The Topic of the Talk:
Interstellar Now!
Missions to Explore Nearby Interstellar Objects

This would not have been possible without With My Colleagues in and Through i4is

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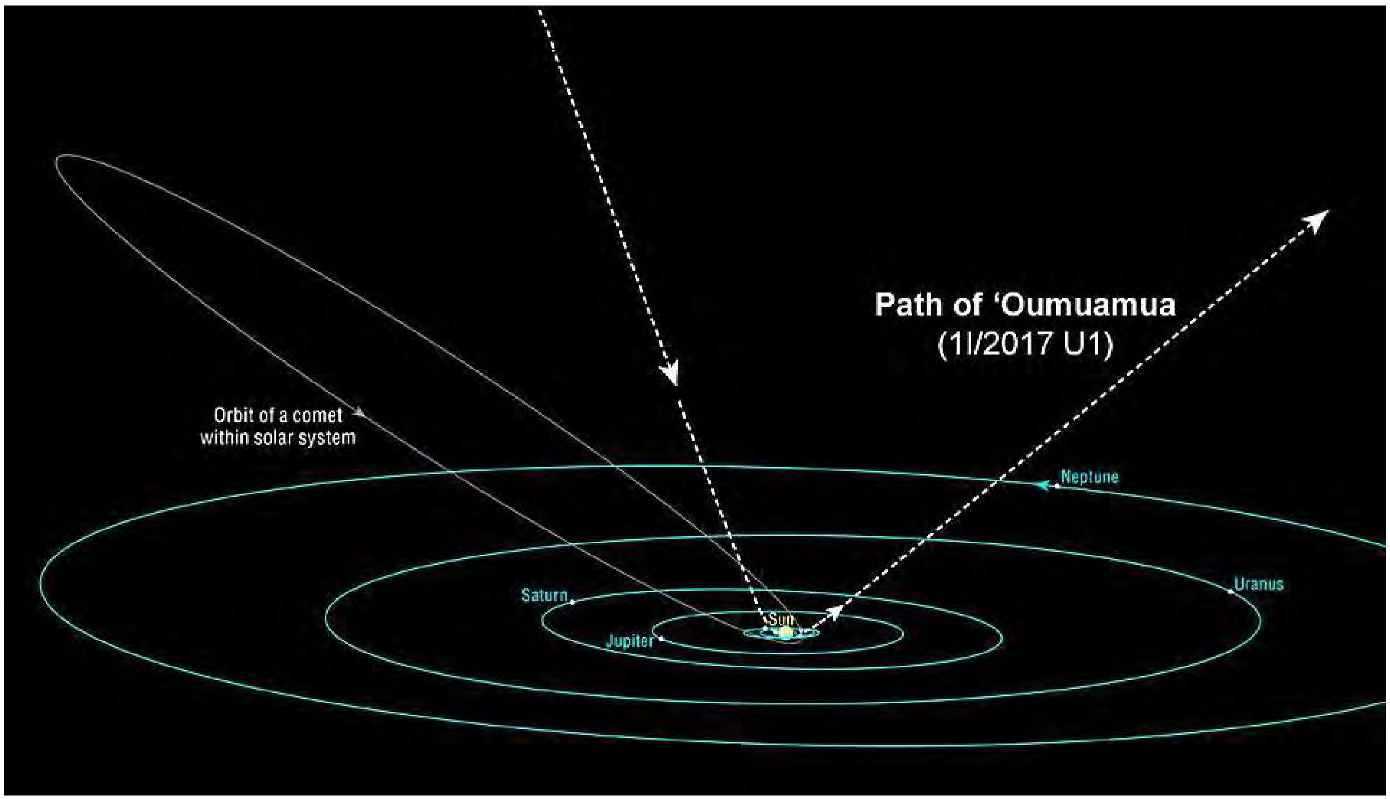
1I/’Oumuamua - The Initiation of a New Means of Studying the Galaxy (and Exoplanets)

You May Have Seen This Picture.

1I/’Oumuamua almost got by us
- it was only detected after perihelion.



1I/'Oumuamua: Interstellar Now

- 1I/'Oumuamua (or 1I) was discovered on October 18 by Pan-STARRS1 with a visual magnitude of 19.8 at a distance from Earth of $\sim$0.208 Astronomical Units (AU) [Bacci et al., 2017].

- Comparisons with stellar catalogs reveal that 1I has not passed extremely close to any star within the last few million years, and its original stellar system remains unknown [Portegies Zwart et al., 2018, Gaidos et al., 2017, Bailer-Jones et al., 2018].

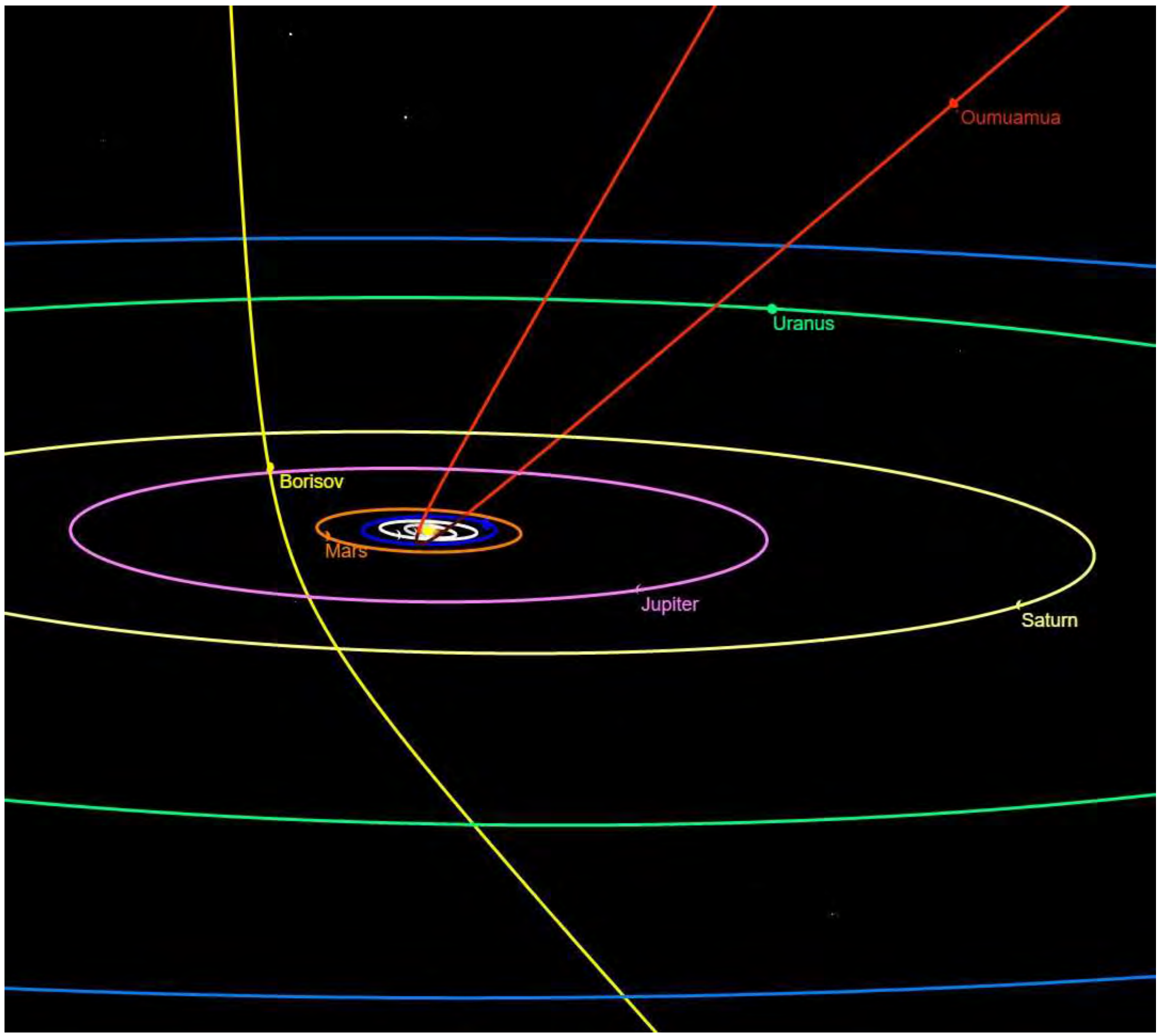
- The incoming 1I velocity vector "at infinity" ($\mathbf{v}_\infty$) is close to the motion of the Pleiades dynamical stream (or Local Association), suggesting that 1I is associated with that stream [Feng and Jones, 2018, Eubanks, 2019a].

- 1I was observed to have a strongly significant anomalous (non-gravitational) acceleration, this being predominately or entirely radial and declining with distance from the Sun [Micheli et al., 2018]. One explanation for this is that it had a very low mass-area ratio, or β [Bialy and Loeb, 2018, Moro-Martín, 2019, Eubanks, 2019b].

- If this hypothesis is valid then it seems that there **must** be two populations of small Interstellar Objects (ISOs) - ones like the asteroids and comets ejected from our solar system, the other, presumably more numerous, being low β objects.

But Wait! Nature (and Gennadiy Vladimirovich) was kind to us.

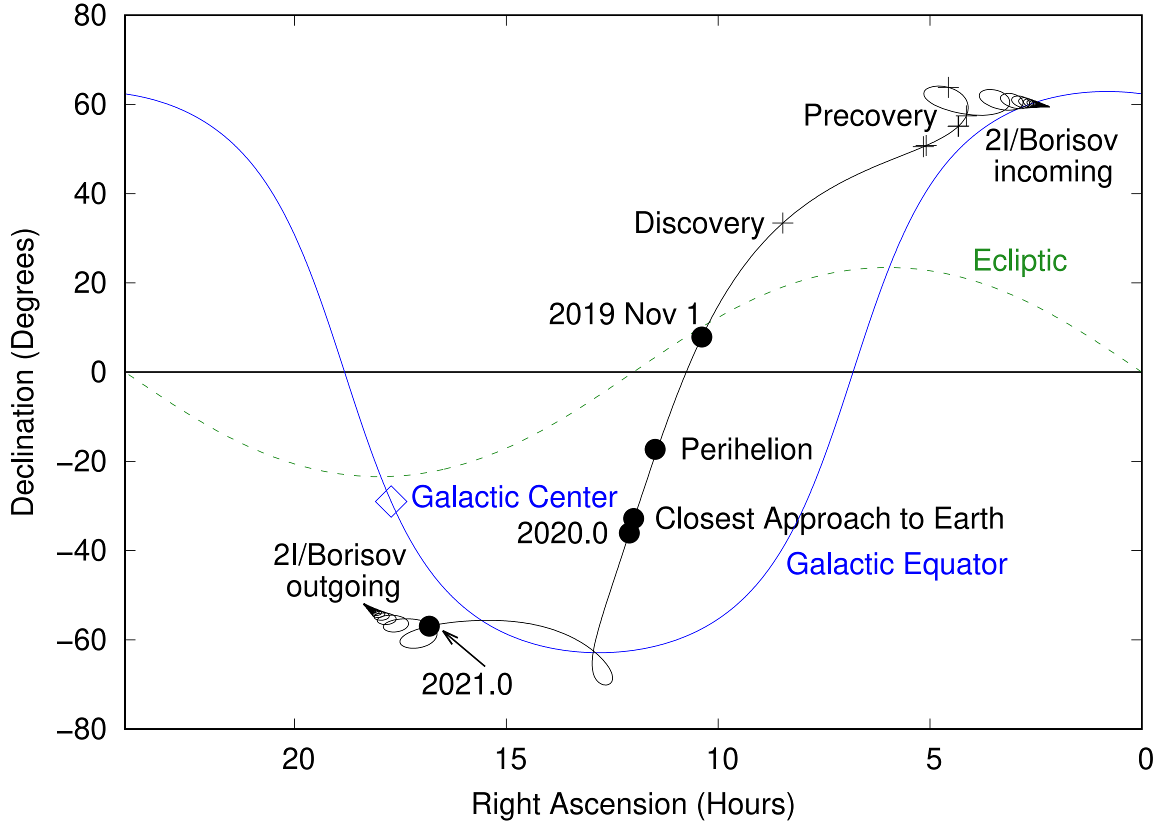
On August 30, 2019, 2I/Borisov was discovered by Amateur Astronomer G. V. Borisov.
It will not pass nearly as close to the Sun as did 1I, and thus its orbit was not nearly as perturbed.



Comet 2I/Borisov near Perihelion in December 2019

Unlike 1I, which never displayed any activity while it was under observation, 2I/Borisov showed activity right from its discovery. This Hubble Space Telescope image shows 2I at a distance of 298 million kilometers. The presence of a cometary coma enables spectroscopic study of the comet and would also facilitate sampling and even sample return, if we had spacecraft ready and able to flyby it.

2I/Borisov in the Sky at Earth



The passage of 2I/Borisov through the celestial sphere during its close approach to the Sun. This is all we will ever see of this object from Earth. Note the "precovery" measurements, from survey images taken Ye Quanzhi and colleagues at the Zwicky Transient Facility before 2I's discovery. (He has told me the software has been adjusted to not miss such unusual objects again.) This long observation period gives a much better orbit for 2I than for 1I.

Stepping into Interstellar Space

Lyra: A Mission to ’Oumuamua

- The *in situ* exploration of 1I by spacecraft presents a so-far unique opportunity for direct spacecraft exploration of an interstellar object, beginning the placement of the formation and development of the solar planetary system into a wider galactic context.

- The outgoing 1I v_∞ of 26.3 km s^{-1} is substantially faster than the fastest human spacecraft to date, Voyager 1, which has a v_∞ = 16.86 km s^{-1}.

- 1I will be $\sim$ three orders of magnitude easier to reach and sample than any exoplanet for the remainder of the century.

- The Lyra studies [Hein et al., 2019, Hibberd et al., 2020] show that an mission to 1I is possible and can provide a substantial science return using existing technology.

- This could possibly be combined with the proposed Interstellar Probe mission [Brandt et al., 2017] intending to explore out to 100’s of AU.

- Another possibility is a “loiter” mission, which would wait for *another* ISO to come through the solar system.

- This will require a better control on the ISO number density, or ways of finding ISOs relatively far from the Sun.

Getting There: The Lyra Mission

- Getting the velocity to catch 1I is not easy, and requires sending a fairly large spacecraft close to a large mass (either the Sun or Jupiter) for an **Oberth Maneuver**, where a ΔV can be added to the parabolic or hyperbolic velocity of a close approach.
  - This is just as simple as $(V + \Delta V)^2 \sim V^2 + 2\ V\ \Delta V$. Adding a velocity change to a large velocity causes an even larger change, on that remains "at infinity" (when the original V will largely be removed by gravity).

- The default mission Lyra spacecraft would have a mass, 5745 kg, close to that proposed for a SLS-launched Europa Clipper spacecraft, and a similar Jovian transfer orbit.

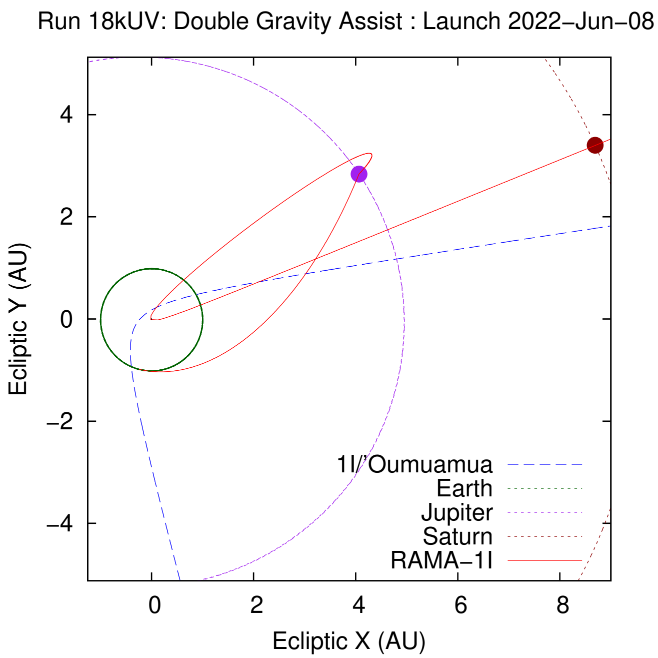
- Lyra, however, would perform a gravity assist to pass within 10 solar radii.

- The two solid fuel stages would fire sequentially close to the Sun, delivering a total ΔV of 4.489 km s^{-1} for the Oberth maneuver close to the Sun.

- A Saturn fly-by would still be needed to get the Lyra probe out of the plane of the solar system.

- The third stage will be permanently attached to the probe, and would be used for terminal encounter navigation, delivering a total possible 815 m s^{-1} ΔV to power a close flyby.

Double Gravity Assist + Solar Oberth Maneuver.



This is a good early launch trajectory, using Jupiter, the Sun and Saturn to speed Lyra on its way. With a launch in March 2022, the 1I flyby is in early 2043 at a distance of about 146 AU, with a payload about the size of *New Horizons*, $\sim$ 500 kg possible with a SLS sized launch vehicle. Unfortunately, the double gravity assists are not possible one synodic period (13 months) later, due to the relative motions of Jupiter and Saturn, and won't repeat for 30 years.

Types of ISO Missions

- ISO missions can be characterized by the resources required to perform them, which are closely related to how the ISO came to be in the solar system, and whether a mission is able to interact with it before its perihelion or afterwards (see Table 1).

- ISOs are either unbound, passing through the solar system on a hyperbolic orbit, or bound, in some elliptical orbit about the Sun or even one of the planets.
  - Unbound ISOs will generally be clearly of interstellar origin, but will only pass through the solar system once.

- If a mission can be launched before or around the time of the ISO's perihelion passage, then travel times can be short (potentially very short if the ISO passes close the Earth), and a fast sample return (capture of cometary Coma or impact probe ejecta material) may be possible.

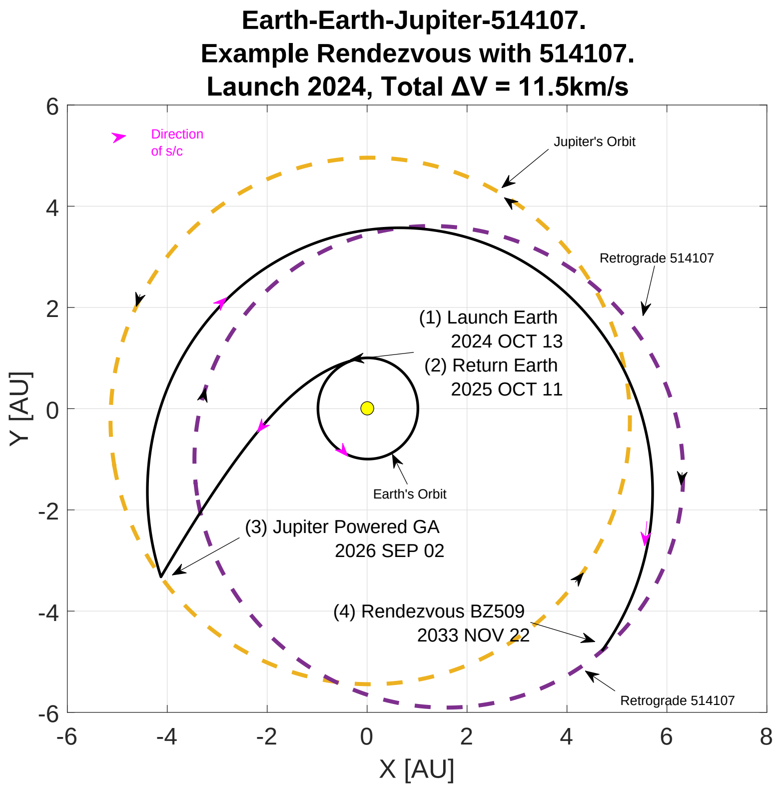
- "New" comets are rarely found much more than 18-24 months before perihelion passage, which indicates that a perihelion passage mission would likely be of the "loiter" type, where the spacecraft is either ready to launch or already deployed at some gravitationally stable point *before* the ISO is discovered.

Types of ISO Missions (2)

Table 1: Types of InterStellar Objects, the associated science and potential near-term mission types

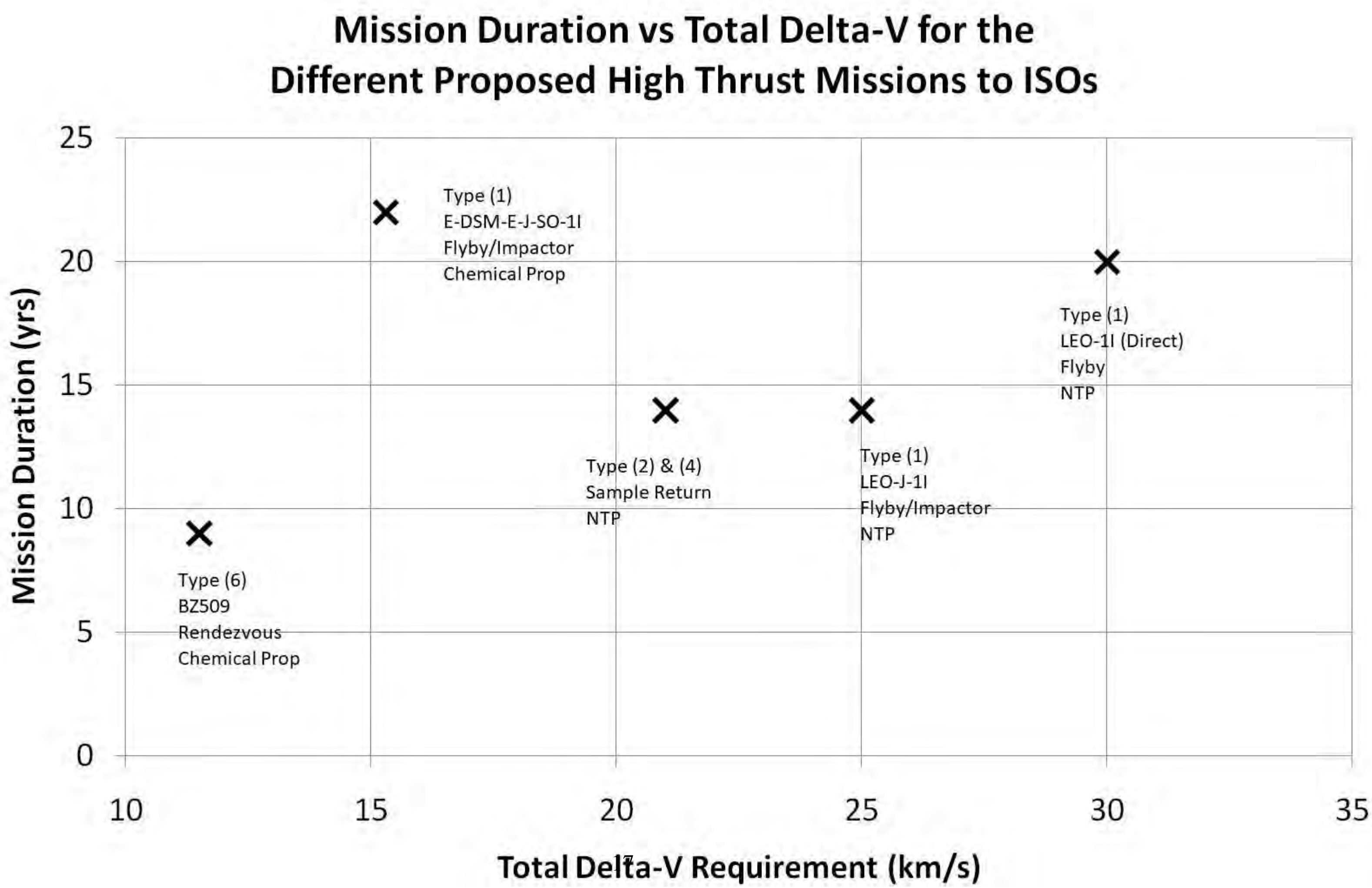
Type	Examples	Mission Type
Clearly hyperbolic objects, which have $v_\infty \gg 1$ km/s	1I/'Oumuamua & 2I/Borisov. Currently detection limited.	Flyby/Impactor
Similar to 1I & 2I but $v_\infty \lesssim 1$ km/s	C/2007 W1 Boattini. Confusion limited.	Sample return
Galactic Stellar Halo objects, low spatial density, of order $\lesssim 1\%$ of Galactic Disk ISOs.	None known so far. Unlikely to be found with current surveys.	Not feasible even if found in next decade.
Comets captured in the Oort cloud at the formation of solar system.	Population unknown, possibly a significant fraction of the long period comets.	Impact sampling or sample return, isotope analysis needed for confirmation.
Material captured primordially by gas drag in early inner solar system.	Unclear if any has survived until now.	Rendezvous depending on inclination. Distinguishing them remotely will be hard.
Captured objects in retrograde and other unusual orbits; see, e.g., Siraj and Loeb [2019], Namouni and Morais [2018] Morbidelli et al. [2020]	Some Centaurs; retrograde objects such as (514107) Ka'epaoka'awela	Rendezvous depending on inclination. Captured orbit objects could be ISOs or long period comets; work needed to find orbits most likely to contain ISOs.
Sednoids, three body traded objects special case of case #4 or case #6	Sedna, 2014 UZ224 2012 VP113, 2014 SR349 2013 FT28	Large distances, but low velocities would facilitate rendezvous or sample return.

Mission To the Retrograde Jupiter Co-Orbital 514107 Ka'epaoka'awela (2015 BZ509).



This is a mission to a Type 6 object, a **possibly** captured ISO in a retrograde orbit. Retrograde orbits have large velocities relative to our prograde orbiting spacecraft, but Adam Hibberd found a Jupiter gravity assist that would make a BZ509 orbiter or lander possible with reasonable total velocity.

Mission Durations and Velocity Requirements for Various Mission Types.



How Many ISOs Should We Expect

Number Density of Interstellar Asteroids

- *Pan-STARRS1* detected 1I after only 3.5 years of observing in its current survey mode.

- Do et al. [2018] calculated that in that period *Pan-STARRS1* scanned $\sim$5 AU^3, implying [Do et al., 2018, Trilling et al., 2017] an upper limit on $\mathrm{n_{IS}}$, the ISO number density, of

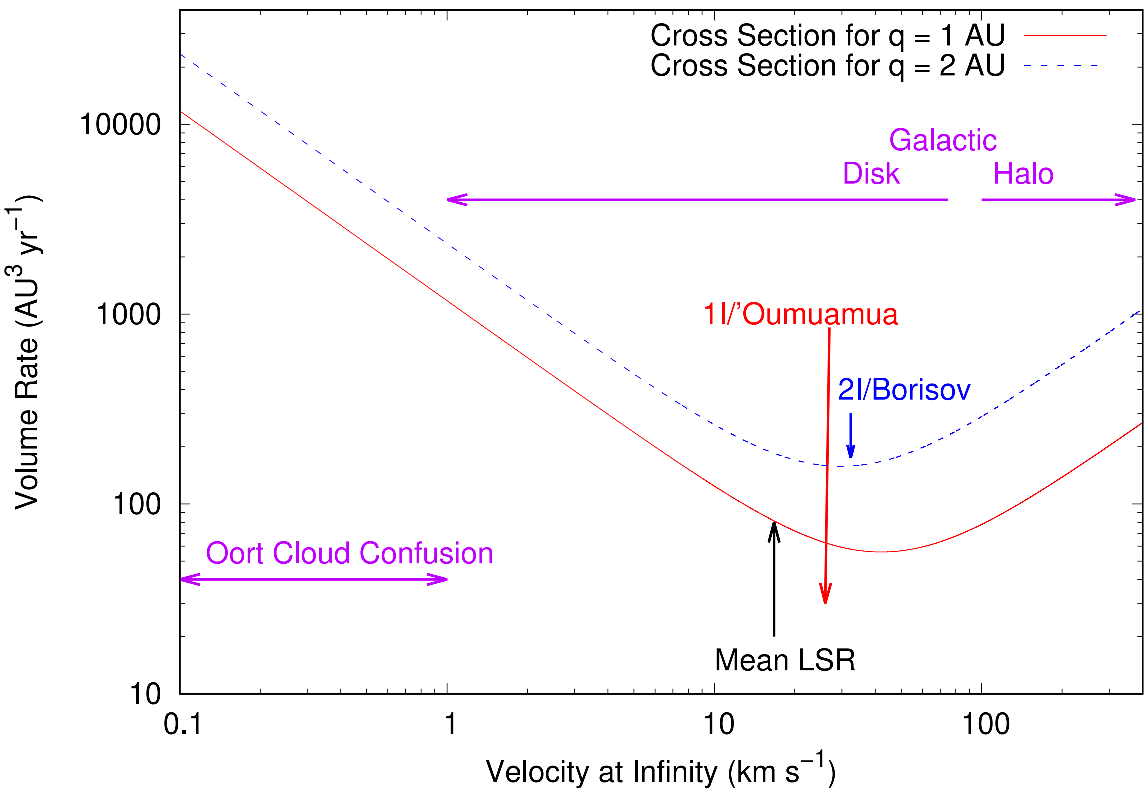
$$\mathrm{n_{IS}} \lesssim 0.2\ \mathrm{AU}^{-3} . \quad (1)$$

- If the upper bound in Equation 1 is indicative of the density of $\sim$100-meter sized ISOs in the galactic disk, then these objects must be very common, with $\sim 10^{16}$ such objects for each star in the Galaxy [Engelhardt et al., 2017, Raymond et al., 2018, Do et al., 2018].

- Theoretical estimates of ISO production from before the discovery of 1I tend to strongly underpredict the rate of 100-meter sized ISOs. Expectations were for number densities as much as three orders of magnitude below that implied by the detection of 1I [Cook et al., 2016, Engelhardt et al., 2017, Raymond et al., 2018, Do et al., 2018]

- This, again, suggests that there may be two types of ISOs - small bodies with normal β ejected from stellar systems, and a new, low β, population.

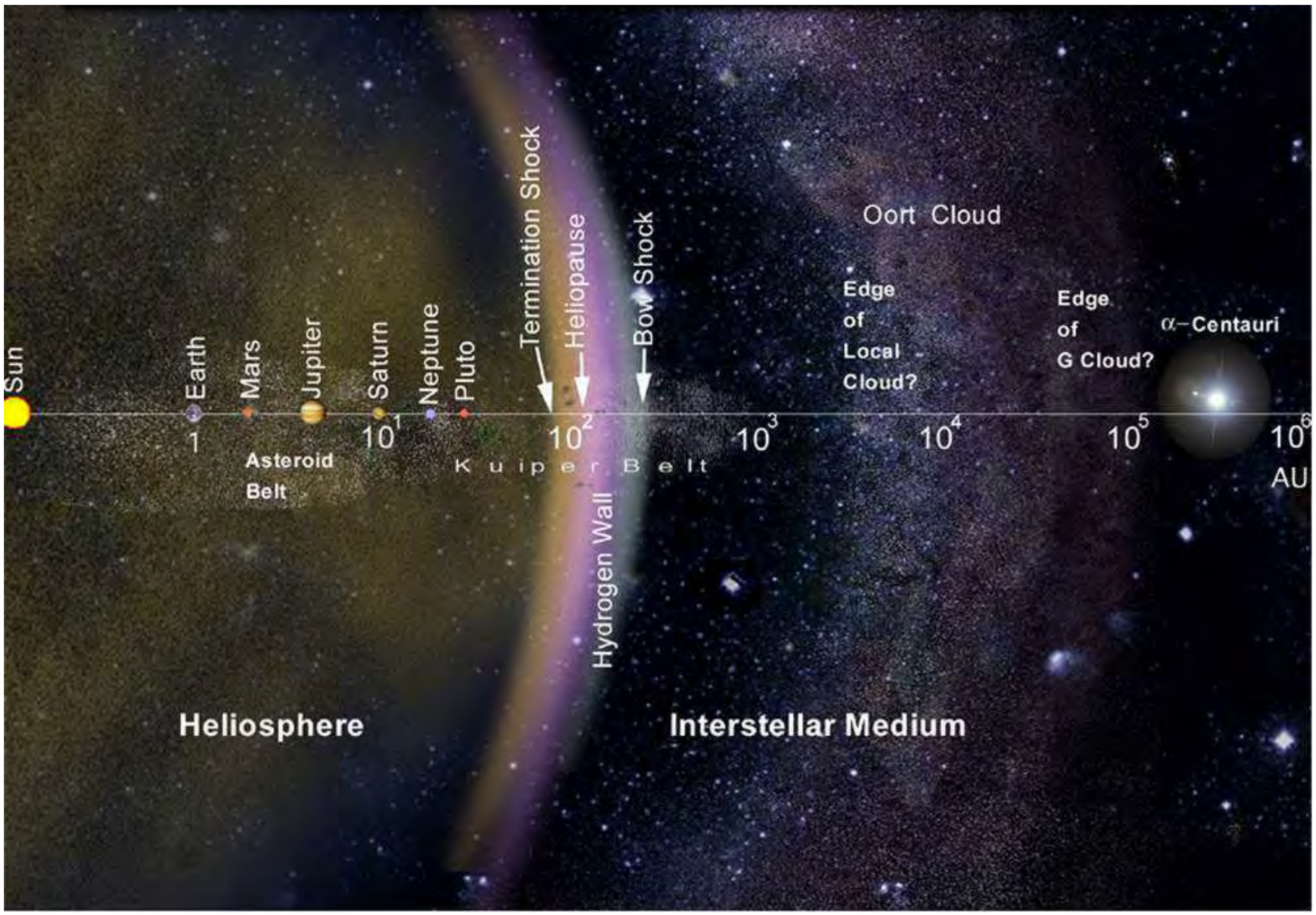
The Gravitational Capture Efficiency of the Solar System



The size of the solar ISO "Net" (the chance that an ISO with a given velocity would pass close to the Sun) as a function of the velocity at infinity for two different perihelions. If there as a roughly uniform density of ISOs of a given mass with velocity, as there is for stars in the galactic disk velocity range, then there should be roughly 100 slow ISOs passing through for every one as fast as 1I or I2. Why haven't we found them? Stellar densities in the Galactic Halo are about 1% of the disk, so halo ISO should be relatively rare.

Putting Interstellar Objects in a Galactic Context

If we catch an interstellar asteroid, it - a true interstellar stepping stone.
What's Next?



Planetary Formation and Small ISOs

- Grishin *et al.* [Grishin et al., 2018] and Pfalzner & Bannister [Pfalzner and Bannister, 2019] pointed out that the large numbers of 100-meters ISOs would provide a means for seeding the growth of planetesimals in molecular clouds and star formation regions.

- The small 1I-type ISOs could thus solve the "meter-barrier" found in models of the growth of meter-sized proto-planetesimals [Brauer et al., 2008, Mordasini et al., 2010], by providing seeds large enough not to be destroyed in the early stages of planetary formation.

- ISOs thus need to be considered in the modeling of planetary formation.

- Low β ISOs will be easily captured even on the outskirts of planetary formation regions [Eubanks, 2019b].
  - As many as 10^{15} low β ISOs could be present in the Oort cloud of the solar system.
  - These orbits would easily distinguishable from the much closer orbits of ISOs captured by three body gravitational (or gravitational+adiation pressure) interactions after the formation of the solar system [Siraj and Loeb, 2019].

- Primordially captured ISOs would be perturbed into the inner solar system by the same interactions that produce long-period comets and should be searched for as small inactive comets on nearly-hyperbolic trajectories with unexpectedly large non-gravitational accelerations.

ISOs in the Galaxy

- An interstellar body passing through the solar system has a velocity "at infinity" (i.e., far from the Sun), v_∞, > 0.
- The incoming v_∞ in both magnitude and direction provides a strong indication of the galactic population sampled by an incoming body.
  - The Sun and most of the nearby stars are in the galactic thin disk, with an rms velocity dispersion of $\sim$ 30 km s^{-1} relative to the Local Standard of Rest (LSR), and relatively small velocities out of the galactic plane [Francis and Anderson, 2009].
  - Objects from other populations may also speed through the galactic disk, with typical rms velocities of $\sim$50 -100 km s^{-1} for objects from the thick disk, and $\sim$300 km s^{-1} for objects from the galactic Halo [Nissen and Schuster, 2010].
  - Intergalactic asteroids and comets are also a possibility; these would be expected to have velocities relative to the Sun $>$ 500 km s^{-1} [Carney and Latham, 1987].
  - All of these higher velocity objects should have near random inclinations, and thus relatively large velocities out of the galactic plane.
- 1I has a v_∞ on both ingress and egress from the solar system of $\sim$26.3 km s^{-1}, quite consistent with it being a long term resident of the galactic thin disk, but much too small for it to be a thick disk or halo object.

1I/'Oumuamua Is a Member of the Pleiades dynamical stream

- The dynamical LSR, defined as the circular orbit velocity at the Sun's location, would be the mean motion near the Sun for an axisymmetric galaxy.

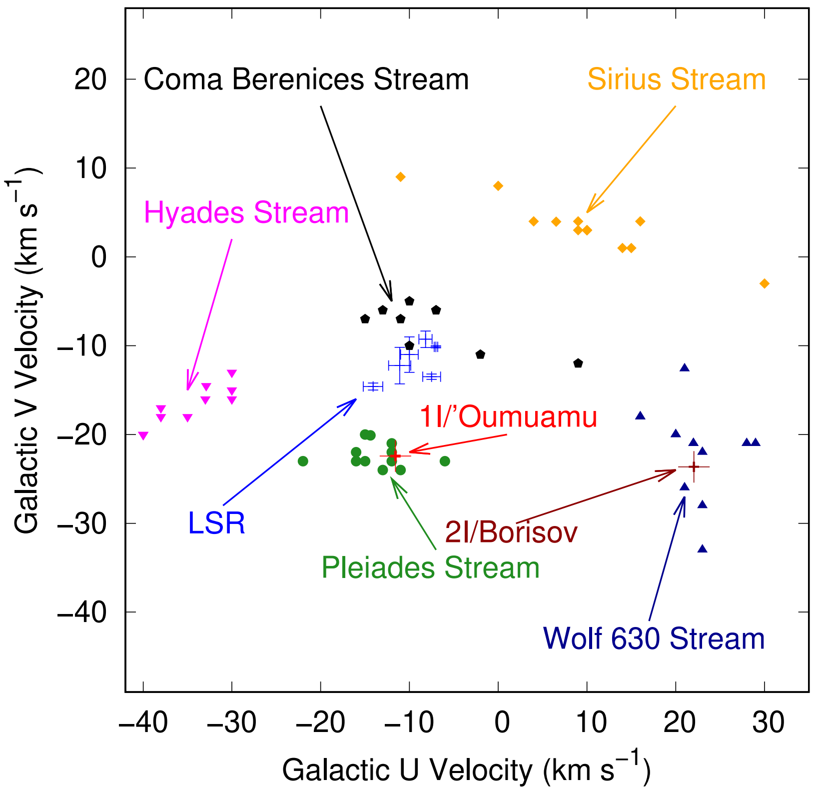
- The Milky Way's velocity fields however are non-uniform, with a substantial fraction of the stars in the solar neighborhood being concentrated in unbound collections of stars called here dynamical streams (but also known as associations or moving groups) [see, e.g., Famaey et al., 2005, Kushniruk et al., 2017, Gaia Collaboration et al., 2018].

- Antoja et al. [2012], using RAVE spectroscopic survey data, found that 14.2% of the stars in the solar neighborhood (out to 300 pc) are in one of the five major streams considered in this paper, the Pleiades, Hyades, Sirius, Coma Berenices and Hercules streams, while Francis and Anderson [2012] used 2MASS data to conclude that almost all local stars are part of unbound kinematic streams

- They also concluded thatthe Pleiades stream was located in the leading edge of the Orion arm, and the Hyades stream was part of the Centaurus arm.

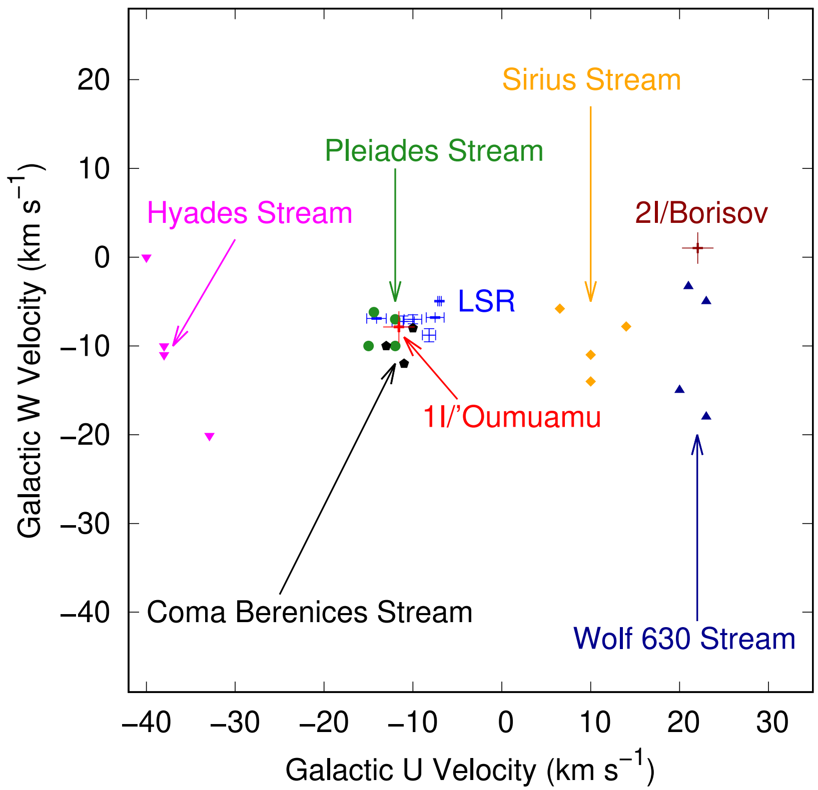
- A comparison of the incoming 1I v_∞ and dynamical stream velocities reveals that it is highly likely that 1I was a member of the Pleiades dynamical stream (but probably not ejected from the well-known Pleiades star formation region).

1I and 2I both belong to galactic dynamical streams



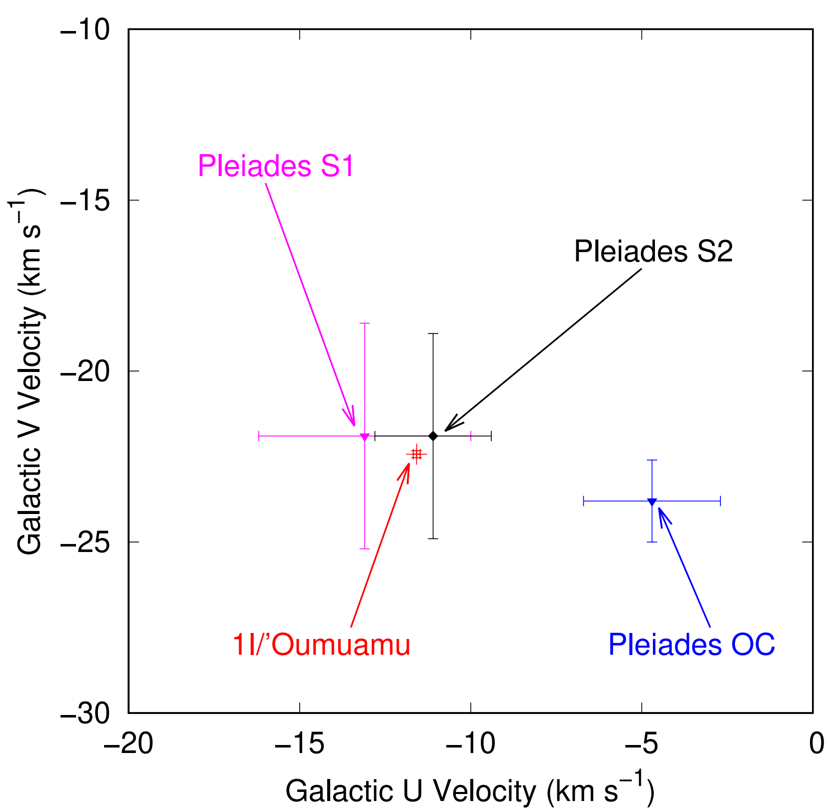
The galactocentric U and V components of velocity for 1I, the LSR and the five largest local dynamical streams in a reference frame centered on the Sun's velocity. The 1I incoming velocity is near the centroid of the determinations of the velocity of the (realtively young) Pleiades stream, while the 2I velocity is near the centroid of the Wolf 630 stream. Neither body seems to have a strong connection with the Local Standard of Rest, which seems to be more a mathematical average than a dynamically favored velocity.

Galactocentric Velocities in Longitude and Out of the Galactic Plane



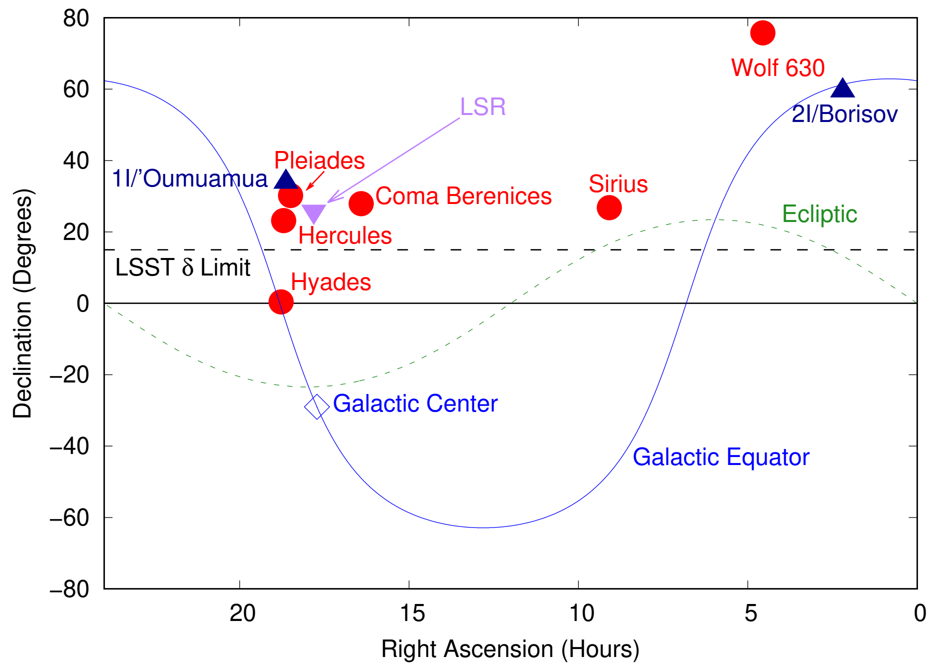
The galactocentric V and W components of velocity for 1I, the LSR and the five largest local dynamical streams in a reference frame centered on the Sun's velocity. The data sources are as described above; there are fewer stream data points as not all surveys report motions out of the galactic plane. The 1I incoming velocity is near the centroid of the determinations of the velocity of the Pleiades stream, and the 2I velocity is close to one set of Wolf 630 velocity estimates.

A Closeup of 1I and the Pleiades SubStreams



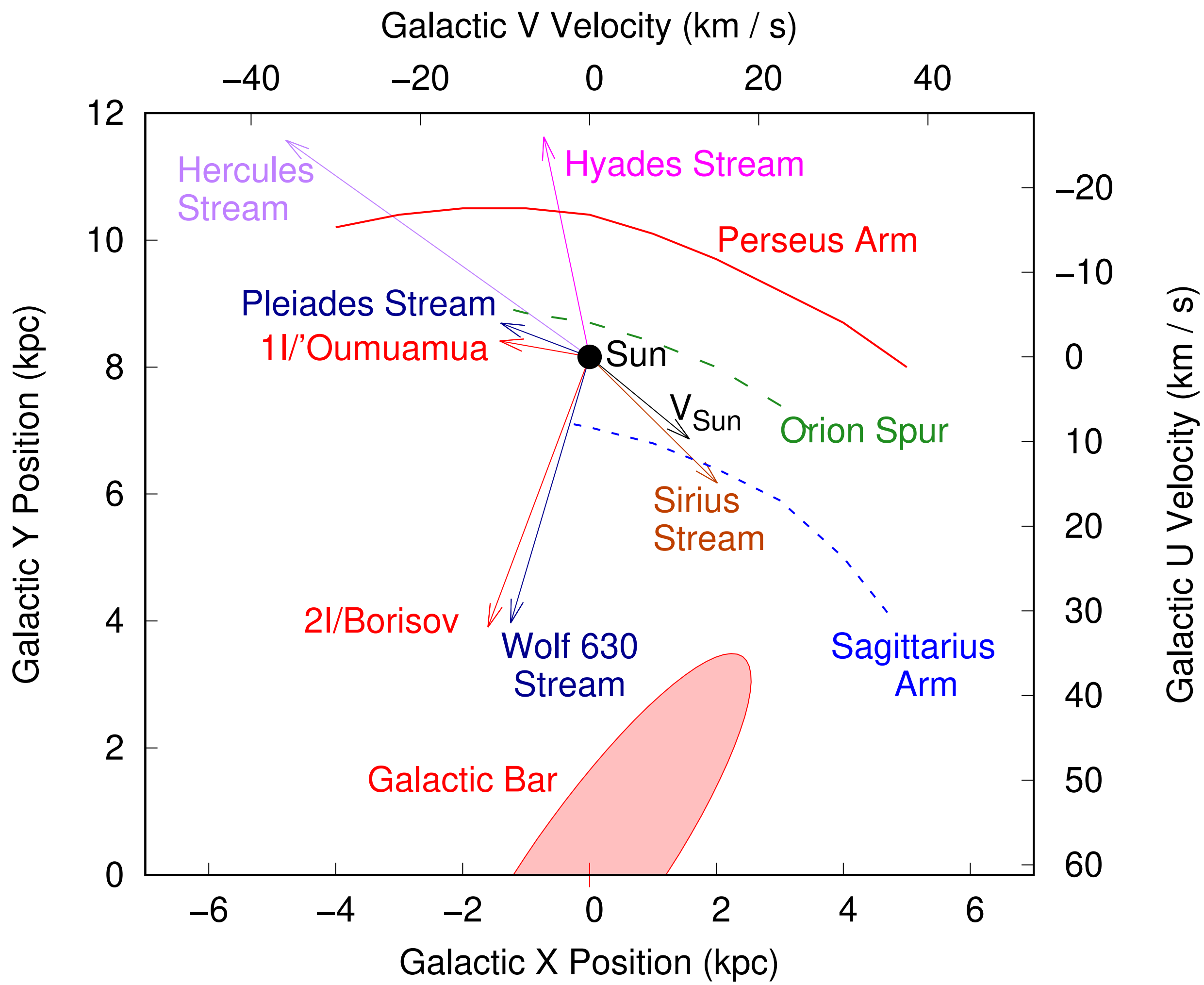
The galactocentric U and V components of the Pleiades Stream Substreams found by [Chereul et al., 1998, 1999]. They found two major substreams in the stream, the Supercluster (SC) and Open Cluster (OC) streams; the SC stream was further divided into two further substreams, S1 and S2, and the OC stream was associated with the Pleiades star formation region. The data clearly favors 1I belonging to the SC substream, and less convincingly favors the younger S2 stream over the S1 stream. Further analysis of stellar data may enable even finer scale determinations of Pleiades substreams, and thus may make it possible to narrow its source population considerably.

Incoming Radiants for Galactic Stream ISOs



Incoming radiants of the 6 largest galactic streams in the solar neighborhood, together with the Solar Apex (the incoming LSR radiant) and the incoming 1I and 2I directions. The dispersion in the stream velocities as seen in the *Gaia* DR2 is comparable to or smaller than the size of the symbols; a substantial fraction of the stars in the solar neighborhood belong to one of these streams, and it is thus reasonable to assume that a substantial fraction of incoming ISOs will come from these radiants.

“Peculiar velocities” relative to the Circular LSR.



The Sun and nearby Galactic arms, together with velocities referenced to the LSR, the local circular velocity. The direction of the velocity vectors in at their relative longitudes and their length is proportional to the velocity magnitude. The Pleiades, Hyades and Hercules streams are coming up from the inner regions from the Galaxy and approaching apoapse, while the Solar System and Sirius stream are nearing their periapse.

What is the Relevance to Exoplanet Studies?

- ISOs passing through the solar system offer unique opportunities for exoplanet science, and for galactic archaeology.
- With a fast flyby mission, we can acquire both images and detailed compositional analysis.
- The questions that could be addressed from the study of local ISOs include
  - Are there really two populations of small ISOs? Why?
  - What are the formation mechanisms for planetesimal production in the Galaxy? How do they differ from the solar system example?
  - Are objects such as 1I formed in a dynamical stream, or captured by it after formation?
  - Do small ISOs play a role in seeding planetary formation?
  - How are the small ISOs released from their formation systems? Or are they formed in deep space?
  - Is there a connection between the formation of small ISOs and the nomadic planets?
  - And, with enough ISOs: Can we derive compositional maps for condensed material in the Galactic Disk.

Conclusions

- We now have known Interstellar Objects penetrating the inner solar system.
  - With two found, we can expect to find more. The Rubin Observatory LSST Camera should find a lot of ISO candidates in the Southern Hemisphere if the number density is anything like the naive estimates based on samples of one.
  - I must admit that I am not yet convinced. Two is much better than one, but there is still the missing low velocity population.
- But even if all we find in the near future are 1I and 2I, for **centuries** to come they will be easier to explore than **any** exoplanet orbiting another star.
- I am sure that these objects will be explored as our first extrasolar targets, and have been glad to work with i4is to help initiate this process.

References

T. Antoja, A. Helmi, O. Bienayme, J. Bland-Hawthorn, B. Famaey, K. Freeman, B. K. Gibson, G. Gilmore, E. K. Grebel, I. Minchev, U. Munari, J. Navarro, Q. Parker, W. Reid, G. M. Seabroke, A. Siebert, A. Siviero, M. Steinmetz, M. Williams, R. Wyse, and T. Zwitter. Kinematic groups beyond the solar neighbourhood with RAVE. *Mon. Not. R. Astron. Soc.*, 426: L1–L5, Oct. 2012. doi: 10.1111/j.1745-3933.2012.01310.x.

P. Bacci, M. Maestripieri, L. Tesi, G. Fagioli, R. A. Mastaler, G. Hug, M. Schwartz, P. R. Holvorcem, J. Bulger, T. Lowe, A. Schultz, M. Willman, K. Chambers, S. Chastel, L. Denneau, H. Flewelling, M. Huber, E. Lilly, E. Magnier, R. Wainscoat, C. Waters, R. Weryk, G. J. Leonard, E. J. Christensen, D. C. Fuls, A. R. Gibbs, A. D. Grauer, J. A. Johnson, R. A. Kowalski, S. M. Larson, R. G. Matheny, R. L. Seaman, F. C. Shelly, H. Sato, D. Abreu, M. Micheli, D. Koschny, M. Busch, A. Knoefel, E. Schwab, and G. V. Williams. Comet C/2017 u1 (panstarrs). *Minor Planet Electronic Circulars*, 2017-U181, Oct. 2017.

C. A. L. Bailer-Jones, D. Farnocchia, K. J. Meech, R. Brasser, M. Micheli, S. Chakrabarti, M. W. Buie, and O. R. Hainaut. Plausible Home Stars of the Interstellar Object 'Oumuamua Found in Gaia DR2. *Astron. J.*, 156:205, Nov. 2018. doi: 10.3847/1538-3881/aae3eb.

S. Bialy and A. Loeb. Could Solar Radiation Pressure Explain 'Oumuamua's Peculiar Acceleration? *Ap. J. Lett.*, 868:L1, Nov. 2018. doi: 10.3847/2041-8213/aaeda8.

P. C. Brandt, R. McNutt, G. Hallinan, M. Shao, R. Mewaldt, M. Brown, L. Alkalai, N. Arora, J. McGuire, S. Turyshev, A. Biswas, P. Liewer, N. Murphy, M. Desai, D. McComas, M. Opher, E. Stone, G. Zank, and L. Friedman. The Interstellar Probe Mission: Humanity's First Explicit

Step in Reaching Another Star. In *Planetary Science Vision 2050 Workshop*, volume 1989 of *LPI Contributions*, page 8173, Feb. 2017.

F. Brauer, C. P. Dullemond, and T. Henning. Coagulation, fragmentation and radial motion of solid particles in protoplanetary disks. *Astron. Astropys.*, 480:859–877, 2008.

B. W. Carney and D. W. Latham. The local galactic escape velocity. In J. Kormendy and G. R. Knapp, editors, *Dark matter in the universe*, volume 117 of *IAU Symposium*, pages 39–48, 1987.

E. Chereul, M. Creze, and O. Bienayme. The distribution of nearby stars in phase space mapped by HIPPARCOS. II. Inhomogeneities among A-F type stars. *Astron. Astrophys.*, 340:384–396, Dec. 1998.

E. Chereul, M. Crézé, and O. Bienaymé. The distribution of nearby stars in phase space mapped by Hipparcos. Clustering and streaming among A-F type stars. *Astron. Astrophys. Sup.*, 135: 5–28, Feb. 1999. doi: 10.1051/aas:1999160.

N. V. Cook, D. Ragozzine, M. Granvik, and D. C. Stephens. Realistic Detectability of Close Interstellar Comets. *Ap. J.*, 825:51, July 2016. doi: 10.3847/0004-637X/825/1/51.

A. Do, M. A. Tucker, and J. Tonry. Interstellar Interlopers: Number Density and Origin of ’Oumuamua-like Objects. *Ap. J. Lett.*, 855:L10, Mar. 2018. doi: 10.3847/2041-8213/aaae67.

T. Engelhardt, R. Jedicke, P. Vereš, A. Fitzsimmons, L. Denneau, E. Beshore, and B. Meinke. An Observational Upper Limit on the Interstellar Number Density of Asteroids and Comets. *Astron. J.*, 153:133, Mar. 2017. doi: 10.3847/1538-3881/aa5c8a.

T. M. Eubanks. Efficient Searches for Galactic Stream Interstellar Asteroids. In *Lunar and Planetary Science Conference*, volume 50 of *Lunar and Planetary Science Conference*, page 3262, Mar. 2019a.

T. M. Eubanks. High-drag Interstellar Objects and Galactic Dynamical Streams. *Ap. J. Lett.*, 874: L11, Apr. 2019b. doi: 10.3847/2041-8213/ab0f29.

B. Famaey, A. Jorissen, X. Luri, M. Mayor, S. Udry, H. Dejonghe, and C. Turon. Local kinematics of K and M giants from CORAVEL/Hipparcos/Tycho-2 data. Revisiting the concept of superclusters. *Astron. Astrophys.*, 430:165–186, Jan. 2005. doi: 10.1051/0004-6361:20041272.

F. Feng and H. R. A. Jones. 'Oumuamua as a Messenger from the Local Association. *Ap. J.*, 852: L27, Jan. 2018. doi: 10.3847/2041-8213/aaa404.

C. Francis and E. Anderson. Calculation of the local standard of rest from 20 574 local stars in the New Hipparcos Reduction with known radial velocities. *New Astronomy*, 14:615–629, Oct. 2009. doi: 10.1016/j.newast.2009.03.004.

C. Francis and E. Anderson. Evidence of a bisymmetric spiral in the Milky Way. *Mon. Not. R. Astron. Soc.*, 422:1283–1293, May 2012. doi: 10.1111/j.1365-2966.2012.20693.x.

Gaia Collaboration, D. Katz, T. Antoja, M. Romero-Gómez, and et al. Gaia Data Release 2. Mapping the Milky Way disc kinematics. *Astron. Astrophys.*, 616:A11, Aug. 2018. doi: 10.1051/0004-6361/201832865.

E. Gaidos, J. Williams, and A. Kraus. Origin of Interstellar Object A/2017 U1 in a Nearby Young Stellar Association? *Research Notes of the American Astronomical Society*, 1:13, Dec. 2017. doi: 10.3847/2515-5172/aa9851.

E. Grishin, H. B. Perets, and Y. Avni. Planet seeding through gas-assisted capture of interstellar objects. *arXiv e-prints*, art. arXiv:1804.09716, Apr 2018.

A. M. Hein, N. Perakis, T. M. Eubanks, A. Hibberd, A. Crowl, K. Hayward, R. G. Kennedy, and R. Osborne. Project Lyra: Sending a spacecraft to 1I/'Oumuamua (former A/2017 U1), the interstellar asteroid. *Acta Astronautica*, 161:552–561, Aug 2019. doi: 10.1016/j.actaastro.2018.12.042.

A. Hibberd, A. M. Hein, and T. M. Eubanks. Project Lyra: Catching 1I/'Oumuamua - Mission opportunities after 2024. *Acta Astronautica*, 170:136–144, May 2020. doi: 10.1016/j.actaastro.2020.01.018.

I. Kushniruk, T. Schirmer, and T. Bensby. Kinematic structures of the solar neighbourhood revealed by Gaia DR1/TGAS and RAVE. *Astron. Astrophys.*, 608:A73, Dec. 2017. doi: 10.1051/0004-6361/201731147.

M. Micheli, D. Farnocchia, K. J. Meech, M. W. Buie, O. R. Hainaut, D. Prialnik, N. Schörghofer, H. A. Weaver, P. W. Chodas, J. T. Kleyna, R. Weryk, R. J. Wainscoat, H. Ebeling, J. V. Keane, K. C. Chambers, D. Koschny, and A. E. Petropoulos. Non-gravitational acceleration in the trajectory of 1I/2017 U1 ('Oumuamua). *Nature*, 559:223–226, June 2018. doi: 10.1038/s41586-018-0254-4.

A. Morbidelli, K. Batygin, R. Brasser, and S. N. Raymond. No evidence for interstellar planetesimals trapped in the Solar system. *Mon. Not. R. Astron. Soc.*, 497(1):L46–L49, June 2020. doi: 10.1093/mnrasl/slaa111.

C. Mordasini, H. Klahr, Y. Alibert, W. Benz, and K.-M. Dittkrist. Theory of planet formation. *ArXiv e-prints*, Dec. 2010. Proceedings Workshop "Circumstellar disks and planets: Science cases for the second generation VLTI instrumentation", to appear in Astronomy and Astrophysics Review, ed. Sebastian Wolf.

A. Moro-Martín. Could 1I/'Oumuamua be an icy fractal aggregate ejected from a protoplanetary disk? A fluffy radiation-pressure-driven scenario. *arXiv e-prints*, art. arXiv:1902.04100, Feb 2019.

F. Namouni and M. H. M. Morais. An interstellar origin for Jupiter's retrograde co-orbital asteroid. *Mon. Not. R. Astron. Soc.*, 477(1):L117–L121, June 2018. doi: 10.1093/mnrasl/sly057.

P. E. Nissen and W. J. Schuster. Two distinct halo populations in the solar neighborhood. Evidence from stellar abundance ratios and kinematics. *Astron. Astrophys.*, 511:L10, Feb. 2010. doi: 10.1051/0004-6361/200913877.

S. Pfalzner and M. T. Bannister. A hypothesis for the rapid formation of planets. *arXiv e-prints*, art. arXiv:1903.04451, Mar 2019.

S. Portegies Zwart, S. Torres, I. Pelupessy, J. Bédorf, and M. X. Cai. The origin of interstellar asteroidal objects like 1I/2017 U1 'Oumuamua. *Mon. Not. R. Astron. Soc.*, 479:L17–L22, Sep 2018. doi: 10.1093/mnrasl/sly088.

S. N. Raymond, P. J. Armitage, D. Veras, E. V. Quintana, and T. Barclay. Implications of the interstellar object 1I/'Oumuamua for planetary dynamics and planetesimal formation. *Mon. Not. R. Astron. Soc.*, 476:3031–3038, May 2018. doi: 10.1093/mnras/sty468.

A. Siraj and A. Loeb. Identifying Interstellar Objects Trapped in the Solar System through Their Orbital Parameters. *Ap. J.*, 872:L10, Feb 2019. doi: 10.3847/2041-8213/ab042a.

D. E. Trilling, T. Robinson, A. Roegge, C. O. Chandler, N. Smith, M. Loeffler, C. Trujillo, S. Navarro-Meza, and L. M. Glaspie. Implications for Planetary System Formation from Interstellar Object 1I/2017 U1 ('Oumuamua). *Ap. J. Lett.*, 850:L38, Dec. 2017. doi: 10.3847/2041-8213/aa9989.