First direct detection constraints on Planck-scale mass dark matter using DEAP-3600

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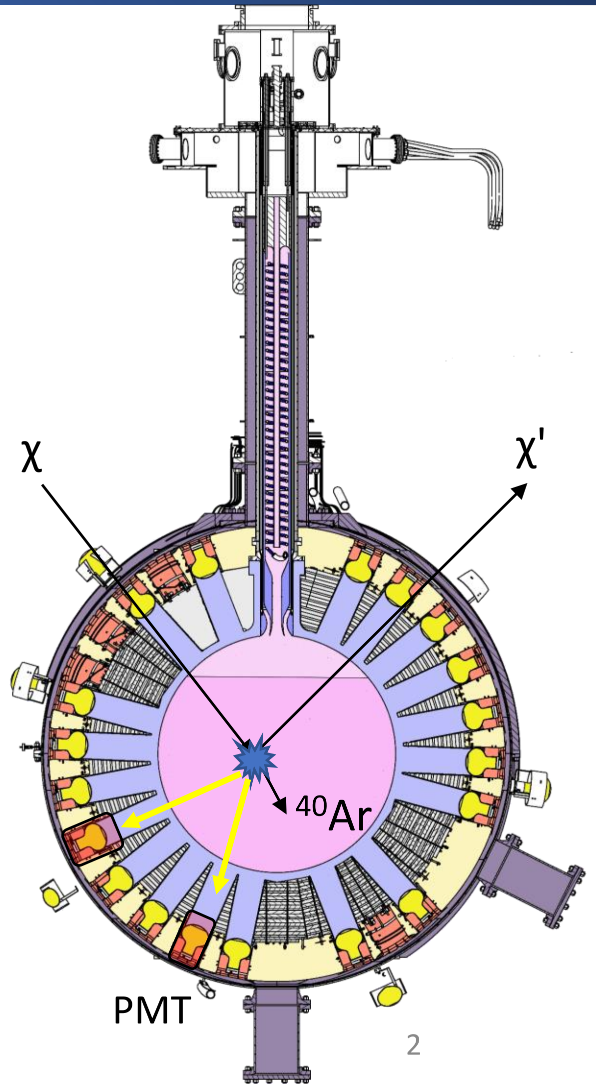
on behalf of the DEAP collaboration

Winter Nuclear Particle Physics Conference 2022
16th February 2022

DEAP-3600

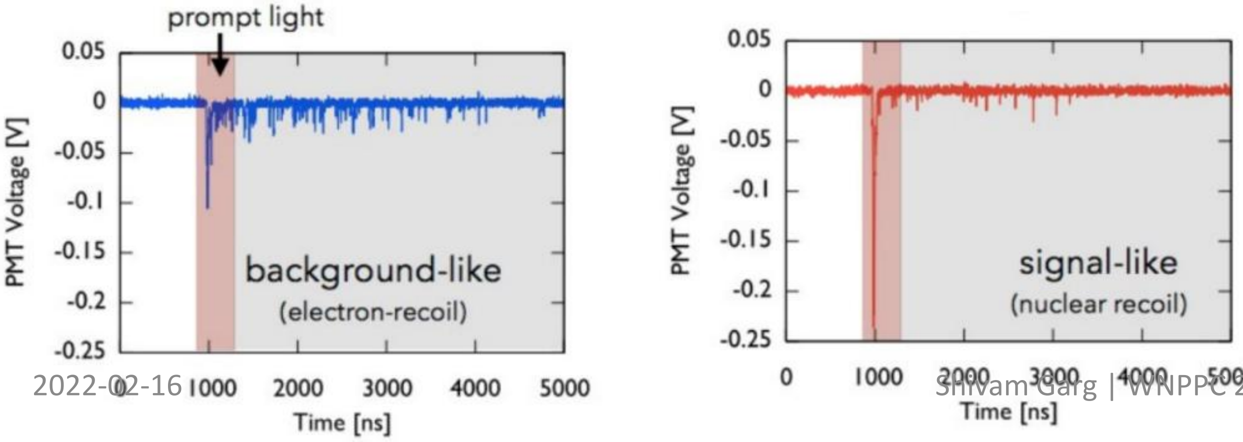
- Liquid argon based dark matter detector located 2km underground at SNOLAB
- Dark matter Experiment using Argon Pulseshape discrimination
- >3 tonnes target mass of LAr in acrylic vessel
- Largest cross-sectional area – surface area ~9.1m^2 (acrylic vessel of 1.7m diameter)
- Collected data from 2016-2020; upcoming hardware upgrades this year

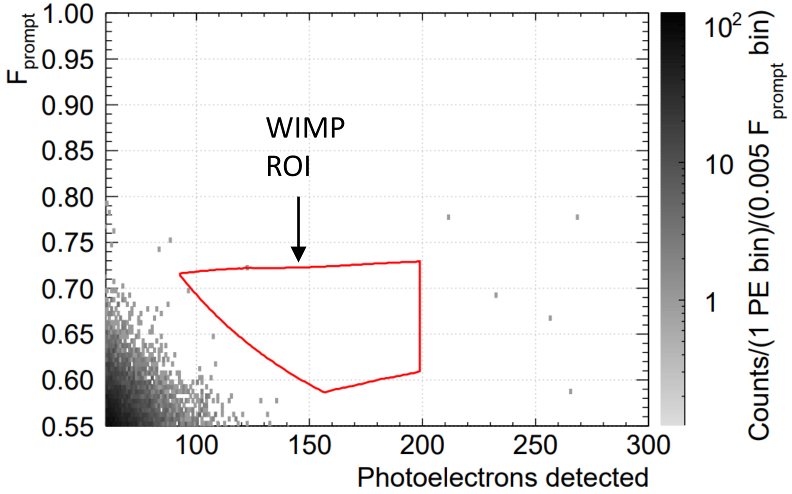


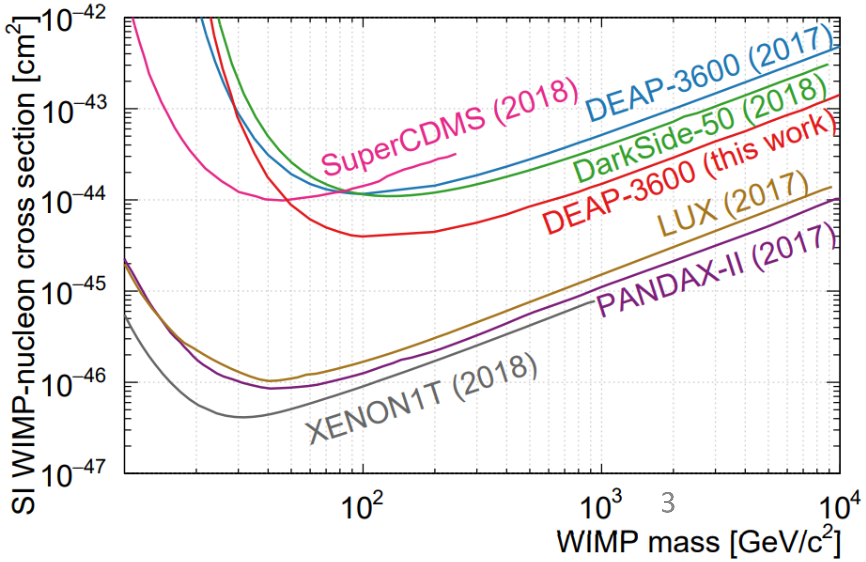
DEAP-3600

- Open data of 231 live days
- No events observed in WIMP ROI
- Leading limit on the WIMP-nucleon spin-independent cross section on a LAr target (published in [Phys. Rev. D. 100, 022004](#))

$$\mathrm{F_{prompt}} = \frac{\int_{-28\,\mathrm{ns}}^{150\,\mathrm{ns}} w(t)\,dt}{\int_{-28\,\mathrm{ns}}^{10\,000\,\mathrm{ns}} w(t)\,dt}$$





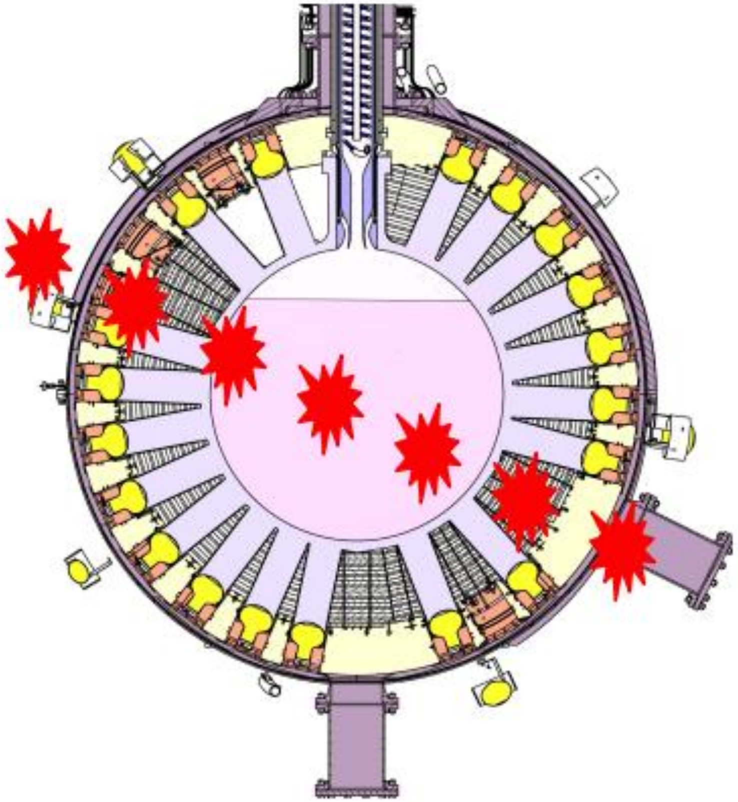


Supermassive dark matter

- Production mechanisms
  - Inflaton decays/gravitational mechanism related to inflation
  - Primordial black hole radiation
  - Thermal production in dark section
- Dark matter candidates above $\sigma_{\chi\text{-}n} \sim 10^{-25}$ cm^2 and $m_\chi > 10^{12}$ GeV loose negligible amount of energy in Earth and can reach underground detectors

Multiscatter signatures in DEAP

- DM will perform tens, hundreds, thousands of scatters in the detector
- Deflection of DM after scattering is negligible, so a collinear track expected
- Multiple scatters create unique PE time distribution
- Single scatter WIMP analysis cuts out these types of events, can't be extrapolated to this regime, so need a dedicated analysis



Monte Carlo simulation

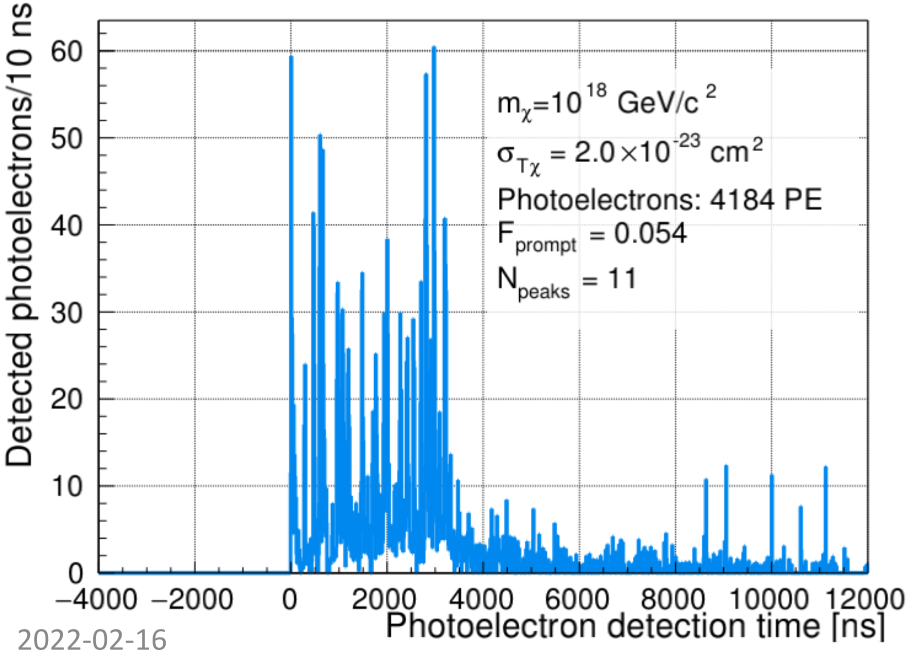
- DM particle generated at 80km from the Earth's surface, at top of the atmosphere, velocity sampled from the usual truncated Maxwell-Boltzmann distribution
- Particle propagated through the atmosphere and Earth, with an average energy loss given by (scattering is continuous)

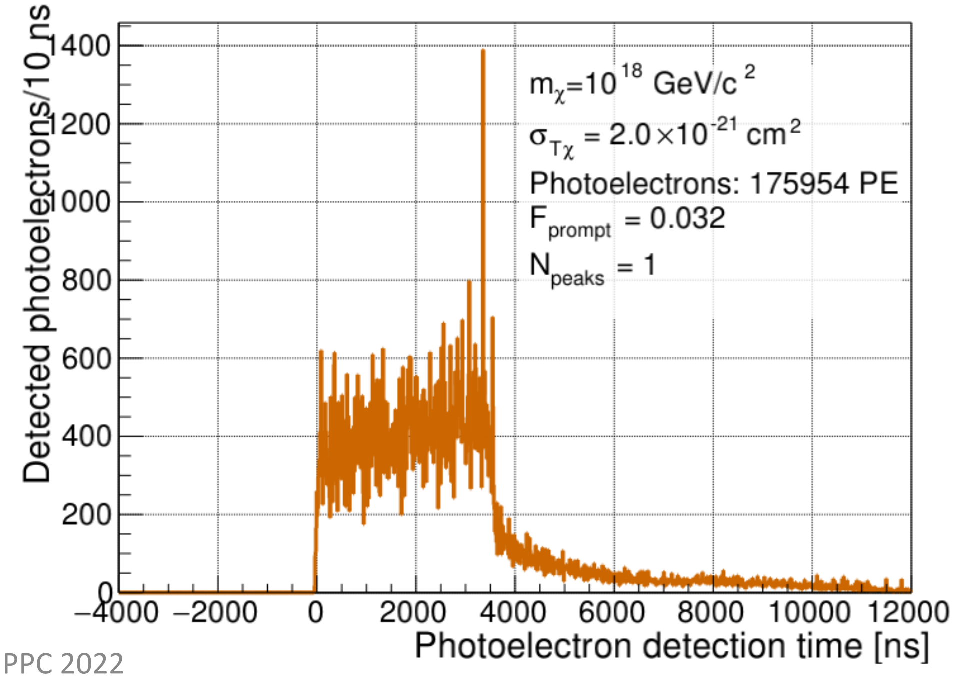
$$\left\langle \frac{dE_\chi}{dt} \right\rangle (\vec{r}) = -\sum_i n_i(\vec{r}) \sigma_{i,\chi} \langle E_R \rangle_i v$$

- DM particle boosted into detector frame and propagated to sphere around the detector of 1.5m radius
- Detector response fully simulated in RAT/GEANT4 from henceforth with a custom developed generator for simulating multiple recoils

Simulated waveforms

- PE distribution shows the multi scattering in the signal
- Signal is reconstructed with a low Fprompt
- Peaks merge together at higher cross sections





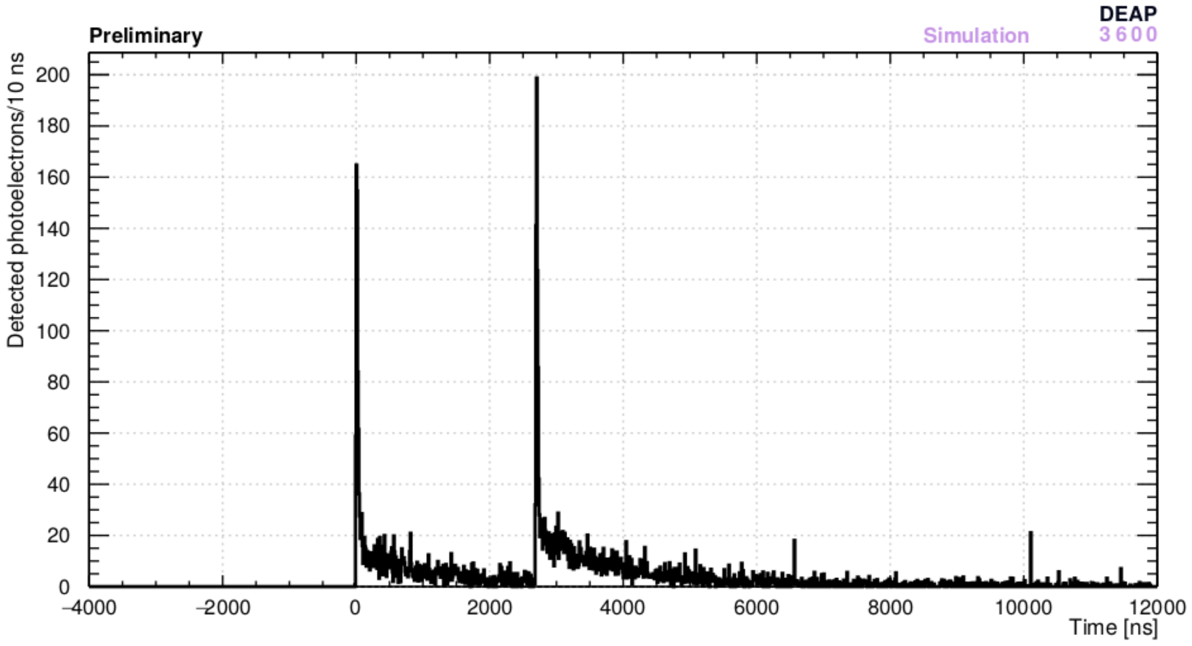
Regions of interest

- Detector response and backgrounds widely change as a function of energy (consequently PE), 4 different ROIs are defined
- DM candidates falling in 1st 3 ROIs could be simulated, allowing for custom selection cuts according to the specific PE range
- DM falling in ROI4 could not be simulated due to high number of scatterings

ROI	PE range	Energy [MeV_{ee}]	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

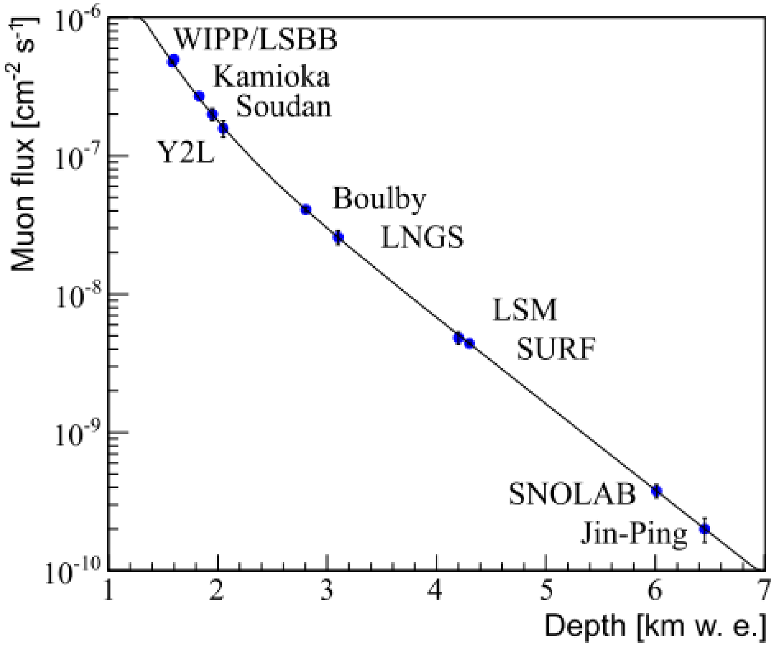
Background estimation – below 10MeV

- Dominant background – pile ups between local radioactivity recoils.
- Need to evaluate distribution of N_{peaks} for pileups in 3 years of data taking.
- Assumed Poissonian statistics for number of pulses in a pile-up
- Predictions tested on a physics run and on a calibration run using an AmBe source
- Agreement between data and simulation within 5% in both datasets



Background estimation – above 10 MeV

- Dominant background – muons entering the detector inner vessel
- Muon flux at SNOLAB is known
- Removal of any event with [-10,90]us from the muon veto trigger
- More than 99% of muons are triggered in coincidence and rejected
- In ROI4, Muons are also removed by requiring fprompt<0.05. Determined by studying muon events in inner detector in the coincidence sideband



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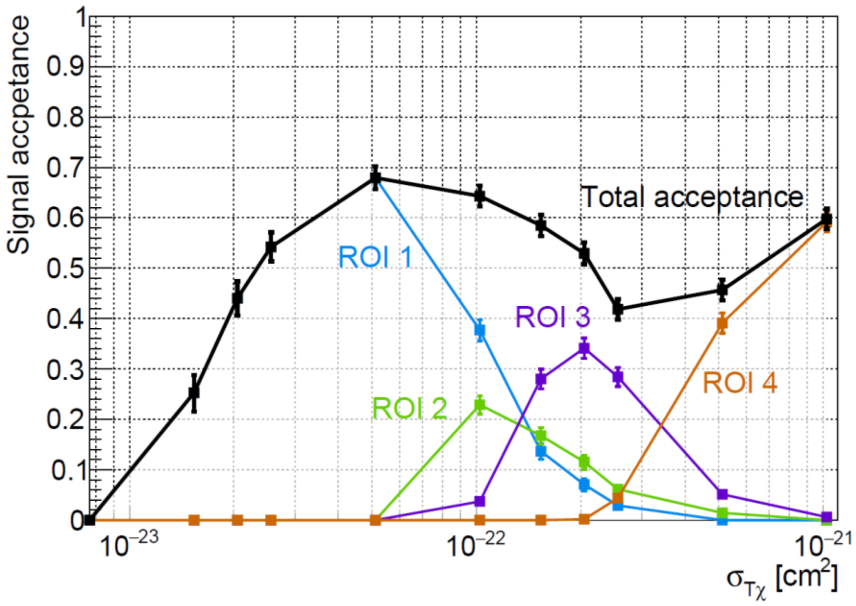
Selection cuts and acceptances

- Two low level cuts applied to ROIs 1-3
  < 5 % PE must be in the brightest channel, acceptance of 87 %
  < 5% PE must be in PMTs in gaseous argon, acceptance of 99 %
- Background level in each ROI is expected to be <<1 event. In all ROIs the background level is 0.05±0.03



ROI	PE range	Energy [MeV_{ee}]	N_{peaks}^{min}	F_{prompt}^{max}	μ_b
1	4000–20 000	0.5–2.9	7	0.10	$(4 \pm 3) \times 10^{-2}$
2	20 000–30 000	2.9–4.4	5	0.10	$(6 \pm 1) \times 10^{-4}$
3	30 000–70 000	4.4–10.4	4	0.10	$(6 \pm 2) \times 10^{-4}$
4	70 000–4×10^8	10.4–60 000	0	0.05	$(10 \pm 3) \times 10^{-3}$

Unblinding results

- No event found in any ROI for 813 days of live data
- Exclusion limits can be set at 90% CL for any DM model predicting at least 2.3 events across all the ROIs (assuming an overall 0.05±0.03 background expectation in all the ROIs)
- Expected number of DM events is evaluated as

$$\mu_s = T \int d^3\vec{v} \int dA \frac{\rho_\chi}{\mathrm{m}_\chi} |v| f(\vec{v}) \epsilon(\vec{v}, \sigma_{\mathrm{T}\chi}, \mathrm{m}_\chi)$$

  from the MC simulations described earlier.
- DM candidates at a given mass and per-nucleon CS are excluded for two different theoretical models

Exclusion curves

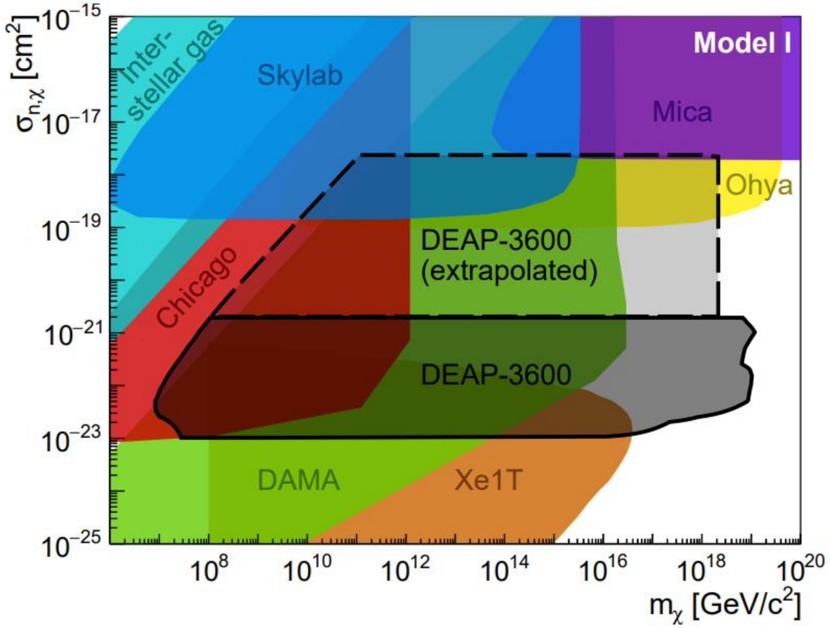
- Model 1 – strongly interacting opaque DM
- Model 2 – A^4 scaling
- Upper mass bound and lower cross section bound are explicitly from the MC simulations
- Lower mass bound set by the overburden attenuation
- Upper cross section bound set by highest cross section that could be accurately simulated
- Extrapolated region - conservatively determined - extrapolated from lower cross section, by conservatively assuming a constant acceptance of 35% in ROI4. The upper bound is set as

$$\sigma_{n\chi}^{max} \times \left(PE_{max}^{ROI4} / PE_{90}^{sim}\right)$$

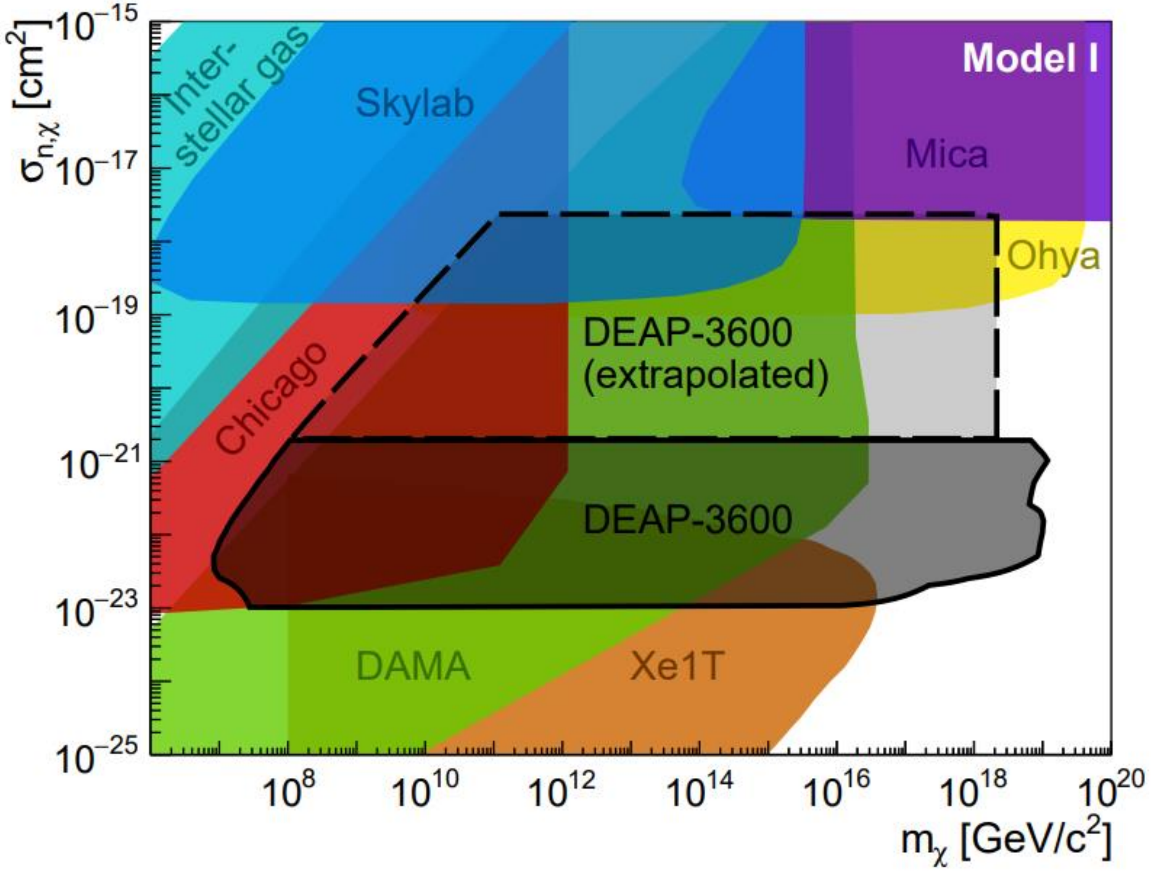
where PE^{ROI4}_{max} = 4e8, and PE^{sim}_{90} is the 90% upper quantile on the PE distribution at $\sigma^{max}_{n\chi}$

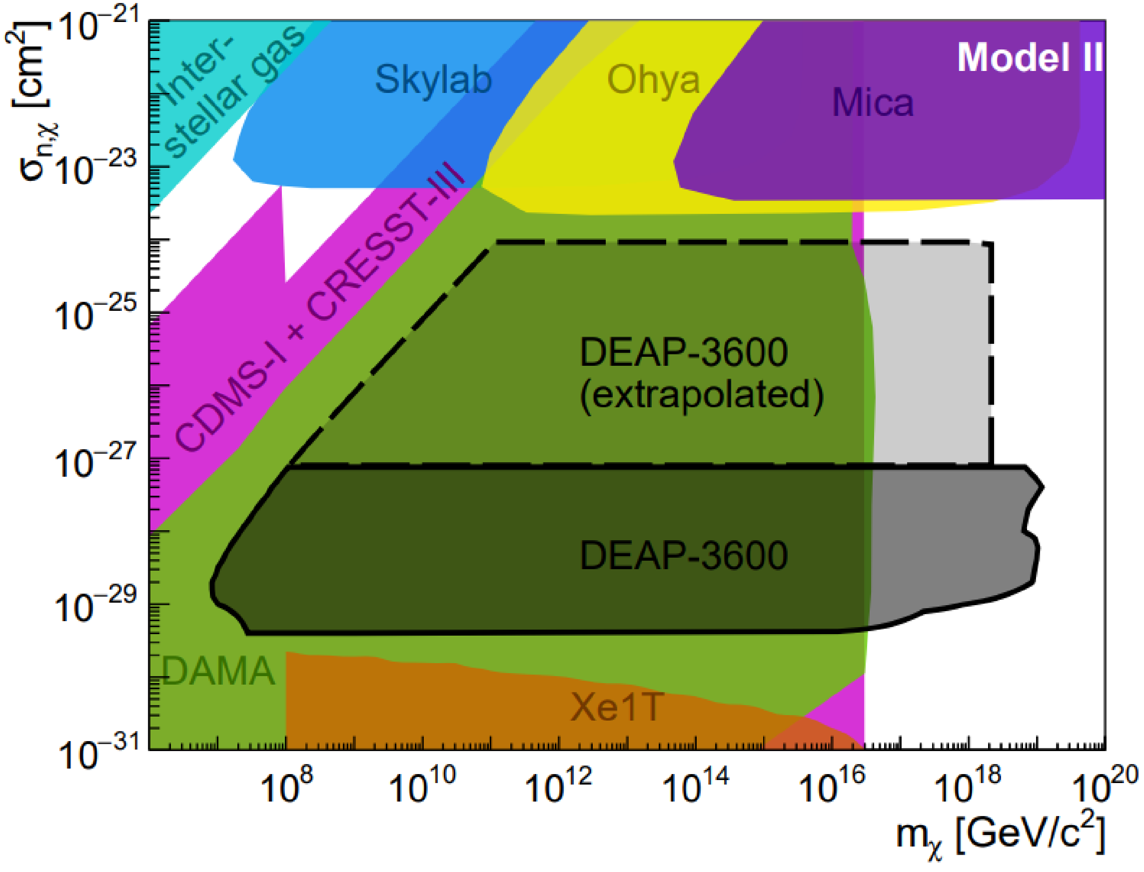
$$\frac{d\sigma_{T\chi}}{dE_R} = \frac{d\sigma_{n\chi}}{dE_R} |F_T(q)|^2$$

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



Exclusion curves





Summary

- DEAP-3600 is largest running DM detector in the world
- Leading exclusion limits in WIMP search in liquid argon
- DEAP will restart data-taking this year, also working on improved dataset for WIMPs
- Underground detectors designed for WIMP searches can be sensitive to heavy multi-scattering candidates at higher cross sections
- Analysis based on search for events with more than one scatter in the waveform
- Main backgrounds are pileups
- 4 ROIs are defined, each with an expected background << 1
- Blinded analysis was performed for a total livetime of 813 days
- No events found in any ROI, setting novel direct detection constraints on DM at Planck-scale mass
- Full results published in Phys. Rev. Lett. 128, 011801 (2022)

The DEAP collaboration

DEAP 3600

University of Alberta
AstroCeNT Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences
Canadian Nuclear Laboratories / Laboratoires Nucléaires Canadiens
Carleton University
Gobierno de España / Ministerio de Ciencia, Innovación y Universidades / Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
INFN Istituto Nazionale di Fisica Nucleare
IF Instituto de Física
Princeton University
Johannes Gutenberg Universität Mainz JGU
National Research Center "Kurchatov Institute"
Laurentian University / Université Laurentienne
Queen's University
Royal Holloway University of London
Particle Physics Rutherford Appleton Laboratory
SNOLAB
US University of Sussex
Technical University of Munich TUM

Extra slides

Simulated waveforms

- As cross section increases, fprompt decreases, number of dominant peaks starts merging