PRISMA

A network of very small telescopes for the monitoring of bright meteors and the recovery of freshly-fallen meteorites in Italy

D. Barghini, A. Carbognani, D. Gardiol, S. Bertocco,
M. Di Carlo, M. Di Martino, C. Falco, M. Morelli,
G. Pratesi, W. Riva, G. M. Stirpe, C. Volpicelli,
and the PRISMA team

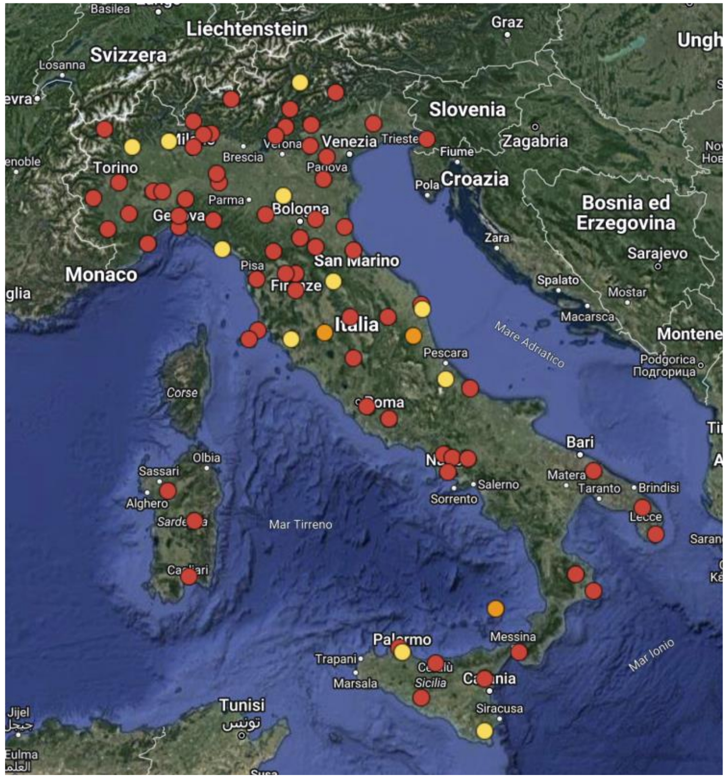
Prima Rete Italiana Sorveglianza Sistematica Meteore & Atmosfera
PRISMA

The PRISMA network

Prima **R**ete **I**taliana per la **S**orveglianza sistematica di **M**eteore e **A**tmosfera
(First Italian Network for the Systematic Surveillance of Meteors and Atmosphere)

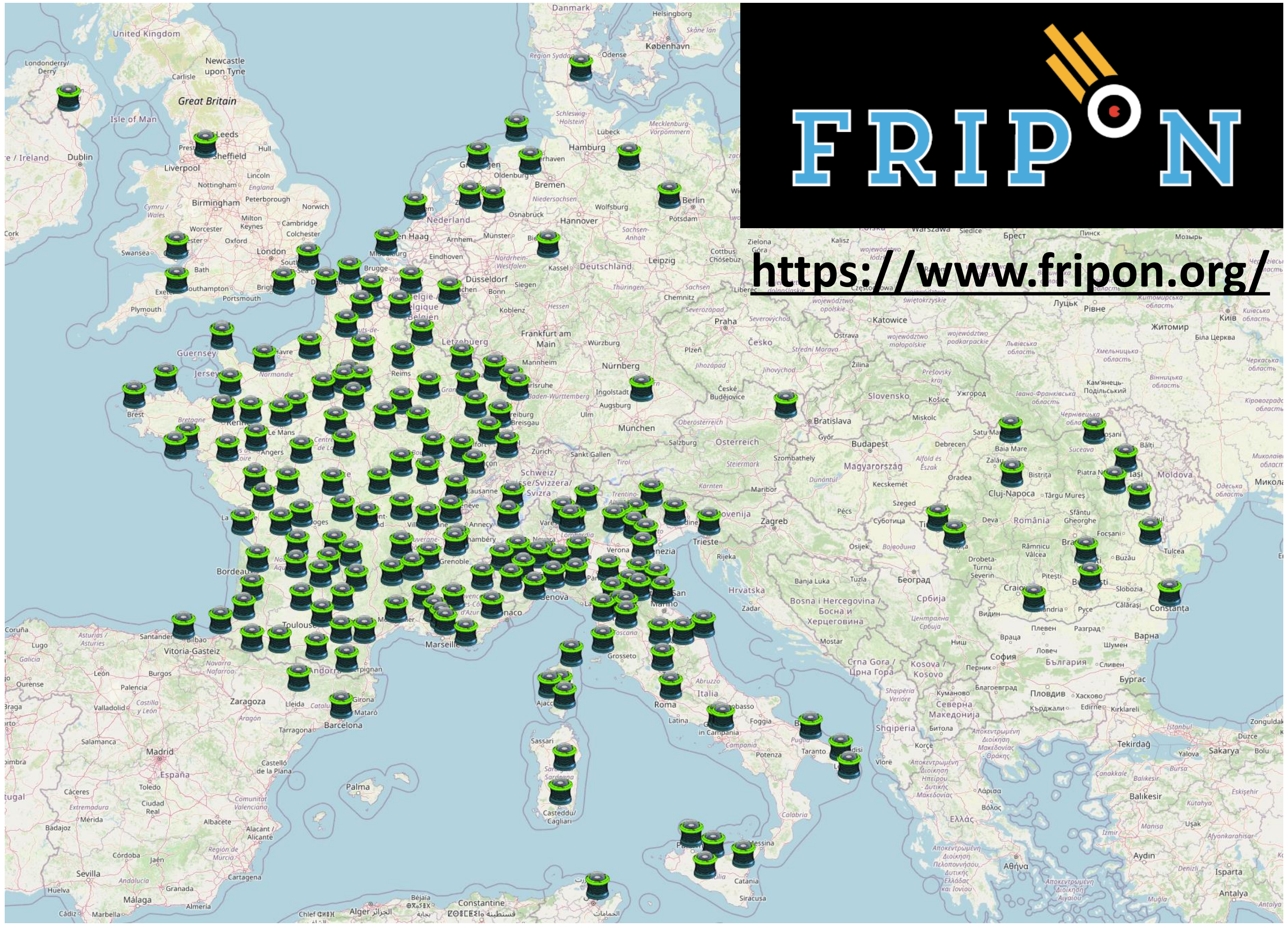
- Deploys **~70 stations** equipped with all-sky cameras for a continous monitoring of the Italian skies
- Started in 2017 and currently **led by INAF** in collaboration with many Italian universities, professional/amateur observatories, schools, associations…
- Partnered with the European project **FRIPON**, which deployed ~180 stations in Europe and worldwide

www.prisma.inaf.it



The FRIPON network

Fireball **R**ecovery and **I**nter**P**lanetary **O**bservation **N**etwork



https://www.fripon.org/

The PRISMA/FRIPON station node

All-sky camera:
[Basler acA1300-30gm]
- **CCD Sony ICX445ALA 1.2 Mp (1296x966 pix)**
- **30 fps – 1/30 s exp. time**

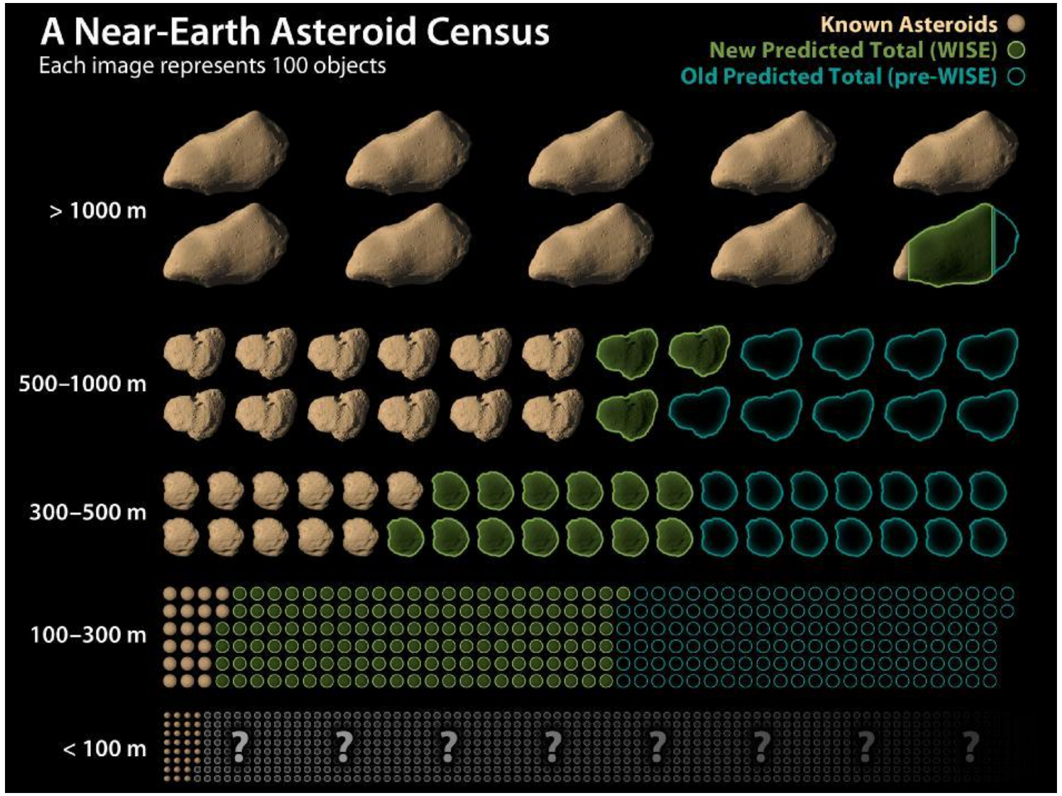
- All-sky camera **operated at 30 Hz** to capture meteors with a suitable sampling rate
- Meteor acquisition triggered by a dedicated software named **FreeTure**
- The central FRIPON server combine **detections of the same meteor** in events
- Every 10 minute the camera performs a 5 s exposure (**capture**) for calibration purposes

PRISMA dataset:

- **Captures**: ~140 / day (x 60 cameras, x 5 years)
- **Events**: ~2.5k since 2017 (multiple events from ≥ 2 cameras)

Why should we observe meteors?

- The **smallest NEA ever observed** by a ground-base telescope is 2015 TC_{25}, estimated to be **2-meter sized**. Its observation was possible only thanks to its high albedo of ~60%
- The **population below 100-meter sized asteroids is poorly constrained** by telescopic observations, while being a source of potential impactors at the Earth over the medium-term horizon
- The observation of meteors allows to probe the sub-meter population of bodies with a significant statistics
- Even smaller objects can be dangerous for **human space operations and satellites**

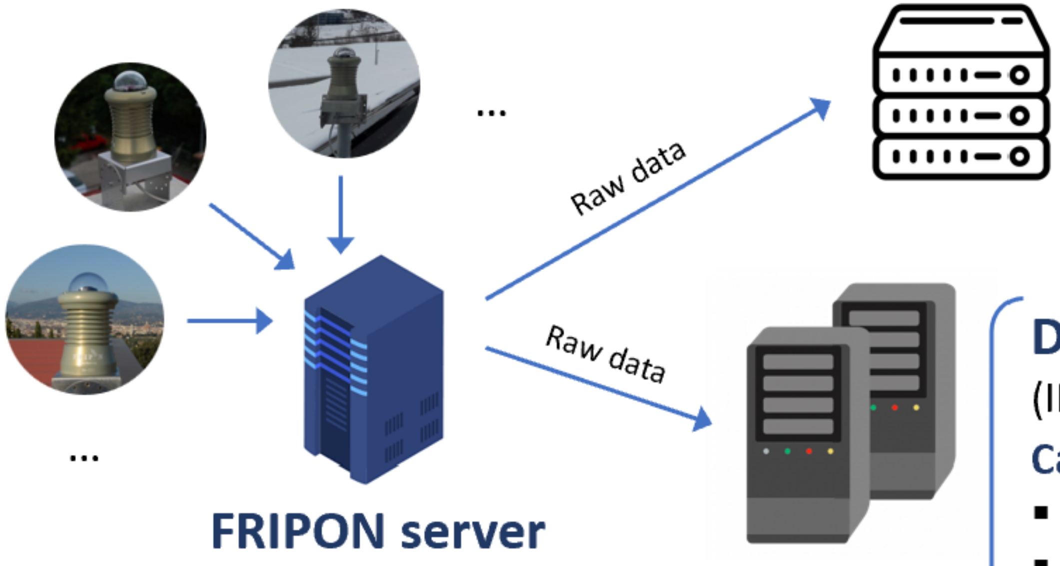


Why should we recover meteorites?

- A meteorite is the **remnant of asteroid of meteoroid** that survived the ablation phase of the meteor and felt on the ground
- Recovering meteorites represents a **easy and «cheap» way to gather extra-terrestrial** material (with respect to sample-return missions)
- The recovery of **freshly fallen meteorites** is even more precious, since these samples are **not affected by terrestrial weathering**
- An accurate and precise observation of the atmospheric entry of a meteoroid allows to reconstruct its **pre-atmospheric orbit**
- This enables the investigation of **links between the NEOs and meteorite classes**

The meteorites collection at the *Museo di Scienze Planetarie* in Prato (http://www.museoscienzeplanetarie.eu/)

Data flow of PRISMA/FRIPON data



Long-term data storage & Web access
at INAF-IA2 (OA Trieste)

FRIPON server
(LAM/OSU Pythéas)

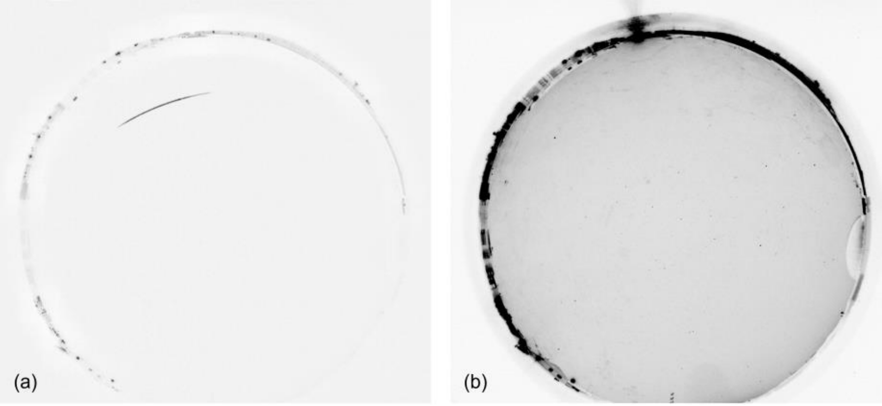
Data processing pipeline
(INAF-OA Torino)

Calibration:
- Astrometry
- Photometry

Processed data

Events analysis:
- Video analysis
  (astrometry and photometry)
- Triangulation
- Dynamic model
- Orbit

Processed data

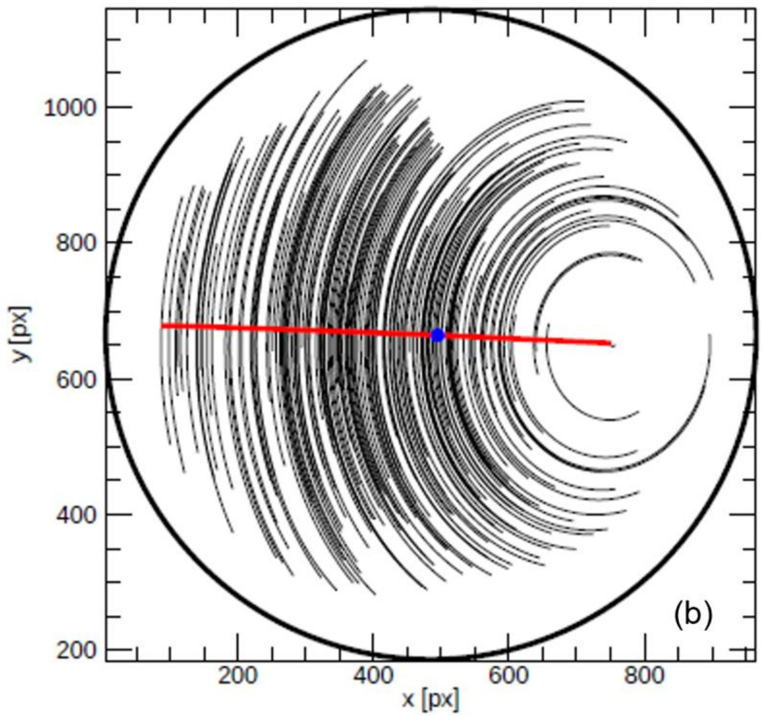


Astrometric calibration (1)

- Captures are used to deduce an **absolute astrometric and photometric calibration** of each PRISMA cameras
- Automatic **identification and catalogue's association** of stars
- Astrometry of fish-eye cameras has to deal with a lot of **distortion components in the FoV**
- **Final astrometric model** accounts for 8 (+2) parameters

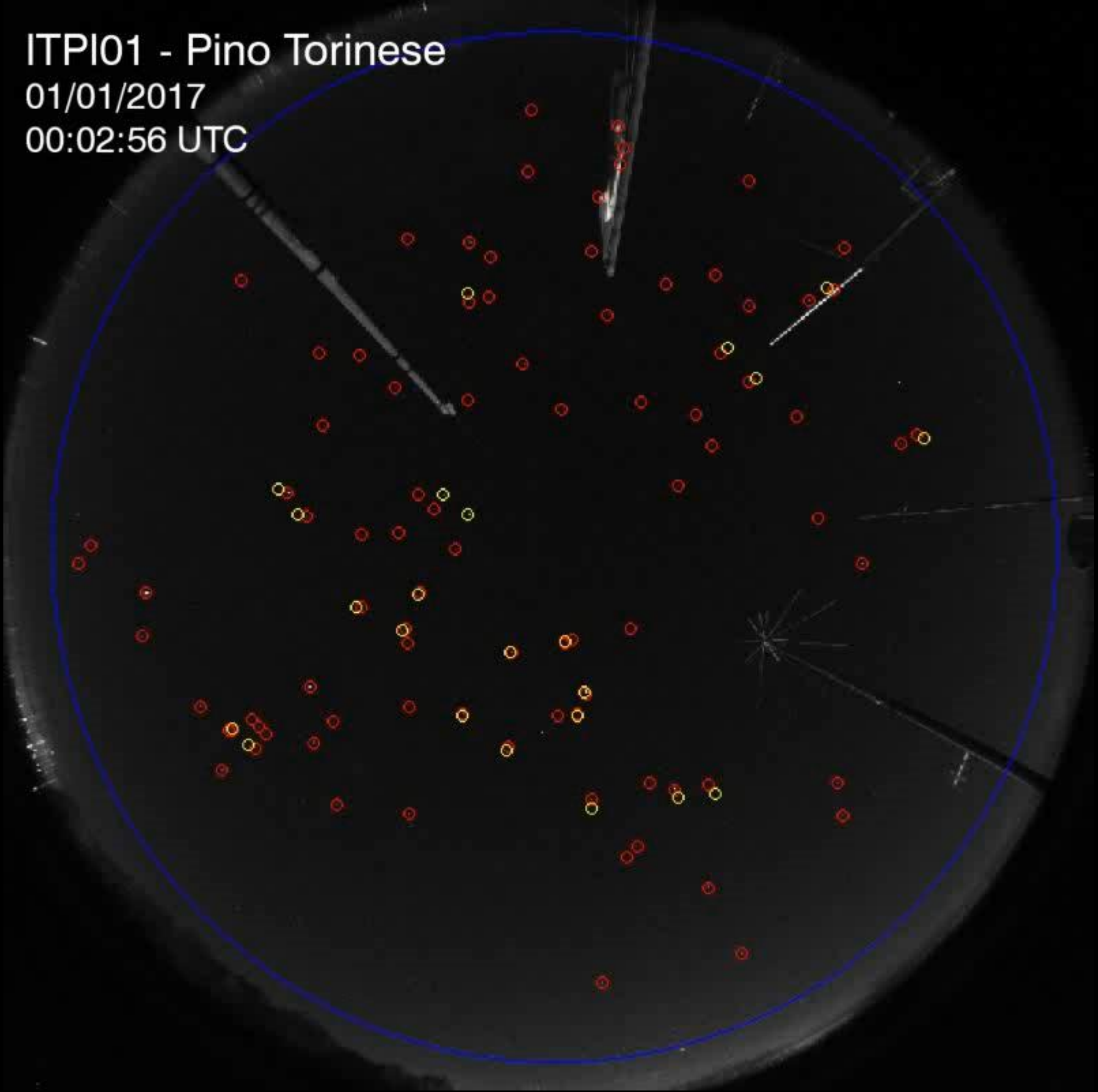
$$\begin{cases} b = a_0 - E + \text{atan}\left(\frac{y-y_O}{x-x_O}\right) \\ u = Vr + S(e^{Dr} - 1) \end{cases} \qquad \begin{cases} a = E + \text{atan}\left(\frac{\sin b \sin u}{\cos u \sin \epsilon + \cos b \sin u \cos \epsilon}\right) \\ z = \arccos(\cos u \cos \epsilon - \cos b \sin u \sin \epsilon)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

$$r = [1 + K \sin(b + E - \phi)] \sqrt{(x - x_O)^2 + (y - y_O)^2} \qquad \begin{cases} E = a_0 + \text{atan}\left(\frac{x_O - x_Z}{y_O - y_Z}\right) \\ \epsilon = V r_\epsilon + S(e^{D r_\epsilon} - 1) \end{cases}$$



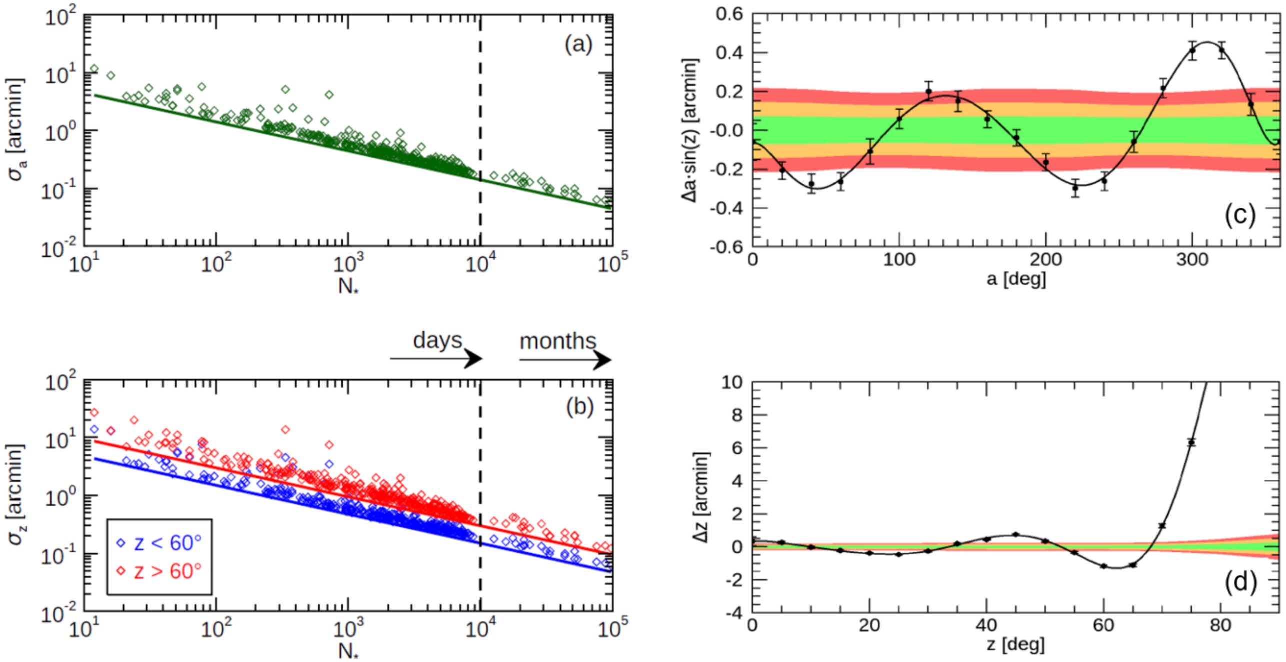
For details about PRISMA astrometric calibration:

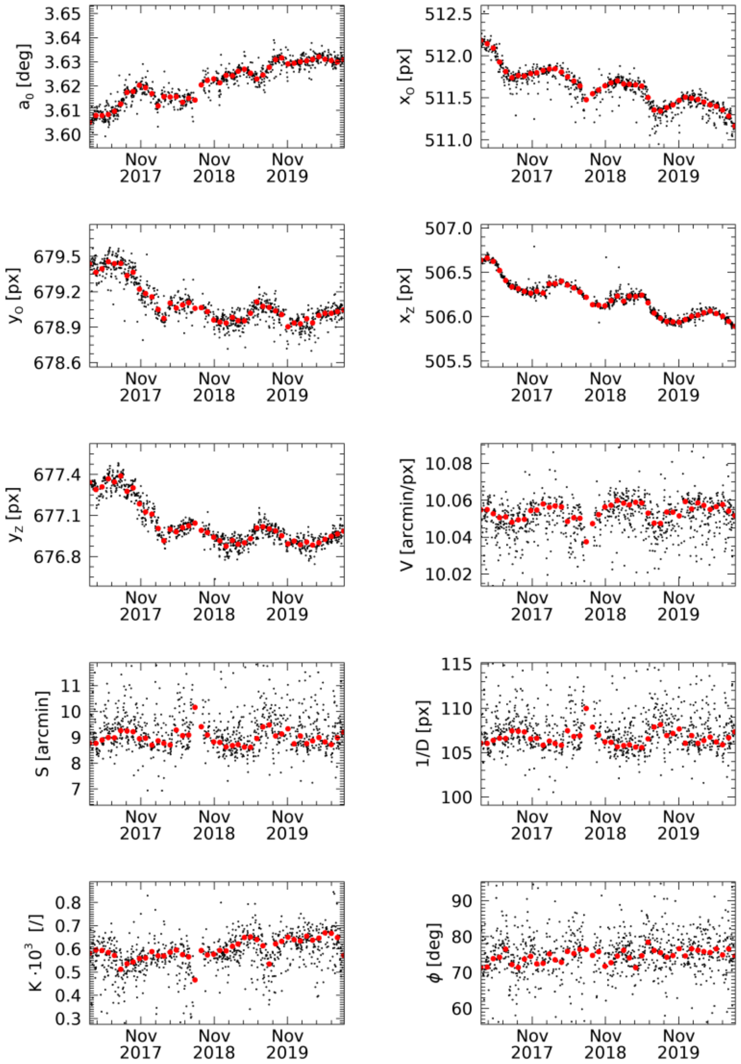
Barghini D., Gardiol D., Carbognani A. and Mancuso S., "Astrometric calibration for all-sky cameras revisited", *Astron. Astrophys.*, **2019**, 626, A105


ITPI01 - Pino Torinese
01/01/2017
00:02:56 UTC

Astrometric calibration (2)

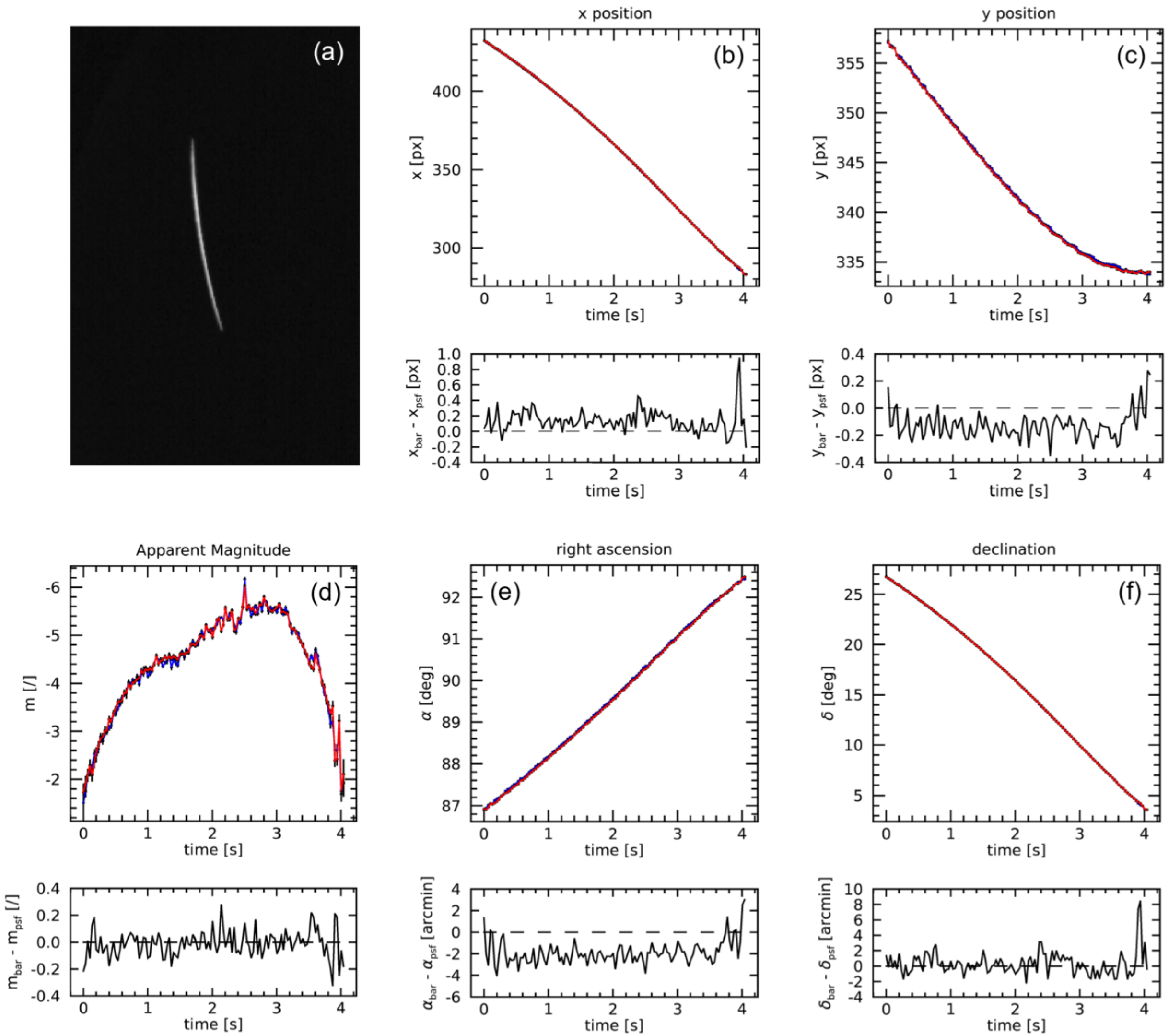
- Astrometric solution for daily and **monthly statistics** for each camera
- We are able to reach a **random projection error or ~ 0.2 arcsec** for a monthly calibration (10k-100k stars)
- The residuals show a **small systematic** (< 1 px) which is numerically corrected

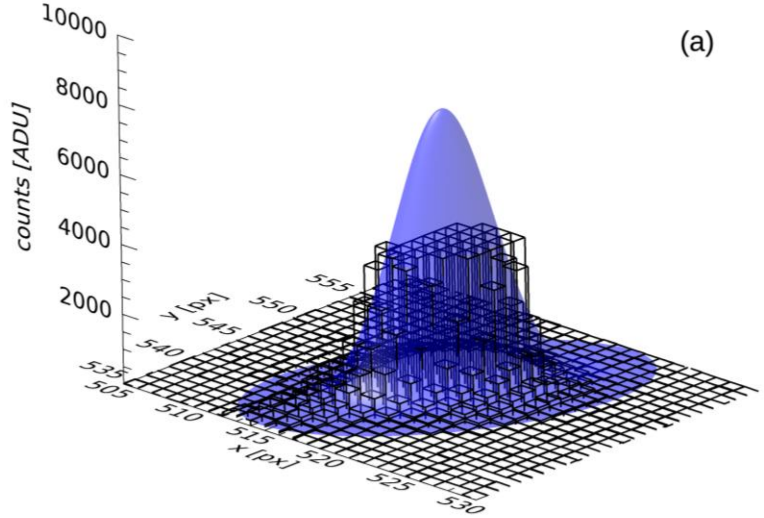




Analysis of events detected by PRISMA

- 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
- We apply a tentative correction by the analysis of the **shape of the unsaturated portion of the PSF**





Triangulation

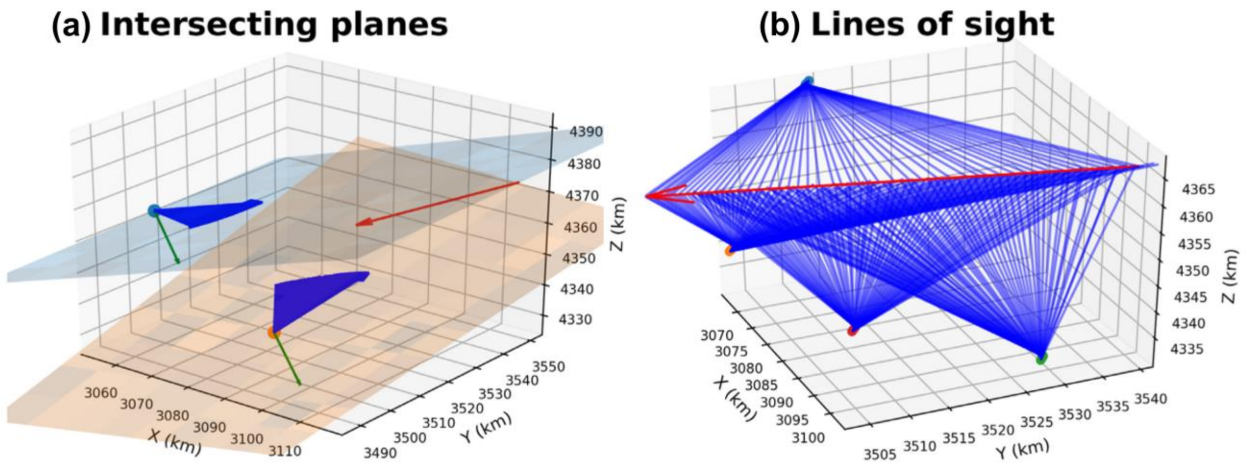
Two approaches:

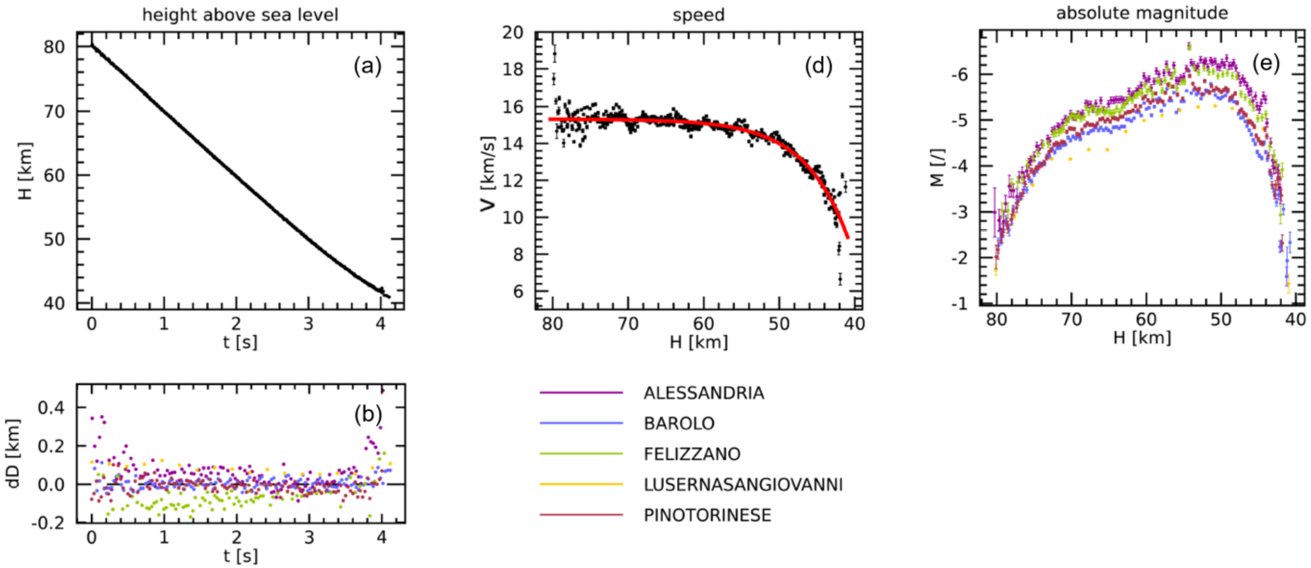
- **a) Plane intersection** from couples of cameras
- **b) Lines of Sight** distance minimization

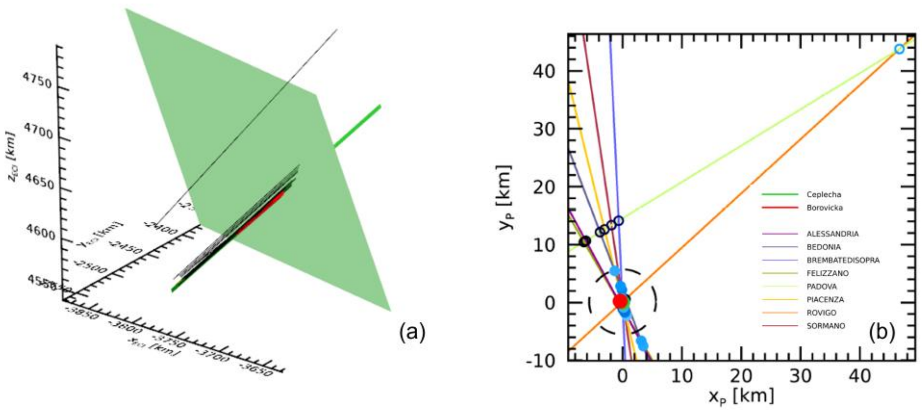
We implemented and combined both approaches in a unique solution

- We use (a) to detect outliers
- and then used (b) to give the final solution

Positioning precision of ~ 100 m







Dynamic model

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

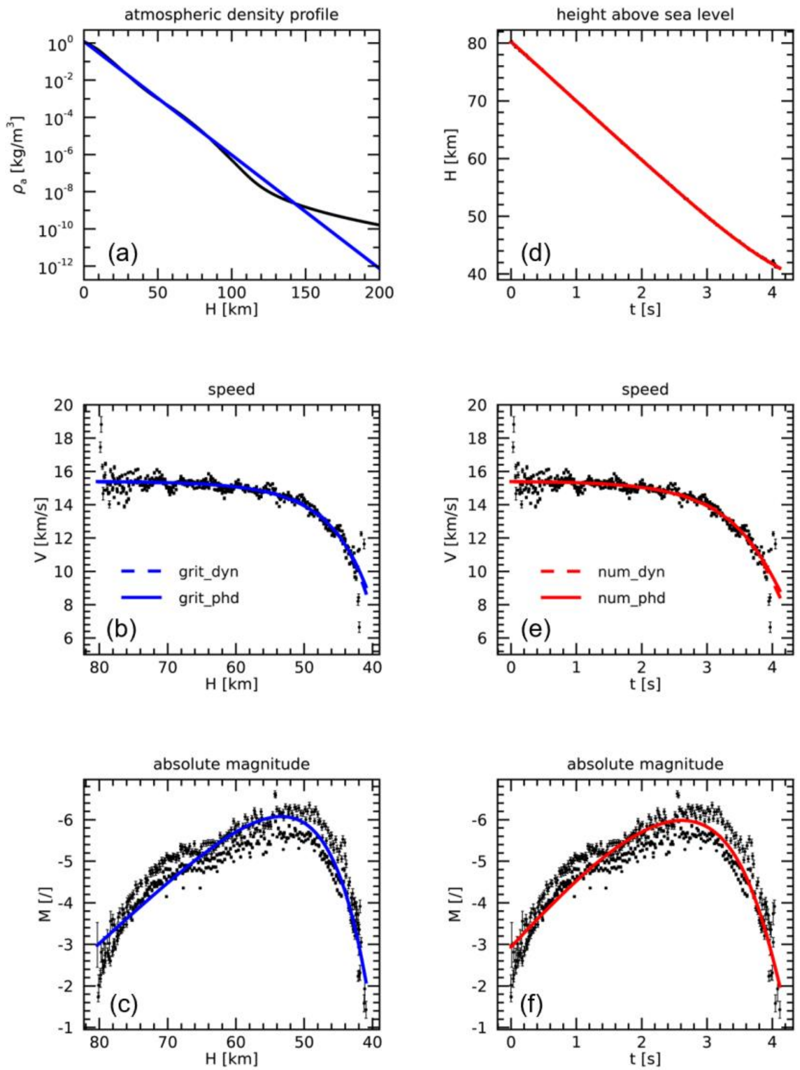
$$\begin{cases} \frac{\mathrm{d}H}{\mathrm{d}t} = -V\sin\gamma \\ M\frac{\mathrm{d}V}{\mathrm{d}t} = -\Gamma S\rho_a V^2 \\ M = M_\infty \exp\left\{\frac{1}{2}\sigma\left(V^2 - V_\infty^2\right)\right\} \\ I = -\tau M V\left(1+\frac{\sigma V^2}{2}\right)\frac{\mathrm{d}V}{\mathrm{d}t} \end{cases}$$

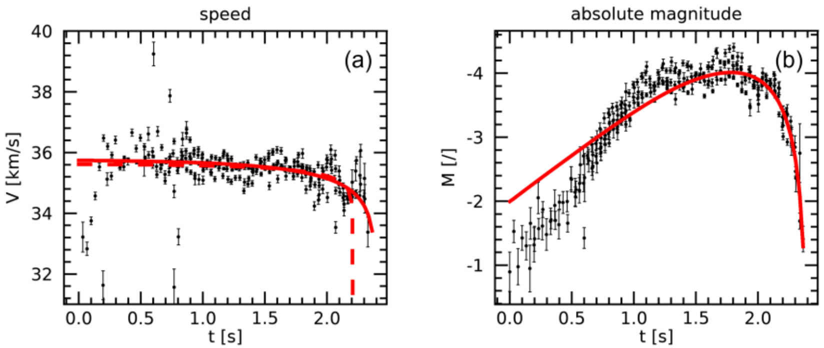
Two approaches:

- a) **Analytical solution**
- b) **Numerical solution**

Usually speed and magnitude data are considered separately.
We implemented a novel approach with a **simultaneous fitting of the deceleration and intensity data**

1. **Purely dynamical model** (only deceleration)
2. **Photo-dynamic model** (deceleration + intensity)



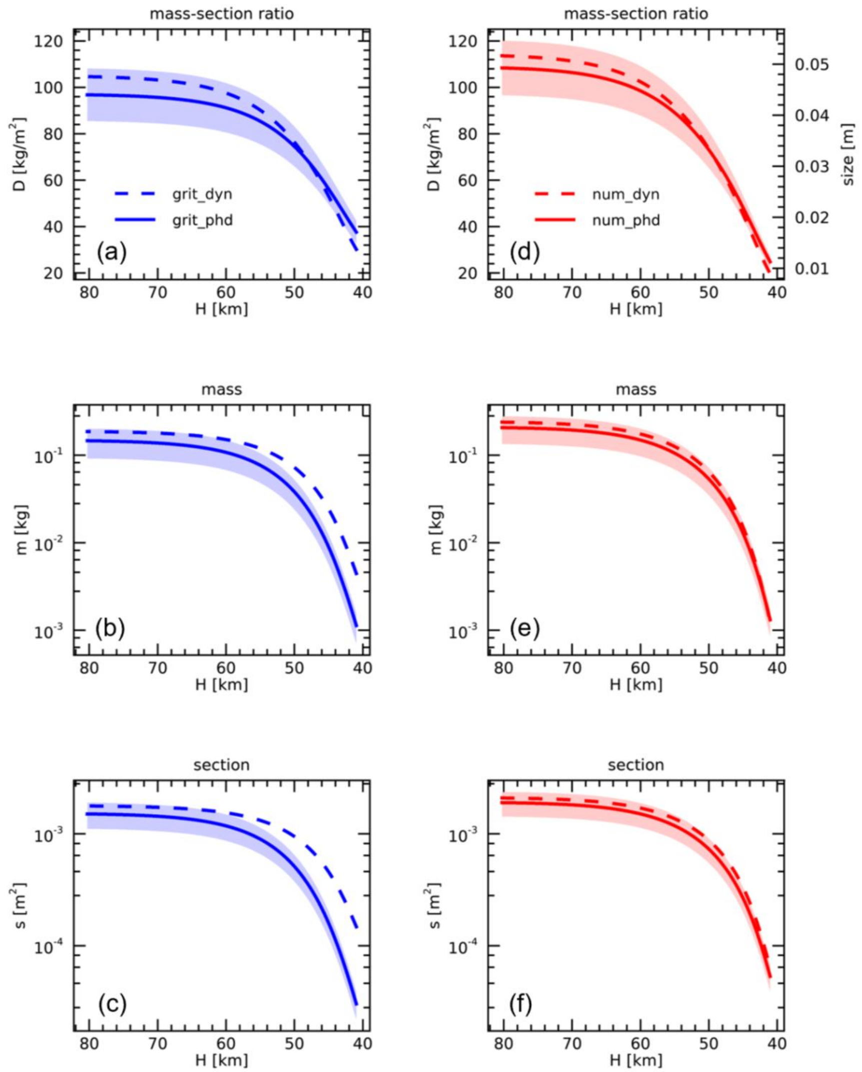


The photodynamical approach is particularly useful when dealing with events which showed **negligible deceleration**

Physical properties of the meteoroid

From **reasonable assumptions on the geometry of the body**, we can retrieve the physical parameters of the body, such as the **pre-atmospheric and final mass** and typical dimensions

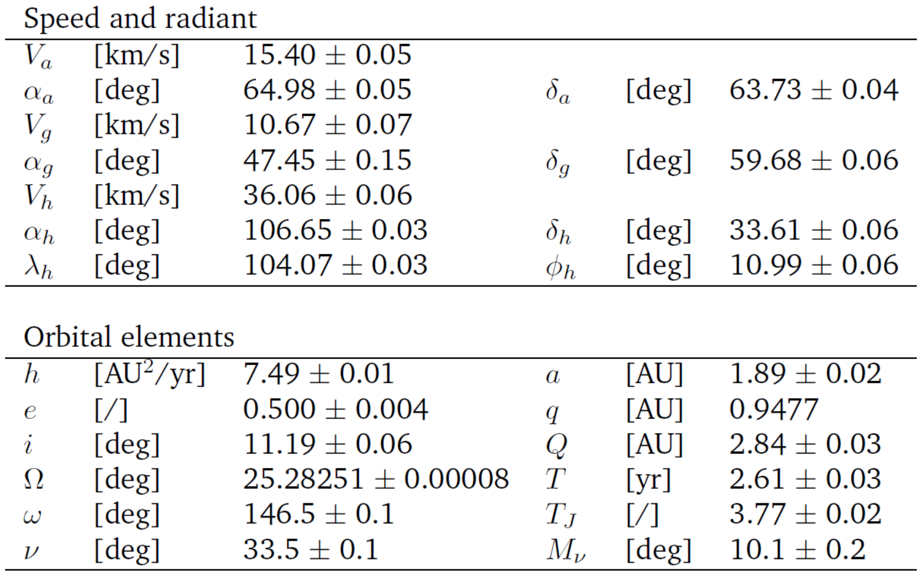
		GRIT_DYN	GRIT_PHD	NUM_DYN	NUM_PHD
V_∞	[km/s]	15.39 ± 0.08	15.41 ± 0.08	15.41 ± 0.05	15.40 ± 0.05
γ	[deg]	42.00 ± 0.20	42.00 ± 0.20	42.02 ± 0.04	42.09 ± 0.04
α	[/]	92 ± 11	100 ± 12	85 ± 10	89 ± 10
β	[/]	1.8 ± 0.1	1.5 ± 0.1	2.50 ± 0.07	2.21 ± 0.07
Ω	[/]	5.5 ± 0.4	7.5 ± 0.2	7.5 ± 0.2	7.6 ± 0.1
$\sigma\ (\cdot 10^2)$	[s^2/km^2]	4.6 ± 0.4	6.3 ± 0.2	6.3 ± 0.2	6.4 ± 0.1
μ	[/]	2/3	0.80 ± 0.01	2/3	0.71 ± 0.01
τ	[%]	–	4.5 ± 1.7	–	3.1 ± 1.1
D_∞	[kg/m^2]	105 ± 12	97 ± 11	114 ± 12	109 ± 12
D_{fin}	[kg/m^2]	30 ± 4	38 ± 5	20 ± 2	25 ± 3
M_∞	[g]	190 ± 70	150 ± 60	240 ± 80	210 ± 70
M_{fin}	[g]	4 ± 2	1.1 ± 0.4	1.3 ± 0.5	1.3 ± 0.5
S_∞	[cm^2]	18 ± 5	15 ± 4	21 ± 5	19 ± 5
S_{fin}	[cm^2]	1.5 ± 0.4	3.0 ± 0.9	0.7 ± 0.2	0.5 ± 0.2
$2r_\infty$	[cm]	4.8 ± 0.6	4.4 ± 0.6	5.2 ± 0.6	5.0 ± 0.6
$2r_{fin}$	[cm]	1.4 ± 0.2	1.7 ± 0.2	0.9 ± 0.1	1.1 ± 0.1



Pre-atmospheric orbit

The deduced **pre-atmospheric speed** (from the dynamic model) and **3D orientation** of the trajectory in ECI coordinates (from the triangulation) are then used to estimate the pre-atmospheric orbit of the meteoroid

1. Correction for the **zenithal attraction effect**
2. Conversion to **heliocentric ecliptic reference system**
3. Computation of the **orbital elements**

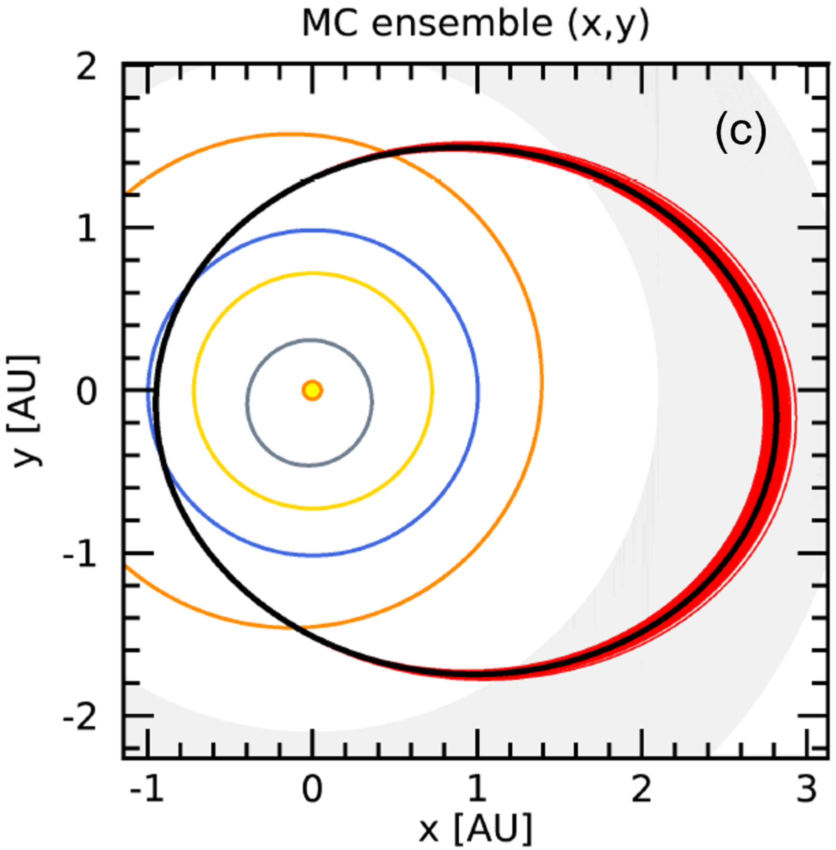


Speed and radiant

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



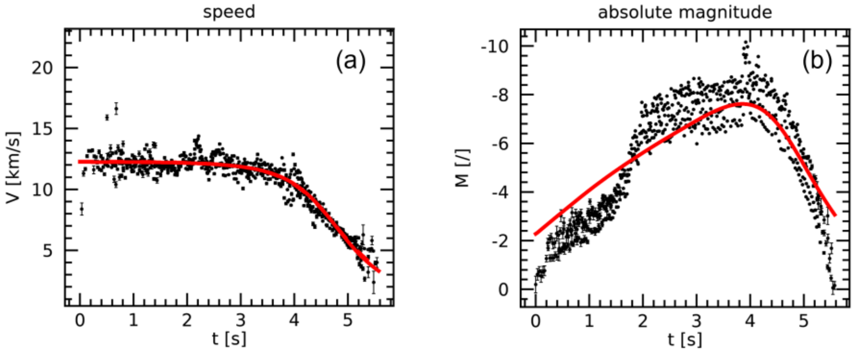
Meteorite-droppers observed by PRISMA

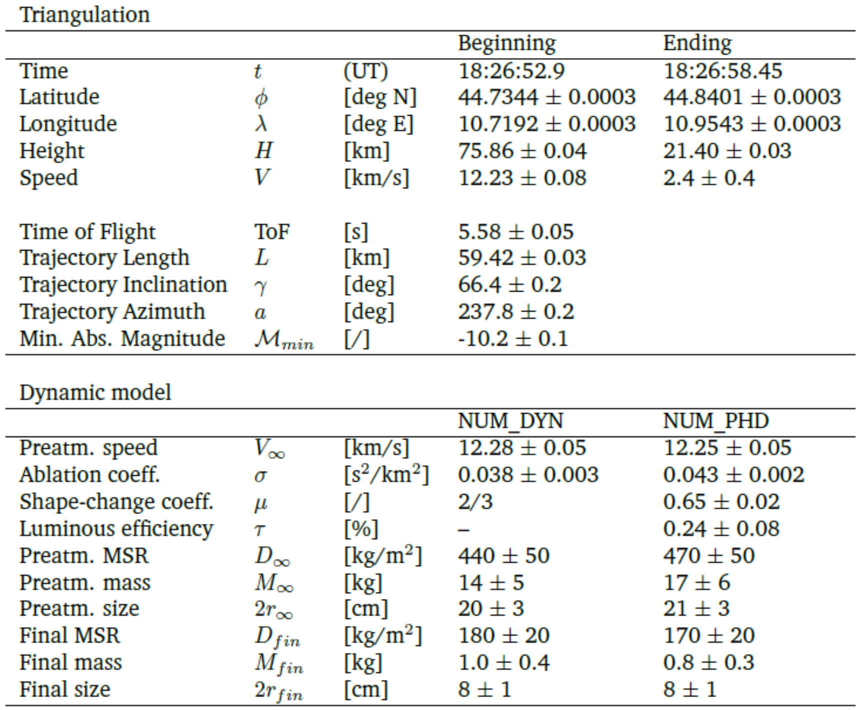
- Since 2017, PRISMA observed 10 bolides for which the final mass was estimated to be **significantly greater than zero**
- i.e., meteorites are expected to be found on the ground … and **computed a strewn-field** for these events
- For two of these events, meteorite hunting was successfull!

Date	Time	Provincia	V_∞ [km/s]	γ [deg]	M_∞ [kg]	M_{fin} [kg]
30/12/2017	21:09	Padova	15.6 ± 0.2	29.1 ± 0.4	4 – 12	0.2 – 4
22/08/2018	21:37	Sondrio	17.9 ± 0.1	72.1 ± 0.3	2 – 5	0.4 – 1.2
01/01/2020	18:26	Modena	12.27 ± 0.05	66.4 ± 0.2	10 – 40	0.5 – 1.5
15/03/2021	19:57	Isernia	~15	~85	~2	~1
01/10/2021	01:04	Pistoia	16.00 ± 0.07	30.8 ± 0.3	3 – 8	0.01 – 0.1
05/03/2022	18:55	Ascoli P.	15.5 ± 0.1	16.5 ± 0.9	10 – 90	0.3 – 1.5
14/02/2023	17:58	Matera	16.4 ± 0.2	56.7 ± 0.3	3 – 21	0.07 – 1.2
23/05/2023	22:21	Cremona	15.41 ± 0.09	34.9 ± 0.4	3 – 10	0.02 - 4
05/08/2023	20:21	Campobasso	13.8 ± 0.1	60.1 ± 0.2	20 – 100	0.1 – 2.5
08/10/2023	21:53	Sud Sardegna	16.5 ± 0.1	77.6 ± 0.5	0.2 – 1	0.02 – 0.22

The IT20200101 bolide

- Detected by 8 PRISMA stations in the skies of Northern Italy on 01/01/2020 at 18:26:53 UT
- The meteoroid entered the atmosphere at a **low speed** of 12.28 ± 0.05 km/s with a **high inclination** of $66.4 \pm 0.2°$, shining at a minimum **absolute magnitude of -10**



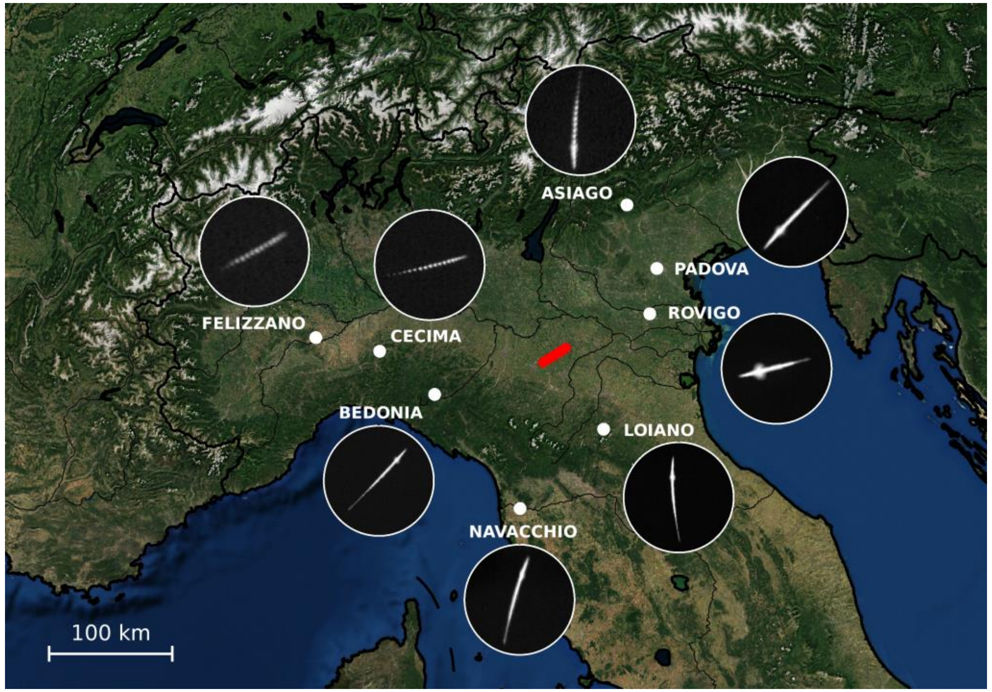


Triangulation

			Beginning	Ending
Time	t	(UT)	18:26:52.9	18:26:58.45
Latitude	ϕ	[deg N]	44.7344 ± 0.0003	44.8401 ± 0.0003
Longitude	λ	[deg E]	10.7192 ± 0.0003	10.9543 ± 0.0003
Height	H	[km]	75.86 ± 0.04	21.40 ± 0.03
Speed	V	[km/s]	12.23 ± 0.08	2.4 ± 0.4
Time of Flight	ToF	[s]	5.58 ± 0.05	
Trajectory Length	L	[km]	59.42 ± 0.03	
Trajectory Inclination	γ	[deg]	66.4 ± 0.2	
Trajectory Azimuth	a	[deg]	237.8 ± 0.2	
Min. Abs. Magnitude	$\mathcal{M}_{min}$	[/]	-10.2 ± 0.1	

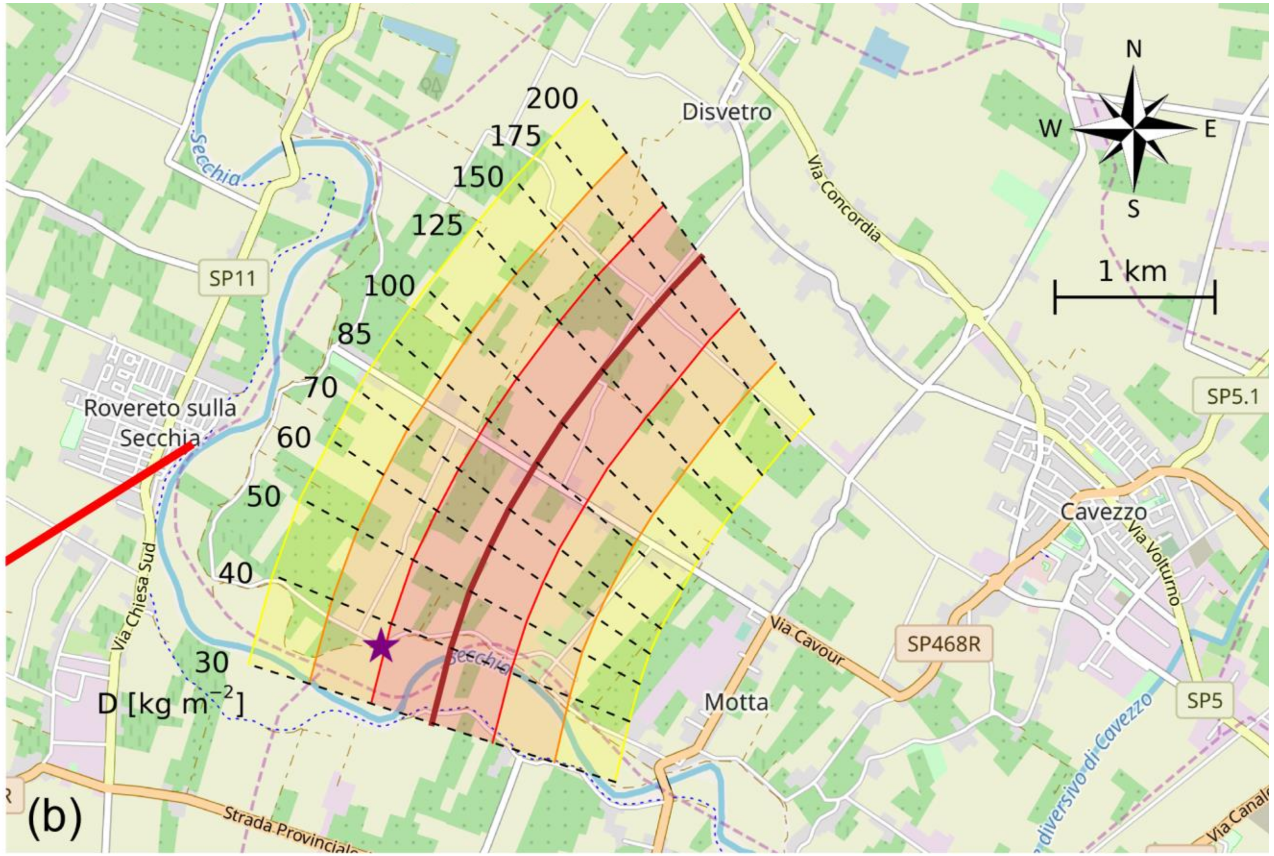
Dynamic model

			NUM_DYN	NUM_PHD
Preatm. speed	V_∞	[km/s]	12.28 ± 0.05	12.25 ± 0.05
Ablation coeff.	σ	[s^2/km^2]	0.038 ± 0.003	0.043 ± 0.002
Shape-change coeff.	μ	[/]	2/3	0.65 ± 0.02
Luminous efficiency	τ	[%]	–	0.24 ± 0.08
Preatm. MSR	D_∞	[kg/m^2]	440 ± 50	470 ± 50
Preatm. mass	M_∞	[kg]	14 ± 5	17 ± 6
Preatm. size	$2r_\infty$	[cm]	20 ± 3	21 ± 3
Final MSR	D_{fin}	[kg/m^2]	180 ± 20	170 ± 20
Final mass	M_{fin}	[kg]	1.0 ± 0.4	0.8 ± 0.3
Final size	$2r_{fin}$	[cm]	8 ± 1	8 ± 1



Strewn-field for the IT20200101 event

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



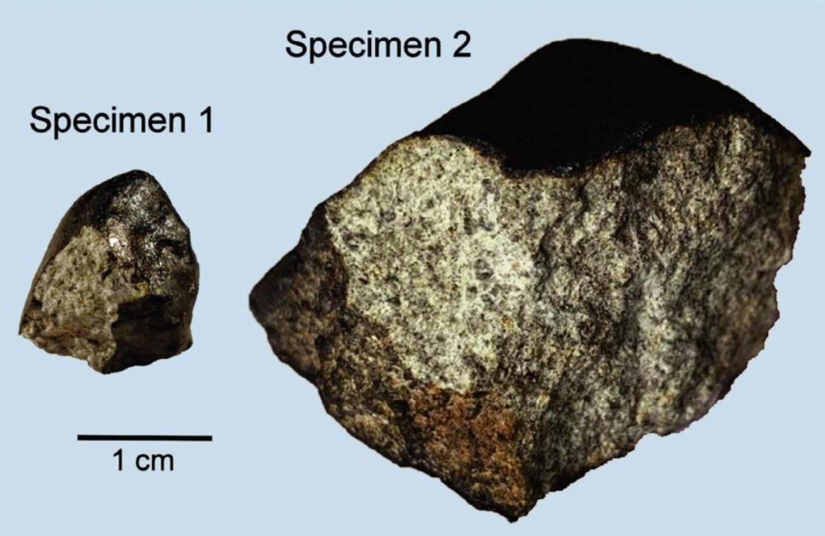
- Due to **intense winds of that night**, the area of probable fall was shifted to East with respect to ground trajectory
- PRISMA **informed and reached the attention of the local population** by press releases and local media coverage

For details about the Cavezzo meteorite recovery:

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**, 501, 1215

The recovery of the Cavezzo meteorite

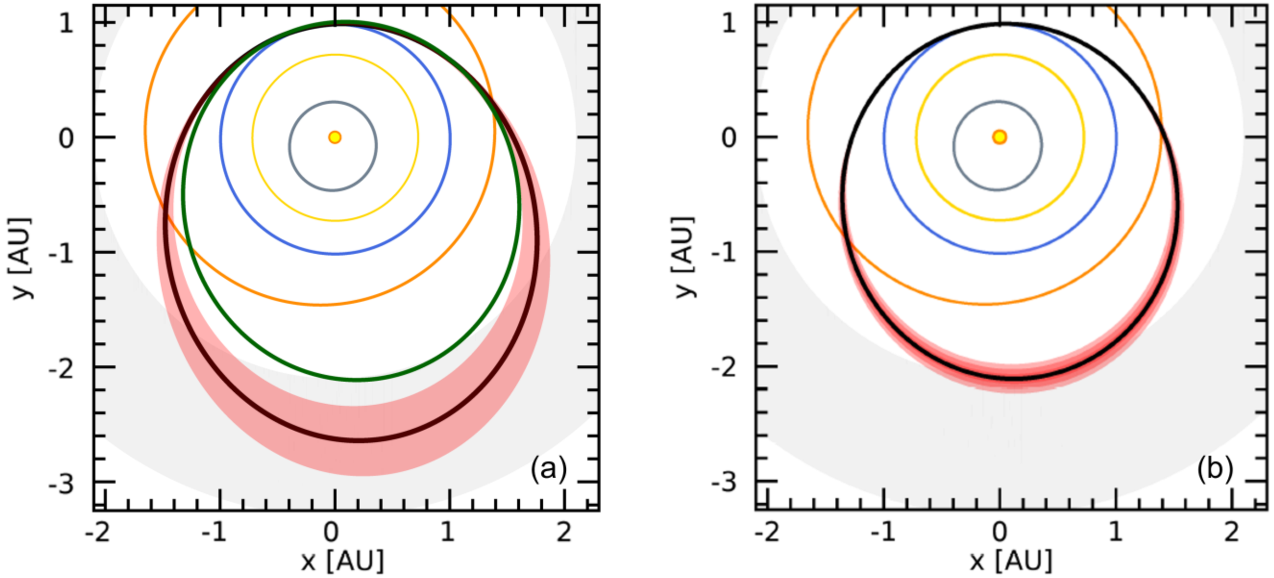
- **Two meteorite pieces were recovered** by a local inhabitant, Mr. Davide Gaddi, **less than three days after the fall** on the afternoon of 04/01/2020 in the municipality of **Cavezzo** (MO)
- The two specimens weigh **3.12 g (F1)** and **52.19 g (F2)** The coordinates of the finding are 44°49’43’’.7 N, 10°58’19’’.5 E
- Due to the morphology of the two recovered pieces, **other fragments should have been found on site**, but further campaigns were unsuccessful up until now
- Both fragments have been **donated to INAF** by the finder
- The main mass is preserved at the «Museo Italiano di Scienze Planetarie» in Prato, Toscana



Orbit of the Cavezzo meteoroid

- The Cavezzo meteoroid had an asteroidal **Apollo-type orbit** with low eccentricity and inclination on the ecliptic plane
- A search over the NEA database highlighted one candidate (**2013 VC$_{10}$**) only as the **possible parent body** of the Cavezzo meteoroid
- It is **50-m size NEA** ($H = 24.8$) observed for 54 days only between 2013 and 2014
- The orbit was recomputed after the original publication (Gardiol et al., 2021) and the updated results points towards an **even better match with 2013 VC$_{10}$**

		This work	FRIPON	G-2021	2013 VC$_{10}$
Epoch		J2000	J2000	J2000	MJD59000
a	[AU]	1.55 ± 0.02	1.545 ± 0.007	1.82 ± 0.22	1.566
e	[/]	0.366 ± 0.009	0.364 ± 0.003	0.46 ± 0.06	0.365
i	[deg]	3.20 ± 0.08	3.17 ± 0.01	4.0 ± 1.6	2.044
Ω	[deg]	280.652 ± 0.003	280.676 ± 0.003	280.52311 ± 0.00001	224.068
ω	[deg]	178.29 ± 0.09	178.26 ± 0.03	179 ± 5	240.264
q	[AU]	0.9832	0.9832	0.983 ± 0.001	0.9944
Q	[AU]	2.12 ± 0.04	2.11 ± 0.01	2.66 ± 0.41	2.1379
T_J	[/]	4.37 ± 0.04	4.38 ± 0.02	4.1 ± 0.2	4.344



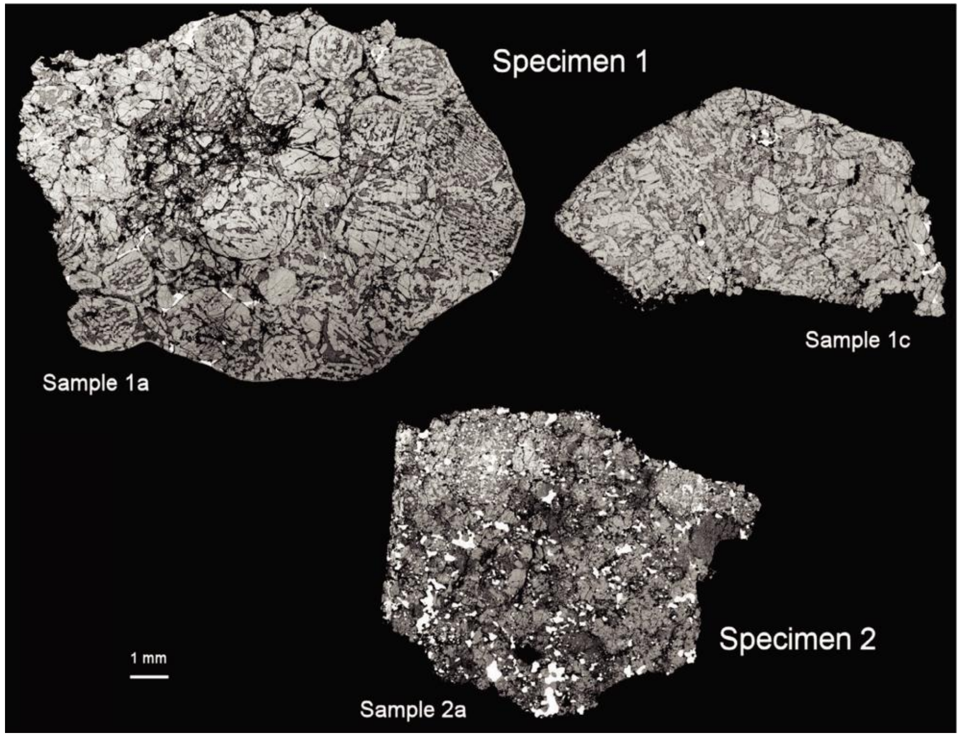
Analysis and classification of Cavezzo

- The two fragments show **peculiar differences** in their petrography and composition, and this is the main reason for the L5-anomalous classification
- F1 is believed to be a **previously unsampled portion of the parent body of L chondrites**
- Cavezzo was classified as a **L5-anomalous chondrite** (the first of this class over ~70k officially classified meteorites)

	F1 (3 g)	F2 (52 g)
Petrography	From well delineated to achondritic	Partially melted (typical for 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

For details about the Cavezzo meteorite analysis:

G. Pratesi, V. Moggi Cecchi, R.C. Greenwood et al., "Cavezzo — The double face of a meteorite: Mineralogy, petrography, and geochemistry of a very unusual chondrite", *Meteoritic Planet. Sci.*, **2021**, 56, 1125



The IT20230214 bolide

An event similar to the Cavezzo bolide occurred on **Saint’s Valentine Day of 2023** at 17:58:29 UT over the Puglia and Basilicata regions and was recorded by three PRISMA cameras

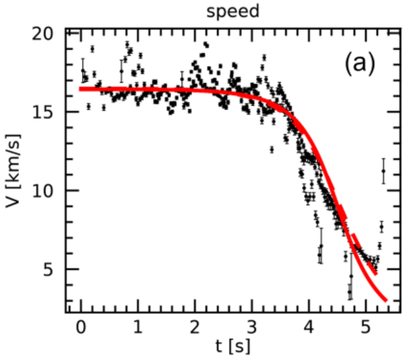
- **Low pre-atmospheric speed** (16.4 ± 0.2 km/s), **high inclination** ($56.7 \pm 0.3°$), absolute magnitude -11
- 0.1 – 0.6 kg of final mass

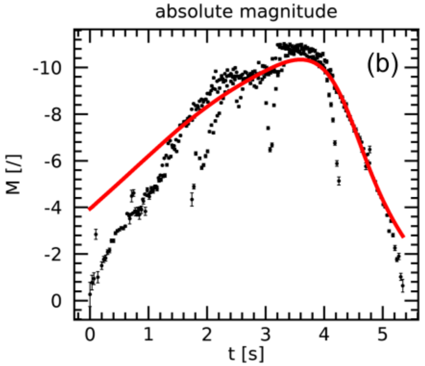
Triangulation

			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	

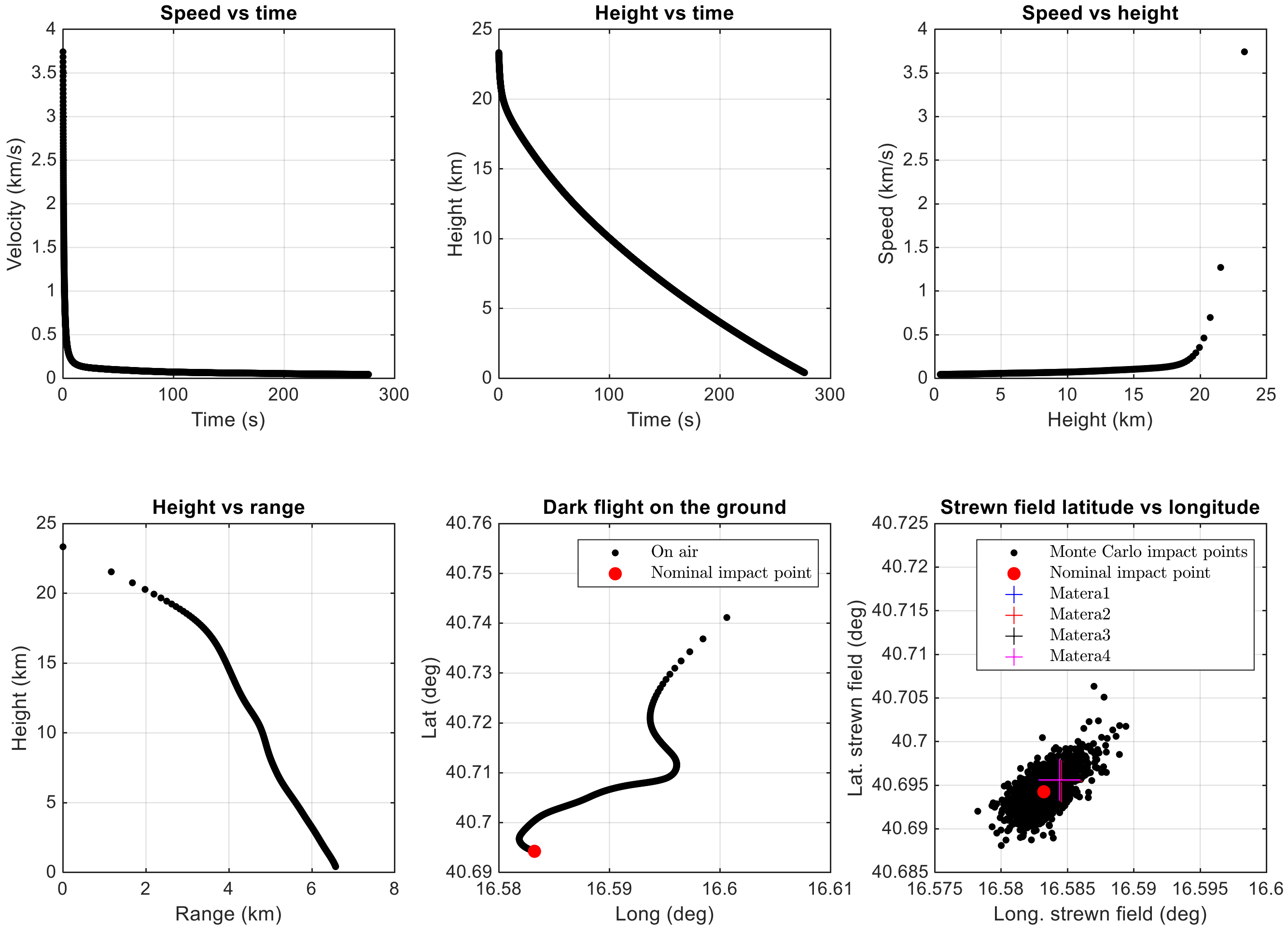
Dynamic model

			NUM_DYN	NUM_PHD
Preatm. speed	V_∞	[km/s]	16.4 ± 0.2	16.4 ± 0.2
Ablation coeff.	σ	[s^2/km^2]	0.020 ± 0.005	0.038 ± 0.002
Shape-change coeff.	μ	[/]	2/3	0.69 ± 0.03
Luminous efficiency	τ	[%]	–	1.5 ± 0.5
Preatm. MSR	D_∞	[kg/m^2]	360 ± 50	460 ± 50
Preatm. mass	M_∞	[kg]	8 ± 3	15 ± 6
Preatm. size	$2r_\infty$	[cm]	17 ± 2	21 ± 3
Final MSR	D_{fin}	[kg/m^2]	150 ± 30	100 ± 10
Final mass	M_{fin}	[kg]	0.6 ± 0.3	0.10 ± 0.04
Final size	$2r_{fin}$	[cm]	7 ± 1	4.4 ± 0.7





Strewn-field for the IT20230214 event


Speed vs time

Height vs time

Speed vs height

Height vs range

Dark flight on the ground

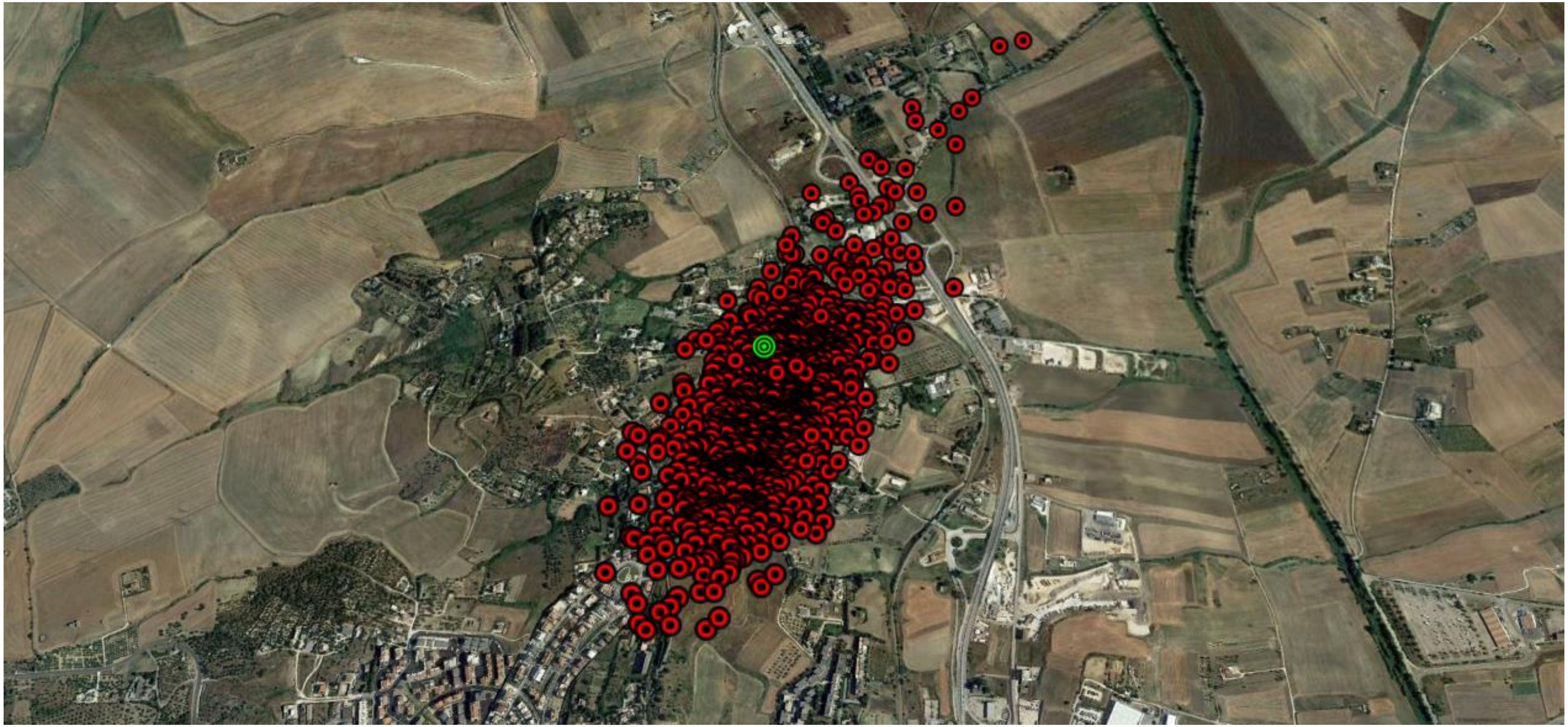
Strewn field latitude vs longitude

On the left the model for the **dark flight** path of the Matera meteorite (for a mass of about 70 g), computed taking into account the **wind speed and direction** from about 22.5 km to the ground. Model equation:

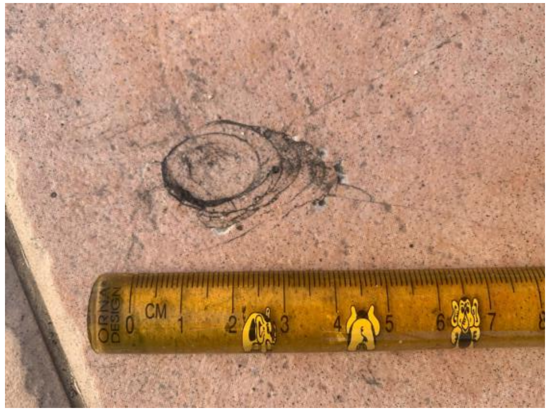
$$\frac{d\vec{v}_m}{dt} = -GMm\frac{\vec{r}}{r^3} - \Gamma\rho_a\left|\vec{v}_m - \vec{W}\right|A\left(\vec{v}_m - \vec{W}\right)$$

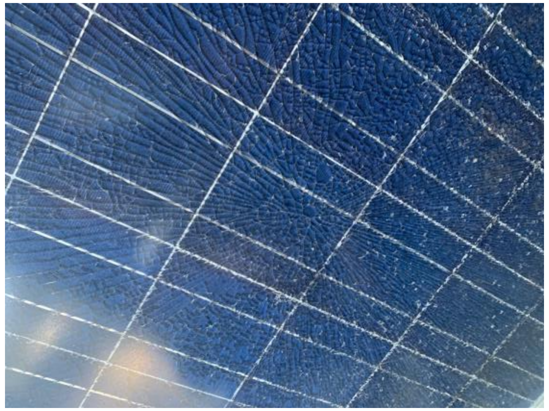
In this equation Γ is the drag coefficient, ρ_a is the atmospheric density, A is the area of the meteoroid, v_m is the speed of the meteoroid and W is the wind speed.

Strewn-field for the IT20230214 event



The recovery of the Matera meteorite





Specimen	Mass (g)	Characteristics	Finder	Fragment	Lat. (°)	Long. (°)
01	24.42	Single piece	Silvia Padilla & Pierluigi Cox	Matera 3	40.695418	16.584402
02	4.34	Single piece	Gianfranco e Pino Losignore	Matera 1	40.695507	16.584413
03	13.48	Single piece				
04	17.06	Single piece				
05	3.92	Many pieces		Matera 2	40.695468	16.584554
06	2.12	Many pieces				
07	3.60	Many pieces				
08	2.26	Many pieces				
09	0.09	Many pieces				
10	46.21	Main mass	—	Matera 4	40.695631	16.584405
11	~ 0.1	Many pieces	Paola Manzari (ASI)	Matera 5	unknown	unknown

TKW = 117.5 g

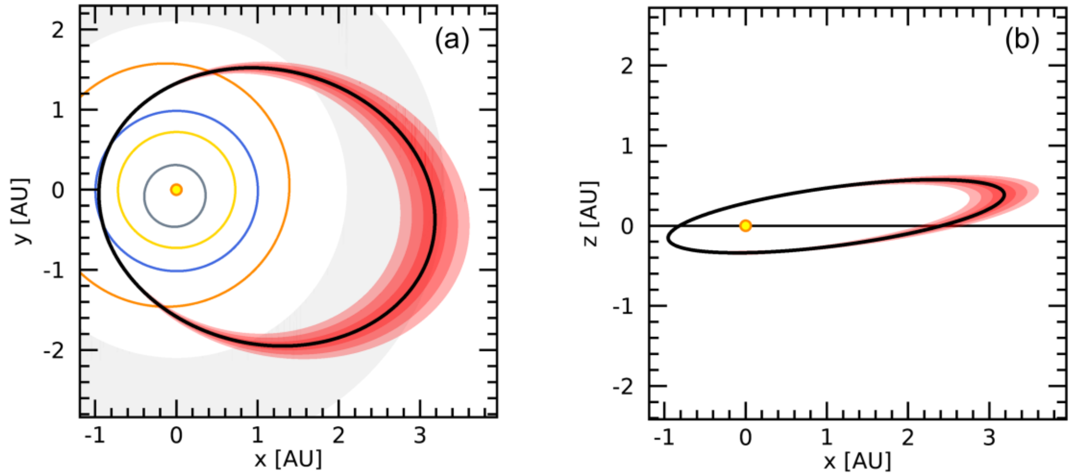
4 main fragments, dozens of small specimes

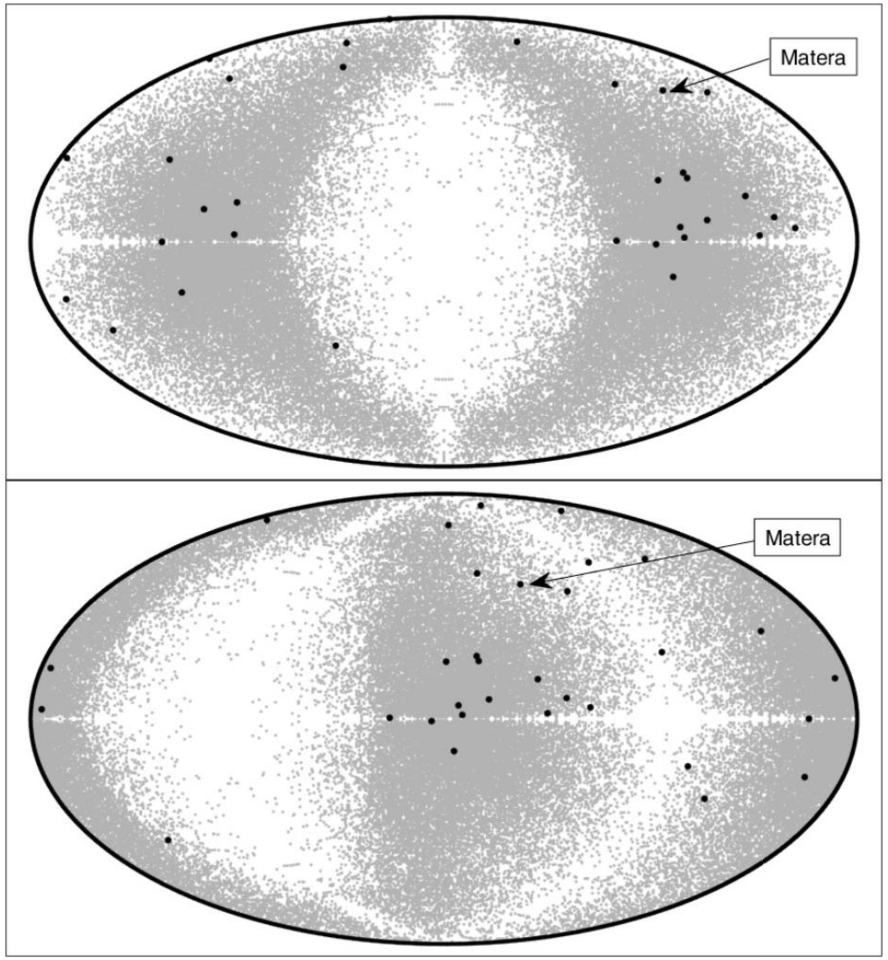
The recovery of the Matera meteorite

- The day after the recovery, all fragments were moved to the Istituto Nazionale di Fisica Nucleare - **Laboratori Nazionali del Gran Sasso** to measure their **γ-activity** with the HPGe detectors of the **STELLA** (Subterranean Low-Level Assay) facility
- The geochemical analysis of the meteorite was carried out at the **Dipartimento di Scienze della Terra of the Università di Firenze**

Approved by the Meteoritical Society as a **H5 ordinary chondrite** on February 2024

Orbit of the Matera meteoroid





- Typically **asteroidal orbit** with aphelion at 3.17 ± 0.19 and Tisserand invariant with respect to Jupiter equal to 3.55 ± 0.11
- Search in the NEODys-2 database with $D_N < 0.06$ (Valsecchi et al., 1999; Carbognani & Fenucci 2023) **1999 LD$_6$** ($D_N = 0.045$) and **2014 TS$_{16}$** ($D_N = 0.047$)

Conclusions and perspectives

- PRISMA established in Italy as the **main stakeholder and reference point for meteor observations** and meteorite recovery
- PRISMA allowed for the recovery of the **first two freshly-fallen meteorites in Italy**
- PRISMA operates in the framework of the **large international collaboration FRIPON**
- It formed a **strong collaboration** among professional astronomers, amateur astronomers, schools and associations interested in the topic
- The network is always evolving and extending to **reach total coverage of Italy**
- PRISMA is a real **citizen science project**, for which the contribution of non-academic people is fundamental in the search of meteorites

THANKS FOR YOUR ATTENTION