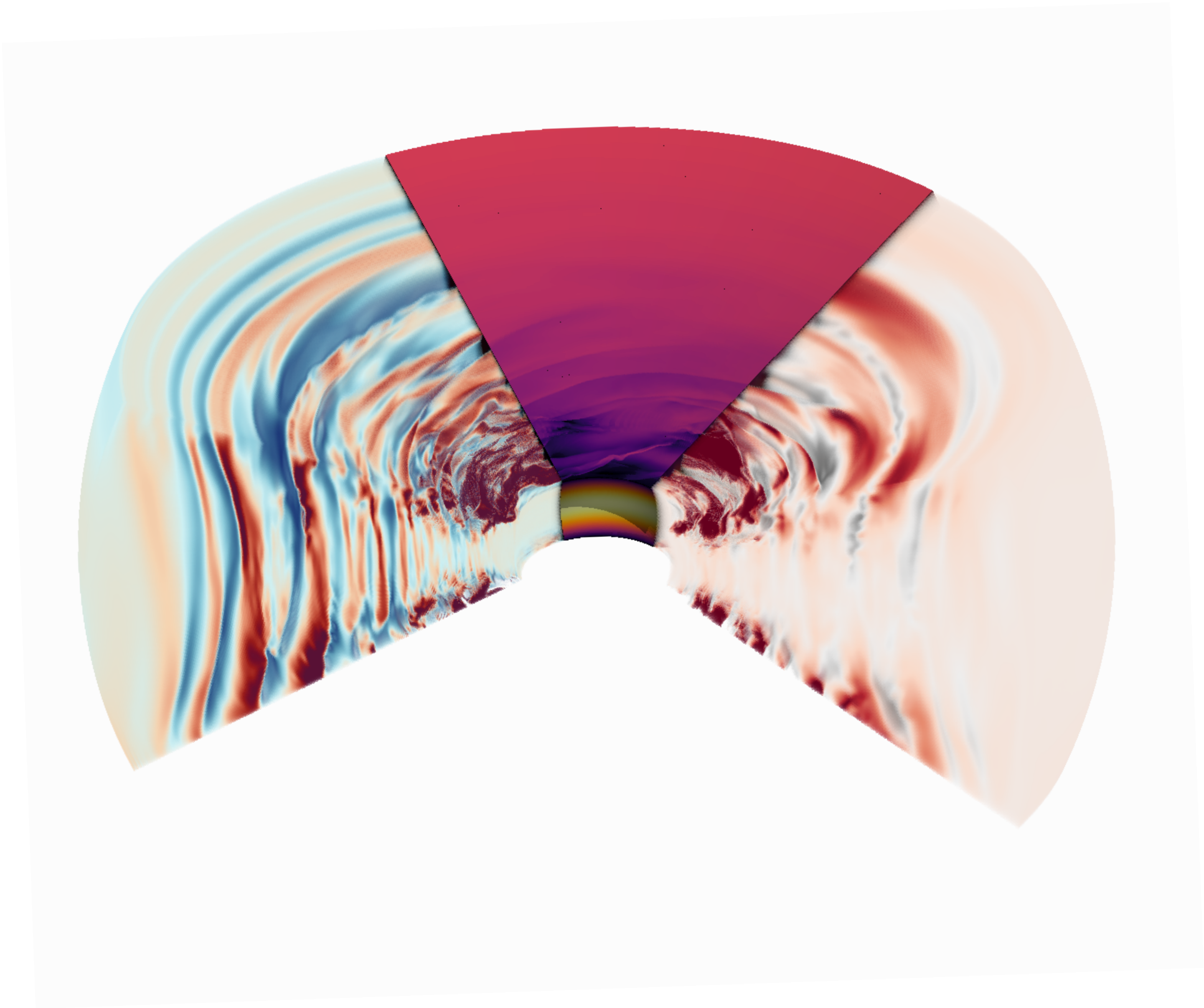
Observability of the vertical shear instability in protoplanetary disk CO kinematics



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collaborators: M. Flock, S. Marino (Cambridge) and S. Perez (USACH)

European Research Council

Established by the European Commission

Why do we care about turbulence in planet formation?

Turbulence

Disk accretion
Shakura & Sunyae1973

Dust evolution
Birnstiel+2010; Fromang+2006, Desch+2017; Flock+2018,2020; Lin+2019

Planetesimal formation
Youdin & Goodman 2005, Lenz+2019: Gole+2020; Klahr & Schreiber 2020; Schäfer+2020

Sub-structures
Pinilla+2015; Fu+2014; Barge & Sommeria 1995: Flock +2015. Manger+2018: Flock+2018,2020

Planet-disk interactions
Kley and Nelson 2012: Fung+2014: Bae+2018: Baruteau+2011; Xu+2017, Ormel & Liu 2018: Picogna+2018

Disk chemistry
Semenov & Wiebe 2011; Heinzeller + 2011

The vertical shear instability (VSI)

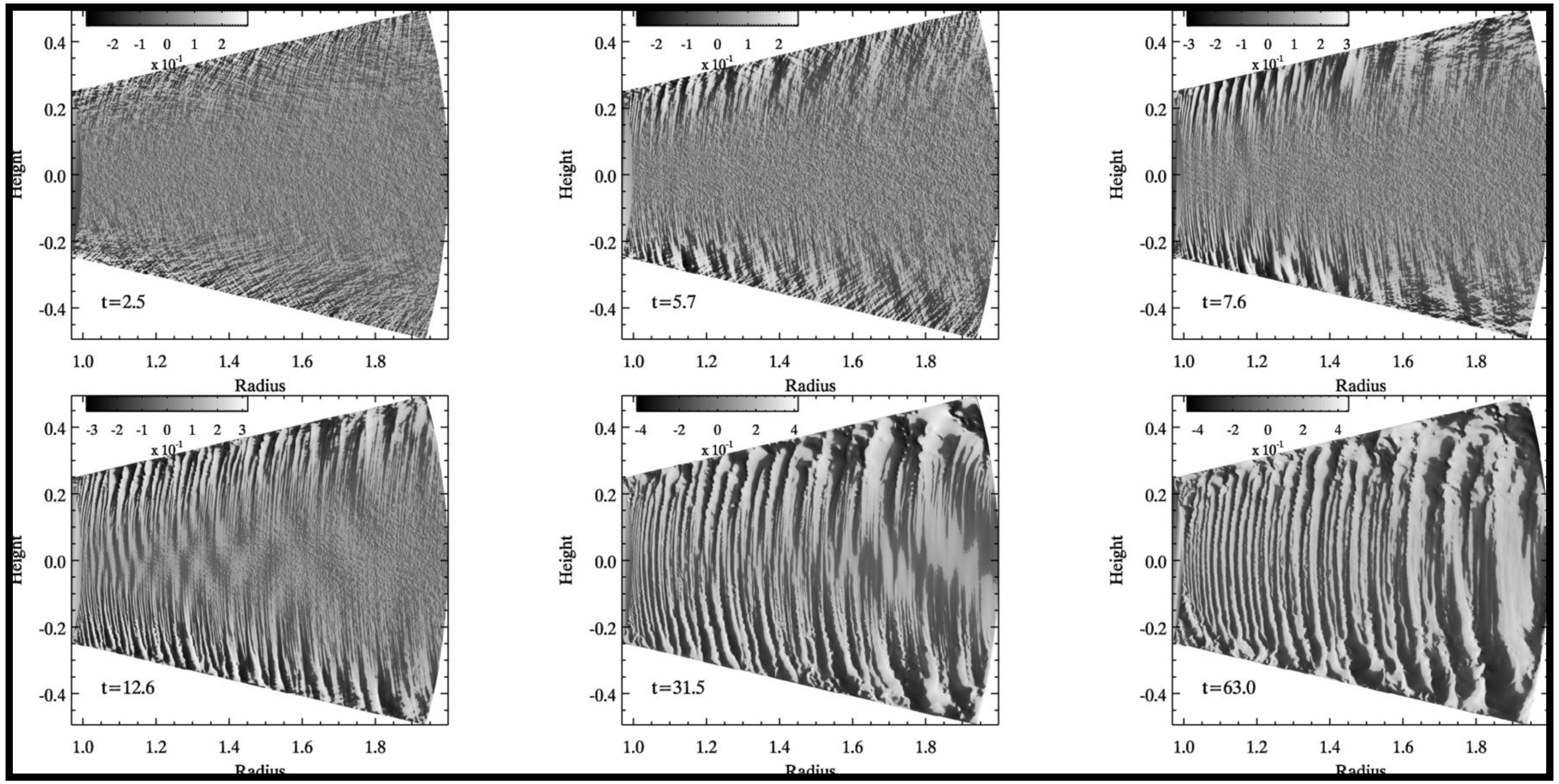
Requirements

- Vertical shear:

  Naturally arises from radial temperature and entropy gradients

- Fast cooling:

  Buoyancy forces *do not* stabilise the disk

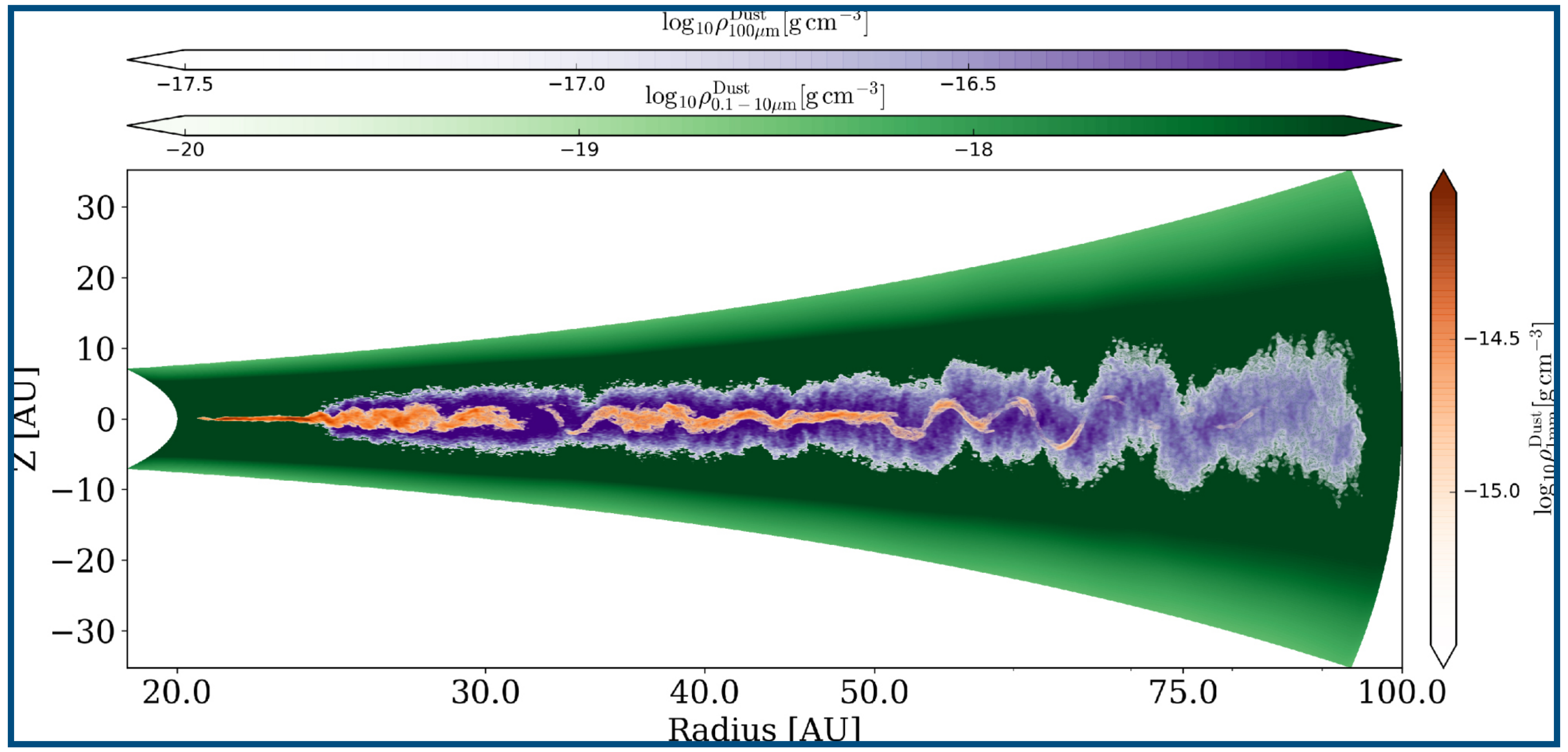


Nelson+2013; see also Baker & Latter 2015; Lin & Youdin 2015

Why do we care about VSI in planet formation?

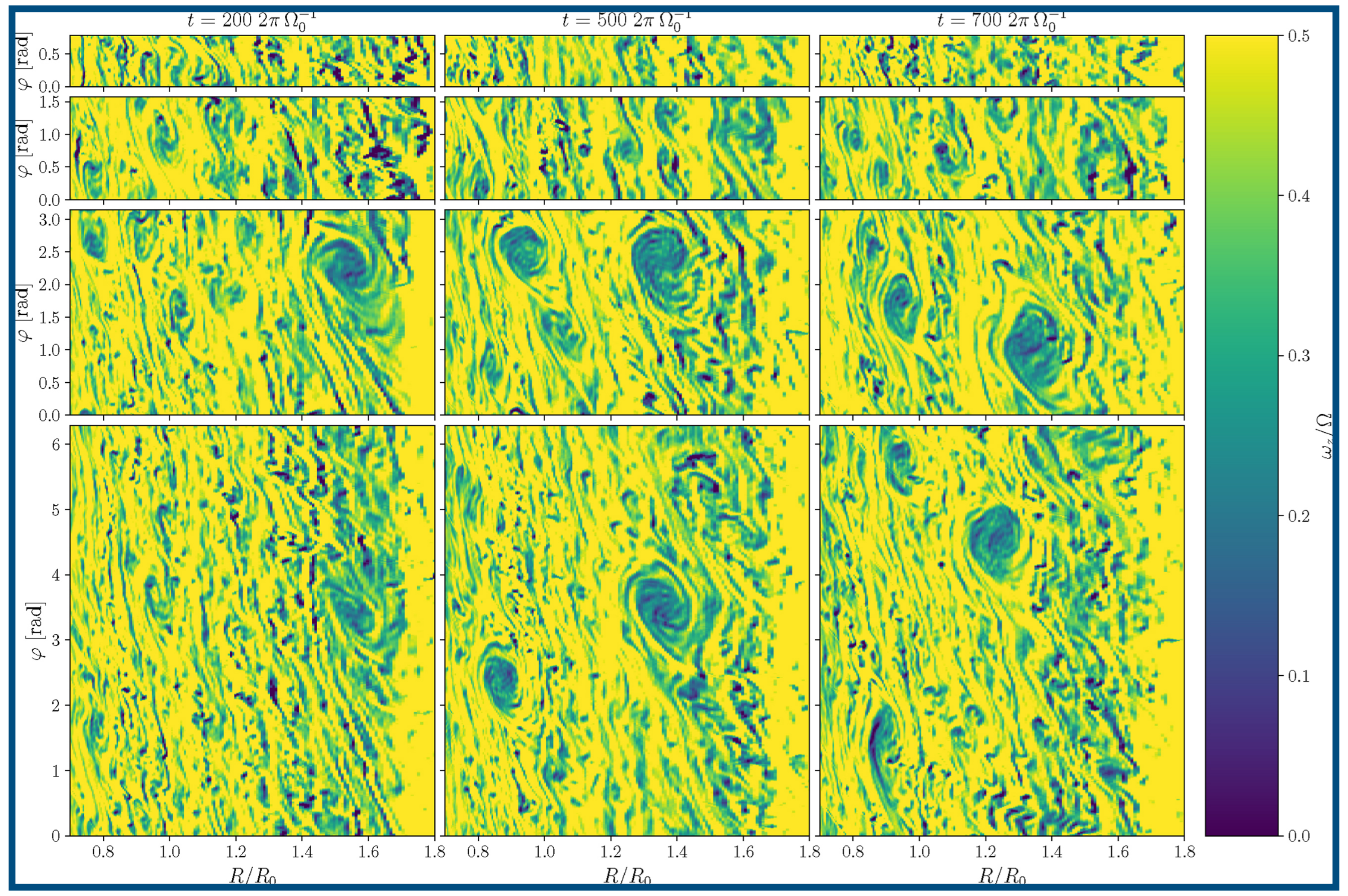
Dust evolution

Flock+2020



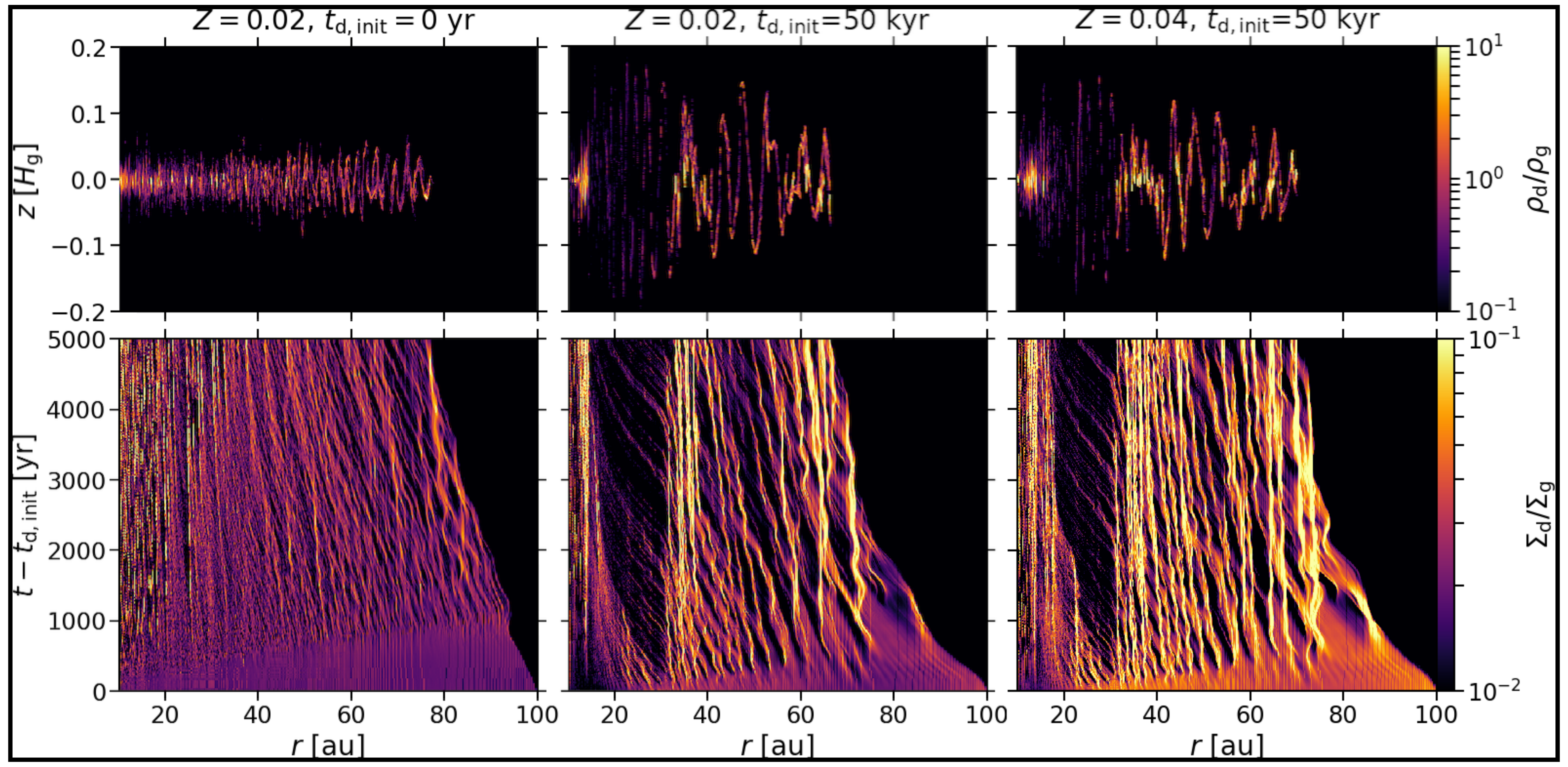
Structure formation

Manger+2018

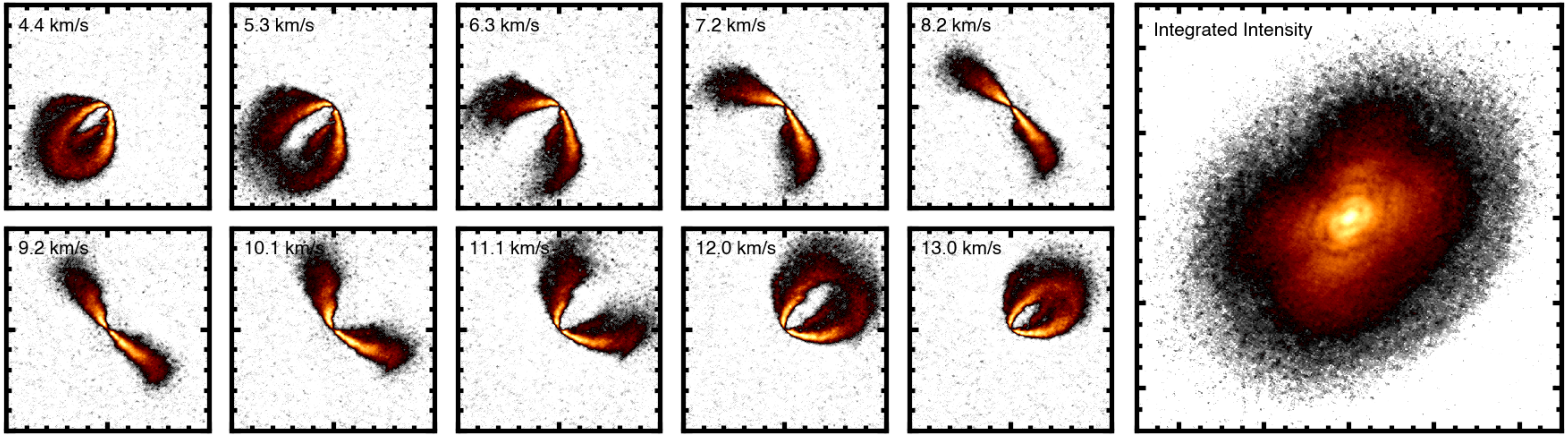


Planetesimal formation

Schäfer+2020

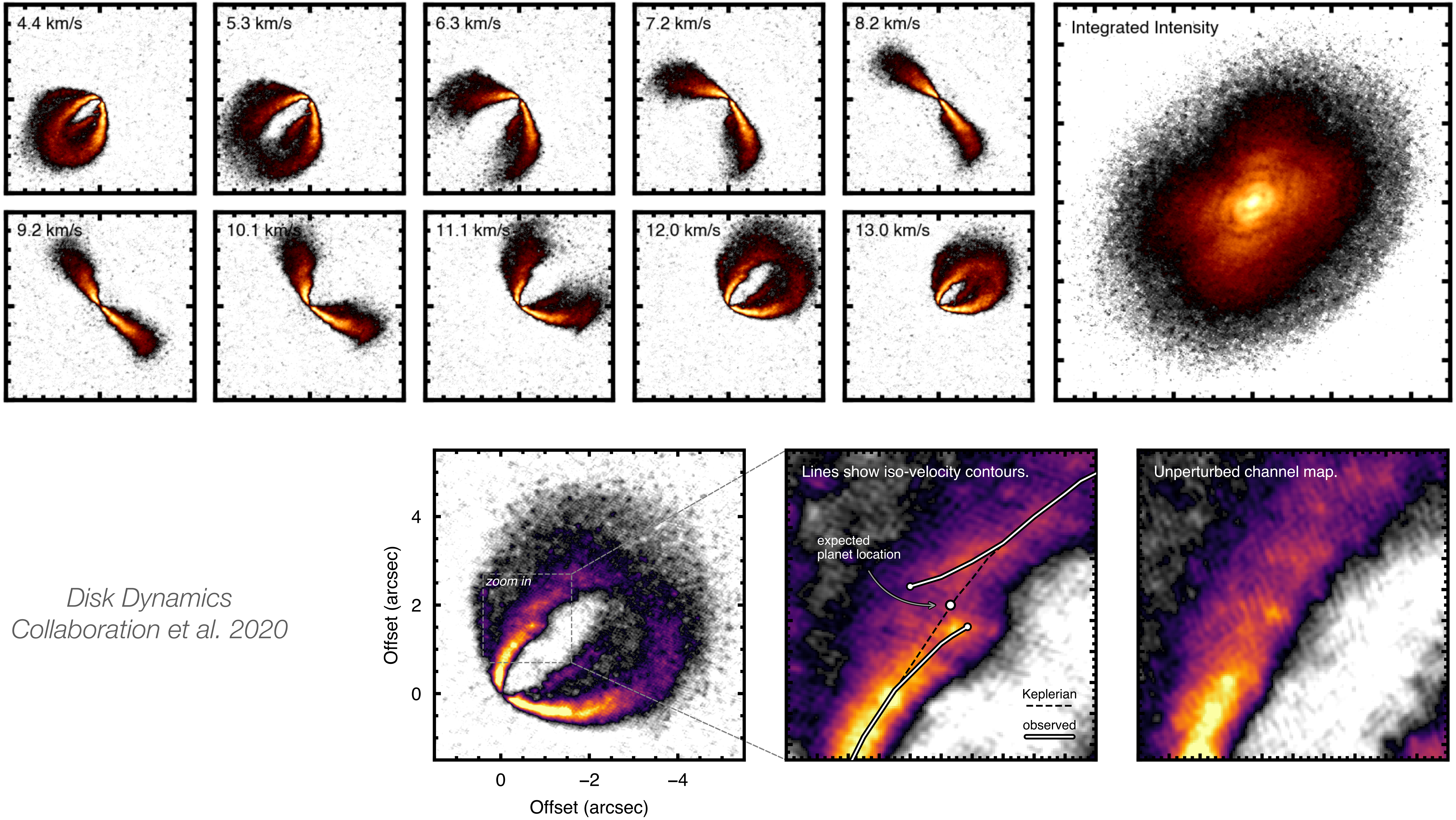


CO kinematic observations



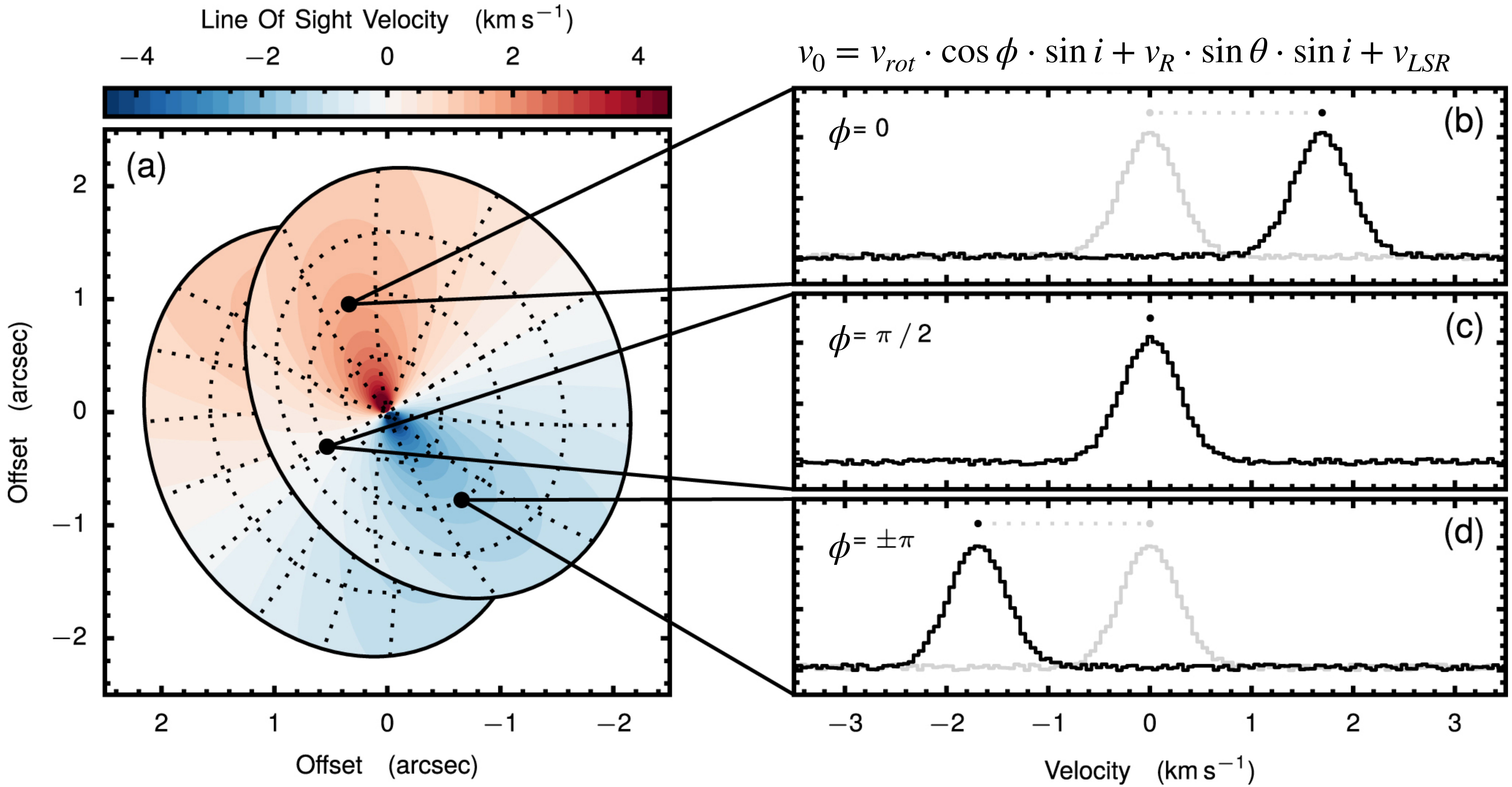
Disk Dynamics Collaboration et al. 2020

CO kinematic observations



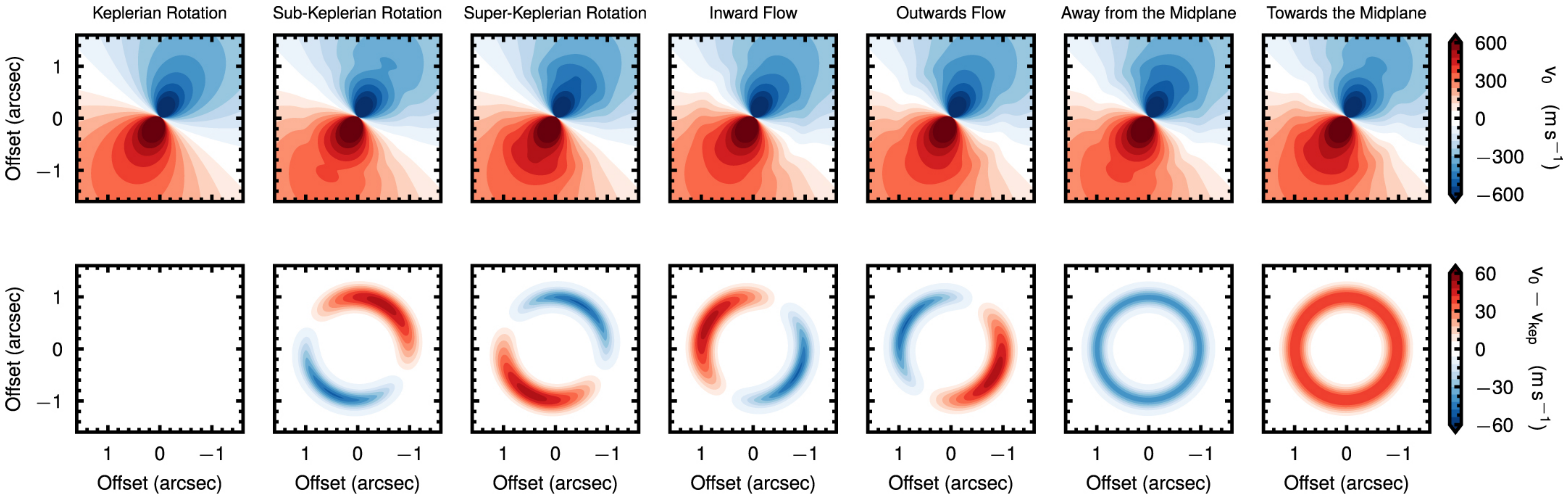
Disk Dynamics Collaboration et al. 2020

Velocity centroid maps



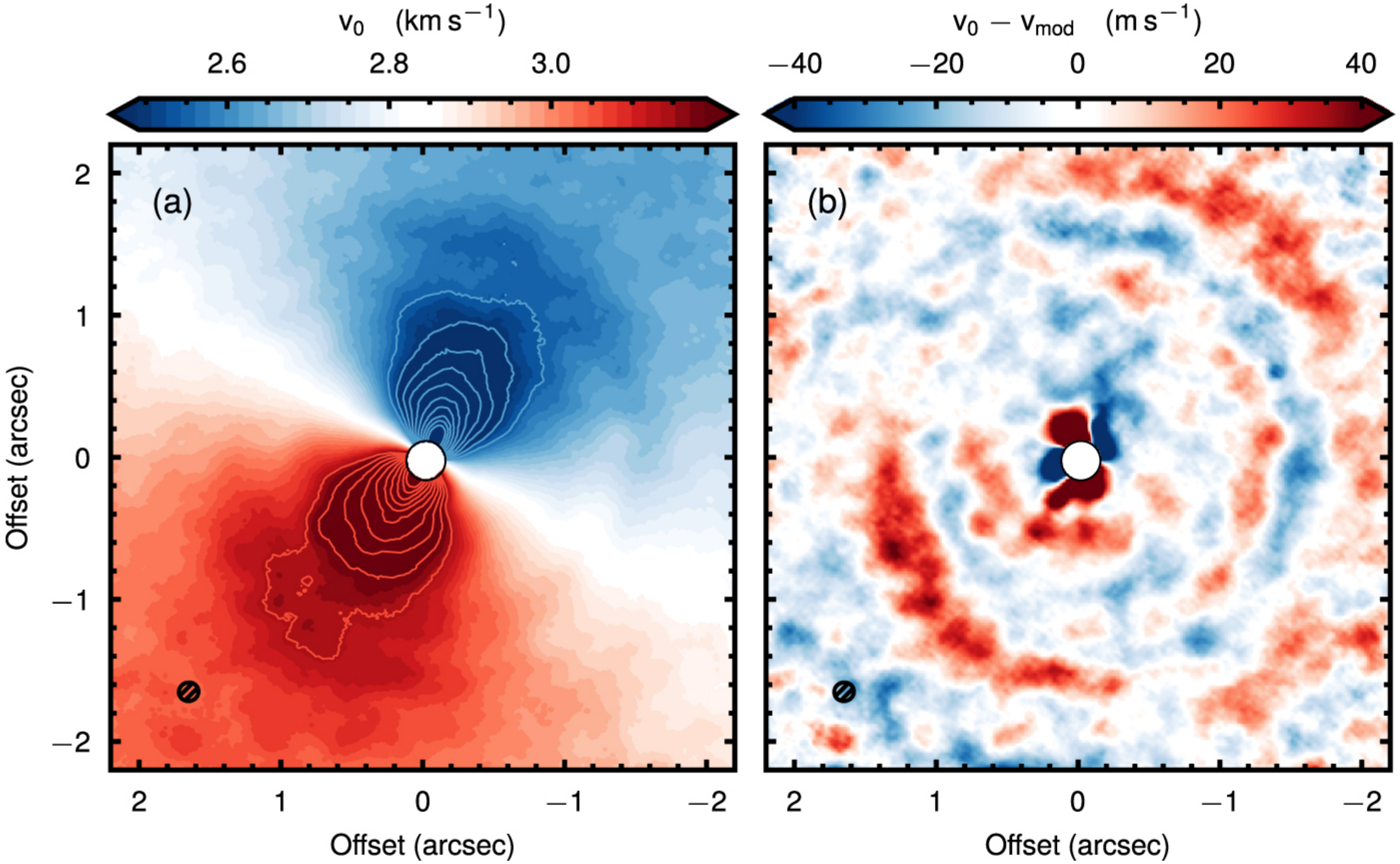
Teague et al. 2018

Non-Keplerian signatures in velocity centroid maps



Teague et al. 2019

Non-Keplerian large scale gas motions in TW Hya



Teague et al. 2019

Our work

- What kinematic signatures are expected in CO observations of VSI-unstable disks?
- Are these kinematic signatures observable with ALMA?
- Does the VSI produce significant non-thermal broadening?

Numerical methods

1. Hydrodynamical simulations

- PLUTO code (Mignone+2007)
- Global in spherical coordinates
- Physical Model of Nelson+2013
- Inviscid and locally isothermal
- Disk aspect ratio of 0.1 at 100 au

2. Radiative transfer

- RADMC3D code (Dullemond+2012)
- Dust thermal Monte Carlo
- Gas line emission for ^{12}CO, ^{13}CO, and $C^{18}O$ for the J:2-1 transition

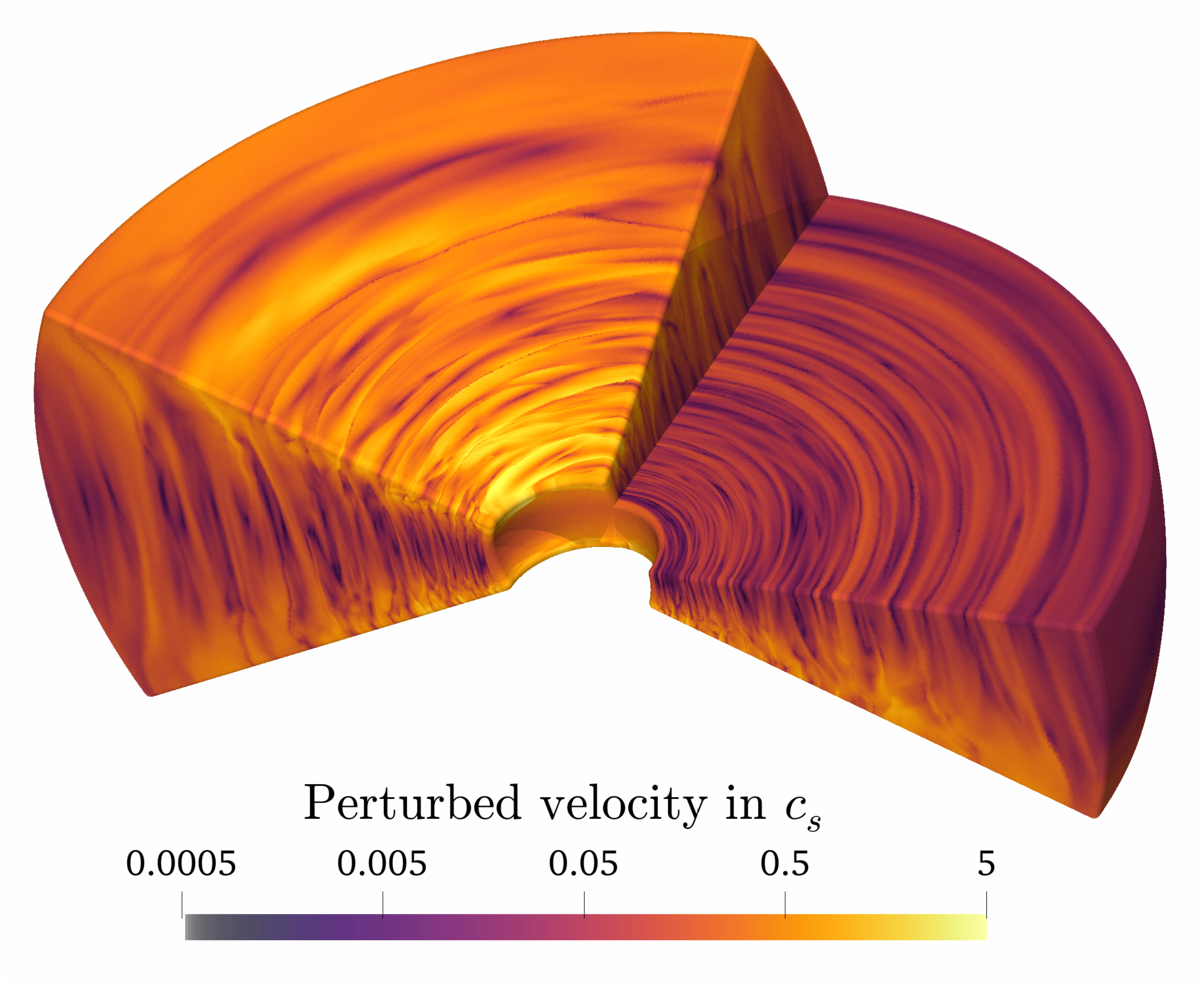
3. Synthetic Images :

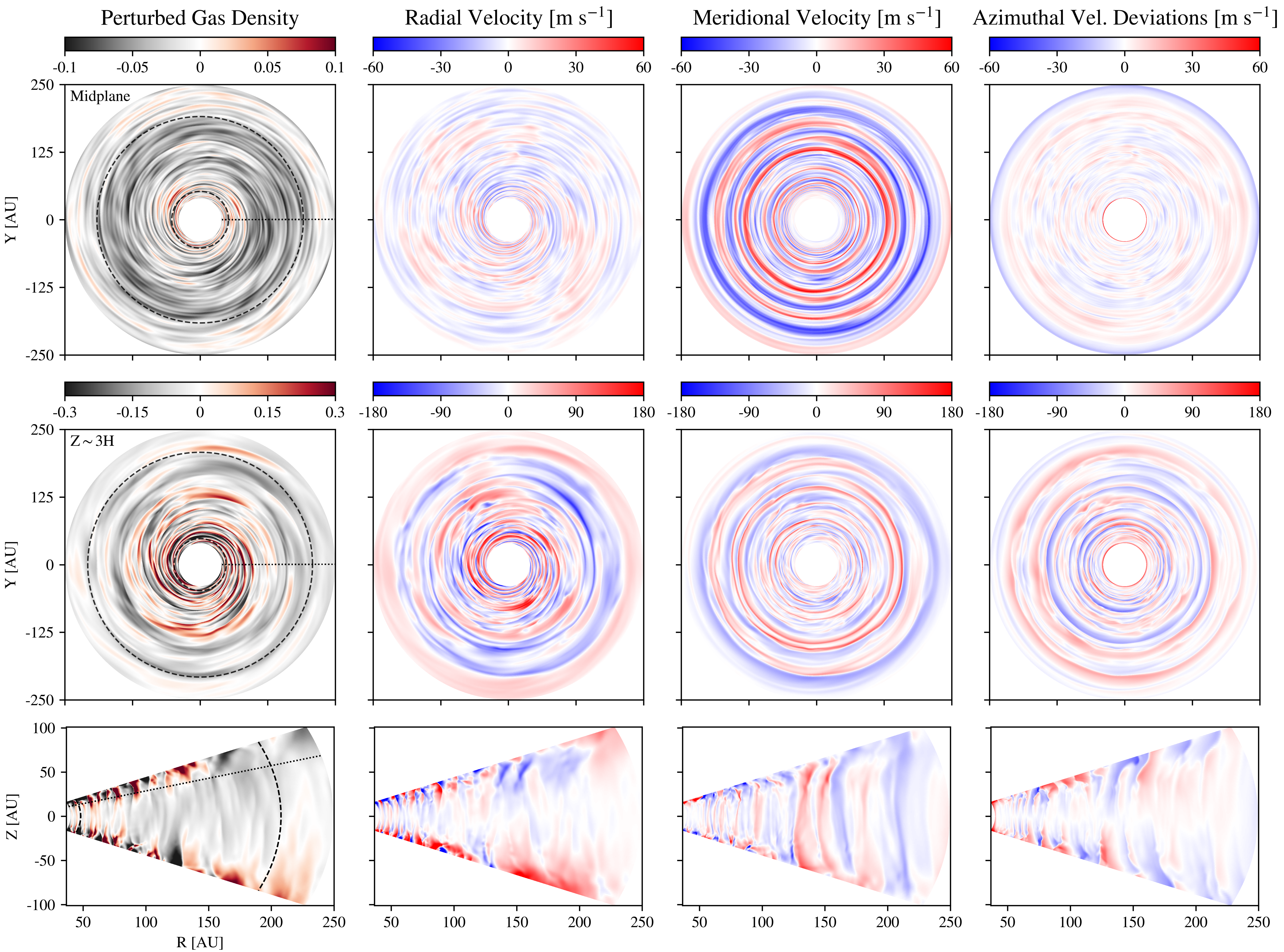
- CASA simobserve + ms.corrupt + tclean

4. Observables :

- Velocity centroid maps Bettermoments (Teague+2018)
- Deviations from Keplerianity Eddy (Teague+2019)

Simulation results

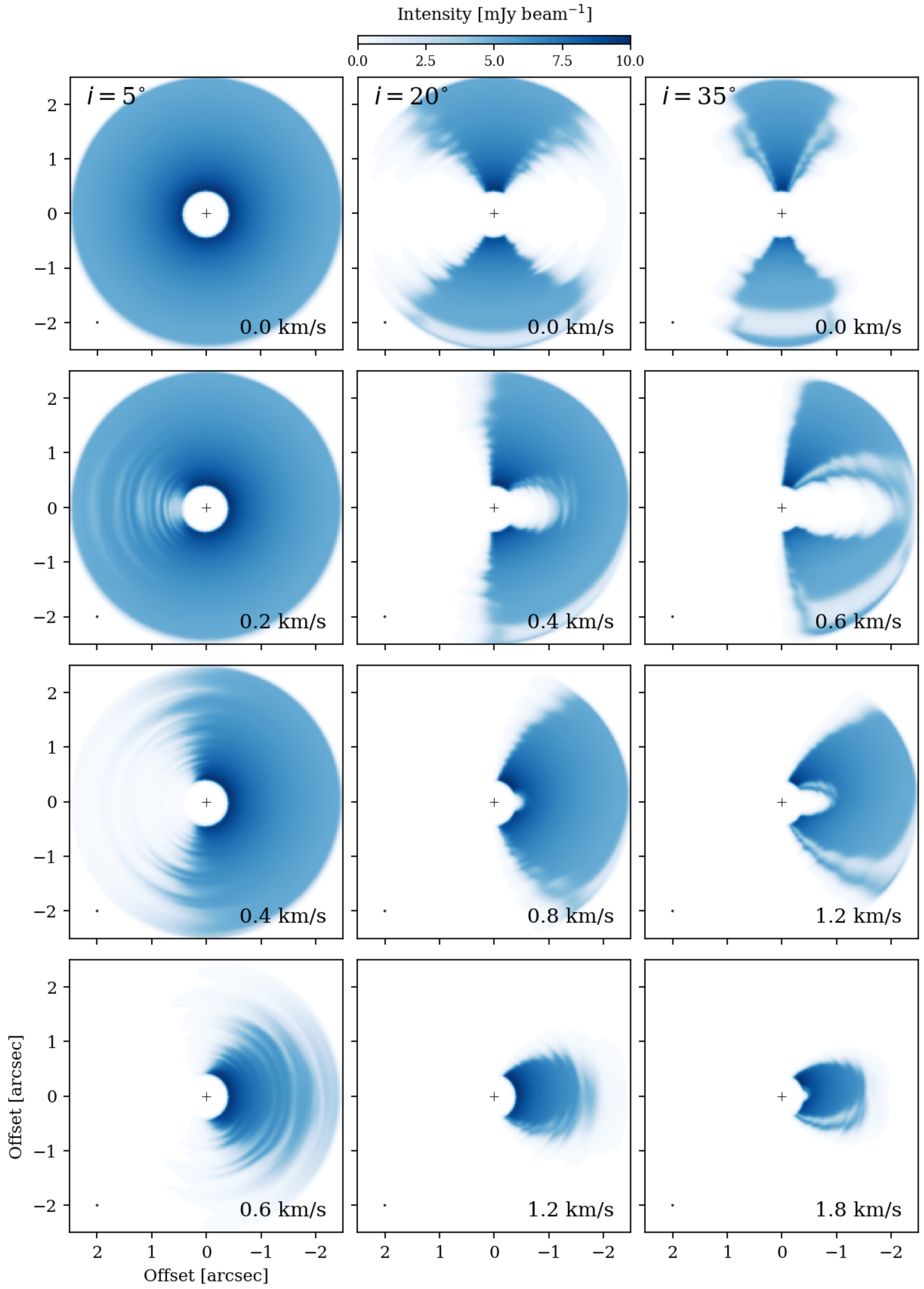


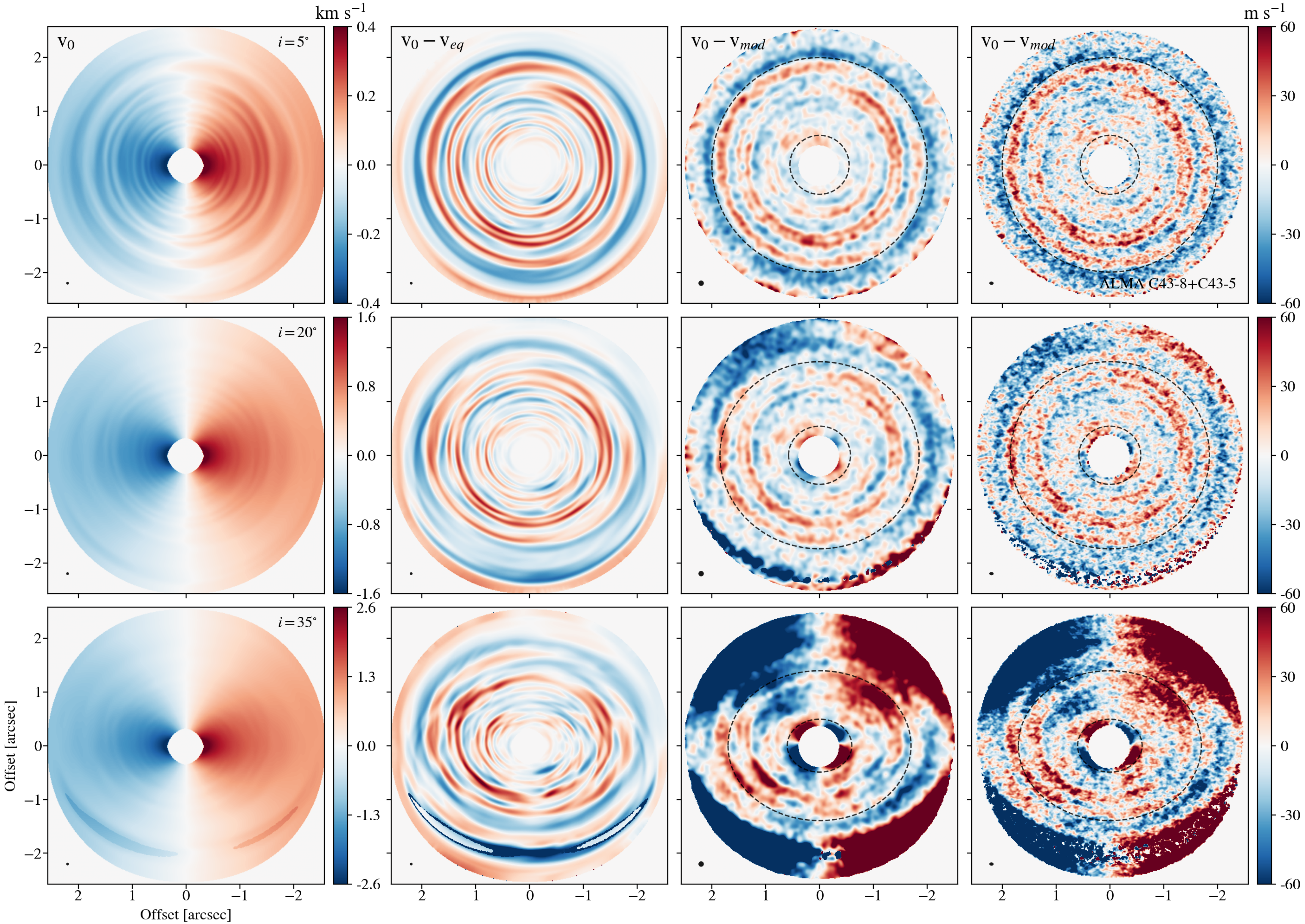


Barraza-Alfaro et al. 2021

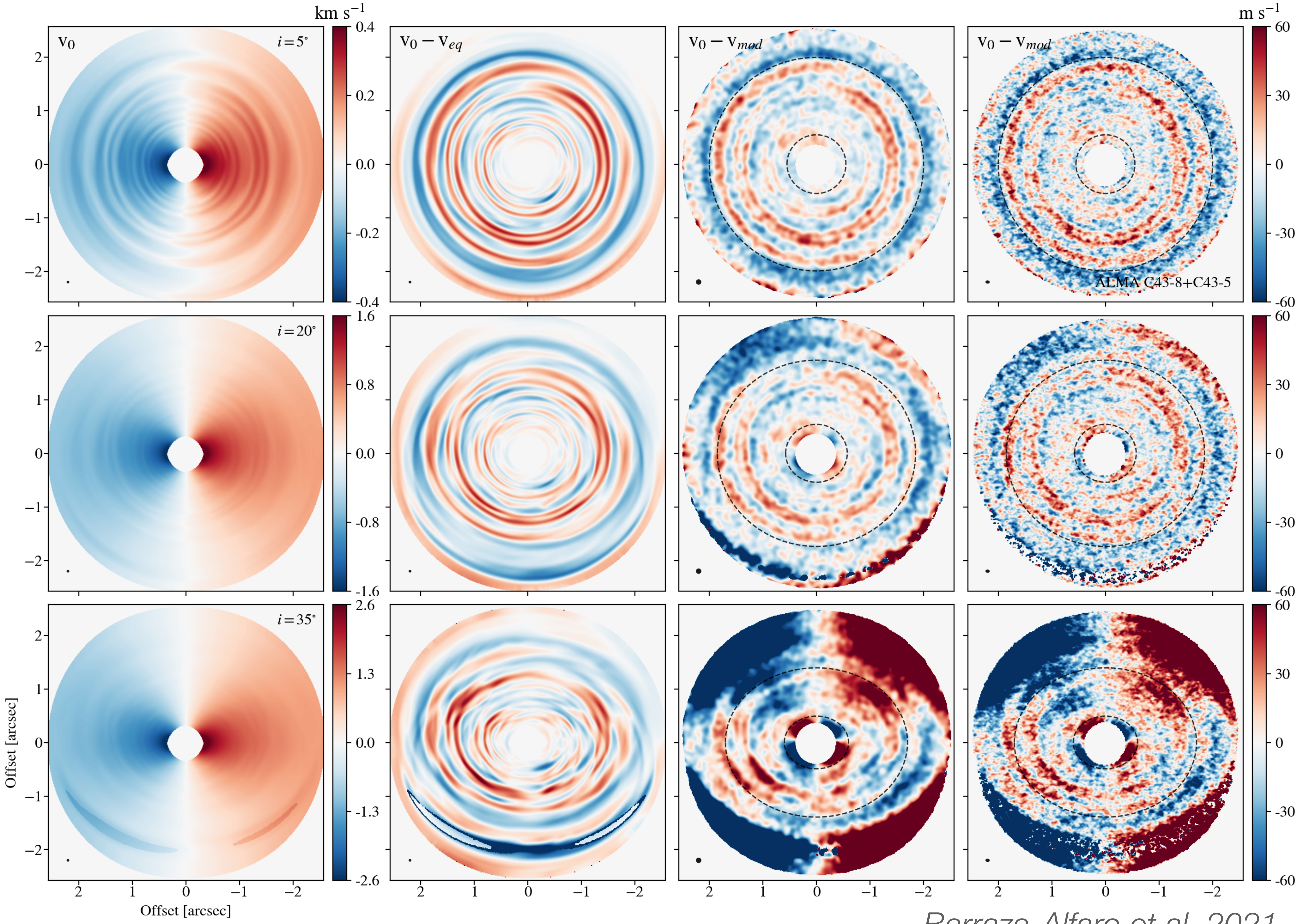
Channel maps

- VSI produces ‘spurs’ in all channel maps
- More visible for low disk inclinations





Barraza-Alfaro et al. 2021



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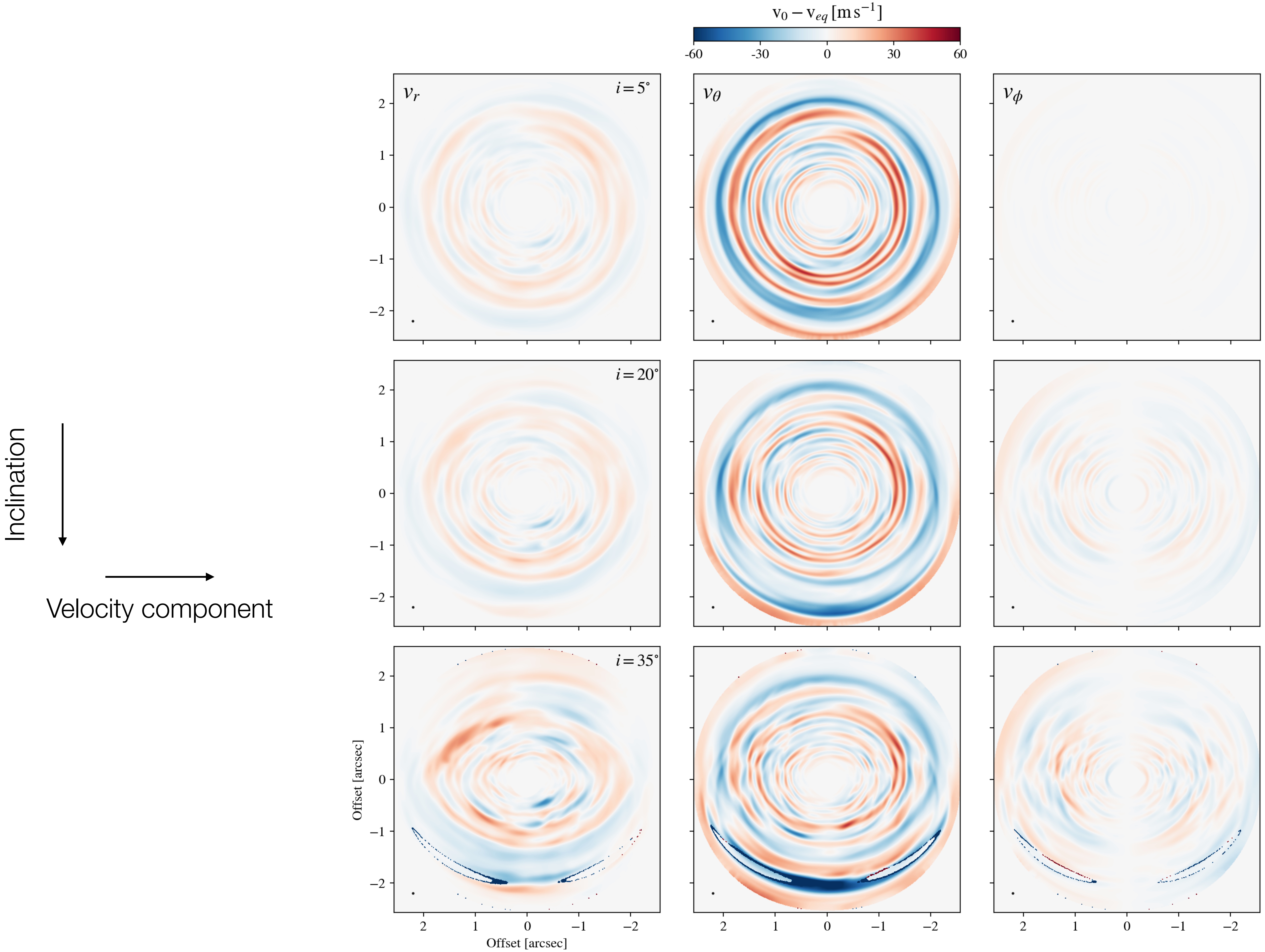
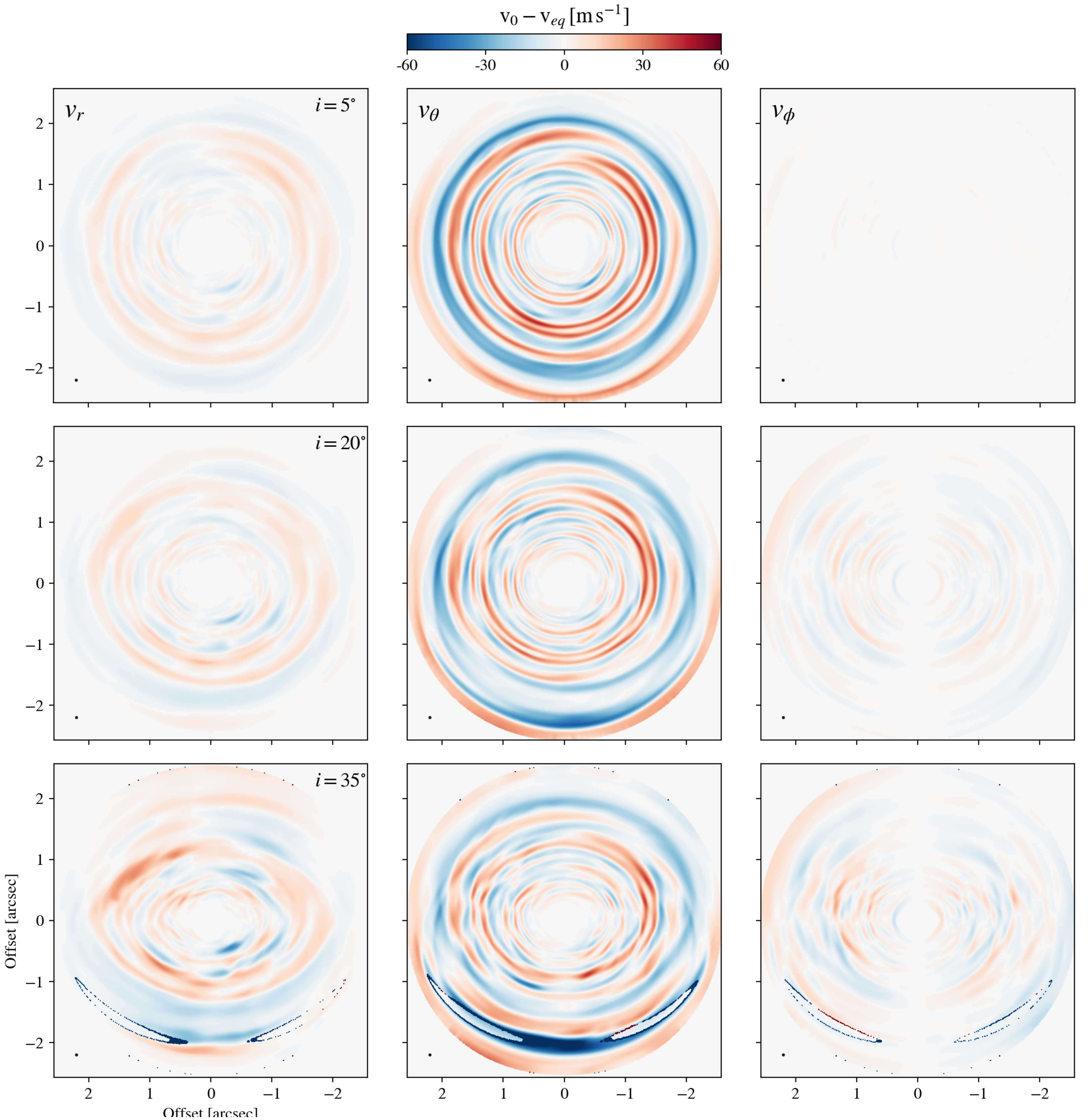
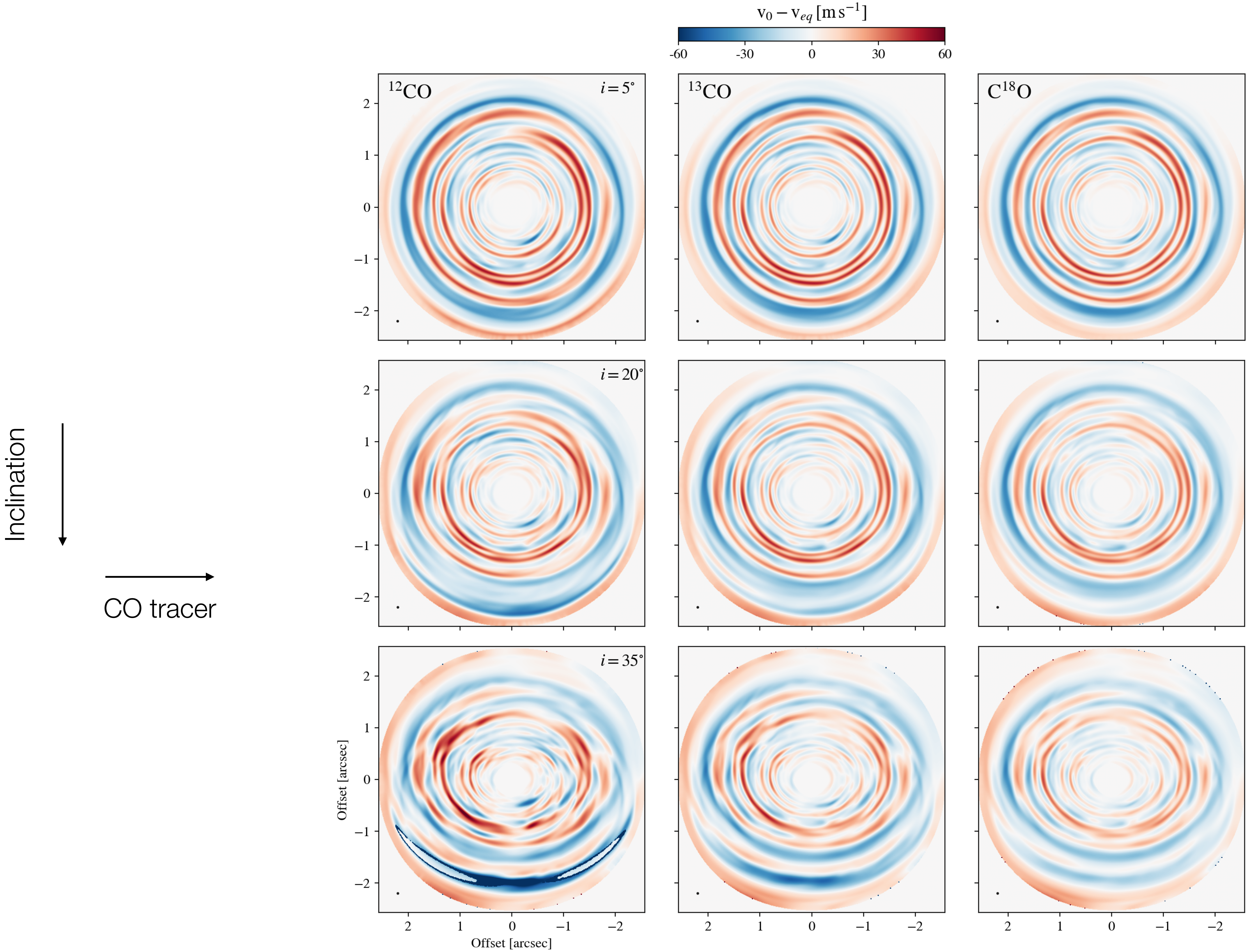
The VSI produces rings and arcs of non-Keplerian gas



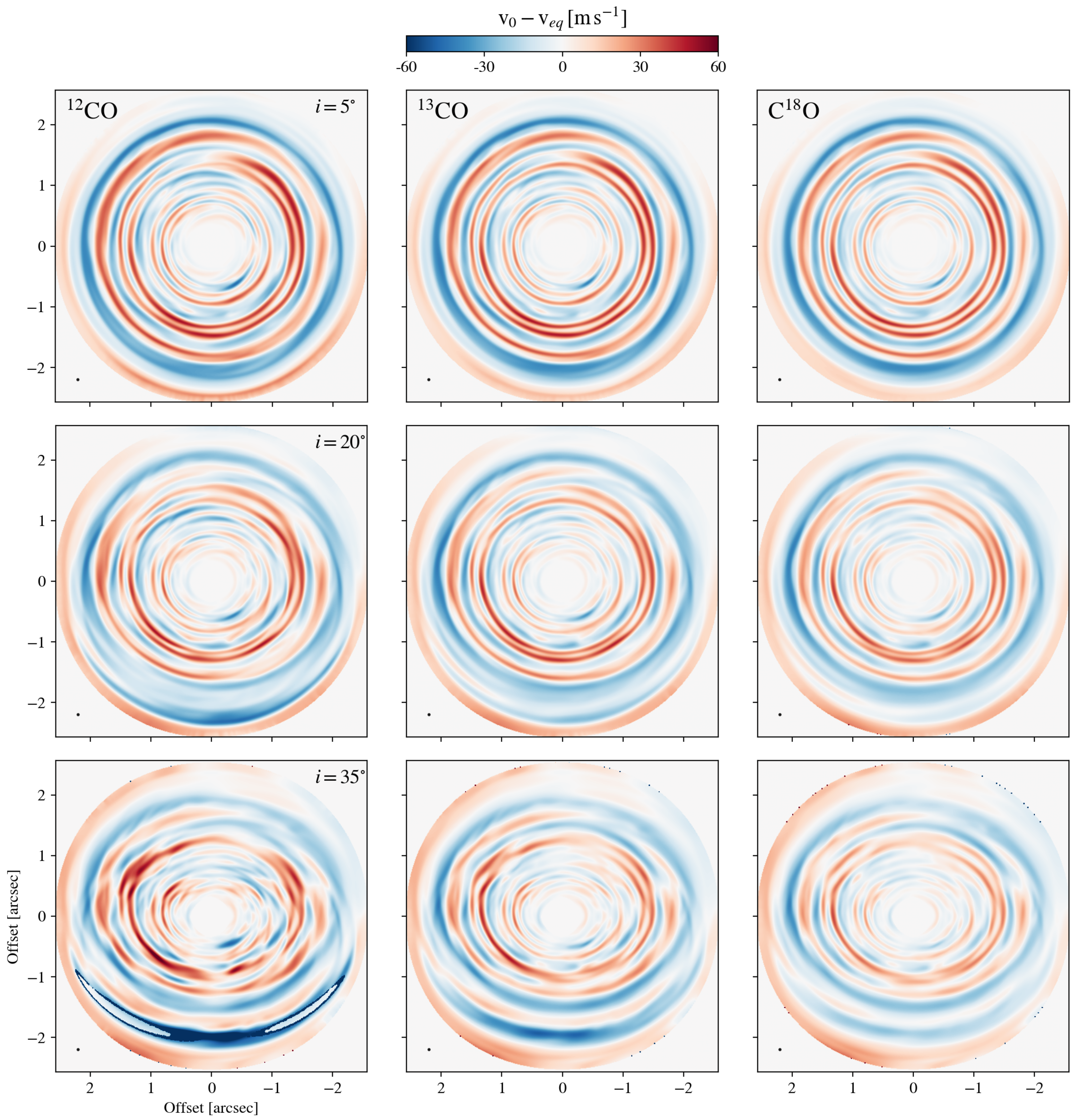
$v_0 - v_{eq}\,[\mathrm{m\,s^{-1}}]$
-60
-30
0
30
60
v_r
v_θ
v_ϕ
$i = 5^\circ$
$i = 20^\circ$
$i = 35^\circ$
Inclination
Velocity component
Offset [arcsec]
Offset [arcsec]



The meridional flows dominate the residuals from Keplerianity



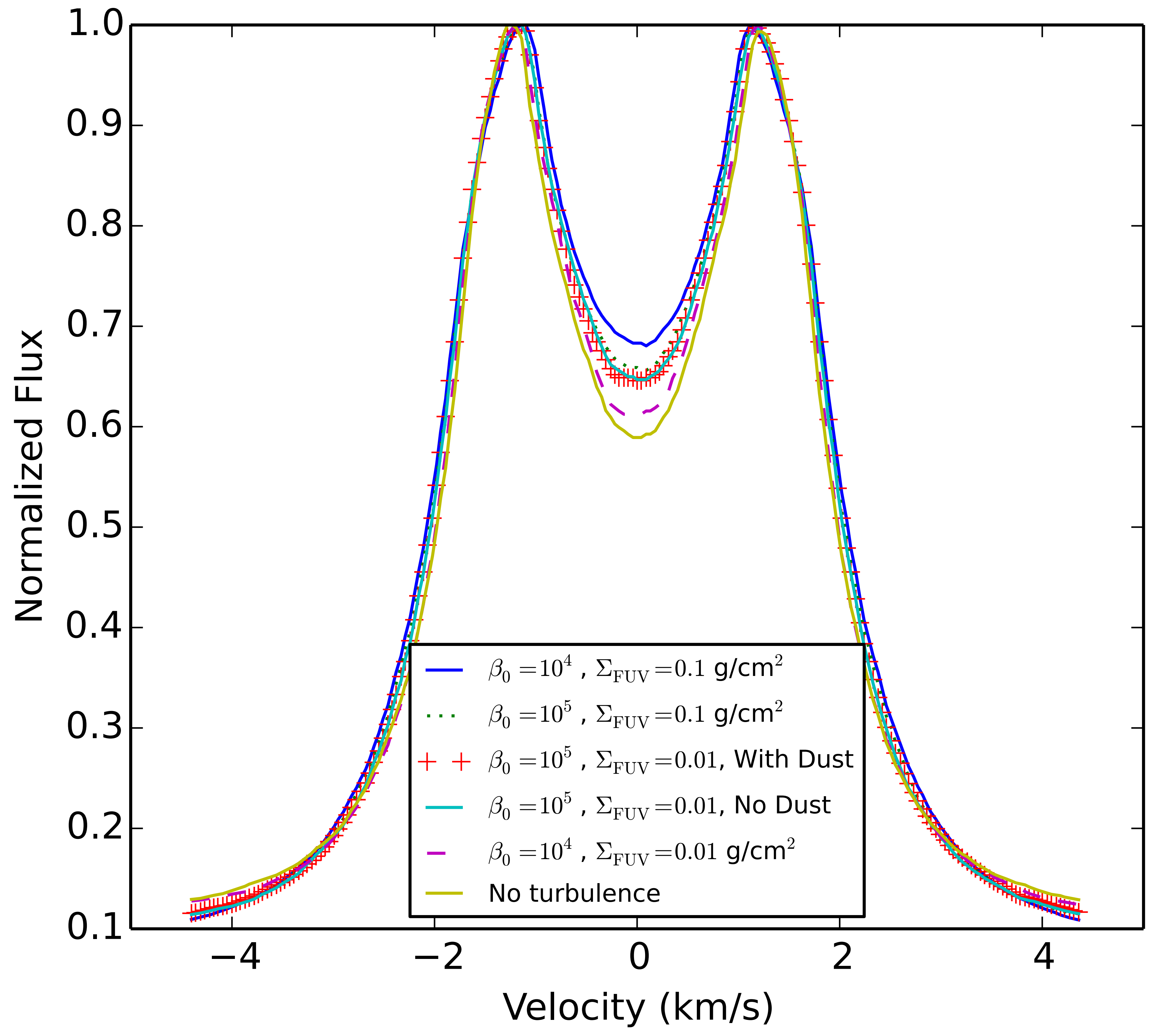
$v_0 - v_{eq}\,[\mathrm{m\,s^{-1}}]$
-60
-30
0
30
60
^{12}CO
^{13}CO
$C^{18}O$
$i = 5^{\circ}$
$i = 20^{\circ}$
$i = 35^{\circ}$
Inclination
CO tracer
Offset [arcsec]
Offset [arcsec]

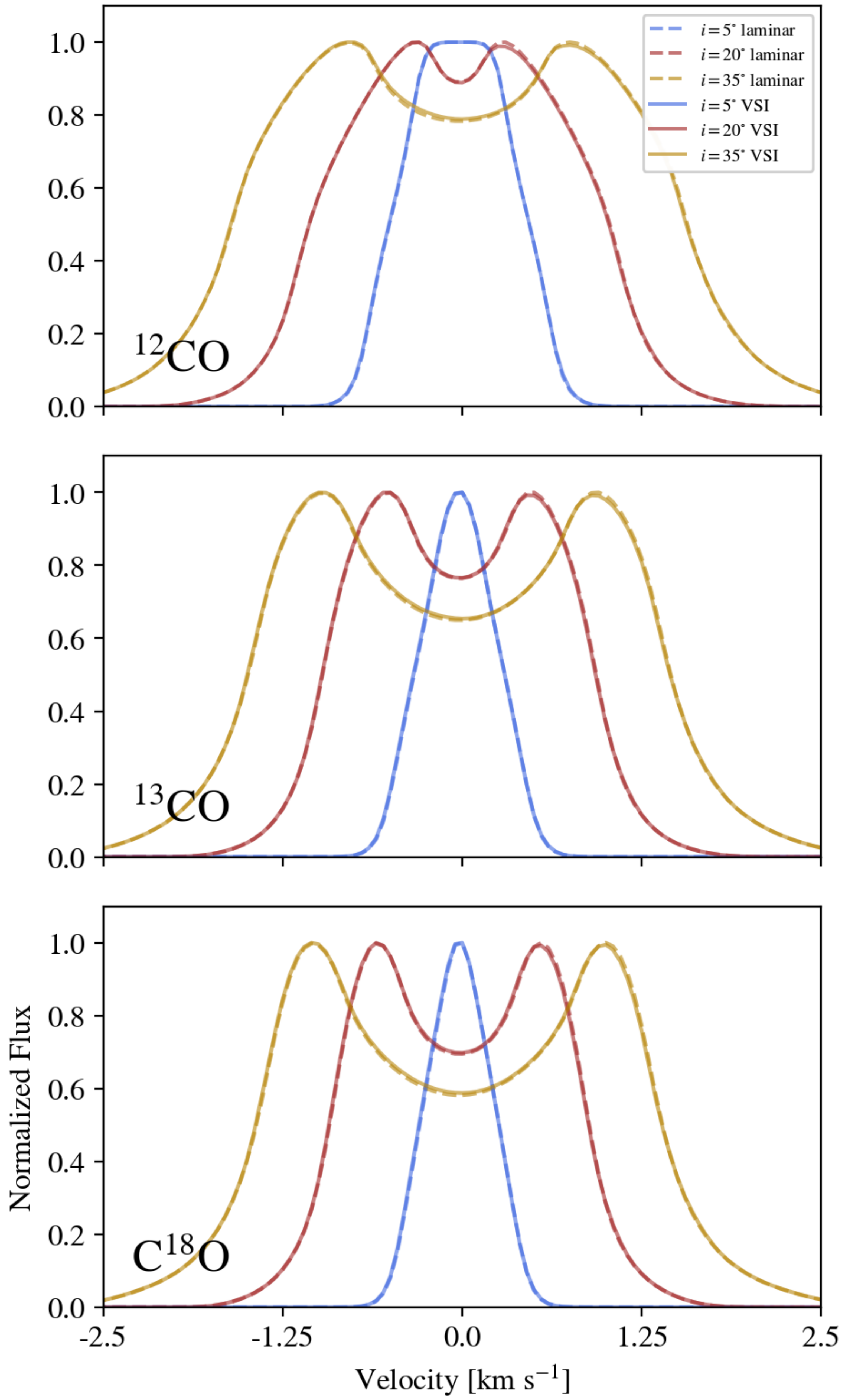


The morphology of the non-Keplerian motion weakly varies with CO tracer

Non-thermal line broadening

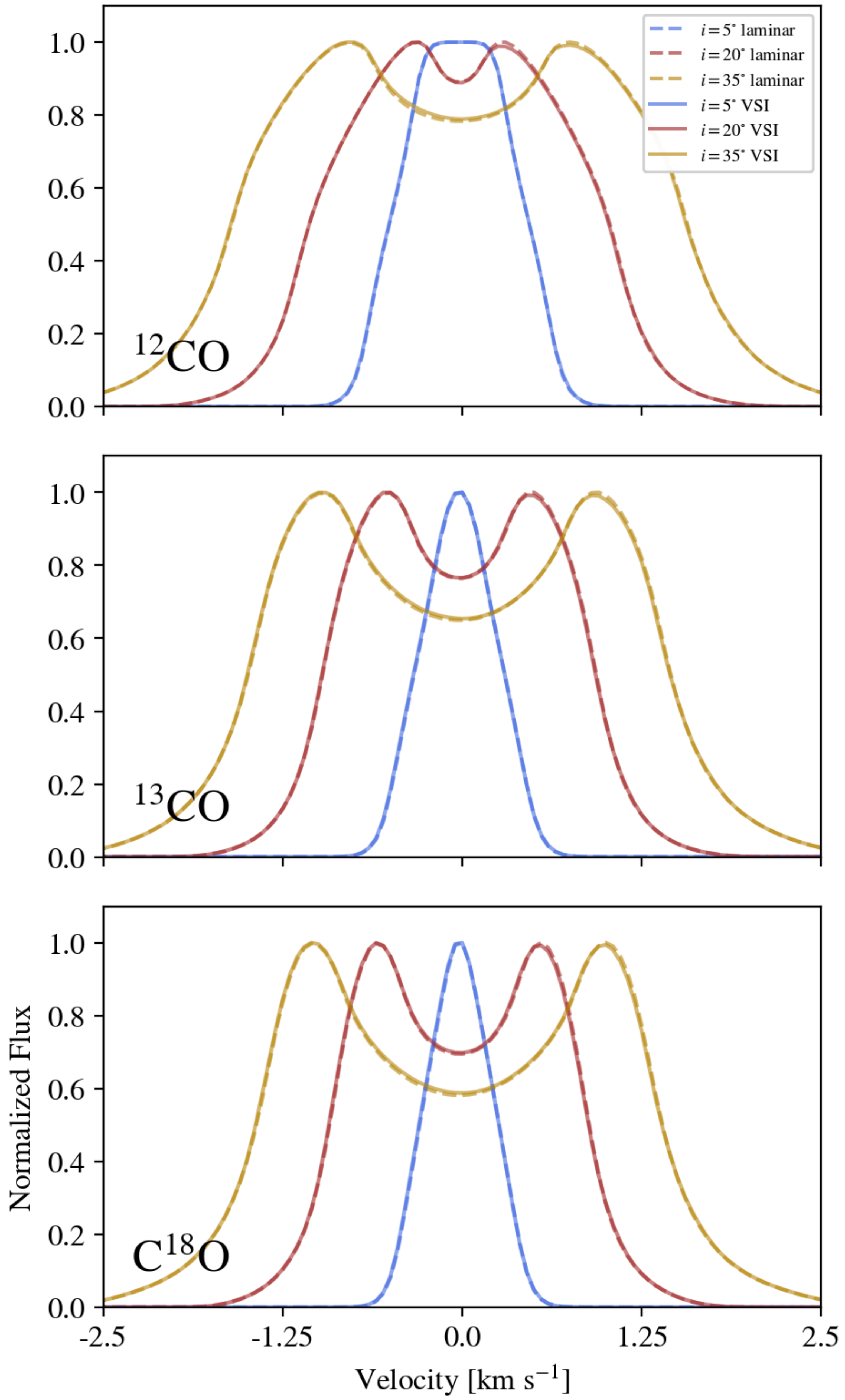
Simon et al. 2018





Non-thermal line broadening

The VSI produces negligible non-thermal broadening



Take home messages

- Kinematic signatures of hydrodynamic turbulence could probe its origin
- 3D global hydro-simulations and high resolution observations are crucial to understand gas kinematics in protoplanetary disks
- VSI can produce observable features in channel maps and velocity centroid maps