Determination of the sensitivity of the DEAP-3600 experiment to supermassive charged gravitinos

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ASTROCENT

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DEAP 3600

Plan

- Overview of theoretical motivation and predictions
- Signature and sensitivity for noble gas detectors
- Fenomenology for DEAP-3600

MOTIVATION

- Conventional models assume the masses of DM constituents usually range from fractions of an eV (for axion-like DM) to the TeV scale (for WIMP-like DM)
- Large mass DM is not stable because superheavy particles participating in standard interactions can be expected to simply decay at a very early stage in the evolution of the Universe, unless a special mechanism is found that guarantees their survival to the present epoch;
- Solution: fractional charge of the eight DM candidates (gravitinos) with SU(3) charge assignments:

$$\left(\mathbf{3},\frac{1}{3}\right)\oplus\left(\bar{\mathbf{3}},-\frac{1}{3}\right)\oplus\left(\mathbf{1},\frac{2}{3}\right)\oplus\left(\mathbf{1},-\frac{2}{3}\right)$$

- Physical motivation for this theory:
  - Incorporates infinite-dimensional duality symmetries into unification;
  - Can make do with the particle content of the SM, i.e. explains indications from the LHC that there may not be much in terms of new physics beyond the electroweak scale

Krzysztof Meissner & Hermann Nicolai:

- DOI: https://doi.org/10.1103/fm6h-7r78
- DOI: 10.1103/PhysRevD.100.035001

SMG PROPERTIES

- Extremely massive with masses $m \sim M_{Pl}$. Provide direct access to Planck- scale physics;
- Strong and electromagnetic interactions but stable. Only g-anti-g annihilations, but extremely rare.
- Interaction with CMB negligible.
- At rest with respect to the cosmic frame; very small velocity dispersion; effective velocity ~10^4 m/s ($\beta=10^{-4}$) with respect to Earth; $E_{kin} \sim ½ M_{Pl}v^2 \sim 10^{20}$eV
- Never in thermal equilibrium during the evolution of the Universe after the Planck era, hance velocity distribution not known;
- Uniformly excite or ionize their surroundings, leaving a straight track all along their path
- Abundance of 3×10^{-14} particles per cubic meter;
- Flux ~ $0.003\ m^{-2}\ yr^{-1}\ sr^{-1}$ (with big uncertainties)

DETECTOR SIGNATURE

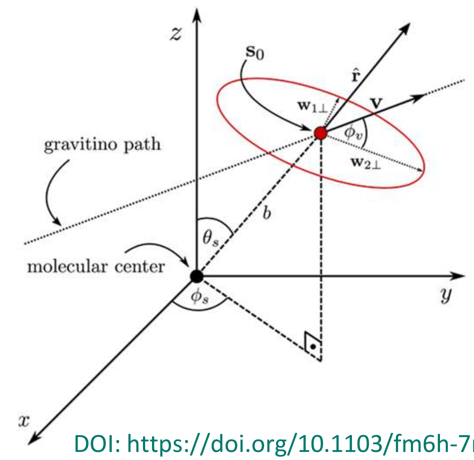
Model assumptions for interactions with DEAP-3600's LAr:

- Average velocity between the virial velocity for a particle bound to the Sun (v_E = 30 km/s) and Galaxy (v_S=230 km/s);
- Nuclear recoils negligible: Meissner & Nicolai, Eur. Phys. J. C (2024) 84:269
- Ionization is negligible i.e. excitation and scintillation dominates;
- Cross section:

$$\sigma_{\mathrm{Ar}^*}(v_E) = 6.84 \cdot 10^{-27},$$
$$\sigma_{\mathrm{Ar}^*}(v_S) = 1.73 \cdot 10^{-24},$$

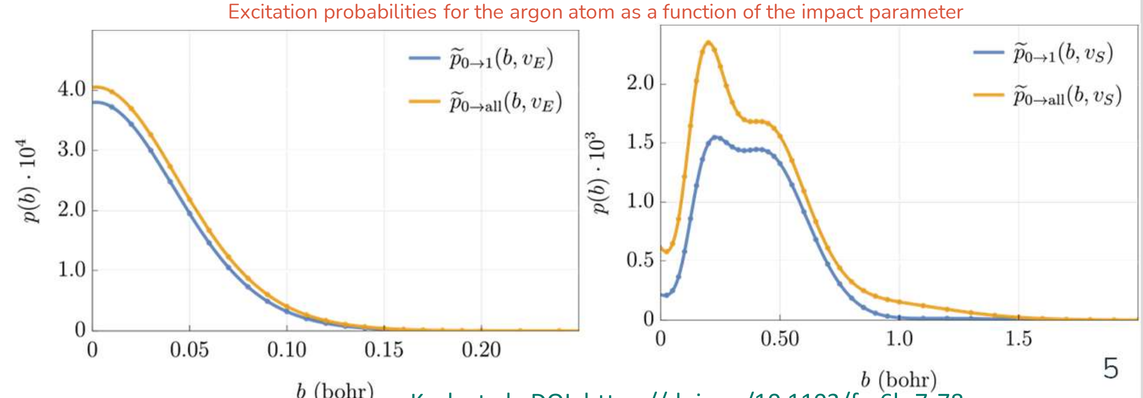
- Mean time between the excitation events:

$$\tau_{\mathrm{Ar}^*}(v_E) = 228\,\mathrm{ns}$$
$$\tau_{\mathrm{Ar}^*}(v_S) = 0.12\,\mathrm{ns}.$$



DOI: https://doi.org/10.1103/fm6h-7r78

Excitation probabilities for the argon atom as a function of the impact parameter



Kruk et al., DOI: https://doi.org/10.1103/fm6h-7r78

Experimental sensitivity[*]

DEAP-3600:

- 0.15 events / 820 days exposure time;
- ~25 μs fly time

LUX: 0.009 events / 427 days

XENONnT: 0.05 events / 316 days

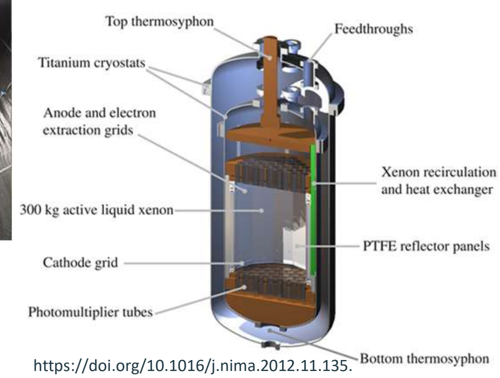
DarkSide-20k: 0.2 (FV) / 0.4 (UAr) events / year

Argo: 1.6 events/year

[*] Assuming 100% detection efficiency.

DEAP-3600

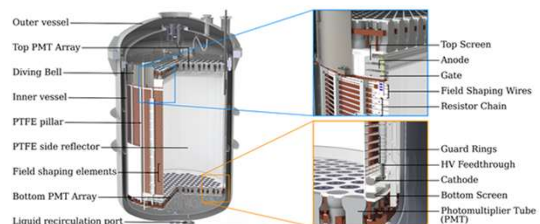
LUX



https://doi.org/10.1016/j.nima.2012.11.135.

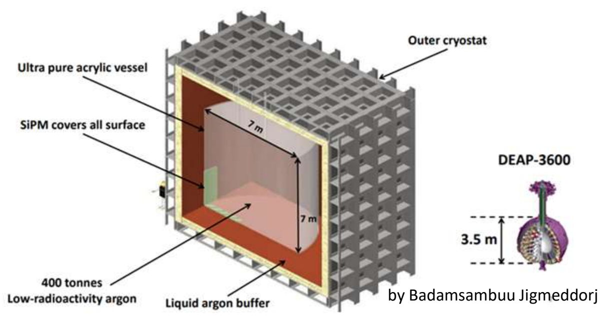
XENONnT

5.9 tonnes active LXe target in 1.6 by 1.3 meters wide TPC



https://arxiv.org/html/2402.10446v1#S1.F1

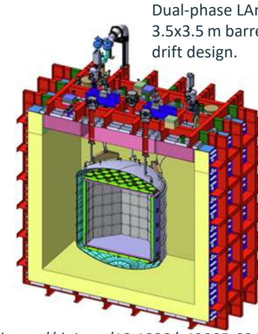
ARGO



by Badamsambuu Jigmeddorj

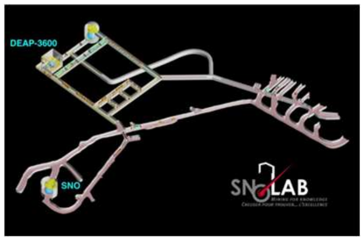
DarkSide-20k

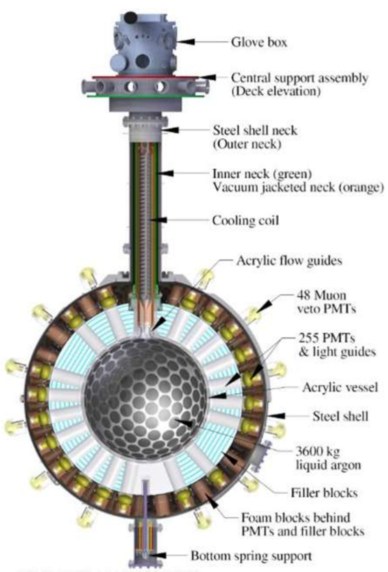
Dual-phase LAr TPC octagonal 3.5x3.5 m barrel with a vertical drift design.



https://doi.org/10.1038/s42005-024-01896-z

DEAP-3600 and Scintillation in Liquid Argon (LAr)





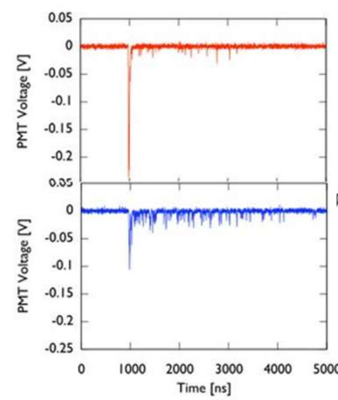
Single-phase 3.3t liquid argon detector

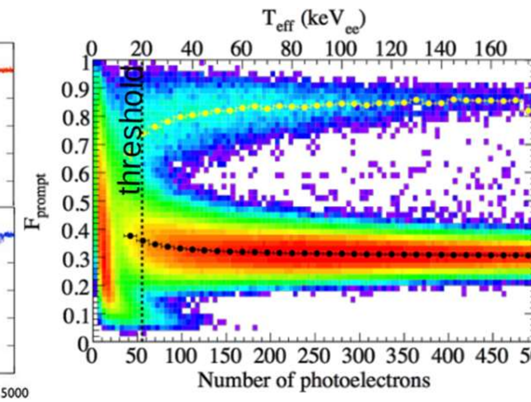
- Inner radius of 85 cm
- 3-µm thin TPB wavelength shifter
- Scintillation light collected by 255 Hamamatsu R5912 PMTs
- Water tank as an external shield and muon veto
- Designed for searches in energy range corresponding to nuclear recoils of about 10^2 - 10^3 keV

Signal dependence on:

- E field
- **Particle type (or dE/dx)**
- Purity

$$\text{FPrompt} = \frac{N_{prompt}}{N_{prompt} + N_{late}}$$





Pulse shape discrimination method PSD

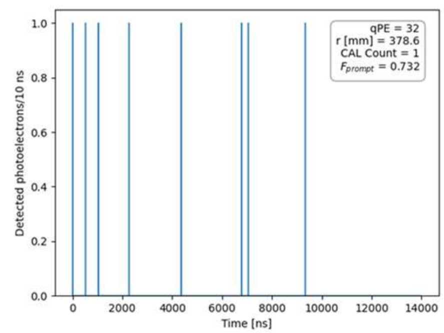
Highly ionizing Nuclear recoils (NR) are dominated by the fast component (singlet -> S1 fast)

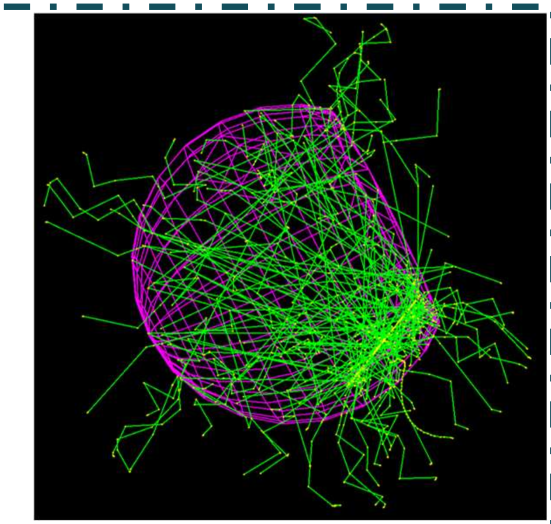
Electron-induced recoils (ER) are dominated by scintillation light slow component (triplet -> S1 slow)

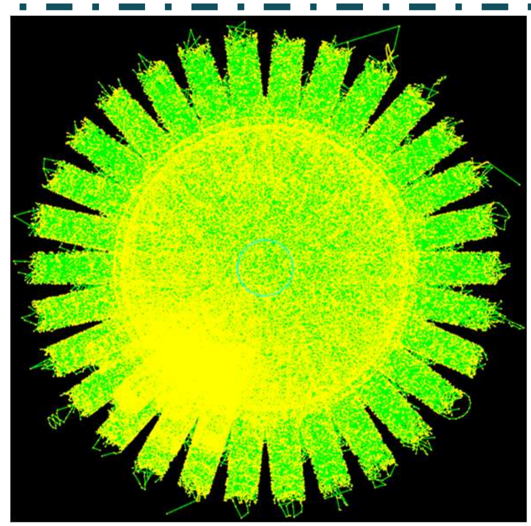
Features of simulated events

- RAT (with gean4) used;
- Simulated LAr scintillation at 128 nm;
- DM direction at random
- Photon emission position as exponential distribution around mean free path;
- Photon emission time corrected on DM velocity and LAr scintillation spectrum;

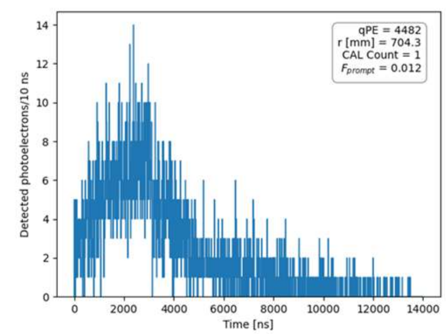
v_E = 30000 m/s
τ_{vE} = 228 ns







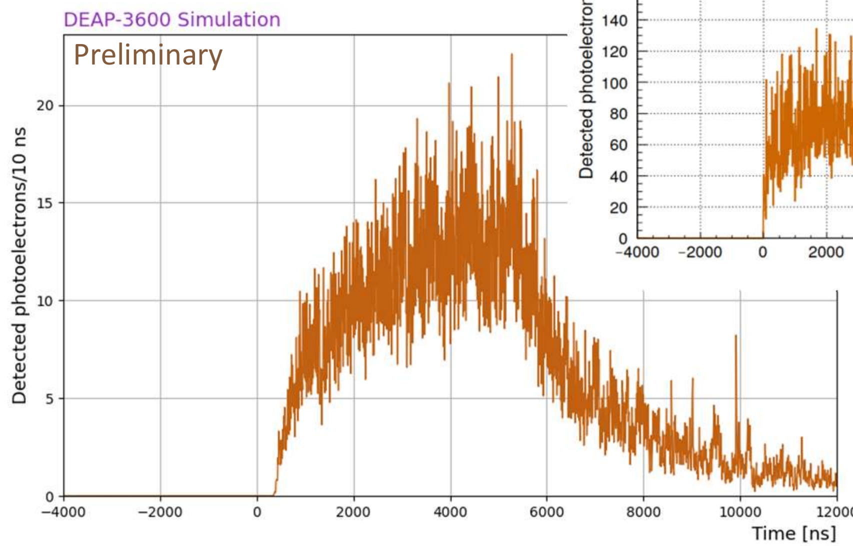
v_S = 230000 m/s
τ_{vS} = 0.12 ns

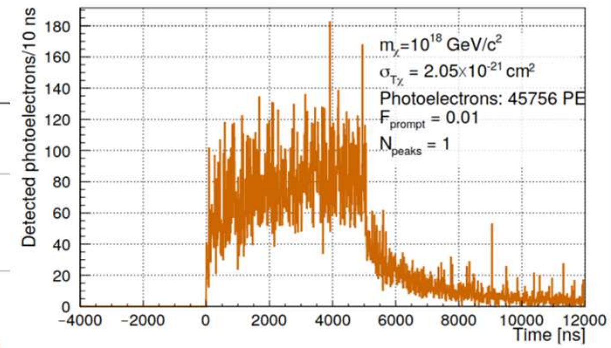


Analysis overview

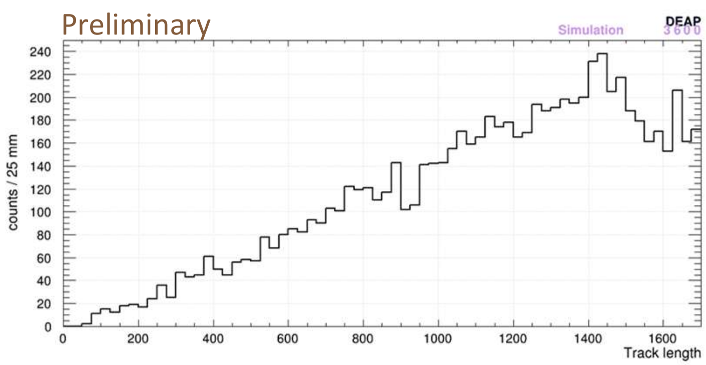
Simulated events detector response

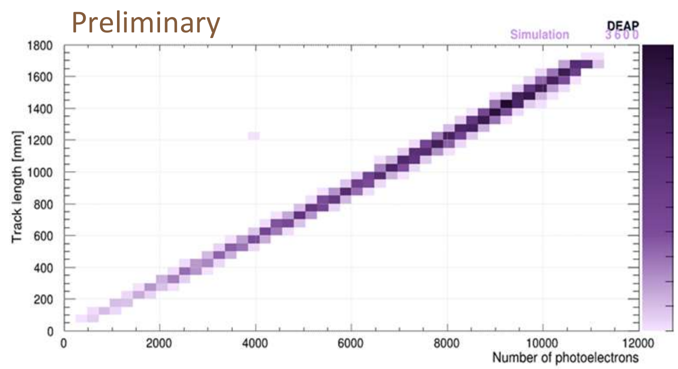
- Number of photoelectrons in event dependent on the gravitino velocity and track length within fiducial volume and in range 10^2-10^4 PE / event;
- For DM velocity $\simeq v_S$ number of PE in prompt window extremely low;
- Maximum number of PE is below 12000
- Pile-up like events can arise due to subevent triggering



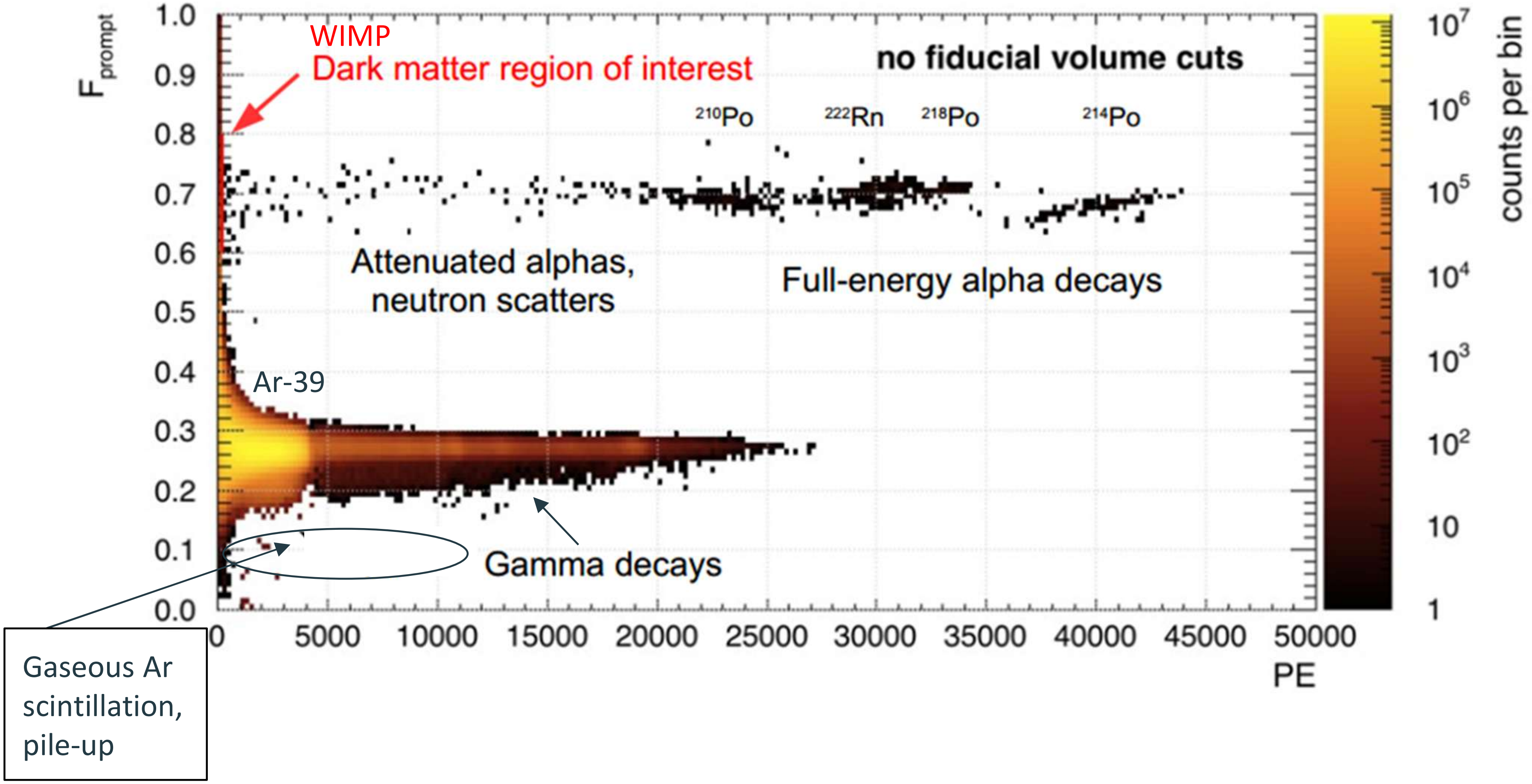


Reference waveform distribution from Multi-scattering Heavy Dark Matter search in DEAP-3600 paper
https://dx.doi.org/10.1088/1742-6596/2156/1/012067

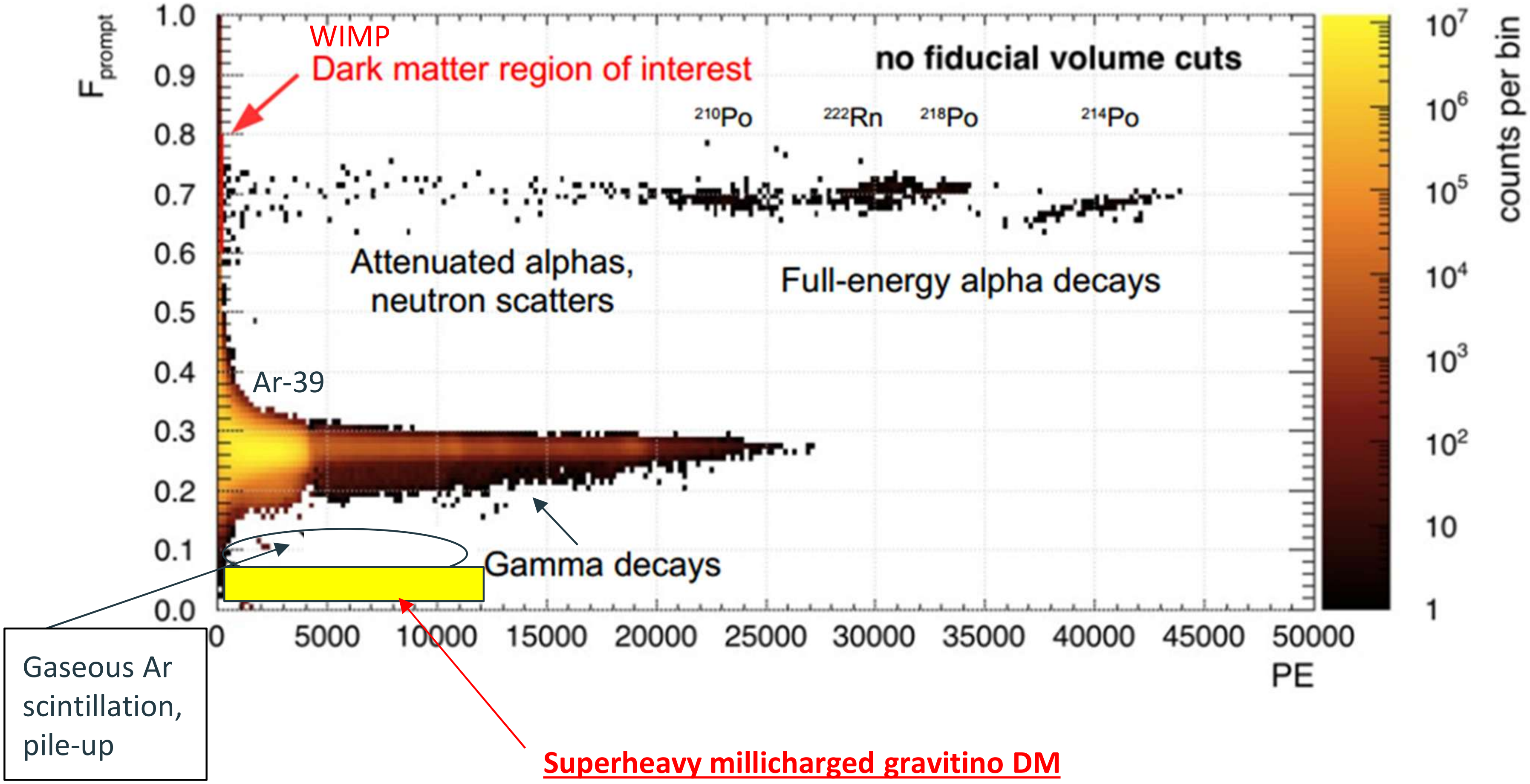




Backgrounds

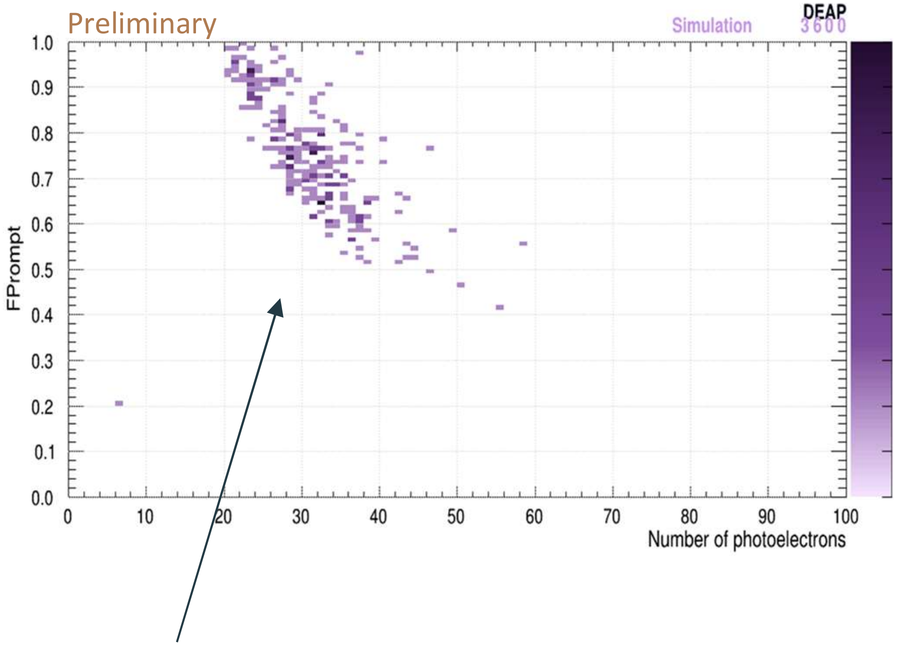


Backgrounds

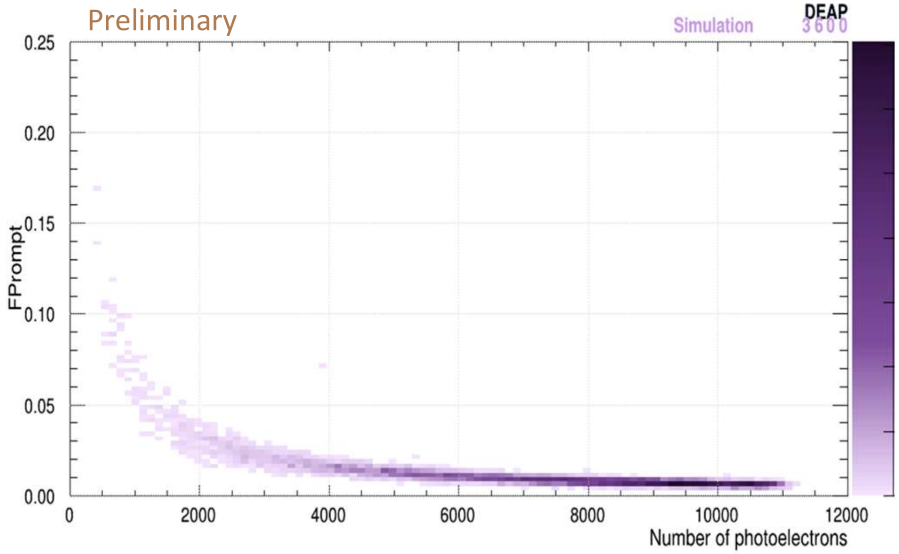


Key signature for limiting velocity cases

MC FPrompt distribution for supermassive charged gravitinos with velocity v_E



MC FPrompt distribution for supermassive charged gravitinos with velocity v_S



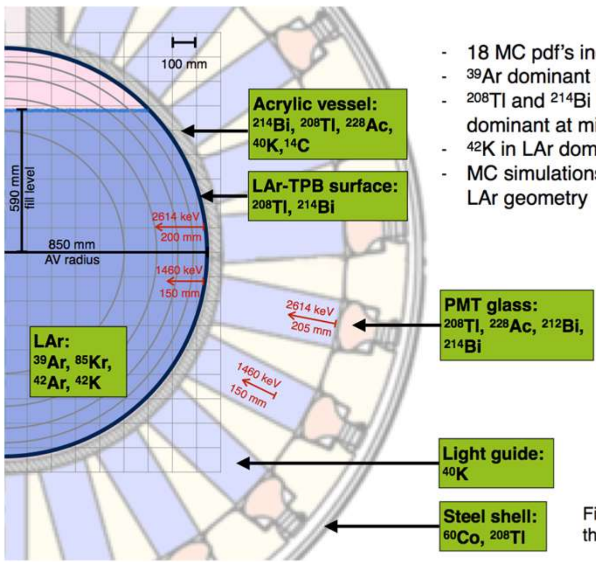
Most events removed by the trigger

Summary

- Supermassive millicharged gravitinos can be interesting alternative to WIMP / axion DM
- SMG generator has been implemented to investigate the properties of such events in DEAP-3600 and explore potential sensitivity
- Analysis of the detector data, including development of the background model, background expectation and signal acceptance is currently starting
- Due to unique signatures, detection within reach of the next generation detectors, and in principle possible in the current detectors (from geometric and flux considerations estimating up to 0.15 events in the collected DEAP-3600 dataset)
- Large dimensions advantageous for the sensitivity of LAr detectors

BACKUP

DEAP-3600 background



- 18 MC pdf's included in model
- ^{39}Ar dominant at low energies
- ^{208}Tl and ^{214}Bi in in PMT glass dominant at mid energies
- ^{42}K in LAr dominant at high energies
- MC simulations done with a fully filled LAr geometry

Fill level roughly equivalent to the final LAr level for DEAP

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

Table 1. List of assumed rates for the main EM background sources in DEAP-3600 [25]. The main contribution comes from the LAr bulk with ^{39}Ar βs and the ^{232}Th and ^{235}U chains in the PMTs.

An example of the pile-up distribution is given for Run 022677, who will be also exploited is Section 7 to validate the Monte-Carlo simulation. In Figure 15 the pile up events at $SubeventN > 1$ and $Fprompt < 0.4$ are shown, for reference. The poissonian statistics together with the aforementioned

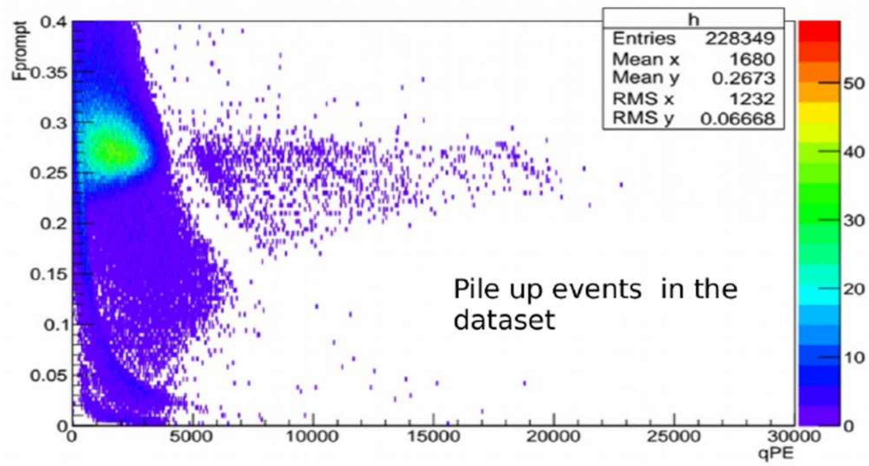


Figure 15. Pile-up events from Physics Run 022677. The performed cut are $Fprompt < 0.4$ and $SubeventN > 1$. As expected from statistics, the main pile-up source is ^{39}Ar due to high activity (RAT v.5.11.8).