MERIT
...brains in motion

Unraveling the history of the Young Local Milky Way: Connecting Molecular Clouds and Stellar Populations (CLOUDS2STARS-6D)

by [redacted]

1. EXCELLENCE

1.1 Quality and pertinence of the project's research and innovation objectives (and the extent to which they are ambitious, and go beyond the state-of-the-art).

I study the history of star formation in the Young Local Milky Way (YLMW) by focusing on major star-forming complexes within the local kiloparsec (kpc). The YLMW is essential for Astrophysical research, offering a high-resolution view of universal Astrophysical processes like cloud/star/planet formation and evolution. While local star-forming regions have been well studied in the past in terms of gas and young stellar content (e.g., [redacted] +2001, [redacted] +2008a,b, [redacted] +2009, [redacted] +2009, [redacted] +2010, [redacted] +2010, [redacted] +2012, [redacted] +2011,2014, [redacted] +2015), we lack detailed information about their formation history. ESA's *Gaia* mission (DR2, (e)DR3; [redacted] Coll. +2016,2018,2021,2023) has started to improve our understanding of the Milky Way structure. Its precise astrometry enables a new 3D view of phenomena that have often been describable in 2D, including updated catalogs for young open clusters (e.g., [redacted] +2018, [redacted] +2018,2020, [redacted] +2018,2022, [redacted] +2018, 2021, [redacted] +2020, [redacted] +2021, [redacted] +2021, [redacted] +2019,2021, [redacted] +2020, [redacted] +2021,2023, [redacted] +2023) and 3D dust maps, delivering molecular clouds' 3D shapes and distances (e.g., [redacted] +2018, [redacted] +2019, [redacted] +2019, [redacted] +2020, [redacted] +2019, [redacted] +2022, [redacted] .+2020,2022). Hence, the post-*Gaia* view allows new interpretations of formation histories (e.g., [redacted] +2021, [redacted] +2022, [redacted] +2023, [redacted] +2022,2023).

Only recently it was shown that star-forming regions are likely connected along local spiral arms and spur-like features in the Milky Way. This supersedes earlier concepts, like the Gould Belt (e.g., [redacted] 1874, [redacted] +2017, [redacted] +2018), which postulated that the star-forming regions within about 500 pc are arranged in a belt around the Sun. The updated 3D maps of gas and stars do not show such a belt, but rather an almost 3 kpc-long wave-like structure, called the *Radcliffe Wave* ([redacted] +2020), and on the other side of the Sun a spur-like feature called the *Split* ([redacted] +2019) (see also [redacted] +2021, [redacted] +2022). For a better understanding of these large-scale features, we first need a better understanding of the role of individual complexes within these structures and their history and evolution, including **the connection and/or interaction of gas and stars**. Along this line, my project will add a crucial puzzle piece to better understand the star formation process in the YLMW.

My aim is to improve our knowledge of formation histories in the YLMW by centring my analysis on two major complexes, Orion & Scorpio-Centaurus (Sco-Cen) plus their wider surroundings [redacted] +2008a,b). The Orion complex is the closest massive star-forming region within 500 pc (incl. a diverse environment and OB association) and will be studied together with Taurus, Perseus, Monoceros, and California (collectively named here ***ORION***+), which all align along the *Radcliffe Wave*. The ***Sco-Cen*** complex ([redacted] 1964a,b) hosts the closest OB association within 150 pc including star-forming clouds (Ophiuchus, Lupus, Corona Australis (CrA), Chamaeleon, Pipe, L134/L183; see [redacted] + 2023a) which are part of the *Split*. I will combine clustering results from the novel **SigMA** tool (see below) with detailed investigations of star-forming molecular clouds using young stellar objects (YSOs) as indicators (e.g., [redacted] +2018,2019,2021), in combination with ESA/*Herschel* ([redacted] +2010, [redacted] +2014) to define cloud boundaries and estimate clouds masses. I will use *Gaia*'s high-precision astrometry and auxiliary radial velocity (RV) data to study the 3D space and time connection (6D phase space) between molecular clouds and young stellar populations within these local complexes. I will focus on questions about the **origin and connection of stellar populations and molecular clouds** on local (<100 pc) and on larger scales (>100 pc), including the influence of previous generations of massive stars on the currently star-forming clouds to **quantify feedback from massive stars** (winds; photoionization; supernovae, SNe). To achieve this, I will work with the Physics of Galaxies (PoG) group at my host organization (HO) in Prague, led by [redacted] and [redacted] (***Sect. 1.3***), who are experts in simulations of molecular cloud environments, the influence of feedback from massive stars, and Milky Way structure.

Recently, we have developed a new, innovative machine-learning-based clustering tool named **SigMA** (Significance Mode Analysis, see [redacted], [redacted] **et al. 2023a**) to provide more insight into the origin and history of young stellar populations and their connection to star-forming regions. **SigMA** is tailored to find significantly clustered overdensities within stellar associations in the 5D phases space as provided by *Gaia*, outperforming similar tools in such rich environments (e.g., (H)DBSCAN, e.g., [redacted] +2021,2023, [redacted] +2023), first applied to Sco-Cen (see ***Fig. 1***). To identify young clusters based on their co-spatial and co-moving nature is an established concept (I use term "*clus-*

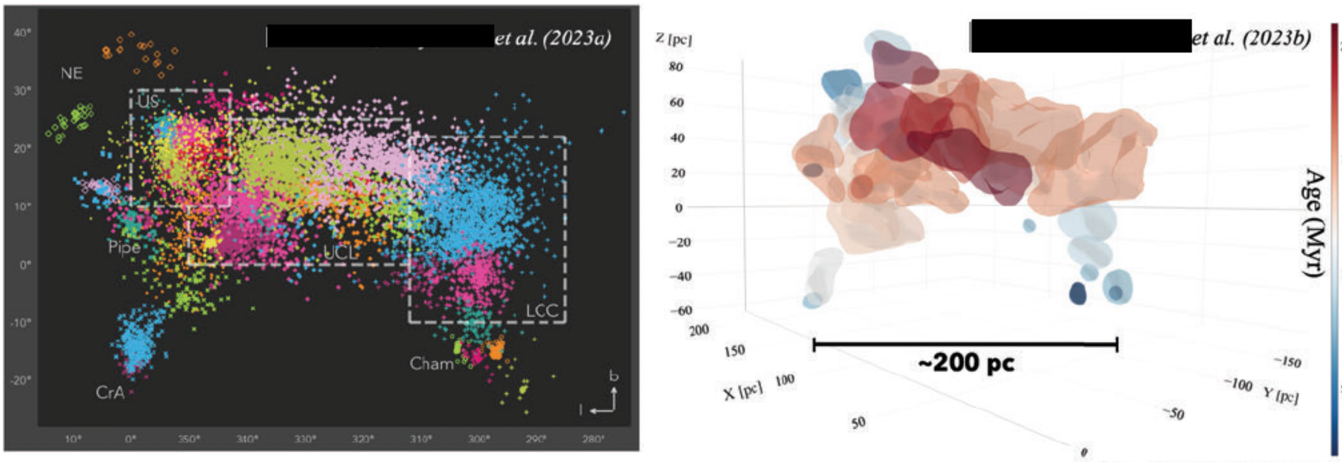

***Fig. 1. Proof of Concept. New clustering (left) and age distribution (right) in Sco-Cen with* SigMA.** *Left: Sco-Cen shows a wider extent, more substructure (37 clusters), and richer clusters as was established previously (e.g., [redacted] 1964, de [redacted] +1999; boxes indicate earlier defined substructure). Right: 3D distribution of clusters (shown as 3D surfaces) in Heliocentric Galactic Cartesian are present in Sco-Cen, ıssociation. Figures from*

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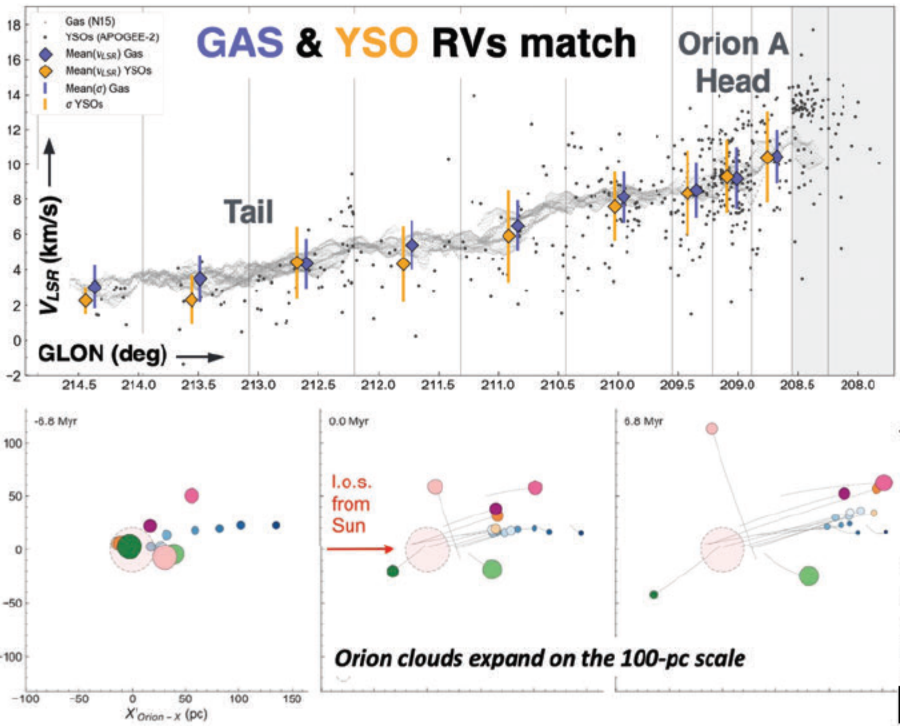

Fig. 2. Proof of cloud's 3D spac *Velocity diagram molecular cloud. 1 blue diamonds, match on average RVs (black dots APOGEE-2), lead YSO PMs trace t space motions of Side-view at thre cartesian average centred on the clu rest frame, possil feedback from m are for Orion A (and two cometar (green). Addition σOri and NGC197 cloud parts and closest about 6 expanding motio indicating the in massive stars in* [redacted] *et al. (*

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ter" in a statistical sense, namely, a significant overdensity above the background, while such clusters do not have to be bound; other designations: stellar population or co-moving stellar group). It was shown that stars that formed together will remain on similar orbits around the Galaxy within some 10^8 yr, before they dissolve into the field (e.g., [redacted]) while they start to disperse and change their shape and extent earlier (e.g., tidal tails, streams, [redacted]). Therefore, the youngest stellar populations (ages <50 Myr) are the best probes to study early cluster evolution. In a subsequent analysis ([redacted] **et al. 2023b**) we studied the ages of the Sco-Cen clusters, measured via isochrone fitting using a Bayesian approach. We find signs of inside-out star formation propagation, indicating sequential star formation from older clusters in the centre to younger clusters in the outskirts of the complex (see ***Fig. 1***). This is an example of relatively simple patterns of star formation propagation (broadly confirming the sequential star formation scenario by [redacted] 1977), which has not been identified as clearly before (see e.g., [redacted]+2023). This highlights the great potential of *Gaia* data in combination with sophisticated machine-learning tools, which enables us to make quick progress in this highly competitive field.

Moreover, we have made the first measurement of molecular cloud shapes and 3D space motions by utilizing the distances and proper motions (PMs) of young stellar objects (YSOs) in Orion as cloud tracers ([redacted] **et al. 2018, 2021**). This is possible since we find that the YSOs, which recently formed in the clouds, are still located near the dense gas (e.g., [redacted] **et al. 2019**) and, in particular, that they still share the same RVs as the gas (see ***Fig. 2*** *top* and [redacted] **et al. 2021**, see also [redacted]). Therefore, we can use **YSOs as proxies for a cloud's 3D space properties.** The analysis in [redacted]**+2021** revealed that molecular clouds in Orion are expanding on the 100-pc scale (***Fig. 2*** *bottom*) and the 3D space motions of the clouds allowed the first measurement of cloud momenta and their quantification by comparing to simulations (e.g., [redacted] 2015). Also recently, we have used a similar approach to study the history of the *Local Bubble (LB)* ([redacted] **et al. 2022**), where we find that all nearby star-forming regions within about 200 pc from the Sun are located on the surface of the *LB* (see also [redacted]+ 2020) and are likely influenced by the bubble expansion (incl. regions that are connected to both *Radcliffe Wave* or *Split*). These pilot studies show the potential when conducting a more detailed analysis of individual local regions. However, there is still a lot to be done to draw a more complete picture of their formation histories and remove existing inconstancies, to study the connection of gas and stars, and their role on larger scales, which calls for a dedicated project, as proposed here.

Building upon my know-how and combining it with theoretical models at my HO allows me to answer several *open questions*. First, the systematic and detailed investigation of individual star-forming regions will **bring together the history of molecular clouds and young stellar populations**. While there exist recent attempts for several nearby regions (e.g., [redacted],b), we are still missing a detailed investigation and understanding of the connection of gas and stars, their history, and also a combined discussion of these regions, of which some lie adjacent to each other (e.g., *ORION+*). The recent studies often focused on subregions within complexes, the stellar or gas component, or only the youngest stars in the regions. My aim is (1) to open the box to first provide an updated, tailored, homogeneous stellar clustering solution and age determination for larger areas and to unravel the connections of the older and younger components (planned with **`SigMA`** for *ORION+*, building upon the pilot-study performed for Sco-Cen), allowing to understand the origin of the stellar populations that are found today in the investigated volumes. (2) On smaller scales (<100 pc) I will investigate the local connection of gas and stars and the possible interactions between the compounds. This further allows to study the possibly different historical background of low- vs high-mass star-forming regions (e.g., Orion vs Taurus). (3) Finally, I will quantify and interpret the observed phenomena using theoretical models, together with my colleagues in Prague, which will be a critical step toward a **better understanding of the history and evolution of local regions, and to quantify the importance of feedback in regulating star formation in the Milky Way.**

1.2 Soundness of the proposed methodology (including interdisciplinary approaches, consideration of the gender dimension, and other diversity aspects if relevant to the research project).

To study the history of star formation within young complexes in the Solar neighborhood, I will investigate both the young stellar populations (*clusters*) and molecular clouds in 3D space and time. To this end, I am combining the 5D phase space provided by *Gaia* DR3 astrometry with auxiliary RV data to determine the 6D phase space of stellar populations and molecular clouds, and consequently their orbits in the Milky Way potential (e.g., [redacted]/ [redacted]). Clusters are extracted with the novel **`SigMA`** tool (as successfully applied to Sco-Cen) and are compared and/ or combined with samples from the literature (see WP2). I will investigate recently published 3D dust maps (e.g., [redacted]+2022) to know the molecular cloud's 3D shapes and distances and to derive cloud masses in combination with dust column-density maps using *Herschel* or extinction maps (e.g., [redacted]+2011, 2014). Cloud masses are needed to estimate momenta and compare to simulations, and to derive star formation efficiencies (e.g., [redacted]+2020) to know the star formation activity of the clouds. The gas RVs will be derived from existing molecular emission line surveys (e.g., CO, [redacted]+2001), or in collaboration with experts in radio astronomy ([redacted]), which will be compared to stellar RVs (see ***Fig. 2***). To gather auxiliary stellar RVs will be a critical step since RVs provided by *Gaia* do not deliver sufficient statistics for most stellar populations (see details in ***Sect. 3.1***).

I am Co-I of **4SYS** (ESO's 4MOST survey of young stars, PI: G.G. [redacted], see [redacted]+2023), which will deliver a wealth of RV measurements for young stars within 500 pc from the Sun. Observations will start in 2024, and I will have access to early data products. Moreover, I am Co-I of the **VISIONS** survey (The VISTA Star Formation Atlas; PI: [redacted]+2023a,b; see also *pilot*-project VISION, [redacted]+2016). With VISIONS we observed all nearby star-forming regions, which are accessible from the southern hemisphere (Orion, Ophiuchus, Pipe, Lupus, CrA, Chamaeleon-Musca) with the near-infrared (NIR) camera VIRCAM at ESO-VISTA *at several epochs*. Hence, **VISIONS will provide PMs in the infrared**, which also includes the youngest and most embedded YSOs, complementary to the optical *Gaia* PMs. PMs of embedded YSOs represent an even more direct link to the motion of the host molecular cloud as compared to optical *Gaia* PMs of the slightly more revealed YSO population (mostly Class II). Therefore, VISIONS IR-PM will improve the 6D phase space analysis of the targeted regions and they will increase the statistics for smaller or low-mass star-forming clouds to achieve a more robust analysis.

By studying the relative positions of stellar populations in 3D space and time, I can reveal yet unseen connections, like common versus different origins; or differences in low-mass versus high-mass star-forming regions (Orion vs. Taurus or California). Moreover, as observed in Orion ([redacted]+2021, ***Fig. 2***), feedback from massive stars could be able to displace molecular cloud parts and "push" them away from each other. This gives me the opportunity to empirically quantify feedback from massive stars. Therefore, it is critical, also in the case of Orion, to study all compounds within the whole complex, because the origins of massive stellar feedback in the region are not yet unraveled. Such analysis brings further challenges, for instance, stars that subsequently form in such "triggered" clouds, could not be traced back easily to their origin place, assuming they were displaced by one or several external forces in the past. These challenges will be taken into account, for instance, by investigating by how much a cloud (or gas clump) can be displaced by feedback from massive stars, without being destroyed and subsequently still form stars. This step will be critically aided by results from models and simulations and will bring us an essential step closer to quantifying the role of feedback in regulating star formation. Another challenge are uncertainties when determining average 3D space positions and motions, while the largest uncertainties are expected for sparse clusters with insufficient data coverage, mainly caused by the lack of RV data (***Sect. 3.1***, WP2). Moreover, when tracing back the orbits, the uncertainties will propagate at each integration step, however, the estimates are expected to be relatively robust for orbital tracebacks within about 20 Myr (e.g., [redacted]+2021), which is the most interesting time frame for my analysis.

Interdisciplinary aspects: As already highlighted earlier, I will combine my observational approach with the theoretical approach at my HO in Prague, who are specialized in analytic analysis and simulations. First, existing simulations will be investigated that deliver information about the feedback processes acting in a molecular cloud environment (e.g., SILCC [redacted] 2022, see also ***Sect. 1.3***). Building upon these, we will be in an advantageous position to establish new simulation setups that are directly informed by my empirical know-how (e.g., Orion-like environment, Radcliffe Wave-like spiral arm structures). Such tailored setups will improve our interpretations and will allow more precise quantification of the star formation history and evolution of stellar populations and molecular clouds in the YLMW, which is a critical step to make progress in the field.

Moreover, I plan my secondment with the group of Dieter Breitschwerdt at TU Berlin (see ***Sect. 3.2***), who have expertise in massive stellar evolution, SNe, and studying radioisotopes that are products of these. Interestingly, such radioisotopes have been found in the Earth's crust and can be linked to massive star-forming regions in our neighborhood (e.g., to SNe from Sco-Cen; [redacted] 2022). This collaboration will allow us to connect the Sun's history with the updated 6D information of the local Milky Way, by locating the origin of feedback from massive stars that could have potentially influenced the Solar system in the past and by relating this to radioisotope dating. This constitutes another interdisciplinary and innovative aspect of my project, tackling not only the origin of stars near the Sun but also the recent history of our Solar system in the context of its environment.

Gender and diversity-related aspects are generally not a part of the scientific content in astronomical research. Nevertheless, also in natural sciences, we aim to strive toward a more inclusive environment, by providing an encouraging environment for women and minorities (see also ***Sect. 2.3***).

I will follow the common *open science practice*, as typical for astrophysical research. Our results will be made available not only via publications in refereed journals (see ***Sect. 2.2***), but we will also provide information on a dedicated webpage to enable easy access to a broader audience. To guarantee early access for the scientific community, we will publish pre-prints of our publications on the arXiv. Resulting data catalogs, will be made freely available in tabular form via the CDS/Vizier, allowing the community to build upon our results. New simulation setups will be communicated via a webpage and will be described in the respective publications. Additionally, I will produce 3D interactive figures for better comprehension of the results, similar to those in the pilot studies, which will be accessible as links via the publications and on a webpage.

To manage the data locally, we will store the data additionally on external drives and also in online clouds (like Dropbox) to guarantee that no data is lost, in particular considering ongoing work and manuscripts. To analyze and process the data I will use new equipment, hence a new Laptop will be acquired to guarantee state-of-the-art analysis. The simulations will be run at the host organization using the local computational cluster Virgo with ~700 CPU cores, or, for larger simulations, we will apply for computational time at the Czech national supercomputer center IT4I (the PoG group has a record of about ten successful applications at IT4I). The data will be managed in line with the FAIR standards; the generated data, results, and know-how will be made available mainly via the planned scientific publications and also on a dedicated webpage, and tabular data will be uploaded to the astronomical online database at CDS/Vizier (see above and ***Sect. 2.2***).

1.3 Quality of the two-way transfer of knowledge between the researcher and the host.

I will work in the Physics of Galaxies (PoG) research group in Prague led by [redacted] at the *Galaxies and Planetary Systems department of the Astronomical Institute of the Czech Academy of Sciences*, which is led by [redacted], with the latter being my direct local supervisor. This collaboration will allow me to improve the interpretations of star formation processes in the YLMW by comparing my empirical results with simulations established in the group, while I will be involved in the development of further simulation setups. For instance, R. Wünsch is an expert in massive stars and clusters (e.g., [redacted] 2019) and he is involved in the SILCC project (Simulating the Life-Cycle of molecular Clouds, e.g., [redacted]+2022,2023), which includes high-resolution zoomed-in simulations of molecular cloud evolution in a Milky-Way-like disk, including feedback processes from massive stars. Such simulations are important to quantify the observed momenta of molecular clouds in environments that include OB associations, to better understand the possible origin and quantity of feedback from massive stars and its influence and importance for subsequent star formation. Moreover, observed cloud shapes can be compared to simulations to see if similar structures can be found and what mechanisms are needed to create these (e.g., the "bent" shape of Orion A, see [redacted]+2018). By working in Prague I will be directly involved in the development of new simulation setups, where my expertise in the observed structures will be combined with the knowledge of the theorists. This will improve the research progress in both ways, by enabling on the one hand more sophisticated interpretations and quantifications of observed phenomena, and on the other hand, by informing the simulations to be more tailored to real observational phenomena. The exact type and setup of such new simulations will be discussed at the start of the project, together with the members of the PoG group, which will allow a more detailed identification of open questions and possible pros and cons of existing setups.

Moreover, the group in Prague has a history of detailed research of the local Milky Way, with [redacted] being experts in the field, in particular including studies of the Gould Belt (e.g., [redacted] & 2015, 2017); a kpc-scale structure which was proposed to connect the local star-forming regions. Recent results with *Gaia* have shown that the connection of local star-forming regions and young stars is likely not related to a belt-like structure surrounding the Sun, but more likely to local spiral arms and spur-like features, like the *Radcliffe Wave* or the *Split* (see also ***Sect. 1.1***). Combining "historical" knowledge with the post-*Gaia* view will be critical to ensure that we are not overinterpreting new results and to connect the earlier established with new interpretations.

Finally, being involved directly in the development of theoretical models and simulation setups will increase my know-how beyond the observational perspective and expose me to a broader scientific community. Therefore, working in the PoG group in Prague will significantly diversify my expertise, which will represent an important booster for my future career.

1.4 Quality and appropriateness of the researcher's professional experience, competencies, and skills.

The research group in Prague will also profit from my know-how since I will bring contemporary research based on *Gaia* astrometry and 3D analysis (see ***Sect. 1.1***). My recent research allowed me to be involved in methods to map local young structures in 3D space and time, which is only possible for about five years (basically since the release of *Gaia* DR2). Using visualization tools to create interactive 3D figures (e.g., with Python/Plotly, Python/Glue, KitWare/Paraview) enables an improved comprehension of the local structures, which have been traditionally studied mostly in 2D projection. Such an updated 3D view is important, allowing us to see the greater picture and unravel new and unforeseeable connections (e.g., [redacted]). This new 3D view will then directly inform the simulations, which were often the only possibility, in the past, to see star-forming regions from all sides, going beyond the state-of-the-art interpretations of how gas transforms stars in the Galaxy. In conclusion, my expertise on the local Milky Way structure, informed by the post-*Gaia* view, and my detailed knowledge of nearby star-forming regions (like Orion or Sco-Cen) will bring valuable know-how to the PoG group in Prague, who are not (yet) as directly involved in *Gaia* related research and observational 3D visualizations. Moreover, my collaboration with data scientists (Uni Vienna) will bring the know-how of sophisticated machine-learning clustering tools (like `SigMA`), which could potentially also be used on simulated data.

2. IMPACT

2.1 Credibility of the measures to enhance the career perspectives and employability of the researcher and contribution to his/her skills development.

A MERIT fellowship will put me in an advantageous position to work within a prestigious European-funded project, which will naturally improve my future perspectives. This fellowship allows me to work in the PoG group of [redacted] and [redacted] in Prague, delivering a perfect synergy between observational, historical, and theoretical expertise. This fellowship will expose me to experts in the field of star formation, simulations of molecular cloud evolution in the Milky Way, and feedback from massive stars. Therefore, it will allow me to develop innovative methods and knowledge, improving the quality of my analysis of the YLMW. The planned investigations will add critical information on the formation and evolution processes of stars and clouds, which will further strengthen my visibility within the star formation community. Hence, this MERIT project will ensure to pursue my goals in the coming years and it will increase my future career perspectives, by exposing me to a wider collaborative network. I will have the chance to improve various skills (e.g., programming, organizing, mentoring, writing, management or leadership skills), which is further supported by at least four training sessions in transferable skills, provided by the SIC, like Open Science/Open Access training. In conclusion, this fellowship will allow me to develop my own research path and facilitate acquiring a permanent position in the future.

2.2 Suitability and quality of the measures to maximize expected outcomes and impacts, as set out in the dissemination and exploitation plan, including communication activities.

The scientific results will be published in refereed journals (like Astronomy & Astrophysics, A&A), and will be made early available via preprint on the arXiv at the time of acceptance (or at the time of submission, considering competitive results). The resulting data catalogs (e.g., cluster membership lists, average properties of stellar clusters and clouds) will be made additionally available in tabular form via the CDS/VizieR, allowing the community to build upon our findings and facilitating reproducibility. I also aim to disseminate our findings on a dedicated webpage, where we will, for instance, provide details of our simulation setups and also easily digestible information for a broader audience. To make our results more widely known I will also report our findings via press releases and look for possibilities to contribute to public outreach events, enabling knowledge transfer to a larger public audience (see ***Sect. 2.3***). The results will be presented at international meetings and conferences, making them known to the scientific community and getting critical feedback. Typically, about three travels to conferences are planned per year (usually taking place in late spring to early autumn, e.g. EAS meeting).

In astronomical basic research, we are generally not requiring patents, etc. It is common to publish results immediately, which makes them instantaneously usable by the community. For outstanding results we aim to publish in *Nature*, which requires to keep results confidential during the review process, while after acceptance we would additionally provide a version on the arXiv, to make sure that such important work will be easily accessible.

2.3 Sustainability of the candidates' research project in the Region. Opportunities to continue the research through regional/international collaboration with relevant industry or academic sectors.

Astronomical phenomena have fascinated us humans since ancient times; the vast unknown space beyond our Earth has inspired a lot of speculations, legends, and religions. Our knowledge about our immediate surroundings in our home Galaxy, the Milky Way, is a hot topic also for an interested public audience. In particular, we can provide information about the role of our Solar system in connection to nearby star-forming regions, and tackle questions like; Has life on Earth been influenced by events beyond the Solar system, such as near-Earth SNe? To enable the knowledge transfer, we aim to make our work known via press releases, and we will contribute to public outreach events and open days in and near Prague, to directly reach a broader community (e.g. Week of Science and Technology, Science Fair, Night of scientists, International Day of Women and Girls in Science). To be in contact with fascinating scientific results could be inspiring especially for a younger audience, and potentially trigger the interest to pursue a scientific career in the future. In particular, seeing female scientists (as myself) as potential role models could be an inspiration for young girls and women, who have often lacked a realistic perspective of pursuing a scientific career in the past.

I am connected to a wide collaborative network (Uni Vienna, [redacted] US, Harvard CfA, STScI Baltimore, [redacted]), including experts in various fields of astronomical research (star formation and the interstellar medium (ISM), Milky Way structure, stellar spectroscopy, molecular emission line surveys, ALMA, filaments, YSOs, visualization tools, etc.). Together with data scientists in Vienna (S. [redacted]), I will contribute to the further development of the machine-learning clustering tool **`SigMA`** (first tested on Sco-Cen), which we are planning to adapt to different and more distant star-forming environments (incl. *ORION+*, as planned for my project). The wide collaboration also ensures that I will be up to date on recent findings and that possible competitive results can be discussed ahead of publication and coordinated between the groups. Working in Prague with [redacted] and in Berlin with [redacted] will connect me to further experts in the field and to experts in modeling and simulations, adding critical know-how in all directions.

My employment in Prague will also expose me to other researchers at the PoG department (e.g., [redacted]) and also colleagues at Ondřejov (hosting the Solar and Stellar physics departments). I aim to integrate master or PhD students in my research from partner departments/universities. This will ensure sustainable knowledge transfer to the next generation, and it will connect my project to universities in the area of Prague, in particular Charles University, and also beyond (e.g., established connections exist with Masaryk University in Brno, Cologne University in Germany, Szeged University in Hungary). Moreover, I will stay in contact with the star formation group at the University of Vienna, where I will also continue to co-supervise students.

3. IMPLEMENTATION

3.1 Quality and effectiveness of the work plan and assessment of risks.

The **work packages (WP)** can be achieved within a 2.5-year project with the approximate work distribution given below in percentages in parentheses. ***Milestones & Deliverables (M&D)*** are summarized (see also the ***Gantt Chart***) and *possible risks* and their mitigation are addressed.

WP1: Project Management (5%). WP1 includes all organizational duties, like communication with MERIT and the host organization regarding employment, or designing the Career Development Plan. It includes the writing of progress reports (every 6 months) and the final report and the planning of travels to conferences and collaborative visits, and the secondment stay in Berlin. At the host institute, administrative support will be available for standard project management tasks, and I will have regular weekly meetings with my supervisor [redacted].

WP2: Data collection and literature work (20%). WP2 will be carried out mainly throughout the first few months, while this is also a continuous process since new data will be incorporated when available. Recent literature will be searched for complementary analysis, data sets, and YSO or clusters catalogs (e.g., Orion, [redacted] 2023). New cluster catalogs will be produced with **`SigMA`** and *Gaia* DR3 data, and they will be compared to existing catalogs, to test the robustness (for Sco-Cen we find that **`SigMA`** finds more or different substructures and richer clusters when compared to [redacted] 2021). Moreover, a supervised machine-learning tool (**Uncover**, [redacted]+ 2020,2022) can be utilized to add more members for already known stellar groups (e.g., [redacted]+2021). If necessary, additional YSO samples will be selected using IR color selection methods (using WISE, [redacted], 2MASS, VISIONS; know-how demonstrated in [redacted]+2019,2021). The cloud-distance catalog by Zhang 2023 will be investigated, which is also based on YSO distances. Further pre-main-sequence stars can be additionally added using X-ray data (XMM-Newton, Chandra, eROSITA; see e.g., [redacted]+2022).

Stellar and cluster positions and velocities will be collected from ***Gaia* DR3** (parallaxes+PMs+RVs), **VISIONS** (NIR photometry+PMs), and **auxiliary RV surveys** (e.g., Gaia-ESO, APOGEE-2, GALAH, LAMOST, RAVE, SoS by [redacted]+2022, 4SYS/4MOST, or other literature samples and our own observations; e.g., ESO/UVES observations granted for Sco-Cen, PI Miret-Roig). If needed, spectral observing proposals will be planned to improve RV statistics. For molecular clouds, I will assemble **molecular emission line maps** (e.g., CO, [redacted]+2001, [redacted]+2015) to know the

Work package	WP Title	Start Date	YEAR 1												YEAR 2												1/2 YEAR 3					
		Month	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
WP1	Project Management	Jan-24							R1						R2						R3						R4					R5
WP2	Data collection & Literature work	Jan-24			D1			D2						D3												D4						
WP3	6D phase space & SFH analysis	Mar-24							P1											P2												P3
WP4	Dissemination & Communication	May-24					C1		C2		C3								C4		C5		C6								C8	C9
SEC	Secondment	Jan-25																														
		Estimated Calender Month	1/24	2	3	4	5	6	7	8	9	10	11	12	1/25	2	3	4	5	6	7	8	9	10	11	12	1/26	2	3	4	5	6

Gantt Chart. *WP1 stretches over the whole period. WP2 will start in the first months, but will continue at least until the end of the second year. The main work for WP3 will start as early as sufficient data is collected, and it will fill the majority of the working-hours of the project. WP4 starts in the first months of the first year, including visits to the first conferences in 2024, and it will continue until the end including final publications and press releases. The secondment* **(SEC)** *is planned for early 2025.* ***Overview: Milestones & Deliverables (M&D)*** *— R1-R4: Progress reports every 6 months; R5: Final Report (submission deadline extends beyond project duration) — D1: Cross-matched Gaia + RV data; D2: expected VISIONS PM; D3: expected 4SYS RVs; D4: expected Gaia DR4 release — P1-P3 : Three main scientific publications — C1–C9: Conferences or international Meetings.*

gas line-of-sight motion (RVs). Cloud masses are derived from column-density maps, like dust emission maps from **ESA's Herschel and Planck** (e.g., [redacted]+2014) or **extinction maps** (e.g. [redacted]+2009, [redacted]+2011, [redacted]+2017+2018, [redacted] 2022), needed to estimate the projected size and structure of the studied clouds, and to calculate momenta. 3D dust maps are available in the literature (e.g., [redacted], which could also be used to measure cloud masses (e.g., [redacted]); improved 3D dust maps will be published soon (by my collaboration at the CfA).

M&D are the collected data catalogs and the data releases, which will be incorporated as soon as available. The data will be published alongside the scientific publications.

Risks: *Data availability:* The most essential data for my project, ESA's *Gaia* DR3, is freely available to the community (DR4 will be used when available, earliest end of 2025, while not necessary to reach my goals). Further key data (YSO catalogs, RV data, IR photometry, CO maps, Herschel, extinction maps, 3D dust maps) are also largely available or can be generated within the collaboration. The VISIONS IR-PM, valuable for embedded sources hidden in the optical, are currently processed (mainly [redacted]) and will be available in 2024 first to the VISIONS members, while the exact release date is not yet fixed. Overall, VISIONS is not critical for reaching the outlined goals, while it will be a bonus and it has the potential to further improve the results for VISIONS-targeted regions. Stellar RVs are the most critical data set, since they need to be gathered and combined from various, heterogeneous sources (see above) to achieve sufficient statistics for robust results, and to reduce the influence of outliers. Additional RV data from 4SYS will be likely available in late 2024, similar for RVs from our own observations. I am planning to submit further observing proposals for undersampled regions, while it is not guaranteed that such proposals will be accepted. Nevertheless, for most regions/clusters, I can do valuable analysis already with the available survey and literature data. Overall, I consider the risk due to data availability low. The rudimentary goal of the project can be reached with already available data, and only a few stellar populations are expected to be affected by low statistics, which will be reflected in the uncertainty estimates.

WP3: Analysis of the 6D phase space & star formation history (65%). WP3 includes the main part of the analysis (studying the connection of clouds and stars in 3D space and time) and will start as soon as sufficient data is assembled, which is expected within the first few months. First, available cluster catalogs are used ([redacted]+2023a for Sco-Cen; or from literature as mentioned in WP2 for *ORION*+), while I will improve on these with `SigMA` for a more detailed and homogenous analysis. The 3D dynamics will be estimated on average for clouds and stellar groups, or subparts within these if distance or velocity gradients are present (see ***Fig. 2***), and if the stellar statistics allow studying smaller substructures. Galactic orbits will be calculated for the selected cloud parts and stellar clusters, and relative motions within the regions will be analyzed. (1) The orbits will deliver a greater picture and will reveal possible connections in the local MW; and (2) relative motions within one complex will give information about internal dynamics and possible interactions within a complex (e.g., ***Fig. 2***). (3) I will analyze the momenta of involved cloud parts by combining the derived 3D space motions and estimated cloud masses. **The observations will then be quantified by comparing to theoretical models and simulations.** The results will be published in at least 3 refereed first-authored papers.

Paper-1 will focus on an immediate follow-up study for the Sco-Cen region, by analyzing the orbital tracebacks of all recently identified clusters ([redacted]+2023a) and by including molecular clouds containing sufficient YSO samples (Ophiuchus, Lupus, CrA, Pipe, Chamaeleon, L134/L183; similar as in [redacted]+2021) to shed more light on the star formation history of this important nearby complex. This will be a critical analysis to further unravel the origin of the age-patterns identified in [redacted]+2023b, and to add to our understanding of sequential star formation propagation.

Paper-2 will focus on a thorough study of the Orion complex plus its wider surroundings (*ORION+*), to study the interaction of gas and stellar clusters and to understand the larger context of this important nearby region. This will also shed more light on the formation history of the *Orion-Eridanus superbubble* (e.g.., [redacted]+1995, [redacted]+2015), the recently identified *Per-Tau shell* ([redacted]+2021), and the *LB* [redacted]+2022, see also [redacted]+2023, also in context with Sco-Cen). Potentially, this study could split into more than one publication, due to the extensive topic, and out of experience, several results might emerge that might be better presented in dedicated papers (e.g., the stellar clustering result could be published before the detailed analysis of the SFH and a dedicated comparison to simulations).

Paper-3 will focus on the planned novel simulation setup, which will be tailored to tackle critical questions, like the interaction of massive stars and OB associations (winds, SNe) with molecular clouds, in an environment that resembles nearby star-forming regions (e.g., Orion, Sco-Cen, Ophiuchus, or spiral arm features like the *Radcliffe Wave*). An additional study will focus on the possible interaction of the Solar system with nearby star-forming regions, in collaboration with TU Berlin, while first authorship will be decided at a later stage.

M&D: At least three scientific publications (plus additional co-authored papers with collaborators) are planned to be submitted to refereed journals, like A&A, or potentially *Nature*. The publications will contain the resulting data products, summarizing the average 6D phase space information of the studied clouds and young stellar groups in overview tables (will be uploaded to the CDS), and our resulting conclusions on their orbits and SFH.

Risks: (a) *Cloud motions:* A potential risk is that the YSO samples do not yield enough information to estimate 3D space motions of star-forming clouds of interest. The *pilot*-cloud, Orion A, contains ~10^3 YSOs (***Fig. 2***), more than the other regions in the sample. However, clouds that are closer than Orion will have higher-accuracy *Gaia* data, which will partially compensate for the lower YSO numbers. Moreover, my work on Orion proved that average 6D phase space information can also be achieved for relatively small clouds (e.g., cometary-shaped outlying clouds, like L1622, which contain only a handful of YSOs). I am confident that valuable results will be produced for virtually all star-forming clouds if several YSO members are observed by *Gaia* (complemented with VISIONS and auxiliary RV data).

(b) *Work Volume:* One might argue that an analysis of all mentioned (sub)regions and the construction of new simulations could exceed the proposed time schedule. Since the simulations will not be constructed by me from scratch, but mostly guided by my colleagues in Prague, this working step can be achieved in a collaborative manner. Moreover, even a partial analysis of *ORION+* will deliver a wealth of important information. If needed, the final content of the planned 3 papers could be readjusted based on the findings and the status in the community. As outlined above, the analysis might produce several results, suitable for separate papers. In conclusion, I consider the risk of getting no new results to be virtually zero, and highly valuable results will be delivered to the community with very high probability.

(c) *Competition:* The Gaia mission is ongoing; the exploitation of its data products has mainly started in 2018 (with DR2) and the field is very competitive. Addressing distances, 3D structure and motion of nearby clouds and clusters is of central importance to the community. Hence, a risk exists that competing groups in the field pursue similar goals and reach competitive results before us. To make quick progress, existing clustering solutions will be used for early analysis ([redacted]), in parallel to applying **`SigMA`** to *ORION+*. Moreover, we are leading the field in using YSOs as proxies for cloud distances and PMs (hence, cloud 3D space motions) and wish to capitalize on our current advantage with this project. Generally, we have proven that we can publish *Gaia* results in a competitive timeframe ([redacted]+2018,2021, [redacted]+2021, [redacted]+2021, [redacted]+2022, [redacted]+2023, [redacted]+2023a,b). I consider the risk acceptable and unavoidable for any work that wishes to target the competitive field of *Gaia* exploitation. To further mitigate this risk, I maintain a wide base of collaborations (***Sect. 2.3***). Should directly competing results/groups surface, I will have the expertise to focus my efforts, and if necessary, adjust the analyses to have complementary perspectives. With these possibilities of re-scoping, I consider that the risk of project failure due to competition is effectively zero and typical for any scientific project at the level of the State-of-the-Art.

WP4: Dissemination & communication (10%). WP4 will be critical throughout the project; it will likely start after about four months when visiting the first conferences or meetings. See ***Gantt Chart*** and details in ***Sect. 2.2***.

3.2. Relevance, feasibility, and benefit for the research project objectives of the planned secondment. Quality of the secondment choice in terms of at least one of the following principles: intersectionality, interdisciplinarity, or international mobility.

The secondment will be carried out at the Berlin Institute of Technology (TU Berlin, Germany) with the research group of [redacted] (SO co-supervisor) and [redacted]; planned for early 2025. The group has expertise in studying feedback from massive stars, the ISM, bubbles, SNe, and their products (e.g, [redacted]). They have further conducted measurements of deep-sea sediments of the Earth's crust that reveal that recent near-Earth SNe were able to deposit relatively "short-lived" radioisotopes (like ^{60}Fe, half-life ~ 2.6×10^6 yr) on Earth several million years ago. This is a direct link to nearby star-forming regions, since it was shown that at least one SN from Sco-Cen is responsible for a 2.5 Myr ^{60}Fe peak measured on Earth (e.g., [redacted]). Moreover, the successful modeling of radioisotopic data also links the origin of the *LB* directly to (several) SN explosions, which might also influence star formation in the adjacent molecular clouds surrounding the *LB* (e.g., Taurus). My know-how on the location and motion of the nearby young regions will be critical for a better understanding of the origin of such signals. At the same time, I will be exposed to experts in studying massive stars and their influence on the environment, and the interdisciplinary field of radioisotope dating. This will help me to put constraints on the observations made in star-forming complexes. Moreover, we will test if certain signatures from radioisotopes measured on Earth can be correlated with encounters of the Sun with star-forming regions in the past (several 10^7 yr ago). Concluding, this research collaboration will improve our knowledge about massive stars and their influence on the environment (including our Solar system), adding another puzzle piece to unravel the local star formation history.

References

[redacted]

Zápis z jednání Steering Committee MERIT ze dne 11.12.2023

Přítomni:

- [redacted]

Omluvena:

- [redacted]

Agenda:

1. **Zahájení, schválení programu schůze**

Program schůze:

- **Rekapitulace stavu úkolů z minulého jednání**
- **Představení výběrového procesu**
- **Schvalování předložených projektů**
- **Termíny následujících jednání + zamyšlení nad informacemi potřebnými pro monitoring vědeckých projektů**

Návrh usnesení:

Řídicí komise MERIT bere na vědomí program jednání.

Výsledky hlasování

Pro: 4; Proti: 0

Přijaté usnesení:

Řídicí komise MERIT bere na vědomí program jednání.

2. **Úkoly z minulého jednání**

- Vytvořeno sdílené úložiště pro členy SC v prostředí Microsoft 365
- Aktualizovaný jednací řád a seznam zúčastněných partnerských institucí programu MERIT poslán členům SC
- Připravena Dohoda o mlčenlivosti (Non-disclosure agreement) kvůli zajištění důvěrnosti informací členů Steering Committee, podepsána všemi členy (přílohy tvořily ještě prohlášení v AJ: Prohlášení o důvěrnosti, neexistenci střetu zájmů a nediskriminaci, kvůli splnění podmínek projektu vůči EU)

Návrh usnesení:

Řídicí komise MERIT bere na vědomí stav úkolů z minulého jednání.

Výsledky hlasování

Pro: 4; Proti: 0

Přijaté usnesení: *Řídicí komise MERIT bere na vědomí stav úkolů z minulého jednání.*

3. **Stručné představení výběrového procesu**

- PPT prezentace Programové manažerky

Návrh usnesení:

Řídicí komise MERIT bere na vědomí informaci o průběhu výběrového procesu první výzvy programu MERIT.

Výsledky hlasování

Pro: 4; Proti: 0

Přijaté usnesení: *Řídicí komise MERIT bere na vědomí informaci o průběhu výběrového procesu první výzvy programu MERIT.*

4. **Schvalování předložených projektů**

- Členům komise byla předem sdílena tabulka s přehledem kandidátů, jejich umístění, včetně navrhovaných secondmentů, stručné abstrakty řešených projektů, a dále kompletní projektové návrhy a hodnotící reporty z obou kol hodnocení
- Všechny projekty prošly hodnocením v mezinárodním transparentním výběrovém řízení v souladu s pravidly programu MERIT.

Návrh usnesení:

Řídicí komise schvaluje celkem 23 projektů předložených do první výzvy programu MERIT, z nichž 15 projektů, které získaly v hodnocení nejvyšší skóre, budou podpořeny, a 8 rezervních projektů může být podpořeno v případě, že některý z podpořených projektů nebude realizován.

Výsledky hlasování

Pro:4 ; Proti: 0

Přijaté usnesení – *Řídicí komise schvaluje celkem 23 projektů předložených do první výzvy programu MERIT, z nichž 15 projektů, které získaly v hodnocení nejvyšší skóre, budou podpořeny, a 8 rezervních projektů může být podpořeno v případě, že některý z podpořených projektů nebude realizován.*

Řídící komise zároveň navrhuje prověřit zejména ruské žadatele a žadatele z třetích zemích z důvodu bezpečnostního rizika realizace jejich projektů (BIS).

5. **Plán pro druhou výzvu a termíny následujících setkání**

- ČERVENEC 2024 – monitoring po prvním reportovacím období (zprávy o průběhu realizace projektů, komunikační a diseminační aktivity vědců, účast vědců na akcích SIC apod.)
- ZÁŘÍ 2024 – schvalování projektů vybraných v druhé výzvě programu

- LEDEN 2025 – monitoring po druhém reportovacím období (zprávy o průběhu realizace projektů, komunikační a diseminační aktivity vědců, účast vědců na akcích SIC apod.)

Návrh usnesení:

Řídicí komise MERIT bere na vědomí plán pro druhou výzvu programu a termíny následujících jednání.

Výsledky hlasování

Pro:4; Proti: 0

Přijaté usnesení

Řídicí komise MERIT bere na vědomí plán pro druhou výzvu programu a termíny následujících jednání.

Řídíce komise stanovila termín na příští setkání k prvnímu reportovacímu období dne 25.7.2024.

6. Zamyšlení nad informacemi potřebnými pro monitoring projektů

- Monitoring bude probíhat jednou za 6 měsíců, informace budou pravidelně poskytovány ze strany výzkumných organizací (supervizor + vybraný stážista)

Návrh usnesení:

Řídicí komise MERIT bere na vědomí obsah monitorovacího reportu a schvalují navržené změny.

Výsledky hlasování

Pro:4.; Proti:0

Přijaté usnesení

Řídicí komise MERIT bere na vědomí obsah monitorovacího reportu a schvaluje navržené následující změny, které budou vloženy do monitorovacího reportu:

- neúspěchy a případné změny projektu,

- informace, zda je projekt v souladu s harmonogramem,

- informace o tom, v jakém stavu se projekt nachází,

- milníky projektu.

Monitorovací Report bude upraven a poslán Řídicí komisi k odsouhlasení.

Zapsala:
[redacted]

Zápis ověřil:
[redacted]

Příloha: Seznam schválených projektů

MERIT
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Seznam 15 kandidátů s nejvyšším skóre

Name of the candidate	Host organisation	Final score
[redacted]	ELI Beamlines Facility - The Extreme Light Infrastructure ERIC	95,8
[redacted]	Institute of Animal Physiology and Genetics of the Czech Academy of Sciences	95,7
[redacted]	National Institute of Mental Health	94,7
[redacted]	Astronomical Institute of the Czech Academy of Sciences	89,9
[redacted]-[redacted]	Astronomical Institute of the Czech Academy of Sciences	89,7
[redacted]	Institute of Animal Physiology and Genetics of the Czech Academy of Sciences	87,8
[redacted]	Institute of Thermomechanics of the Czech Academy of Sciences	85,6
[redacted]	Astronomical Institute of the Czech Academy of Sciences	84,1
[redacted]	ELI Beamlines Facility - The Extreme Light Infrastructure ERIC	83,3
[redacted], [redacted]	Czech University of Life Sciences Prague	82,3
[redacted]	Institute of Physics of the Czech Academy of Sciences / HiLASE	81,5
[redacted]	Czech Technical University in Prague, Czech Institute of Informatics, Robotics, and Cybernetics	81,4
[redacted]	Research Institute of Geodesy, Topography and Cartography	81,1
[redacted]	Institute of Physics of the Czech Academy of Sciences / HiLASE	80,1
[redacted]	UCEEB Czech Technical University in Prague, University Centre for Energy Efficient Buildings	78,9

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Seznam 8 rezervních kandidátů

Name of the candidate	Host organisation	Final score
[redacted], [redacted]	National Institute of Mental Health	76,8
[redacted]	Institute of Microbiology of the Czech Academy of Sciences	76,1
[redacted]	Research Institute of Geodesy, Topography and Cartography	76,1
[redacted]	Astronomical Institute of the Czech Academy of Sciences	74,7
[redacted], [redacted]	UCEEB Czech Technical University in Prague, University Centre for Energy Efficient Buildings	74,6
[redacted], [redacted]	National Institute of Mental Health	74,5
[redacted]	Institute of Animal Physiology and Genetics of the Czech Academy of Sciences	73,8
[redacted]	ELI Beamlines Facility - The Extreme Light Infrastructure ERIC	73,6