NELIOTA: A long term monitoring campaign for lunar impact flashes

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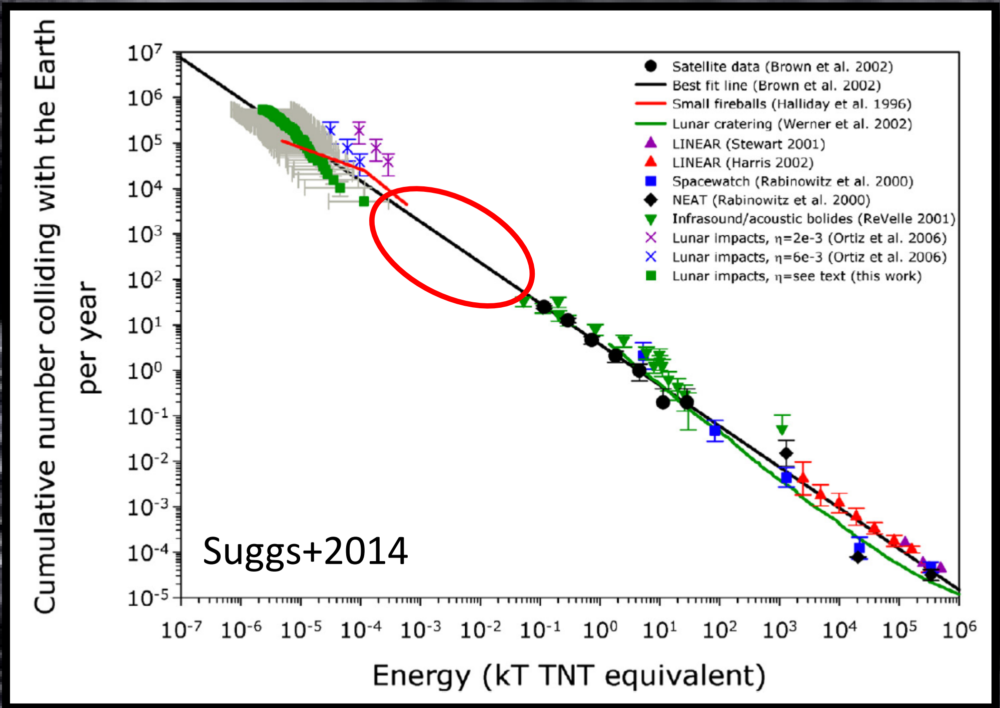
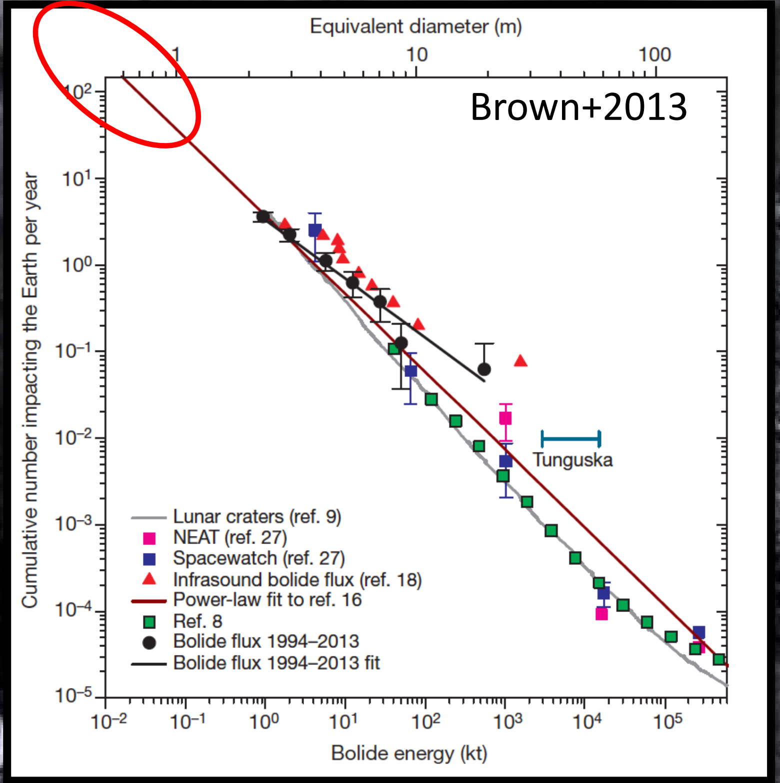
[2]Technical University of Munich, Germany
[3]ESOC/PDO, European Space Agency, Germany
[4]ESRIN/PDO/NEO CC, European Space Agency, Italy
[5]National Technical University of Athens, Greece

Lunar Environment Analysis Package Science Workshop, 4 Feb 2026, ESA/ESTEC

Problem statement

No info regarding the frequency appearance of meteoroids with cm-dm sizes





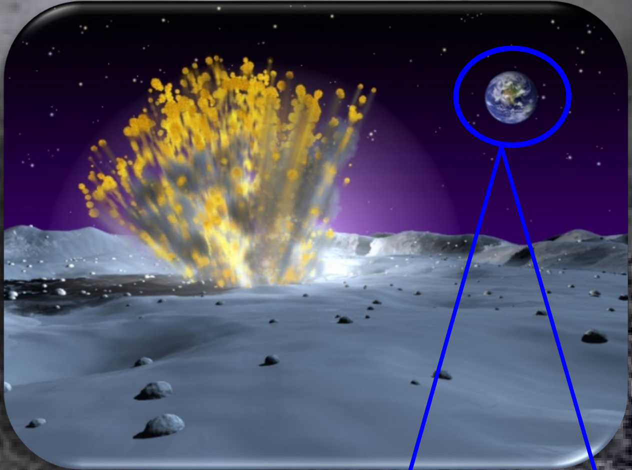
Goals + importance

Size-frequency distribution of meteoroids/small asteroids in the vicinity of the Earth

Satellite and space missions shielding

Future lunar bases establishment

Why Moon?



Disadvantages of meteors observations

- Small area coverage (~60,000 km^2)
- Small size meteoroids are instantly burned

Advantages of meteoroids lunar impacts observations

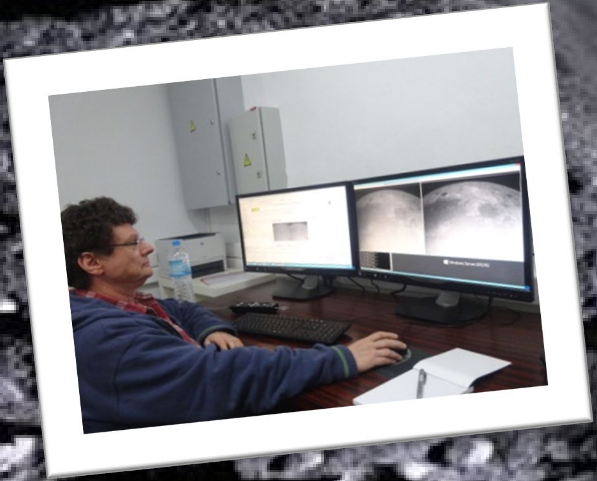
- Lack of atmosphere on Moon = Impacts of incoming meteoroids on the surface
- Impact: Part of the kinetic energy converts to luminous energy → FLASH!
- Flash = Optical+IR radiation → Recording using a telescope
- Large effective area→ ~19×10^6 km^2 (Side facing Earth)

Near Earth objects Lunar Impacts and Optical TrAnsients

Collaboration between **ESA-NOA/IAASARS**

2015-2023: Funded by ESA

2025-2028: Funded by Horizon Europe Programme of the European Union and implemented by ESA



Brief timeline

Paper I: Bonanos+ 2018

Paper II: Xilouris+ 2018

Paper III: Liakos+ 2020

Paper IV: Liakos+ 2024

2015	2016	2017	2018	2019
1 3 5 7 9 11	1 3 5 7 9 11	1 3 5 7 9	1 3 5 7 9 11	1 3 5

Kick off (2/2015)
Procurements
Telescope upgrade
Software development

Testing period

Phase I: 1st observing period

Phase I:

2019	2020	2021	2022	2023	2024
7 9 11	1 3 5 7 9 11	1 3 5 7 9 11	1 3 5 7 9 11	1 3 5 7 9 11	1 3

2nd observing period

Phase II – Observing period as part of ESA/CARMEN project

2024	2025	2026	2027	2028
5 7 9 11	1 3 5 7 9 11	1 3 5 7 9 11	1 3 5 7 9 11	1 3 5 7 9 11

You are here

Phase III – Observing period

?

Team 2015-2023

neliota

Principal Investigator
& Project manager
Dr Alceste Bonanos

Director of Kryoneri
Observatory
Dr Manolis Xilouris

Telescope astronomical
support
Dr John Alikakos

Telescope technical support
Mr Alexis Gourzelas

Postdoctoral Researcher
Dr Alexios Liakos

IT Manager
Dr Athanasios Maroussis

ESA Science Officer
Dr Detlef Koschny

ESA Technical Officer
Mr Vicente Navarro

Software Engineer
Mr Andreas Noutsopoulos

Software Manager
Dr Ioannis Bellas-Velidis
(retired)

Instrumentation Manager
Dr Panayotis Boumis

Advisory Board
Prof. Vassilis Charmandaris

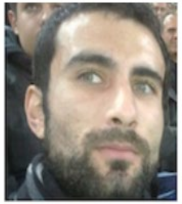
Assistant
Project Manager
Ms Stavroula Papatheochari

Advisory Board
Prof. Kleomenis Tsiganis

Technical Officer
Dr Richard Moissl

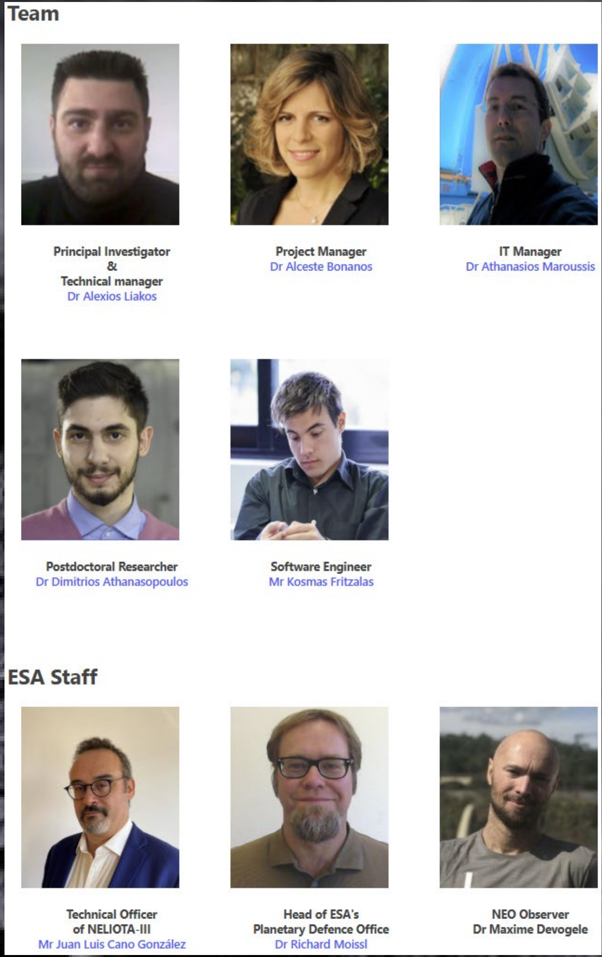
Telescope
Operations Manager
Dr Anastasios Dapergolas
(retired)

Technical support
Mr George Dimou (retired)



Software Engineer
Mr Anastasios Fytsilis

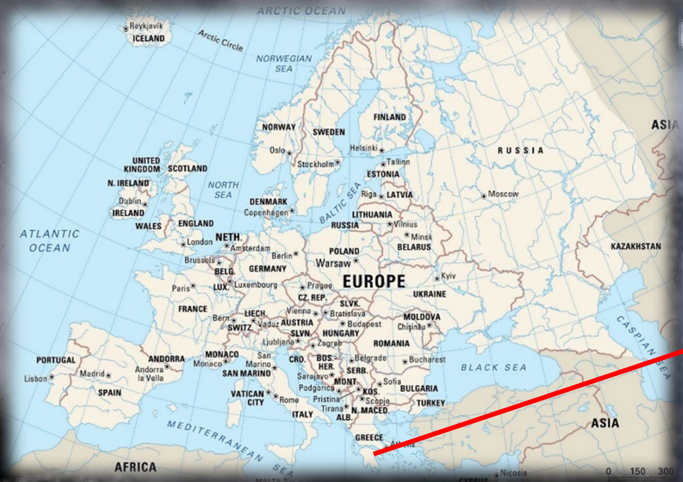
Team 2025-2028

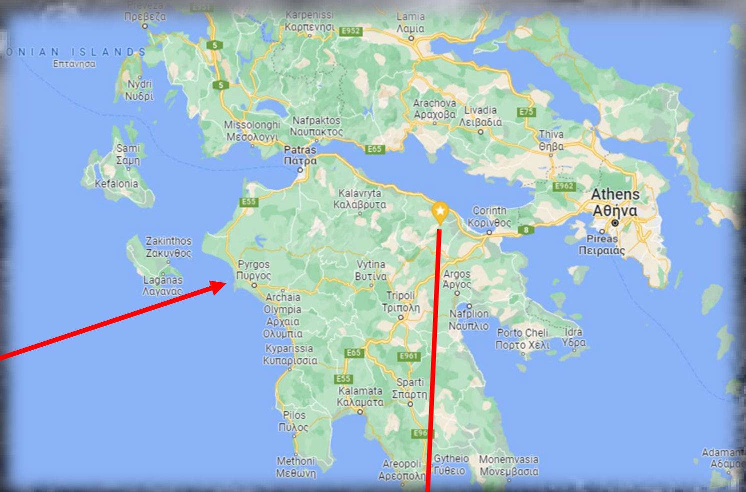


Dr D. Koschny
(Planetary Scientist, Technical Univ. of Munich)

- ✓ *the inspirer behind the idea*
- ✓ *former science officer*
- ✓ *close friend*
- ✓ *advisor*

Location

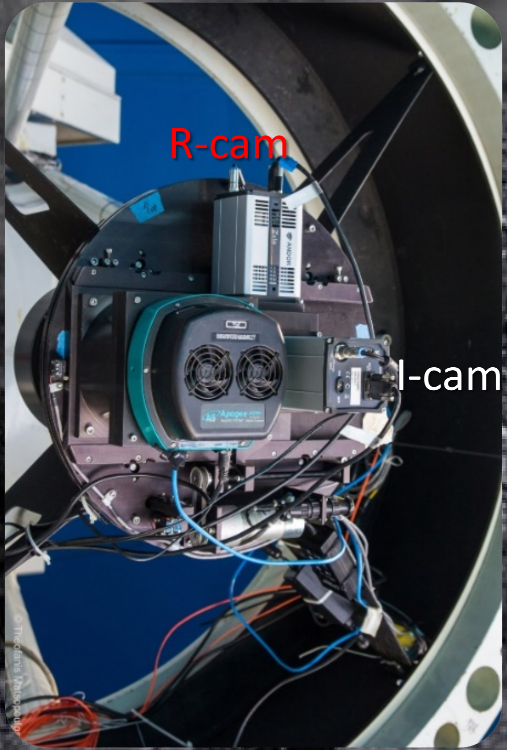




- *South-East Europe*
- *Corinthia, Northern Peloponnese, Greece*
- *Altitude: 930 m*
- *~120 km west of Athens*
- *~200 clear nights per year*
- *Accessible during all seasons*
- *Established in 1972 – Upgraded in 2015*

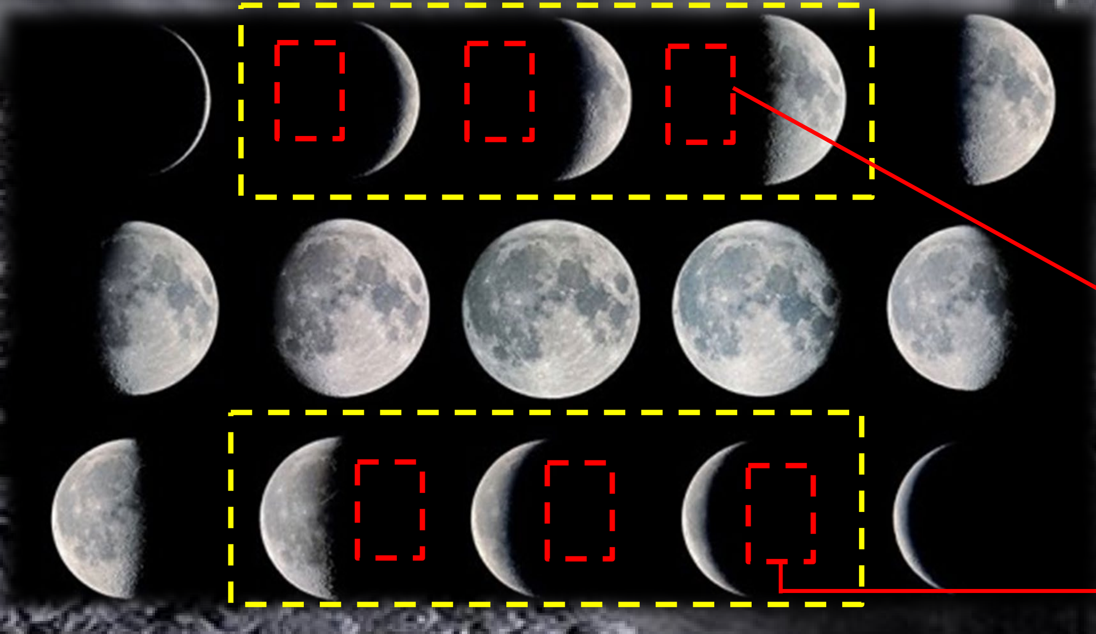
Infrastructure

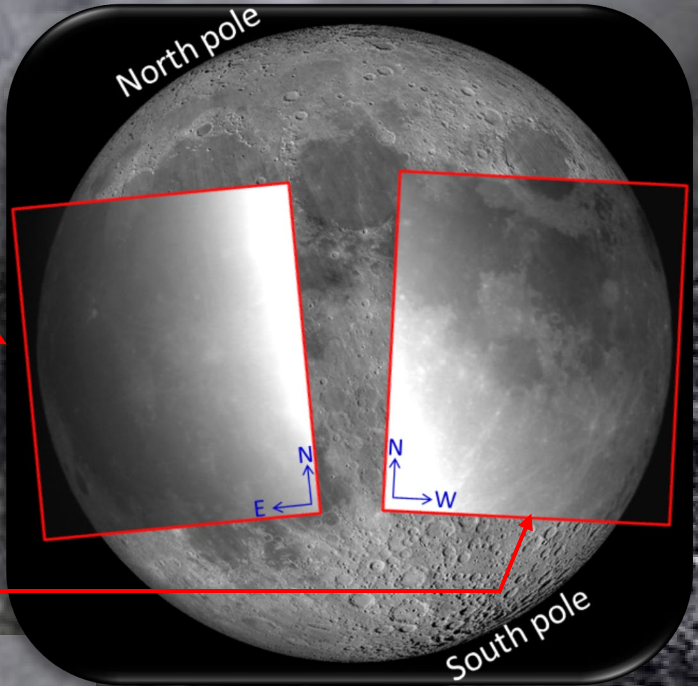
- Kryoneri telescope (1.2 m, f/2.8, prime focus)
- Twin sCMOS camera system on a dichroic beam splitter
- R and I Filters
- 36 TB storage capacity
- GPS receiver
- Meteo station



Xilouris+2018

Observing strategy





❖Non-sunlit (night) side

❖Phases between 0.1-0.45 → ~5-8 nights/month → 20´- 5 hr

❖Simultaneous recording in R and I bands with 30 fps (23 ms exposures)

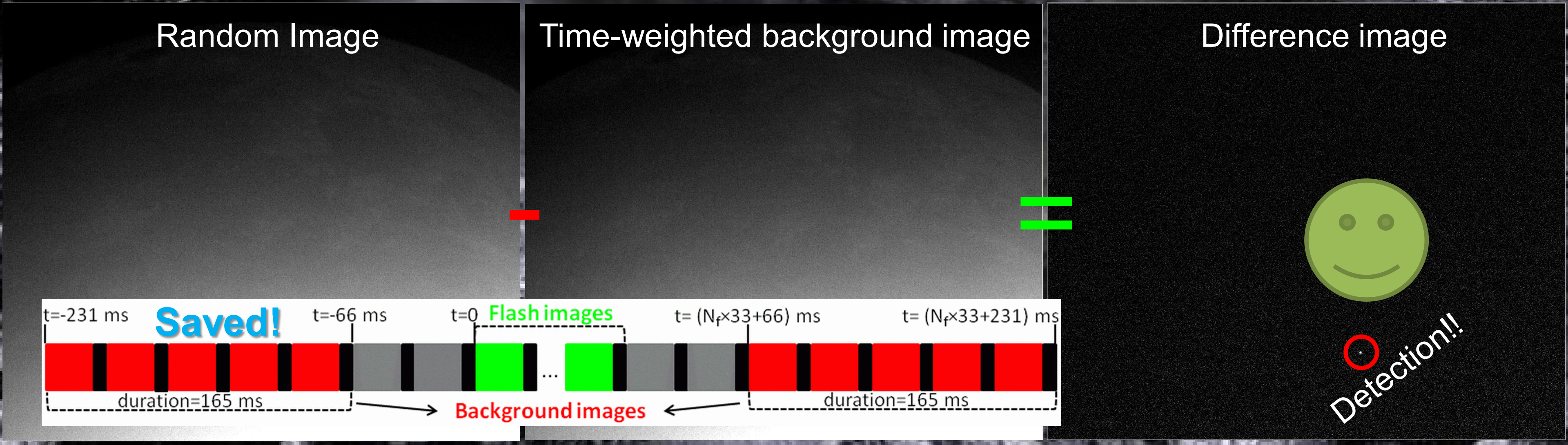
❖Moon elevation >~12 deg

FoV: 16´×14.4´
<Observable area>: 3×10^6 km^2

Data reduction and event detections

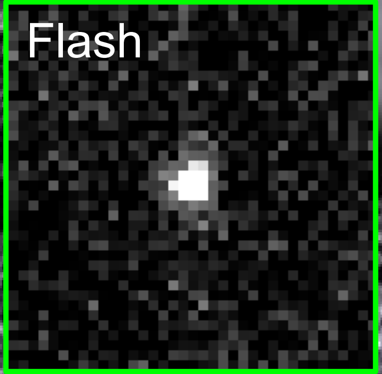
- Image calibration (flat dark)
- Lunar background subtraction
- Events detection

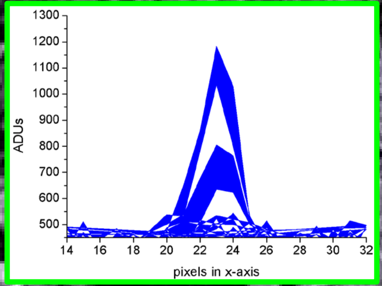
Software pipeline

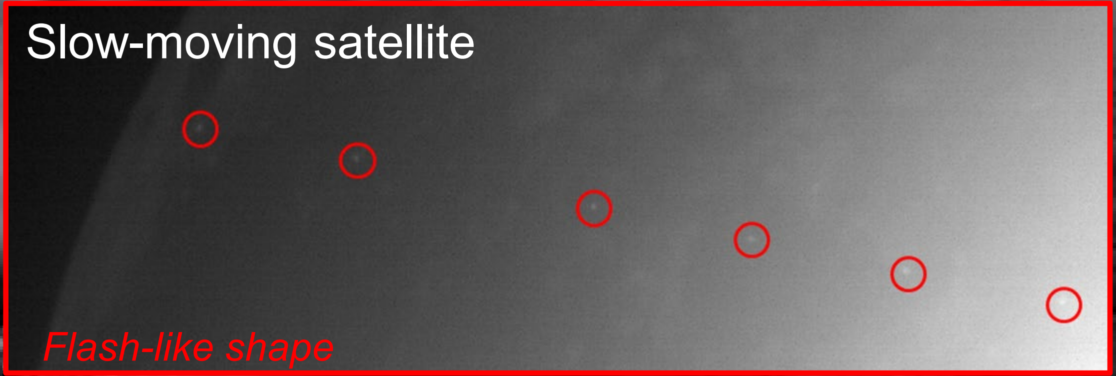


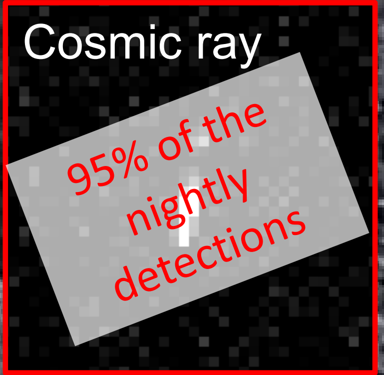
Evaluation of the events

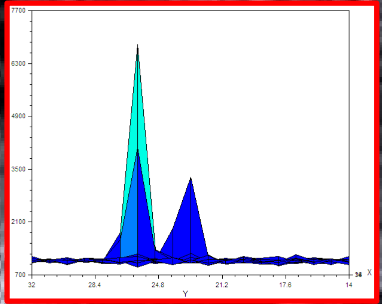
Visual inspection by the expert user (cosmic rays, satellites exclusion)









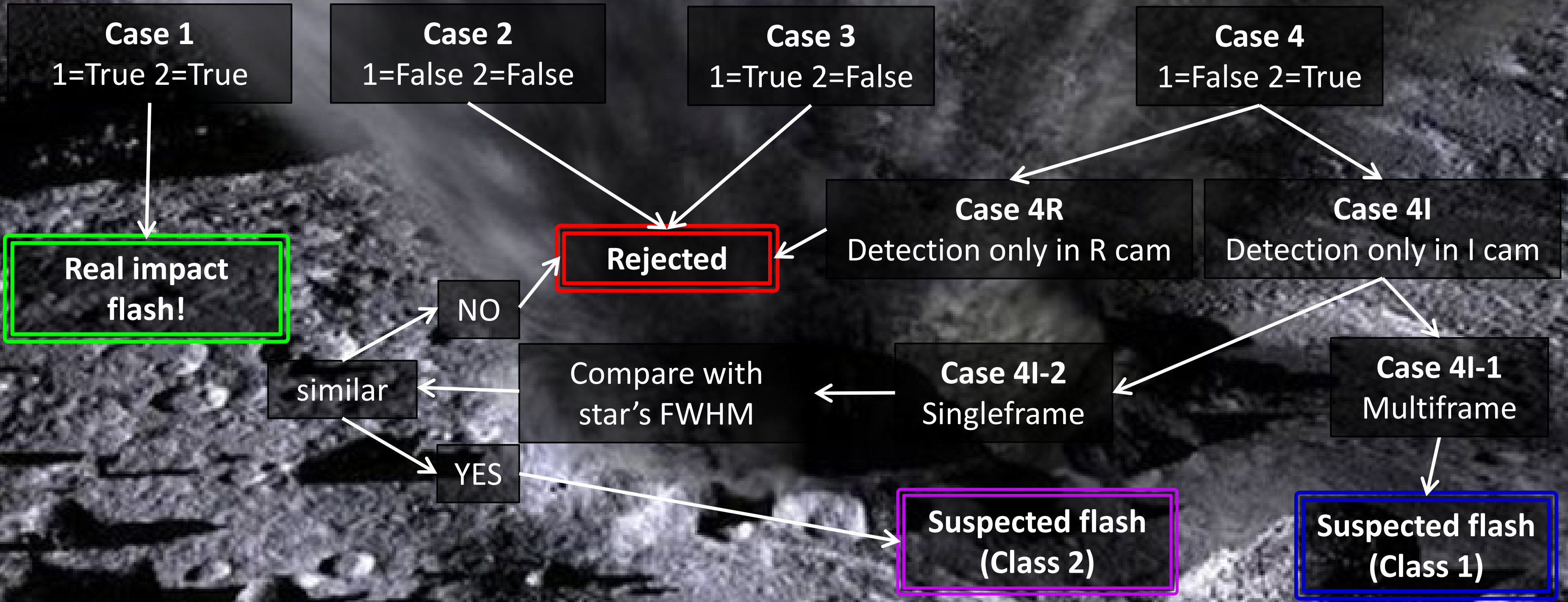


Evaluation of the events

Criteria

The true impact flash **must**:

1. **be visible in the frames of both cameras (same pixels)**
2. **not move on successive frames (e.g. satellite or star)**



Data analysis

- Aperture photometry
- Magnitude calculation (standard stars)

Expert user

$$m_{flash} = m_{star} + 2.5\log(F_{star}/F_{flash})$$

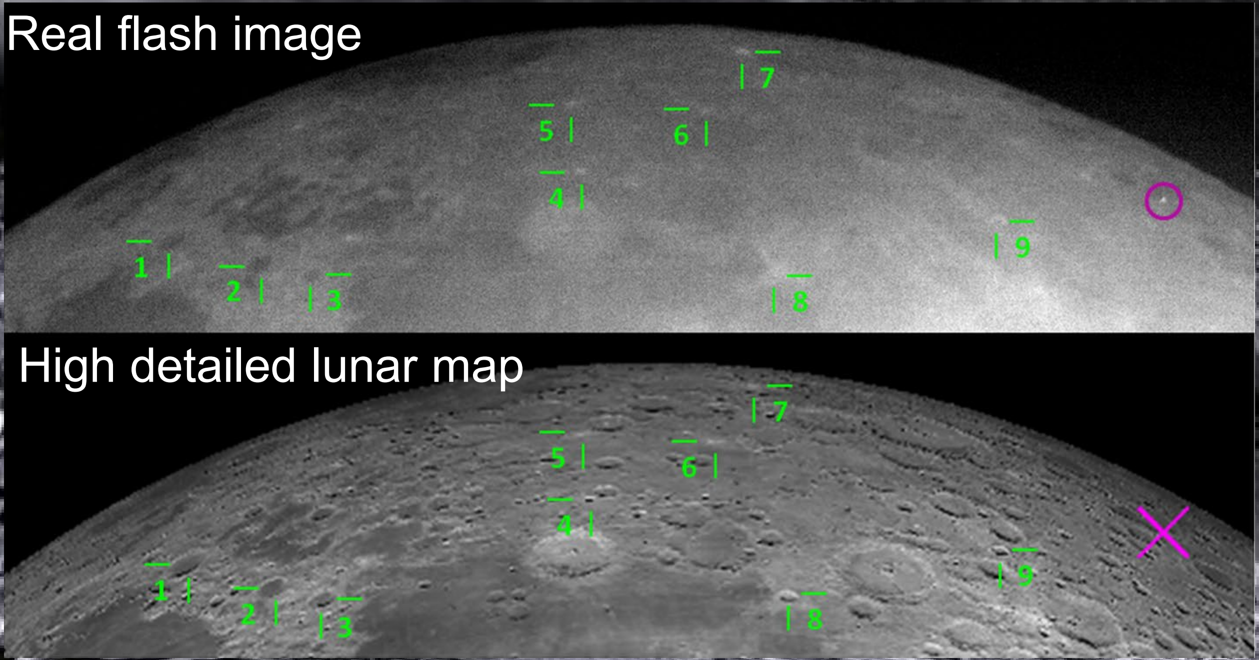
Real flash difference image

Standard star image

Localization

- Software tool
- Lunar features comparison between observed image and high detailed lunar map

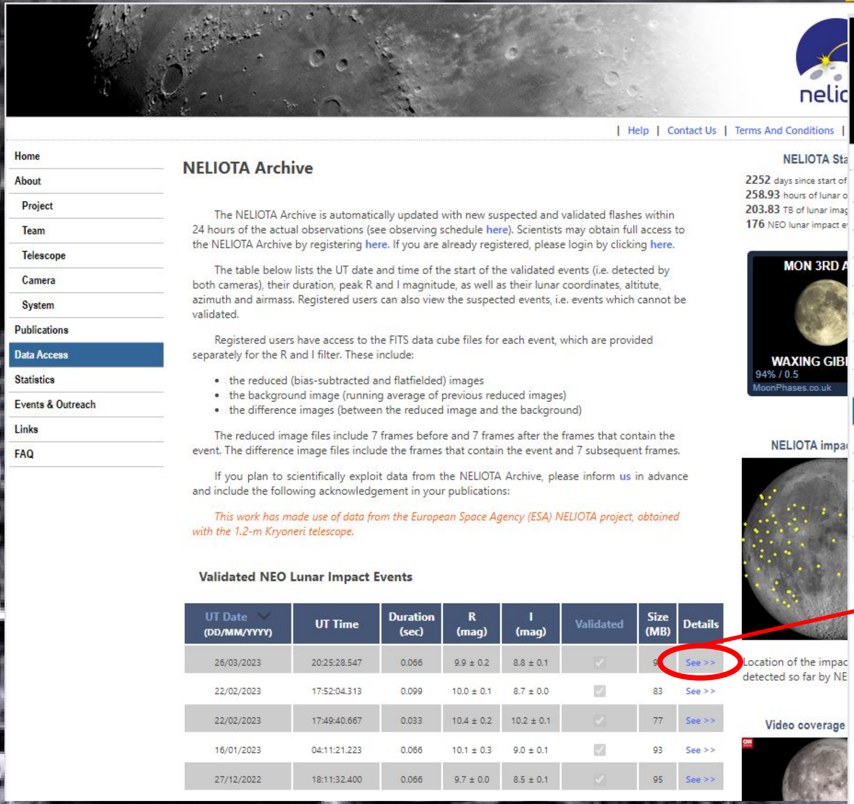
Expert user

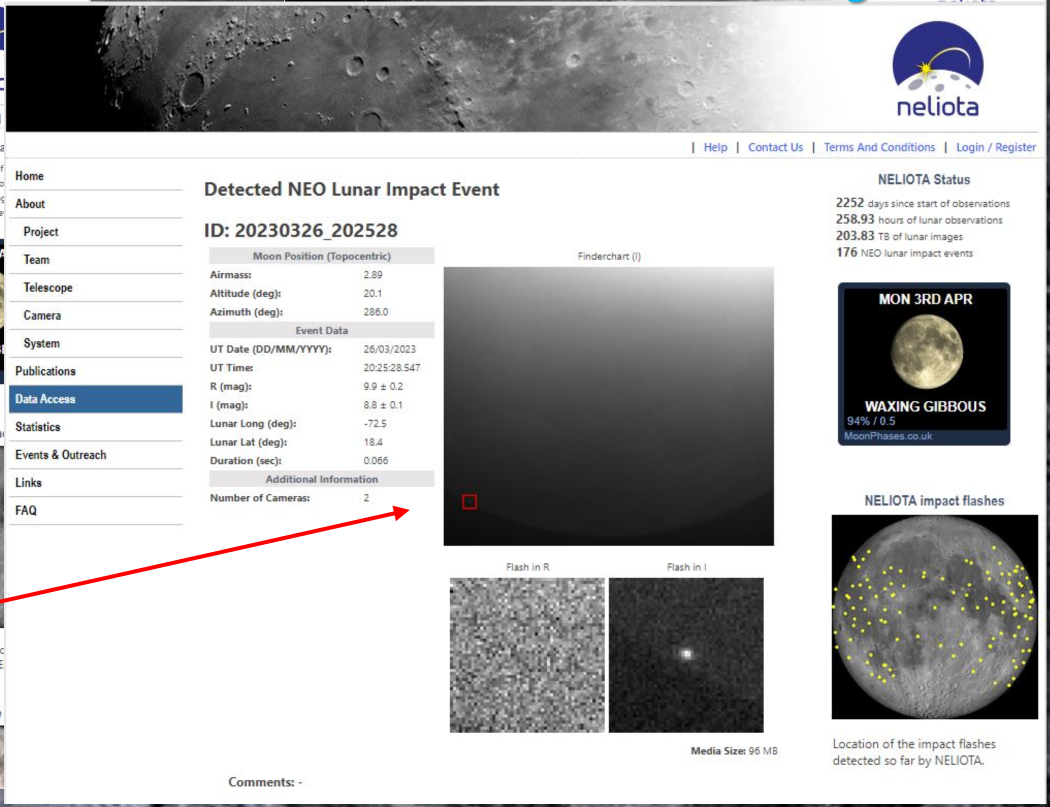


Web database

❖ Online database update } Expert user

www.neliota.astro.noa.gr





Web database

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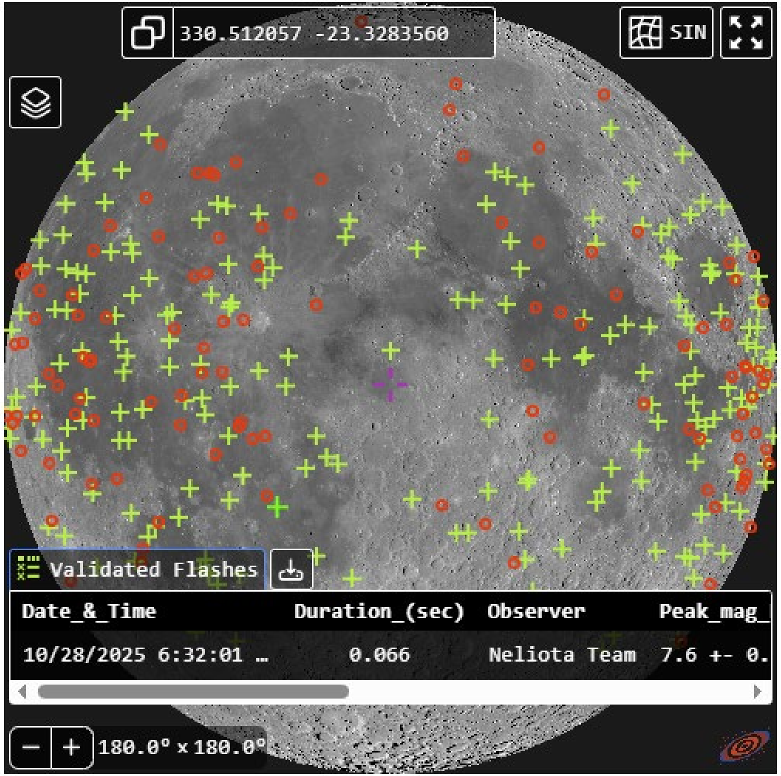
Event Statistics

Location of the impact flashes

Symbols
+ Validated
○ Suspected



Web database

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March 2026 - Global database

- ✓ External Observers data
- ✓ Validation by NELIOTA experts
- ✓ Observing sessions

Physical parameters

observations

- **Flux:** $f_\lambda = 10^{-(m-21.1-ZP)/2.5}$ (Bessell 1998)
- **Luminous energy:** $E_{lum} = f_\lambda \, \Delta\lambda \, f \, \pi d^2 t$ [J] (Suggs+2014)
- **Kinetic energy:** $KE = E_{lum} / \eta$ (Suggs+2014)
- **Mass:** $m = 2KE\,V^{-2}$
- **Radius:** $r = (3m/4\pi\rho_p)^{1/3}$
- **Crater diameter:** $D=0.25\rho_p^{0.167}\,\rho_m^{-0.5}\,g^{-0.165}\,KE^{0.29}\,\sin^{1/3}\theta$ (Melosh 1989)

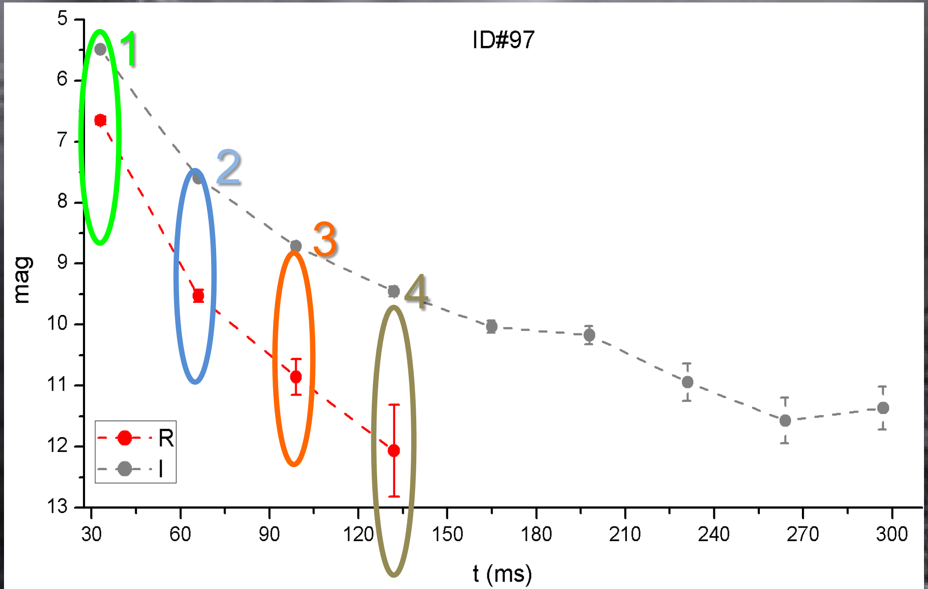
Critical

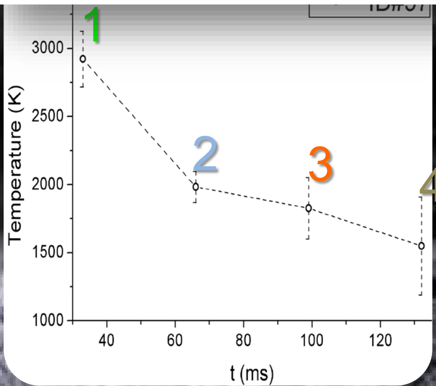
η -> estimated from meteor showers and lunar impact flashes from meteoroid streams

V → accurate only for streams but ranges between 17-24 km/s for sporadics

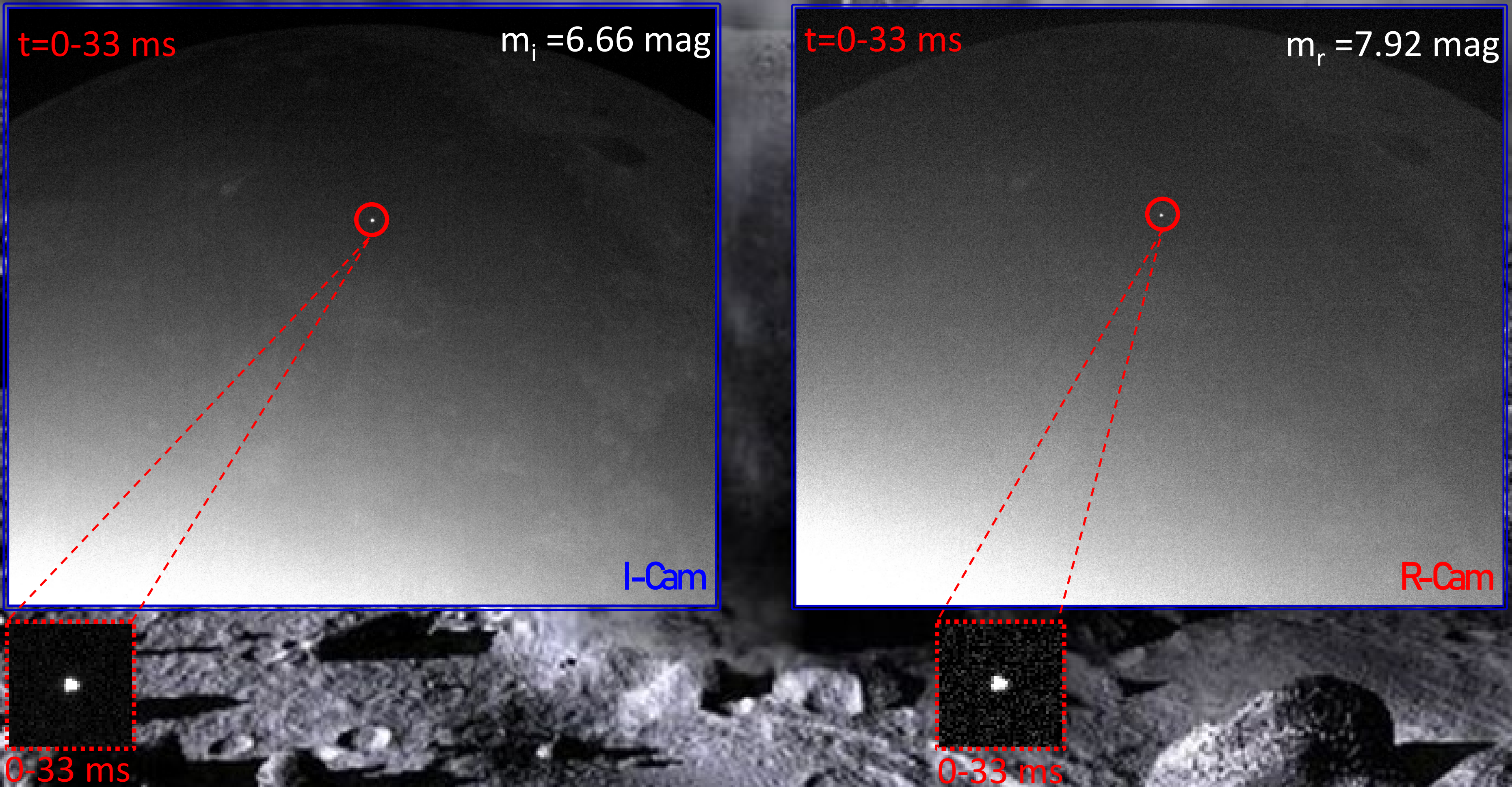
Temperature

$$\frac{F_R}{F_I} = \left(\frac{\lambda_I}{\lambda_R}\right)^5 \frac{e^{hc/k\lambda_R T} - 1}{e^{hc/k\lambda_I T} - 1}$$

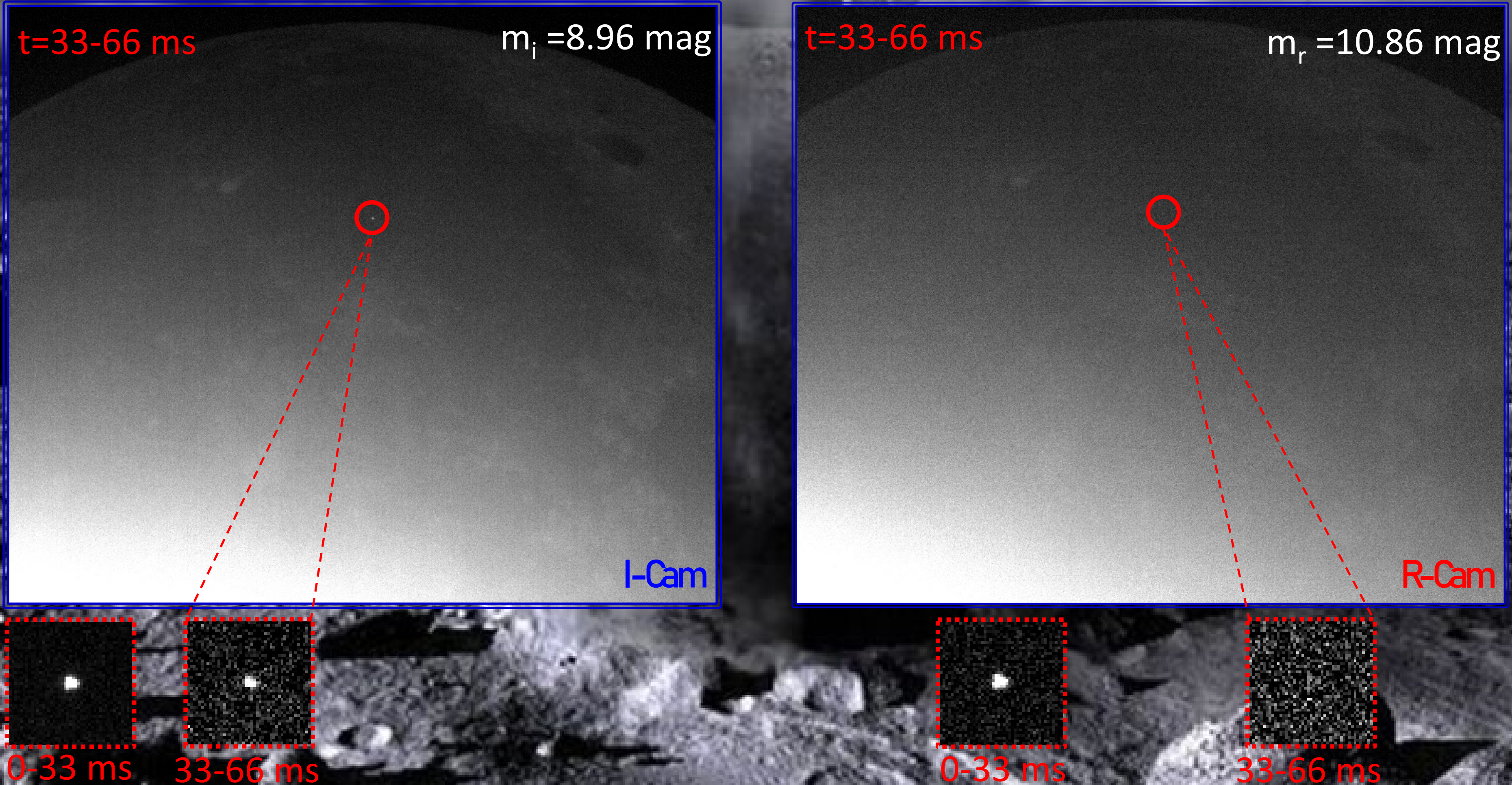




Data sample

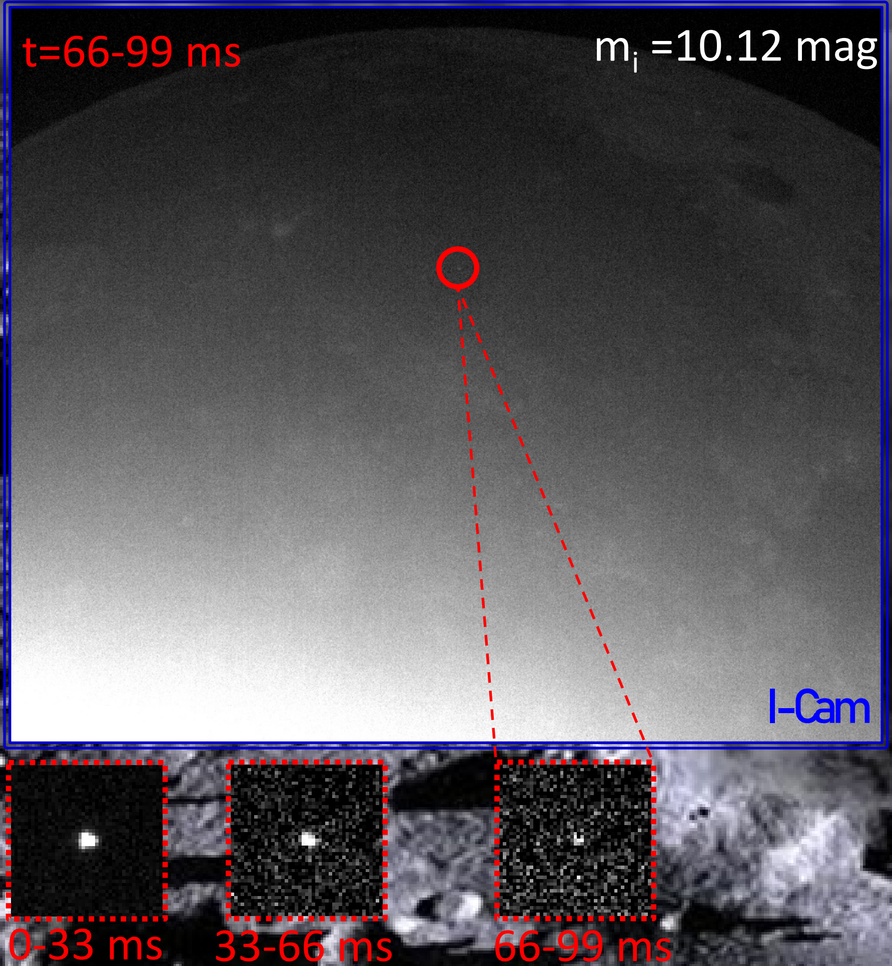


Data sample

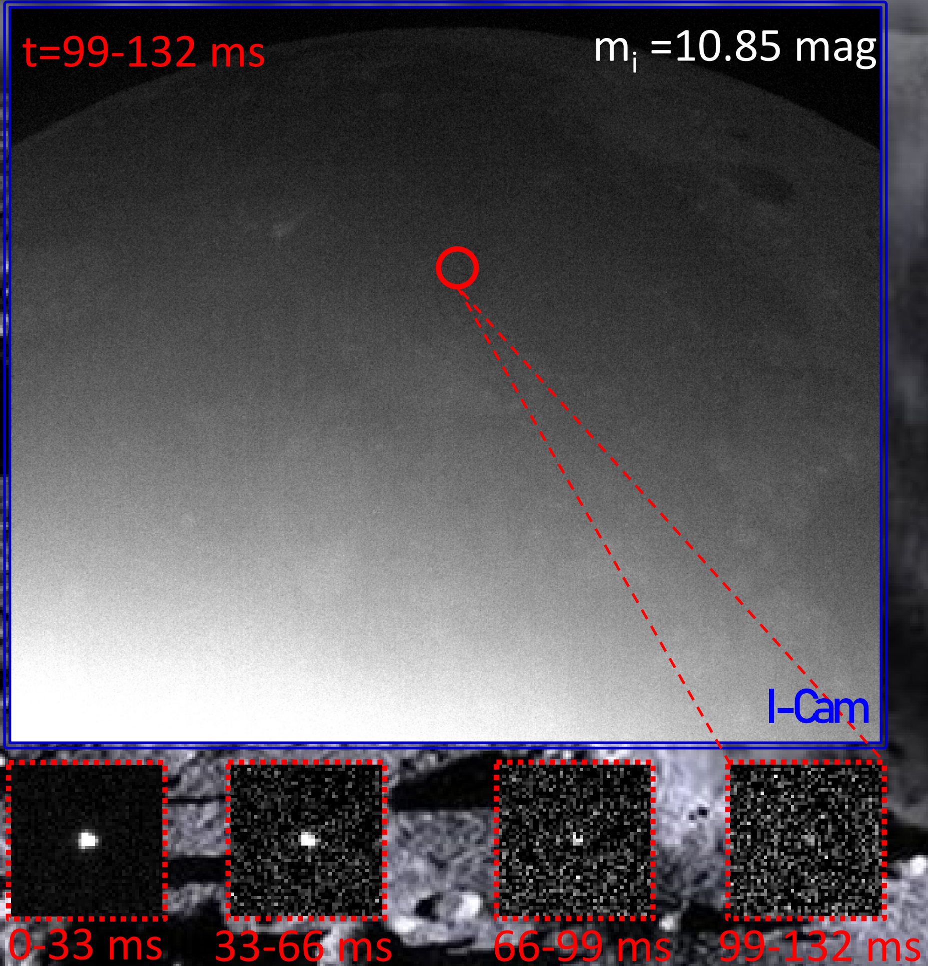


t=33-66 ms
m$_i$ =8.96 mag
I-Cam
0-33 ms
33-66 ms
t=33-66 ms
m$_r$ =10.86 mag
R-Cam
0-33 ms
33-66 ms

Data sample

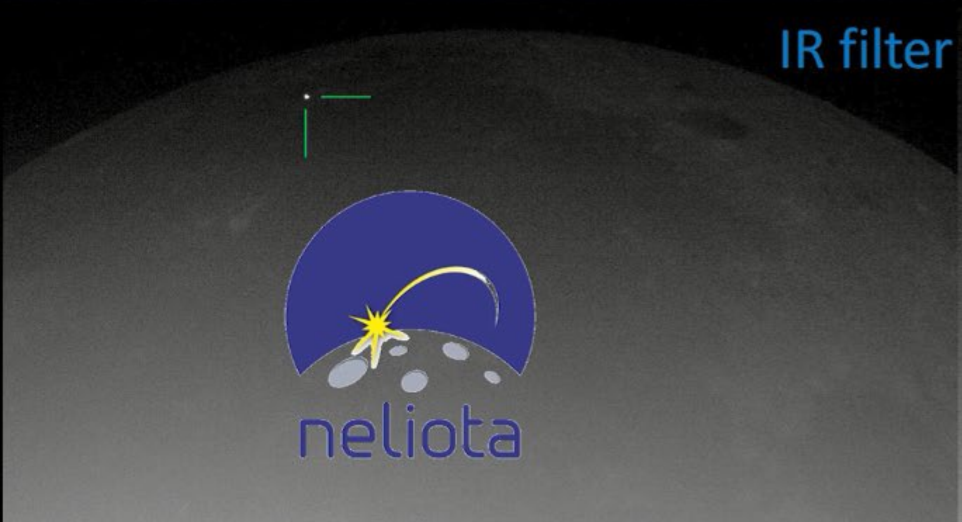


Data sample



Data sample

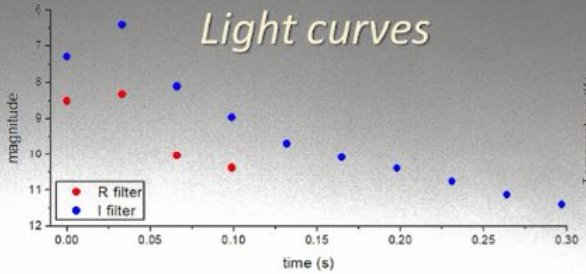
Data sample



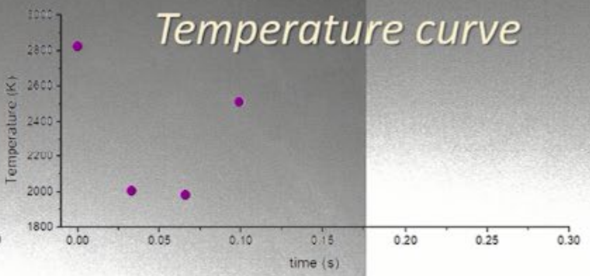
Parameters

Date/time: 2023 05 24 20:11:10.028 UT
I mag (peak) = 6.41 ± 0.08 mag
R mag (peak) = 8.32 ± 0.11 mag
Duration (max) = 0.330 s
Peak temperature = 2824 ± 237 K
Origin: Sporadic
Mass (for $\eta=1.5\times10^{-3}$) = 2.37 ± 0.04 kg
Radius (for $\eta=1.5\times10^{-3}$) = 13 ± 2 cm
Crater diameter (for $\eta=1.5\times10^{-3}$) = 5.3 ± 0.2 m

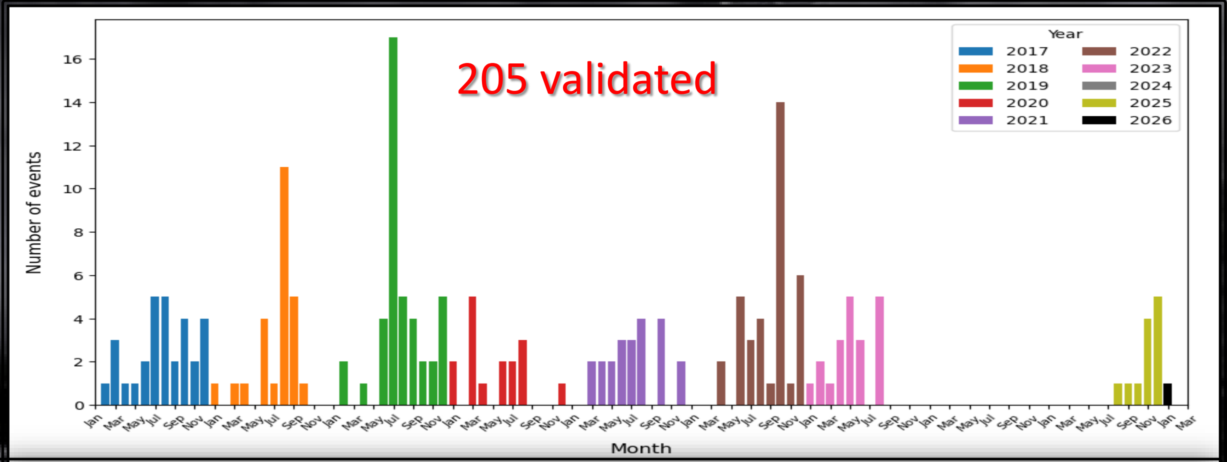
Light curves



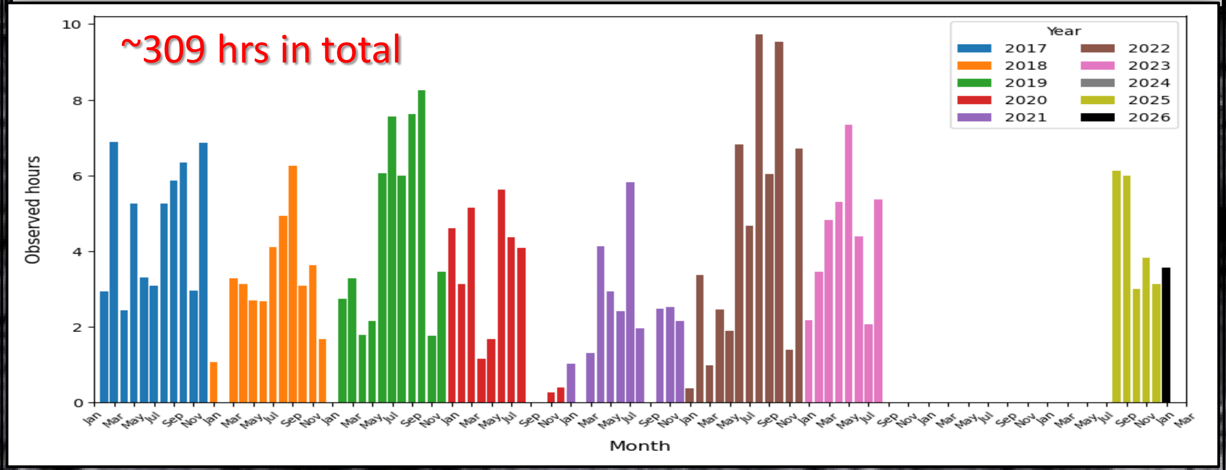
Temperature curve



Statistics

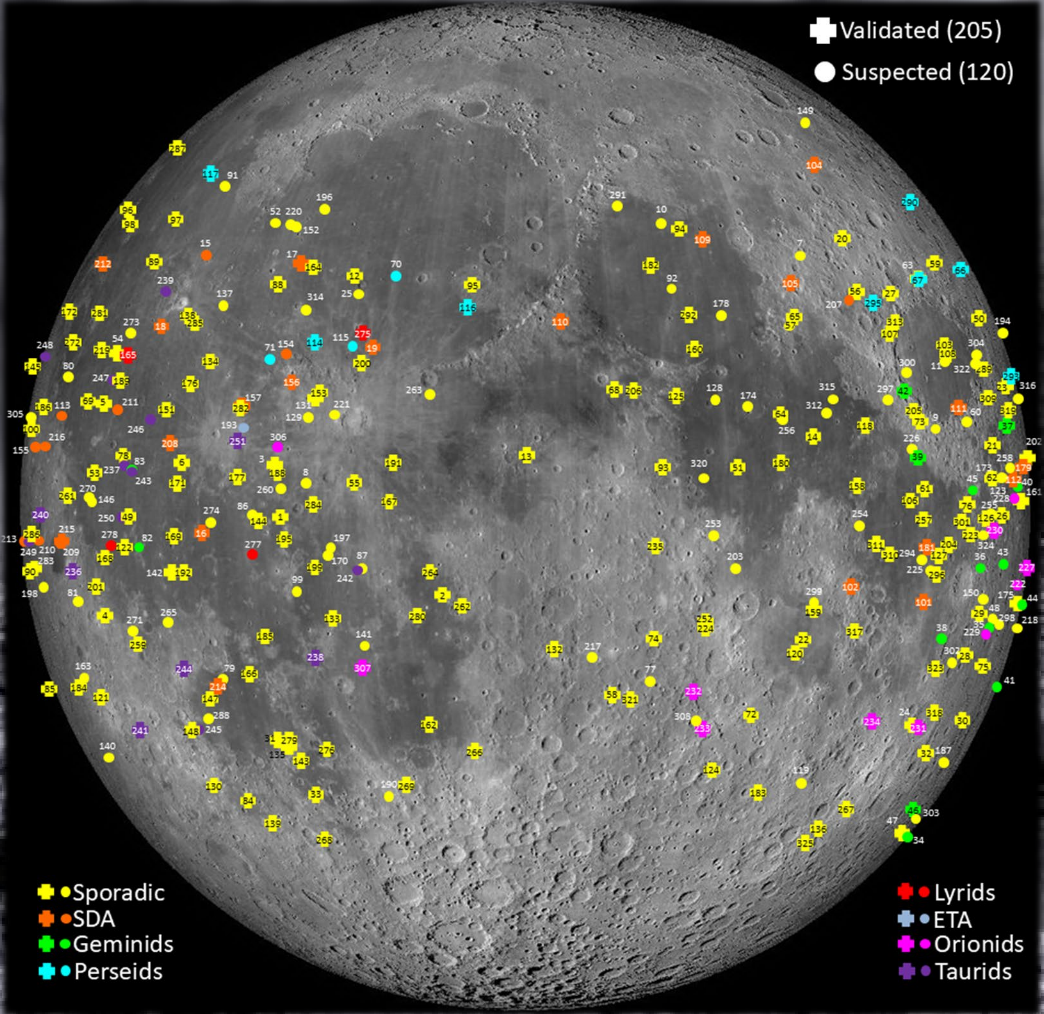


205 validated
Number of events
Month
Year
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

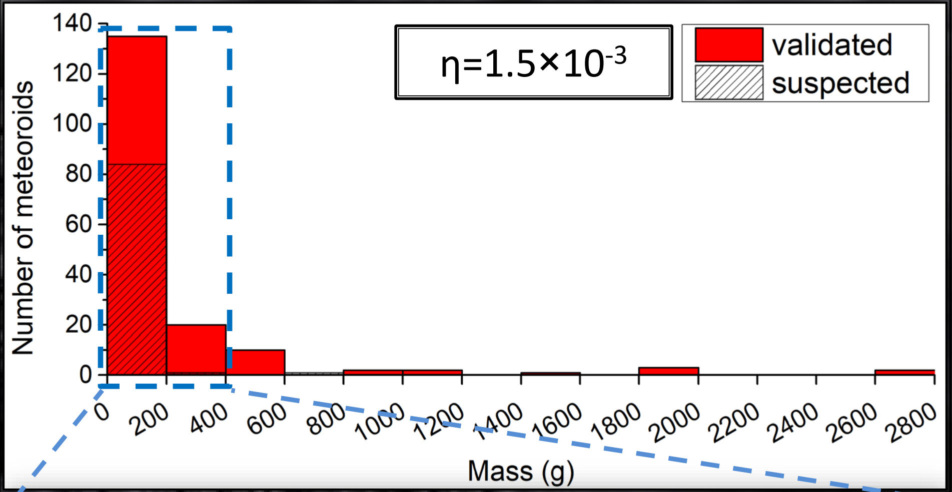


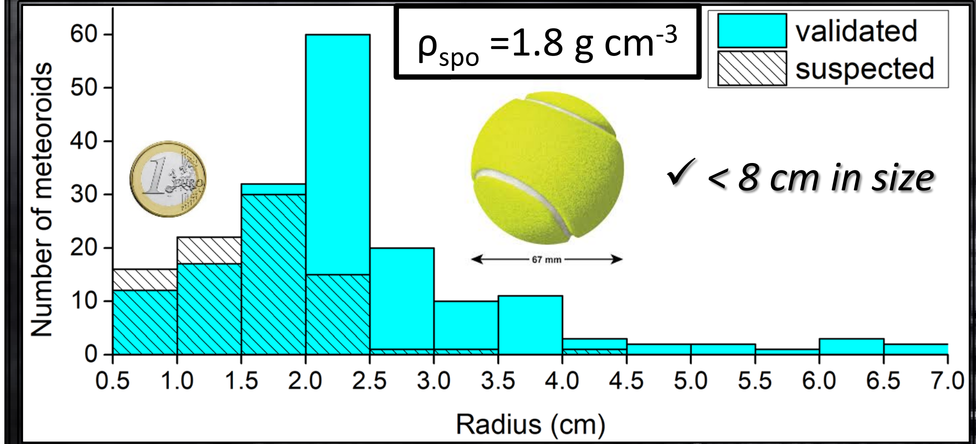
~309 hrs in total
Observed hours
Month
Year
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026

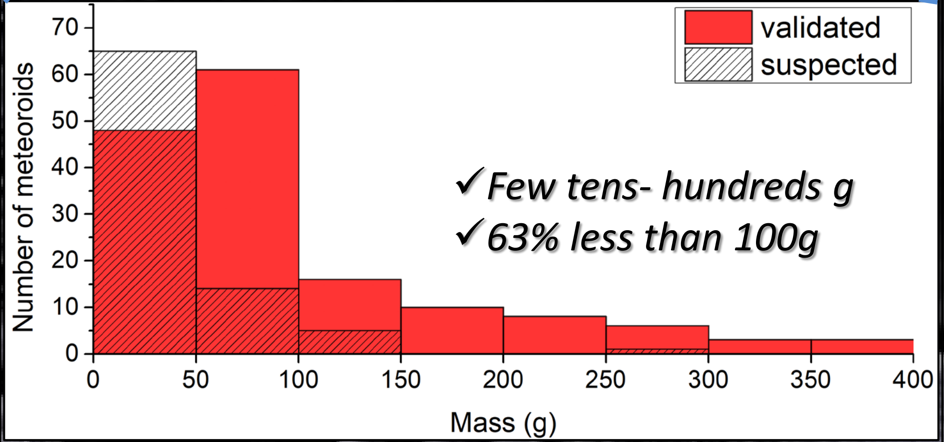
Localization

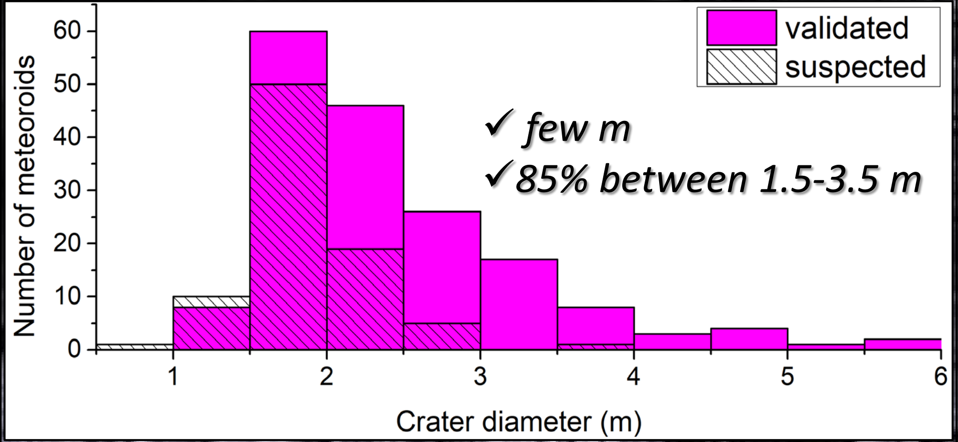


Physical parameters

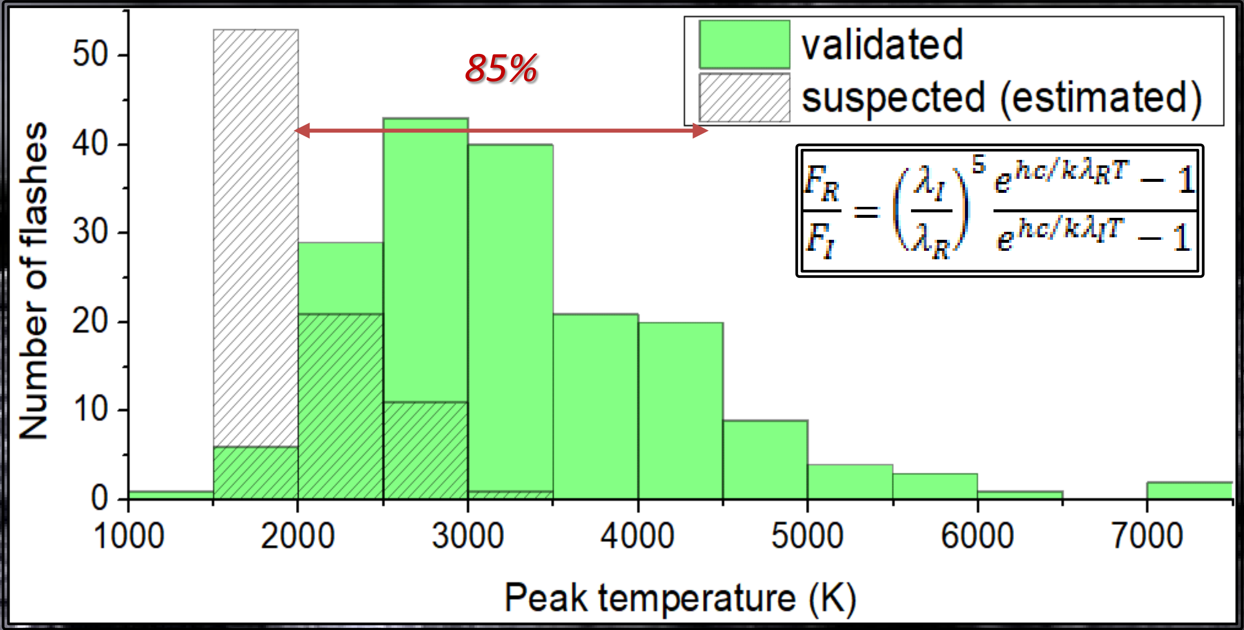




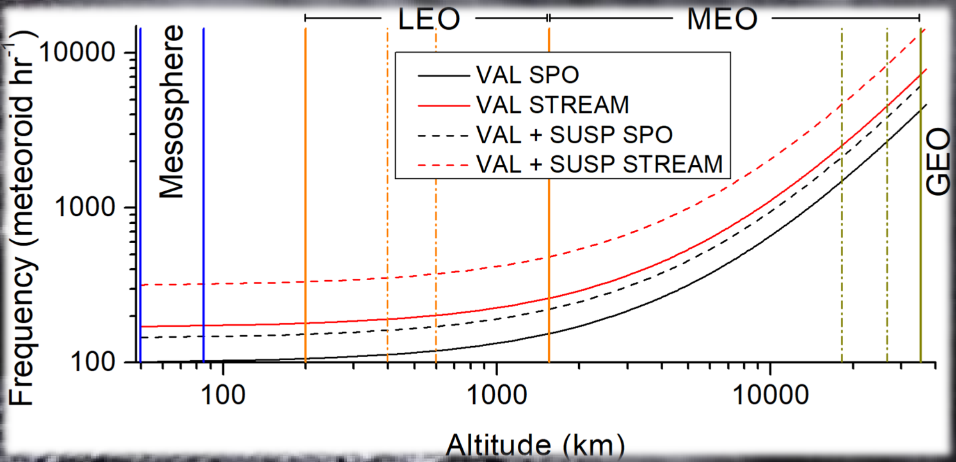




Peak temperatures and thermal evolution



Appearance frequency



In the FoV	Detection Rate (flash/hr)
Validated Sporadic	0.6
Validated Stream	1.0
Validated Total	0.7

Validated only

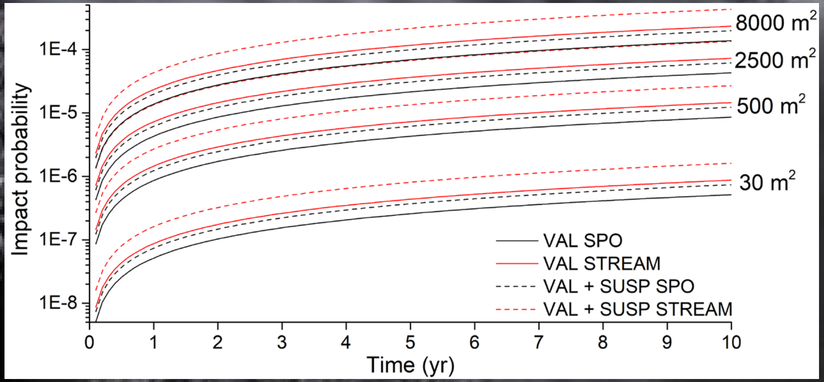
	Moon	Earth		
type	Surf	MS (90 km)	LEO (2000 km)	GEO (36000 km)
Sporadic	7.4	102	116	4420
Stream	12.6	173	197	7481

Validated+suspected

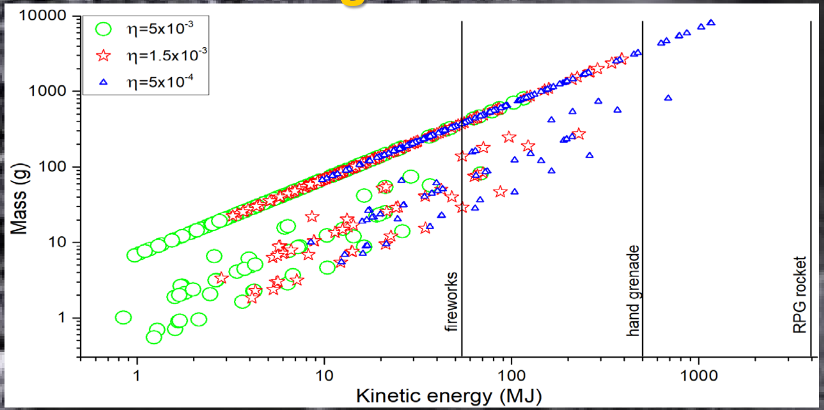
	Moon	Earth		
type	Surf	MS (90 km)	LEO (2000 km)	GEO (36000 km)
Sporadic	10.7	147	167	6341
Stream	23.3	321	364	13848

Appearance frequency

Collision probability

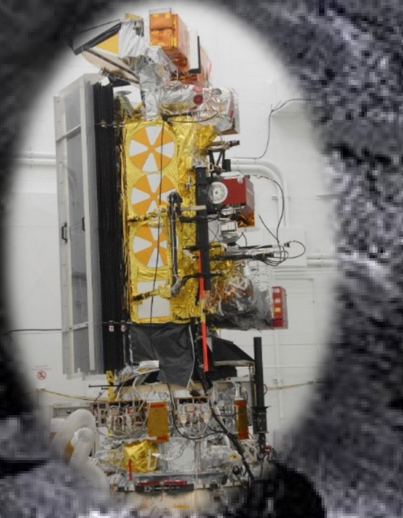


Damage assessment



Lunar base

ISS

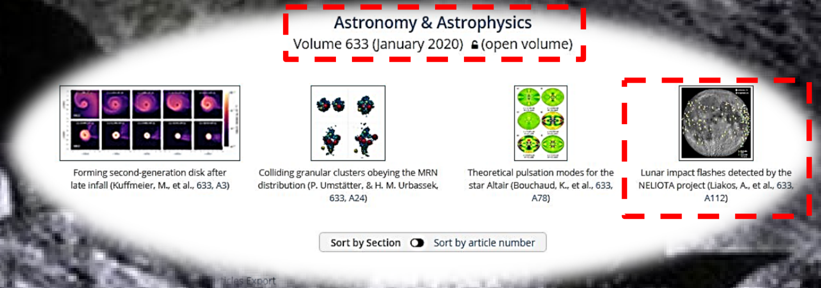


METEO SATELLITE

Publications

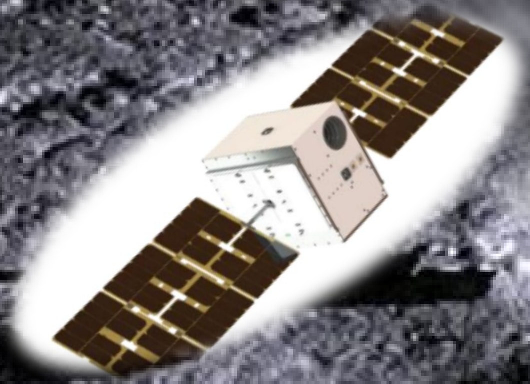
- ✓Bonanos et al., 2018, Astronomy & Astrophysics, 612, 76
  NELIOTA: First Temperature Measurement of Lunar Impact Flashes
- ✓Xilouris et al., 2018, Astronomy & Astrophysics, 619, 541
  NELIOTA: The wide field, high-cadence lunar monitoring system at the prime focus of the Kryoneri telescope
- ✓Liakos et al., 2020, Astronomy & Astrophysics, 633, 112
  NELIOTA: Methods, statistics and results for meteoroids impacting the Moon
- ✓Liakos et al., 2024, Astronomy & Astrophysics, 687, 14
  NELIOTA: New results and updated statistics after 6.5 years of lunar impact flashes monitoring

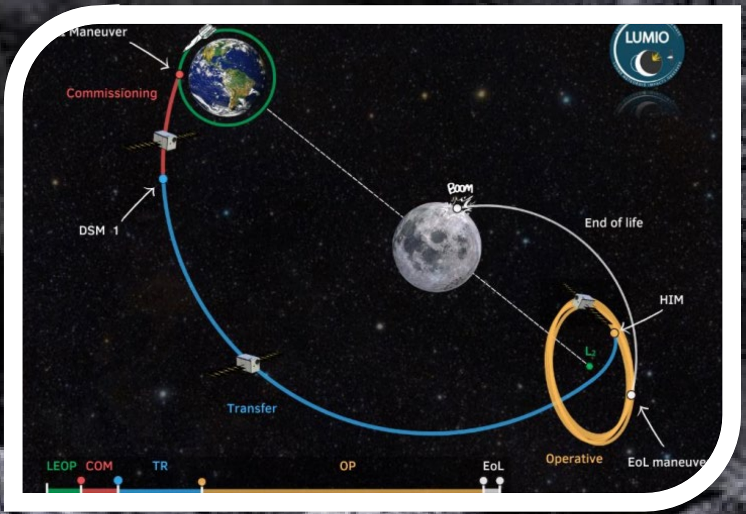
+5 more in conference proceedings



Synergy with ESA/LUMIO

- ESA – Politechnico Di Milano (IT), TU Delft (NL), EPFL (SZ), S&T (NO), Leonardo S.p.A (IT) and University of Arizona (US)
- Cubesat @ L2
- Observations on the far side of the Moon
- Beam splitter (R and I bands)
- 15-20 fps
- Launch: 2027?
- Liakos, Bonanos → members of the Science team
- Cervone+2022 & https://www.eoportal.org/satellite-missions/lumio





Take home notes

- *NELIOTA is the most efficient lunar impact flashes campaign to date*
- *The meteoroids have typical* ***masses*** *of* ***few tens of grams*** *and* ***sizes*** *of a* ***few cm***
- *The typical* ***temperatures*** *of impacts range between* ***2000-4500 K***
- ***Moon*** *is bombarded sporadically with a rate of* ***~7.5 met/hr****, while* ***Earth*** *with a rate of ~****100 met/h*** *(mesosphere→ meteors) and with a rate of ~****154 met/h*** *at LEO*

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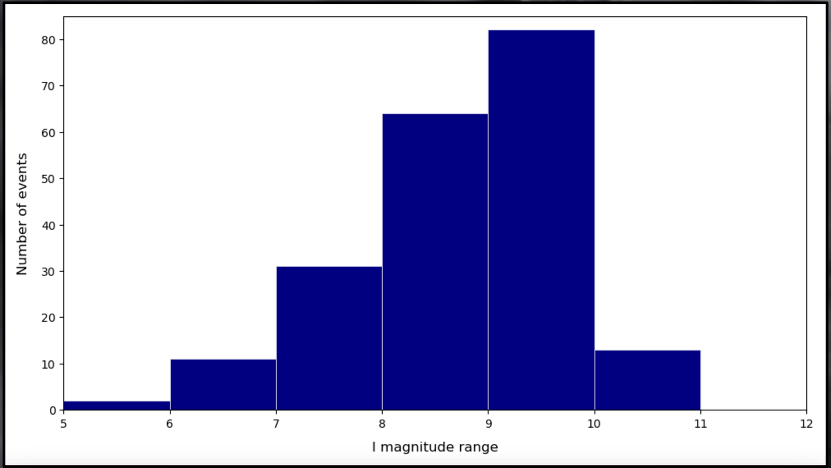
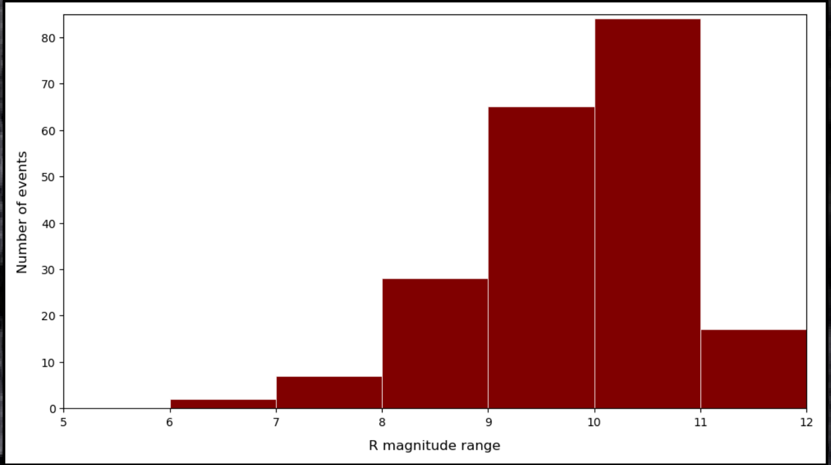
Statistics

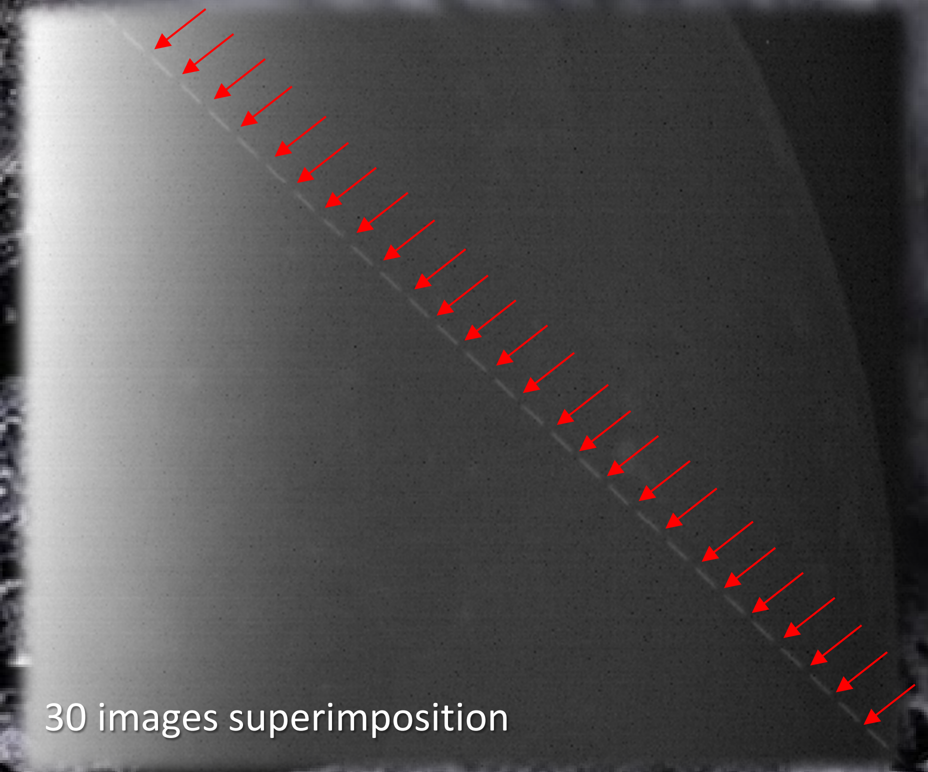


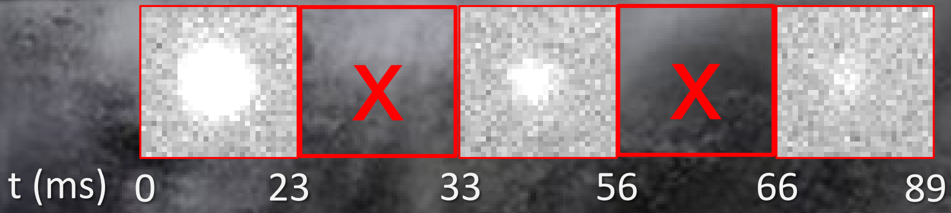
Number of events
I magnitude range
0
10
20
30
40
50
60
70
80
5
6
7
8
9
10
11
12

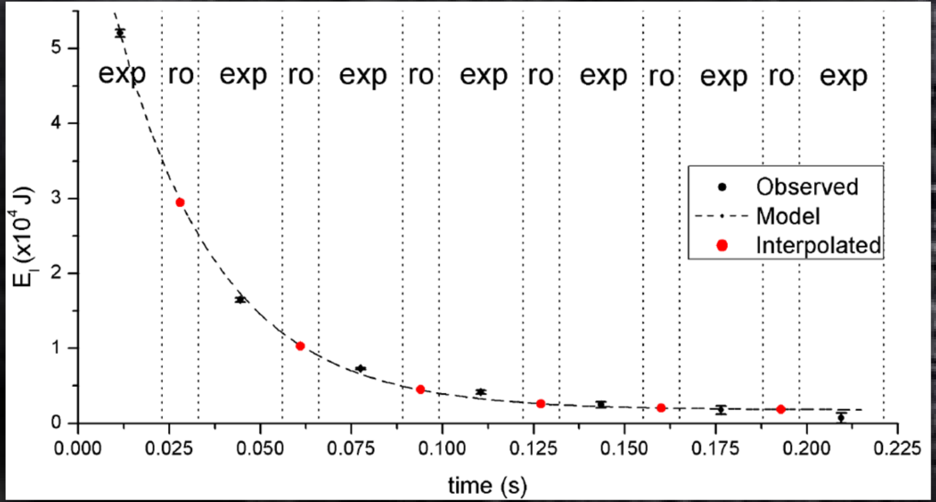


Number of events
R magnitude range
0
10
20
30
40
50
60
70
80
5
6
7
8
9
10
11
12

Lost energy + correction



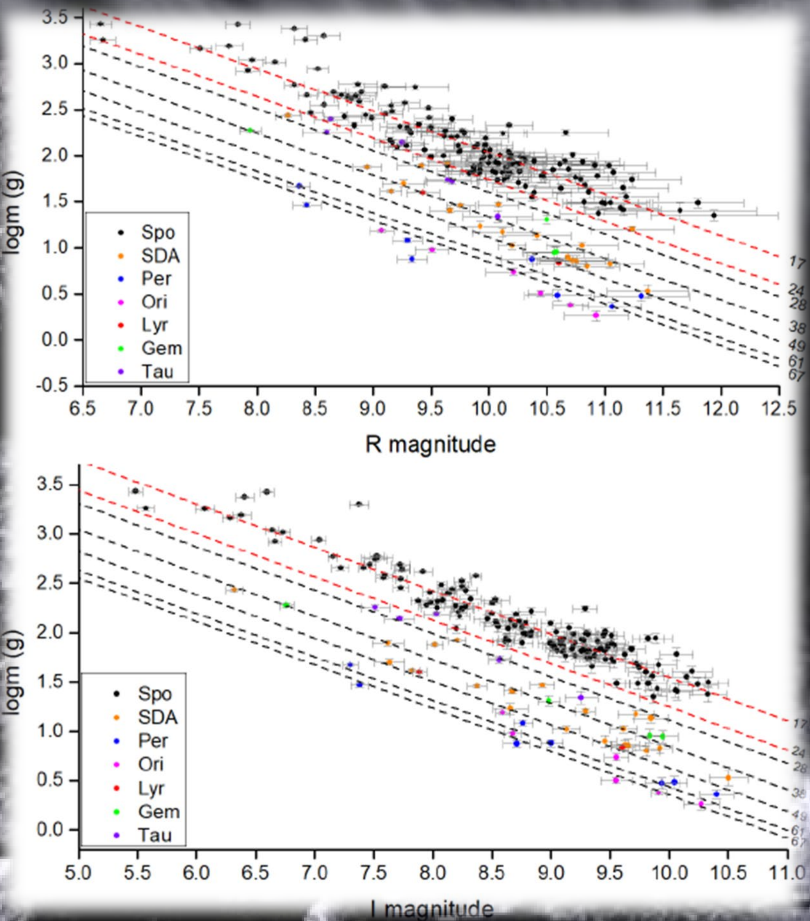


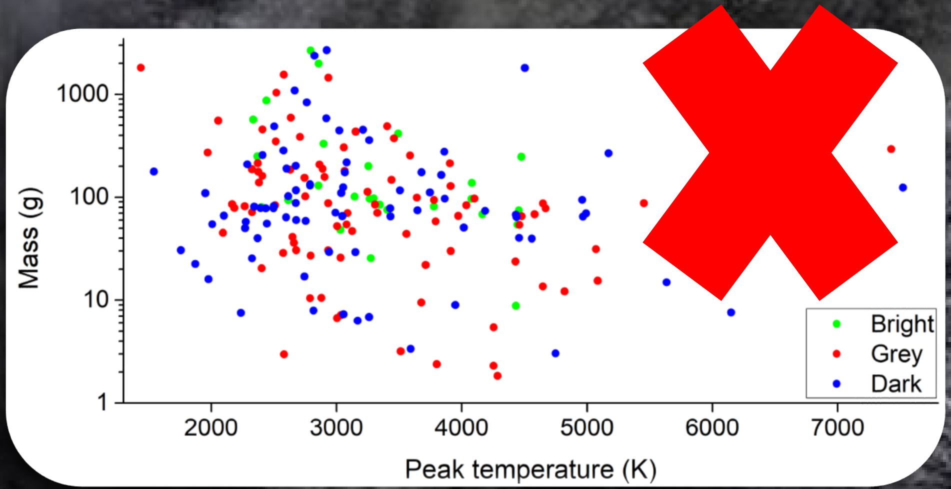


$$E_\lambda\,(\text{total}) = E_\lambda(t)\,\Big|_0^{t_1} + E_\lambda(t)\,\Big|_{t_1}^{t_1+t_{ro}} + \dots + E_\lambda(t)\,\Big|_{t_{n-1}+t_{ro}}^{t_n} \quad \text{in J}$$

Liakos+2020

Correlations





Evaluation of the events

- ❖ Orbit information from US Strategic Command (USSTRATCAM) and Github (B. Gray)
- ❖ Simplified General Perturbations (SGP4) orbit propagator
- ❖ SPICE library (JPL) for calculation of RA, Dec
- ❖MASTER/PROOF tool of ESA → statistical analysis (objects in the FoV for a given time period)