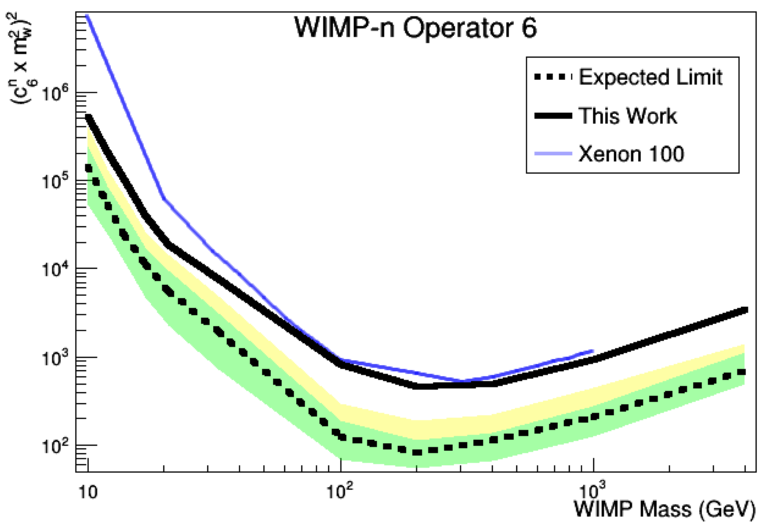


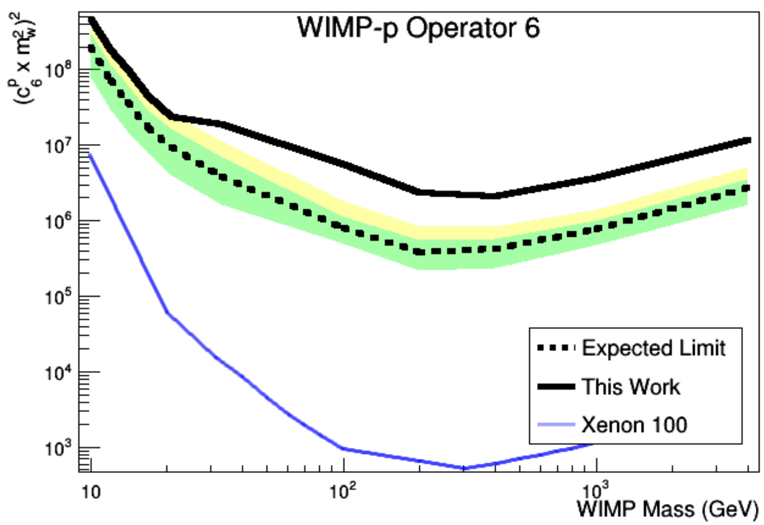


EFT Analysis - Limits

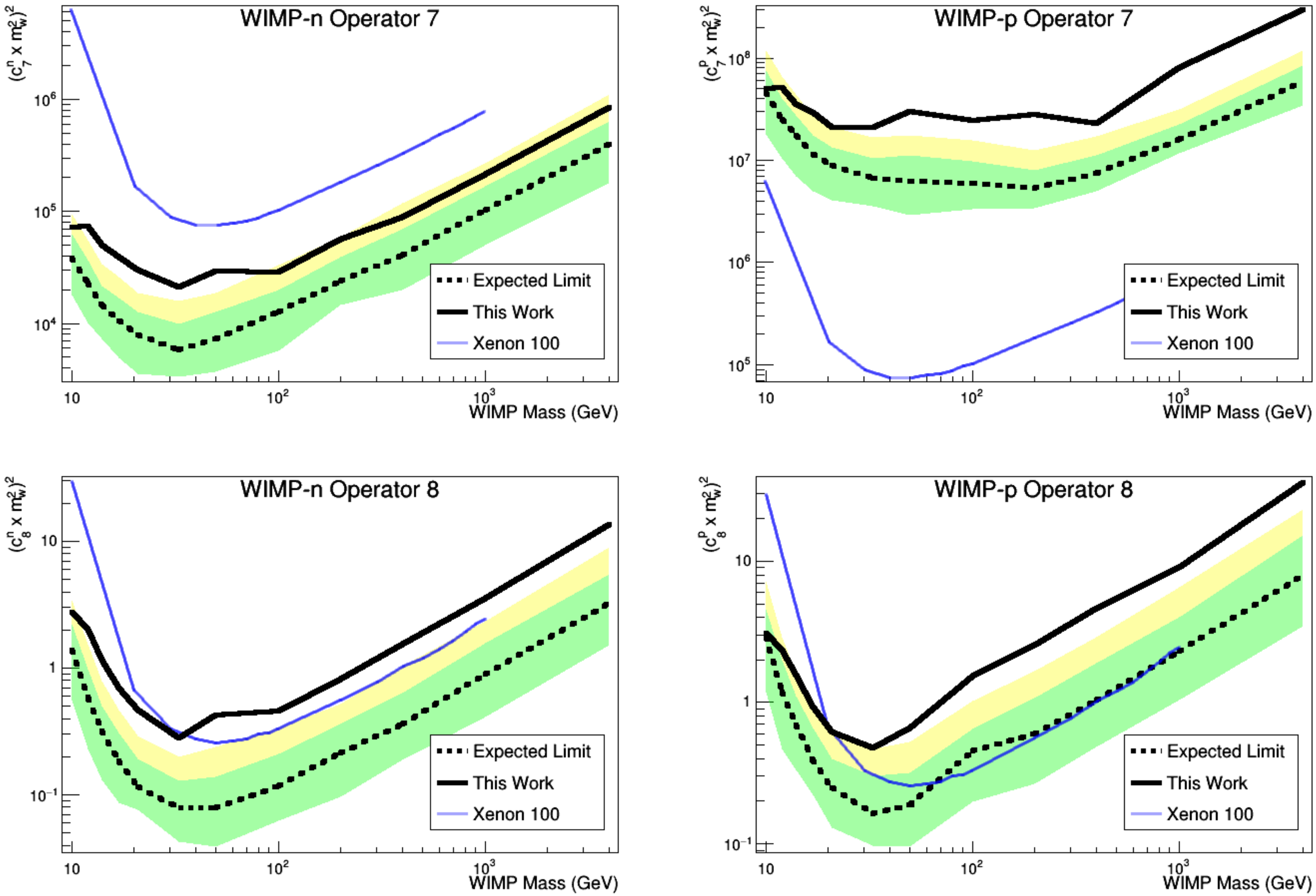




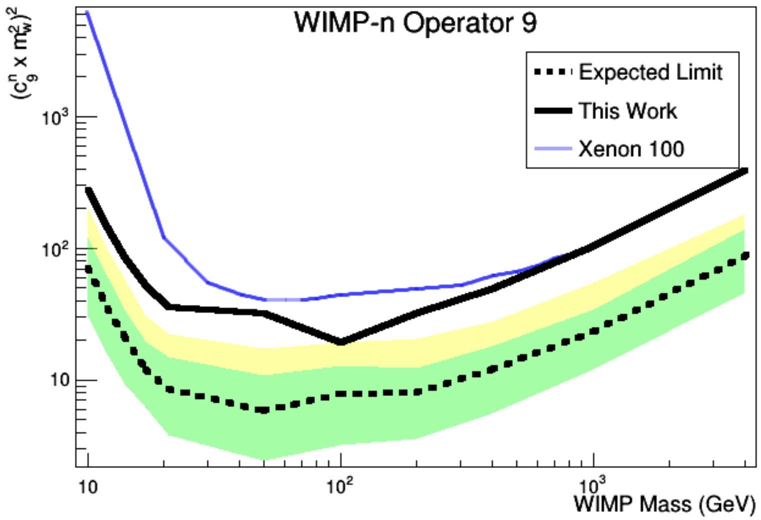


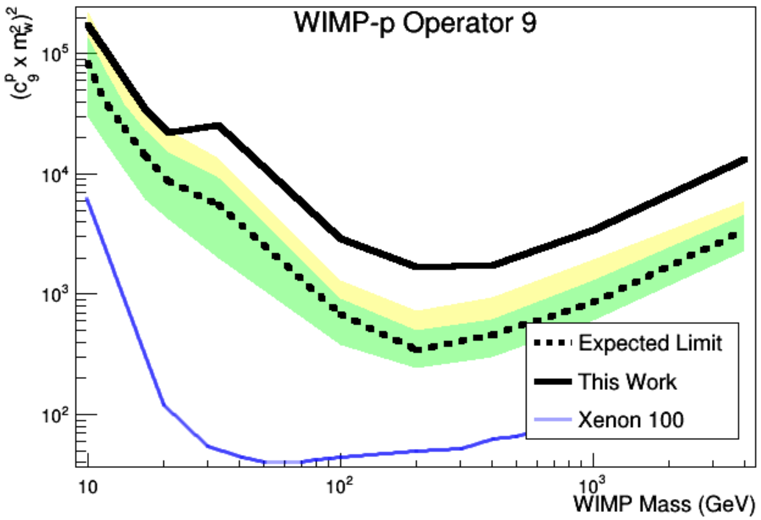


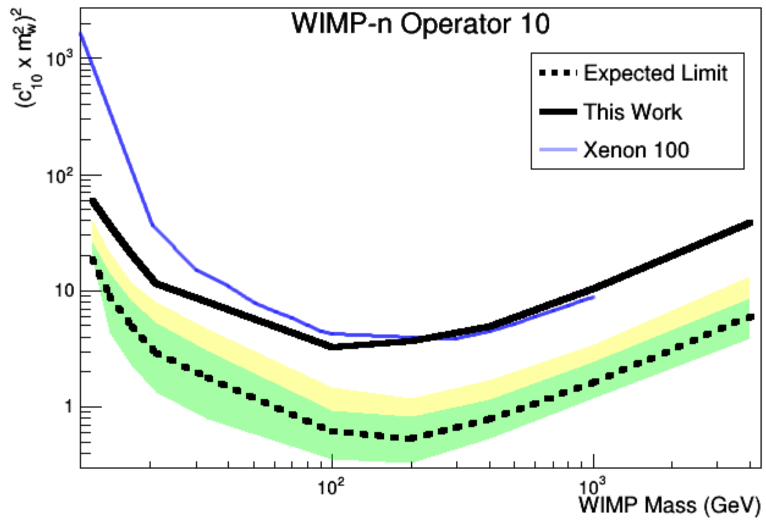
EFT Analysis - Limits

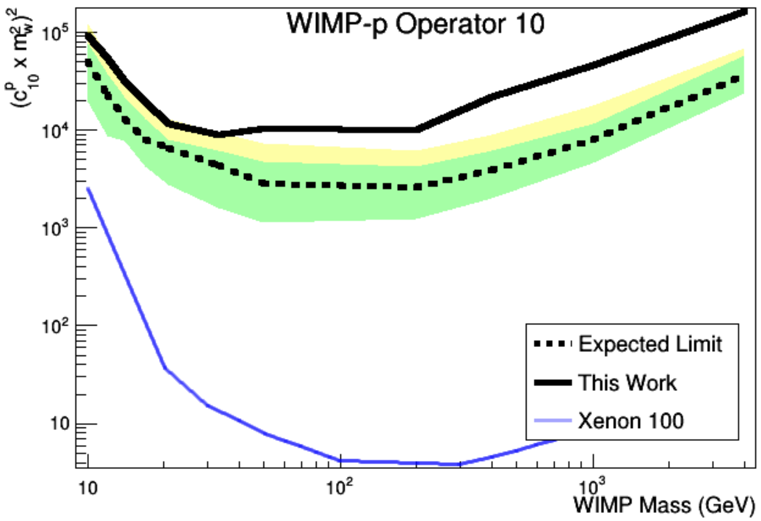


EFT Analysis - Limits

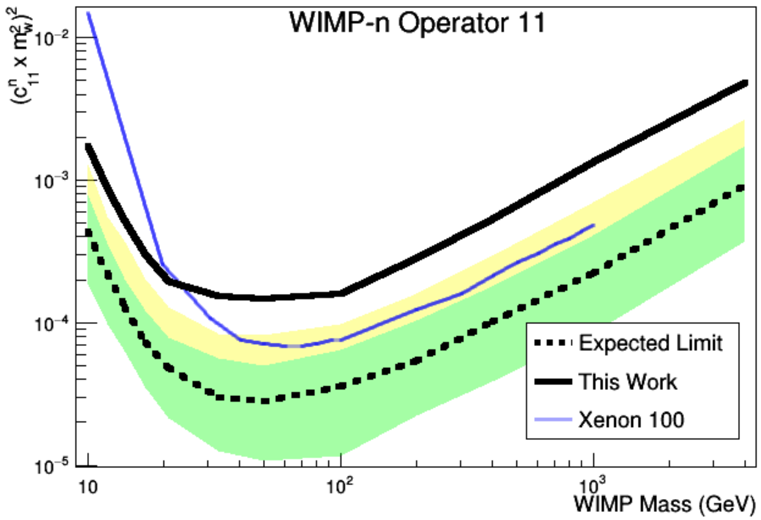


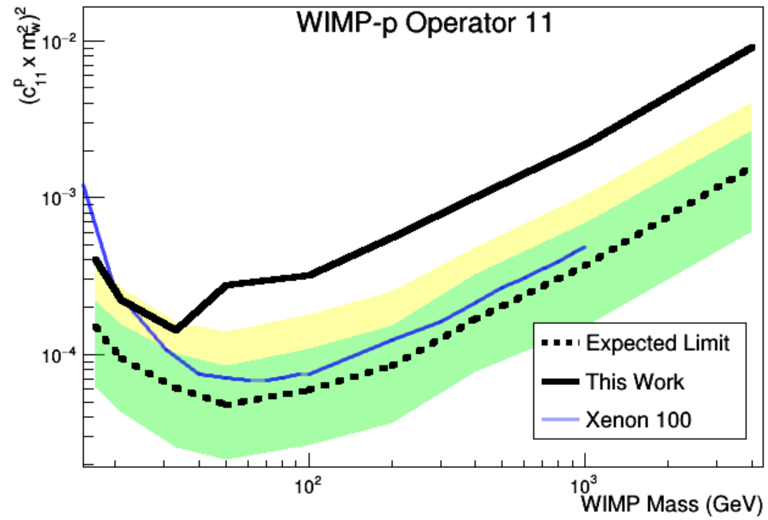


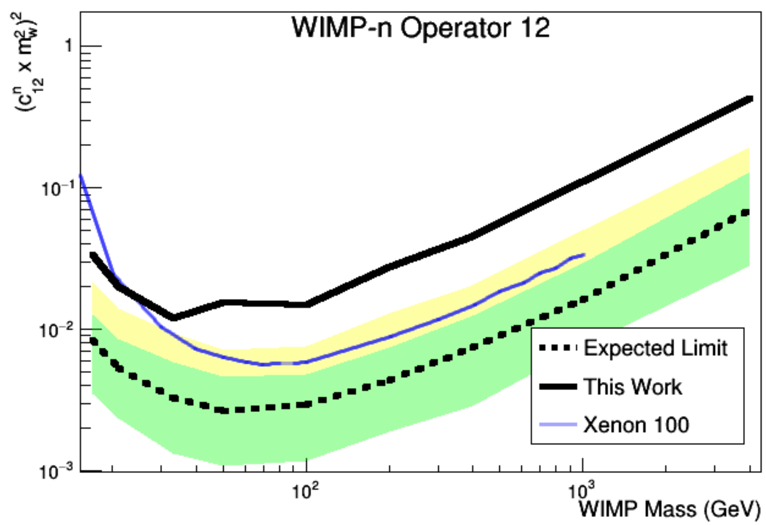


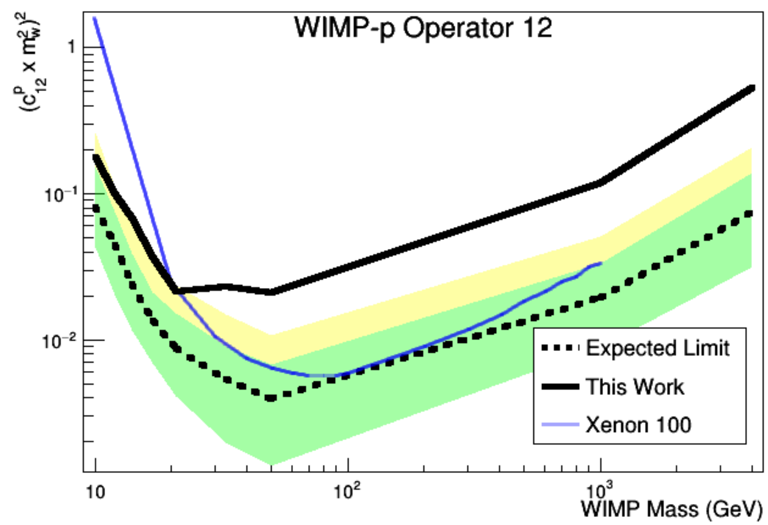


EFT Analysis - Limits

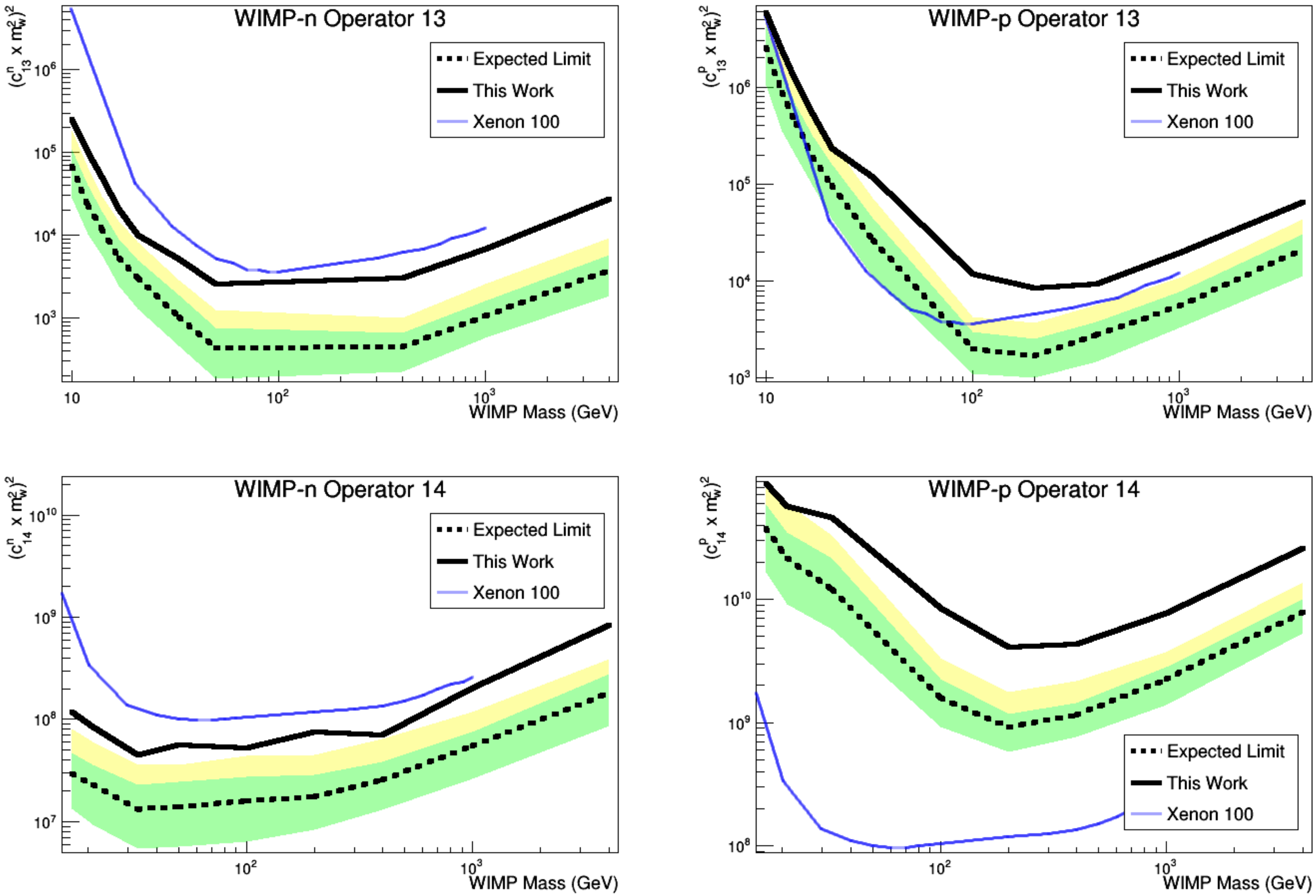




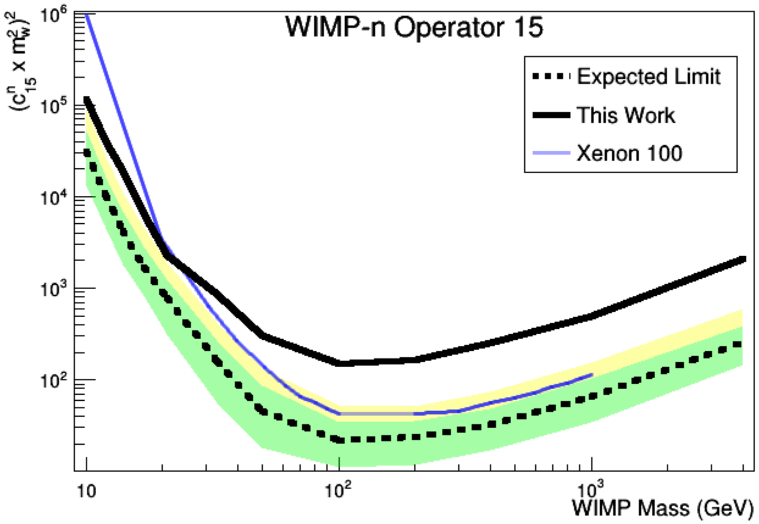


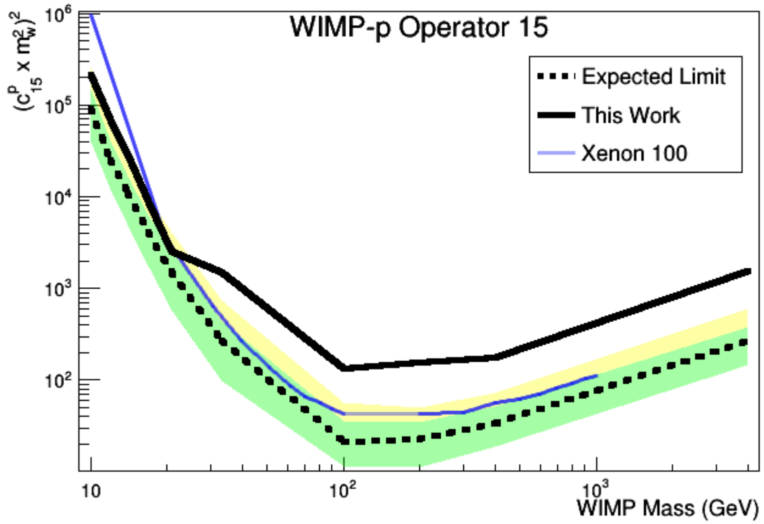


EFT Analysis - Limits



EFT Analysis - Limits





EFT Analysis - Summary

- EFT provides a model-independent way of limiting interaction types
- Some interactions peak at energies higher than the SI search window
- Data Quality Cuts were re-developed to extend to higher energies (and be more comprehensive)
- Background Models were re-developed to extend to higher energies
- The Profile Likelihood Ratio test statistic was used in a hypothesis test inversion to put bounds on the EFT couplings.
- In most cases, data was found to be inconsistent with the background-only model with significance α
  - This is suspected to be due to the ER background model underestimating leakage down into the NR band region
- Calculated limits are on par with those computed by the xenon 100 experiment, though a direct comparison could not immediately be made.

Overall Summary

- Dark Matter exists
- We can search for it with direct detection experiments like LUX and LZ
- Time Projection Chambers are cool
- I helped LUX get a good limit on the spin-independent cross-section
- I built, designed, and operated auxiliary detectors at SLAC
- I set limits on a plethora of EFT couplings


LUX

Backup

Bin Defs

Time Bin	1	2	3	4
Dates	2014/09/09 - 2014/12/31	2015/01/01 - 2015/03/31	2015/04/01 - 2015/09/30	2015/10/01 - 2016/05/03
Live Days	46.8	46.7	91.6	146.9

Table 6.1: Time Bin Definitions and Live Times.

z-slice	1	2	3	4
slice definition	40 - 105 µs	105 - 170 µs	170 - 235 µs	235 - 300 µs
Time Bin 1	31.85 kg	28.24 kg	24.92 kg	20.36 kg
Time Bin 2	33.10 kg	29.19 kg	24.92 kg	19.99 kg
Time Bin 3	31.40 kg	26.97 kg	22.84 kg	17.97 kg
Time Bin 4	32.01 kg	27.00 kg	22.57 kg	16.83 kg

Table 6.2: Definitions of the z-slices and the active mass contained in the fiducial volume for each time bin z-slice combination.