The Challenges of Hypervelocity Microphysics Research in Meteoroid Impacts into the Atmosphere

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Meteors are important for:

- Astronomy
- Aeronomy
- Geophysics
- Evolutionary biology
- Planetology
- Science popularization

Meteors are difficult to explore:

- Brief transient events
- Large angular size
- Radom spatial position
- Three different flow regimes

Technological advancements have yielded drastic improvements in

- Quality
- Quantity
- Diversity

of meteor data.

Even more ambitious instruments are about to become operational.

METEOR HYPERSONIC FLIGHT FLOW REGIMES

Knudsen number: $Kn=\lambda/L$

λ= the mean free path of the gas molecules

L= characteristic length scale of the body

Reynolds number: $Re=\rho vL/\mu$

ρ is the gas density

v is the flow speed

μ is the gasdynamic viscosity

(i) Free molecular regime, $Kn>10$

The number of intermolecular collisions is scarce. Single molecules hit the immersed body.

(ii) Transitional-flow regime, $0.1<Kn<10$ or $Re^{-1/2}<Kn<10$

The mean free path of the molecules is of the same order of magnitude as the characteristic size of the body. There are collisions between molecules. Formation of the vapor cloud.

(iii) Slip-flow regime, $0.01<Kn<0.1$ or $0.01Re^{-1/2}<Kn<Re^{-1/2}$

There is a slightly tangential component of the flow velocity in the boundaries of the body's surface, but there is no adhesion of the flow to the body's surface.

(iv) Continuum-flow regime, $Kn<0.01$ or $Kn<0.01Re^{-1/2}$

The flow is considered to be continuous.

Moreno-Ibáñez et al. (2018) ApJ, 863, 174

Past terrestrial impacts

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

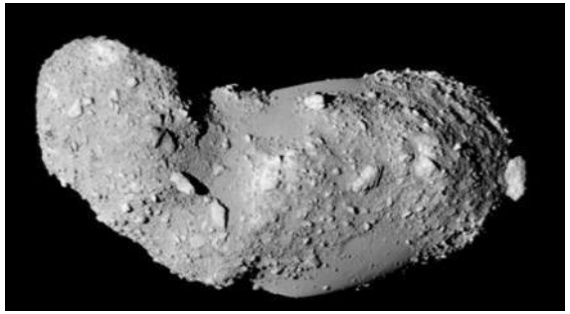
Past terrestrial impacts


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

Past terrestrial impacts

Tunguska

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). *Meteorite (fall) recovery is exciting since it is a cheap analogue to the sample return mission.*

Interpretation of meteor observations

Photometric

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

Usually simplified case used is:

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

“Full” scenario utilized e.g. in Gritsevich & Koschny, 2011 and Bouquet et al. 2014

Dynamical

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

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

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

Sometimes precise meteor time & position require corrections to the Standard Atmosphere models (Lyytinen & Gritsevich, 2016)

Gritsevich (2009) Advances in Space Research 44, 323

The key dimensionless parameters used

$$\alpha = \frac{1}{2} c_d \frac{\rho_0 h_0 S_e}{M_e \sin\gamma} = \frac{1}{2} c_d \frac{M^{(air-in-front-of-the-body)}}{M_e}$$

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 pre-atmospheric 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 (Gritsevich, Koschny, 2011; Bouquet et al. 2014)

Gritsevich (2009) Advances in Space Research 44, 323

The key dimensionless parameters used

$$\beta = (1-\mu)\frac{c_h V_e^2}{2c_d H^*} = (1-\mu)\frac{c_h V_e^2 M_e}{2c_d H^* M_e} =$$

$$= (1-\mu)c_h / c_d \, \frac{E_{kin}}{E^{(required-to-fully-destroy-the-object-in-the-atmosphere)}}$$

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

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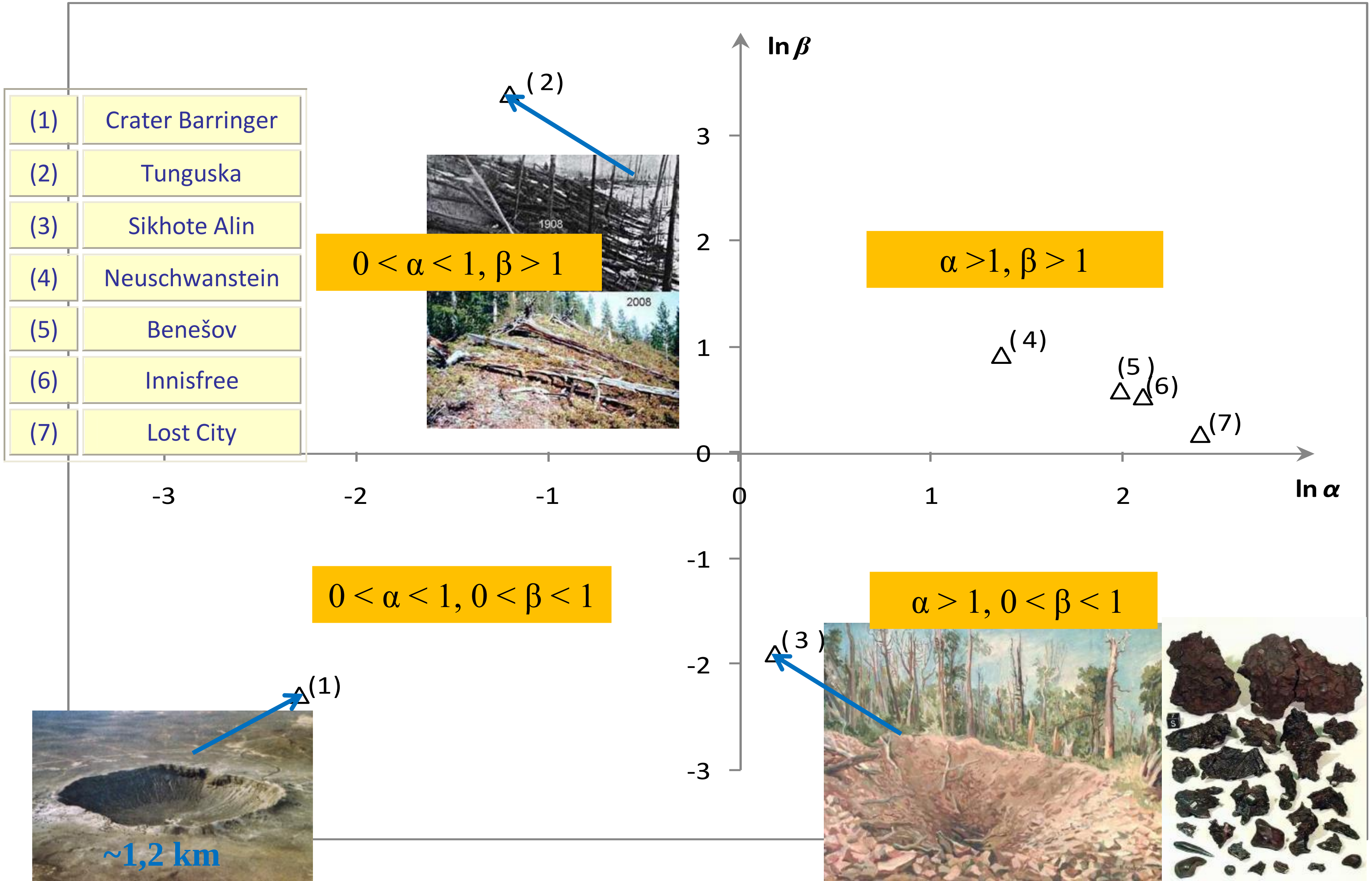
Gritsevich et al. (2011) EPSC-DPS Joint Meeting 2011, p.1453

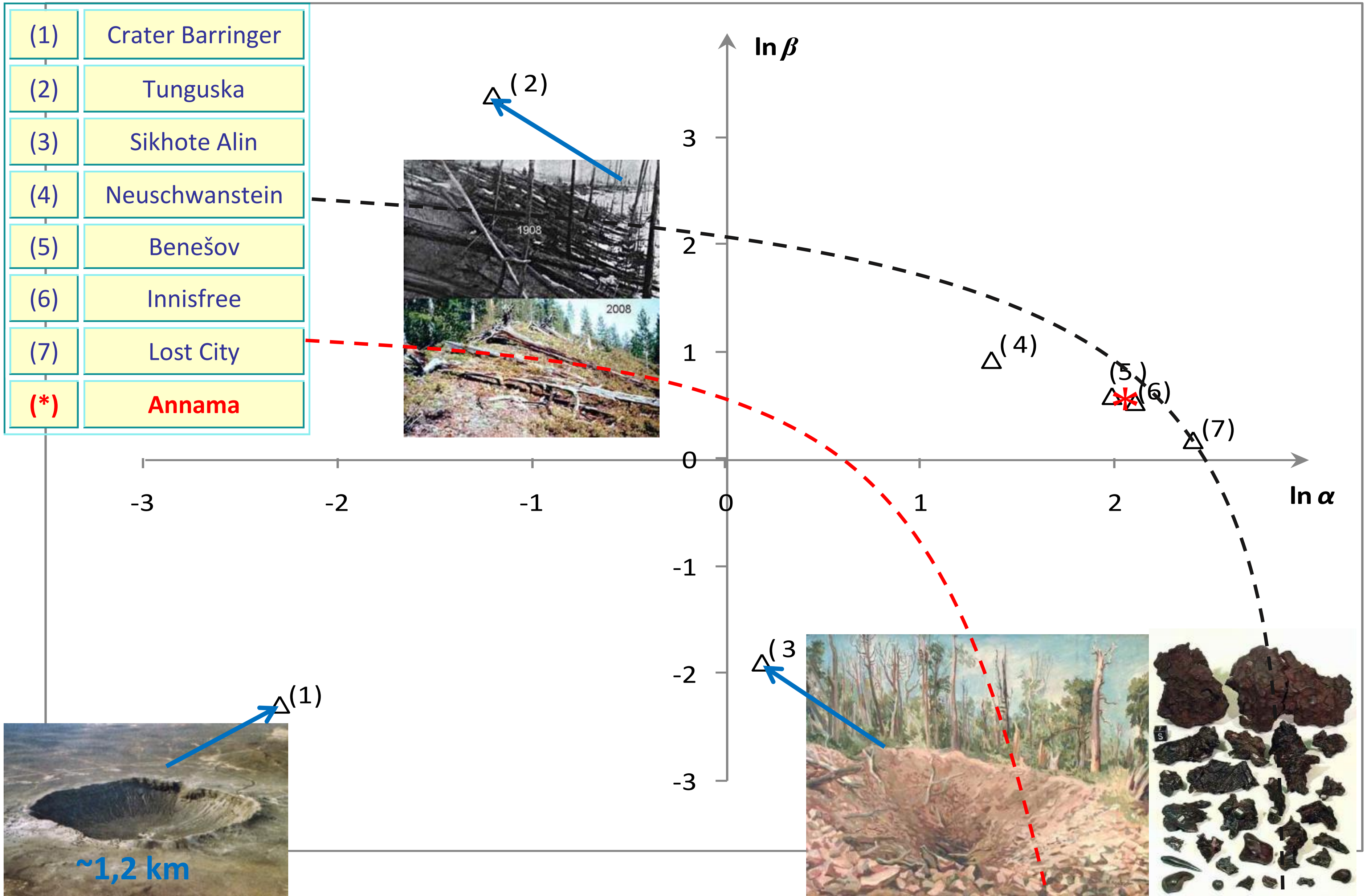
Meteorite / crater production criteria



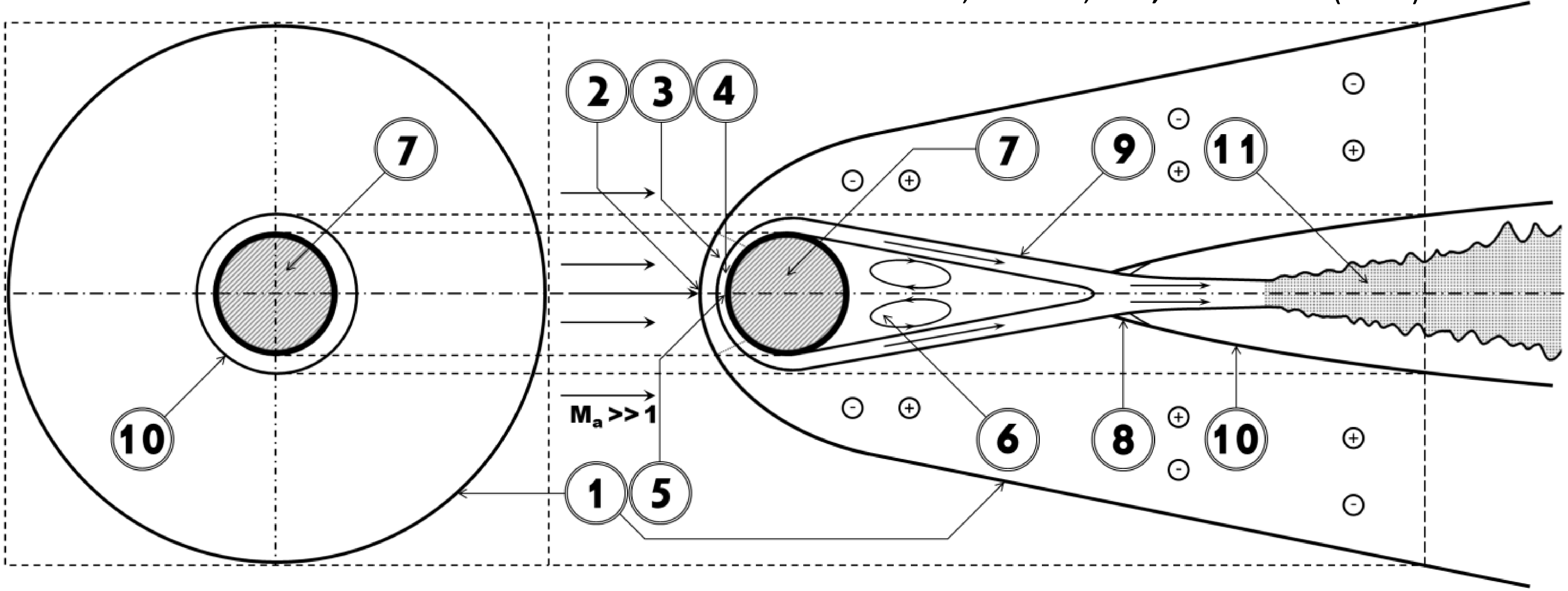
Gritsevich et al. (2011) EPSC-DPS Joint Meeting 2011, p.1453

Meteorite / crater production criteria

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



Silber E.A. et al, MNRAS, **469,** 1869–1882 (2017)



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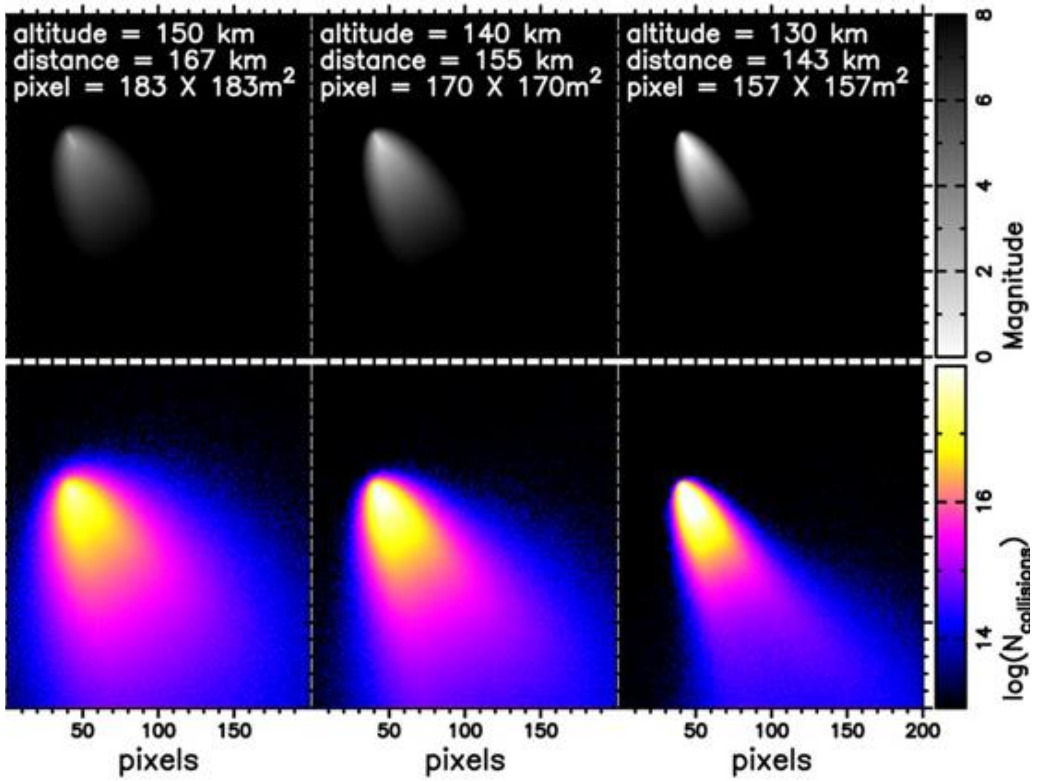
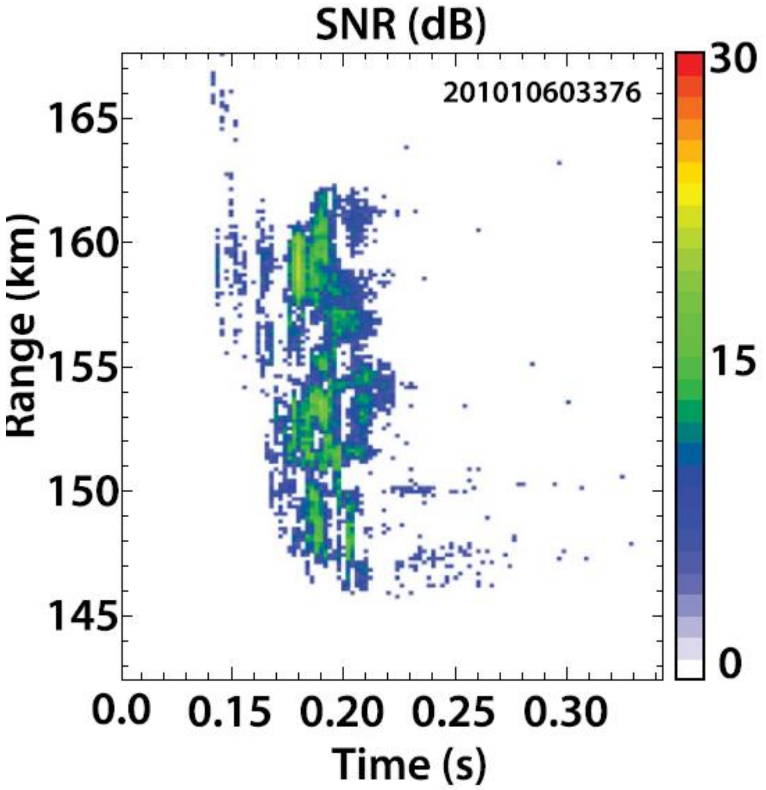
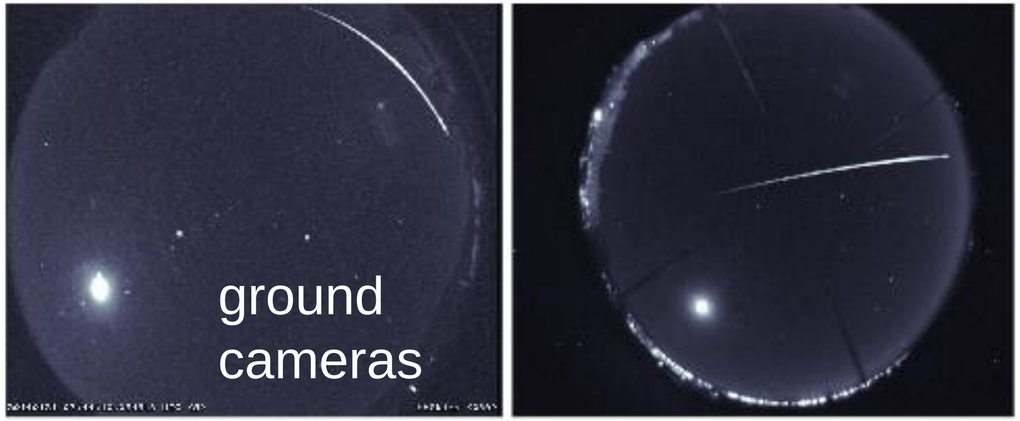
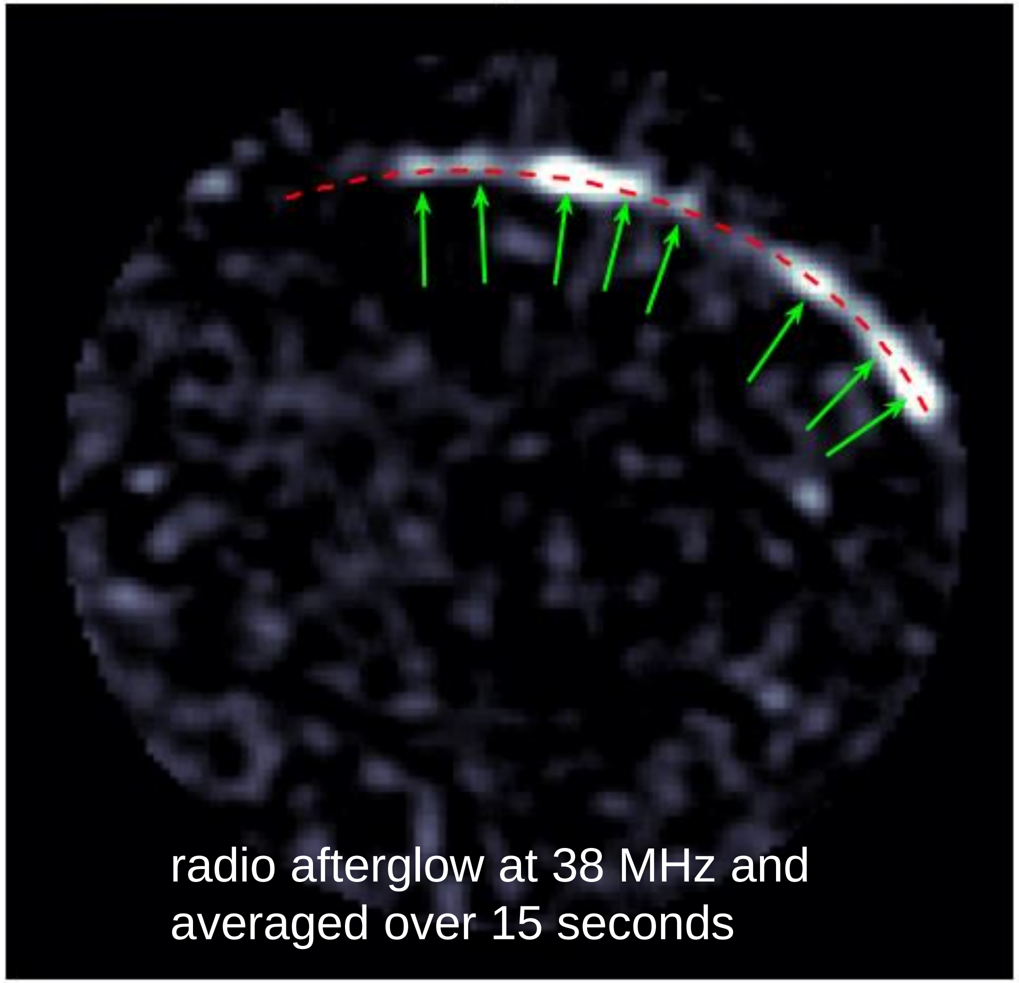


High altitude meteors (above 130 km) from sputtering (Vinković 2007), but microphysics is missing



High altitude ”dragon” events from a high-power, large-aperture radar (49.92 MHz) (Gao and Mathews, 2015)



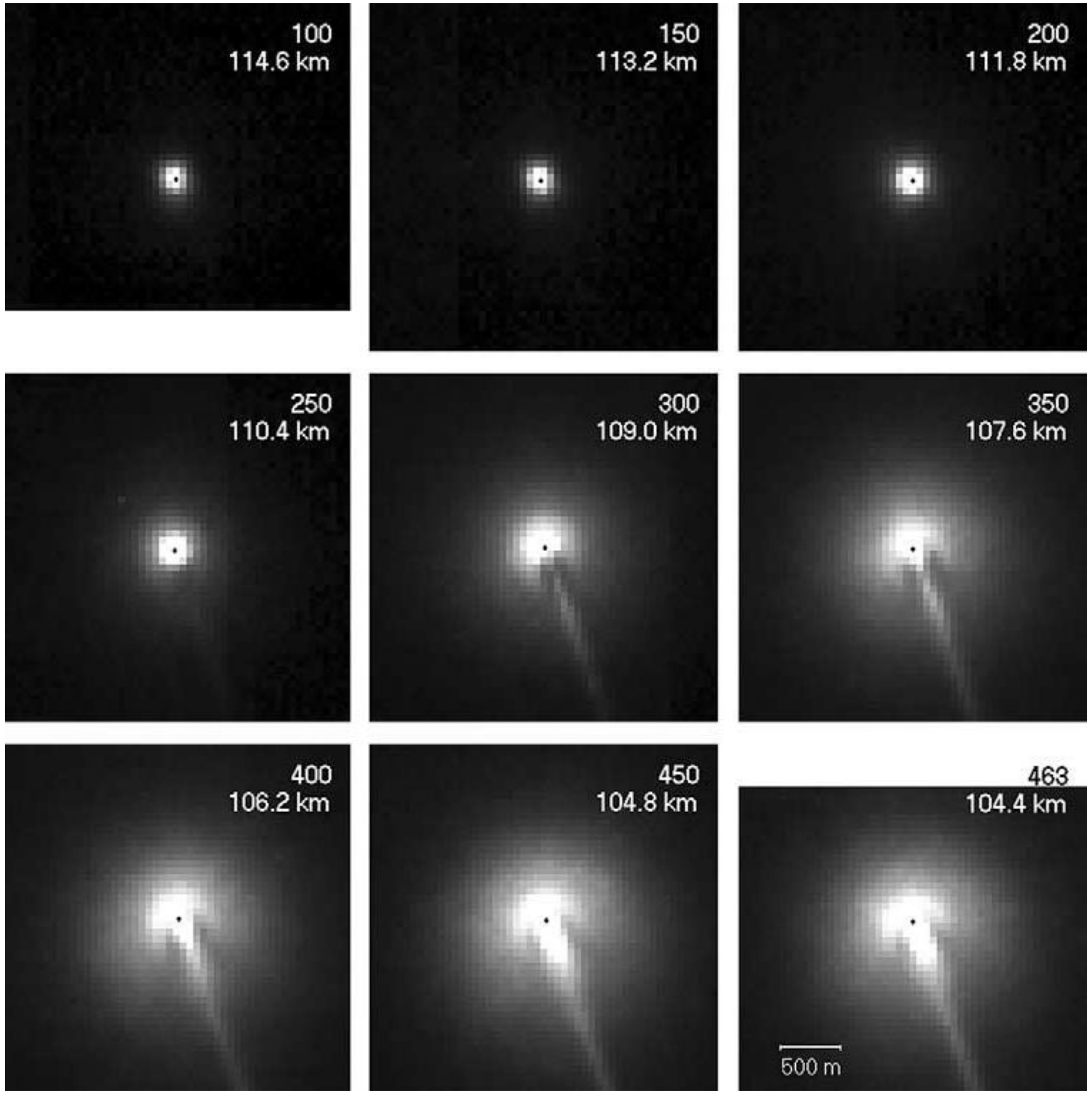


Observing meteors outside the traditional visual bands and comfort zone of meteor astronomers

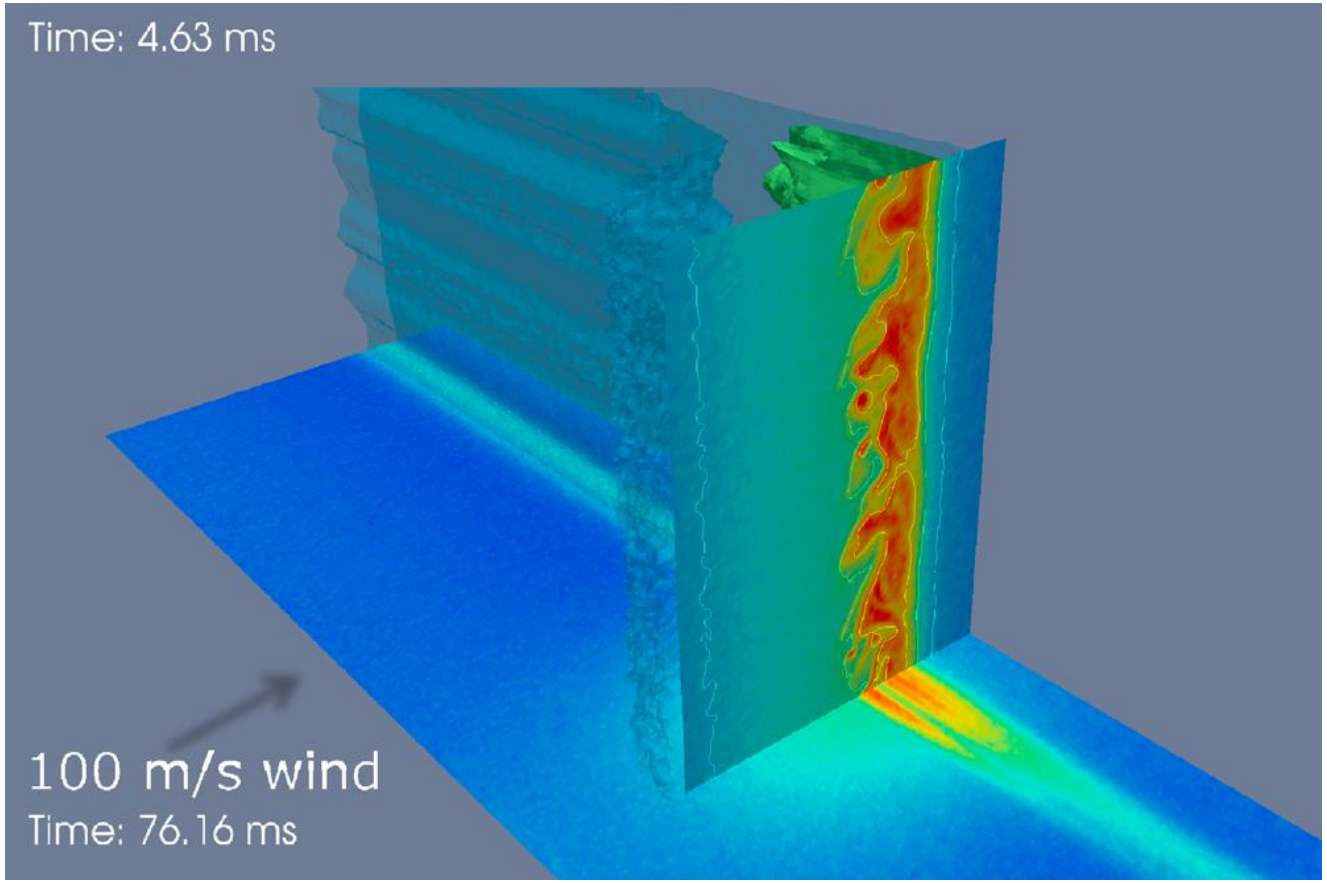
Discovery of 20-60 MHz emission from meteors in the VHF radio band using the LWA1 Radio Telescope (Obenberger, 2014)

A cutoff below ~90 km: agrees with hypothesis that **meteor radio afterglows are the result of electron plasma wave emission from turbulent meteor trails**, though the true cause may indeed be unrelated (Obenberger et al, 2016)

The ongoing and upcoming radio sky surveys will produce petabytes and soon exabytes of data (LOFAR, SKA).



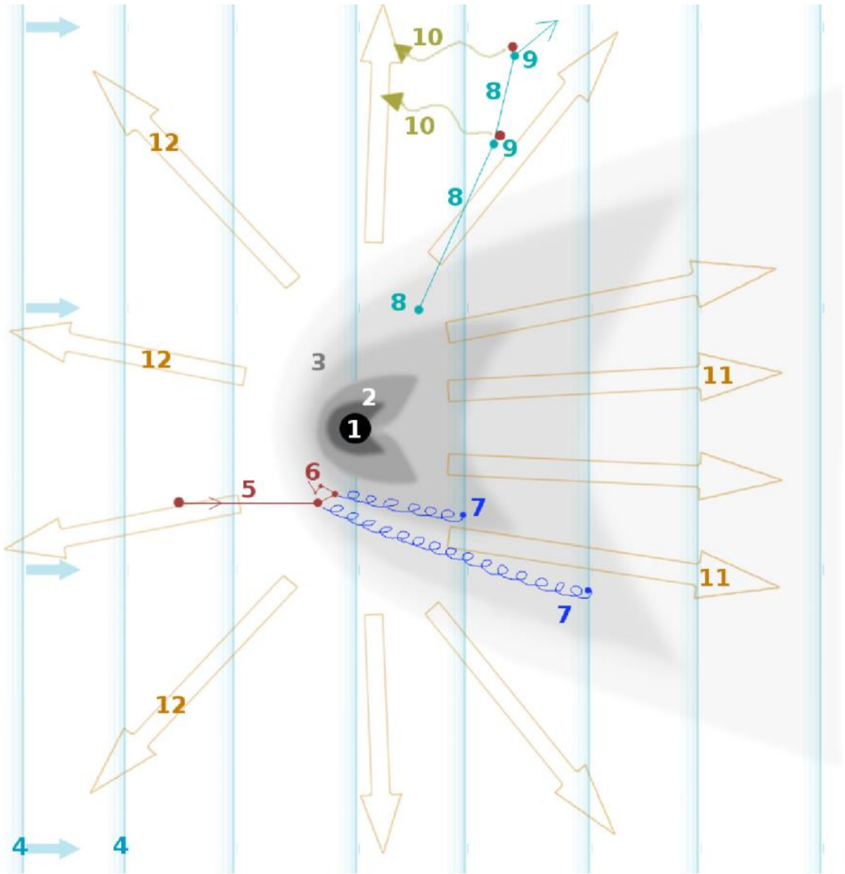
large halo around a meteor detected in a high-speed recording (Stenbaek-Nielsen and Jenniskens, 2004)

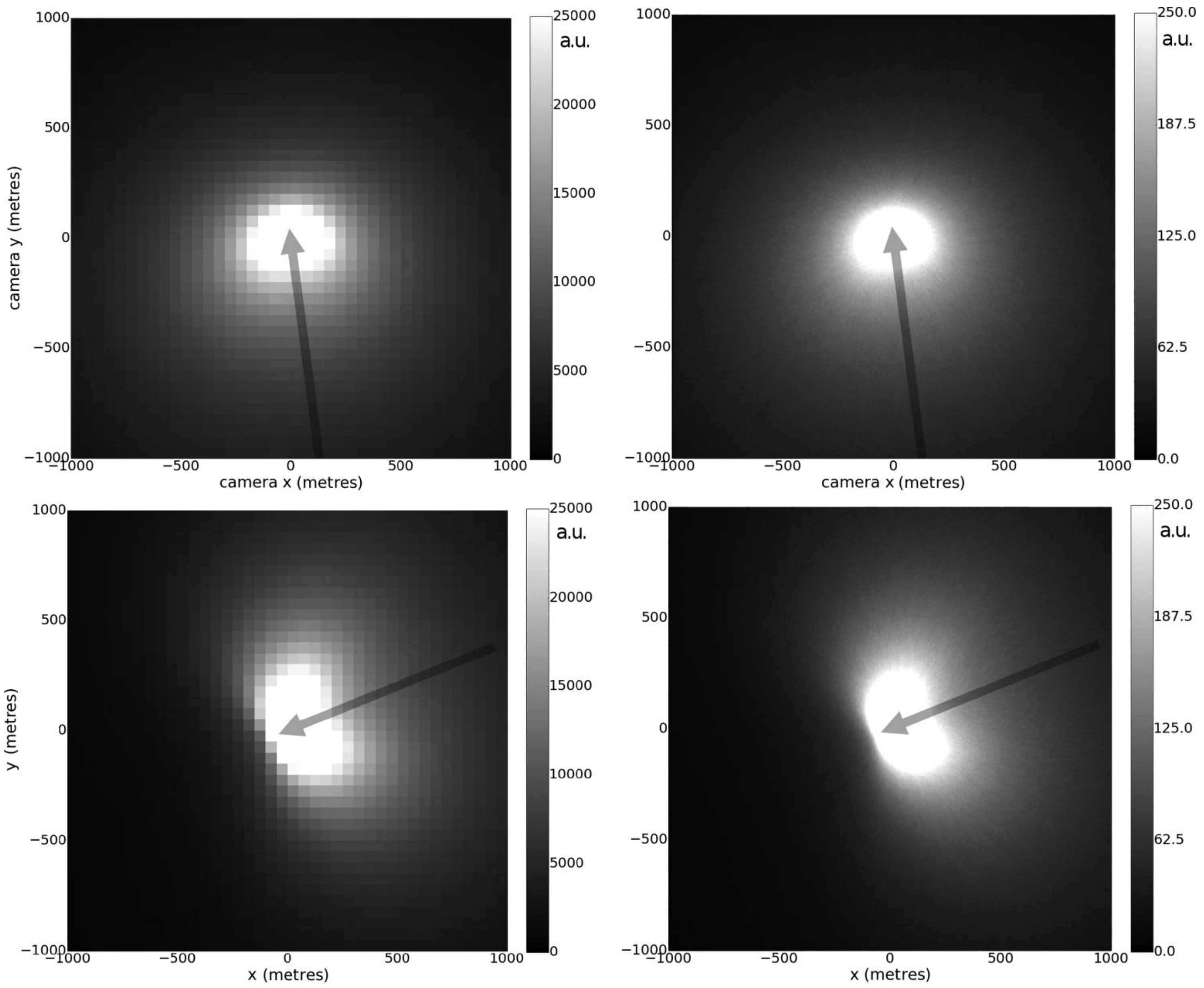


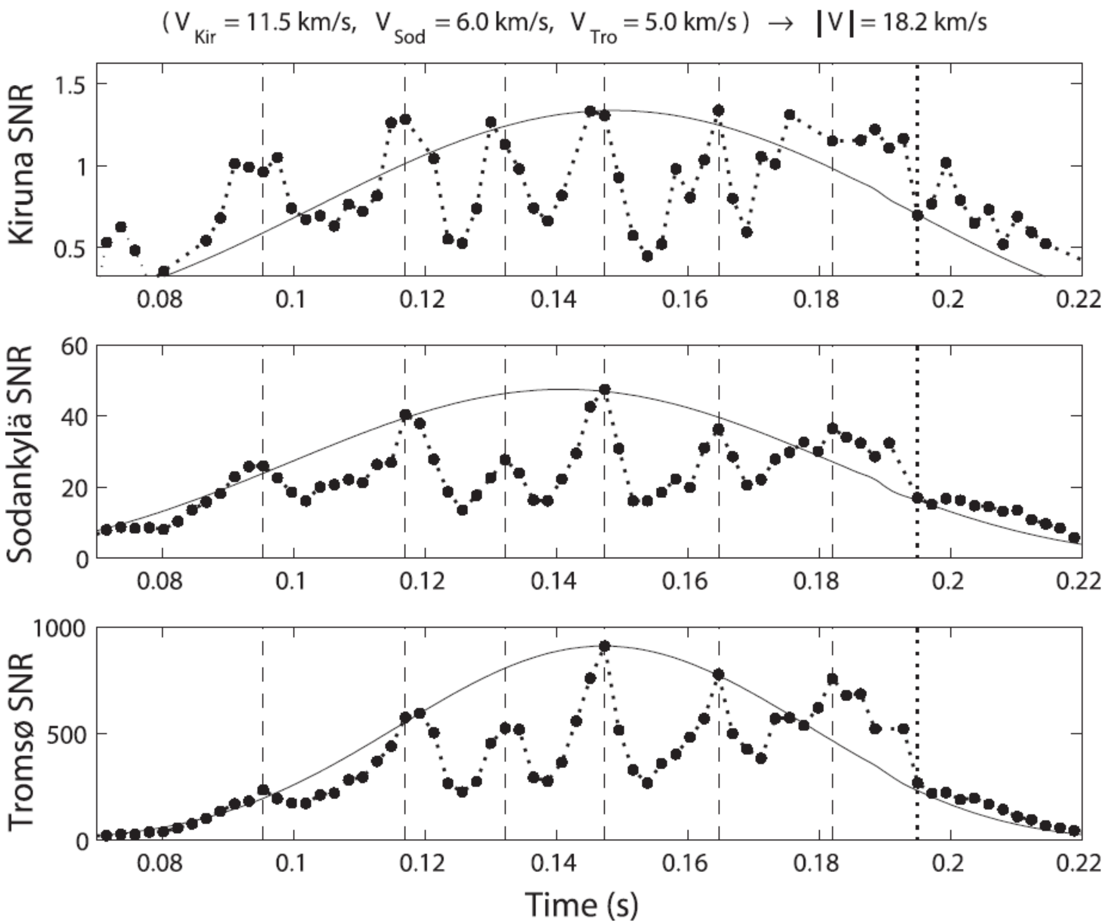
magnetization of trail electrons = faster drift along B (Oppenheim and Dimant, 2015).

Proton-induced halo formation in charged meteors

Šiljić et al, MNRAS, 481, 2858 (2018)

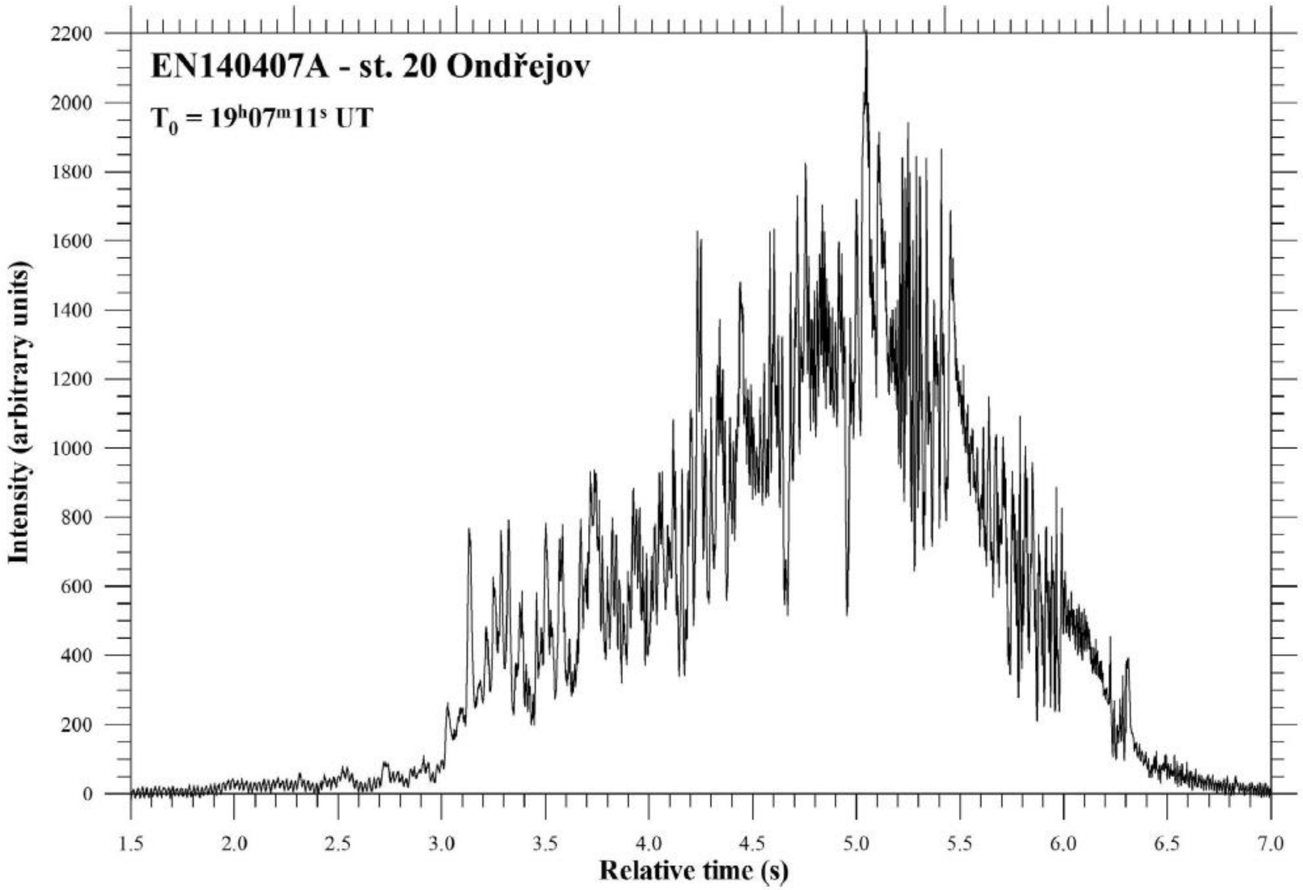






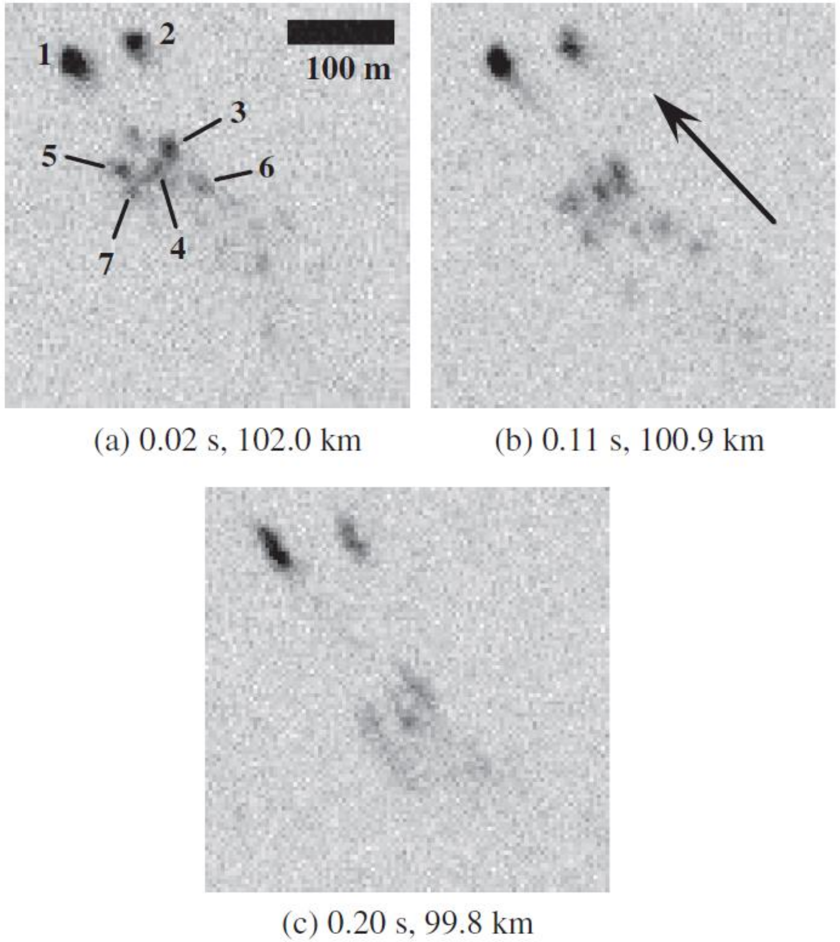
Pulsations of meteor head plasma detected using tristatic 930 MHz EISCAT UHF radar system (Kero et al 2008)

(and submillimeter fragmentation events from radars)



Millisecond flares (Spurný & Ceplecha, 2008)

Charged meteors might be the explanation!

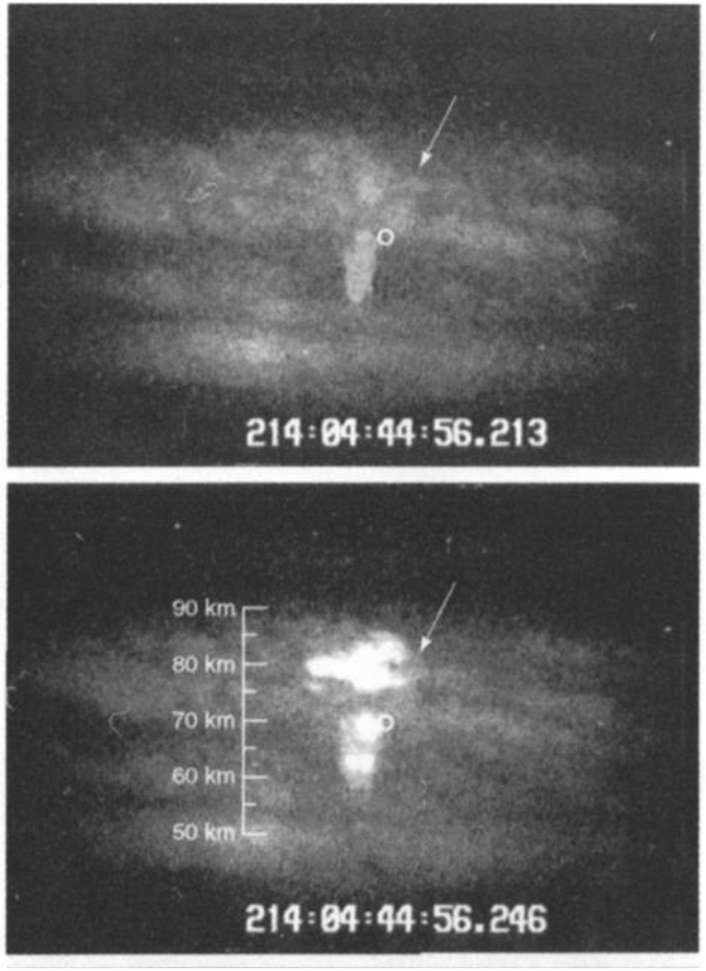


(a) 0.02 s, 102.0 km

(b) 0.11 s, 100.9 km

(c) 0.20 s, 99.8 km

Fragmentation above 100km with high transverse speeds (Stokan & Campbell-Brown, 2014)



meteors triggering sprites?
(Suszcynsky et al 1999)

Charged meteors might be important!

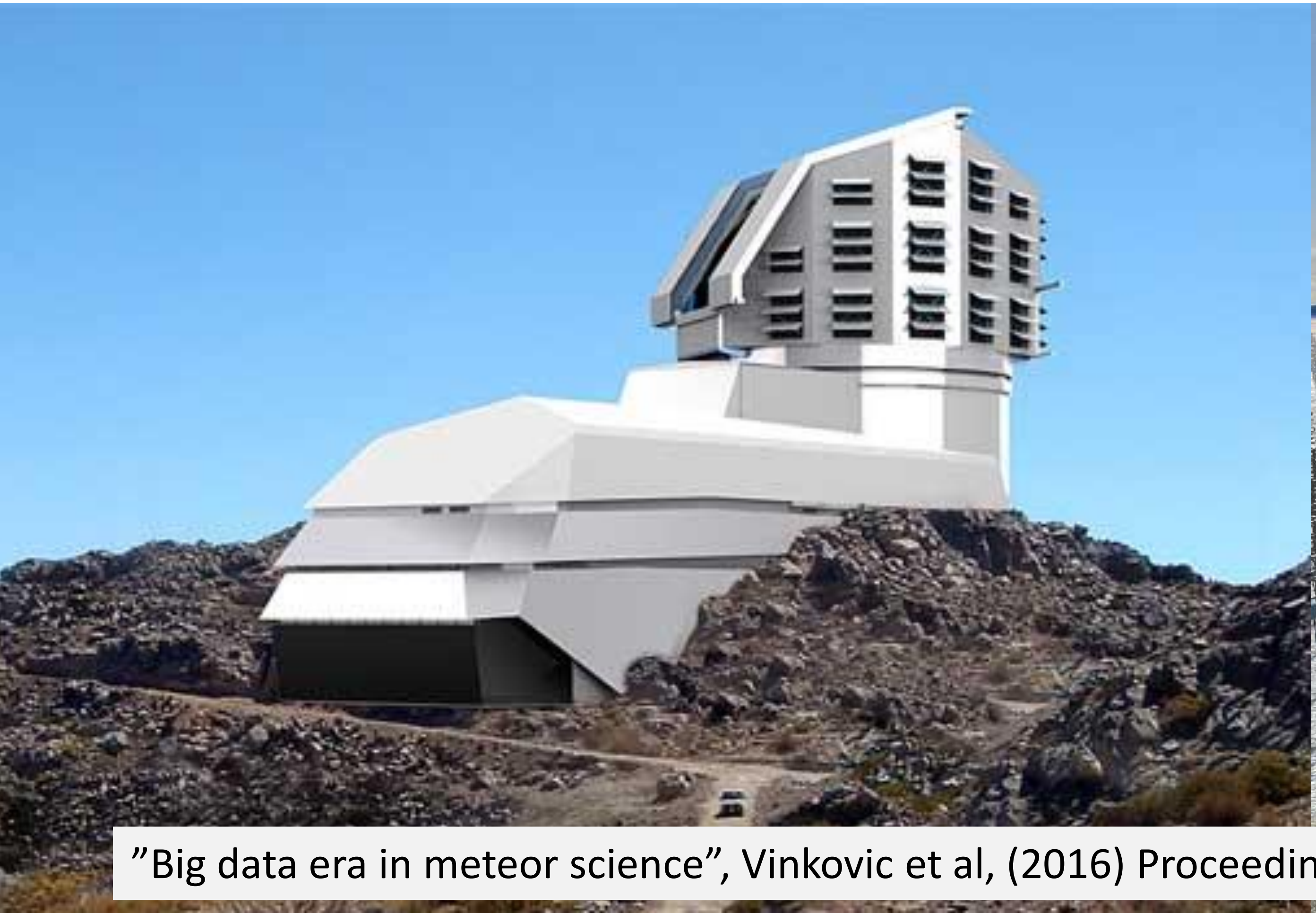
LSST can map the entire visible sky in just a few nights

- 3200-megapixel camera (FoV of 40 times the full moon)
- 37 billion stars and galaxies
- 10 year survey of the sky
- EVERY NIGHT: 10 million alerts, 1000 pairs of exposures,15 Terabytes of data

EISCAT_3D: a multistatic radar composed of

- five phased-array antenna fields
- each field ~10,000 crossed dipole antennas
- will act as receivers, transmitting at 233 MHz (VHF band)
- spread over Finland, Norway and Sweden.

~190,000 meteor orbits per day

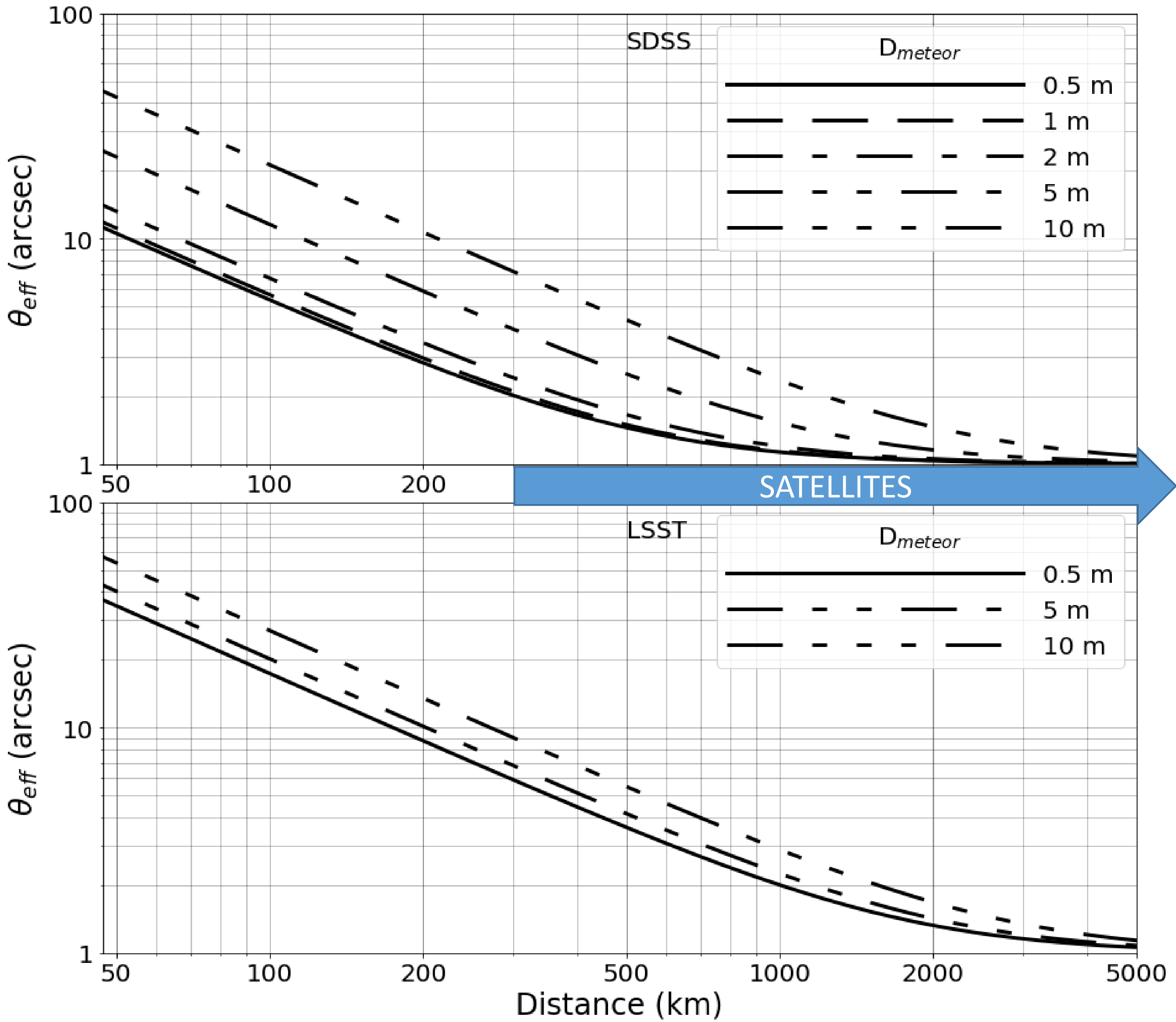


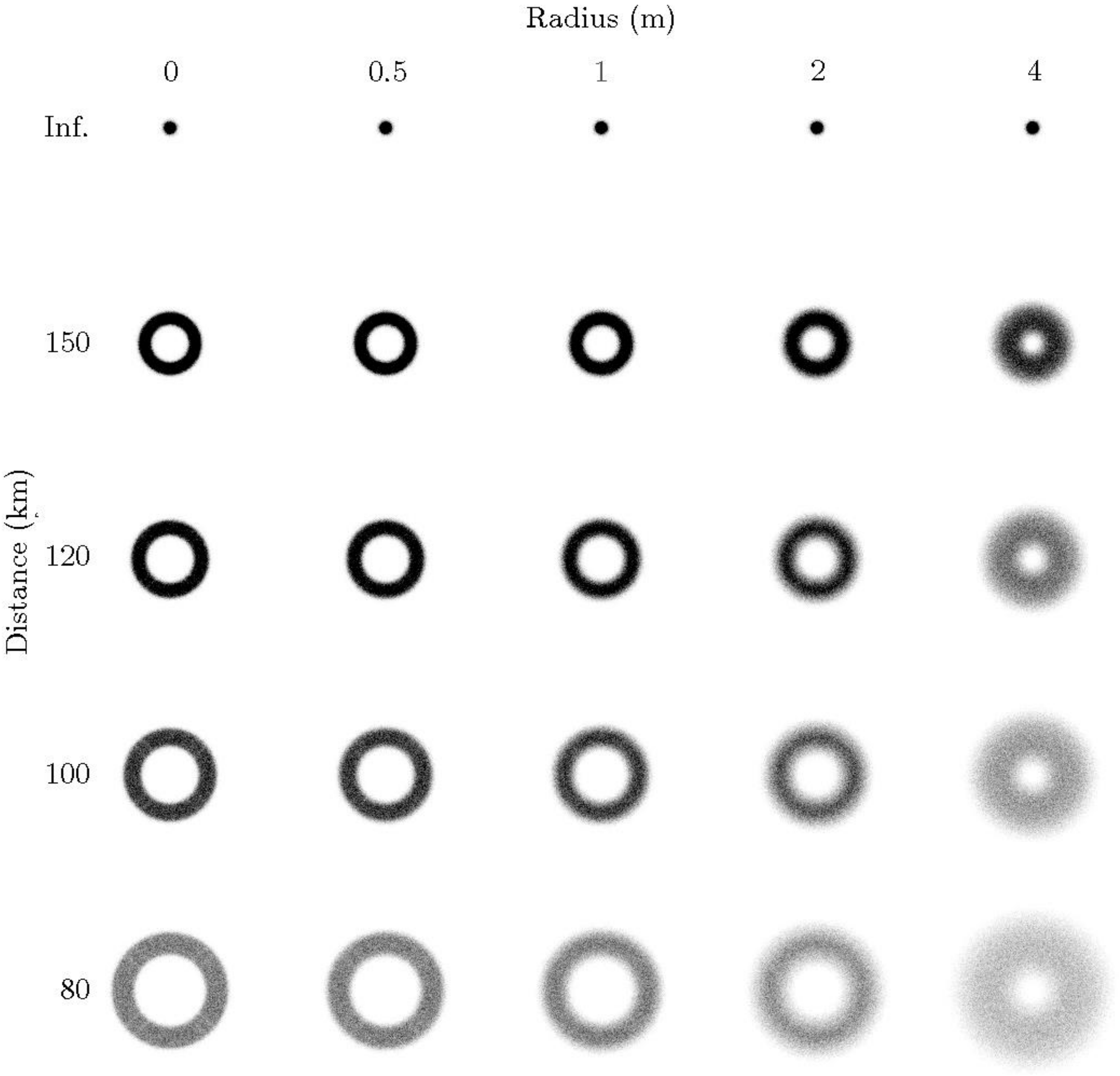
”Big data era in meteor science”, Vinkovic et al, (2016) Proceedings of the International Meteor Conference, Egmond

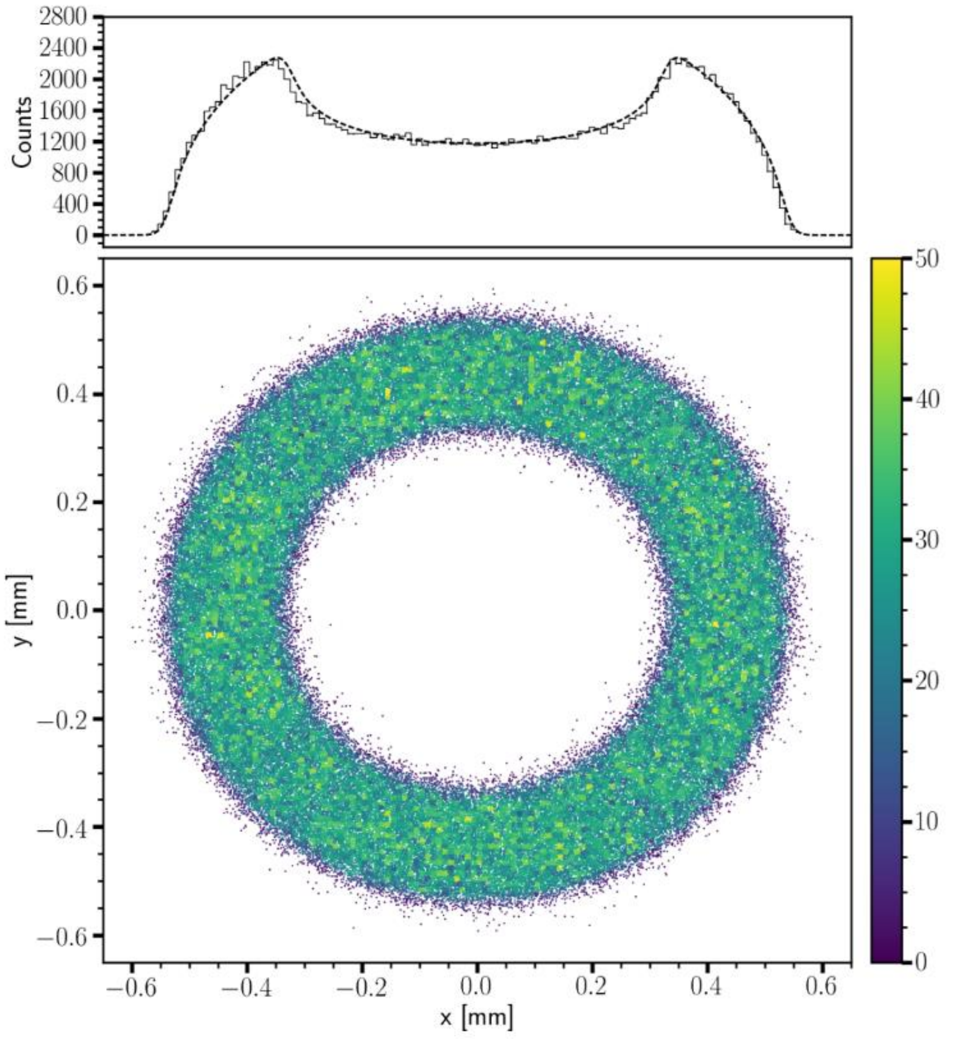
Defocusing of meteor tracks

Bektešević et al. (2017) MNRAS, 474, 4837

approximate →



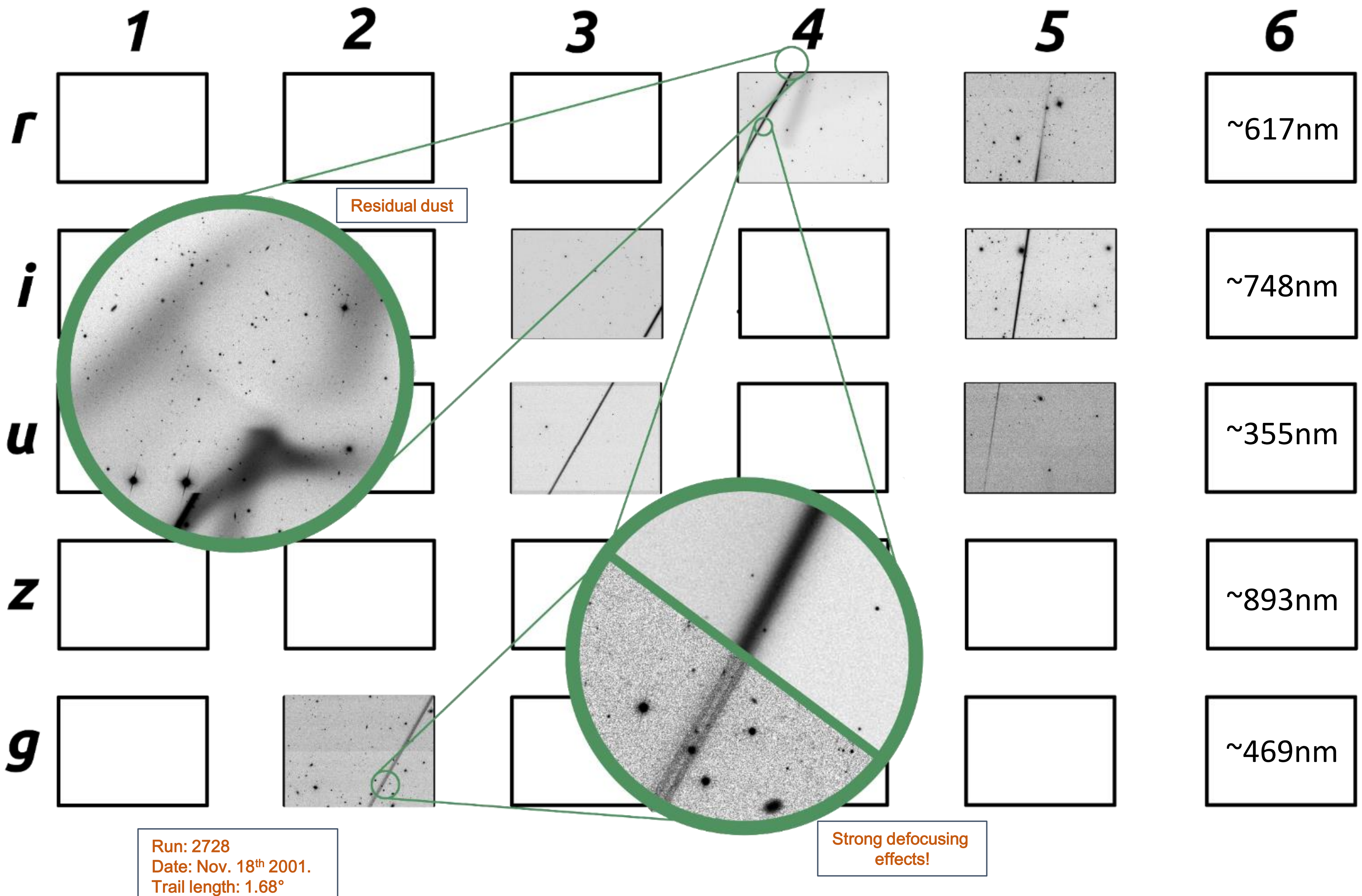




ray-tracing simulations of meteors observed with LSST

meteor detections on images from sky survey telescopes

high-resolution
&
high-sensitivity
&
high-precision photometry
&
resolved (defocused)

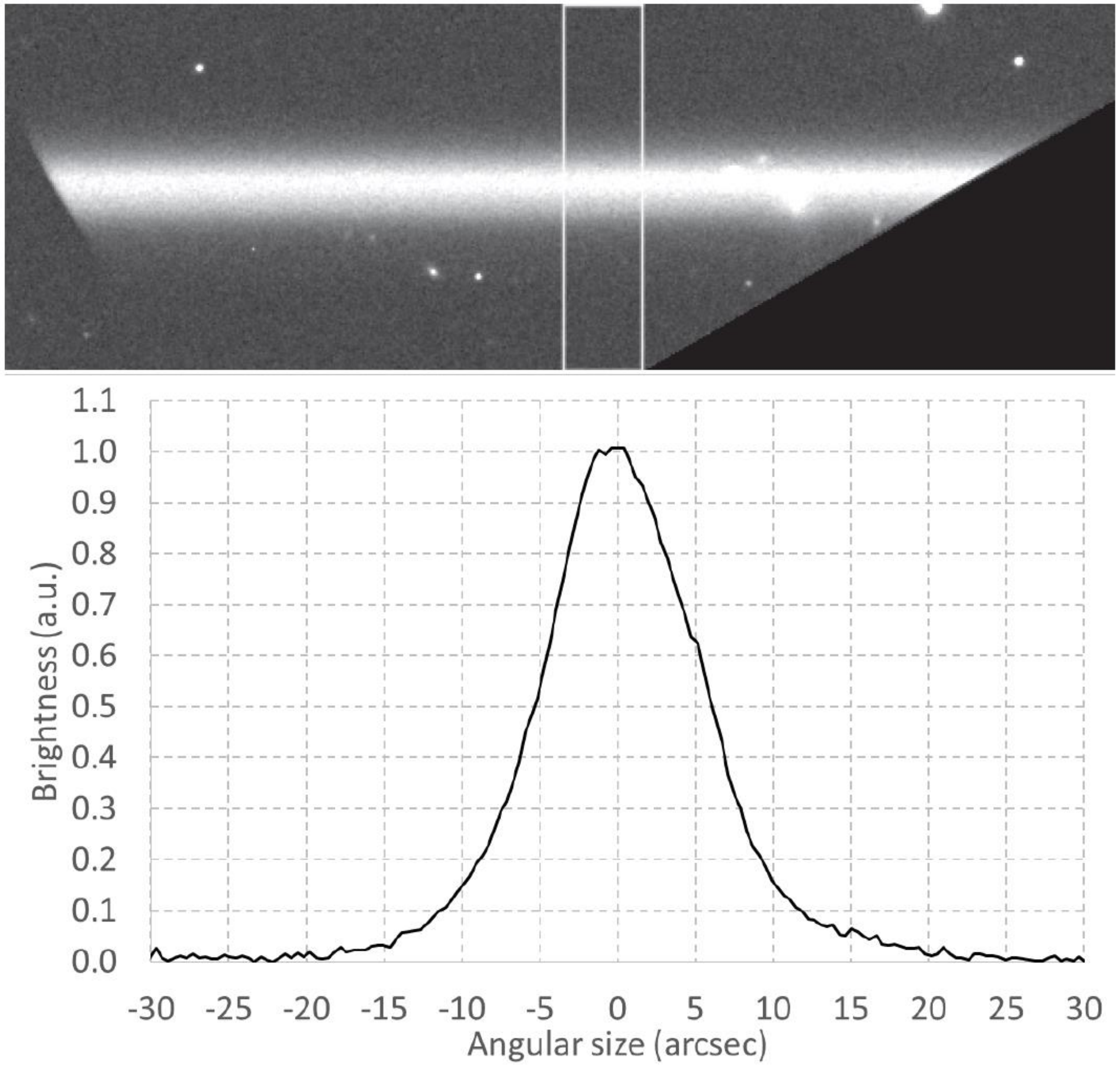


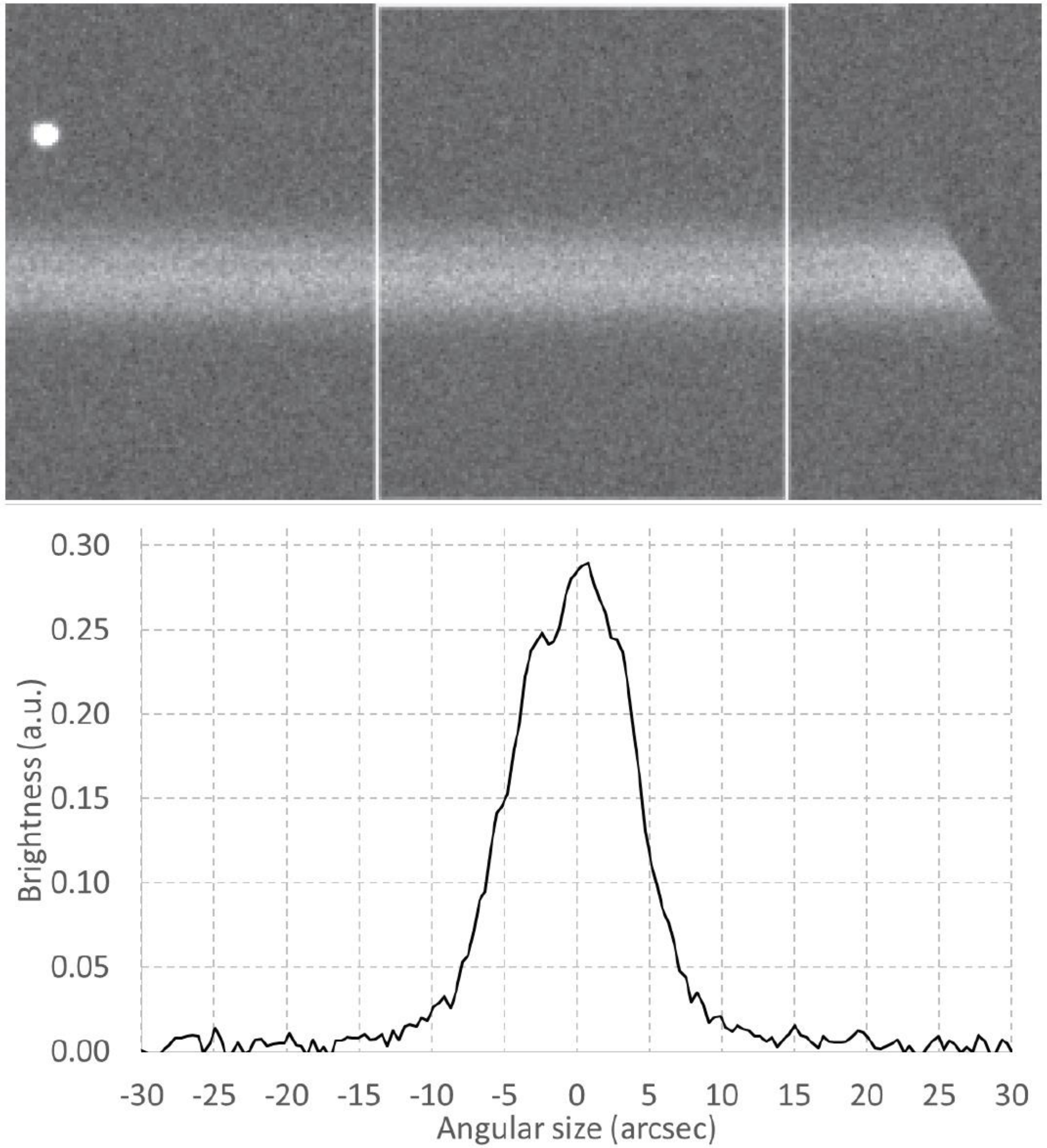
Run: 2728
Date: Nov. 18th 2001.
Trail length: 1.68°
Angular speed: 6.63°/s

Bektesevic & Vinkovic (2017) MNRAS, 471, 2626

SDSS example

November 18, 2001, at 04:57:21.39 TAI.
probably a Northern Taurid meteor



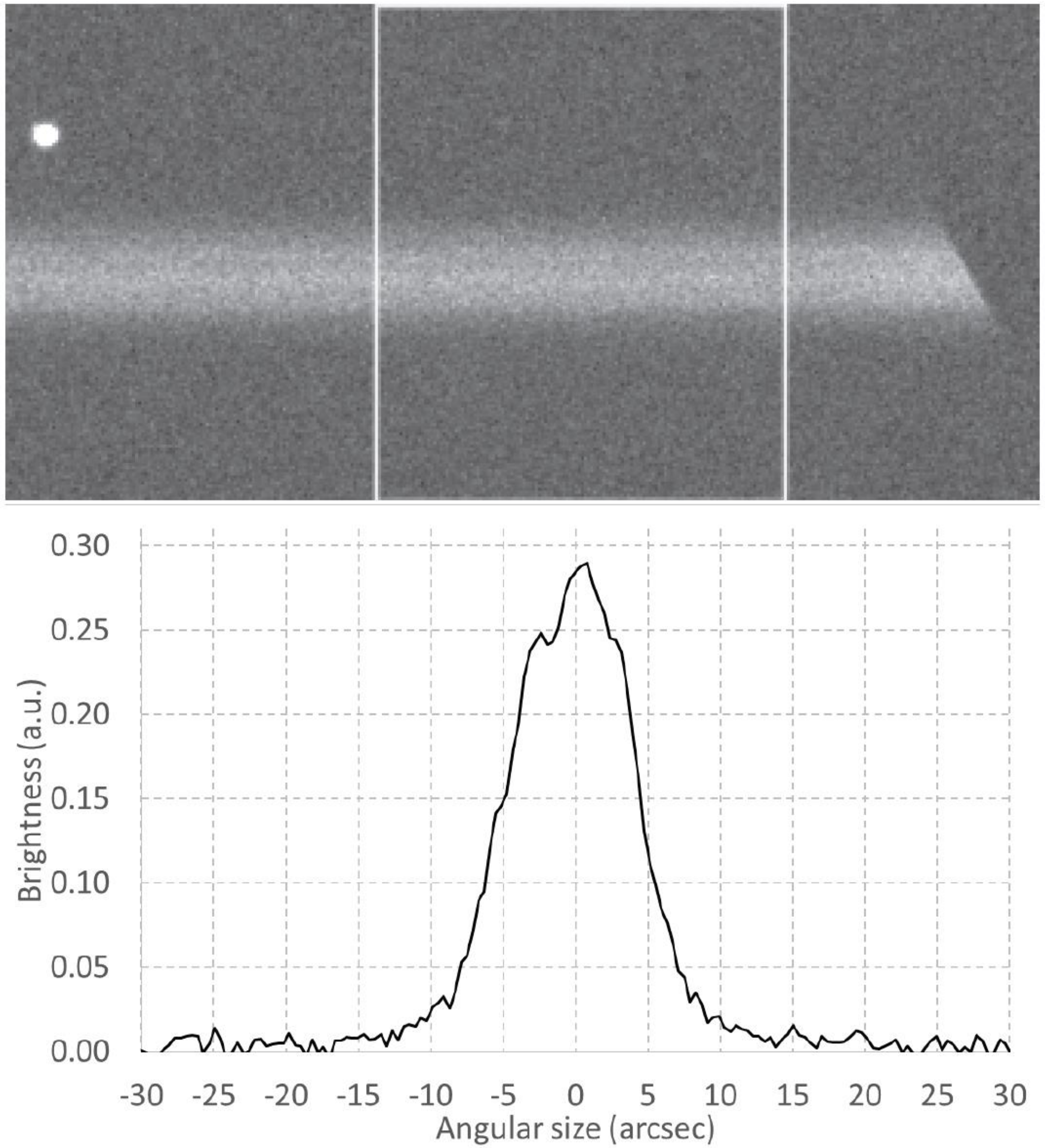


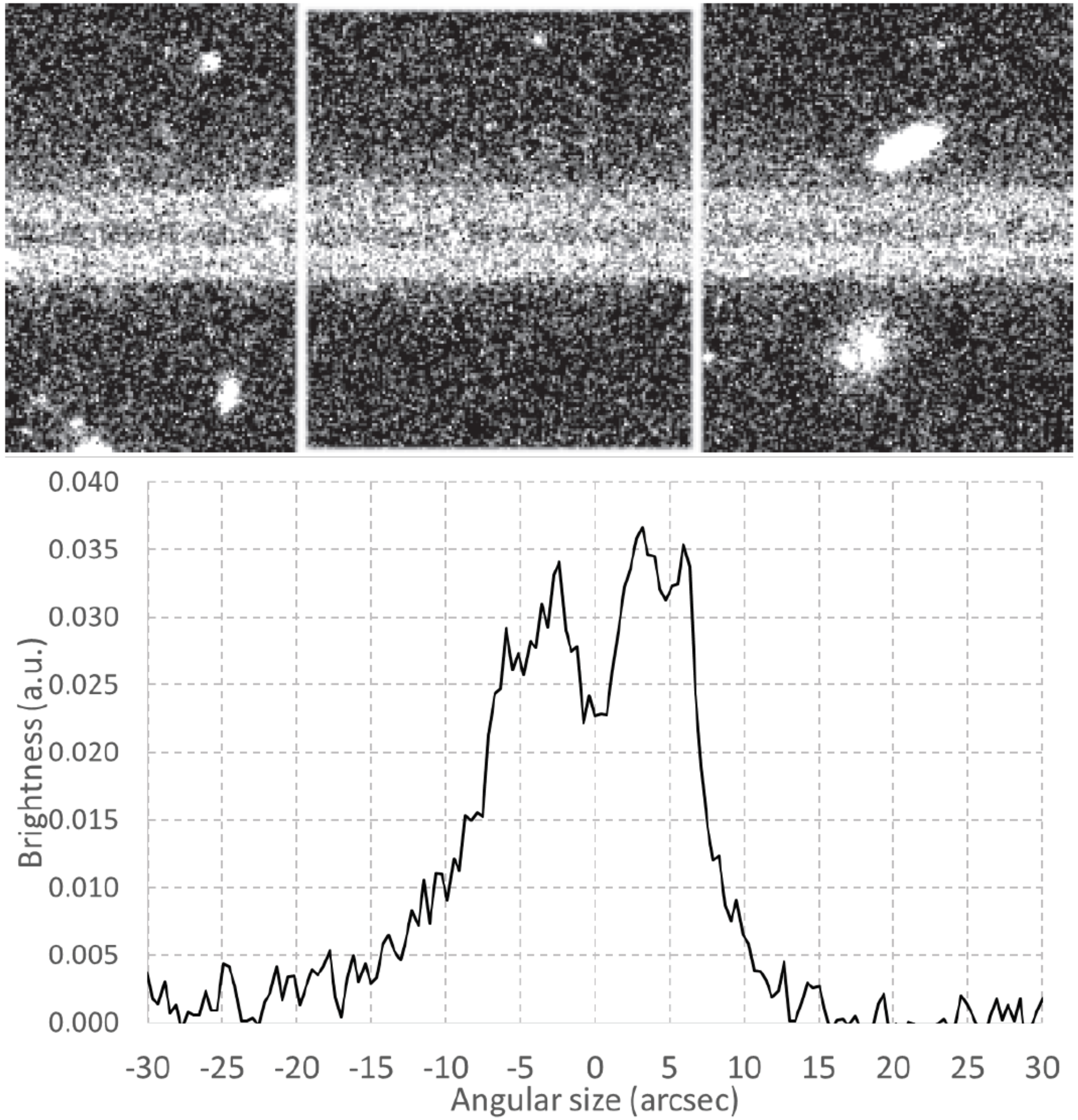
SDSS *i* filter: ~10m plasma ball

~100m later →

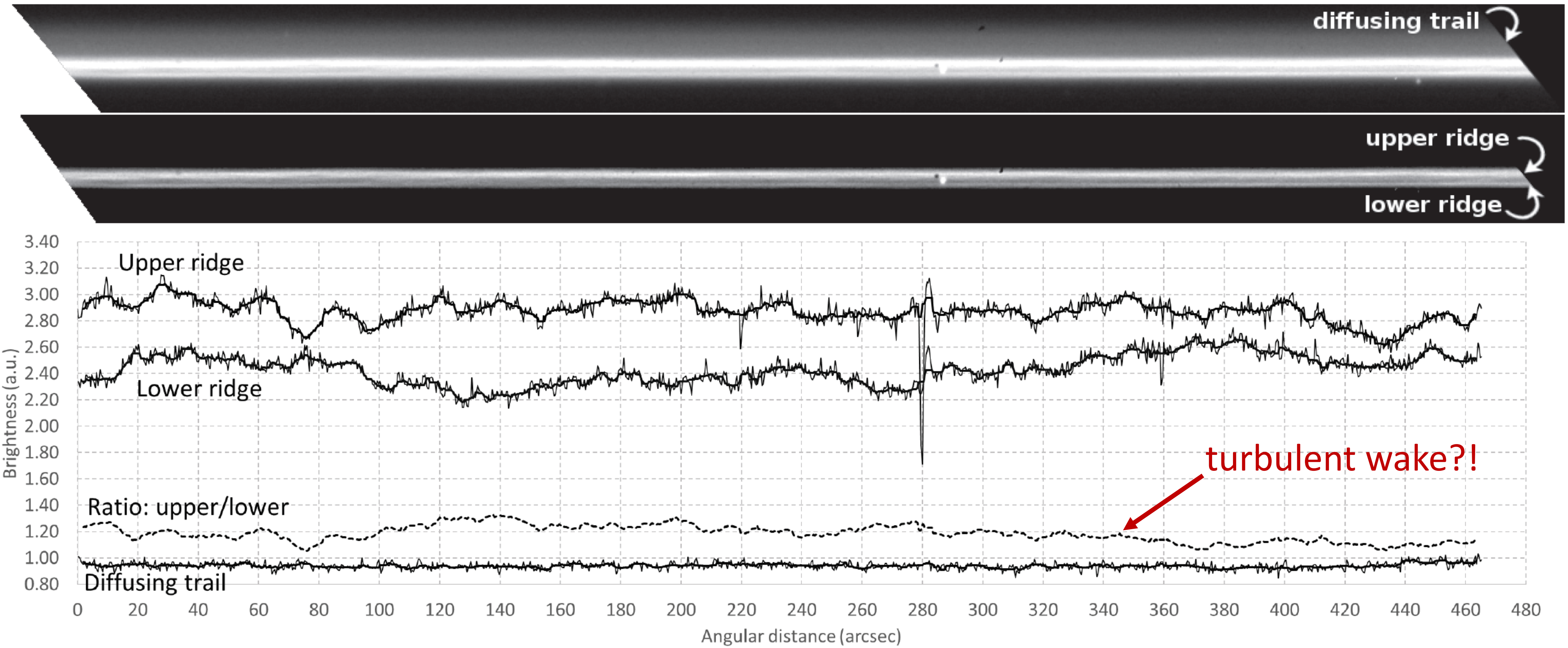
SDSS *u* filter

November 18, 2001, at 04:57:21.39 TAI.
probably a Northern Taurid meteor





SDSS *u* filter → ~2km later → SDSS *g* filter: 2 objects <1m; separated ~6m



Bektešević et al. (2017) MNRAS, 474, 4837

Our understanding of meteor plasma and hypervelocity shock physics in rarefied partially ionized and partially magnetized ionospheric plasma is NOT complete.

Diverse observational techniques:

- Cameras on the ground (images, spectra, triangulation, photometry)
- Detectors in orbit (images, spectra – UV)
- Images and spectra from big telescopes and sky surveys
- Three dimensional radar observations (EISCAT_3D)
- ELF/VLF/LF radio signals
- etc.

Theory should go beyond the standard phenomenology!