Ottimizzazione globale e stima delle incertezze per il modello dinamico della rete PRISMA

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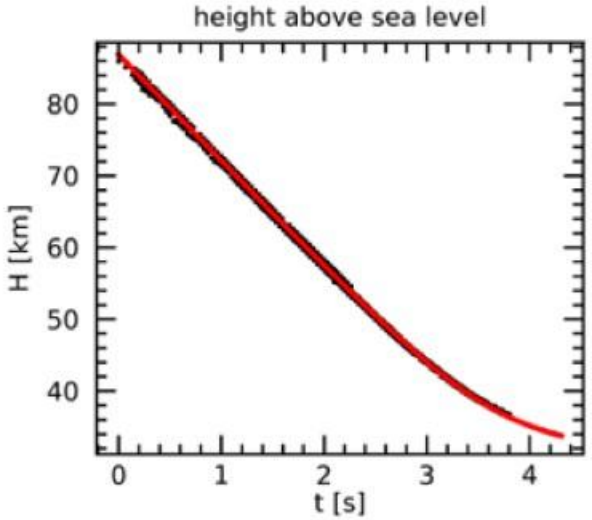
PRISMA

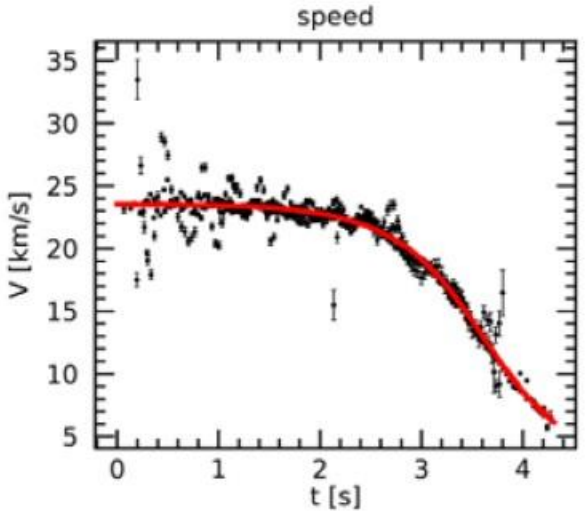
PRISMA PIPELINE - DYNAMICS

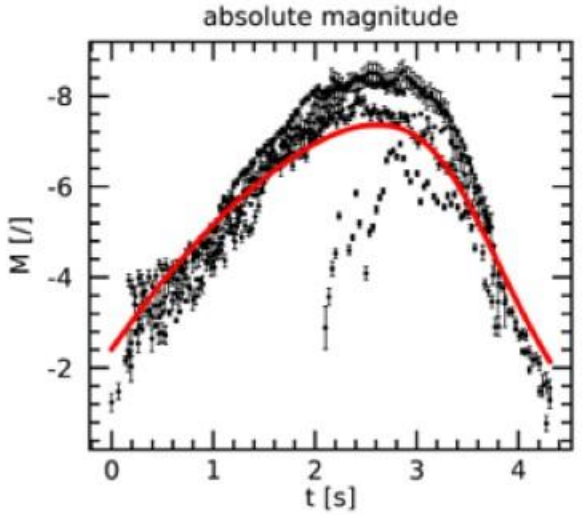
Solution and fitting of the dynamic model over observed data (height = $\{H\}_i$, speed = $\{v\}_i$, magnitude = $\{M\}_i$).

The **starting point** for processing the dynamic model is **to solve** the following **set of equations**.

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







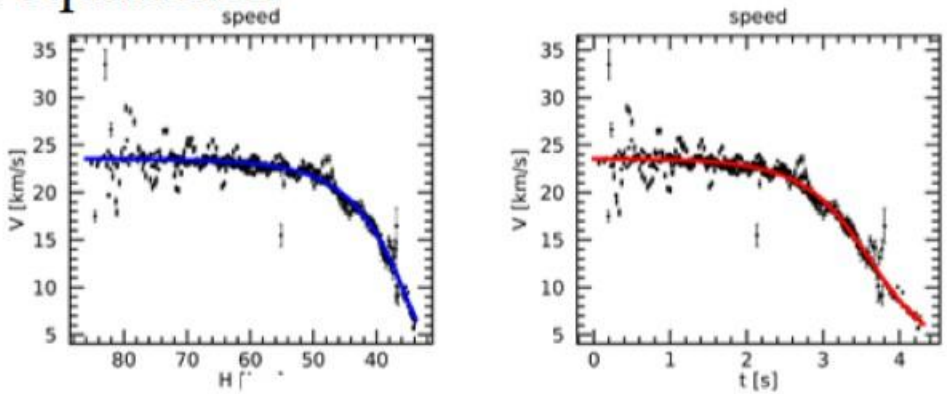
PRISMA PIPELINE - DYNAMICS

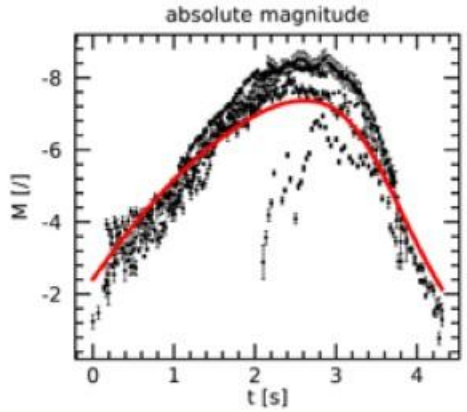
There are **two approaches** to solving this set of equations:

a) Analytical —— (Gritsevich 2009, 2011)

b) Numerical solution ——

Speed and magnitude data are most often considered separately.





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)

→ Particularly useful when dealing with events showing small deceleration

PRISMA PIPELINE - DYNAMICS

The fitting sequence

Preliminary steps: - Read the **triangulation output**
- **Estimate α** and **β** from the deceleration alone — **the starting point of the first fit**

Six optimisations per event, each one starting from the previous result:

		fit	*data used*	*starting guess*
a) **Analytical:**	**1**	**dynamic**	$\{v\}_i$	α and β estimate
	2	**magnitude**	$\{M\}_i$	Fit 1
	3	**photo-dynamic**	$(\{v\}_i, \{M\}_i)$	Fit 1+2
b) **Numerical:**	**4**	**dynamic**	$(\{H\}_i, \{v\}_i)$	Fit 1
	5	**Magnitude**	$\{M\}_i$	Fit 3
	6	**photo-dynamic**	$(\{H\}_i, \{v\}_i, \{M\}_i)$	Fit 4+5

LOCAL OPTIMISATION

Inside one fit

MPFIT (Levenberg–Marquardt) is a local optimiser: it follows the gradient downhill from the **initial guess** and stops at the first minimum it meets.

What the pipeline does for each of the six fits:

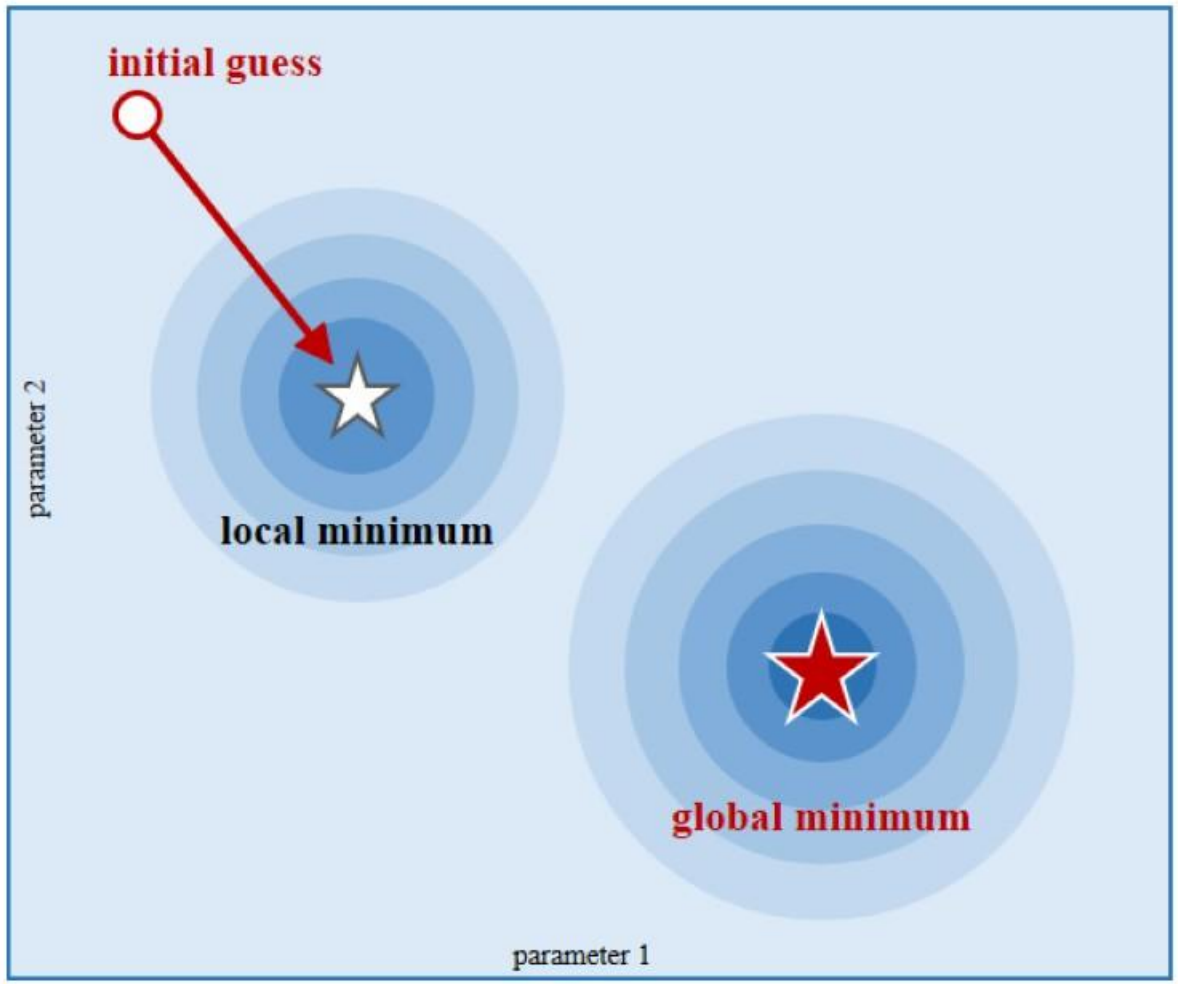
1. **Damped pass:** **MPFIT** with unit errors and damped residuals, to approach the solution safely
2. **Fit:** **MPFIT** with the real uncertainties, starting from step 1 — this is where the parameters are determined
3. **Physical checks:** $v\infty > 0$, α and the derived quantities finite; otherwise the fit is flagged as not converged
4. **Uncertainties:** **MPFIT** with maxiter = 0: the parameters do not vary, only the covariance matrix is computed

FAILURES OF THE LOCAL FIT

Convergence of dynamic model fitting: a small but significant fraction of events (< 5%) ***shows diverging results***, with biased estimates of meteoroid parameters

The fit relies on **MPFIT**, a local optimiser: its convergence depends critically on the initial guess.

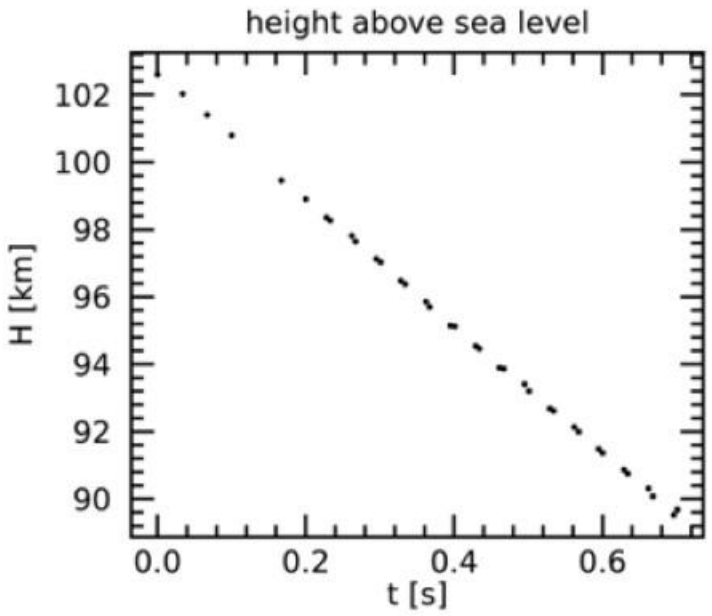
Local optimiser (MPFIT)

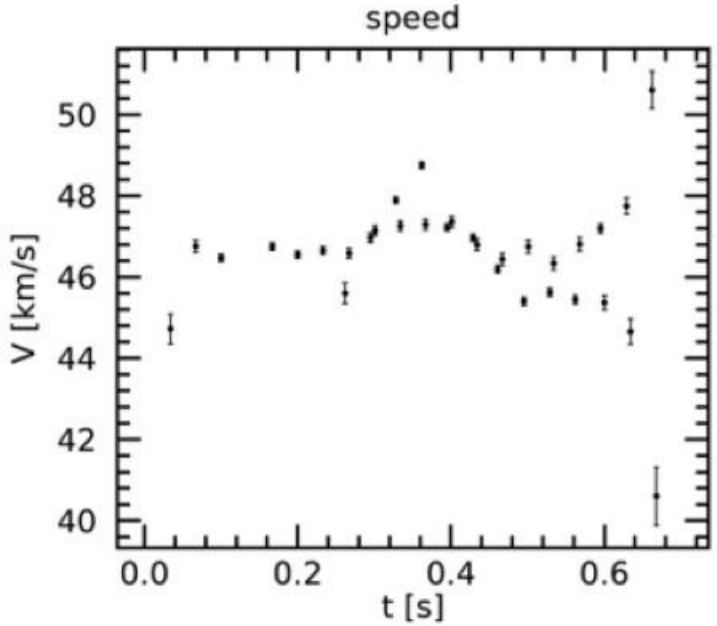


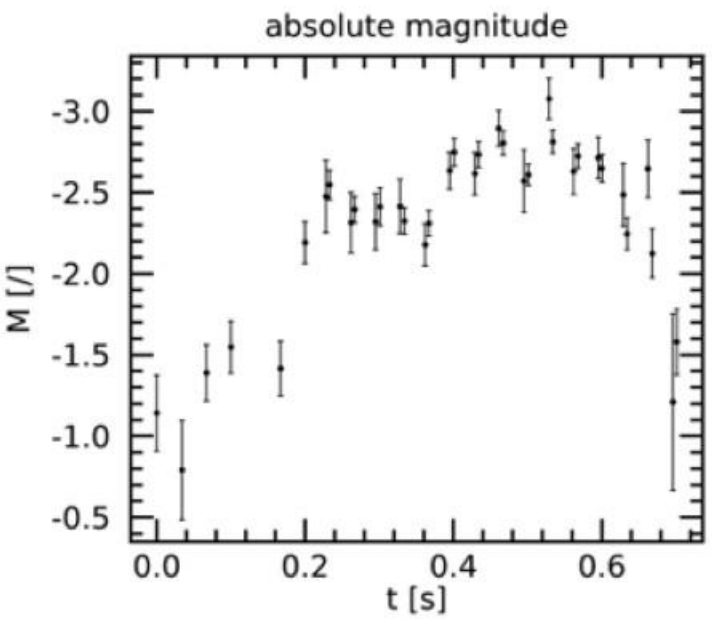
one starting point: it goes downhill and stops in the nearest valley

FAILURES OF THE LOCAL FIT

CASE 1: fireball event detected by the PRISMA network on 24/09/2018 at 02:19 UT, south-east of Turin





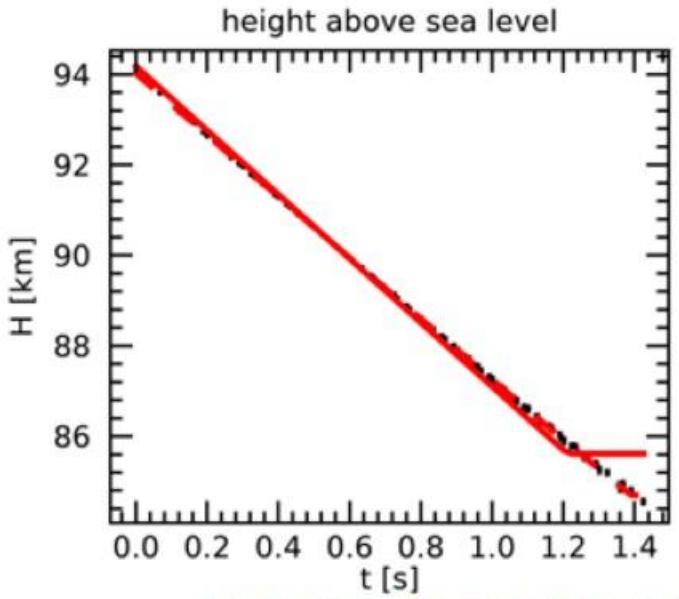


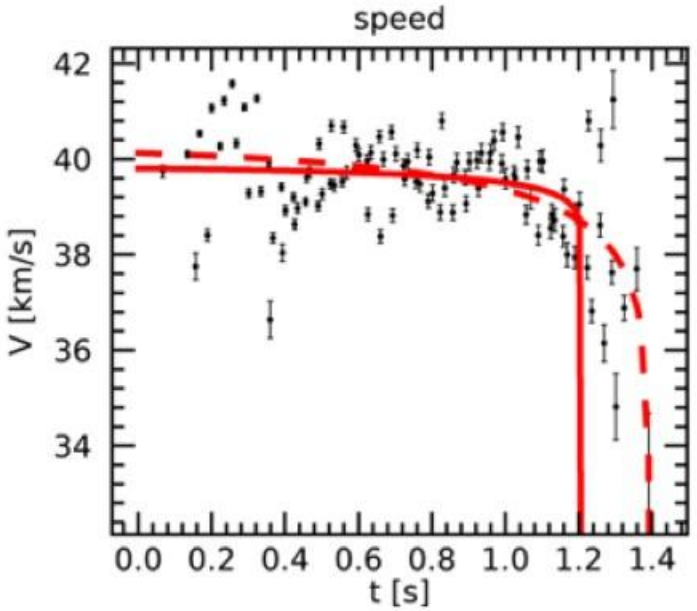


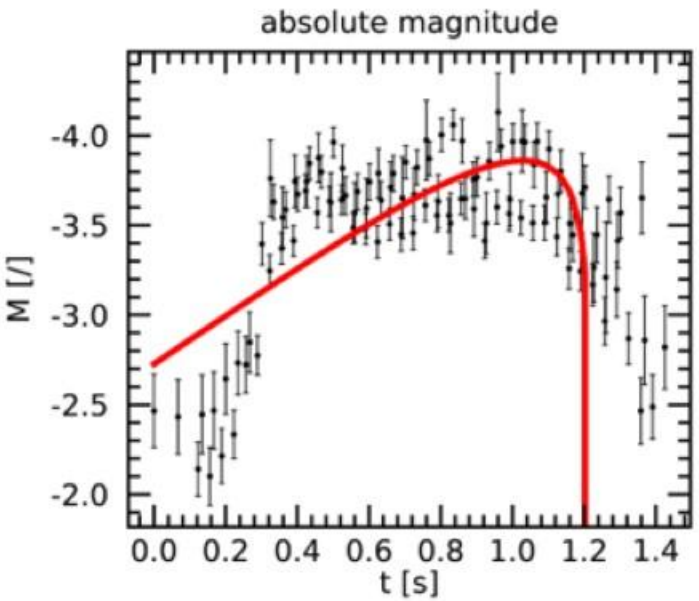
Numerical photo-dynamic	MPFIT
Pre-atmospheric mass [kg]	/
Ballistic coeff. α	/
MSR -loss param. β	/
Ablation coeff. σ [s^2/km^2]	/
Final velocity [km/s]	/

FAILURES OF THE LOCAL FIT

CASE 2: fireball event detected by the PRISMA network on 11/07/2017 at 22:38 UT, south-west of the Garda Lake.





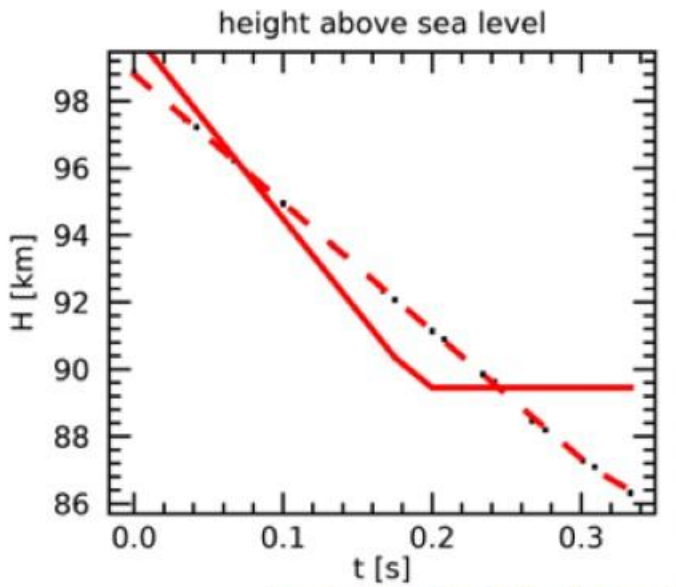


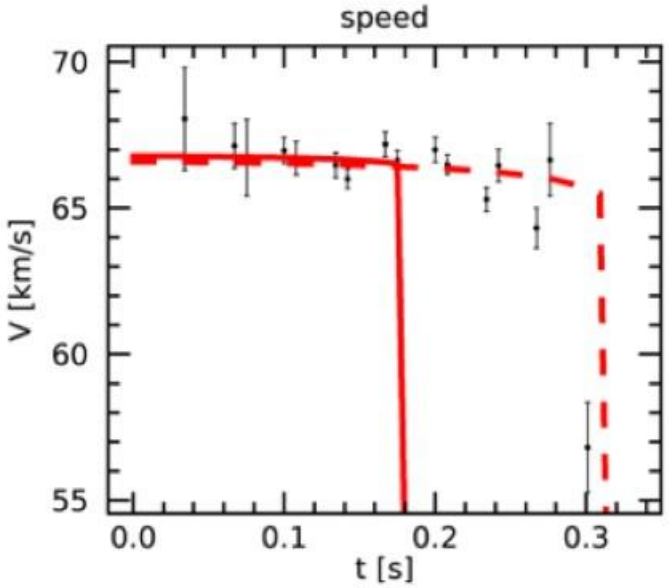


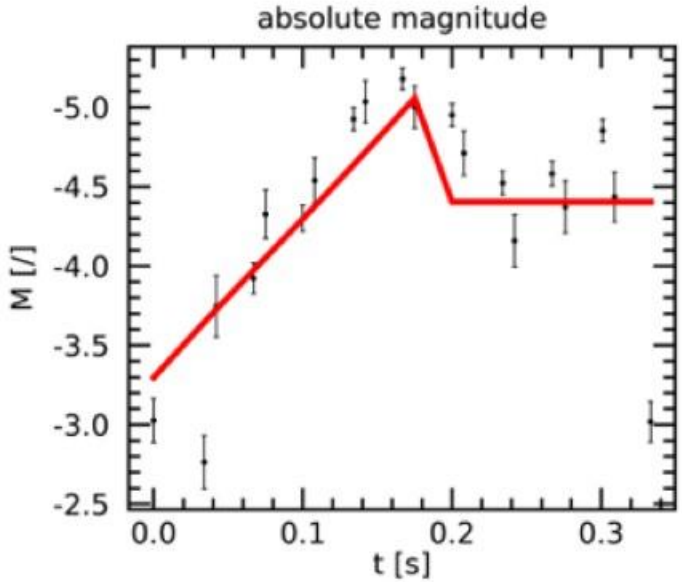
Numerical photo-dynamic	MPFIT
Pre-atmospheric mass [kg]	$(3.1 \pm 1.4) \times 10^{-2}$
Ballistic coeff. α	$(6 \pm 1) \times 10^{2}$
MSR -loss param. β	79 ± 5
Ablation coeff. σ [s^2/km^2]	0.124 ± 0.012
Final velocity [km/s]	0

FAILURES OF THE LOCAL FIT

CASE 3: fireball event detected by the PRISMA network on 14/05/2019 at 01:26 UT, in the Ligurian Sea, south-west of La Spezia









Numerical photo-dynamic	MPFIT
Pre-atmospheric mass [kg]	$(2.7 \pm 1.0) \times 10^{-2}$
Ballistic coeff. α	$(1.4 \pm 0.5) \times 10^{2}$
MSR -loss param. β	$(2.2 \pm 1.4) \times 10^{2}$
Ablation coeff. σ [s^2/km^2]	$(9 \pm 3) \times 10^{-2}$
Final velocity [km/s]	(0 ± 20)

GLOBAL OPTIMISATION

A population-based **global optimiser** (Storn & Price 1997), recently applied to fireball data by Peña-Asensio & Gritsevich (2025): **Differential Evolution (DE)**

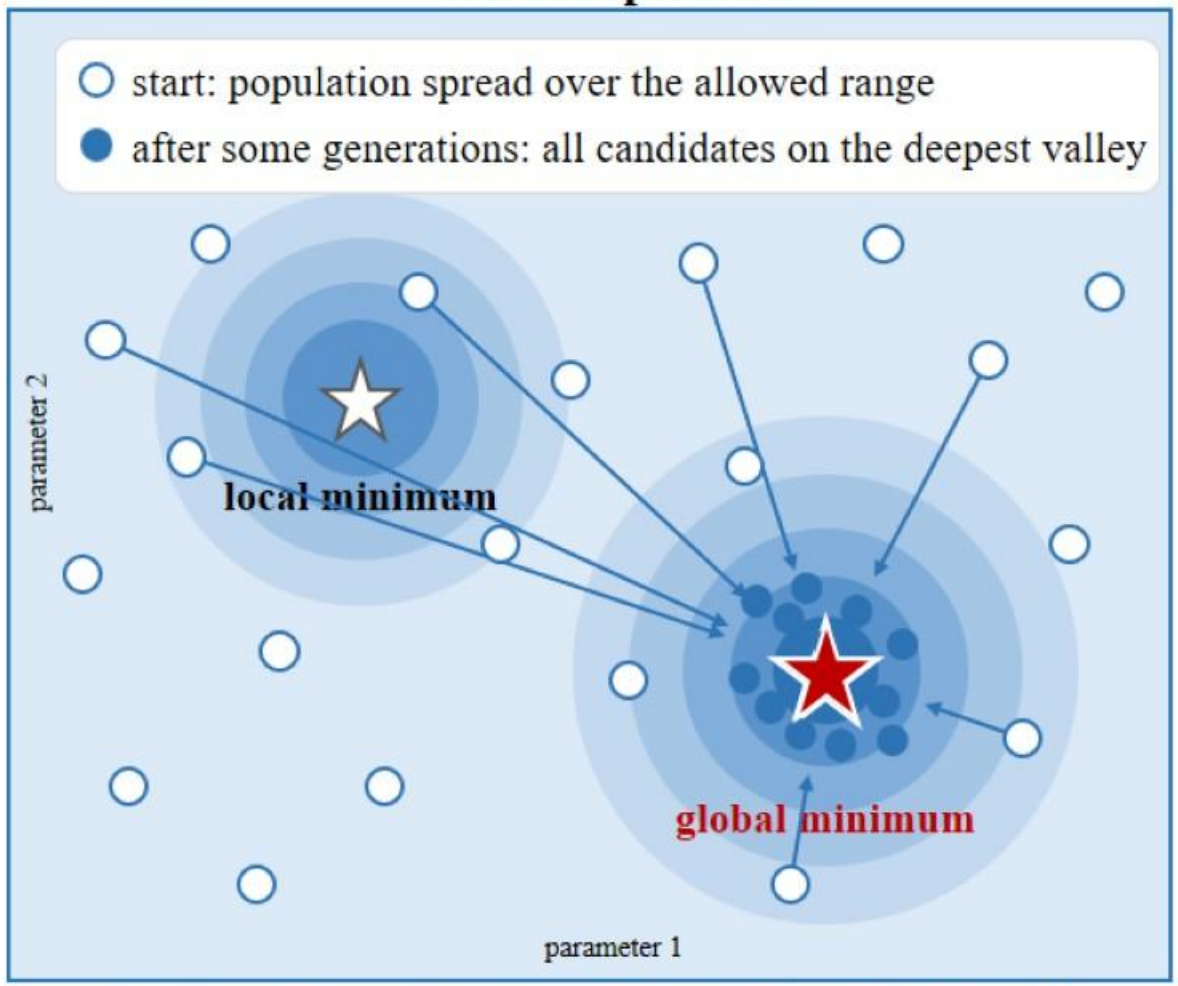
1) Population — many **sets of parameters**, spread over the allowed range — no initial guess
Evaluates χ^2 of each candidate

2) Mutation — **Combines** the current *best* with two distinct random candidates ($r_2, r_3 \neq i$).
$\mathbf{b' = best + F \cdot (r_2 - r_3)}$

3) Crossover — Builds **trial vector** mixing mutant $b'$and original i
$\mathbf{trial = mix\ (\ b'\ ,\ i\ )}$

4) Selection — Evaluates χ^2(trial). Replaces candidate i if lower
$\mathbf{\chi^2(trial) < \chi^2(i)\ ?}$

Global optimiser



no starting point: a whole population explores the allowed range and converges to the deepest valley

GLOBAL OPTIMISATION

Inside one fit

Differential Evolution replaces the damped pass, nothing else changes:

1. **Global search:** scipy differential_evolution inside finite bounds; no initial guess, no derivatives
2. **Local polish:** MPFIT with the real uncertainties, starting from the DE solution
3. **Physical checks:** unchanged
4. **Uncertainties:** unchanged: MPFIT with maxiter = 0, covariance matrix

What DE preserves

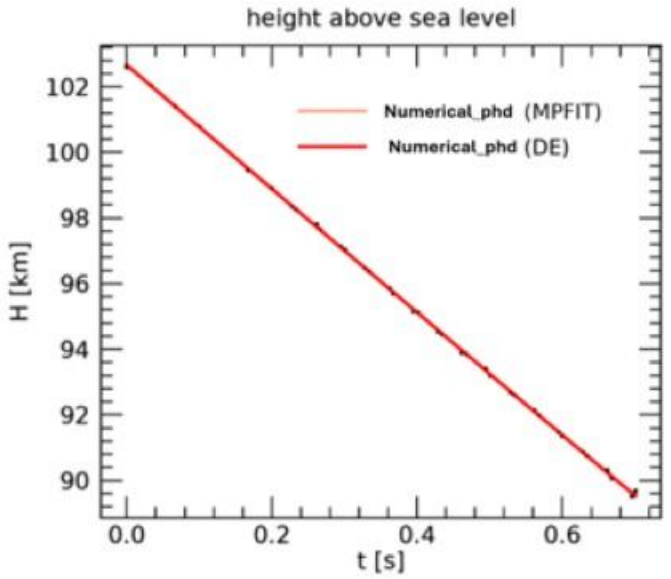
the order of the fits, which parameters are free, the function being minimised, the uncertainties estimation

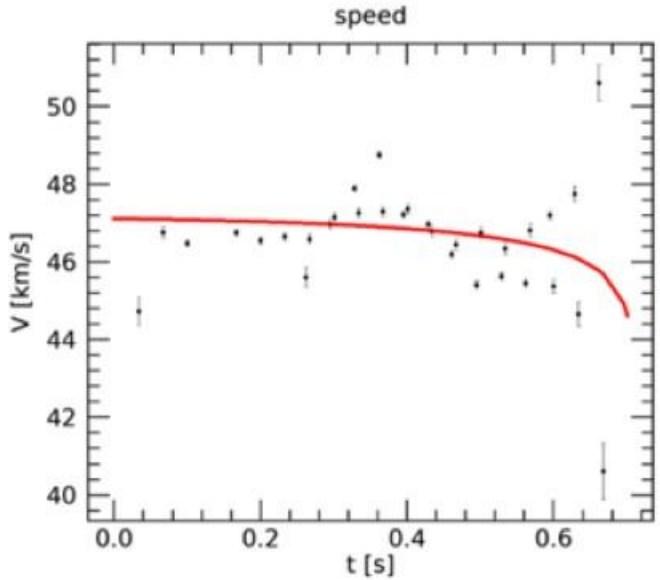
Computational cost

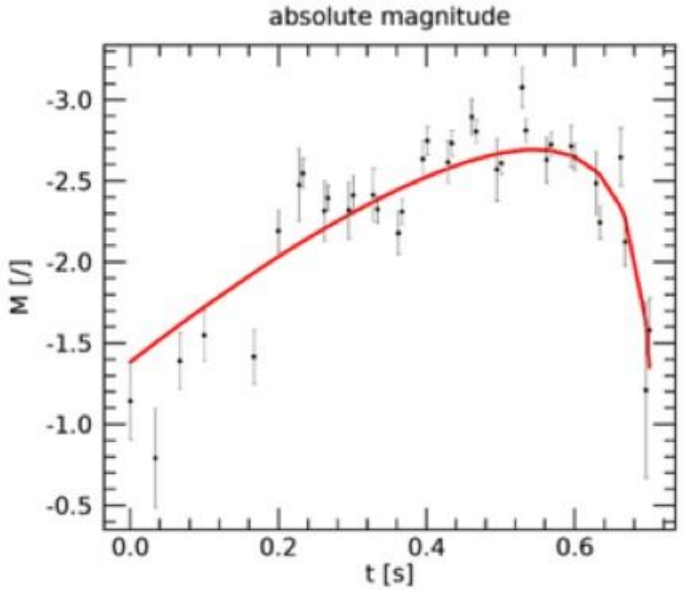
~4 min/event vs. ~30 s with standard MPFIT
2500 – 16000 model evaluations per fit

RESULTS OF THE GLOBAL FIT

CASE 1: fireball event detected by the PRISMA network on 24/09/2018 at 02:19 UT, south-east of Turin





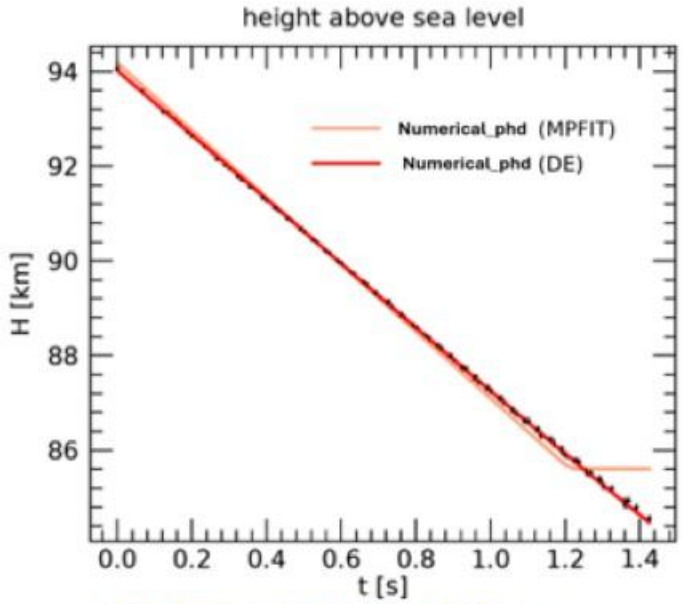


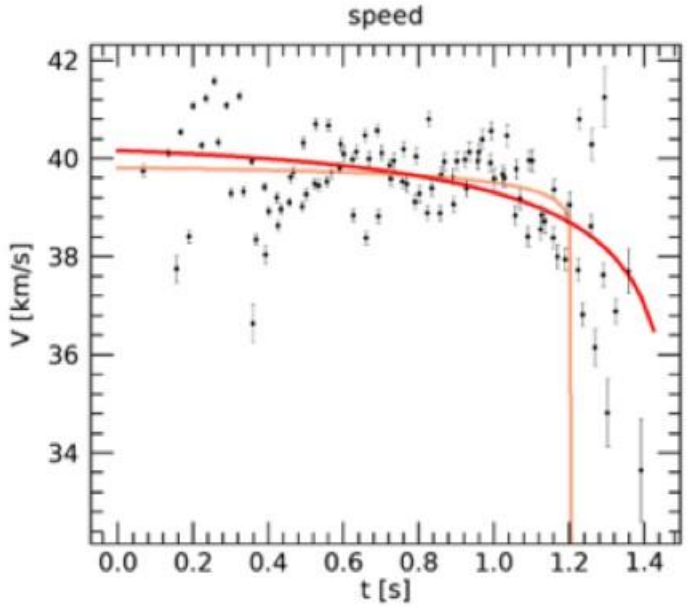


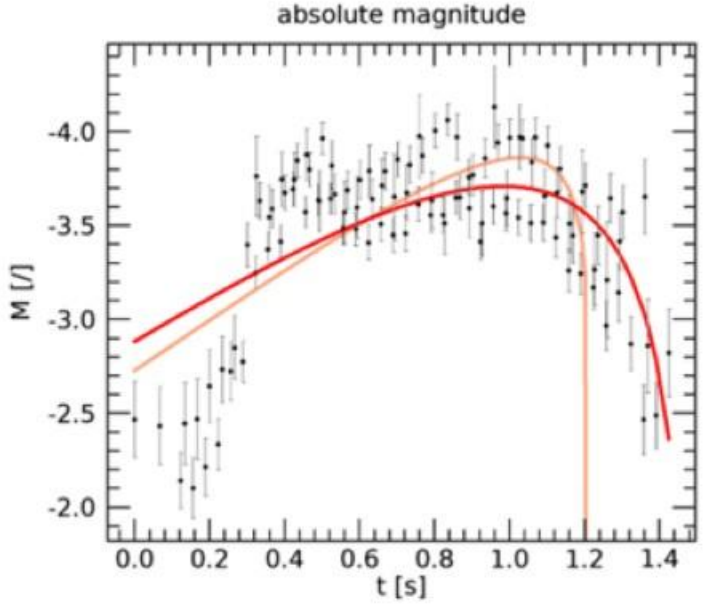
Numerical photo-dynamic	MPFIT	DE + MPFIT
Pre-atmospheric mass [kg]	/	$(2 \pm 3) \times 10^{-6}$
Ballistic coeff. α	/	$(7 \pm 3) \times 10^{3}$
MSR-loss param. β	/	$(3.6 \pm 0.3) \times 10$
Ablation coeff. σ [s^2/km^2]	/	$(5 \pm 2) \times 10^{-2}$
Final velocity [km/s]	/	$(4 \pm 2) \times 10$

RESULTS OF THE GLOBAL FIT

CASE 2: fireball event detected by the PRISMA network on 11/07/2017 at 22:38 UT, south-west of the Garda Lake.





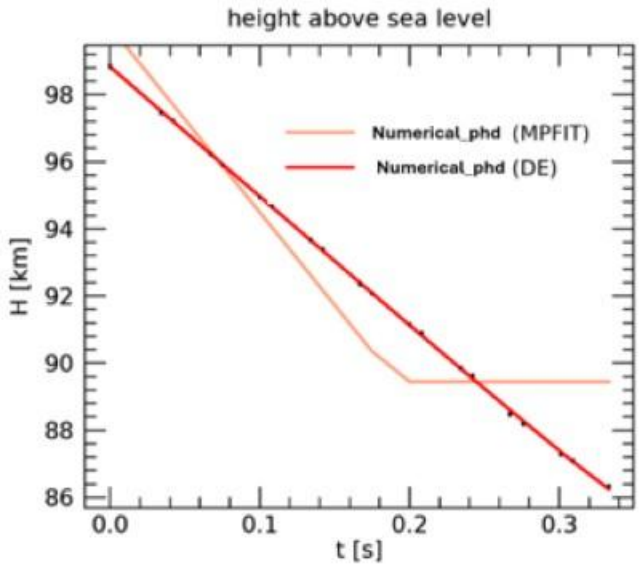


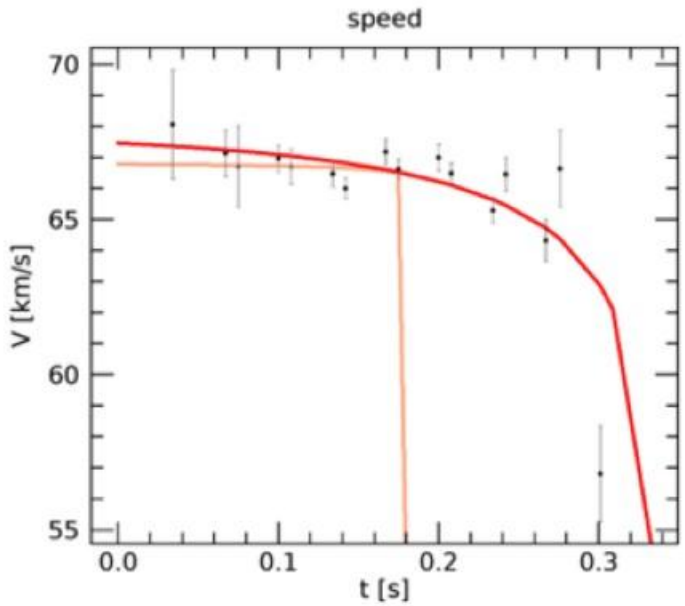


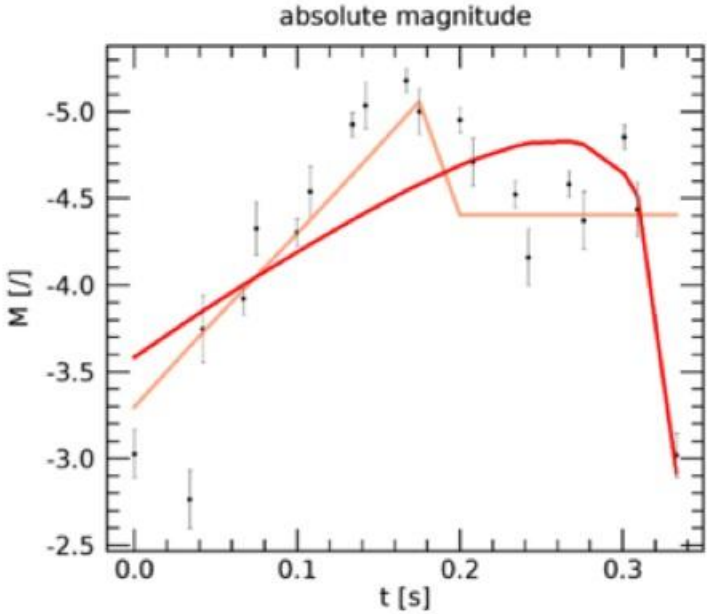
Numerical photo-dynamic	MPFIT	DE + MPFIT
Pre-atmospheric mass [kg]	$(3.1 \pm 1.4) \times 10^{-2}$	$(4 \pm 3) \times 10^{-5}$
Ballistic coeff. α	$(6 \pm 1) \times 10^{2}$	$(5.9 \pm 1.3) \times 10^{3}$
MSR-loss param. β	(79 ± 5)	$(1.6 \pm 0.3) \times 10$
Ablation coeff. σ [s^2/km^2]	(0.124 ± 0.012)	$(3.3 \pm 0.5) \times 10^{-2}$
Final velocity [km/s]	0	$(4 \pm 1) \times 10$

RESULTS OF THE GLOBAL FIT

CASE 3: fireball event detected by the PRISMA network on 14/05/2019 at 01:26 UT, in the Ligurian Sea, south-west of La Spezia





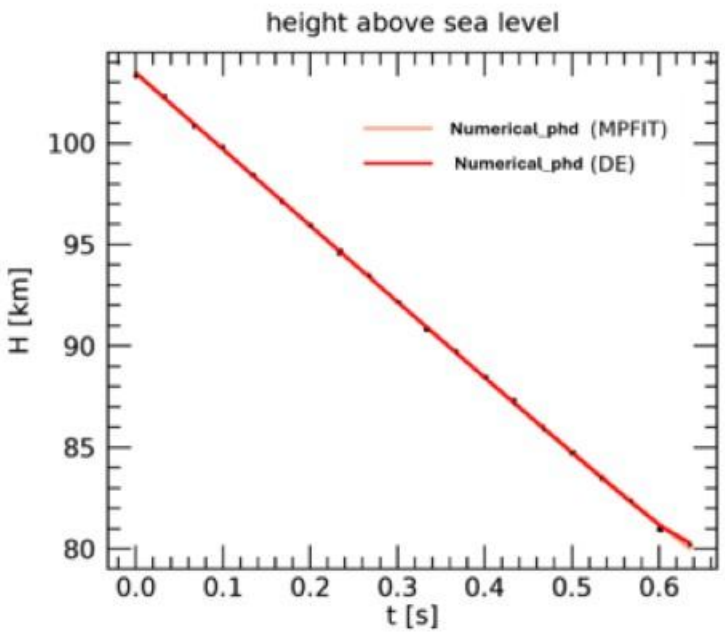


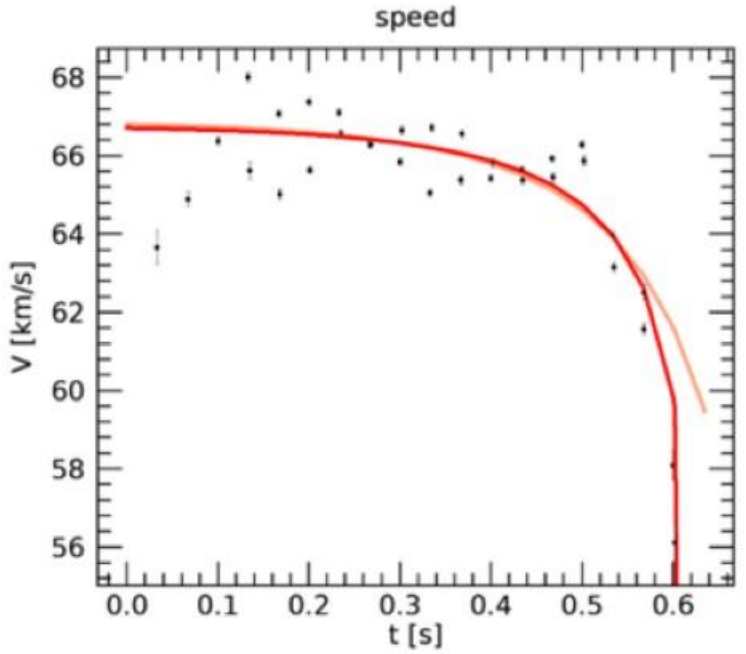


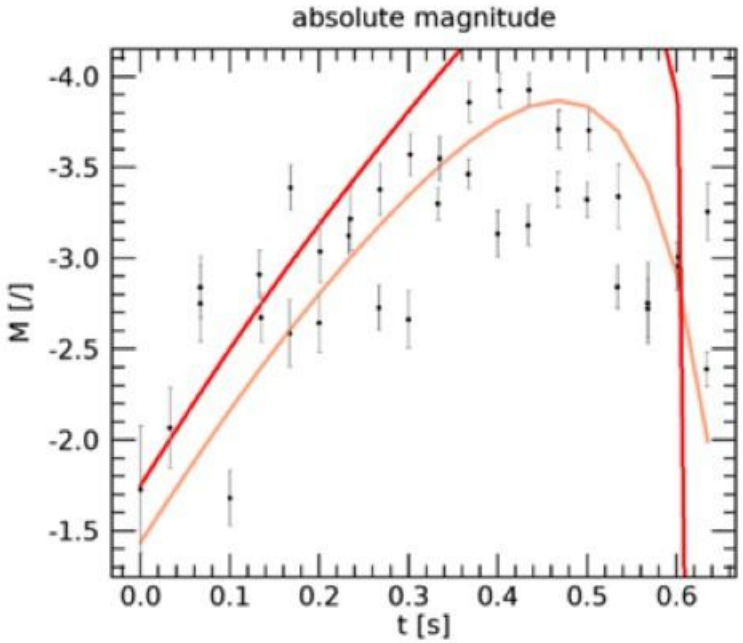
Numerical photo-dynamic	MPFIT	DE + MPFIT
Pre-atmospheric mass [kg]	$(2.7 \pm 1.0) \times 10^{-2}$	$(1.6 \pm 1.1) \times 10^{-7}$
Ballistic coeff. α	$(1.4 \pm 0.5) \times 10^{2}$	$(1.1 \pm 0.3) \times 10^{4}$
MSR-loss param. β	$(2.2 \pm 1.4) \times 10^{2}$	$(1.3 \pm 0.2) \times 10$
Ablation coeff. σ [s^2/km^2]	$(9 \pm 3) \times 10^{-2}$	$(8 \pm 2) \times 10^{-3}$
Final velocity [km/s]	0 ± 20	$(5 \pm 3) \times 10$

DEGENERATIVE FINDINGS OF THE GLOBAL FIT

CASE 4: fireball event detected by the PRISMA network on 04/09/2017 at 02:59 UT, south-west of Venice.



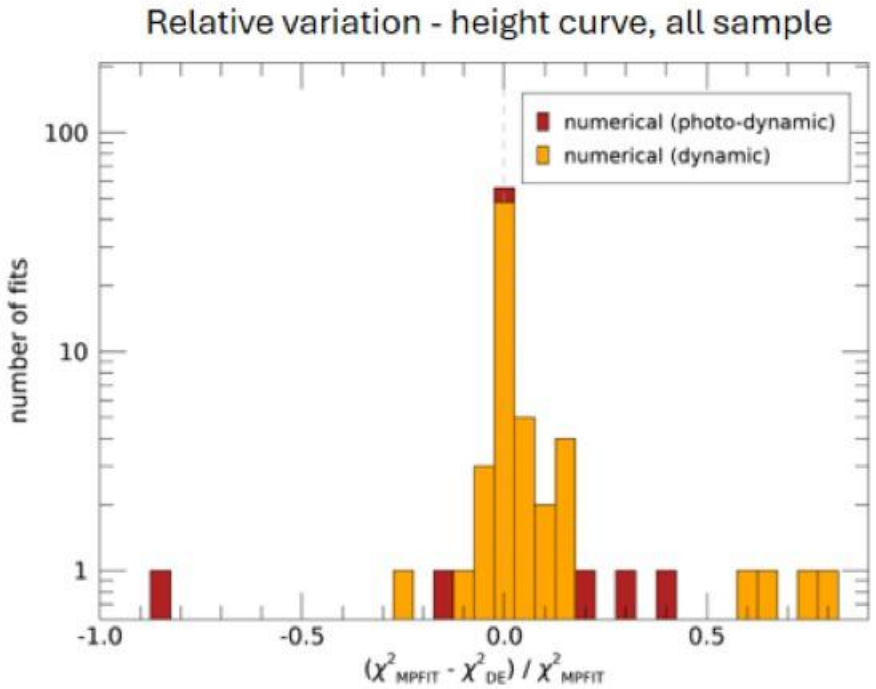


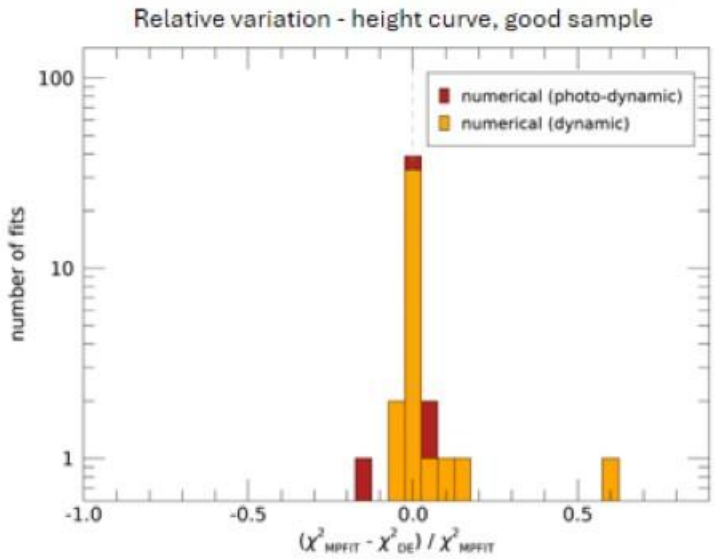


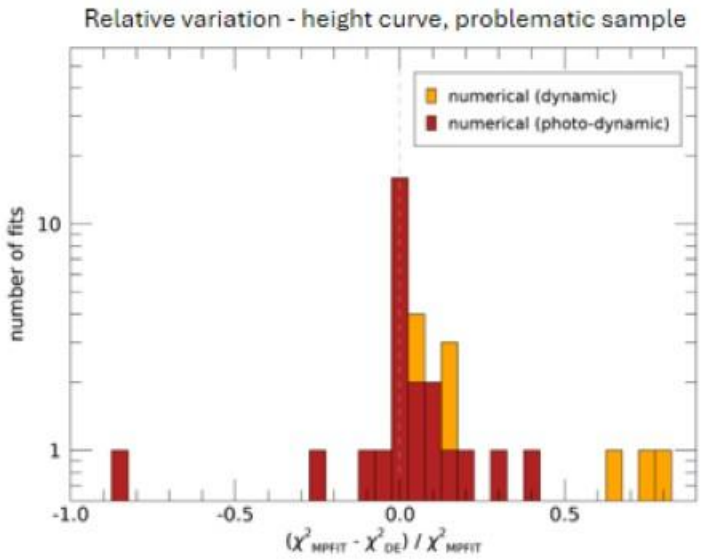


Numerical photo-dynamic	MPFIT	DE + MPFIT
Pre-atmospheric mass [kg]	$(9 \pm 5) \times 10^{-7}$	$(2.0 \pm 0.9) \times 10^{-6}$
Ballistic coeff. α	$(6.4 \pm 1.3) \times 10^{+3}$	$(4.8 \pm 0.3) \times 10^{+3}$
MSR-loss param. β	(5 ± 2)	(11.0 ± 0.3)
Ablation coeff. σ [s^2/km^2]	$(9.2 \pm 1.2) \times 10^{-3}$	$(8.5 \pm 0.6) \times 10^{-3}$
Final velocity [km/s]	59 ± 3	(0 ± 9)

HEIGHT CURVE EVALUATION





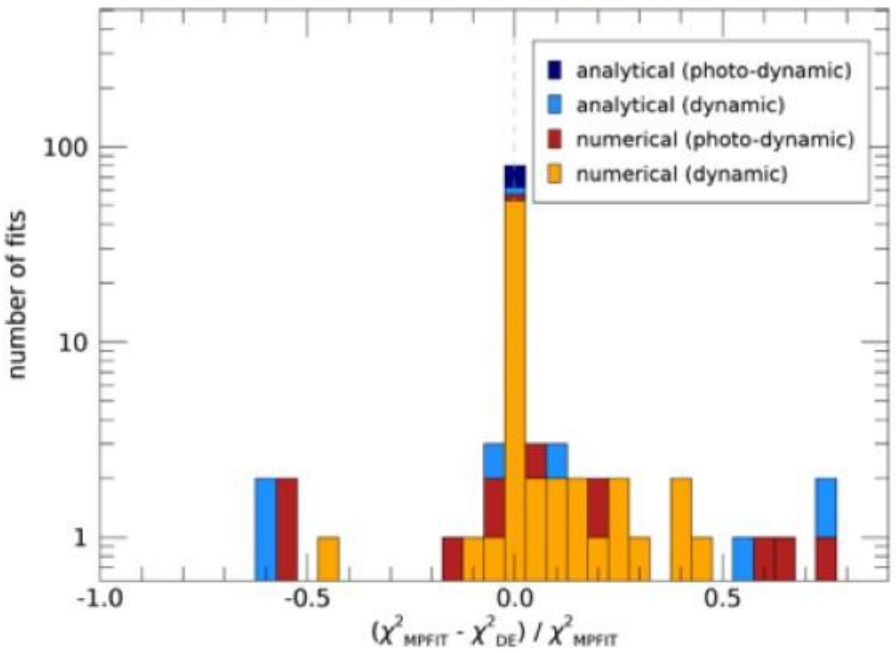


Sample	Fits	Same	χ^2_{DE} better	χ^2_{DE} worse
All events (85)	170	56%	33%	8%
Good (43)	86	81%	15%	2%
Problematic (42)	84	31%	51%	13%

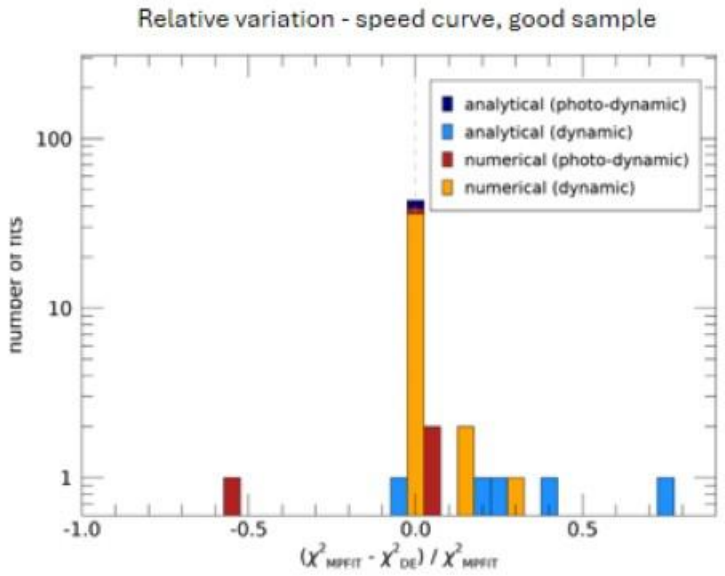
Not shown: fits where only MPFIT converges, or neither does (5% of all events)

SPEED CURVE EVALUATION

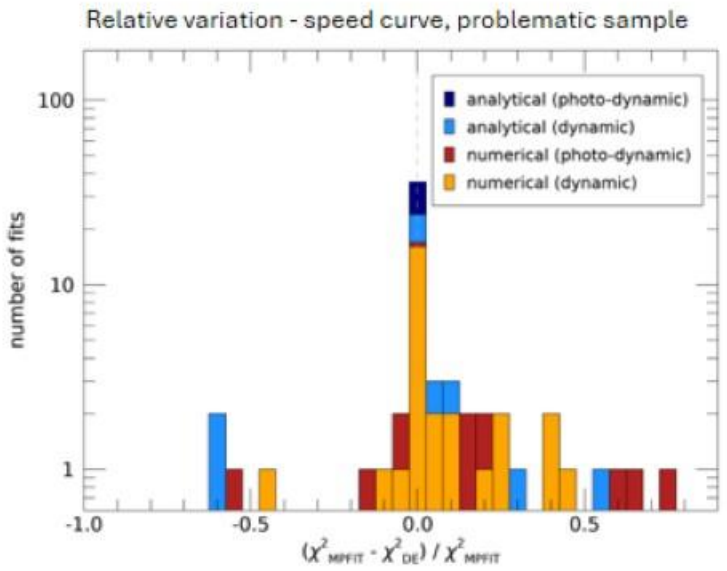
Relative variation - speed curve, all sample



Relative variation - speed curve, good sample



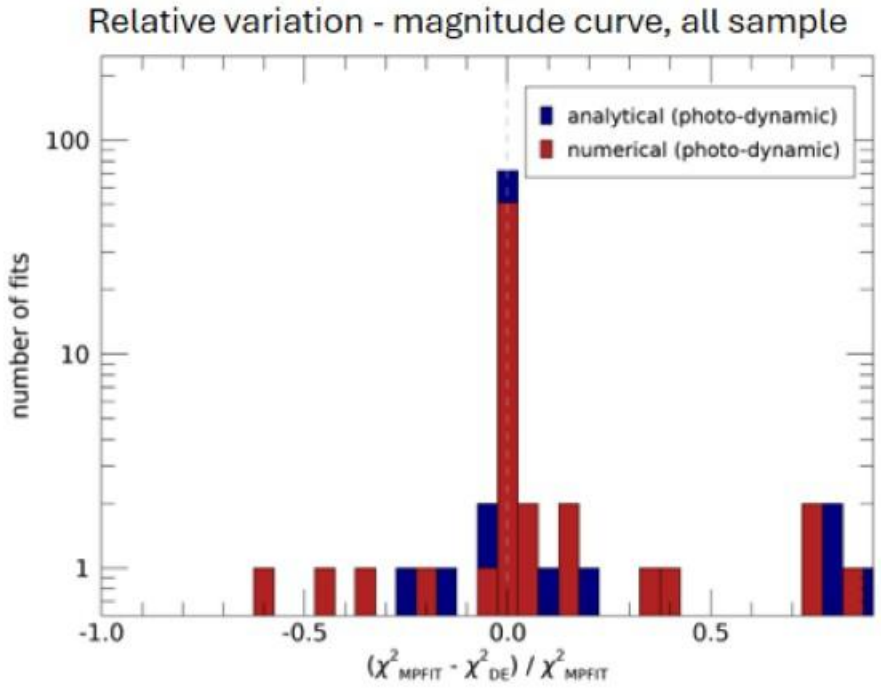
Relative variation - speed curve, problematic sample

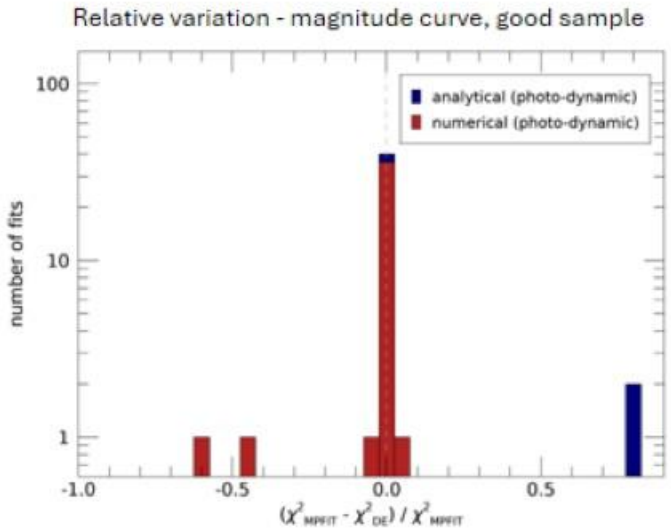


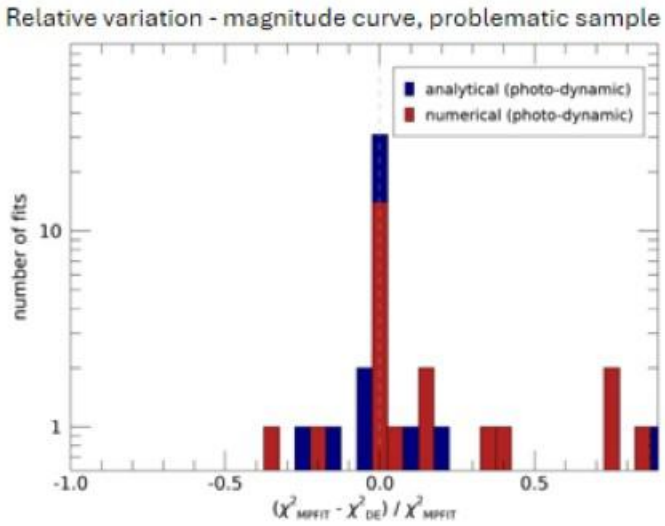
Sample	Fits	Same	χ^2_{DE} better	χ^2_{DE} worse
All events (85)	340	71%	24%	4%
Good (43)	172	87%	11%	<1%
Problematic (42)	168	54%	37%	7%

Not shown: fits where only MPFIT converges, or neither does (2% of all events)

MAGNITUDE CURVE EVALUATION







Sample	Fits	Same	χ^2_{DE} better	χ^2_{DE} worse
All events (85)	172	71%	22%	6%
Good (43)	86	88%	8%	3%
Problematic (42)	84	52%	37%	10%

Not shown: fits where only MPFIT converges, or neither does (<1% of all events)

FROM THE FIT TO THE UNCERTAINTIES

What DE gives us

No initial guess: the global search replaces the initial guess

Same or better fits: 81–88% of good fits unchanged, 37–51% of problematic fits improved

Cost: ~4 min/event vs. ~30 s with MPFIT

The next question

The **uncertainties** still come from the MPFIT covariance matrix: **are they reliable?**

Test: Processing DIMS meteor observations with the PRISMA pipeline

DIMS Dark matter and Interstellar Meteoroid Study

- **Objectives:** → Search for macroscopic dark matter.
  → Study of interstellar meteoroids.
- **Method:** Optical observations using ultra-high sensitivity CMOS cameras.
- **International Collaboration:** Japan, Italy, USA, Czech Republic, Slovakia, Poland, South Korea.

DATASET

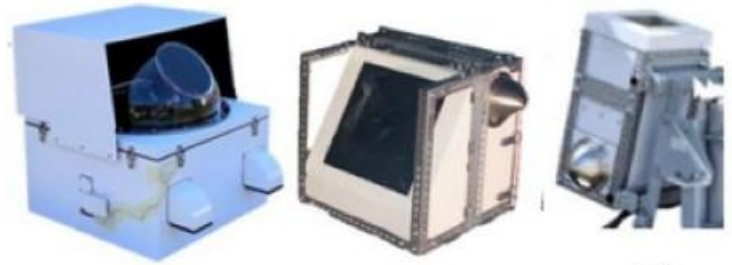
500,000+

videos recorded

~450 h

of observation (2021-2025)

- **Instrument setup:**
  - *Monochrome Cameras* Canon ME20F-SH (a, b)
  - *Color Camera* Canon ME20F-SHN (c)
  - *Resolution:* 1920×1080 pixel
  - *FOV:* 57° × 34°
  - *Frame rate:* 30 frames per second



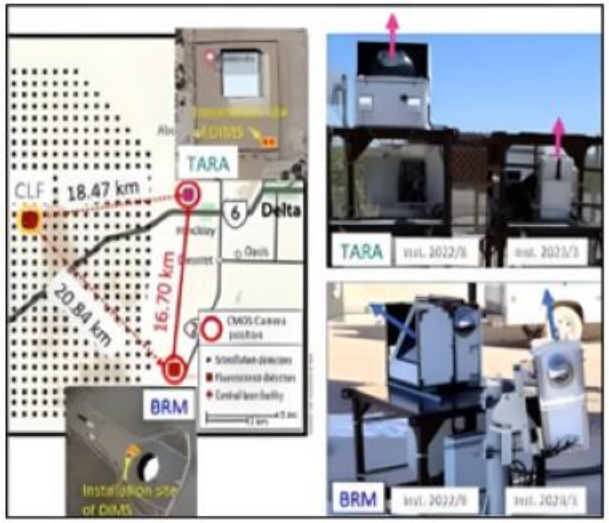
(a) (b) (c)

DIMS - Observation sites & Dataset



Japan (2021-2023):

- Akeno Observatory
- Kiso Observatory
- Shinshu University



Utah, USA (2022-2025):

- Black Rock Mesa (BRM)
- TARA (Telescope Array)

OBSERVATIONAL DATA

Stations
TARA & BRM – Utah, USA

Period
September – December 2022
January – April 2023

Initial events	15024
Rejected events	1803

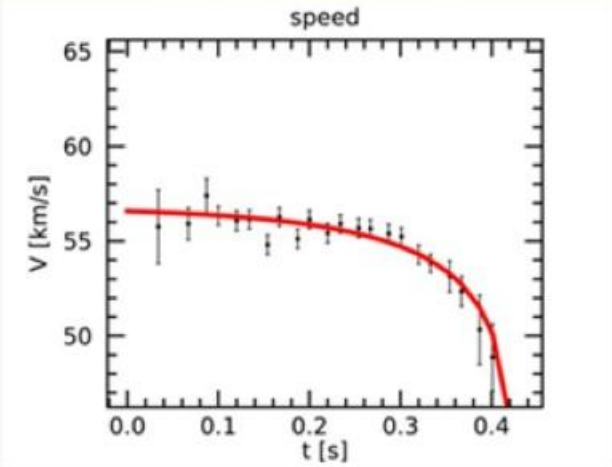
DIMS - OUTPUT RESULTS

Triangulation, Dynamic & Orbital Analysis — Retrograde Meteoroid

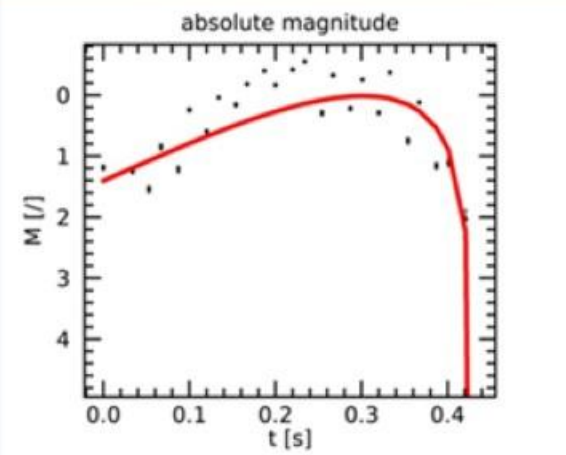
TRAJECTORY MAP · UTAH, USA



SPEED PROFILE



ABSOLUTE MAGNITUDE



Event: 20221119T125138_UT_0

Initial Height [km] : 109.4± 0.3

Final Height [km] : 95.7 ± 0.2

Initial velocity [km/s] : 56.6 ± 0.4

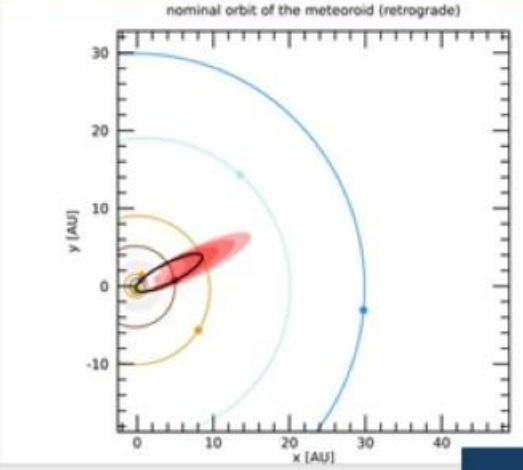
Final velocity [km/s] : 49 ± 1

Min. Absolute Magnitude[/]: -0.55@101.9 km

Eccentricity [/] : 0.966 ± 0.008

Orbit Inclination [deg] : 112.8 ± 0.6

NOMINAL ORBIT (RETROGRADE)

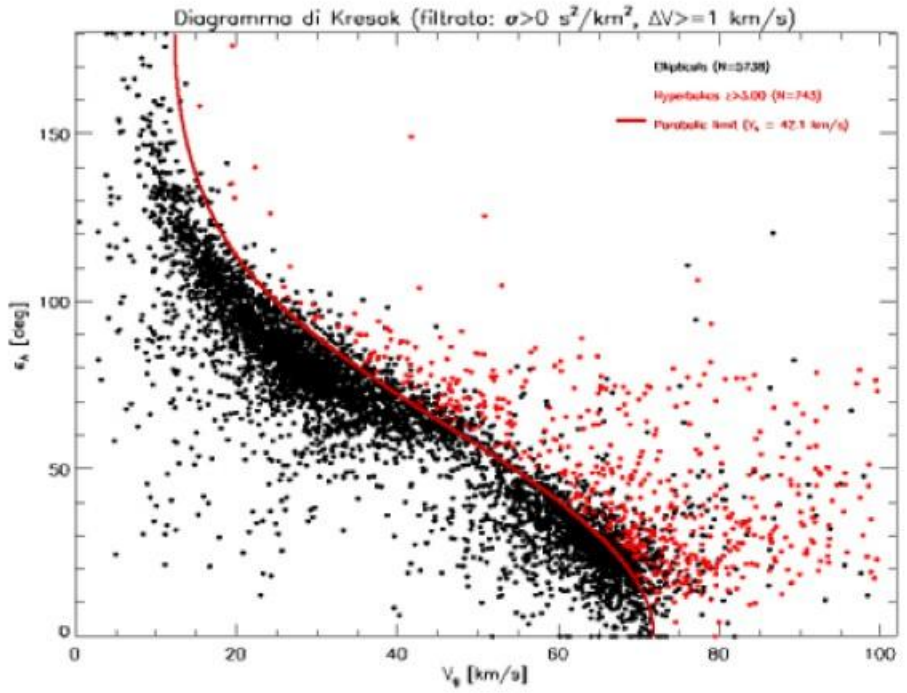


DIMS - KRESAKS' DIAGRAM

The Kresáks' diagram

- Looking for potential **interstellar meteor candidates**.
- Each meteor is mapped onto the **(V_g, ε_A) diagram**: geocentric velocity vs. radiant elongation from the Earth's apex.
- Applying a **one-tailed Gauss test** with z-score greater than **3** (C.L. 99.87%), the percentage of **significantly hyperbolic events** is found (**red points**).

KRESAKS' DIAGRAM z_crit = 3 (99.87% conf.)



Barghini et al. (2025)

Valid events	**6481**	
Elliptical orbit ($V_h \leq V_p$)	**4872**	~75%
Geometrically hyperbolic	**1609**	~ 25%
Significantly hyperbolic (z > 3)	**743**	**~11%**

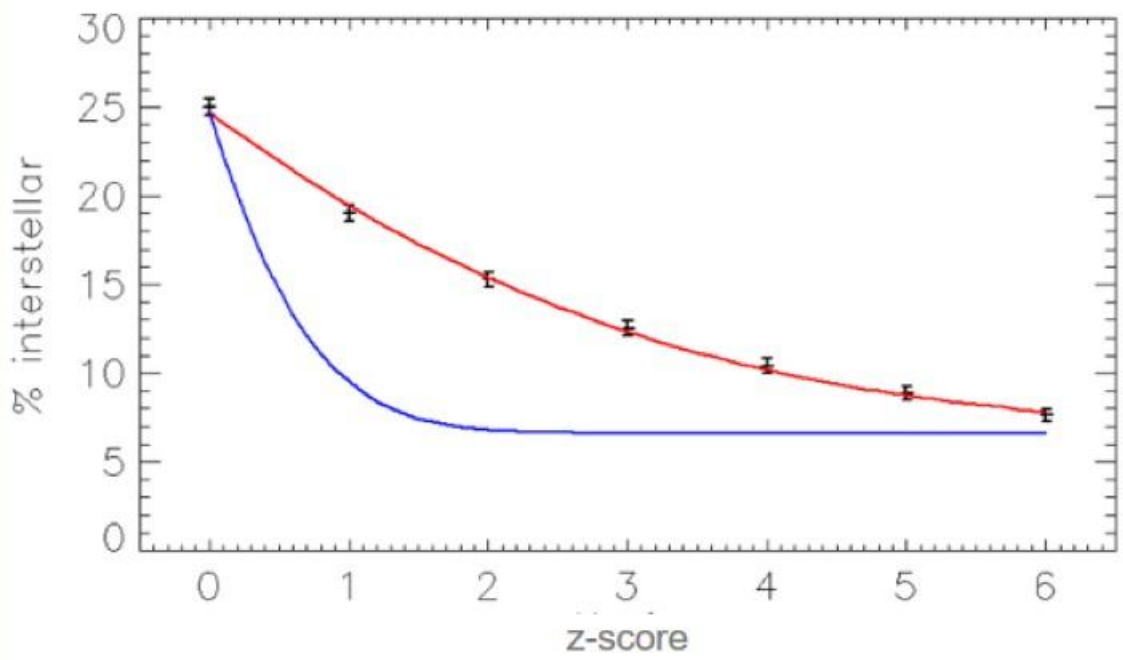
TESTING ERROR UNDERESTIMATION

Model: Assumes two mixed populations: false positives (vanishes with stricter thresholds) and true positives (survives filtering). The fit finds the values that best match the observed curve.

Plot: percentage of significantly hyperbolic events for each value of z-score.

Red curve: best fit to the data.
Blue curve: same population, if measurement errors had been correctly estimated (R = 1).

Result: the reported σ is underestimated by a factor R ≈ 4.2 on average



R (σ underestimation factor)	**4.2 ± 0.3**

CONCLUSIONS

Limitations of MPFIT: Standard local optimization relies heavily on the initial guess and fails or gets trapped in local minima in ~**5% of cases**.

Differential Evolution (DE): Global optimization (DE + MPFIT) appear to resolve a good fraction of problematic cases without needing an initial guess.

Computational Cost: The runtime increase (~4 min/event)

Tests of the PRISMA pipeline on data from the DIMS project showed that **uncertainties may be underestimated**

Next Steps & Future Objectives

- **Implementation in PRISMA Automated Pipeline**
- **Large-Scale Validation**
- **Revise the uncertanties**

THE PRISMA NETWORK

PRISMA (Prima Rete Italiana per la Sorveglianza sistematica di Meteore e Atmosfera)

Italian All-Sky Network:

- founded in **2016** by **INAF** and partner of the **FRIPON** international collaboration
- counting **more than 100 stations** and more than **80 institutions**
- Celebrating the 10 years anniversary this years, with more than **3000 observed fireballs**

Core Objective: **Systematic monitoring** of meteors and fireballs to enable **meteorite recovery** and **orbit reconstruction**.



METEORITE FALLS AND RECOVERIES

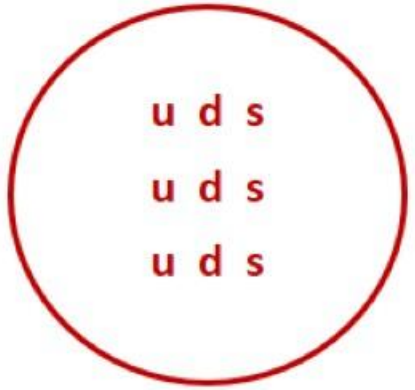


- PRISMA can detect fireballs of **apparent magnitude m<0**
- Estimated meteorite-dropping fireball rate of **1 per year over Italy**
- **Two successful recoveries:**
  - **Cavezzo** (L5-an, 55 g), fall 01/01/2020, rec. 04/01/2020
  - **Matera** (H5, 117 g), fall 14/02/2023, rec. 17/02/2023

Date	Time	V_∞ [km/s]	γ [deg]	M_∞ [kg]	$M_{\rm fin}$ [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	12:31	14.1 ± 0.1	29.1 ± 1	1.4 – 4.6	0.02 – 3.4

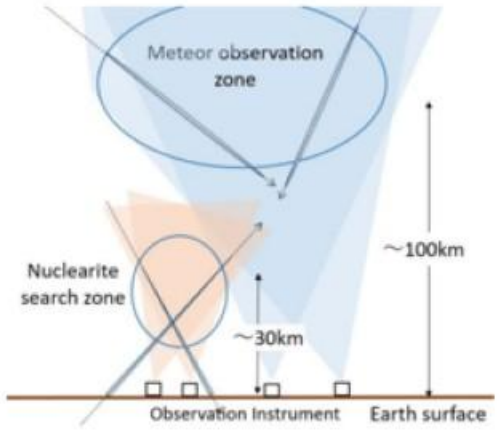
NUCLEARITES

- **Witten (1984)**: la **strange quark matter** (SQM, made by u, d, and s quarks) may be more stable than ordinary matter.
- **De Rújula and Glashow (1984)**: theoretical description of interaction with the Earth's atmosphere of such compact objects, named **nuclearites**.

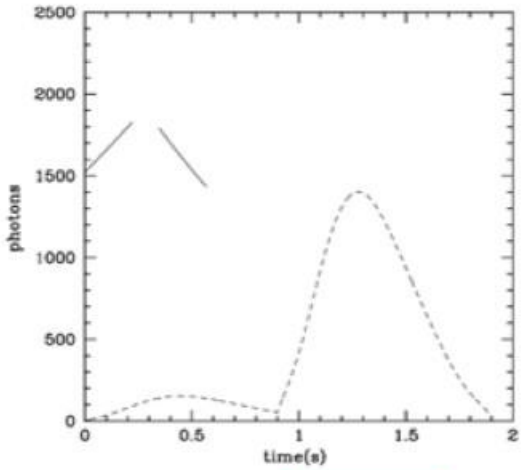


nuclearites

Nuclearites vs meteors:



	Meteors	Nuclearites
Speed	From 11 to 72 km s^{-1}	~ 250 km s^{-1} (up to 550 km s^{-1})
Initial Altitude	70 – 130 km	< 30 km
Motion	Downwards	May move upwards
Lightcurve	Various	Flat

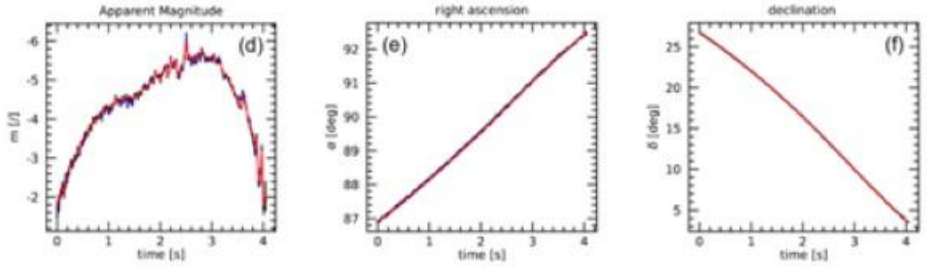


PRISMA PIPELINE

From the **video** to the **orbit**, fully automated:

Astrometry and photometry

- each camera is **calibrated daily and monthly** on 100–300 stars per image, down to magnitude +4 / +5
- fish-eye projection with 8+2 parameters to absorb the strong **radial distortion**
- **Centring precision** of the order of **0.1 px** (few arcmins)



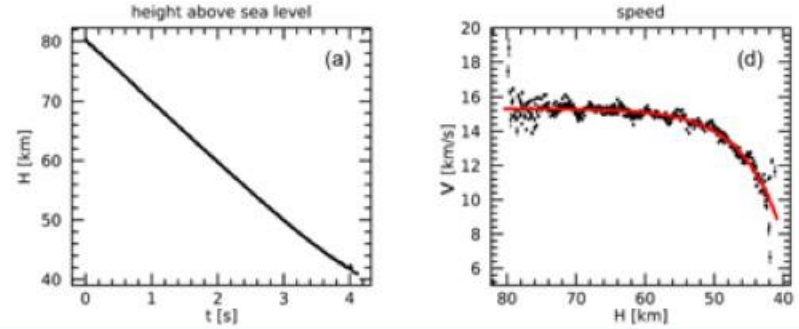
Triangulation

Combination of two 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**

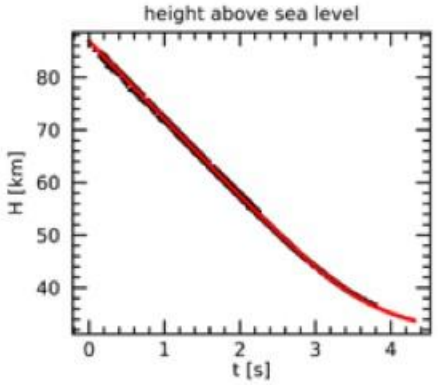


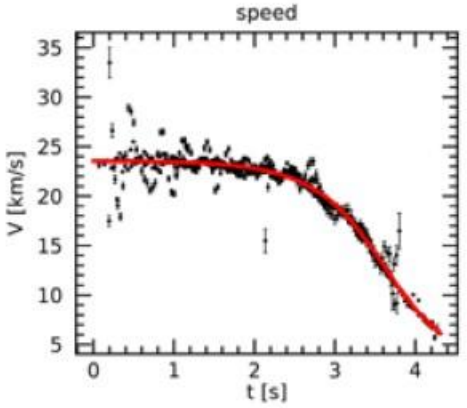
PRISMA PIPELINE

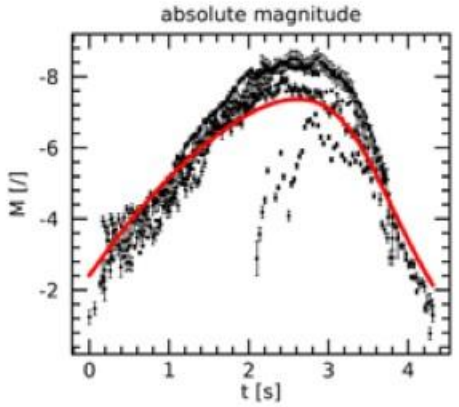
From the **video** to the **orbit**, fully automated:

Dynamic model

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

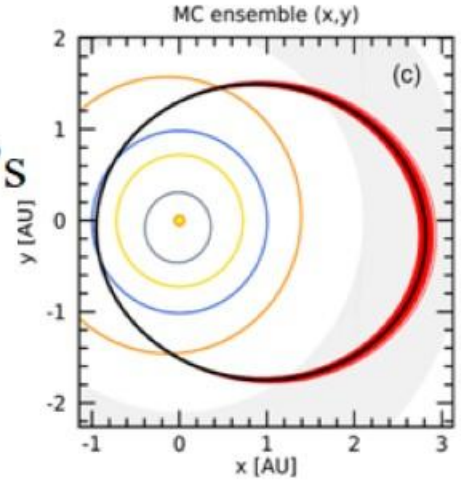






Orbit reconstruction

- **Pre-atmospheric orbit** from trajectory versor and preatmospheric speed (V_∞).
- corrected for Earth's gravity and **zenith attraction**



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