Snowmass 2021 Letter of Interest

CYGNUS: A nuclear recoil observatory with directional sensitivity to dark matter and neutrinos

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Thematic Area(s):

■ (CF01) Dark Matter: Particle-like
■ (NF10) Neutrino Detectors
■ (NF04) Neutrinos from Natural Sources
■ (NF07) Neutrino Applications
■ (IF04) Trigger and DAQ
■ (IF05) Micro-Pattern Gaseous Detectors

Abstract: Now that conventional weakly interacting massive particle (WIMP) dark matter (DM) searches are approaching the neutrino floor, there has been a resurgence of interest in detectors with sensitivity to nuclear recoil directions. A large-scale directional detector is attractive in that it would have sensitivity below the neutrino floor, be capable of unambiguously establishing the galactic origin of a purported dark matter signal, and could serve a dual purpose as a neutrino observatory.

A recent strawman-design study suggest that such an observatory is feasible. A modular and multi-site observatory consisting of time projection chambers (TPCs) filled with helium and SF_6 at atmospheric pressure could meet the performance requirements. Such a detector could distinguish WIMPs from neutrinos at 90% CL with only 3-4 events. Detectors based on this concept are interesting on many scales, and could perform a variety of competitive, novel physics measurements starting from 1 m^3 up to a DUNE-scale facility and beyond. A 1000 m^3-scale experiment, which we name CYGNUS-1000, will be able to observe $\sim$ 10–40 neutrinos from the Sun, depending on the final energy threshold. With the same exposure, the sensitivity to spin independent cross sections will extend into presently unexplored sub-10 GeV c^{-2} parameter space. For spin dependent interactions, already a 10 m^3-scale experiment could compete with upcoming generation-two detectors, but CYGNUS-1000 would improve upon this considerably. Larger volumes would bring sensitivity to neutrinos from an even wider range of sources, including galactic supernovae, nuclear reactors, and geological processes.

To understand and fully maximize the physics reach of gas TPCs as envisioned here, further phenomenological work on dark matter and neutrinos, improved micro-pattern gaseous detectors (MPGDs), customized front end electronics and novel region-of-interest triggers are needed. We encourage the wider dark matter, neutrino, and instrumentation communities participating in Snowmass to contribute their physics and instrumentation ideas relevant to this concept.

The community has advanced the idea of building a large-scale directional detector sensitive to both WIMPs and neutrinos. A recent strawman design study[1] suggests that this idea is feasible at the 1000 m^3-scale. Physics reach estimates via nuclear recoils, which include experimental considerations, are shown in Figs. 1 and 2 (left), and already look quite promising. Snowmass is an excellent opportunity to pursue further the physics potential of such a detector. For example, measurements via directional detection of elastic neutrino-electron scattering are highly promising, see Fig. 2 (right) but have not been studied in detail.

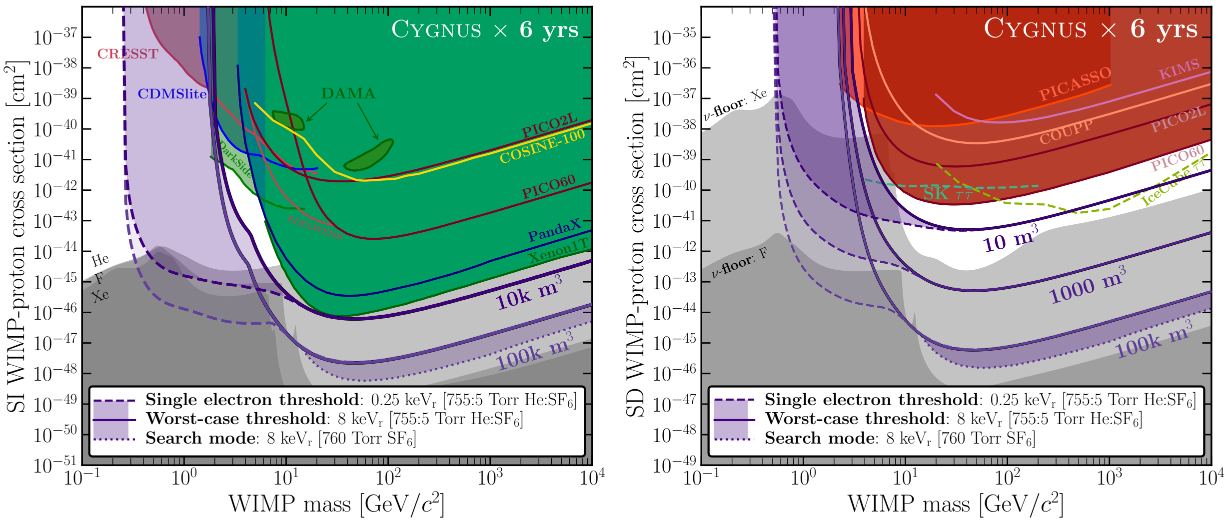

Figure 1: Constraints on the spin-independent WIMP-nucleon (left) and spin-dependent WIMP-proton (right) cross sections. We show the existing constraints and detections from various experiments as labeled (see text for the associated references). In purple solid and dashed lines we show our projected 90% CL exclusion limits for the CYGNUS experiment operating for six years with 10 m^3 up to 100,000 m^3 of He:SF$_6$ gas at 755:5 Torr (where 6 years$\times$1000 m^3 corresponds to a $\sim$1 ton-year exposure). For each volume we show limits for two possible thresholds, ranging from the worst-case electron discrimination threshold of 8 keV$_r$ to a very best-case minimum threshold corresponding to a single electron, 0.25 keV$_r$. We emphasize however that we anticipate electron discrimination well below 8 keV$_r$. For the 100k m^3 limits we add a third dotted line which corresponds to a mode with purely SF$_6$ gas at 760 Torr. This non-directional 'search mode' could be used to extend the high mass sensitivity to just within reach of the neutrino floor. For the SI panel, we shade in gray the neutrino floor for helium, fluorine, and xenon targets (top to bottom), and for SD we show only fluorine and xenon. We define the neutrino floor as the cross section limit at which the rate of improvement with increasing exposure is the slowest in standard direct detection–the effect that CYGNUS aims to circumvent. This definition corresponds to $\mathcal{O}(100)$ neutrino events.

Below is a list of ideas for Snowmass study items relevant to the CYGNUS concept.

- Instrumentation: Front-end electronics with µs shaping time suitable for large scale strip detector charge readout of negative ion drift TPCs.
- Instrumentation: Ultra-high-radiopurity, highly segmented MPGDs with high gain even for negative ion drift and low density gas operation.

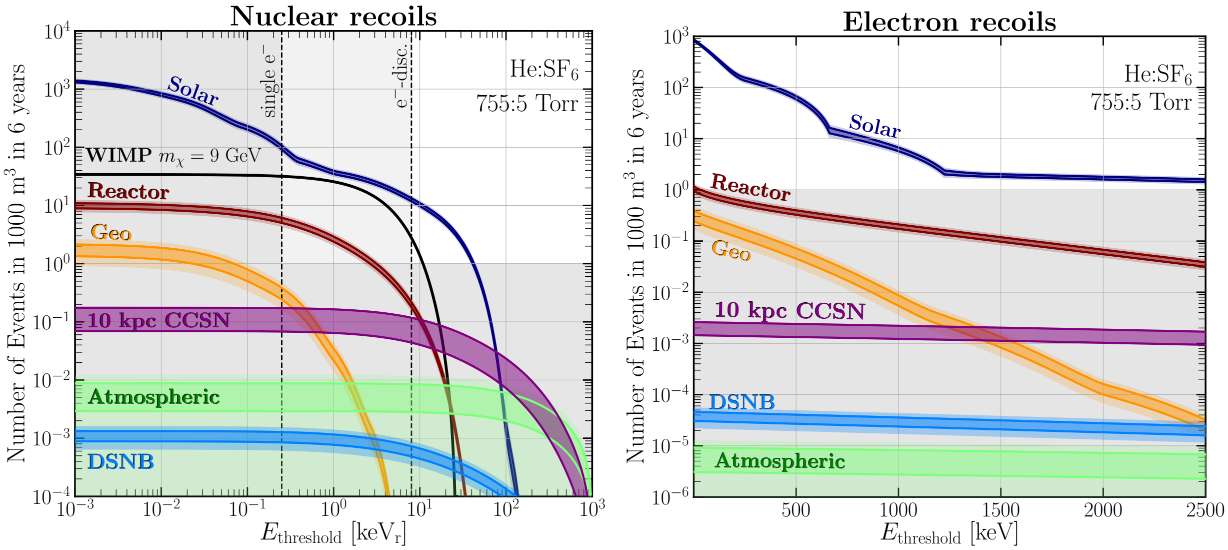

Figure 2: Number of neutrino-nucleus (left) and neutrino-electron (right) recoil events observed in a Cygnus-1000 m^3 detector filled with atmospheric pressure He:SF$_6$ at a 755:5 Torr ratio (the event rates are summed over each target nuclei). We calculate the expected number of observed events by integrating the event rate for each background component above a lower energy threshold $E_{\rm threshold}$. The background components are shown as darker and lighter shaded regions indicating the 1 and 2σ uncertainties from the predicted flux. For comparison we also show the nuclear recoil event rate expected from a $m_\chi = 9\,{\rm GeV}\,c^{-2}$ WIMP with a SI WIMP-proton cross section of $\sigma_p^{\rm SI} = 5 \times 10^{-45}$ cm^2 as a black line. For the reactor and geoneutrinos, we assume the entire 1000 m^3 is located at Boulby, UK. The purple region indicates the range of expected numbers of events from the neutrino bursts from 11–27 $M_\odot$ core-collapse supernovae located 10 kpc away from Earth. For clarity we shade in gray parts of the plot which give fewer than one event in this exposure. In the left panel we also show as dashed lines the 0.25 and 8 keV$_{\rm r}$ best-case and worst-case thresholds respectively.

- Instrumentation: Trigger-multiplexed readout for cost reduction in very large scale, but low-rate detectors. Trigger-level background rejection in such readouts.
- Computing: Nuclear recoil, electron recoil, and overlapping recoil recognition via 3d ionization distributions via deep learning.
- DM Physics: DM reach via electron scattering, Migdal effect measurements in gas TPCs, DM scattering with multi-particle final states. Extended low-mass DM reach via hydrogen.
- Neutrino Physics: Directional neutrino detection with coherent elastic neutrino nucleus scattering and electron nucleus scattering. Event-by-event neutrino energy measurements for known artificial and natural neutrino source directions. Physics at neutrino beams.

We welcome your creative contributions, studies, and ideas of any kind relevant to directional detection and/or gas TPCs.

References

[1] S. E. Vahsen, C. A. O'Hare, *et al.* (CYGNUS), (2020), arXiv:2008.12587 [hep-ex] .