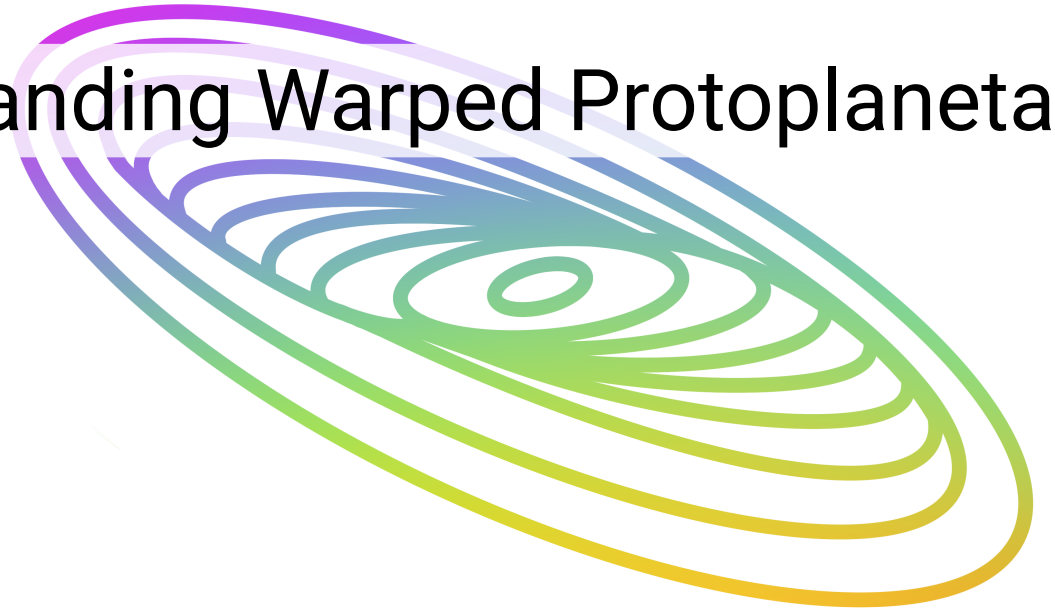
Inclined to Misalign

Understanding Warped Protoplanetary Disks



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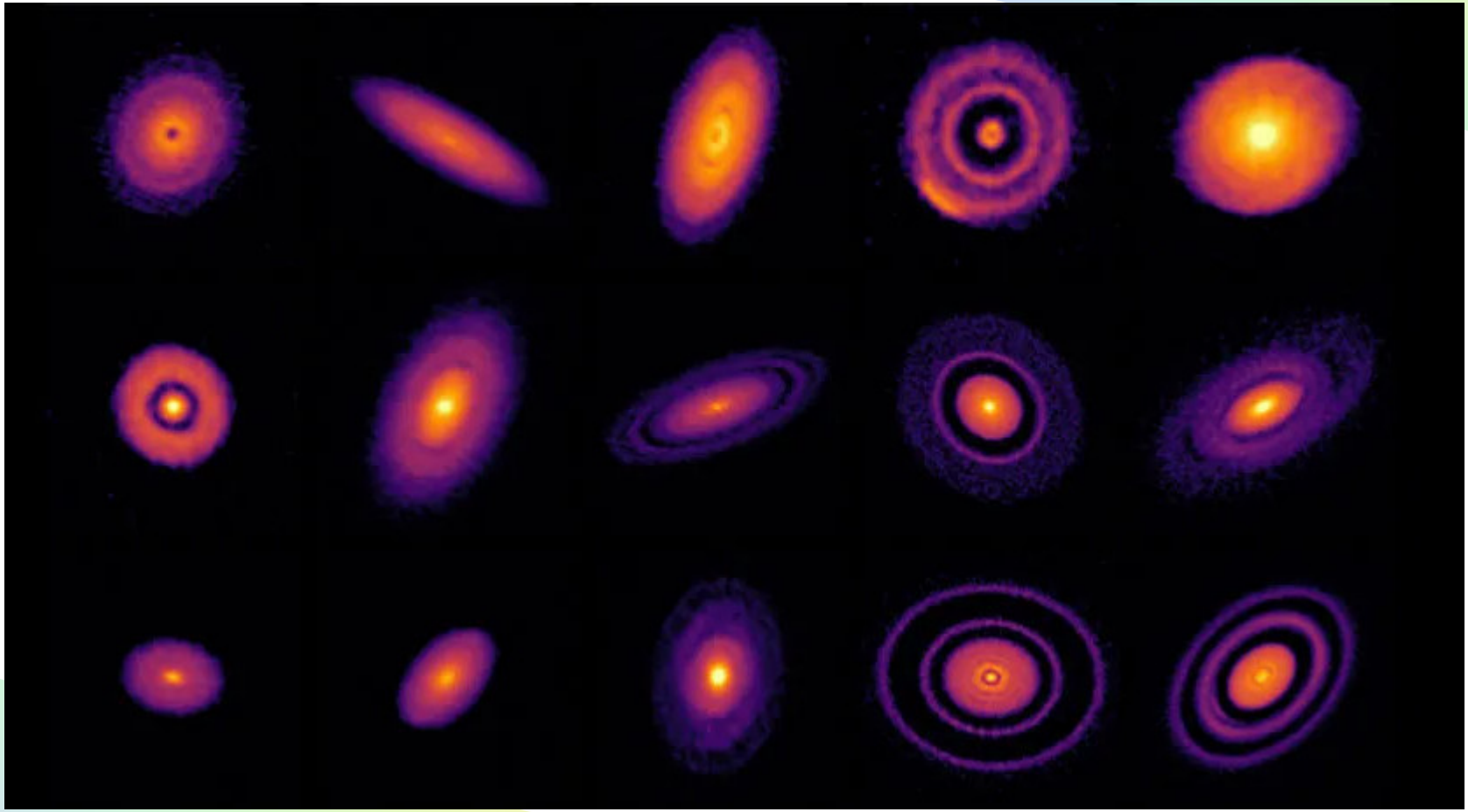
with Giovanni Rosotti

Como Lake centre
for Astrophysics (CLAP)
September 11th 2025

UNIVERSITAS STUDIORUM MEDIOLANENSIS

erc

DFG Deutsche Forschungsgemeinschaft



DSHARP (Andrews et al. 2018)

Structure

What?

Structure and Formation of Warped Disks

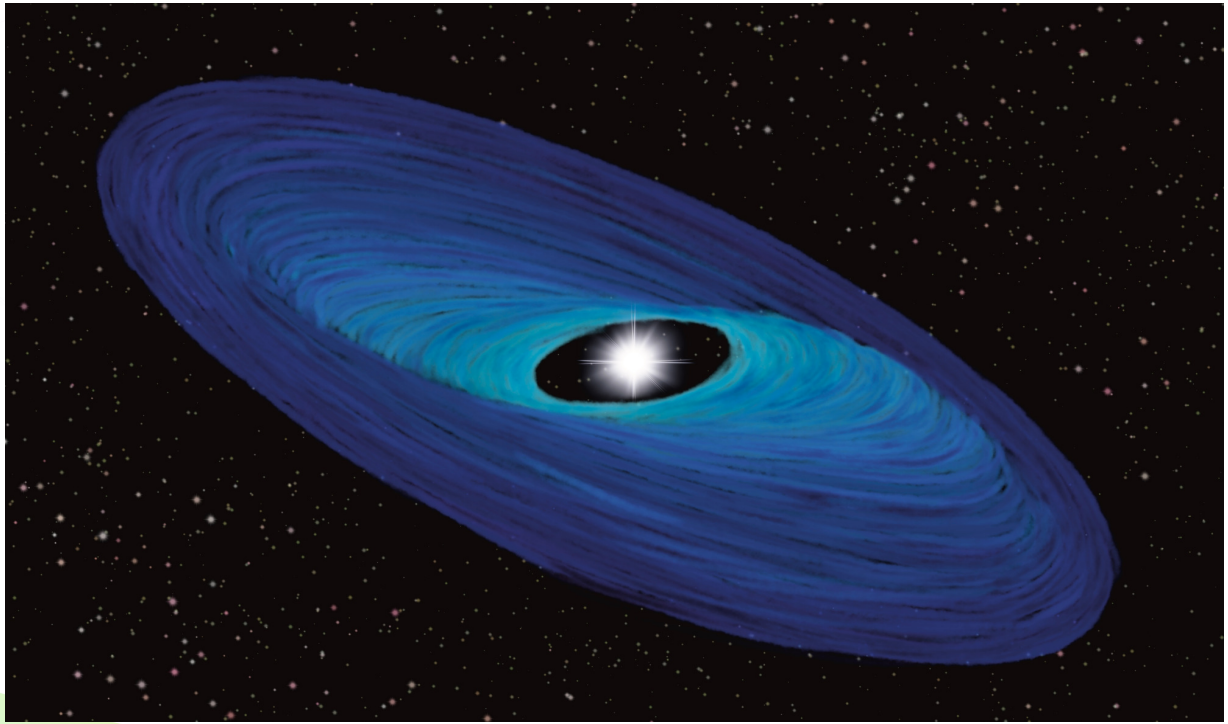
So What?

Observational Evidence

Now What?

Understanding their Dynamics

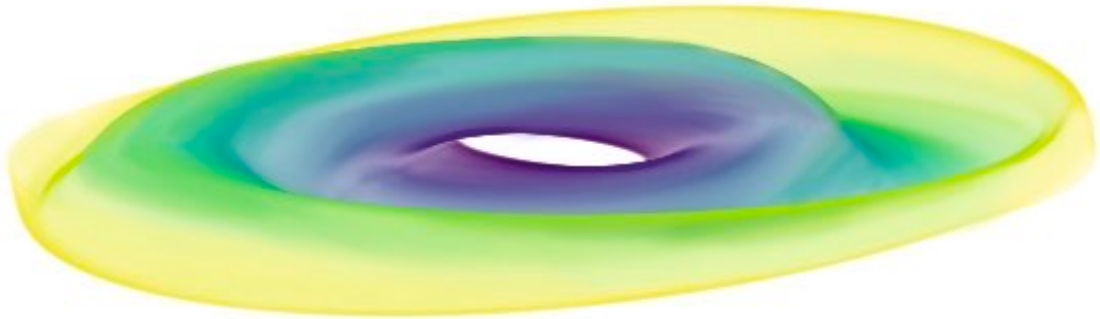
What? – Structure of Warped Disks



What? – Structure of Warped Disks

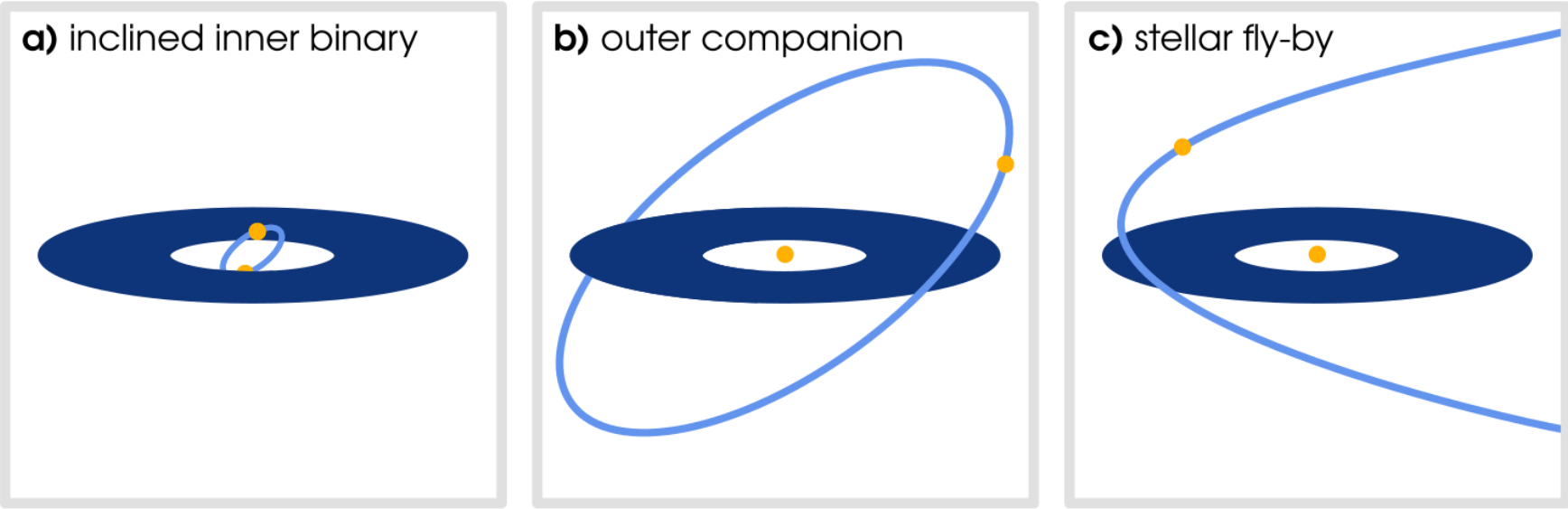
MWC 758

exoALMA
Teague et al. 2025

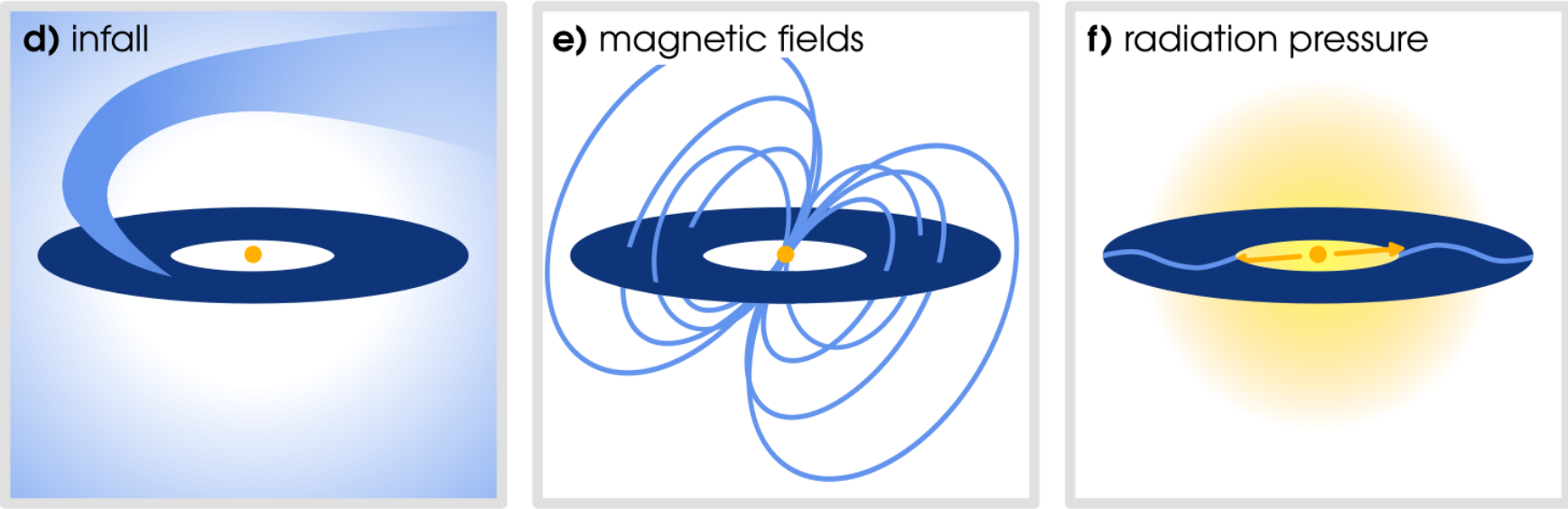


Winter, Benisty, Izquierdo et al. 2025
ApJL 990 L10 (incl. Lodato, **Kimmig**, Facchini, Rosotti)

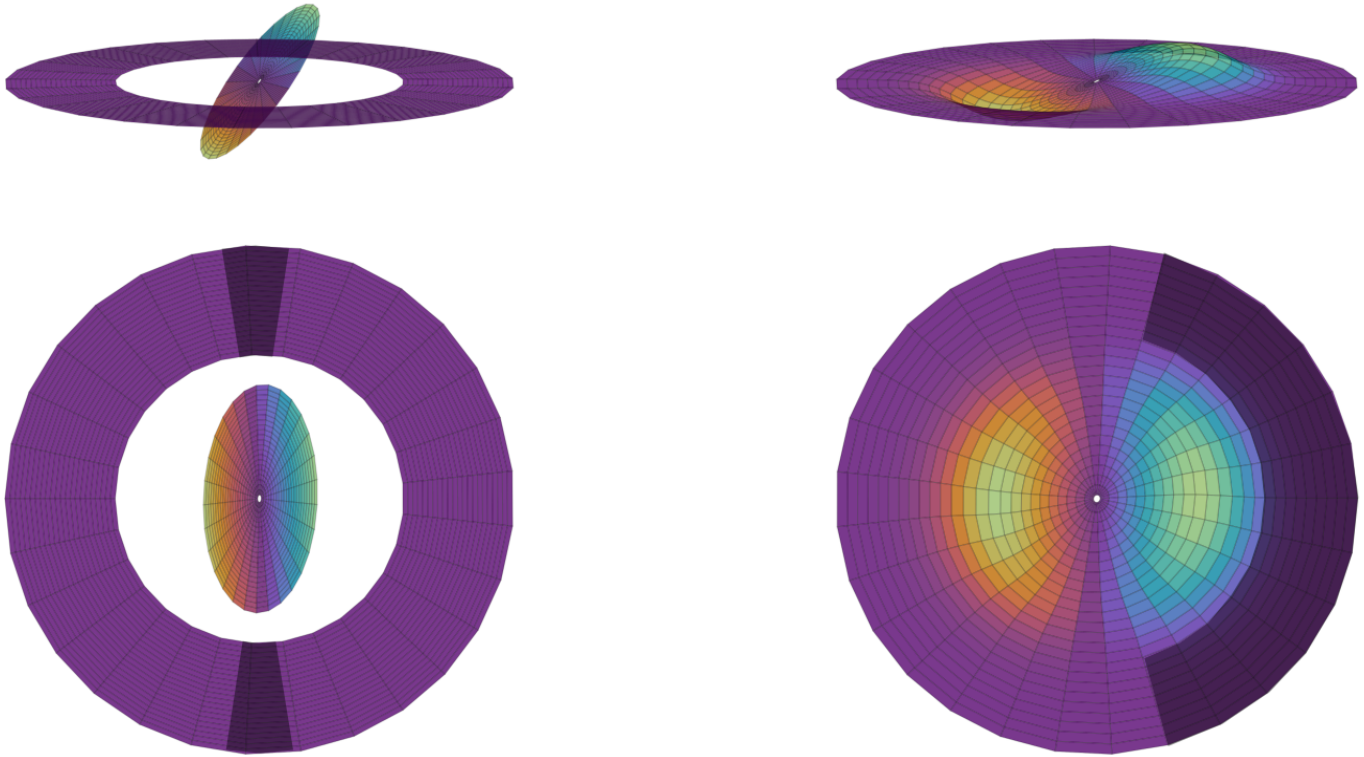
What? – Formation of Warped Disks



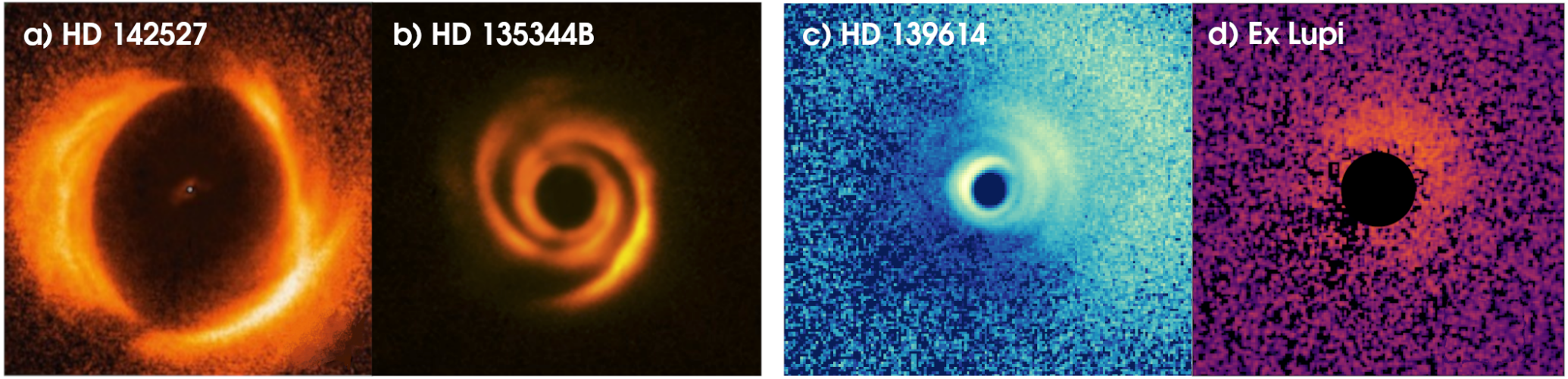
What? – Formation of Warped Disks



So What? – Observational Evidence

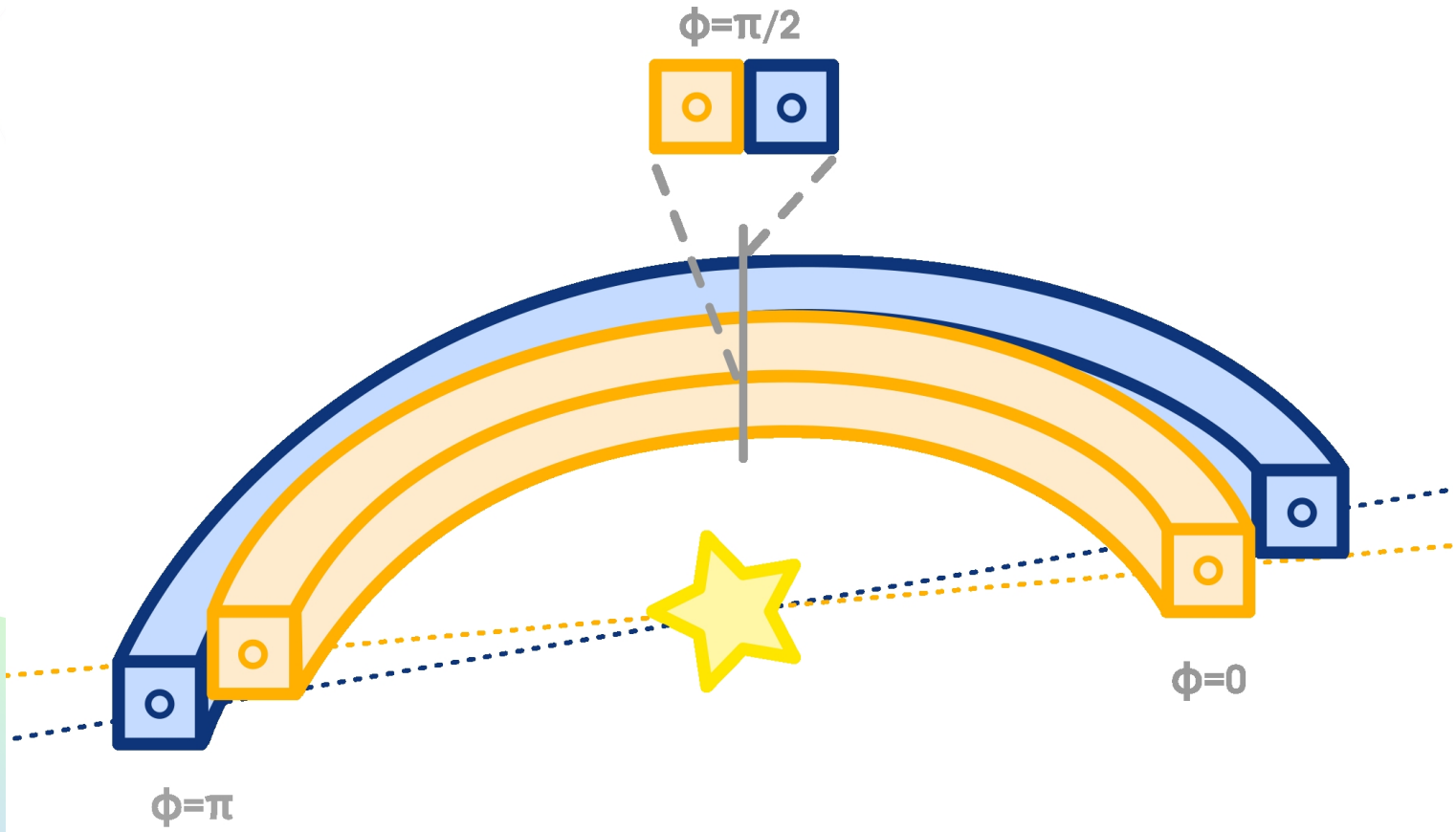


So What? – Observational Evidence



a) Avenhaus et al. 2017
b) Stolker et al. 2016
c) Muro-Arena et al. 2020
d) Zurlo et al. 2024

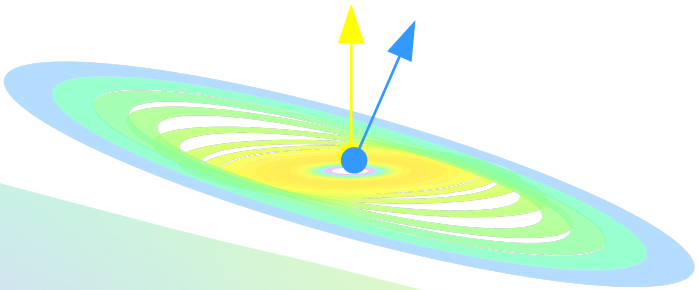
Now What? – Dynamical Evolution



Now What? – Dynamical Evolution

$$\frac{\partial \vec{G}}{\partial t} + \omega \vec{l} \times \vec{G} + \alpha \Omega \vec{G} - \left(\vec{l} \times \frac{\partial \vec{l}}{\partial t} \right) \times \vec{G} = \frac{\Sigma H_{\mathrm{p}}^2 r^3 \Omega^3}{4} \frac{\partial \vec{l}}{\partial r} - \frac{3}{2} \alpha \nu \Sigma r^2 \Omega^2 \vec{l}$$

$$\vec{L} = \Sigma r^2 \Omega \vec{l}$$



$$\frac{\partial \Sigma}{\partial t} = -\frac{2}{r} \frac{\partial}{\partial r} \left[\frac{\frac{\partial \vec{G}}{\partial r} \cdot \vec{l}}{r\Omega} \right]$$

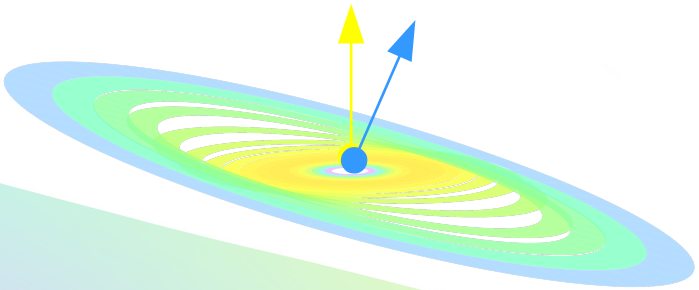
$$\frac{\partial \vec{L}}{\partial t} = -\frac{2}{r} \frac{\partial}{\partial r} \left[\frac{\frac{\partial \vec{G}}{\partial r} \cdot \vec{l}}{\Sigma r \Omega} \vec{L} \right] + \frac{1}{r} \frac{\partial \vec{G}}{\partial r} + \mathbf{T}.$$

Martin et al. 2019
Dullemond, **Kimmig** & Zanazzi 2021

Now What? – Dynamical Evolution

$$\frac{\partial \vec{G}}{\partial t} + \omega \left(\vec{l} \times \vec{G} \right) + \alpha \Omega \vec{G} = \frac{\Sigma H_p^2 r^3 \Omega^3}{4} \frac{\partial \vec{l}}{\partial r}$$

$$\vec{L} = \Sigma r^2 \Omega \vec{l}$$

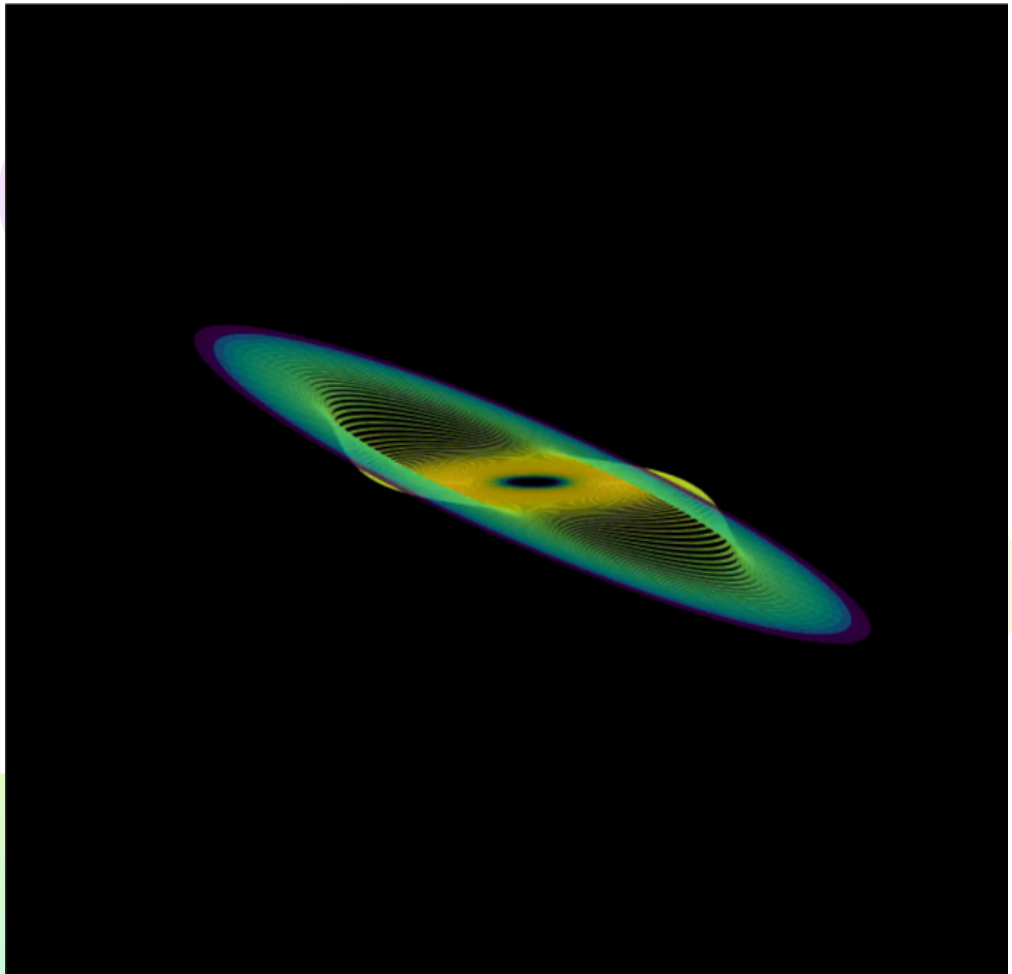


$$\frac{\partial \vec{L}}{\partial t} = \frac{1}{r} \frac{\partial \vec{G}}{\partial r} + \mathbf{T},$$

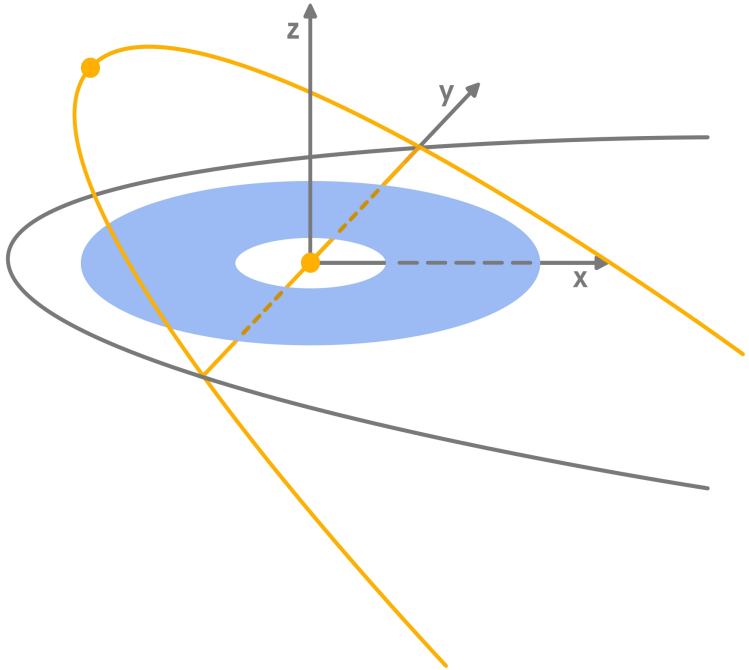
$$\boxed{\frac{\partial^2 \vec{l}}{\partial t^2} = \frac{1}{\Sigma r^3 \Omega} \frac{\partial}{\partial r} \left(\frac{\Sigma H_p^2 r^3 \Omega^3}{4} \frac{\partial \vec{l}}{\partial r} \right)}$$

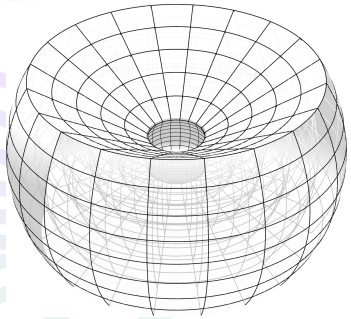
“pure wave-like equation set”
Papaloizou & Lin 1995
Lubow & Ogilvie 2000

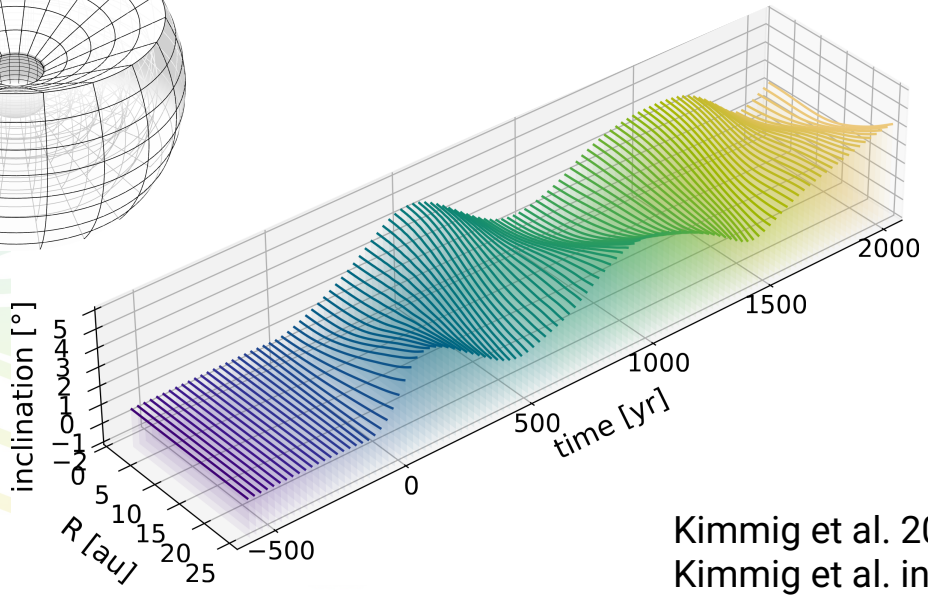
Now What? – Dynamical Evolution



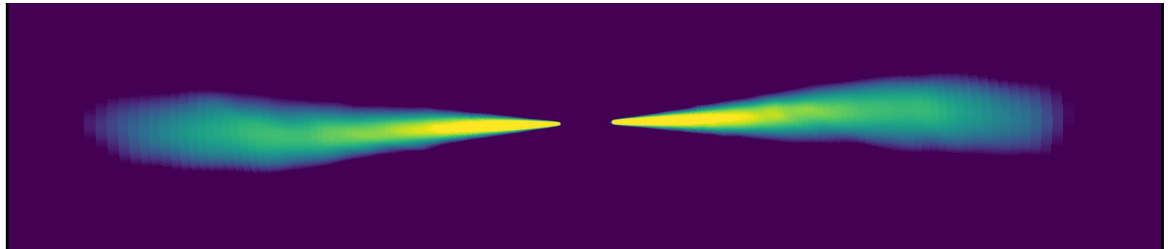
Now What? – Modelling Warps in 3D







Kimmig et al. 2024,
Kimmig et al. in prep.

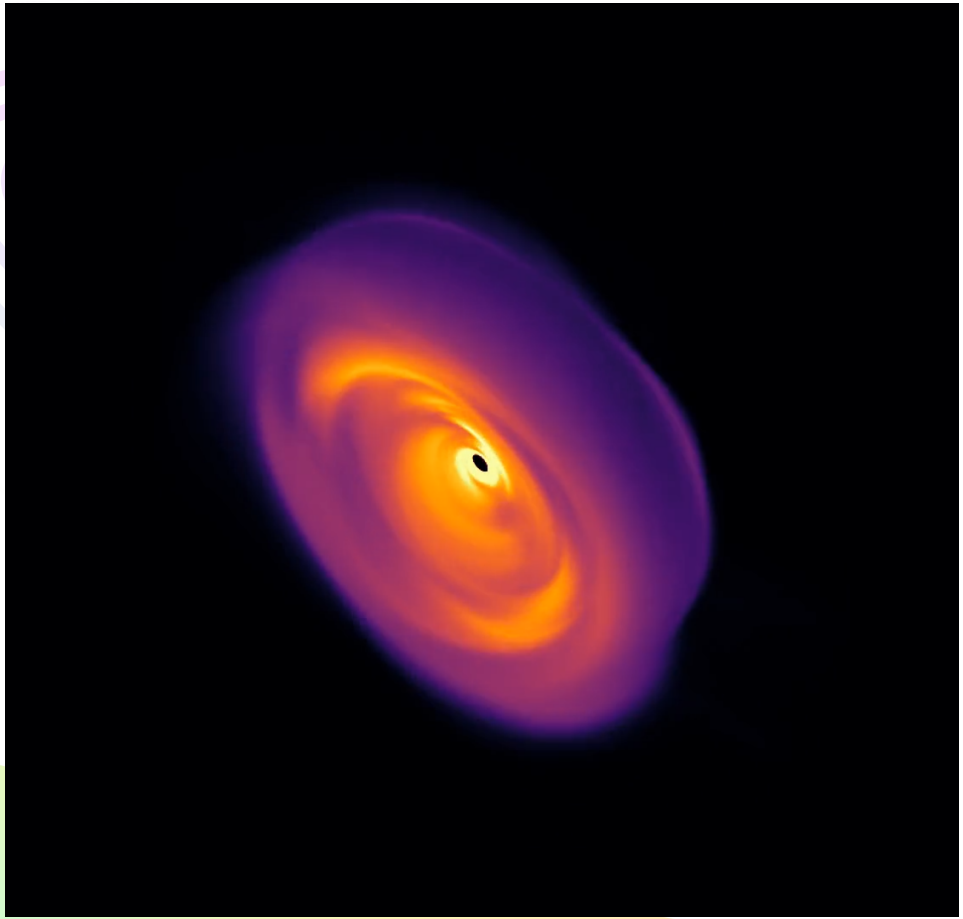


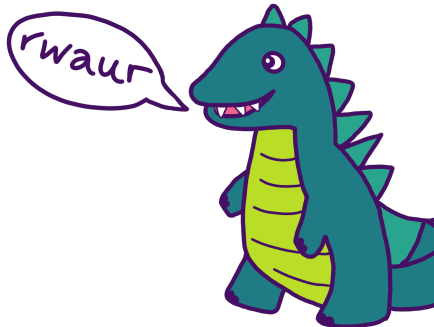
Now What? – Modelling Warps in 3D

RW Aur A

recent close encounter (300yr ago)

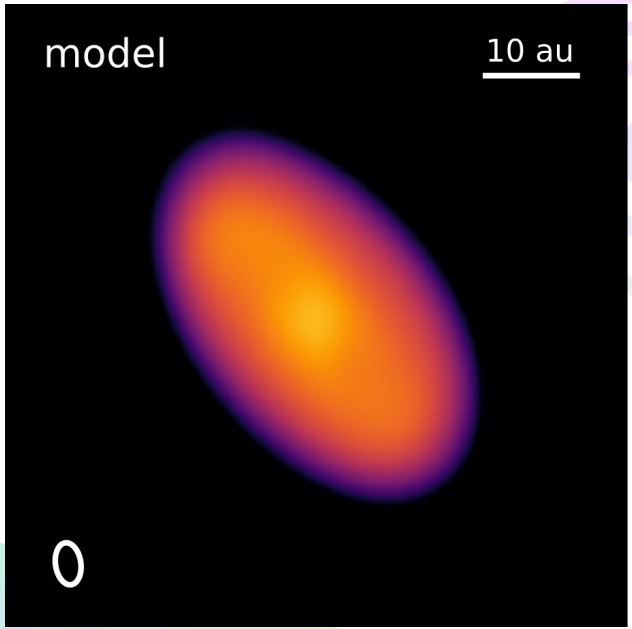
observational indications of a warp (Kurtovic et al. 2024)

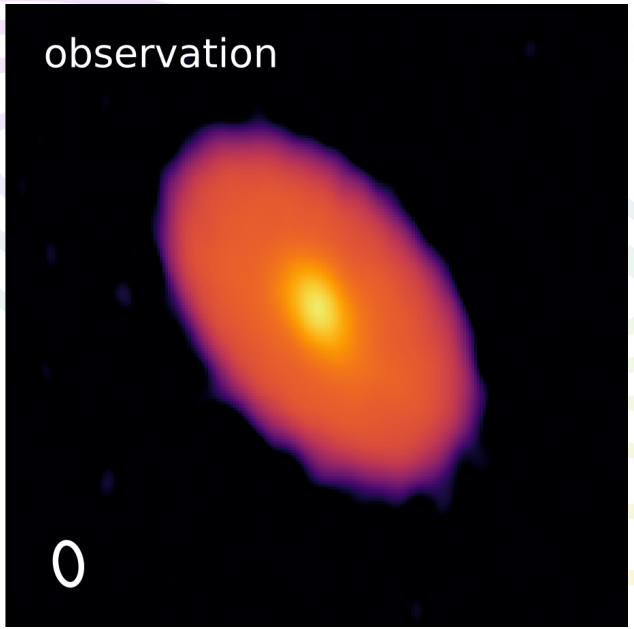




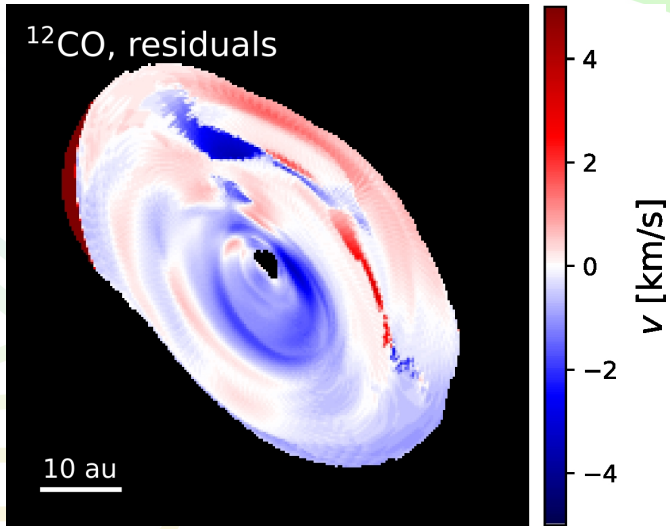
Now What? – Synthetic Observations

dust continuum





kinematics



RW Aur A

Kimmig et al. in prep.

What am I working on?

- Understanding the hydrodynamics of warps in 3D / 1D
- Forming warps in fly-bys
- Warps in disks embedded in turbulent environments
- Linking warp dynamics to observed wiggling jets
- Kinematic signatures to infer warp parameters from observations
- Influence of radiation and cooling on the warp dynamics

Summary

- Warped protoplanetary disks are common
- Warping fundamentally changes the disk dynamics
- Theory-observation synergy is key to probing warp parameters and determining the prevalence of warps