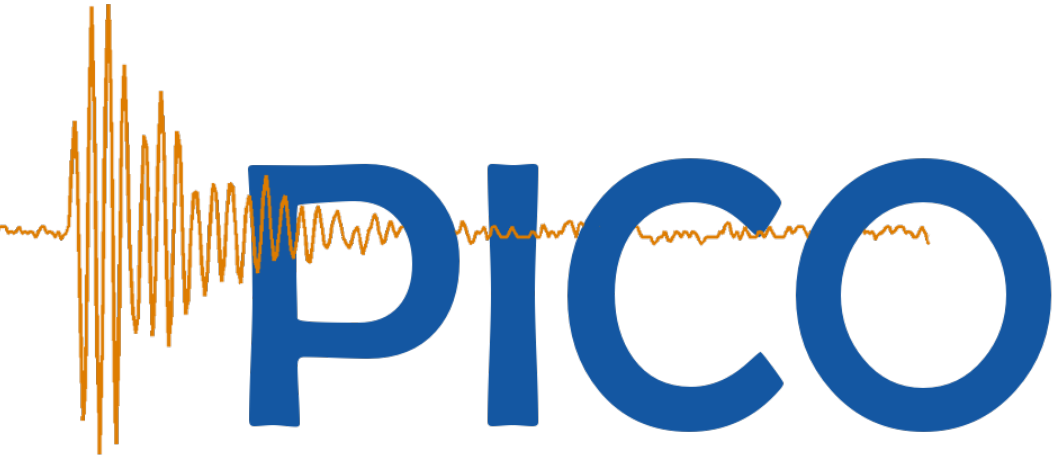


Queen's UNIVERSITY

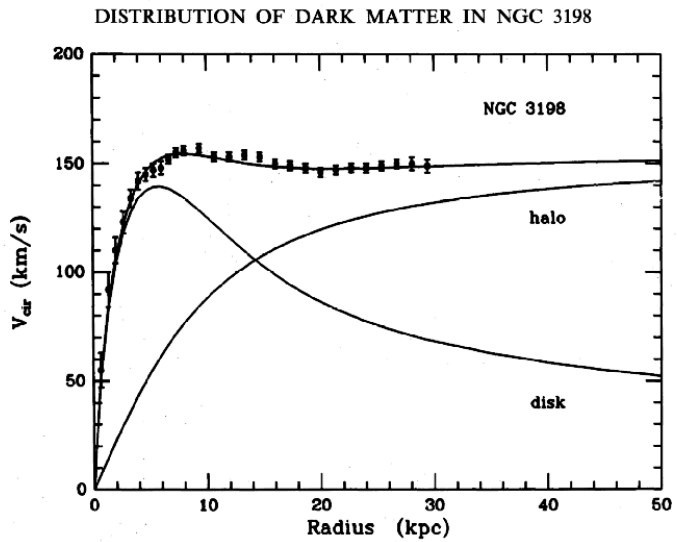
Determining the Physics Reach of PICO-40L and PICO-500

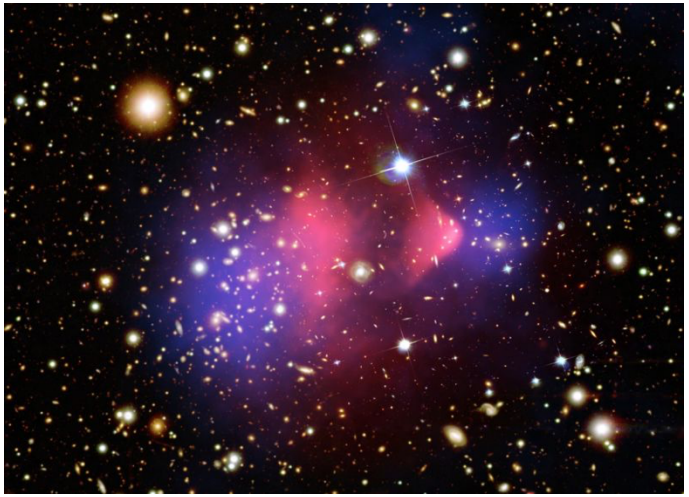
Clarke Hardy
Queen's University

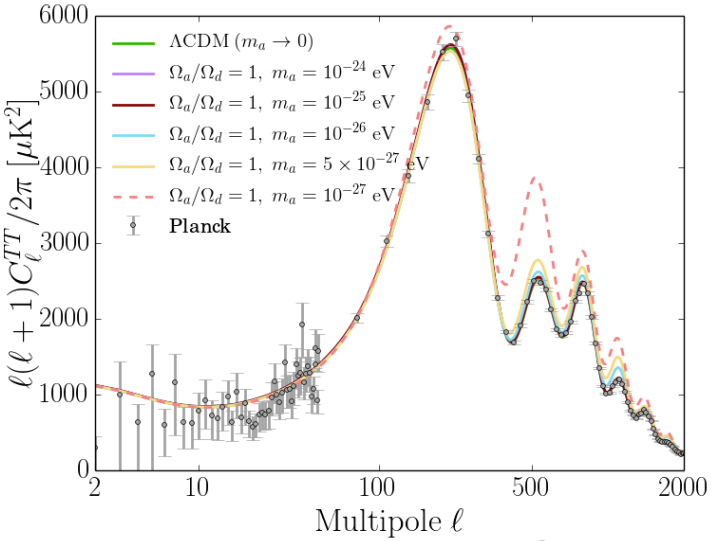
CAP Congress
June 5, 2019

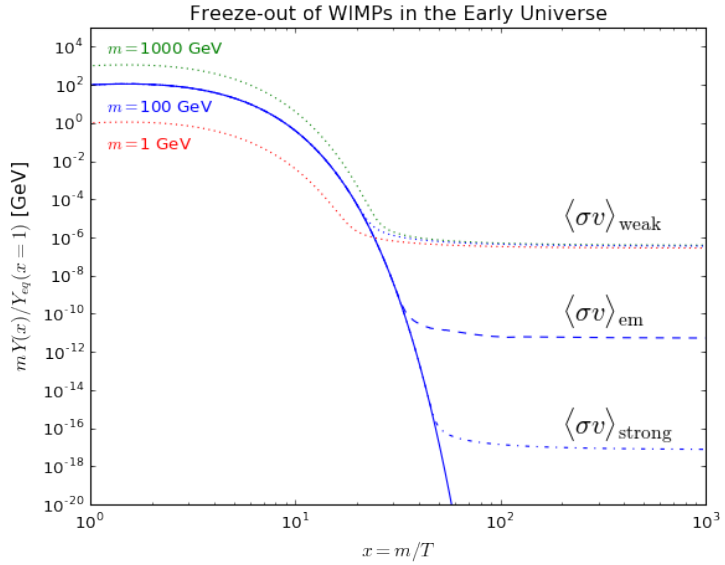
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Dark Matter


DISTRIBUTION OF DARK MATTER IN NGC 3198
NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)
0
50
100
150
200
0
10
20
30
40
50

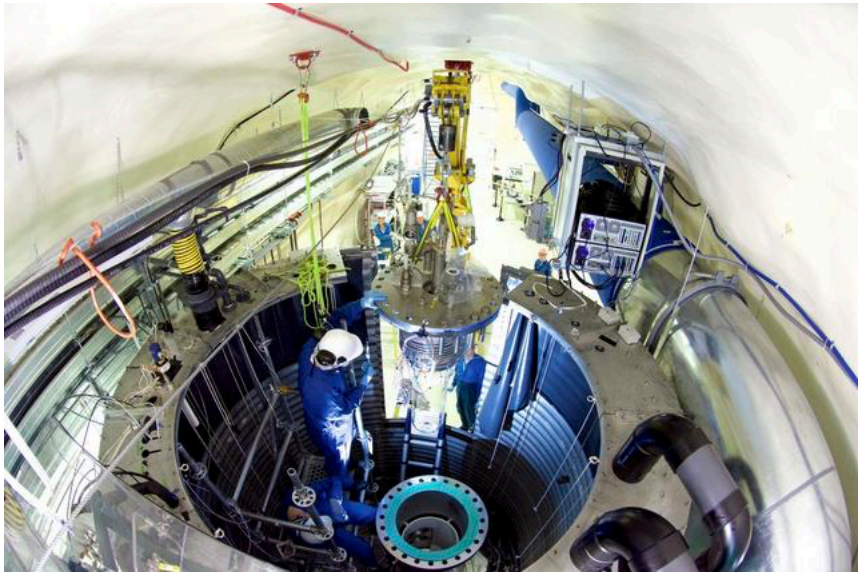


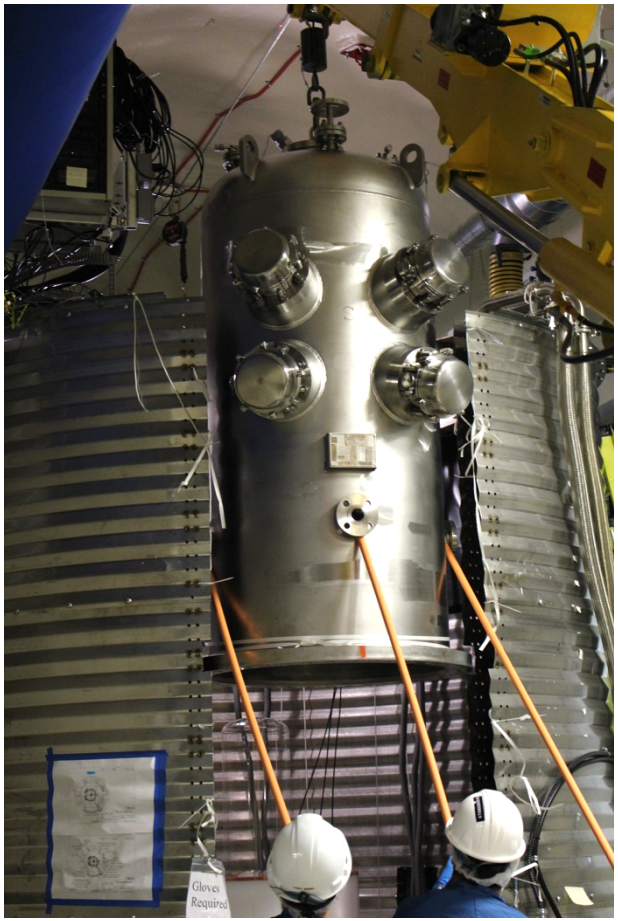

ΛCDM ($m_a \to 0$)
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-24}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-25}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-26}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 5 \times 10^{-27}$ eV
$\Omega_a/\Omega_d = 1,\ m_a = 10^{-27}$ eV
Planck
$\ell(\ell+1)C_\ell^{TT}/2\pi\ [\mu\mathrm{K}^2]$
Multipole ℓ
0
1000
2000
3000
4000
5000
6000
2
10
100
500
2000


Freeze-out of WIMPs in the Early Universe
$m = 1000$ GeV
$m = 100$ GeV
$m = 1$ GeV
$\langle\sigma v\rangle_{\mathrm{weak}}$
$\langle\sigma v\rangle_{\mathrm{em}}$
$\langle\sigma v\rangle_{\mathrm{strong}}$
$mY(x)/Y_{eq}(x=1)$ [GeV]
$x = m/T$
10^{-20}
10^{-18}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{0}
10^{1}
10^{2}
10^{3}

PICO Experiment

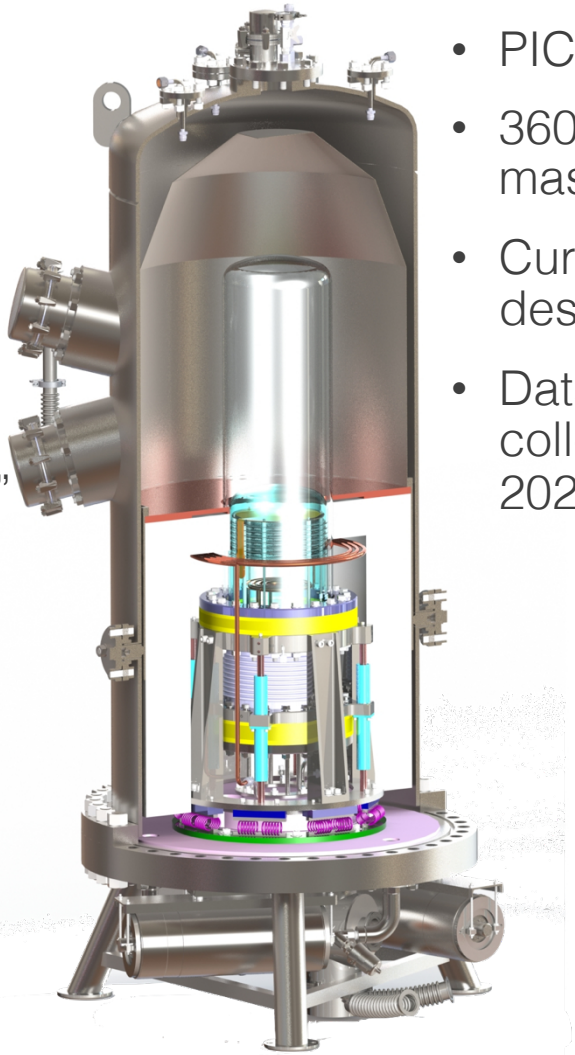
- Detect nuclear recoils causing bubble nucleation in superheated C_3F_8
- Sensitive to spin-dependent interactions on ^{19}F
- Inherently insensitive to electron recoils
- Located at SNOLAB in Sudbury, ON



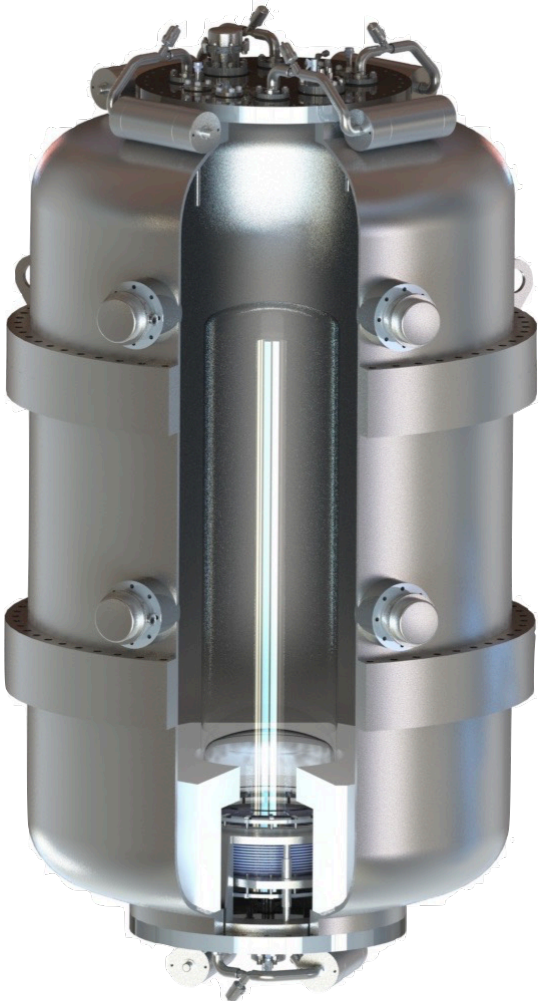


Current and Future Chambers

- PICO-40L
- 58.5 kg active mass
- Currently in commissioning phase
- Proof-of-concept for “right-side-up” design

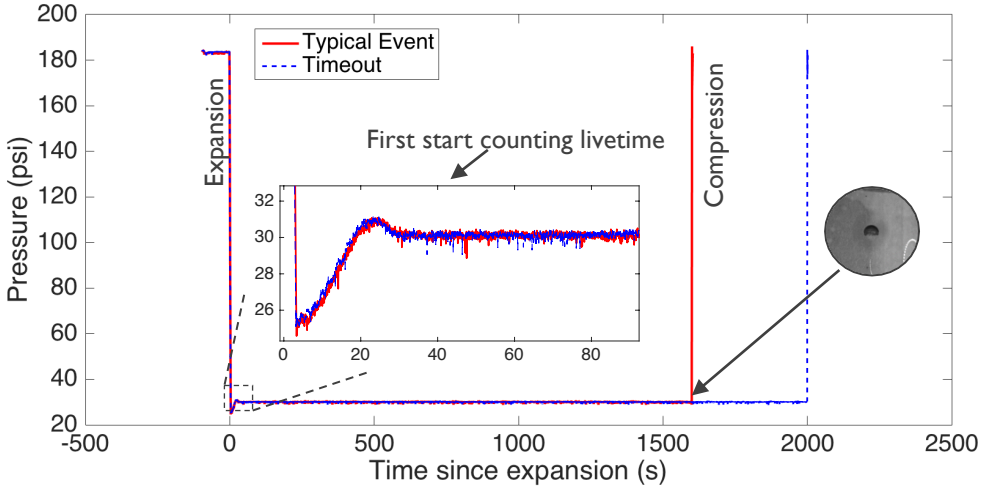


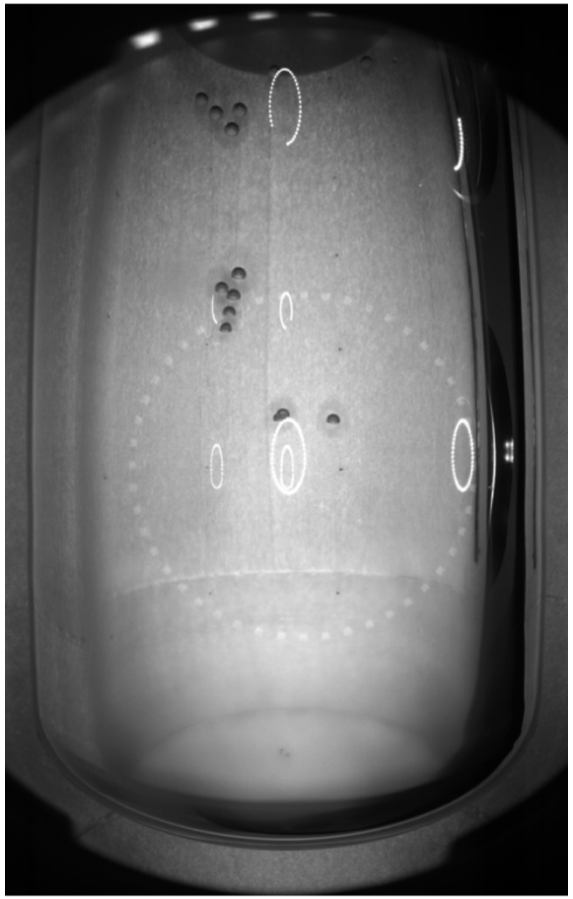
- PICO-500
- 360 kg active mass
- Currently in design phase
- Data collection in 2021

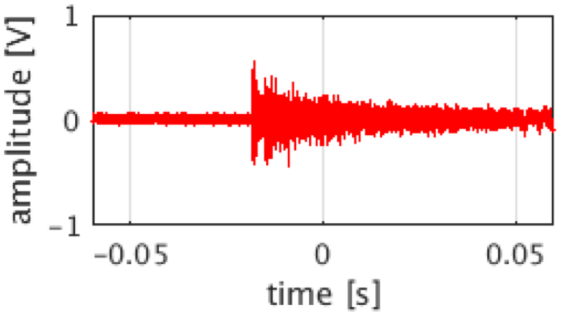


PICO Data

- Expansion to superheated state → trigger on timeout or bubble formation → compression
- Trigger on changes in “image entropy” between frames
- Piezoelectric sensors around jar capture acoustic signal from bubble formation
- No energy resolution

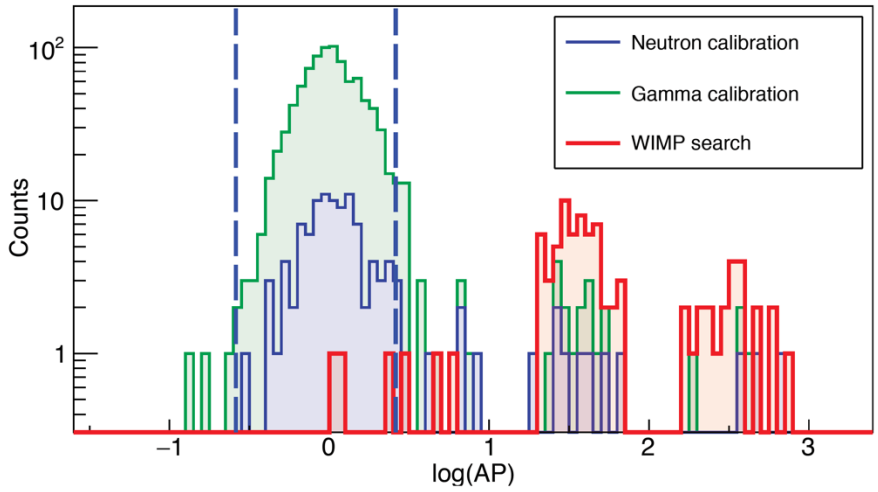


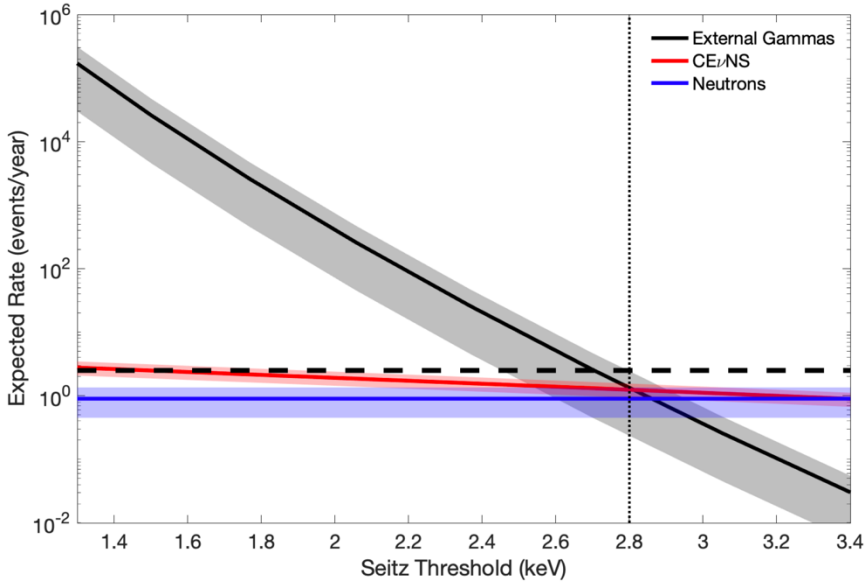




Backgrounds

- Good electron recoil rejection of beta and gamma backgrounds
- Discrimination of alpha backgrounds using cut on acoustic power
- Nuclear recoils
  - Neutron single bubble events
  - Coherent elastic neutrino-nucleus scattering (CEvNS)

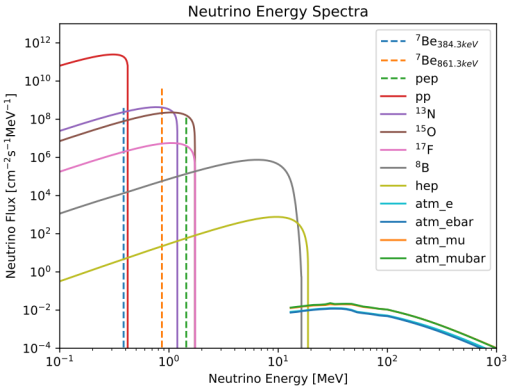




CEvNS on C_3F_8

$$\frac{dR}{dE_R} = N_T \int_{E_\nu^{min}}^{\infty} \frac{dN}{dE_\nu} \frac{d\sigma}{dE_R} dE_\nu$$

CEvNS on C_3F_8

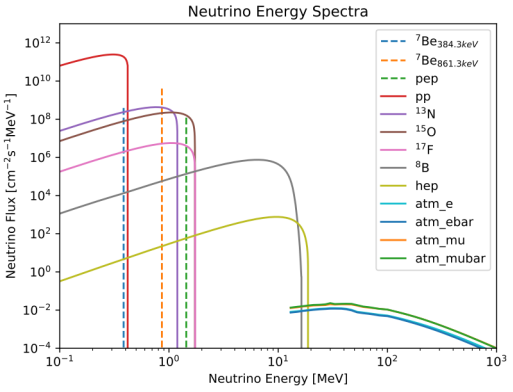


# of target atoms per unit mass

$$\frac{dR}{dE_R} = N_T \int_{E_\nu^{min}}^{\infty} \frac{dN}{dE_\nu} \frac{d\sigma}{dE_R} dE_\nu$$

$$\frac{G_f^2}{4\pi} Q_w^2 M_A \left(1 - \frac{M_A E_R}{2E\nu^2}\right) F^2(E_R)$$

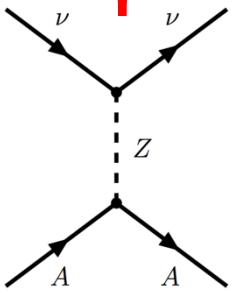
CEvNS on C_3F_8

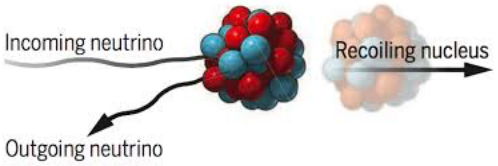


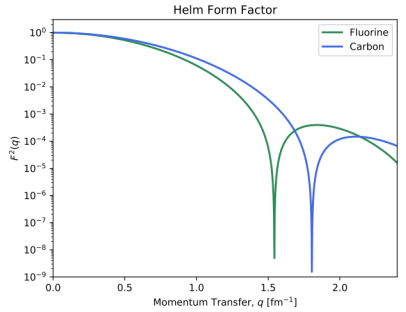
# of target atoms per unit mass

$$\frac{dR}{dE_R} = N_T \int_{E_\nu^{min}}^{\infty} \frac{dN}{dE_\nu} \frac{d\sigma}{dE_R} dE_\nu$$

$$\frac{G_f^2}{4\pi} Q_w^2 M_A \left(1 - \frac{M_A E_R}{2E\nu^2}\right) F^2(E_R)$$

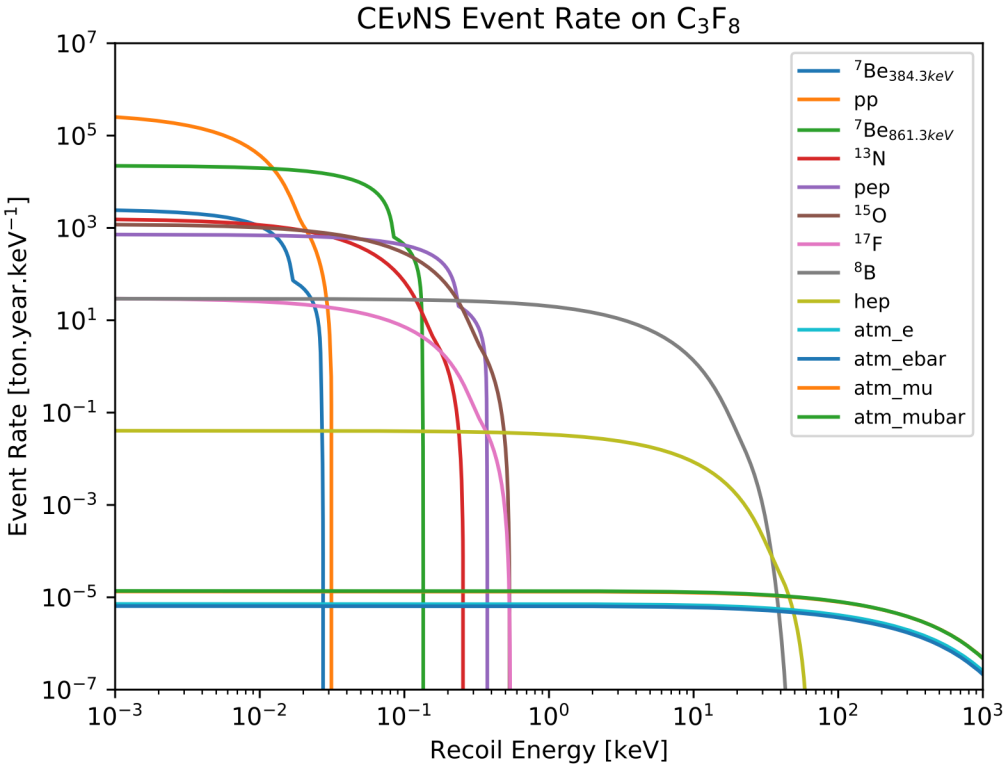






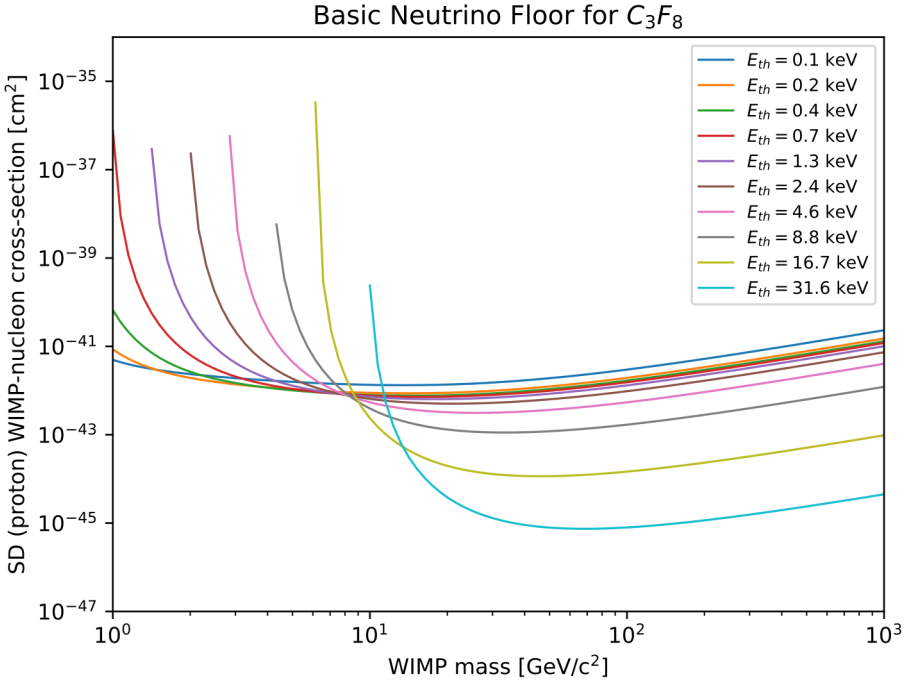
CEvNS on C_3F_8

- 1.3 events expected per year in PICO-40L
- 8.0 events expected per year in PICO-500
- Sensitive to supernova neutrinos in PICO-500 [arXiv: 1806.01417]



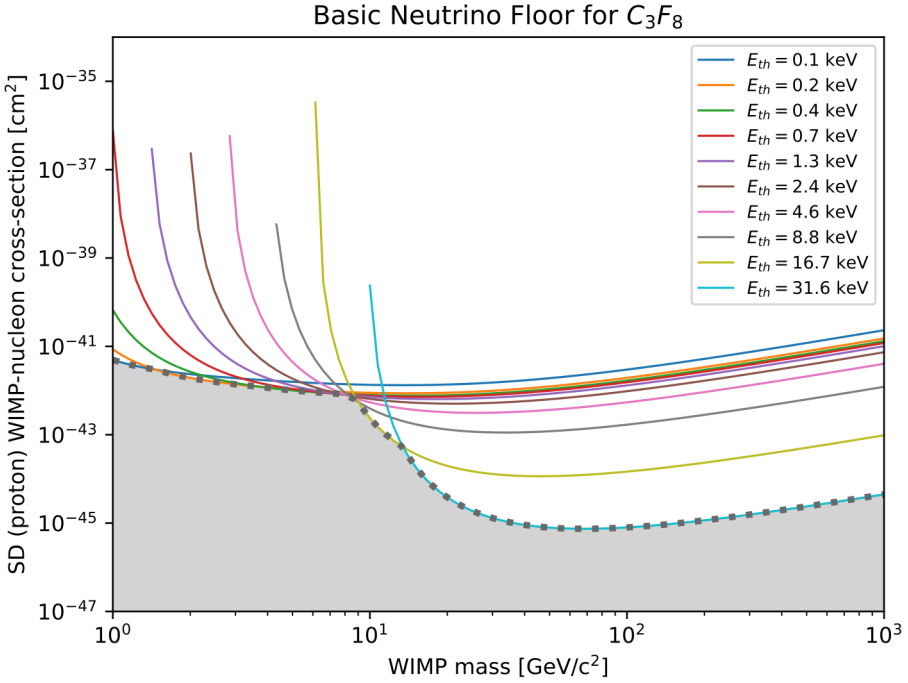
Basic Neutrino Floor

- Defined as the cross section at which an equal number of events from neutrinos and WIMPs are expected, for the optimum threshold at that mass
- Calculate iso-event contours for each threshold
- Take minimum at each mass



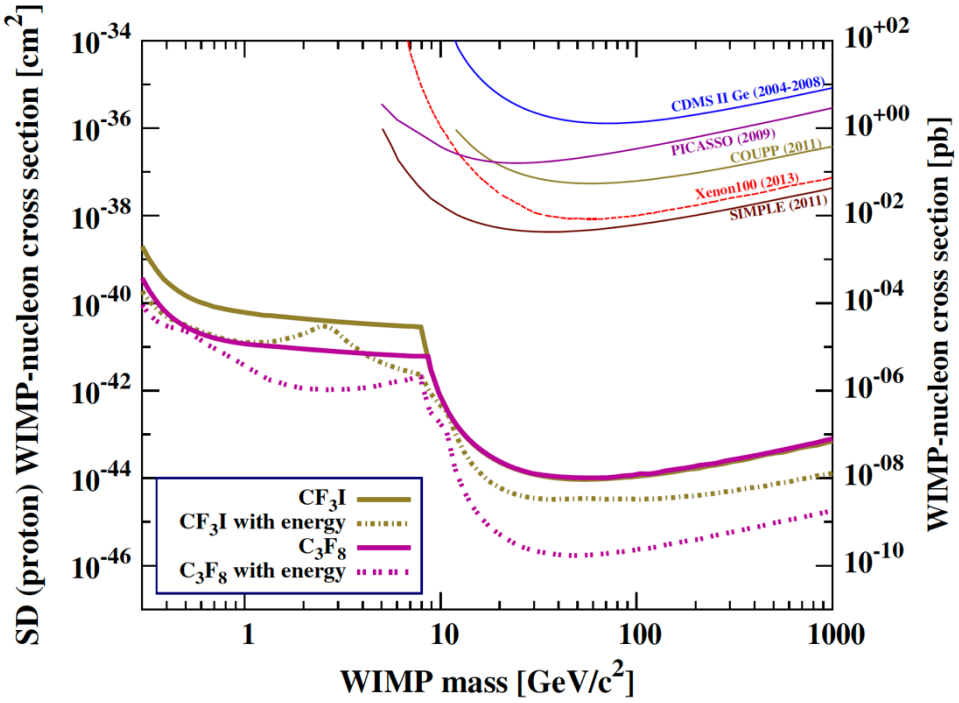
Basic Neutrino Floor

- Defined as the cross section at which an equal number of events from neutrinos and WIMPs are expected, for the optimum threshold at that mass
- Calculate iso-event contours for each threshold
- Take minimum at each mass



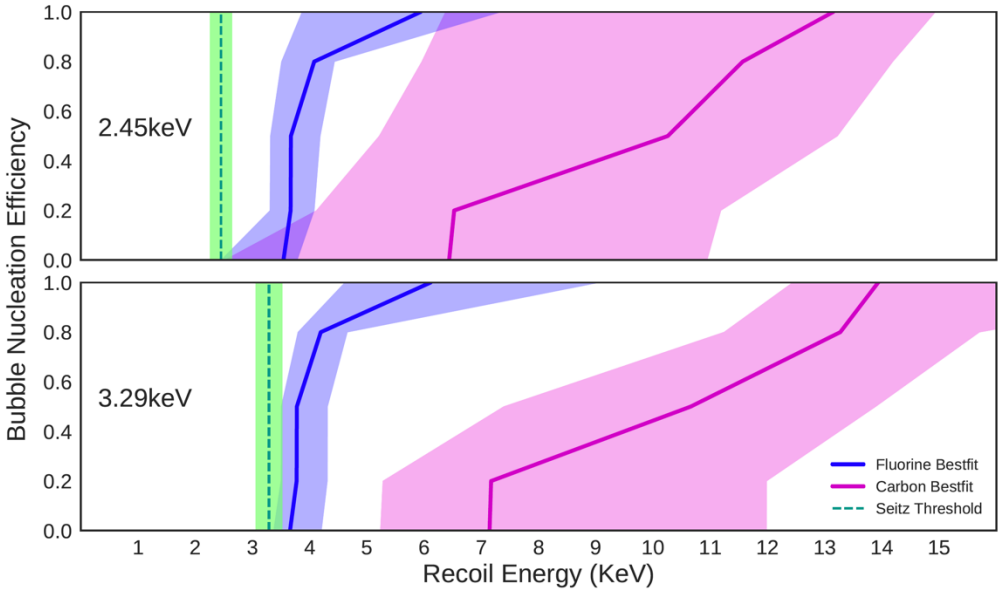
Existing Work

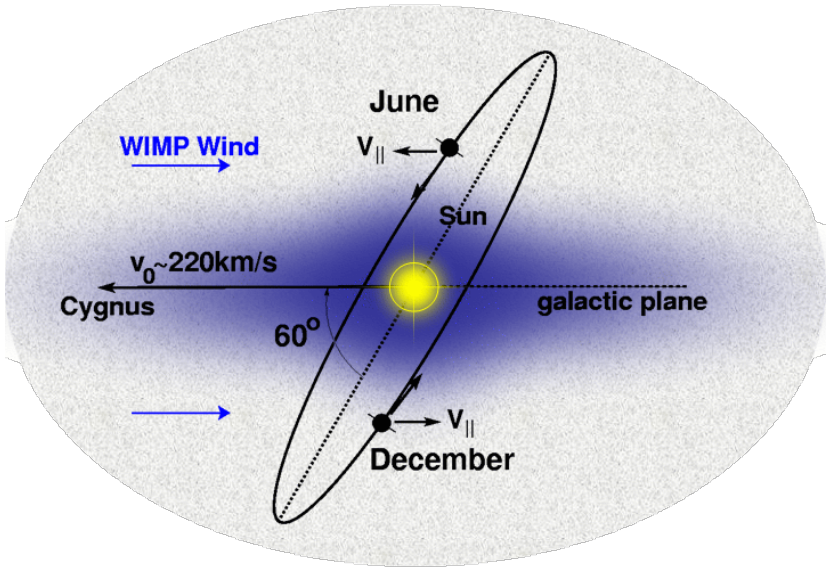
- Find the cross-section at which a 3σ discovery can be claimed for each WIMP mass given CEvNS backgrounds
- Standard neutrino floor for C_3F_8 without energy resolution [arXiv:1408.3581]
- Multiple ways to improve discovery limits without energy resolution



Alternatives to Recoil Energy Spectra

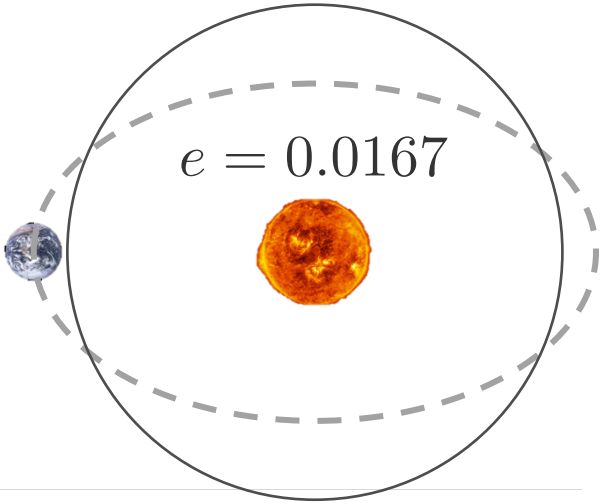
- Use event directionality to increase discovery potential
  - First results from University of Alberta PICO group show potential for extracting directional information from radial distribution of acoustic energy at high frequencies
- Scan over multiple recoil energy thresholds to observe differences in rate
- Exploit time dependence of WIMP signal

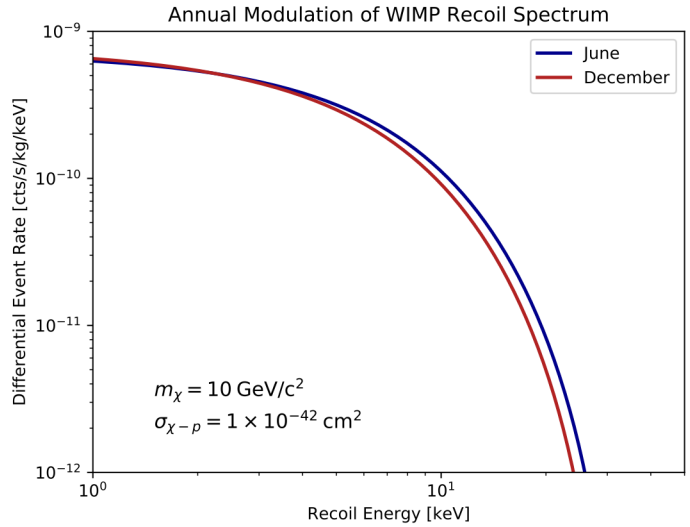


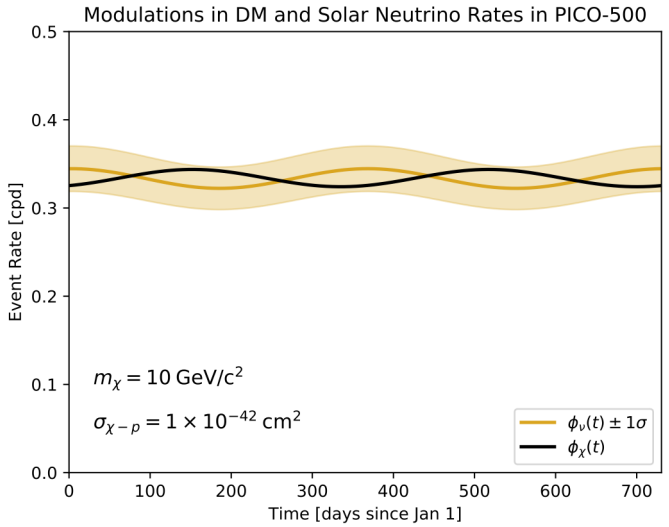


Annual Modulation

- WIMP spectrum varies due to changes in relative motion of Earth and DM halo
- Solar neutrino fluxes vary annually due to eccentricity of Earth's orbit







$$R(t) = A\cos\left(2\pi\left(t - P_\chi\right)\right) + B\left(1 + 2e\cos\left(2\pi\left(t - P_\nu\right)\right)\right) + C$$

Discovery Limits with Time Information

- Define log-likelihood function describing the likelihood of a dataset $\{t_i\}$ as a function of rate parameters (WIMP-nucleon cross section, neutrino fluxes etc.)

$$\ln \mathcal{L} = -\int_{T_0}^{T_1} R(t)dt + \sum_{i=1}^{N} \ln R\left(t_i\right) - \frac{1}{2}\sum_{j=1}^{n_\nu}\left(\frac{\mu_{\nu_j} - \overline{\mu_{\nu_j}}}{\sigma_{\nu_j}}\right)^2$$

- Use profile likelihood ratio to construct test statistic q_0 from ratio of conditional maximum likelihood under the null hypothesis (no WIMP events) to true maximum likelihood

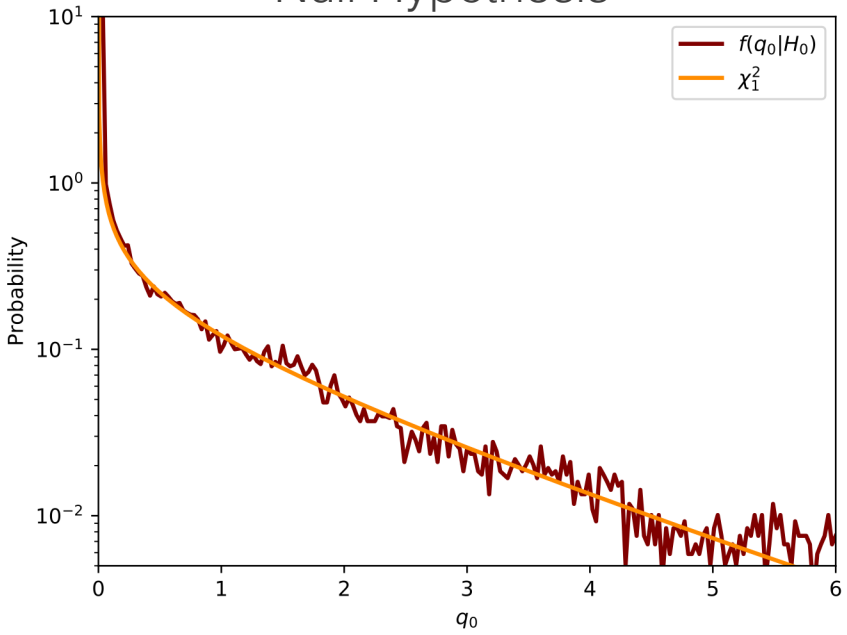
$$q_0 = -2\ln\left(\frac{\max \mathcal{L}\left(\sigma_\chi = 0, \vec{p}\right)}{\max \mathcal{L}\left(\sigma_\chi, \vec{p}\right)}\right)$$

- Simulate datasets with a particular WIMP cross-section and neutrino backgrounds
- Test statistic for a dataset quantifies significance of a deviation from the null hypothesis

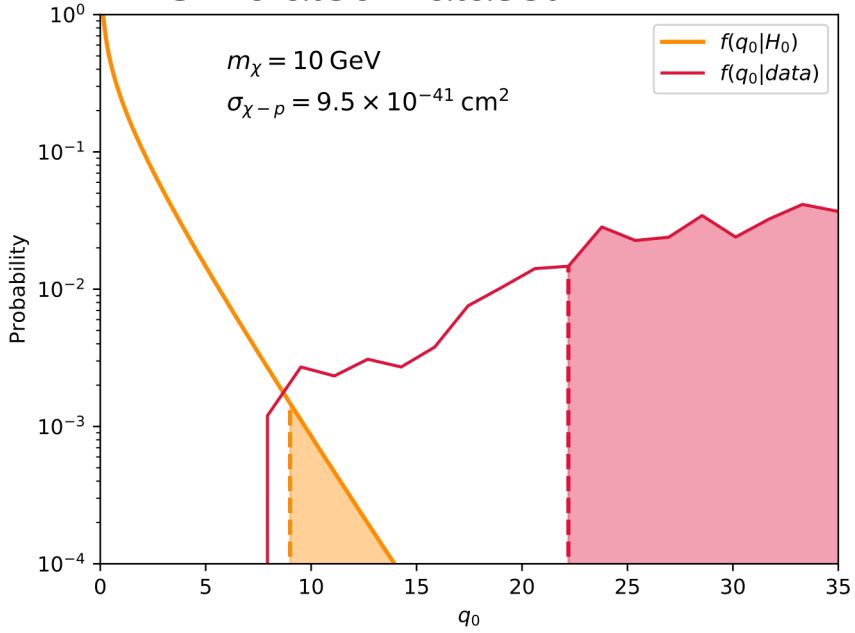
3σ Discovery Limits

- Wilks' theorem: test statistic under null hypothesis is distributed as χ^2 distribution, so significance is given by $Z = \sqrt{q_0}$
- Find the cross-section that gives 3σ significance ($q_0 = 9$) for 90% of datasets at each WIMP mass

Null Hypothesis



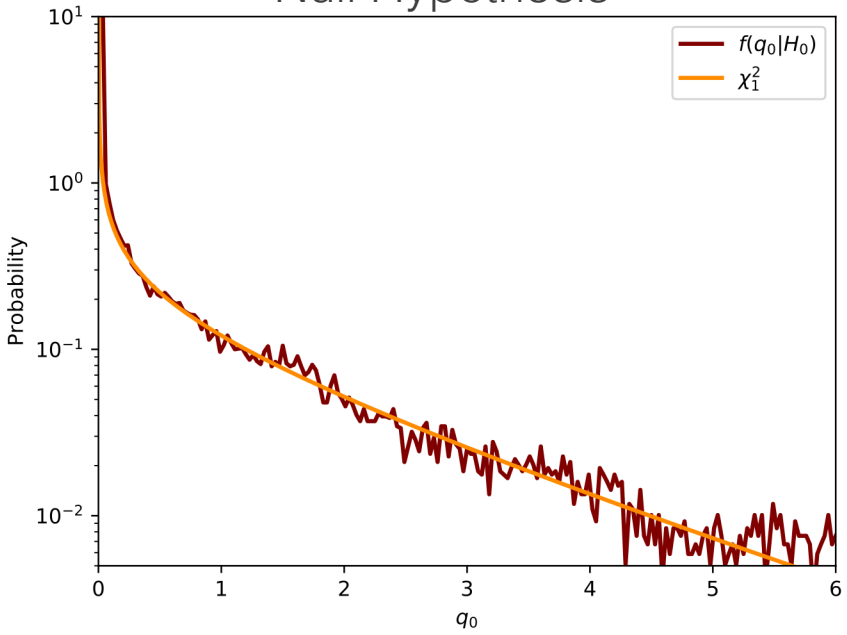
Simulated Dataset



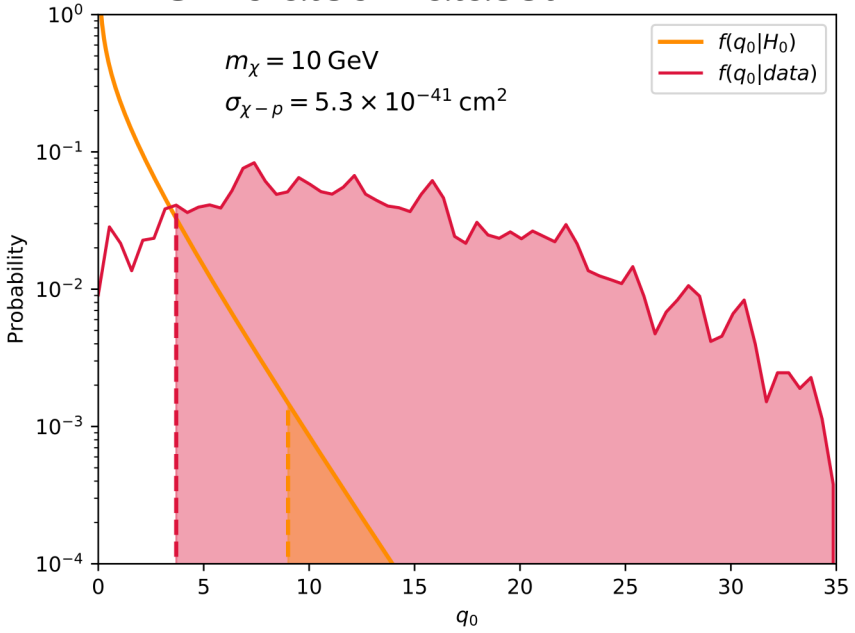
3σ Discovery Limits

- Wilks' theorem: test statistic under null hypothesis is distributed as χ^2 distribution, so significance is given by $Z = \sqrt{q_0}$
- Find the cross-section that gives 3σ significance ($q_0 = 9$) for 90% of datasets at each WIMP mass

Null Hypothesis



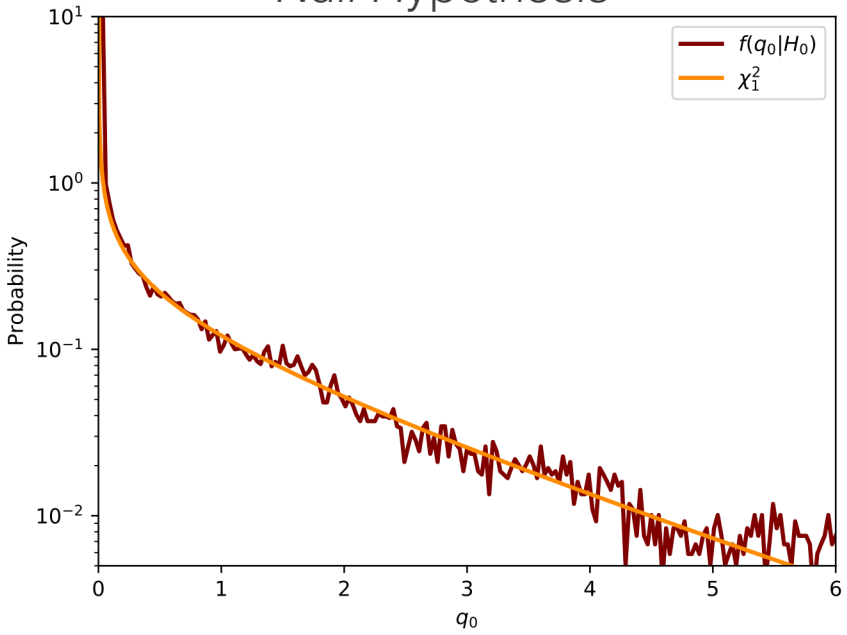
Simulated Dataset



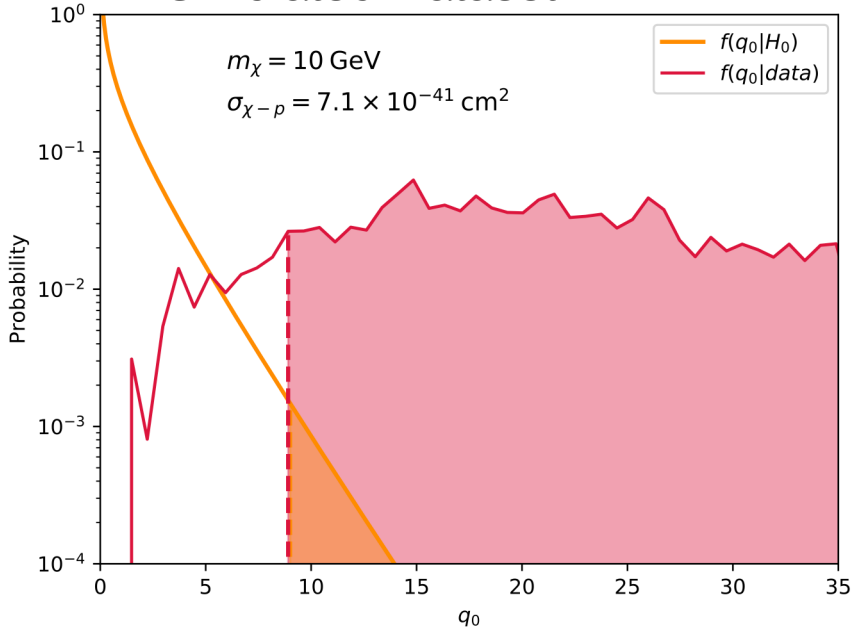
3σ Discovery Limits

- Wilks' theorem: test statistic under null hypothesis is distributed as χ^2 distribution, so significance is given by $Z = \sqrt{q_0}$
- Find the cross-section that gives 3σ significance ($q_0 = 9$) for 90% of datasets at each WIMP mass

Null Hypothesis

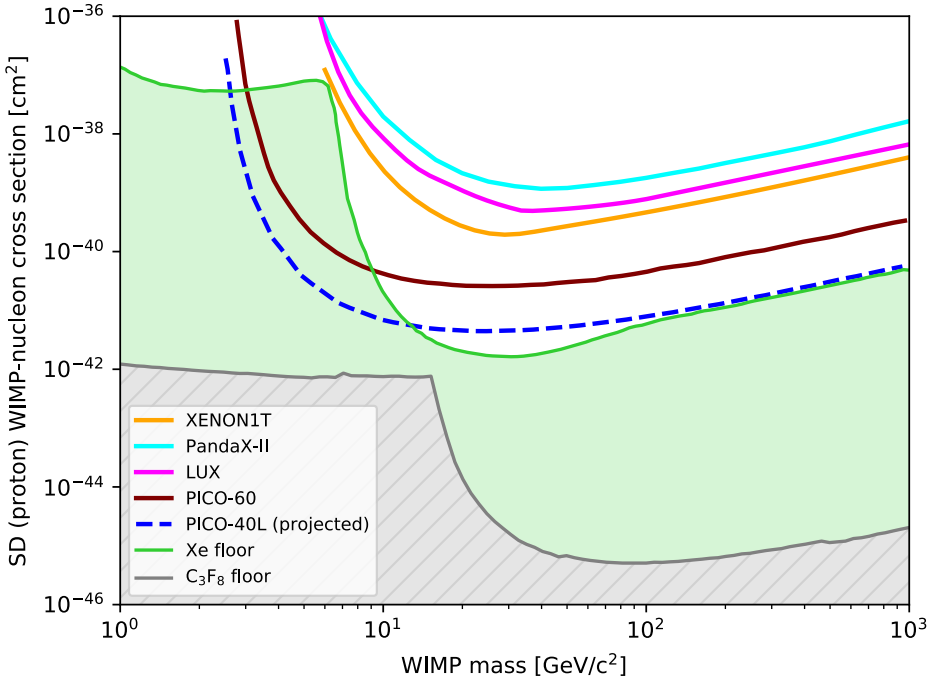


Simulated Dataset



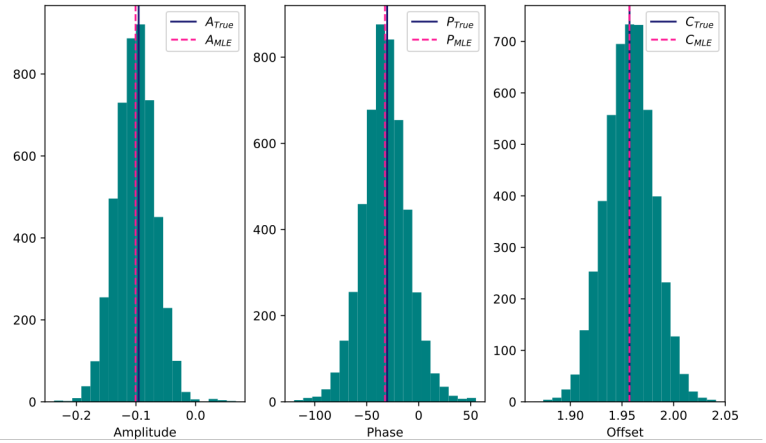
Preliminary Results

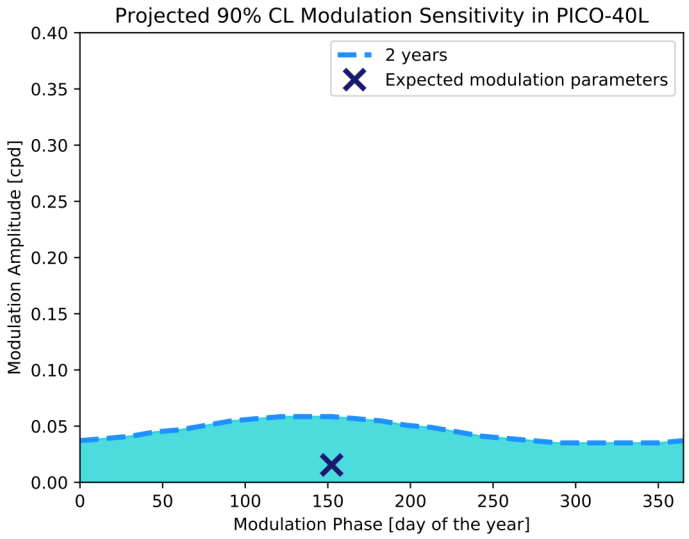
- More work required to better account for neutrino flux uncertainties
- PICO-60 has already reached beyond Xenon neutrino floor
- Large region of parameter space inaccessible to Xenon experiments is within reach of future PICO detectors

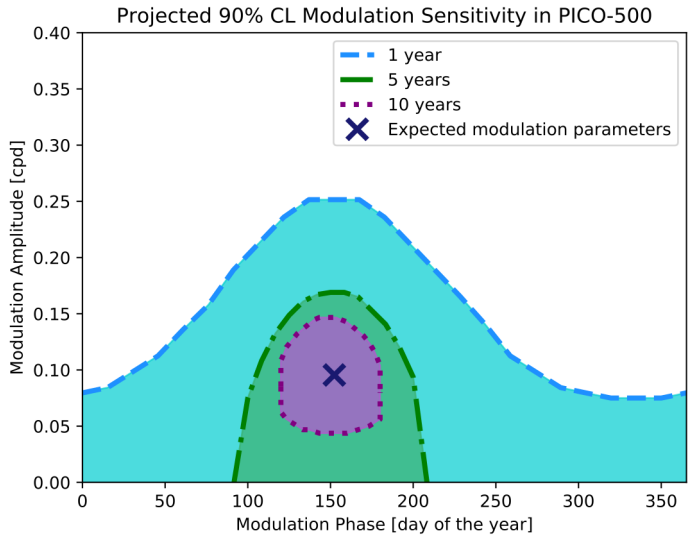


Projected Annual Modulation Sensitivity

- Simulated data using lowest excluded cross section at 25 GeV
- Cannot exclude 0 modulation amplitude at any phase in PICO-40L
- PICO-500 sufficiently sensitive to exclude 0 modulation at phase of interest







Conclusions and Future Work

- Implemented a method to determine discovery potential by exploiting time-dependence of event rates
- Determined sensitivity to annual modulations in dark matter signal
- More accurate calculation would include all nuisance parameters – all neutrino fluxes, standard halo model parameters, phases of annual modulations, etc.
- Need a more realistic neutrino floor for PICO detectors

PICO

Northwestern University
C.E. Dahl, M. Jin, J. Zhang

PennState
S. Priya, Y. Yan

České vysoké učení technické v Praze
R. Filgas, I. Stekl

SNOLAB
I. Lawson

Universitat Politècnica de València
M. Ardid, M. Bou-Cabo, I. Felis

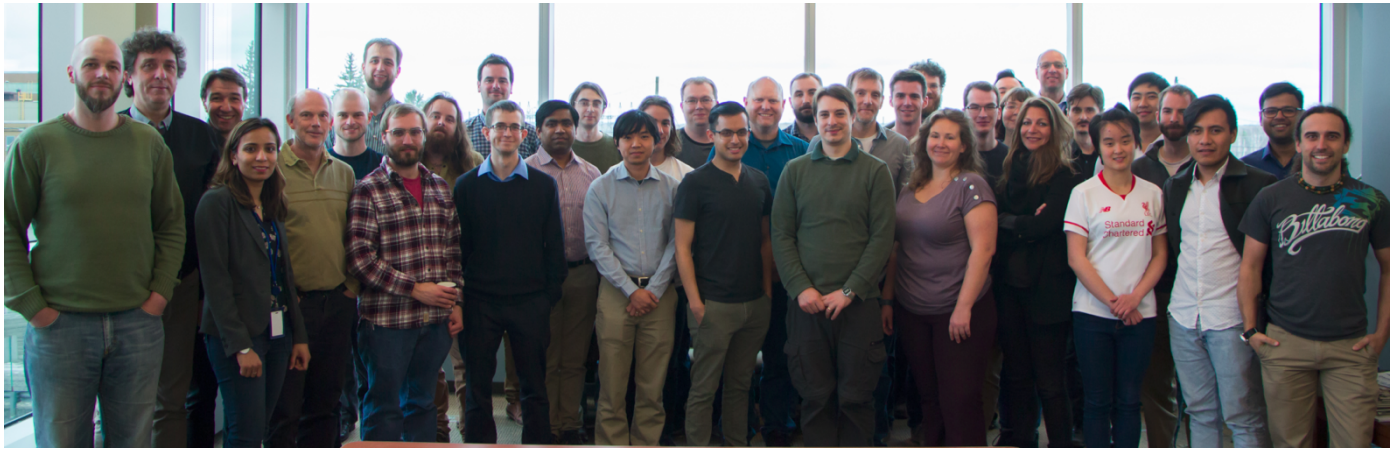
Drexel University
M. Bressler, R. Neilson

F. Flores, A. Gonzalez, E. Noriega-Benítez, E. Vázquez-Jáuregui

Fermilab
P.S. Cooper, M. Crisler, W.H. Lippincott, A. Sonnenschein

Northeastern Illinois University
O. Harris

Queen's University
B. Broerman, G. Cao, K. Clark, G. Giroux, C. Hardy, H. Herrera, C. Moore, A. Noble, T. Sullivan



S. Ali, M. Das, S. Sahoo

Kavli Institute for Cosmological Physics at The University of Chicago
D. Baxter, J.I. Collar, J. Fuentes

University of Alberta
C. Coutu, N.A. Cruz-Venegas, S. Fallows, T. Kozynets, C. Krauss, S. Pal, M.-C. Piro, W. Woodley

Indiana University South Bend
K. Allen, E. Behnke, I. Levine, N. Walkowski, A. Weesner

Université de Montréal
S. Chen, M. Laurin, J.-P. Martin, A.E. Robinson, N. Starinski, D. Tiwari, V. Zacek, C. Wen Chao,

Pacific Northwest National Laboratory
I. Arnquist , T. Grimes, B. Hackett, A. Hagen, C.M. Jackson, K. Kadooka, B. Loer

Laurentian University / Université Laurentienne
J. Farine, A. Le Blanc, T. Hillier, C. Licciardi, O. Scallon, U. Wichoski