Modeling of fireballs
or
speaking stones

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~~Make a wish!~~

Observe!

Motivation

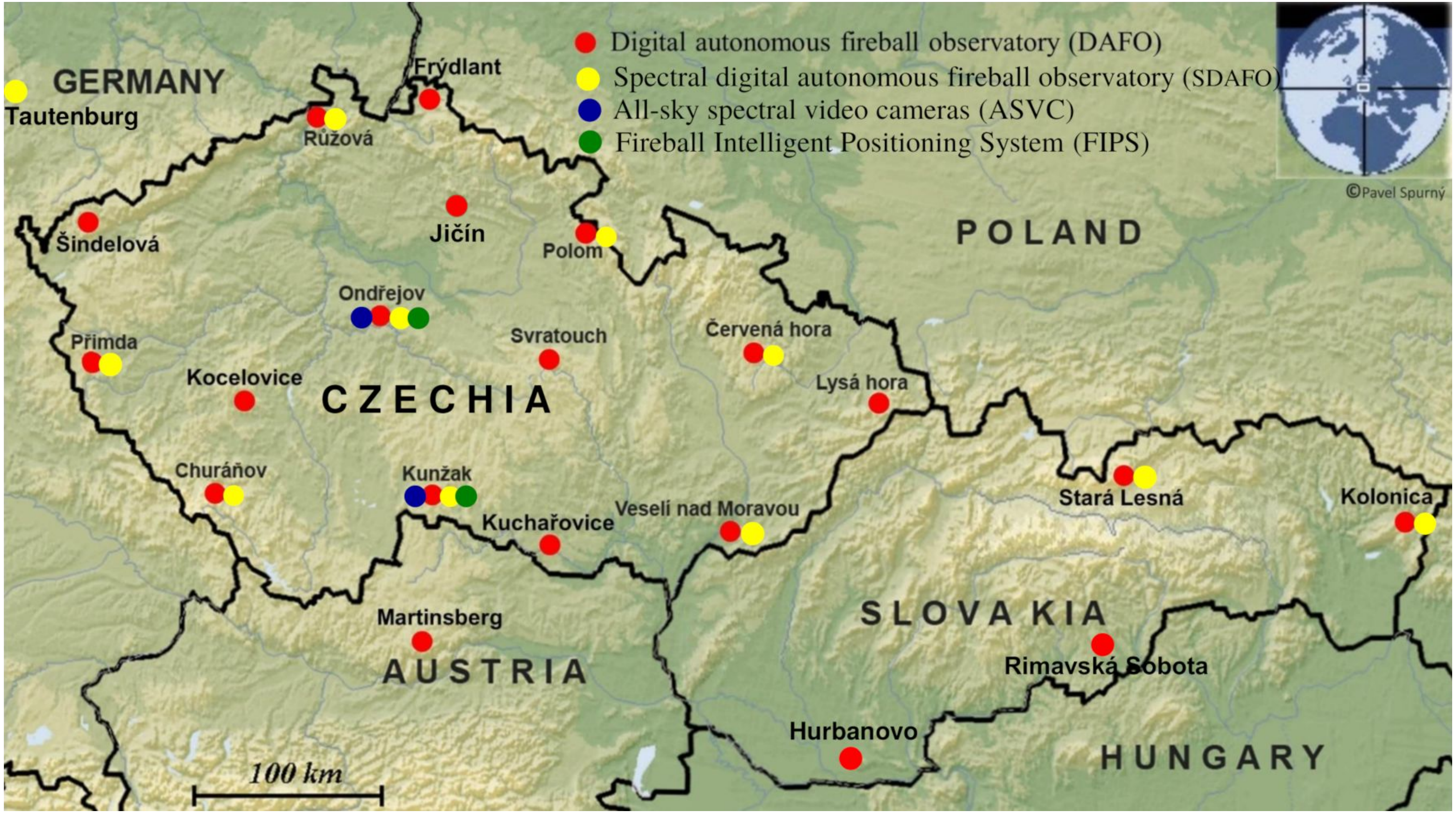
- meteoroids are pieces of asteroids and comets
- we observe them when they collide with the atmosphere as meteors or bolides (fireballs)
- detailed modeling yields their physical and mechanical properties
- long-term observations bring information on their population
- parts of them can survive as meteorites

European Fireball Network

observes while we’re sleeping

European Fireball Network

- automatically observes fireballs over Central Europe
- 21 stations in Central Europe
- covers some 1.5 mil. km^2
- operates every partly clear night without rain / snow
- radiometers operate every night
- all data digital and available on the central server
- Spurný et al. 2007 Proc. IAU Symp. 236; Spurný et al. 2017 A&A 605


Digital autonomous fireball observatory (DAFO)
Spectral digital autonomous fireball observatory (SDAFO)
All-sky spectral video cameras (ASVC)
Fireball Intelligent Positioning System (FIPS)
©Pavel Spurný
GERMANY
Tautenburg
Frýdlant
Růžová
Jičín
Šindelová
Polom
POLAND
Ondřejov
Svratouch
Červená hora
Přimda
Kocelovice
CZECHIA
Lysá hora
Churáňov
Kunžak
Kuchařovice
Veselí nad Moravou
Stará Lesná
Kolonica
Martinsberg
AUSTRIA
SLOVAKIA
Rimavská Sobota
Hurbanovo
HUNGARY
100 km

fotka vsech pristroju

DAFO, SDAFO (Spectral) Digital Autonomous Fireball Observatory

- high-resolution all-sky images
- radiometric record of the sky brightness
- spectra

➜ astrometry and photometry

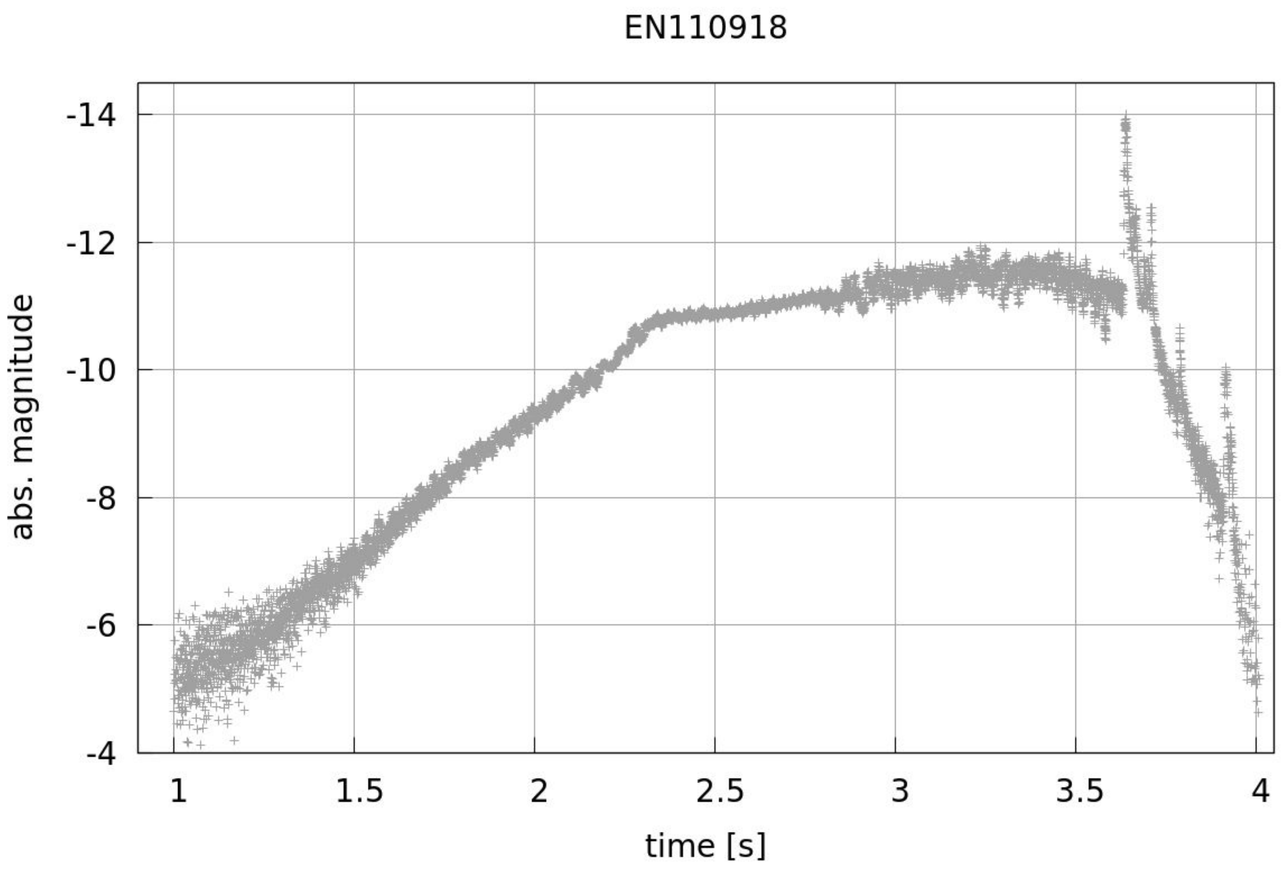
➜ length along the trajectory (dynamics, deceleration)

➜ radiometric lightcurve

➜ photometric lightcurve

DAFO all-sky

DAFO cut


EN110918
abs. magnitude
time [s]
-14
-12
-10
-8
-6
-4
1
1.5
2
2.5
3
3.5
4


EN181117_011515

ASVC All-sky Spectral Video Cameras

IP kamery

ASVC All-sky Spectral Video Cameras

IP spektrum

FIPS Fireball Intelligent Positioning System

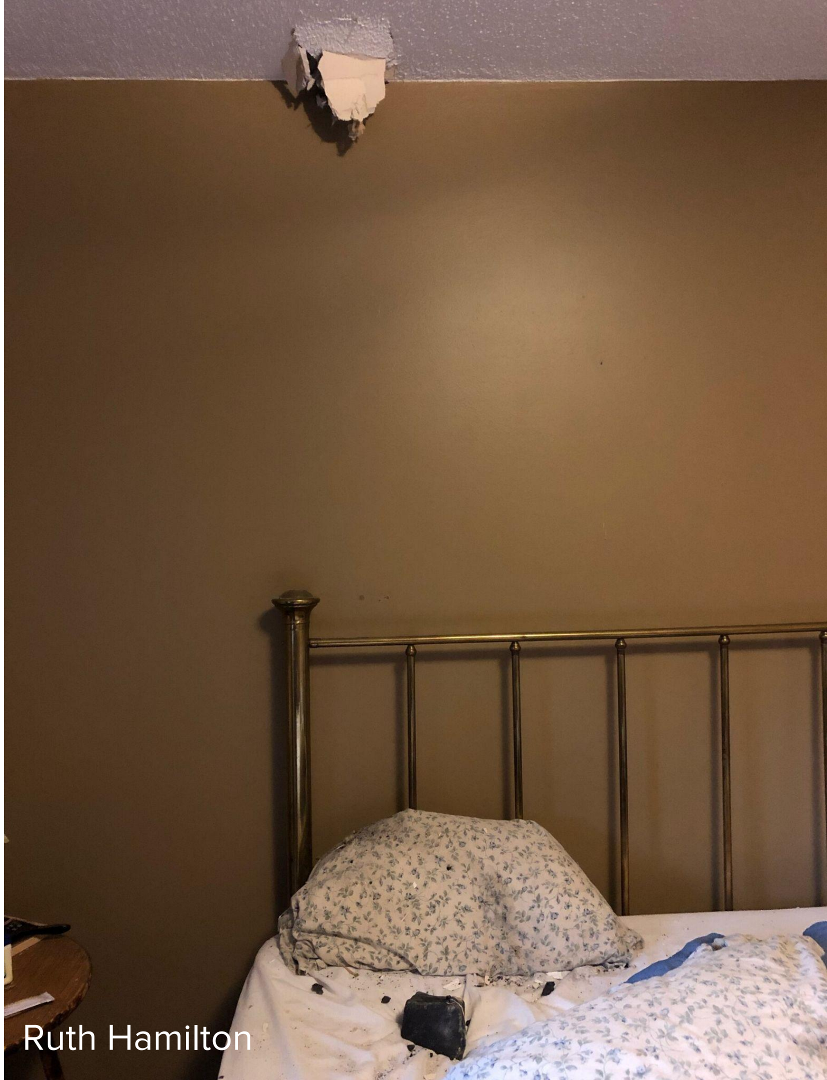
FIPS all-sky

FIPS positioning

FIPS record

Golden meteorite

- Golden, B.C., Canada on 3 Oct 2021
- 1270-g L/LL5 ordinary chondrite
- 2389 g total in two pieces
- casual videos and photos



Golden

- Golden, B.C
- 1270-g L/LL
- 2389 g in to
- observed i


Ruth Hamilton


Ruth Hamilton

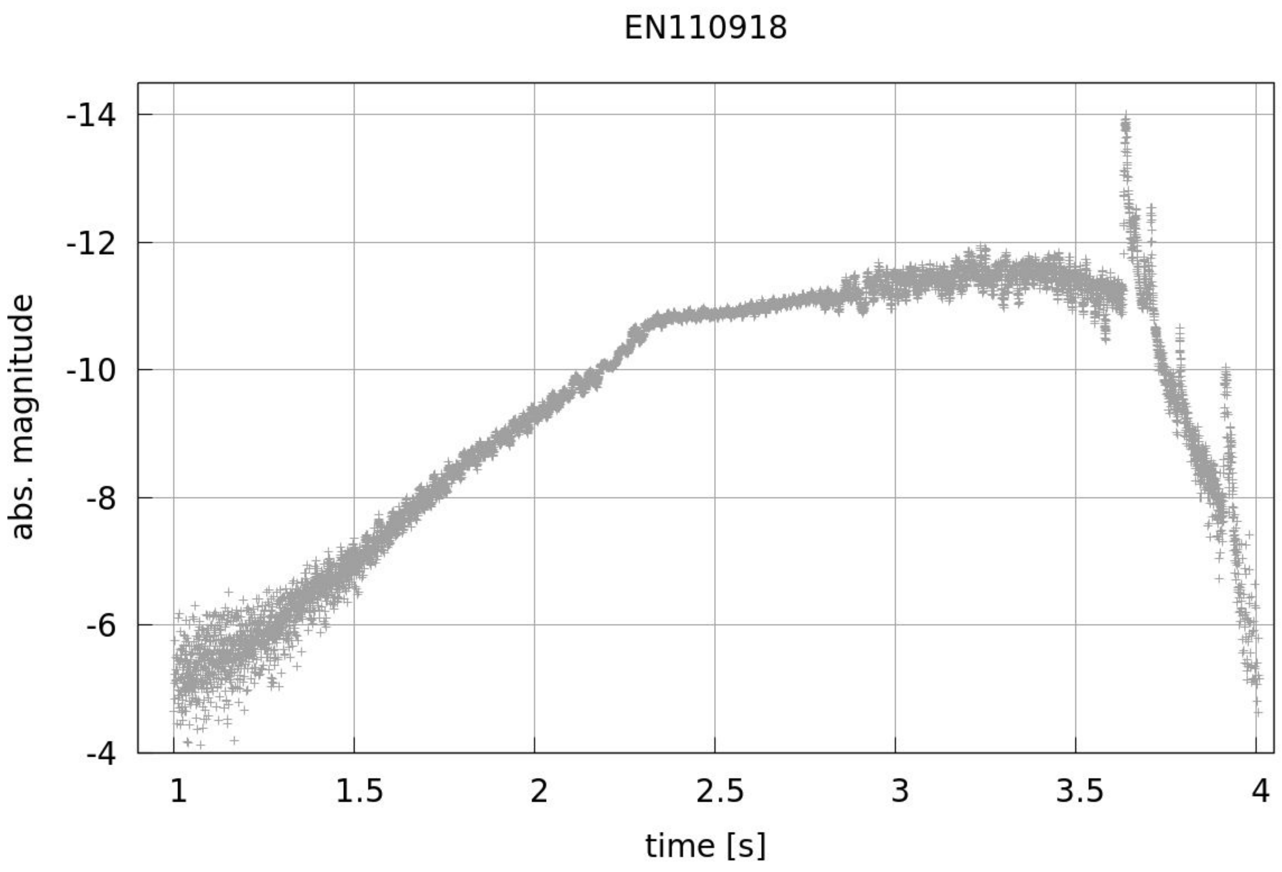

Hao Qin Photography

Fragmentation modeling

drag equation (eq. of motion) +
ablation equation (mass-loss eq.) +
fragmentation

fragmentation model

- semi-empirical fragmentation model (Borovička et al. 2020 AJ 160)
- meteoroid ablates and decelerates in the atmosphere
- it breaks either into several discrete fragments and instantly releases dust grains causing a short and bright flare (gross fragmentation)
- or it erodes dust grains over a longer period of time causing a gradual brightening
- individual fragments then ablate separately and can later also fragment or erode


EN110918
abs. magnitude
time [s]
-14
-12
-10
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1
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2.5
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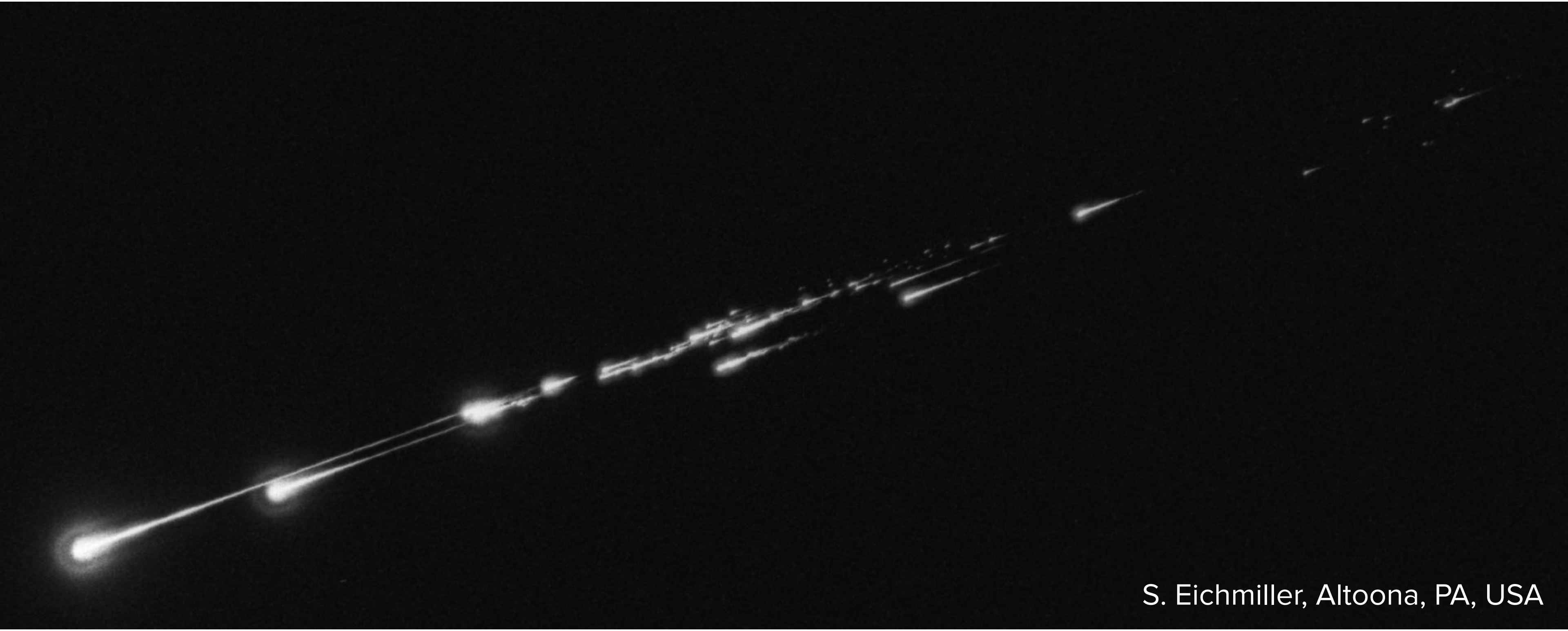
3.5
4


S. Eichmiller, Altoona, PA, USA

fragmentation model semi-automatic approach

Q Can we find an automatic way to model the data?

- usually several and up to many tens of fragments resulting in tens to a few hundreds of free parameters ➜ vast parametric space
- too demanding for systematic search, gradient-based methods get usually stuck in a local extreme
- genetic algorithm (parallelized with Message Passing Interface) can find a global extreme (Charbonneau 1995 ApJ SS 101)
- MPIKAIA (Metcalfe & Charbonneau 2003 J. Comp. Phys. 185)

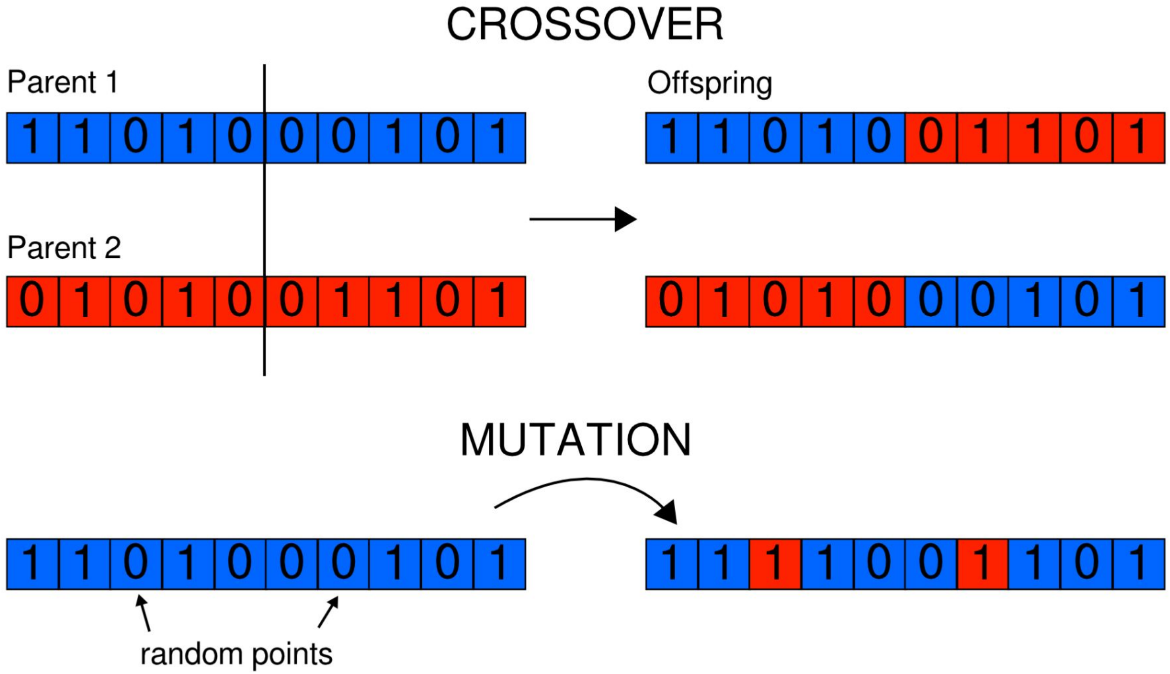
genetic algorithm

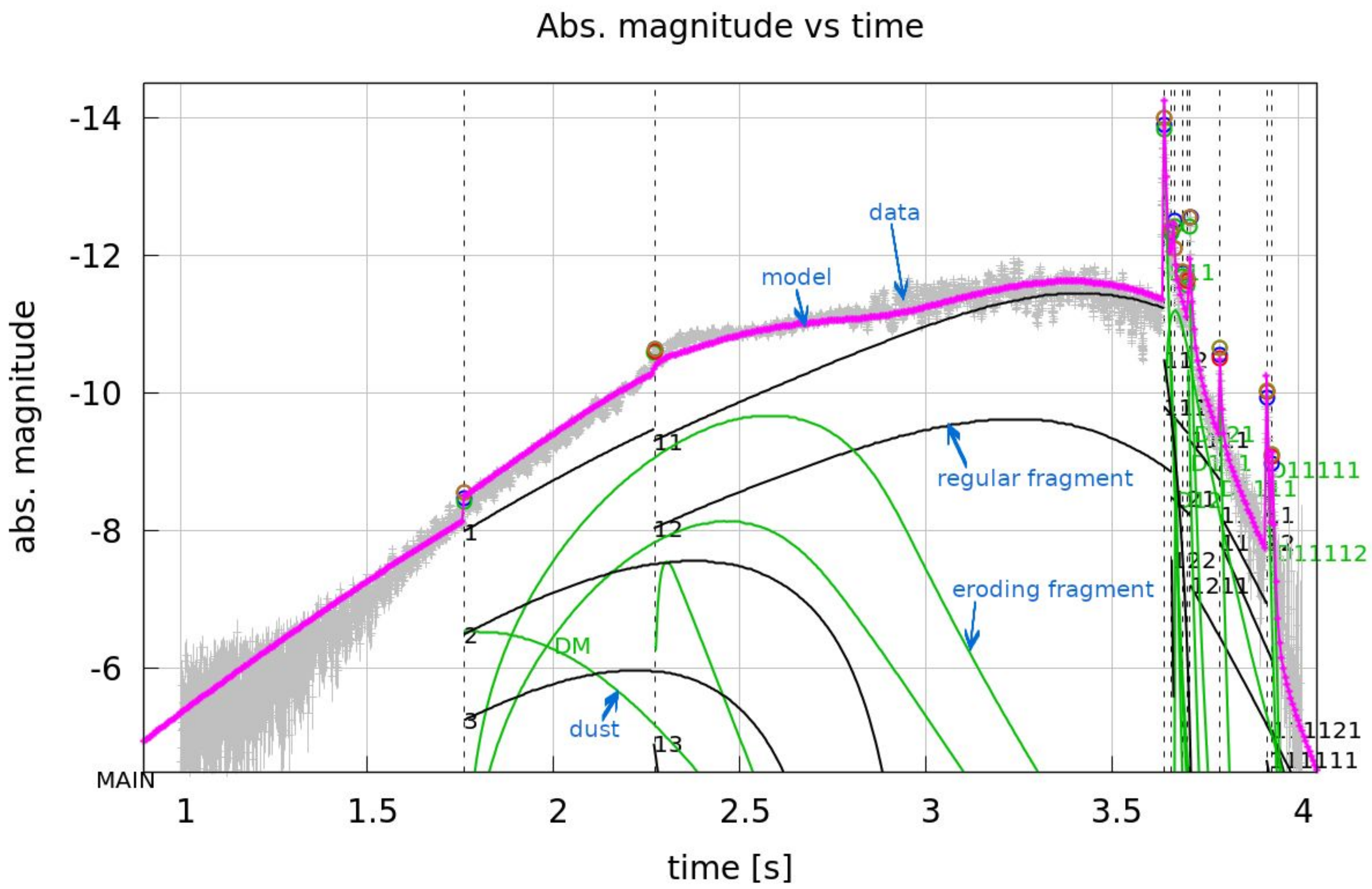
- algorithm inspired by simplified evolution rules
- create a population of **random solutions** (50–100) = 0^{th} generation
- values of free parameters (fenotype) are encoded to a sequence of numbers (genotype), to which we apply three basic rules:
  1. selection (only the fittest survive)
  2. inheritance (offspring take after their parents)
  3. variation (random mutations of the genotype)

genetic algorithm

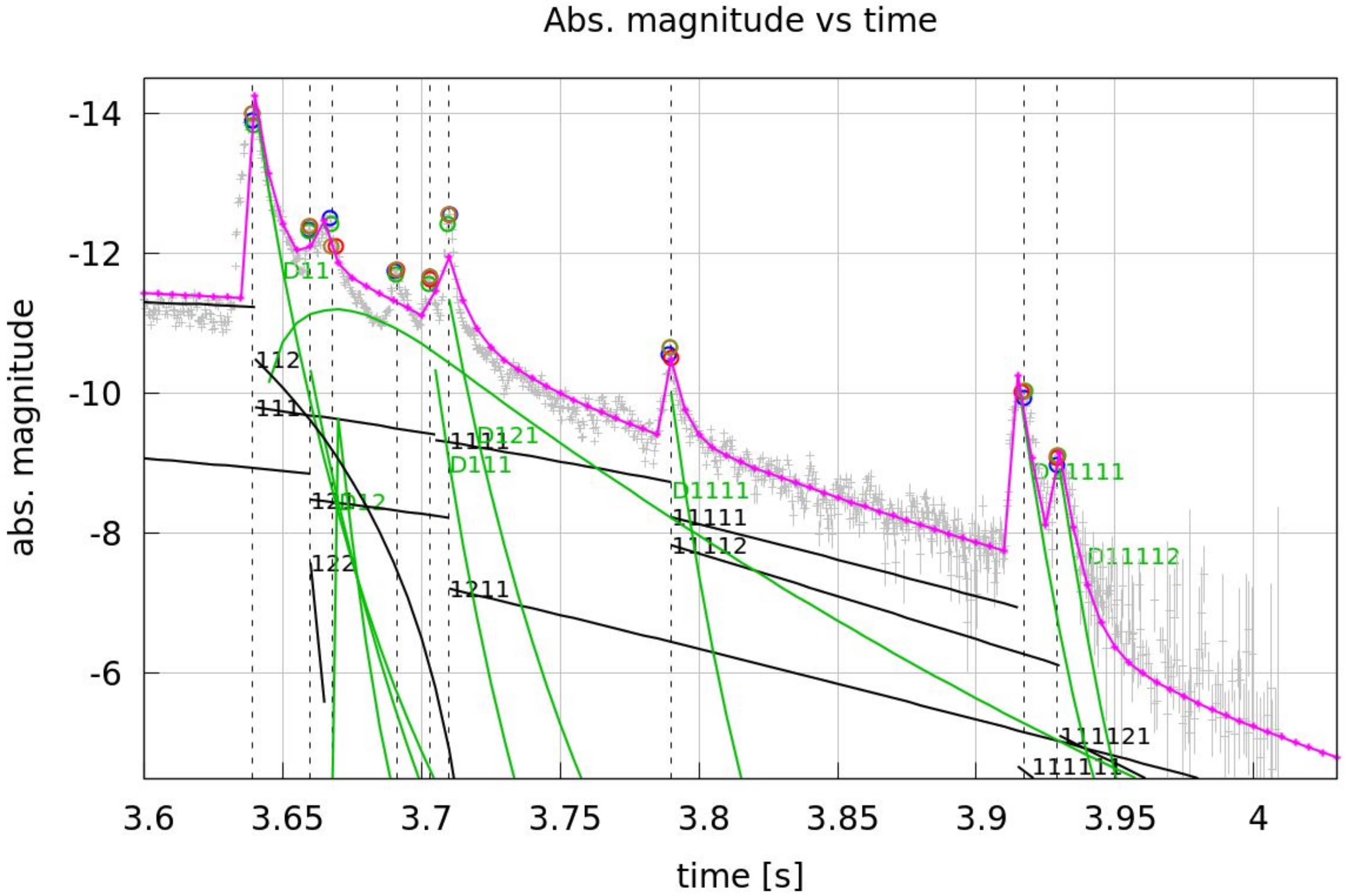
- for each solution calculate **fitness function** ($1/\chi^2$ or some other) ← *expensive part*
- **select** the best solutions (based on their fitness), create pairs and mix their genomes (**crossover**)
- apply **mutations** (random changes in the genome)
- replace an old generation with a new one and calculate the fitness for all new solutions
- proceed until we reach some (value, small change) of $1/\chi^2$ or number of generations (several hundred to several thousand)

genetic algorithm

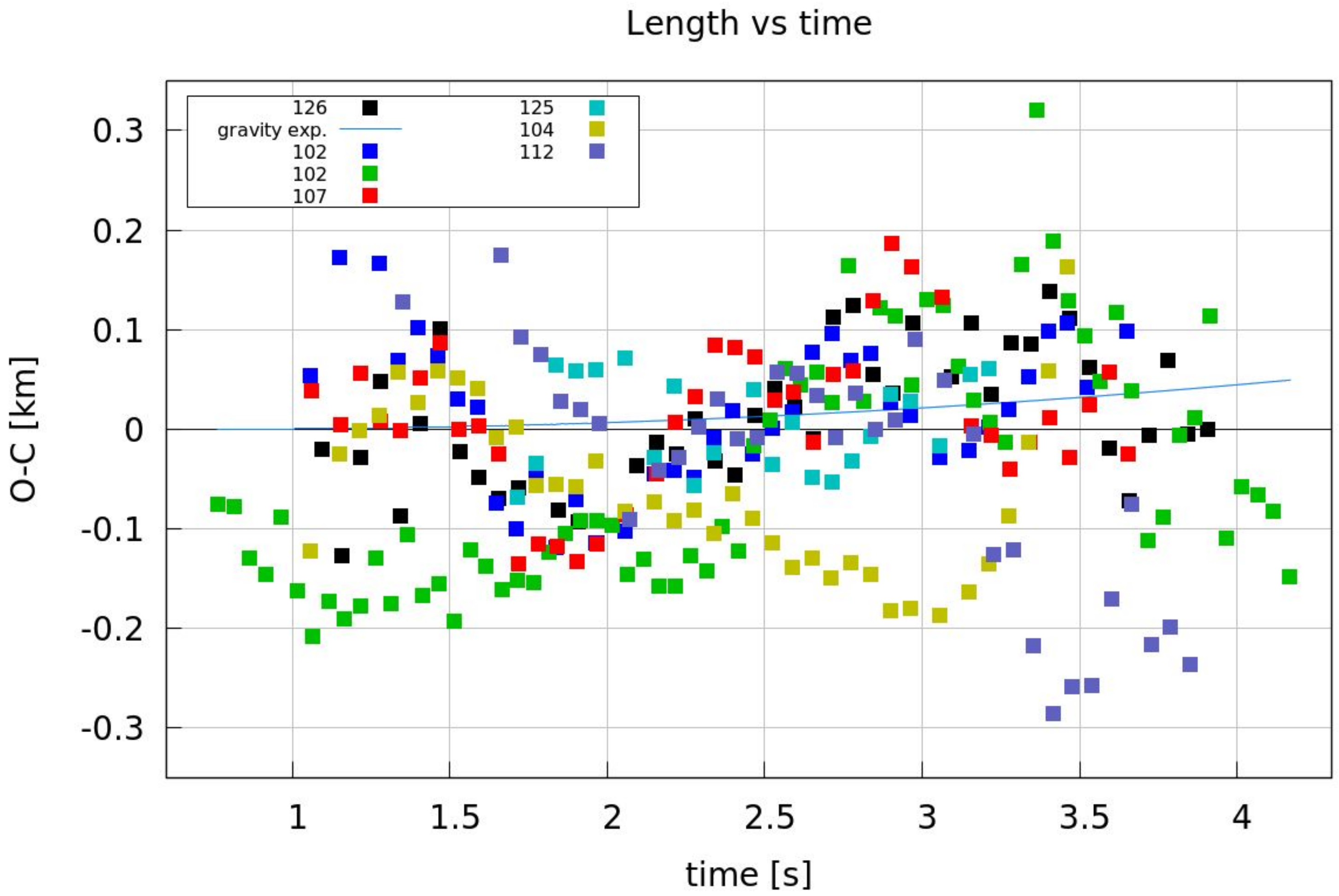




Abs. magnitude vs time
abs. magnitude
time [s]
-14
-12
-10
-8
-6
1
1.5
2
2.5
3
3.5
4
data
model
regular fragment
eroding fragment
dust
DM
MAIN
1
2
3
11
12
13



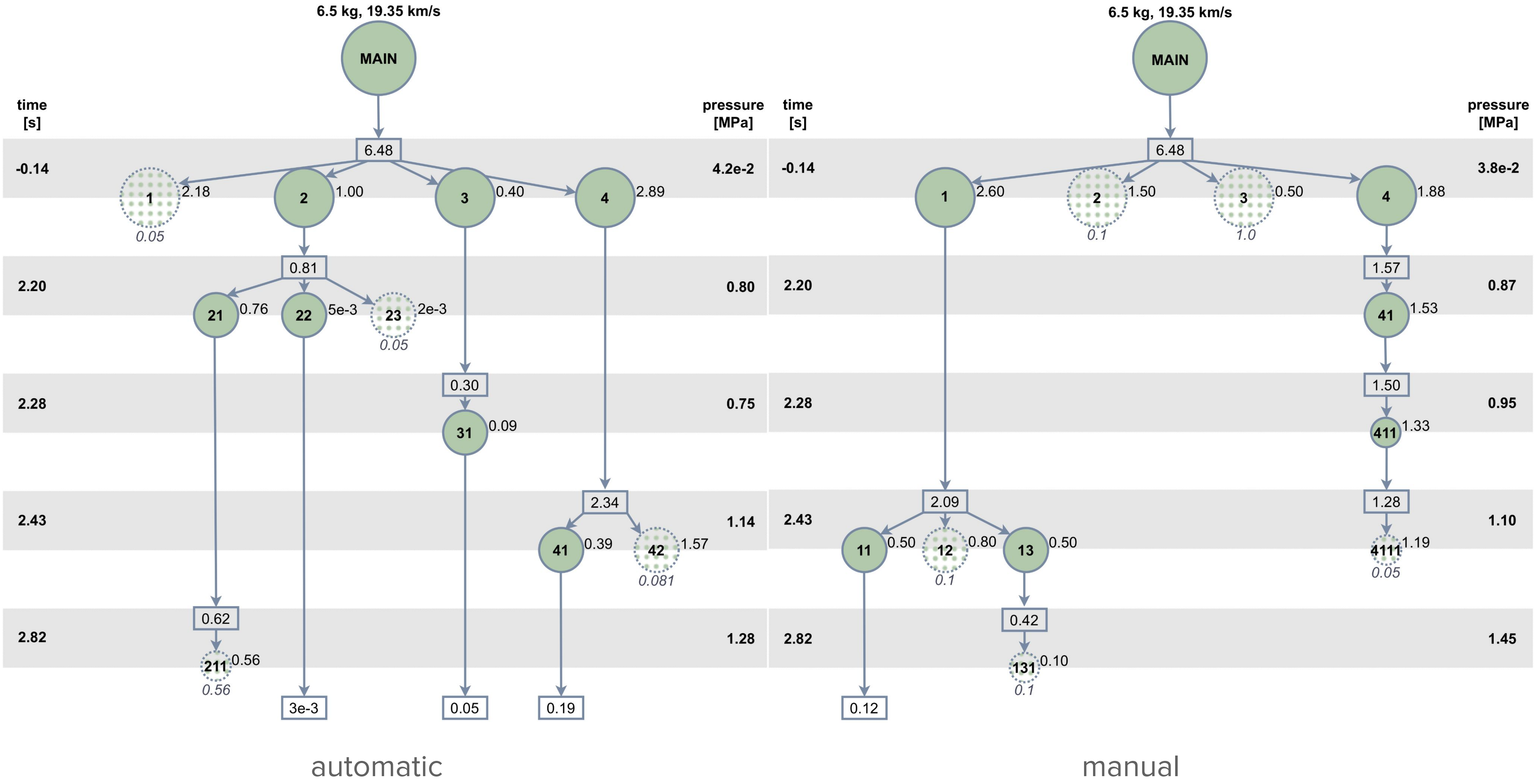
Abs. magnitude vs time
abs. magnitude
time [s]
-14
-12
-10
-8
-6
3.6
3.65
3.7
3.75
3.8
3.85
3.9
3.95
4
D11
112
111
1111
D121
D111
122
1211
D1111
11111
11112
D11111
D11112
111121
111111



Length vs time
126
gravity exp.
102
102
107
125
104
112
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
O-C [km]
1
1.5
2
2.5
3
3.5
4
time [s]

modeling results

- precise initial velocity and mass of the meteoroid
  (velocity vector ⇒ heliocentric orbit, origin)
- fragmentation times and heights (⇒ dynamic pressure)
- number of fragments, their masses, eroding fragments, released dust mass, mass distribution of dust grains
- possible meteorites (dark flight modeling ⇒ strewn field)
- Henych et al. (2023) A&A 671


6.5 kg, 19.35 km/s
MAIN
time [s]
pressure [MPa]
-0.14
4.2e-2
6.48
1 2.18 0.05
2 1.00
3 0.40
4 2.89
2.20
0.80
0.81
21 0.76
22 5e-3
23 2e-3 0.05
2.28
0.75
0.30
31 0.09
2.43
1.14
2.34
41 0.39
42 1.57 0.081
2.82
1.28
0.62
211 0.56 0.56
3e-3
0.05
0.19
automatic
6.5 kg, 19.35 km/s
MAIN
time [s]
pressure [MPa]
-0.14
3.8e-2
6.48
1 2.60
2 1.50 0.1
3 0.50 1.0
4 1.88
2.20
0.87
1.57
41 1.53
2.28
0.95
1.50
411 1.33
2.43
1.10
2.09
11 0.50
12 0.80 0.1
13 0.50
1.28
4111 1.19 0.05
2.82
1.45
0.42
131 0.10 0.1
0.12
manual

dynamic pressure

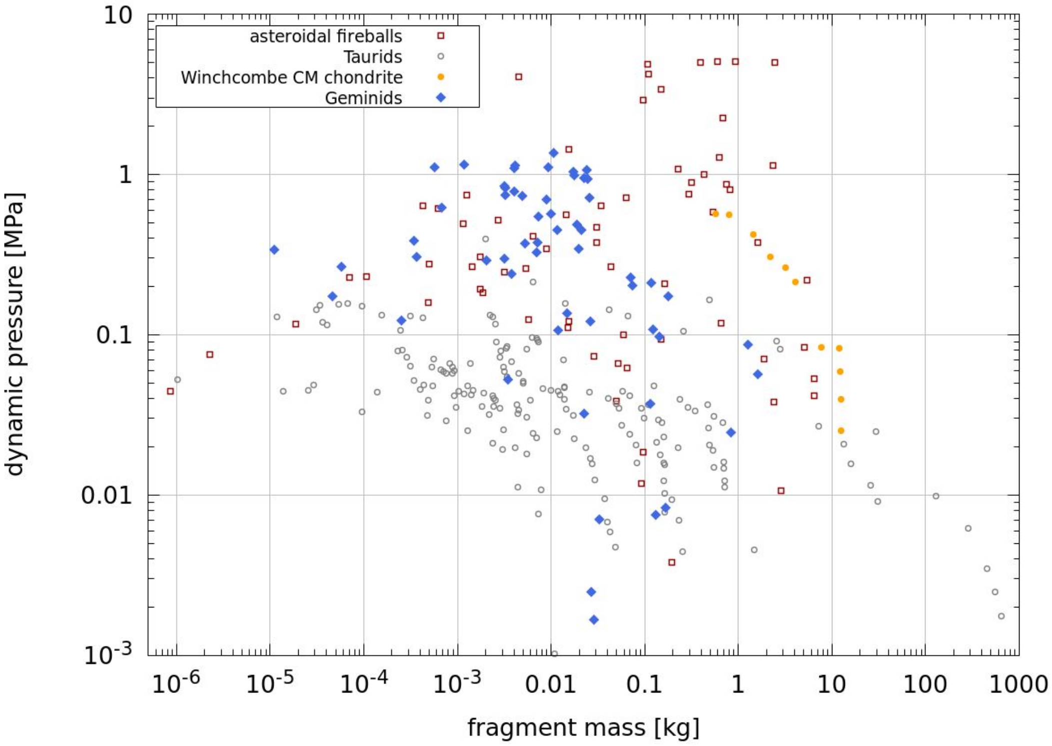
- pressure exerted on a meteoroid: $p_{\mathrm{dyn}} = \Gamma \rho_{\mathrm{atm}} v^2$
- proxy for tensile strength of the meteoroid at fragmentation points
- calculated in the model for any fragment that further crumbles
- mechanical strength of shower meteoroids and their parent bodies from fragmentation modeling
- very soft cometary material (τ Herculids, Draconids) ✕ hard asteroidal material (fireballs dropping ordinary chondrites)

Geminids

- major annual meteor shower ~14 Dec
- the parent body is an active asteroid 3200 Phaethon

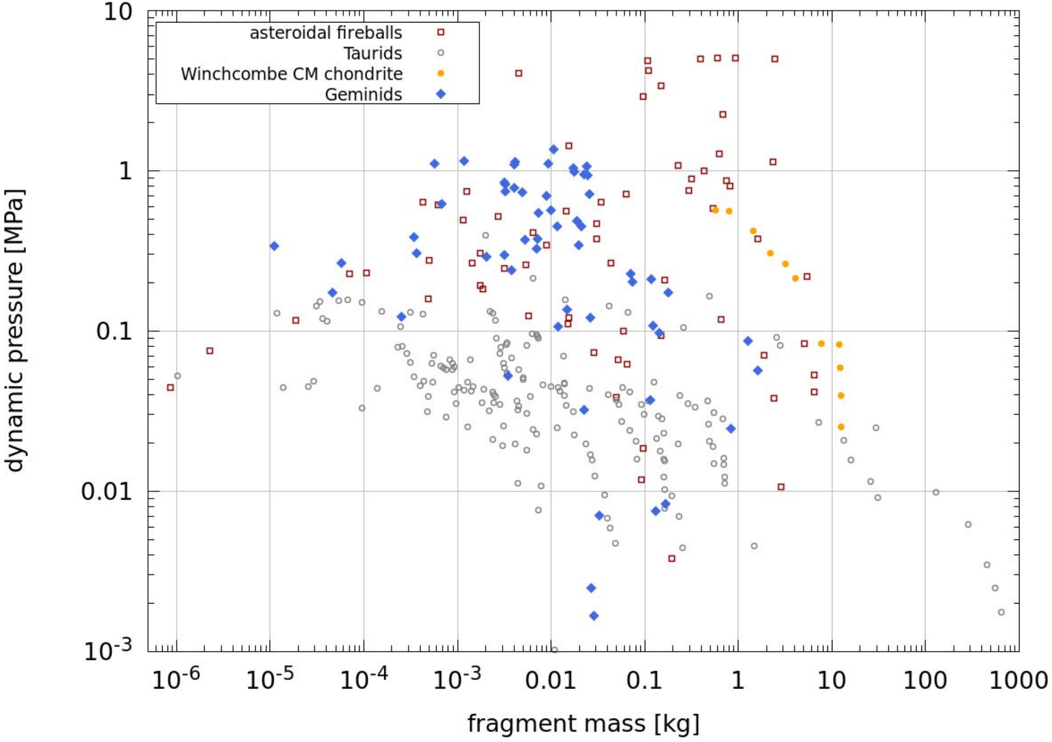
Geminid fireballs

- detailed modeling of 8 Geminids and 9 asteroidal fireballs of similar masses
- derived dynamic pressures for all fragments
- Winchcombe CM chondrite (UK, Feb 2021, McMullan et al. 2023 eprint arXiv:2303.12126)
- Taurids (Borovička & Spurný 2020 Plan. & Space Sci. 182)



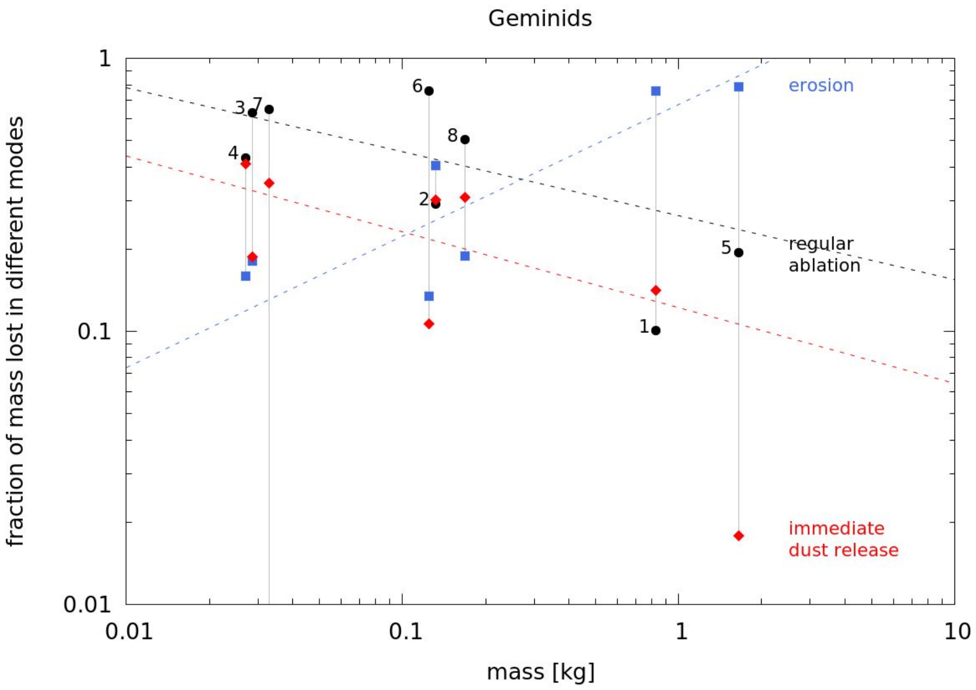
Geminid fireballs

- maximum strength of Geminids about 4x lower than in asteroidal fireballs
- about 2.5x higher than in the Winchcombe fireball
- order of magnitude higher than in Taurids
- may be composed from compact carbonaceous material



Geminid fireballs

- meteoroid initial mass affects how it looses mass
- gradual erosion of dust grains increases with mass (as in Taurids)
- both regular ablation and dust release (flare) decrease with mass (same trend in Taurids but the two regimes reversed)



Speaking stones

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Photoacoustic Sounds from Meteors

Richard Spalding[1], John Tencer[1], William Sweatt[1], Benjamin Conley[1], Roy Hogan[1], Mark Boslough[1], GiGi Gonzales[1] & Pavel Spurný[2]

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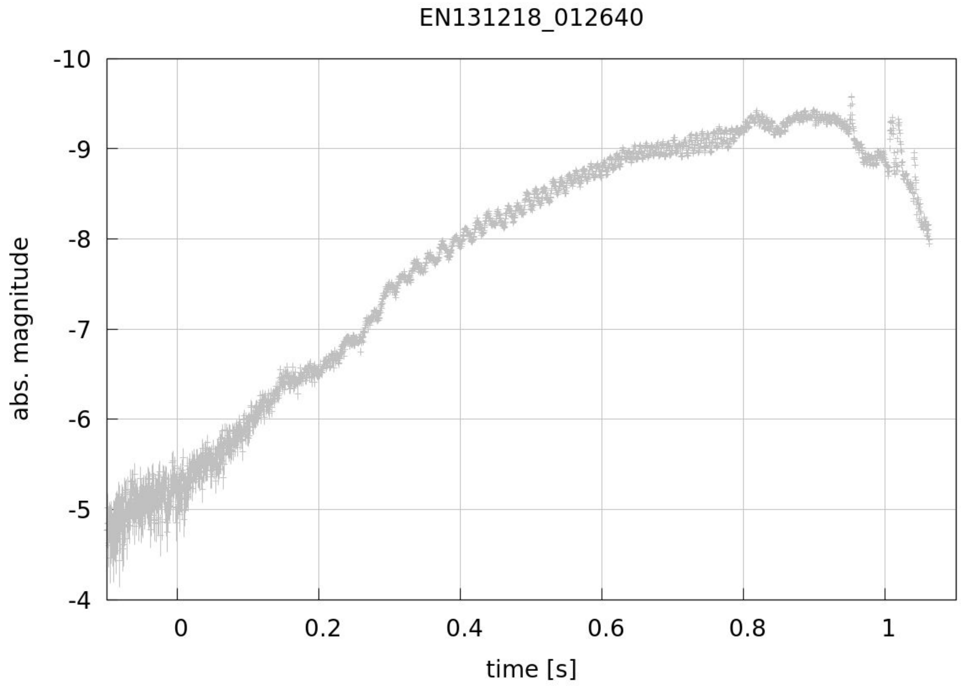
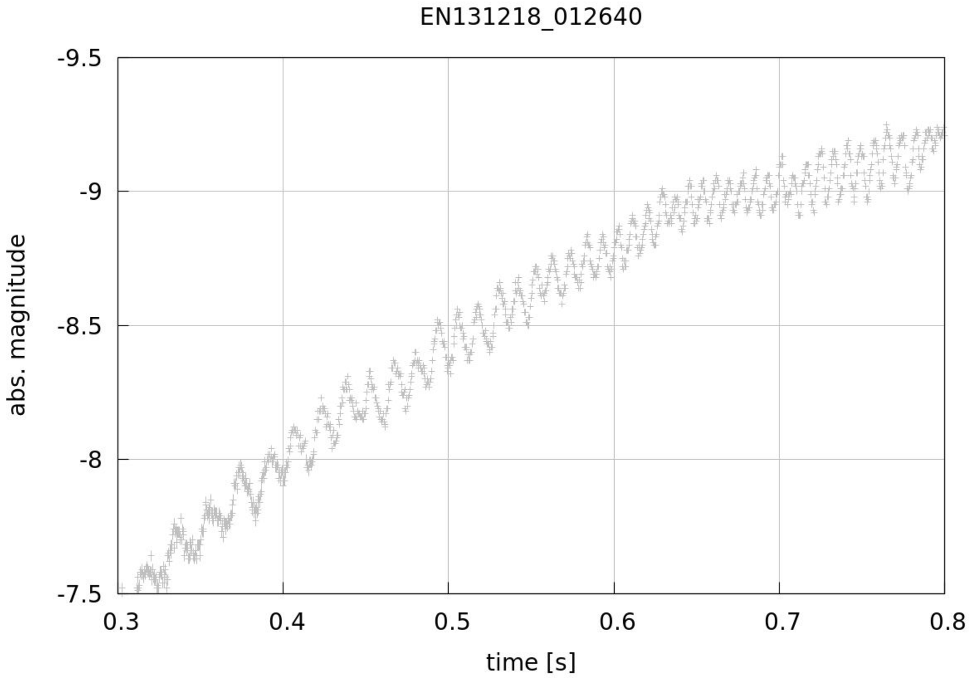
Concurrent sound associated with very bright meteors manifests as popping, hissing, and faint rustling sounds occurring simultaneously with the arrival of light from meteors. Numerous instances have been documented with −11 to −13 brightness. These sounds cannot be attributed to direct acoustic propagation from the upper atmosphere for which travel time would be several minutes. Concurrent sounds must be associated with some form of electromagnetic energy generated by the meteor, propagated to the vicinity of the observer, and transduced into acoustic waves. Previously, energy propagated from meteors was assumed to be RF emissions. This has not been well validated experimentally. Herein we describe experimental results and numerical models in support of photoacoustic coupling as the mechanism. Recent photometric measurements of fireballs reveal strong millisecond flares and significant brightness oscillations at frequencies $\geq$40 Hz. Strongly modulated light at these frequencies with sufficient intensity can create concurrent sounds through radiative heating of common dielectric materials like hair, clothing, and leaves. This heating produces small pressure oscillations in the air contacting the absorbers. Calculations show that −12 brightness meteors can generate audible sound at ~25 dB SPL. The photoacoustic hypothesis provides an alternative explanation for this longstanding mystery about generation of concurrent sounds by fireballs.

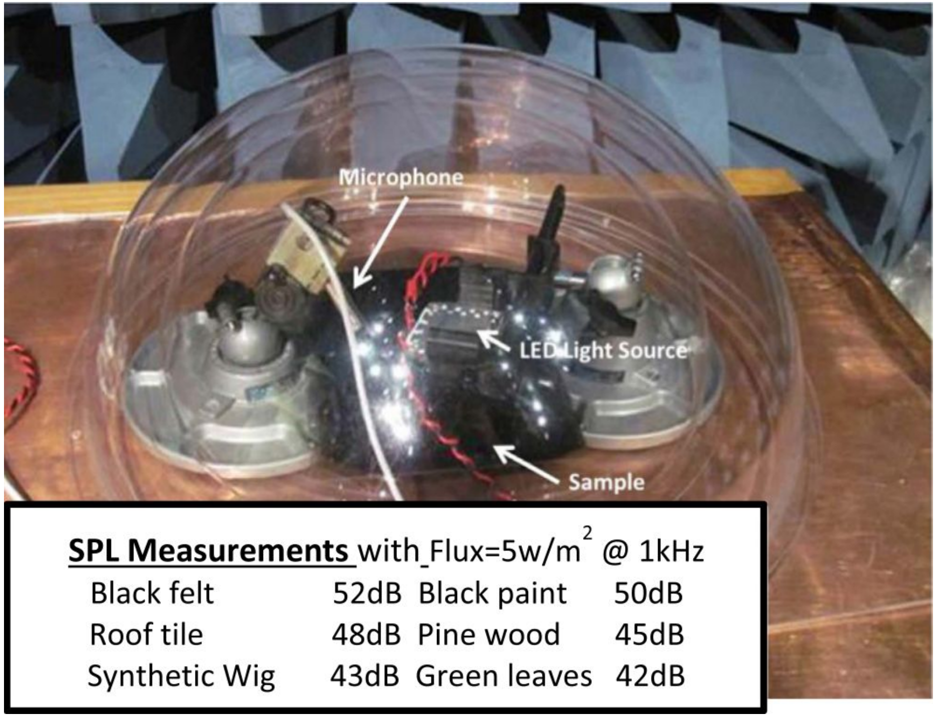
Speaking stones



Speaking stones



Speaking stones



SPL Measurements with Flux=5w/m^2 @ 1kHz

Black felt	52dB	Black paint	50dB
Roof tile	48dB	Pine wood	45dB
Synthetic Wig	43dB	Green leaves	42dB

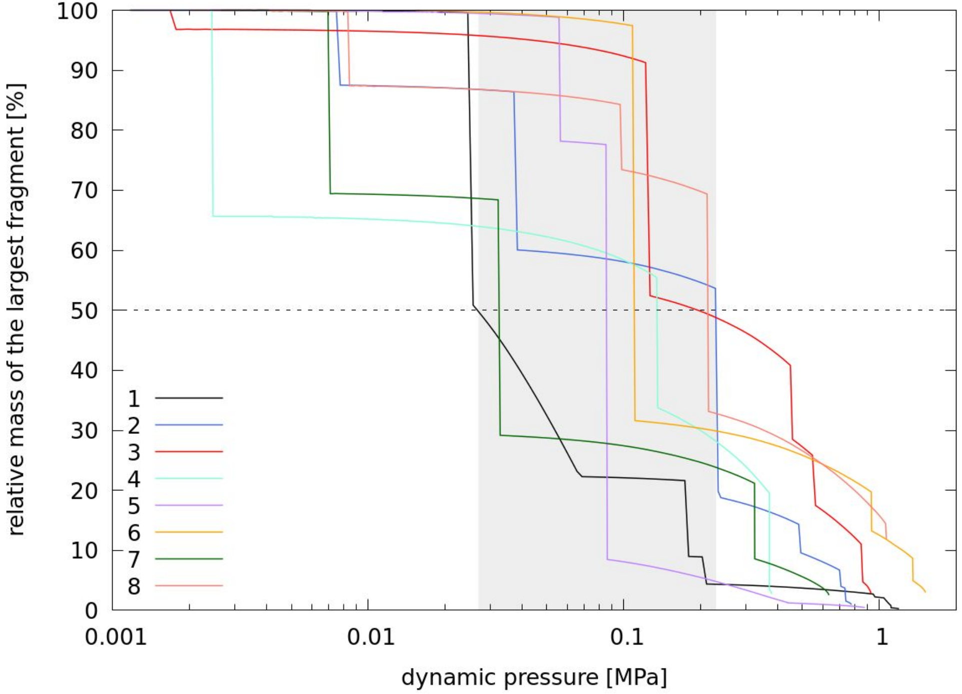
Fig. 2, Spalding et al. (2017) Sci. Rep. 7

Take away messages

1. Fireball modeling unveils their structure and mechanical strength.
2. Shower fireballs map physical properties of a specific comet or asteroid.
3. Bright fireballs can be heard during observation.

Geminid fireballs

- catastrophic disruption (50% mass loss) at 0.027–0.23 MPa
- need more data



meteorite falls

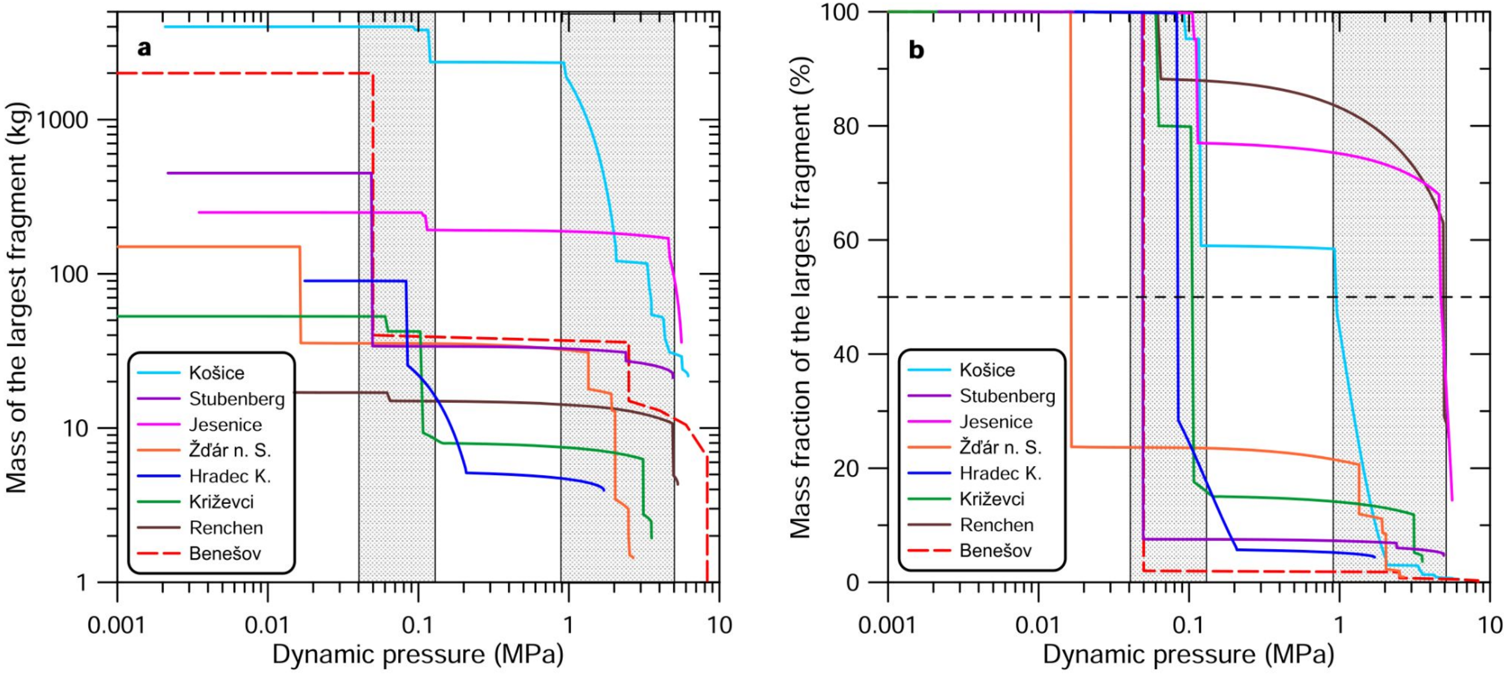


Fig. 5, Borovička et al. (2020) AJ 160

asteroidal fireballs

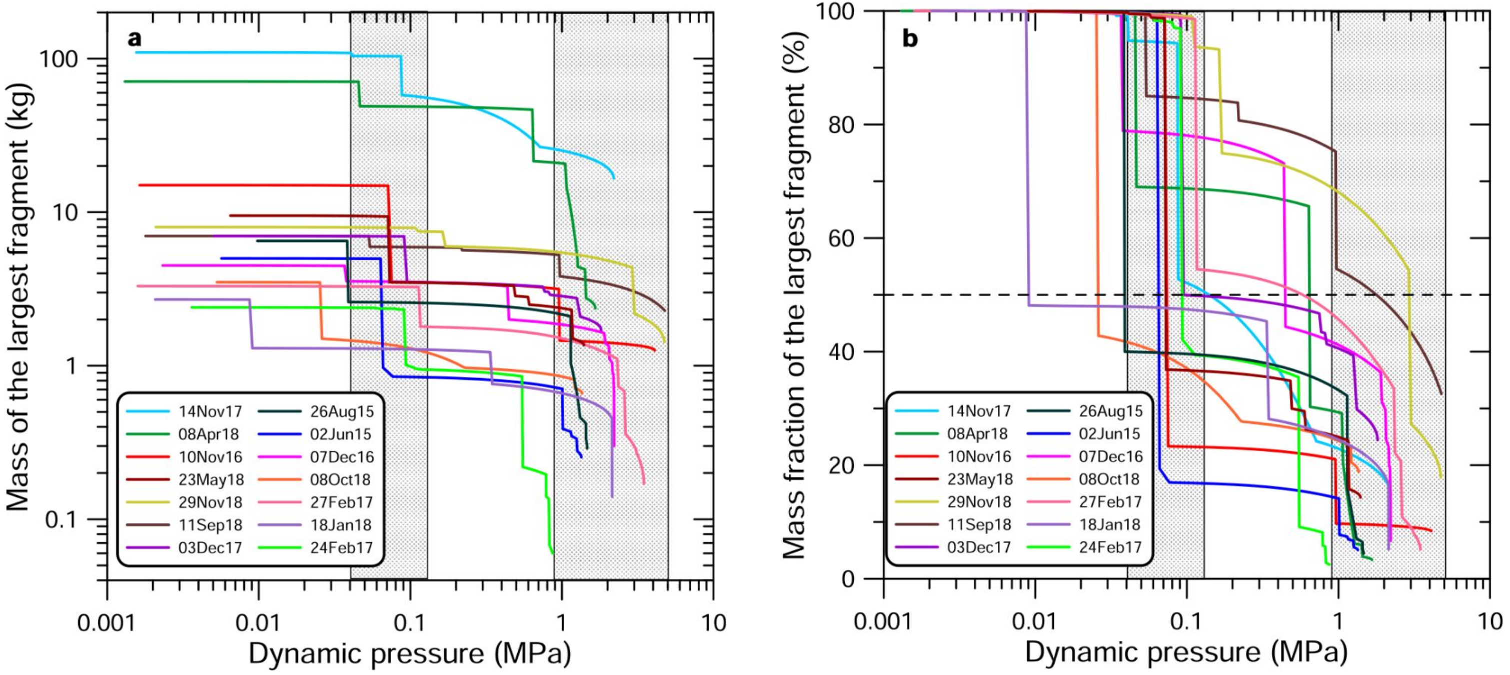


Fig. 7, Borovička et al. (2020) AJ 160

European Fireball Network

- high-resolution all-sky images to derive positions and luminosity
- precise radiometers, 5000 samples/s
- IP surveillance cameras for detailed spectral video observations (all-sky coverage at 2 stations)
- FIPS: fragmentation in detail

fragmentation model manual approach

- trial-and-error modeling
- takes a long time & occupies much of a workforce
- the solutions may not be unique
- difficult to estimate uncertainties

Q Can we find an automatic way to model the data?