The Chelyabinsk Airburst Event

SAND2013-8399C

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Sandia National Laboratories

AAS 45th Annual Meeting, Division for Planetary Sciences
October 6-11, 2013, Denver, Colorado

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. Mark Boslough's funding provided by Sandia National Laboratories LDRD program.

Chelyabinsk Consortium Funding provided by the NASA-Meteoroid Environment Office.

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Outline

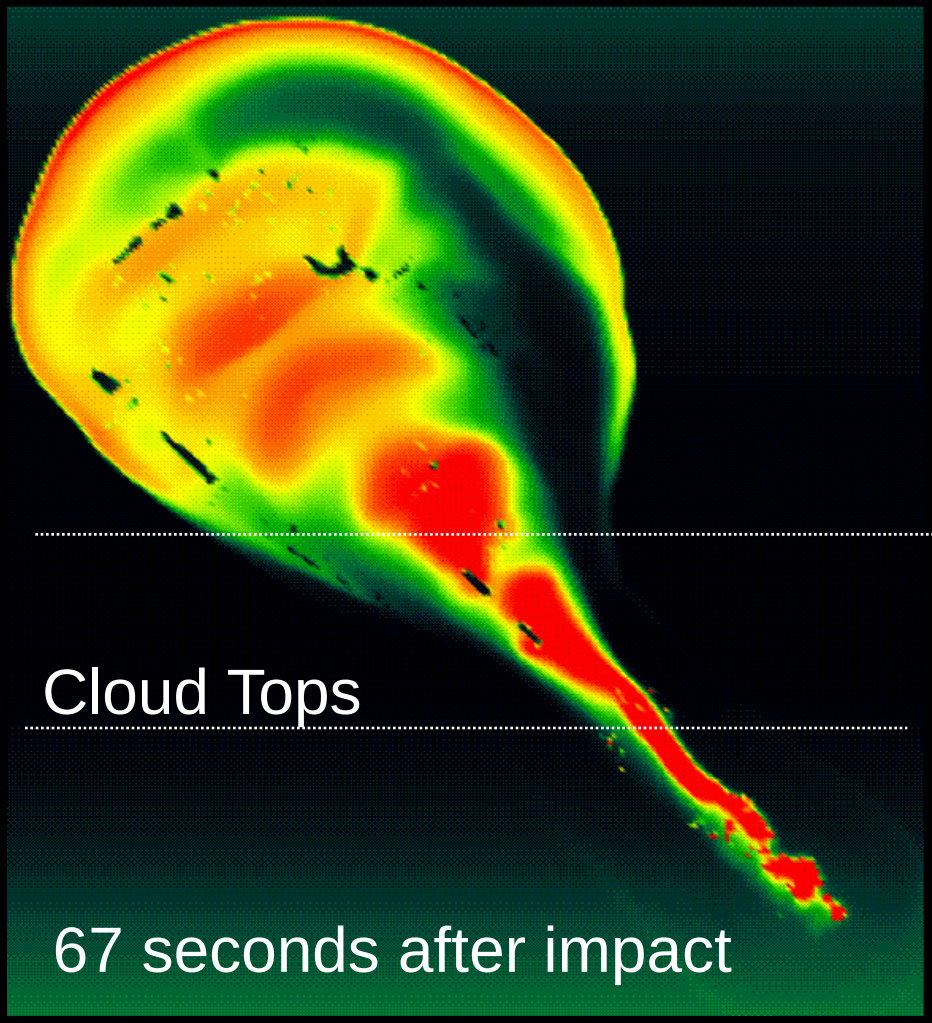
1) **Background: collisional airbursts**
2) The Chelyabinsk event
3) Computational modeling

First direct observation of atmospheric collision: Shoemaker-Levy 9 comet crash: Jupiter, 1994

Shoemaker-Levy 9

"The gift that keeps on giving"

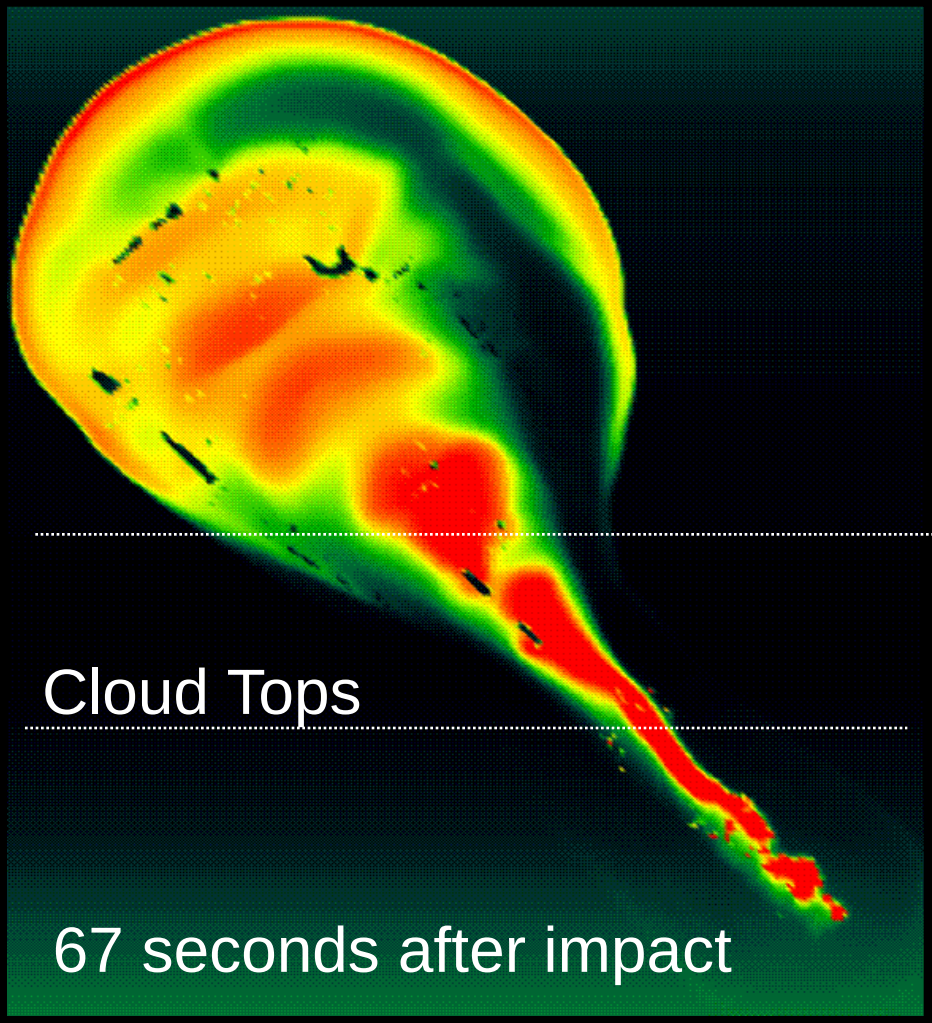
Plumes from collisional airbursts: Emergent phenomenon
Discovered in 1993 by computation of Shoemaker-Levy 9



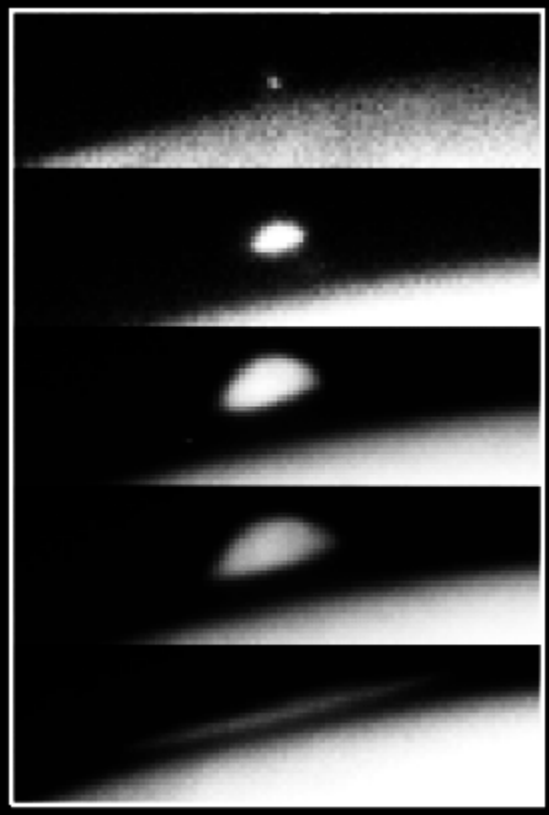
Visible From Earth

Behind Jupiter

Airburst is a line explosion that ejects a plume: Observational validation by Shoemaker-Levy 9 impact

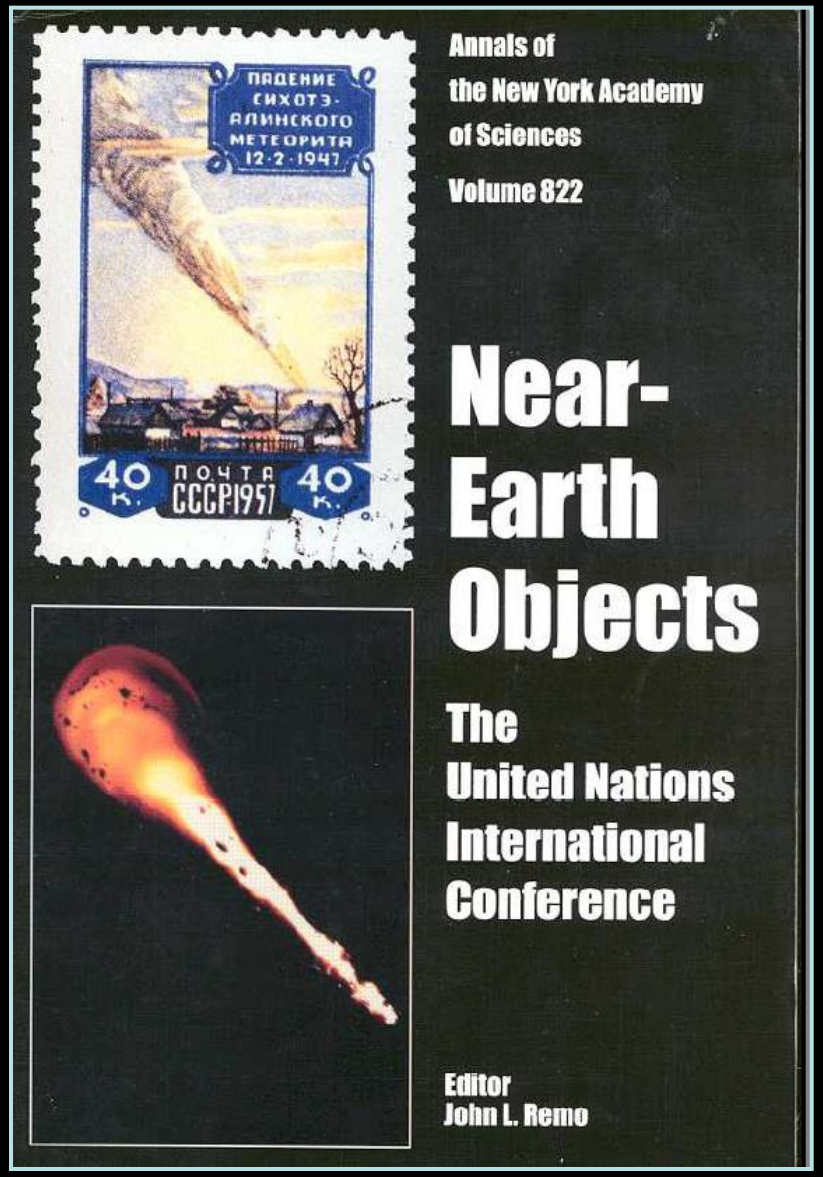


Impact G



Hubble Space Telescope Image

Plumes and line explosions on Earth



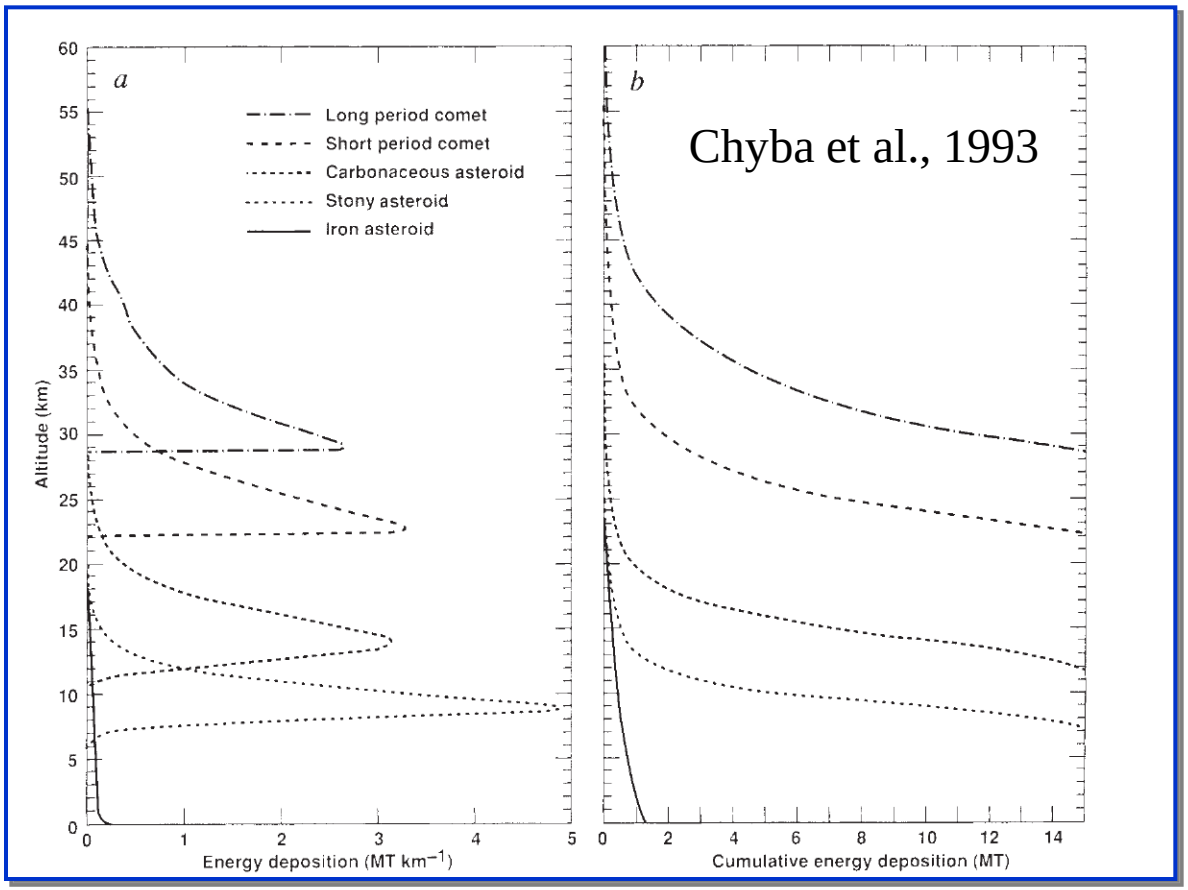
Pancake model: Earth's atmosphere protects us from low-altitude airbursts

Chyba et al. (1993), "The 1908 Tunguska explosion: atmospheric disruption of a stony asteroid" *Science*.

$$m\frac{dv}{dt} = -\tfrac{1}{2} C_D \rho A v^2$$

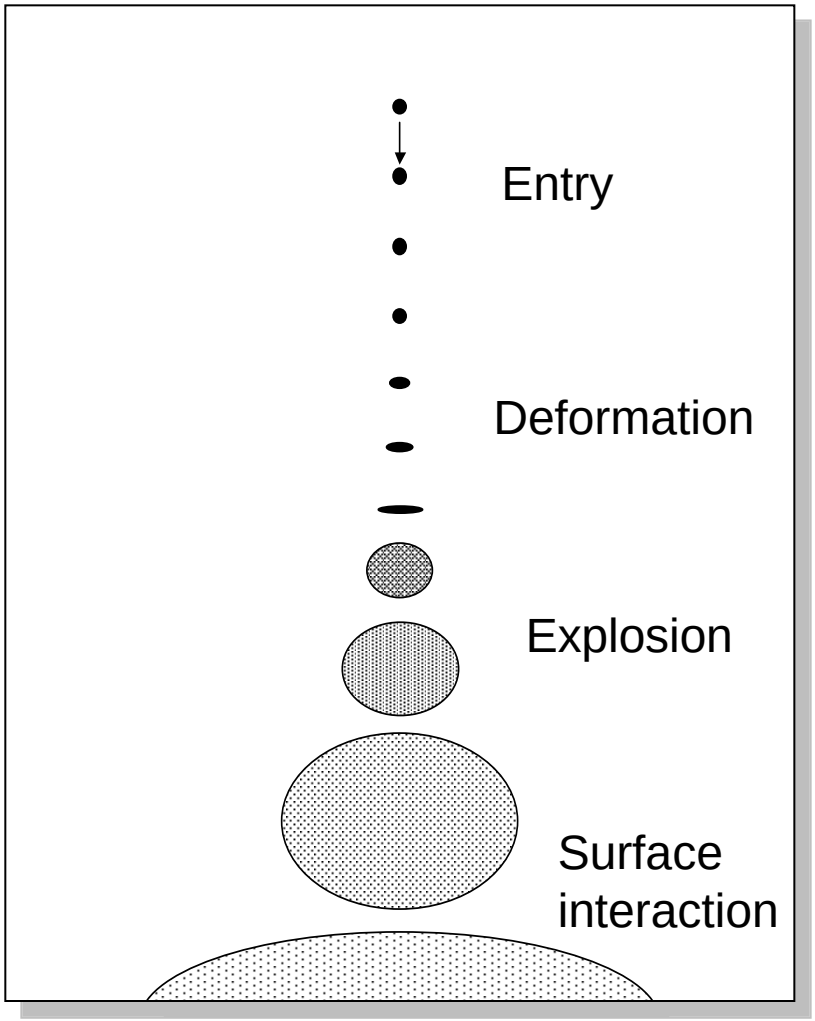
$$q\frac{dm}{dt} = -\tfrac{1}{2} C_H \rho A v^3$$

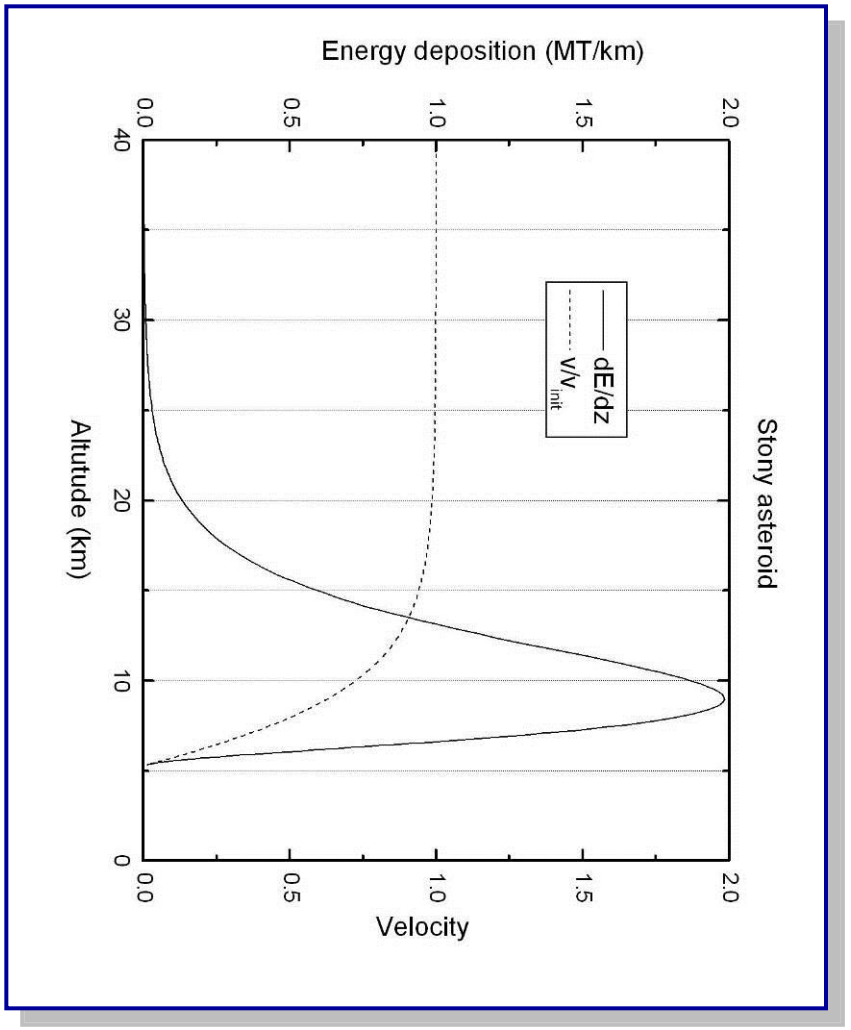
$$\mathrm{r}\frac{d^2 r}{dt^2} = -\tfrac{1}{2} C_D \frac{\rho}{\rho_m} v^2$$



A stony asteroid deposits essentially all of its kinetic energy above 7 km. In this model the energy deposition curve is sharply peaked because of the mutually-reinforcing effects of atmospheric drag and deformation. Subsequent modeling has been based on point-source explosions and nuclear weapons effects.

Pancake model revisited: Earth's atmosphere is actually penetrated by hot vapor jet





The "point source explosion" model is a poor approximation.

Difference between explosion and impact

Temperature: 500 K  3000 K

5 megatons: first 20 seconds

Explosion

5 km

15 km

Difference between explosion and impact

Temperature: 500 K  3000 K

5 megatons: first 20 seconds

Impact Airburst

5 km

15 km

Two types of Low-Altitude Airburst

Tunguska tree-fall

Libyan Desert Glass

Type 1: Tunguska

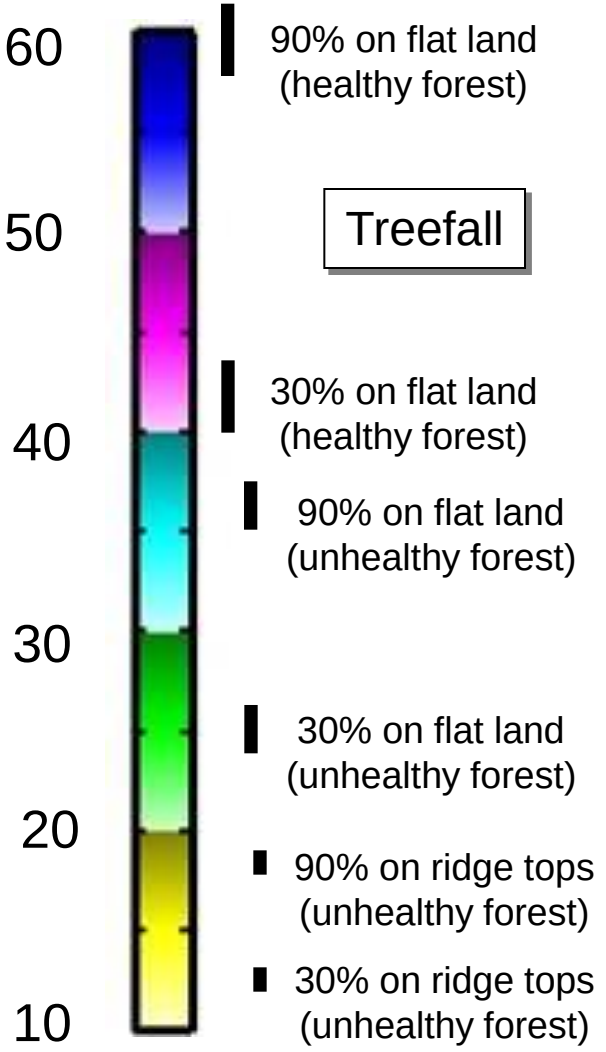
Scorches and blows down trees

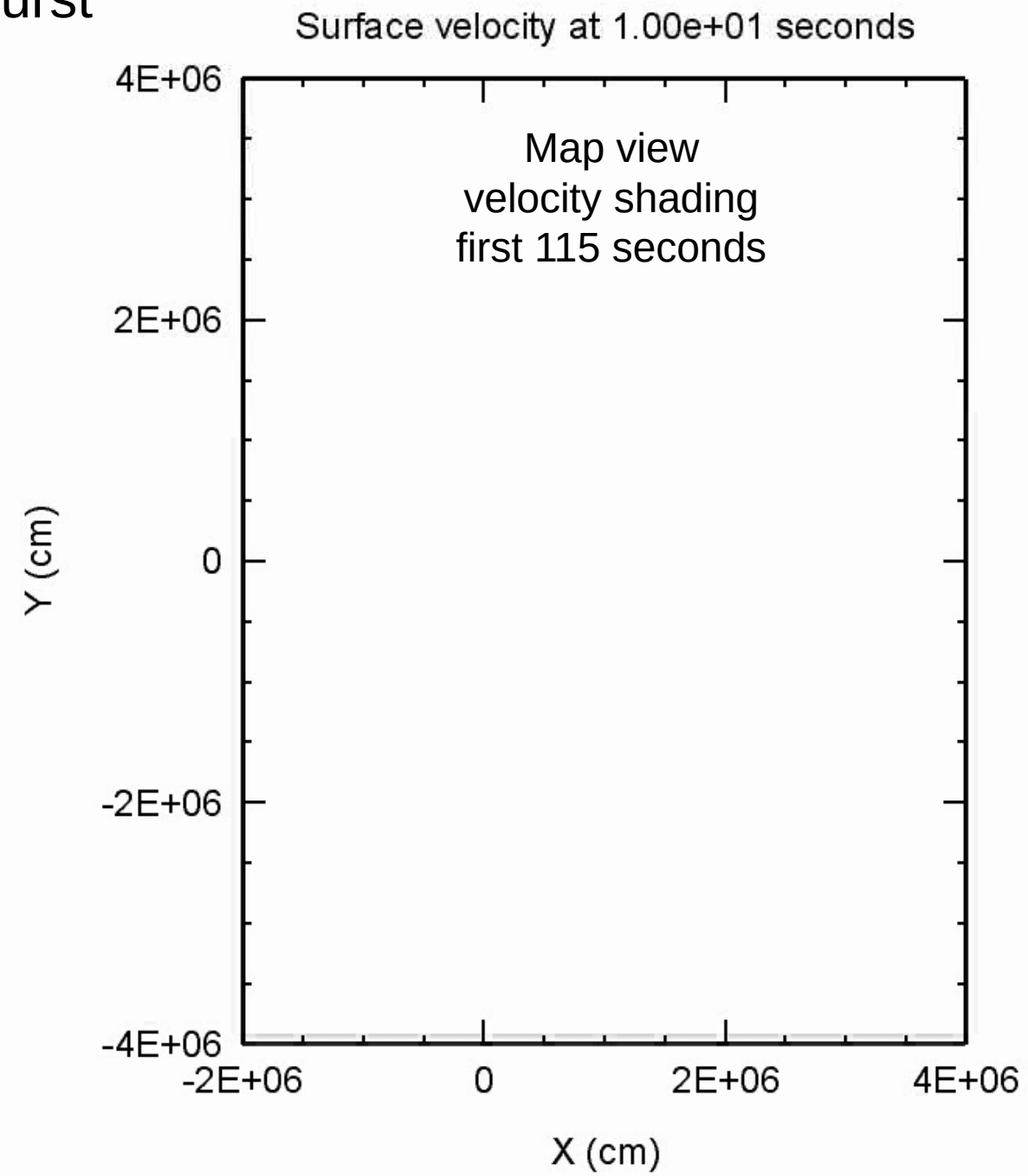
Type 2: Libyan Desert

Vaporizes trees and melts rocks

Tunguska airburst simulation: 5 Mt

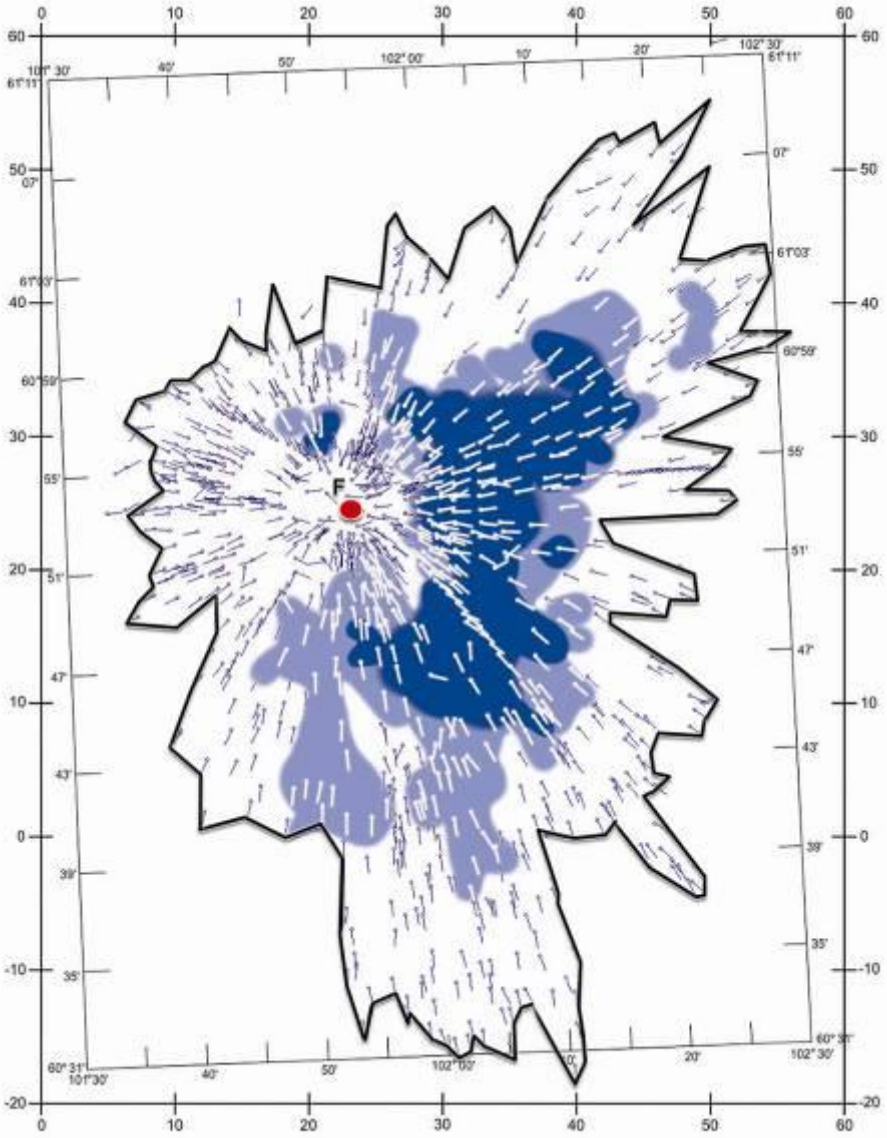
Modeling Type 1 airburst



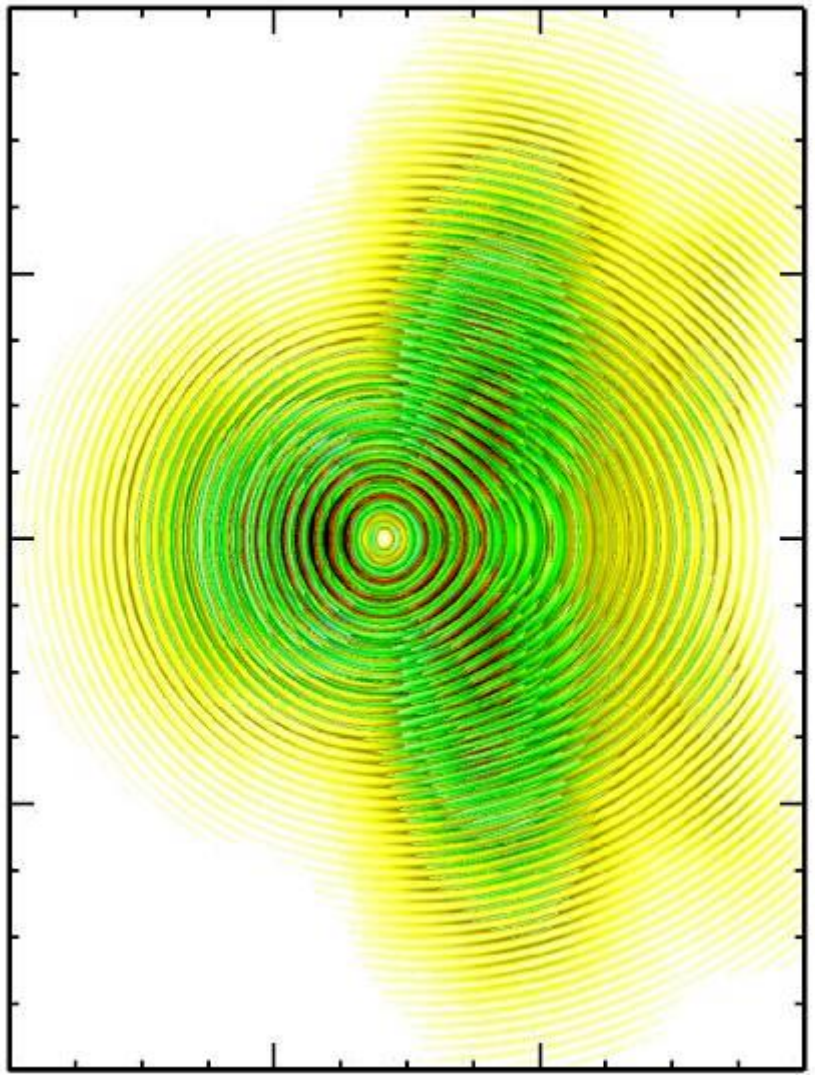


5 Mt explosion at 12 km above surface, 35° entry angle

"Experimental" data demonstrate that event was below threshold

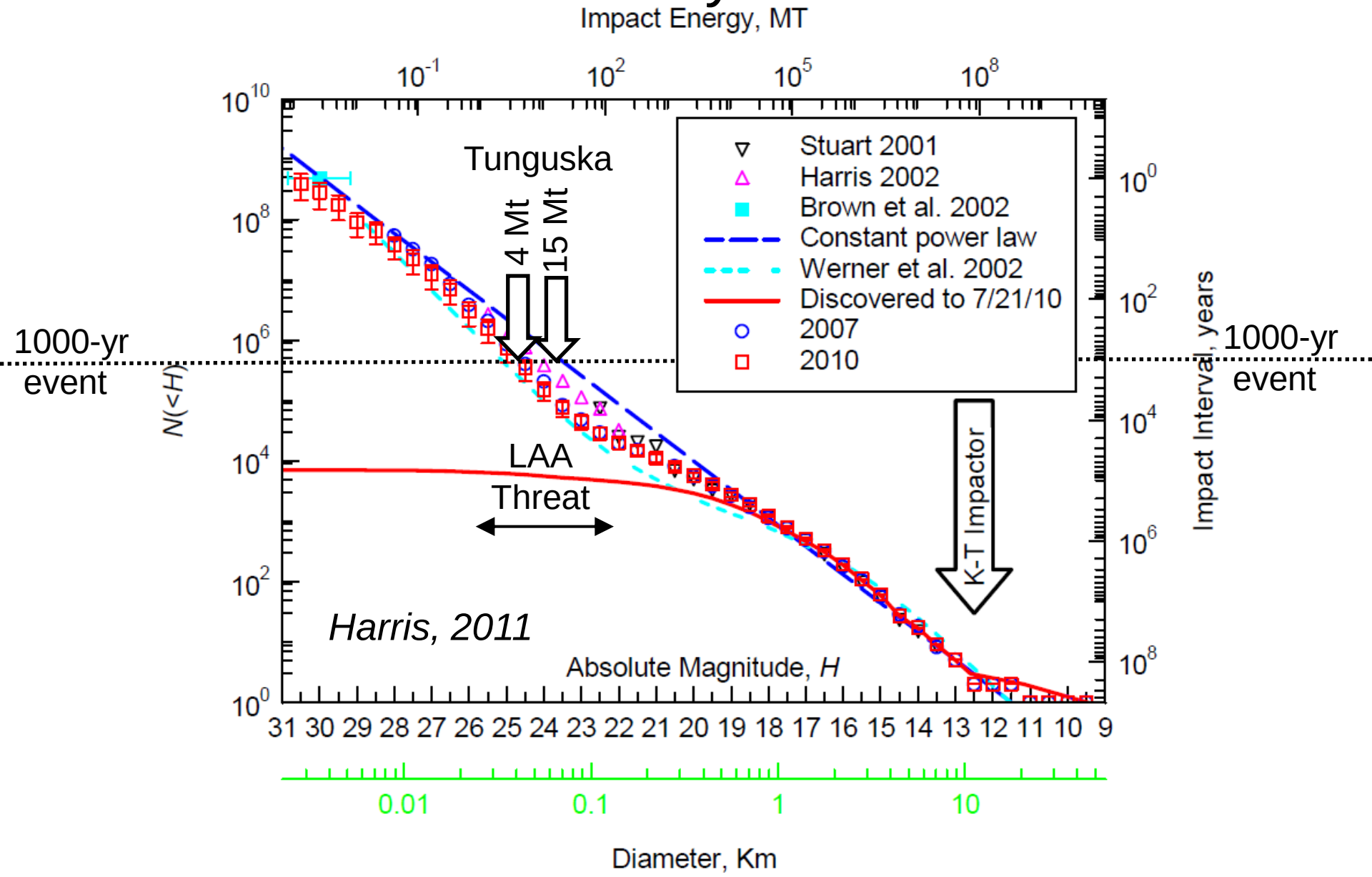


Tunguska treefall map (Longo et al, 2005)



Wind speed map (this study)

Tunguska yield reduced from ~15 to ~4 Mt
Still a 1000-year event

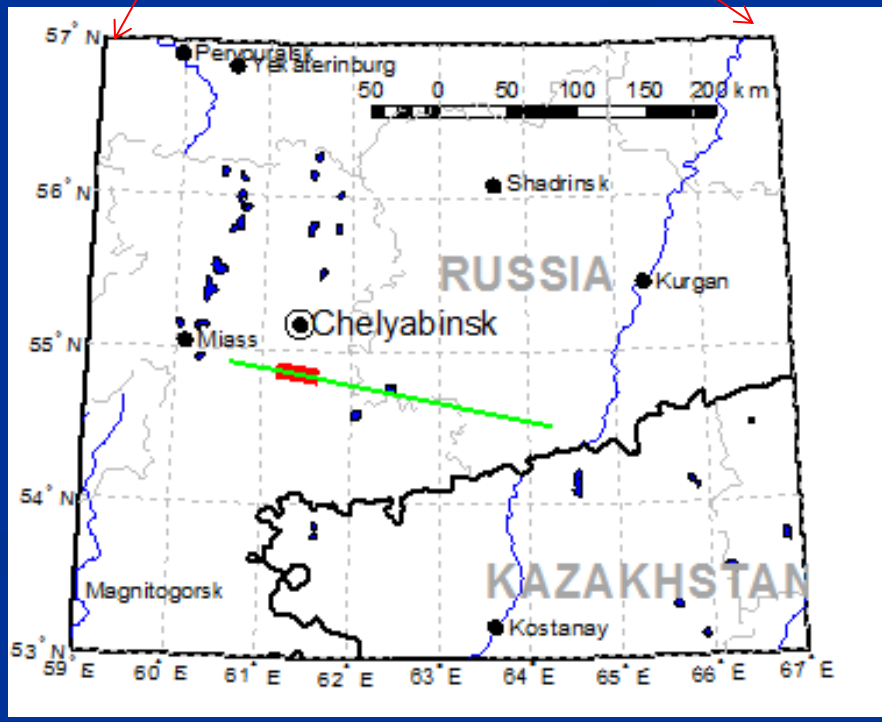


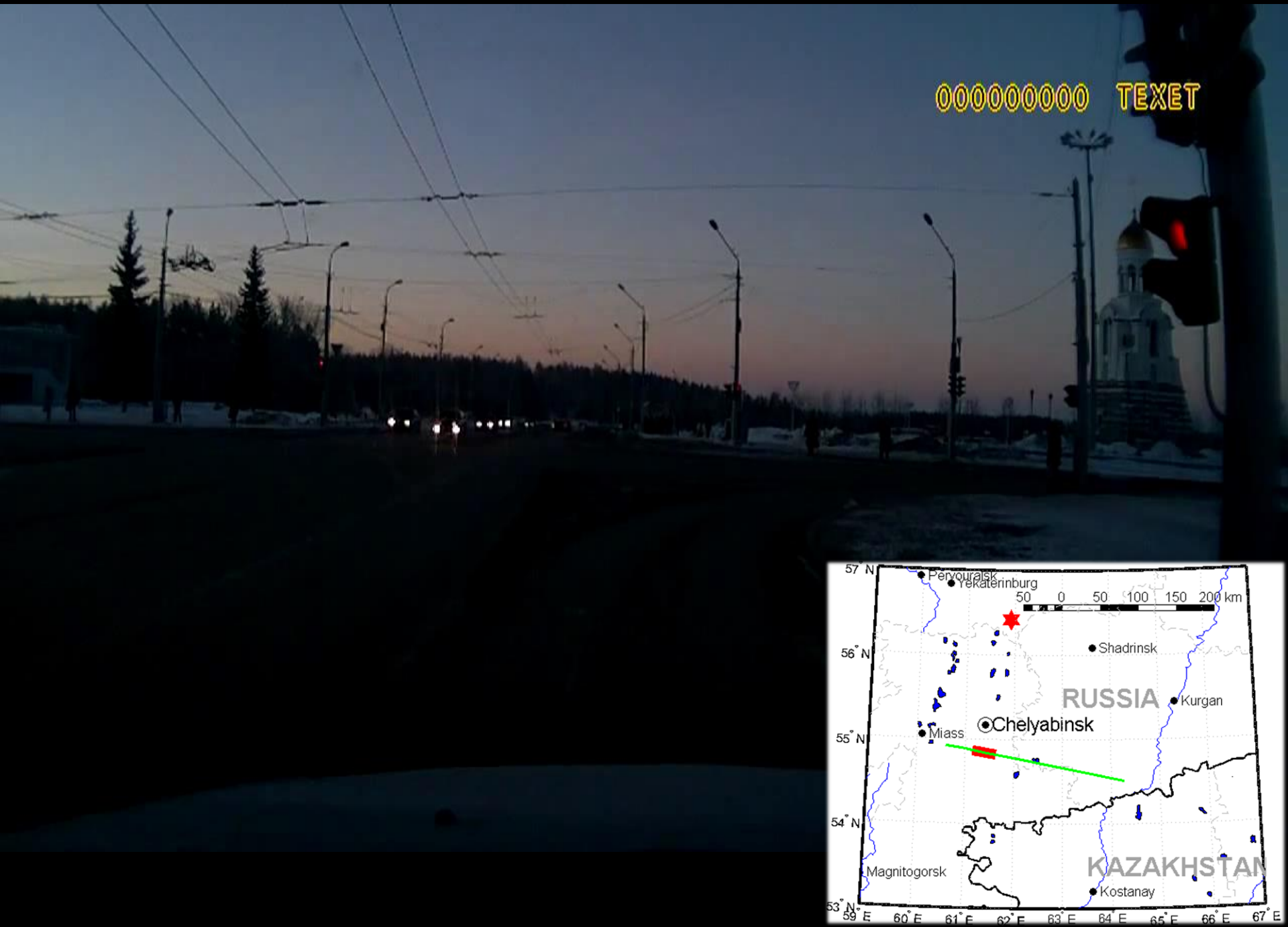
Outline

1) Background: collisional airbursts
2) **The Chelyabinsk event**
3) Computational modeling

Chelyabinsk Fireball - Feb 15, 2013

- Bright fireball occurs at 03:20:33 UT (09:20:33 local) just S. of Chelyabinsk, Russia
- Airblast damaged windows over several thousand km^2; ~1500 persons injured, mainly due to flying glass
- Large number of videos – 452 catalogued to date, 49% show direct fireball or lightflash
- Ordinary chondrite (LL5) meteorites recovered

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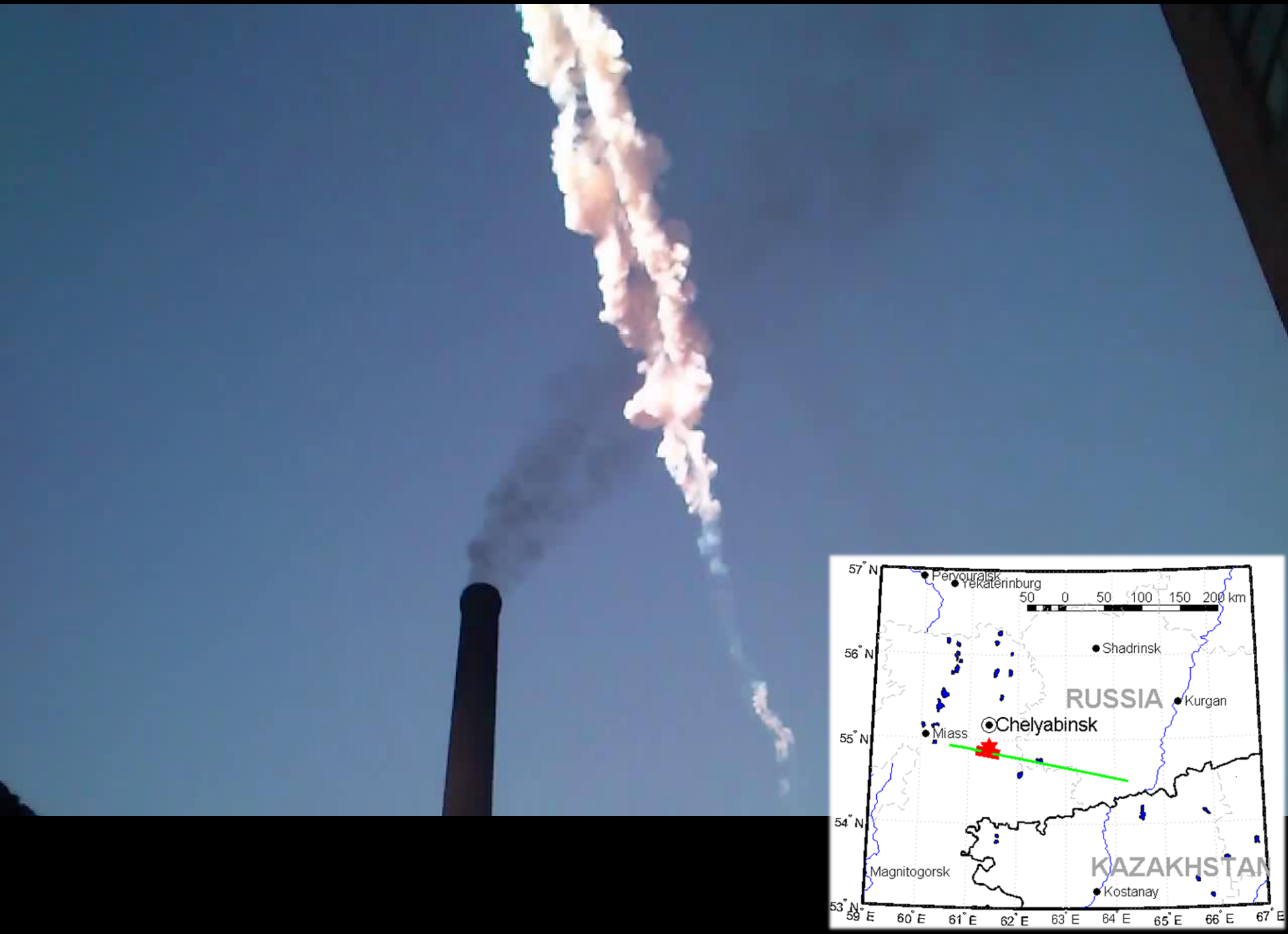
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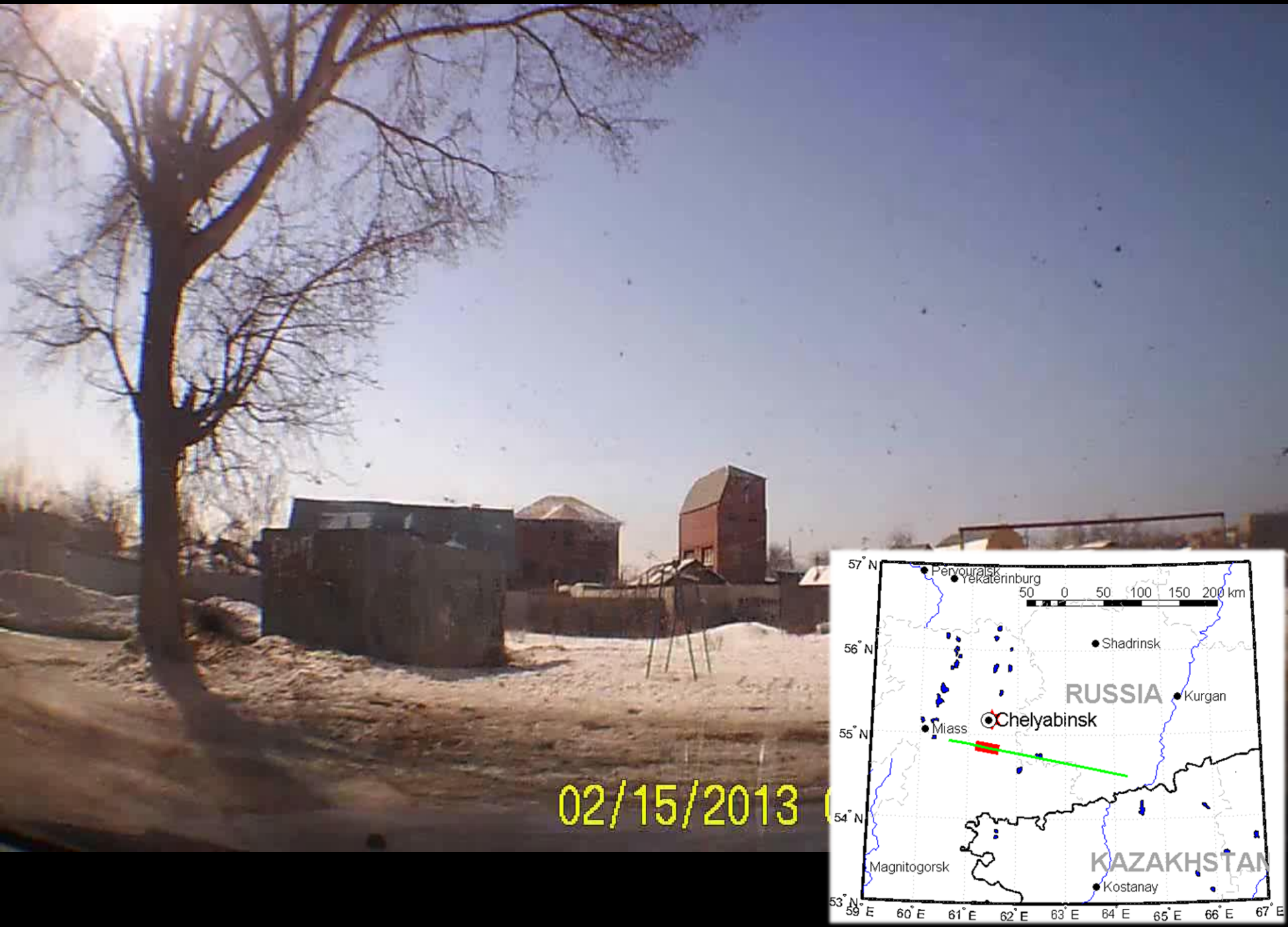
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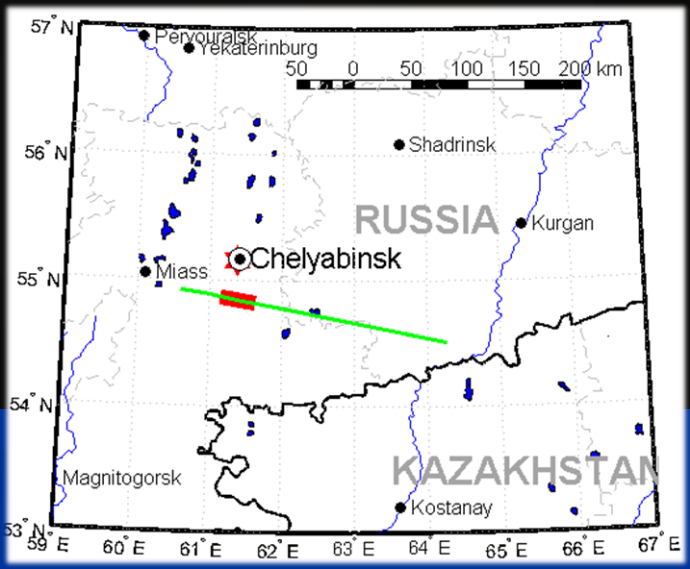
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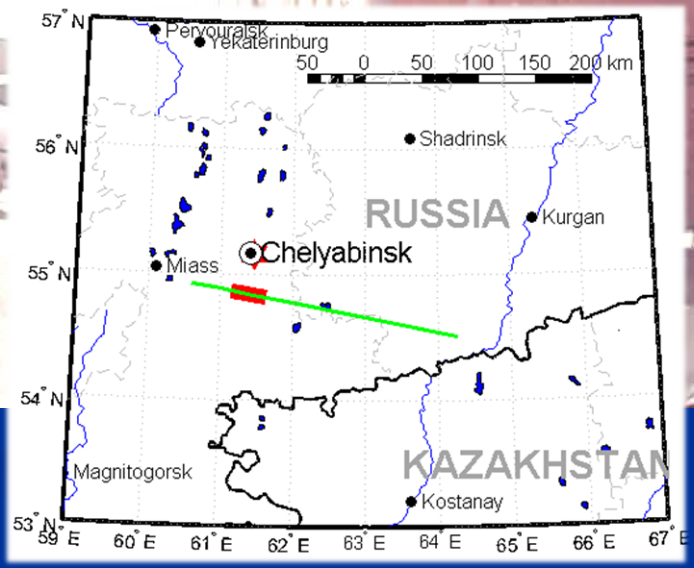


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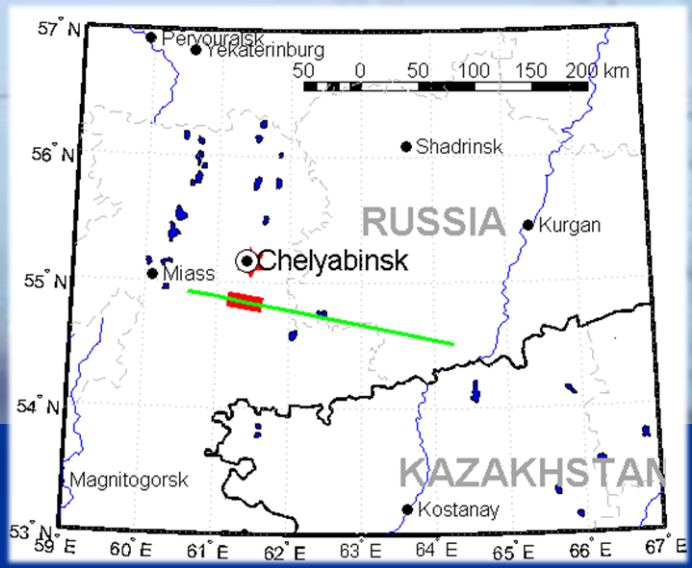
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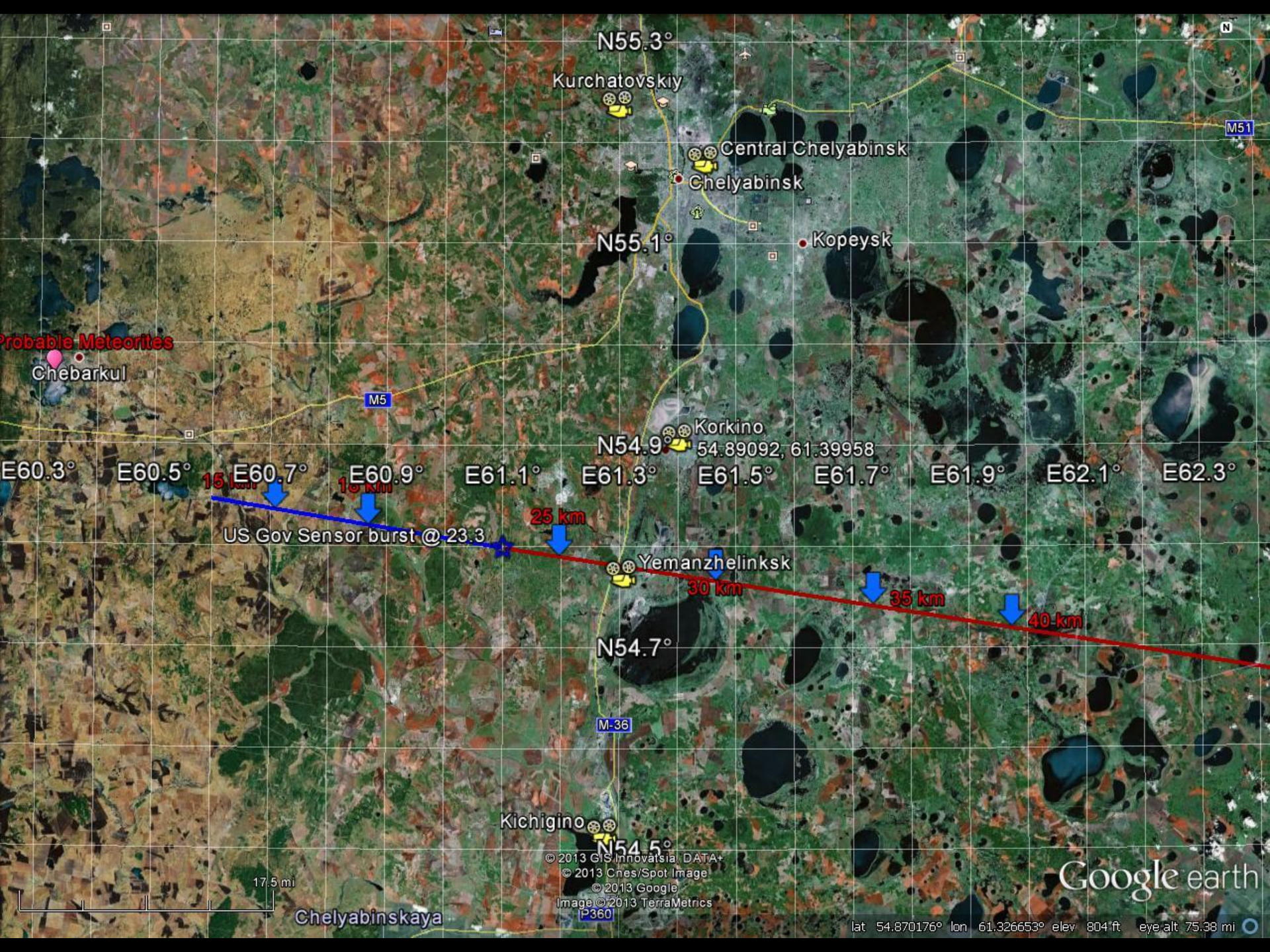
Dashcam videos validate models


N55.3°
Kurchatovskiy
Central Chelyabinsk
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M51
N55.1°
Kopeysk
Probable Meteorites
Chebarkul
M5
Korkino
N54.9°
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E60.3°
E60.5°
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E60.9°
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US Gov Sensor burst @ 23.3
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© 2013 GIS Innovatsia, DATA+
© 2013 Cnes/Spot Image
© 2013 Google
Image © 2013 TerraMetrics
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Chelyabinskaya
Google earth
lat 54.870176° lon 61.326653° elev 804 ft eye alt 75.38 mi


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2013/02/15 09:42:16


15. 02. 2013 09:42:56

ВНИМАНИЕ!!!

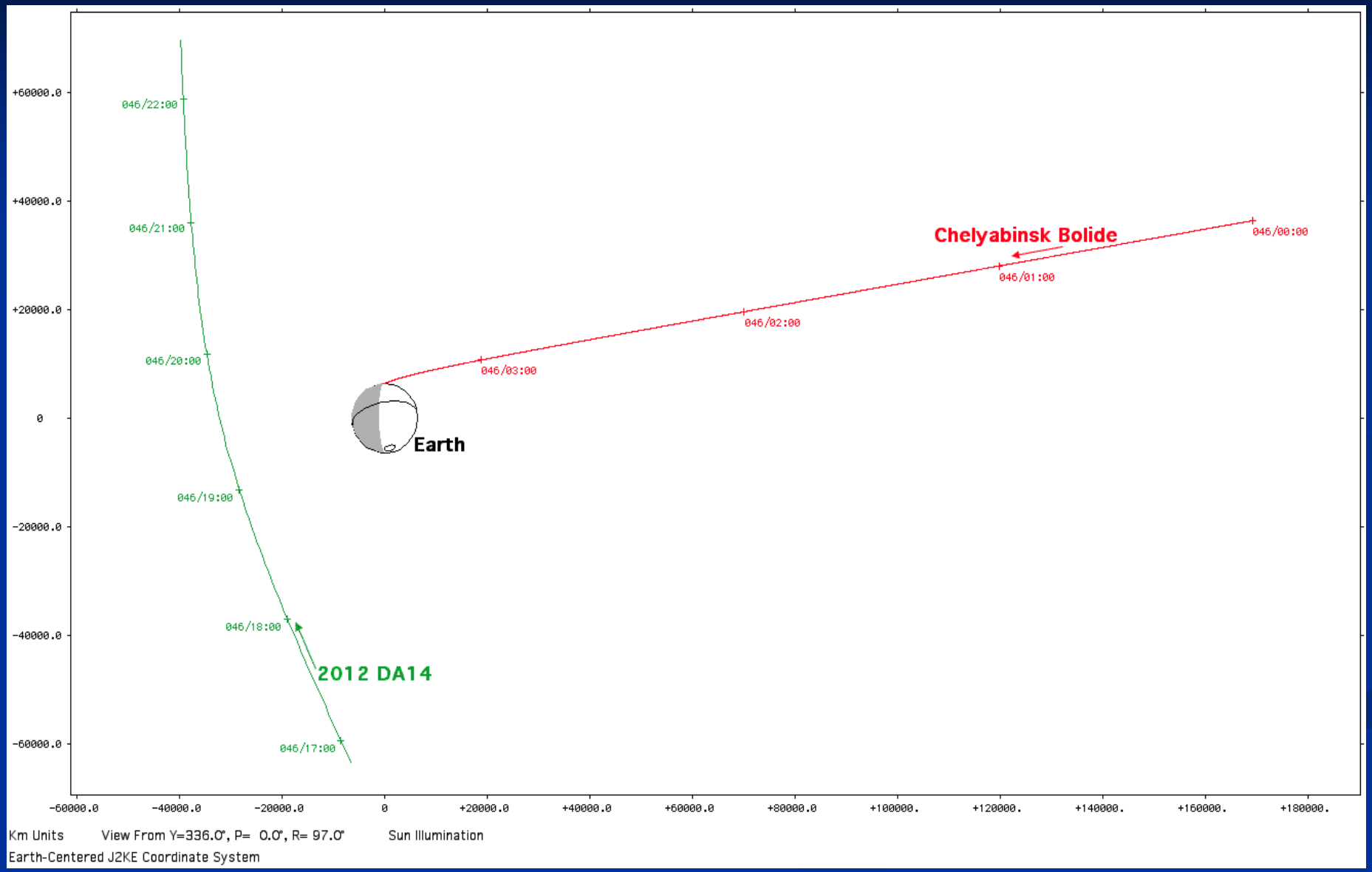
на территории ВЕДЁТСЯ
ВИДЕОНАБЛЮДЕНИЕ

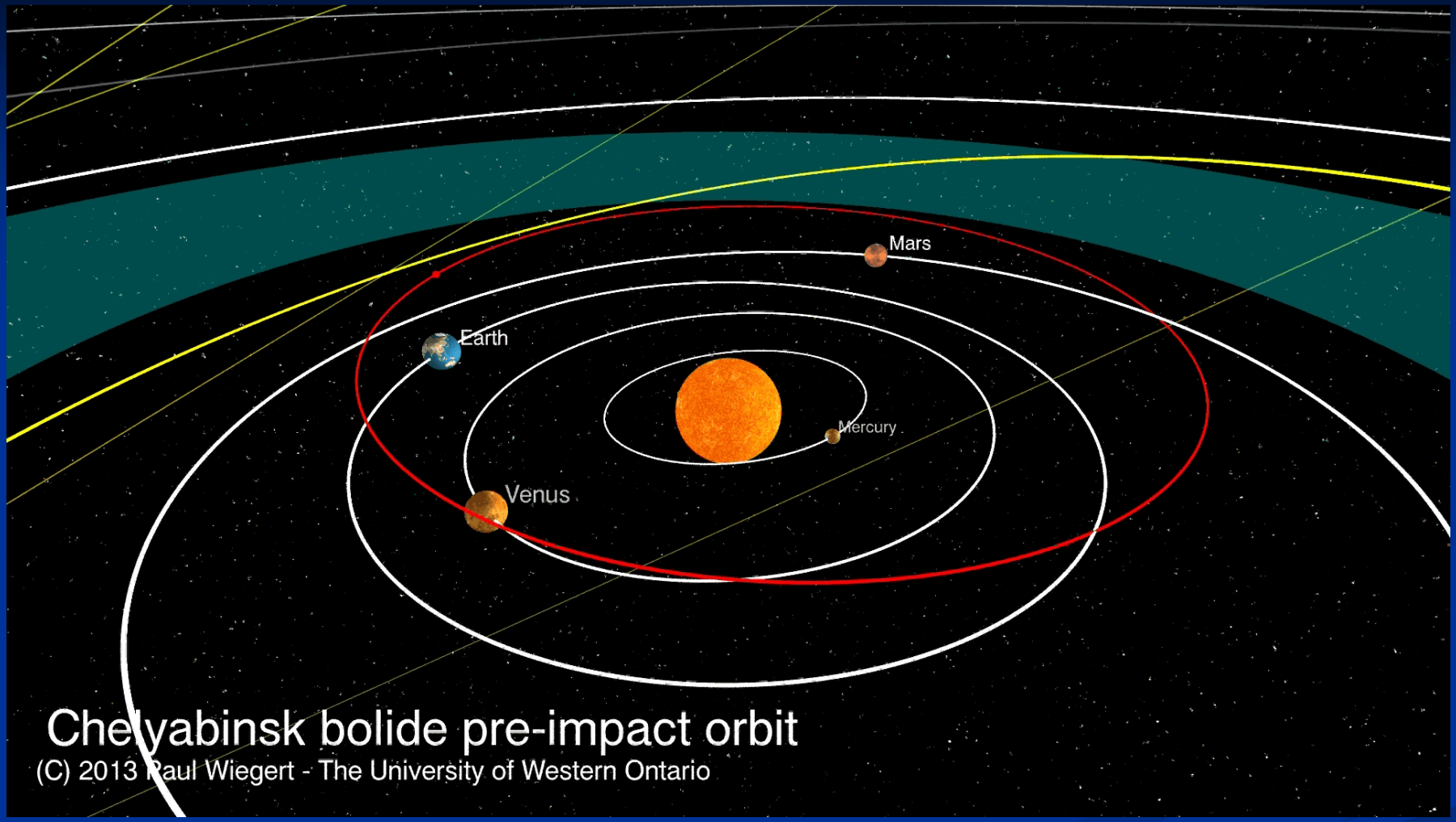

15.02.2013 09:08:26

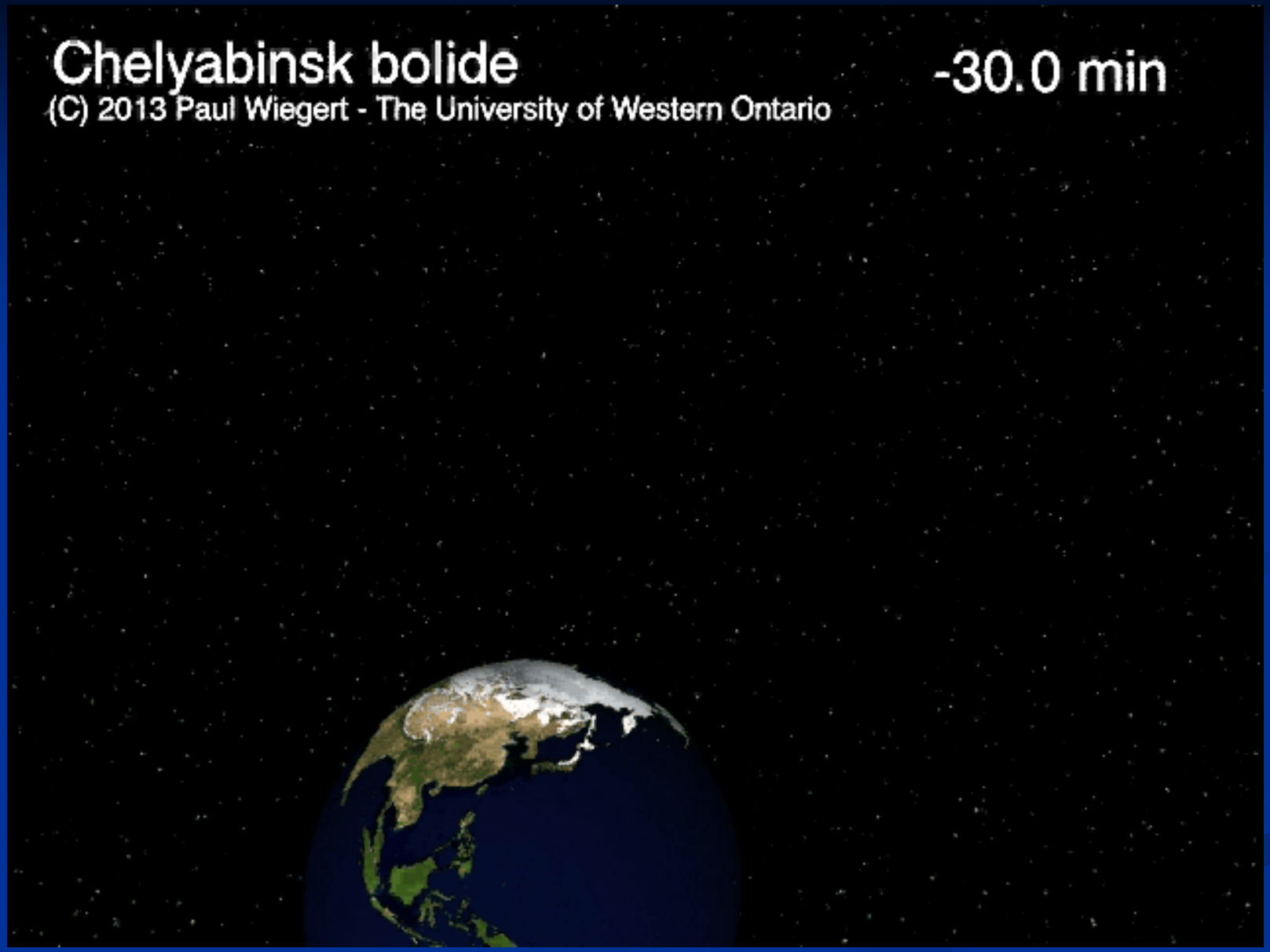
High-fidelity validation data

High-fidelity validation data

Two Unrelated Events




Mars
Earth
Mercury
Venus
Chelyabinsk bolide pre-impact orbit
(C) 2013 Paul Wiegert - The University of Western Ontario


Chelyabinsk bolide
(C) 2013 Paul Wiegert - The University of Western Ontario
-30.0 min

US Government sensors

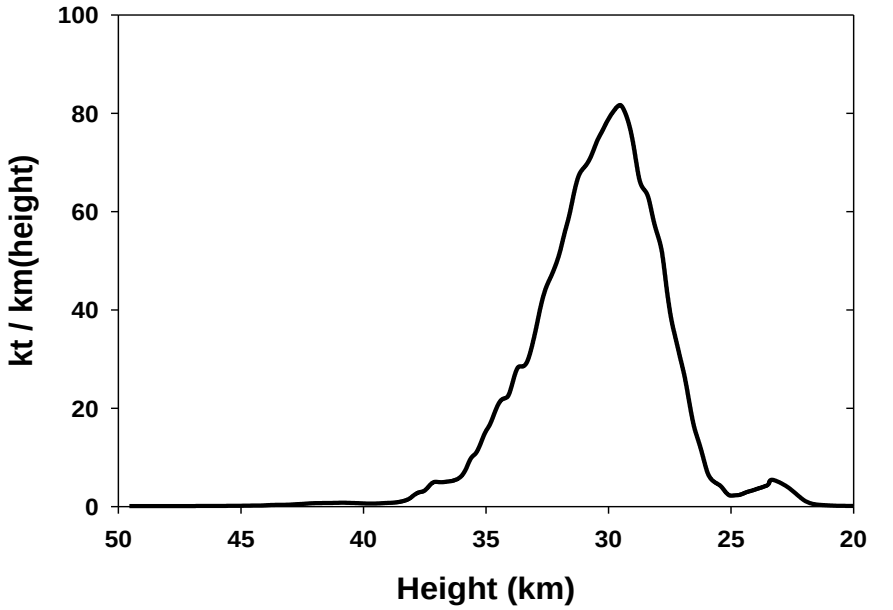
IIIIIIIIIIIIIIII START OF REPORT IIIIIIIIIIIIIIII

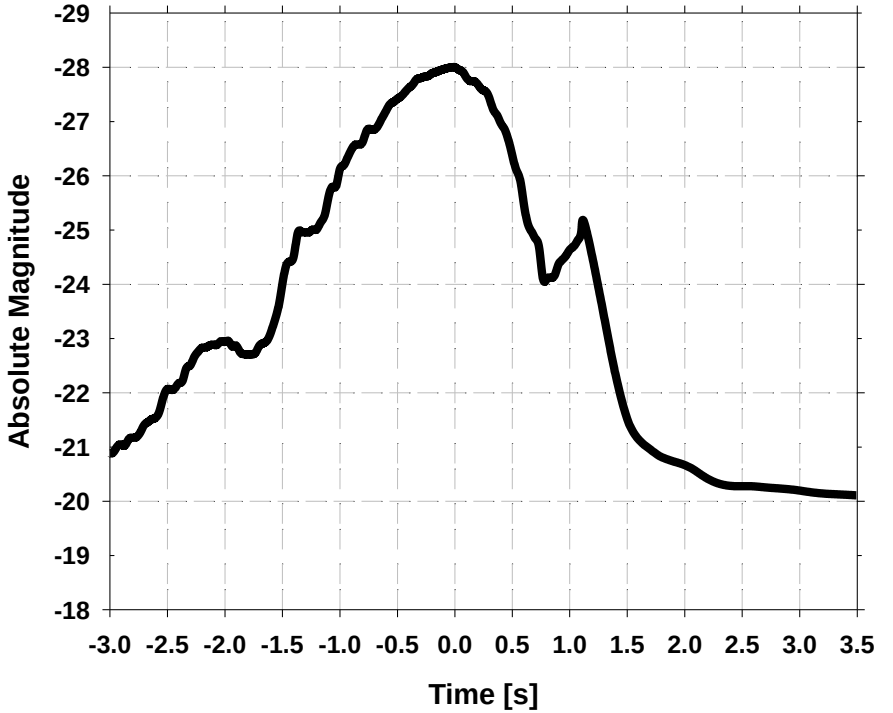
FOR PUBLIC RELEASE Distribution A
Bolide: On 15 February 2013
Sensors detected the following indications of a meteoroid entry into Earth's atmosphere:
a. Dateltime at peak brightness: 15 February 2013/03:20:33 GMT
b. Location at peak brightness: Latitude 54.8o N, Longitude 61.1o E
c. Altitude at peak brightness: 23.3 km
d. Velocity at peak brightness: 18.6 km/sec
e. Approximate total radiated energy: 90 kT TNT
f. Pre-entry velocity vector (ECF): X= +12.8 km/sec; Y = -13.3 km/sec;
Z=-2.4 km/sec

IIIIIIIIIIIIIIII END OF REPORT IIIIIIIIIIIIIIII

Video Calibrations - Lightcurve

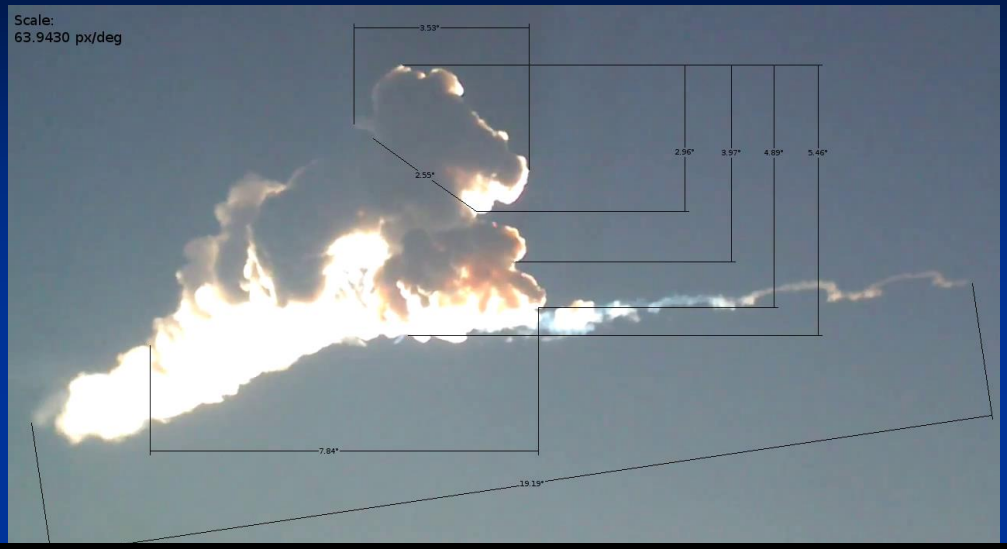
- Uses indirect scattered light and corrected for autogain
- Calibrated using both meteorite-fireball events and kiloton class and larger airbursts
- Total deposited energy assuming $\eta = 17\%$ is >471 kT





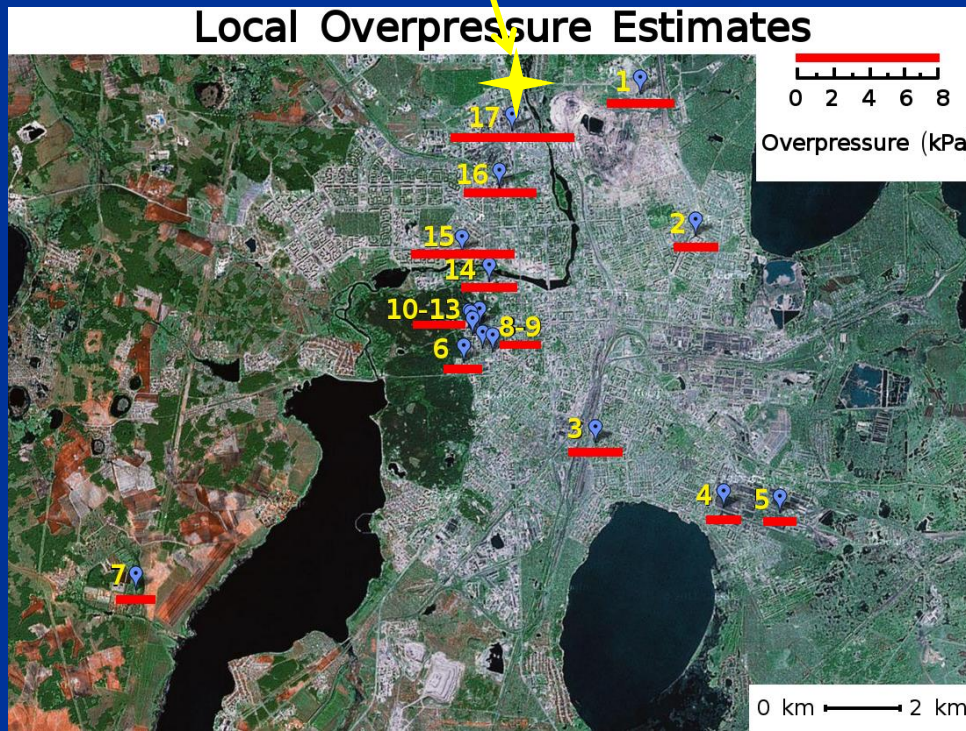
Videos - Features

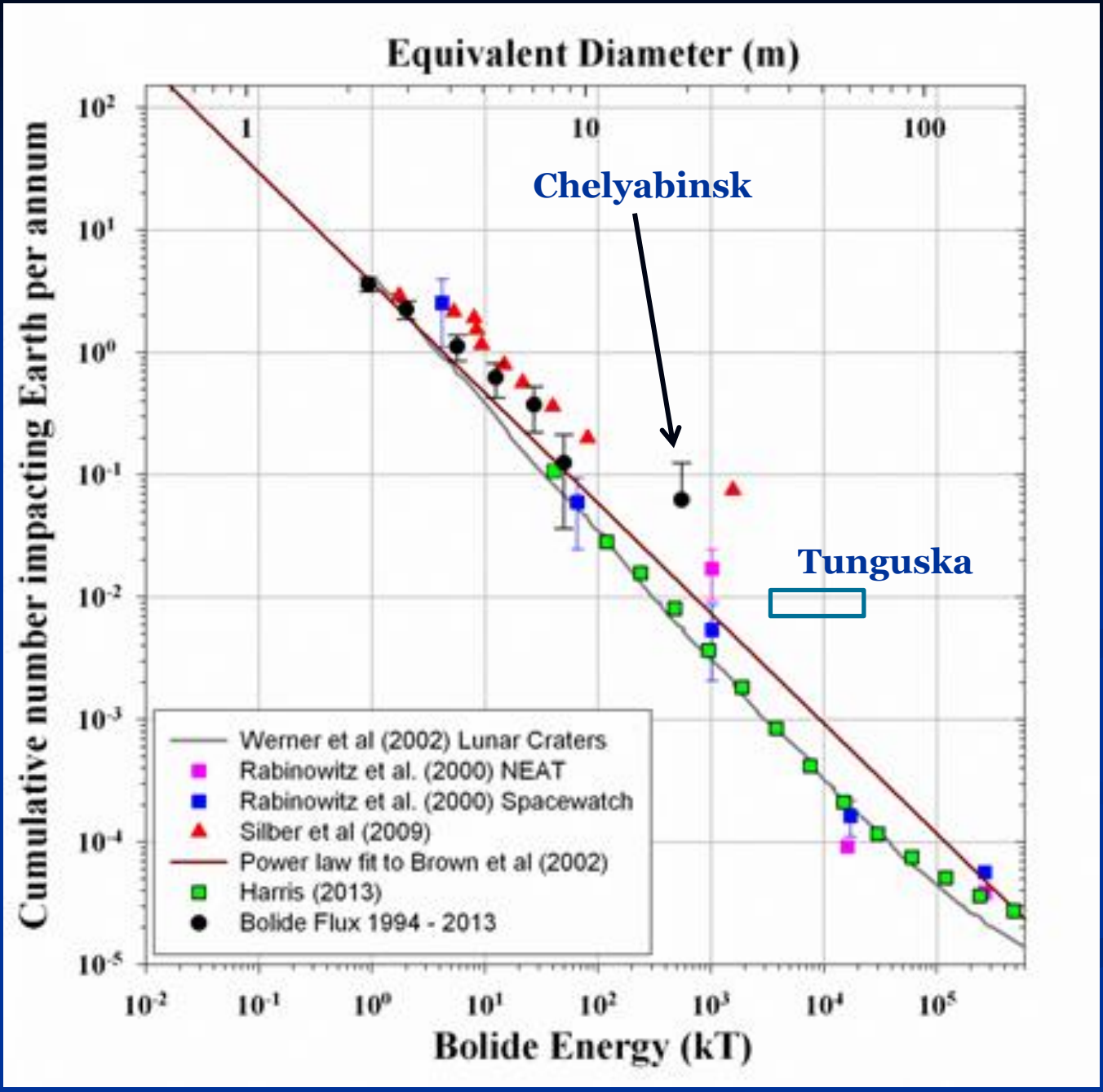
- Mushroom cloud @ 28 km height
- Cloud 5 km in diameter having risen to 35 km altitude ~2 mins after fireball
- Twin vortices (2D moving mushroom cloud feature) showing 2-3 km separation 1 min after fireball each of 1 km width



Airblast Damage in Chelyabinsk

- Of >5000 windows examined, ~10% broke due to initial shock
- Window glass velocity 5 – 7 m/s
- Shock is a few percent atmospheric pressure
- Zinc factory roof collapse near focusing?
- Temperature inversion may have played a role




Equivalent Diameter (m)
1
10
100
Chelyabinsk
Tunguska
Cumulative number impacting Earth per annum
10^{2}
10^{1}
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10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Werner et al (2002) Lunar Craters
Rabinowitz et al. (2000) NEAT
Rabinowitz et al. (2000) Spacewatch
Silber et al (2009)
Power law fit to Brown et al (2002)
Harris (2013)
Bolide Flux 1994 - 2013
10^{-2}
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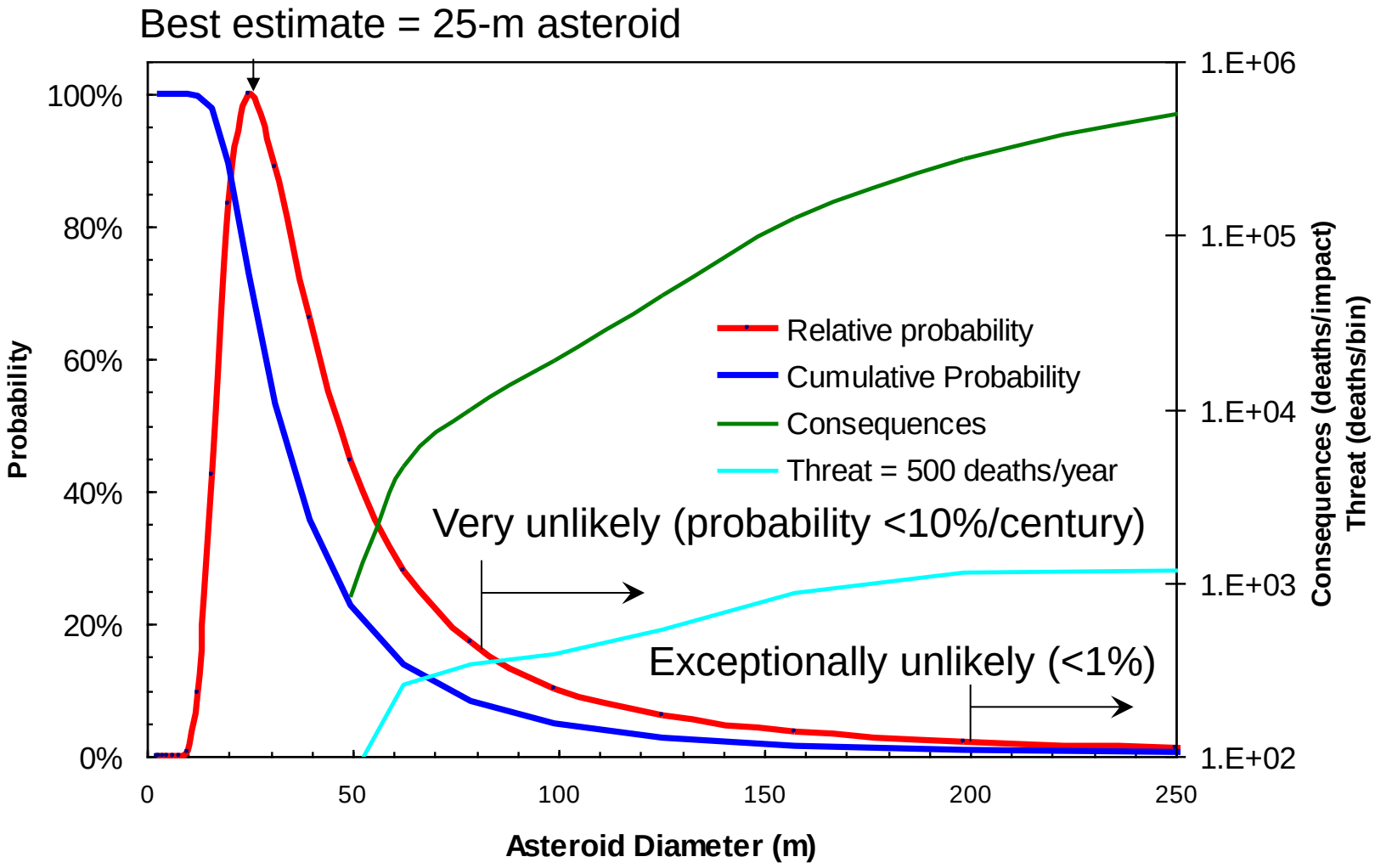
Bolide Energy (kT)

Size distribution plot can be transformed to PDF (probability density function for 100-year largest)

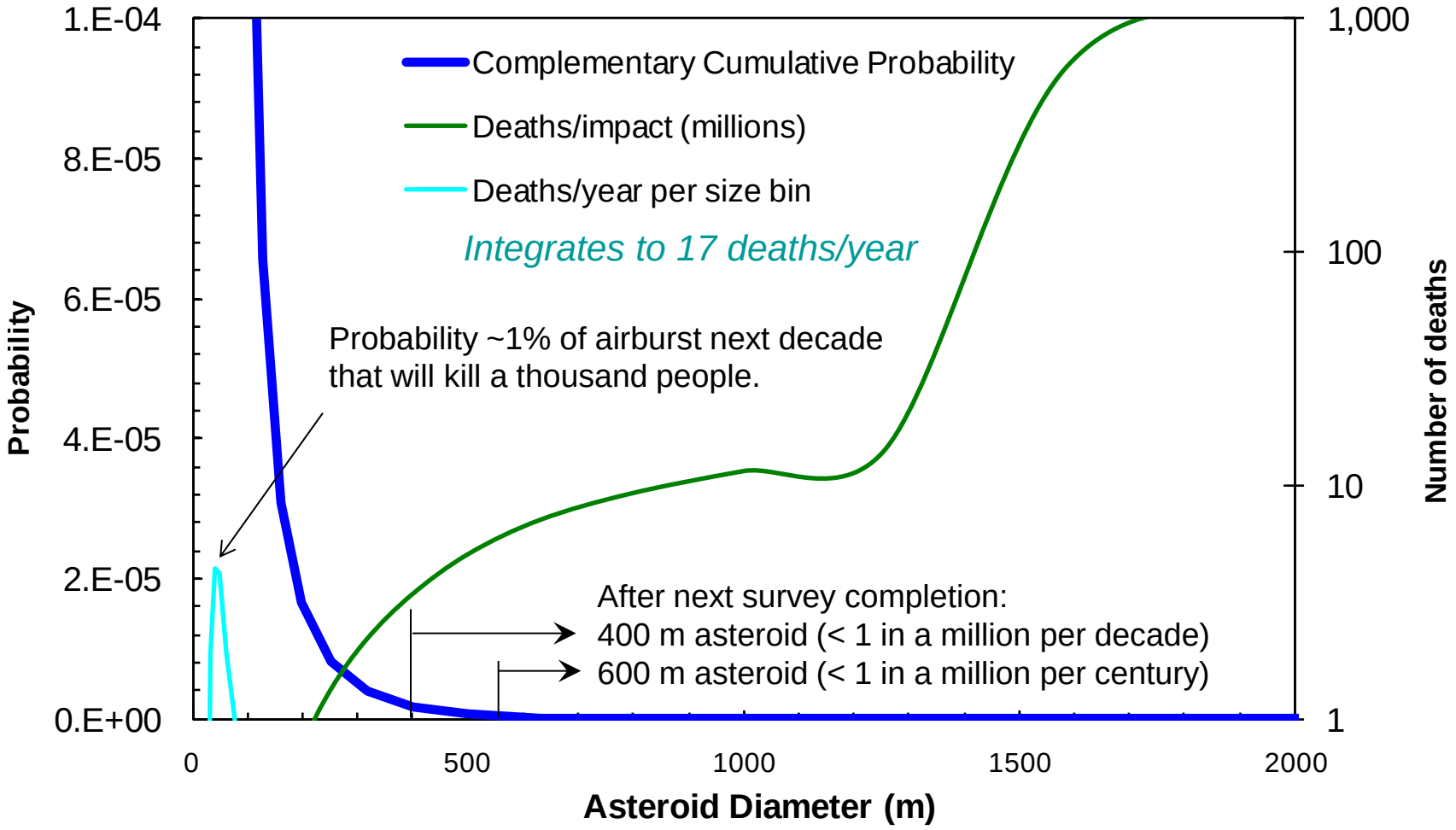


Directed-source airbursts: probability per decade

Original assessed threat = 1409 deaths/year (3% increase)

Current assessed threat = 152 deaths/year (21% increase)

Future (after next survey) threat = 17 deaths/year (240% increase)

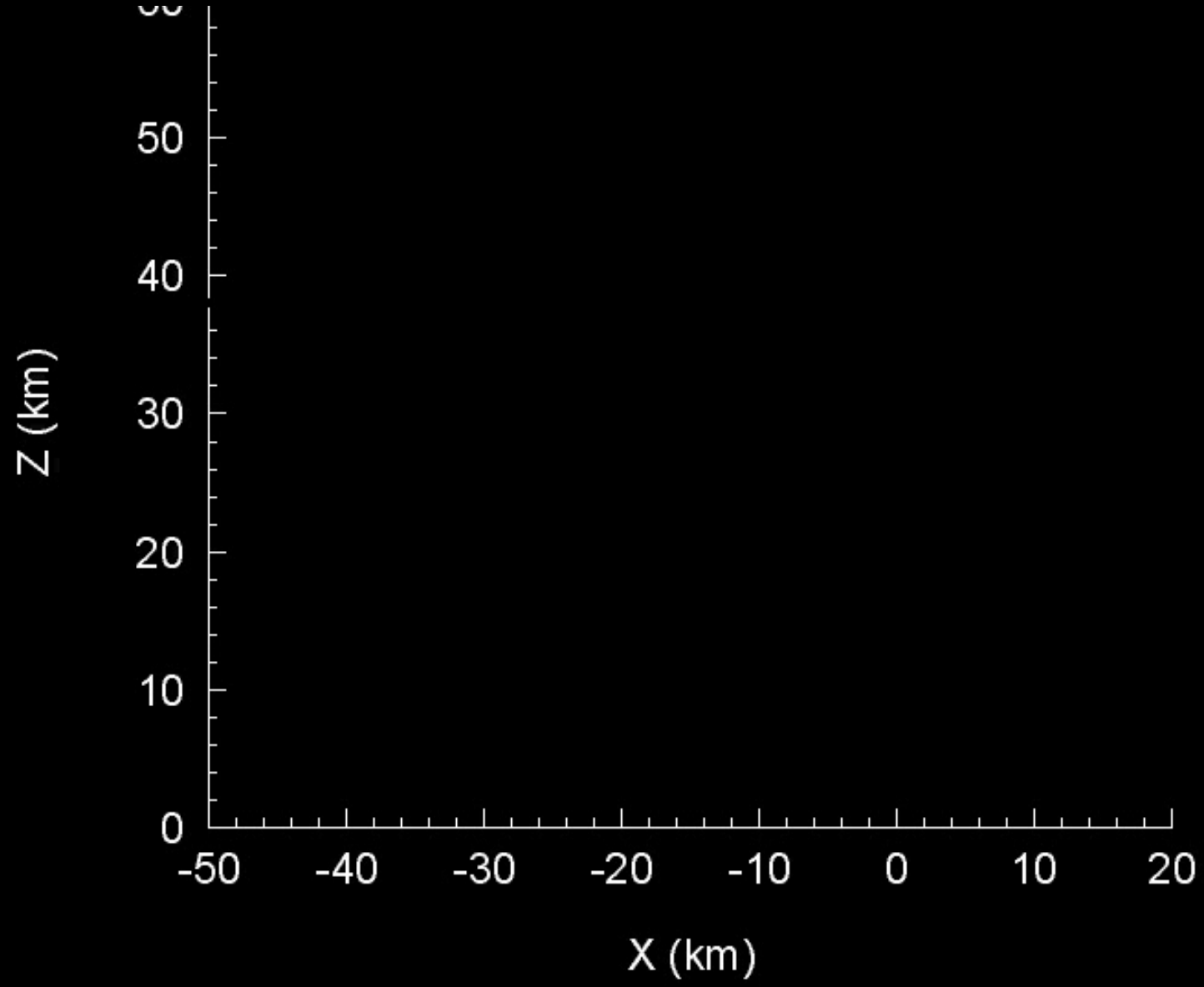


- Best estimate of total energy ~500 kT with 50% uncertainty
- Entry speed 18.6 km/s; peak brightness absolute mag -28
- Original size of meteoroid ~20m diameter; mass ~10 000 tonnes
- Overpressure in Chelyabinsk reached a few tenths of PSI (3 kPa) range.
- Reflection and building interactions mean some structures subject to more than this value
- Airburst centered near 30 km altitude and extending ~7 km above and ~4 km below.

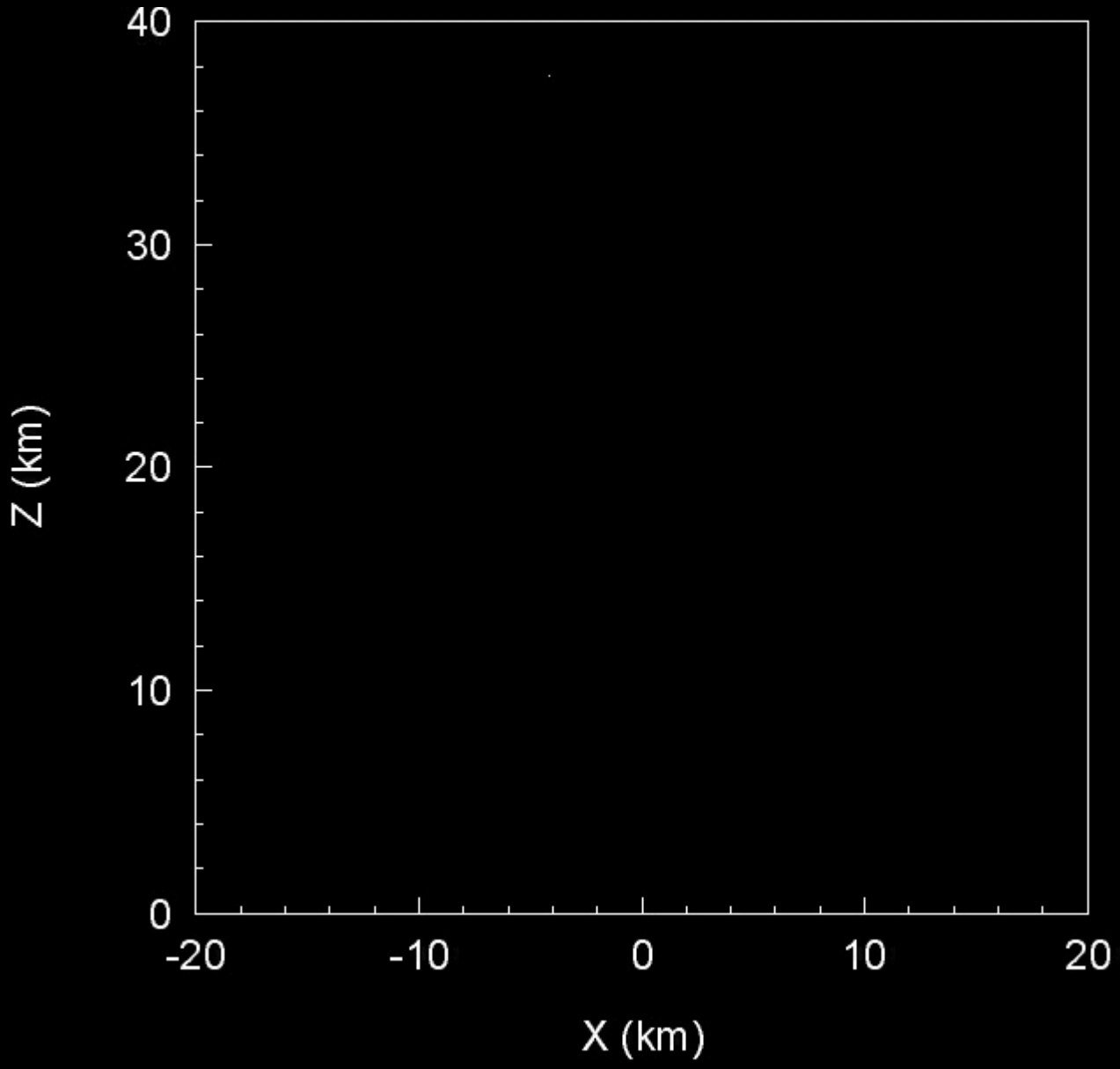
Outline

1) Background: collisional airbursts
2) The Chelyabinsk event
3) **Computational modeling**

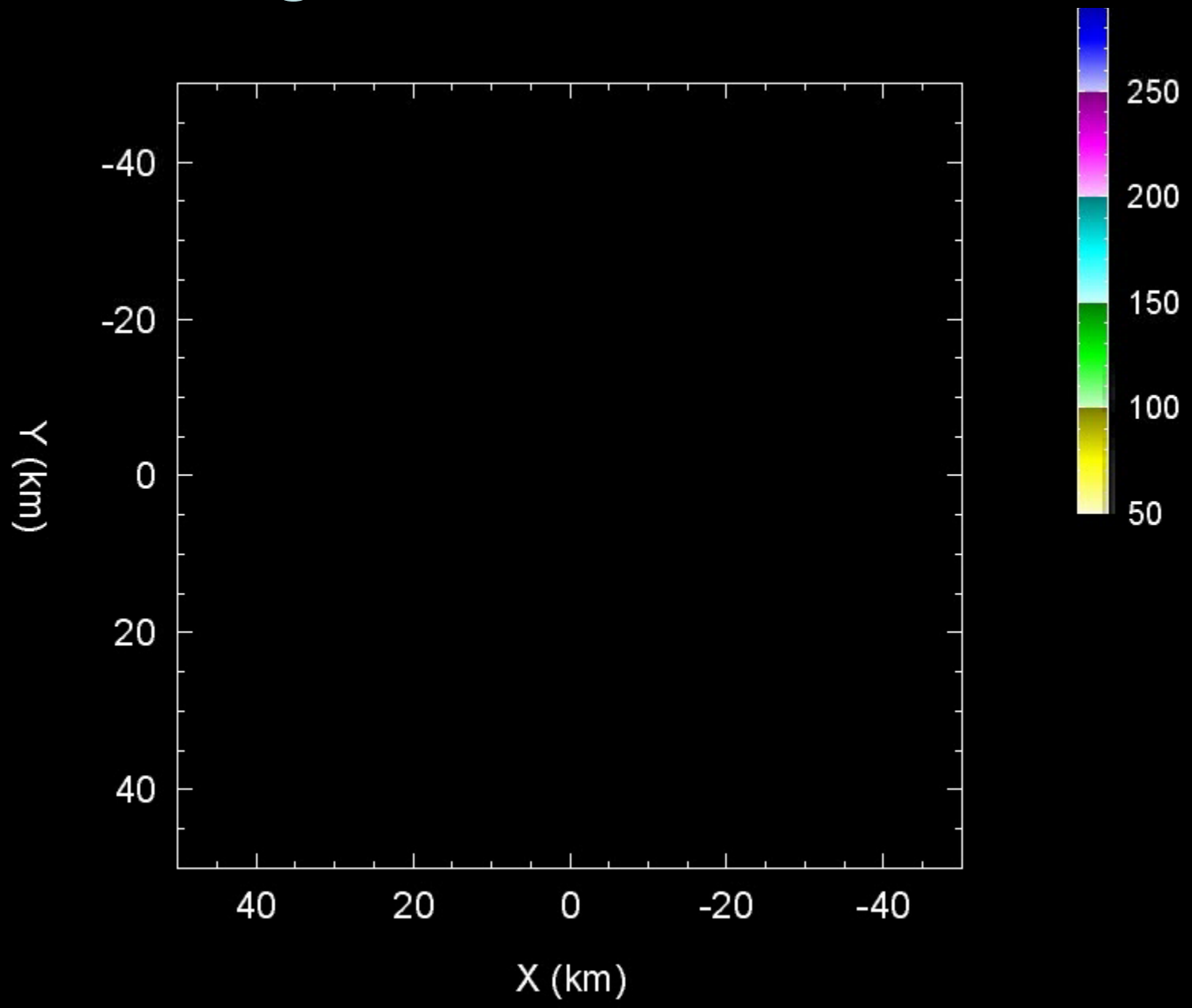
Chelyabinsk airburst simulation: 0.5 Mt



Steep airburst simulation: 0.5 Mt



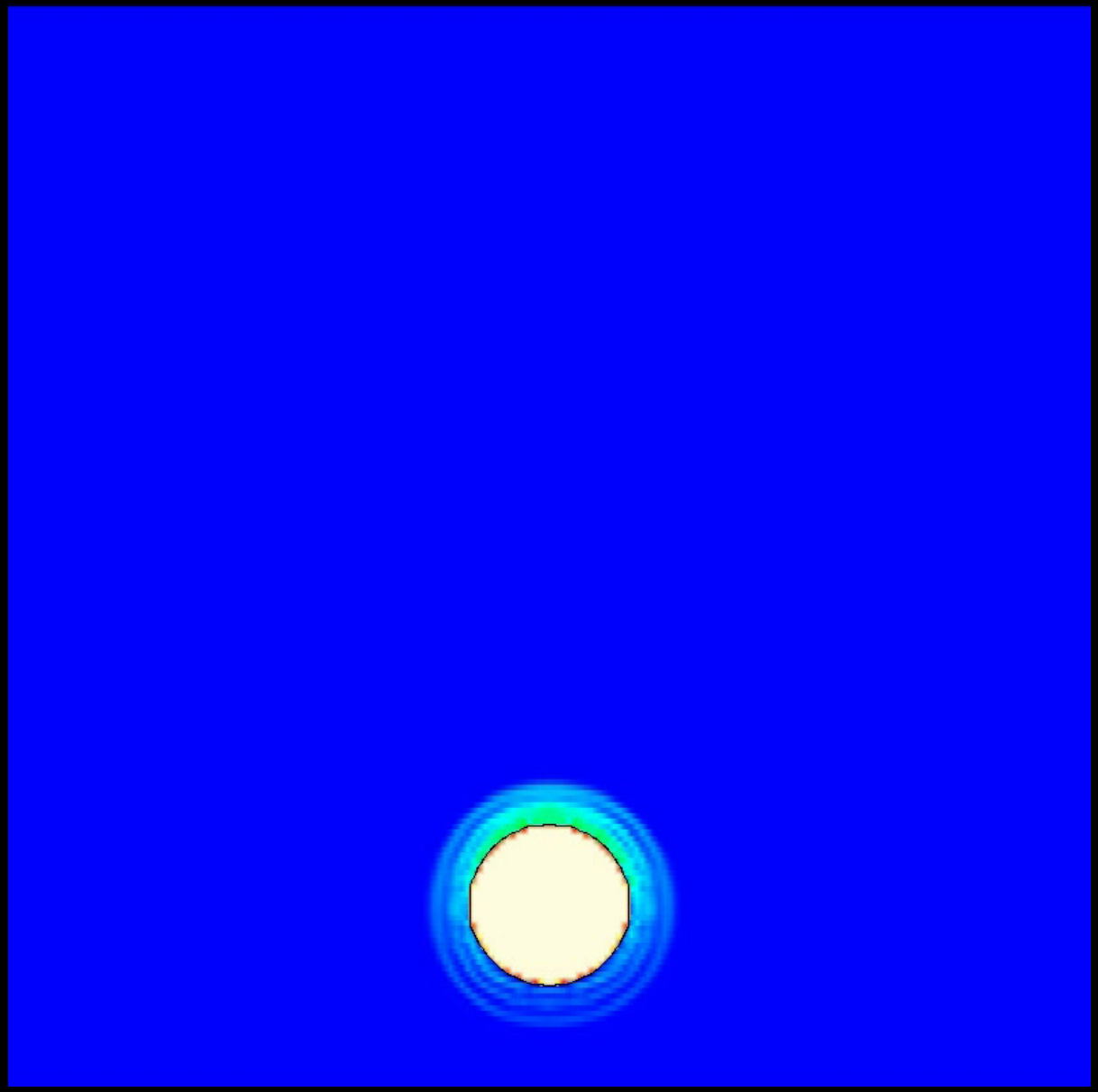
3D ground blast wave



3D ground blast wave

Why were there two trails?

2D wake simulation



- Tunguska models show that an impact airburst is very different from a nuclear airburst
- Chelyabinsk models show that explosion energy continues to move horizontally along flight path
- Blast pattern on the ground is sensitive to details of event (angle of incidence, burst height, etc.)
- Idealized simulations of wake suggest reason for two widely-spaced condensation trails
- Chelyabinsk provides “high fidelity” validation for airburst models
- Airburst hazard is greater than previously thought

Questions?