Deceleration Rate of a Fireball as a tool to predict consequences of the impact

Maria Gritsevich [1,2], Daria Kuznetsova [2], Vladimir Stulov [2], Leonid Turchak [3]

(1) Department of Physics, University of Helsinki

(2) Institute of Mechanics and Faculty of Mechanics and Mathematics, Moscow State University

(3) Dorodnitsyn Computing Center, Russian Academy of Sciences

gritsevich@list.ru

Basic definitions

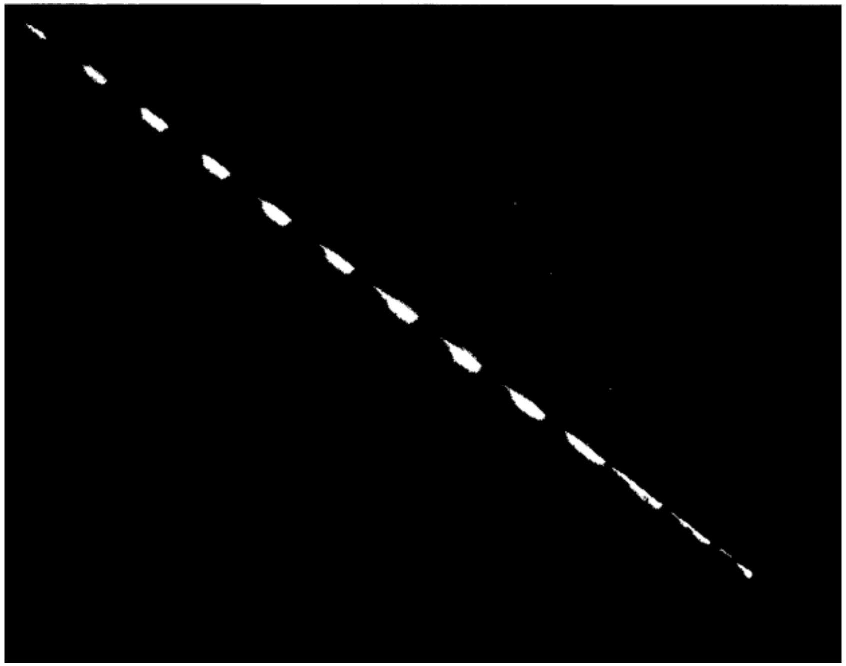
- A **meteoroid** is a solid object moving in interplanetary space, of a size considerably smaller than an asteroid and larger than an atom

- A **meteor** is a visible path of a meteoroid that enters Earth's atmosphere. Most meteors are visible in altitude range 70 to 100 km

- A **fireball** (or **bolide**) is essentially bright meteor with larger intensity

- A **meteorite** is a part of a meteoroid or asteroid that survives its passage through the atmosphere and impact with the ground

Groundbased observations



The information on meteor body entry into the atmosphere contains detailed dynamic and photometric observational data. The important input parameters are: the **fireball brightness** ***I (t)***, its **height** ***h (t)*** and its **velocity** ***V (t)***

Interpretation of Earth observations

Photometric

$$I = -\tau \cdot \frac{dE}{dt}$$

Usually simplified case used is:

$$\frac{dV}{dt} = 0$$

$$M = -\int_{t_1}^{t_0} \frac{I}{\tau V^2} dt$$

Dynamical

$$M \frac{dV}{dt} = -\frac{1}{2} c_d \rho_a V^2 S,$$

$$\frac{dh}{dt} = -V \sin \gamma,$$

$$H * \frac{dM}{dt} = -\frac{1}{2} c_h \rho_a V^3 S$$

-> Dimensionless variables

$$m\frac{dv}{dy}=\frac{1}{2}c_d\frac{\rho_0 h_0 S_e}{M_e}\frac{\rho vs}{\sin\gamma};\qquad \frac{dm}{dy}=\frac{1}{2}c_h\frac{\rho_0 h_0 S_e}{M_e}\frac{V_e^2}{H^*}\frac{\rho v^2 s}{\sin\gamma}$$

- $m = M/M_e$; M_e – pre-atmospheric mass
- $v = V/V_e$; V_e – velocity at the entry into the atmosphere
- $y = h/h_0$; h_0 – height of homogeneous atmosphere
- $s = S/S_e$; S_e – middle section area at the entry into the atmosphere
- $\rho=\rho_a/\rho_0$; ρ_0 – gas density at sea level

Two additional equations

- variations in the meteoroid shape can be described as (Levin, 1956)

$$\frac{S}{S_e} = \left(\frac{M}{M_e}\right)^{\mu}$$

- assumption of the isothermal atmosphere

$$\rho = \exp(-y)$$

Analytical solutions of dynamical eqs.

- Initial conditions

$y = \infty,\ v = 1,\ m = 1$

$$m(v) = \exp\left(-\beta \frac{1-v^2}{1-\mu}\right)$$

$$y(v) = \ln 2\alpha + \beta - \ln(\overline{E}i(\beta) - \overline{E}i(\beta v^2))$$

where by definition: $\overline{\mathrm{E}}\mathrm{i}(x) = \int_{-\infty}^{x} \frac{e^z dz}{z}$

The key dimensionless parameters used

$$\alpha = \frac{1}{2} c_d \frac{\rho_0 h_0 S_e}{M_e \sin\gamma}, \quad \beta = (1-\mu)\frac{c_h V_e^2}{2 c_d H^*}, \quad \mu = \log_m s$$

α characterizes the aerobraking efficiency, since it is proportional to the ratio of the mass of the atmospheric column along the trajectory, which has the cross section S_e, to the body's mass

β is proportional to the ratio of the fraction of the kinetic energy of the unit body's mass to the effective destruction enthalpy

μ characterizes the possible role of the meteoroid rotation in the course of the flight

Next step: determination of α and β

On the right:
Data of observations of Innisfree fireball (Halliday et al., 1981)

$$y(v) = \ln 2\alpha + \beta +$$

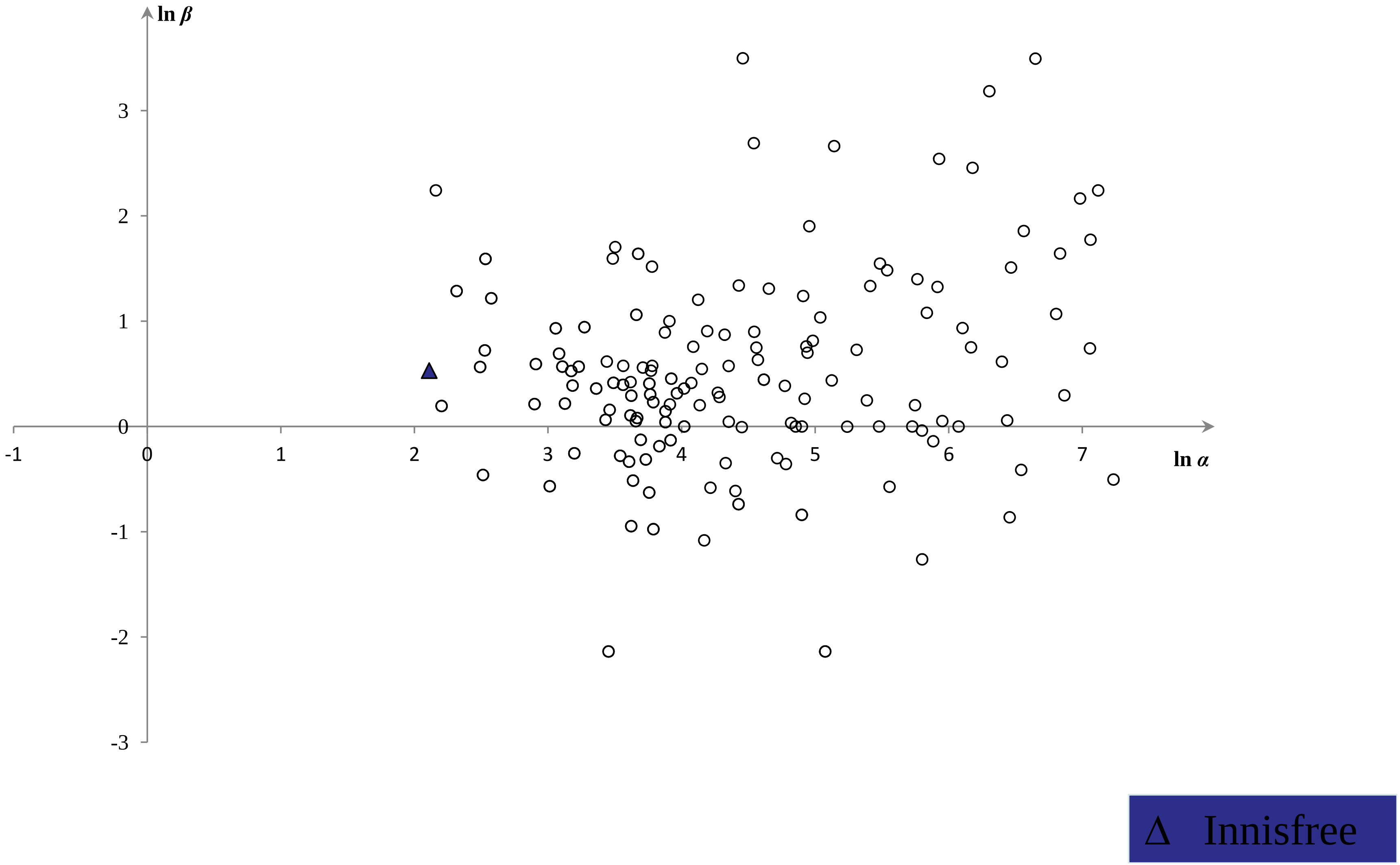
$$-\ln(\overline{Ei}(\beta) - \overline{Ei}(\beta v^2))$$

$$\overline{\mathrm{Ei}}(x) = \int_{-\infty}^{x} \frac{e^z dz}{z}$$

- **The problem is solved by the least squares method**

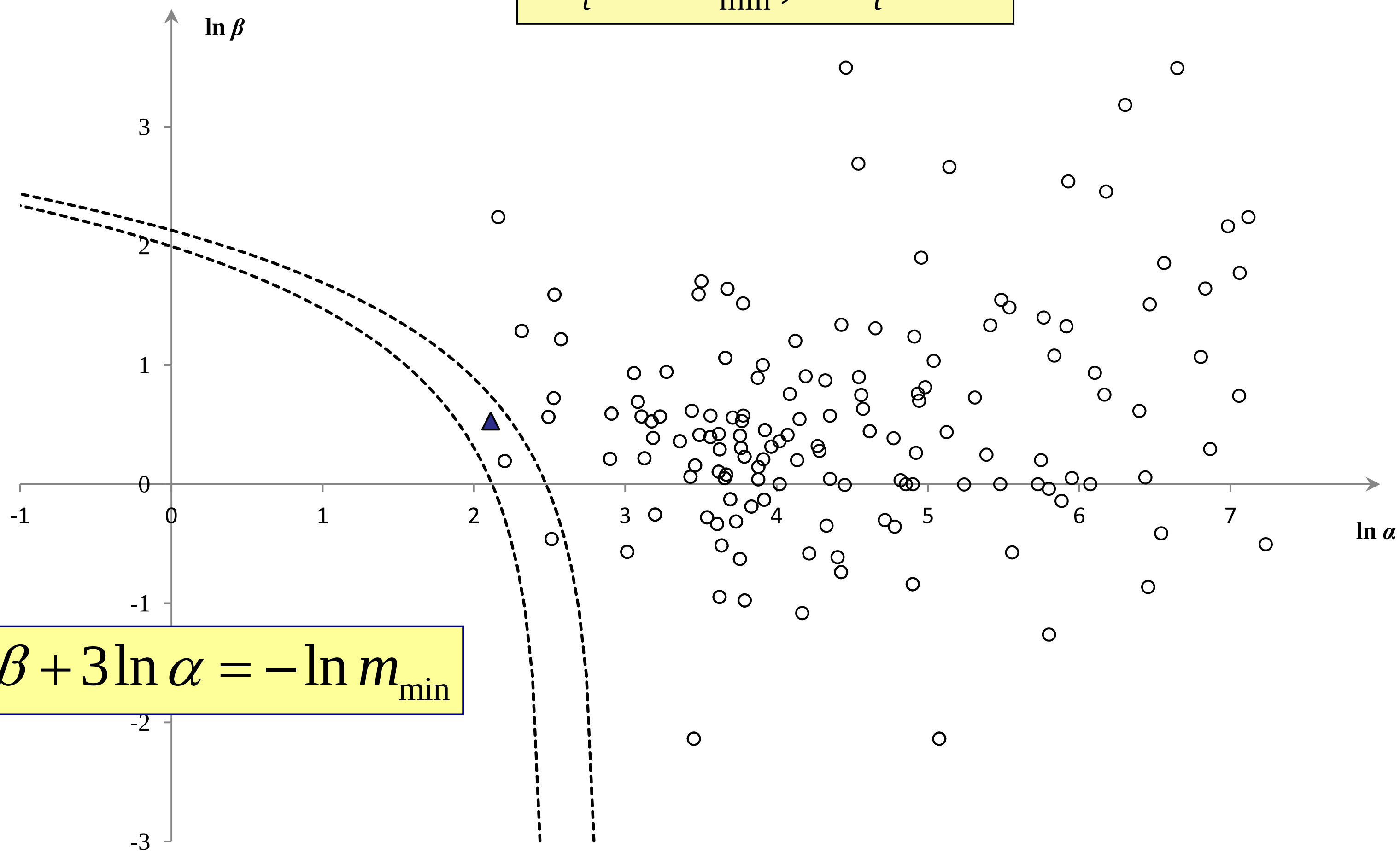
t, sec	*h, km*	*V, km/sec*
0,0	*58,8*	*14,54*
0,2	*56,1*	*14,49*
0,4	*53,5*	*14,47*
0,6	*50,8*	*14,44*
0,8	*48,2*	*14,40*
1,0	*45,5*	*14,34*
1,2	*42,8*	*14,23*
1,4	*40,2*	*14,05*
1,6	*37,5*	*13,79*
1,8	*35,0*	*13,42*
2,0	*32,5*	*12,96*
2,2	*30,2*	*12,35*
2,4	*27,9*	*11,54*
2,6	*25,9*	*10,43*
2,8	*24,2*	*8,89*
3,0	*22,6*	*7,24*
3,2	*21,5*	*5,54*
3,3	*21,0*	*4,70*

Distribution of parameters α and β for MORP fireballs



Looking for a Meteorite 'region'

$$M_t \geq M_{\min}, \quad v_t << 1$$

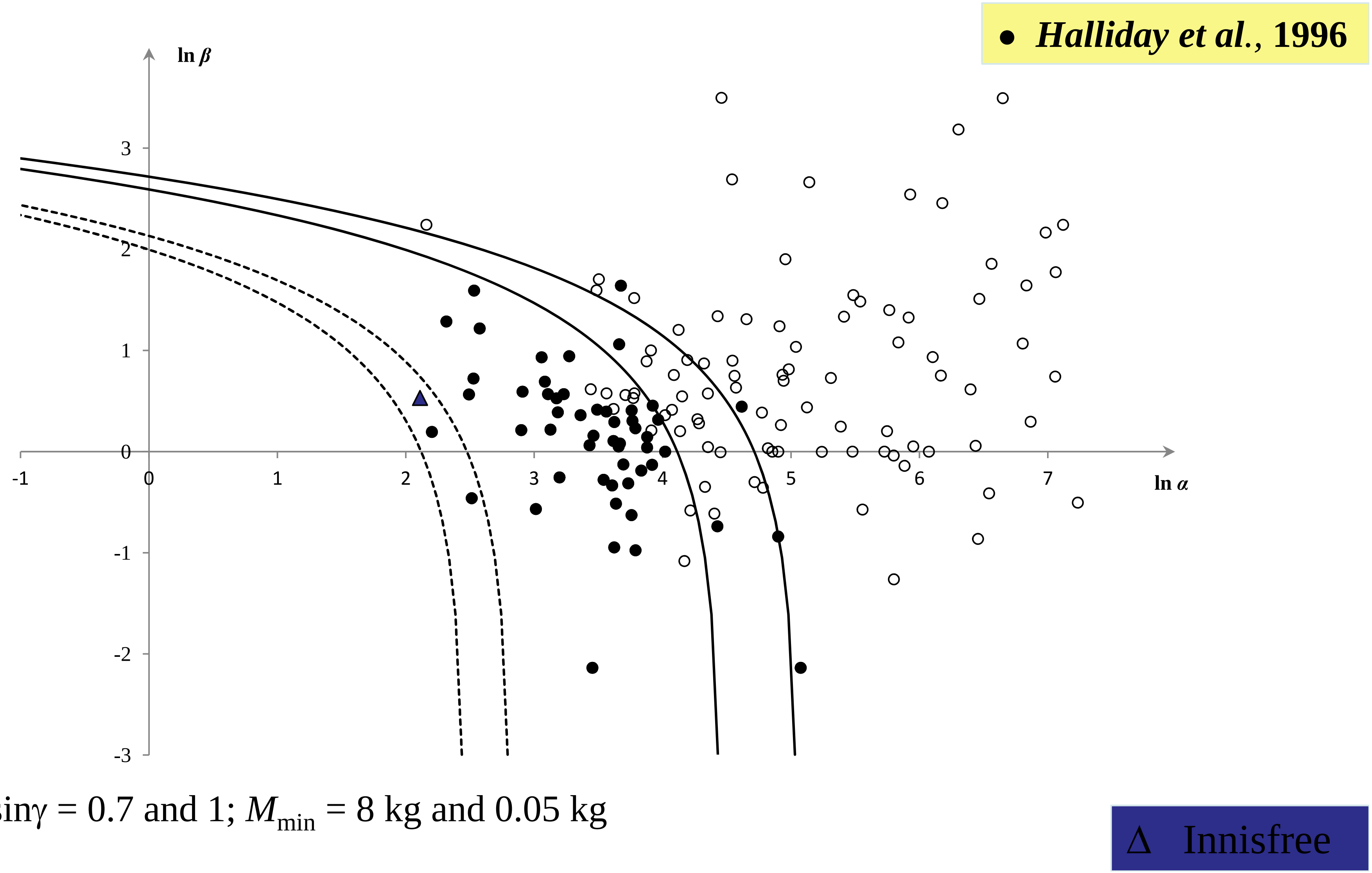


$$\beta + 3\ln\alpha = -\ln m_{\min}$$

sinγ = 0.7 and 1; $M_{\min}$ = 8 kg

Δ Innisfree

Meteorite falls prediction (down to 50 g)



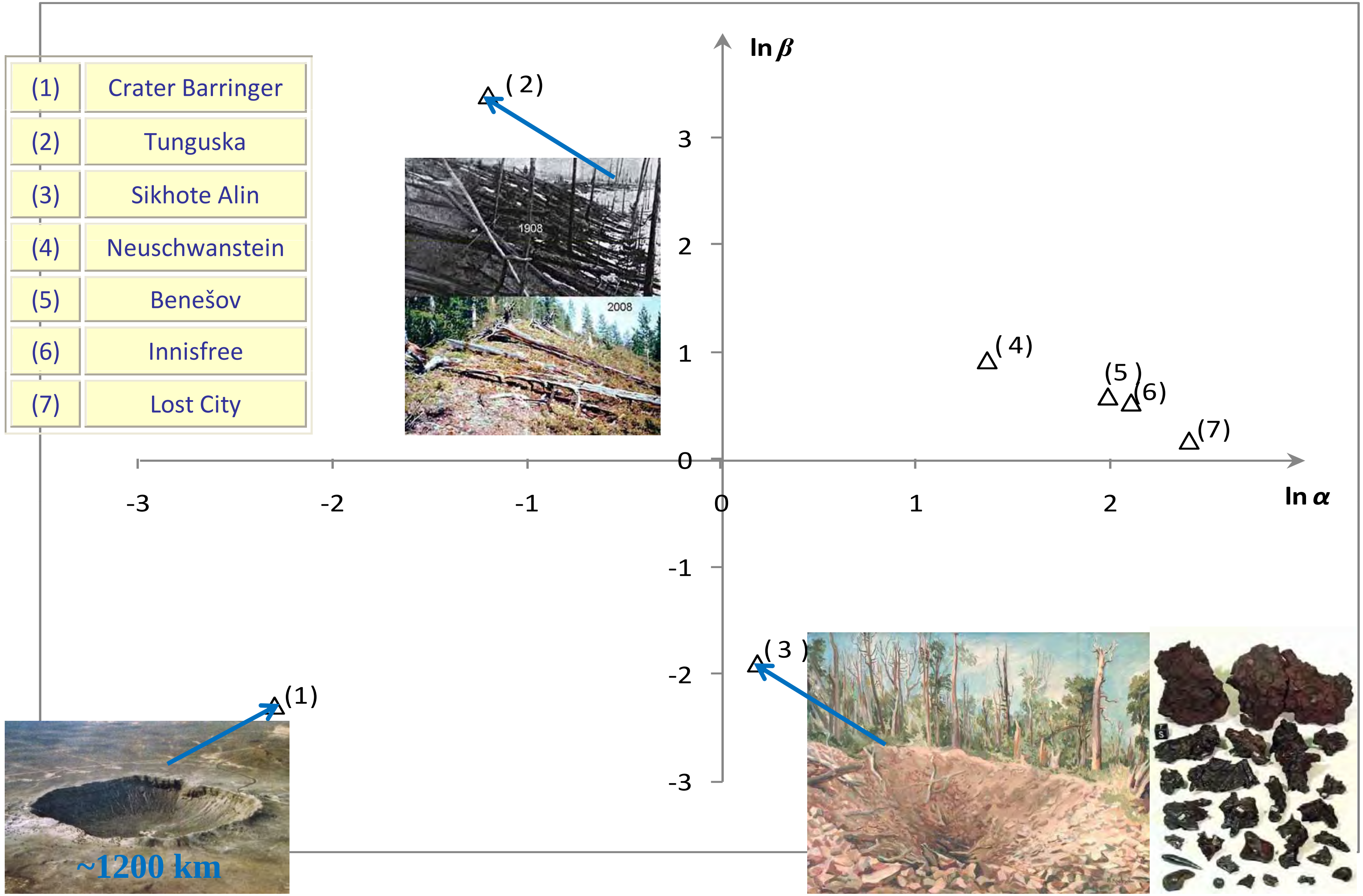
sinγ = 0.7 and 1; $M_{\min}$ = 8 kg and 0.05 kg

Some historical events

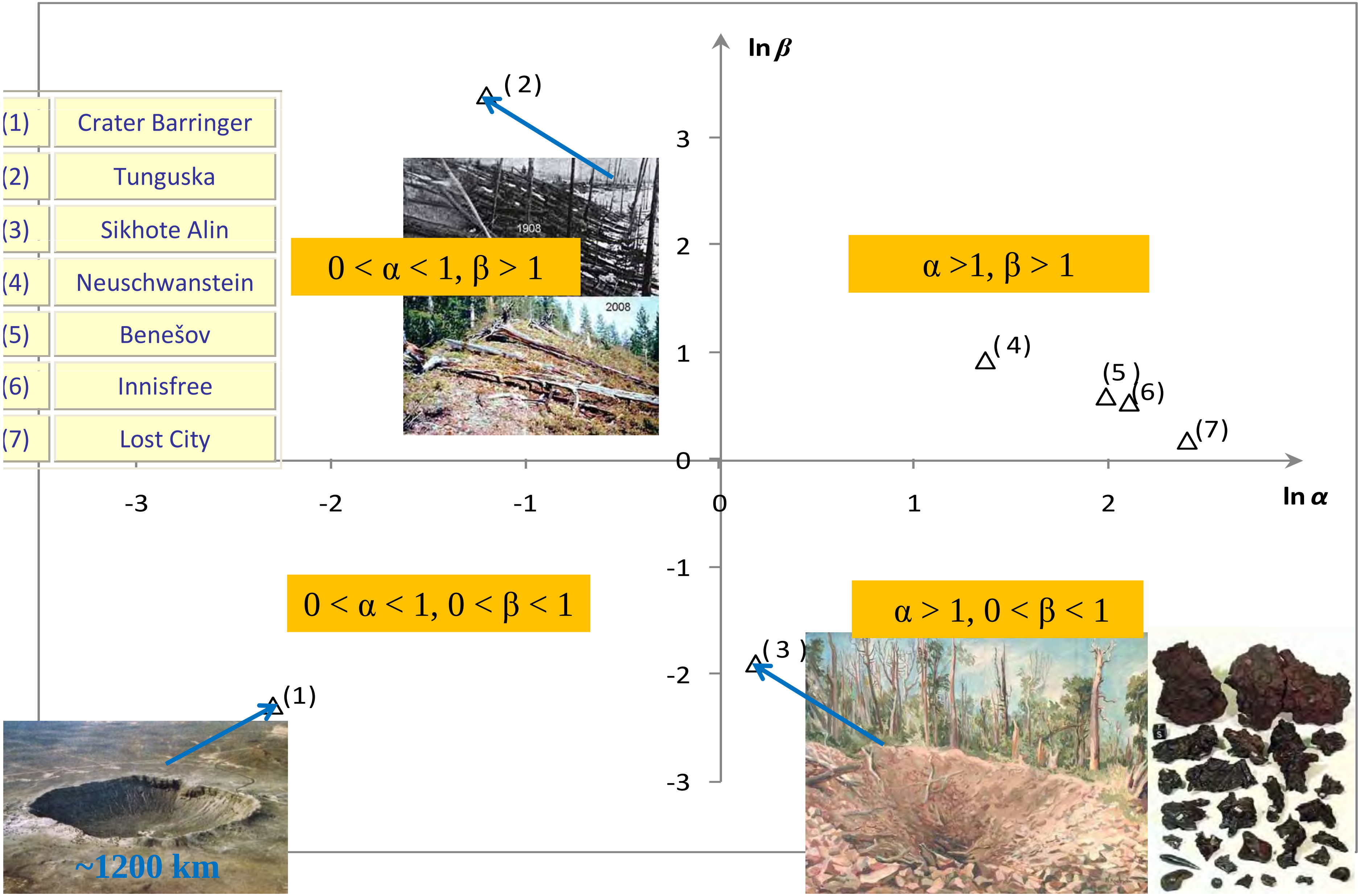
№	Event	Original mass, t	Collected meteorites, kg	α	β
1	Canyon Diablo meteorite (Barringer Crater)	$> 10^6$	$> 30 \cdot 10^3$	0.1	~ 0.1
2	Tunguska	$0.2 \cdot 10^6$	-	0.3	30
3	Sikhote Alin	200	$> 28 \cdot 10^3$	1.2	0.15
4	Neuschwanstein	0.5	6.2	3.9	2.5
5	Benešov	0.2	?	7.3	1.8
6	Innisfree	0.18	4.58	8.3	1.7
7	Lost City	0.17	17.2	11.1	1.2

Same events on the plane (lnα, lnβ)

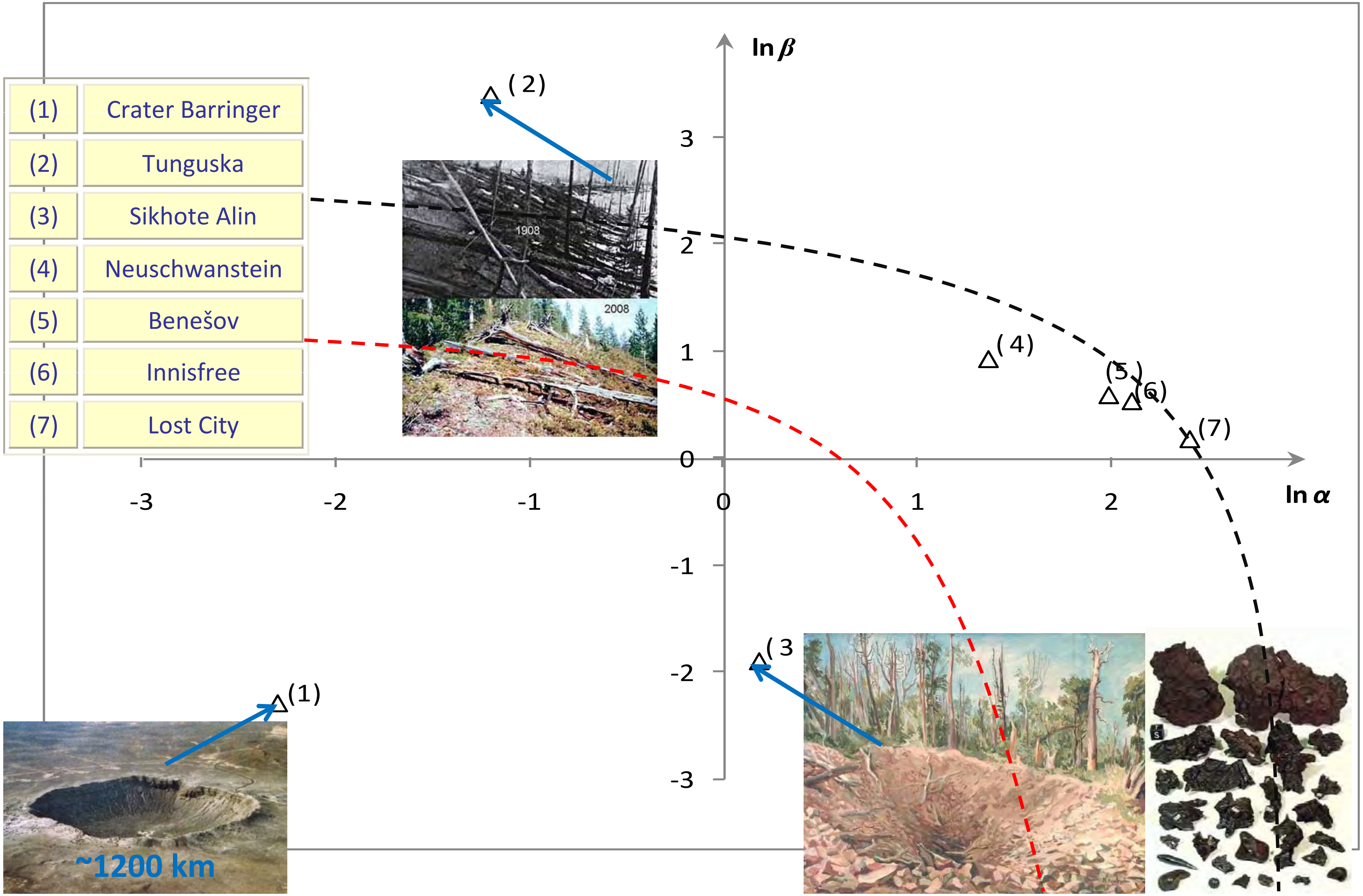
(1)	Crater Barringer
(2)	Tunguska
(3)	Sikhote Alin
(4)	Neuschwanstein
(5)	Benešov
(6)	Innisfree
(7)	Lost City



Same events on the plane (lnα, lnβ)



Meteorites /craters prediction



Conclusions

- Consideration of non-dimensional parameters α, β and μ allow us to predict consequences of the impact. These parameters effectively characterize the ability of entering body to survive an atmospheric entry and reach the ground

- The results are applicable to study the properties of near-Earth space and can be used to predict and quantify fallen meteorites, and thus to speed up recovery of their fragments

Thanks for your attention!

Mass computation

$$M_e = \left(\frac{1}{2} c_d \frac{\rho_0 h_0}{\alpha \sin\gamma} \frac{A_e}{\rho_m^{2/3}} \right)^3$$

Initial Mass depends on ballistic coefficient

$$M(v) = \left(\frac{1}{2} c_d \frac{\rho_0 h_0}{\alpha \sin\gamma} \frac{A_e}{\rho_m^{2/3}} \right)^3 \cdot \exp\left(-\frac{\beta}{1-\mu}(1-v^2) \right)$$