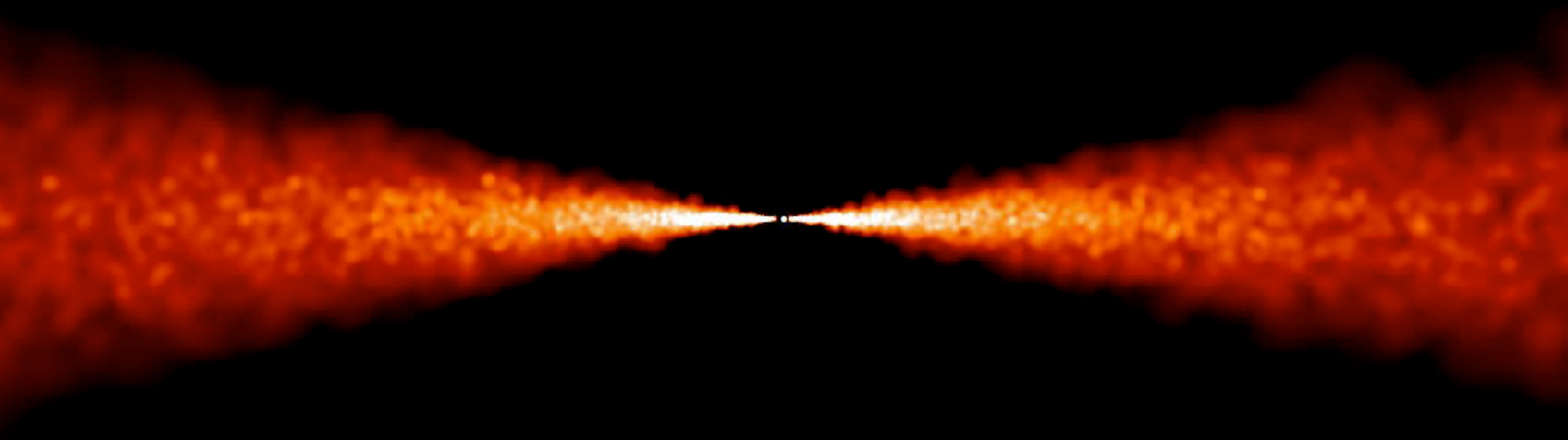

Warping a protoplanetary disc with a planet on a misaligned orbit

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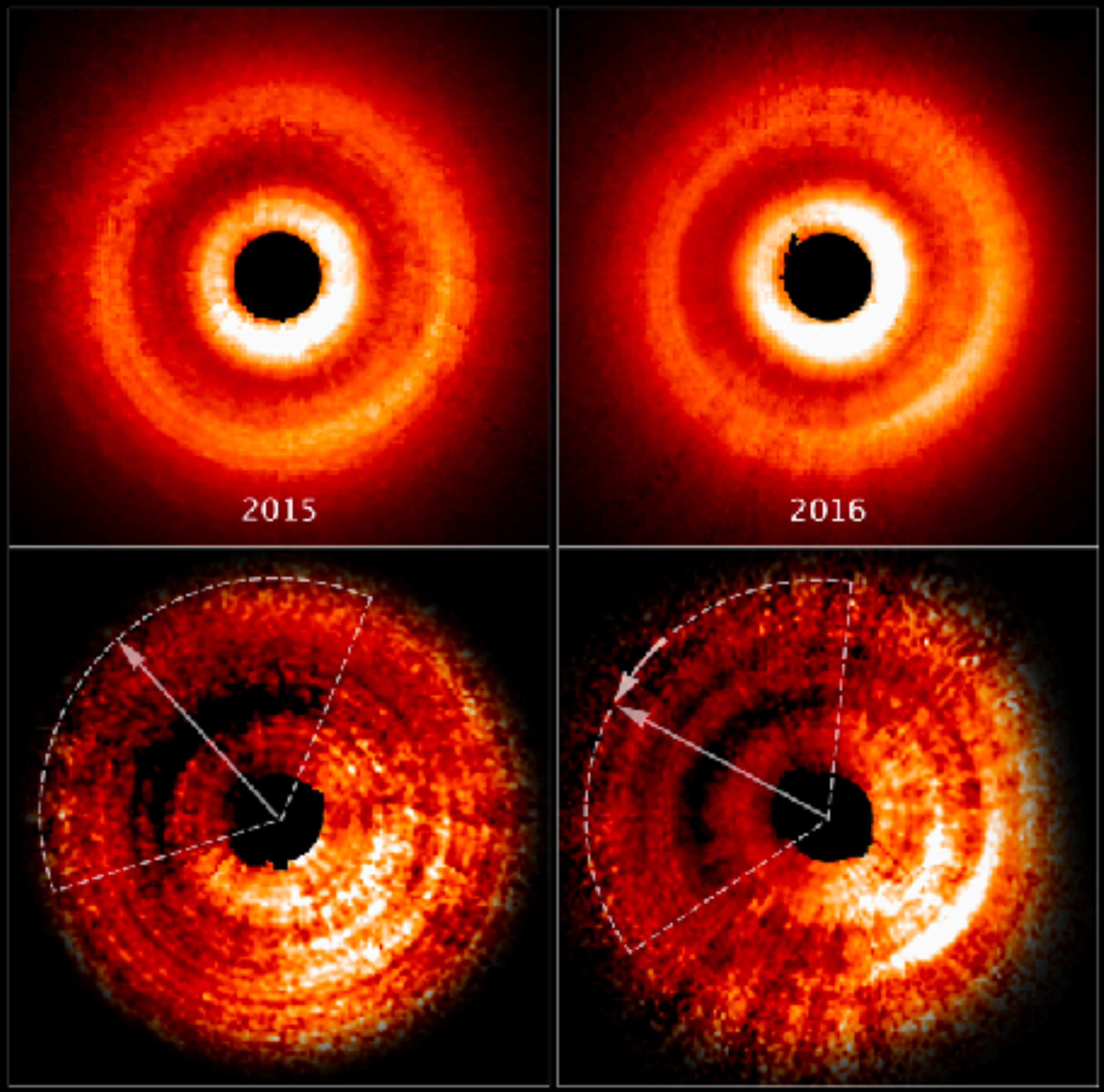
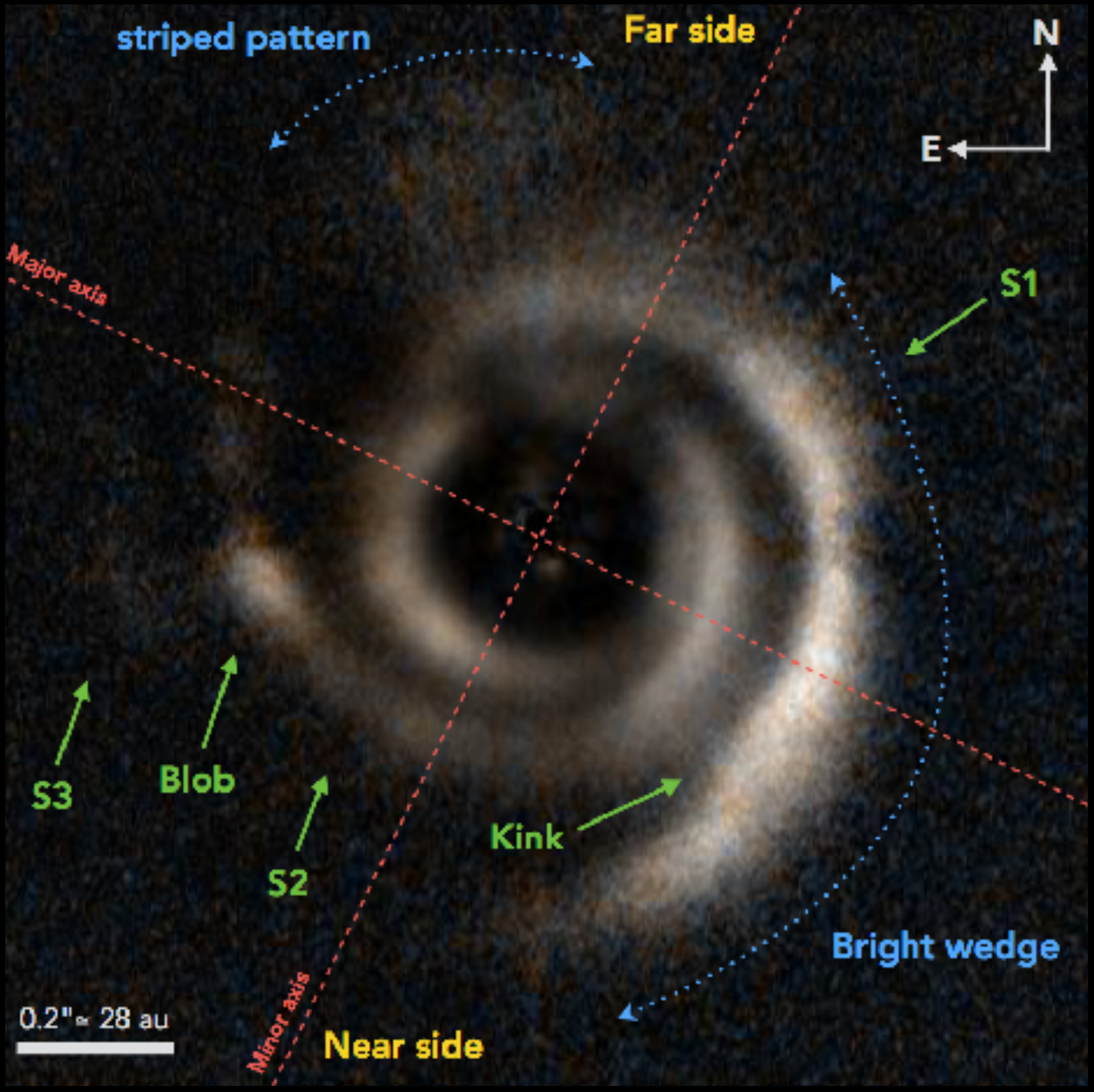
Warp driven shadows



TW Hya
Debes et al. 2017

HD 135344B
Figure 4,
Stolker et al. 2016



Planets misaligned to the mid-plane?

+ Low mass, so not currently observed

+ Know that planets affect disc structure

- Formation?

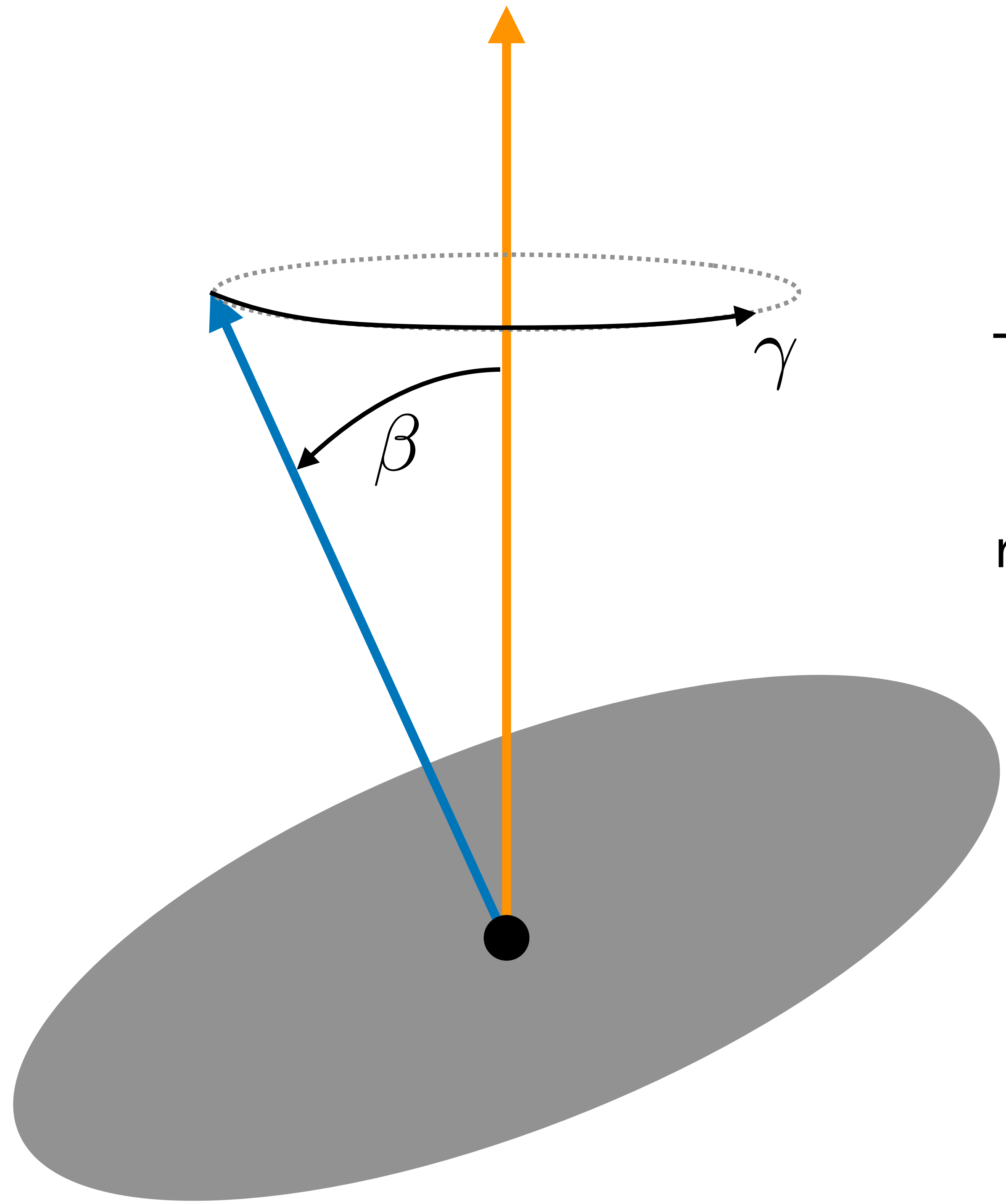
- How do they stay there?

1. Can we make interesting disc structures using misaligned planets?

2. Are these structures consistent with observations?

Tilt, twist and warp of the disc

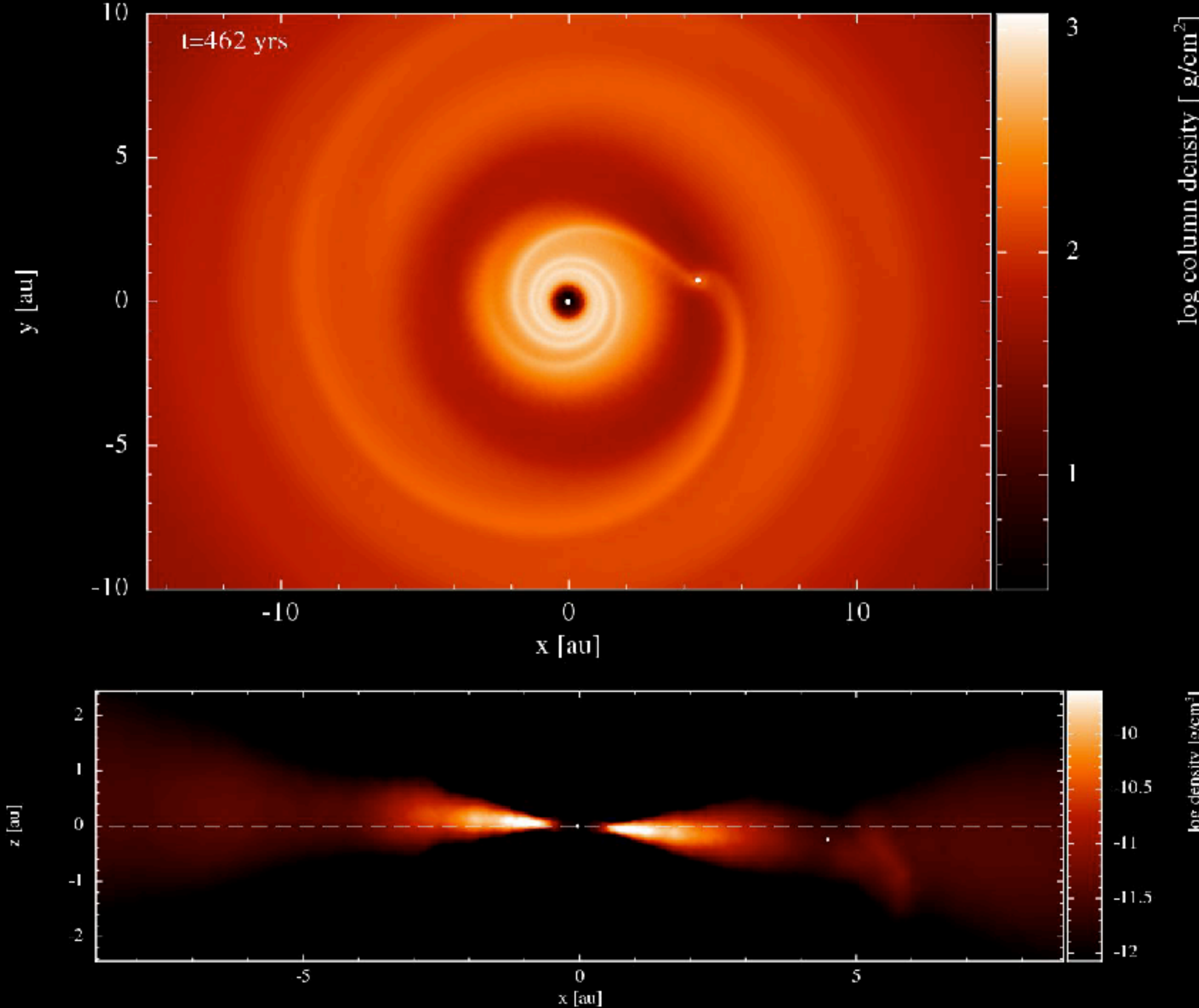
Tilt
The angle between the angular momentum vector and some reference



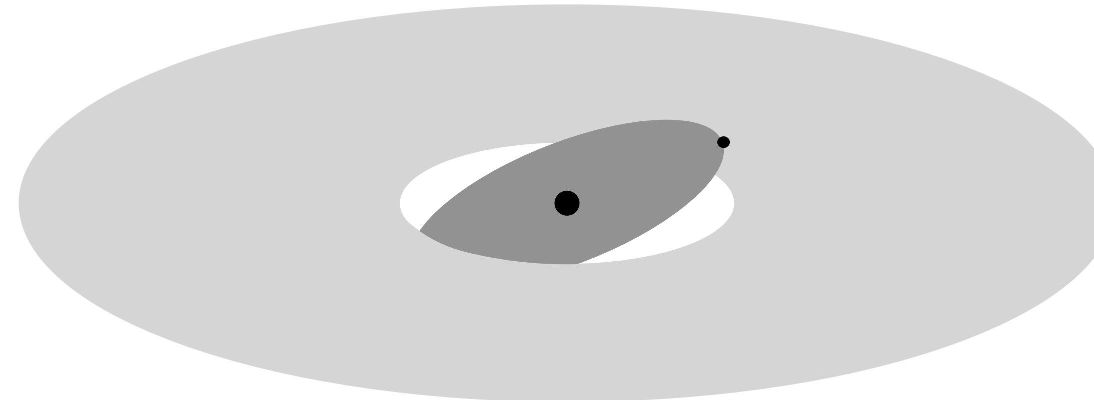
Twist
The angle the angular momentum vector traces around the reference vector from some point

$$\boldsymbol{\ell}(R,t) = (\cos\gamma\sin\beta, \sin\gamma\sin\beta, \cos\beta)$$

4 Jupiter mass planet inclined at 19 degrees



Timescales



(Dramatic schematic)

Time to open a gap:

$$t_{\rm gap} = \left(\frac{H}{R}\right)^2 t_\nu$$

(for a disc with 0.01 solar masses between 0.1 and 100 AU)

~160 planet orbits

Inclination damping of the orbit (e.g. Tanaka and Ward 2004):

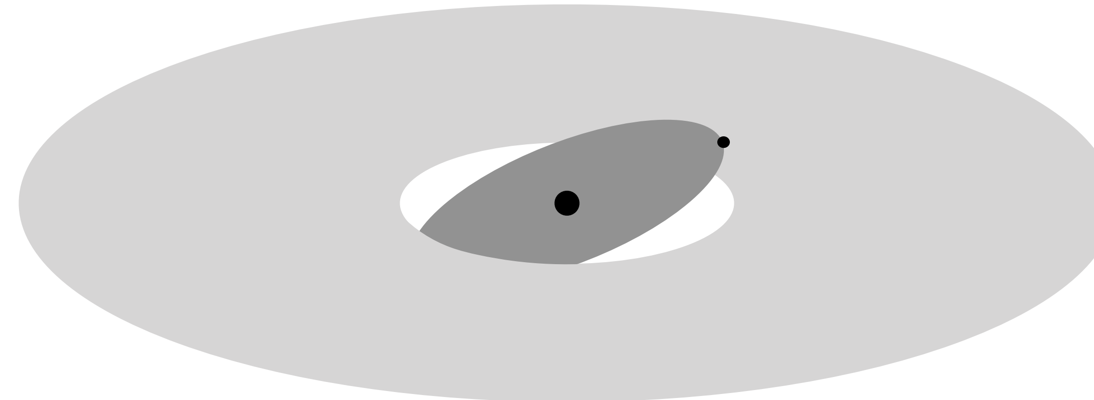
$$t_{\rm inc} = \Omega_p^{-1} \left(\frac{H}{R}\right)_p^4 \left(\frac{m_p}{M_*}\right)^{-1} \left(\frac{\Sigma_p r_p^2}{M_*}\right)^{-1}$$

Assuming a low mass planet, > 600 planet orbits

$$t_{\rm gap} < t_{\rm inc} \ll t_\nu$$

The planet will carve a gap before the inclination damps significantly.

Timescales



(Dramatic schematic)

Communication:

$$t_{\rm s} = \int \frac{2}{c_{\rm s}} dr$$

Inner disc: 3 planet orbits
Outer disc: ~150 planet orbits (Rout ~ 100 au)

Precession of the inner disc (Larwood et al. 2006):

$$t_{\rm prec} = 2\pi \left[\left(\frac{3Gm}{4a^3} \right) \cos\beta \frac{\int \Sigma r^3 dr}{\int \Sigma \Omega r^3 dr} \right]^{-1}$$

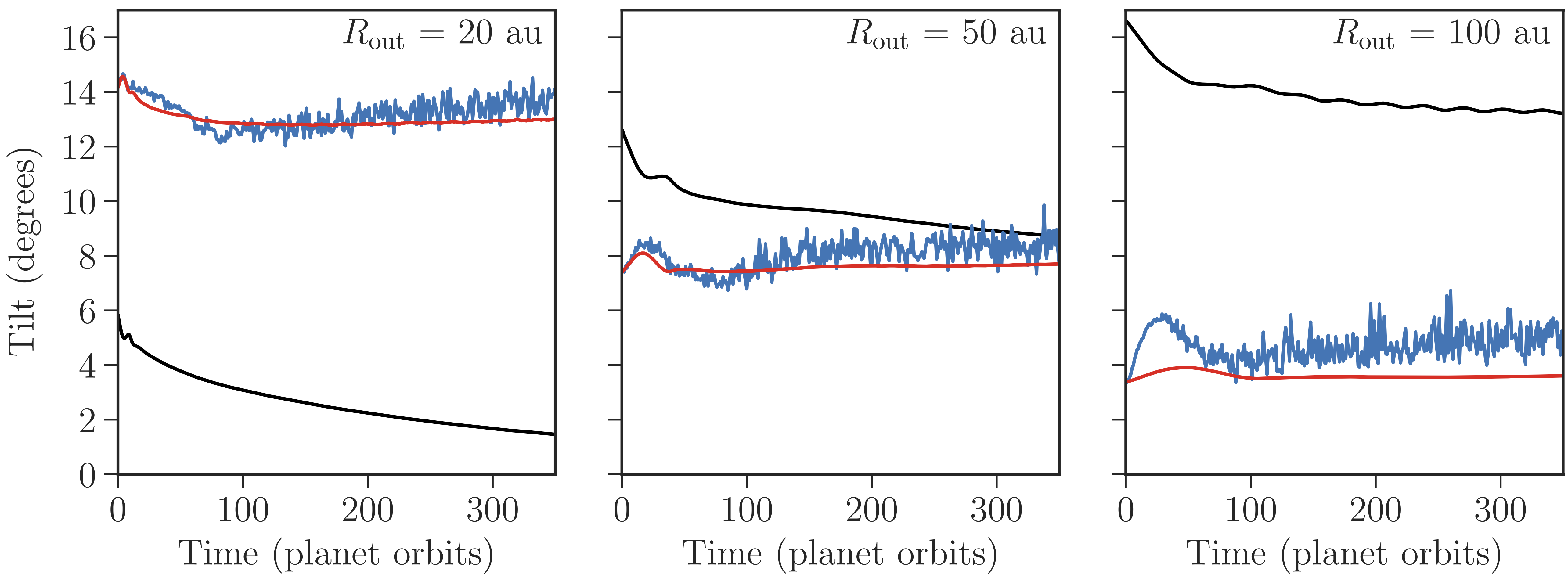
~490 planet orbits

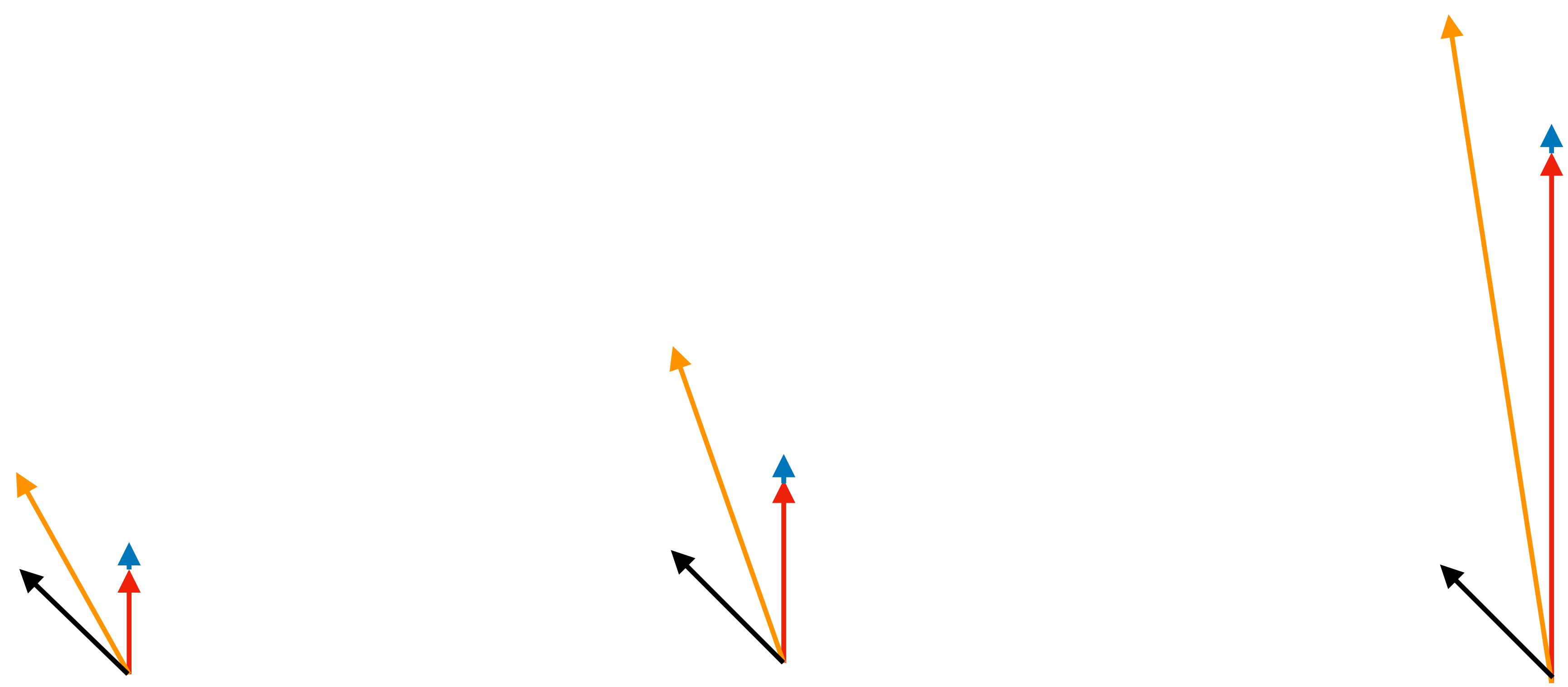
$$t_{\rm s} < t_{\rm prec}$$

The planet will carve a gap before the inclination damps significantly.

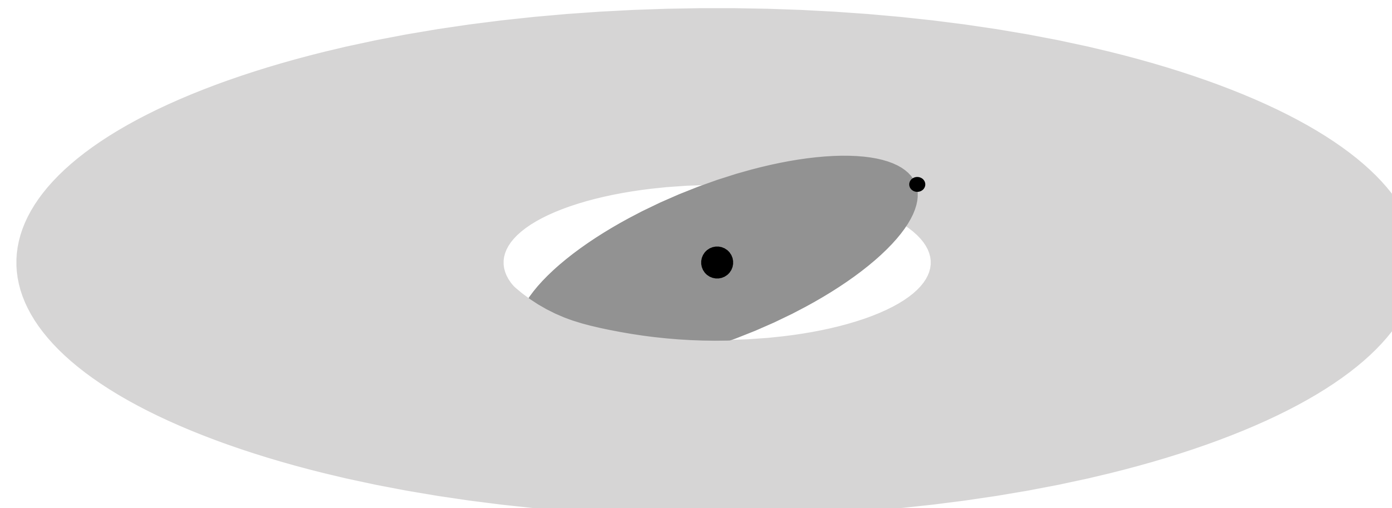
Both the inner and outer disc will precess due to the planet.

How large should Rout be?



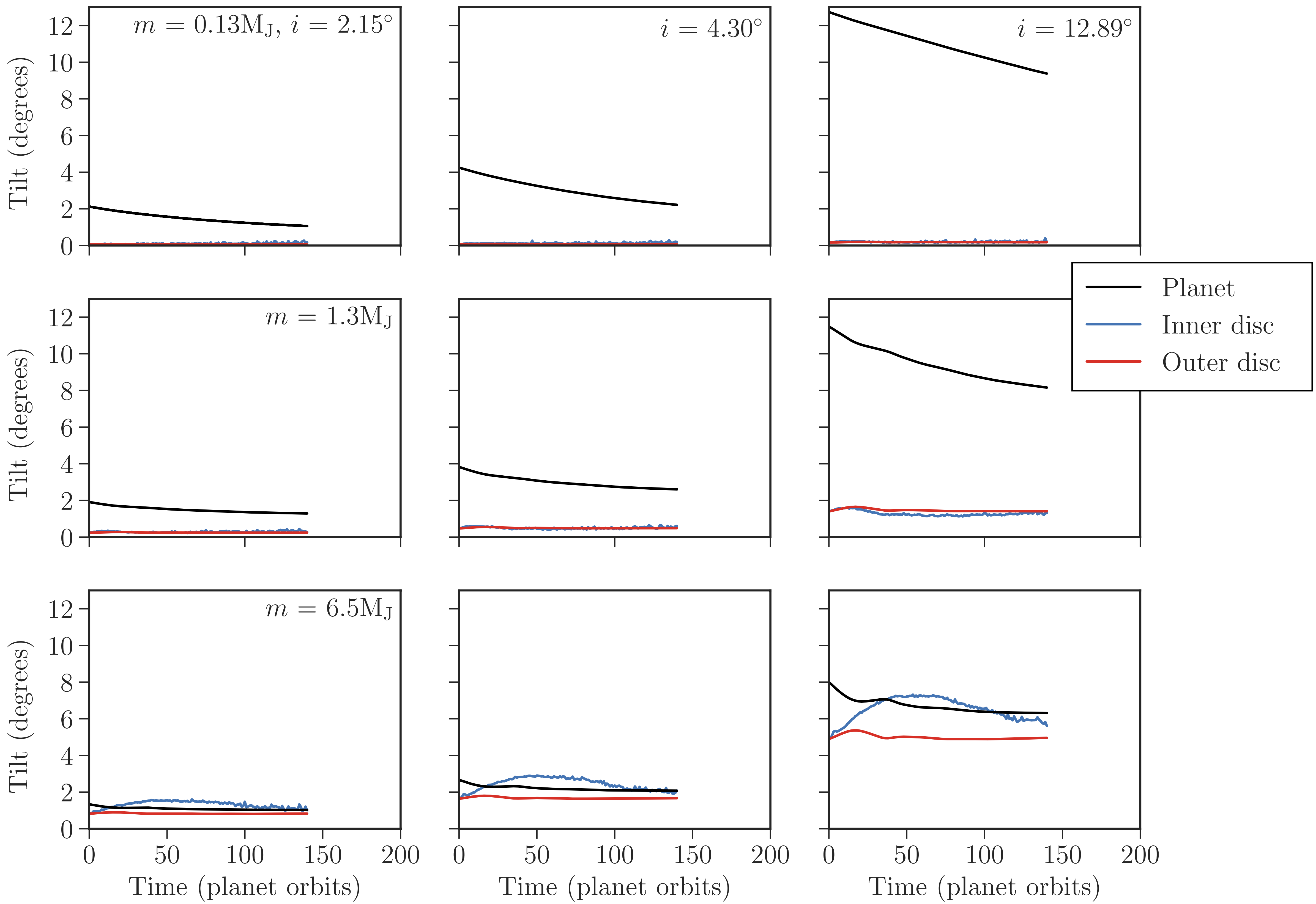


What drives the largest warp?

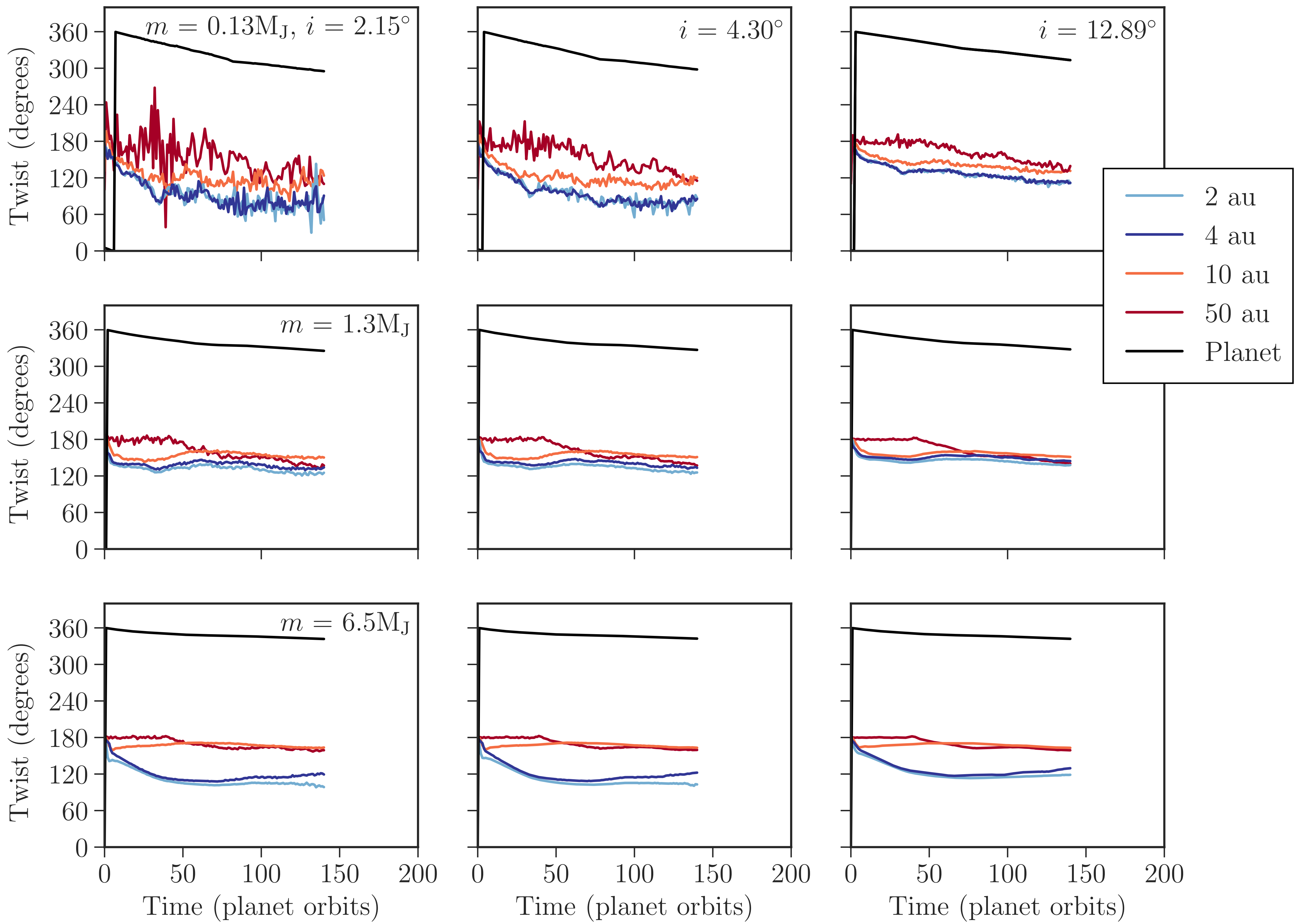


- Locally isothermal
- Outer radius of 50 au
- Disc mass of $0.01M_{\odot}$
- Consider both tilt and twist of inner vs. outer disc
- Planet masses of 0.13, 1.3 and 6.5 Jupiter mass
- Inclinations of 2.15, 4.30 and 12.89 degrees

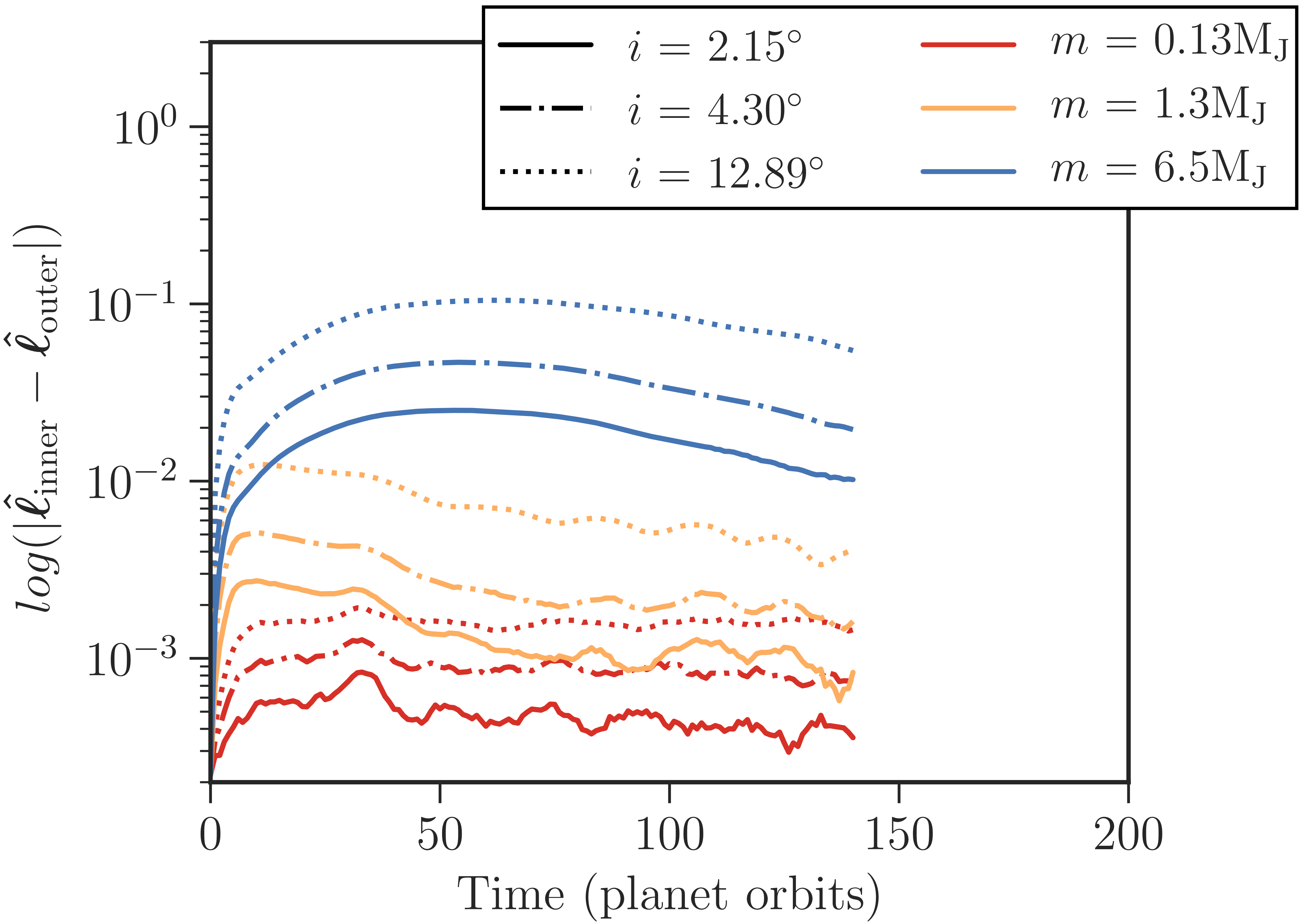
Driving warps: tilt



Driving warps: twist



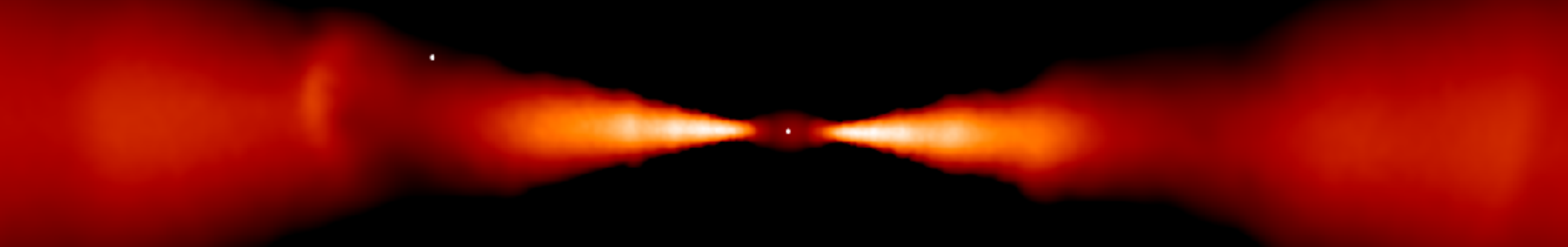
What drives the largest warp?



Summary

We demonstrate that SPH can model the **radial migration** and **inclination damping** timescales in the linear mass regime.

Modelling of the outer disc is **critical to determining the evolution of the warp** in the innermost region.



A massive misaligned planet will **tilt the disc**, and cause **precession of the inner and outer discs**. This movement of the disc occurs rapidly, **while the planet inclination damps**.

For a planet to create a warp that is observationally relevant, its **mass is more important** than the inclination it is on.