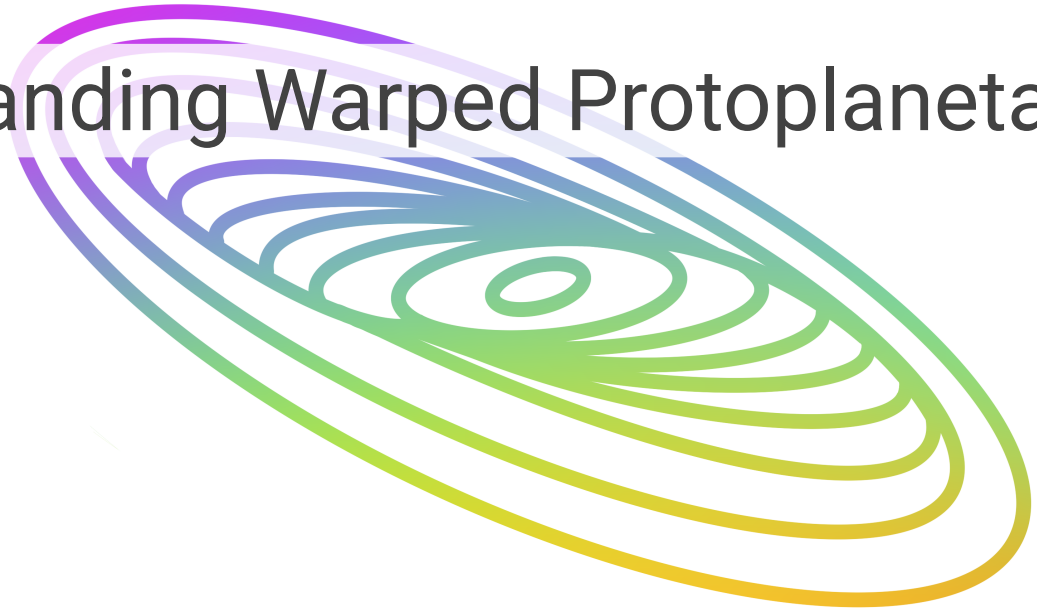
Inclined to Misalign

Understanding Warped Protoplanetary Disks



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Postdoc

University of Milan
Group of Giovanni Rosotti

Flatiron Workshop on
Hydrodynamic and Dusty Turbulence
in Protoplanetary Disks

February 4th 2026

Fondazione CARIPLO

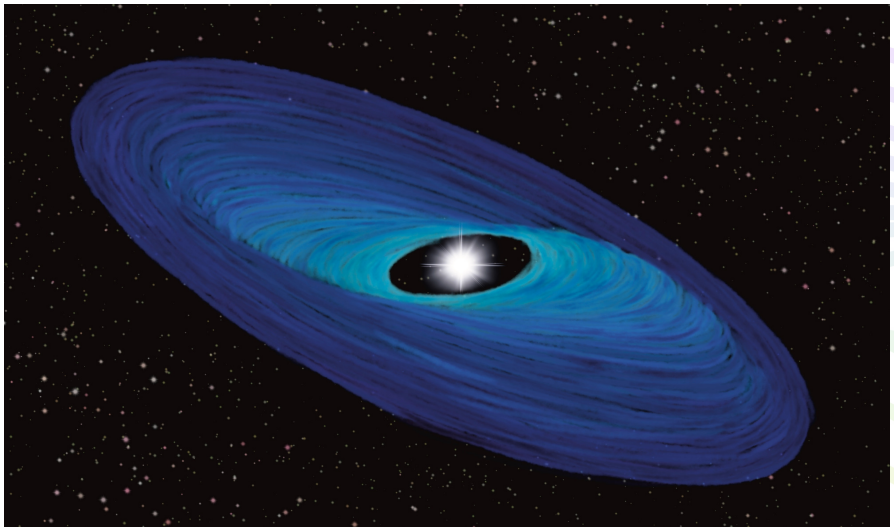
Structure

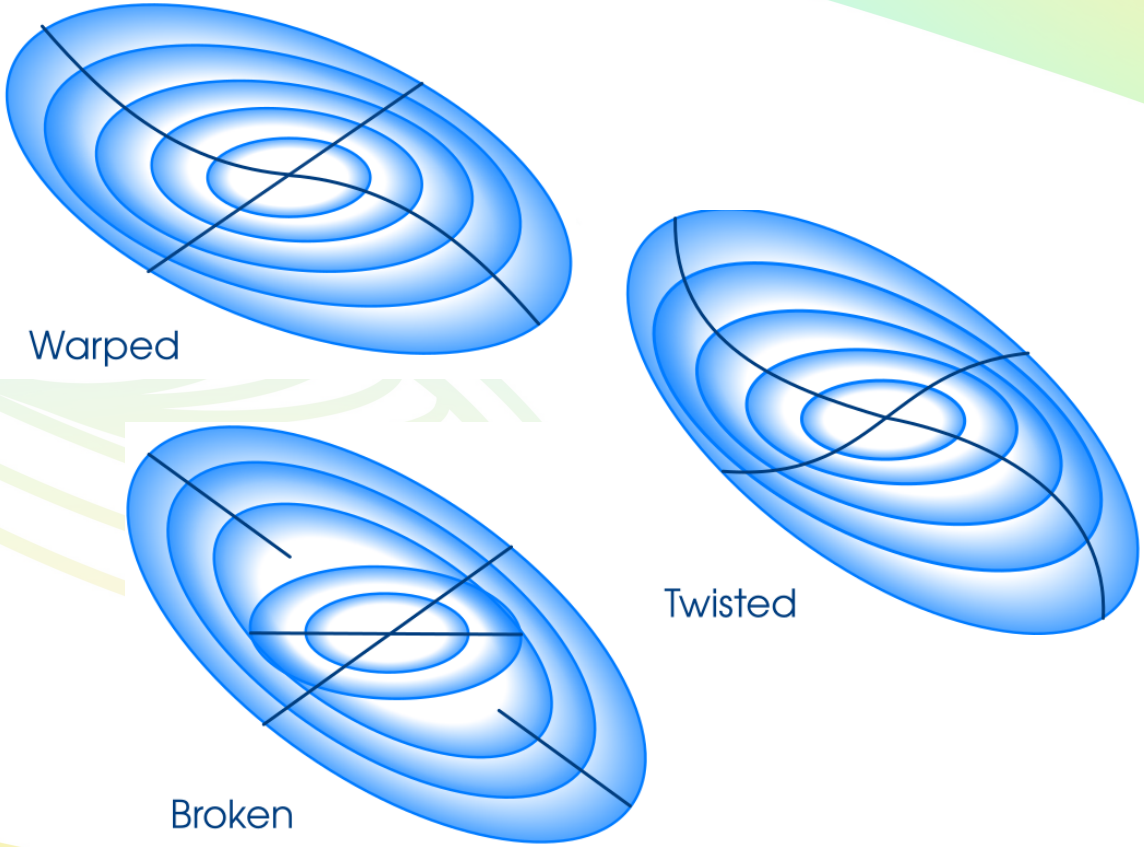
1) Warped disks and observational signatures

2) Evolution of warps

3) Grid-based 3D hydrodynamic simulations of warps

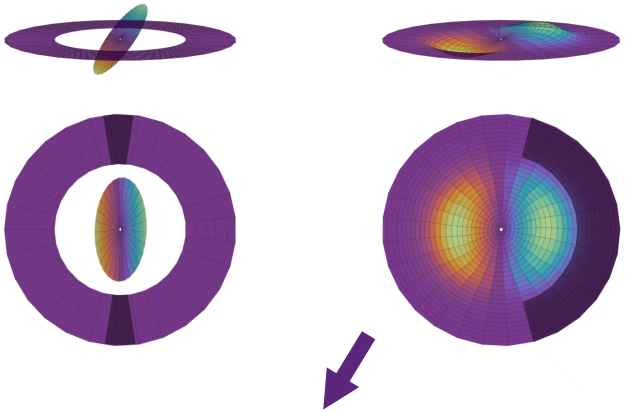
Warped disks

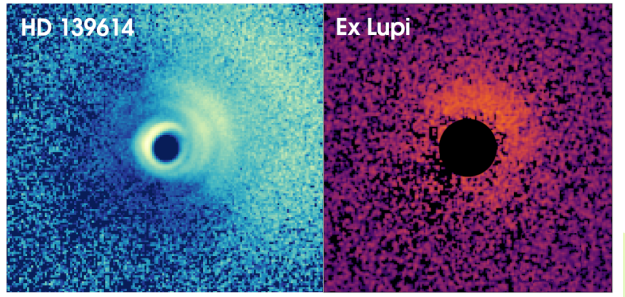




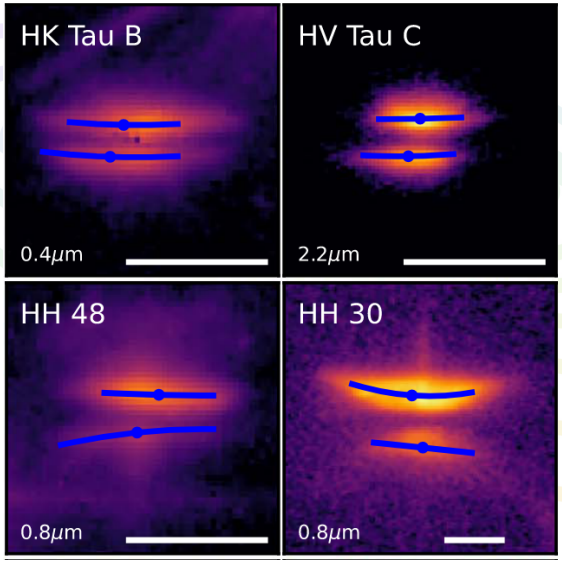
Observations of warps

Shadows

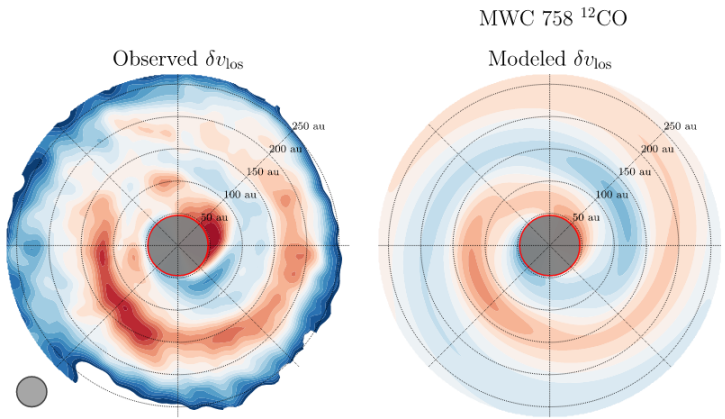




Asymmetries

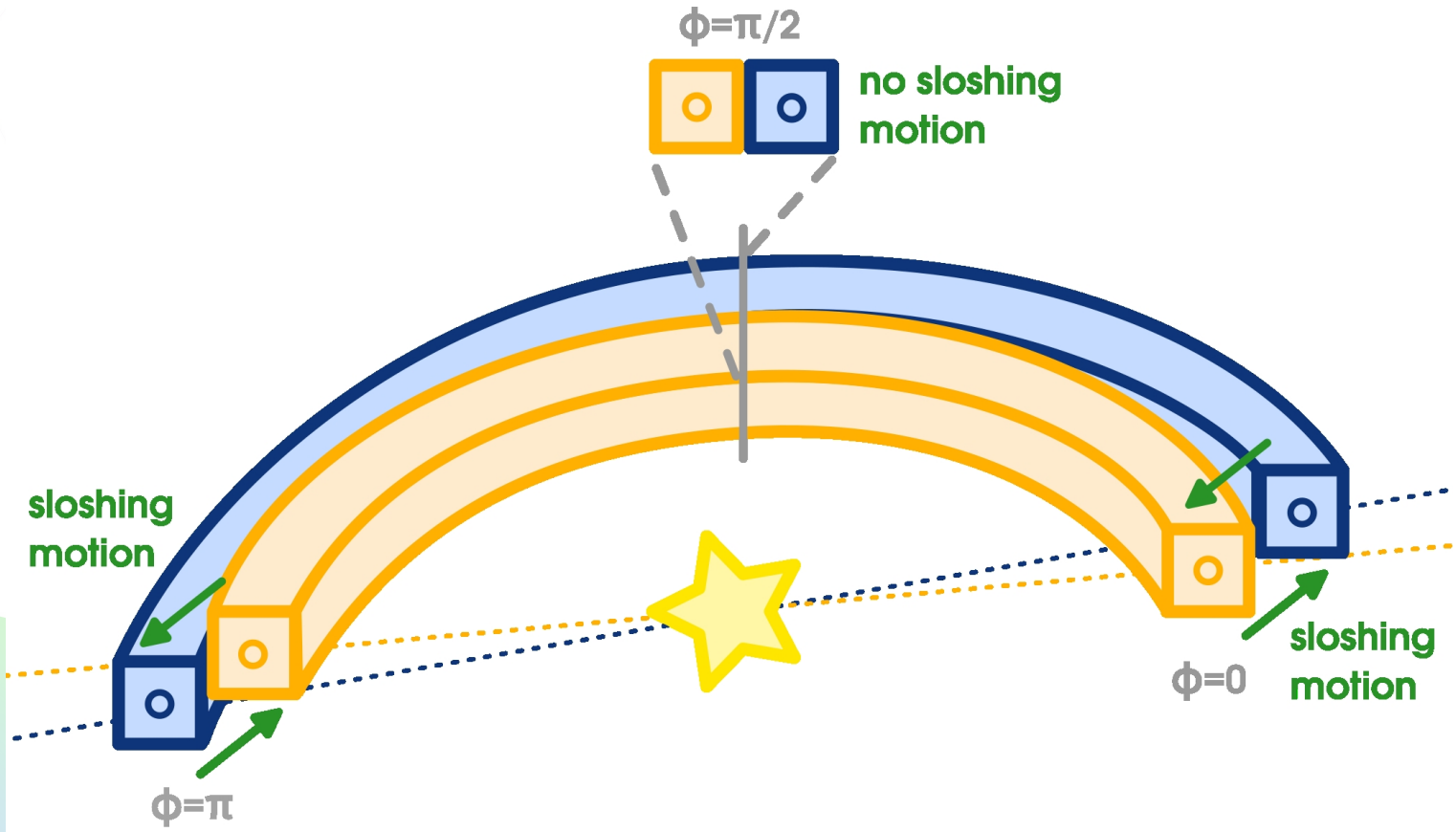


Kinematics

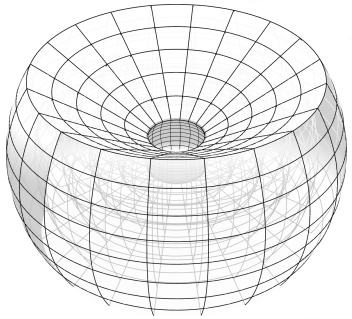


Shadows: Muro-Arena et al. 2020
Zurlo et al. 2024
Asymmetries: Villenave et al. 2024
Kinematics: Andrews et al. 2025

Evolution of warps



Grid-based simulations

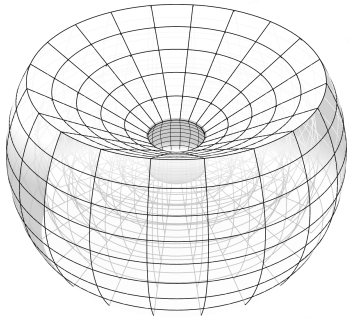


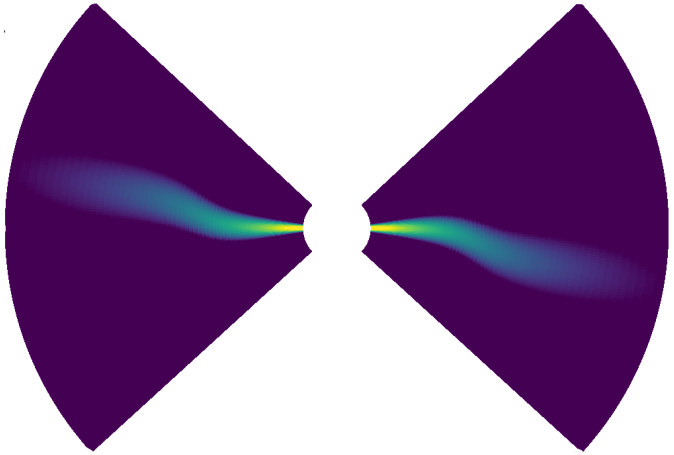
- advantage over SPH (Smoothed Particle Hydrodynamics):
  models of low-viscosity disks possible!

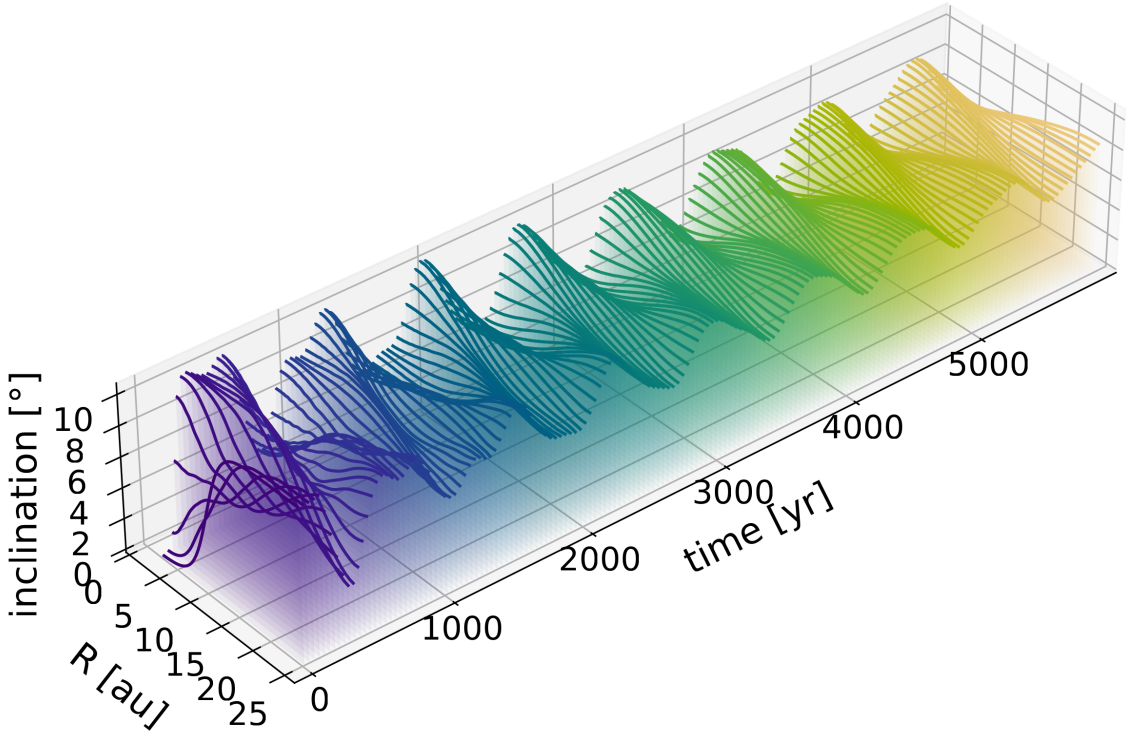
- BUT: grid effects
  → spherical coordinate system
  → resolution in vertical direction needs to be high enough

Kimmig et al. 2024

Grid-based simulations

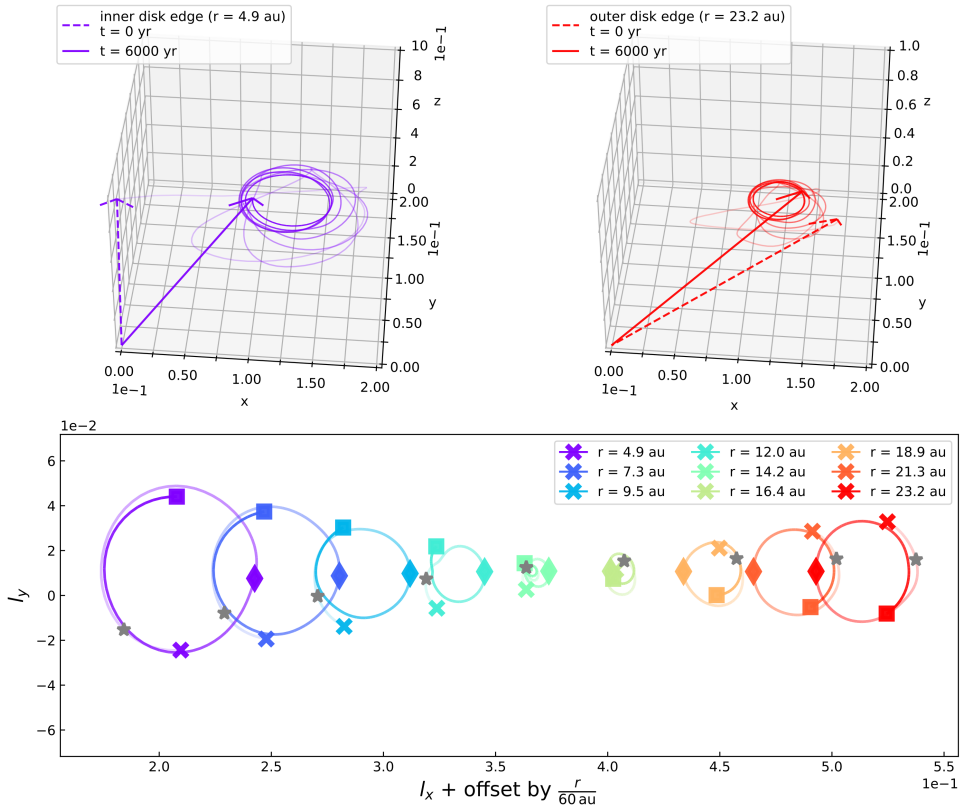


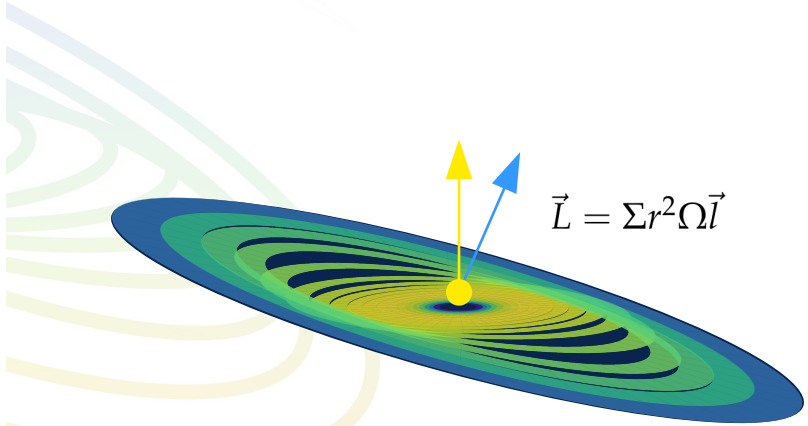




Kimmig et al. 2024

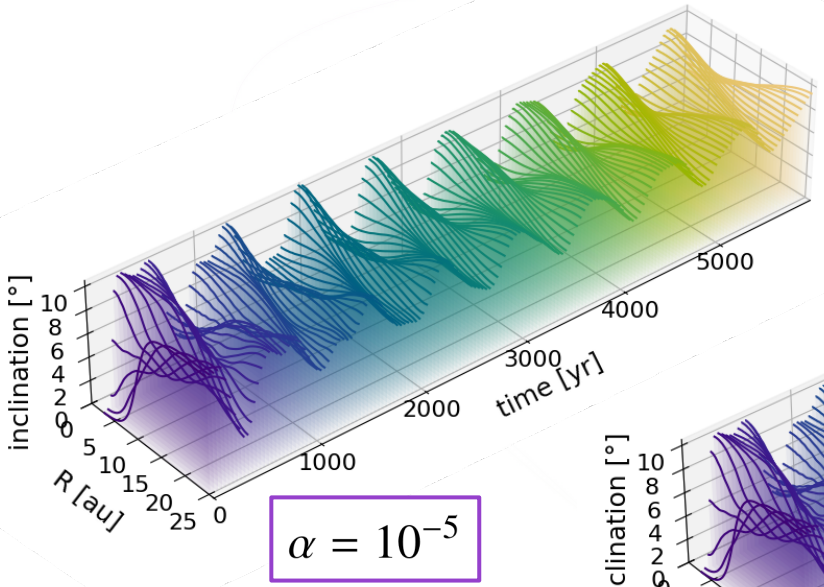
Grid-based simulations: internal precession

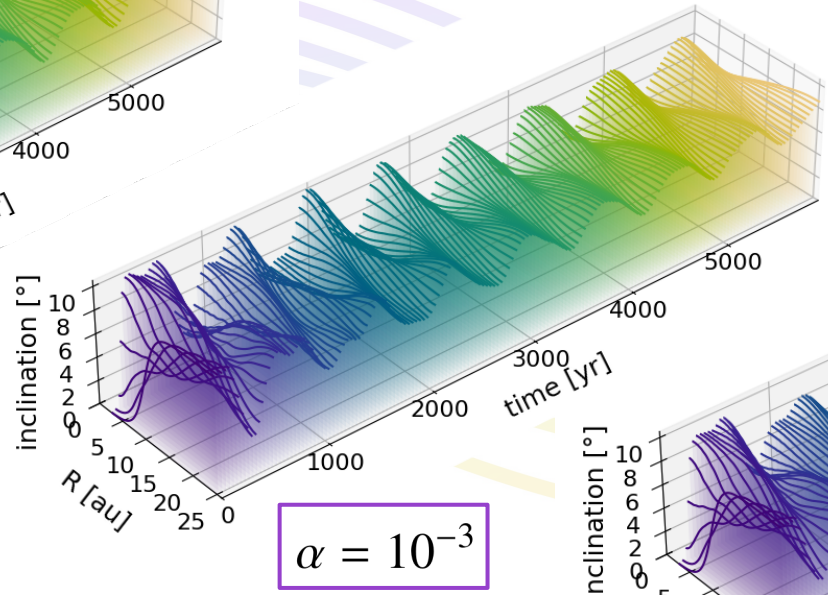


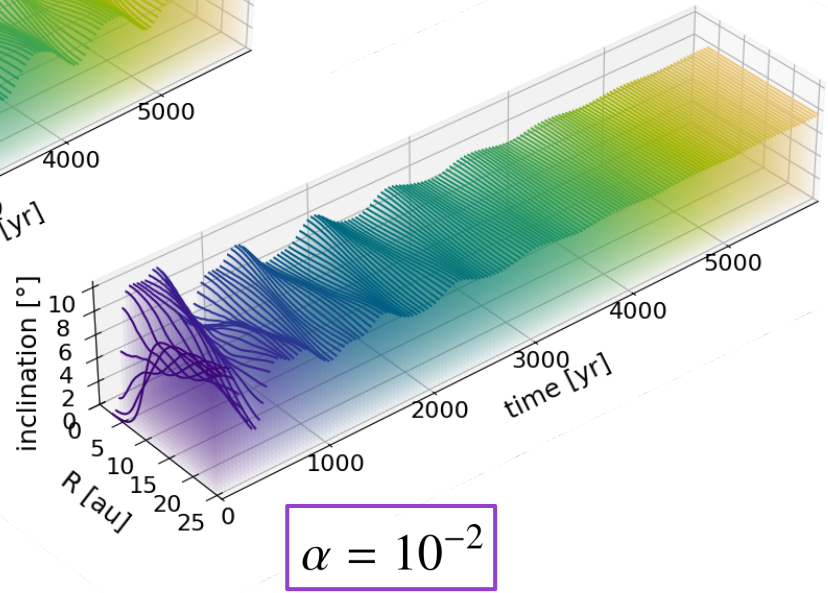


Kimmig et al. 2024

Grid-based simulations: viscosity

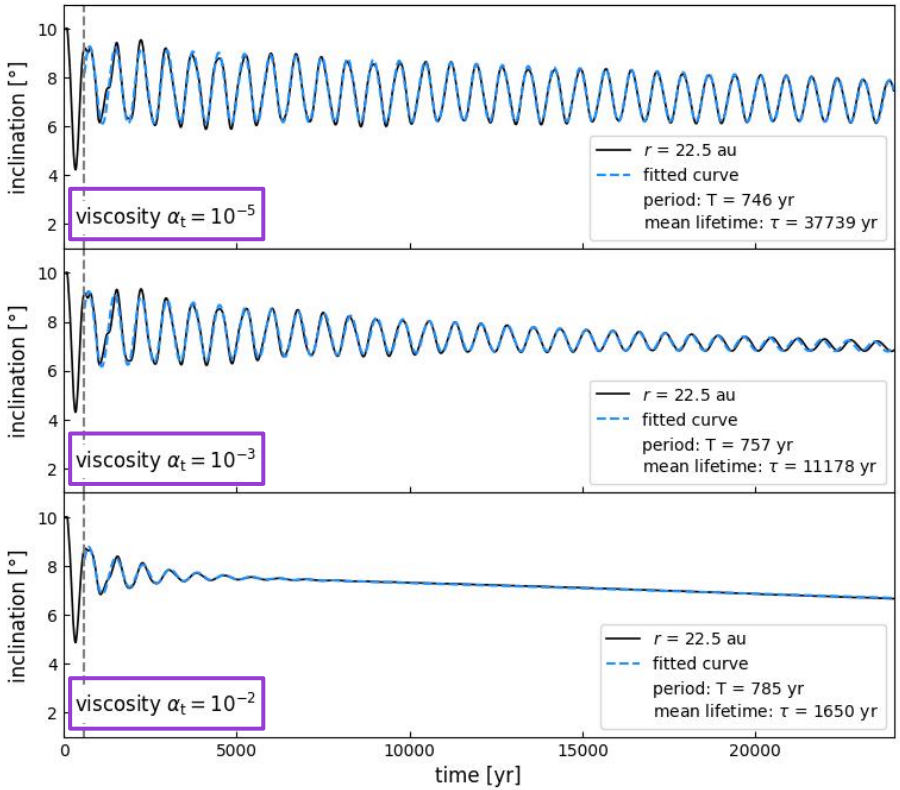


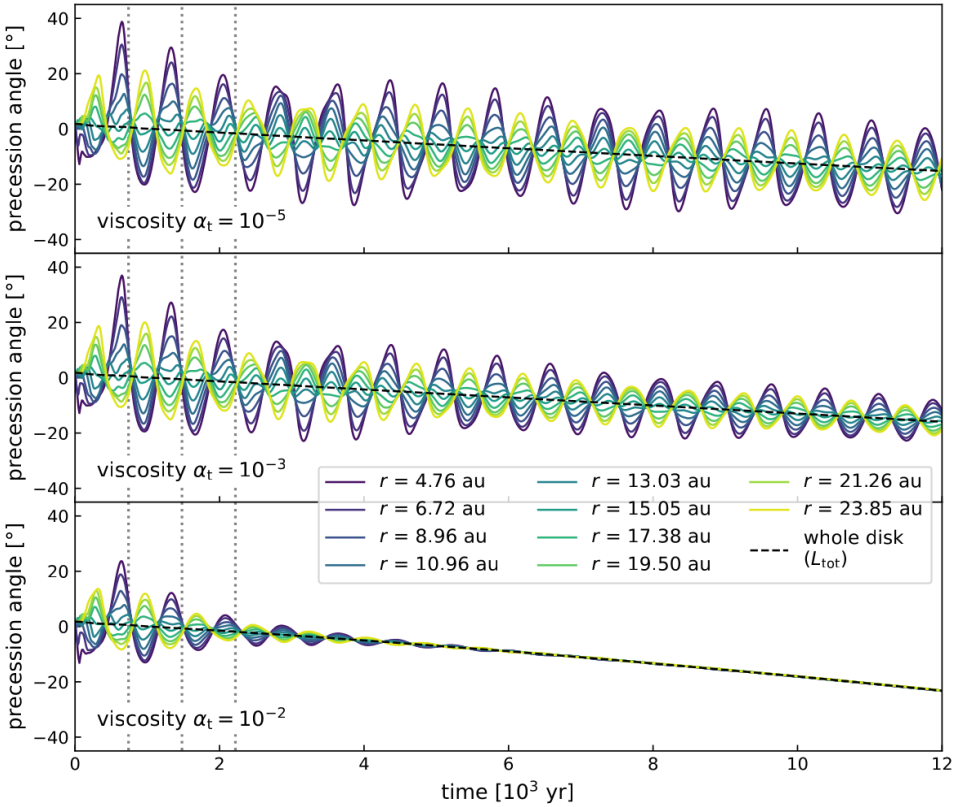




Kimmig et al. 2024

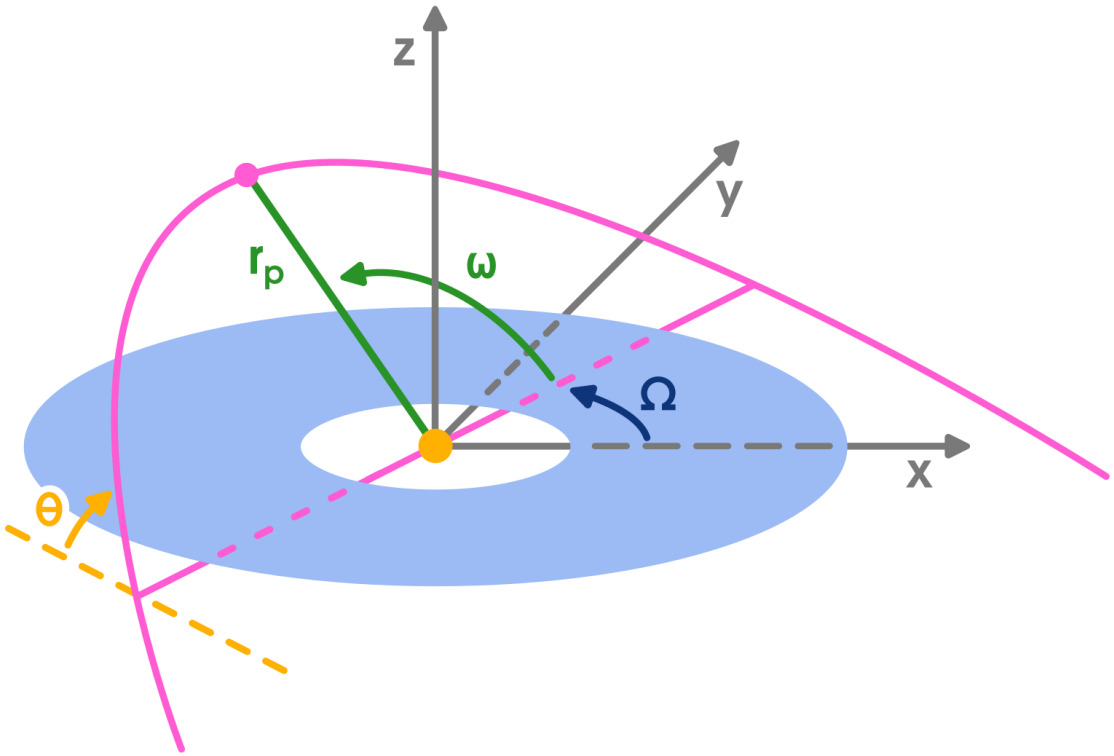
Grid-based simulations: viscosity





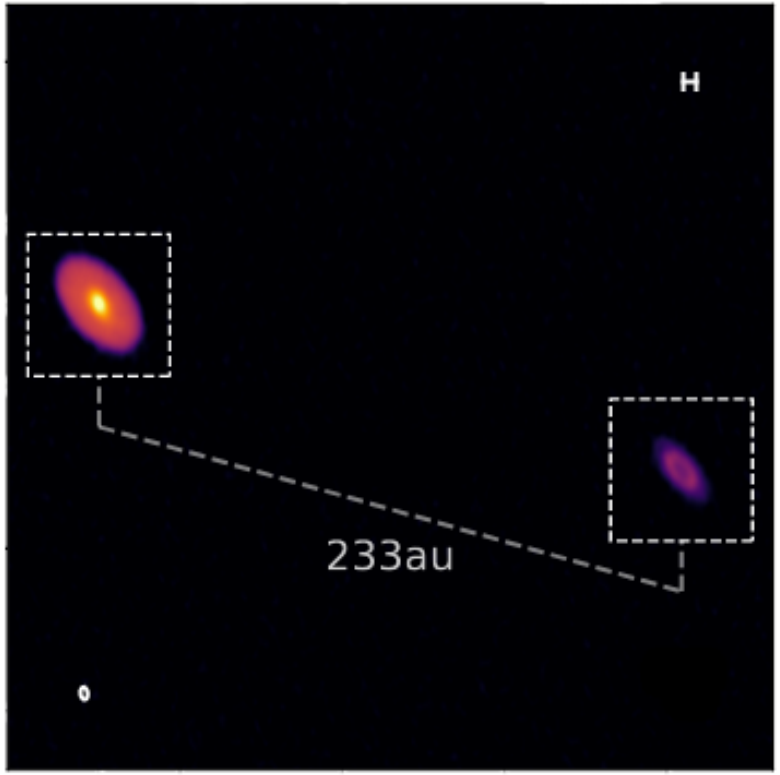
Kimmig et al. 2024

Stellar fly-by warping the disk



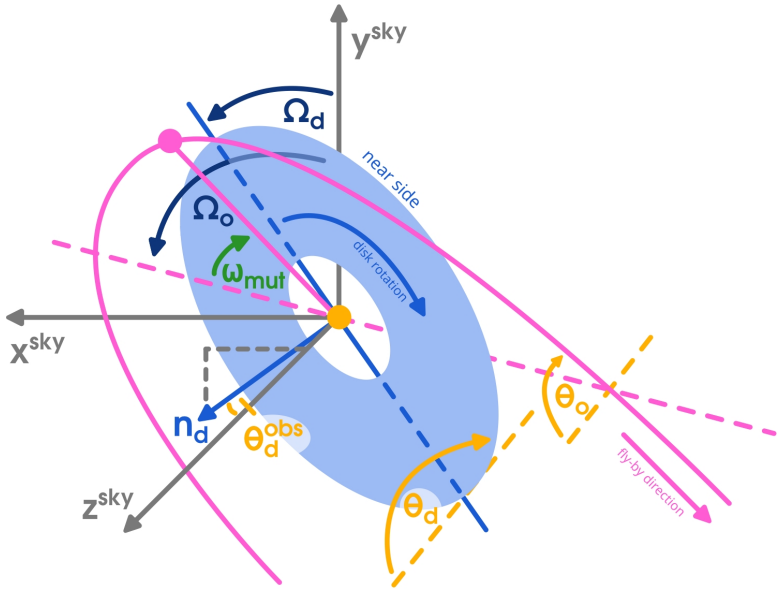
Kimmig et al. 2026

Fly-by in the RW Aur system



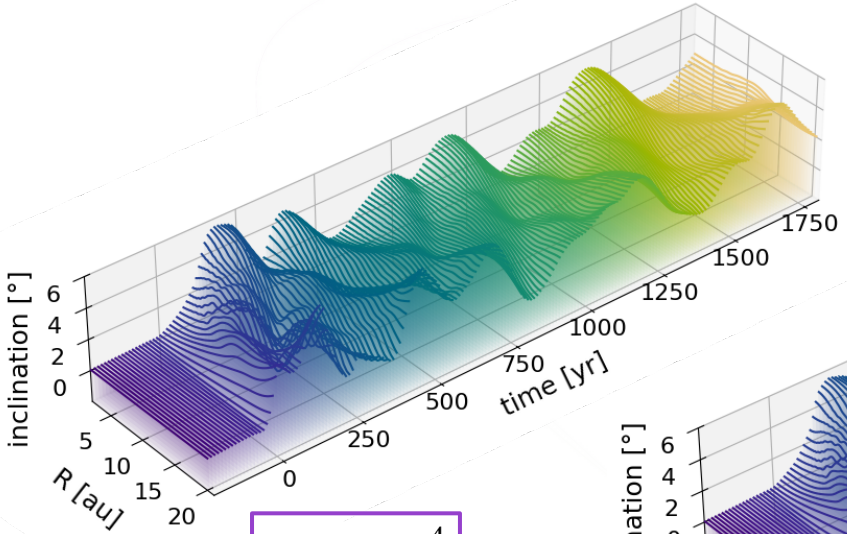
Kurtovic et al. 2024

recent close encounter
(300 yr ago)

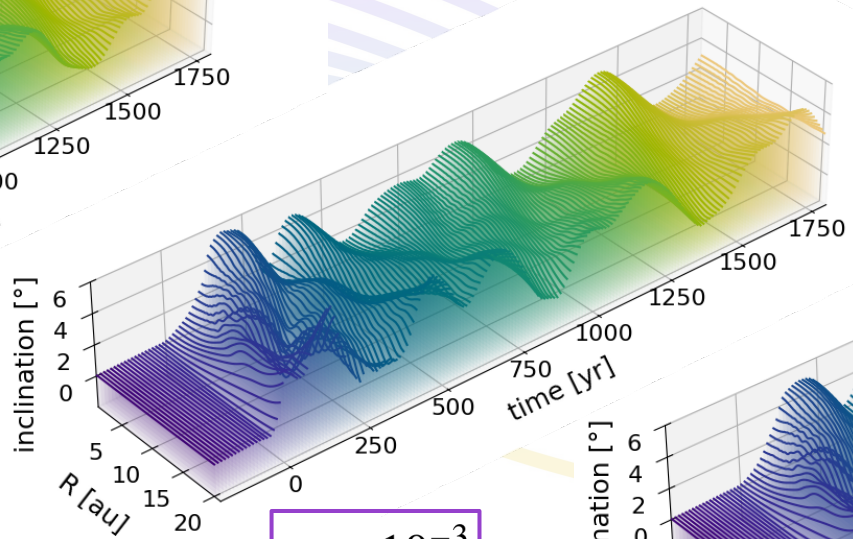


Fly-by in the RW Aur system

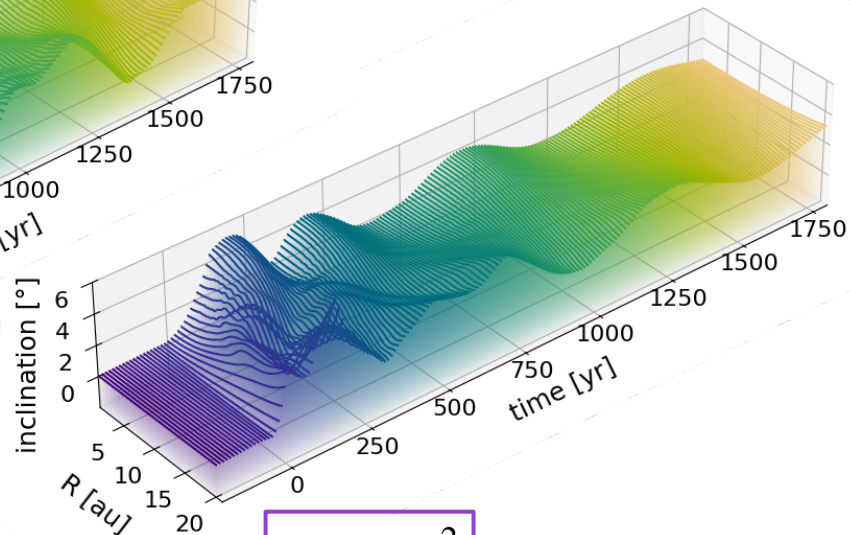
Kurtovic et al. 2024
→ observations indicate a misalignment of 6°



$\alpha = 10^{-4}$



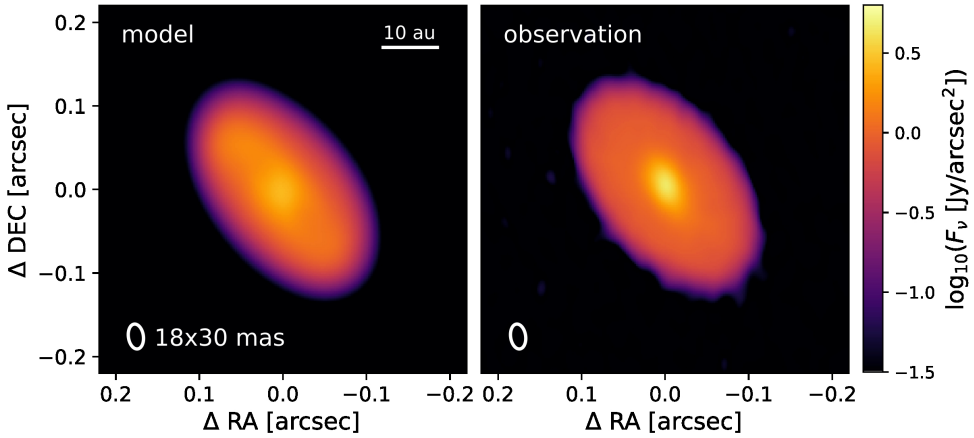
$\alpha = 10^{-3}$

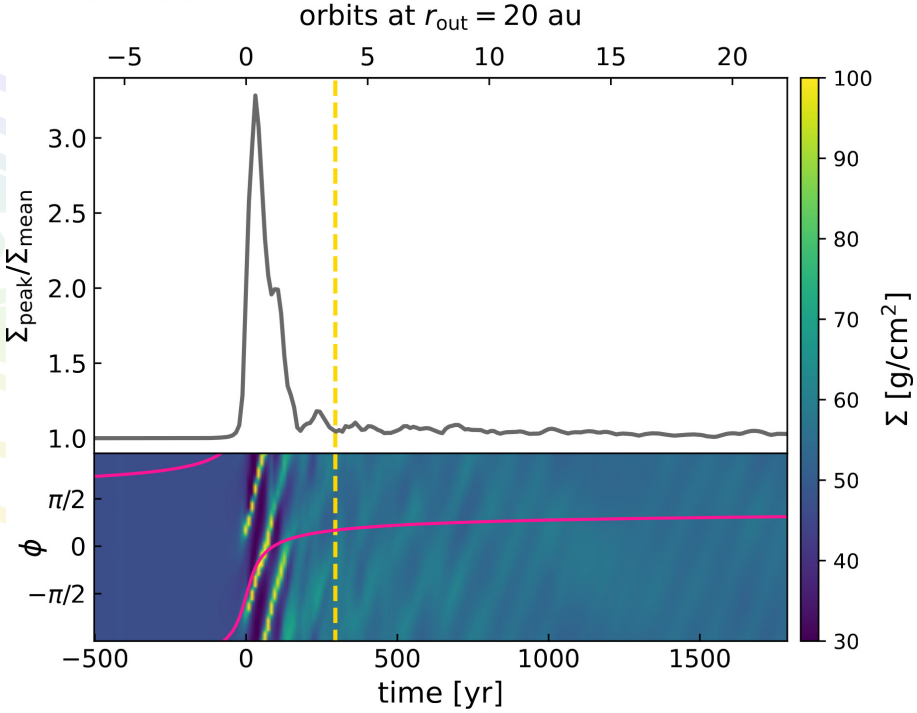


$\alpha = 10^{-2}$

Kimmig et al. 2026

Fly-by in the RW Aur system

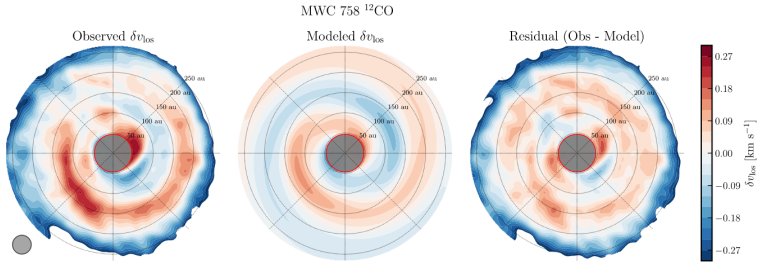




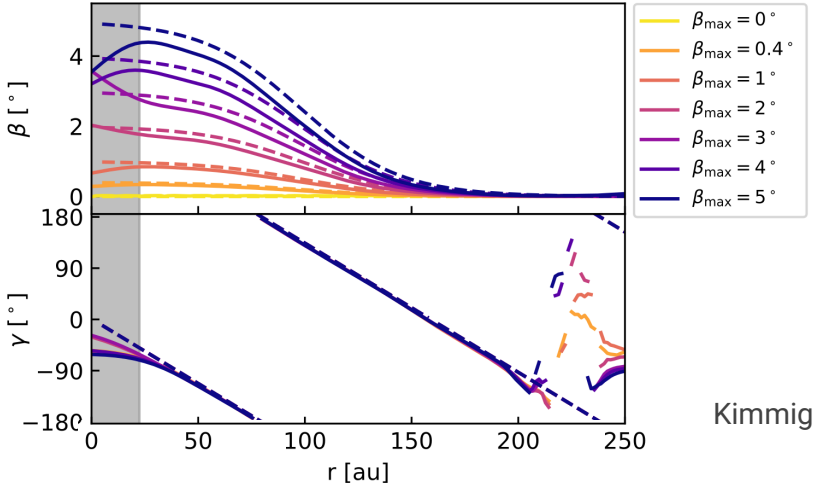
Kimmig et al. 2026

Current projects

- Kinematics as a tracer of warps



Winter et al. 2025



Kimmig et al. in prep.

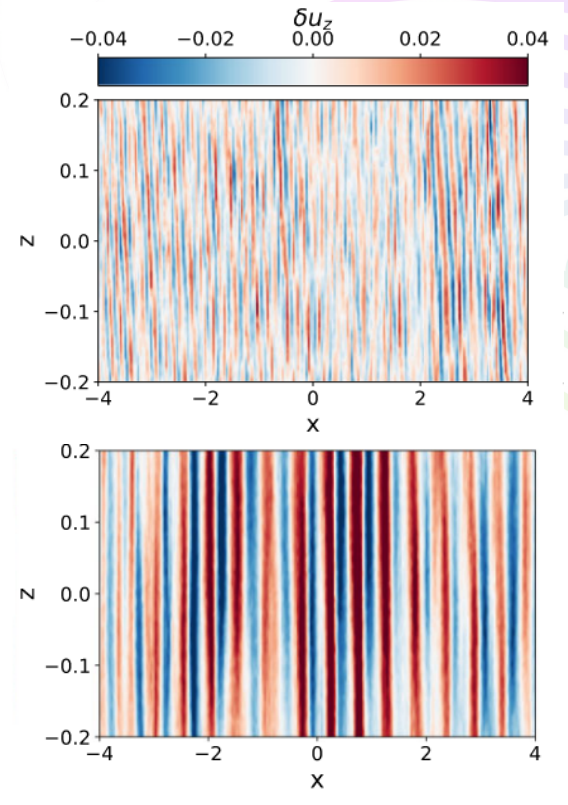
- Warp dynamics in non-isothermal disks
- Statistics of warp excitement through fly-bys
- Warping in late-infall events (Hühn et al. subm.)

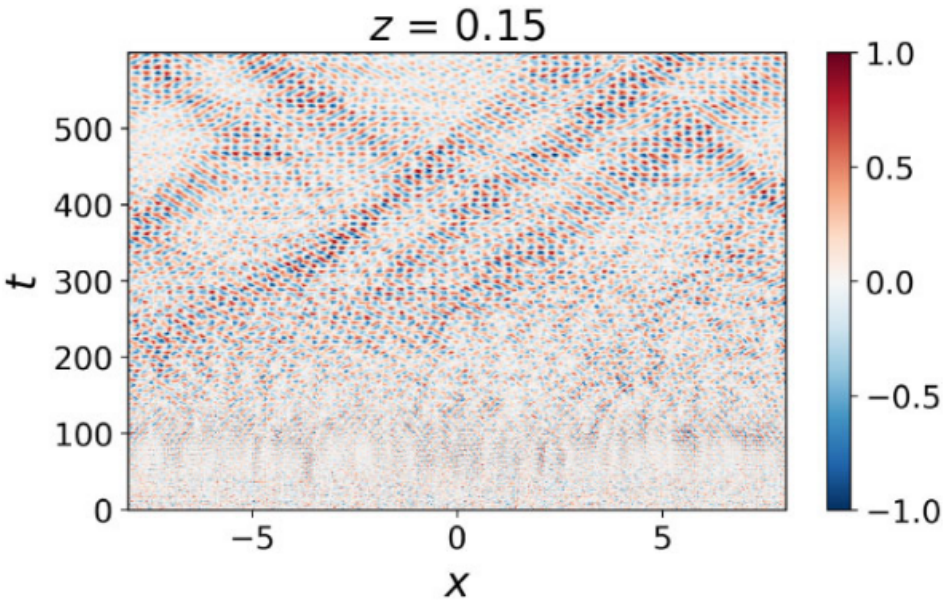
Summary

- Grid-based simulations are a powerful tool to model warp evolution for low-viscosity disks
- Fly-bys can warp the disk
  - The warp can survive until the fly-by star is no longer dynamically associated with the disk
  - The warp evolution is sensitive to the viscosity in the disk
- Observational signatures of warps may give insight into the formation history

Parametric instability?

deviation of the vertical velocity from a laminar flow

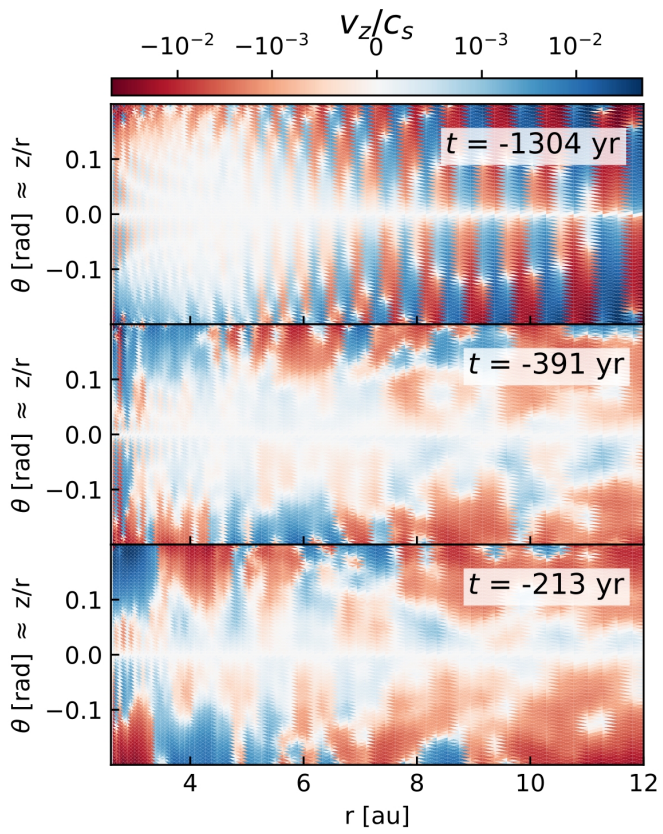


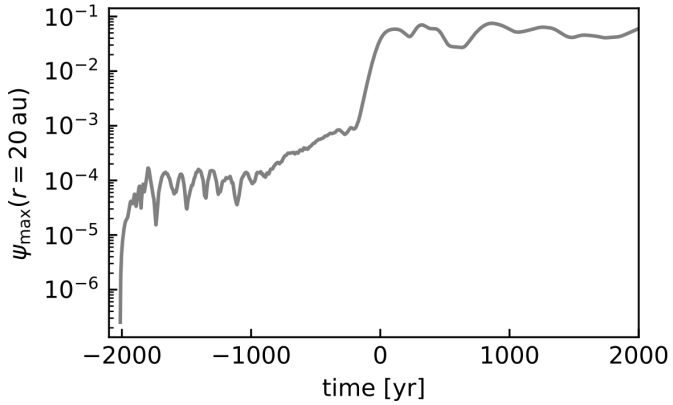


Fairbairn & Ogilvie 2023

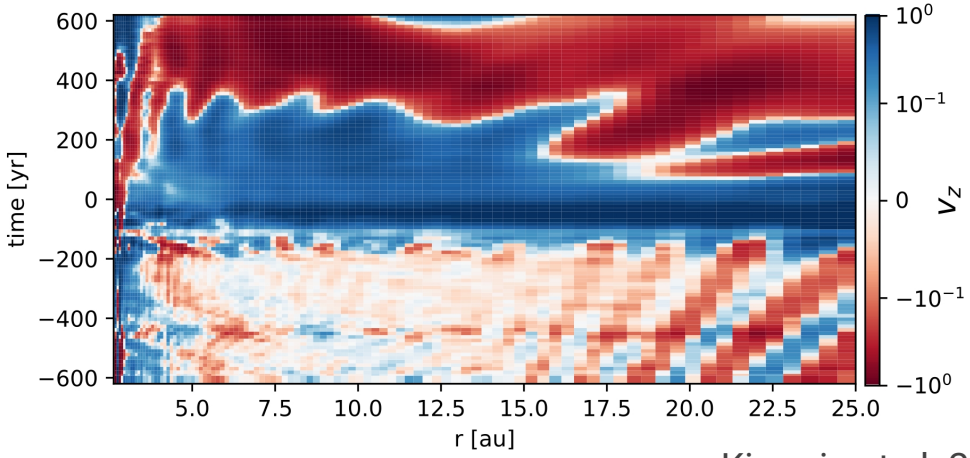
Parametric instability?

deviation of the vertical velocity from a laminar flow





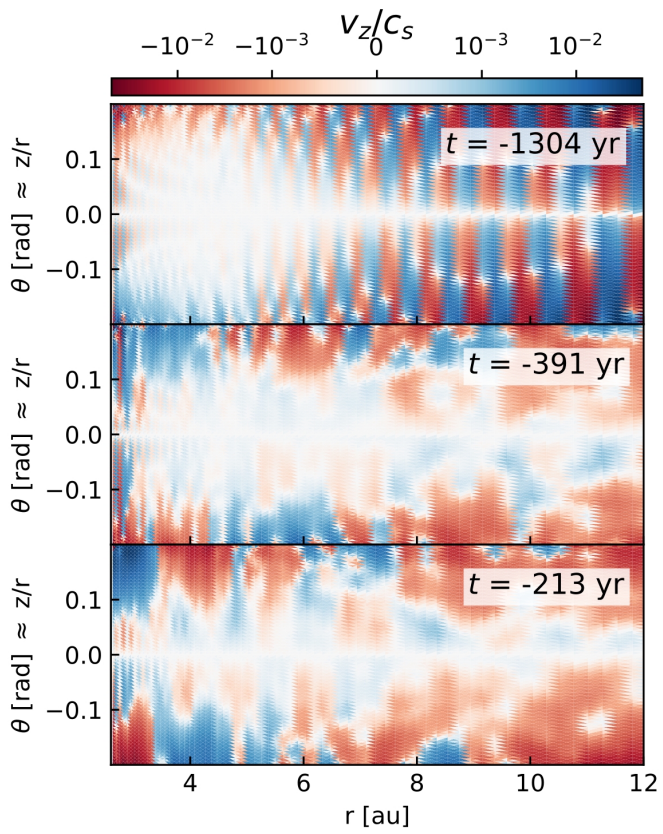
$$\psi(r) = \frac{\mathrm{d}l}{\mathrm{d}\ln r}$$

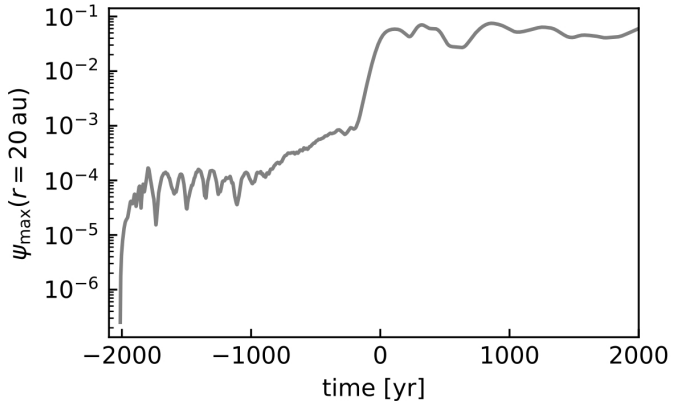


Kimmig et al. 2026

Parametric instability? → maybe!

deviation of the vertical velocity from a laminar flow





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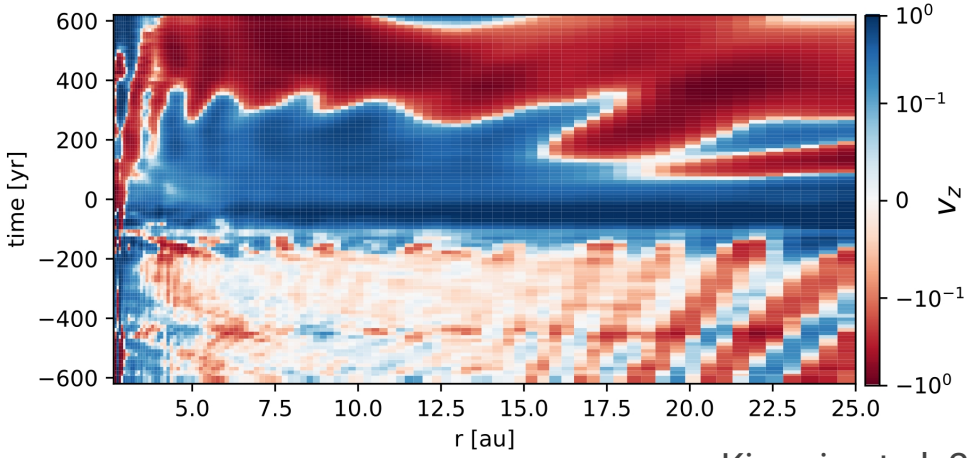

Kimmig et al. 2026