Warping through the Universe

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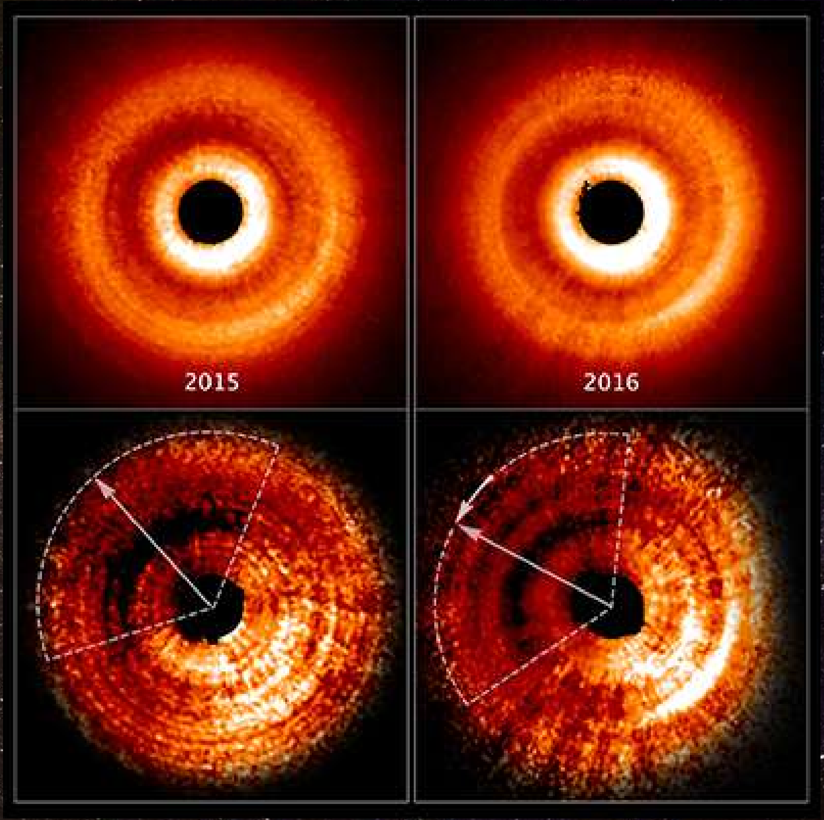
Spinning Fluids 2021
Ringberg castle

Structure

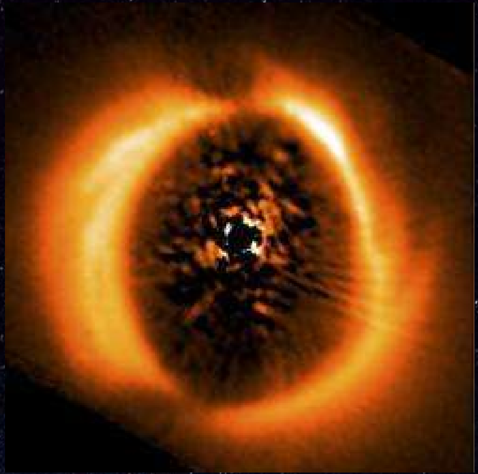
1. Introduction
   - Warped Disks
   - Formation
   - Simulations

2. Global Equations
   - Wave-Like and Diffusive Regimes
   - Generalized Equations

3. Inclined Companion



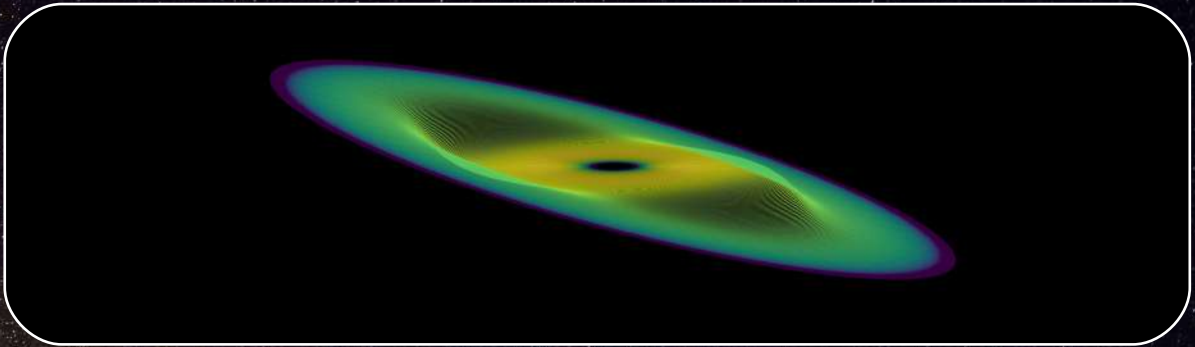
TW Hydra
Credit: NASA, ESA, and J. Debes (STScI)

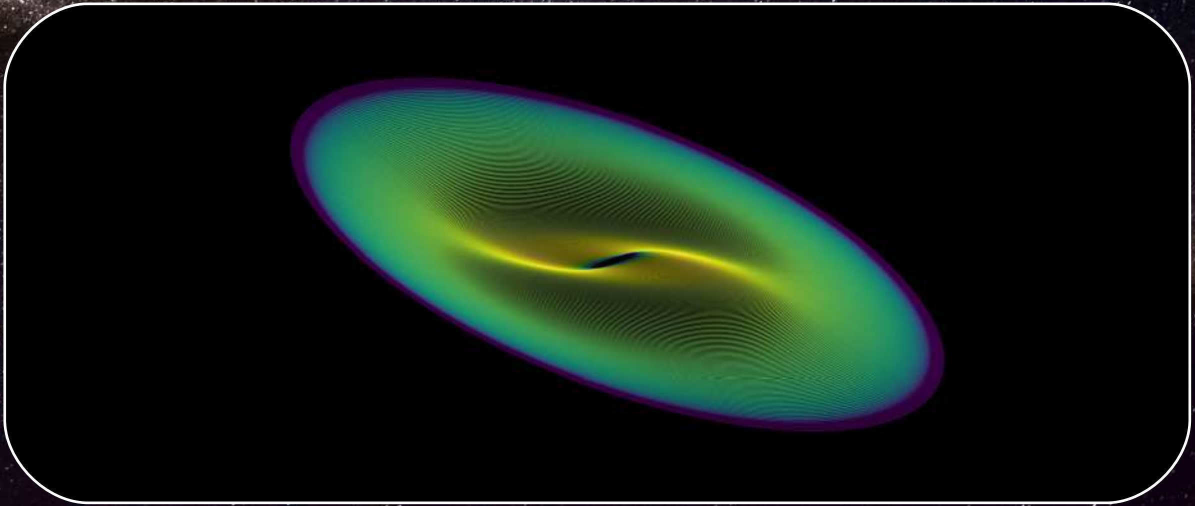


HD 142527
Credit: S. Marino et al.

HD 135344B
Credit: ESO, T. Stolker et al.

How does a warped disk look like?



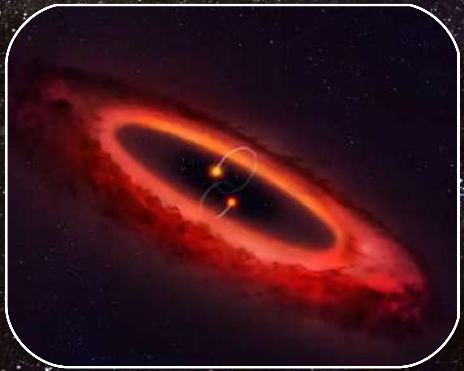


Structure

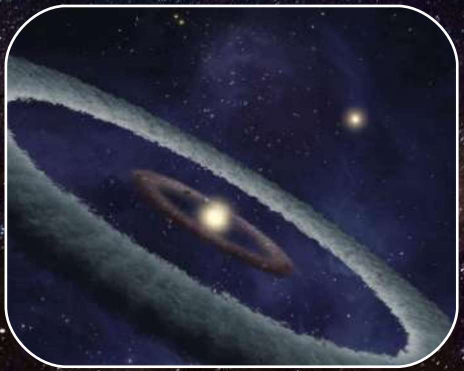
How does a warped disk form?

misalignment is the key!

inclined binary



inclined planet



magnetic field

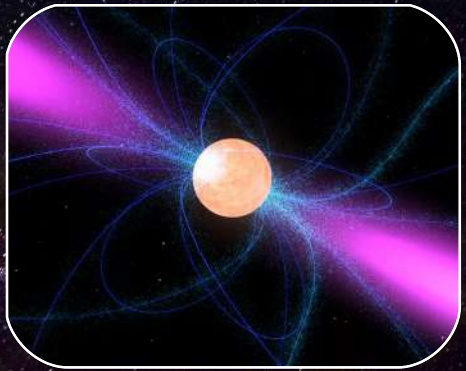
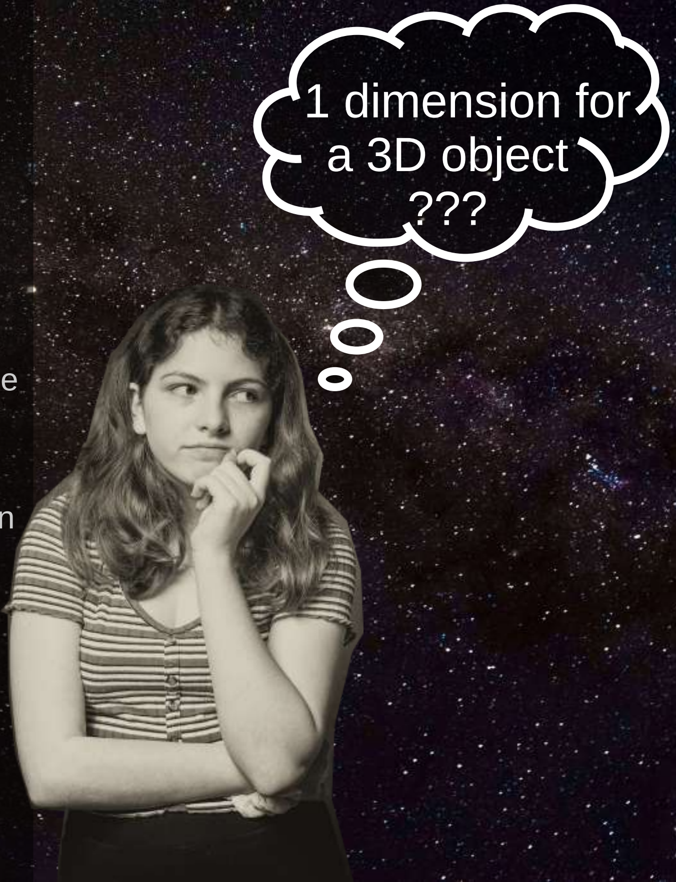


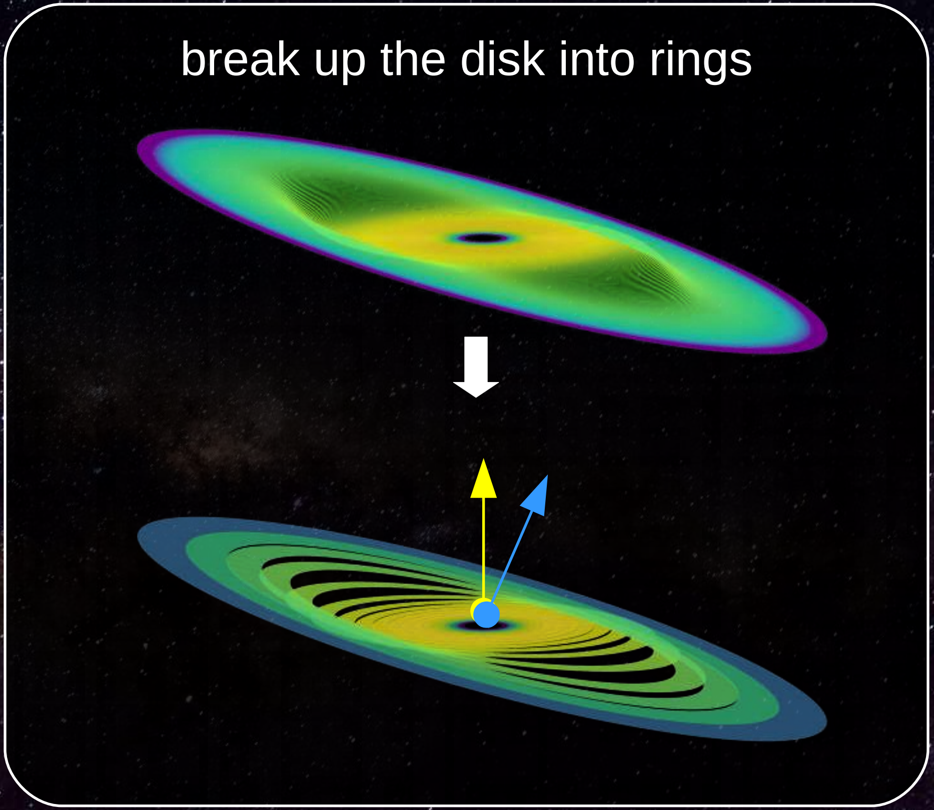
Image Credits: University of Warwick/Mark Garlick, NASA/JPL-Caltech, NASA

Numerical Simulations

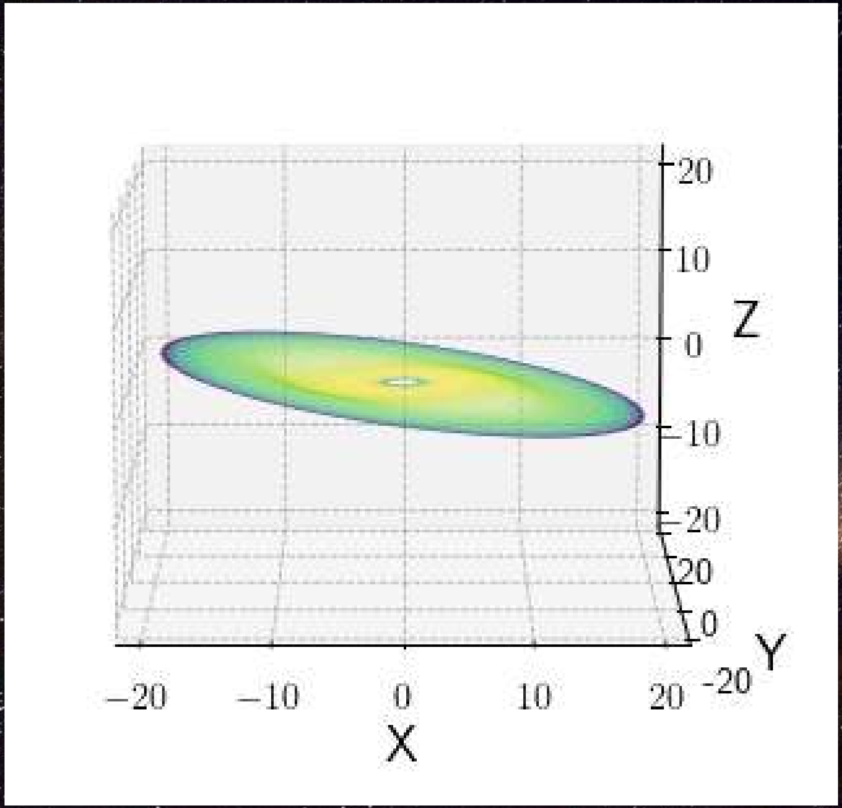
Structure



1-dimensional model



Numerical Simulations



1D Code

Dwarpy

Credit: HourglassHero

How does a warped disk evolve?

1-dimensional model

Structure

wave-like regime

$$\alpha < \frac{H}{R}$$

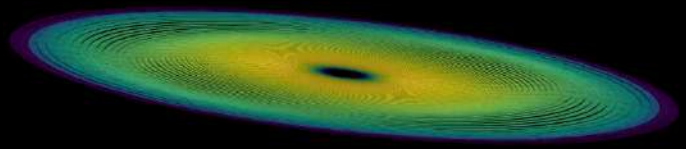
diffusive regime

$$\alpha > \frac{H}{R}$$

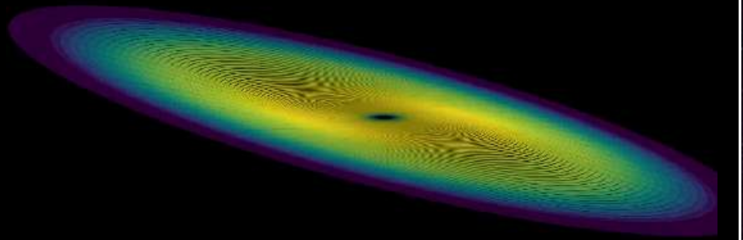
How does a warped disk evolve?

1-dimensional model

wave-like regime



diffusive regime



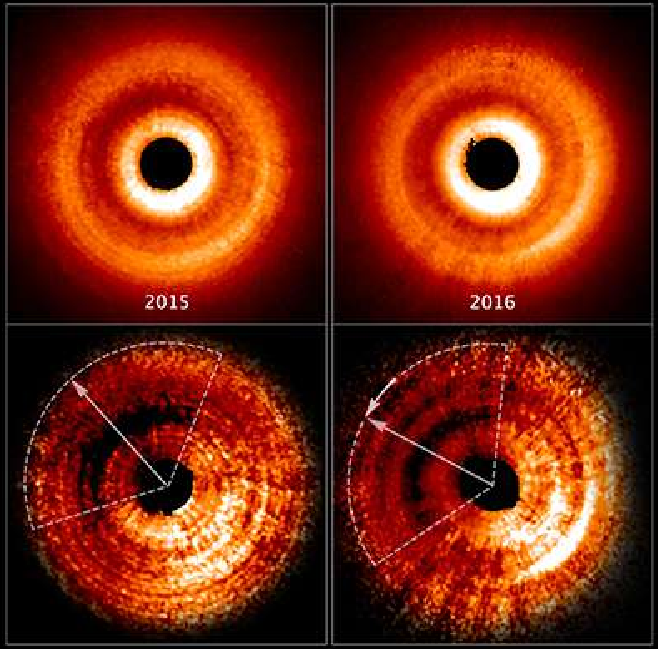
Structure

How does a warped disk evolve?

1-dimensional model

wave-like regime

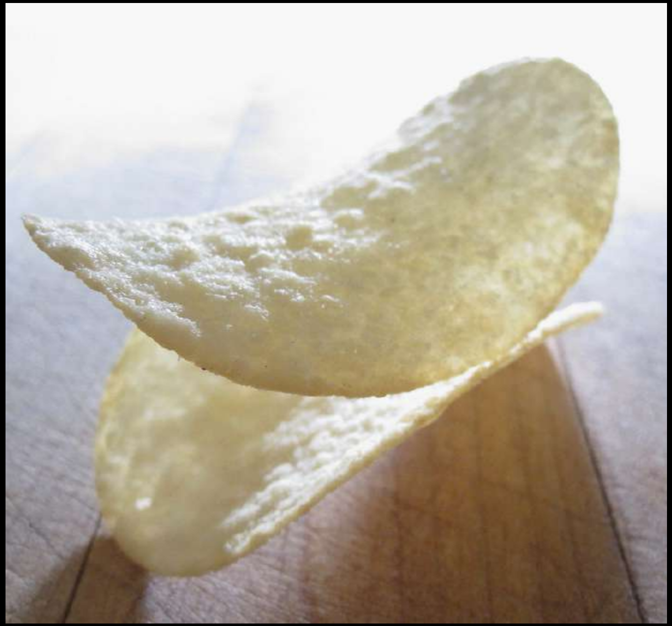
Lubow & Ogilvie 2000



Credit: NASA, ESA, and J. Debes (STScI)

diffusive regime

Pringle 1992



Credit: TheDeliciousLife

Generalized Equations – Martin et al. 2019

$$\frac{\partial \vec{G}}{\partial t} + \omega \vec{l} \times \vec{G} + \alpha \Omega \vec{G} = \frac{\Sigma H^2 R^3 \Omega^3}{4} \frac{\partial \vec{l}}{\partial R} - \frac{3}{2} (\alpha \quad) \nu_1 \Sigma R^2 \Omega^2 \vec{l}$$

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

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

$$\vec{G} = \text{internal torque}$$

$$\vec{L} = \Sigma R^2 \Omega \vec{l} = \text{angular momentum}$$

Martin et al. 2019

Generalized Equations – Martin et al. 2019

$$\frac{\partial \vec{G}}{\partial t} + \omega \vec{l} \times \vec{G} + \alpha \Omega \vec{G} + \beta \Omega \left(\vec{G} \cdot \vec{l} \right) \vec{l} = \frac{\Sigma H^2 R^3 \Omega^3}{4} \frac{\partial \vec{l}}{\partial R} - \frac{3}{2} (\alpha + \beta) \nu_1 \Sigma R^2 \Omega^2 \vec{l}$$

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

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

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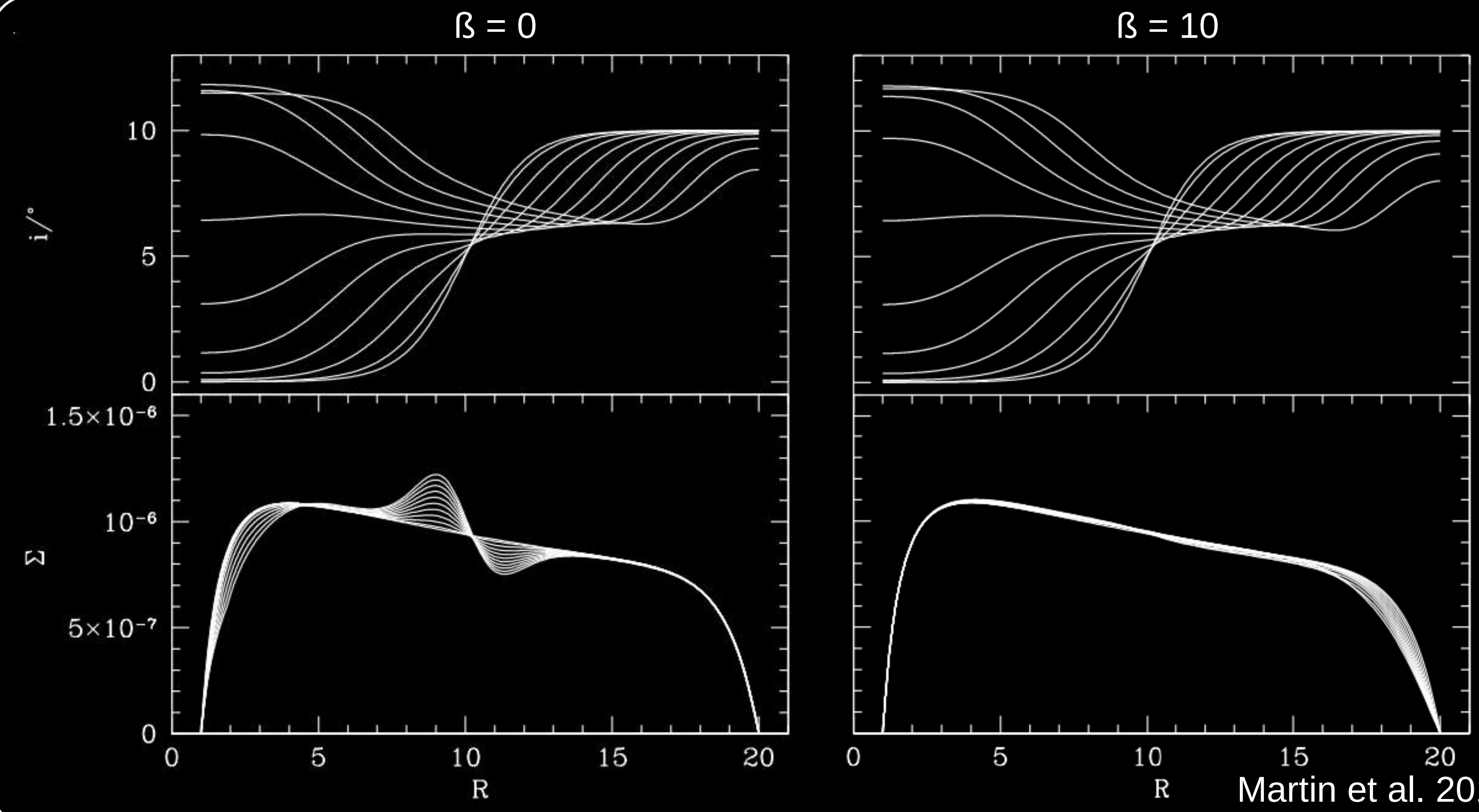
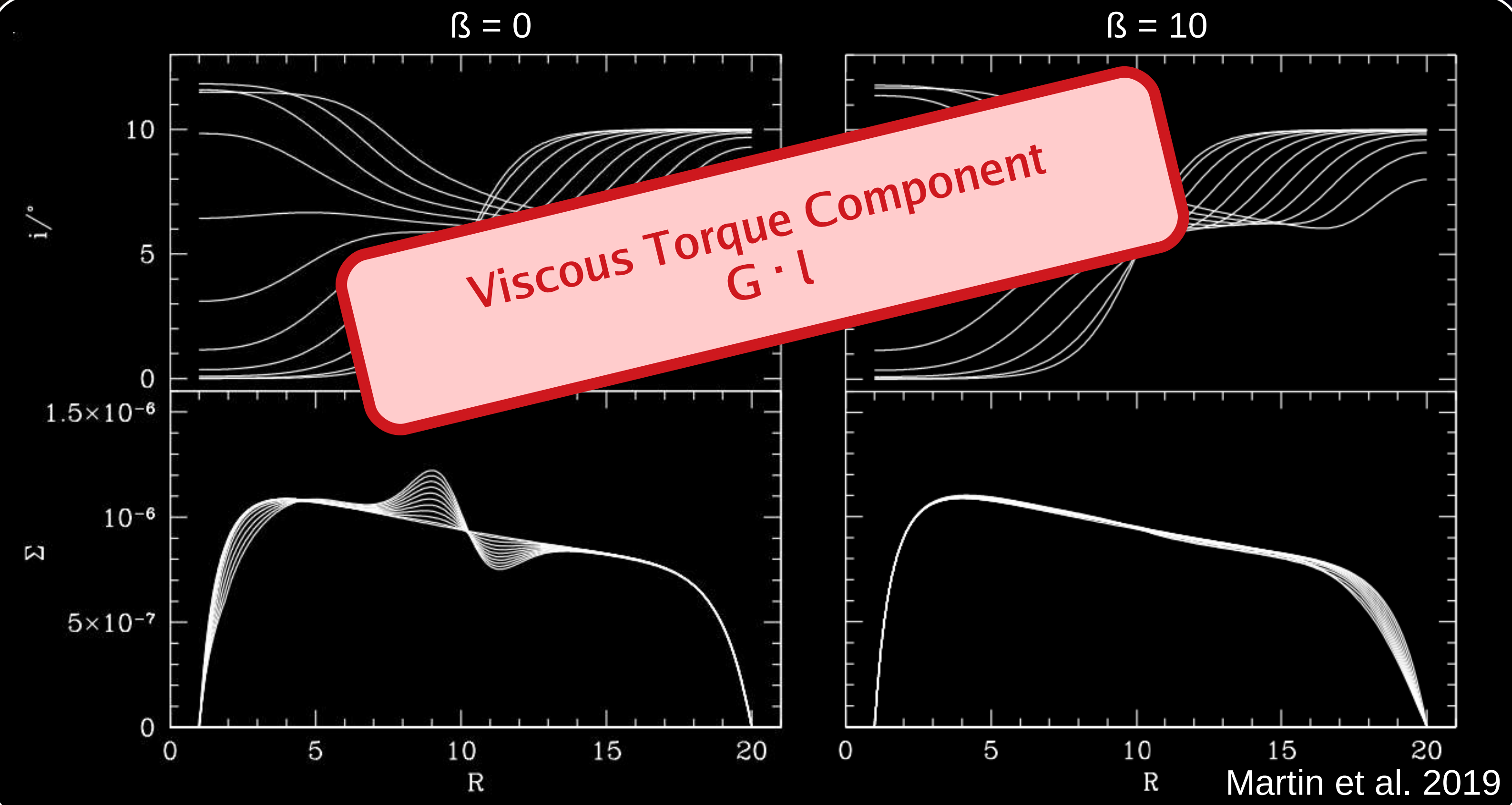


Martin et al. 2019

Generalized Equations – Martin et al. 2019



Martin et al. 2019

Generalized Equations – Martin et al. 2019

$$\vec{G} \cdot \vec{l} = -\frac{3}{2}\nu_1 \Sigma R^2 \Omega(R)$$

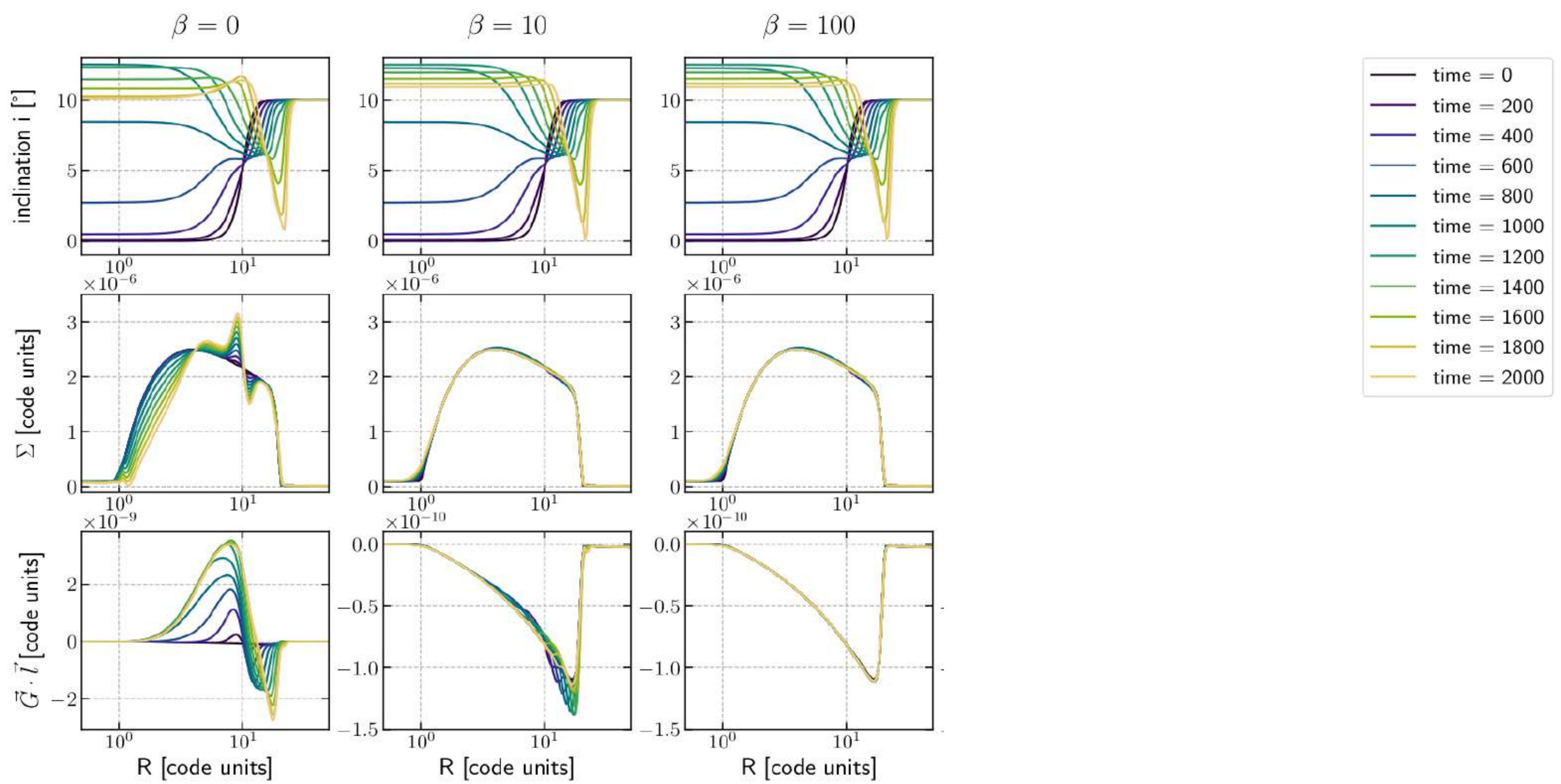
Generalized Equations – Martin et al. 2019

Structure

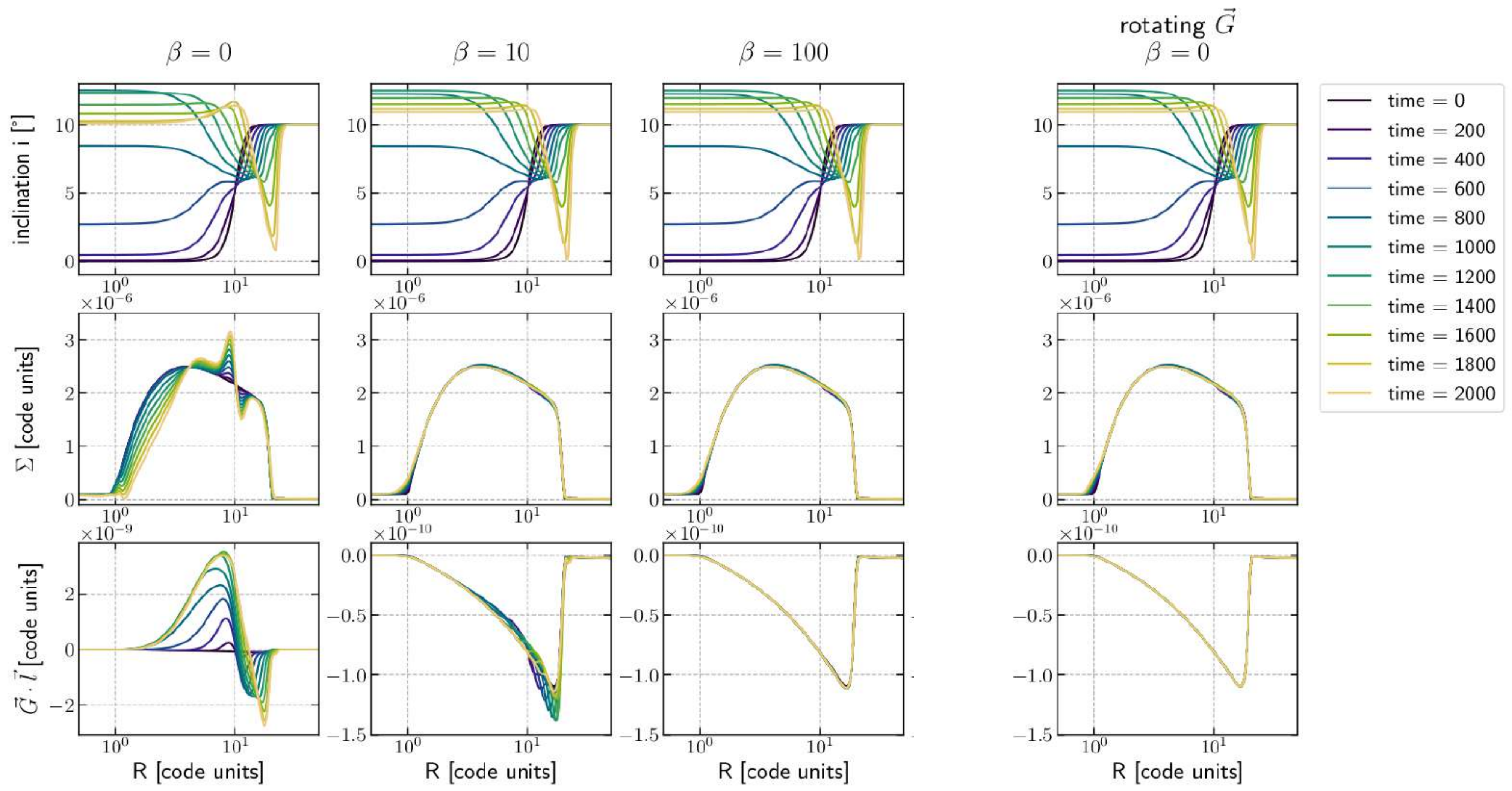
$$\frac{\partial \vec{G}}{\partial t} + \omega \vec{l} \times \vec{G} + \alpha \Omega \vec{G} + \beta \Omega \left(\vec{G} \cdot \vec{l} \right) \vec{l} = \frac{\Sigma H^2 R^3 \Omega^3}{4} \frac{\partial \vec{l}}{\partial R} - \frac{3}{2} (\alpha + \beta) \nu_1 \Sigma R^2 \Omega^2 \vec{l}$$

$$\vec{G} \cdot \vec{l} = -\frac{3}{2} \nu_1 \Sigma R^2 \Omega(R) - \frac{\partial \vec{G}}{\partial t} \cdot \vec{l} \frac{1}{\Omega(R)(\alpha + \beta)}$$

Martin et al. 2019

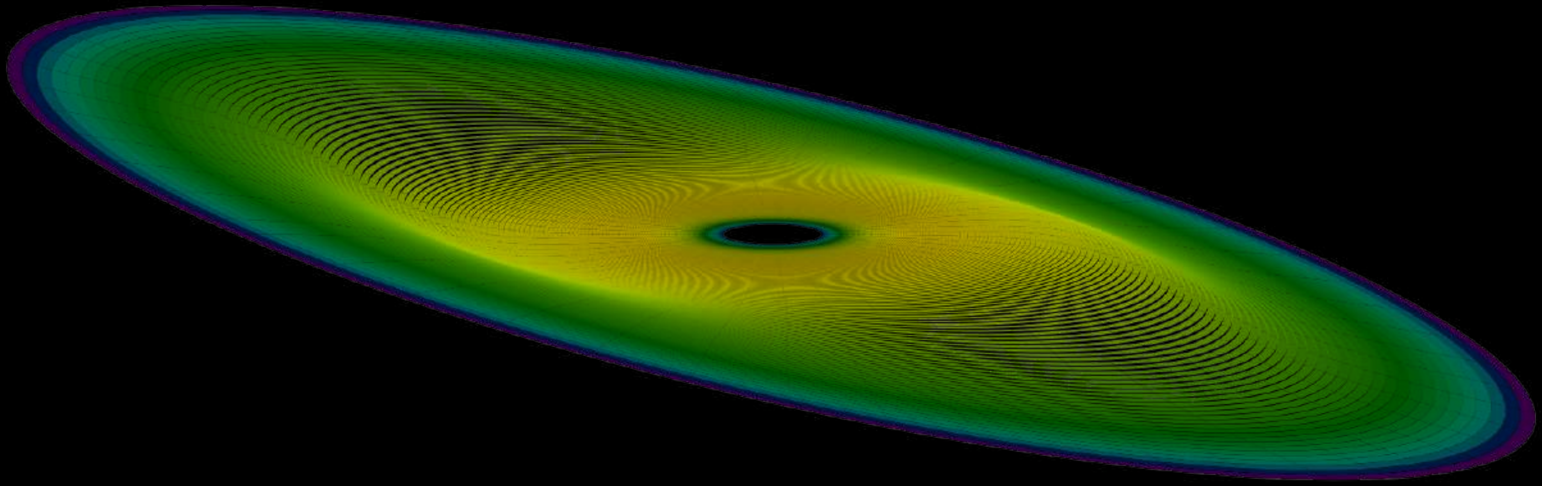


Dullemond, Kimmig & Zanazzi, subm.



Dullemond, Kimmig & Zanazzi, subm.

Generalized Equations – Martin et al. 2019



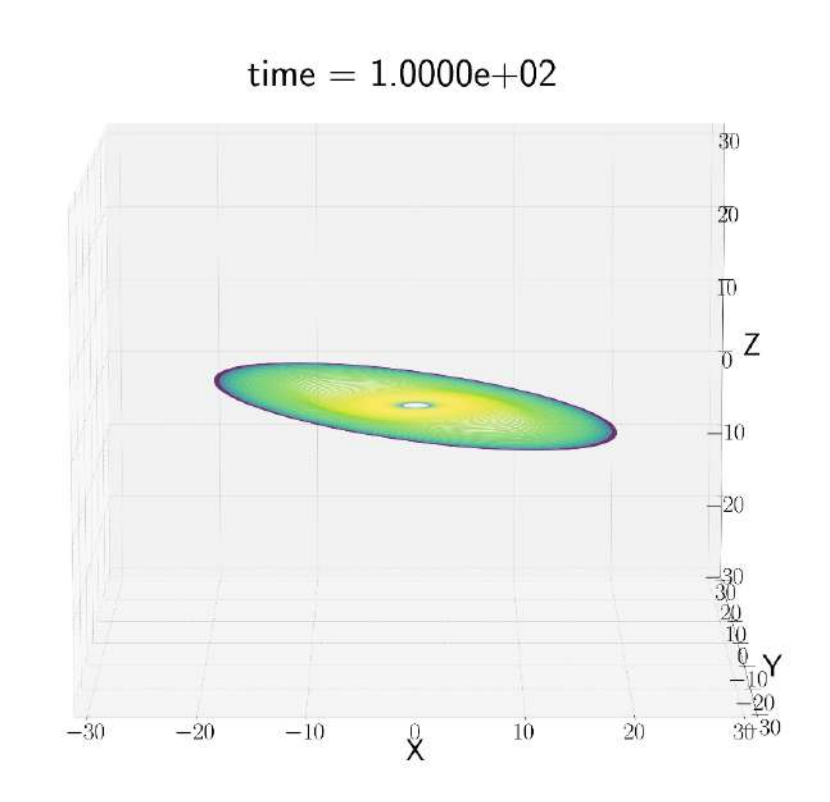
$$\frac{\partial \vec{G}}{\partial t} = \ldots + \left(\vec{l} \times \frac{\partial \vec{l}}{\partial t} \right) \times \vec{G}$$

Confused?

Structure

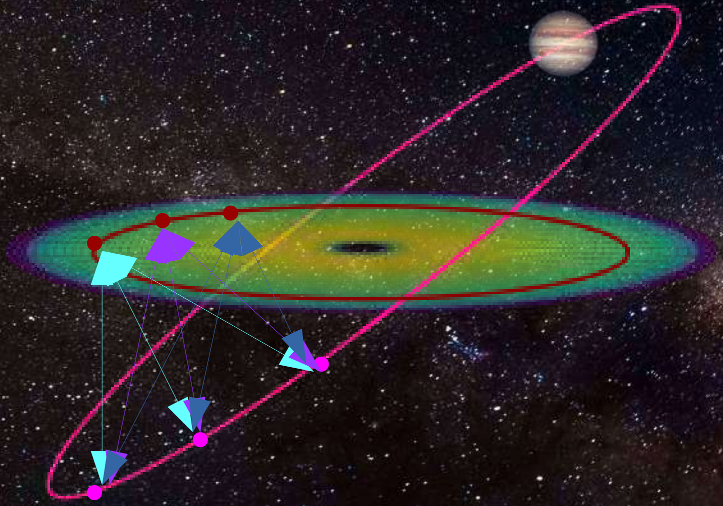
Simulation of a Warped Disk

YouTube: https://youtu.be/hngxVBO_3_o



Inclined Companion

Structure



Gravity of two point masses

$$\vec{F}_G = \frac{G m_1 m_2}{d^2} \frac{\vec{d}}{d}$$

$$\frac{\partial \vec{L}}{\partial t} = \vec{\tau} = \vec{r} \times \vec{F}_G$$

Conclusion

- Dwarpy can be a powerful tool to simulate warped disks
- Gained insight to the Martin at al. 2019 equations
- Inclined planets can cause a warp

Future work:

- 3D simulations to compare the 1D model
- Planets with eccentricity or resonances
- Synthetic observations using RADMC3D

Structure

Questions?