Seasonal Variation of Dark Matter Signals in the LZ Experiment and for a Proposed LArTPC Low-Background Module at Sanford Lab

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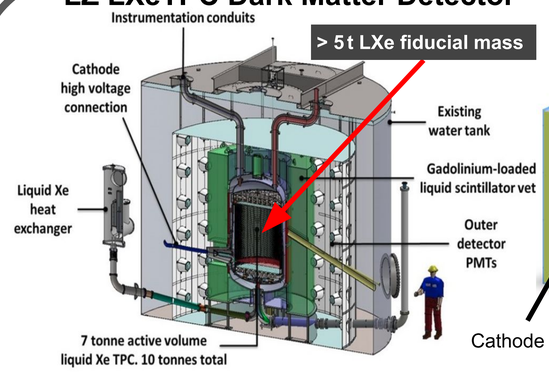
Introduction

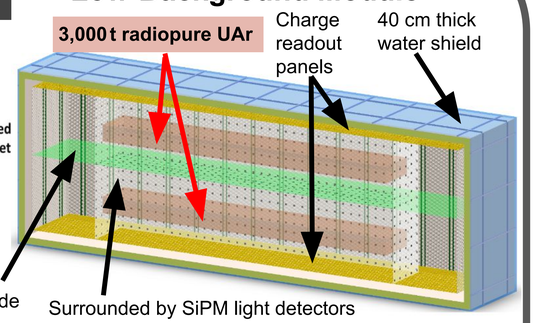
Despite the lack of direct evidence, there is already an abundance of indirect evidence that points to a non-luminous new form of matter that exists in significant quantities throughout our universe. Many theories of physics beyond the Standard Model predict the existence of Weakly Interacting Massive Particles (WIMPs) as preferred candidates for Dark Matter (DM). Due to the rotation of our Sun around the center of our galaxy, and the orbit of Earth around the Sun, a seasonally varying relative "WIMP wind" is induced for detectors on Earth. LUX-ZEPLIN (LZ) is an ultra-quiet dual-phase Liquid Xenon (LXe) Time Projection Chamber (TPC) located at the Sanford Underground Research Facility (SURF). We studied the prospects for detection of an annual modulation of detected WIMP events in LZ with more than 5 t of LXe. Furthermore, we show that a proposed 3,000 t radiopure Liquid Argon (LAr) TPC can offer the most promising means for detecting the seasonal variation of WIMP rate, characteristic for the nature of WIMPs.

LZ LXeTPC Dark Matter Detector



B. J. Mount et al 2017, Nucl.Instrum.Meth.A 953 (2020) 163047

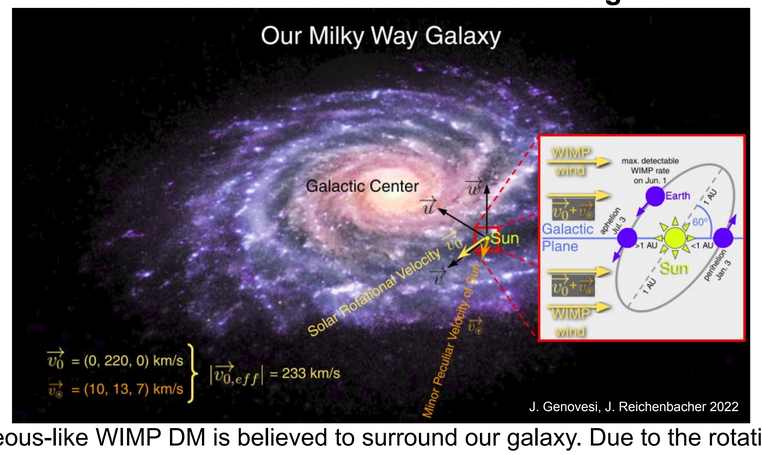
Proposed LArTPC Low-Background Module



Low BG kTon-Scale LArTPC [arXiv: 2203.08821]

LZ's detection method consists of using two light signals from a two-phase medium whose properties are strongly tied to the type of interaction while the proposed LArTPC low-background module uses charge readout panels instead. Using these technologies, it is possible to categorize the nature of the interactions to probe relevant phase-space for low-energy events.

Annual Modulation of Potential DM Signal

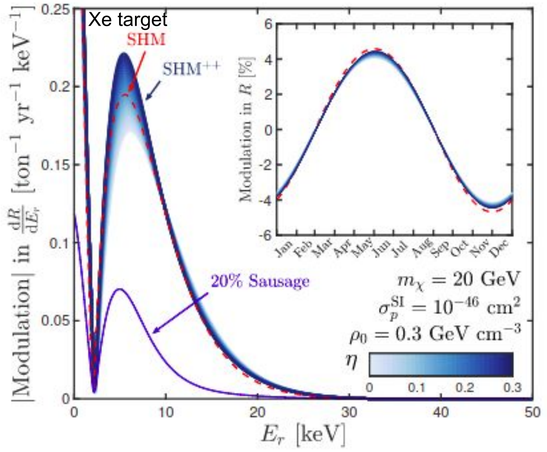


A halo of gaseous-like WIMP DM is believed to surround our galaxy. Due to the rotation of our Sun around the galactic center, our own solar system experiences an induced "WIMP wind" when moving through the DM halo featuring a Maxwell-Boltzmann velocity distribution. Due to the rotation of Earth around the Sun, there would be then a seasonally changing detection rate of WIMP DM in a detector on Earth. Slanted Earth orbit relative to the galactic plane and a peculiar motion of the our Sun out of the galactic plane are accounted for.

Exemplary Selected WIMP Parameters and Nuclear Recoil Energy Spectrum

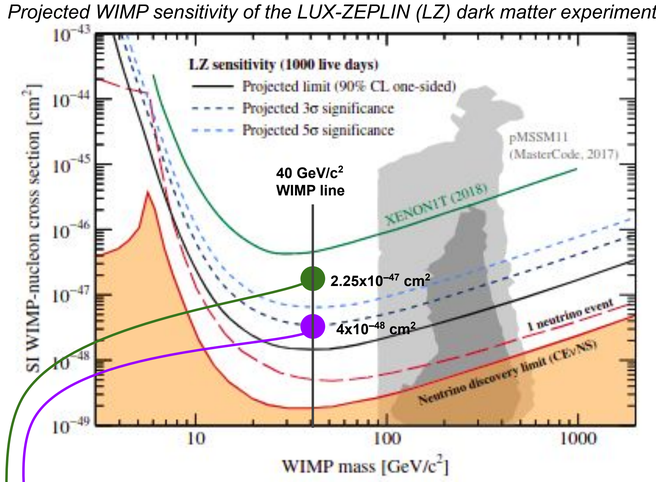
The two dots in the right figure show the two selected WIMP parameters that were used in two detector analyses for this presentation. The left figure shows for Xe the difference of differential WIMP rate as a function of Nuclear Recoil (NR) energy as it varies seasonally (inset shows the relative oscillation of the WIMP interaction rate over the period of a year). We use the Standard Halo Model (SHM) for all of our seasonally time dependent WIMP search analyses with both Xe and Ar targets.

Difference in differential WIMP rate due to seasonal variation:



N. Evans et al 2015, Phys Rev D 99.023012 [arXiv: 1810.11468]

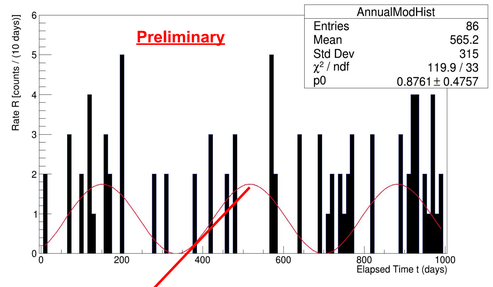
Projected WIMP sensitivity of the LUX-ZEPLIN (LZ) dark matter experiment:



D.S. Akerib et al Phys Rev D 101.052002 [arXiv: 1802.06039]

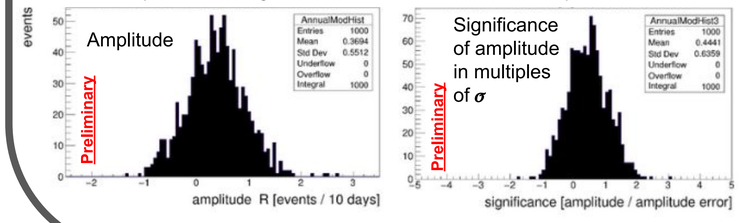
Annual Modulation Analysis of LZ LXeTPC

Single exemplary dataset of simulated LZ experiment over 1,000 livedays:



We took a frequentist approach by simulating 1,000 instances of LZ experiments with no backgrounds using NEST* each with 1,000 days of 40 GeV/c^2 SI WIMPs with a cross section of 2.25x10^{-47} cm^2 selected. The frequency of fitted amplitudes had too low significance, even under optimal conditions for detecting an annual modulation of nuclear recoils induced by WIMPs.

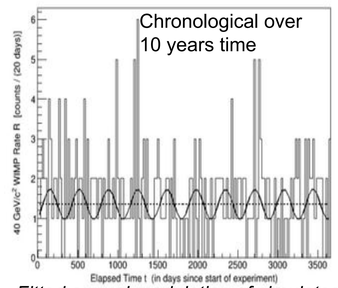
Fitted amplitude and significance of 1,000 simulated LZ experiment runs



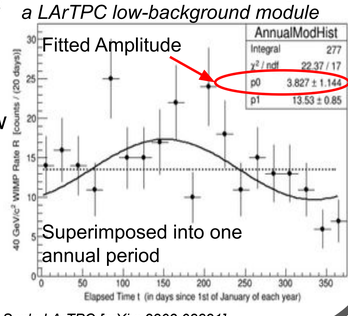
NEST* (Noble Element Simulation Technique), M Szydagis *et al* 2011 *JINST* **6** P10002

Annual Modulation Analysis of Proposed LArTPC Low-Background Module

A simulated no background dataset using NEST was generated for 40 GeV/c^2 SI WIMPs with a lower cross section of 4x10^{-48} cm^2 for the proposed 3 kt LArTPC module w/ radiopure UAr. When applying the annual modulation WIMP search analysis to this simulated dataset, but with a 50 keV threshold, a higher fit weight is now found for the fitted amplitude, due to 3 kt of lighter Ar nuclei as WIMP target.



Fitted annual modulation of simulated WIMP data for 10 years running with a LArTPC low-background module



Low BG kTon-Scale LArTPC [arXiv: 2203.08821]

Conclusion

- **LZ** (>5 t) over the course of the intended 1,000 livedays is unlikely to observe an annual modulation of 40 GeV/c^2 WIMP dark matter (generation-3 LXe DM experiment will have ~100 t, generation-3 LAr DM experiment will have 300 t).
- A proposed 3,000 t LArTPC low-background module could even observe the seasonal variation of the galactic WIMP rate for a lower SI cross section of σ_{SI}=4x10^{-48} cm^2 @ 40 GeV/c^2, providing a smoking gun detection for the WIMP nature of dark matter!