IMEX – Interplanetary Meteoroid Environment for eXploration:

Towards a robust model of the dust hazard

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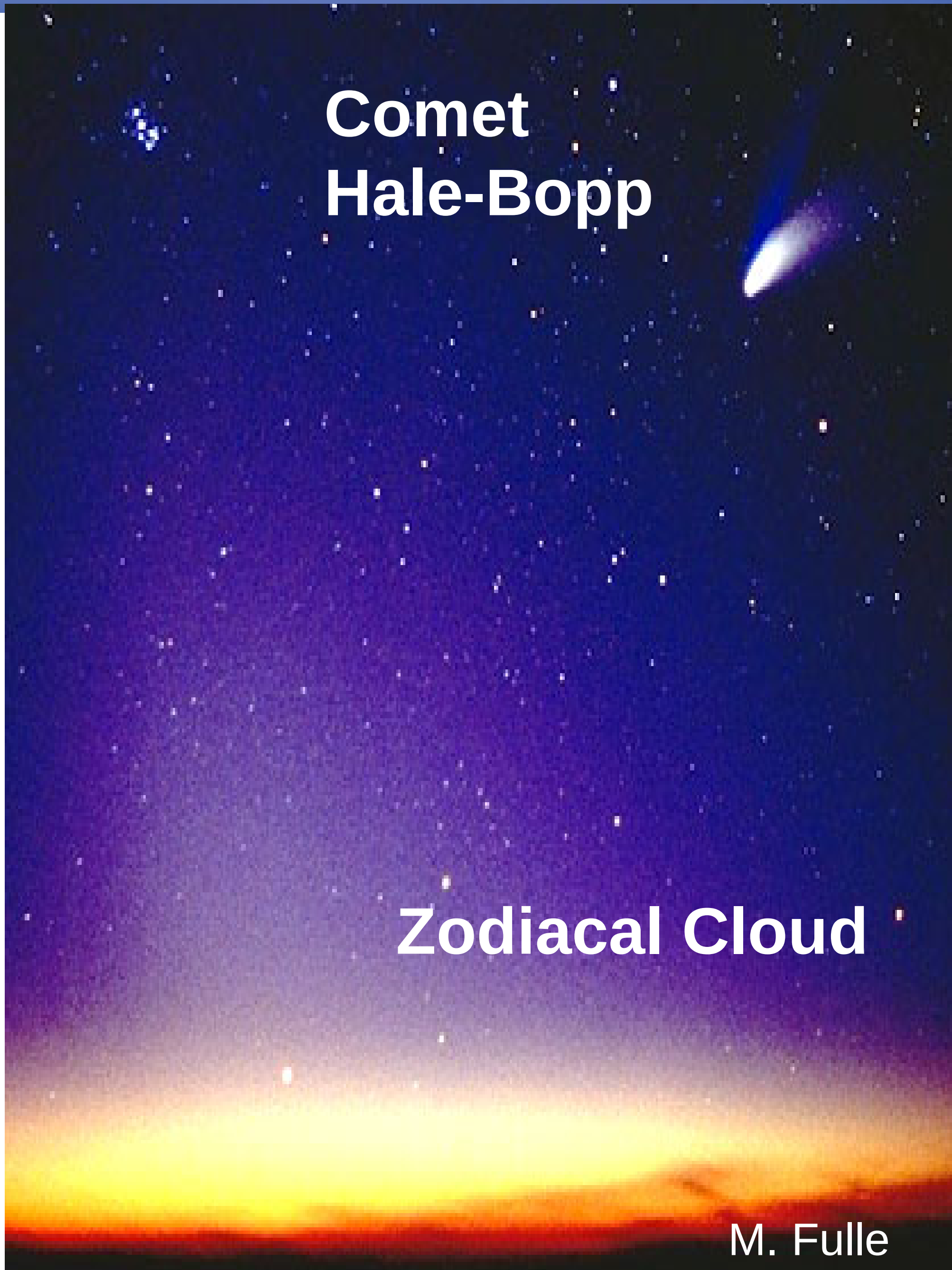
Outline

1) **Motivation**
   – The meteoroid hazard
   – Existing meteoroid models
2) **The IMEX model**
   – The interstellar dust model
   – Details of the meteoroid stream model
3) **Applications of the stream model**
   – The trail of Comet 67P/Churyumov-Gerasimenko
   – Meteor showers at Earth
   – Streams along the trajectory of Solar Probe Plus
4) **The next step**
   – Next steps for the IMEX model
   – Development of a full interplanetary dust model.

Dust in the Solar System

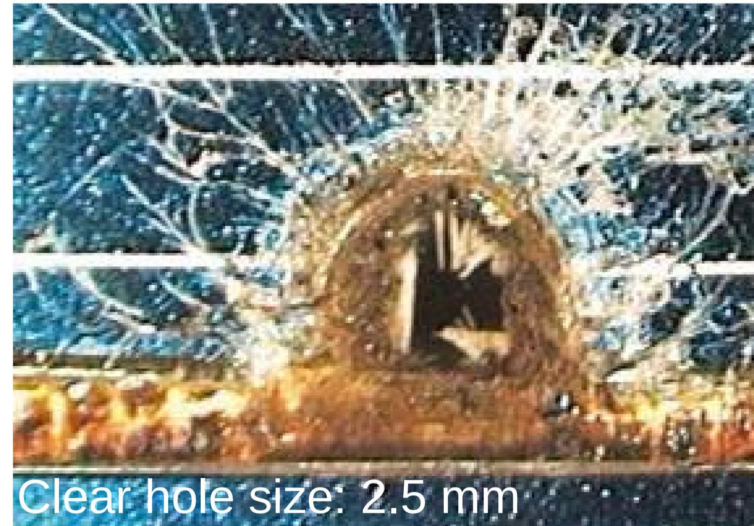
- Cometary and asteroidal streams
- Interplanetary background dust cloud
- Interstellar

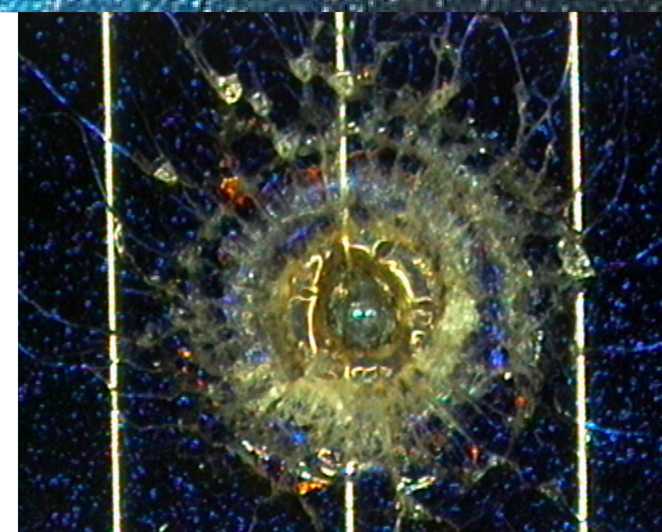
→ Cometary streams are not included in current interplanetary meteoroid models: ESA's IMEM, NASA's MEM



Why model Solar System dust?:
The impact hazard from hypervelocity particles

- **Cratering and Ejecta**
  - Surface erosion
  - Degradation of instruments, windows
- **Structural damage**
  - Penetration of surfaces
  - Puncturing of tanks
  - Severing of cables
- **Plasma effects**
- **Momentum transfer**
  - Loss of pointing, attitude





Impacts on to Hubble Space Telescope solar cells ESA, Drolshagen, 2008

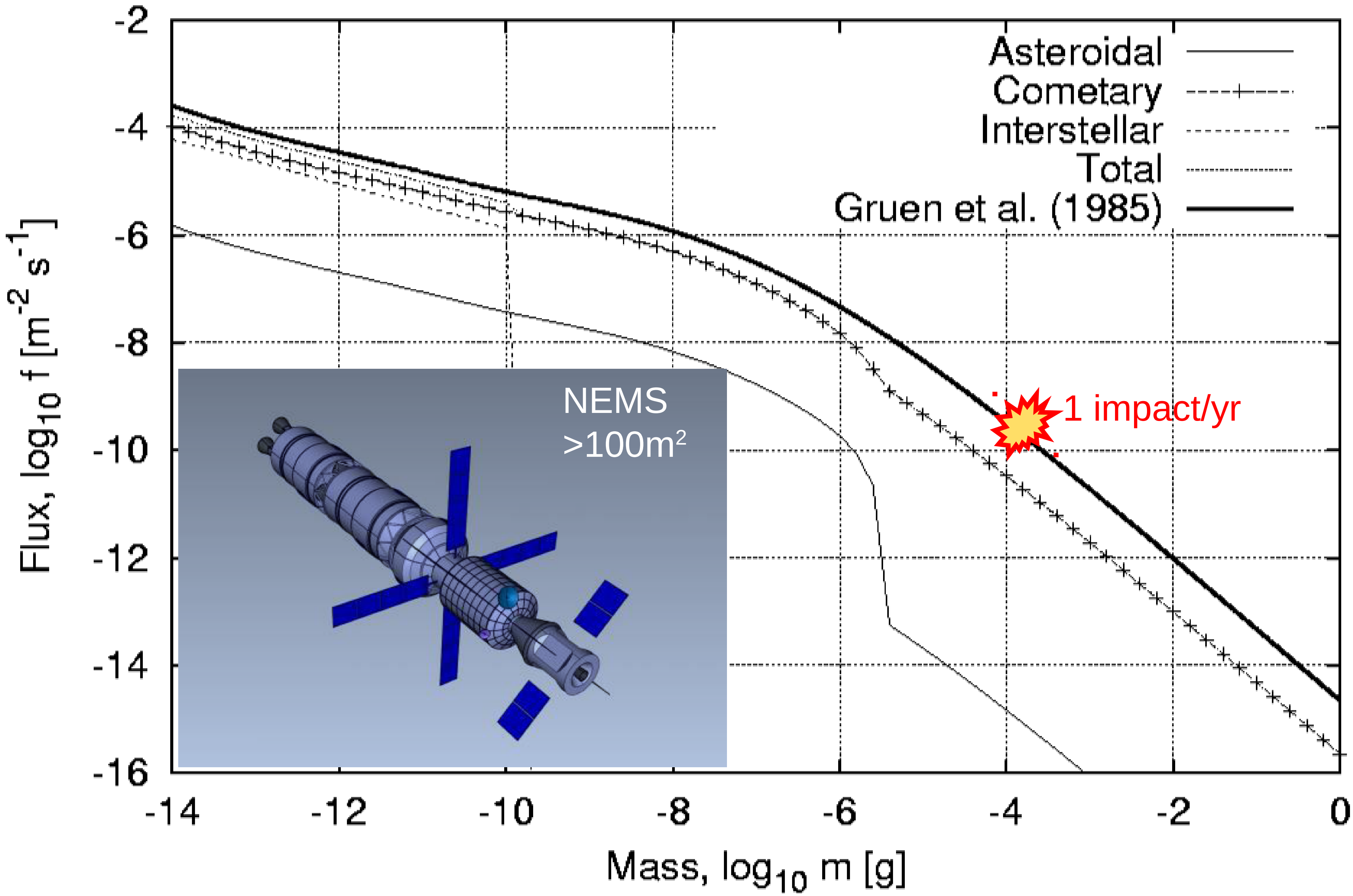
Spacecraft damaged/destroyed by impacts

Olympus	Lost Pointing in 1993 **Perseids**. Attributed to plasma effects
Landsat-5	Lost gyroscopic control during 2009 **Perseids**. Plasma/electrical effects
DAICHI	Shifted itself to low power mode in 2011 and was not recovered
XMM-Newton	A sudden increase of ‘bright pixels’ on the pn-CCD camera attributed to a micrometeoroid impact that entered the detector through the X-ray mirror system.
Hipparcos	A large number of impacts (>100) resulted in a detectable change in attitude
HST solar array	Significant cratering and cutting of a spring
IMAGE	Three of the antenna booms were cut by small impact Mar 2000-Aug 2002
Giotto	Attitude change as a result of meteoroid impacts
JASON 1	Semi-major axis change by 30cm after an impact to the left solar panel in 2002

IMEX Motivation

- **ESA's Near Earth Exploration Minimum System (NEMS) study:**
  - Identified the interplanetary meteoroid environment as a major Strategic Knowledge Gap
  - "The meteoroid population appears to be **one of the most uncertain space environment components**" (Drolshagen, G. et. al., IADC-09-03, 2009).
  - Manned space activities are especially vulnerable because of:
    - lower tolerance level,
    - size (several 100 square meters for NEMS), and
    - months long exposure time

Background Meteoroid Flux at 1 AU



Current Meteoroid Environment Models

- **ESA IMEM**
  - Model: evolutionary
  - Applicability: 0.1 – 5 AU
  - Mass range: 10^{-18} – 1 g
- **NASA MEM**
  - Model: Empirical
  - Applicability: 0.2 – 2 AU
  - Mass range: 10^{-6} – 10 g

→ **Both model only the interplanetary dust cloud**

Model Deficiencies

- **MEM**
  - orbital evolution **not** considered
  - **Unrealistic** radial variation of orbital elements
  - **No** consideration of large-scale spatial distribution

- **IMEM**
  - **Inconsistent** orbital evolution of big and small particles
  - Several missing dust source contributions: Halley type, long-period comets, Kuiper belt objects)
  - meteor data **not** considered

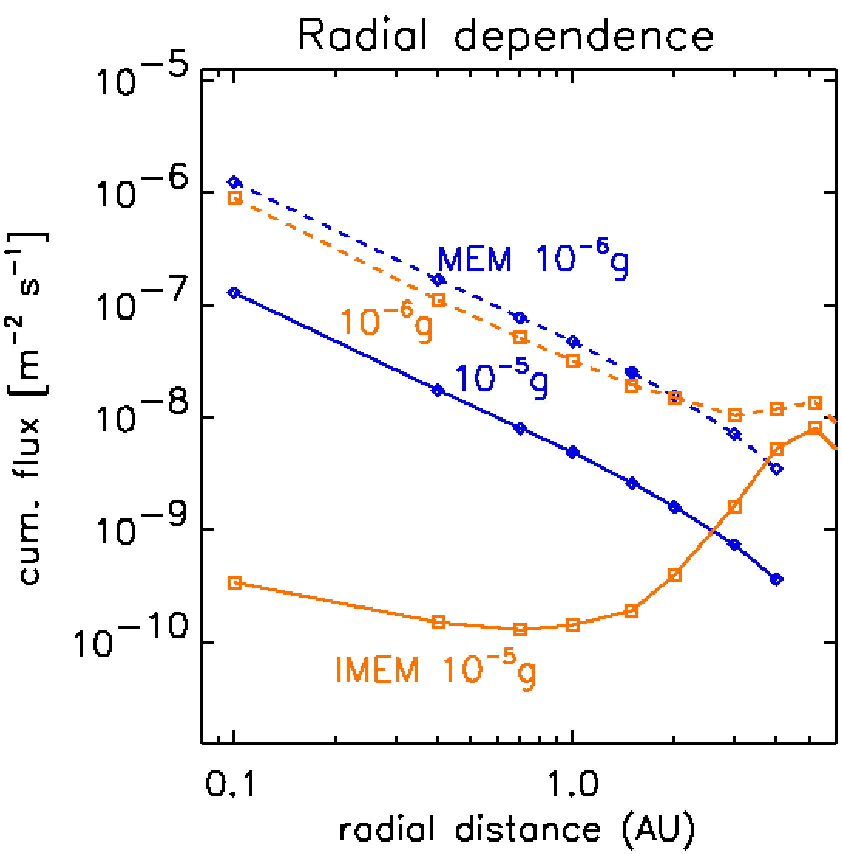
Both models:

No meteoroid streams → No spatial or temporal variations

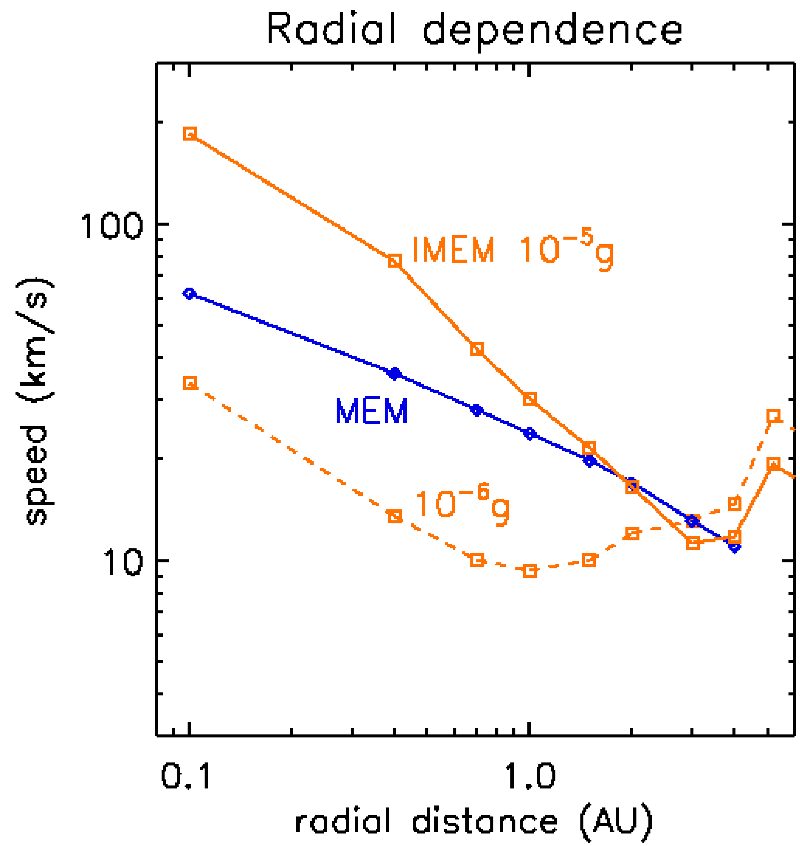
Problems with the Current Models: Radial Variations

- **IMEM and MEM are not consistent (except for cratering flux at 1 AU).**

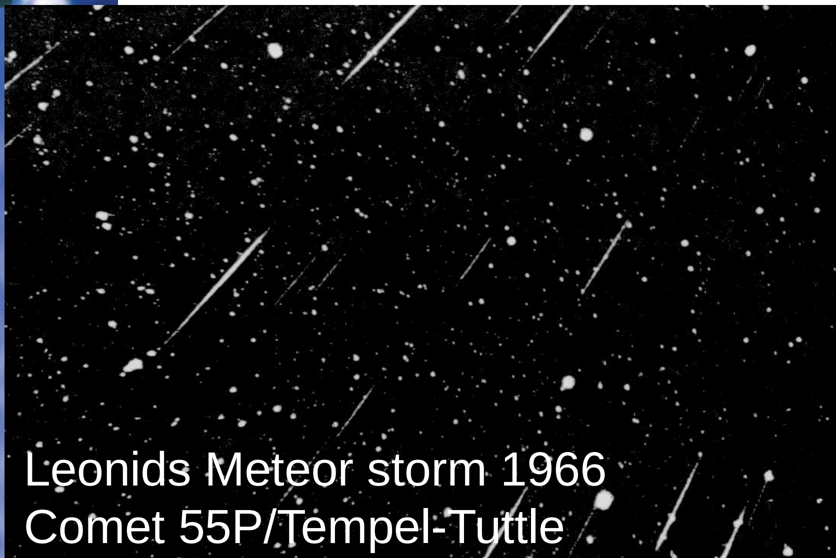
Ram Flux

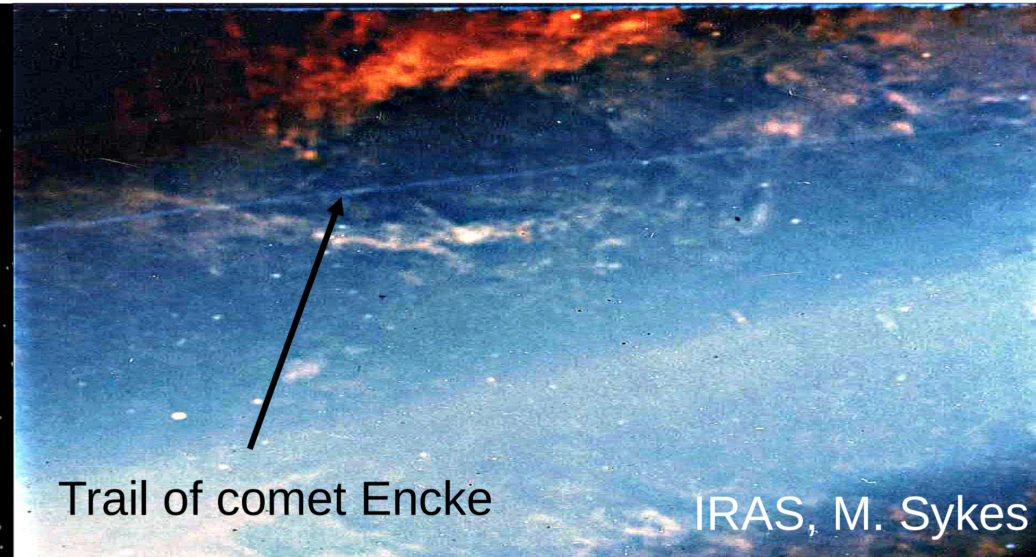


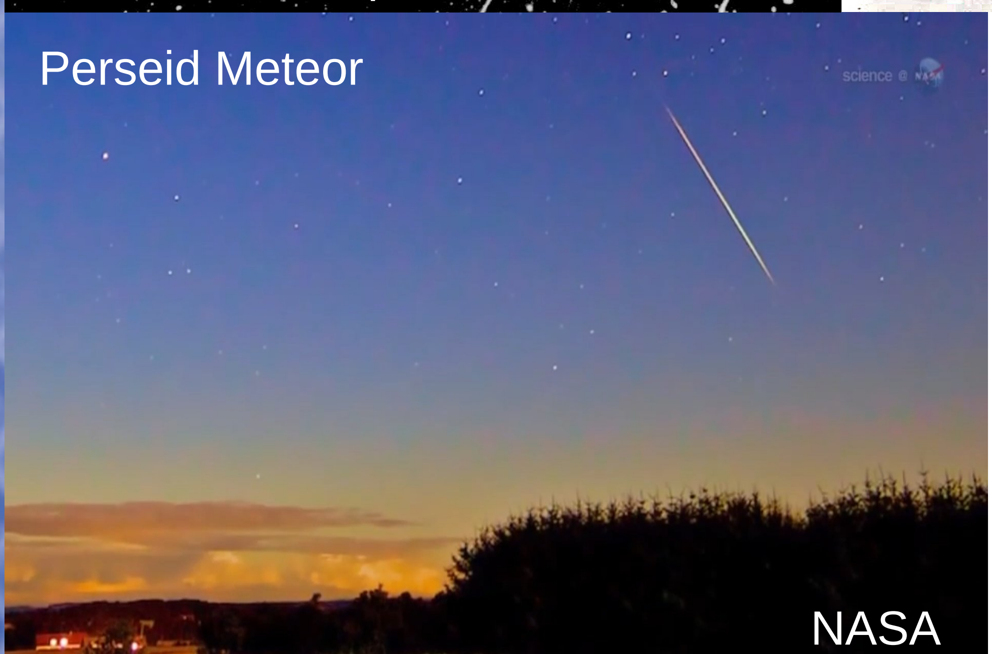
Ram Speed



Fine Structure in the Dust Cloud







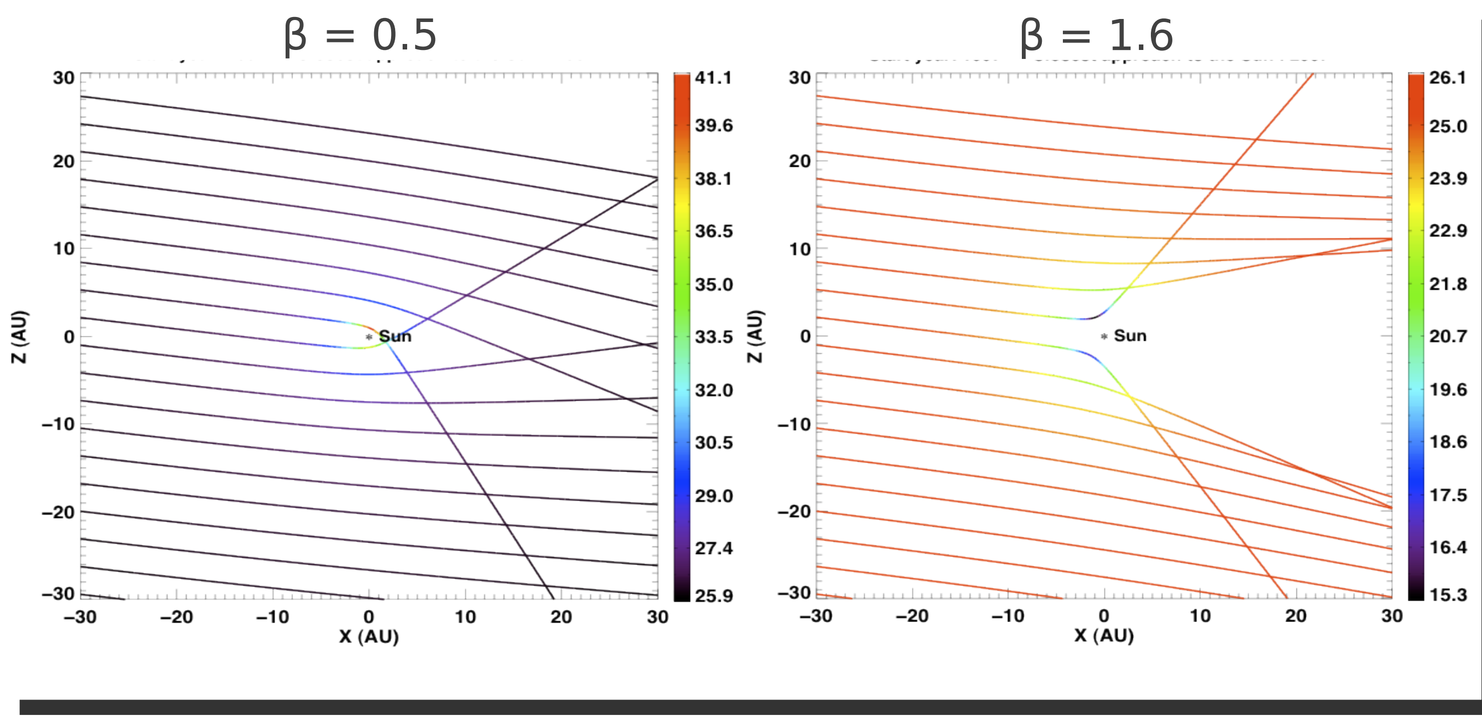
Current meteoroid models do not include stream structure in the dust cloud: No details about Meteoroid storms.

The IMEX Project:
Interplanetary Meteoroid Environment for eXploration

- What is the spatial and temporal distribution
  - in the interplanetary dust cloud due to **cometary trails/meteoroid streams**?
  - of **interstellar dust**?

The Interstellar Dust (ISD) Module

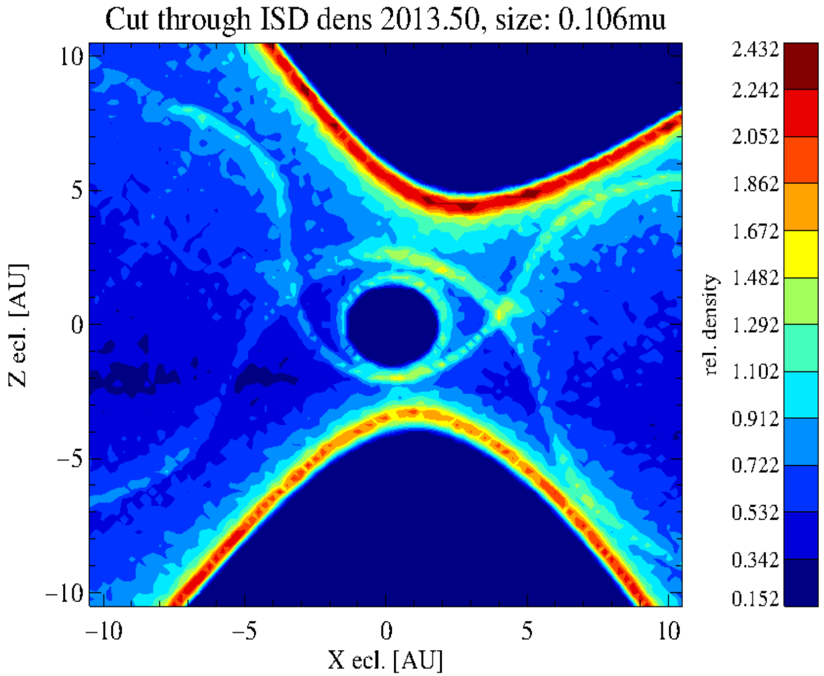
Purpose: Create ISD model that accounts for the time and space dependent movement of ISD grains with respect to solar radiation pressure and the interaction of charged grains with the heliosphere.

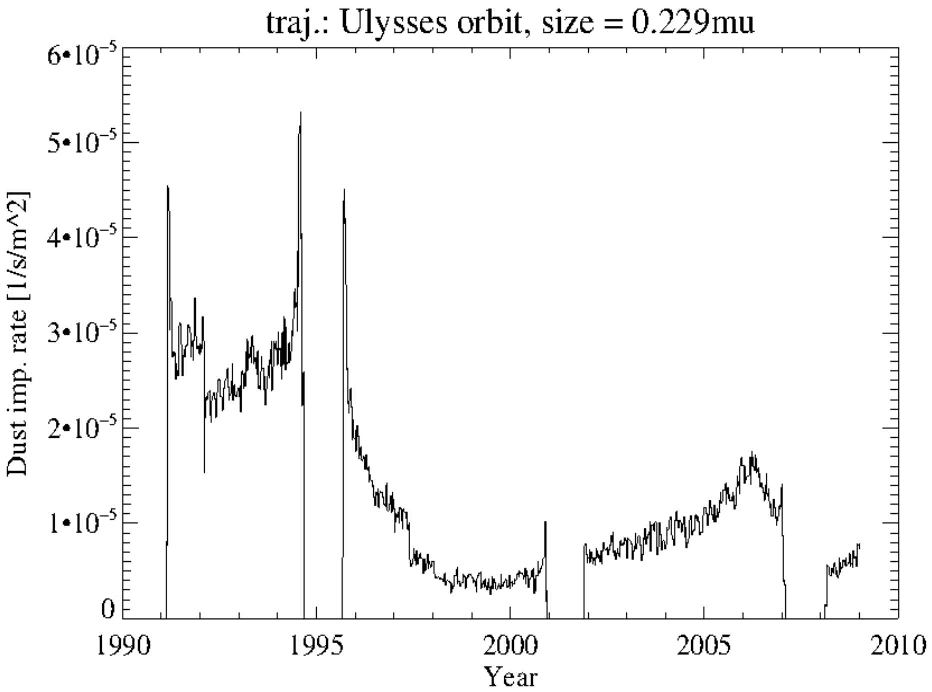


The Interstellar Dust (ISD) Module

Outcome: Time and space-dependent distributions for speed and direction of interstellar dust moving through the solar system

- Maps of the distribution of ISD dust in time and space
- The ISD flux and velocity along a spacecraft trajectory.

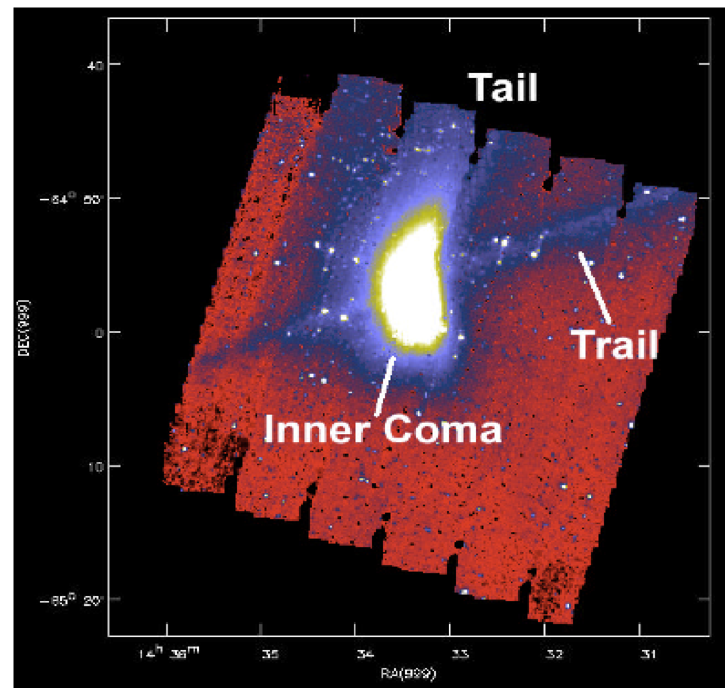




Meteoroid Streams Model

- **Purpose:** To develop a model that can define the risks to spacecraft from cometary trails/streams.
- **Output:** A model for the positions and velocities of recently released cometary grains >100 µm within the inner solar system.

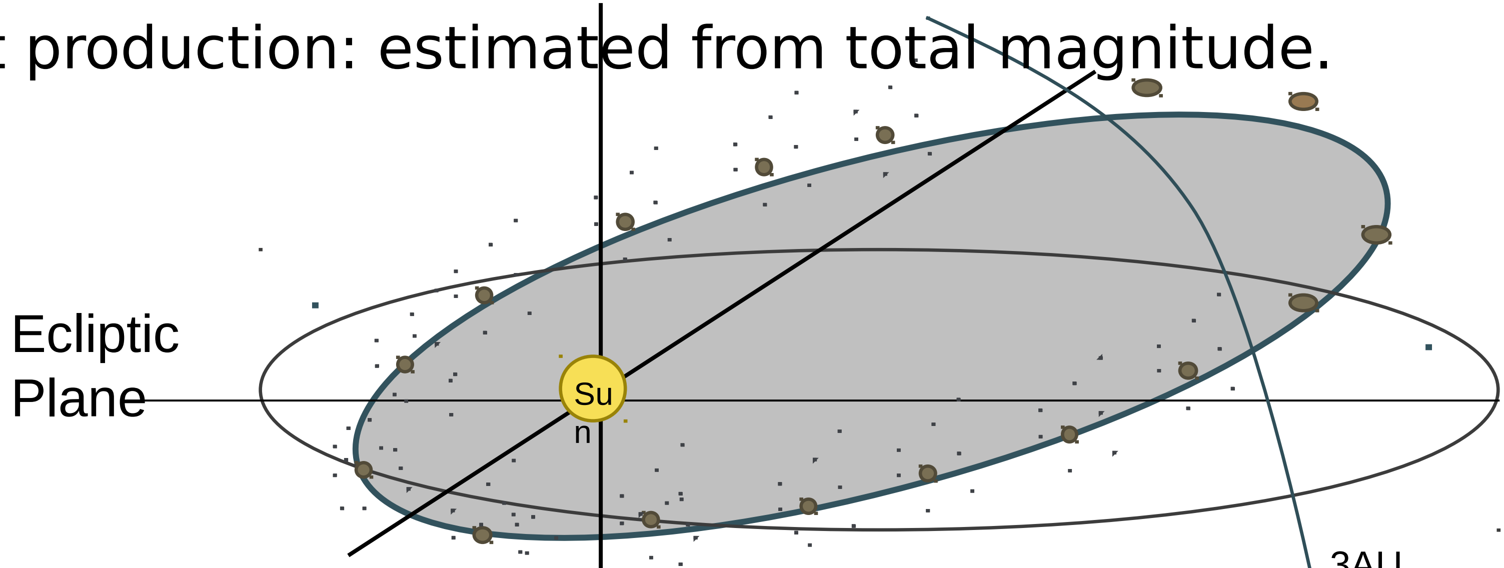
NASA/JPL



Reach et. al. (2000)

(1) Emitting dust particles

- **Input:**
  - Source: 428 short period comets
  - Timespan: 200-400 years
  - Emission velocity: Crifo and Rodionov (1997)
  - Emission: inwards of 3AU from sunlight hemisphere
- **Output:**
  - Number: around 0.33 million particles/ comet/ mass
  - Masses: 8 masses 100µm to 1cm.
  - Dust production: estimated from total magnitude.

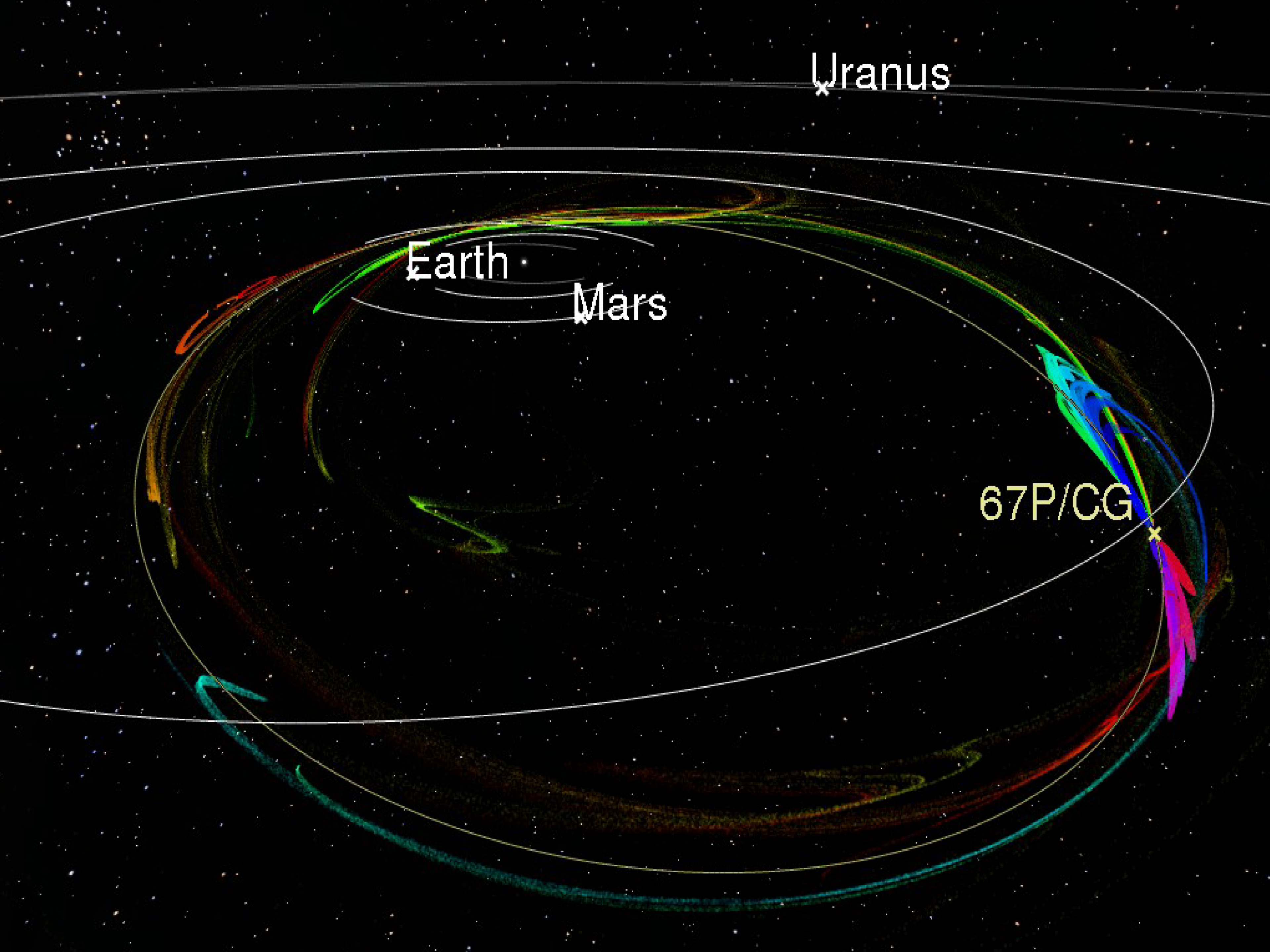


(2) Creating the meteoroid stream database

- **Orbit integration with Constellation (gravity and radiation effects)**
  - Distributed computing platform
  - Citizen science project: 12478 users with 57,521 PCs world wide
- **Database of cometary dust**
  - Each integrated particle saved several times per orbit between 1980-2080
- **Result: a database from which we can reconstruct the orbits of all stream particles from 428 comets.**

Constellation

Andreas Hornig and Lars Bausch:
aerospaceresearch.net

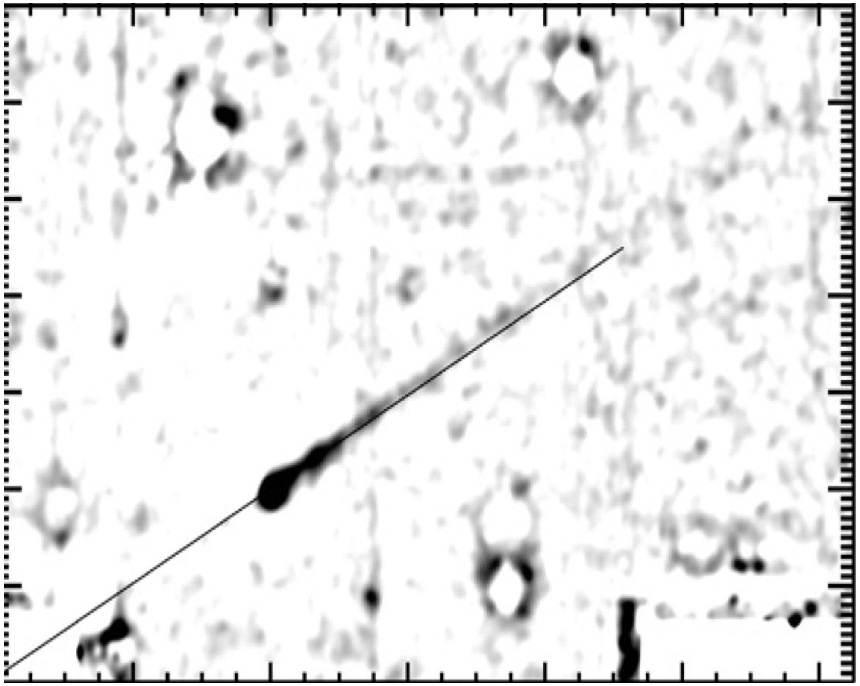

Uranus
Earth
Mars
67P/CG

The trail of comet Churyumov-Gerasimenko

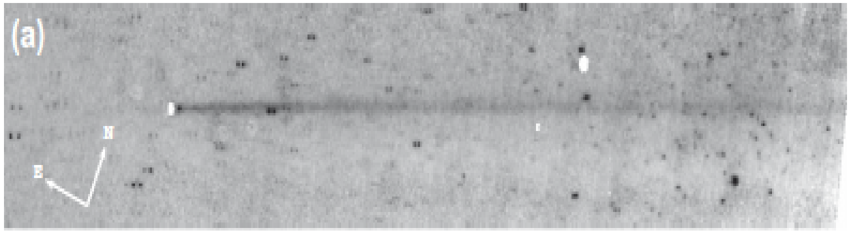
- IR observations of the trail of CG provide:
  - Dust particles ~mm sized
  - Mass loss at perihelion: 100-1000kg/s
  - Mass distribution of fairly typical comet.
  - Low ejection velocities

These parameters define the dust production of the comet

24µm Spitzer images



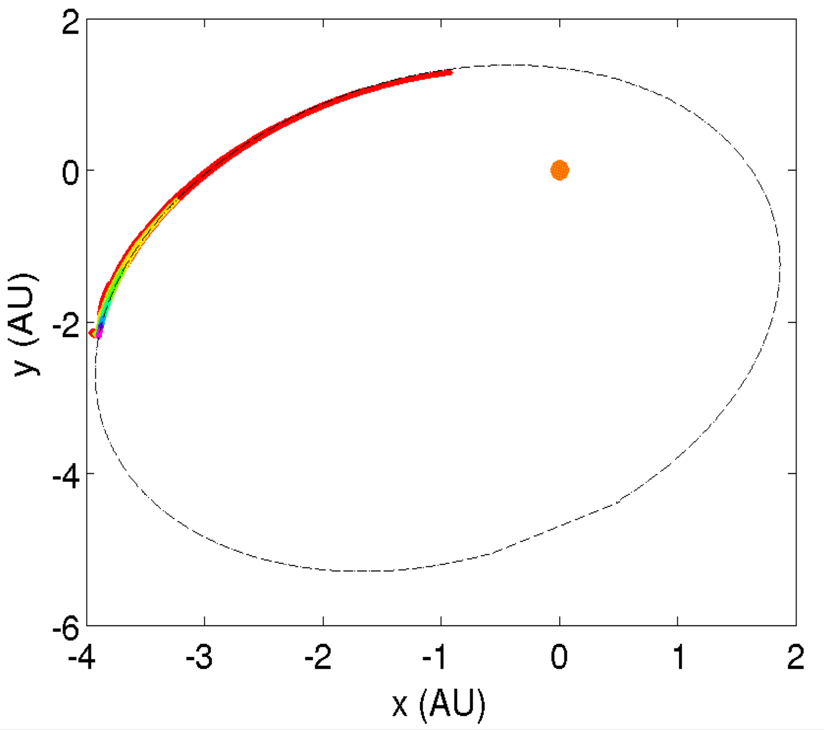
Kelley et. al. 2008: Feb 2004

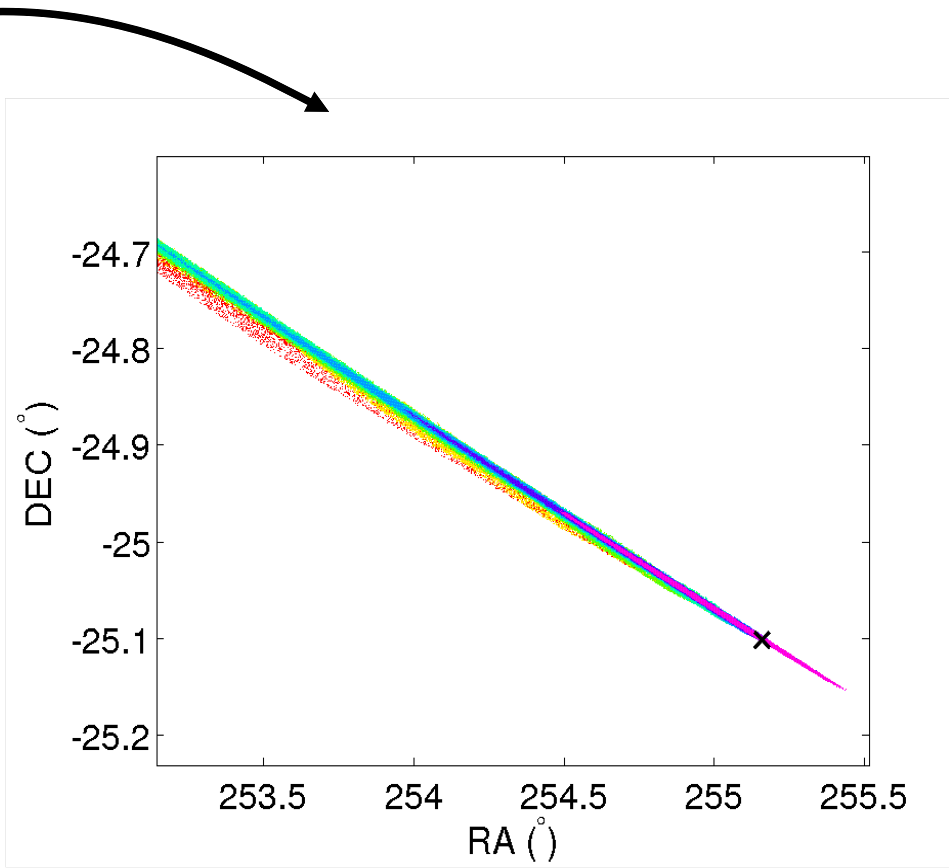


Agarwal et. al. 2010: Aug 2006

The trail of 67P/Churyumov-Gerasimenko

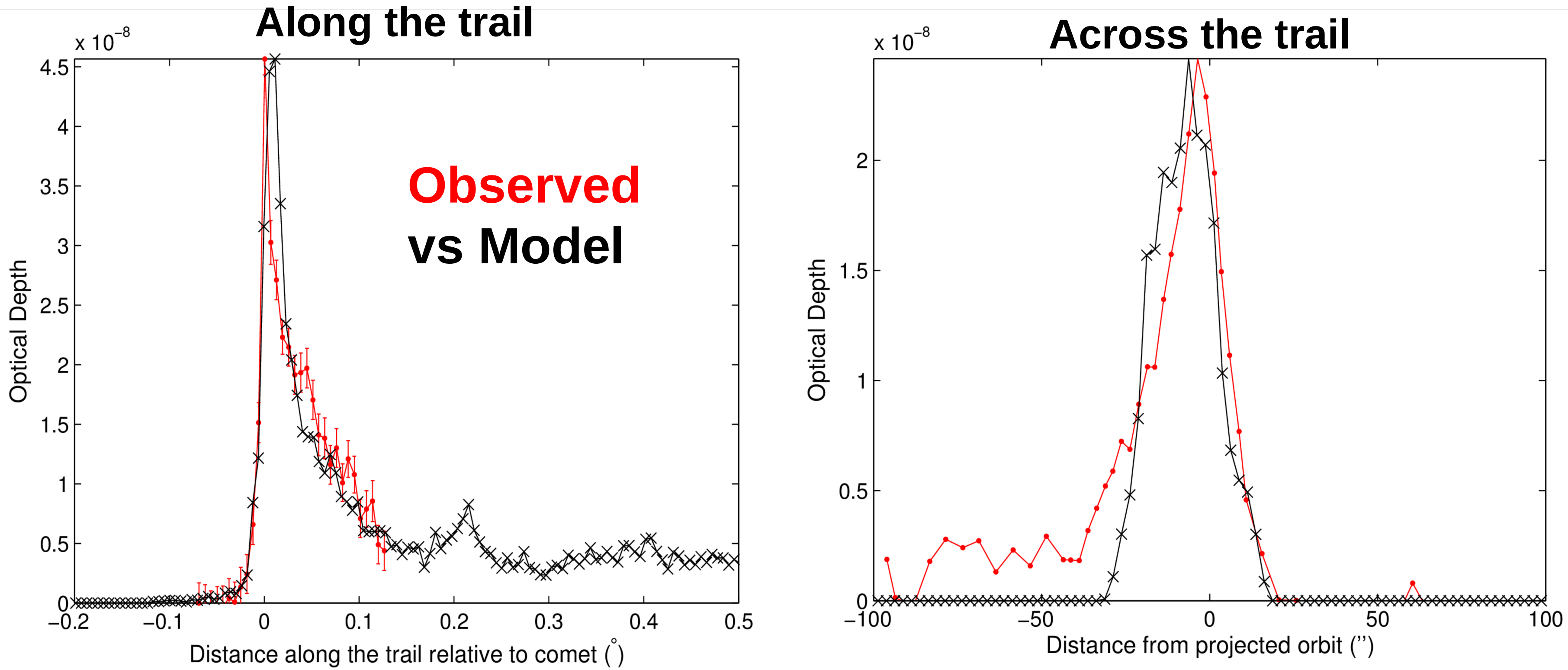
Modelled stream converted into a trail projected on the sky





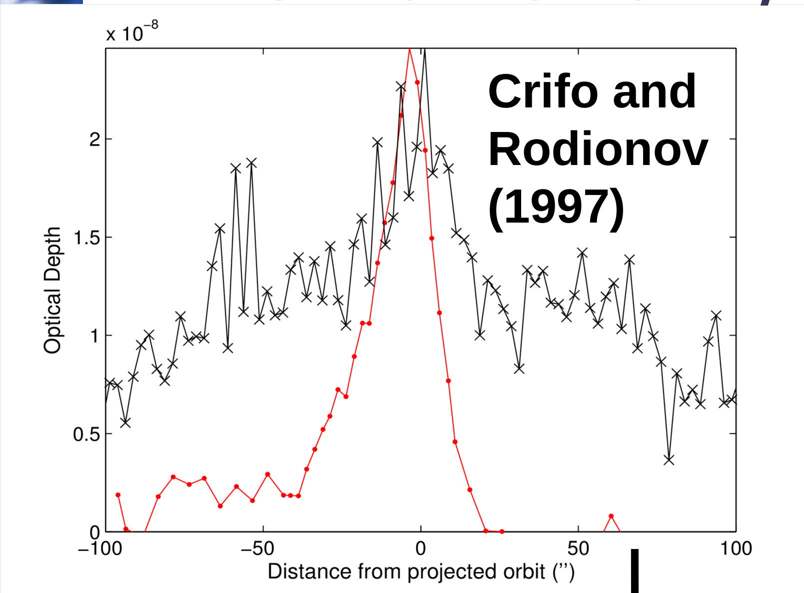
The trail of 67P/Churyumov-Gerasimenko

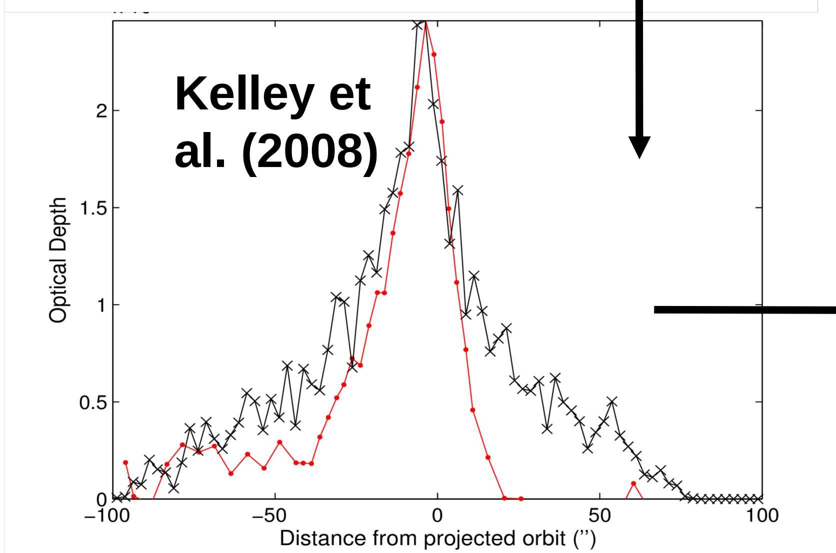
- **Brightness: matches when a high comet dust to gas ratio is used**
  - **Observations suggest dust to gas ratio 3-4**



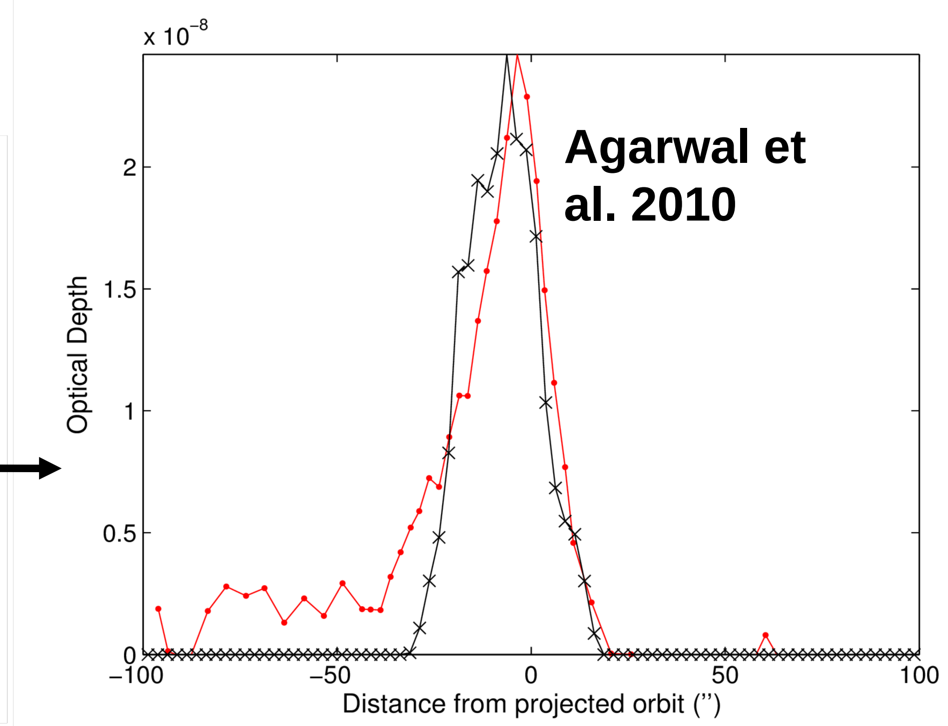
Kelley et al. 2008 Spitzer image

The trail of 67P/Churyumov-Gerasimenko





Trail width: matches when a low emission velocity is used

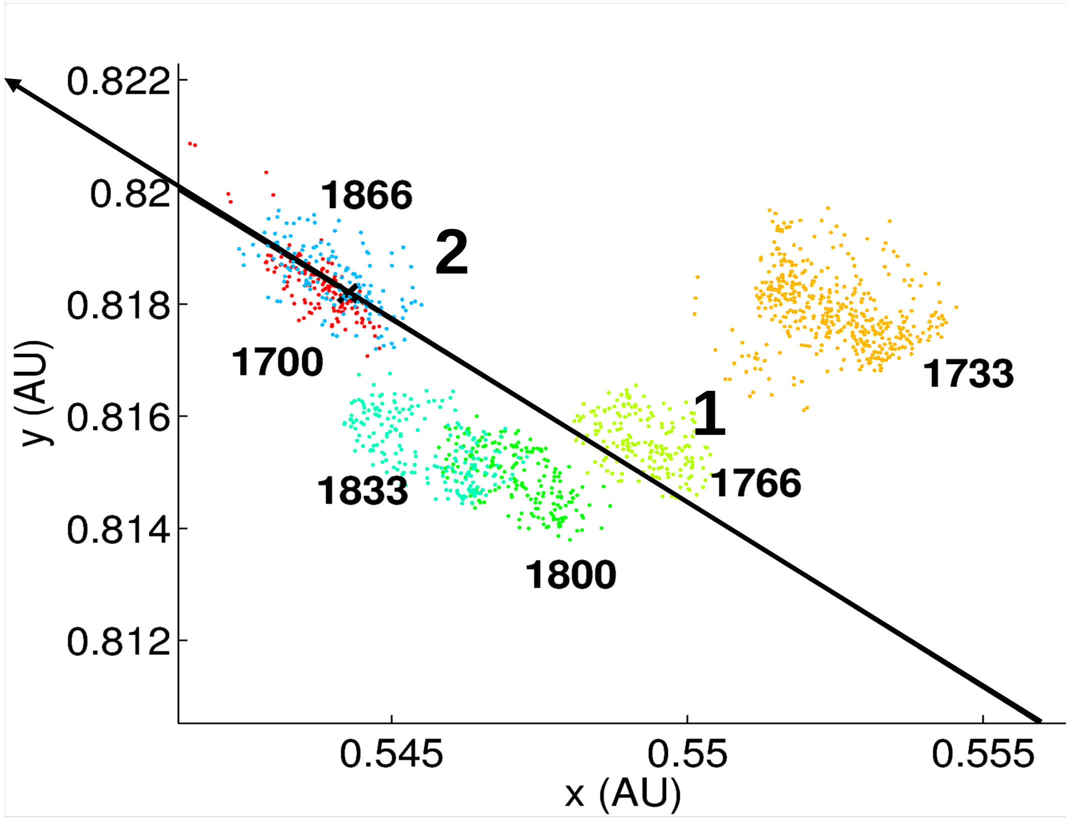


Observed vs Model

Kelley et al. 2008 Spitzer image

Meteor Storms

- Comet: **55P/Tempel-Tuttle**
- Shower: **Leonids**
- Apparitions: **1690-1998**
- Observation to compare: at Earth in **2001**

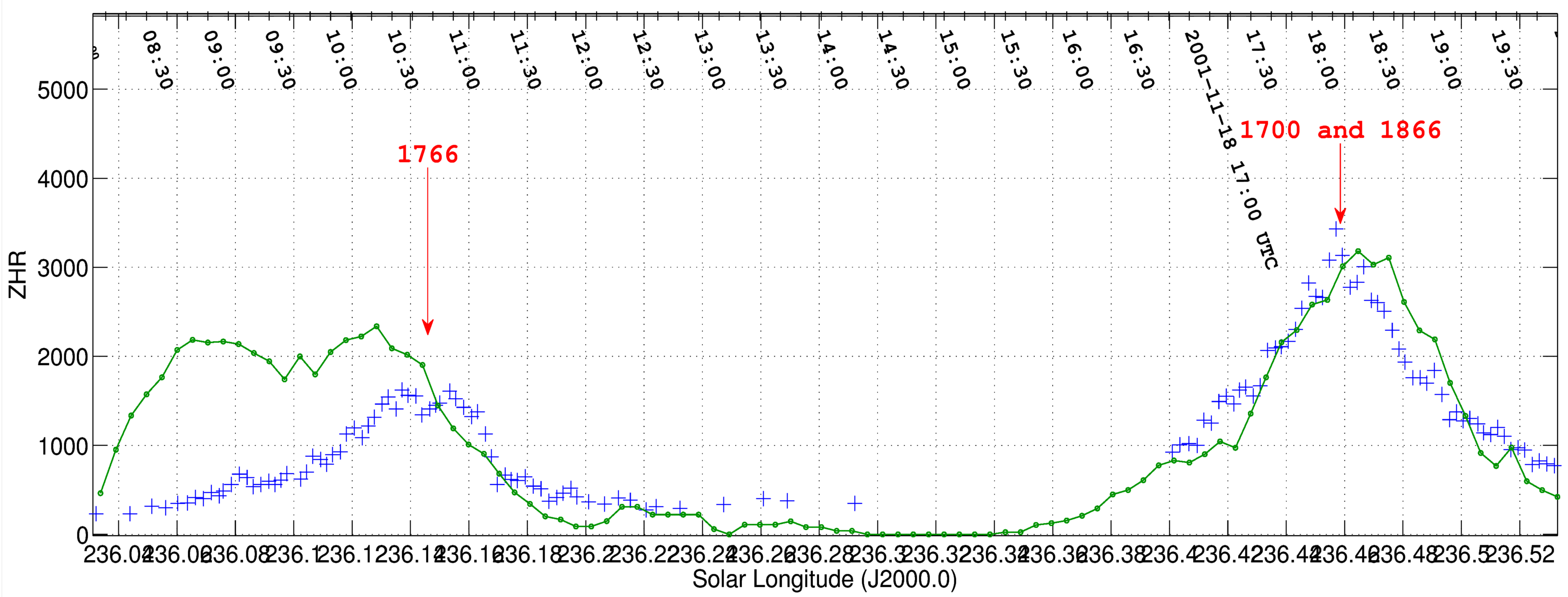


1) Earth impacts 1766 stream

2) Earth impacts 1700 and 1866 streams

Meteor Storms

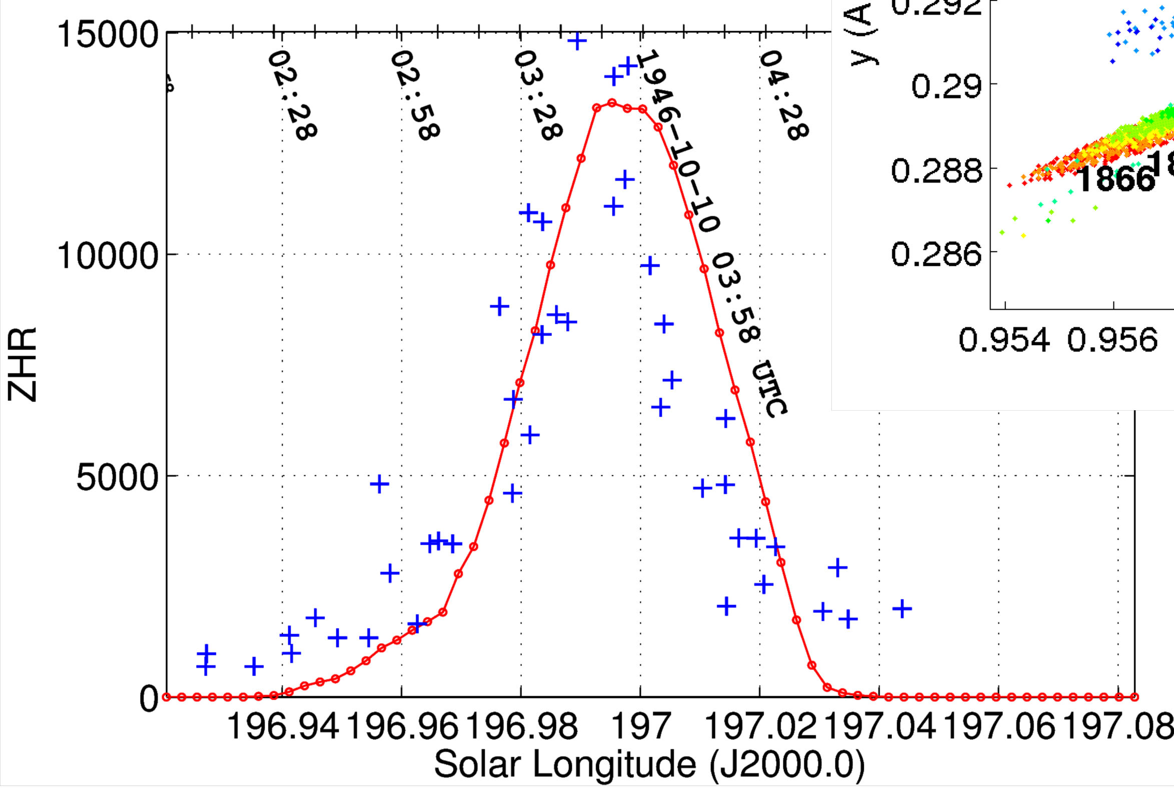
ZHR profiles for Leonids in 2001:
We can predict the time and flux of meteor storms.

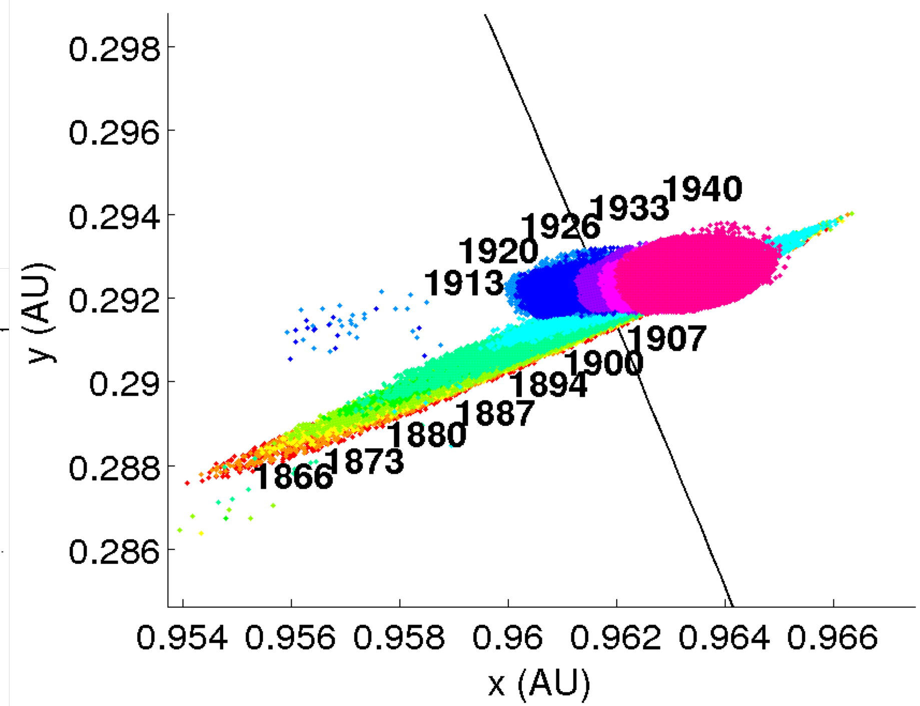


Observed vs Modelled

Meteor Storms

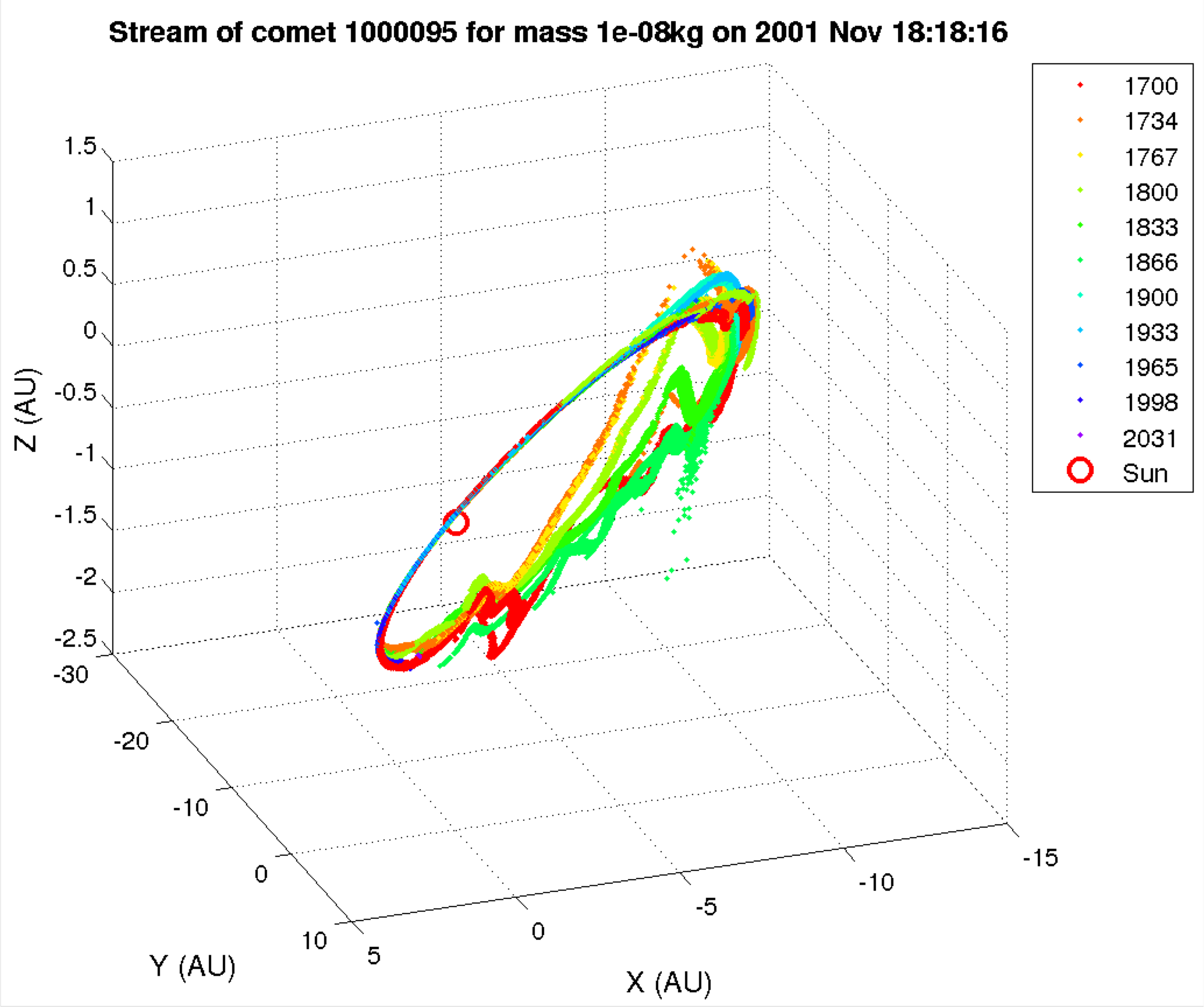
Draconids 1946:
Our reconstruction of activity is better for stronger streams



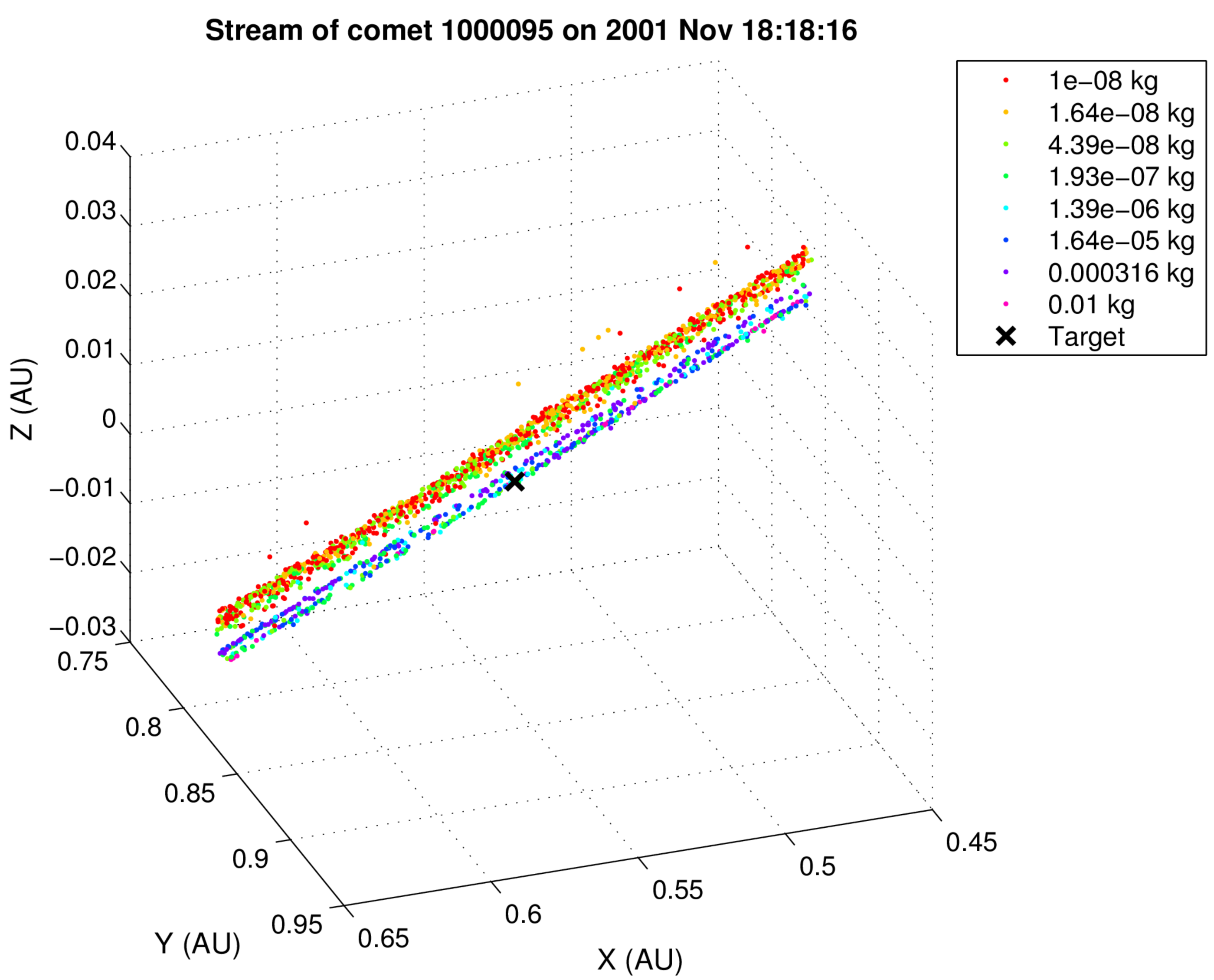


All using velocity model of Crifo and Rodionov (1997)

55P/Tempel-Tuttle (heliocentric)

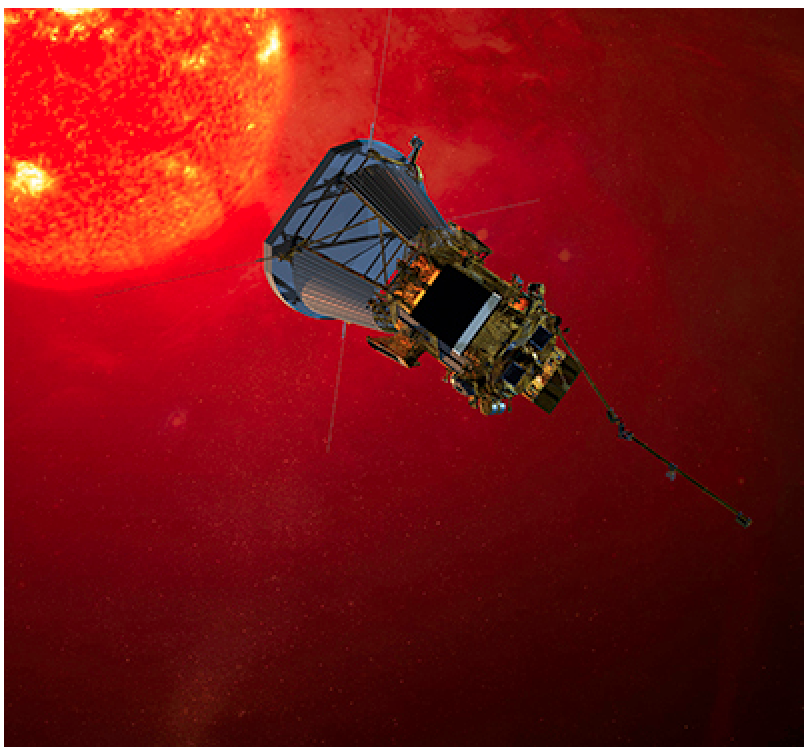


55P/Tempel-Tuttle (at Earth)

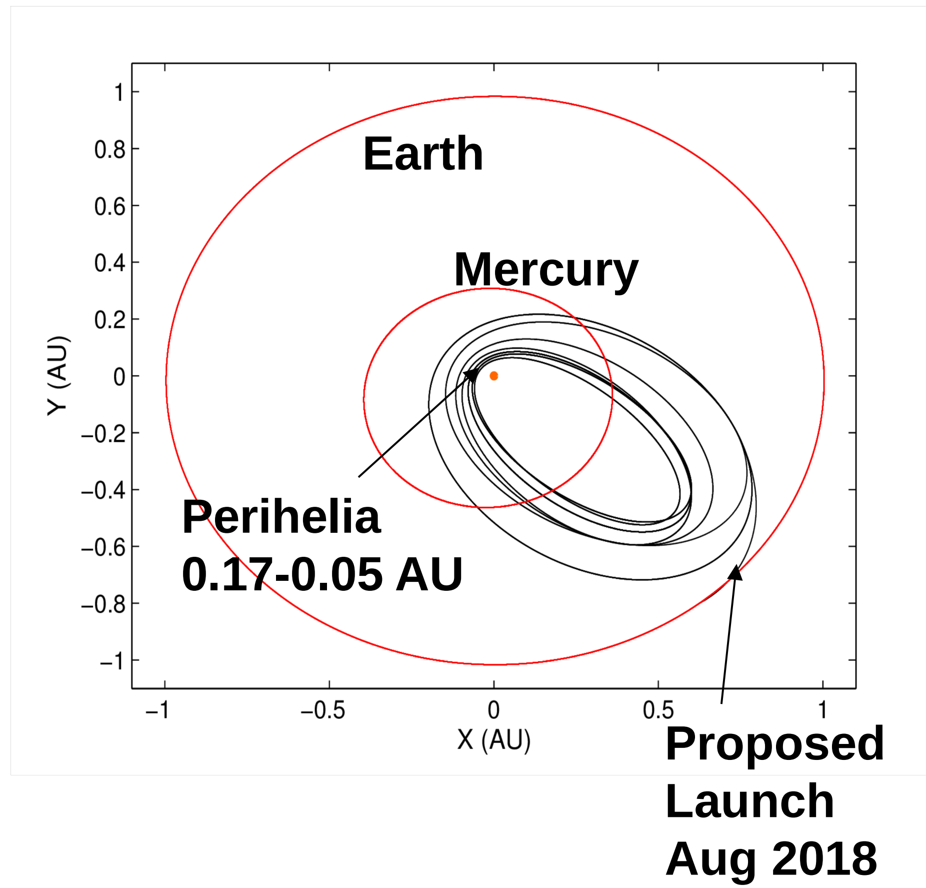


Streams at Solar Probe Plus

Use IMEX to analyse streams at NASA's proposed near-Sun mission



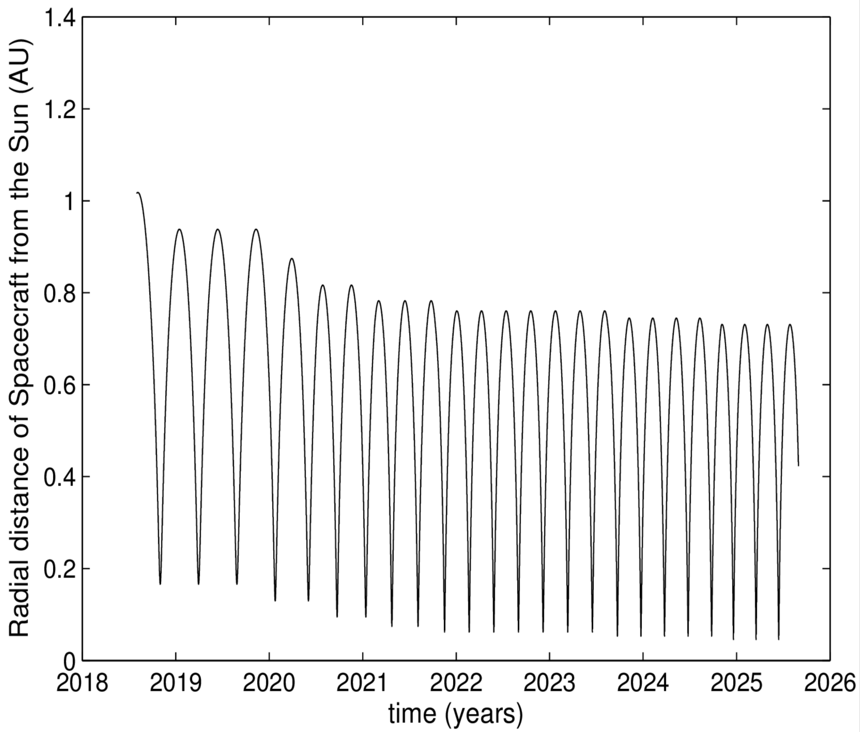
NASA/Johns Hopkins University Applied Physics Laboratory



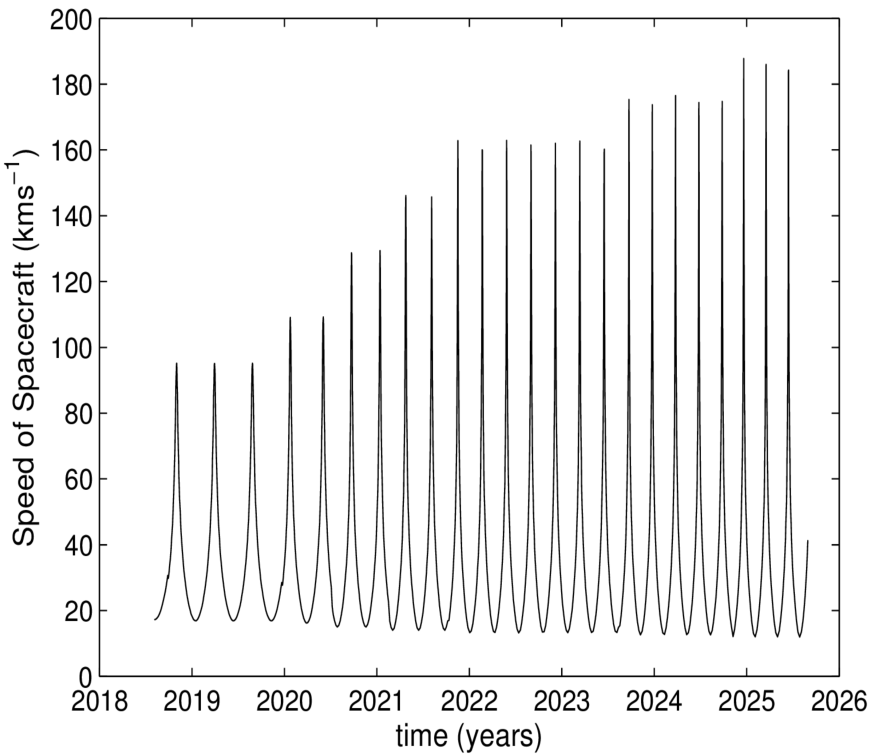
Streams at Solar Probe Plus

Use IMEX to analyse streams at NASA's proposed near-Sun mission

Radial distance



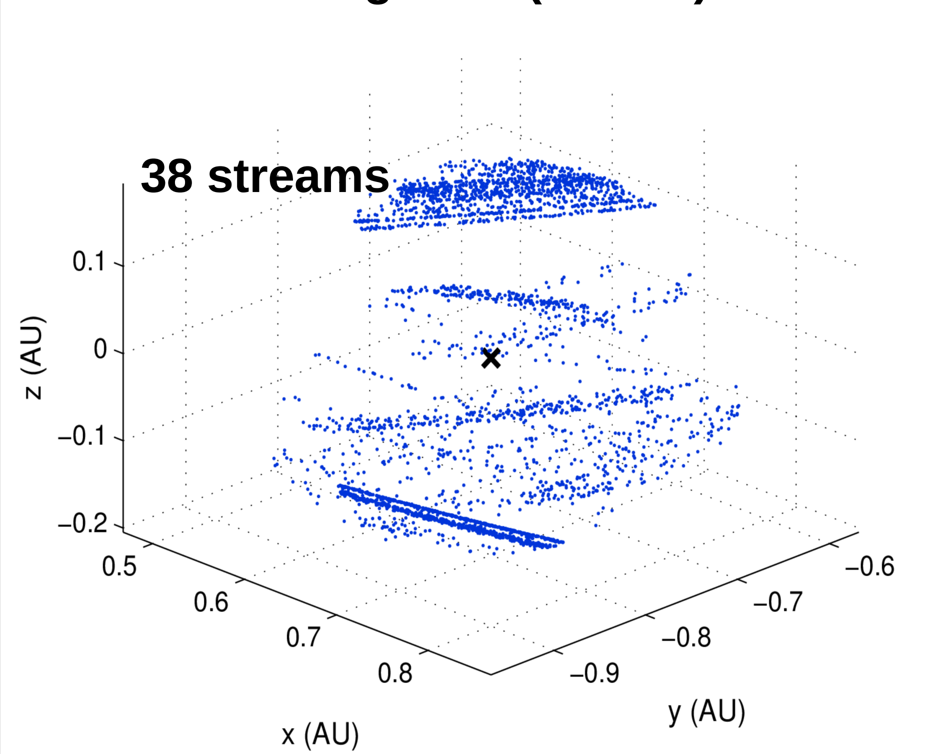
Speed



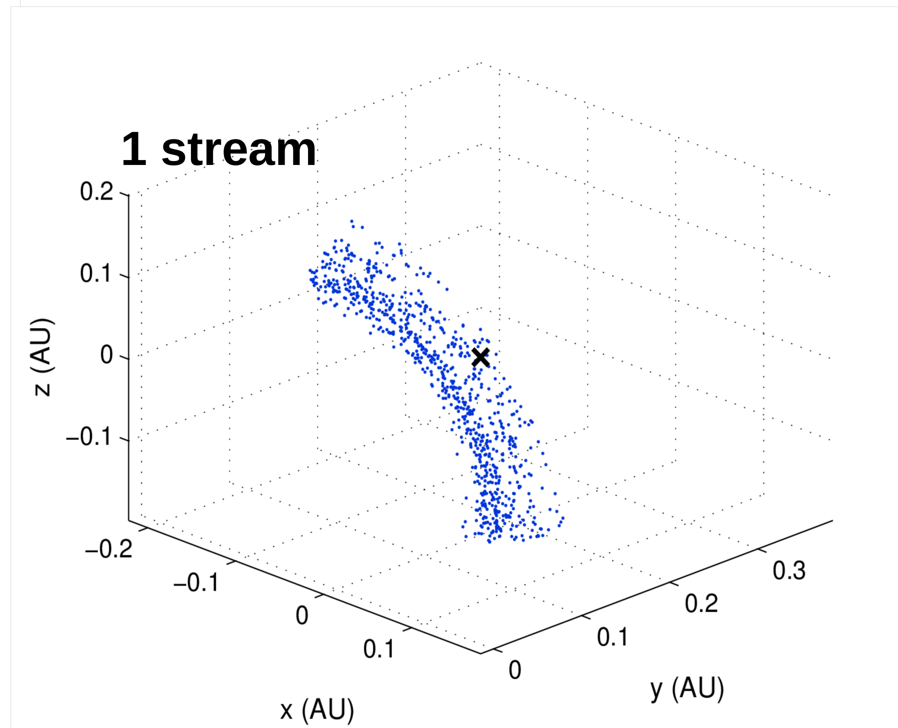
Streams at Solar Probe Plus

(1) Simple Kepler Model: Determine the streams within 0.2AU of Solar Probe Plus

1 Aug 2018 (at 1AU)

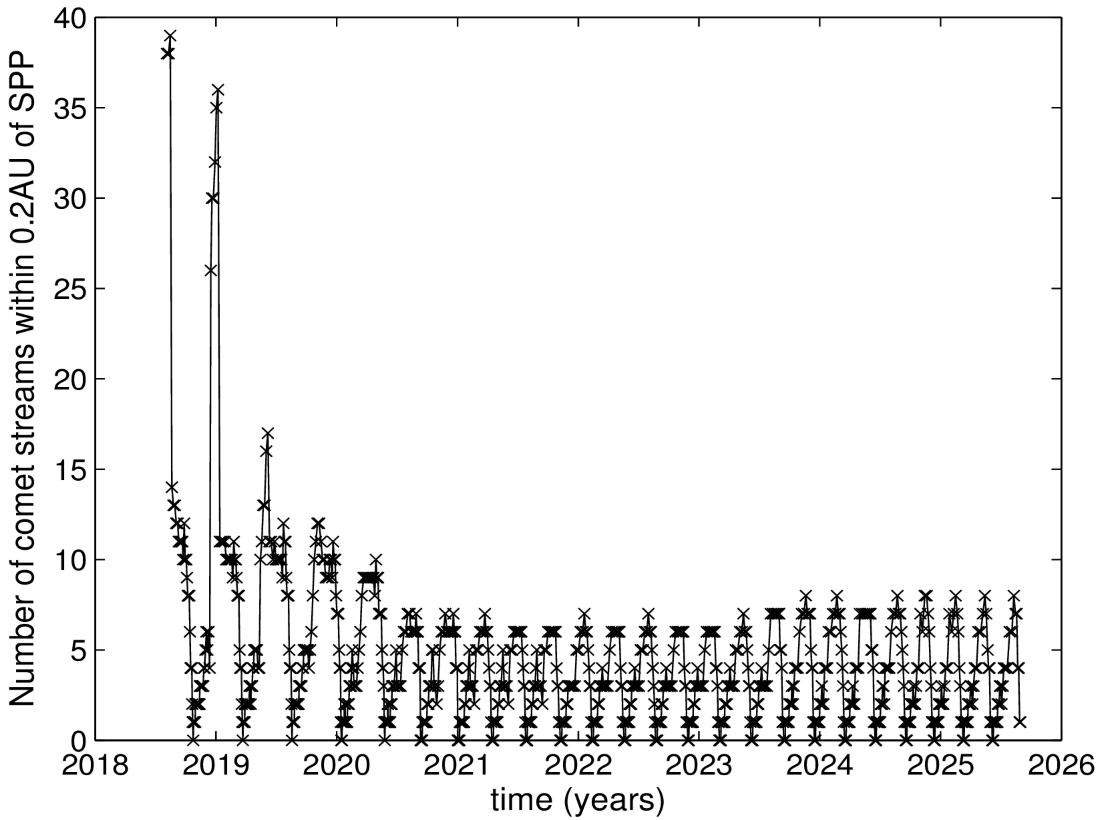


30 Oct 2018 (at perihelion)



Streams at Solar Probe Plus

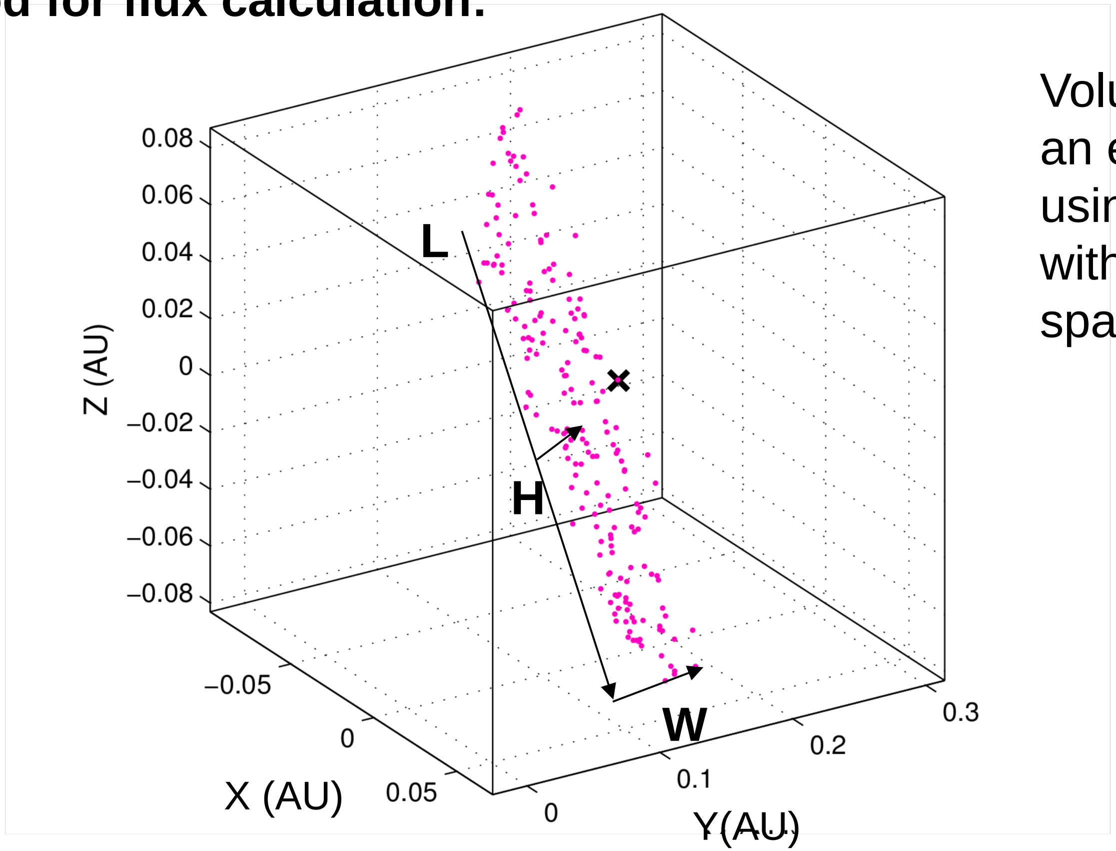
(1) Simple Kepler Model: Determine the streams within 0.2AU of Solar Probe Plus



Streams at Solar Probe Plus

(2) Fully integrated trajectories: Determine the streams **at** Solar Probe Plus

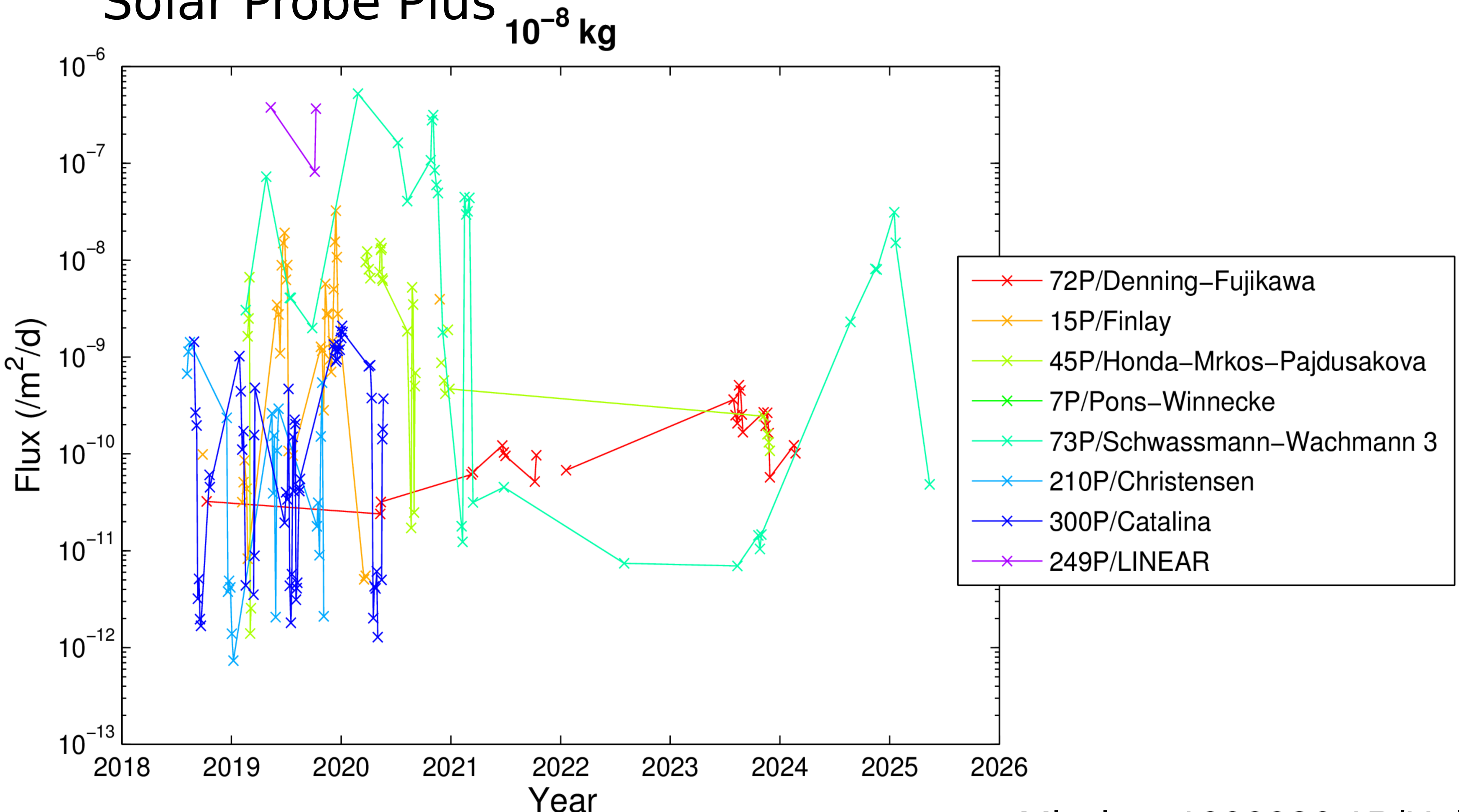
Method for flux calculation:



Volume calculated as an elliptical cylinder using trail dimensions within 0.1AU of the spacecraft

Streams at Solar Probe Plus

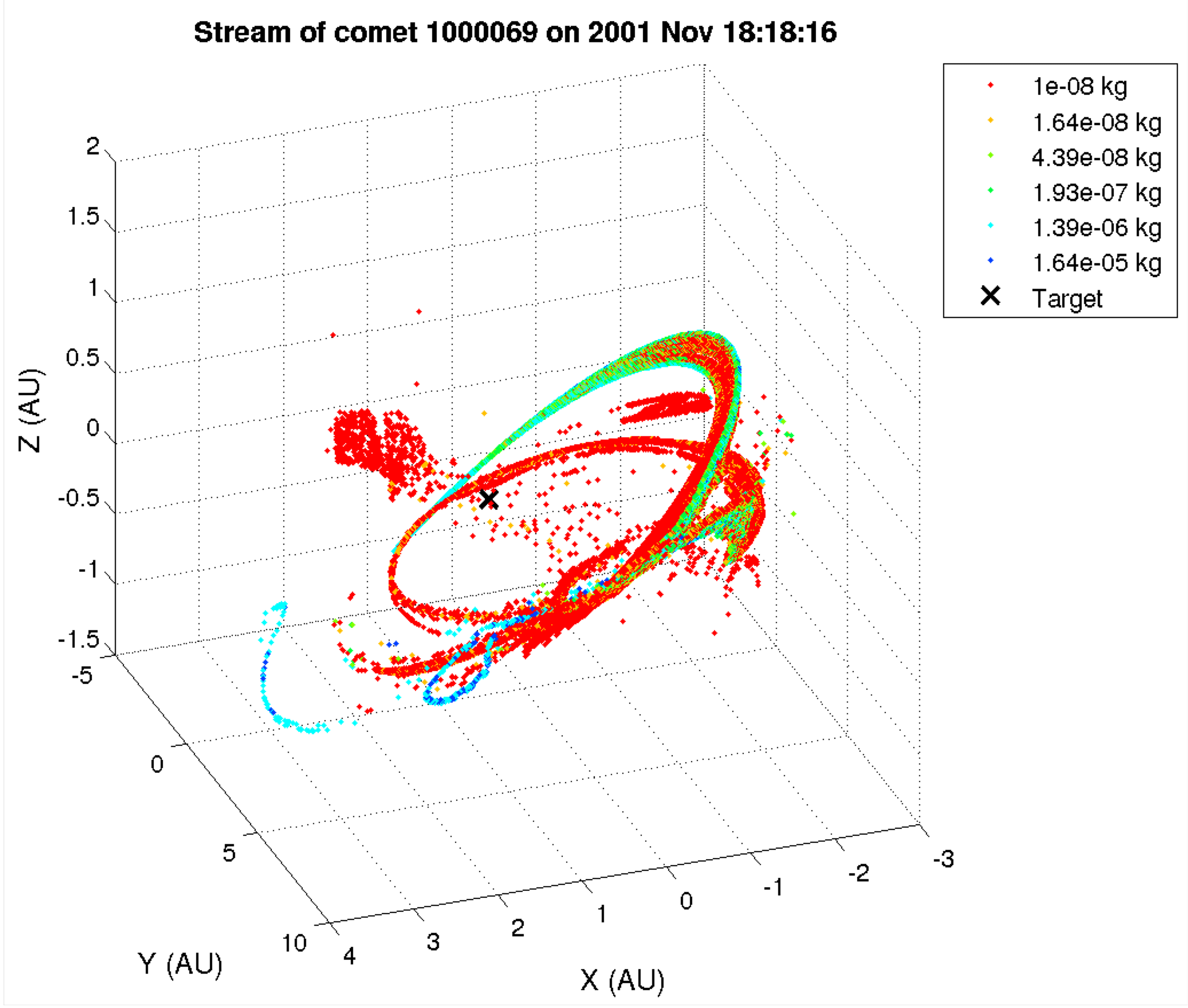
(2) Fully integrated trajectories: Determine the streams **at** Solar Probe Plus



Missing: 1000036 1P/Halley

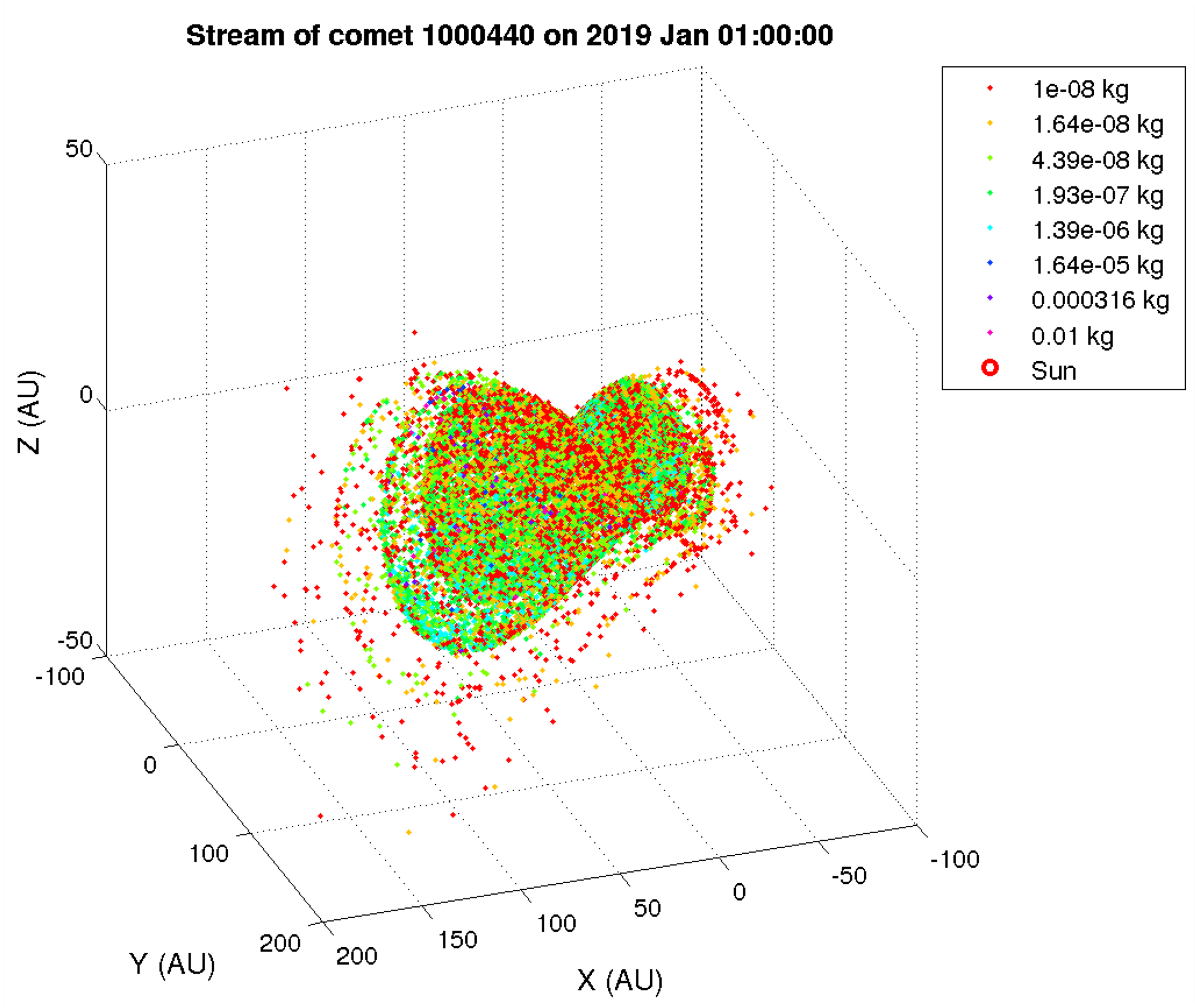
Streams at Solar Probe Plus

7P/Pons-Winnecke



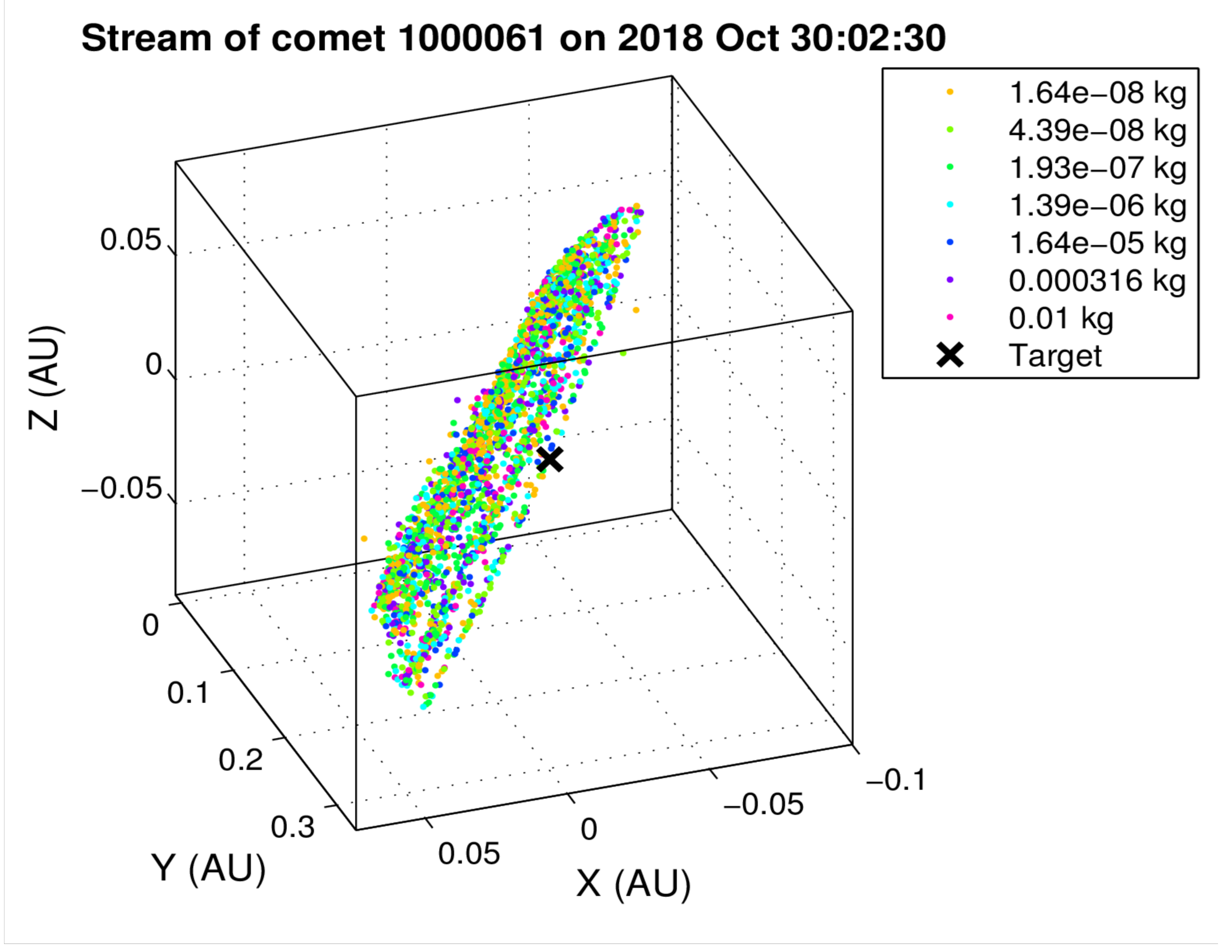
Streams at Solar Probe Plus

210P/Christensen



Streams at Solar Probe Plus

(3) Evaluating the Results: How dangerous is the dust from comet 96P/Machholz 1 in October 2018?



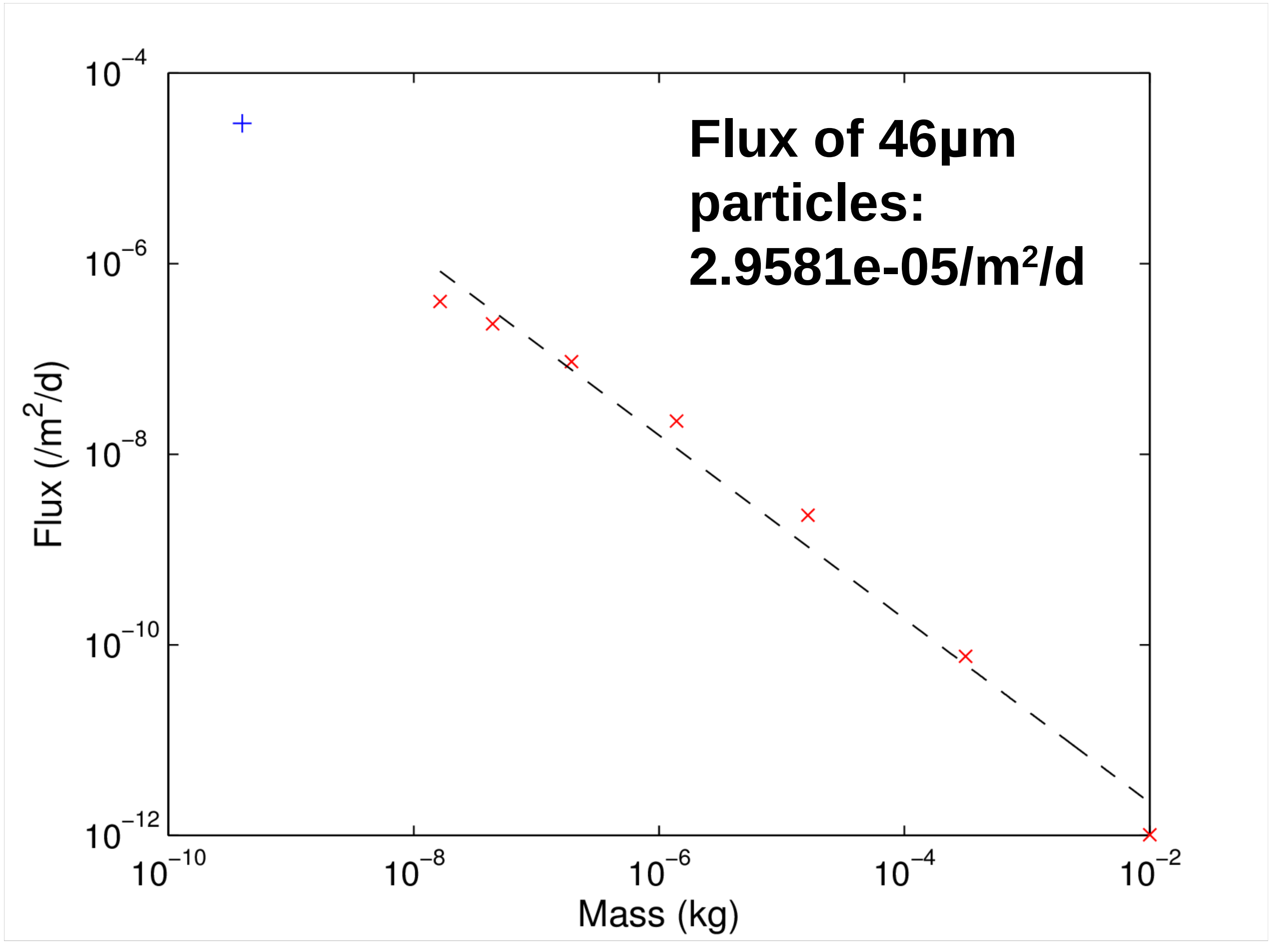
Streams at Solar Probe Plus

(3) Evaluating the Results: How dangerous is the dust from comet 96P/Machholz 1 in October 2018?

- **The dust speed is high:**
  - 95-100km/s
  - A 46micron grain at this speed has the same kinetic energy as a 100micron grain at 20km/s.
- **Even large particles are present at the spacecraft**
  - 1.64×10^{-8}kg – 10^{-2}kg (160µm – 1.3cm)
- **The time the spacecraft spends within the stream is low:**
  - About 8hours
- **The flux is not high (10^{-12} – 10^{-7}), but much smaller particles can create damage at these speeds**

Streams at Solar Probe Plus

(3) Evaluating the Results: How dangerous is the dust from comet 96P/Machholz 1 in October 2018?



Streams at Solar Probe Plus

(3) Evaluating the Results: How dangerous is the dust from comet 96P/Machholz 1 in October 2018?

- **The impact probability of 46μm particles is 0.001%:**
  - 1 in 100,000 chance of a hit (per m^2)
- **The impact probability of 4μm particles is 1%:**
  - 1 in 100 chance (per m^2) (spacecraft bus diameter 1m).
- **IADC Protection manual:**
  - 1 in $5x10^7$ chance of an impact that can penetrate the 15cm thick thermal shield (area about $5.81m^2$)
  - 1 in 6000 chance of an impact that can shatter the solar cell glass (for area $3.4x10\text{-}3m^2$)
- **What is the accuracy of our model prediction?**
  - **Non-gravitational perturbations:** not included
  - **Emission velocity:** highly unknown

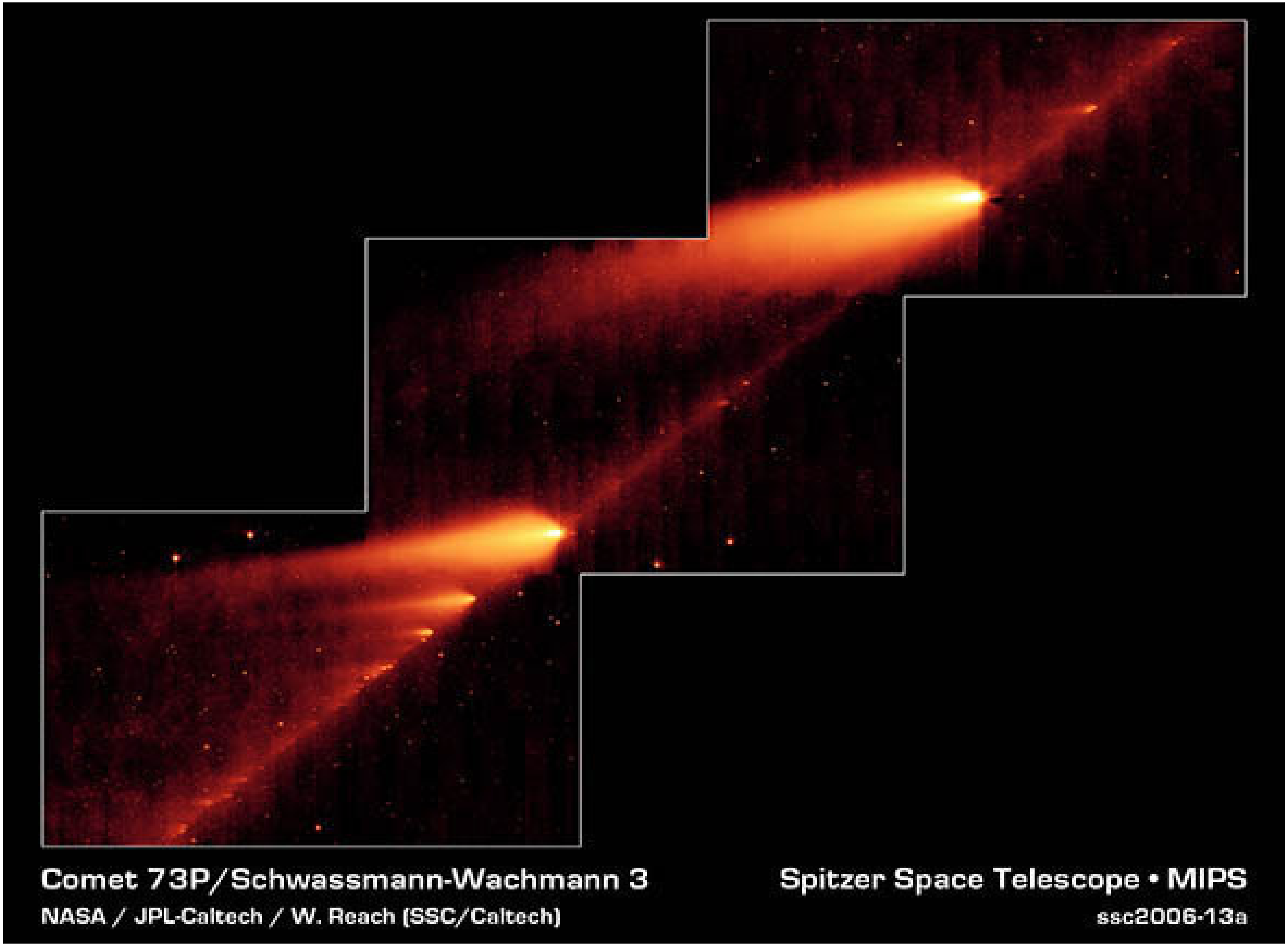
Conclusions

- **The MEM and IMEM models are in serious disagreement.**
  - Also does not include all the available data.
- **IMEX extends IMEM by considering dust streams in space by**:
  - Determining the input to the meteoroid cloud from Jupiter Family, Encke type and Halley type comets.
  - Calculating the orbital evolution of these meteoroids.
  - Improving the interpretation of meteor and comet trail observations.
  - Providing estimates of the temporal and spatial variations of the meteoroid flux in the solar system inside Jupiter's orbit.
- The interstellar dust flux is scientifically highly interesting but it poses no risk to manned space activity.

Further Development of the IMEX model

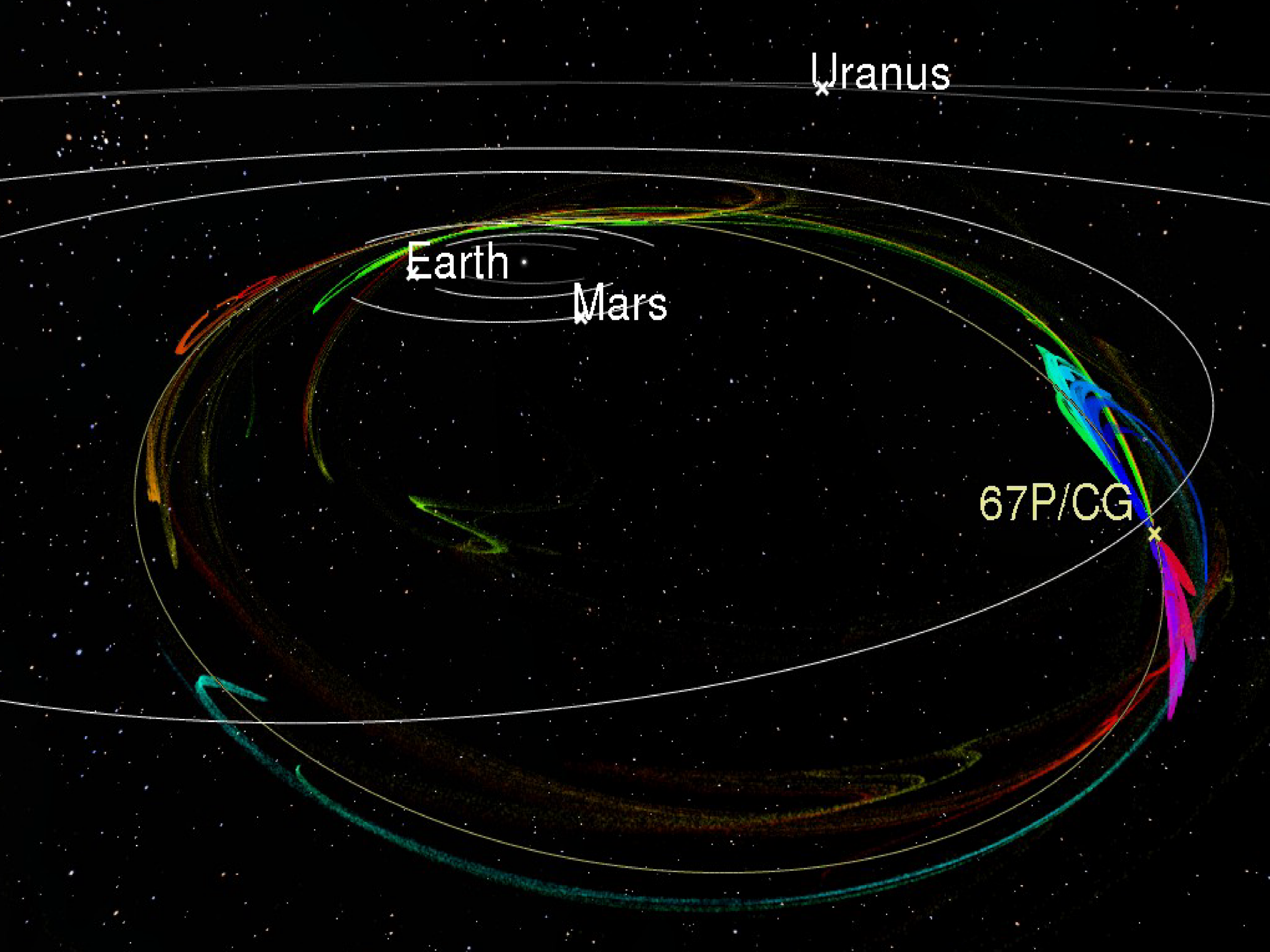
- **Improvement of comet orbits**
  - Non-gravitational forces
- **Additional objects**
  - As new comets are discovered, and their orbits improved
  - Asteroids
- **Improvement of emission physics**
  - Emission velocities
  - Dust production rates and characteristics
  - Can be updated for individual cases (e.g., 67P/C-G)

New comet trails



Future Development:
Towards a new model of the interplanetary dust cloud

- **The MEM and IMEM models are in serious disagreement.**
- **An update of the IMEM model is required, to add new physics and include more data**
- **This could be based on the IMEX model**:
  - Characterise the interplanetary background dust cloud over 100,000 years
  - Including meteor data and thermal background emission
  - Impact hazard assessment for particles 1µm-1mm in size


Uranus
Earth
Mars
67P/CG