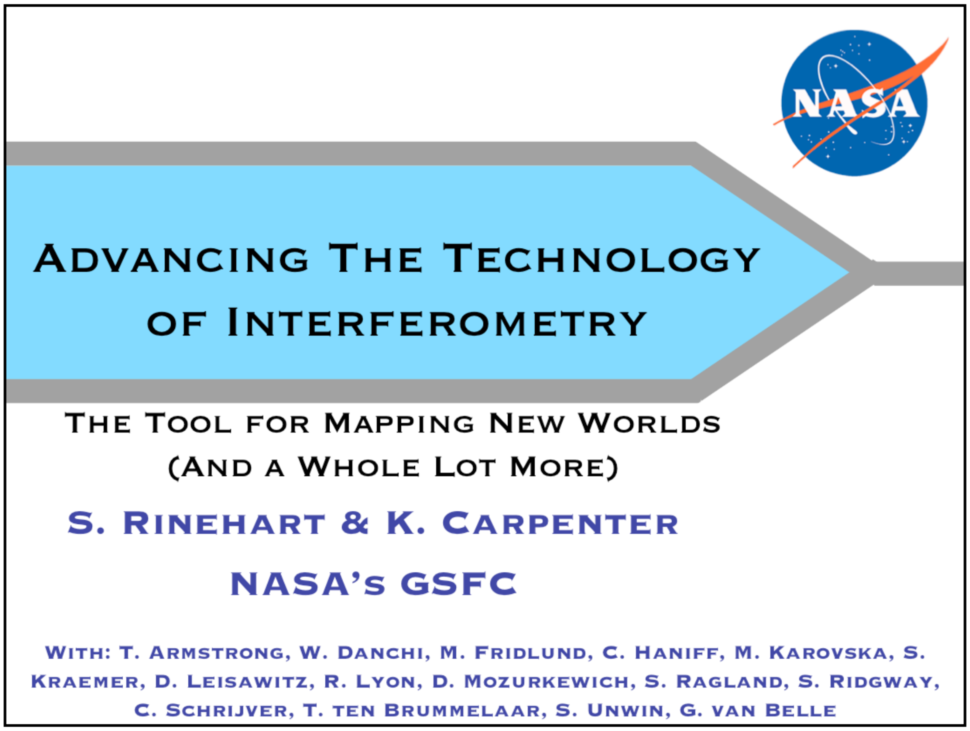


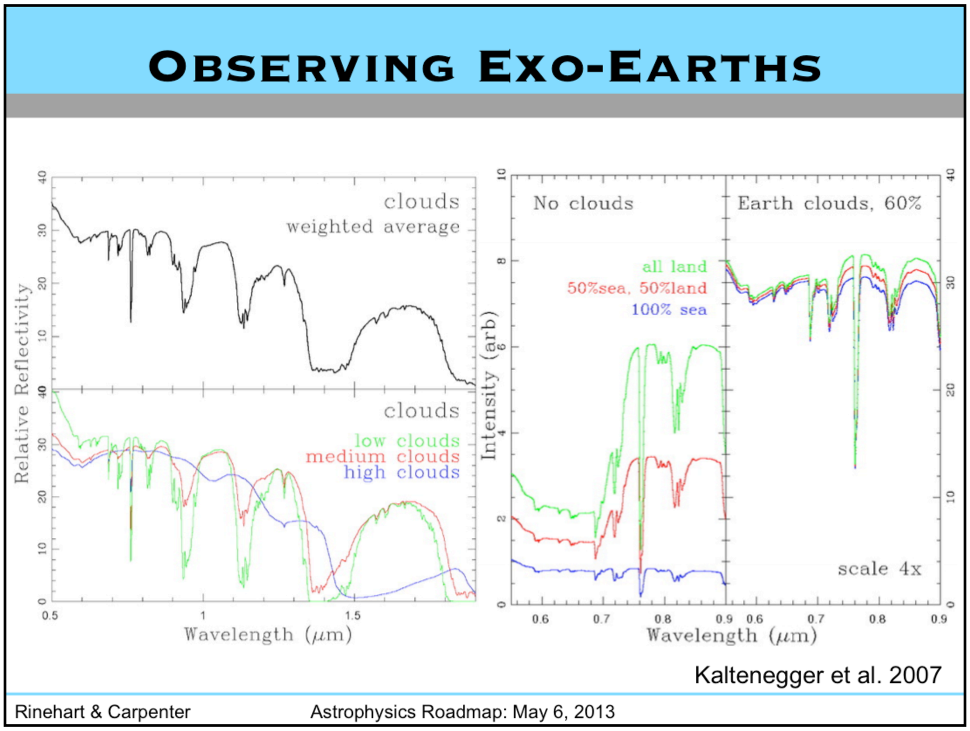
Good morning, etc.

For the Roadmap exercise, we were encouraged to think big – to provide a grand, long-term vision. We have attempted to do just that, as you will soon see. At the same point, we should also emphasize that we believe there are both clear technical and scientific steps to this grand vision.

The long-term, visionary goal behind this talk is the scientifically powerful goal of mapping the surface and/or atmosphere of earth-like exoplanets around other stars, ideally with spatially-resolved spectroscopy. This will require angular resolution about four orders of magnitude beyond what is currently available. This sounds daunting, but we believe that it is within reach.

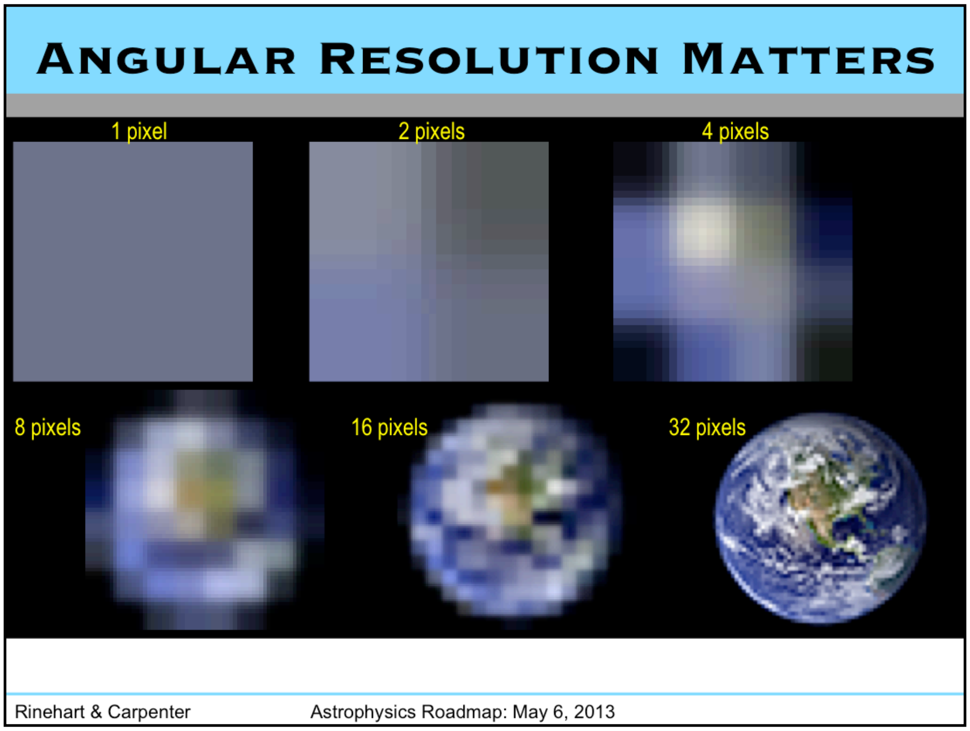
Such capability would have application across all of astrophysics. It has been said that when we increase a capability by an order of magnitude, we discover the new and unexpected. The most significant discoveries at four orders of magnitude may truly be beyond our ability to imagine - but the road to that capability will be filled with momentous scientific results, a sample which we will describe today.

This capability would require enormously large telescopes; in fact, the visionary science goal makes interferometry inevitable. And, in order to get to this vision, there is a compelling need for modest space-based interferometers that push the technologies while also carrying out their own revolutionary scientific investigations.



What is the importance of mapping an exoplanet? Spatially-unresolved spectroscopy will be a powerful tool, and will lead to a tremendous improvement in our understanding of both the diversity of exoplanets and the nature of individual exoplanets.

Models, such as at left, show that a single-pixel spectrum of an exo-Earth could not only detect clouds, but differentiate between different types of clouds. The models on the far right, however, reveal the obvious drawback – the clouds obscure the surface of the planet. Even with partial cloud cover, like the Earth, learning about the surface of the planet becomes extremely difficult.



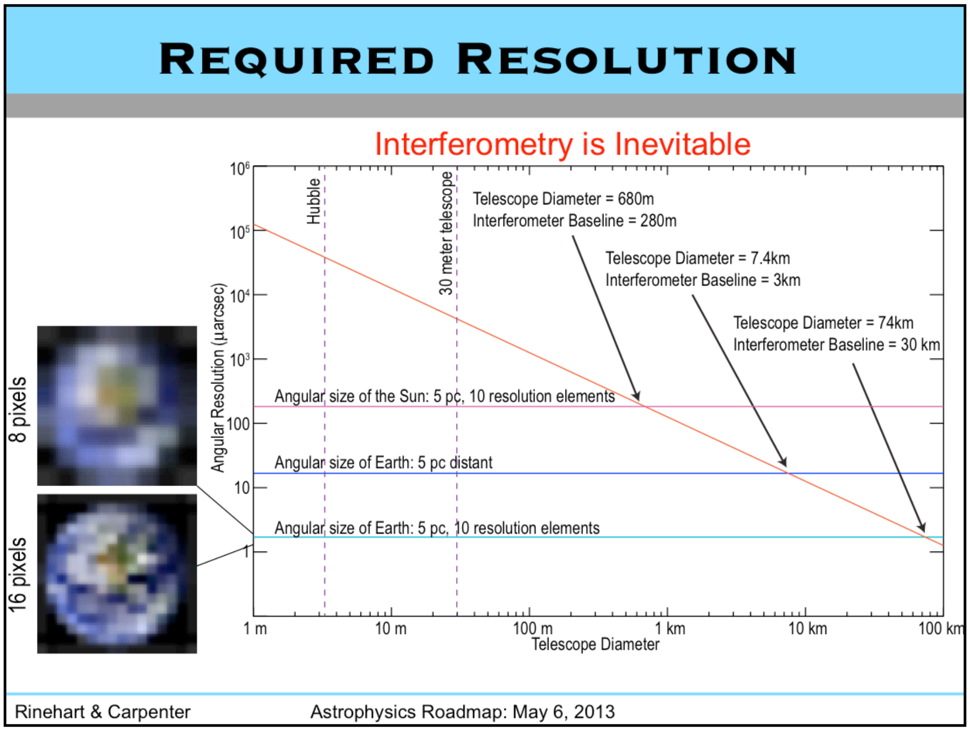
Mapping a planet, however, allows you to differentiate between clouds, land, and water. Of particular note here is the ability to confirm the presence of large bodies of water.

So, what does it mean to image an exoplanet? A few pixels doesn't help all that much, but by the time one has the resolution to achieve ~10 pixels across the planet, water, land, and clouds start to separate. ~30 pixels across the planet starts to reveal the shapes of continents, oceans, and clouds. You can see something that looks like the Earth.

This will allow us to break degeneracies within a spectrum, providing details on where different spectral features come from. We will be able to study energy transport and atmospheric dynamics on these planets. We will learn about diurnal cycles and seasonal variations. Monitoring of polar ice will tell us about the climate of exoplanets. And, through mapping, we will be able to resolve biomarkers, such as chlorophyll, features that would be lost in a spatially unresolved spectrum. This will be a whole new area of science, enabled by high spatial resolution

From a scientific perspective, this would be revolutionary; it would potentially mark the coming-of-age of the nascent field of comparative planetology. And, it would connect to Earth Science, by helping place our planet in a broader context.

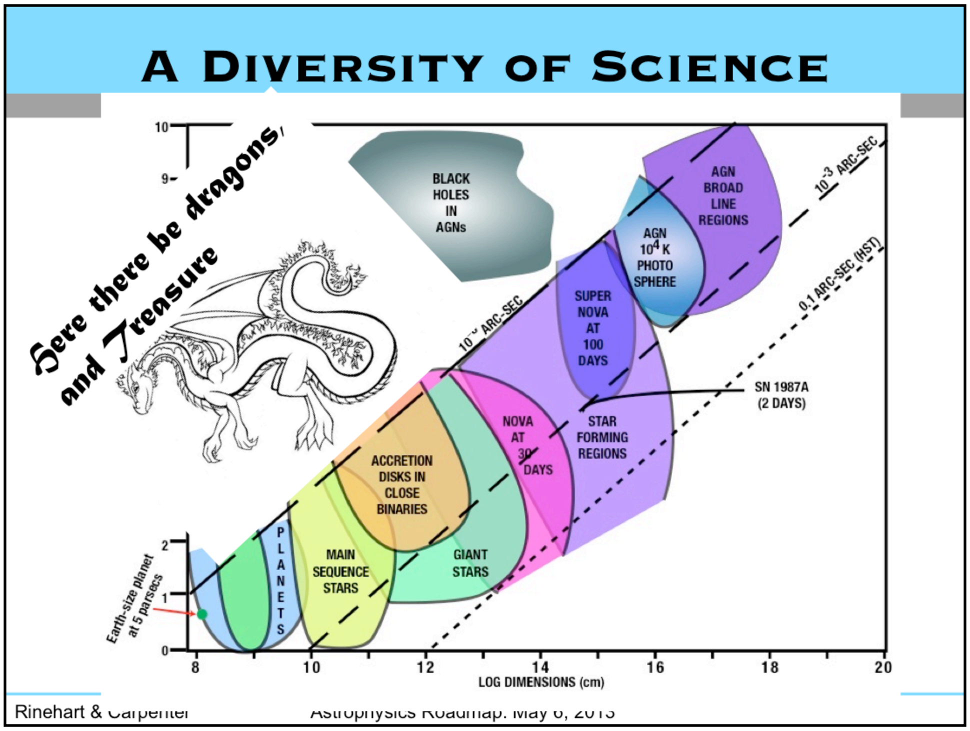
From a cultural perspective, the first map of a distant exoplanet would be on the front page of every newspaper in the world. It would potentially be a transformative event within society, much like the Apollo landing: and, it would continue to be exciting as astronomers learn about the planets, their climates, and their dynamics.



So, what angular resolution is needed for this scientific goal? Here, we show angular resolution as a function of telescope diameter, assuming a wavelength of 500 nm. Horizontal lines mark the level of angular resolution needed for mapping a sun-like star, resolving an exo-earth, and for mapping an exo-earth, using a distance of 5 parsecs.

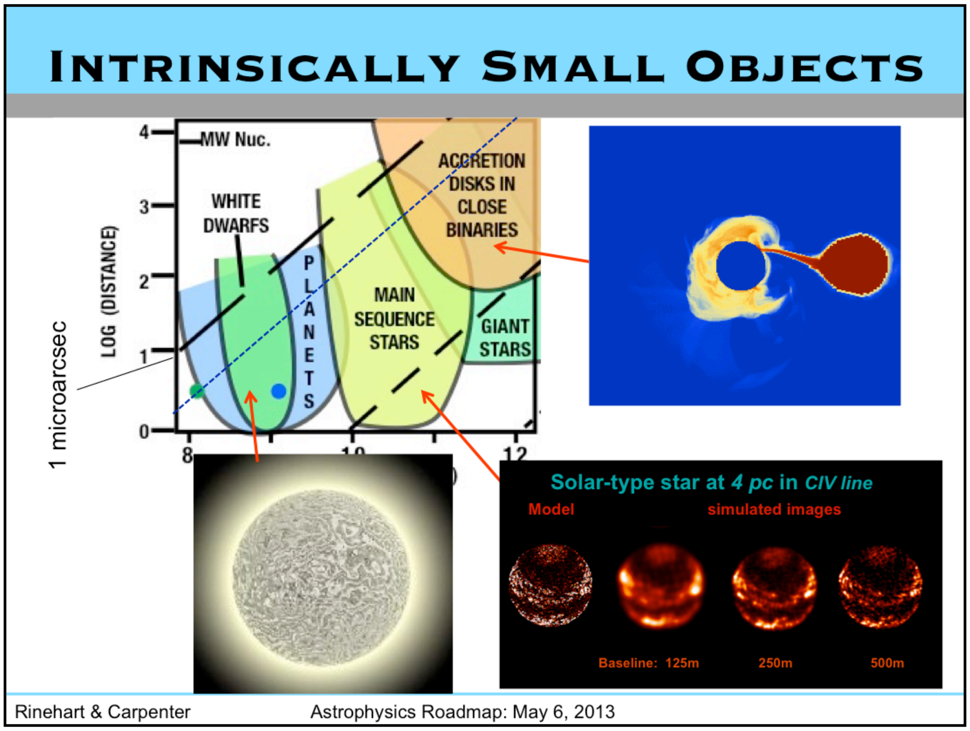
From this, we see that to achieve the 1.7 microarcsecond resolution needed to obtain 10 resolution elements across an exo-Earth at 5 parsecs, a single aperture telescope would require a diameter of 74 kilometers. This is a staggering amount of mirror, and obviously impractical on several levels. An interferometer, on the other hand, would require a maximum baseline of 30 km. While also daunting, it has a number of practical advantages -- such as reducing launch mass. Interferometry is inevitable.

This brings me to a key point: historically, astronomers have been limited by both collecting area and angular resolution, and both of these limitations have driven us to larger and larger apertures. However, collecting area grows faster than angular resolution, and there comes a point when the value of additional collecting area is overshadowed by the need for angular resolution. In the far-infrared, where photons are plentiful but angular resolution is intrinsically lower, we are already very near this point. Interferometry effectively allows us to separate these two capabilities, allowing true optimization of a mission to provide both the right collecting area and the right angular resolution.



While the scientific driver for our stated angular resolution requirement is the mapping of exoplanets, the capability developed would have application across all of astrophysics, including Exoplanets, Cosmic Origins, and Physics of the Cosmos themes.

Here, we plot the range of distances to various types of astrophysical objects against the intrinsic size of these objects, to give some idea of the broad scientific benefits of high angular resolution. The diagonal lines show different levels of angular resolution. From this, it is clear that there exists significant astrophysics beyond our current capability in angular resolution. Modest interferometers, in the relatively near-term, could address much of this science. Recall the axiom that an order of magnitude improvement leads to new and unexpected discoveries. Four orders of magnitude? is is so far beyond our capabilities that it is truly the unknown. Undoubtedly, scientific treasures wait for us there.

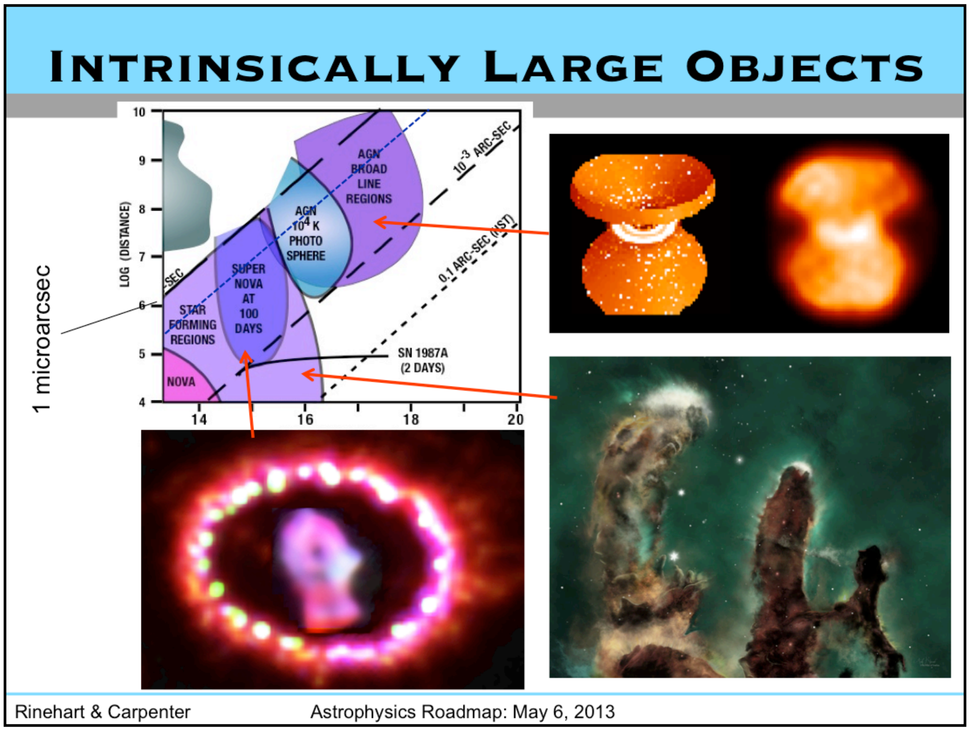


There are, however, several clear examples where significant advances could be made with this level of spatial resolution.

We could, for instance, image the surfaces of white dwarfs, directly witnessing pulsation and starquakes. This would give new data on the equation of state of degenerate matter, providing a unique new laboratory for fundamental physics.

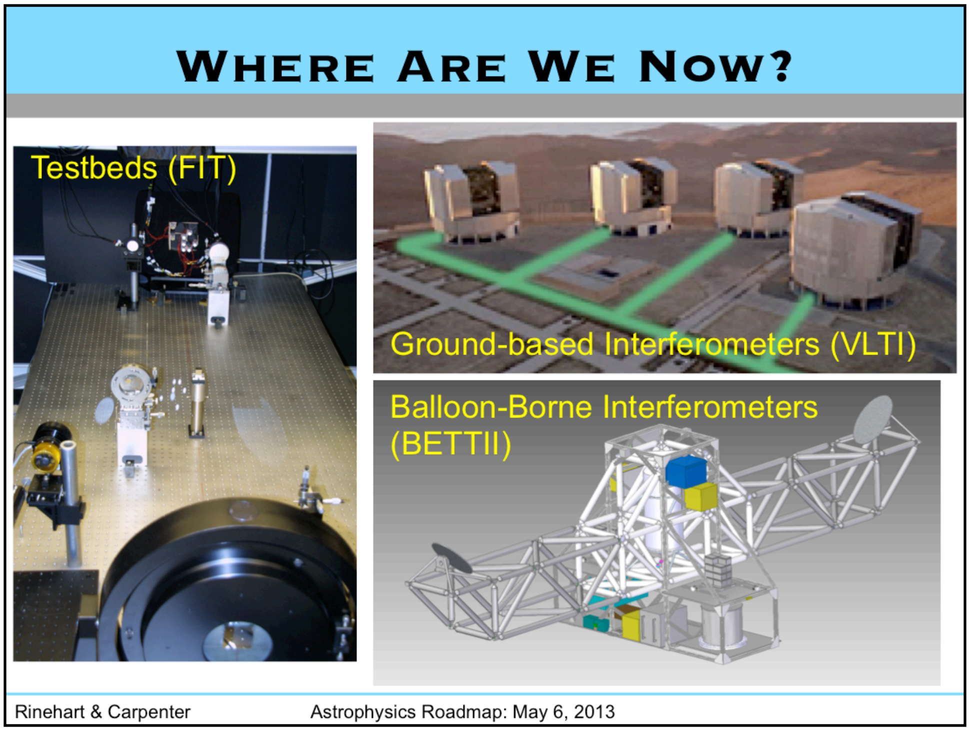
Or, we could image main sequence stars. We could study the interiors of these stars via spatially-resolved asteroseismology, leading to new understanding of stellar structure and evolution. We could observe surface signatures of stellar magnetic activity to solve the puzzle of solar/stellar magnetic dynamos and enable a true predictive model of their magnetic cycles. Further, studies of the stars themselves would help us learn about the evolution of planetary systems, and would provide insight into the potential habitability of planets around these stars.

And there's more. New studies of accretion disks, mass transfer in binary systems, and studies of giant stars and the final stages of stellar evolution would all be enabled.



At the other end of the size spectrum, this type of interferometer would allow us to make detailed studies of distant galaxies. We would be able to map the broad line regions of Active Galactic Nuclei, see the accretion disk of the black hole at the heart of the galaxy, and ultimately, gain new insight into the engine and feedback mechanisms that drive the evolution of these galaxies.

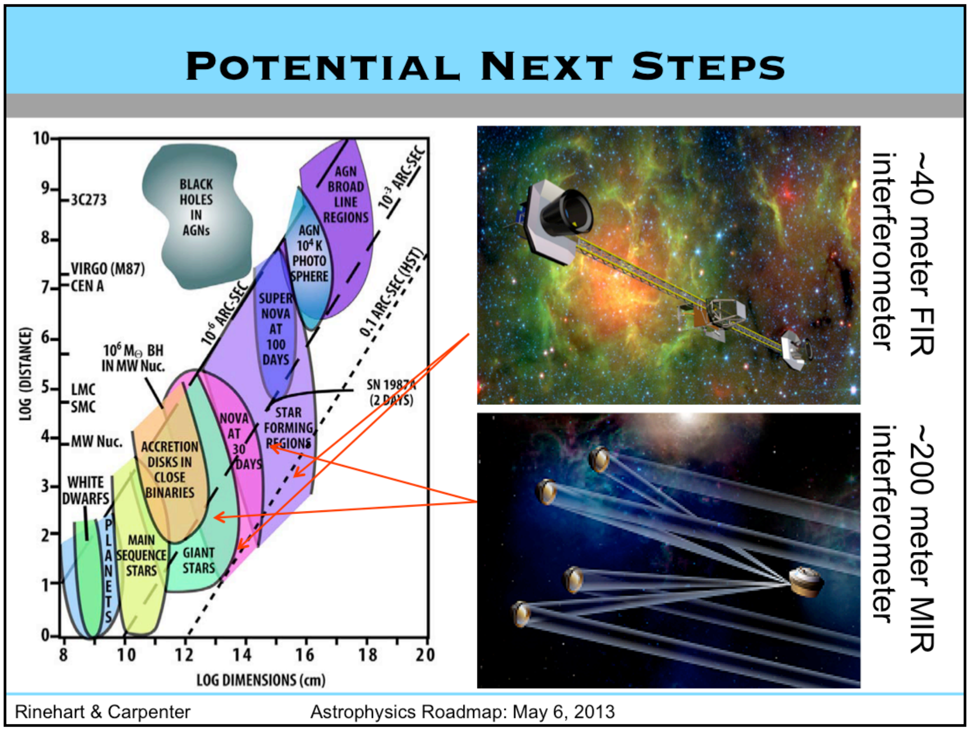
In between the extremes of size, additional angular resolution will provide details of processes in star formation regions and protoplanetary disks, as well as the interaction of the shock wave of a supernova with the ISM.



The vision of a planet mapping mission is ambitious, and it is clear that there is much work to be done in developing both individual technologies and systems. A planet mapping mission is likely decades away, but research and technology development currently underway is laying the foundation. The feasibility of interferometry has been demonstrated by a large variety of successful ground-based interferometers. However, we are approaching the limit of what can be done from the ground, due to several major challenges. The atmosphere limits spatial and temporal coherence, which limits the maximum baseline of ground-based interferometers. Long and complicated delay lines are needed for off-axis observations. The rotation of the earth limits pointing. And, wavelength coverage is severely limited from the ground. None of these challenges are faced by space-based interferometers. Interferometry is easier in space!

A wide variety of laboratory testbeds have and are addressing many of the most pressing technology needs, as we'll note shortly.

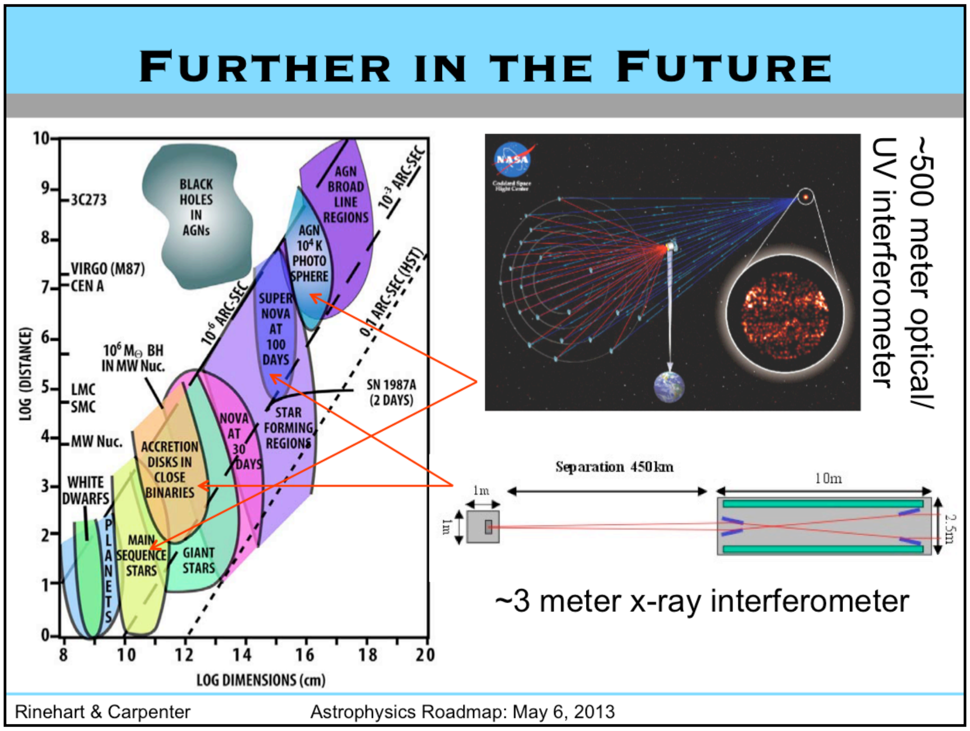
Balloon-borne interferometers are under development now, and will push both technologies and scientific boundaries. By flying on a balloon, an interferometer avoids some of the challenges of ground-based interferometers, trading those for a different set of challenges that arise from the balloon environment. Effectively, these balloon-borne interferometers will provide a bridge from interferometers on the ground to modest space-based interferometers



Such modest interferometers will push the technologies for interferometry, and will have powerful scientific capabilities in their own right.

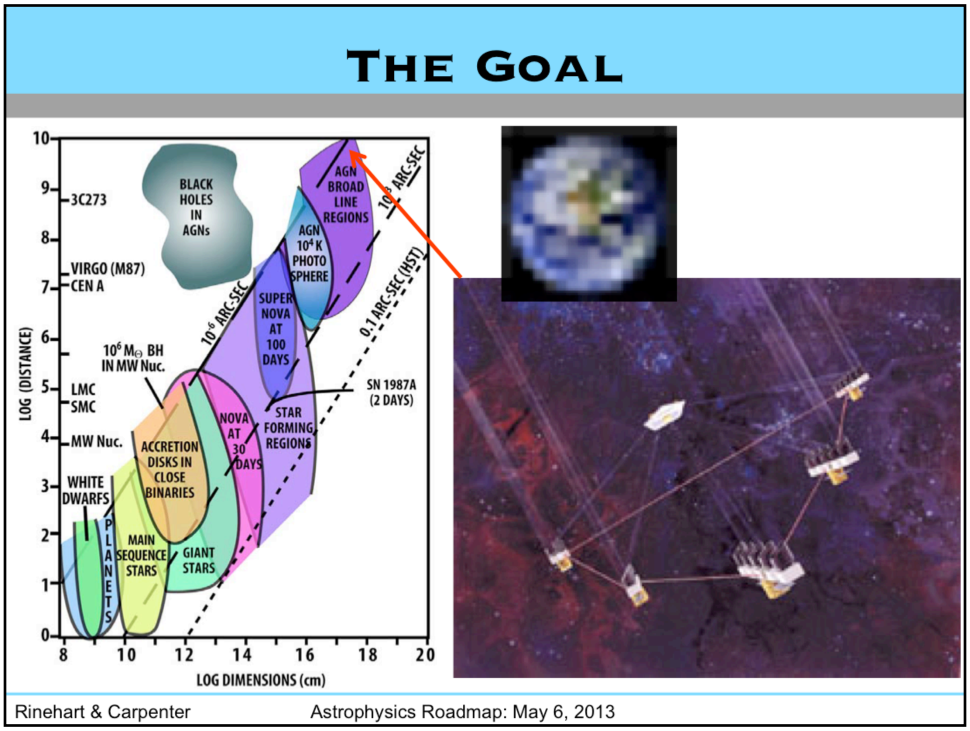
For example, a far-infrared interferometer with a very modest baseline of 30-50 meters would improve angular resolution at these wavelengths by over an order of magnitude.This would provide fantastically powerful new data for understanding the formation of stars and planetary systems, as well as the evolution and mergers of galaxies. A specific science case would be the exploration of the composition of protoplanetary disks, including the quantity and location of water within these systems.

Another concept would be a somewhat larger mid-infrared interferometer, such as proposed and studied for spectroscopy of exoplanets. This would provide angular resolution of better than 10 milliarcseconds. In addition to the exoplanets application, such an interferometer could have a strong general astrophysics component. For example, such an interferometer could be used to image the wind-formation regions around late-type stars.



A UV-optical interferometer, with a baseline of up to around 500 meters, would achieve angular resolution better than a milliarcsecond, and would enable studies of white dwarfs, stellar magnetic activity, and the central engines of AGN. There is an important connection to heliophysics here, as by understanding the magnetic behavior of main sequence stars more generally, we will gain insight into the activity of our own sun.

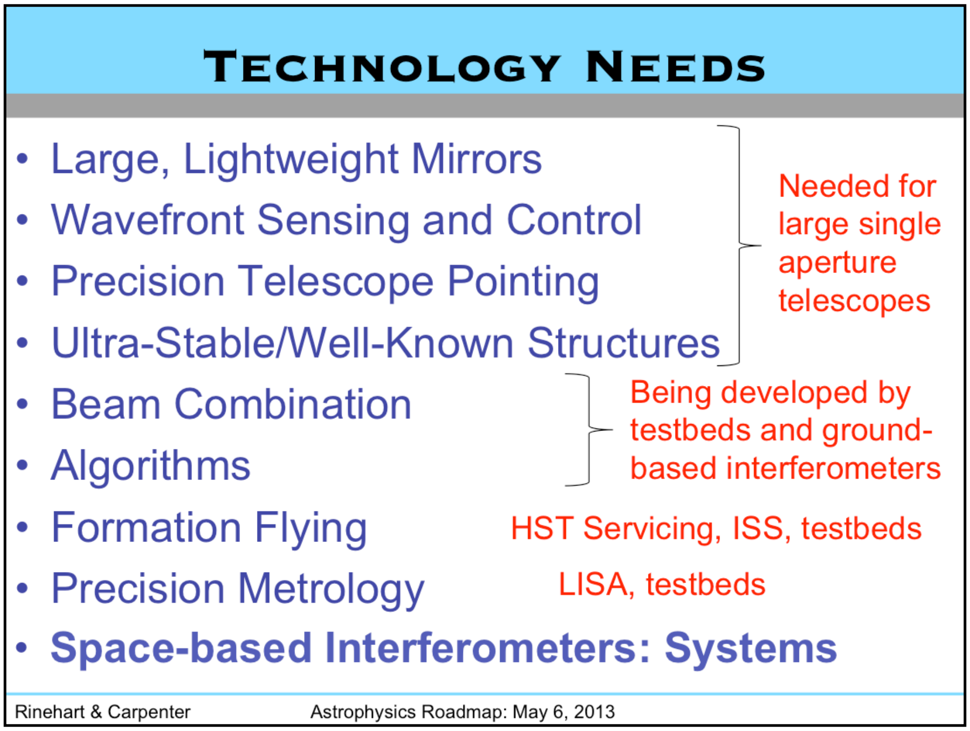
Finally, x-ray interferometers with baselines of only a few meters could also achieve sub-milliarcsecond resolution, probing the accretion disks in close binaries and around compact objects in our galaxy. Larger x-ray interferometers could potentially achieve sufficient angular resolution to image the event horizon of black holes in AGNs, though perhaps such a mission would benefit more from a planet mapping mission than vice versa.



The ultimate destination, though, is something like this artist's conception – a 30 kilometer baseline interferometer. This destination is a long way to travel from where we are now. We could get there through a multi-decade, dedicated technology development effort – i.e. letting this concept pull the technology. However, a better path would use smaller interferometers to push and prove the necessary technologies while pursuing other significant scientific objectives.

It is important to note that interferometry is easily extensible. With a demonstration of a modest interferometer, it is relatively straightforward to extend to longer baselines, larger apertures, and different wavelengths.

At this point, I hope that the value of this capability is apparent. I hope it's also apparent that this is only possible with interferometric systems. In fact, I hope that the inevitability of interferometry is obvious.

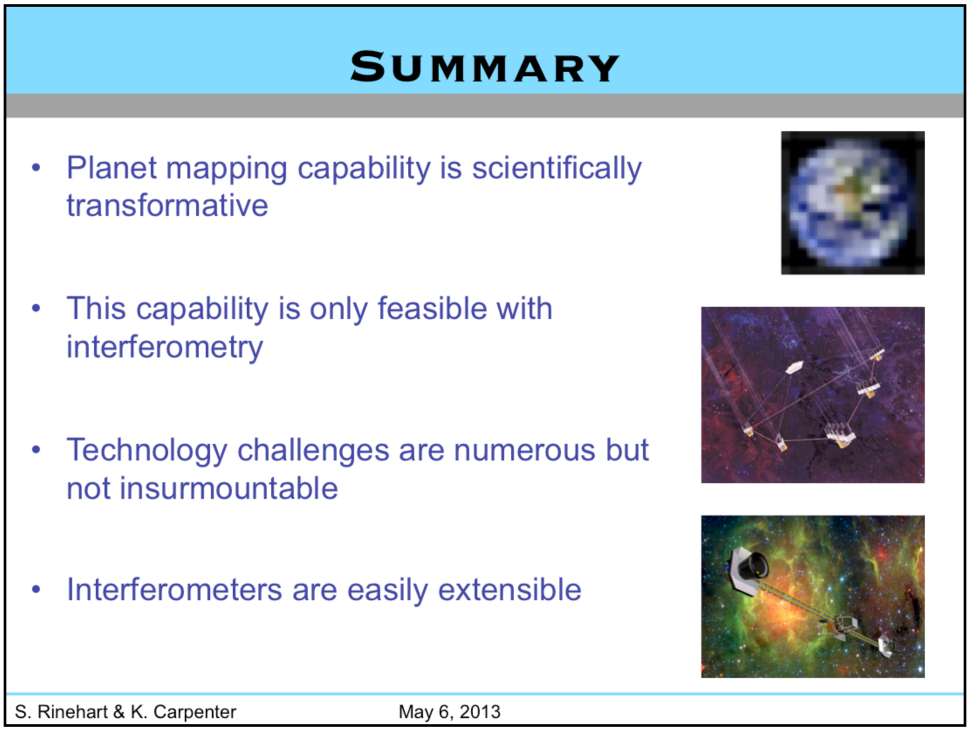


But we have not yet addressed the technologies that are needed to achieve this. Do we need unobtainium? Or transparent aluminum? No, in fact – the technologies needed are relatively mundane. We've put together a list, and there may be other technologies that we haven't thought to include, but it is important to note that none of these are fundamentally new, and none are beyond our technological reach.

The first four of these are also needed for single aperture telescopes; we have already seen this in the development of JWST. And, in fact, because interferometry effectively decouples the "telescope" resolution from the resolution of individual apertures, in many cases the requirements for interferometers are less demanding than for single aperture telescopes.

Beam combiners have been developed for ground-based interferometers, and the basics of these are well-understood. Algorithms are perhaps one of the greatest challenges, but there are groups working with laboratory testbeds to develop the techniques and algorithms that will be needed for future space-based interferometers. That leaves formation flying and precision metrology. We already do formation flying – robotic delivery to the International Space Station has been demonstrated, and robotic servicing of Hubble and future missions has been and is being studied. And precision metrology has been explored thoroughly under the auspices of the LISA mission and through a variety of ground-based testbeds (e.g. for SIM).

Ultimately, none of these technologies represent an insurmountable challenge, and most of them will naturally progress towards the requirements of a planet mapping optical interferometer. The real challenge will not be in the individual technologies, but in the design, modeling & testing, and implementation of the entire system. And that can only be pushed through the development of space-based interferometers.



This talk has gone quickly, and we have tried to convey a lot of information in this short time. However, there are several key points I would like you to take away

1) Mapping planets is a whole new scientfic realm, and the capability to do this will enable revolutionary science across all of astrophysics.
2) This level of angular resolution is only achievable with interferometry.
3) The technological challenges for interferometry are within our grasp. We are on the path now, and could arrive at the destination within decades through the development of more modest space-based interferometers. These interferometers each have their own scientific merits, and would push both individual technologies and demonstrate interferometric systems in space.
4) Interferometry is extensible; while modest space-based interferometers would provide ground-breaking science, they would naturally lead to the bold vision of a planet mapping interferometer.