Results and Upgrades of DEAP-3600

Lake Louise Winter Institute - February 21, 2022
Courtney Mielnichuk on behalf of the DEAP-3600 Collaboration

DEAP-3600 Collaboration

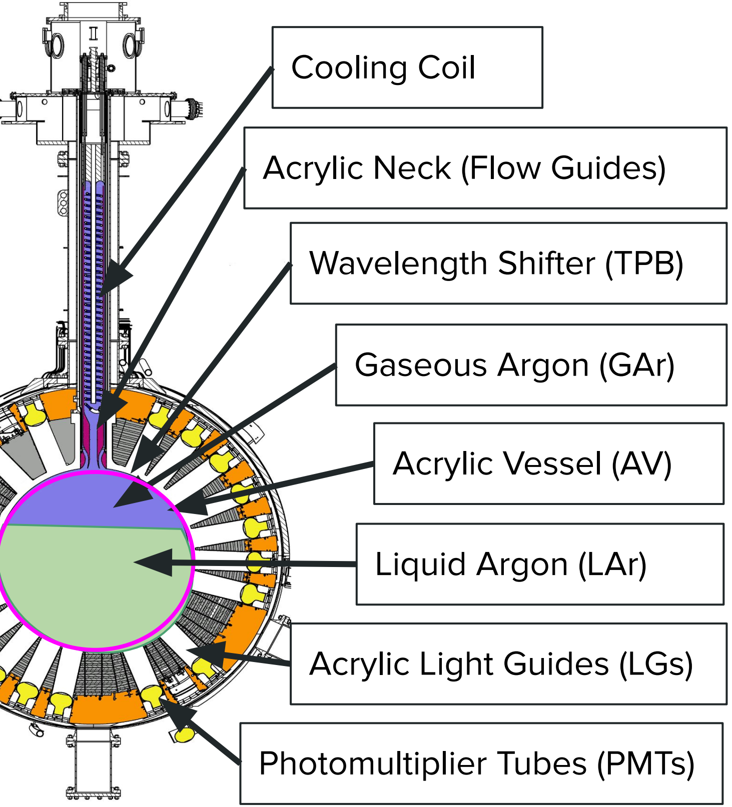
- Approximately 100 collaborators
- Canada, UK, Germany, Mexico, Italy, USA, Russia, Spain, Poland

February 2021 Collaboration Meeting

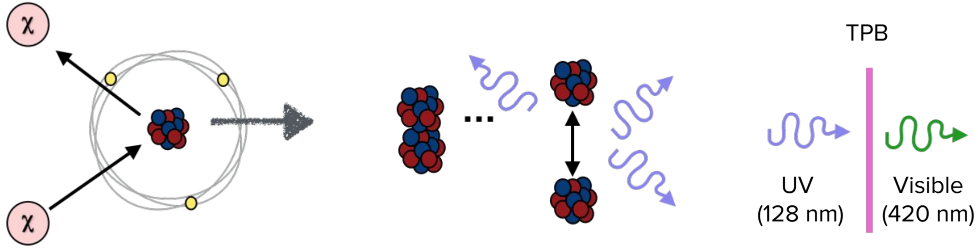
Technical University of Munich
TUM
US University of Sussex
SNOLAB
TRIUMF
JOHANNES GUTENBERG UNIVERSITÄT MAINZ JG|U
ROYAL HOLLOWAY UNIVERSITY OF LONDON
NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"
Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens
Particle Physics Rutherford Appleton Laboratory
Instituto de Física
INFN Istituto Nazionale di Fisica Nucleare
ASTROCENT NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES
Queen's UNIVERSITY
UNIVERSITY OF ALBERTA
GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES Ciemat
LaurentianUniversity UniversitéLaurentienne
Carleton UNIVERSITY
PRINCETON UNIVERSITY

DEAP-3600 Detector

- 3.3 tons of liquid argon
- 2 km underground at SNOLAB (Sudbury, ON)

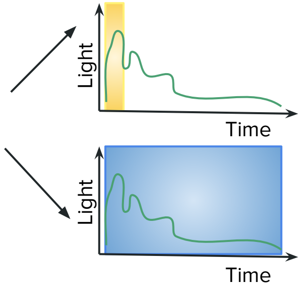


Liquid Argon Scintillation:



Pulse Shape Discrimination:

$$F_{prompt} = \frac{\text{Prompt PE}}{\text{Total PE}}$$

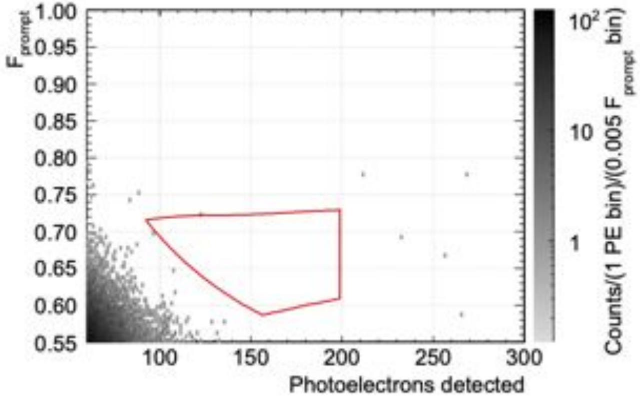


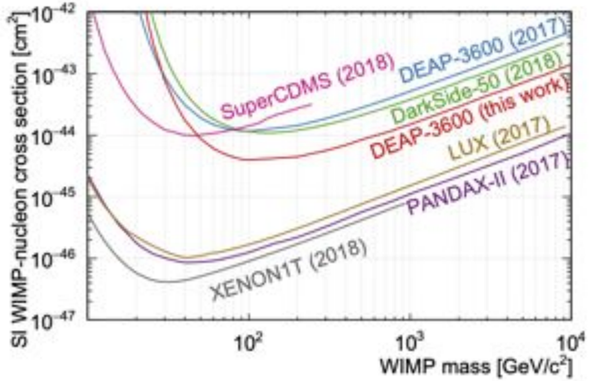
Full PSD model published in Eur. PHys. J. C 81,823 (2021)

Particle Type	F_{prompt}
LAr Alpha	0.75
Nuclear Recoil (WIMPs)	0.7
Beta/Gamma	0.3
GAr Alpha	0.12

WIMP Dark Matter Search

- 231 live day exposure recorded during first year of operation
- **No candidate signal events in WIMP-search region of interest**
- Leading limit on the WIMP-nucleon spin-independent cross section on a **LAr target**
  - $3.9 \times 10^{-45} cm^2$ for a 100 GeV/c^2 WIMP mass at 90% C.L
- **Full results published in Phys. Rev. D. 100, 022004**.
- Current cumulative background model for WIMP search includes:
  - Cherenkov in acrylic
  - Radiogenic & cosmogenic neutrons
  - Surface alpha's
  - Neck alpha decays
  - Dust alpha decays in LAr





Dark Matter Interaction - Astrophysical Parameters

Courtesy of A. Zuñiga-Reyes

WIMP-nucleus scattering rate:

$$\frac{dR(t)}{dE_r} = N_T \frac{\rho_0}{m_\chi} \int_{v>v_{min}} f(\mathbf{v} + \mathbf{v}_E(t)) \frac{d\sigma_T(v, E_r)}{dE_R} d^3v$$

Velocity distribution function:

Maxwell Boltzmann Distribution

$$f(\mathbf{v}) = \frac{1}{\sqrt{2\pi\sigma}} exp\left(-\frac{|\mathbf{v}|^2}{2\sigma^2}\right)$$

DM velocity distribution with substructure

$$f_{DM}(\vec{v}) = (1 - \eta_\chi) f_R(\vec{v}) + \eta_\chi f_{sub}(\vec{v})$$

- $\mathbf{f_R}$: velocity distribution of a nearly round dark halo - SHM (Maxwell Boltzmann distribution
- $\mathbf{F_{sub}}$: velocity distribution of the substructure (3D Gaussian distribution)
- η_χ: relative DM density in substructure (0-30% for streams and ICs, 0-70% for Gaia Sausage)

Dark Matter Interaction - Particle/Nuclear Physics Parameters

Courtesy of A. Zuñiga-Reyes

WIMP-nucleus scattering rate:

$$\frac{dR(t)}{dE_r} = N_T \frac{\rho_0}{m_\chi} \int_{v>v_{min}} f(\mathbf{v} + \mathbf{v}_E(t)) \frac{d\sigma_T(v, E_r)}{dE_R} d^3v$$

Differential Cross Section:

Spin-independent cross-section

$$\frac{d\sigma_T(v, E_r)}{dE_r} = \frac{m_N A^2 \sigma_p^{SI}}{2\mu_p^2 v^2} F^2(E_r)$$

NREFT cross-section

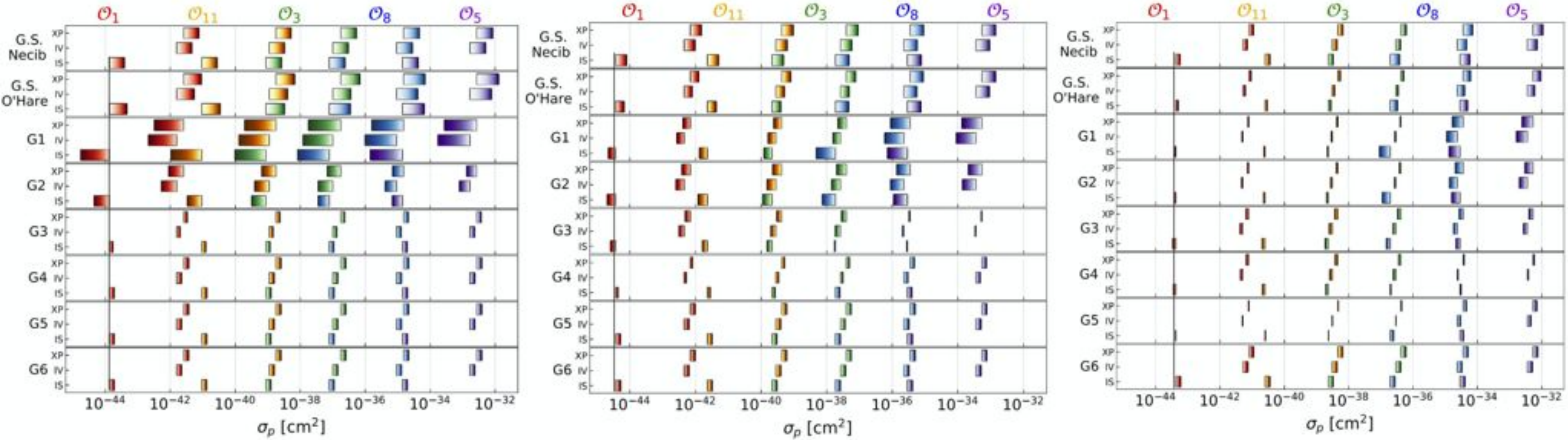
$$\frac{d\sigma_T(v, E_r)}{dE_r} = \frac{4\pi}{2J+1} \sum_k \sum_{\tau=0,1} \sum_{\tau'=0,1} R_k^{\tau\tau'} \left[v_R^{\perp 2}, \frac{q^2}{m_N^2}, (c_i^\tau c_j^{\tau'}) \right] W_k^{\tau\tau'}(y)$$

- **R**: DM response function (contains the coupling strengths)
- **W**: nuclear response function (depends on the target used)
- K-index: represents 6 interactions (M, ϕ'', ϕ''M are the non-zero terms for ^{40}Ar)
  - M describes the nucleon density inside the nucleus
  - ϕ'' related to the angular momentum and spin of nuclei. It favours heavier elements with large, not fully occupied orbitals
  - ϕ''M interference term, product of ϕ'' and M

Simultaneous Effects of all Model Variables

Courtesy of A. Zuñiga-Reyes

- Reinterpret 231-day null result of DEAP-3600 data with NREFT framework and potential dark matter substructures in the local halo



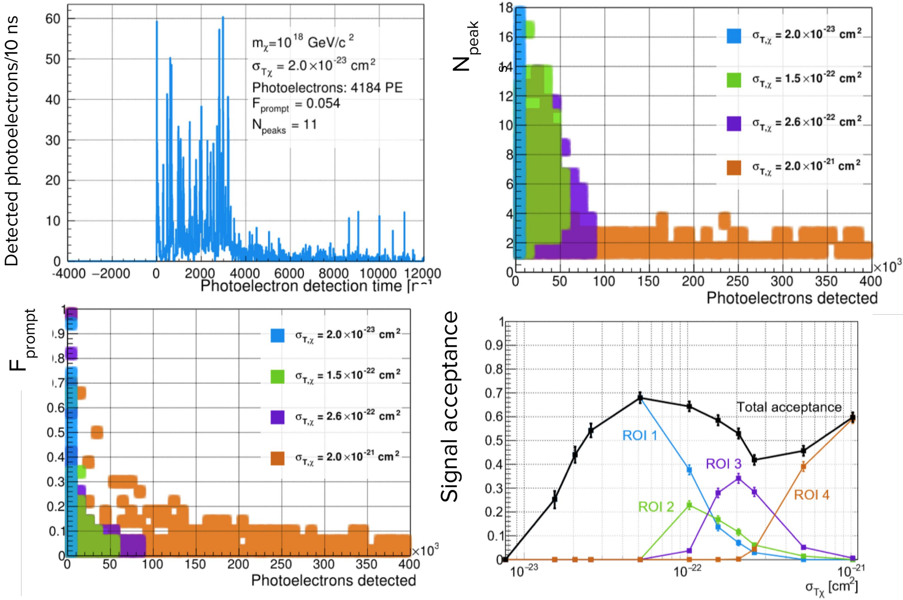
(a) m_χ=40 GeV/c^2 (b) m_χ=100 GeV/c^2 (c) m_χ=3 TeV/c^2

Full results published in Phys. Rev. D 102, 082001 (2020)

Multiple Scatter Signals from Supermassive Dark Matter

Courtesy of M. Lai

- Production mechanisms:
  - Inflation decays/gravity during inflation, thermal production in dark sectors, primordial black hole radiation
- Supermassive dark matter:
  - $\sigma_{\chi\text{-n}} \cong 10^{-25}\text{cm}^2$ and $m_\chi \gtrsim 10^{12}\text{GeV}$
- DM particle loses a negligible amount of energy traveling through Earth and can reach underground detectors
  - Signal is multiply scattering particle depositing energy in LAr
- Multiple-scattering interactions create distinct photoelectron time distribution



Possible backgrounds:
- Pile-up of single scatter events
- Muons passing through LAr

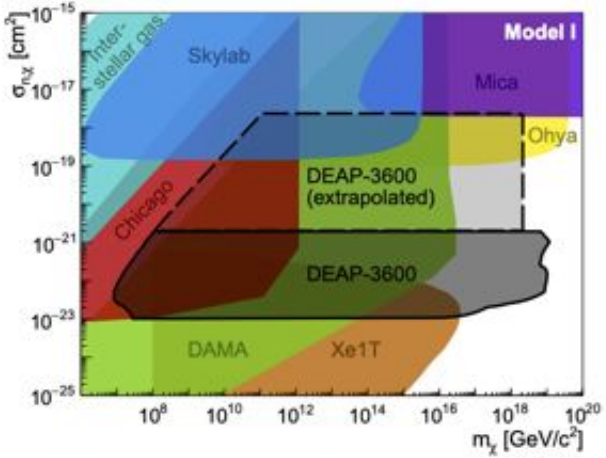
ROI	PE range	Energy [MeV]	N_{peaks}^{min}	F_{prompt}^{max}
1	4000–20 000	0.5–2.9	7	0.10
2	20 000–30 000	2.9–4.4	5	0.10
3	30 000–70 000	4.4–10.4	4	0.10
4	70 000–4×10^8	10.4–60 000	0	0.05

Results of Blind Analysis of 813 Day Livetime with DEAP-3600

Courtesy of M. Lai

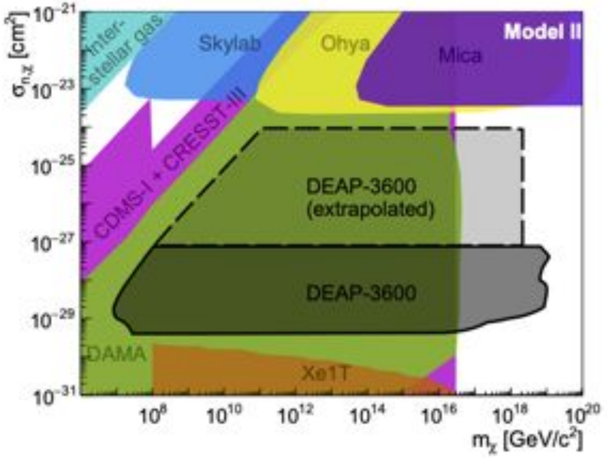
No candidate signals observed – full results published in Phys. Rev. Lett. 128, 011801

Model 1: $$\frac{d\sigma_{T\chi}}{dE_R} = \frac{d\sigma_{n\chi}}{dE_R}|F_T(q)|^2$$



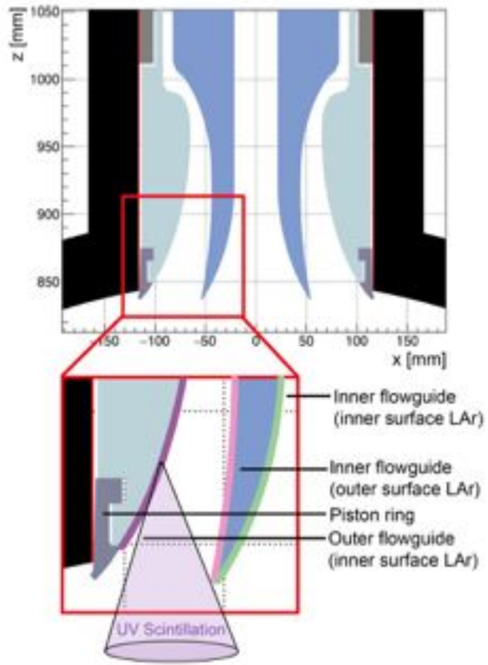
- Scattering cross section at zero momentum transfer, q, is the geometric size of the dark matter, regardless of target nucleus
- Strongly interacting dark matter

Model 2: $$\frac{d\sigma_{T\chi}}{dE_R} = A^4\frac{d\sigma_{n\chi}}{dE_R}|F_T(q)|^2$$

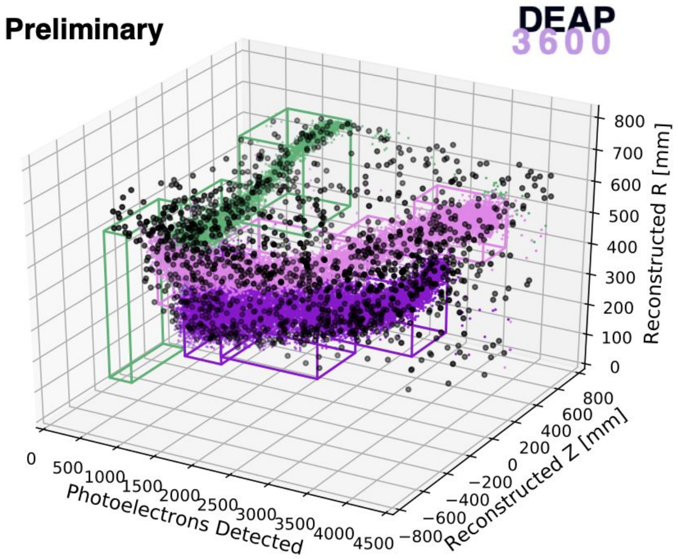


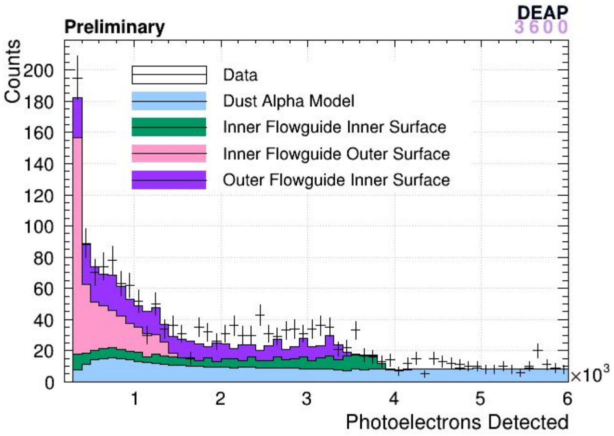
- May arise from nuclear dark matter models with N_D nucleons, each with mass m_D and radius r_D resulting in a total mass of $m_\chi = N_D m_D$

Constraining Neck Alpha Backgrounds



Condensing 4.9 g/s LAr in neck region
→ model as 50 micron LAr film

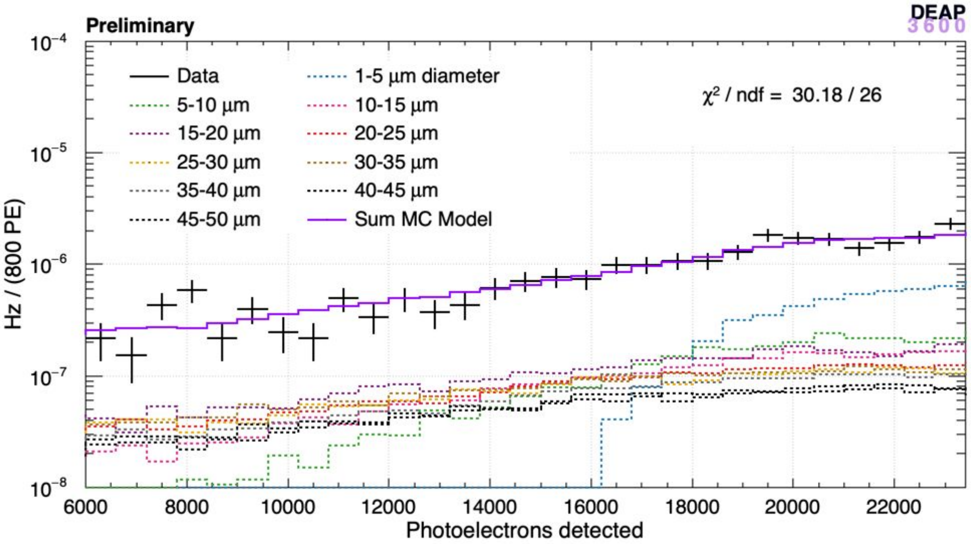


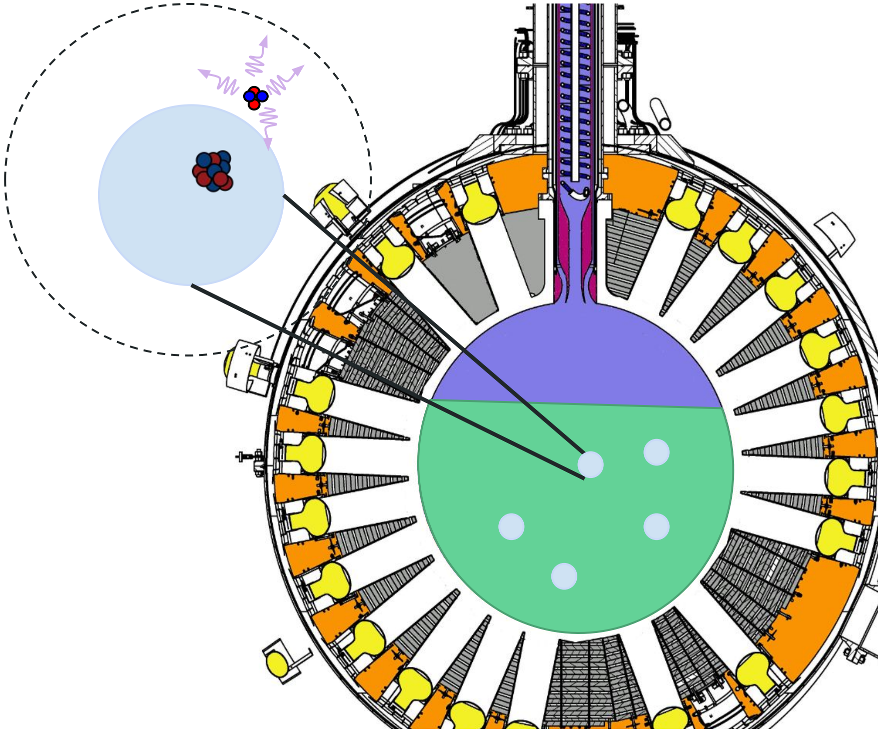


Component	Activity/Rate
^{210}Po inner FG, IS	(12.5 ± 1.1) μHz
^{210}Po, inner FG, OS	(18.9 ± 1.2) μHz
^{210}Po, outer FG, IS	(22.1 ± 1.3) μHz

Simulating Dust Alpha Backgrounds

- Alpha decay embedded in dust particulate will have reduced energy deposition in LAr and isotropic photon emission



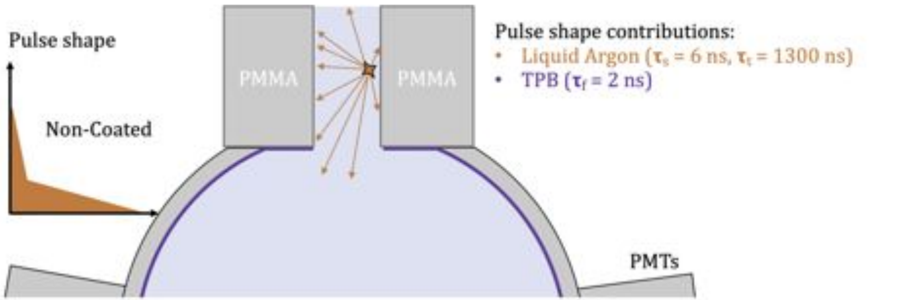


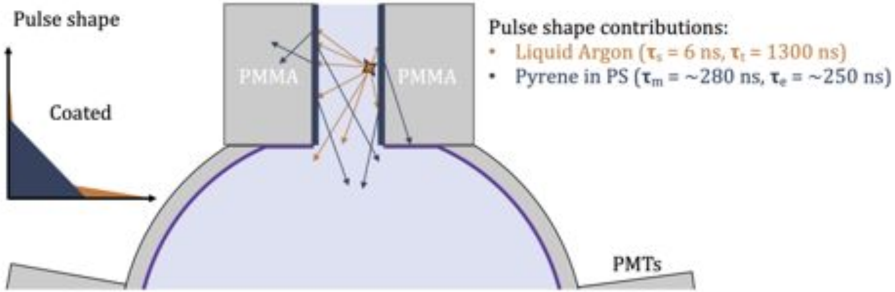
Detector Hardware Upgrades

Objectives:

1. Tag/remove neck alpha backgrounds
2. Filter LAr to remove dust particles

Slow WLS Acrylic Flow Guide Coating





- WLS characterization published in JINST
- Technical paper on slow WLS coating for background rejection in LAr submitted to NIMA

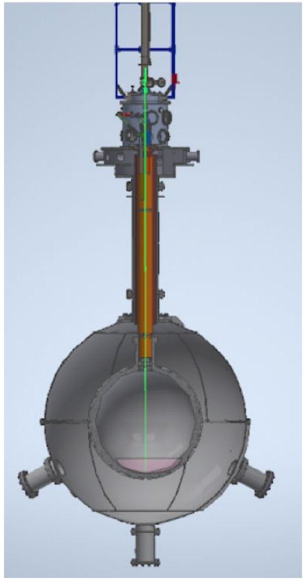
- Shift F_{prompt} of alpha decays occurring in the neck region out of the WIMP region of interest
- Specific PSD variables can be tuned to tag neck alpha decays and verify the existing background model and surface activities

New flow guide construction:

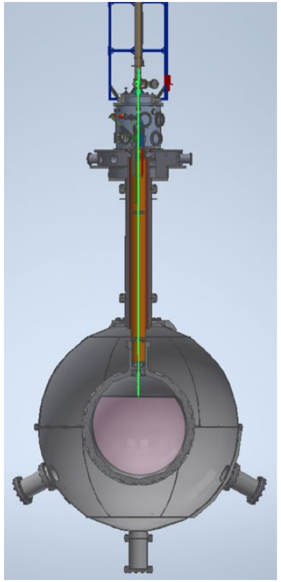
External Cooling/Dust Removal System

- Vacuum deployment system used to insert pipes through the existing neck/glove box
- Dust removal pipe:
    - extract argon in a liquid state and ability to filter liquid argon through existing purification system
- Alternate LAr delivery pipe:
    - internal cooling coil disabled achieving subsequent warming of the neck region.
    - Warm neck region ➔ no LAr film on flow guide surfaces

Dust removal pipe



LAr fill pipe



Testing deployment system

Summary

- DEAP-3600 recorded LAr physics data from November 2016 to March 2020
    - 231 live day WIMP search
    - Constraints using NREFT and halo substructure (231 live day dataset)
    - Search for multi-scattering dark matter (831 live day dataset, blind analysis)
    - More analyses coming soon...
        - Full 802 live day WIMP search (blind analysis)
- Detector Hardware Upgrades underway
    - Fix of internal neck seal to allow full fill with 3600 kg LAr
    - Slow WLS coating of acrylic flow guides to tag/remove neck alpha backgrounds
    - External cooling and filtration system
        - remove dust particulates from LAr
        - operation with warm neck region

BACK UP SLIDES…

Extra Slide - Multiply Interacting Dark Matter (Analysis)

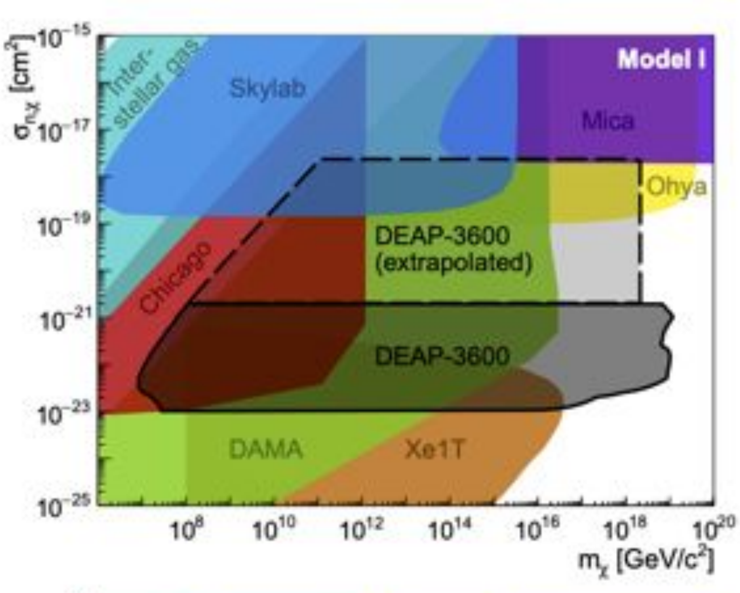
Courtesy of M. Lai

- Excluded data:
  - (3 ± 3) µs/trigger for signal spanning two events
  - 9 days to test selection cuts
  - 6 days from the muon coincidence sideband
- Low level cuts
  - < 5 % PE in the brightest channel (acceptance of 87%)
  - <5% PE in GAr PMTs (acceptance of 99%)
- Background below 10 MeV
  - Pile-up event
    - Simulation of pile-up (assume Poissonian statistics for the number of pulses)
    - Agreement between data and simulation within 5%
- Background above 10 MeV
  - Muon flux ~ 17 muons per day at SNOLAB
  - Removal of any event within [-10,90]µs from muon veto trigger
  - > 99% of muons triggered in coincidence are rejected
  - Muons removed by $F_{prompt}<0.05$
- In all the ROI's the background level is 0.05 ± 0.03

Extra Slide - Multiply Interacting Dark Matter Exclusion Boundaries

Courtesy of M. Lai

- Lower and upper exclusion boundaries are flat because the cross section sensitivity is only dependent on the detector's multi-scatter acceptance
- Right-hand boundary is nearly vertical due to the drop in DM flux with increasing m_D (above the notch is the region where the Earth overburden is dominated by the crust
- Left-hand boundary $\sigma_{T\chi} \propto m_D$ due to attenuation in the overburden



Extra Slide - Effective Operators for NREFT

Slide Credit: A. Zuñiga-Reyes

Effective operators for ^{40}Ar

$$\mathcal{O}_1 = 1_\chi 1_N,$$

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

$$\mathcal{O}_5 = i\vec{S}_\chi \cdot \left(\frac{\vec{q}}{m_N} \times \vec{v}_\perp\right),$$

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

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

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

$$\mathcal{O}_{15} = -\left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left[(\vec{S}_N \times \vec{v}_\perp) \cdot \frac{\vec{q}}{m_N}\right].$$

S_χ: DM spin, S_N: nuclear spin, q: momentum transfer, $v_\perp$: velocity perpendicular to q

Interaction Lagrangian (L_{int}): a sum over i effective operators, where c_i is the coupling constant associated with the O_i operator

$$\mathcal{L}_{int} = \sum_i c_i \mathcal{O}_i$$

Photon mediated operators can also be parametrized as a linear combination of NREFT operators

Anapole

$$\mathcal{O}_{\mathcal{A}} = c_{\mathcal{A}} \sum_{N=n,p} (Q_N \mathcal{O}_8 + g_N \mathcal{O}_9)$$

Millicharge

$$\mathcal{O}_{\mathcal{M}} = e^2 \epsilon_\chi \frac{\mathcal{O}_1}{q^2}$$

Electric dipole

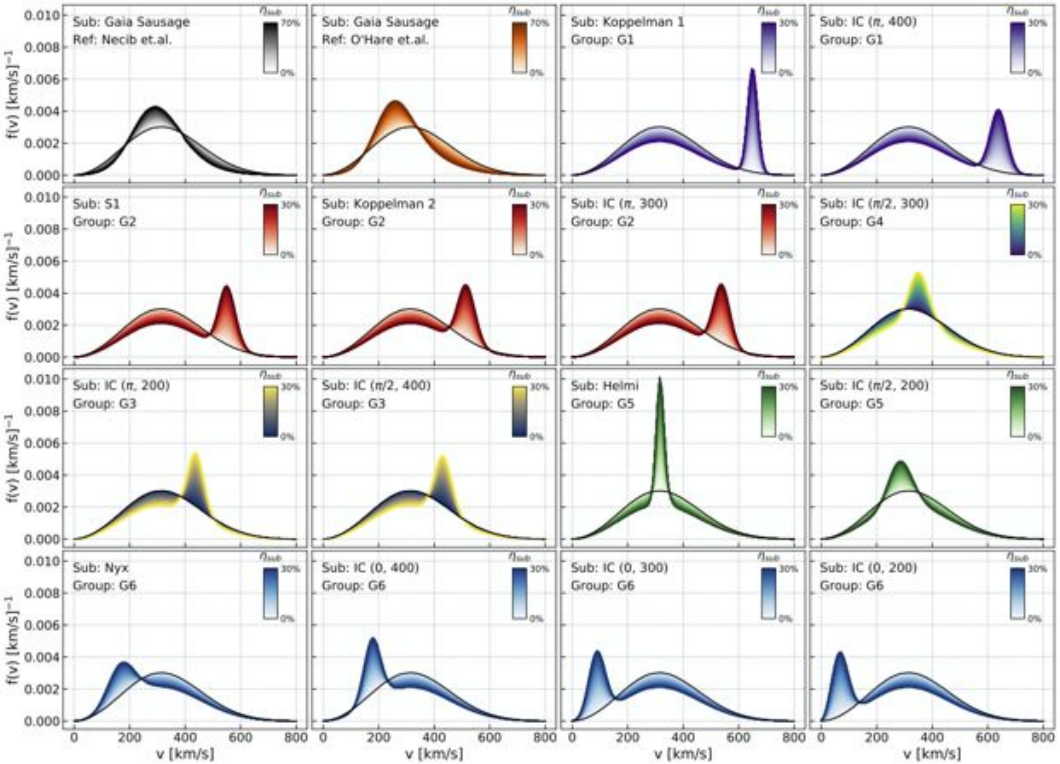
$$\mathcal{O}_{\mathcal{ED}} = 2 e d_\chi \frac{\mathcal{O}_{11}}{q^2}$$

Magnetic dipole

$$\mathcal{O}_{\mathcal{MD}} = 2 e \mu_\chi \sum_{N=n,p} \left[Q_N m_N \mathcal{O}_1 + 4 Q_N \frac{m_\chi m_N}{q^2} \mathcal{O}_5 + 2 g_N m_\chi \left(\mathcal{O}_4 - \frac{1}{q^2}\mathcal{O}_6\right)\right]$$

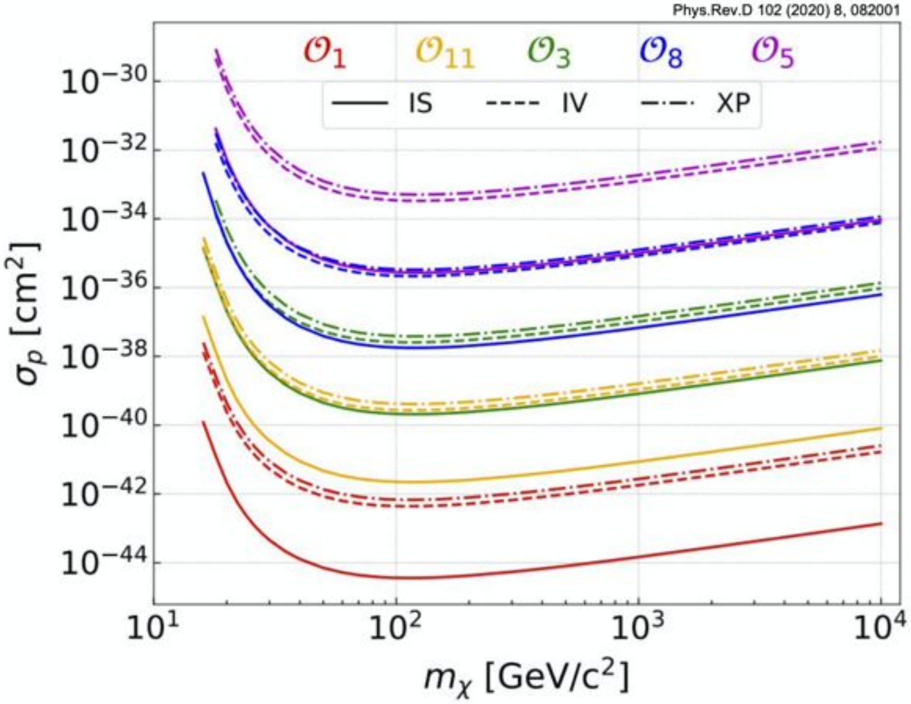
Extra Slide - Dark matter velocity distributions

Slide Credit: A. Zuñiga-Reyes



Extra Slide - Constraints for effective operators

Slide Credit: A. Zuñiga-Reyes



Effective DM-proton cross section

$$\sigma_p \equiv \frac{(c_i^p\ \mu_p)^2}{\pi}$$

Isoscalar **(IS)** -- c_n/c_p = 1

Isovector **(IV)** -- c_n/c_p = -1

Xenonphobic **(XP)** -- c_n/c_p = -0.7

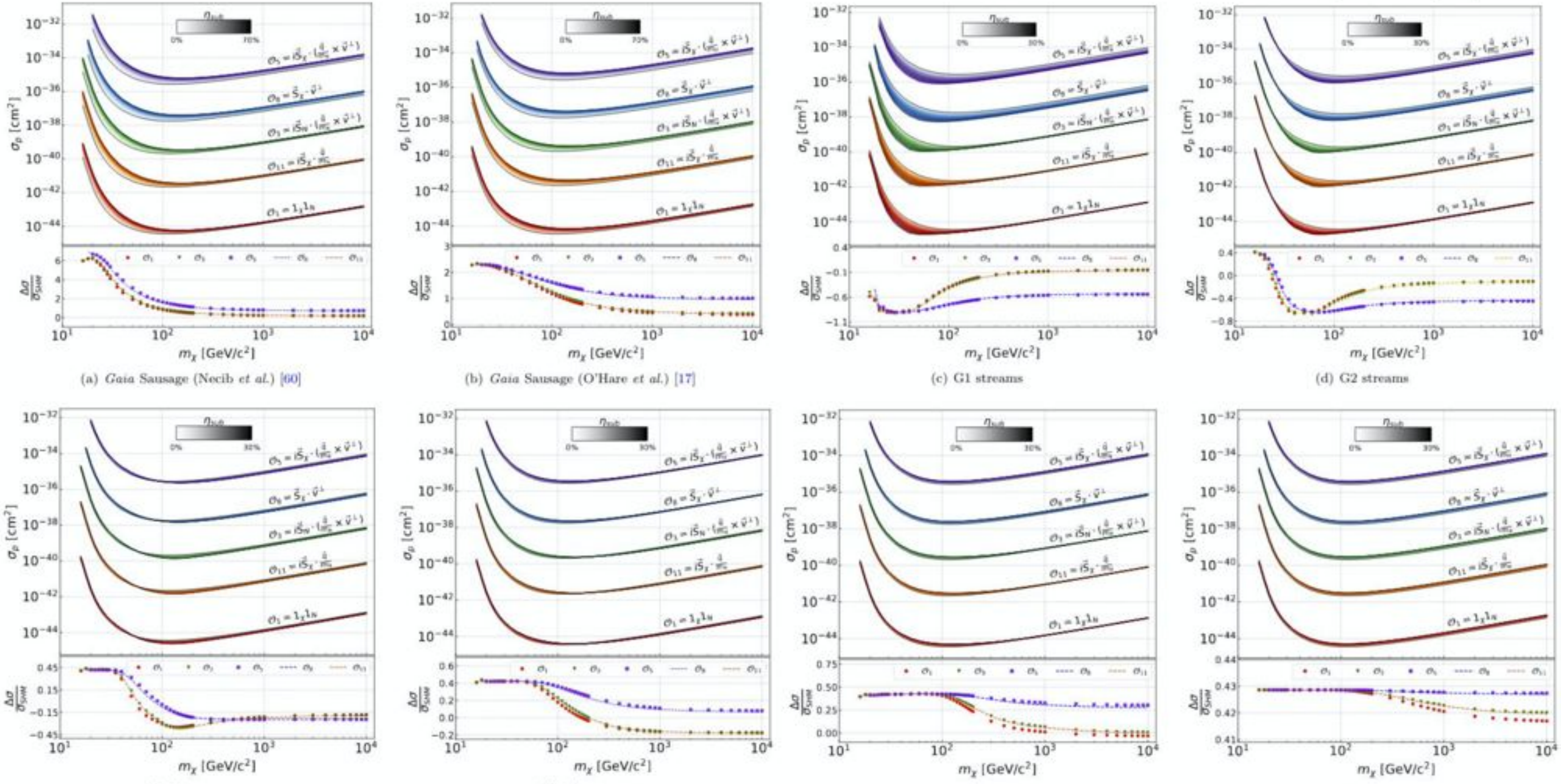
Isospin-violating scenarios

Traditional SHM parameters used:

- Local DM density (ρ_0) : 0.3 GeV/cm^3
- Circular speed (v_0) : 220 km/s
- Escape speed (v_{esc}) : 544 km/s
- Velocity distribution : Maxwell-Boltzmann (boosted to the Earth reference frame).

Extra Slide - Effect on different sub-structures

Slide Credit: A. Zuñiga-Reyes



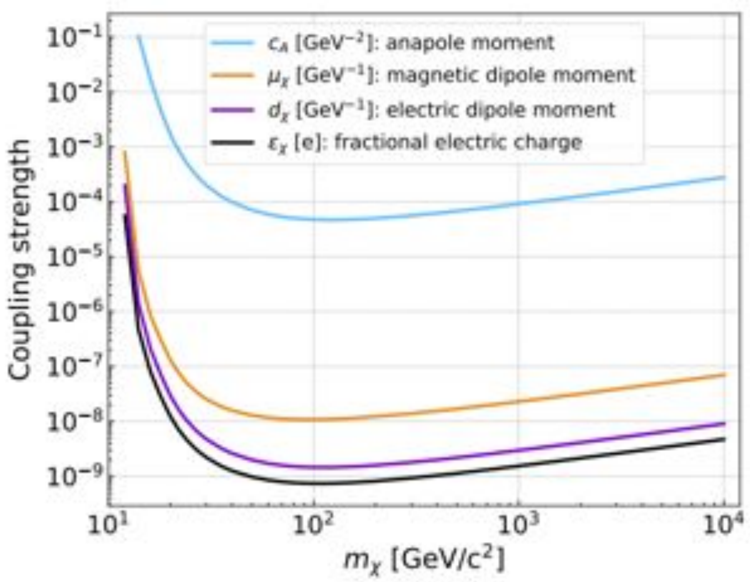
(a) *Gaia* Sausage (Necib *et al.*) [60]
(b) *Gaia* Sausage (O'Hare *et al.*) [17]
(c) G1 streams
(d) G2 streams

(a) G3 streams
(b) G4 streams
(c) G5 streams
(d) G6 streams

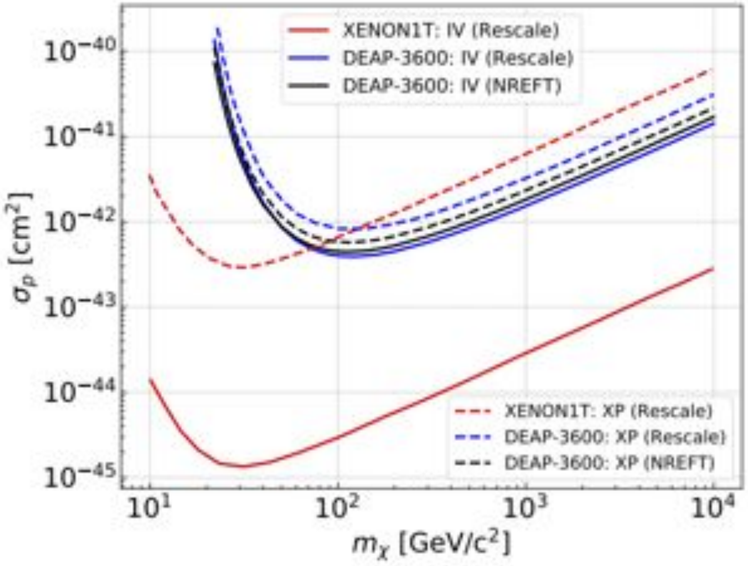
Extra Slide - Limits on specific interactions for NREFT

Slide Credit: A. Zuñiga-Reyes

Specific Interactions



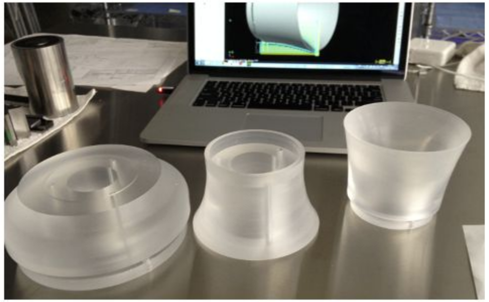
Xenonphobic Dark Matter

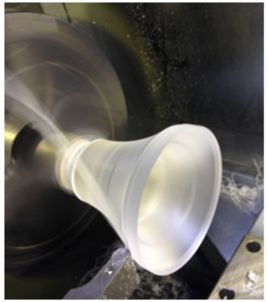


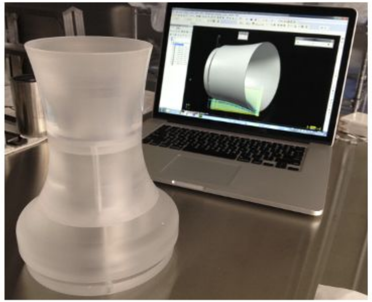
Extra Slide - Flow guide machining

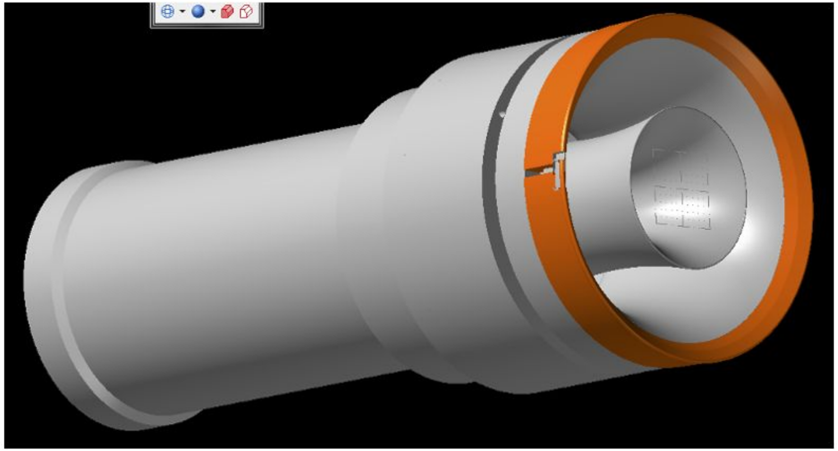
Center for Particle Physics - DEAP-3600 - Dark Matter Experiment using Argon Pulseshape discrimination

FlowGuide component machined in a low-radon environment







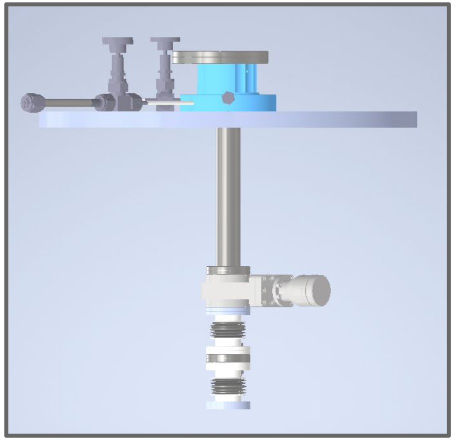


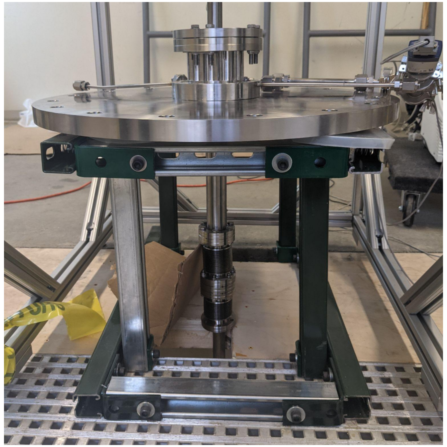
University of Alberta - Physics Machine Shop - Low-Radon Cleanroom - Tony.Vinagreiro@uaberta.ca 2014/2020

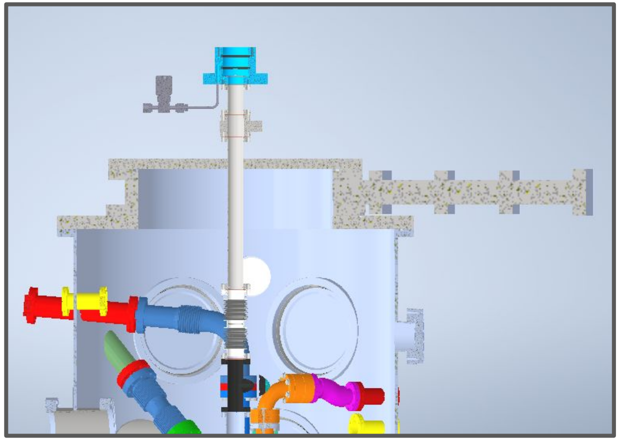
Extra Slide - Alternative Cooling Deployment System

- Designed to deploy stainless steel tubes through the neck of the existing detector
- Deployment will be done under vacuum in a metal sealed system that goes through the existing DEAP glovebox to prevent radon from entering the detector

1. Install lower small-diameter-deployment-device (SDDD) on top of glovebox







Extra Slide - Alternative Cooling Deployment System

2. Assemble upper SDDD and installation tower (contains LAr-fill or dust pipe)

Extra Slide - Alternative Cooling Deployment System

3. Lower dust or fill pipe into inner detector




Extra Slide - Alternative Cooling Deployment System

3. Lower dust or fill pipe into inner detector