

METEOR OBSERVATIONS OF INTERSTELLAR PARTICLES

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Slovak Academy of Sciences
Bratislava, Slovakia



1. INTERSTELLAR PARTICLES

2. HYPERBOLIC ORBITS

Discovery of interstellar dust in the Solar System

1993

LETTERS TO NATURE

Discovery of jovian dust streams and interstellar grains by the Ulysses spacecraft

E. Grün, H. A. Zook*, M. Baguhl, A. Balogh†,
S. J. Bame‡, H. Fechtig, R. Forsyth§, M. S. Hanner§,
M. Horanyi||, J. Kissel, B.-A. Lindblad¶, D. Linkert,
G. Linkert, I. Mann*, J. A. M. McDonnell**,
G. E. Morfill††, J. L. Phillips, C. Polanskey§,
G. Schwehm†‡, N. Siddique, P. Staubach,
J. Svestka§ & A. Taylor*
Max-Planck-Institut für Kernphysik, 6900 Heidelberg, Germany
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|| University of California, Los Alamos,

TABLE I Dust burst characteristics						
Days from CA	-67.7	-32.1	31.4	59.8	66.9	117.4
Date (yr/d)	93/346	92/7	92/71	92/99	92/126	92/157
Duration (h)	4.7	6.8	25.0	43.4	19.8	16.3
Number of particles	3	6	124	7	4	4
Mass range ($\times 10^{-15}$ g)	3.6	0.1–7	1.90	2.9	6.20	3.4
Mean mass ($\times 10^{-15}$ g)	4	3	9	4	9	4
Speed range (km s ⁻¹)	28–37	27–56	28–44	28–44	20–37	28–37
Mean speed (km s ⁻¹)	35	37	42	33	29	30
Mean rotation angle	201°	211°	51°	54°	24°	32°
Distance to Sun (AU)	4.93	5.14	5.60	5.39	5.38	5.36
Distance to Jupiter (R_J)	995	562	563	1025	1480	1950

(a) The time corresponds to the centre of the burst. Closest approach (CA) to Jupiter occurred at 12:39.5. The definition of stream particles and hence the number of members is somewhat arbitrary, but here it refers only to small mass ($>5 \times 10^{-15}$ g) and collimated ($\pm 70^\circ$ from mean rotation angle) particles. Jupiter radius, $R_J = 71,400$ km.

The Ulysses dust detector is a multi-coincidence impact ionization detector with a sensitivity 10⁶ times higher than any dust detector in the outer Solar System. Masses and speeds are determined from the charge signals.

Discovery of interstellar dust in the Earth's atmosphere

1996

LETTERS TO NATURE

Discovery of interstellar dust entering the Earth's atmosphere

A. D. Taylor*†‡, W. J. Baggaley§ & D. I. Steel**

* Department of Physics and Mathematical Physics, University of Adelaide, SA 5005, Australia

† Unit for Space Sciences, University of Kent, Canterbury, UK

§ Department of Physics and Astronomy, University of Canterbury, Christchurch, New Zealand

|| Anglo-Australian Observatory, Private Bag, Coonabarabran, NSW 2537, Australia

All known asteroids and comets are believed to have been gravitationally bound to the Sun since they formed (together with the Sun and planets) from the solar nebula. This is because no such object has been observed with a speed exceeding the solar escape velocity, although some comets have been close to this limit¹. As comets are occasionally ejected from the Solar System, interstellar comets might be expected to arrive every few centuries, having been ejected from similar systems around other stars². The flux of interstellar dust into the Solar System should be much higher, but its detection poses significant technological challenges. Recently, the Ulysses spacecraft detected a population of dust particles near Jupiter, identified as being of interstellar origin on the basis of their speeds and trajectories^{3,4}. Here we report the radar detection of interstellar particles in the Earth's atmosphere. From intra-annual variations in particle flux, we infer the existence of two discrete sources, one associated

with criteria applied⁵. Comparison between Fresnel and time-lag speed determinations for meteors with $V < 50$ km s⁻¹ leads to an estimated uncertainty $\sigma \approx 6$ km s⁻¹ in the speeds near $V = 73$ km s⁻¹, a value substantiated by inspection of the measured speeds in the ~ 65 km s⁻¹ η -Aurigid shower^{6,7}. The data set therefore comprises meteors with speeds $>3\sigma$ above any possible bound Solar System orbit. This means that an ISP whose real (not measured) geocentric speed was $v = 90$ km s⁻¹ would not have been gathered into the data set used here unless its speed was erroneously measured as being $V > 100$ km s⁻¹; thus the majority of ISPs were probably excluded from the data set analysed but this was necessary in order to exclude mis-measurements of meteoroids from bound orbits. The mean speed for this ISP data set is $V \approx 164$ km s⁻¹ with an uncertainty of ± 30 km s⁻¹, in agreement with a crude estimate of $V \approx 140$ km s⁻¹ derived solely from their mean ionization height⁷.

The meteoric ionization produced is a strong function of speed, so ISPs near our limiting magnitude ($M_{lim} = 12.5$) will be smaller than the typically ~ 100 μ m meteoroids from bound orbits we detect. Verniani^{8,9} determined an empirical relation $q = 0.0509 m^{0.92} v^{1.91}$ between the mass (m in g), the speed (v in m s⁻¹), and the electron line density (q , electrons per metre). Our M_{lim} corresponds to $q = 2.5 \times 10^{11}$ m⁻¹. At $v = 100$ km s⁻¹ the diameter of the smallest detectable meteoroid (assumed spherical with density 1 g cm⁻³) is ~ 40 μ m; at $v = 200$ km s⁻¹ it is ~ 15 μ m. Far-infrared observations require a substantial ~ 30 - μ m interstellar grain component¹⁰, and Pioneer 10 and 11 dust impact data, indicating a constant flux at heliocentric distances from 3 to 18 AU, have been interpreted as being due to ~ 10 - μ m interstellar grains penetrating the Solar System¹¹. Interstellar particles of order tens of micrometres are therefore not unexpected. Our data set displays strong seasonal variations (Fig. 1), arguing

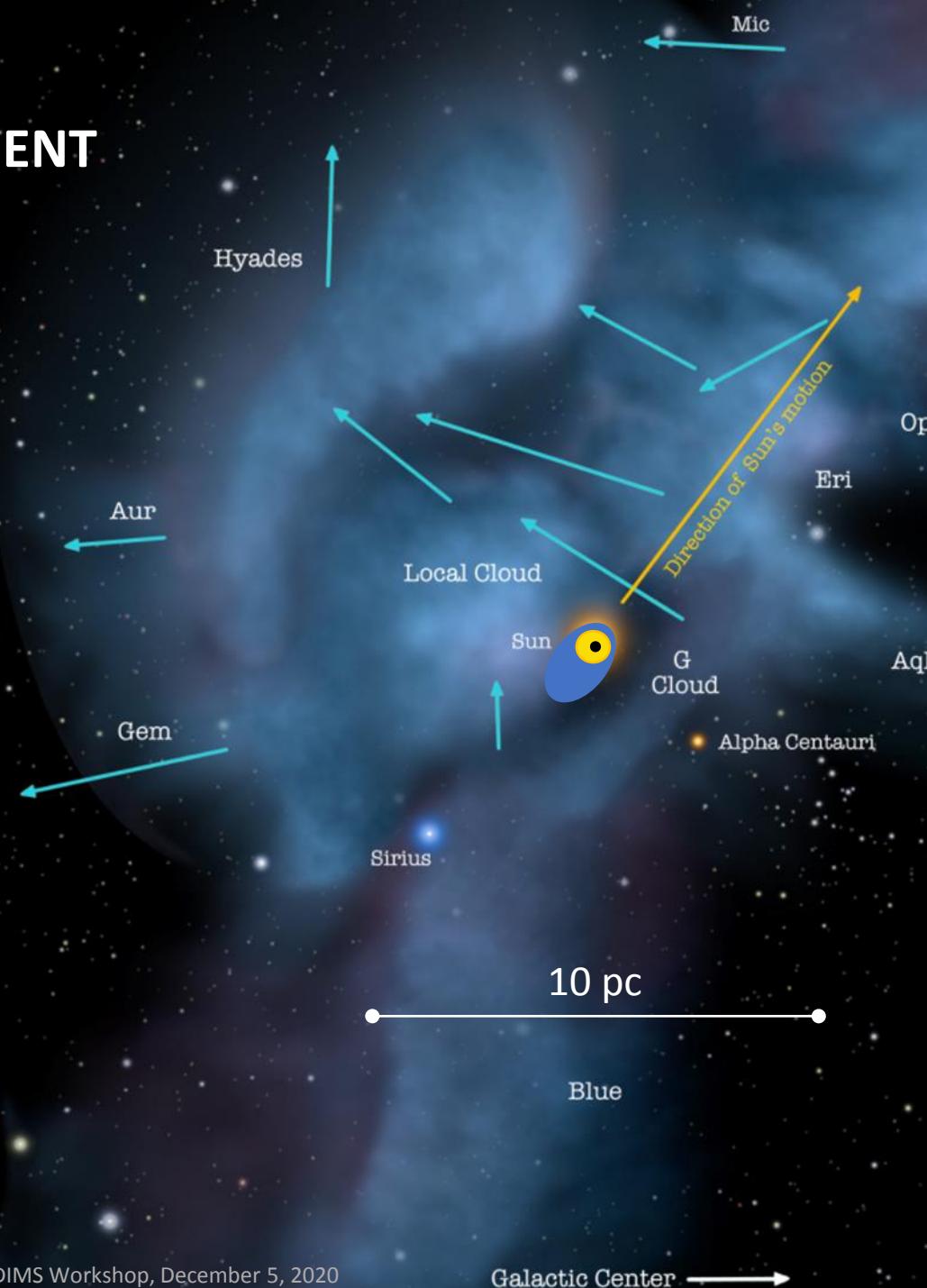
SPACE-BORN DUST MEASUREMENTS

EARTH-BASED METEOR OBSERVATIONS

2020 open questions:

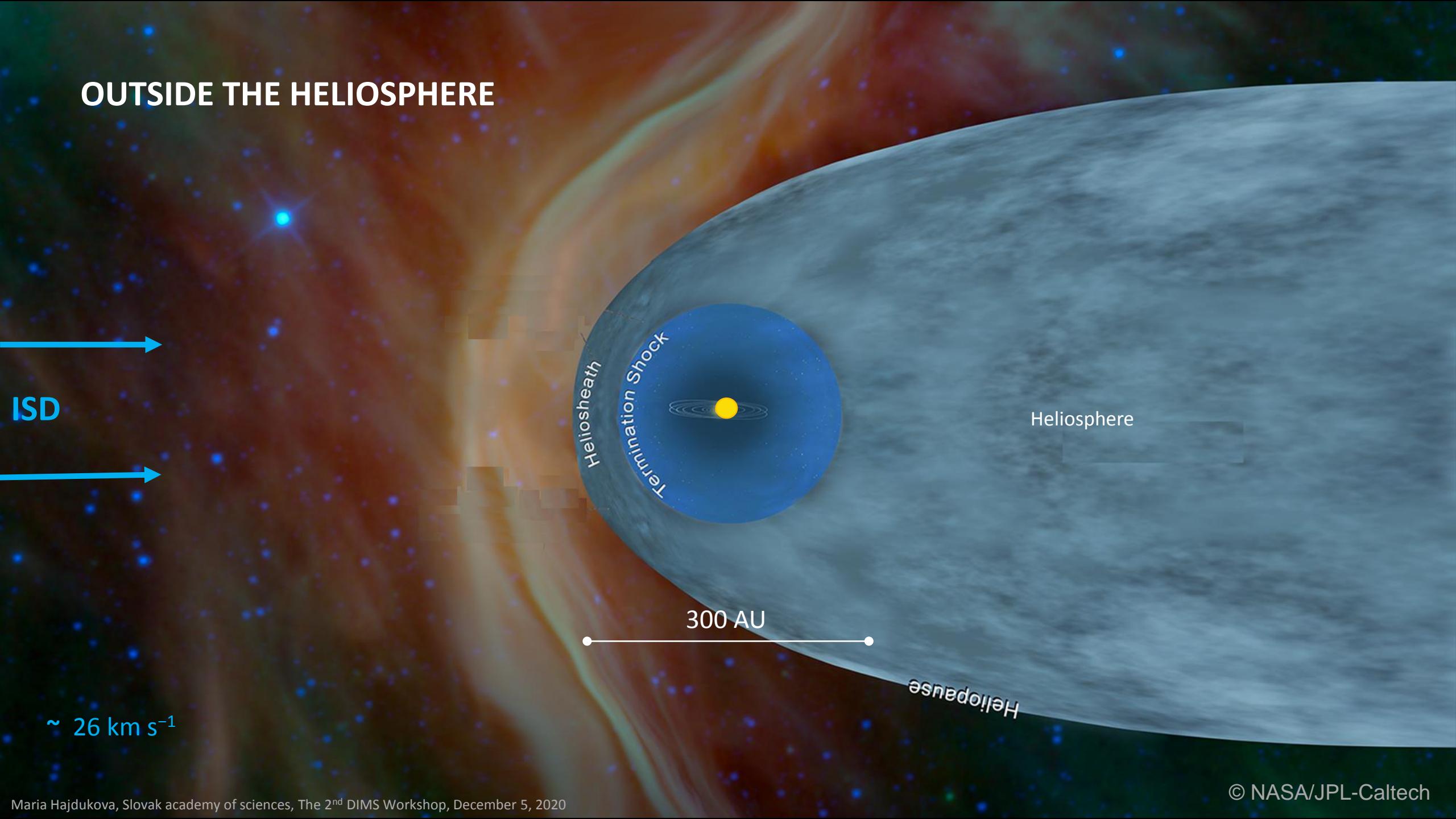
- How much of the dust population originates locally in the Solar System and how much comes from beyond?
- Do we observe interstellar meteoroids from the Earth?
- What fraction of observed hyperbolic meteors is caused by interstellar meteoroids?

SUN'S ENVIRONMENT

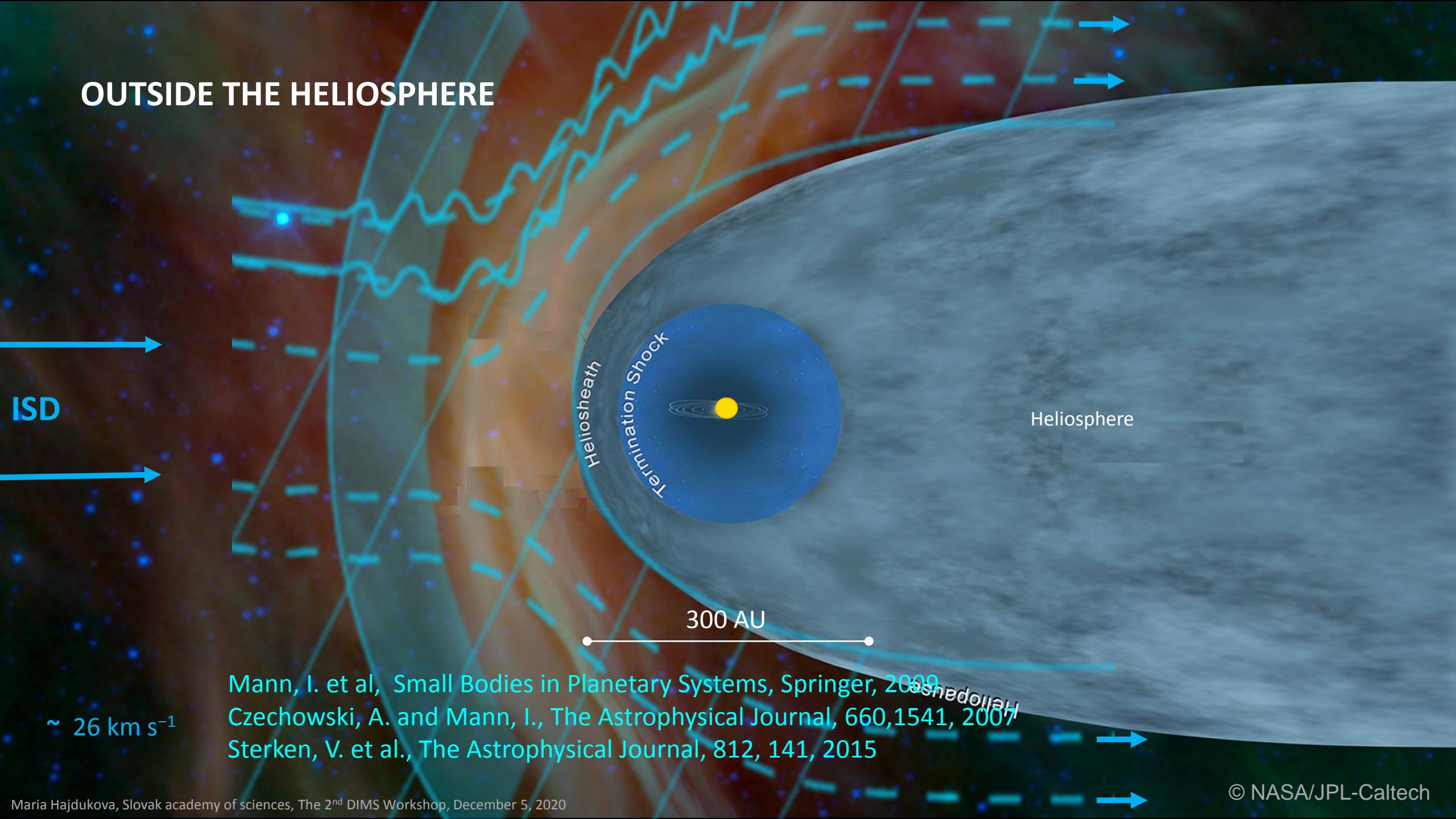


$\sim 26 \text{ km s}^{-1}$

OUTSIDE THE HELIOSPHERE



OUTSIDE THE HELIOSPHERE



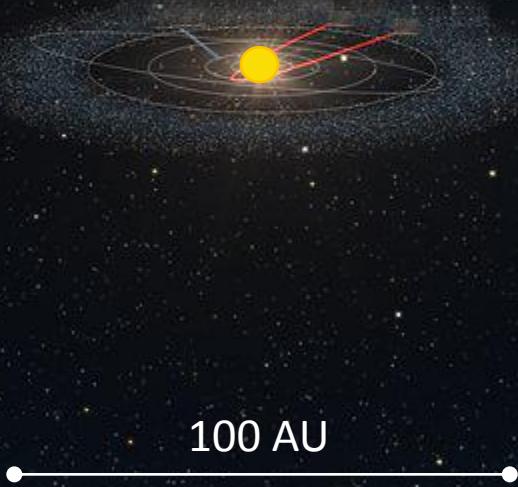
$\sim 26 \text{ km s}^{-1}$

Mann, I. et al, *Small Bodies in Planetary Systems*, Springer, 2009
Czechowski, A. and Mann, I., *The Astrophysical Journal*, 660,1541, 2007
Sterken, V. et al., *The Astrophysical Journal*, 812, 141, 2015

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INSIDE THE HELIOSPHERE

ISD



- Solar gravity
- Solar radiation pressure

$$\beta = F_{SRP}/F_{grav}$$

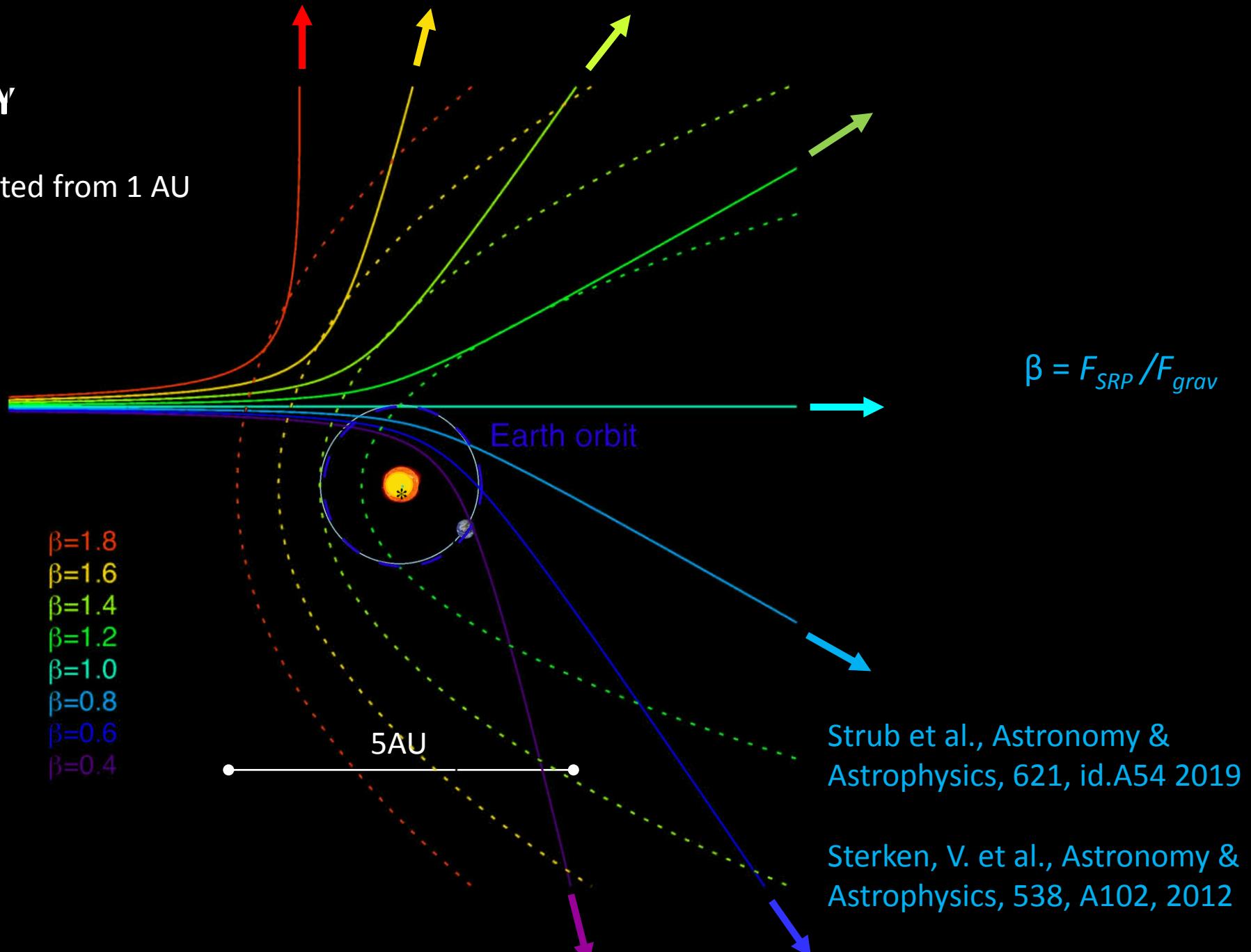
- Lorentz force from the solar magnetic field
 Q/m

Sterken, V. et al., Space Science Reviews, 215, 43, 2019

Sterken, V. et al., Astronomy & Astrophysics, 538, A102, 2012

THE EARTH'S VICINITY

dust with $\beta > 1.4$ cannot be detected from 1 AU

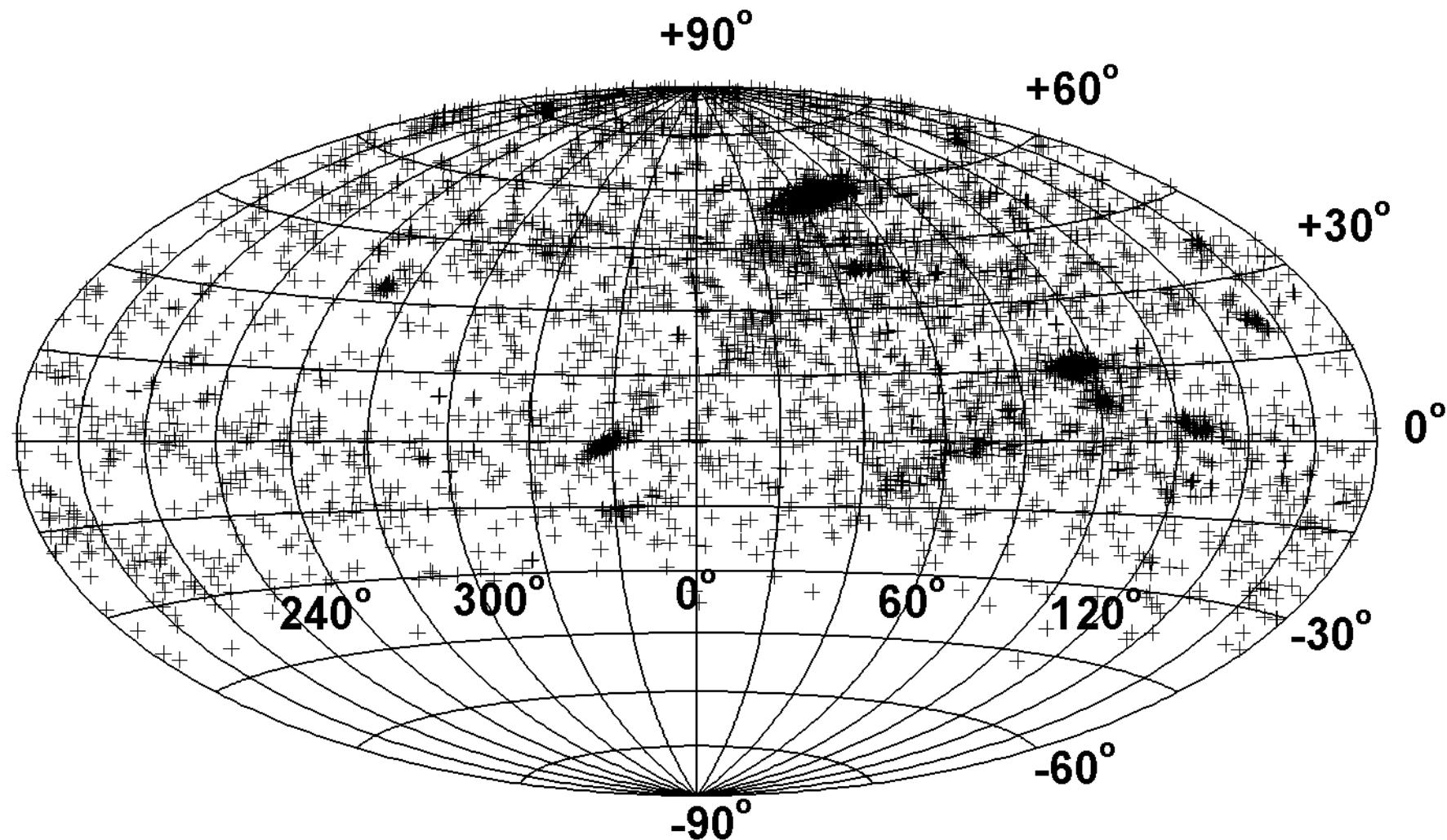


METEOR OBSERVATIONS

- > hyperbolic orbits .
 - > velocity larger than Sun's escape velocity $v_H^2 \approx v_0^2(2 - 1/a)$
- $1/a < 0 \rightarrow$ unbound orbit
- $1/a > 0 \rightarrow$ bound orbit

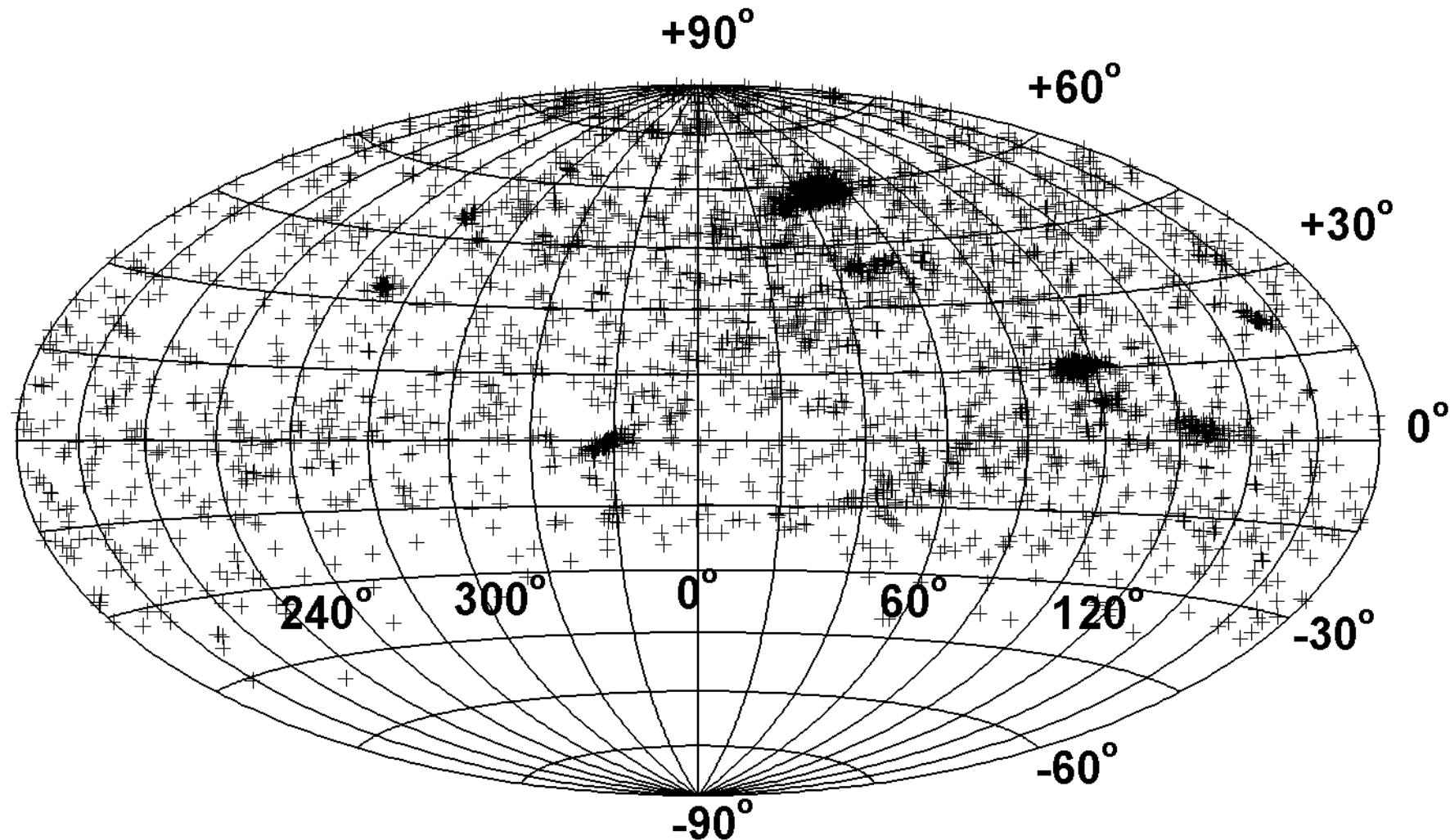
All-sky Meteor Orbit System AMOS
Toth, J. et al., Planetary and Space Science, 118, 102, 2015
Toth, J. et al, European Planetary Science Congress, Berlin, 2018

$$0.2 < 1/a < 0.1$$



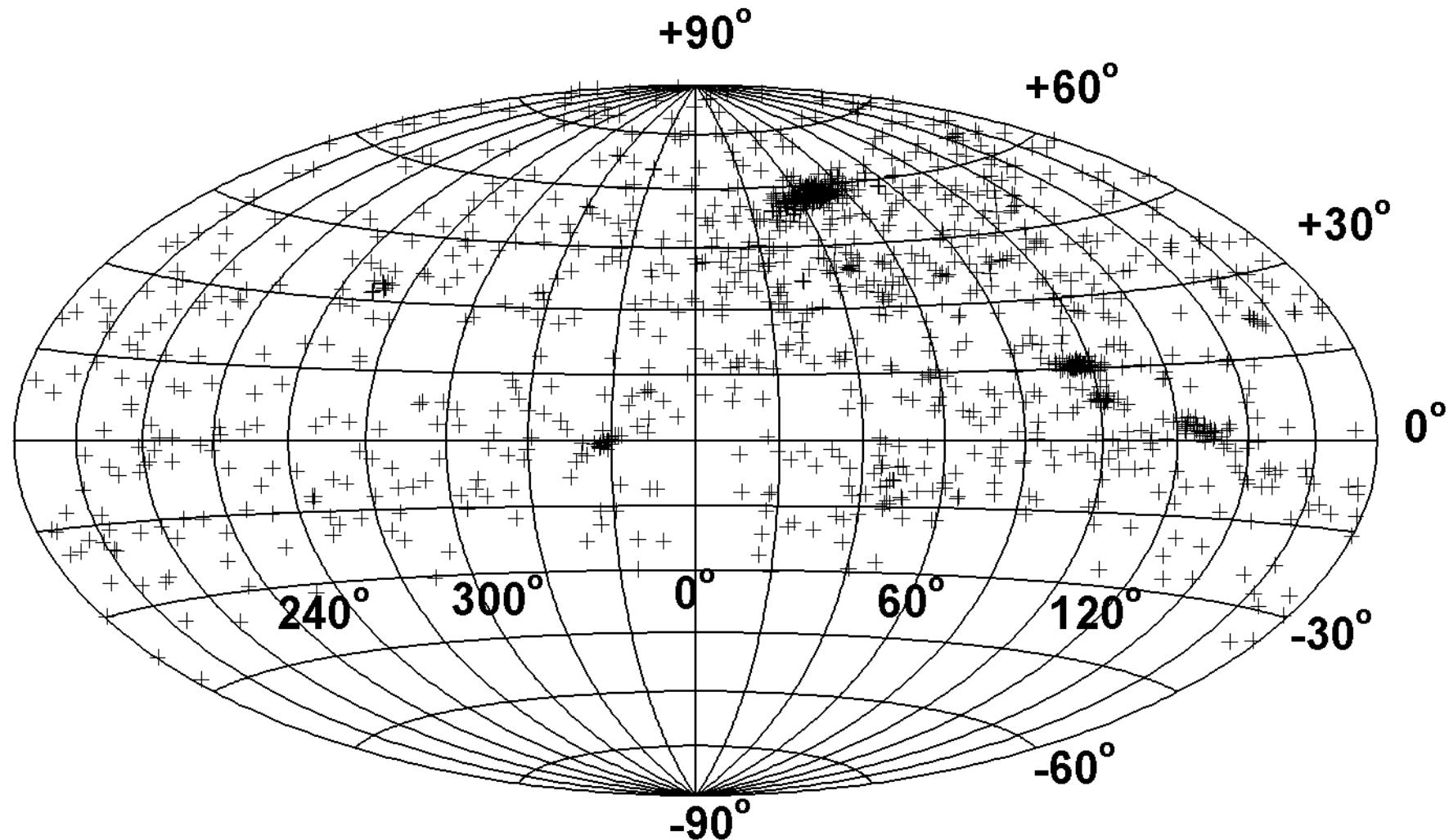
EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznań, Poland, IMO, 2013

$0.0 < 1/a < 0.1$



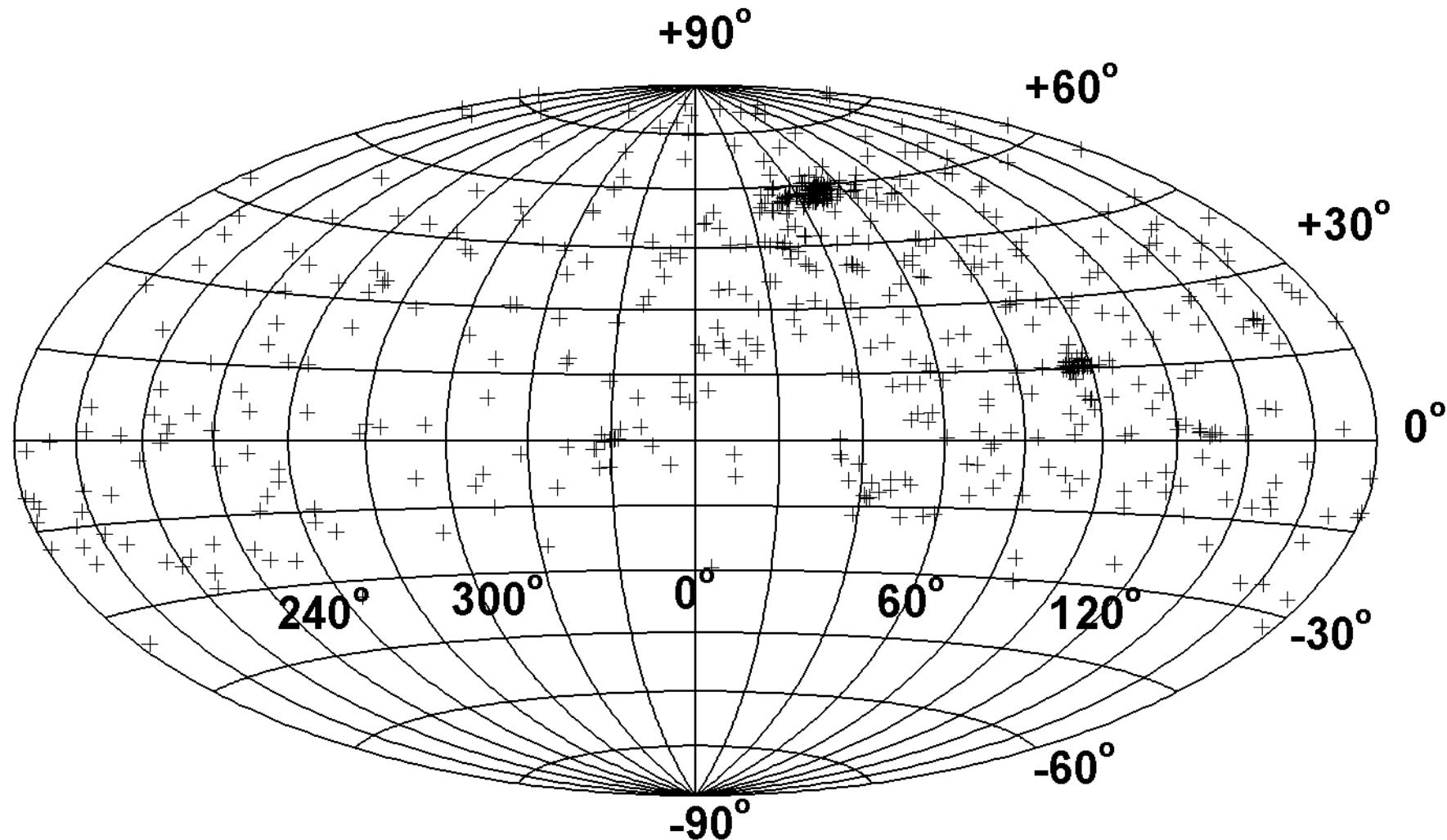
EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznań, Poland, IMO, 2013

$-0.1 < 1/a < 0.0$



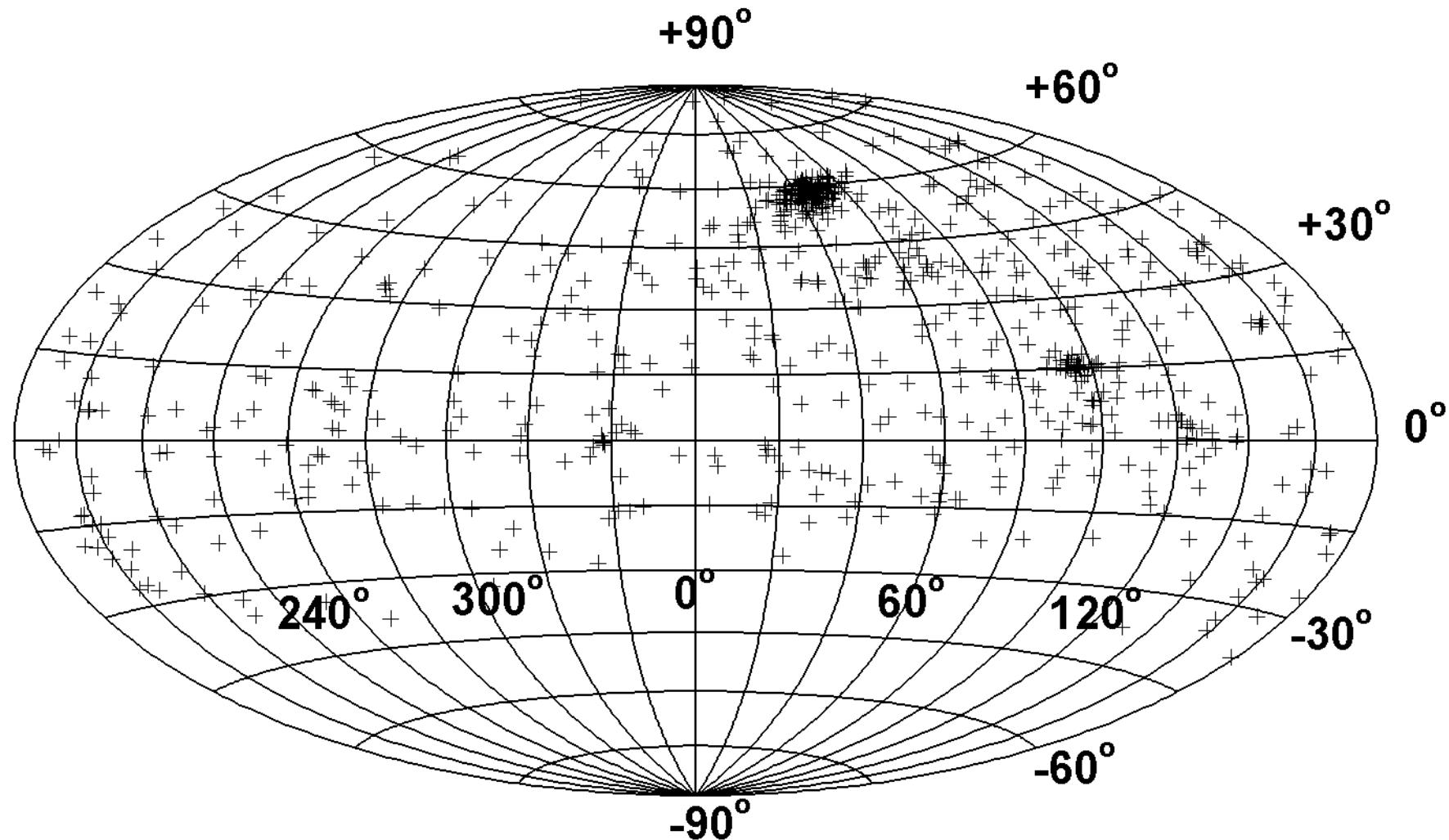
EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznań, Poland, IMO, 2013

$-0.2 < 1/a < -0.1$



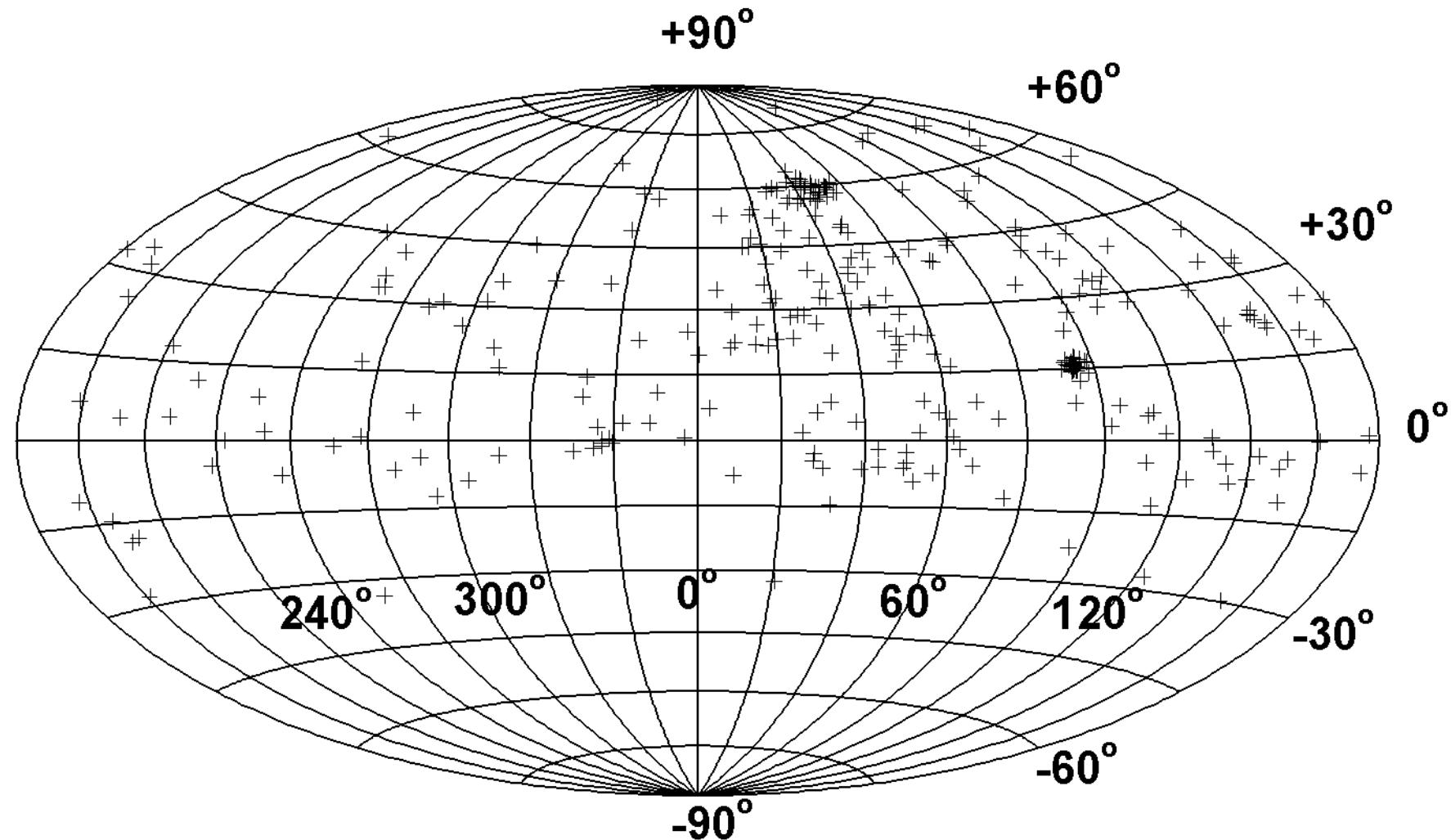
EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznań, Poland, IMO, 2013

$-0.5 < 1/a < -0.2$



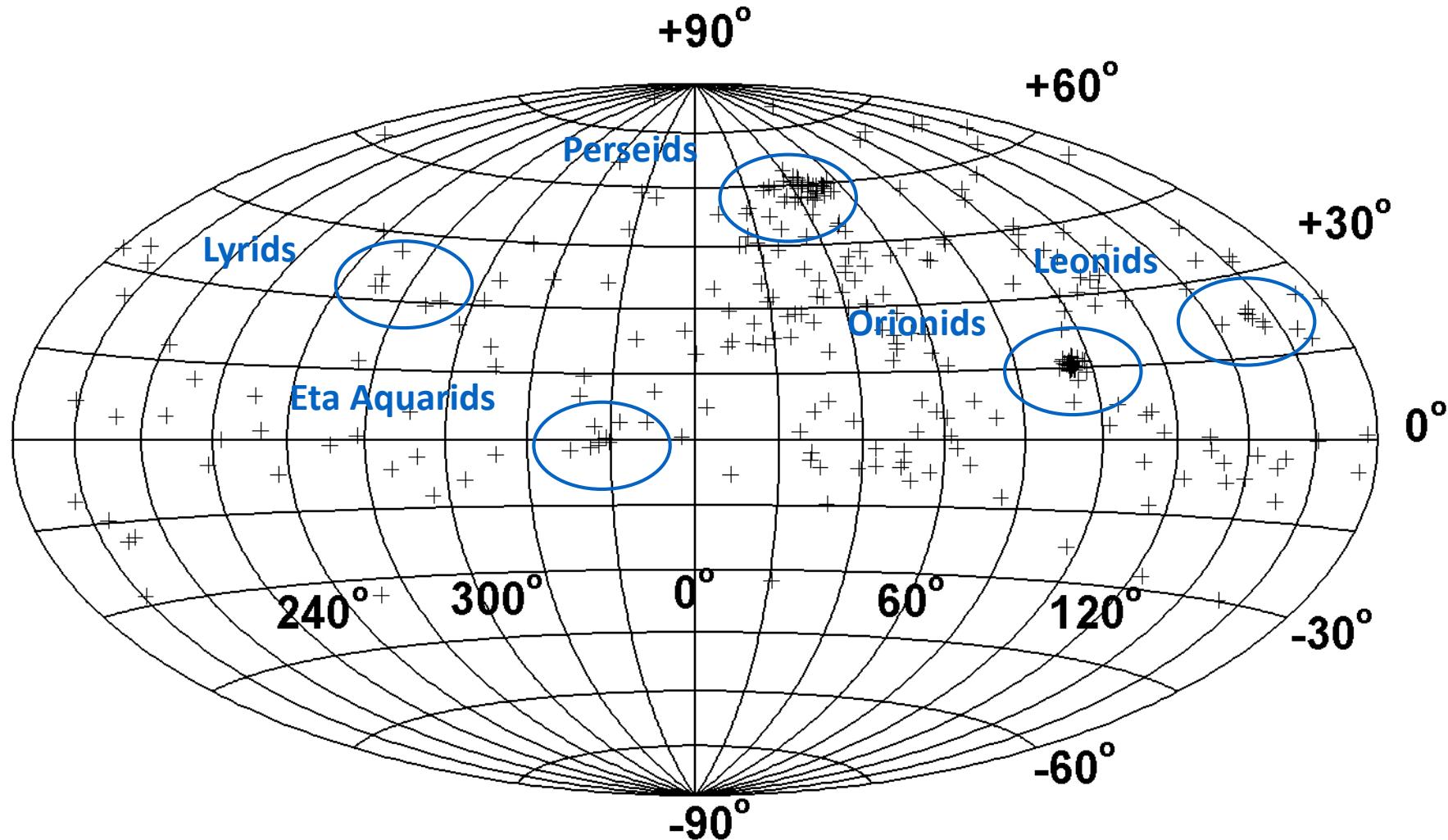
EDMOND database
Kornoš et al., Proceedings of the International
Meteor Conference, Poznan, Poland, IMO, 2013

$1/a < -0.5$



EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznań, Poland, IMO, 2013

$1/a < -0.5$



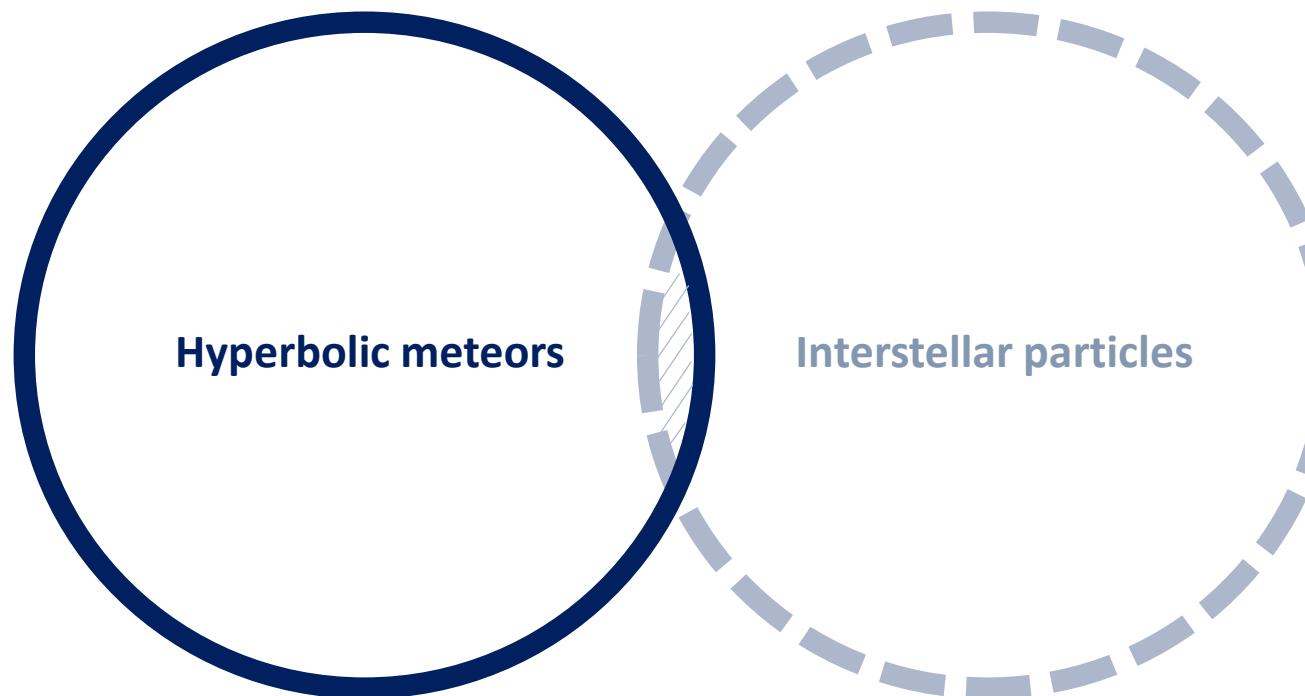
Hajdukova, M., Earth Moon Planets, 102, 67, 2008

Hajdukova, M. et al., Proceedings of the Meteoroids 2013, Poznan, 289, 2013

EDMOND database

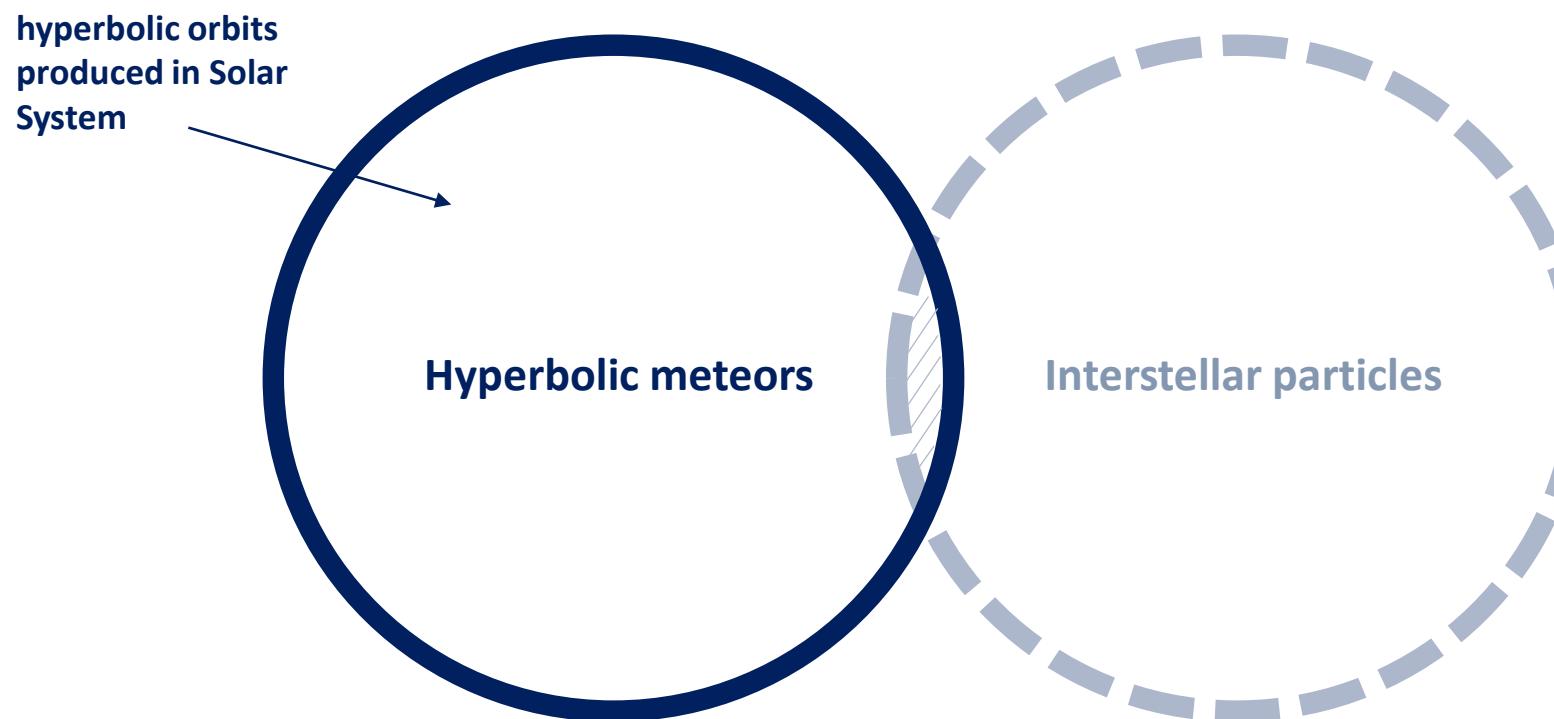
Kornoš et al., Proceedings of the International Meteor Conference, Poznan, Poland, IMO, 2013

- How many observed hyperbolic meteors are interstellar?



- How many observed hyperbolic meteors are interstellar?

Wiegert, P., et al.,
Icarus, 242, 112, 2014

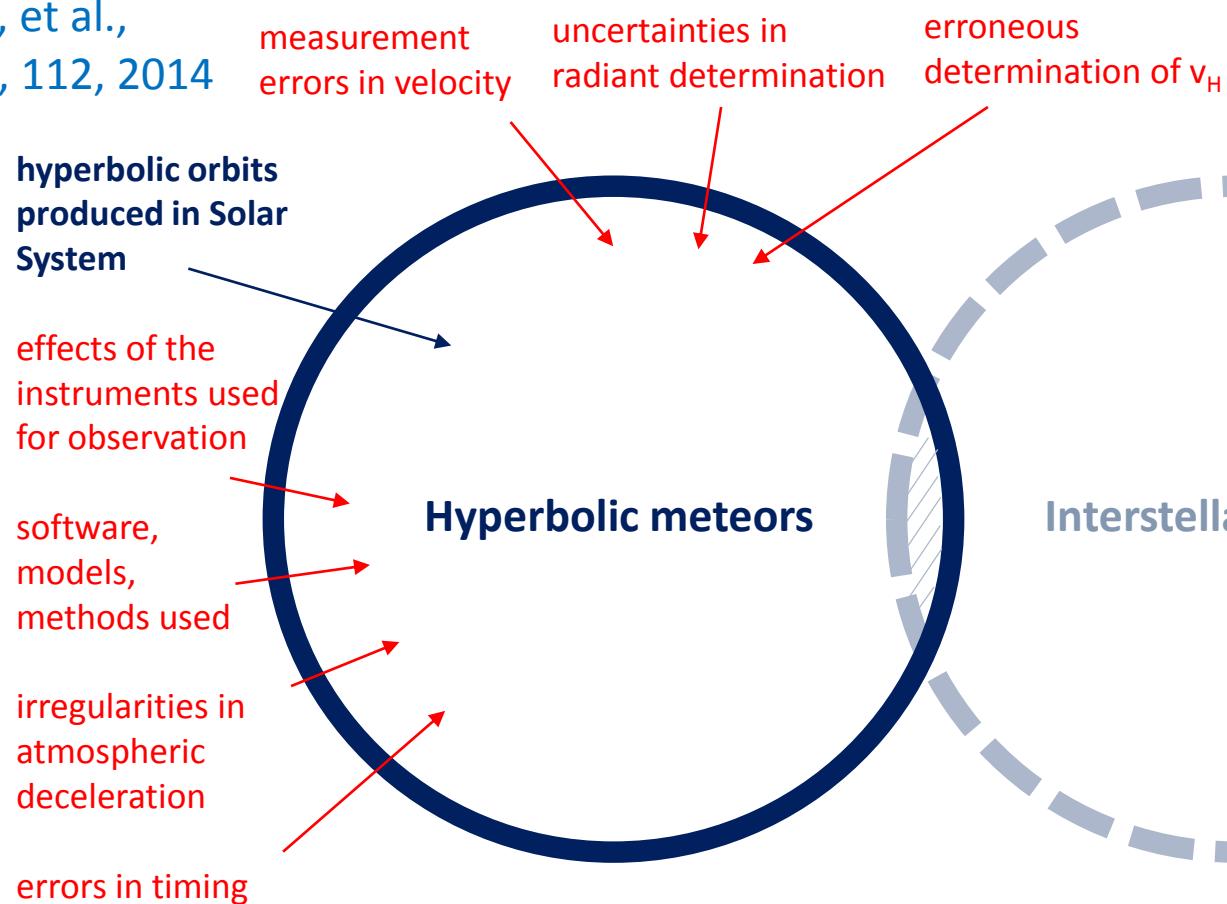


INFLUENCE OF ERRORS

-> FALSE POSITIVES

- How many observed hyperbolic meteors are interstellar?

Wiegert, P., et al.,
Icarus, 242, 112, 2014



Musci, R., et al., The Astrophysical Journal,
745, 161, 2012

Moorhead, A., et al., Planetary and Space
Science, 143, 209, 2017

Vida, D., et al., Monthly Notices of the
Royal Astronomical Society, 479, 4, 4307,
2018

Interstellar particles

Hajduková, M., Kornos, L., Planetary and
Space Science, 190, 104965, 2020

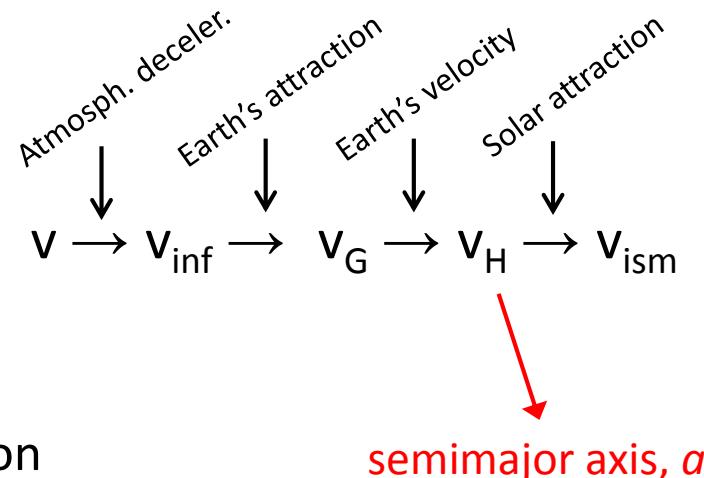
Froncisz, M., et al., Planetary and Space
Science, 190 104980, 2020

Chen, H., Tambaux, N., Vaubaillon, J.,
Astronomy & Astrophysics, 642, L11, 2020

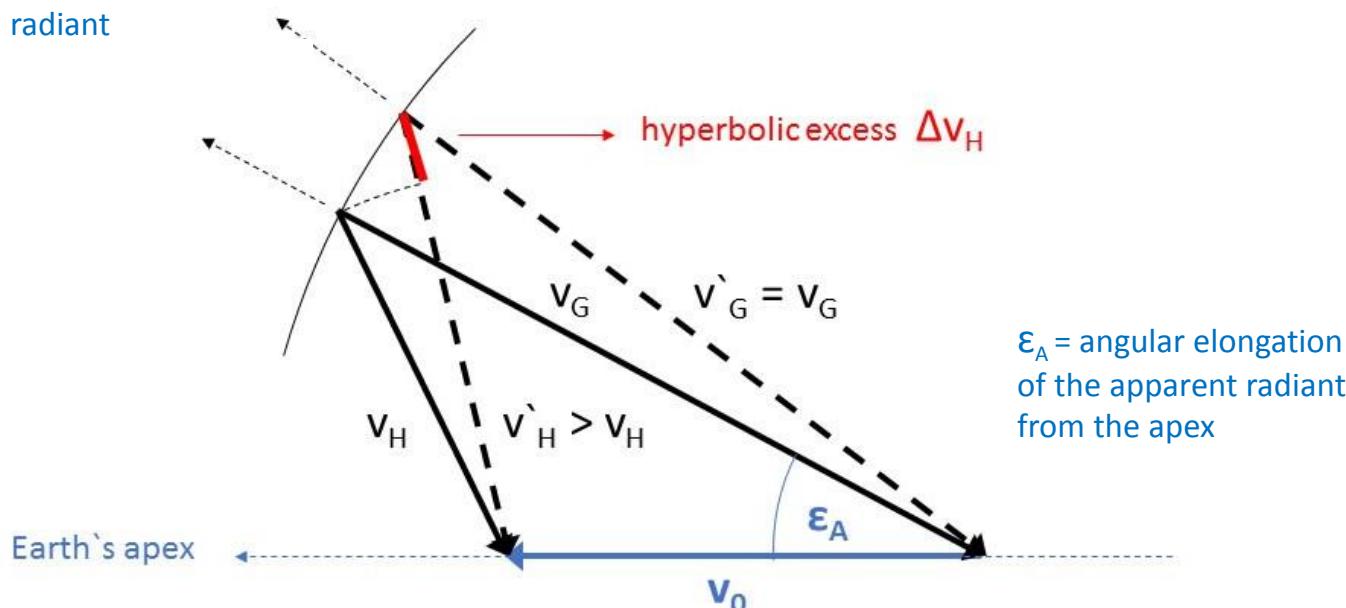
INFLUENCE OF ERRORS

-> Error in the speed

(r, v)



-> Error in the radiant position



-> FALSE POSITIVES

106
1976BAICz...27..106K

Vol. 27 (1976), No. 2
A NOTE ON METEOR AND MICROMETEOROID ORBITS DETERMINED FROM ROUGH VELOCITY DATA

L. Kresák, M. Kresáková, Astronomical Institute, Slovak Academy of Sciences, Bratislava
Received 17 July 1975

Some effects of the errors in velocity measurements on the determination of meteor orbits are discussed. Acceptable limits of measuring accuracy for discriminating between different types of the parent bodies are examined, and the questions which can be answered using inaccurate or incomplete velocity data are assessed. A significant bias towards small perihelion distances in the case of low-accuracy measurements is pointed out. This also applies to the orbits of small dust particles the motion of which is determined by the solar system.

10

Vol. 21 (1970), No. 1

ON THE PROBLEM OF HYPERBOLIC METEORS

J. Štohl, Astronomical Institute of the Slovak Academy of Sciences, Bratislava

Received 7 August 1969

The generally accepted explanation of the observed hyperbolicity of meteors is studied in somewhat greater detail on the basis of the statistics of meteors and their radiant distributions. The effect of perturbations on meteor orbits is investigated, and the conditions are derived under which an orbital change caused by perturbations could be observed in the course of time.

ASTRONOMY
AND
ASTROPHYSICS

Astron. Astrophys. 288, 330–334 (1994)

On the frequency of interstellar meteoroids

M. Hajduková Jr.
Department of Astronomy and Astrophysics, Comenius University, 842 15 Bratislava, Slovakia
Received 11 October 1993 / Accepted 8 February 1994

Abstract. Analysis of 2910 photographic meteor orbits collected in the IAU Meteor Data Center in Lund from different catalogues shows that the vast majority of the 347 hyperbolic meteoroids are subject to erroneous determination. The results show that the question of hyperbolic and

1 - 2 % for the most precise data and 5 % for radar orbits with a lower precision. Similar results were presented by Andrejev et al. (1987). Recently Baggaley et al. (1992) on the basis of new radar detection system speak about the possible significant contribution of non-closed orbits for meteors down a size of 100 m.

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journal homepage: www.elsevier.com/locate/pss



Review Article

The challenge of identifying interstellar meteors

Maria Hajdukova ^{a,*}, Veerle Sterken ^b, Paul Wiegert ^c, Leonard Kornoš ^d

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^b Institute for Particle Physics and Astrophysics, ETH Zürich, Switzerland

^c Department of Physics and Astronomy, University of Western Ontario, London, ON, Canada

^d Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia



INFLUENCE OF ERRORS

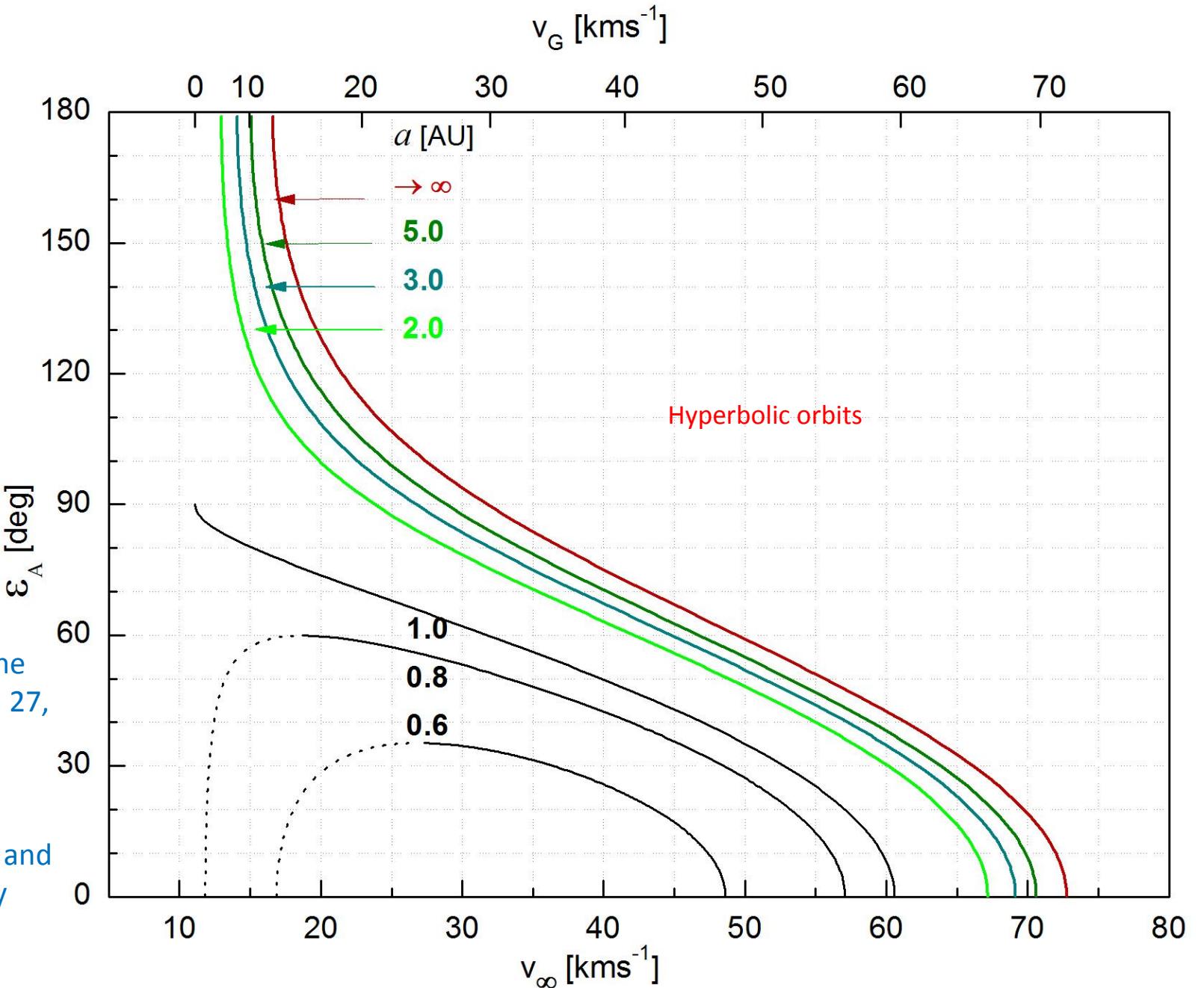
wide range v_G
11 - 72 km/s



narrow range v_H
36 - 42 km/s

Kresák, L. and Kresáková, M., Bulletin of the
Astronomical Institute of Czechoslovakia, 27,
106, 1976

Hajduková , M., Sterken, V., Wiegert, P.,
Meteoroids: Sources of Meteors on Earth and
Beyond, Cambridge, Cambridge University
Press, 235, 2019



INFLUENCE OF ERRORS

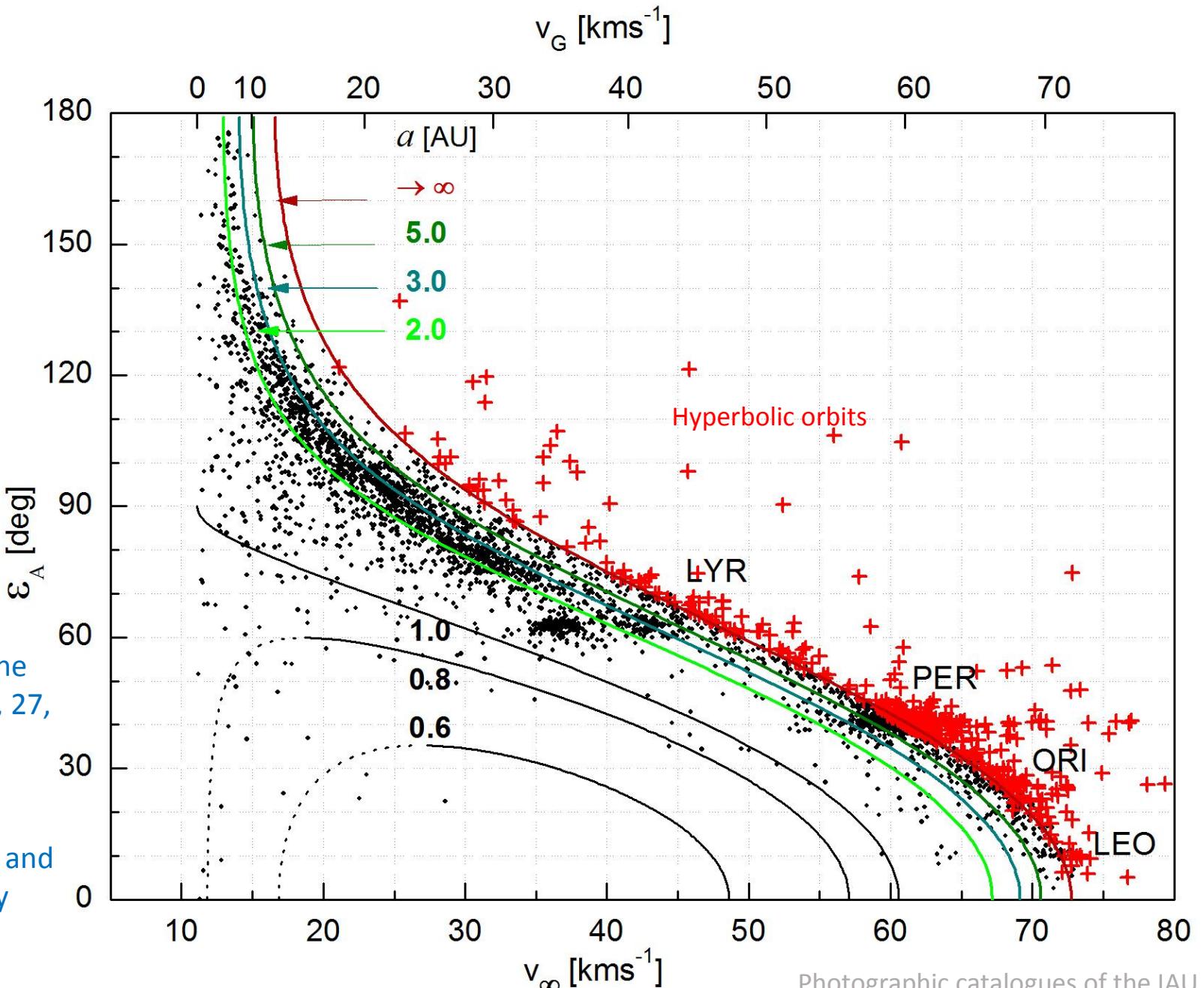
wide range v_G
11 - 72 km/s



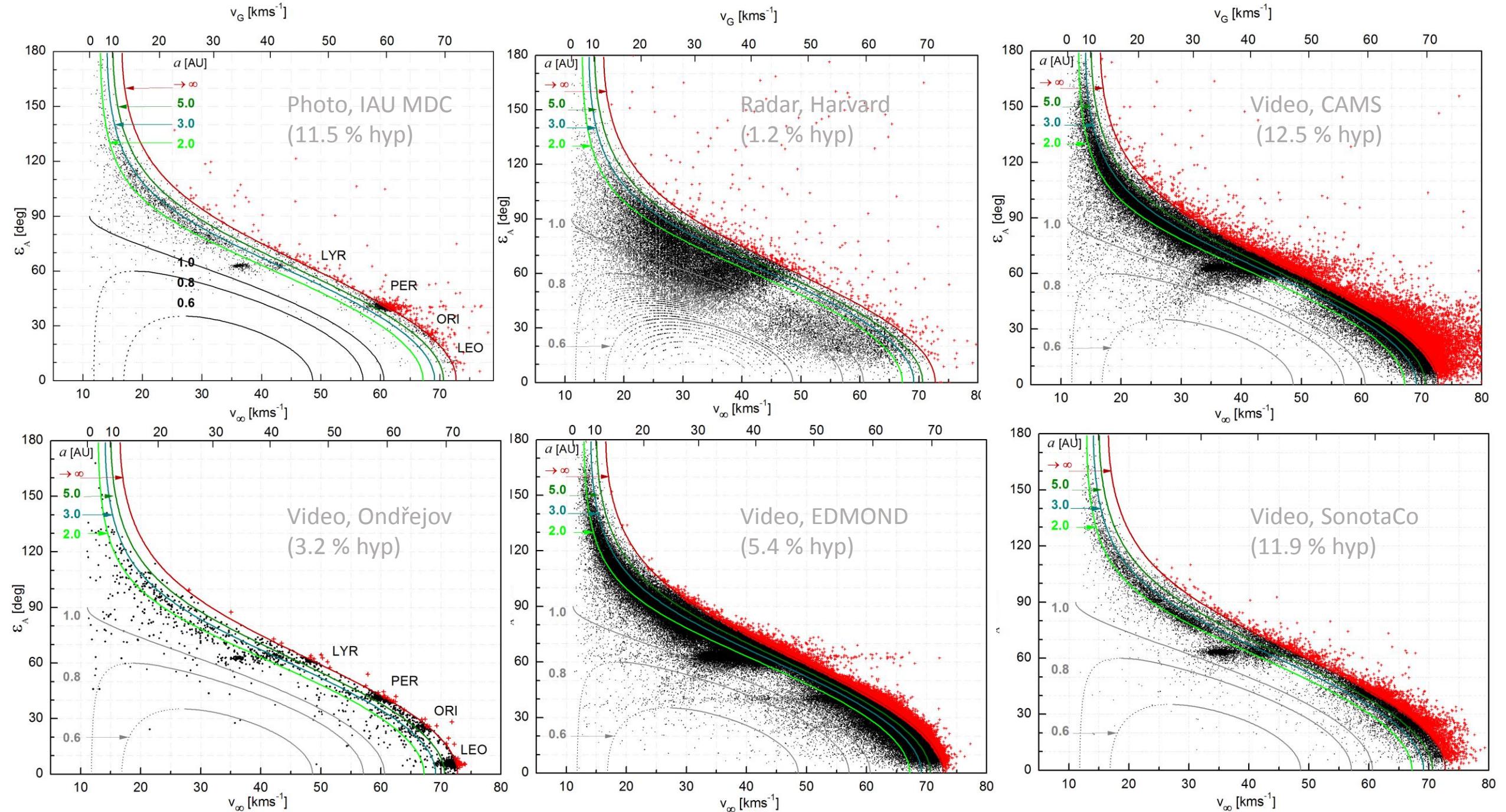
narrow range v_H
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Kresák, L. and Kresáková, M., Bulletin of the
Astronomical Institute of Czechoslovakia, 27,
106, 1976

Hajduková , M., Sterken, V., Wiegert, P.,
Meteoroids: Sources of Meteors on Earth and
Beyond, Cambridge, Cambridge University
Press, 235, 2019



Photographic catalogues of the IAU MDC
Lindblad, B. A., et al., EM&P, 93, 249, 2005.

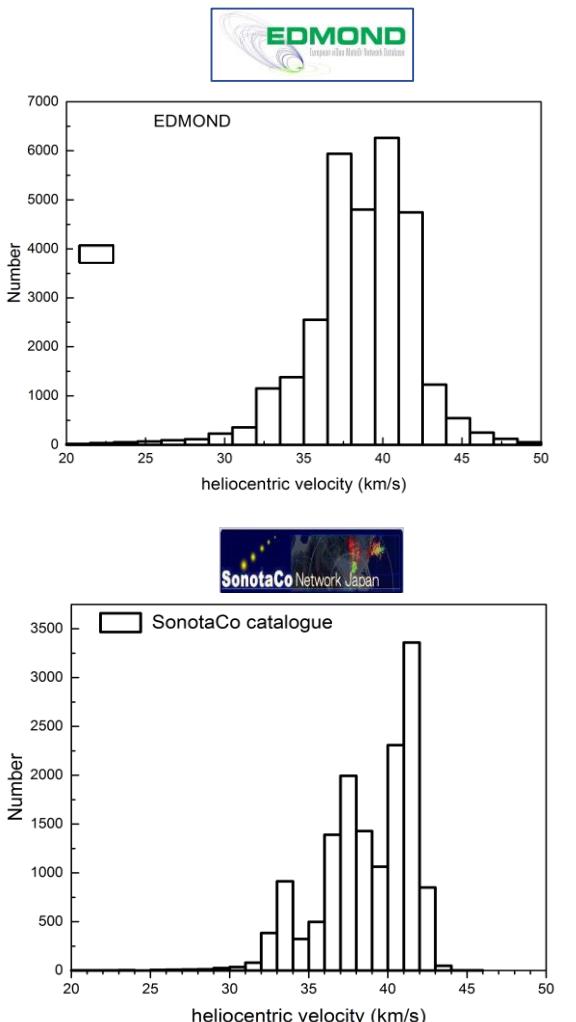
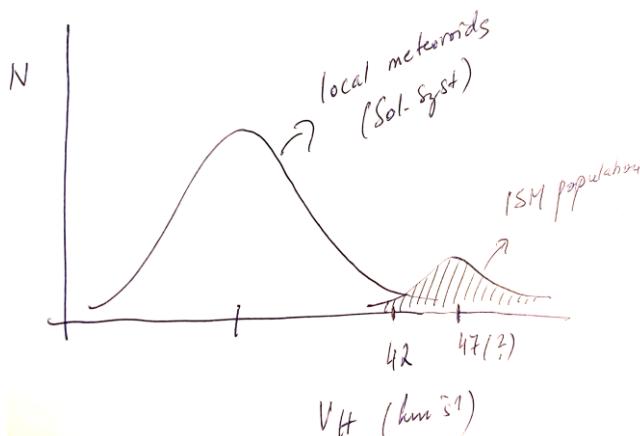


INFLUENCE OF ERRORS

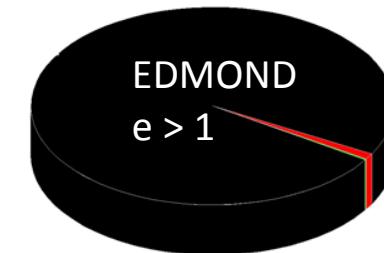
-> FALSE POSITIVES

WHY?

should be observed
but is not !



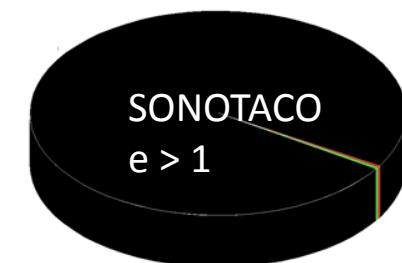
Hyperbolic orbits in the database **due to errors** 98,9%
Upper limit of possible interstellar meteoroids
Close planetary encounters



$N_{\text{all}} = 83\,369$
 $N_{e>1} = 4\,712$

after an error analysis:
 $N_{\text{ism}}/N_{\text{all}} = 0.9 \times 10^{-3}$

Hyperbolic orbits in the database **due to errors** 99,5%
Upper limit of possible interstellar meteoroids
Close planetary encounters



$N_{\text{all}} = 14\,763$
 $N_{e>1} = 484$

after an error analysis:
 $N_{\text{ism}}/N_{\text{all}} = 1.3 \times 10^{-3}$

Hajdukova, M., Publications of the Astronomical Society of Japan, 63, 3, 481, 2011
Hajdukova, M., et al., Proceedings of the Meteoroids 2013 Conference, 289, 2014

INFLUENCE OF ERRORS

MODEL

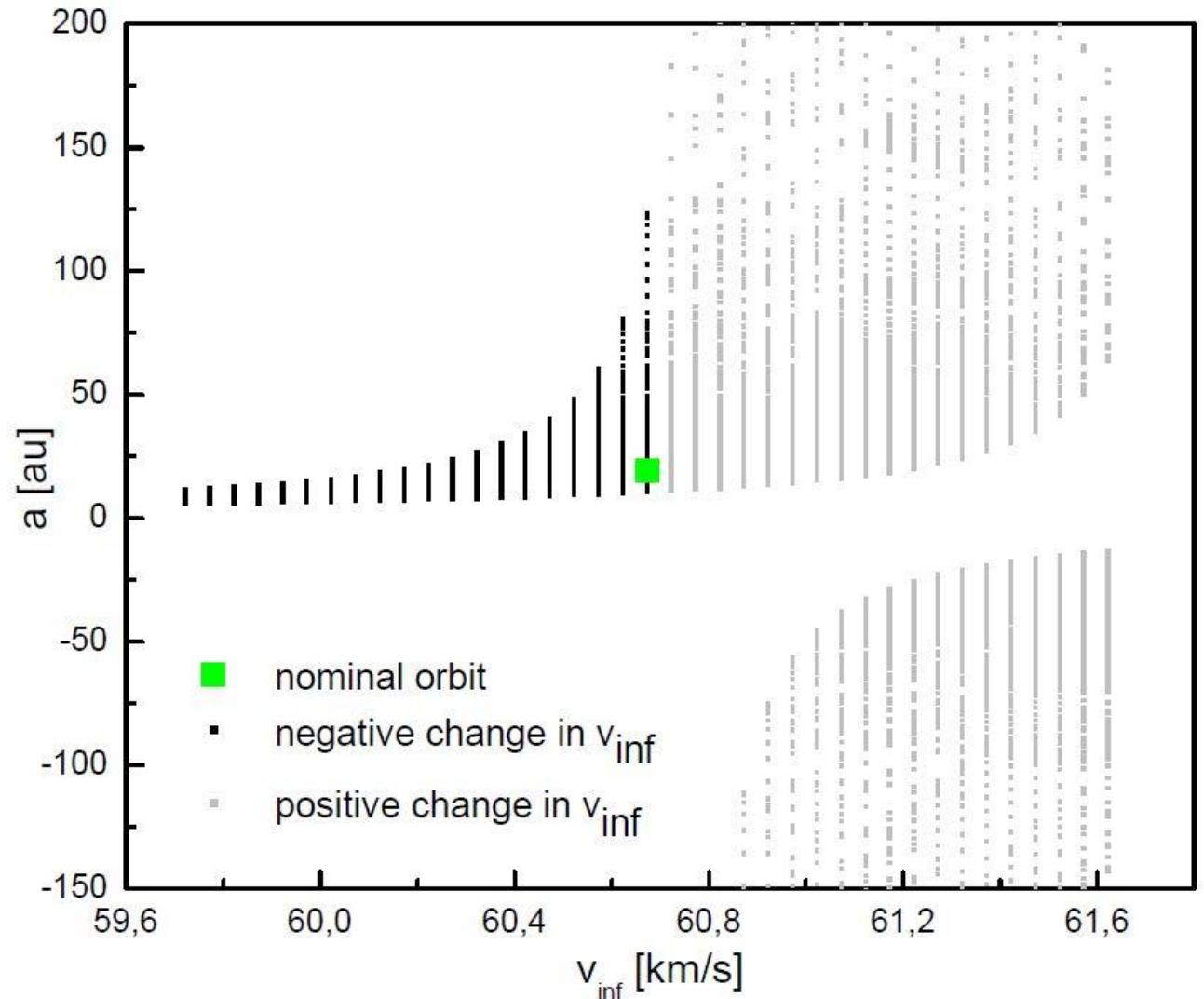
Creation of 14 000 clones of a perseid-like orbit by simulating an error in the speed and radiant:

v_{inf} $\pm 1 \text{ km/s}$
radiant $\pm 1^\circ$

Nominal orbit:
 $q = 0.945 \text{ au}$
 $a = 19 \text{ au}$
 $e = 0.95$
 $Q = 37 \text{ au}$
 $i = 113^\circ$

-> any small errors in velocity and/or radiant position can change the type of orbit

-> 1/3 of clones
created
hyperbolic orbits



Hajduková, M., Kornoš, L., Planetary and Space Science, 190, 104965, 2020

Discovery of interstellar dust entering the Earth's atmosphere

A. D. Taylor^{*†‡}, W. J. Baggaley[§] & D. I. Steel^{*}||

^{*} Department of Physics and Mathematical Physics, University of Adelaide, SA 5005, Australia
[†] Unit for Space Sciences, University of Kent, Canterbury, UK
[‡] Department of Physics and Astronomy, University of Canterbury, Christchurch, New Zealand
[§] Anglo-Australian Observatory, Australia

LETTERS TO NATURE

Discovery of jovian dust and interstellar grains by the Ulysses spacecraft

E. Grün, H. A. Zook*, M. Baguhl, A. Baldwin, S. J. Barnes, H. Fechtig, R. Forsyth, M. Horanyi, J. Kissel, B.-A. Lindblad, G. Linkert, I. Mann, J. A. M. McDonnell, G. E. Morfill†‡, J. L. Phillips, C. Polanyi, G. Schwehm‡, N. Siddique, P. Staubach, A. Taylor**

All known asteroids are gravitationally bound to the Sun and planets) no such object has been observed escape velocity, although limit*. As comets are occasional interstellar comets might tures, having ejected

In Situ Measurements of Interstellar Dust

M. Landgraf and E. Grün

Max-Planck-Institut für Kernphysik
D-6902 Heidelberg

Abstract. We by the Galileo a distribution pe by fitting ext significantly to t dust-to-gas

1 Intro

Dust alterna tant heating So underst interstell aments medium a tion curv power-la 0.005 μ 1977). T 1978), T was fir Ulysses identic detect impac by th in De ment end to i by I whi the str

Interstellar Dust in the Solar System

Harald Krüger · Markus Landgraf · Nicolas Altobelli

AND MANY OTHERS ...

Received: 14 February 2007 / Accepted: 28 March 2007 / Published online: 22 May 2007
 © Springer Science+Business Media, Inc. 2007

Abstract. The Ulysses spacecraft has been orbiting the Sun on a highly inclined most perpendicular to the ecliptic plane (inclination 79°, perihelion distance 1.3 AU) since it encountered Jupiter in 1992. The in situ dust detector continuously measured interstellar dust grains with masses up to 10^{-13} kg, penetrate into the solar system. The flow direction is close to the mean apex of the Sun's interstellar cloud (LIC). While Ulysses monitored the interstellar dust stream at high latitudes between 3 and 5 AU, interstellar impactors were also measured with the dust detectors on board Cassini, Galileo and Helios, covering a heliocentric distance between 0.3 and 3 AU in the ecliptic plane. The interstellar dust stream in the inner system is altered by the solar radiation pressure force, gravitational focussing and interaction of charged grains with the time varying interplanetary magnetic field. We review the results of in situ interstellar dust measurements in the solar system and present the results from the historical literature.

criteria applied². Comparison between Fresnel and time-lag speed determinants indicated once a value sub- ~ 65 km s⁻¹ meteors with orbit. This centric speed into the data measured a was probably necessary if from bound $v \sim 164$ km s⁻¹.

Research Note

OPTICAL DETECTION OF TWO METEOROIDS FROM INTERSTELLAR SPACE

BY ROBERT L. HAWKES AND SEAN C. WOODWORTH

*Mount Allison University, Fredericton, Canada
 @mtu.ca
 997*

first 24.4 hours of multi-station observations (1995) we detected two small meteoroids (10^3 kg) that have come from interstellar space was observed at 02:21:43 UT on June 2 with a perihelion velocity of 49.9 ± 1.7 km s⁻¹. The trajectory of 1.82 ± 0.19 and an inclination of 1.9° . The radiant point (prior to encountering the solar system) was at a galactic galactic latitude of 39° . The meteor had 1.9° . The second interstellar meteor was at 02:21:43 UT on June 27, 1995, with a heliocentric velocity of 6.6 km s⁻¹. The orbit had an eccentricity of 0.27 and an inclination of 123.2° . The radius vector at the perihelion was 1.01 AU.

Earth, Moon, and Planets (2004) 95: 221–227
 DOI 10.1007/s11038-005-9034-x

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A SEARCH FOR INTERSTELLAR METEOROIDS USING THE CANADIAN METEOR ORBIT RADAR (CMOR)

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doi:10.1088/0004-637X/745/2/161

AN OPTICAL SURVEY FOR MILLIMETER-SIZED INTERSTELLAR METEOROIDS

R. MUSCI, R. J. WERYK, P. BROWN, M. D. CAMPBELL-BROWN, AND P. A. WIEGERT
Department of Physics and Astronomy, University of Western Ontario, London, Ontario N6A 3K7, Canada; rmusci@uwo.ca

Received 2011 June 17; accepted 2011 October 20; published 2012 January 16

We report high-resolution multi-station

ABSTRACT

*Meteoritics & Planetary Science 1–6 (2013)
 doi: 10.1111/maps.12119*

Frequency of hyperbolic and interstellar meteoroids

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² Institute of Mathematics, Physics and Informatics, Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia, Slovak Republic

*The Astrophysical Journal, 579:895–904, 2003 November 10
 © 2002. The American Astronomical Society. All rights reserved. Printed in U.S.A.*

(Received 24 August 2012;

hyperbolic meteor orbits from

ian Automated Meteor Observatory n magnitude of +5 mag in R band, tory accuracy (of the order of 30 m locities with average uncertainty of id measured orbits. The data have illar origin. We found 22 potential s at millimeter sizes in a weighted potentially hyperbolic meteors to its. Detailed examination leads us to error. We find an upper limit of niting mass of $m > 2 \times 10^{-7}$ kg.

THE SIZE DISTRIBUTION OF ARECIBO INTERSTELLAR PARTICLES AND ITS IMPLICATIONS

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DIEGO JANCHES¹
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AND

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ABSTRACT

Size histograms of all Arecibo ultra-high-frequency radar micrometeors detected in 1997–1998 whose radii were measured by atmospheric drag are presented. Most can be fitted with either a lognormal function or alternatively, one or more power-law functions. Either form is indicative of significant fragmentation. The interplanetary dust particle (IDP) histogram results are discussed and compared with those considered to be extrasolar particles, including a subset of those deemed to be true interstellar particles (ISPs). The Arecibo IDP power-law results are shown to agree well with those derived from *IRAS* dust bands and *Long Duration Exposure Facility* cratering, thus confirming the applicability of the sample to the derivation of mass estimates. A dichotomy between size histograms of particles with preperihelion Earth encounters and those with postperihelion encounters is evident that significant size histogram change occurs when the smallest particles, including all ISPs, pass close to the Sun, even if only once. A small sample of previously undetected Arecibo postperihelion ISPs coming from the direction of the known *Ulysses* gas and dust flow are shown to have a size distribution and solar system dynamical properties similar to other Arecibo ISPs and therefore can be combined with previous ISP results to obtain a more robust sample. Derived mass flux points for the Arecibo ISPs agree well (over 5 orders of magnitude of mass) with a previously derived mass flux distribution function for *Ulysses*/Galileo spacecraft dust. This combined spacecraft and ground-based mass flux function is then used to infer a number of interesting mass-related solar system and astrophysical quantities. Subject headings: interplanetary medium — meteors, meteoroids — supernovae: general

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Possible interstellar meteoroids detected by the Canadian Meteor Orbit Radar

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ABSTRACT

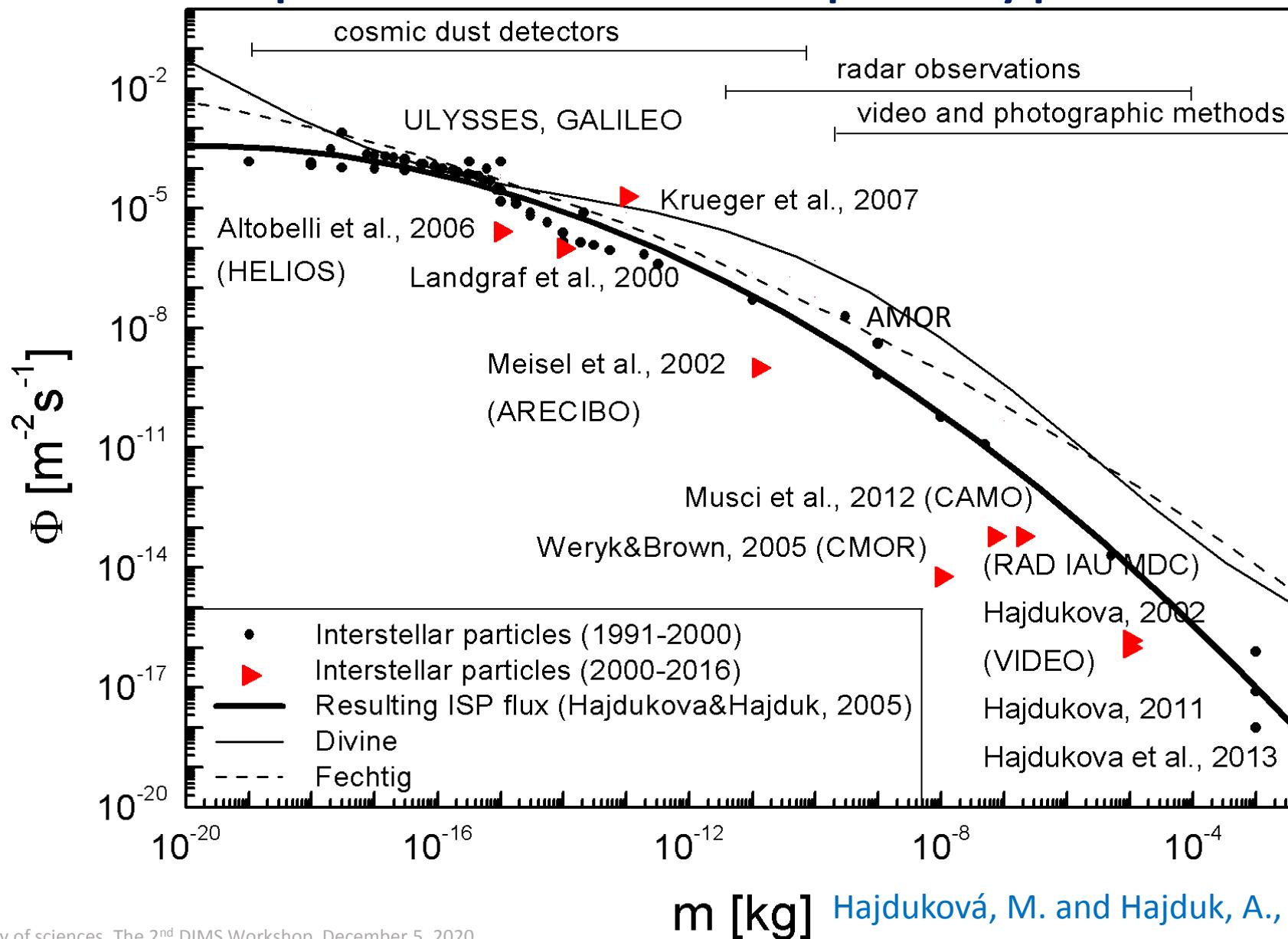
We examine meteoroid orbits recorded by the Canadian Meteor Orbit Radar (CMOR) consisting of just over 11 million orbits in a search for potential interstellar meteoroids. An integrated time-area product of 7×10^6 km² hours. Selecting j having the highest measured velocity accuracy from within our survey events. These five potential interstellar meteoroids were found to be rare measured speed. Applying a new atmospheric deceleration correction

1. INTRODUCTION

The Canadian Meteor Orbit Radar (CMOR) is a ground-based radar system located in the

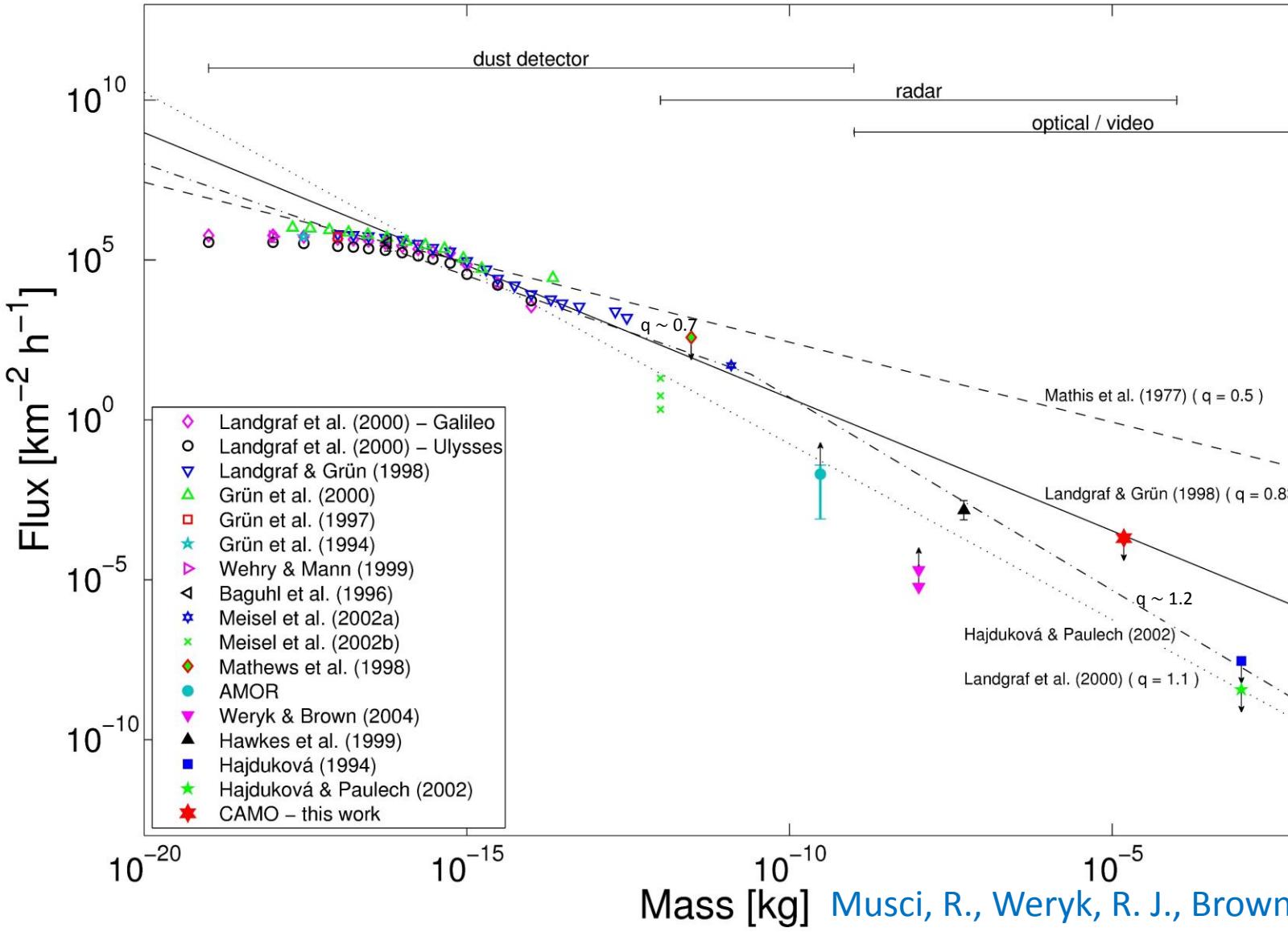
FLUX OF ISP

compared with the flux of interplanetary particles



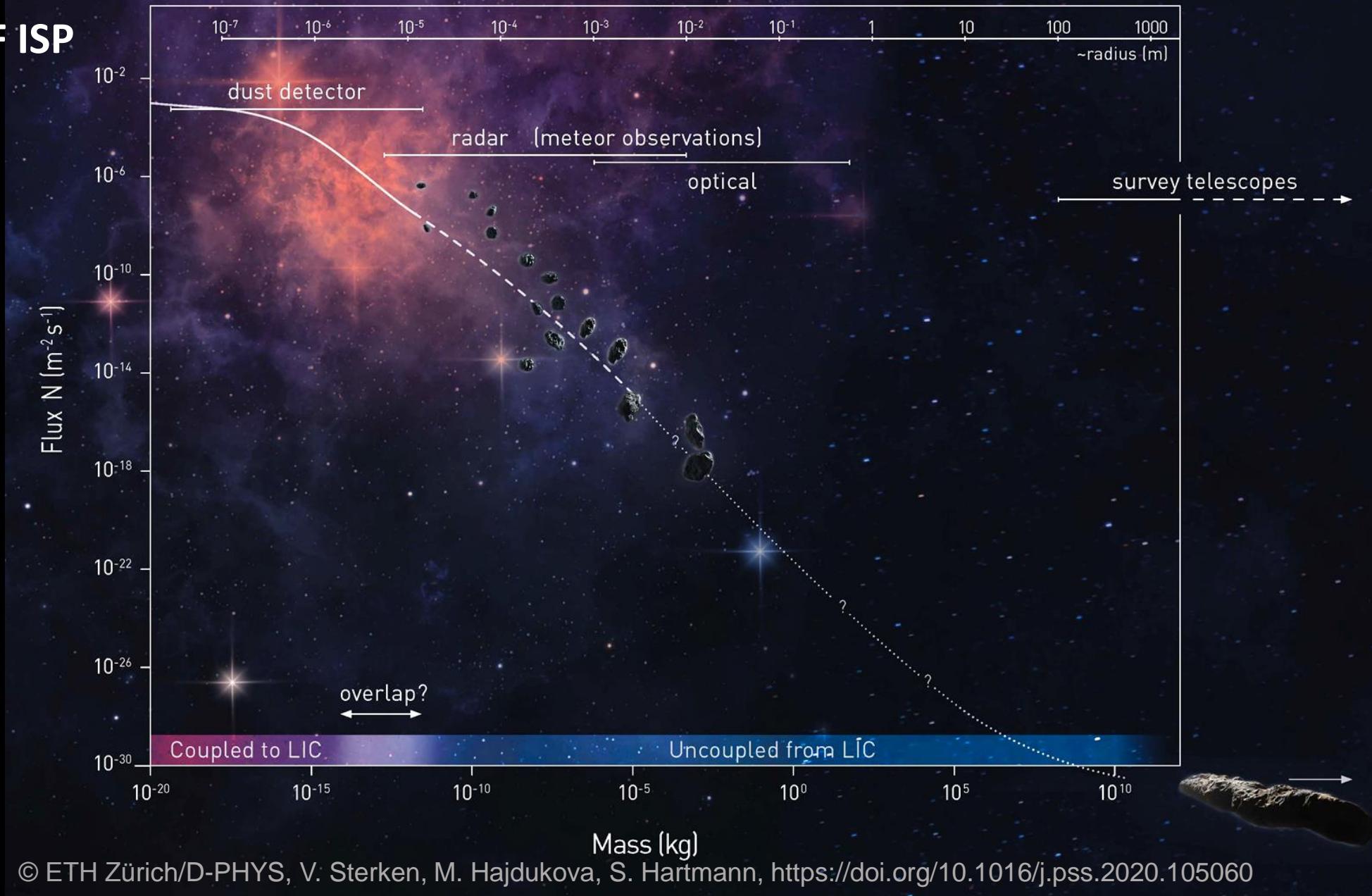
FLUX OF ISP

compared with the size distribution of interstellar grains from the observed interstellar extinction

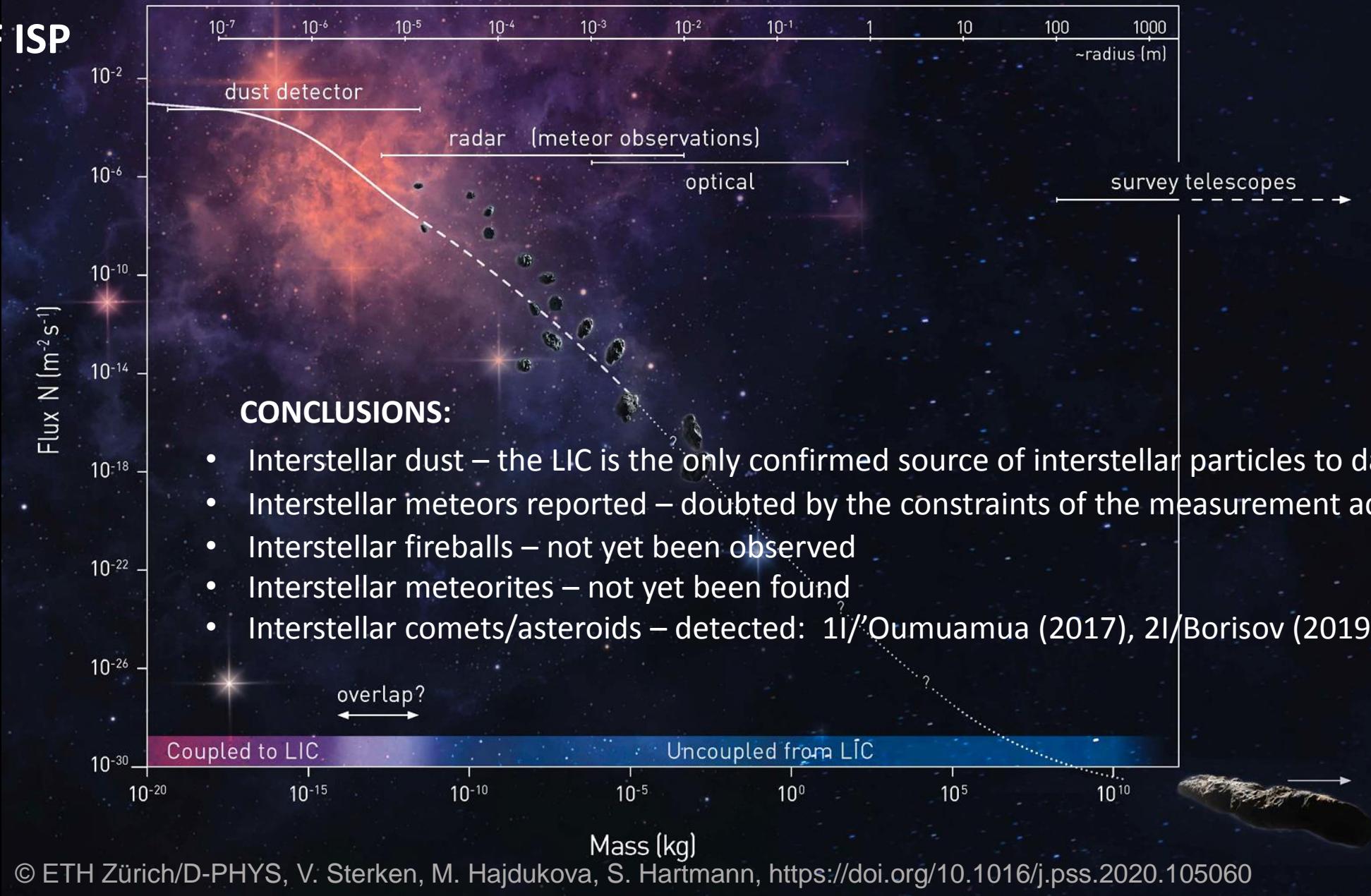


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FLUX OF ISP



FLUX OF ISP



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Thank you for your attention