

Enabling the Recovery of Freshly-Fallen Meteorites and Probing the Sub-metre Meteoroid Population with the Italian PRISMA Fireball Network

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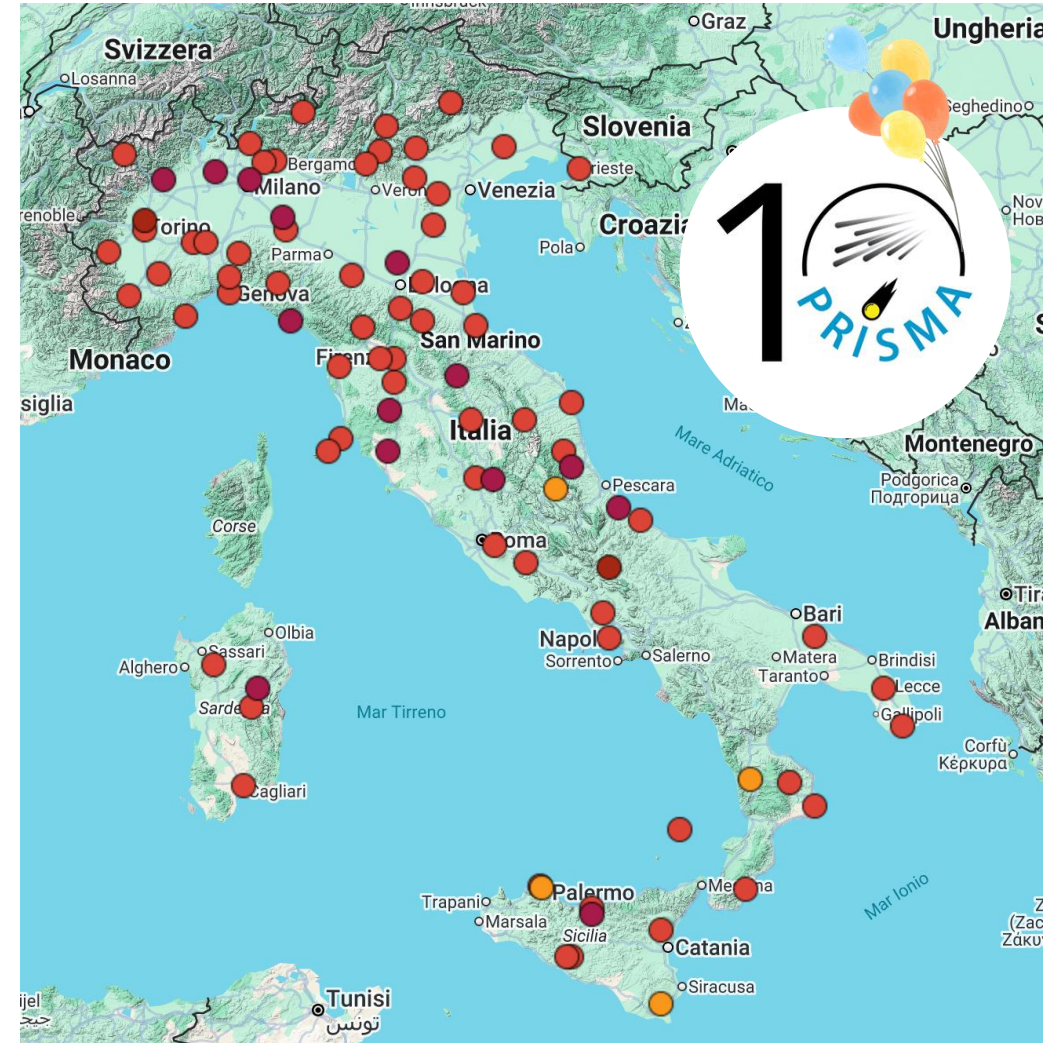
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¹¹Osservatorio Astronomico del Righi, Via Mura delle Chiappe 44, Genova, Italy



The PRISMA Network

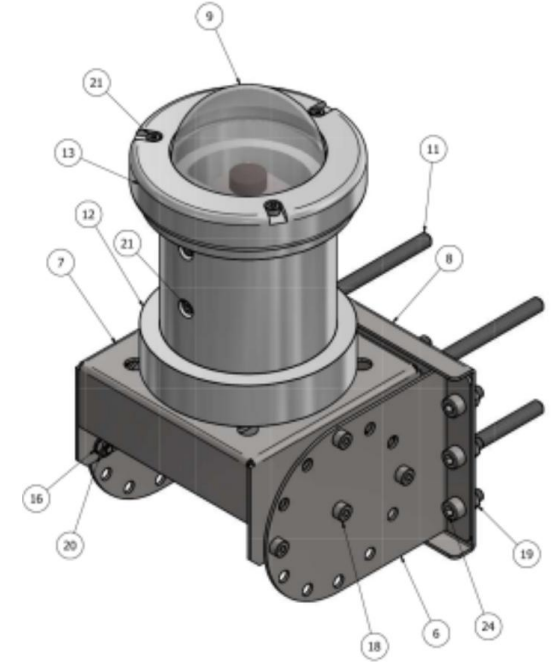
- All-sky fireball network **born in 2016** thanks to the partnership with the **FRIPON** international consortium
- Coordinated by **INAF**, counting **more than 100 stations** and more than **80 institutions**
- Celebrating the 10 years anniversary this years, with more than **3000 observed fireballs**
- Recent enlargement of the network abroad thanks to the **StAnD project** (Erasmus+ KA220 2024)



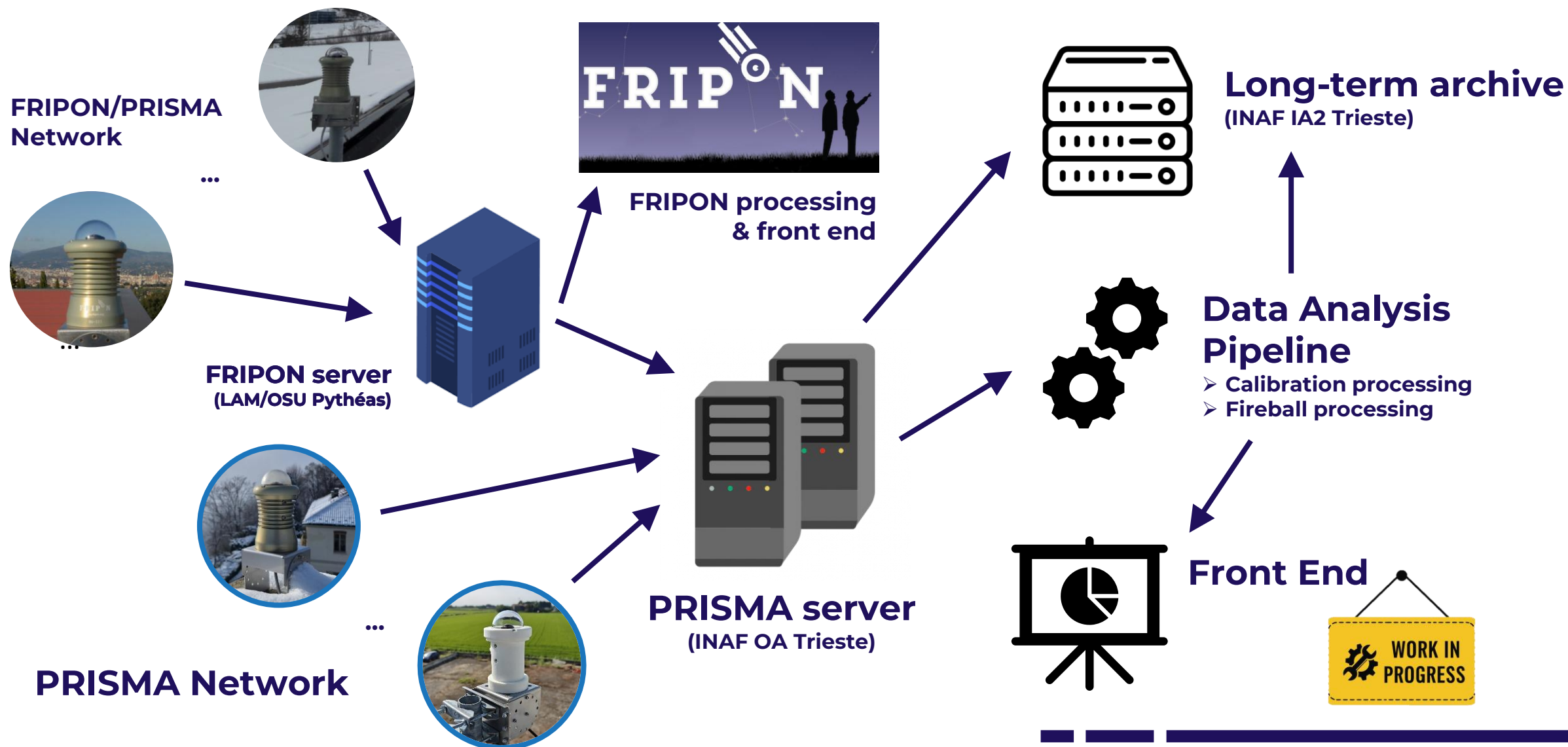
Upgraded All-Sky Station

The new node technology now features:

- New **CMOS sensor** (Lucid Vision PHX032-MS / Sony IMX265, 3.2 MP) with improved sensitivity and resolution ($\sim 7''/\text{px}$)
- Automatic **temperature active control** to reduce hardware failure, implementing a Schmitt trigger to avoid continuous on/off switching
- **3D-printed external case** for cheaper production, better thermal control and easier dome replacement (work in progress)
- **Browser graphical user interface** for easy data access and maintenance
- Assistance and maintenance **user portal to report and track HW and SW issues** with dedicated access for each station owner



Network Infrastructure



Meteorite Falls and Recoveries



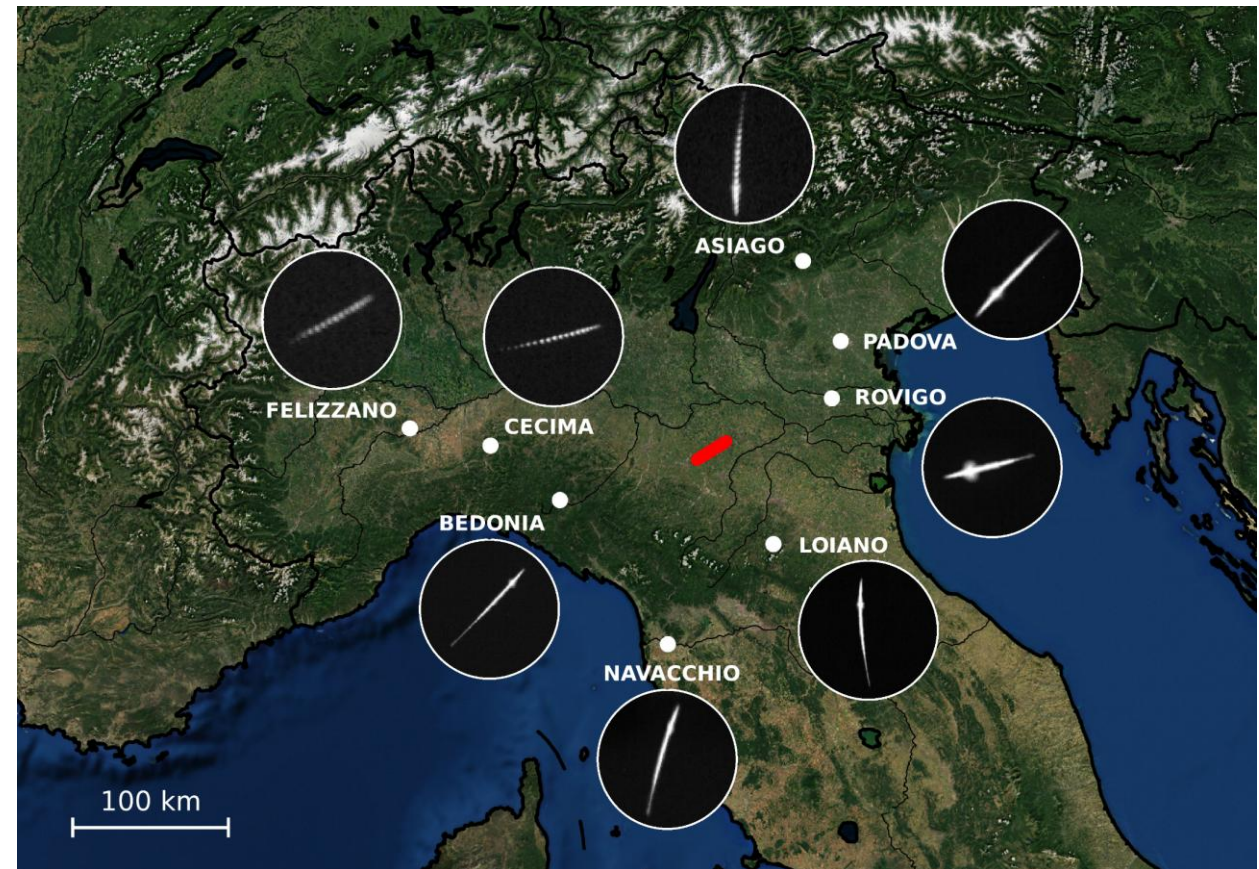
- PRISMA can detect fireballs of **apparent magnitude $m < 0$**
- Estimated meteorite-dropping fireball rate of **1 per year over Italy**
- **Two successful recoveries:**
 - **Cavezzo (L5-an, 55 g)**, fall 01/01/2020, rec. **04/01/2020**
 - **Matera (H5, 117 g)**, fall 14/02/2023, rec. **17/02/2023**

Date	Time	V_{∞} [km/s]	γ [deg]	M_{∞} [kg]	M_{fin} [kg]
30/12/2017	21:09	15.6 ± 0.2	29.1 ± 0.4	4 – 12	0.2 – 4
22/08/2018	21:37	17.9 ± 0.1	72.1 ± 0.3	2 – 5	0.4 – 1.2
01/01/2020	18:26	12.27 ± 0.05	66.4 ± 0.2	10 – 40	0.5 – 1.5
15/03/2021	19:57	~ 15	~ 85	~ 2	~ 1
01/10/2021	01:04	16.00 ± 0.07	30.8 ± 0.3	3 – 8	0.01 – 0.1
05/03/2022	18:55	15.5 ± 0.1	16.5 ± 0.9	10 – 90	0.3 – 1.5
14/02/2023	17:58	16.4 ± 0.2	56.7 ± 0.3	3 – 21	0.07 – 1.2
23/05/2023	22:21	15.41 ± 0.09	34.9 ± 0.4	3 – 10	0.02 – 4
05/08/2023	20:21	13.8 ± 0.1	60.1 ± 0.2	20 – 100	0.1 – 2.5
08/10/2023	21:53	16.5 ± 0.1	77.6 ± 0.5	0.2 – 1	0.02 – 0.22
04/06/2024	19:23	17.2 ± 0.1	70.3 ± 0.2	5 – 24	0.01 – 3
23/07/2024	19:31	14.1 ± 0.1	29.1 ± 0.3	1.4 – 4.6	0.02 – 3.4

The 2020 New Year's Bolide

- Captured by **eight PRISMA cameras** on 01/01/2020 at 18:26:52.9 – 58.5 UT (5.6 s)
- The meteoroid entered the atmosphere at **$12.8 \pm 0.2 \text{ km s}^{-1}$** with an inclination angle of about **68°** w.r.t. the ground
- Bolide shone from 76 km to 22 km altitude and reached **-9.5 abs. mag.**

		Beginning	Terminal
Time (UT)	t	18:26:52.9	18:26:58.5
Height (km)	h	75.9 ± 0.2	21.5 ± 0.1
Latitude (N)	ϕ	$44^\circ 44' 03'' \pm 7''$	$44^\circ 50' 24'' \pm 7''$
Longitude (E)	λ	$10^\circ 43' 09'' \pm 7''$	$10^\circ 57' 25'' \pm 7''$
Velocity (km s^{-1})	v	12.2 ± 0.2	4.0 ± 0.2
Mass–section ratio (kg m^{-2})	D	280 ± 20	210 ± 20
Mass (kg)	m	3.5 ± 0.8	1.5 ± 0.4
Diameter (m)	d	0.13 ± 0.01	0.09 ± 0.01
Luminous path-length (km)	L	59	
Duration (s)	T	5.6	
Trajectory inclination ($^\circ$)	T_i	68.4 ± 0.3	
Trajectory azimuth ($^\circ$)	az	238.1 ± 0.2	
Min. absolute magnitude	M	-9.5 ± 0.5 @ 32.6 km	
Pre-atmospheric velocity (km s^{-1})	v_∞	12.8 ± 0.2	
Ablation coefficient ($\text{s}^2 \text{ km}^{-2}$)	σ	0.012 ± 0.003	
Max. dynamic pressure (MPa)	P_{max}	1.0 ± 0.3 @ 28.2 km	
Impact Energy (T TNT)	E	0.07 ± 0.02	



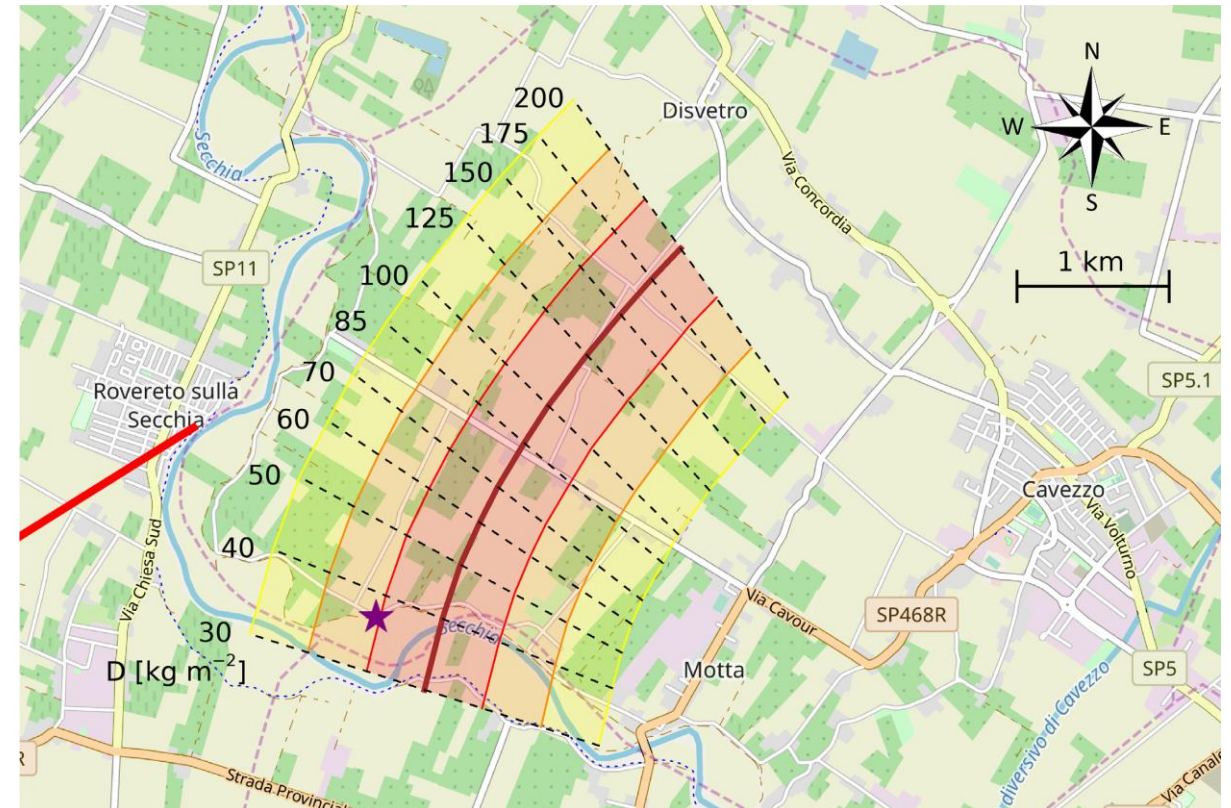
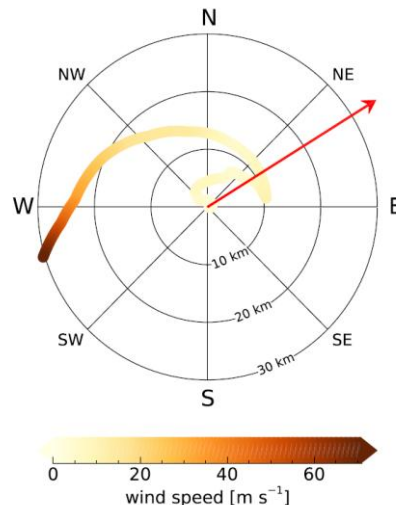
Meteorite Strewn-Field

A **strewn field of about 2 km x 3 km** was identified from trajectory, dynamics and dark-flight computation from PRISMA observations

- Due to intense winds of that night, the area of probable fall was shifted to East with respect to ground trajectory
- PRISMA informed and **reached the attention of the local population** by press releases and local media coverage

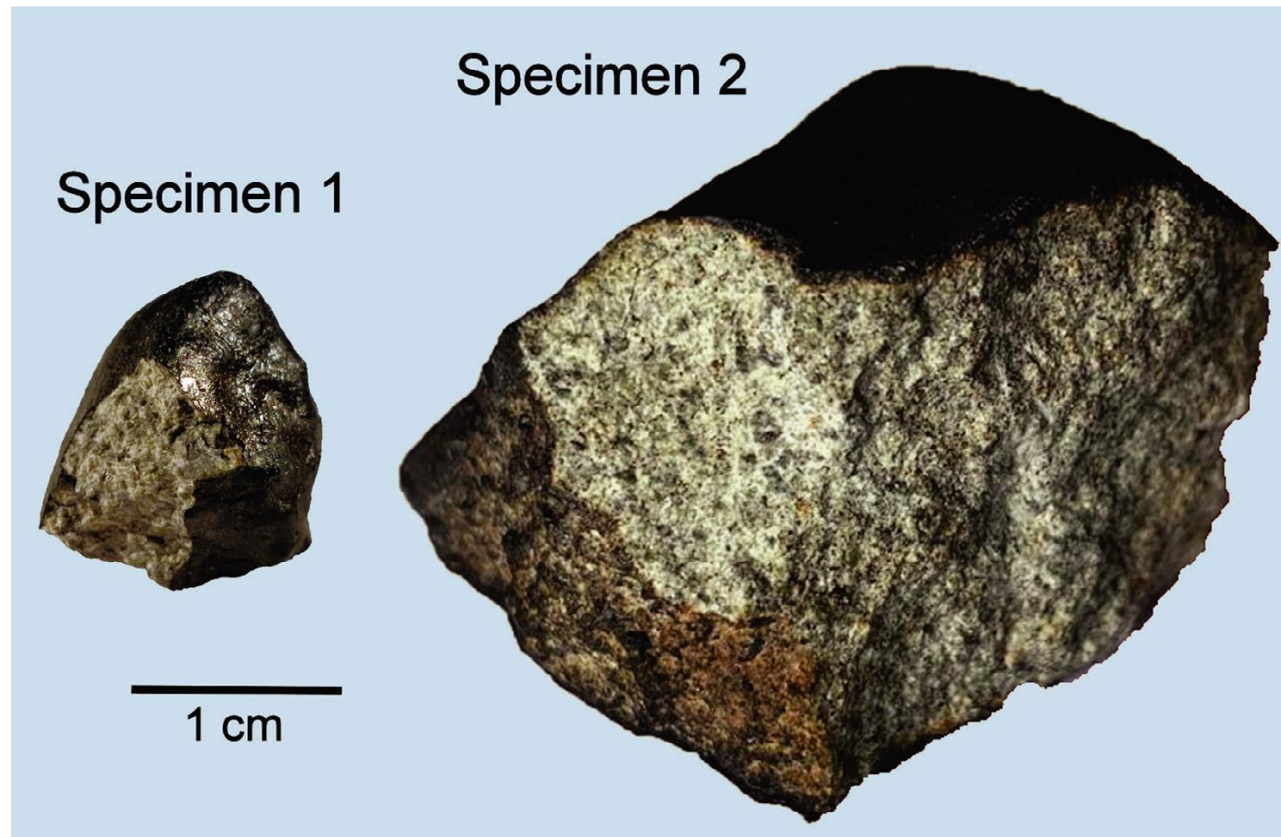
For details about the recovery of the Cavezzo meteorite:

Gardiol D., Barghini D. et al., "Cavezzo, the first Italian meteorite recovered by the PRISMA fireball network. Orbit, trajectory, and strewn-field", *Mon. Not. R. Astron. Soc.*, **2021**, 01, 1215–1227



The Cavezzo meteorite finding

Two meteorite pieces were recovered by a local inhabitant, Mr. Davide Gaddi, **less than three days after the fall** on the afternoon of 04/01/2020 in the municipality of Cavezzo (MO)

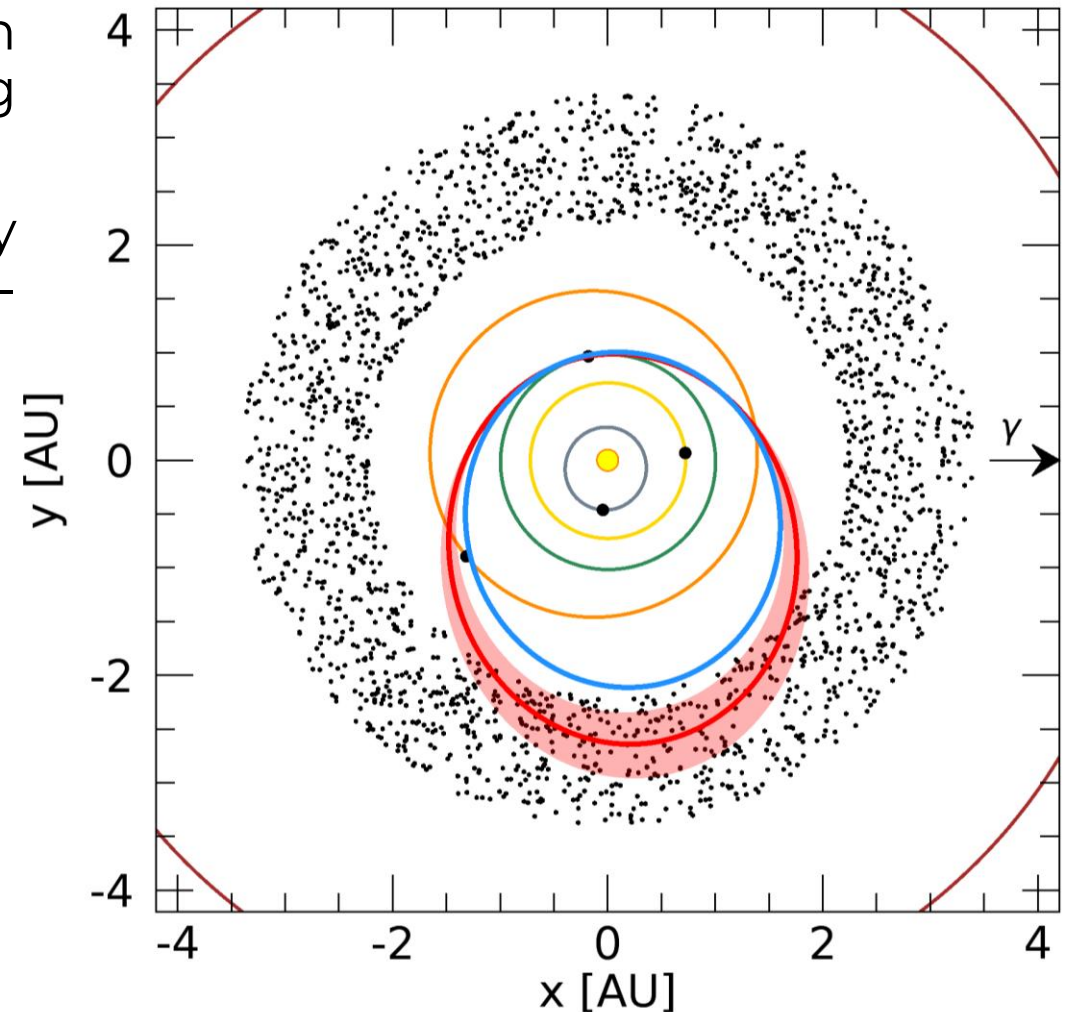


- The coordinates of the finding are $44^{\circ}49'43''.7$ N, $10^{\circ}58'19''.5$ E
- The two specimens weigh **3.12 g (F1)** and **52.19 g (F2)** respectively
- Due to the **morphology of the two recovered pieces**, other fragments should have been found on site
- Further campaigns were unsuccessful up until now

Possible parent of Cavezzo?

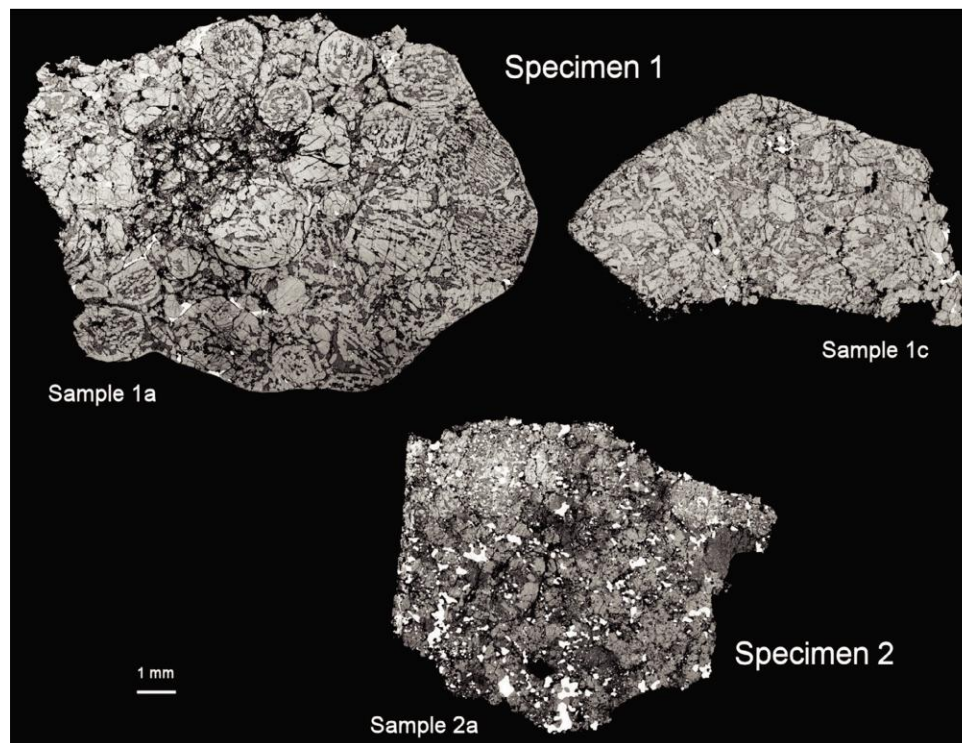
- Cavezzo meteoroid orbit compatible with the orbit of one object only among currently known NEOs: **2013 VC₁₀**
- It is an **Apollo type asteroid** observed only for 54 days in 2013 of +24.8^H abs. mag. (10-meters sized) and ~2 y orbital period

Quantity	Cavezzo	2013 VC ₁₀
Epoch	J2000	MJD59000
Semimajor axis (AU)	1.82 ± 0.22	1.56622
Eccentricity	0.460 ± 0.063	0.365295
Inclination (°)	4.0 ± 1.6	2.044
Long. of ascending node (°)	280.52311 ± 0.00001	224.068
Argument of Perihelion (°)	179.2 ± 4.8	240.264
Longitude of Perihelion (°)	99.7 ± 4.8	104.332
Perihelion passage (JD)	2458849.6 ± 0.5	2458808.1
Perihelion distance (AU)	0.983 ± 0.001	0.9941
Aphelion distance (AU)	2.66 ± 0.41	2.1383



Cavezzo - A Peculiar Find

- The two fragments show **peculiar differences** in their petrography and composition, and this is the main reason for the L5-anomalous classification
- In particular, F1 may be **xenolithic material** and represented a previously unsampled portion of the L-chondrites parent body



	F1 (3 g)	F2 (52 g)
Petrography	From well delineated to achondritic	Partially melted (typical L5)
Mineralogy	High content of olivine, almost absent metals	Standard metal and olivine content
Cristal chemistry	Similar to the one of L5 chondrites	
Oxygen isotopes	At the boundary between H and L	At the boundary between L and LL

2023 Valentine's Day Bolide

- The bolide was detected from a **starting altitude of 85.5 ± 0.1 km** at an initial speed of 16.3 ± 0.1 km/s.
- It traversed the atmosphere for about 5.3 s at an inclination angle of **$56.7 \pm 0.3^\circ$** ,
- Projected on the ground, its trajectory began SW of Bari and ended NE of Matera, where the visible flight **terminated at an altitude of 22.8 ± 0.1 km**, while the meteoroid was travelling at a low speed of 3 ± 1 km/s.

Triangulation

			Beginning	Ending
Time	t	(UT)	17:58:29.54	17:58:34.89
Latitude	ϕ	[deg N]	41.0893 ± 0.0006	40.7496 ± 0.0006
Longitude	λ	[deg E]	16.8053 ± 0.0004	16.5996 ± 0.0004
Height	H	[km]	85.5 ± 0.1	22.8 ± 0.1
Speed	V	[km/s]	16.3 ± 0.1	3 ± 1
Time of Flight	ToF	[s]	5.34 ± 0.05	
Trajectory Length	L	[km]	75.0 ± 0.1	
Trajectory Inclination	γ	[deg]	56.7 ± 0.3	
Trajectory Azimuth	a	[deg]	24.3 ± 0.1	
Min. Abs. Magnitude	$\mathcal{M}_{min}$	[/]	-11.1 ± 0.1	



Matera Meteorite

Many fragments were recovered just the next day on the property of **brothers Losignore in Matera** – Contrada Rondinelle.

Classified and approved as an **H5 ordinary chondrite** on 14 February 2024 (on Saint's Valentine Day!)



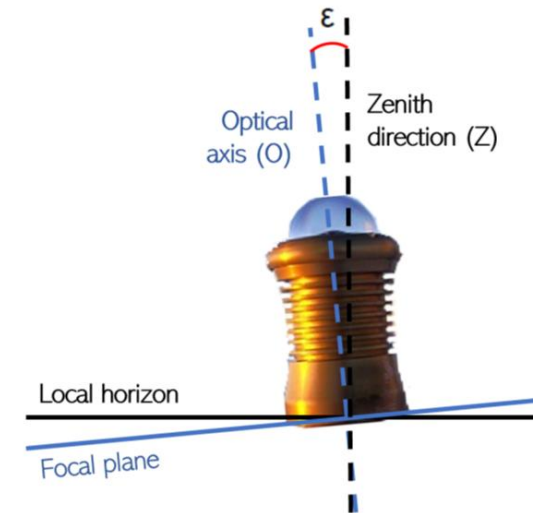
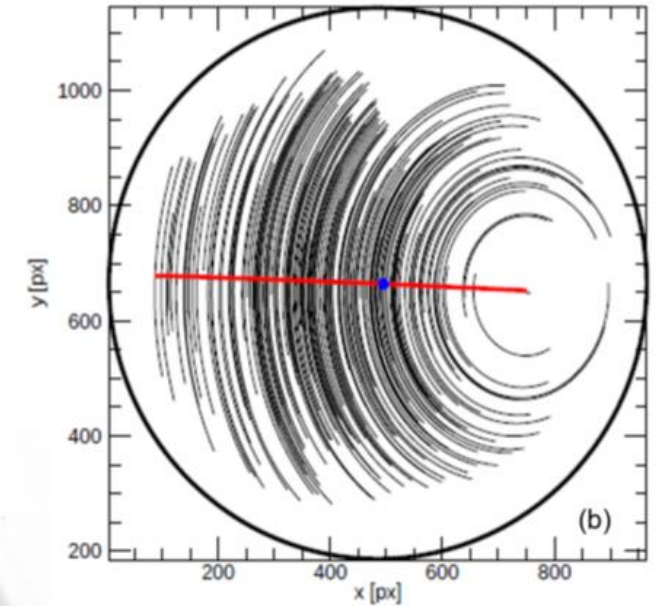
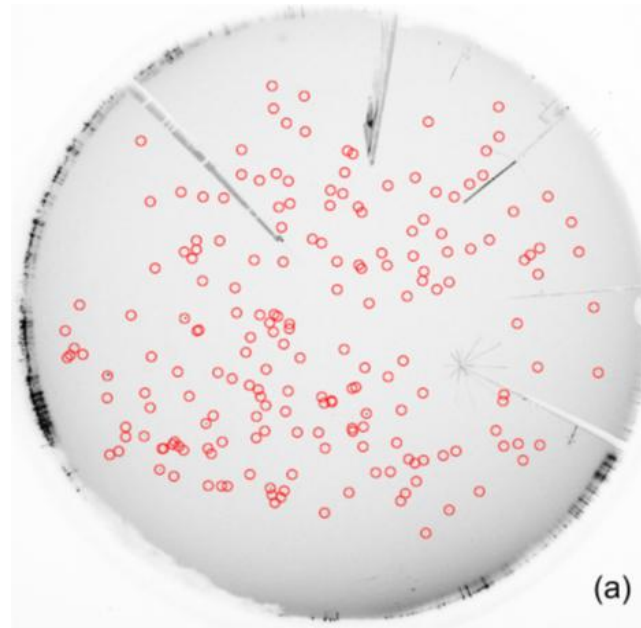
Calibration pipeline

Captures images used to perform **astrometric and photometric calibration** for each camera on a **daily and monthly basis**

- Automatic star identification and catalogue correlation
- 100 - 300 stars per image, down to **+4 / +5 limiting magnitude**
- Astrometry suffers from high **distortion** (fish-eye, 8+2 params)
- Photometry limited by sensor characteristics

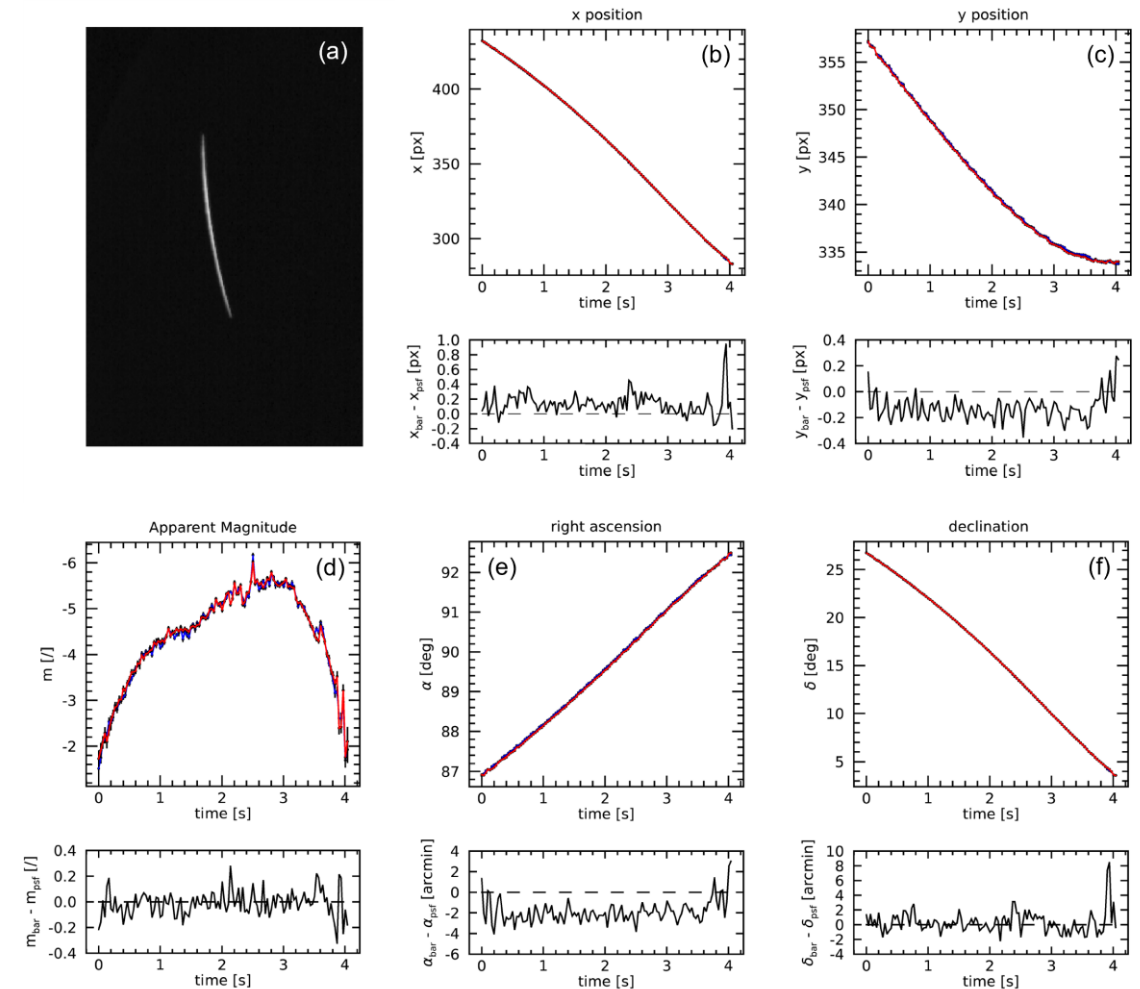
$$\begin{cases} b = a_0 - E + \text{atan}\left(\frac{y-y_O}{x-x_O}\right) \\ u = Vr + S(e^{Dr} - 1) \end{cases} \quad \begin{cases} E = a_0 + \text{atan}\left(\frac{x_O-x_Z}{y_O-y_Z}\right) \\ \epsilon = Vr_\epsilon + S(e^{Dr_\epsilon} - 1) \end{cases} \quad \begin{cases} a = E + \text{atan}\left(\frac{\sin b \sin u}{\cos u \sin \epsilon + \cos b \sin u \cos \epsilon}\right) \\ z = \arccos(\cos u \cos \epsilon - \cos b \sin u \sin \epsilon) \end{cases}$$

$$r = [1 + K \sin(b + E - \phi)] \sqrt{(x - x_O)^2 + (y - y_O)^2}$$



Fireball pipeline / Astrometry

- The astrometric and photometric calibration is then used to reduce each detection video
- **Centring precision of the order of 0.1 px** (few arcmins)
- Bright bolides often saturates
 - Analysis of the **shape of the unsaturated PSF portion**
- **Major challenges** for automation:
 - Faint beginning and final portion of the trajectory **sensitive to image noise**
 - Automated centering subject to **stray light** (moon / neighbouring lights)
 - **Greatly variable aperture** radius



Fireball pipeline / Triangulation

Combination of two of the most common approaches, to provide a unique solution:

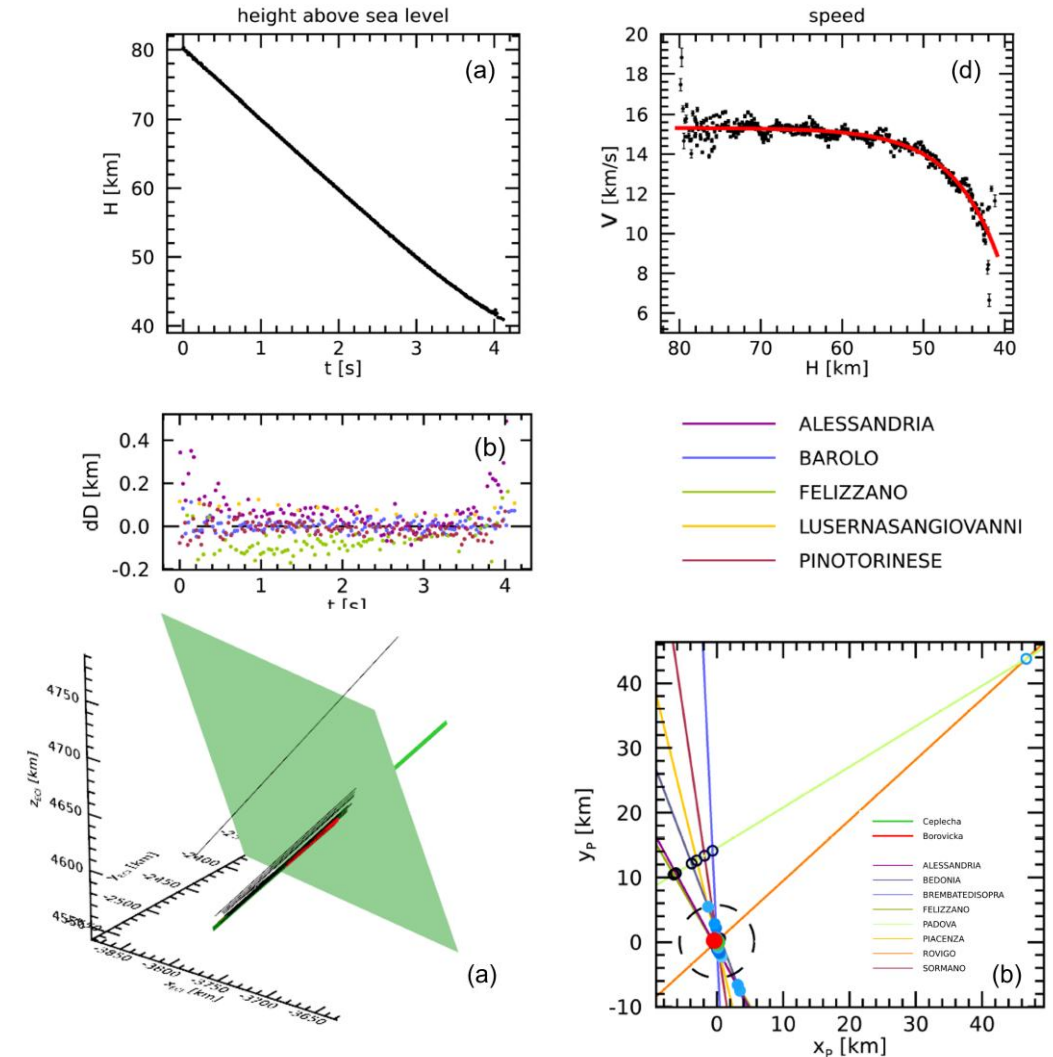
- a) **Plane intersection** from couples of stations
- b) **Lines of Sight** distance minimization

Typical **positioning precision of 100 m**

Major challenges for automation:

- Identifying and **excluding outliers** among observations from different stations
- Providing **meaningful estimation of uncertainties**

Both addressed by inspecting results of **plane intersections** with respect to average trajectory weighted for parallax angle.



Fireball pipeline / Dynamics (1)

- **Solution and fitting of the dynamic model** over observed data (height, speed, magnitude)

a) **Analytical solution**

b) **Numerical solution**

- We implemented a novel approach with a **simultaneous fitting** of the **deceleration and lightcurve data**

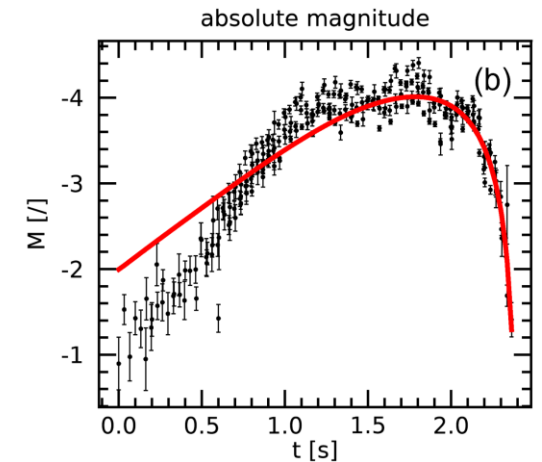
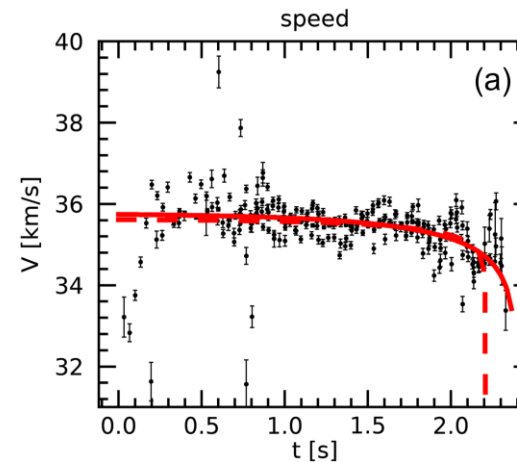
1) **Purely dynamical model**

(only deceleration)

2) **Photo-dynamic model**

(deceleration + lightcurve)

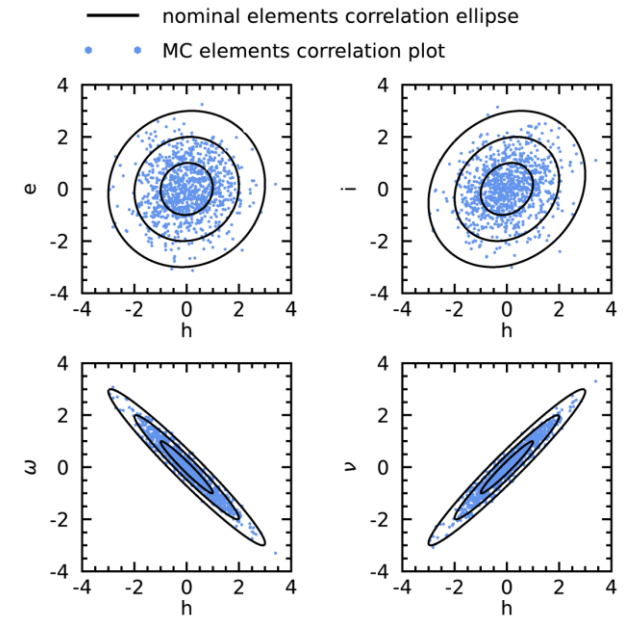
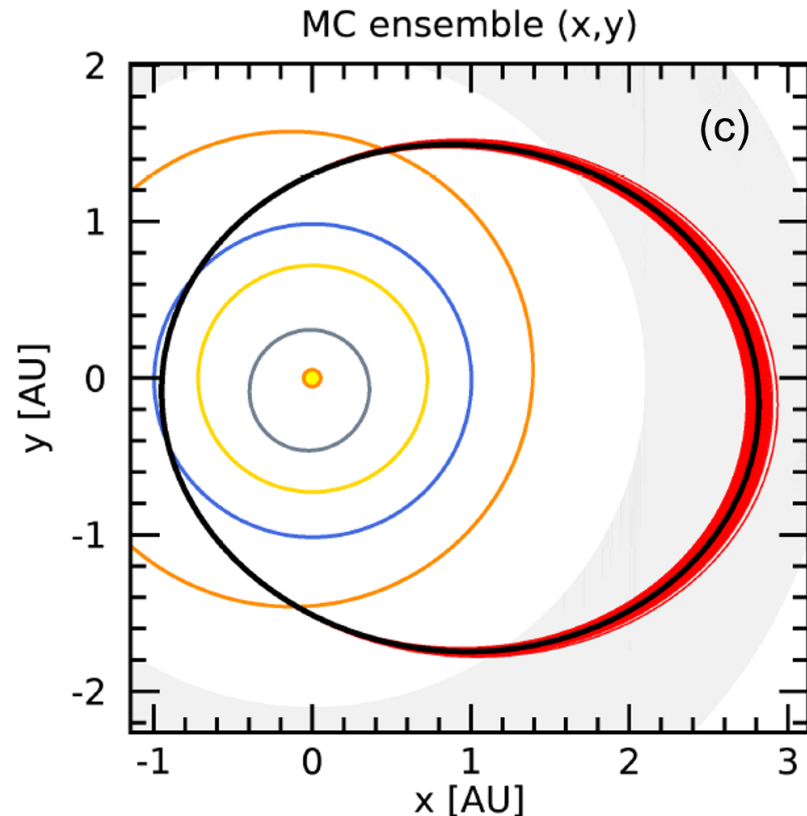
$$\begin{cases} \frac{dH}{dt} = -V \sin \gamma \\ M \frac{dV}{dt} = -\Gamma S \rho_a V^2 \\ M = M_{\infty} \exp \left\{ \frac{1}{2} \sigma (V^2 - V_{\infty}^2) \right\} \\ I = -\tau M V \left(1 + \frac{\sigma V^2}{2} \right) \frac{dV}{dt} \end{cases}$$



Particularly useful when dealing with events showing **small deceleration**

Fireball pipeline / Orbit

Retrieving **pre-atmospheric orbit** from trajectory versor (after **zenith attraction** correction) and pre-atmospheric speed module from dynamic model fit



Speed and radiant

V_a	[km/s]	15.40 ± 0.05			
α_a	[deg]	64.98 ± 0.05	δ_a	[deg]	63.73 ± 0.04
V_g	[km/s]	10.67 ± 0.07			
α_g	[deg]	47.45 ± 0.15	δ_g	[deg]	59.68 ± 0.06
V_h	[km/s]	36.06 ± 0.06			
α_h	[deg]	106.65 ± 0.03	δ_h	[deg]	33.61 ± 0.06
λ_h	[deg]	104.07 ± 0.03	ϕ_h	[deg]	10.99 ± 0.06

Orbital elements

h	[AU ² /yr]	7.49 ± 0.01	a	[AU]	1.89 ± 0.02
e	[/]	0.500 ± 0.004	q	[AU]	0.9477
i	[deg]	11.19 ± 0.06	Q	[AU]	2.84 ± 0.03
Ω	[deg]	25.28251 ± 0.00008	T	[yr]	2.61 ± 0.03
ω	[deg]	146.5 ± 0.1	T_J	[/]	3.77 ± 0.02
ν	[deg]	33.5 ± 0.1	M_ν	[deg]	10.1 ± 0.2

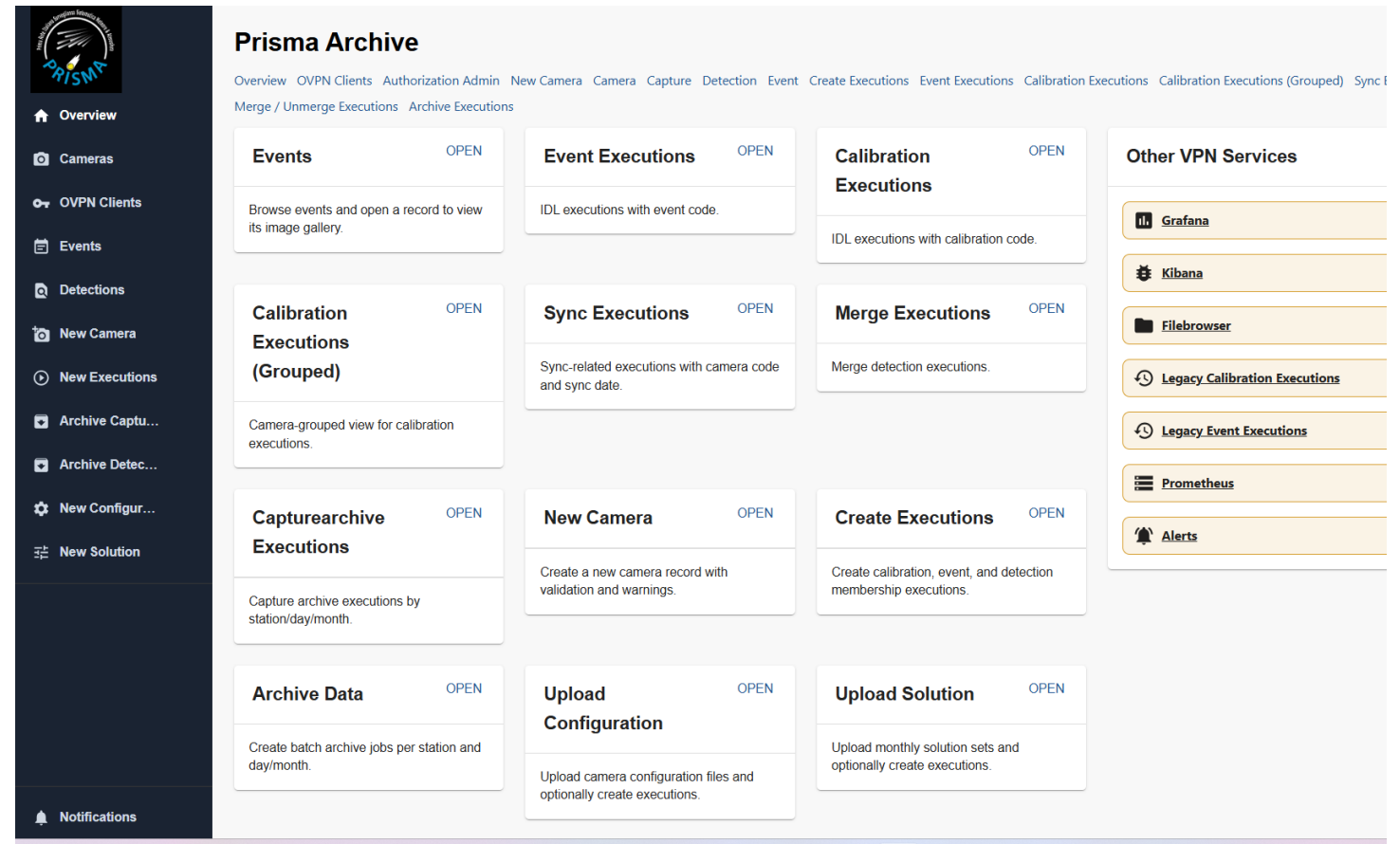
PRISMA Backstage

Serves as the **web gateway to all services for PRISMA scientific users.**

Allows users to:

- **view analysis results**
- **submit execution requests** (for calibrations and event analysis)
- manually **merge single events** missed by automatic detection
- **manage the network** (create and configure new camera, etc...)

Designed for a **distributed effort!**



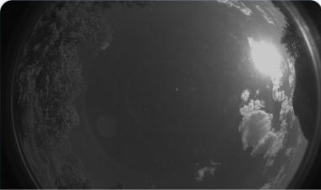
PRISMA Front End



PRISMA Public Archive

[Camera Mosaic](#) [Camera List](#) [Camera Map](#) [Events](#)

Search code/name Code ASC



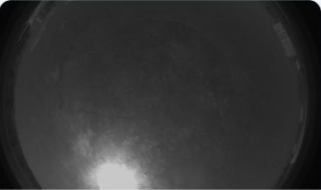
DEBW21
FTP01
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[Open camera detail](#)



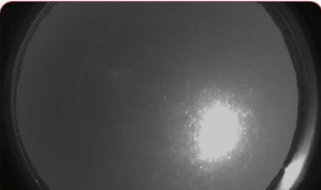
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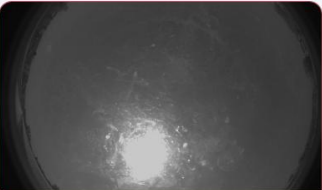
DEBY20
MUENSTERSCHWARZACH
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[Open camera detail](#)



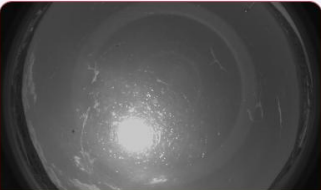
FRCA20
NICE
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[Open camera detail](#)



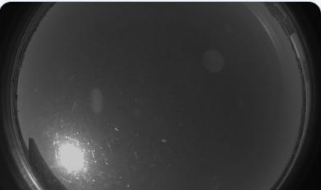
FRCA21
FREJUS
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[Open camera detail](#)



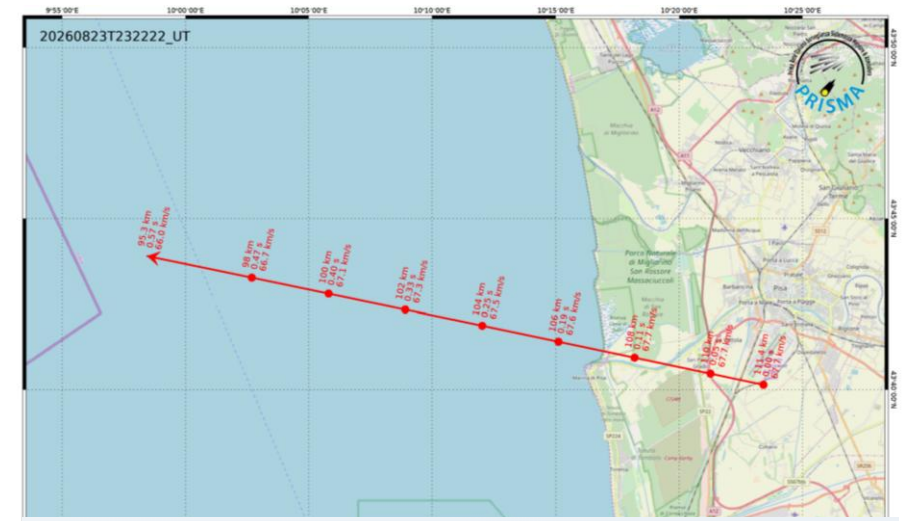
FRCA22
VINON
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[Open camera detail](#)



GREA20
EA01
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[Open camera detail](#)



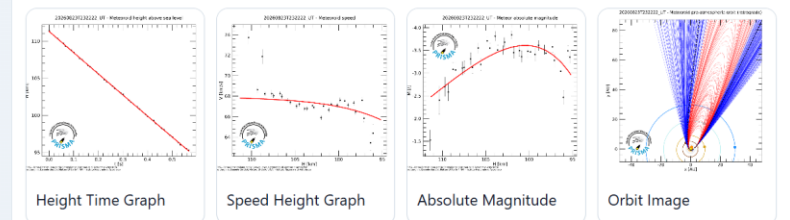
GREV21
EA02
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[Open camera detail](#)



Metadata

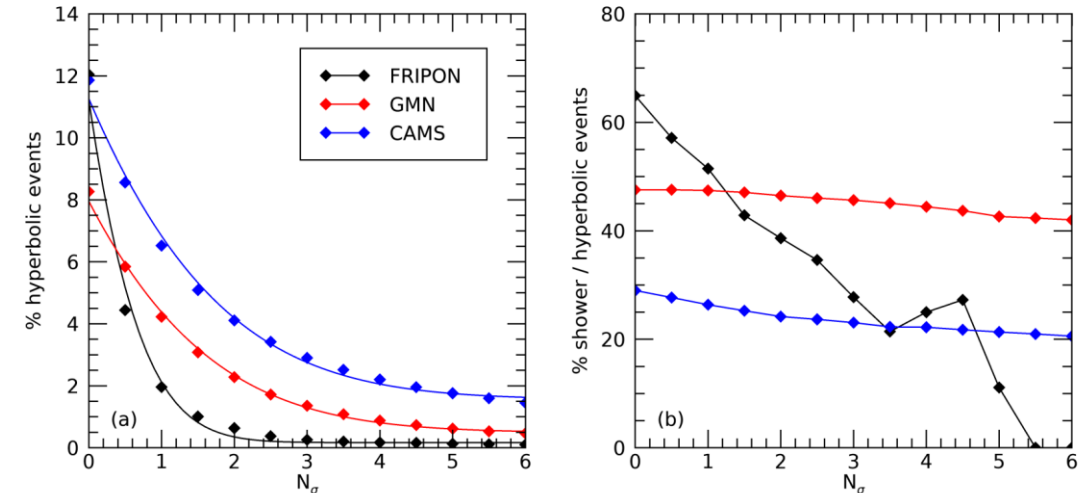
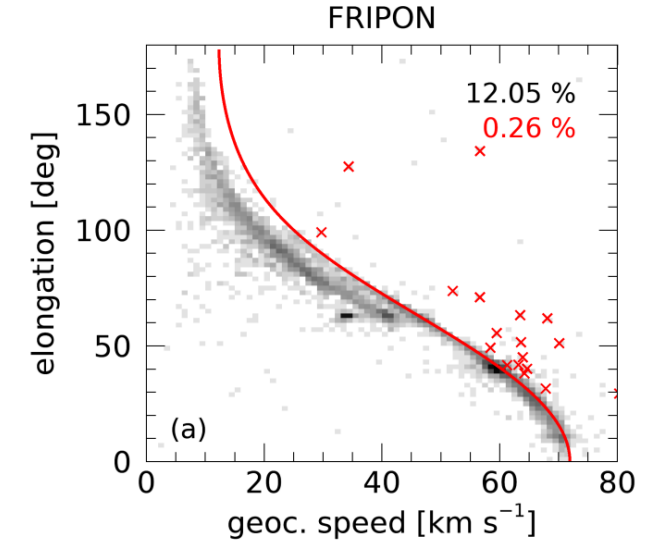
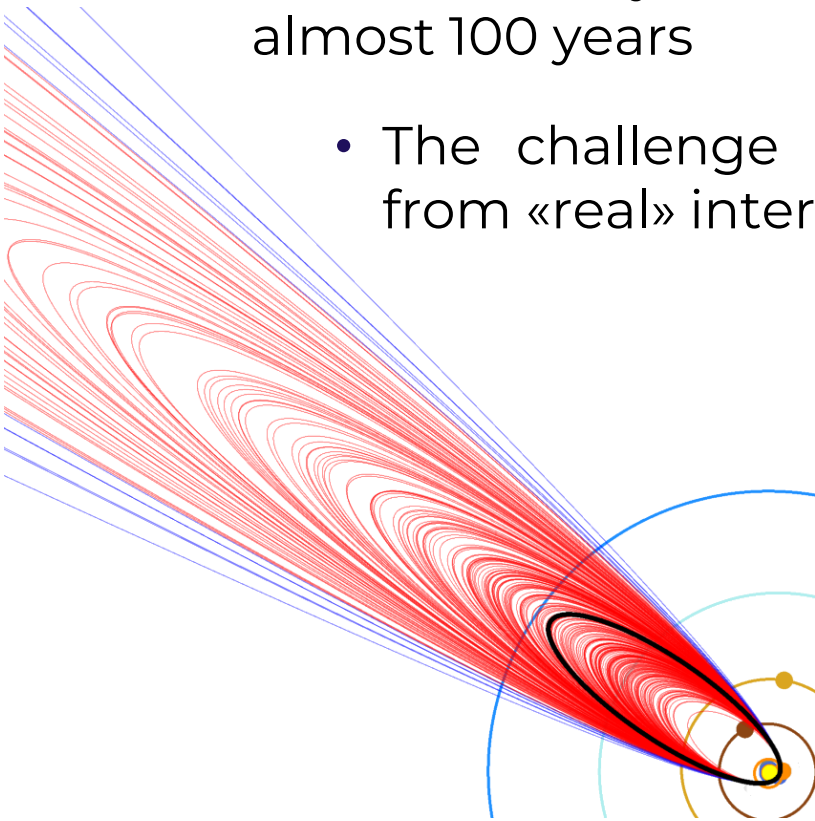
Code	20260823T232222_UT
Event Type	Meteor
Occurred At	23/08/2026, 23:22:22
Min Absolute Magnitude	-3.843
Magnitude Line	[/] -3.843 ± 0.090 @ 102.0 km
Velocity	66.0328
Velocity Line	[km/s] 67.7419 ± 1.1736 66.0328 ± 3.5831
Height	95.2908
Height Line	[km] 111.3984 ± 0.0502 95.2908 ± 0.0700

Event Images



Investigating Hyperbolic Orbits

- The last decades witnessed an increasing interest in **interstellar objects**, since the first telescopic detections
 - Meteor surveys observe **hyperbolic orbits** since almost 100 years
 - The challenge is to **separate false positives** from «real» interstellar candidates



Conclusions

- **PRISMA celebrates 10 years in 2026** and it's working towards achieving all its **major milestones** needed to consolidate its scientific output
- The last four years have seen a significant research and development effort to **deploy an IT infrastructure** able to support the routine operations of the network
- **Two meteorites recovery since 2016**, we're expecting the next any days now!
- **Scientific pipeline** has been tested thoroughly, also on **data from other surveys** (such as the one from the DIMS project)
- Fireball processing for the whole database is underway. Expected preliminary data release at the end of 2026. **Stay tuned!**

