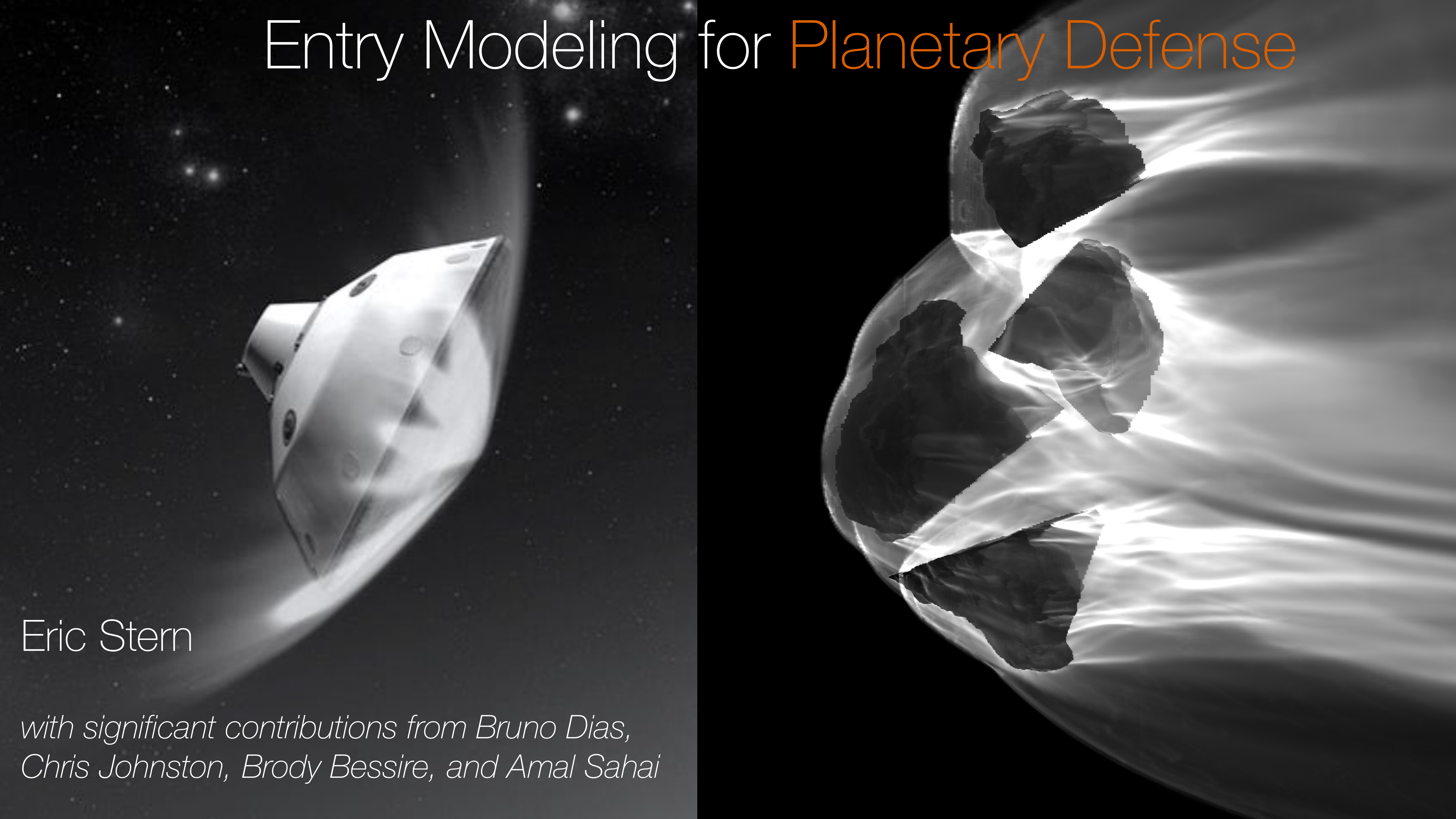


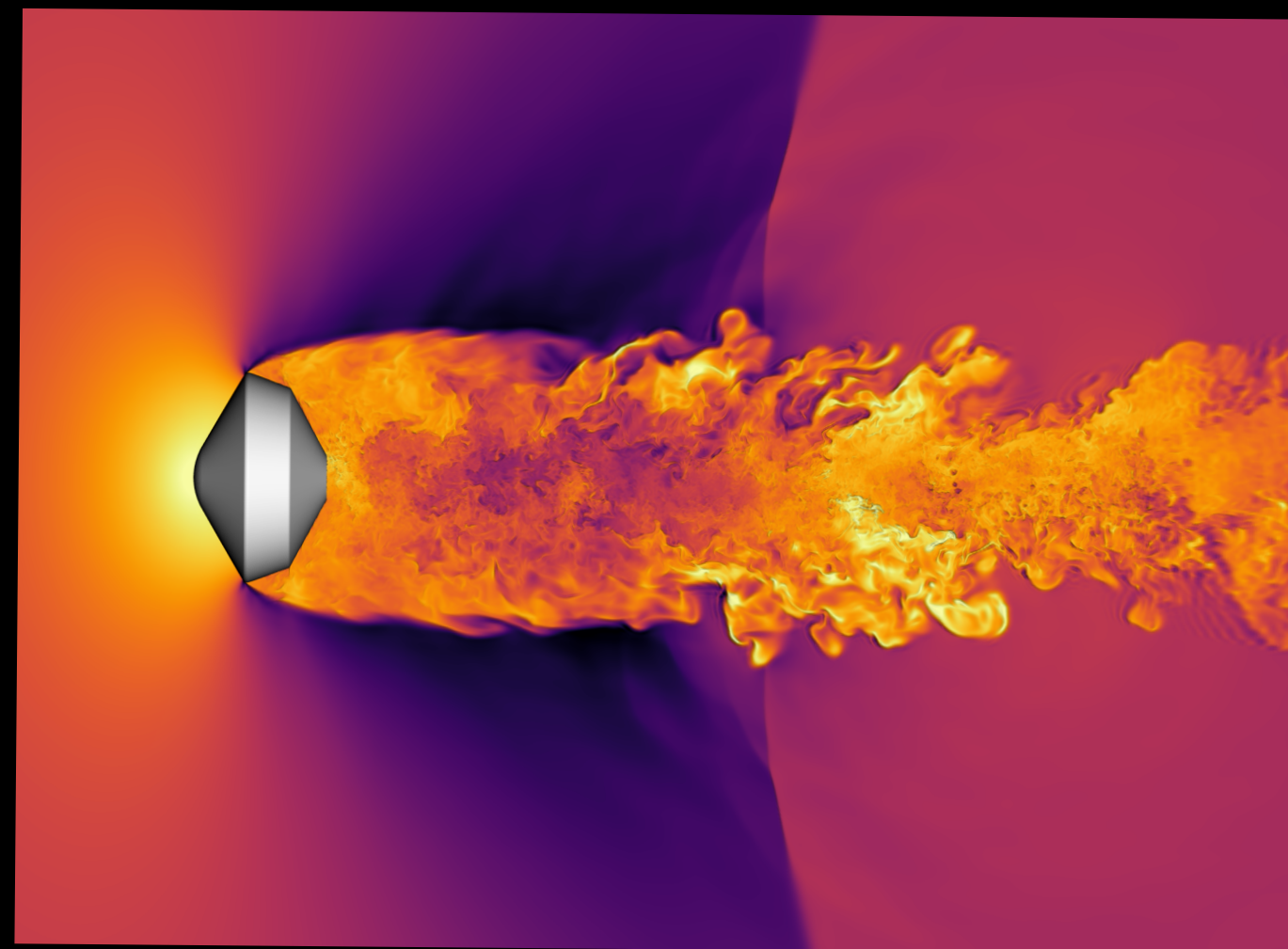
Entry Modeling for Planetary Defense

Eric Stern

*with significant contributions from Bruno Dias,
Chris Johnston, Brody Bessire, and Amal Sahai*

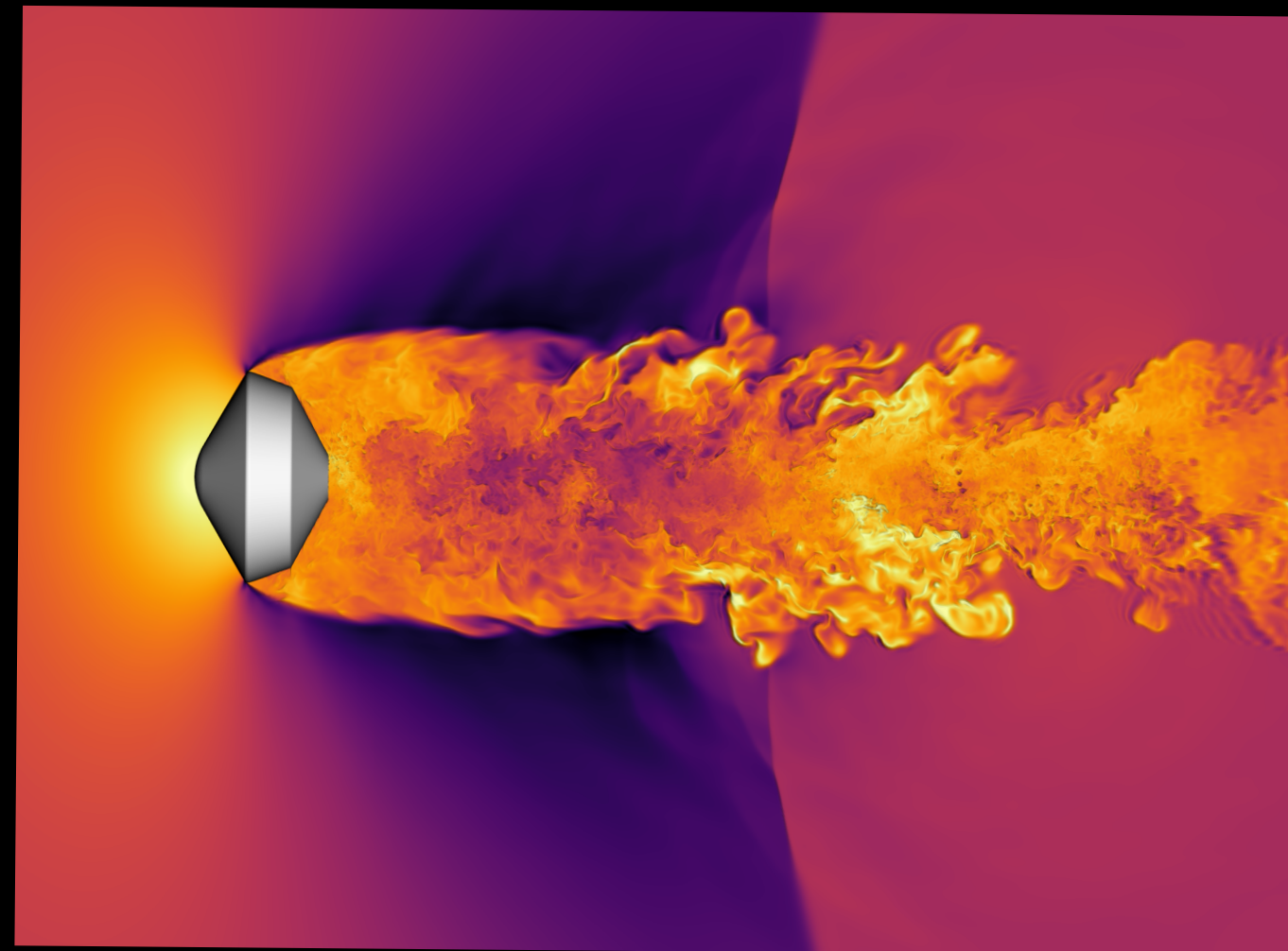


Who am I? Why Am I here?



Who am I? Why Am I here?

- Eric Stern
- Ph.D. from University of Minnesota
- NSTRF (now NSTGRO)
- Joined NASA in 2014
- Original author of FF-CFD tool
- Originator of the Icarus material response solver
- TPS analysis lead for Dragonfly
- Entry Modeling lead for the Asteroid Threat Assessment Project (ATAP)



Above Chelyabinsk, Russia: February 15, 2013, ~9:30am



... a 20m asteroid entered Earth's atmosphere at around 19 km/s

Above Chelyabinsk, Russia: February 15, 2013, ~9:30am



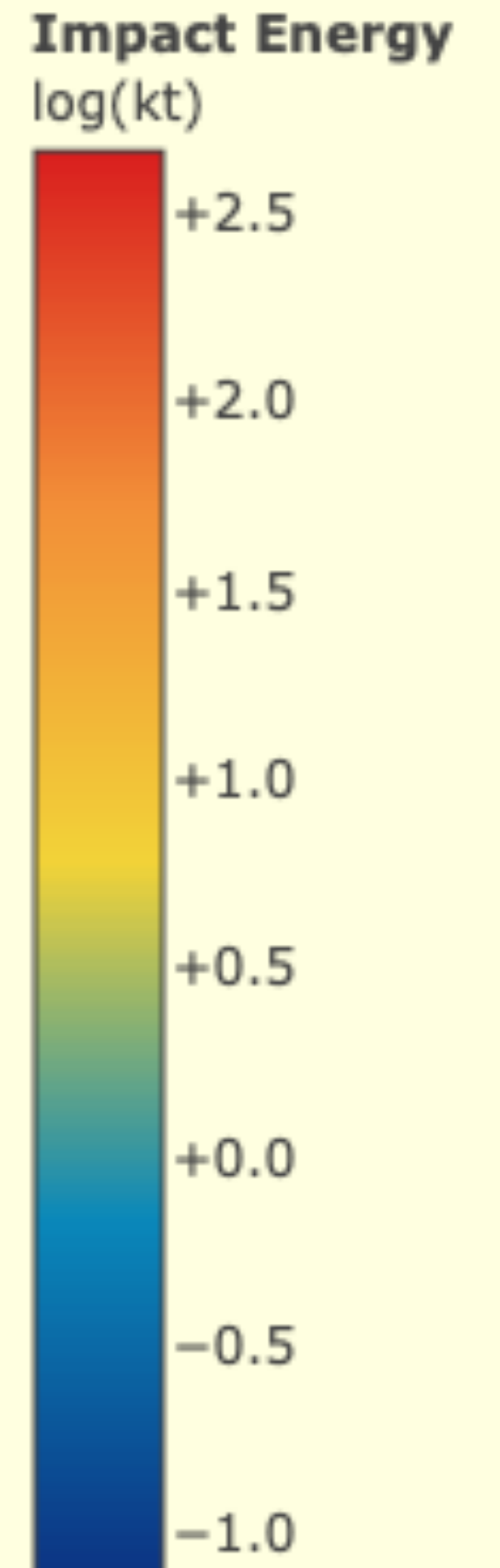
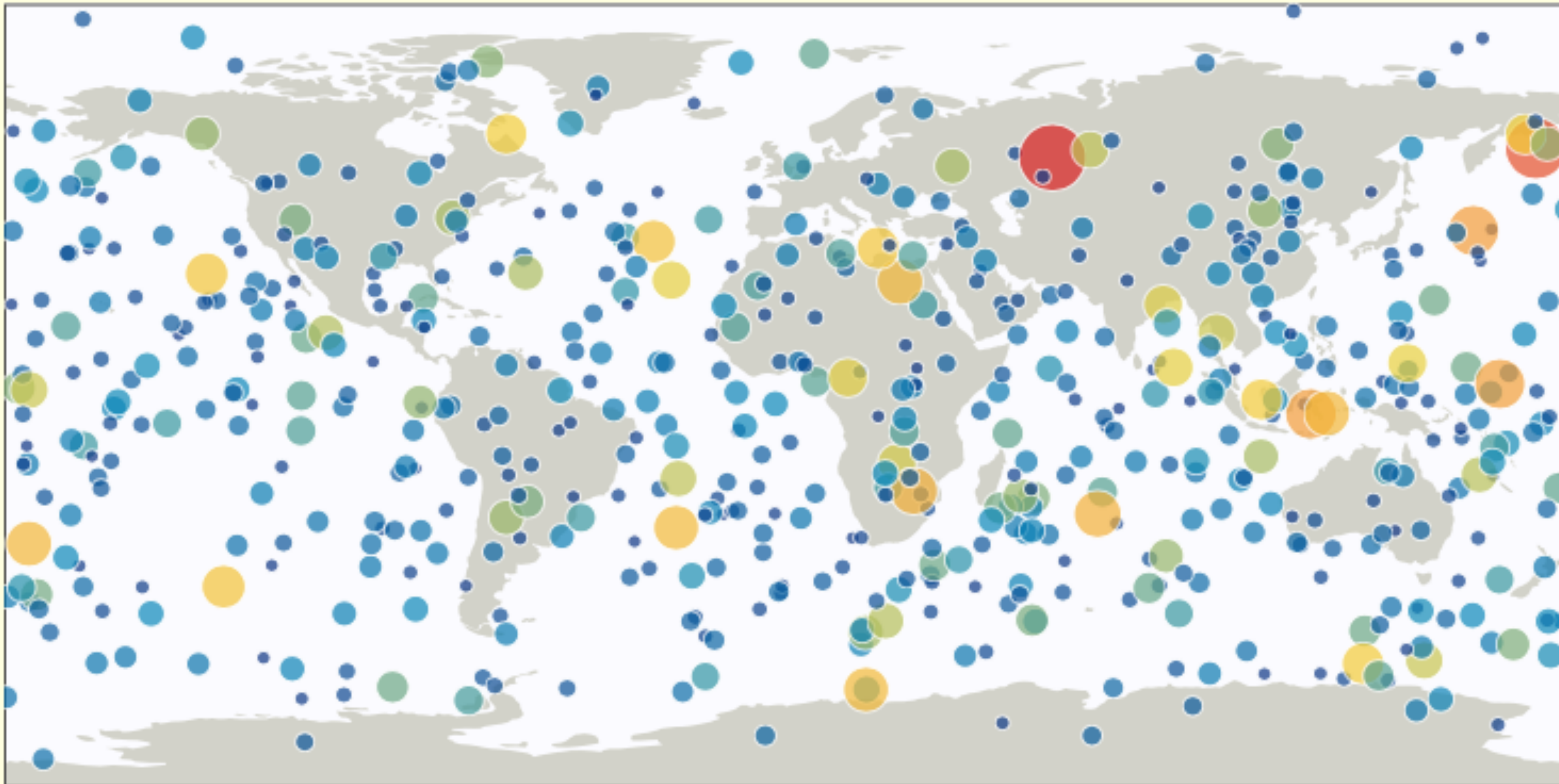
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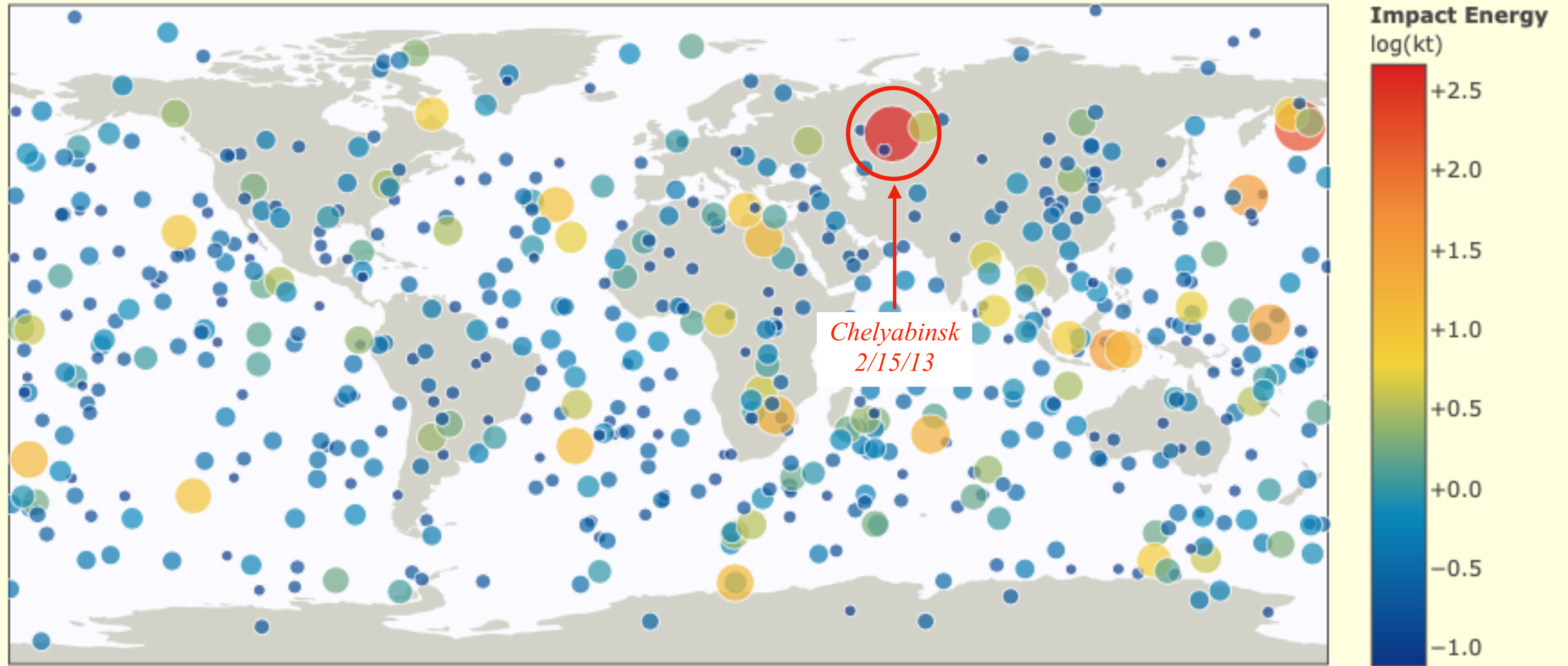


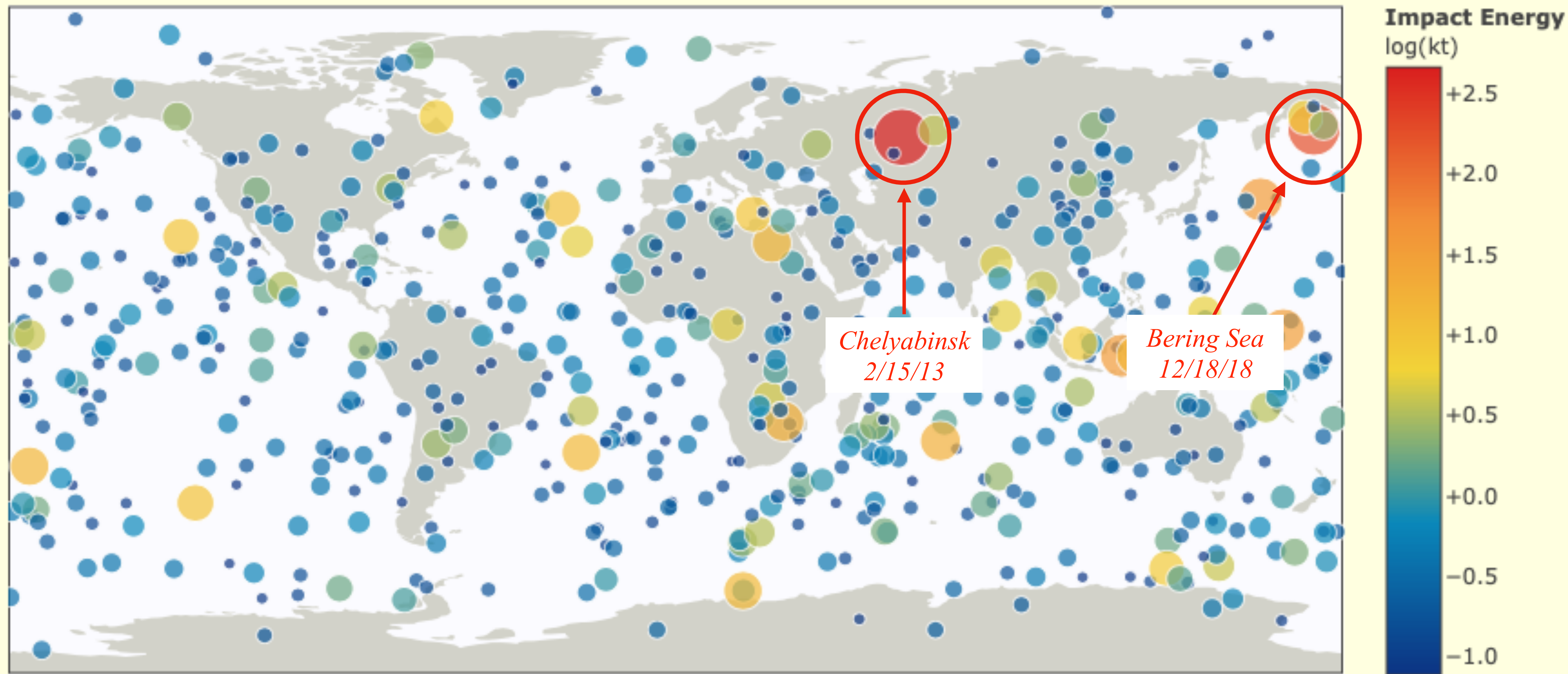


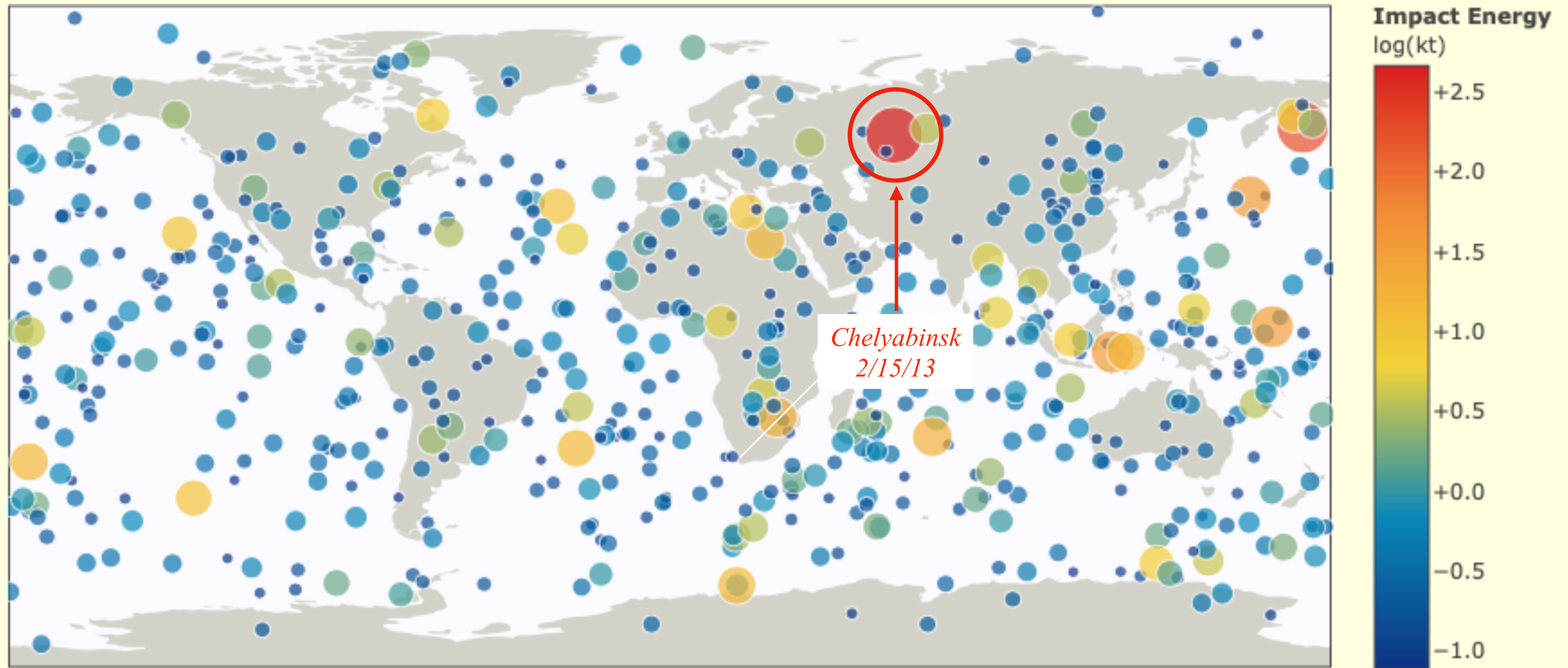




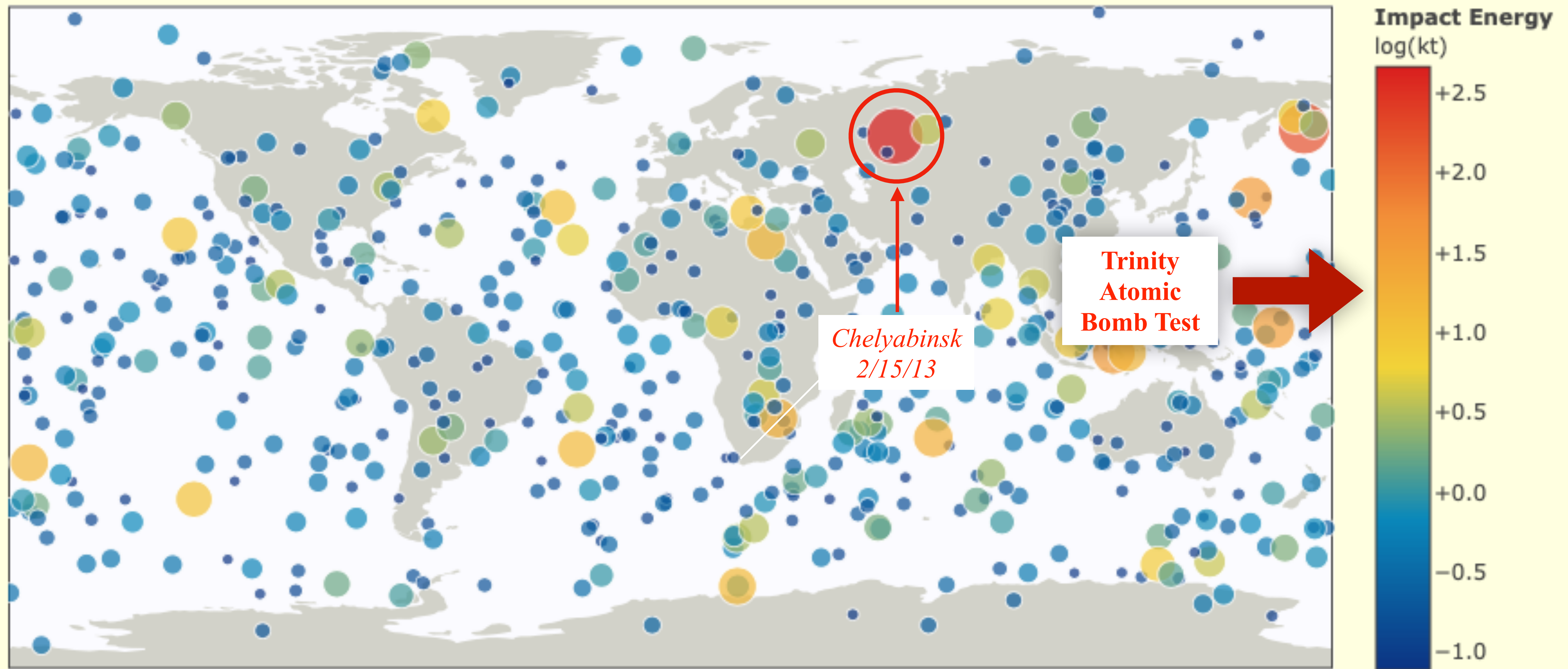








The Asteroid Threat Assessment Project (ATAP) was initiated to better characterize the threat posed by Near-Earth Objects (NEOs)



The Asteroid Threat Assessment Project (ATAP) was initiated to better characterize the threat posed by Near-Earth Objects (NEOs)

ASSESS

Determine NEO population survey completeness and hazard from NEOs that pose the highest risk

CENTER FOR NEAR-EARTH
OBJECT STUDIES (CNEOS)



SEARCH, DETECT & TRACK

Find the natural near-Earth objects – asteroids and comets – and track to determine those whose orbits create an impact hazard to Earth

GROUND & SPACE-BASED OBSERVATORIES,
MINOR PLANET CENTER (MPC),
INTERNATIONAL ASTEROID WARNING NETWORK

PLANETARY DEFENSE

MITIGATE

Demonstrate technologies and techniques to divert or disrupt asteroids in space or inform emergency response activities on the ground

DOUBLE ASTEROID REDIRECTION
TEST (DART), FEMA EXERCISES

PLAN & COORDINATE

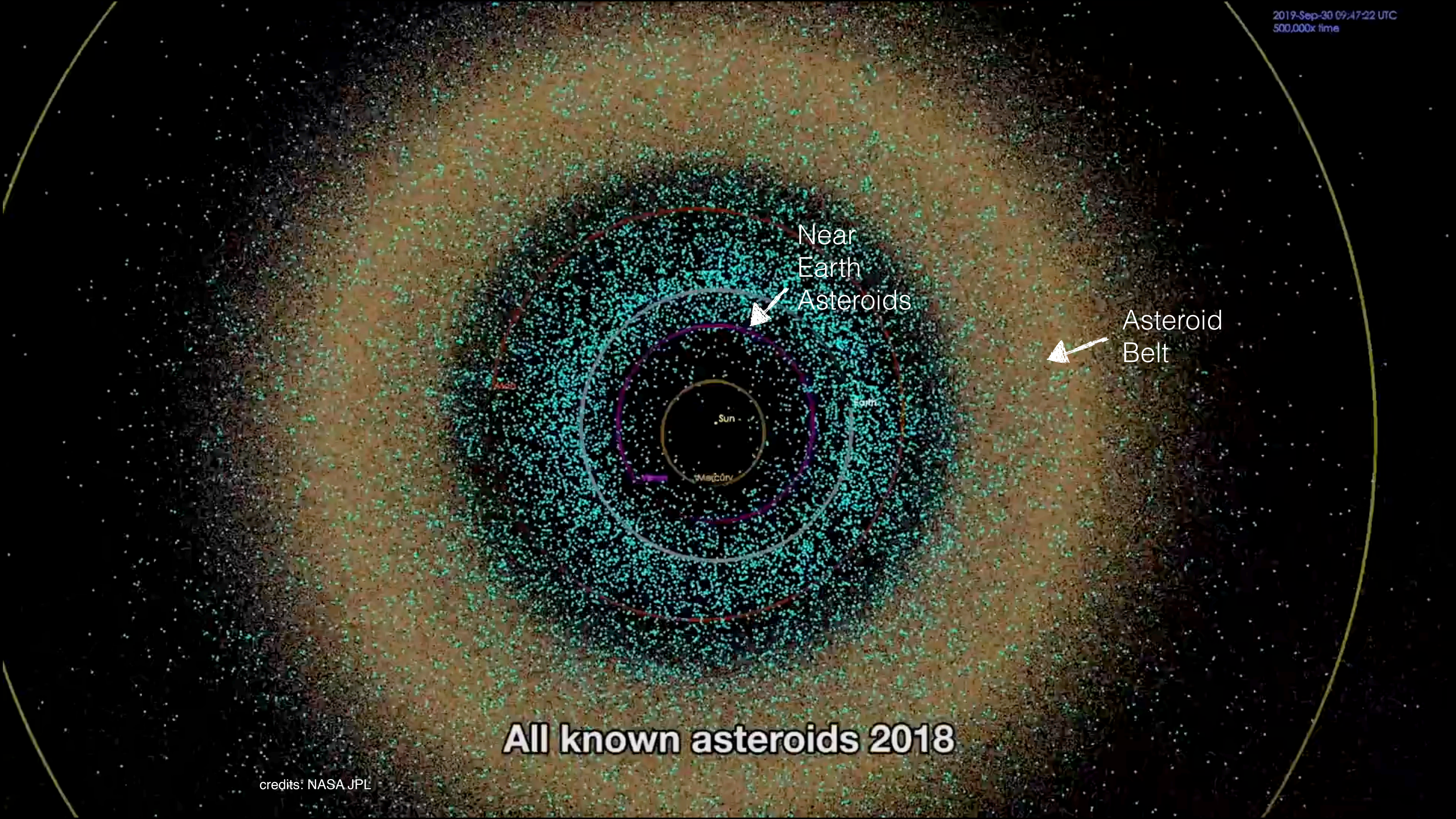
Work with the U.S. interagency and international collaborations on effective actions for impact threat response

SPACE MISSION PLANNING ADVISORY GROUP,
PLANETARY IMPACT EMERGENCY RESPONSE WG,
PLANETARY DEFENSE IWG

CHARACTERIZE

Determine physical characteristics of NEOs (size, shape, composition, rotation) to understand their natural state

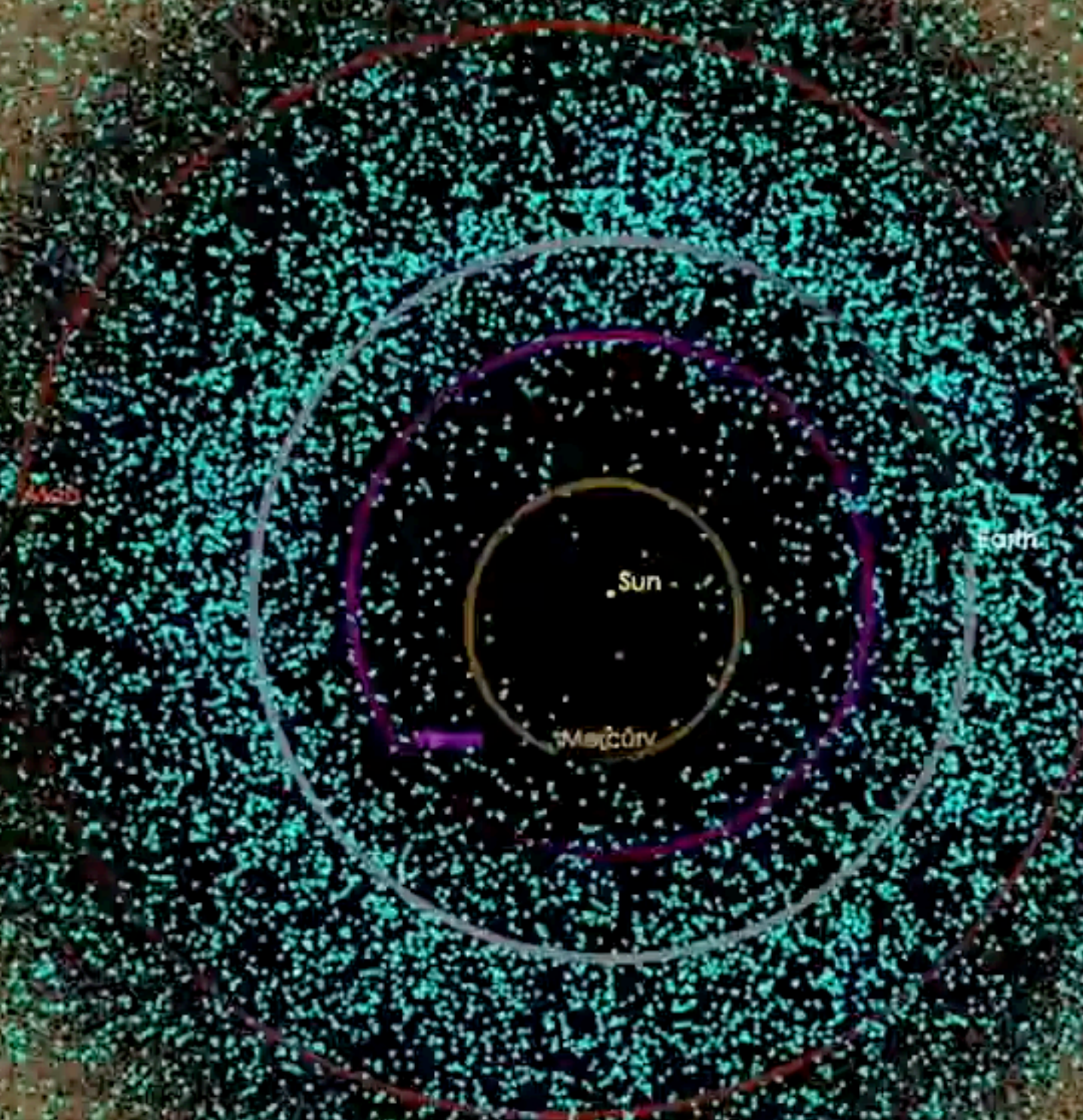
INFRARED TELESCOPE FACILITY,
GOLDSTONE SOLAR SYSTEM RADAR,
NEOWISE



Near
Earth
Asteroids

Asteroid
Belt

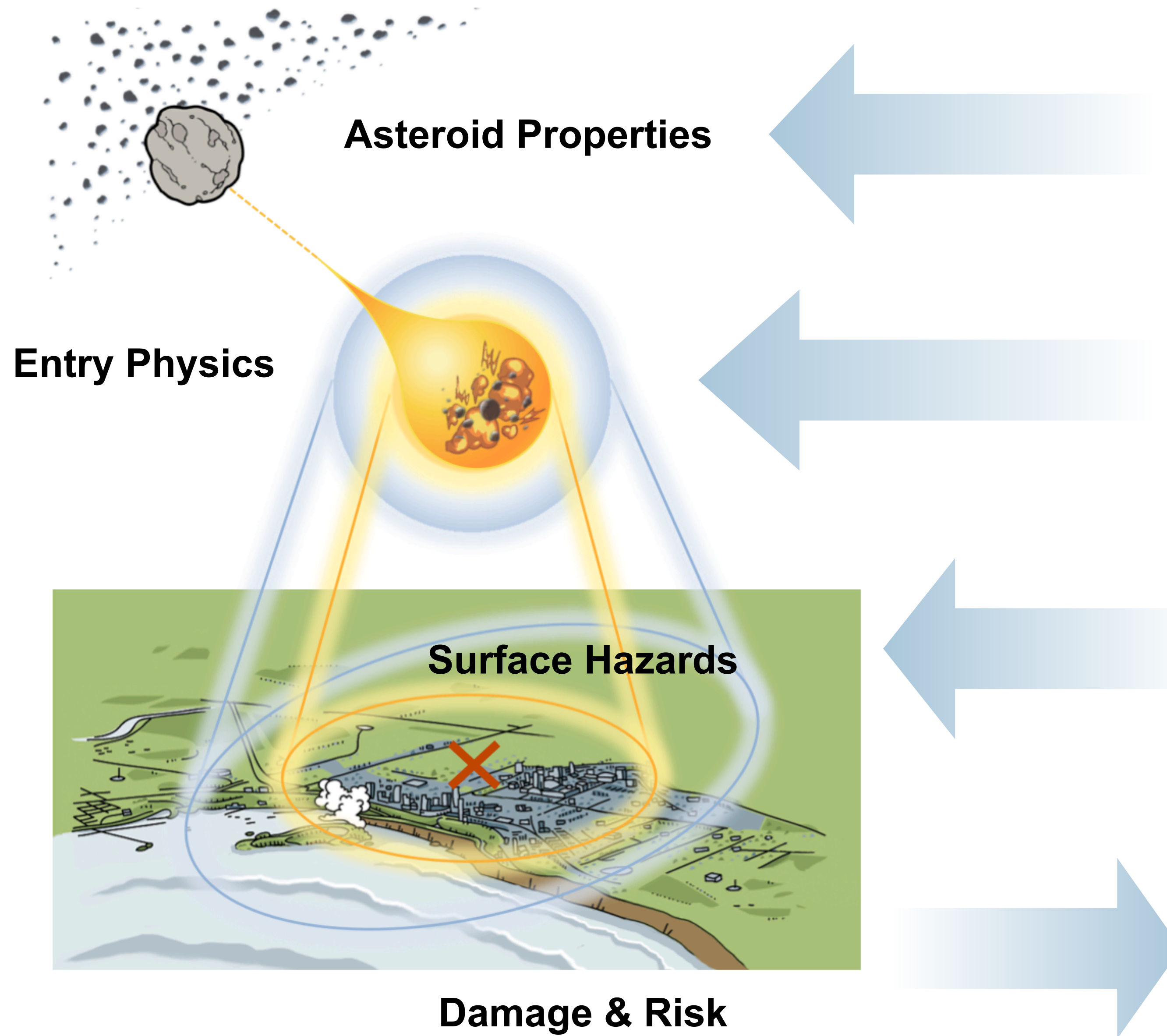
All known asteroids 2018



All known asteroids 2018



Asteroid Threat Assessment Project (ATAP)



Characterization

- Measurements
- Inference
- Data aggregation
- Property database website

Entry Simulations & Testing

- Flow modeling and radiation
- Ablation modeling and testing
- Fragmentation and break-up

Hazard Simulations

- 3D blast simulations
- Impact crater simulations
- Tsunami simulations
- Thermal radiation models
- Global effects

Probabilistic Risk Assessment

- Analytic physics-based entry and damage models
- Probabilistic Monte Carlo simulation using uncertainty distributions

Don't panic: Scientists are practicing for a killer asteroid impact

81



An artist's rendering of a meteor disintegrating as it enters the Earth's atmosphere. (solarseven/Getty Images/iStockphoto)

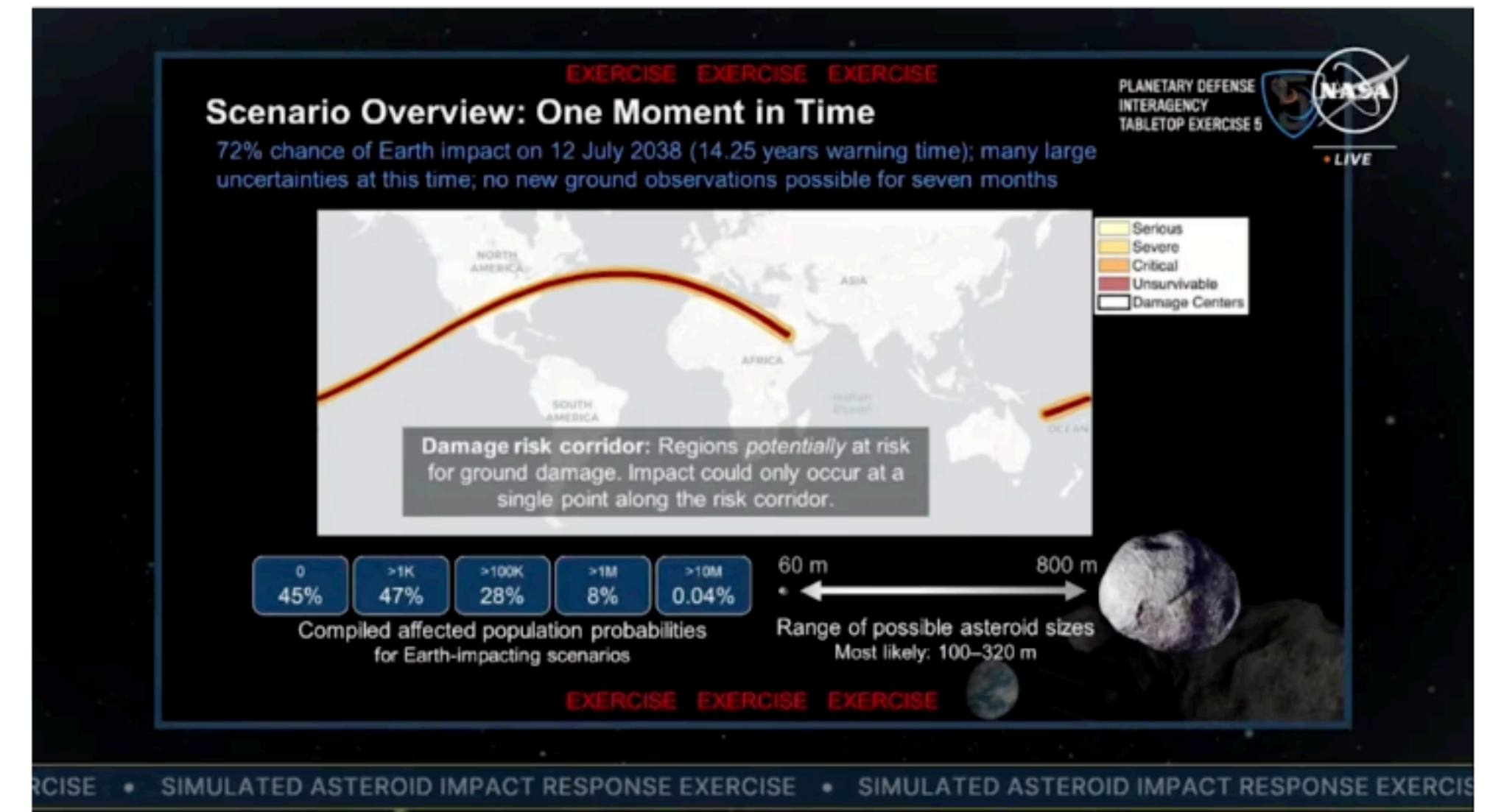
US NEWS

NASA plans for doomsday scenario of asteroid with 72 percent chance of hitting Earth in 14 years

By Isabel Keane

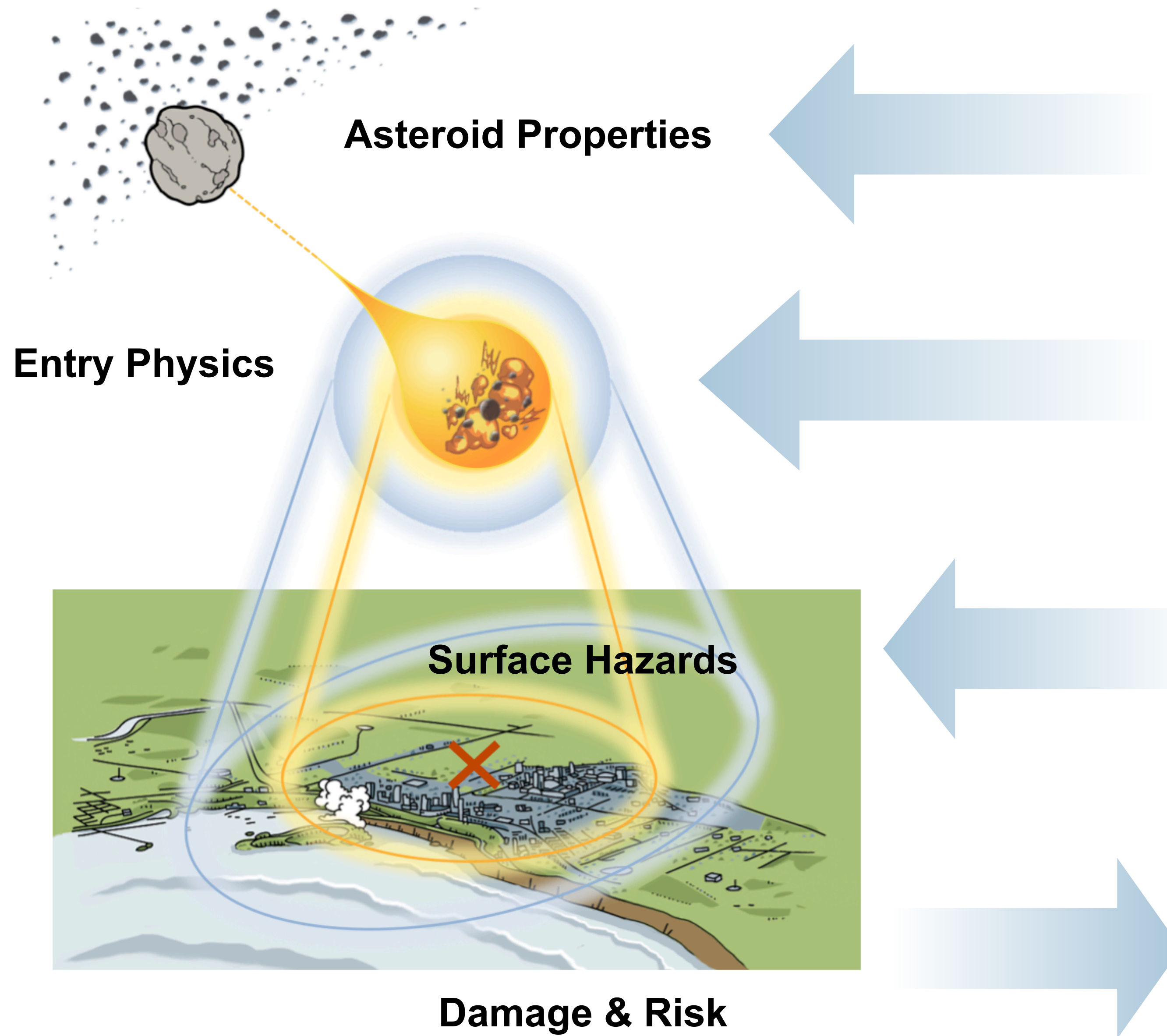
Published June 25, 2024, 1:50 p.m. ET

217 Comments



What if a never-before-seen asteroid barreling in our direction was likely to strike Earth?

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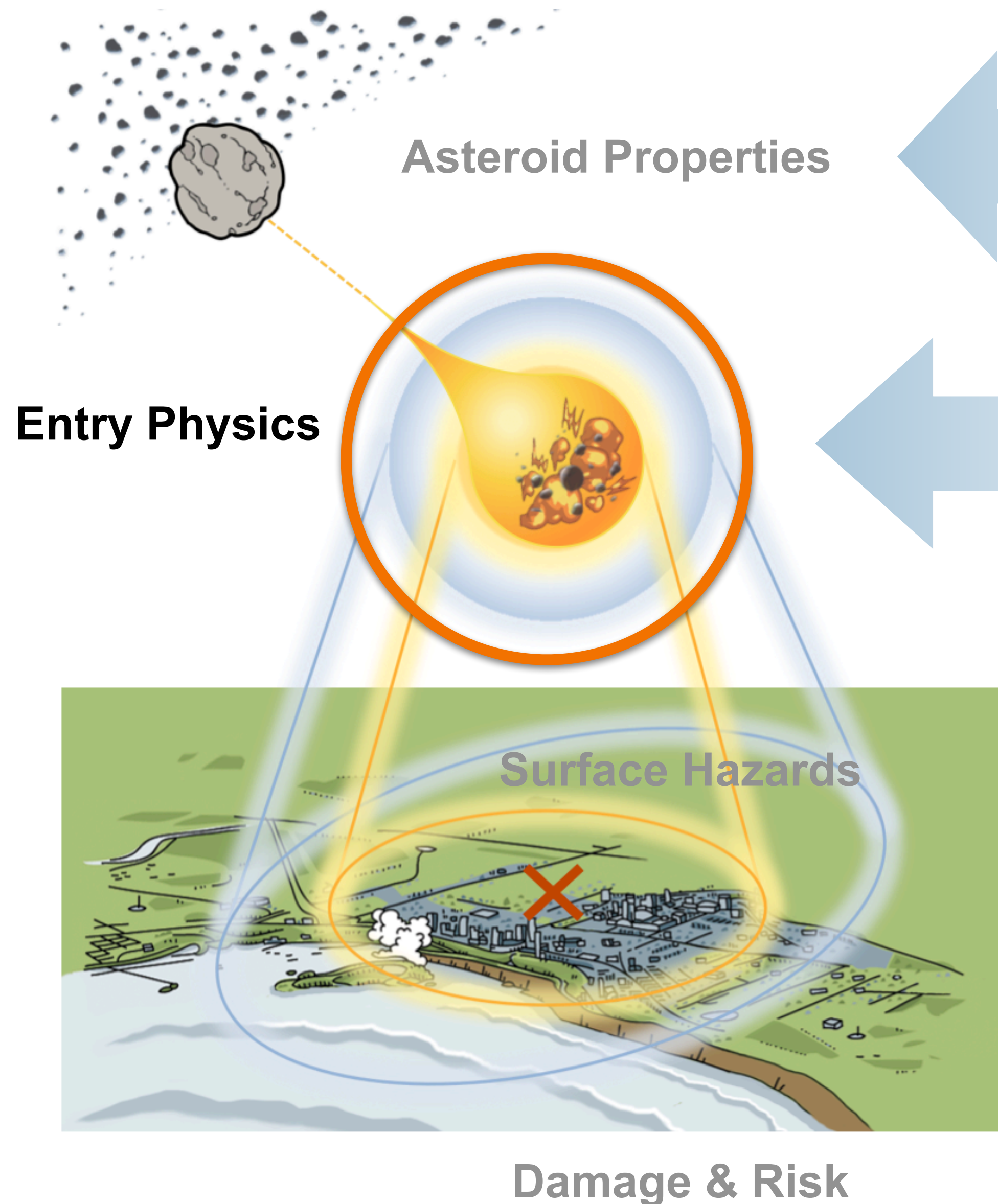
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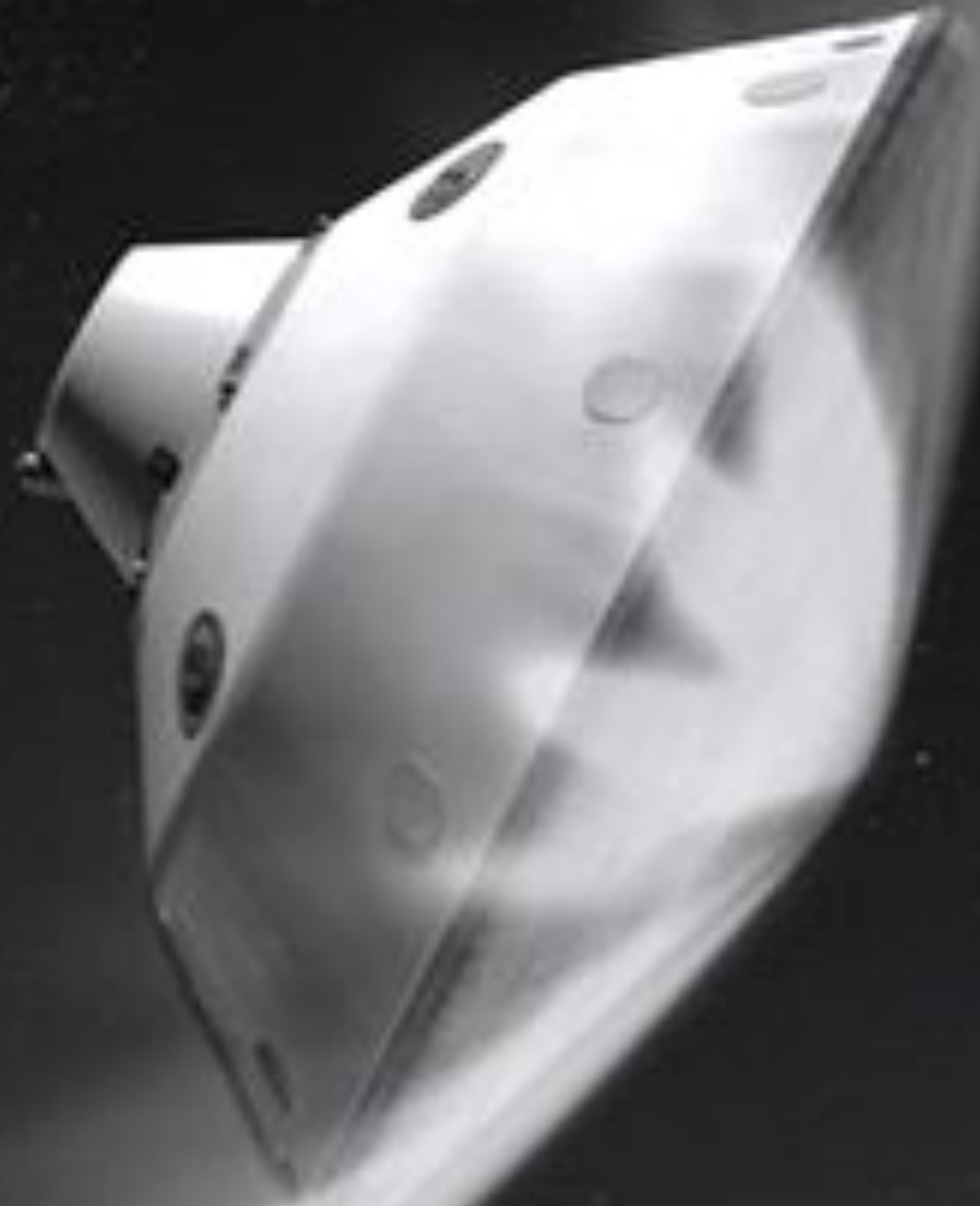
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Entry Vehicles



Asteroids



Entry Vehicles



Asteroids



Entry Vehicles

Aerothermodynamics

- Molecular dissociation
- Non-equilibrium shock layer
- Convection dominated
- Uncoupled radiation

Asteroids



Entry Vehicles

Aerothermodynamics

- Molecular dissociation
- Non-equilibrium shock layer
- Convection dominated
- Uncoupled radiation

Ablation

- Oxidation dominated
- Catalycity important
- Quasi-steady interface

Asteroids



Entry Vehicles

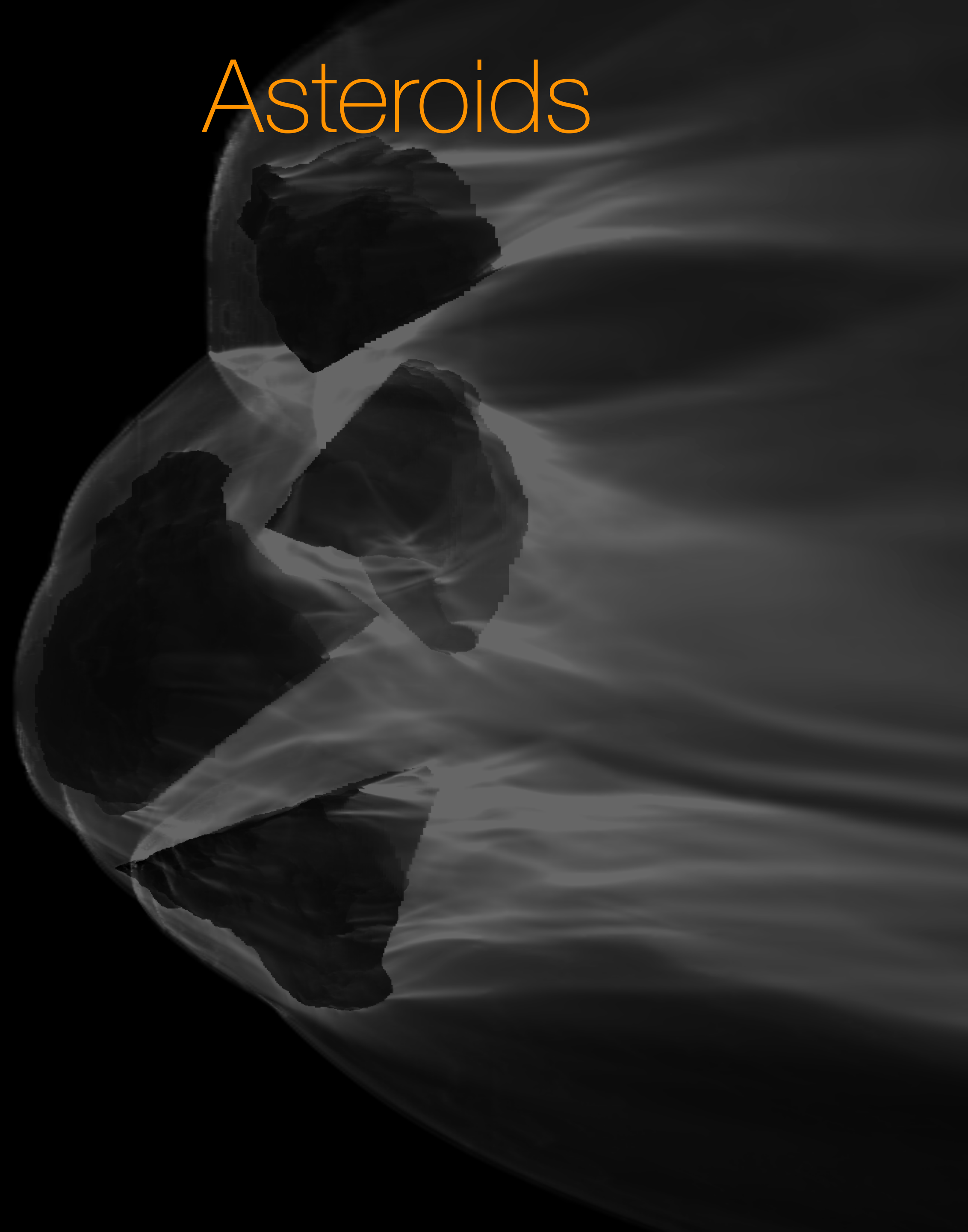
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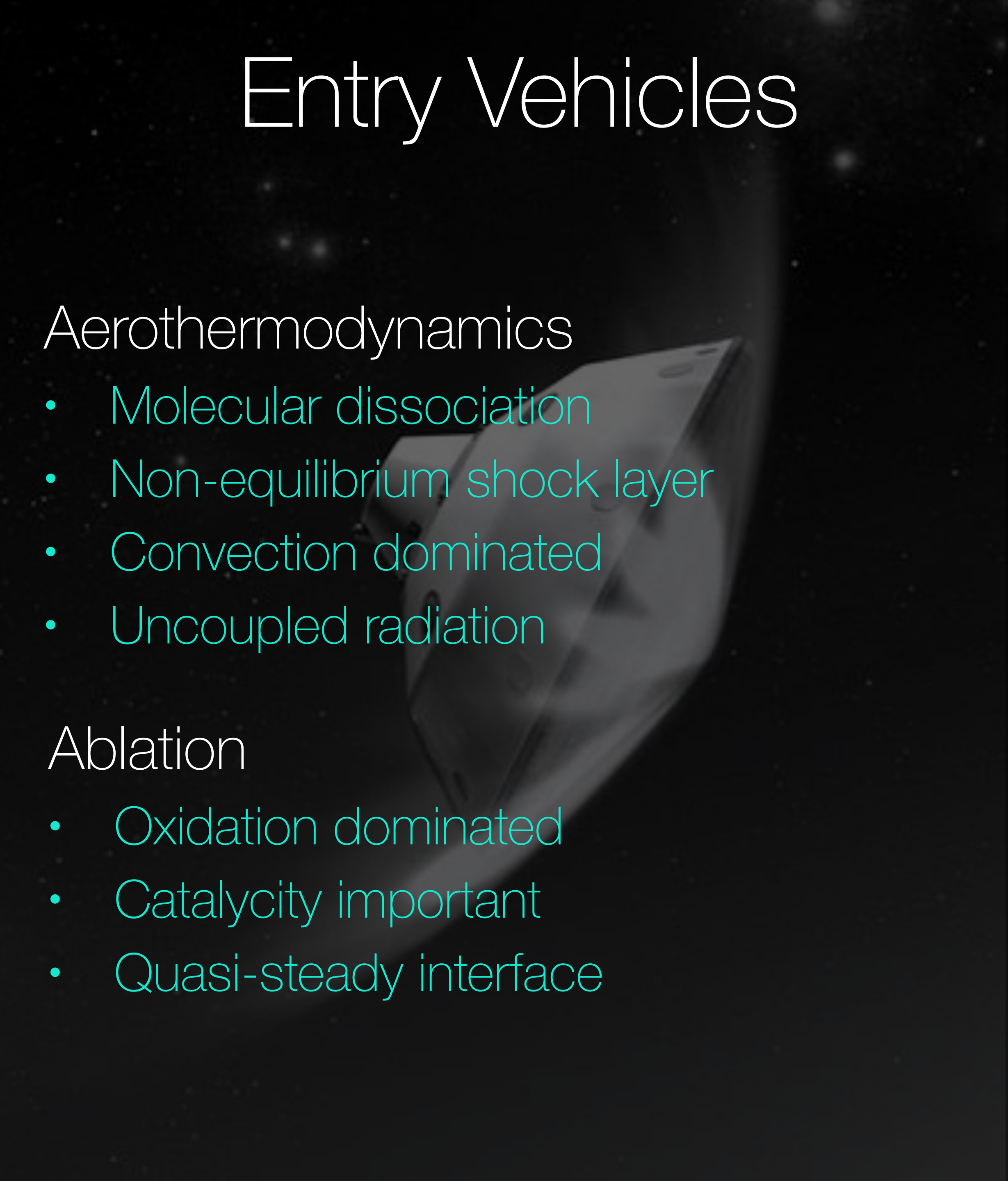
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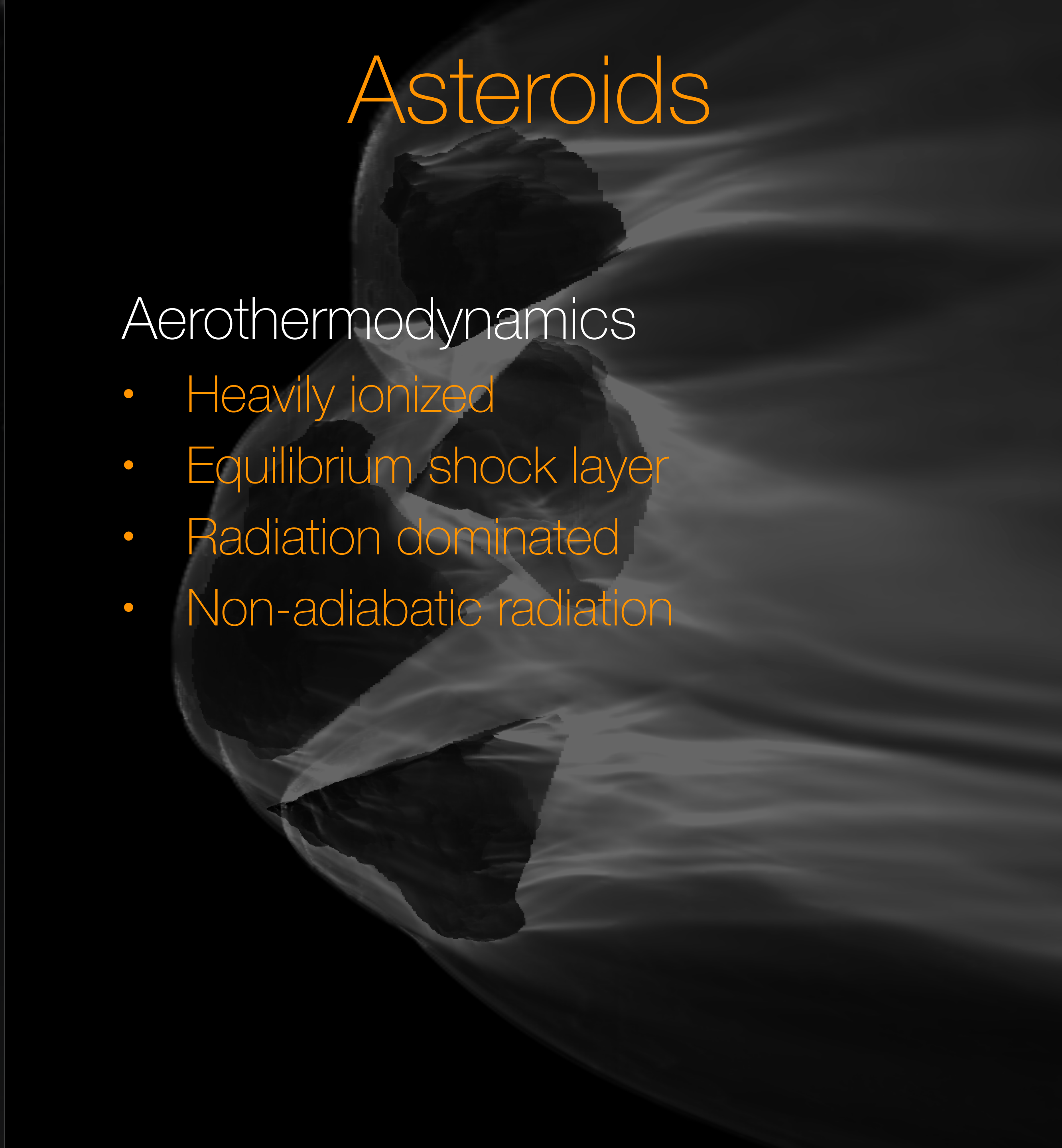
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Aerothermodynamics

- Heavily ionized
- Equilibrium shock layer
- Radiation dominated
- Non-adiabatic radiation

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Ablation

- Vaporization dominated
- Melt flow
- Rapid recession

Entry Vehicles

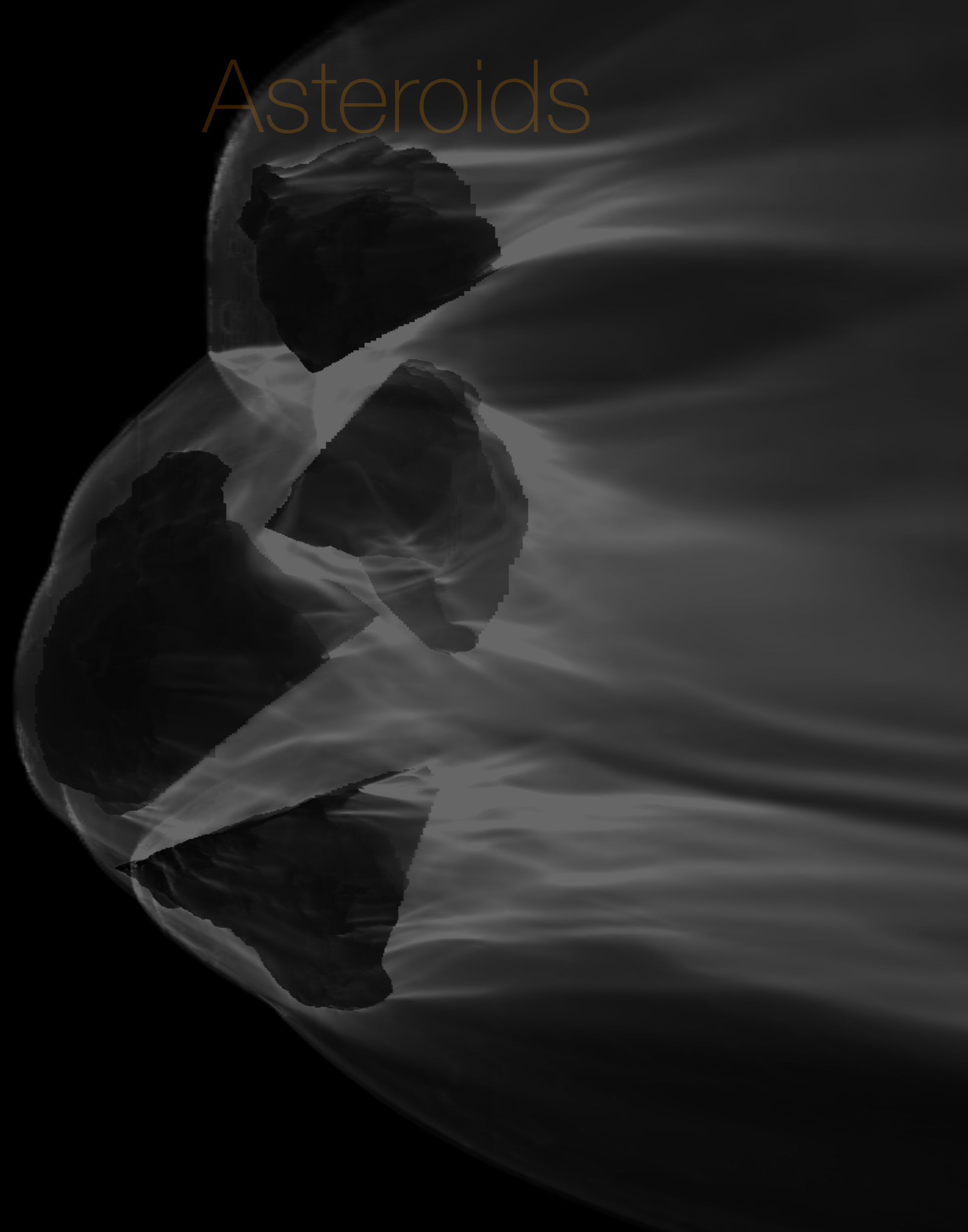
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Asteroids



Entry Vehicles

Aerothermodynamics

- Molecular dissociation
- Non-equilibrium
- Convection dominated
- Uncoupled radiation

Validation

- Flight similitude for entry vehicles achievable in ground-test facilities in a *piecewise* manner
- For planetary defense, flight similitude is effectively impossible

Ablation

- Oxidation dominated
- Catalycity important
- Quasi-steady interface

Asteroids

Aerothermodynamics

- Heavily ionized
- Freezing temperatures

- vaporization dominated
- Melt flow
- Rapid recession



For the rest of the talk:

- The classical approach to modeling meteoroid entry
- Relevant phenomena
- NASA-led Advancements in...
 - ▶ Aerothermodynamics
 - ▶ Radiation
 - ▶ Ablation
- Challenges and opportunities ahead

The Classical Meteor Physics Equations

Velocity $\frac{dV}{dt} = -\Gamma V^2 \frac{3\rho_a}{4\rho_m R},$

Mass Loss $\frac{dm}{dt} = -\frac{1}{2}\rho_A v^3 \frac{C_H}{Q^*}$

Height $\frac{dH}{dt} = -V \cos \gamma,$

Luminosity $I = -\tau \left(\frac{V^2}{2} \frac{dm}{dt} + mV \frac{dV}{dt} \right).$

The Classical Meteor Physics Equations

Drag coefficient
(Shape)

Effective Radius
(fragmentation state)

Velocity

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Aerothermodynamics

Height

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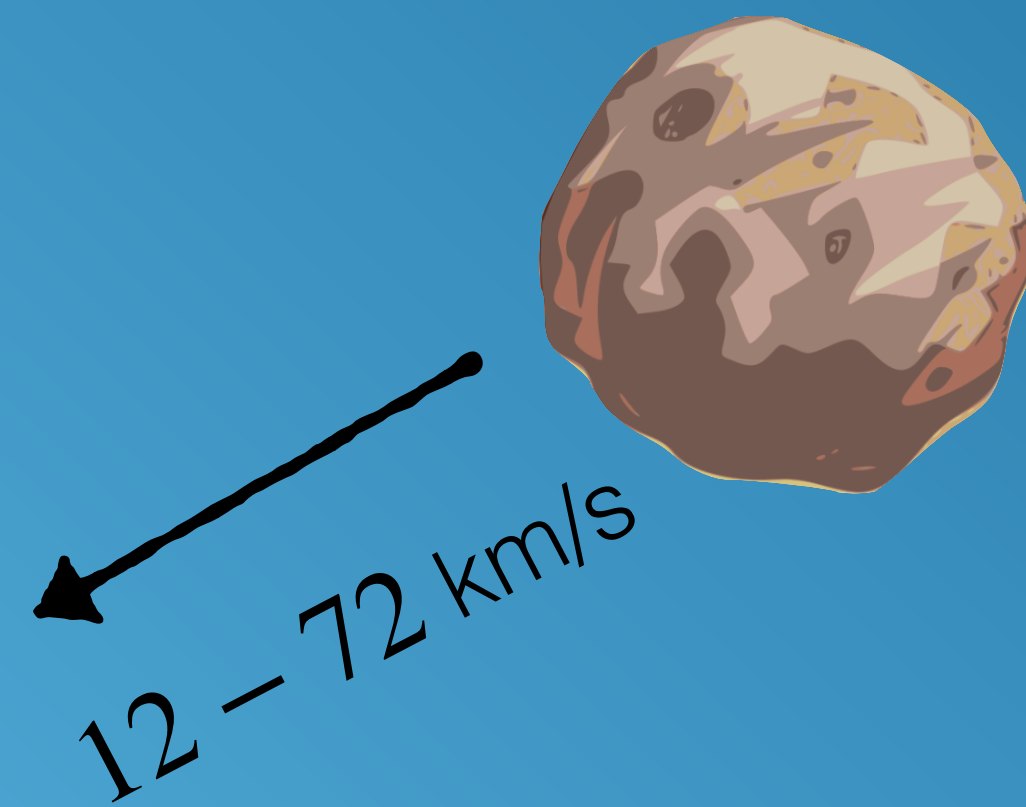
Ablation Physics

Luminosity

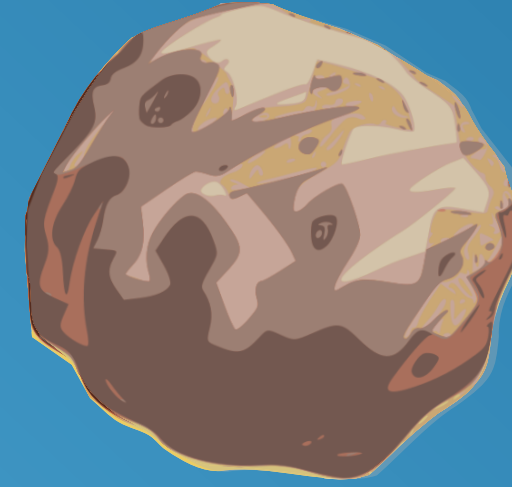
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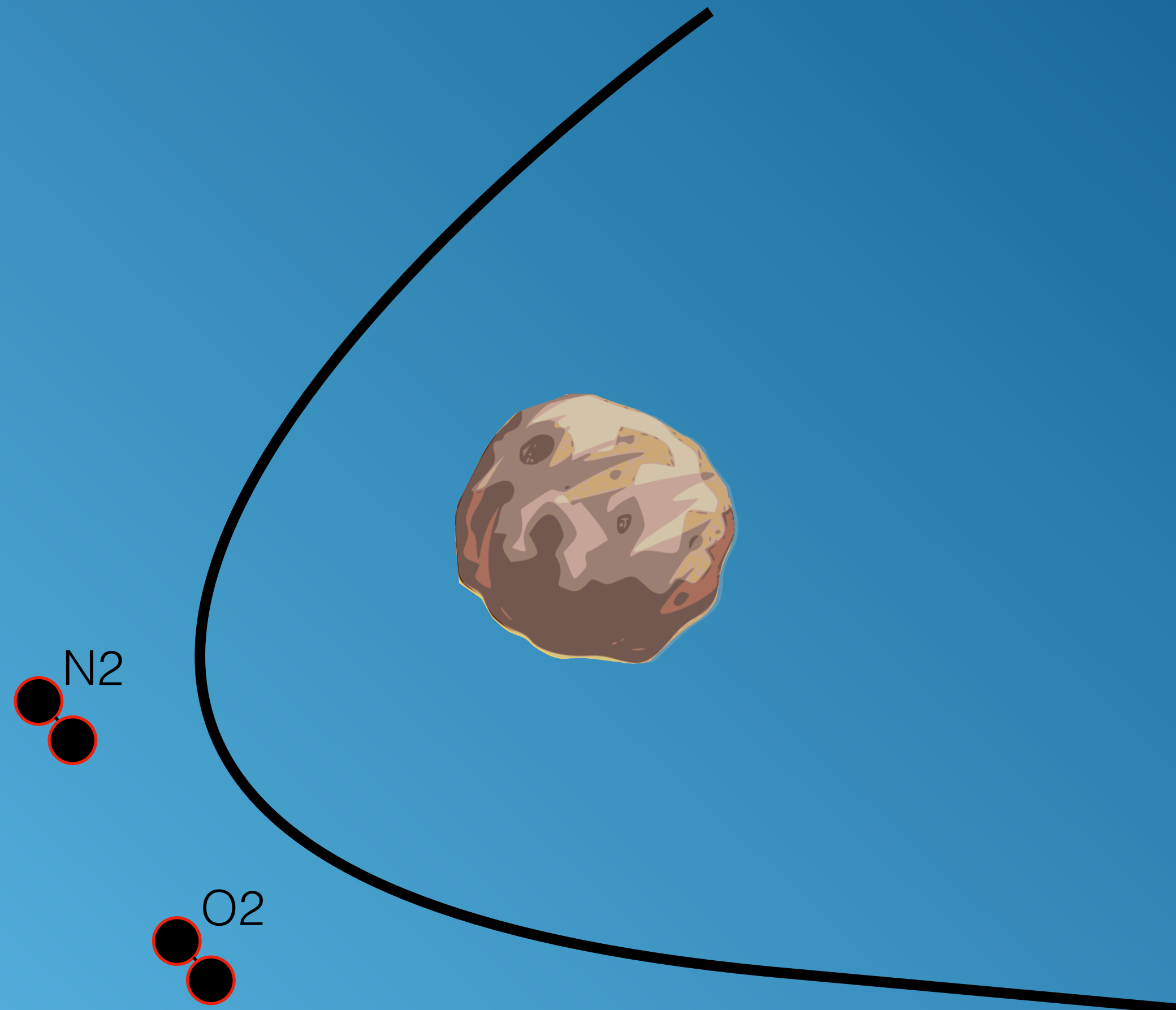
Luminous Efficiency

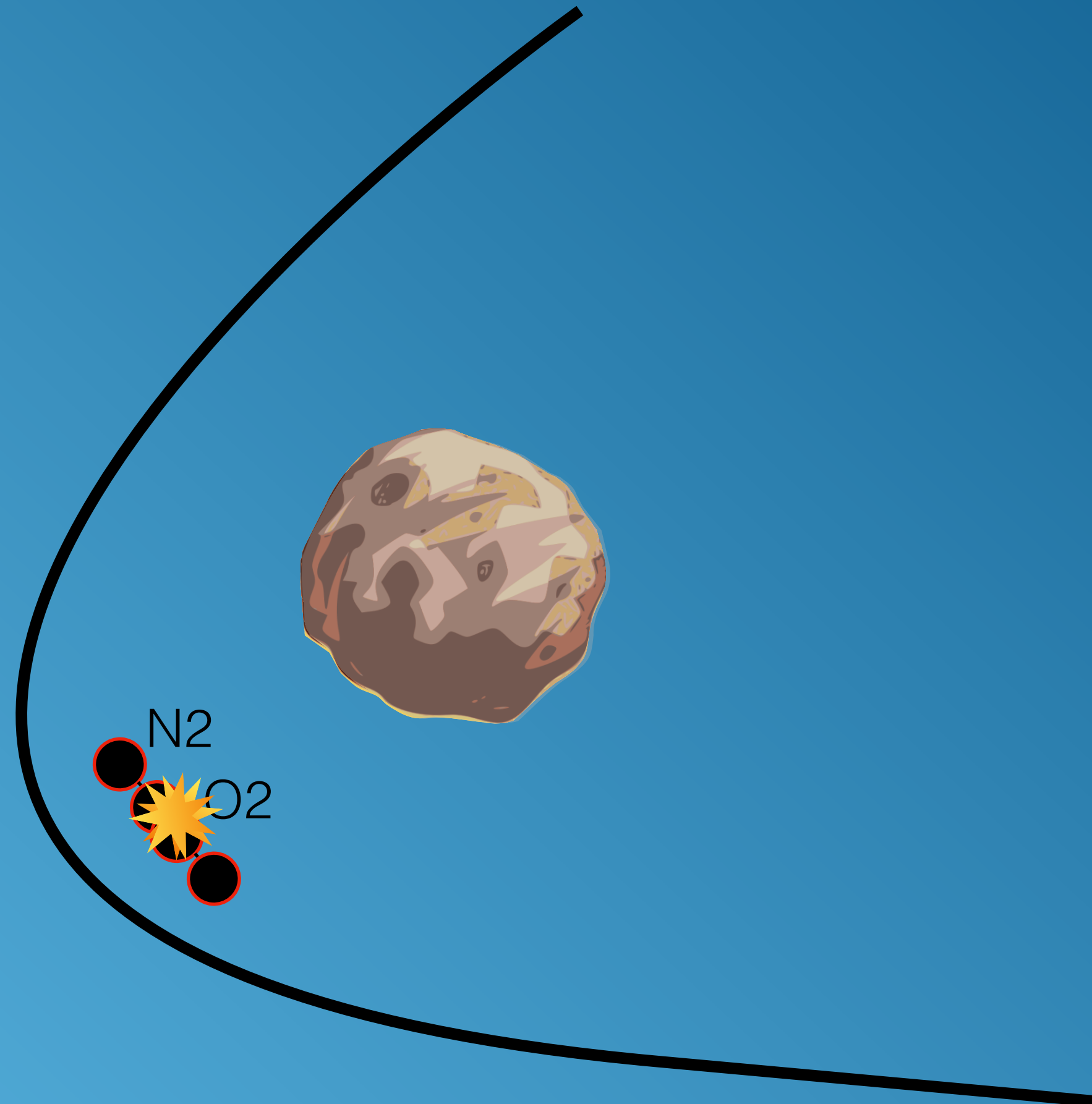
Surrounding free-stream
atmosphere above 60 km
 $\approx 250 \text{ K}$ & 20 Pa

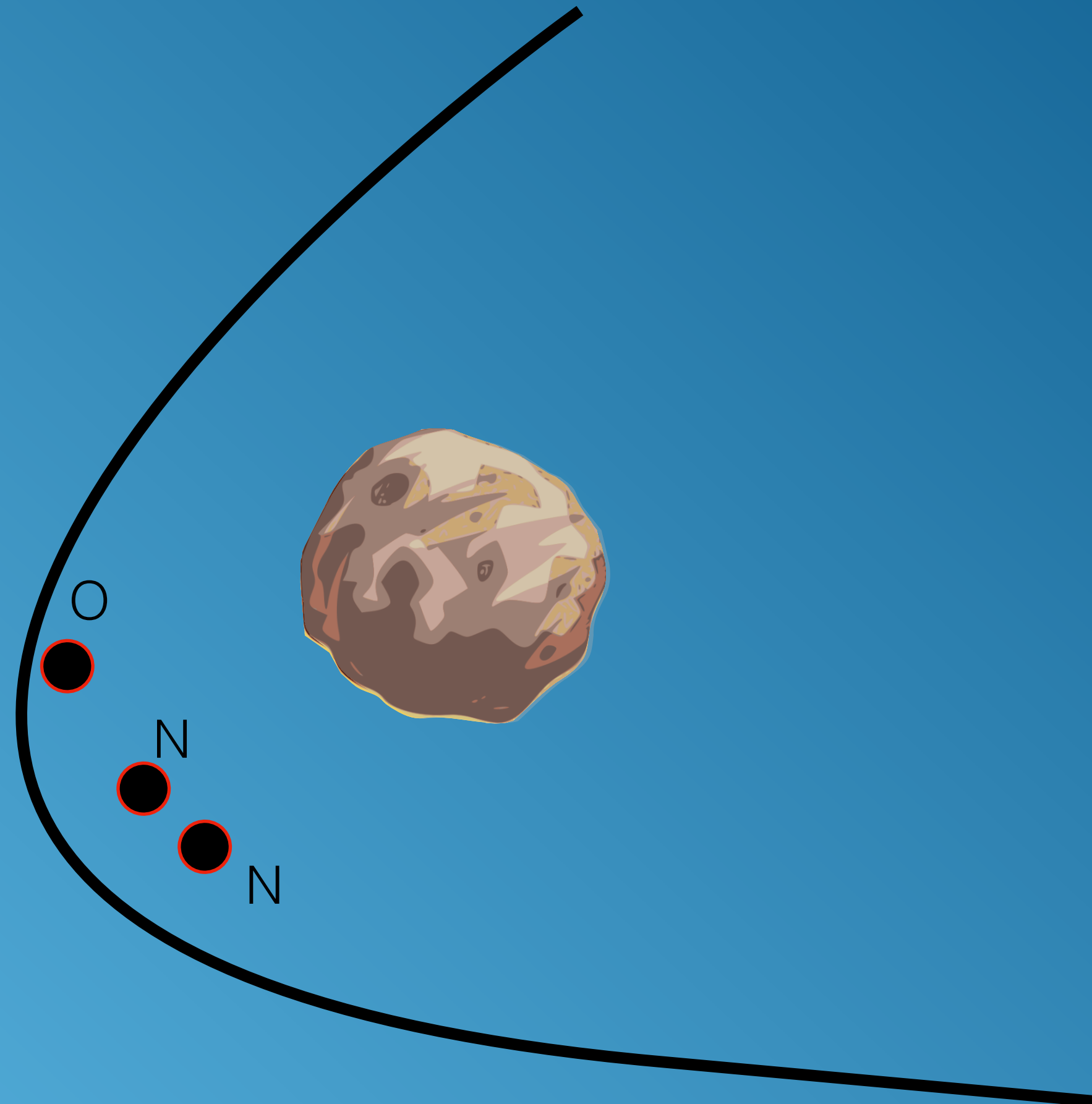


Strong shock-wave
 $\approx 15000 \text{ K}$ & 60000 Pa

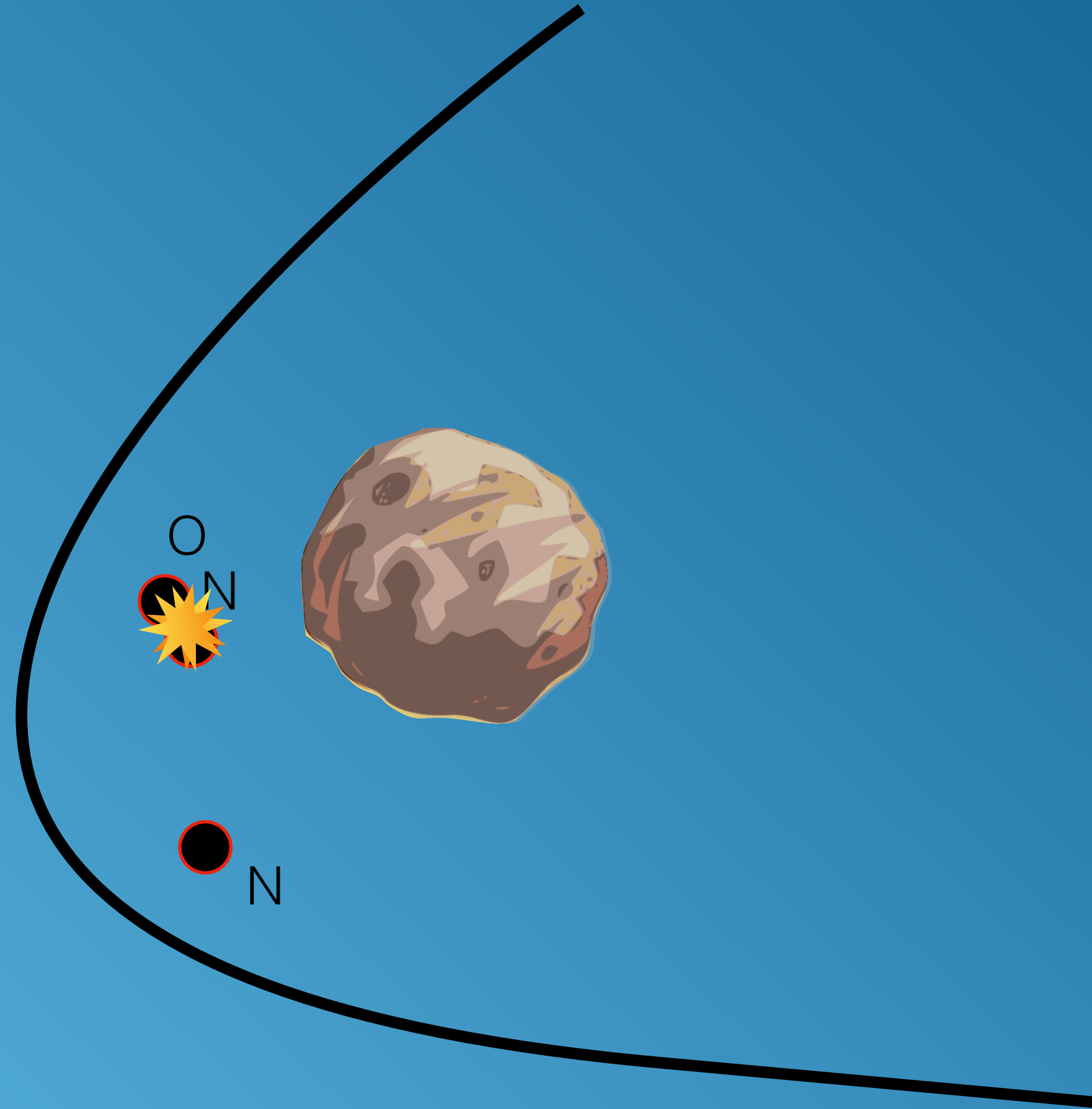


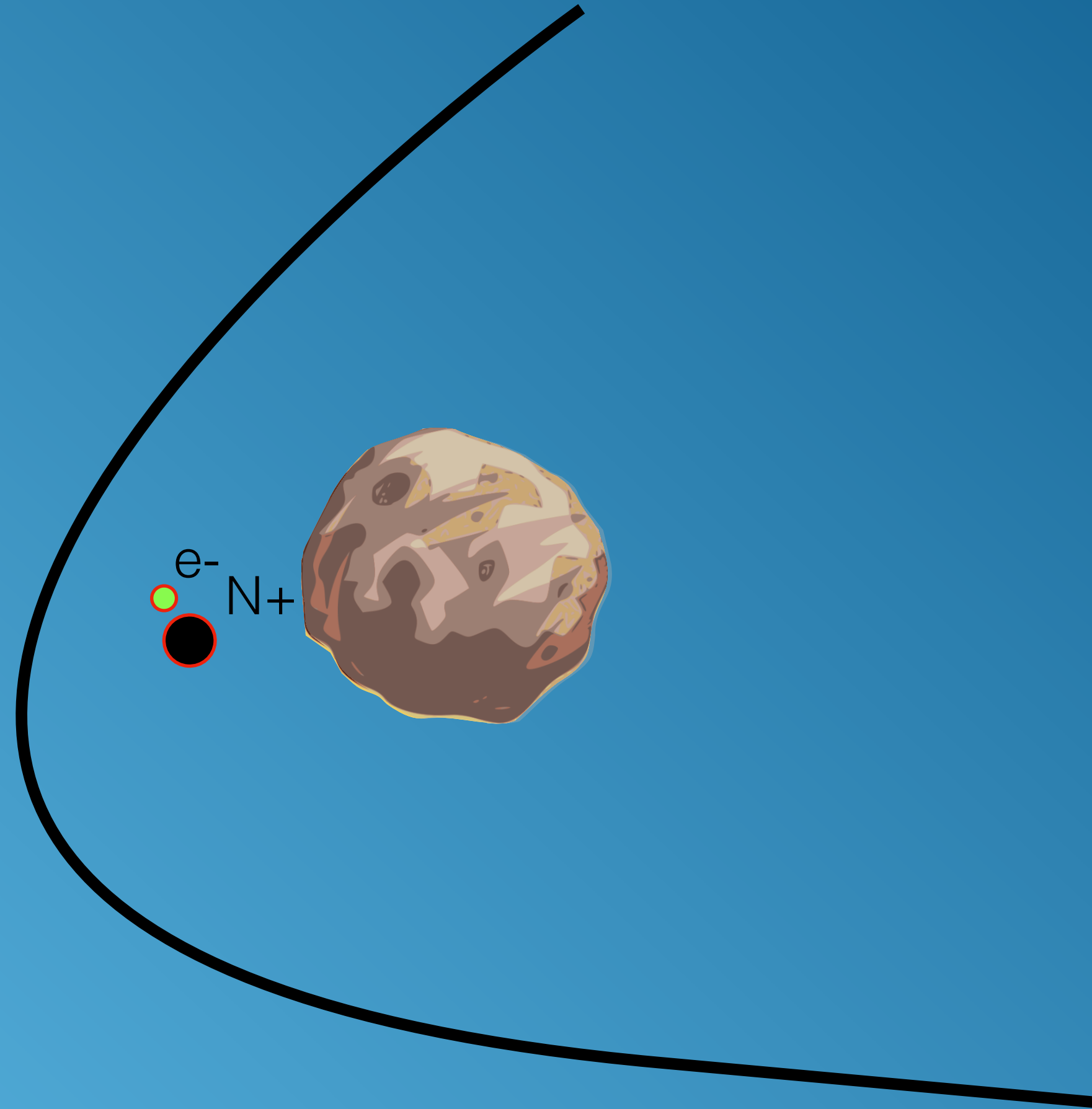




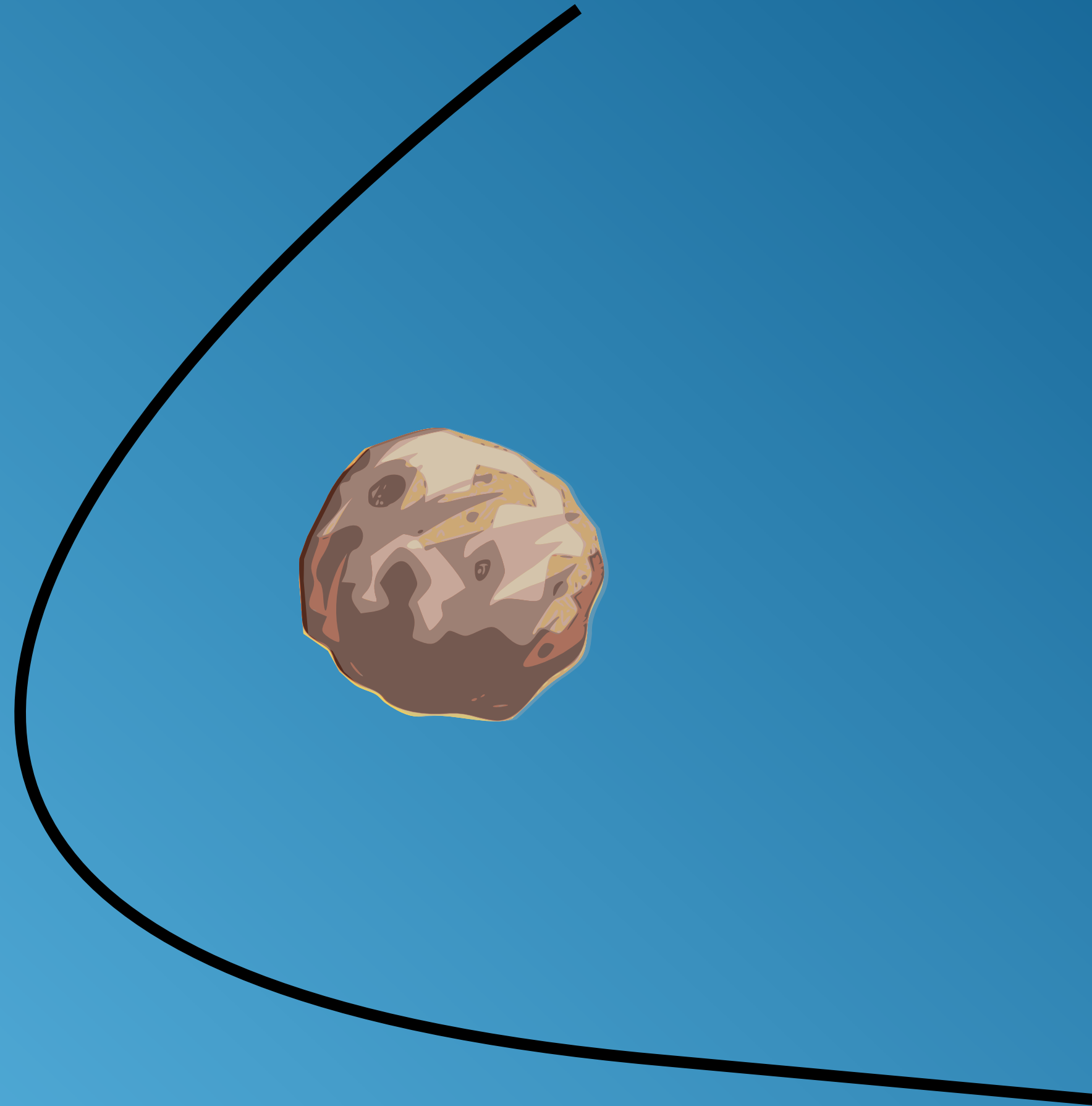


Dissociation

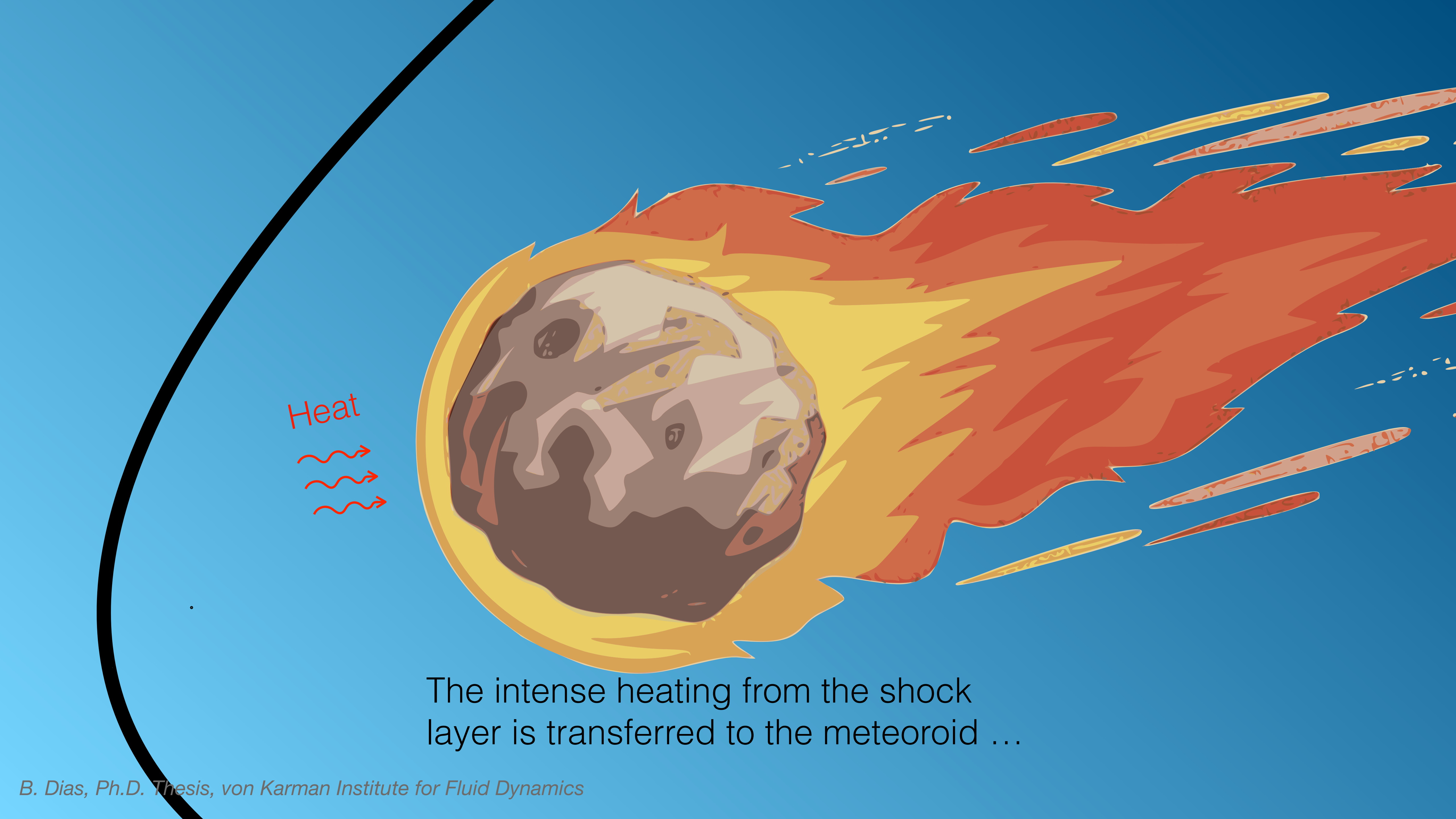




Ionization



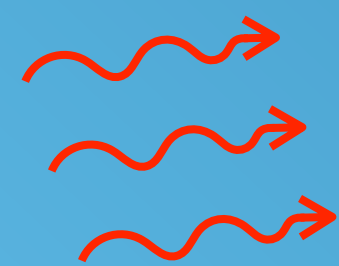


A stylized illustration of a meteoroid entering Earth's atmosphere. The meteoroid is a grey, irregularly shaped rock with several dark spots, moving from the left towards the right. It is surrounded by a large, bright yellow and orange fireball. A thick, dark blue shock layer is visible behind the meteoroid, with several smaller, elongated orange and yellow streaks trailing behind it. The background is a solid blue sky. A large, curved black line on the left side of the image represents the Earth's horizon. To the left of the meteoroid, the word "Heat" is written in red, with three red wavy arrows pointing towards the meteoroid.

Heat

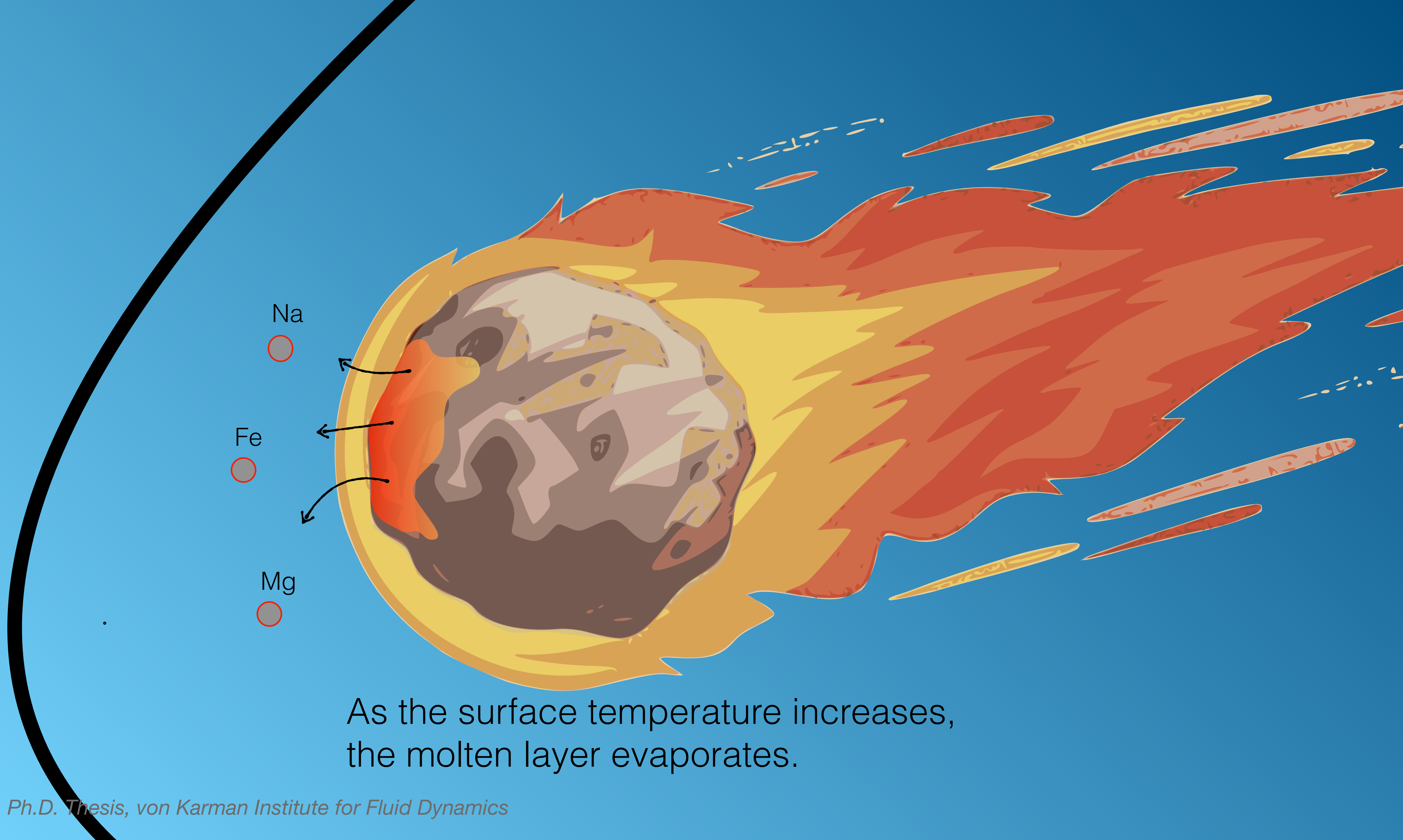
The intense heating from the shock layer is transferred to the meteoroid ...

Heat



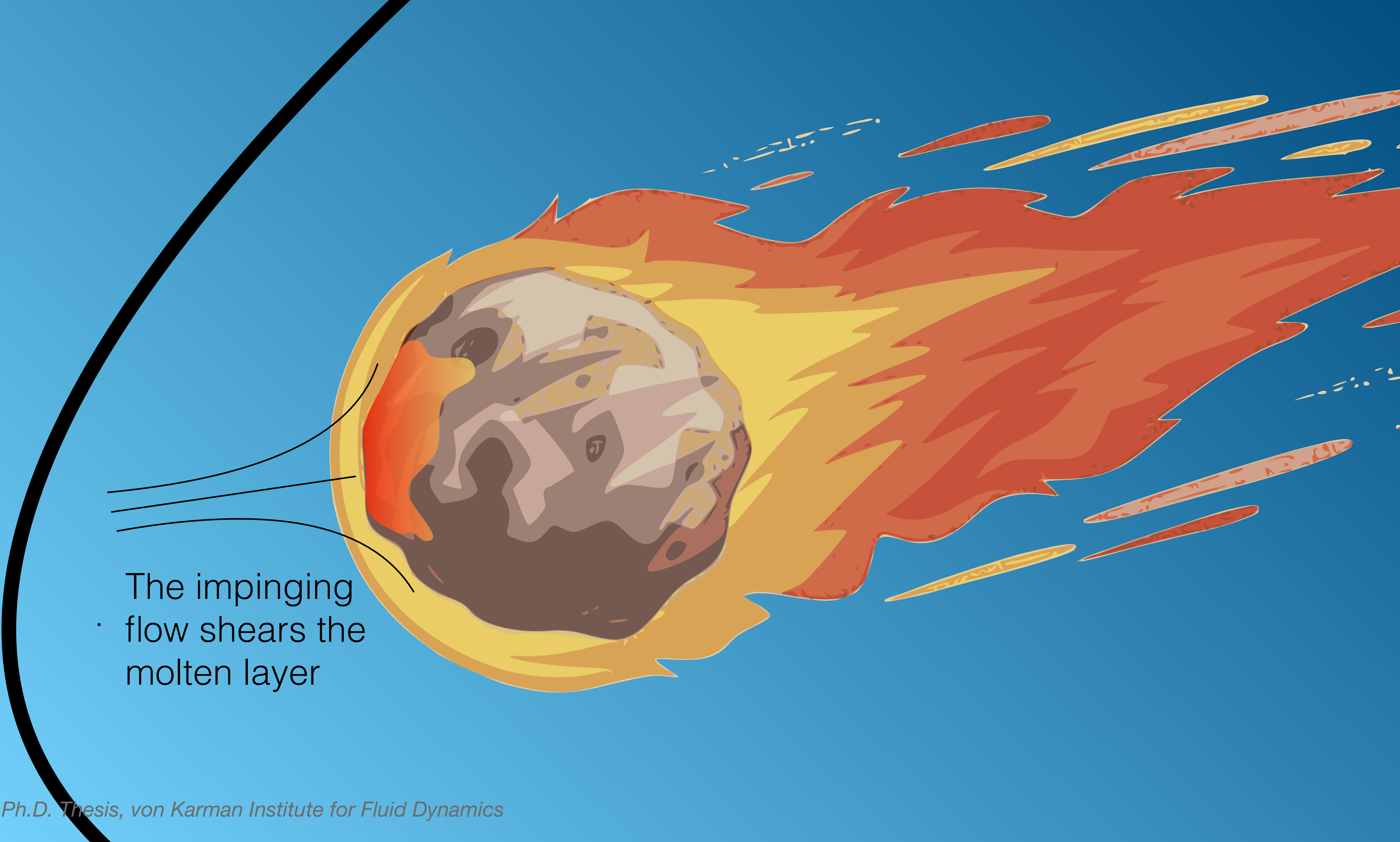
...and eventually the space rock melts.



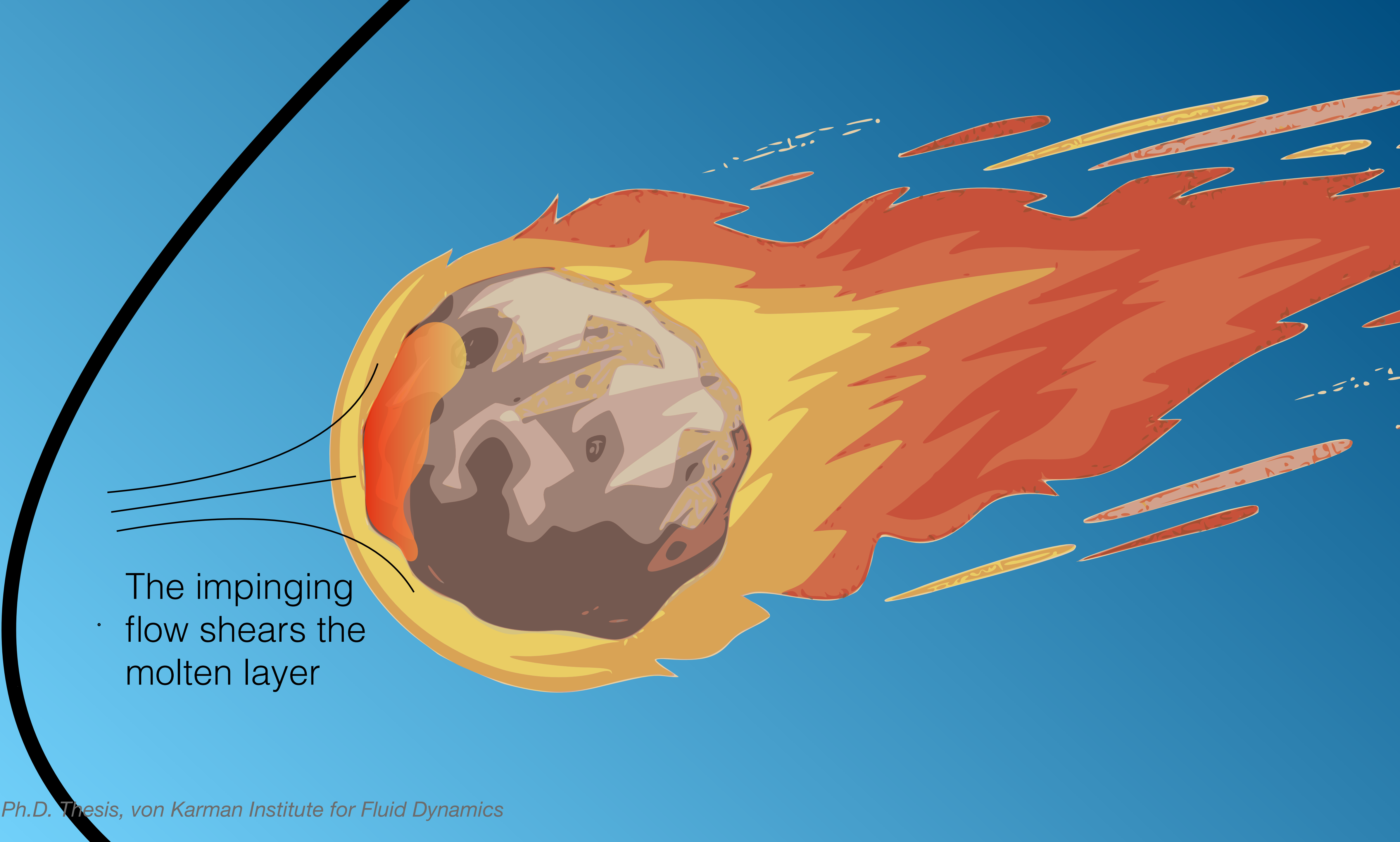


As the surface temperature increases,
the molten layer evaporates.

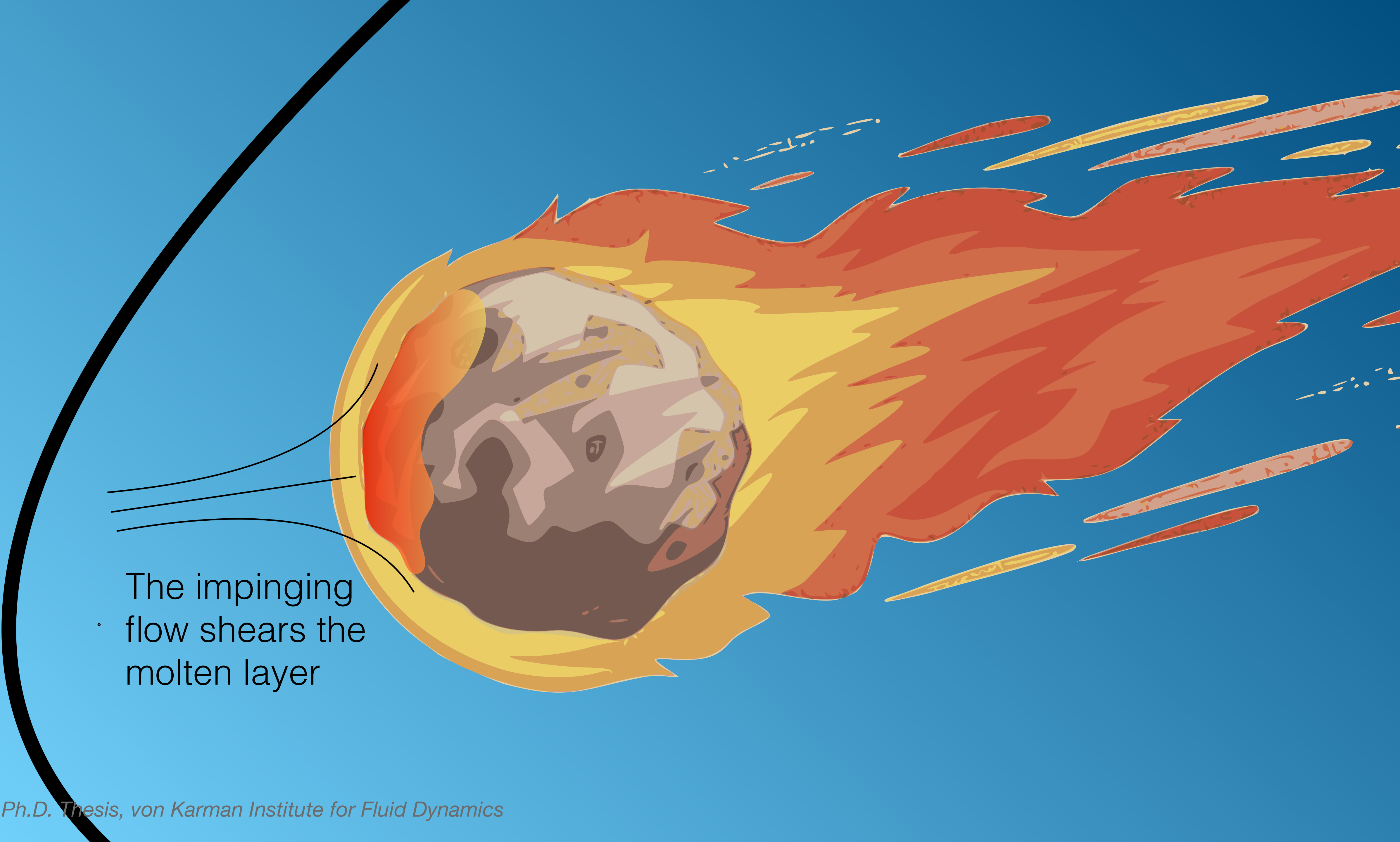




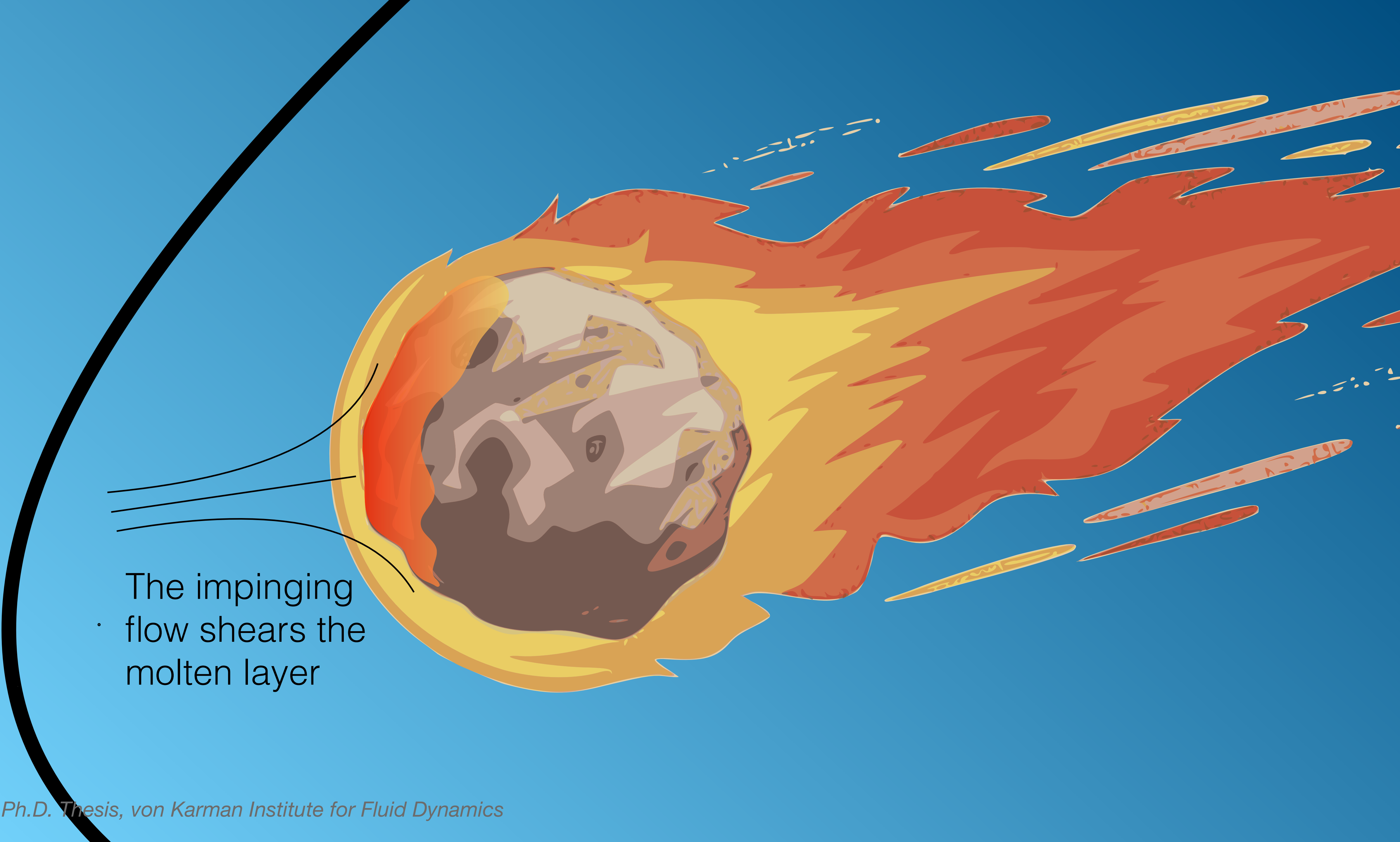
The impinging
flow shears the
molten layer



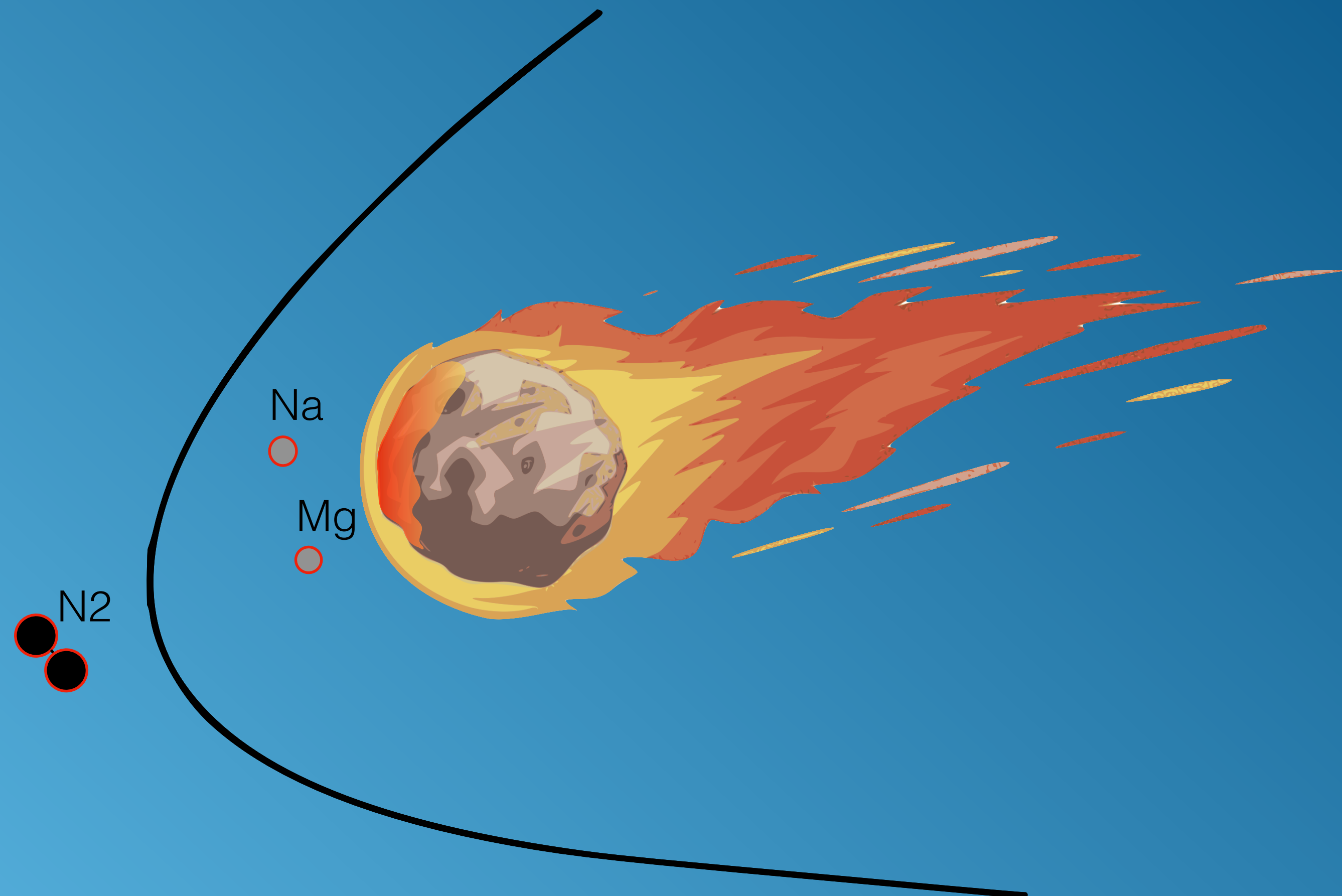
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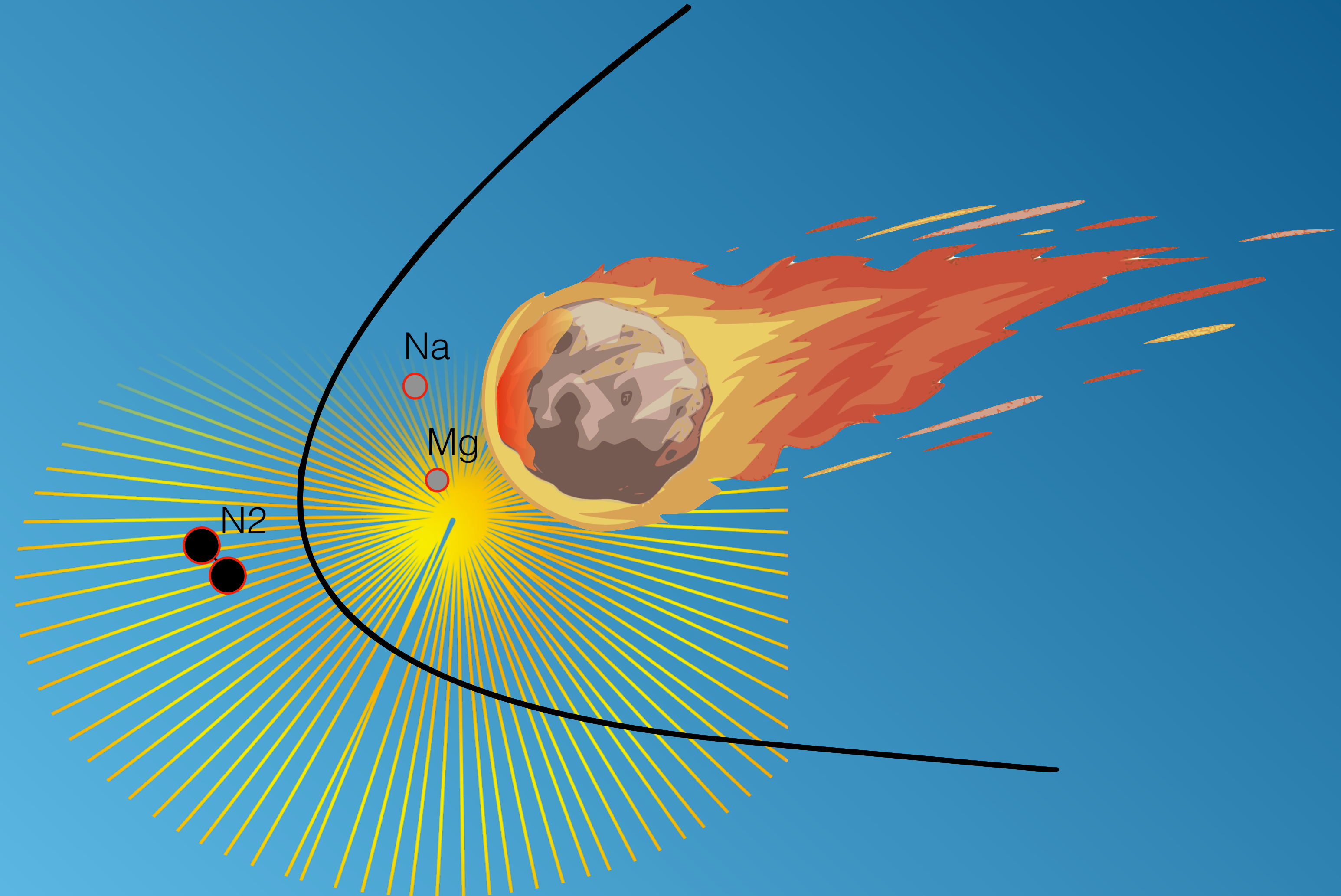


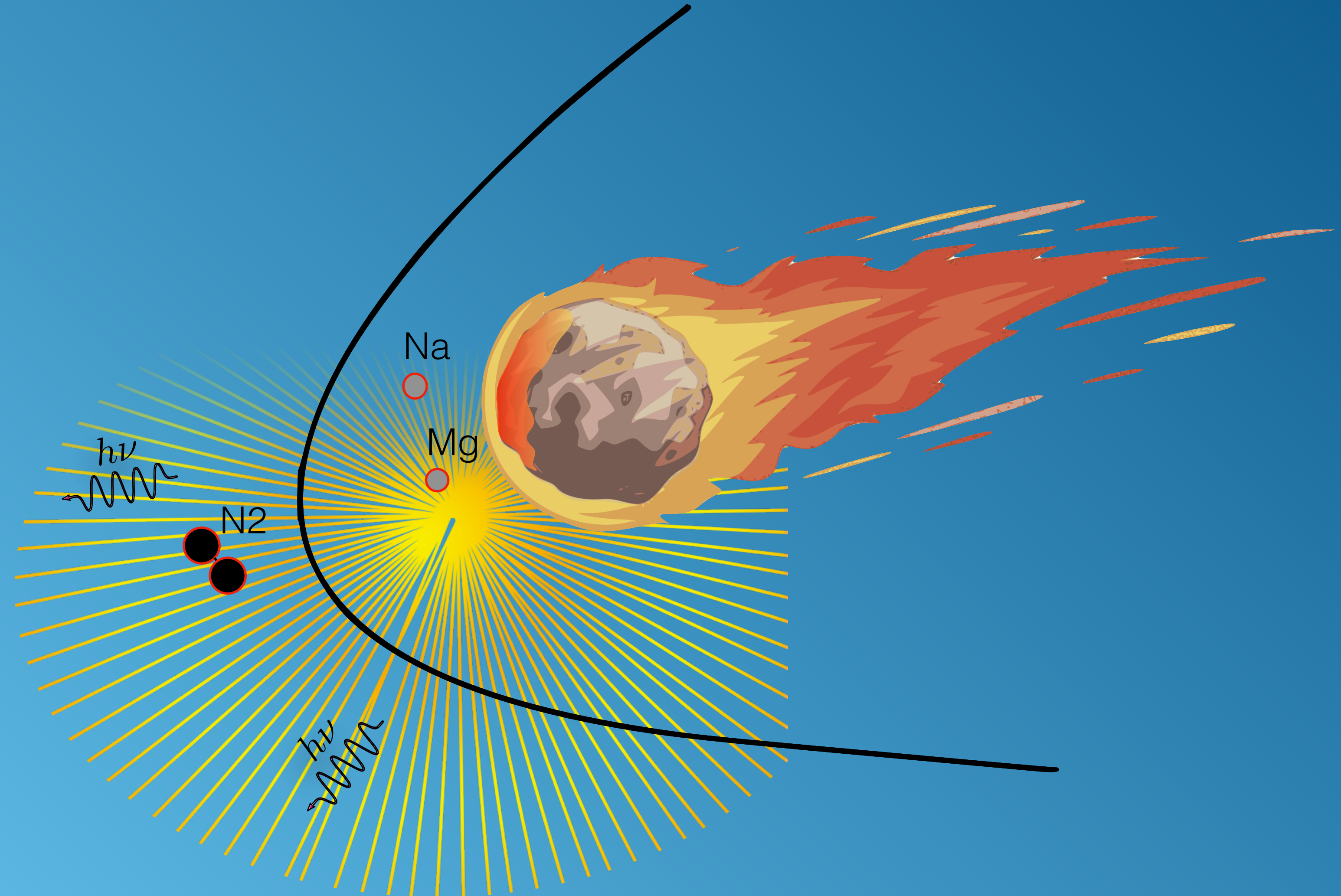
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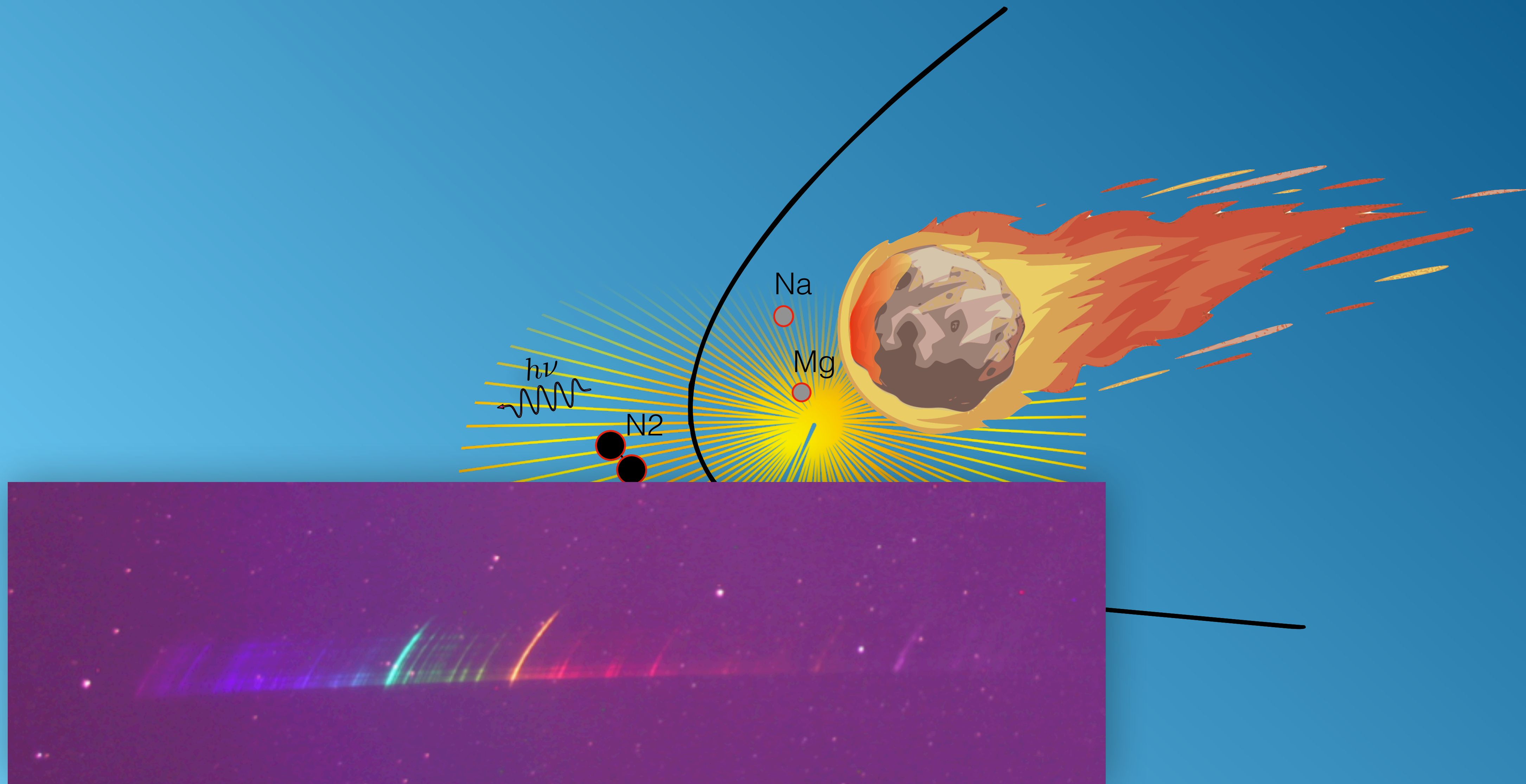


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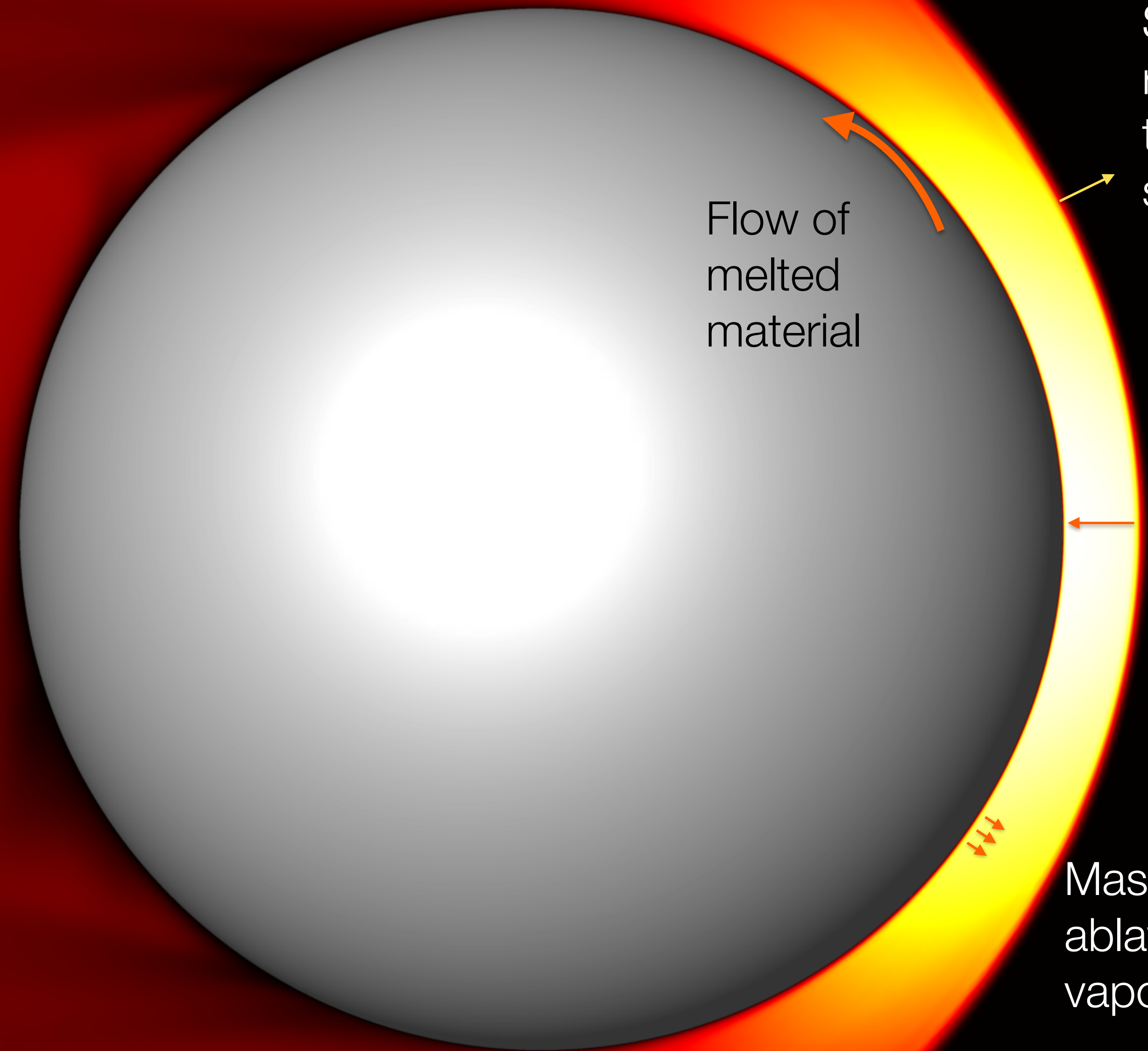








Heated ablation products
emit radiation, producing
observed light curves and
spectra



Shock layer
radiates out
to the
surroundings

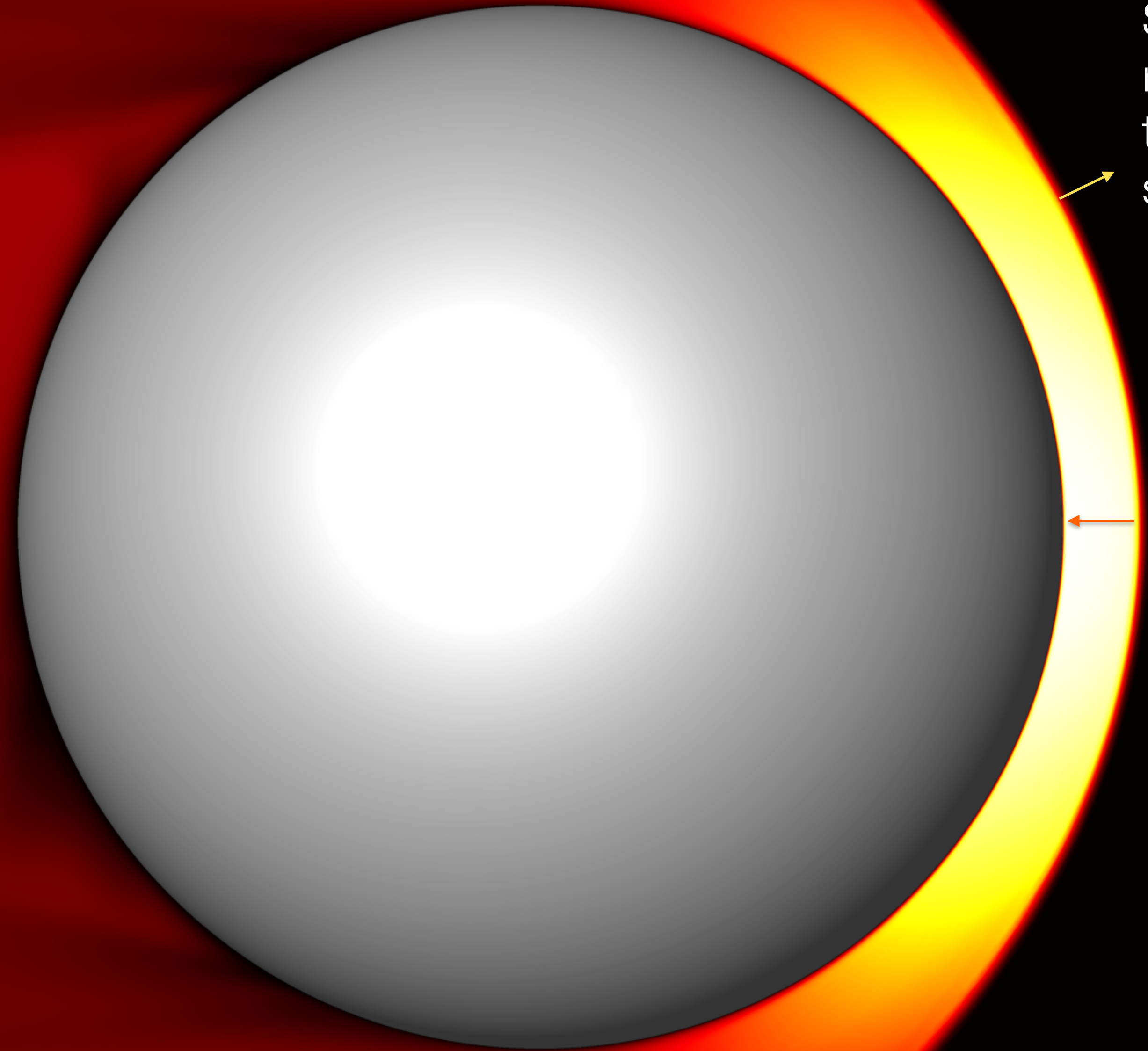
Strong
radiative
heat flux to
the surface

Massive
ablation from
vaporization

Flow of
melted
material

Aerothermodynamics

Heated ablation products emit radiation, producing observed light curves and spectra



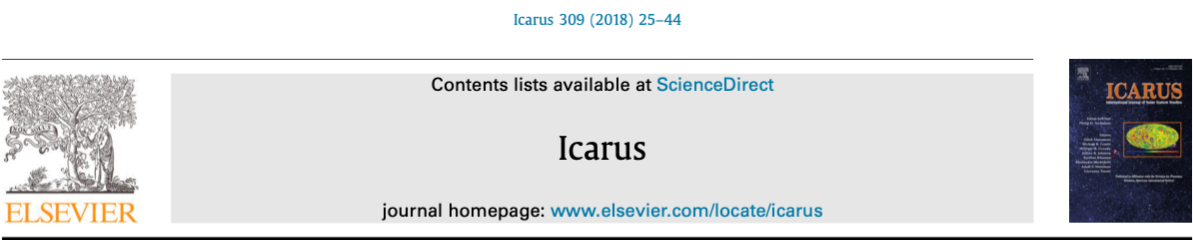
Shock layer radiates out to the surroundings

Strong radiative heat flux to the surface

Toward a complete aerothermodynamic description of the meteor flowfield...

Toward a complete aerothermodynamic description of the meteor flowfield...

Computational Approach and Heat Transfer



Radiative heating of large meteoroids during atmospheric entry

Christopher O. Johnston^{a,*}, Eric C. Stern^b, Lorien F. Wheeler^c

^aNASA Langley Research Center, Hampton, VA, 23681, United States
^bNASA Ames Research Center, Moffett Field, CA, 94035, United States
^cCSRA, NASA Ames Research Center, Moffett Field, CA, 94035, United States

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Meteoroids
Meteors
Simulation

ABSTRACT

A high-fidelity approach for simulating the aerothermodynamic environments of meteor entries was developed, which allows the commonly assumed heat transfer coefficient of 0.1 to be assessed. This model uses chemically reacting computational fluid dynamics (CFD), coupled with radiation transport and surface ablation. Coupled radiation accounts for the impact of radiation on the flowfield energy equations, while coupled ablation explicitly models the injection of ablation products within the flowfield and radiation simulations. For a meteoroid with a velocity of 20 km/s, coupled radiation is shown to reduce the stagnation point radiative heating by over 60%. The impact of coupled ablation (with coupled radiation) is shown to provide at least a 70% reduction in the radiative heating relative to cases with only coupled radiation. This large reduction is partially the result of the low ionization energies of meteoric ablation products relative to air species. The low ionization energies of ablation products, such as Mg and Ca, provide strong photoionization and atomic line absorption in regions of the spectrum that air species do not. MgO and CaO are also shown to provide significant absorption. Turbulence is shown to impact the distribution of ablation products through the shock-layer, which results in up to a 100% increase in the radiative heating downstream of the stagnation point. To create a database of heat transfer coefficients, the developed model was applied to a range of cases. This database considered velocities ranging from 14 to 20 km/s, altitudes ranging from 20 to 50 km, and nose radii ranging from 1 to 100 m. The heat transfer coefficients from these simulations are below 0.045 for the range of cases, for both laminar and turbulent, which is significantly lower than the canonical value of 0.1. When the new heat transfer model is applied to a Tunguska-like 15 Mt entry, the effect of the new model is to lower the height of burst by up to 2 km, depending on assumed entry angle. This, in turn, results in a significantly larger ground damage footprint than when the canonical heating assumption is used.

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1. Introduction

A meteor's mass loss rate is an important factor in determining the potential ground damage threat for a given size, entry velocity, entry angle, and composition (Aftosis et al., 2016; Mathias et al., 2017; Revelle, 2004a; Hills and Goda, 1993; Wheeler et al., 2017). The mass loss rate is written as follows:

$$\frac{dM}{dt} = -C_H \frac{S \rho_\infty V_\infty^3}{2Q} \quad (1)$$

where M is the total mass of the meteoroid, C_H is the heat transfer coefficient, S is the cross-sectional area, V_∞ is the free-stream

velocity, and Q is the heat of ablation. A significant uncertainty in applying this equation is C_H , which assuming a spherical geometry for the meteoroid, is written as Prabhu et al. (2016):

$$C_H = \frac{2 \int_0^{\pi/2} q_{rad} \sin \theta d\theta}{\frac{1}{2} \rho_\infty V_\infty^3} \quad (2)$$

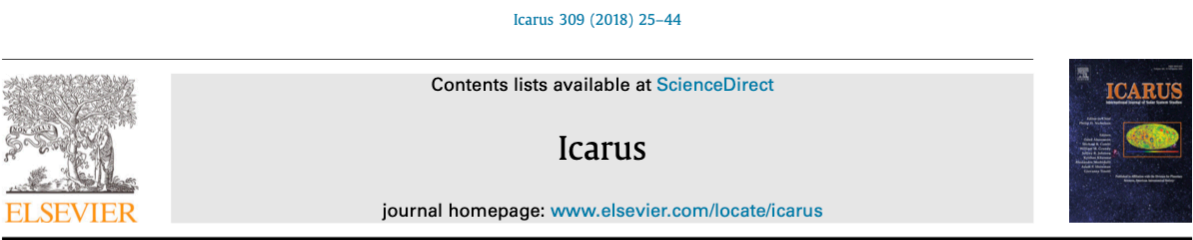
where θ is the angle from the stagnation point, q_{rad} is the radiative heating as a function of θ , and ρ_∞ is the free-stream density. This equation assumes convective heating is negligible relative to radiative heating, which is true for all cases considered in this work that include coupled ablation. A common assumption in asteroid threat assessment studies (Mathias et al., 2017; Wheeler et al., 2017) is to set C_H to 0.1. This constant value is based on the nonablating, inviscid, stagnation-line analysis by Page et al. (1968), Baldwin and Sheaffer (1971), which included coupled radiation (meaning the radiative energy source terms are coupled to the flowfield energy

* Corresponding author.
E-mail addresses: christopher.o.johnston@nasa.gov (C.O. Johnston), eric.c.stern@nasa.gov (E.C. Stern), lorien.wheeler@nasa.gov (L.F. Wheeler).

Toward a complete aerothermodynamic description of the meteor flowfield...

Computational Approach and Heat Transfer

Ground Heating and View Angle



Radiative heating of large meteoroids during atmospheric entry

Christopher O. Johnston^{a,*}, Eric C. Stern^b, Lorien F. Wheeler^c

^a NASA Langley Research Center, Hampton, VA, 23681, United States
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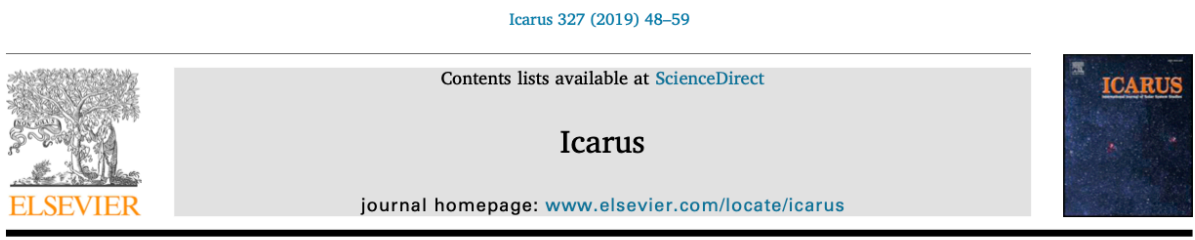
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ARTICLE INFO

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ABSTRACT

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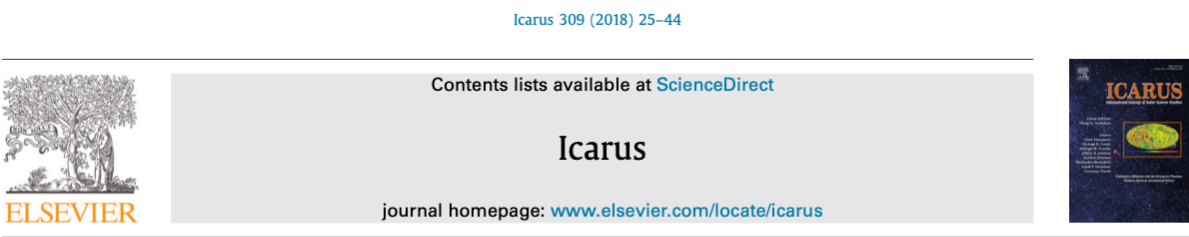
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Computational Approach and Heat Transfer

Ground Heating and View Angle

Detailed Bolide Radiation Model



Radiative heating of large meteoroids during atmospheric entry

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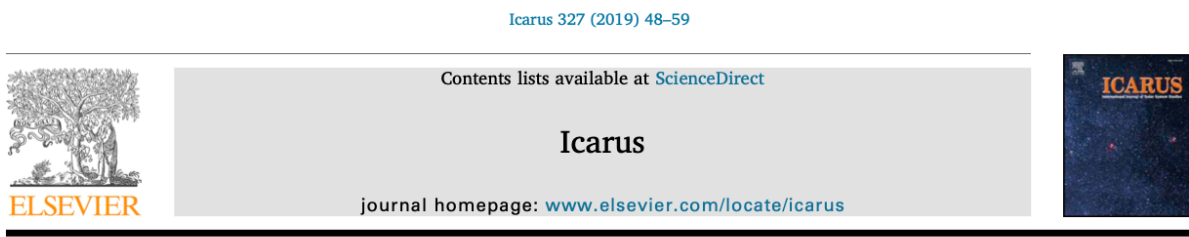
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Simulating the Benešov bolide flowfield and spectrum at altitudes of 47 and 57 km

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ABSTRACT

This paper develops a computational fluid dynamics capability for simulating the radiative emission from a meteor shock-layer and wake to an external observer. The developed capability includes the impact of radiation and ablation on the meteor flowfield, where coupled radiation accounts for the impact of radiation on the flowfield energy equations and coupled ablation accounts for the injection of ablation species from the meteoroid surface into the flow. This capability includes updated flowfield chemistry and nonequilibrium radiation models, which are compiled from the literature. To provide a level of validation for this capability, the Benešov spectral measurements are considered. Although the meteoroid was likely fragmented at the 47 and 57 km altitudes considered, and the measurement uncertainty is roughly ±50%, these measurements represent the best available spectral measurements for a relatively large (meter-class) bolide. To determine the equivalent meteoroid diameter for the Benešov simulations, the continuum component of the spectrum in the 570 to 610 nm range is considered. This wavelength range is dominated by air emission from the high pressure and temperature shock-layer in front of the meteoroid, which is simulated with a relatively small uncertainty (compared to the wake emission) and is sensitive to the equivalent meteoroid diameter. Because of these characteristics, the simulated meteoroid diameter is adjusted until the continuum component in this wavelength range matches the measurements. This results in equivalent diameters ranging from 0.62 to 0.9 m. The range of equivalent diameters is due to the various meteoroid geometries considered, where increasing the bluntness decreases the required diameter. Applying these diameters to simulations at 47 and 57 km results in simulated spectra that compare within 30% of the measured values, considering the wavelength integrated values between 400 and 650 nm. This agreement is well within the estimated measurement uncertainty of ±50%. All major spectral features are captured by the simulations. A comparison with the measured wake-only spectrum suggests that emission from wake locations over 150 m from the meteoroid are the primary source of the small disagreement seen between the measurements and simulations. Overall, the relatively good agreement between the simulations and measurements provides a level of validation for the developed model that has not been previously available.

1. Introduction

The 1991 Benešov bolide represents a notable meteor event because it was both bright (−19.5 mag) and its radiative spectrum was measured throughout a significant fraction of the trajectory by Borovička and Spurný (1996). Furthermore, the meteor was observed by three all-sky cameras, which allowed its entry trajectory and radiated energy to be accurately determined. Using this information, studies by Borovička et al. (1998a), Cepicka and Revelle (2005), Wheeler et al. (2018), and Tárano et al. (2019) determined initial entry masses for this event ranging from 2000–4100 kg, which implies a diameter ranging from

1.0–1.4 m assuming a meteoroid density ranging from 3.2 to 3.4 g/cm³. Subsequent refinements of the reconstructed trajectory by Spurný et al. (2014) allowed for better estimation of the strewn field such that the first Benešov meteorites were found 20 years after the event. The meteorites recovered by Spurný et al. were of various mineralogical types, which suggests that the meteoroid was a rubble pile that fragmented at relatively high altitude (Borovička, 2015).

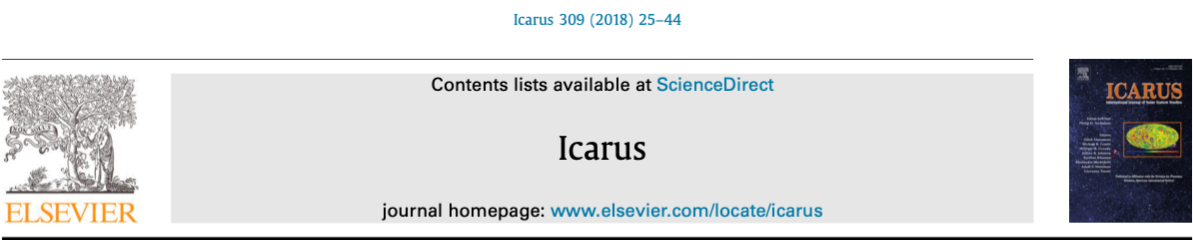
With the entry trajectory known, the recently re-calibrated spectra by Borovička and Berezchnoy (2016) provide a benchmark case for potential meteor radiation and luminous efficiency models. This

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Computational Approach and Heat Transfer



Radiative heating of large meteoroids during atmospheric entry

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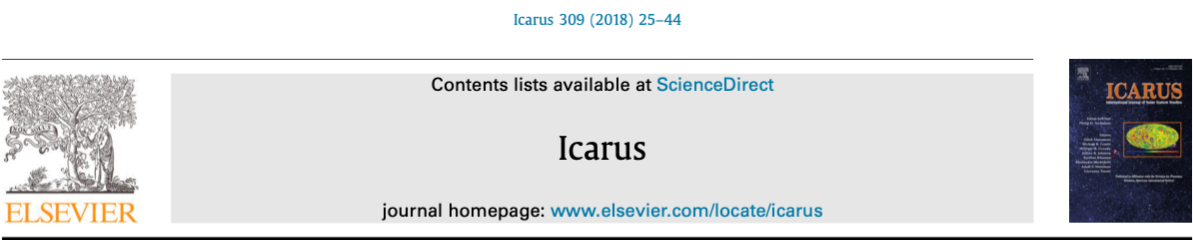
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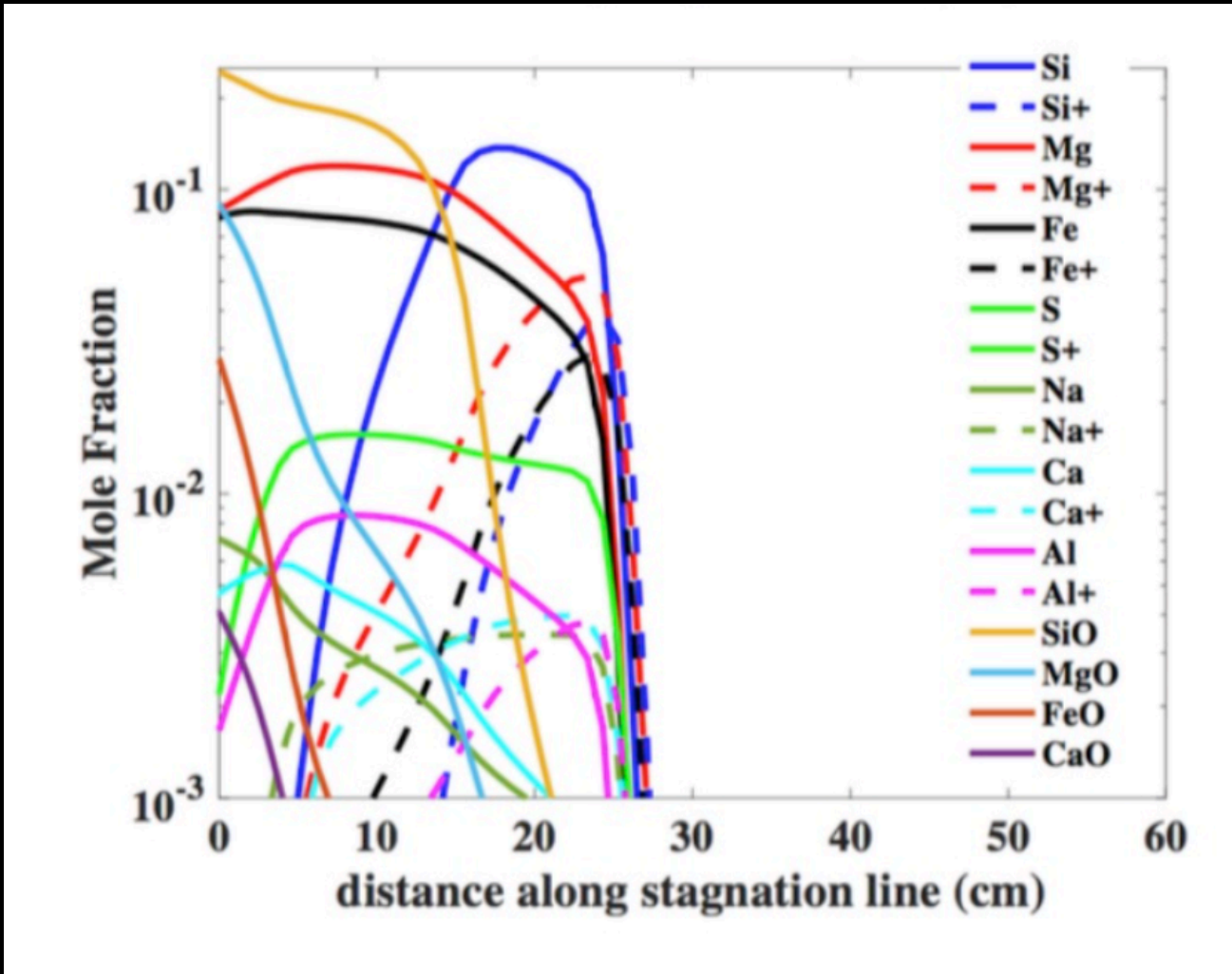
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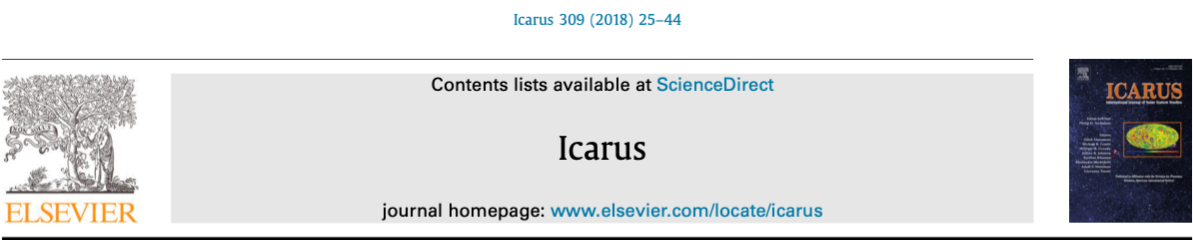
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ABSTRACT

A high-fidelity approach for simulating the aerothermodynamic environments of meteor entries was developed, which allows the commonly assumed heat transfer coefficient of 0.1 to be assessed. This model uses chemically reacting computational fluid dynamics (CFD), coupled with radiation transport and surface ablation. Coupled radiation accounts for the impact of radiation on the flowfield energy equations, while coupled ablation explicitly models the injection of ablation products within the flowfield and radiation simulations. For a meteoroid with a velocity of 20 km/s, coupled radiation is shown to reduce the stagnation point radiative heating by over 60%. The impact of coupled ablation (with coupled radiation) is shown to provide at least a 70% reduction in the radiative heating relative to cases with only coupled radiation. This large reduction is partially the result of the low ionization energies of meteoric ablation products relative to air species. The low ionization energies of ablation products, such as Mg and Ca, provide strong photoionization and atomic line absorption in regions of the spectrum that air species do not. MgO and CaO are also shown to provide significant absorption. Turbulence is shown to impact the distribution of ablation products through the shock-layer, which results in up to a 100% increase in the radiative heating downstream of the stagnation point. To create a database of heat transfer coefficients, the developed model was applied to a range of cases. This database considered velocities ranging from 14 to 20 km/s, altitudes ranging from 20 to 50 km, and nose radii ranging from 1 to 100 m. The heat transfer coefficients from these simulations are below 0.045 for the range of cases, for both laminar and turbulent, which is significantly lower than the canonical value of 0.1. When the new heat transfer model is applied to a Tunguska-like 15 Mt entry, the effect of the new model is to lower the height of burst by up to 2 km, depending on assumed entry angle. This, in turn, results in a significantly larger ground damage footprint than when the canonical heating assumption is used.

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1. Introduction

A meteor's mass loss rate is an important factor in determining the potential ground damage threat for a given size, entry velocity, entry angle, and composition (Aftosis et al., 2016; Mathias et al., 2017; Revelle, 2004a; Hills and Goda, 1993; Wheeler et al., 2017). The mass loss rate is written as follows:

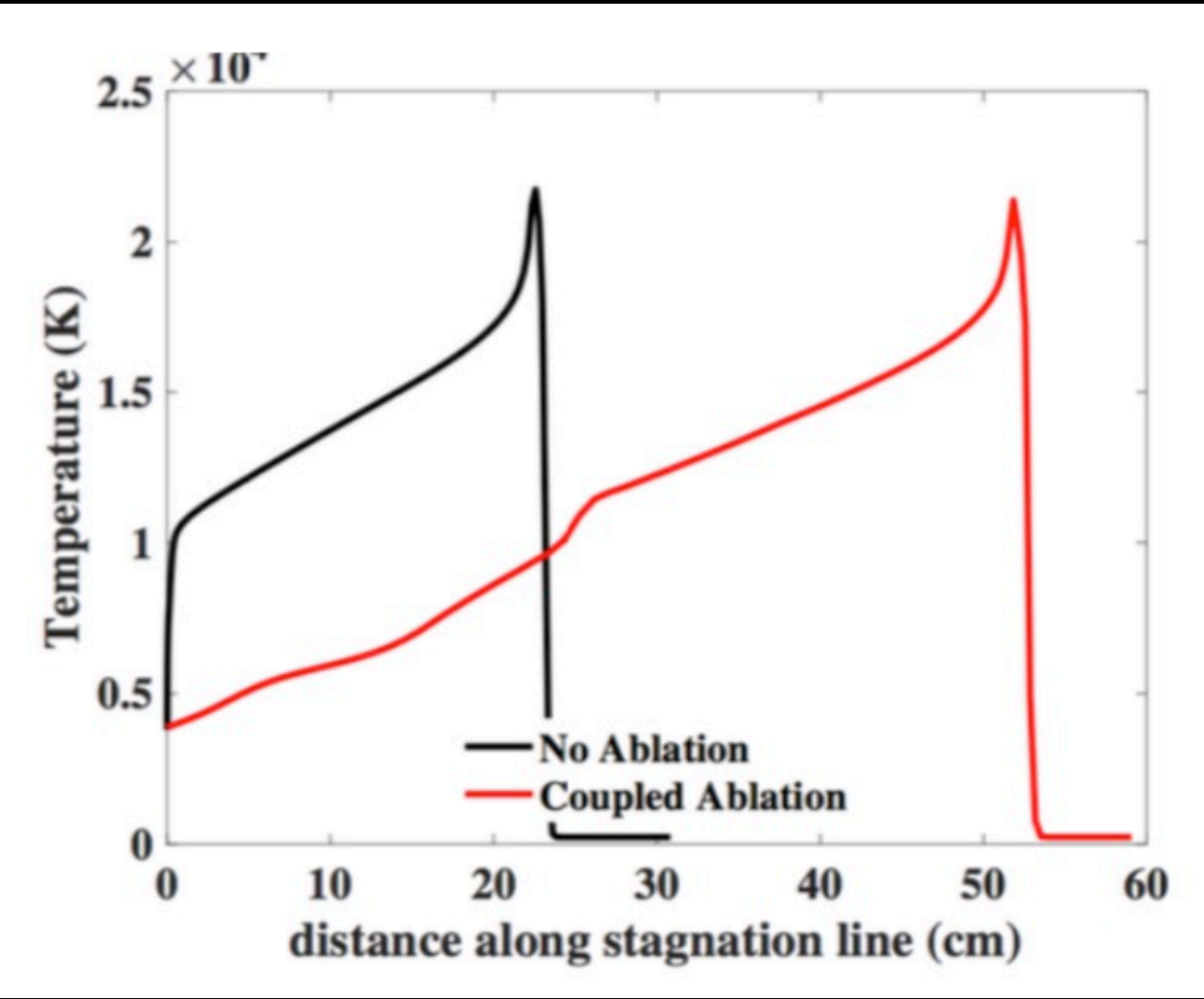
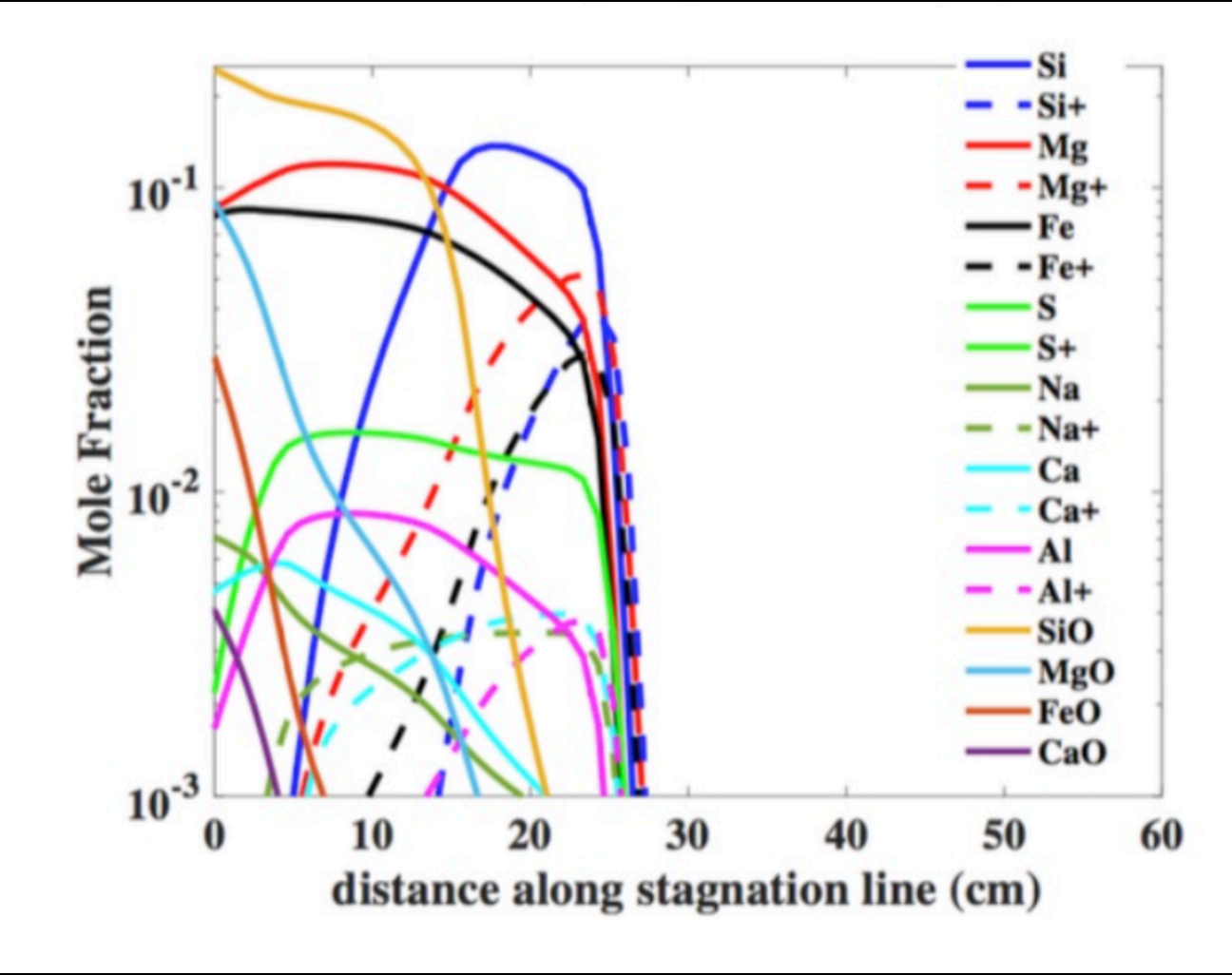
$$\frac{dM}{dt} = -C_H \frac{S \rho_\infty V_\infty^3}{2Q} \quad (1)$$

where M is the total mass of the meteoroid, C_H is the heat transfer coefficient, S is the cross-sectional area, V_∞ is the free-stream

velocity, and Q is the heat of ablation. A significant uncertainty in applying this equation is C_H , which assuming a spherical geometry for the meteoroid, is written as Prabhu et al. (2016):

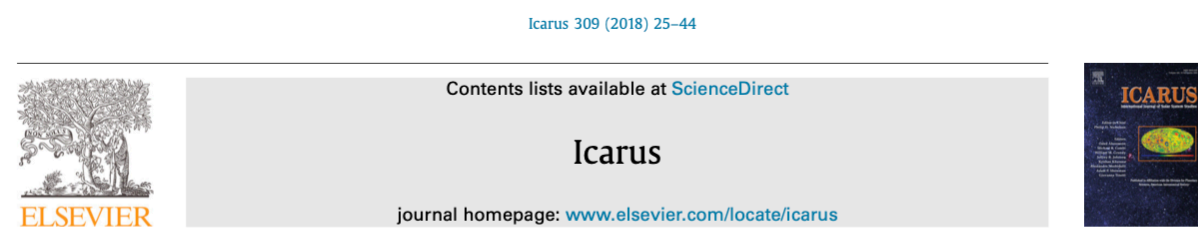
$$C_H = \frac{2 \int_0^{\pi/2} q_{rad} \sin \theta d\theta}{\frac{1}{2} \rho_\infty V_\infty^3} \quad (2)$$

where θ is the angle from the stagnation point, q_{rad} is the radiative heating as a function of θ , and ρ_∞ is the free-stream density. This equation assumes convective heating is negligible relative to radiative heating, which is true for all cases considered in this work that include coupled ablation. A common assumption in asteroid threat assessment studies (Mathias et al., 2017; Wheeler et al., 2017) is to set C_H to 0.1. This constant value is based on the nonablating, inviscid, stagnation-line analysis by Page et al. (1968), Baldwin and Sheaffer (1971), which included coupled radiation (meaning the radiative energy source terms are coupled to the flowfield energy



Toward a complete aerothermodynamic description of the meteor flowfield...

Computational Approach and Heat Transfer



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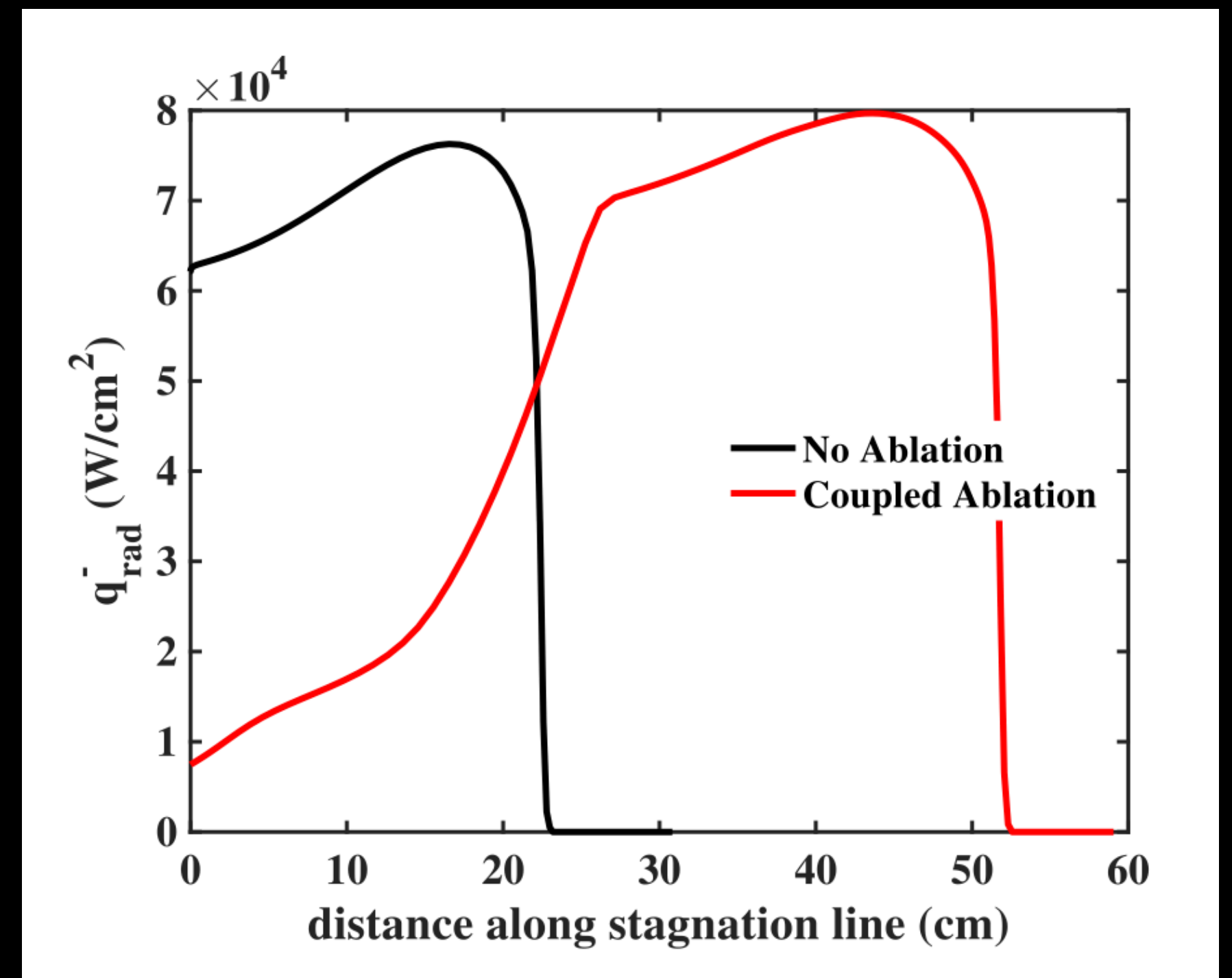
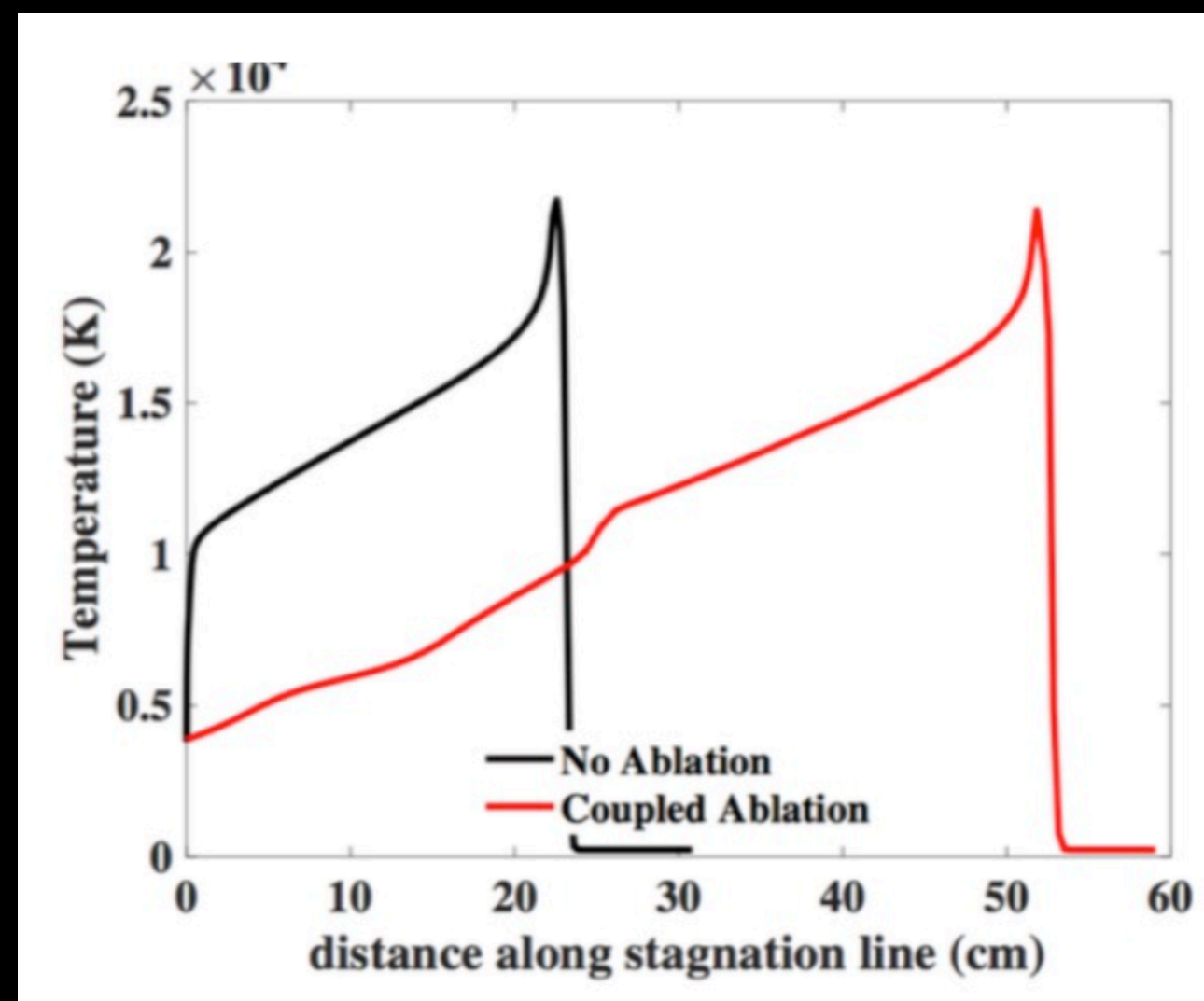
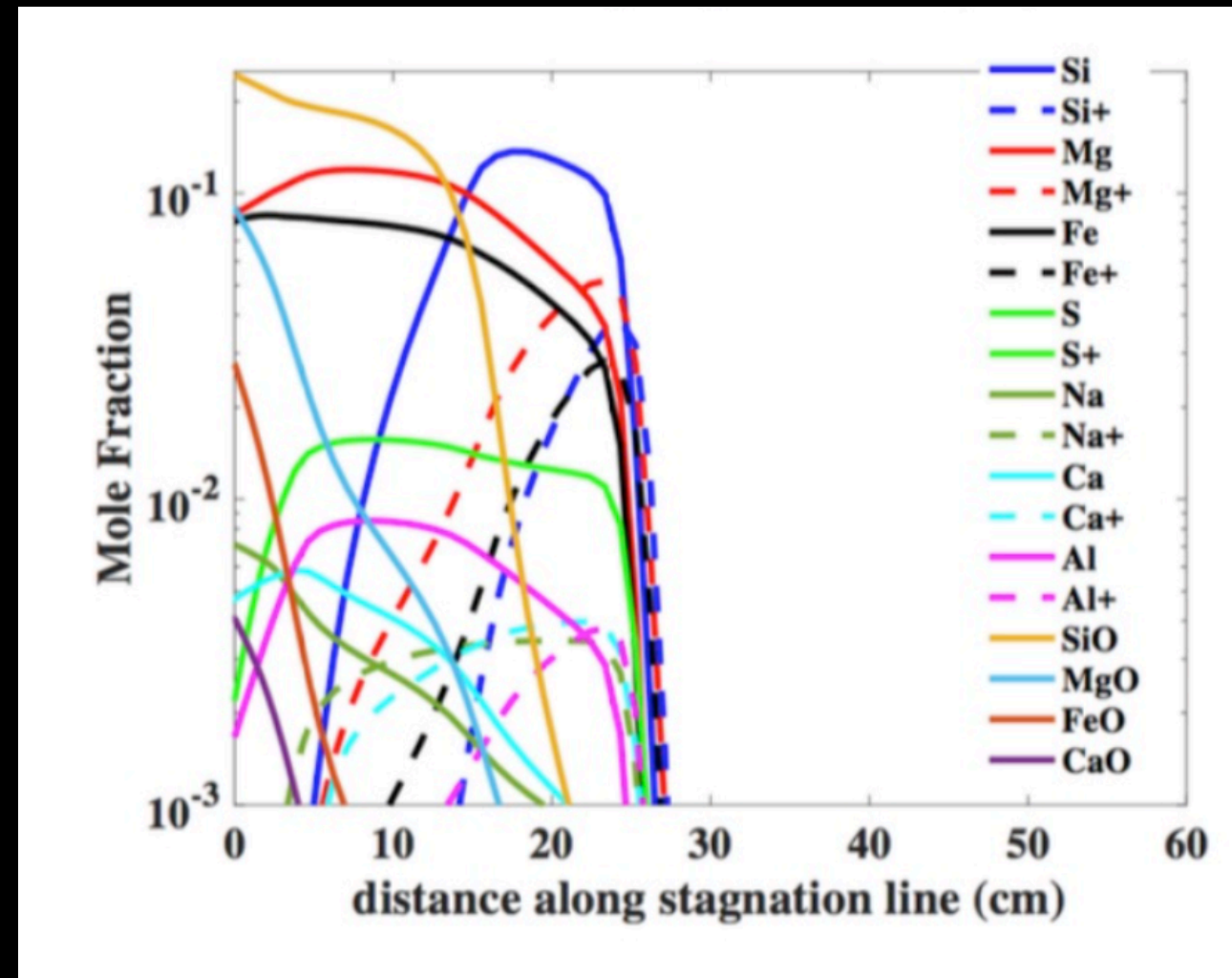
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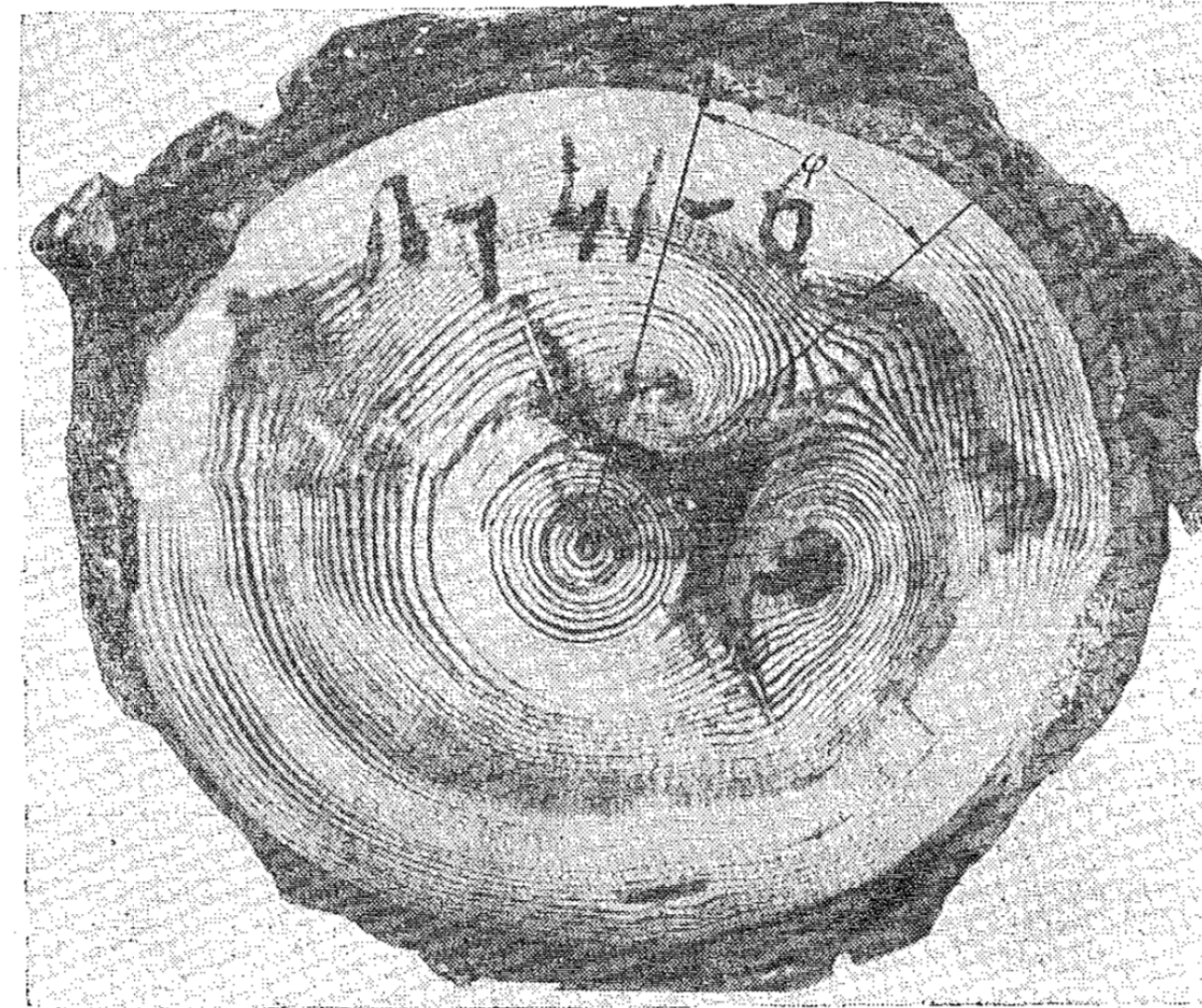
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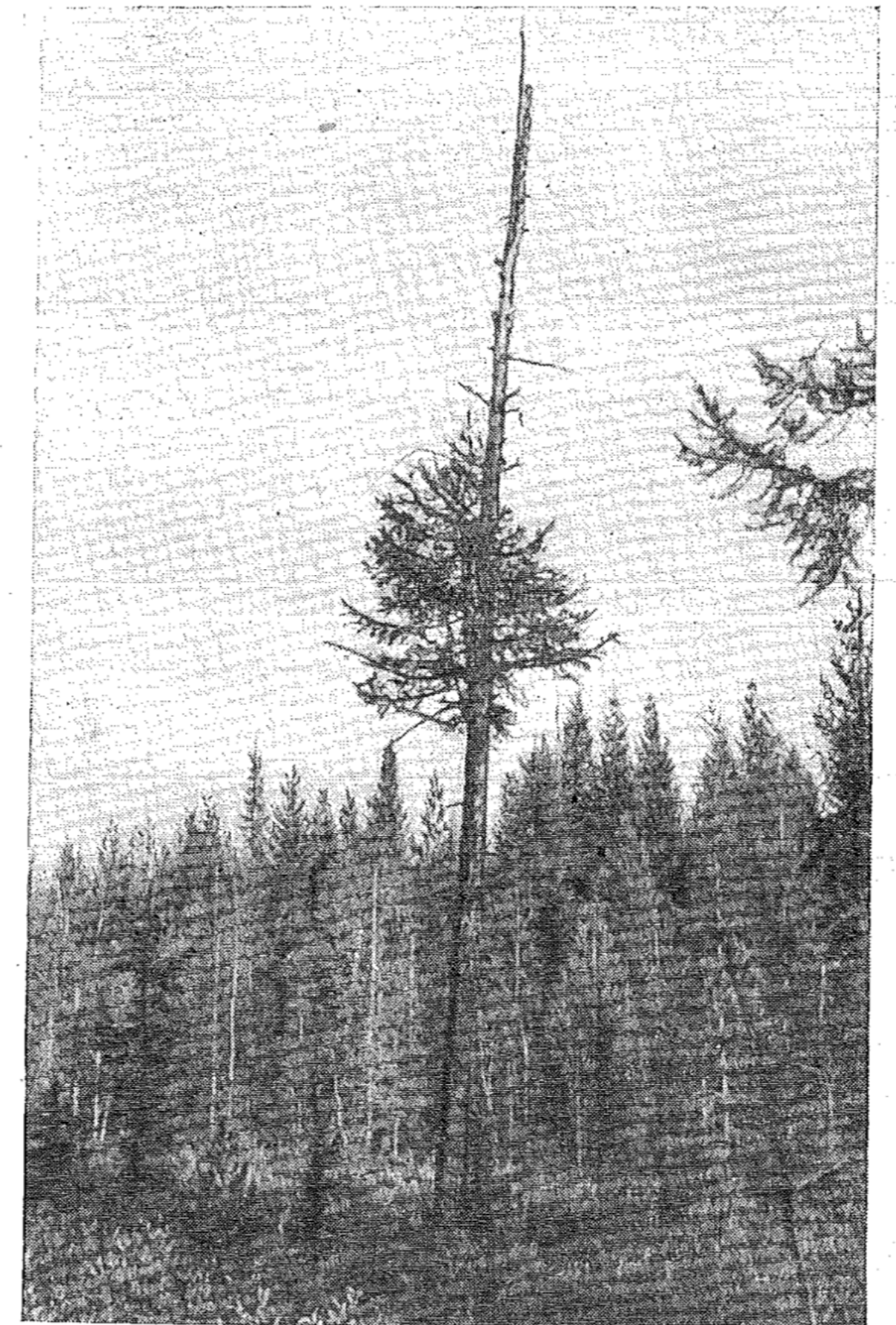
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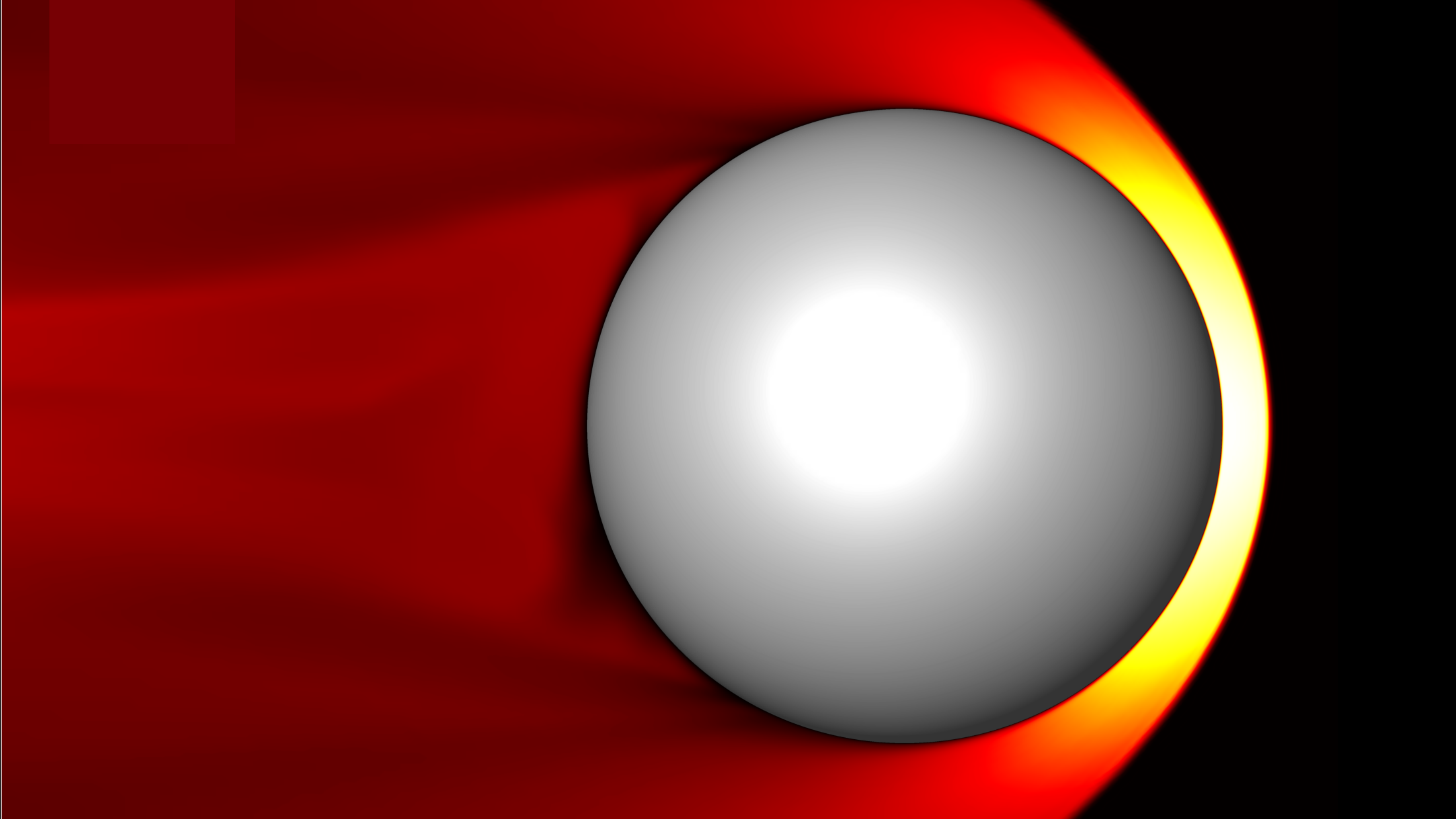


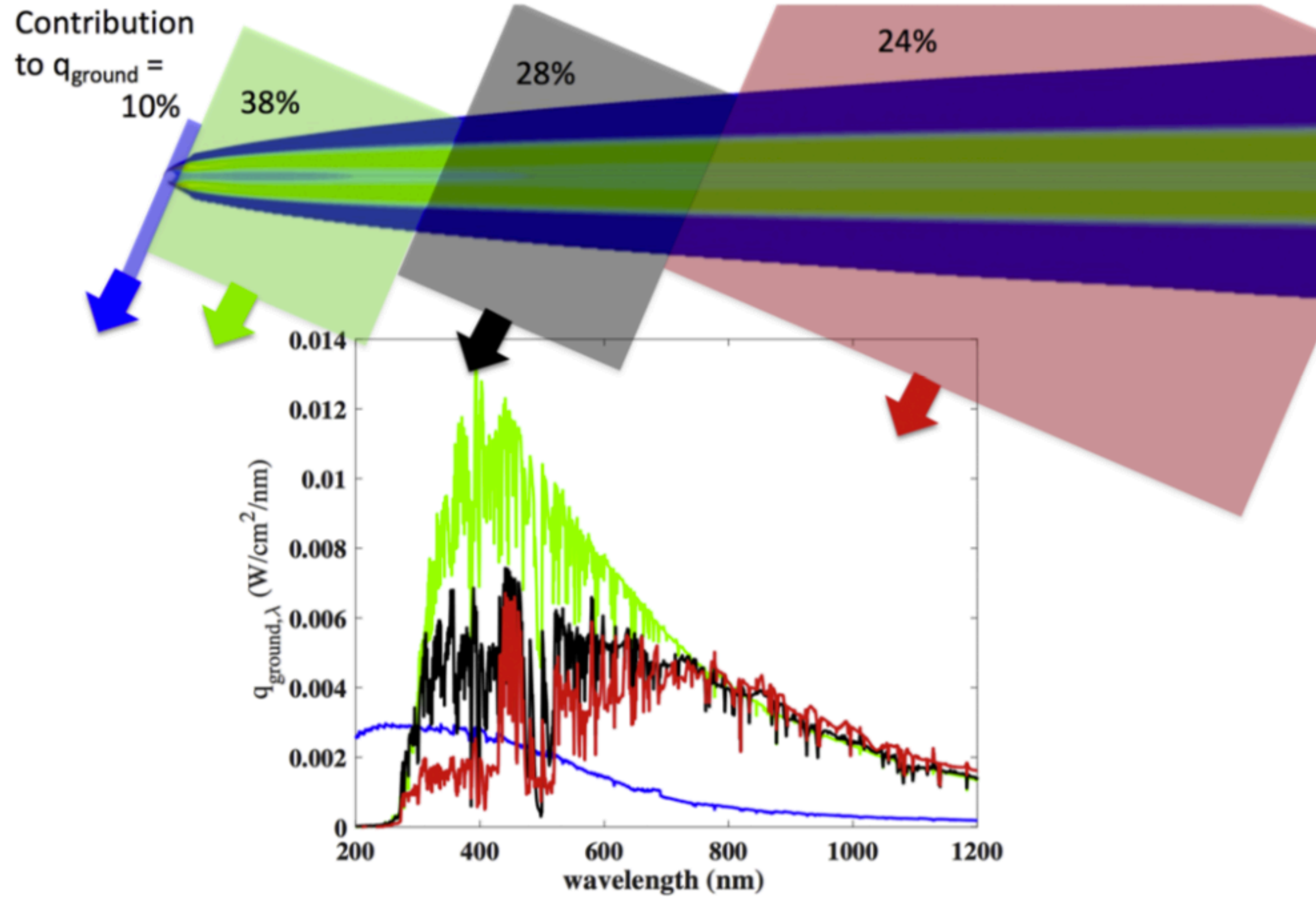




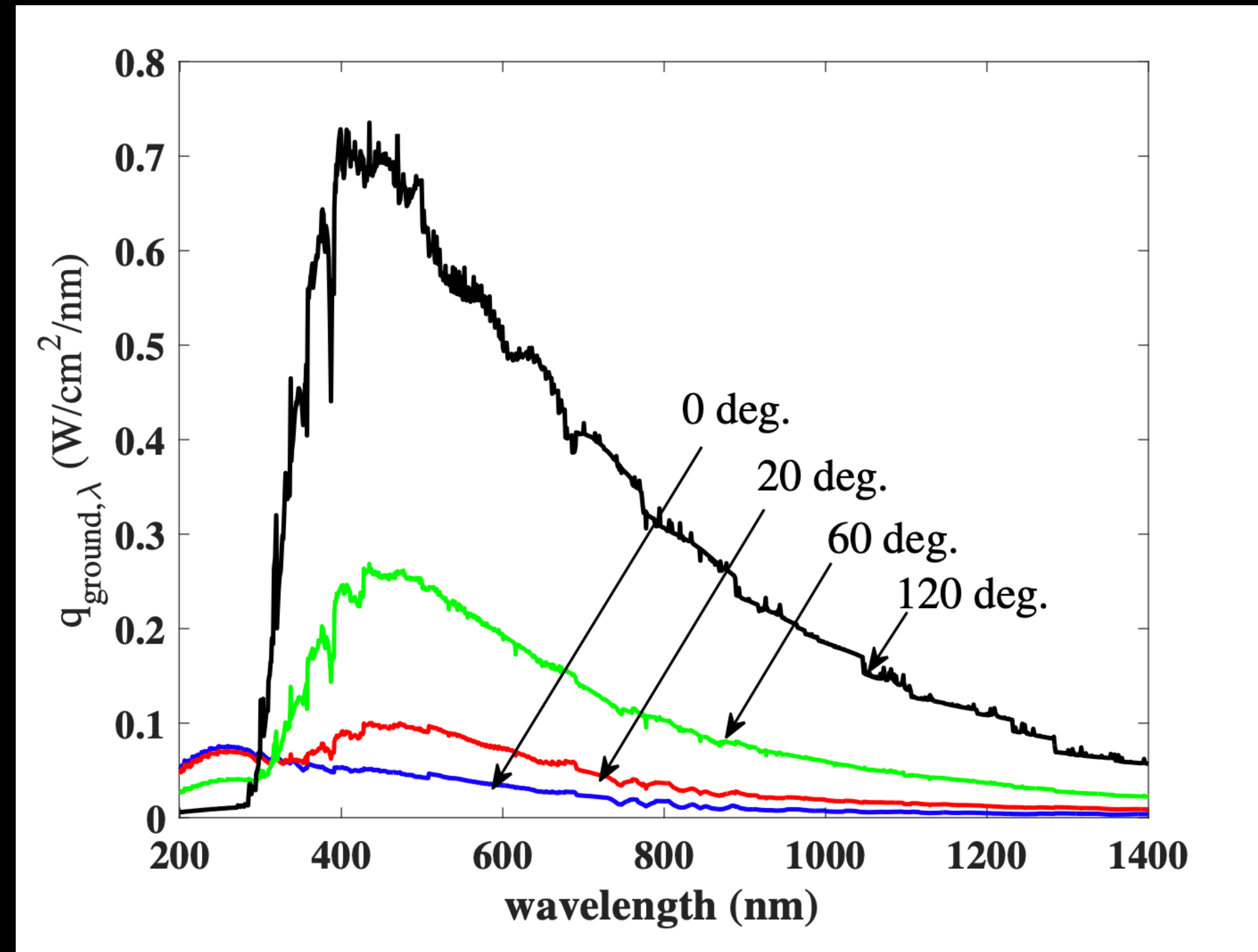
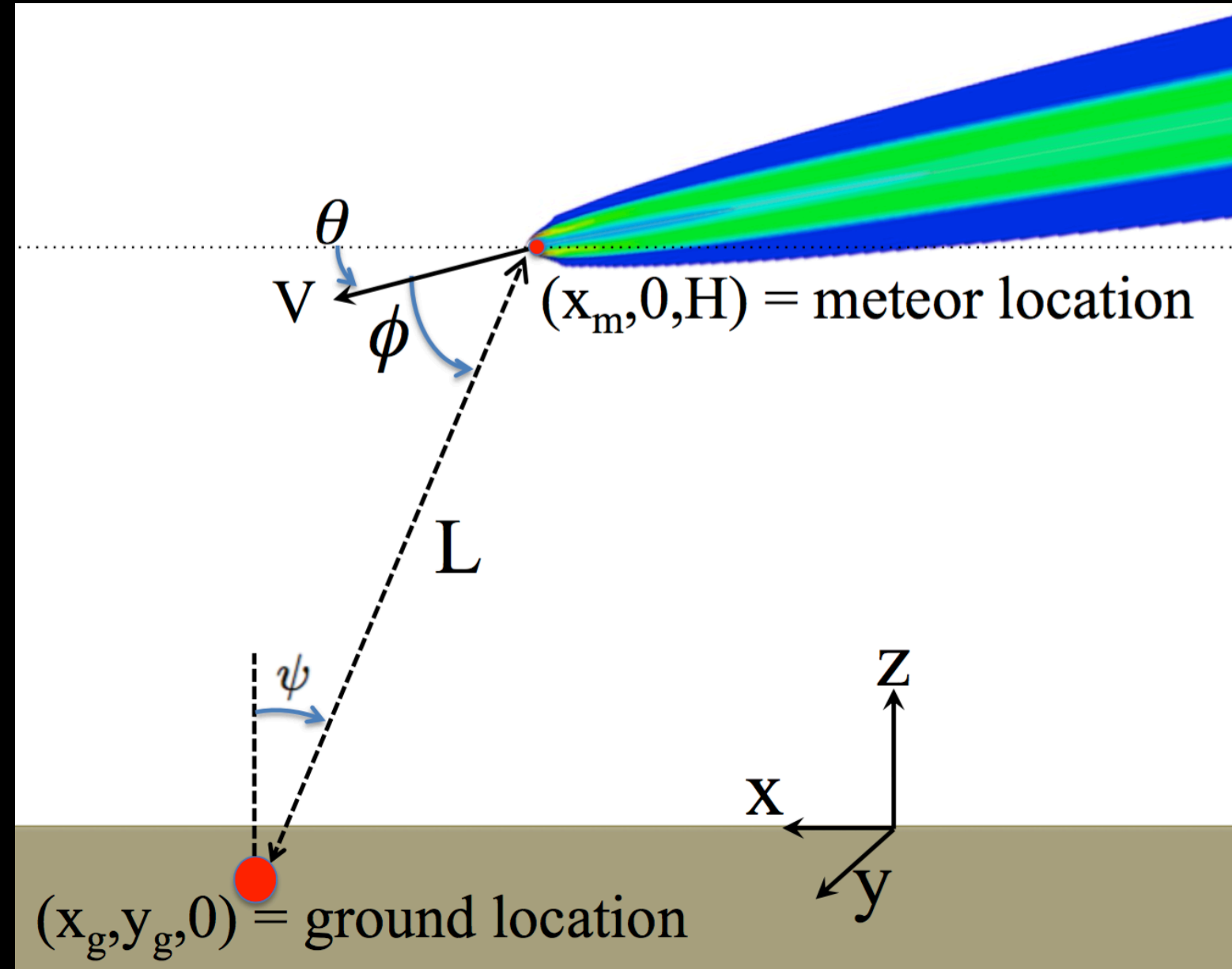
Фиг. 4. Типичное термическое повреждение ветки лиственницы в 1908 г.
φ — угол повреждения от вертикали



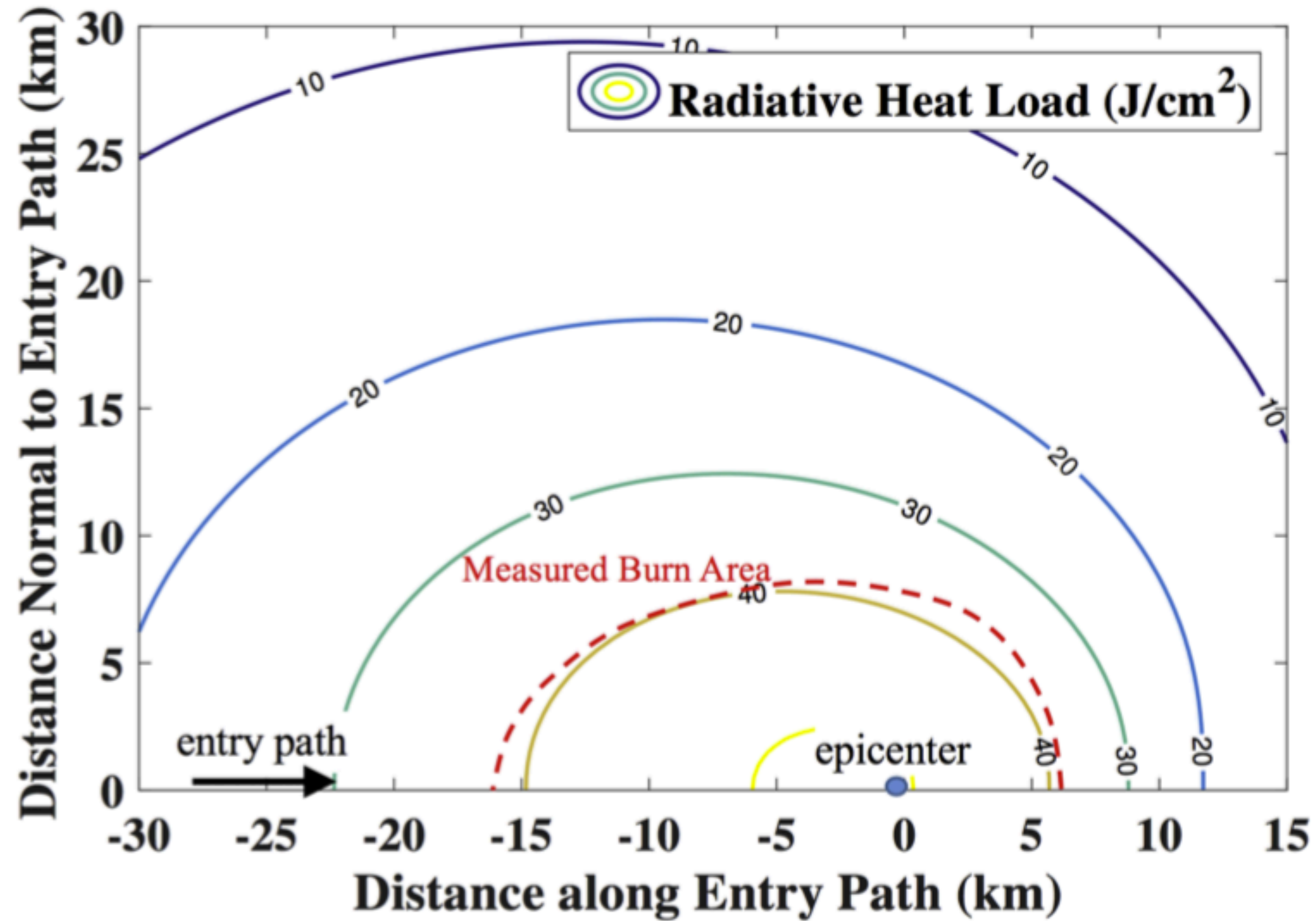




A Model for Ground Damage from Thermal Radiation

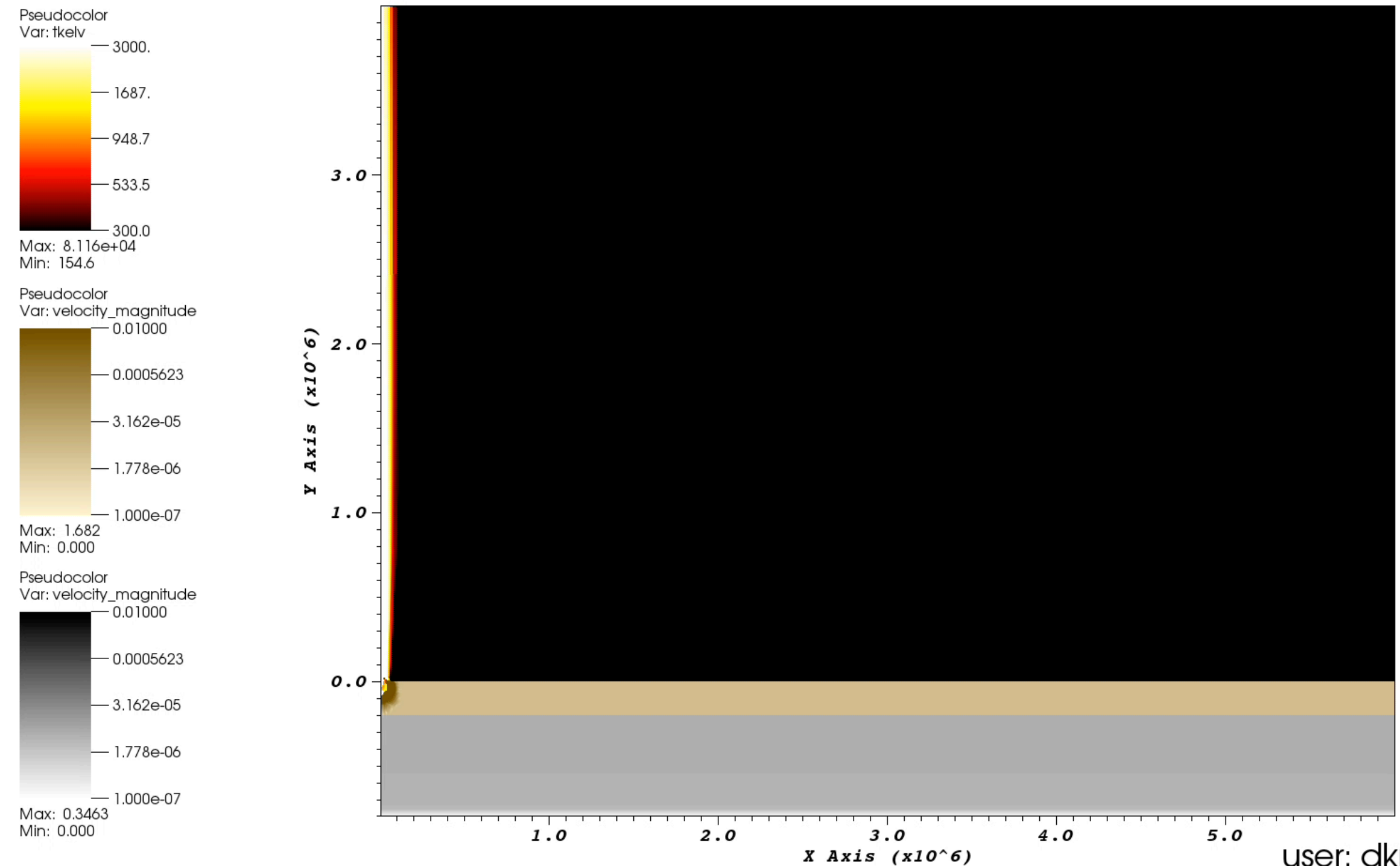


$$q_{\text{ground}} = \left[2.75 + 9.6 \left(\frac{\phi}{60} \right)^a \right] (4.15 e^{-0.1423H})^b \left(\frac{R}{25} \right)^{1.7} \left(\frac{10}{L} \right)^2 e^{4.1267 - 0.0357V - \frac{54.137}{V}}$$

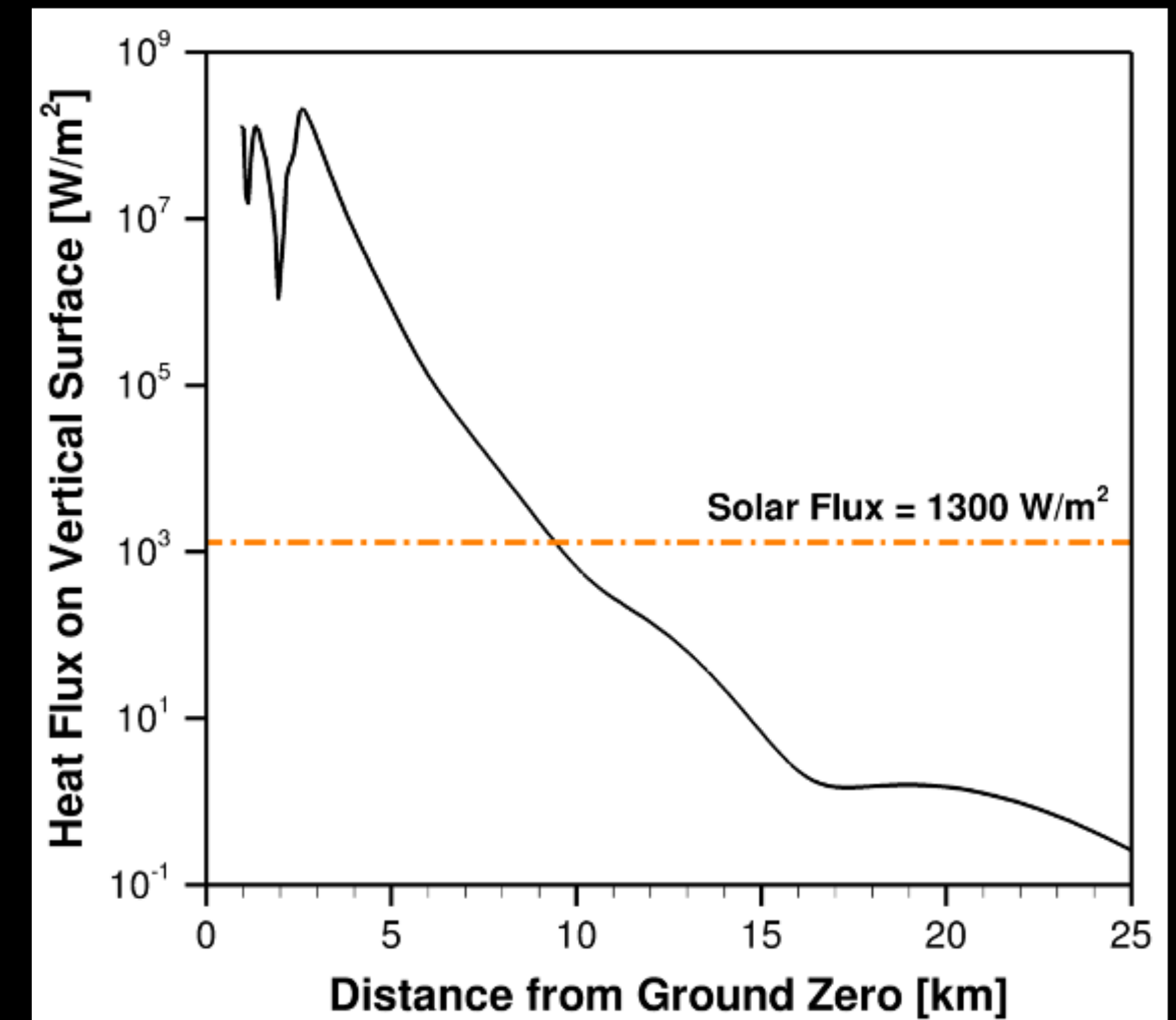


Radiation from Impact Plumes

DB: 1GT_GobiDesert_240.004307792
Cycle: 4307792 Time: 3.72165e+06



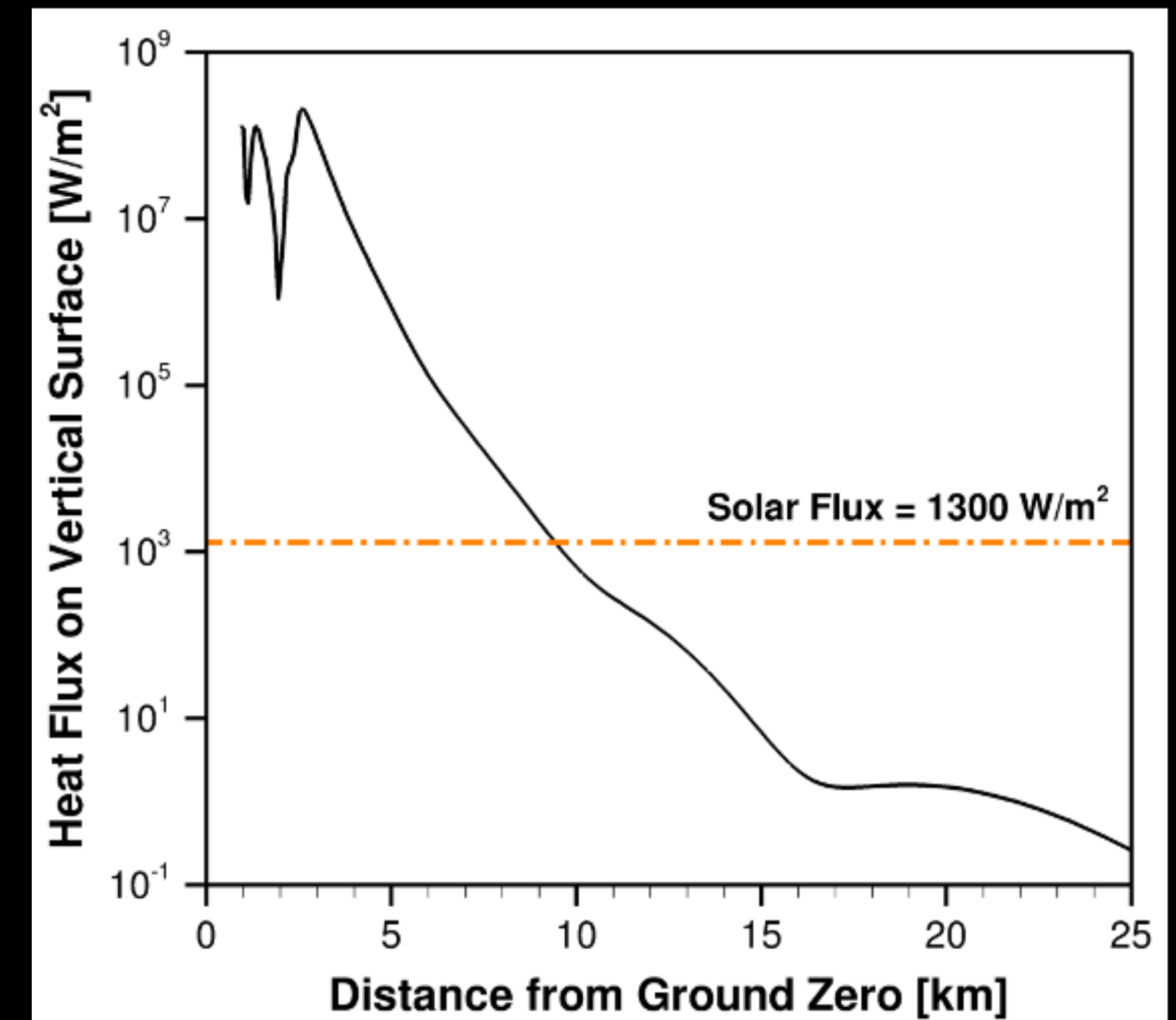
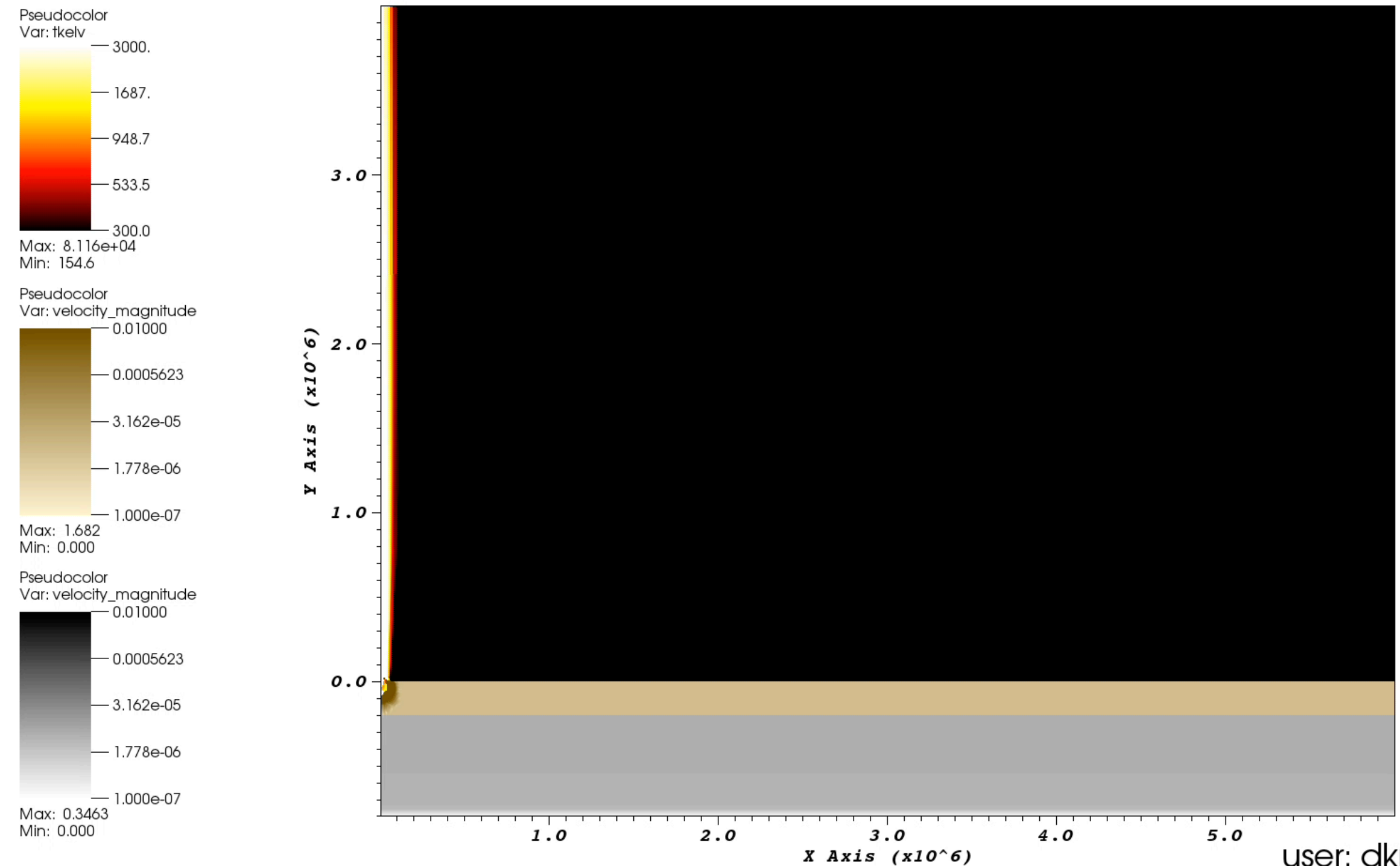
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Fri Mar 24 10:15:31 2017



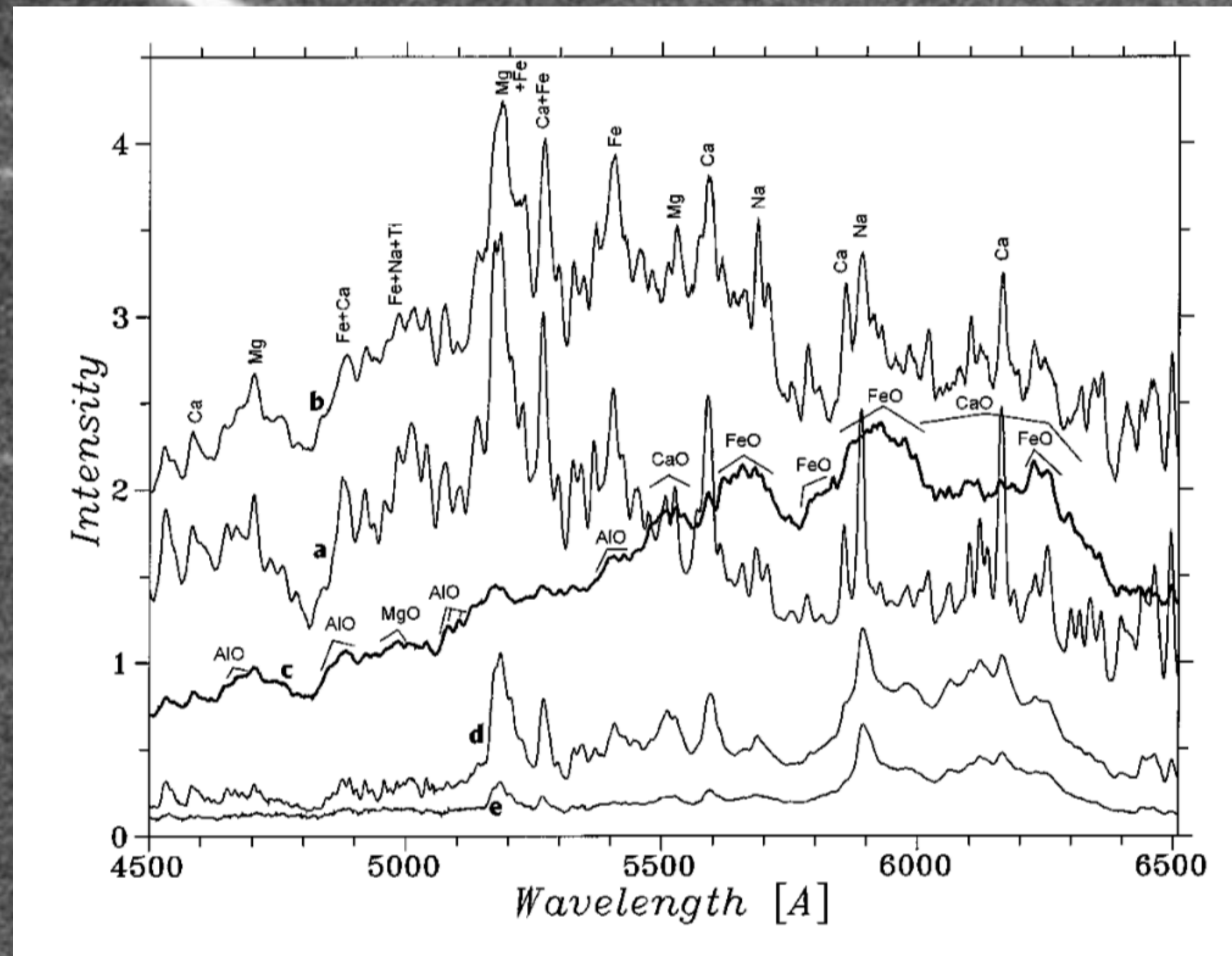
Coates et al., Update on Detailed Simulations of Impact Plume Radiation, MWG 2024.

Radiation from Impact Plumes

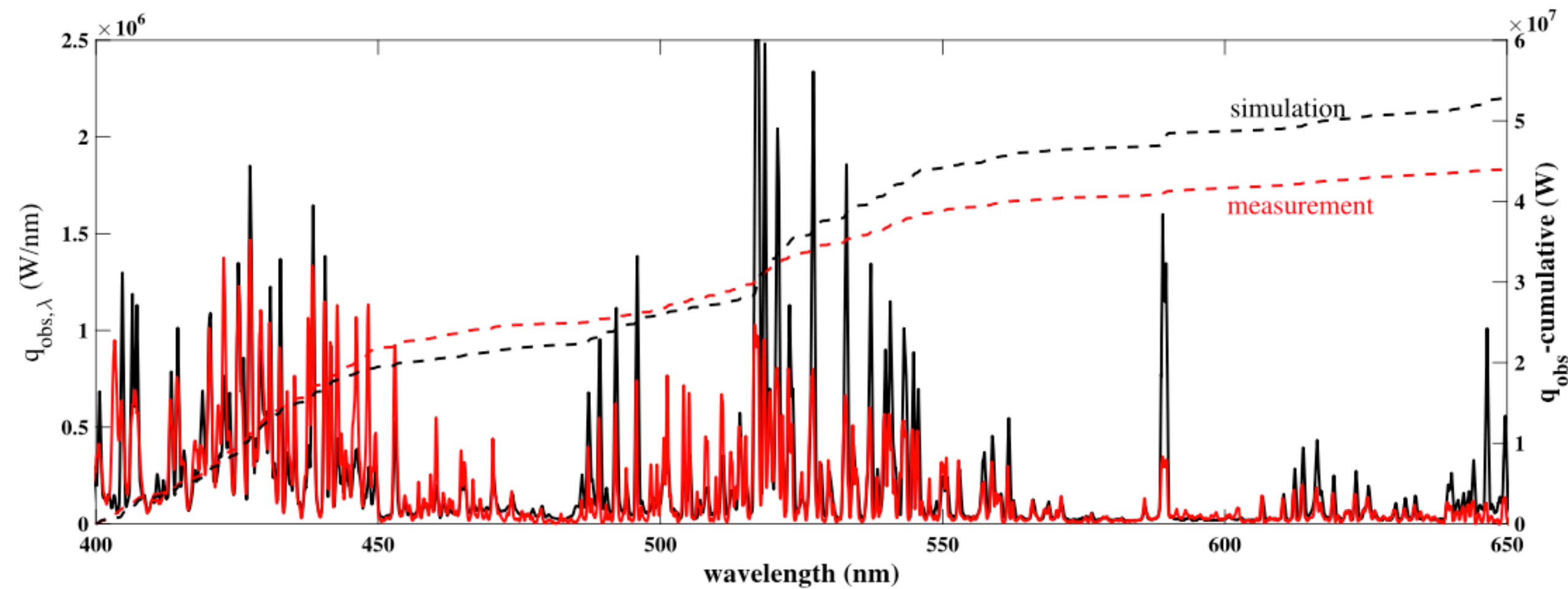
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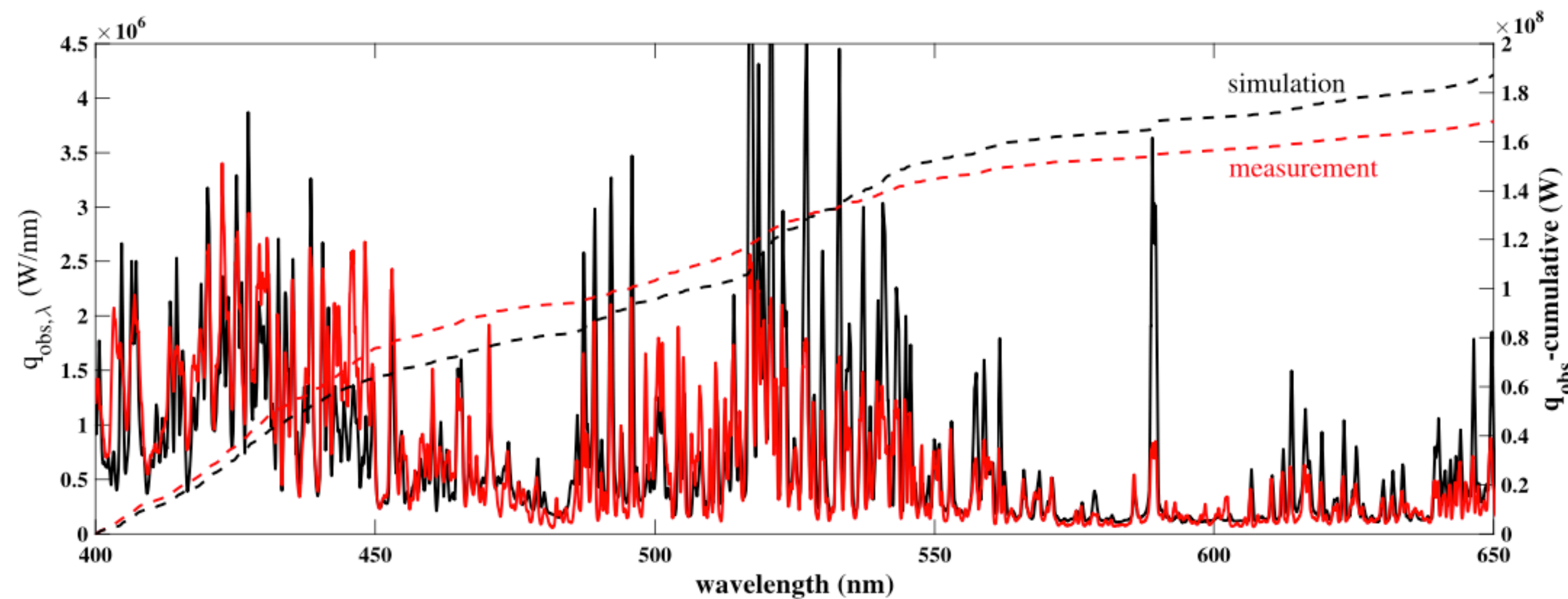
Coates et al., Update on Detailed Simulations of Impact Plume Radiation, MWG 2024.



*Benesov Bolide, May 7, 1991,
Czech Republic (Borovicka &
Spurny, 1996)*



- ▶ Simulated spectra able to capture most of the significant spectral features from the observation
- ▶ For both altitudes simulated, the integrated luminosity from simulation is within 30% of observed spectrum



- ▶ Based on this analysis, we have confidence that our approach could be used to improve luminous efficiency models, and thus help to better constrain inferred asteroid properties

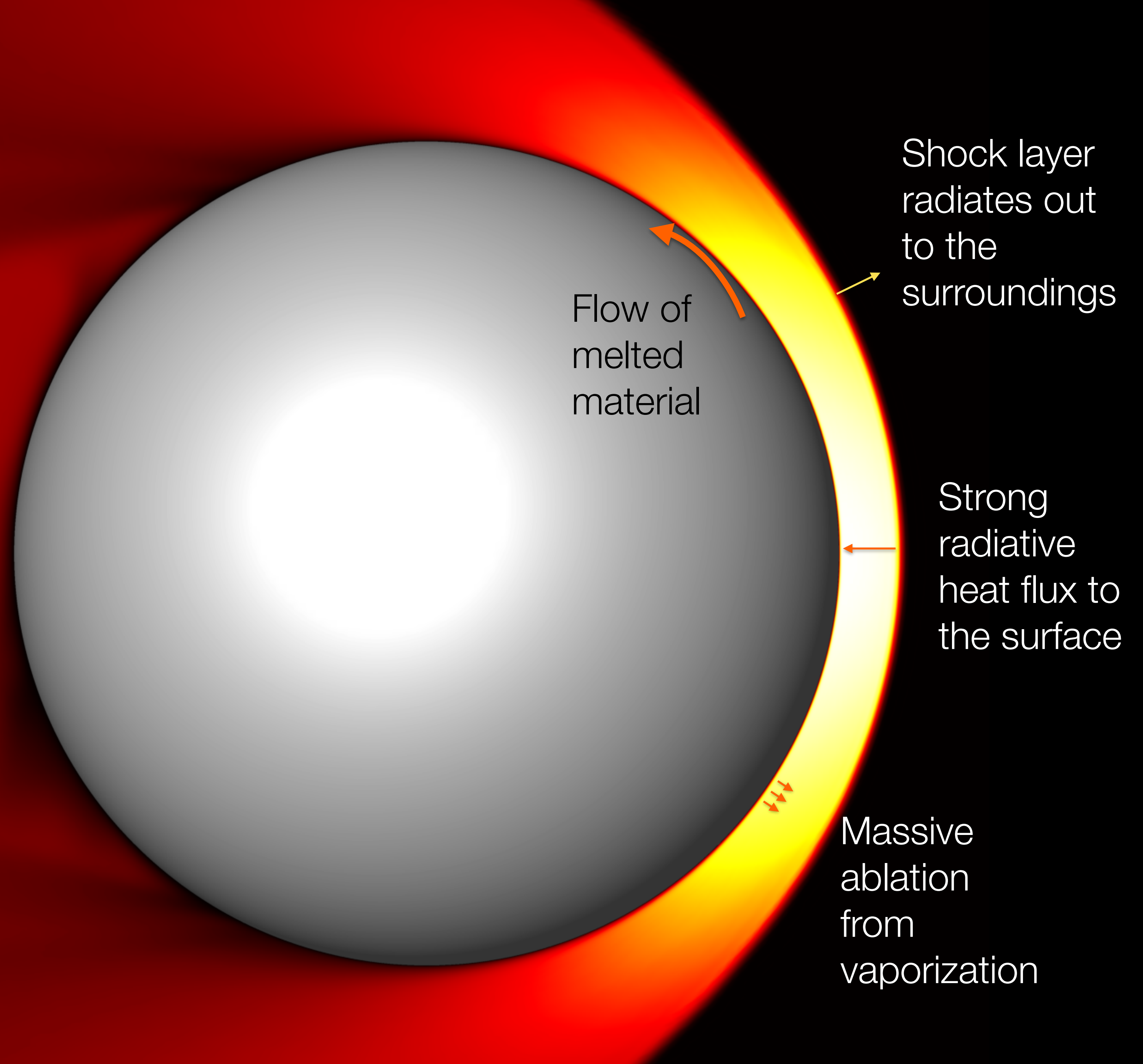
Heated ablation
products emit radiation,
producing observed
light curves and spectra

Flow of
melted
material

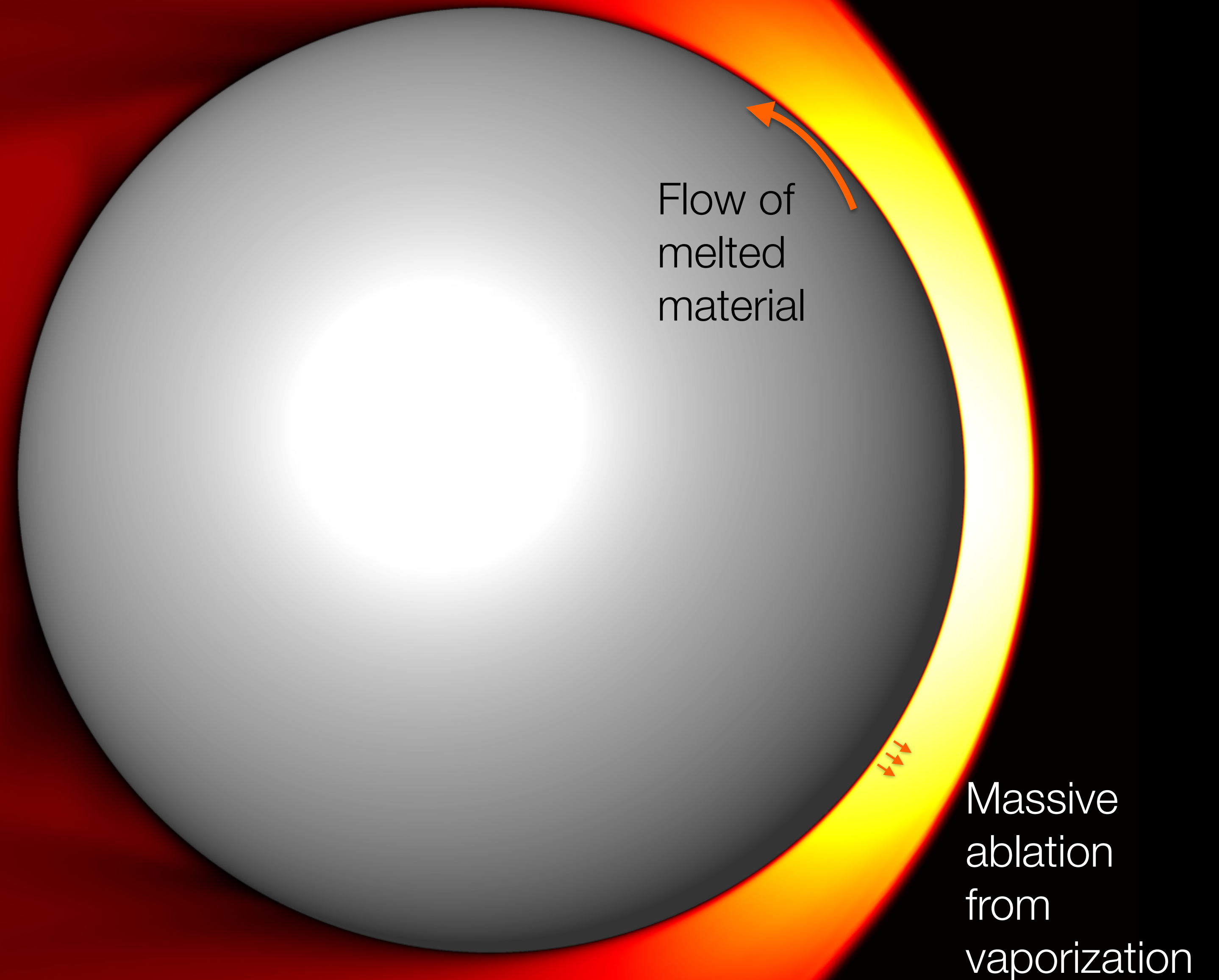
Shock layer
radiates out
to the
surroundings

Strong
radiative
heat flux to
the surface

Massive
ablation
from
vaporization

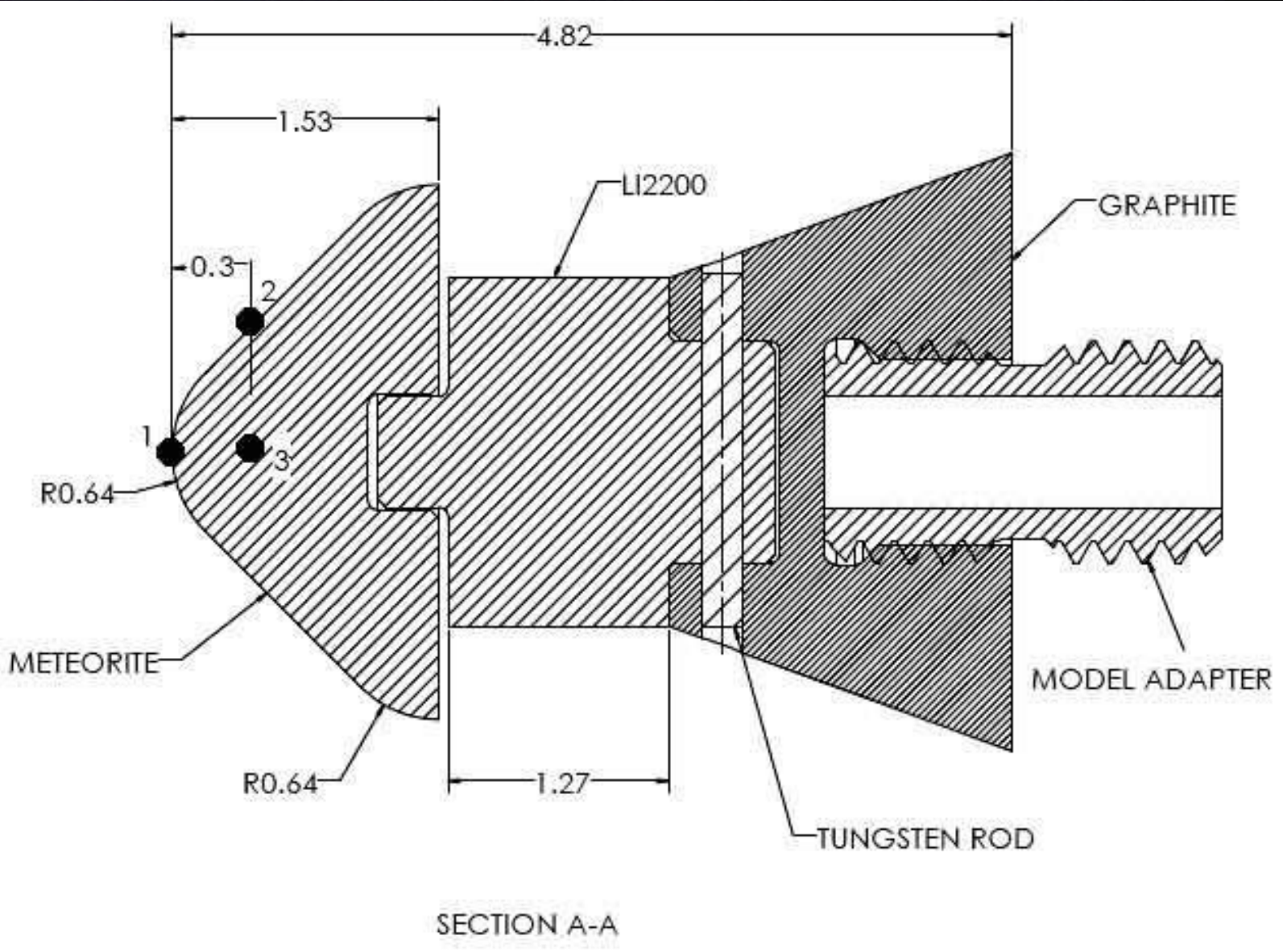


Ablation



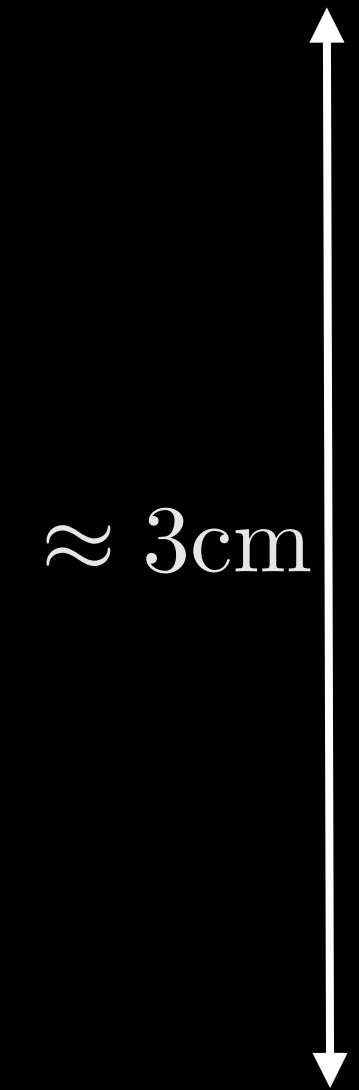


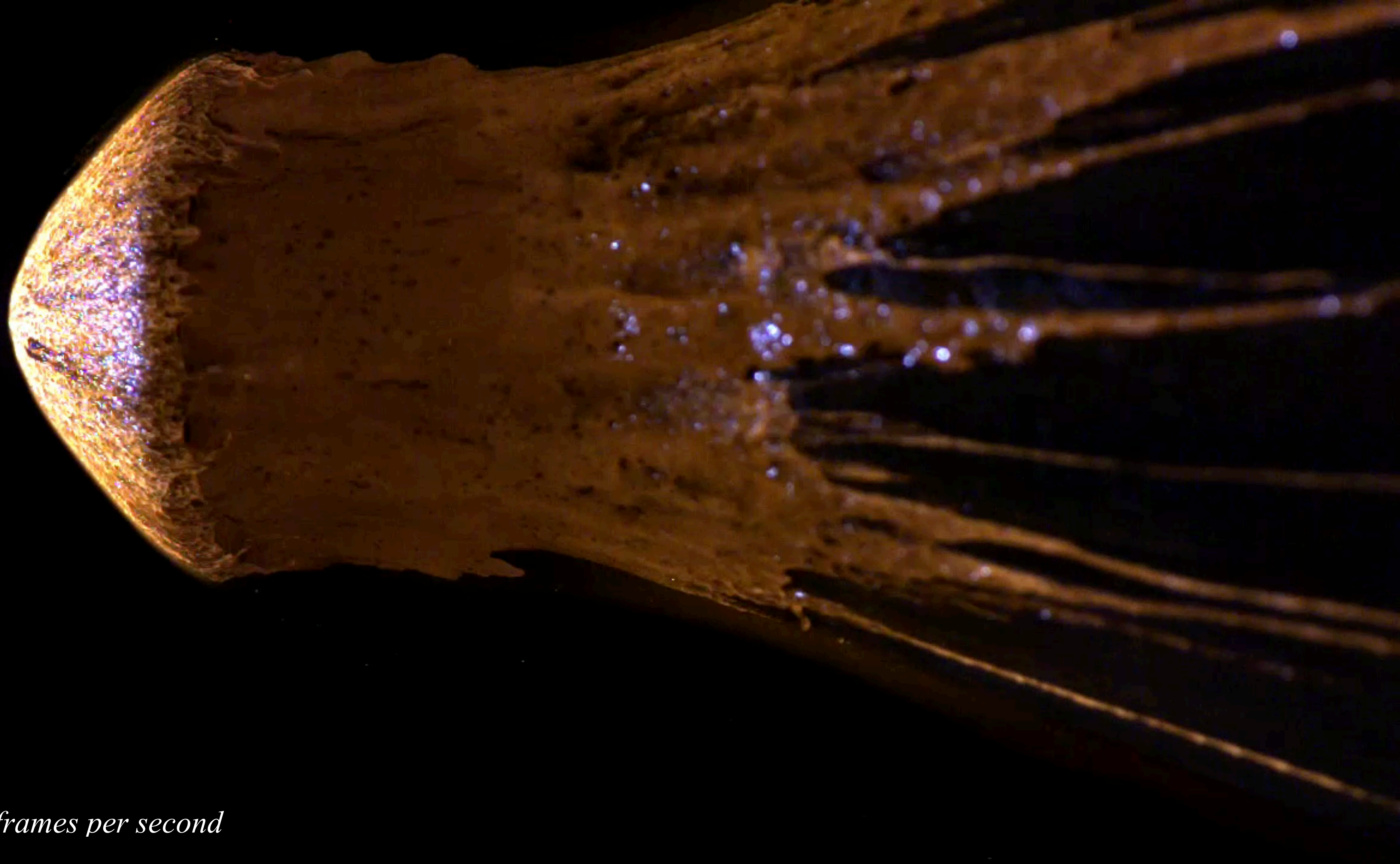




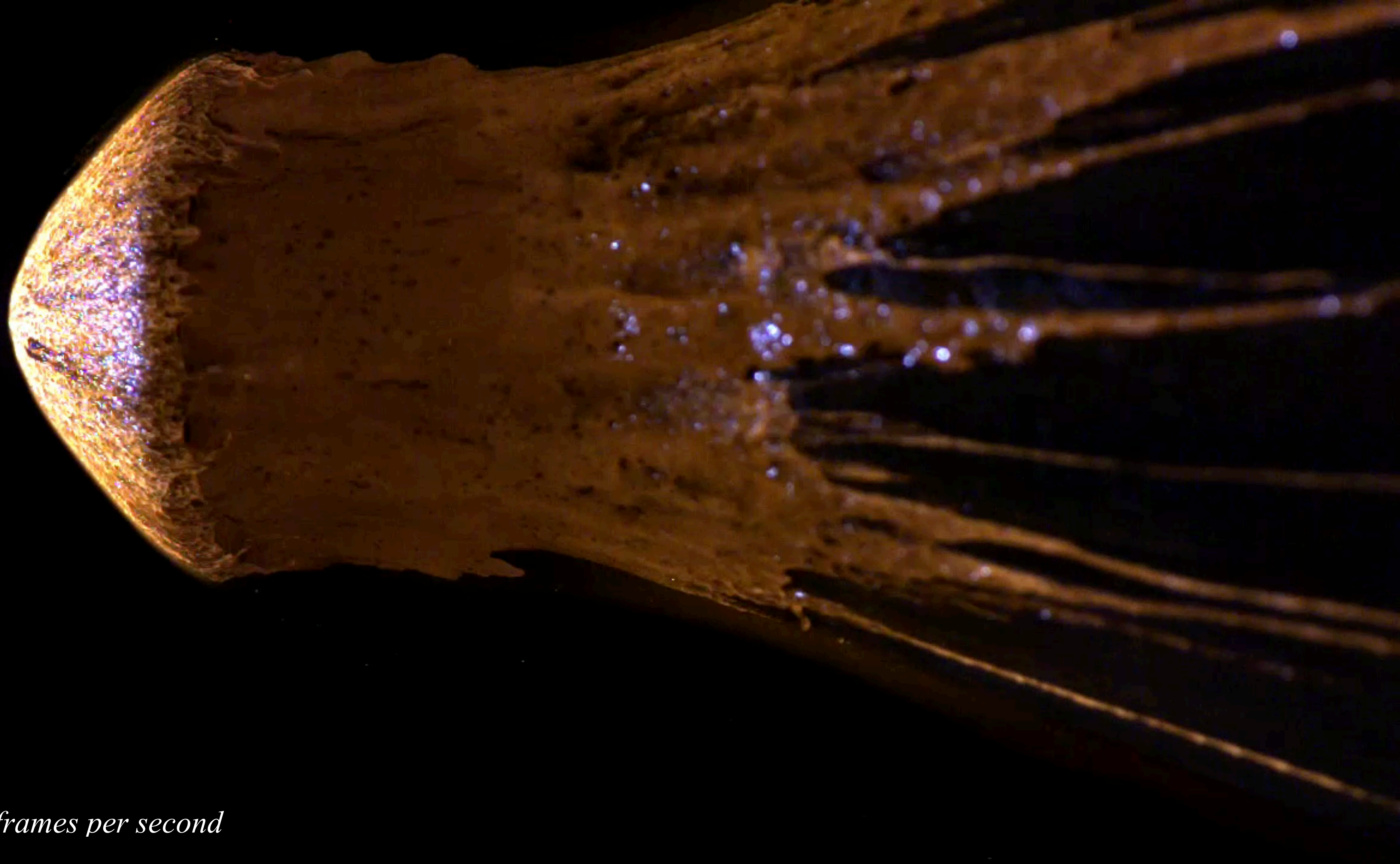
Tamdakht H5 Ordinary Chondrite

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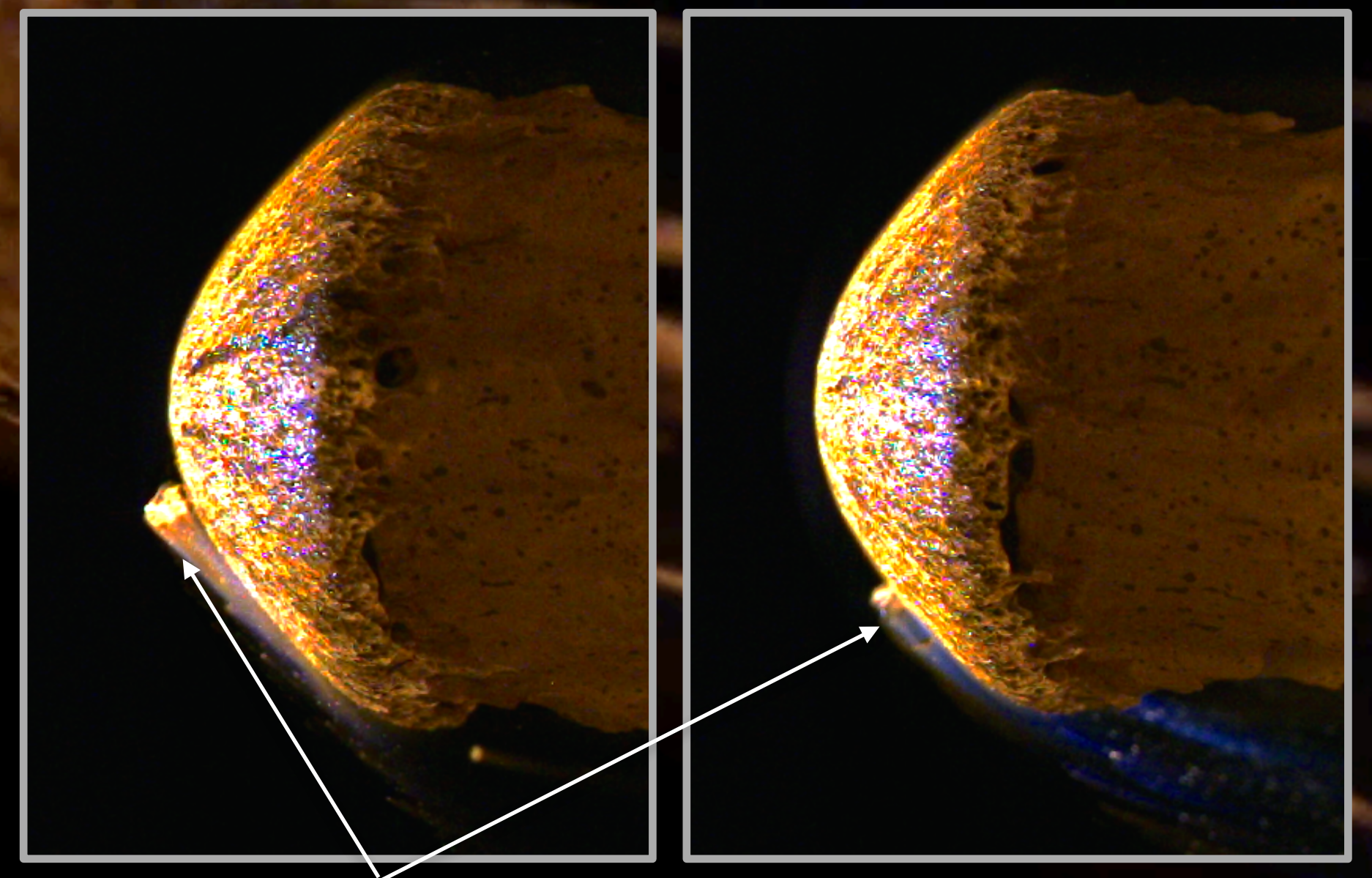


1500 frames per second

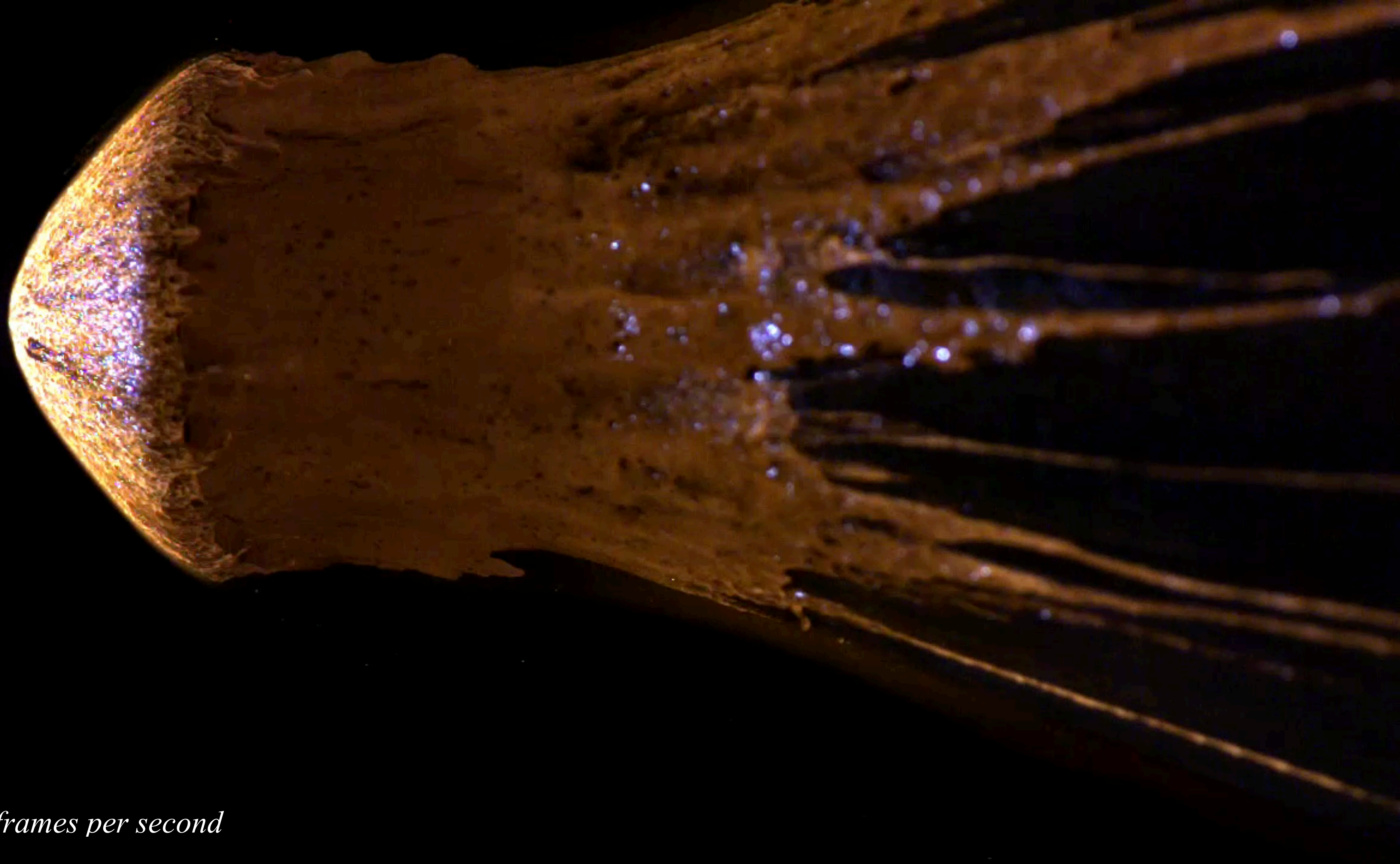


1500 frames per second

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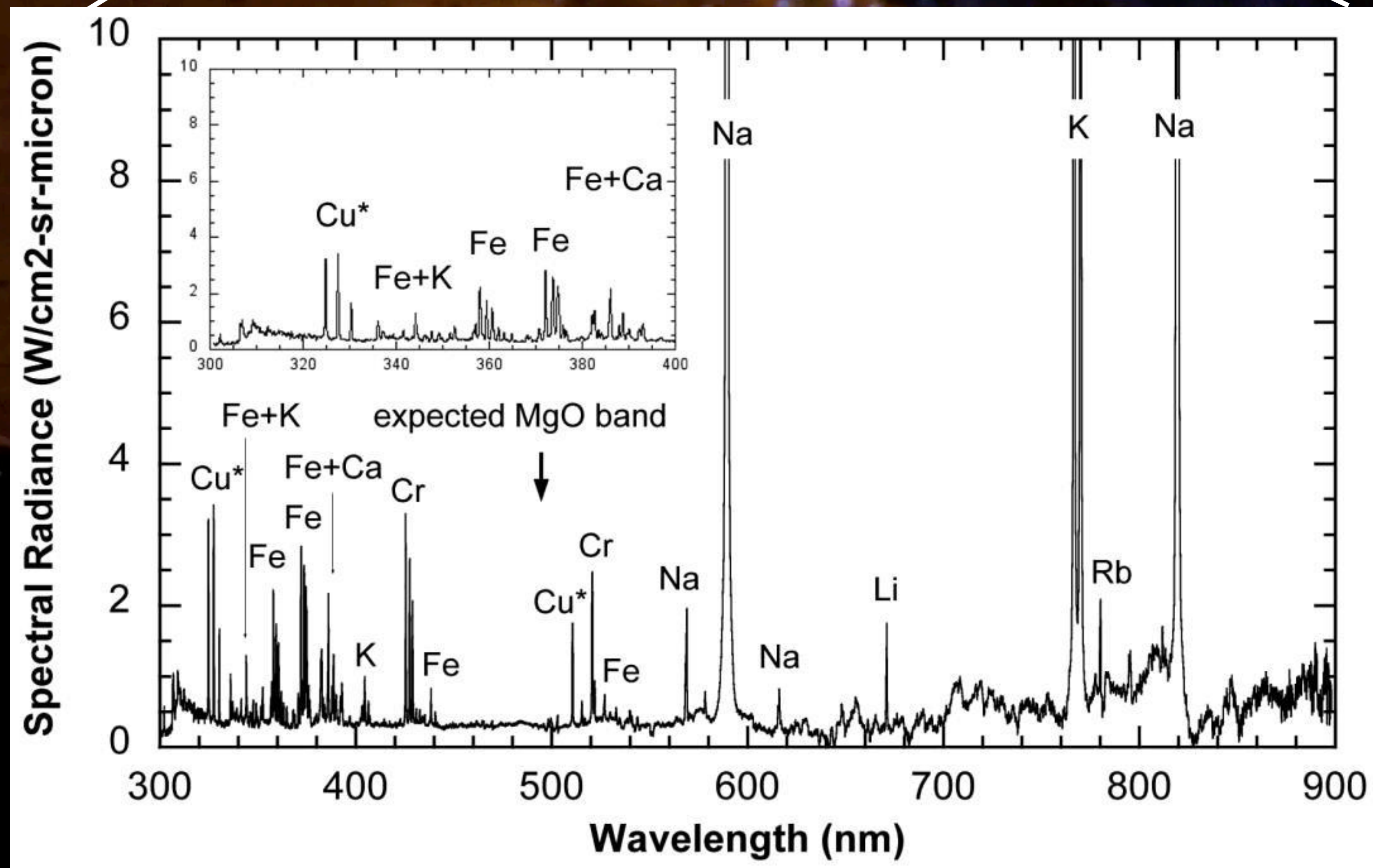
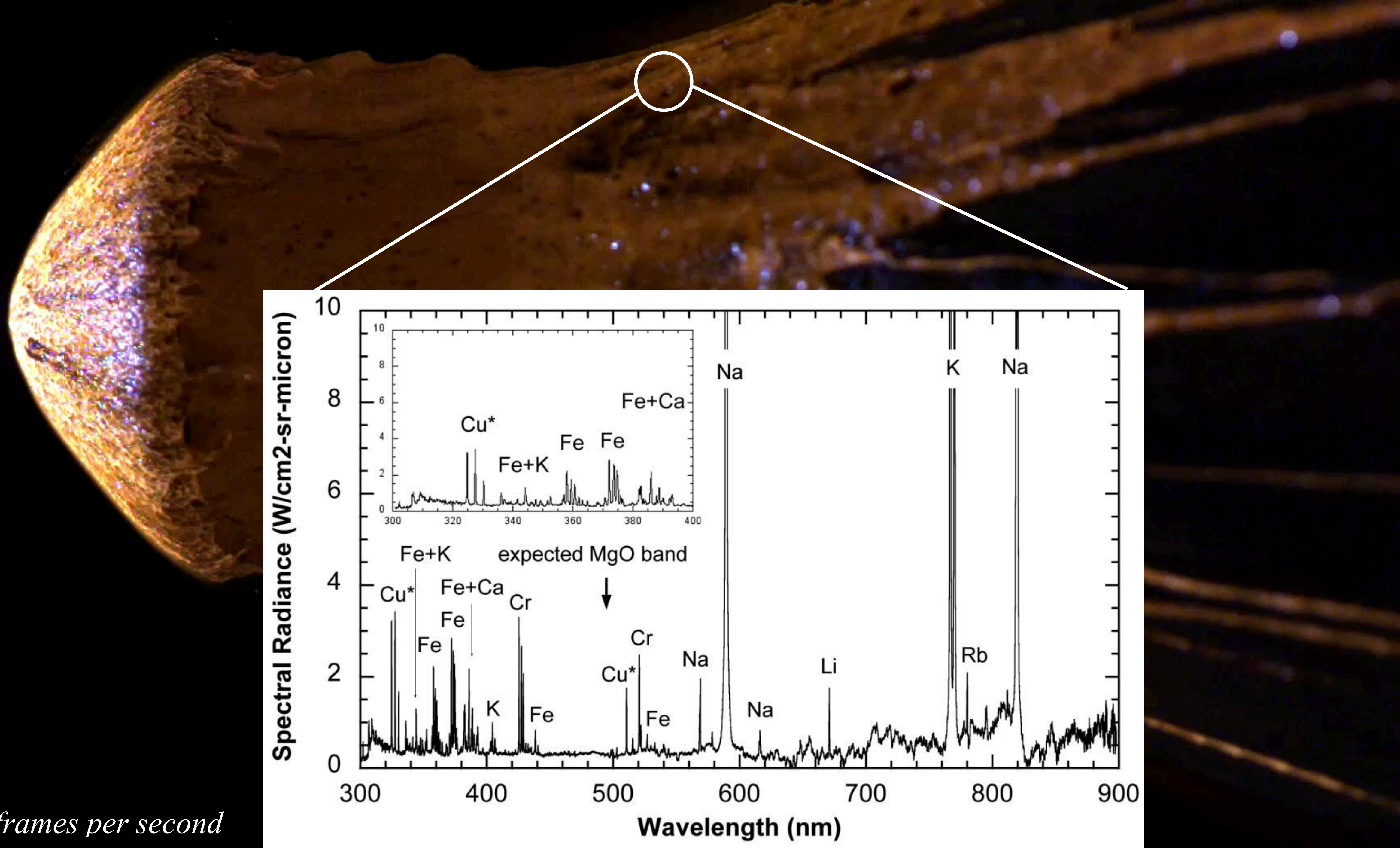
spalled fragments

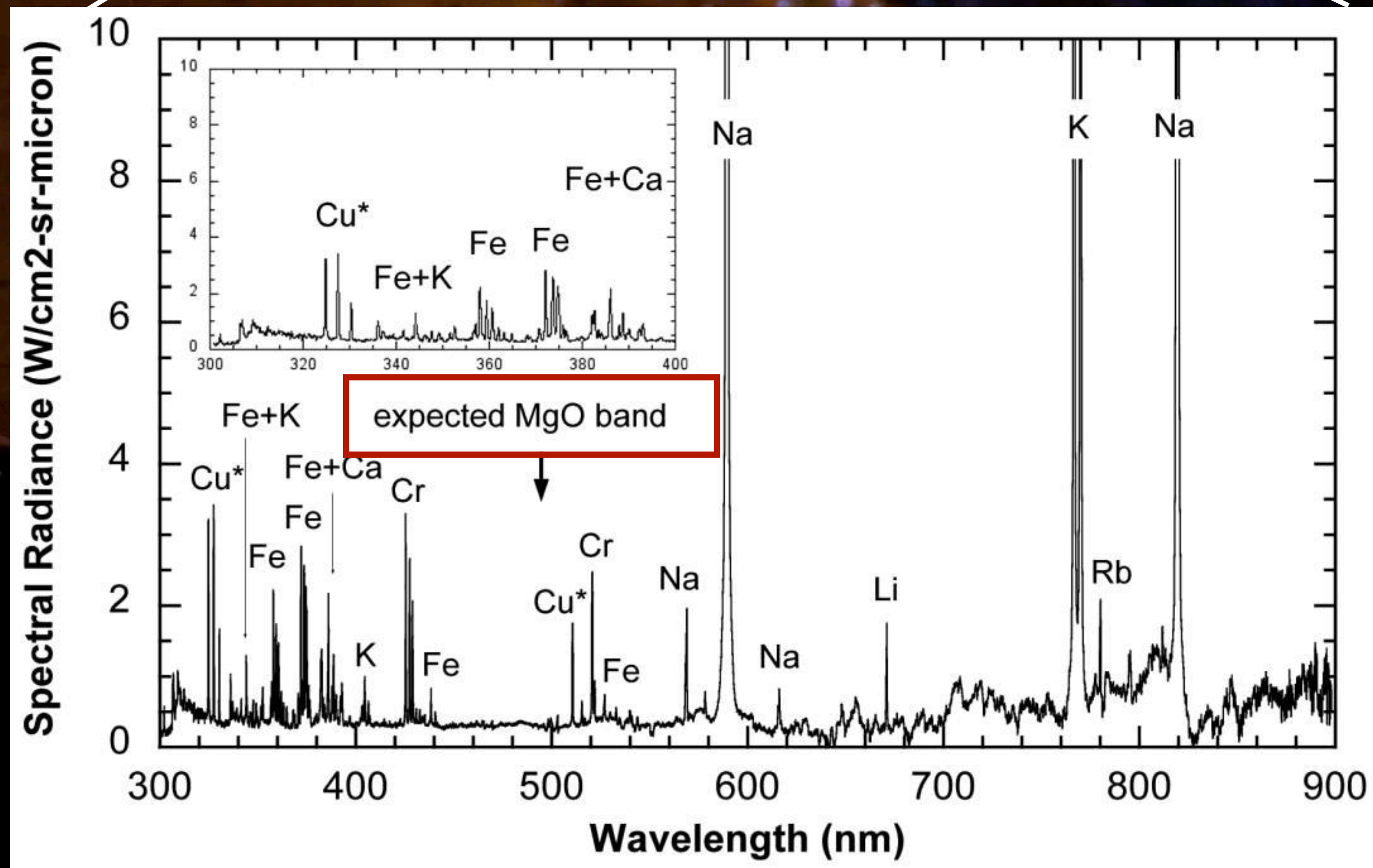
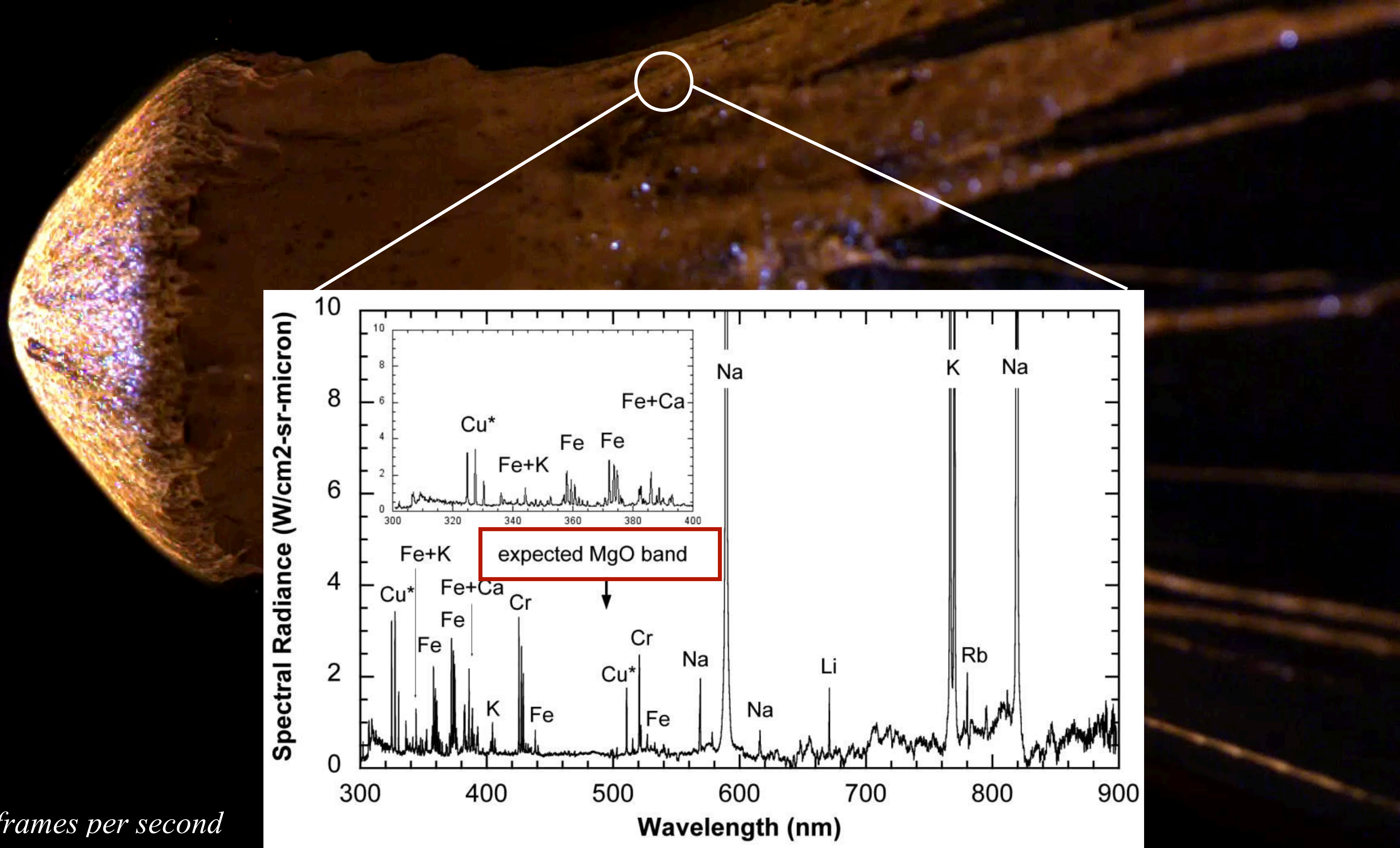


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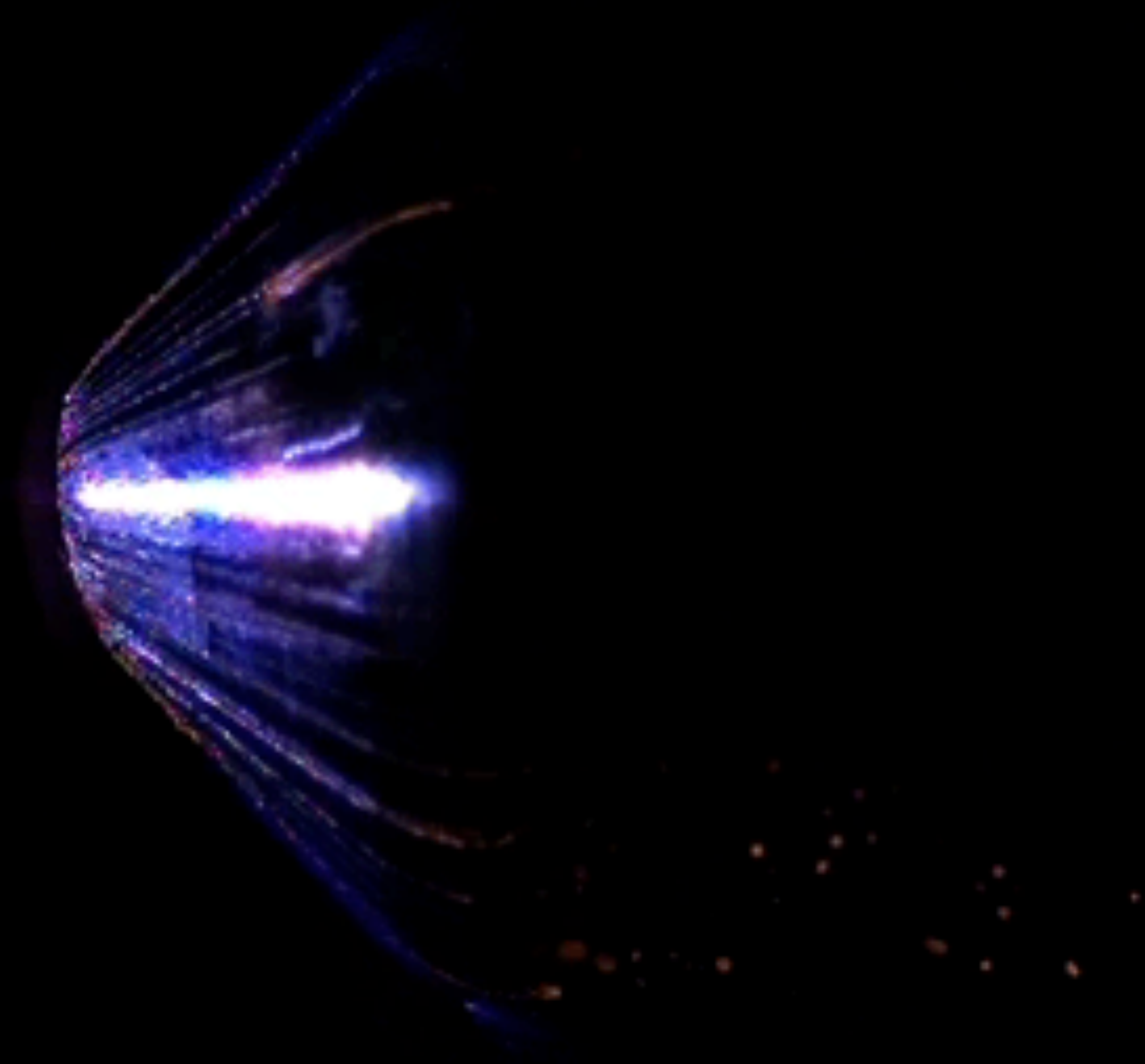
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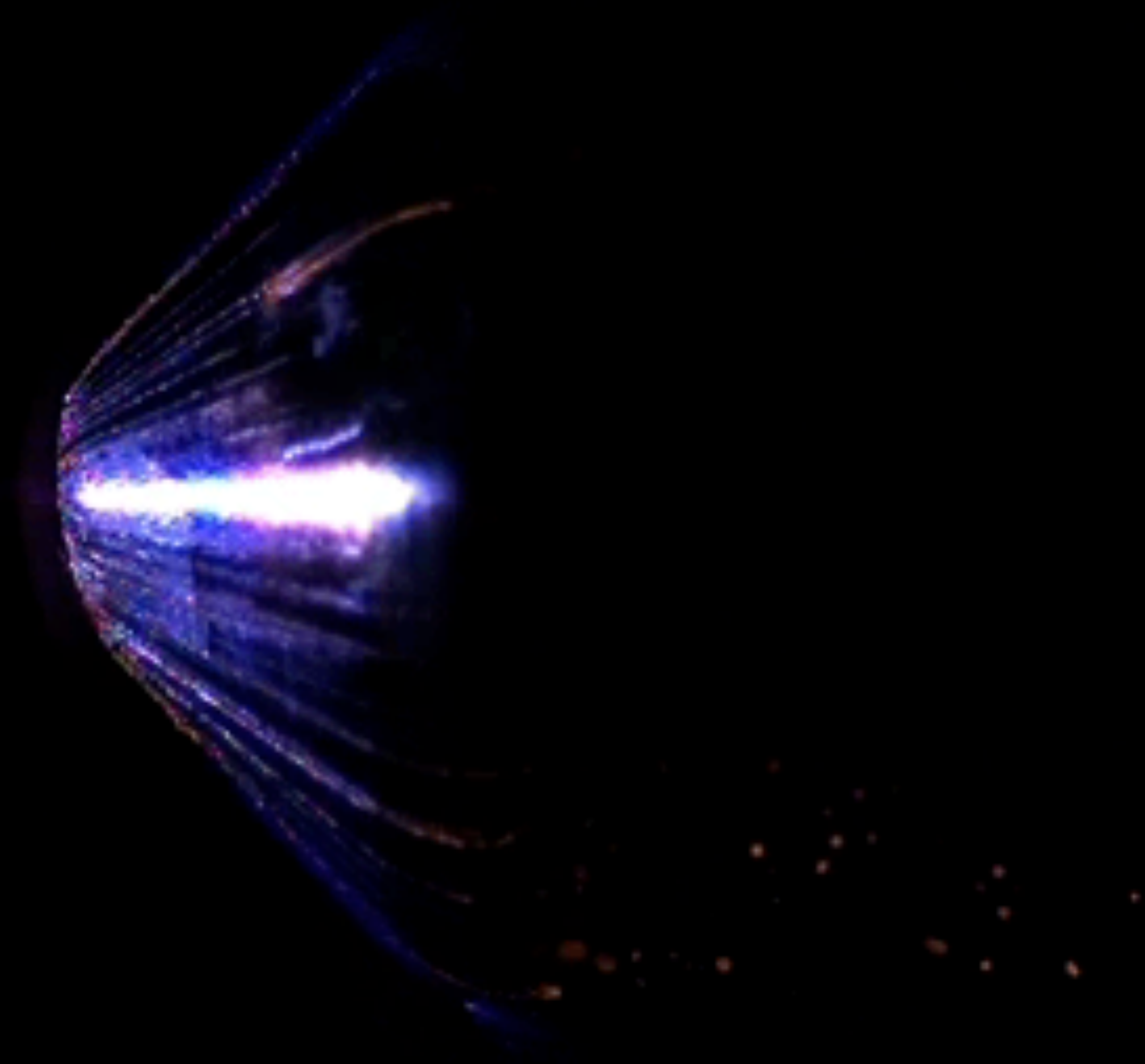


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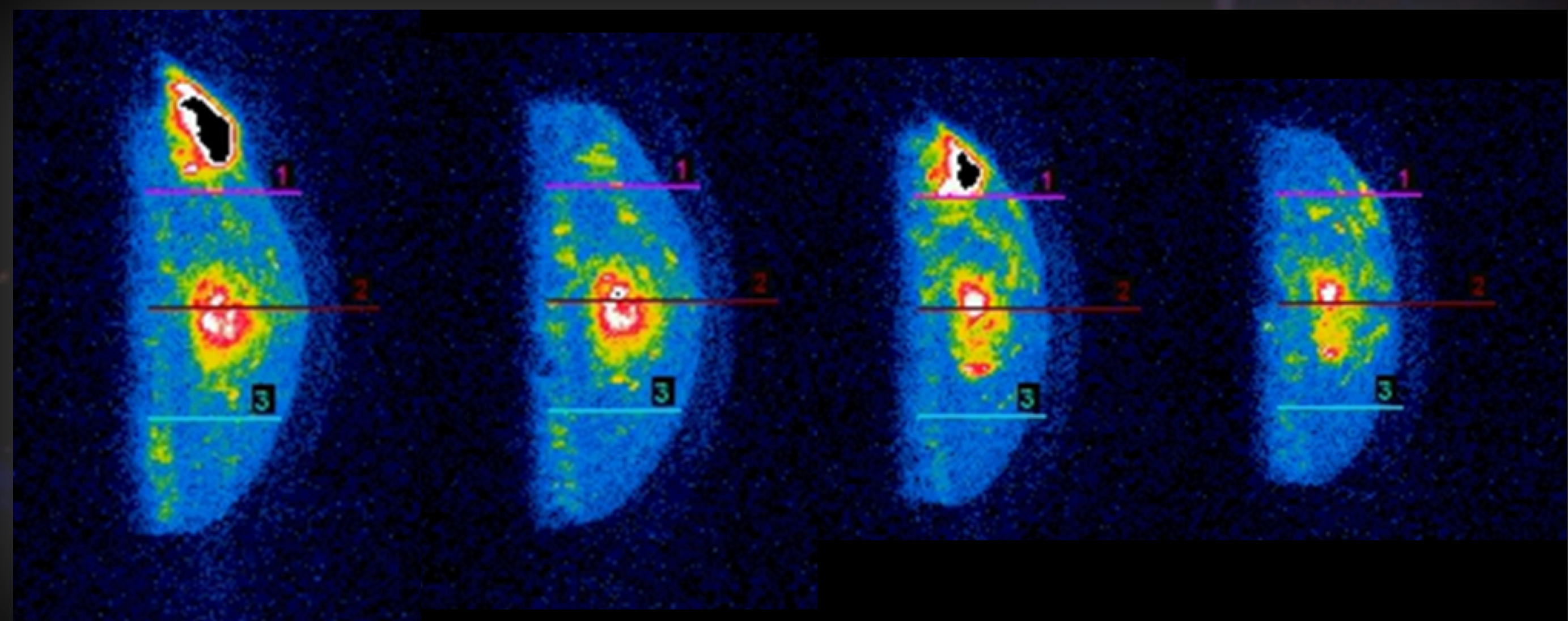
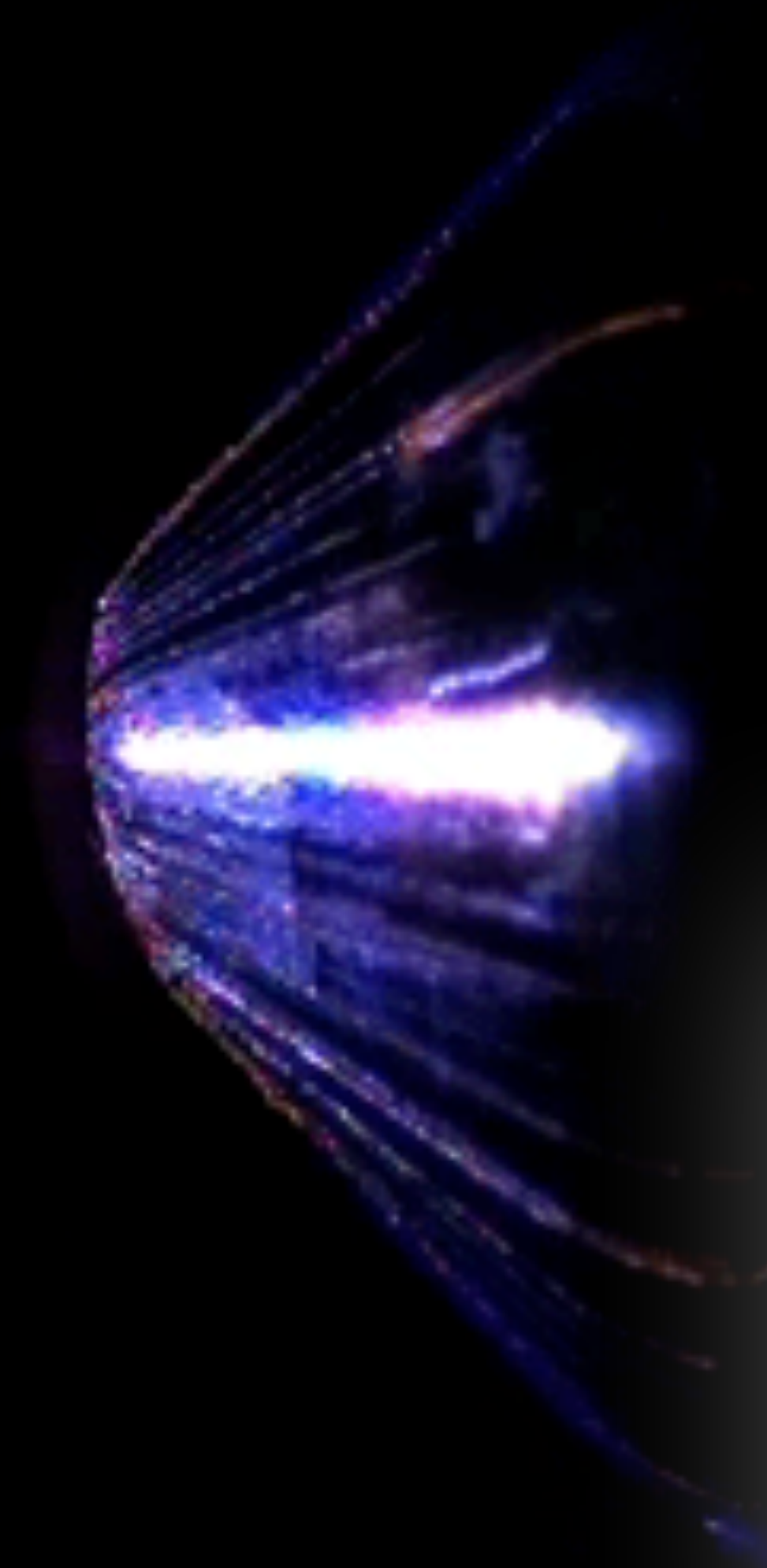
Campo del Cielo Iron Meteorite



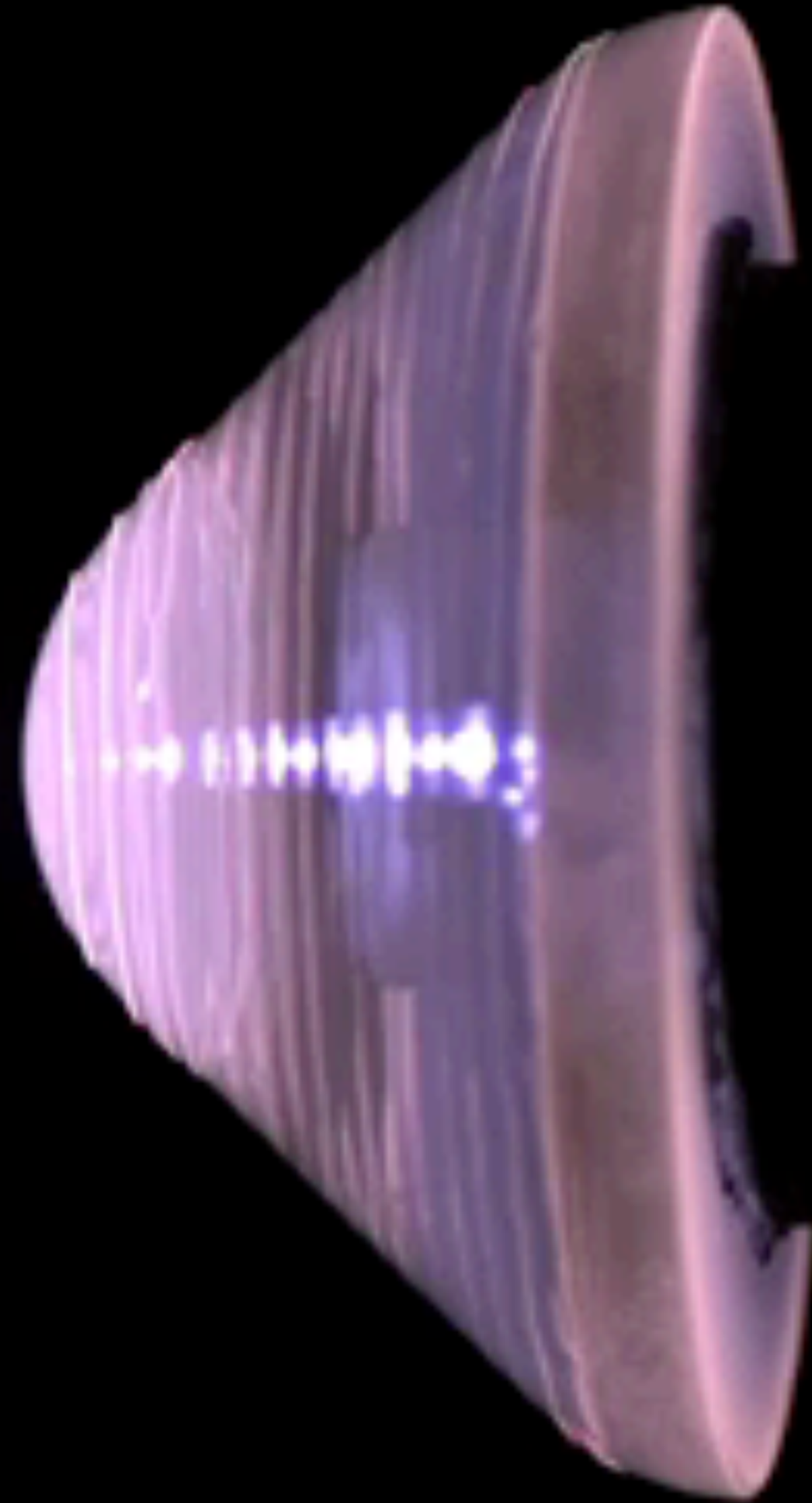
Campo del Cielo Iron Meteorite



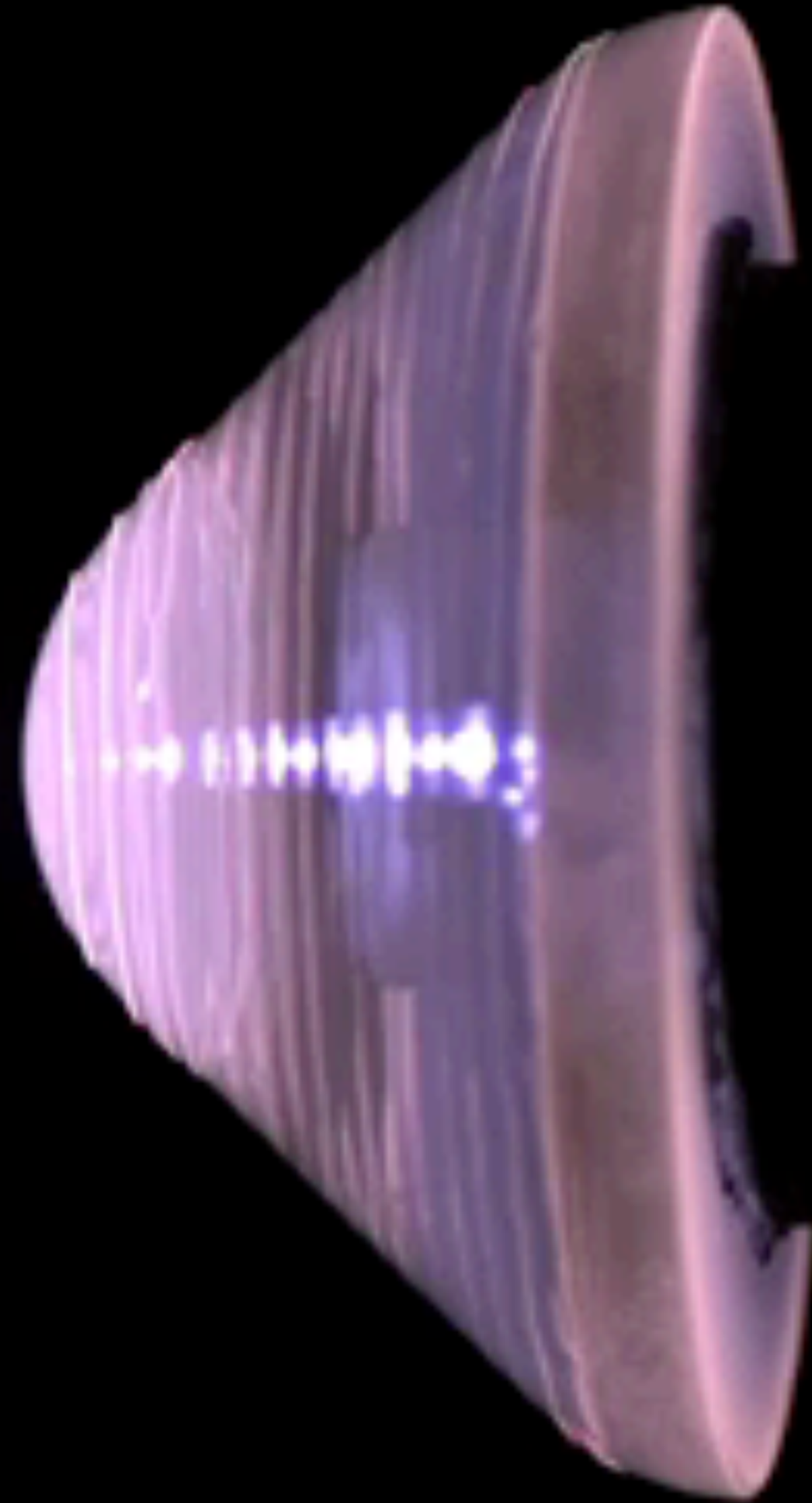
Campo del Cielo Iron Meteorite



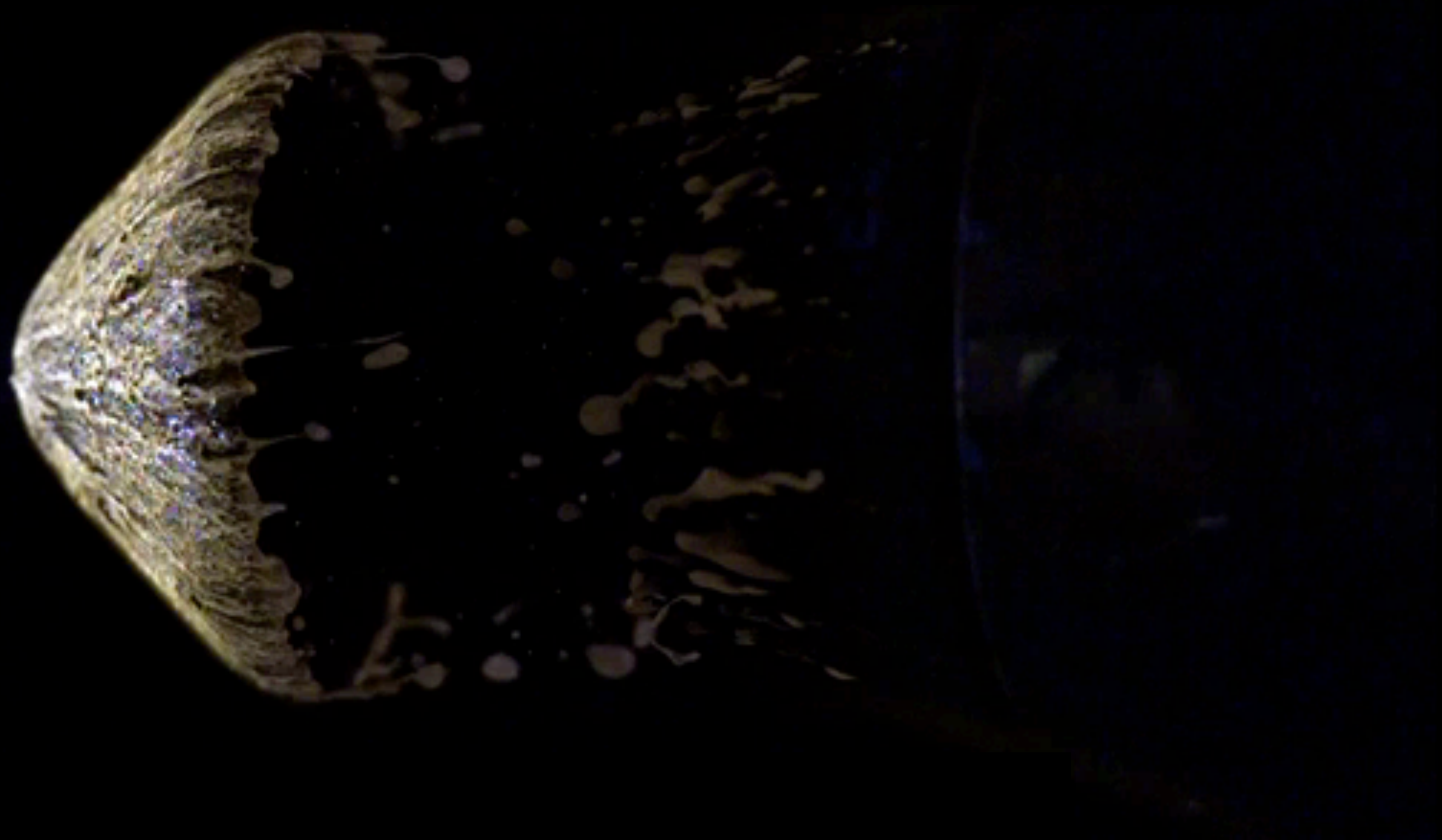
Fused Silica



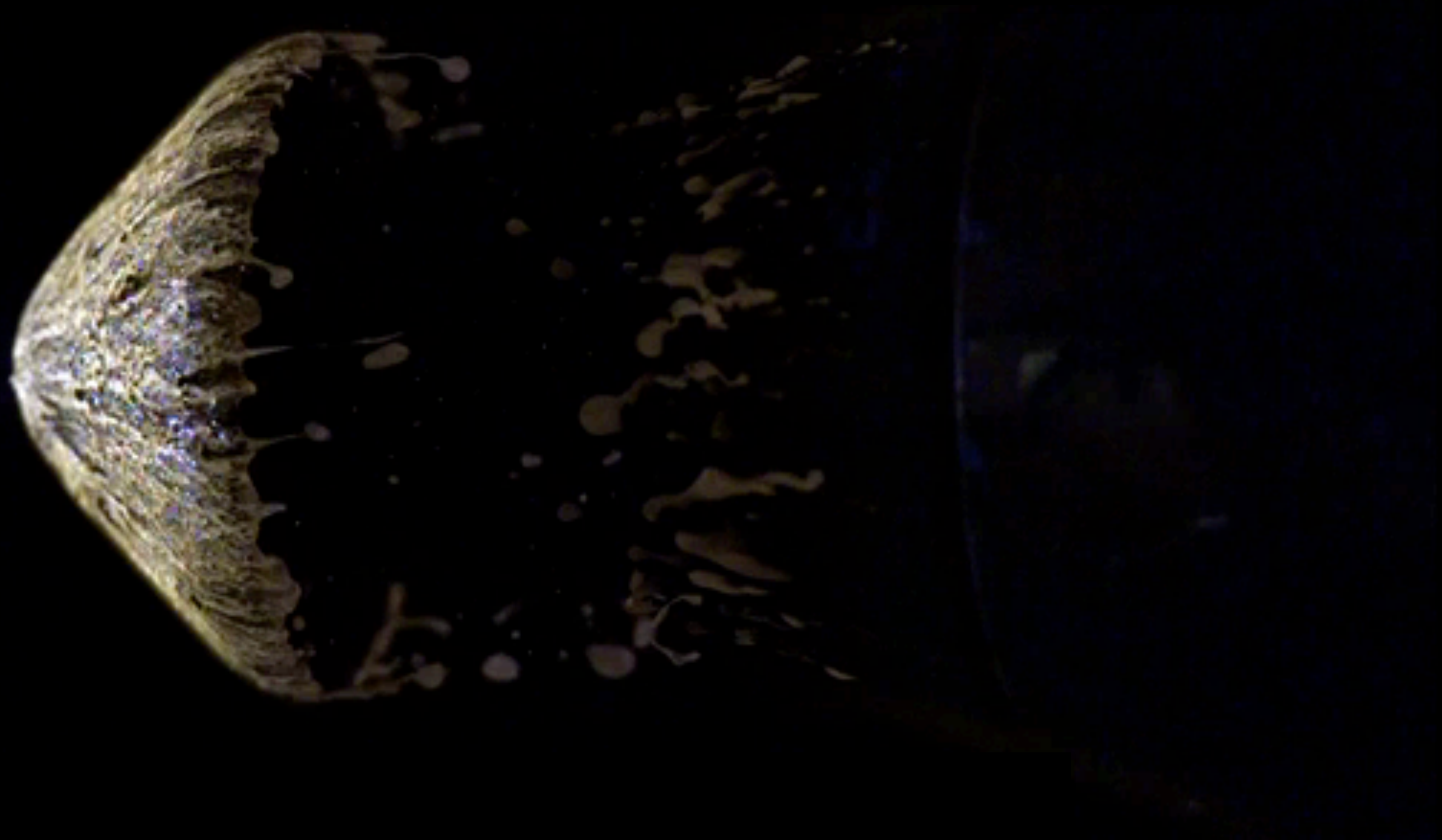
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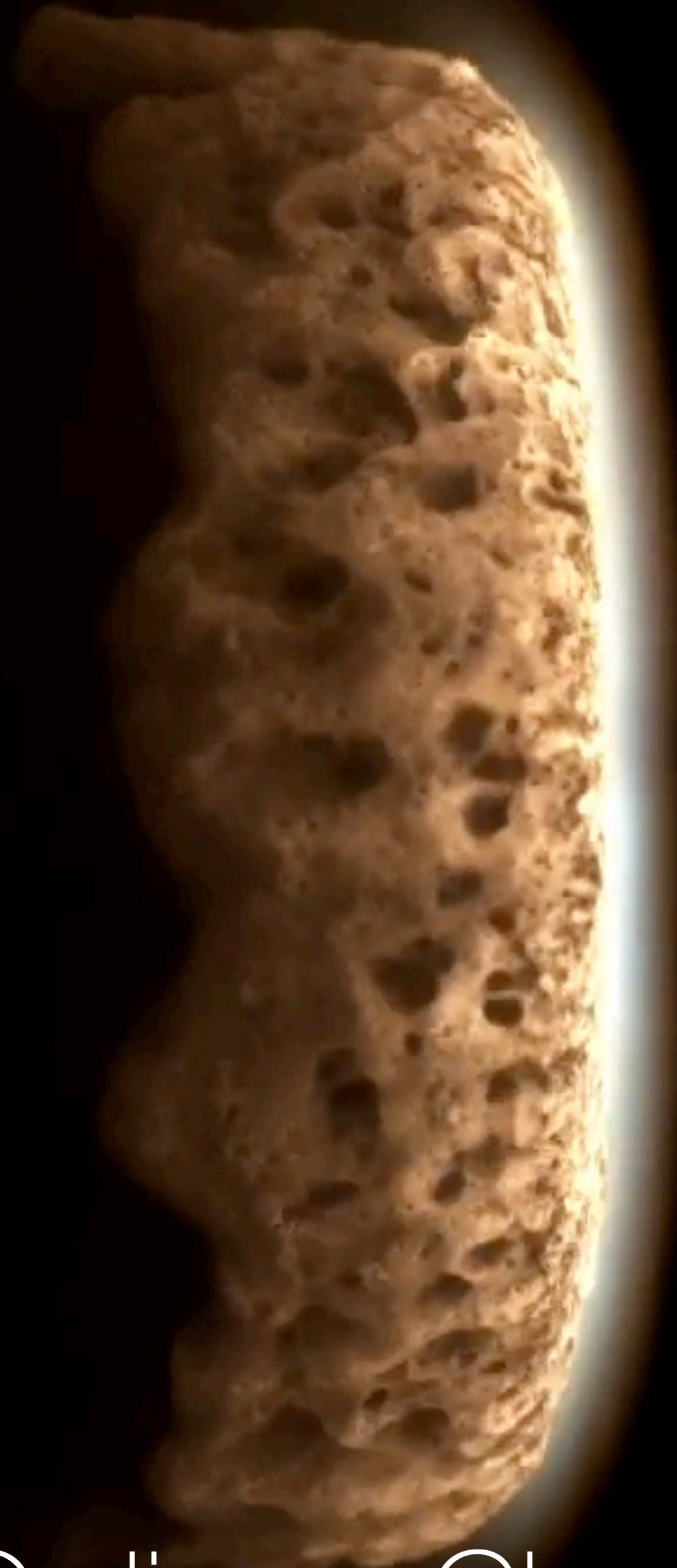


Basalt



Basalt





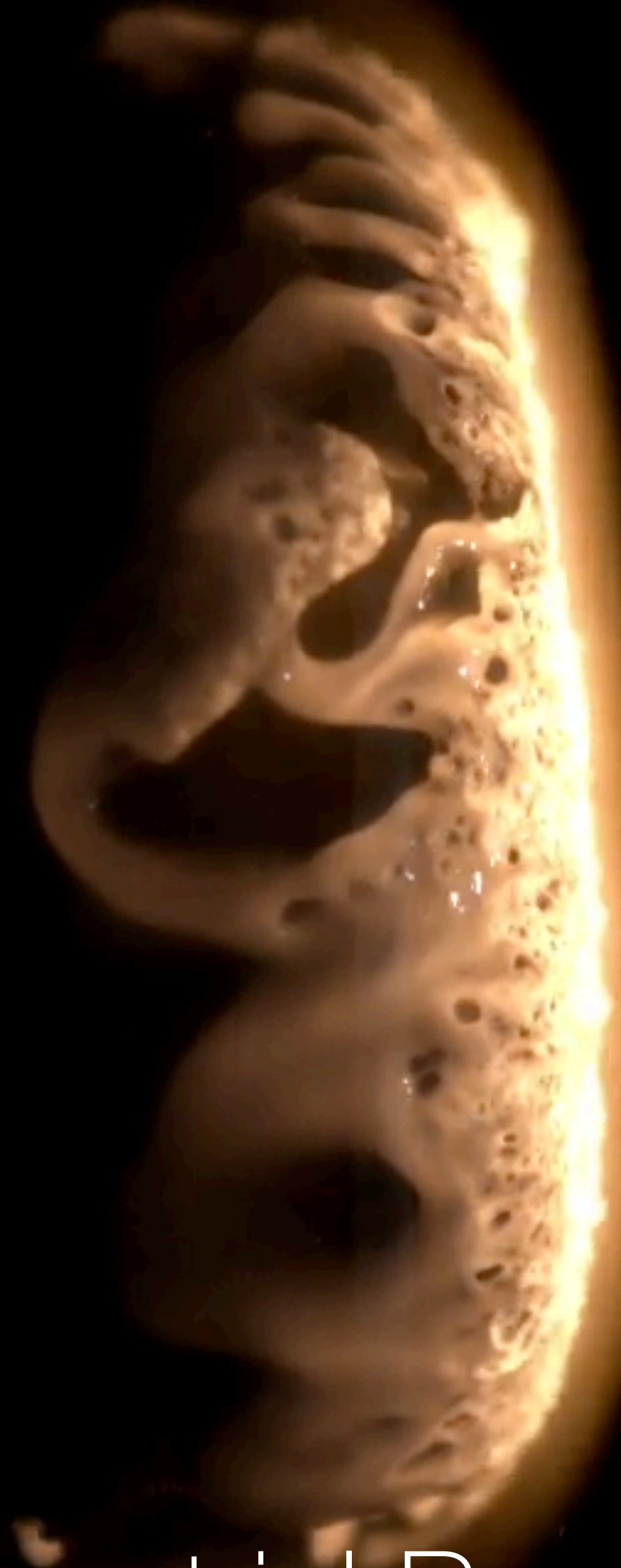
H5 Ordinary Chondrite



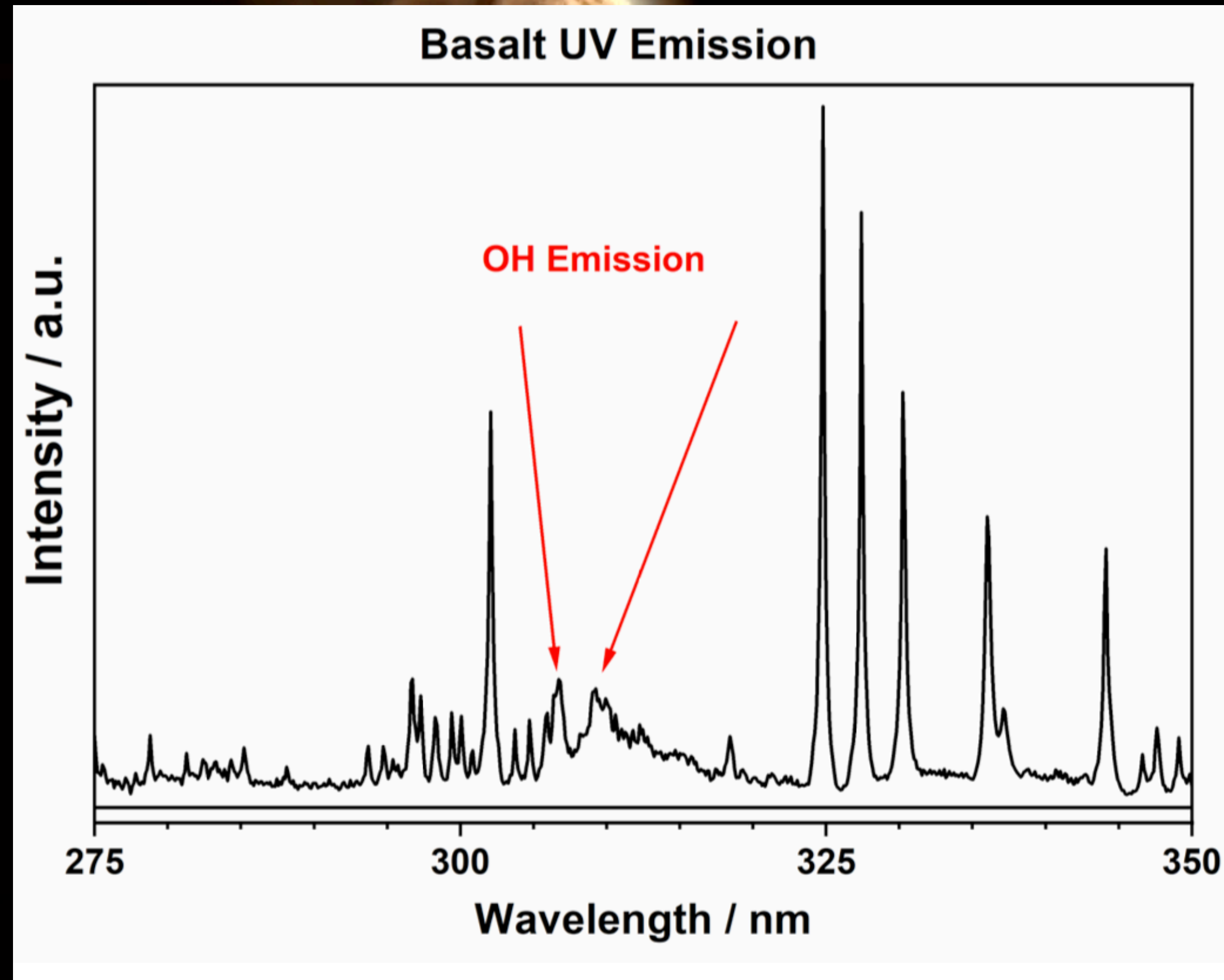
Terrestrial Basalt



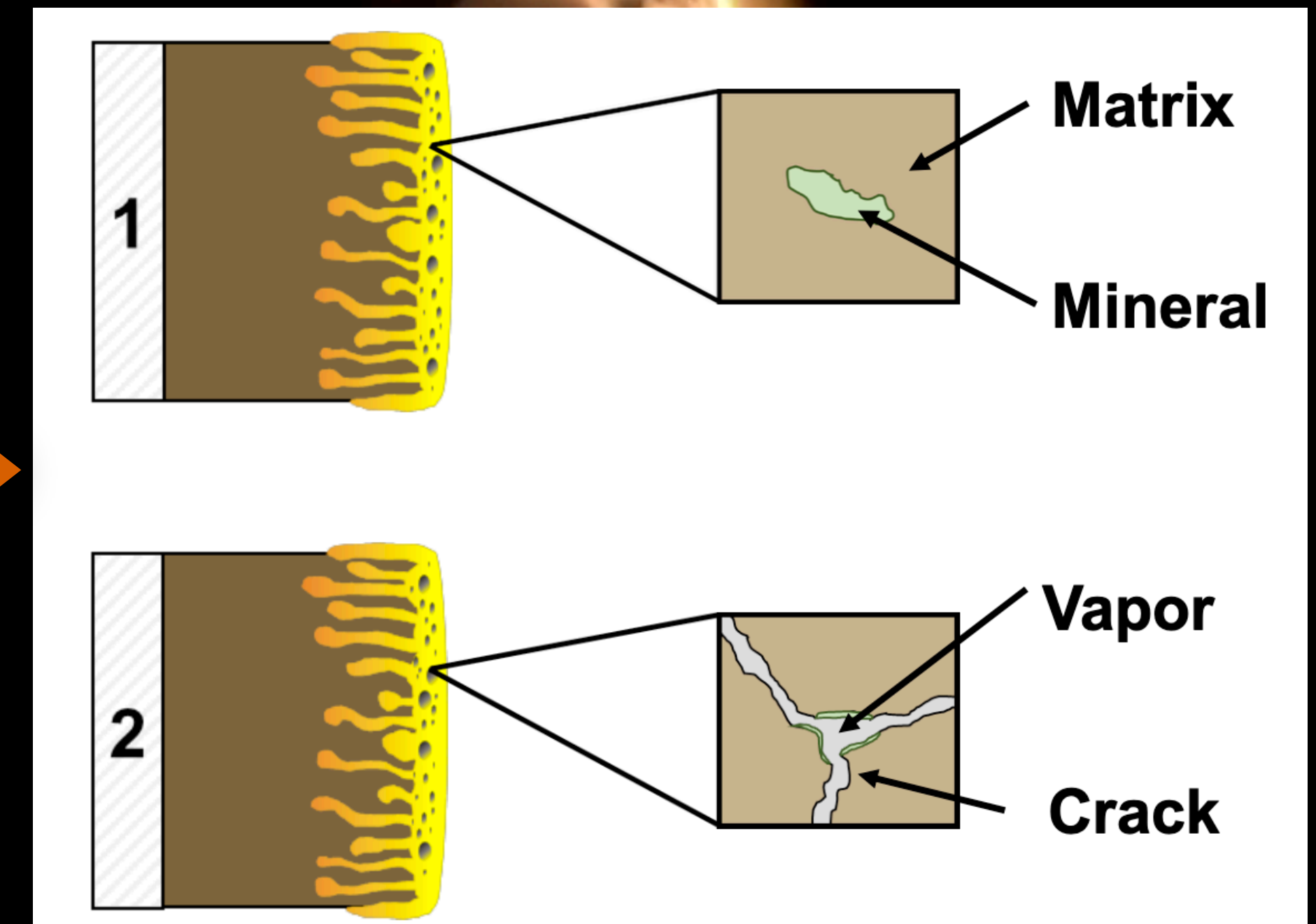
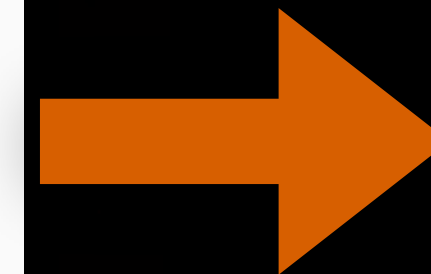
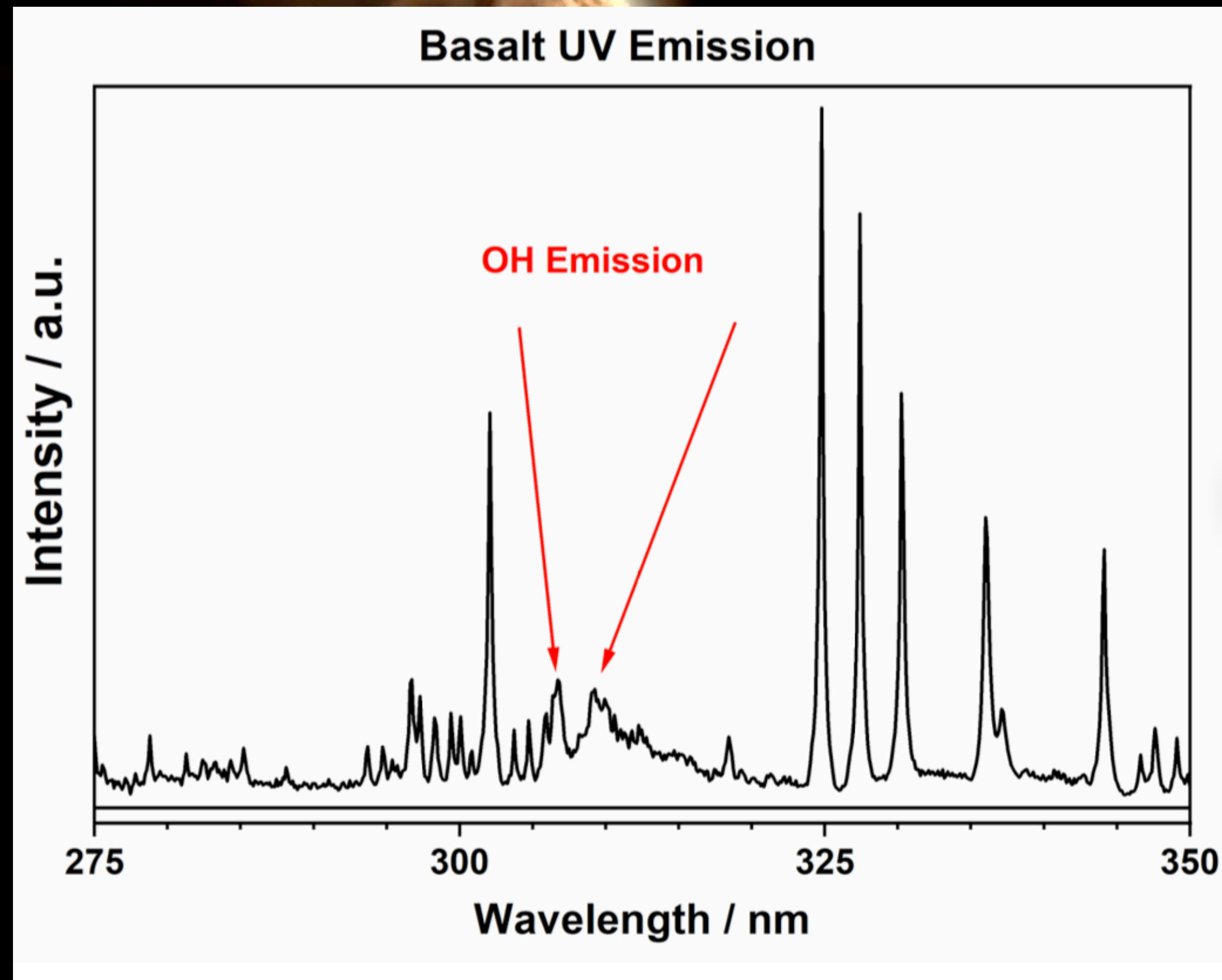
H5 Ordinary Chondrite



Terrestrial Basalt



Terrestrial Basalt



Terrestrial Basalt

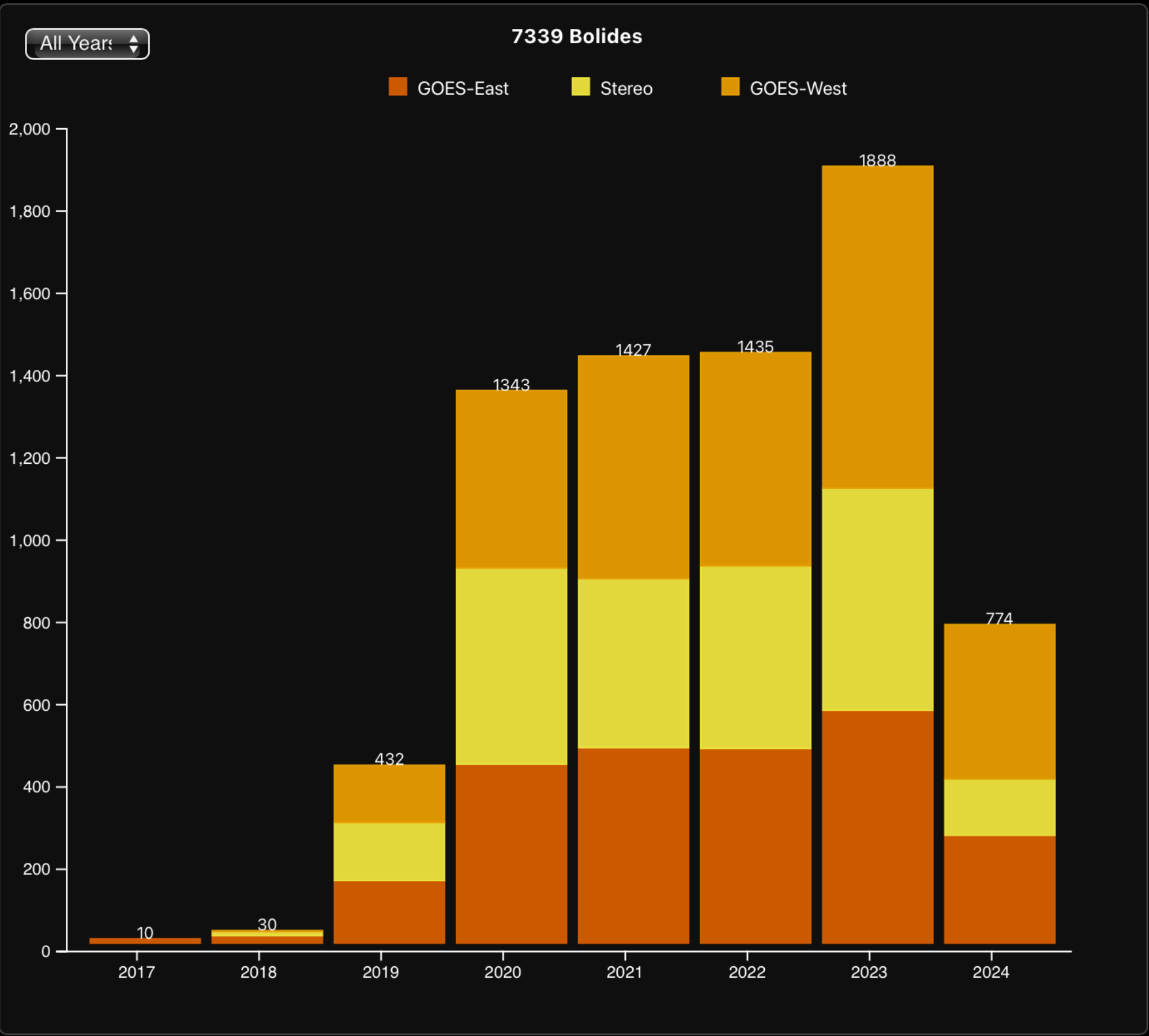
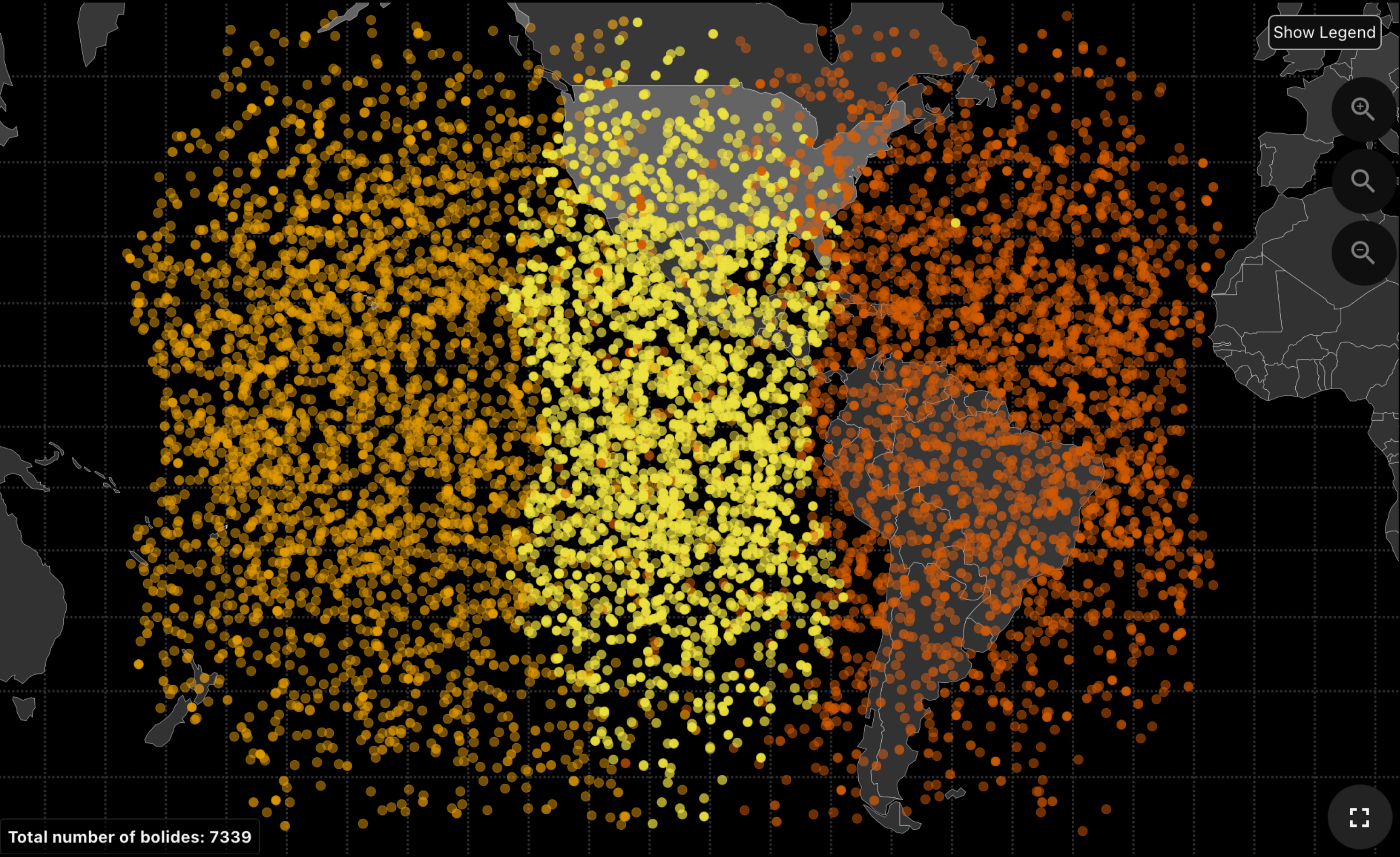


Outlook...

- Synthesizing insights from ablation experiments with the theoretical modeling to derive new ROM for effective heat of ablation (Q^*)
- Broadband luminous efficiency model based on detailed simulations
- Leveraging space-based observations of bolides

Bolide Detections from Geostationary Lightning Mapper

The Geostationary Lightning Mapper (GLM) aboard the GOES East and GOES West satellites, is designed to capture natural lightning activity, but it is also capable of detecting bright meteors, called bolides. GLM's large coverage area allows it to capture unprecedented numbers of meteors and its data is publicly accessible. More background about this data, hints on how to use this website, and the latest news and updates can all be found [here](#).





ATAP Entry Modeling Team:

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Georgios Bellas-Chatzigeorgis

Bruno Dias

Chris Johnston

Amal Sahai

Olivia Schroeder

Eric Stern

Thank you!