

Towards Resolving Terrestrial-Scale Planet Formation

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CENTER FOR

ASTROPHYSICS

HARVARD & SMITHSONIAN

*"The Scientific Quest for
High Angular Resolution"*

NRAO Special Session

*235th AAS Meeting
Honolulu, HI
January 7, 2020*

Looking for reminders of home

The screenshot displays the WorldWide Telescope (WWT) software interface. At the top, a navigation bar includes icons for Home, Explore (selected), Guided Tours, Search, Communities, View, and Settings. Below this is a 'Collections' section with nine folders: Latest Imagery, Constellations, Solar System (Sky), All-Sky Surveys, Spitzer Studies, Chandra Studies, Hubble Studies, Astrophotography, and Radio Studies. On the left, a 'Layers' panel is open, showing a tree view of visible elements: Sky (checked), Overlays (checked), Constellations (checked), and Grids (checked). Under Constellations, 'Constellation Figures' and 'Constellation Boundaries' are checked, while 'Constellation Pictures' and 'Constellation Names' are unchecked. Under Grids, 'Ecliptic Overview' is checked, while 'Equatorial Grid', 'Galactic Grid', 'AltAz Grid', 'Ecliptic Grid', and 'Precession Chart' are unchecked. Below the layers panel is a 'Time Scrubber' with a slider. At the bottom, the 'Look At' dropdown is set to 'Earth' and the 'Imagery' dropdown is set to 'Bing Maps Streets'. The main view is a 3D map of Earth centered on North America, with labels for 'NORTH-AMERICA', 'UNITED STATES', 'MEXICO', 'Gulf of Mexico', 'Caribbean Sea', 'Sargasso Sea', 'Atlantic Ocean', 'CUBA', 'VENEZUELA', 'COLOMBIA', and 'VENEZUELA'.

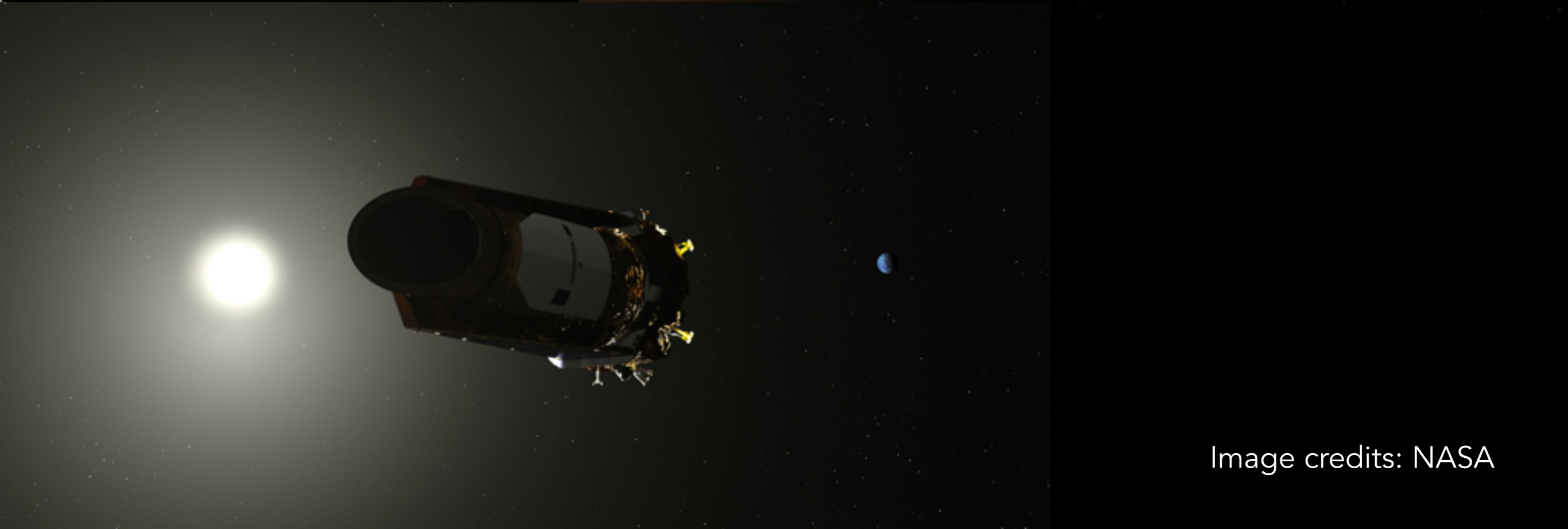
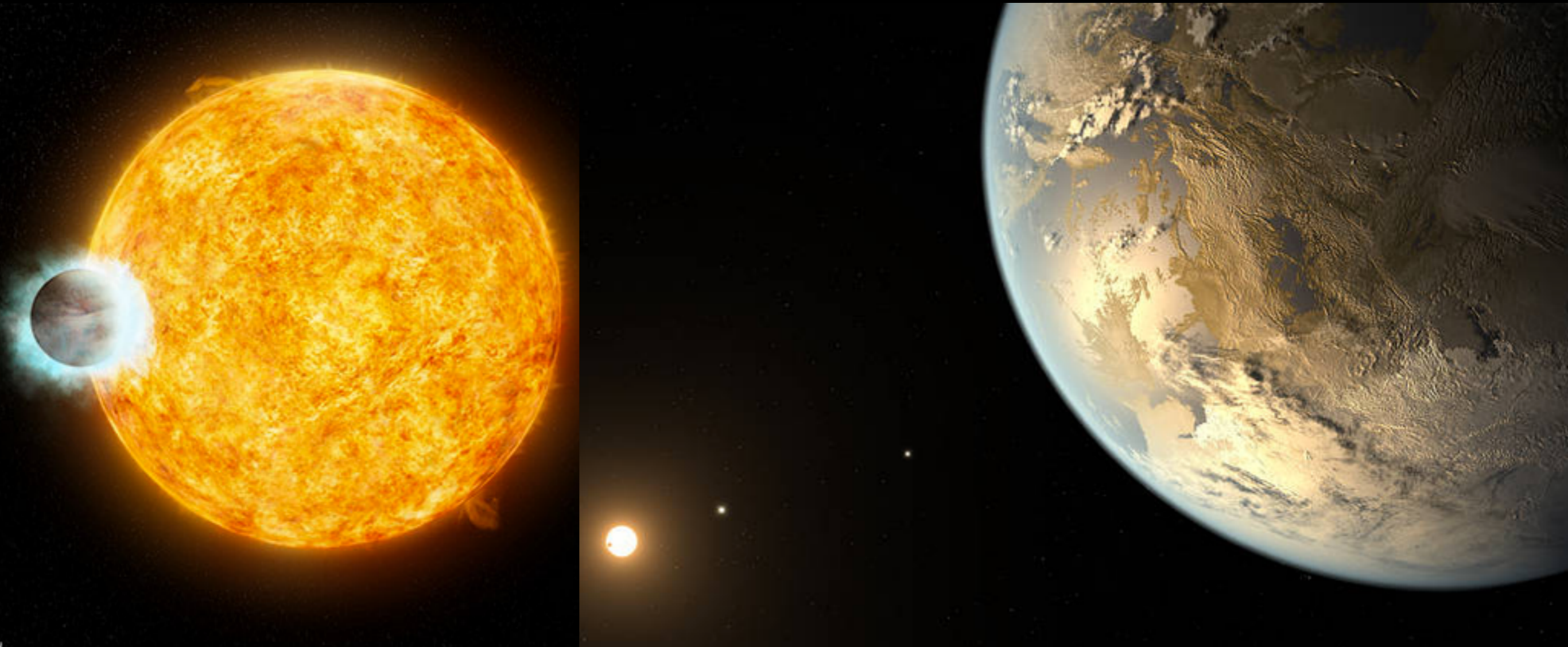


Image credits: NASA

Very massive protoplanets can be studied via direct imaging

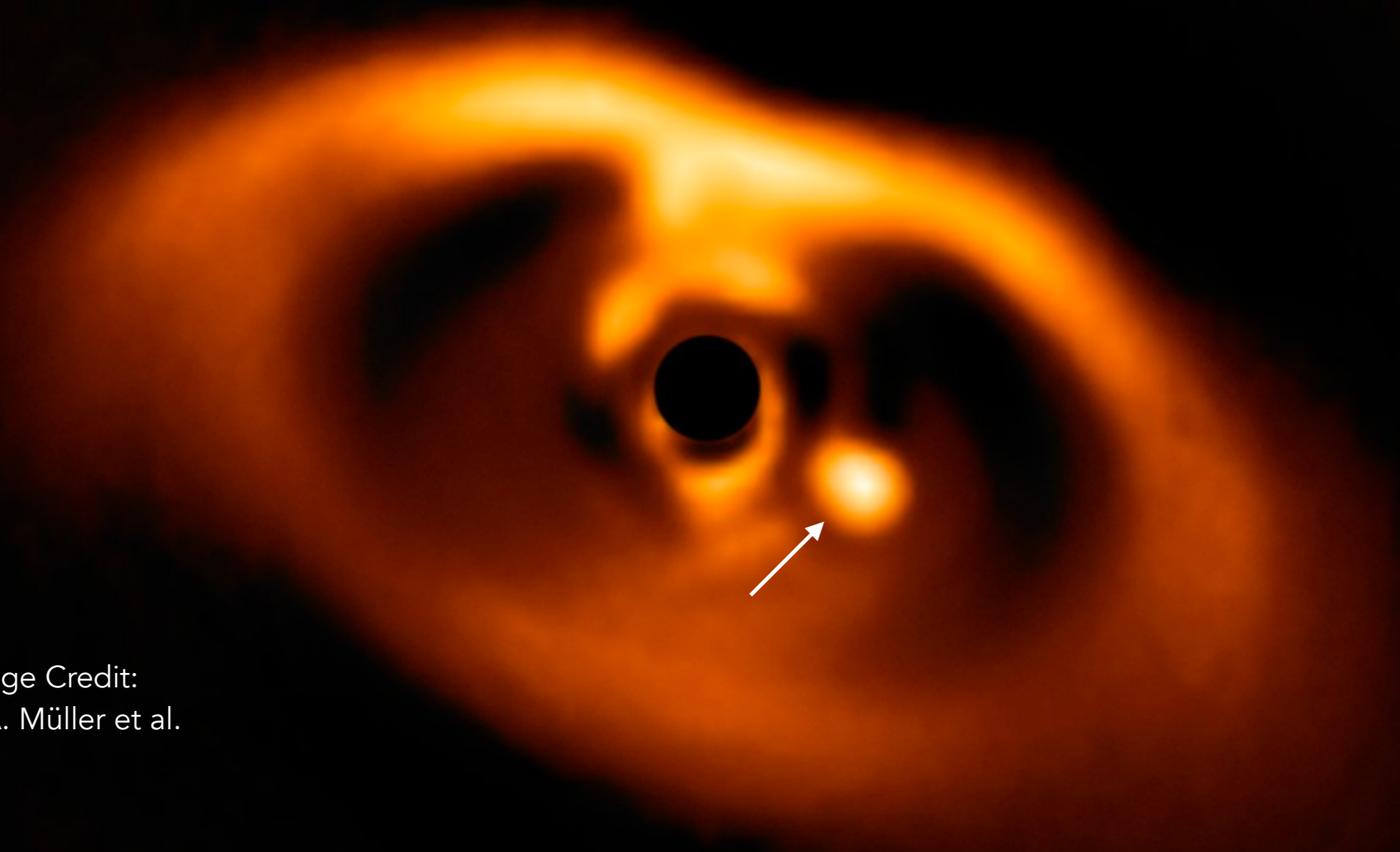
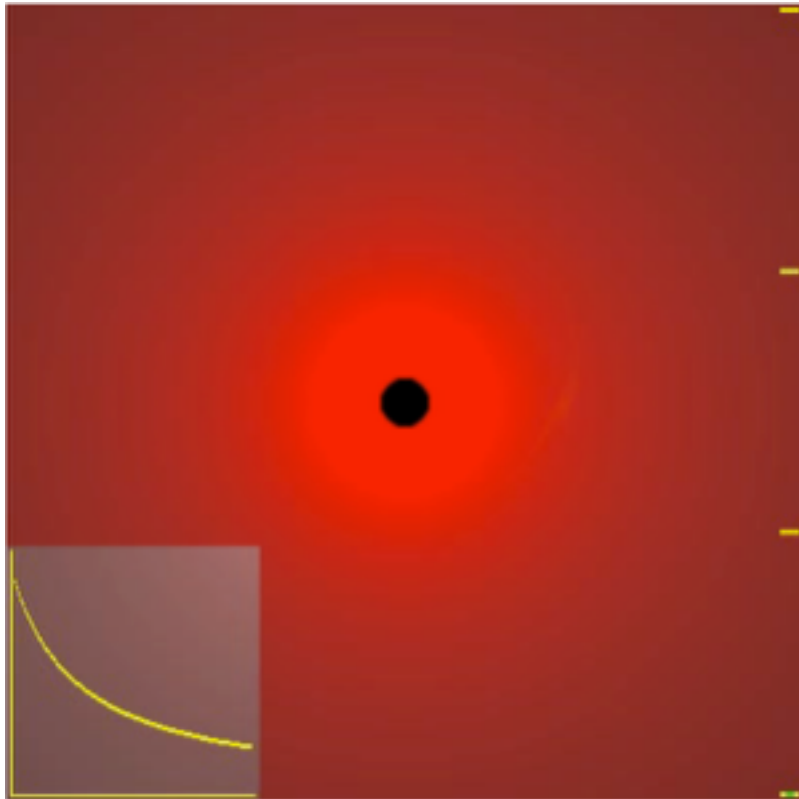


Image Credit:
ESO/A. Müller et al.

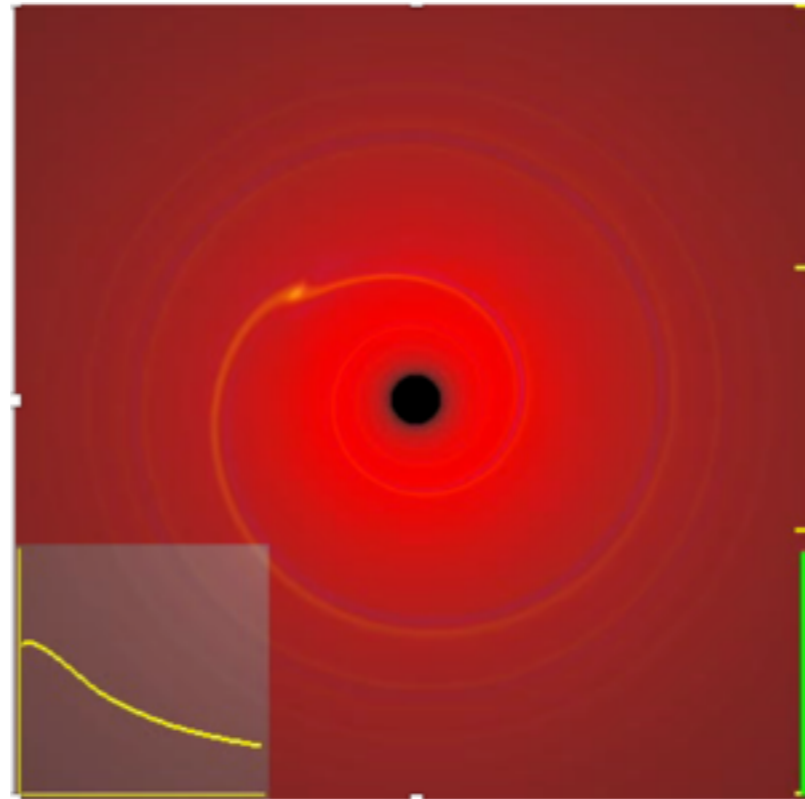
Planets too faint to be imaged can still create large disturbances in disks

Credit: P. Armitage

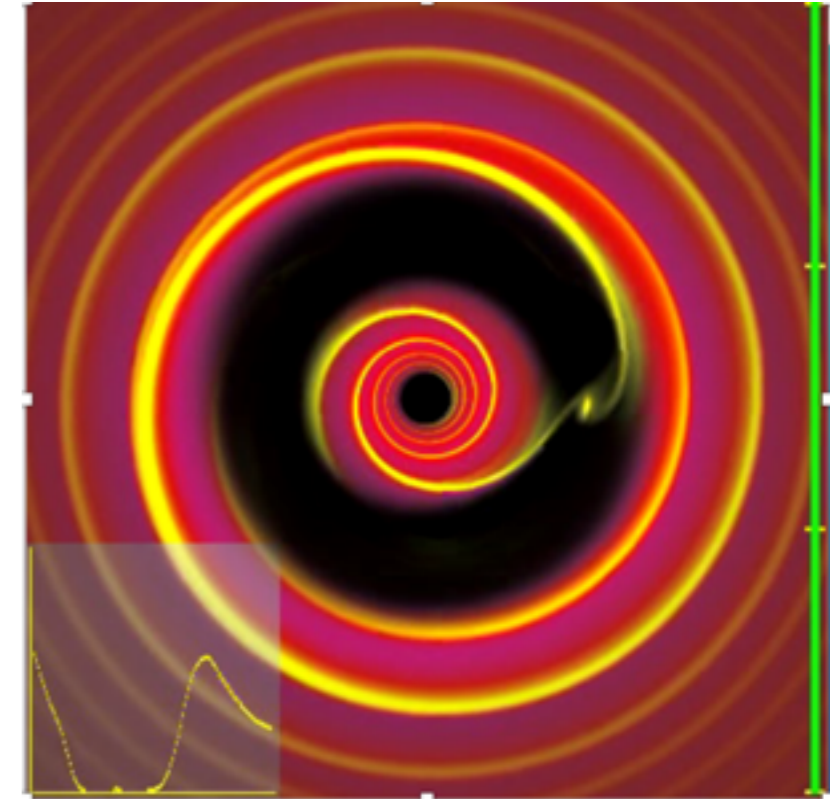
http://jila.colorado.edu/~pja/planet_migration.html



Disk is smooth initially



Perturbation by a planet triggers a spiral density wave

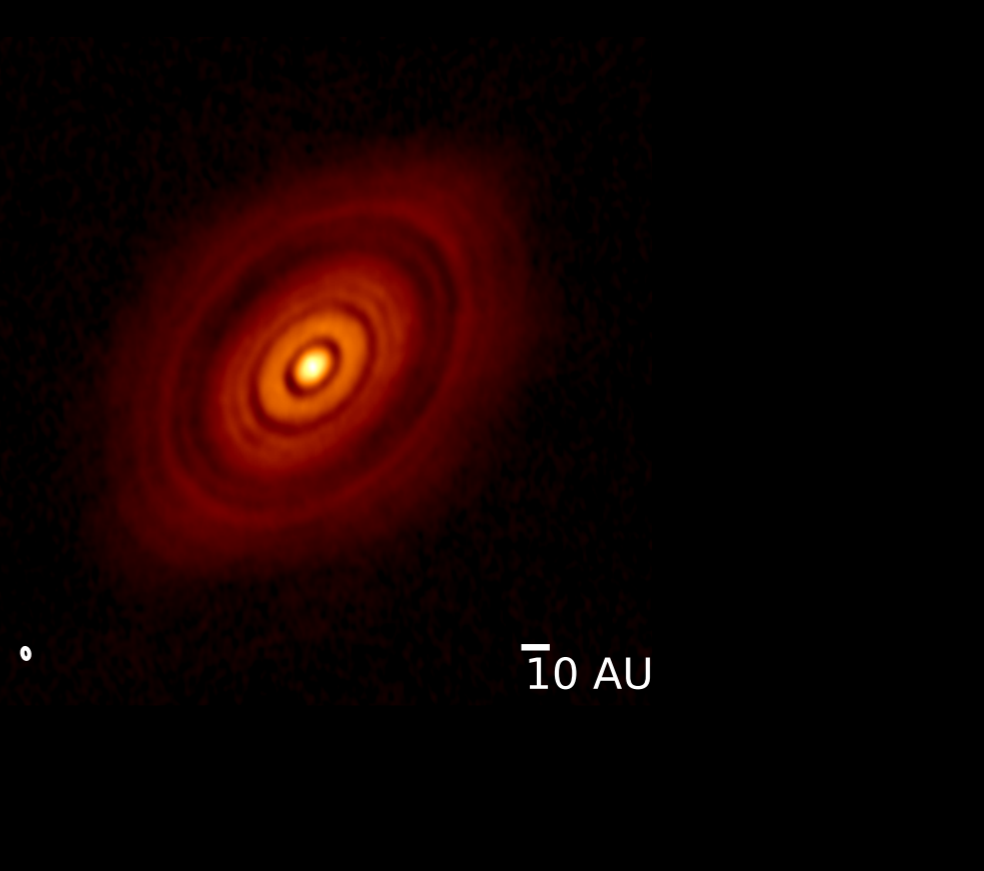


As the planet grows, the spiral density wave shocks and opens a gap

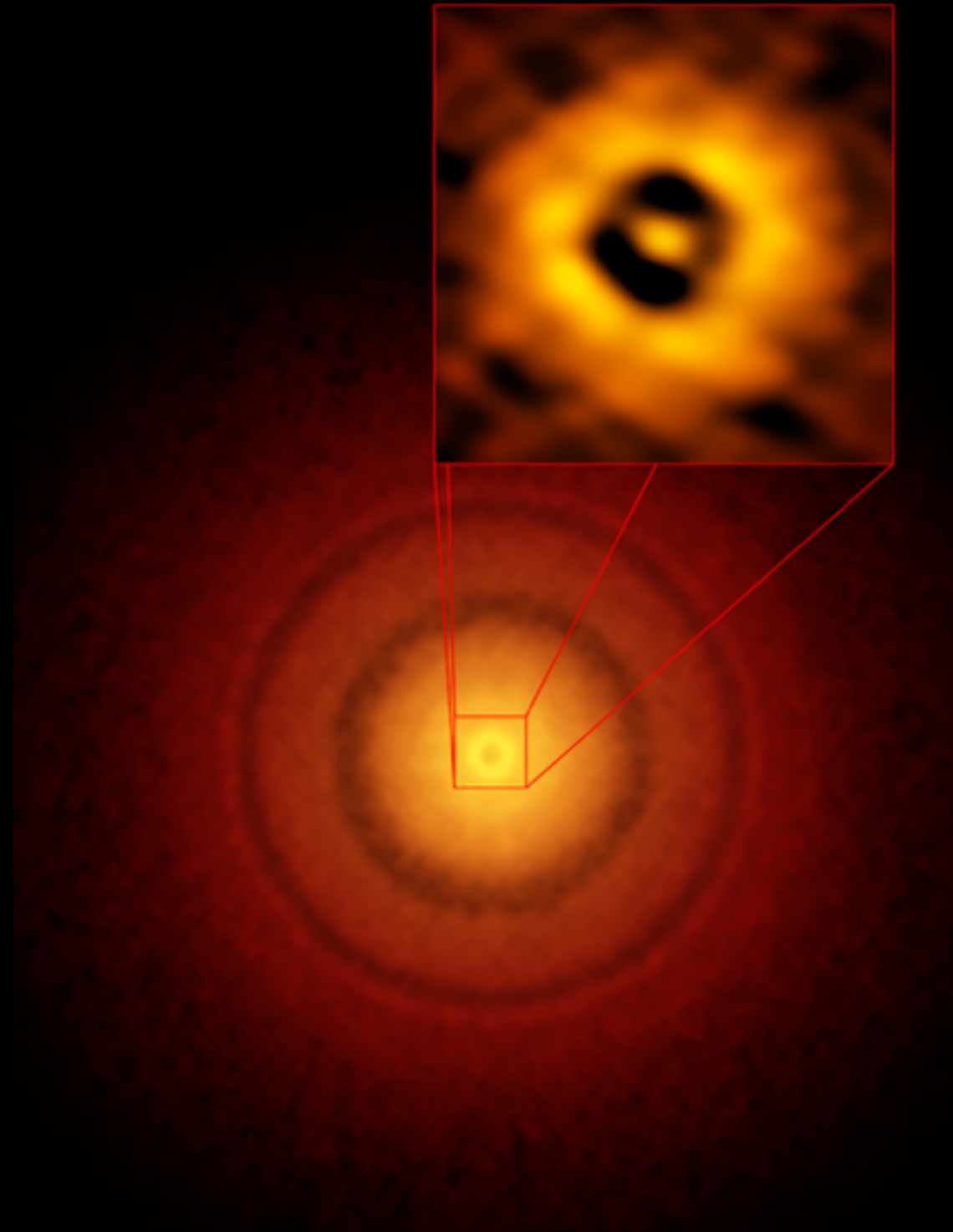
In low-viscosity disks, a single planet may open multiple gaps (e.g., Duffell & MacFayden 2013, Zhu+ 2014, Dong+ 2017, Bae+2017)

ALL PROTOPLANETARY TALKS...

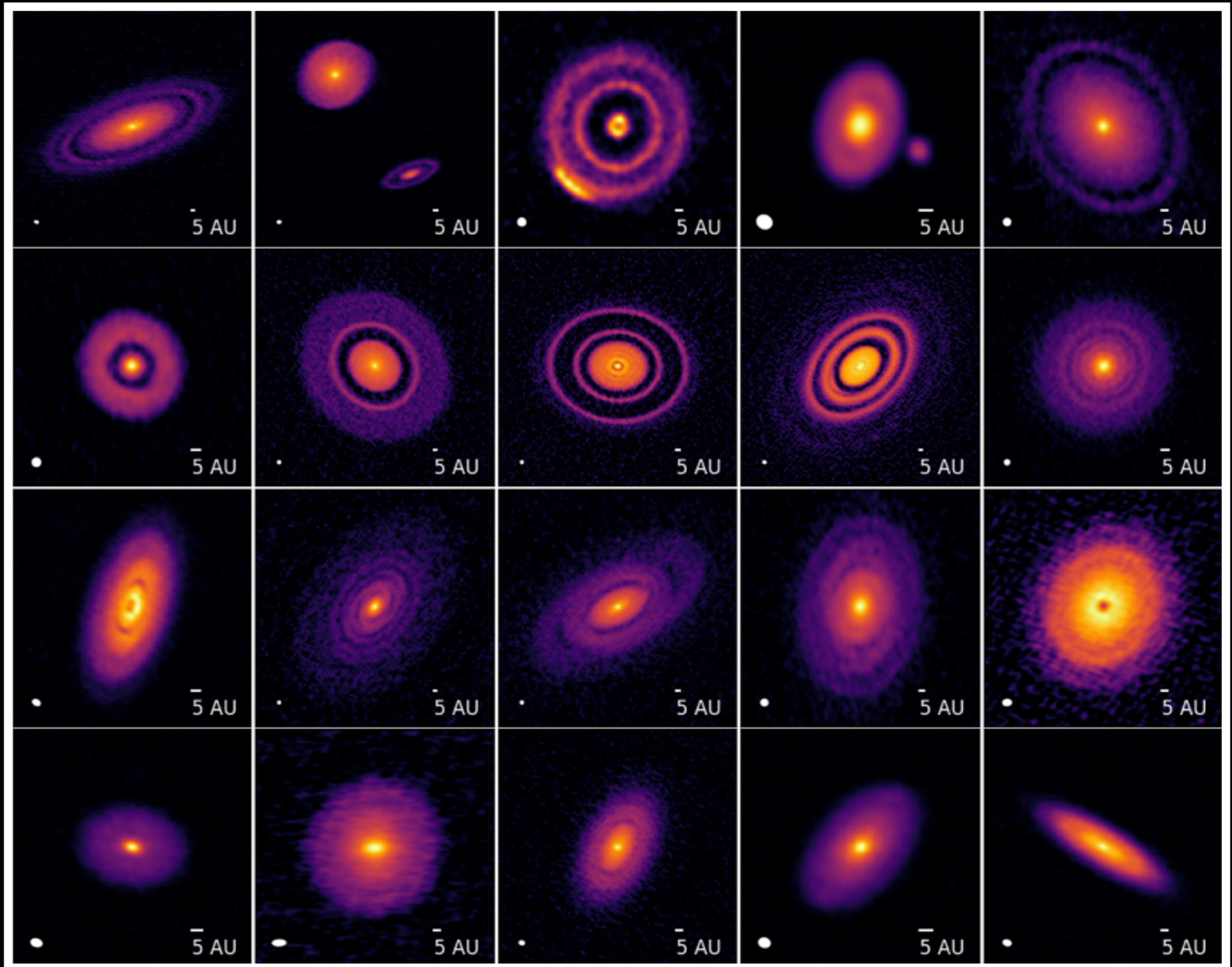
Illustration credit: Melissa Hoffman (NRAO)



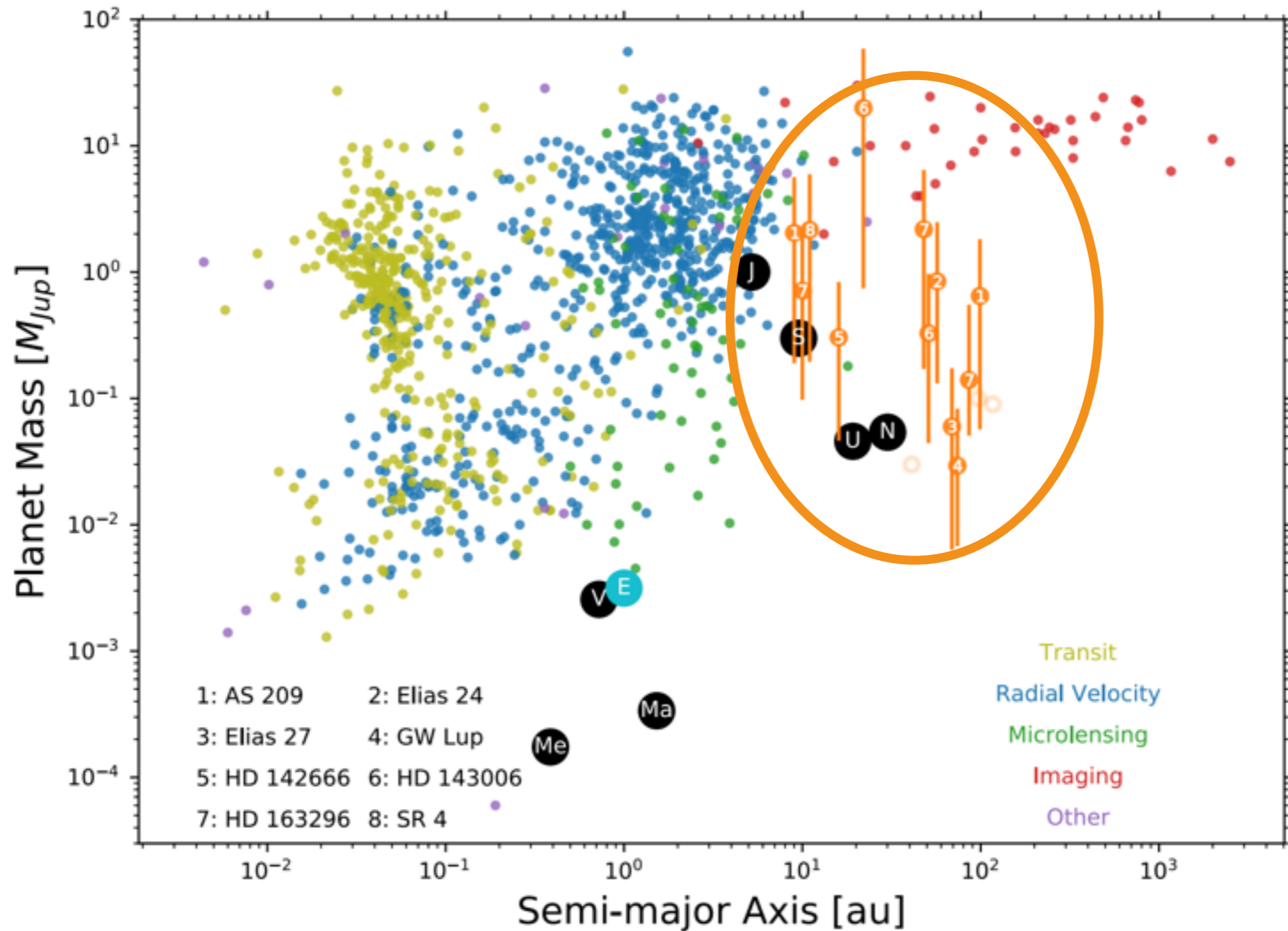
A gap at 1 au in the TW Hya disk









The Disk Substructures at High Angular Resolution Project (DSHARP)



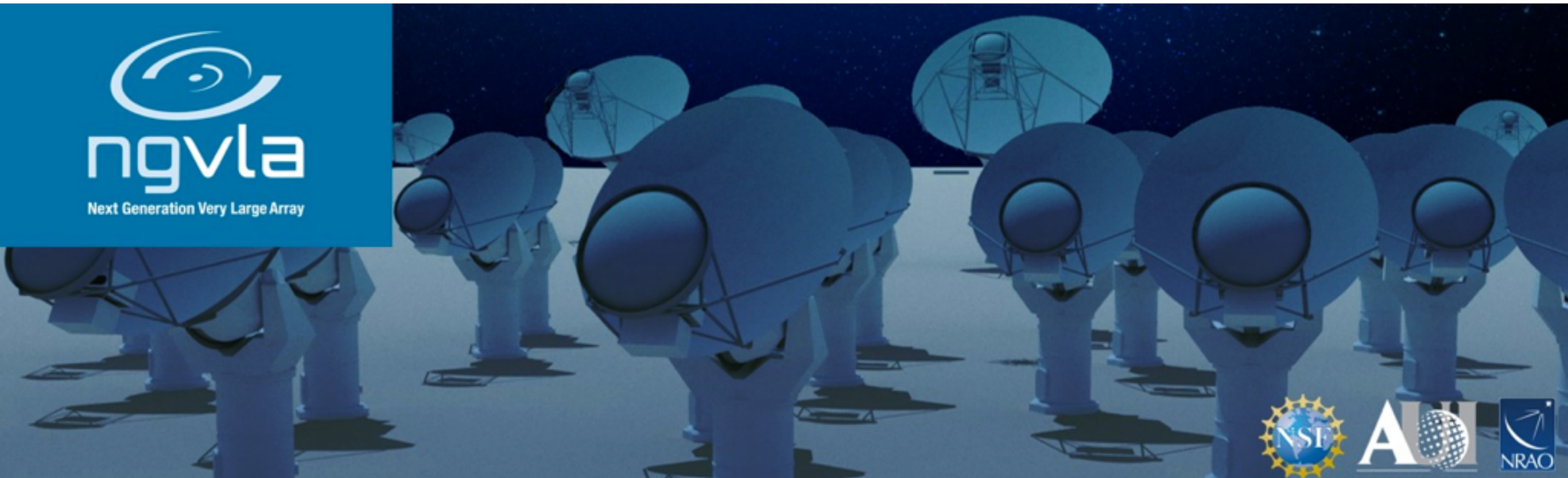
Most disk gaps detected so far with ALMA seem to be consistent with giant planet formation at tens of au



Disk observations: ALMA vs. VLA

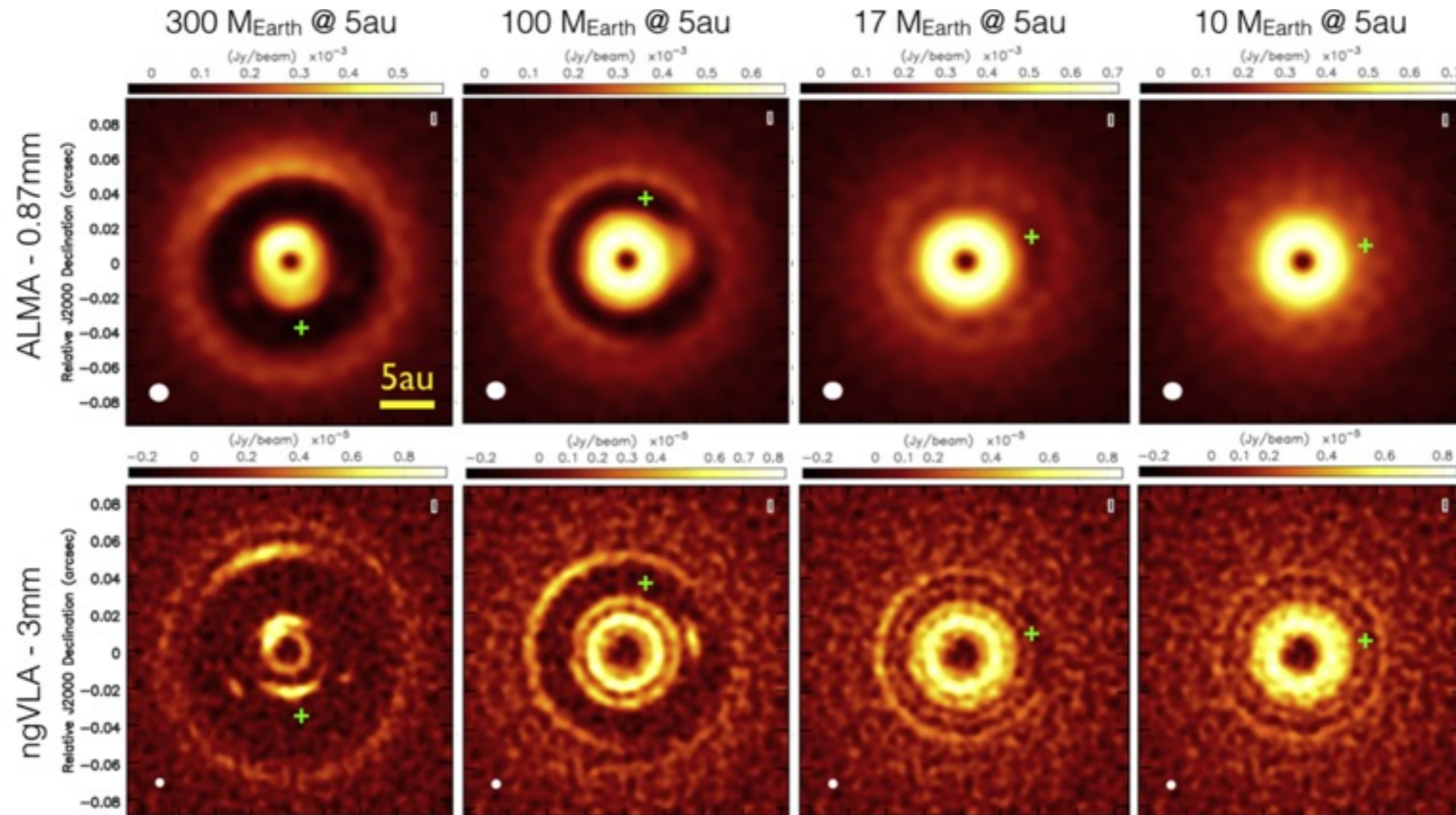
	ALMA	VLA
Access to frequencies where dust is optically thin		
High spatial resolution		
High signal-to-noise ratio		

The case for a next-generation VLA



- Coverage of key frequencies where **dust is optically thin** but still the dominant source of emission (~30-100 GHz)
- Spatial resolution **< 1 au** to resolve substructures in the inner disk at distance of nearby star-forming regions (~160 pc)
- **10x improvement in sensitivity** to detect substructures carved by planets smaller than Solar System ice giants

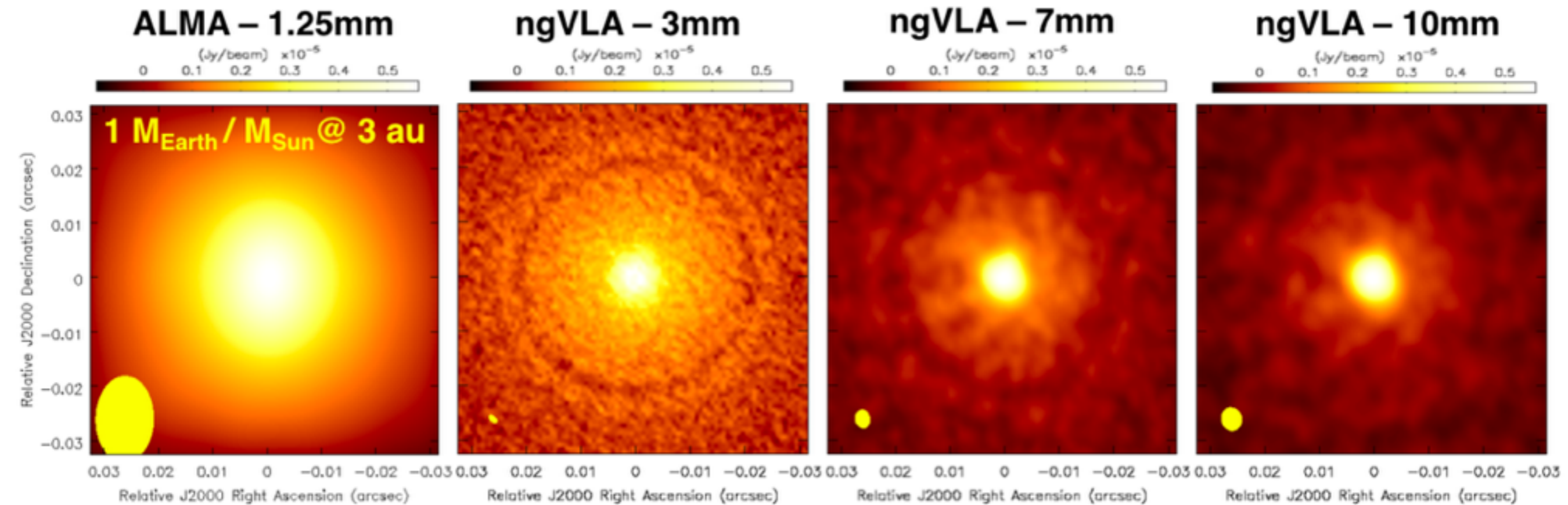
Tracing the formation of Super-Earths



Ricci+ 2018

Gaps induced by super-Earths are predicted to be detectable in low-viscosity disks ($\alpha=10^{-5}$) with 20 h on-source with the ngVLA

Tracing the formation of Earths?



Harter+ 2019

Gaps induced by Earths are predicted to be detectable in low-viscosity disks ($\alpha=10^{-5}$) with 100 h on-source with the ngVLA

Summary

- ALMA is well-suited for characterizing the giant planet formation zone in disks
- The ngVLA is necessary to access the appropriate frequencies, spatial resolution, and sensitivity to study the terrestrial planet formation zone
- Selection of high-priority ngVLA targets will rely on present efforts to constrain dust grain sizes, disk turbulence, and pressure scale heights with facilities such as ALMA and the VLA

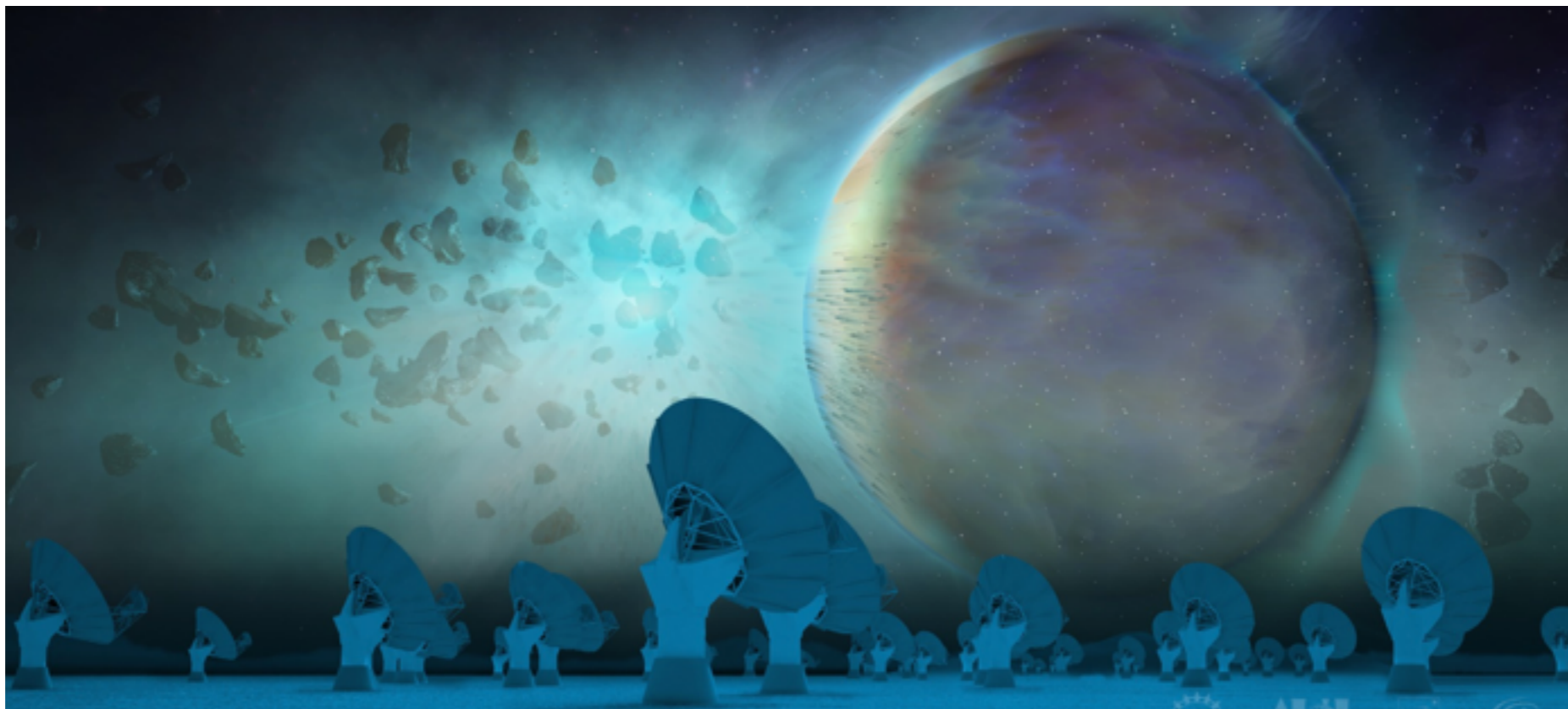


Image credit:
NRAO