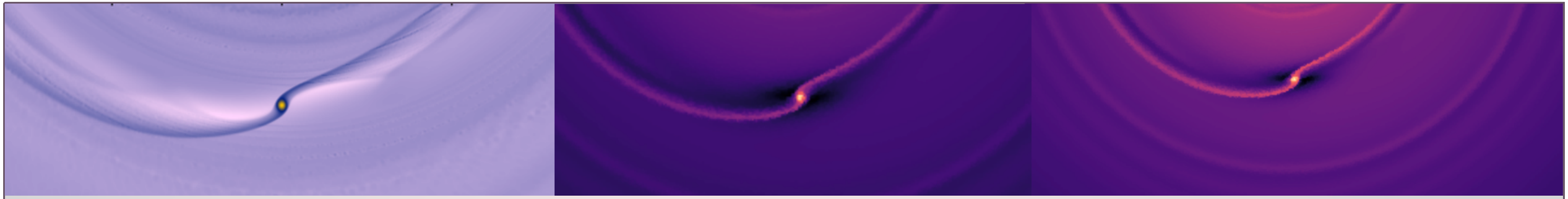


Disc IMRI Code Comparison

LISA Astro Working Group Project

Andrea Derdzinski (Fisk University) she/they

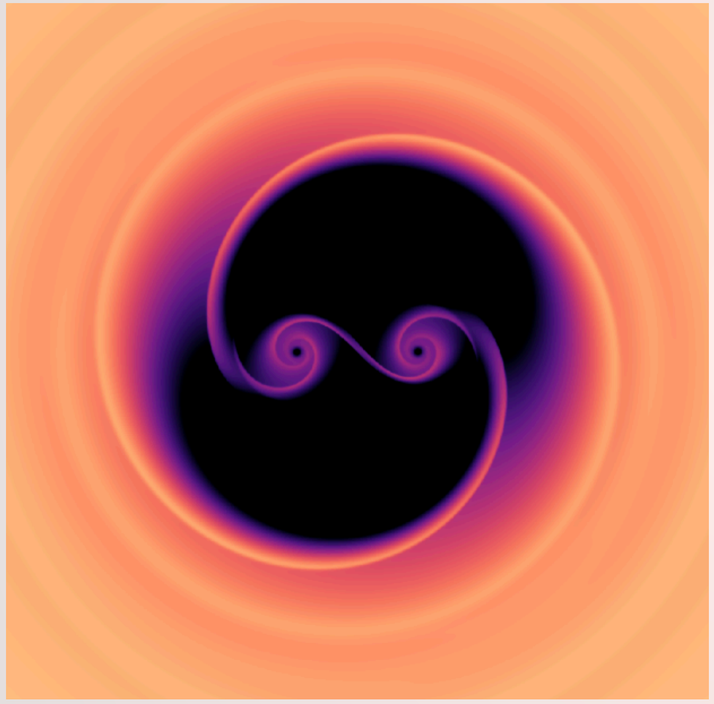
with Alexander Dittmann, Alessia Franchini, Alessandro Lupi,
Noé Brucy, Pedro Capelo, Daniel J D'Orazio, Mudit Garg, Frédéric Masset, Lucio Mayer, Jonathan Menu, Raphaël Mignon-Risse,
Michael Rizzo Smith, Roberto Serafinelli, Olga Sergijenko, Martina Toscani, David, A. Velasco Romero, Robert Wissing

LISA Astrophysics Working Group meeting, MPA Garching, 4 November 2024

Science Target

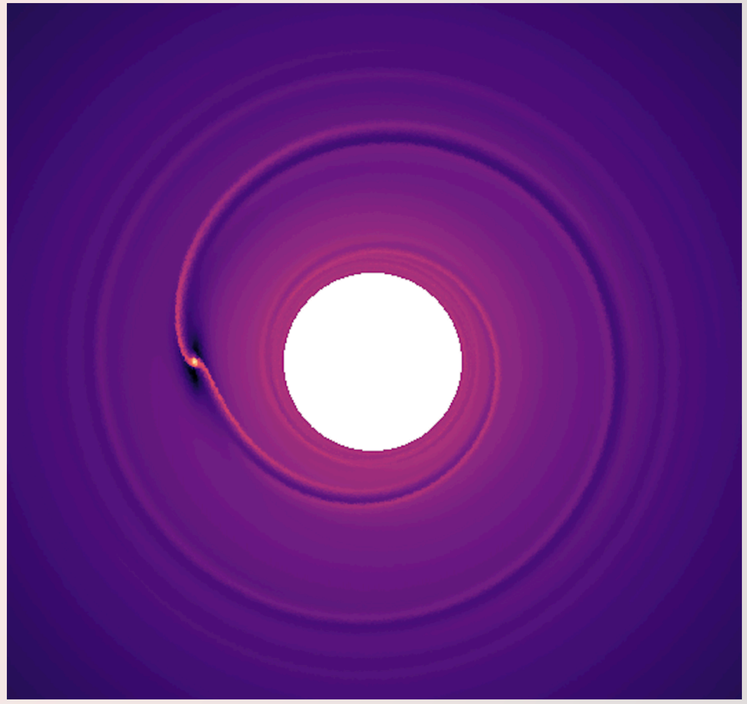
Study the convergence of torques and flow of gas around highly unequal mass binary system.

$$q = M_2/M_1 = 1$$



Duffell et al. 2024

$$q \ll 1$$



This work

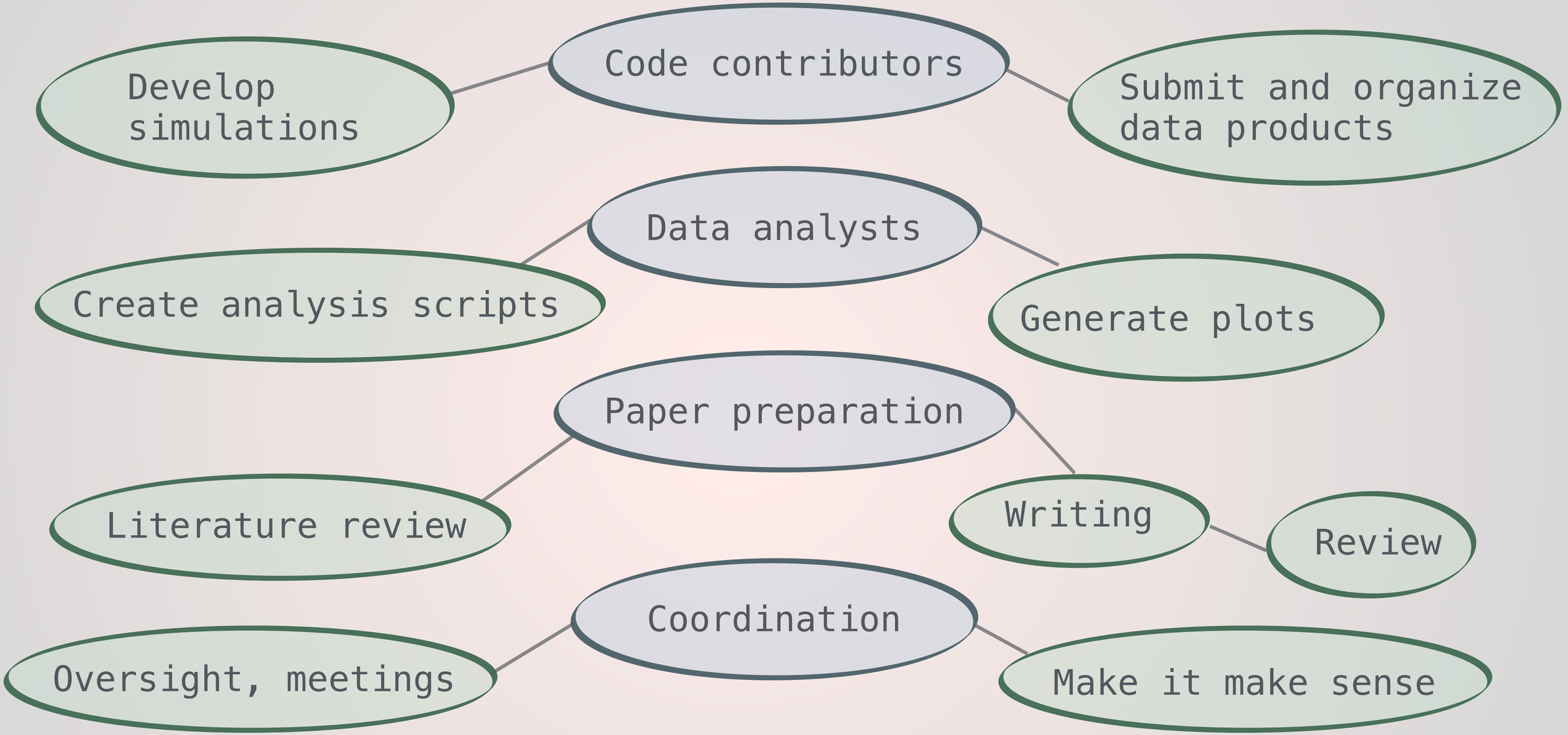
Motivation

- How does gas impede or drive the binary inspiral?
- Are there characteristic EM counterparts?
- Implications for binary formation and merger rates
- How will gas interactions manifest in gravitational waves?

The Team

Noé Brucy, Pedro Capelo, Daniel J D'Orazio, **Andrea Derdzinski**, **Alexander Dittmann**, **Alessia Franchini**, Mudit Garg, **Alessandro Lupi**, Frédéric Masset, Lucio Mayer, Jonathan Menu, Raphaël Mignon-Risse, Michael Rizzo Smith, Roberto Serafinelli, Olga Sergijenko, Martina Toscani, David, A. Velasco Romero, Robert Wissing

Collaboration structure



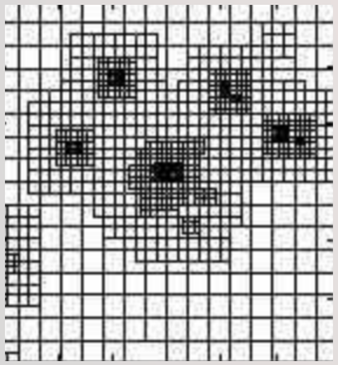
Codes and techniques

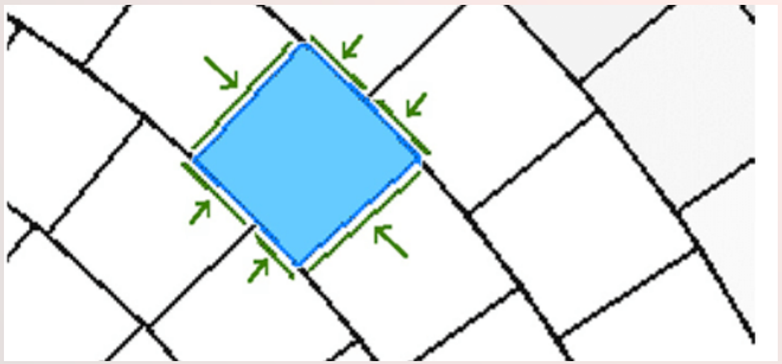
Eulerian (2D)

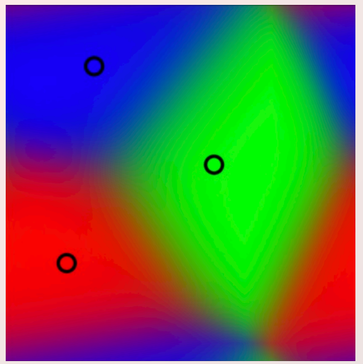
- Athena++ (Fixed mesh / AMR)
  Stone et al, 2020
- DISCO (Cylindrical moving mesh)
  Duffell 2016
- FARGO3D (Staggered mesh)
  Benítez-Llambay & Masset 2016
- RAMSES (Cartesian AMR)
  Teyssier 2001

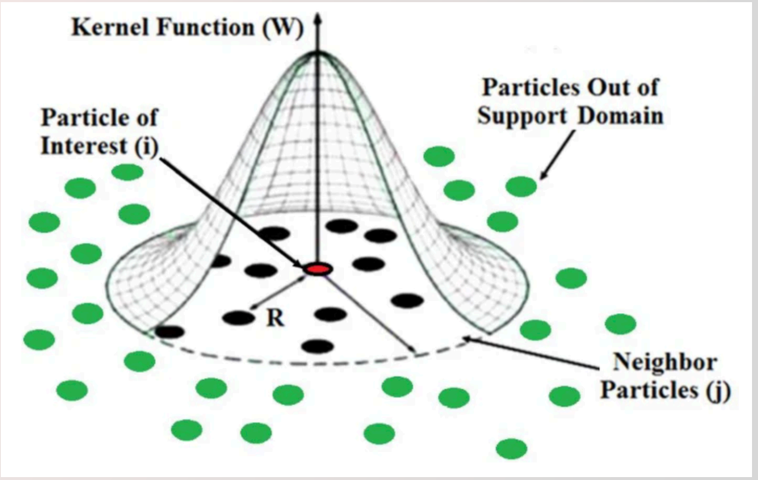
Lagrangian (3D)

- GIZMO (Meshless Finite Mass)
  Hopkins 2014
- PHANTOM (SPH)
  Price et al. 2018
- GASOLINE2 (SPH)
  Wadsley et al. 2017









Simulation setup

sub-parsec scale accretion disk around an SMBH

Disk:

- Geometrically thin h<<r
- Disk mass << binary mass
- Isothermal
- Viscosity: alpha = 0.1

Binary:

- q = M2/M1 = 10^{-4}
- Fixed, circular orbit

Disk thickness:

Mach = $(h/r)^{-1}$

Parameter choices

Pushing towards the ‘AGN-like’ regime: highly viscous thin disk

$$r_{\mathrm{Hill}} = \left(\frac{q}{3}\right)^{1/3} r$$

Run 1: $r_{\mathrm{Hill}} < h$

Linear predictions:
Tanaka & Ward 2002,
Tanaka & Okada 2024,
Paardekooper et al. 2010

Run 2: $r_{\mathrm{Hill}} > h$

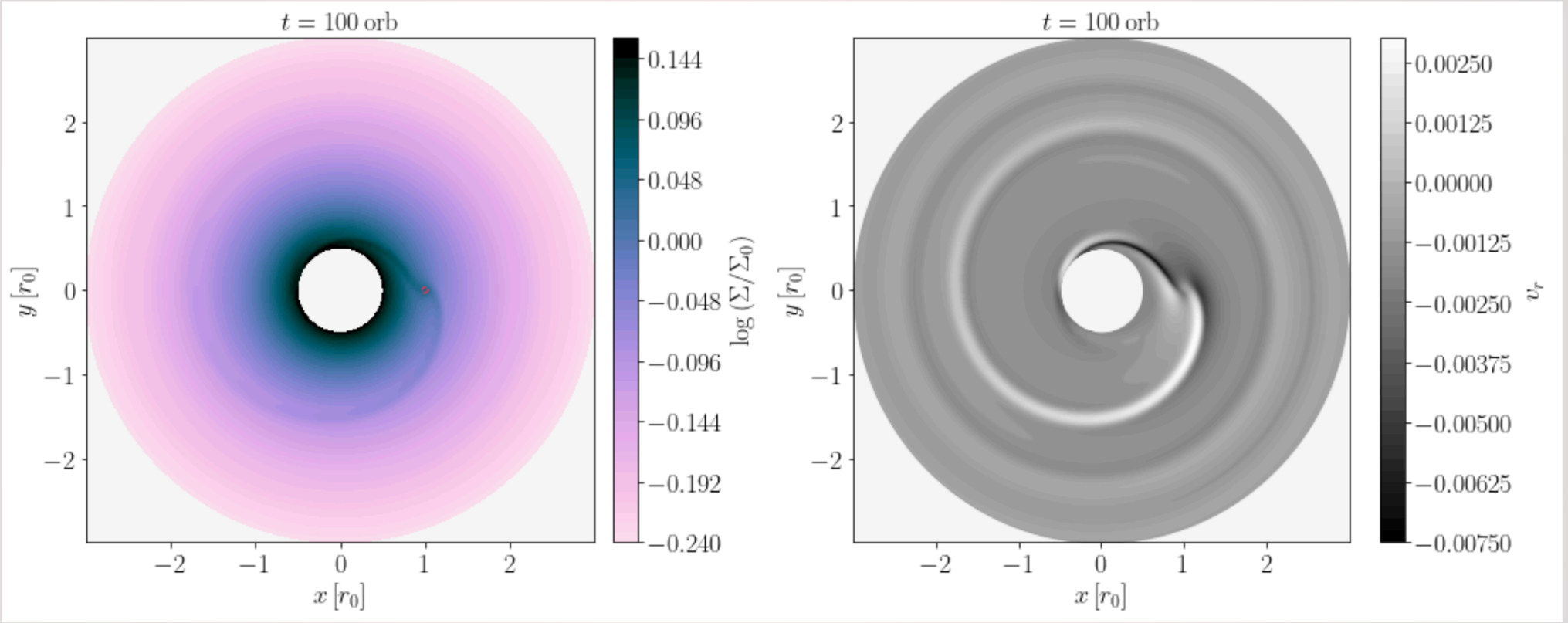
Mass exceeds the thermal mass – no analytical predictions!

Gas morphology

Formation of spiral density waves, diffuse with high viscosity

Surface density

Radial velocity

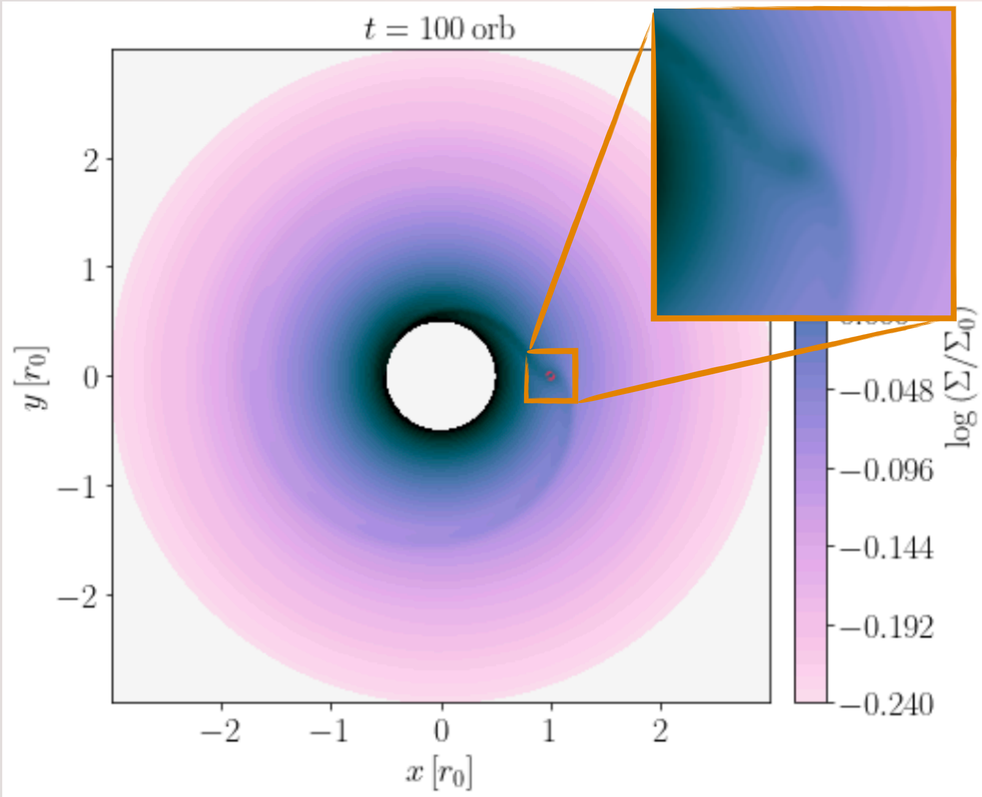


DISCO

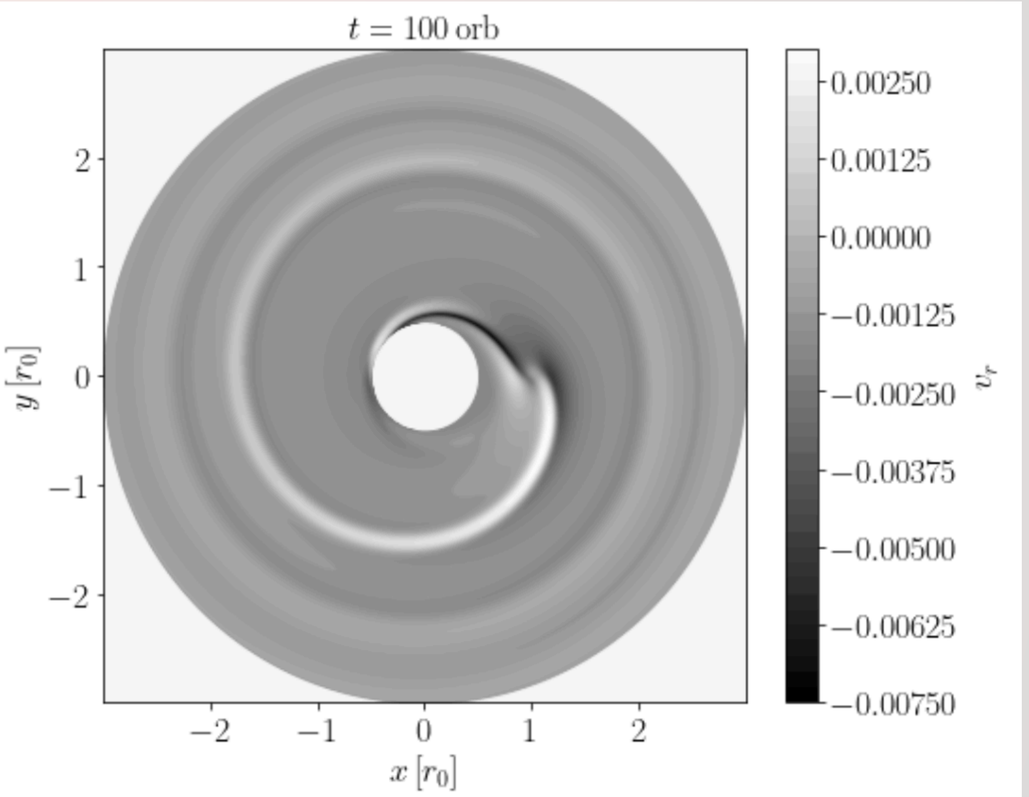
Gas morphology

Formation of spiral density waves, diffuse with high viscosity

Surface density



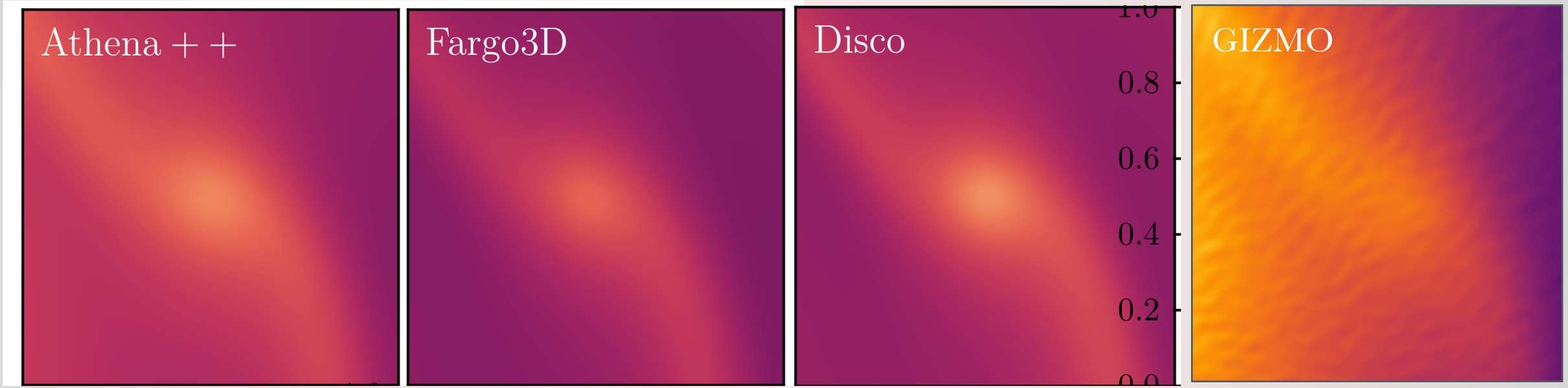
Radial velocity



DISCO

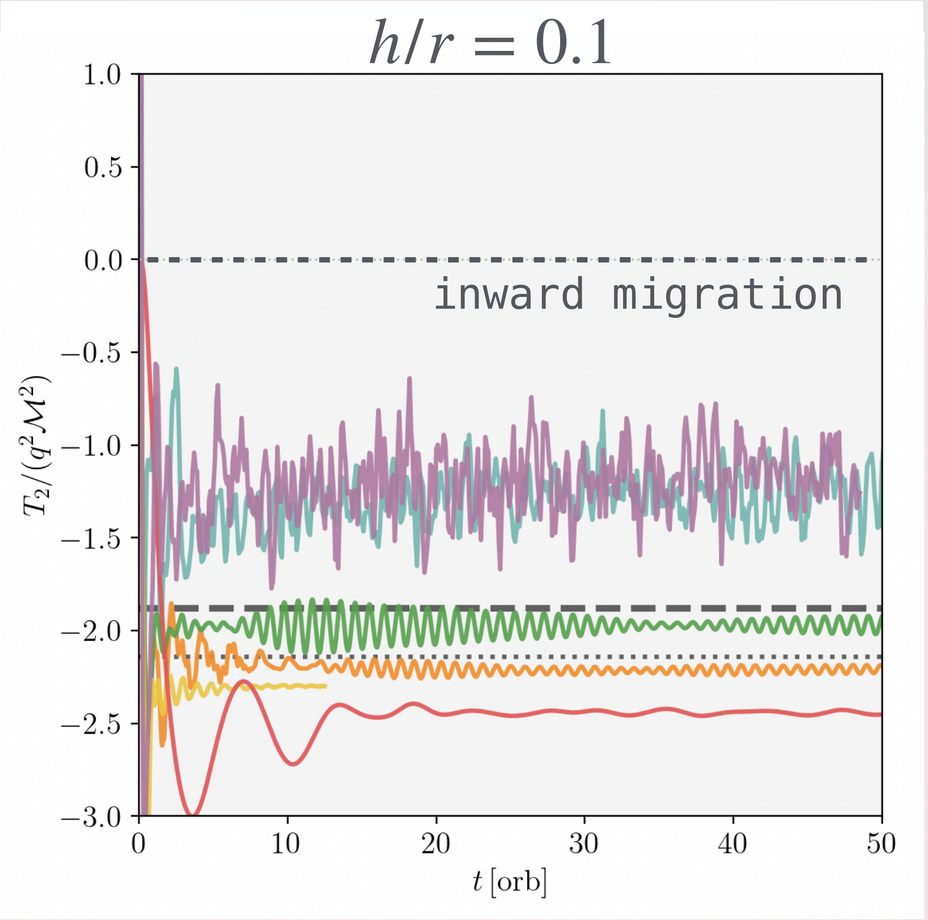
Gas morphology

Moderately thin disk (h/r = 0.1)



Nonaxisymmetries exert torques

Torque on secondary
vs time

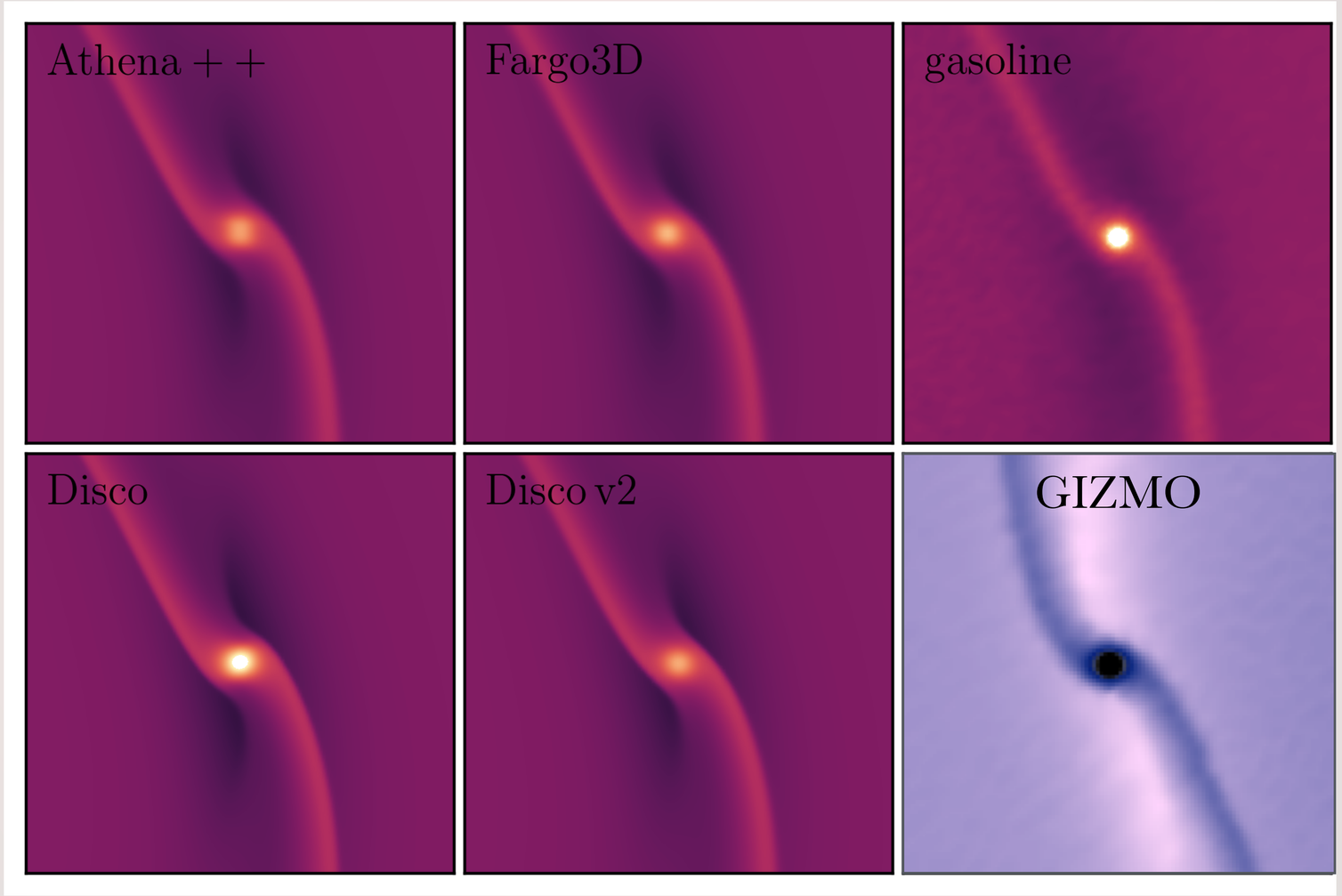


Analytical estimates

athena++ fargo3d disco Paardekooper + 2010
gizmo ramses phantom Tanaka&Okada2024(3D)

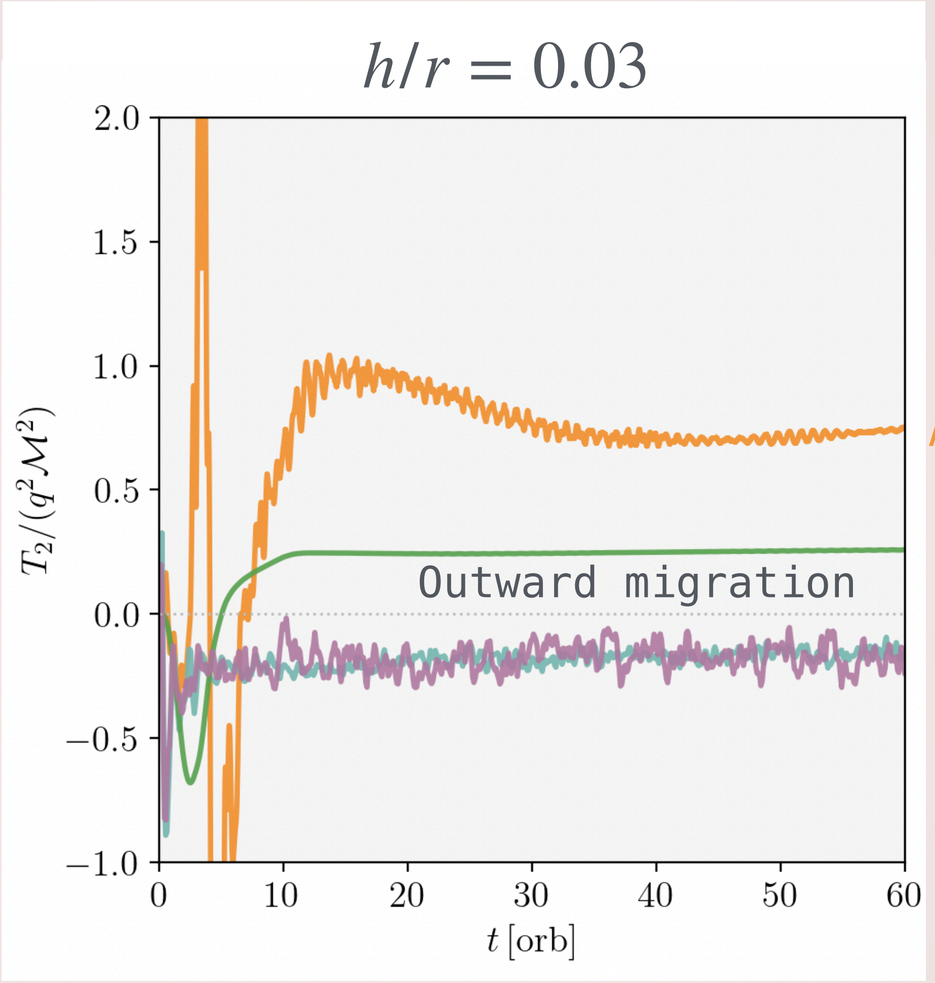
Gas morphology

Thin disk run (h/r = 0.03): sharper features



(Mostly) positive torques for thinner disk

Torque on secondary
vs time



Athena++

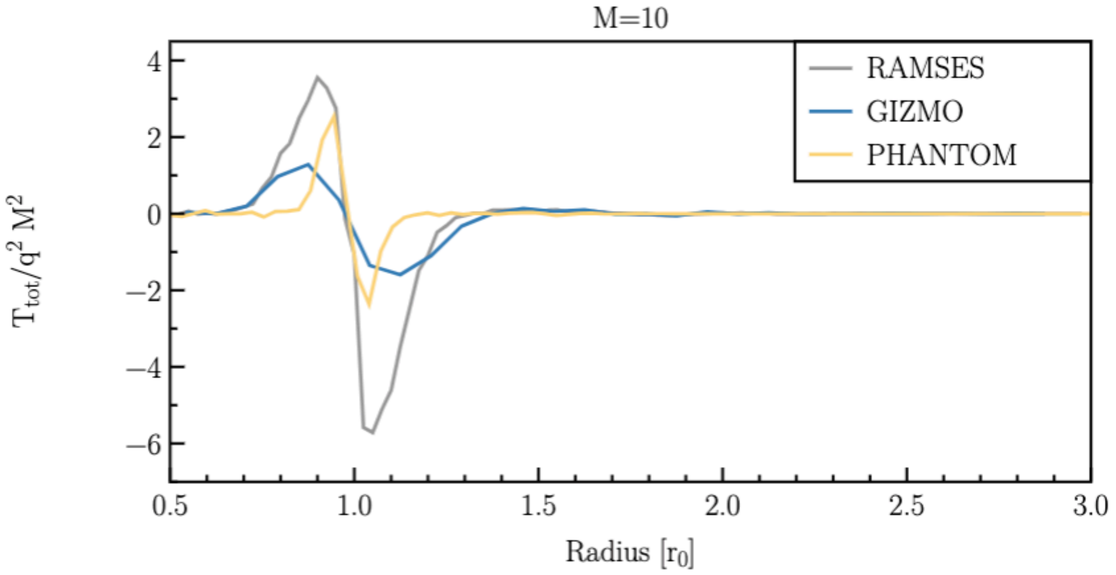
FARGO3D

GIZMO
Phantom

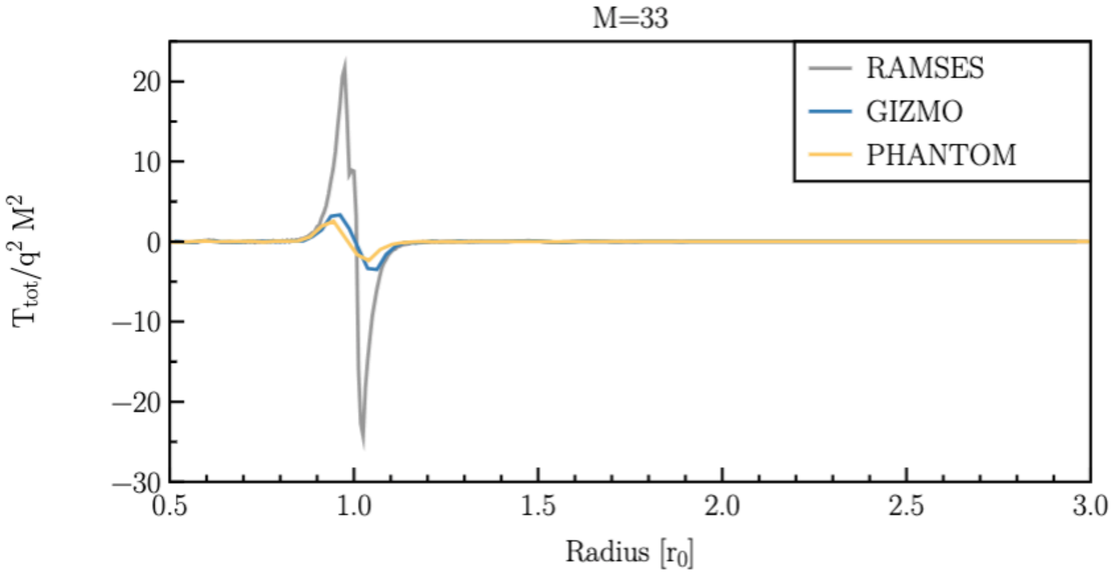
Dissecting the torque

Azimuthally averaged torque density profile

$h/r = 0.1$

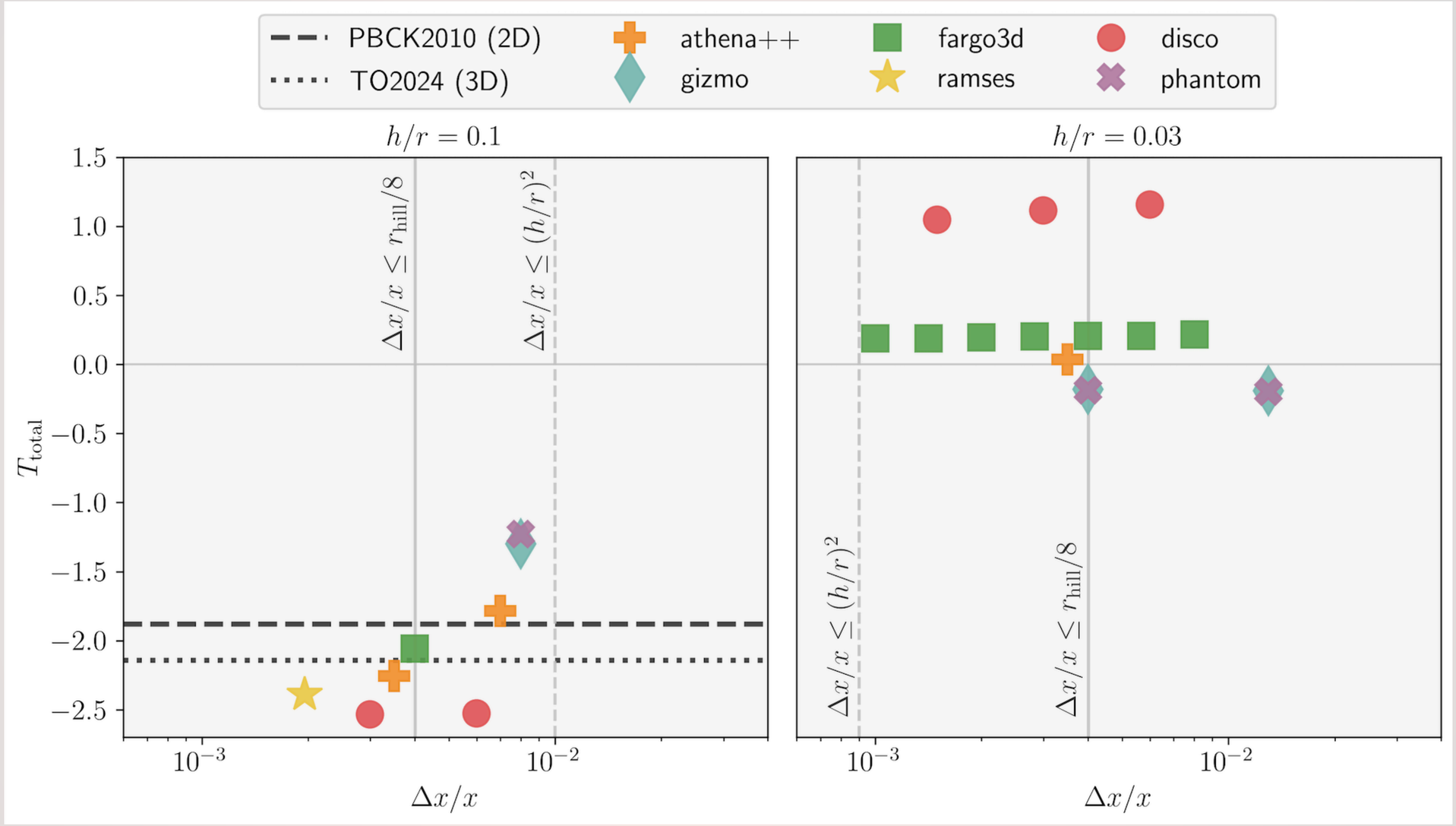


$h/r = 0.03$



Convergence?

More data points on the way :)

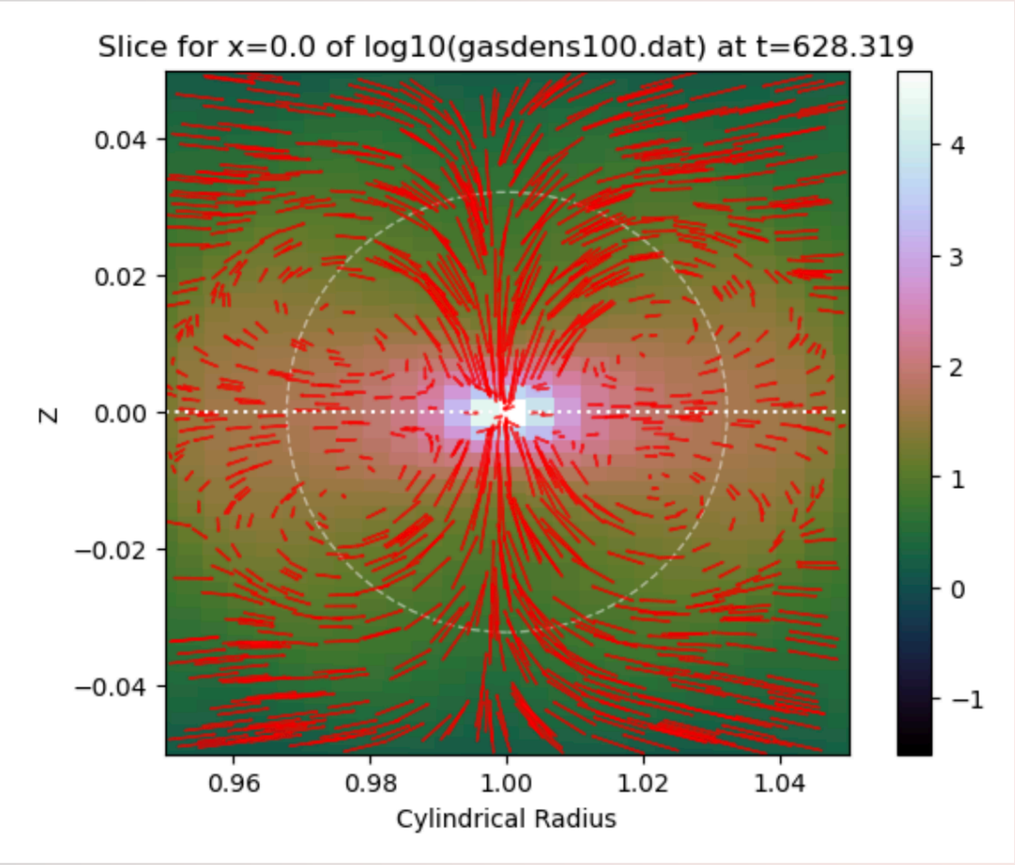


Total torque on binary

Spatial resolution

2D versus 3D

Thin disk run $h/r = 0.03$



FARGO3D

Grid code:

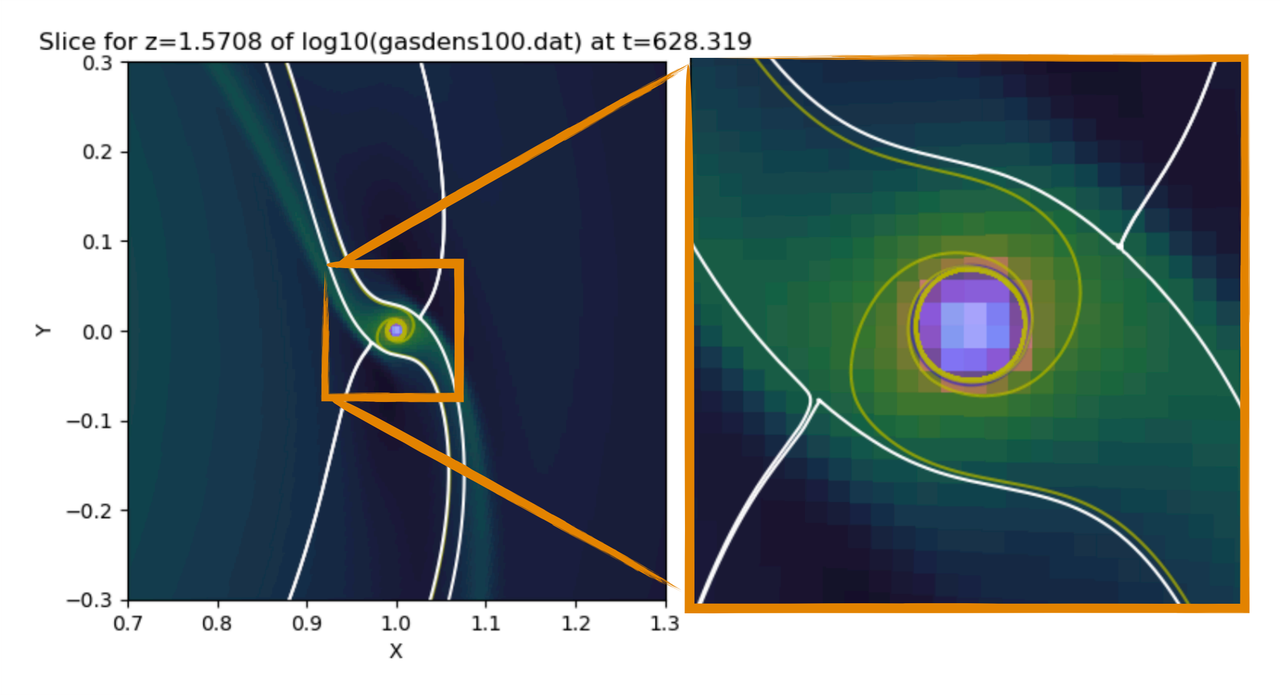
Strongly positive torques in Hill region

Particle codes:

Hill sphere torque positive if gravitational softening is sufficiently small

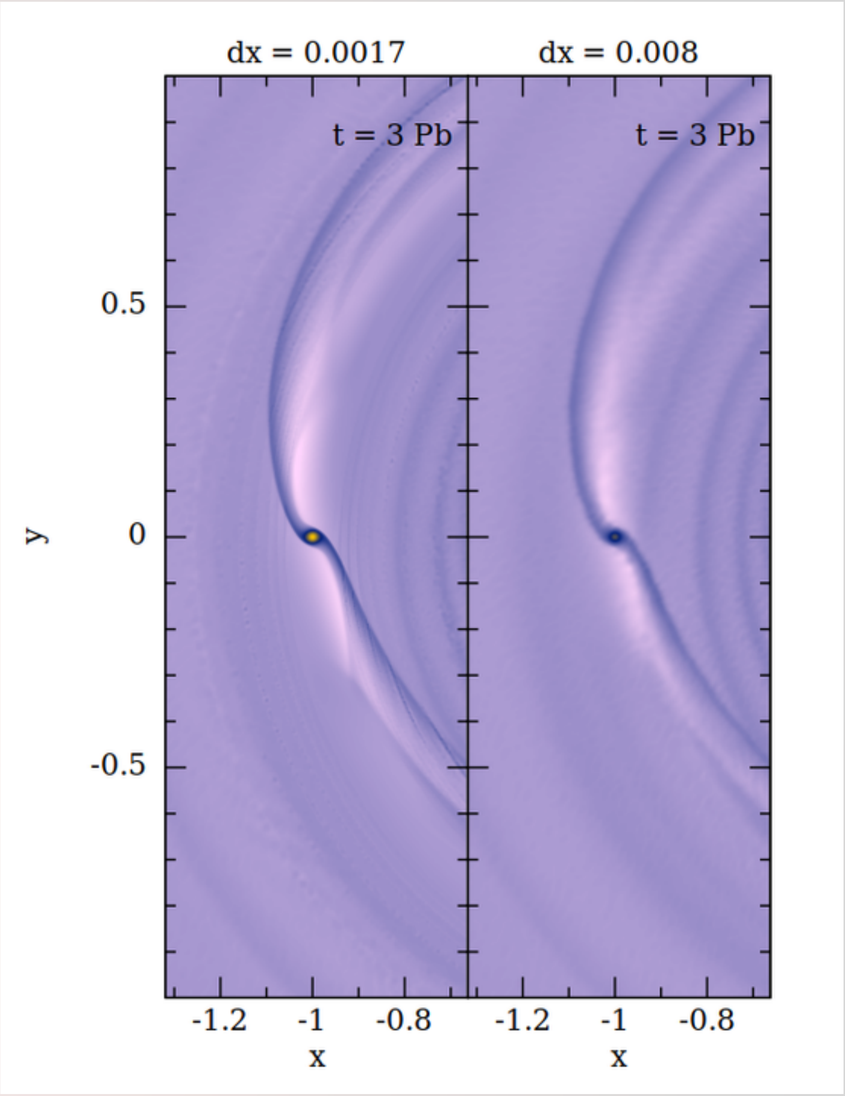
Diagnostic tests ongoing

FARGO3D



Streamlines around the secondary BH

GIZMO



Particle resolution tests

Preliminary results

awg_discimri_chairs @ lisamission.org

- The runs are running!
- Good agreement between all codes for the thicker disk run
- Sensitivity to gas morphology in the co-orbital region leads to the strongest differences amongst codes (determines torque sign)
- Particle runs show weaker torques than 2D?

Upcoming:

- Analysis of streamlines and gas flow through the coorbital region
- Analysis of torque oscillations (origin?)
- Applying results to LISA binaries

★ Computational resources and environmental impact assessment