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A Long-Term Vision for Space-Based Interferometry

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Abstract (optional):

A Long-Term Vision for Space-Based Interferometry

The processes leading to the formation of planets; the extreme physics occurring near the event horizon of black holes; detailed studies of exoplanets through spectral-spatial mapping: new and unique insights into the physical processes involved across nearly the whole gamut of astrophysics await discovery at small angular scales (Figure 1). The fine spatial resolution needed to explore these processes, however, lies beyond the capabilities of current astronomical facilities and nearly all proposed future facilities. Interferometers can crack this angular resolution problem, and **space-based interferometry missions promise to explore entirely new regions of scientific phase space, providing unique new insights into the physical processes lurking at small angular scales.**

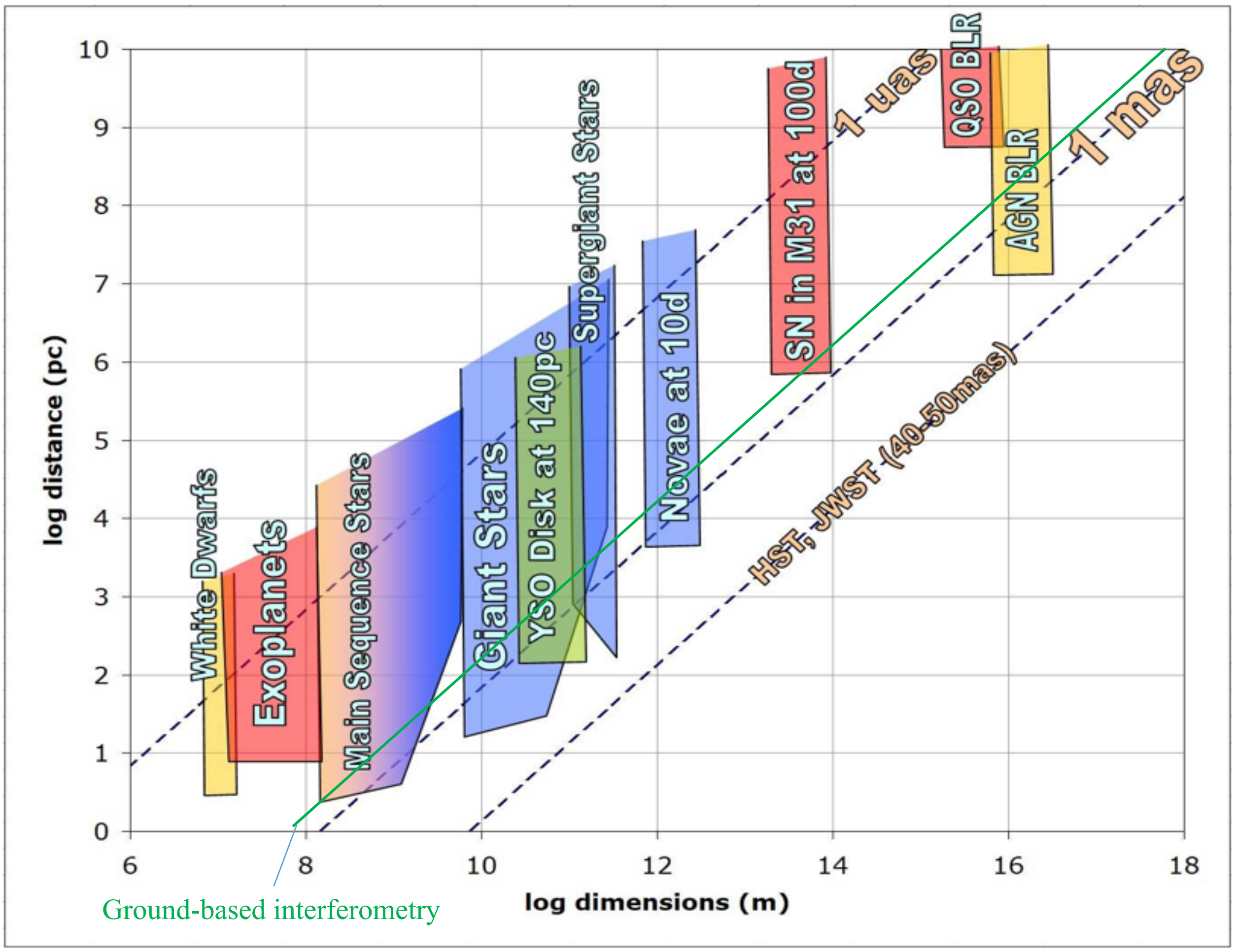


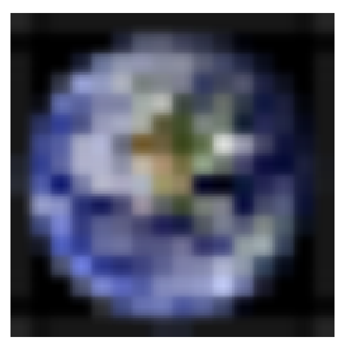
Figure 1: The Hubble Space Telescope (HST) provided dramatic new insights into the universe around us, and the James Webb Space Telescope (JWST) promises to push boundaries even further. However, if we consider the typical distances to different types of astronomical objects relative to their intrinsic size, it is clear that a wealth of information lies hidden at the 1milliarcsecond (mas) level and below, beyond the capabilities of either HST or JWST. Color coding goes from brighter objects (blue) to fainter objects (green, yellow) to faintest (red).

The Need for High Angular Resolution

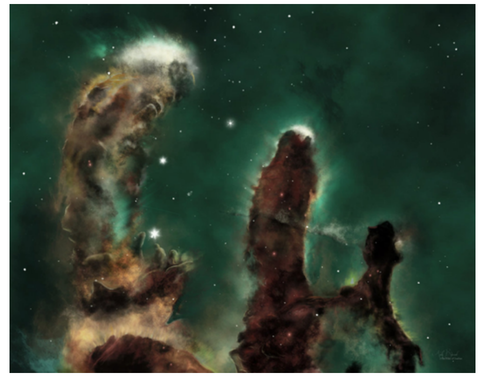
"*Several of the notional missions listed in our roadmap rely on interferometry to answer key science questions, from radio to X-rays. All notional missions in the Visionary Era are interferometers, and technology maturation of interferometric techniques is thus highly relevant to realizing the science vision.*" -- "Enduring Quests, Daring Visions [1]

In 2012, NASA HQ convened a panel - the Astrophysics Roadmap Committee - to develop a long-term vision for the future of space-based astronomy. The result of this group's efforts was "Enduring Quests, Daring Visions." The Roadmap envisioned three eras of astrophysical exploration, including the Near-Term Era, the Formative Era, and the Visionary Era. As reflected by the quote above, the Roadmap highlighted the need for high angular resolution across the electromagnetic spectrum and spanning a diverse set of scientific questions. In December 2018, members of the astronomical community, representing a wide range of scientific interests, gathered in Columbia, MD for the *Interferometry from Space Workshop*. Through this Workshop, the attendees were able to outline a number of scientific investigations that **require** angular resolution beyond current capabilities. A diverse set of examples include:

The Formation of Planets: The field of exoplanets has burgeoned over the past few decades, but mysteries surrounding the processes of planet formation remain, and details of the early evolution of these worlds including volatile delivery to young planets are beyond the reach of existing telescopes. The high resolution from the ALMA interferometer has shed new light on the distribution of gaseous material and cold dust in protoplanetary disks, but a complete picture requires complementary observations in the FIR to understand the distribution of water in solid and gaseous form and the development of habitable conditions during formation. Large FIR single aperture telescopes being considered will not be able to spatially resolve disks; though with Doppler tomography, the distribution of gaseous water in these disks can be modeled. But water ice beyond the snow line, with their intrinsically broad spectral features, are unsuited to similar modeling efforts. High-resolution observations of the detailed structure of protoplanetary disks and of the distribution of water (and other molecules/solid state constituents) within them in the near- to far-infrared are critical for understanding important factors that impact the assembly of planets and the process of volatile delivery to these young worlds. Such observations would also help illuminate the mechanisms that drive migration of planets within young planetary systems.

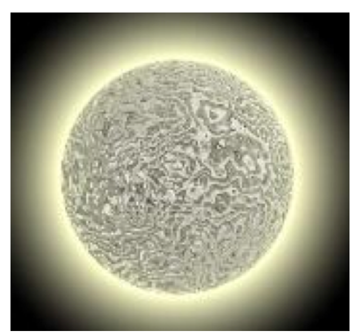


Exoplanets, Comparative Planetology, and the Search for Life: Powerful new single-aperture facilities will provide high signal-to-noise spectra for terrestrial exoplanets, and have the potential to provide the first unambiguous detection of life beyond the Solar System (in fact, beyond Earth). An interferometric follow-up mission operating in the mid-infrared (e.g., TPF-I/Darwin) would complement these observations by providing additional details on the composition of these worlds and on their thermal properties. However, the planets observed with either currently proposed missions or a TPF-I will be unresolved point sources, and detection of life will be through observations of disequilibrium chemistry. The ExoEarth Mapper is an ambitious mission concept discussed in the Roadmap. This mission would be able to image distant worlds and resolve clouds, continents, and oceans, providing enormously valuable data for Comparative Planetology. Observations of clouds over time would allow study of Exoclimates; geography would allow study of Exogeology; and maps would provide direct evidence for life and the distribution of flora on these distant worlds (Exoecology?).



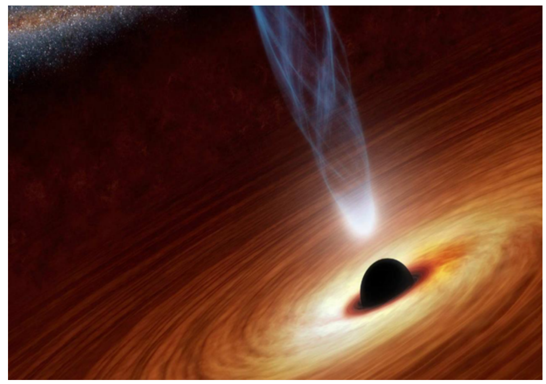
The Formation of Stars: While astronomers continue to develop a new and better understanding of the physics behind star formation, a wealth of information lies concealed in the cool material enshrouded by dust and gas. Modest improvements in angular resolution (~0.1”) would enable direct observation of the multiple cores in proto-binary systems (and systems with greater multiplicity) near the peak of their spectral energy distribution. This would allow unique determination of the evolutionary status of the individual protostellar cores in clusters and would definitively test theories of clustered star formation and of the formation of the most massive stars. With additional angular resolution, particularly at far-infrared (FIR) wavelengths, even more detailed observations could allow us to observe and measure the kinematics of infall throughout the star formation process, particularly during the earliest (and least understood) stages.

The Physics of Stars: With the advent of high-precision time-domain astronomy, asteroseismology has entered a new era. Time-domain observations can reveal vibrational frequencies (for bright stars) that in turn can give insight into the structure and evolution of main sequence stars and their giant counterparts. However, as we observe with our own sun, the behavior of stars can be extremely complex, with a wide range of vibration and pulsation frequencies. By imaging stars in the ultraviolet with high resolution, it would become possible to directly observe the vibration/pulsation of these stars while also allowing detailed study of stellar activity. These data would then allow much more refined understanding of stellar structure and evolution; they would also have implications for the potential habitability of exoplanets orbiting these stars.



Studying the Equation of State of Degenerate Matter: Very high angular resolution observations in the ultraviolet could be used to image White Dwarf stars. Much like imaging of main sequence stars, discussed above, these observations would allow astronomers to monitor the behavior of these compact objects, and to witness starquakes, pulsation/vibration, and other activity. In effect, this advance in imaging would make white dwarfs a unique new laboratory for studying fundamental physics such as the equation of state of degenerate matter - a laboratory that cannot be replicated on Earth.

Mapping Black Holes: Recent results from the Event Horizon Telescope [2] have shown for the first time the silhouette of the Black Hole in M87 and the matter in the inner orbits around it. High angular resolution x-ray imaging provided by the Black Hole Mapper envisioned in the Astrophysics Roadmap would explore the innermost regions of accretion disks; combined with spectroscopy, it would be possible to determine the structure of the accretion disk as well as details of jets, providing unique new insights into the extreme physical regime near black holes. This combination would address questions surrounding the accretion flow to black holes and the impacts of these objects on their surrounding environment. Further, complementing high angular resolution observations in the FIR, it would illuminate how black holes serve as the engines of activity within these distant galaxies. Kinematic measurements would also provide the most accurate measure of the mass of these black holes. More modest x-ray interferometers could study the 4 million $M_\odot$ black hole at the center of the Milky Way, helping us understand its apparent quiescence; they could also study the physics of accretion in close-binary stars.



Probing Active Galaxies: The discovery of luminous infrared galaxies has helped shape our understanding of how galaxies have evolved, and detailed observations of active galaxies have revealed complex structures including a powerful central engine, a circumnuclear torus, and regions of high star formation activity in an outer ring. High angular resolution FIR observations could map the detailed distribution of star formation activity [3]. Combined with interferometric observations at shorter wavelengths (uv, optical, near and mid-IR), it would be possible to image the torus and accretion disk around the central engine, allowing us to further understand the physics of accretion and jet formation [4], probe the interface between the active nucleus and their host galaxy, and accurately place these galaxies in the proper evolutionary context. The wide wavelength range and higher sensitivity allowed by space interferometry will play a critical role in this field, where only the brightest targets can be interferometrically observed from the ground [5]. Further, the combination of accurate angular sizes measured interferometrically with reverberation mapping would provide a new and independent calibration of the distance ladder needed for cosmology.

Table 1: There are myriad scientific questions that can only be answered by exploring angular scales finer than practically achievable with single aperture telescopes. A few examples of such science cases are shown here.

A few science example science investigations	Wavelengths	Angular Resolution
Formation of Planets and Enrichment with Volatiles	Far-Infrared	<100 mas
Studying climate and life on distant worlds	Optical	<17 μas
Exploring the extreme physics surrounding black holes	X-Ray	<10 μas
Understanding the equation of state of degenerate matter.	Ultraviolet	<30 μas

This list of science questions is far from complete (e.g., studies of novae and supernovae), and it seems likely that the most exciting scientific discoveries will be completely unexpected. With an order of magnitude or more improvement in angular resolution, we can anticipate a wide range of new discoveries (see Figure 1); historically, orders-of-magnitude improvements in capabilities lead to unanticipated discoveries [6]). In the long-term, advanced facilities pushing angular resolution several additional orders of magnitude will result in even more dramatic discoveries - in this part of the scientific phase space, to quote ancient cartographers, “here there be dragons…”

Finally, we note that development of facilities for high angular resolution are likely to have broader impacts, as many of the techniques, technologies, and tools will be relevant for the development of future large gravitational wave observatories and for the development of a space- or lunar-based radio interferometer shielded from the radio-loud Earth environment — the Cosmic Dawn Mapper envisioned by the Astrophysics Roadmap.

Achieving High Angular Resolution

Figure 1 demonstrates that even modest improvements in angular resolution open new discovery space. How can these improvements be achieved? The science discussed above goes beyond the capabilities of the current generation of proposed missions, all single aperture telescopes approaching the limit of current launch vehicle capability. New launch vehicles may enable slightly larger facilities, but nothing close to the order of magnitude needed for angular resolution requirements. It is possible that on-orbit assembly could enable the construction of even larger single aperture telescopes, provided that an orbital infrastructure exists. However, practical considerations would likely still limit such telescopes to sizes incommensurate with the angular resolutions described here. And, even with a massive infrastructure investment, very large apertures would face other daunting issues: a 500-m diameter single aperture telescope would have a primary mirror mass (assuming areal density half of JWST) of nearly 2,000 metric tons -- requiring 16 Stage 2 SLS launches to low Earth orbit (or 20 SpaceX Starship launches). **There is enormous scientific discovery potential at angular scales not accessible with single aperture telescopes.**

Historically, the increasing sizes of single aperture telescopes have been driven by both the need for higher angular resolution and the need for better sensitivity. As telescope diameter increases, angular resolution improves linearly while collecting area goes as diameter squared - this can result in a capability mismatch. In the FIR, for example, cold space telescopes can reach the spatial confusion limit in a matter of seconds and never achieve their angular resolution potential. In essence, at some point, larger telescopes actually become less cost effective due to capability mismatch.

Interferometers provide a path to achieve the angular resolution needed for the variety of science cases discussed above (Figure 2). **Interferometers with baselines 10+ meters would probe an important new scientific phase space that cannot be explored with existing or proposed single-aperture facilities.** At the same time, interferometers possess the unique advantage that their design can be separately optimized for angular resolution (maximum baseline) and for sensitivity (collector diameter). With a detailed Design Reference Mission (DRM), an optimized design would provide all the required scientific capabilities while avoiding the complications of ever-larger single aperture telescopes. Further, interferometer operation could also be optimized. For example, to obtain the MIR spectrum of an exoplanet, short baselines (accessing the distribution of light at large spatial scales) are not needed - only long baselines that provide maximal information content would be used. More generally, the *u-v* plane coverage can be tailored to optimally match the interferometric point spread function to the observational target and the scientific information being gleaned.

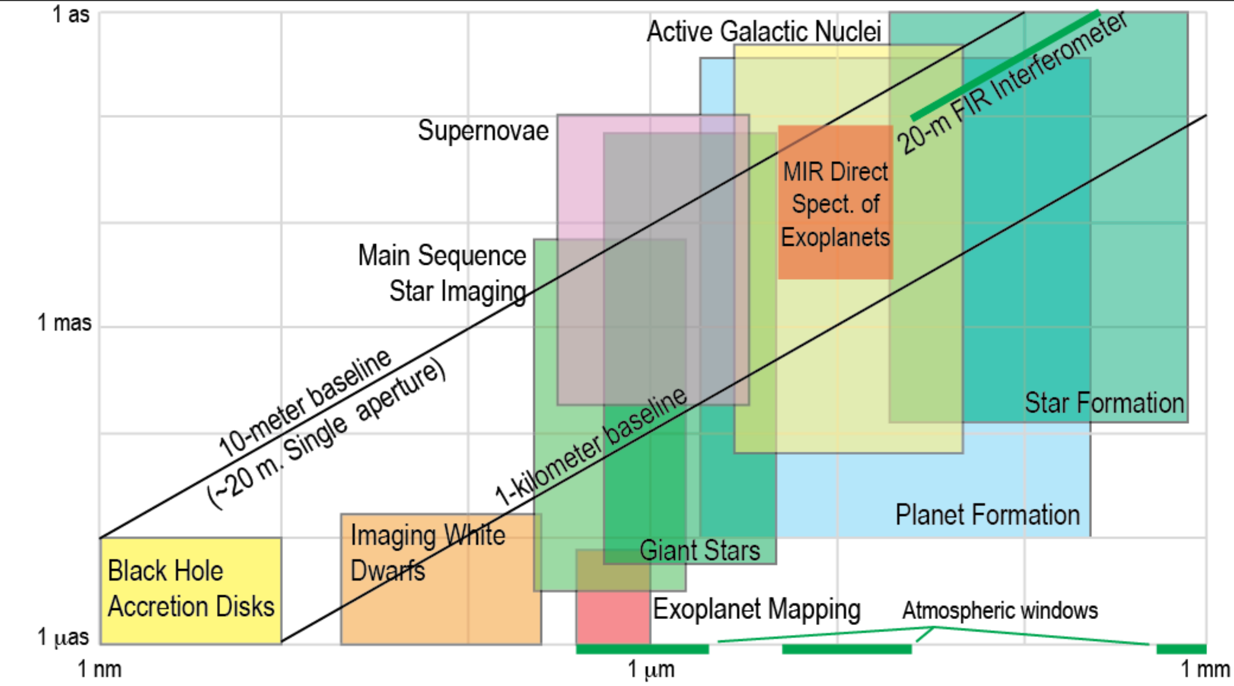


Figure 2: Looking at the same types of astrophysical objects as shown in Figure 1: now comparing the required angular resolution range versus the optimal wavelength range for observations shows that the largest proposed single aperture telescopes can probe some of the edges of some of these topics, but the majority of the science lurks at smaller angular scales.

Given these advantages, what barriers have prevented the adoption of space-based interferometry? From an observer's standpoint, the primary limitation of interferometric architectures is observing time. An interferometer needs time on target both to achieve the required sensitivity and to provide the needed *u-v* plane coverage. For faint sources, the time needed is dominated by sensitivity requirements; the total time required is effectively the same as for a single aperture of the same collecting area to reach the same sensitivity. For bright sources, the time needed to fill the synthetic aperture dominates, resulting in longer overall observing times. Effectively, for faint targets, an ideal interferometer has approximately the same sensitivity as a single aperture telescope with the same collecting area while gaining in spatial resolution (practical interferometers will have slightly lower sensitivity due to the increased number of optical surfaces). For bright targets, interferometers trade time for angular resolution. This can be mitigated by using only partial coverage of the *u-v* plane; as shown with ground-based interferometers (e.g. ALMA, VLTI, CHARA), even partial coverage can yield excellent results.

From a technical standpoint, there is little standing in the way of space-based interferometers, and most of the required technical progress is shared by single-aperture cousins. For instance, whether interferometric or monolithic, astronomical facilities gain access to new wavelength regimes by operating in space. Furthermore, even where there are atmospheric windows, interferometers in space benefit from improved system stability, longer coherence times (leading to better sensitivity than ground-based counterparts), and from the increased flexibility of collector positioning. At the component level, additional technology developments are needed for the more ambitious interferometric missions. For example, nulling interferometry is needed for a mission like

TPF-I/Darwin. In the FIR, however, technologies such as improved detectors and advanced cryocoolers are valuable, but the same technologies (with larger detector arrays) are needed for single-aperture FIR telescopes.

The biggest obstacle, however, is cultural. While nearly every astronomer has experience with data from single aperture telescopes, only a fraction of astronomers have experience with interferometric data. This leads to a perception that interferometers, and the data from them, are difficult to work with. This is beginning to change, as more and more astronomers begin using ground-based interferometric data (such as that from ALMA, VLTI, and CHARA), and as these interferometric facilities start to produce dazzling new scientific results (e.g. APC white papers [7,8,9,10]). As the community gains exposure to and confidence in interferometers and their data, this obstacle will begin to vanish, but more work is needed to help astronomers understand how interferometric missions can directly benefit their individual research programs.

The value proposition: To argue for future interferometry missions, understanding the costs and the cost drivers of these missions is critical. Fortunately, over the past two decades, multiple interferometric mission concepts have been studied (Table 2), and through these we are developing intuition for the costs associated with these architectures. Not all of these studies were completed with the same level of fidelity, but two of have particularly well-validated cost estimates: SPIRIT, (with a ~40 meter baseline and 1.5 meter collectors, was estimated in 2009 at $1.3B (full life-cycle cost including a Guest Observer program); FIRI, with ~100 meter baseline and 2.0 meter collectors was estimated in 2014 at €1.5B. This actually reflects an important lesson learned: cost for interferometers is largely driven by collector size but is only weakly affected by baseline length. In fact, estimated costs for interferometers typically compare favorably to the projected costs for single aperture telescopes with similar collecting area. And in fact, the modular nature of interferometers may result in lower costs due to simplification of integration and test.

Table 2: A wide range of interferometric mission concepts have been studied over the past 15 years, both in the United States and in Europe (highlighted in red).

Mission Concept	Wavelengths	Angular Res.	Ref
SPIRIT	FIR	100 mas	[11]
SPECS	FIR	4 mas	[12]
Stellar Imager	UV/Optical	0.5 mas	[13]
MAXIM	X-ray	1 μas	[14]
FKSI	MIR	100 mas	[15]
TPF-I	MIR	10 mas	[16]
Darwin	MIR	10 mas	[17]
SHARPIR	FIR	250 mas	[18]
FIRI	FIR	30 mas	[19]
ESPRIT	FIR (Heterodyne)	20 mas	[20]
Pegase	MIR	100 mas	[21]

As highlighted in the Astrophysics Roadmap: “To peer into young star-forming regions on scales of a few thousand light-years will require high-spatial-resolution observations from a space-based far-infrared interferometer”. A Probe-class mission (e.g. SHARPIR) operating in the FIR could provide this capability, but Probe-class missions operating in other wavelength regimes may also be possible, providing unique scientific returns.

A Logical Path to Space-Based Interferometry

“…the technical requirements for interferometry in the FIR are not as demanding as for shorter wavelength bands, so FIR interferometry may again be a logical starting point that provides a useful training ground while delivering crucial science.” [1]

As envisioned by “Enduring Quests, Daring Visions,” and as described here, critical astrophysical questions **require** spatial resolution that is simply unachievable with single aperture telescopes. In this perhaps-not-so-distant future, we envision a series of interferometric missions, each focused on and designed to answer a few key science questions. Each of these missions will build on the experience and expertise gained from previous generations of interferometers and will result in powerful revelations about the universe on small angular scales.

While the scientific drivers for space-based interferometry are compelling, to attain this capability we need to have a path from the present to this future. The physical principles underlying interferometry have been known for over a century, and interferometry has been used as an astronomical tool for nearly that long. In the past 30 years, ground-based interferometry has made enormous strides, and the substantial discoveries of the past few years preview the potential discoveries enabled by high angular resolution [7]. Ground-based interferometers continue to make advances, but cannot explore critical portions of the electromagnetic spectrum, and will ultimately be limited in size by coherence distances.

Ground-based interferometers (CHARA, NPOI, MROI, VLTI, ALMA, VLBI, EHT etc.) serve as the first pillar upon which future space-based interferometers will rest, by giving astronomers experience with both the technical operation of such systems and the mechanics of working with interferometric data. Laboratory testbeds serve as a second pillar, exploring technologies and techniques (e.g., wide-field techniques [21], nullers [22], practical exploration of partial *u*-*v* plane coverage [23]) will enhance the scientific return from future space-based interferometers. The third pillar is provided by balloon experiments, which serve as practical system-level demonstrators of “free-flying” interferometers. These three elements provide a solid foundation for the first spatial interferometer in space.

With this foundation, what are the next steps towards space-based interferometry? As stated in the Roadmap, the logical starting point for space-based interferometers is in the far-infrared. A modest FIR interferometer, either as a Probe or as a Probe+ (<$2B) would provide unique new data for addressing multiple scientific topics, such as star formation, the formation and evolution of planetary systems, and the energetics of Active Galactic Nuclei. At the same time, a first-generation FIR interferometer would serve as a pathfinder for future more ambitious interferometry missions (Figure 3). With the experience gained, it would be possible to explore other Probe-class interferometric mission concepts and to leverage the design to build more ambitious missions focused on new science questions. For example, small improvements in metrology and the use of nullers would enable a mission like Darwin/TPF-I (obtaining direct MIR spectra of exoplanets). Ultimately, as each space-based single aperture telescope has built on its predecessors, generations of space-based interferometers would build on their predecessors, leading to the development of missions such as the ExoEarth Mapper and the Black Hole Mapper as envisioned in the Astrophysics Roadmap.

What needs to be done? While there are several well-developed concepts for space-based interferometers, investments in the next decade will further mature these concepts.

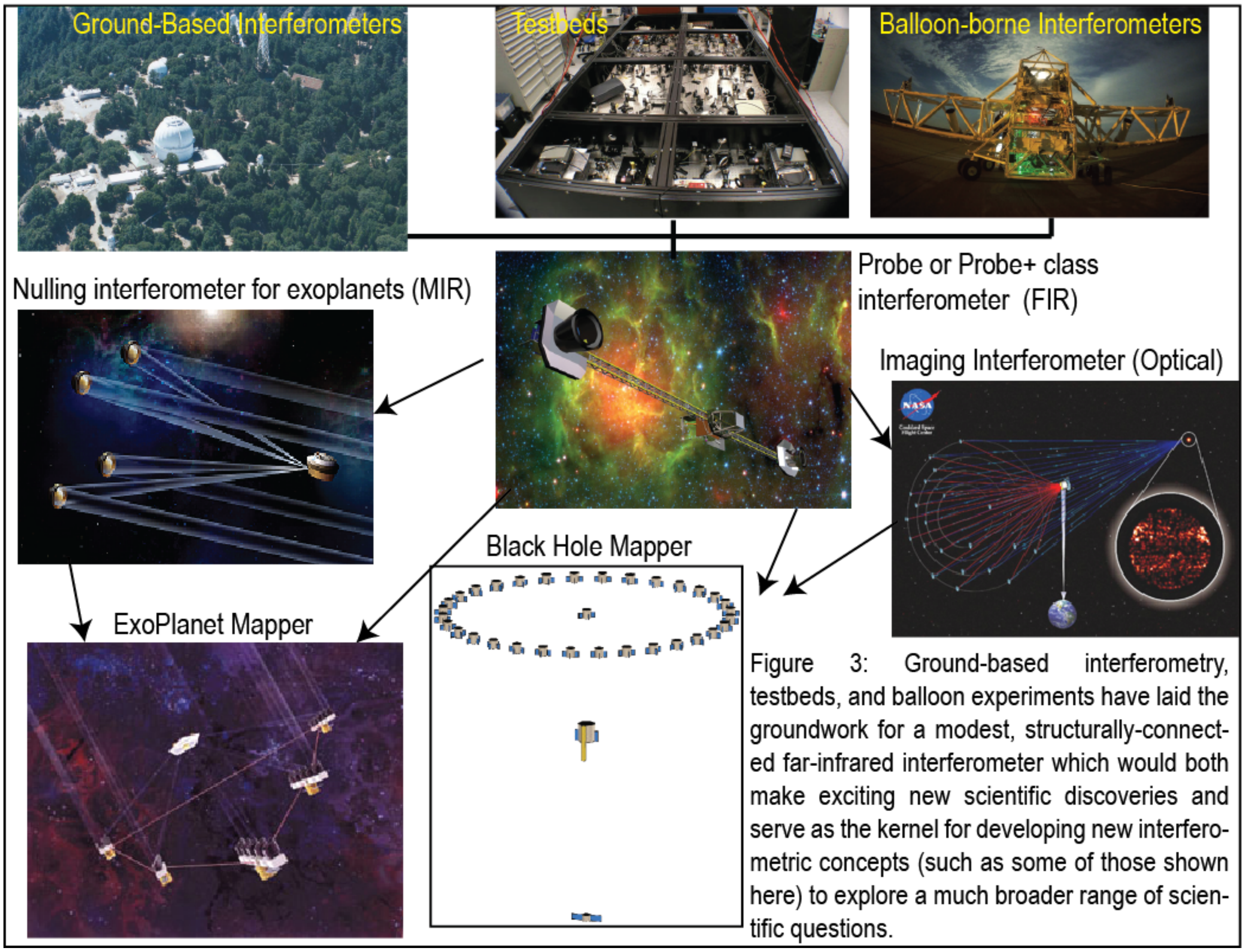


Figure 3: Ground-based interferometry, testbeds, and balloon experiments have laid the groundwork for a modest, structurally-connected far-infrared interferometer which would both make exciting new scientific discoveries and serve as the kernel for developing new interferometric concepts (such as some of those shown here) to explore a much broader range of scientific questions.

To move towards the promise held by future space-based interferometers, we envision the following set of goals for the next decade:

- Carry out trade studies of mission architectures to optimize the balance between scientific return and cost.
- Develop simulations to support these trade studies and to validate the scientific potential of interferometry for specific scientific questions.
- Support development of key enhancing technologies (e.g. detectors).
- Continue work with ground-based interferometers, testbeds and balloon experiments to improve expertise in the design and operation of interferometers.
- Develop a detailed design to compete as a potential Probe-class mission (should such a line be recommended and implemented).
- Present a compelling case for a specific space-based interferometer concept as a (small) flagship mission to the next Decadal Survey.

The overall costs of these activities would be very modest while helping make high angular resolution astronomy possible. The last Decadal Survey highlighted the need for development of tools to enable studies of exoplanets, resulting in detailed mission studies for this Decadal; a similar emphasis on enabling future interferometric missions will open the door for powerful new facilities that provide unique data for exploring critical astrophysical questions.

References

1. Kouveliotou, C., Agol, E., Batalha, N., Bean, J., Bentz, M., Cornish, N., Dressler, A., Figueroa-Feliciano, E., Gaudi, S., Guyon, O., Hartmann, D., Niemack, M., Ozel, F., Reynolds, C., Roberge, A., Straughn, A., Sheth, K., Weinberg, D., & Zmuidzinas, J. 2014. "Enduring Quests – Daring Visions (NASA Astrophysics in the Next Three Decades)", http://go.nasa.gov/1gGVkZYor at http://arxiv.org/abs/1401.3741.
2. The Event Horizon Telescope Collaboration 2019. "First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole" ApJL, 875, 1.
3. Lopez-Rodriguez, E. et al. 2019. "Tracing the Feeding and Feedback of Active Galaxies" Astro2020 White Paper.
4. Perlman, E. et al. 2019. "Relativistic Jets in the Accretion and Collimation Zone: New Challenges Enabled by New Instruments" Astro2020 White Paper.
5. Kishimoto, M. et al. 2019. "Exploring Active Supermassive Black Hole at 100 Micro-arcsecond Resolution" Astro2020 White Paper.
6. Harwit, M., 2019, *Cosmic Discovery*, Cambridge University Press.
7. Ridgeway, et al. 2019. APC White Paper.
8. van Belle, et al. 2019 "High Angular Resolution Astrophysics: Fundamental Stellar Parameters", APC White Paper.
9. Creech-Eakman, et al. 2019. "Pulsation as a Laboratory for Understanding Stellar Physics", APC White Paper..
10. ten Brummelaar, et al. 2019. APC White Paper.
11. Leisawitz, *et al*., (55 Co-authors) 2007. "The Space Infrared Interferometric Telescope (SPIRIT): High-resolution imaging and spectroscopy in the far-infrared," *Adv. Sp. Res*., **40,**689.
12. Harwit, Leisawitz, & Rinehart 2006. "A Far-Infared/submillimeter kilometer baseline interferometer in space", New Astronomy Reviews, 50, 228.
13. Carpenter, K.G., Schrijver, C.J., Karovska, M., & the SI Study Team. 2008, "SI - The Stellar Imager", in NASA Space Science Vision Missions, ed. M. Allen, Progress in Astronautics and Aeronautics, vol. 224, pp. 191-227; AIAA (available at :https://hires.gsfc.nasa.gov/si/documents/SI_Stellar062606_AIAA_colorpreprint.pdf)
14. Gendreau, K., Cash, W., Shipley, A., & White, N. 2004. "MAXIM x-ray interferometry mission," Proc. SPIE 5168, 420.
15. Danchi, W. & Lopez, B. 2007. "The Fourier-Kelvin Stellar Interferometer (FKSI) -- A practical infrared space interferometer on the path to the discovery and characterization of Earth-like planets around nearby stars," *Comptes rendus - Physique (C.R. Physique),* 8, 396-407 (2007).
16. Lawson, P., Lay, O., Johnston, K., & Beichman, C. 2007. "Terrestrial Planet Finder Interferometer Science Working Group Report", JPL Publication 07-1, available at TPF-I SWG Report (2007).
17. C.S. Cockell, T. Herbst, A. Leger, L. Kaltenegger, O. Absil, C. Beichman, W. Benz, A. Brack, A. Chelli, L., Colangeli, H. Cottin, V. Coude du Foresto, W. Danchi, D. Defrere, J.W. den Herder, C. Eiroa, M. Fridlun, J. Greaves, T. Henning, K. Johnston, H. Jones, L. Labadie, R. Launhardt, P. Lawson, O. P. Lay, J.-M. LeDuigou, R. Liseau, F. Malbet, S.R. Martin, D. Mawet, D. Mourard, C. Moutou, L.

Mugnier, F. Paresce, A. Quirrenbach, Y. Rabbia, J. Raven, H. J.A. Rottgering, D. Rouan, N. Santos, F. Selsis, E. Serabyn, H. Shibai, M. Tamura, E. Thiebaut, F. Westall, G. White 2009. *"Darwin* – A Mission to Detect, and Search for Life on, Extrasolar Planets," *Astrobiology*, 9, 1.

18. Rinehart, S., Rizzo, M., Leisawitz, D., Staguhn, J., DiPirro, M., Mentzell, J., Juanola-Parramon, R., Dhabal, A., Mundy, L., Moseley, S. H., Mather, J., Padgett, D., Stapelfeldt, K., Roberge, A., Cordiner, M., Milam, S., Veach, T., Fixsen, D. 2016 "The Space High Angular Resolution Probe for the Infrared (SHARPIR)" Proc. SPIE 9904, 2L.
19. Helmich, F. &; Ivison, R. 2009. "FIRI - A far-infrared interferometer," Experimental Astronomy, v 23, p 245.
20. Wild, W., de Graauw, Th., Helmich, F., Baryshev, A., Cernicharo, J., Gao, J. R., Gunst, A., Bos, A., den Herder, J.-W., Jackson, B., Koshelets, V., Langevelde, H.-J., Maat, P., Martin-Pintado, J., Noordam, J., Roelfsma, P., Venema, L., Wesselius, P. and Yagoubov, P., 2008. "ESPRIT: a study concept for a far-infrared interferometer in space", Proc. SPIE7013, 70132R.
21. Leisawitz, D., Bolcar, M., Lyon, R., Maher, S., Memarsadeghi, N., Rinehart, S., & Sinukoff J. 2012. "Developing wide-field spatio-spectral interferometry for far-infrared space applications,", in *Optical and Infrared Interferometry III*, eds F. Delplancke, Jayadev K. Rajagopal, F. Malbet, *Proc. SPIE* **8445**, 0A.
22. Ollivier, M., Léger, A., Sekulic, P., & Labèque, A. 2017. "Nulling interferometry for the darwin mission: laboratory demonstration experiment," Proc. SPIE 10569, id. 1056911.
23. Juanola-Parramon, R., Fenech, D. M., & Savini, G. 2016. "Architecture and performance of the space-based Far-Infrared Interferometer Instrument Simulator," MNRAS 457, 345.