Kinetic energy estimation of ton-TNT scale impacts based on well-known events

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INTRODUCTION

Cosmic objects are impacting the Earth's atmosphere on a daily basis. Due to their small size, these meteoroids cannot be seen before interacting with the air particles. Thus, to better **constrain the size of an impactor, we need calibrated multi-detector observations** of meteoroid impacts into our atmosphere. These recording instruments range from **cameras** and **radio** antennas [1], to detections of meteoroid airwaves using **infrasound** arrays, and **seismic** detectors, which measure the signal produced by airwave-to-ground coupling of large events.

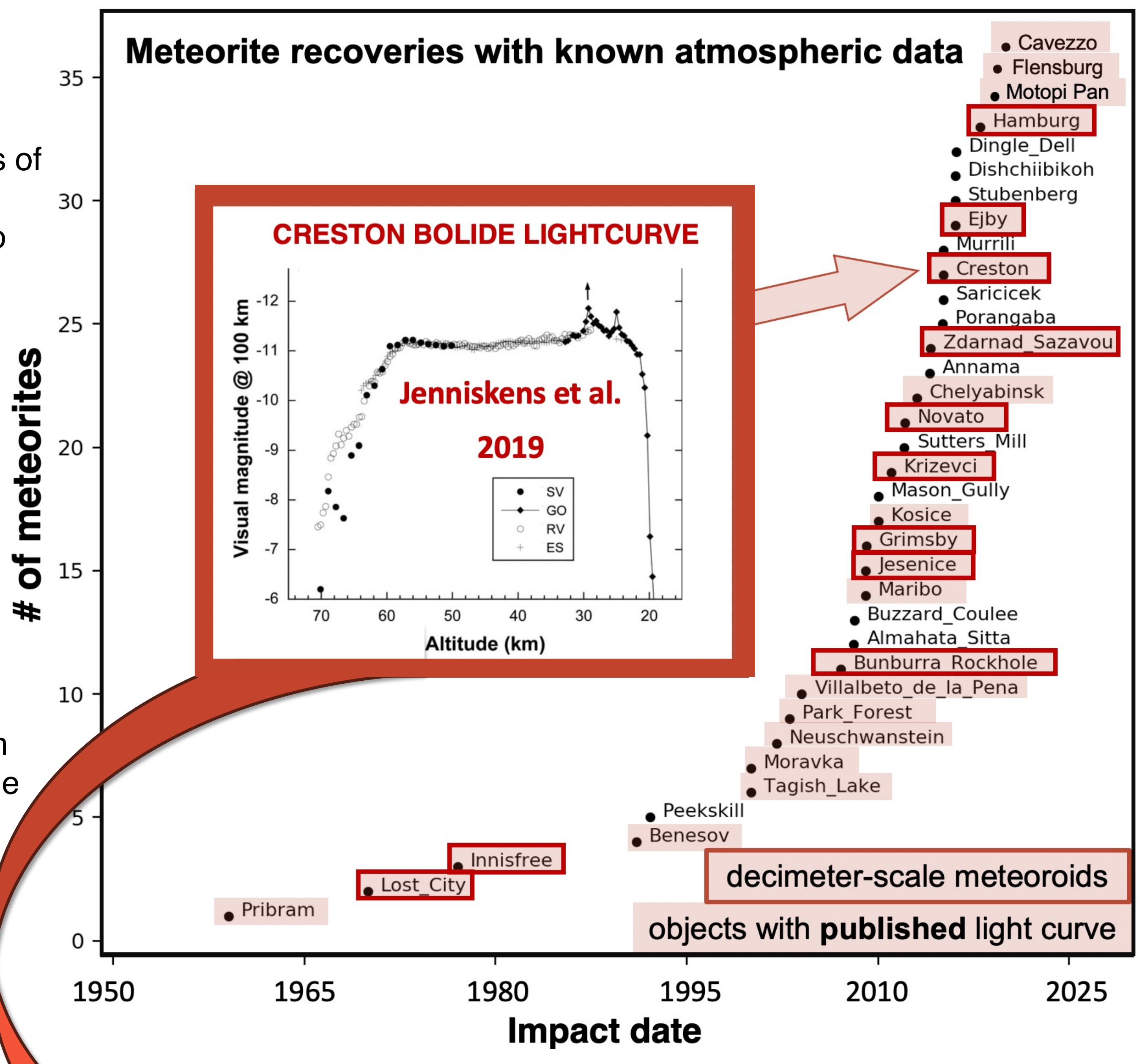
METHODOLOGY

Object selection

In this study we explore several techniques of measuring the pre-atmospheric mass of meteoroids with well-known trajectory (also a subject of meteorite recoveries), at the source of **ton TNT-scale atmospheric impacts** [2]. On this scale, the impact is less likely to cause an airwave signal detectable on multiple specialized stations, or the estimation methods carry high uncertainty [e.g. 3, 4], hence, their **mass is poorly constrained**.

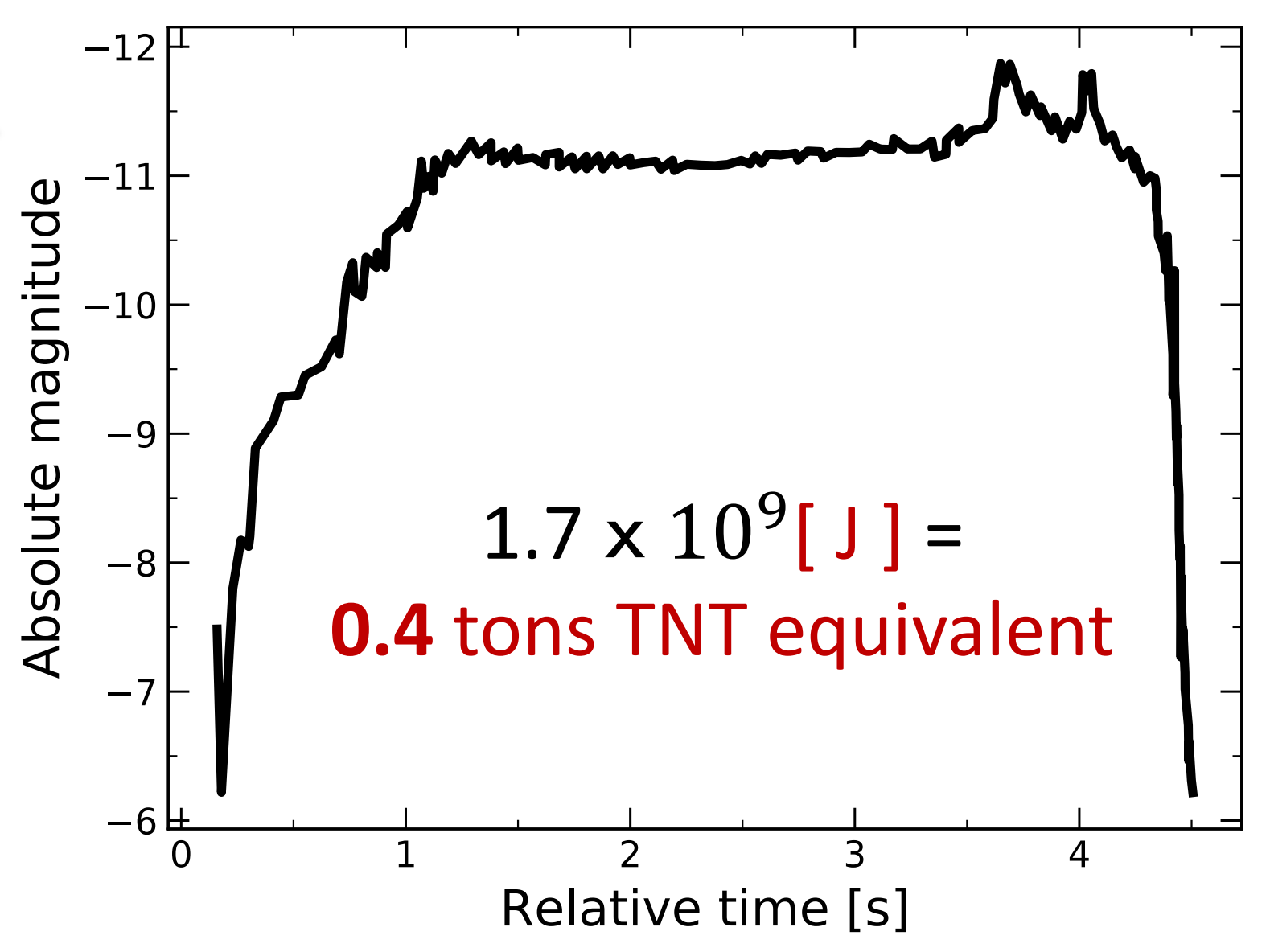
The bolides

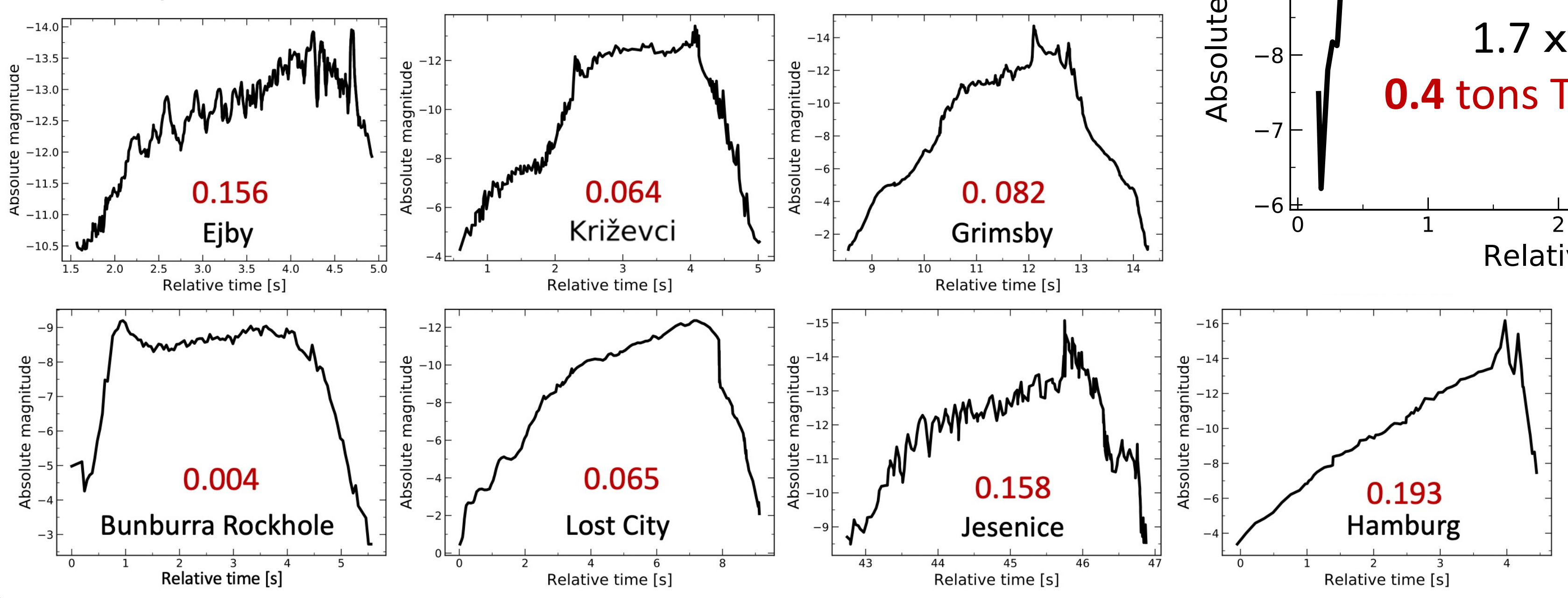
To compare the reliability of the energy estimation methods, first, the meteoroid-derived measurements were collected from the literature. The resulted list pointed to the **object's radiation as the most common measured property** of the event. Thus, the analysis focused on the optical energy signature of the objects.



Radiated light integration

Most of the bolides **did not have their total radiated energy** estimated, hence, this was obtained based on the published light curve via **digitization** [5] **and integration**.





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

$$I_0 = 1500\ W$$

(intensity of a 0 mag light source)
Ceplecha et al. 1998

Calibrated bolides data

To find impact energy relation, first, the **kinetic energy (*KE*)** was computed based on given estimates of the pre-atmospheric **velocity** and **mass**.

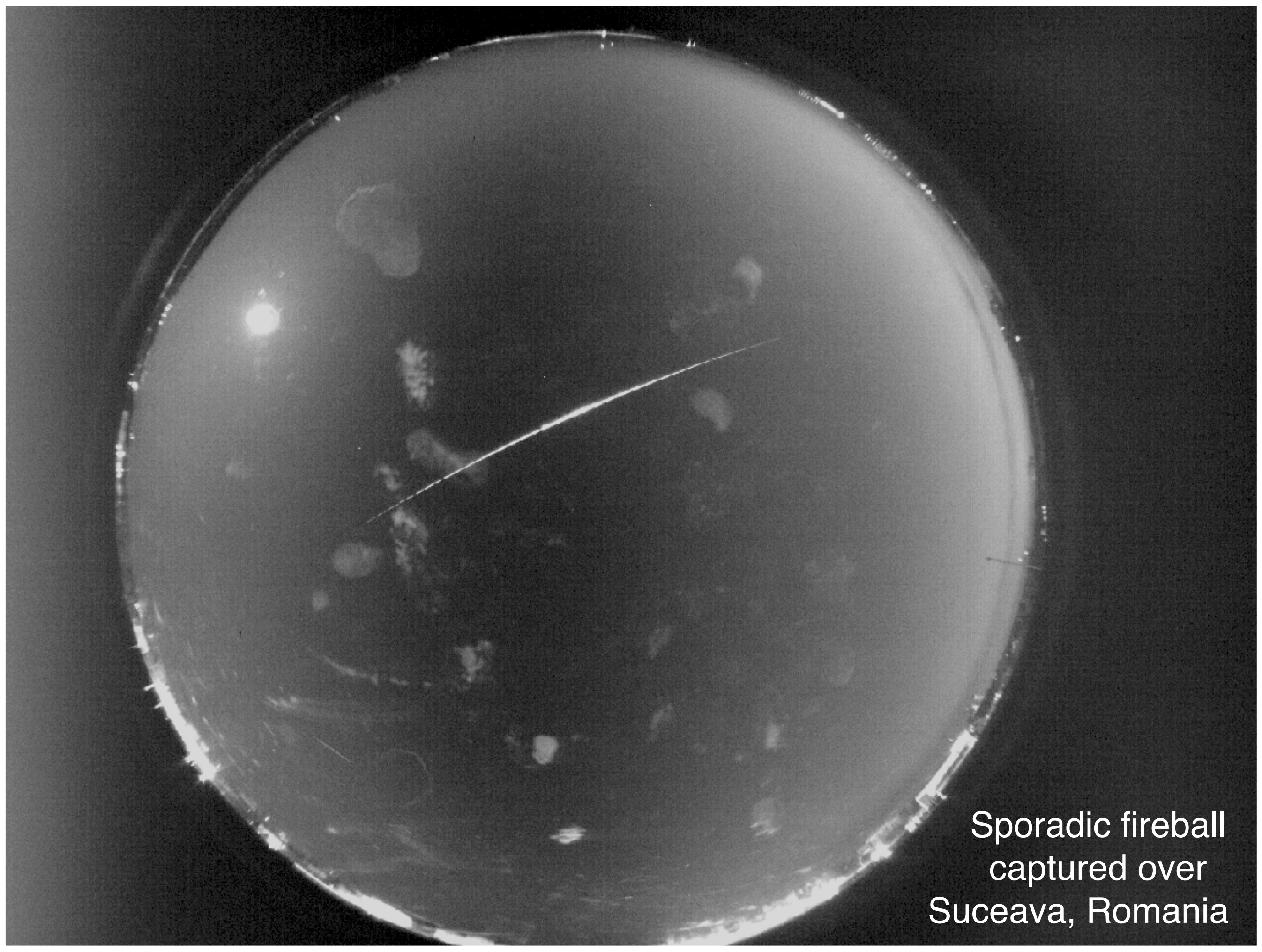
$$\frac{1}{2} \cdot m\, V^2 = KE$$

KE is measured in Tons TNT (1 T = 4.184 · 10^9 J)

Table 1

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

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).



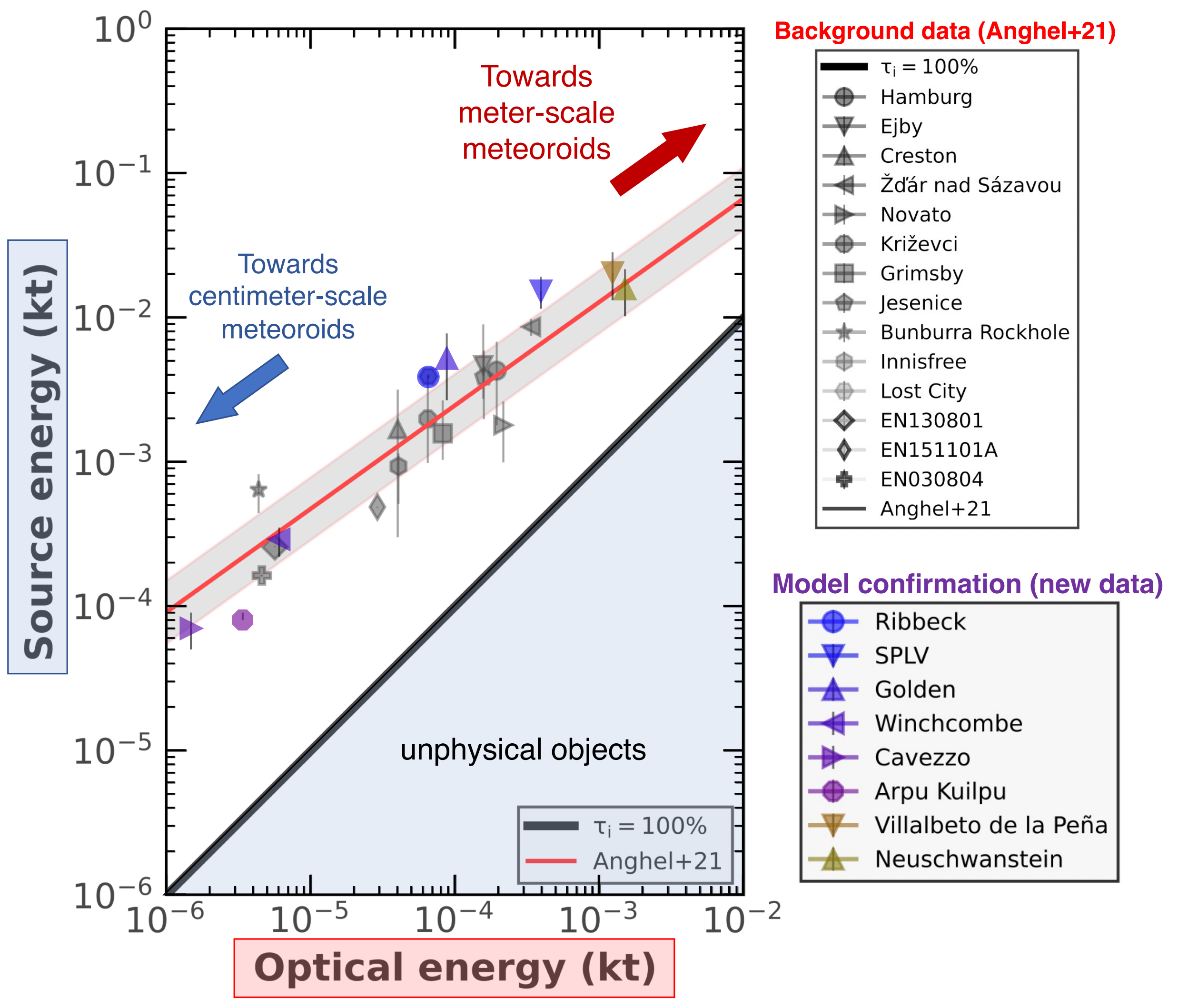
Composite image of the fireball detected on March 03, 2021 at 03:58:40 UT, on ROSV01 all-sky camera of the Meteorites Orbits Reconstruction by Optical Imaging (MOROI) network. The bright light in the left represents the Moon with a 82% illumination.

RESULTS & IMPLICATIONS

To derive the empirical relation, a best fit was obtained from the **source energy** vs the **optical energy**. When fitting the full set of objects from Table 1 as source energy vs optical energy, we obtain the best fit relation:

$$log(E) = 0.7165 \cdot log(Eo) + (0.5932 \pm 0.5020) \qquad (1)$$

where *E* represents the impact energy.
Although the radiated light and mass would ideally be modelled as a function of velocity, the obtained relation (Eq. **1**) shows a **good correlation between the object's kinetic energy** at entry and its **capability of radiating light during deceleration**, regardless of the object's fragmentation and ablation profile.



*The source energy vs radiated energy correspondence for the well-known list of bolides (grey data). The thick line represents a luminous efficiency of 100%. The relation presented by [6]. The **red line represents the best fit line thorough the gray data (Anghel+21)**. The **new data** represents bolides with independent energy estimations.*

A better estimate of the radiated light can be obtained with calibrated **radiometers** e.g., [7] or from the next generation **lightning mappers** [8]. Their relative luminosity is not affected by clouds, and can be coupled with the trajectory triangulation obtained by the currently expanding ground-based fireball networks e.g., [1], [9], [10], etc. to compute the object's mass. This, in turn, will help **to cross-calibrate the methods**, which can be further used to **constrain the size-frequency distribution of impacts**, thus, estimating the mass of objects endangering the rapidly increasing civilian infrastructure surrounding the Earth.

CONCLUSIONS

- The **bolide radiation** is the most **realiable method** of estimating the **source energy** of ton TNT scale impacts;
- A **more accurate relation** of estimating the source energy was obtained, **and tested with new data**. The applicability of this relation is **not limited to cameras**.
- the method can be used to **calibrate empirically other instrumental methods** of estimating the source energy of meteoroids.

References:
[1] Colas F. et al. (2020) *Astronomy & Astrophysics* 644:A53. [2] Anghel S. et al. (2021a) *Monthly Notices of the Royal Astronomical Society* 508:5716. [3] Edwards W. N. et al. (2006) *Journal of Atmospheric and Solar-Terrestrial Physics* 68:1136. [4] Ens T. A. et al. (2012) *Journal of Atmospheric and Solar-Terrestrial Physics* 80:208. [5] Anghel S. Birlan M. (2017) *Romanian Astronomical Journal,* 27:3 [6] Brown P. G. et al. (2002) *Nature* 420:294, [7] Rault J. L. and Colas F. (2019) *arXiv*: 1911:04290. [8] Stuhlmann R. et al. (2005) *Advances in Space Research* 36:975. [9] Anghel S. et al. (2021b*) in LPI Contributions Vol. 84*, Abstract #6027. [10] Vida D. et al. (2021) *Monthly Notices of the Royal Astronomical Society* 506:5046.