Detecção Directa de Matéria Escura com a Experiência LUX-ZEPLIN

Direct Detection of Dark in the LUX-ZEPLIN Experiment

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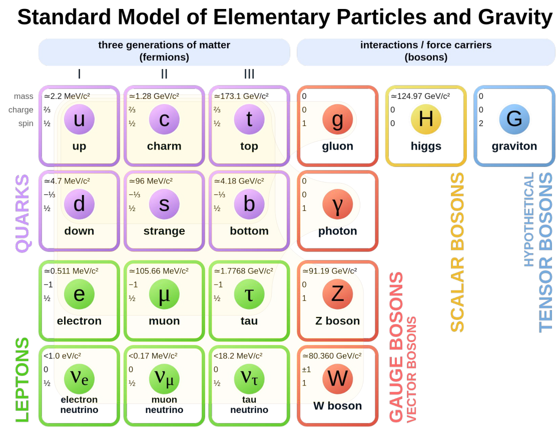
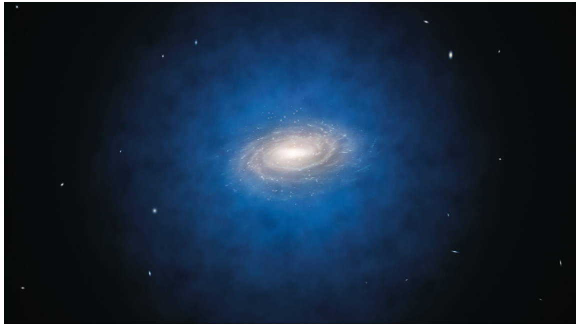
What is Dark Matter?

- There are certain phenomena in physics that cannot be explained by gravity using only the Standard Model, like the rotation of galaxies, gravitational lensing, and others
- This led scientists to hypothesise about a new type of matter, dark matter, outside of the Standard Model, which should represent 85% of the Universe's matter content
- In order to agree with observations, it should have neutral electric charge, and its mass must be non-zero
- A leading candidate for dark matter are called WIMPs (Weakly Interacting Massive Particles)
- The aim of the LUX-ZEPLIN Experiment is to detect and characterise these WIMPs

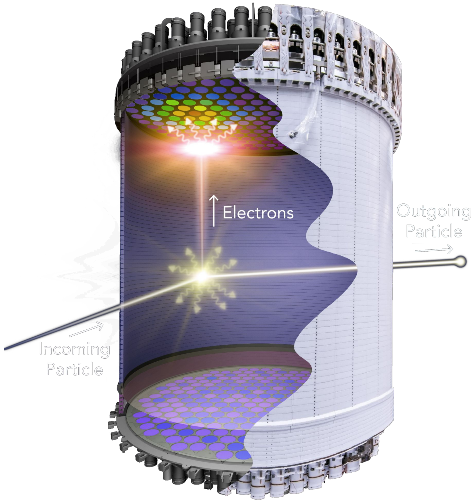




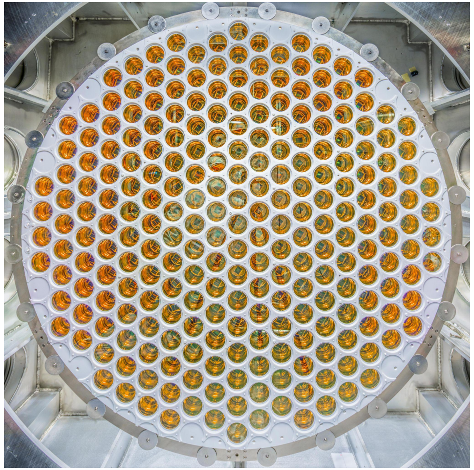
What is Dark Matter?

The LUX-ZEPLIN Experiment

- The objective of this experiment is to directly observe interactions between WIMPs and regular matter
- The detector consists mainly of a cylindrical dual-phase Xenon Time Projection Chamber (TPC) with 494 photomultiplier tubes (PMTs)
- The PMTs are distributed at the top and at the bottom of the detector, and the walls are reflective
- Every interaction inside the TPC produces a scintillation signal (S1) and a ionisation signal (S2)
- The photons produced by the scintillation are promptly detected by the PMTs, while the electrons produced by the ionisation are pushed to the top of the TPC by an electric field, and they emit photons once they cross into the gaseous Xenon
- The XY position of the interaction can be determined by the top PMTs that receive the S2 signal, while the depth can be derived from the difference in time between the S1 and S2 signals



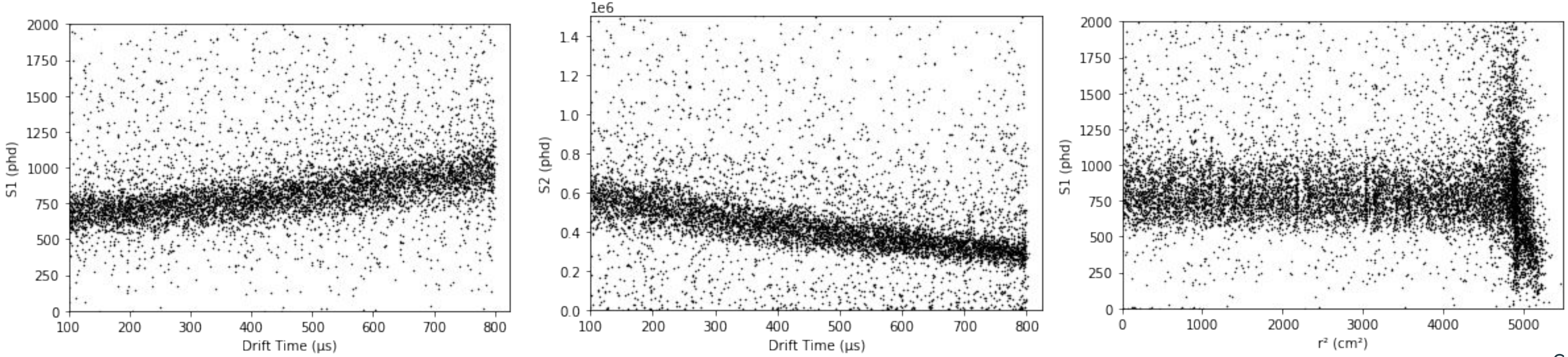
The LUX-ZEPLIN Experiment



- The main part of the data analysis consists of removing all of the background
- Only events that happened in the innermost region (called the fiducial volume) of the TPC are considered
- There is a secondary "skin" detector located around the TPC, filled with Xenon and observed by 131 PMTs
- There is an Outer Detector, filled with 17 tonnes of Gadolinium-loaded liquid scintillator
- These detectors can be used to discard events caused by neutrinos, gamma rays and muons
- The detector is located at a depth of 1.5km, built with materials with a low natural radioactivity, and shielded with materials that have a strong stopping power
- It has a good position resolution in order to distinguish single scatters from multiple scatters

Analysing Xe-131m Data

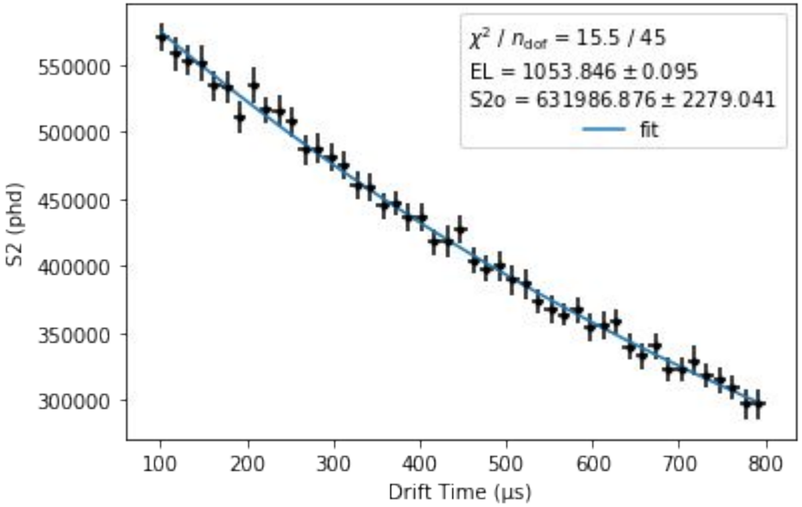
- Xe-131m is an unstable isotope of Xenon that emits a photon with an energy of 164keV when it decays
- This decay produces a single scatter
- Since it occurs naturally, there is some Xe-131m in the mixture that fills the TPC
- It is used to calculate signal corrections and to understand the detector response in all the TPC volume

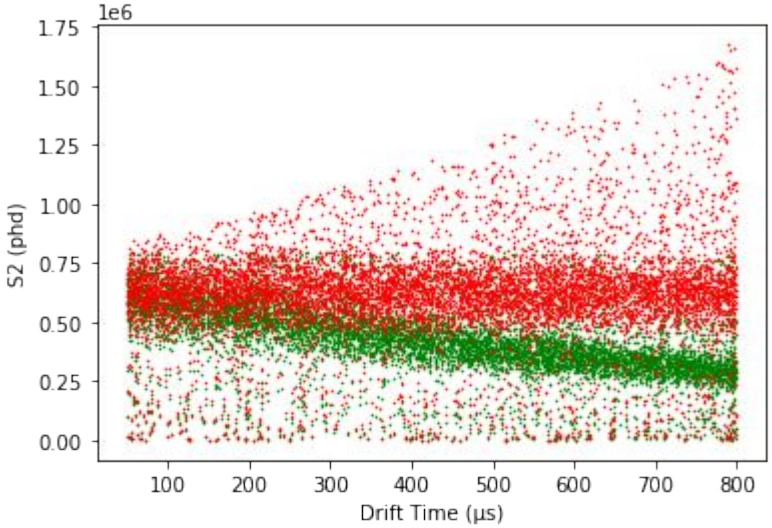


Correcting S1 & S2

- The S1 and S2 signals varied depending on the drift time, but the interaction is the same at any depth inside the TPC
- Our first challenge was to correct this data, using the following expression:

$$\mathrm{S2_{unc}} = \mathrm{S2_{corr}} \cdot \exp\left(-\tau/\mathrm{EL}\right)$$





Calculating the Energy

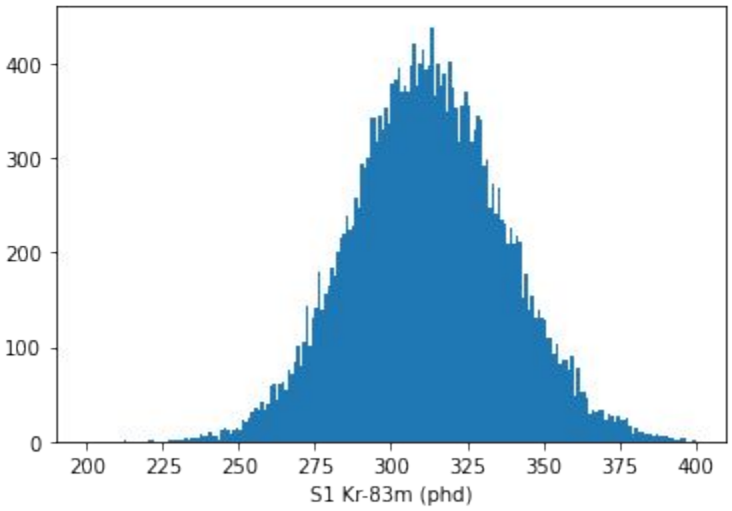
- Our model tells us that the energy of an interaction is given by the following expression:

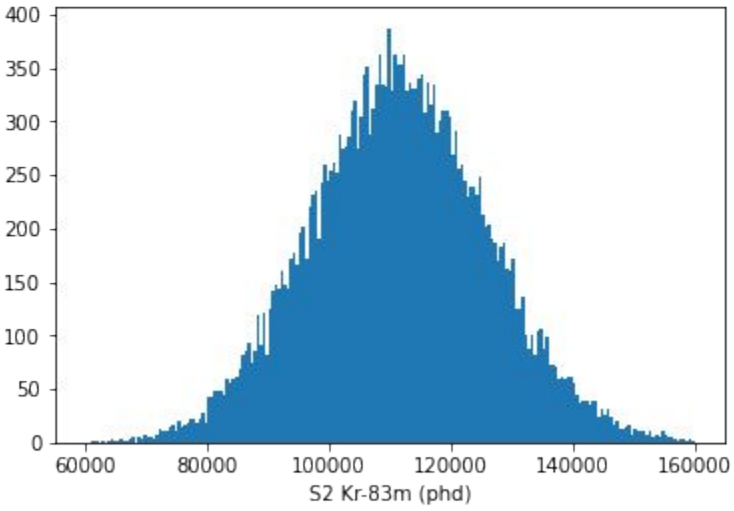
$$E = \frac{W_q}{L\left(E\right)}\left[\frac{S1}{g_1} + \frac{S2}{g_2}\right]$$

- E is the energy
- S1 and S2 are the signals observed
- L(E)=1
- W_q=13.7 eV
- g_1 is the probability of a photon generated in the centre of the TPC being detected
- g_2 is the average number of detected photons that an electron generates when it goes from the liquid Xenon into the gaseous Xenon
- We can determine values of g1 and g2 in our detector by measuring events with a previously known energy

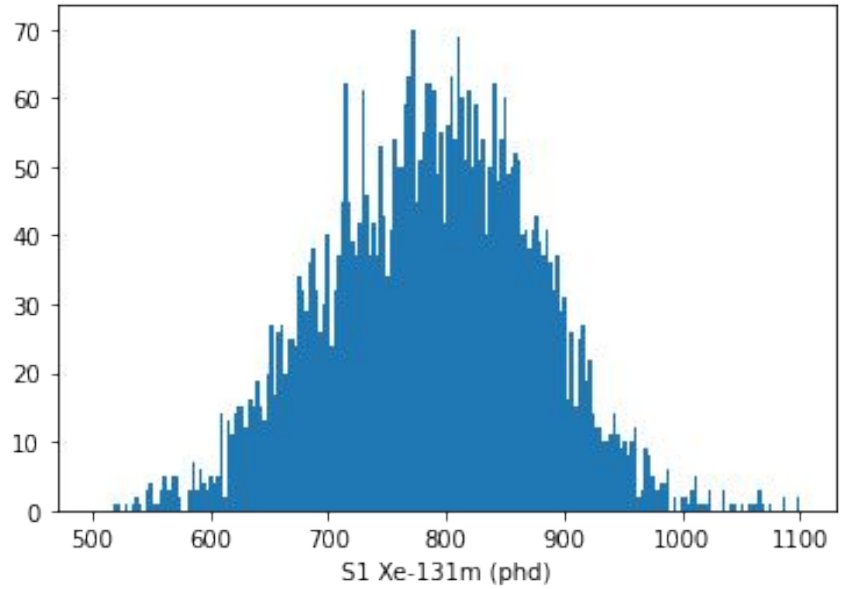
Determining g_1 and g_2

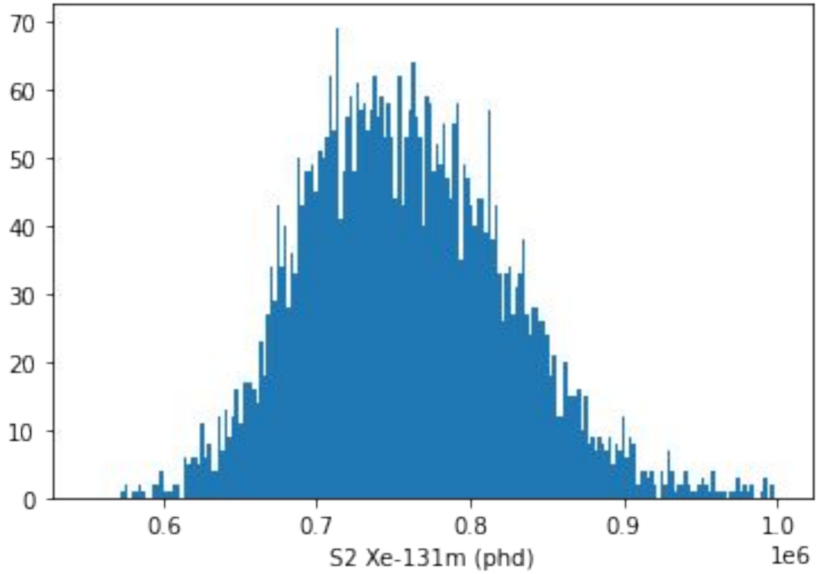
- Kr-83m is an unstable isotope of Krypton, which releases 41.5keV of energy when it decays
- This energy is released in two steps separated by a few nanoseconds
- Since we know the energy of this decay with a high precision, we can use this and the Xe-131m data to determine the values of g_1 and g_2





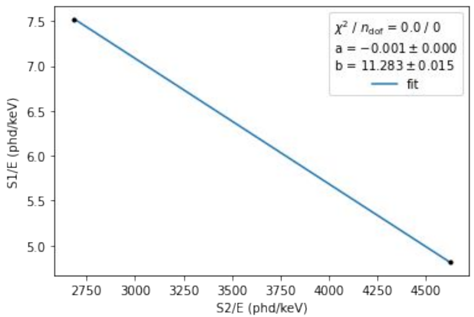
Determining g_1 & g_2

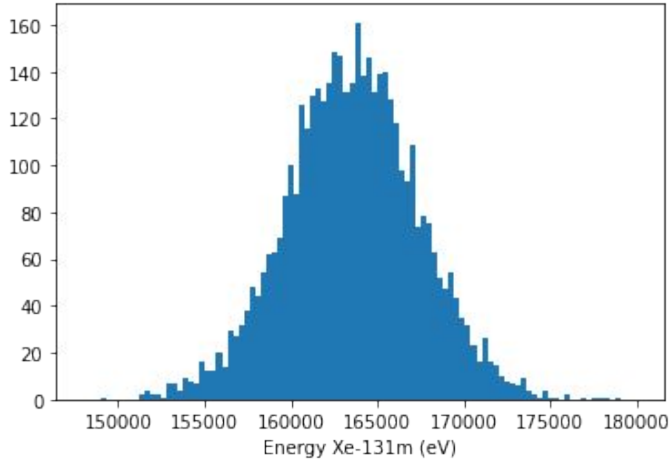


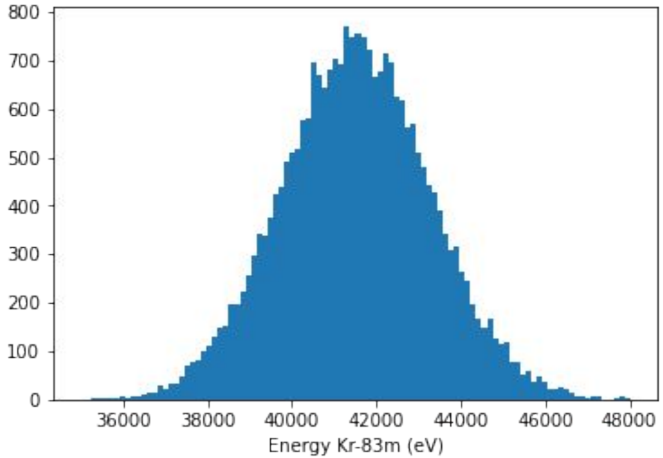


Determining g_1 & g_2

- Using the mean values from those histograms, we plotted S1/E vs S2/E
- We fit a linear regression and used the slope and the y-intercept to calculate g_1 and g_2
- The values we obtained were:
  - g_1=0.1545
  - g_2=110.436

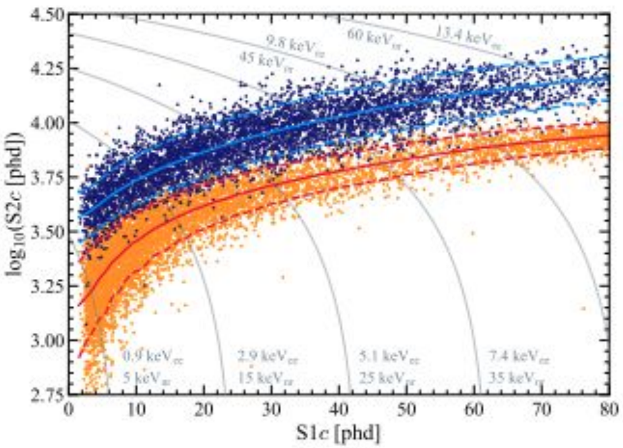






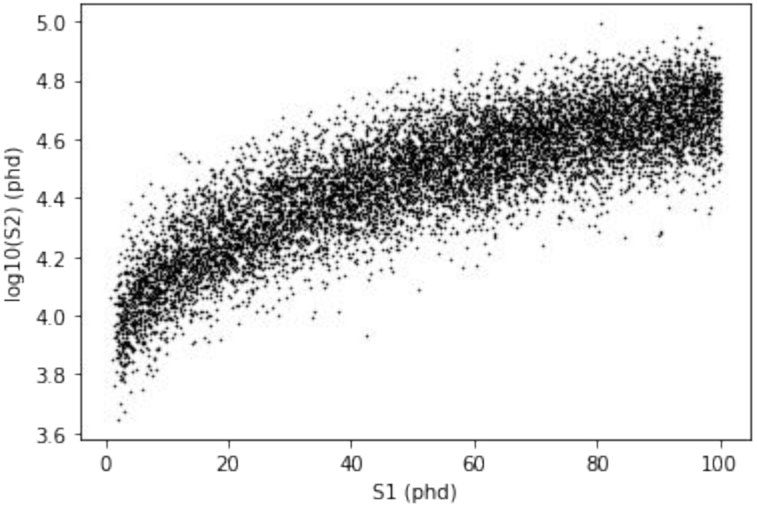
Electron Recoil vs Nuclear Recoil

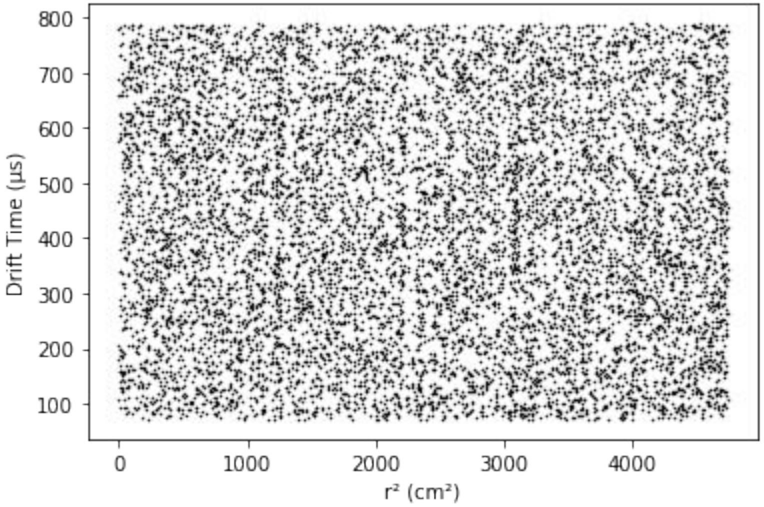
- There are two types of interactions that can happen inside the TPC: Electron Recoils (ER) and Nuclear Recoils (NR)
- All of the interactions we have previously analysed are ER, but we expect WIMPs to produce NR
- If we plot S2 vs S1, we find that ER and NR generate two separate bands (ER tipically have a larger S2 signal than a NR with the same S1 signal)



Analysing Rn-220 Data

- Rn-220 is an unstable isotope of Radon that is a part of the Thorium-232 decay chain
- One of the products of this decay is Pb-212, which has a beta decay
- This beta decay produces an ER inside the TPC, and the S1 and S2 signals it produces are in the range that we expect WIMP signals to be in
- We can use the Rn-220 data as a calibration, to calculate the probability of an ER appearing inside of the NR band

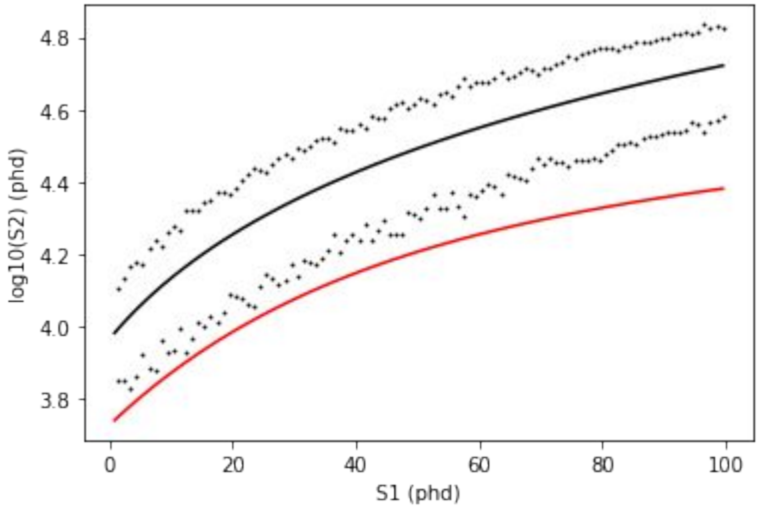




Analysing Rn-220 Data

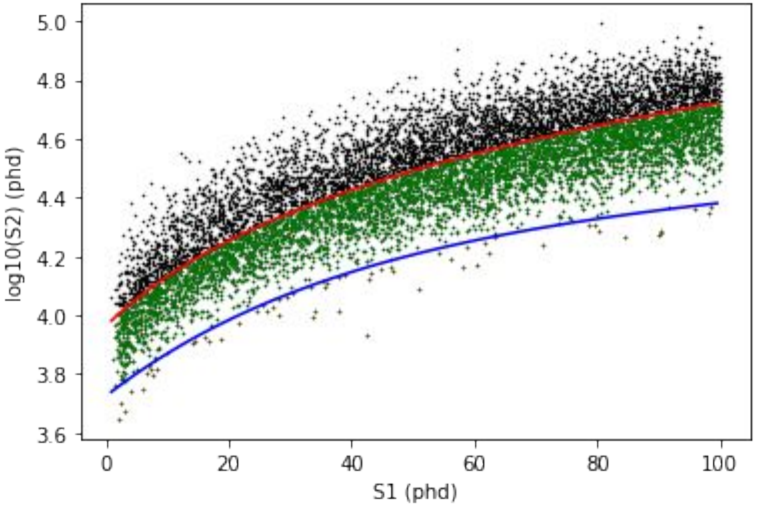
- Using the information contained in the first scatter plot, we can get the median curve and the curves that limit the ER band (defined as being 1.28 standard deviations away from the median)
- We can also plot the median curve of the NR, which is given by:

$$S2 = 4.2926 + 0.0013 * S1 - 0.56825 * \exp(-0.02636*S1)$$



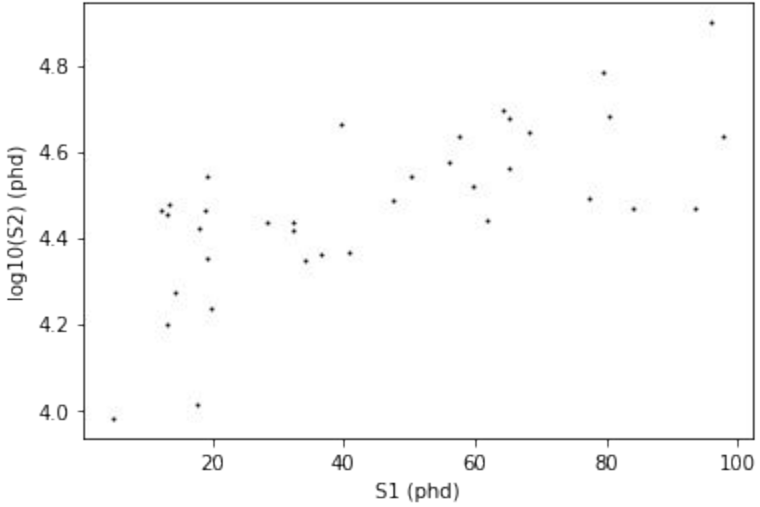
Analysing Rn-220 Data

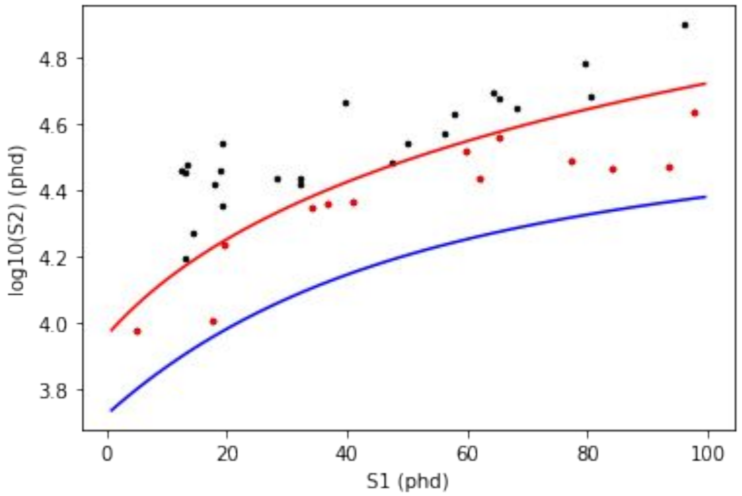
- Out of all the points that we considered initially, 49.534% of them were located below the ER median, and only 0.598% of them were located below the NR median
- This means that we should only expect 0.598% of all ER events caused by background sources to be below the NR median



Analysing WIMP Search Data

- We can now use these curves to determine whether there was a WIMP interaction in our simulated dataset
- In this specific case, we can see that there are no points below the NR median
- Therefore, we can conclude that there is no conclusive evidence of a WIMP interaction in this dataset
- With this result, we determined, using the TRolke method in Root, the median value of the upper limit of NR events to be 3.54992, in a 90% confidence interval





Analysing WIMP Search Data

- Our final objective was to determine the WIMP-nucleon cross section, which can be derived from the WIMP-nucleus cross section, given by the following expression:

$$\hat{R}_0 = \frac{2}{\sqrt{\pi}} \frac{N_A}{A} m_{FV} \frac{\rho_{DM}}{M_{DM}} \sigma_0 \, v_0 \, t_{exp} \epsilon_0 \quad [counts]$$

- σ_0 is the WIMP-nucleus cross-section
- M_{DM} is the mass of each WIMP (which we expect to be between 10GeV/c² and 1000GeV/c²)
- R_0 = 3.54992 (the value we obtained in the previous slide)
- ε_0 is given by:

$$\epsilon_0 \equiv \frac{R}{R_0} = \frac{1}{E_0 r} \int_{E_{th}}^{\infty} e^{-\frac{E_R}{E_0 r}} dE_R = e^{-\frac{E_{th}}{E_0 r}}$$

- All of the other parameters a
- Once we obtain the values o cross section using this expression:

$$\sigma_{0WN,SI} = \frac{4\mu_n^2 f_n^2}{\pi} \frac{\mu_A^2}{\mu_n^2} A^2 = \sigma_{SI} \frac{\mu_A^2}{\mu_n^2} A^2.$$

- σ_{SI} is the WIMP-nucleon cross section
- $\sigma_{0W\,N,SI}$ is the WIMP-nucleus cross section

Analysing WIMP Search Data

- Finally, since the WIMP-nucleon cross section depends on the mass of each WIMP, we cannot obtain its exact value, but we can plot it against the mass of each WIMP: