Direct Imaging of Protoplanet Candidates in Protoplanetary Disks Using NIX L-band Observations

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Scientific Motivation

Planet Formation via Disk-Planet Interaction

- Proto-planets form within natal disks, creating gaps and triggering spiral density waves. High-resolution imaging reveals widespread rings and spirals in protoplanetary disks, suggesting that hidden planets commonly shape these structures.
- Gravitational interactions between disks and embedded planets leave clear signatures in the disk's gas kinematics, including spiral velocity patterns and localized velocity "kinks."
- Such kinematic signatures provide indirect but compelling evidence of planet formation occurring within disks.

Limitations of Short-NIR Imaging

- Previous direct imaging attempts at short near-infrared (NIR) wavelengths (~2 μm) or using accretion indicators (such as Hα) have often failed to detect embedded protoplanets.
- These shorter wavelengths suffer significant extinction due to dust along the observational line of sight.
- Dust within circumstellar disks and around the planets themselves (circumplanetary dust) strongly reduces observational sensitivity, possibly hiding existing protoplanets.

Need for L-band Imaging

- Observations at longer infrared wavelengths, specifically the L-band (~3.8 μm), drastically reduce dust extinction effects.
- The VLT/ERIS NIX imager, equipped with a new vortex coronagraph, significantly enhances detection capabilities compared to traditional K-band imaging, improving sensitivity by about a factor of four in terms of detectable planet mass.
- Recent commissioning results demonstrate sensitivity to detect young giant planets of approximately 0.5–1 Jupiter masses (MJ) at separations greater than ~0.5″.
- L-band imaging thus provides a crucial opportunity to detect cooler, dust-enshrouded planets invisible at shorter wavelengths.

EXO-ALMA : Kinematic Signatures of Proto-planets

ALMA Kinematic Evidence (Example: J1604)

- The velocity field in CO line emission from J1604 shows a clear Keplerian rotation pattern.
- Subtraction of a perfectly Keplerian disk model reveals velocity residuals indicating a large-scale spiral distortion.
- Such spirals ("velocity kinks") deviate significantly from pure rotation, suggesting the presence of an embedded giant planet interacting gravitationally with the gas disk.

ALMA Disk Survey (exoALMA)

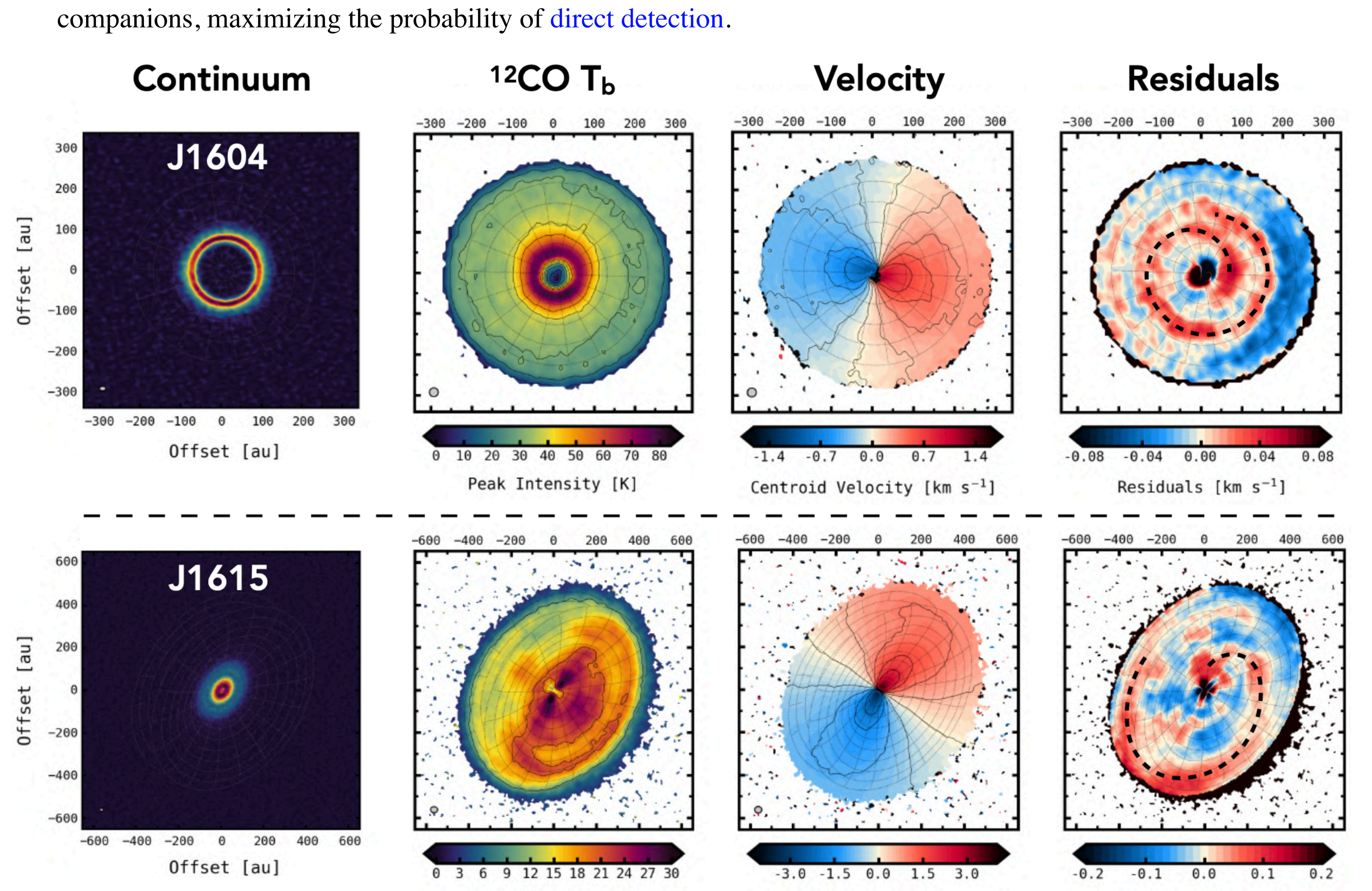
- Our targets were selected from the exoALMA Large Program, designed to study gas kinematics in protoplanetary disks at high angular resolution (~0.1″, corresponding to ~15 au).
- ALMA data revealed six disks (including our targets) exhibiting pronounced deviations from pure Keplerian rotation.
- These disks display characteristic annular gaps and rings in continuum emission (likely planet-induced), alongside non-Keplerian spiral flows in CO gas.

Planetary Interpretation

- Observed gas kinematic features closely align with theoretical predictions for planet-driven wakes.
- Hydrodynamic models suggest massive embedded planets (≥1 MJ) create spiral density waves, perturbing the local gas velocity.
- The exoALMA survey modeling infers giant protoplanets (~1–4 MJ) orbiting at radii between ~0.5″–1.8″.
- These candidate planets lie within the detection capabilities of our ERIS L-band imaging observations.
- Confirming these candidates through direct infrared imaging would validate ALMA's indirect detections and greatly advance our understanding of planet formation.

Why L-band?

- While ALMA kinematics strongly suggest planetary companions, infrared detections are necessary to directly measure these planets' thermal emissions (luminosity).
- Previous searches at shorter infrared wavelengths (H and K-band: 1.6–2.2 μm) have largely failed to detect planets due to dust obscuration.
- L-band imaging (~3.8 μm) penetrates dust more effectively, revealing thermal emission from young, embedded planets that remain hidden at shorter wavelengths.
- Protoplanets around 1–4 MJ at typical disk ages (few Myr) emit strongly at wavelengths ≥3 μm, making L-band imaging crucial.
- ERIS L-band imaging specifically targets regions already identified by ALMA as having potential planetary companions, maximizing the probability of direct detection.



Observational Program (VLT/ERIS)

Instrument & Setup

- Observations were performed with the NIX imager on VLT/ERIS at 3.8 μm (L-band). A newly commissioned focal-plane vortex coronagraph enabled deep suppression of stellar glare at close separations. Total integration times were approximately ~2.5 hours per target in the NGS mode.

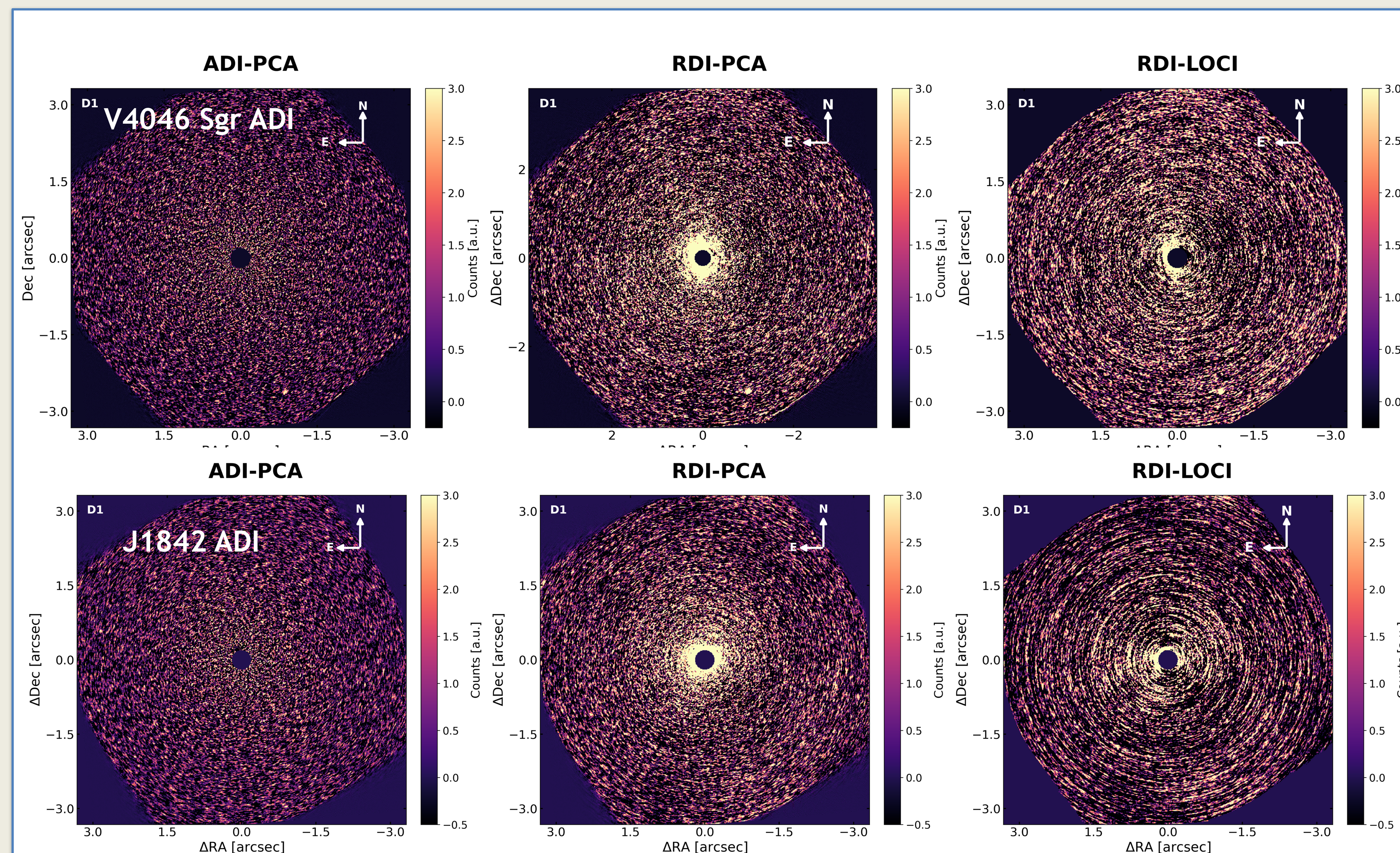
Target Sample

- Six planet-forming disks were initially selected as prime proto-planet candidates from the exoALMA survey: HD 143006, J1604, J1615, J1842 (WRAY 15-1880), J1852 (IRAS 18489–3703) and V4046 Sgr. We were allotted time for only for only three targets marked in blue.
- Each disk shows clear substructures and ALMA-detected kinematic indications suggesting embedded proto-planets.
- Reference stars of similar brightness were observed for calibration of the fainter targets.

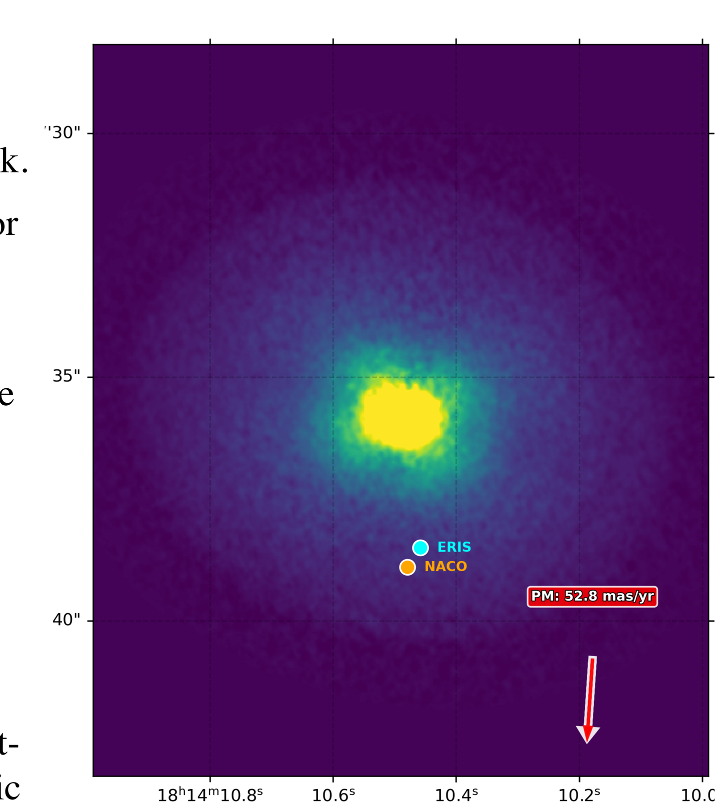
Adaptive Optics & Differential Imaging

- Brighter targets (J1842, V4046 Sgr) were observed using Natural Guide Star (NGS) adaptive optics with the coronagraph, analyzed through Reference star difference imaging (RDI).
- Field rotation during exposures allowed efficient subtraction of static speckle noise.
- Fainter disks (J1615), unsuitable for coronagraphic imaging, were observed without a coronagraph but used Reference Differential Imaging (RDI) technique with dedicated PSF reference stars.

Results

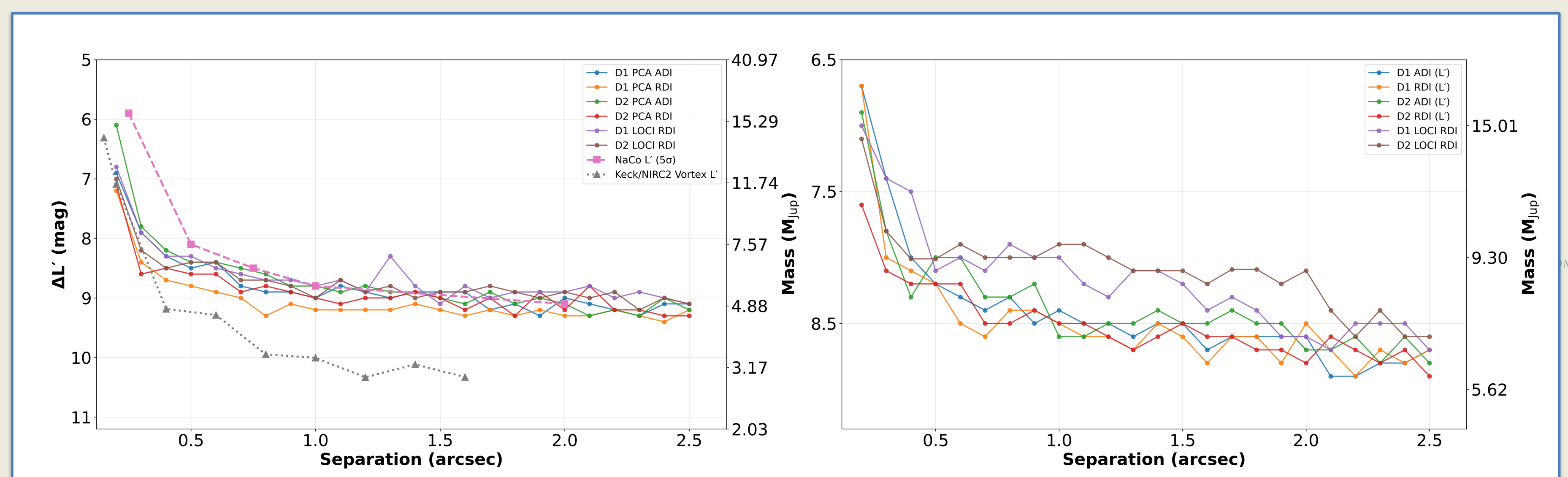


ADI vs RDI reductions



- We present the first ever ERIS images for these two targets in L-band.
- Coronagraphic image after post processing, with a 14-pixel central mask.
- We find that there is no significant disk signal in the ADI reductions. For the RDI reductions we find some faint disk signals in both the images.
- No obvious point source is visible in both ADI and RDI reductions.
- It is important to note that the airy ring in both the science and reference PSF was not symmetric so some minor artefacts can be due to non-symmetric PSF subtraction.
- Our disk rotation was also quite low ~ 17 degrees and thus we need a dataset with much larger rotation to distinguish the actual disk signals from PSF subtracted noises.
- ALMA kinematics imply ≥ 1 MJ planets in these disks; such planets should have been visible at our achieved sensitivity if they followed hot-start luminosities.The non-detections suggest either much lower intrinsic luminosity ("cold-start" formation) or significant dust obscuration even at 3.8 μm.
- We see a bright background source ~ 8.8 mag contrast in the southwest part of the disk. We find that this source is inside the ALMA 13CO-moment map and also seen in previous NACO images.

Where are the planets ?



Contrast Curve Estimates

- We estimate the first ever contrast curve of J1842. The corresponding planet masses quoted here for both V4046sgr and J1842 are from AMES-COND model.
- We didn't find any new planets in the system as was expected from the Exo-Alma data.
- The absence of bright IR detections supports "cold-start" formation scenarios or substantial local dust extinction (e.g., in circumplanetary material).