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

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on behalf of the DEAP collaboration

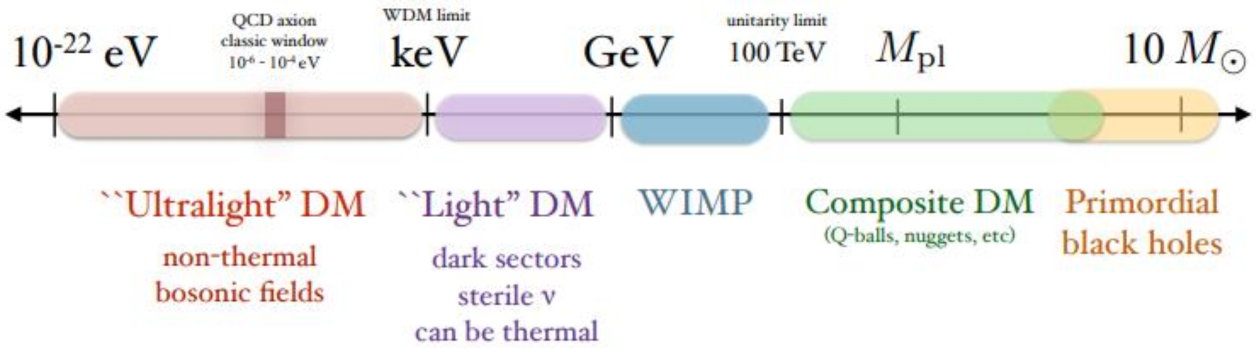
CAP Congress 2022
6th June 2022

DEAP 3600

Carleton UNIVERSITY

Dark matter

- Missing matter component of the universe
- Galaxy rotation curves
- Dark matter candidates
  - WIMPs
  - Superheavy dark matter (WIMPZillas)
  - Axions



T. Lin (link)

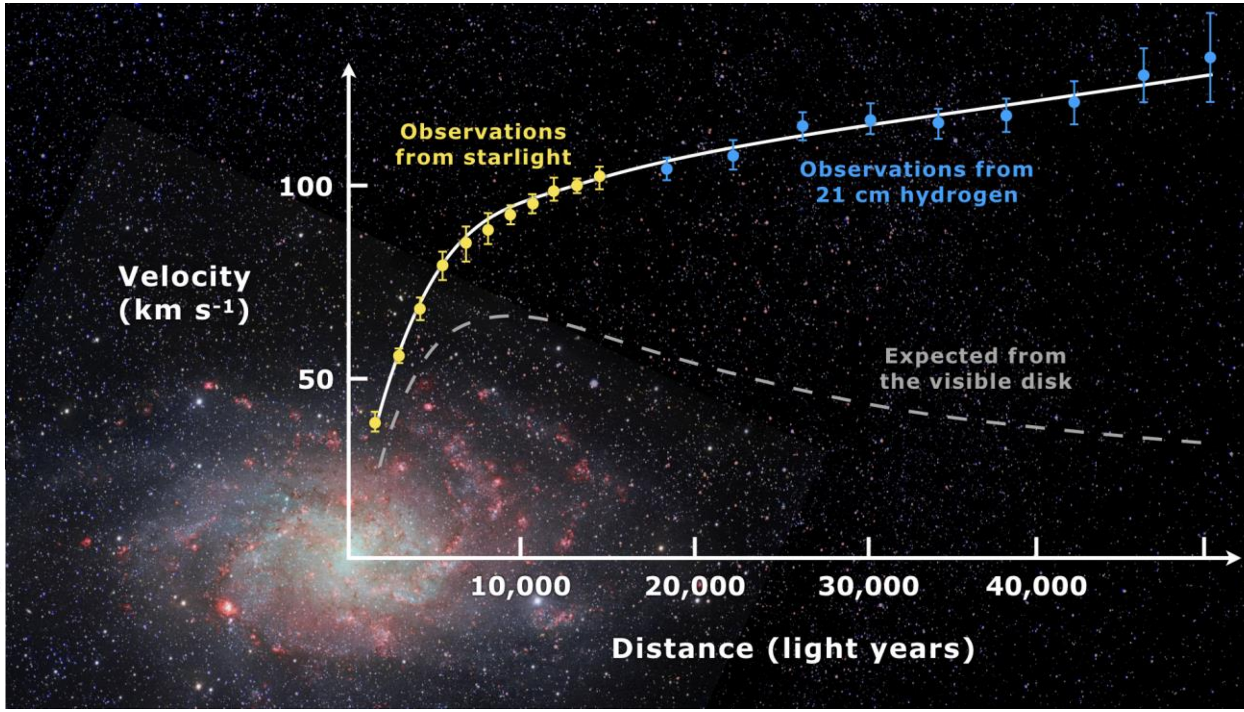
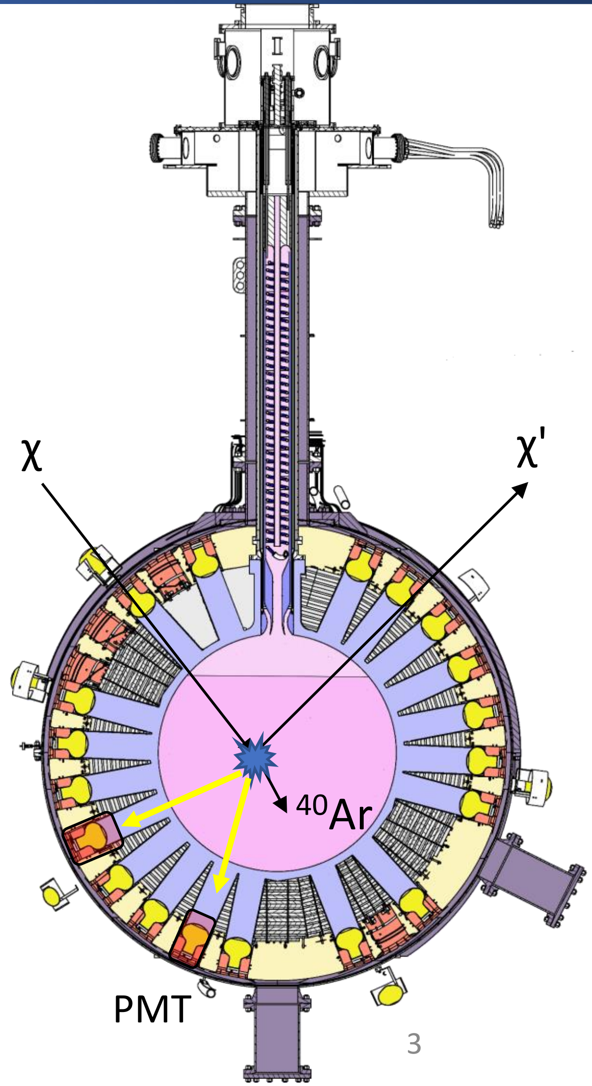


Image Credits: M. De Leo (link)

DEAP-3600

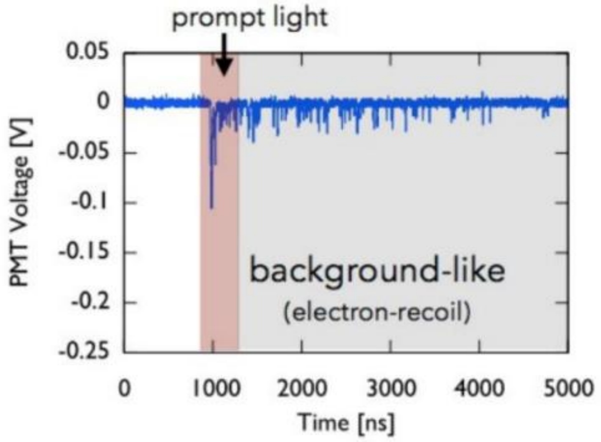
- Liquid argon based dark matter detector located 2km underground at SNOLAB
- Dark matter Experiment using Argon Pulseshape discrimination
- >3 tonnes target mass of LAr in acrylic vessel

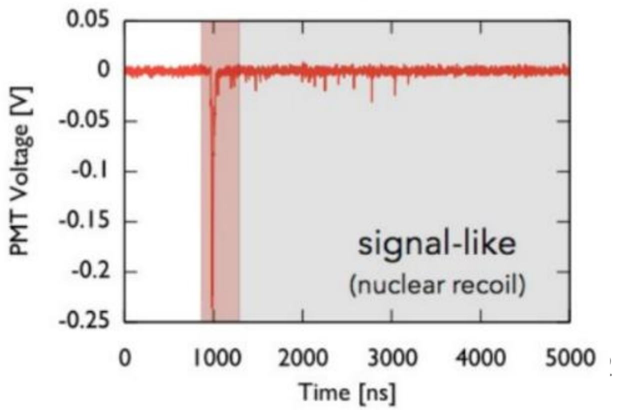


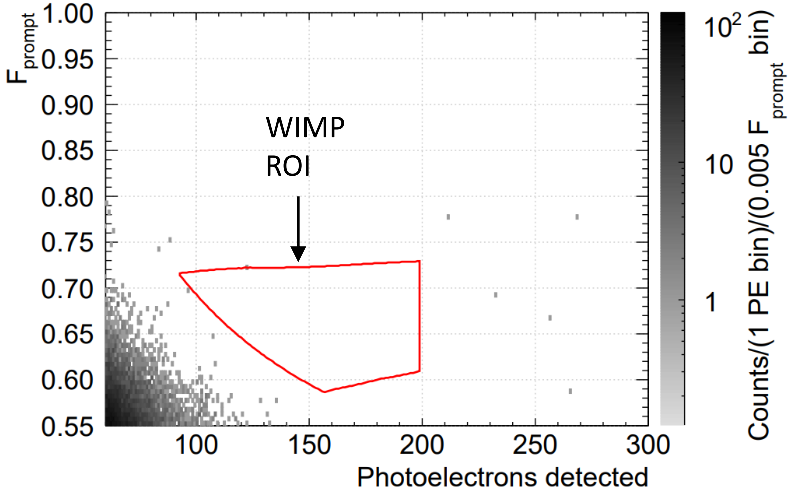
DEAP-3600

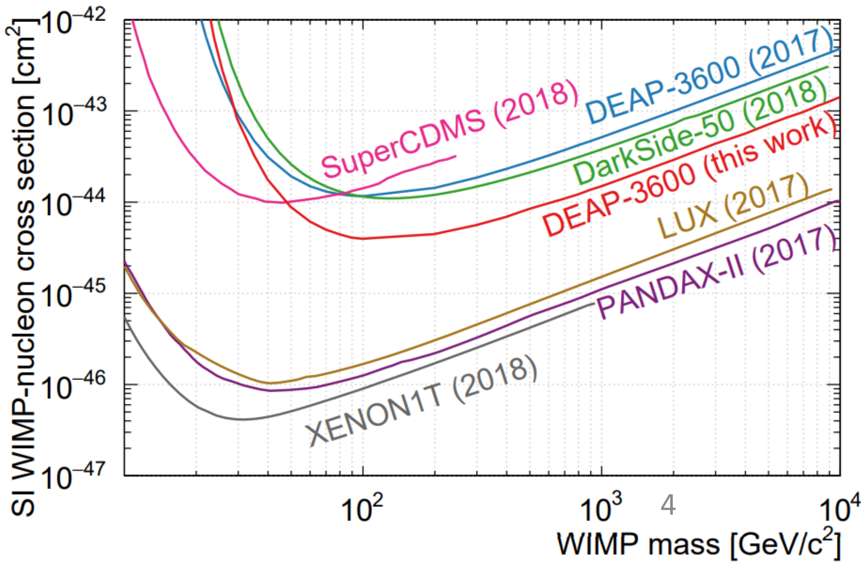
- Open data of 231 live days
- No events observed in WIMP ROI
- Leading limit on the WIMP-nucleon spin-independent cross section on a LAr target (published in Phys. Rev. D. 100, 022004)

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



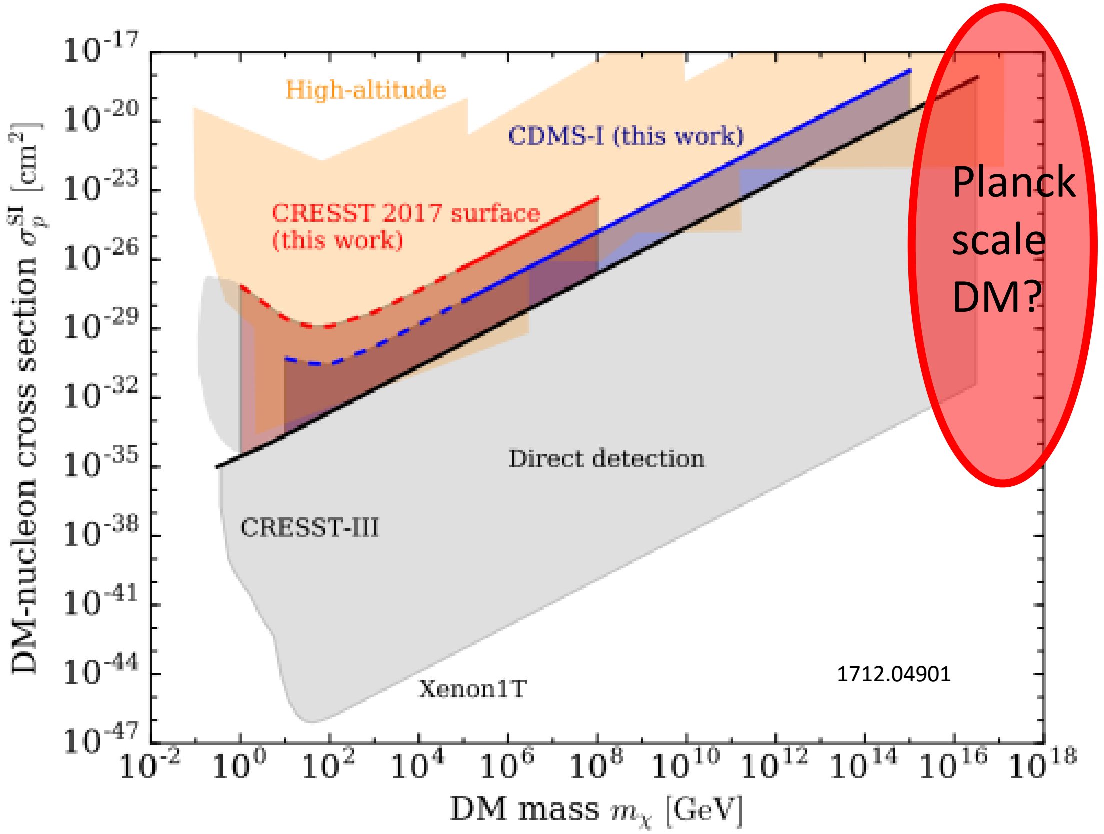






Supermassive dark matter

- Production mechanisms
  - Inflaton decays/gravitational mechanism related to inflation
  - Primordial black hole radiation
  - Extended thermal production in dark sector
- Supermassive DM limited by flux
- DEAP has large cross-sectional area – surface area ~9.1m^2 (acrylic vessel of 1.7m diameter)



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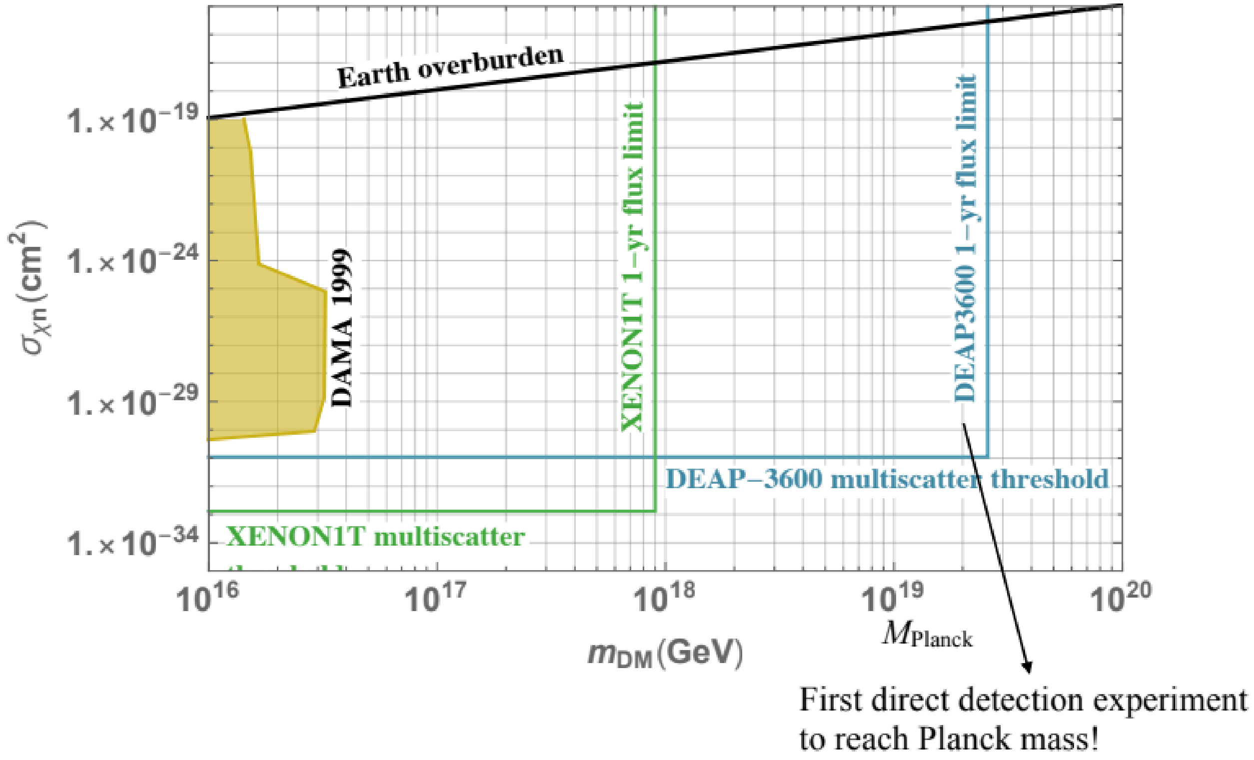
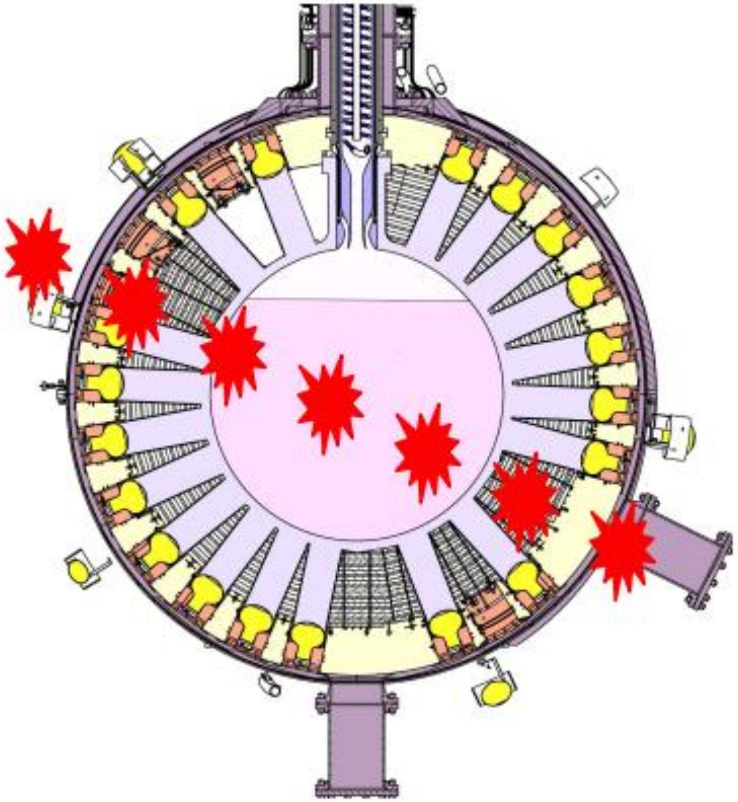


Preliminary estimates by N. Raj

Multiscatter signatures in DEAP

- Supermassive DM performs tens, hundreds, thousands of scatters in the detector
- Deflection of SDM after scattering is negligible, so a collinear track expected
- Multiple scatters create unique PE time distribution
- Single scatter (WIMP) analysis cuts out multiscatter events, so need a dedicated analysis



Outline of the analysis

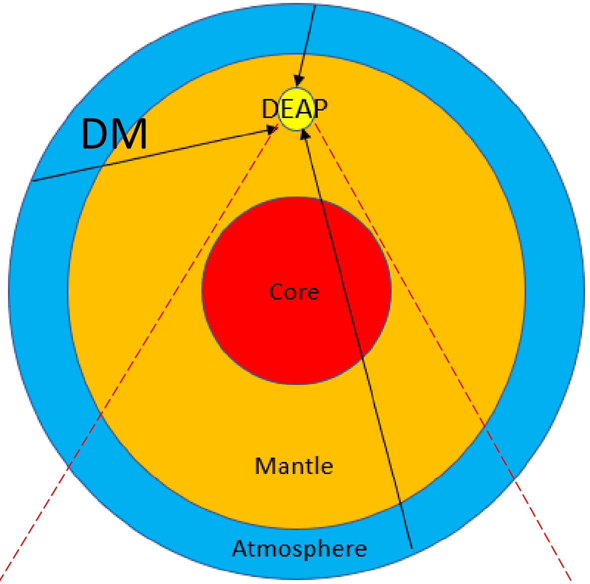
- Monte Carlo simulation
- Background estimation
- Regions of interest and selection cuts and acceptances
- Results and exclusion curves

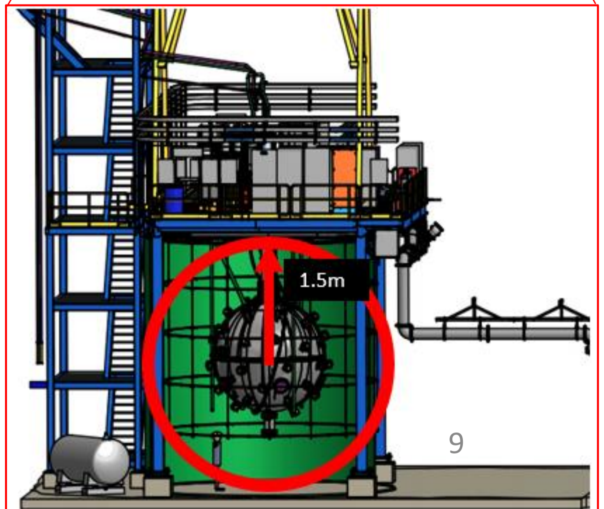
Monte Carlo simulation

- DM particle generated in the MC at top of the atmosphere, velocity sampled from the usual truncated Maxwell-Boltzmann distribution
- Propagated through the atmosphere and Earth overburden, average energy loss given by

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

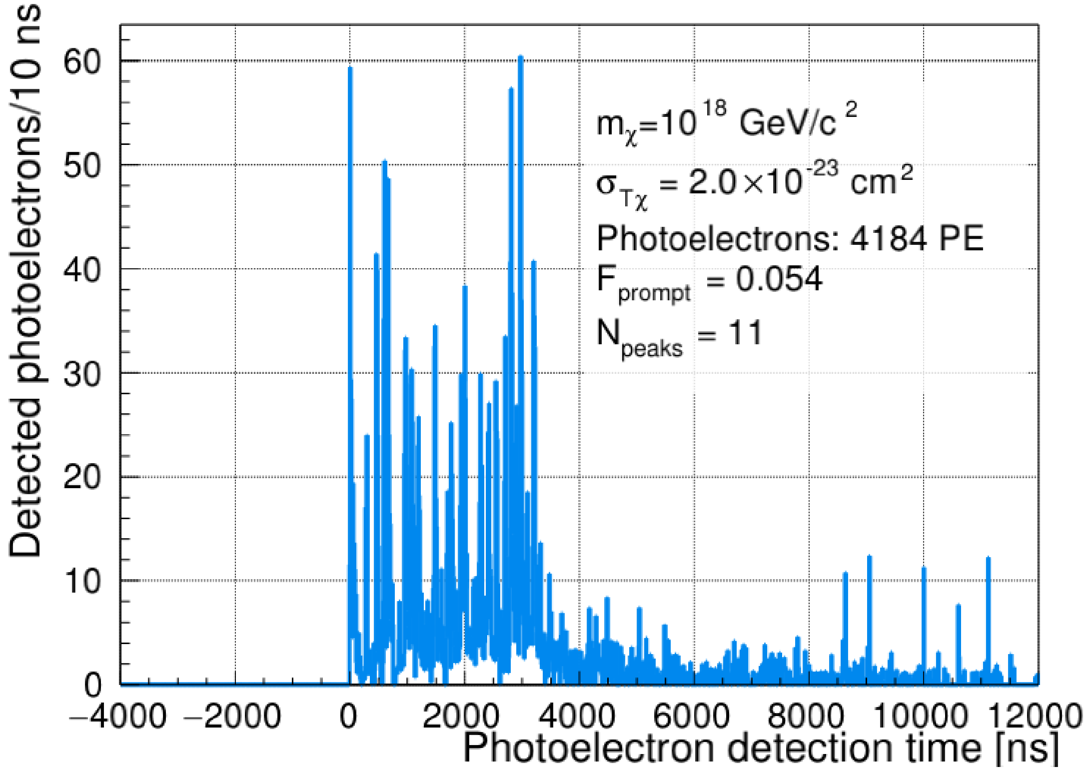
- Detector response simulated in RAT/GEANT4 from henceforth with a custom developed generator for simulating multiple recoils





Simulated waveform

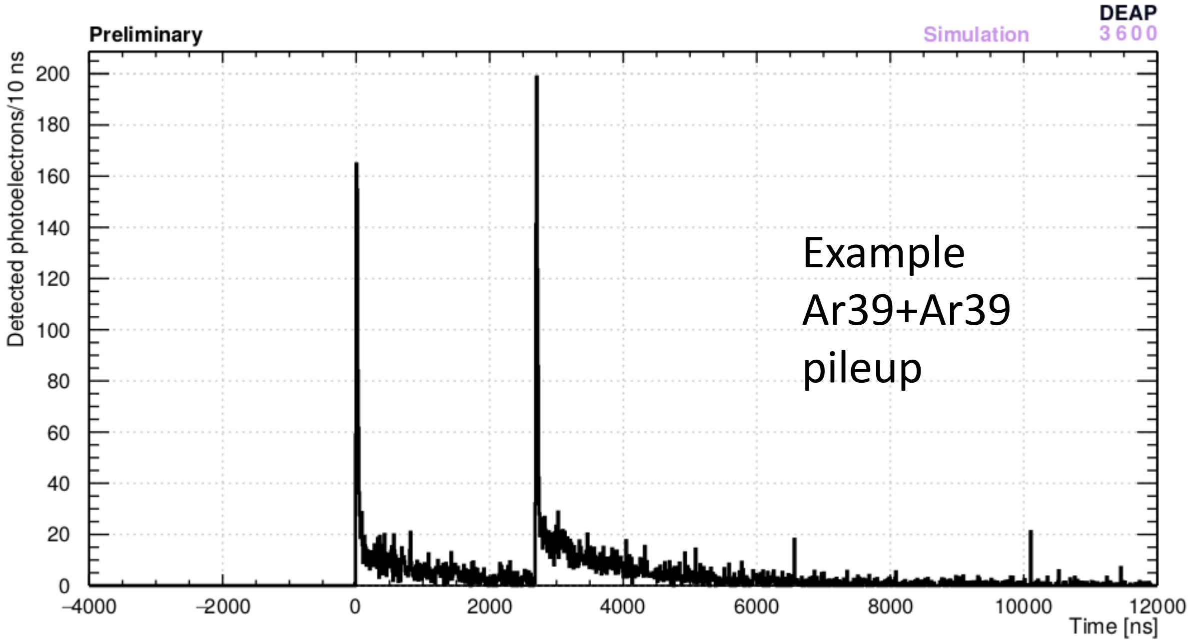
- **PE** distribution shows the multi scattering in the signal
- Signal is reconstructed with a low **Fprompt**
- **N_peaks** characterizes number of scatters in the waveform



Background estimation – below 10MeV

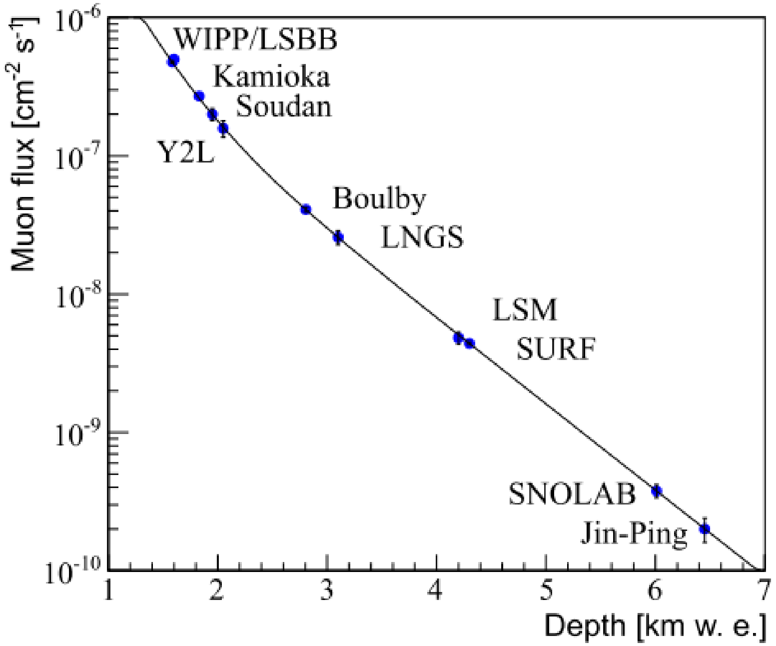
- Dominant background – pile ups between local radioactivity recoils.
- Need to evaluate distribution of N_{peaks} for pileups
- Assumed Poissonian statistics for number of pulses in a pile-up
- Predictions tested on a physics run and on a calibration run using an AmBe source
- Agreement between pileup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

Decay Source	Rate [Hz]
^{39}Ar	3287
^{40}K	472
^{226}Ra	227
^{232}Th	51



Background estimation – above 10 MeV

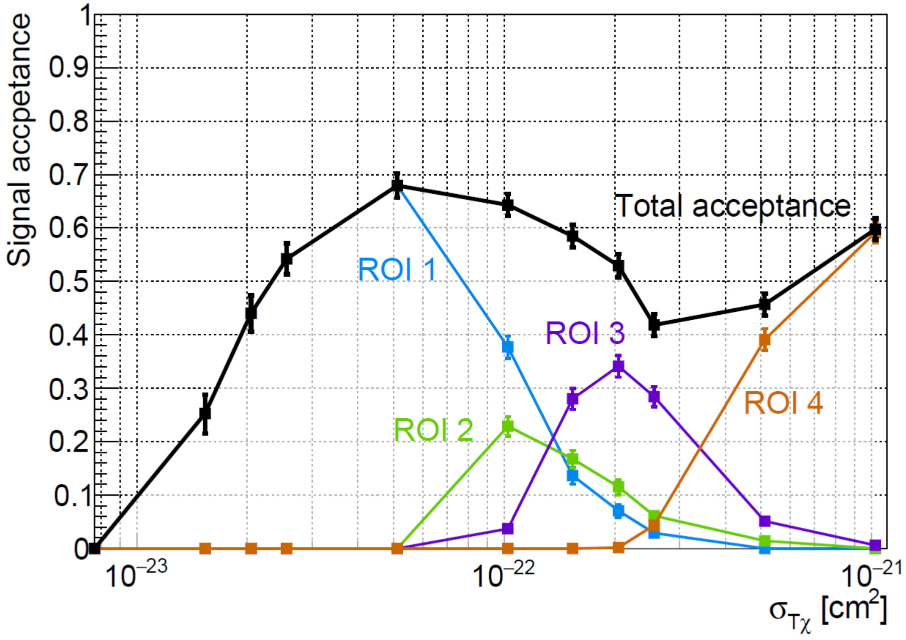
- Dominant background – muons entering the detector inner vessel
- Muon flux at SNOLAB is known
- Removal of any event with [-10,90]us from the muon veto trigger
- More than 99% of muons are triggered in coincidence and rejected
- In ROI4, Muons are also removed by requiring fprompt<0.05. Determined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



J.Phys.G 43 (2016) 1, 013001

Regions of interest

- Detector response and backgrounds widely change as a function of energy (consequently PE), 4 different ROIs are defined
- Selection cuts and acceptances shown
- Background level in each ROI is expected to be <<1 event. In all ROIs the background level is 0.05±0.03



could be simulated, allowing for custom selection cuts according to the PE range (ROIs 1–3)

Couldn't be simulated due to high number of scatterings (ROI 4)

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	$(10 \pm 3) \times 10^{-3}$

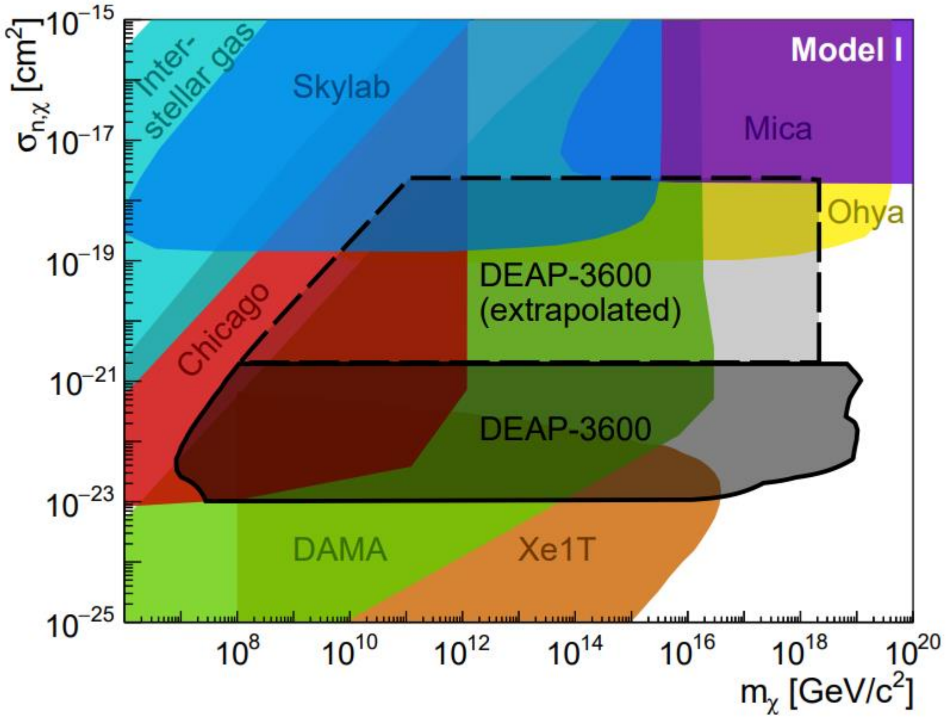
Results

- Blind analysis performed for 813 days of live data
- No event found in any ROI
- 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

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

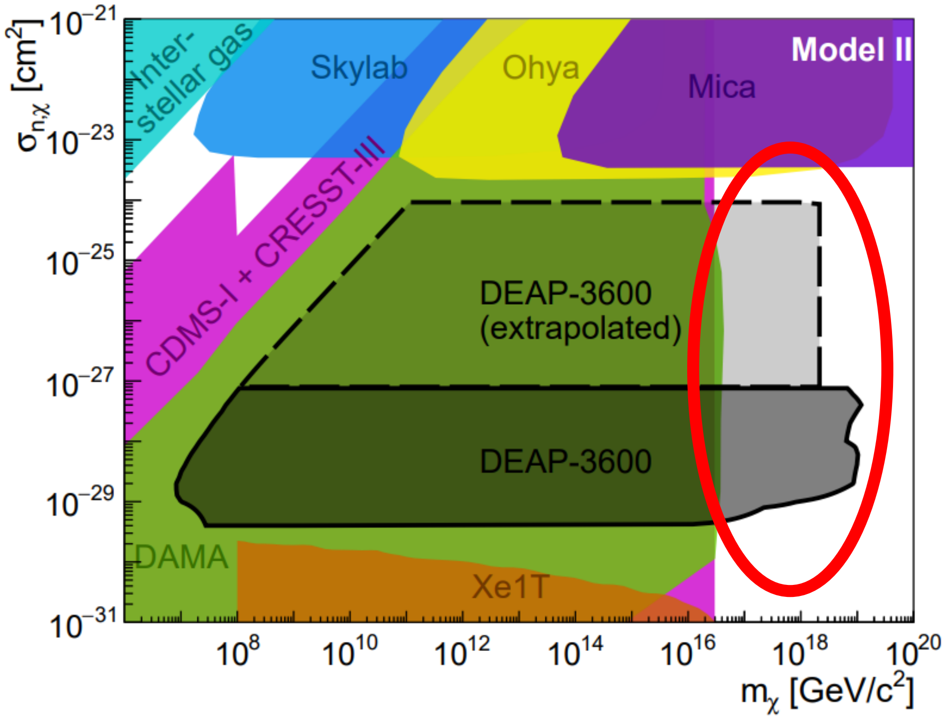
  from the MC simulations described earlier.
- DM candidates at a given mass and per-nucleon CS are excluded for two different theoretical models

Exclusion curves



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

Model 1 – opaque, strongly interacting composite DM



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

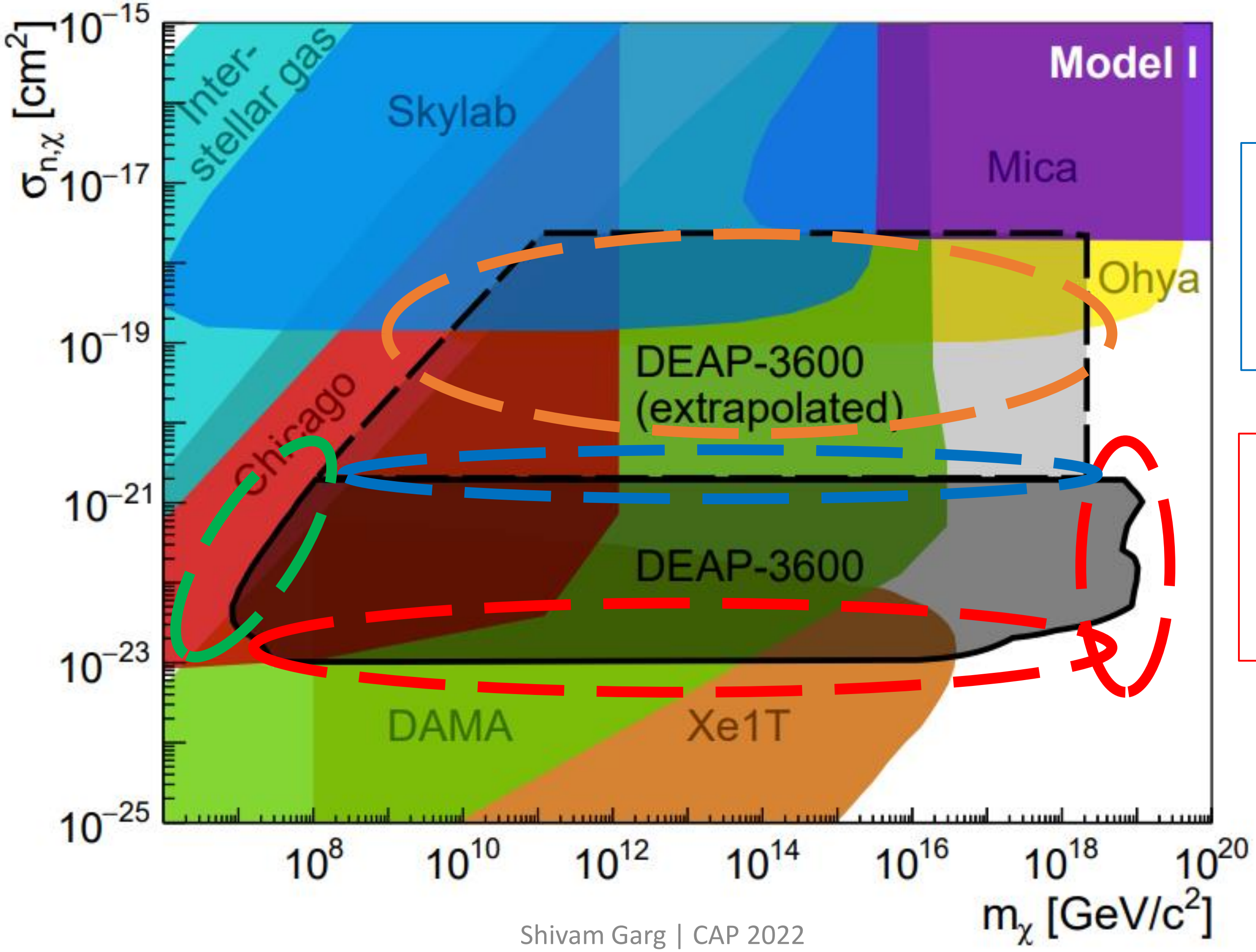
Model 2 – A^4 scaling

First direct detection constraints in the Planck mass range!

Exclusion curves

Extrapolated region conservatively determined by extrapolating from lower cross section

Lower mass bound set by the overburden attenuation



Upper cross section bound set by highest cross section that could be accurately simulated

Upper mass bound and lower cross section bound are explicitly from the MC simulations

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

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MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat

INFN
Istituto Nazionale di Fisica Nucleare

IF Instituto de Física

PRINCETON UNIVERSITY

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NATIONAL RESEARCH CENTER "KURCHATOV INSTITUTE"

LaurentianUniversity
UniversitéLaurentienne

Queen's UNIVERSITY

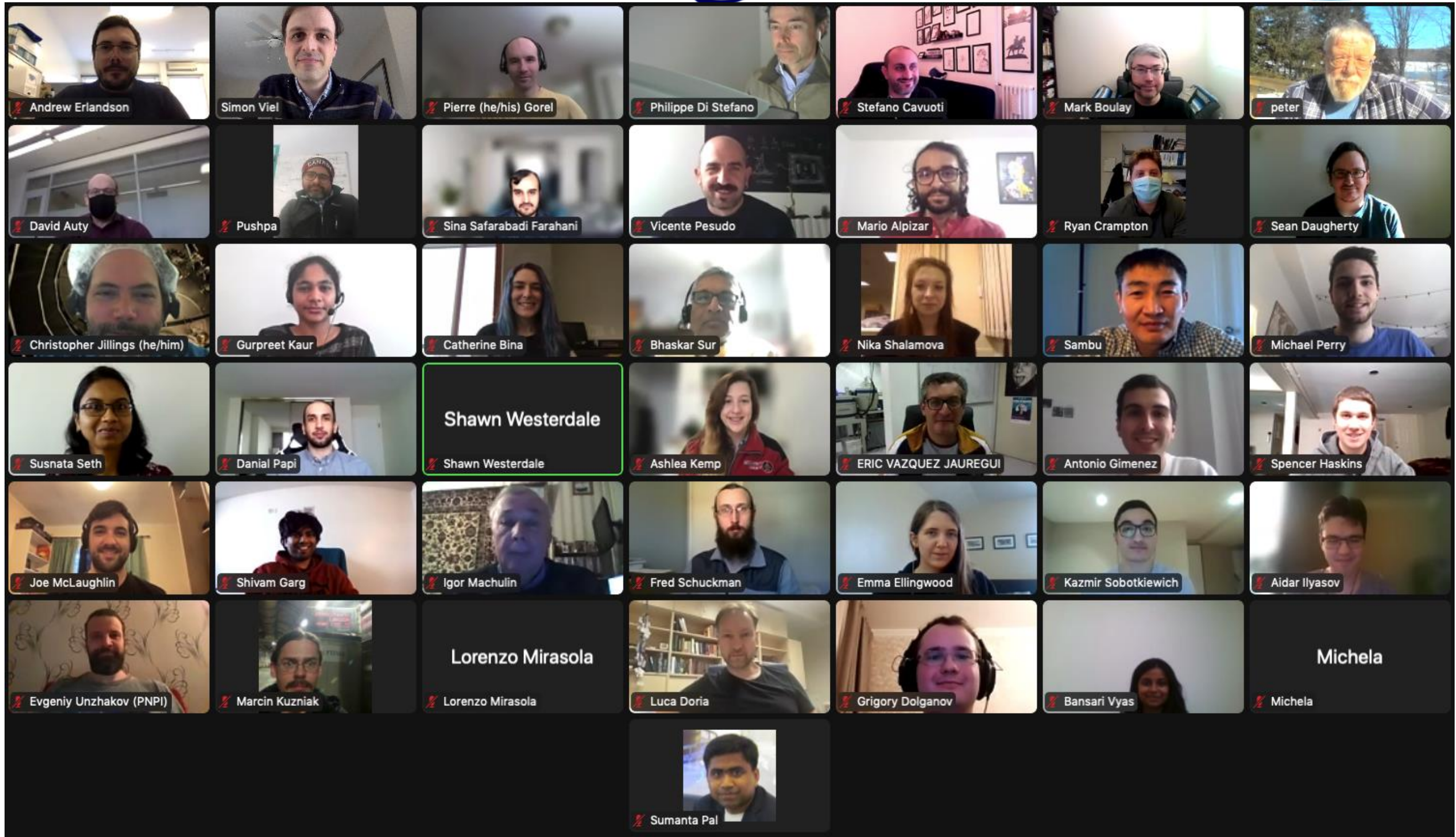
ROYAL HOLLOWAY UNIVERSITY OF LONDON

Particle Physics
Rutherford Appleton Laboratory

SNOLAB

US
University of Sussex

Technical University of Munich
TUM

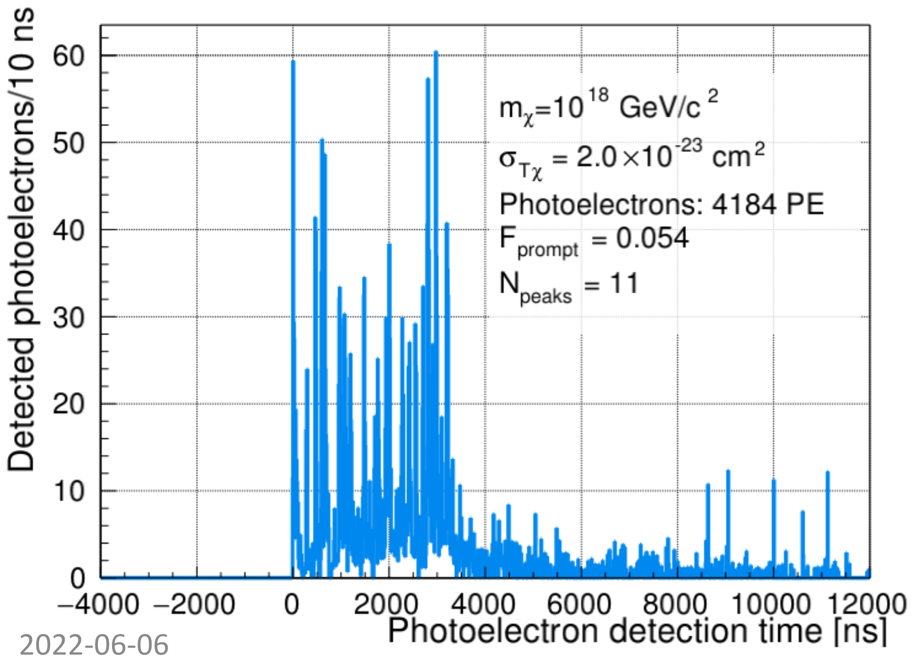


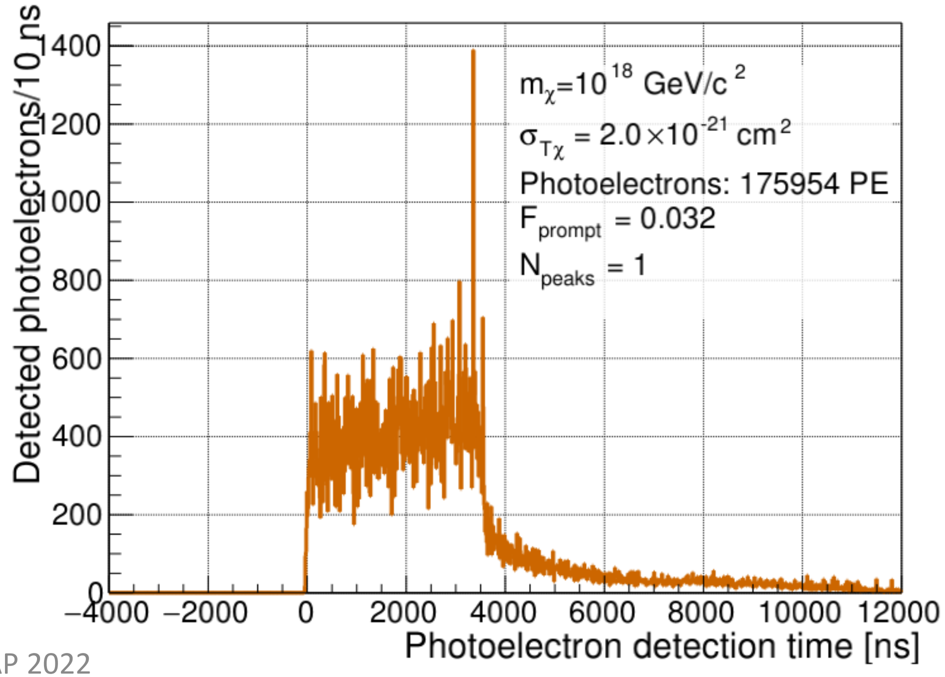
2022-06-06

Extra slides

Simulated waveforms

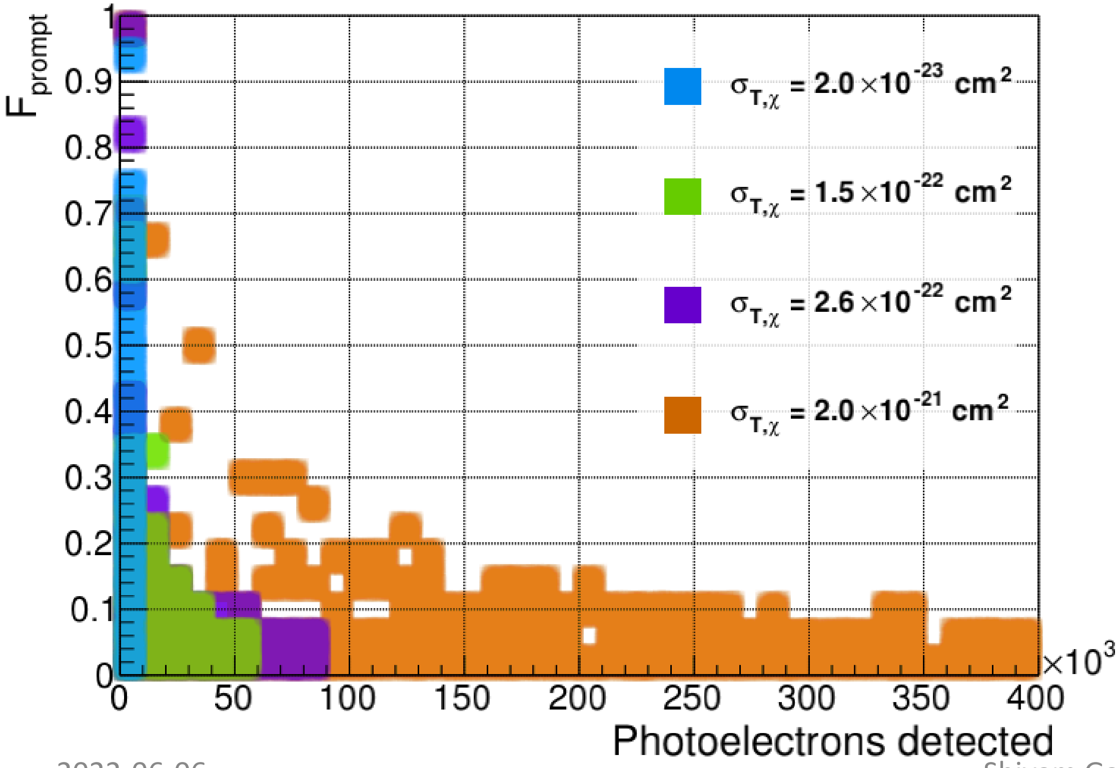
- PE distribution shows the multi scattering in the signal
- Signal is reconstructed with a low Fprompt
- Peaks merge together at higher cross sections

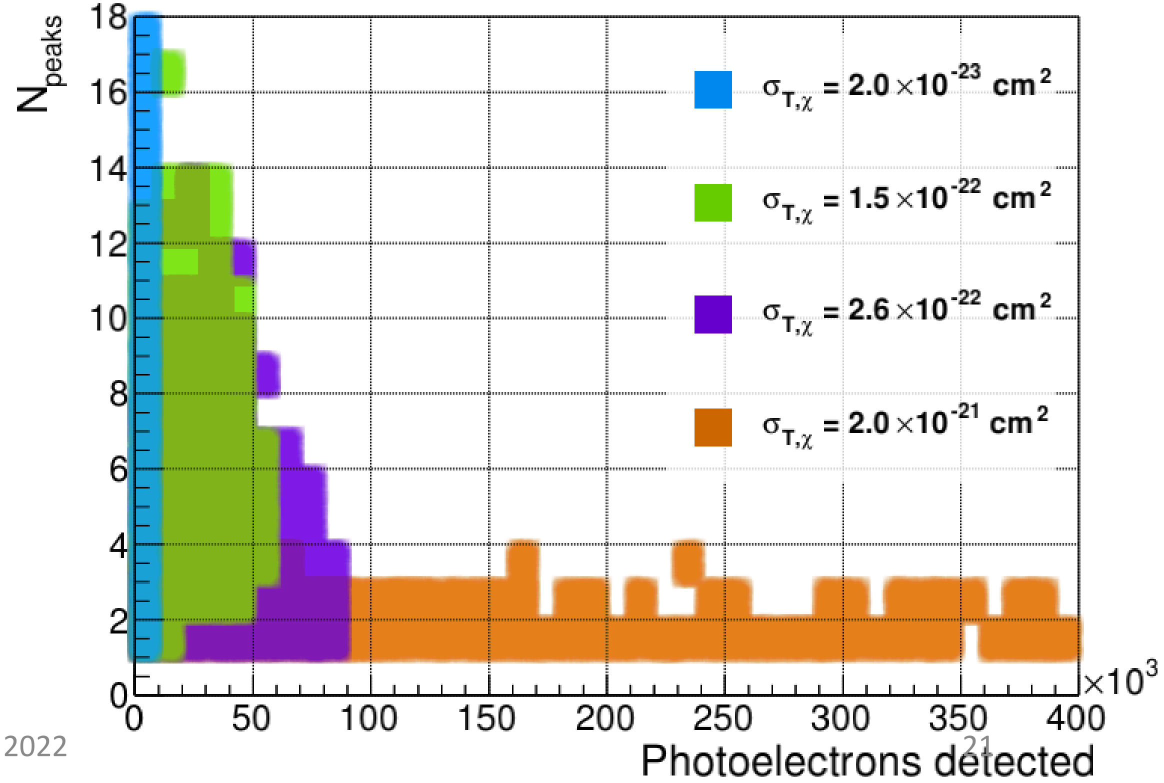




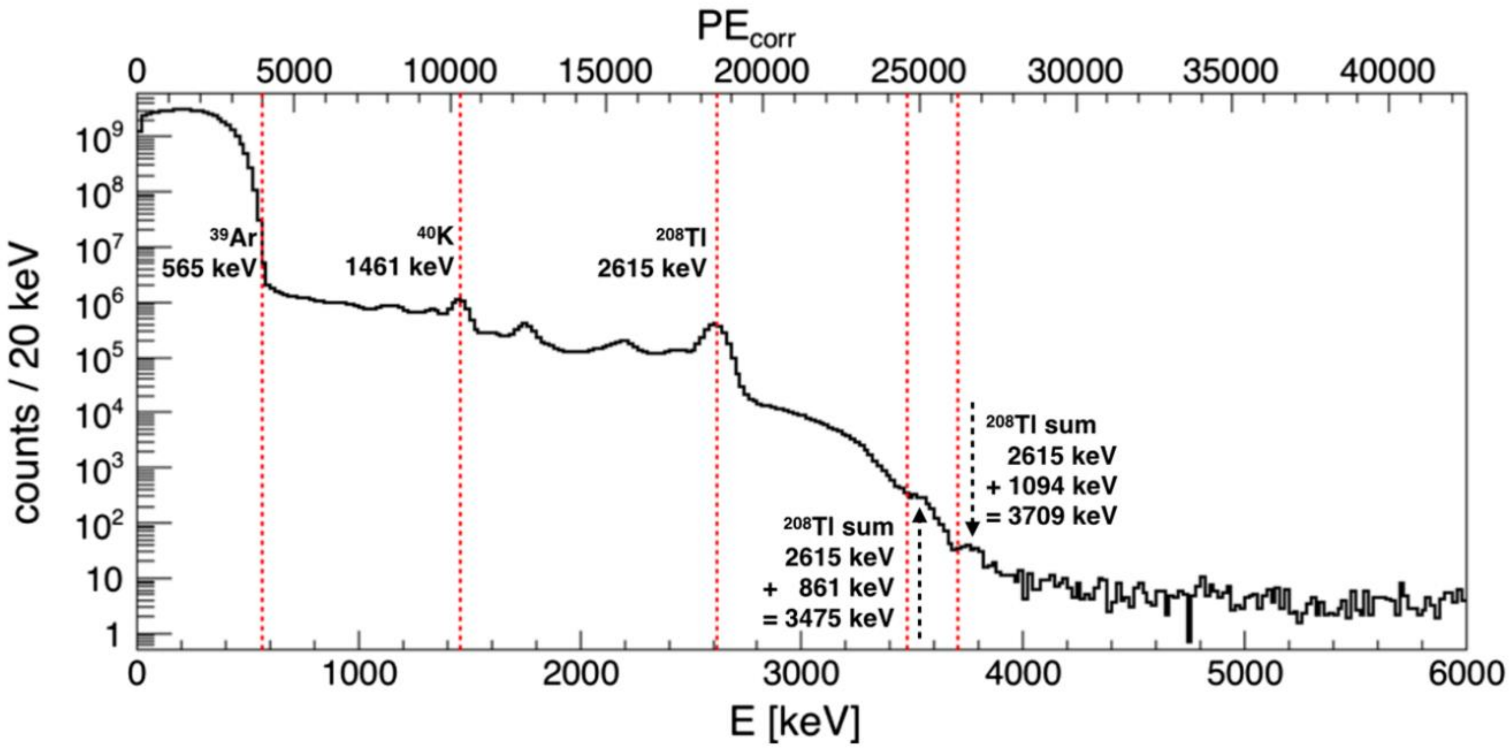
Simulated waveforms

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





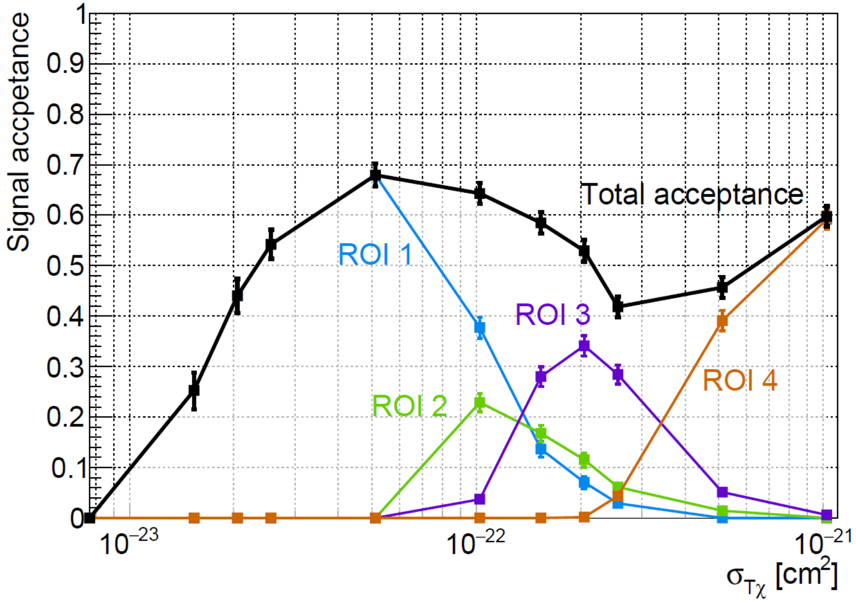
Single scatter ER background spectra



Phys. Rev. D **100**, 072009

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



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Exclusion curves

- 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

$$\sigma^{\max}_{n\chi} \times \left(\mathrm{PE}^{\mathrm{ROI4}}_{\max} / \mathrm{PE}^{\mathrm{sim}}_{90}\right)$$

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