Search for gamma-ray emission from interstellar visitors 1I/‘Oumuamua and 2I/Borisov with Fermi-LAT data

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Outline

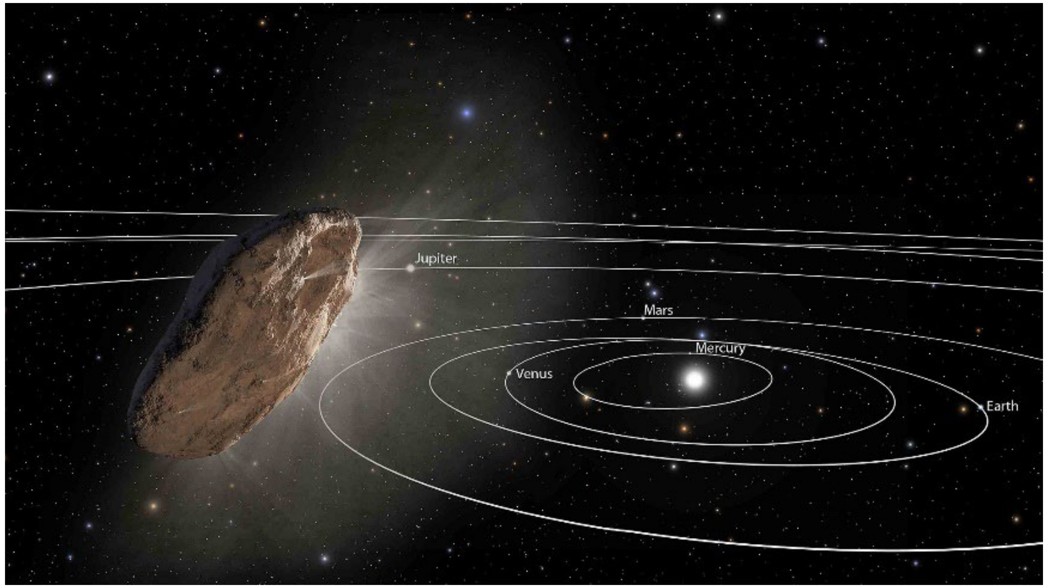
- Context and motivation
- Fermi-LAT analysis description and results:
  - Data selection
  - ON/OFF method
  - Quasi-static point source method
- Discussion and interpretation

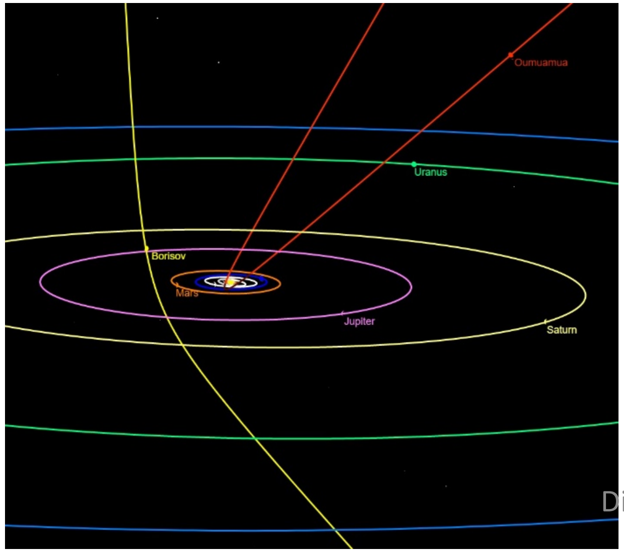
Motivation

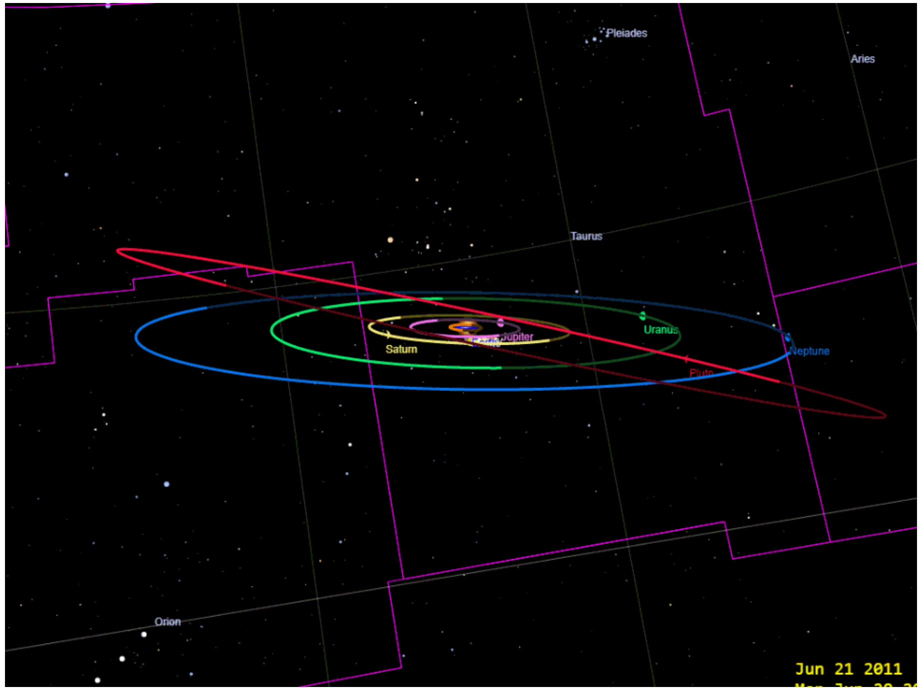
- Gamma-ray emission search from two interstellar objects (ISOs)
- Oumuamua:
  - First interstellar visitor
  - Unknown origin and nature
  - Triggered many follow-up observations (Spitzer, HST, Gaia, 71 SOHO, STEREO, Swift)
  - Close passage to the Earth
- 2I/Borisov:
  - Interstellar origin
  - Similar to ‘usual’ Solar system comets
- Possible gamma-ray emission from
  - Cosmic rays (CR) interacting with the object surface
  - Particle acceleration mechanisms
  - Exotic/dark matter origin

Objects details

	1I/'Oumuamua	2I/Borisov
Discovery date	October 18, 2017	August 30, 2019
Probable size	< 1km	≈ 1km
Minimum distance from Earth reached	October 2017	December 2019
Minimum distance	0.2 A.U.	1.9 A.U.

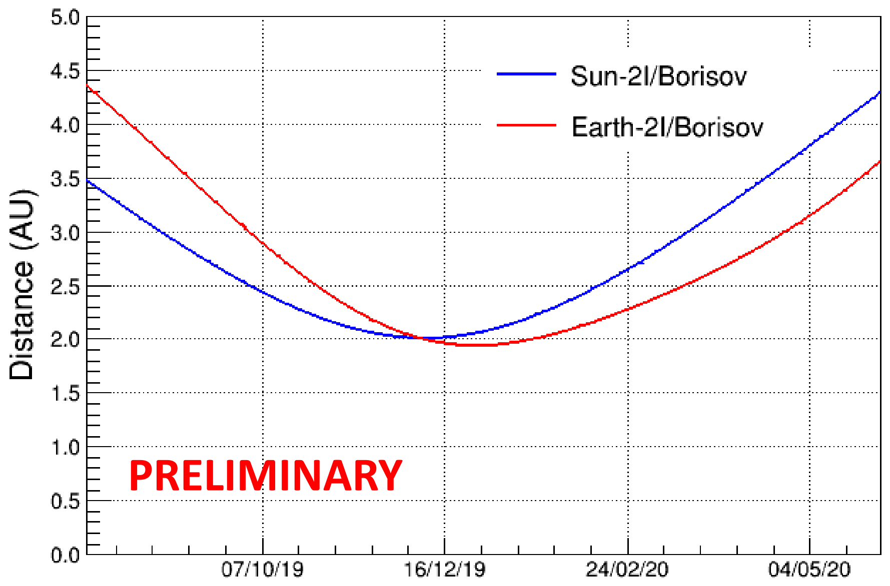


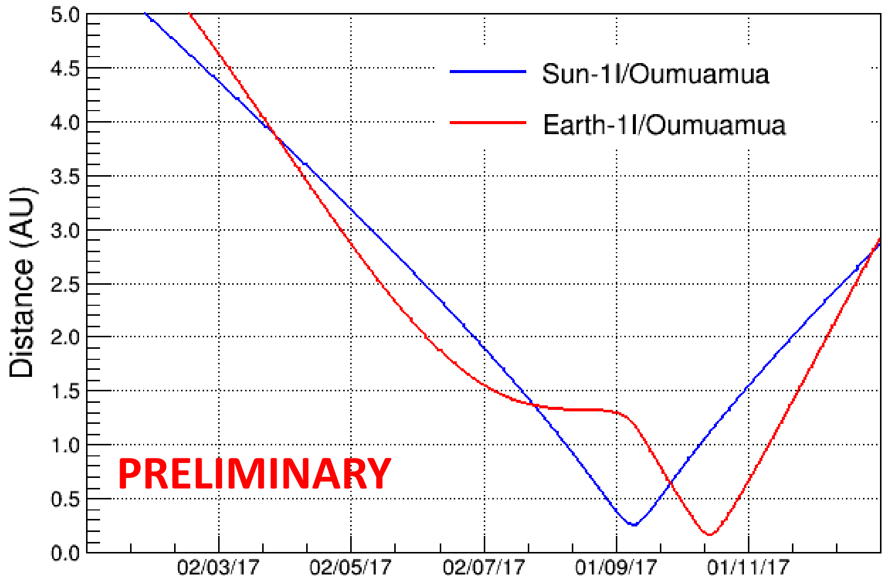




Fermi-LAT analysis

- Both sources analysed around the period of their respective minimum distance from the Earth
- Time range:
  - 1I/'Oumuamua: Jan 01, 2017 – Dec 31, 2017
  - 2I/Borisov: Jun 01, 2019 – Jun 30, 2020
- Time range divided in small time bins
  - Object ephemerides with equal spatial separation of 600 arcsec ≈ 0.2°
- Two independent analysis developed:
  - ON/OFF analysis
  - Quasi-static point source analysis





ON/OFF analysis

- Same approached used for other moving sources (Moon, Sun)
- Region of Interest (RoI) defined as a cone centered in the source position (5 deg)
- Background defined as a cone of the same size centered on a time-offset position
  - Time offset is ±1, ±2, …, ±5 months , always al least 15° from the source
- Other selection:
  - Background sources (Sun, Moon, bright known gamma-ray sources) are removed
  - Source at least 10 deg away from the galactic plane

ON/OFF analysis – model fit

- Combined fit with ON and OFF counts
- Two independent PL models for background and source:

$$\Phi_{OFF}(E) = k_b \left(\frac{E}{E_0}\right)^{-\gamma_b}$$

$$\Phi_{ON}(E) = k_b \left(\frac{E}{E_0}\right)^{-\gamma_b} + k_s \left(\frac{E}{E_0}\right)^{-\gamma_s}$$

- Fit performed folding the model with the 2D exposure including the energy dispersion
- Significance of the source defined with Test Statistic (TS):

$$TS = 2\,\Delta \log L = 2\,(\log L_1 - \log L_0)$$

ON/OFF analysis – fit results

No significant signal was found, upper limits at 95% c.l. were calculated

1I/‘Oumuamua

Upper limits at 95% CL

Flux (>56 MeV) : 1.6 e-8 cm^{-2} s^{-1}

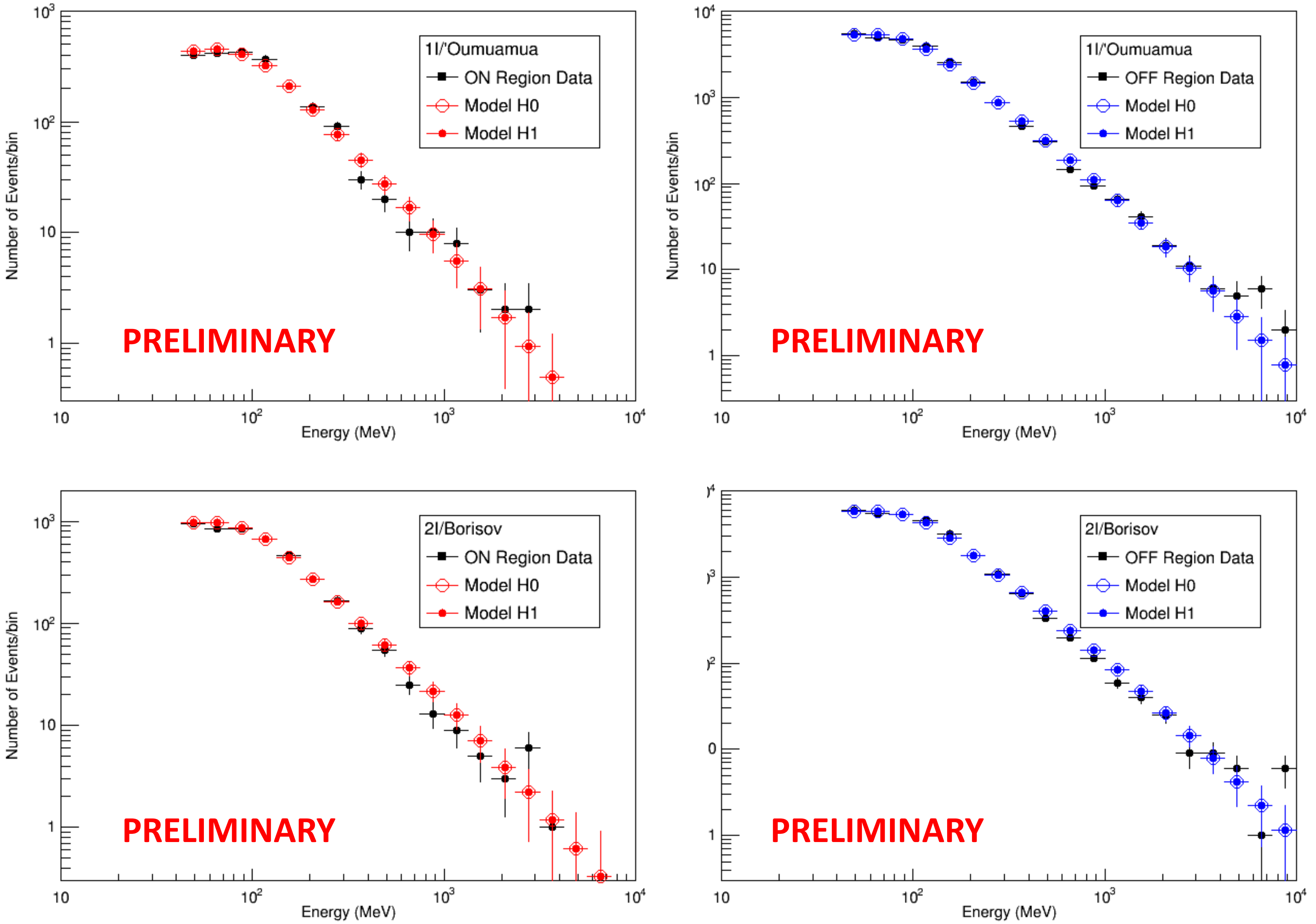
Flux (>100 MeV) : 8.2 e-9 cm^{-2} s^{-1}

2I/Borisov

Upper limits at 95% CL

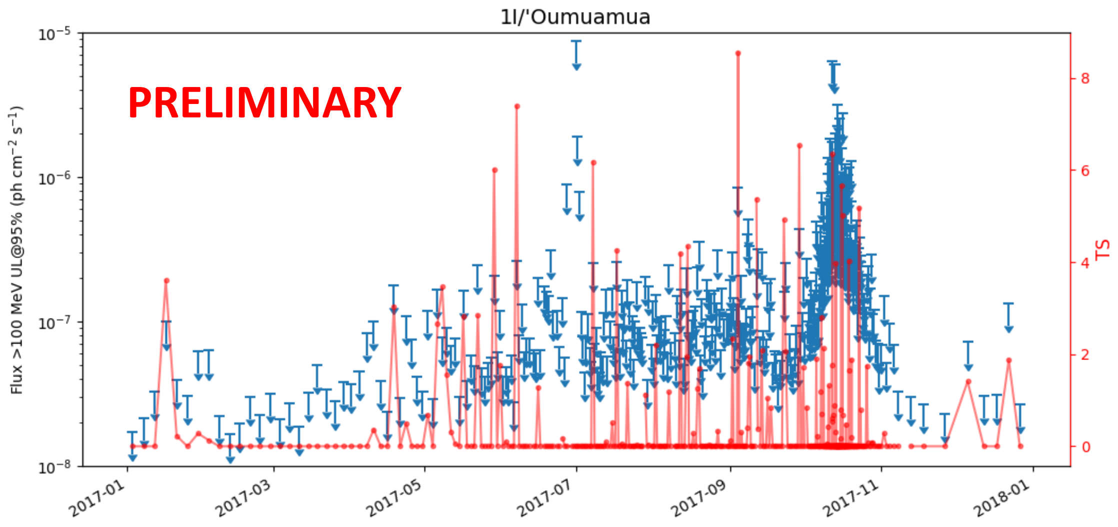
Flux (>56 MeV) : 6.3 e-9 cm^{-2} s^{-1}

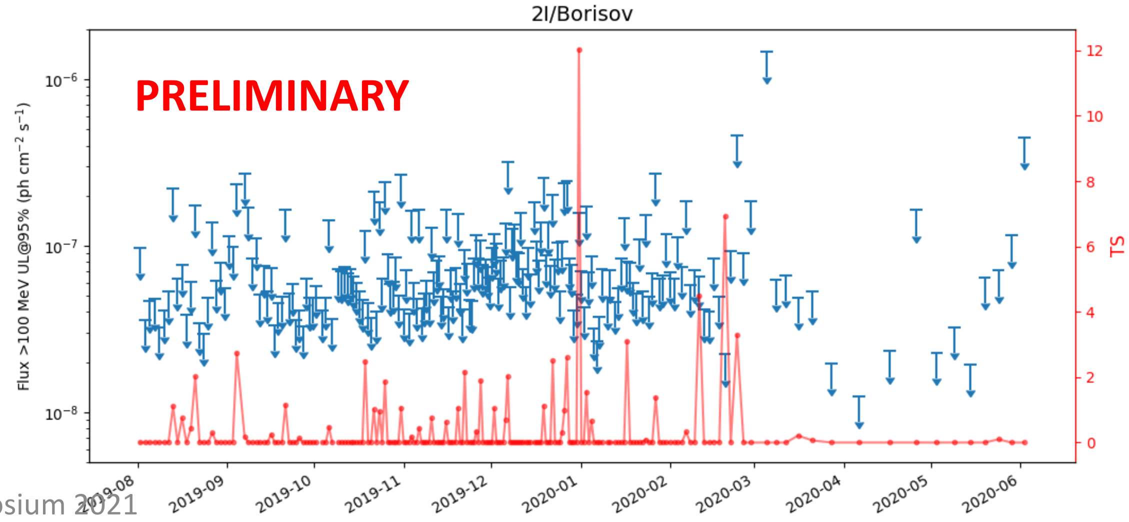
Flux (>100 MeV) : 3.1 e-9 cm^{-2} s^{-1}



Quasi-static analysis

- Standard likelihood analysis using *fermitools* and *fermipy* package
- Performed in small time bins: source position changes of ≈ 0.8° between two consecutive time bins
- Photon Flux upper limits and Spectral energy distribution (SED) calculated in each time bin





Quasi-static analysis

- In order to look for a detection over the full time range, we summed the log-likelihood of each time bin
- For each time bin we calculate the likelihood profile in small energy bins
- We assume a simple power-law spectral shape

$$\frac{dN}{dE} = k \left(\frac{E}{E_0}\right)^{-\Gamma}$$

- We calculate the log-likelihood for each energy and time bin and sum

$$\log L = \sum_t \sum_k \log L_k \Big|_{Flux(E_k)}$$

- 2-dimensional log-likelihood is obtained varying the prefactor and the spectral index in the range [1.5,3.5]
- No detection was found and the upper limit @95% c.l. is obtained for $\Delta \log L = 4.61/2$

	Oumuamua	2I/Borisov
Flux ($> 56\ MeV$) ($cm^{-2}s^{-1}$)	$1.1 \cdot 10^{-9}$	$1.4 \cdot 10^{-9}$
Flux ($> 100\ MeV$) ($cm^{-2}s^{-1}$)	$5.9 \cdot 10^{-10}$	$7.3 \cdot 10^{-10}$

Upper limits are approximately a factor of 10 more stringent than ON/OFF method

Discussion – cosmic ray interaction

- γ-ray emission from CR interaction with the object surface
- We use the spectrum of the Moon as reference

$$\Phi_\gamma(E_\gamma) = \frac{\pi R_{moon}^2}{d_{moon}^2} \int Y(E_\gamma, E_k) I(E_k) dE_k$$

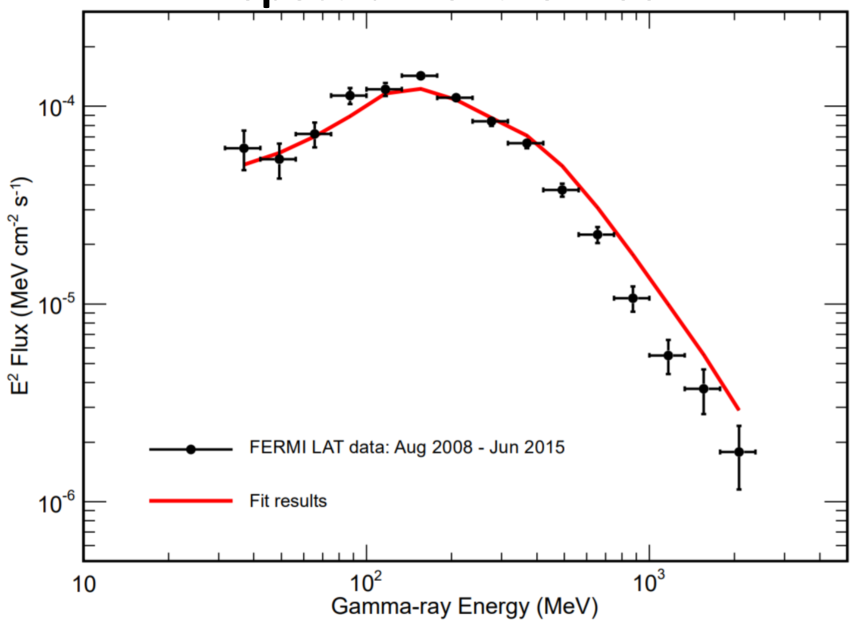
being $I(E_k)$ the CR intensity on the Moon surface and $Y(E_\gamma, E_k)$ the gamma-ray yield due to CR interaction

- A dedicated simulation on small 'solid' objects (size ≥ 100 m) showed that the emission has the same spectral shape as the Moon
- We scale the Moon flux to obtain the objects' flux by taking into account the different size and distance of the two sources

$$\Phi_{source} = \Phi_{moon} \left(\frac{R_{source}}{R_{moon}}\right)^2 \left(\frac{d_{source}}{d_{moon}}\right)^{-2}$$

- Since the distance is known from the ephemerides, we can put an upper limit on the object size

Spectrum of the Moon



Ackermann et al., PRD 93, 082001 (2016)

Discussion – cosmic ray interaction

- For the two objects, the average distance is assumed
- For the quasi-static method we implemented a distance-weighted stacking
  - the flux in each time bin is scaled by a factor $1/d^2$
- Size upper limits

	Oumuamua	2I/Borisov
ON/OFF analysis	$5.1 \cdot 10^4 km$	$1.2 \cdot 10^5 km$
Quasi-static (distance-weighted)	$9.2 \cdot 10^3 km$	$5.4 \cdot 10^4 km$

- Upper limits are much higher than expected sizes (approx. < 1 km for Oumuamua and ≈ 1 km for 2I/Borisov)

Conclusions

- Fermi-LAT is capable of tracking and observing moving objects thanks to its all-sky survey capability
- First two interstellar objects observe and analyzed with two independent methods
- No significant signal
  - Flux upper limits derived
- Simple interpretation for a CR interaction model