METEOR OBSERVATIONS OF INTERSTELLAR PARTICLES

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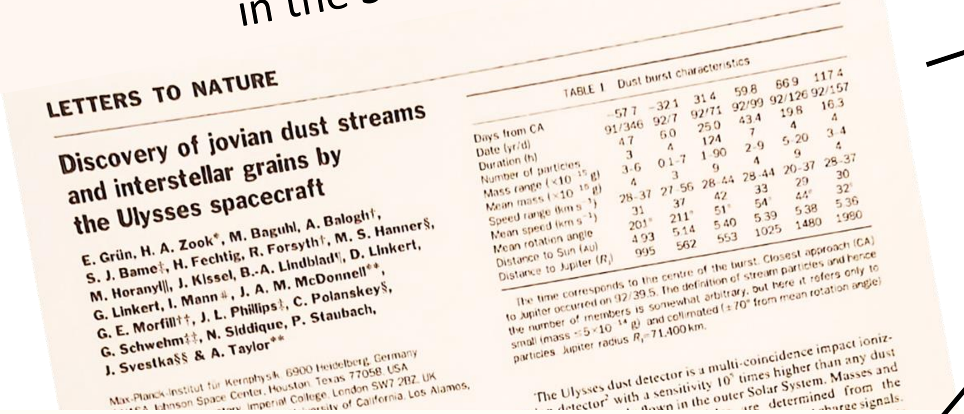
Slovak Academy of Sciences
Bratislava, Slovakia

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
NASA Johnson Space Center, Houston, Texas 77058, USA
... Imperial College, London SW7 2BZ, UK
... University of California, Los Alamos,

TABLE 1 Dust burst characteristics

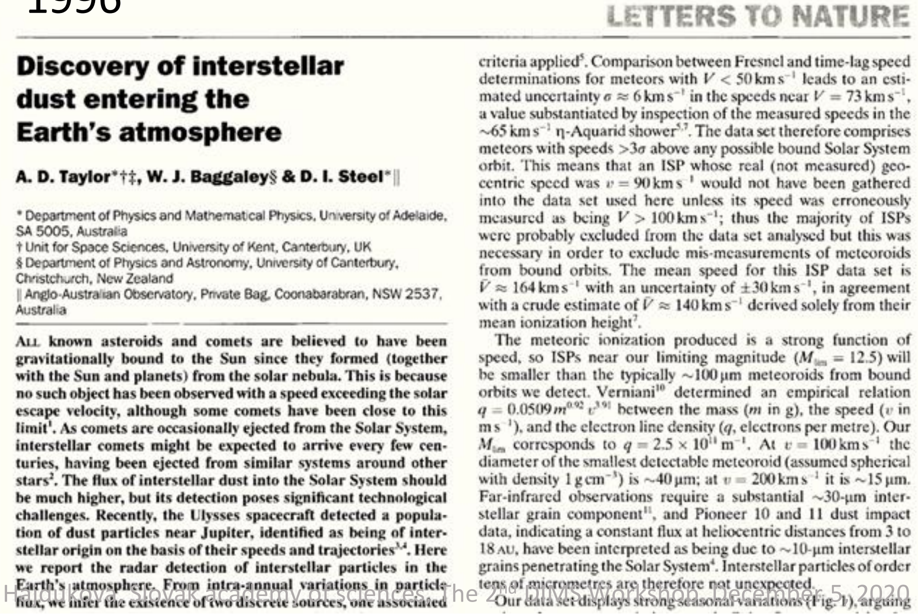
Days from CA	−57.7	−32.1	31.4	59.8	86.9	117.4
Date (yr/d)	91/346	92/7	92/71	92/99	92/126	92/157
Duration (h)	4.7	6.0	25.0	43.4	19.8	16.3
Number of particles	3	4	124	7	4	4
Mass range (×10⁻¹⁵ g)	3-6	0.1-7	1-90	2-9	5-20	3-4
Mean mass (×10⁻¹⁵ g)	4	3	9	4	9	4
Speed range (km s⁻¹)	28-37	27-56	28-44	28-44	20-37	28-37
Mean speed (km s⁻¹)	31	37	42	33	29	30
Mean rotation angle	201°	211°	51°	54°	44°	32°
Distance to Sun (AU)	4.93	5.14	5.40	5.39	5.38	5.36
Distance to Jupiter (R_J)	995	562	553	1025	1480	1980

The time corresponds to the centre of the burst. Closest approach (CA) to Jupiter occurred on 92/39.5. The definition of stream particles and hence the number of members is somewhat arbitrary, but here it refers only to small (mass $<5\times10^{-14}$ g) and collimated (±70° from mean rotation angle) particles. Jupiter radius R_J=71,400 km.

The Ulysses dust detector is a multi-coincidence impact ionization detector[2] with a sensitivity 10^5 times higher than any dust ... flown in the outer Solar System. Masses and ... 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 limit[1]. 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 stars[2]. 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

criteria applied[5]. Comparison between Fresnel and time-lag speed determinations for meteors with $V < 50\,\mathrm{km\,s^{-1}}$ leads to an estimated uncertainty $\sigma \approx 6\,\mathrm{km\,s^{-1}}$ in the speeds near $V = 73\,\mathrm{km\,s^{-1}}$, a value substantiated by inspection of the measured speeds in the $\sim 65\,\mathrm{km\,s^{-1}}$ η-Aquarid shower[5,7]. 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 $v = 90\,\mathrm{km\,s^{-1}}$ would not have been gathered into the data set used here unless its speed was erroneously measured as being $V > 100\,\mathrm{km\,s^{-1}}$; 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 $\bar{V} \approx 164\,\mathrm{km\,s^{-1}}$ with an uncertainty of $\pm 30\,\mathrm{km\,s^{-1}}$, in agreement with a crude estimate of $\bar{V} \approx 140\,\mathrm{km\,s^{-1}}$ derived solely from their mean ionization height[7].

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 $\sim 100\,\mu m$ meteoroids from bound orbits we detect. Verniani[10] determined an empirical relation $q = 0.0509 m^{0.92} v^{3.91}$ 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 $q = 2.5 \times 10^{11}\,\mathrm{m^{-1}}$. At $v = 100\,\mathrm{km\,s^{-1}}$ the diameter of the smallest detectable meteoroid (assumed spherical with density 1 g cm^{-3}) is $\sim 40\,\mu m$; at $v = 200\,\mathrm{km\,s^{-1}}$ it is $\sim 15\,\mu m$. Far-infrared observations require a substantial ~ 30-μm interstellar grain component[11], 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-μm interstellar grains penetrating the Solar System[4]. Interstellar particles of order tens of micrometres are therefore not unexpected.

Our data set displays strong seasonal variations (Fig. 1), arguing

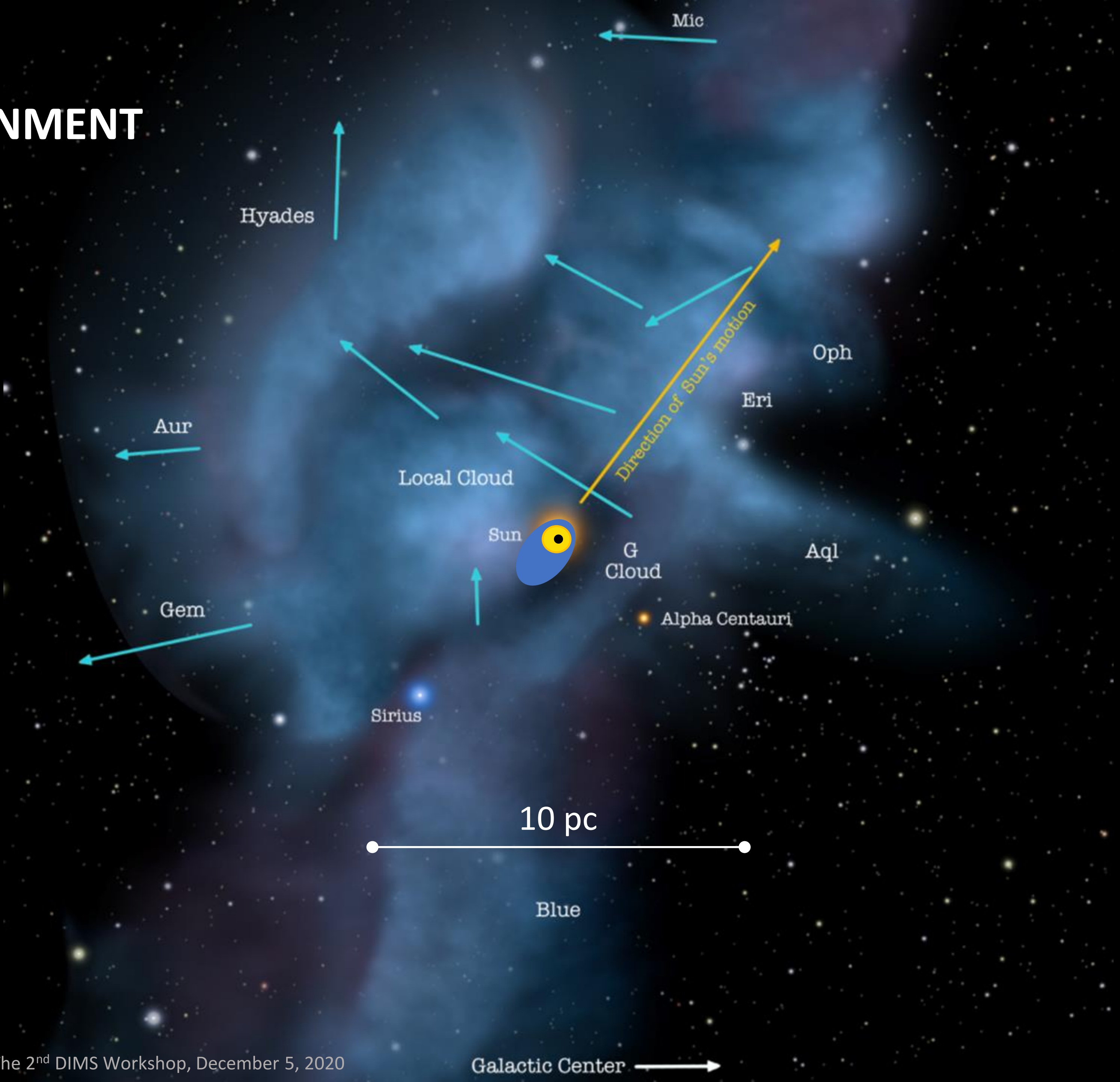
SPACE-BORN
DUST MEASUREMENTS

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?

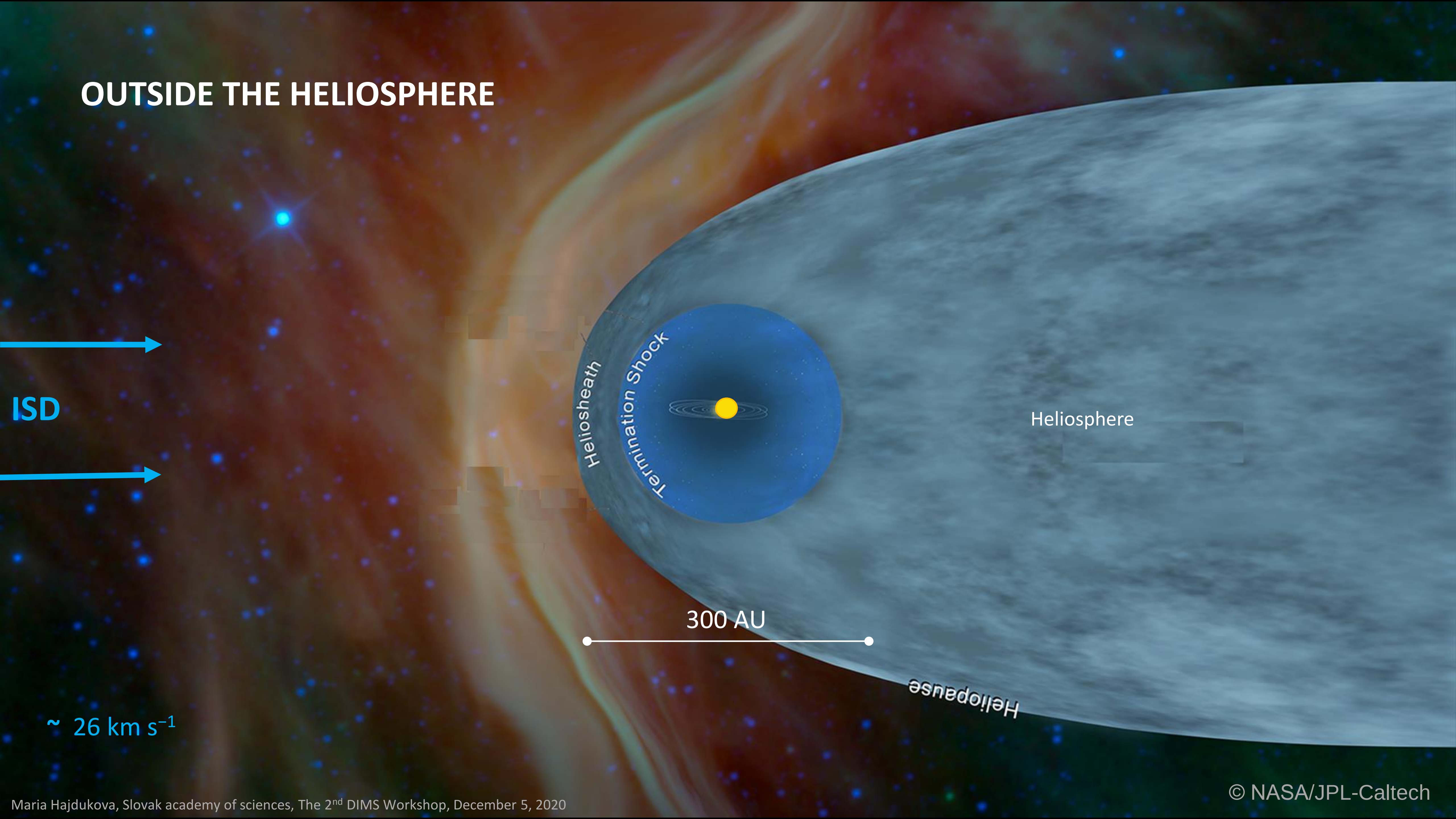
SUN’S ENVIRONMENT



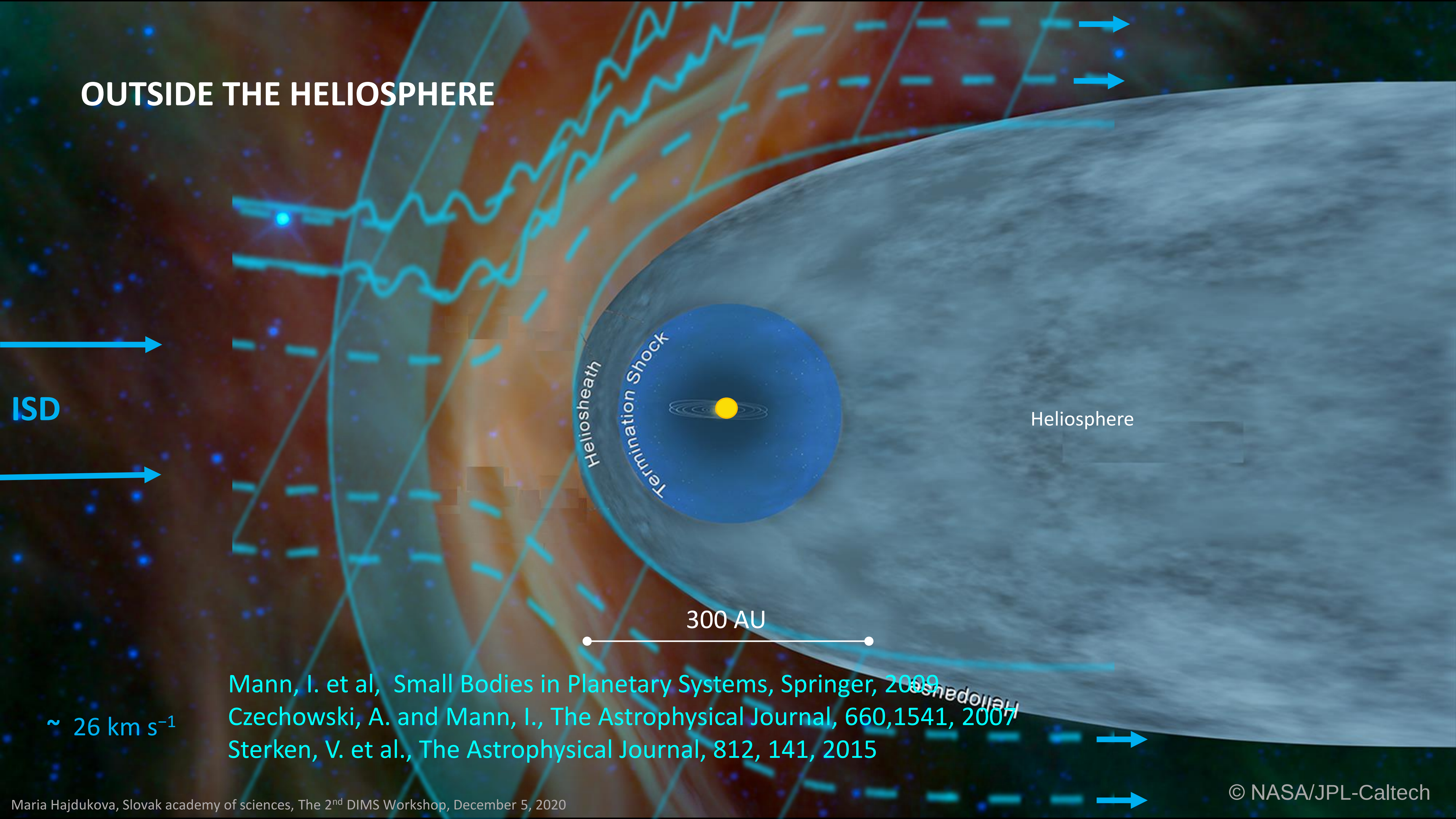
~ 26 km s^{-1}

© Redfield, 2012, Science

OUTSIDE THE HELIOSPHERE



OUTSIDE THE HELIOSPHERE



ISD

~ 26 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

INSIDE THE HELIOSPHERE

- Solar gravity
- Solar radiation pressure

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

- Lorentz force from the solar magnetic field

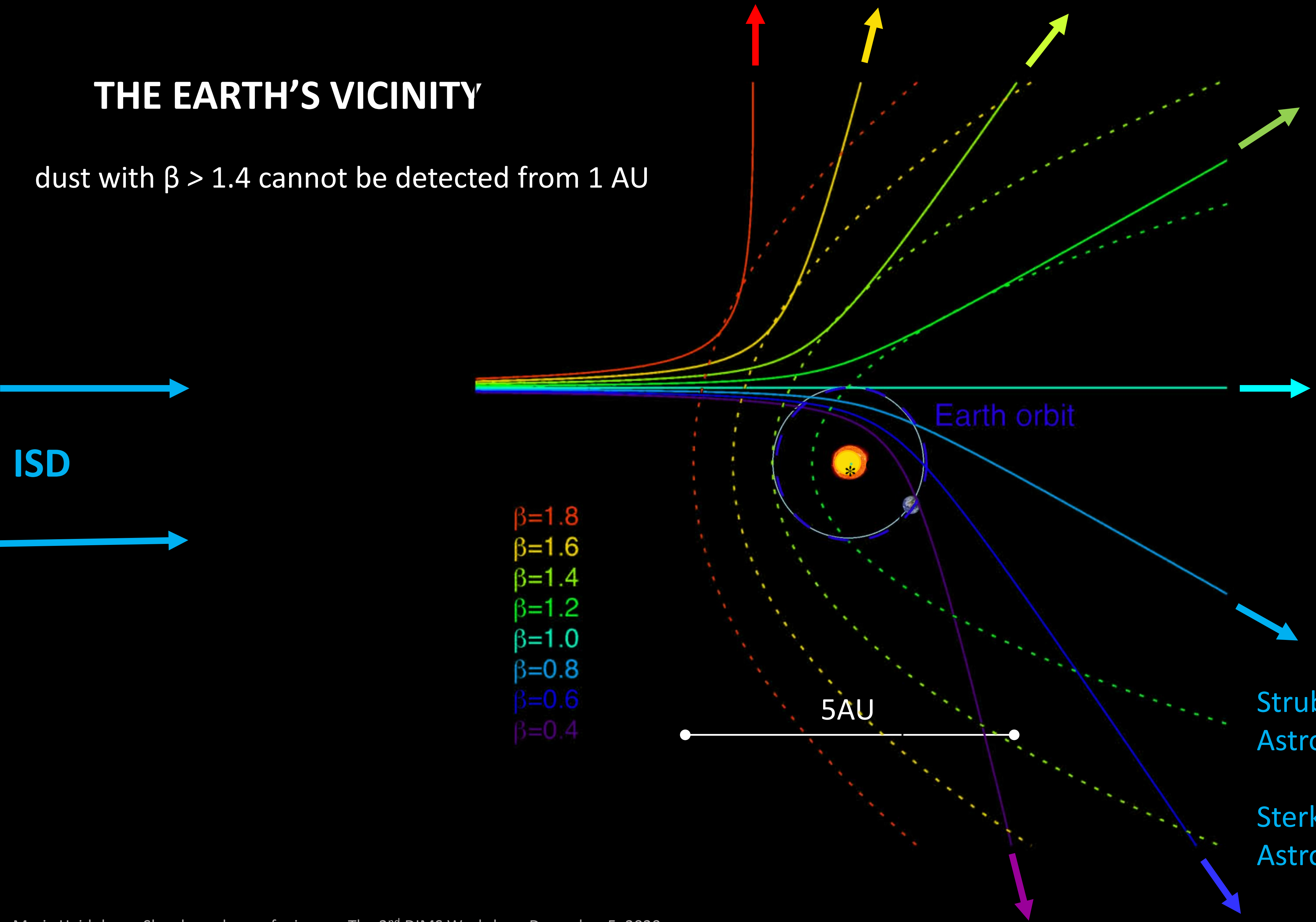
Q/m

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 β > 1.4 cannot be detected from 1 AU

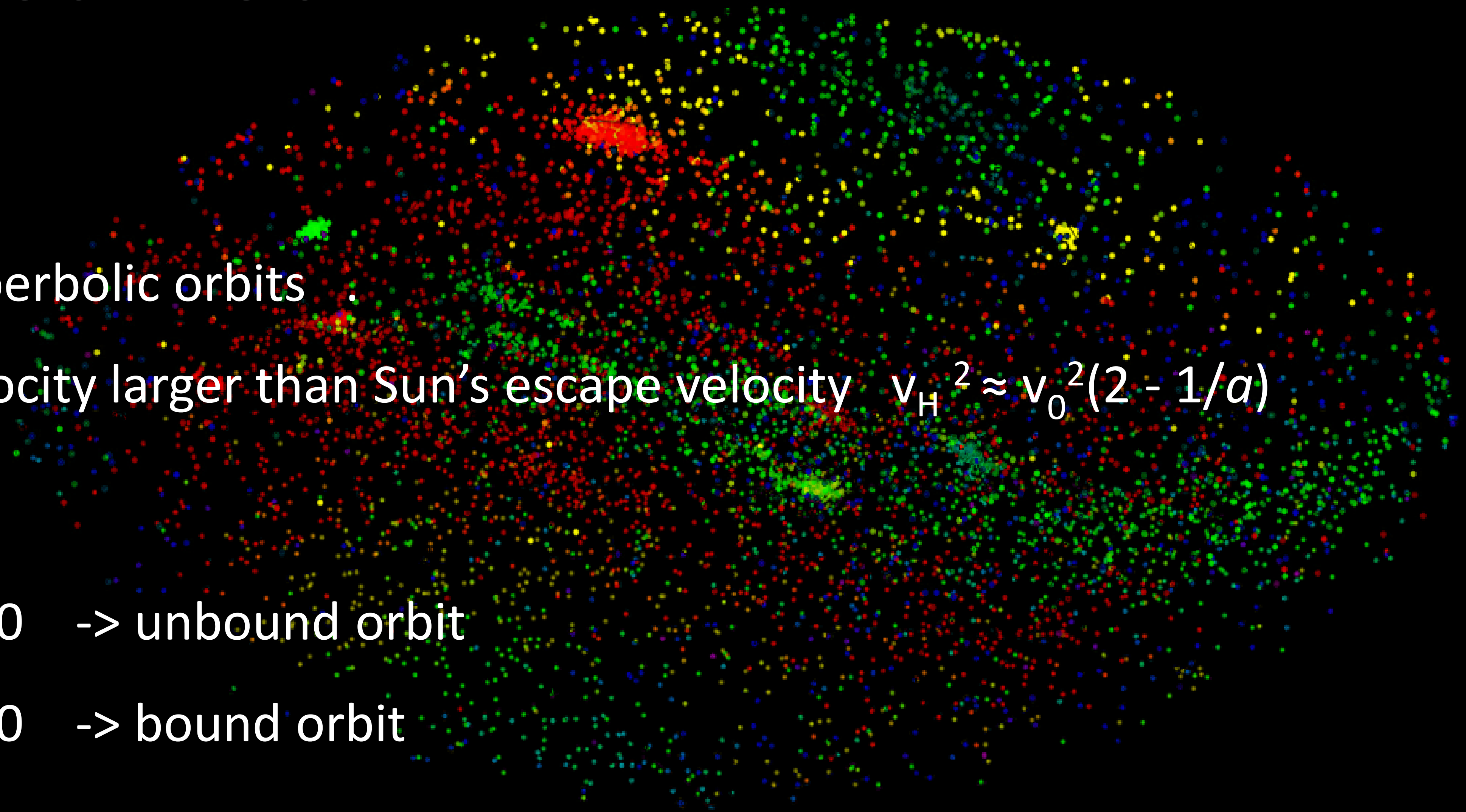


$\beta = F_{SRP} / F_{grav}$

Strub et al., Astronomy & Astrophysics, 621, id.A54 2019

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

METEOR OBSERVATIONS



-> hyperbolic orbits .

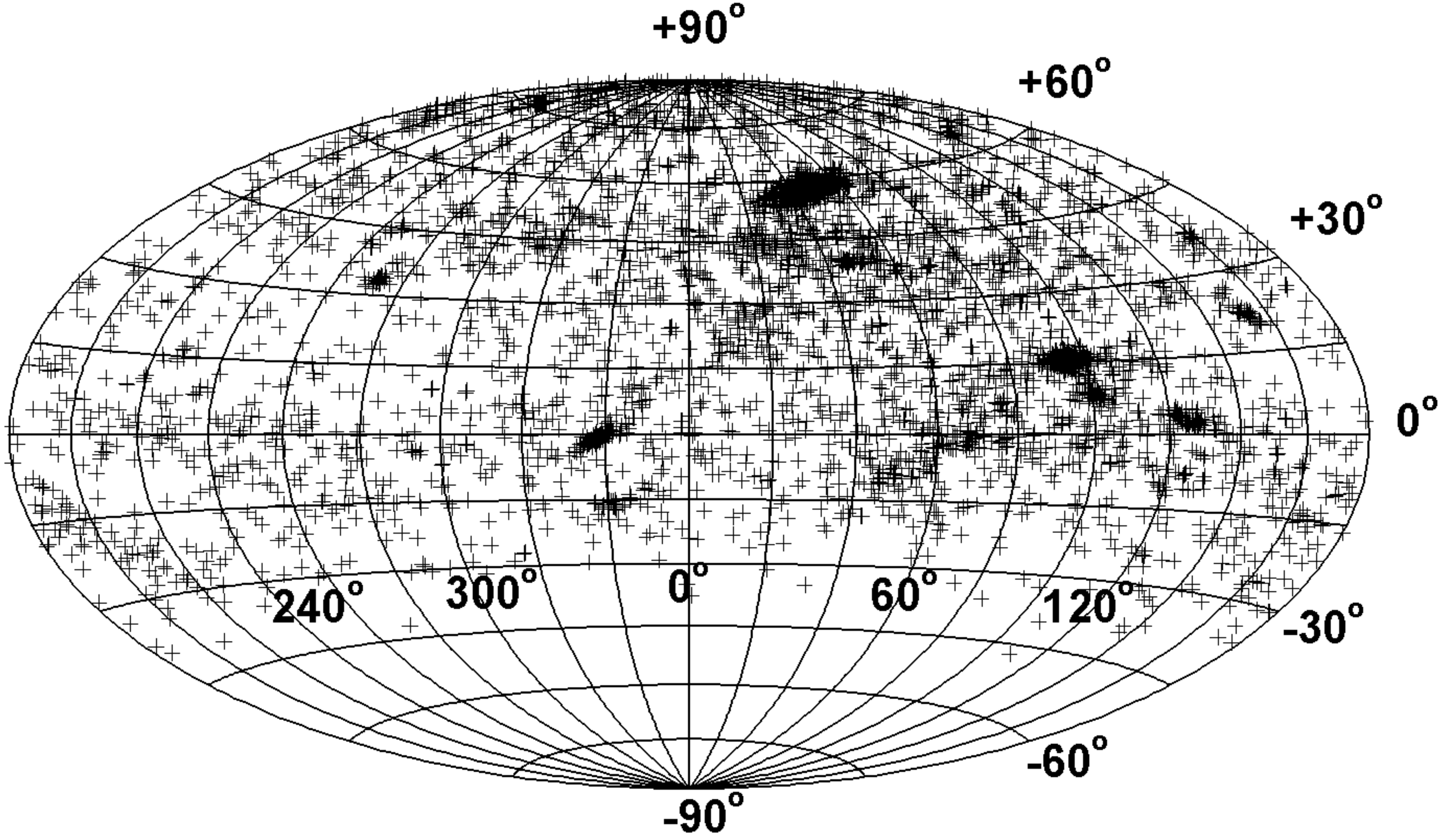
-> velocity larger than Sun's escape velocity $v_H^2 \approx v_0^2(2 - 1/a)$

$1/a < 0$ -> unbound orbit

$1/a > 0$ -> bound orbit

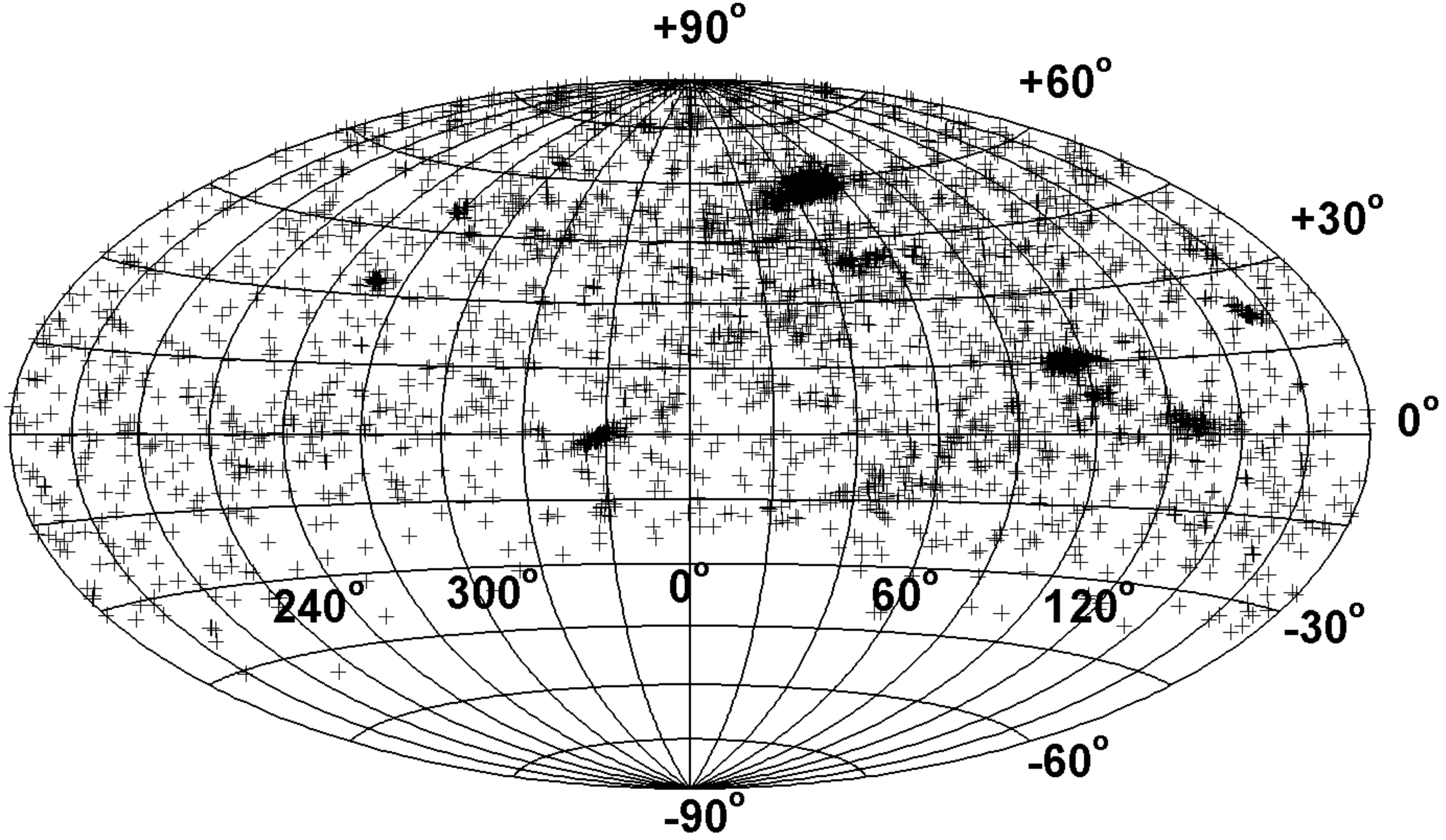
All-sky Meteor Orbit System AMOS
Toth, J. et al., Planetary and Space Science, 118, 102, 2015
Toth, J. et al, European Planetary Science Congress, Berlin, 2018

0.2 < 1/a < 0.1



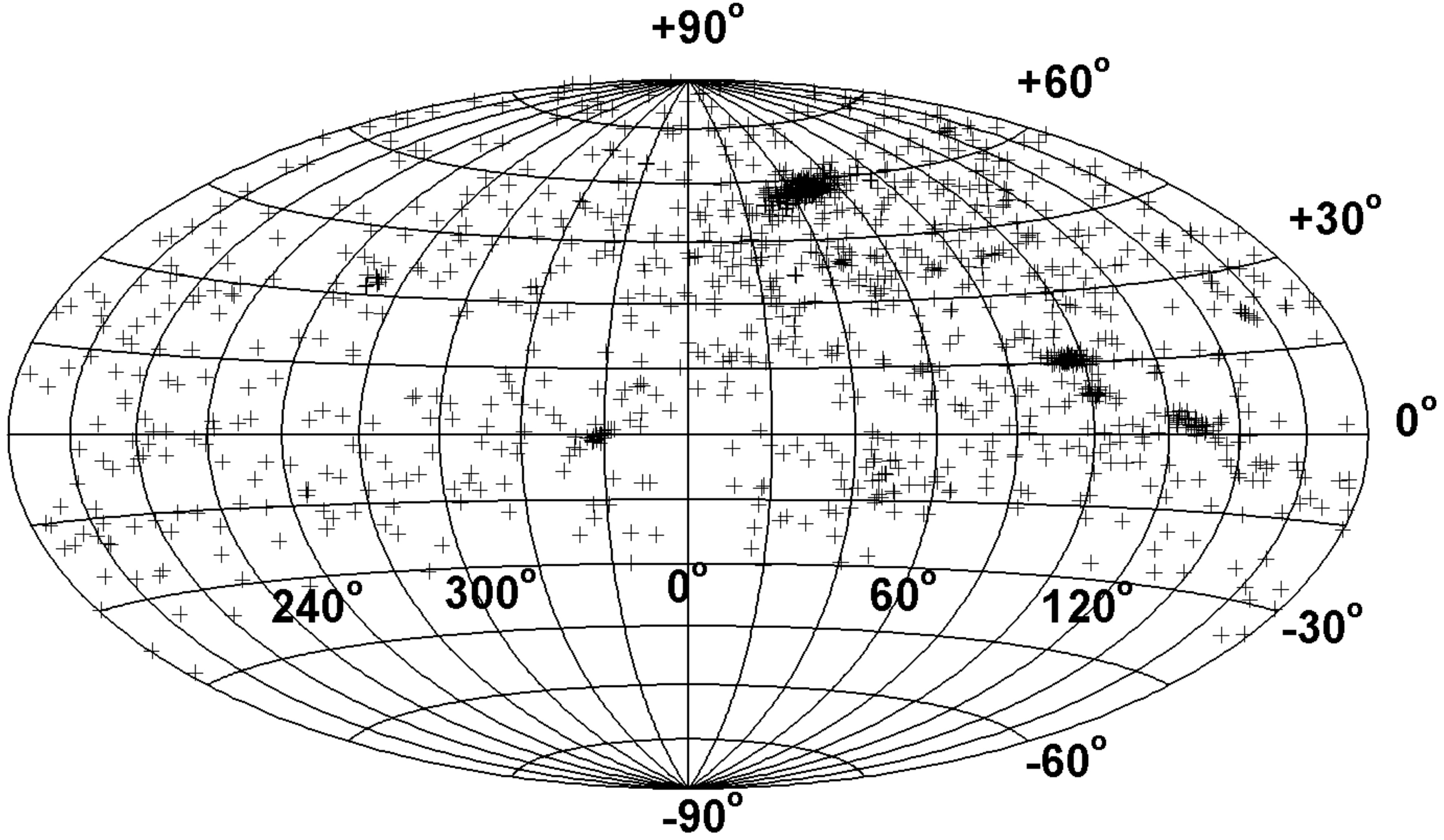
EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznan, Poland, IMO, 2013

0.0 < 1/a < 0.1



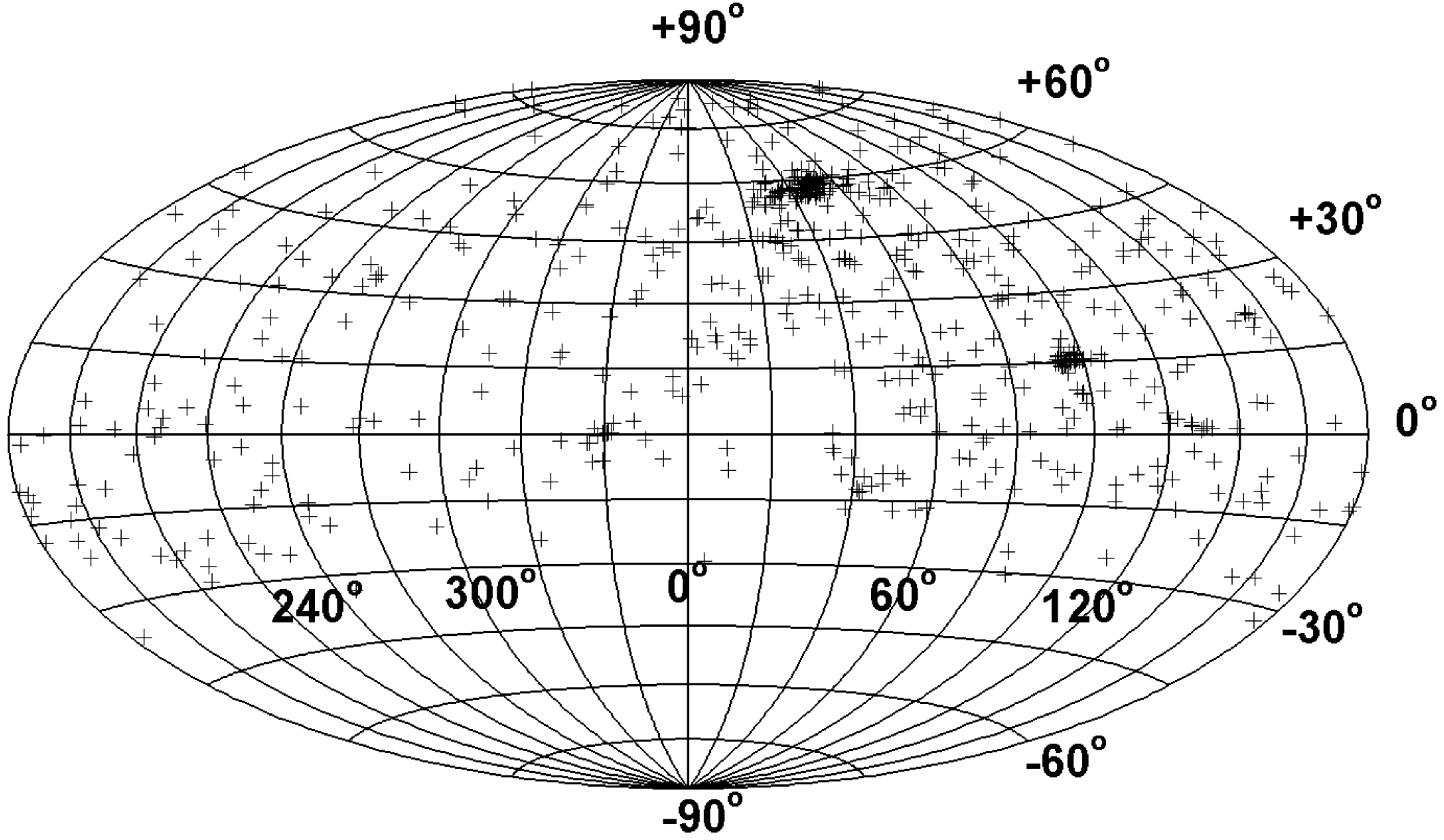
EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznan, Poland, IMO, 2013

-0.1 < 1/a < 0.0



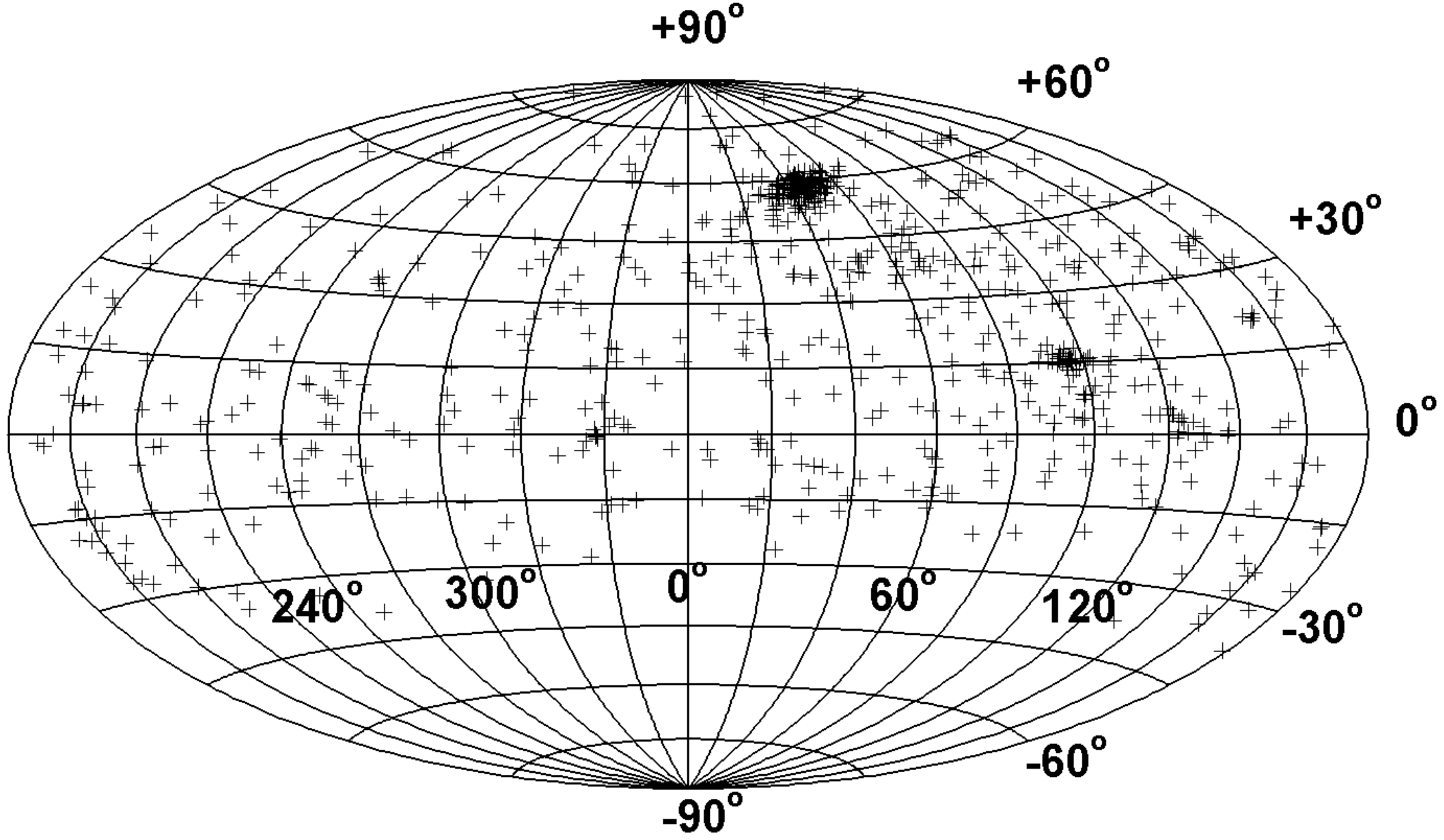
EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznan, Poland, IMO, 2013

-0.2 < 1/a < -0.1



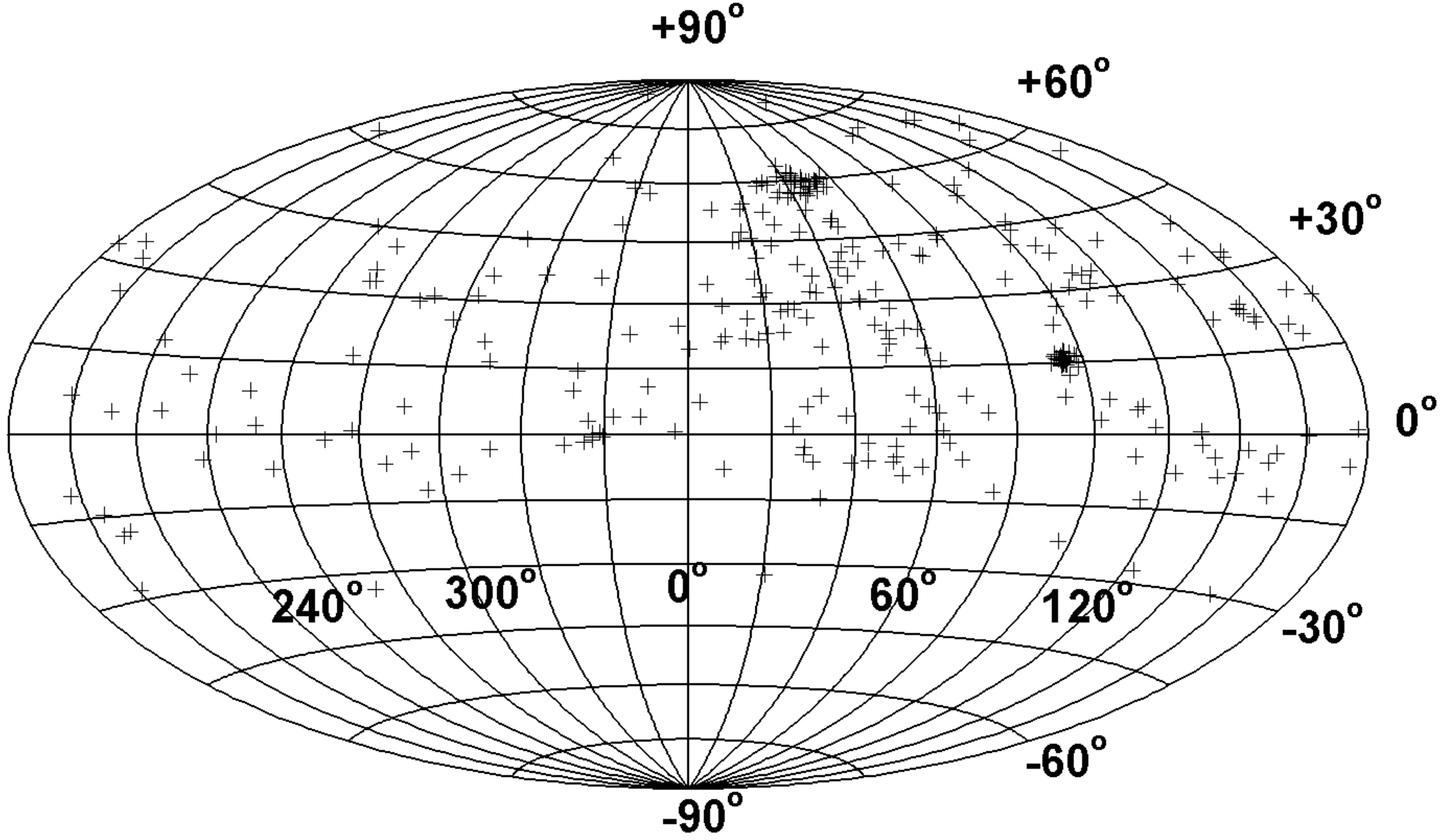
EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznan, Poland, IMO, 2013

-0.5 < 1/a < -0.2



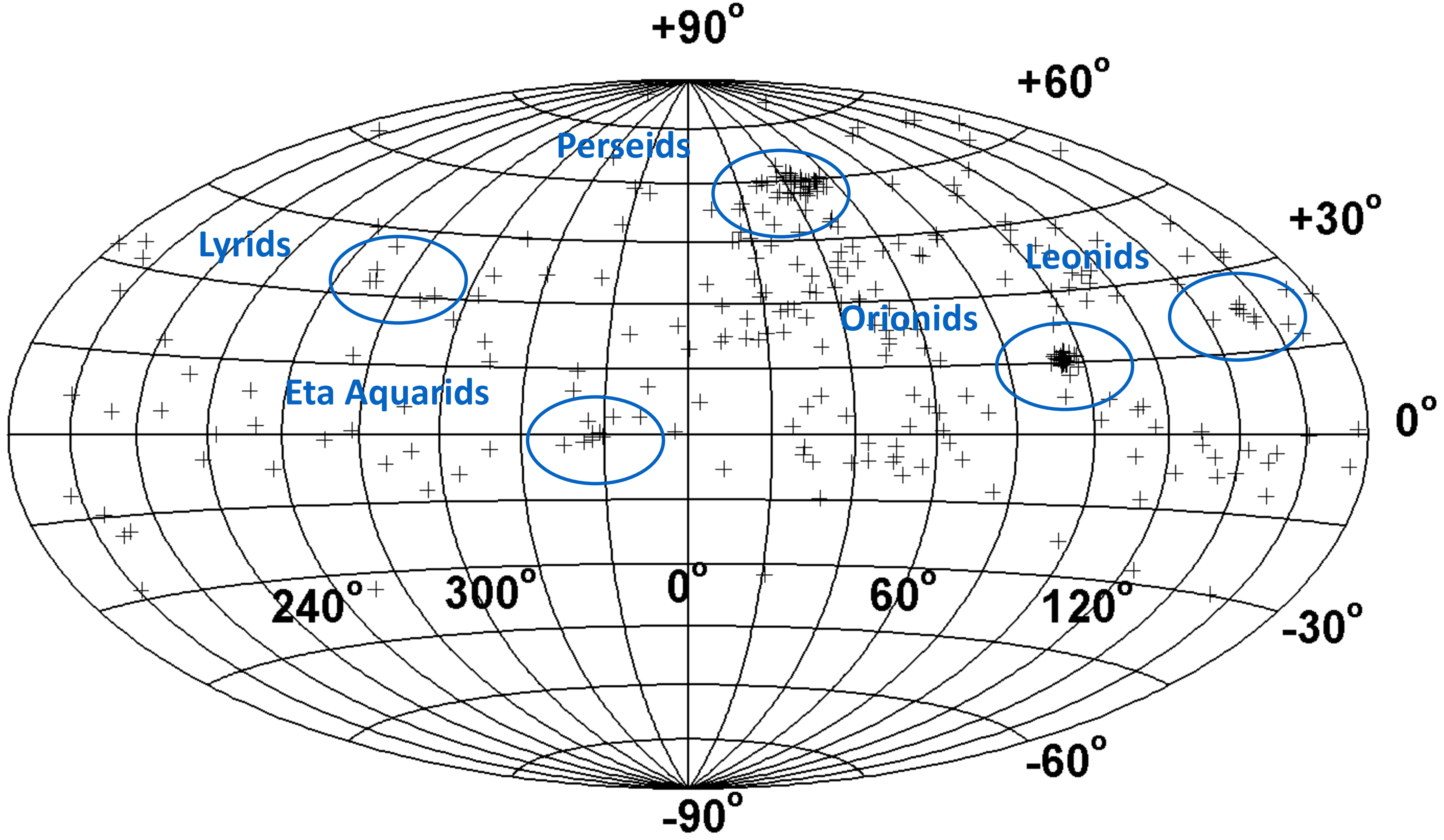
EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznan, Poland, IMO, 2013

1/a < -0.5



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

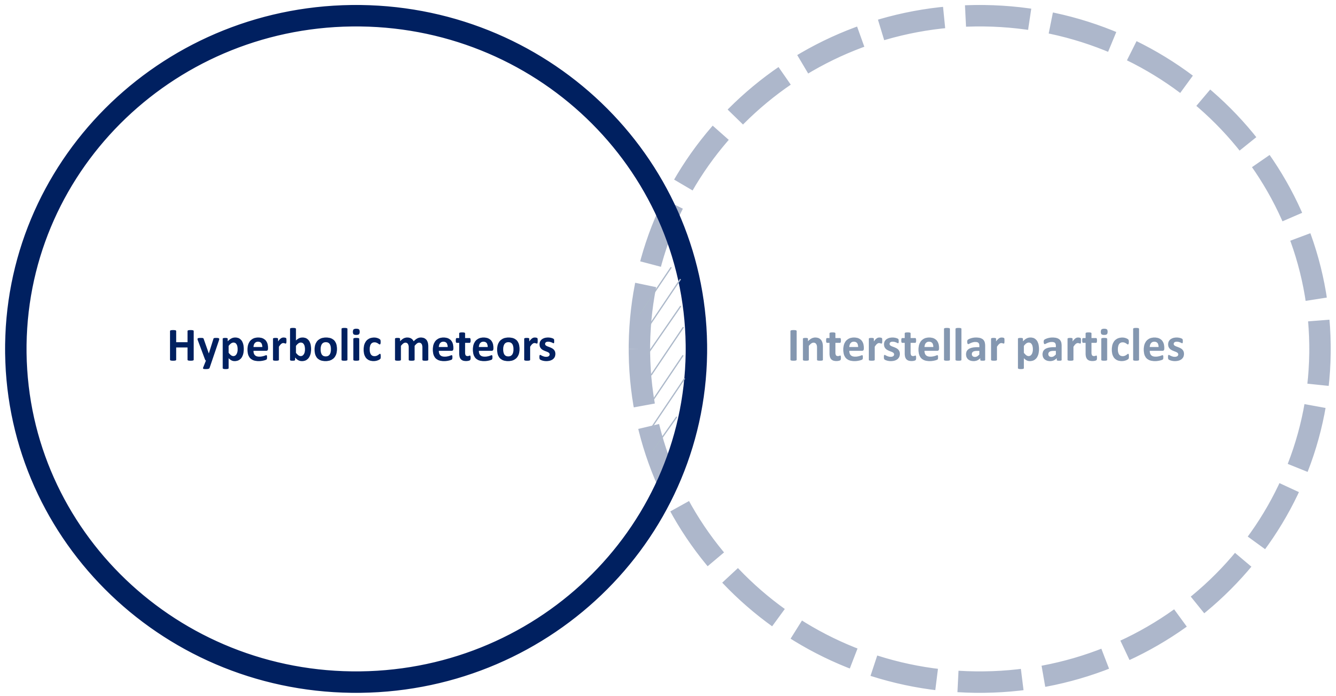
1/a < -0.5



Hajdukova, M., Earth Moon Planets, 102, 67, 2008
Hajdukova, M. et al., Proceedings of the Meteoroids 2013, Poznan, 289, 2013

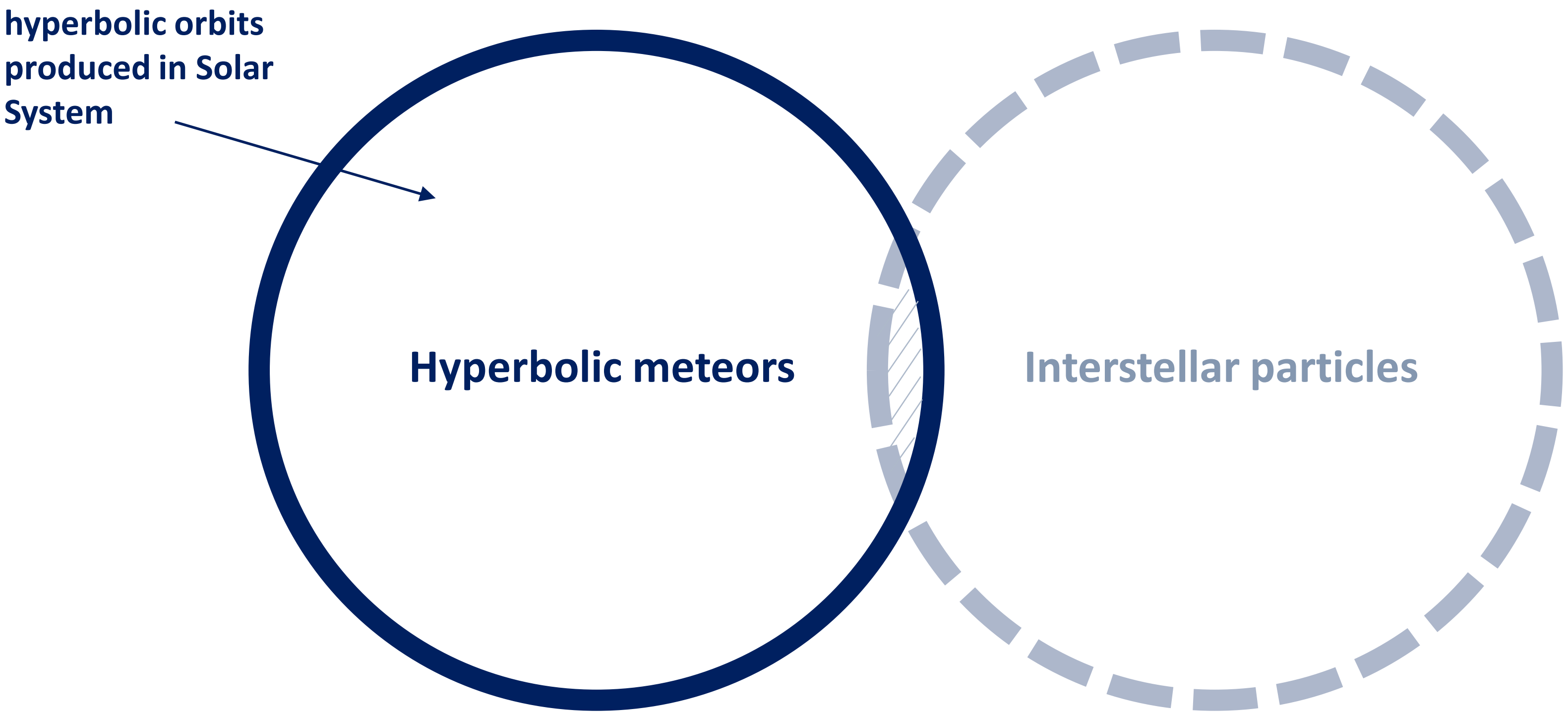
EDMOND database
Kornoš et al., Proceedings of the International Meteor Conference, Poznan, Poland, IMO, 2013

- How many observed hyperbolic meteors are interstellar?



- How many observed hyperbolic meteors are interstellar?

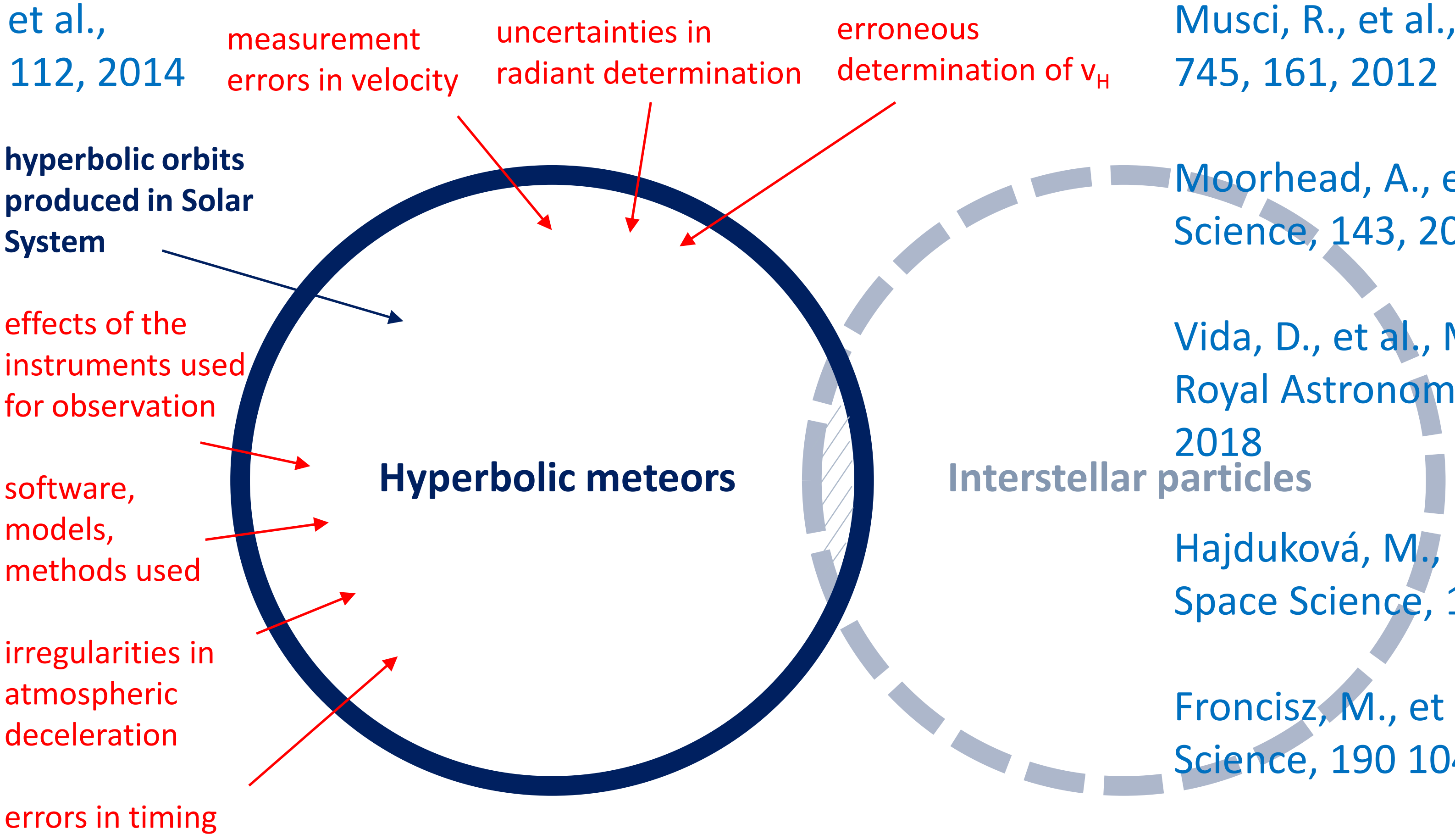
Wiegert, P., et al.,
Icarus, 242, 112, 2014



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

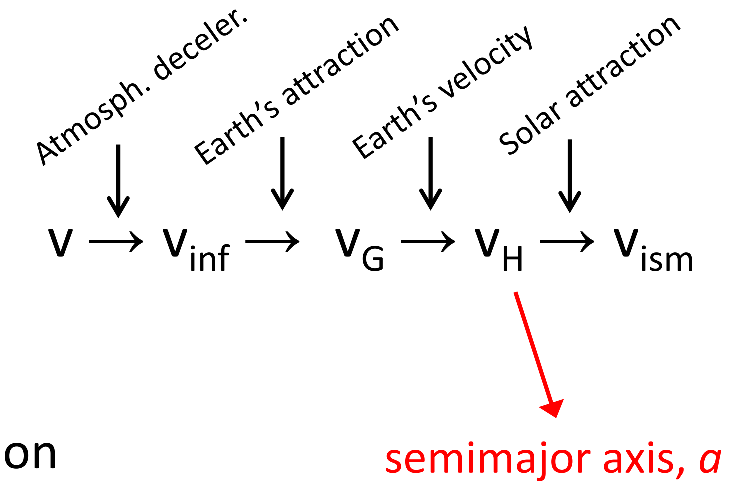
Hajduková, M., Kornos, L., Planetary and Space Science, 190, 104965, 2020

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

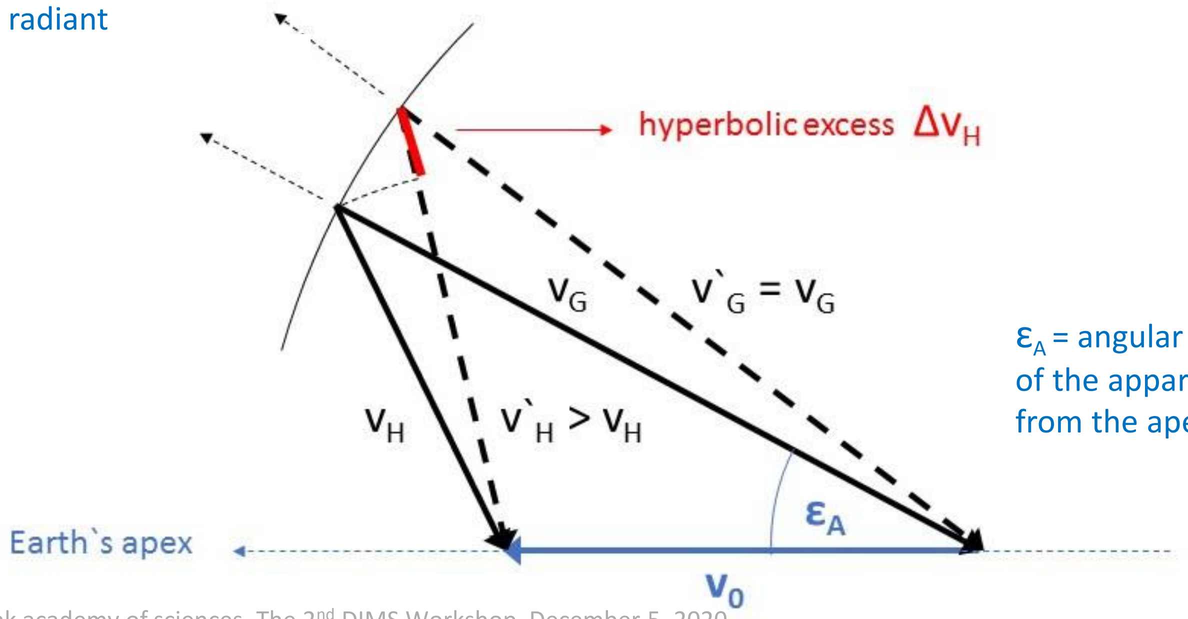
Chen, H., Tambaux, N., Vaubaillon, J., Astronomy & Astrophysics, 642, L11, 2020

INFLUENCE OF ERRORS (r, v) -> FALSE POSITIVES

-> Error in the speed



-> Error in the radiant position



ε_A = angular elongation of the apparent radiant from the apex

106 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 affected ...

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 ... orbit caused by perturbations could be observed ... be observable in the course ...

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

ASTRONOMY AND ASTROPHYSICS

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 vasting majority of the 347 hyperbolic ... are subject to erroneous determi- ... 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 ... results show that the question of hyperbolic and ... open and to a certain

Planetary and Space Science 192 (2020) 105060

Contents lists available at ScienceDirect

Planetary and Space Science

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

ELSEVIER

Review Article

The challenge of identifying interstellar meteors

Maria Hajdukova [a,*], Veerle Sterken [b], Paul Wiegert [c], Leonard Kornoš [d]

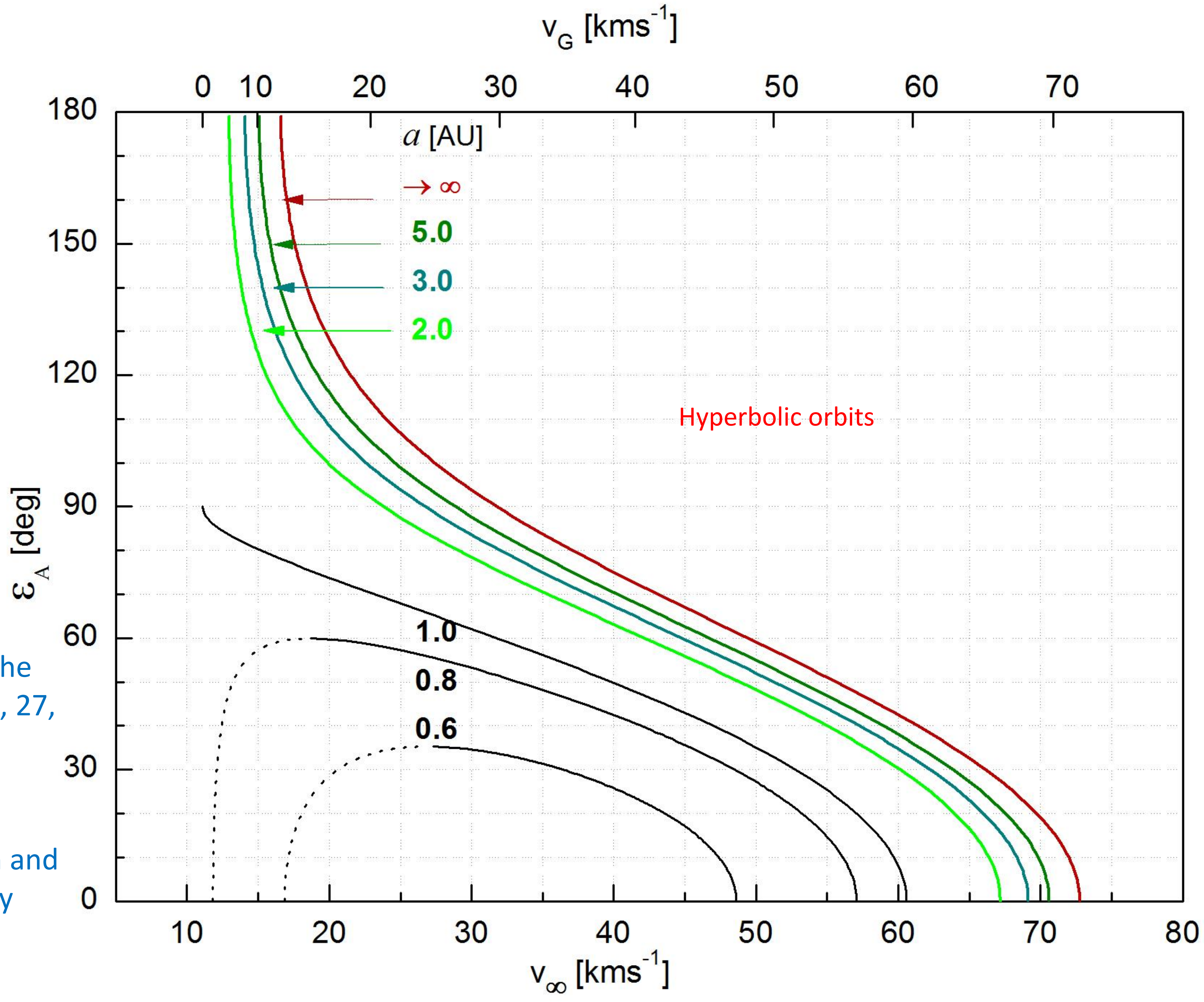
[a] Astronomical Institute, Slovak Academy of Sciences, Bratislava, Slovakia
[b] Institute for Particle Physics and Astrophysics, ETH Zürich, Switzerland
[c] Department of Physics and Astronomy, University of Western Ontario, London, ON, Canada
[d] Faculty of Mathematics, Physics and Informatics, Comenius 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 Czecho-slovakia, 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

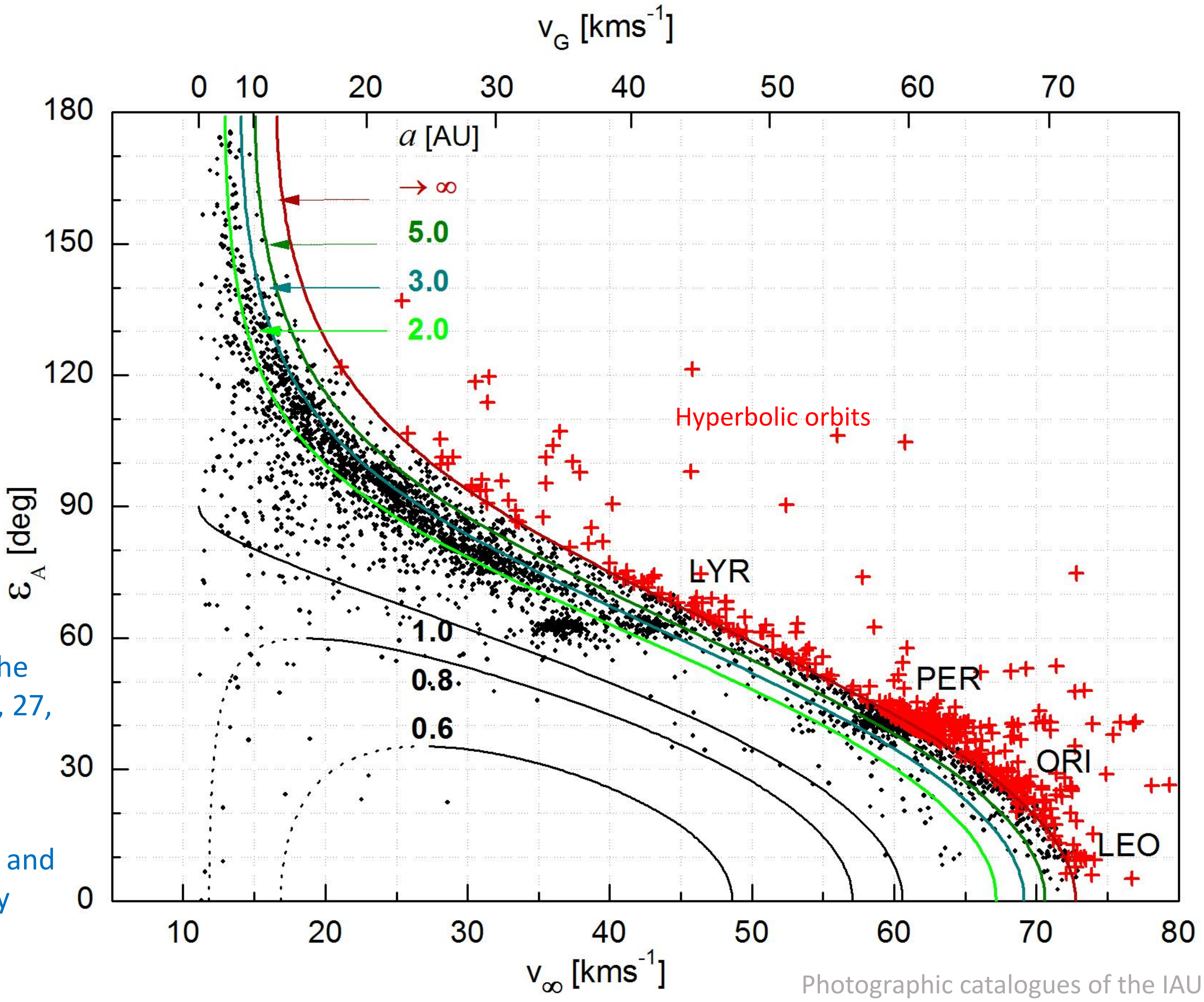
wide range v_G
11 - 72 km/s

⇣

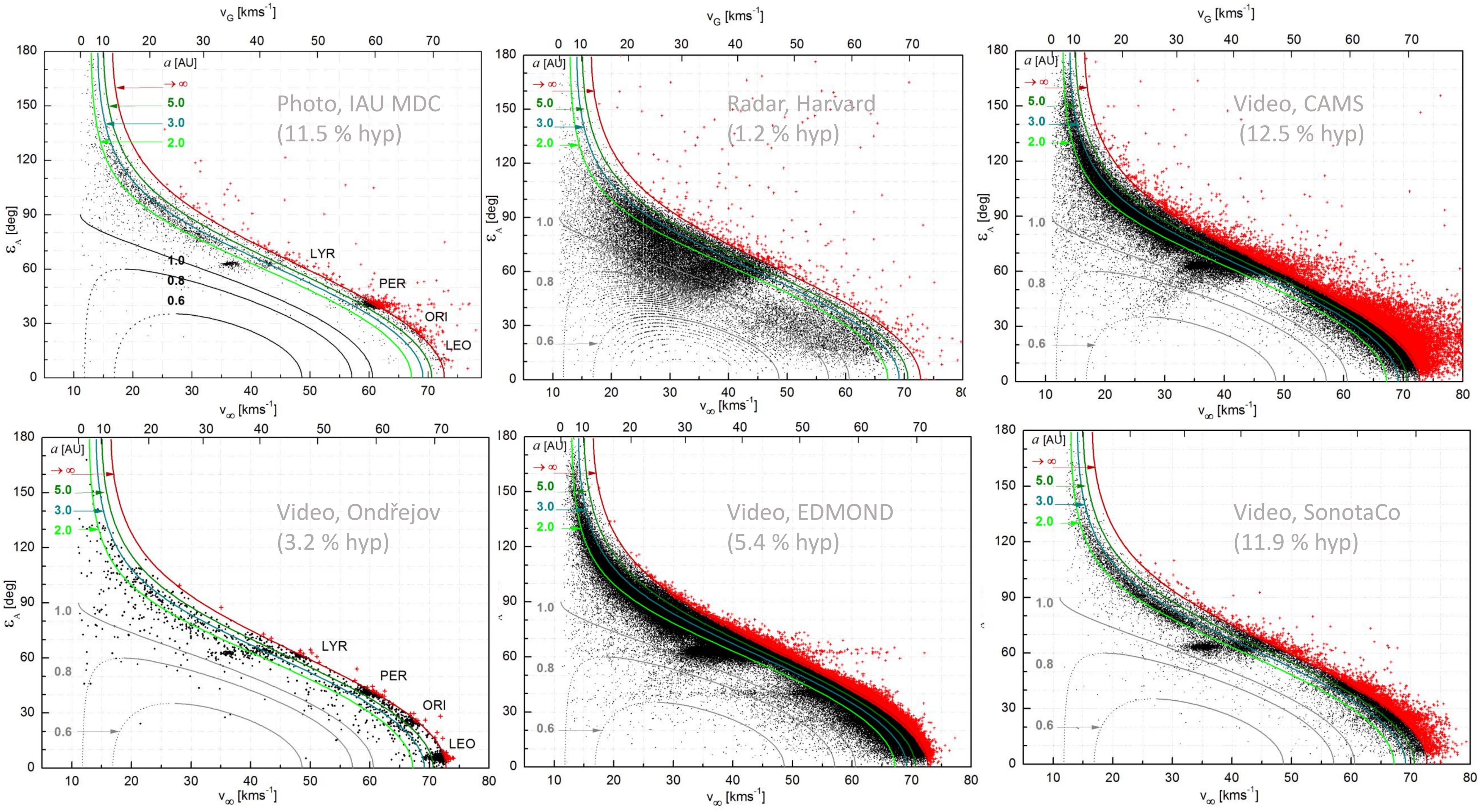
narrow range v_H
36 - 42 km/s

Kresák, L. and Kresáková, M., Bulletin of the Astronomical Institute of Czecho-slovakia, 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.

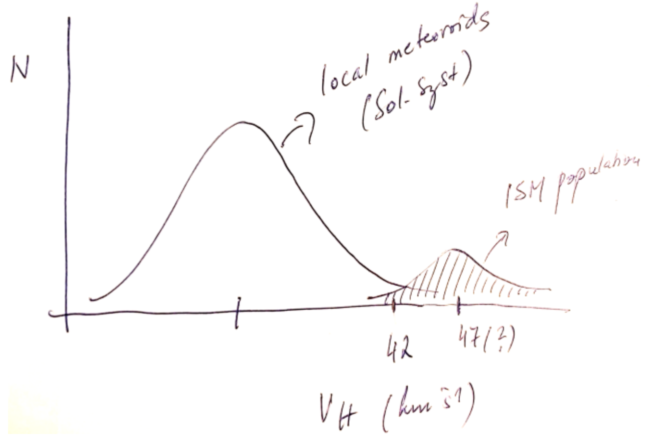


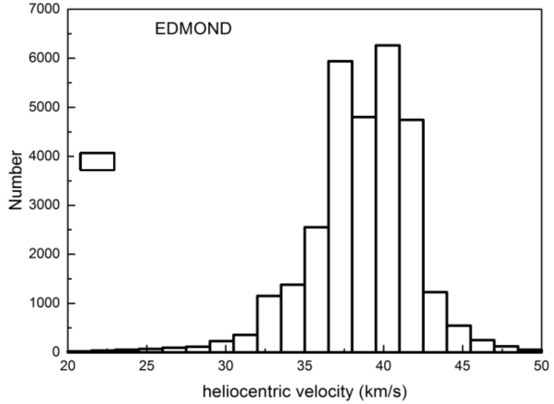
Hajdukova, M., et al., Planetary and Space Science, 192, id. 105060, 2020

INFLUENCE OF ERRORS -> FALSE POSITIVES

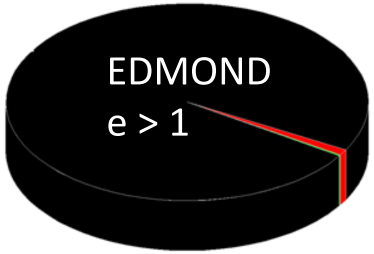
WHY?

should be observed
but is not !



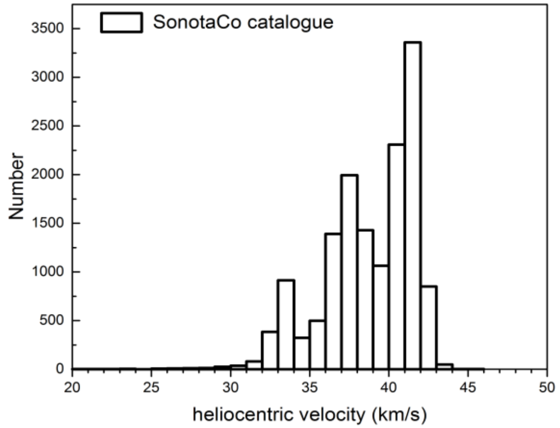


Hyperbolic orbits in the database **due to errors** **98,9%**
Upper limit of possible interstellar meteoroids
Close planetary encounters

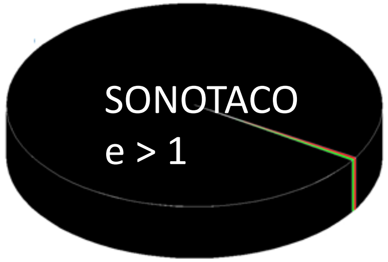


N_{all} = 83 369
$N_{e>1}$ = 4 712

after an error analysis:
N_{ism}/N_{all} = 0.9×10^{-3}



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



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

after an error analysis:
N_{ism}/N_{all} = 1.3×10^{-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} ±1 km/s

radiant ±1°

Nominal orbit:

q = 0.945 au

a = 19 au

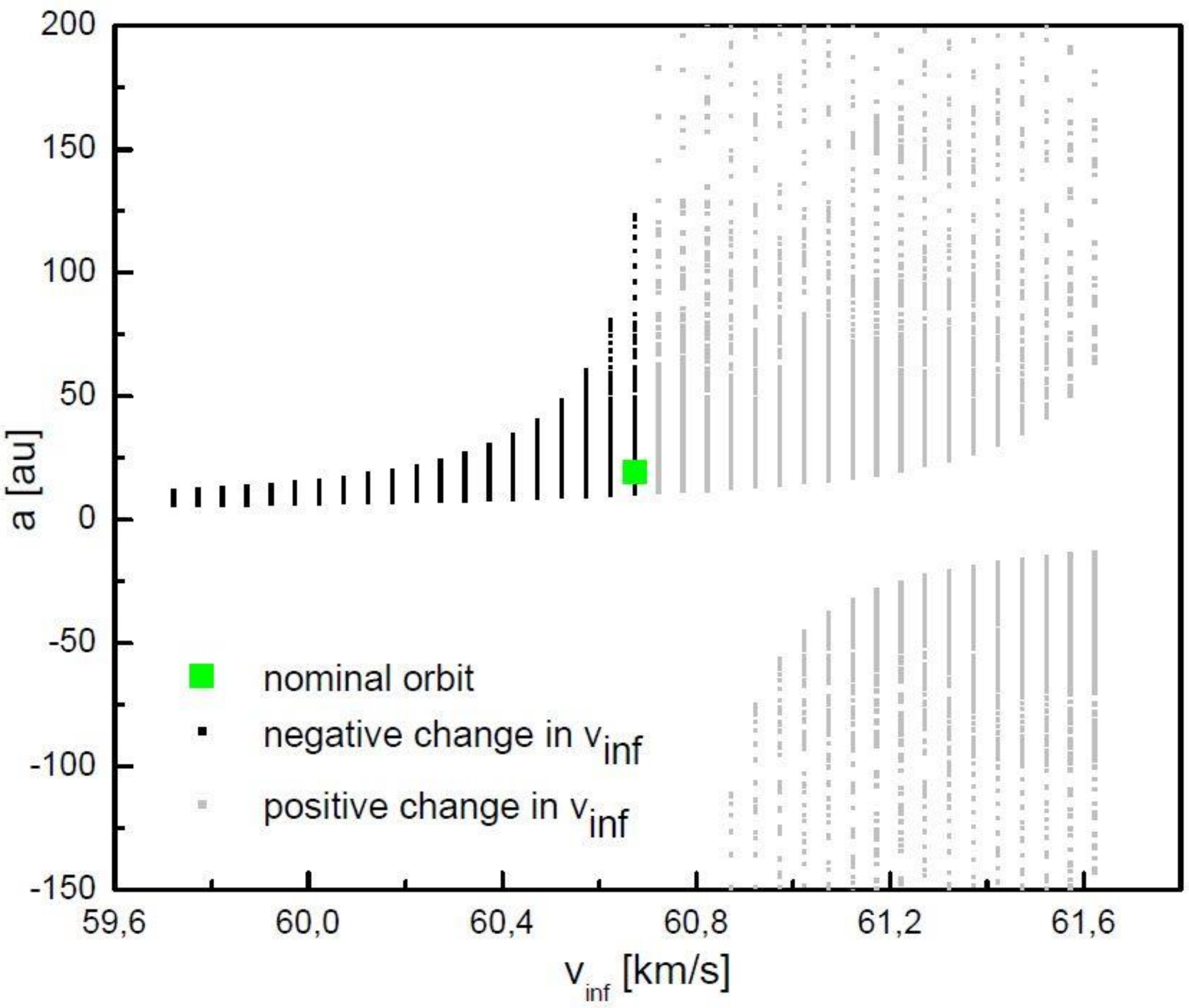
e = 0.95

Q = 37 au

i = 113°

-> 1/3 of clones created hyperbolic orbits

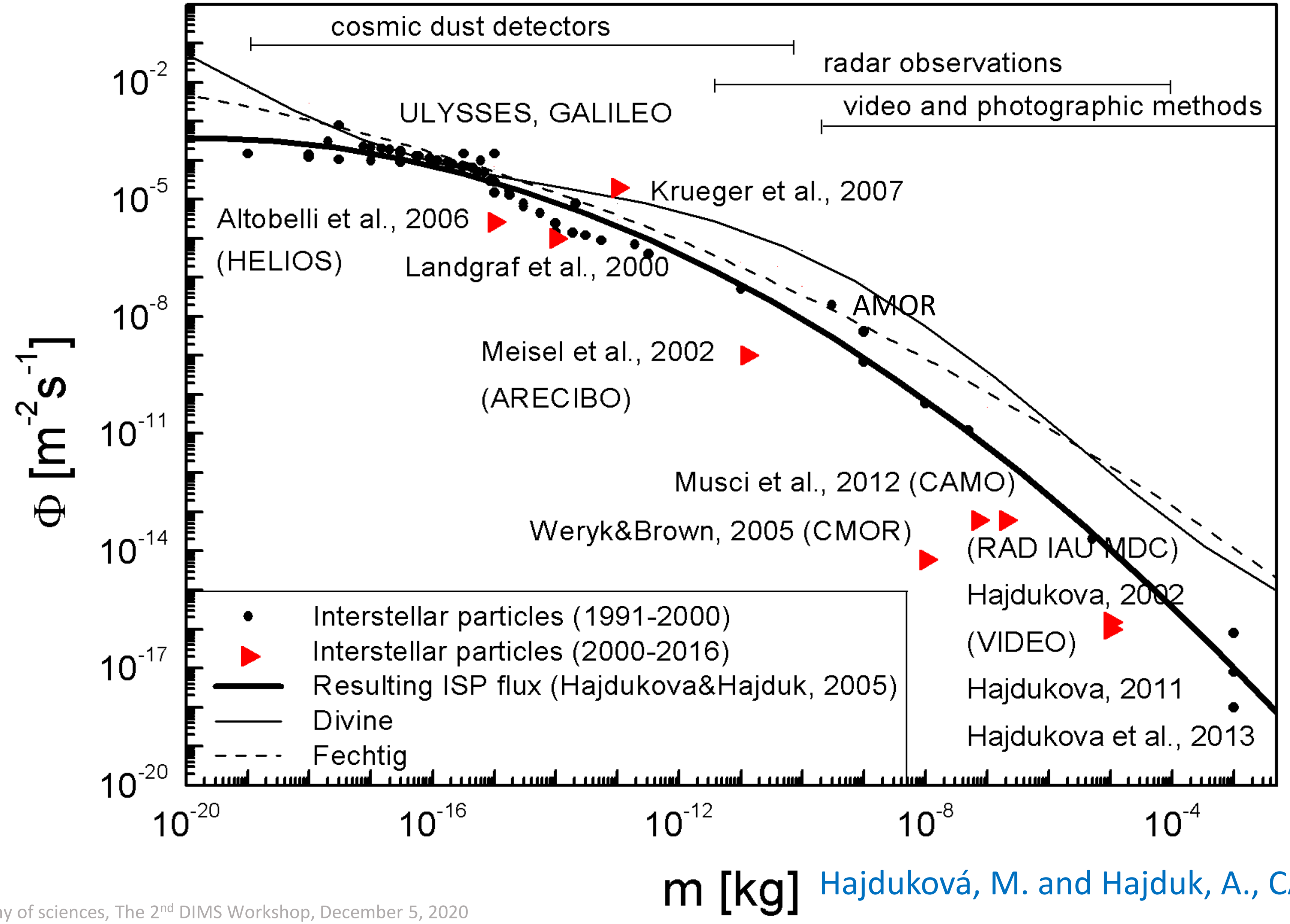
-> any small errors in velocity and/or radiant position can change the type of orbit



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

AND MANY OTHERS …

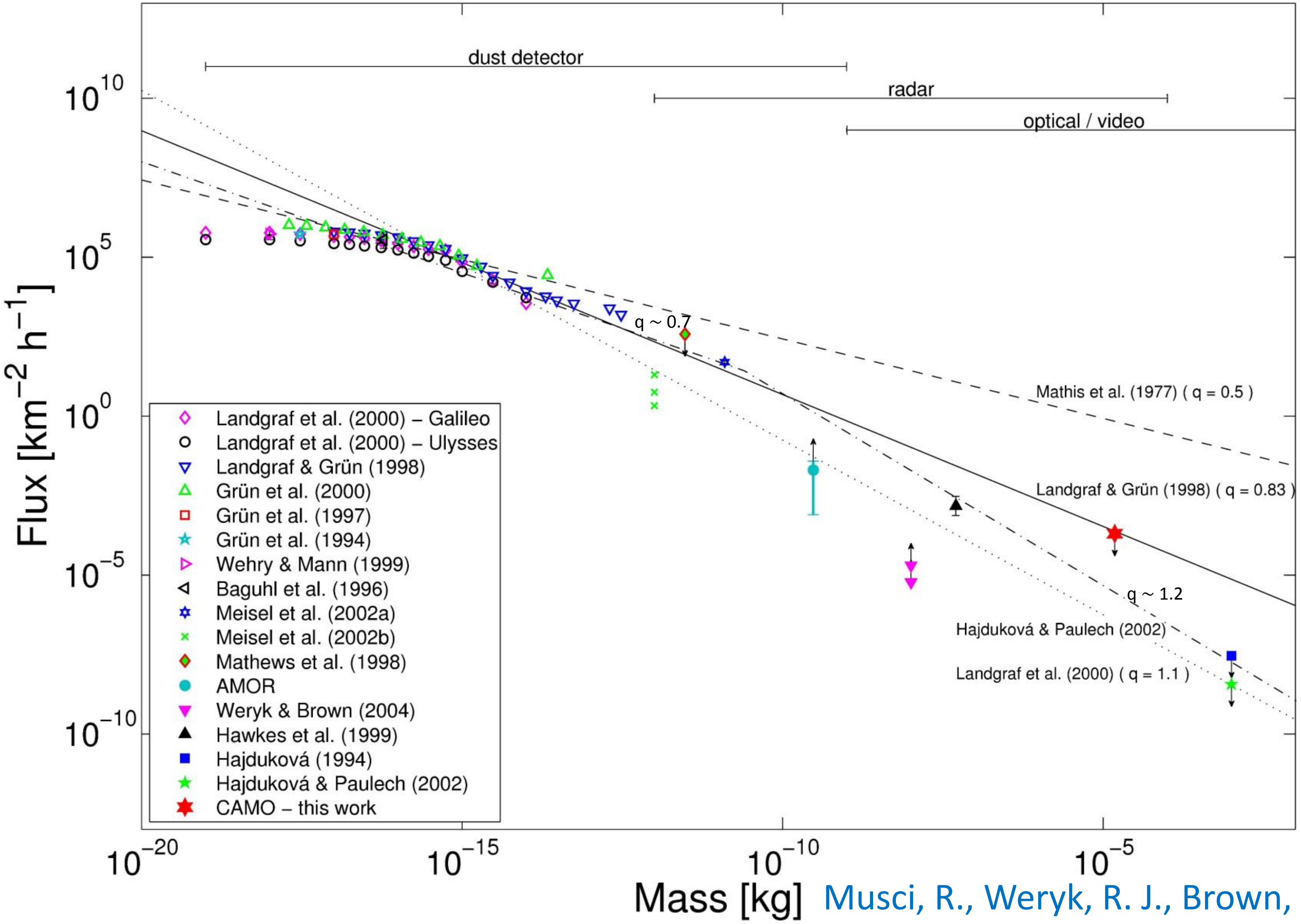
FLUX OF ISP compared with the flux of interplanetary particles



Hajduková, M. and Hajduk, A., CAOSP, 36, 15, 2006

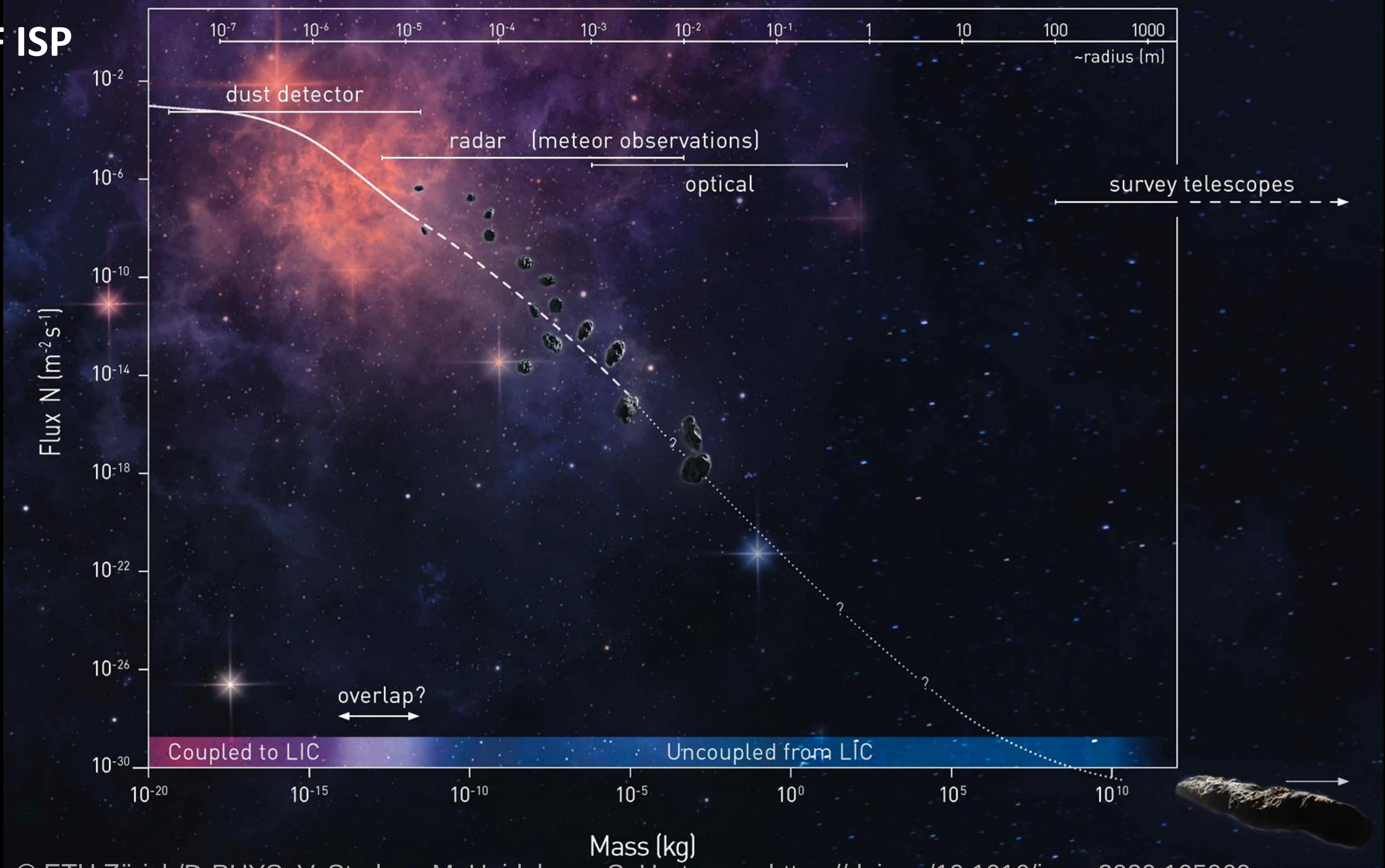
FLUX OF ISP

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



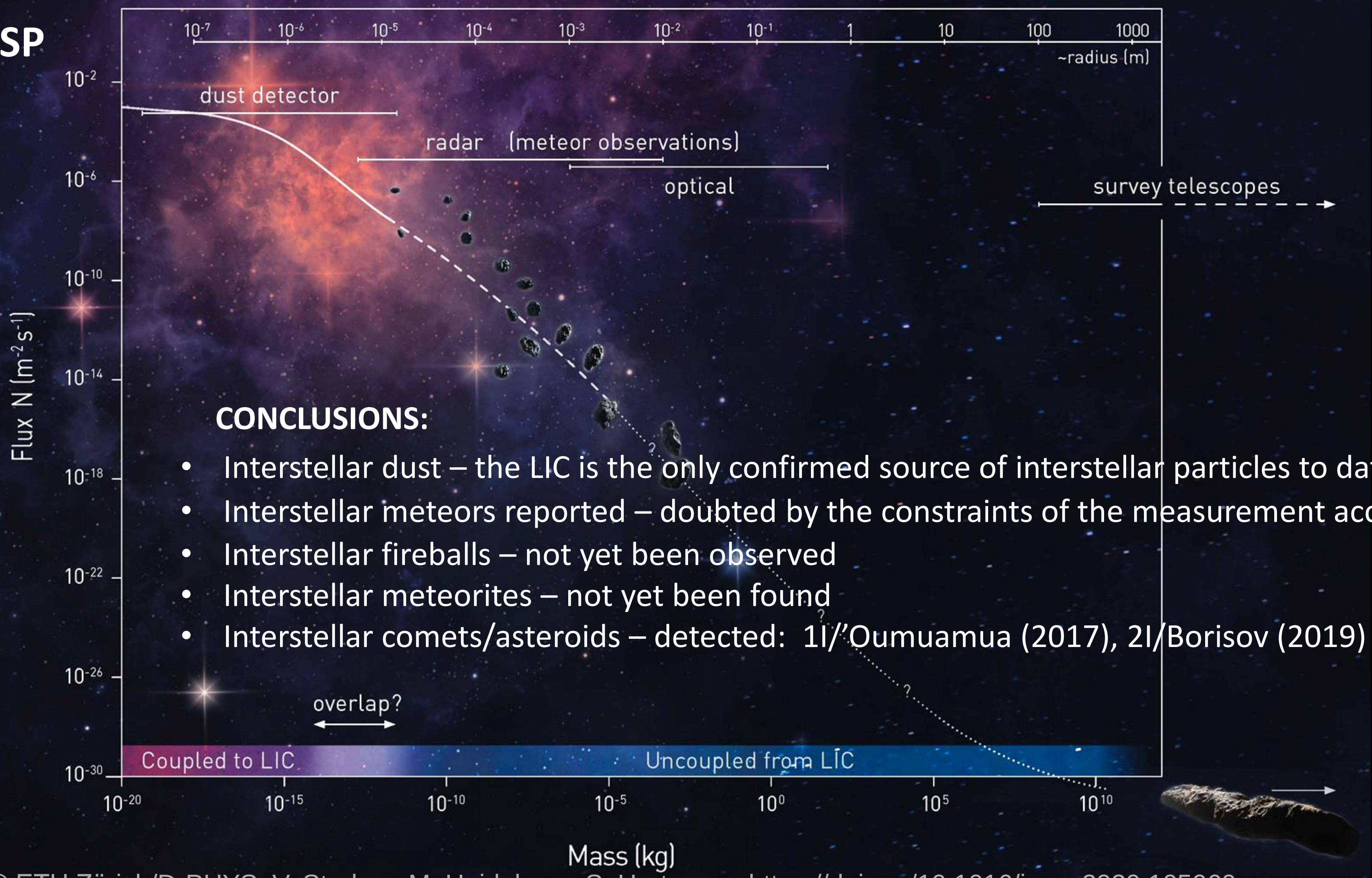
Musci, R., Weryk, R. J., Brown, P., Campbell-Brown M., Wiegert, P., Astrophysical Journal, 745, 161, 2012

FLUX OF ISP



10-7
10-6
10-5
10-4
10-3
10-2
10-1
1
10
100
1000
~radius (m)
dust detector
radar
(meteor observations)
optical
survey telescopes
Flux N (m-2 s-1)
10-2
10-6
10-10
10-14
10-18
10-22
10-26
10-30
overlap?
Coupled to LIC
Uncoupled from LIC
10-20
10-15
10-10
10-5
100
105
1010
Mass (kg)

FLUX OF ISP



CONCLUSIONS:

- Interstellar dust – the LIC is the only confirmed source of interstellar particles to date
- Interstellar meteors reported – doubted by the constraints of the measurement accuracy
- Interstellar fireballs – not yet been observed
- Interstellar meteorites – not yet been found
- Interstellar comets/asteroids – detected: 1I/'Oumuamua (2017), 2I/Borisov (2019)

ACKNOWLEDGMENTS

This work was supported by by the Slovak Research and Development Agency, contract No. APVV-16-0148.

REFERENCES

Chen, H., Tambaux, N., Vaubaillon, J., *Astronomy & Astrophysics*, 642, L11, **2020**
Czechowski, A. and Mann, I., *The Astrophysical Journal*, 660,1541, **2007**
Froncisz, M., Brown, P., Weryk, R., *Planetary and Space Science*, 190 104980, **2020**
Hajduková , M., *Astronomy & Astrophysics*, 288, 330, **1994**
Hajduková, M. and Hajduk, A., *Contributions of the Astronomical Observatory Skalnaté Pleso*, 36, 15, **2006**
Hajduková, M., *Earth Moon Planets*, 102, 67, **2008**
Hajduková, M., Kornoš, L., Tóth, J., *Proceedings of the Meteoroids 2013*, Poznan, 289, **2013**
Hajduková , M., Sterken, V., Wiegert, P., *Meteoroids: Sources of Meteors on Earth and Beyond*, Cambridge University Press, 235, **2019**
Hajduková, M., Sterken, V., Wiegert, P., Kornoš, L., *Planetary and Space Science*, 192, id. 105060, **2020**
Hajduková, M., Kornoš, L., *Planetary and Space Science*, 190, 104965, **2020**
Kresák, L. and Kresáková, M., *Bulletin of the Astronomical Institute of Czechoslovakia*, 27, 106, **1976**
Mann, I., Nakamura, A.M., Mukai, T., *Small Bodies in Planetary Systems*, Springer, **2009**
Moorhead, A., Brown, P., Campbell-Brown, M., Heynen, D., Cook, W., *Planetary and Space Science*, 143, 209, **2017**
Musci, R., Weryk, R., Brown, P., Campbell-Brown, M., Wiegert, P., *The Astrophysical Journal*, 745, 161, **2012**
Sterken, V., Altobelli, N., Kempf, S., Schwehm, G., Srama, R., Grün, E., *Astronomy & Astrophysics*, 538, A102, **2012**
Sterken, V., Strub, P., Jrueger, H., von Steiger, R., Frisch, P., *The Astrophysical Journal*, 812, 141, **2015**
Sterken, V., Westphal, A., Altobelli, N., Malaspina, D., Postberg, F., *Space Science Reviews*, 215,43, **2019**
Strub, P., Sterken, V., Soja, R., Grün, E., Srama, R., *Astronomy & Astrophysics*, 621, id.A54, **2019**
Vida, D., Brown, P., Campbell-Brown, M., *Monthly Notices of the Royal Astronomical Society*, 479, 4, 4307, **2018**
Wiegert, P., *Icarus*, 242, 112, **2014**

Thank you for your attention