Commissioning of the MIGDAL experiment with fast neutrons

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The Migdal Effect

- Migdal effect: following a nuclear recoil there is a small probability that an atomic electron may be emitted [1, 2, 3, 4]).
- Growing interest in sub-GeV dark matter [5], sensitivity enhanced by Migdal efect producing additional energy in detector.
- Observed in α- and β-decays [6, 7, 8].
- Not yet observed in nuclear scattering where relevant for dark matter searches.
- Migdal searches are taking place in CF_4 (+noble gases) [9], liquid xenon [10] and high pressure argon and xenon [11].

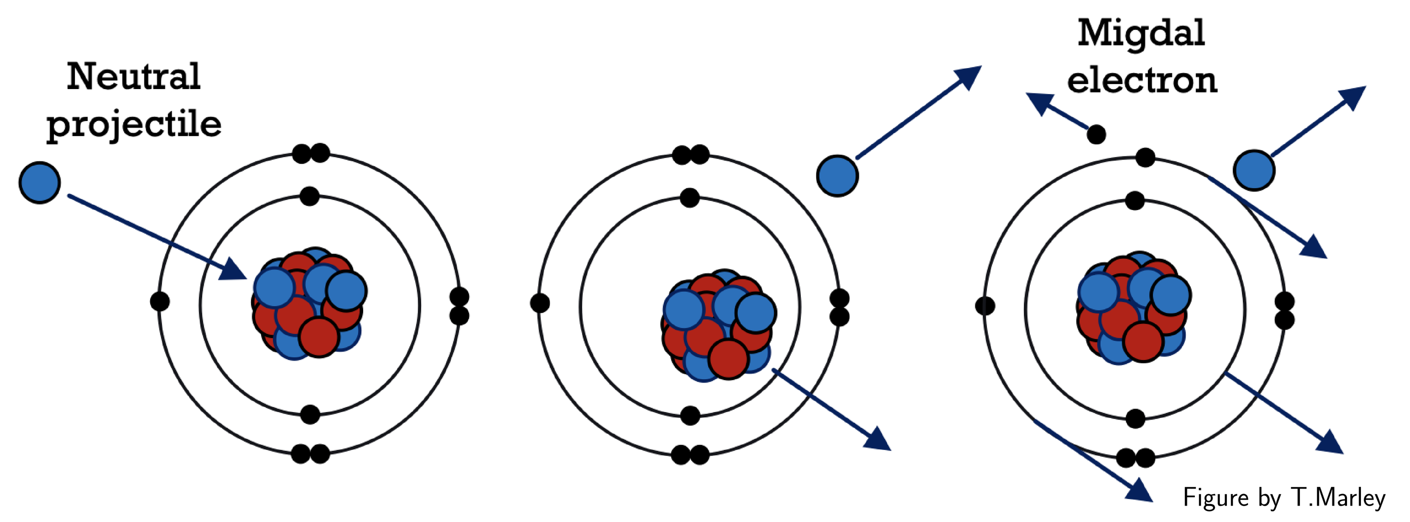
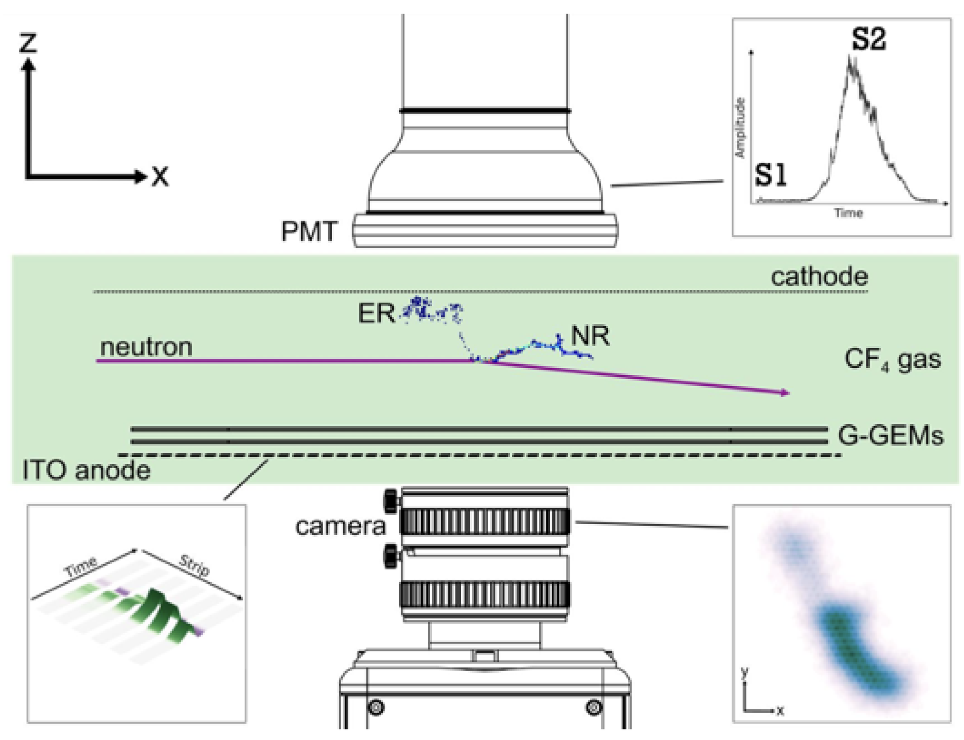
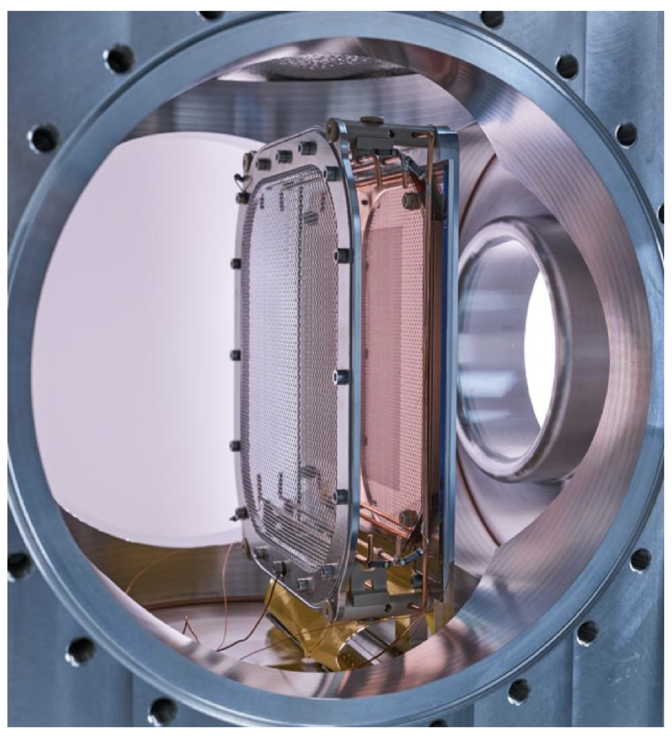


Figure by T.Marley

The MIGDAL Optical Time Projection Chamber

- The MIGDAL experiment [9] utilises an optical Time Projection Chamber, operating in low pressure (50 Torr) CF_4, combining charge and light read-out.
- Electron amplification with double glass GEM structure.
- Charge read-out by Indium Tin Oxide (ITO) anode; 120 strips giving x-z information.
- Light read out by fast, low noise qCMOS camera providing x-y information.
- Primary and secondary scintillation measured with PMT.
- 3-D track reconstruction capability within 3 cm x 10 cm x 10 cm active volume.





Scintillation

- Use Hamamatsu PMT R11410 provides trigger for experiment.
- Two channel read-out with different gains to measure both primary and secondary scintillation.
- Provides timing information.

Secondary scintillation

- Hamamatsu Orca-Quest scientific fast qCMOS camera.
- Imaging with 2048 x 1152 pixels with 120 frames/s.
- Use a 25 mm f/0.85 EHD Imaging lens.

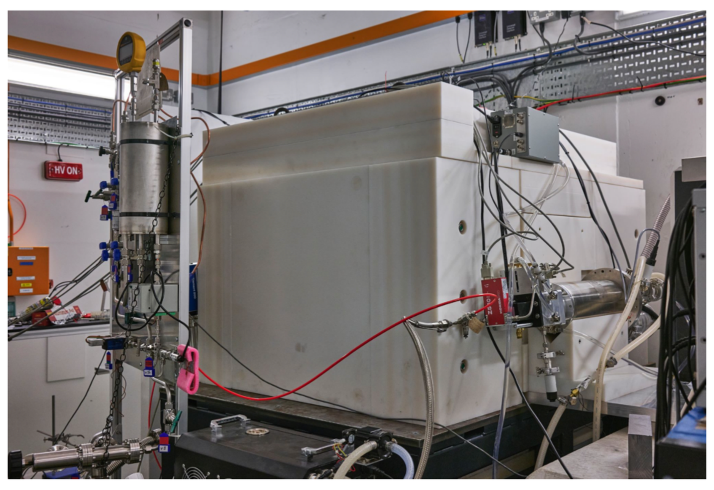
Electron Amplification: GEMs

- Charge amplification by two glass Gas Electron Multipliers (GEMs) [12] with gas gain of $\sim 10^5$.
- Composed of a dielectric "sandwiched" between two conductive layers with a potential difference.
- MIGDAL GEMs feature 0.5 mm glass between 2 µm thick layers of copper with 170 µm diameter holes, of 280 µm pitch, arranged in a hexagonal pattern.
- Strong electric field in holes allows for amplification.

Charge read-out

- Anode of 120 ITO strips (0.6/0.8mm width/pitch) readout with 60 channel 8-bit Acquiris with 2 ns sampling rate.

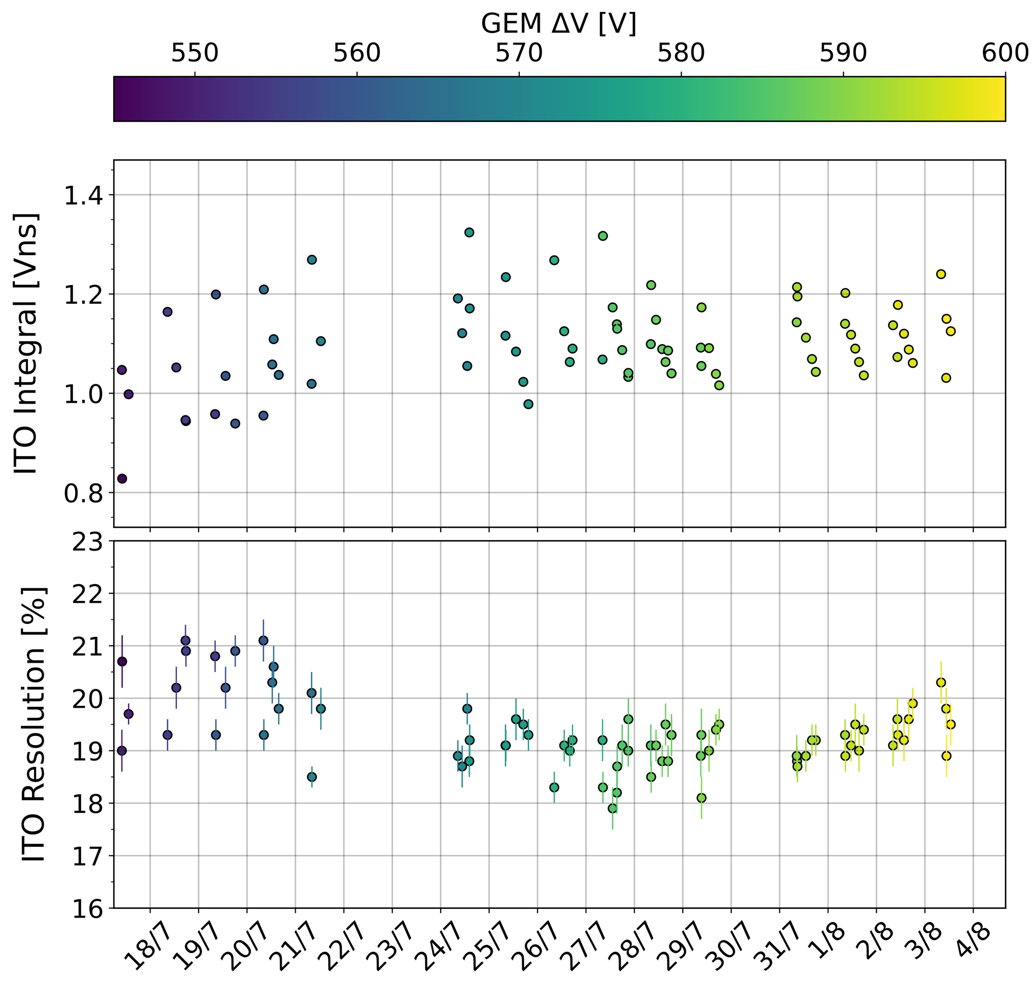
The MIGDAL Experiment



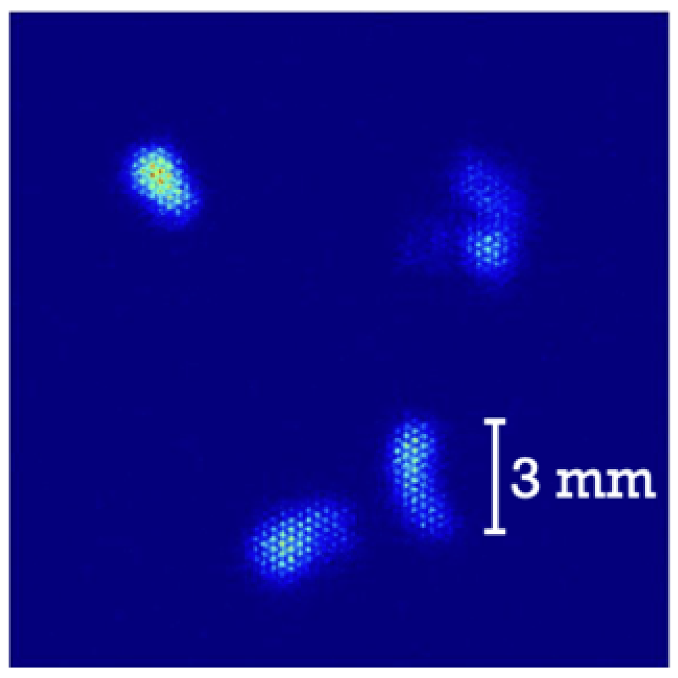
- Aim to make the first unambiguous measurement of the MIGDAL effect in nuclear scattering.
- Detector is at NILE/ISIS shielded by lead and borated polyethylene, with collimated high intensity 2.45 MeV neutrons from a DD generator.
- Pure CF_4 and then CF_4 + noble gas mixtures.
- Two dedicated science runs have taken place.

Calibration

- ^{55}Fe calibrations performed at regular intervals throughout each day.
- Voltage across both GEMs adjusted daily.
- Charge read-out resolution is $\sim$20%.
- Same calibration process for camera.

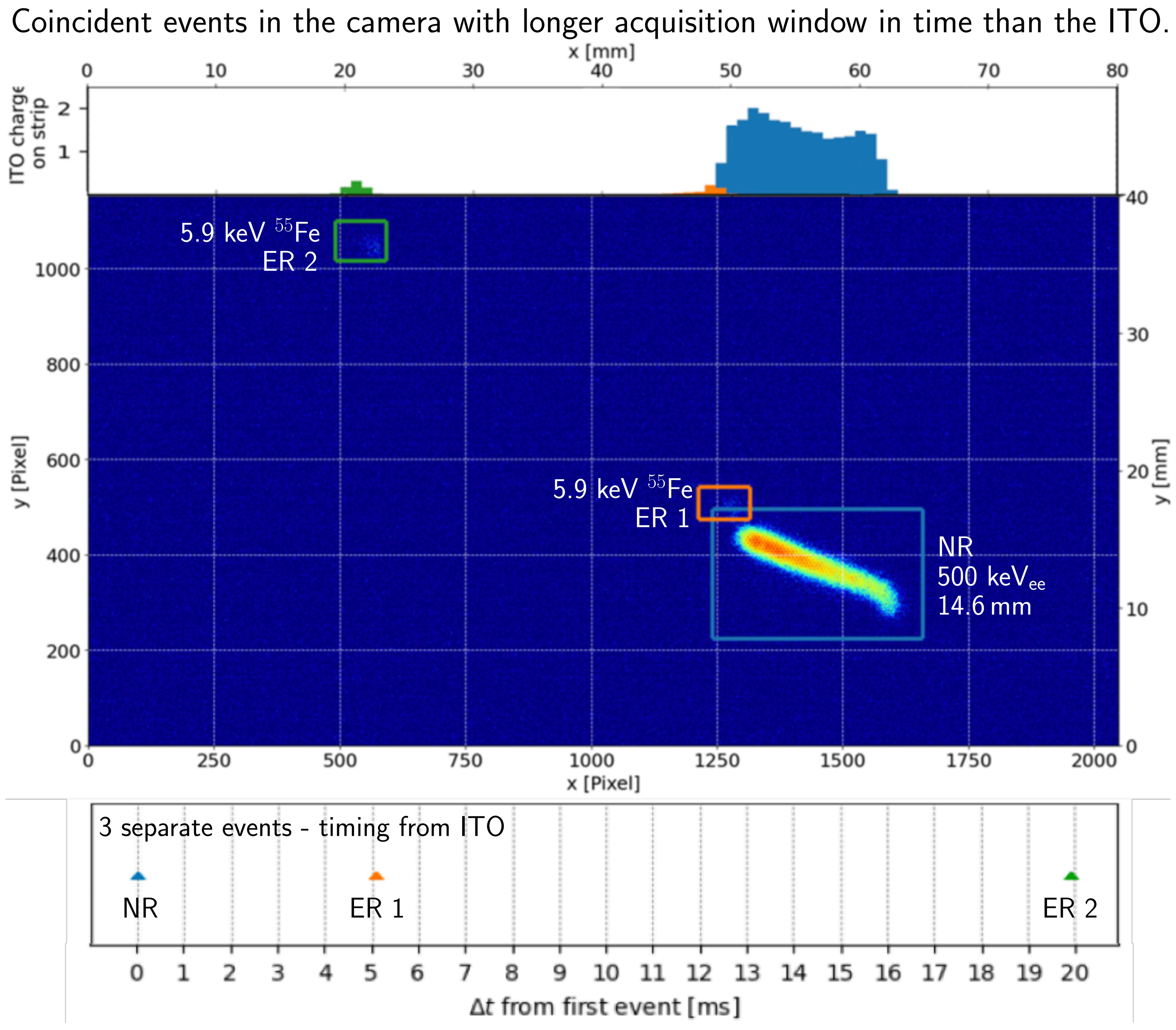


Example tracks in the camera produced by 5.9 keV ^{55}Fe X-ray.



Commissioning with DD neutrons

- DD neutrons induce fluorine nuclear recoils with energies up to 470 keV, and carbon nuclear recoils up to 710 keV.
- Nuclear recoils and electrons are discriminated based on energy and track length.
- Run with simultaneous DD neutrons and ^{55}Fe source producing Migdal like topology from nuclear recoil and ^{55}Fe photoelectron shown below.
- Coincident events in the camera with longer acquisition window in time than the ITO.



Summary

- Migdal effect of great interest to dark matter community as leads to additional visible energy above threshold in the detector.
- The MIGDAL experiment aims to make first unambiguous observation of the Migdal effect using an optical Time Projection Chamber allowing for precise 3D reconstruction of tracks.
- Two science runs have taken place, analysis ongoing.
- Ability to measure $\mathcal{O}$(5 keV) electrons and $\mathcal{O}$(700 keV$_{ee}$) nuclear recoils simultaneously.

References

[1] A. Migdal. "Ionizatsiya atomov priyadernykh reaktsiyakh". *ZhETF* 9 (1939).

[2] A. Migdal. "Ionization of atoms accompanying alpha- and beta-decay". *J. Phys. Acad. Sci. USSR* 4 (1941).

[3] M Ibe et al. "Migdal Effect in Dark Matter Direct Detection Experiments". *JHEP* 03 (2018).

[4] P Cox et al. "Precise predictions and new insights for atomic ionization from the Migdal effect". *Phys. Rev. D* 107.3 (2023).

[5] R. L. Workman et al. "Review of Particle Physics". *PTEP* 2022 (2022).

[6] M. S. Rapaport et al. "L- and M-shell electron shake-off accompanying alpha decay". *Phys. Rev. C* 11 (1975).

[7] M. S. Rapaport et al. "K-shell electron shake-off accompanying alpha decay". *Phys. Rev. C* 11 (1975).

[8] Couratin C et al. "First Measurement of Pure Electron Shakeoff in the beta Decay of Trapped ^{6}He$^+$ Ions". *Phys. Rev. Lett.* 108 (24 June 2012).

[9] H. M. Araújo et al. "The MIGDAL experiment: Measuring a rare atomic process to aid the search for dark matter". *Astropart. Phys.* 151 (2023).

[10] J Xu et al. "Search for the Migdal effect in liquid xenon with keV-level nuclear recoils". *Phys. Rev. D* 109.5 (2024).

[11] K. D. Nakamura et al. *Detection capability of Migdal effect for argon and xenon nuclei with position sensitive gaseous detectors*. 2020.

[12] T. Fujiwara et al. "Fine-pitch glass GEM for high-resolution X-ray imaging". *J. Instrum* 11.12 (Dec. 2016).

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