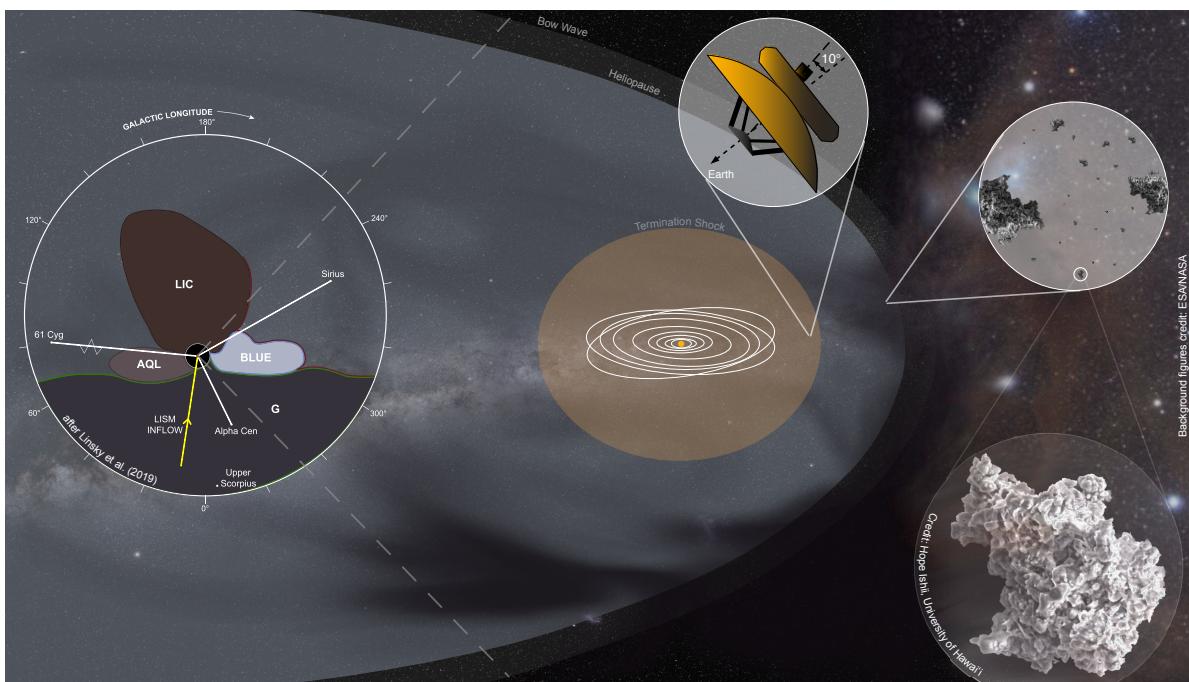


# Synergies between interstellar dust and heliospheric science with an Interstellar Probe

Decadal Survey for Solar and Space Physics (Heliophysics) 2024 – 2033 – 7 Sept. 2022

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## Synopsis

This white paper focuses on the **synergies**<sup>1</sup> between **heliosphere and dust science**, and the technological endeavors / programmatic aspects that are important to develop or maintain in the decade to come. In particular, we illustrate how we can use interstellar dust in the solar system as a tracer for the (dynamic) heliosphere properties, and emphasize the fairly unexplored, but potentially important science question of the role of cosmic dust in heliospheric and astrospheric physics. We show that an Interstellar Probe mission with a dedicated dust suite would bring unprecedented advances to interstellar dust research, and can also contribute – through measuring dust – to heliosphere science. This can in particular be done well if we work in synergy with other missions inside the solar system, hereby using multiple vantage points in space to measure the dust, as it ‘rolls’ into the heliosphere. Synergies between missions inside the solar system and far out are crucial to disentangle the spatially and temporally varying dust flow.

We refer to Sterken+ 2019 for a review of the current state of the art of interstellar dust research in our solar system (dynamics and composition, measurements and models). Hunziker+ 2022 describes how interstellar dust measurements on an **Interstellar Probe** can provide a major leap forward for both dust *and* heliosphere science. The authors also illustrate with simulations how dust measurements on the way out through the heliosphere can provide for the first time new constraints (i.e., the boundary conditions) for heliosphere models, in addition to the already existing magnetic field, plasma, Galactic Cosmic Ray (GCR) and other data from the Voyagers and other spacecraft. Two accompanying white papers are being submitted for this decadal survey: Hsu+ 2022, “*Science opportunities enabled by in situ cosmic dust detection technology for heliophysics and beyond*”, and Poppe+ 2022, “*The interactions of Interstellar Dust with our Heliosphere*”.

## A. Background and state of knowledge

### **Introduction: the solar system in the Local Interstellar Cloud**

The Sun and planets move through the outer edges of the local interstellar cloud (LIC) and into the neighbouring G-cloud after a journey of nearly 60.000 years in the LIC [Linsky+ 2022]. The interstellar dust (ISD) in this diffuse cloud may have its origins in supernovae and atmospheres of cool stars or may be recondensed in the interstellar medium after being shattered by supernova shocks. These particles cross the solar system due to its relative velocity with the LIC (of about 26 km/s). They can be measured in situ by dust detectors on spacecraft, and hereby provide *unique* ground truth information about their make-up and dynamics. This ground truth information is complementary to measurements of the dust by more classical astronomical methods like observations of extinction, scattering, and polarisation of starlight as well as dust thermal emission, and by observing the gas in comparison to a reference (the so-called “cosmic abundances”, usually the solar composition), where the “missing component” in the gas phase hints at what must be locked up in the dust [Mathis+ 1977, Draine 2003, Draine and Li 2007, Draine 2009, Wang+ 2015]. Directly measuring these particles is of utmost importance for astrophysics and is also part of humanity’s exploration of our local interstellar neighbourhood.

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<sup>1</sup> A Synergy: the interaction or cooperation of two or more organizations, substances, or other agents to produce a **combined effect greater than the sum of their separate effects**. [Oxford Languages dictionary]

## Dynamics of interstellar dust in the heliosphere

The ISD size distribution reaches from nanometers to several micrometers and decreases with increasing particle size<sup>2</sup> (Fig 1). The **dynamics of the dust** in the heliosphere depends on the particle size, optical properties, and on the space environment. This dependence on the space environment turns ISD into a very interesting tracer for the dynamic heliosphere. **Micron-sized ISD** particles passing through the solar system are gravitationally dominant, may be uncoupled from the LIC, and could, in theory, come from any other direction than the heliosphere nose (note that the *interstellar meteoroids* are still a controversial topic in the field [Hajdukova+ 2020]). **Mid-sized ISD** particles (ca. 0.1 - 0.6  $\mu\text{m}$  radius) can reach the solar system depending on their size, optical properties, composition, and phase in the solar cycle. Their dynamics in the solar system are governed by solar gravitation, by solar radiation pressure force, and by Lorentz forces due to (charged) ISD passing through the magnetic fields of the solar wind plasma that changes with the 22-year solar cycle, leading to an alternating focussing and defocussing of the dust towards the solar equatorial plane during the solar minima. However, there is an additional (probably time-dependent) mechanism of filtering in the heliosheath [Slavin+ 2012, Sterken+ 2015]. **Small ISD** particles (30-100 nm) are dominated by the Lorentz force and may partially reach the solar system during the solar focussing phase (e.g., 2029-2036) if the heliospheric boundary regions do not filter the particles already upfront. The higher the charge-to-mass ratio of the dust is, the more the particles move on complicated patterns (e.g., Fig. 2, from Sterken+ 2012), which may cause ‘waves’ of higher dust densities to ‘roll’ into the heliosphere for specific particle sizes (Fig. 3 from Hunziker+

Figure 2 (below): A complicated pattern of ISD trajectories for charge-to-mass ratio 12 C/kg, assuming they made it through the heliosheath [Sterken+ 2012]

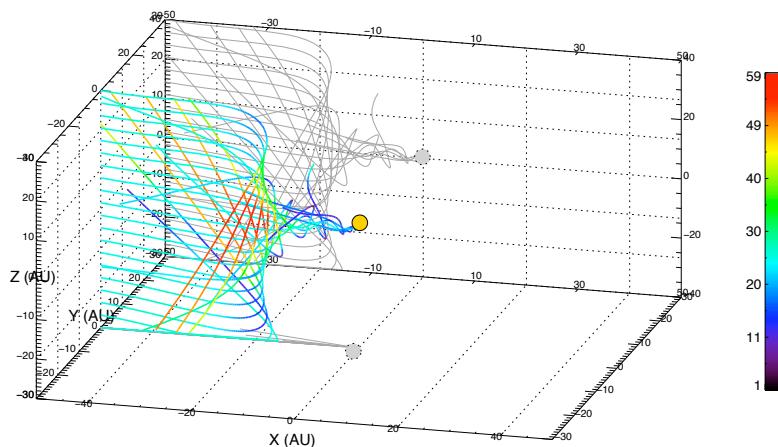
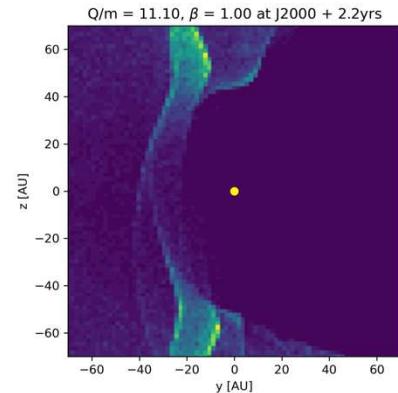


Figure 3 (below): Higher dust densities ‘rolling’ into the heliosphere for  $Q/m = 11.1$  C/kg [Hunziker+ 2022]. Click on the Figure for a larger version.



<sup>2</sup> In contrary, its *mass distribution increases* with particle size (e.g. Krüger+ 2015, Fig. 6), and thus the largest ISD are the most important for determining the gas-to-dust mass ratio in the LIC.

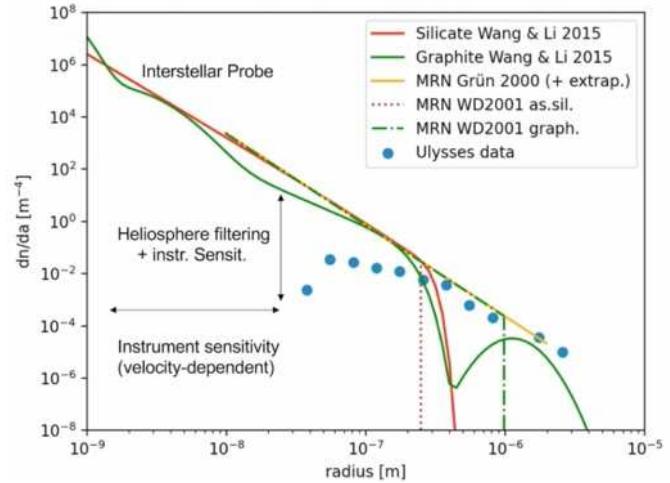


Fig. 1 The interstellar dust size distribution from astronomical models and in situ data by Ulysses [Sterken et al. 2022a]. For a larger version, click on the Figure.

2022a). The exact lower cut-off size of particles that can enter the solar system, and their time-dependence, is not yet exactly known. However, Ulysses and Cassini already measured ISD particles with radii between 50 and 100 nm [Altobelli+ 2016, Krüger+ 2015]. **Nanodust** (2-30 nm) cannot enter the heliosphere because it is coupled to the magnetic field lines of the very local interstellar medium (VLISM), and is diverted around the heliopause boundary [Linde & Gombosi, 2000, Slavin+ 2012]. These particles may also pile-up at the heliopause [Slavin+ 2012, Frisch+ 2022].

### **Filtering of dust in the most outer and inner regions of the heliosphere**

The **filtering** of interstellar dust in the heliosphere happens mainly at the **heliosphere boundary regions** (i.e., at the heliopause and in the heliosheath) and in the region **closer to the Sun** because (1) the dust acquires the highest charges in the heliosheath [Kimura+ 1998, Slavin+ 2012, Ma+ 2013], and (2) the azimuthal component of the interplanetary magnetic field causing the focusing and defocusing effects, is the largest closer to the Sun. Flying a spacecraft through all these regions to measure all parameters simultaneously (magnetic field, plasma densities, dust charging, pickup ions, dust flux, velocity, and direction), would be of utmost value to understand the mechanisms of the dynamics of the dust, the dust-plasma interaction, and the role of dust for heliosphere physics, in particular since this has never been done before. We thus need in-situ measurements of dust and plasma parameters in interplanetary space, at the termination shock, in the heliosheath, at the heliopause and – especially – beyond the heliopause, over the solar cycle, from a future Interstellar Probe.

In situ ISD measurements with Ulysses up to 5.4 AU indeed contained a signature of the dynamic heliosphere [Landgraf+ 2003, Strub+ 2015, Sterken+ 2015]. These particles were measured for the first time in 1993, using an impact ionization dust detector [Grün+ 1993]. Ulysses monitored the ISD throughout the solar cycle (for 16 years), giving us impressions of the fluxes and (roughly) the flow directionality of the dust. The dust flow direction changed in particular in the latitudinal direction in 2006 [Krüger+ 2007], which may have been caused by the Lorentz force [Sterken+ 2015]. Simulations of ISD dynamics in the solar system (without heliosphere boundaries) were piecewise compatible with the data, *if* the larger dust particles are porous or aggregates (hence, if they have a higher charge-to-mass ratio) [Sterken+ 2015]. A second time-dependent mechanism of filtering in the heliosheath was suggested to be needed in order to explain the Ulysses data [Sterken+ 2015]. Time-dependent models of the heliosphere-dust interaction including a heliosheath are currently under development [e.g., Sterken+ 2022c] and this type of research is gaining a lot of traction in the community (e.g., [Alexashov+ 2016, Strub+ 2019, Godenko+ 2021]).

### **B. An interdisciplinary science case and its importance for a wider field**

Here we summarize the most pressing science questions covering the fields of heliospheric (**H**) and dust science (**D**), and questions related to the heliosphere-dust interaction (**HD**). Addressing in depth this broad spectrum of questions is also important for the astrospheric community and for understanding our local interstellar neighborhood. In the following, we divided the questions according to the dust size, so that they can be linked more easily to the type of measurements that are needed. Apart from ISD, interplanetary (nano)dust (IDP) may also play a role in these questions.

**Micron-sized ISD:** What is the gas-to-dust mass ratio in the ISM, and hence, what is the biggest size of ISD residing in the Interstellar Medium (ISM)?<sup>(D)</sup> Do large grains as detected at ground as (interstellar) meteors exist in the ISM?<sup>(D)</sup> Is any of the dust coming from a direction other than the heliosphere nose and what does it imply for our current interstellar environment

near the interface between LIC and G-cloud?<sup>(D)</sup> What is the composition and morphology of micron-sized ISD (porous, aggregate, compact?) and its implication for the formation of the dust and processes in the VLISM?<sup>(HD)</sup> What are the characteristics of Oort cloud dust, and what will the Kuiper belt dust reveal about its sources?<sup>(D)</sup>

**Submicron-sized ISD:** How does ISD dynamics depend on the heliosphere, and particularly how does the heliosheath filter out these particles?<sup>(HD)</sup> How is the time-variable size and structure of the heliosphere (using dust measurements as additional boundary conditions for the heliosphere models)?<sup>(H)</sup> From which distance to the Sun can we measure carbonaceous ISD and why was there low detection evidence so far?

**Nanodust ISD:** How much nanodust is filtered (time-dependent or permanently) at the heliopause and heliosheath?<sup>(HD)</sup> What role does the nanodust inside and outside of the heliopause/heliosheath play in heliospheric physics?<sup>(HD)</sup> Does nanodust pile-up near the heliopause?<sup>(HD)</sup> Where does ‘outgoing’ (interplanetary) nanodust from the solar system and the ISD that can come in, reside in the heliosphere; i.e. will they flow to the heliosphere flanks?<sup>(HD)</sup> Can it affect the heliosphere size and structure throughout the solar cycle?<sup>(HD)</sup> What are carbon nanodust species made of and will we measure Polycyclic Aromatic Hydrocarbon (PAH) clusters outside of the heliopause?<sup>(D)</sup>

**All dust sizes:** How much charging does ISD acquire in different regions of the heliosphere, in particular in the heliosheath, and how does this charging depend on dust size, composition and local environment properties?<sup>(HD)</sup> Does dust – and what sizes of the dust – play a role in the pressure balance of the heliosphere?<sup>(HD)</sup> How does the dust affect the production of pickup ions and how does it depend on the solar cycle? Do ISD/IDP contribute to mass-loading of the solar wind?<sup>(HD)</sup> What are the different dust populations in the ISM and what are their compositions, particle morphologies, and bulk densities?<sup>(D)</sup> How do they comply to astronomical measurements and cosmic abundances?<sup>(D)</sup> How much do they affect the plasma / heliosphere physics, and at which spatial scales?<sup>(HD)</sup> What species of carbonaceous ISD exist and for which dust sizes and abundances?<sup>(D)</sup> How much of the ISD is likely recondensed, or pristine stardust?<sup>(D)</sup> What is the role of the dust for astrospheres?<sup>(HD)</sup> What is the role of the dust in the history and habitability of the heliosphere?<sup>(HD)</sup>

**Importance:** Probing the heliosphere-dust interaction using modelling and in situ measurements is essential to understand our own immediate interplanetary and interstellar environment. It is also a test-bed to understand how other astrospheres work, as well as to unravel the history of our own solar system and its interaction with various environments during its journey through the Galaxy, of which tracers can now be found in deep-sea sediments (e.g., from supernovae [Miller+ 2022] or from passing through denser clouds [Opher+ 2022a]). Dust from the VLISM is of particular astrophysical interest in light of recent near-Earth supernovae whose debris is still falling on Earth today [Koll+ 2019] and must arrive in the form of dust [Miller+ 2022]. It is also important for galaxy evolution and physics of the ISM.

### **C. Assessment of infrastructure, research strategy to answer these science questions, and technological development needs**

#### **1. Dust measurements on an Interstellar Probe**

First and foremost, a mission into interstellar space like the Interstellar Probe [McNutt+ 2022, Brandt+ 2022] with a dedicated dust detection suite on board would be optimal for compelling ISD and heliosphere research. Such an Interstellar Probe (ISP) would – for the first time – be

able to measure the smallest ISD particles beyond the heliopause that are blocked from entering the solar system. With this, ISP would be entering unexplored scientific territory! Also, these dust particles of a few to tens of nanometers are orders of magnitude more numerous than the particles Ulysses could measure (see Fig. 1). In addition, ISP can detect whether there is really a pile-up of particles near the heliopause. For the first time, we would be able to measure how and until what size the particles follow the flow of the VLISM, which sizes can cross the heliopause (heliopause permeability), and how far some particles can travel through the heliosheath. This, in combination with measurements of the local magnetic field, plasma properties, pickup ions, and the surface charge for dust particles larger than a few hundred nm, will help tremendously in understanding the heliosphere-dust interaction *and* the potential role of dust in heliosphere physics. Also, ISP moves fast (ca. 7-8 AU per year outward) into the stream of ISD (coming at 5.5 AU per year inwards). On the one hand, this results in higher fluxes (cf., detection rates), and on the other hand, in an enhanced detector sensitivity for the dust impacts, making the detection of tiny particles easier as well as allowing particles to be fully ionized for all compositional elements. Last but not least, ISP will fly throughout approximately 16 years of a solar cycle passing through interplanetary space, the termination shock, the heliosheath, up to the heliopause and beyond, making it an optimal mission for studying the heliosphere-dust coupling and using this knowledge for other astrospheres. Beyond the heliopause, the tiny dust with gyroradii of only a few to 100 AU (for dust radii  $<0.1 \mu\text{m}$ ), will help to study the interstellar environment (magnetic field, plasma) and may detect local enhancements of smaller as well as bigger ISD. The strength of the mission lies in flying through all these diverse regions, and in simultaneous magnetic field, dust, plasma and pickup ion measurements. No mission so far has flown a dedicated dust dynamics and composition suite into the heliosheath and the vast space beyond.

## 2. Continuous observations and observations from different vantage points in space

The optimal way to disentangle the spatially and temporally variable dust dynamics in the heliosphere is on the one hand, by ensuring **long-term monitoring** of the dust flux ( $> 22$  years), and on the other hand, by combining measurements from **different vantage points** in space. Hence, the science yield of an ISP mission would be much enhanced by simultaneous measurements inside the solar system by another mission, with a dust suite tailored to measuring dust dynamics (and composition) over an extended period of time. One example of such a mission could be the DOLPHIN(+) mission concept that was proposed to ESA 2022 [Sterken+ 2022c], or a mission with a Ulysses-type of orbit (out of the ecliptic and perpendicular to the ISD stream). Such a dust suite could contain a Large Area Mass Spectrometer [Sternovsky +2007, Srama+ 2007], combined with several charge grids / trajectory sensors, eventually augmented by a large-area PVDF.

## 3. Synergies between heliosphere and dust measurements, inclusion of ‘serendipity instruments’, and modelling

Simultaneous measurements of **complementary instruments**, i.e., for plasma and magnetic field properties and pickup ion detections, together with dust fluxes, velocities, directions and – if possible – dust surface charge, will yield particularly strong synergies between dust and heliospheric science. The inclusion of ‘**serendipity dust instruments**’ that collect information on dust impacts but were originally not designed to do so, will enlarge the pool of data to be used from different vantage points in space. Plasma wave instruments on various satellites, which pick up a sharp signal when a dust particle impacts the spacecraft, are very good examples of this. The Wind mission yielded a yearly recurring ISD signature in the more than 25 years of plasma wave dust data, including a solar cycle variability [Malaspina+ 2014, Malaspina+ 2016, Hervig+ 2022]. Also Voyager has detected some (limited) impacts [Gurnett

1983]. A challenge is that the operations and observations were not tailored to dust impacts; hence, retrieving the dust flux and direction is a challenging task. Also, information like impact velocity, particle mass or particle charge is missing. Therefore, it is difficult in the solar system to distinguish between interplanetary dust particles (IDP) and interstellar dust (ISD) impacts. A **long-term dust monitoring** mission, with sufficiently **large detector surfaces**, and **dust trajectory, surface charge, and velocity sensing capabilities** (and composition), would be a tremendous leap forward, and a significant increment to this pool of data. In any case, Wind has fuel for another 50 years [Darling 2019], IMAP (with dust detector) could keep monitoring the compositions and fluxes of incoming ISD, and **Deep Space Gateway** may be a good platform for long-term monitoring during the flight time of an Interstellar Probe.

When such a data set (multiple places, long-term) is combined with state-of-the-art **computer modelling** of the heliosphere-dust flow, then the particle properties (e.g., size distribution in the LIC) and the dynamical structure of the heliosphere can be retrieved by fitting a model of the heliosphere, including time-variable heliosheath, to the pool of data. Fig. 4 illustrates that even a simple model with only dust filtering in the solar system can already yield valuable information about the filtering at the heliosheath if sufficient data are available. The model used is the IMEX model [Strub+ 2019].

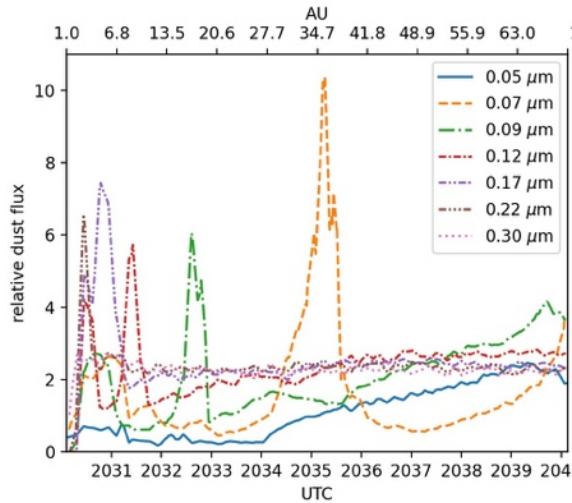


Figure 4 [Hunziker+ 2022a]: An example of how computer simulations of dust fluxes can teach us about the filtering at the heliosheath, when compared to spacecraft data for the respective dust sizes. The ISD waves ‘rolling’ in can be seen as sharp increases in relative flux, at different times for different particle sizes. An additional filtering at the heliosphere boundaries would alter this pattern. These fluxes are predicted along an ISP trajectory with launch date in 2030, during the focusing phase of the solar cycle. Dust observations along the path of ISP at high impact velocities may be able to shed light on the heliospheric filtering, through monitoring whether such patterns are present inside of the heliosphere, in addition to the direct measurements in the heliosheath. Similar such investigations can be undertaken in the solar system. Click on the Figure for a larger version.

#### 4. Ground-based facilities

An on-going calibration effort of different dust detectors with a **dust accelerator** is crucial for success. Since ISP moves very **fast**, calibrations with a dust accelerator are needed with high velocities and for dust particle analogs with different properties (e.g., lower bulk density dust analogs are important for measurements of  $\mu\text{m}$ -sized ISD [Hunziker+ 2022b]). New dust analogs need to be further developed, measurements with plasma wave instruments need to be further understood (e.g., [Shen+ 2021]), and high-level computing facilities are needed for the modelling. The dust accelerator at LASP, Univ. Colorado Boulder is an indispensable tool for any space mission with a dust detector on board. Complementary efforts are also made in Europe: developments are underway at the University of Stuttgart for a linear staged accelerator (faster velocities), and at ETH Zürich and FU Berlin for the next generation of dust analogs. High-precision and high-power ( $> 100$  kW pulse) ground-based radars are needed for interstellar meteor research [Hajdukova+ 2020].

The technological risk for these types of missions, instruments and ground-based facilities is relatively low, since most have been developed already, or are based on heritage.

#### **D. International landscape, state of profession, and connection to other disciplines**

At the international level, a large interest exists in the cross-disciplinary field of dust and heliosphere science. For instance, the Wind satellite dust impact data are currently being analyzed together, by a team of scientists from Europe and the USA, and are being compared to state-of-the-art computer simulations of dust dynamics in the heliosphere. This is done in the context of a 1.5 Meuro project to model the dust flow in the heliosphere, which was selected for funding by the European Research Council [Sterken+ 2022b]. A European COST action about ‘Carbon molecular nanostructures in space’, approved in 2022 [Garcia Hernandez 2022], brings together scientists from different disciplines who work on the topic of macromolecules and nanodust in space: highly relevant for ISP beyond the heliopause. Meanwhile in the USA, NASA has selected the SHIELD drive center for a second period of operations [Opher+ 2022b] and the IMAP mission with an interstellar dust composition analyzer (IDEX) is being prepared for launch in 2025 [McComas+ 2018]. JAXA and DLR are preparing the Destiny+ mission (launch in 2024) with a European dust instrument, the Destiny+ Dust Analyzer, that will measure the ISD and dust from the active asteroid Phaeton. This instrument has a charge grid sensor at its entrance for measuring dust surface charges and impact velocities (for particles  $\sim > 0.5 \mu\text{m}$ ). It relies on heritage from the highly successful Cassini Cosmic Dust Analyzer, that also had a grid. Last but not least, the “DOLPHIN(+)” mission was proposed to ESA in response to the latest F-class call for proposals (2022). Its main objective is to measure ISD (and IDP) in the solar system during the next focusing phase of the solar cycle with a focus on the dust-heliosphere interaction, dynamics and composition [Sterken+ 2022c]. All in all, the strong need for new tailored missions and more data from different vantage points in space drives a diversity of initiatives across national borders that calls for international collaboration. The new capabilities offered by the private space industry (e.g., Starship) may reinforce this trend and help the deployment of larger detection surfaces in space.

#### **E. Conclusions**

Many compelling science questions exist concerning the interaction of ISD (and IDP) with the heliosphere. We highlighted the synergies between the two sciences, and what tremendous progress we could make if a dedicated dust suite would fly on an Interstellar Probe to measure dust properties together with the plasma, magnetic field, and pickup ions, during its journey through all the regions inside and outside of the heliosphere. The science yield would be increased even more by simultaneous measurements by other missions inside the solar system, while ISP is on its journey. The science results may be crucial for understanding the physics and pressure balance of the heliosphere, and the pool of new dust measurements can be used as an extra boundary condition for heliosphere models to help reveal the time-dependent structure and size of the heliosphere. We described the major advantages for the dust measurements on ISP, like being outside of the heliopause highly abundant nano-ISD resides, and flying at very high speeds against the flow of ISD – good for detecting dust. From a programmatic point of view, a mission like ISP with dust detector is crucial, but there is also a need for an optimized long-term monitoring of ISD dynamics parameters (and composition) with broad temporal and spatial coverage in the solar system. The topic of dust-heliosphere science is gaining a lot of traction in the community and collaborations between the continents are important. The new space industry may allow for larger detection surfaces or optimized orbits. Finally, solving the science questions presented here will not only benefit dust science and heliosphere science: it will also foster broader synergistic cross-divisional science between heliophysics, astronomy, planetary science and astrobiology, addressing for instance the role of astrospheres in habitability of planetary systems. Such cross-divisional science that not only “crosses” the borders of divisions, but also augments science in each of them, thus meeting the exact definition of a true “synergy”.

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