Kinematic signatures of circumbinary discs

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THE FORMATION AND LONG-TERM EVOLUTION
OF CIRCUMBINARY PLANETARY SYSTEMS
ACROSSTHE H-R DIAGRAM

Florence, 14th Jan 2025

erc European Research Council Established by the European Commission
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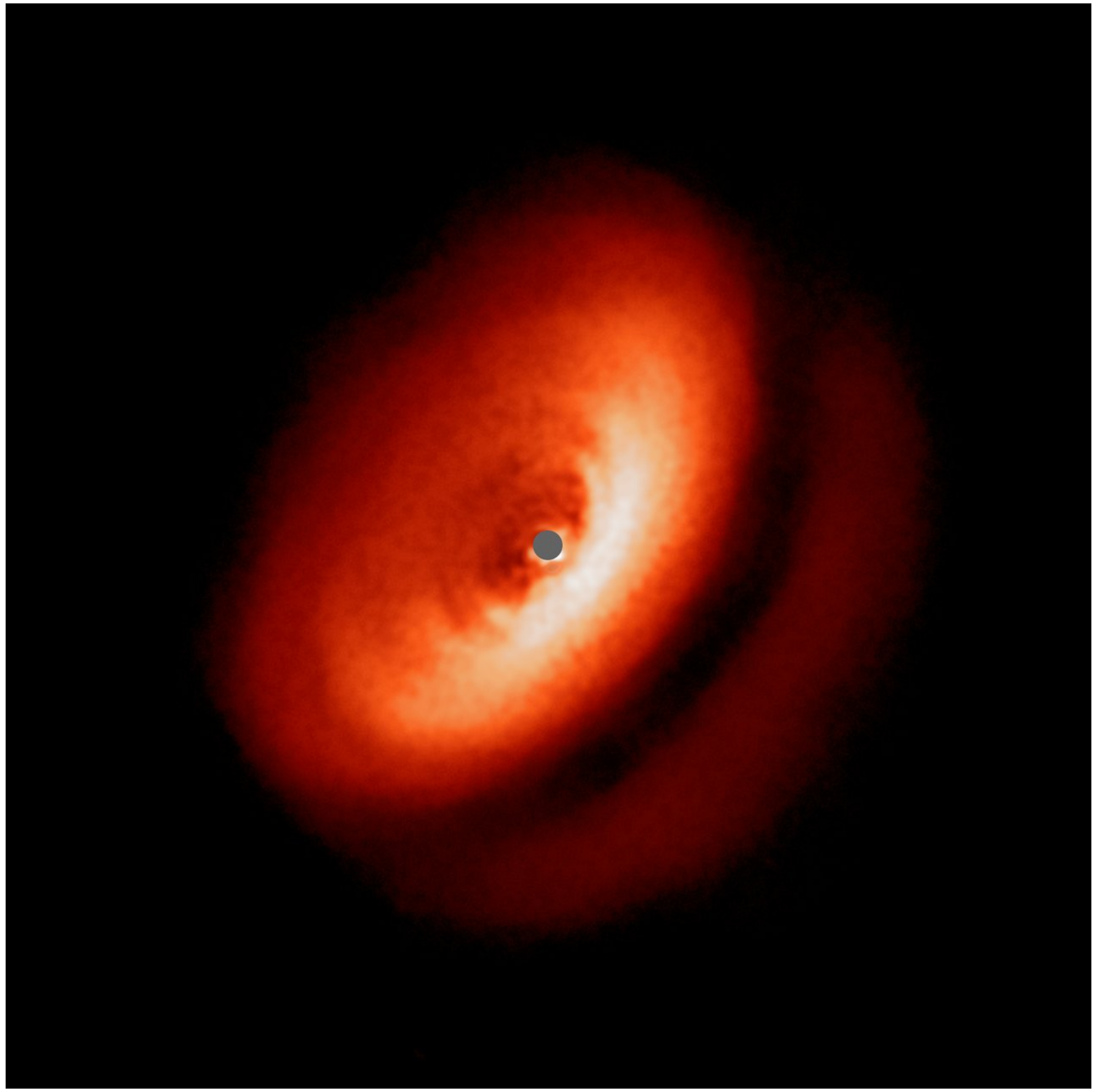
UNIVERSITAS STUDIORUM MEDIOLANENSIS
PHANTOM
DUST BUSTERS Dust and gas in planet forming discs
ENS DE LYON

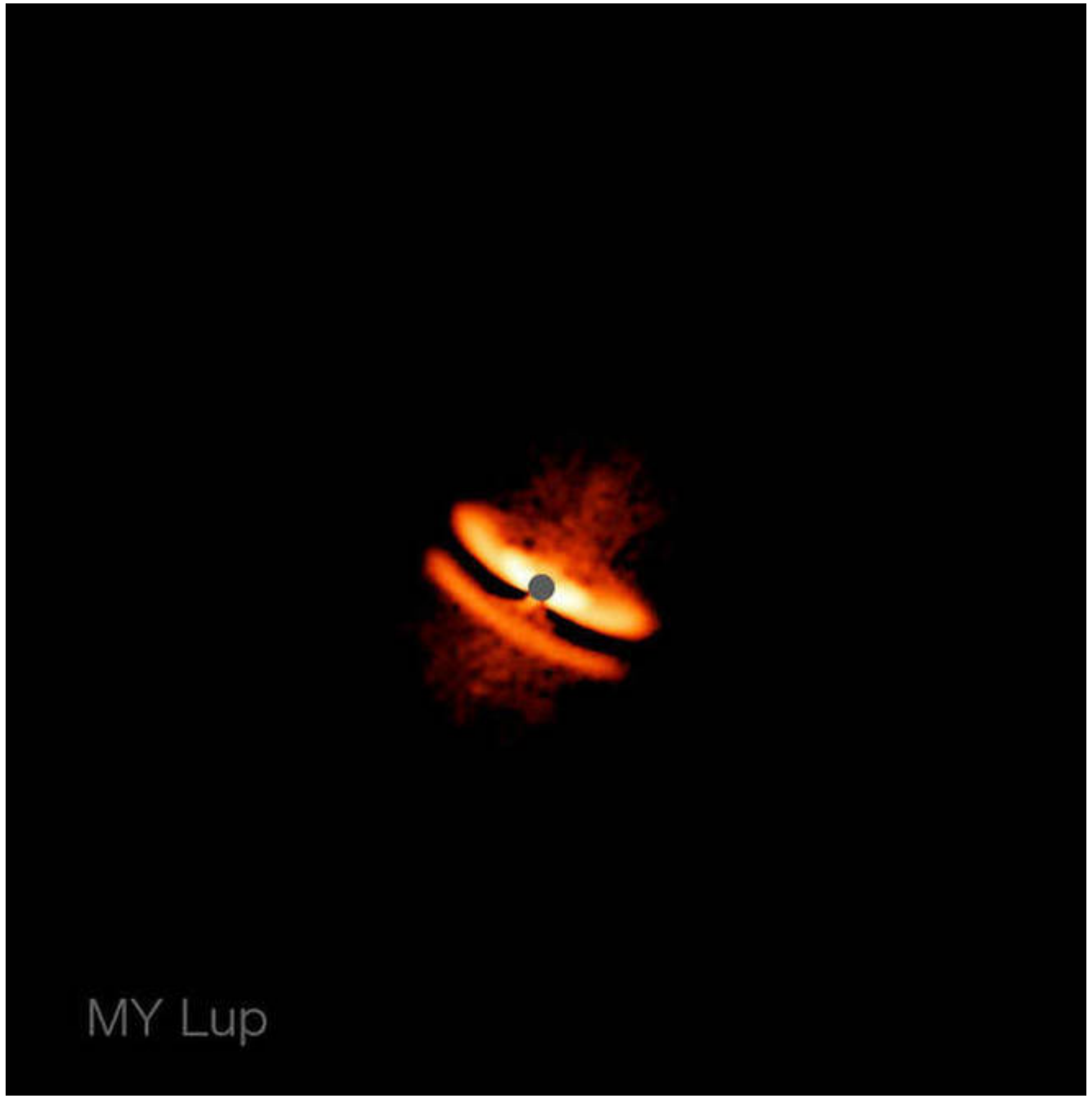
Outline

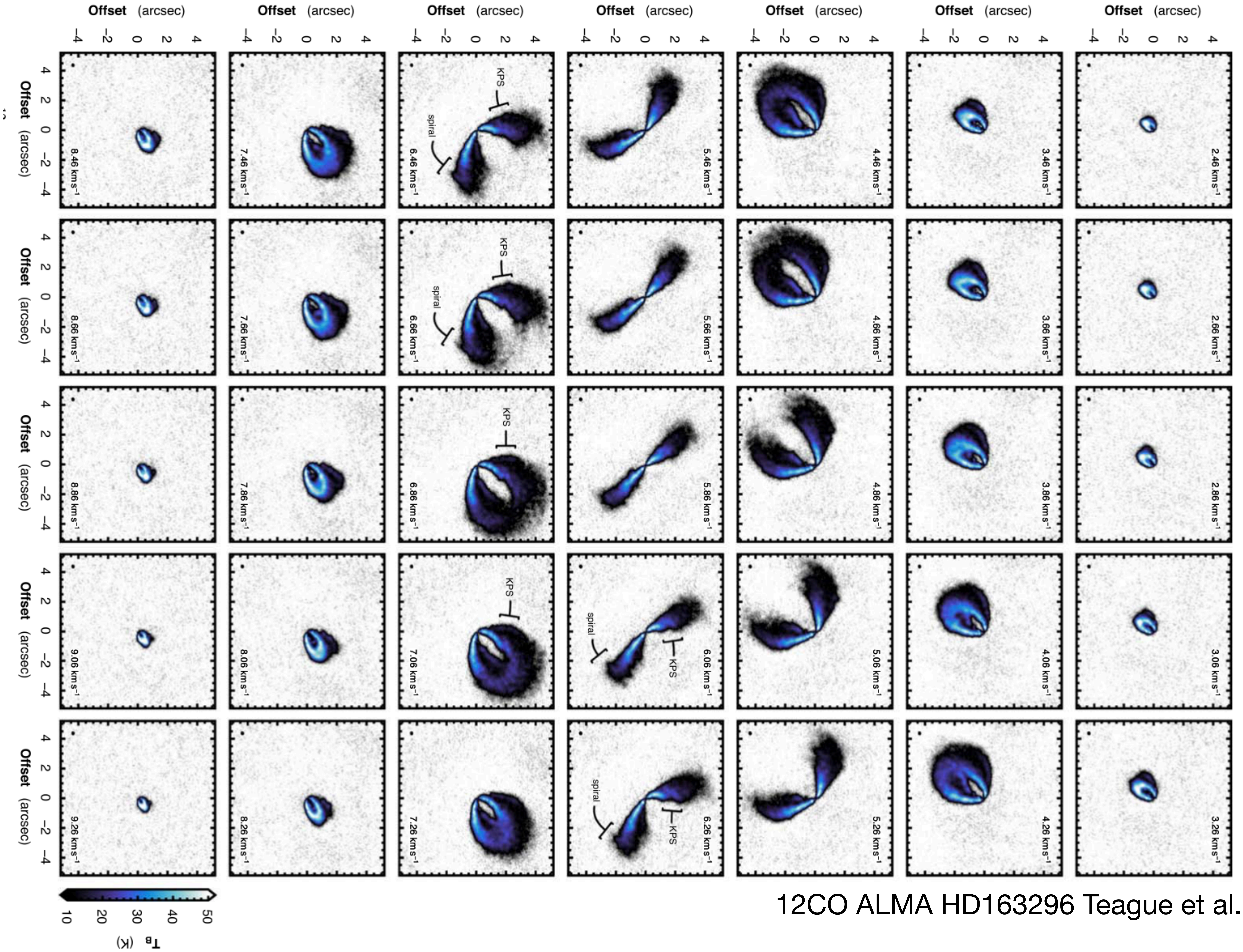
- What is disc kinematics through the eyes of ALMA
- Kinematics in the BINARY-disc interaction problem
- Kinematics of discs surrounding stellar binaries
- THE smoking gun features of binaries in discs…The real challenge in modelling CBDs (….**suspense**)
- Conclusion


A large, diffuse interstellar gas cloud (solar nebula) contracts due to gravity.
Contraction: As it contracts, the cloud heats, flattens, and spins faster, becoming a spinning disk of dust and gas.
The Sun will be born in the center.
Planets will form in the disk.
Clearing: The remaining gas is clea
sealing the compositional fates of t
main in the inner solar system.
Jovian planets remain in the outer solar system.
"Leftovers" from the formation process become asteroids (metal/rock) and comets or Kuiper belt objects (ice/rock).
Not to scale

SPHERE/VLT; Avenhaus et al. (2018)





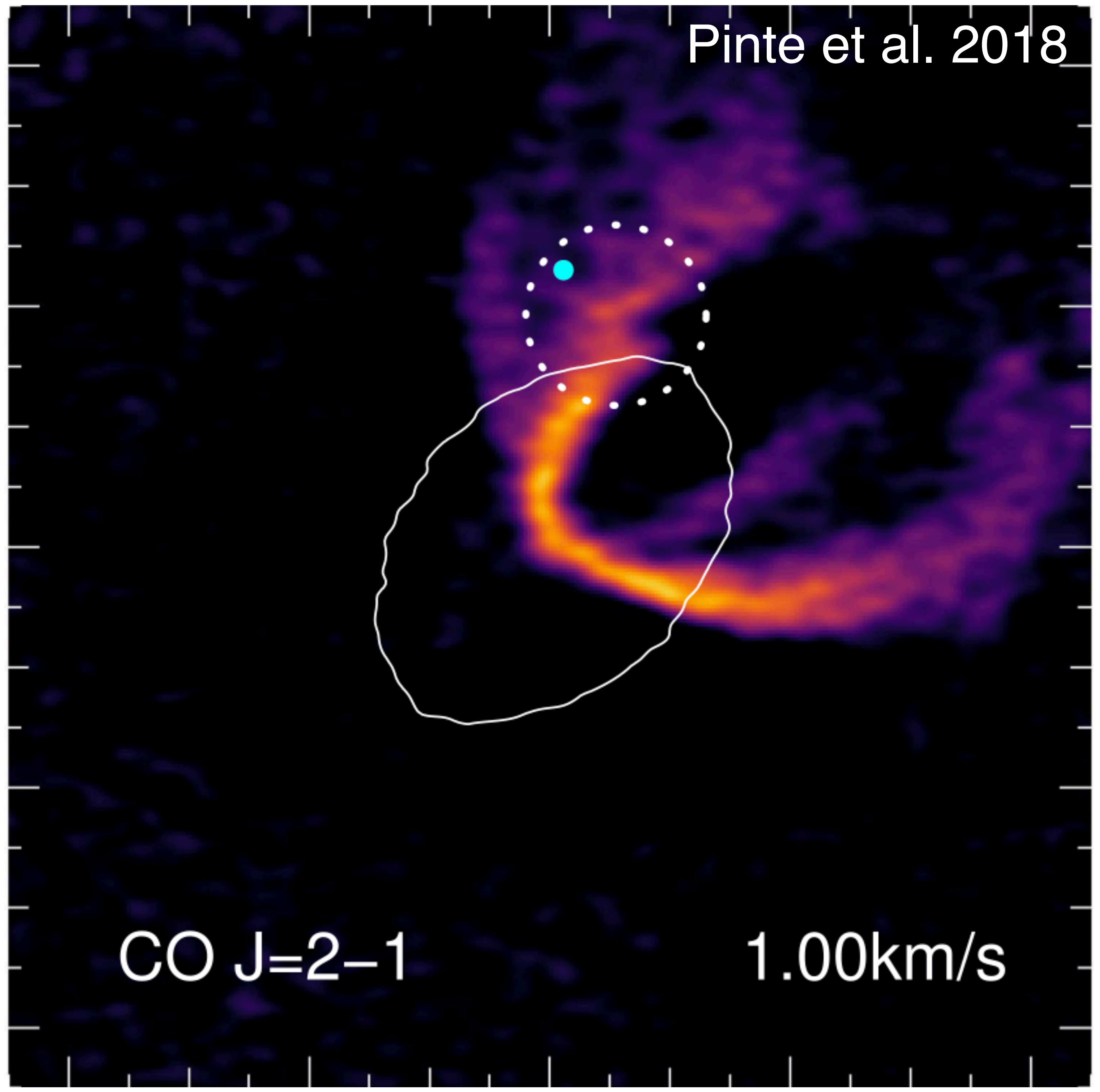


12CO ALMA HD163296 Teague et al. 2021

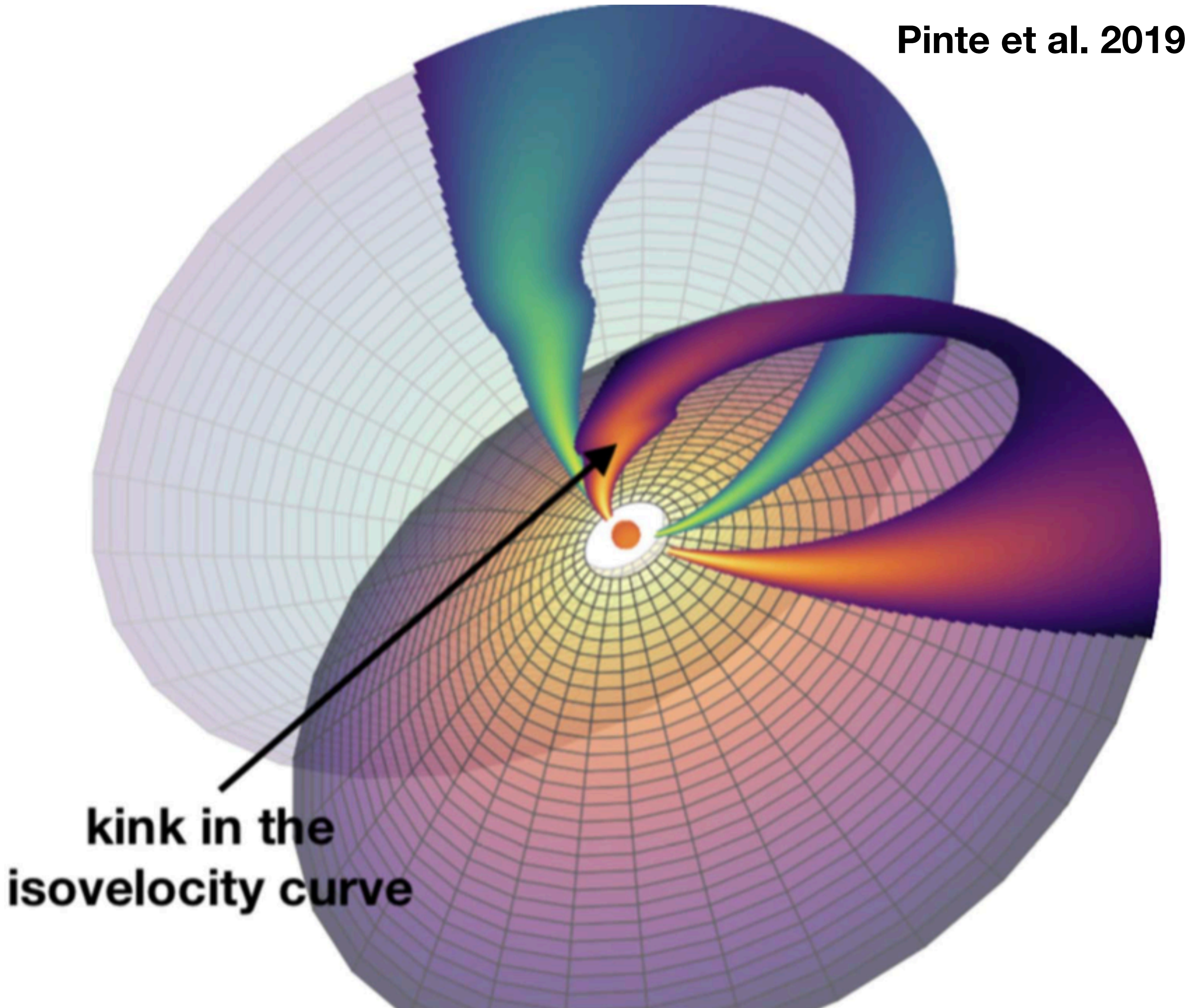
What is disc kinematics through the eyes of ALMA

- Emission lines emit at very precise wavelengths, the peak of the line will redshift or blueshift depending on its velocity along the line of sight.

- ALMA takes a “picture” (brightness map) of gas line emission in a small given velocity window.



Pinte et al. 2019



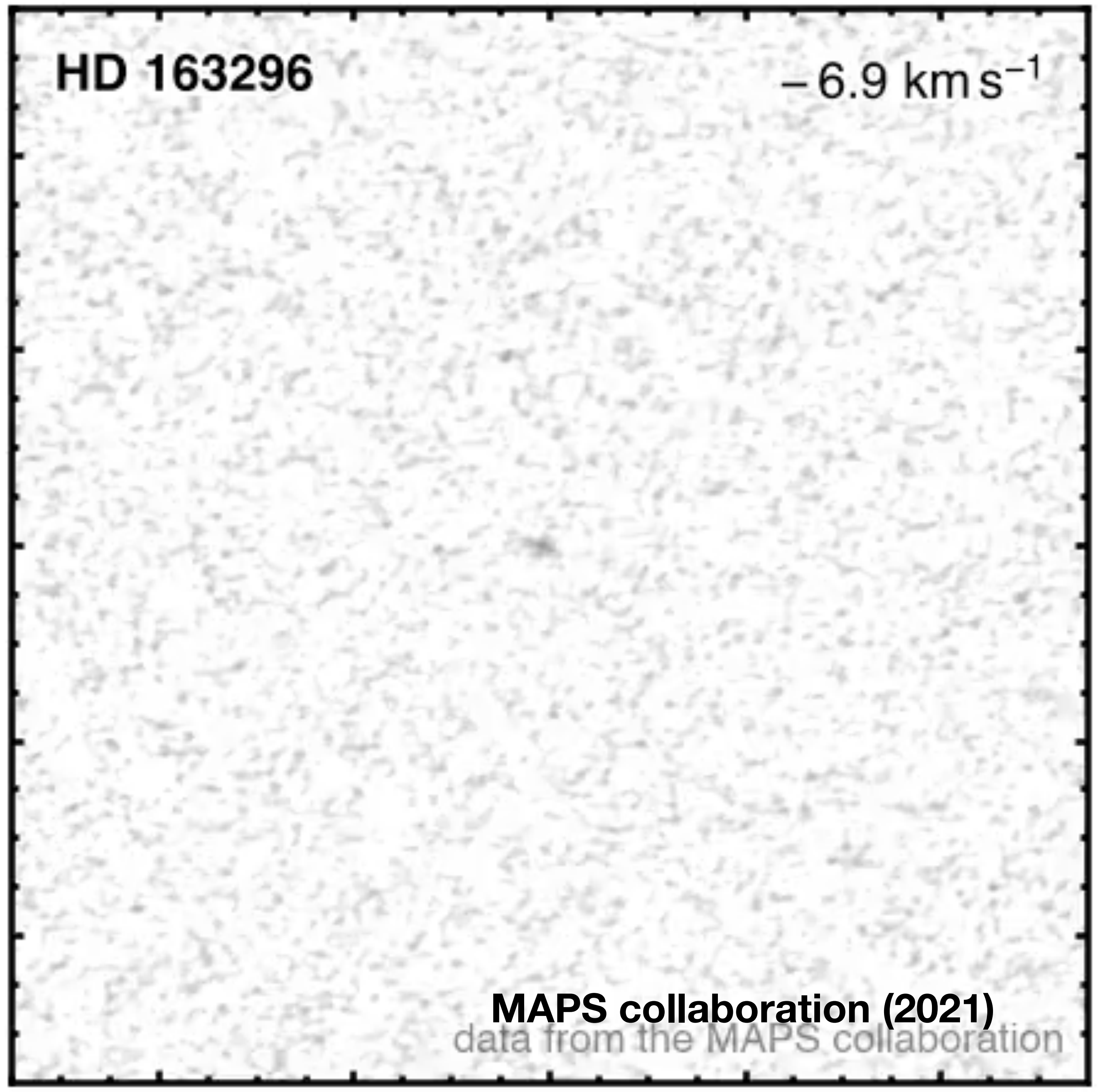
What is disc kinematics through the eyes of ALMA

- Emission lines emit at very precise wavelengths, the peak of the line will redshift or blueshift depending on its velocity along the line of sight.

- ALMA takes a “picture” (brightness map) of gas line emission in a small given velocity window.

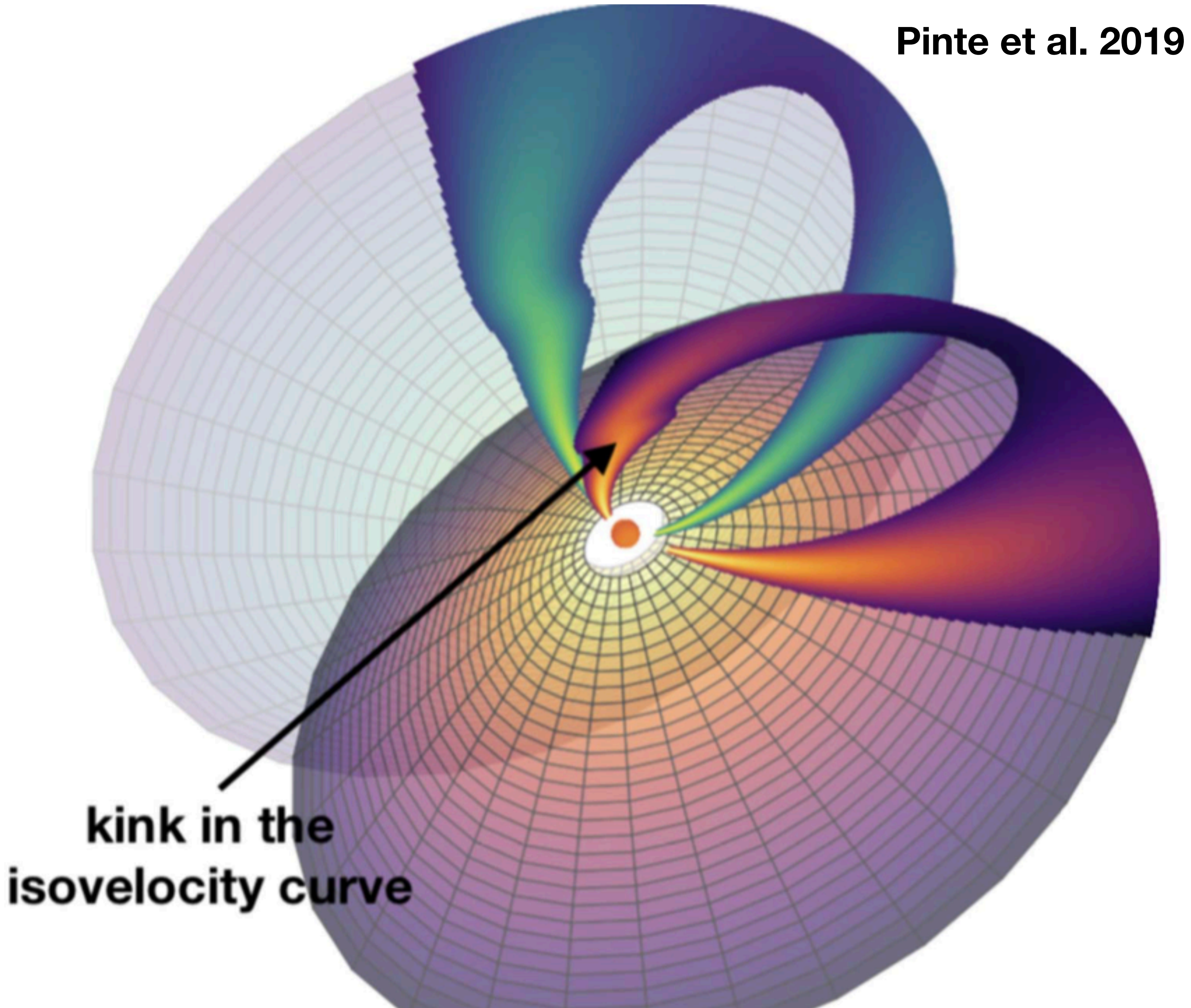
- we collect a scan of the disc at multiple velocities and we have a sort of tomography of the disc at different velocities

- From the shape of the channel we can define disc surfaces and determine the disc vertical structure



MAPS collaboration (2021)

Pinte et al. 2019



In[1]:= Vkep = 1 / R ^ 0.5

Out[1]= $\frac{1}{R^{0.5}}$

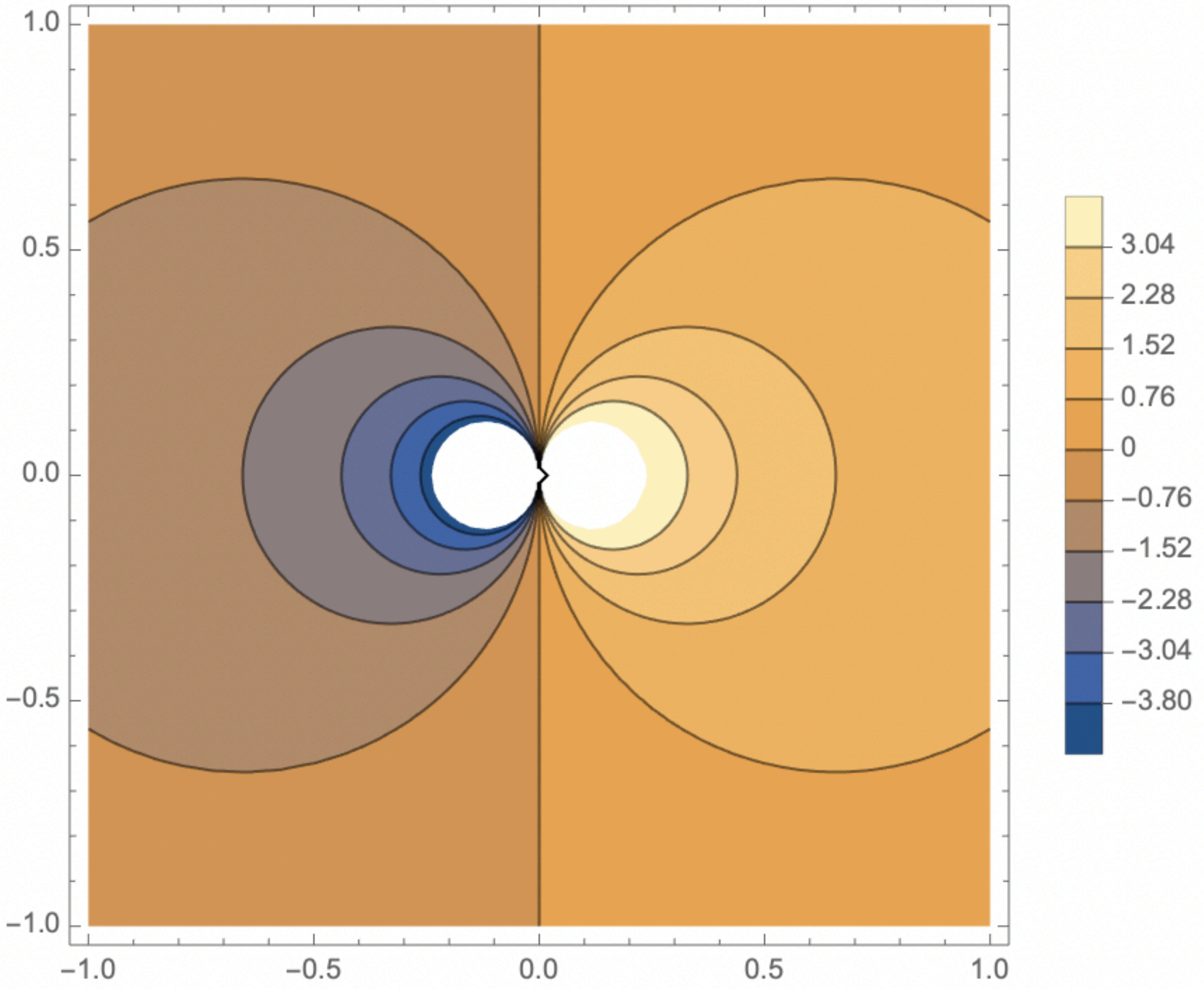
In[2]:= Vproj = Vkep * Cos[theta]

Out[2]= $\frac{\text{Cos[theta]}}{R^{0.5}}$

In[3]:= Vproj2[x_, y_] := Vproj /. {R → (x ^ 2 + y ^ 2), theta → ArcTan[x, y]}

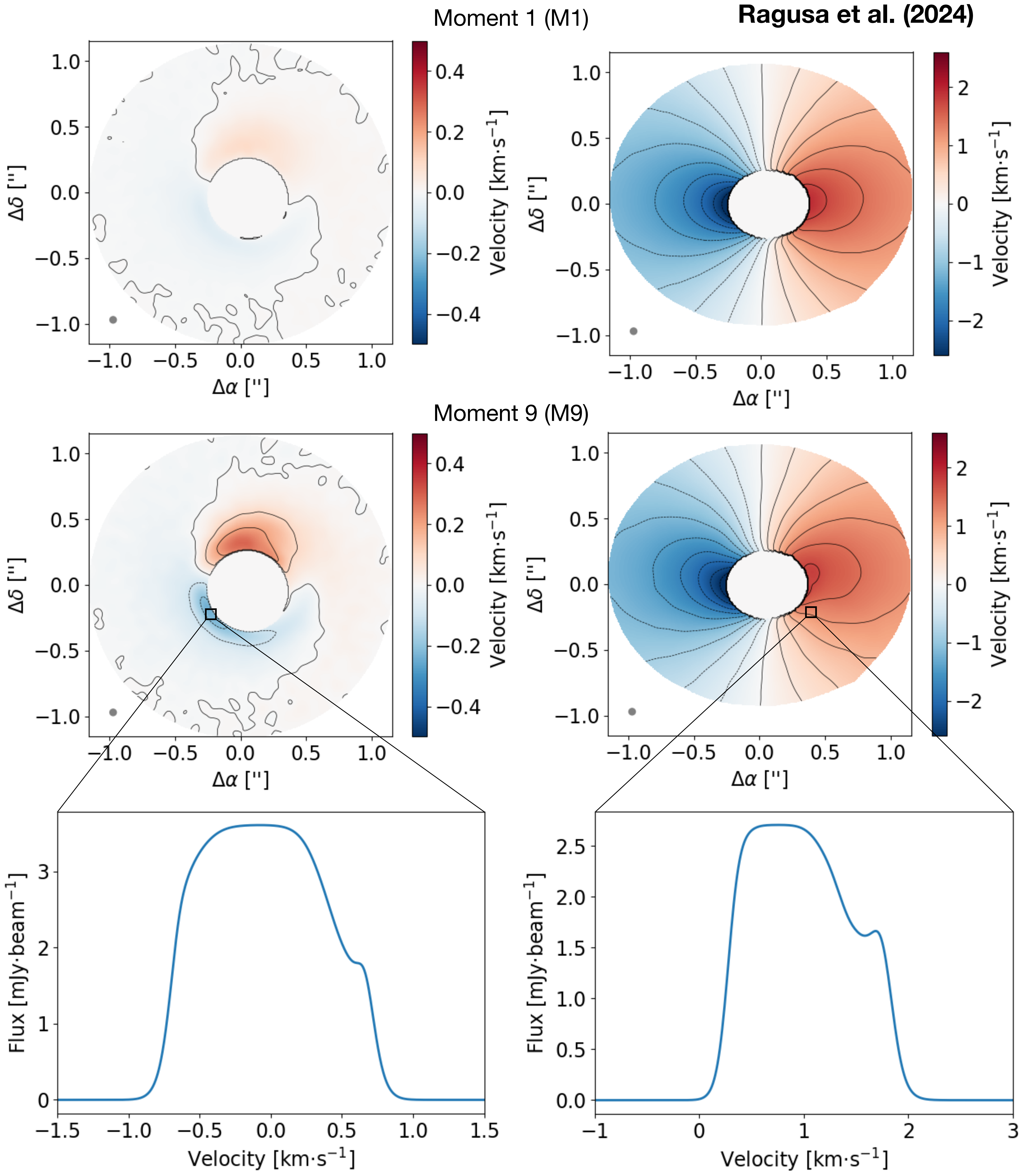
In[4]:= ContourPlot[Vproj2[x, y], {x, -1, 1}, {y, -1, 1}, Contours → 10, PlotLegends → Automatic]

Out[4]=



What is disc kinematics through the eyes of ALMA

- The kinematic dataset at this point is a cube, where each spatial pixel has a velocity spectrum
- from the momenta of this spectrum (integrated flux, mean, variance, maximum brightness, velocity of the brightest channel) we can define moment maps (M0, M1, M2, M8, M9)



Kinematics in the BINARY-disc interaction problem

- What is a binary? Two gravitationally bound masses
- From the theoretical perspective, theory cares only that two masses are gravitationally bound and surrounded by a disc of material (for theory check e.g. Goldreich & Tremaine 1980; Miranda & Lai 2015)
- Interaction with companion generates epicyclic motion

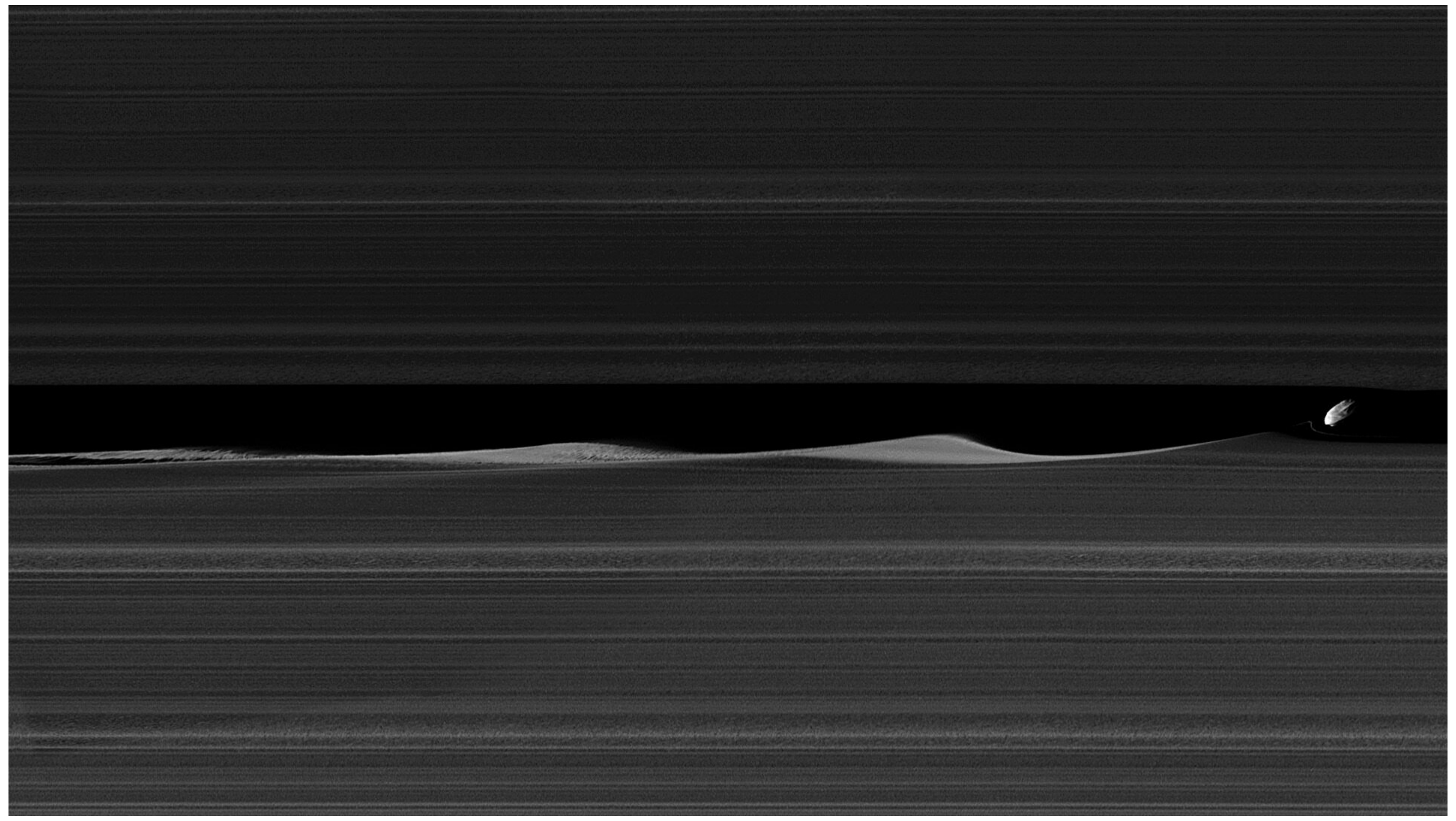
$$v_{R,1} = -\frac{i}{D(R)}\left\{[m\Omega(R)-\omega]\frac{\partial}{\partial R}+\frac{2m\Omega(R)}{R}\right\}(\Phi_1^m+\Phi_{\Sigma_1}+h_1)$$

$$v_{\varphi,1} = \frac{1}{D(R)}\left\{2B(R)\frac{\partial}{\partial R}+\frac{m}{R}[m\Omega(R)-\omega]\right\}(\Phi_1^m+\Phi_{\Sigma_1}+h_1)$$

Classic linear theory, (Meyer-Vernet & Sicardy 1987)

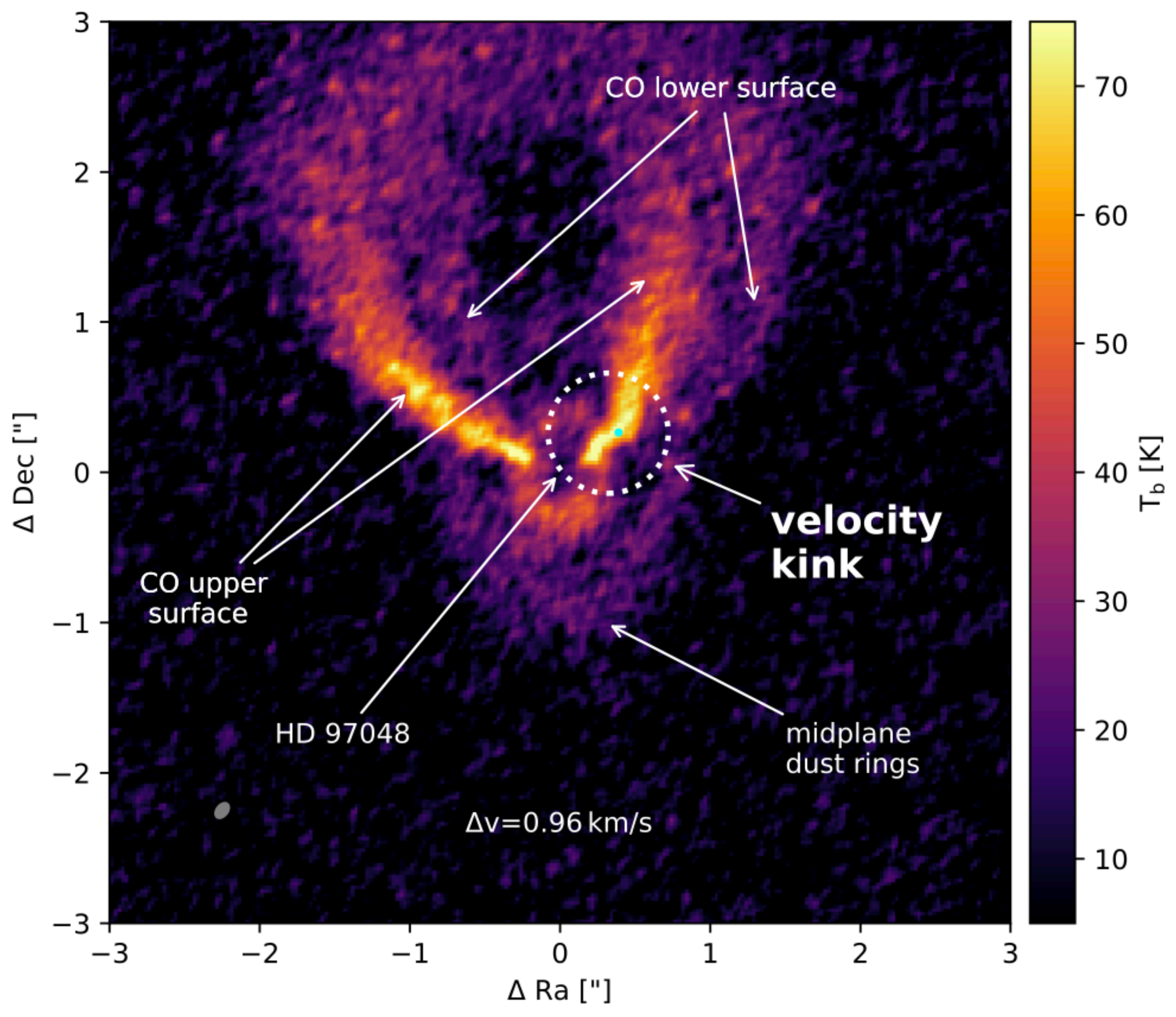
243 Ida, binary asteroids, Galileo probe

Saturn's moon Daphnis, Cassini, ESA

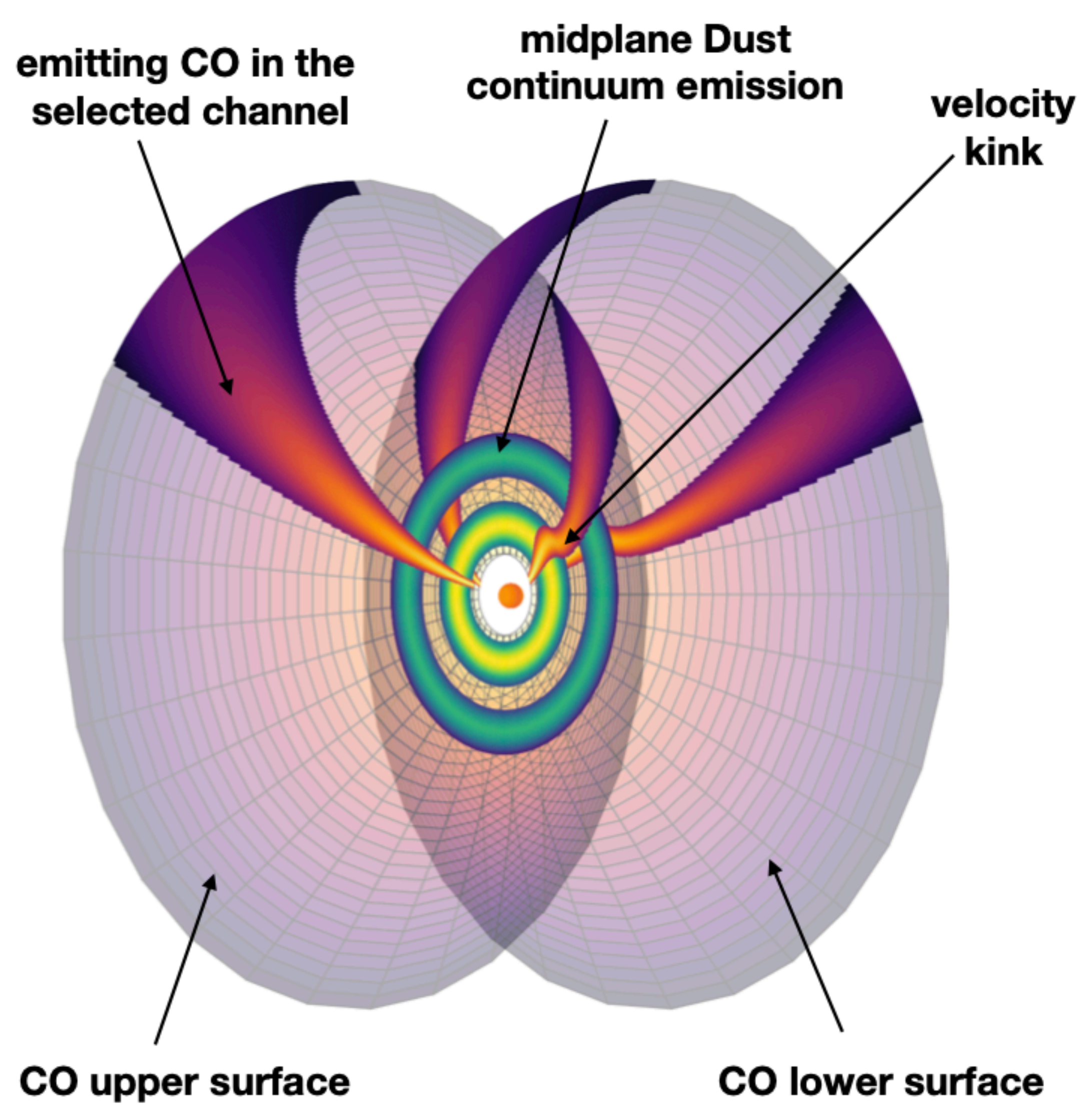


Kinematics of discs surrounding stellar binaries

- Planets (mass ratio q<0.015):
  - a gap in the continuum and
  - a wake in the kinematics visible as a velocity kink



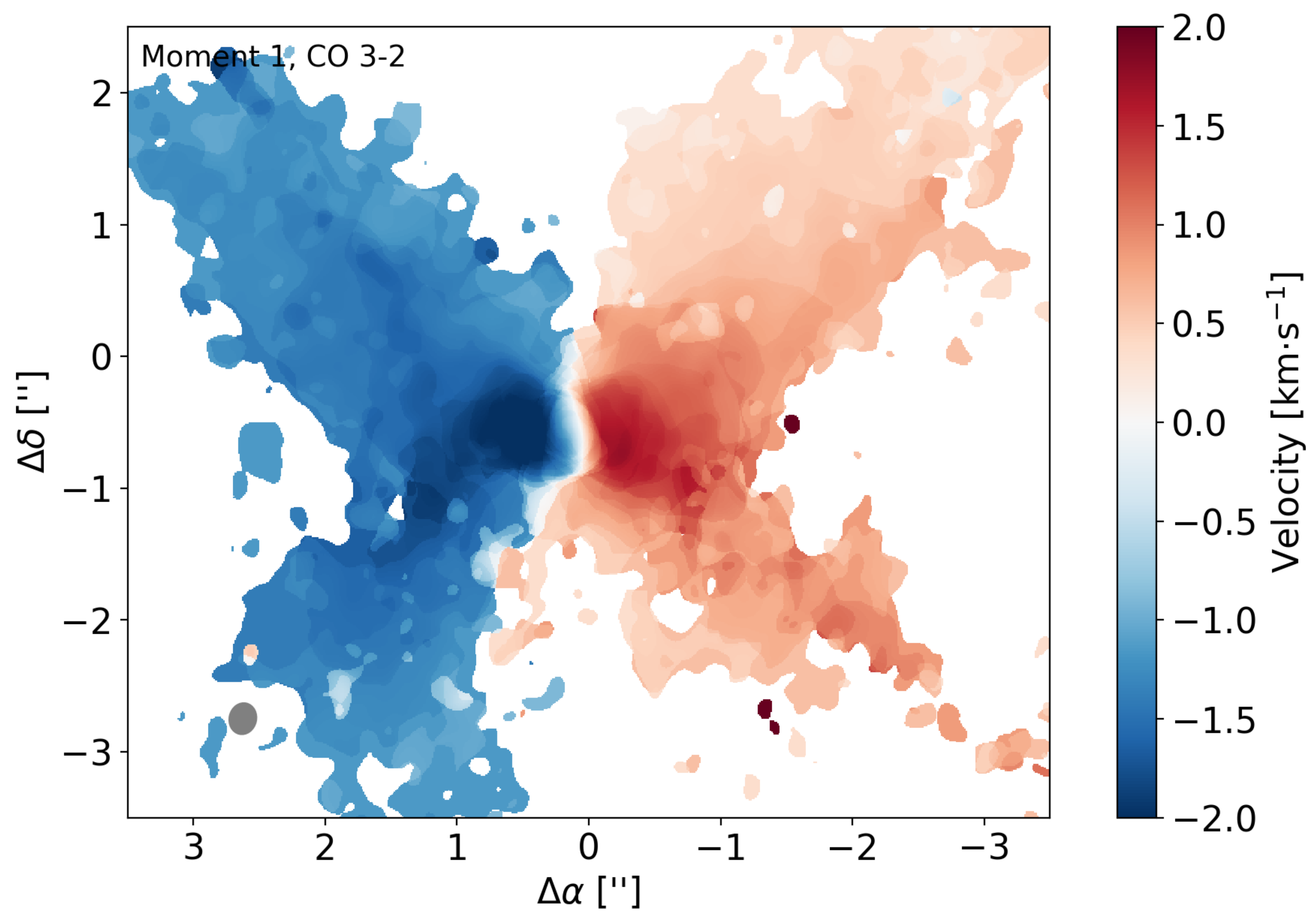
Pinte et al. 2019



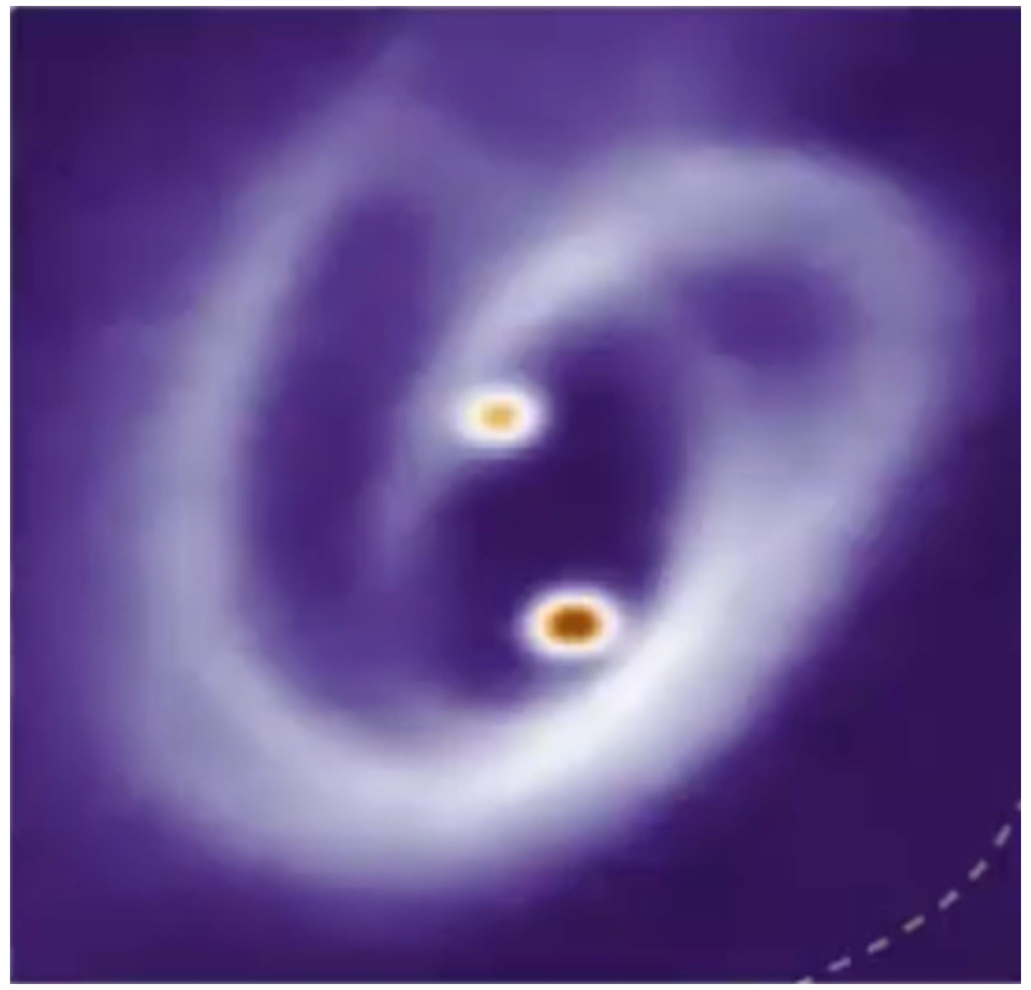
Kinematics of discs surrounding stellar b

- Planets (mass ratio q<0.015):
  - a gap in the continuum and
  - a wake in the kinematics visible as a velocity kink
- Stellar binaries:
  - Large gap or cavity (q>0.05) continuum
  - **Messy kinematics:**
    - Quantify how messy (Calcino et al. 2023,2024)

IRAS 04158+2805, Ragusa et al. 2021

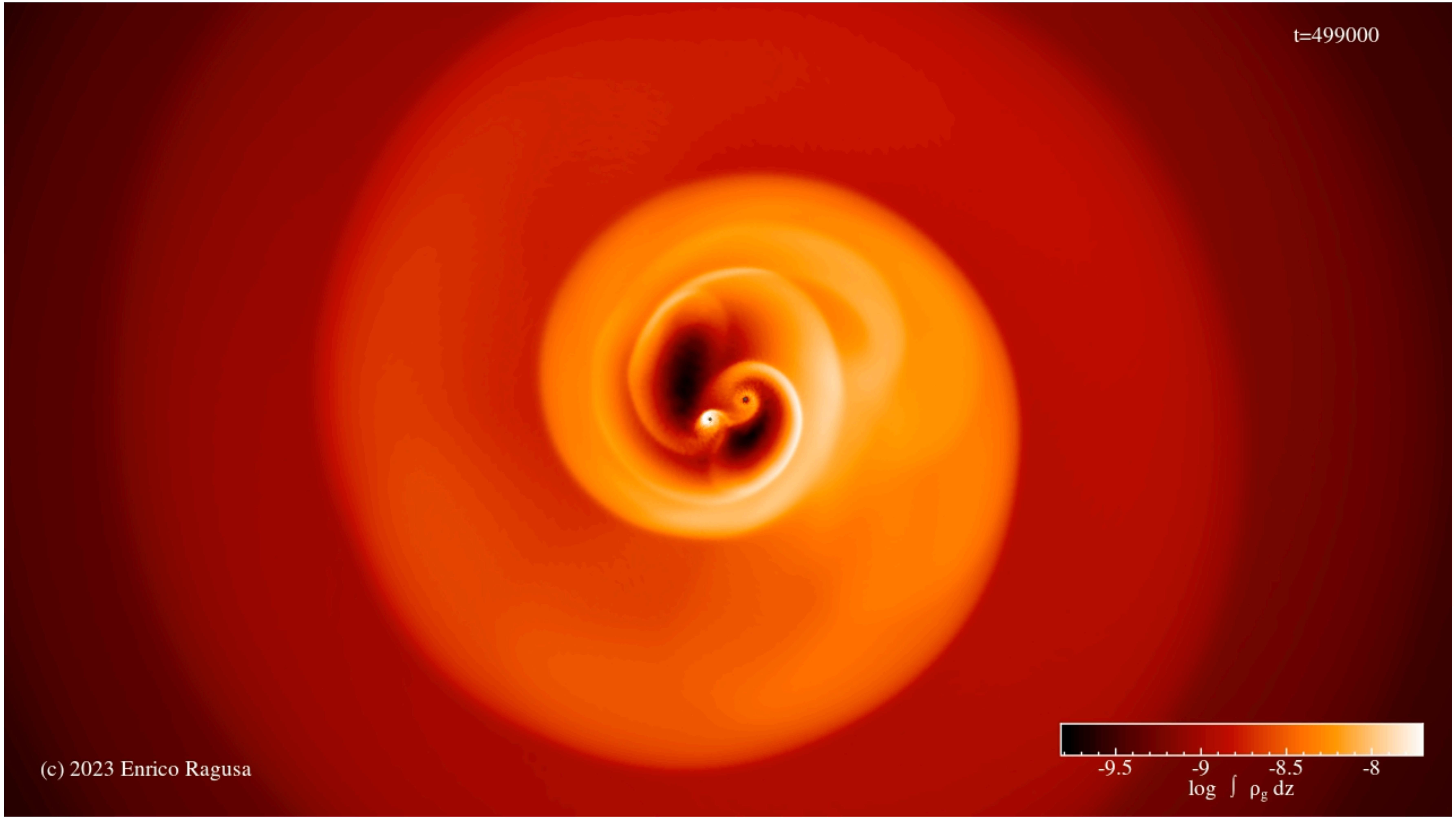


BHB2007 Alves et al. 2019



L1448 IRS38B Reynolds et al. 2021

Kinematics of discs surrounding stellar binaries



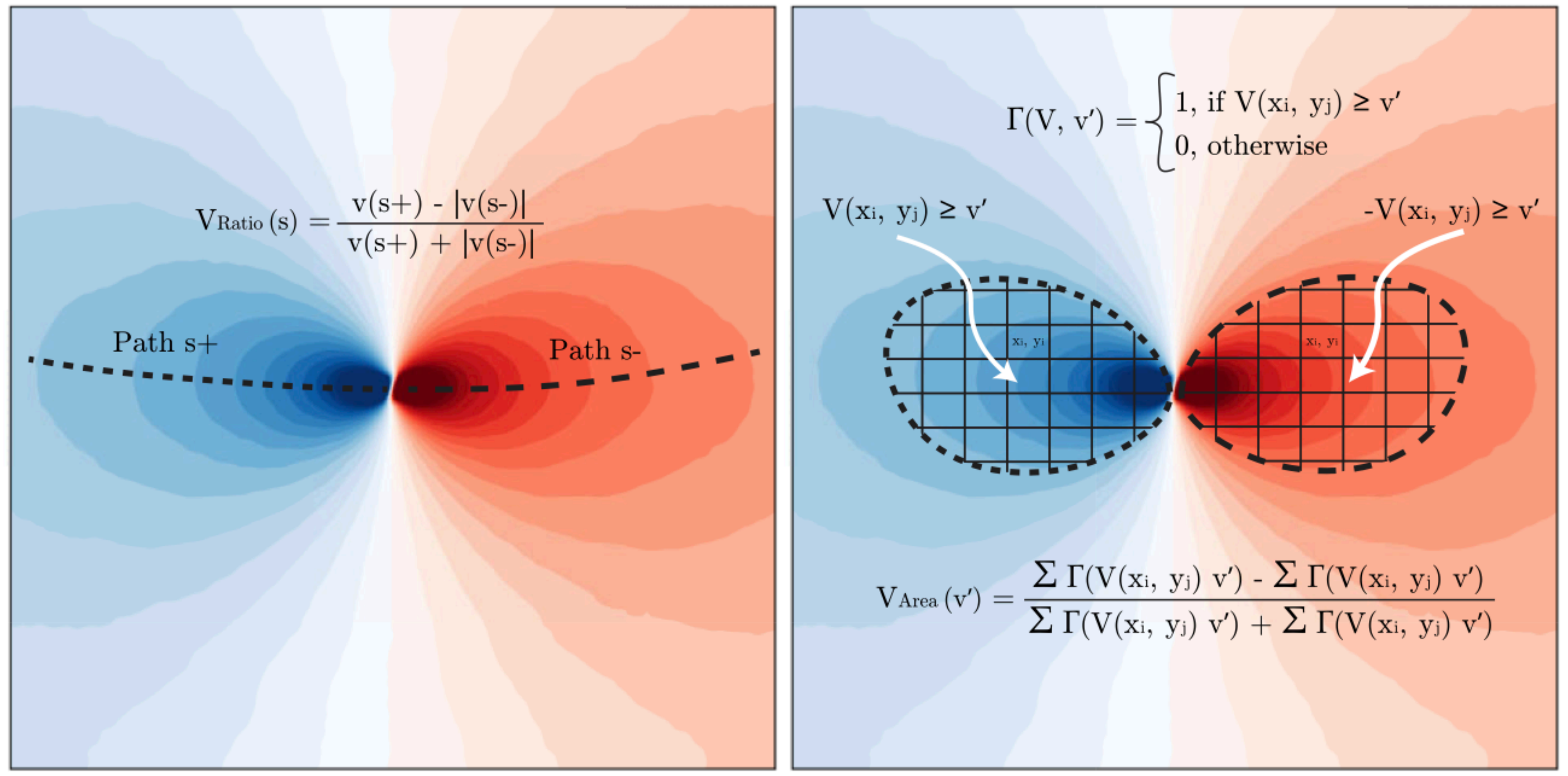
Kinematics of discs surrounding stellar bir

- Doppler-flips, spiral arms, eccentric gas motion, fast flows inside of the cavity… Large residuals

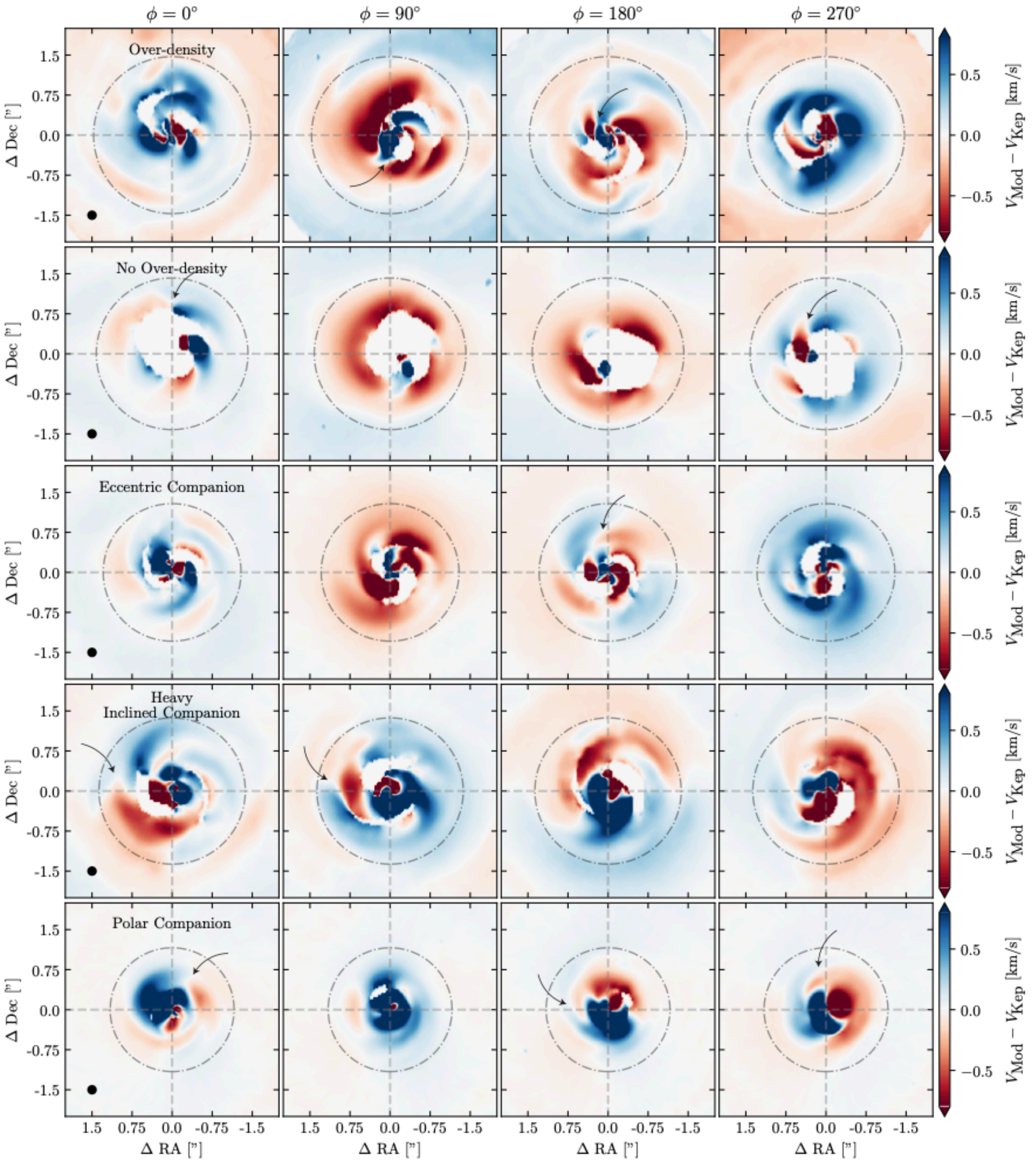
- Asyemmtry diagnostics (Calcino et al. 2021)

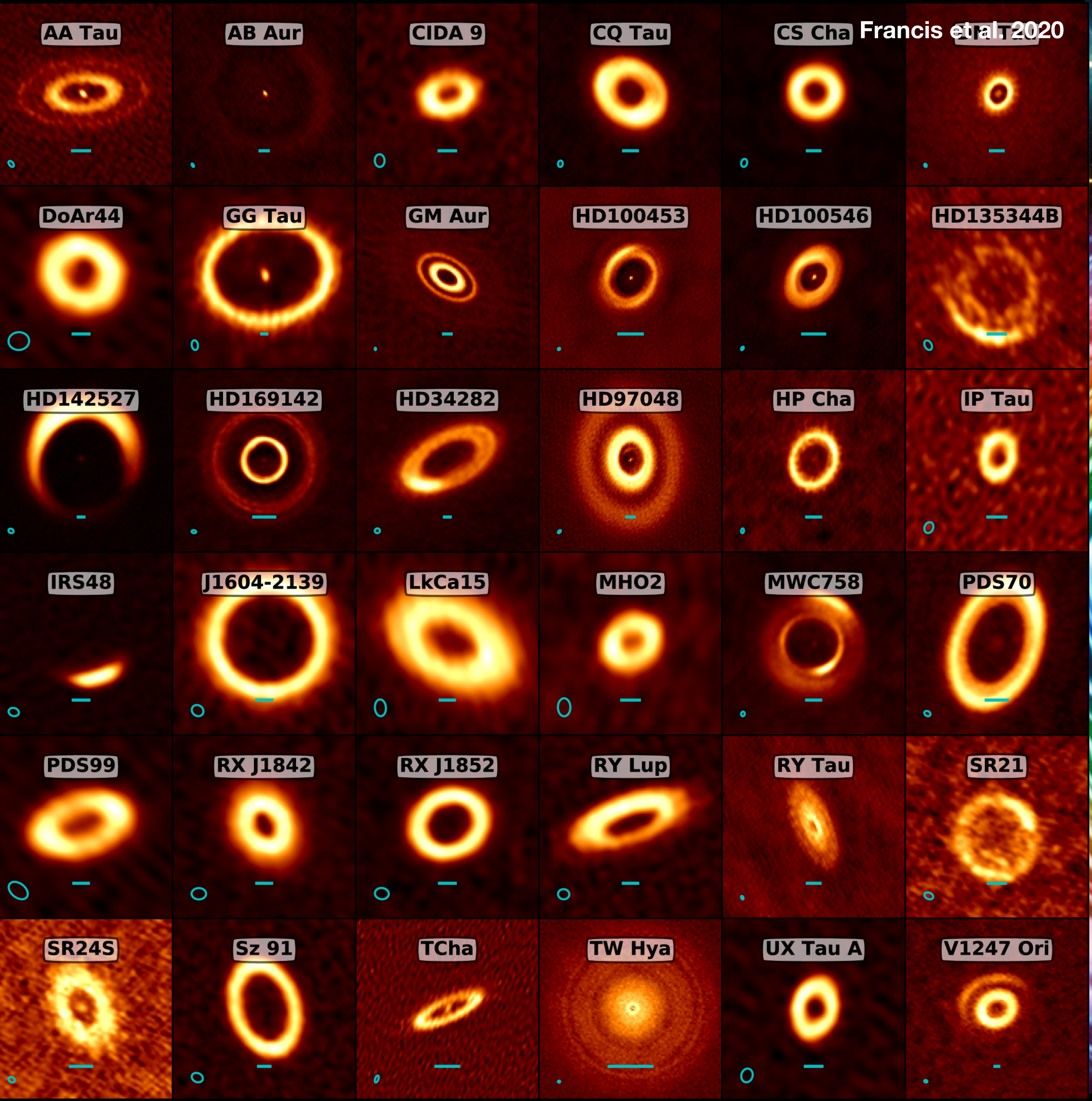
- Cool, but not informative. We should start attempting some quantitative modelling

Calcino et al. 2023



Residuals, Calcino et al. 2024



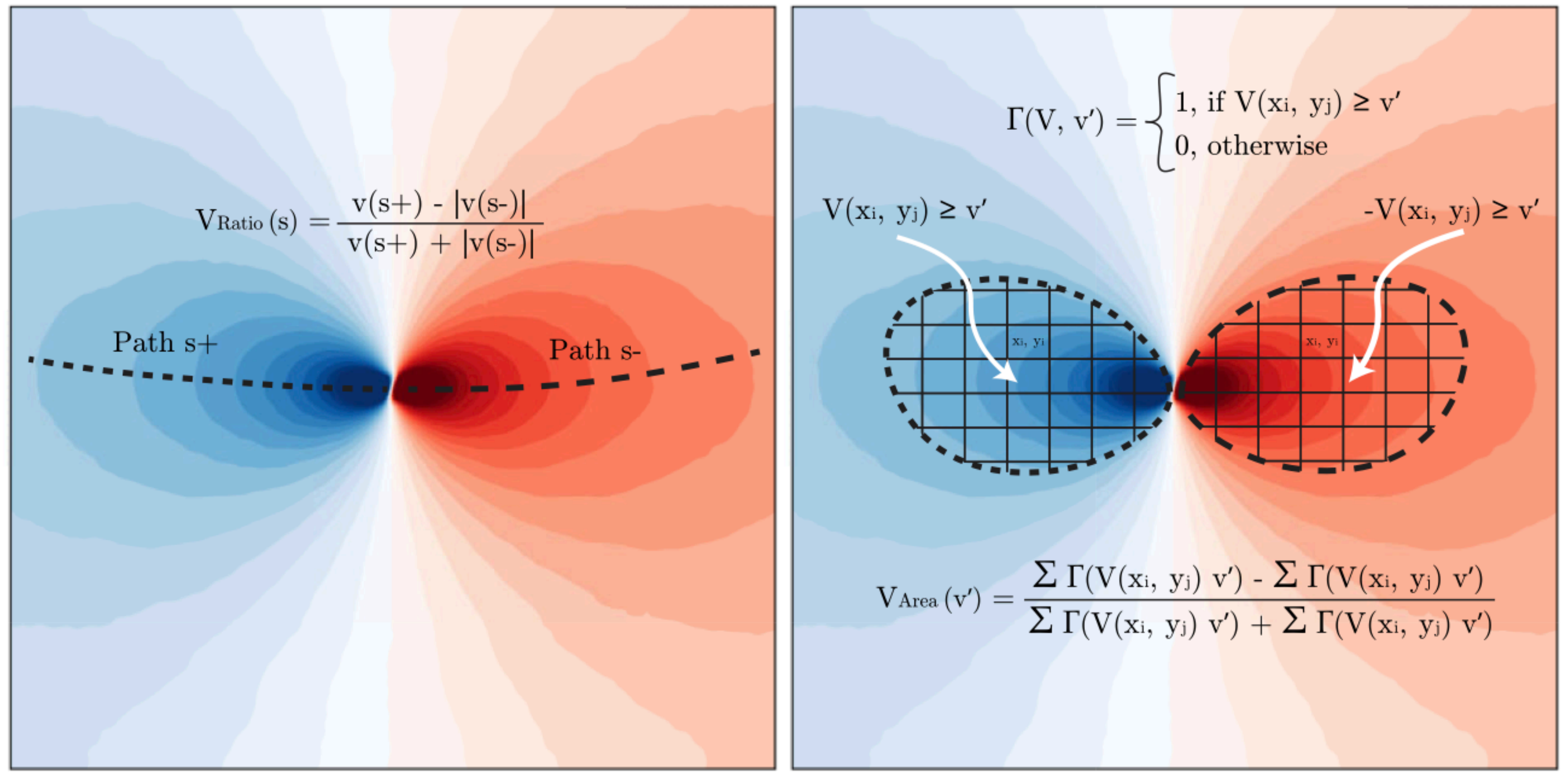


Francis et al. 2020

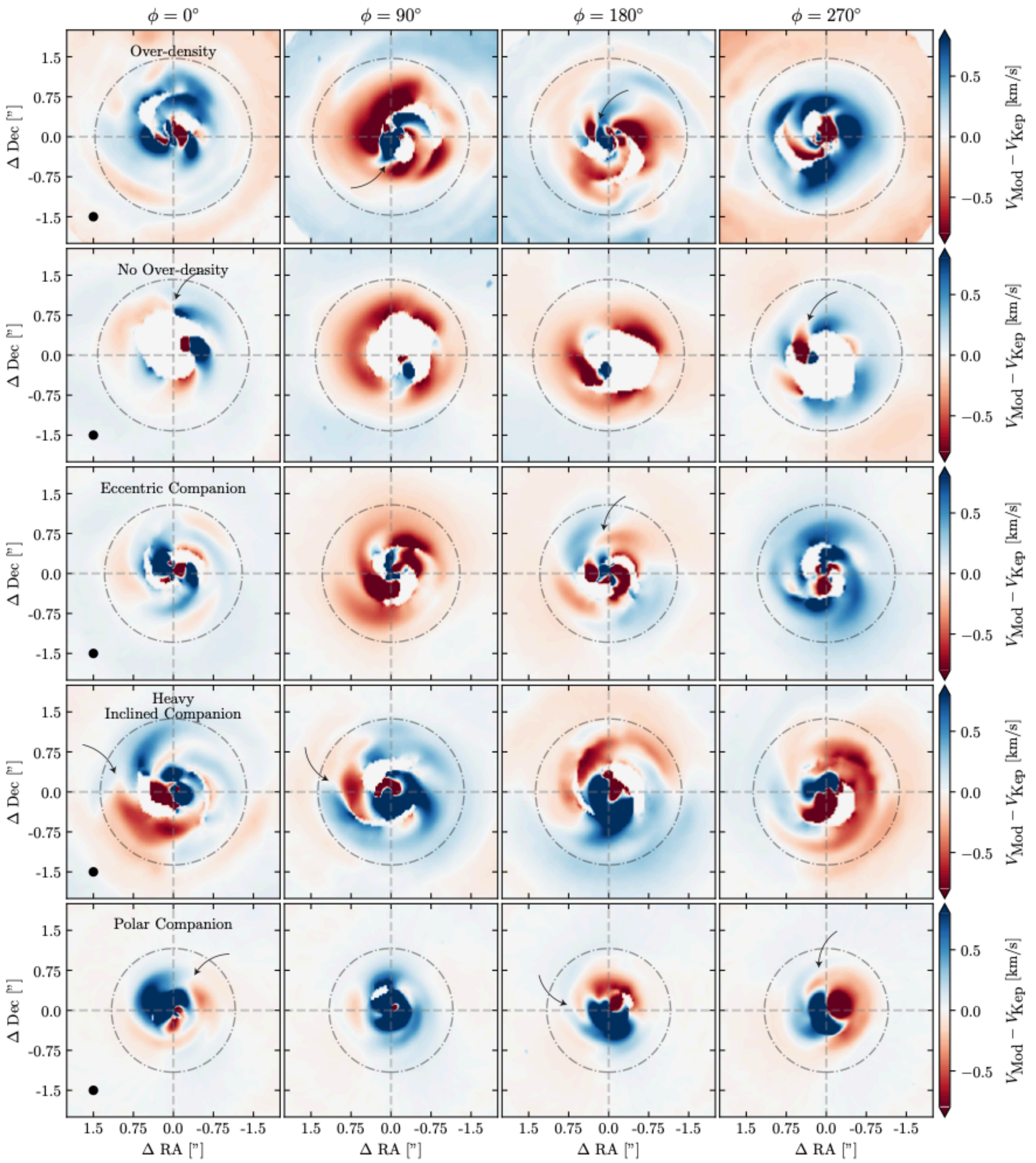
Kinematics of discs surrounding stellar bir

- Binary systems have very strong residuals when circular coplanar motion is subtracted
- Doppler-flips, spiral arms, eccentric gas motion, fast flows inside of the cavity, and
- Cool, but not informative. We should start attempting some quantitative modelling

Calcino et al. 2023

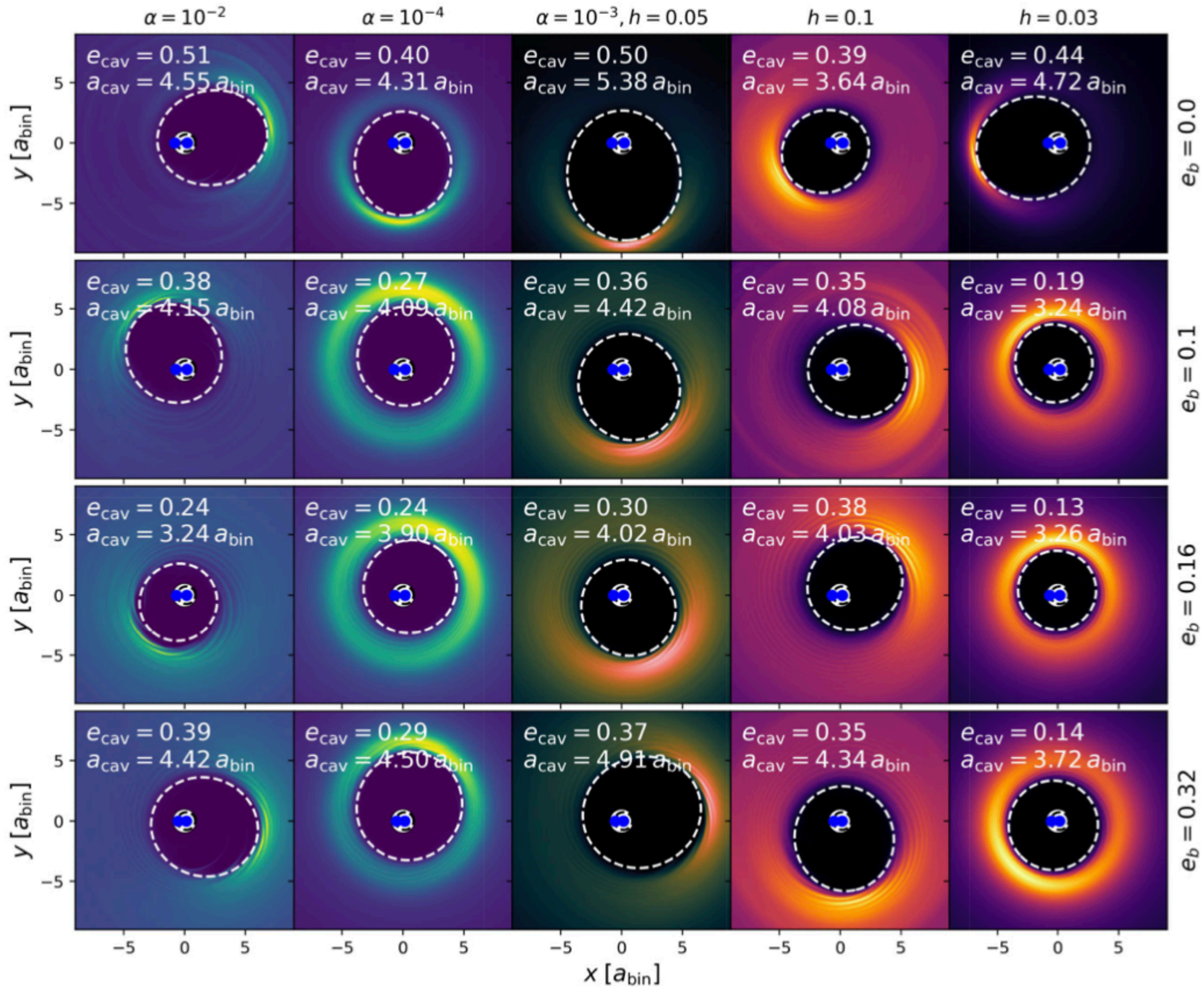


Residuals, Calcino et al. 2024



THE smoking gun signature(s) of binaries…

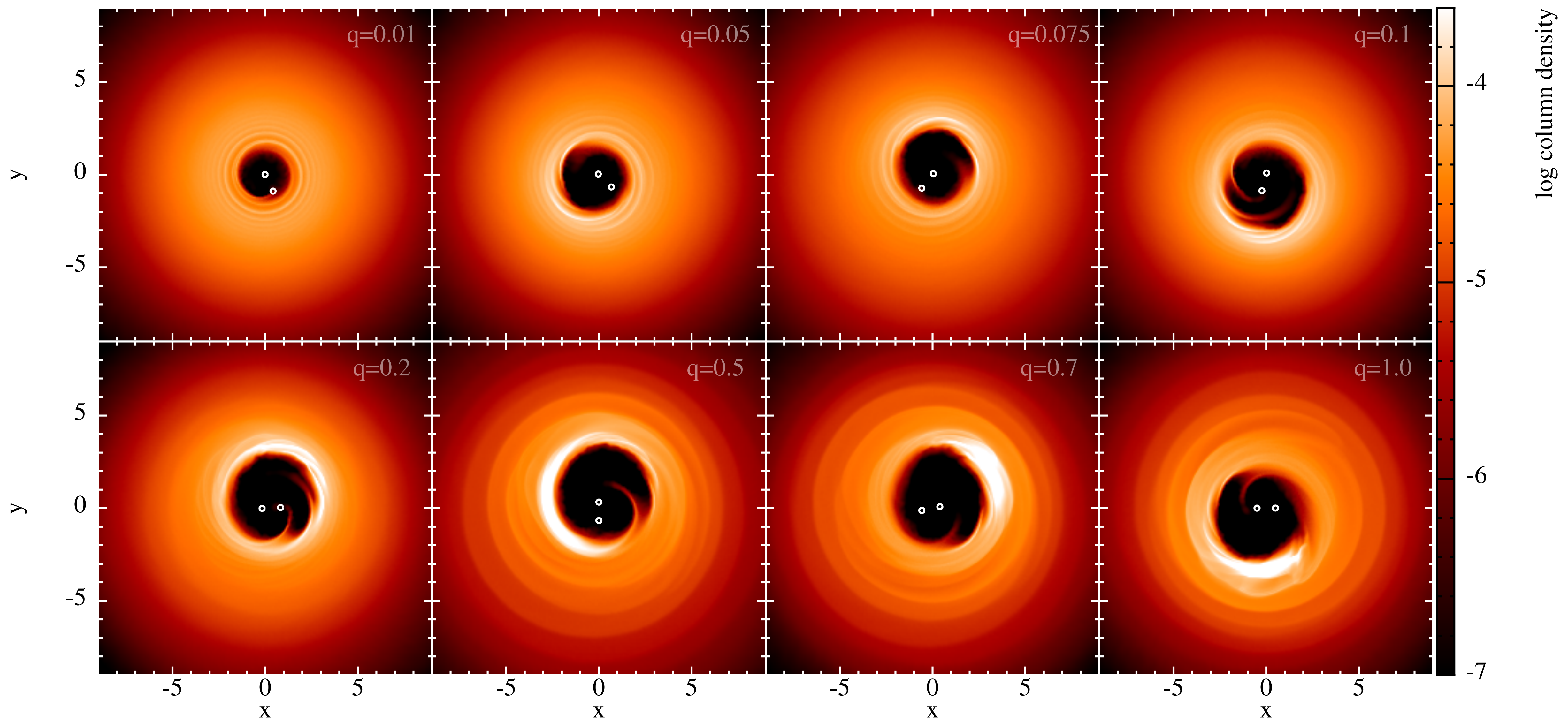
Penzlin et al. 2024



- For planets disc unperturbed state is circular/coplanar! BUT not for binaries

- Around stellar binaries,
    - discs eccentricity grows (e.g., Munoz et al. 2017, Ragusa et al. 2020, Toci et al. 2024, Penzlin et al. 2024)

Ragusa et al. 2020

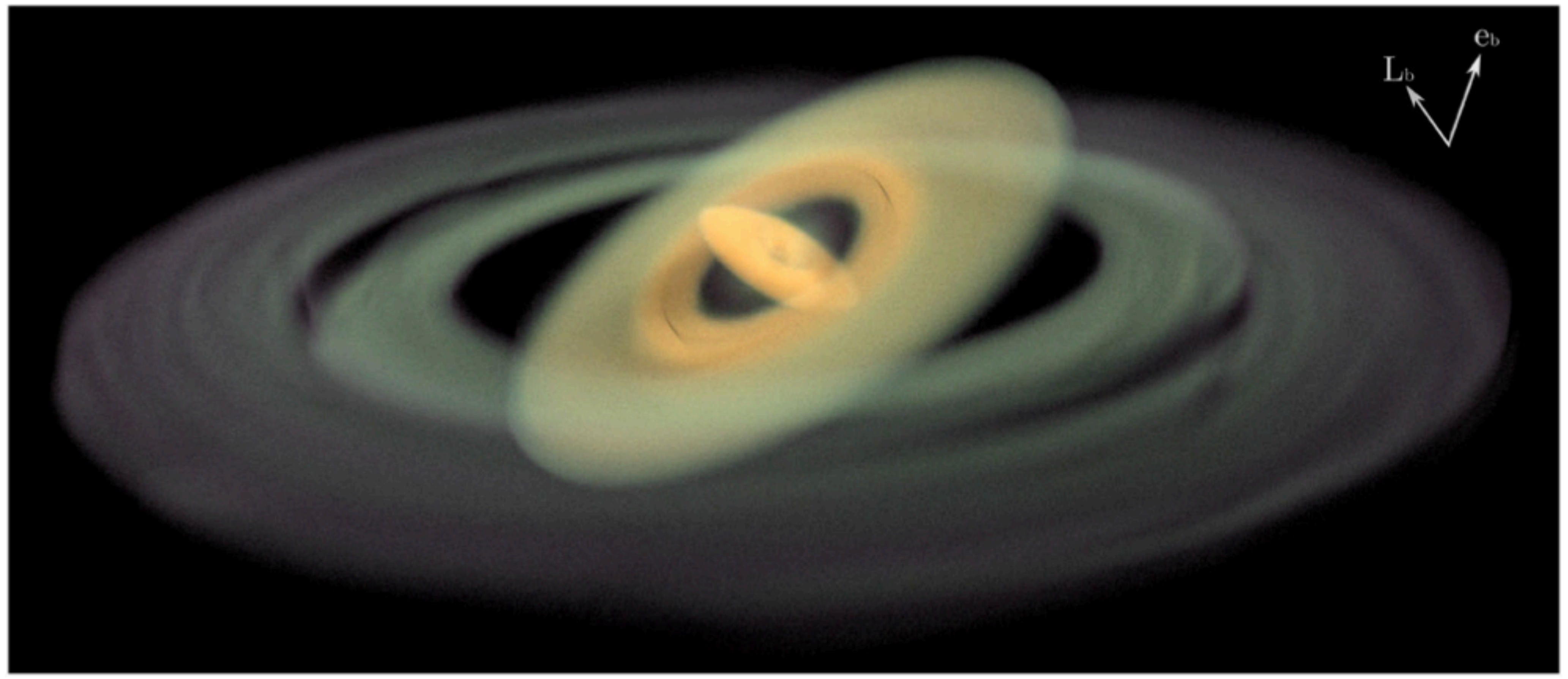


THE smoking gun signature(s) of binaries…

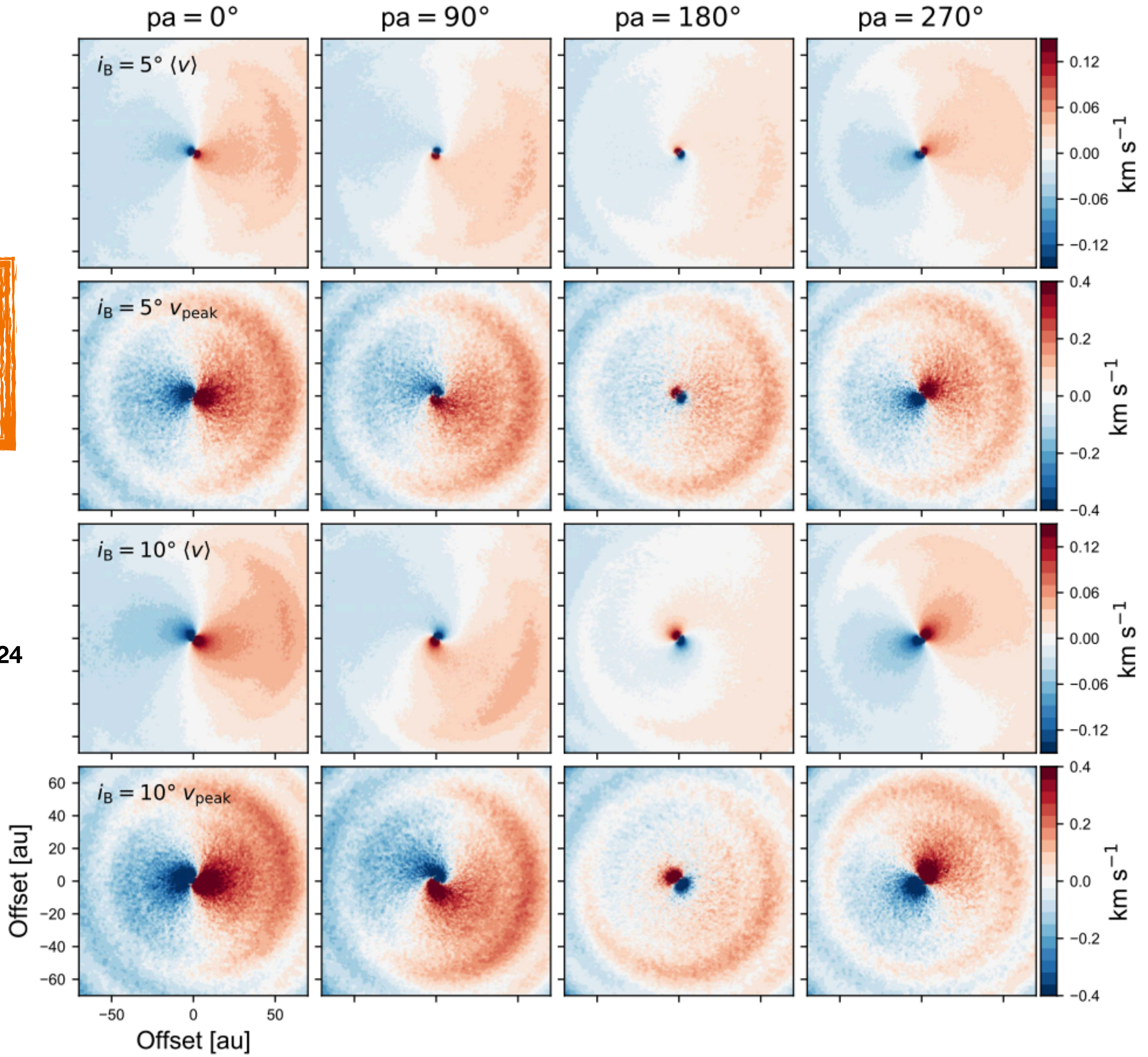
- For planets disc unperturbed state is circular/coplanar! BUT not for binaries

- Around stellar binaries,
  - discs eccentricity grows (e.g., Munoz et al 2017, Ragusa et al. 2020, Toci et al. 2024, Penzlin et al. 2024)
  - Discs become warped (e.g. Nixon et al. 201 Facchini et al. 2018; Young et al. 2022, recently incorporated in EDDY Zuleta et al. 2024)

Rabago et al. 2024



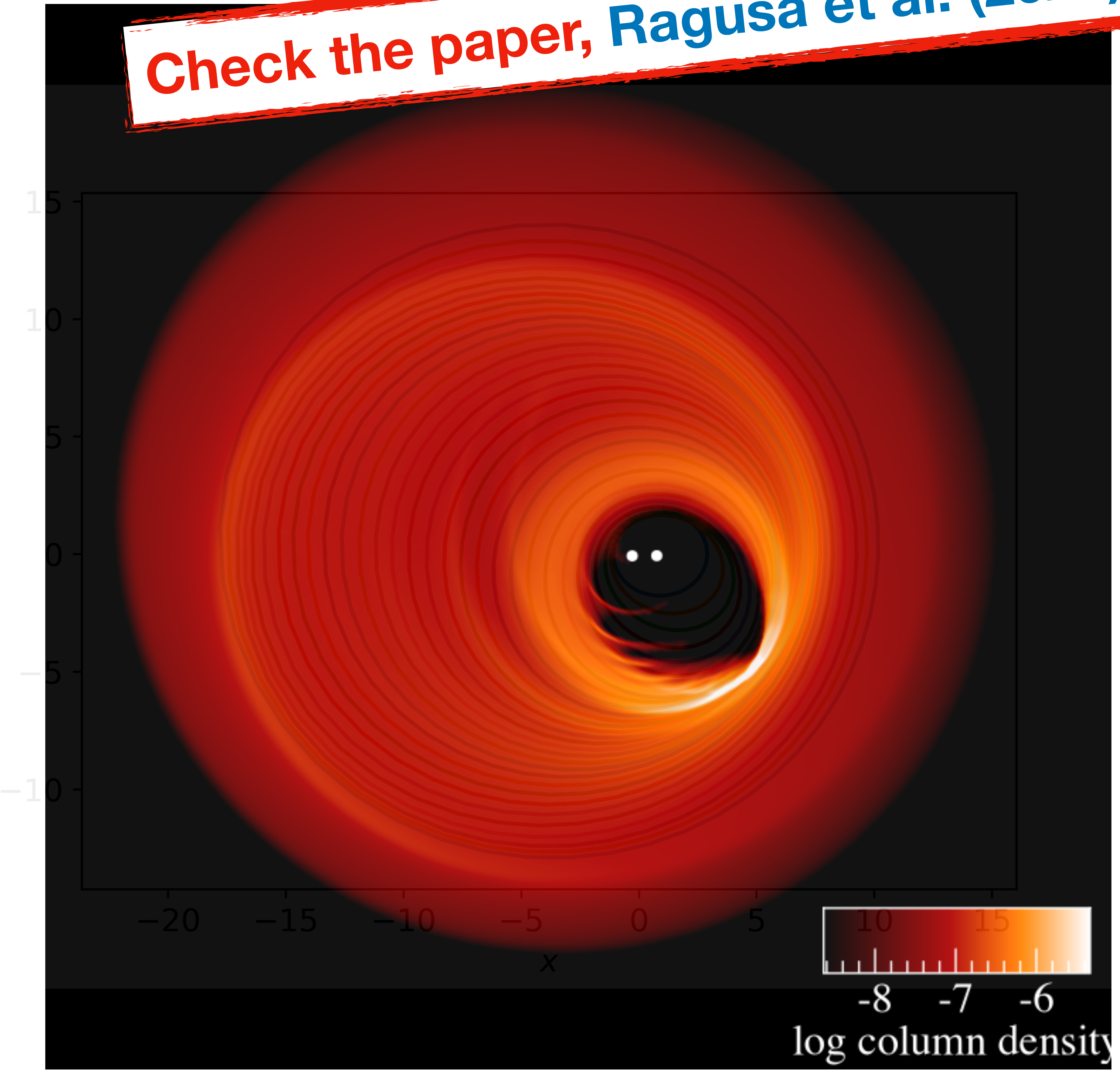
Young et al. 2022



What are eccentric discs?

- We generally assume accretion discs are circular…
- If the material has eccentric orbits you have an eccentric accretion disc

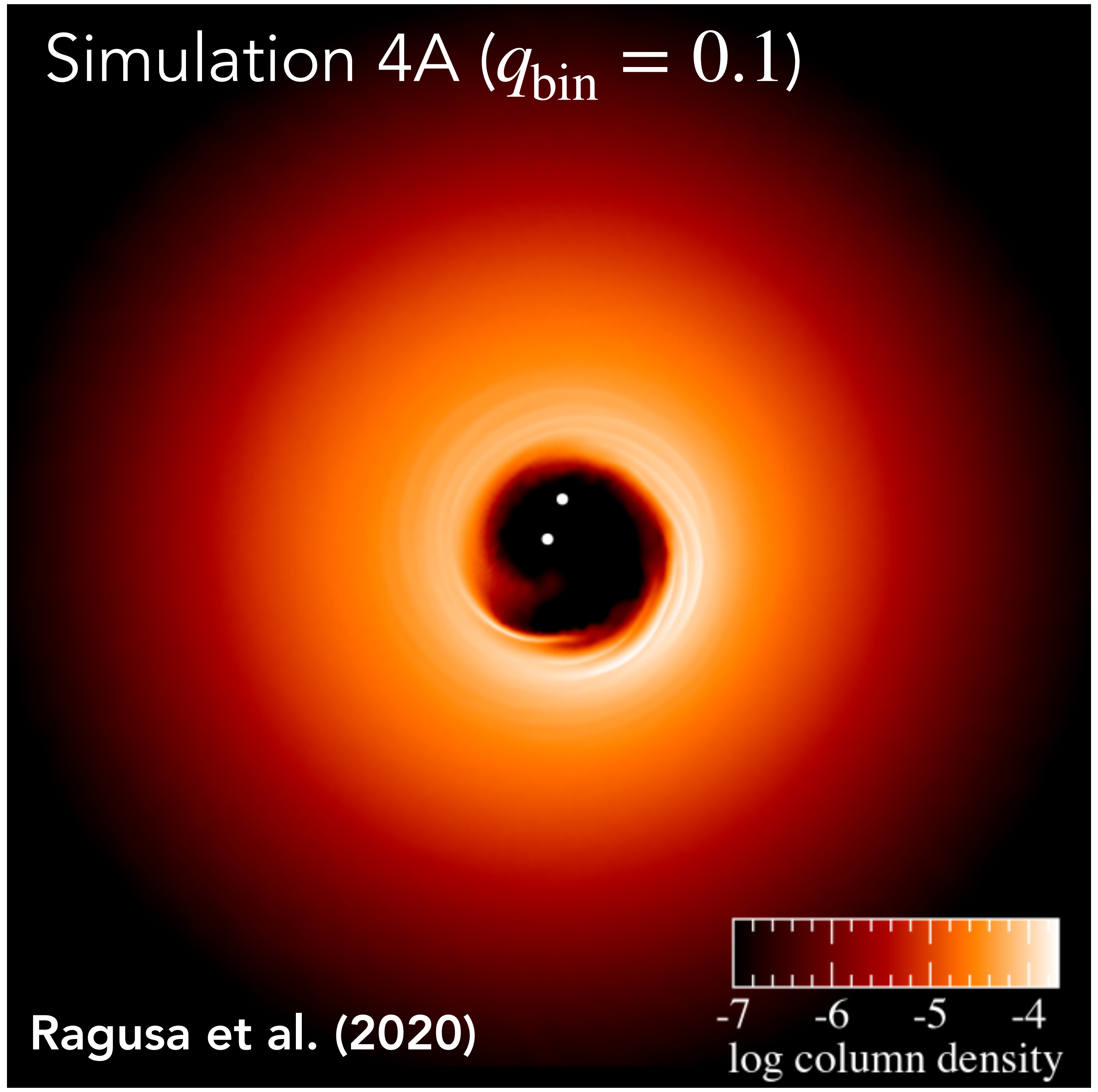
Check the paper, Ragusa et al. (2024)

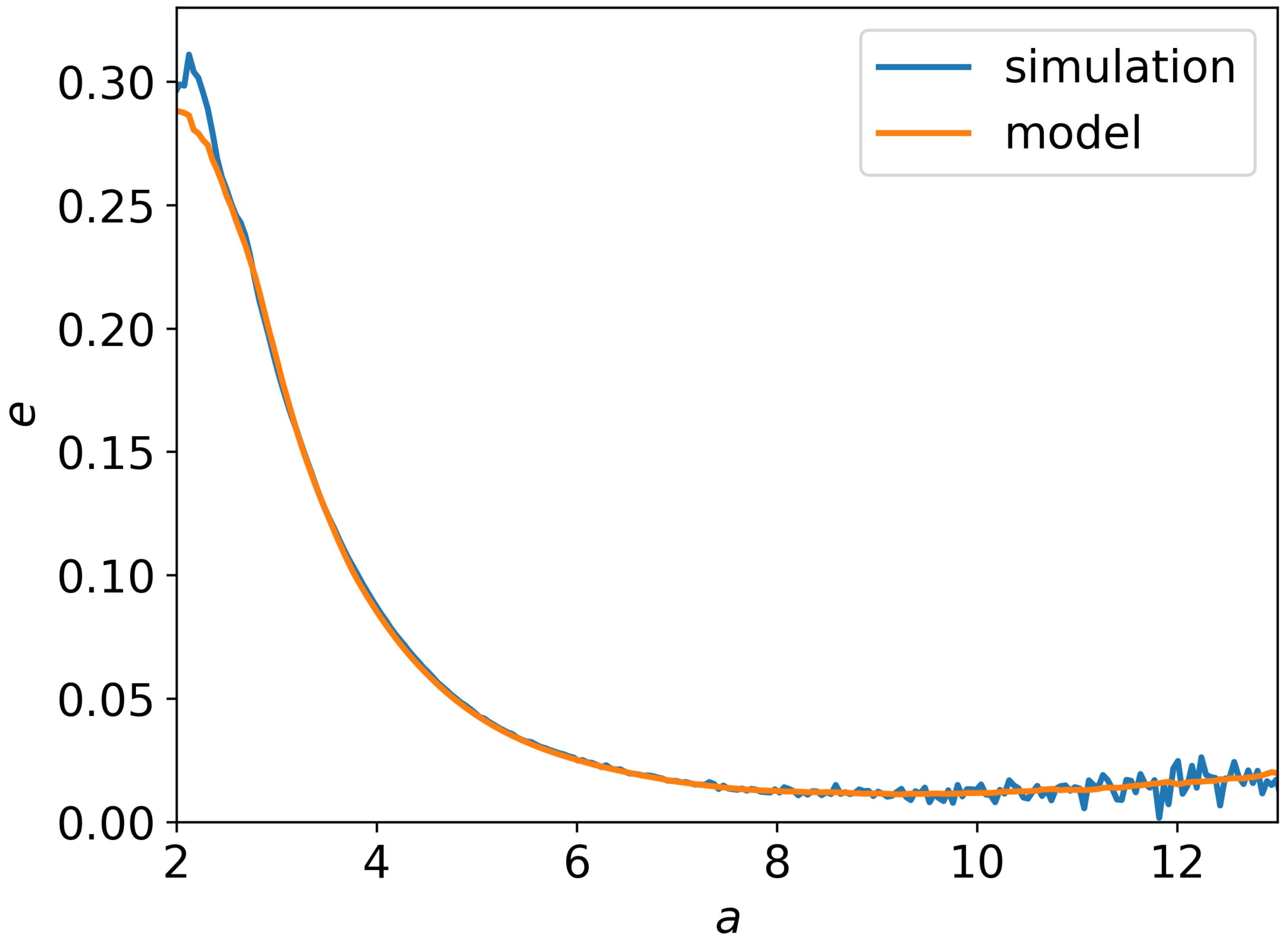


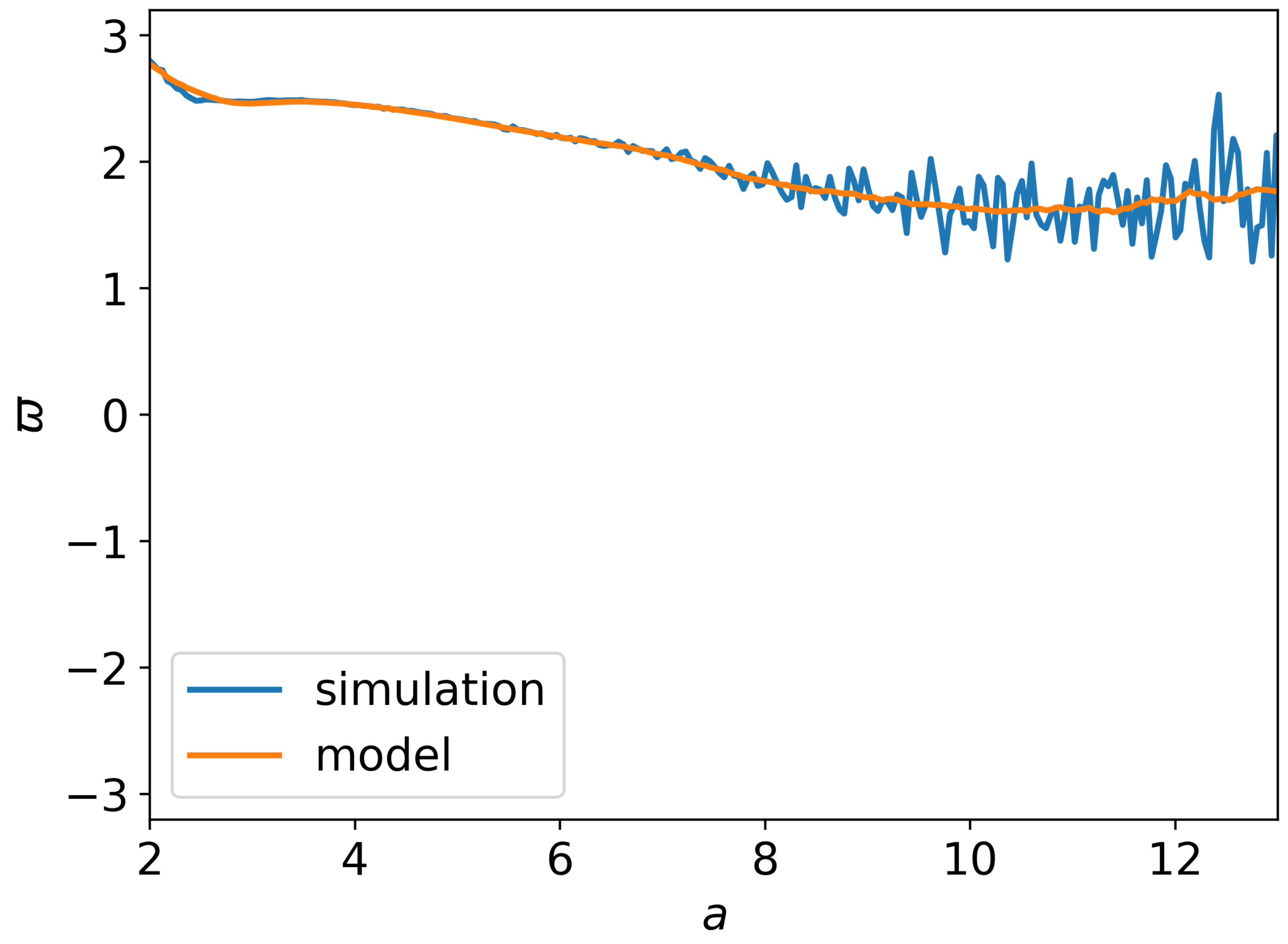
Analytical model

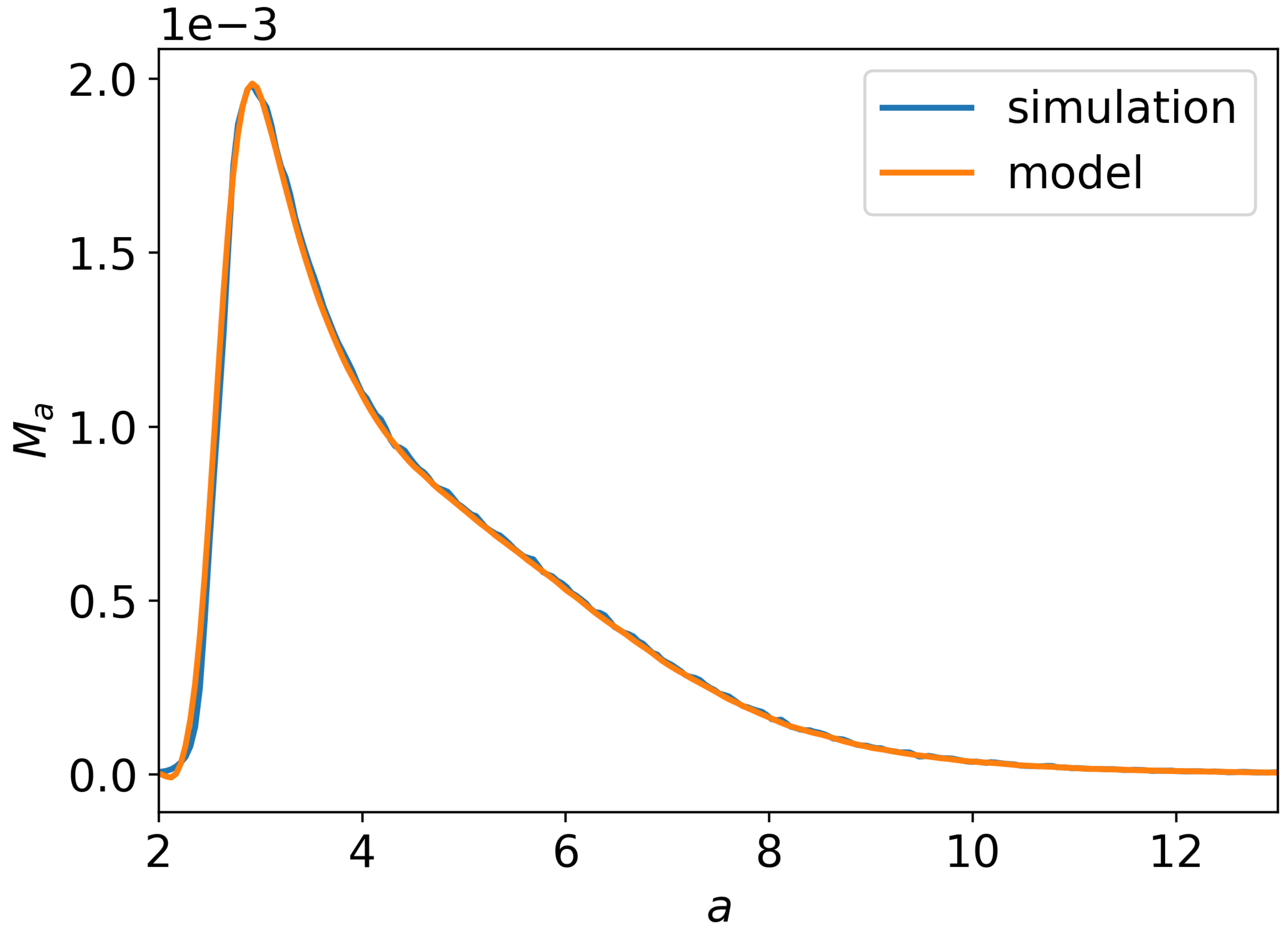
- Set of multiple Keplerian nested ellipses
  - For fixed semi-major axis:
    - $e(a)$
    - $\varpi(a)$
- Pressure prescription, e.g.:

$$P(a) \propto M_a(a)$$









Analytical description

- **Orbital motion:** Keplerian+ simplified pressure correction

$$v_R(a,\phi) = \dot{R} = a\Omega_0 \frac{e(a)}{\sqrt{1-e^2(a)}} \sin[\phi - \varpi(a)],$$

$$v_{\theta,\mathrm{K}}(a,\phi) = R\dot{\theta} = a\Omega_0 \frac{1 + e(a)\cos[\phi - \varpi(a)]}{\sqrt{1-e^2(a)}}$$

$$v_\theta = v_{\theta,\mathrm{K}}\sqrt{1+\eta},$$

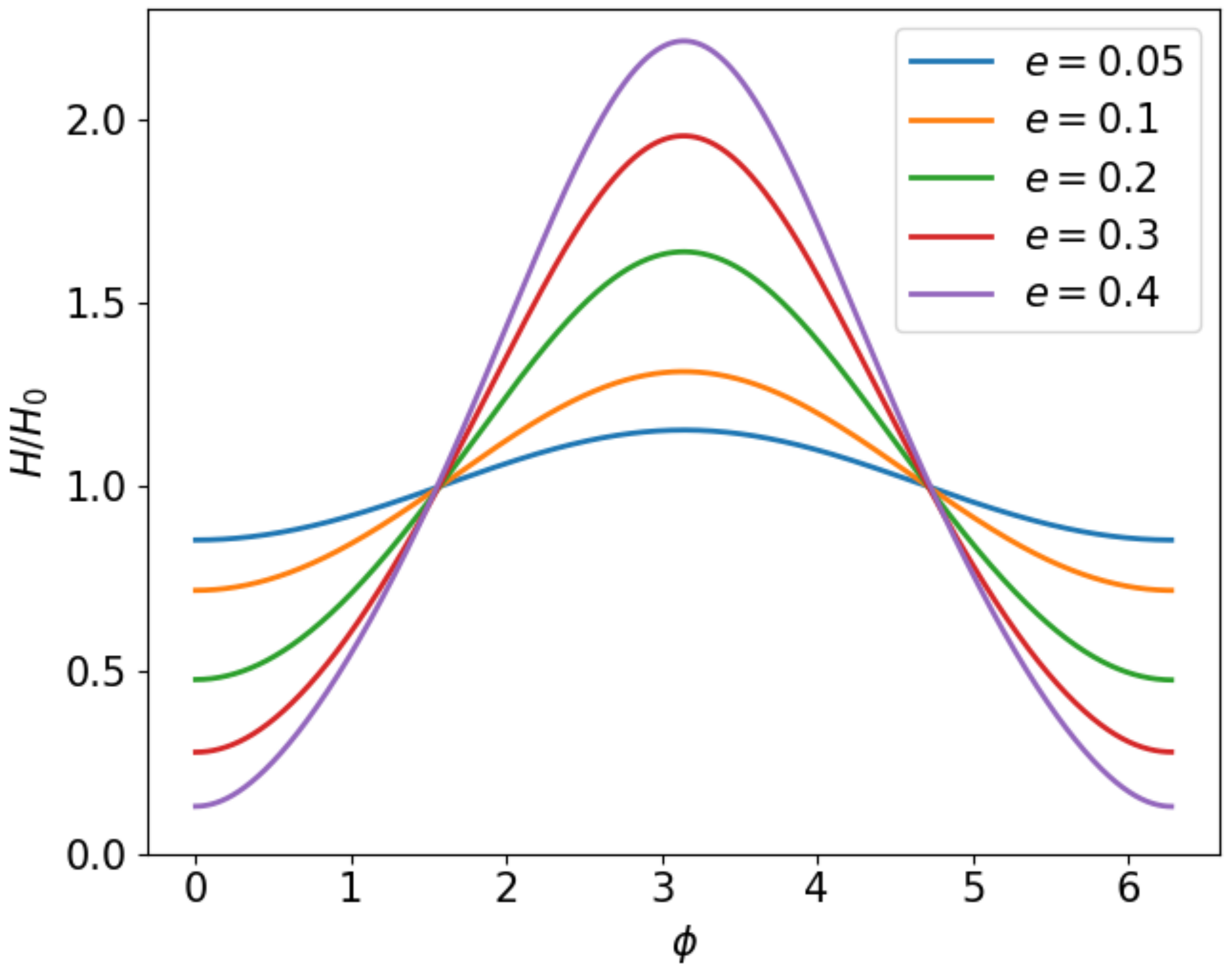
$$\eta = (\Omega_0 a)^{-2}\left(\frac{a}{\Sigma_0}\frac{\mathrm{dP}}{\mathrm{da}}\right)$$

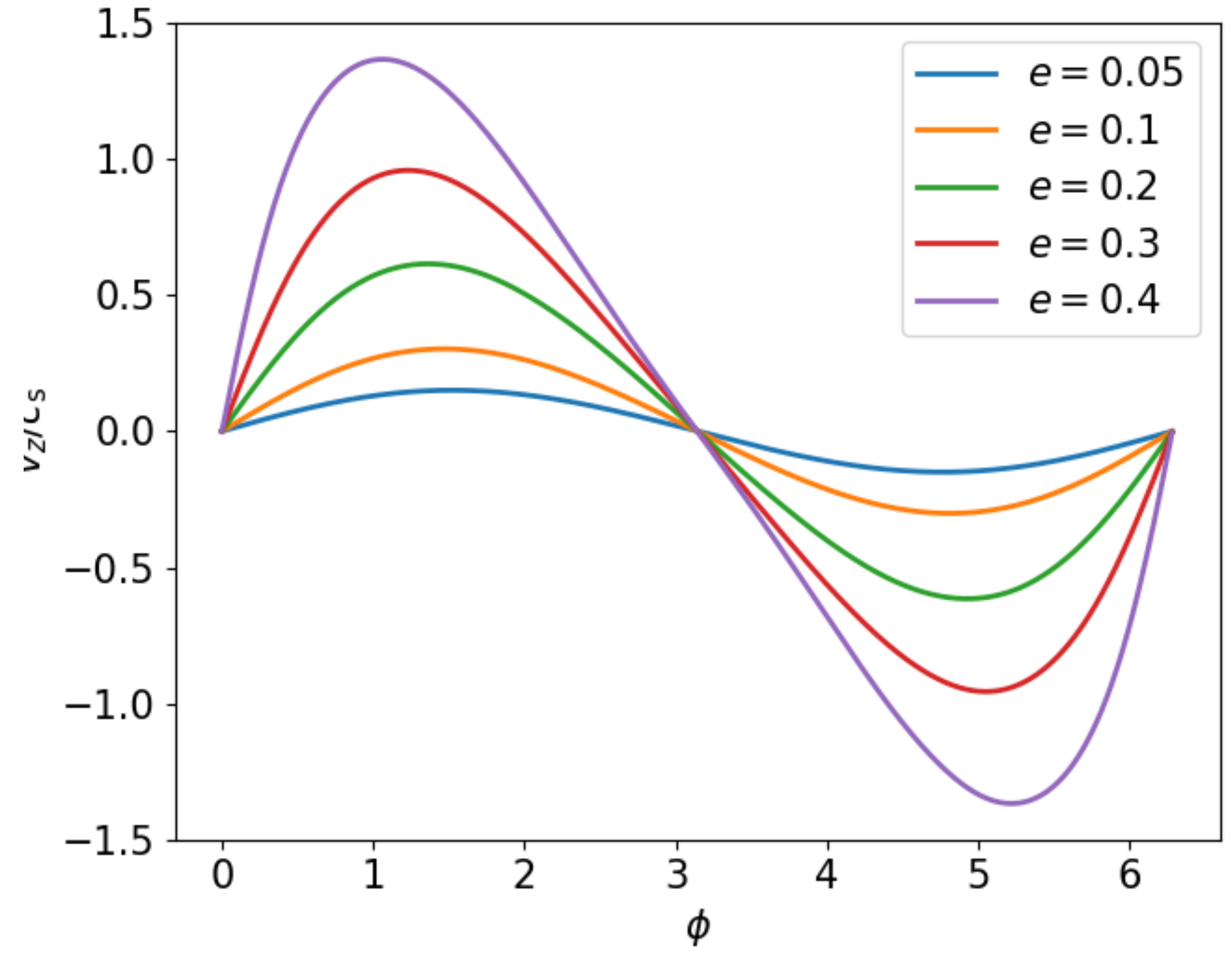
$$P = \langle c_\mathrm{s}\rangle^2 \Sigma_0, \qquad \Sigma_0 = \frac{M_a}{2\pi a}$$

- **Vertical motion:** Driven by change of the vertical gravitational pull along the orbit (e.g. Ogilvie & Barker 2014)

$$\Omega^2 \frac{\partial^2 H}{\partial \phi^2} = -\Omega \frac{\partial H}{\partial \phi}\frac{\partial \Omega}{\partial \phi} - \frac{GM}{R^3}H + \frac{c_\mathrm{s}^2}{H}.$$

$$v^z = \Omega \frac{\partial H}{\partial \phi}\frac{z}{H}. \qquad \Omega(a,\phi) = \frac{v_{\theta,\mathrm{K}}}{R} = \dot{\theta}$$





- **Morphology:** Orbit compression along the orbit + conservation of flux

$$\Sigma(a,\phi) = \Sigma_0(a)\frac{a\Omega_0(a)}{J(a,\phi)\Omega(a,\phi)}$$

- **Jacobian:** sets the geometry

$$J(a,\phi) = R(a,\phi)^3 \frac{1 - e(a)[e(a) + 2ae_a(a)]}{a^2[1-e(a)^2]^2} \cdot \{1 - q\cos[\phi - \varpi(a) - \alpha]\},$$

$$q\cos(\alpha) = \frac{[1+e(a)^2]ae_a(a) - [1-e(a)^2]e(a}{1 - e(a)[e(a) + 2ae_a(a)]}$$

$$q\sin(\alpha) = \frac{e(a)[1-e(a)^2]a\varpi_a(a)}{1 - e(a)[e(a) + 2ae_a(a)]}.$$

Aspect ratio

- Aspect ratio H/R, the model predicts well highs and lows of H along the orbit

Vertical velocity v_z

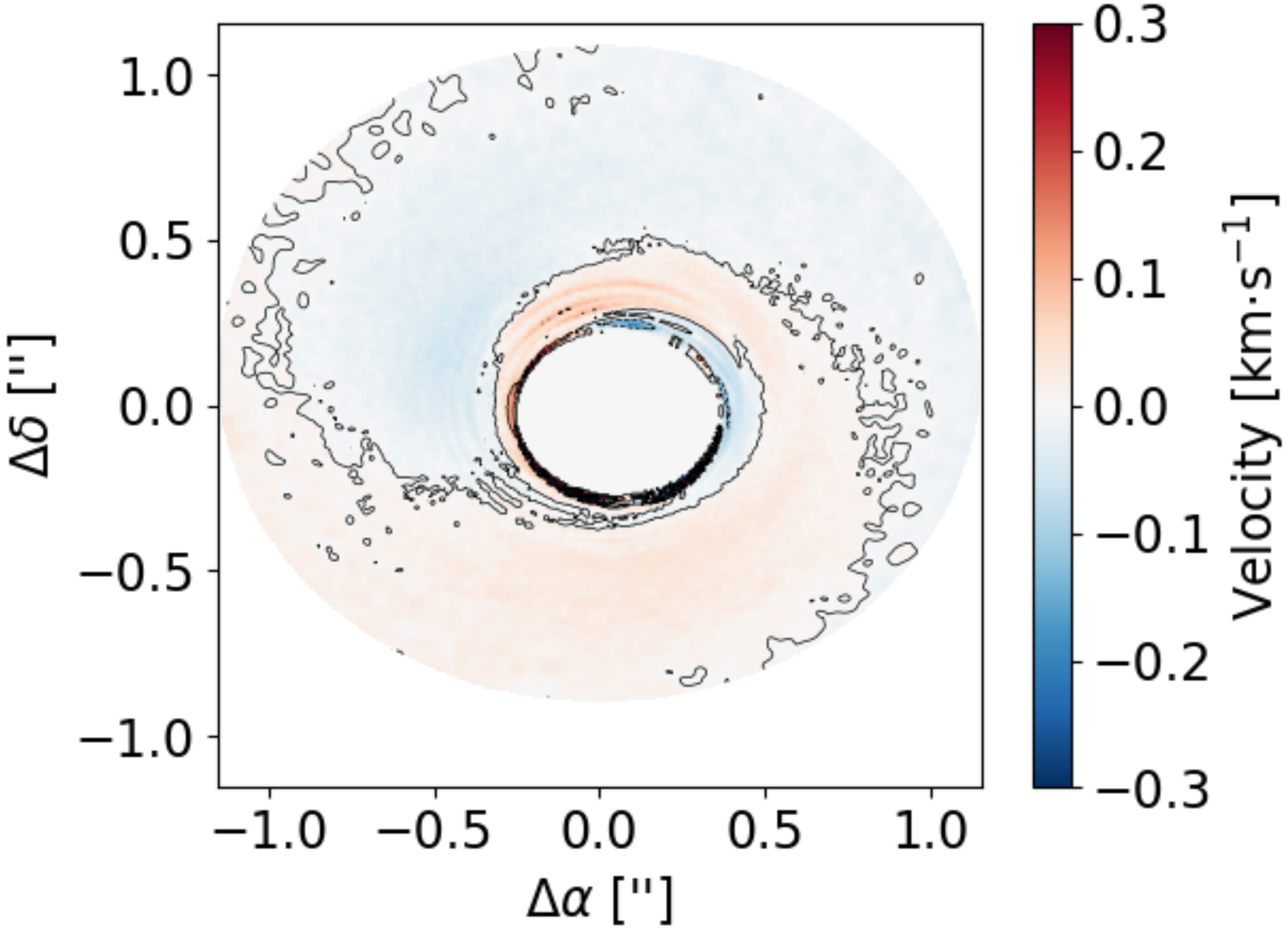
- Residuals of v_z show a spiral pattern not captured by the model likely due to the presence of the binary. Note that the circular case $v_z = 0$ performs much worse.
- Rescale the system: $a_{\mathrm{bin}} = 15\,\mathrm{au},\ a_{\mathrm{cav}} \sim 40\,\mathrm{au}$, $d = 130\,\mathrm{pc}$

Observational perspectives

- Residuals of projected velocities (sim-eccentric/circular model), guide the eye to appearance of eccentric discs.
- Prominent residual spiral features due to vertical motion, triggered by binary (similar buoyancy spirals in Bae et al. 2021, but our is isothermal so no buoyancy!)

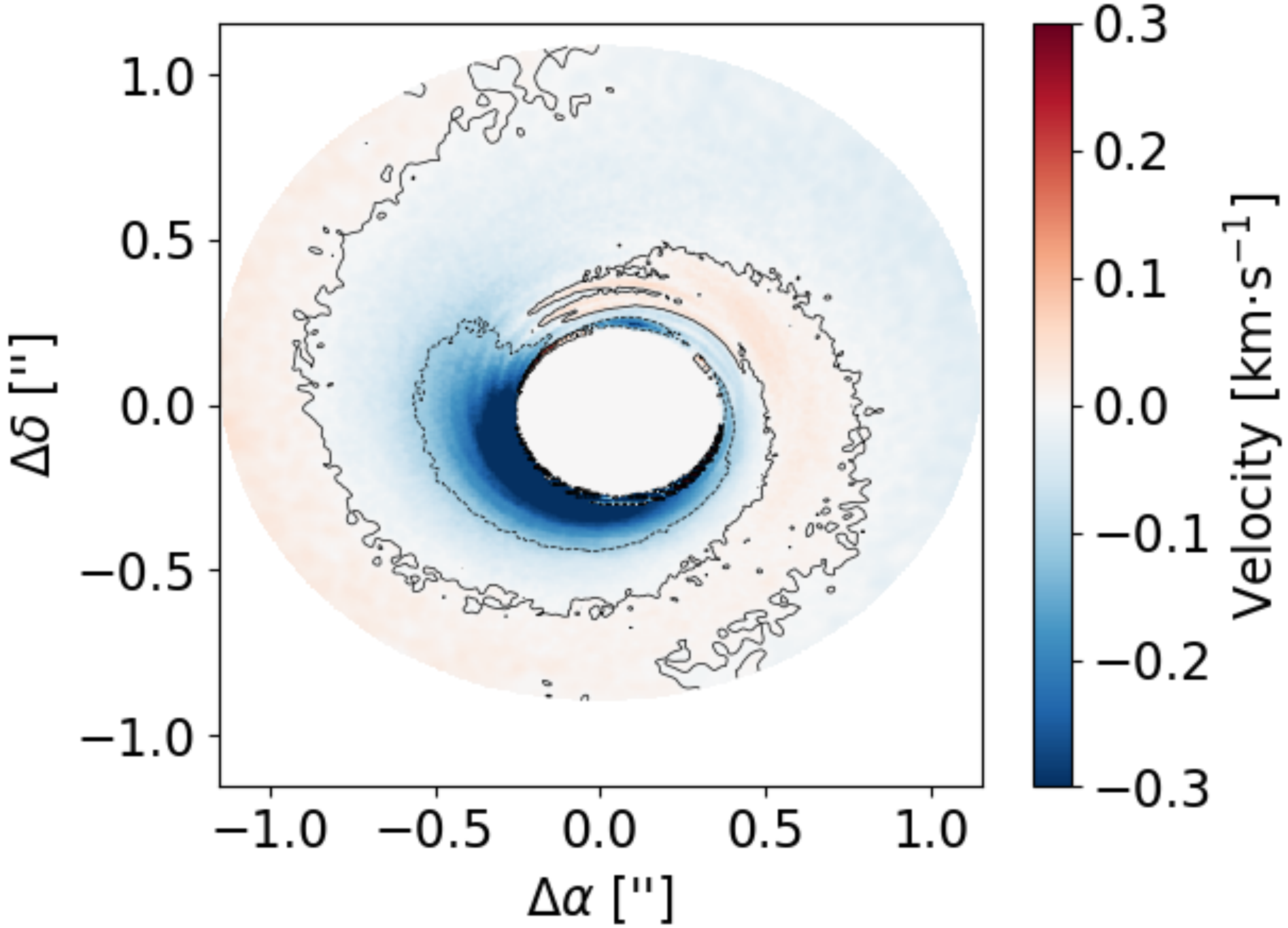
- Rescale the system: $a_{\rm bin} = 15\,{\rm au},\ a_{\rm cav} \sim 40\,{\rm au}$, $d = 130\,{\rm pc}$

Eccentric model



Circular model

Ragusa et al. (2024)



Take home messages

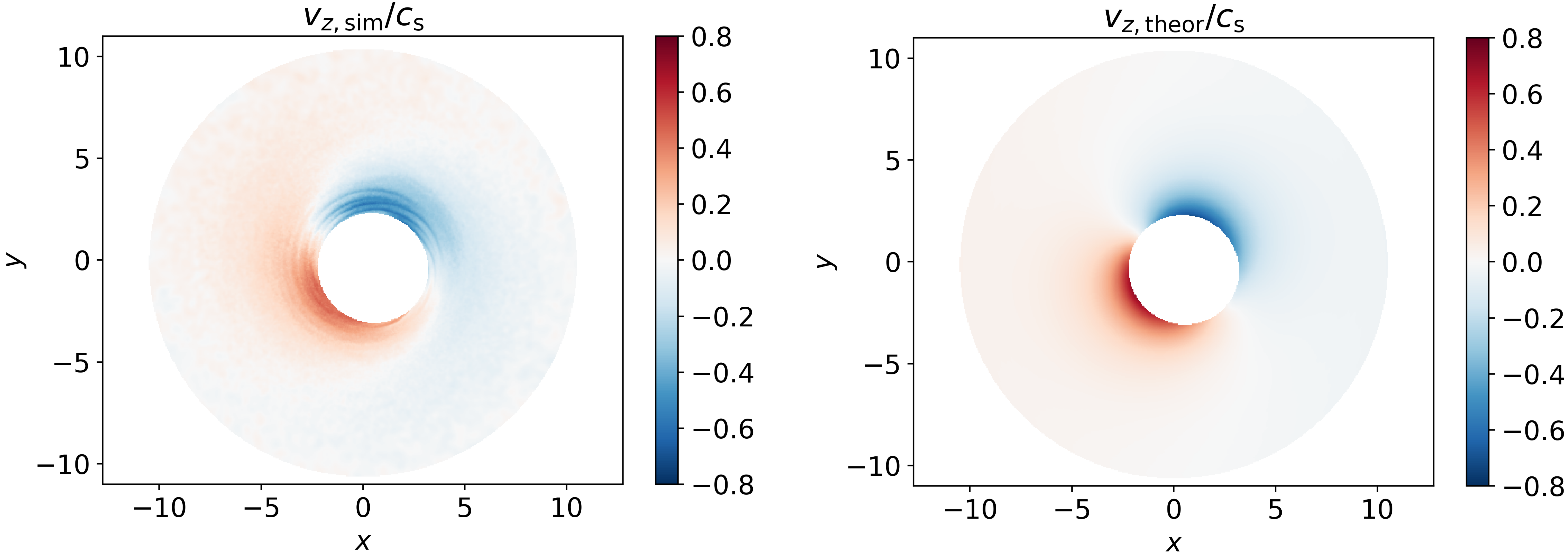
- Kinematics datasets are cubes where each pixel has a spectrum, informing us about gas properties at that location
- Circumbinary disc kinematics share the same theoretical framework used for planets but more “messy”
- Approach to modelling should abandon circular coplanar models and use eccentric warped models
- **Eccentric discs (inclined in the future)**
    - Detectable velocities even when face-on, besides difference between pericentre and apocentre
    - Vertical velocity spirals that remain to be explained
    - There is more to understand: not all CBD observed are eccentric, in contrast with numerics, what are we missing? (See Sec. 8.1 of Toci et al. 2024)

Check the paper, Ragusa et al. (2024)

Vertical velocity v_z

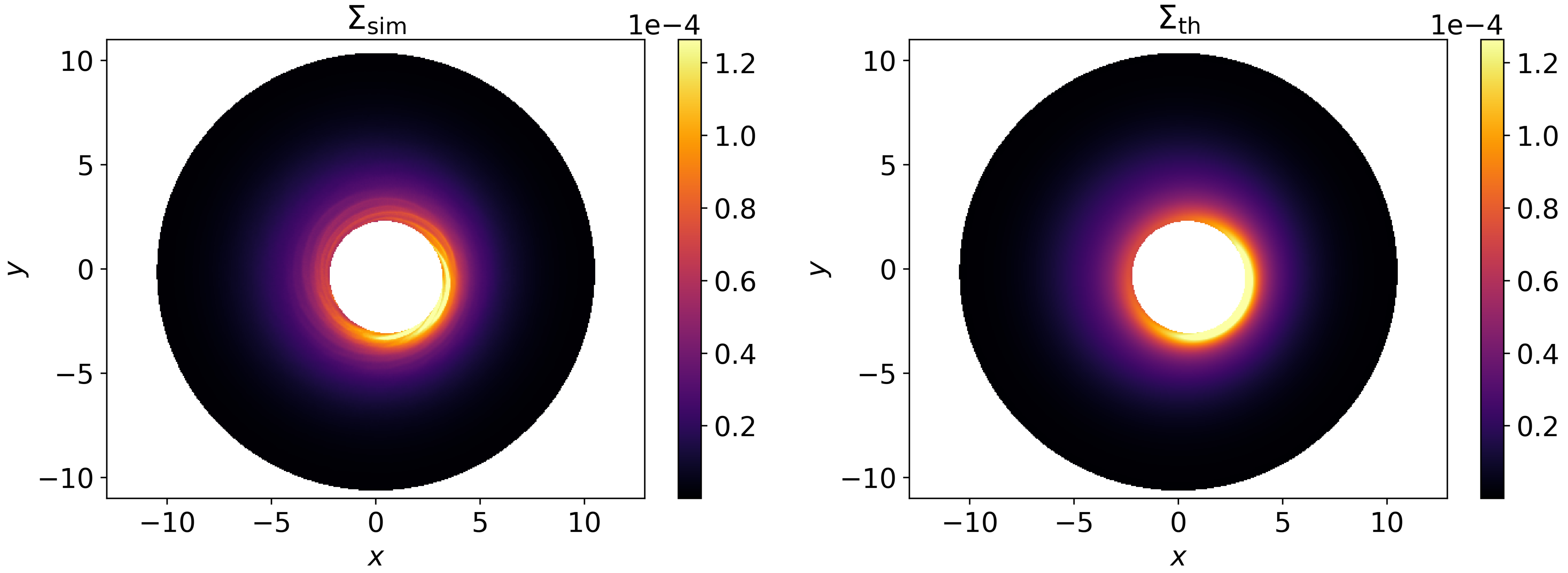
- Vertical velocity v_z, again not perfect, but it works well!

$$v^z = \Omega \frac{\partial H}{\partial \phi} \frac{z}{H}.$$



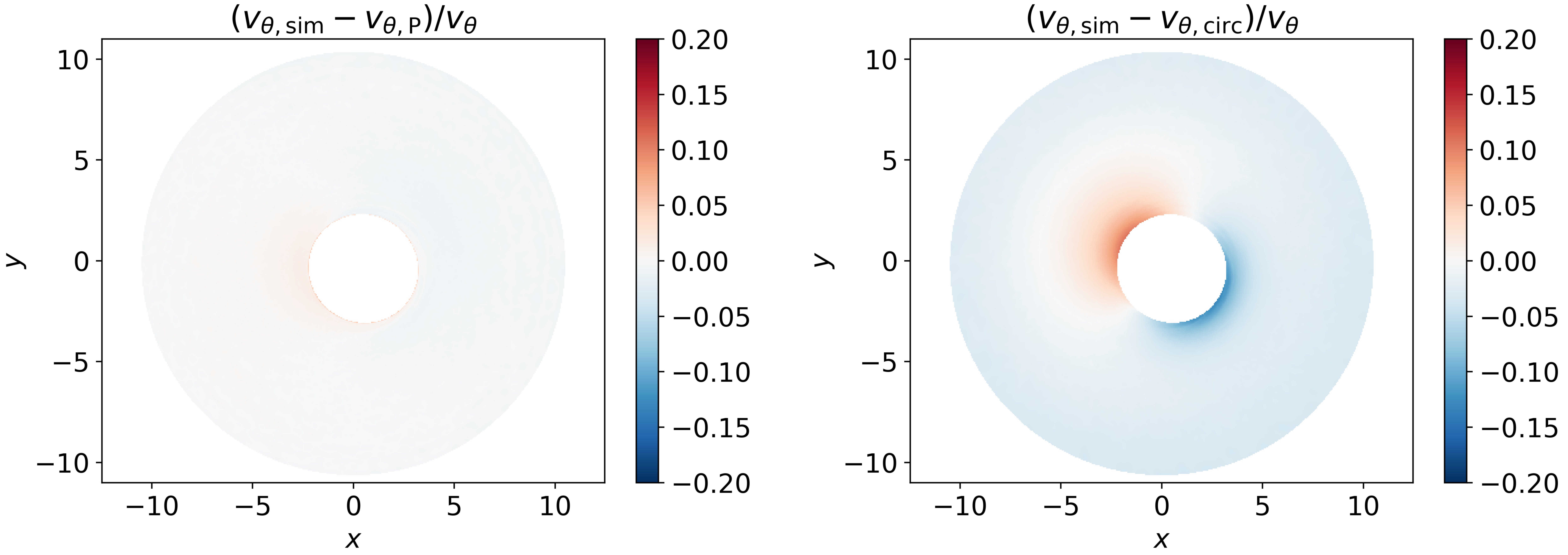
Morphology

- Morphology is based on both flux conservation along the orbit and stretching of the disc geometry due to eccentricity and pericentre phase gradients.



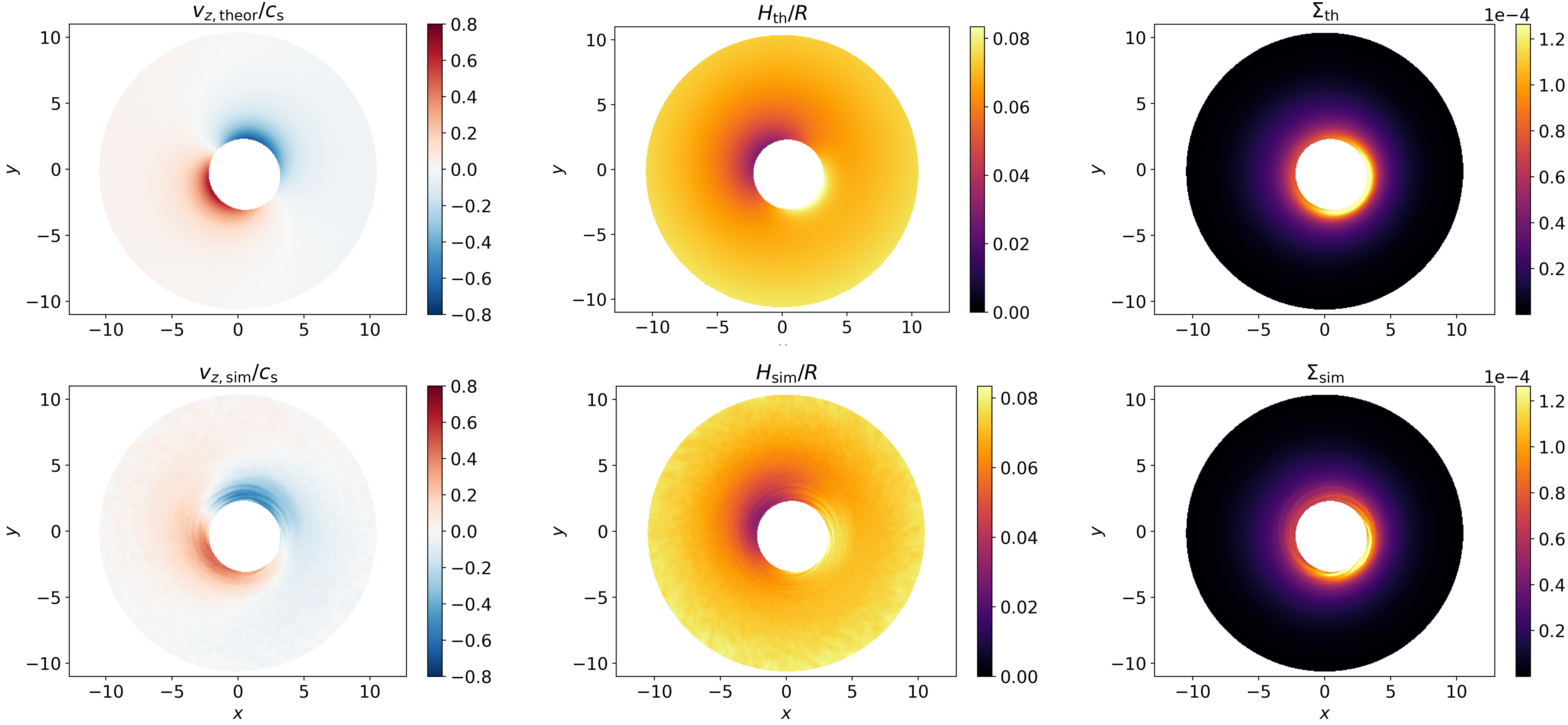
Velocity field v_θ

- Note how better than the circular case without pressure corrections



Eccentricity in protostellar discs as smoking gun for binaries/planets?

Ragusa et al. (2024)



Velocity field v_R

- Same applies to v_R