Instability and warping in vertically oscillating accretion disks

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PART I:
BACKGROUND & METHODS

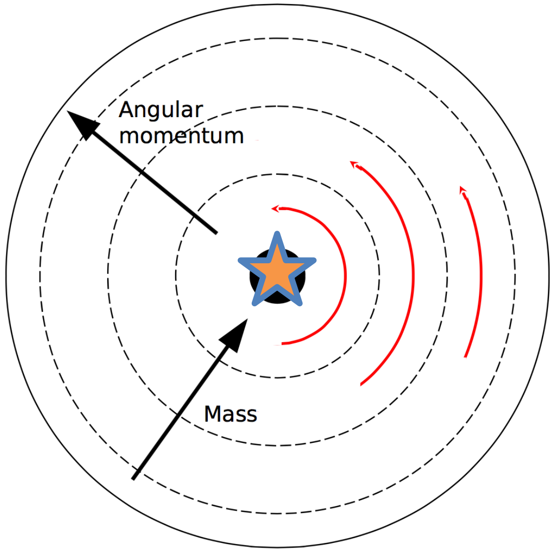
Types of distorted accretion disk

Classical picture of an accretion disk:

flat,

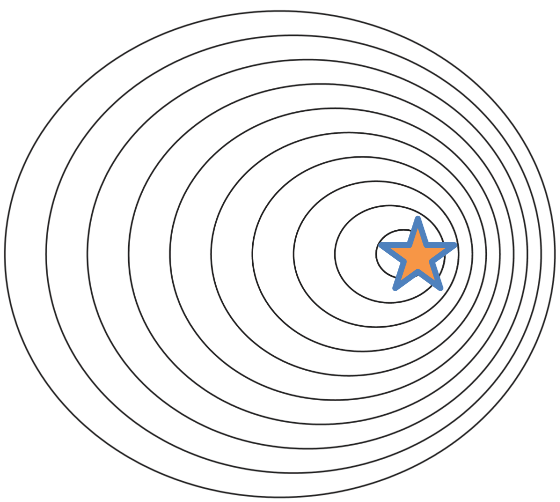
circular,

co-planar (e.g. with binary orbital plane)



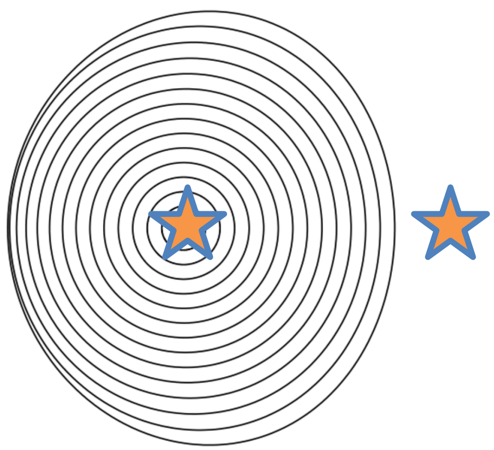
But can also get disks that are:

eccentric



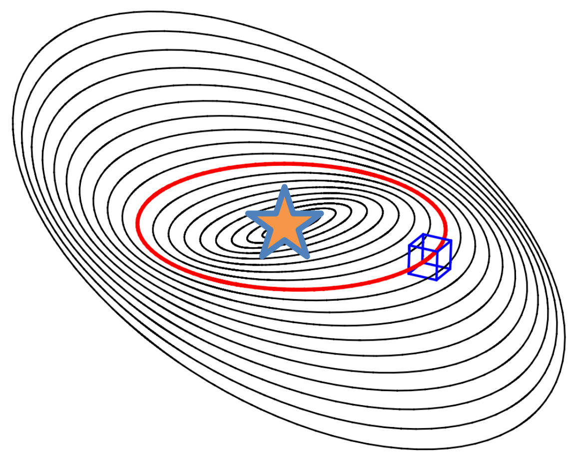
Ogilvie & Barker [2014]

tidally distorted



Ogilvie [2002]

tilted (or even warped)

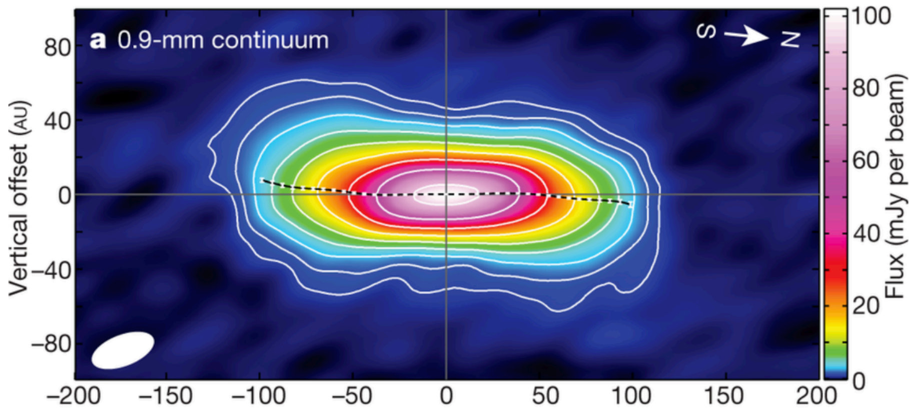


Ogilvie & Latter [2013]

Observations of distorted disks

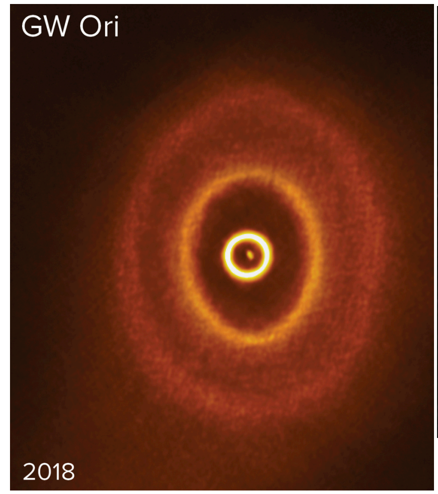
PROTOPLANETARY DISKS

IRAS 04368+2557

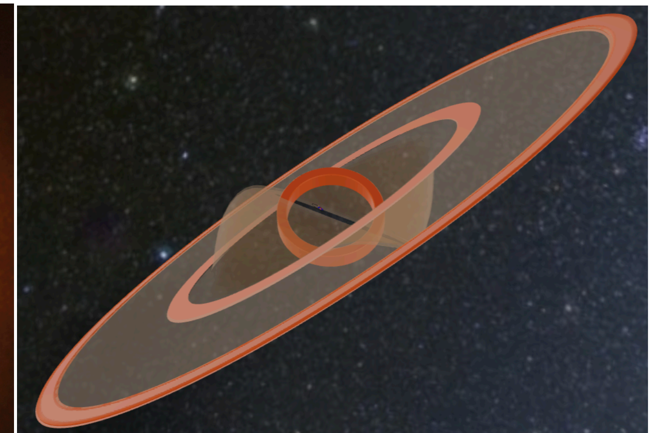


Sakai+2019: A warped disk around an infant protostar

GW Ori



ALMA/NRAO/AUI/NSF



NRAO/AUI/NSF

Kraus+2020: A triple-star system w/ a misaligned & warped disk

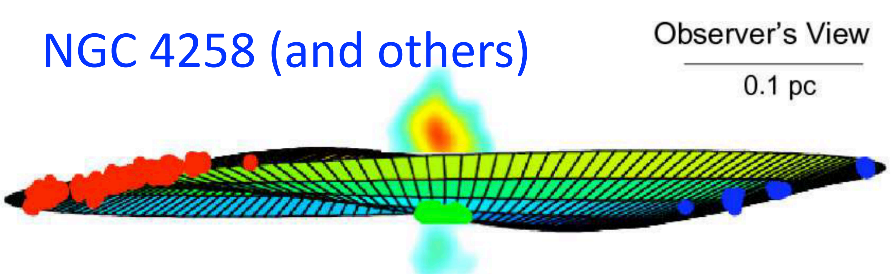
Other examples of distorted PPDs:

tilted/misaligned single disks: HK Tau, KH 15D

aligned circumbinary disks: GG Tau, DQ Tau, UZ Tau E

ACTIVE GALACTIC NUCLEI

NGC 4258 (and others)



Moran+2008: The Black Hole Accretion Disk in NGC 4258

X-RAY BINARIES

Her X-1, S433,

SMC MAXI J1820+070 (and others)

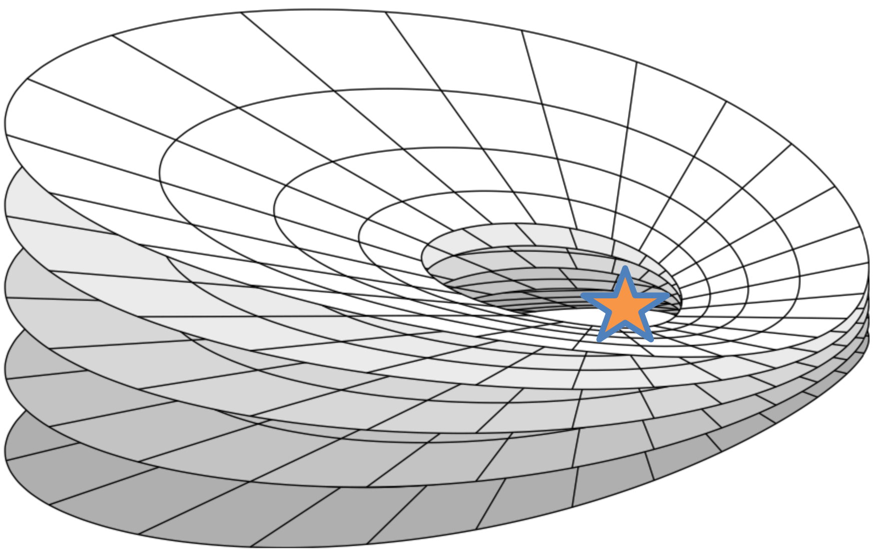
Processes in distorted disks

- precession (apsidal and/or nodal) Deng+2022
- disk tearing / breaking Lodato+2010, Nealon+2021, Young+2023
- **hydrodynamic "parametric instability" (resonant excitation of inertial waves)**
- **vertical oscillations** (also called: breathing modes / bouncing) ⟵ this talk

ORIGIN OF VERTICAL OSCILLATIONS IN DISTORTED DISKS:

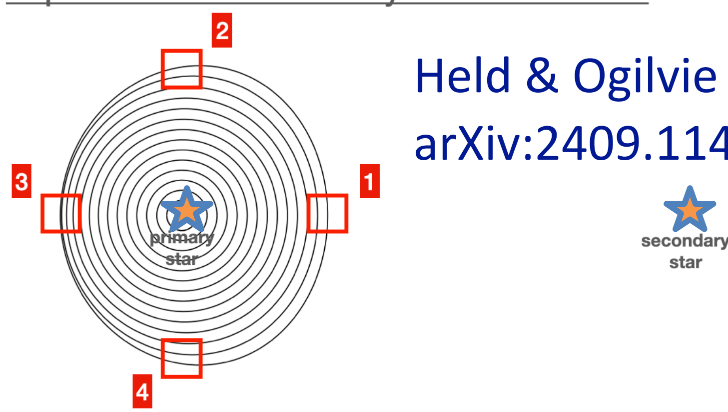
1. Eccentric & tidally distorted disks:

vertical component of gravity varies around a deformed (non-circular) orbit



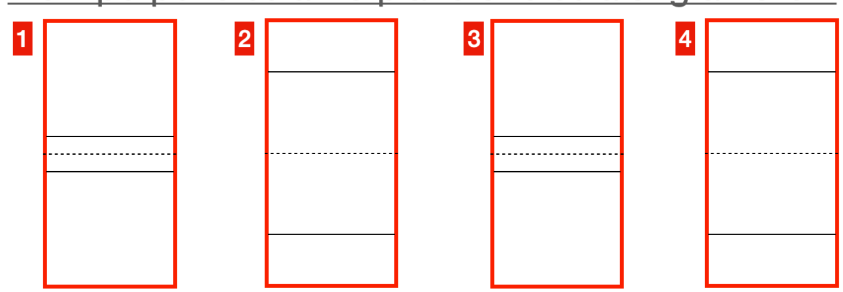
Global view of eccentric disk [Chan+2023]

Top down view of tidally distorted disc:



Held & Ogilvie (2024) arXiv:2409.11490

View perpendicular to plane of disc along an orbit:

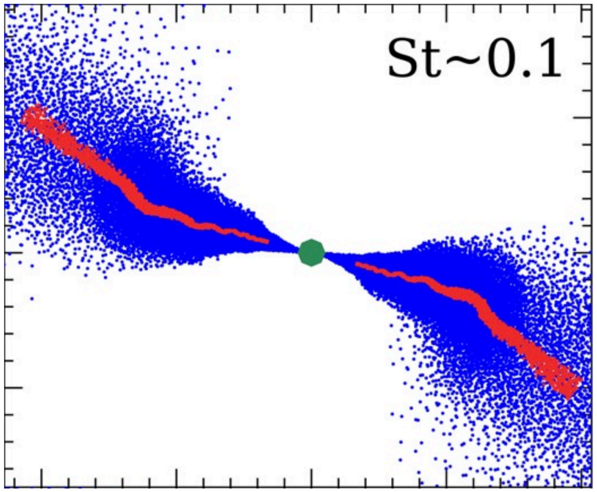


2. Warped disks: also get vertical oscillations due to combination of tilt and shear [Ogilvie & Latter 2013]

Modeling distorted disks

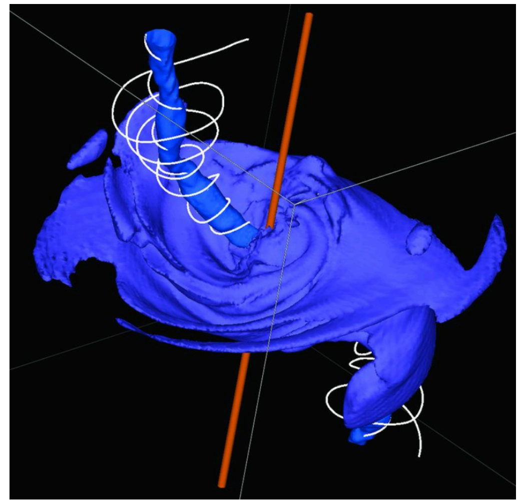
GLOBAL SIMULATIONS:

SPH simulations of **protoplanetary disks**:



Aly, Nealon+2024: A Warp-Induced Dust Instability in protoplanetary discs

Grid-based simulations of disks round **black holes**:

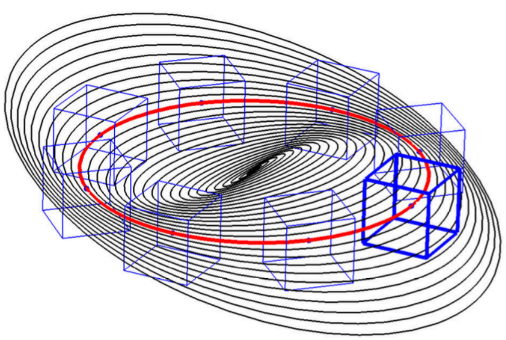


Mckinney+2012: Alignment of Magnetized Accretion Disks and Relativistic Jets with Spinning Black Holes

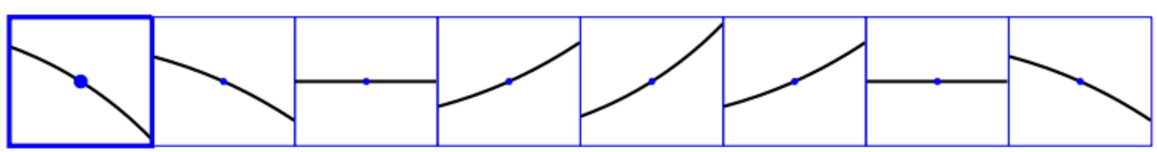
LOCAL MODELS:

Warps, eccentricity, tidal distortion…"feels" like an inherently global phenomenon.

In fact, much of the salient physics can also be captured in local models [see Ogilvie+2022]



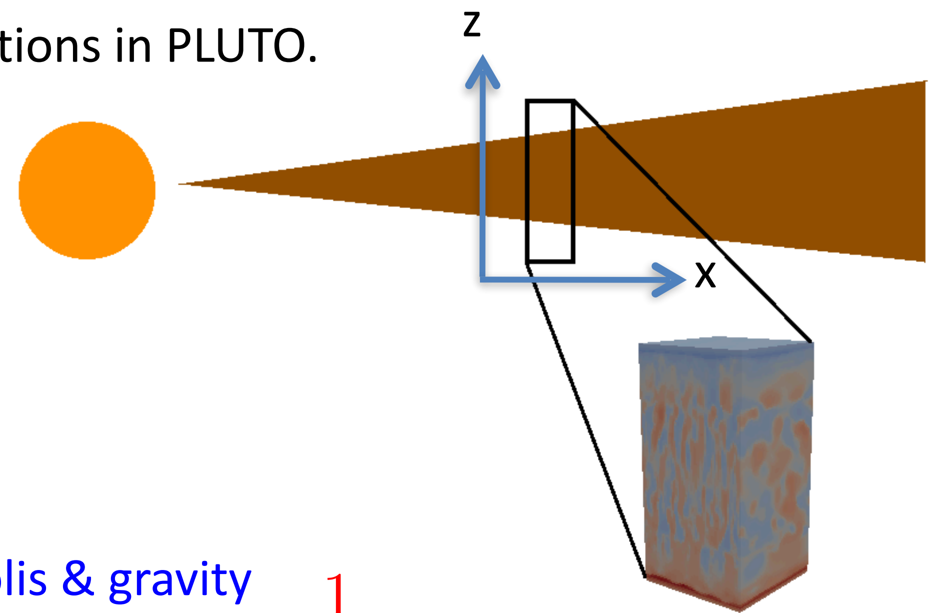
View of warped disk along orbit:



Methods: governing equations

Fully compressible 3D HYDRO shearing box simulations in PLUTO.

simulate a local patch of disk



CONSERVATION OF:

mass $$\partial_t \rho + \nabla \cdot (\rho \mathbf{u}) = 0,$$

coriolis & gravity

momentum $$\partial_t \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho}\nabla P - 2\boldsymbol{\Omega} \times \mathbf{u} + \mathbf{g}_{\mathrm{eff}} + \frac{1}{\rho}\nabla \cdot \mathbf{T}$$

viscosity

Close with **isothermal equation of state**: $$P = c_s^2 \rho$$

Tidal expansion of effective gravitational potential: $$\mathbf{g}_{\mathrm{eff}} = q\Omega^2 x\hat{\mathbf{x}} \boxed{- \Omega^2 z\hat{\mathbf{z}}}$$

include z-component of gravity

Remark: to force oscillations can include periodic variation in time in z-component

CODE USED FOR SIMULATIONS:

PLUTO (finite-volume code for astrophysical fluid dynamics)

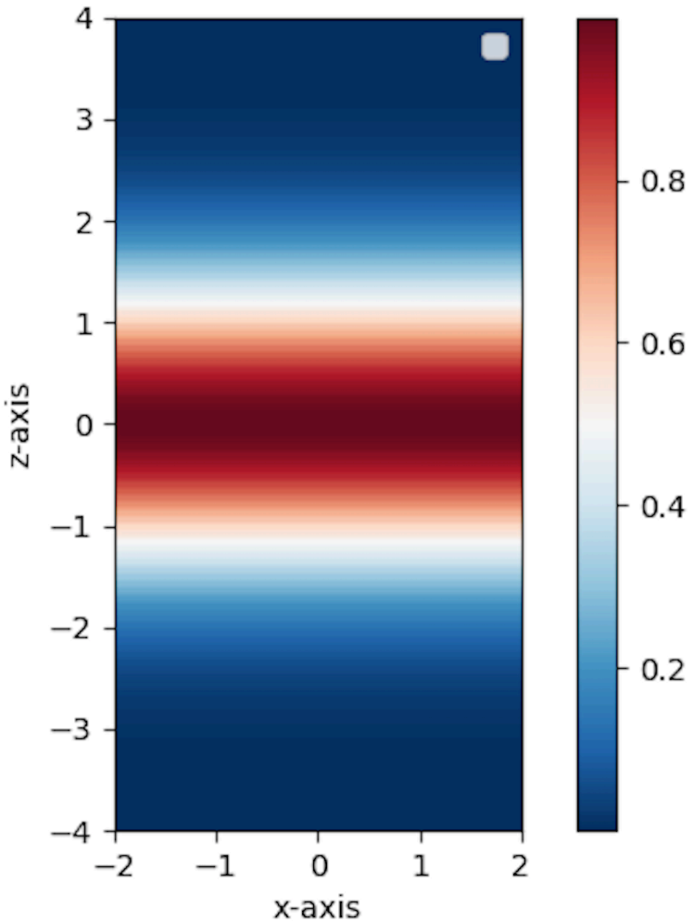
Mignone+2007,2012

Methods: set-up and initial condition

To facilitate vertical oscillation rescale initial density profile.
[Useful for studying free (unforced) oscillations.]

Equilibrium profile:

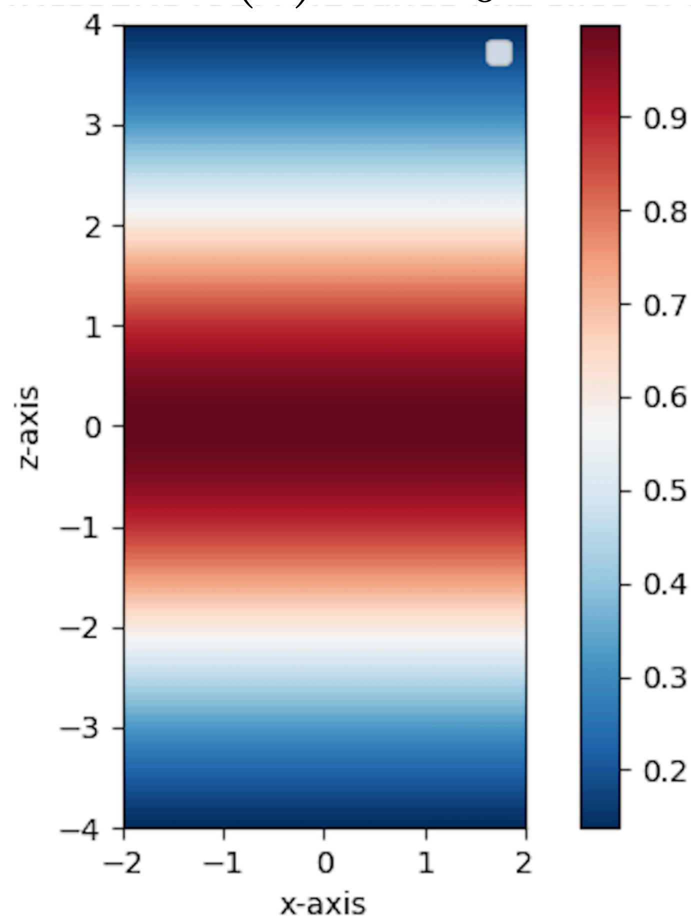
$$\rho = \rho_0 \exp(-z^2/2H_0^2)$$



Rescaled profile:

$$\rho = \rho_0 \exp(-z^2/2H(0)^2)$$

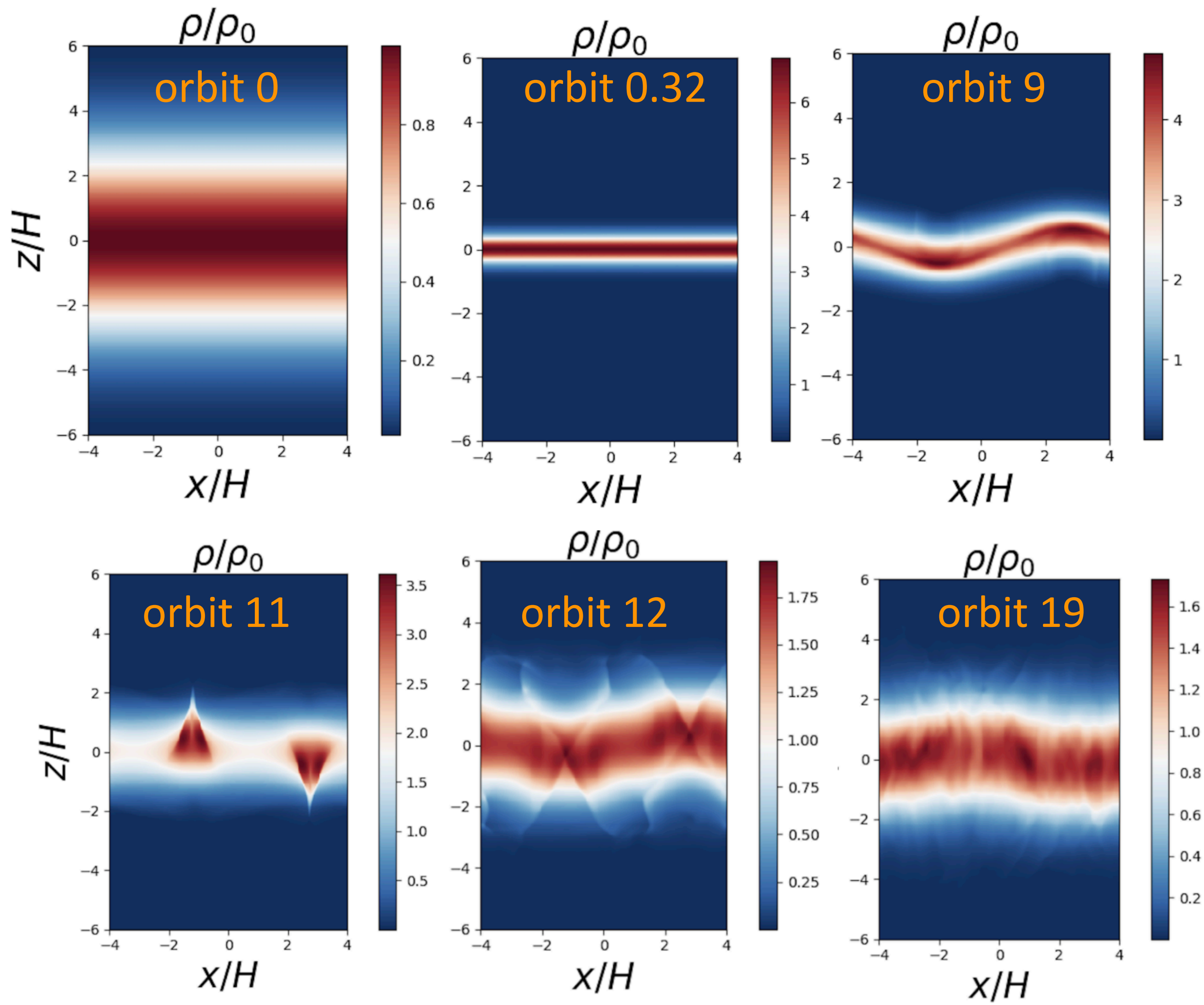
$$H(0) > H_0$$



PART II:
RESULTS

RESULTS: unforced oscillations

Density evolution in plane perpendicular to the disk

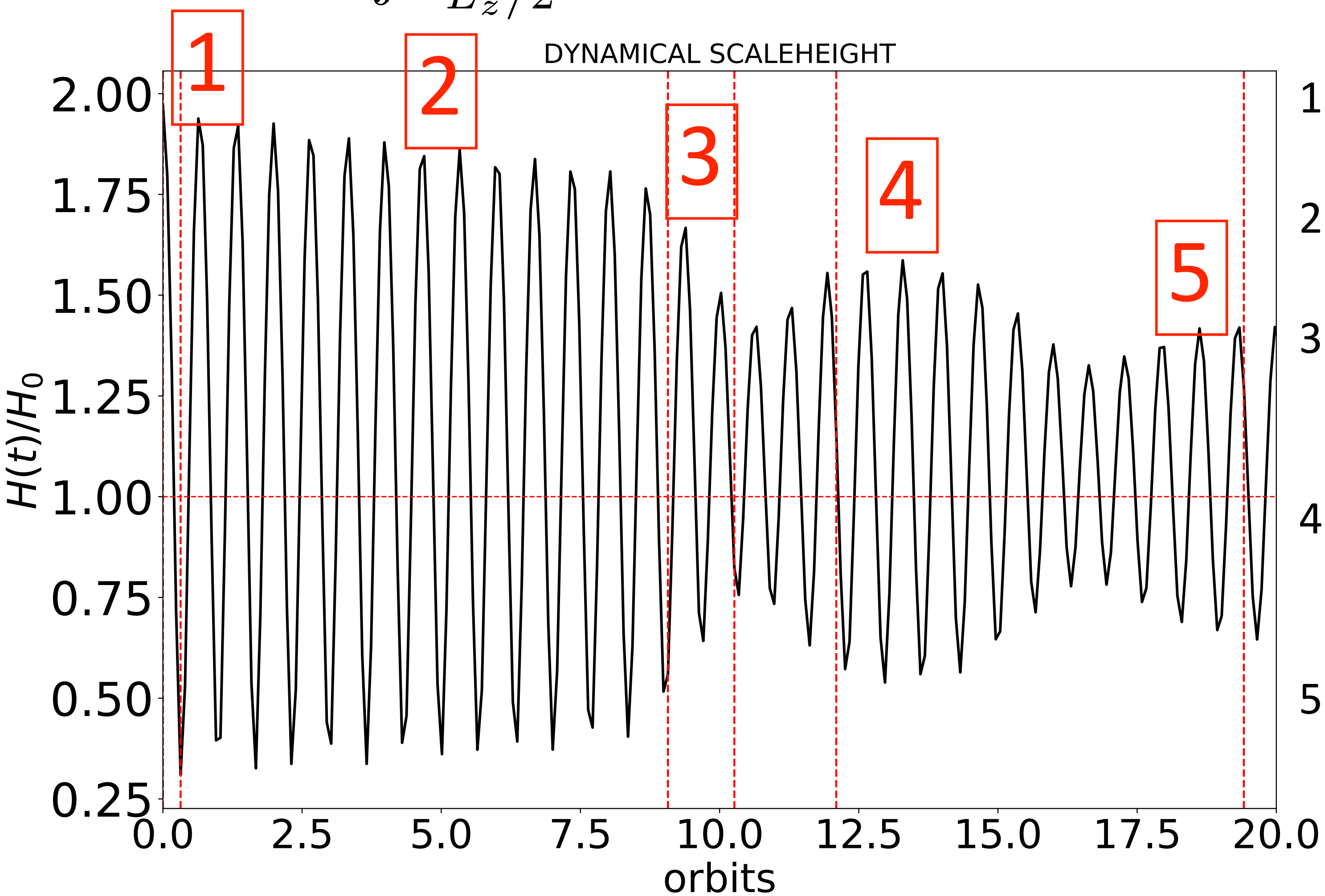


RESULTS: unforced oscillations

Disk thickness (scale-height) changes with time.

Suitable diagnostic is "dynamical scale-height" defined as

$$H^2(t) = \frac{1}{\Sigma}\int_{-L_z/2}^{L_z/2} \langle\rho\rangle_{xy} z^2 dz$$



1. **Period** (1.5 times per orb) (set by amplitude)
2. Dissipation of oscillation small during first few orbits
3. Large dissipation after corrugation develops due to **shocks**
4. Oscillation can be "re-invigorated" on short time-intervals
5. On long time-scales oscillation is damped since there is no forcing

RESULTS: theoretical modeling of behavior

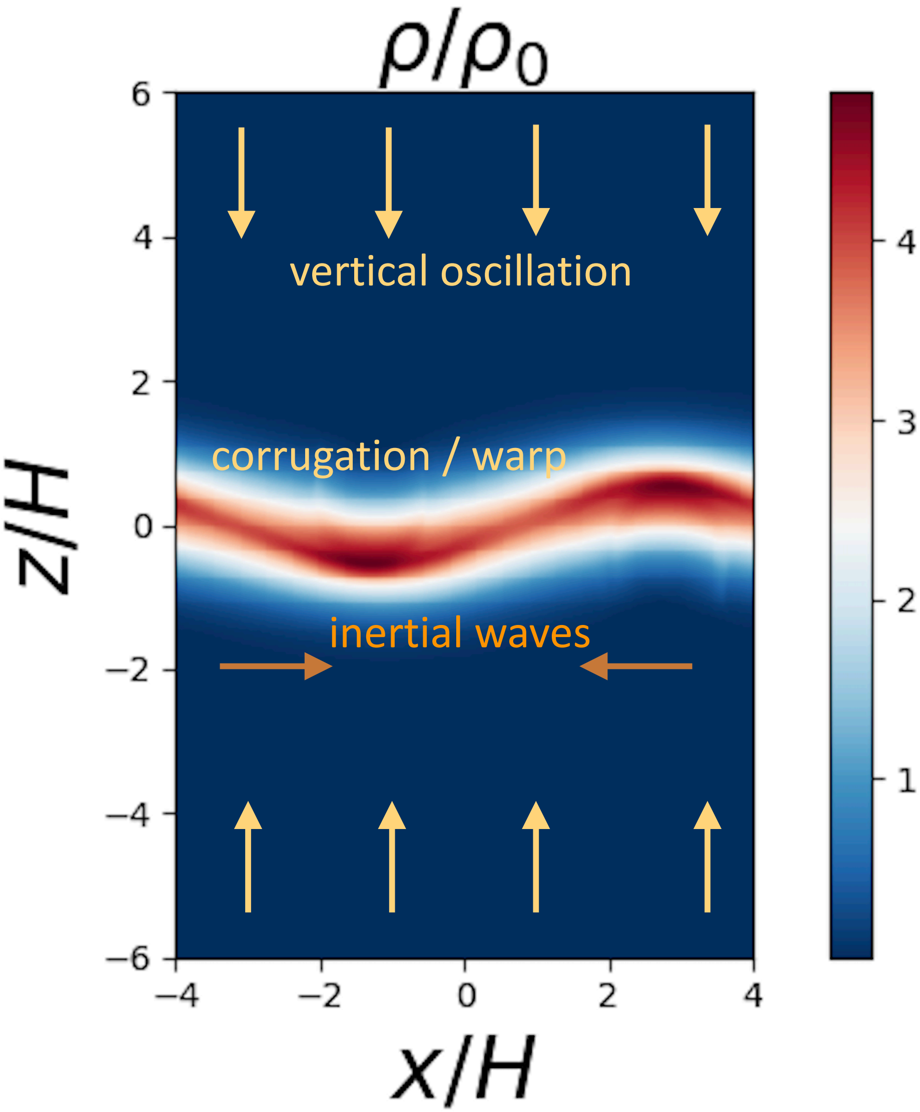
1. Oscillation frequency can be predicted from simple 1D model of vertical oscillations

$$\ddot{H} = -H + H^{-1}$$

predicted frequency: ~1.5 oscillations / orbit (agrees with simulation)

2. Investigated stability of vertically oscillating background to radial perturbations

predicted growth rate in very good agreement with simulation



3. Mechanism:

- **Vertical oscillations destabilize inertial waves causing them to grow (parametric instability)**
- Two such growing traveling waves propagating in opposite directions combine to form a standing wave (**the corrugation / bending wave**)
- An example of **three-mode coupling**: parent mode (the vertical oscillation) couples with two daughter modes (inertial waves propagating inwards and outwards)

[also see: Barker+2014]

Conclusions and Future Work

Hydrodynamic instability in vertically oscillating discs

Held & Ogilvie (2024) arXiv:2409.11490

- distorted disks <u>not</u> in vertical hydrostatic equilibrium => vertical oscillations

- new result: oscillations destabilize inertial waves (by means of hydrodynamic parametric instability), leading to <u>growth of a corrugation/ bending wave / warp</u>

- dissipation of oscillations is dominated by shocks

- local formalism very useful for studying these kinds of dynamics

Future work: interaction of parametric instability and MRI

- disks often ionized: gas interacts (and can grow) magnetic fields

- study interplay between hydrodynamic parametric instability (HPI) and magnetorotational instability (MRI)