Interactions of meteoroids with the Earth's atmosphere

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“A space rock a few metres across exploded in Earth’s atmosphere above the city of Chelyabinsk, Russia today at about 03:15 GMT. The numerous injuries and significant damage remind us that what happens in space can affect us all…”

Sourse: **www.esa.int** (News, 15 February 2013)

Outline

- ❑ Introduction
- ❑ A new method implemented for parameters' identification
- ❑ Result testing
- ❑ General statistics and consequences

Basic definitions

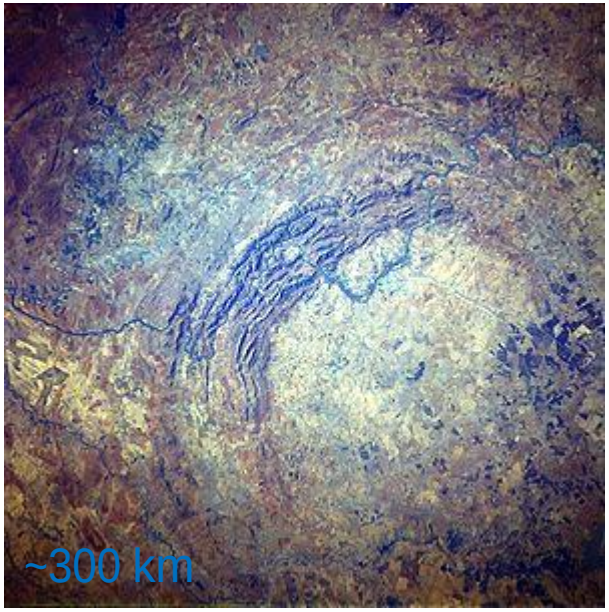
- A **meteoroid** is a solid object moving in interplanetary space, of a size considerably smaller than an asteroid and larger than an atom

- A **meteor** is event produced by a meteoroid entering atmosphere. On Earth most meteors are visible in altitude range 70 to 100 km

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

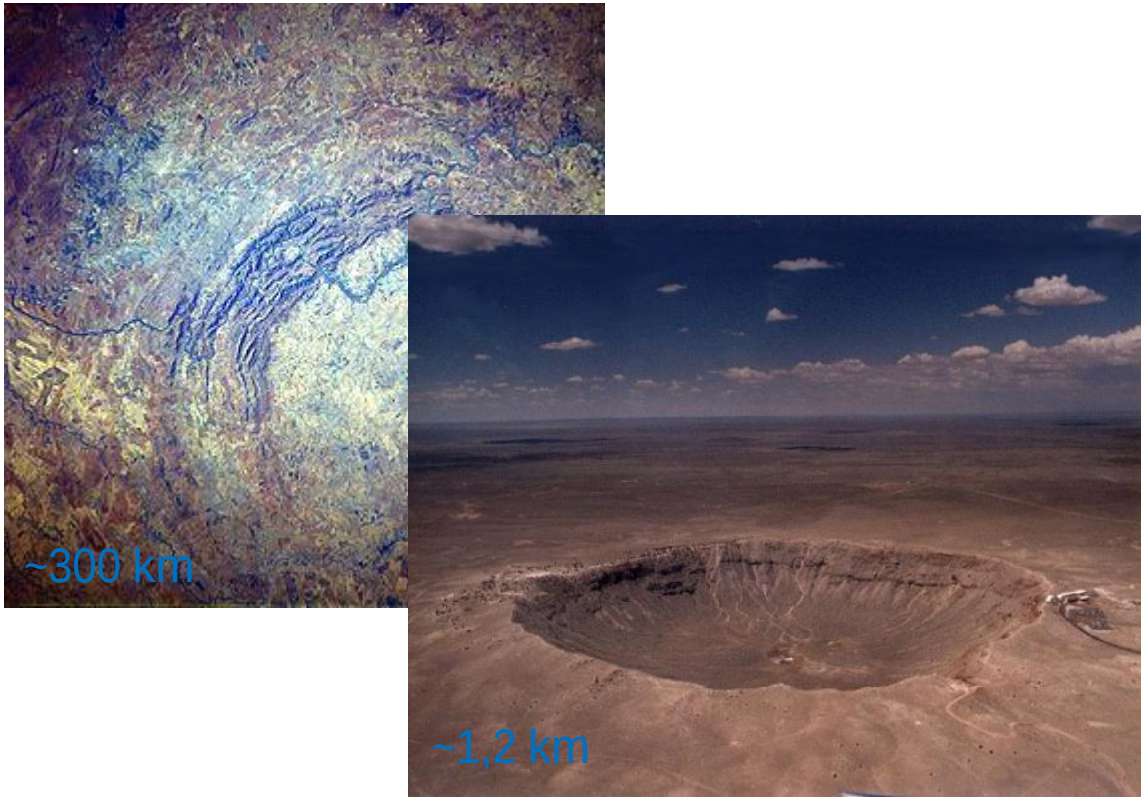
- A **meteorite** is a part of a meteoroid or asteroid that survives its passage through the atmosphere and impact the ground

Past terrestrial impacts



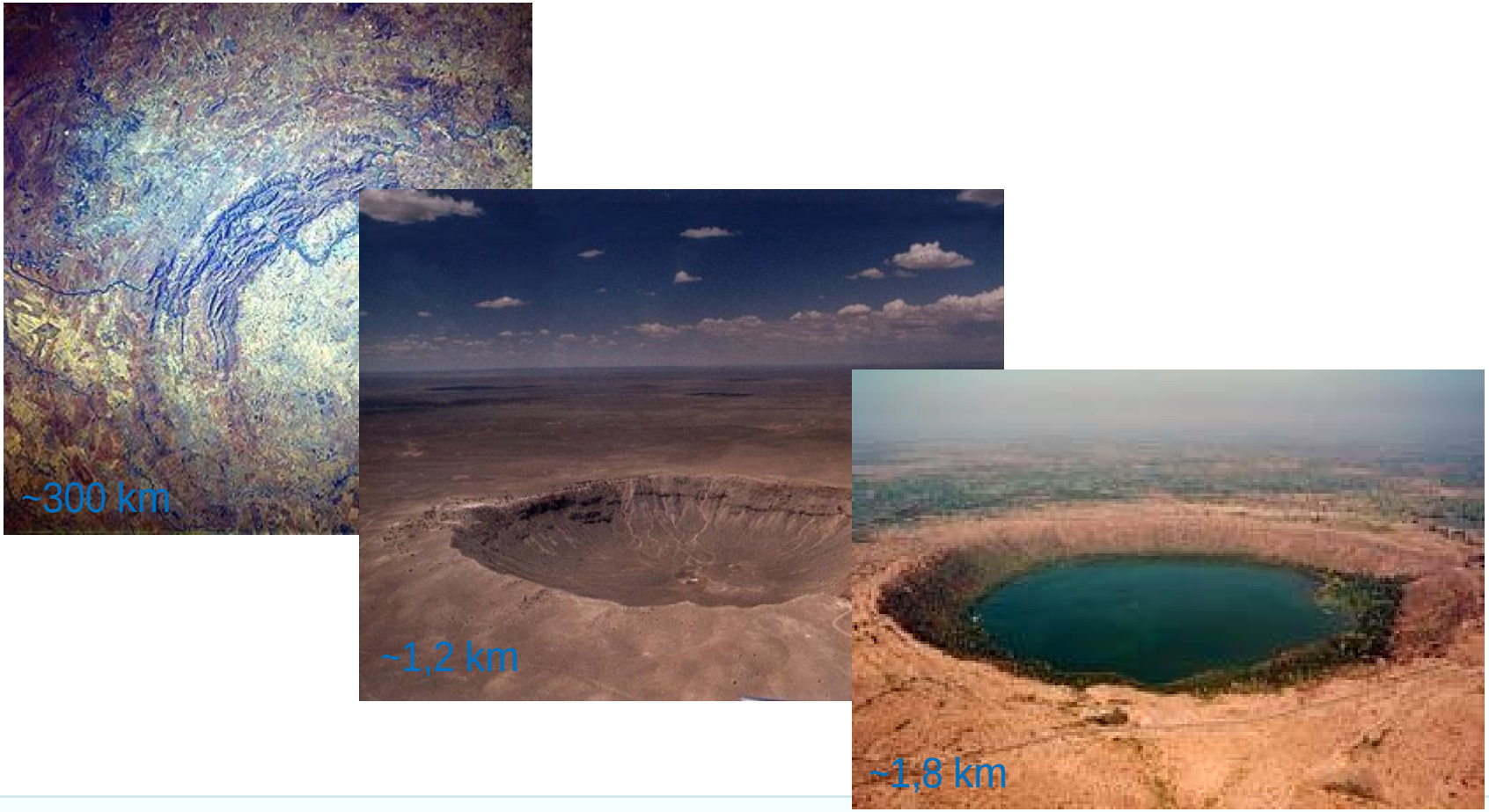
The largest verified impact crater on Earth (Vredefort)

Past terrestrial impacts



Different types of impact events, examples: formation of a massive single crater (Vredefort, Barringer)

Past terrestrial impacts



Different types of impact events, examples: formation of a massive single crater (Vredefort, Barringer, Lonar Lake)

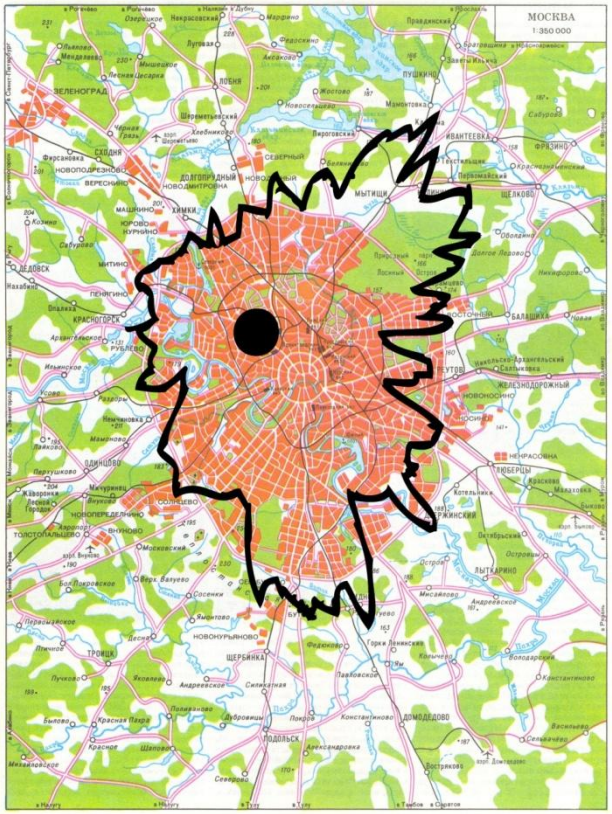
Past terrestrial impacts

Dispersion of craters and meteorites over a large area (Sikhote-Alin)

Past terrestrial impacts

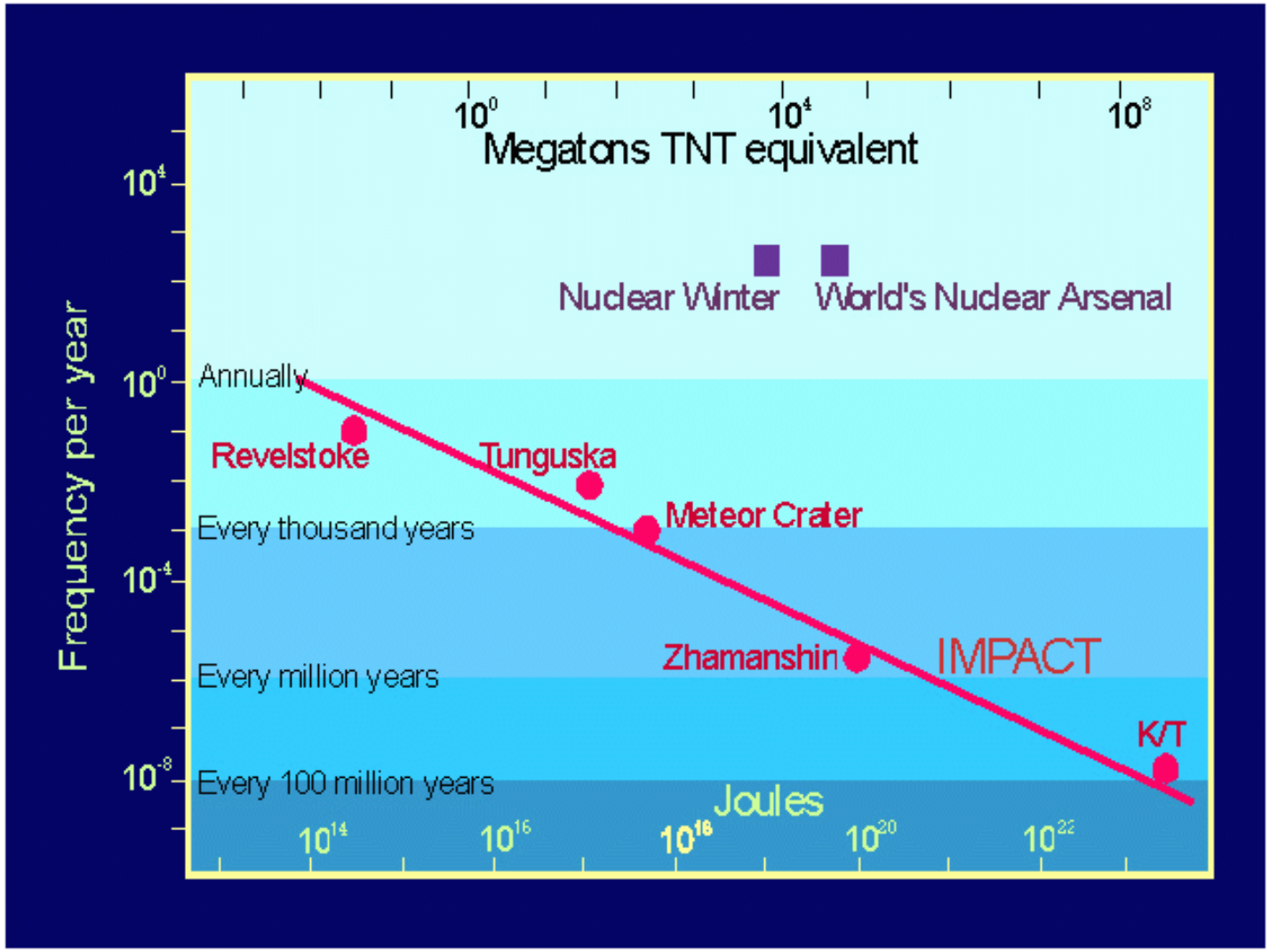
Tunguska

Tunguska after 100 years…

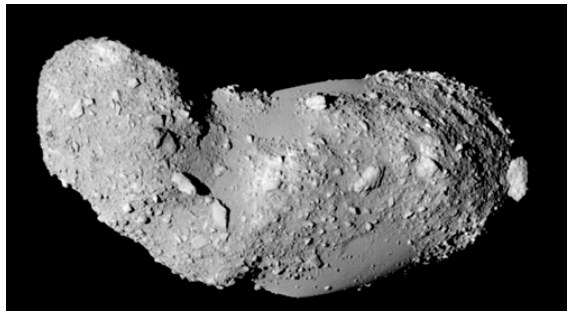


Area over 2000 km^2

Impacts as a hazard



Another reason why we are interested



…or:

The three forms of extraterrestrial bodies. *Meteorites* (right) are remnants of the extraterrestrial bodies (asteroids, comets, and their dusty trails, left) entering Earth's atmosphere and forming an event called a *meteor* or *fireball* (middle). The dark fusion crust on the meteorite is a result of ablation during atmospheric entry.

What can we do in the lab?

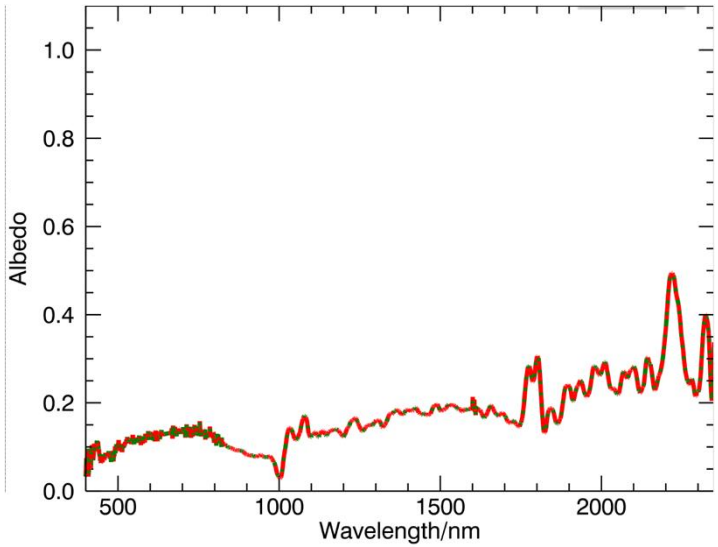
Nondestructive physical properties, including measurements of extraterrestrial materials:

- BRF measurements
- Bulk and grain density (i.e. also porosity)
- Magnetic susceptibility
- Internal structure (x-ray microtomography)
- Development of methods for nondestructive thermal and mechanical properties measurements
- Some of the parameters can be determined at wide temperature range (5-1080 K)

Our combined database contains thousands of individual meteorites. Results are published and/or shared within the scientific community

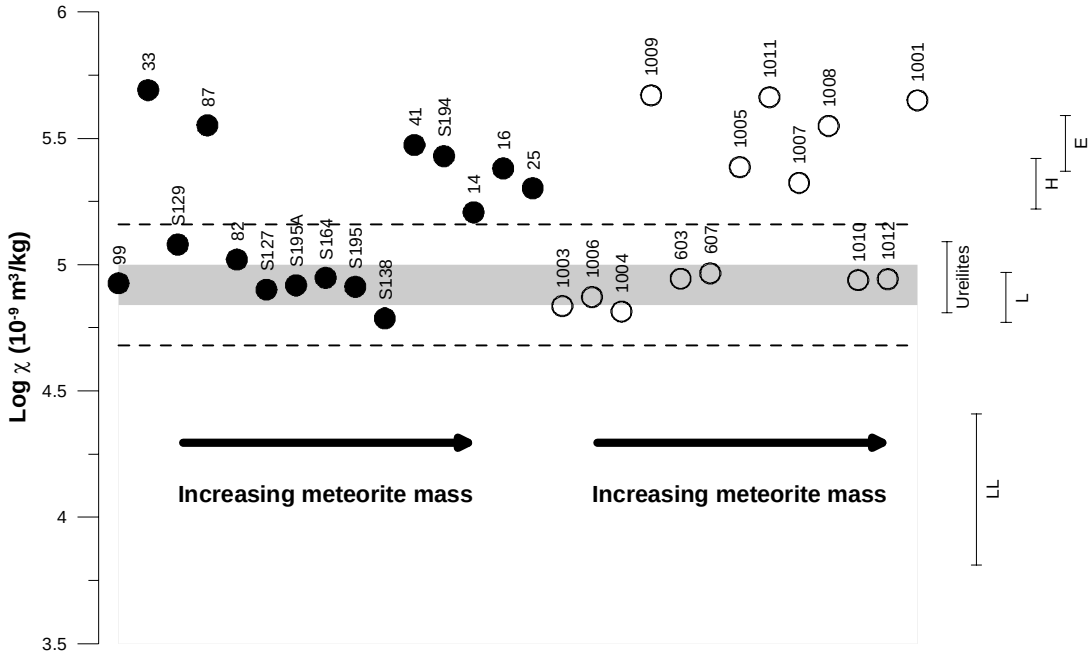
Example of recent results (1/2)

Example of measured albedo:
Bruderheim L6 meteorite



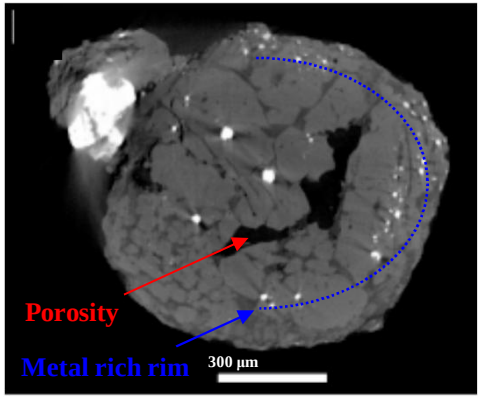
The FIGIFIGO measuring BRF of selected sample Gibeon (left). The active optics system is located horizontally at the top of the measuring arm, and is looking down to the target through a mirror. FIGIFIGO consists of the following main components: casing, measurement arm, rugged computer, and a sunphotometer on a tripod. The casing contains the main sensor ASD FieldSpec Pro FR optical fiber spectroradiometer (350 – 2500 nm), most of the electronics, and batteries.

Example of recent results (2/2)



Magnetic susceptibility was used as a tool to identify of non-ureilitic meteorites within Almahata Sitta (2008 TC_3) meteorite collection

Porosity mapping using XMT



Classical double-station program

allow us to calculate:

- *meteor height*
- *length along trajectory*
- *meteor intensity*
- *spectrum*

first attempts:

- *Harvard Meteor Project*
- *Ondrejov Observatory in Czechoslovakia*

first success:

- bright fireball photographed on April 7, 1959: four meteorites were found near Příbram in Czechoslovakia in the area predicted from the double-station photographic data (Ceplecha, 1961)

Fireball from the Příbram bolide, cutting across star trails, photographed by the Czech meteor network in 1959. The image shows the first part of the trajectory, from 97.8 to 68 km altitude. Chops in the fireball result from a rotating shutter above the lens, and allow the velocity to be calculated.

The largest piece (Luhy, 4.5 kg)

The largest programs

	European Fireball Network	**Prairie (Meteorite) Network**	**Meteorite Observation & Recovery Project**
Operational time	Since 1963	1963-1975	1971-1985
Number of Stations	~ 50	16	12
Station Spacing, km	~ 90	250	193
Cameras per Station	1	4	5
Availability of obtained data	partly published	published	published

Immediate objectives

- more reliable and rapid meteorite recovery from the Earth's surface
- understanding of meteorite origins, physical properties and chemical composition
- meteor orbital characteristics and their association with parent objects
- possible identification of when and where a meteor can enter the Earth's atmosphere and potentially become a meteorite
- understanding of how to predict the consequences based on event observational data

Registered meteorite falls

Meteorite name	country	year	mass found	type
Příbram	**Czechoslovakia**	**1959**	**5.8**	**H5**
Lost City	**USA**	**1970**	**17.2**	**H5**
Innisfree	**Canada**	**1977**	**4.58**	**L5**
Peekskill	USA	1992	12.57	H6
Tagish Lake	Canada	2000	~ 10	CI
Morávka	Czech Republic	2000	1.4	H5
Neuschwanstein	**Germany/Austria**	**2002**	**6.2**	**EL6**
Park Forest	USA	2003	18	L5
Villalbeto de la Peña	Spain	2004	5	L6
Bunburra Rockhole	**Australia**	**2007**	**0.34**	**eucrite**
Buzzard Coulee	Canada	2008	~ 41	H4
Almahata Sitta	Sudan	2008	~ 4	ureilite
Grimsby	Canada	2009	0.22	H5
Jesenice	**Slovenia**	**2009**	**3.67**	**L6**
Košice	Slovakia	2010	3.92	H5

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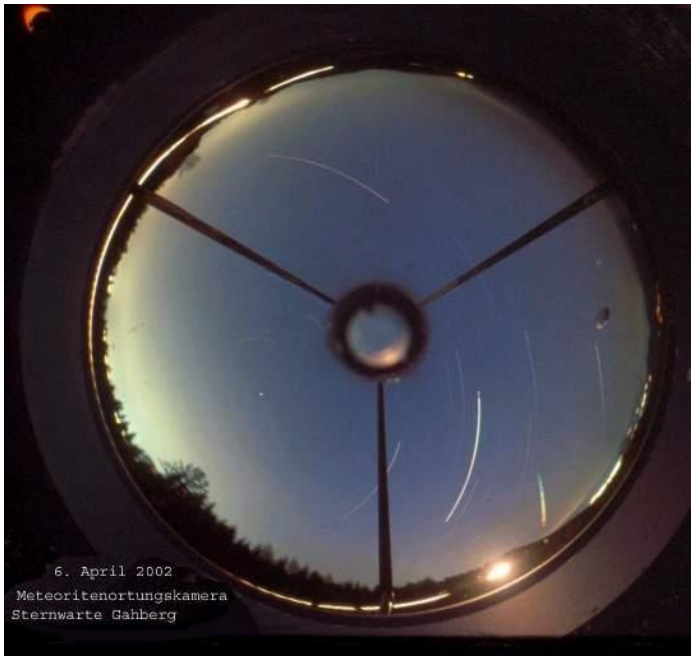
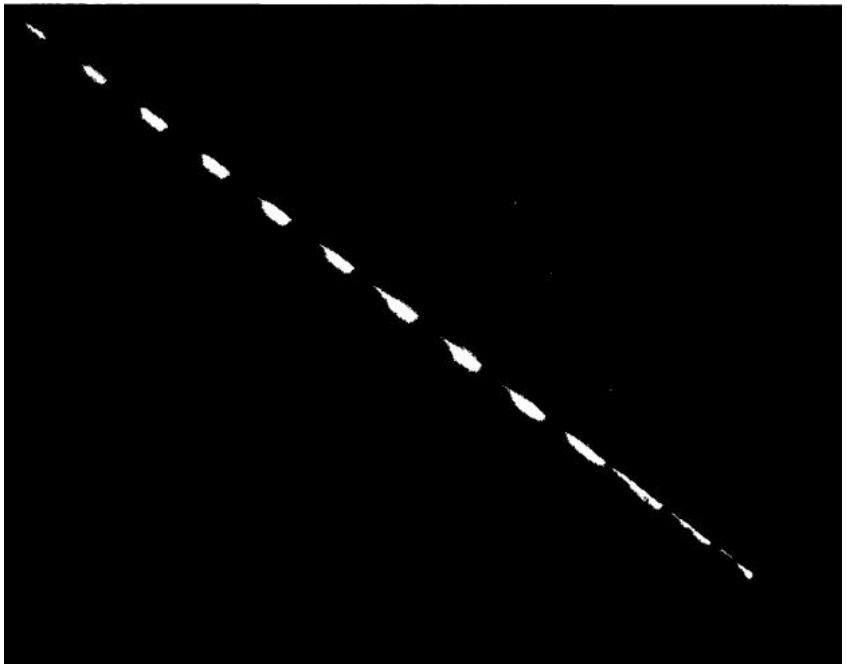
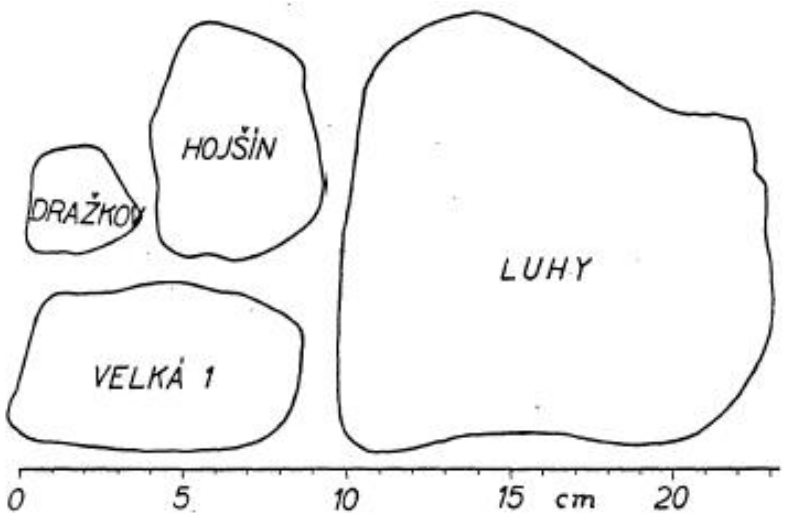
Groundbased observations



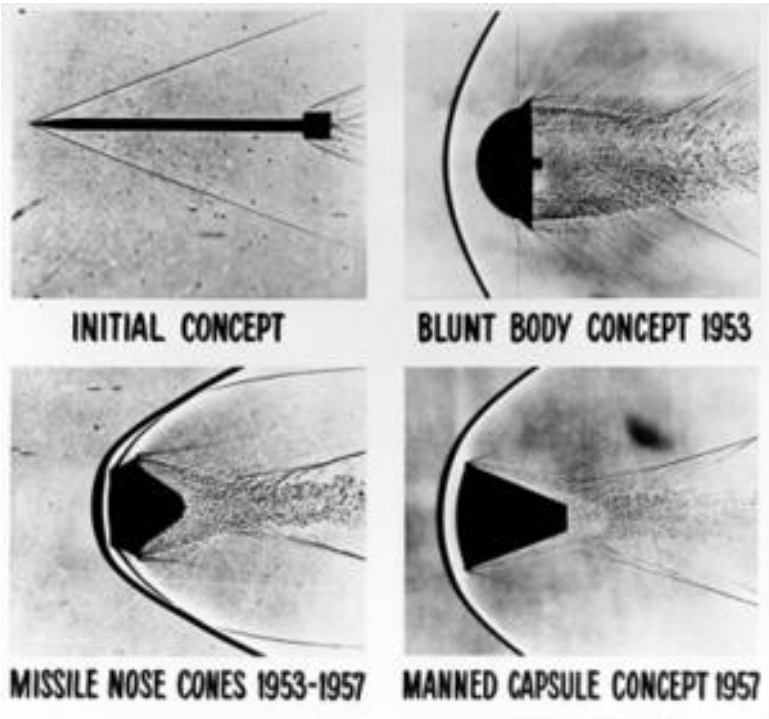


The information on meteor body entry into the atmosphere contains detailed dynamic and photometric observational data. The important input parameters are: the **fireball brightness** ***I (t)***, its **height** ***h (t)*** and its **velocity** ***V (t)***

’Reentry’ concept



Příbram meteorite



- **Entry starts with a rarefied hypersonic flow (usually defined as those with a Knudsen number above 0.1), do not follow the Navier-Stokes equations**
- **The introduction of non-equilibrium real gas effects becomes important**

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

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

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

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

A dynamical methods: special case

$$\begin{cases} M\dfrac{dV}{dt} = -\dfrac{1}{2}c_d\rho_a V^2 S, \\ A = \dfrac{S\cdot\rho_b^{2/3}}{M^{2/3}} \end{cases}$$

$$M_d = \frac{(A\cdot c_d)^3}{\rho_b^2}\left(-\frac{\rho_a V^2}{2\dot{V}}\right)^3$$

Halliday et al.

$$M_d = 0{,}306\left(-\frac{\rho_a V^2}{2\dot{V}}\right)^3$$

Wetherill, ReVelle

$$M_d = 0{,}101\left(-\frac{\rho_a V^2}{2\dot{V}}\right)^3$$

- **The main drawback is approximation of constant meteoroid shape, which adopted in the majority of publications in Meteor Physics**
- **The values of deceleration are obtained with the numerical differentiation**

More general approach

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

- $m = M/M_e$; 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)

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

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

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

❑ **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*

The desired parameters are determined by the following formulas:

the necessary condition for extremum:

$$\alpha = \sum_{i=1}^{n} e^{-\beta - y_i} \cdot \Delta_i \Big/ 2\sum_{i=1}^{n} e^{-2y_i};$$

$$\sum_{i=1}^{n}\left[\left(\Delta_i\left(\sum_{i=1}^{n}\exp(-2y_i)\right)-\left(\sum_{i=1}^{n}\Delta_i\exp(-y_i)\right)\exp(-y_i)\right)\cdot(\Delta_i-(\Delta_i)'_\beta)\right]=0$$

the sufficient condition:

$$\frac{\sum_{i=1}^{n} e^{-2y_i}\sum_{i=1}^{n}\left(((\Delta_i)'_\beta-\Delta_i)^2+(\Delta_i-2\alpha\exp(\beta-y_i))\right)((\Delta_i)''_\beta-2(\Delta_i)'_\beta+\Delta_i)}{\left(\sum_{i=1}^{n}\exp(-y_i)(\Delta_i-(\Delta_i)'_\beta)\right)^2}>1$$

Final step: determination of μ

- From the current dynamical model the intensity of fireball luminosity can be rewritten as:

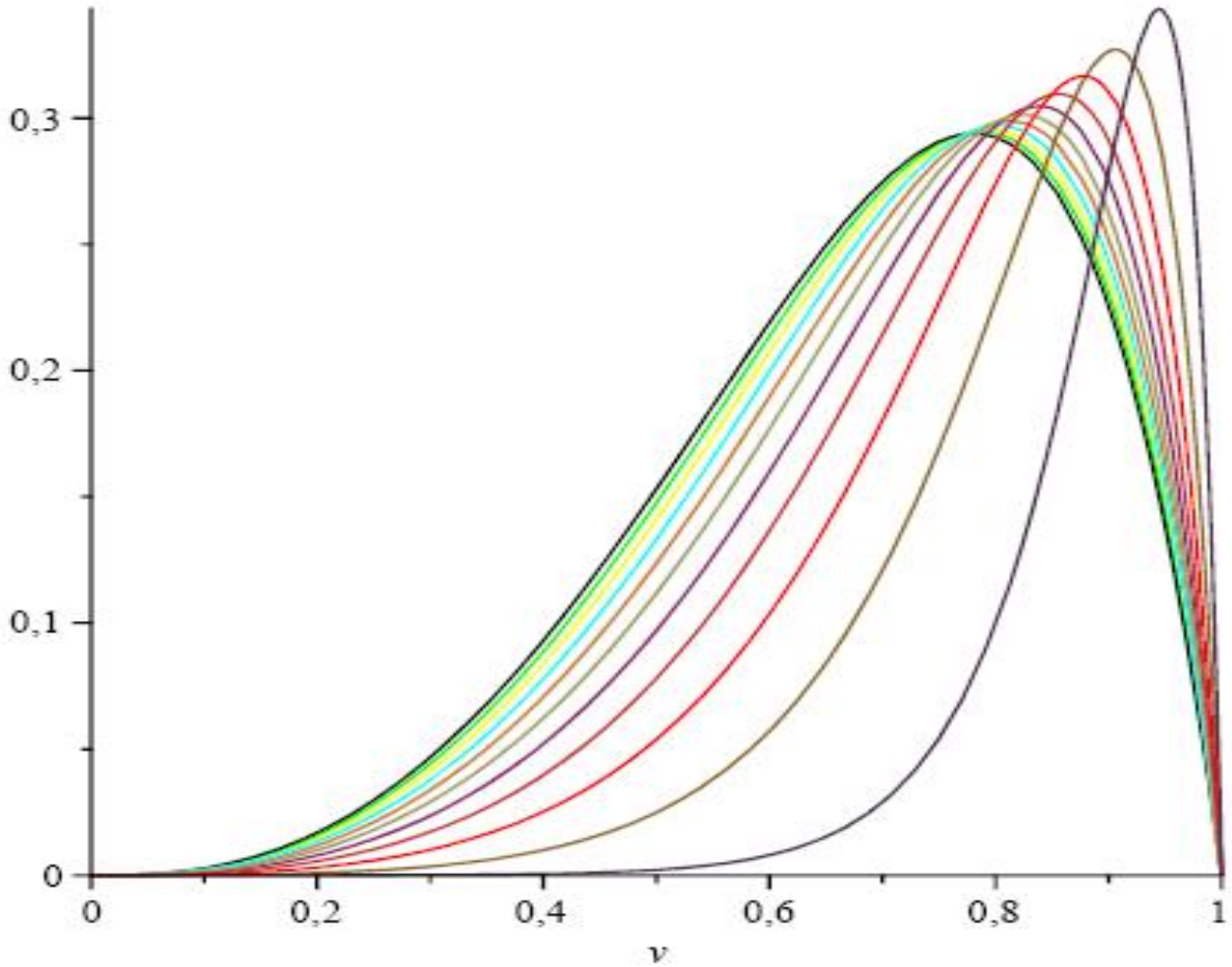
$$I = -\tau \cdot \frac{d(MV^2/2)}{dt} = -\tau \cdot \left(\frac{V^2}{2}\frac{dM}{dt} + MV\frac{dV}{dt} \right) =$$

$$= -\tau \cdot \left(M_e V_e \frac{\beta v^3}{1-\mu} + M_e V_e v \right) \exp\left(-\beta \frac{1-v^2}{1-\mu} \right) \frac{dV}{dt} =$$

$$= \tau \cdot \frac{M_e V_e^3 \sin\gamma}{2h_0} v^3 \cdot (\overline{\mathrm{Ei}}(\beta) - \overline{\mathrm{Ei}}(\beta v^2)) \cdot \left(\frac{\beta v^2}{1-\mu} + 1 \right) \cdot \exp\left(\beta \frac{\mu v^2 - 1)}{1-\mu} \right)$$

- This can be compared with values $I(v)$ calculated from the observed magnitude

The dependence between light curve and shape change coefficient μ



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Result of calculations for well registered meteorite falls

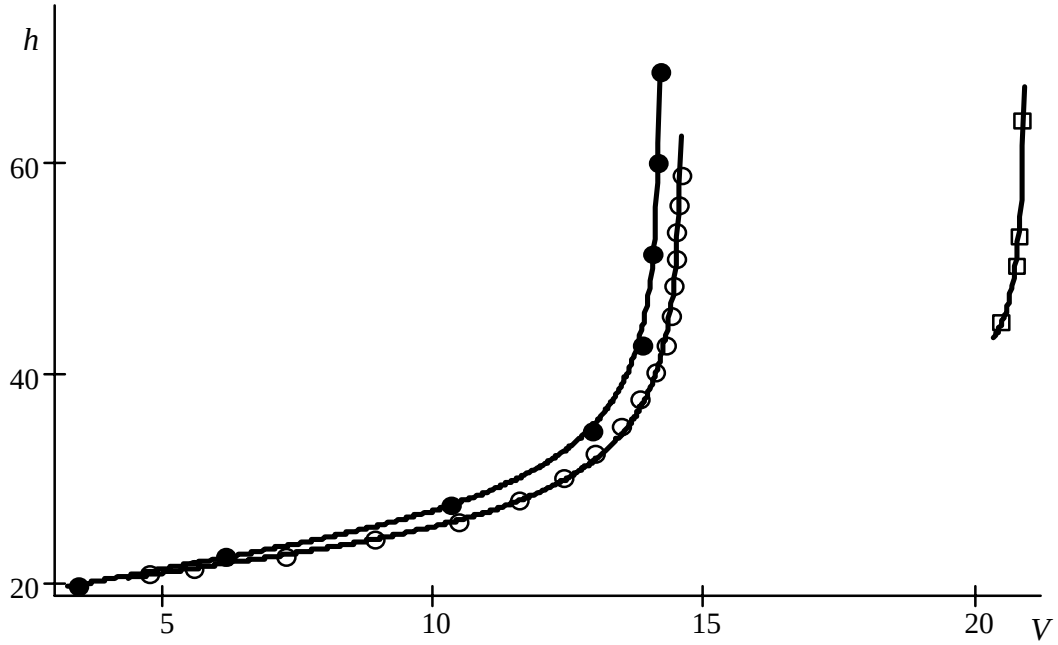
fireball	**V*e*, km/s**	**sinγ**	**α**	**β**	**$10^2 \cdot \sigma$, s^2/km^2**
Příbram	20,887	0,68	8,34	13,64	6,25
Lost City	14,1485	0,61	11,11	1,16	1,16
Innisfree	14,54	0,93	8,25	1,70	1,61
Neuschwanstein	20,95	0,76	3,92	2,57	1,17

Graphical comparison

□ Příbram

● Lost City

○ Innisfree



Analytical solution with parameters found by the method (solid lines) is compared to observation results (dots)

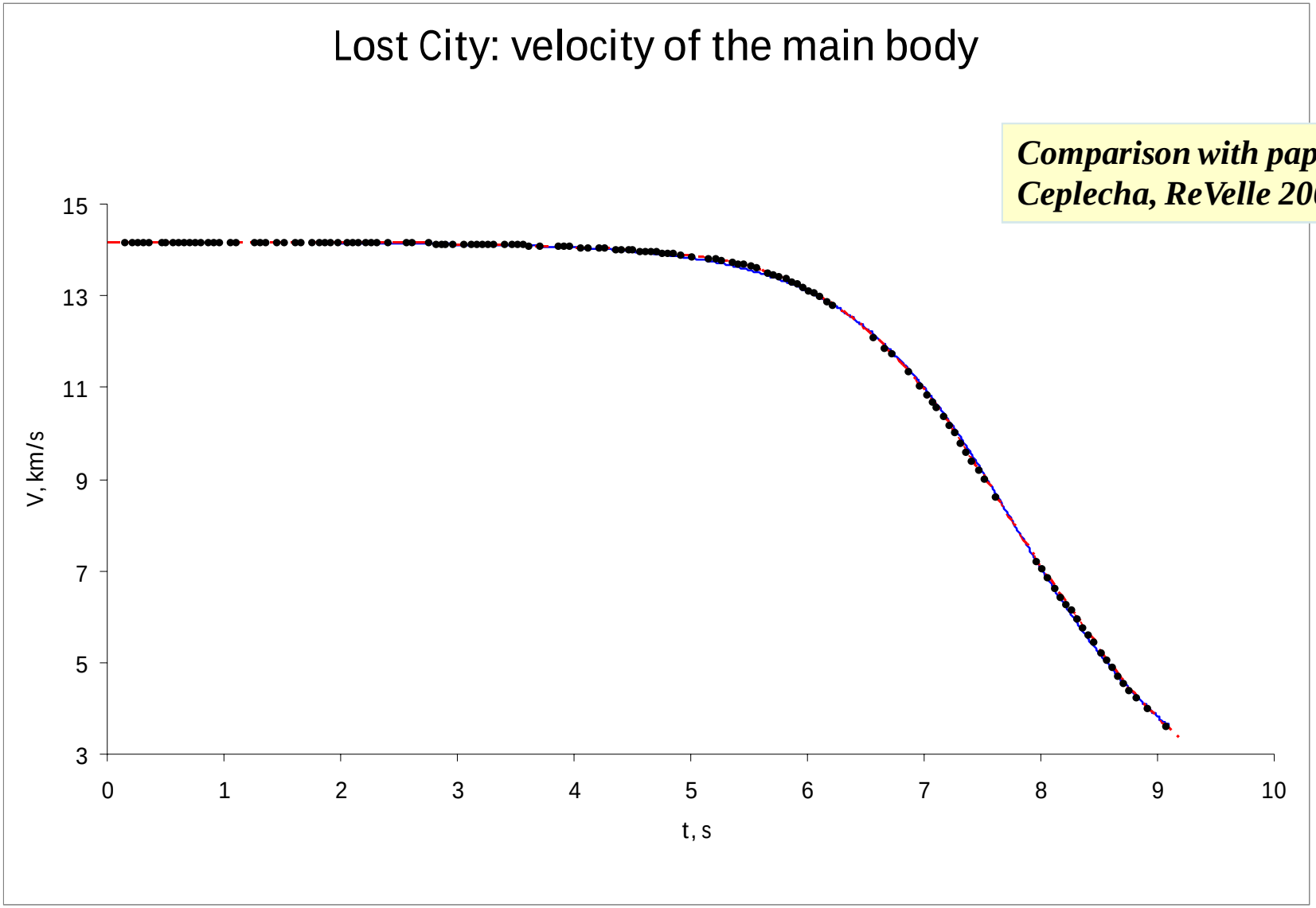
Meteoroid's Deceleration

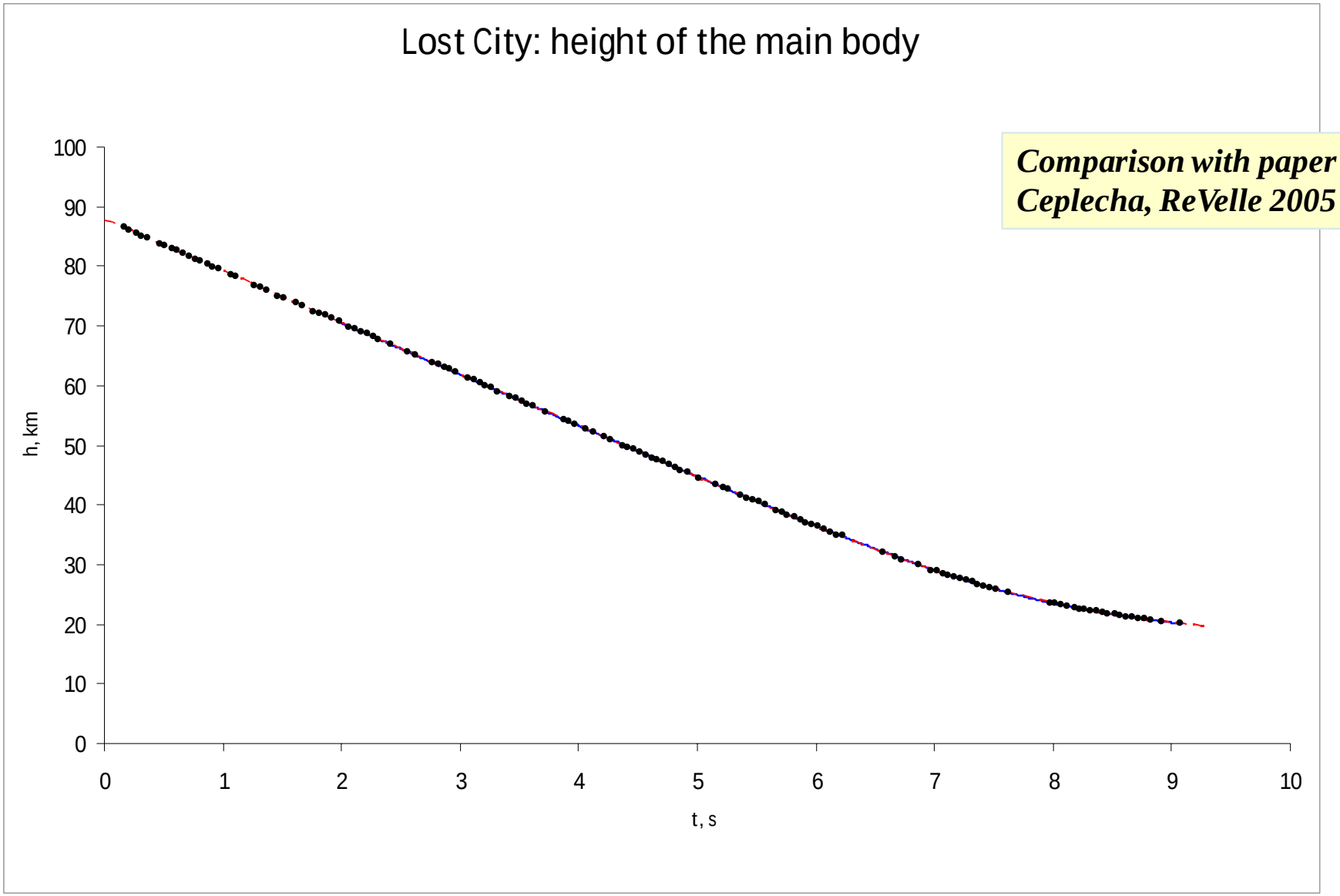
$$\begin{cases} y(v) = \ln 2\alpha + \beta - \ln(\overline{E}i(\beta) - \overline{E}i(\beta v^2)) \\ \dfrac{dy}{dt} = -\dfrac{V_e}{h_o} v \sin\gamma \end{cases}$$

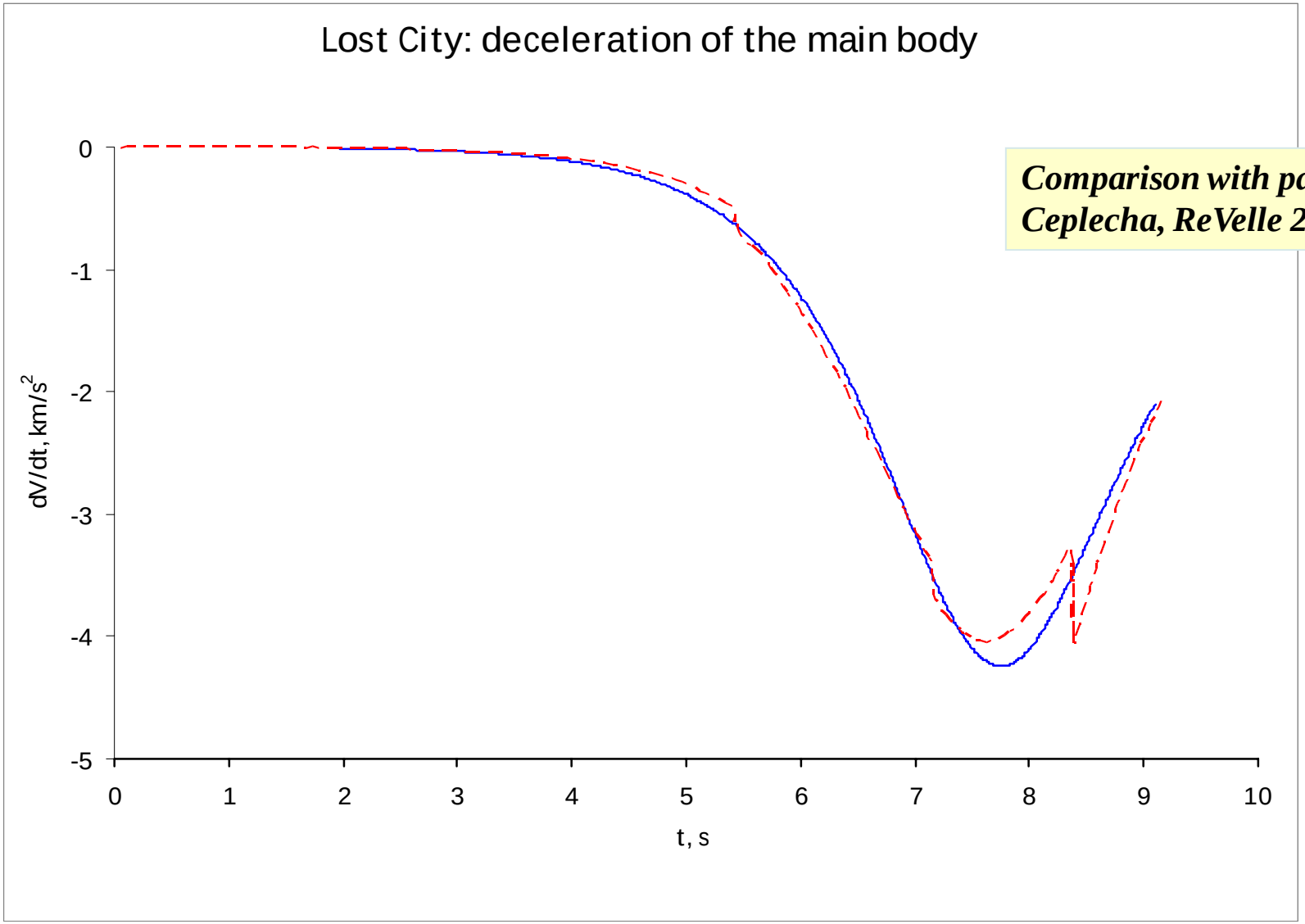
$$\frac{dV}{dt} = V_e \frac{dv}{dy}\frac{dy}{dt} = -\frac{V_e^{\,2} v^2 \sin\gamma}{2h_0} \cdot \frac{\overline{\mathrm{E}}\mathrm{i}(\beta) - \overline{\mathrm{E}}\mathrm{i}(\beta v^2)}{\exp(\beta v^2)}$$

We can compare data in the planes (t, V) and (t, h)

Coupling of parameters used in meteoroid entry modelling



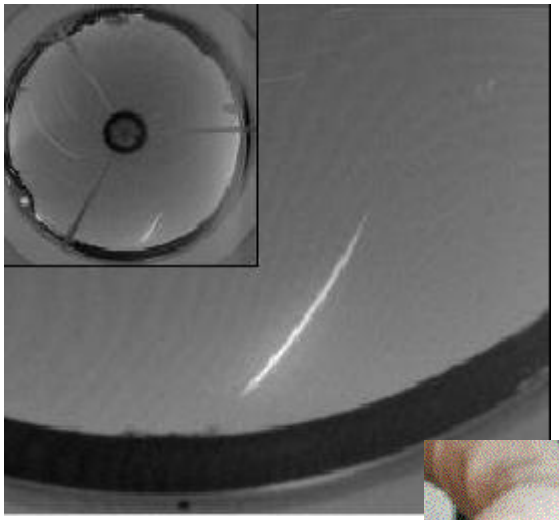

Lost City: height of the main body
Comparison with paper
Ceplecha, ReVelle 2005
h, km
t, s
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10


Lost City: deceleration of the main body
Comparison with paper
Ceplecha, ReVelle 2005
dV/dt, km/s2
0
-1
-2
-3
-4
-5
0
1
2
3
4
5
6
7
8
9
10
t, s

Terminal mass prediction: comparison with found meteorites' mass

fireball	**ρ, g/cm^3**	**V_t, km/s**	**M(V_t), kg**	**M_t, kg**
Lost City	3,73	3,4	**43**	17,2
Innisfree	3,5	4,7	**27**	4,58
Neuschwanstein	3,49	2,3	**28**	6,2

Neuschwanstein



[1]Spurny et al.

[2]ReVelle et al., 2004

Initial mass, kg
520 - 670 *
300 – 600 [1]
400 – 530 [2]

Our result corresponds to the estimates done based on the analysis of recorded acoustic, infrasound and seismic waves caused by the meteorite fall

Initial masses for earlier meteorite falls

	Příbram	**Lost City**	**Innisfree**
M, kg	**317**	**169**	**179**
M[1], kg	1300	52	18
M_{ph}, kg	21500[2]	490[3]	318[4]
M, kg	320[5]	65[5]	?
M[6], kg	–	165	42
M, kg	250[7]	210[7]	–
M[5], kg	1700	38	25

[1] (*ReVelle, Rajan*, 1979), [2] (*Ceplecha*, 1977; *Oberst et al*., 1998), [3] (*Мак-Кроски et al*., 1978), [4] (*ReVelle*, 1980), [5] (*Wetherill, ReVelle*, 1981), [6] (*Ceplecha, ReVelle*, 2005), [7] (*Bagolia et al*., 1980)

Characteristic heights for the fireball trajectories

$$L = \left(\frac{M_e}{30\rho_m} \right)^{1/3}, \quad R = \left(\frac{30L^3}{4\pi/3} \right)^{1/3}$$

h_l – the height at which the size L is equal to the mean free path of air molecules

$$h_l = h_0 \ln\left(L / l_0\right), \; l_0 = 0.19 \cdot 10^{-4} \text{ см}$$

h_{sw} – the height below which the flow around the equivalent sphere of radius R takes place in the thin viscous shock layer regime (i.e. a thin shock is formed)

$$h_{sw} = 53 + 17.05 \lg R$$

h_{bl} – the height corresponding to the formation of a thin boundary layer on the equivalent sphere

$$h_{bl} = 40.7 + 15 \lg R$$

Calculated characteristic heights

№	h_b, km	h_{mI}, km	h_t, km	M_e, kg	L, cm	h_l, km	R, cm	h_{sw}, km	h_{bl}, km
18	75,5	**44,9**	27,5	11,5	4,8	89,0	9,2	69,4	**55,2**
169	78,9	**44,2**	34,0	6,1	3,9	87,5	7,5	67,9	**53,8**
195	77,4	**40,6**	30,4	3,3	3,2	86,1	6,1	66,4	**52,5**
204	61,9	**40,6**	29,5	187,9	12,1	95,7	23,4	76,3	**61,2**
205	72,5	**38,0**	28,9	0,6	1,8	81,9	3,4	62,1	**48,7**
219	67,7	**33,5**	26,1	33,5	6,8	91,6	13,2	72,1	**57,5**
223	78,5	**49,0**	27,1	141,7	11,1	95,0	21,3	75,6	**60,6**
276	81,8	**32,4**	24,4	8,2	4,3	88,2	8,3	68,6	**54,4**
285	58,8	**35,0**	19,8	104,1	10,0	94,3	19,2	74,9	**60,0**

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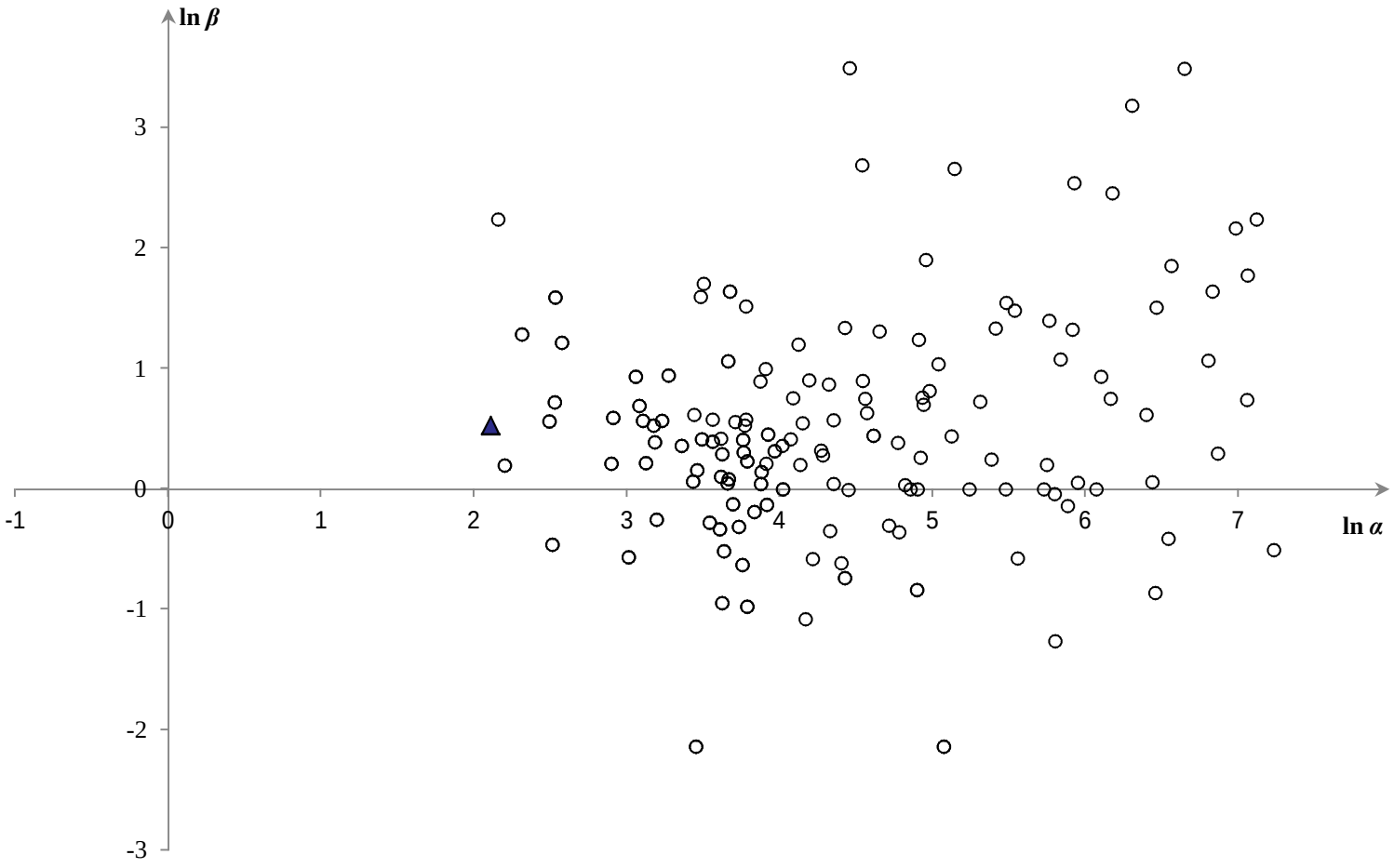
- ❑ General statistics and consequences

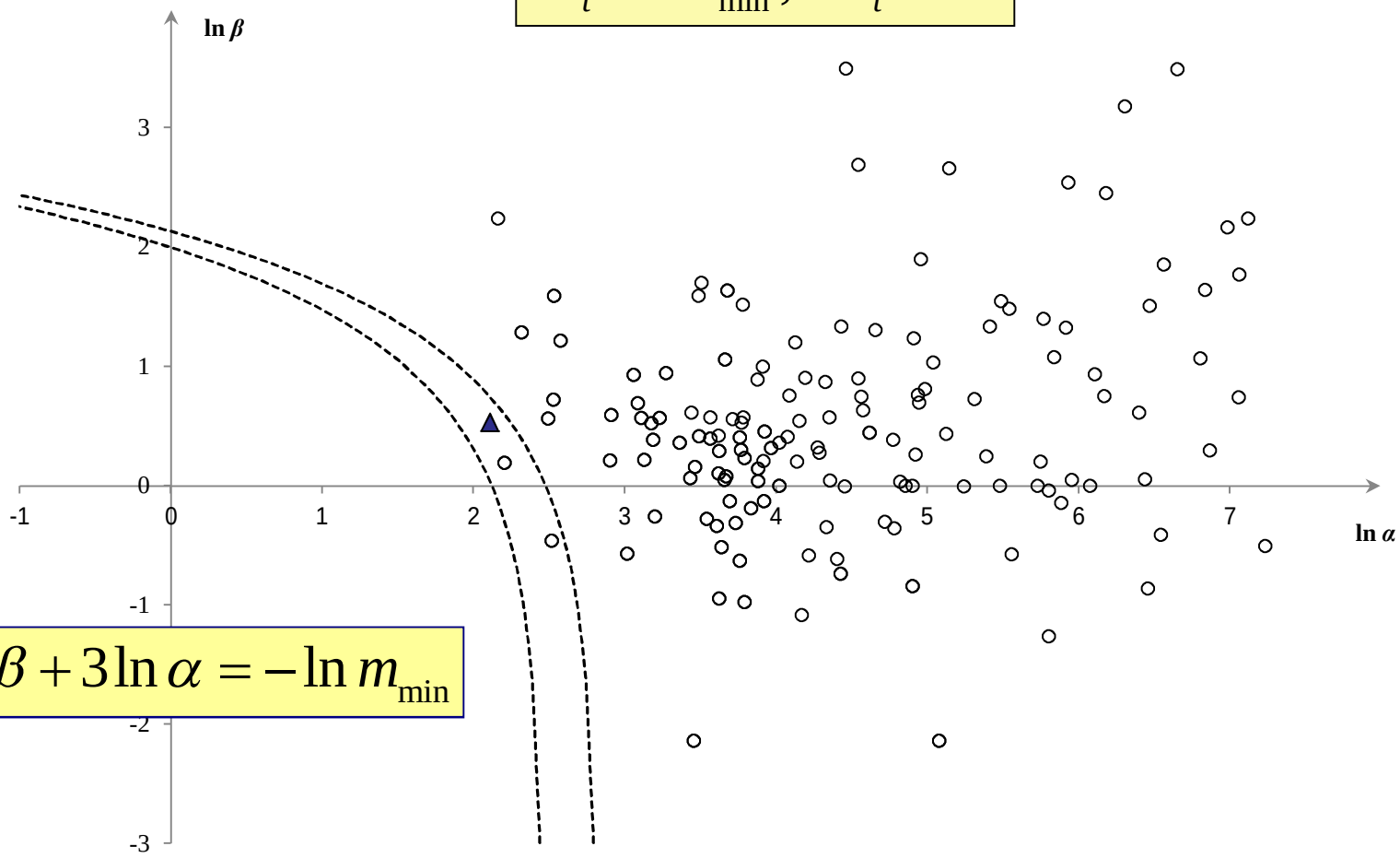
Distribution of parameters α and β for MORP fireballs



Δ Innisfree

Looking for Meteorite 'region'

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



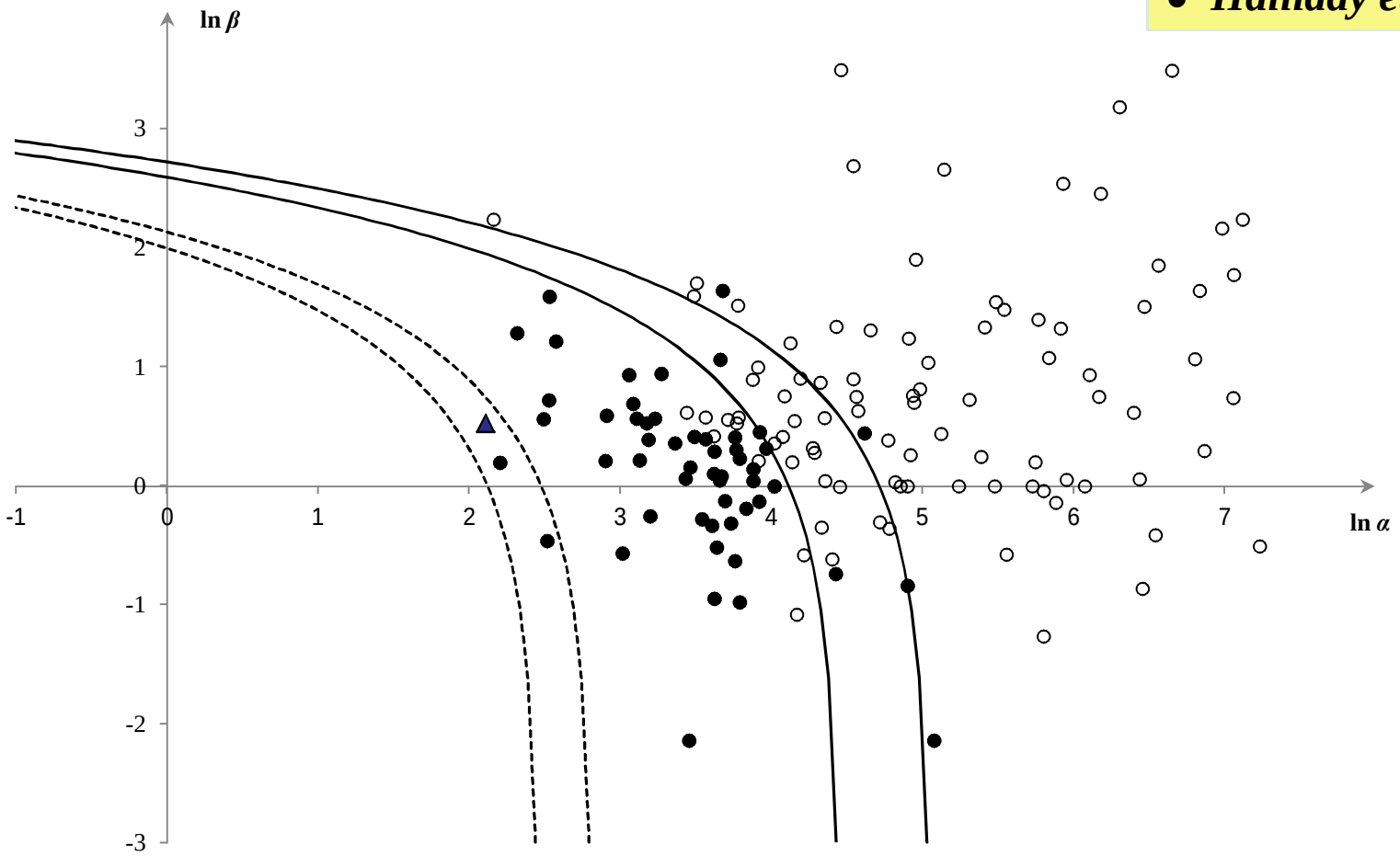
$$\beta + 3\ln\alpha = -\ln m_{\min}$$

sinγ = 0.7 and 1; $M_{\min}$ = 8 kg

Δ Innisfree

Meteorite falls prediction (down to 50 g)

- ***Halliday et al.*, 1996**



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

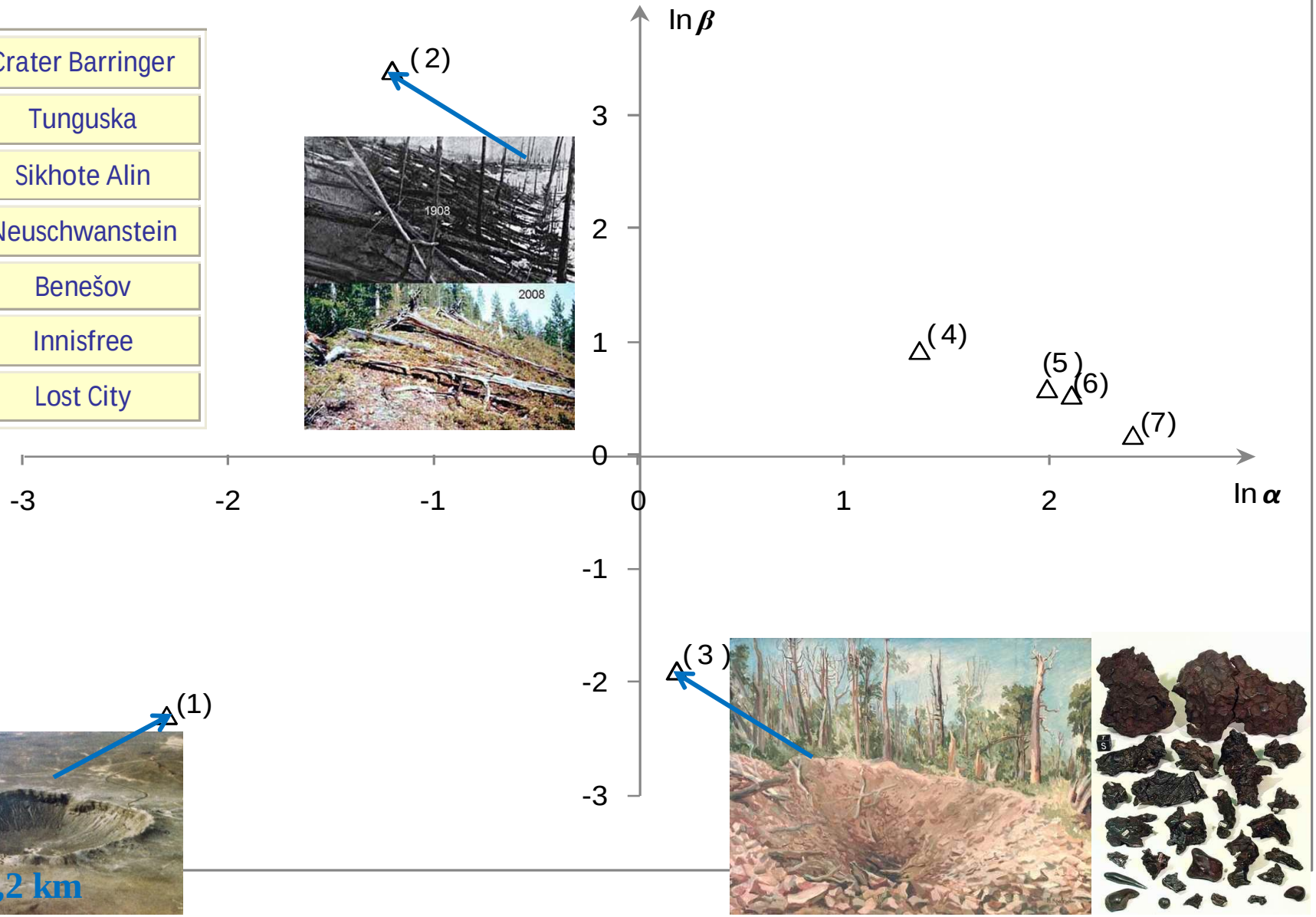
Δ Innisfree

Some historical events

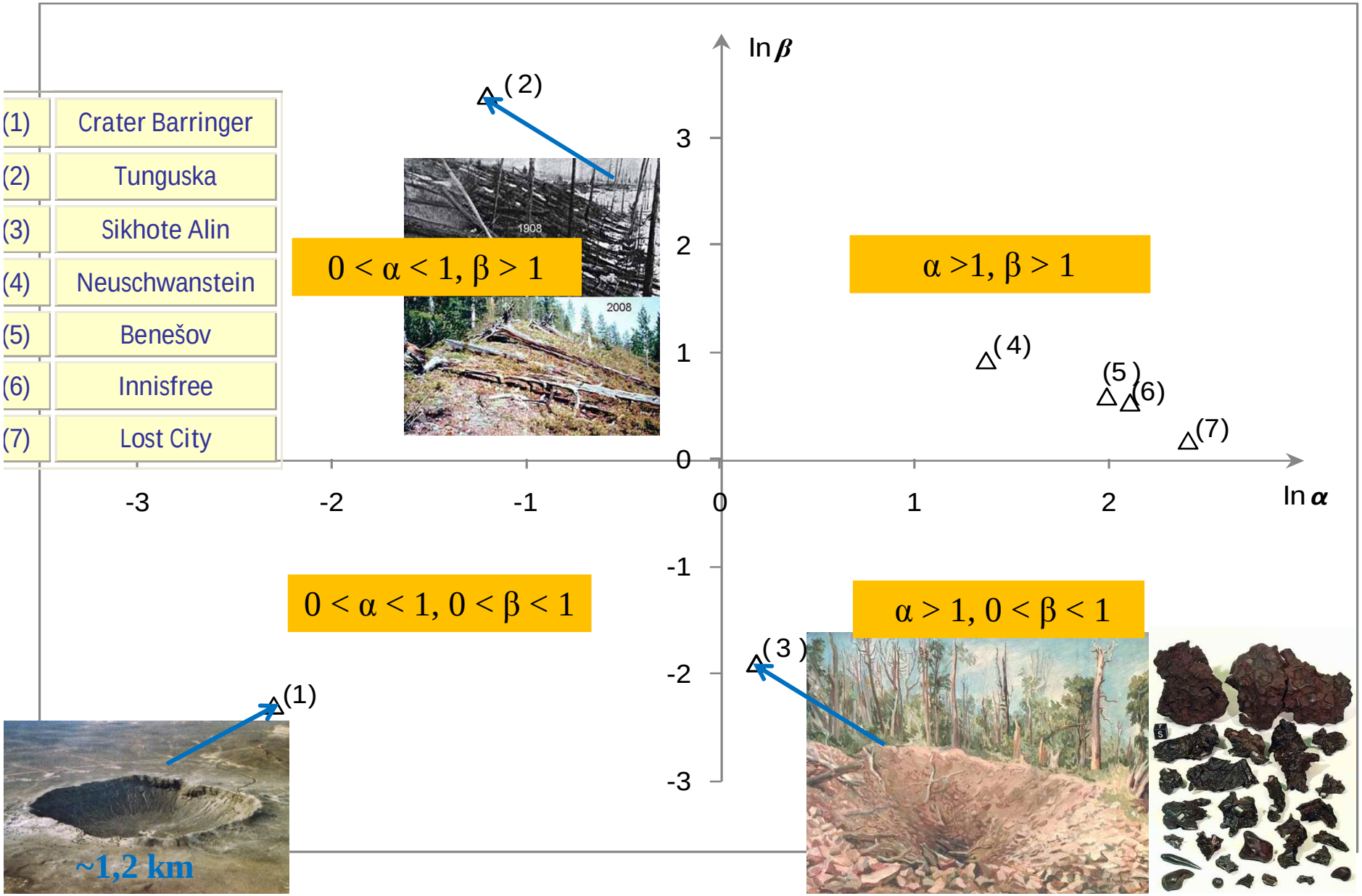
№	Event	Original mass, t	Collected meteorites, kg	α	β
1	Canyon Diablo meteorite (Barringer Crater)	$> 10^6$	$> 30 \cdot 10^3$	0.1	~ 0.1
2	Tunguska	$0.2 \cdot 10^6$	-	0.3	30
3	Sikhote Alin	200	$> 28 \cdot 10^3$	1.2	0.15
4	Neuschwanstein	0.5	6.2	3.9	2.5
5	Benešov	0.2	-	7.3	1.8
6	Innisfree	0.18	4.58	8.3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

Same events on the plane (lnα, lnβ)

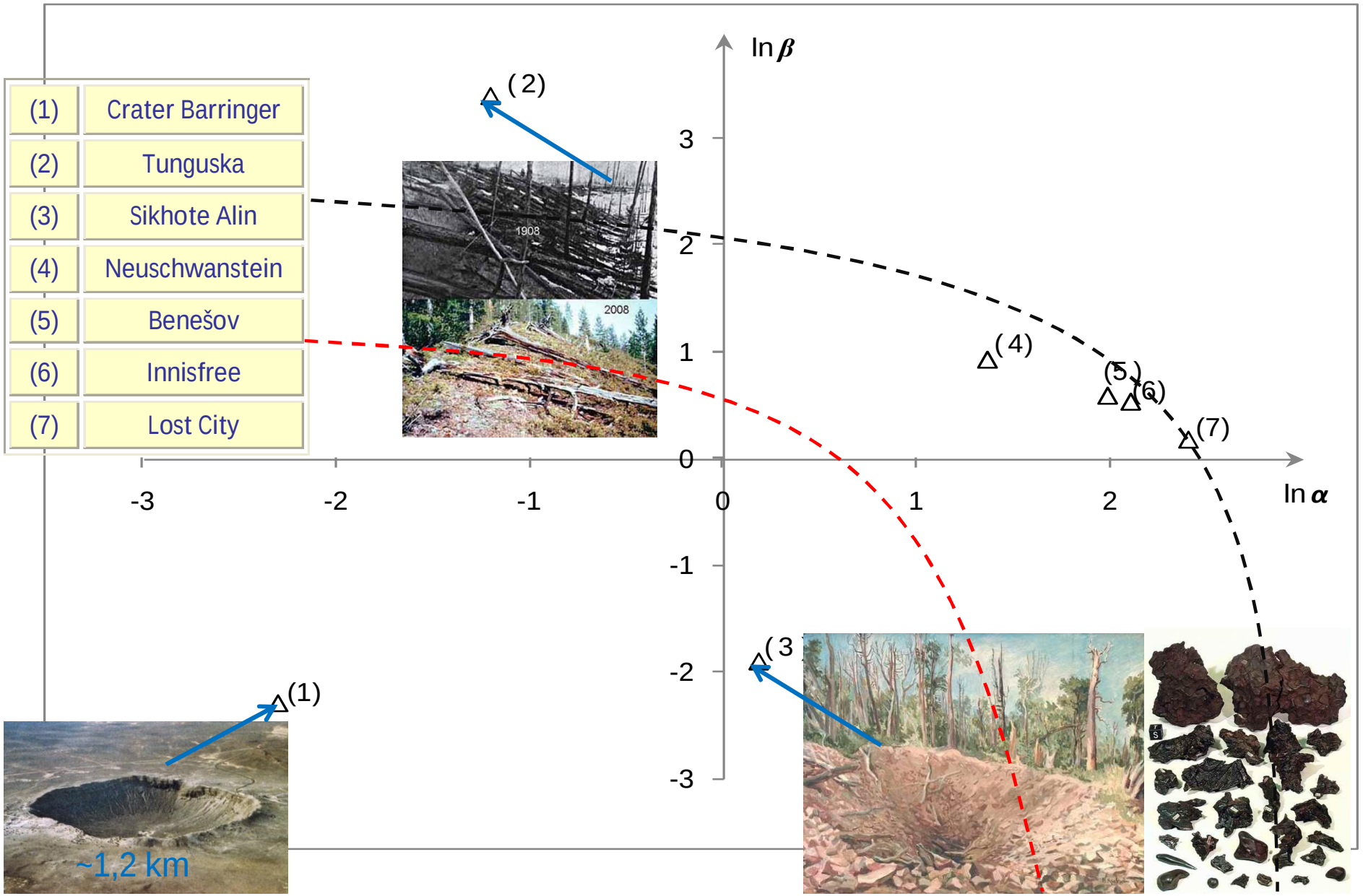
(1)	Crater Barringer
(2)	Tunguska
(3)	Sikhote Alin
(4)	Neuschwanstein
(5)	Benešov
(6)	Innisfree
(7)	Lost City



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 meteor impact. These parameters effectively characterize the ability of entering body to survive an atmospheric entry and reach the ground. The set of these parameters can be also used to solve inverse problems, when we have to evaluate properties of the entering body based on observations.

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.

Some relevant papers

- Gritsevich, M.I., Stulov, V.P., and Turchak, L.I. (2012): *Consequences for Collisions of Natural Cosmic Bodies with the Earth Atmosphere and Surface* // Cosmic Research, 50(1), 56–64

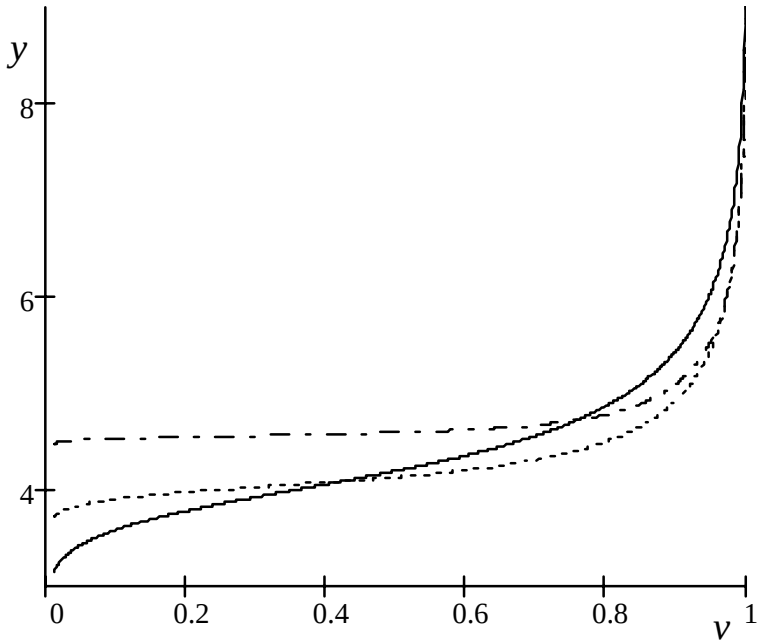
- Gritsevich, M., and Koschny, D. (2011): *Constraining the luminous efficiency of meteors* // Icarus, 212(2), 877-884.

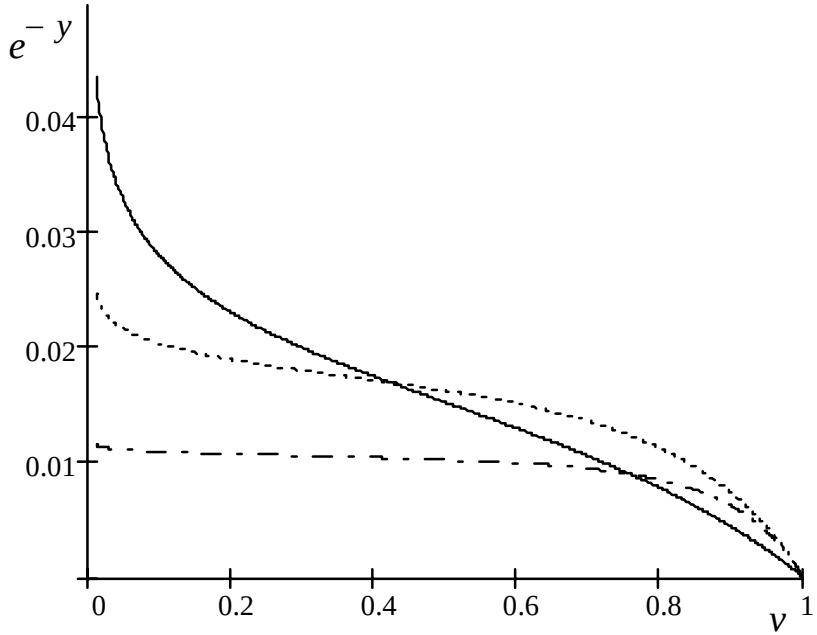
- Gritsevich, M.I. (2009): *Determination of Parameters of Meteor Bodies Based on Flight Observational Data* // Advances in Space Research, 44(3), 323-334.

- Gritsevich, M.I. (2008): *The Pribram, Lost City, Innisfree, and Neuschwanstein Falls: An analysis of the Atmospheric Trajectories* // Solar System Research, 42(5), 372-390.

Thank you very much!

Why do we pass from y to exp(-y) ?





$$e^{-y} = \frac{\Delta \cdot e^{-\beta}}{2\alpha}, \quad \Delta = \overline{\mathrm{Ei}}(\beta) - \overline{\mathrm{Ei}}(\beta v^2), \quad \overline{\mathrm{Ei}}(x) = \int_{-\infty}^{x} \frac{e^z dz}{z}$$

Newton's Second Law of Motion

$$M\frac{dV}{dt} = -\frac{1}{2}c_d\rho_a V^2 S + Mg\sin\gamma \quad \Rightarrow \quad \boxed{M\frac{dV}{dt} = -\frac{1}{2}c_d\rho_a V^2 S}$$

$$\frac{dM\vec{V}}{dt} = \lim_{\Delta t \to o}\frac{\Delta M\vec{V}}{\Delta t}$$

$$\Delta M\vec{V} = \left[(M - \Delta M)(\vec{V} + \Delta\vec{V}) + \Delta M(\vec{V} + \vec{U})\right] - M\vec{V}$$

$$\frac{dM\vec{V}}{dt} = \lim_{\Delta t \to o}\frac{\Delta M\vec{V}}{\Delta t} = \lim_{\Delta t \to o}\frac{M\,\Delta\vec{V} + \Delta M\vec{U}}{\Delta t} = M\,\frac{d\vec{V}}{dt}$$

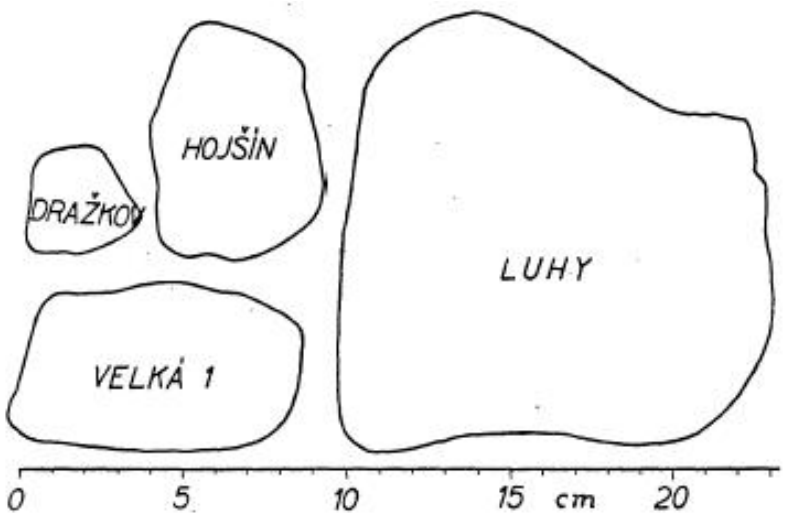
Mass computation

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

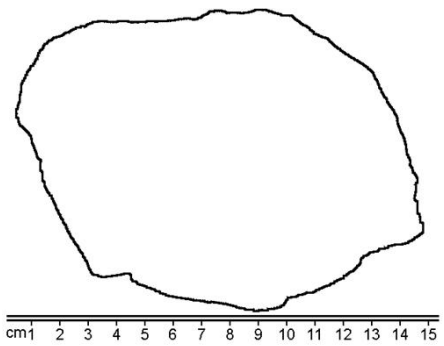
Initial Mass depends on ballistic coefficient

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

Forms of some recovered meteorites



Příbram



Innisfree

Определение внеатмосферной массы

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

где $A_e = S_e / W_e^{2/3}$ коэффициент начальной формы тела

Используемые параметры

- плотность атмосферы на уровне моря ρ_0,
- высота однородной атмосферы h_0,
- угол траектории с горизонтом γ

- коэффициент формы тела при входе в атмосферу A_e
- коэффициент сопротивления c_d,
- плотность тела ρ_m,

Определение динамических параметров

1. Преобразование точного аналитического решения к виду:

$$2\alpha \exp\left(-y\right) - \Delta \exp(-\beta) = 0, \quad \Delta = \overline{\mathrm{Ei}}\left(\beta\right) - \overline{\mathrm{Ei}}(\beta v^2)$$

2. Определение величины расхождения данных наблюдений и теоретической зависимости

$$F(y_i, v_i, \alpha, \beta) = 2\alpha \exp\left(-y_i\right) - \Delta_i \exp(-\beta)$$

3. Применение метода наименьших квадратов для определения параметров α и β

$$Q_4(\alpha, \beta) = \sum_{i=1}^{n} (F(y_i, v_i, \alpha, \beta))^2 \to \min$$