Hunting for young planets at the inner rim of protoplanetary disks

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I. Context and aims

Inner rim is the terminal evaporation front of dust grains irradiated under a high incidence angle. The rim overlaps with a viscosity transition (the MRI operates inwards; the disk is 'dead' outwards). The transition leads to a drop in the surface density that can trap migrating planets or prevent a loss of planets formed in situ (Masset et al. 2006, Flock et al. 2019).

Q: Can we detect traces of planet-induced perturbations (gaps) at the inner disk rim using the VLTI?

II. Radiative hydrostatic models

We reimplemented the model of Flock et al. (2016, 2019) in Fargo3D#. It iterates between a hydrostatic gas-dust distribution and a thermal disk-radiation equilibrium. Stellar irradiation and flux-limited diffusion are considered. A viscous disk with a uniform mass accretion rate is assumed.

Main parameters:

- **HD 163296:** $M_\star = 1.95\,M_\odot$, $L_\star \simeq 21\,L_\odot$, $M_{acc} = 3.24 \times 10^{-8}\,M_\odot\,yr^{-1}$
- α viscosity: 10^{-2} in the MRI zone, 10^{-3} in the dead zone, $T_{MRI} = 900$ K
- Dust-to-gas ratio of sub-μm (opacity-dominating) grains: 10^{-3}
- Planet positioned just outside the surface density drop, the **planet-to-star mass ratio *q* is a free parameter.**

Gap profile of Duffell (2020) was adopted as a disk perturbation. The gap gets deeper/wider with increasing q, decreasing α, and decreasing aspect ratio H/r (H being the pressure scale height).

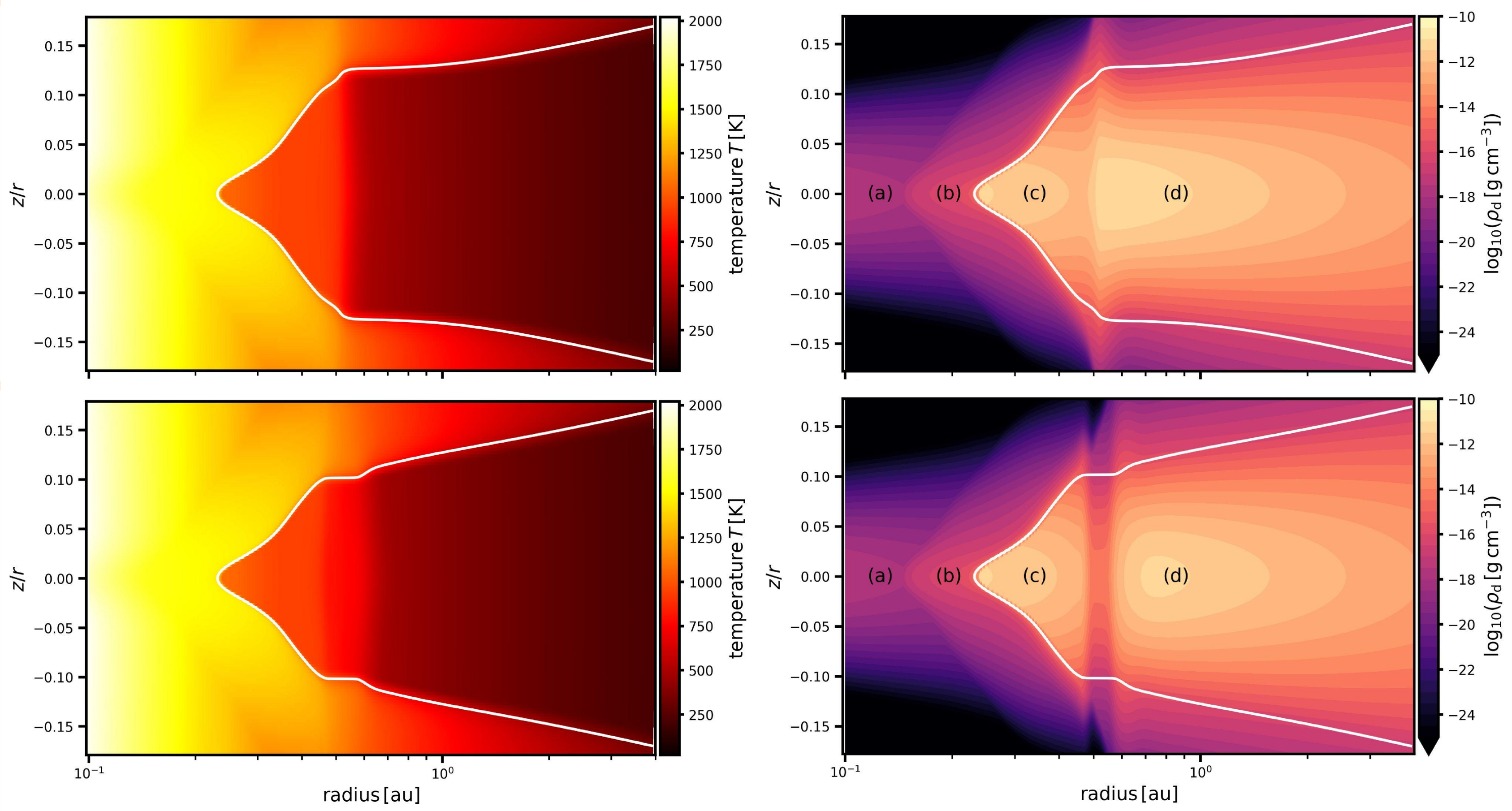

Fig. 1: Temperature (left) and dust density (right) at the inner rim of HD 163296 with no perturbation (top) and a gap (bottom) induced by a hypothetical $q = 3 \times 10^{-4}$ planet located at 0.52 au. The white curve is where the optical depth with respect to stellar irradiation reaches $\tau = 1$.

III. Synthetic images

Dust distributions from Sect. II were fed into the RADMC-3D## code to derive the intensity maps of gapped stellar-irradiated disk rims. For deep enough gaps, the gap centre is dark (shadowed) and a **secondary ring of dust emission appears at the outer gap edge.**

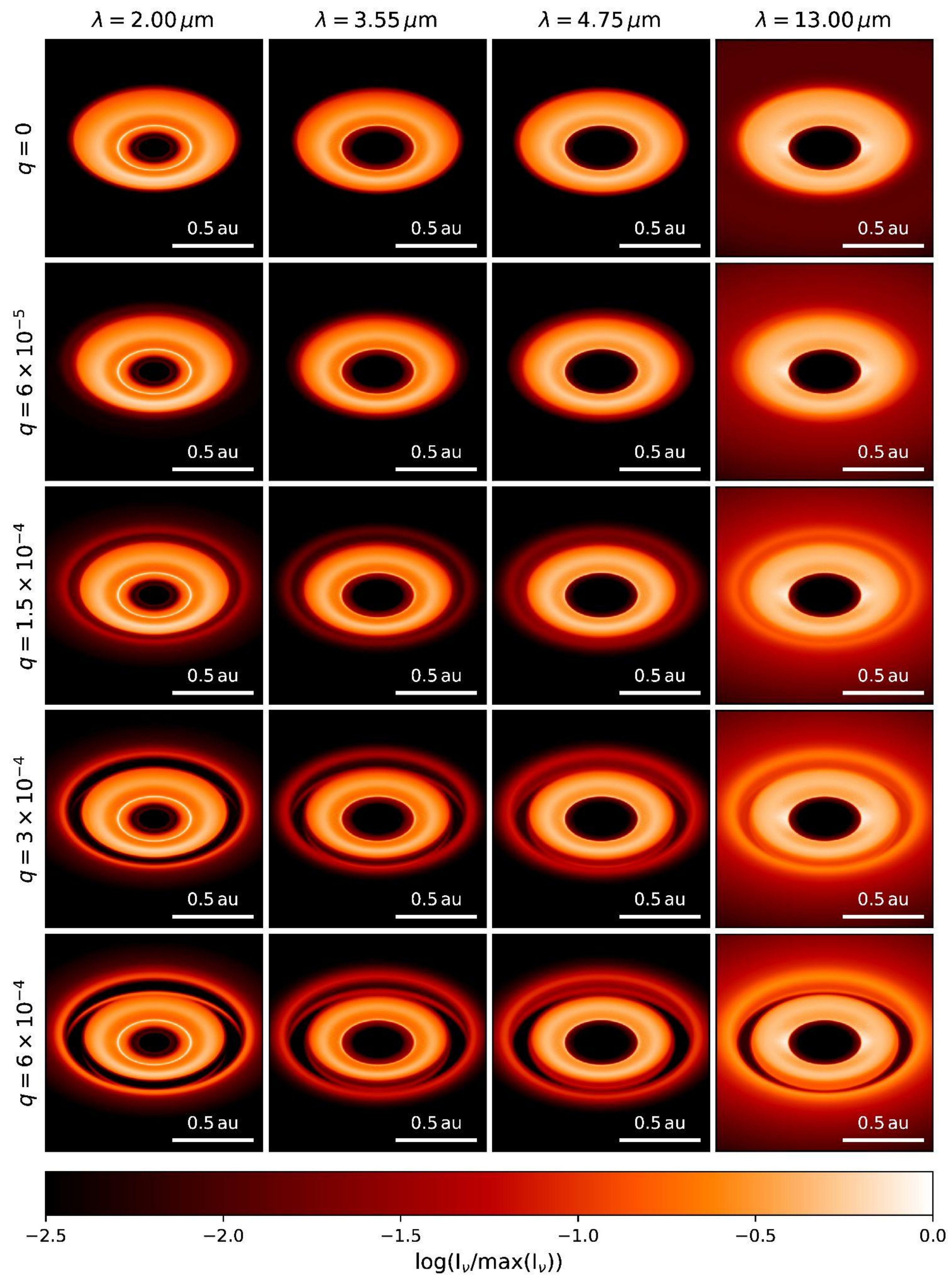

Fig. 2: Normalized monochromatic emission intensity obtained by **Monte-Carlo radiative transfer simulations** for **different wavelengths (columns)** and **mass ratios (rows)**. **HD 163296** is viewed at the inclination of 52 degrees and the respective planet masses (top to bottom) are **0, 39, 97.5, 195 and 390 M_E**. The VLTI bands are H and K (first column), L (second column), M (third column) and N (fourth column). The displayed disk region covers ±0.7 au.

IV. Morphological fitting (work in progress)

Images from Sect. III were used to perform simulated VLTI observations.

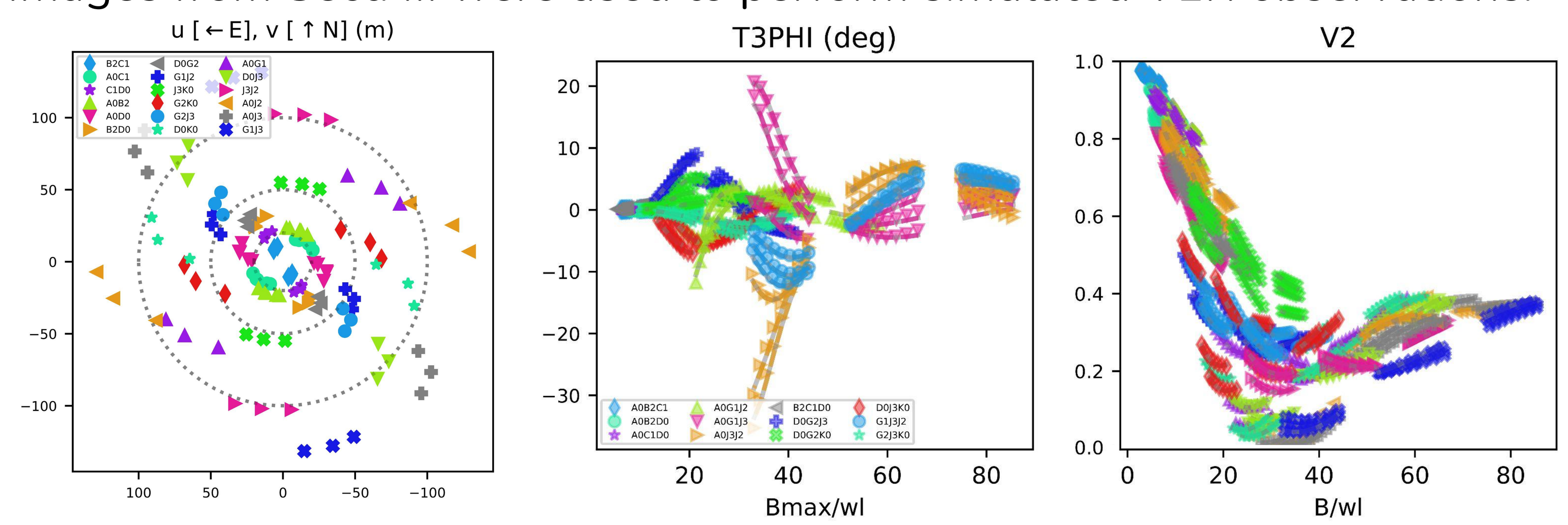

Fig. 3: Interferometric data based on the synthetic image with no planet ($q = 0$). Left to right: Coverage of the (u,v) plane, phase closure, visibility squared.

With a realistic coverage of the (u,v) plane, the **interferometry is sparse** (no image reconstruction) **and needs to be fitted with a morphological model**. The fit considers three bands H, K, L (1.5–4 μm), an unresolved star, a gaussian ring with two FWHMs and an azimuthal variation.

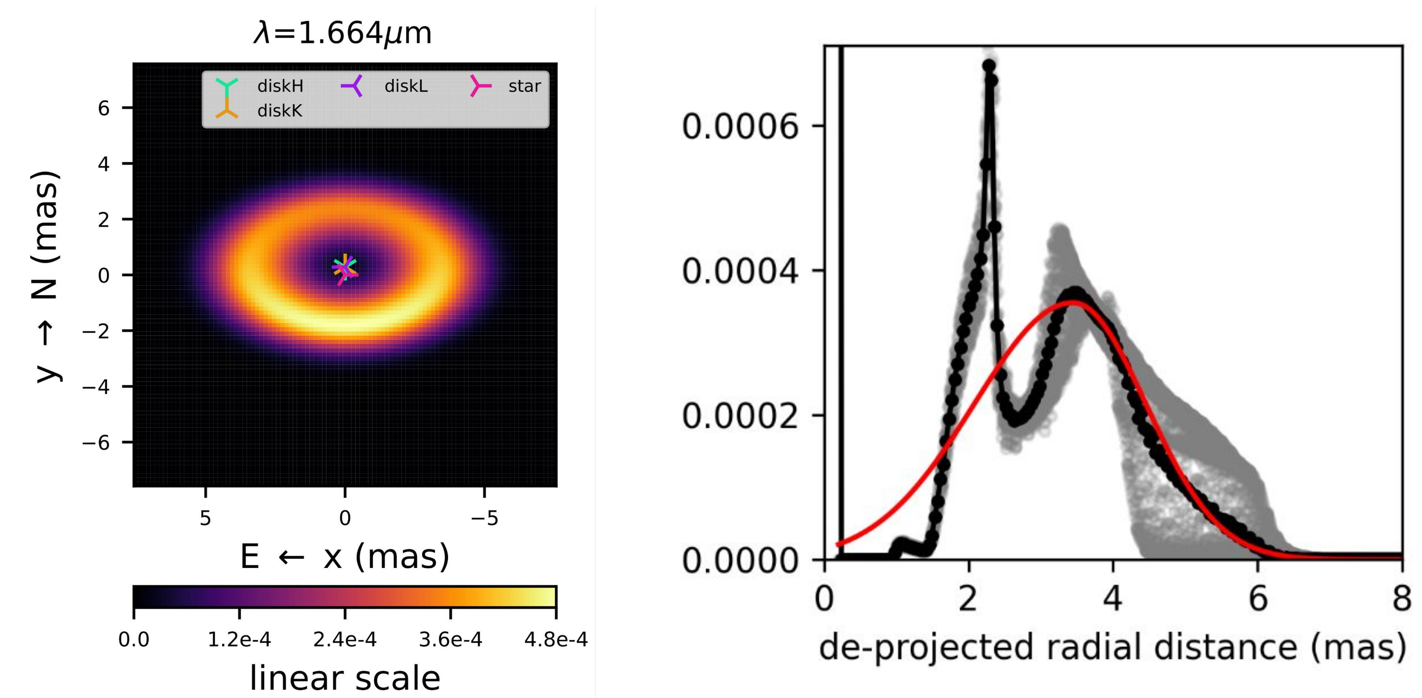

Fig. 4: Morphological fit in the H band (left) and its de-projected radial profile (right, red curve) compared to the physical model (right, black curve) for the case with $q = 0$. **Problem of the fit:** The extent of the rim is correct but the shape of the inner edge is not. **Problem of the physical model:** Too low total near-infrared flux when computing the SED. Improvements needed...

V. Summary

- With a planet-induced gap, main features of the inner rim (see Flock et al. 2016, 2019) still remain in place; more prominent perturbations can appear if the parking location of the planet shifts inwards.
- **Two emission rings appear for $q \gtrsim 1.5 \times 10^{-4}$ (~100 M_E).**
- **The minimal planet mass leading to the double-ringed emission can be even lower,** e.g.
  - ~40 M_E when $\alpha = 10^{-4}$ in the dead zone,
  - ~20 M_E when modeling T Tauri stars.
- Finding reliable predictions for the VLTI observations requires improved morphological fits for the unperturbed rim first.

Fargo3D can be downloaded at https://bitbucket.org/fargo3d/public/

RADMC-3D can be downloaded at https://www.ita.uni-heidelberg.de/~dullemond/software/radmc-3d/

Acknowledgment: This work was supported by the Czech Science Foundation (grant 21-23067M), the Charles University Research program (No. UNCE/SCI/023) and the Ministry of Education, Youth and Sports of the Czech Republic through the e-INFRA CZ (ID:90140, LM2018140).