

NELIOTA: A long term monitoring campaign for lunar impact flashes

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J. L. Cano³, R. Moissl⁴, D. Athanasopoulos¹,
K. Fritzas^{1,5}, A. Maroussis¹, and
M. Devogèle⁴

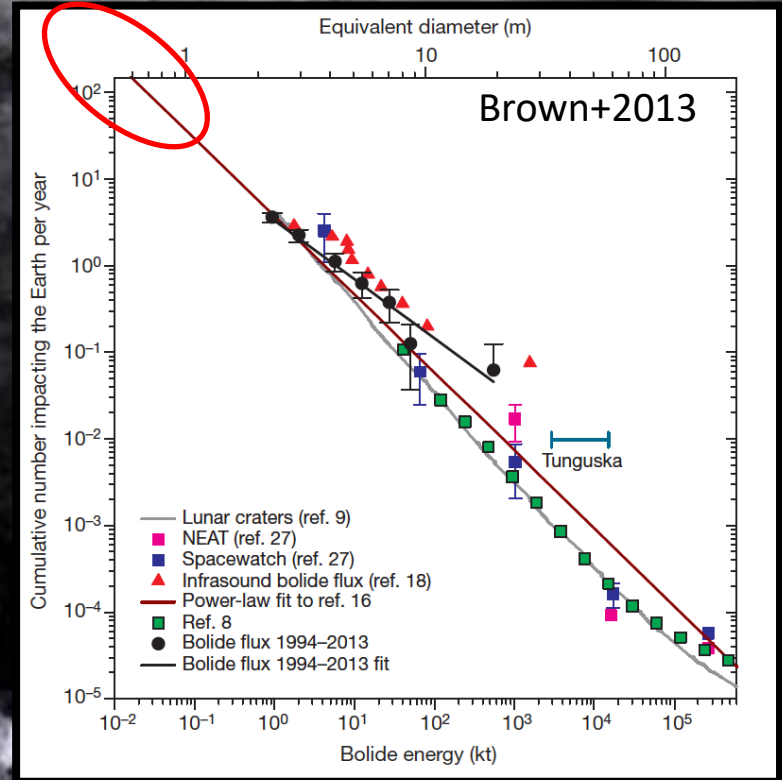
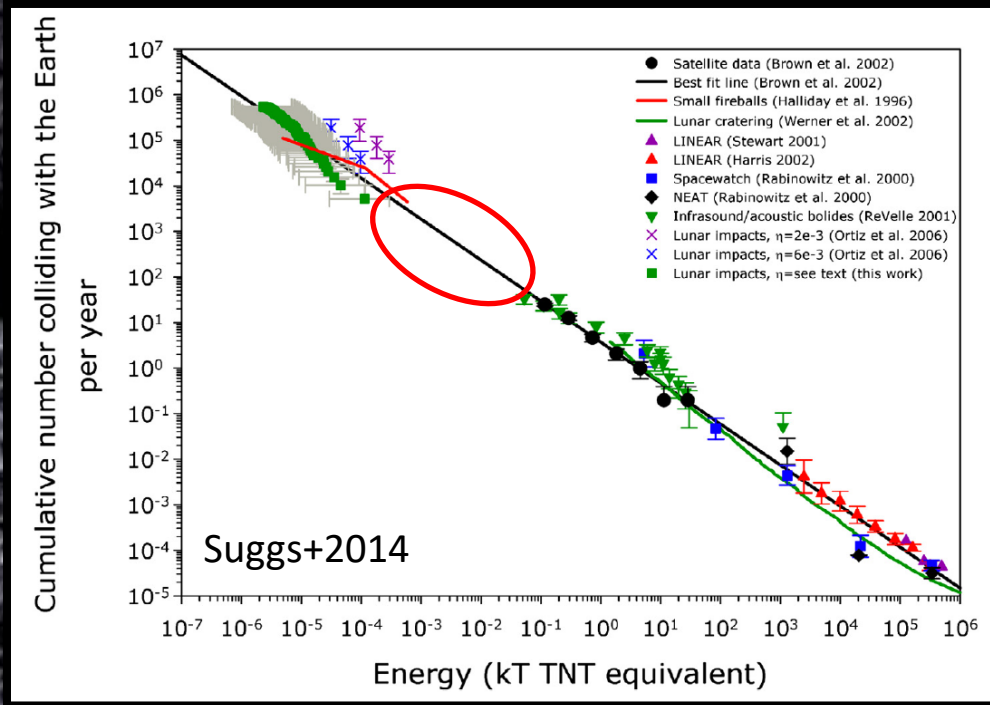


- ¹IAASARS, National Observatory of Athens, Greece
²Technical University of Munich, Germany
³ESOC/PDO, European Space Agency, Germany
⁴ESRIN/PDO/NEO CC, European Space Agency, Italy
⁵National Technical University of Athens, Greece



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

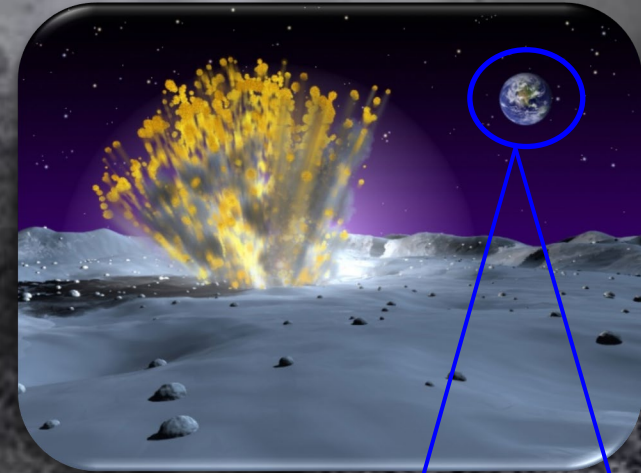


Why Moon?



Disadvantages of meteors observations

- ❖ Small area coverage ($\sim 60,000 \text{ km}^2$)
- ❖ 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 \rightarrow FLASH!
- ❖ Flash = Optical+IR radiation \rightarrow Recording using a telescope
- ❖ Large effective area $\rightarrow \sim 19 \times 10^6 \text{ km}^2$ (Side facing Earth)





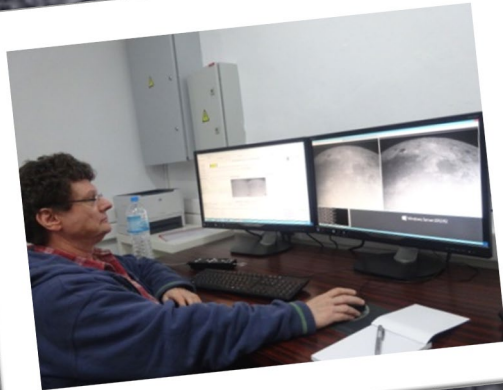
Near Earth objects Lunar Impacts and Optical TrAnsients



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

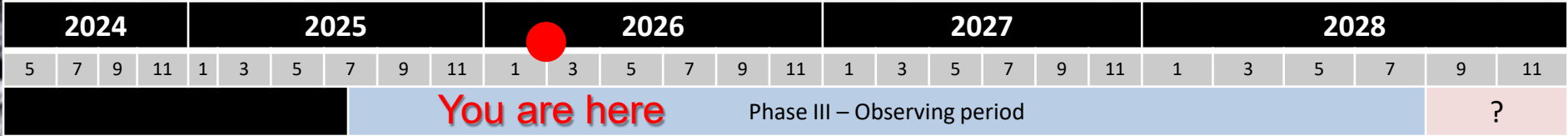
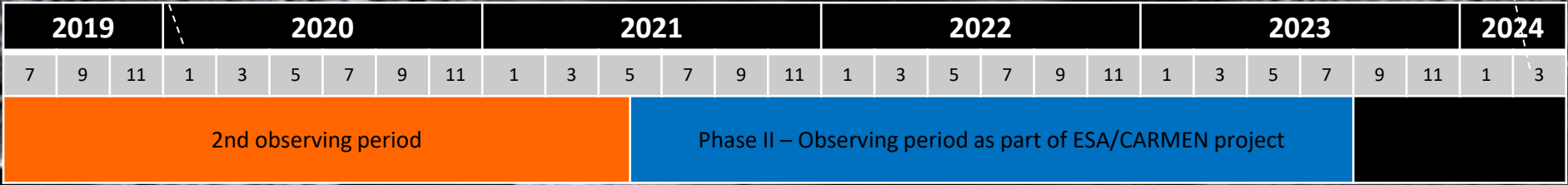
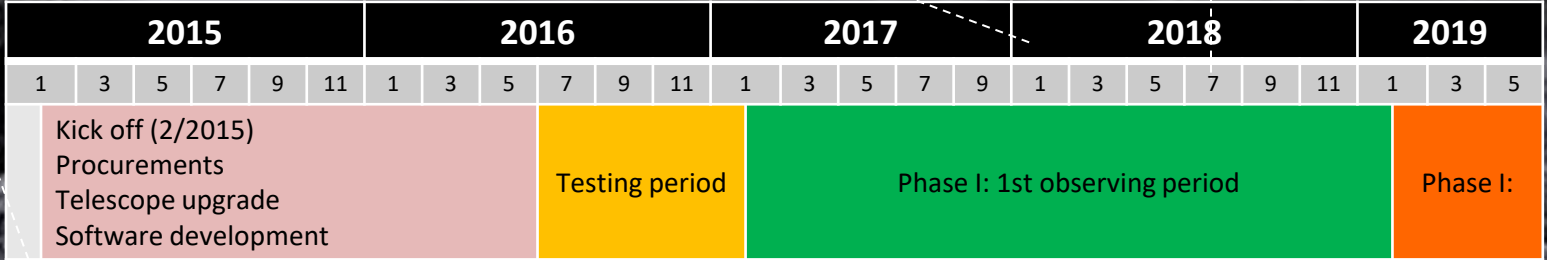


Paper I: Bonanos+ 2018

Paper II: Xilouris+ 2018

Paper IV: Liakos+ 2024

Paper III: Liakos+ 2020



Team 2015-2023



**Principal Investigator
& Project manager**
Dr Alceste Bonanos



**Director of Kryoneri
Observatory**
Dr Manolis Xilouris



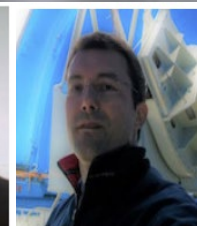
**Telescope astronomical
support**
Dr John Alikakos



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 Dapergolos
(retired)



Technical support
Mr George Dimou (retired)



Software Engineer
Mr Anastasios Fytisilis

Team 2025-2028

Team



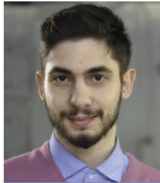
Principal Investigator
&
Technical manager
Dr Alexios Liakos



Project Manager
Dr Alceste Bonanos



IT Manager
Dr Athanasios Maroussis



Postdoctoral Researcher
Dr Dimitrios Athanasopoulos



Software Engineer
Mr Kosmas Fritzas

ESA Staff



Technical Officer
of NELIOTA-III
Mr Juan Luis Cano González



Head of ESA's
Planetary Defence Office
Dr Richard Moissl



NEO Observer
Dr Maxime Devogele

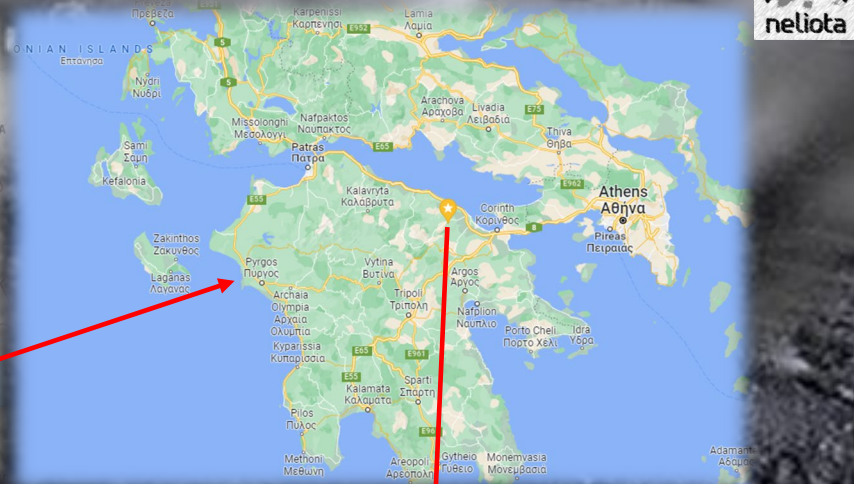
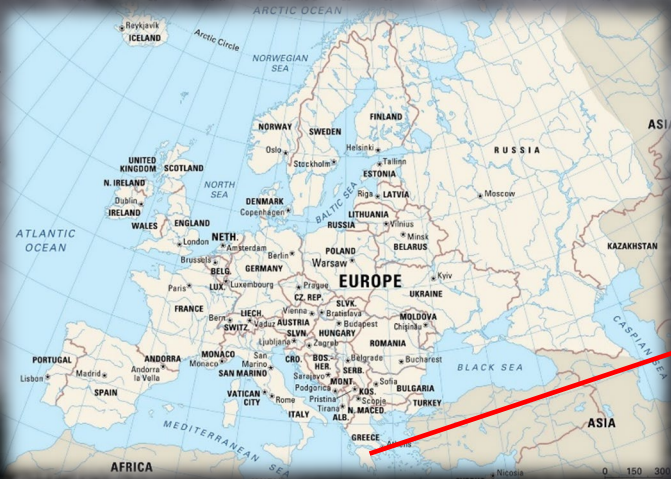


Dr D. Koschny

(Planetary Scientist, Technical Univ. of Munich)

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

Location

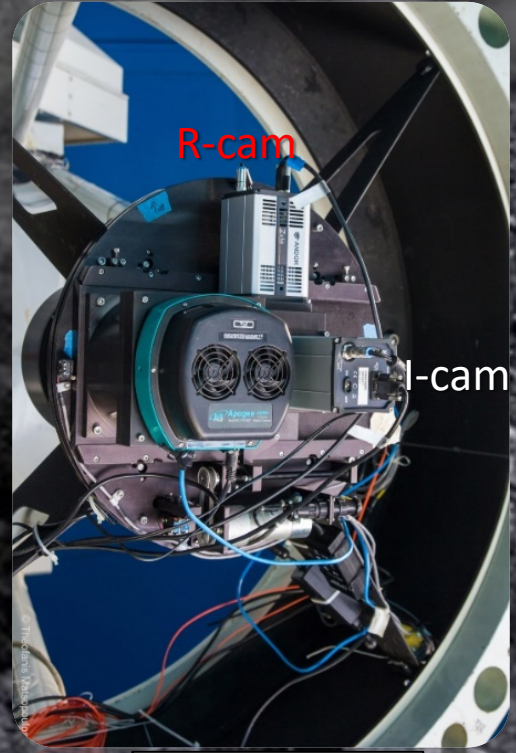


- ❖ South-East Europe
- ❖ Corinthia, Northern Peloponnese, Greece
- ❖ Altitude: 930 m
- ❖ ~120 km west of Athens
- ❖ ~200 clear nights per year
- ❖ Accessible during all seasons
- ❖ Established in 1972 – Upgraded in 2015

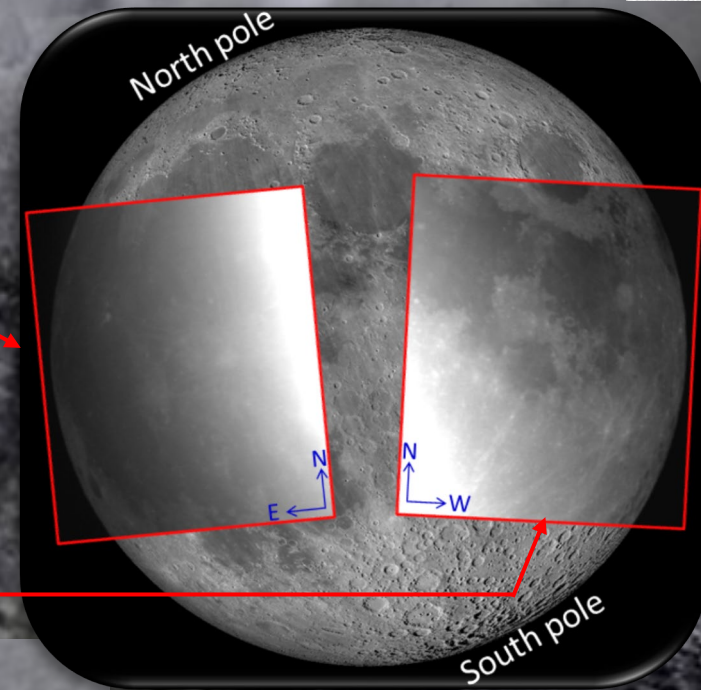
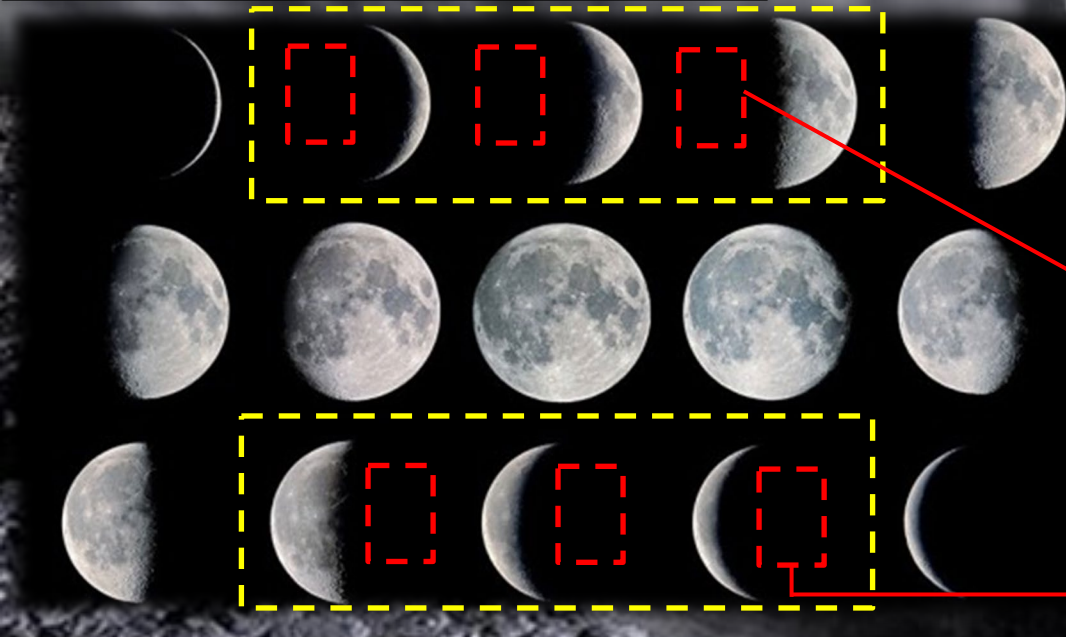


Infrastructure

- ❖ 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



Observing strategy



- ❖ Non-sunlit (night) side
- ❖ Phases between 0.1-0.45 \rightarrow \sim 5-8 nights/month \rightarrow 20' - 5 hr
- ❖ Simultaneous recording in R and I bands with 30 fps (23 ms exposures)
- ❖ Moon elevation $>$ \sim 12 deg

FoV: 16' \times 14.4'
<Observable area>: 3×10^6 km²

Data reduction and event detections

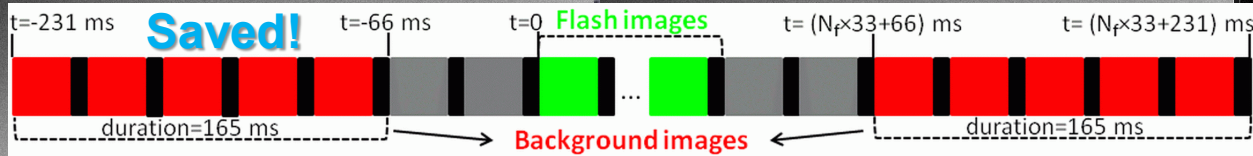
- ❖ Image calibration (flat dark)
- ❖ Lunar background subtraction
- ❖ Events detection

Software pipeline

Random Image

Time-weighted background image

Difference image



Detection!!

Evaluation of the events

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

Slow-moving satellite

Flash-like shape

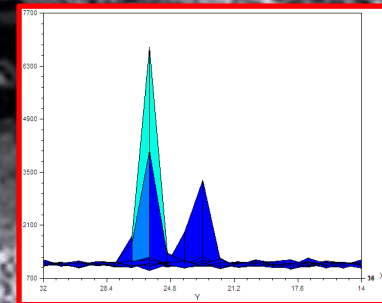
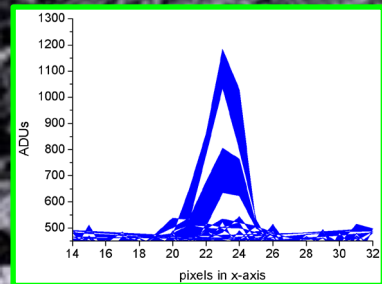
Flash

Cosmic ray

95% of the
nightly
detections

Fast-moving satellite

Streak shape



Data analysis

❖ Aperture photometry

❖ Magnitude calculation (standard stars)

Expert user

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

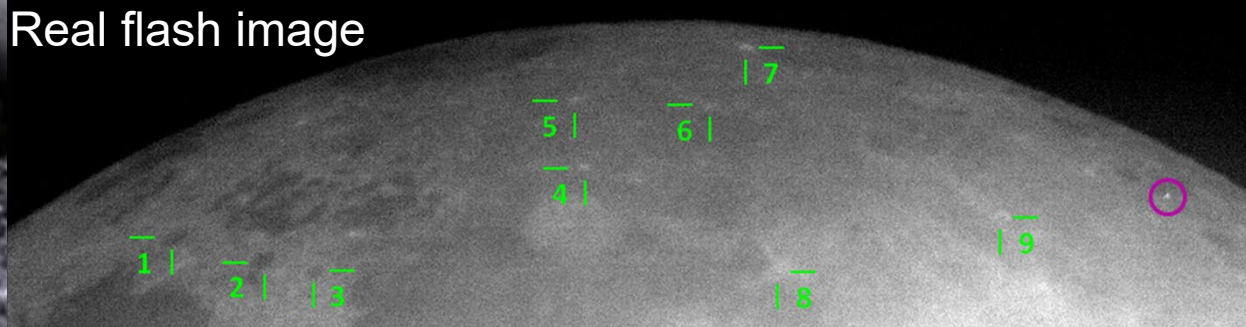


Localization

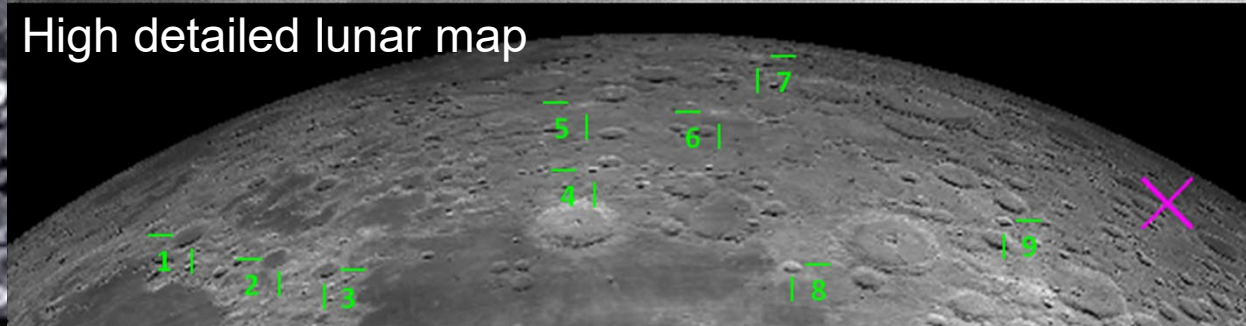
- ❖ Software tool
- ❖ Lunar features comparison between observed image and high detailed lunar map

Expert user

Real flash image



High detailed lunar map



❖ Online database update

Expert user

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NELIOTA Archive

2252 days since start of observations
258.93 hours of lunar observations
203.83 TB of lunar images
176 NEO lunar impact events

The NELIOTA Archive is automatically updated with new suspected and validated flashes within 24 hours of the actual observations (see observing schedule [here](#)). Scientists may obtain full access to the NELIOTA Archive by registering [here](#). If you are already registered, please login by clicking [here](#).

The table below lists the UT date and time of the start of the validated events (i.e. detected by both cameras), their duration, peak R and I magnitude, as well as their lunar coordinates, altitude, azimuth and airmass. Registered users can also view the suspected events, i.e. events which cannot be validated.

Registered users have access to the FITS data cube files for each event, which are provided separately for the R and I filter. These include:

- the reduced (bias-subtracted and flatfielded) images
- the background image (running average of previous reduced images)
- the difference images (between the reduced image and the background)

The reduced image files include 7 frames before and 7 frames after the frames that contain the event. The difference image files include the frames that contain the event and 7 subsequent frames.

If you plan to scientifically exploit data from the NELIOTA Archive, please inform us in advance and include the following acknowledgement in your publications:

This work has made use of data from the European Space Agency (ESA) NELIOTA project, obtained with the 1.2-m Kryoneri telescope.

Validated NEO Lunar Impact Events

UT Date (DD/MM/YYYY)	UT Time	Duration (sec)	R (mag)	I (mag)	Validated	Size (MB)	Details
26/03/2023	20:25:28.547	0.066	9.9 ± 0.2	8.8 ± 0.1	<input checked="" type="checkbox"/>	83	See >>
22/02/2023	17:52:04.313	0.099	10.0 ± 0.1	8.7 ± 0.0	<input checked="" type="checkbox"/>	83	See >>
22/02/2023	17:49:40.667	0.033	10.4 ± 0.2	10.2 ± 0.1	<input checked="" type="checkbox"/>	77	See >>
16/01/2023	04:11:21.223	0.066	10.1 ± 0.3	9.0 ± 0.1	<input checked="" type="checkbox"/>	93	See >>
27/12/2022	18:11:32.400	0.066	9.7 ± 0.0	8.5 ± 0.1	<input checked="" type="checkbox"/>	95	See >>

Detected NEO Lunar Impact Event

ID: 20230326_202528

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NELIOTA Status
2252 days since start of observations
258.93 hours of lunar observations
203.83 TB of lunar images
176 NEO lunar impact events

MON 3RD APR WAXING GIBBOUS
94% / 0.5
MoonPhases.co.uk

MON 3RD APR WAXING GIBBOUS
94% / 0.5
MoonPhases.co.uk

NELIOTA impact flashes

Location of the impact detected so far by NELIOTA.

Location of the impact flashes detected so far by NELIOTA.

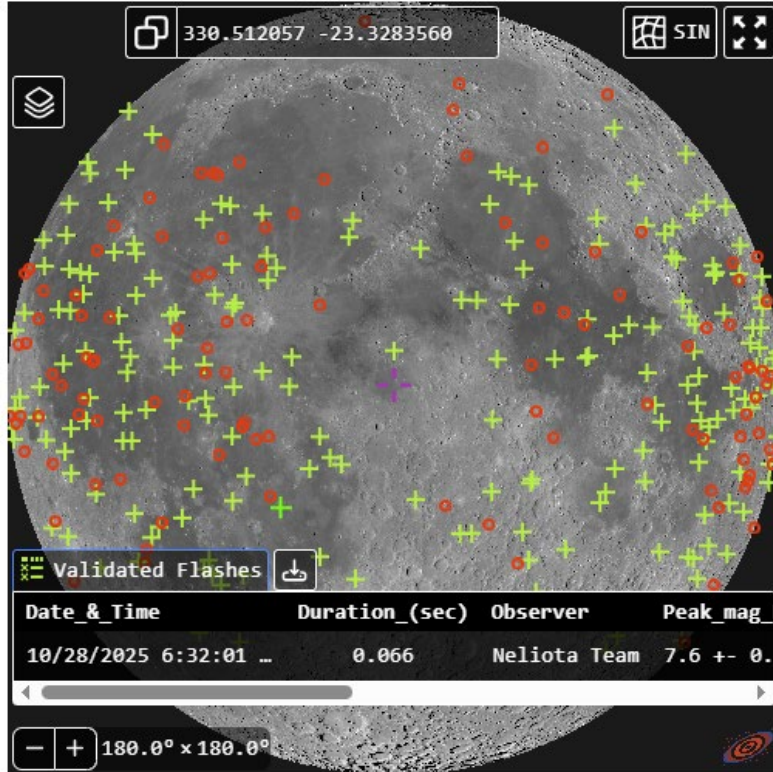
Media Sizes 96 MB

Comments: -

Event Statistics

Location of the impact flashes

Symbols
+ Validated
○ Suspected



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)

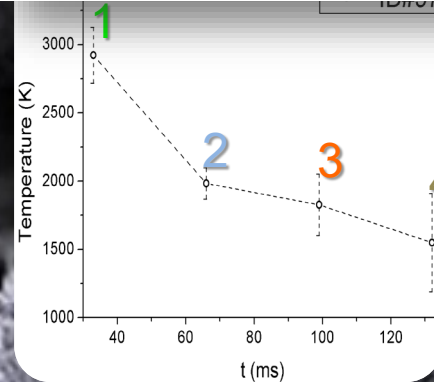
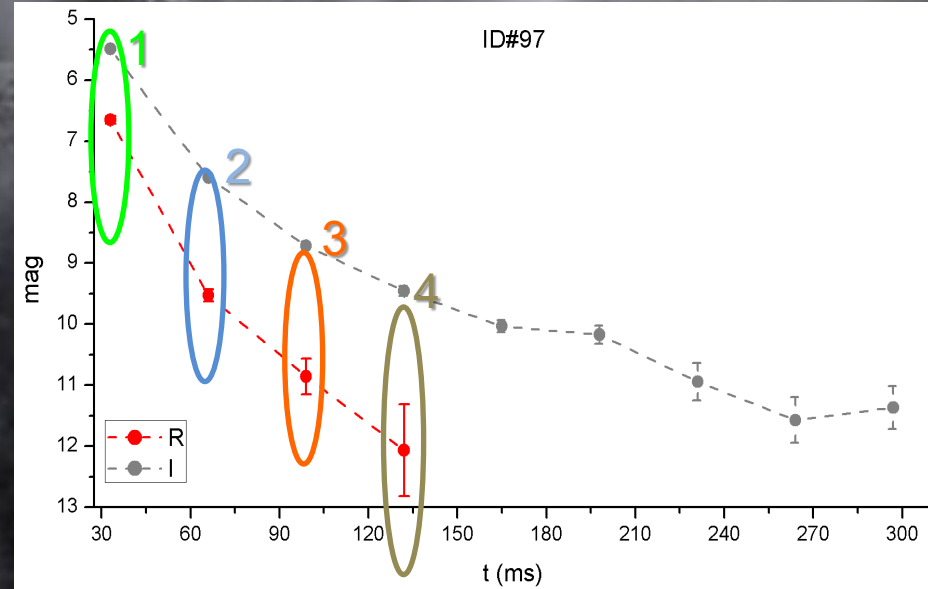
Critical

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

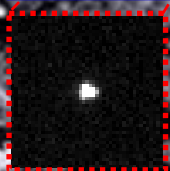
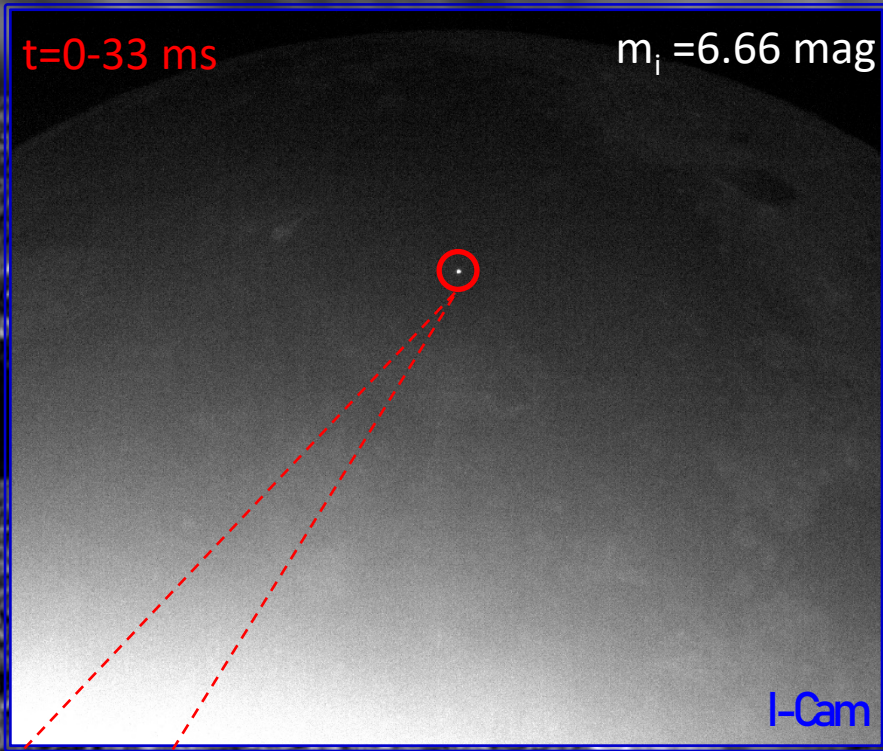
$$\frac{F_R}{F_I} = \left(\frac{\lambda_I}{\lambda_R}\right)^5 \frac{e^{hc/k\lambda_R T} - 1}{e^{hc/k\lambda_I T} - 1}$$



Data sample

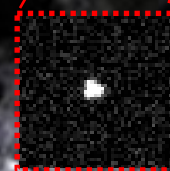
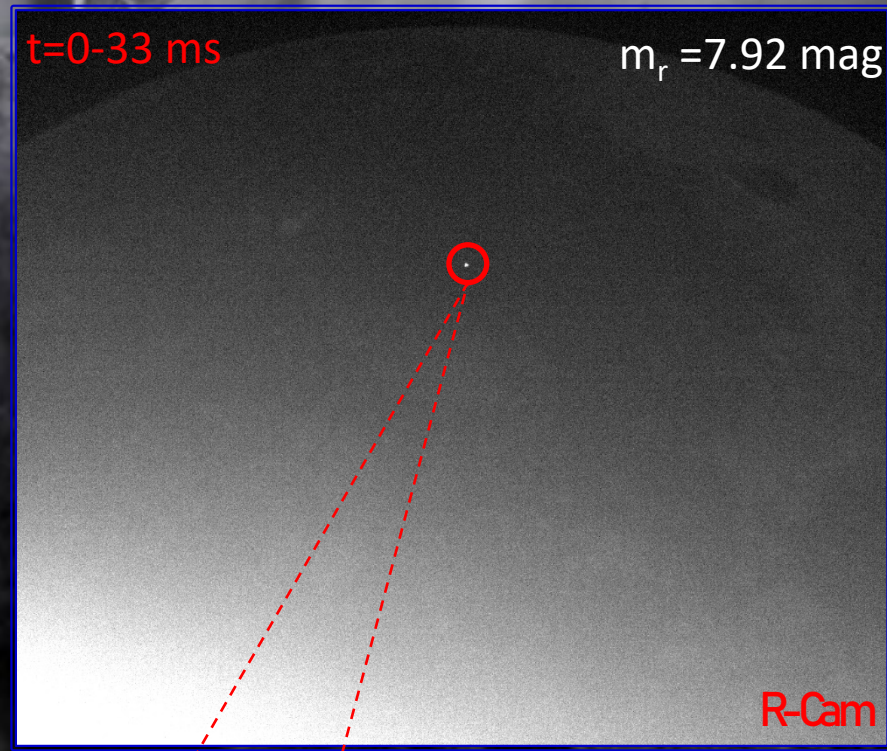
$t=0-33$ ms

$m_i = 6.66$ mag

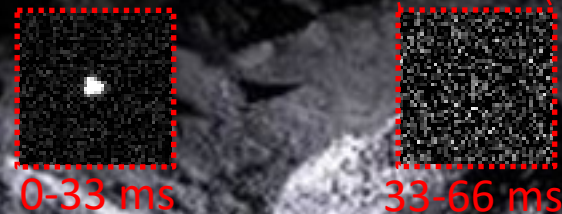
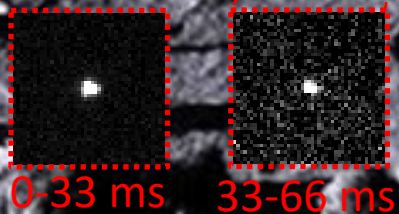
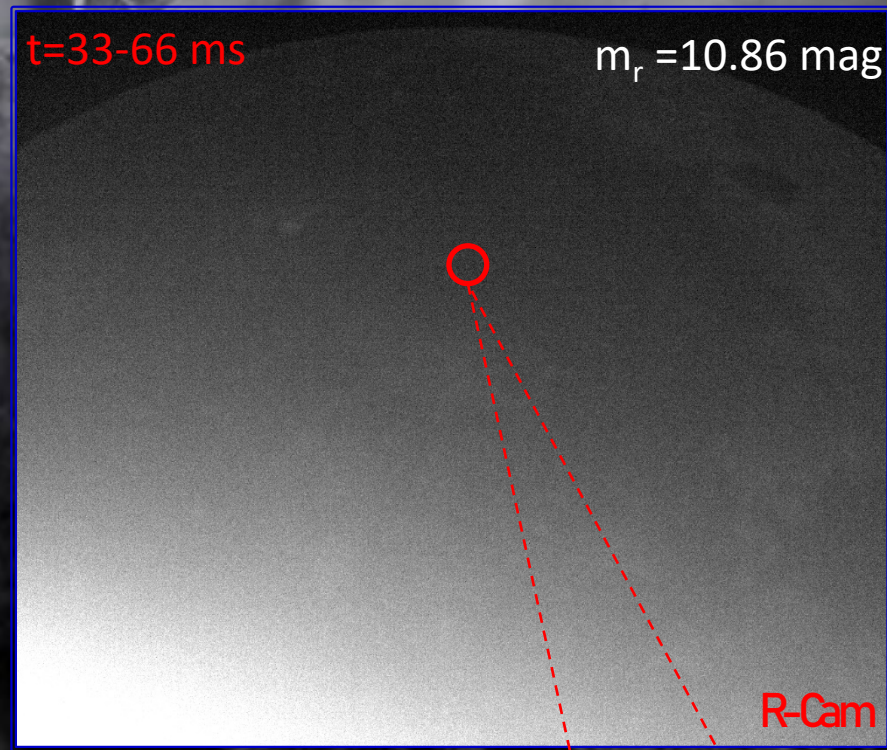
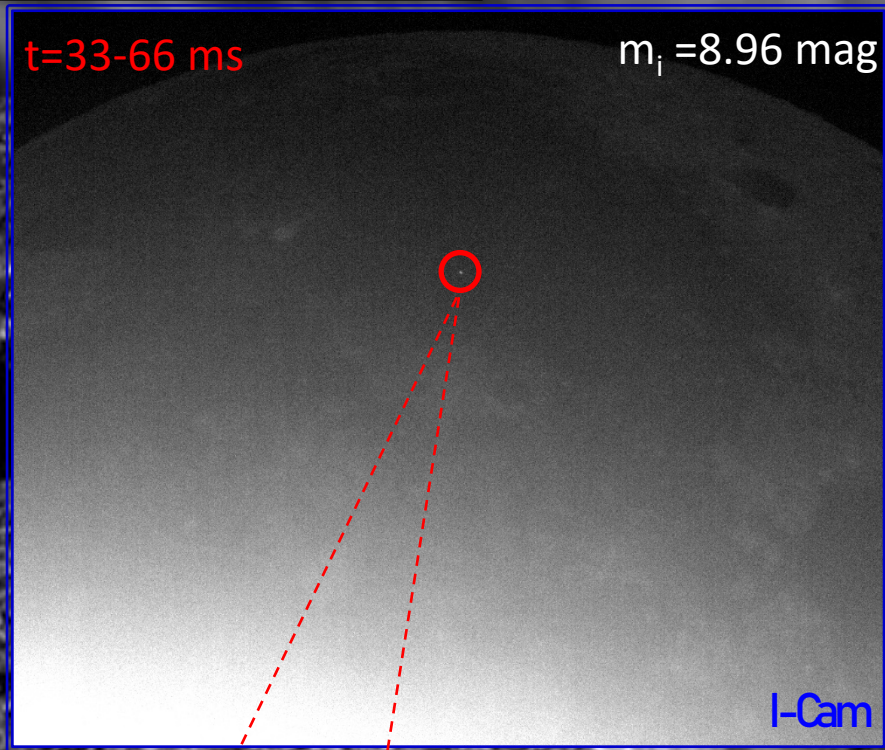


$t=0-33$ ms

$m_r = 7.92$ mag



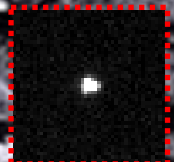
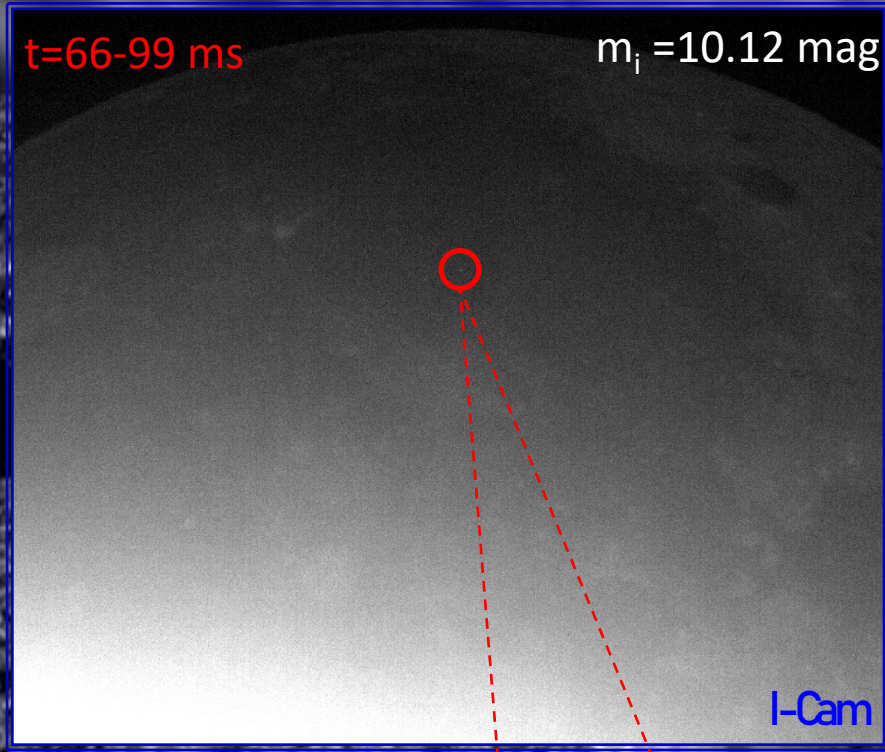
Data sample



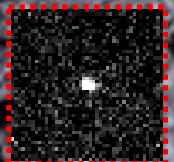
Data sample

t=66-99 ms

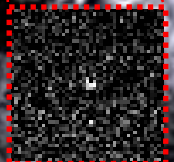
$m_i = 10.12$ mag



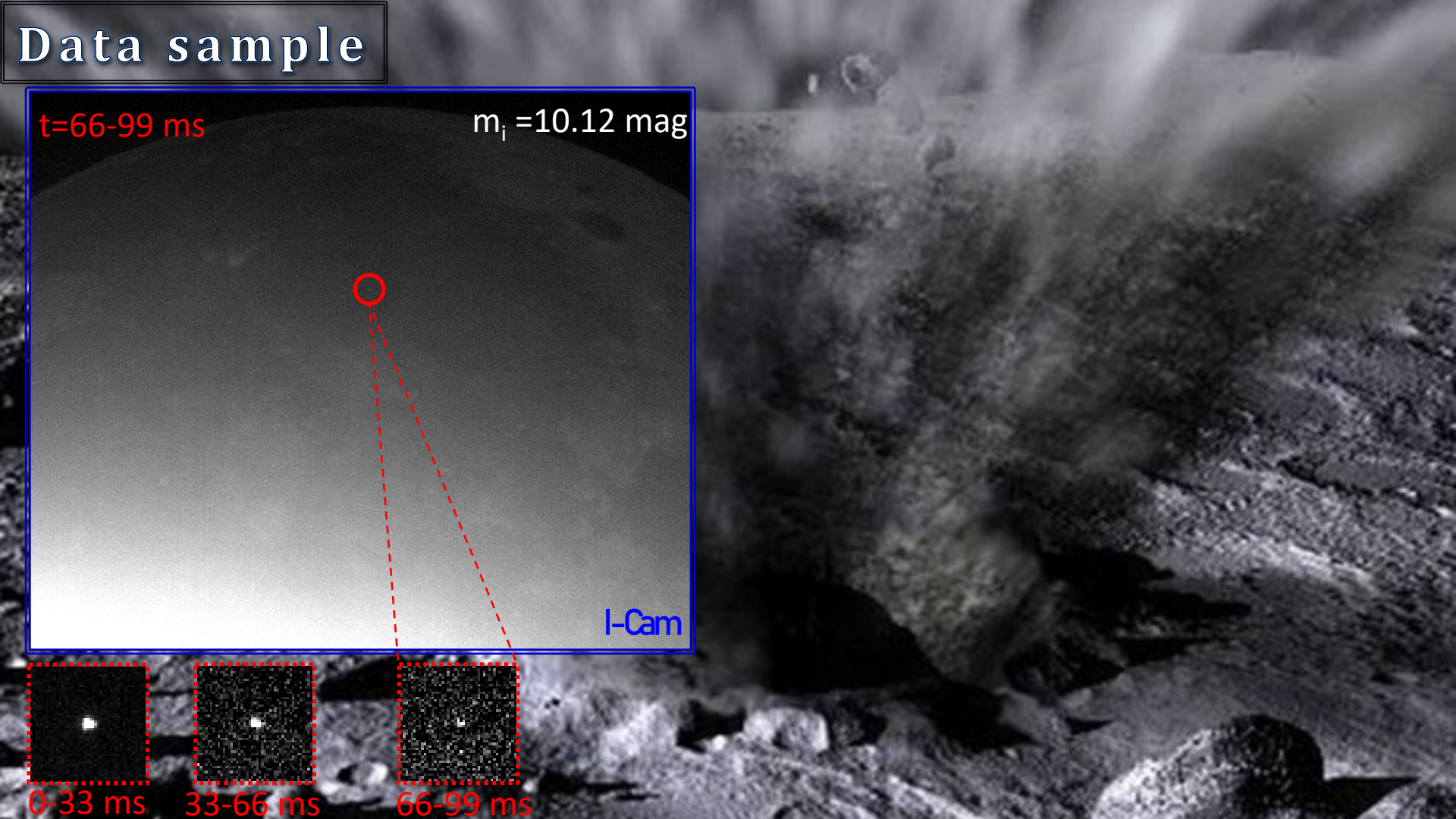
0-33 ms



33-66 ms



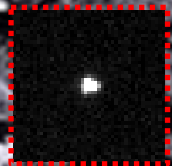
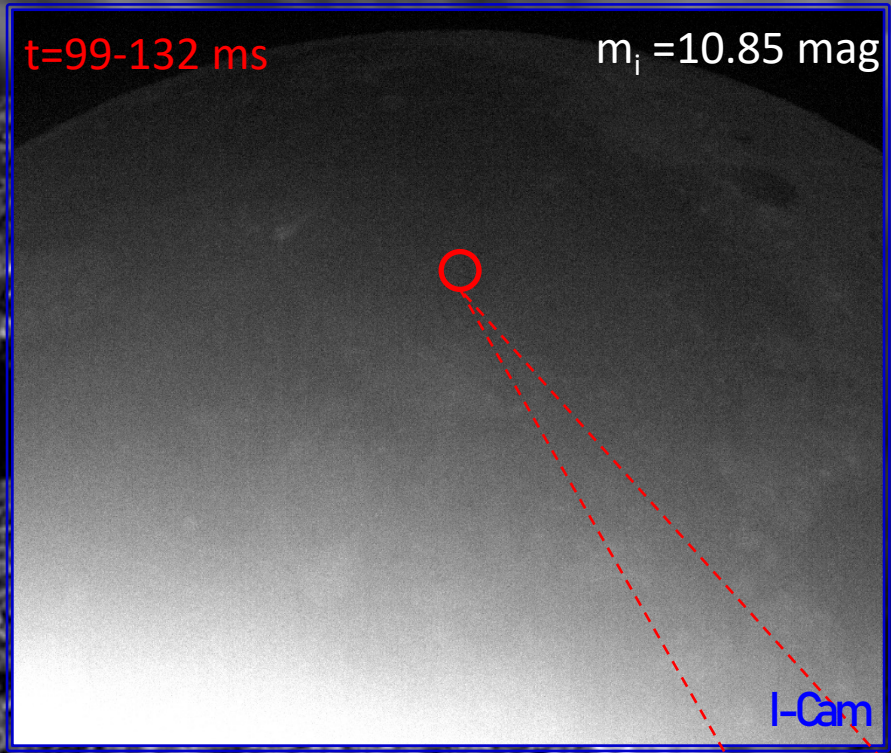
66-99 ms



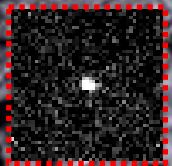
Data sample

t=99-132 ms

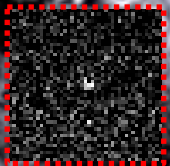
$m_i = 10.85$ mag



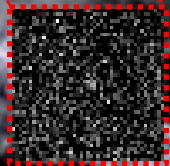
0-33 ms



33-66 ms



66-99 ms



99-132 ms

Data sample

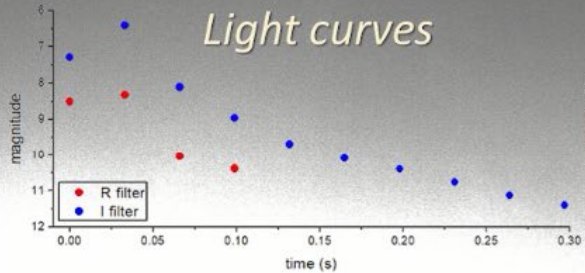


Data sample

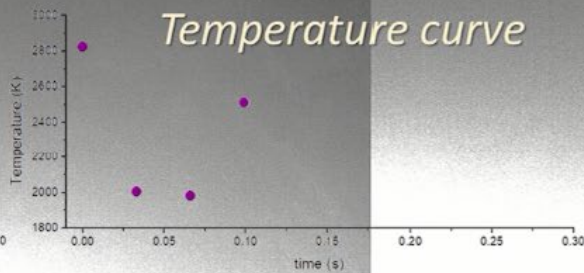
IR filter



Light curves



Temperature curve



R filter

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

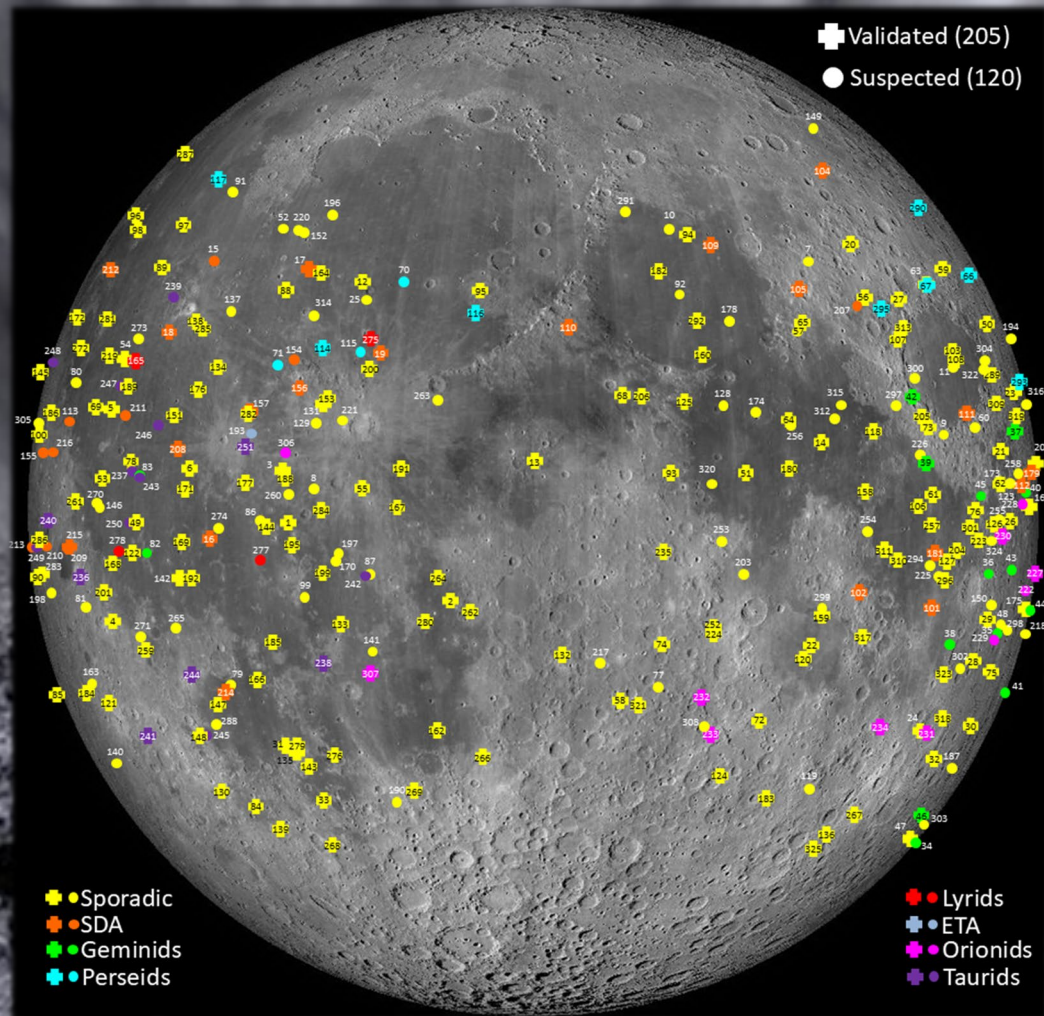
Origin: Sporadic

Mass (for $\eta=1.5 \times 10^{-3}$) = 2.37 ± 0.04 kg

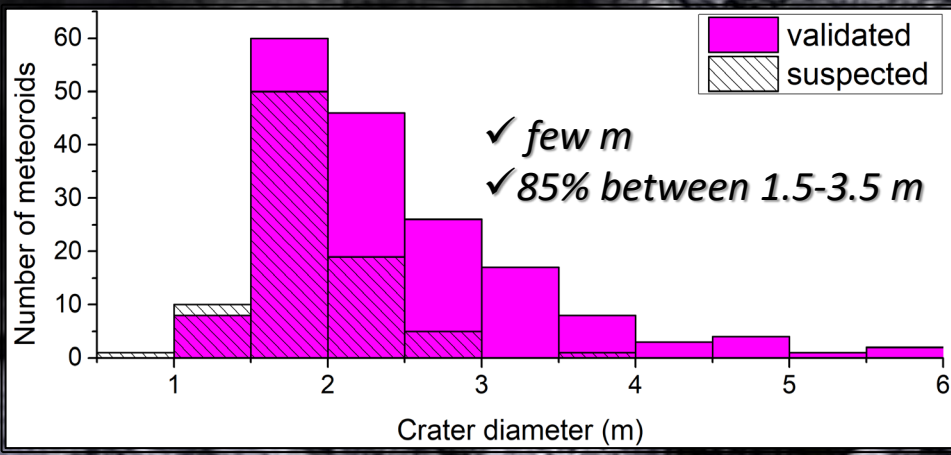
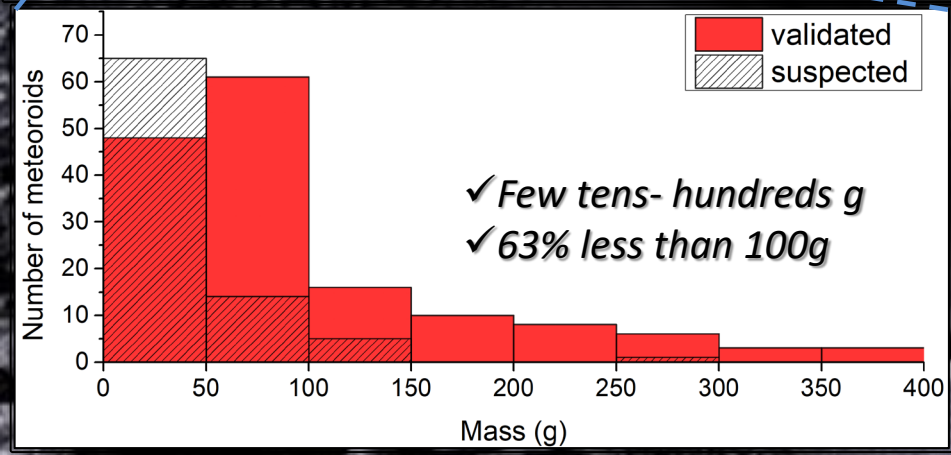
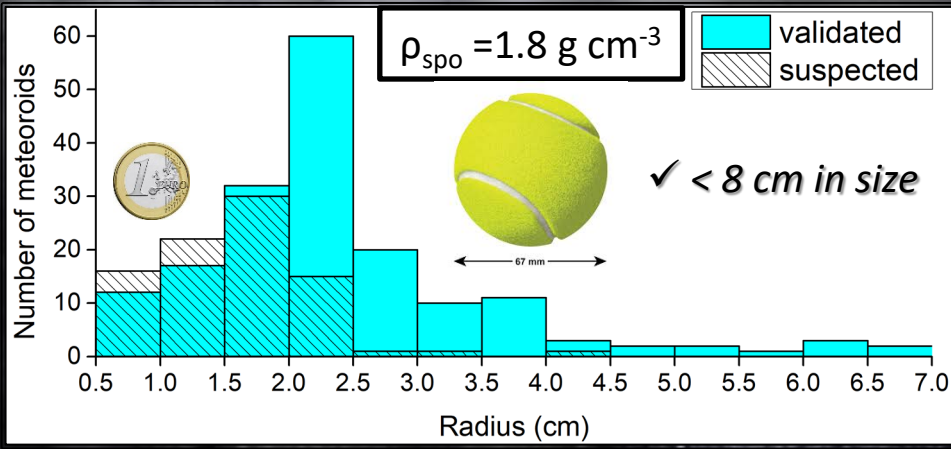
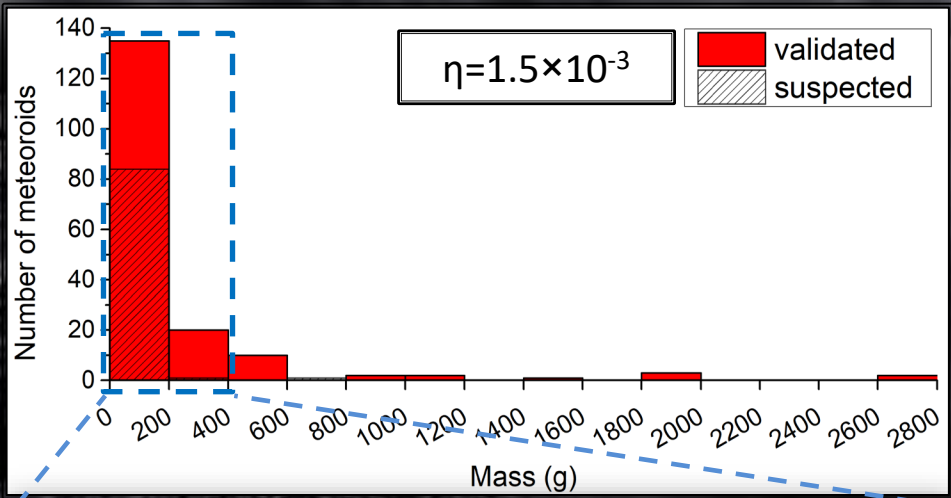
Radius (for $\eta=1.5 \times 10^{-3}$) = 13 ± 2 cm

Crater diameter (for $\eta=1.5 \times 10^{-3}$) = 5.3 ± 0.2 m

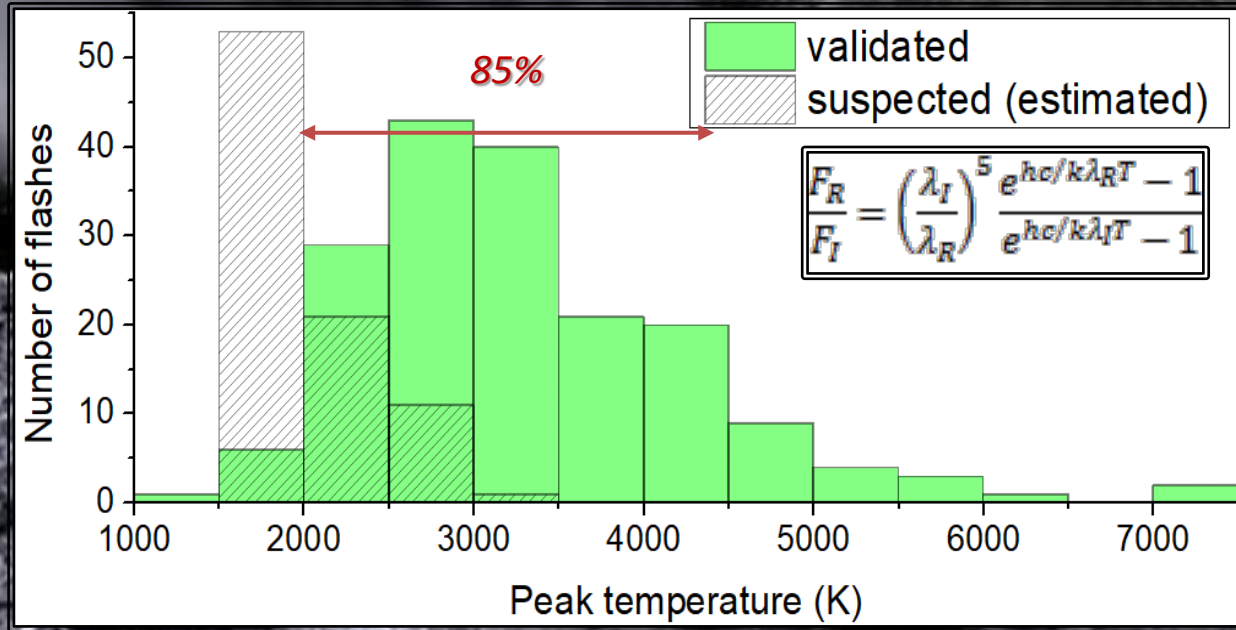
Localization



Physical parameters

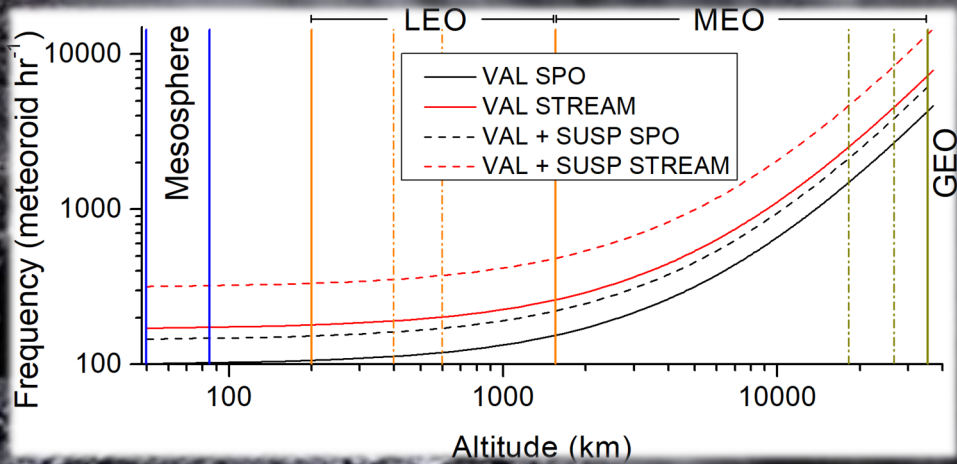


Peak temperatures and thermal evolution





Appearance frequency



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

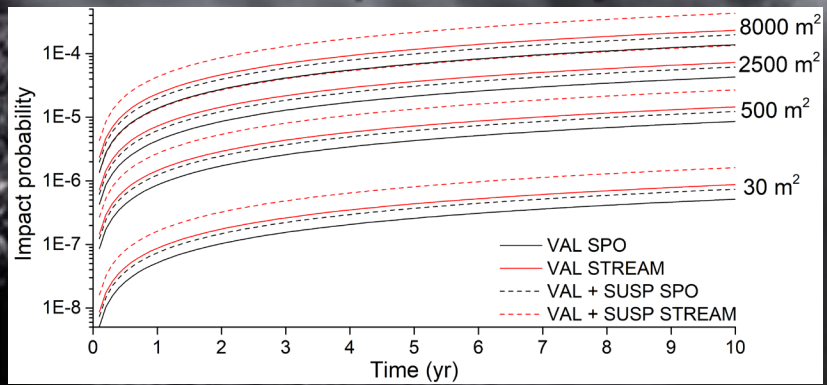
In the FoV	Detection Rate (flash/hr)
Validated Sporadic	0.6
Validated Stream	1.0
Validated Total	0.7

Validated+suspected

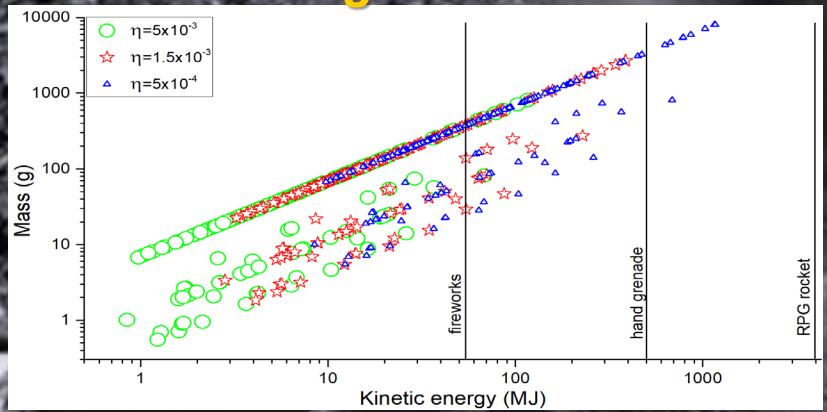
	Moon	Earth		
type	Surf	MS (90 km)	LEO (2000 km)	GEO (36000 km)
Sporadic	10.7	147	167	6341
Stream	23.3	321	364	13848

Appearance frequency

Collision probability



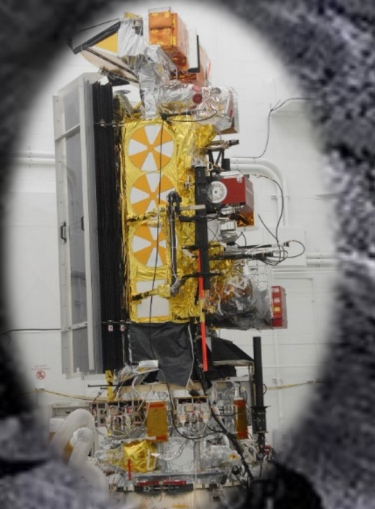
Damage assessment



Lunar base



ISS

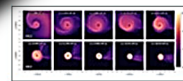


METEO SATELLITE

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



Forming second-generation disk after late infall (Kuffmeier, M., et al., 633, A3)



Colliding granular clusters obeying the MRN distribution (P. Umstätter, & H. M. Urbassek, 633, A24)



Theoretical pulsation modes for the star Altair (Bouchaud, K., et al., 633, A78)



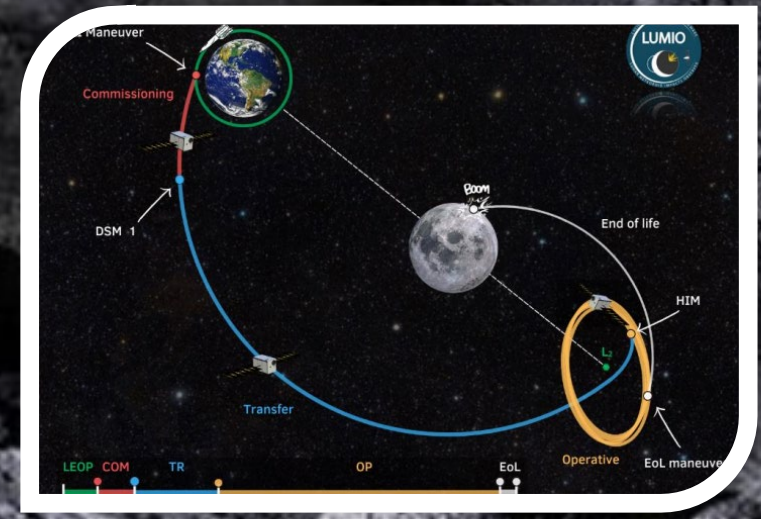
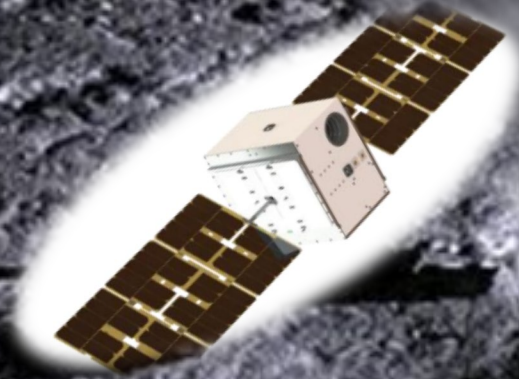
Lunar impact flashes detected by the NELIOTA project (Liakos, A., et al., 633, A112)

Sort by Section Sort by article number

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>

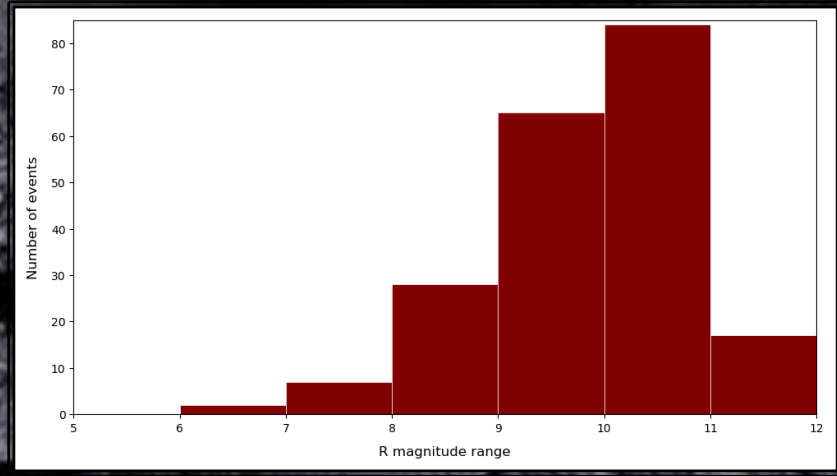
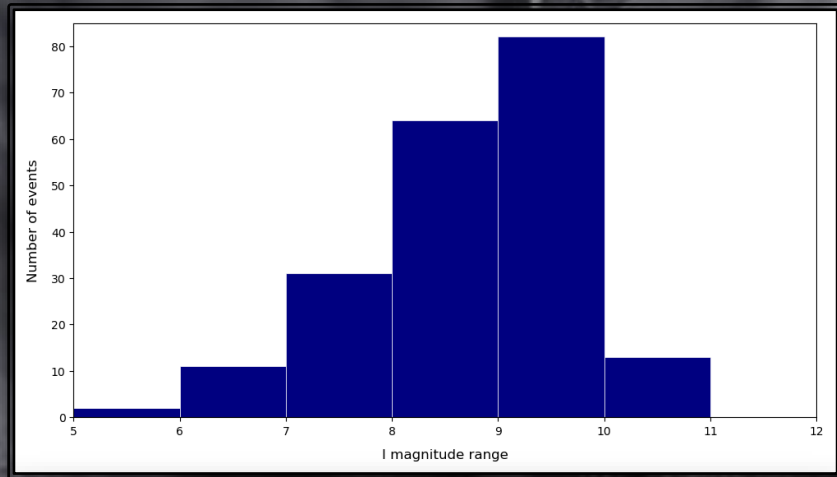


Take home notes

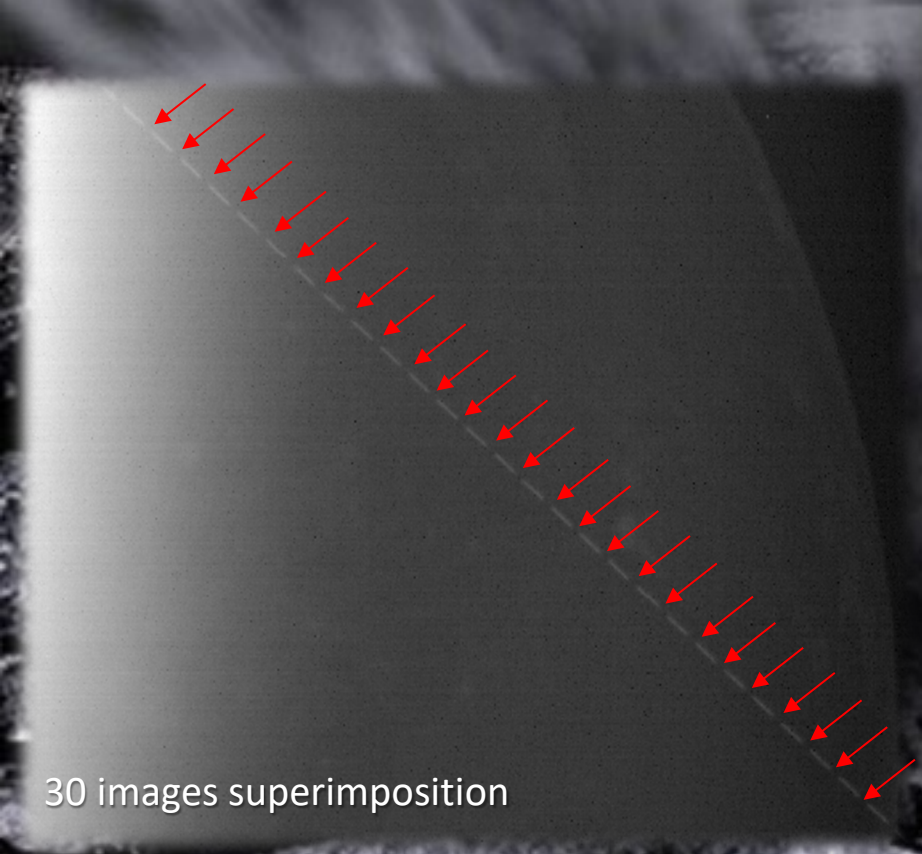
- ❖ NELIOTA is the most efficient lunar impact flashes campaign to date
- ❖ The meteoroids have typical **masses** of **few tens of grams** and **sizes** of a **few cm**
- ❖ The typical **temperatures** of impacts range between **2000-4500 K**
- ❖ **Moon** is bombarded sporadically with a rate of **~7.5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



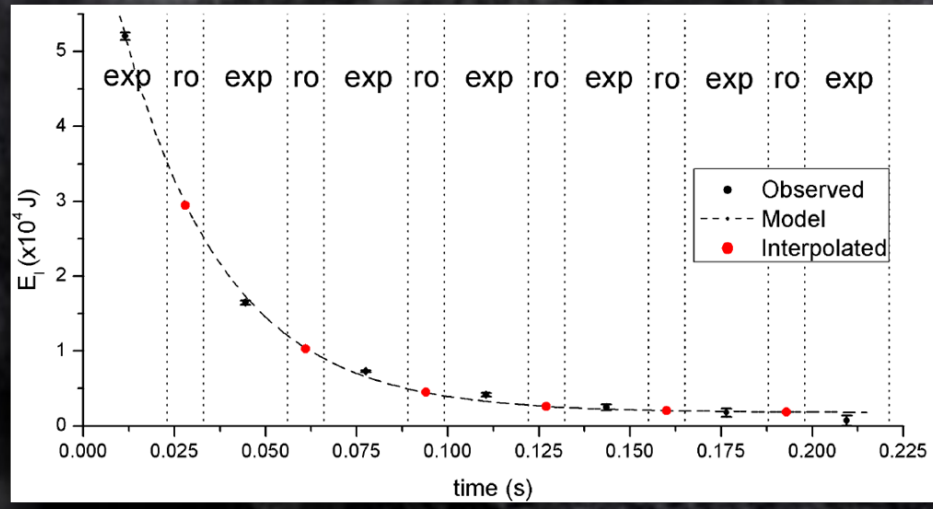
Statistics



Lost energy + correction



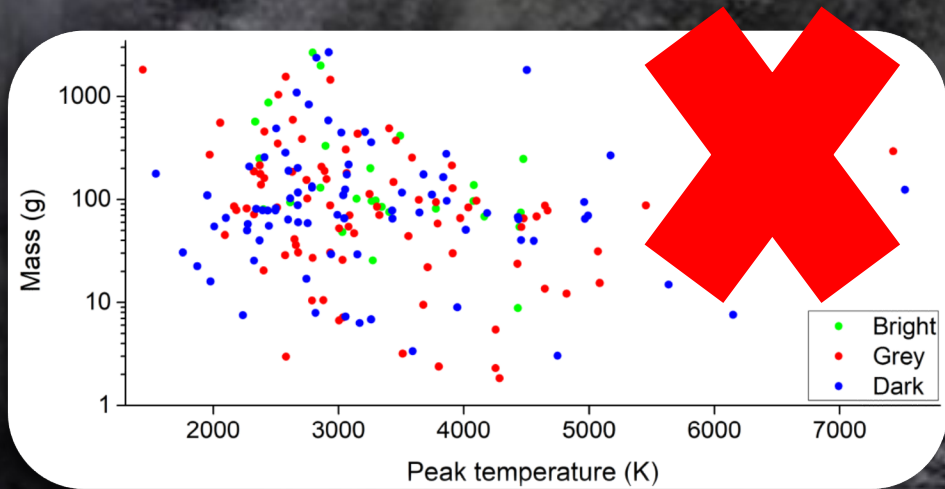
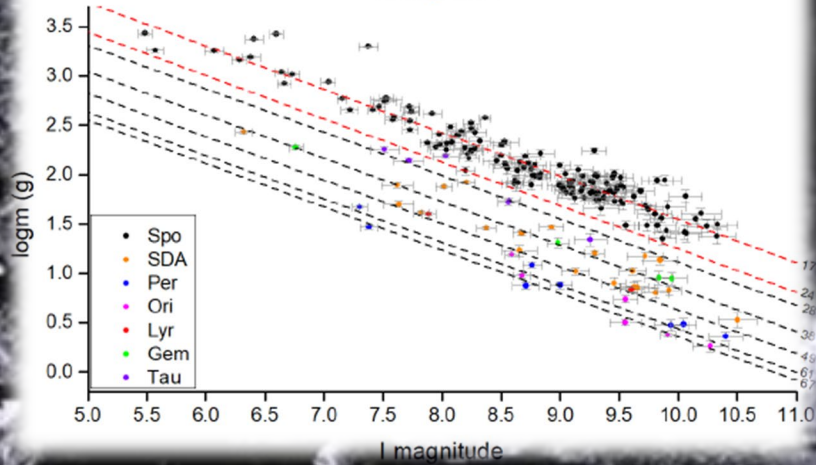
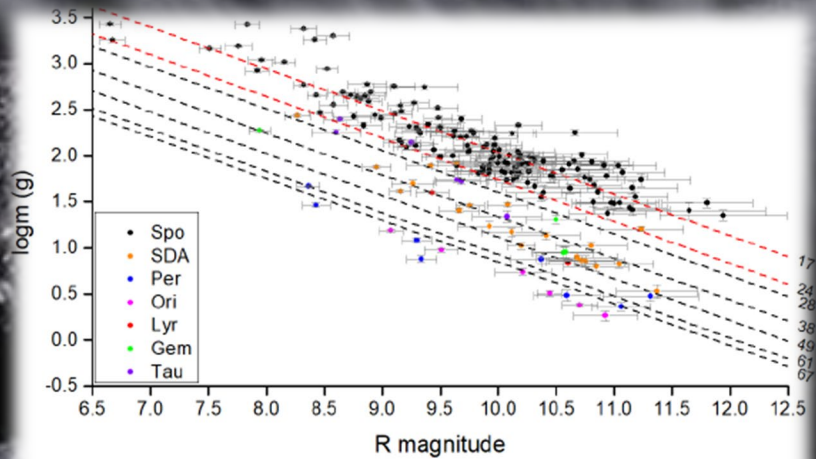
30 images superimposition



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

in J

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)

