Planet-driven dusty substructure in ALMA disks

how dust growth and dynamics change the picture

Alex Ziampras[1,2], P. Sudarshan[3], C. P. Dullemond[4], M. Flock[3], V. Berta[5], R. P. Nelson[1], A. Mignone[5]

[1]QMUL, London, UK — [2]LMU, Munich, DE — [3]MPIA, Heidelberg, DE — [4]ITA, Heidelberg, DE — [5]UniTo, Turin, IT

Planets as the cause of substructure

Substructure is ubiquitous in Class-II protoplanetary disks in millimeter (mm) **continuum** emission [1], and popularly attributed to **unseen planets**. Planets can robustly generate **gaps** and **vortices** in the gas, **trapping** dust grains and forming bright **rings** and **crescents** in mm emission [2]. In the cold outer disk, these trapped mm grains contribute to both the dust **mass and opacity**, and especially so during **dust growth** and within pressure traps. We investigate how these effects **influence the features shaped by planets**.

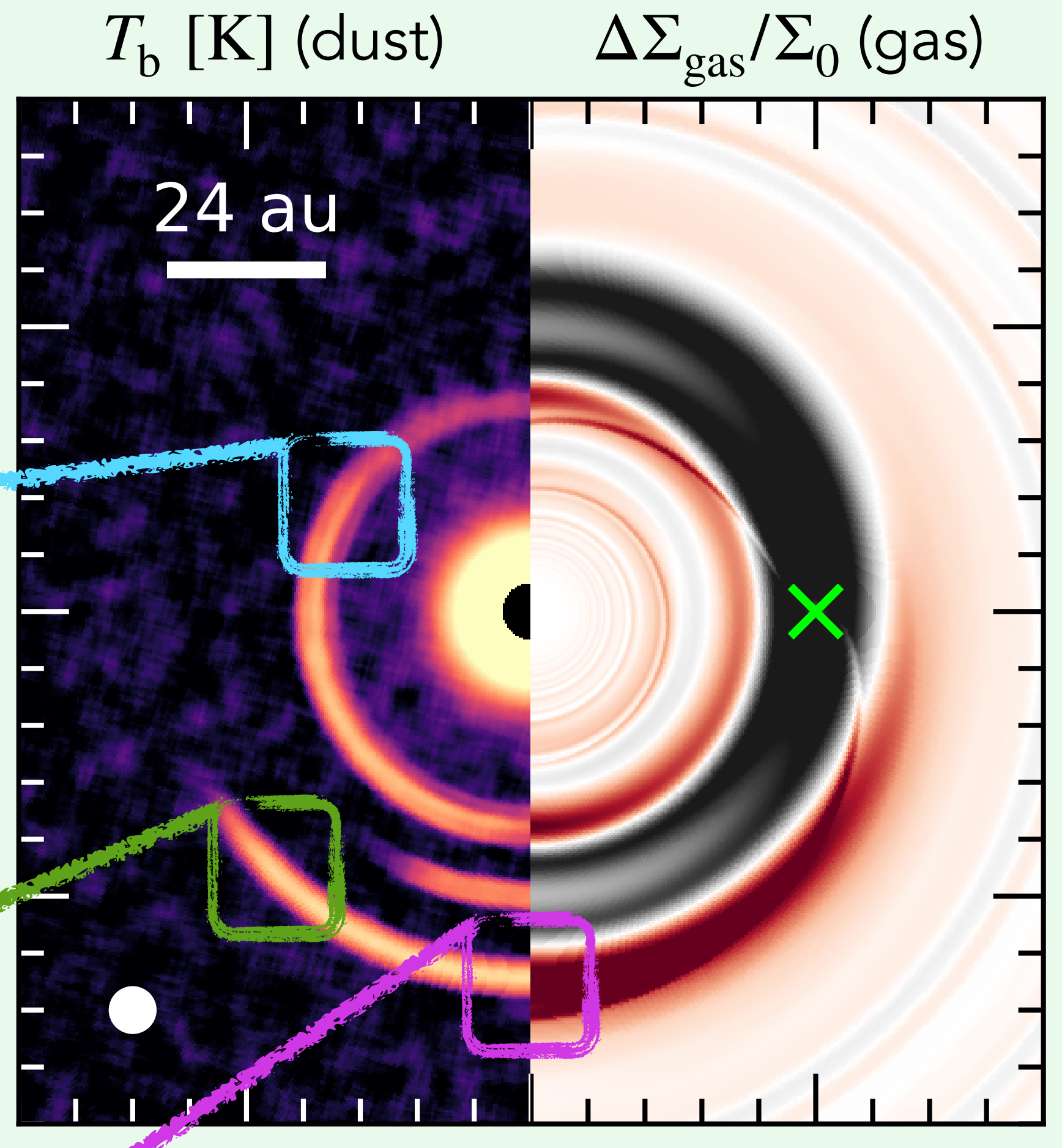
Methods: radiation hydrodynamics

We perform 2D RHD (irradiation, cooling, radiative diffusion [3]) simulations with PLUTO [4], including a **planet** and **dust–gas** interaction at different stages of **dust growth**, with a **time-** and **dust size-dependent opacity model**.

Why dust evolution matters

Even though dust amounts to ~1% of the total disk mass, it determines the **cooling efficiency**, the **brightness** of observed substructure in mm, and even interacts with the gas **aerodynamically**.

Fig. 1: Disk state after 0.26 Myr in the fiducial model. An × marks the planet.



momentum exchange between dust and gas (***backreaction***) can help **dissolve vortices** into rings

dust growth results in more large (mm) grains and **brighter substructure** in mm

trapping mm grains enhances the local ***opacity***, affecting **cooling/gap opening**

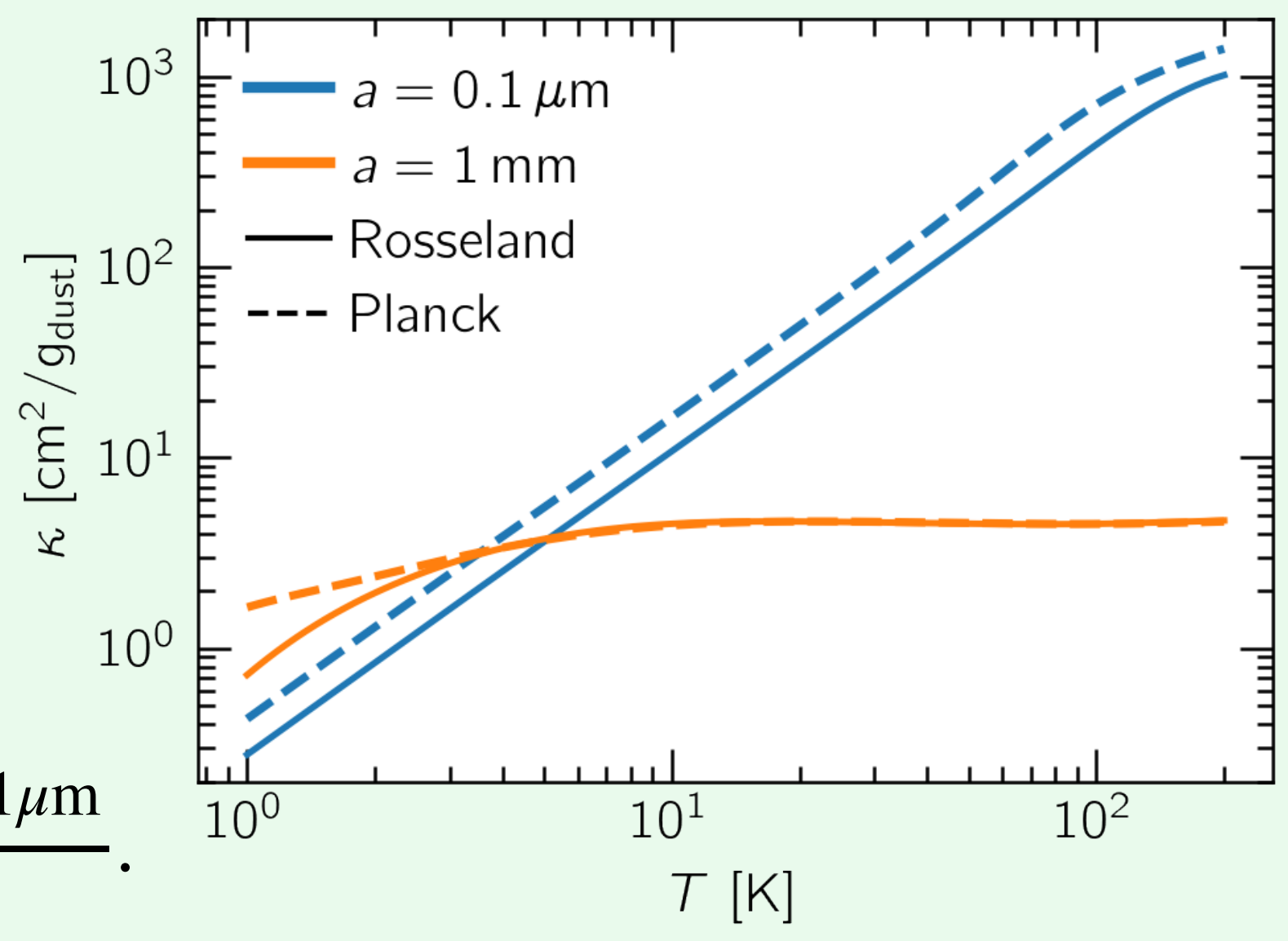


Fig. 2: Our opacity model, with $\kappa_{\rm dust} = \dfrac{\Sigma_{\rm mm}\kappa_{\rm mm} + \Sigma_{0.1\mu m}\kappa_{0.1\mu m}}{\Sigma_{\rm mm} + \Sigma_{0.1\mu m}}$.

Main results: two mechanisms with opposite effects near dust traps

All models here assume 90% dust growth, or a dust-to-gas ratio of {0.1%, 0.9%} for {0.1μm, mm} grains.

- **Opacity feedback** due to trapped dust renders the flow optically thick, driving **baroclinic forcing** which strengthens and compacts azimuthal features such as vortices [5].
- **Backreaction** acts to diffuse azimuthal features, spreading them into **rings** [6].
- Their combined effects result in a **very different** disk state compared to a fiducial model.

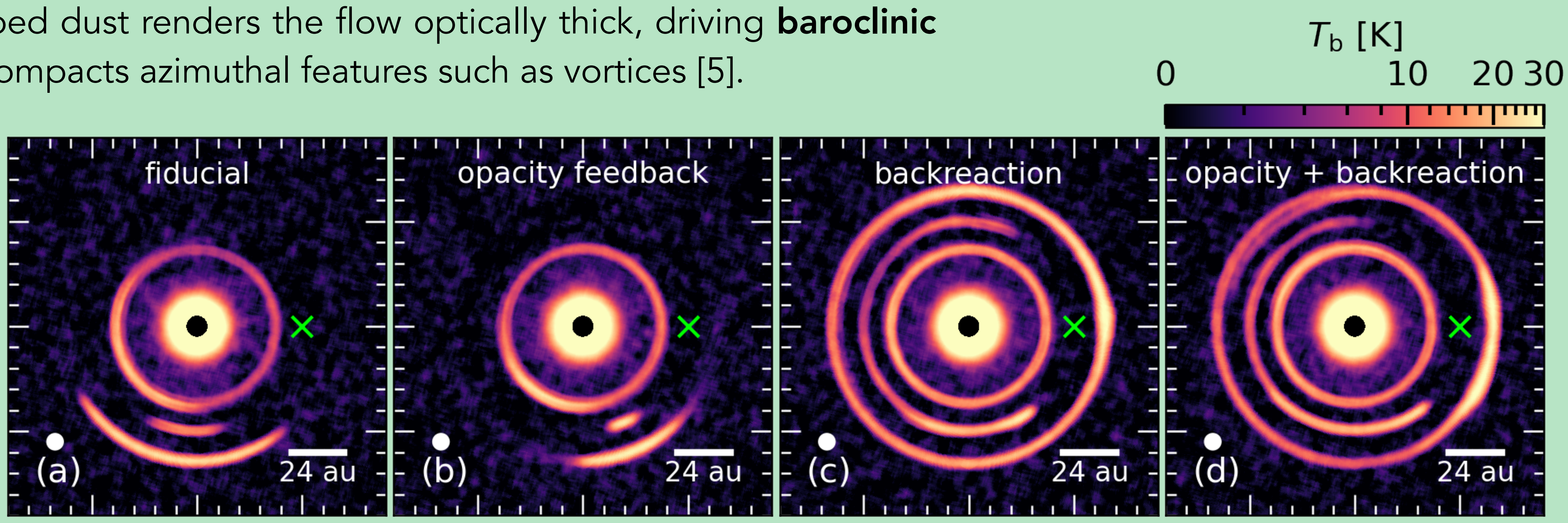
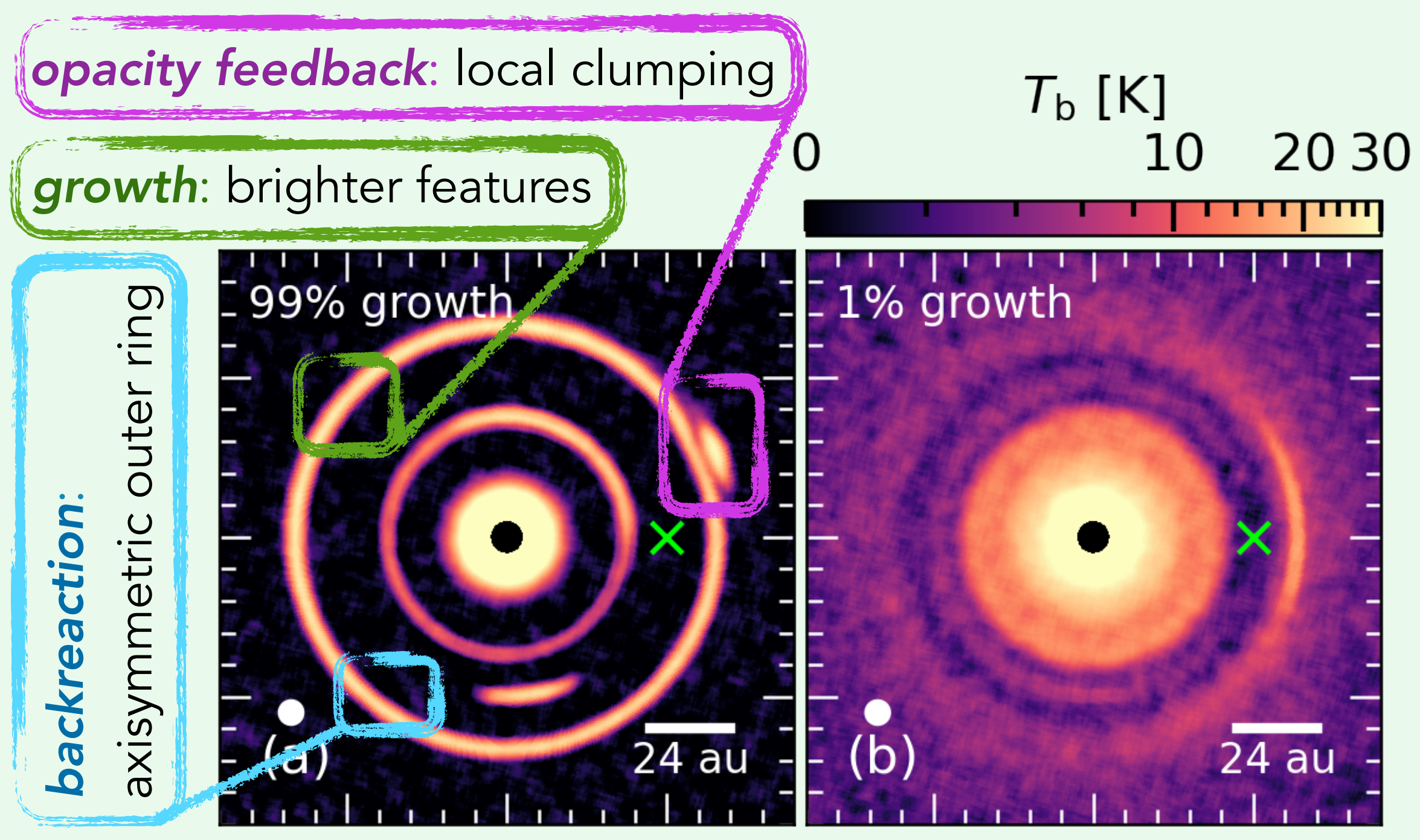


Fig. 3: Brightness temperature similar to Fig. 1, highlighting the effects of opacity feedback and backreaction.

A mix of rings and vortices

Both effects are amplified at later stages of dust growth, and very weak early on.



opacity feedback: local clumping

growth: brighter features

backreaction: axisymmetric outer ring

Fig. 4: Similar to Fig. 3 panel d, at different "ages".

Dust dynamics with PLUTO

A second-order explicit and a first-order implicit dust–gas drag solver, now tested and publicly available!

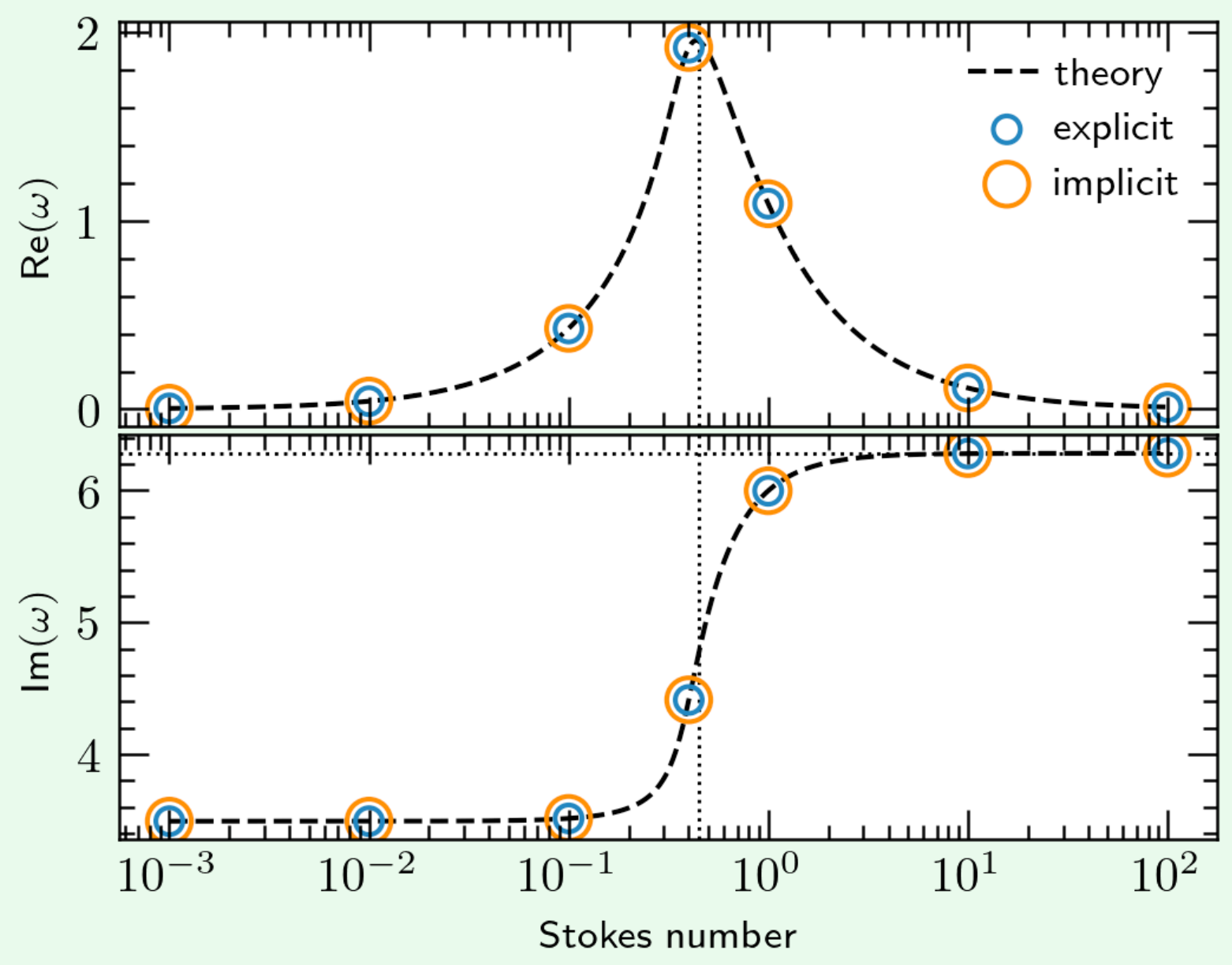


Fig. 5: Linear dust–gas coupling test.

Summary

As mm dust accumulates on planet-driven features (e.g., rings, vortices):

- **aerodynamic drag** diffuses non-axisymmetric features into rings
- trapped dust **enhances the local opacity**, compacting vortices
- **dust growth** amplifies both effects.

These processes can **coexist**, creating interesting patterns of substructure!

References

[1] Andrews et al. (2018) — **[2]** Zhang et al. (2018) — **[3]** Ziampras et al. (2023)
[4] Mignone et al. (2007) — **[5]** Petersen et al. (2007a, b) — **[6]** Lovascio et al. (2022)

About me

Link to paper:

Alex Ziampras [he/him] — Postdoc at LMU, Munich
✉ `a.ziampras@lmu.de` 🌐 `alexziab.github.io`