The debris disk of HR 8799 seen with ALMA at 870 microns
Do we need an extra planet ?

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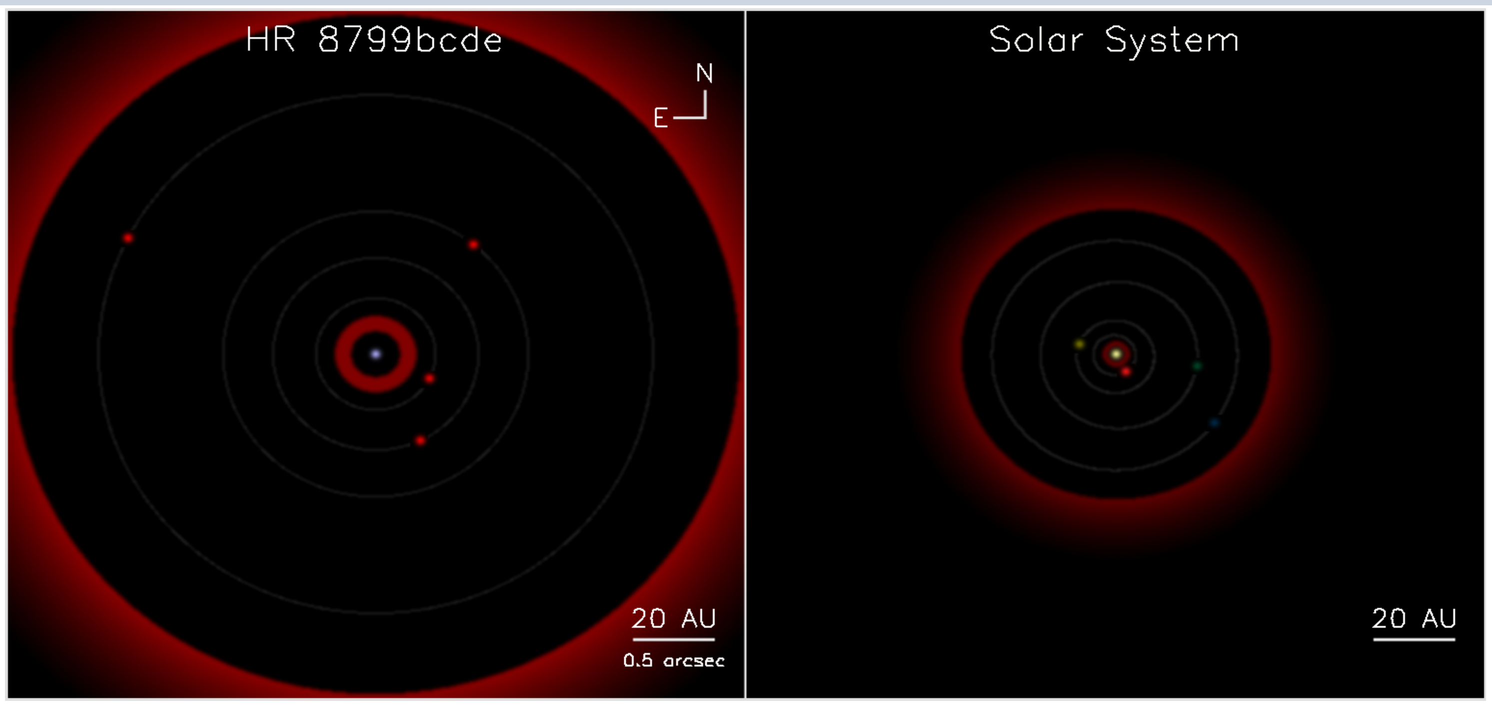
Debris disks contain solid bodies in collisional cascade, ranging from km-sized down to micron-sized dust grains. They are remainders of planetary formation processes. As example, our own Solar system hosts the Main Asteroid and the Kuiper belts, which shape and extent is driven by interactions with planets.
Debris disks can be seen at multiple wavelengths, from visible scattered-light to millimeter radio emission. Observations at longer wavelengths reveal bigger solids, which are less affected by stellar radiation effects, and provide a clearer view of any gravitational imprint of a planetary system.

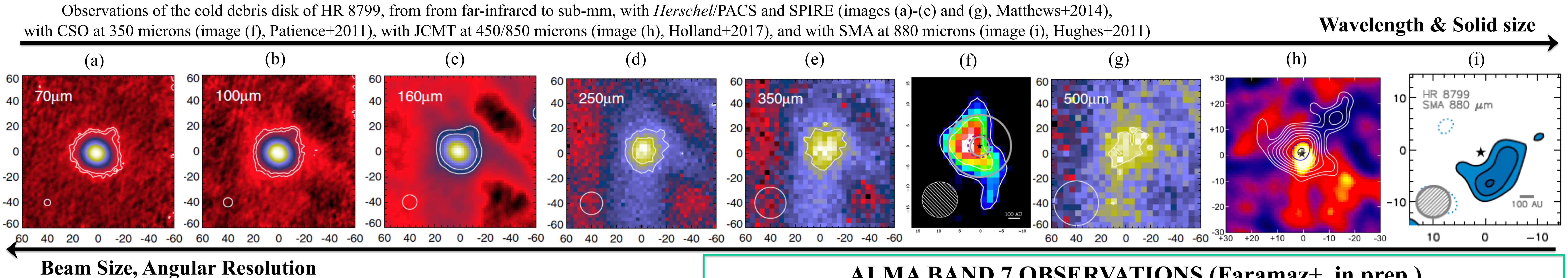
HR 8799 is the only star so far around which multiple planets system have directly been imaged (Marois+2008, 2010). Its four giant planets (5-7 M_{Jup}) are surrounded by a cold debris disk, first detected with IRAS (Sadakane & Nishida, 1986). A detailed study combining IRAS, ISO, Spitzer and JCMT/SCUBA flux measurements allowed Su+2009 to infer the presence of three debris components : a large halo of faint grains, an asteroid belt analogue, and a Kuiper belt analogue.

HR 8799's architecture is strikingly similar to that of the Solar System, but rescaled at wider separations. It is a younger, broader, and more massive version of it, and is an excellent laboratory to test planet formation models and theories.



The HR8799 system compared to our own solar system, showing the four HR8799 planets and Jupiter, Saturn, Uranus and Neptune in our solar system, as well as the cold and warm debris belts in both cases. (Credit: NRC-HIA, Christian Marois, and the W.M. Keck Observatory)

Observations of the cold debris disk of HR 8799, from from far-infrared to sub-mm, with *Herschel*/PACS and SPIRE (images (a)-(e) and (g), Matthews+2014), with CSO at 350 microns (image (f), Patience+2011), with JCMT at 450/850 microns (image (h), Holland+2017), and with SMA at 880 microns (image (i), Hughes+2011)



PREVIOUS RESULTS

The inner edge of the cold belt resolved with *Herschel*/PACS (70-160 microns) is found to be located at ~100 AU from the star (Matthews+2014). This is consistent with the photometry modeling of Su+2009. This is also consistent with the outermost planet HR 8799 b sculpting the belt's inner edge (Wang+2018).

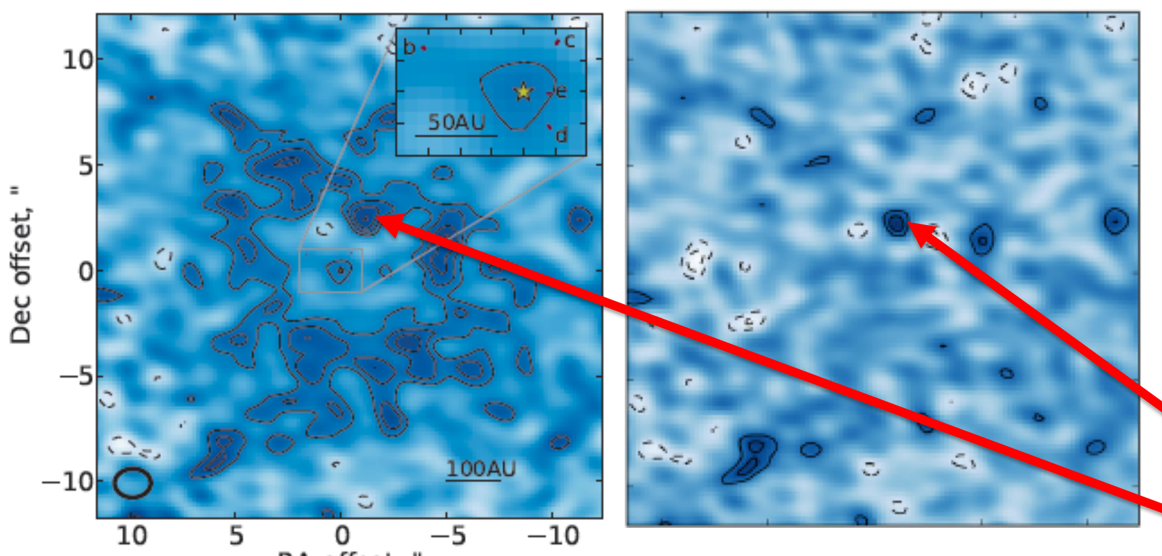
However, observations at longer wavelengths - which reveal bigger grains less affected by stellar radiation effects - hint at a more complicated story: the disk appears clumpy and asymmetric (Patience+2011, Hughes+2011). The resolution of these observations is poor though, and it will have to wait the advent of ALMA and of interferometry at radio wavelengths to obtain detailed enough observations.

First ALMA observations: To be or not to be discrepant

ALMA 1.3mm (Booth+2016)

Inner edge at $145 \pm 12\ AU$

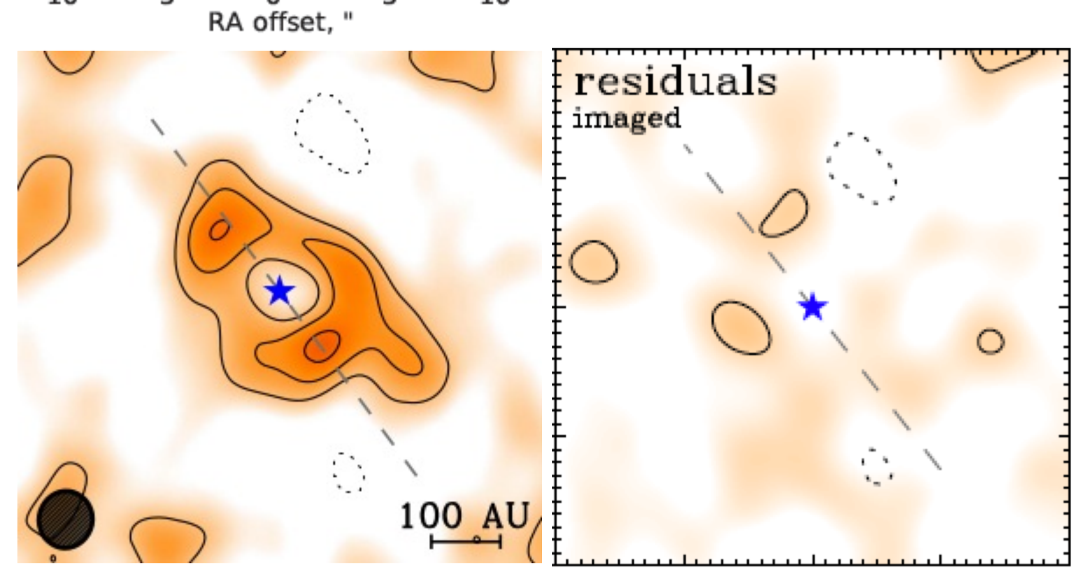
There is room for a ~1M_{Jup} planet beyond HR 8799 b



SMA+ ALMA 1.3mm (Wilner+2018)

Inner edge at $104^{+8}_{-12}\ AU$

HR 8799 b sculpts the inner edge

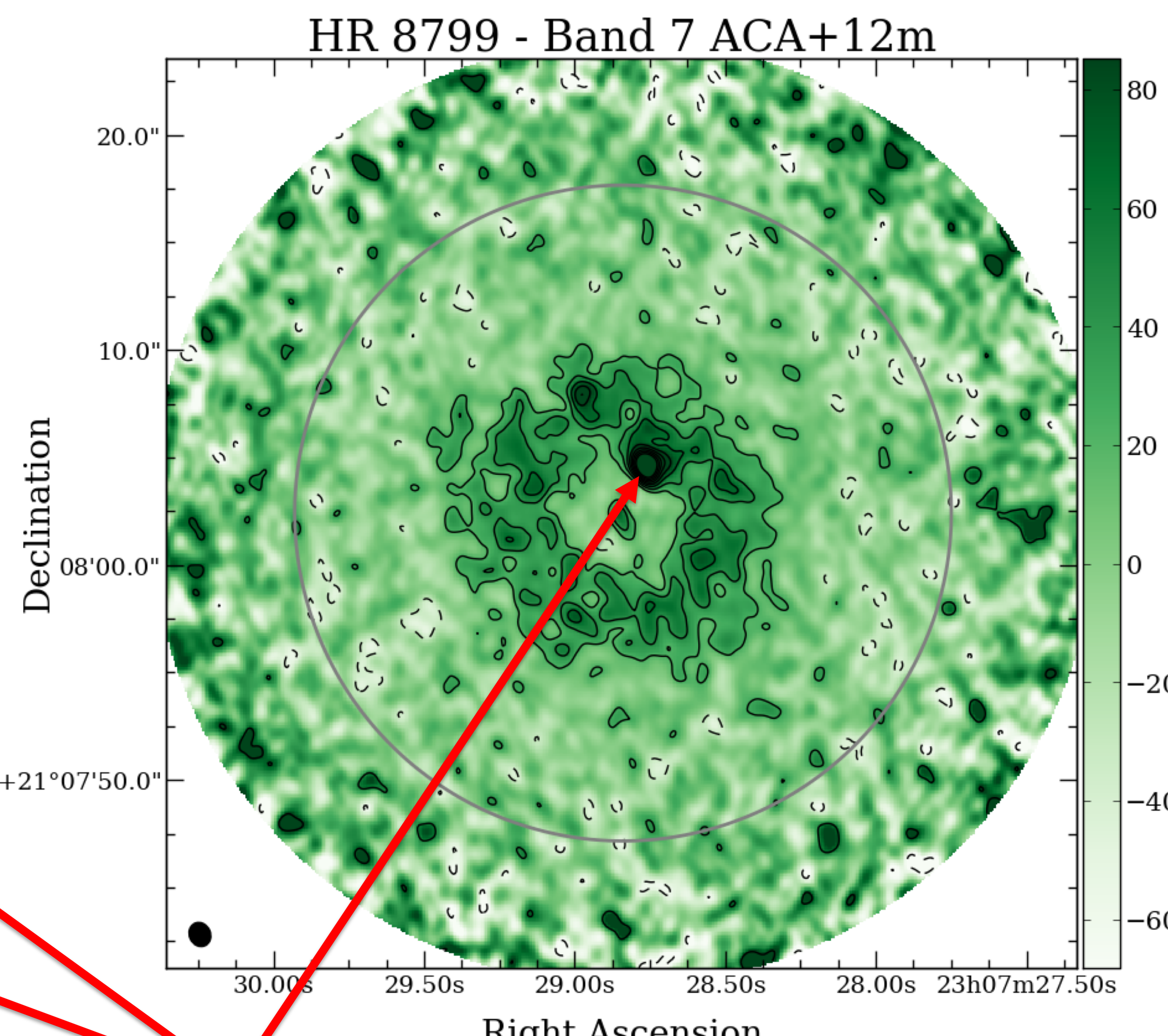


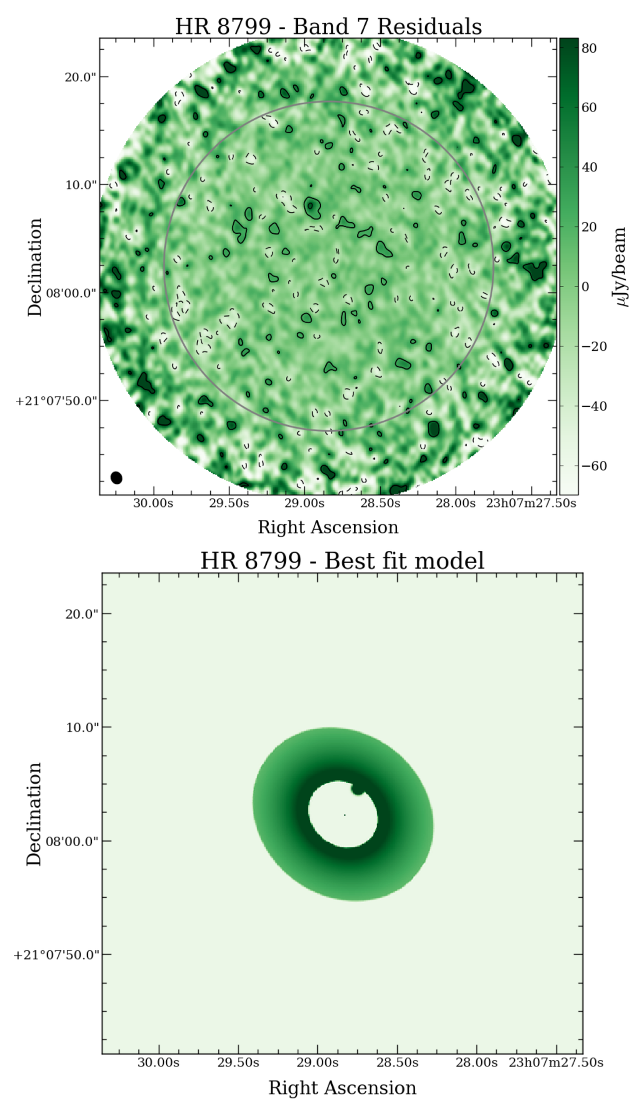
OBSERVATIONS

RESIDUALS AFTER BEST FIT MODEL SUBTRACTION

ALMA BAND 7 OBSERVATIONS (Faramaz+, in prep.)

Left: ALMA 870 microns continuum observations of HR 8799 (PI= V. Faramaz). Contours show the 2, 4, 6,... σ significance levels, with σ = 10.5 Jy/beam. The disk is mostly detected at SNR 3-4.
With a resolution of ~1", this is the most sensitive and detailed map obtained so far for this debris disk.
Right: Residuals after best fit model subtraction (top) and best fit model (bottom).





The clump of contention: we find that a clump seen in the Booth+2016 image appears much brighter at 870 microns (SNR>10). Seen at SNR 4 at 1.3mm, it was thus unclear whether it was part of the disk or not. Hence, when considered part of the disk, the inner edge of the best fit model will be forced further in, explaining why the results of Wilner+2018 contradict those of Booth+2016. While we do not know if this clump is part of the system (comoving), it should at least be included in our models as a source that is separated from the disk.
The inner edge: our best fit model returns an inner edge located at $132 \pm 5\ AU$, confirming the findings of Booth+2016, leaving room for a ~1 M_{Jup} planet beyond planet b. Note that Read+2018 found that this planet should in fact rather be ~0.1 M_{jup}, in order not to jeopardize the stability of the four imaged planets. While this mass regime is not accessible as of now to direct imaging, *it should however be a target of choice for JWST*.

Finally, Geiler+2019 found that similar to the Kuiper Belt, the debris disk of HR 8799 includes a population of solids excited on high eccentricity orbits, which clearly hints at interactions with a planet. Planet b being too massive as of now to excite solids without ejecting them, this either means that there is indeed an extra planet, or alternatively, that planet b interacted with the disk while forming and being less massive.
As both core accretion and gravitational instability models struggle to explain the formation the imaged planets, the latter scenario offers a perspective that might be even more exciting than the presence of an additional planet, as it would provide strong constraints on the conditions in which planet b formed and the dynamical history of the system, ultimately leading us to a much better understanding of planet formation processes.

While the search for an extra planet could be ventured with *JWST*, additional information could also be gleaned with new ALMA observations. If there is no additional planet, then the inner edge of the disk should become smaller at shorter wavelengths, as smaller grains spiral inwards due to Poynting-Robertson drag, until they reach the ~100 AU distance where planet b can carve an inner edge.

References: Booth+2016, MNRAS, 460, L10-L14 • Geiler+2019, MNRAS, 483, 332-341 • Holland+2017, MNRAS, 470, 3606-3663 • Hughes+2011, ApJ, 740, 38 • Marois+2008, Science, 322, 1348 • Marois+2010, Nature, 468, 1080-1083 • Matthews+2014, ApJ, 780, 97 • Patience+2011, A&A, 531, L17 • Read+2018, MNRAS, 475, 4953-4966 • Sadakane & Nishida 1986, PASP, 98, 685 • Su+2009, ApJ, 705, 314 • Wang+2018, AJ, 156, 192 • Wilner+2018, ApJ, 855, 56

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