# Heavy compact objects flux limits from Pi of the Sky experiment

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# Heavy compact objects

**Heavy Compact Objects** - hypothetical extremely heavy (and dense) objects of (usually) extremely small size, for example:

**Strangelets** (microscopic?) / **nuclearites** (macroscopic?) – hypothetical lumps of matter consisting of up, down and strange quarks, that could be more stable that proton/neutron based hadronic matter

- Could have been produced in very early universe
- Maybe are produced in astrophysical objects (neutron/strange stars)

Rujula & Glashow, Nature, vol. 312, 1984

- Could traverse through Solar System and Earth
- Could produce light tracks in the atmosphere due adiabatic compression of air
- Assumptions: cosmological origin, isotropic flux, “galactic speeds“ of 250 km/s
- Can be detected in similar manner as meteors

# The Pi of the Sky experiment

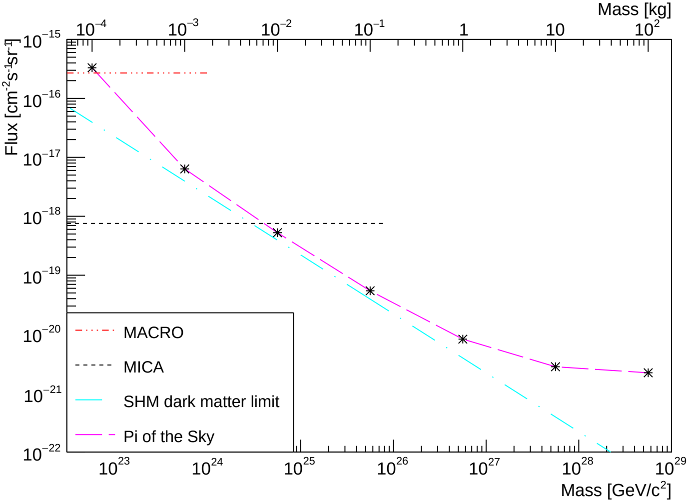
Closed GRB optical follow-up project consisting of 16+2 cameras monitoring the sky.

- FoV: 2 sr
- Temporal resolution: $\sim 10s$
- $\sim$2000-3000 frames/night/camera
- Large data stream: $\sim$ 0.5 TB/night
- Detection of flashes in the real time
- Fully autonomous operation
- Range $12^m$ - $14^m$

Finished operations in 2016

# 90% CL limits on the flux of nuclearites

Assumptions like in the paper: isotropic flux from upper hemisphere, 250 km/s speed




L. W. Piotrowski et al., **Phys. Rev. Lett. 125, 091101** – Published 28.08.2020

# The road to the flux limit

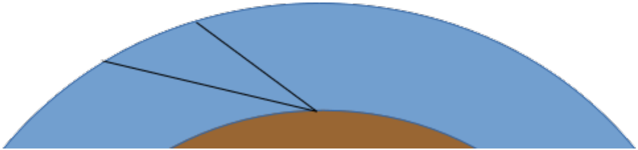
Assuming no detection, 90% CL isotropic flux limit approximation:

$$\Phi_{90CL}(m) = \frac{2.3}{S_E(m) \cdot t_e \cdot 2\pi}$$

where $t_e$ is exposure time of a single frame,

$$S_E(m) = \sum_{\alpha=0^\circ}^{90^\circ} s_{FoV\alpha m} \cdot \epsilon_{\alpha m} \cdot n_\alpha \cdot \varepsilon_S$$

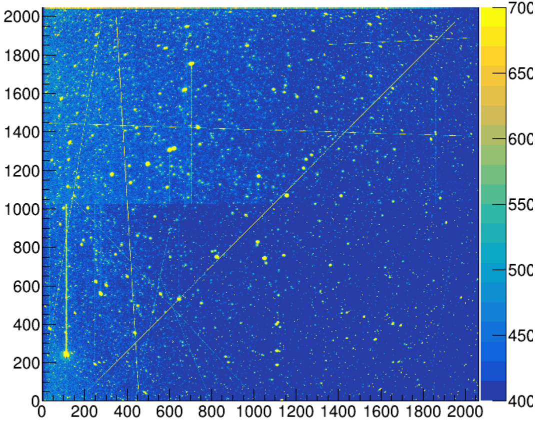
is the detector's effective area, $s_{FoV\alpha m}$ is FoV surface, $\epsilon_{\alpha m}$ is detection efficiency for given zenith angle and mass, $n_\alpha$ is the number of frames taken with given zenith angle, and $\varepsilon_S$ is efficiency of separation from detected events (cuts to fulfil no-detection).



# Detection efficiency

Efficiency of strangelets detection – from simulation of strangelets on Pi of the Sky sky photographs:

- Simulate trimmed (minimal burning altitude) FoV pyramid for range of masses and zenith angles – surface of walls of the pyramid as effective area of the detector
- Calculate track position and brightness on the frame: altitude, distance to the detector, atmospheric extinction



# Separation efficiency

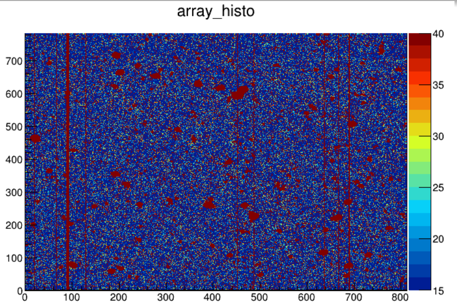
How well the strangelet tracks can be distinguished from other tracks.

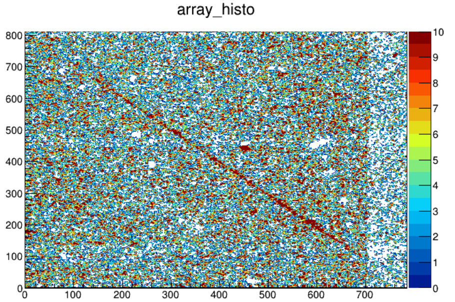
- Find real events on the frame
- Find cuts that will eliminate all of them
- Find how much of simulated strangelets the cuts cut

# Data and events statistics

Search for track in archival Pi of the Sky data:

- Initially 337674 10 s frames, 34004 20*10 s summed frames
- 185258 10 s frames and 22237 20*10 s after frame quality cuts (clouds, tracking errors, horizon, dusk, down, etc.) = 1766.05 h eq. for single camera
- 35870 tracks in frames found by OpenCV HoughLinesP based algorithm, after merging and cuts



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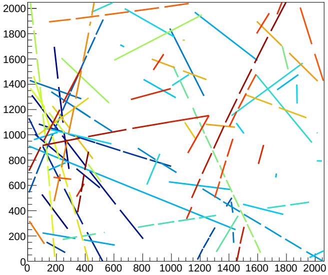


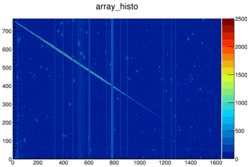


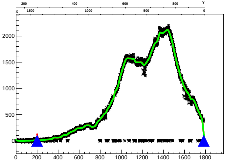

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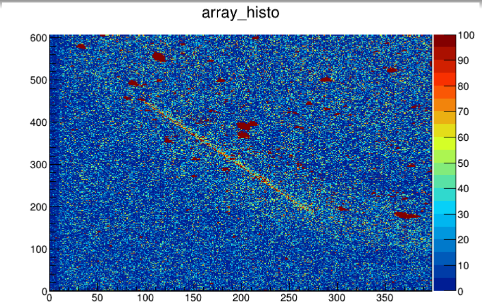


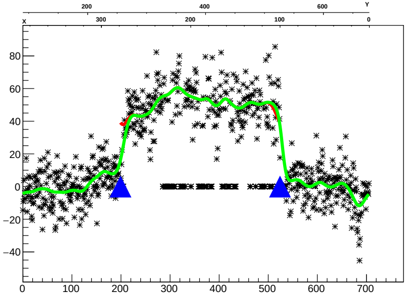

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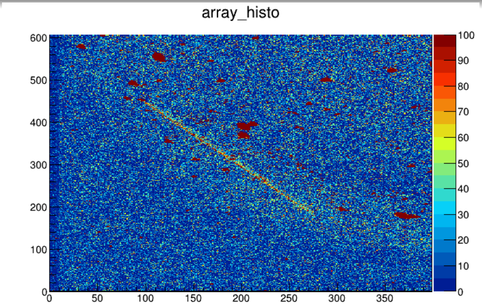
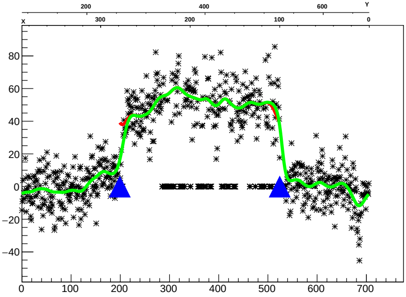
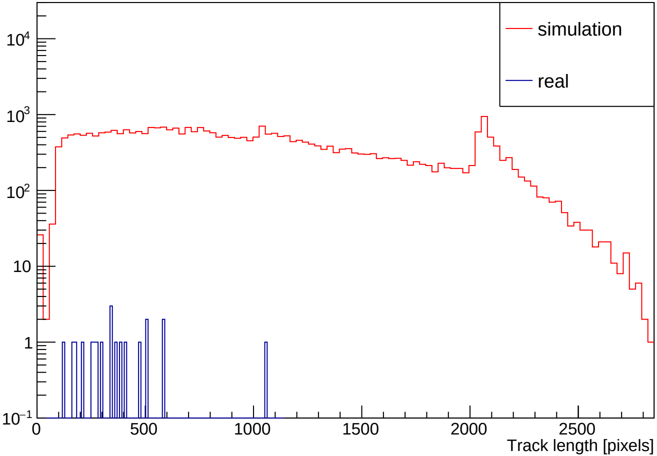
- After cat. sat. cut: 20 candidates



# Separation efficiency

The easiest, very drastic (but controversial) cut:




Compatible with "maximum gap" method, but I could not find a good statistical method for this cut.

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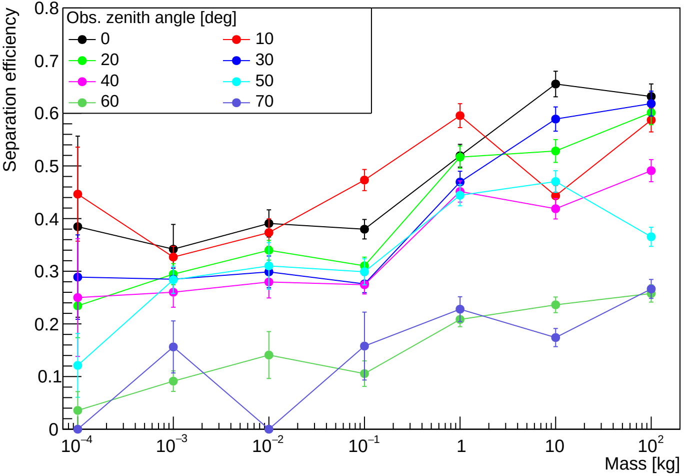


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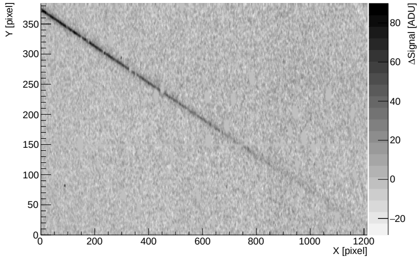
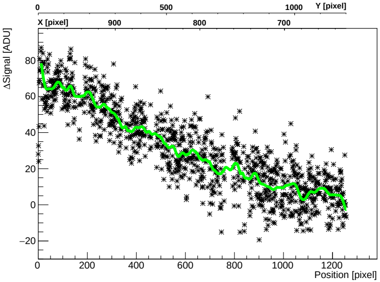
# Longest candidate

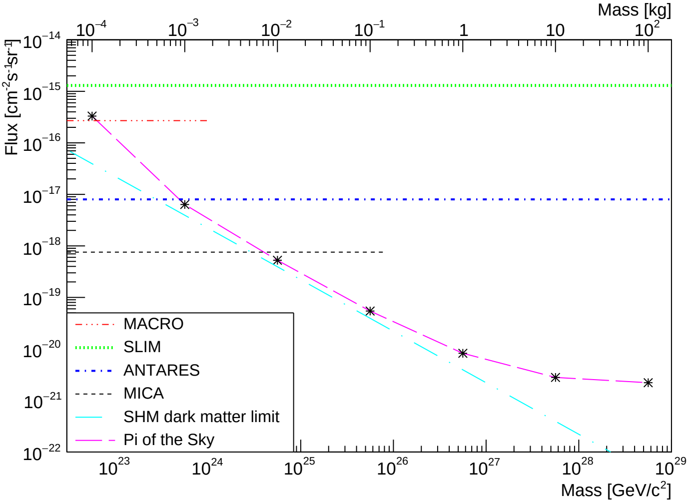
Probably a satellite – flat start and flat top



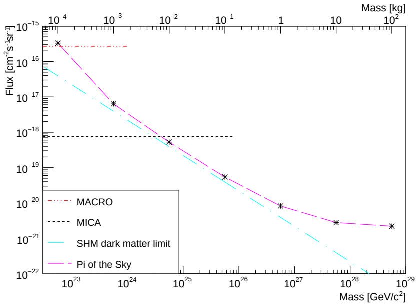
# Separation efficiency

Removes all “candidates”, leaves above 50% for heavy masses




SLIM and ANTARES limits removed in the paper – requested by reviewers.

# The assumptions of the original paper

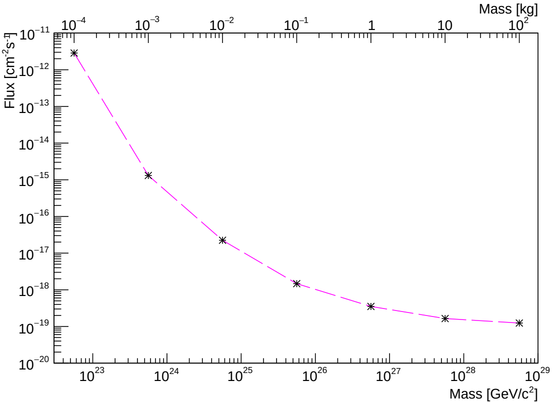



- Why isotropic shower of cosmological strangelets of speed 250 km/s?
  - "chaotic velocities characteristic of the Sun's galactic rotation"
  - Due to the movement of Sun in the galaxy, direction would be highly unisotropic
  - Non uniform, non-gaussian (?) speed distribution modulated by Earth's movement, etc., somewhat similar to dark matter
- Nuclearites have a mass spectrum!
- Maybe not cosmological at all?
  - Extragalactic – most likely isotropic (short GRBs, etc.)
  - Gal. neutron stars, strange stars mergers/explosions, etc. – v? distribution?

# Directional flux

Perhaps more plausible ideas for cosmological strangelets:

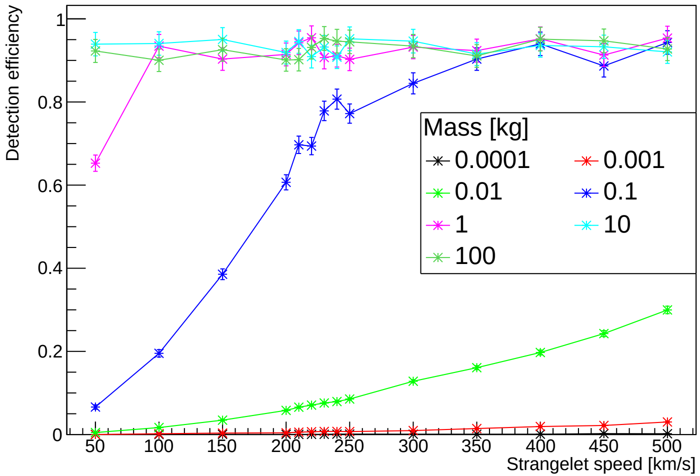
- A "sea" of immobile strangelets
- A "dipol" of strangelets having all possible Keplerian orbits around the centre of the galaxy convolved with Sun's/Earth's movement
- Some more complicated speed/direction distribution, like WIMPs isothermal sphere




A "sea" of immobile strangelets – a starting point for specific sources distribution

# Efficiency vs speed

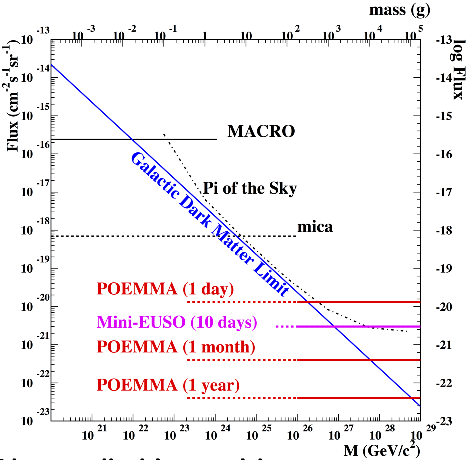
$$\left.\begin{array}{r}\text{Strangelets' luminosity} \propto v^3 \\ \text{Signal deposited in pixel} \propto t \propto 1/v\end{array}\right\} \text{Detection efficiency } \epsilon \propto v^2$$



# Beyond nuclearites and dark matter

**Heavy compact objects:**

- magnetised nuclearites – $\sim 1e9$ mass shift – real constraints on DM
- Q-balls – <1.5 ng SECS, > SENS
- magnetic monopoles
- fermionic exotic compact stars
- primordial black holes...
- ...and their remnants
- mirror matter
- Fermi balls
- electroweak symmetric dark matter balls
- anti-quark nuggets
- axion quark nuggets
- six-flavour quark matter
- non-strange quark matter*




**Almost all objects with mass spectrum**

Objects taken mainly from:
Burdin et al., *Non-collider searches for stable massive particles*, Physics Reports 582, 2015

# Strange events