

Semiautomatic fragmentation modeling of meteoroids

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Motivation

- shower meteors/bolides with a known parent body carry information about a specific asteroid or comet
 - detailed modeling of the meteoroid fragmentation yields its physical and mechanical properties
 - it also provides clues to its structure
 - size effects in physical properties can be described by modeling a wider range of meteoroid masses
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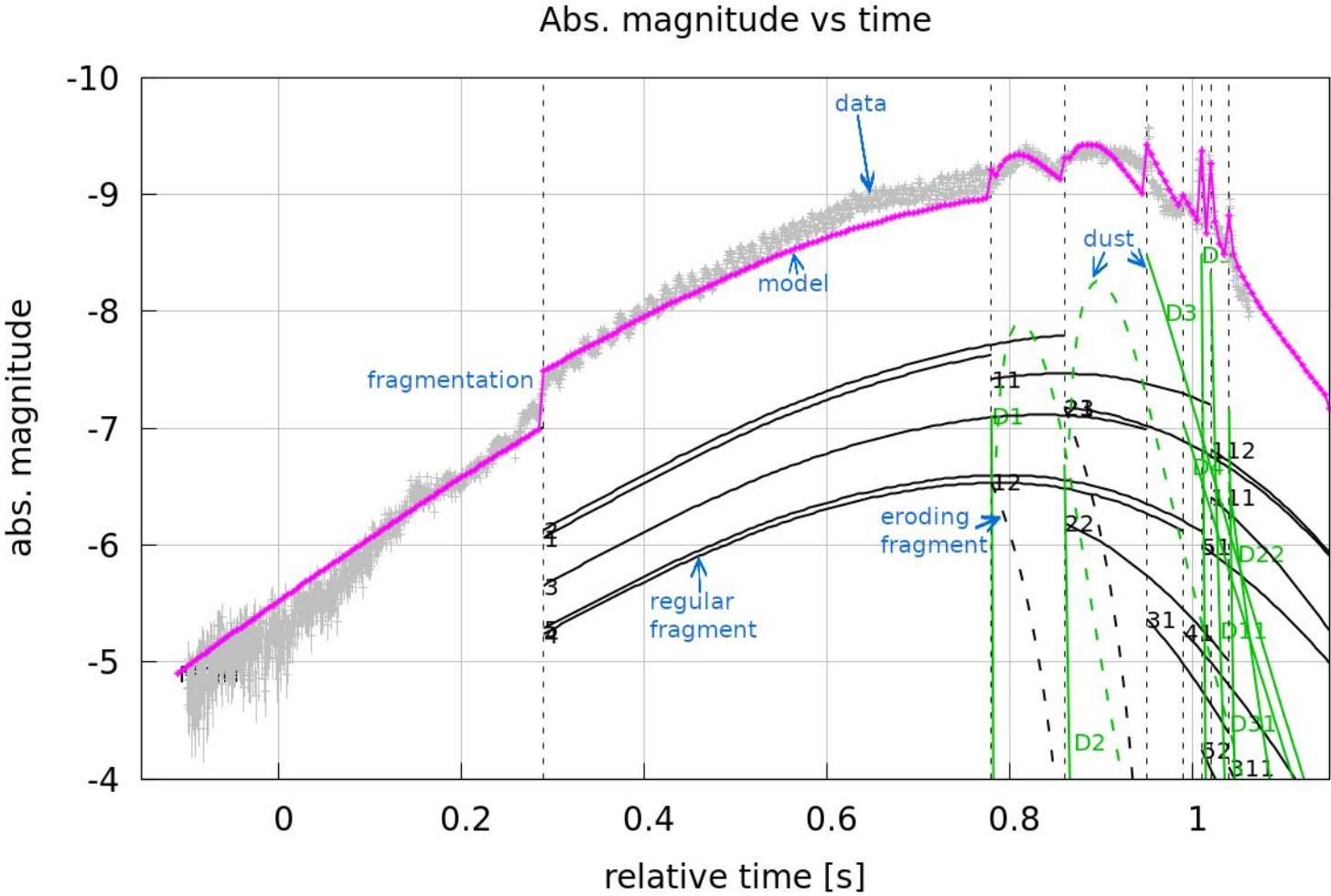
Data

- fireballs observed by the European Fireball Network
- radiometric LC, photometric LC (from all-sky images), foremost fragment dynamics
- faint video meteor data from dedicated observations during major showers from Ondřejov and Kunžak
- photometric LC (from video frames), meteor dynamics (photocenter)

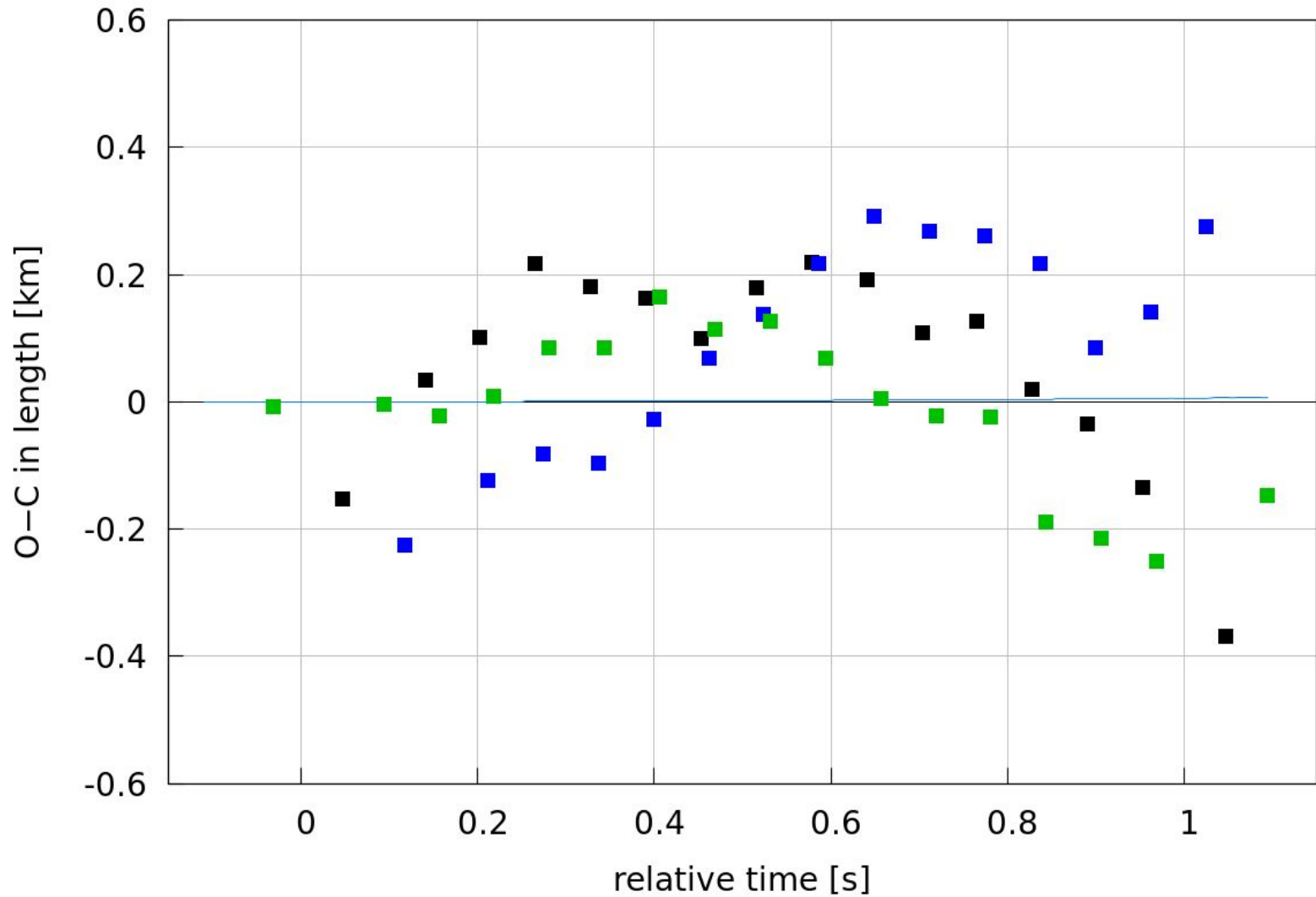
Modeling of fireballs

- semiempirical fragmentation model of Borovička et al. (2020)
- meteoroid fragmentation times visible in the radiometric LC
- discrete number of fragments, regular or eroding
- dust grains released immediately upon fragmentation or gradually via erosion of fragments
- opt: initial mass, velocity, height, fragmentation times, # of fragments, fragment masses, dust & eroding grains properties, ...
- fixed: ablation, drag & shape coeffs., bulk density, $\tau(m,v)$

Radiometric light curve



Dynamics residua



Genetic algorithm optimizer

- the model is used together with a parallel genetic algorithm optimizer MPIKAIA (MPI + PIKAIA)
- usually 50 random solutions are evolved over ~1000 generations (hours to days)
- we experiment with dataset weights to construct an objective function
- update of fragtimes and other values informed by the solution
- several good solutions fitting the data – the detailed characteristics not unique
- described in detail in Henych et al. (2023) *A&A* 671

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- update

the

solution

- several

led

character

- described in detail in Henry et al. (2025) *A&A* 671

$$\chi^2 = \frac{w_{\text{rlc}}\chi_{\text{rlc}}^2 + w_{\text{lc}}\chi_{\text{lc}}^2 + w_{\text{len}}\chi_{\text{len}}^2}{N_{\text{data}} - N_{\text{parm}}}$$

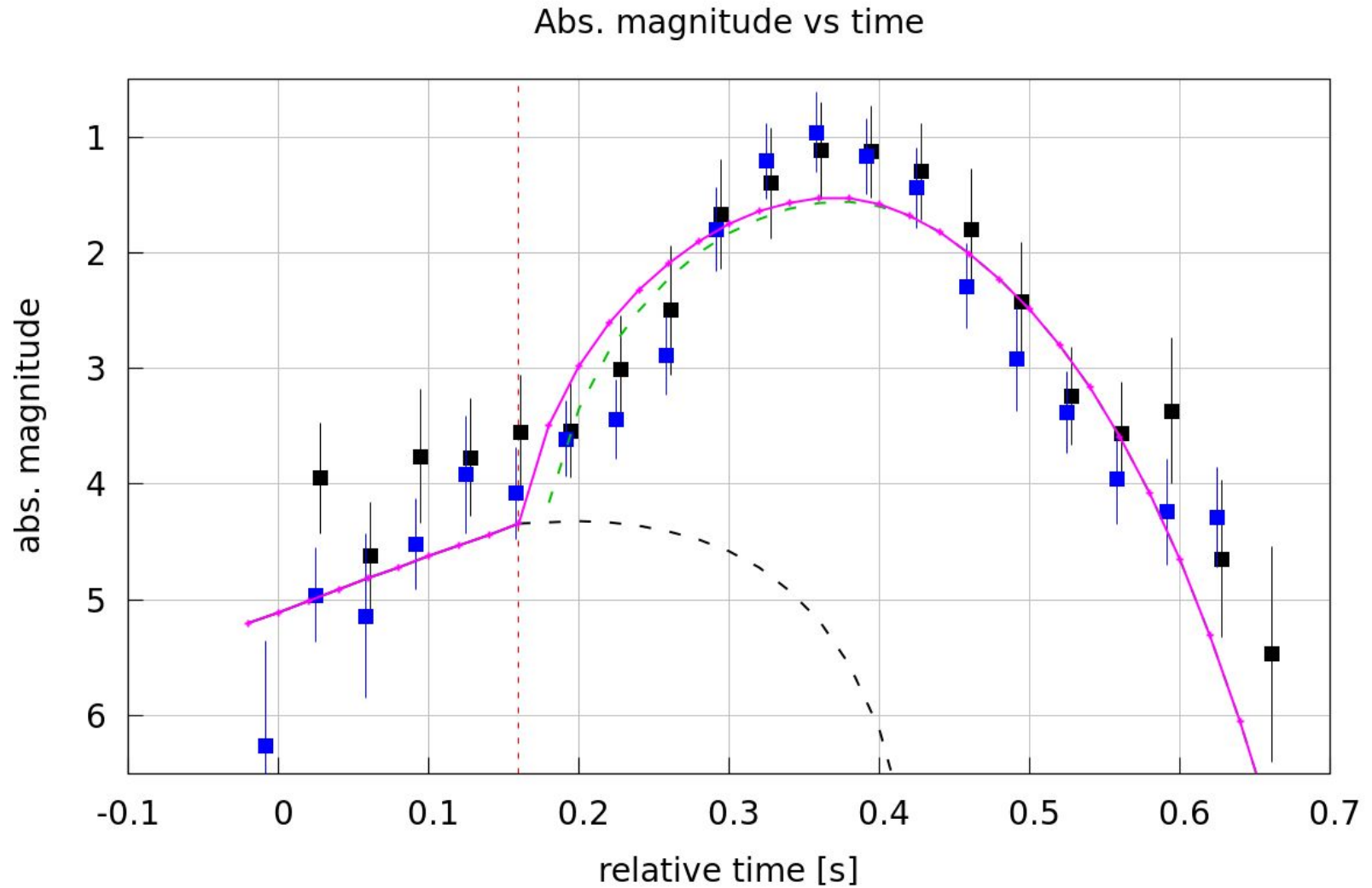
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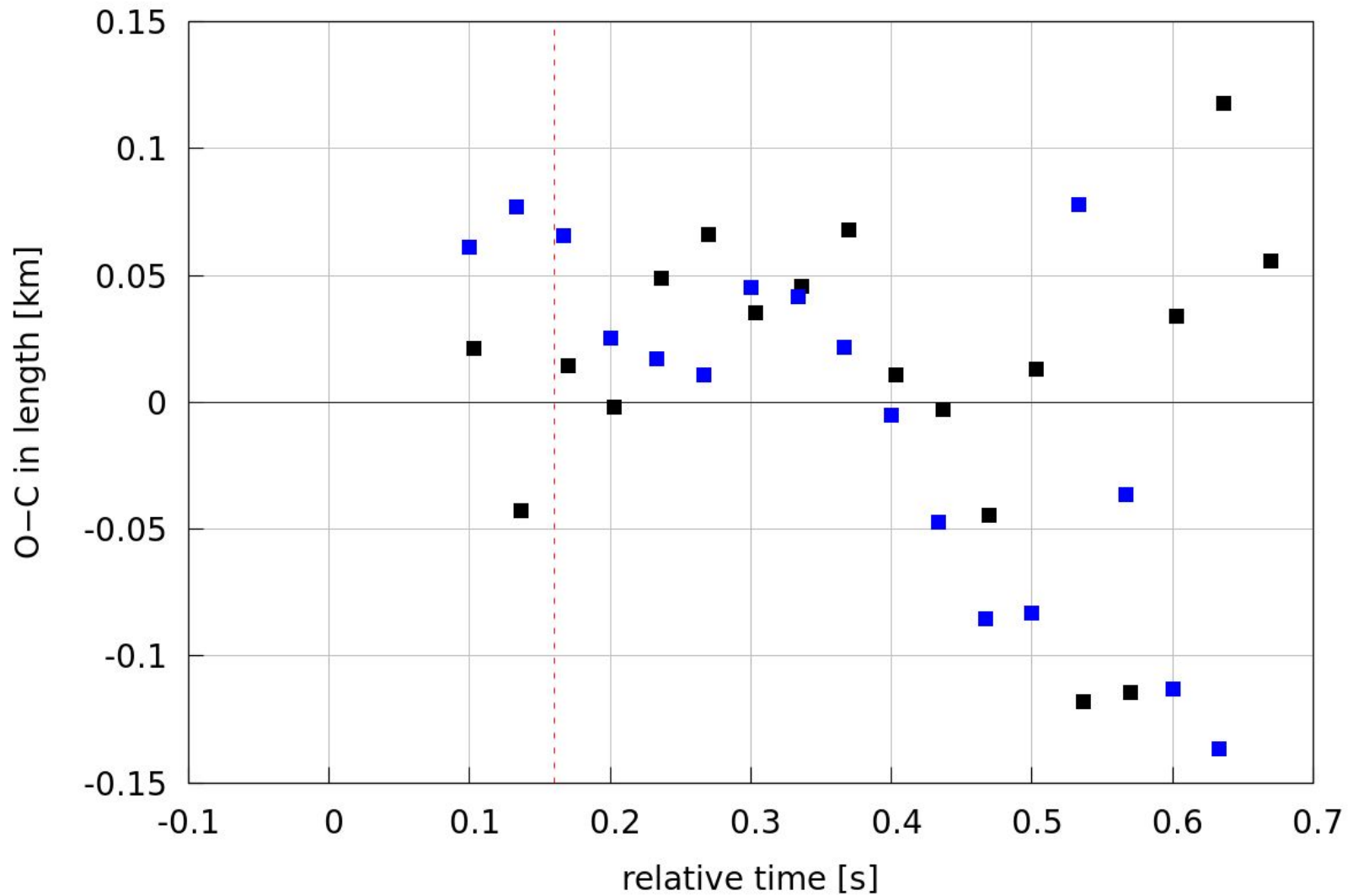
Modeling of video meteors

- erosion model of Borovička et al. (2007)
- one or two eroding fragments
- dust grains released gradually
- opt: initial mass, velocity, height, ablation coeff., (bulk density), fragmentation time(s), % eroded mass, eroding grains properties, grain mass distr. power-law index
- fixed: drag & shape coeffs., $\tau(v)$

Work in progress



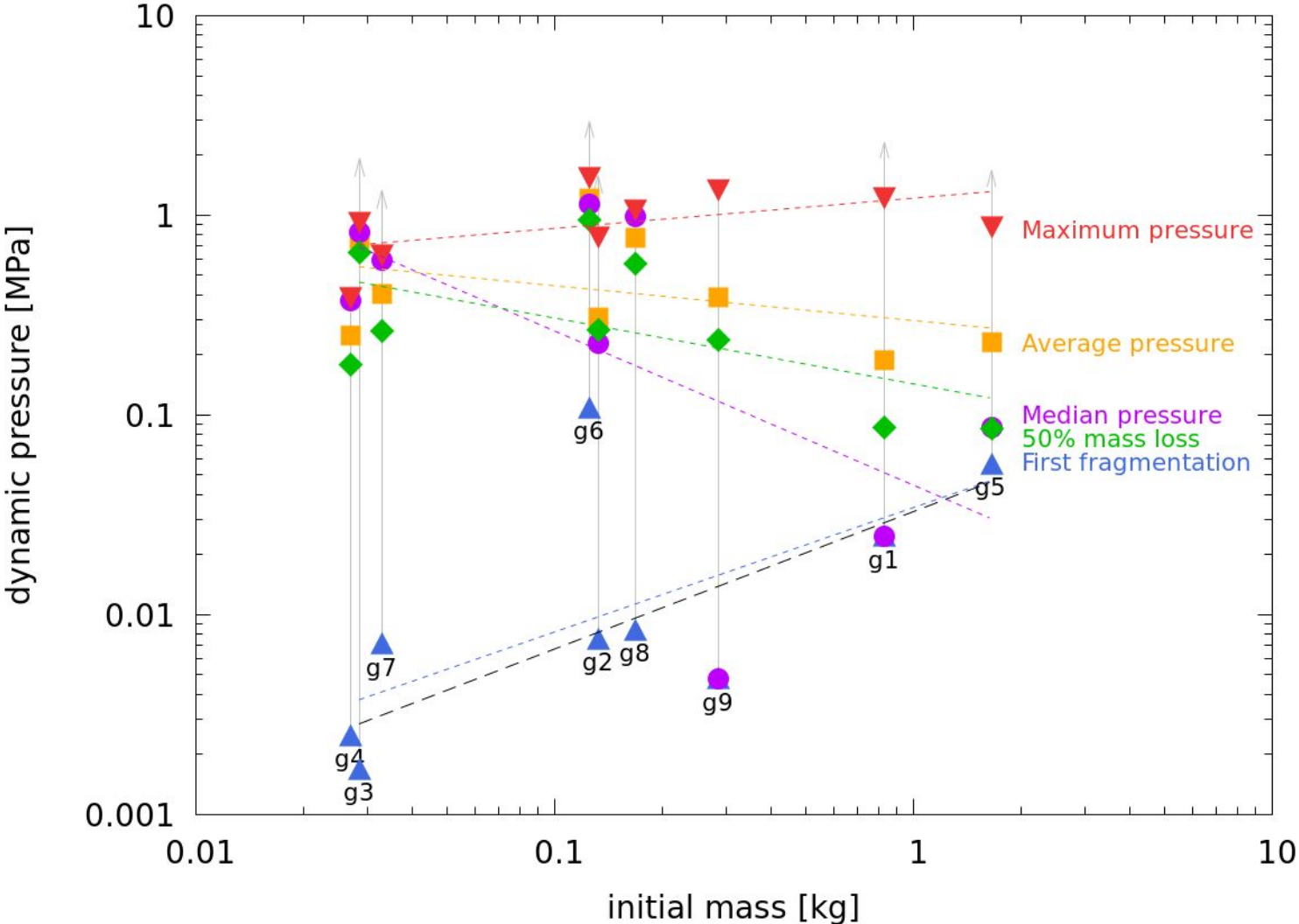
Work in progress



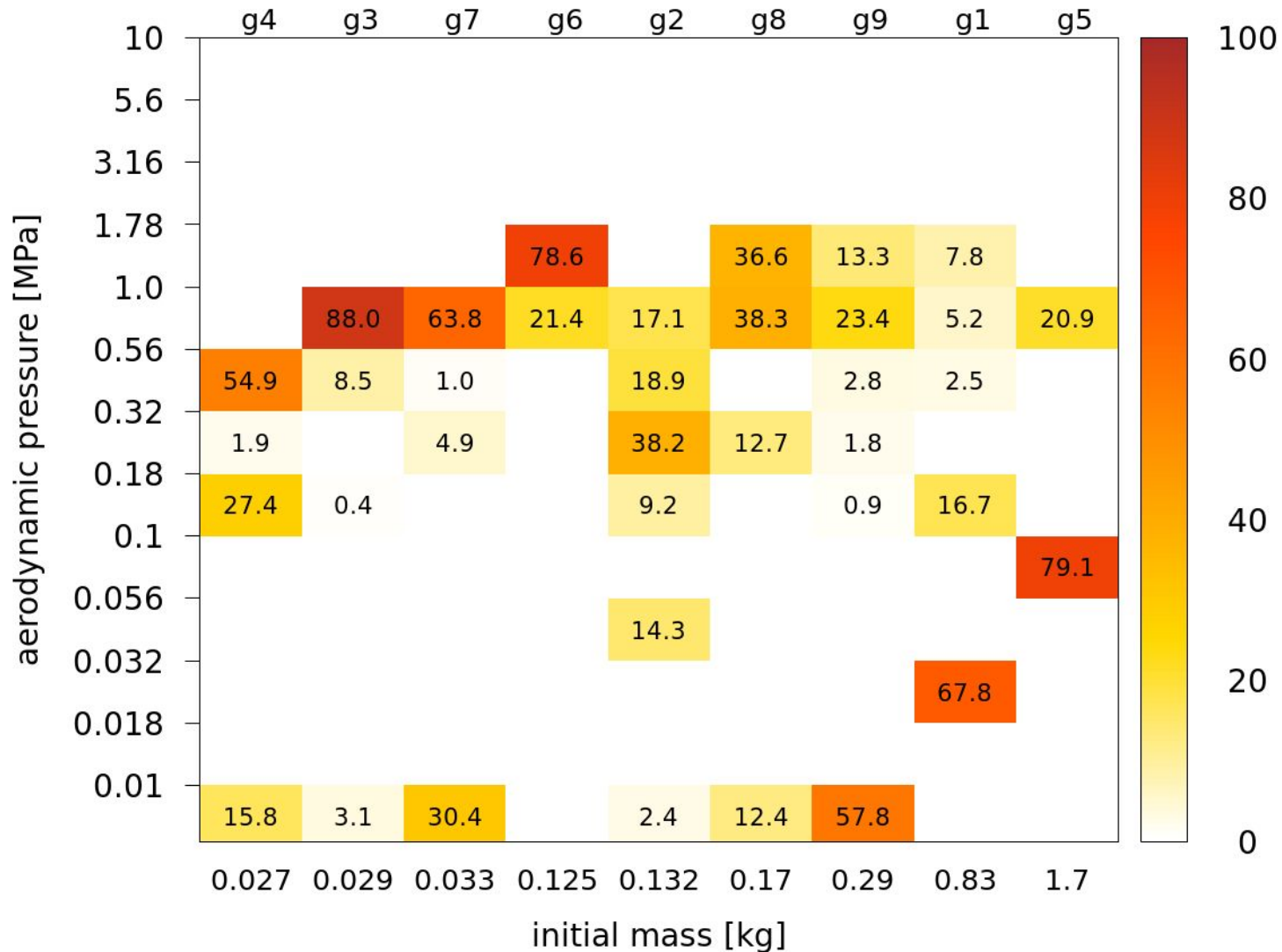
Results: Geminid fireballs

- modeled 9 Geminids, 8 asteroidal fireballs
- probably formed by compact carbonaceous material
- smaller Geminids fragment at lower pressures than larger ones => thermal stresses destroy larger and weaker meteoroids (Čapek & Vokrouhlický 2012)
- large Na variation seen in mm-sized Geminids but not in cm-sized Geminids
- all results in Henych et al. (2024) *A&A* 683

Pressure statistics in Geminids



Strength proxy distribution in Geminids



Take away messages

- we can semiautomatically fit fireball data with the fragmentation model of Borovička et al. (2020)
- we use this approach to describe the physical properties of meteoroids of some major showers
- we are currently adapting this method for faint video meteors
- in the future, we want to use more observational constraints to better justify our results

Genetic algorithm optimizer

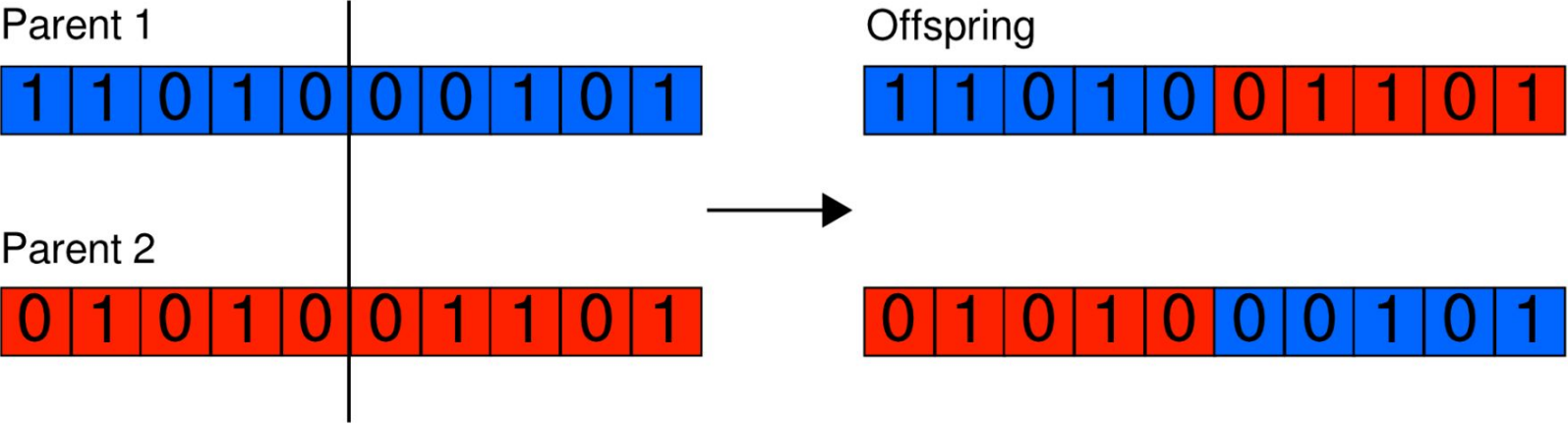
- algorithm inspired by simplified evolution rules
- create a population of random solutions (50–100) = 0th generation
- values of free parameters (phenotype) are encoded to a sequence of numbers (genotype), to which we apply three basic rules:
 1. selection (only the fittest survive)
 2. inheritance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

Genetic algorithm optimizer

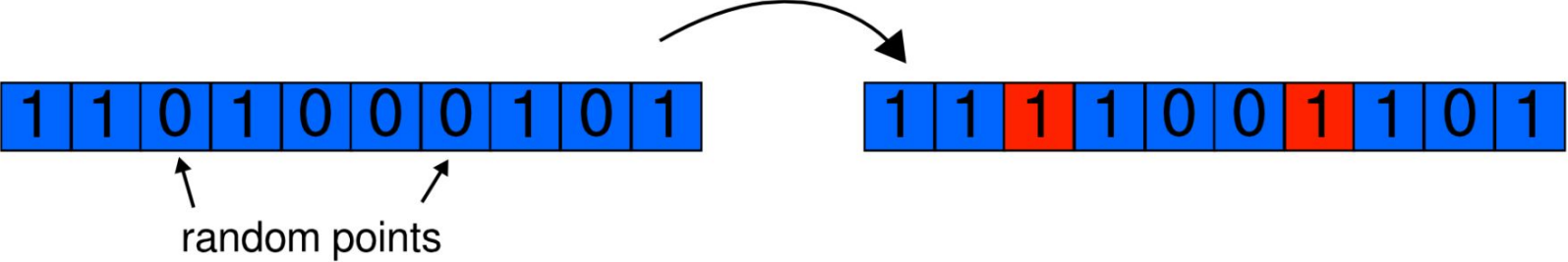
- for each solution calculate **fitness function** ($1/\chi^2$ or some other) ← *expensive part*
- **select** the best solutions (based on their fitness), create pairs and mix their genomes (**crossover**)
- apply **mutations** (random changes in the genome)
- replace an old generation with a new one 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 optimizer

CROSSOVER



MUTATION



Future plans

- debug & test the code for video meteors
- use it for faint Geminids, Quadrantids, and compare to manual solutions
- use the profile calculation in fireball modeling program to model bright meteor wakes (data from FIPS, IP cameras)