Meteoroids impacting the atmosphere
How can we measure them?

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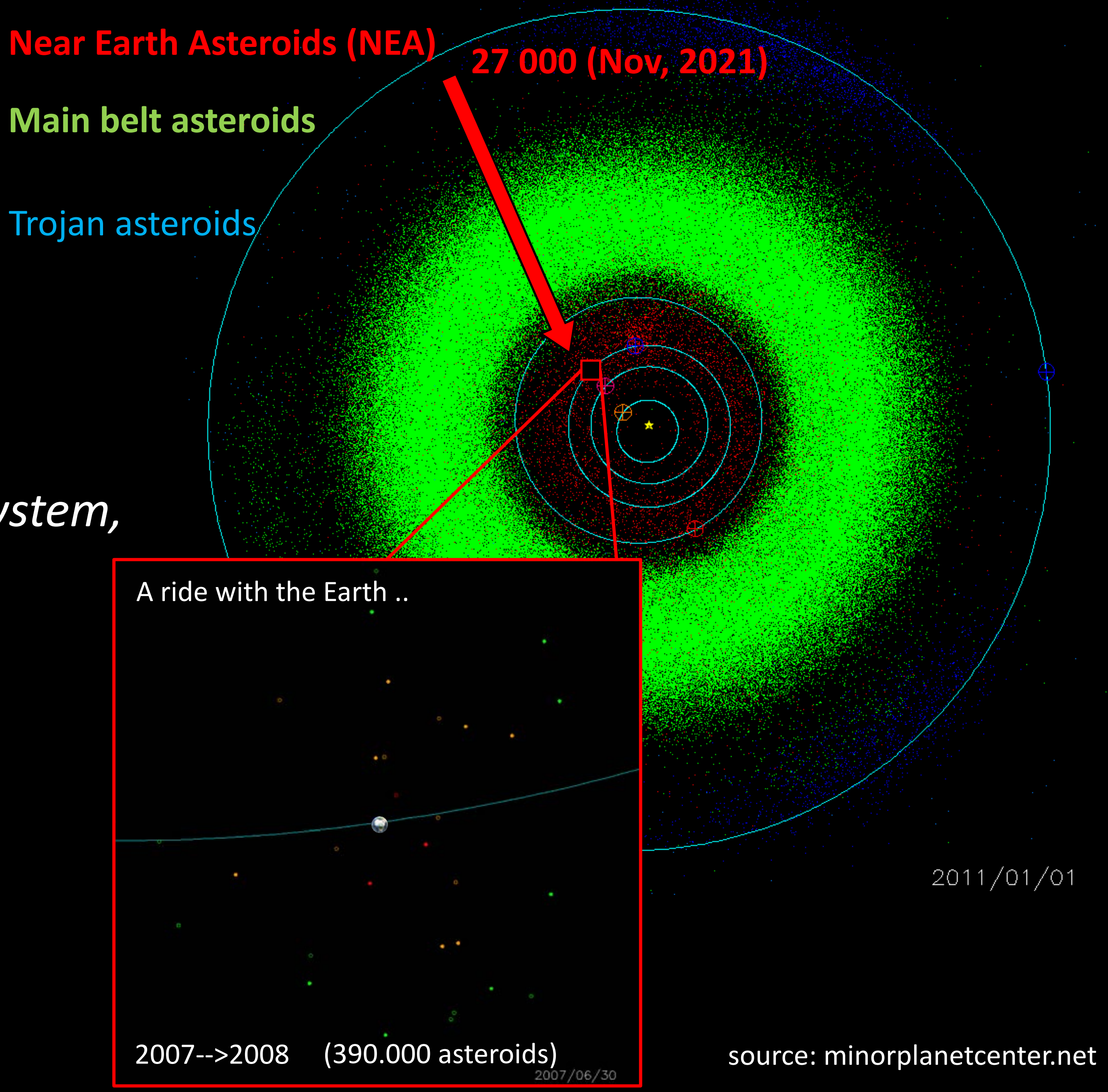
What are Asteroids?

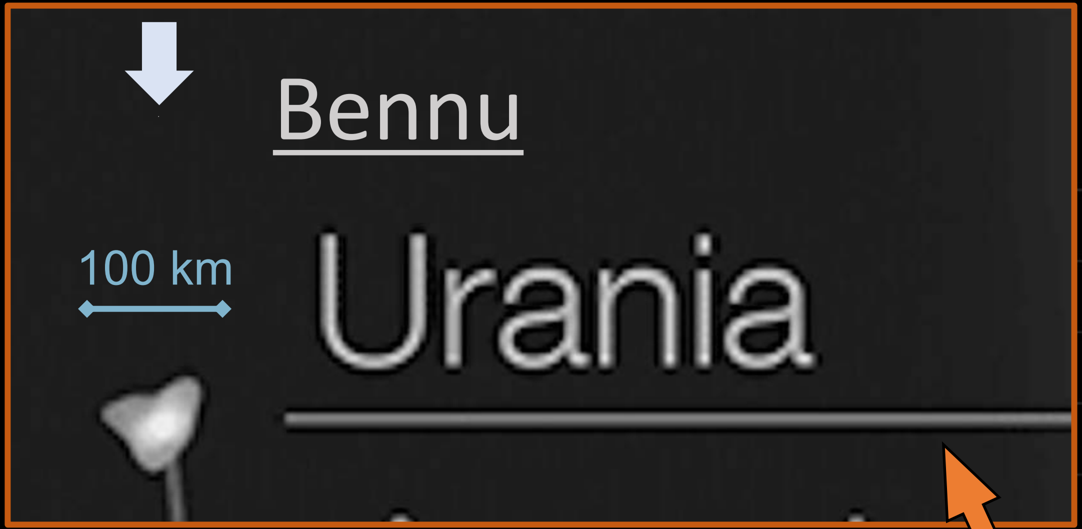
Asteroids are small objects in the Solar System, also known as minor planets.

Asteroid sizes ranges between

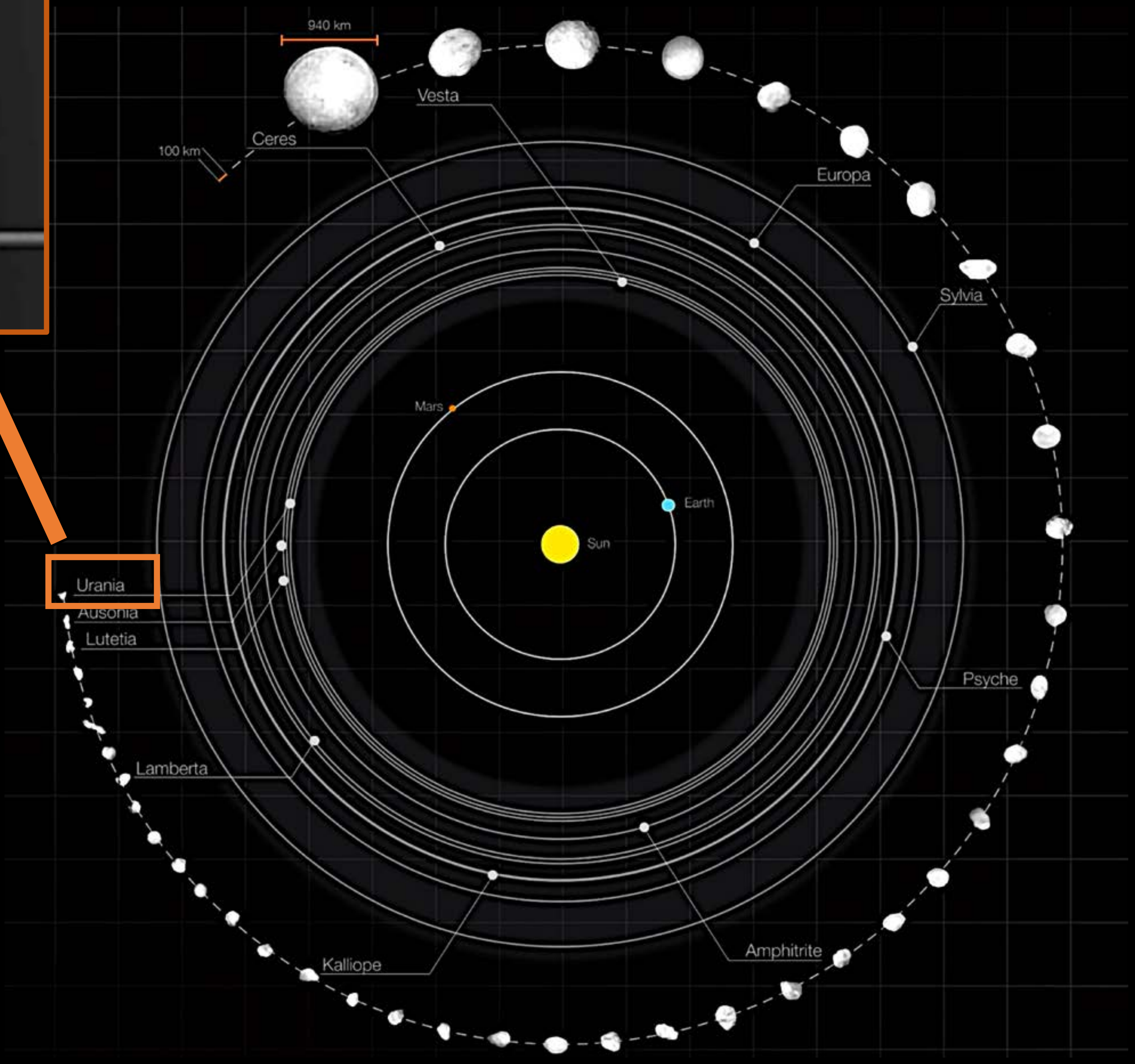
meters -> hundreds of kilometers.

> 1.100.000 known asteroids (Nov, 2021)





Vernazza et al. 2021



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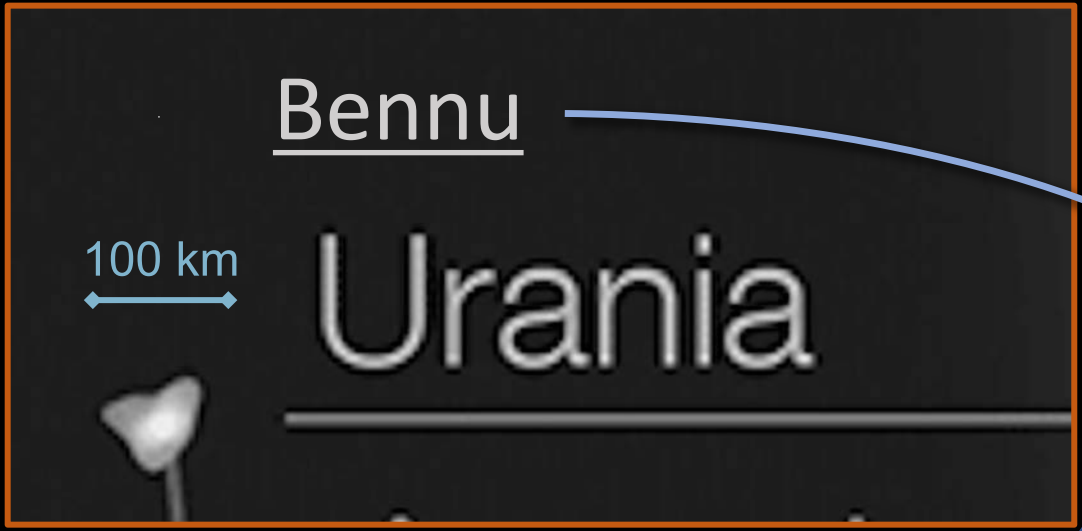
(Nov, 2021)

credit: ESO public release



Bennu = 1/200 Urania

= 500 m

Object's diameter:

Asteroid:

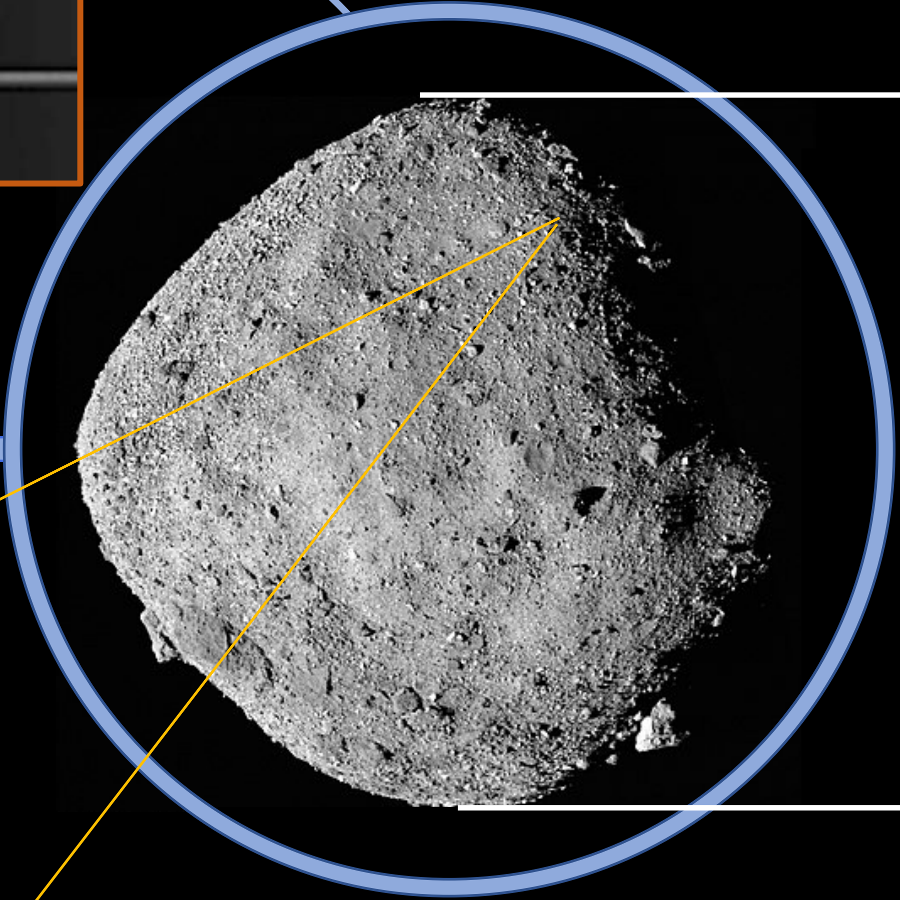
> 1m

Meteoroid:

< 1m

Micrometeoroid:

< 30 µm



Credit : Osiris REX

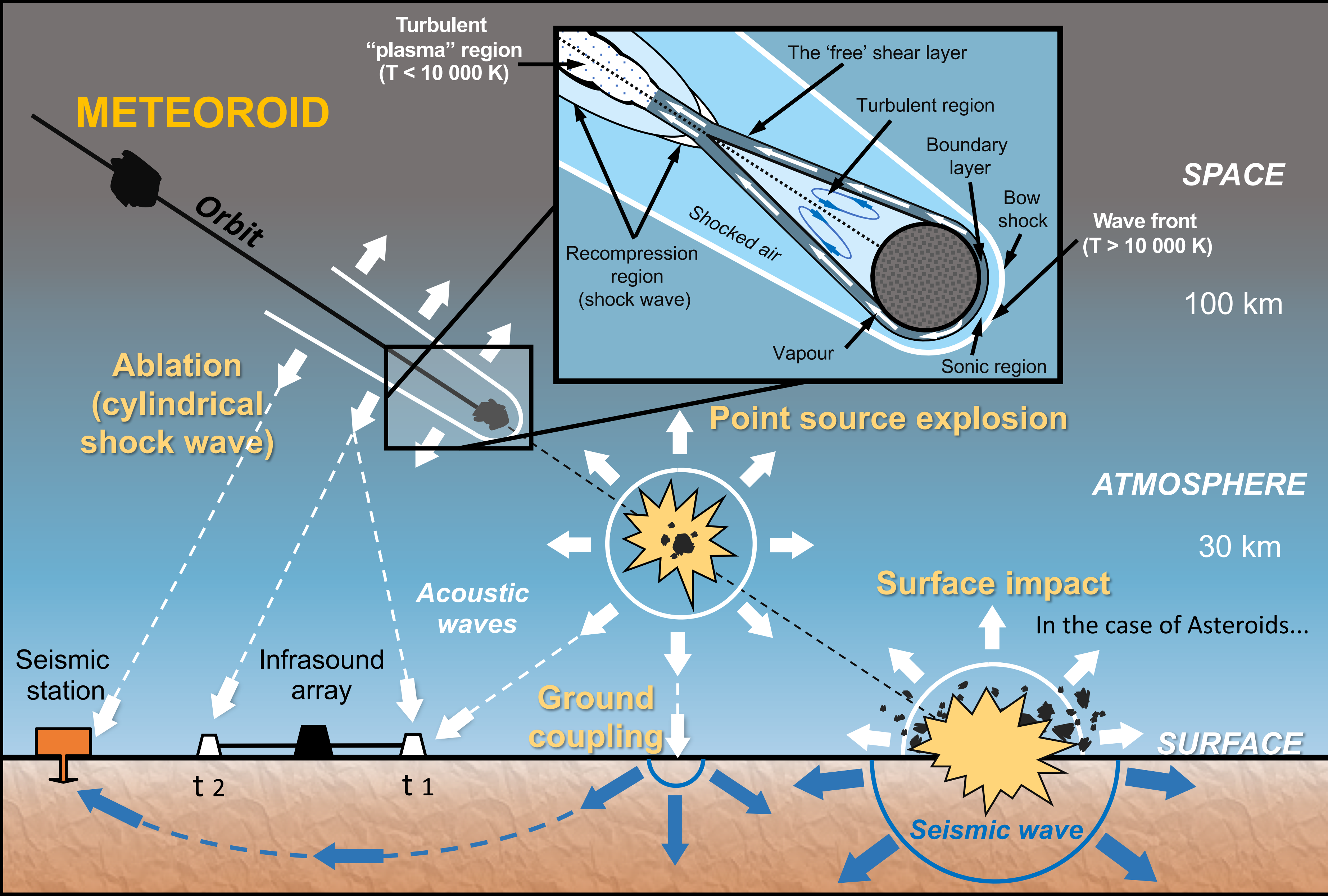
Empire State Building

What happens when a meteoroid enters the atmosphere?

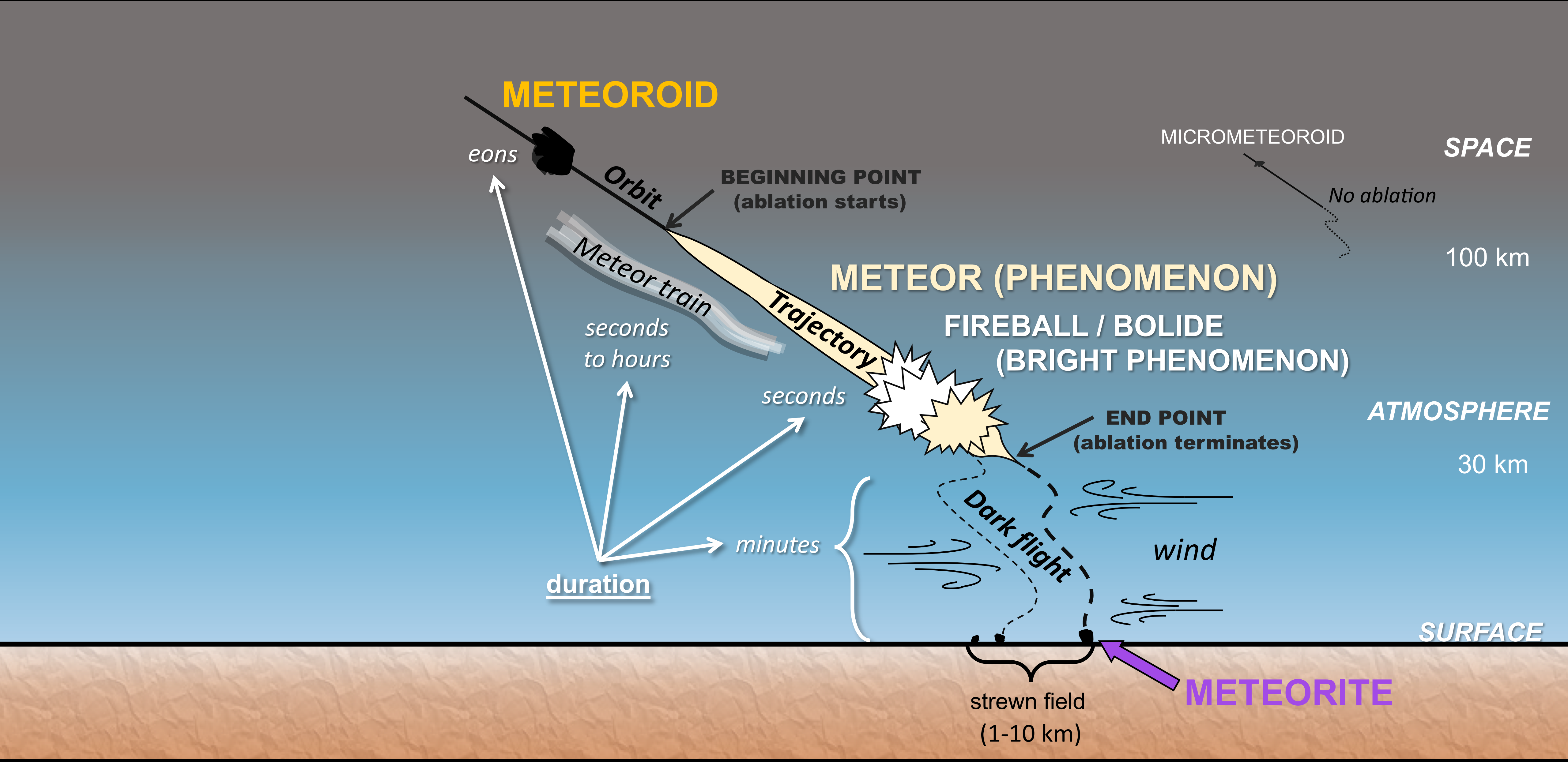
Study Motivation

- Meteoroid mass scale is uncertain
- Meteoroids keep the memory of the early Solar System
- Meteoroids as analogues for Asteroids and Comets
- Meteoroid size / flux density estimations are important for spacecraft shielding

➢ *Make multi-sensor simultaneous observations using the atmosphere as a „detector"*

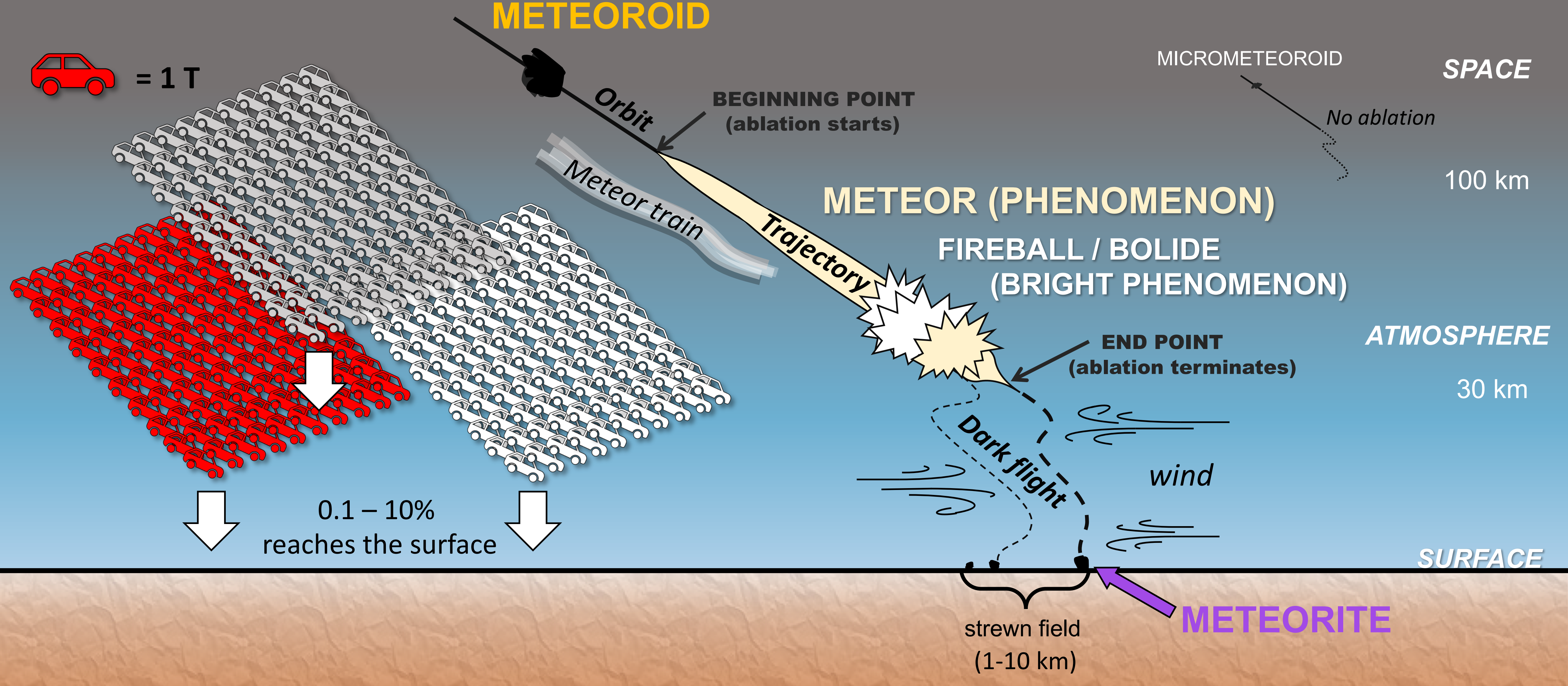


What happens when a meteoroid enters the atmosphere?



How much cosmic material enters the atmosphere every day?

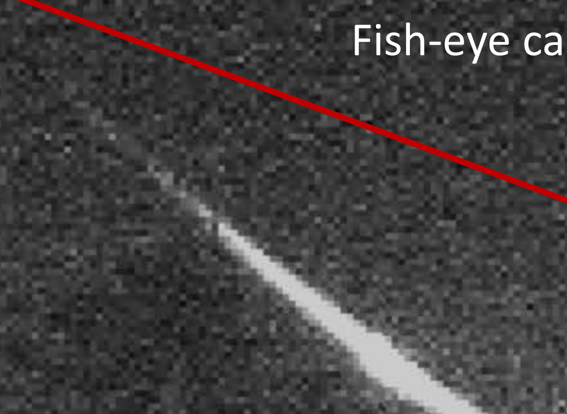
Answer : 50 - 300 T



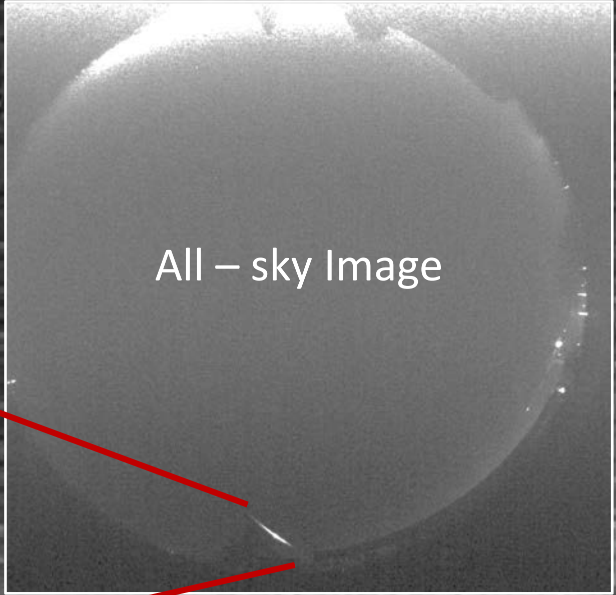
Bolide (greek, ***bolis*** **=** projectile)

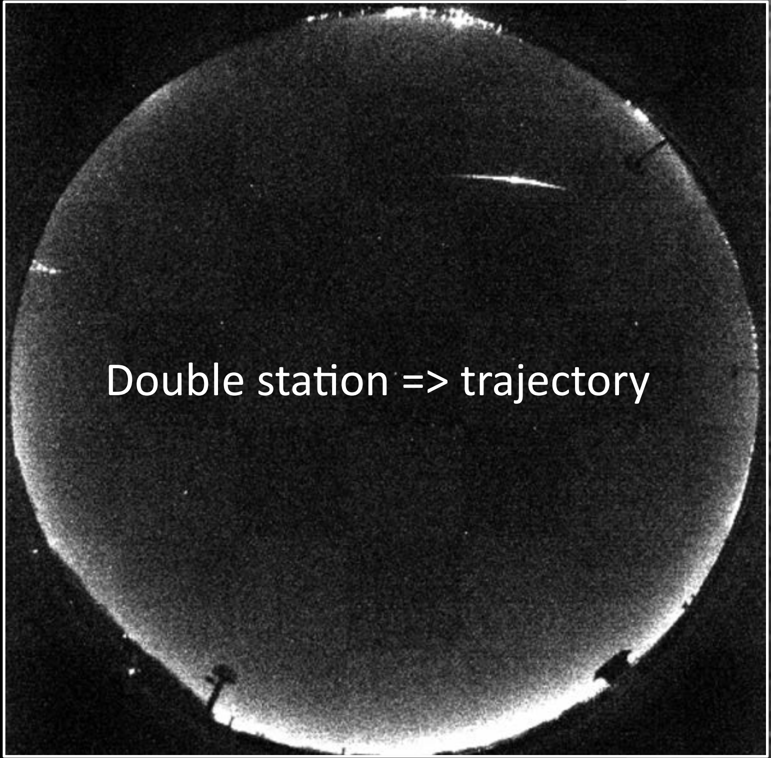
Meteor brighter than magnitude -4

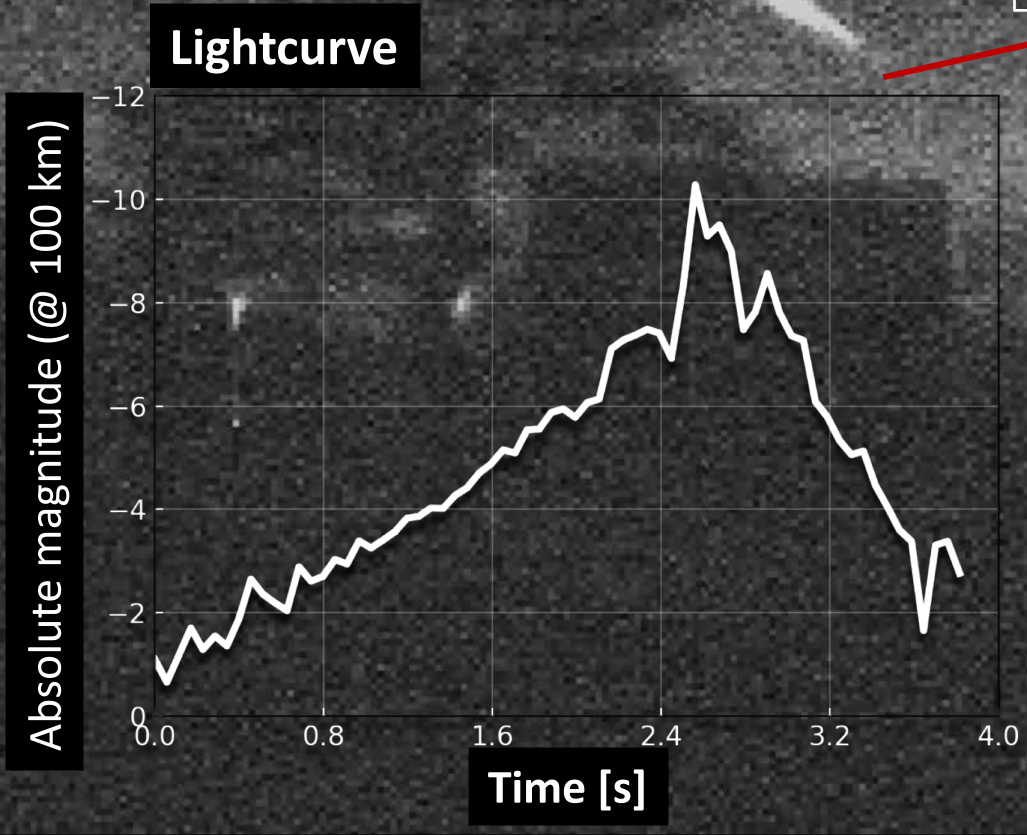
The variation in luminosity indicates the properties of the meteoroid
(e.g. fragmentation, rotation, strength)

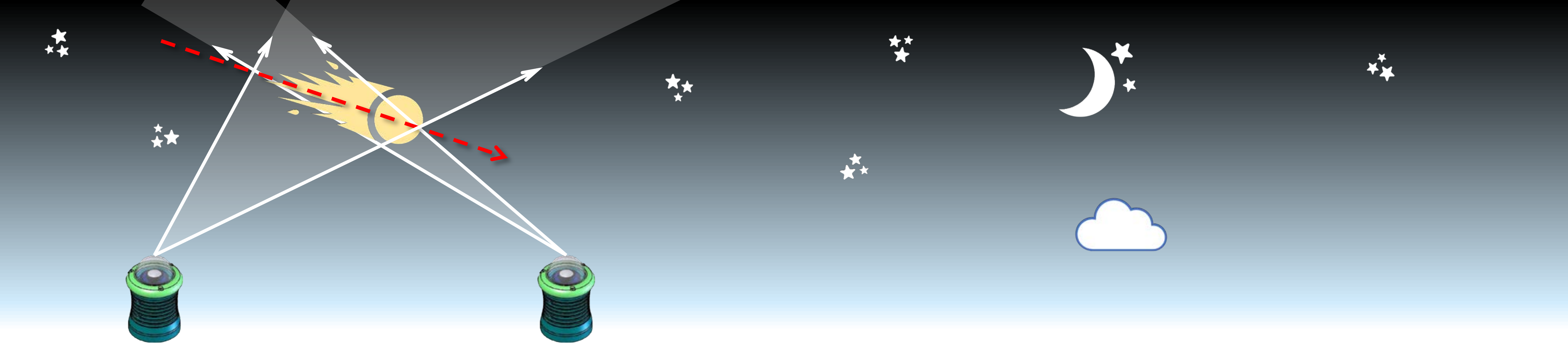


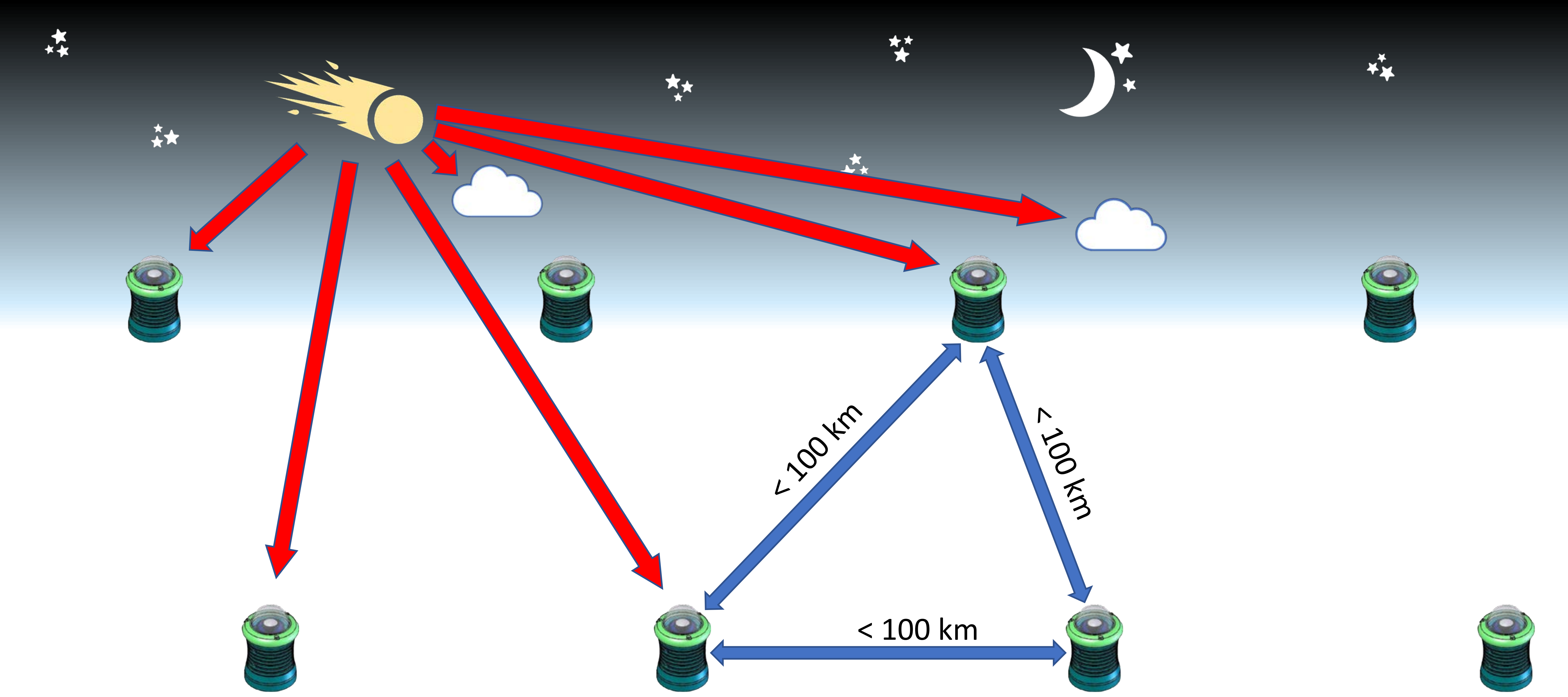

Fish-eye camera











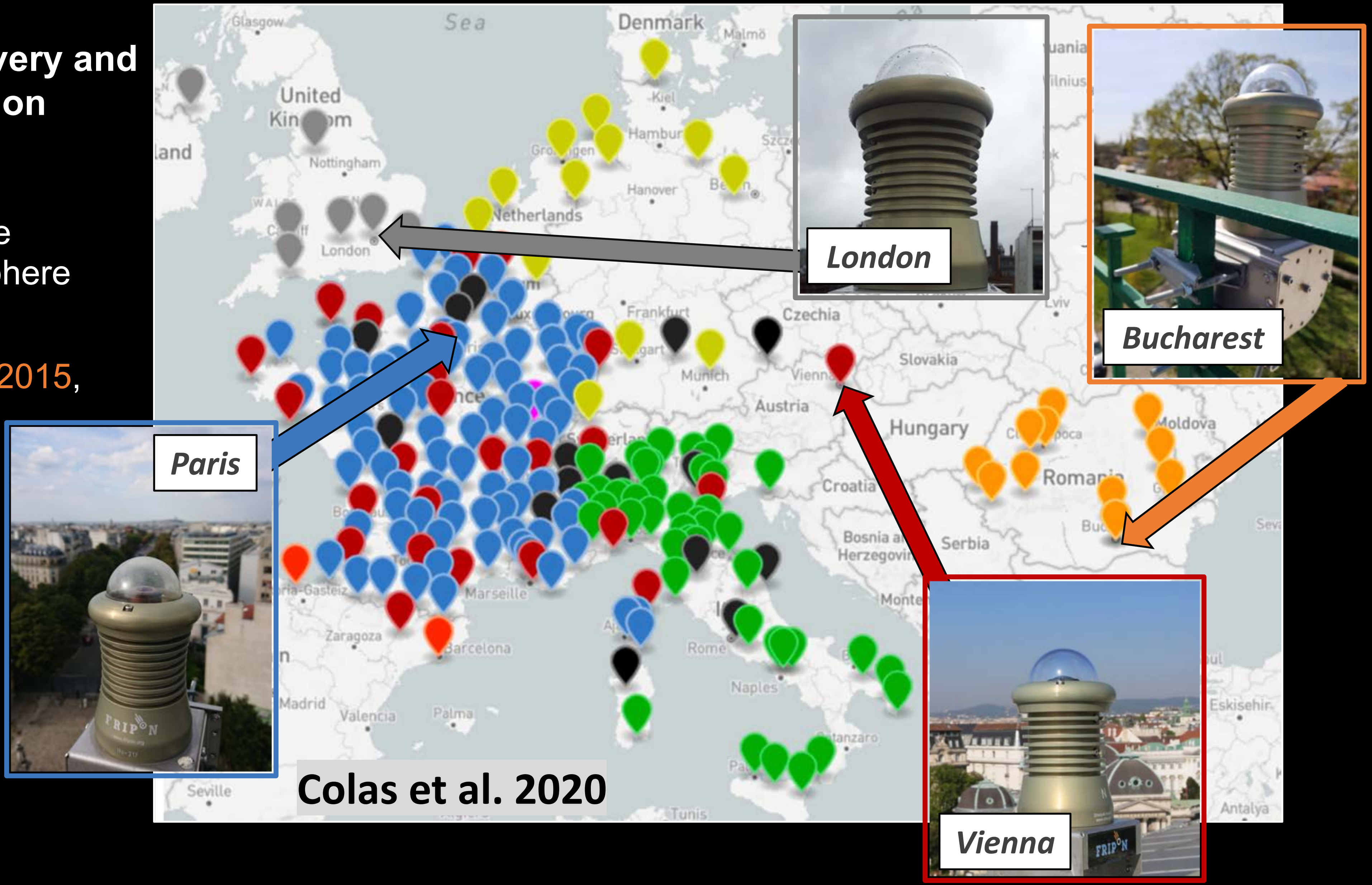
Fireball Network

The FRIPON Consortium

FRIPON = Fireball Recovery and InterPlanetary Observation Network

- Track and recovery of the objects entering the atmosphere

- First camera installed in 2015, at Paris Observatory



The FRIPON Consortium

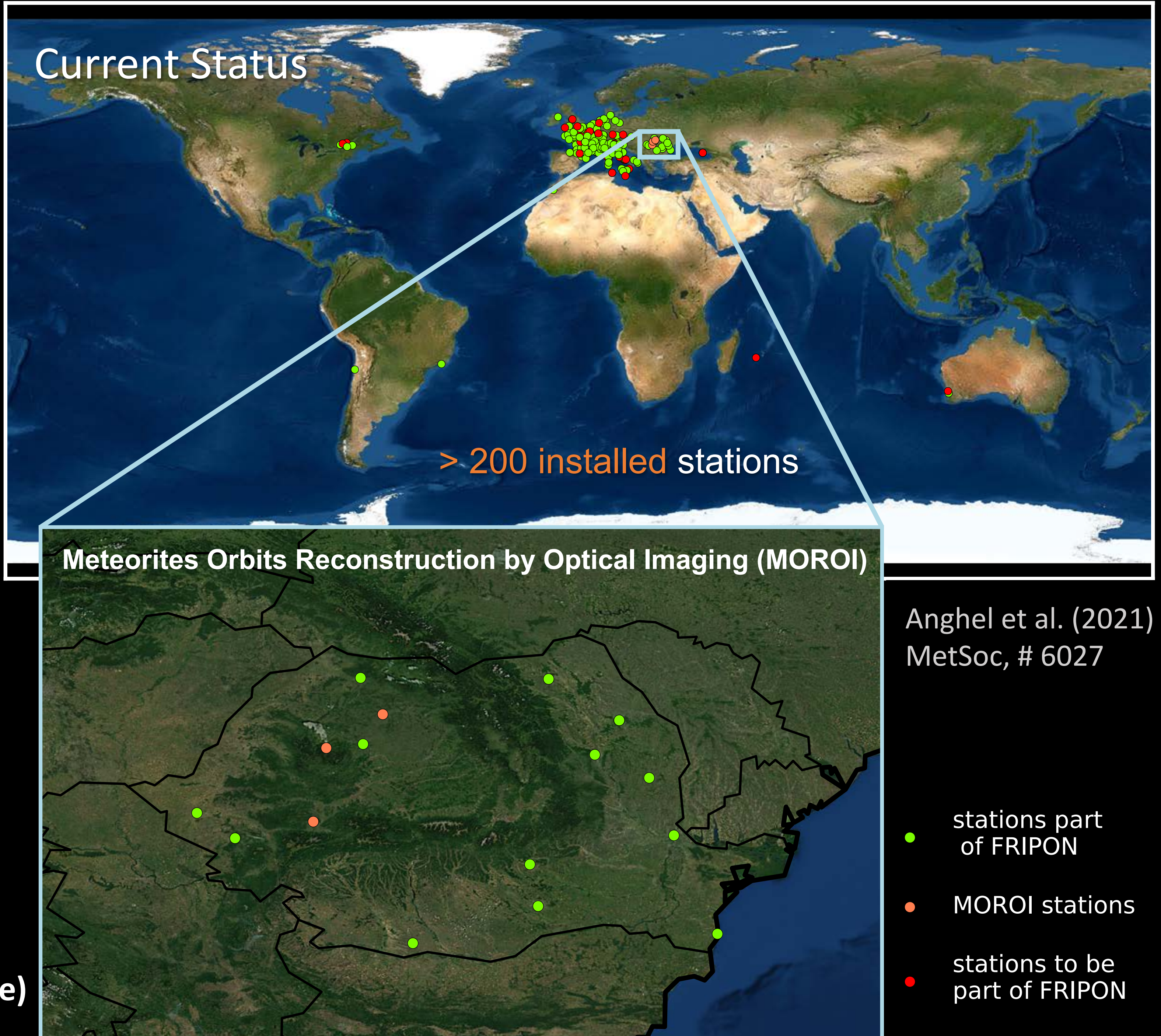
FRIPON = Fireball Recovery and InterPlanetary Observation Network

- Track and recovery of the objects entering the atmosphere
- First camera installed in 2015, at Paris Observatory

MOROI network current status:

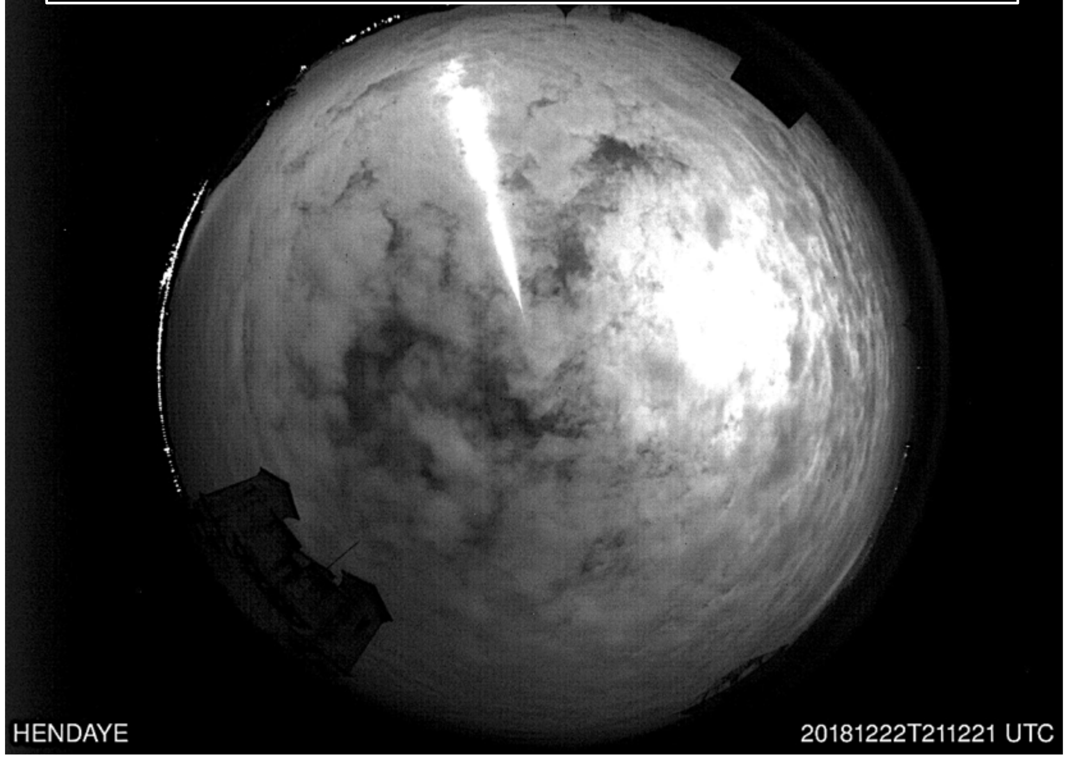
- 13 stations connected to **FRIPON**
- meteoroid trajectory & orbit (Nedelcu et al. 2018, RoAJ; Anghel et al. 2021, RoAJ)
- meteoroid mass (Anghel et al. 2021, MNRAS)
- meteorite strewn field (Boaca et al. 2021, RoAJ)
- night sky quality (Anghel et al. 2019, RoAJ)
- night cloud coverage (Birlan et al. 2021, RoAJ)

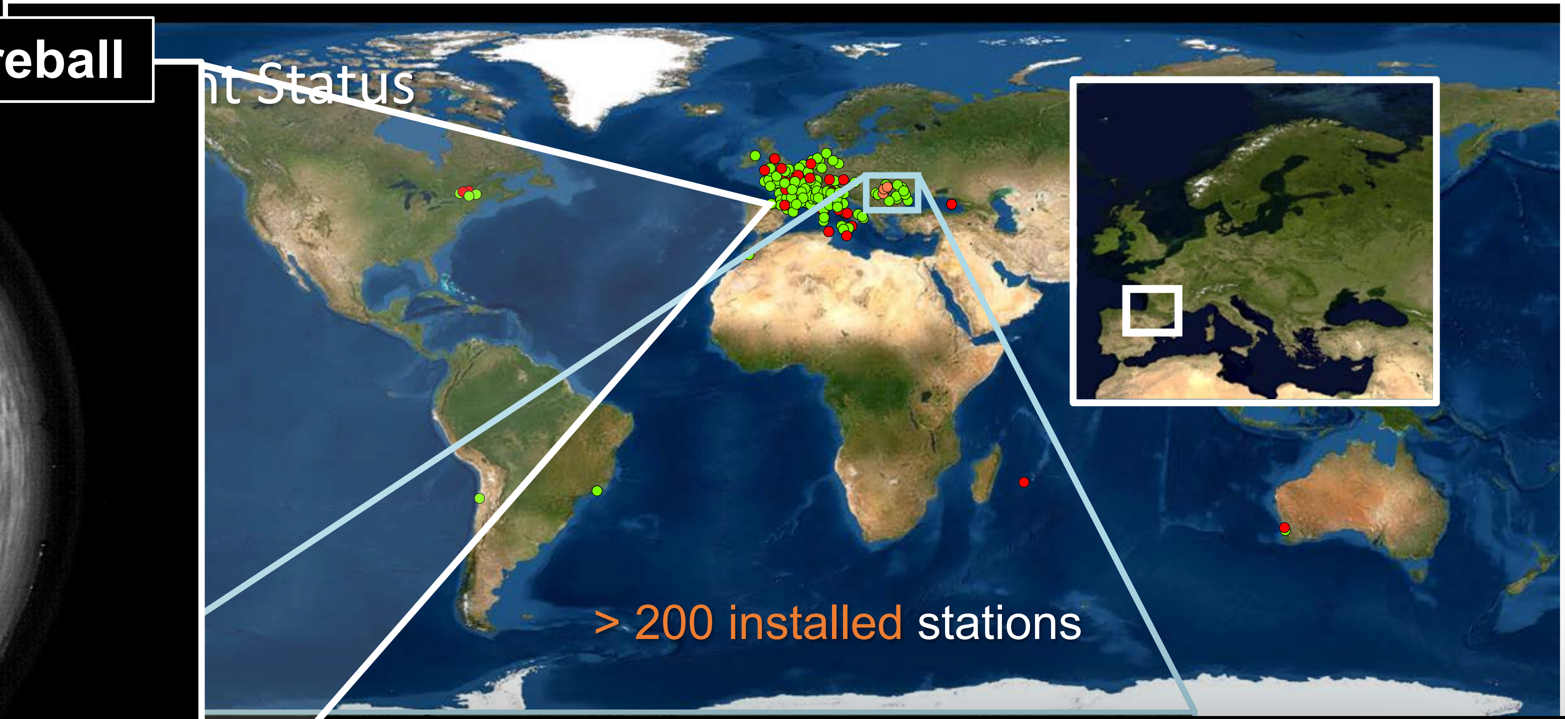
https://www.fripon.org/ **(Open-access database)**



Anghel et al. (2021) MetSoc, # 6027

22 December 2018 Pyrenean Fireball





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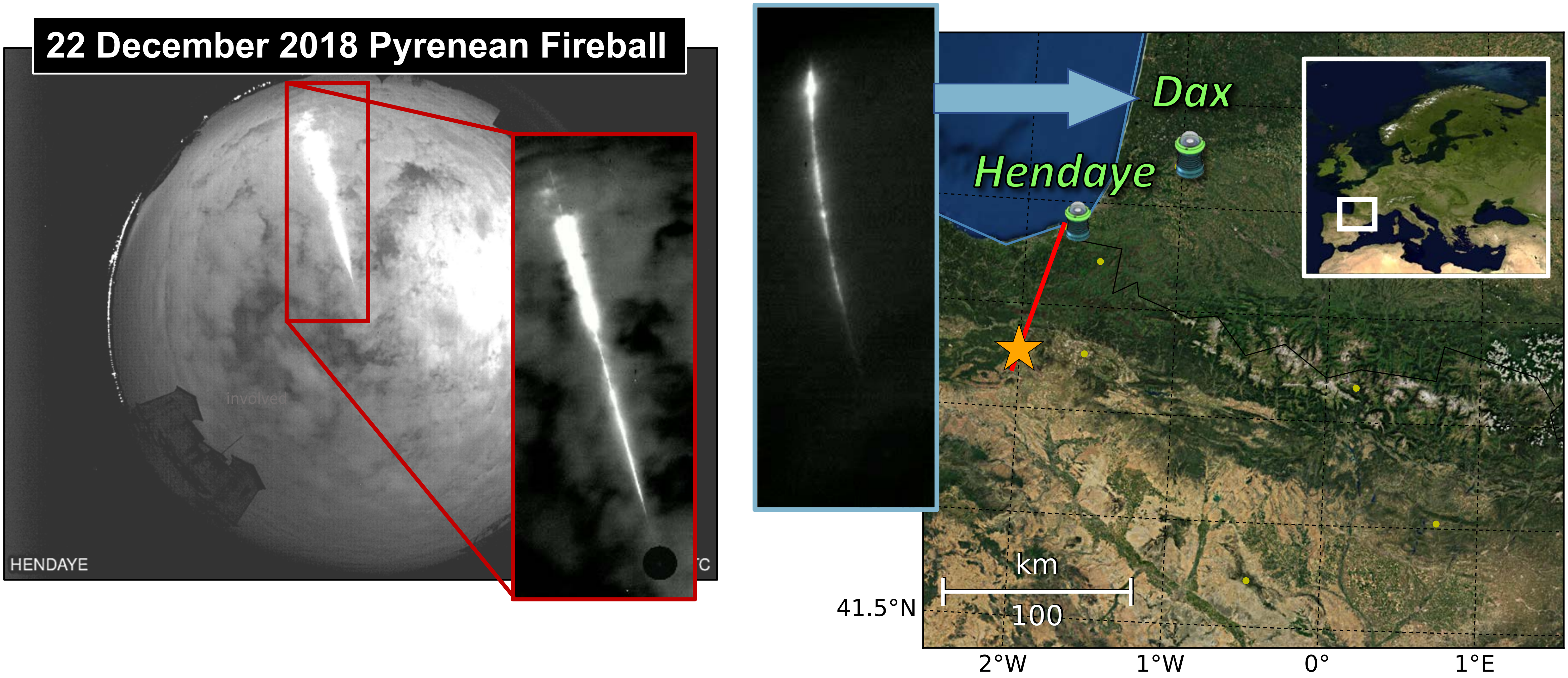
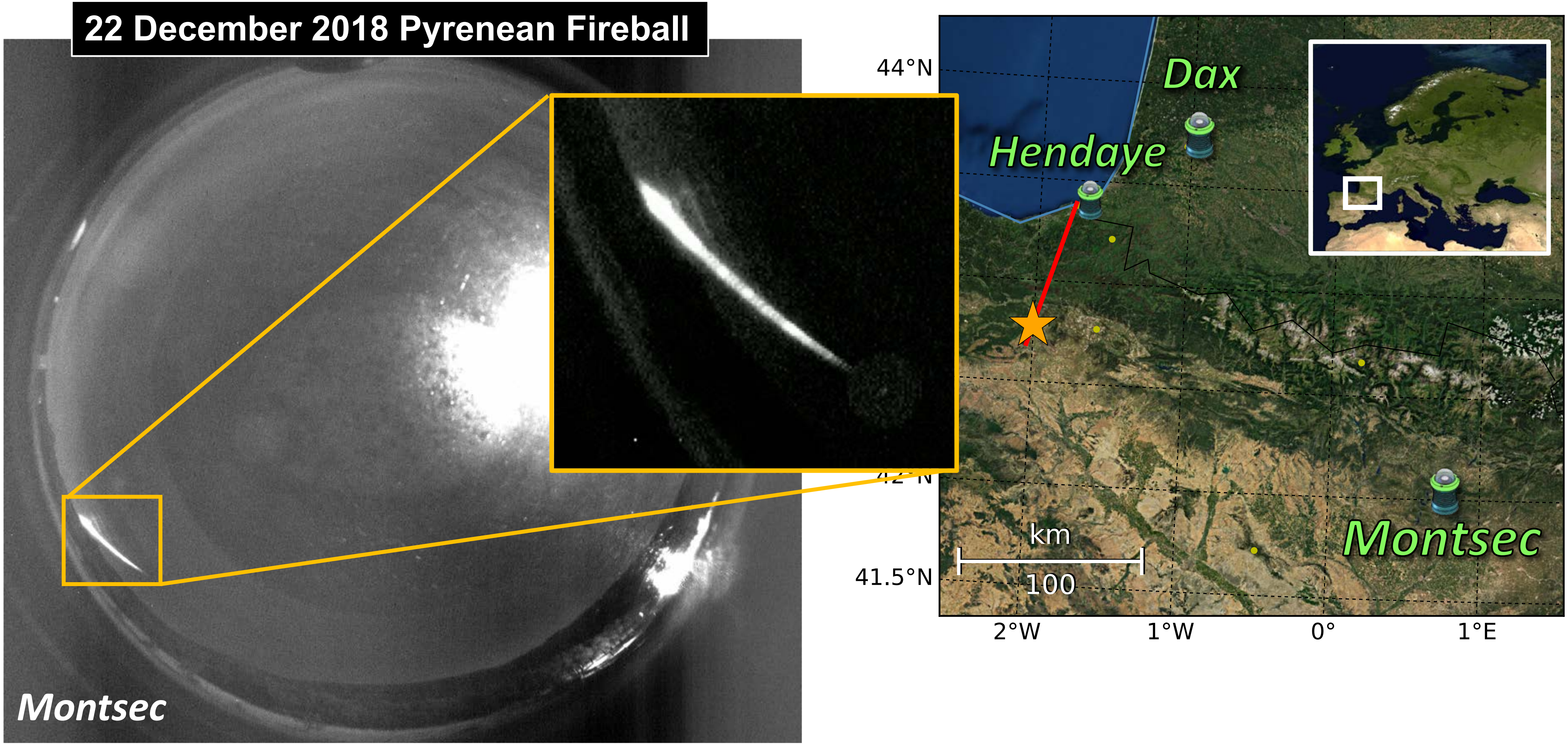
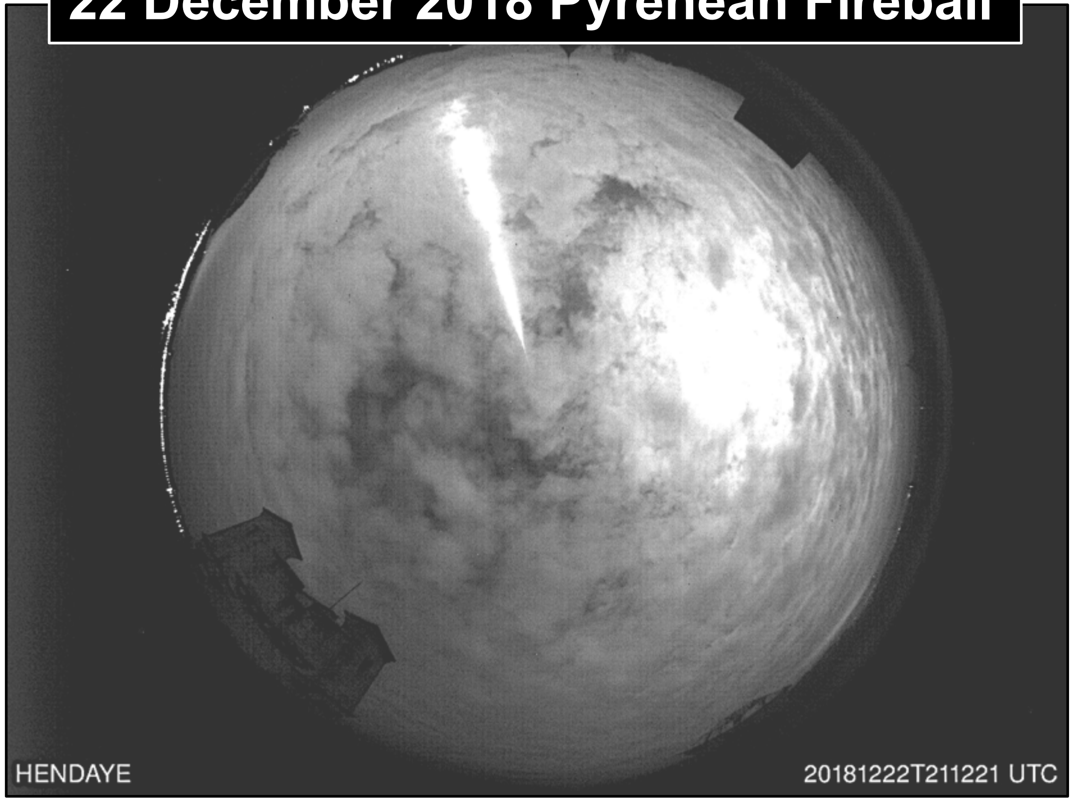
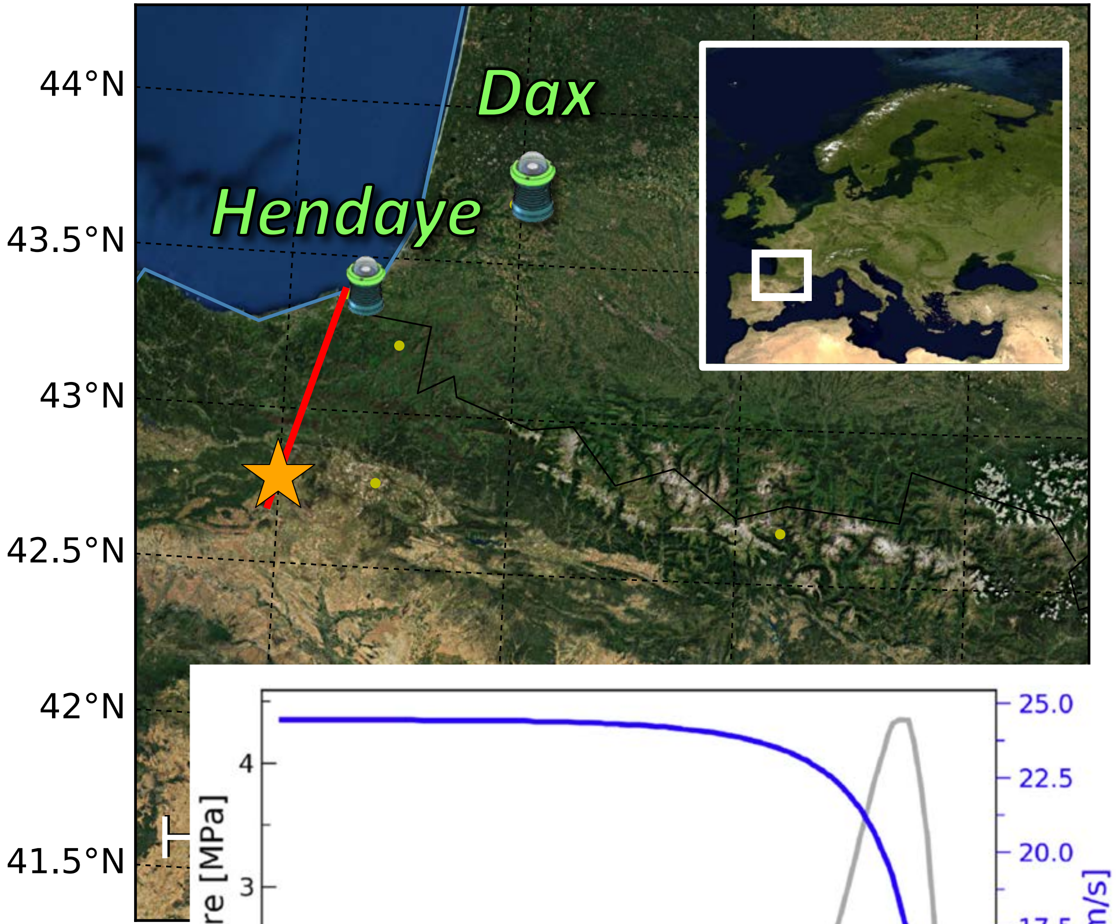


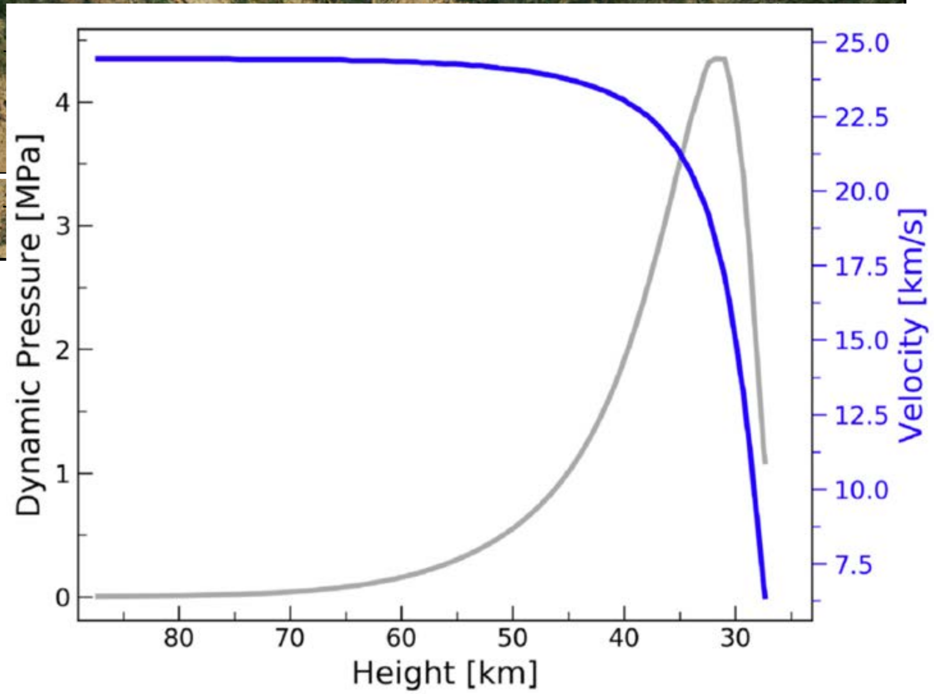
22 December 2018 Pyrenean Fireball
HENDAYE
Dax
Hendaye
km
100
41.5°N
2°W
1°W
0°
1°E


22 December 2018 Pyrenean Fireball
Montsec
Dax
Hendaye
Montsec
44°N
41.5°N
km
100
2°W
1°W
0°
1°E

22 December 2018 Pyrenean Fireball







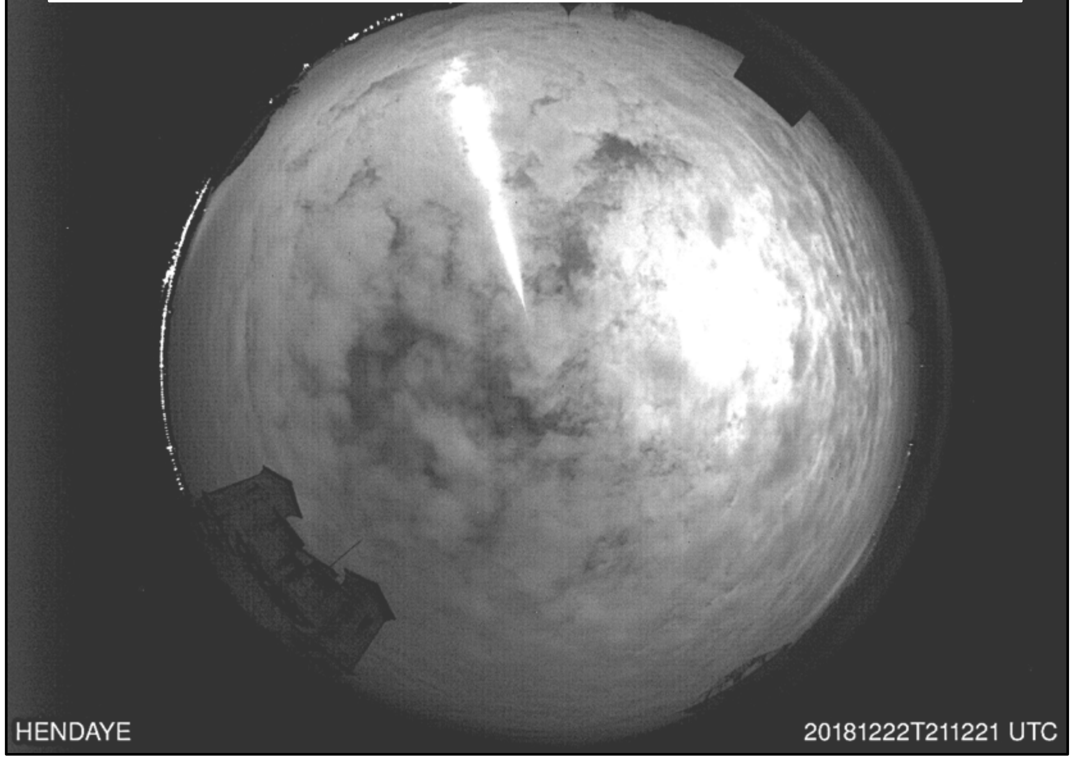
Energy estimation methods:

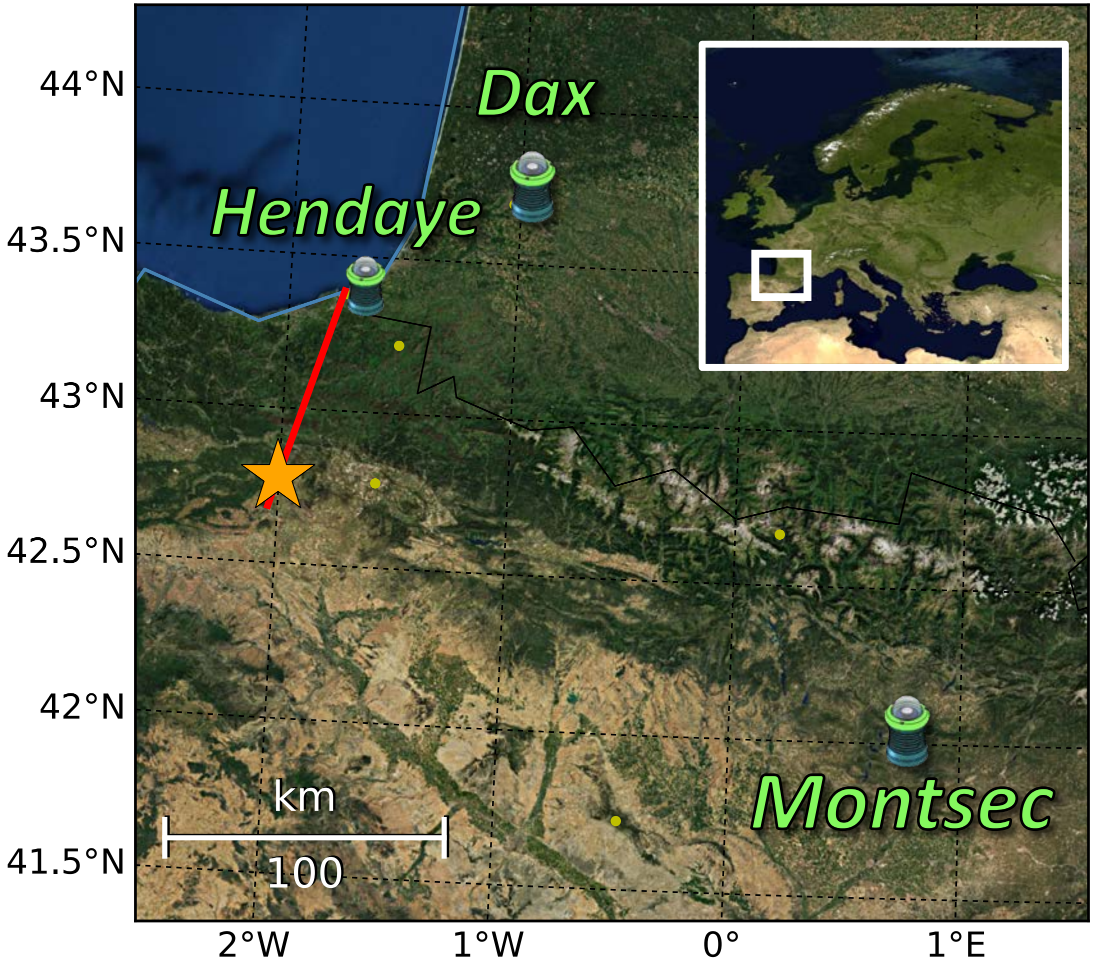
Dynamic (Ballistic & Mass loss parameters)

theoretical (Gritsevich **2009**, Jeane et al. **2019**)

Accurate tracking of the change in velocity

22 December 2018 Pyrenean Fireball





Energy estimation methods:

Dynamic (Ballistic & Mass loss parameters)
theoretical (Gritsevich **2009**, Jeane et al. **2019**)

$$\alpha = \frac{1}{2} c_d \frac{\rho_0 h_0 S_e}{M_e \sin\gamma} = \frac{1}{2} c_d \frac{M^{(air-in-front-of-the-body)}}{M_e}$$

$$\beta = (1-\mu)\frac{c_h V_e^2}{2 c_d H^*} = (1-\mu)\frac{c_h V_e^2 M_e}{2 c_d H^* M_e} = (1-\mu) c_h / c_d \frac{E_{kin}}{E^{(required-to-fully-destroy-the-object-in-the-atmosphere)}}$$

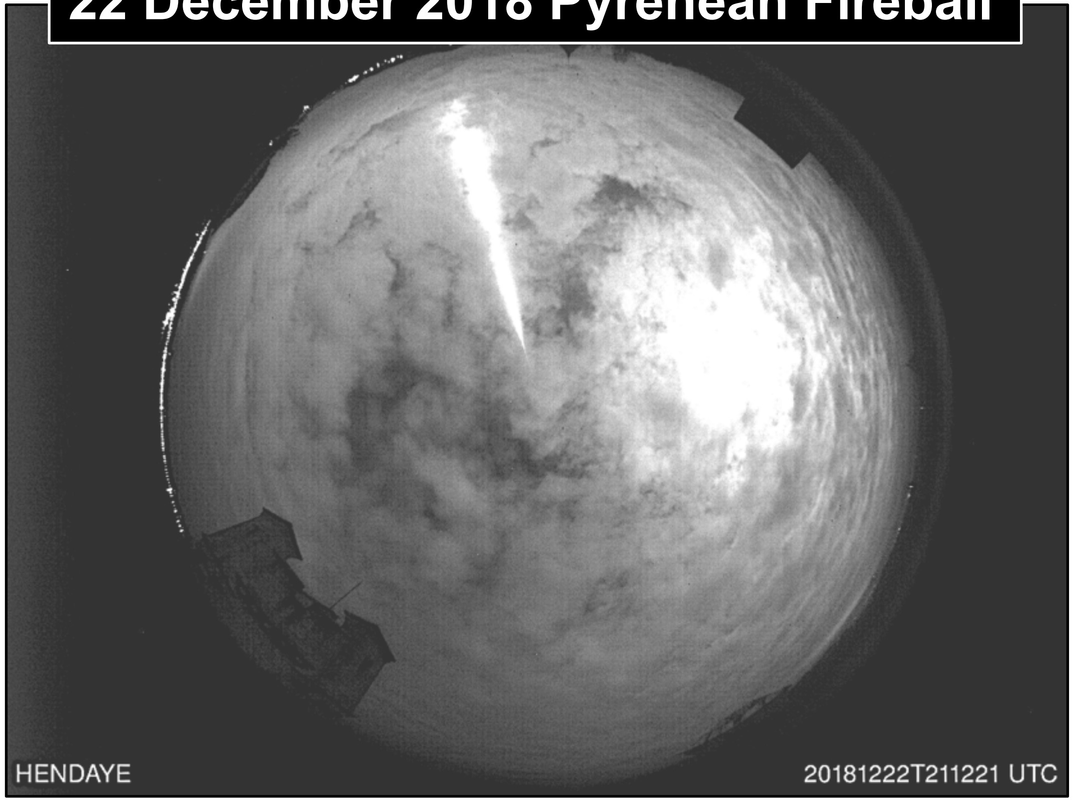
α characterizes aerobraking efficiency

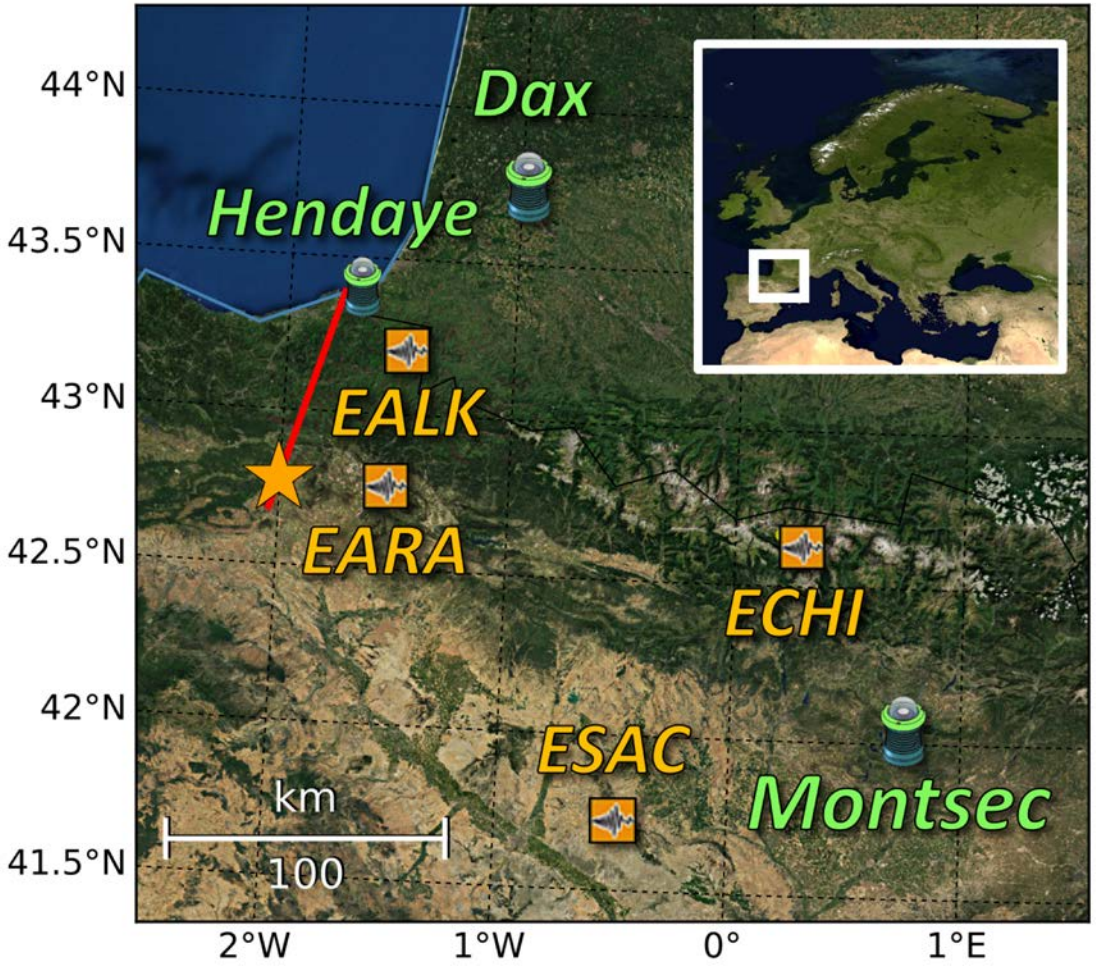
β characterizes the mass loss

Gritsevich, 2018

ρ_0 = gas density at sea level	V_e = pre-entry velocity	h_0 = the scale height
M = meteoroid mass	c_d = drag coefficient	γ = entry angle
M_e = pre-entry mass	c_h = heat-transfer coefficient	S = middle section area
μ = shape change coefficient	H = destruction enthalpy by *kg*	S_e = pre-entry middle section area

22 December 2018 Pyrenean Fireball

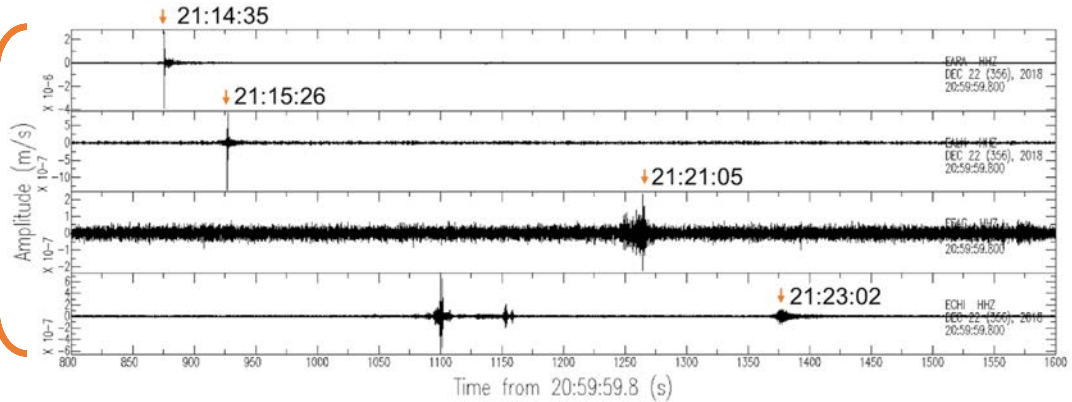




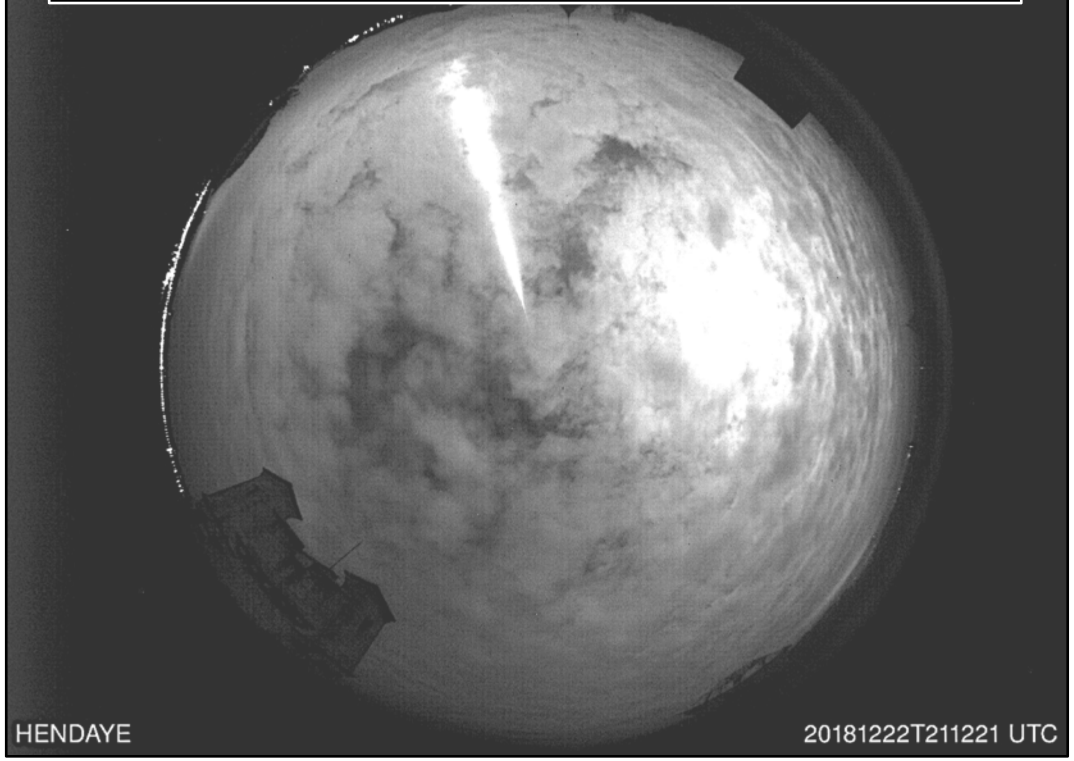
Energy estimation methods :

Seismic (Acoustic-Seismic Coupling)
semi-empirical (Kanamori **1977**, ReVelle & Whitaker **1996**)

When bolide shockwave hits the ground it turns into seismic signal



22 December 2018 Pyrenean Fireball



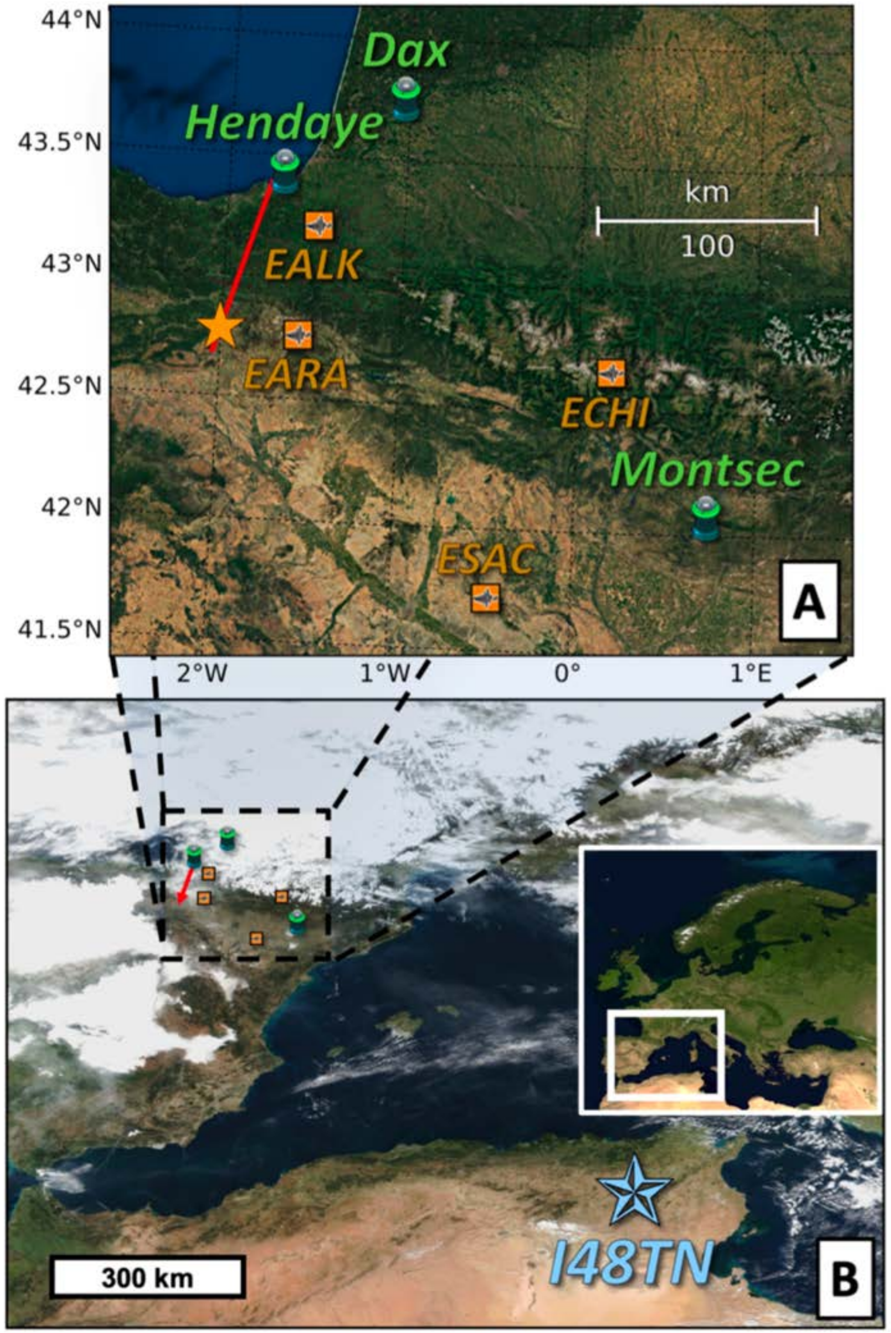


Figure 1. Satellite view of the Western Mediterranean. The ground projection

Energy estimation methods :

Infrasound (**Period at Maximum Amplitude**)

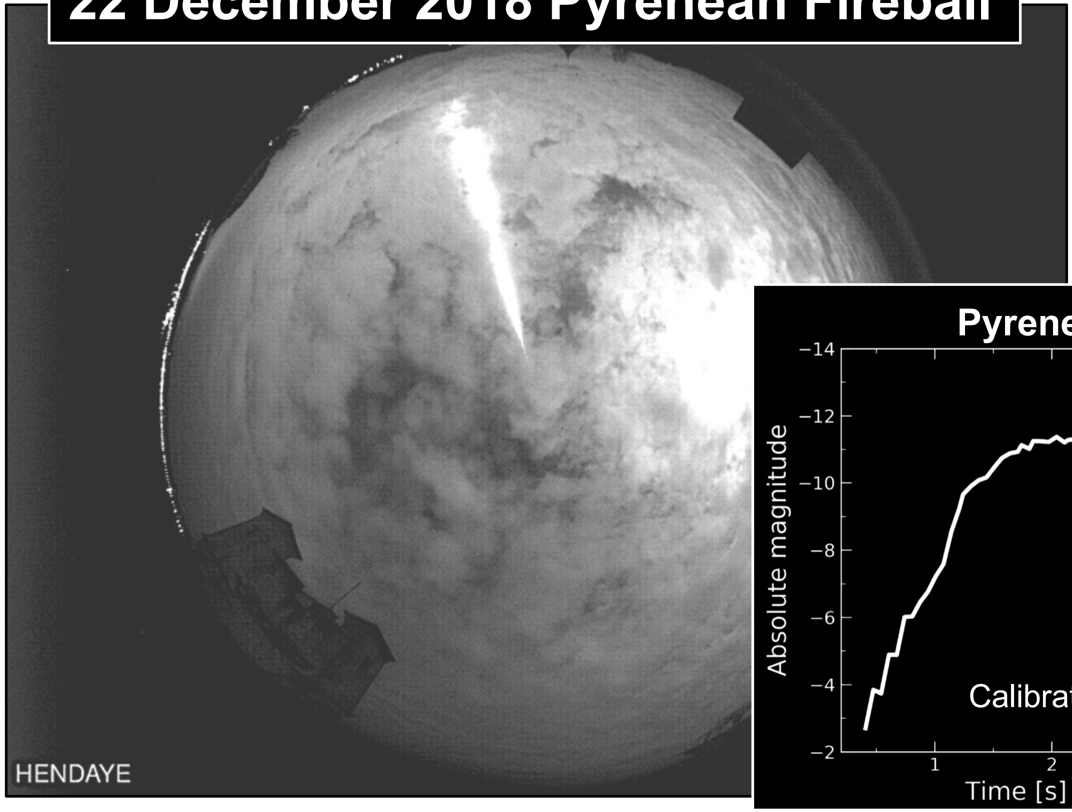
empirical, wave properties (ReVelle **1997**, Ens et al. **2012**)

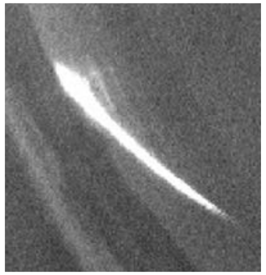
$$\log \frac{W}{2} = 3.34 \log \tau - 2.58, \quad \frac{W}{2} \leq 100 \text{ kt}$$

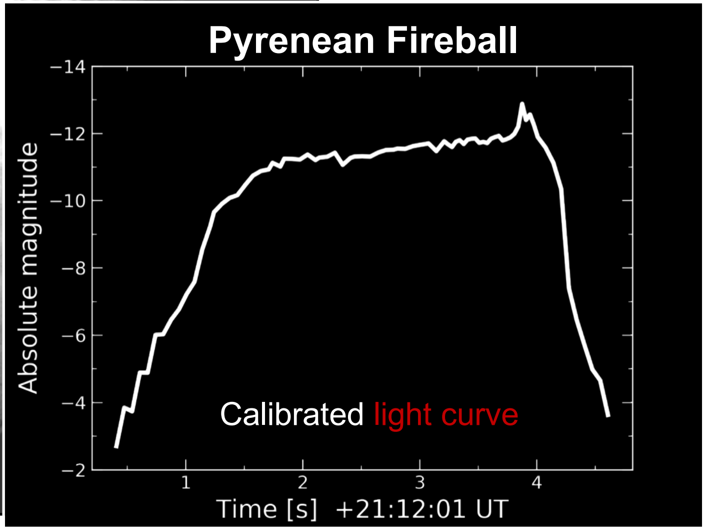
W = Source Yield (kt)
τ = period [s]

When bolide shockwave is detected at infrasound stations

22 December 2018 Pyrenean Fireball







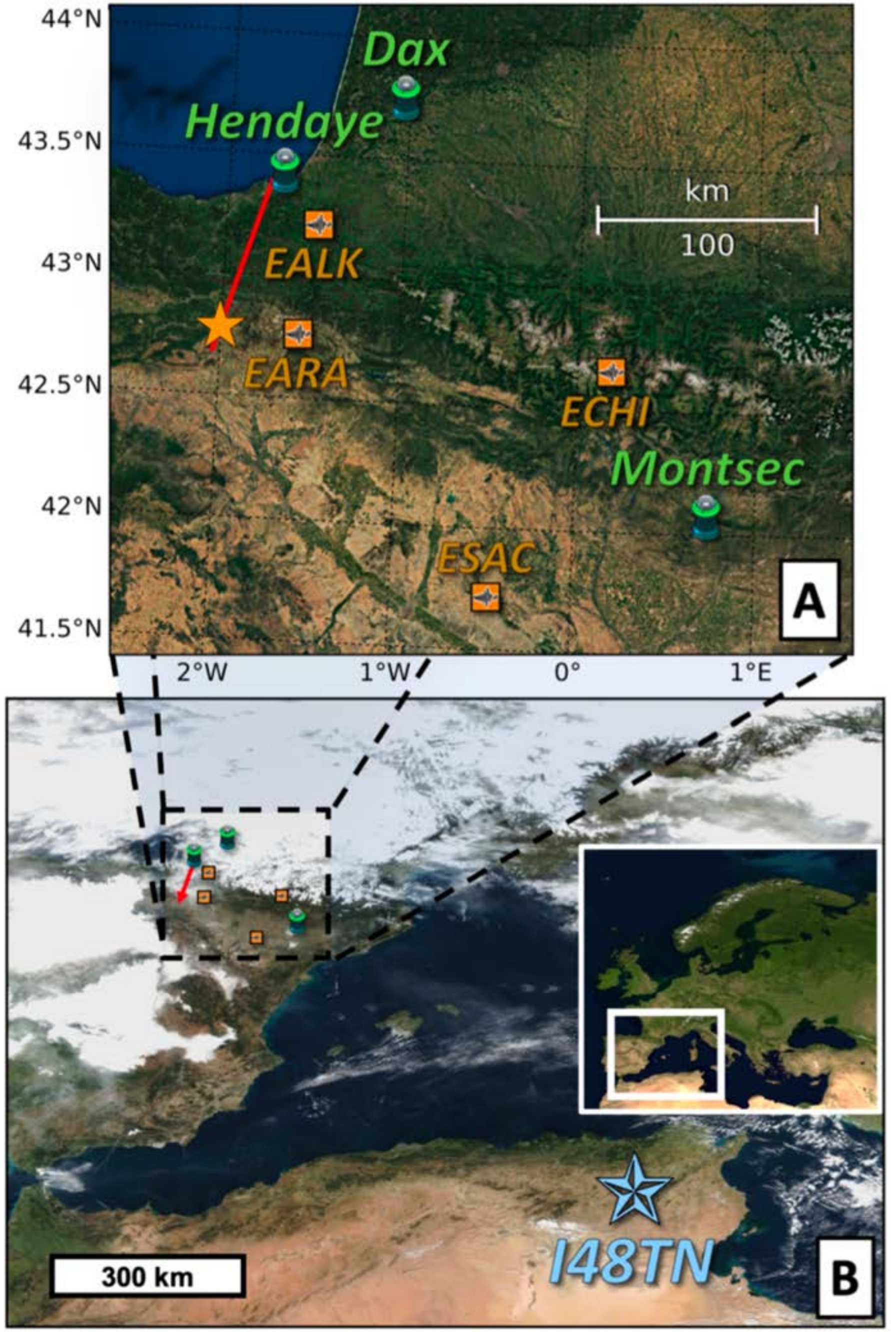


Figure 1. Satellite view of the Western Mediterranean. The ground projection

Energy estimation methods :

Radiation (**Integration of light curve**)

empirical (Ceplecha et al. **1998**)

$$I = \tau \frac{dm}{dt} \frac{v^2}{2}$$

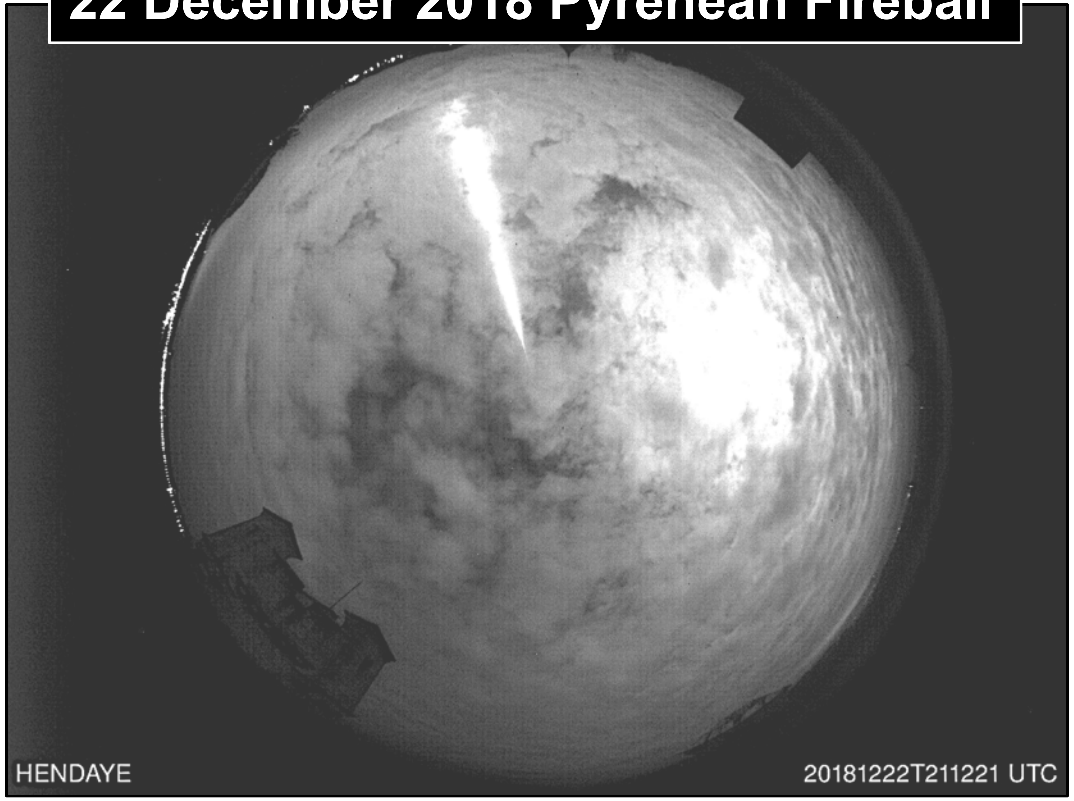
where:

τ = luminous efficiency

m = mass

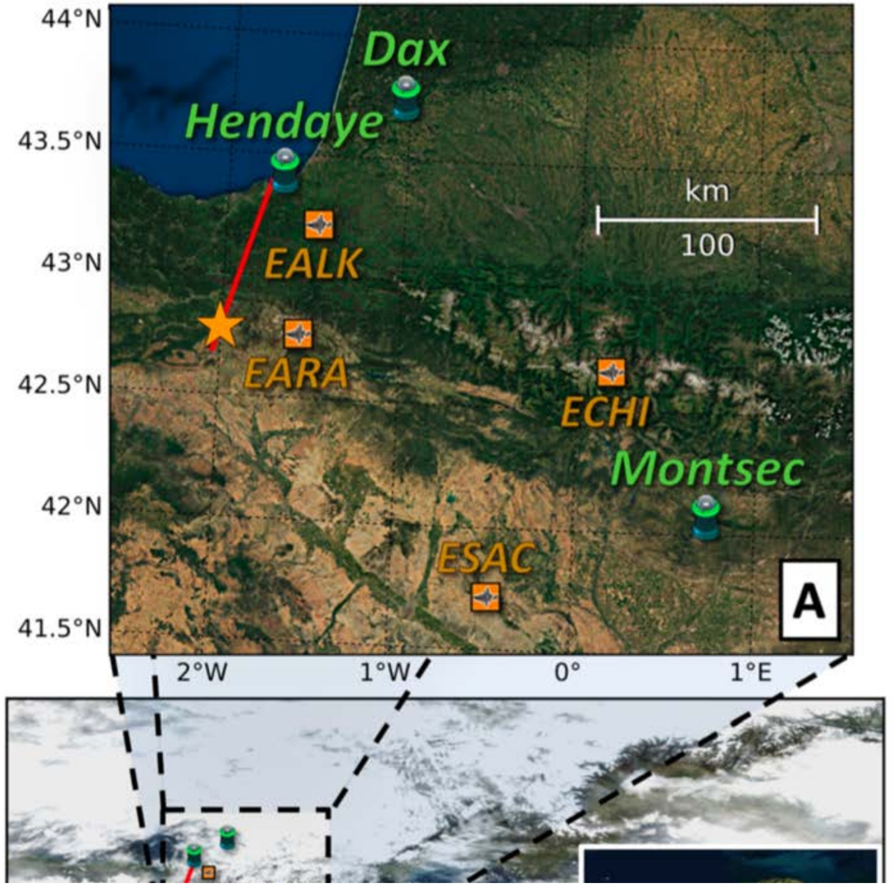
v = velocity

22 December 2018 Pyrenean Fireball



Energy estimation methods used:

1. **Dynamic (Ballistic & Mass loss parameters)**
   theoretical (Gritsevich **2009**, Jeane et al. **2019**)
2. **Seismic (Acoustic-Seismic Coupling)**
   semi-empirical (Kanamori **1977**, ReVelle & Whitaker **1996**)
3. **Infrasound (Period at Maximum Amplitude)**
   empirical, wave properties (ReVelle **1997**, Ens et al. **2012**)
4. **Radiation (Integration of light curve)**
   empirical (Ceplecha et al. **1998**; Brown et al. **2002**)



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Energy signature of ton TNT-class impacts: analysis of the 2018 December 22 fireball over Western Pyrenees

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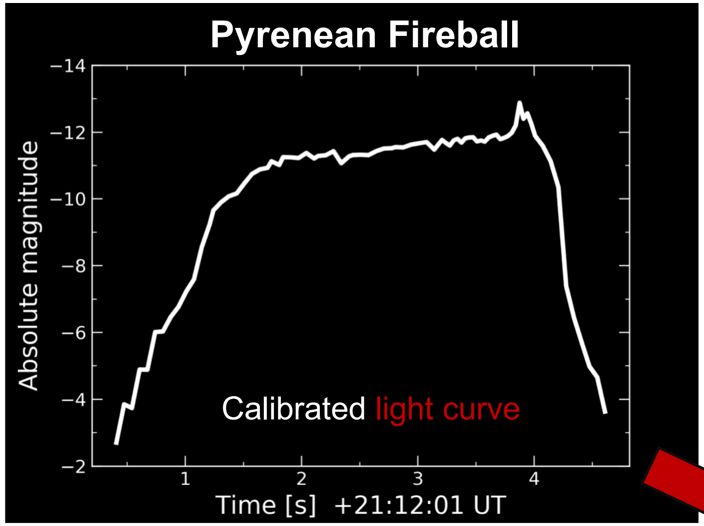
Affiliations are listed at the end of the paper

Problem:

It is **not clear** how the **high energy impact** calibrations translate to **lower impact scales.**



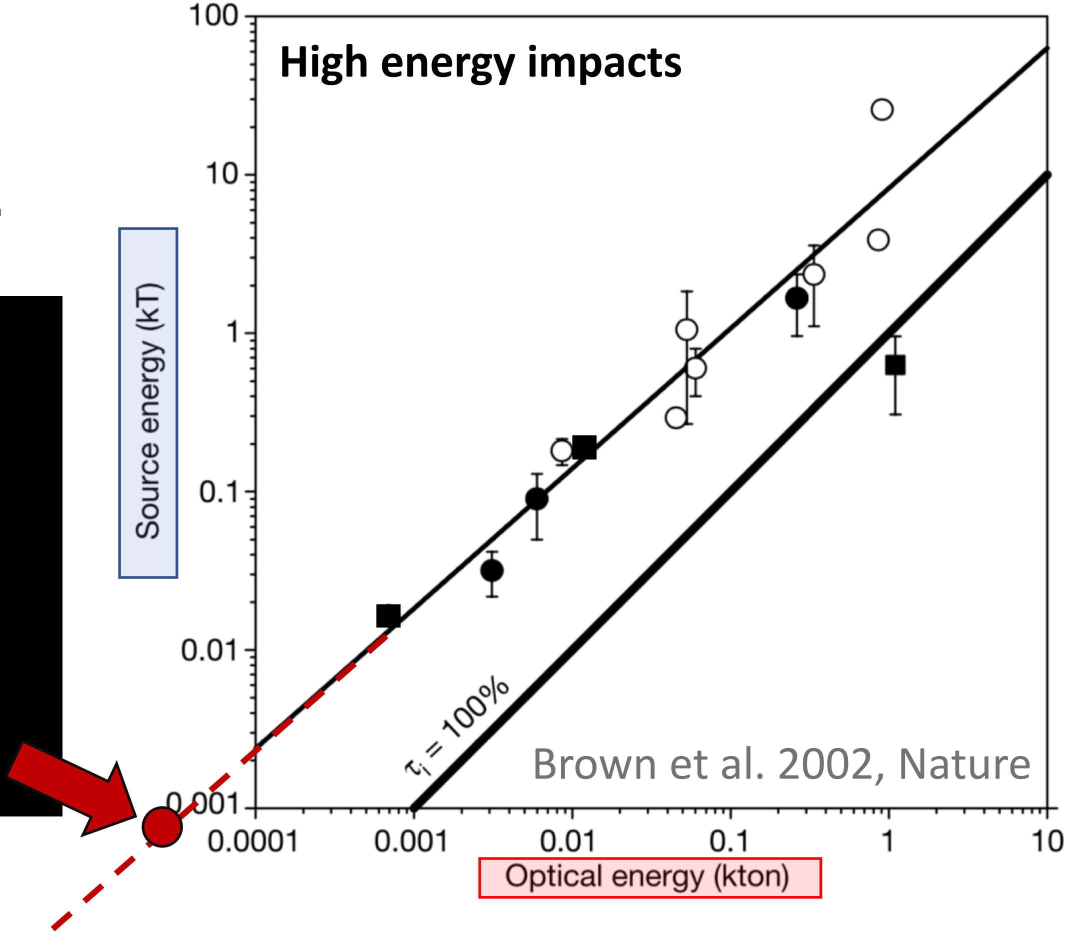


Figure 2 Bolide energy calibrations. These are based on simultaneous observations by optical sensors (or equivalent) and energy estimated from another technique. The optical

Objective : Find a new relation for lower scale impacts

The fit between optical energy and total calibrated energy (Fig. 2) leads to:

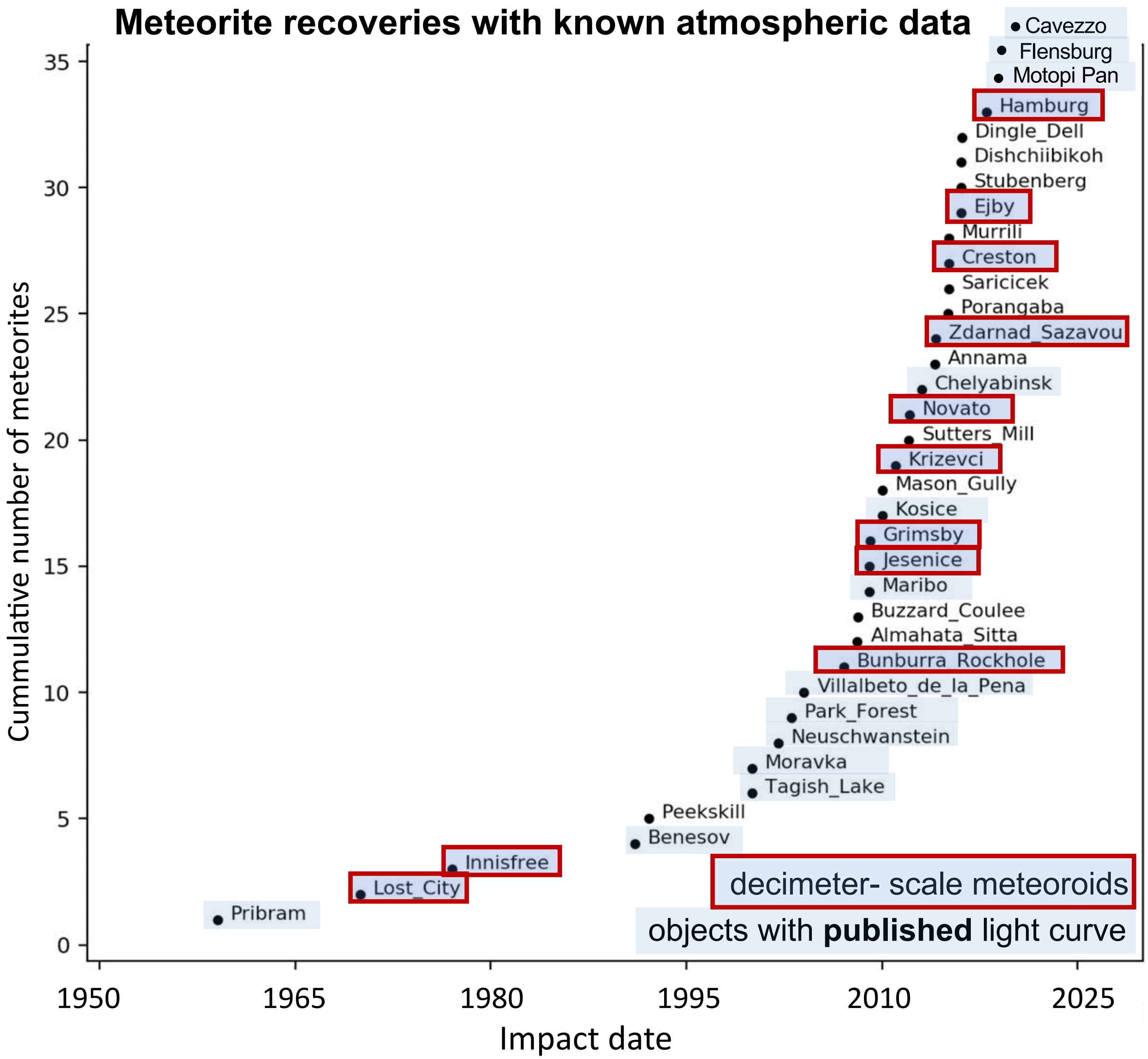
$$\tau_I = (0.1212 \pm 0.0043) E_o^{0.115 \pm 0.075} \quad (1)$$

where E_o is the optical energy (in kilotons TNT equivalent,

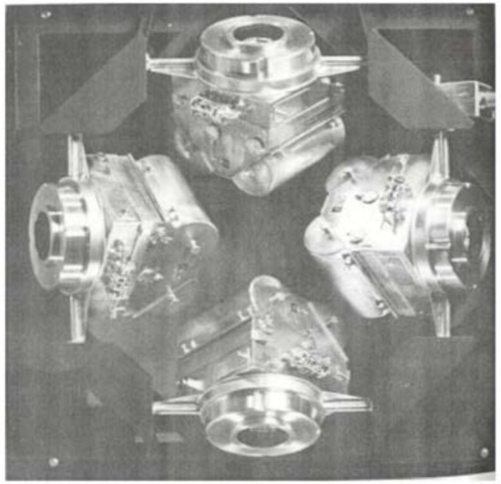
The search for decimeter-scale meteoroids

<u>Best bet</u> :

Collect data from <u>known impacts</u> with **meteorite** recoveries

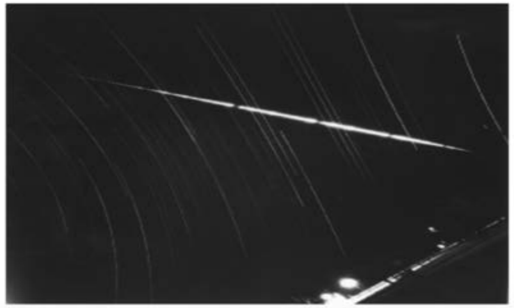


The search for decimeter-scale meteoroids



4 meteorites = 17 kg

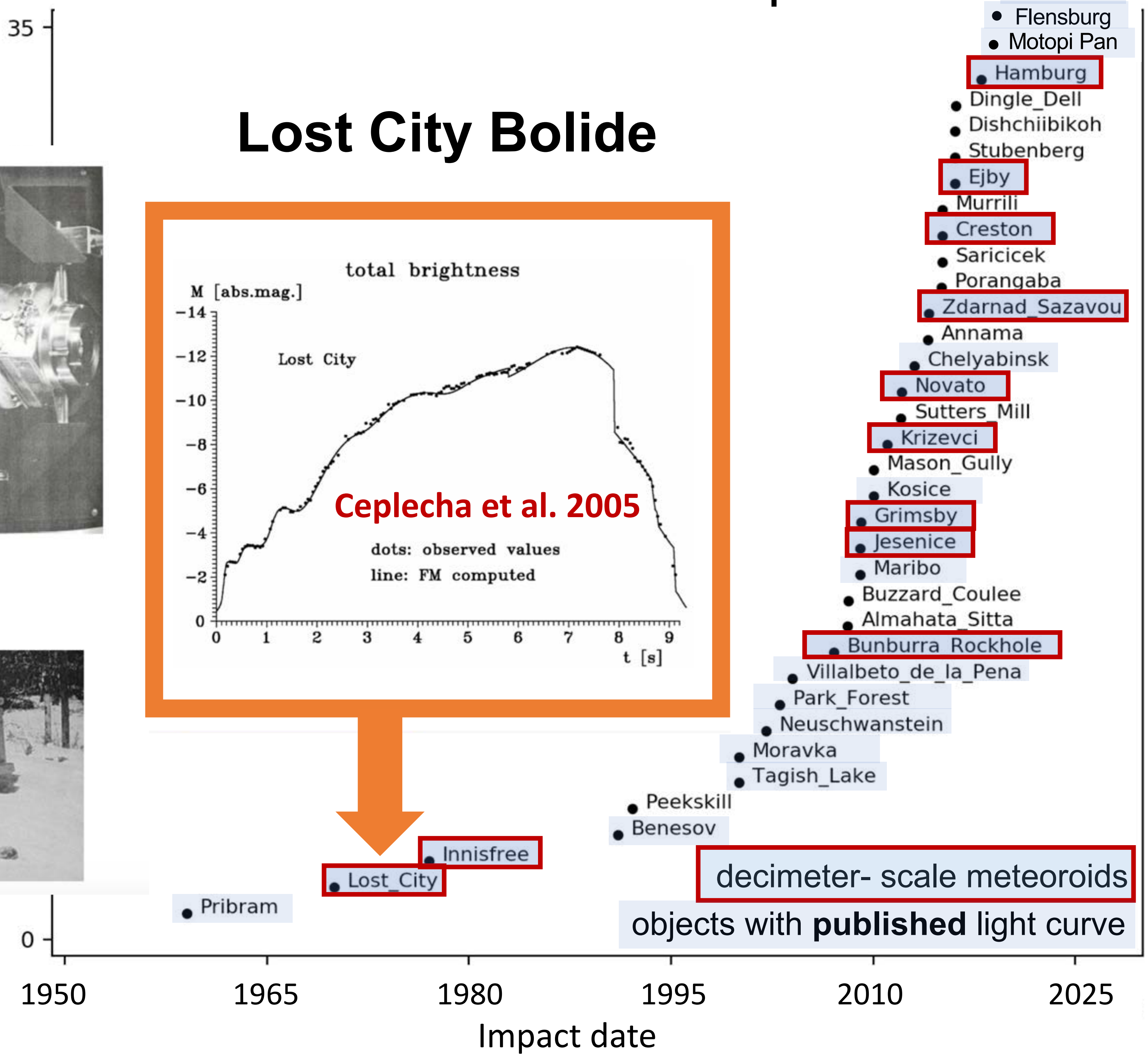
=> 1 trouvaille en 10 ans : météorite de « Lost city »



McCrosky et al. 1971

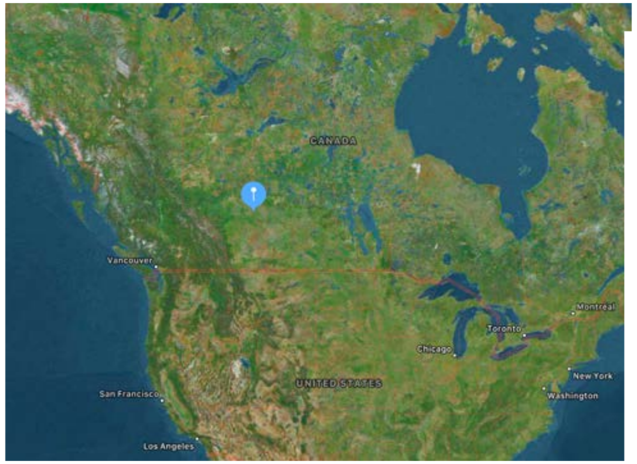
Meteorite recoveries with known atmospheric data

Lost City Bolide



Ceplecha et al. 2005

The search for decimeter-scale meteoroids



The Innisfree Meteorite and the Canadian Camera Network 29

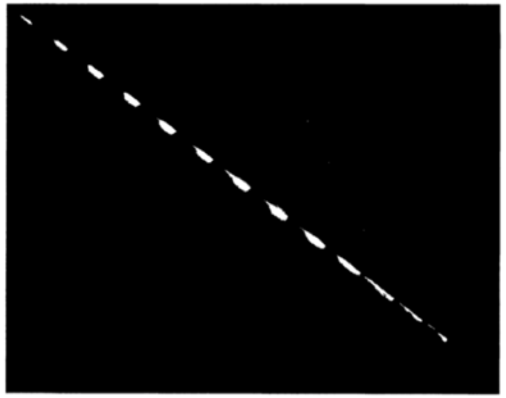
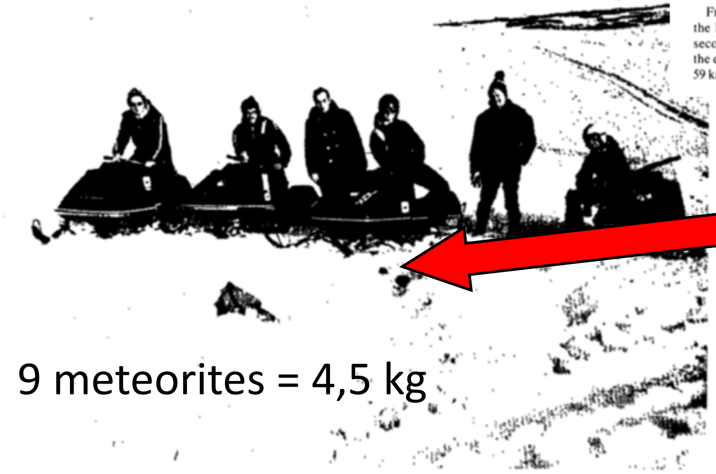


FIG. 4—The Innisfree meteorite in flight, from upper left to lower right, photographed from the MORP station at Vegreville. The rotating filter wheel produces 4 segments of trail per second. The bright stars crossing the meteor trail near the middle are Castor and Pollux. Note the evidence of separate fragments low on the path. The meteor entered the field at a height of 59 km and was observed over a path length of 37.8° in 3.82 seconds.



9 meteorites = 4,5 kg

FIG. 6—Six of the seven members of the search team shown with the four snowmobiles used in the search. From left to right, E. Hubbs, V. Kuzz, A. T. Blackwell, K. Fried, I. Halliday and M. Freed, with the photo taken by A. A. Griffin. The meteorite is seen in front of the third snowmobile from left, a small haversack used to protect the camera and maps lies to the left of the meteorite.

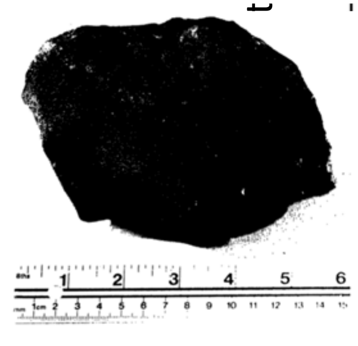
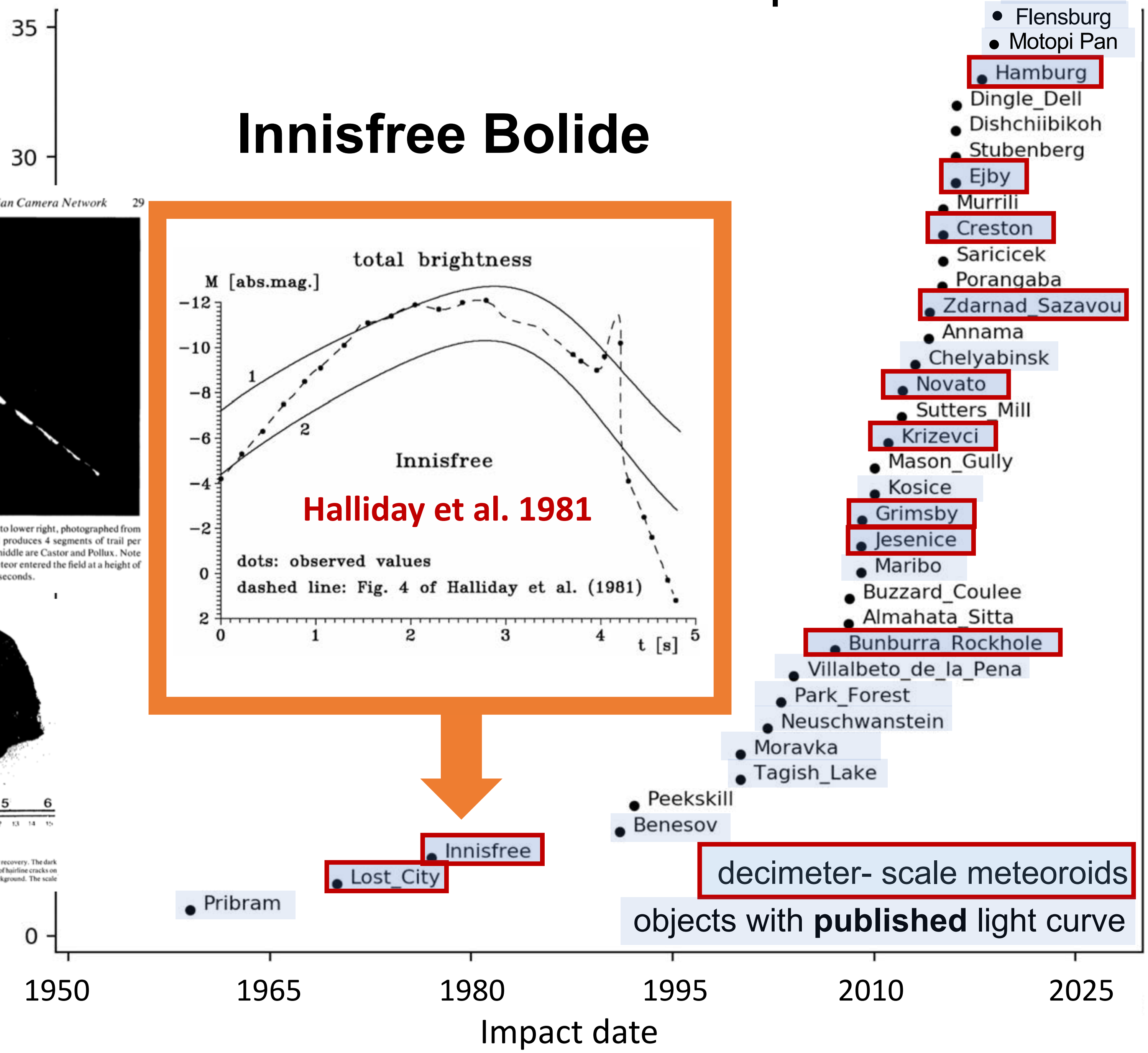


FIG. 7—The 2-kg piece of the meteorite photographed seven hours after recovery. The dark fusion crust exhibits a fine pebbled texture on the vertical face, a network of hairline cracks on the upper surface and a potential fracture near the corner in the right background. The scale shows inches (upper) and cm (lower).

Halliday, Blackwell and Griffin, 1978

Meteorite recoveries with known atmospheric data



The search for decimeter-scale

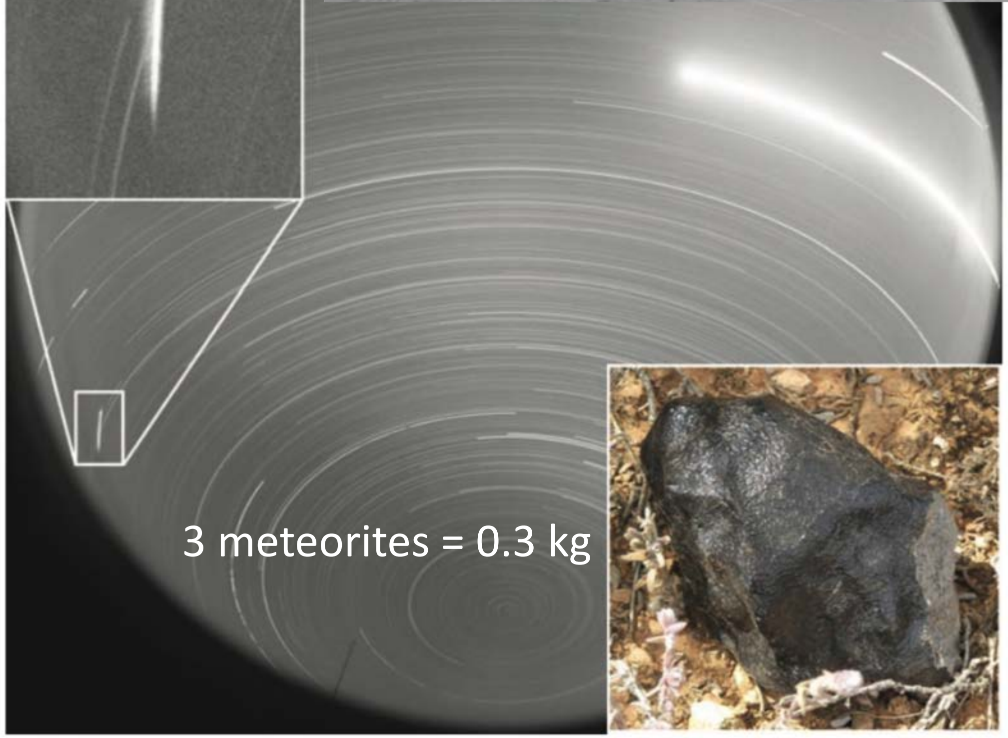
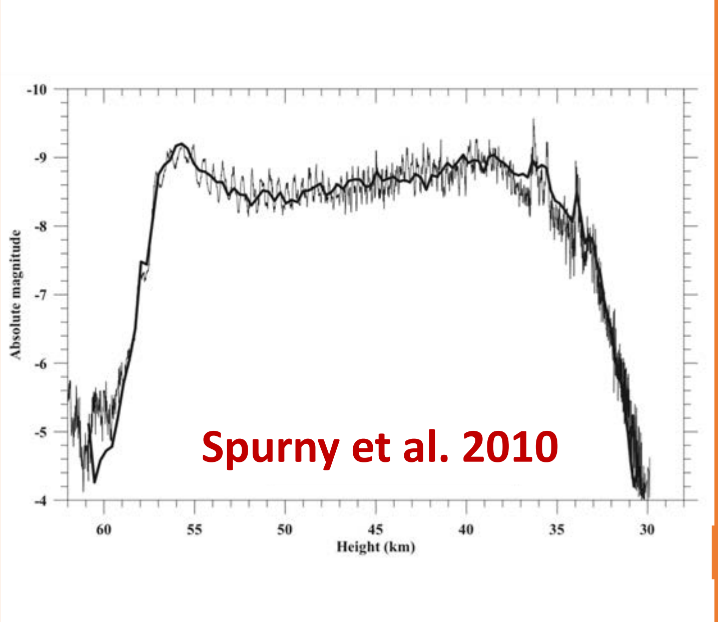


Fig. 1. All-sky image from the easternmost station in the Desert Fireball Network, showing the track of the fireball at left (and **inset**), close to the horizon, and Bunburra Rockhole (BR) at the recovery site (**inset**).

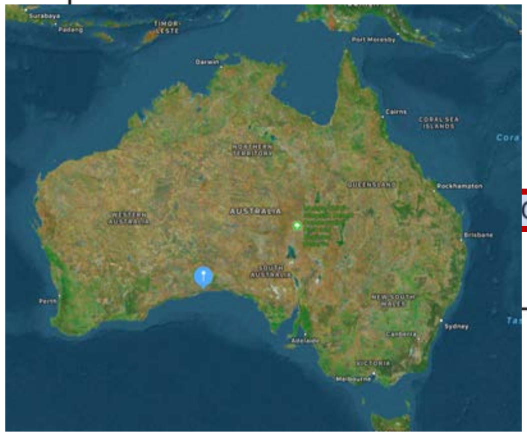
Bland et al. 2009

Meteorite recoveries with known atmospheric data

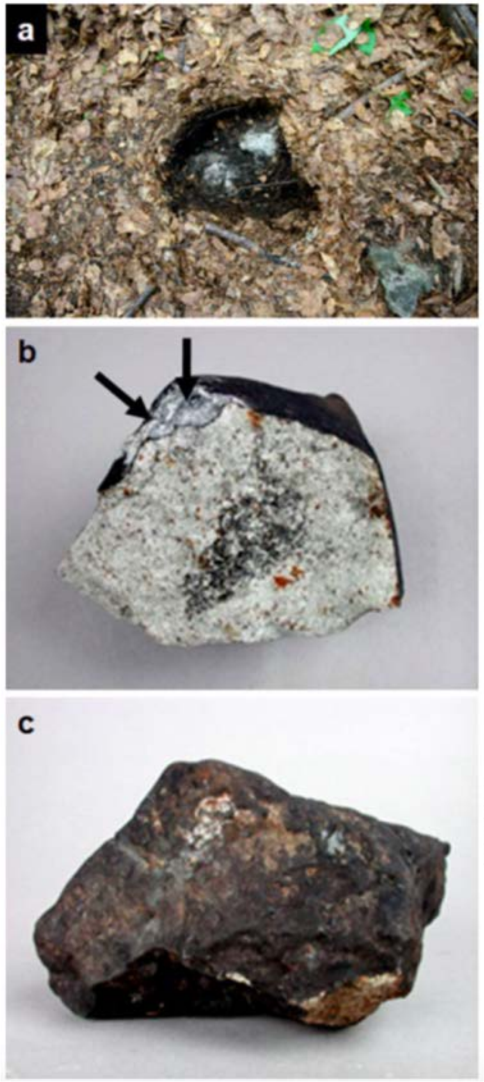
Bunburra Rockhole Bolide



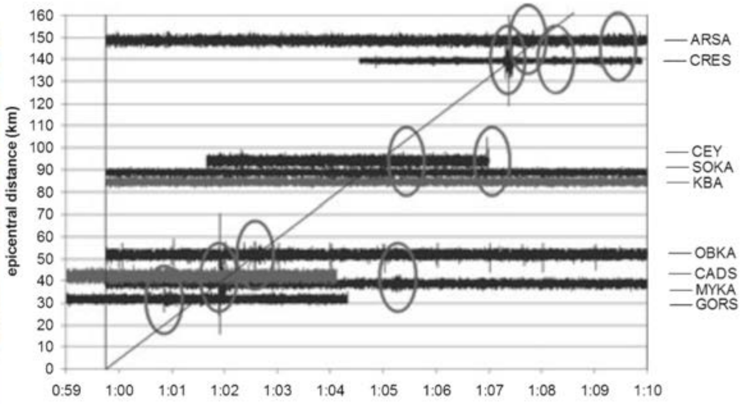
Spurny et al. 2010

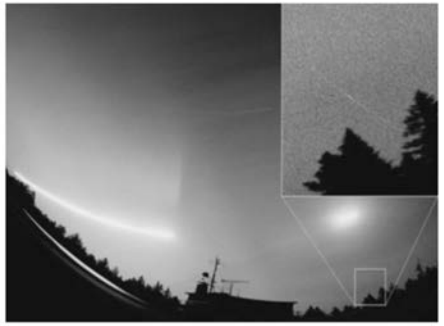


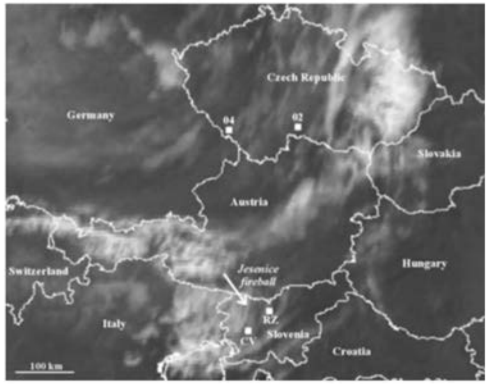
The search for decimeter-scale meteoroids



Bischoff et al. 2011



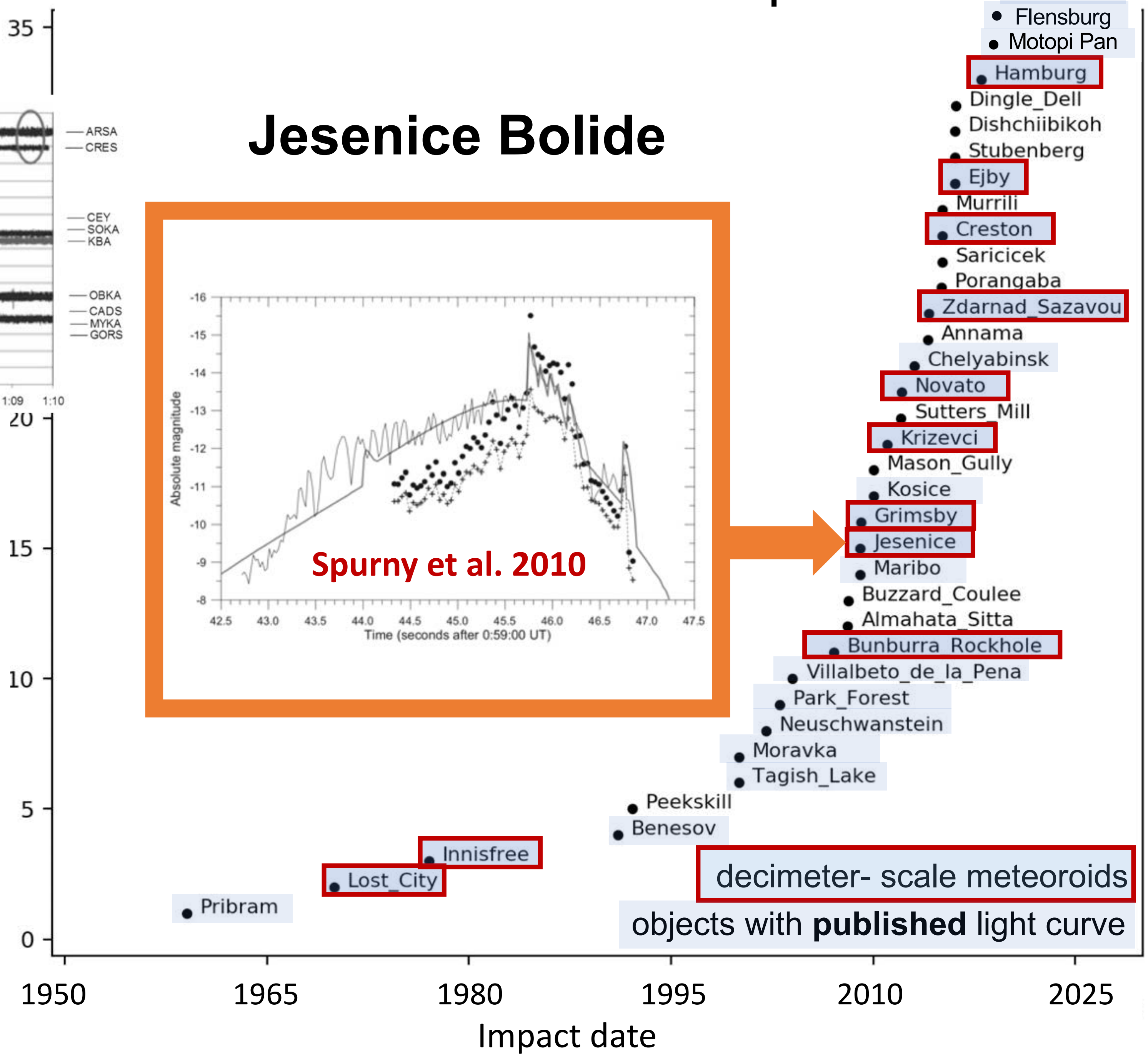




3 meteorites = 3,7 kg

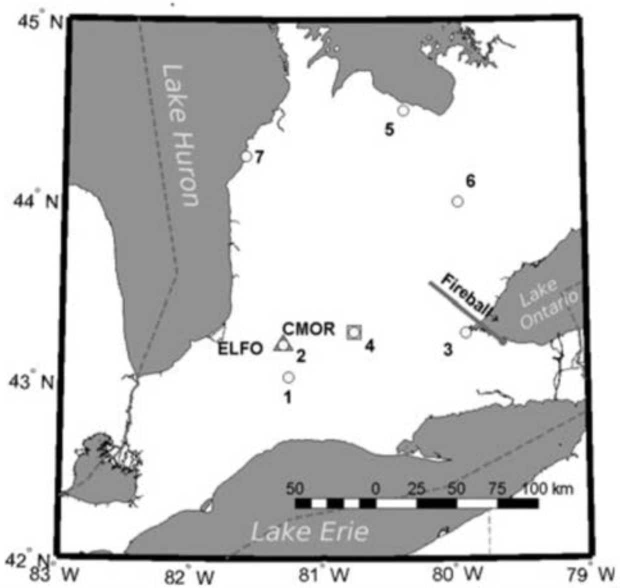
Meteorite recoveries with known atmospheric data

Jesenice Bolide



Spurny et al. 2010

The search for decimeter-scale meteoroids



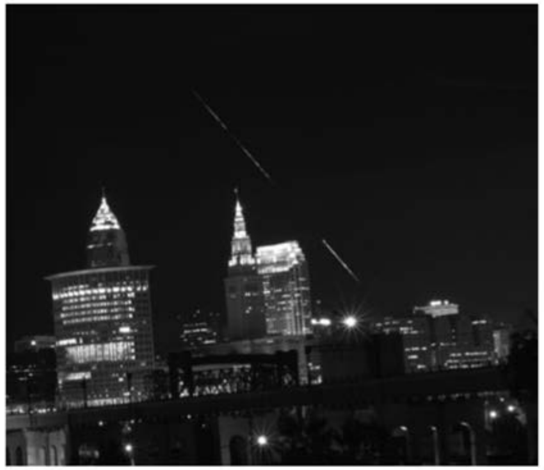


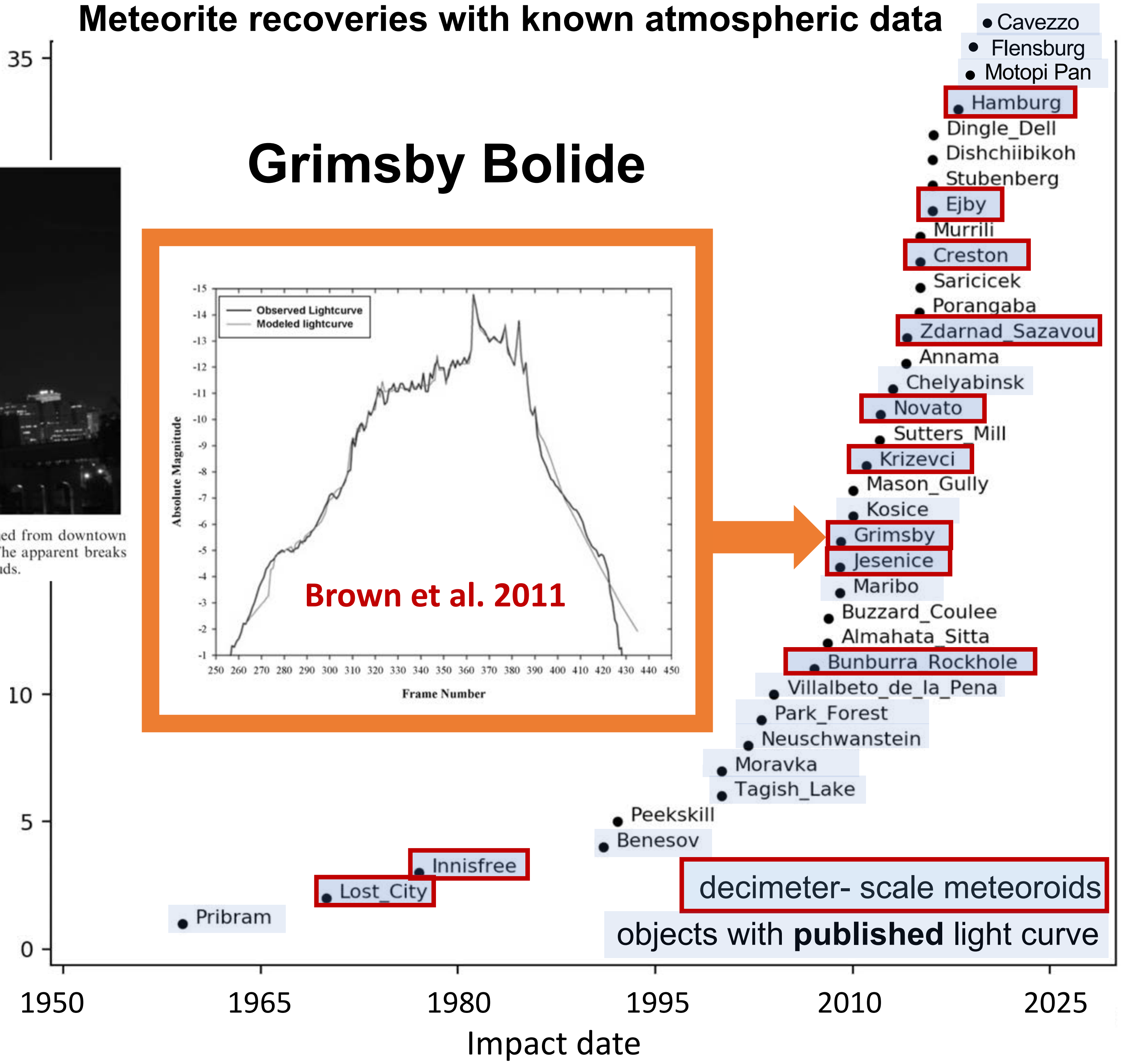
Fig. 1. The Grimsby fireball as photographed from downtown Cleveland, OH, by Miranda Nenadovich. The apparent breaks in the trajectory are an artifact of local clouds.

13 meteorites = 0,22 kg

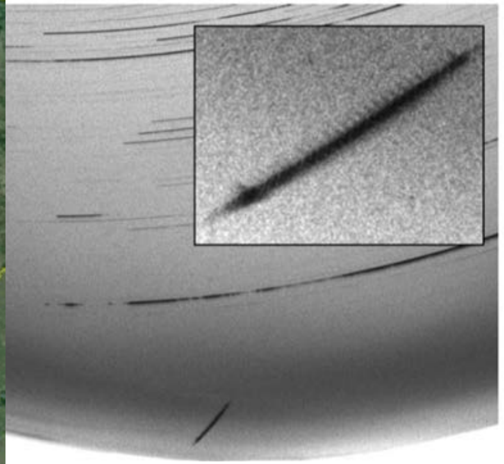
McCausland et al. 2010

Meteorite recoveries with known atmospheric data

Grimsby Bolide



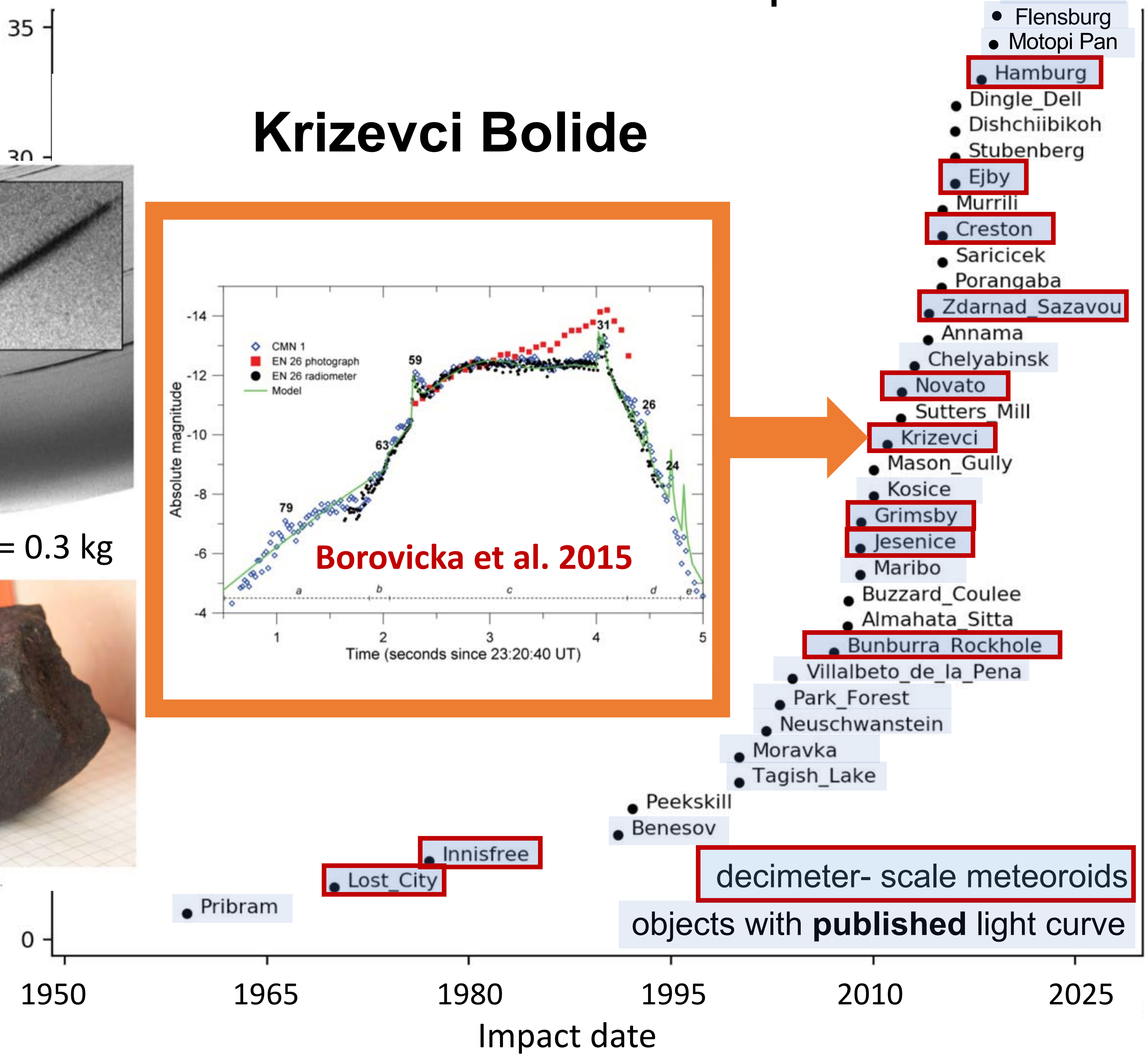
The search for decimeter-scale meteoroids



1 meteorite = 0.3 kg

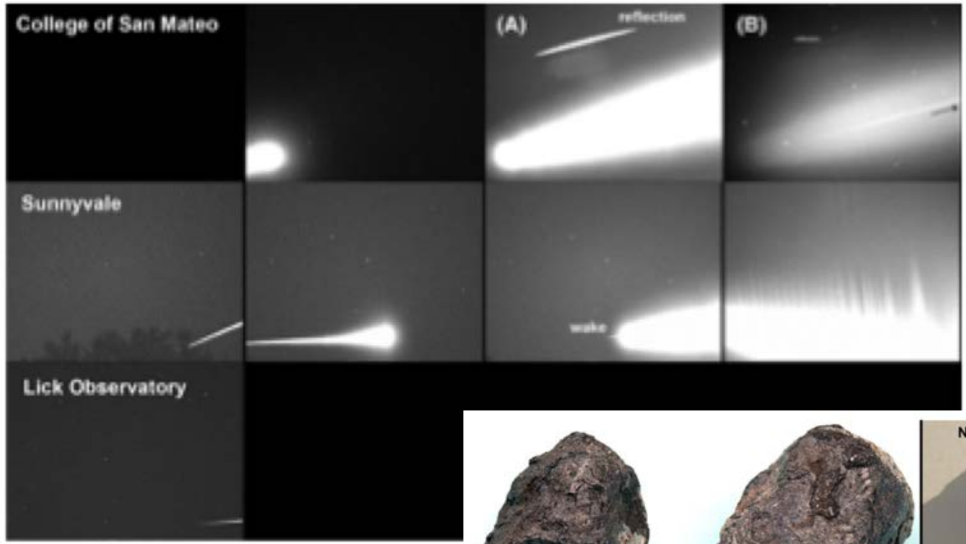

Fig. 1. The Križevci H6 chondrite.

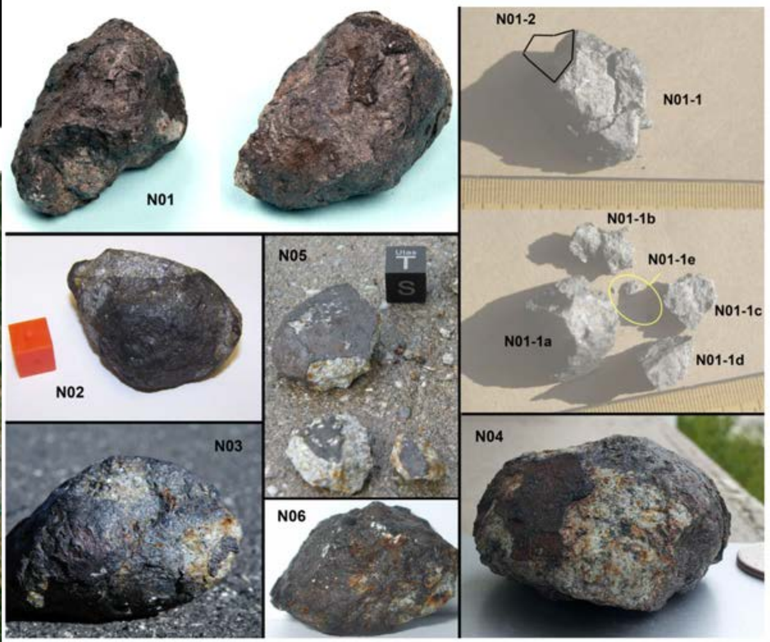
Krizevci Bolide

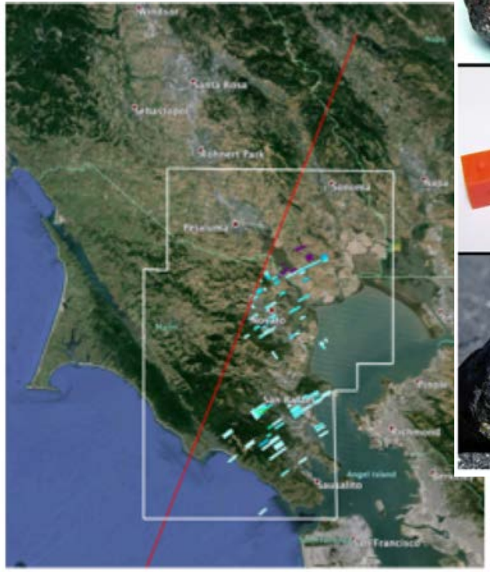


Borovicka et al. 2015

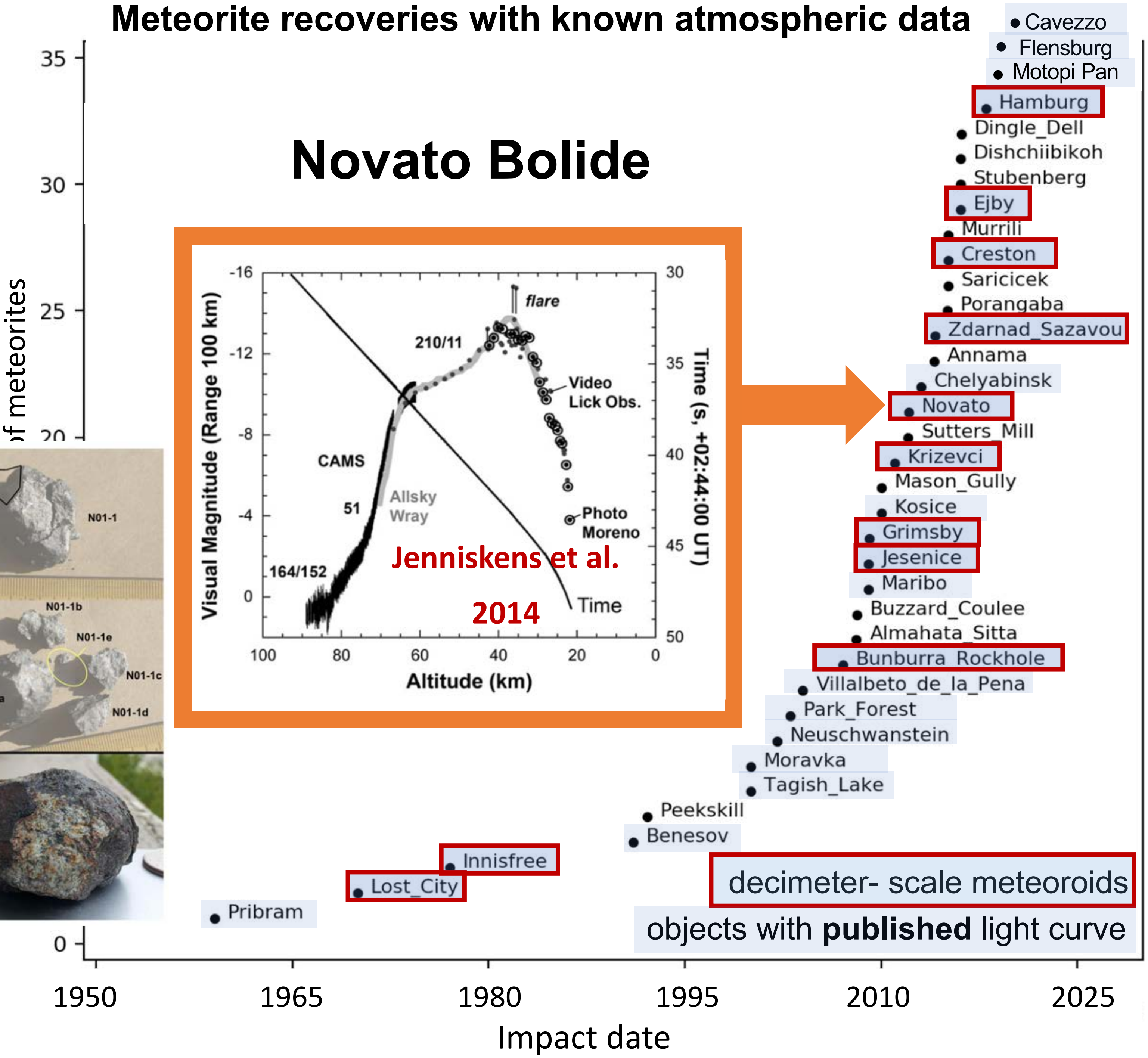
The search for decimeter-scale meteoroids







6 meteorites = 0.3 kg



The search for decimeter-scale meteoroids

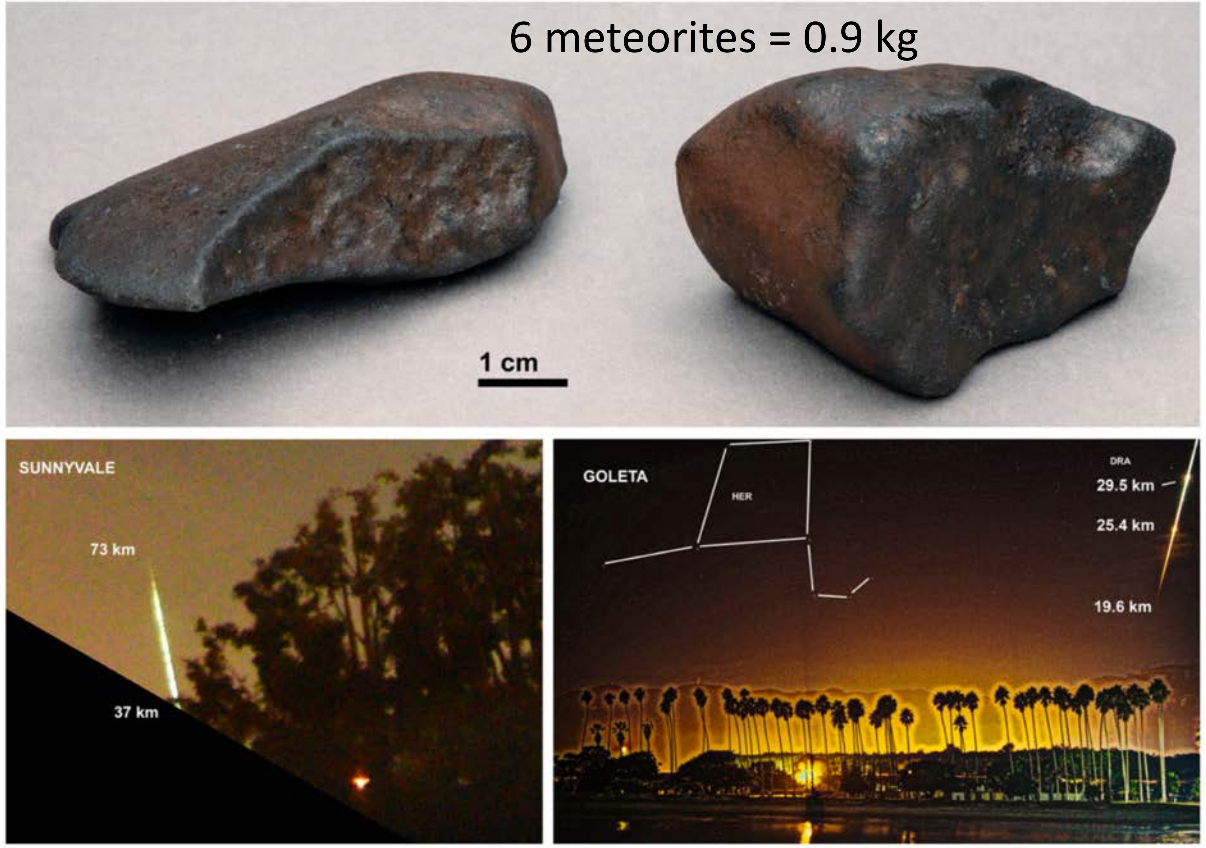
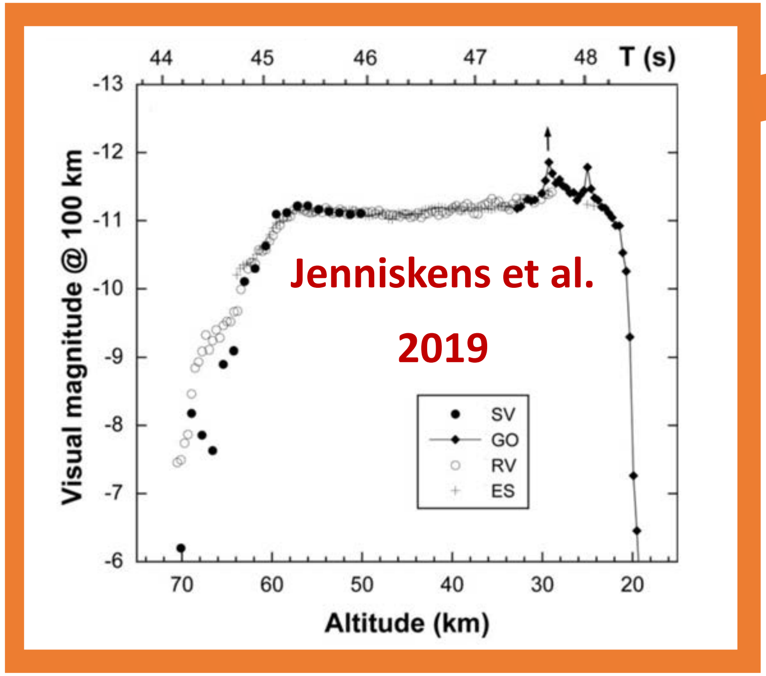


Fig. 1. Top) Optical photographs of Creston meteorites #5 (left) and #6. Notice how each meteorite has one side that is more reddish colored, the irregular surface in the case of C05 and the fresher flatter surface in the case of C06, respectively. Bottom) Creston bolide from Sunnyvale (cropped image) and Goleta.

Meteorite recoveries with known atmospheric data

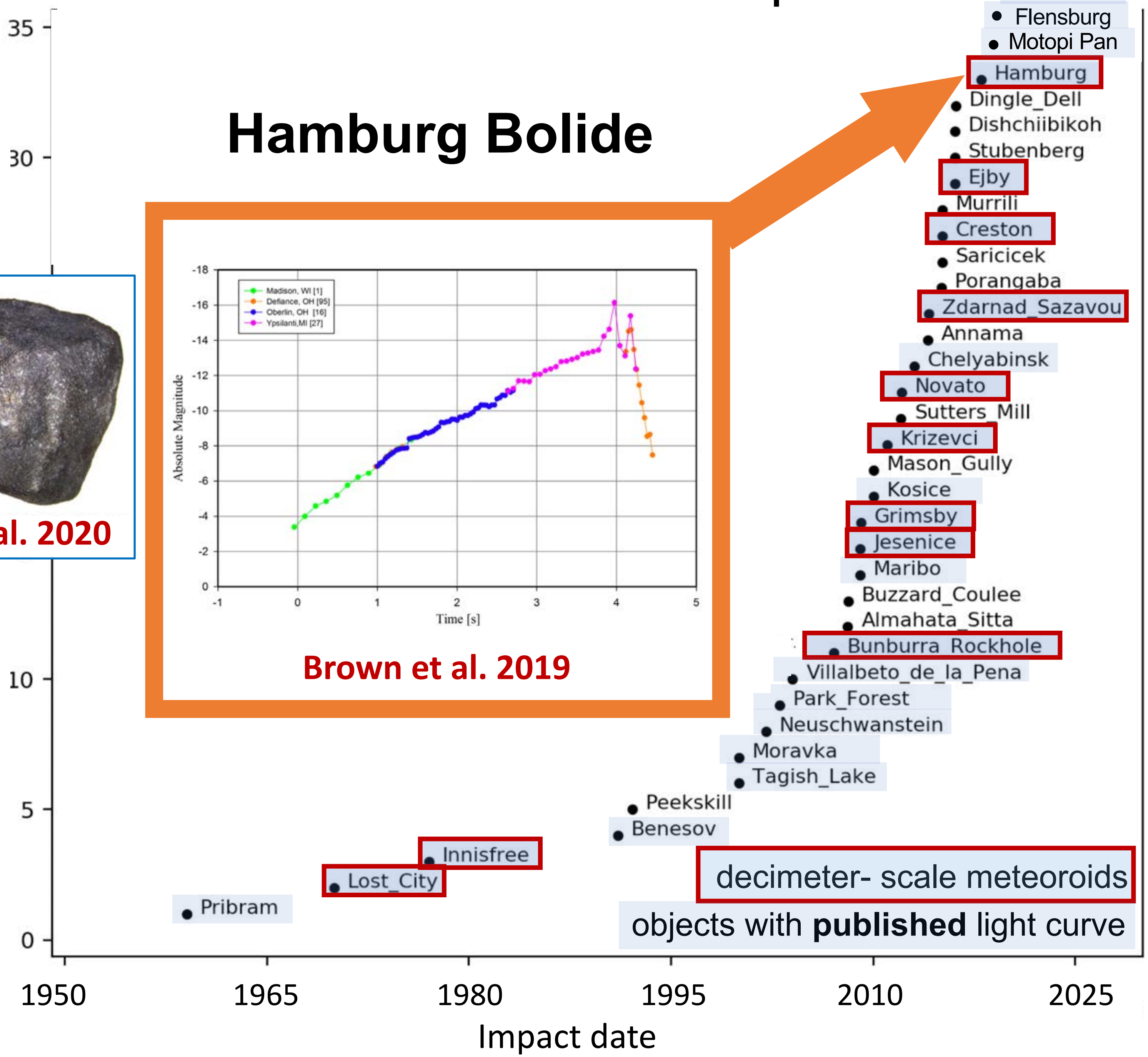
Creston Bolide



The search for decimeter-scale meteoroids

Heck et al. 2020

Meteorite recoveries with known atmospheric data



Fireball
radiated light
(tons TNT)

The Creston Bolide

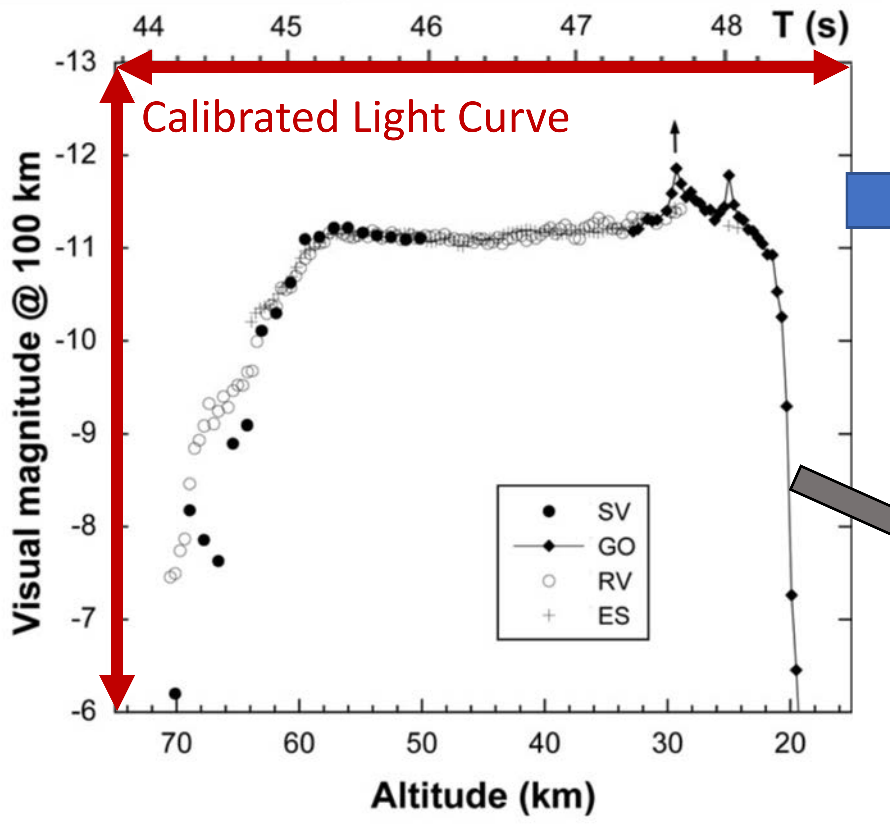


Fig. 7. The meteor visual light curve as seen from each camera station, normalized to a common distance of 100 km, as a function of time after 05:47:00 UTC and altitude.

Jenniskens et al. 2019

$$I = I_0 \cdot 10^{\left(\frac{M}{-2.5}\right)}$$

[J]

$I_0 = 1500\ W$

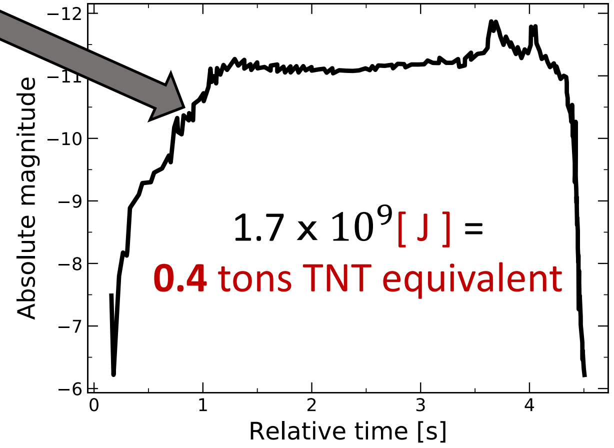
(intensity of a 0 mag light source)

Ceplecha et al. 1998

Light curve integration

light curve extracted via digitization

(Anghel & Birlan 2017)



1.7×10^9 [J] =

0.4 tons TNT equivalent

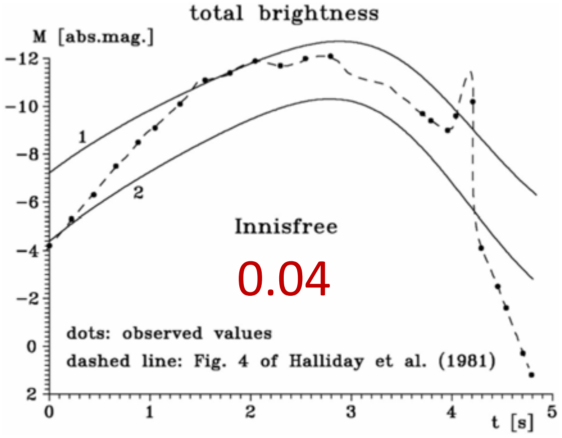
Next step

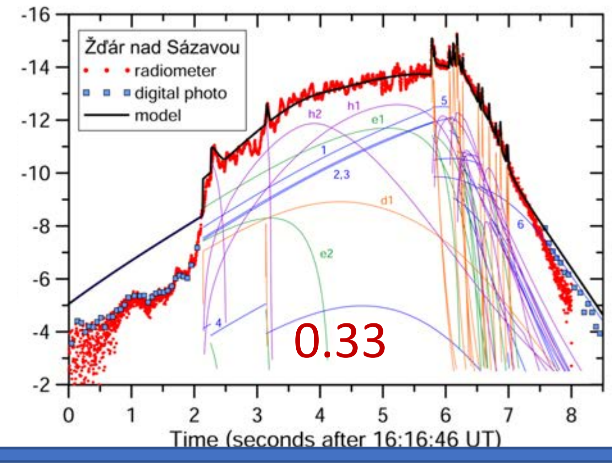
obtain the radiated light for:

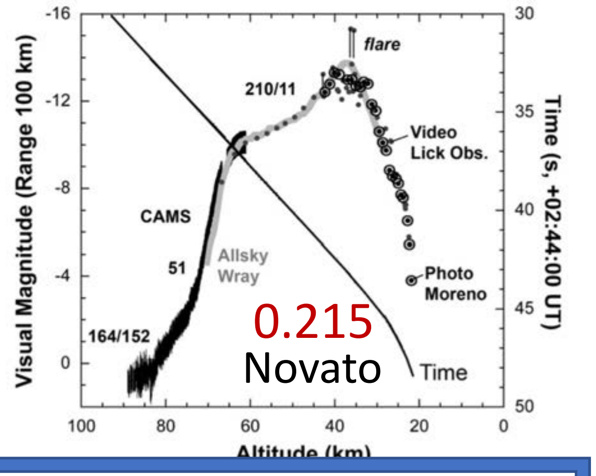
Hamburg
Ejby
Žďár nad Sázavou
Novato
Križevci
Grimsby
Jesenice
Bunburra Rockhole
Innisfree
Lost City

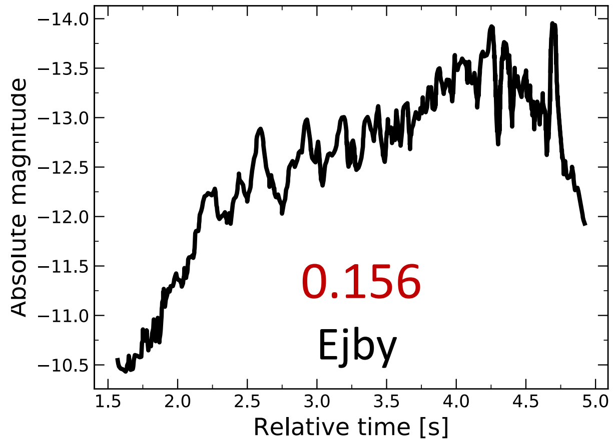
Fireball
radiated light
(tons TNT)

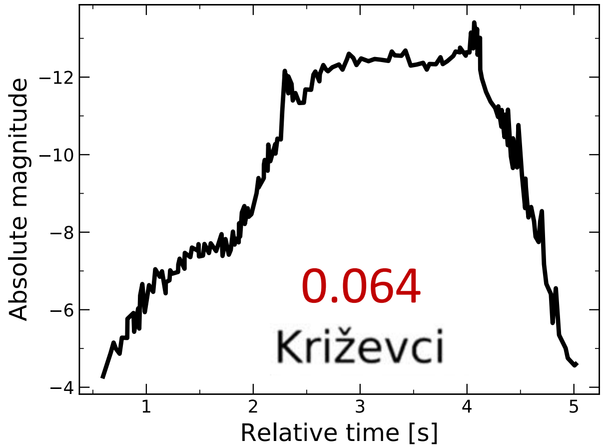
Lightcurves obtained via digitization

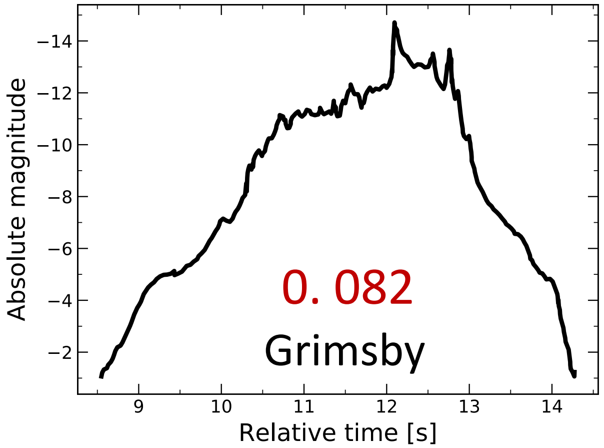


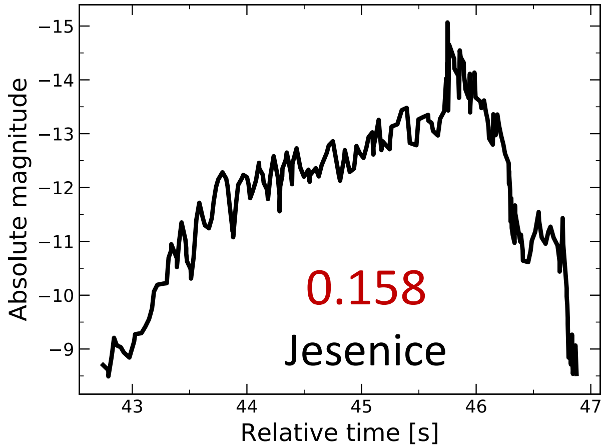


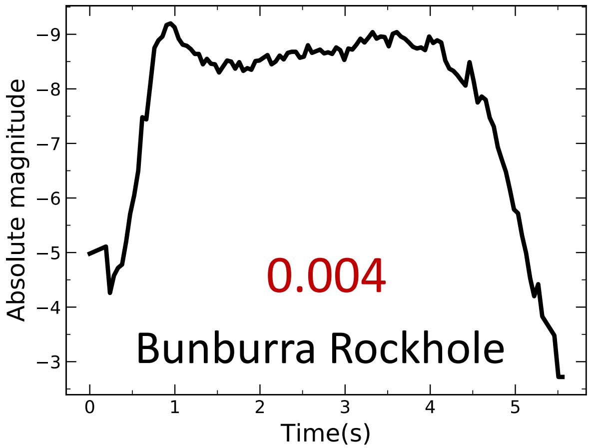


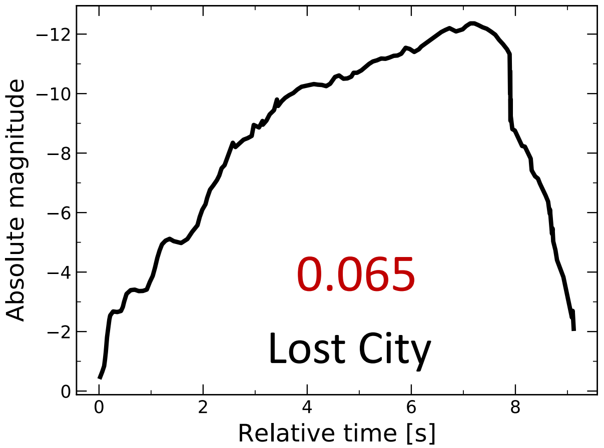


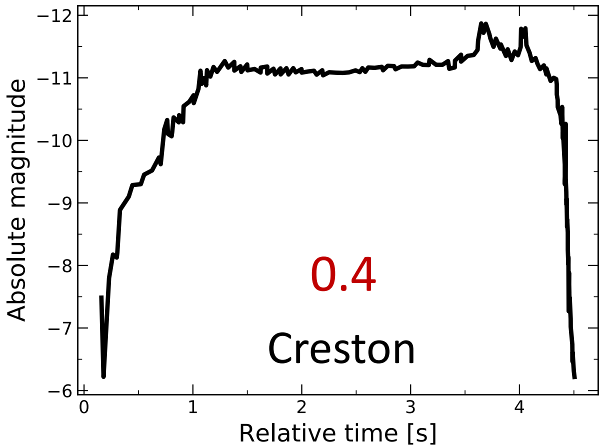


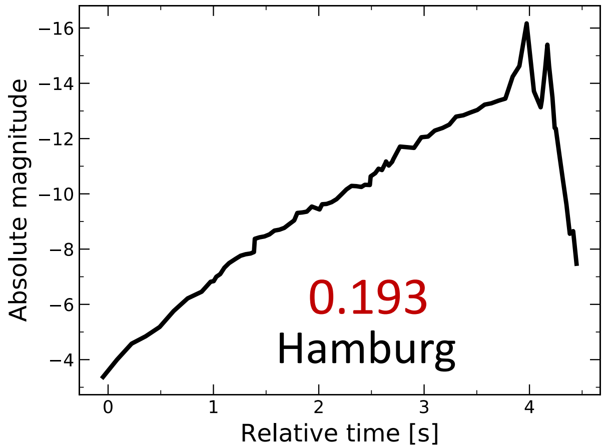












Calibrated bolides **radiated light** correspondence

+3 high energy shower meteors

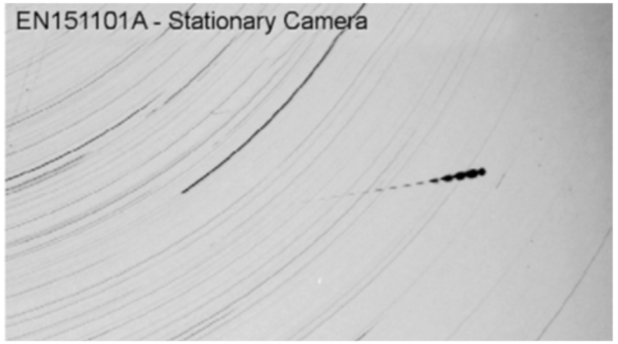
Bolide Name	Date (yyyy/mm/dd)	V_∞ (km/s)	m_∞ (kg)	M_{max}	Optical energy (T TNT)	Source energy [b] (T TNT)	Reference
Hamburg	2018/01/17	15.83 ± 0.05	142 (60 – 225)	-16.3	0.193 [a]	4.27 (1.79 – 6.78)	1, 2
Ejby	2016/02/06	14.52 ± 0.10	185 (110 – 350)	-14.0	0.156 [a]	4.66 (2.73 – 8.94)	3, 4
Creston	2015/10/24	16.00 ± 0.26	55 (10 – 100)	-12.0	0.040 [a]	1.68 (0.30 – 3.16)	5
Žďár nad Sázavou	2014/12/09	21.89 ± 0.02	150 (130 – 170)	-15.3	0.335	8.59 (7.43 – 9.75)	6
Novato	2012/10/18	13.67 ± 0.12	80 (45 – 115)	-13.8	0.215	1.79 (0.99 – 2.61)	7
Križevci	2011/02/04	18.21 ± 0.07	50 (25 – 100)	-13.7	0.064 [a]	1.98 (0.98 – 3.99)	8
Grimsby	2009/09/26	20.91 ± 0.19	30 (20 – 50)	-14.8	0.082 [a]	1.57 (1.03 – 2.66)	9
Jesenice	2009/04/09	13.78 ± 0.25	170 (90 – 250)	-15.0	0.158 [a]	3.86 (1.97 – 5.88)	10, 11, 12
Bunburra Rockhole	2007/07/20	13.37 ± 0.01	30 (21 – 38)	-9.6	0.004 [a]	0.64 (0.44 – 0.82)	13, 14, 15
EN130801	2001/08/13	59.89 ± 0.13	0.600	-13.3	0.006	0.257	16
EN151101A	2001/11/15	71.30 ± 0.11	0.800	-14.9	0.029	0.486	16
EN030804	2004/08/03	60.80 ± 0.20	0.370	-12.5	0.005	0.163	16
Innisfree	1977/02/06	14.70 ± 0.04	36 (20 – 44)	-12.1	0.040	0.93 (0.51 – 1.14)	17, 18
Lost City	1970/01/04	14.14 ± 0.01	163 (158 – 168)	-12.4	0.065 [a]	3.90 (3.78 – 4.02)	18, 19

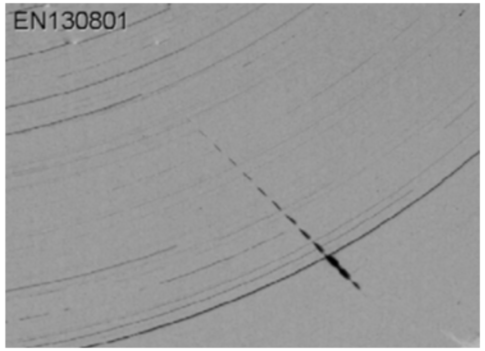
Calibrated bolides **radiated light** correspondence

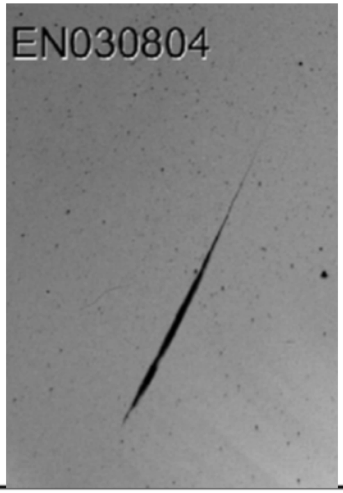
+ 3 high altitude shower meteors, with high quality multi-instrument observations:

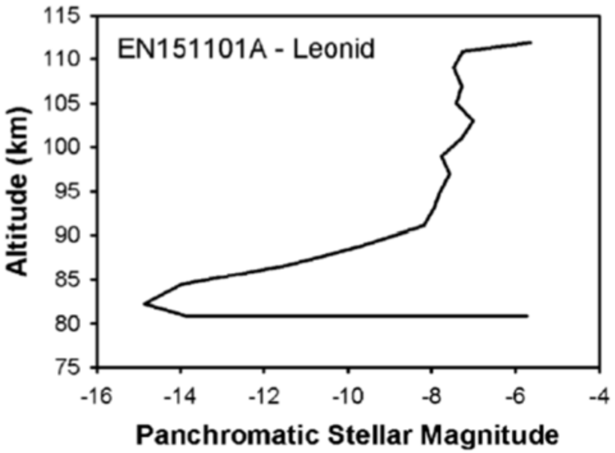
- all-sky cameras
- radiometer
- infrasound
- seismic

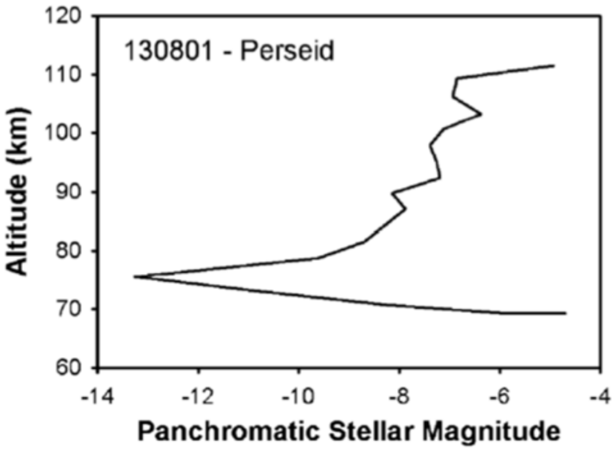
Brown et al. 2007

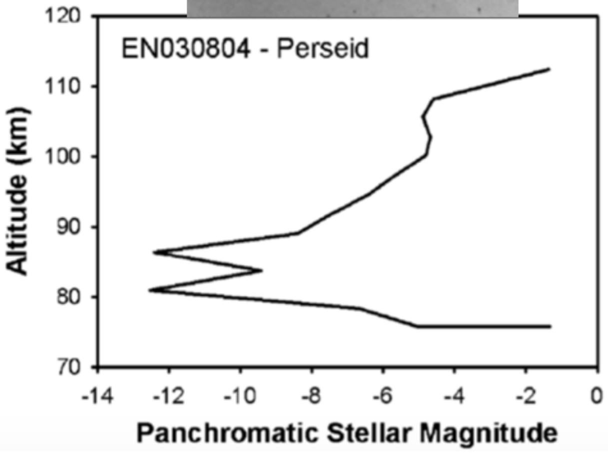












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References: [1] Brown et al. (2019); [2] Heck et al. (2020); [3] Spurný et al. (2017); [4] Haack et al. (2019); [5] Jenniskens et al. (2019); [6] Spurný et al. (2020); [7] Jenniskens et al. (2014); [8] Borovička et al. (2015a); [9] Brown et al. (2011); [10] Spurný et al. (2010); [11] Bischoff et al. (2011); [12] Ott et al. (2010); [13] Sansom et al. (2015); [14] Spurný et al. (2012); [15] Welten et al. (2012); [16] Brown et al. (2007); [17] Halliday et al. (1981); [18] Ceplecha & Revelle (2005); [19] Ceplecha (1996).

Anghel et al. (2021) MNRAS

Calibrated bolides **radiated light** correspondence

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$$\frac{1}{2} * m V^2 = KE$$

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Calibrated bolides **radiated light** correspondence

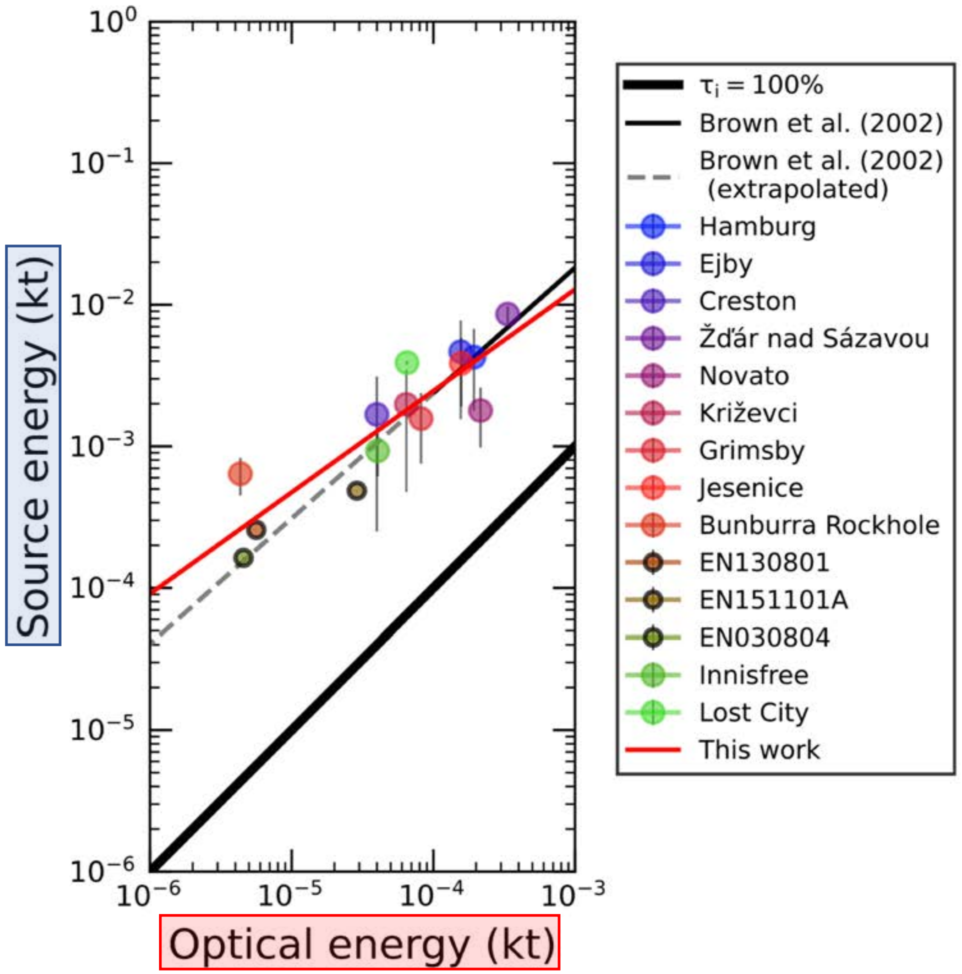

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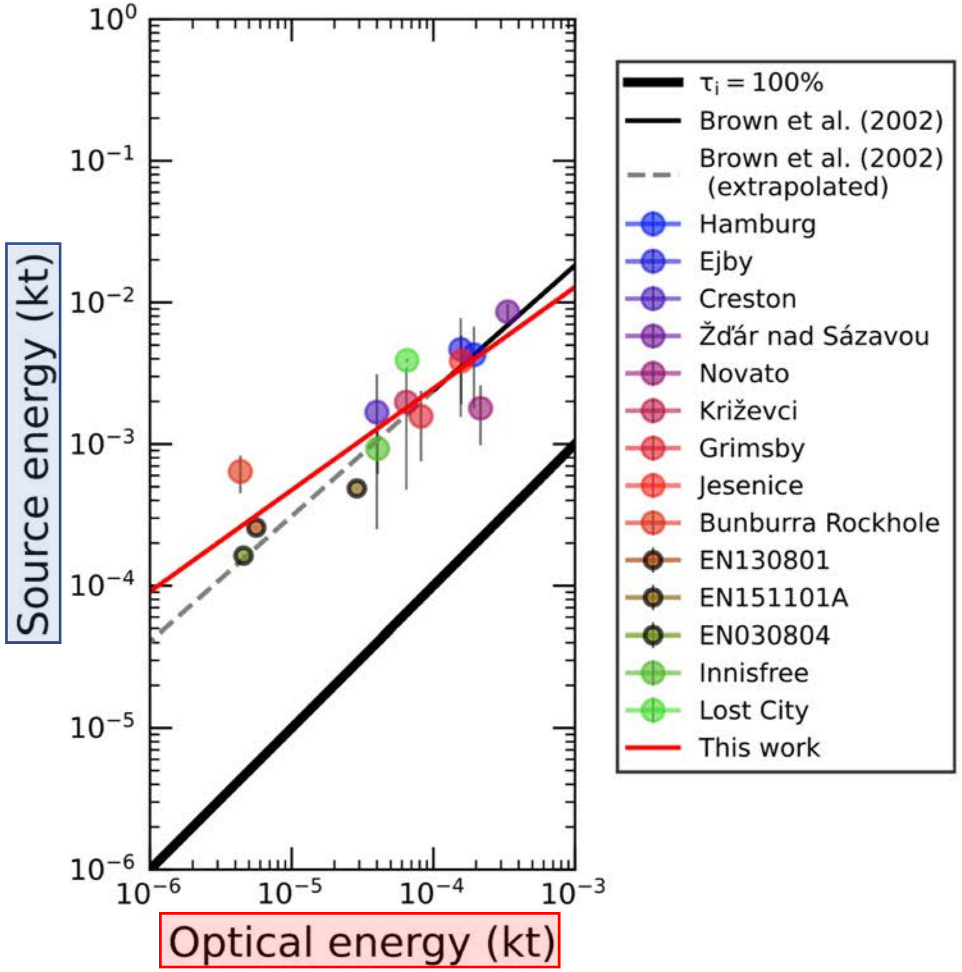
Figure 12. Energy calibrations of well known bolides around the ton-scale TNT. The error bar on the source energy represents the combined uncertainties from mass and velocity. The thin black line is the fit obtained by (Brown et al. 2002) corresponding to source energies greater than 0.1 kt TNT. This is

Anghel et al. (2021) MNRAS

Calibrated bolides **radiated light** correspondence



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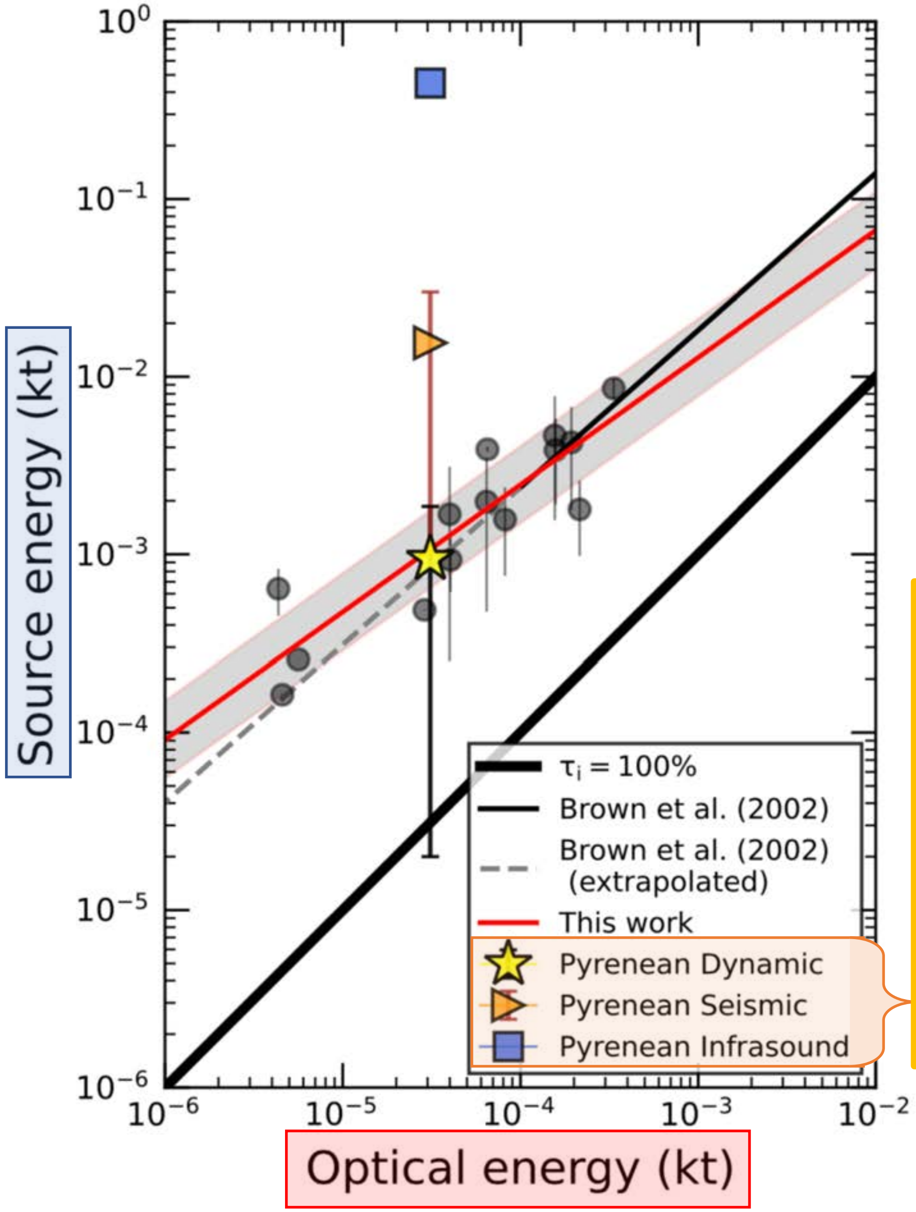
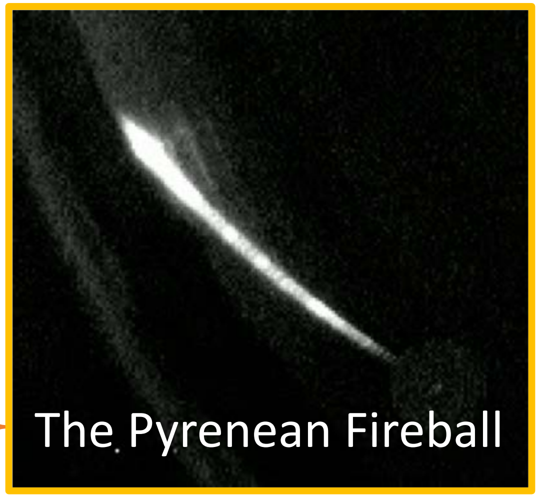


bolide radiation is the most **realiable method** of estimating the **source energy**



Anghel et al. (2021) MNRAS

Summary

- **Meteoroids** are orders of magnitude more numerous than asteroids, and can be studied when interacting with the atmosphere
- Recovering a meteorite fall allow us to build **better models** for studying **meteoroids**
- So far, the **bolide radiation** is the most **realiable method** of estimating the **source energy**
- Fireball networks are needed to estimate **stochastic** and **systematic errors** of atmospheric impacts

Future work:

- Understand how the **bolide radiation method** changes the meteoroid **flux density** around 1 ton TNT energy scale
- combine meteor observations via radar and high-speed radiometers
- Expand the existing fireball networks

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