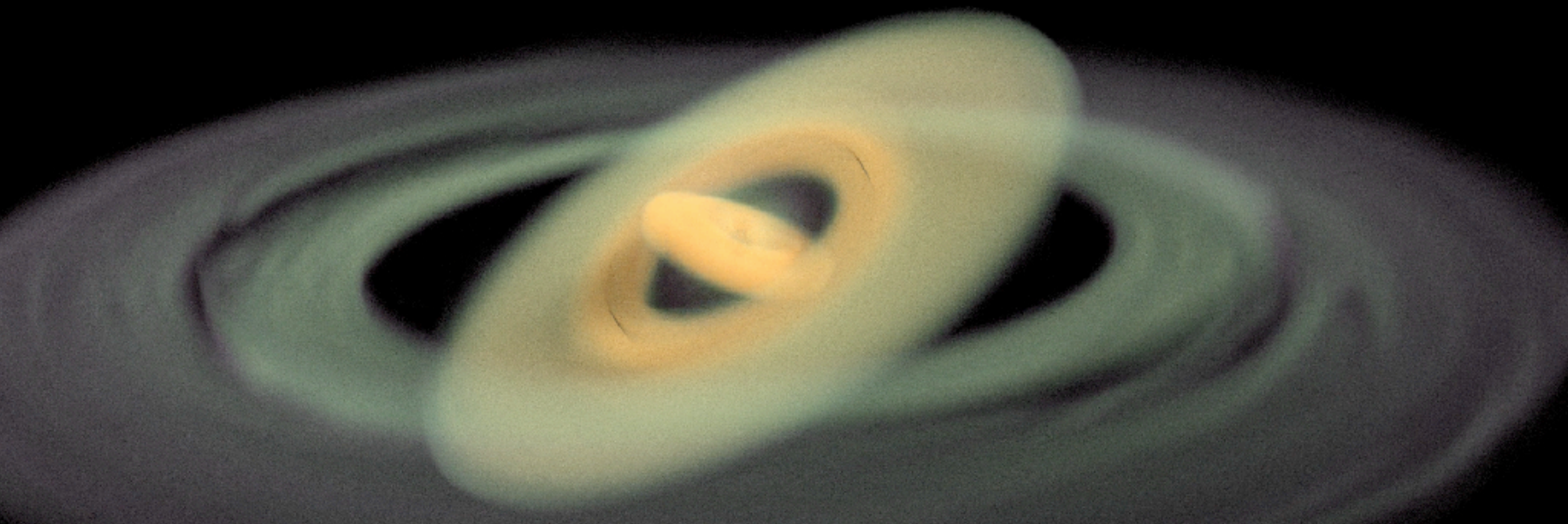
Companion-Disk Interaction

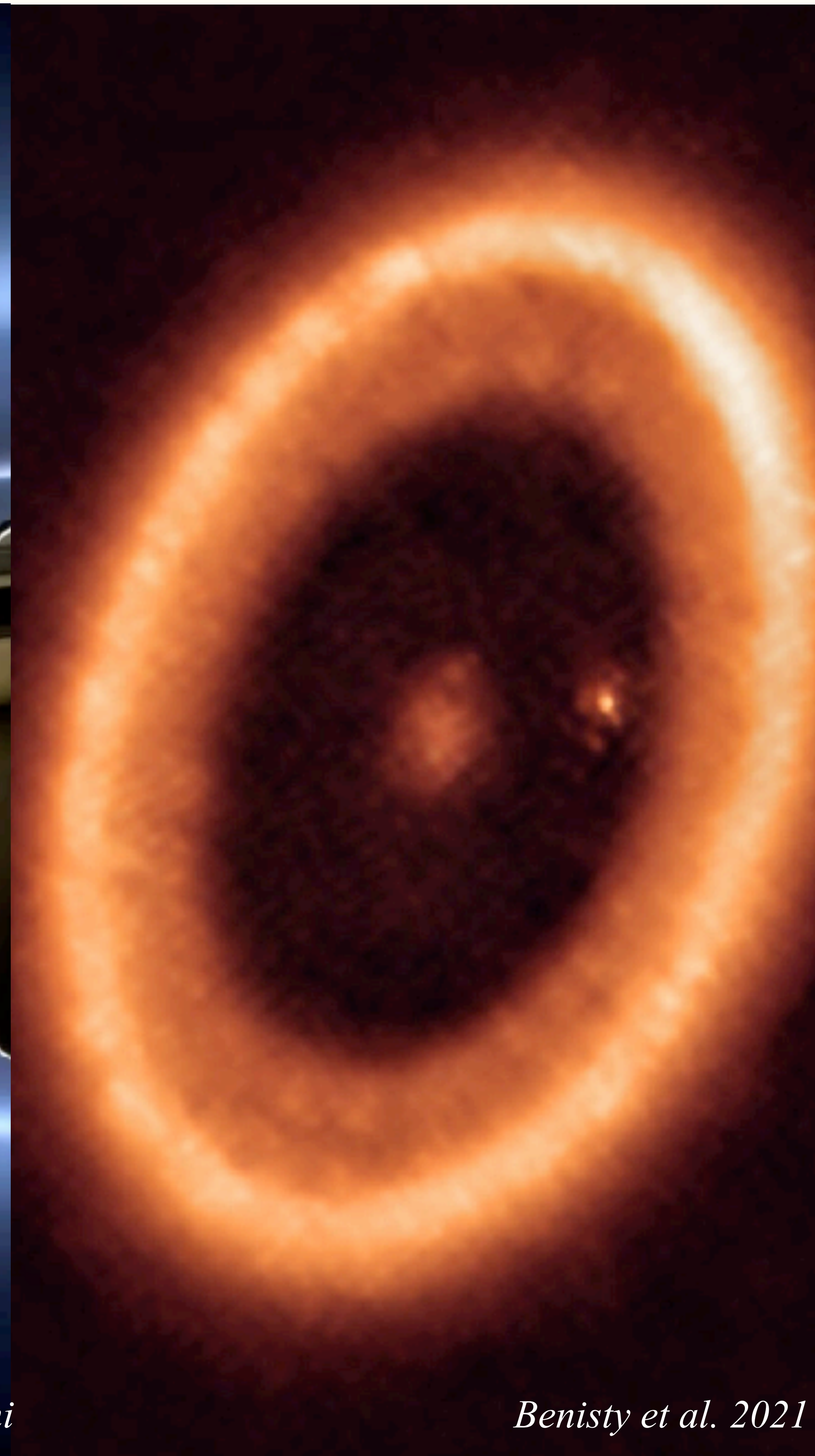


Zhaohuan Zhu
University of Nevada, Las Vegas
Nevada Center for Astrophysics

AthenaK summer school, PSU, July 8th, 2026

Companion-disk interaction

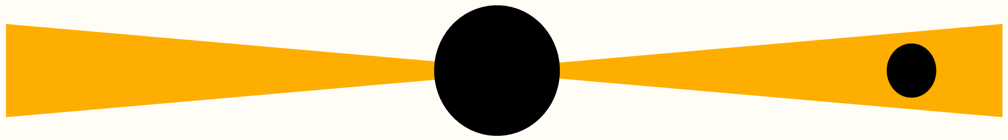

Cassini


Benisty et al. 2021


NASA/ESA

Companion-disk interaction across scales

	Protoplanetary disk	AGN
Central object:	$M_\odot$	10^6 - 10^{10} $M_\odot$
Companions:	0.1 - 1000 $M_\oplus$	1 - 100 $M_\odot$
Mass ratio(q):	10^{-7} - 10^{-3}	10^{-10} - 10^{-4}
Disk aspect ratio:	0.03-0.1	0.01-0.1
Angular size:	Disk: 100 au 100 pc 1``	Disk: 1 pc 10 Mpc 0.02``



Disk substructures

Optical/Near-IR(**μm dust**)

Radio (**mm dust**)

Axisymmetric

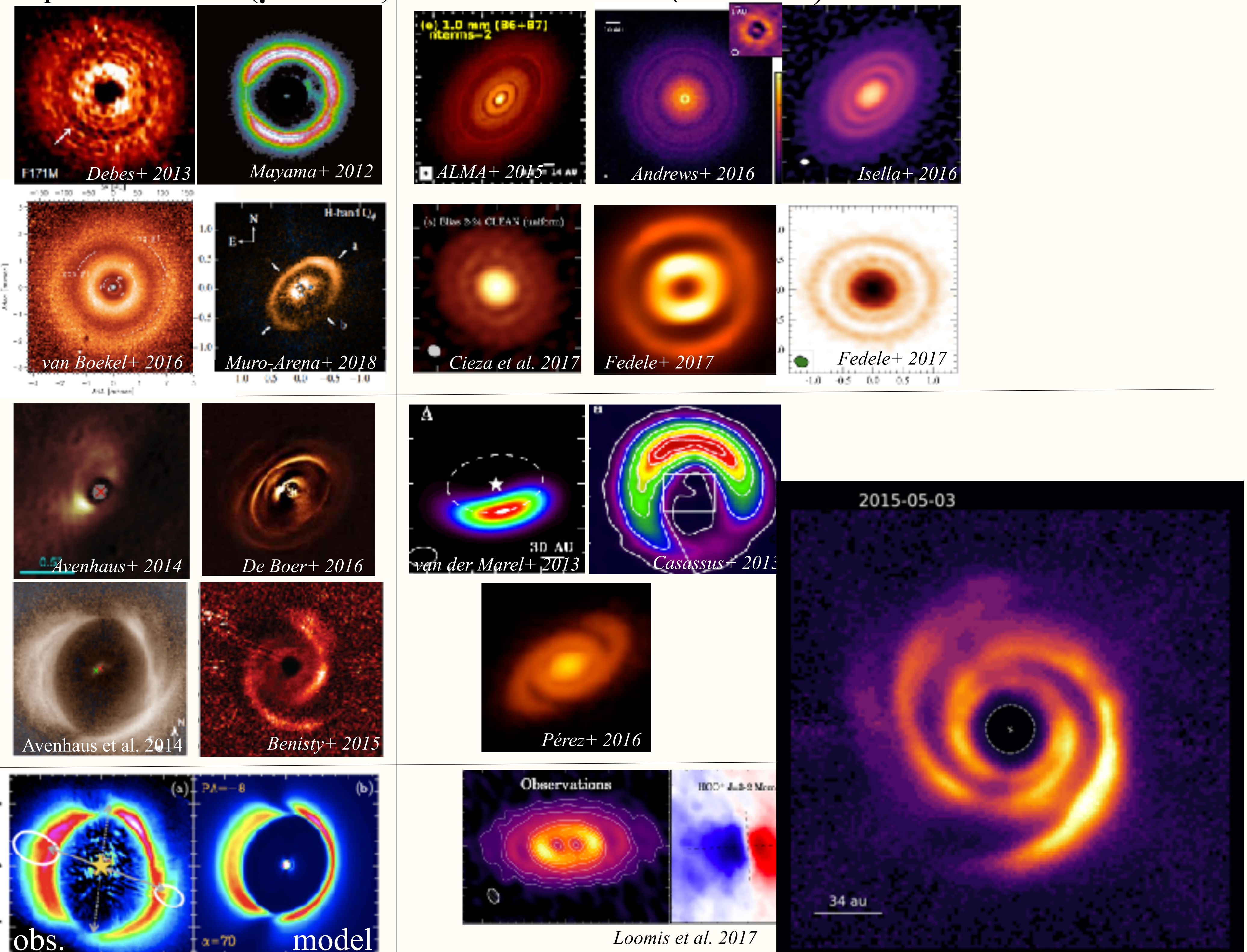
Rings/gaps

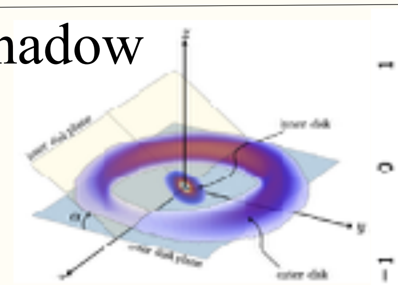
nonaxisymmetric

Crescents

Spirals

Disk Shadow





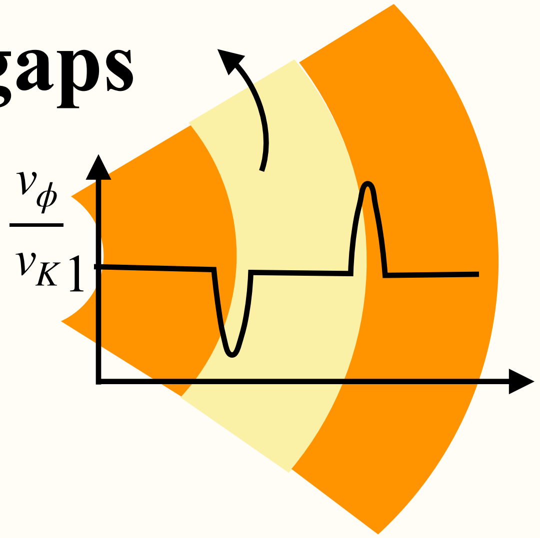
Marino et al. 2015

Loomis et al. 2017

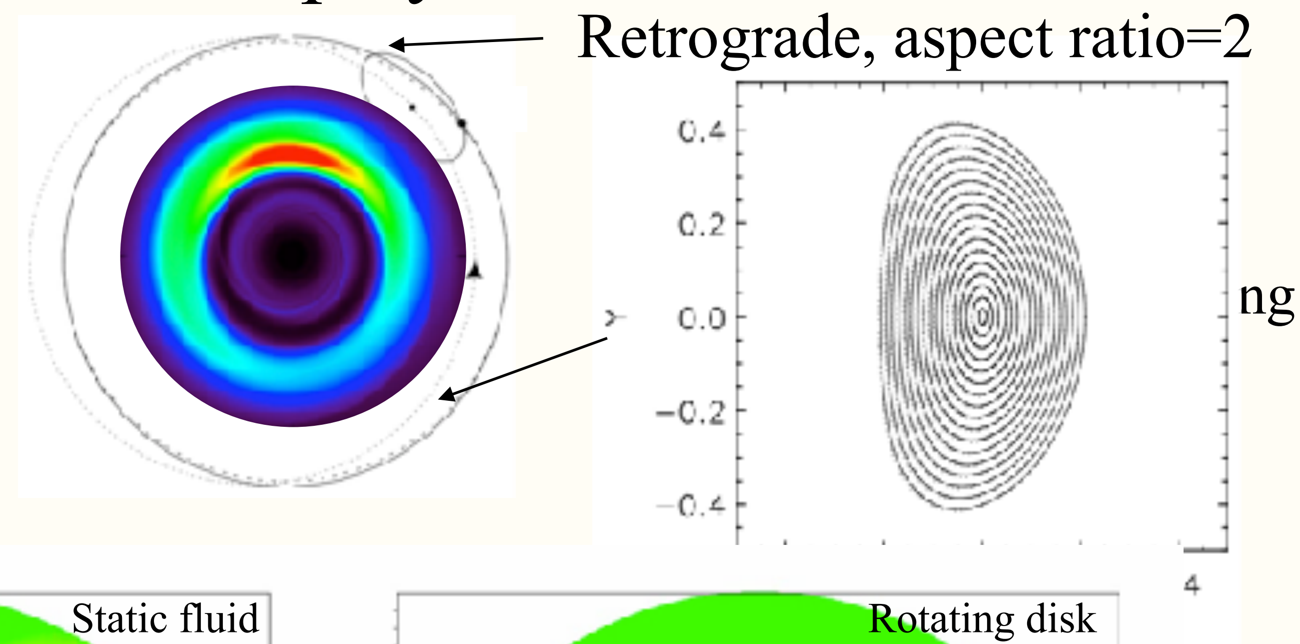
Why gaps/crescents/spirals in Protoplanetary

Basic properties of a **rotating** disk

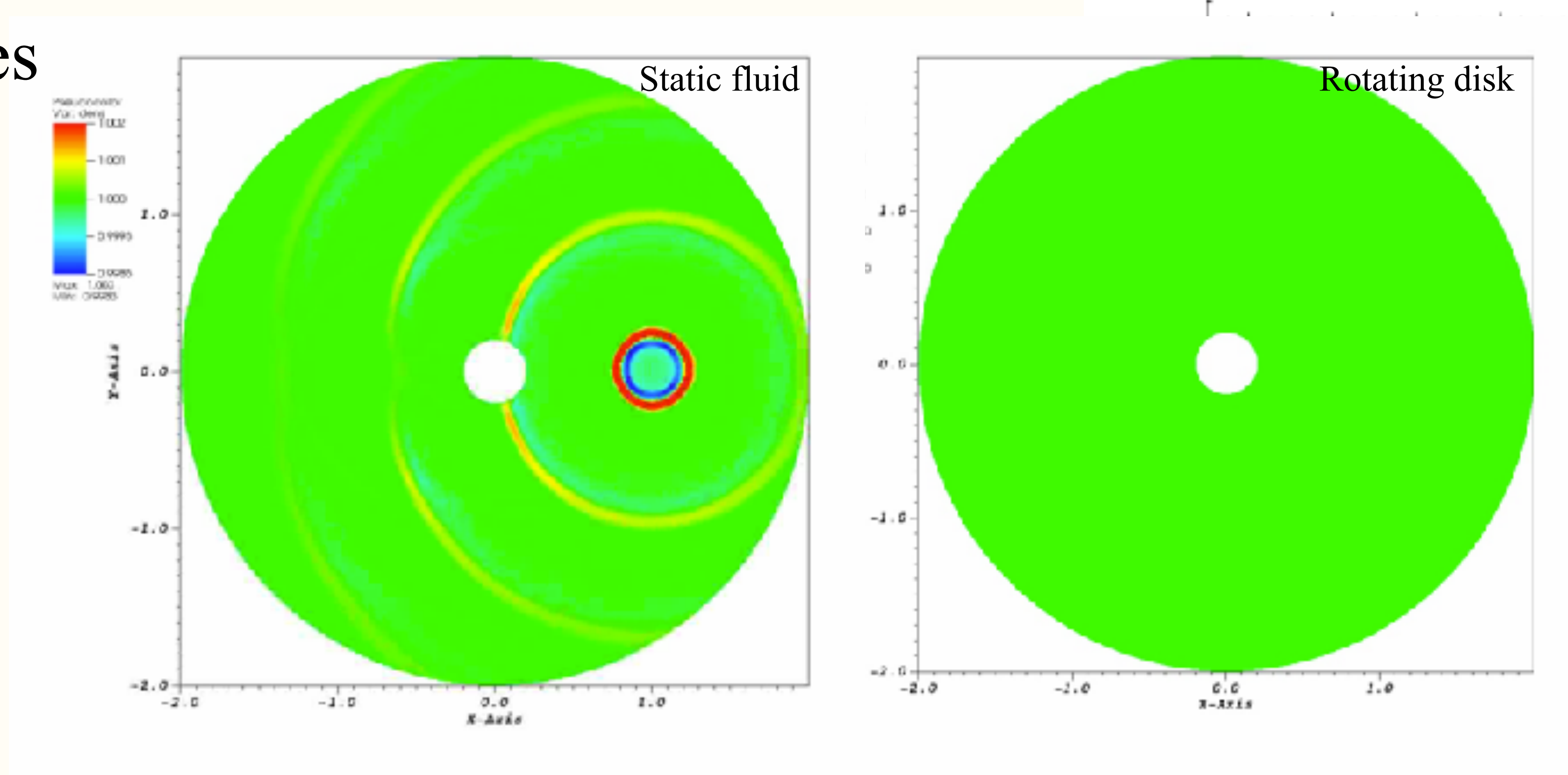
Rings/gaps



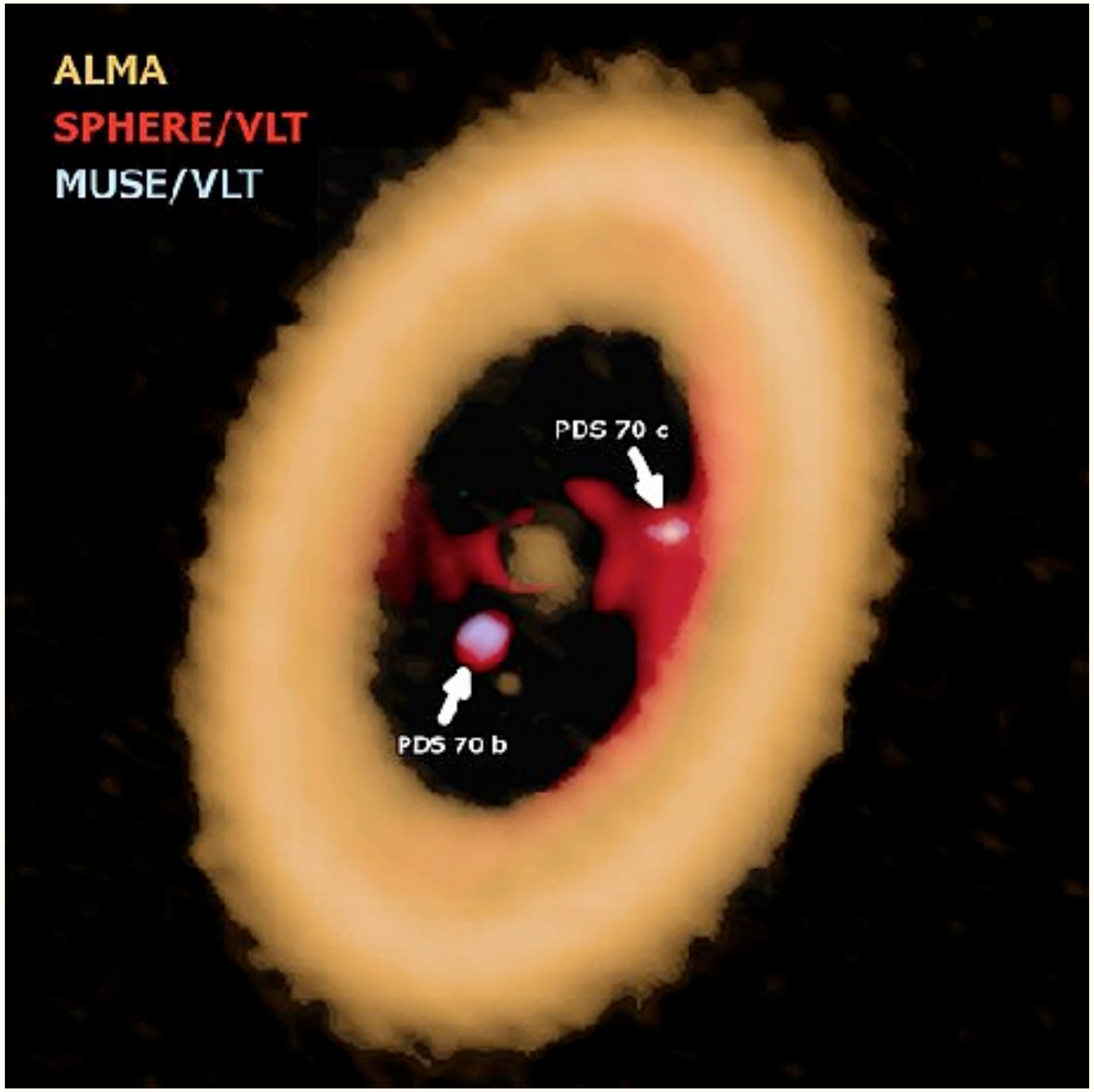
Vortex: epicyclic motion



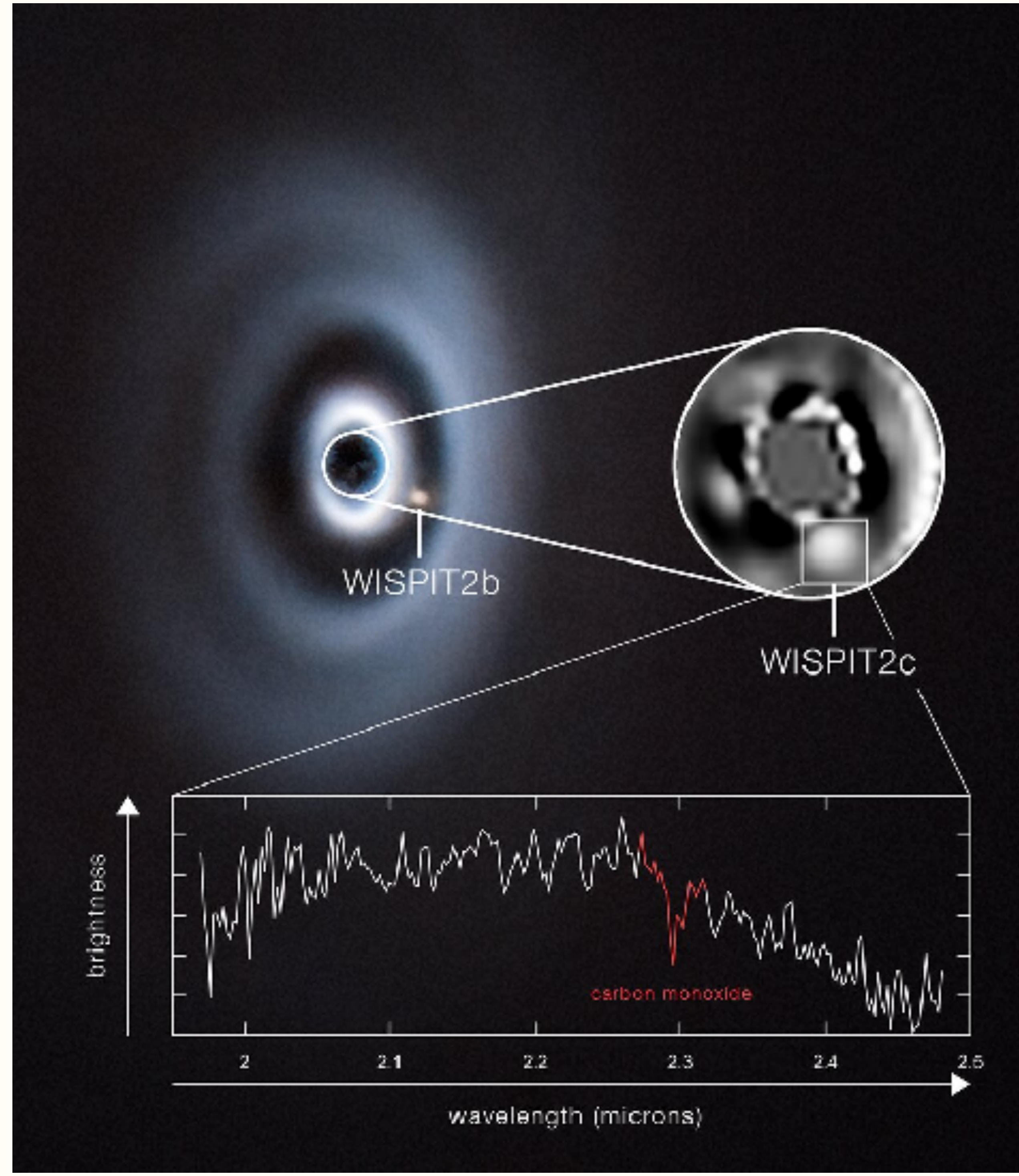
Spirals: waves



Planets in disks: two cases



Keppler et al. 2018
Muller et al. 2018
Haffert et al. 2019
Benisty et al. 2021,…



ESO/C. Lawlor, R. F. van Capelleveen et al.

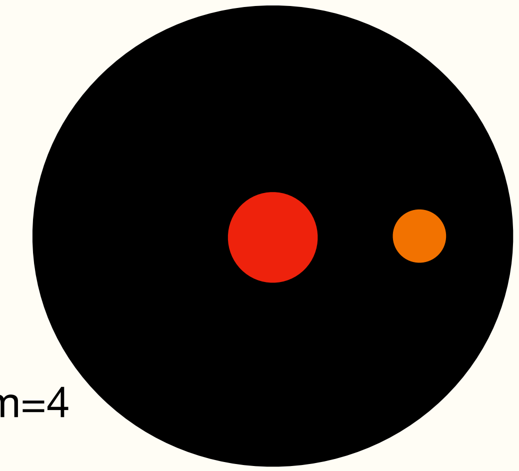
Outlines

- Planets in protoplanetary disks
  - Coplanar circular orbit planets (linear, non-linear theory)
  - misaligned planets and broken disks
  - Eccentric and misaligned planets (planet's evolution)
- Stars/BHs in AGN disks
  - Orbital evolution
  - QPE (high velocity impacts)

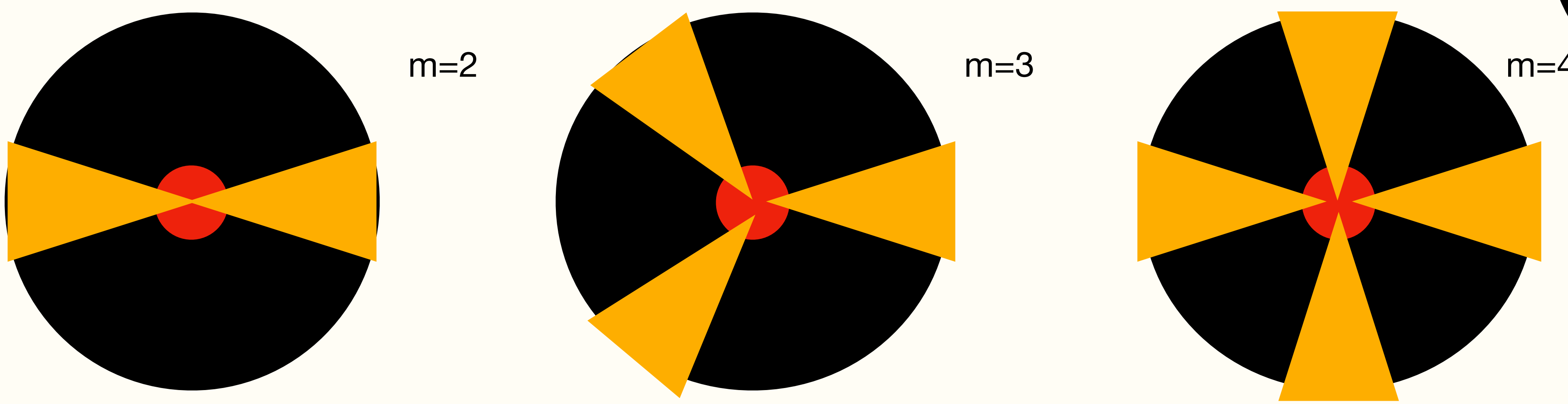
Coplanar circular: Linear theory

Goldreich & Tremaine 1979, 1980

A rotating potential: $\Phi_1(R, \phi - \Omega_p t)$



Fourier decomposition: $e^{i(m\phi - \omega t)}$ with pattern speed $\Omega_p = \omega/m$



A fluid element on a circular orbit $\phi(t) = \phi_0 + \Omega t$

It feels a forcing frequency at $\tilde{\omega}(R) \equiv \omega - m\Omega(R) = m\left[\Omega_p - \Omega(R)\right]$

The disk's natural radial frequency is epicyclic frequency κ

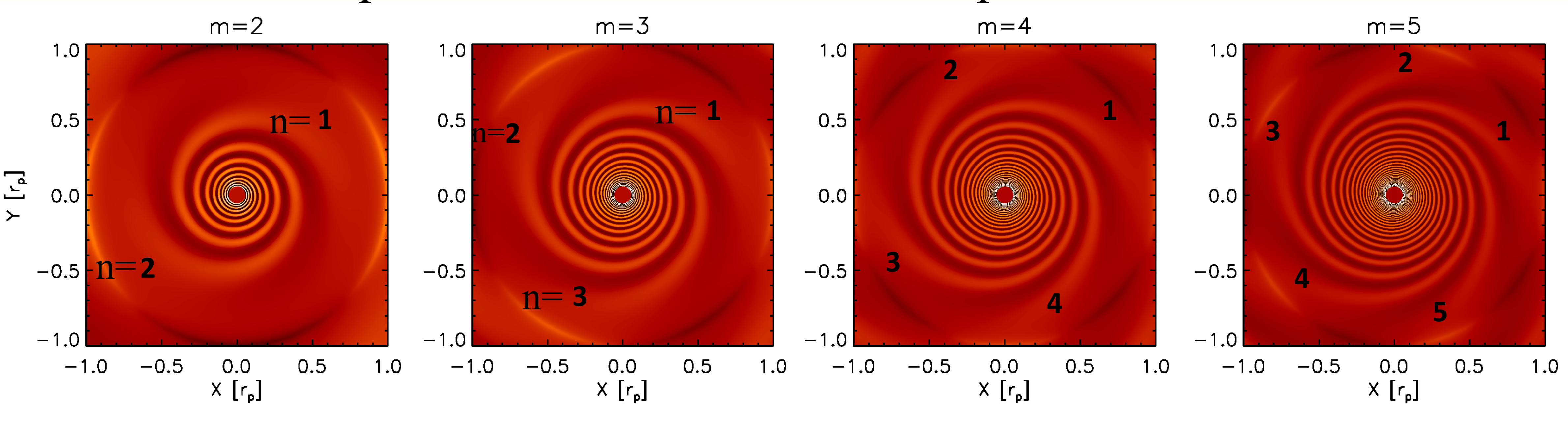
Resonances occur when

$$\underbrace{\tilde{\omega} = 0}_{\text{corotation (CR)}} \quad , \quad \underbrace{\tilde{\omega} = -\kappa}_{\text{inner Lindblad (ILR)}} \quad , \quad \underbrace{\tilde{\omega} = +\kappa}_{\text{outer Lindblad (OLR)}} \quad ; \quad R_{\mathrm{ILR,OLR}} = \left(1 \mp \frac{1}{m}\right)^{2/3} R_p$$

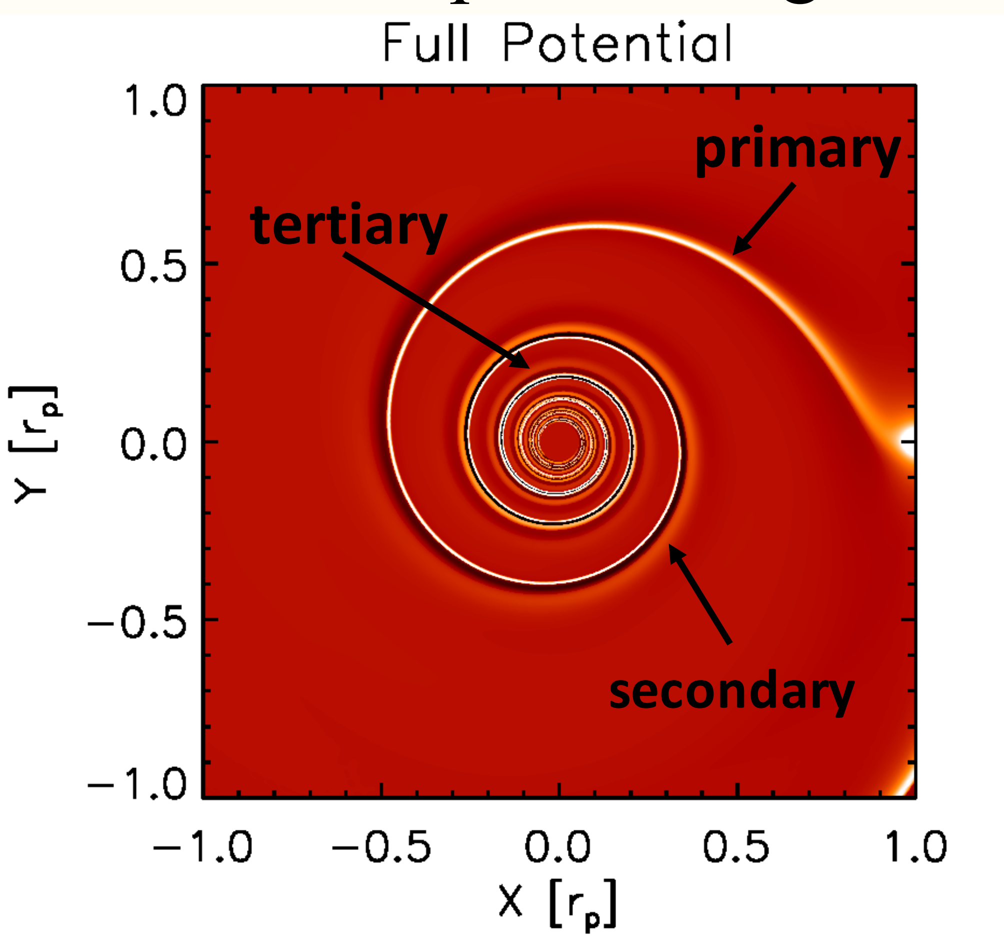
Waves are launched at resonances

Coplanar circular: Linear theory

Disk's wave response to various Fourier components:



Add all components together:



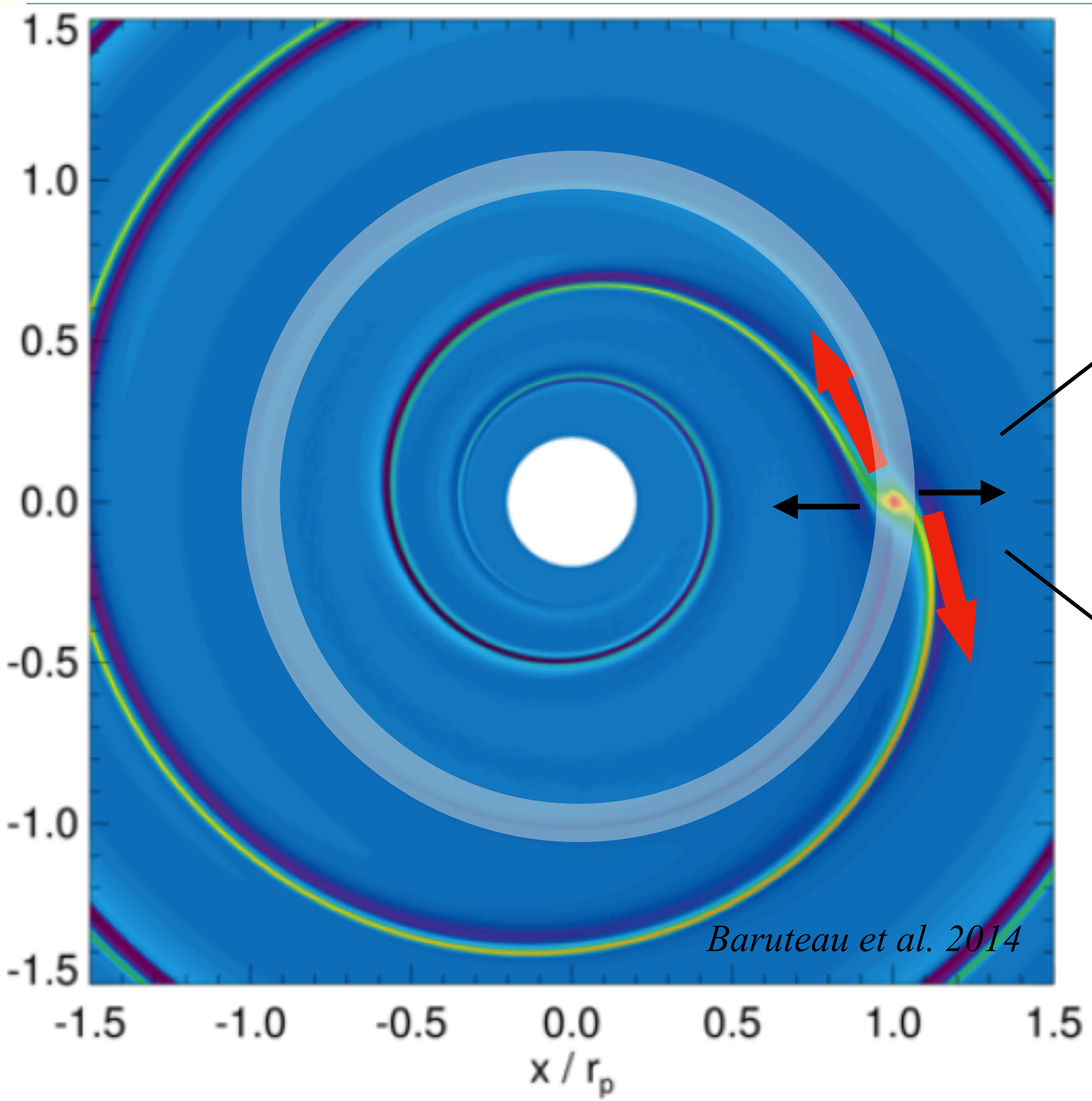
Primary arm:
Coherent Constructive Interference from n=1 arms.

Secondary arm:
Interference from n=2 arms.

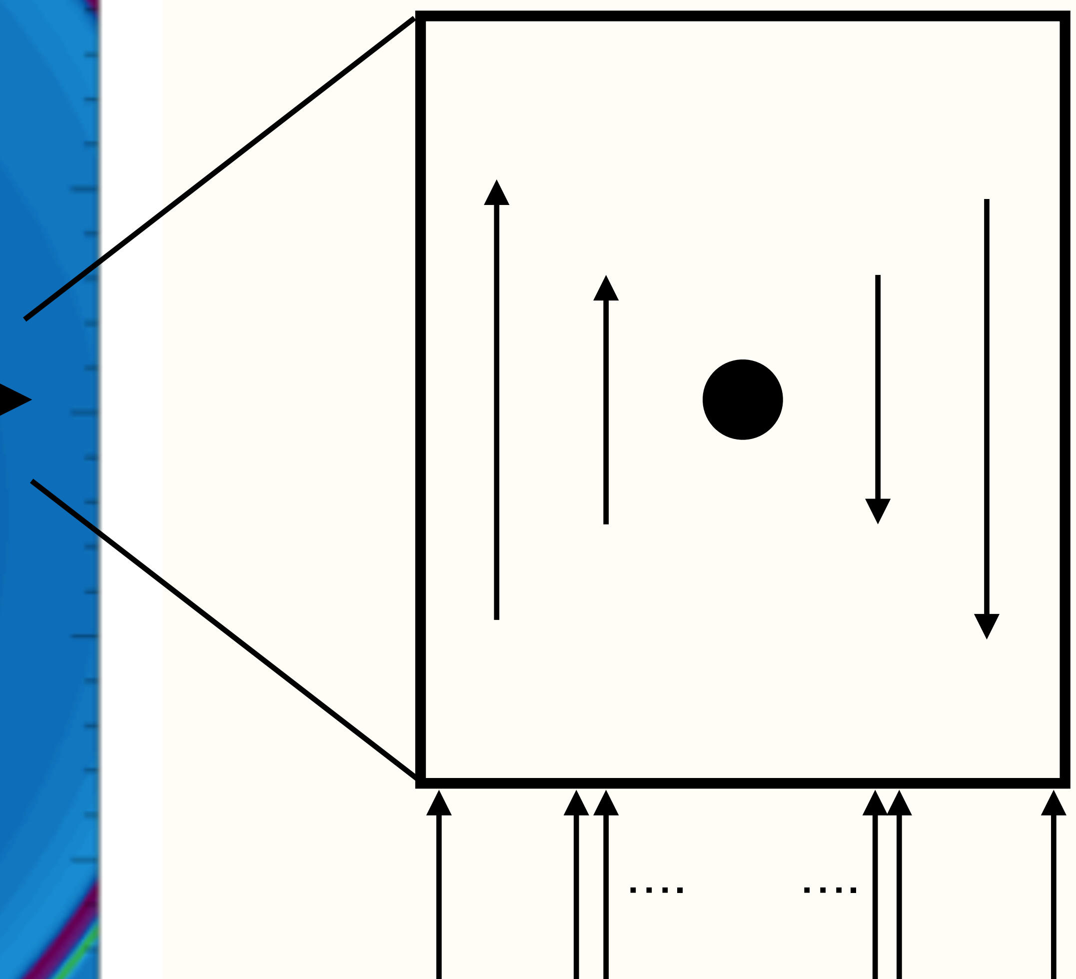
Tertiary arm:
Interference from n=3 arms.

……

Planets in protoplanetary disks



The planet is stationary in the local fluid frame



Lindblad resonances

migration timescale for both Earth and Neptune ~10^5 years

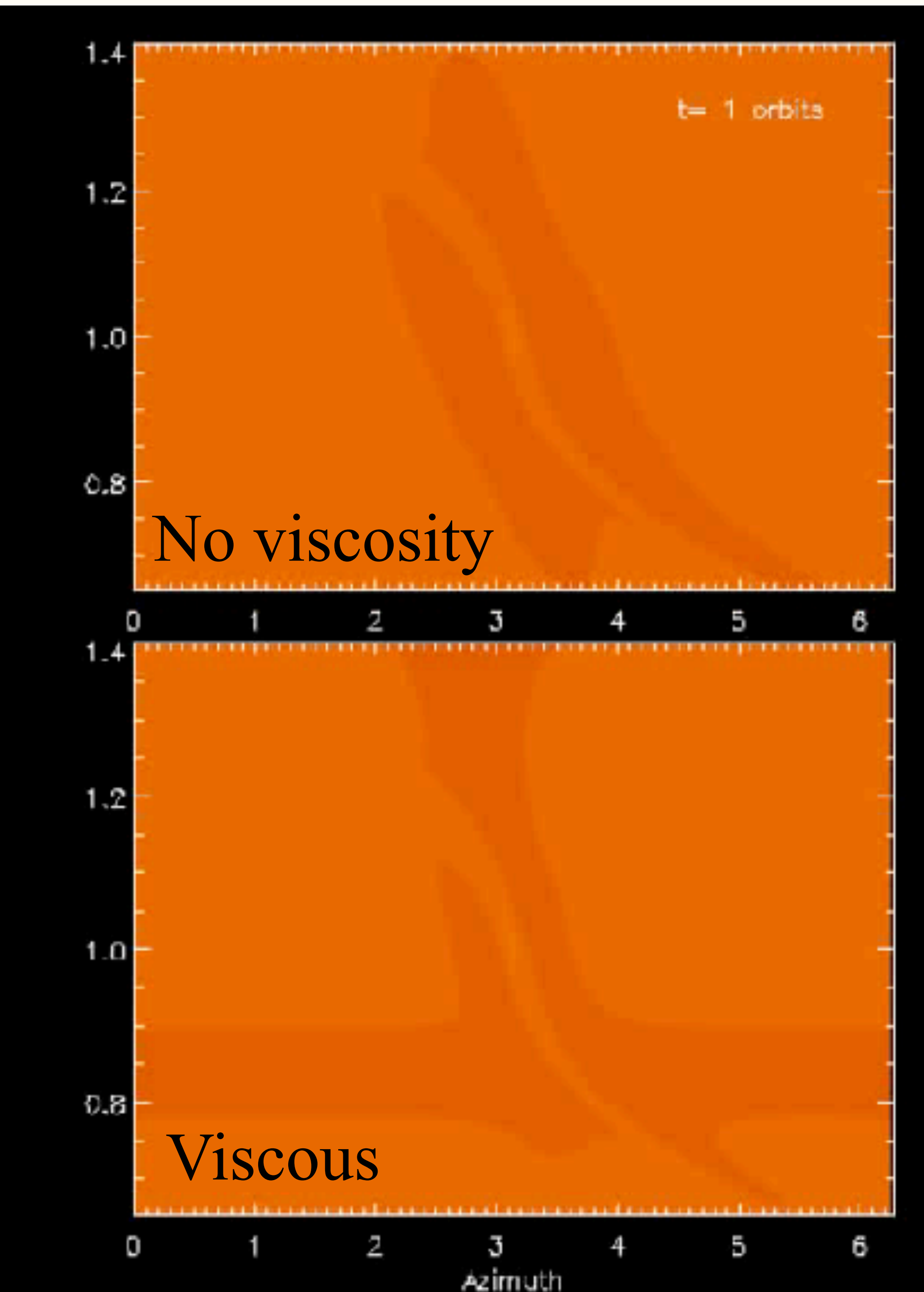
Wave torque Migration

(*Goldreich & Tremaine 1979, Ward 1997*)

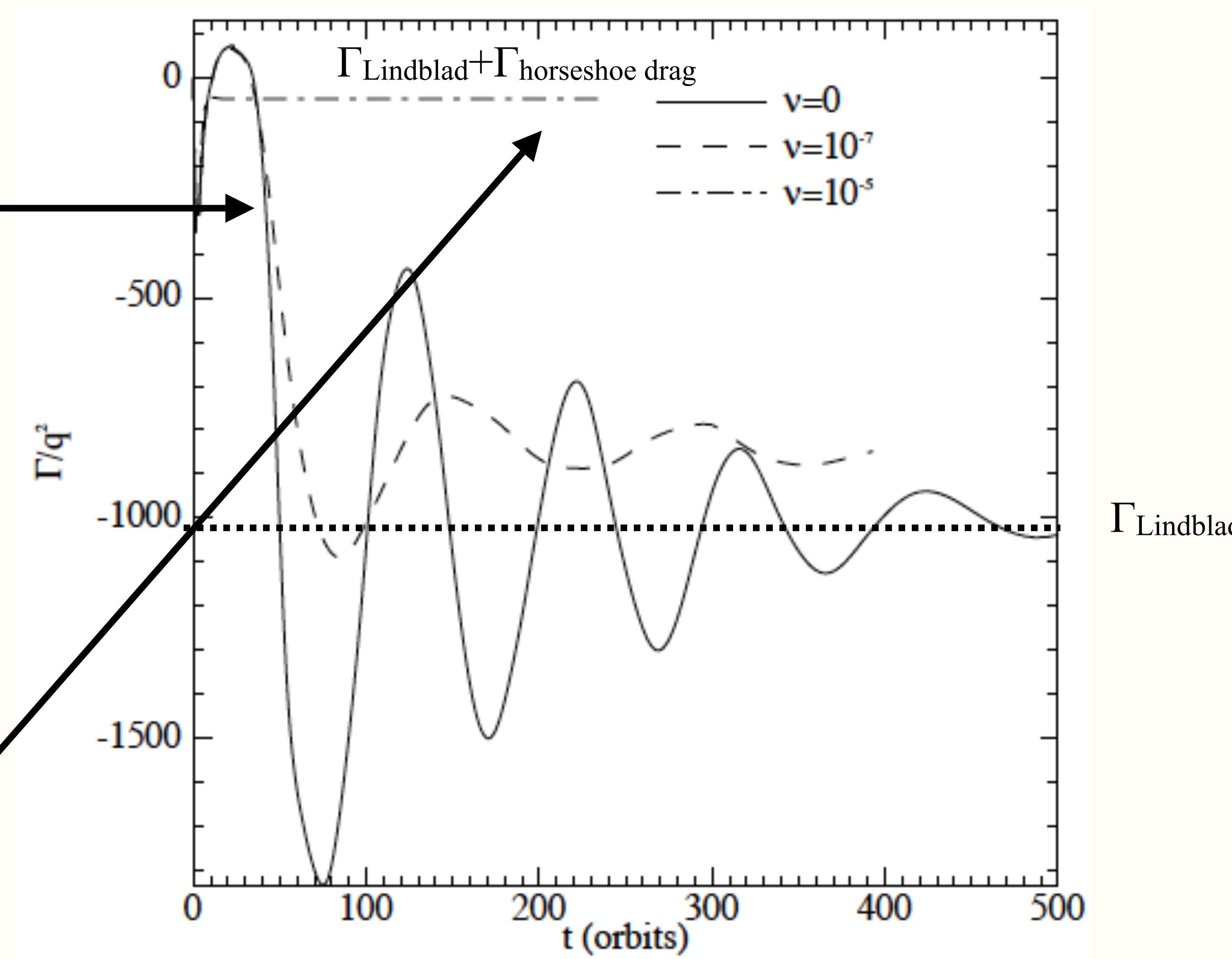
Corotation torque

Corotation torque

Depends on the vortensity/entropy gradient, viscosity, energy diffusivity



Goldreich & Tremaine 1979, Ward 1991, Baruteau & Masset 2008, Paardekooper & Papaloizou 2008, 2009, Paardekooper et al. 2010



Paardekooper & Papaloizou 2008

Nelson & Kley 2012

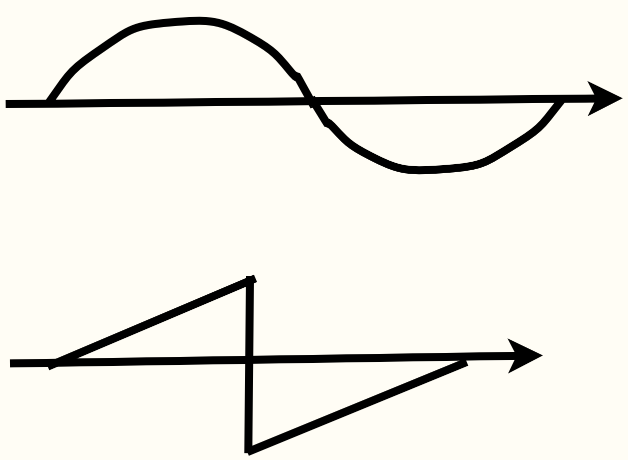
Coplanar circular: weakly non-linear theory

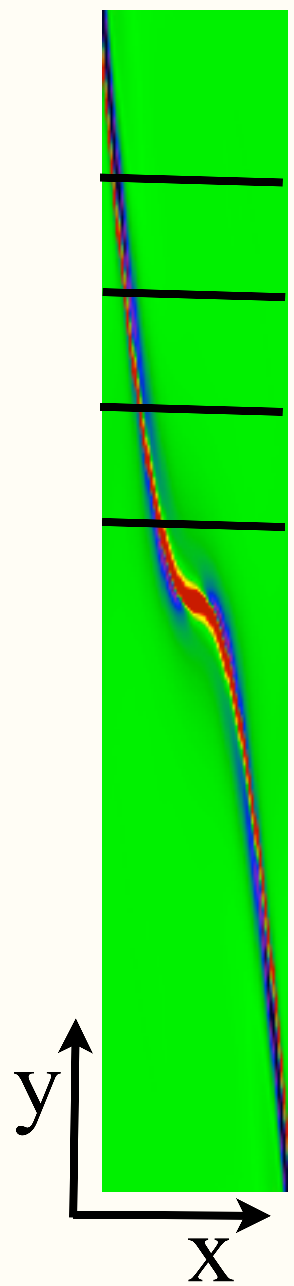
When small amplitude spiral wakes propagate in disks, they will gradually steepen to **shocks**, leading to gap opening.

1-D Gas Flow

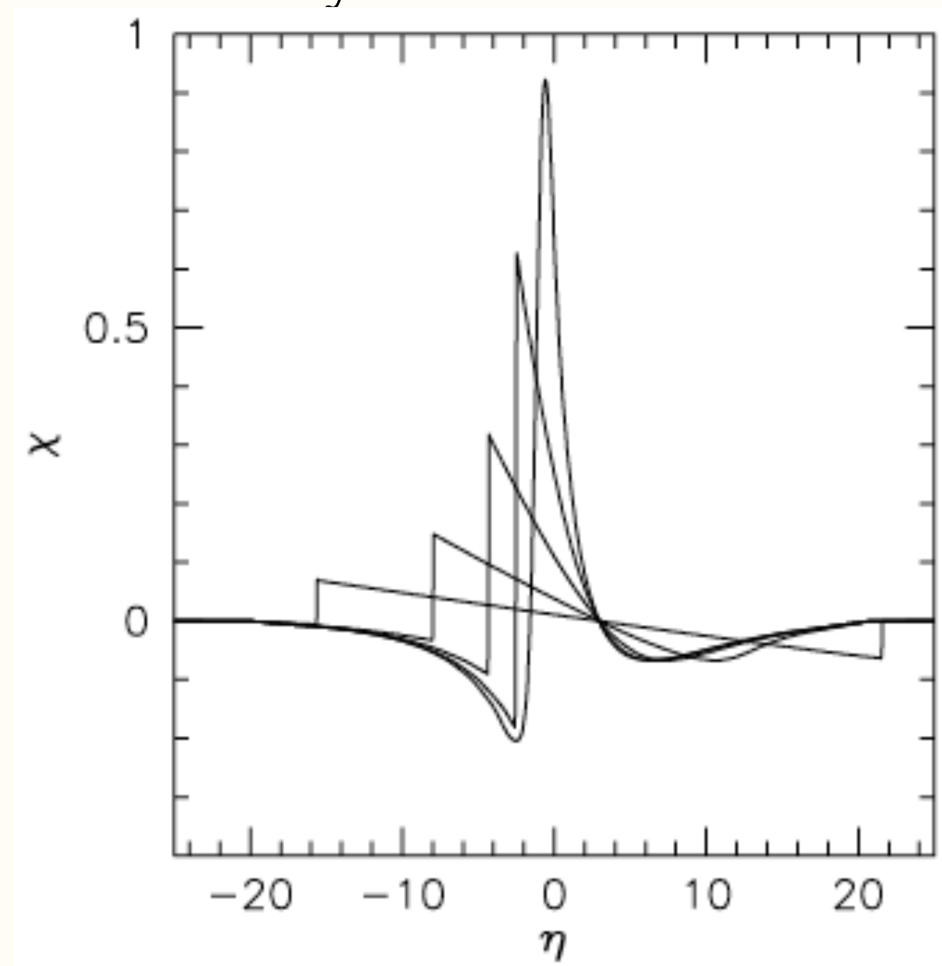
$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial v}{\partial x} + v \frac{\partial \rho}{\partial x} = 0,$$

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} = -\frac{1}{\rho} \frac{\partial p}{\partial x};$$





2-D Steady Flow in Disks

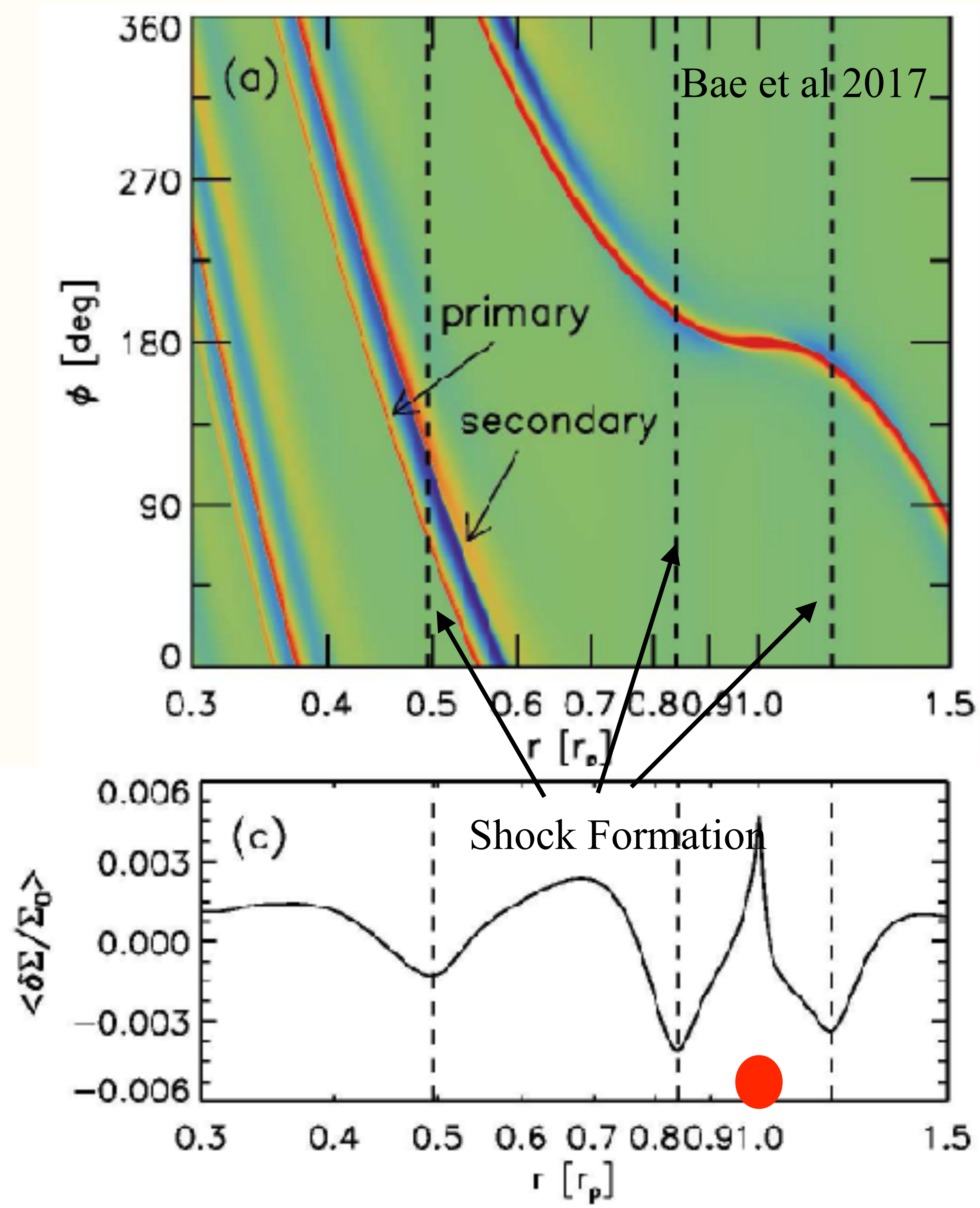


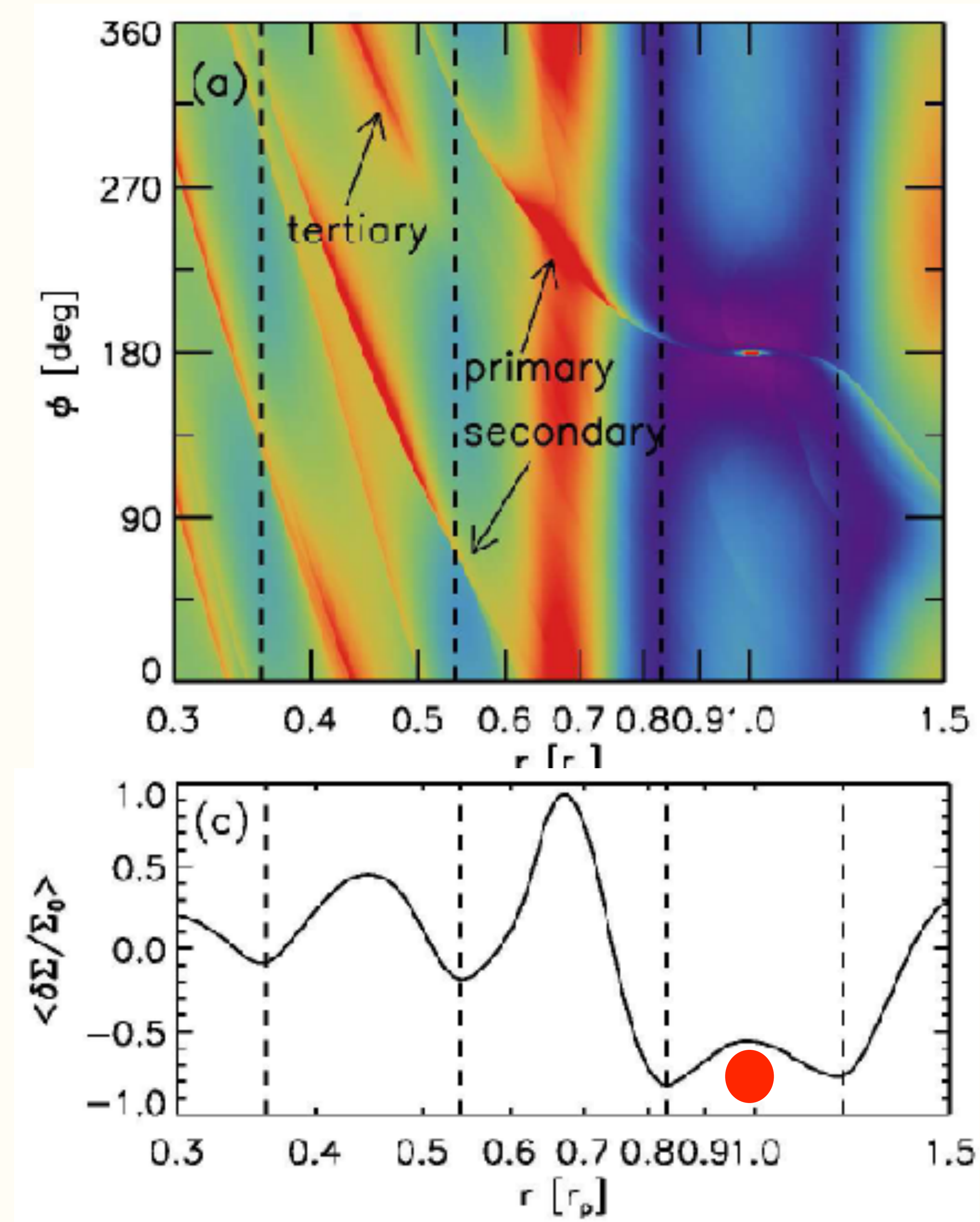
Shocking distance: $|x| \approx 0.93 \left(\frac{\gamma + 1}{12/5} \frac{M_p}{M_t} \right)^{2/5} H$

(Goodman & Rafikov 2001, Dong et al 2009)

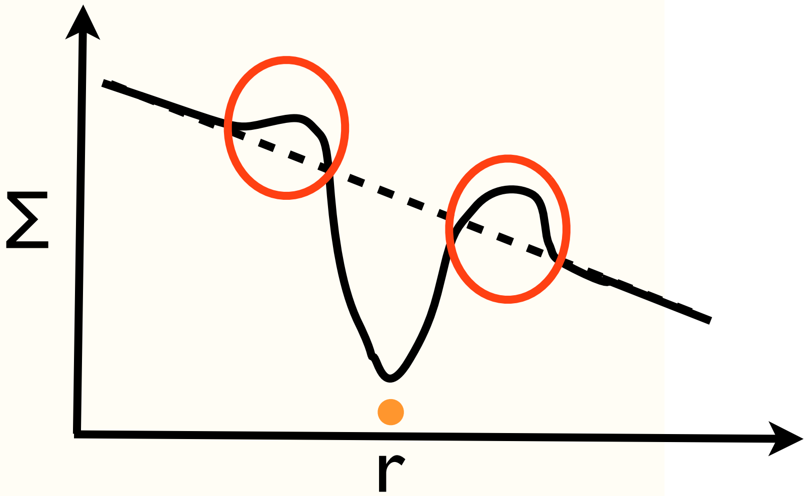
Coplanar circular: gap opening in weakly non-linear theory

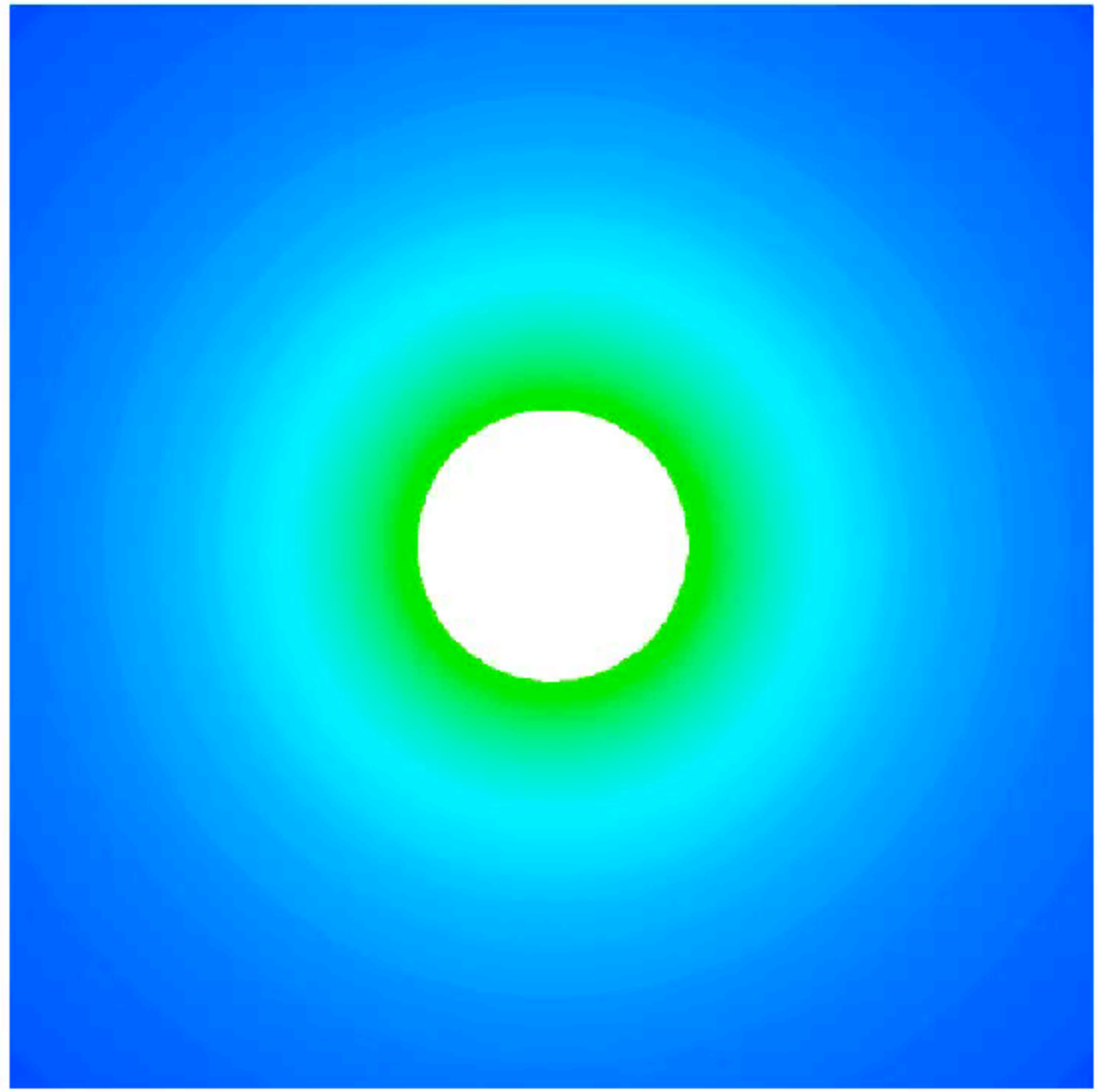
Spiral waves eventually steepen to shocks (Goodman & Rafikov 2001, Rafikov 2002)





Gap edge could be unstable, forming vortices

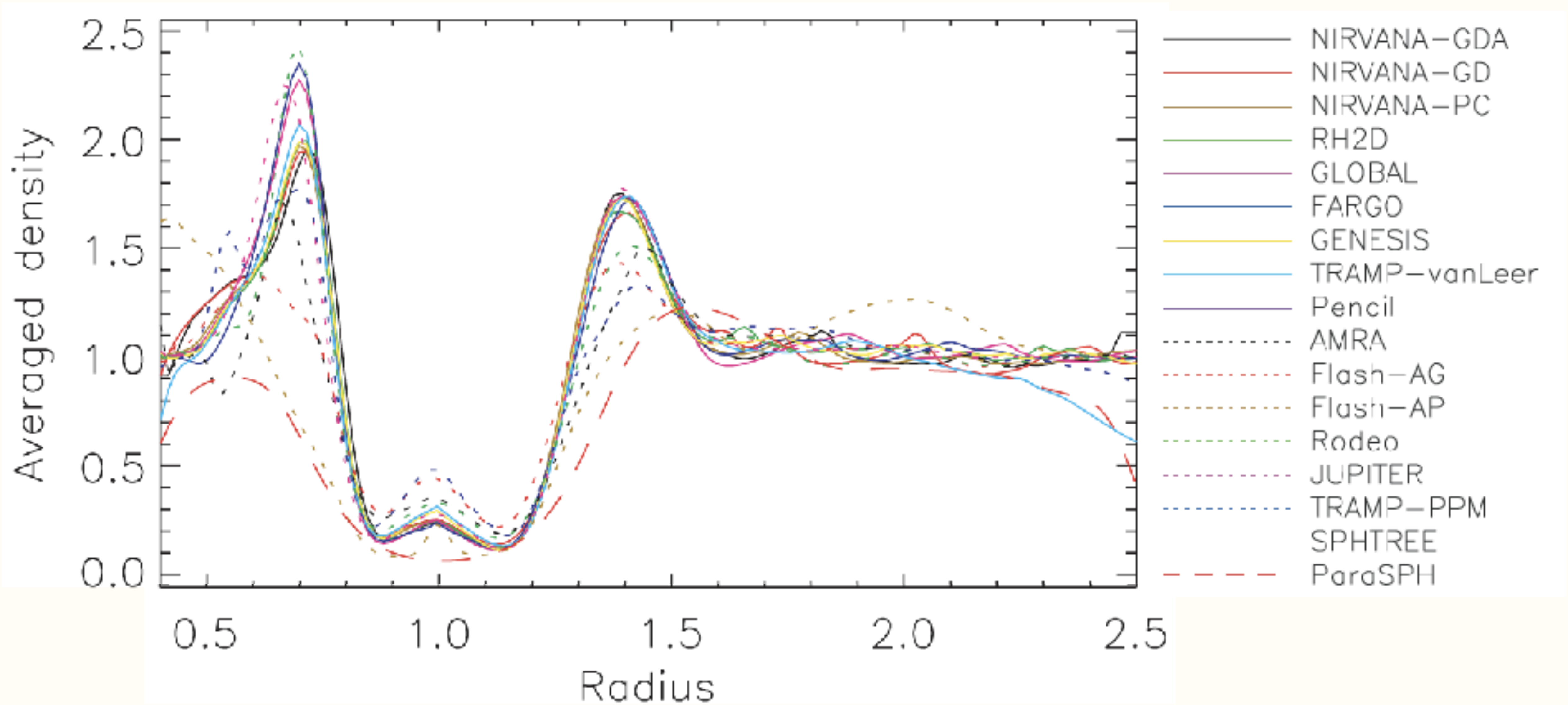




Coplanar circular: gap opening by a massive planet

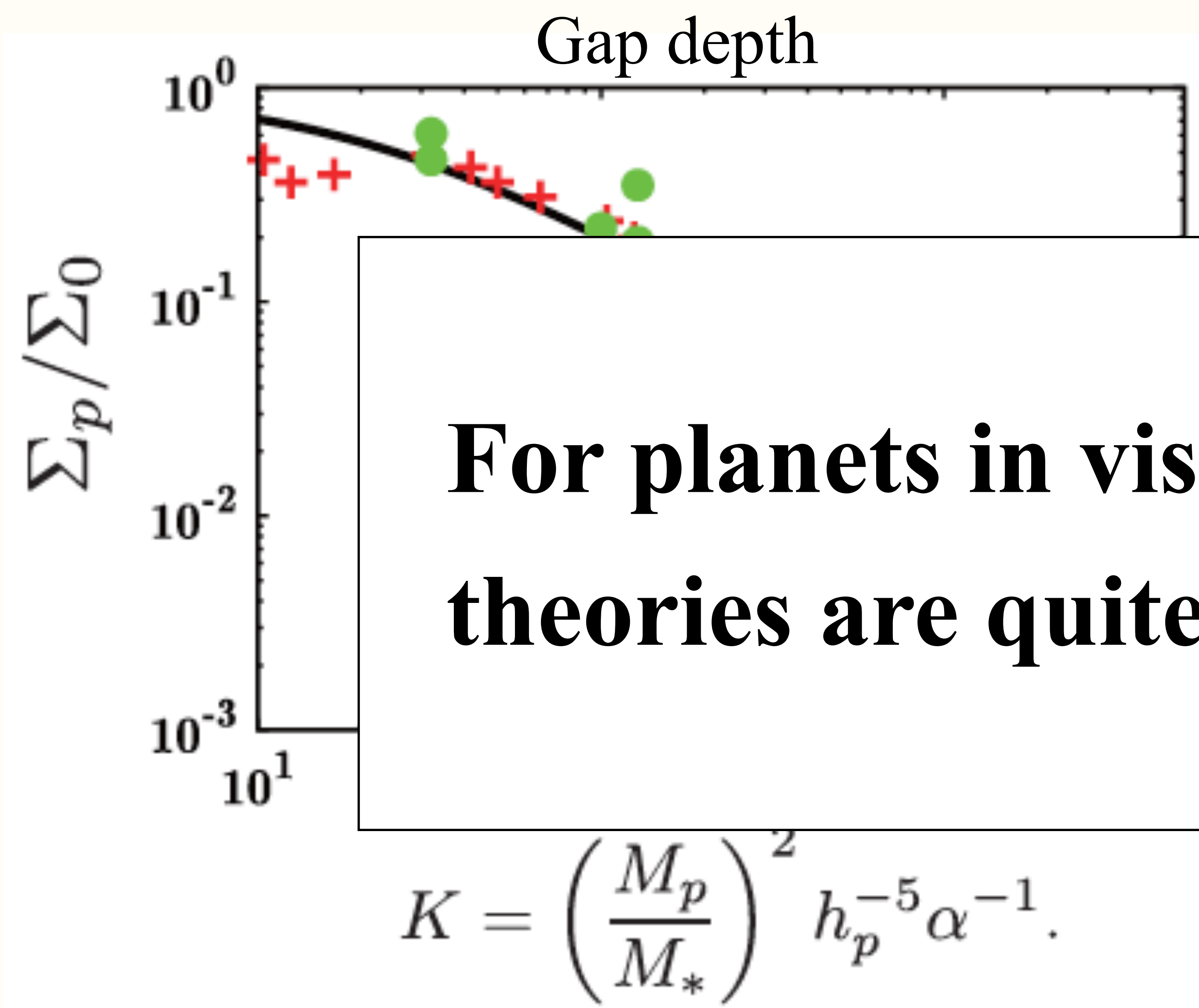
When planetary torque > viscous torque, a gap is opened

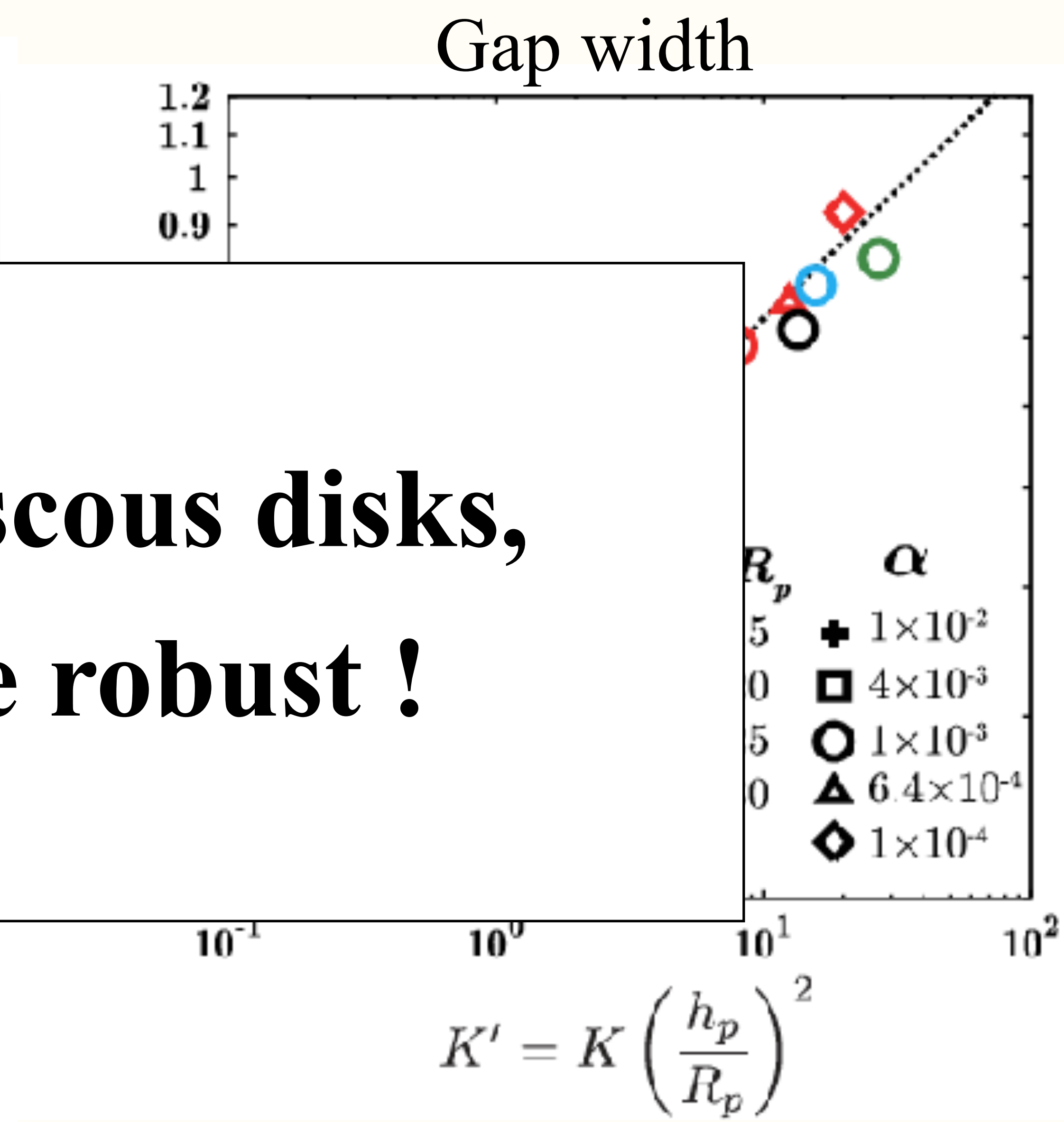
0.1 M_J in α=0.01, H/R=0.05 disks



de Val-Borro et al. 2006

Gap depth in viscous disks





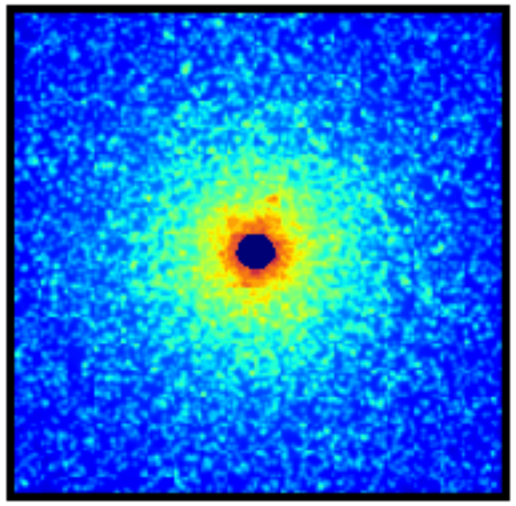
For planets in viscous disks,

theories are quite robust !

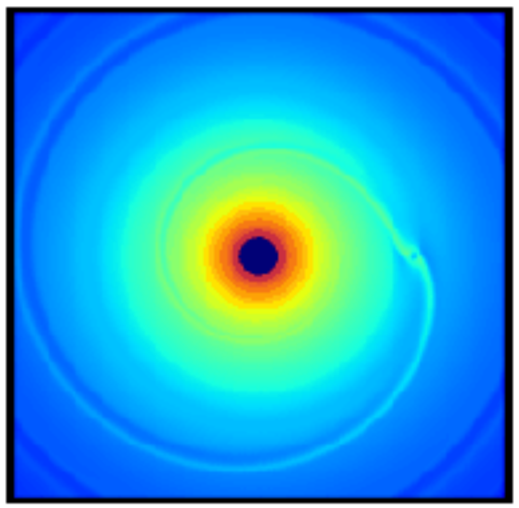
Kanagawa+2015, 2016
Ginzburg & Sari 2018

Include dust dynamics + synthetic observations

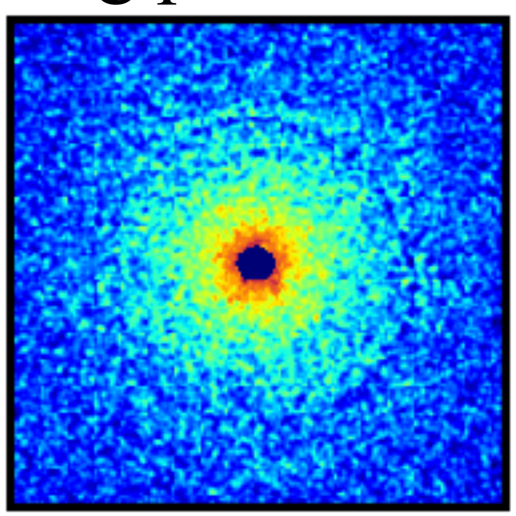
Small particles



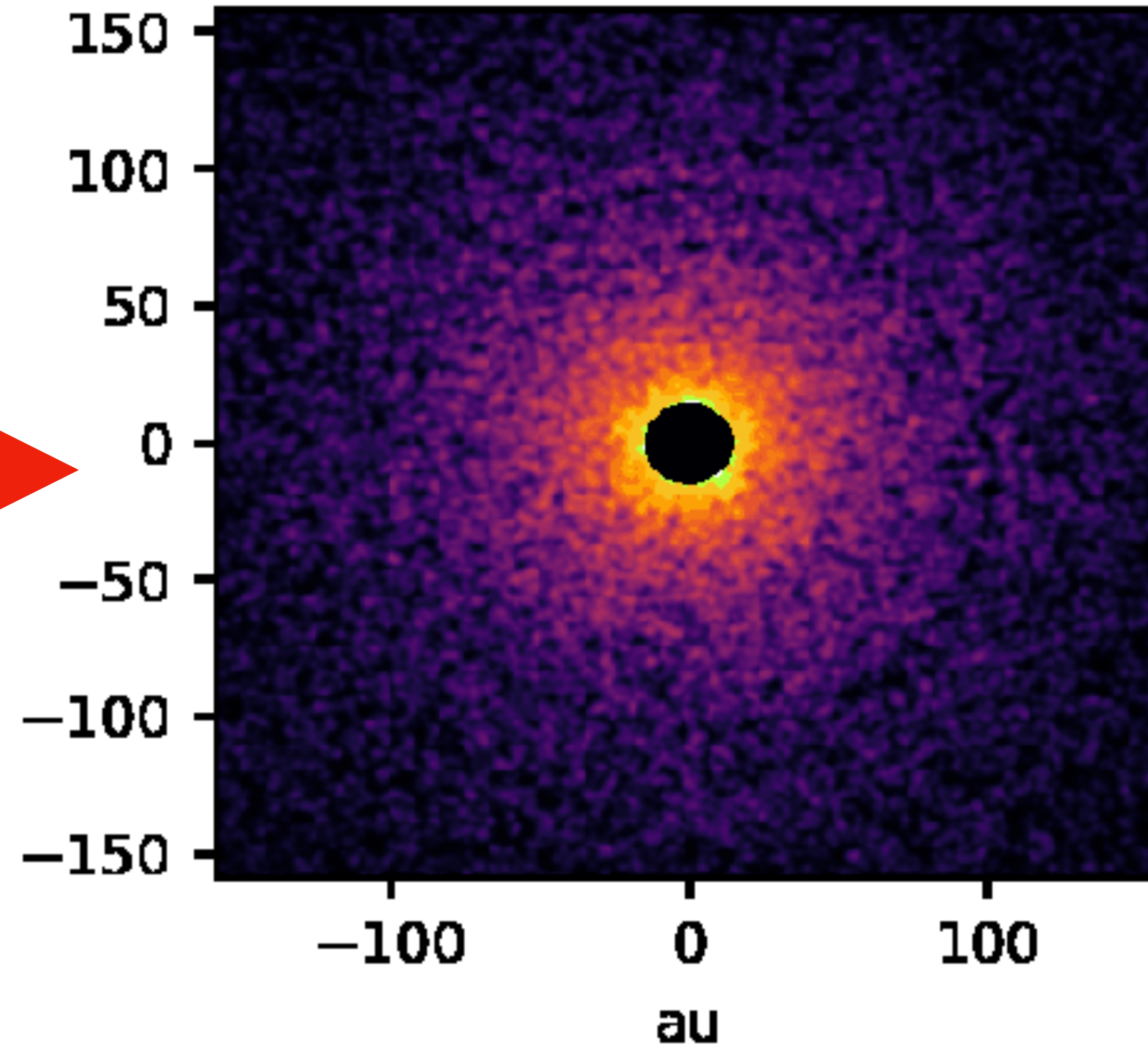
Gas



Big particles



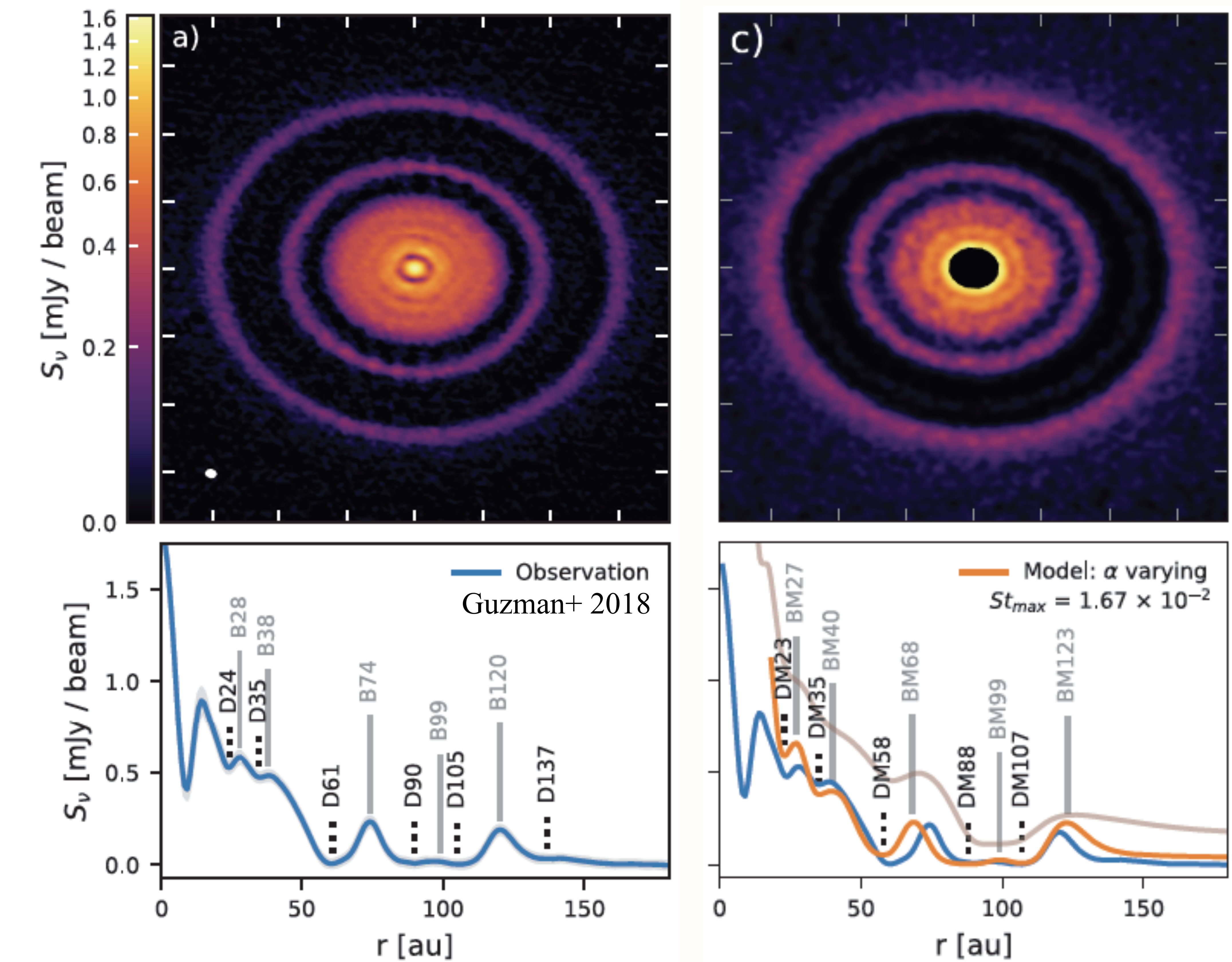
Submm intensity



St= $T_s = 1.55 \times 10^{-3}(s/1\,\mathrm{mm})(100\,\mathrm{g\,cm^{-2}}/\Sigma_g)$

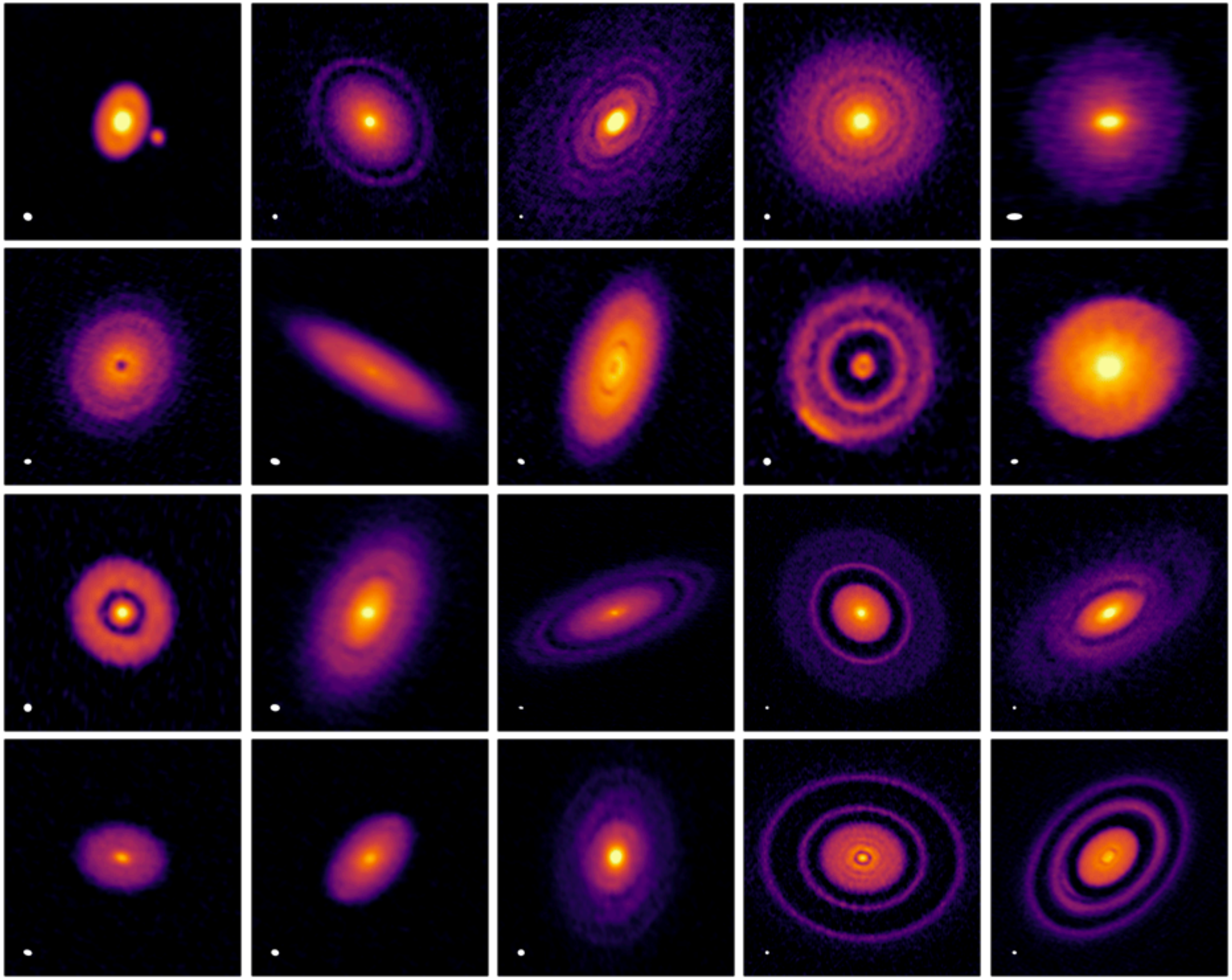
Zhang et al. 2018

Highlights: AS 209

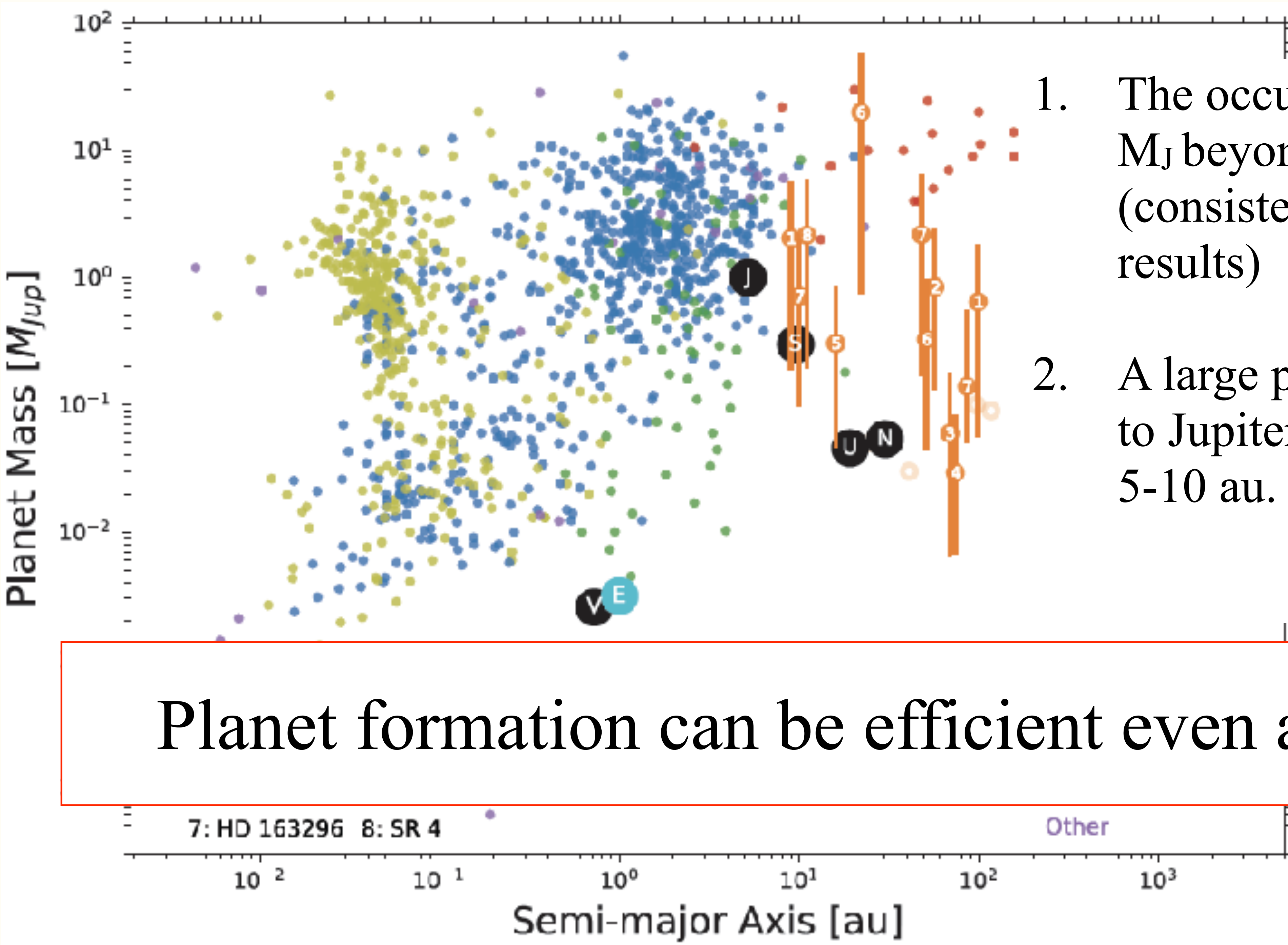


M_p=0.3 M_{saturn}

Young planet population



Young planet population

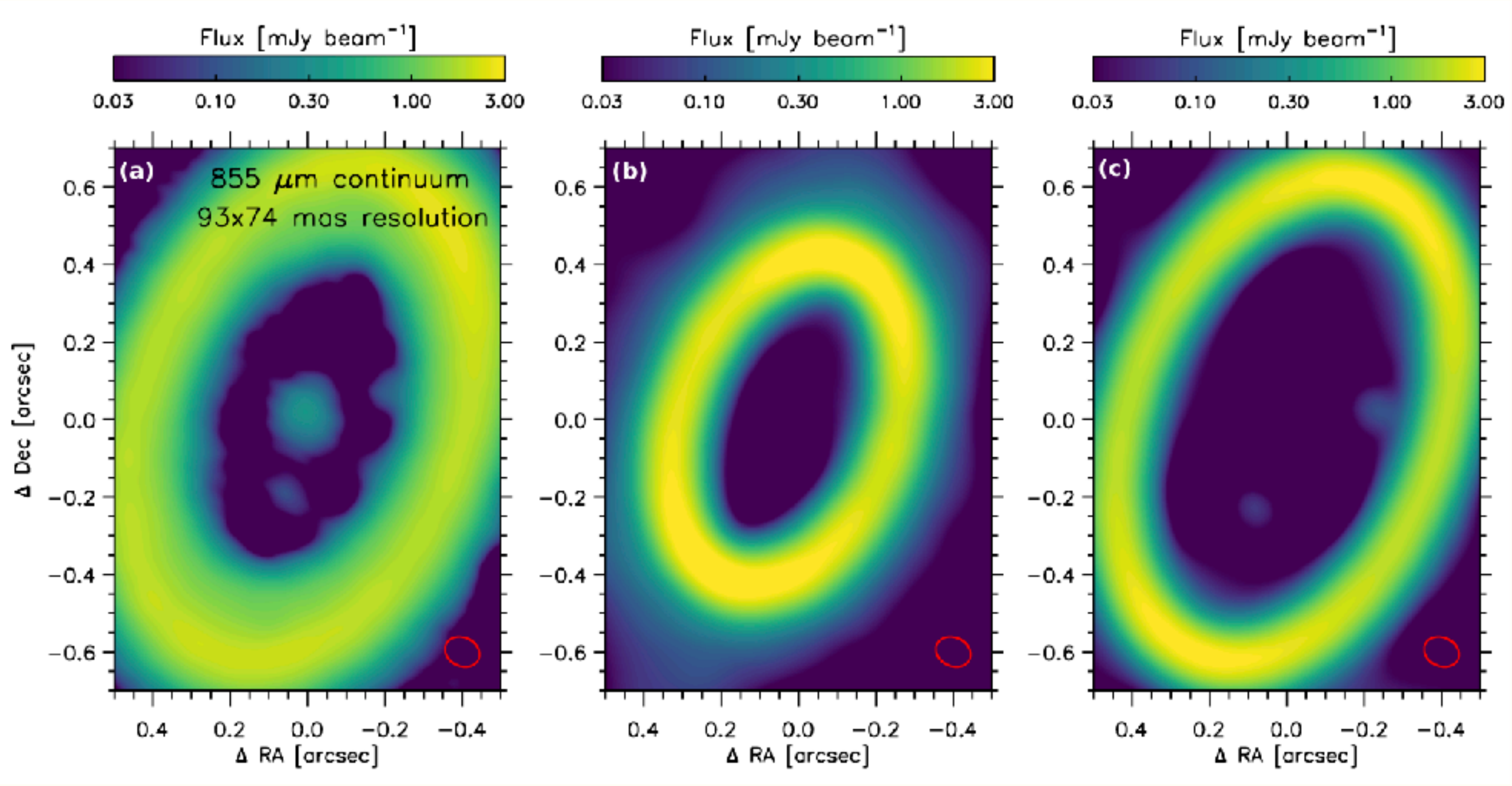


1. The occurrence rate for M_p>5 M_J beyond 5-10 au is 6% (consistent with direct imaging results)

2. A large population of Neptune to Jupiter mass planets beyond 5-10 au. (occurrence rate 56%)

Planet formation can be efficient even at 10-100 au

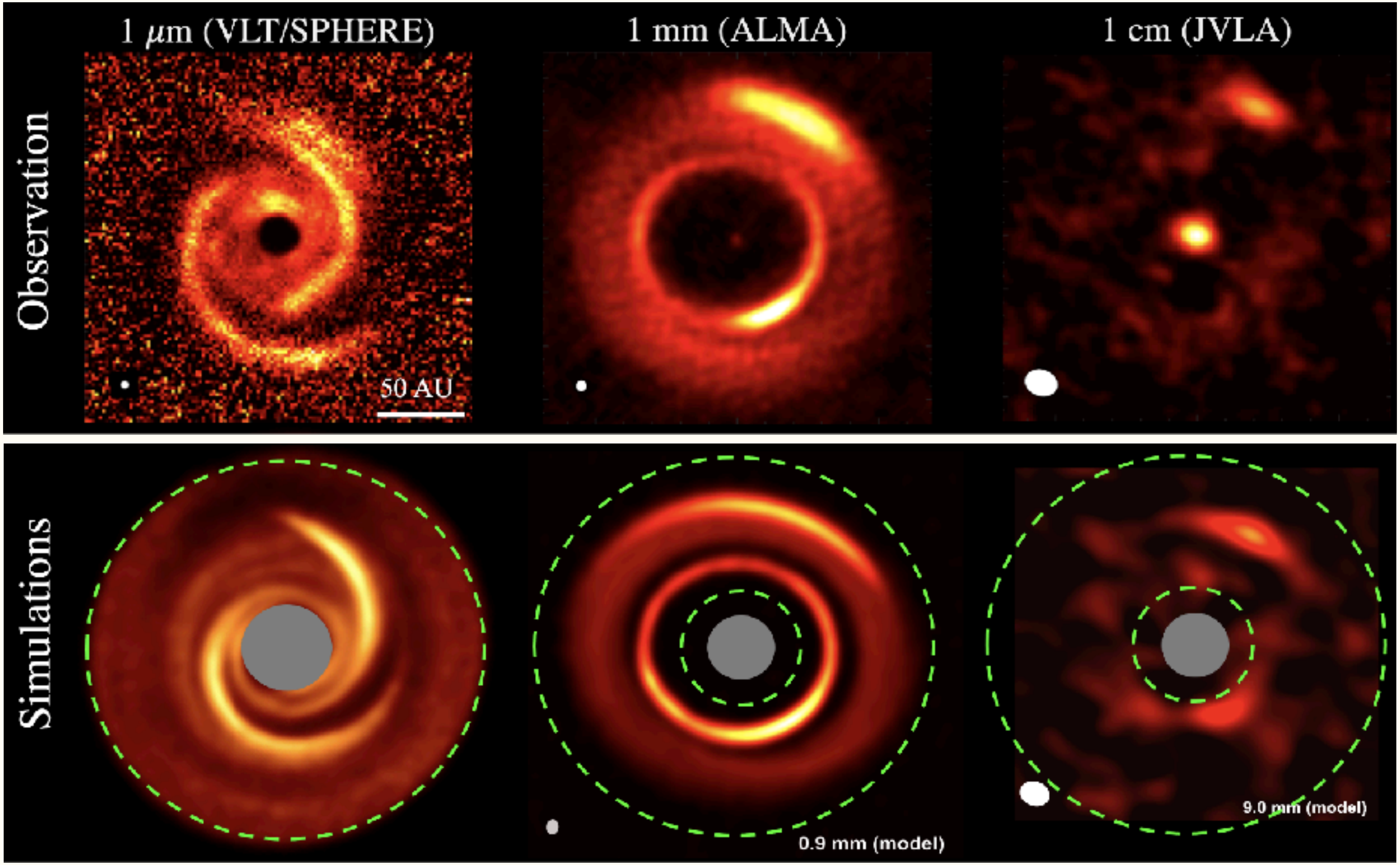
PDS 70 observations vs theory



Bae et al. 2019

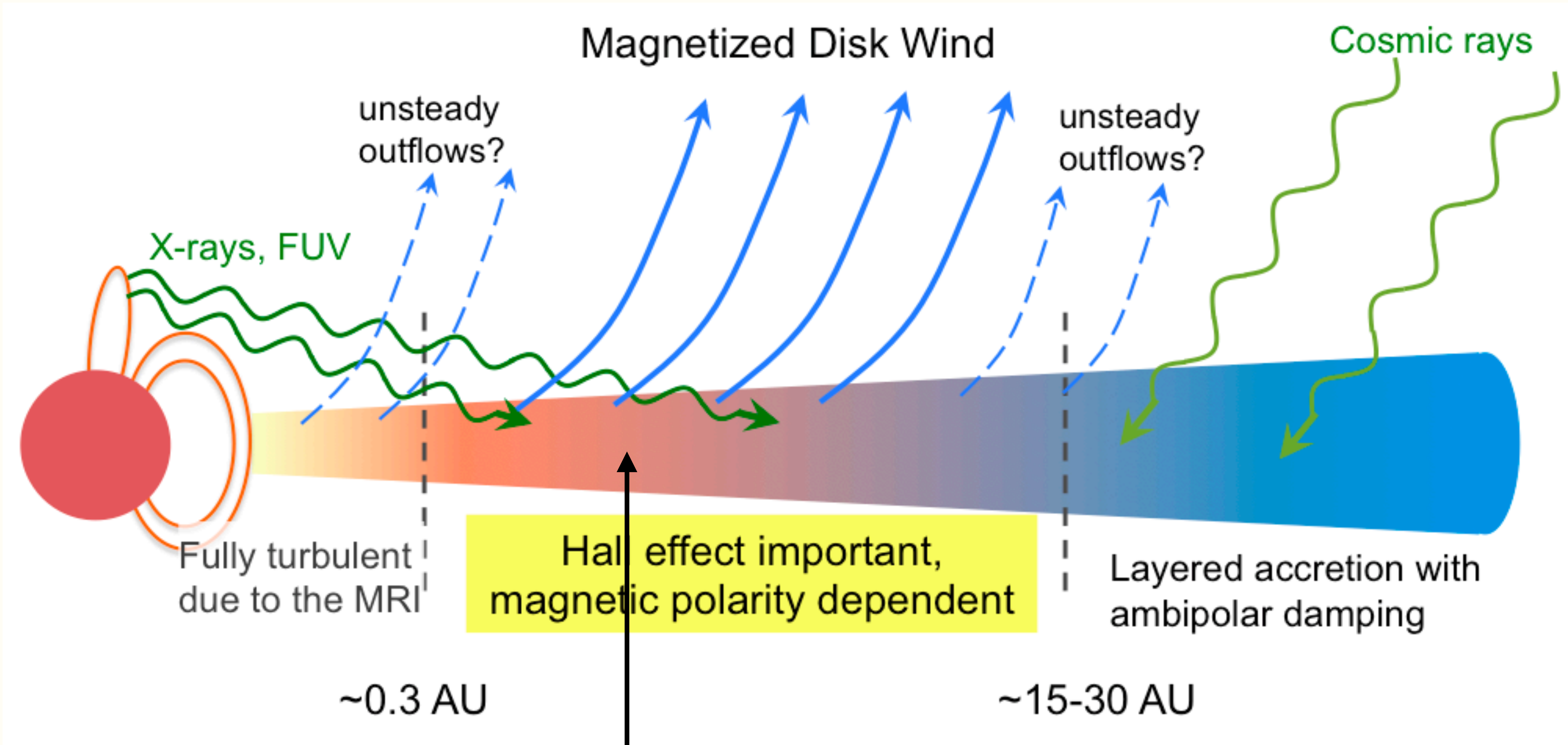
Simulations by Chao-Chin Yang & Zhaohuan Zhu
Rendered by California Academy of Sciences
“Big Astronomy” https://www.youtube.com/watch?v=qV5nkCLutH8

MWC 758 disk



Paardekooper et al. 2022 PPVII

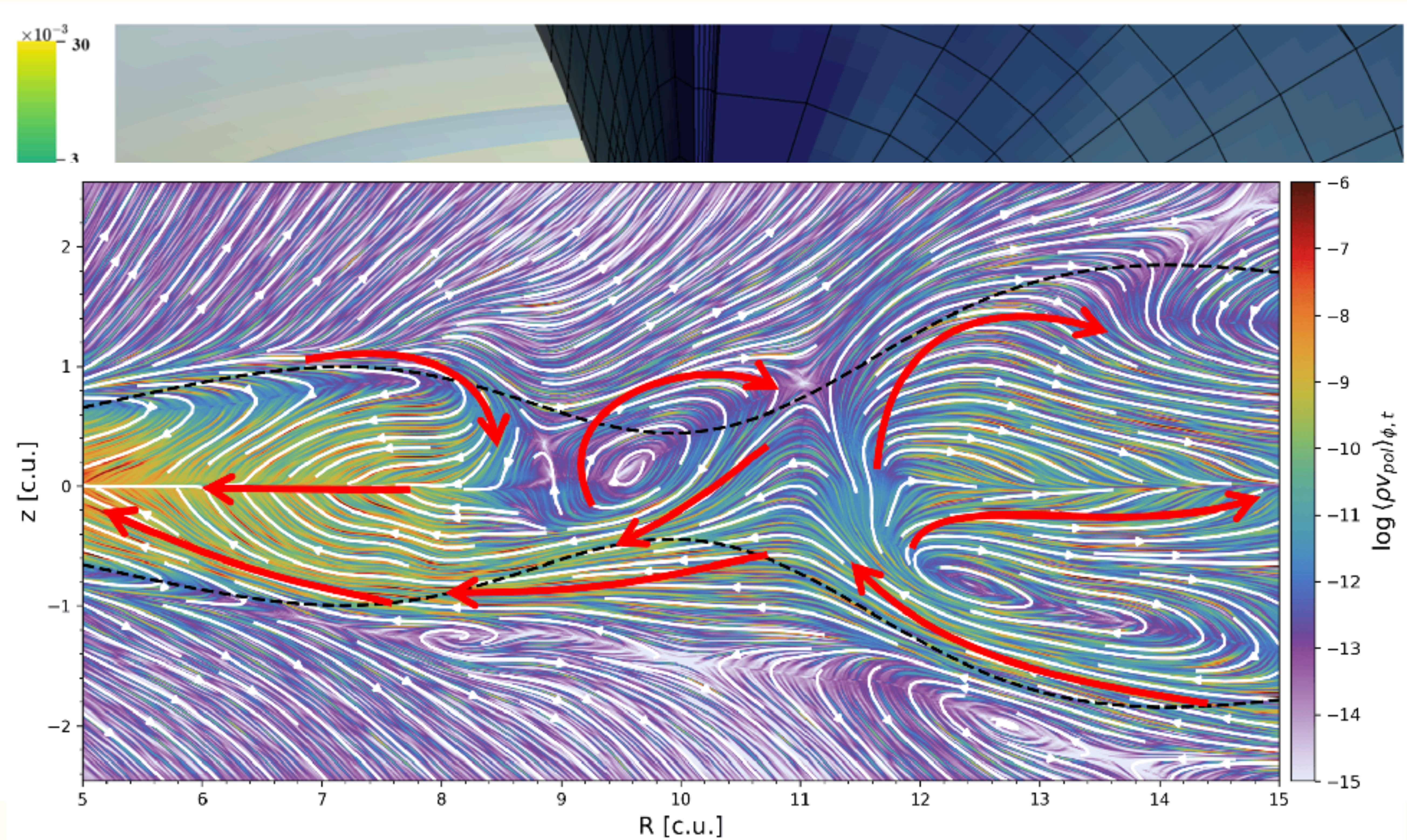
More realistic disks



Xuening Bai

Laminar Region

Planets in a non-ideal MHD disk



Hu et al. 2025, Aoyama & Bai 2023, Wafflard-Fernandez & Lesur 2023

Outlines

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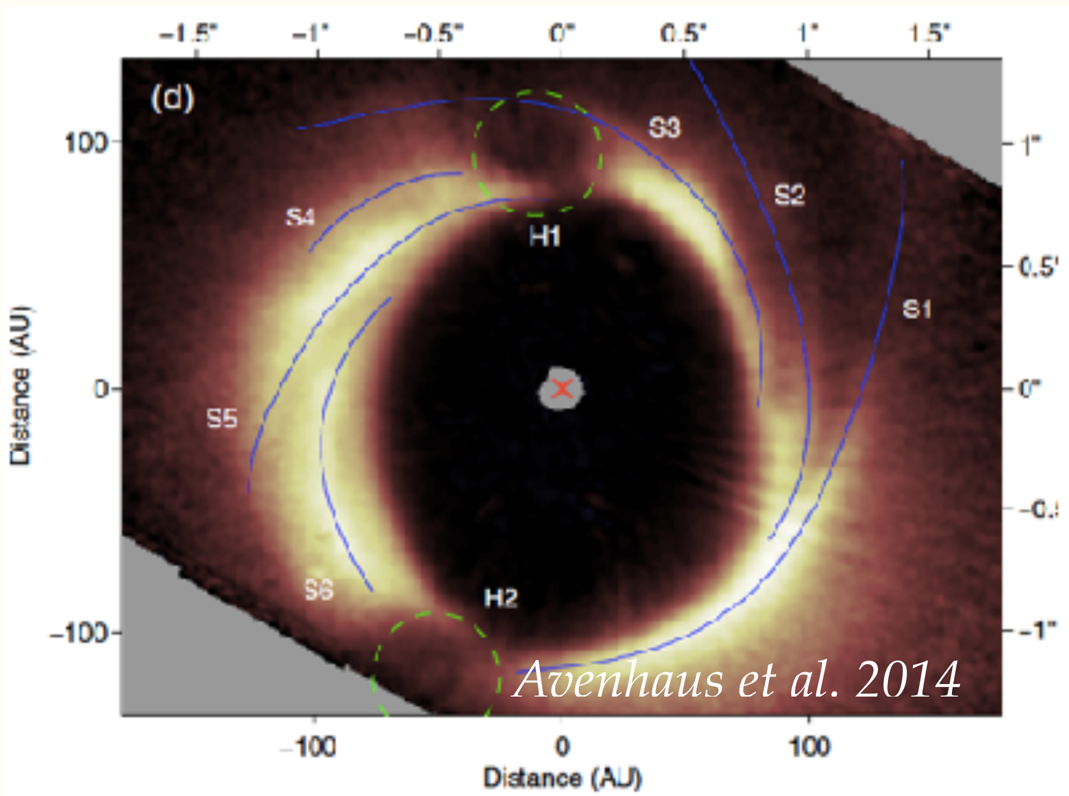
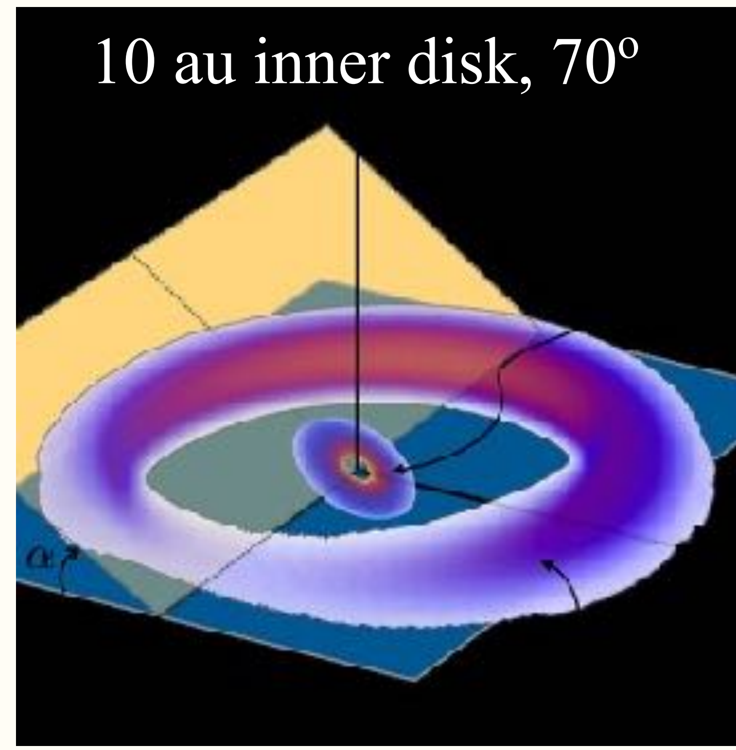
  - QPE (high velocity impacts)

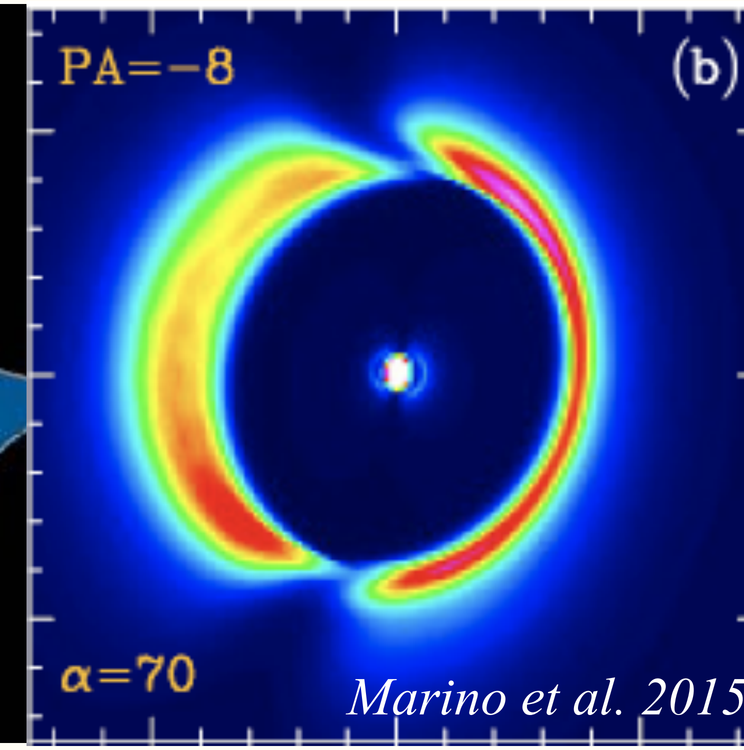
Broken disks

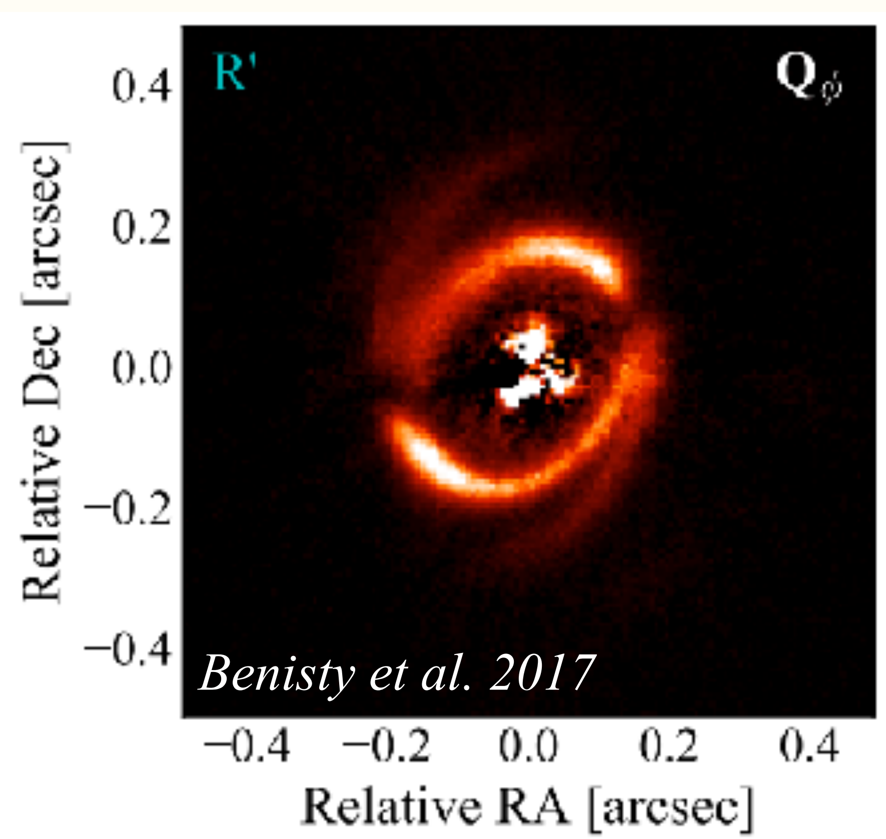
near-IR

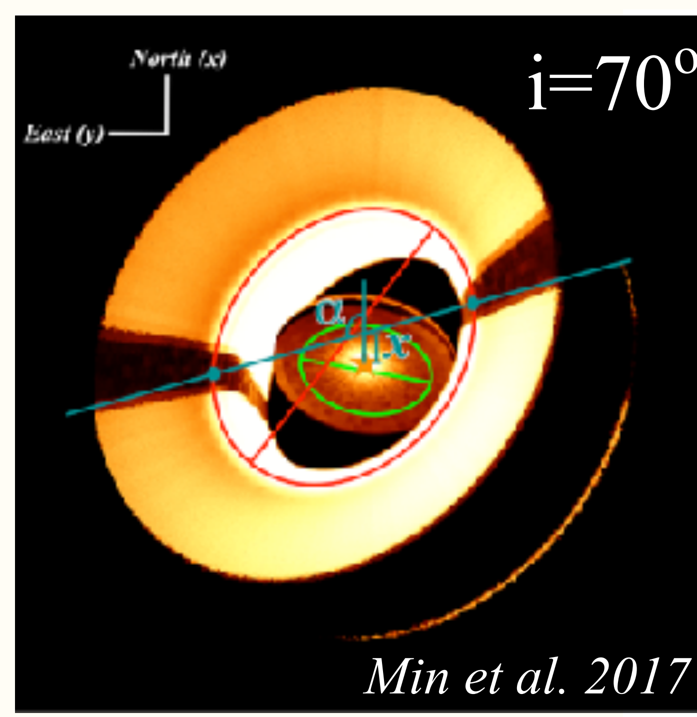
Synthetic image

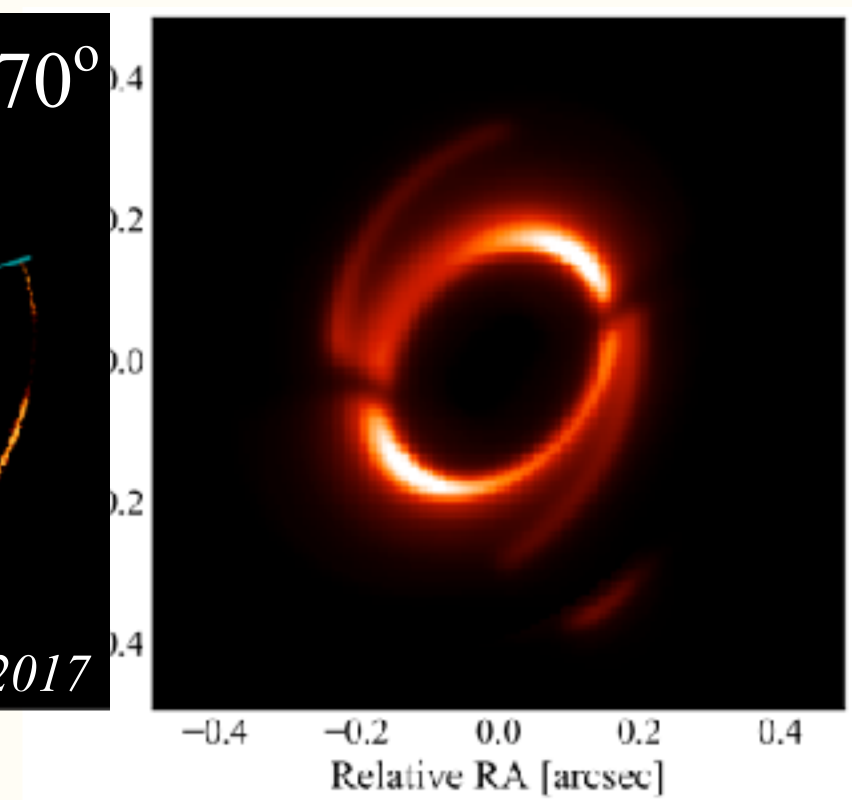






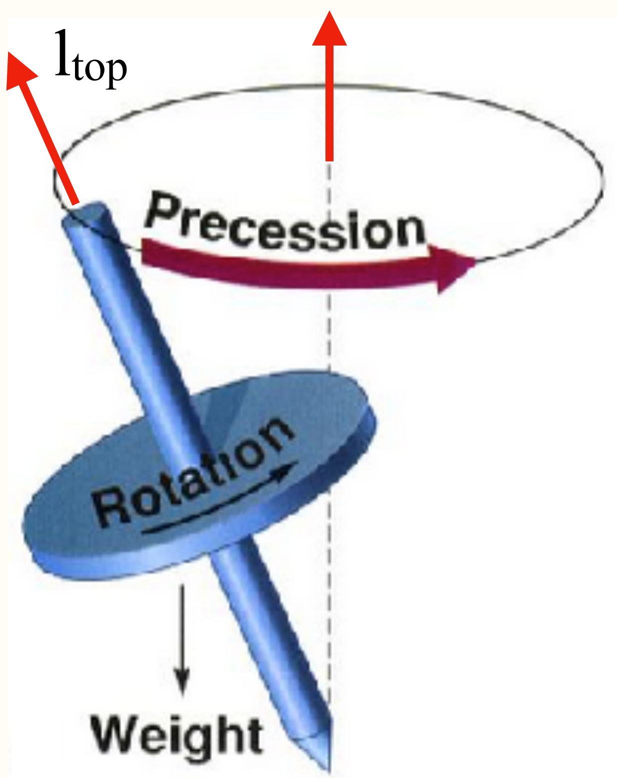


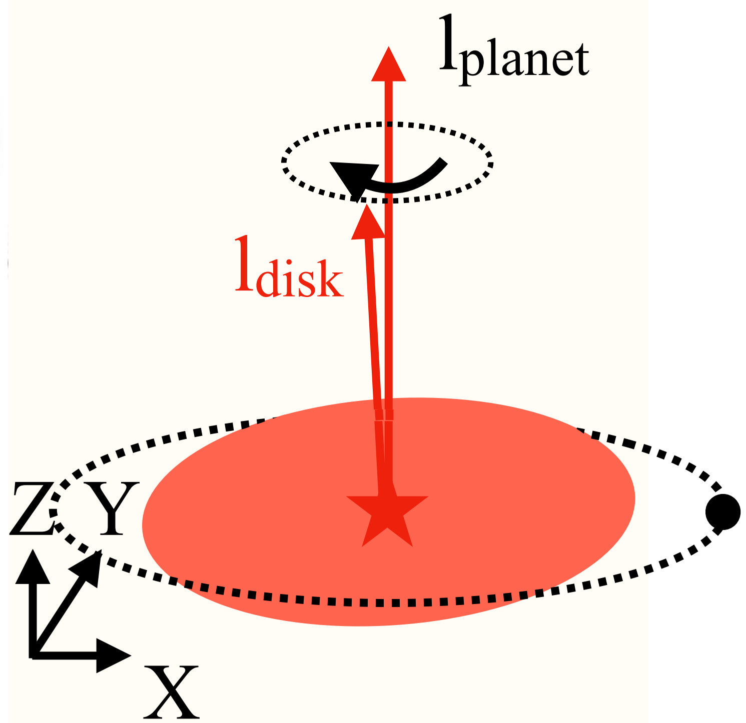


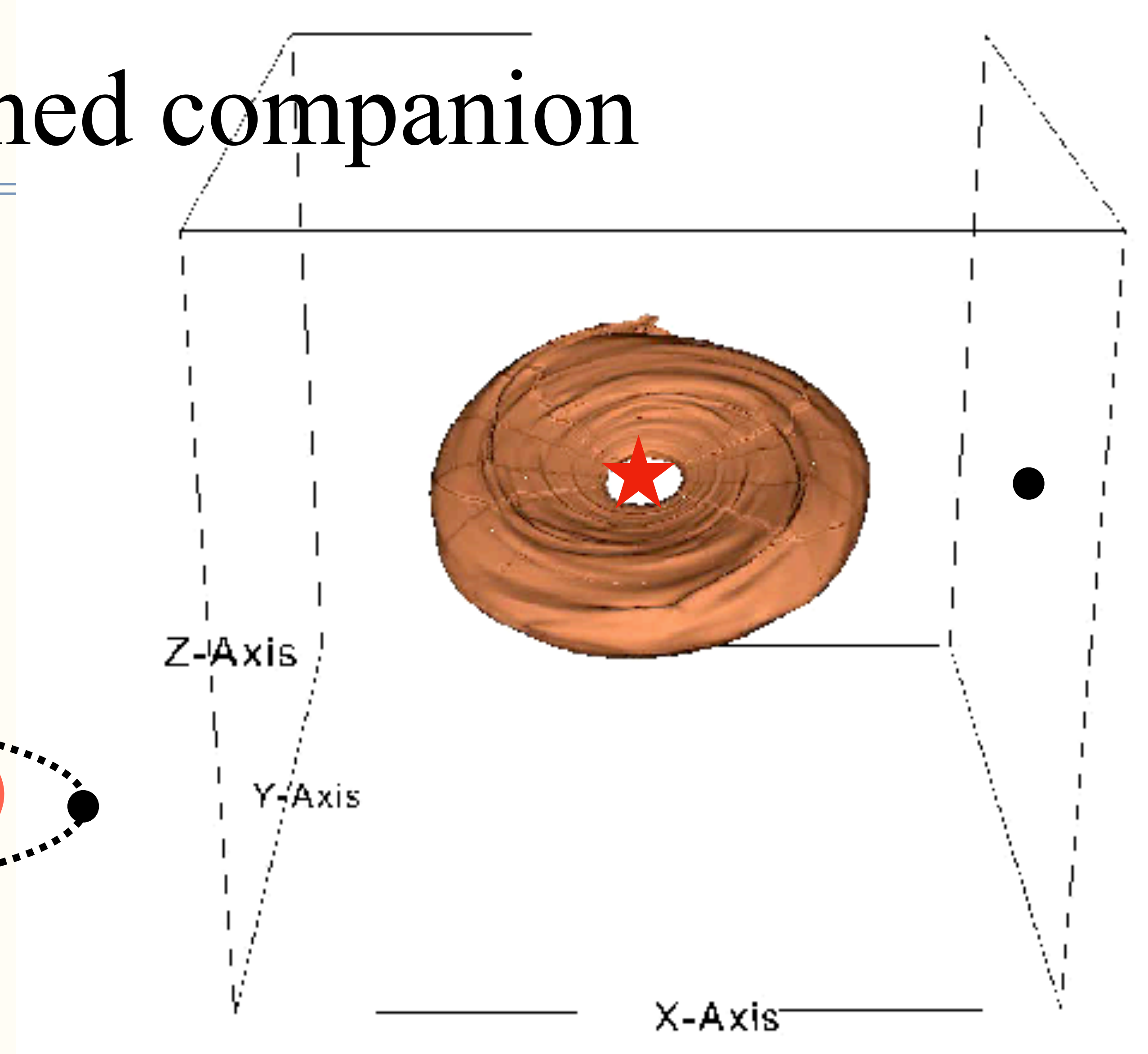


Disk breaking by a misaligned companion

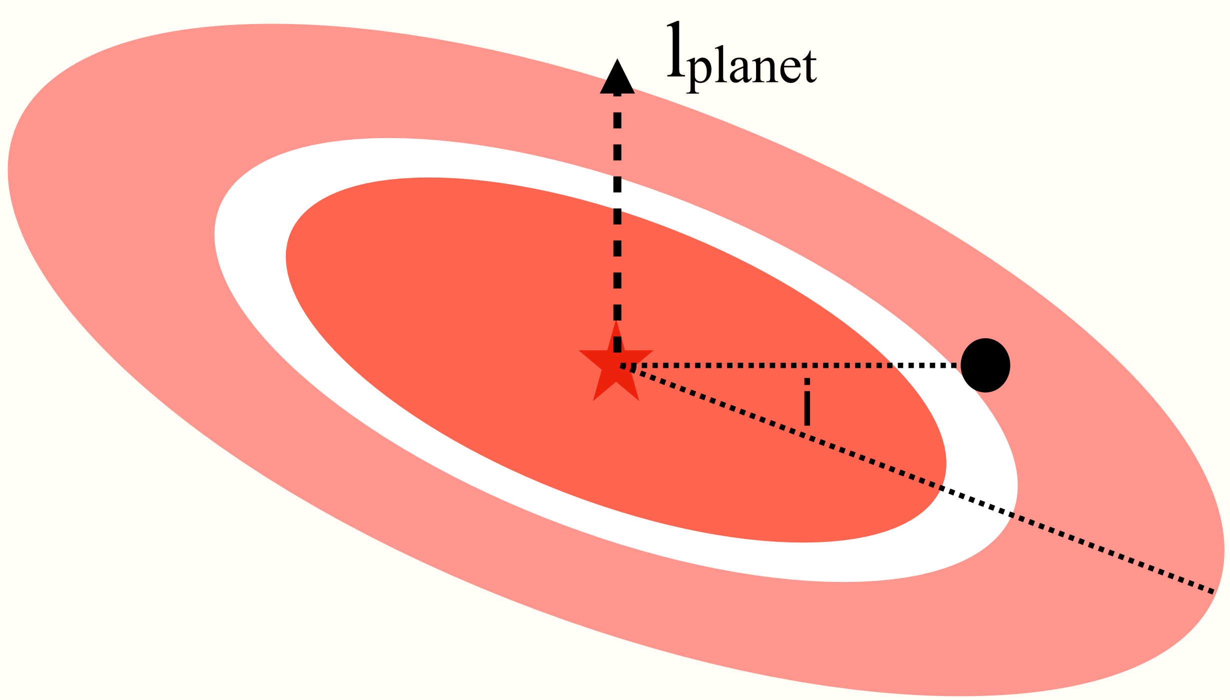
Disk precession

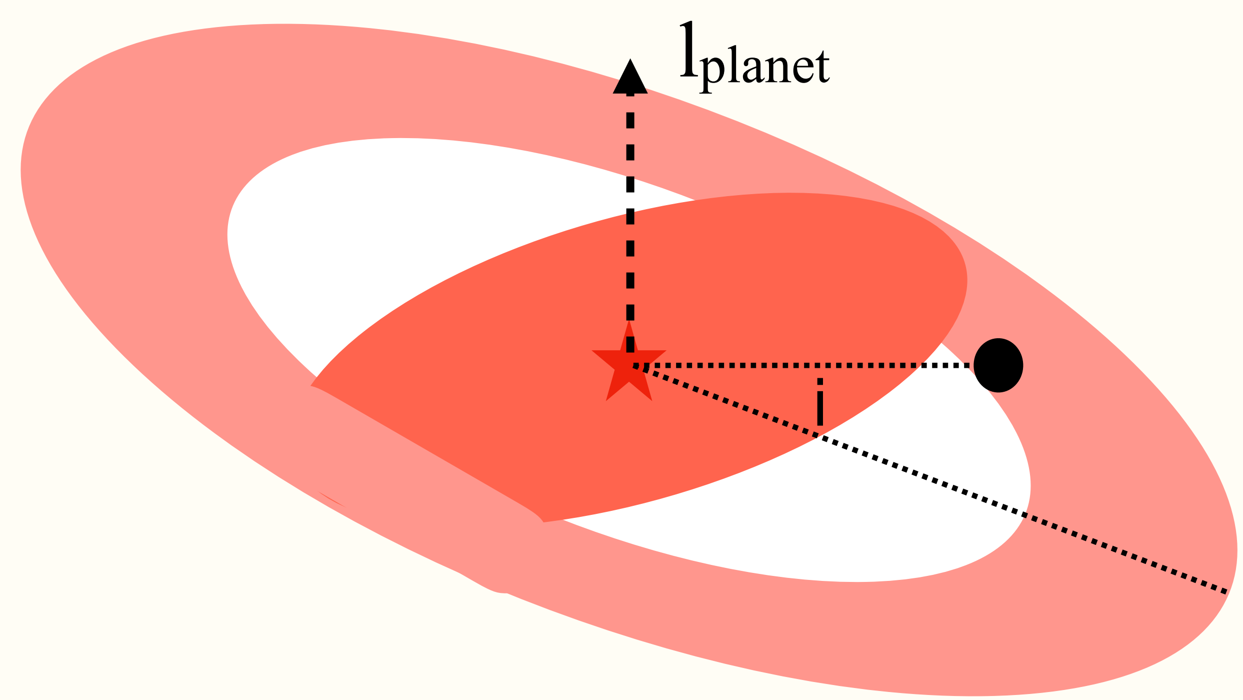






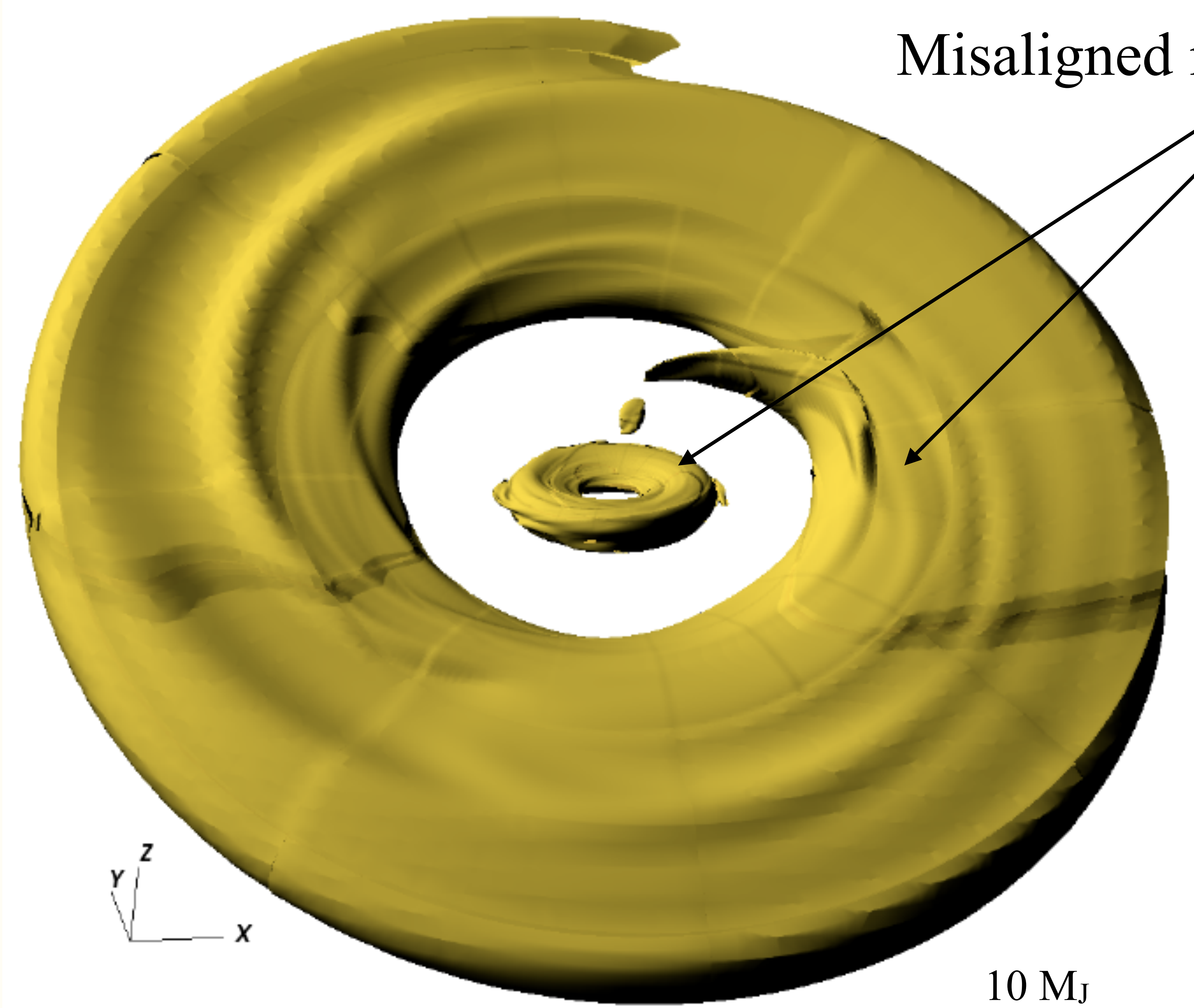
A misaligned companion in a disk

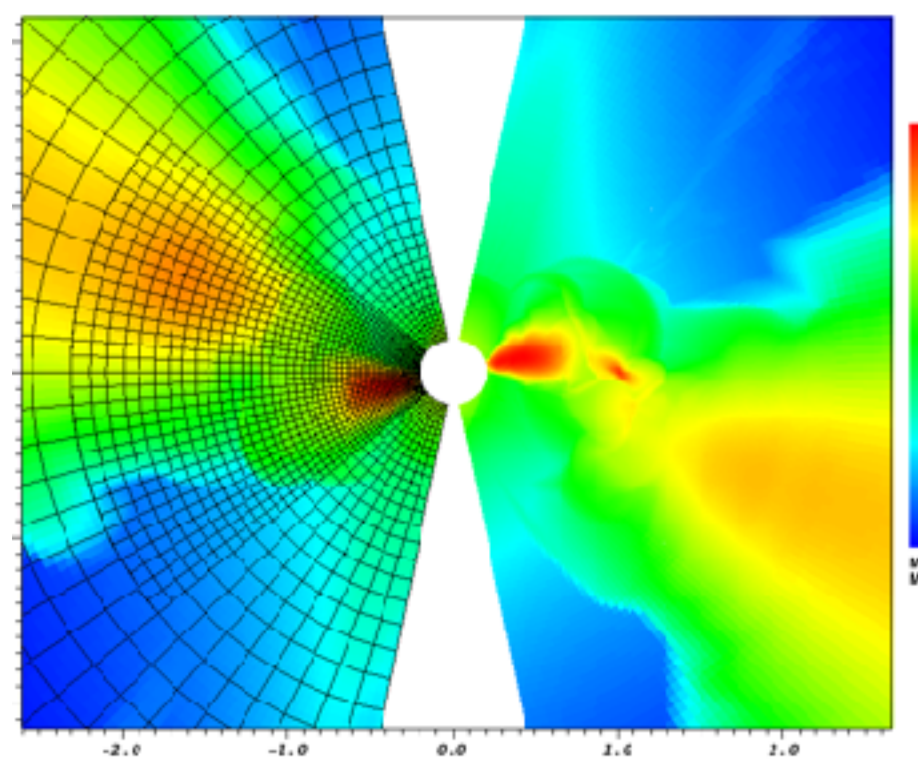




Grid-based simulations for inclined planets:

Misaligned inner and outer disks



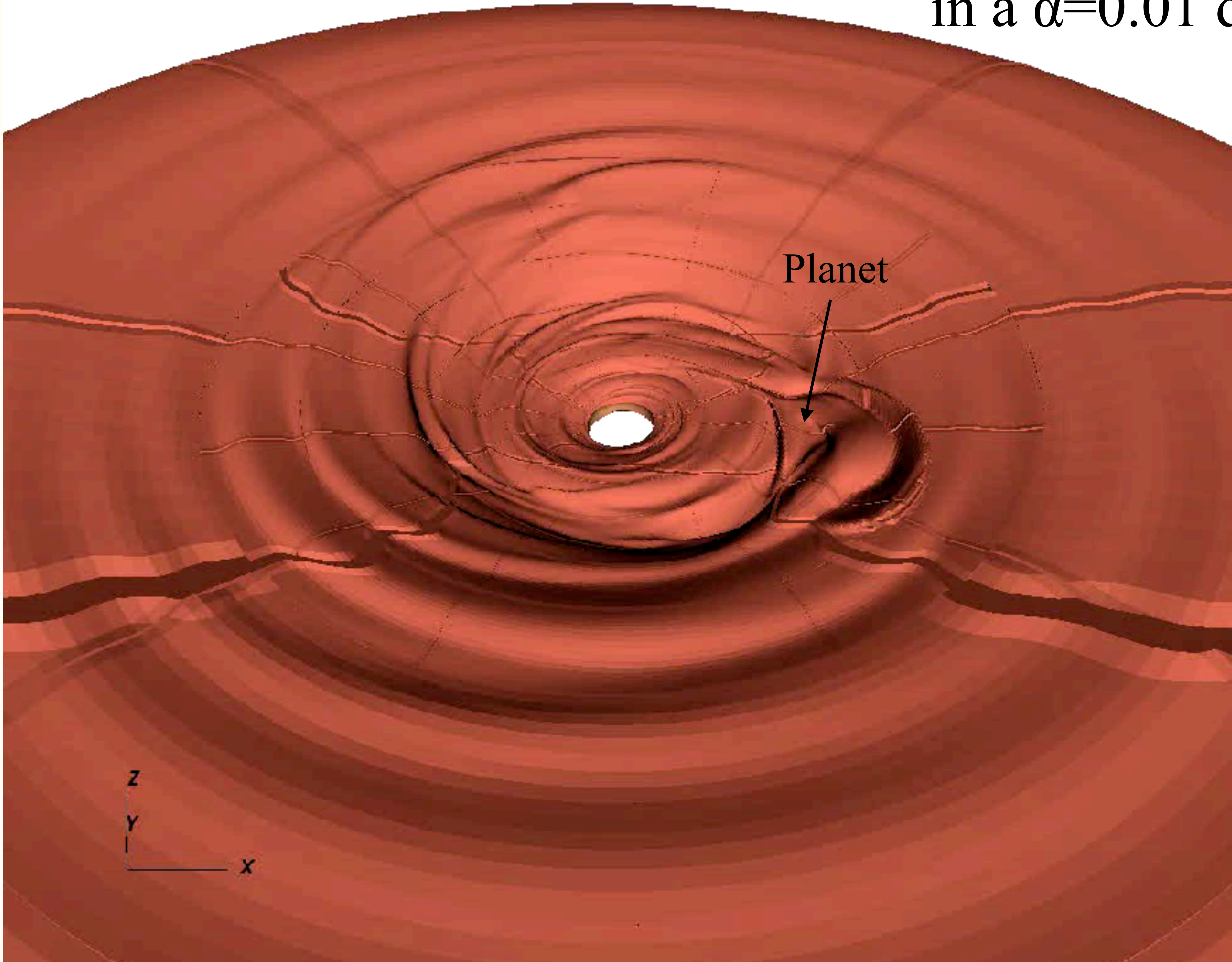


Zhu 2019

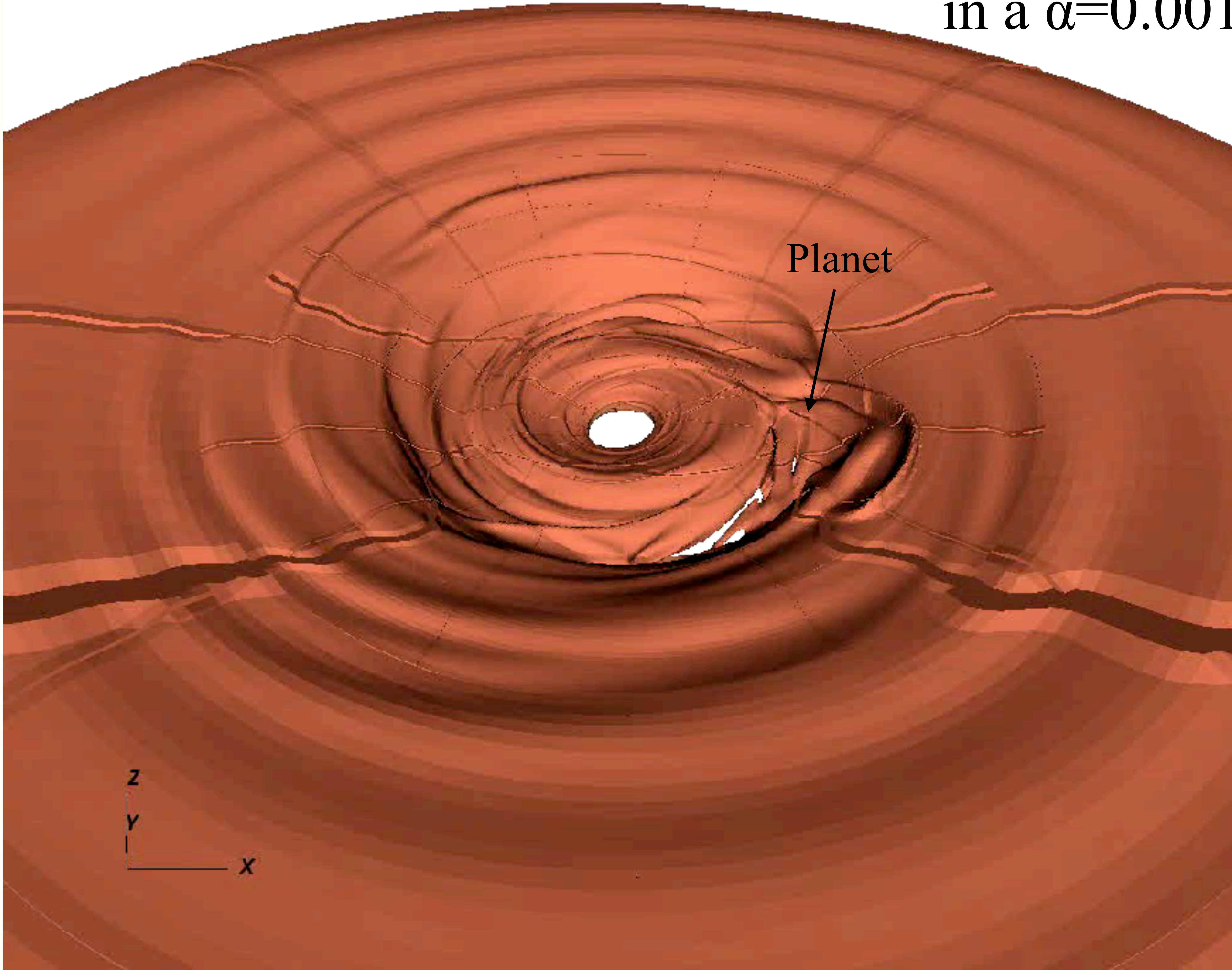
10 M_J
I~19^{o}
inviscid

Misaligned planets in disks

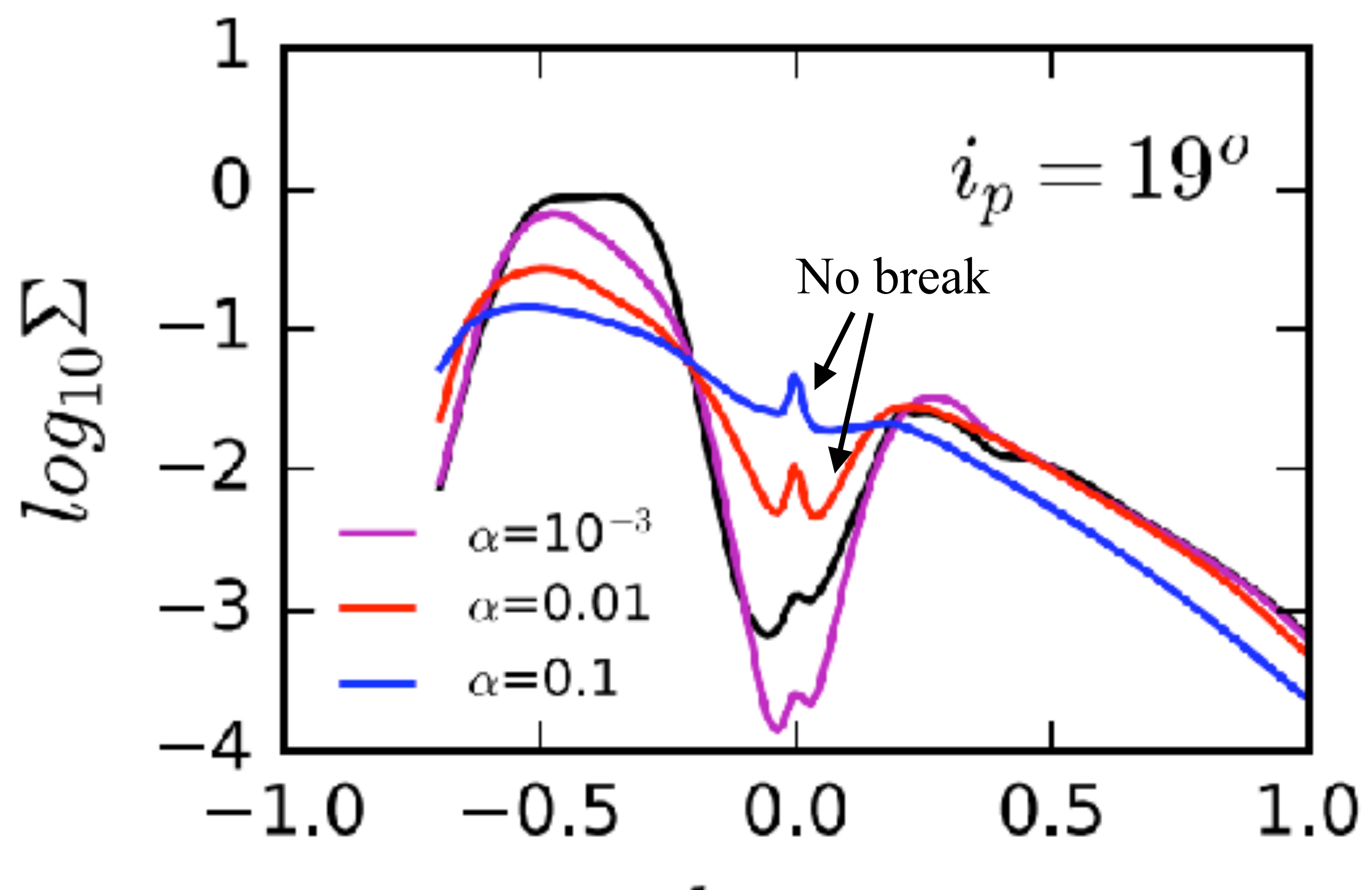
a 19^{o} inclined 10 M_J in a α=0.01 disk



a 19^{o} inclined 10 M_J in a α=0.001 disk



The disk breaks when the gap is deep enough!



1) the gap depth

planet mass (q), viscosity (α)

$$\frac{\Sigma_{gap}}{\Sigma_0} = \frac{1}{1+0.04K}$$

$$K = \alpha^{-1} h^{-5} q^2 \frac{4}{\pi^2(n+1)} K\left(\frac{n}{n+1}\right)^2$$

2) deep enough to break the disk

$$\frac{2R}{c_s} > \sqrt{\frac{\Sigma_{gap}}{\overline{\Sigma}}} \frac{1}{\omega_{rb}}$$

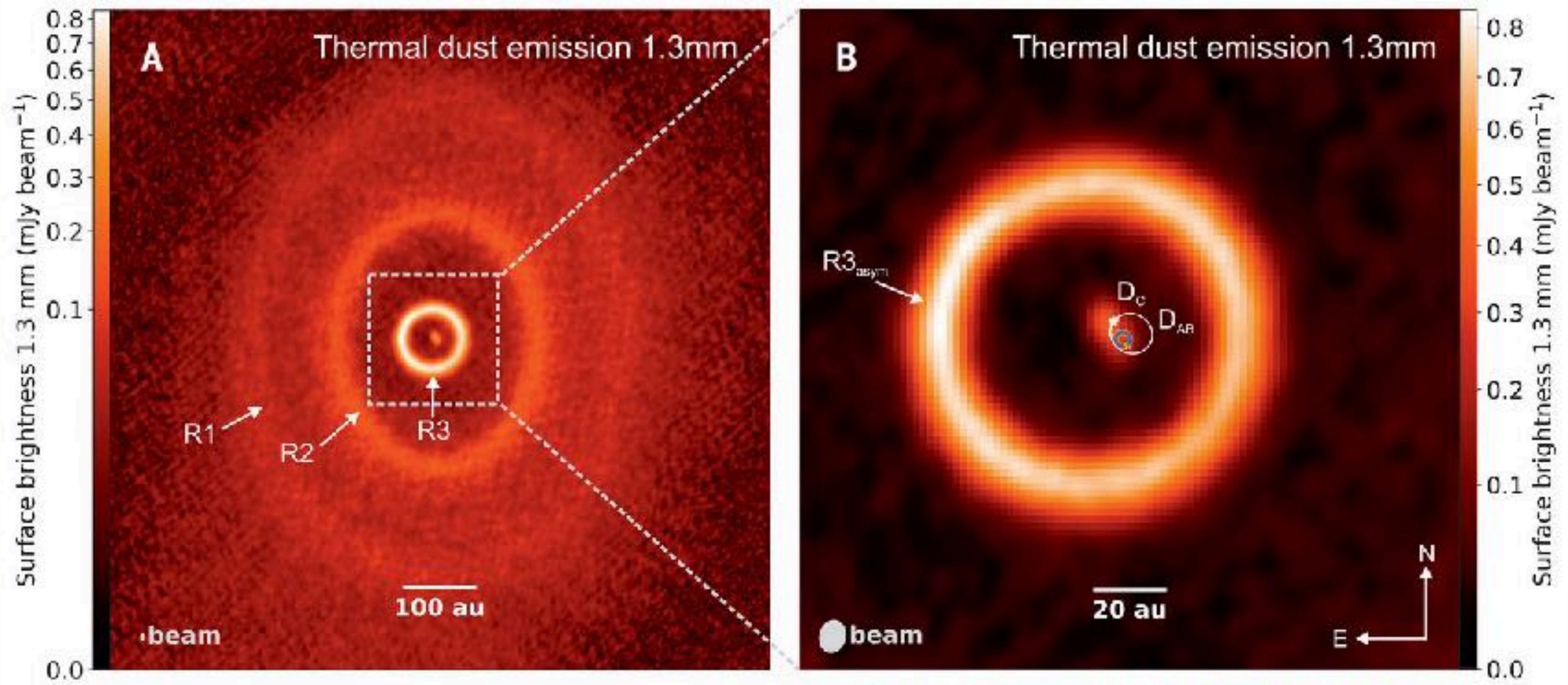
A planet with Jupiter mass or above is needed to break a protoplanetary disk.

The minimum planet mass to break the disk:

$$q > \sqrt{20/3}\alpha^{1/4} h^{7/4}$$

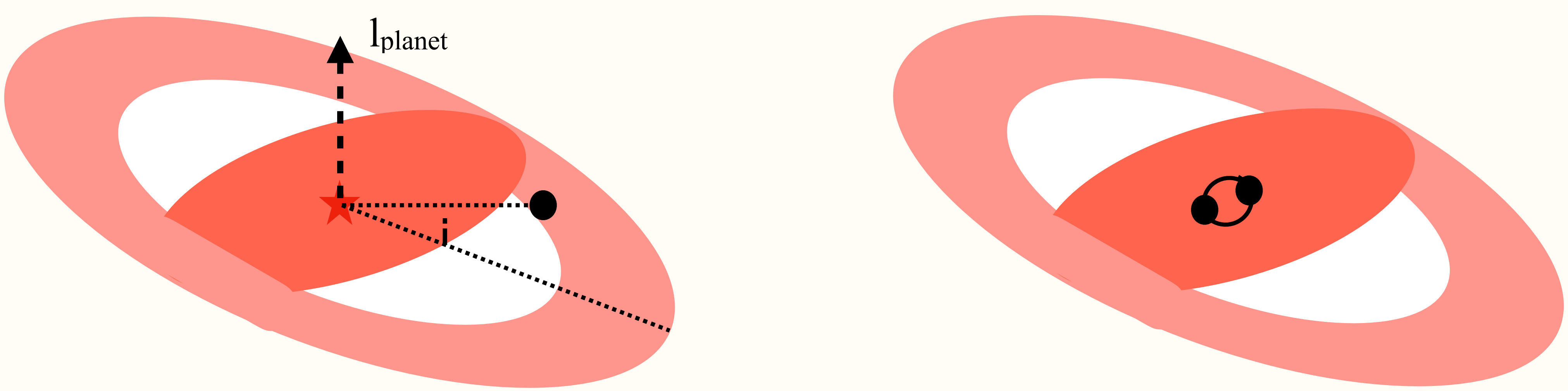
$\alpha=10^{-4}$, h=0.05, **q>0.0014**

Another way to break a disk: binary torque



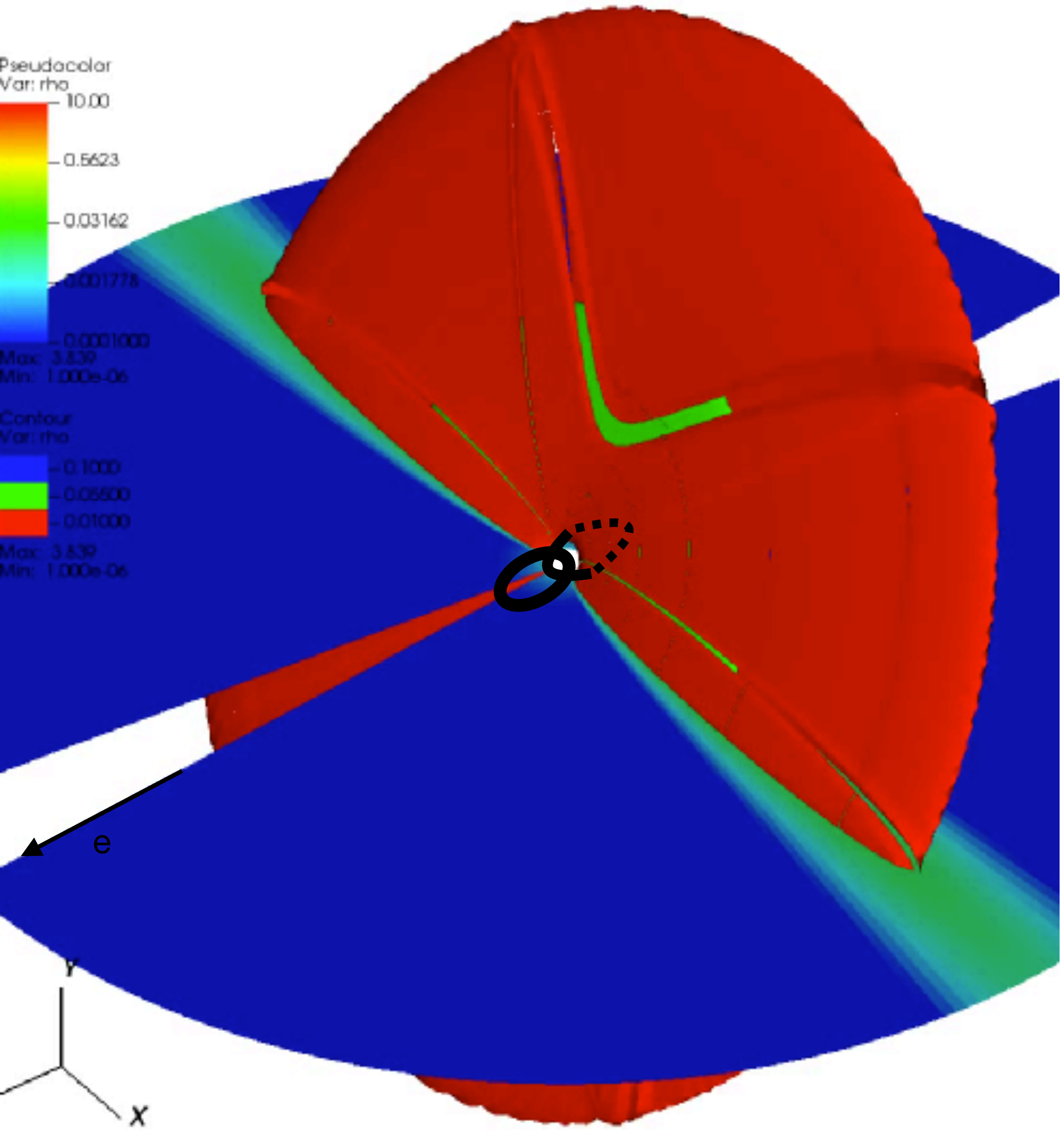
Binary at the center: e=0.38, a=8.9 au

Kraus et al. 2020, Bi et al. 2020

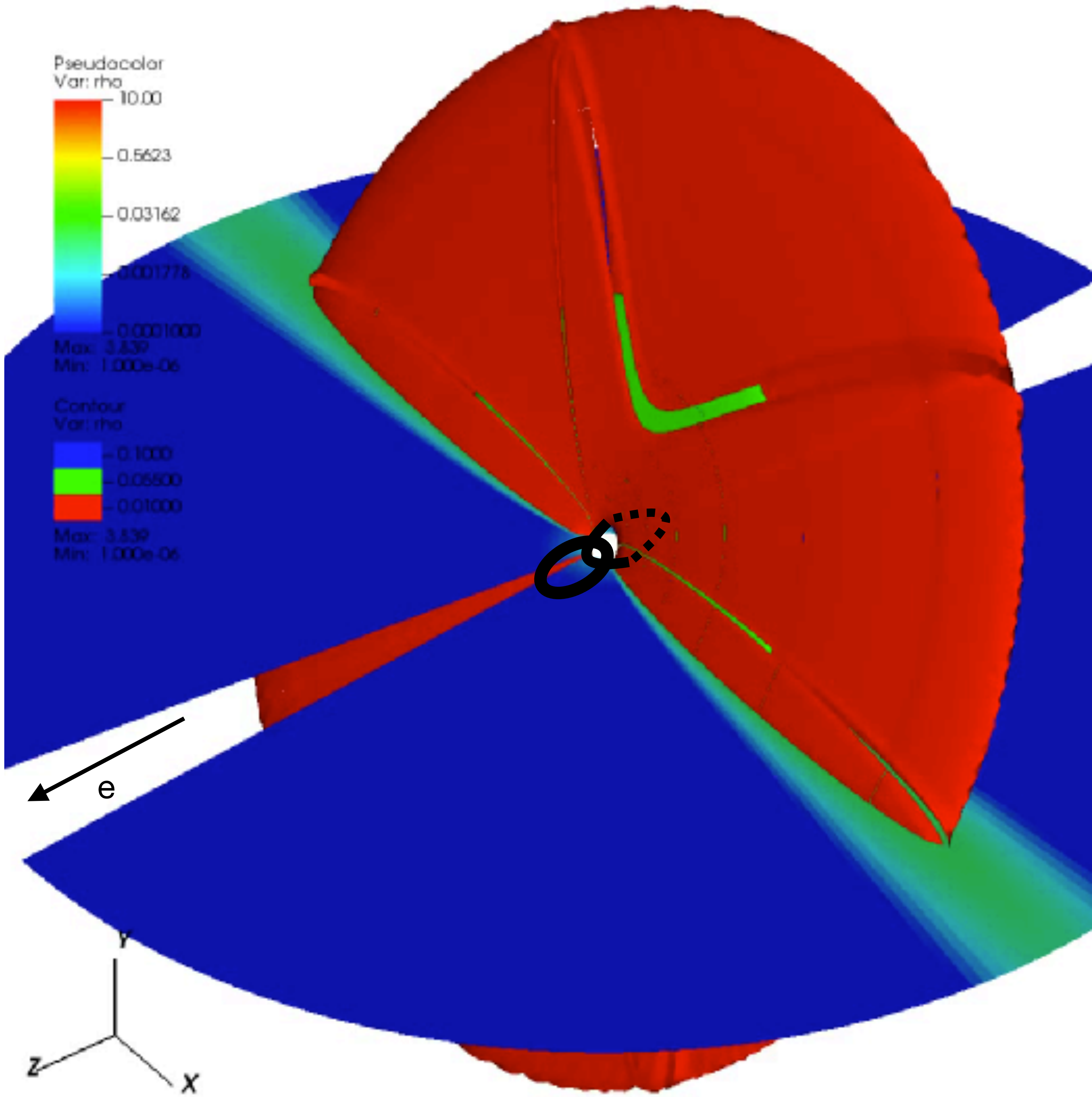


Disk breaking by binary torque

- An e=0.5 equal-mass binary, polar alignment



α=0.1

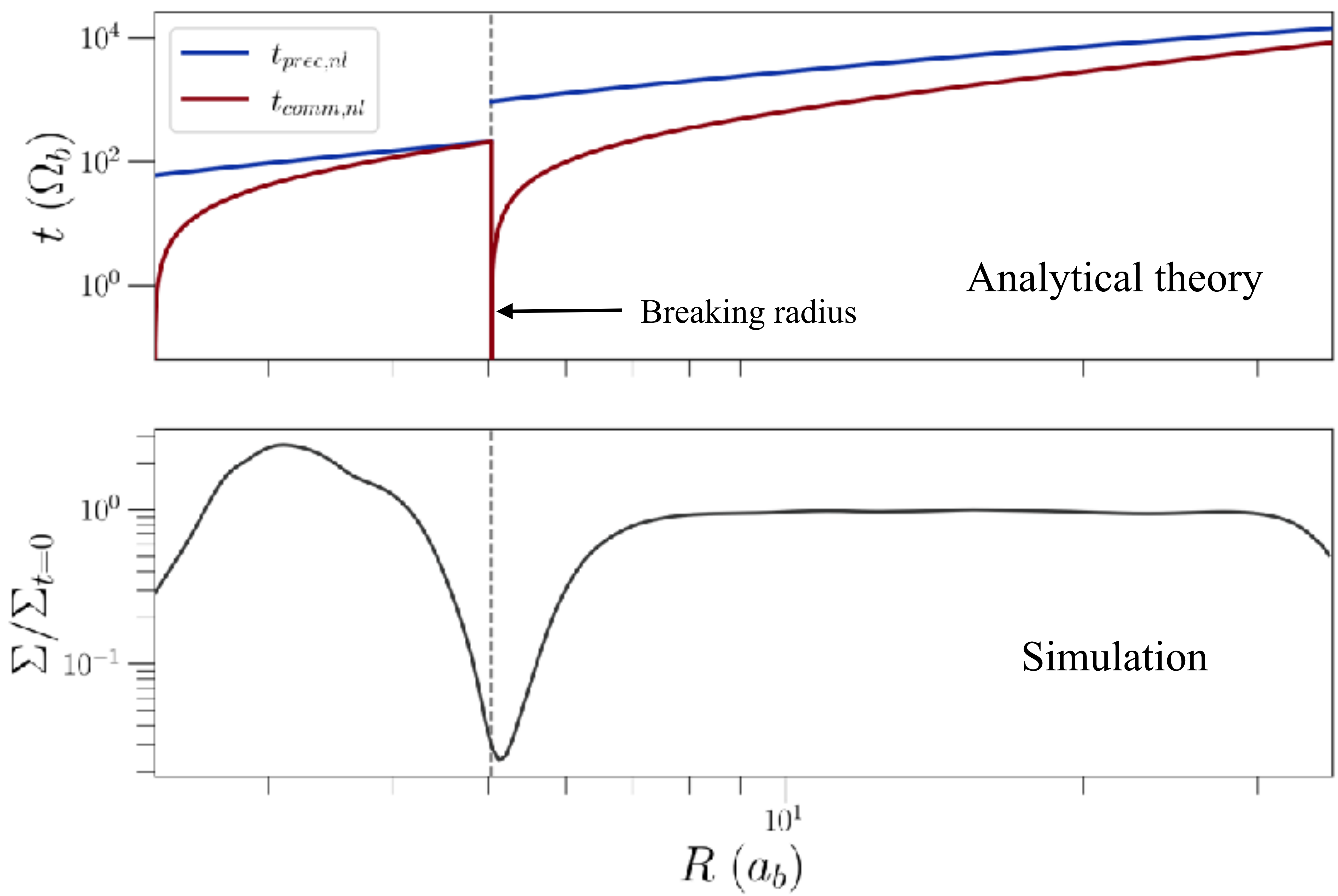


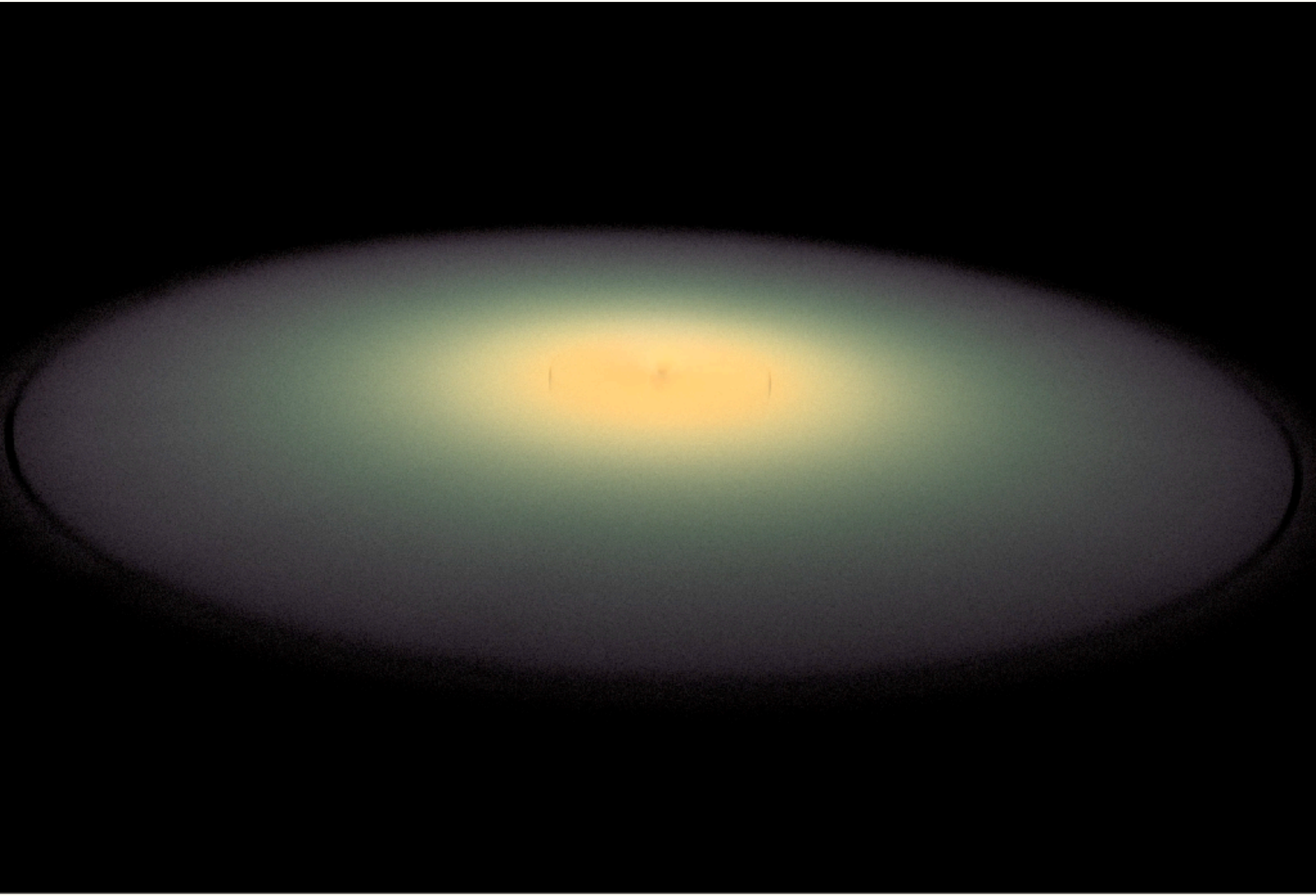
α=0.001

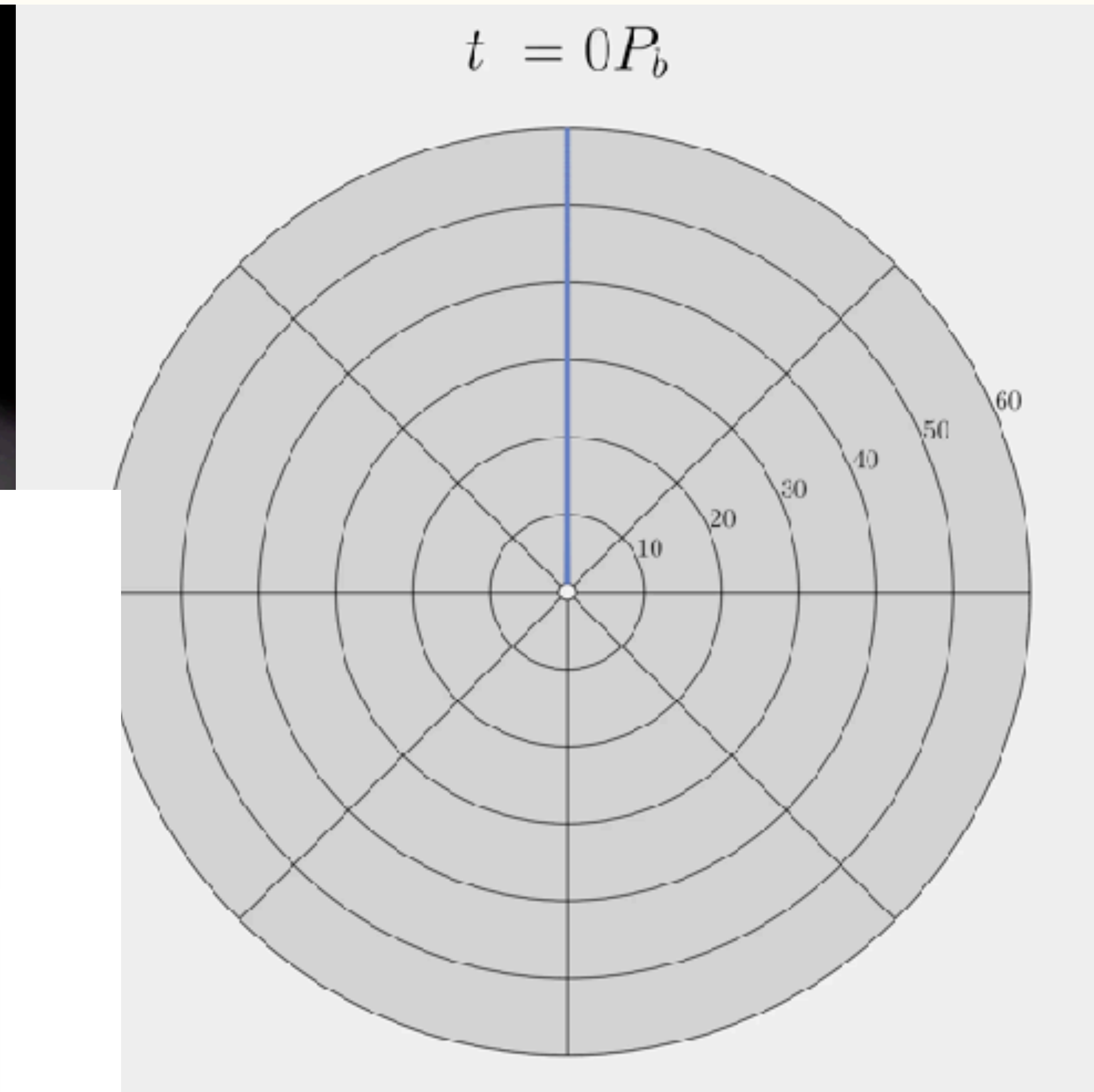
Rabago et al. 2023

Disk breaking by binary torque

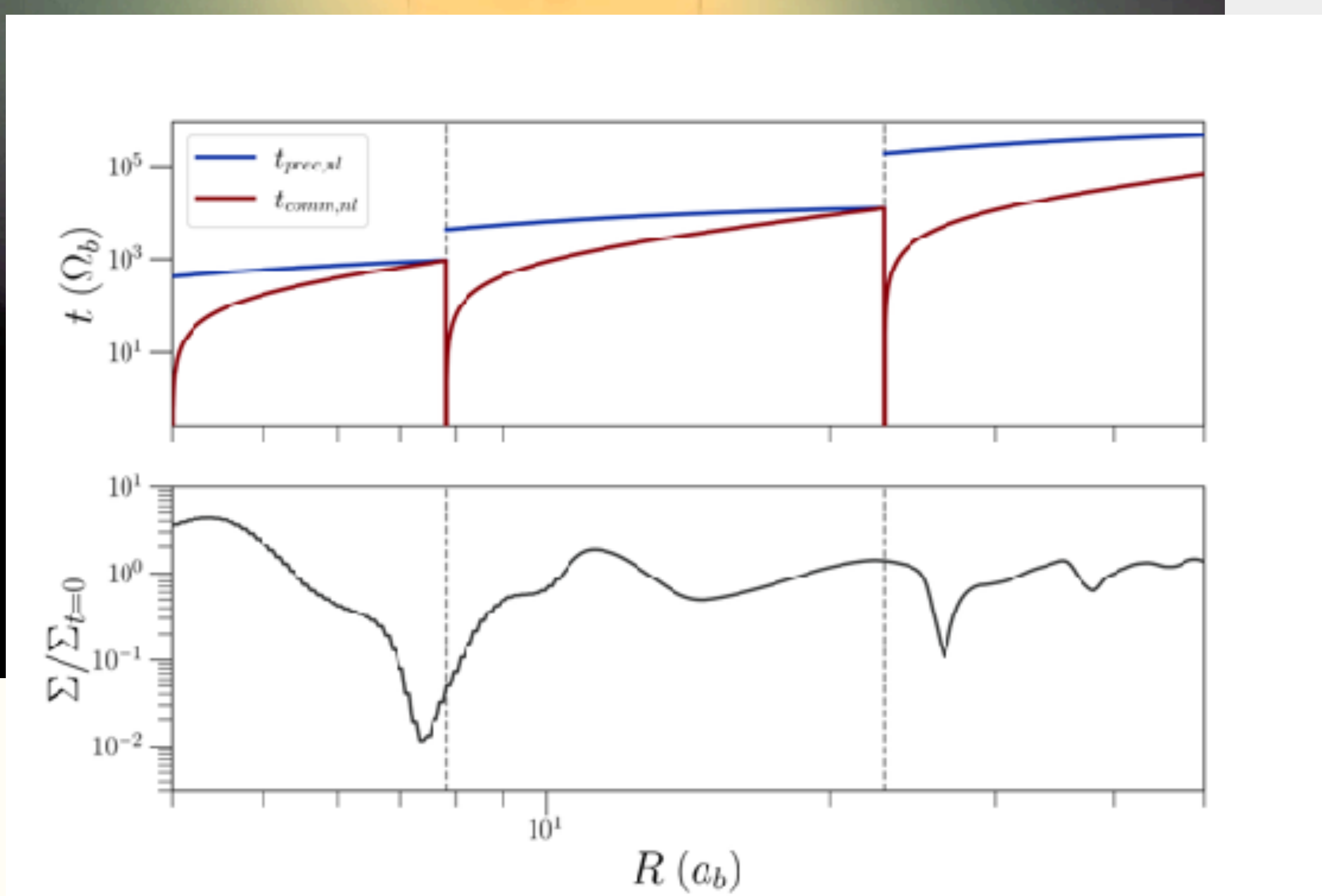
To break: Sound crossing timescale > precession timescale







$t = 0P_b$
10
20
30
40
50
60



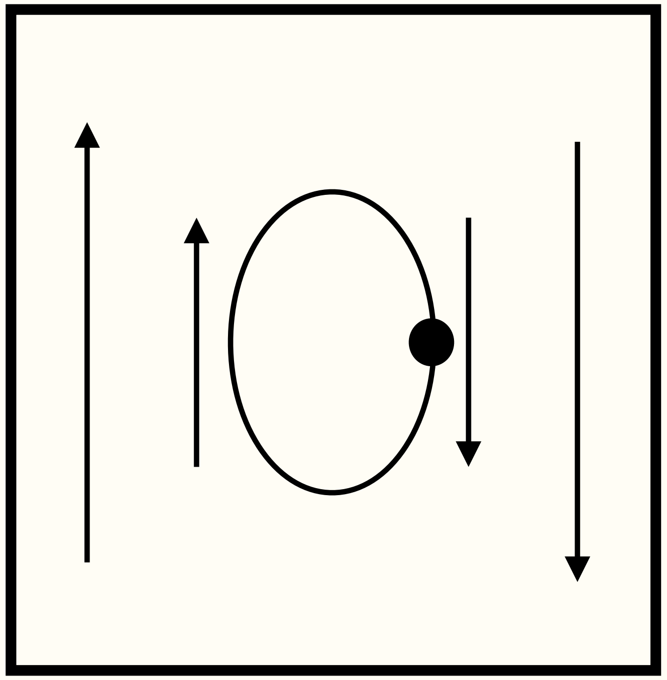
$t_{prec,nl}$
$t_{comm,nl}$
$t\ (\Omega_b)$
$\Sigma/\Sigma_{t=0}$
$R\ (a_b)$

Outlines

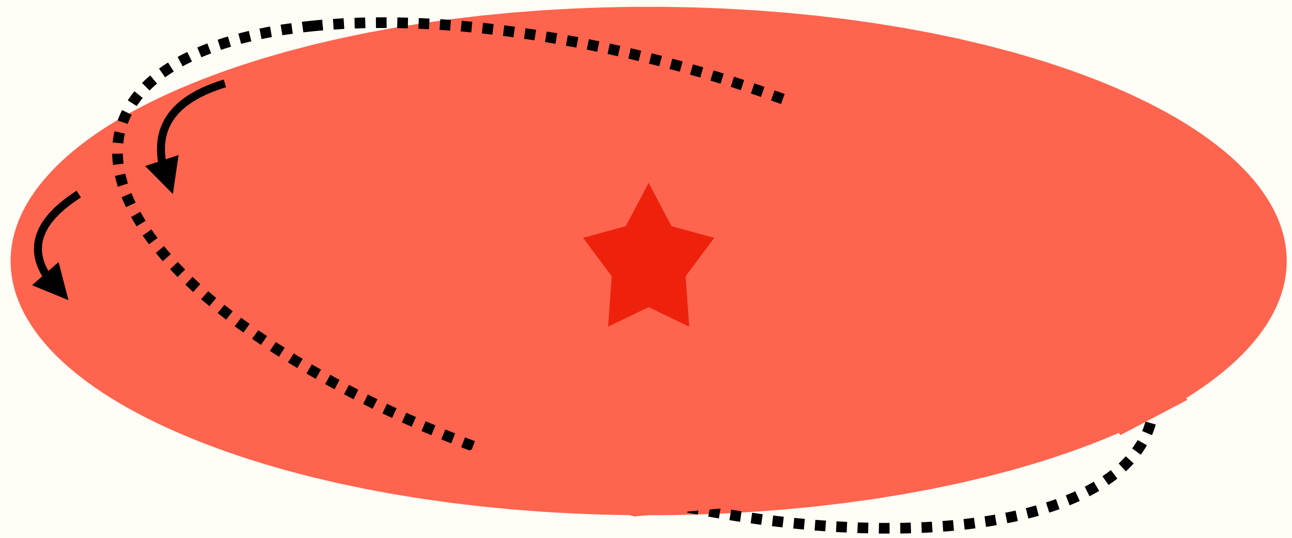
- Planets in protoplanetary disks
  - Coplanar circular orbit planets (linear, non-linear theory)
  - misaligned planets and broken disks
  - Eccentric and misaligned planets (planet’s evolution)
- Stars/BHs in AGN disks
  - Orbital evolution
  - QPE (high velocity impacts)

Eccentric and misaligned companions

Eccentric perturber

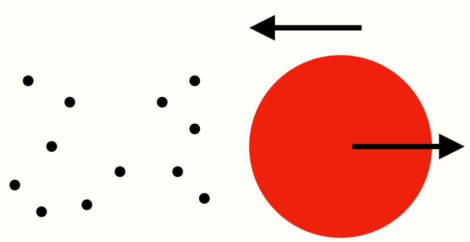


Misaligned perturber

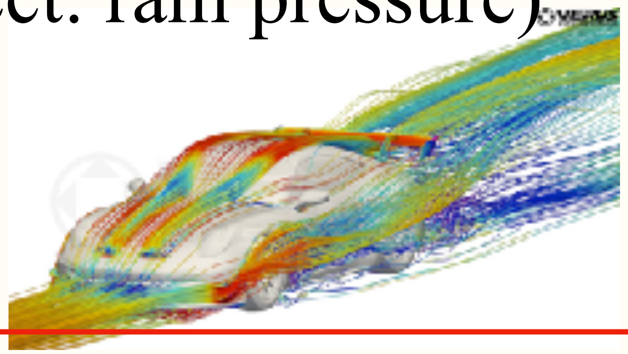


The planet moves **through** the gas

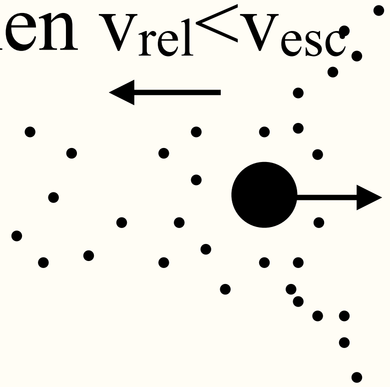
When $v_{rel} > v_{esc}$ Aerodynamic drag (geometric effect: ram pressure)



$$F \propto R_p^2 \rho v_{rel}^2$$

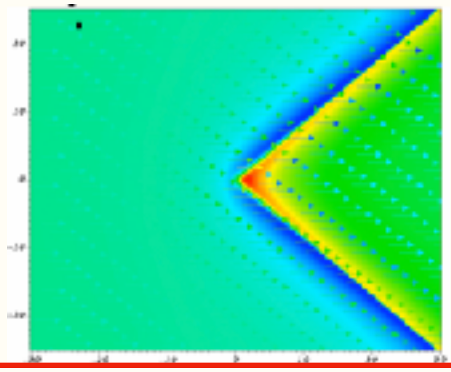


When $v_{rel} < v_{esc}$ Dynamical friction (gravitational effects with the wake)

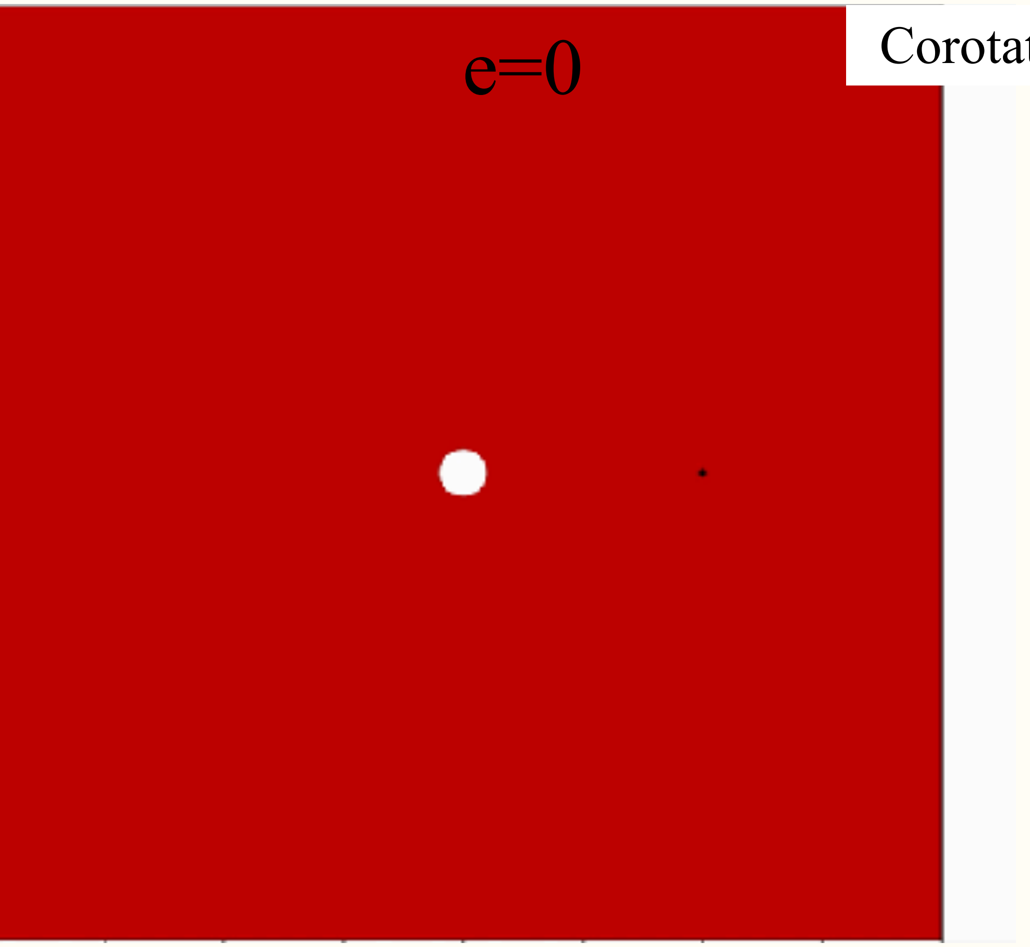


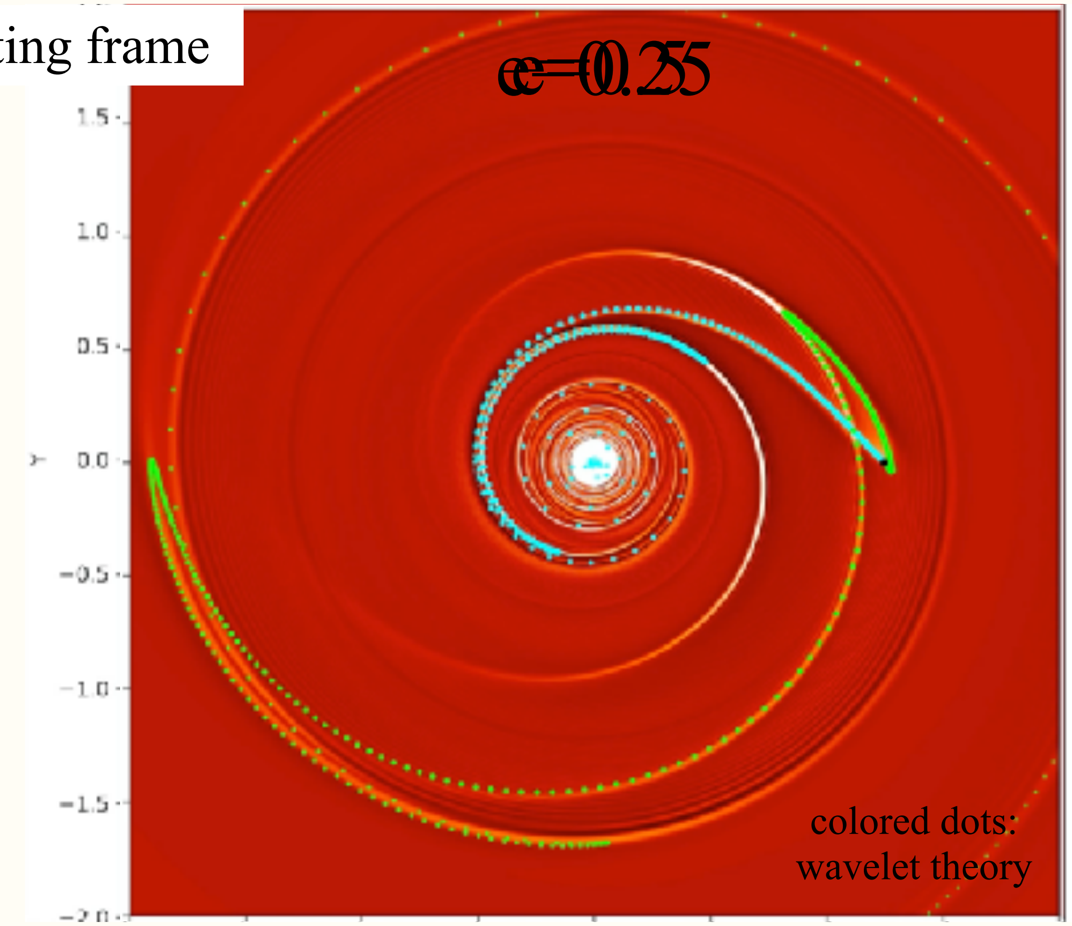
$$F \propto m_p^2 \rho v_{rel}^{-2}$$

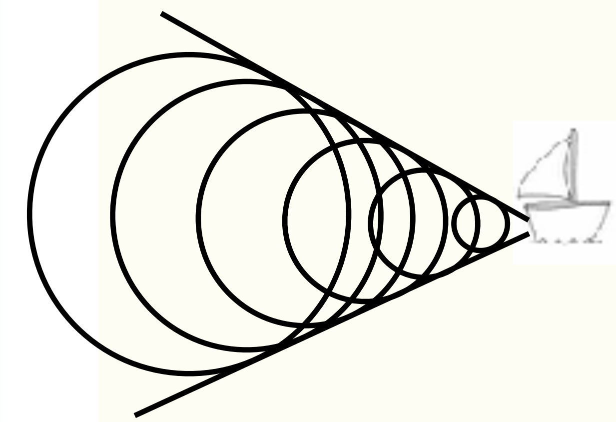
E. Ostriker 1998



Eccentric Companion: spirals





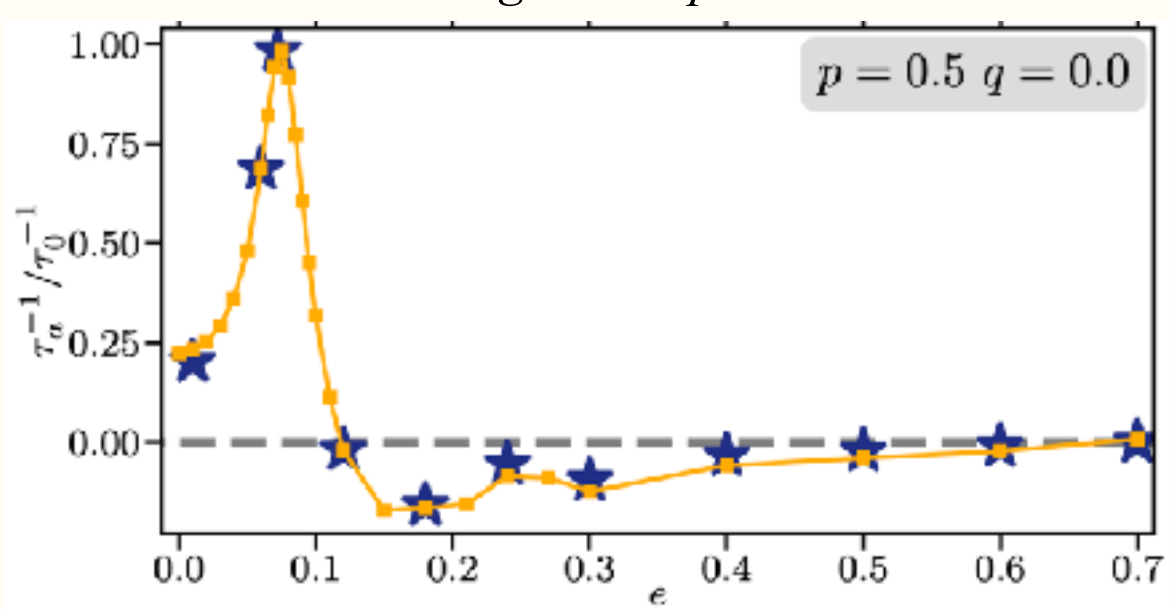


dynamical spirals!

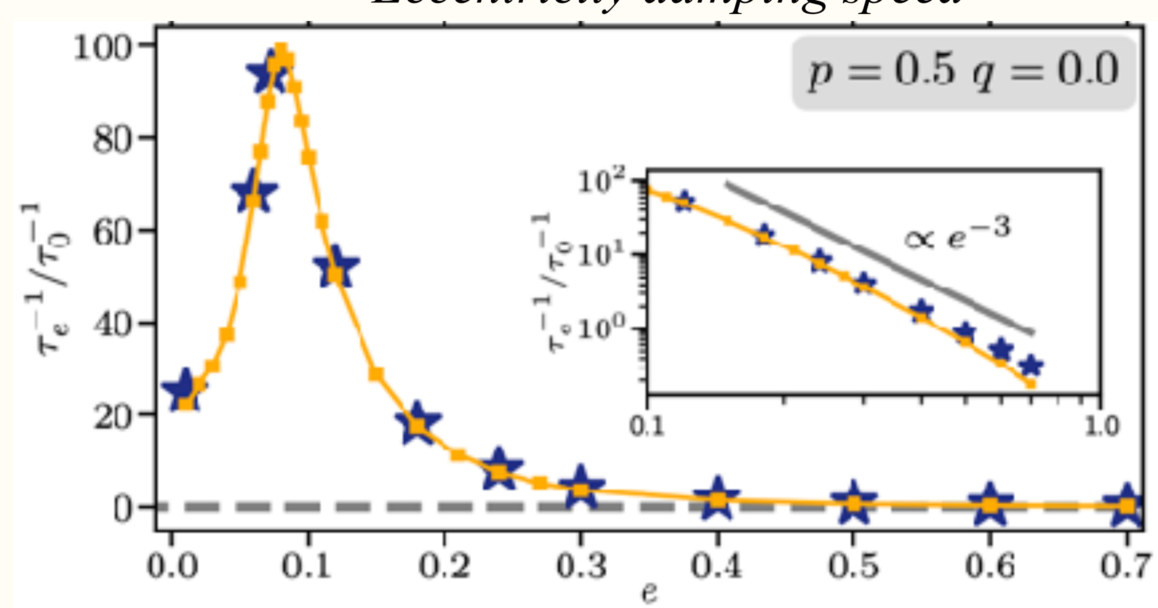
Zhu & Zhang 2022

See also Fairbairn & Rafikov 2022

Migration speed



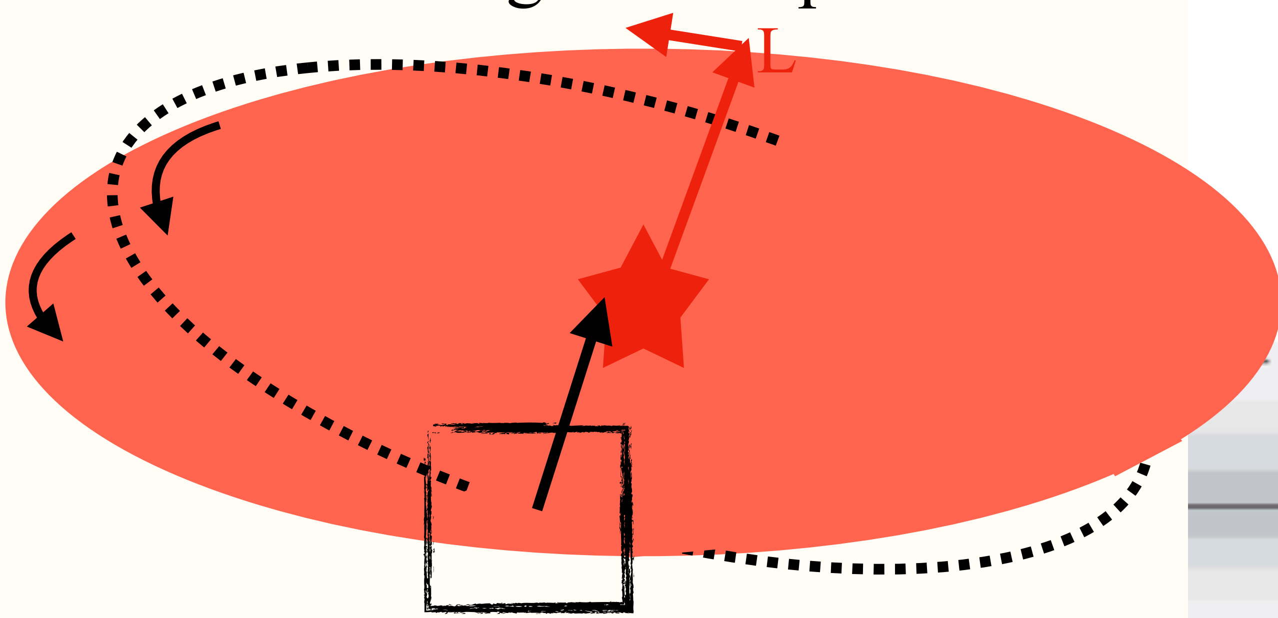
Eccentricity damping speed

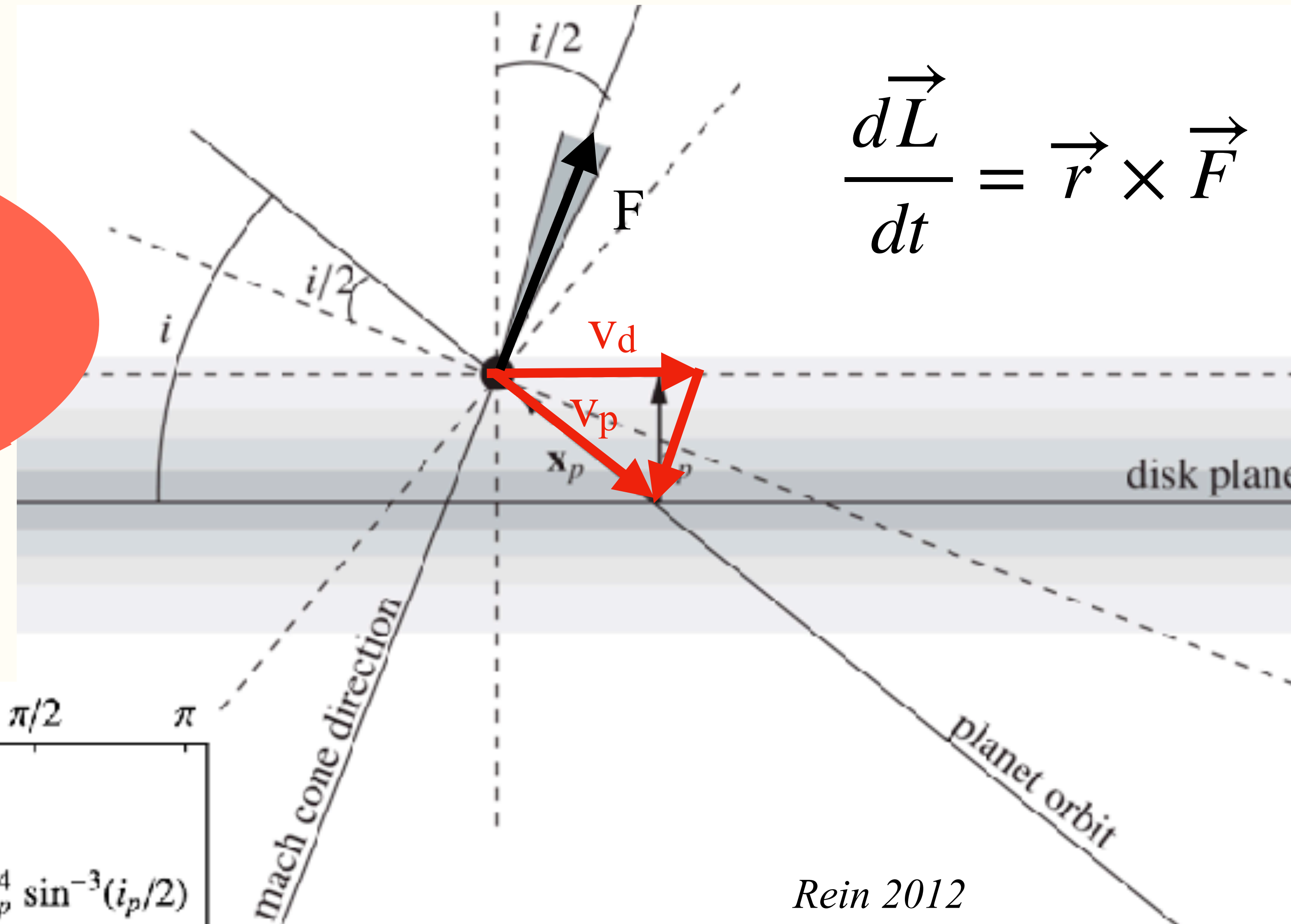


Fairbairn & Dittmann 2025, Fairbairn & Rafikov 2022, 2025,
Papaloizou & Larwood 2000, Cresswell & Nelson 2006, Muto et al. 2011

Misaligned companions

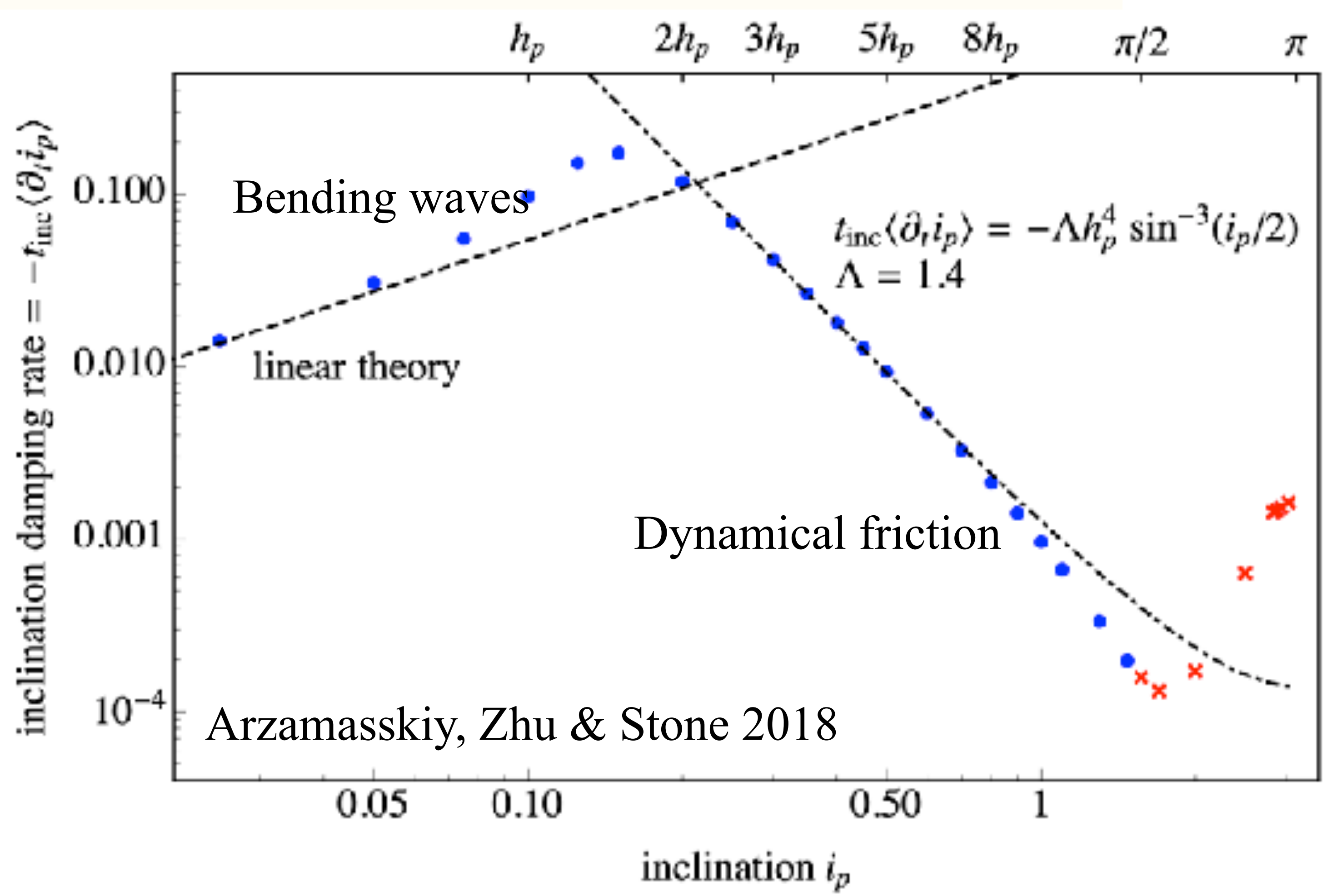
Misaligned companion





Rein 2012

$$\frac{d\vec{L}}{dt} = \vec{r} \times \vec{F}$$



Arzamasskiy, Zhu & Stone 2018

- Fast migration
- Inclination damping (disk capture)

Outlines

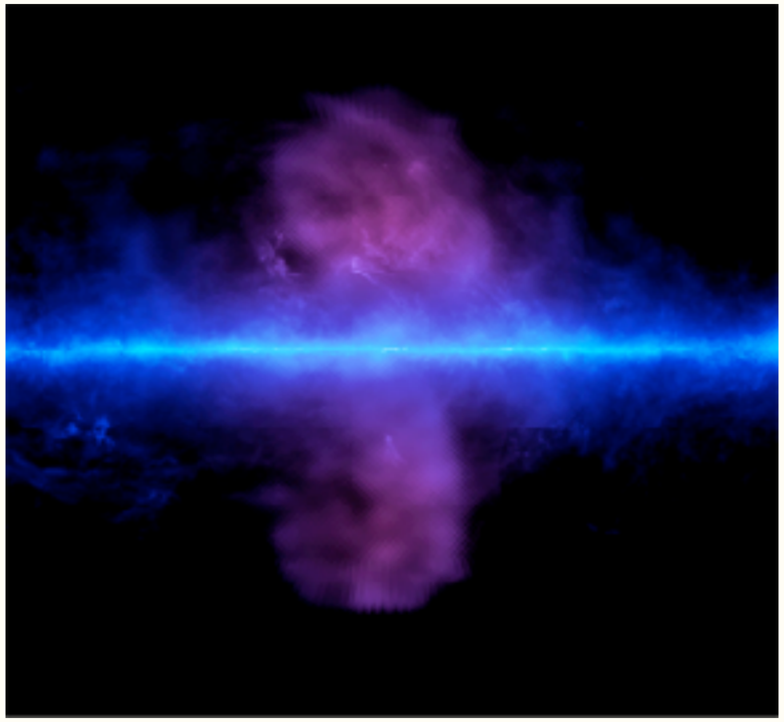
- Planets in protoplanetary disks
  - Coplanar circular orbit planets (linear, non-linear theory)
  - Eccentric and misaligned planets
- Stars/BHs in AGN disks
  - Orbital evolution
  - QPE (high velocity impacts)

Nuclear star cluster + AGN interaction

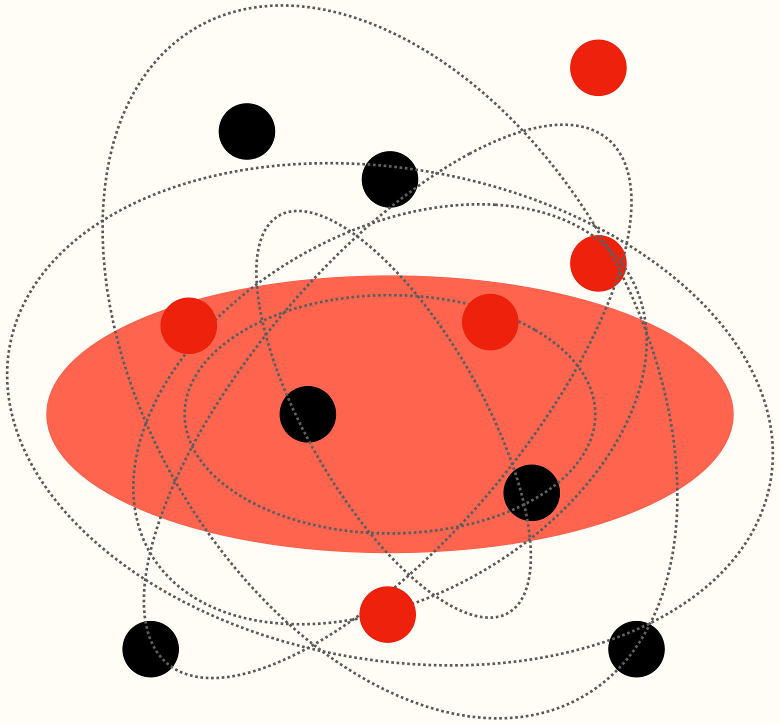
At the galaxy center,
nucleus star cluster
and SMBH coexist

During the AGN phase,
stars/BHs can interact
with the disk around SMBH

Milky Way Center



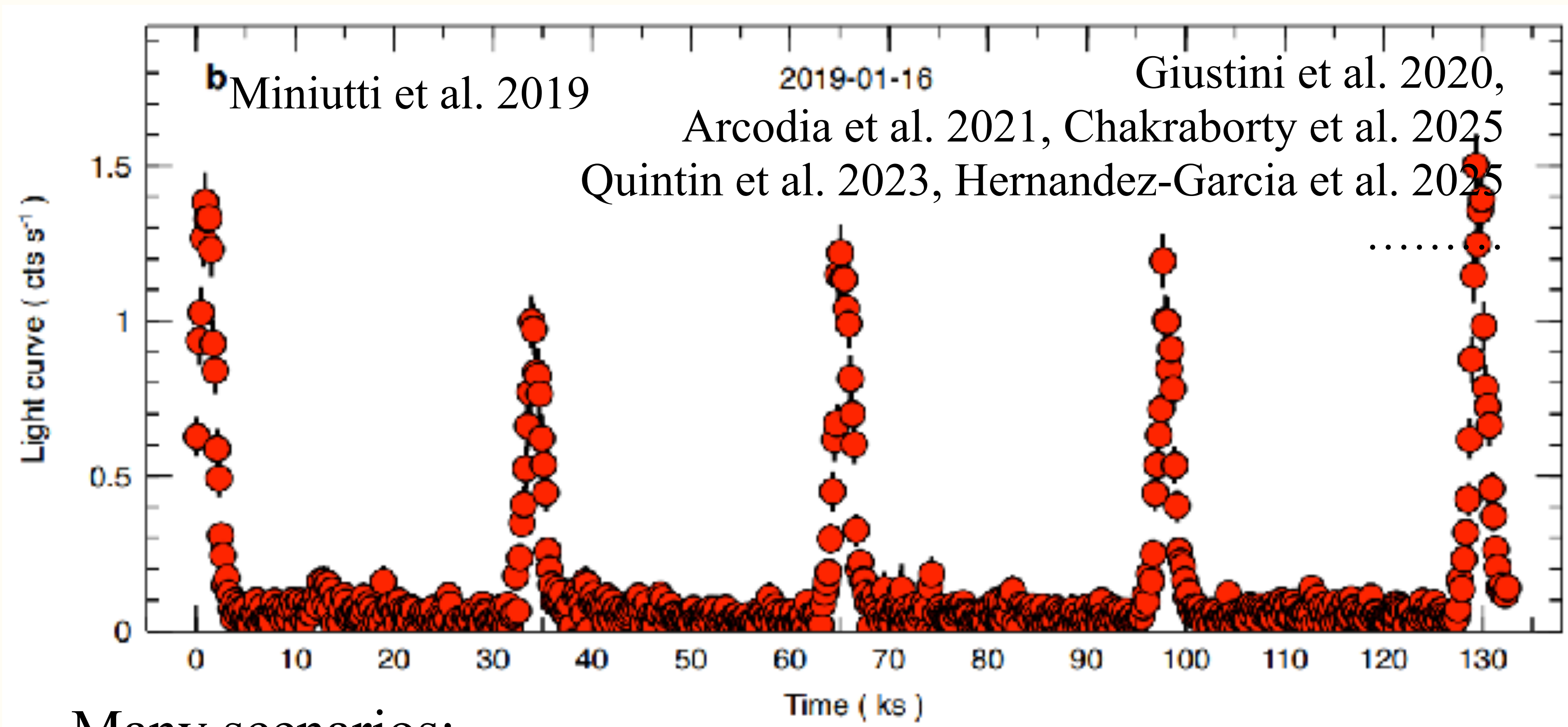
Milky Way Fermi Bubble



Stellar mass BH: dynamical friction

Stars: aerodynamical drag

QPE



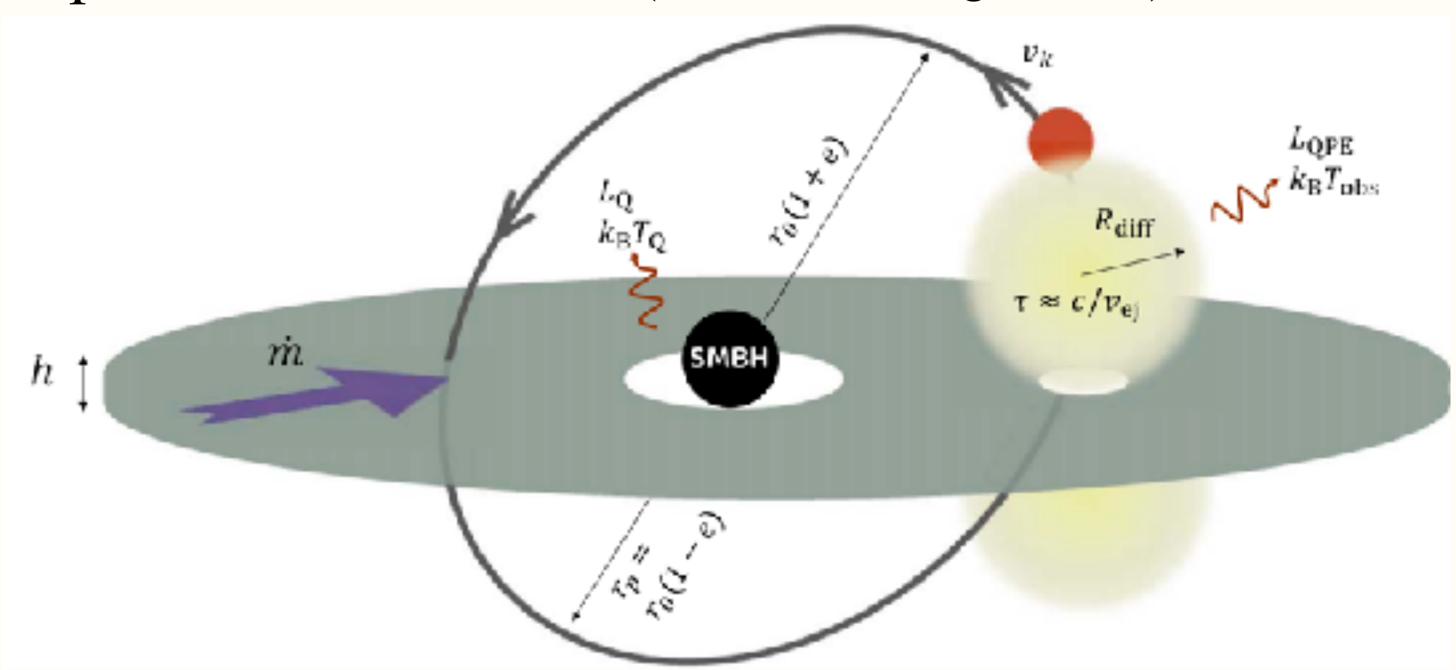
Miniutti et al. 2019

Giustini et al. 2020, Arcodia et al. 2021, Chakraborty et al. 2025 Quintin et al. 2023, Hernandez-Garcia et al. 2025 ……

Soft X-ray (1e41-1e43 erg/s)
Blackbody T: 100-200 ev
recurrence a few hours to days
flare 10-20% of recurrence time

Nuclei of low mass galaxies (Wevers et al. 2022)
Some after TDE (Nicholl et al. 2020, Newsom et al. 2024)

Many scenarios:
Disk instabilities (Raj & Nixon 2021)
Mass transfer from a companion (Zalamea et al. 2010)
Companion disk collision (Linial & Metzger 2023)

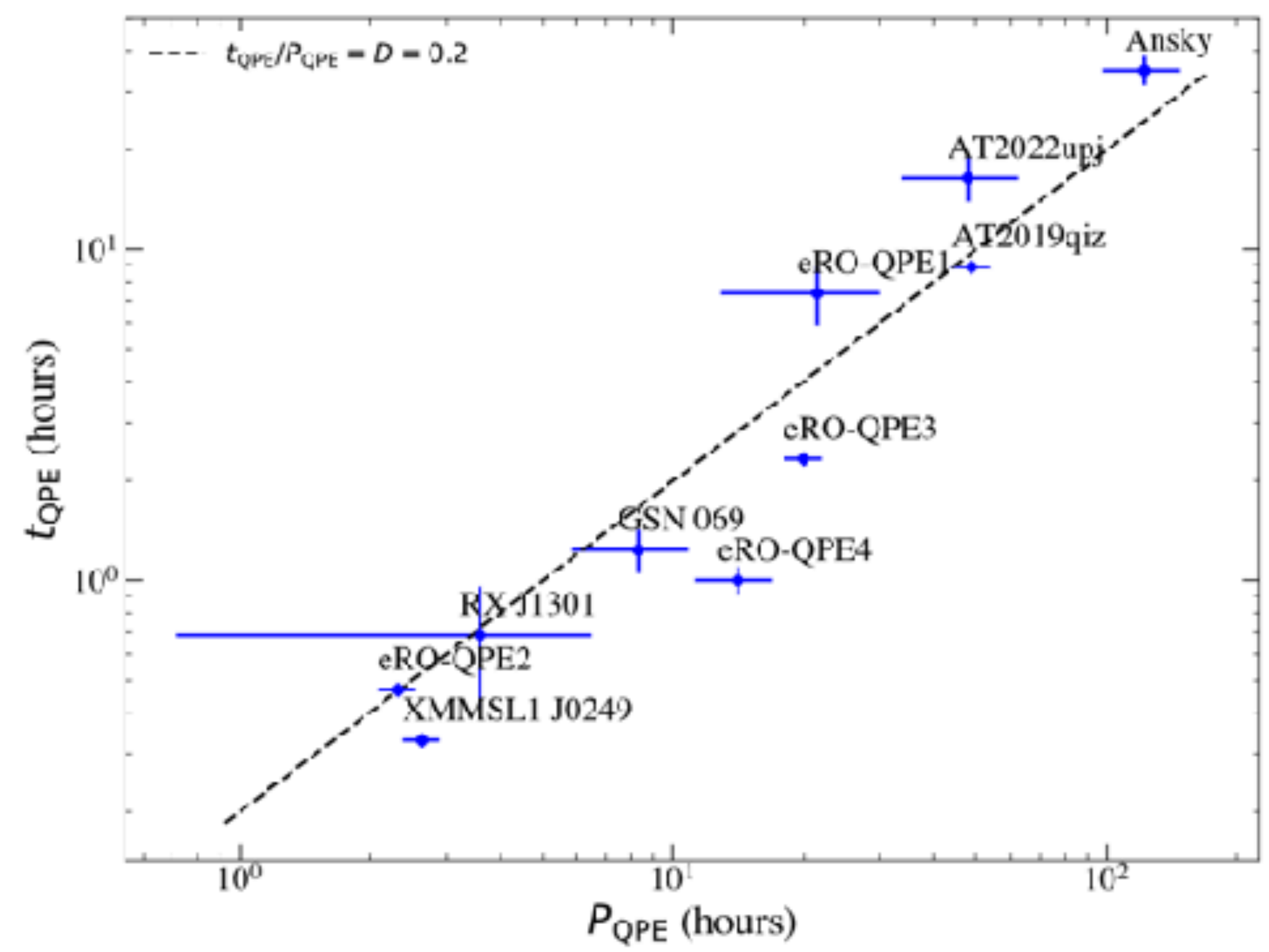


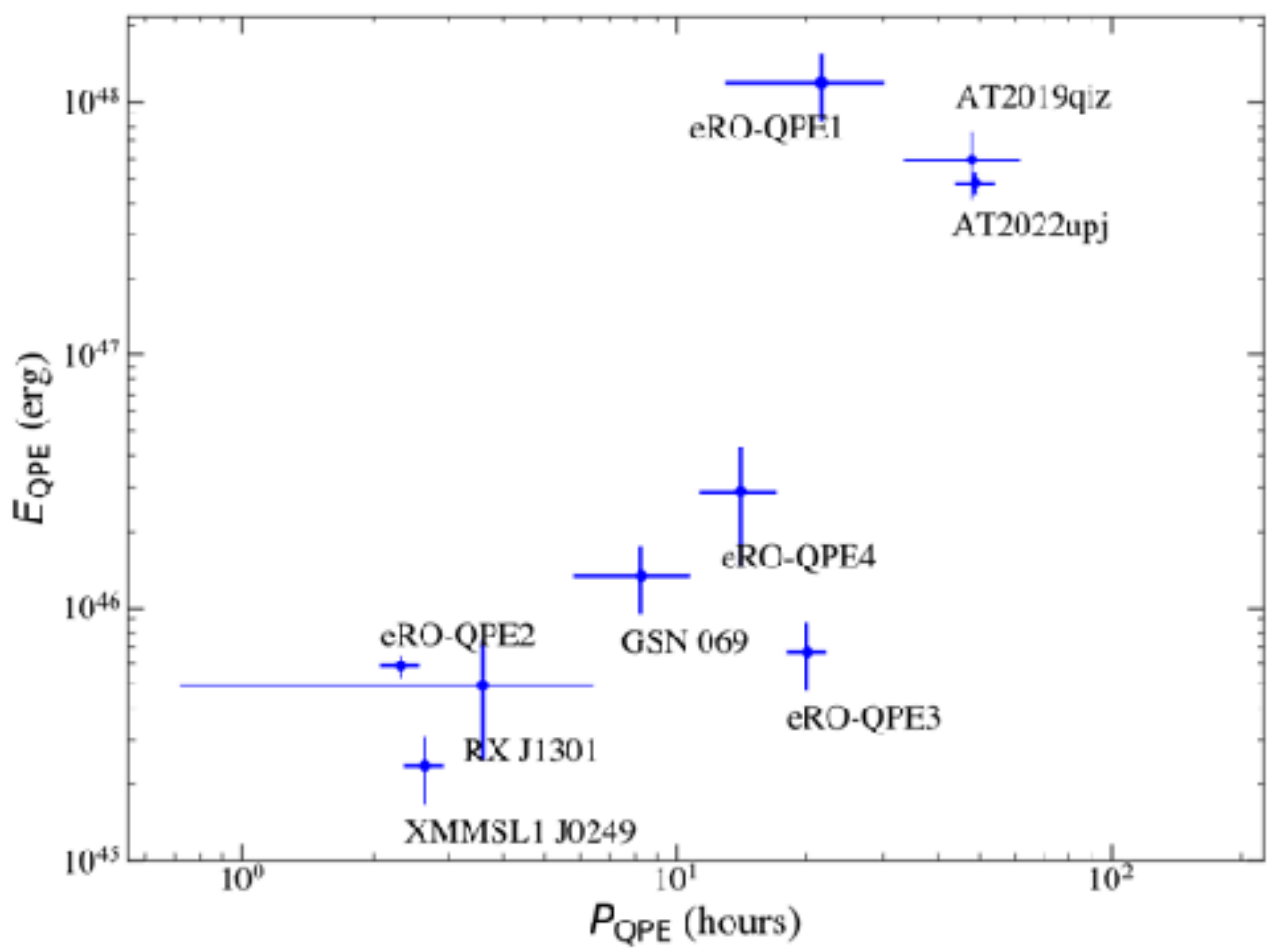
Simulations:
Yao et al. 2025, mass loss by stars
X. Huang, Linial & Jiang 2025, RHD

Both explicitly include a real star

Pressure scale height of the sun is ~0.02% of its radius.
We treat it as a solid sphere, focusing on the shock dynamics

Two clear observational trends





Flare time ~10-20% recurrence time

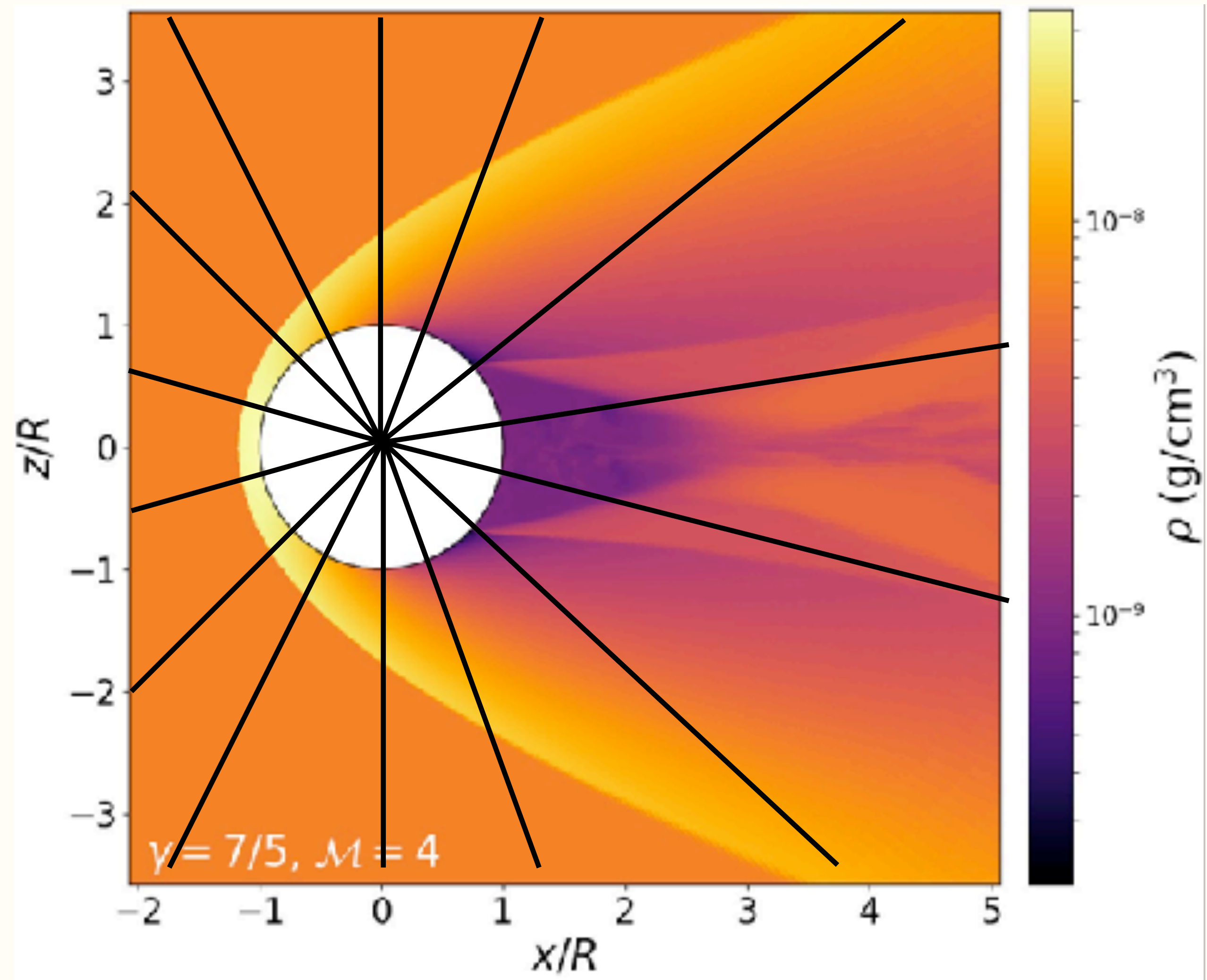
Longer QPEs are brighter

Solid sphere fluid interaction (Aerodynamic drag)

Less-well studied in astronomy

Traditionally using spherical grid

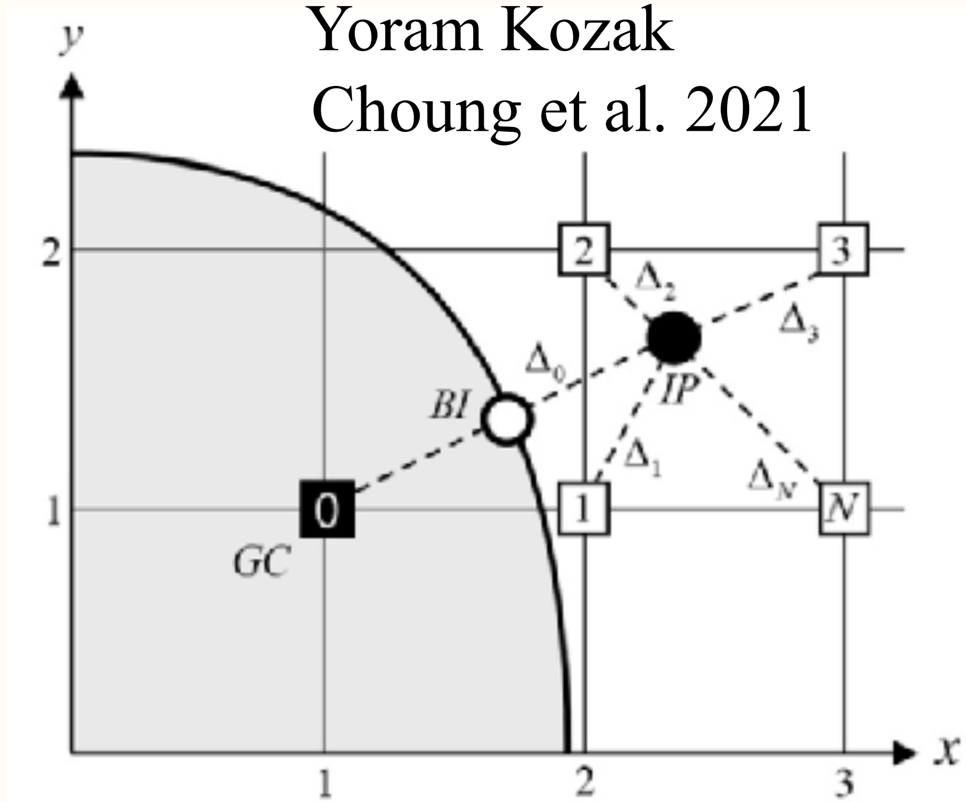
Thun et al. 2016, Prust & Bildsten 2024



Well studied in engineering

Yoram Kozak

Choung et al. 2021

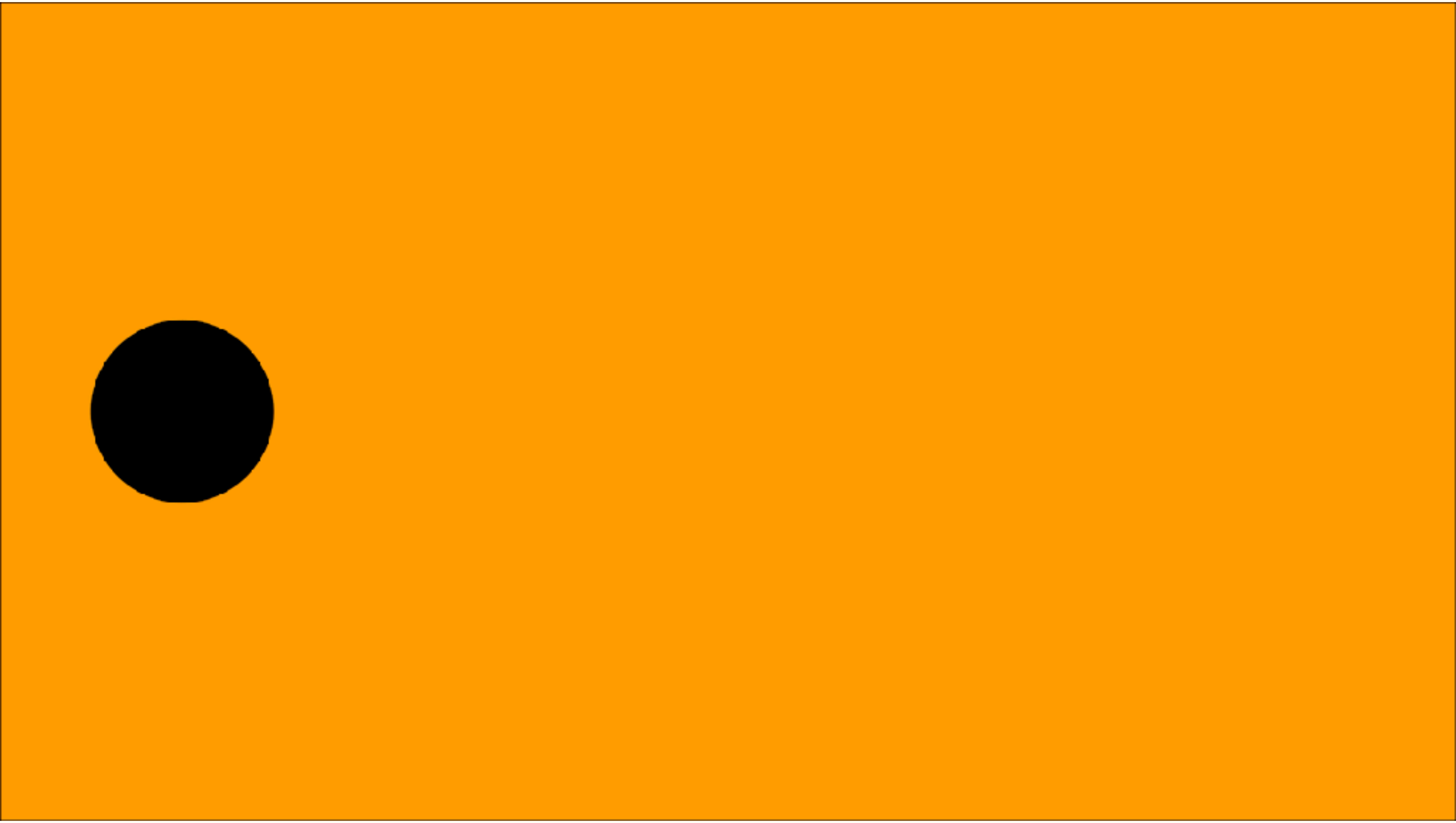


Immersed Solid Boundary Method

Shunquan Huang

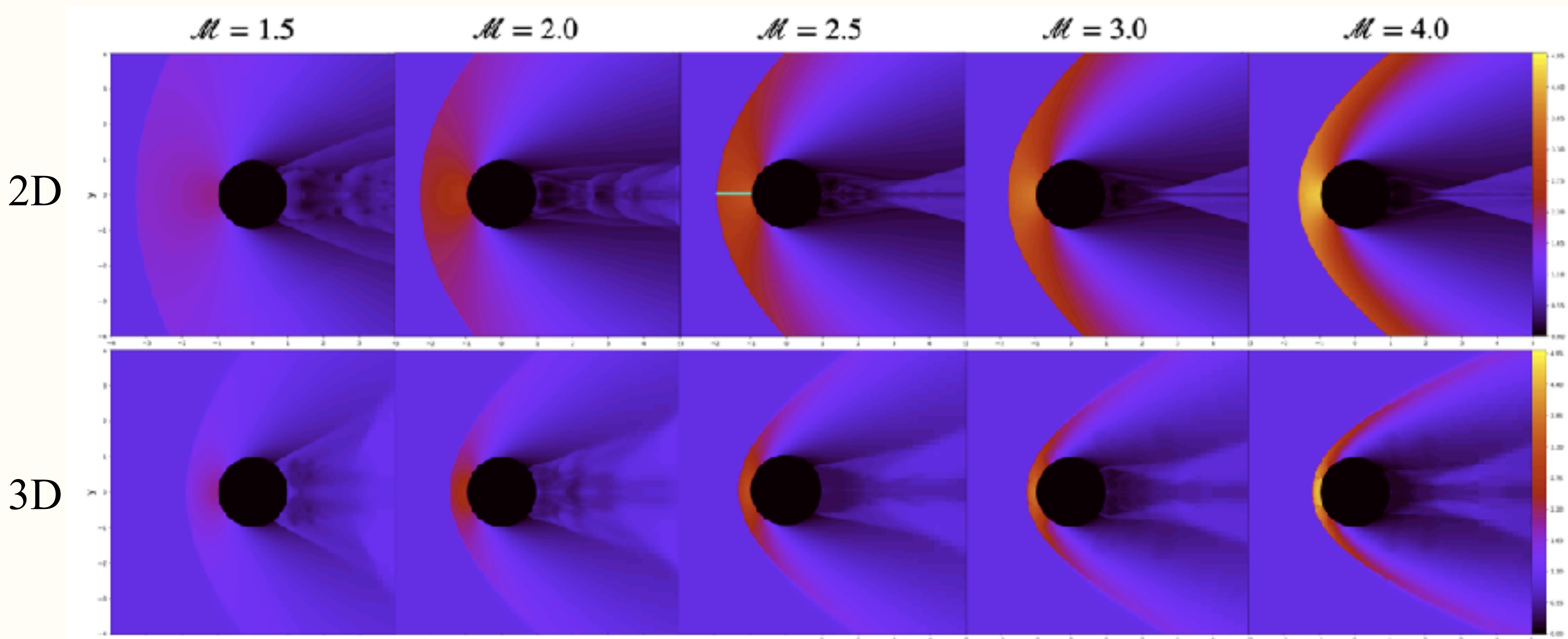
Ph.D. candidate, UNLV

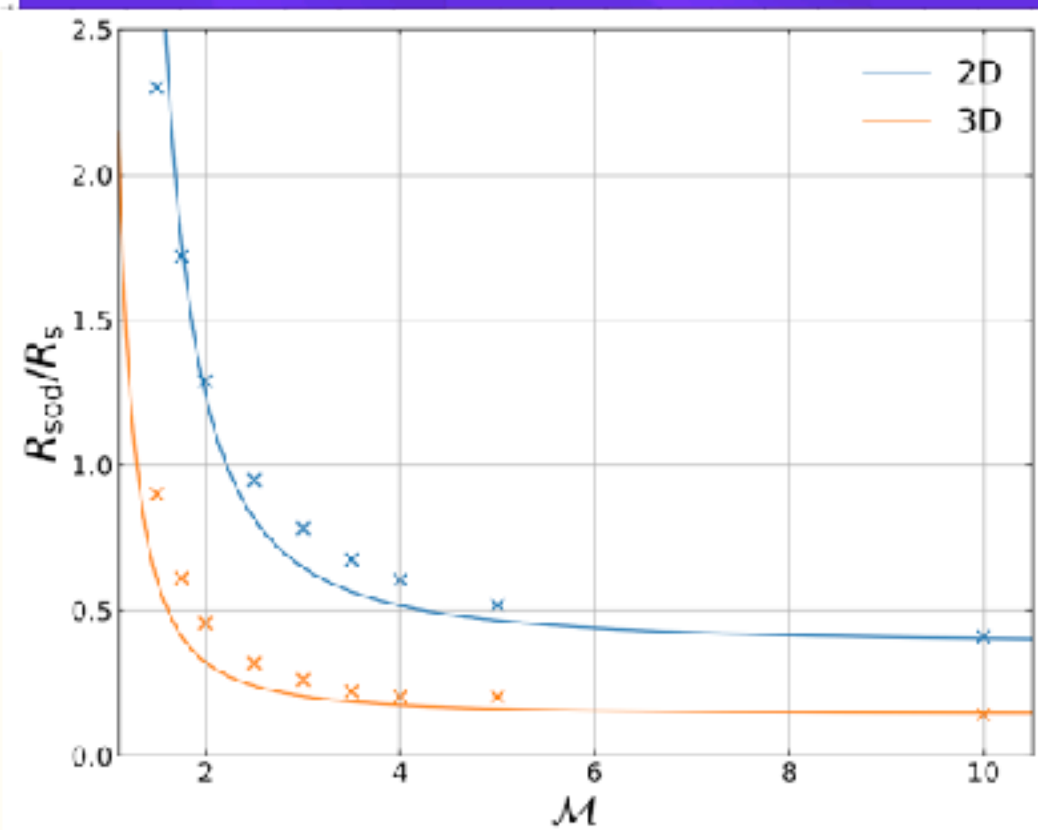
Immersed Solid Boundary



Shunquan Huang

Code verification (shock stand-off distance)

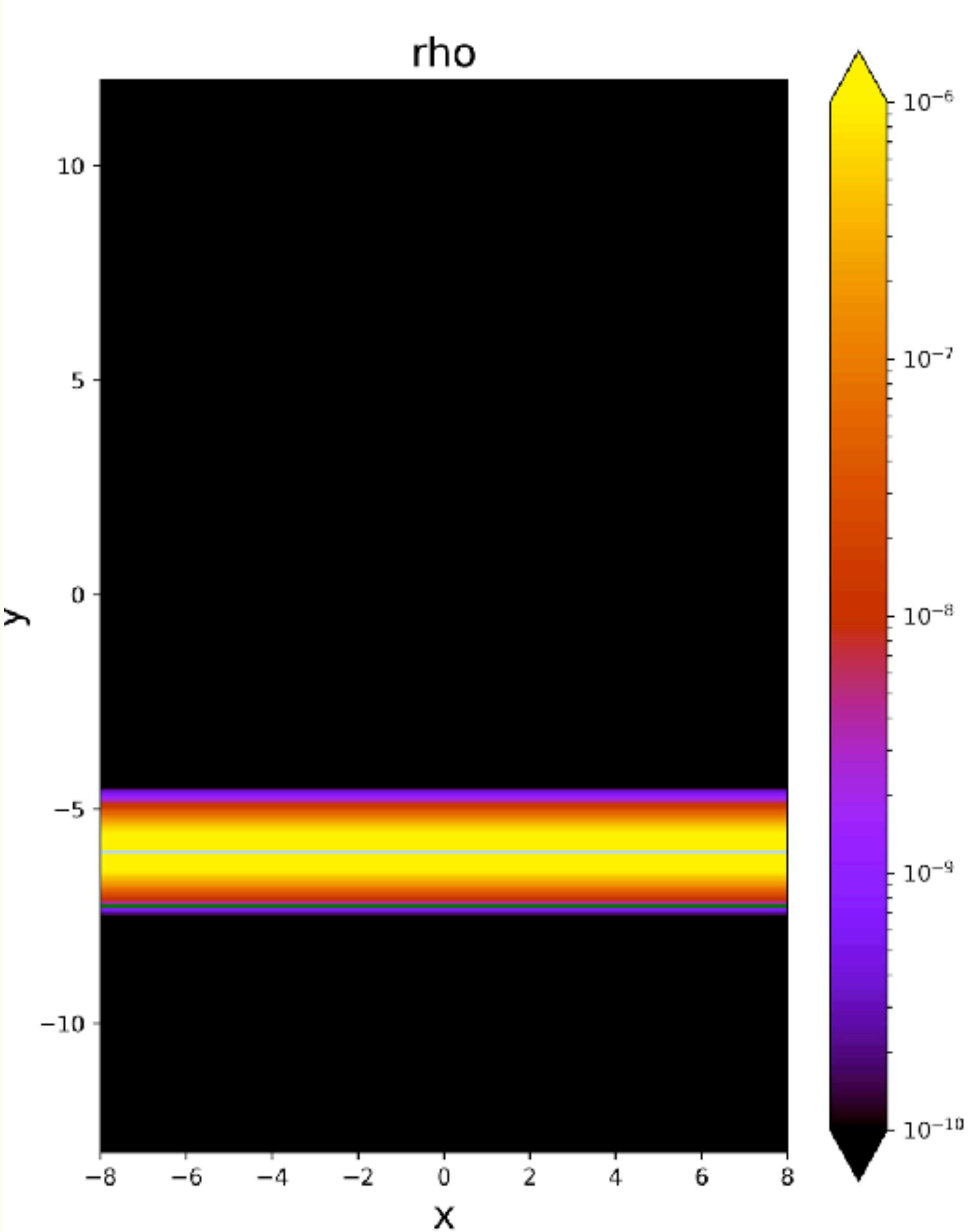




From wind tunnel experiments for cylinder wedge and spherical body (Billig 1967)

Huang, S; Huang, X; Zhu; Martin 2026

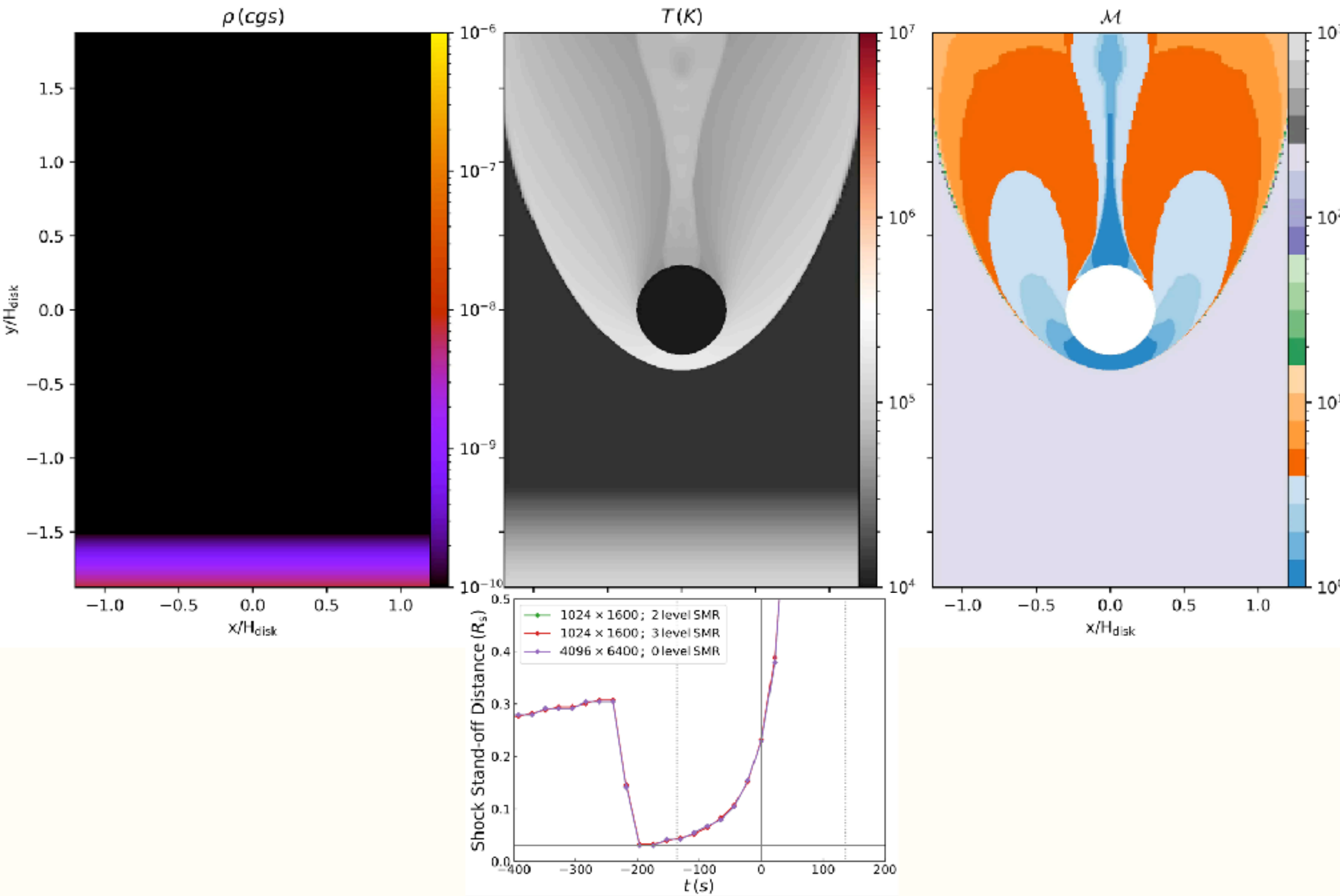
Star-disk collision



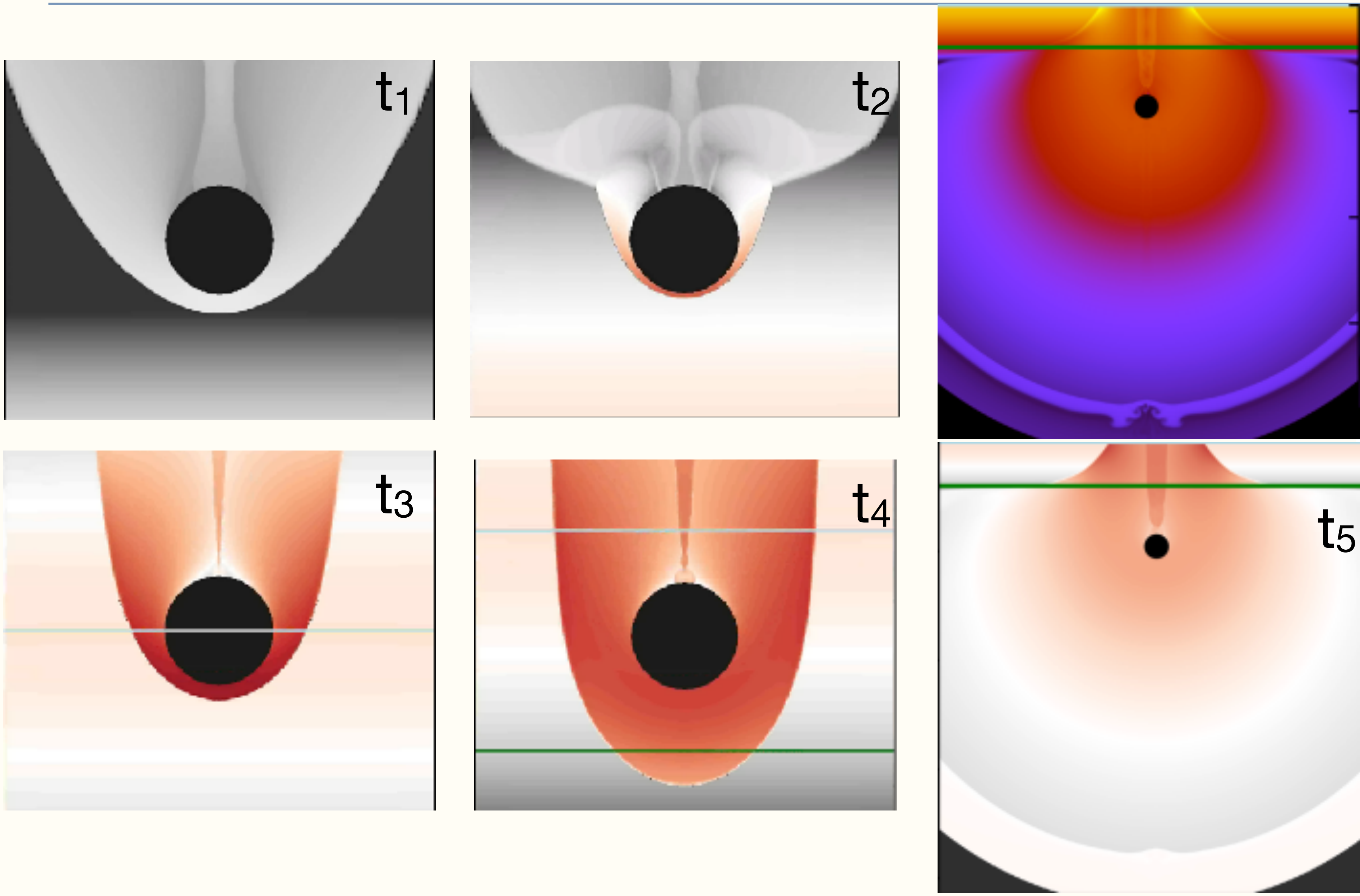
Adiabatic simulation with γ=4/3
Disk scale height ~ stellar radius

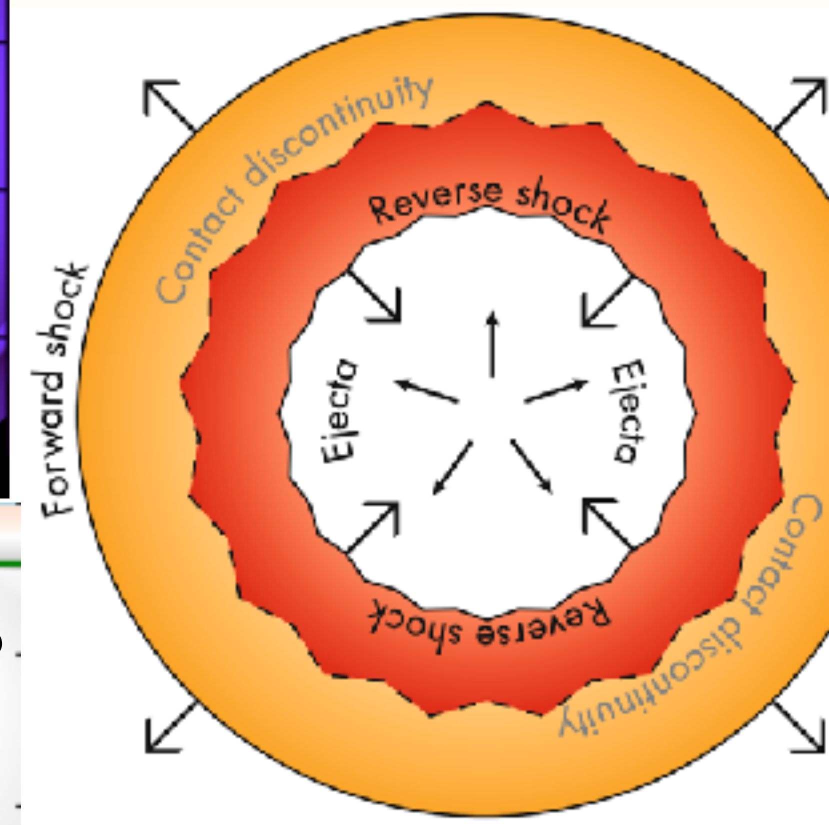
- 2-D and 3-D
- direct and oblique collision

Star-disk collision:



Star-disk collision: 4 phases





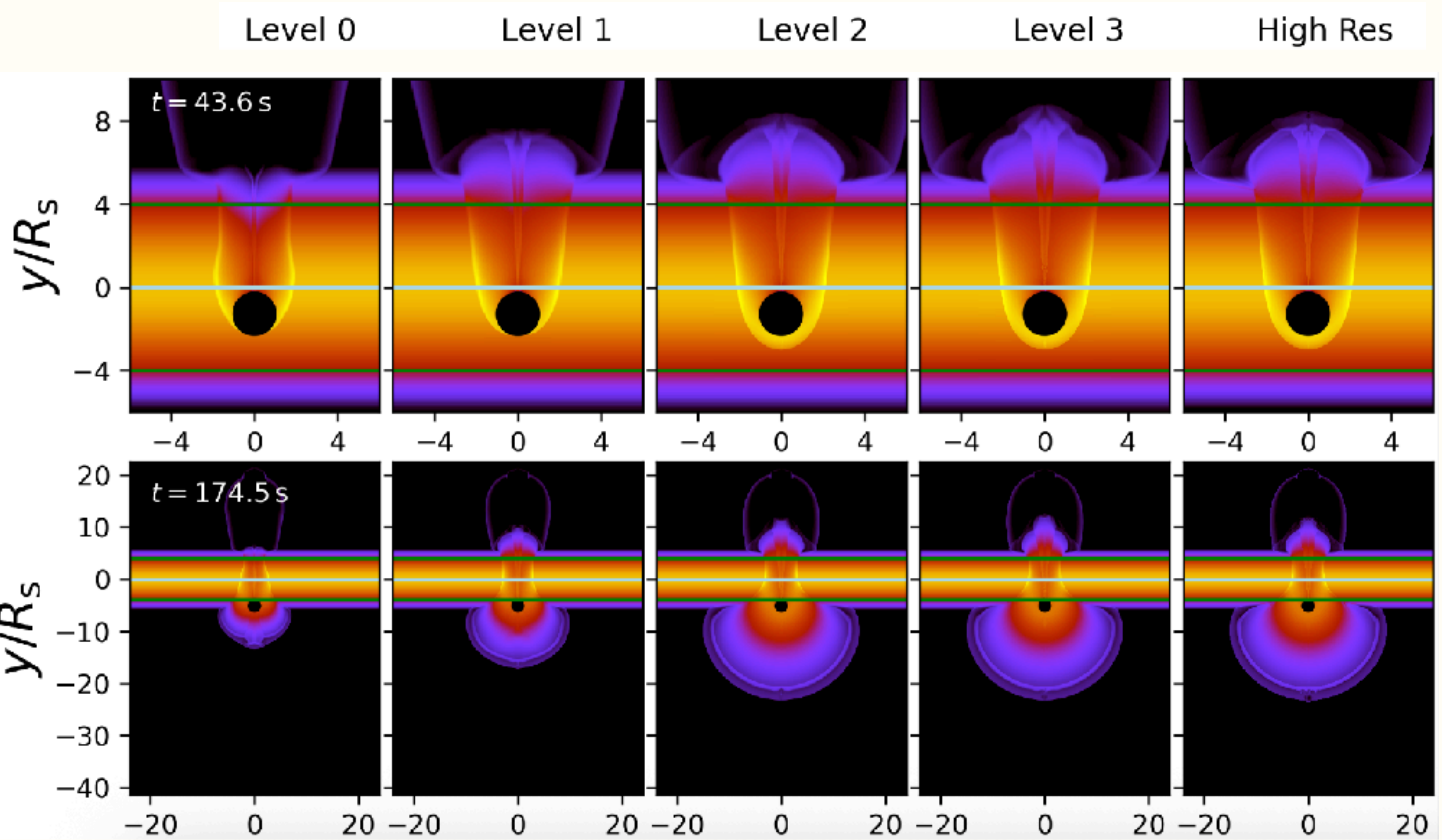
Credit: Jacco Vink

Phase 1: entering the disk, the cap region is compressed
Phase 2: exiting the disk, the cap region expands
Phase 3: shock breakout, energy in the capped region pushes the shock forward

$$\dot{E}_{cap} > F_s \qquad\qquad y \gtrsim H_d^2/4R_{sod}$$

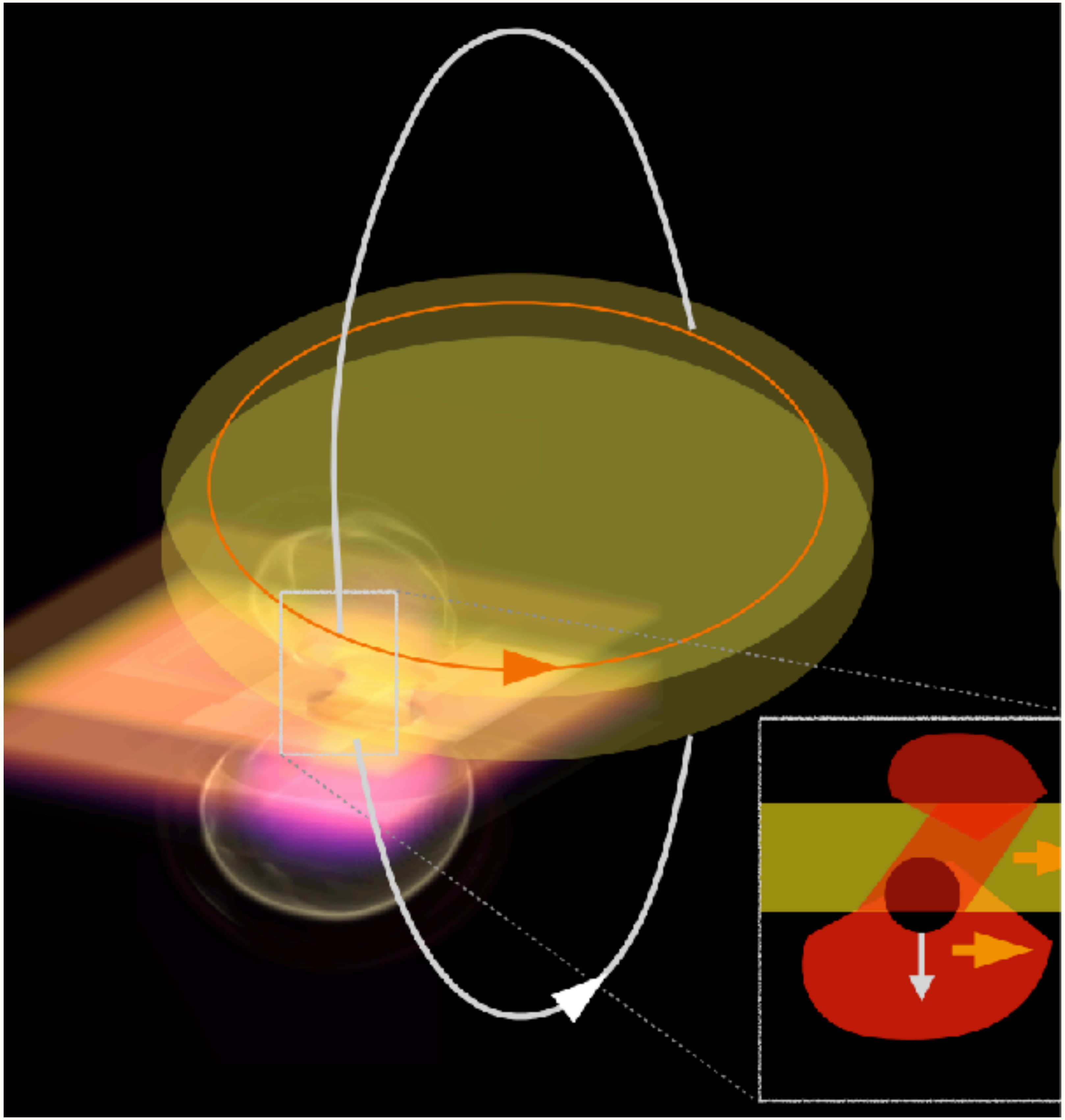
Phase 4: Shocked ISM

Star-disk collision: Resolution requirement



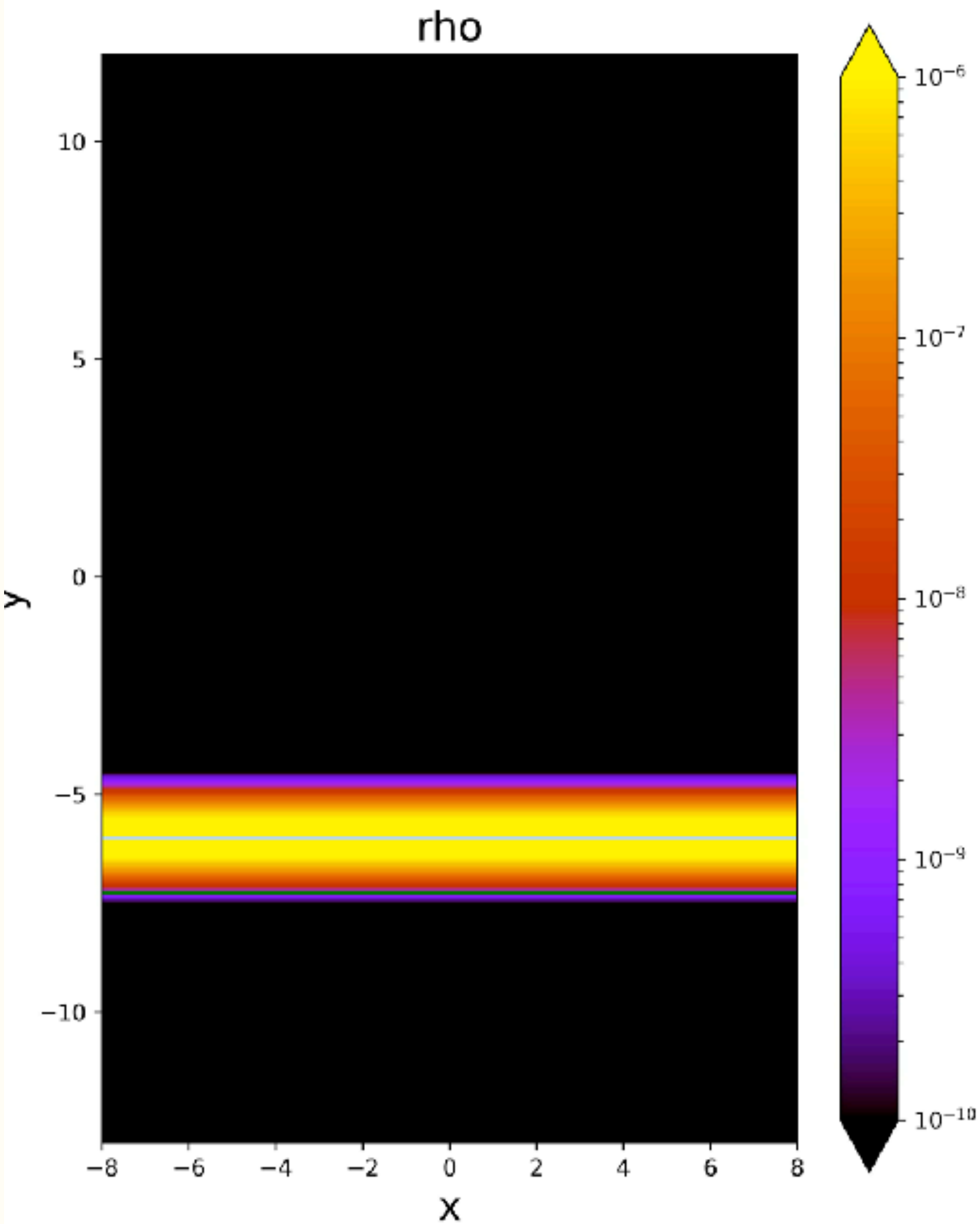
Huang, S et al. 2026

Star-disk collision: Oblique crossing

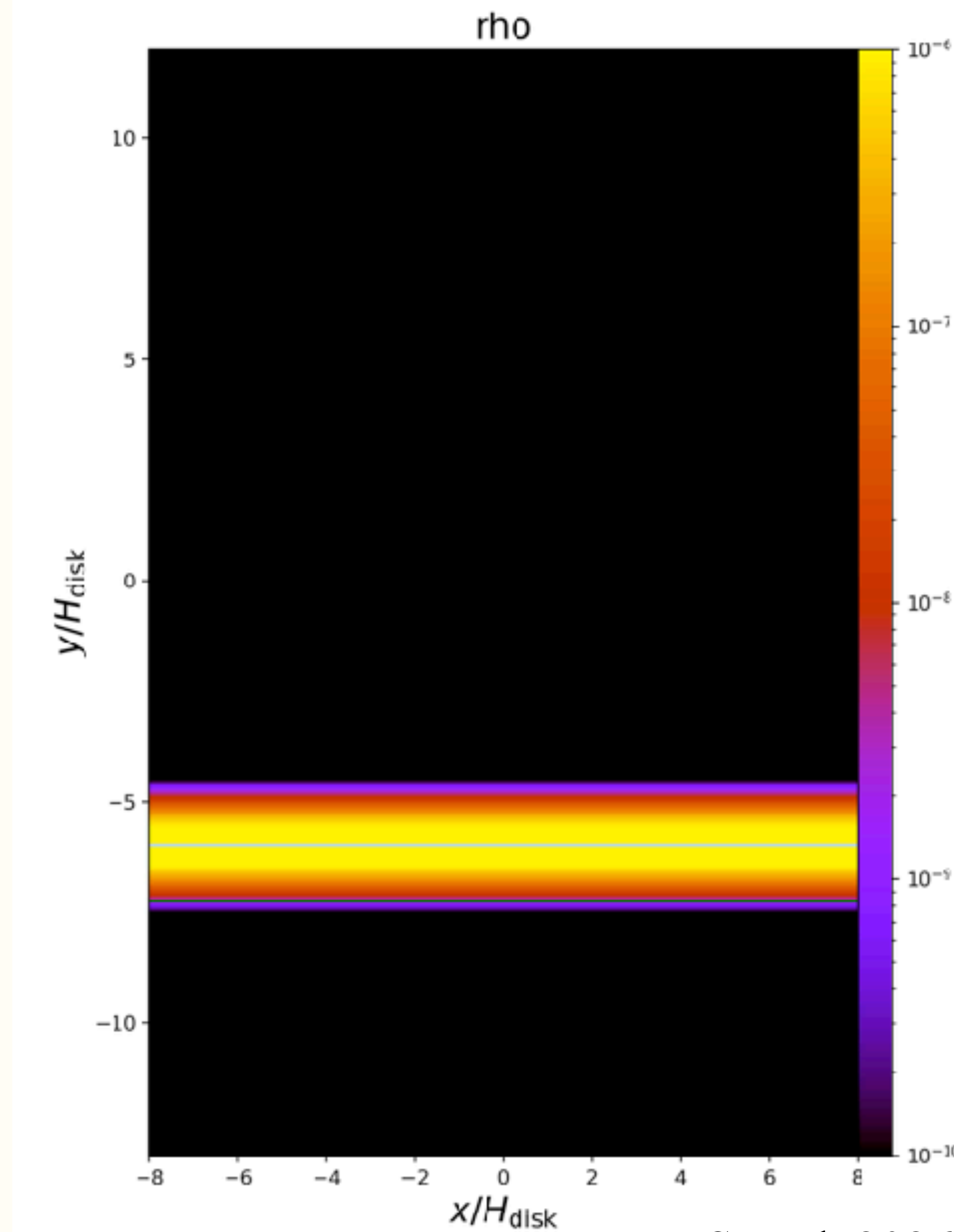


Huang, S et al. 2026

Star-disk collision: Oblique crossing

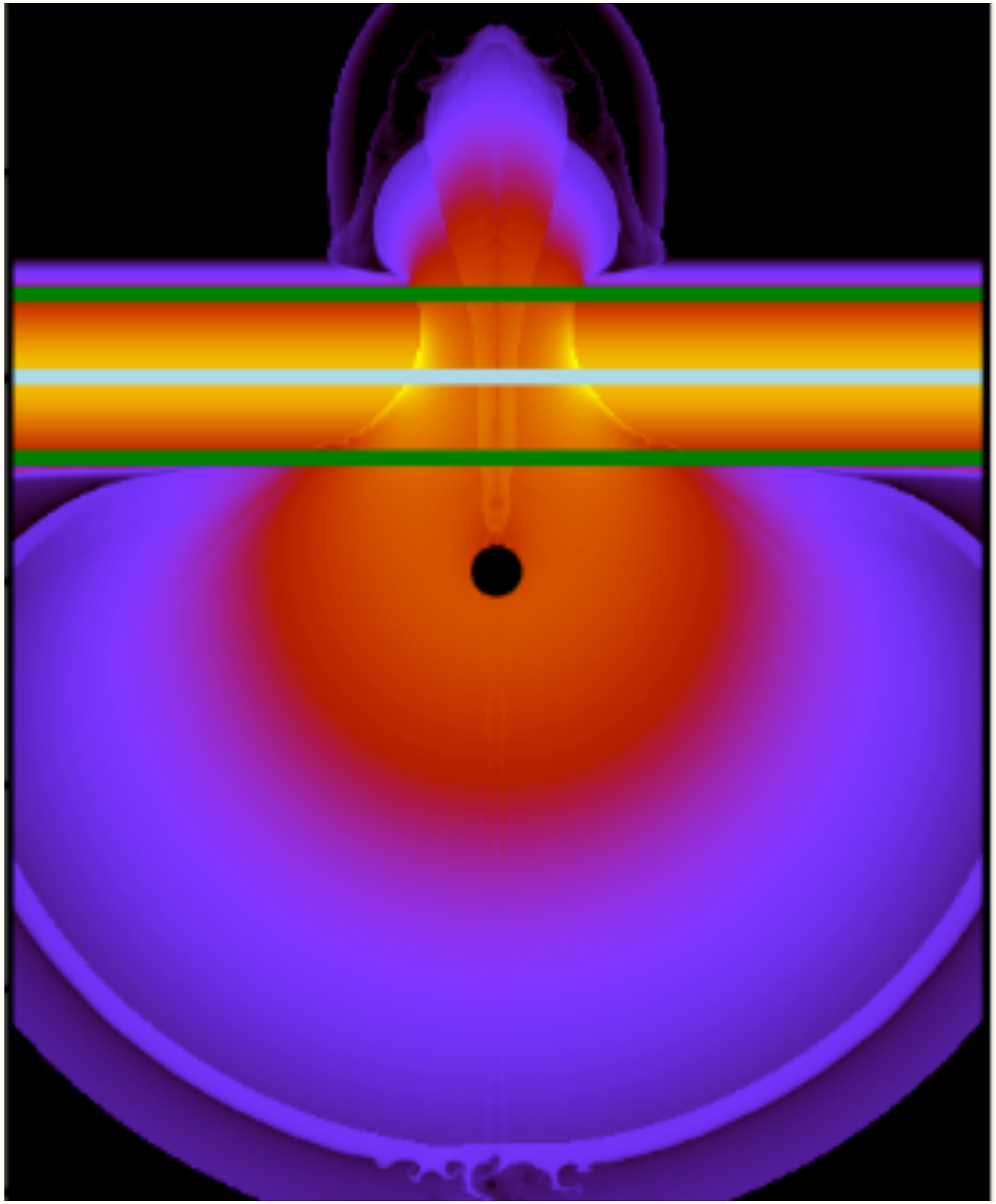


Yao et al., 2025, Huang, X et al. 2025

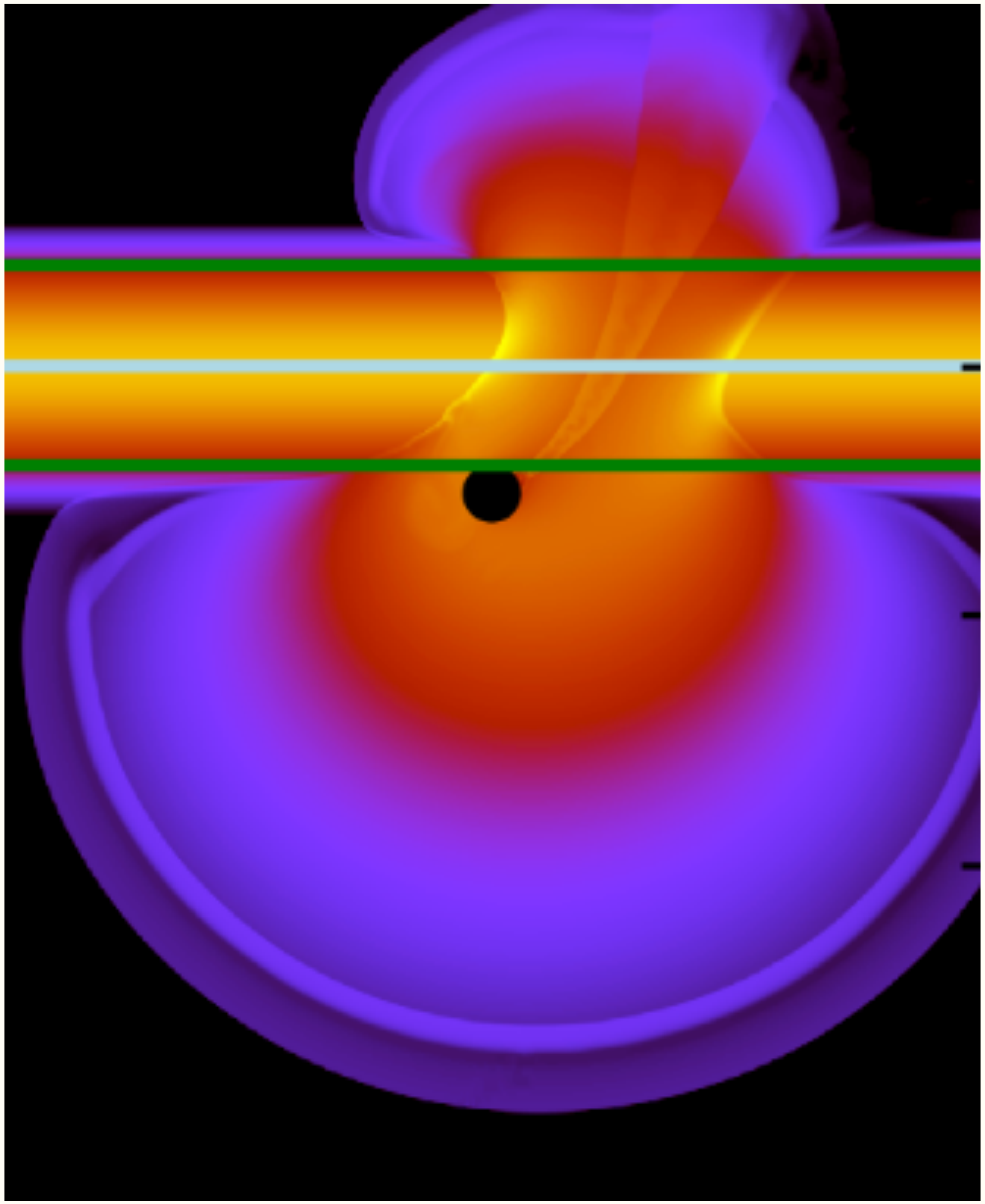


Huang, S et al. 2026

Star-disk collision: Oblique crossing

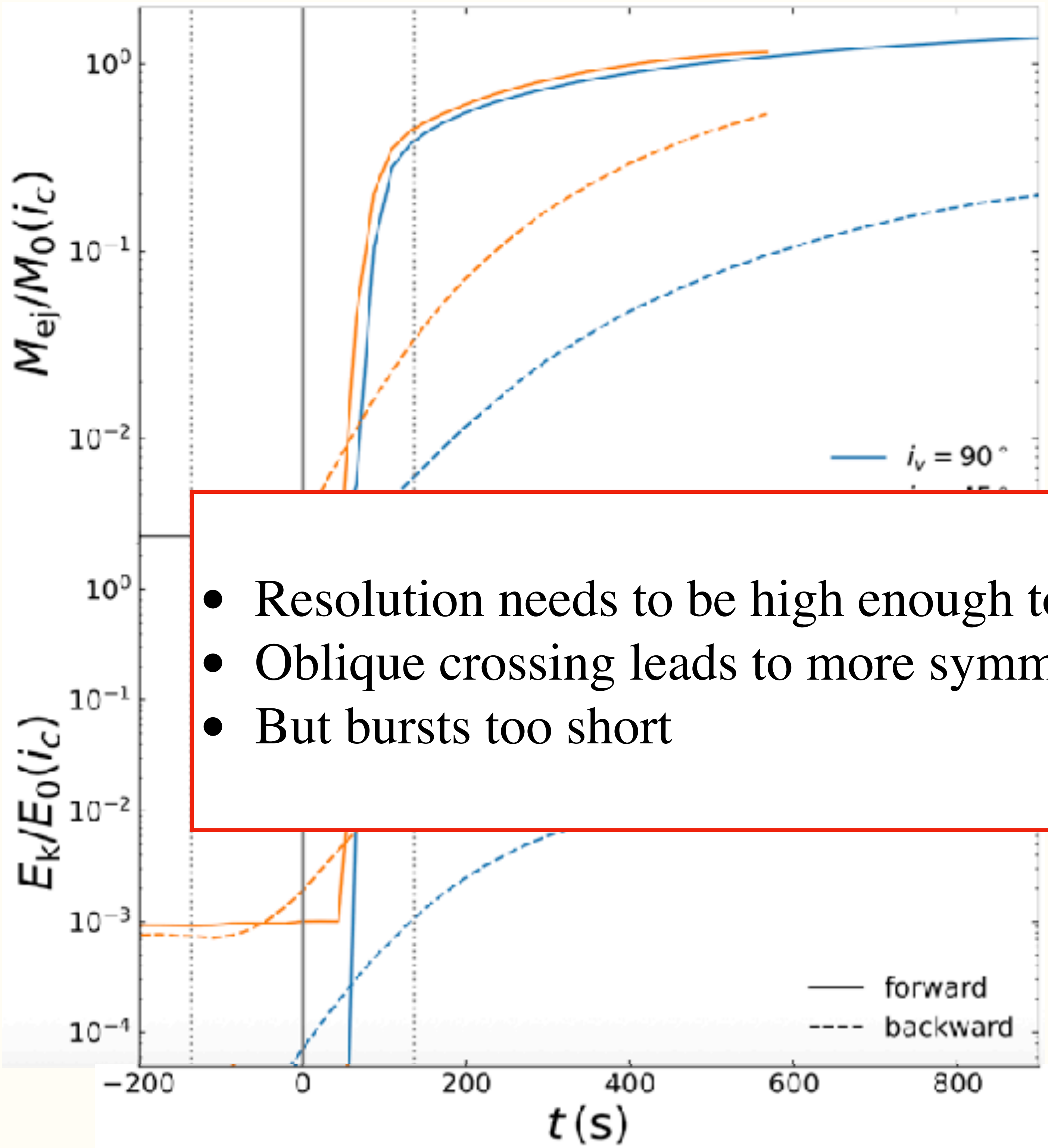


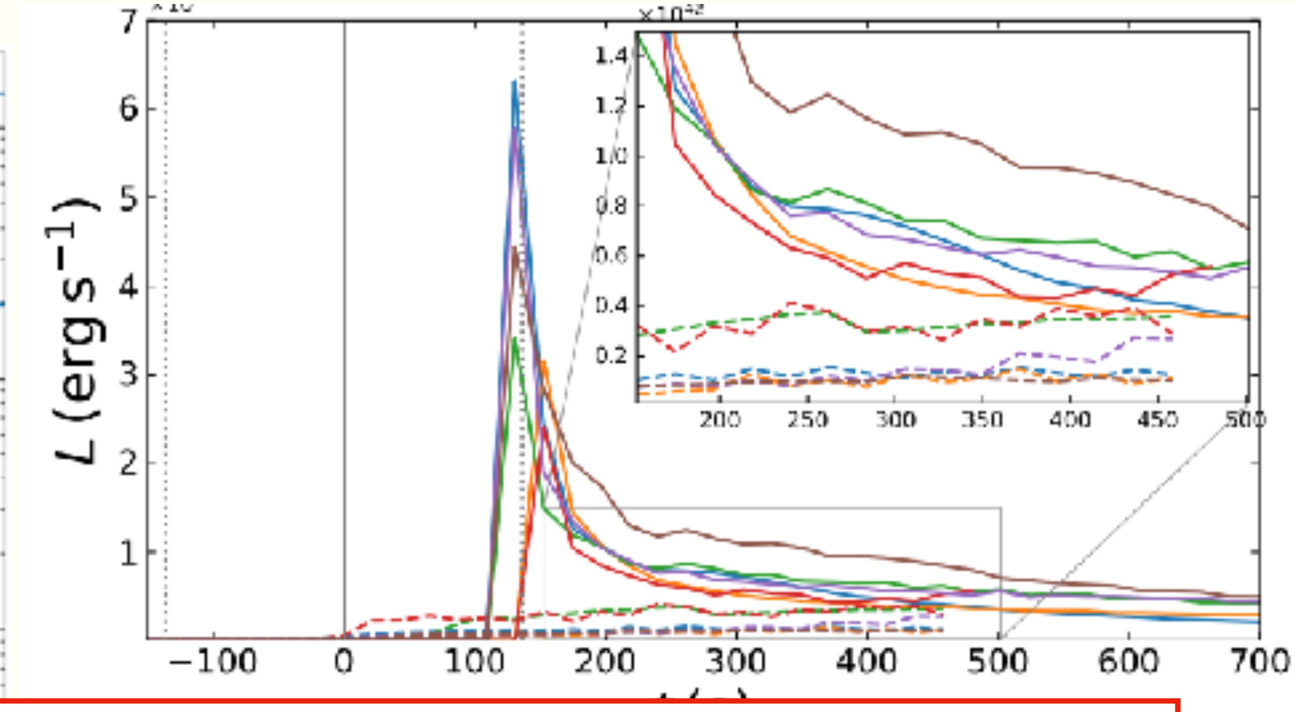
Yao et al., 2025, Huang, X et al. 2025

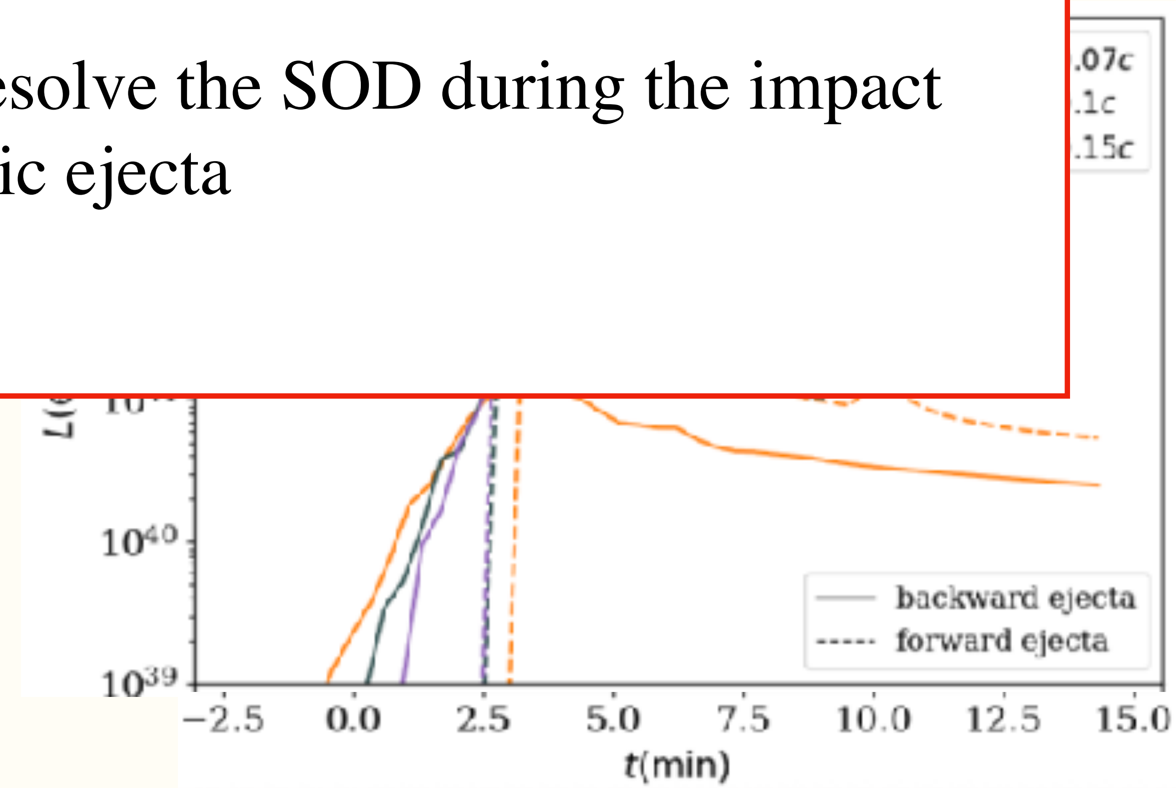


Huang, S et al. 2026

Star-disk collision: Oblique crossing



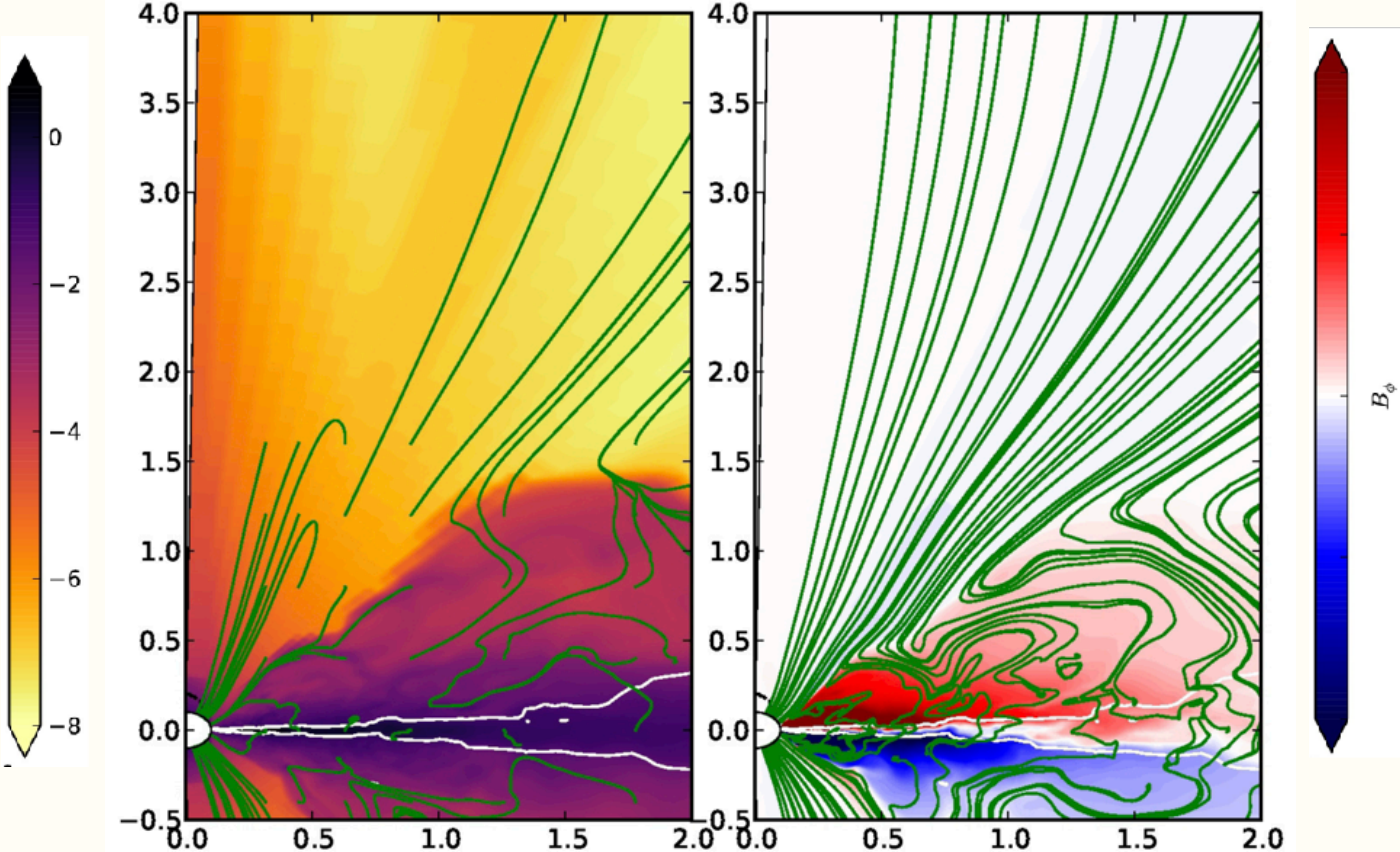




- Resolution needs to be high enough to resolve the SOD during the impact
- Oblique crossing leads to more symmetric ejecta
- But bursts too short

X. Huang et al. 2025, RHD

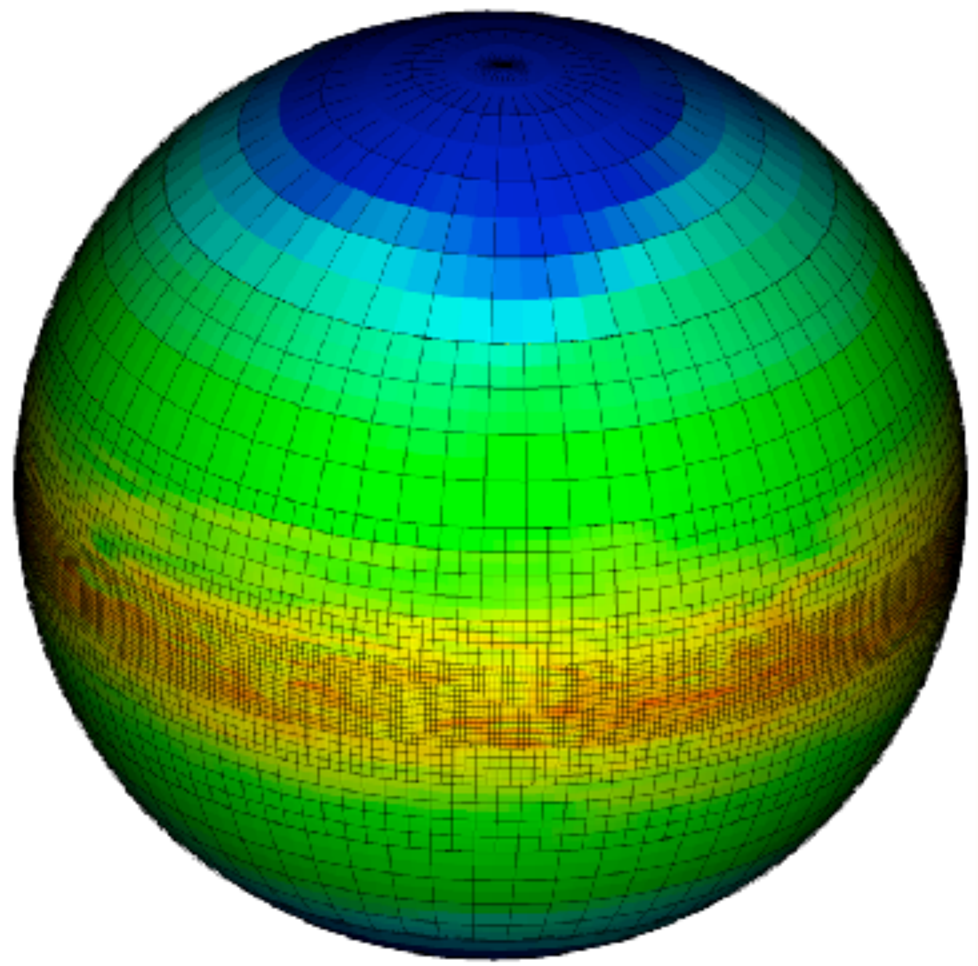
Accretion disks are not thin



Zhu & Stone 2018

Realistic disk condition:

AGN/TDE disk simulation

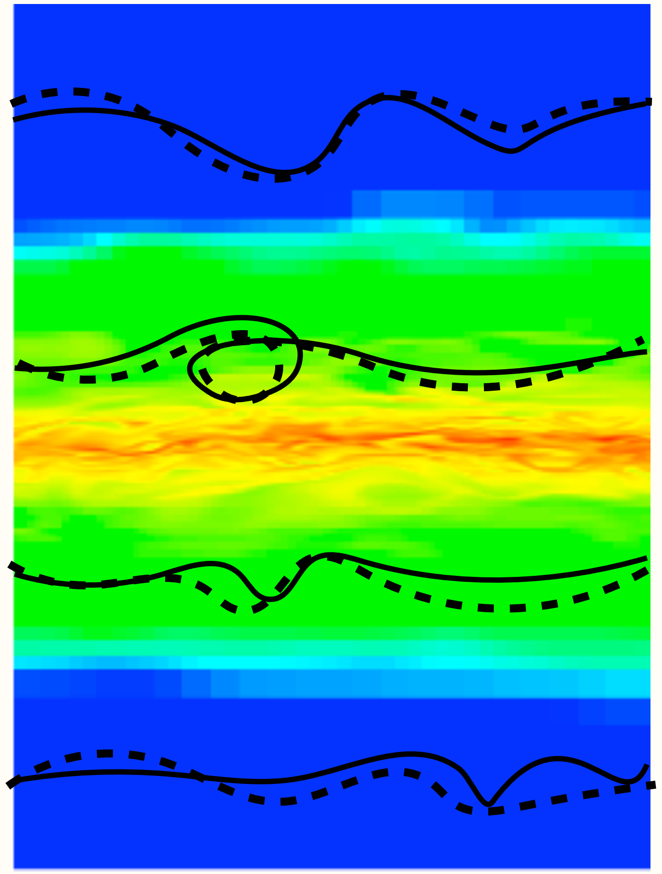


Jiang et al. 2019

M_{BH}=5e8 $M_\odot$
20% Eddington rate

Rescaled to
M_{BH}=1e6 $M_\odot$
20% Eddington rate

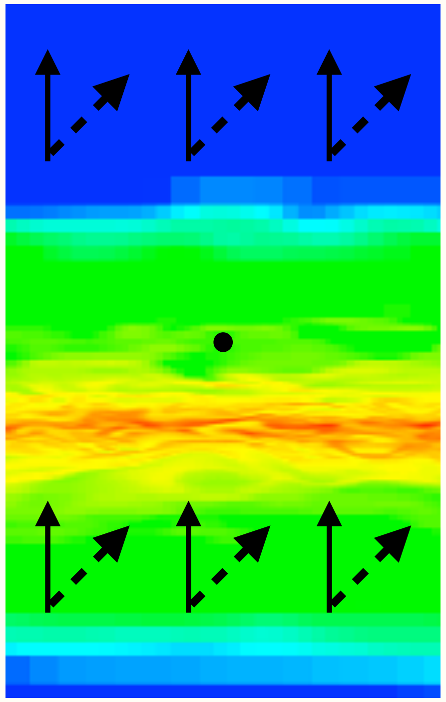
Expand the sphere to a plane



50 r_g, P_{rad}/P_{gas}~2000
T~1e6 K
Σ=17,639 g/cm^2
v_{kep}=0.14 c

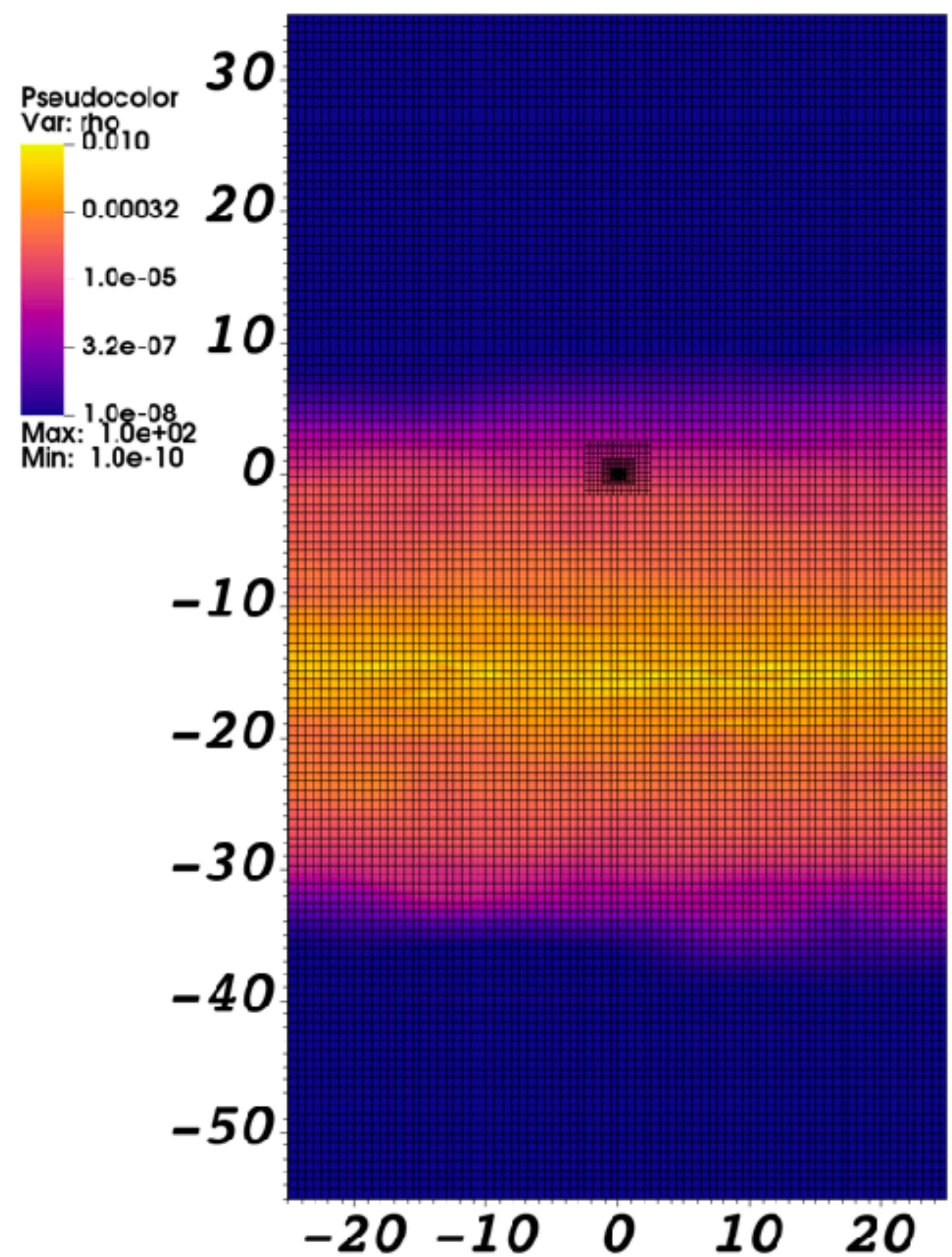
$\nabla \cdot$B cleaning
Hydro smoothing

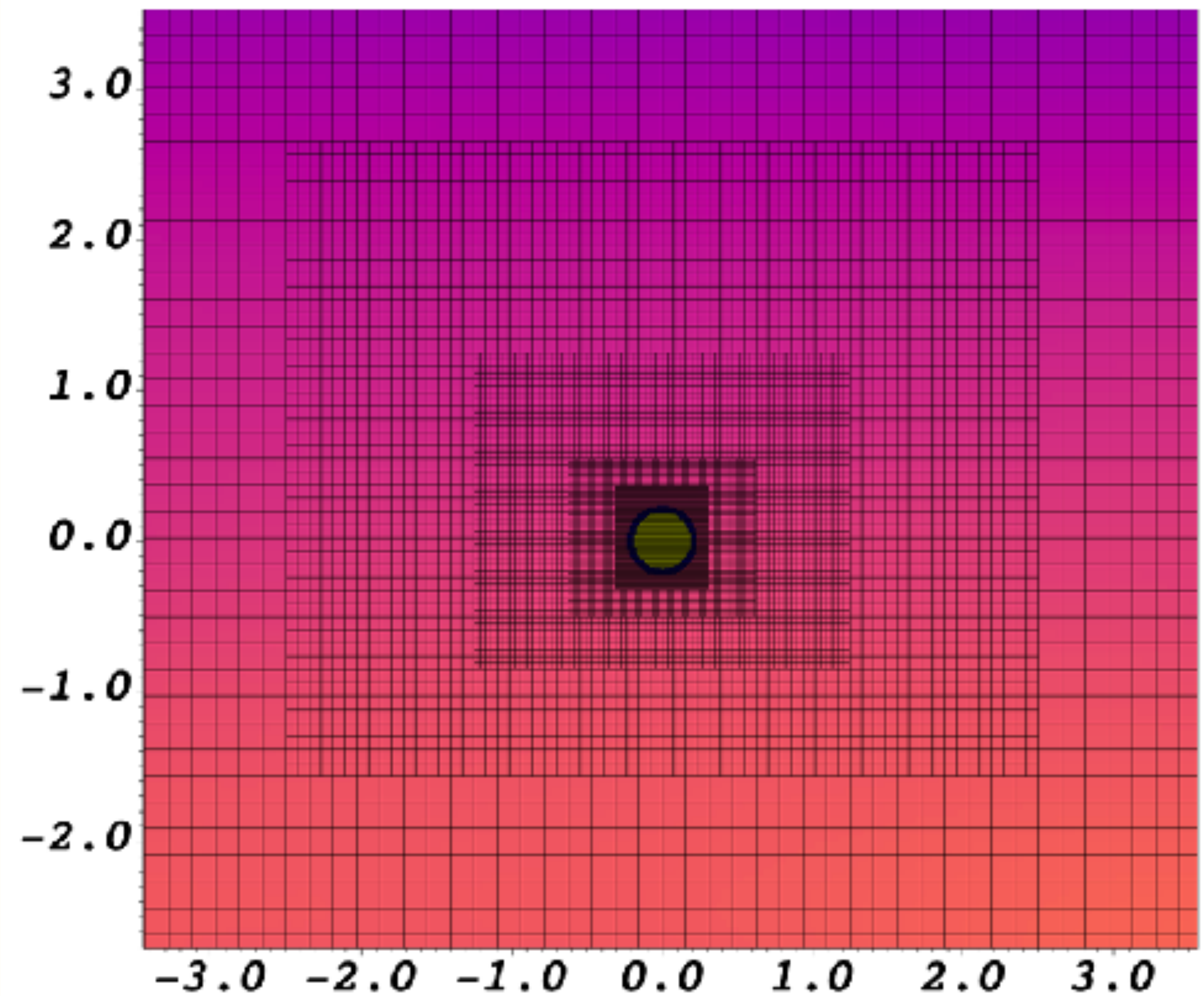
Multigroup RHD with immersed boundary



Zhu et al. to be submitted

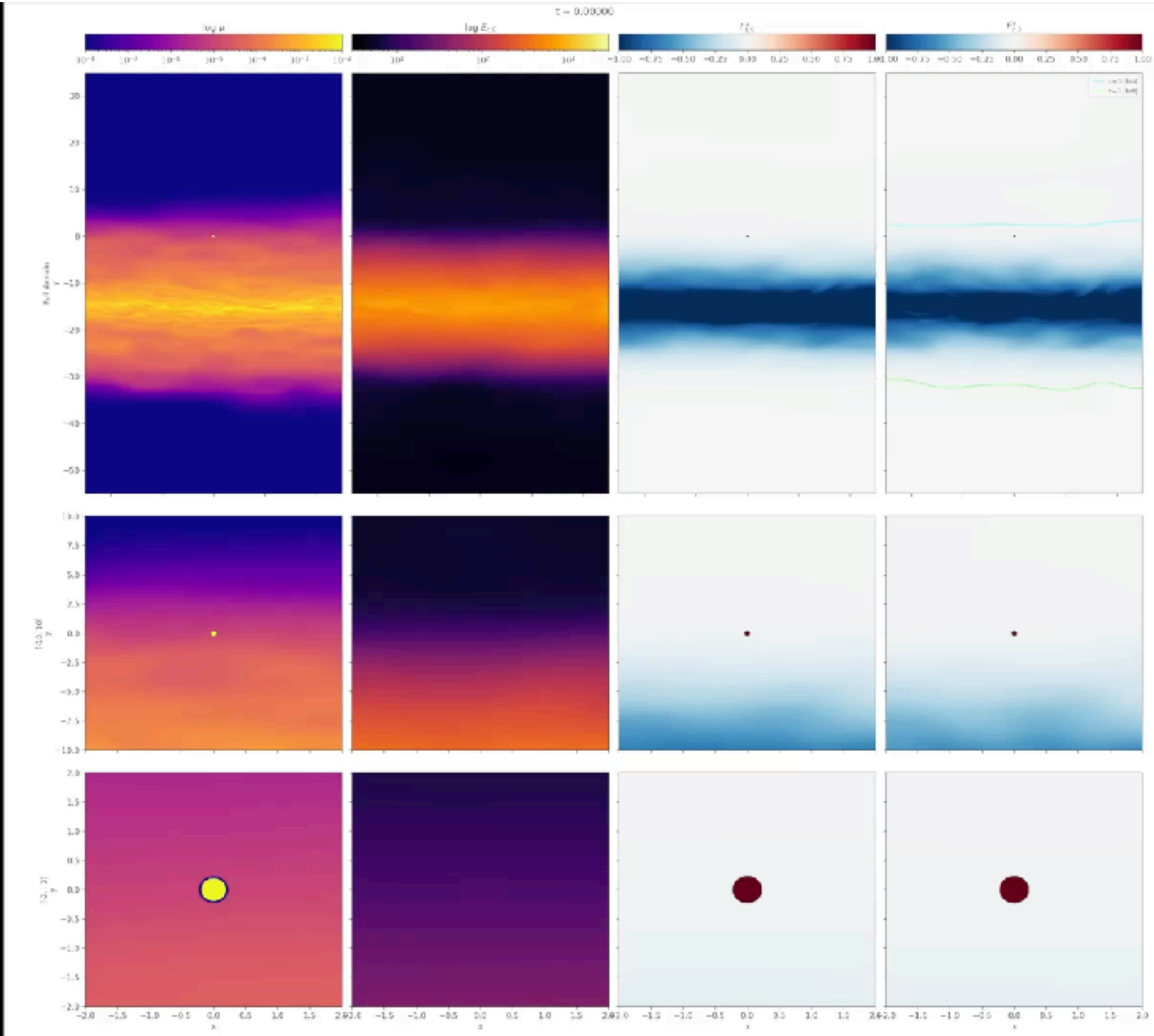
Setup



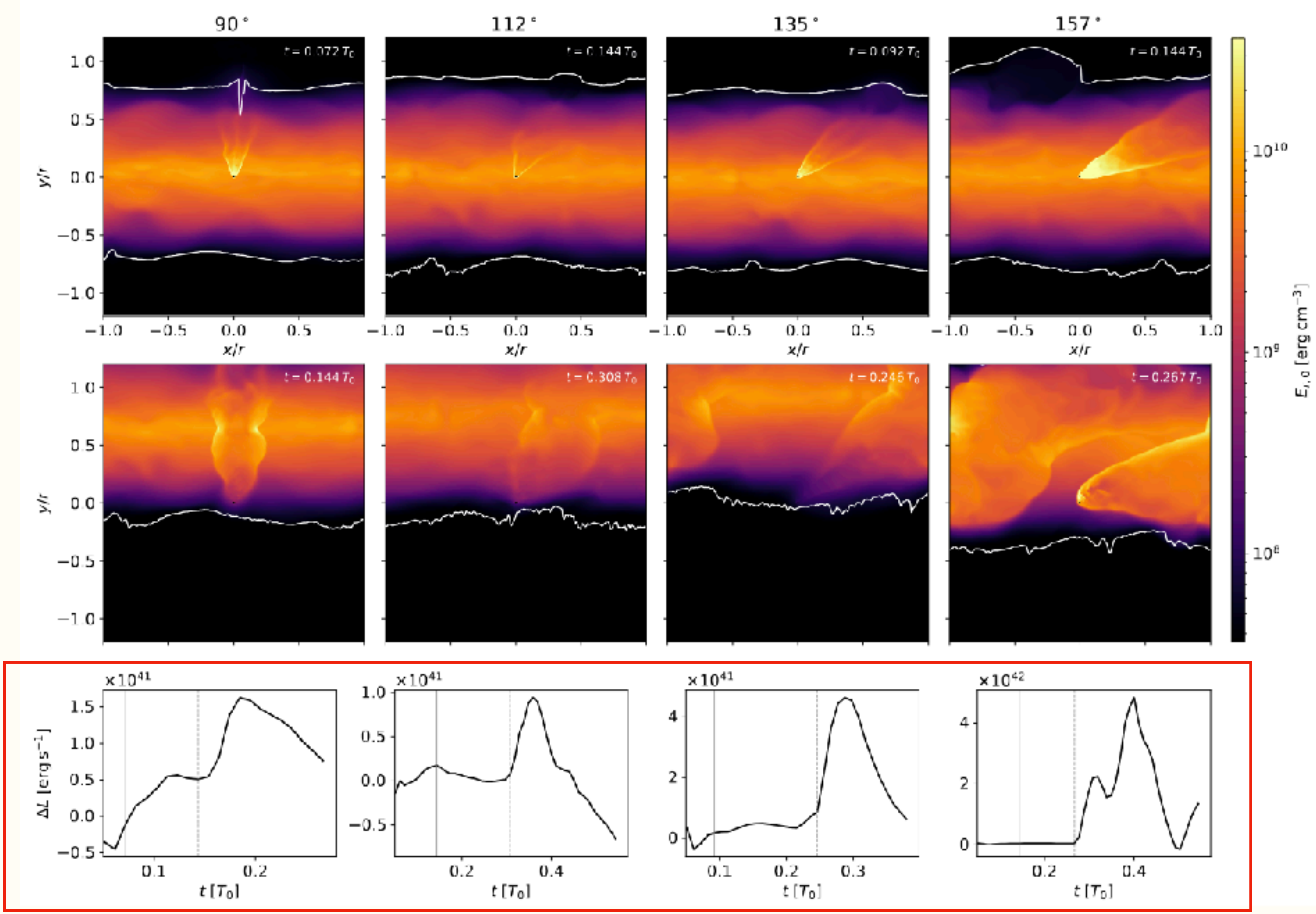


Hydro reflecting sphere at R*
Radiation scattering sphere at 0.85 R*

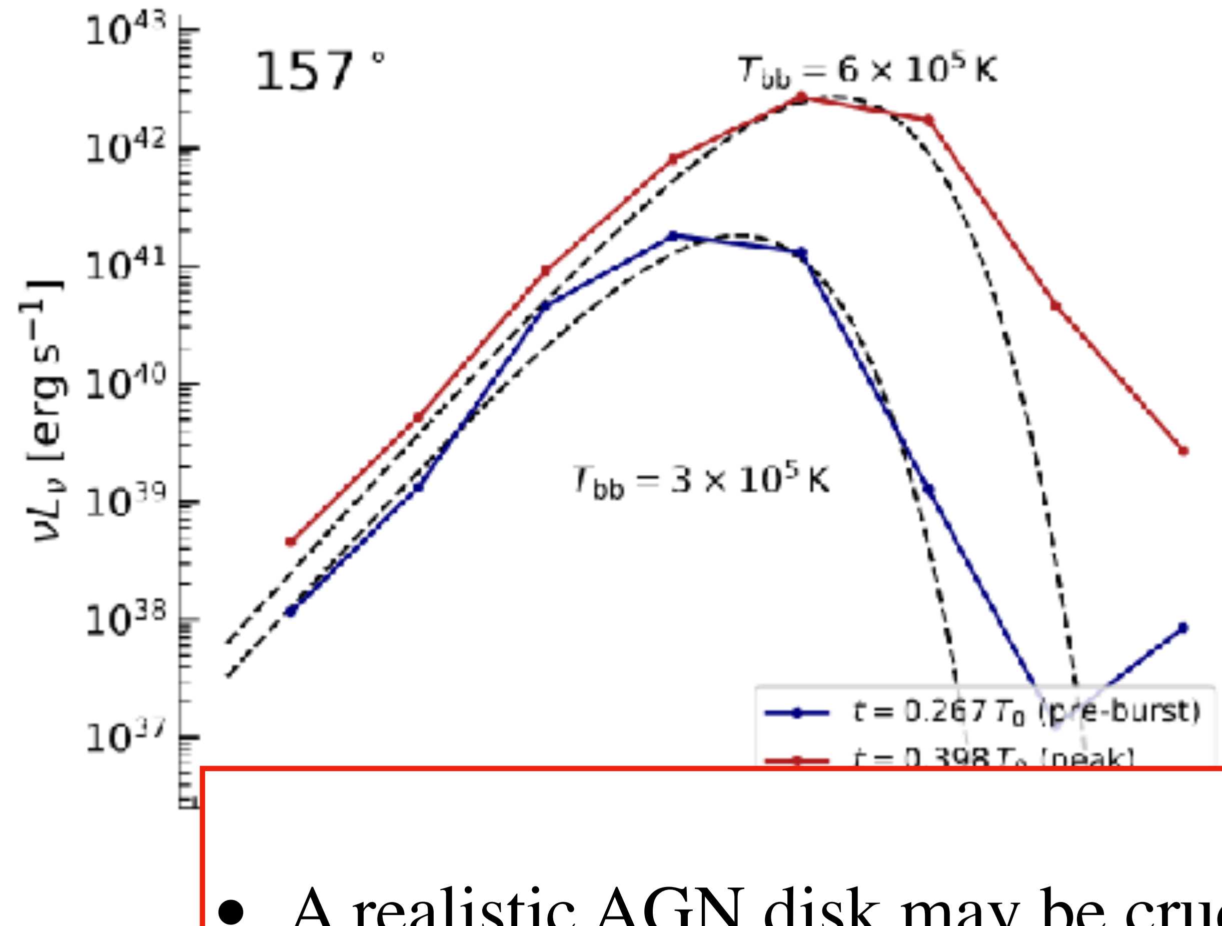
Multi-group RH

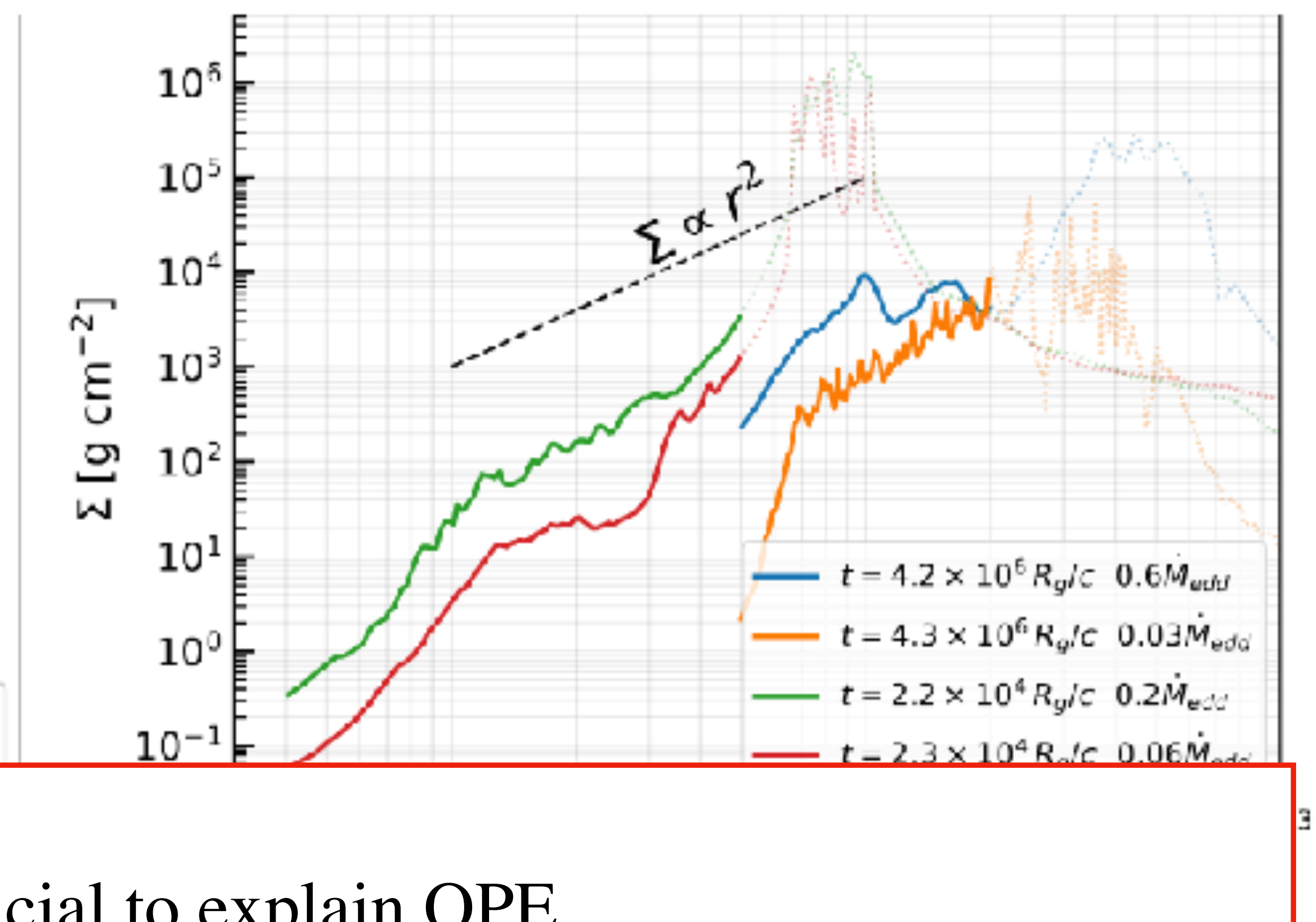


Different crossing angles



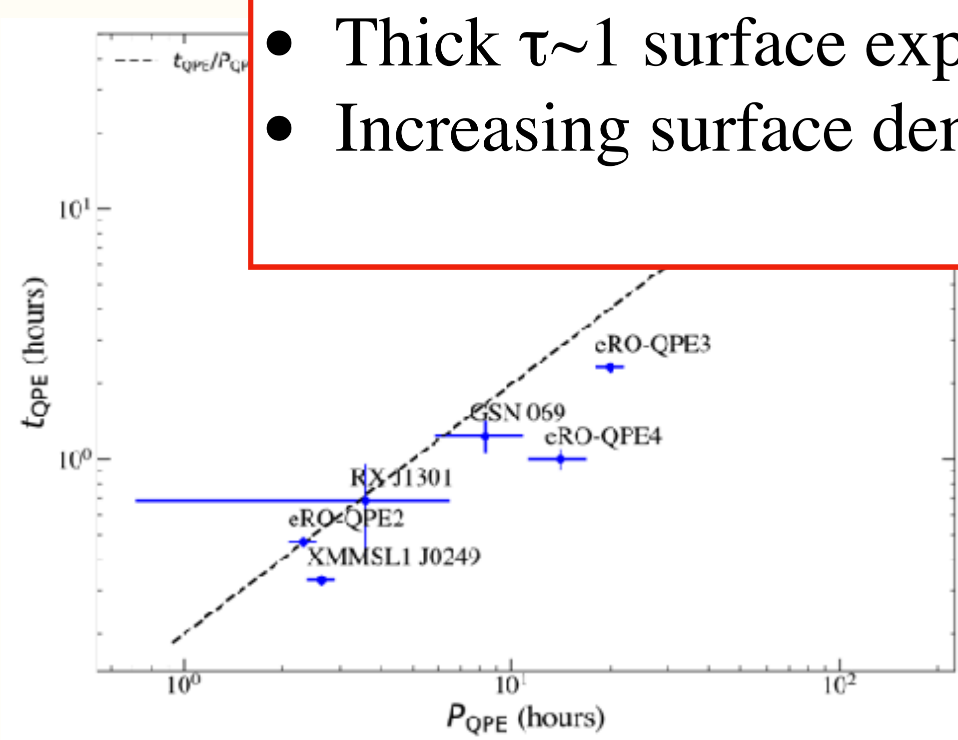
Hardening and energetics

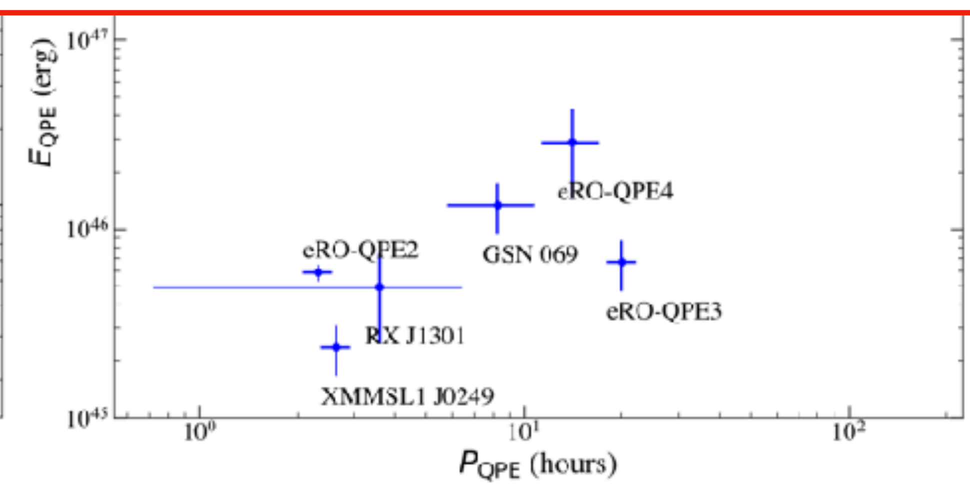




- A realistic AGN disk may be crucial to explain QPE.
- Thick τ~1 surface explains the timescale.
- Increasing surface density explains the energetics.

v_{rel}^2





$E_{imp} \propto r \propto P^{2/3}$

Summary:

Coplanar circular orbit =>Eccentric/inclined orbits

Wave interaction => Dynamical friction/aerodynamic drag

Protoplanetary disks => QPE and EMRI

Potential AthenaK projects

- HD: a hydrostatic disk (Nelson et al 2013)
- HD+self-gravity: Code comparison project (Hans Baehr)
- MHD: implementing Hall
- Companion-disk interaction
- Implementing immersed solid boundary