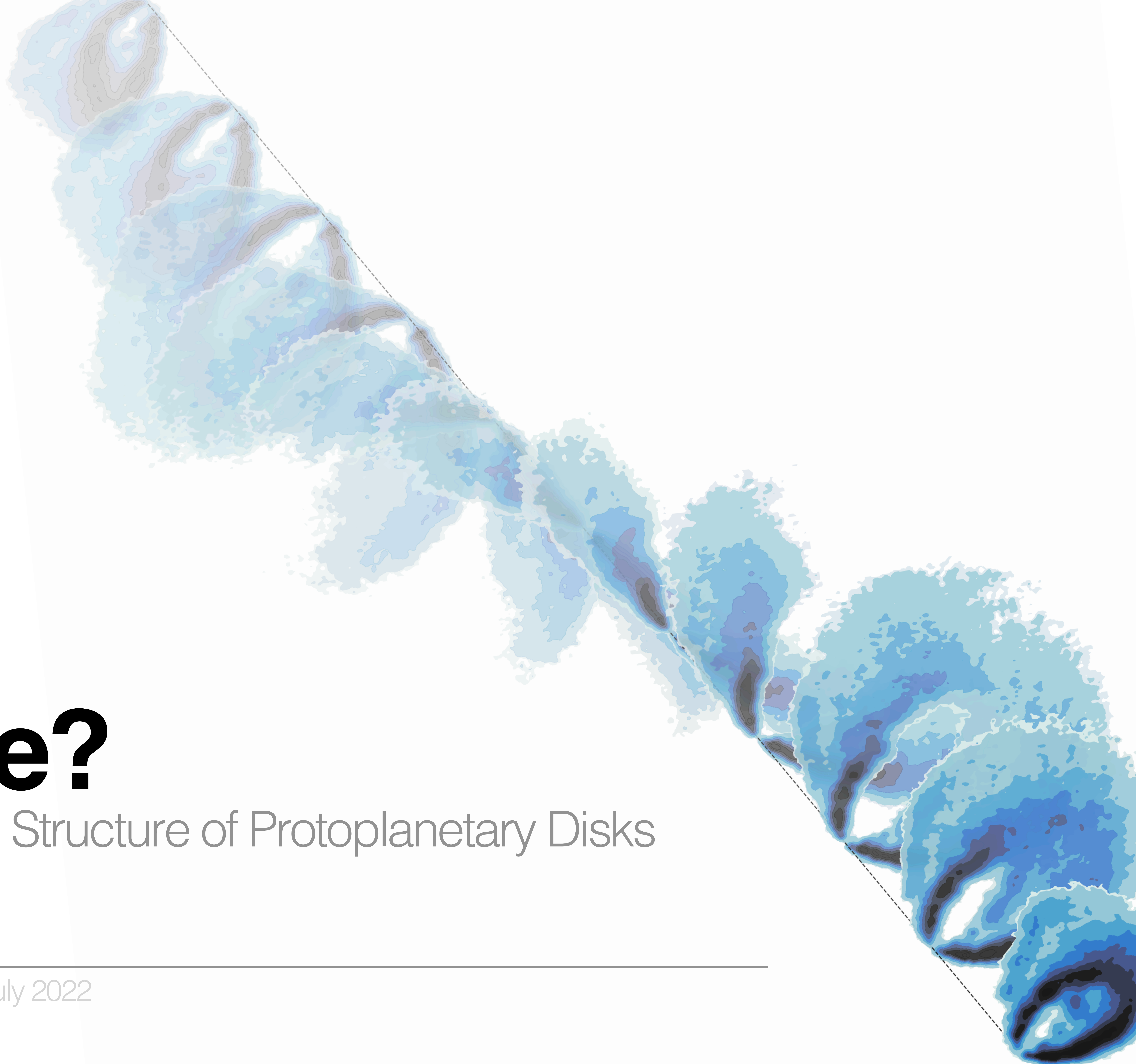
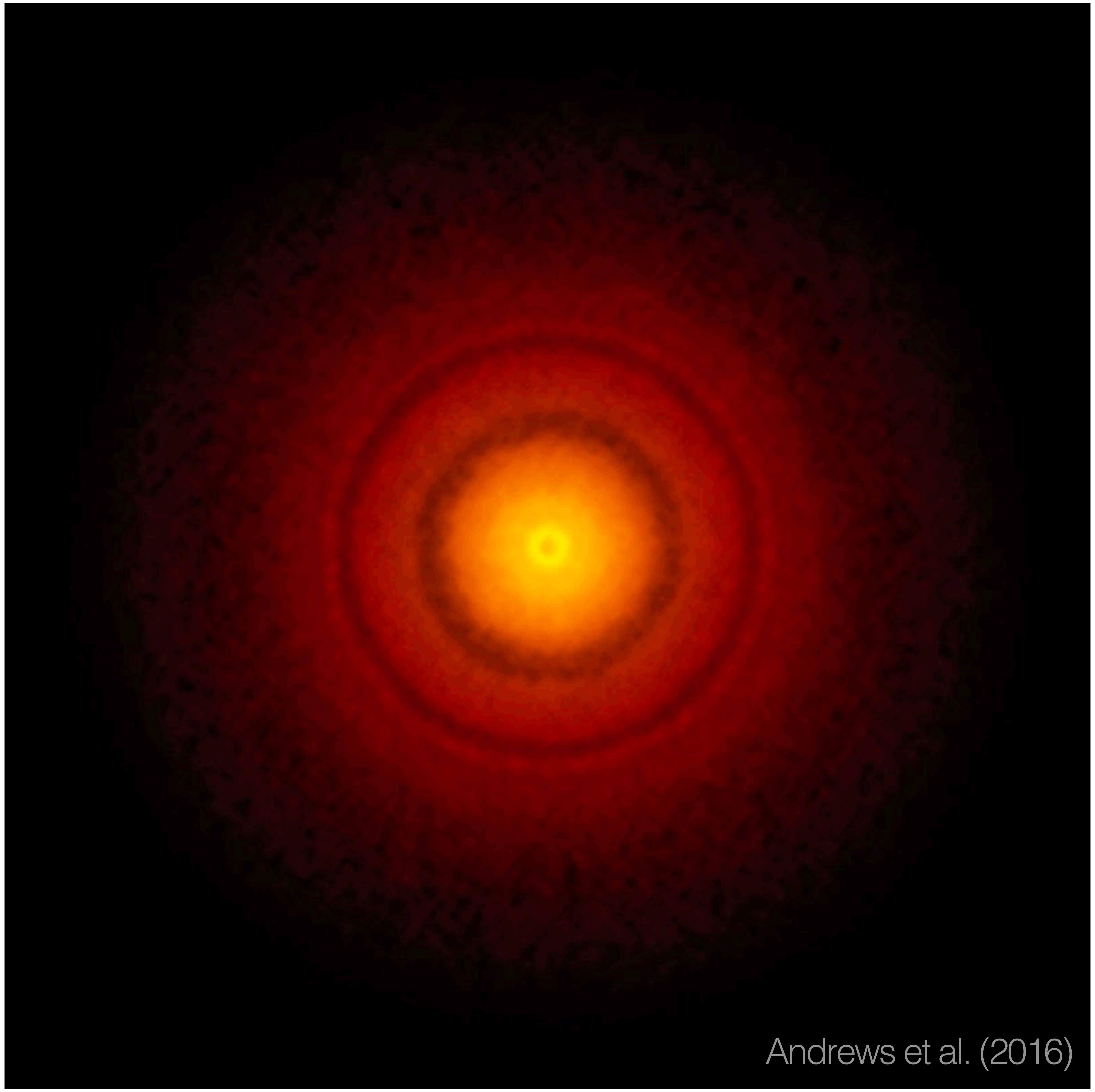


What’s In a Line?

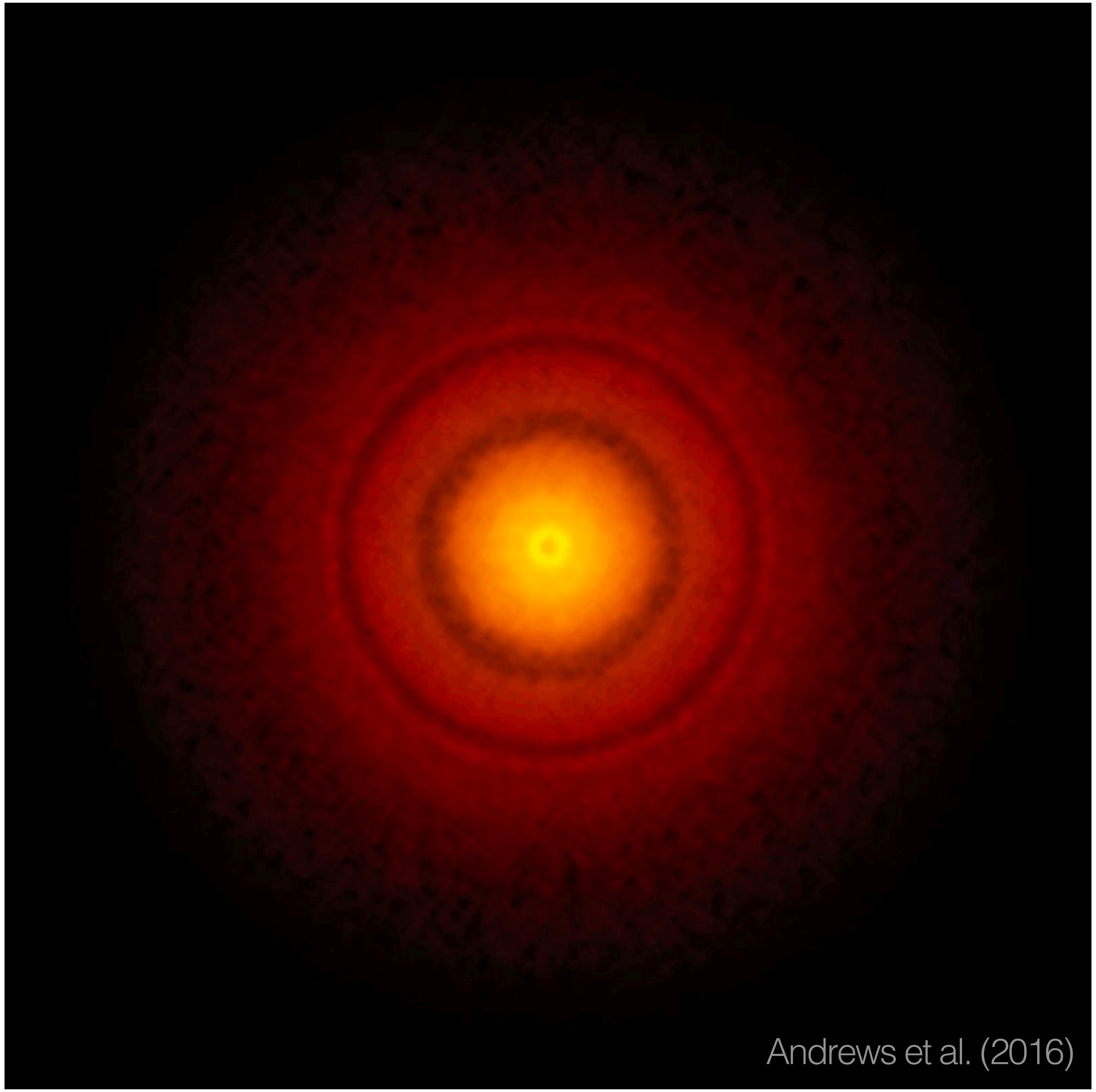
How We’re Mapping the Dynamical Structure of Protoplanetary Disks

Richard Teague

Harvard & Smithsonian | Center for Astrophysics —> MIT July 2022

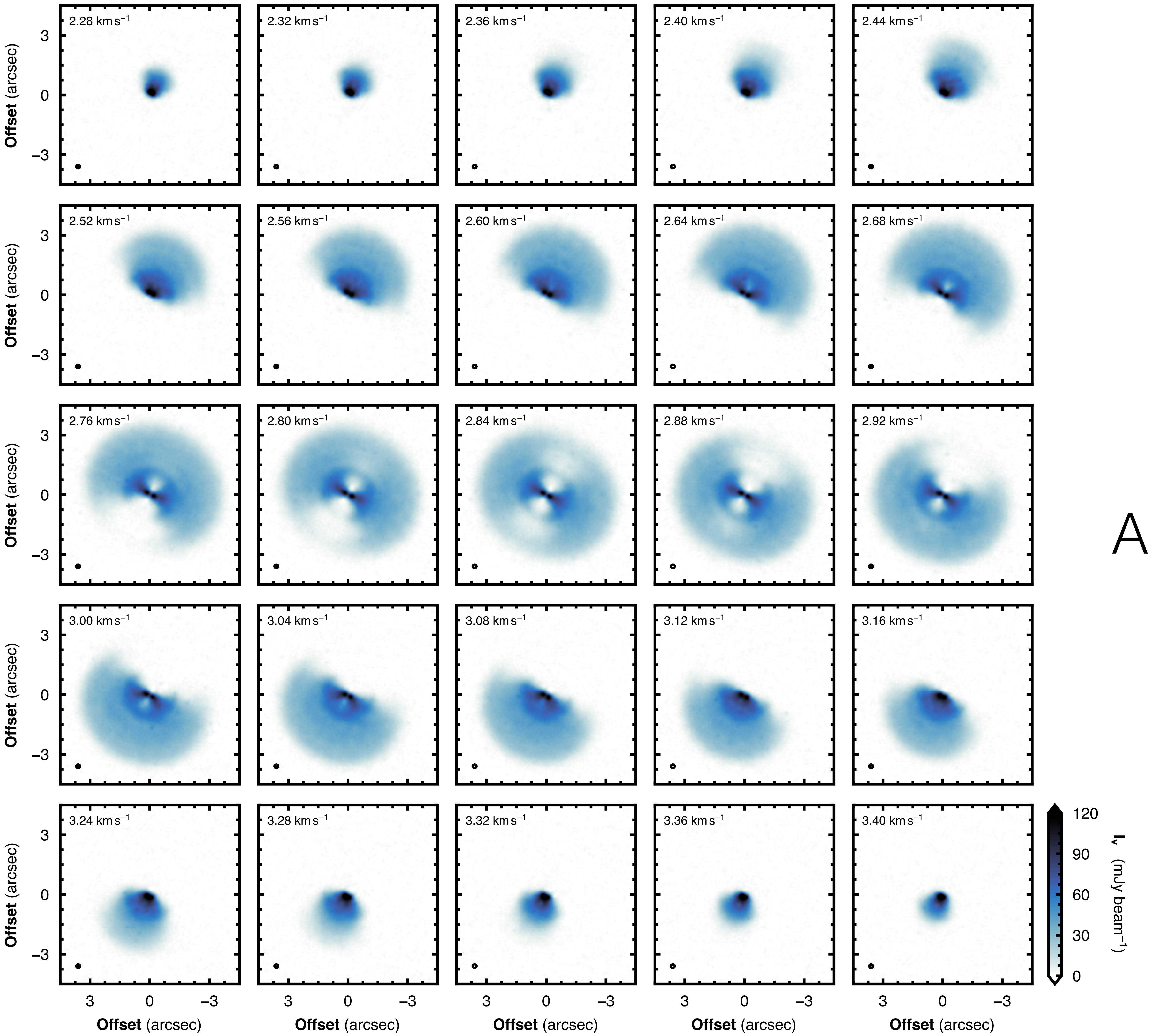


Andrews et al. (2016)



Andrews et al. (2016)

A picture is worth a thousand words.

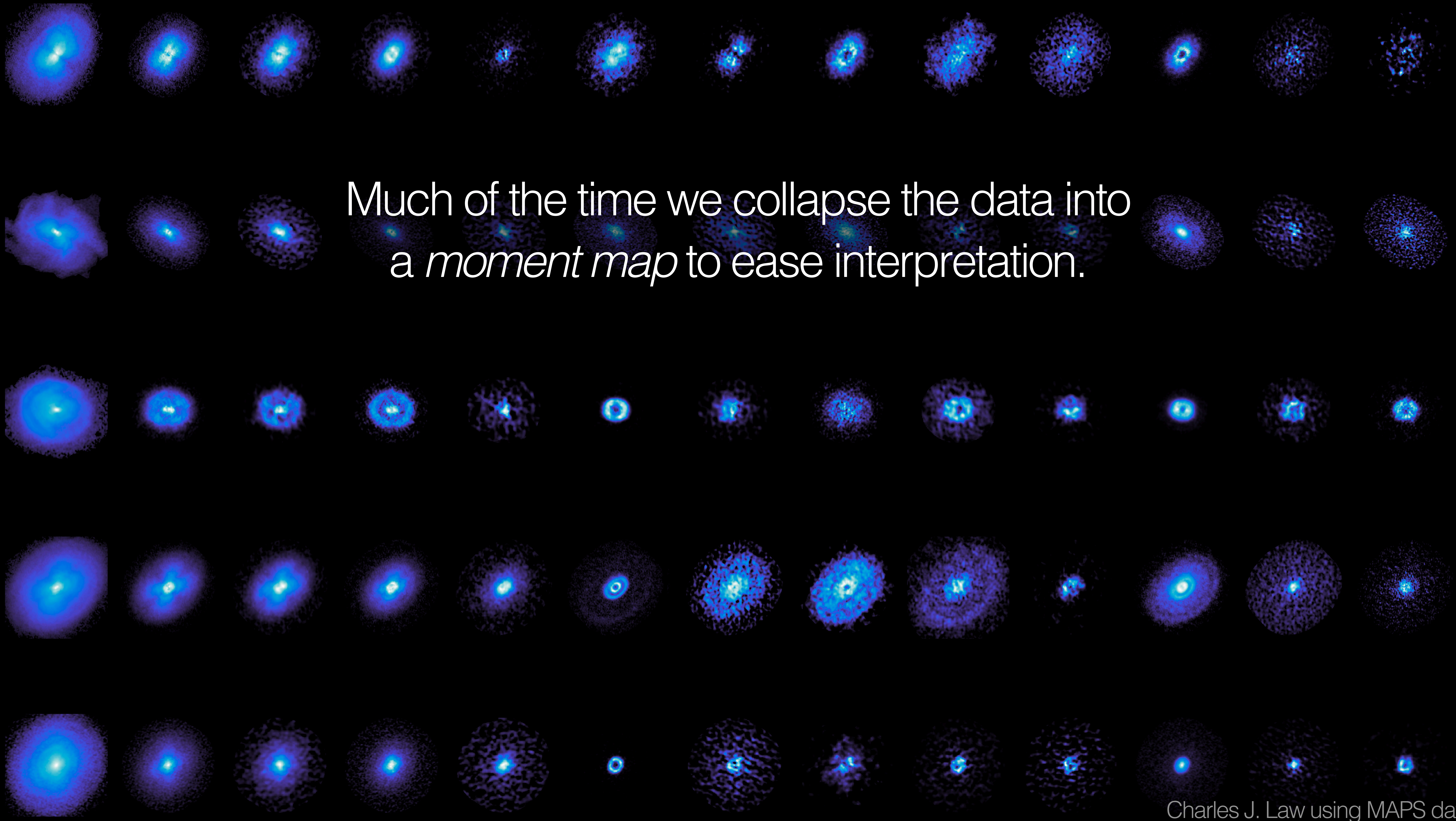


A picture is worth a thousand words.

An ALMA observation is worth **3.8 million**.

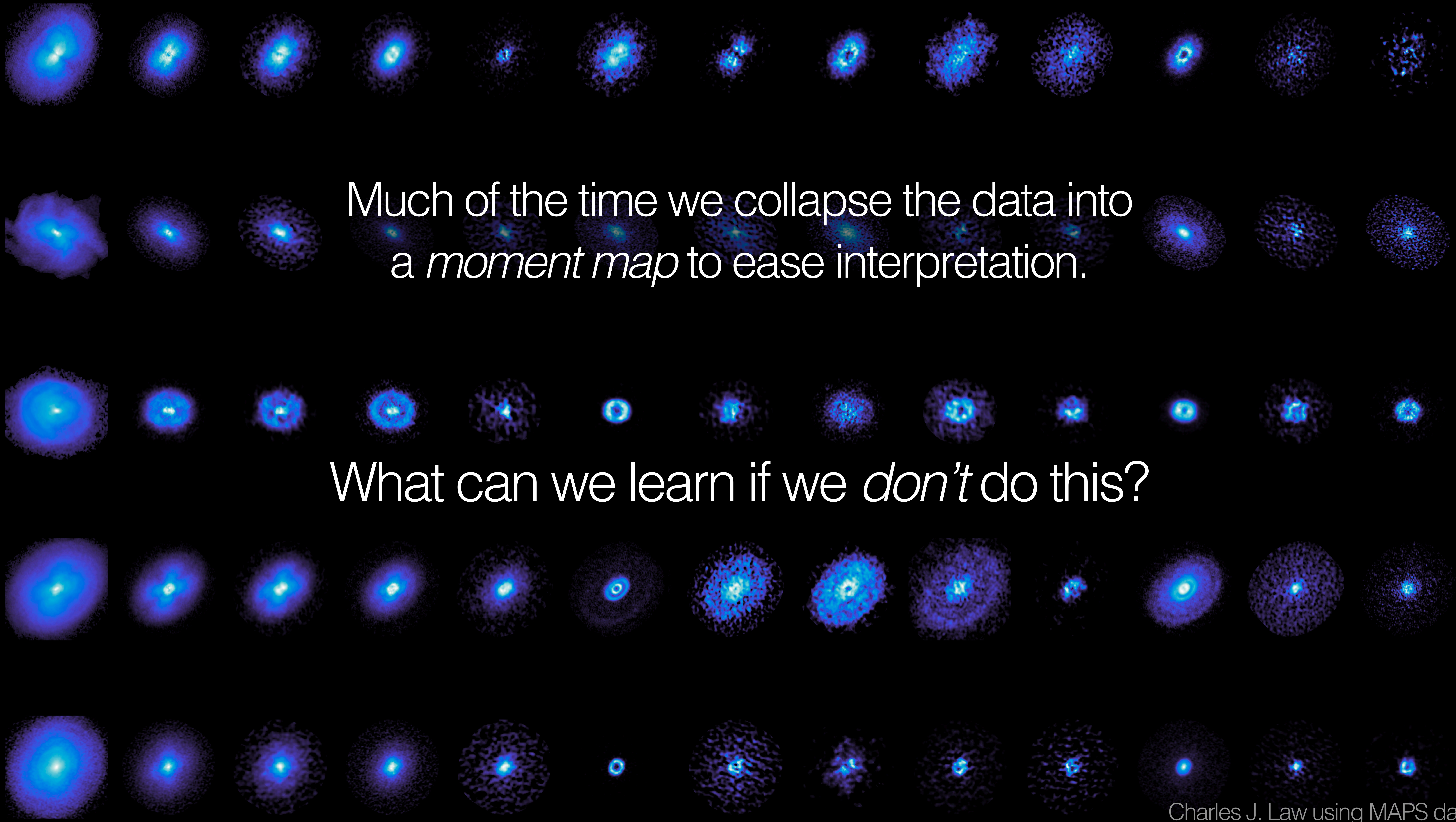
(almost 8 copies of War & Peace)

Teague et al. (in prep.)



Much of the time we collapse the data into a *moment map* to ease interpretation.

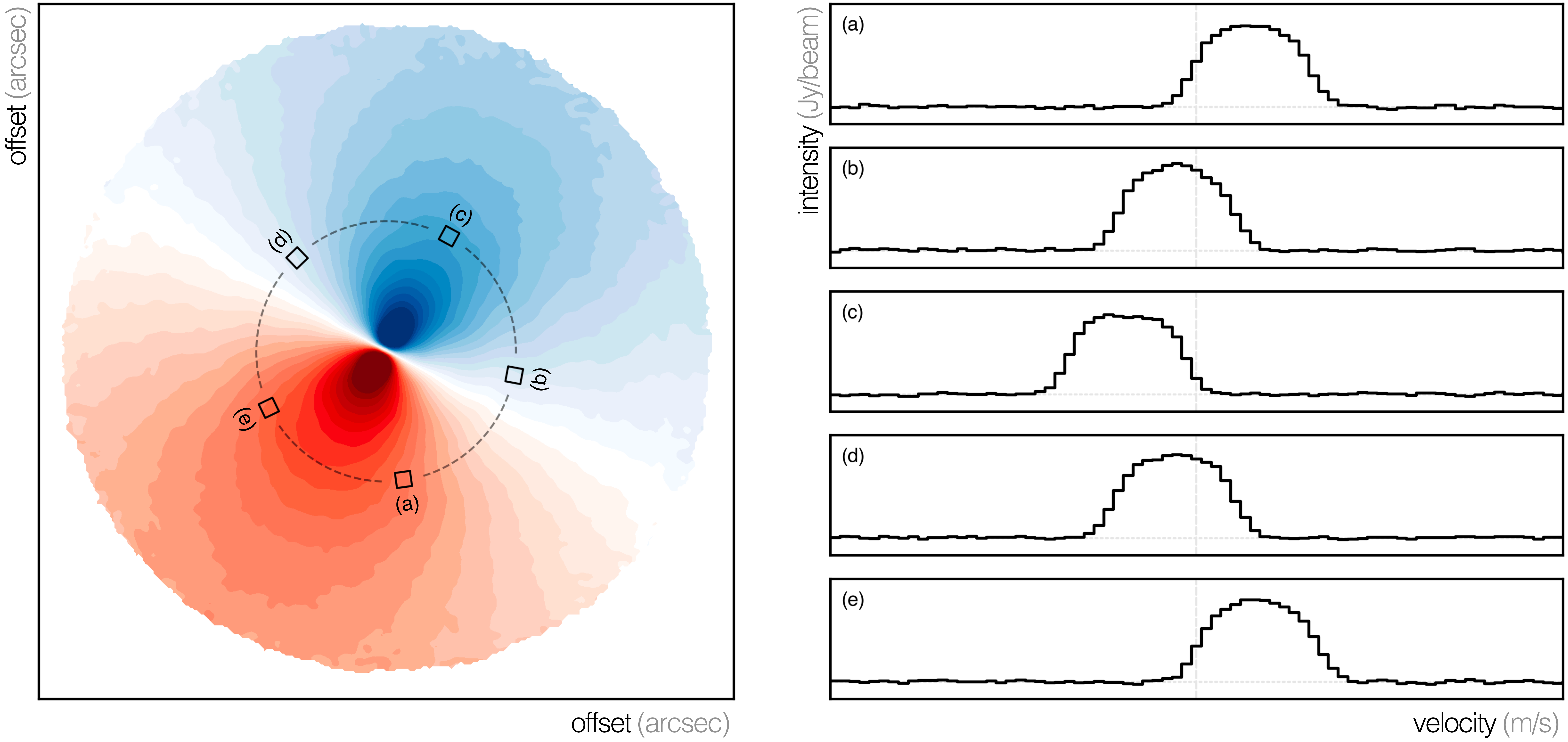
Charles J. Law using MAPS data.



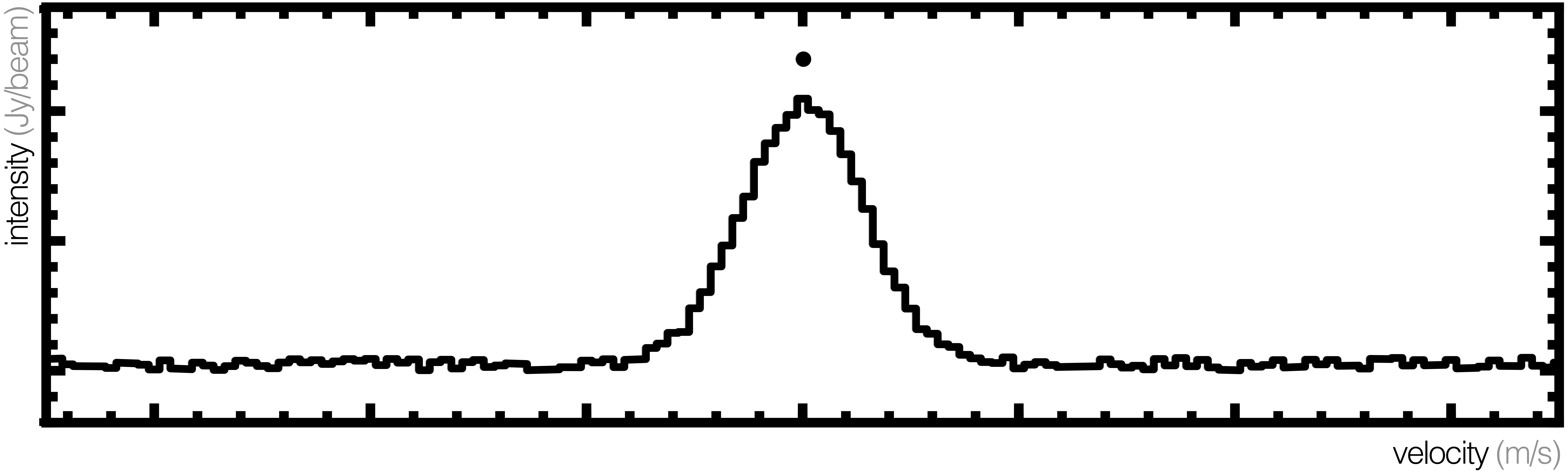
Much of the time we collapse the data into a *moment map* to ease interpretation.

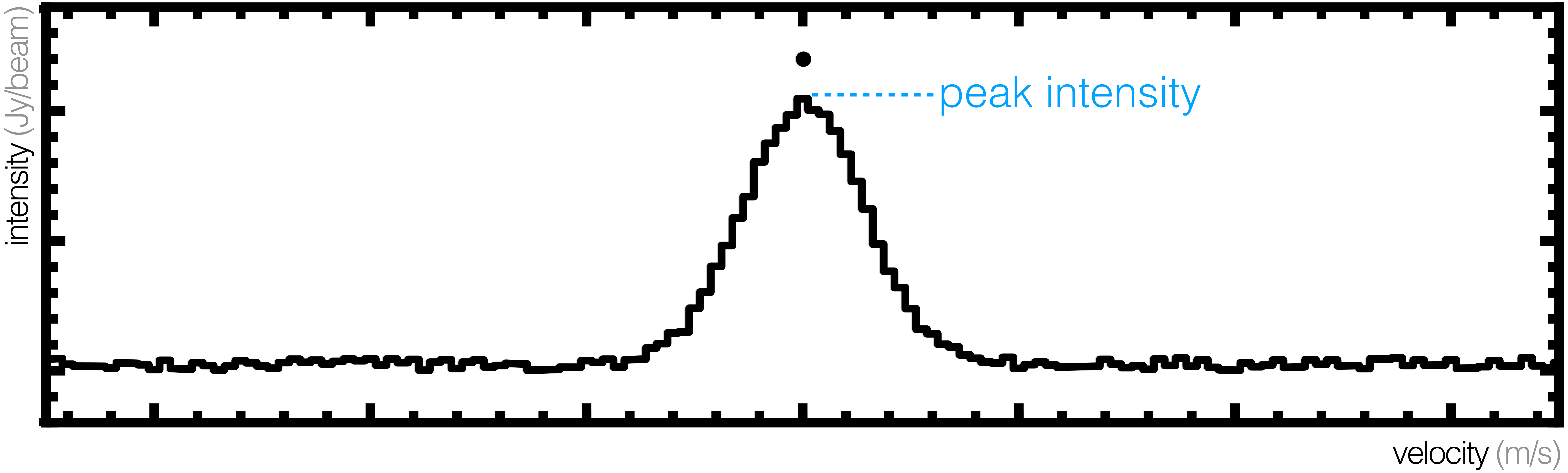
What can we learn if we *don’t* do this?

Charles J. Law using MAPS data.

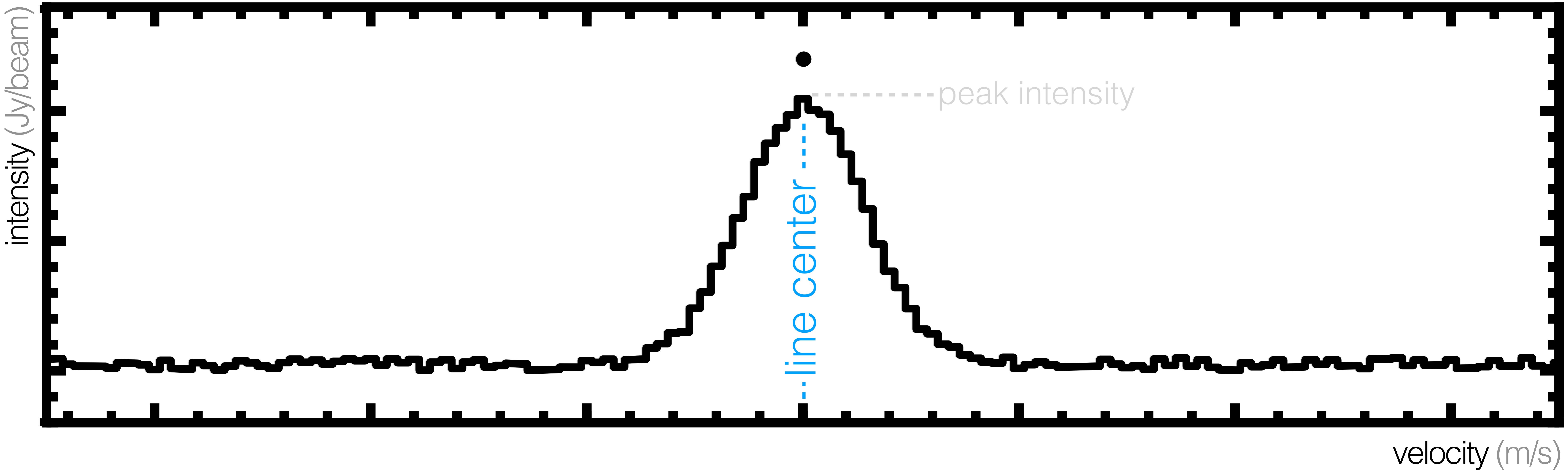


Each pixel is an emission line that has been Doppler shifted relative to the systemic velocity.


intensity (Jy/beam)
velocity (m/s)

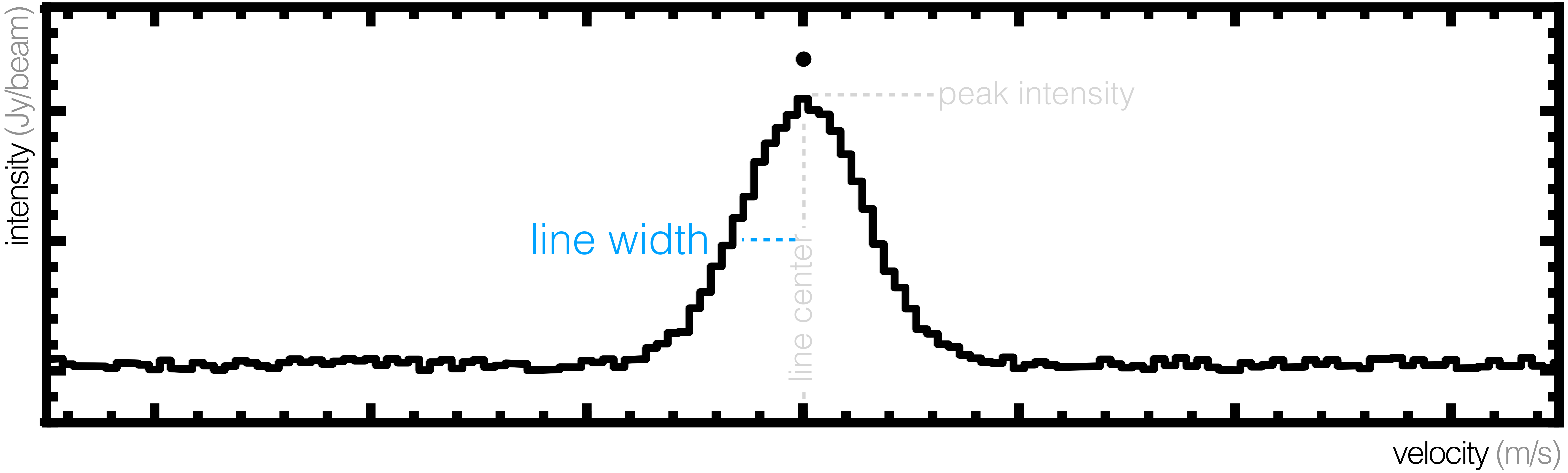


Peak Intensity: gas temperature, molecular column density.



Peak Intensity: gas temperature, molecular column density.

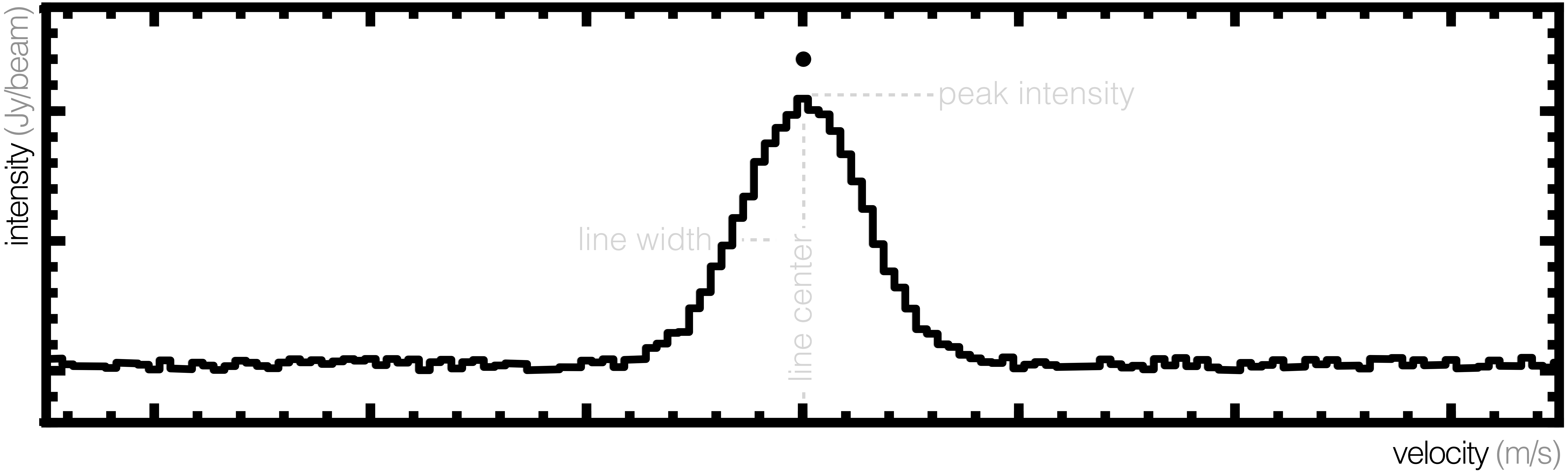
Line Center: (coherent) velocity structure.



Peak Intensity: gas temperature, molecular column density.

Line Center: (coherent) velocity structure.

Line Width: velocity dispersions.



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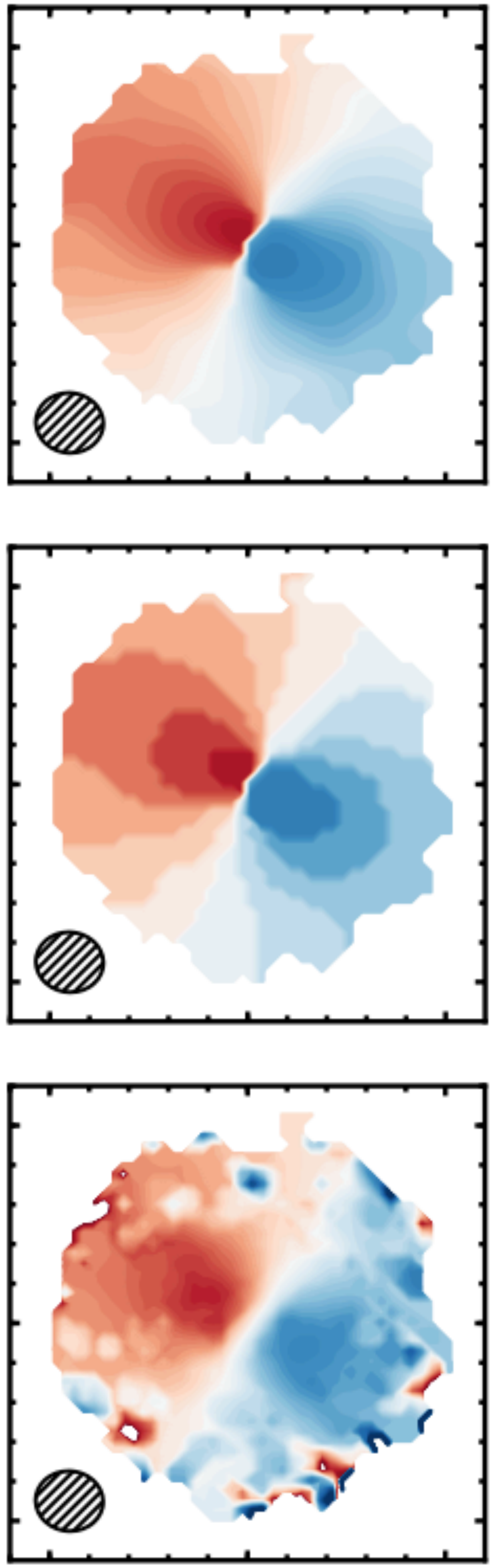


Fit an Analytical Form

pro: will always give the most accurate results
con: requires the line to be spectrally resolved

Fit a Quadratic Curve

pro: excellent approximation for low resolution data
con: very sensitive to noise in the data

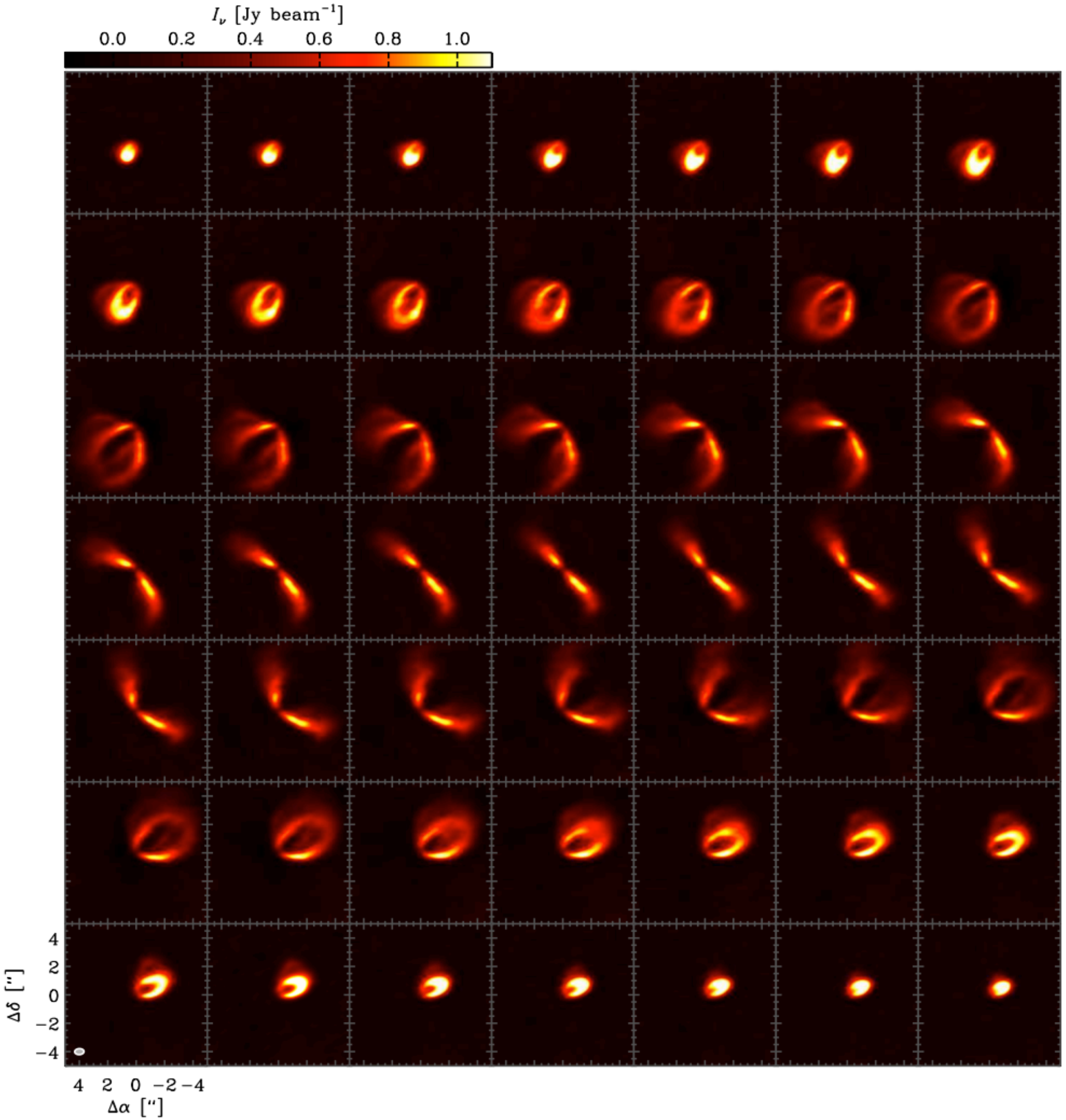
Take Peak Value

pro: minimal assumptions about underlying profile
con: precision limited by spectral resolution

Take Statistical Moments

pro: implemented in CASA
con: horrendously noisy

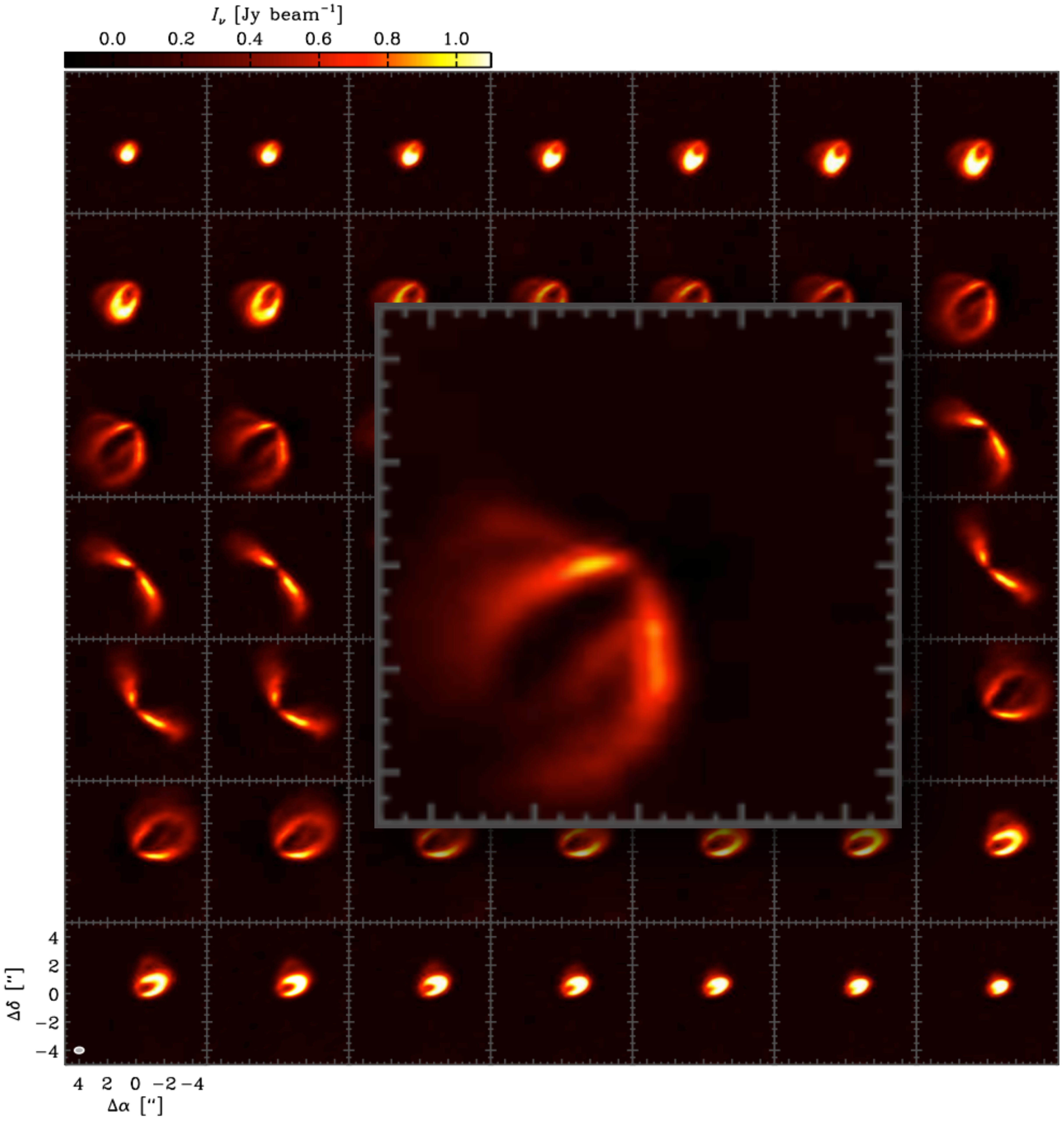
Teague & Foreman-Mackey (2018)



We're actually tracing *two* sides of the disk and we can start to map out the 3D structure of the disk.

Pinte et al. (2018), Teague et al. (2019), Keppler et al. (2019), Rich et al. (2021), Casassus et al. (2021), Law et al. (2021c)

Rosenfeld et al. (2013)



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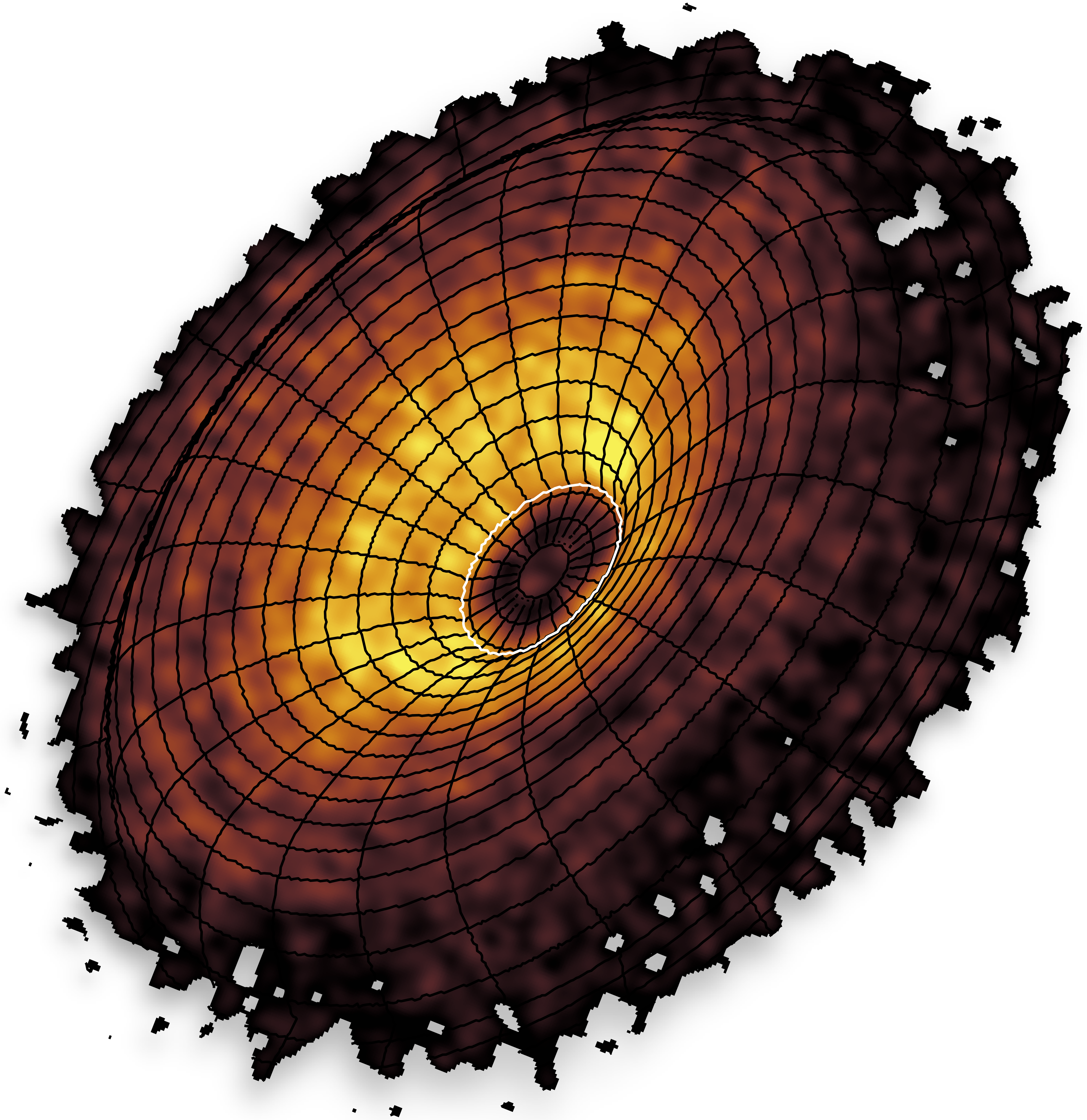

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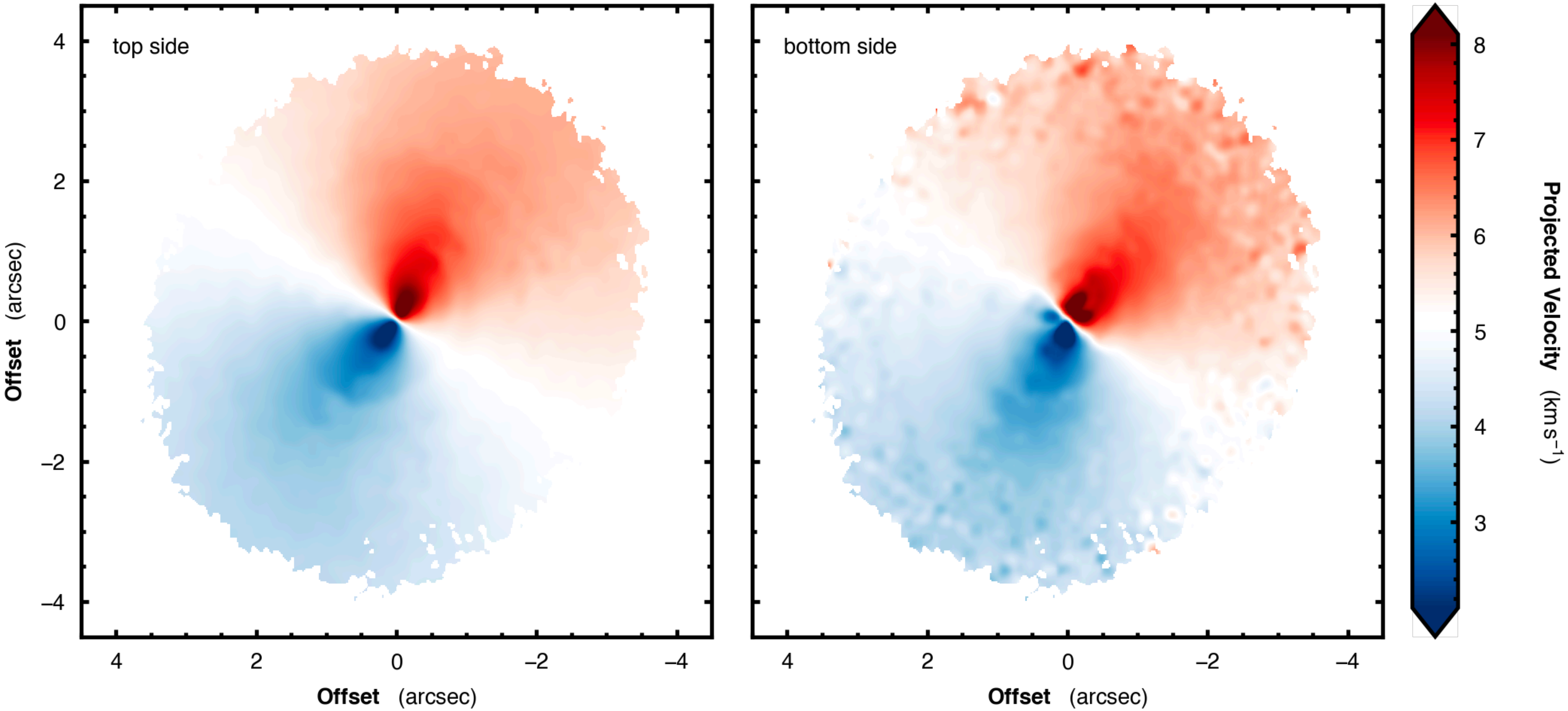

We can now map out the line properties of the front *and* the back of the disk with the same observation!

see Casassus et al. (2021) for application to HD 135344B

The velocity structure of the disk is dominated by rotation.

$$\frac{v_\phi(r,z)^2}{r} = \frac{GM_\star r}{(r^2+z^2)^{3/2}} + \frac{1}{\rho_{\rm gas}}\frac{\partial P_{\rm gas}}{\partial r} + \frac{\partial \phi_{\rm gas}}{\partial r}$$

Keplerian Rotation: Stellar mass, 3D structure of the emission surface.

Simon et al. (2000, 2017, 2019), Czekala et al. (2015, 2016, 2017)

Pressure Support: Radial temperature and density gradients.

Teague et al. (2018ac, 2019), Dullemond et al. (2020), Rab et al. (2020), Rosotti et al. (2020), Yu et al. (2021)

Self-Gravity: Disk surface density.

Veronesi et al. (2021)

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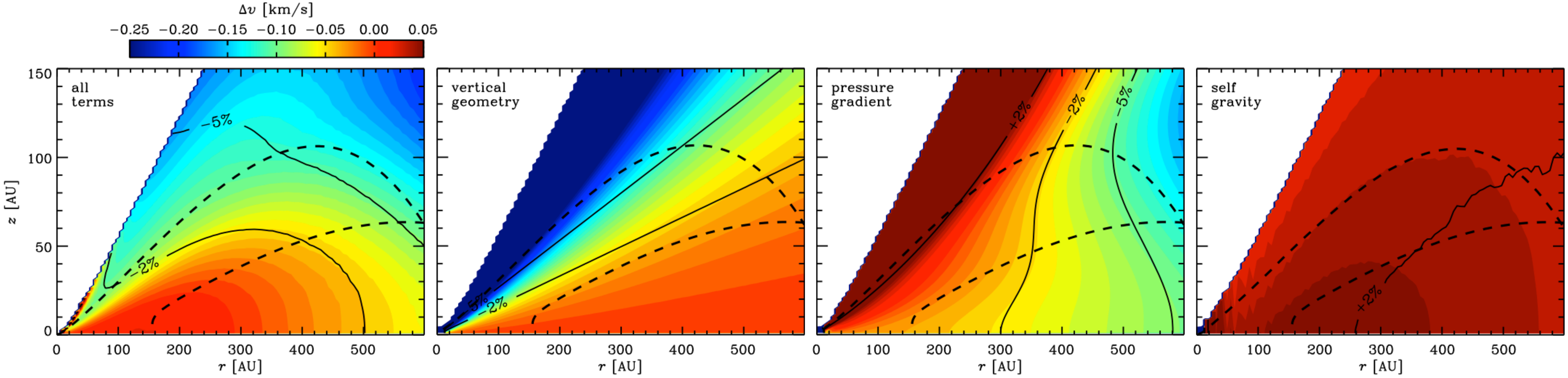
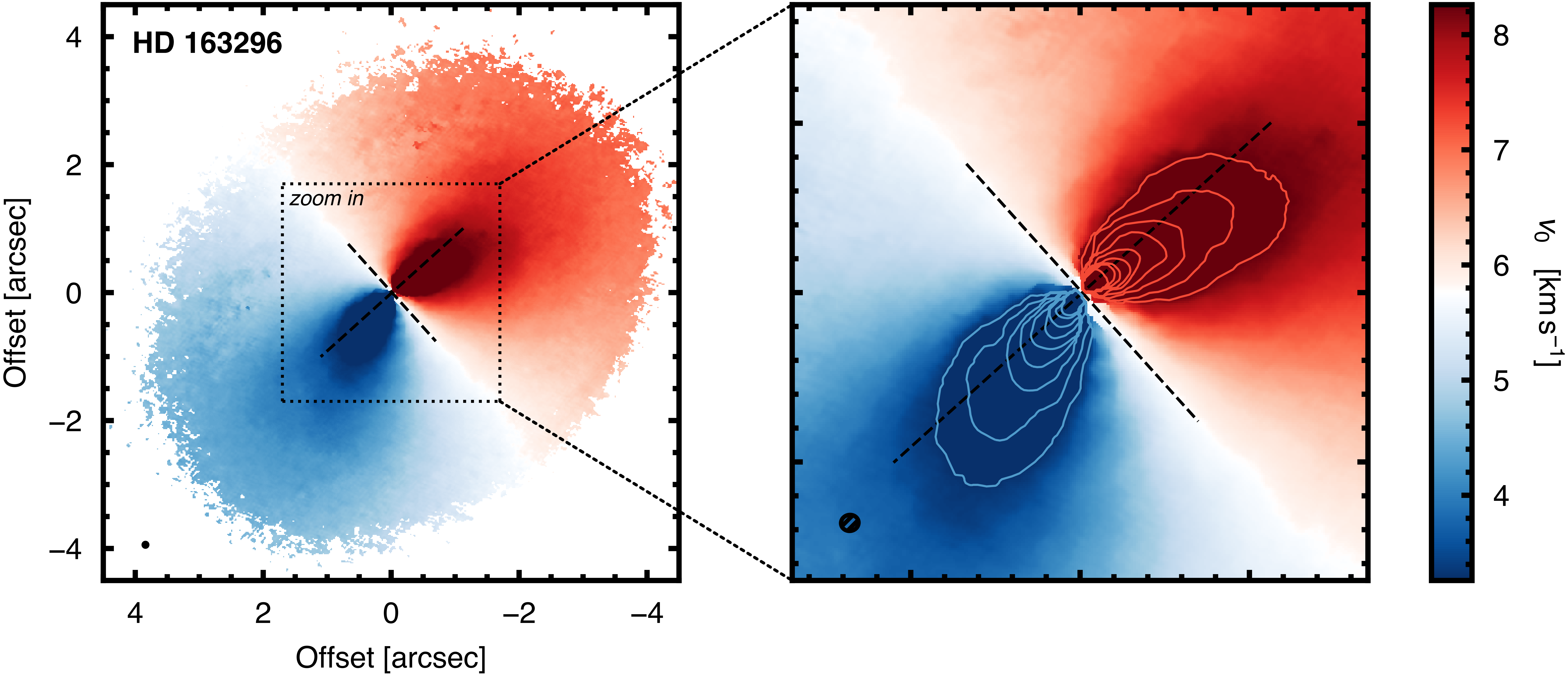
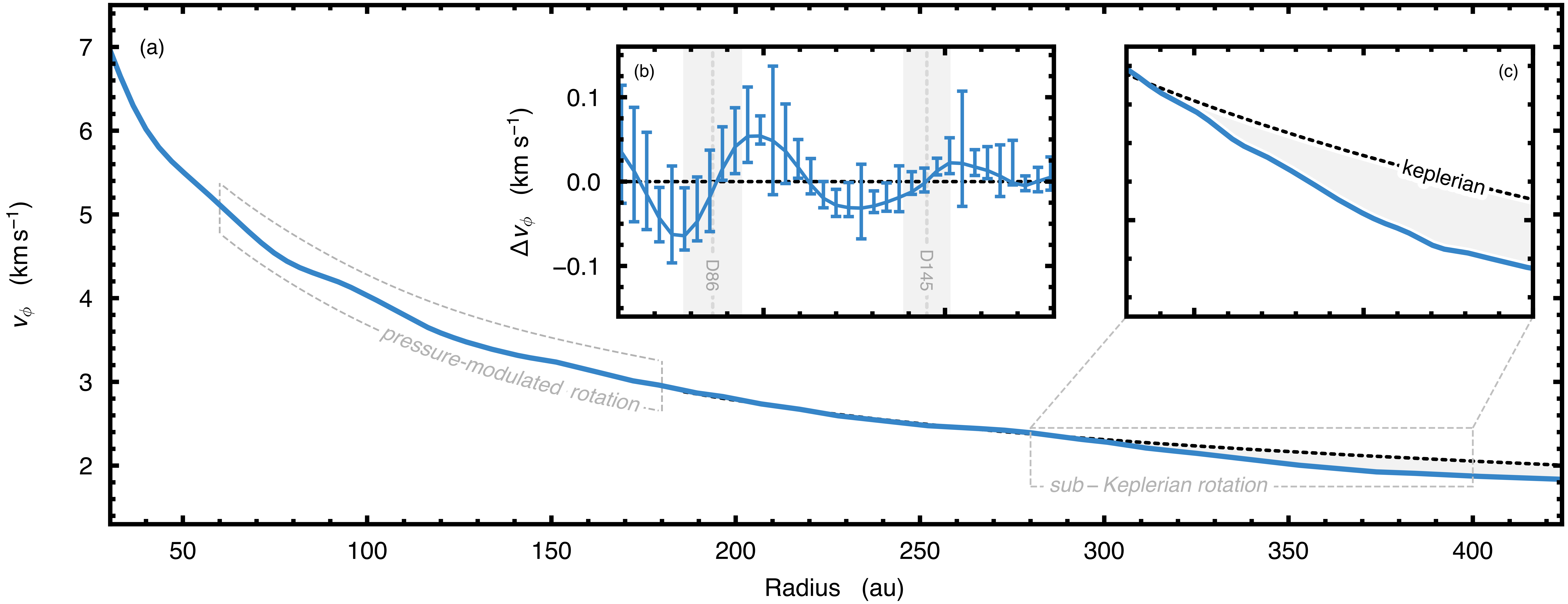


adapted from Rosenfeld et al. (2013)



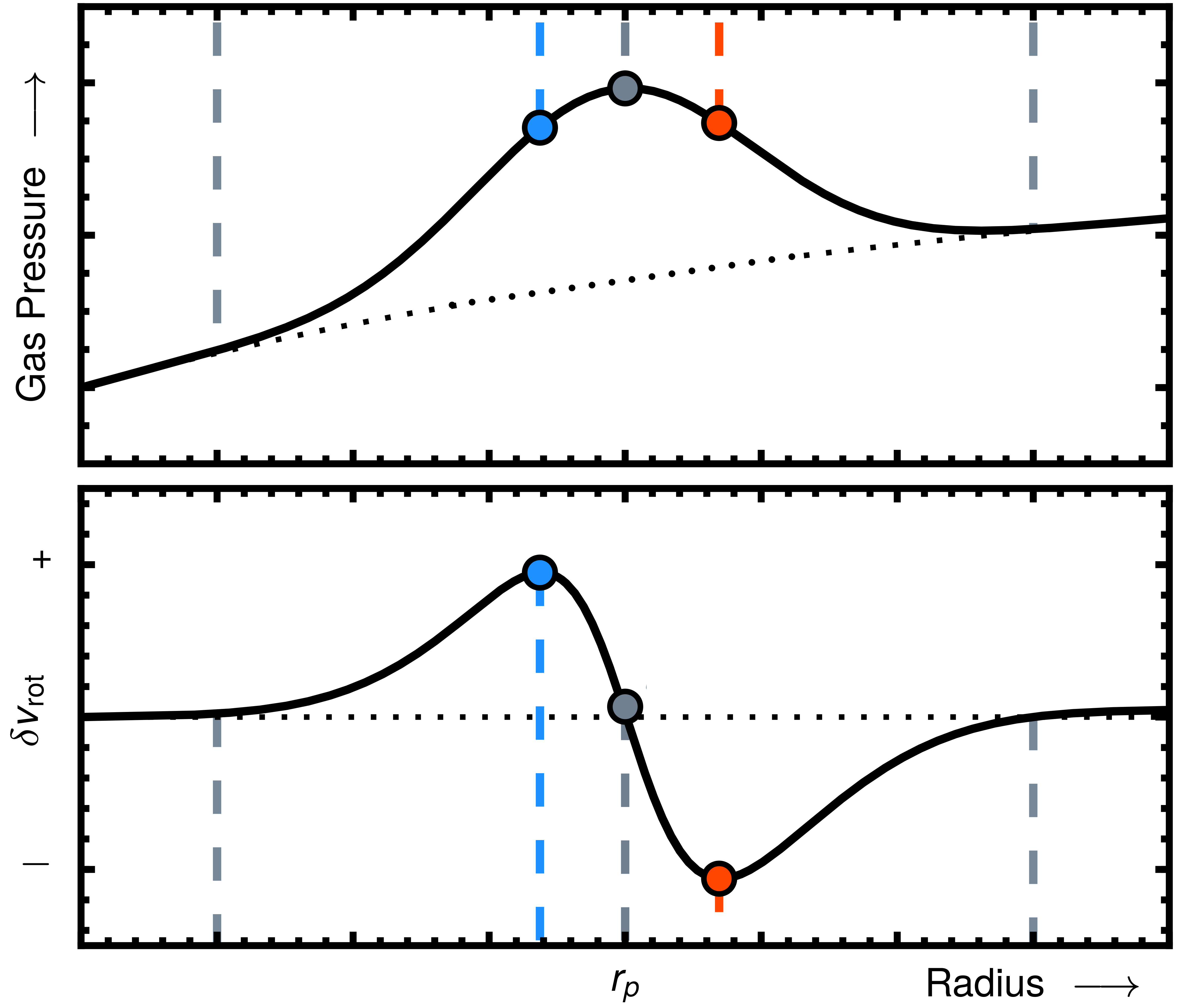
data from DSHARP; Andrews et al. (2018), Isella et al. (2018)



By assuming azimuthal symmetry, we can extract a rotation curve achieving a precision of less than 10 ms^{-1}.

conerot (Casassus et al., 2021) // eddy (Teague 2019)

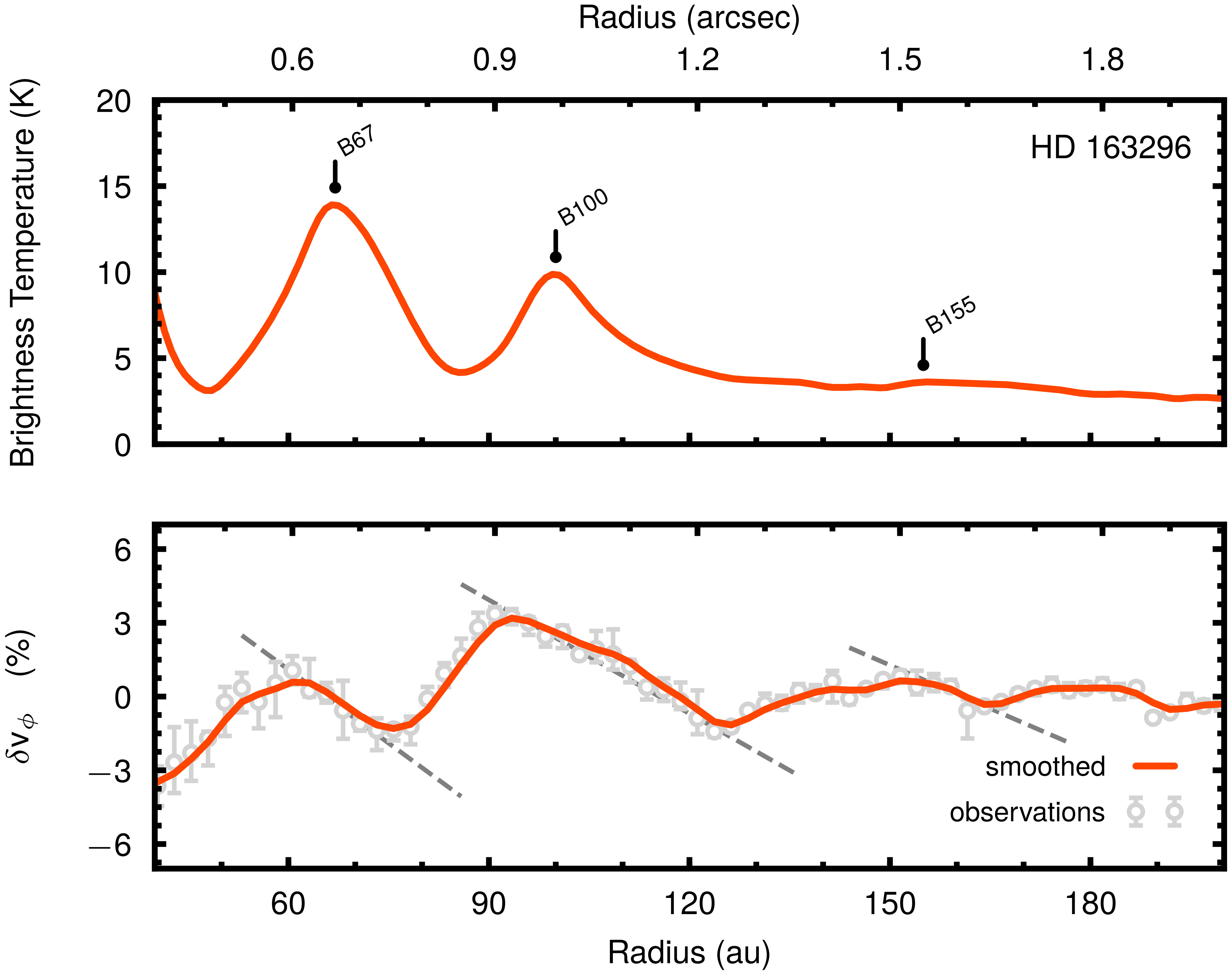
adapted from Pinte et al. (PPVII Review)



Localized changes in the rotation velocity allow us to infer the presence of substructure in the gas pressure.

see also Kanagawa et al. (2015)

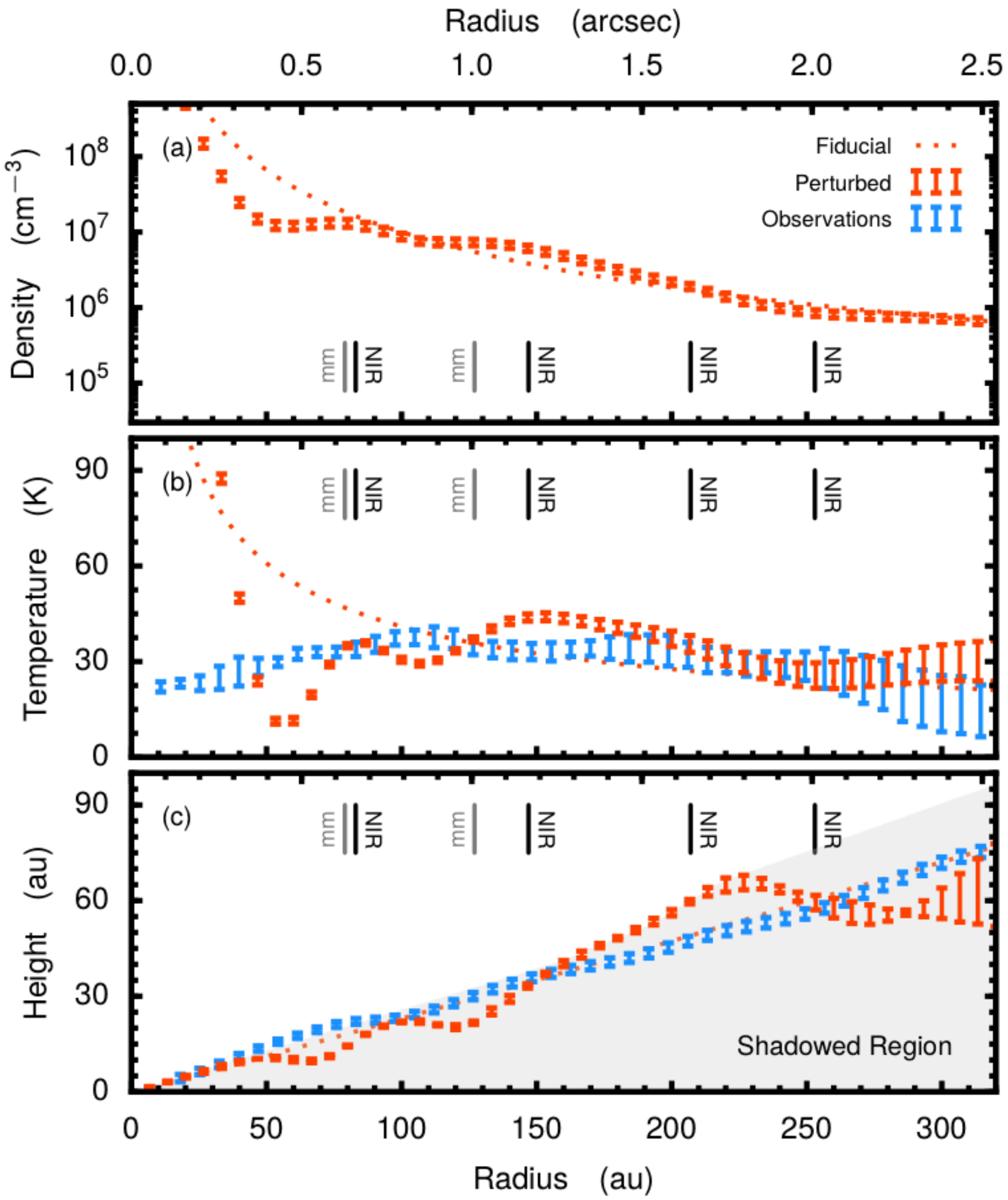
adapted from Teague et al. (2018)



We can also use this to test the efficiency of grain trapping and the coupling between gas and dust.

$$\frac{\alpha_{\mathrm{turb}}}{\mathrm{St}} = \left[\left(\frac{w_{\mathrm{gas}}}{w_{\mathrm{dust}}}\right)^2 - 1\right]^{-1}$$

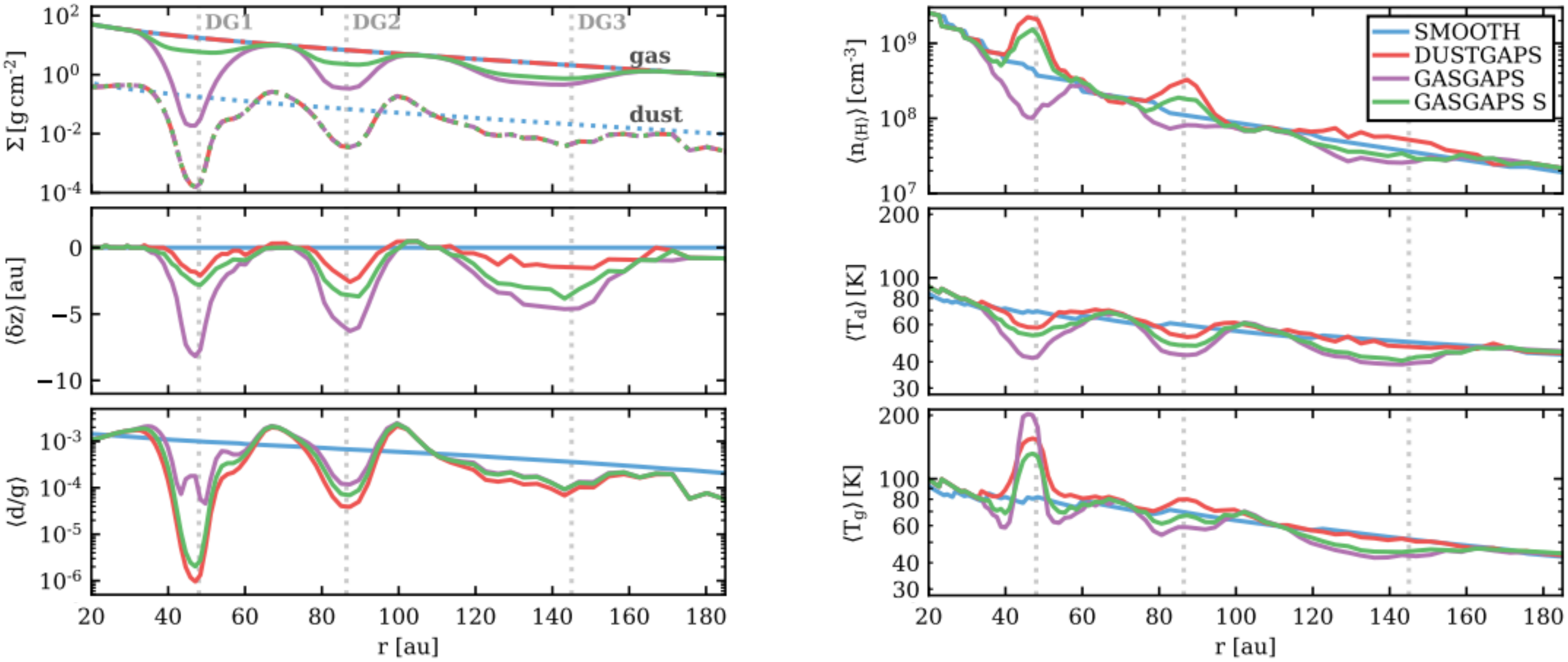
Dullemond et al. (2018), Rosotti et al. (2020)



Under certain assumptions we can start to reconstruct the underlying density and temperature profiles.

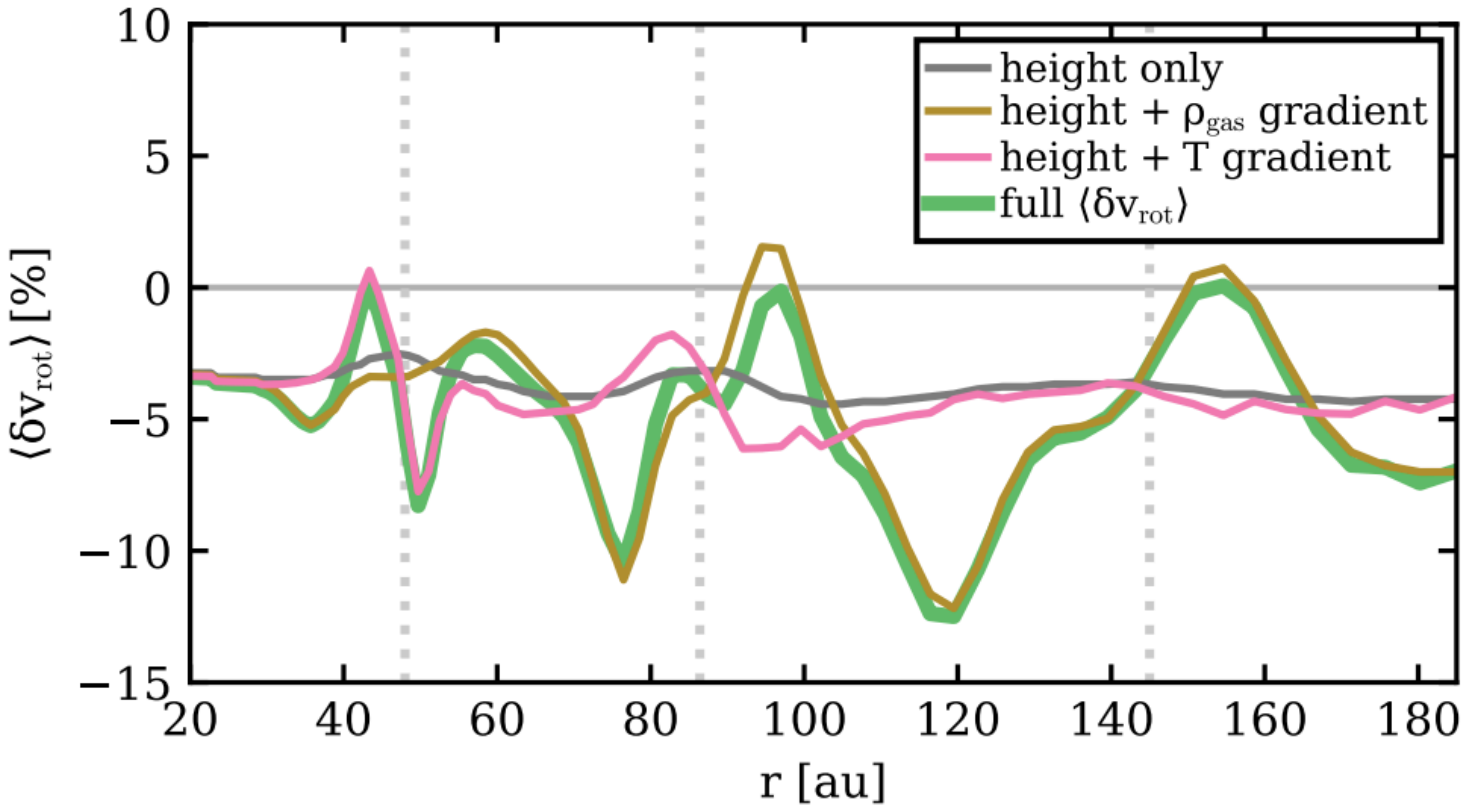
see also Yu et al. (2021)

Teague et al. (2018c)



Velocity perturbations sensitive to both temperature *and* density in the gap.

Rab et al. (2020)



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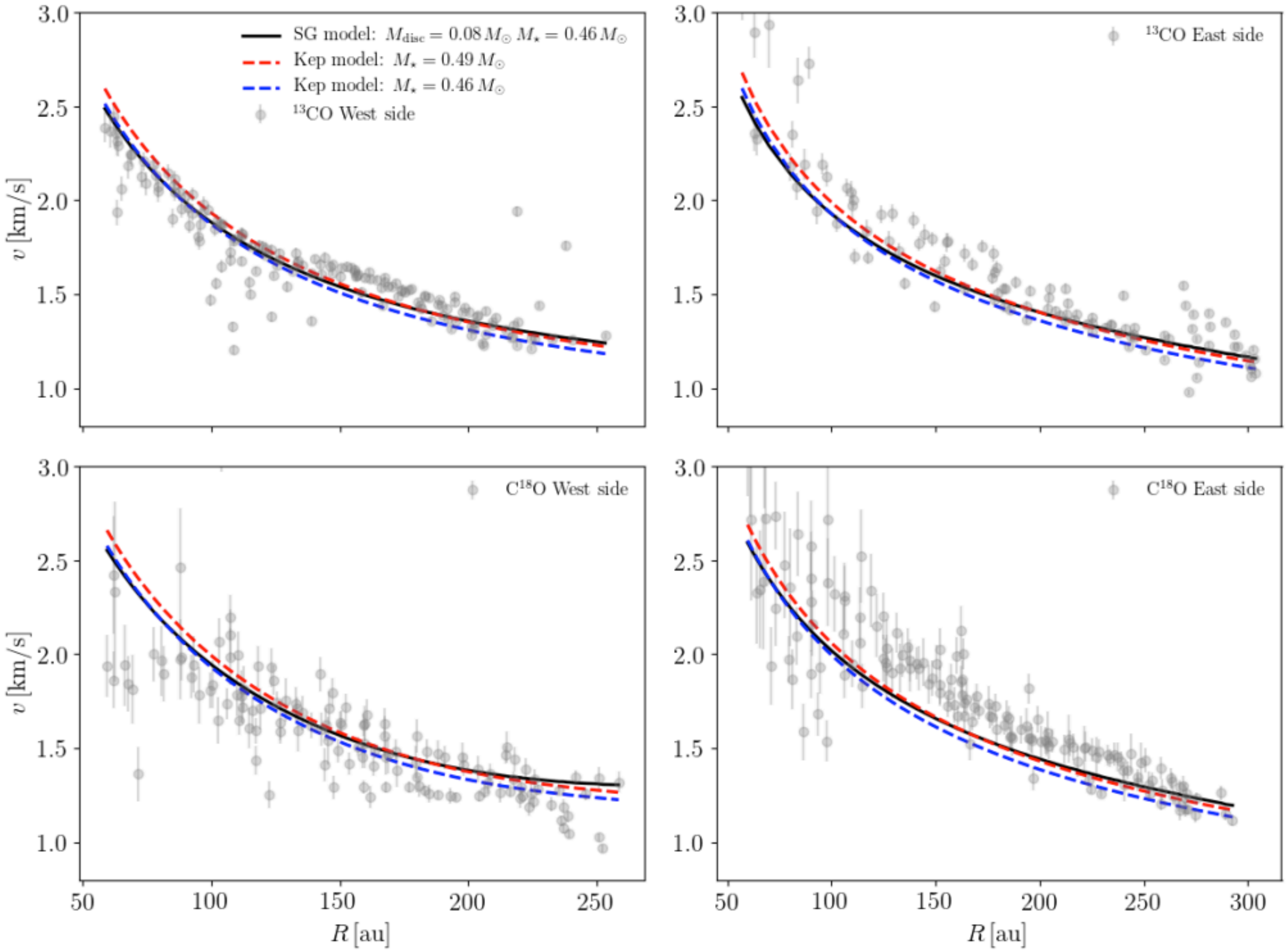


With sufficiently sensitive observations we can search for the imprints of self-gravity.

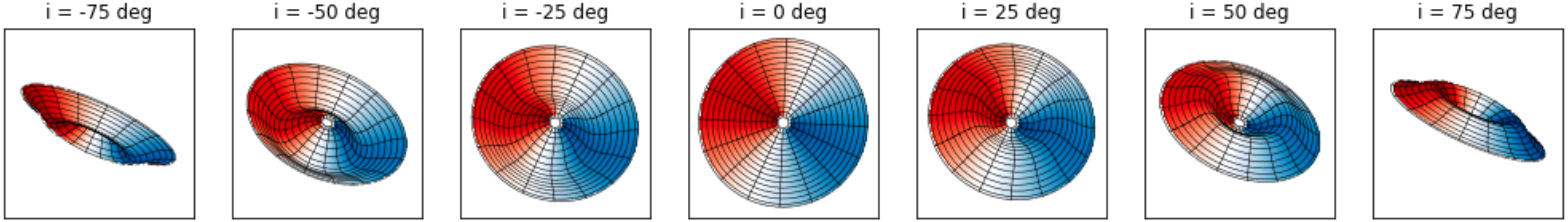
Caveat: Can we disentangle pressure support and self-gravity?

Veronesi et al. (2021)

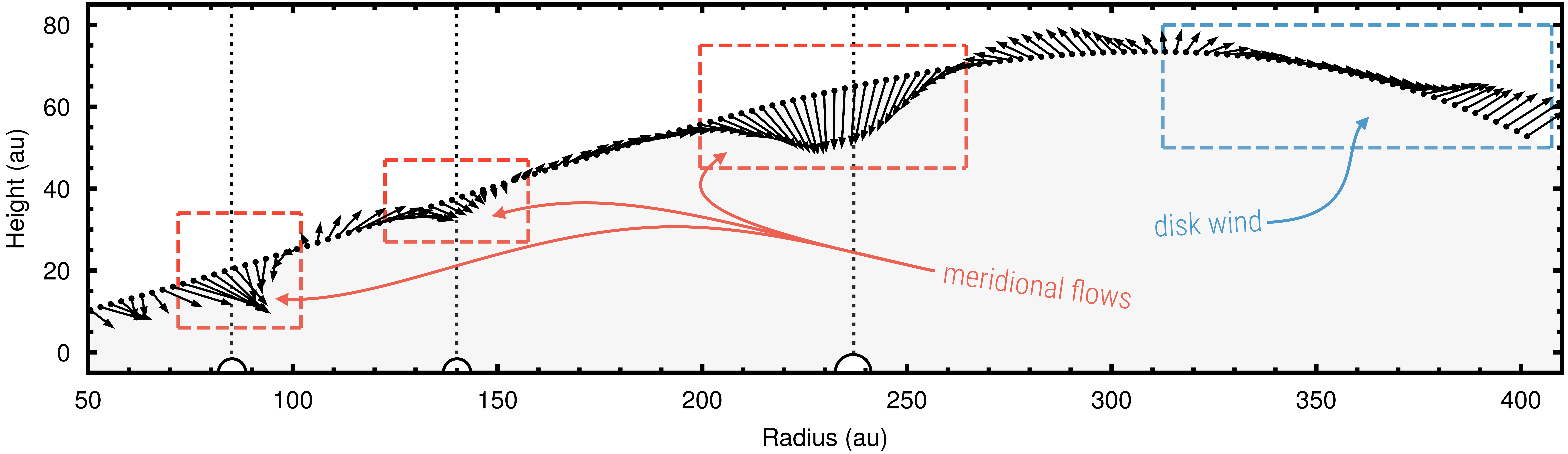
Really what we see if the superposition of *all* velocity components projected along the line of sight.

$$v_0 = v_\phi \cos(\phi)\,|\sin(i)| + v_r \sin(\phi)\sin(i) + v_z \cos(i) + v_{\mathrm{LSR}}$$

We can leverage our 3D reconstruction to account for that projection.



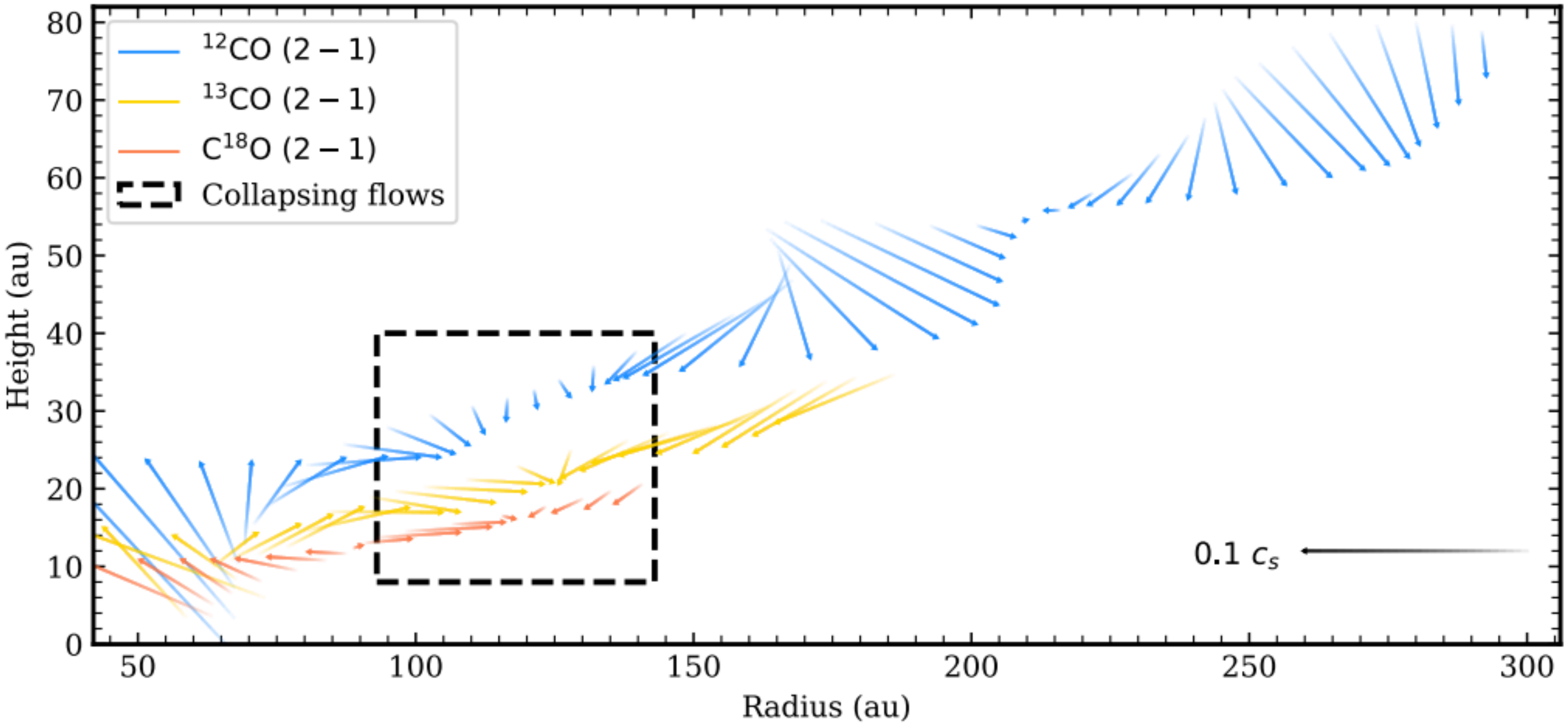
plots made with GoFish



It is now possible to map out the velocity structure in the (r, z) plane allowing for a direct comparison to numerical simulations.

also see Casassus et al. (2021)

Teague et al. (2019a)



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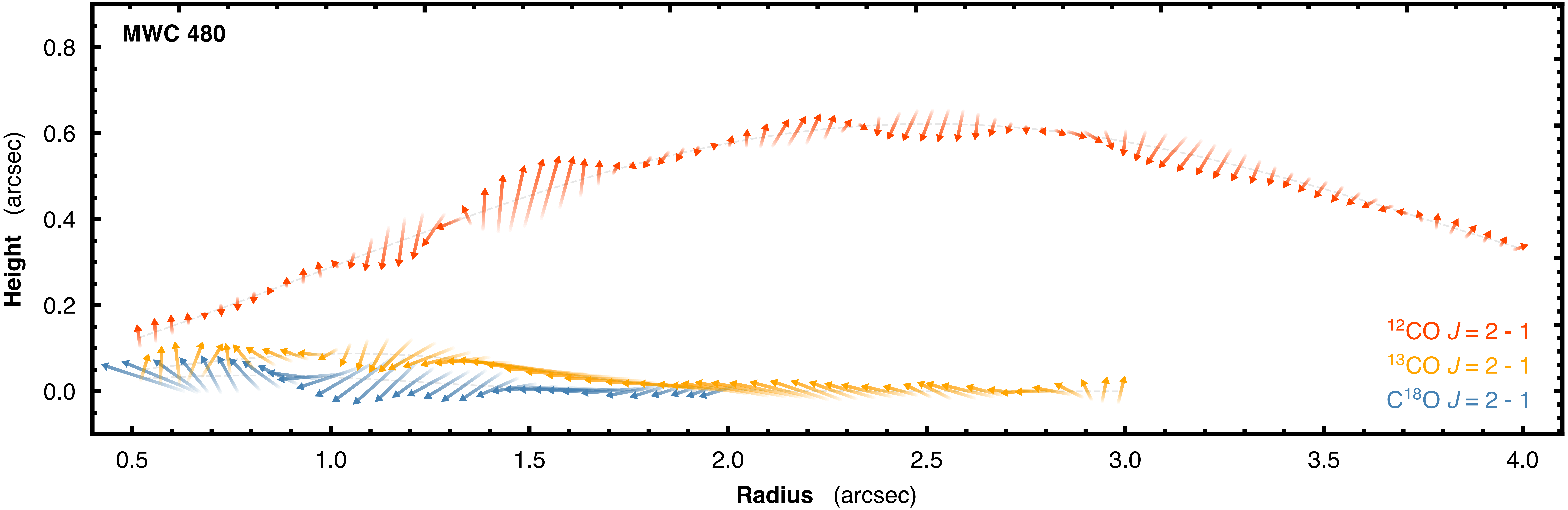


It is now possible to map out the velocity structure in the (*r*, *z*) plane allowing for a direct comparison to numerical simulations.

also see Casassus et al. (2021)

Teague et al. (in prep.)

These sort of profiles will allow us to better compare with simulations.

see Szulagi et al. (2014), Morbidelli et al. (2014), Fung & Chiang (2017), Teague et al. (2019) for similar predictions from meridional flows.

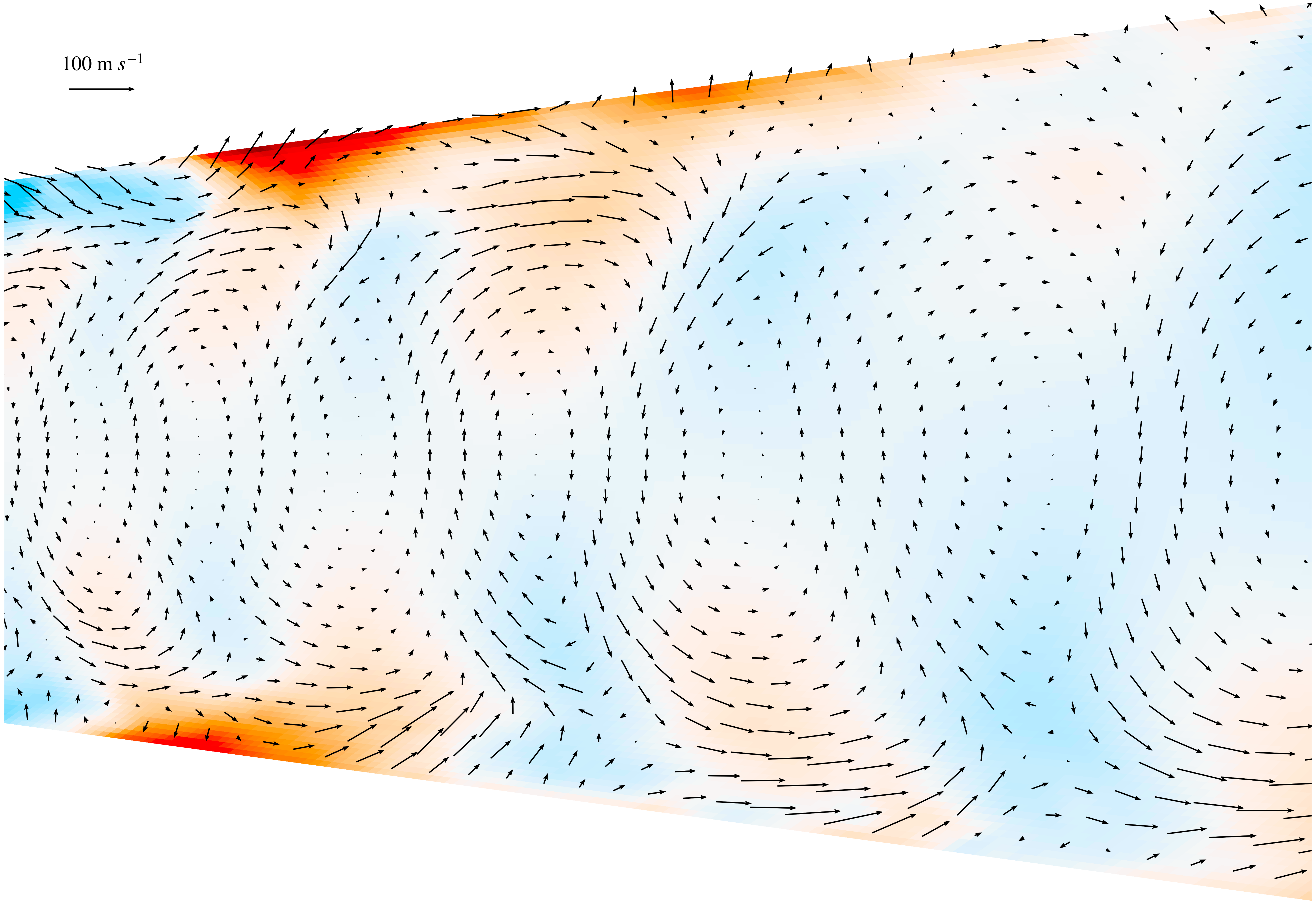
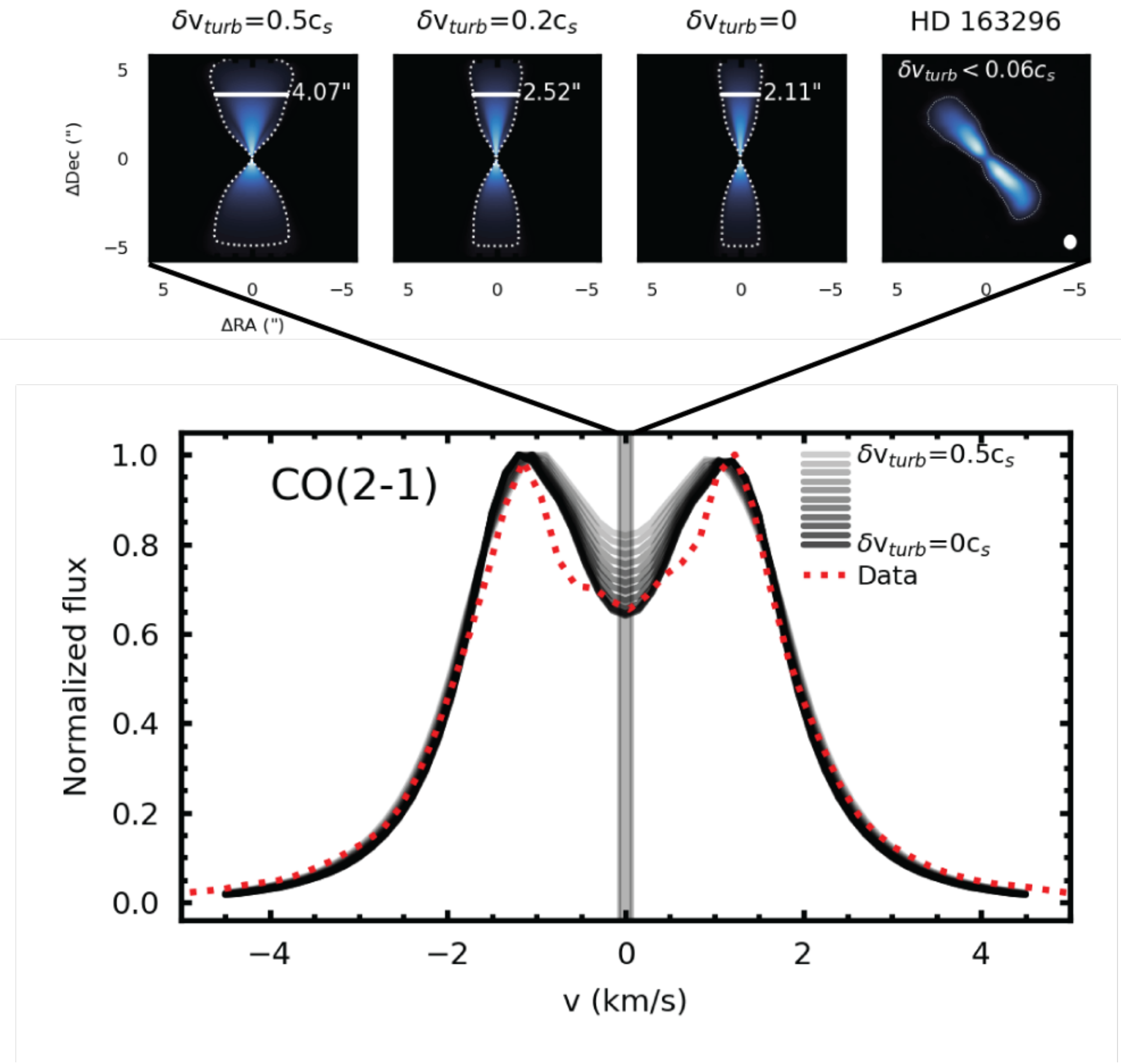


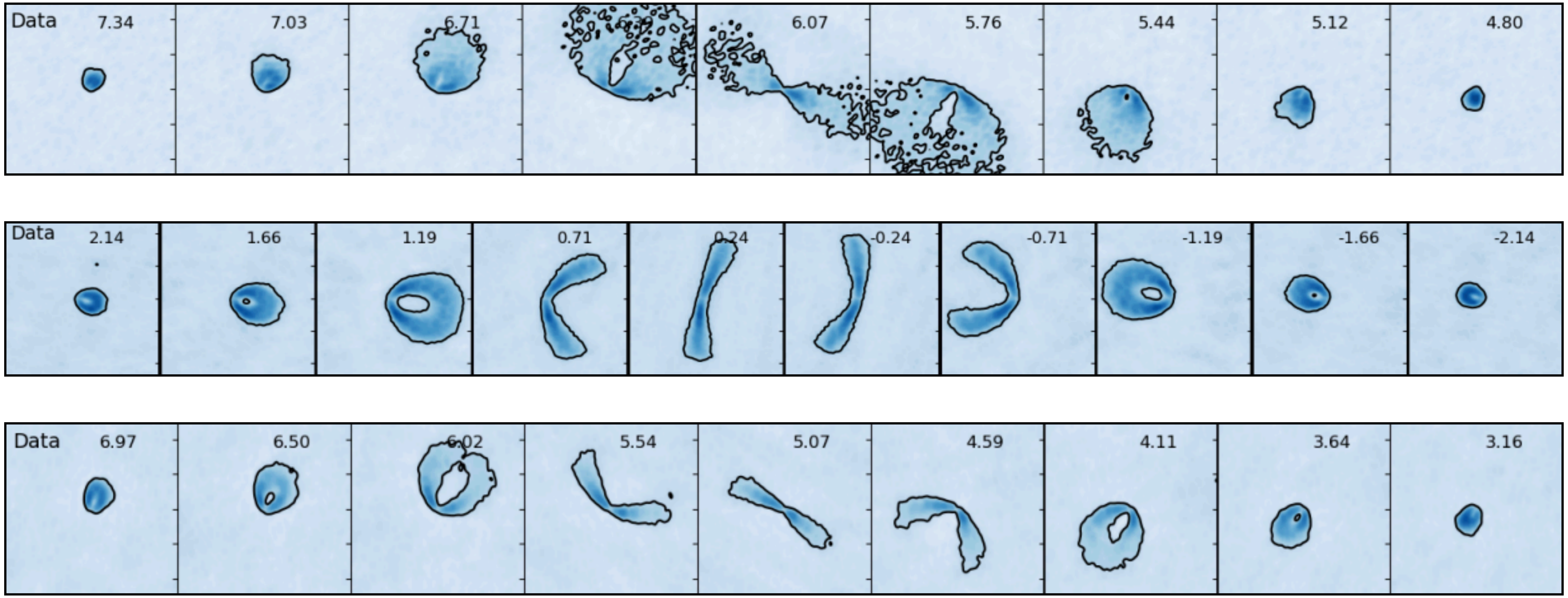
figure courtesy of Marcelo Barraza

By modeling the resolved line profile we can try and measure any non-thermal contribution to broadening.

Hughes et al.(2011), Guilloteau et al. (2012),
Flaherty et al. (2015, 2017, 2018, 2020),
Teague et al. (2016, 2018)



Pinte et al. (PPVII Review)



DM Tau
$\alpha \sim 8 \times 10^{-2}$

V4046 Sgr
$\alpha \lesssim 10^{-3}$

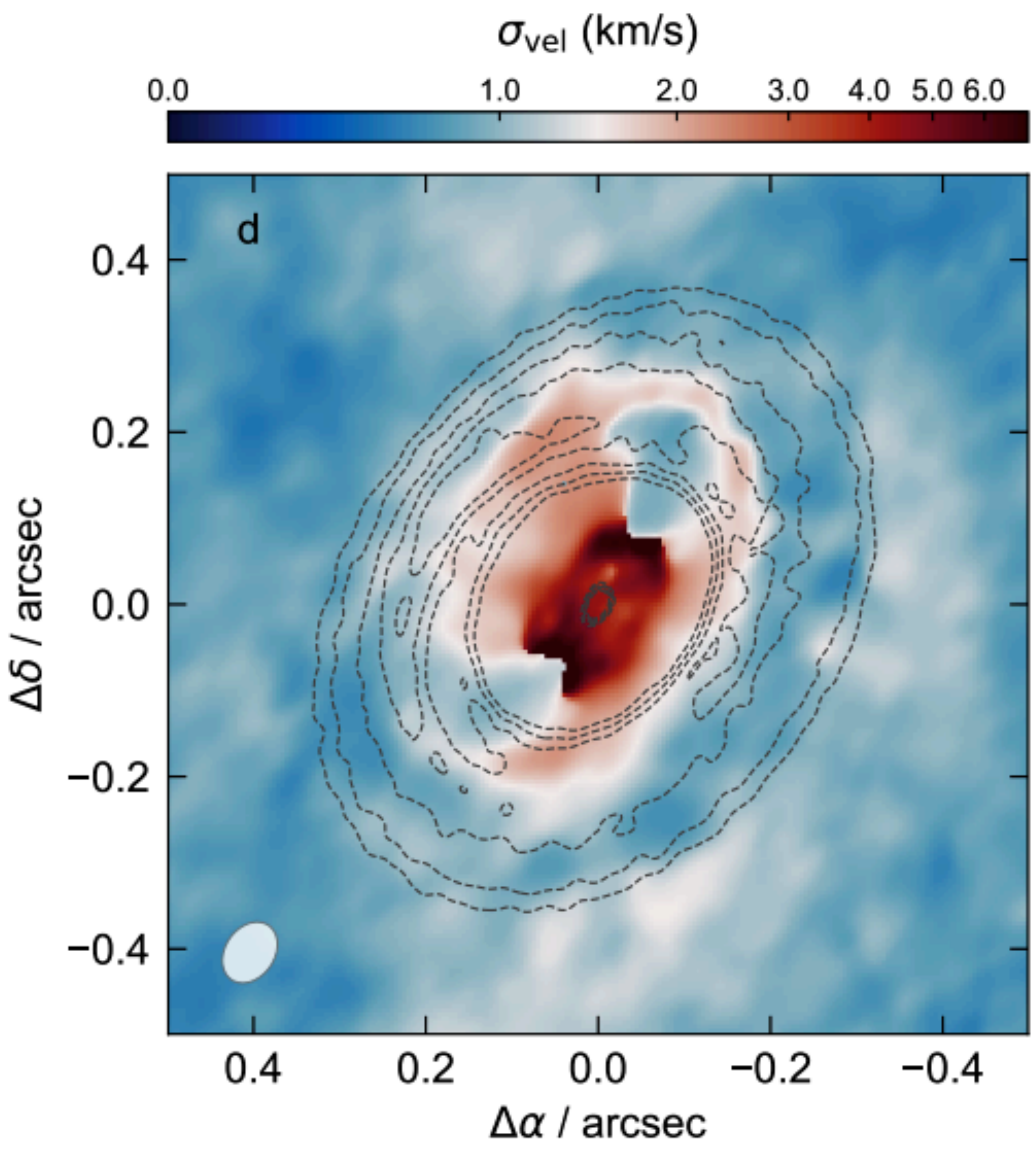
MWC 480
$\alpha \lesssim 10^{-3}$

Spatially resolved observations suggest DM Tau has turbulent motions, consistent with Guilloteau et al. (2012).

Caveat: Do we know the systematics?

see, for example, Teague et al. (2016) and Andrews et al. (in prep.)

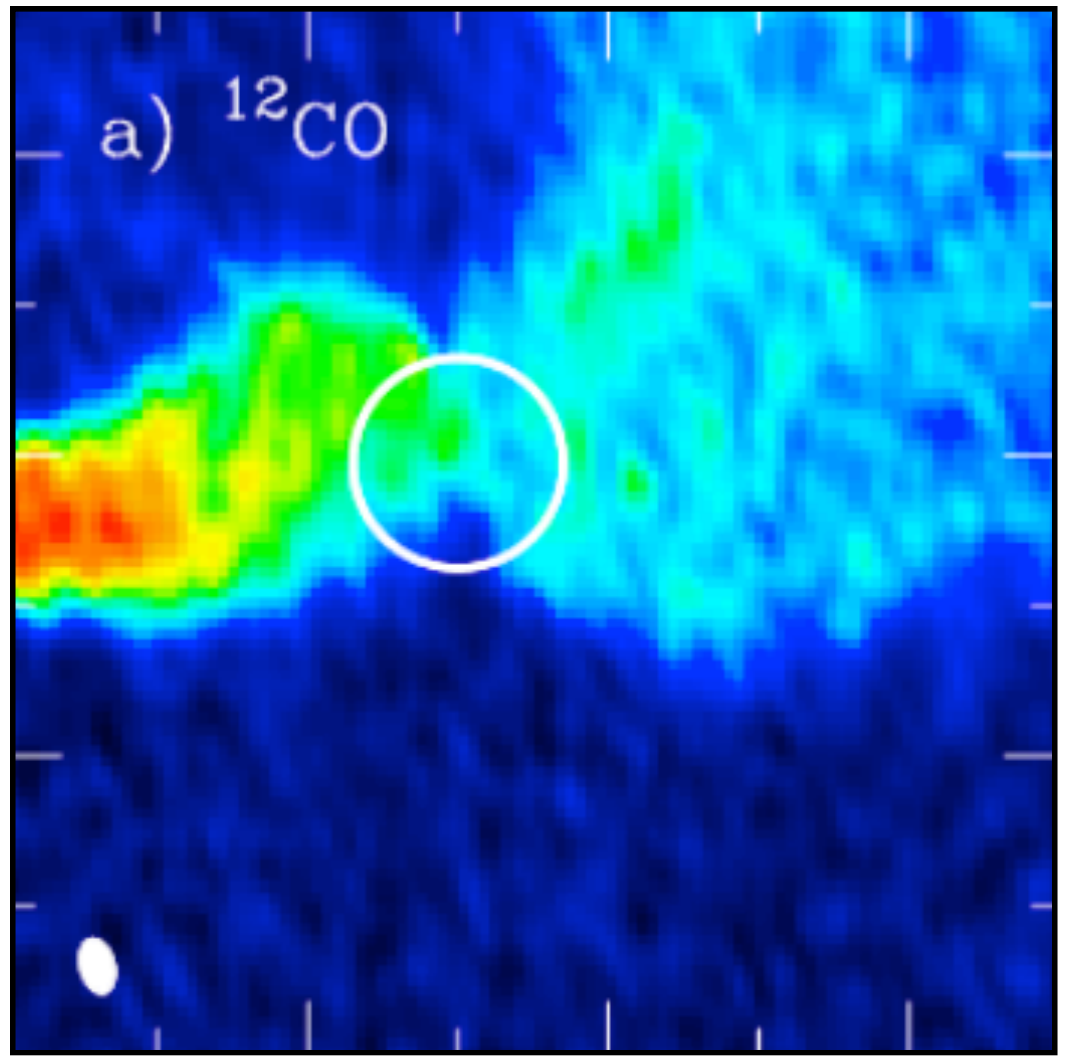
Flaherty et al. (2020)

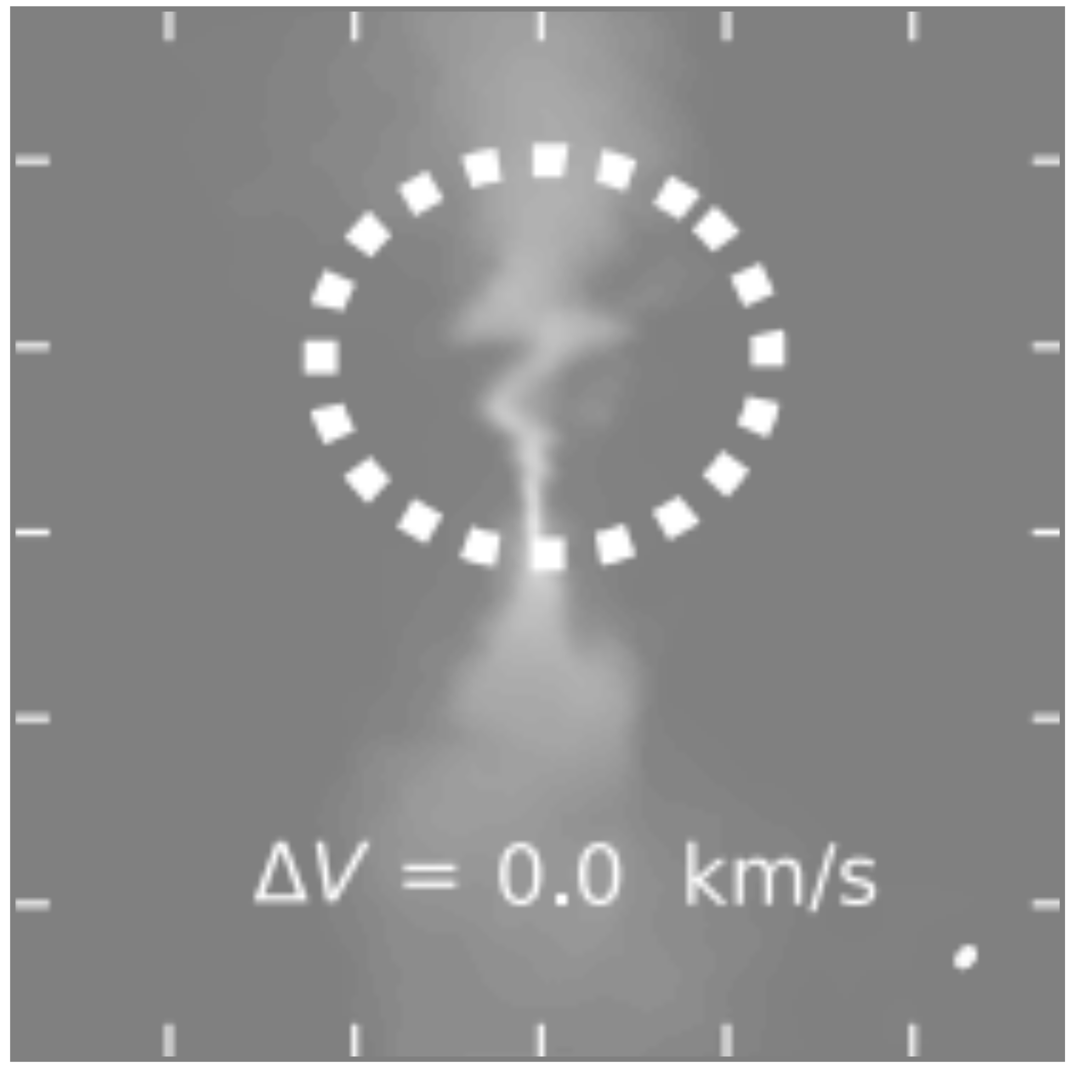


We can start to do this in a spatially resolved manner to search for localized broadening.

See also Casassus et al. (2021)

Perez et al. (2020)





Embedded Planets: ‘kinks’ around the planet’s location.

Perez et al. (2015), Pinte et al. (2018, 2019, 2020)

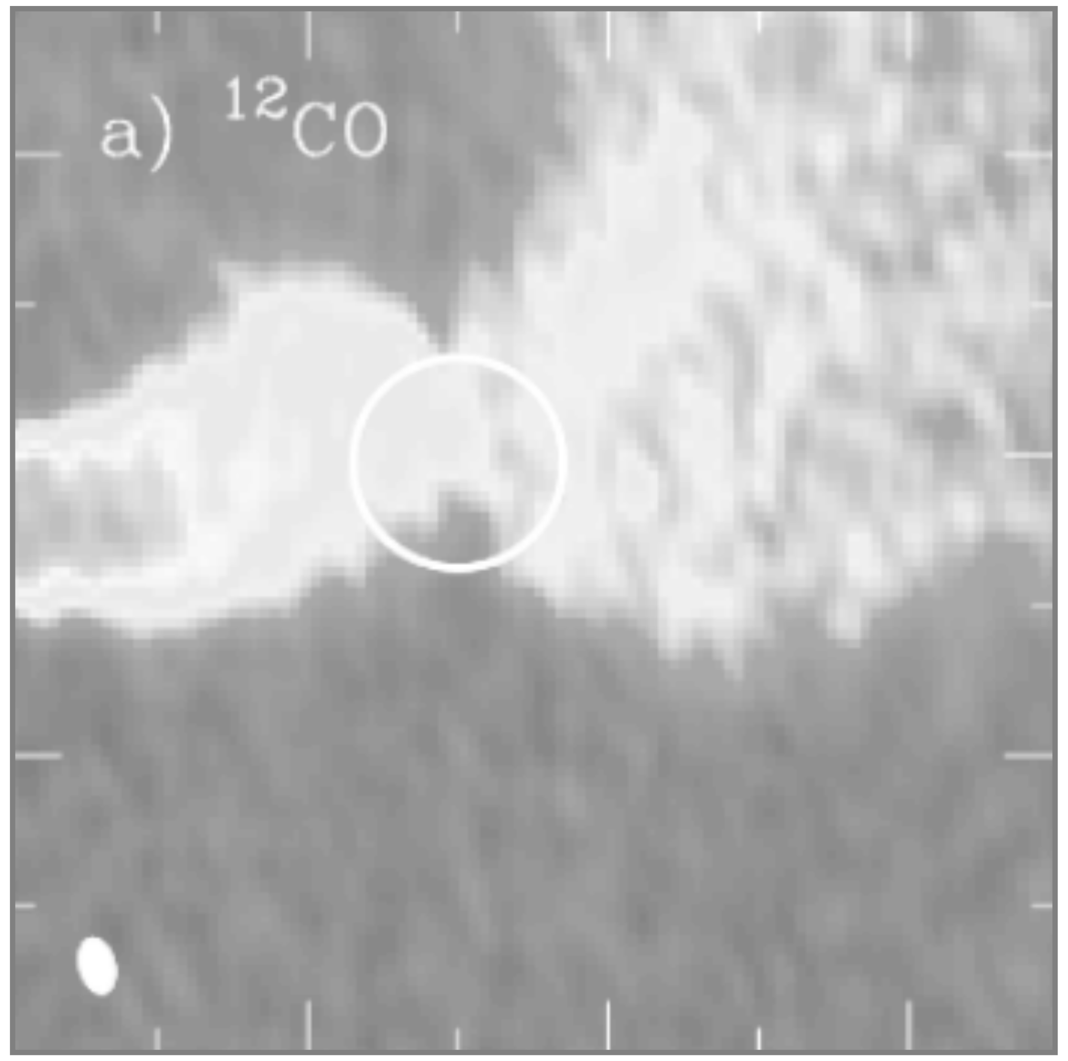
Buoyancy Resonances: ‘spurs’ in the central channel and ‘arcs’ across the major axis.

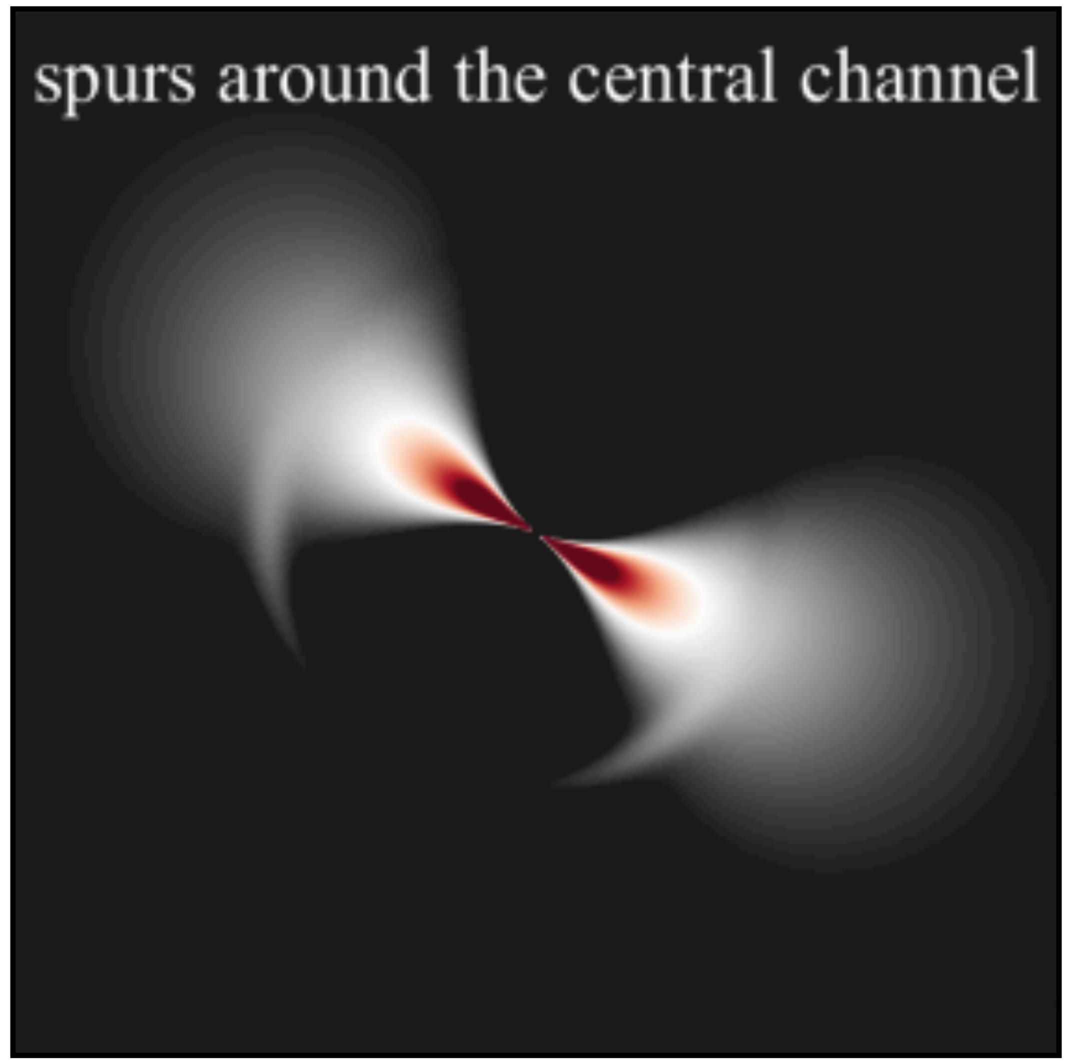
Bae et al. (2021)

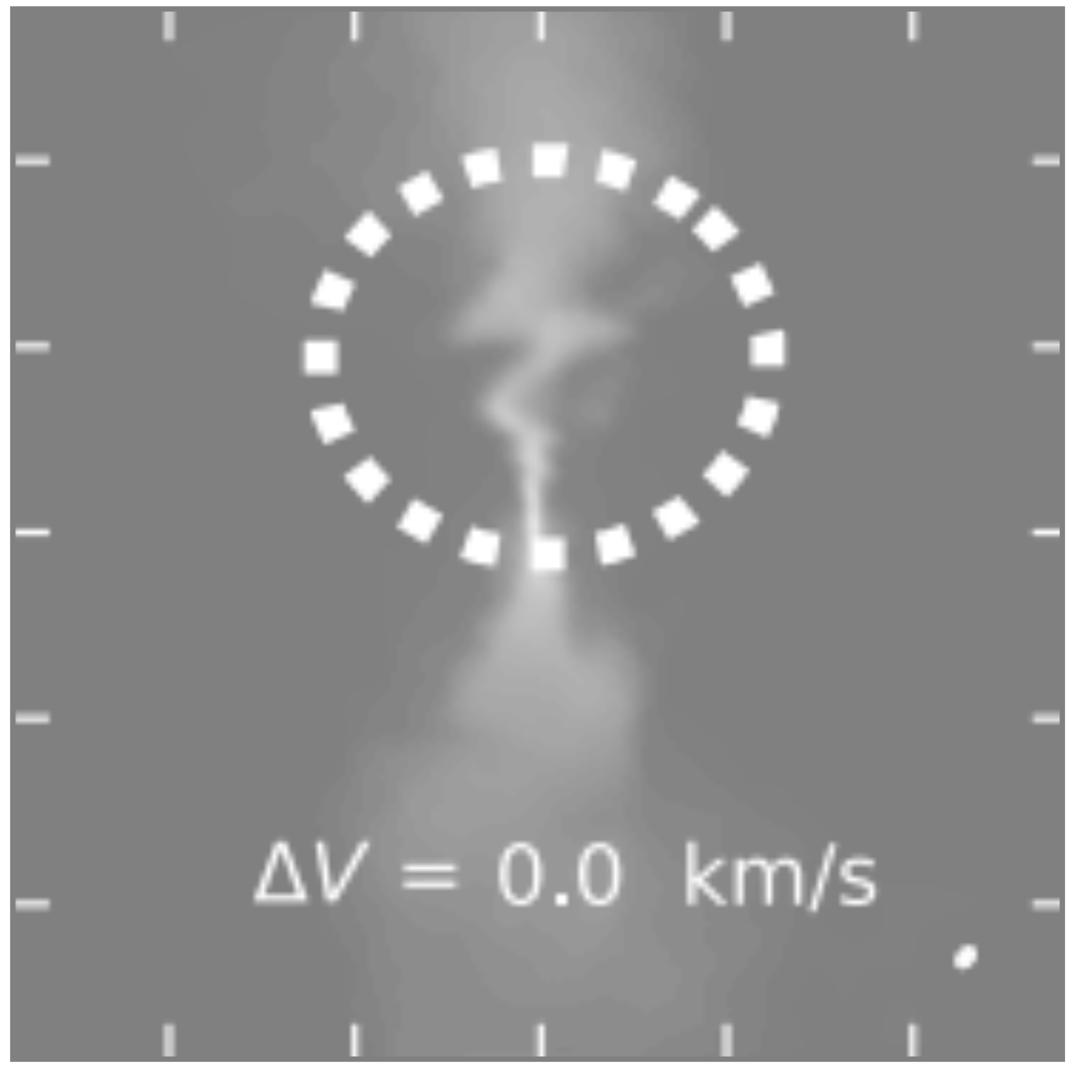
Gravitational Instability: ‘wiggles’ seen in most channels.

Hall et al. (2020), Paneque-Carreño et al. (2021), Longarini et al. (2021)

Perez et al. (2015), Hall et al (2020), Bae et al. (2021)







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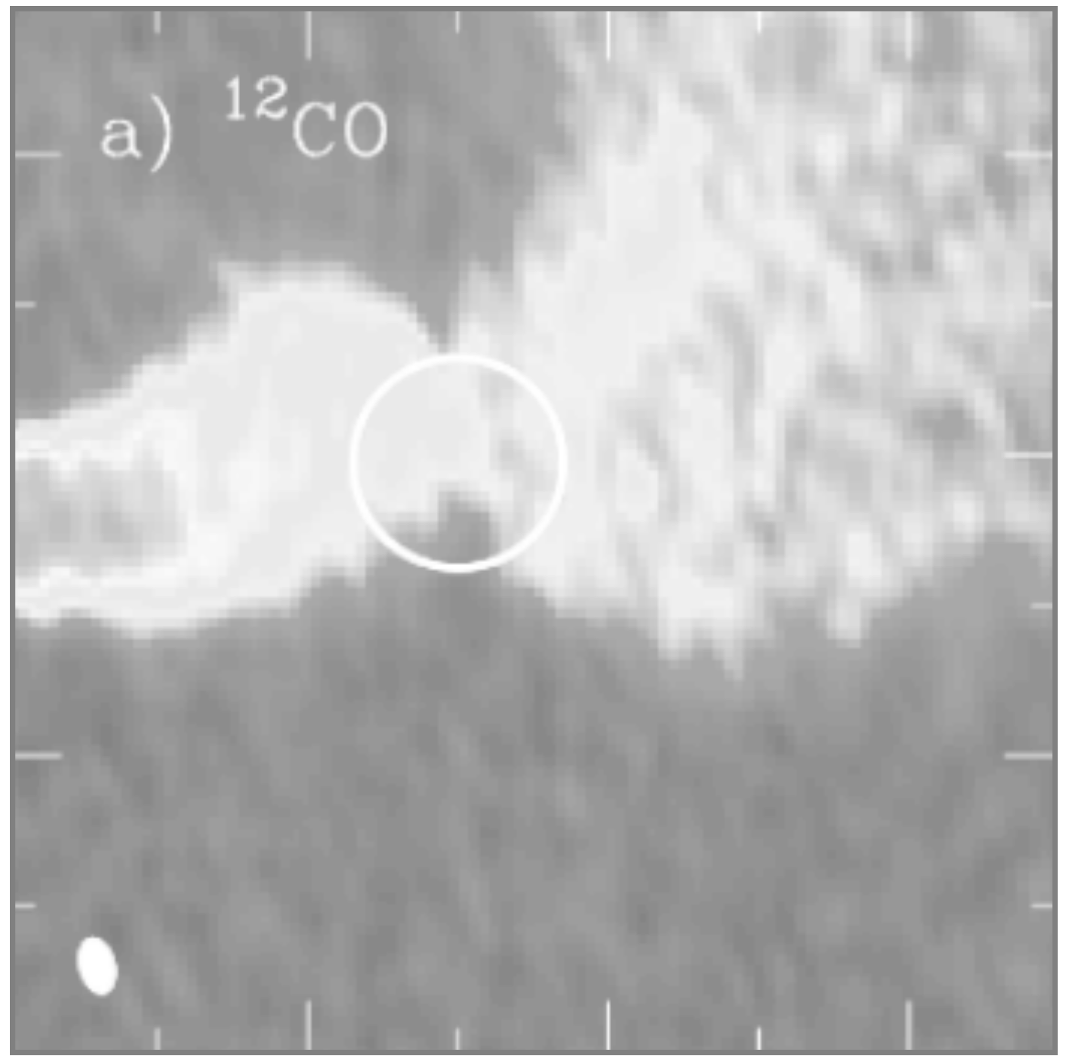
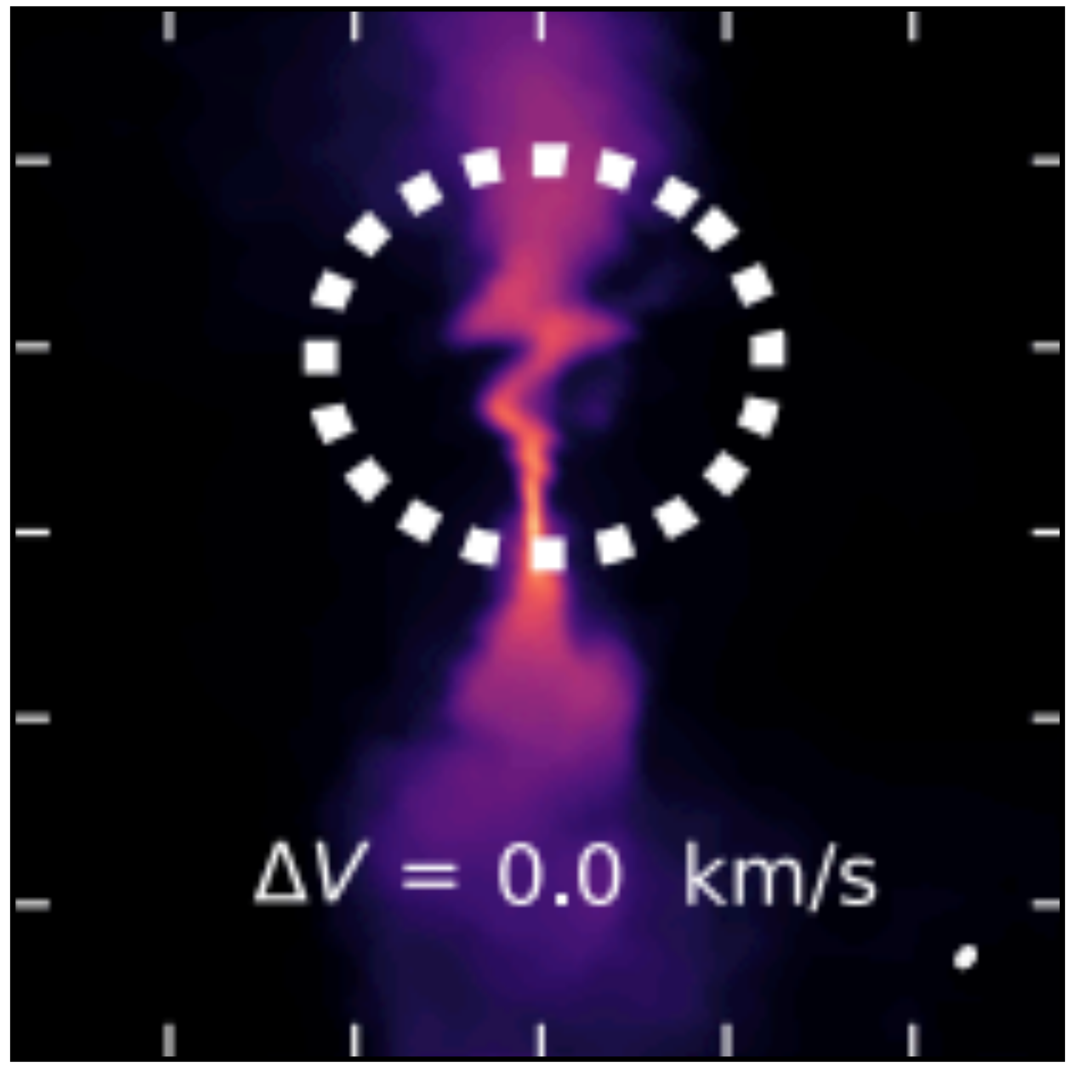



spurs around the central channel


arc connecting Keplerian wings across the major axis



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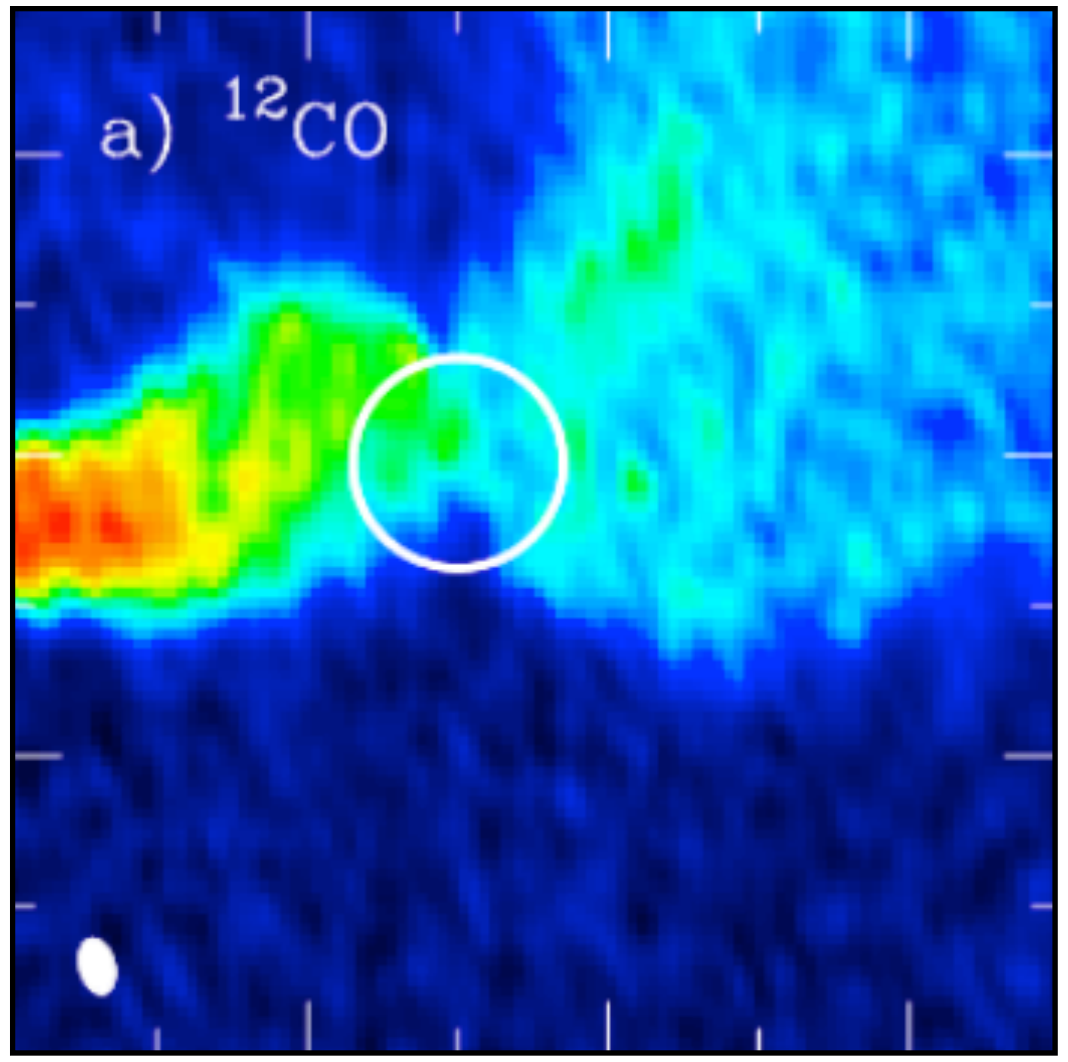

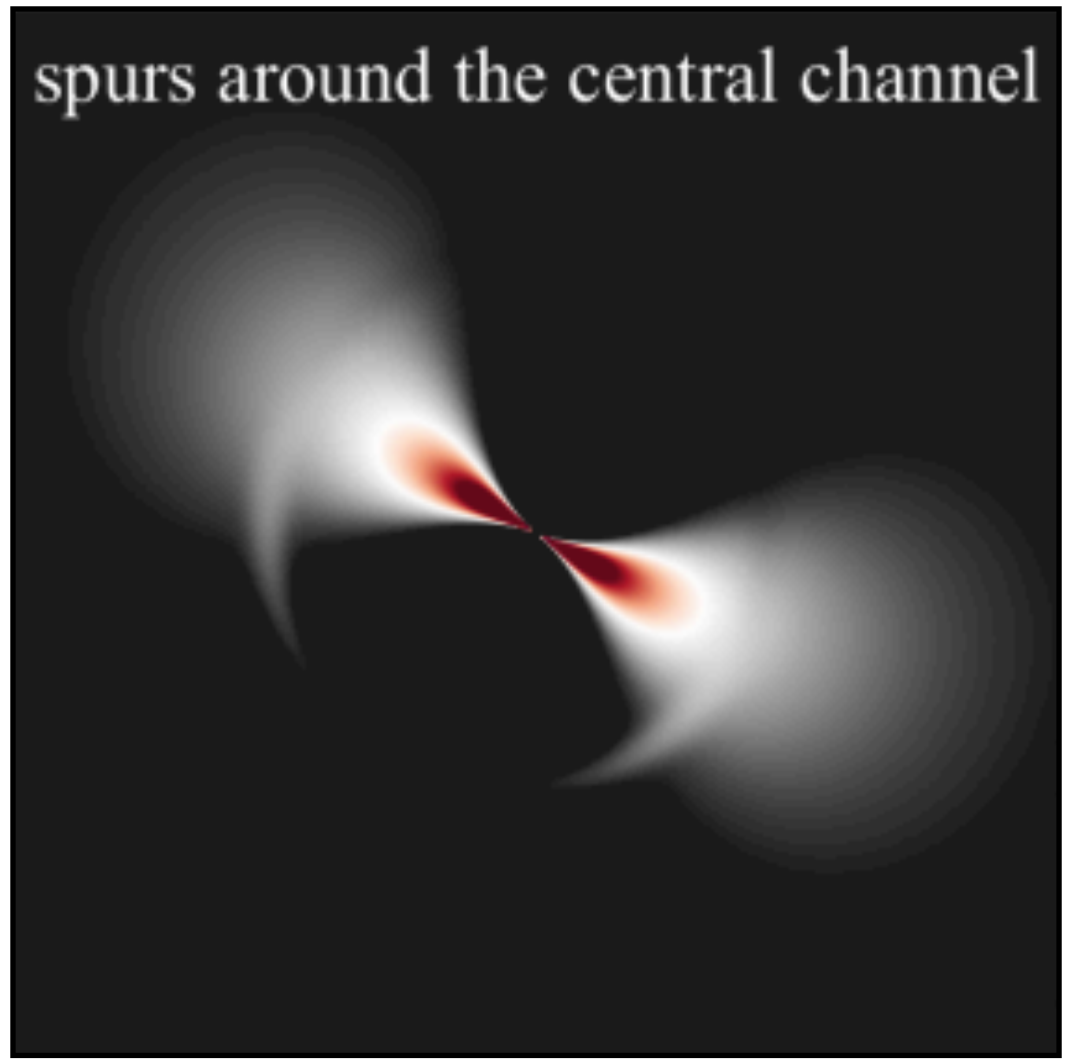

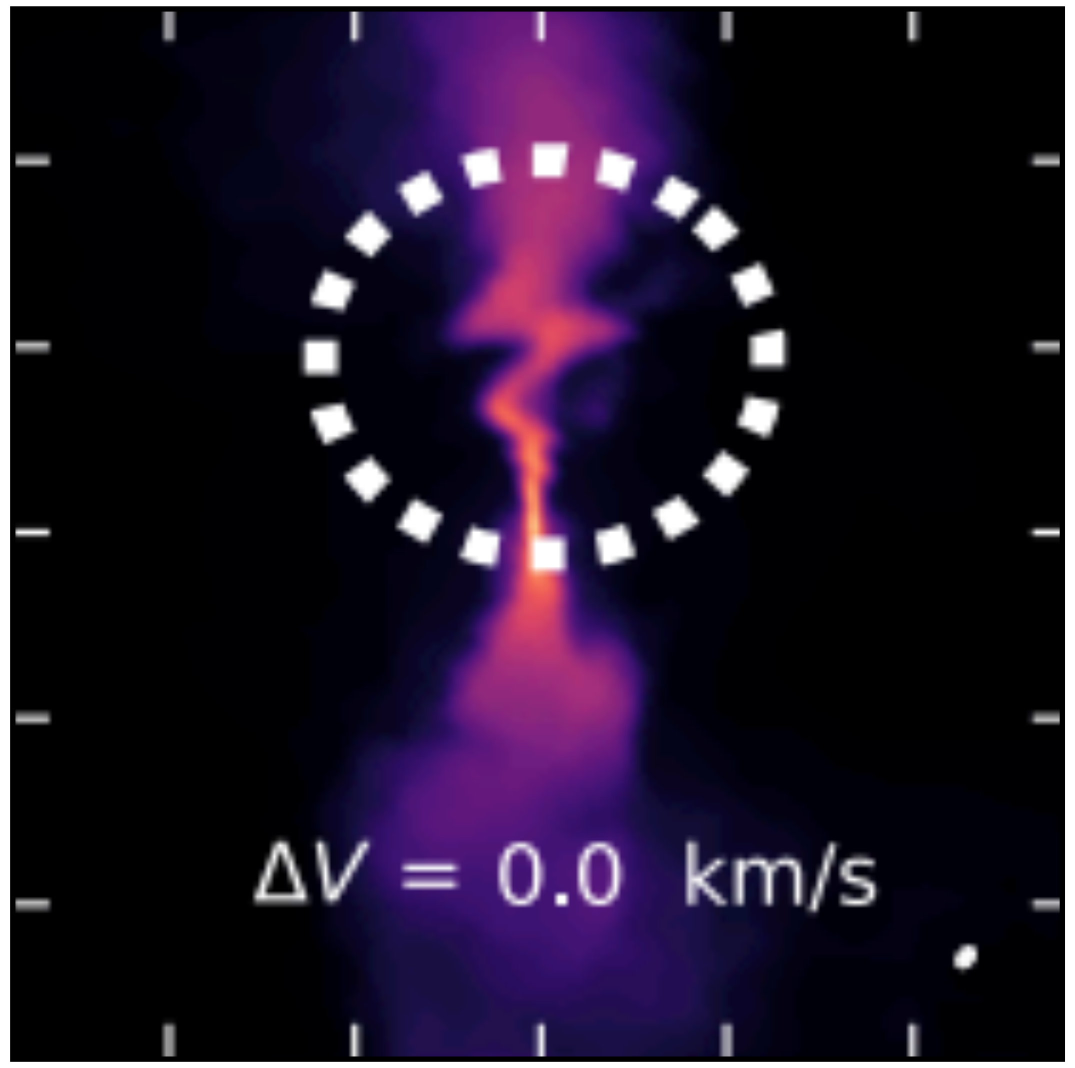

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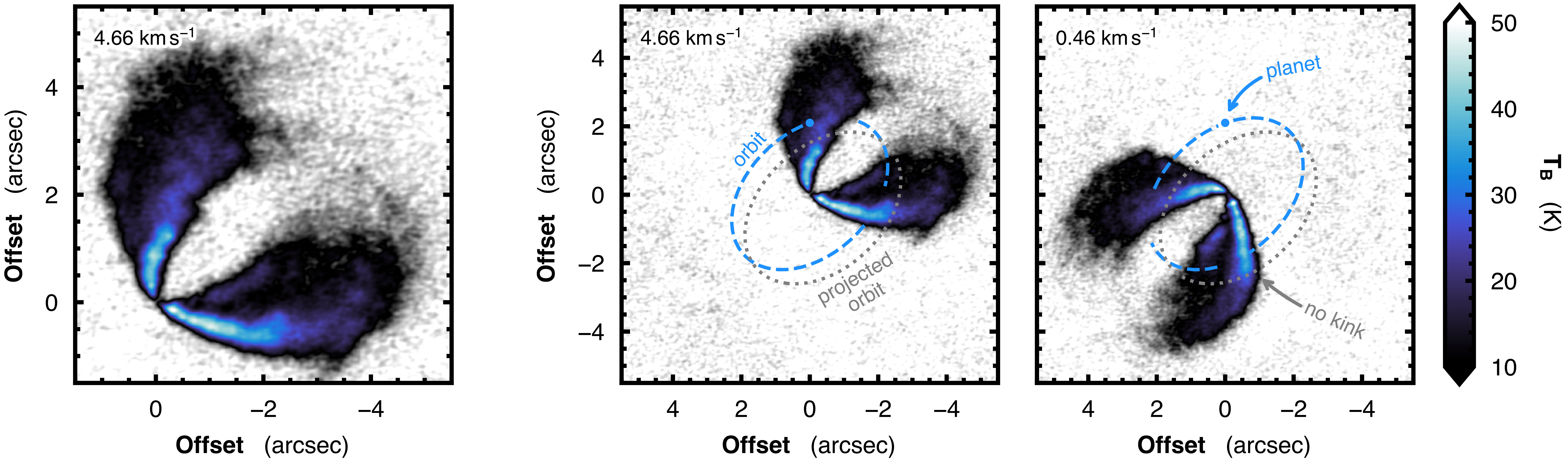


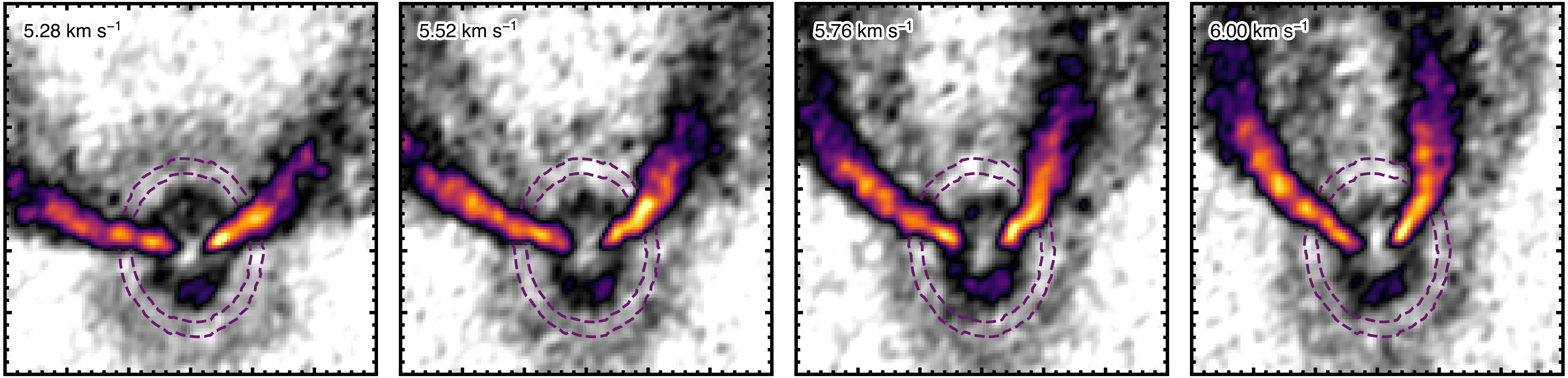
Caveat: The perturbation depends entirely on the inclination of the disk and the position angle of the planet.

also see Disk Dynamics Collaboration et al. (2009.04345)

Pinte et al. (2018b), Pinte et al. (PPVII Review)

Embedded Planets: ‘kinks’ around the planet’s location.

Perez et al. (2015), Pinte et al. (2018, 2019, 2020)



In HD 97048, the coincidence with a gap in the continuum is compelling evidence for an embedded planet.

adapted from Pinte et al. (2019)

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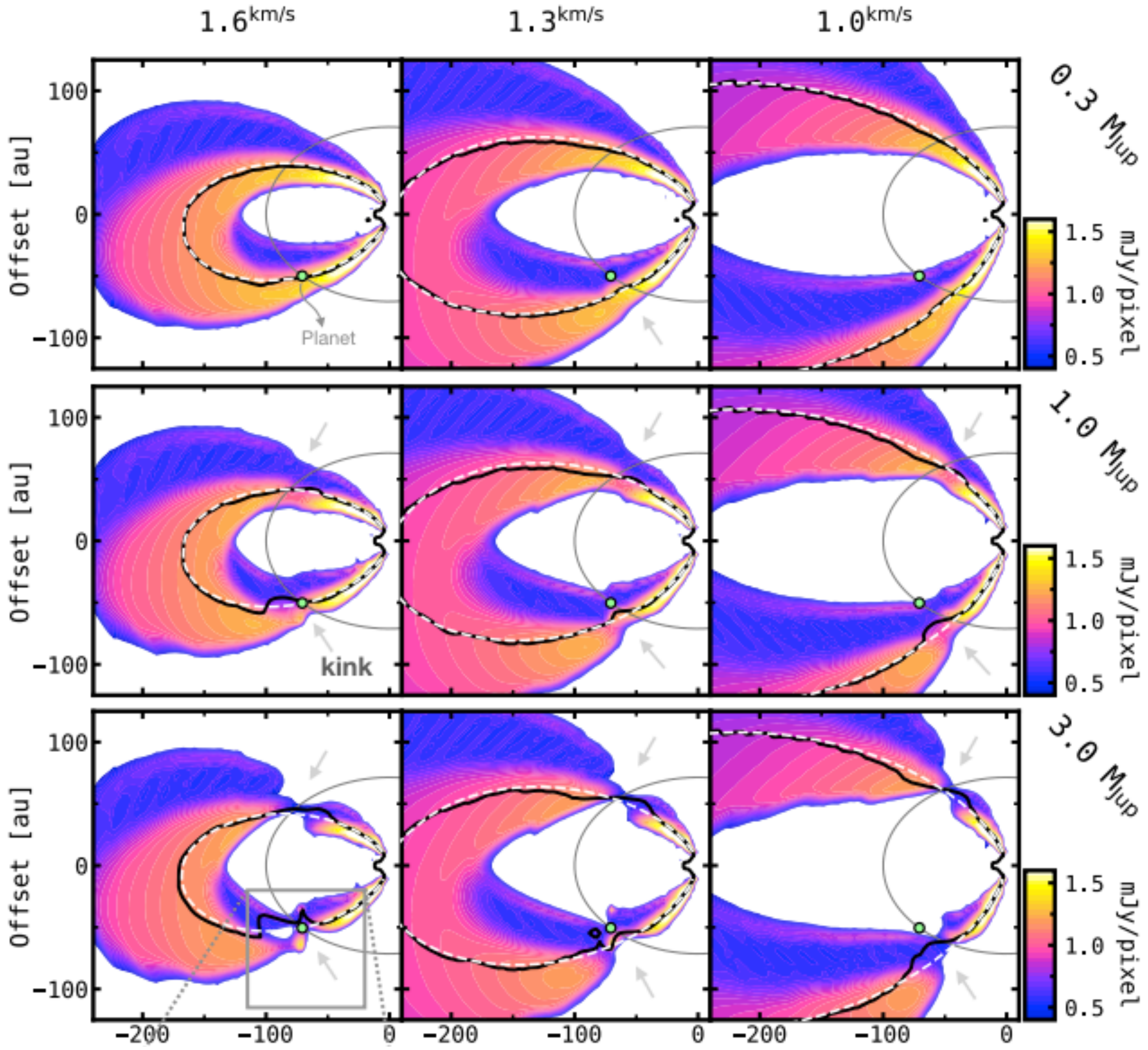

Using an empirical background model it is possible to search for features in a more quantitative manner.

see Friday’s talk to hear more about discminer.

Izquierdo et al. (2021)

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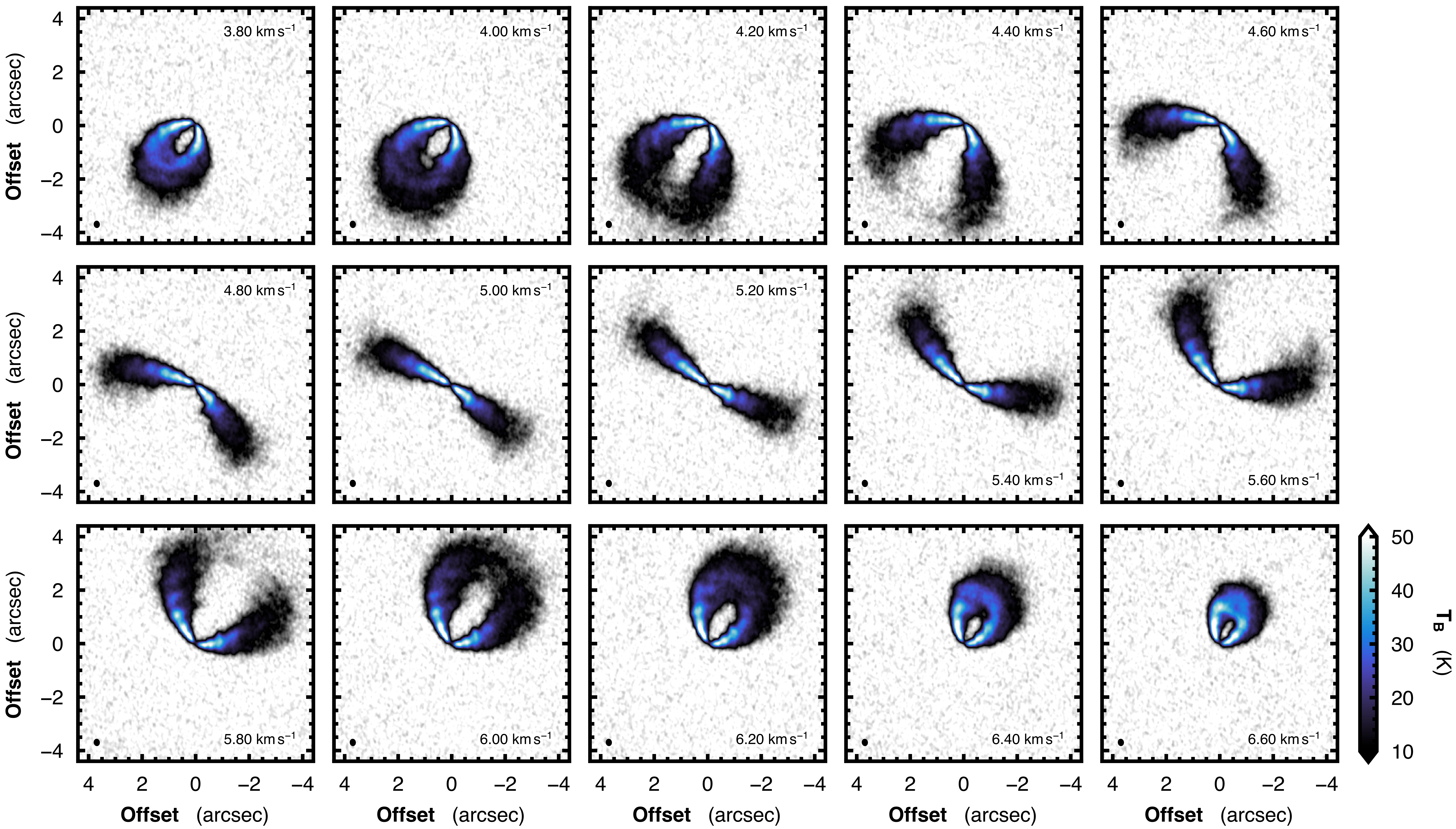
Bae et al. (2021)



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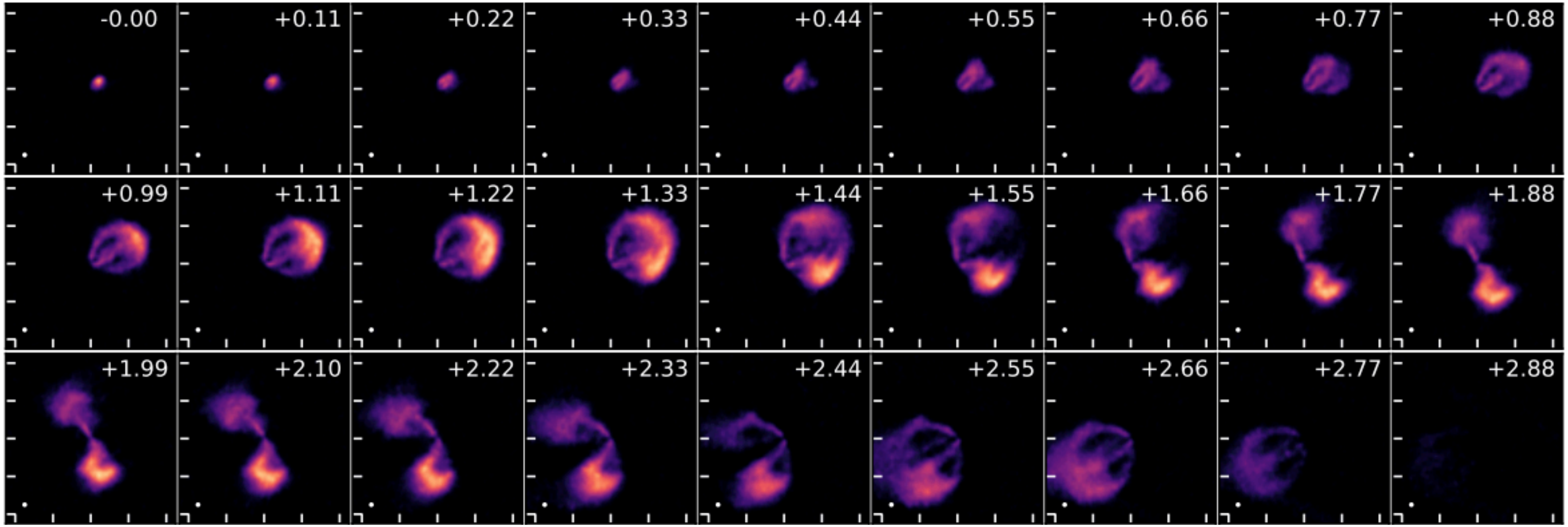
Gravitational Instability: 'wiggles' seen in most channels.

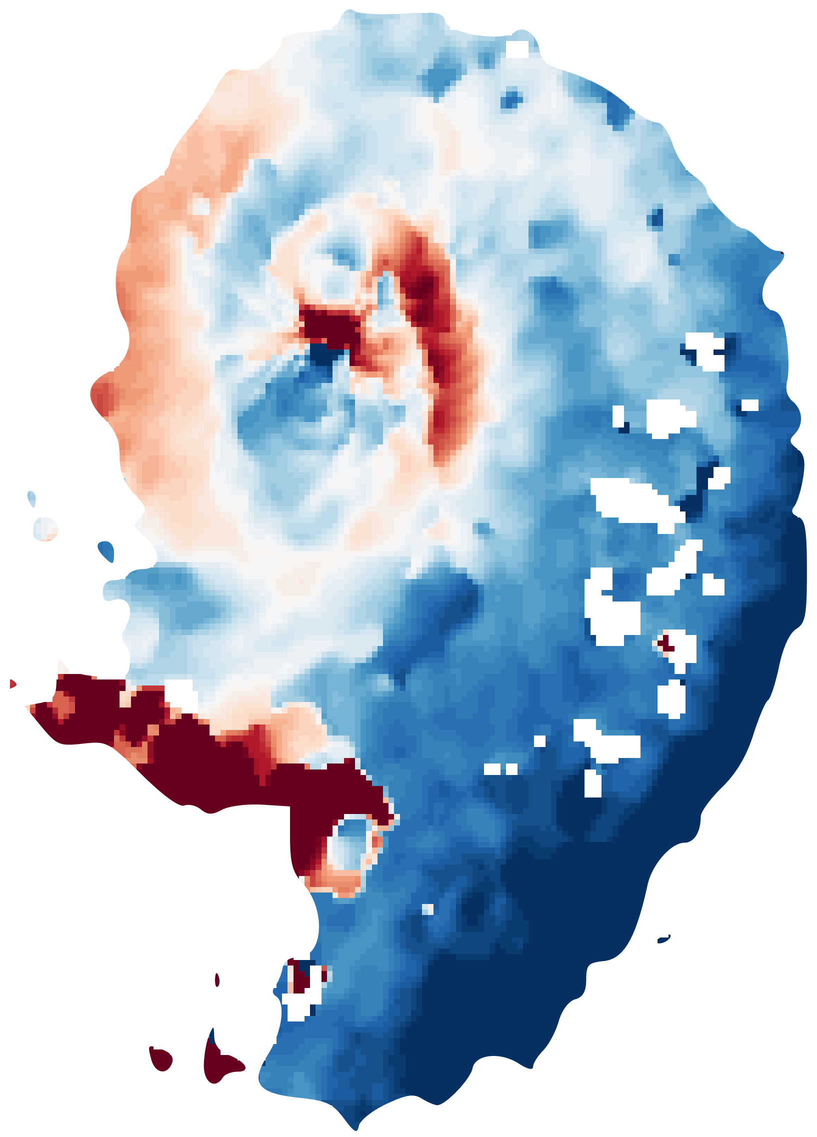
Hall et al. (2020), Paneque-Carreño et al. (2021), Longarini et al. (2021)



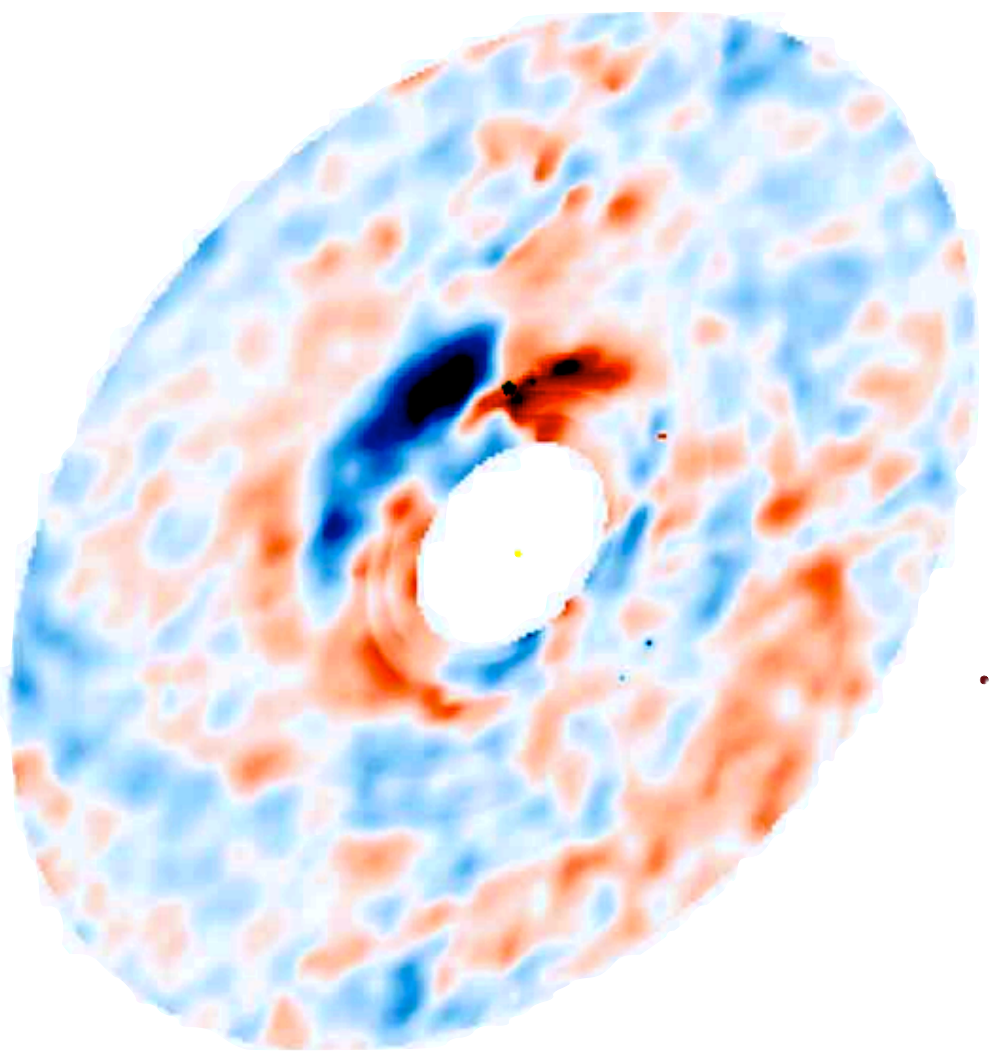
Subtraction of complex continuum emission may hamper interpretation.

Paneque-Carreño et al. (2021)

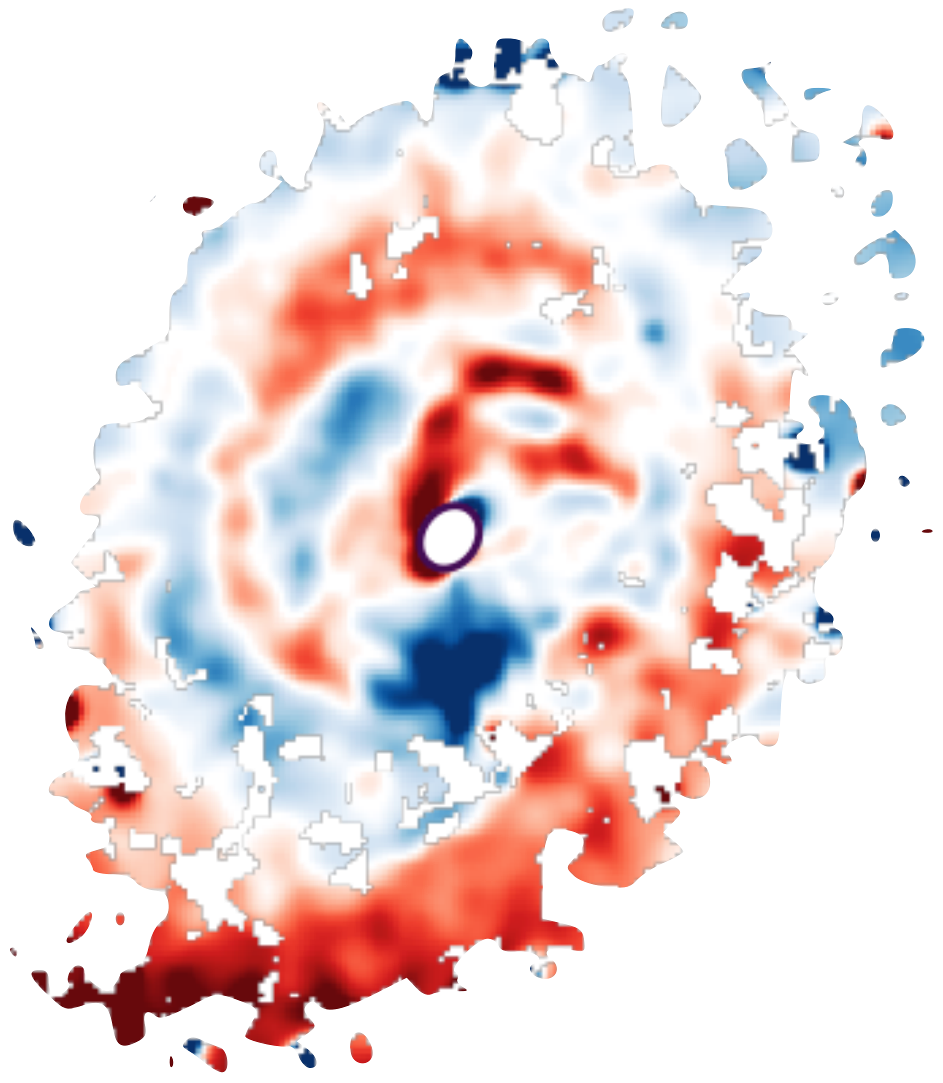
Now we have good models for the background, we are starting to see more structure in the residuals.



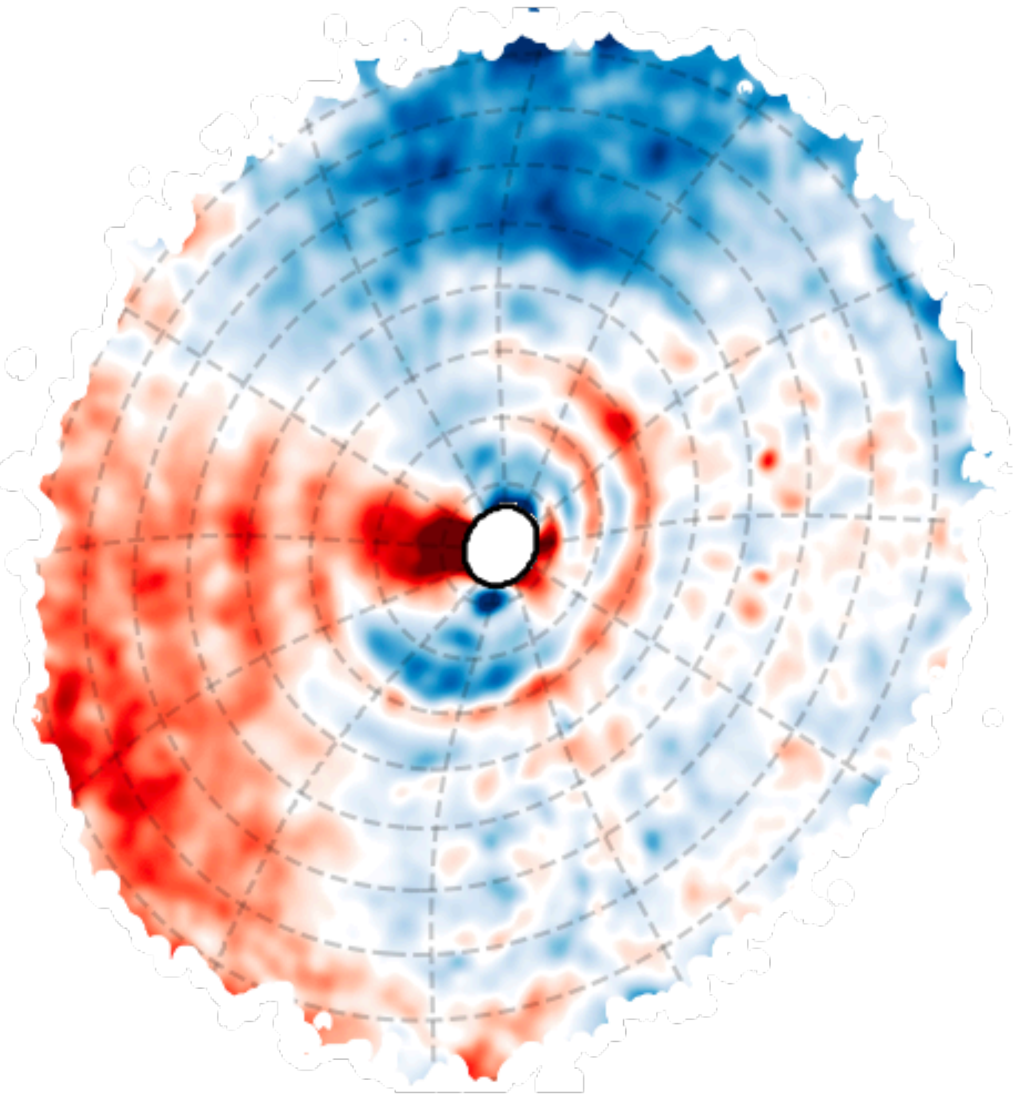
UX Tau a



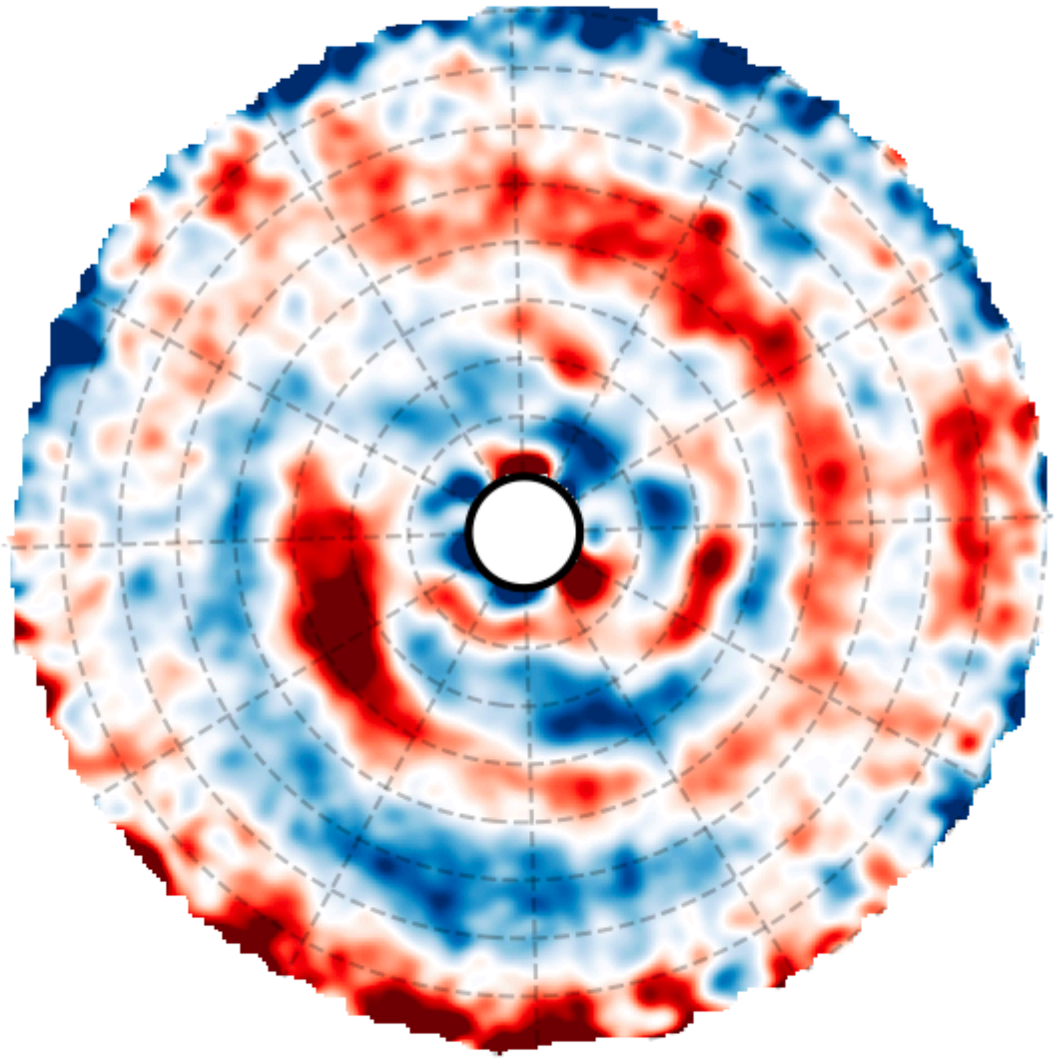
HD 100546



HD 100453



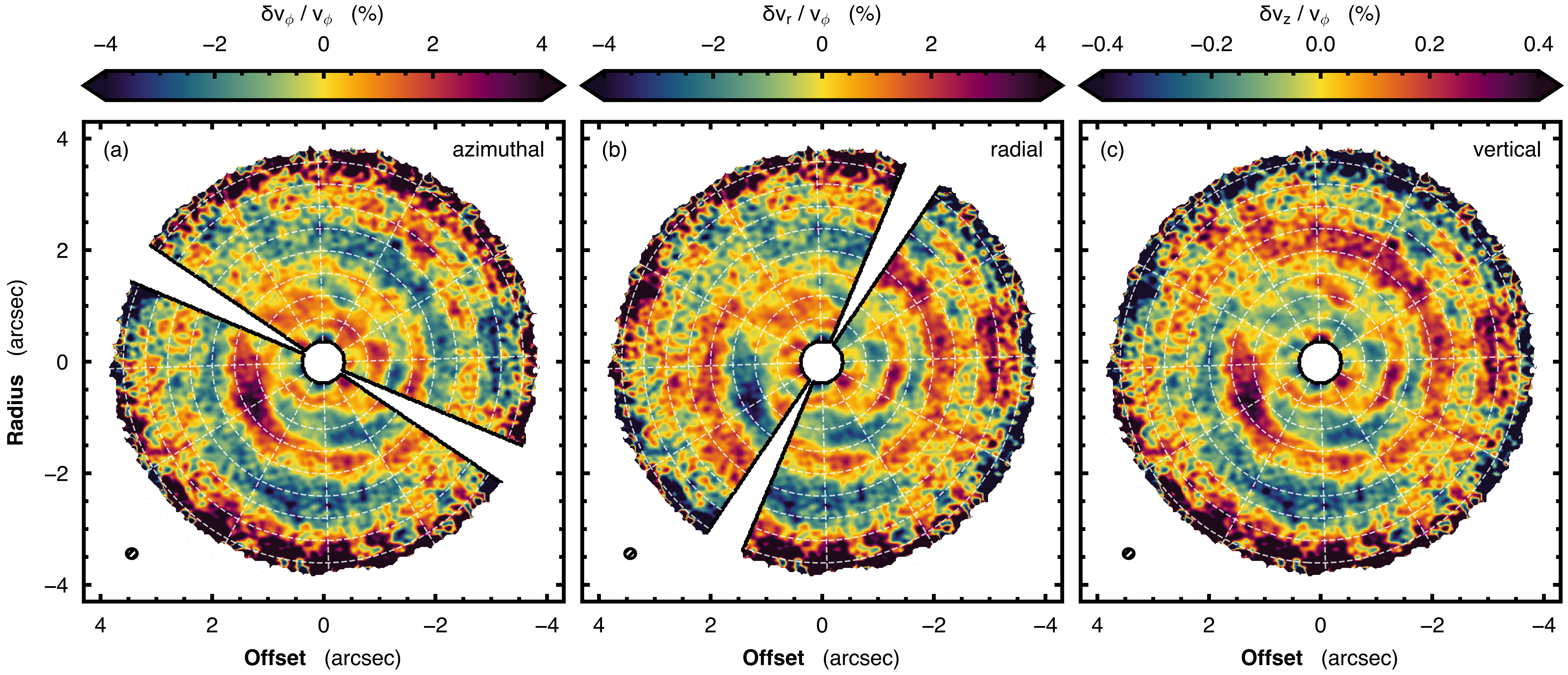
MWC 480



TW Hya

And there are many more coming…

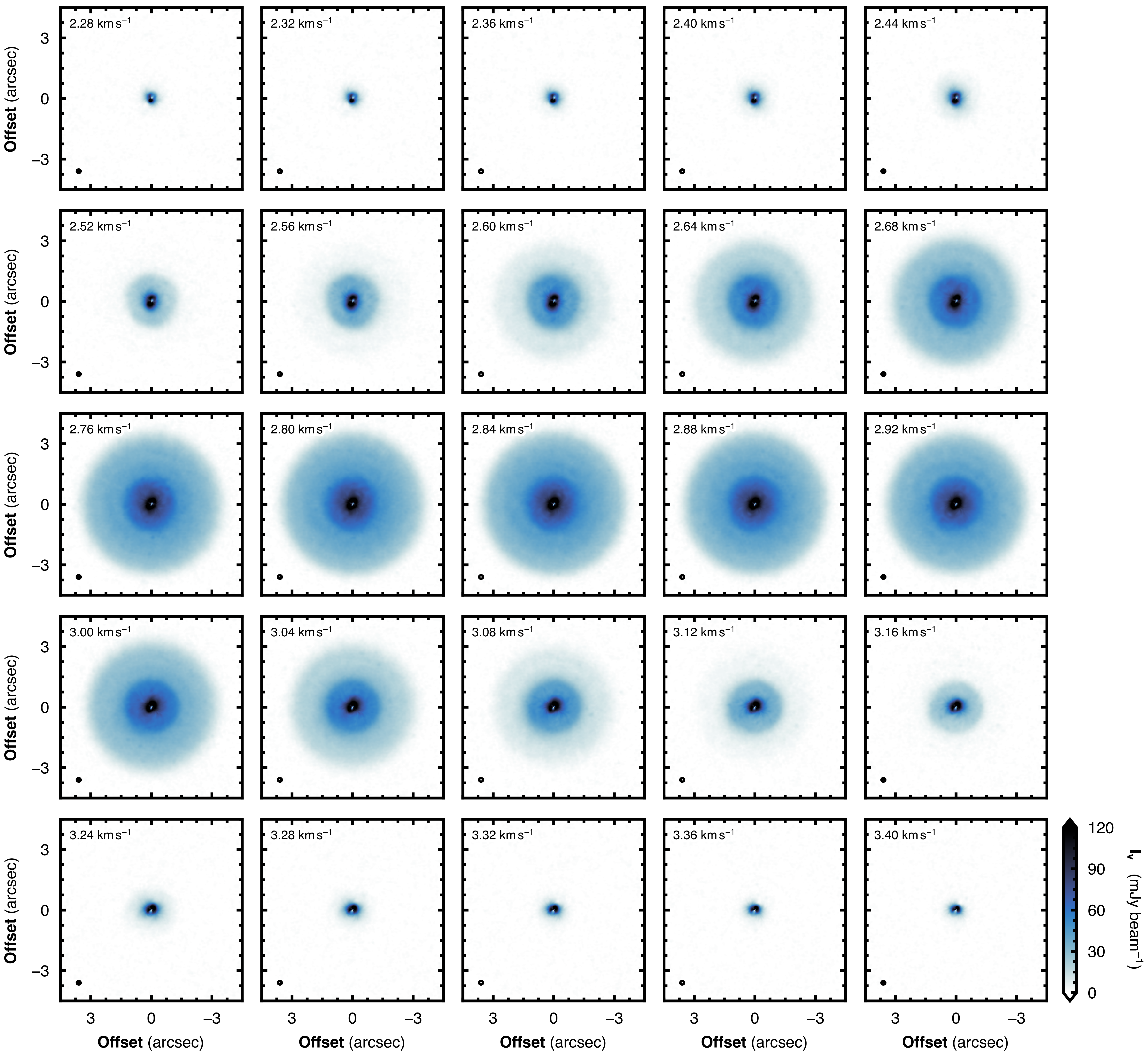
Wölfer et al. (in prep.), Casassus et al. (2019), Rosotti et al. (2019), Teague et al. (2021, in prep.)



We can leverage the azimuthal dependence of the residuals to rule out specific directions.

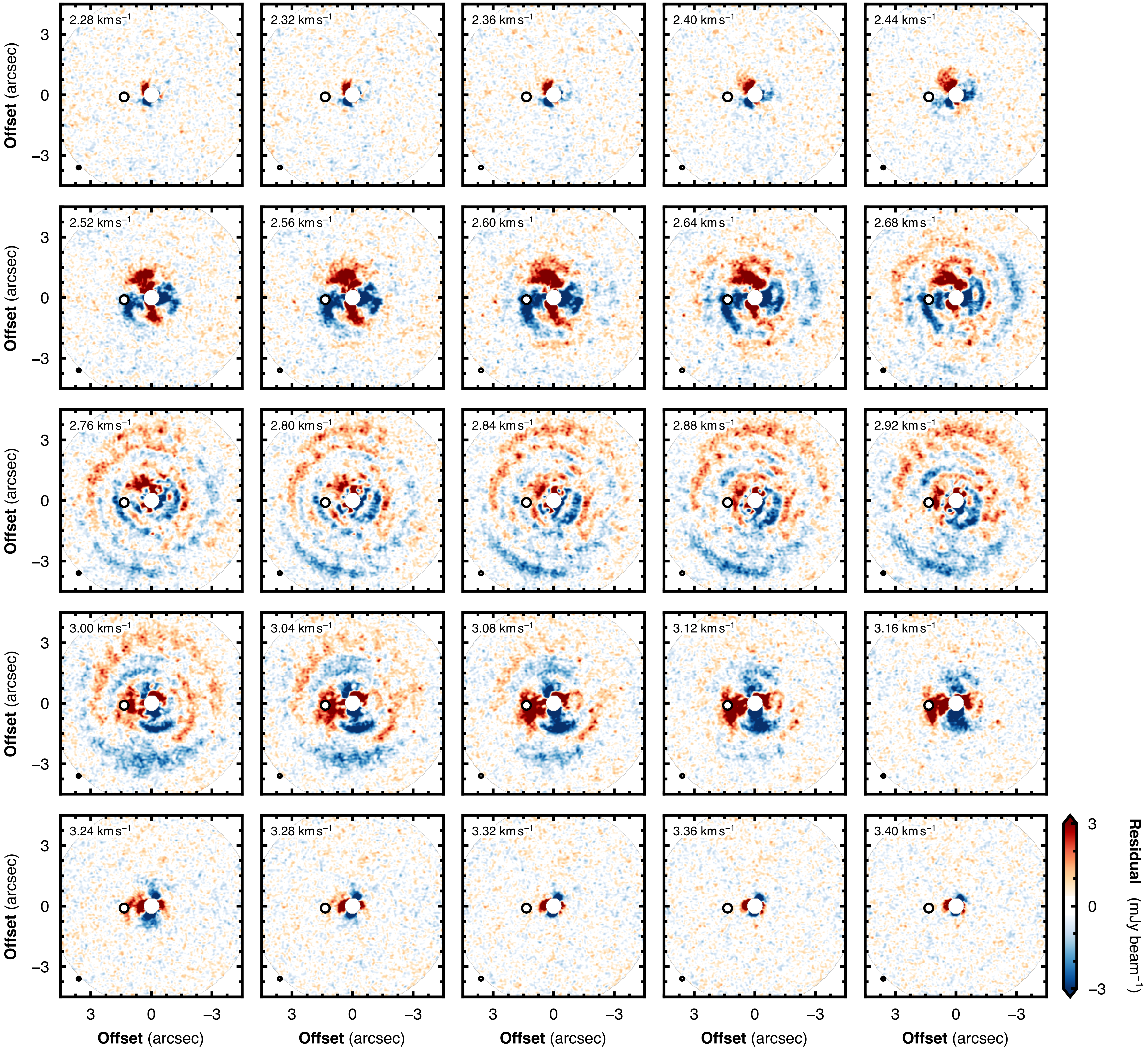
Caveat: Are the features azimuthally symmetric?

Teague et al. (in prep.)



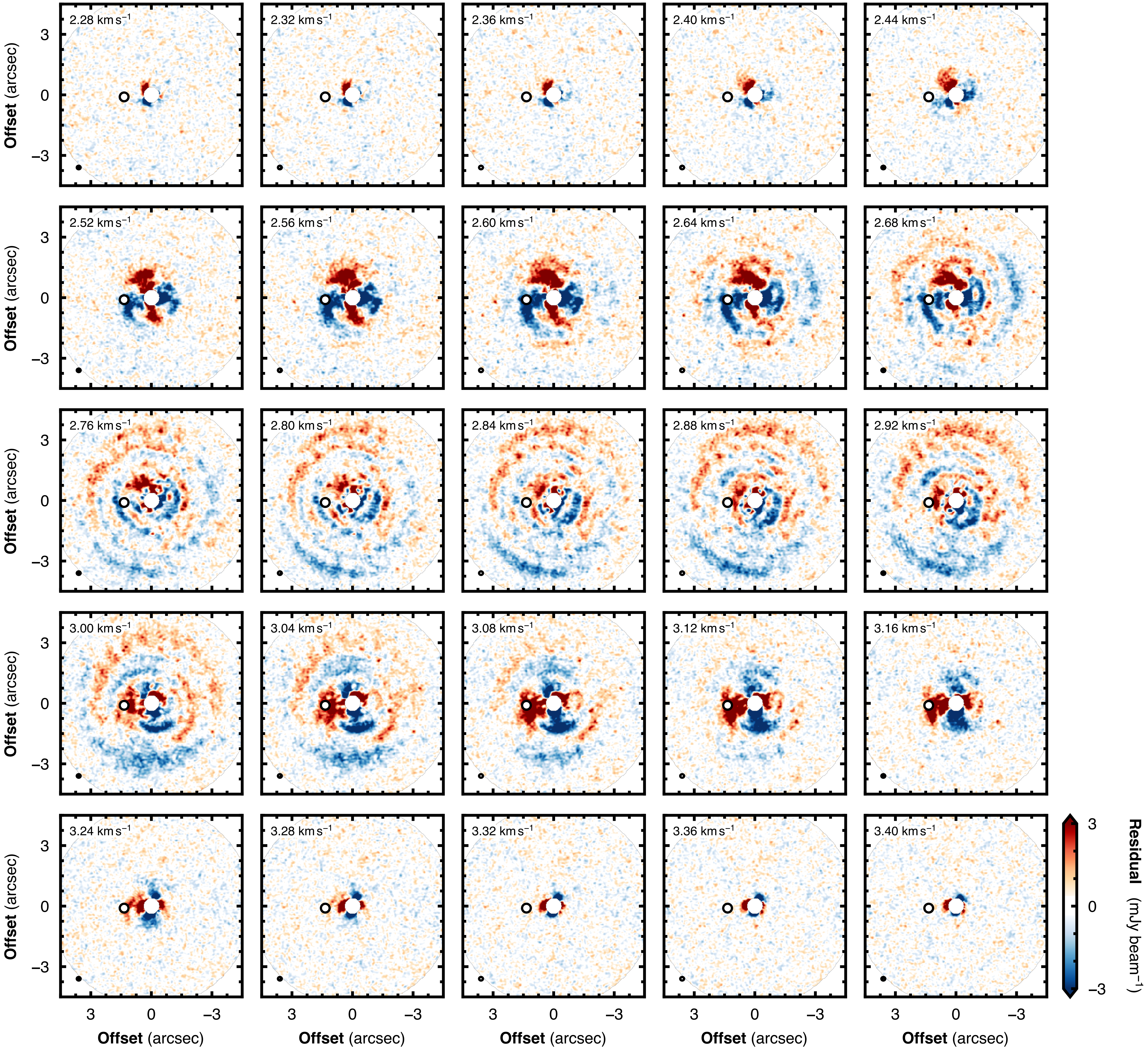
1. Measure the velocity structure of the disk.
2. Shift all lines back to a common center.

Teague et al. (in prep.)



1. Measure the velocity structure of the disk.
2. Shift all lines back to a common center.
3. Subtract a background model.

Teague et al. (in prep.)



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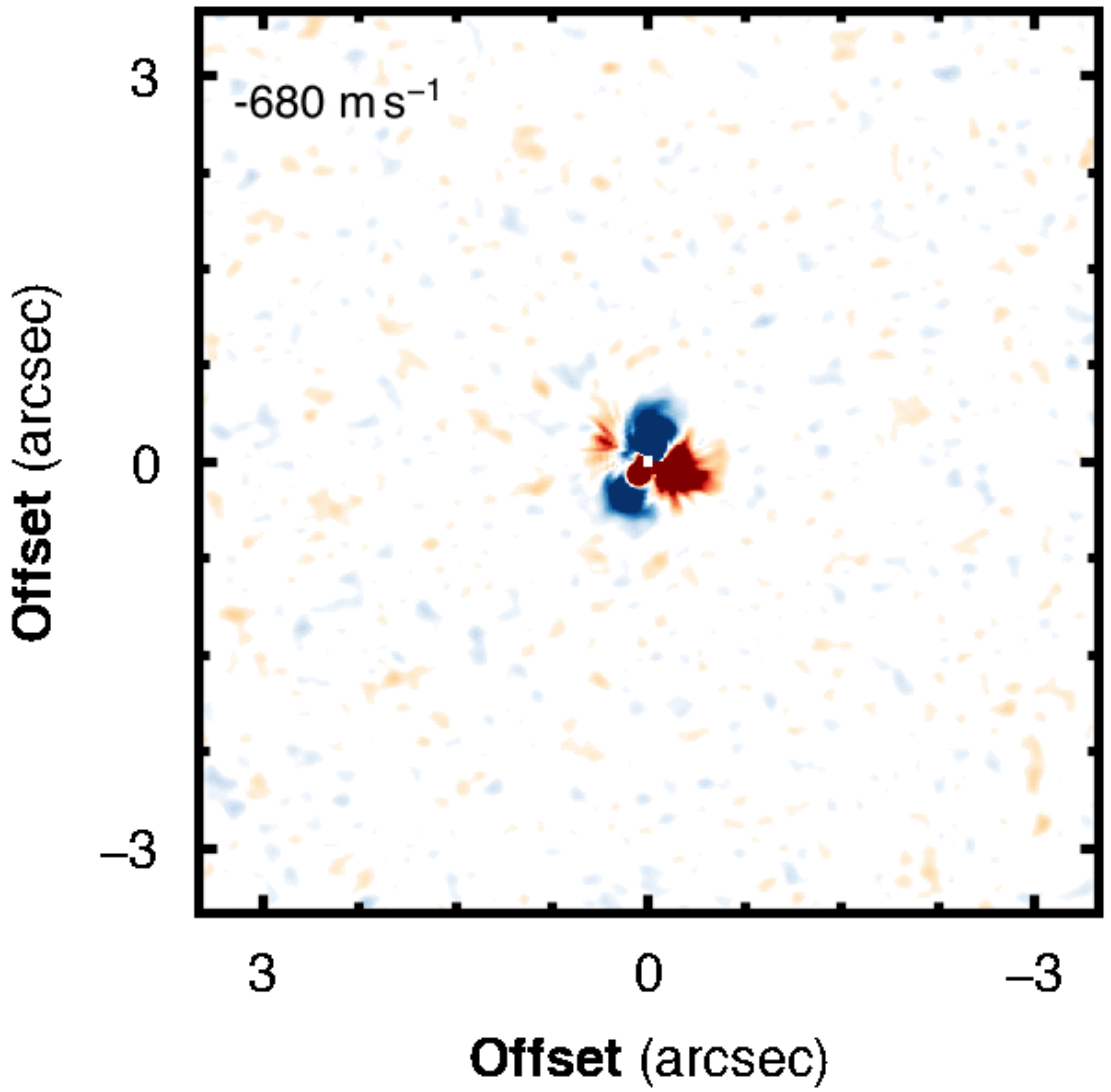
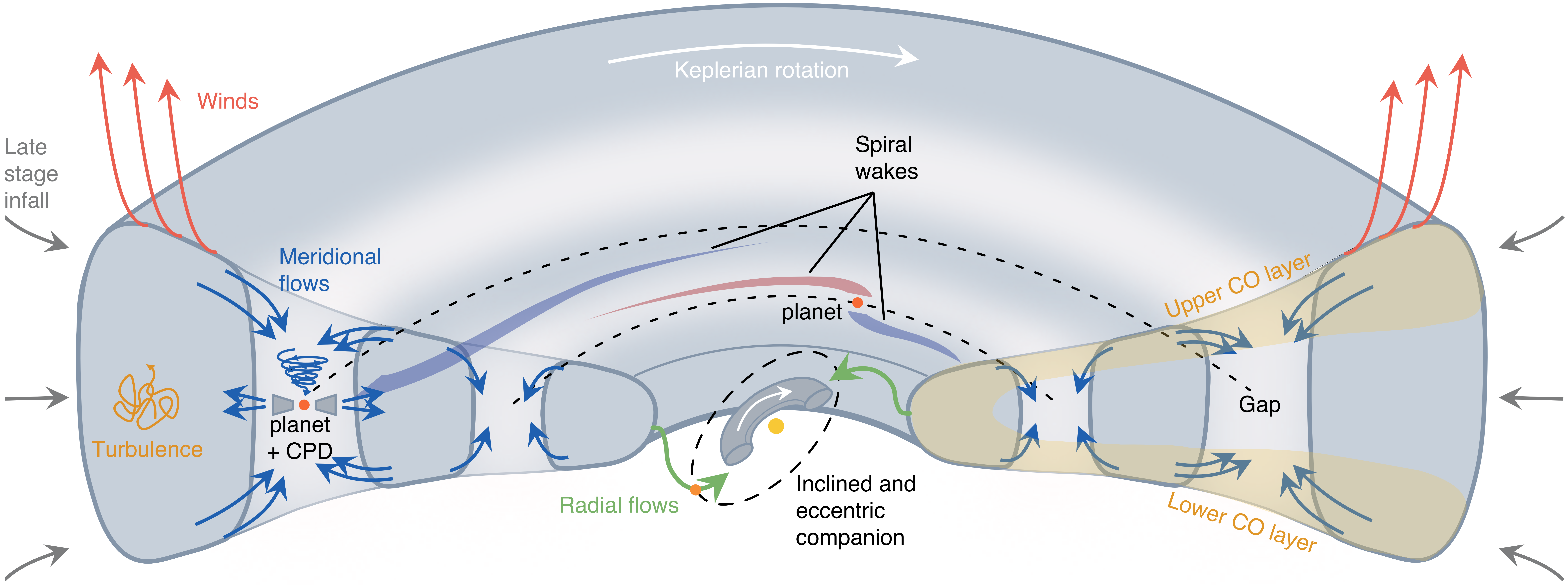


Teague et al. (in prep.)

exoALMA

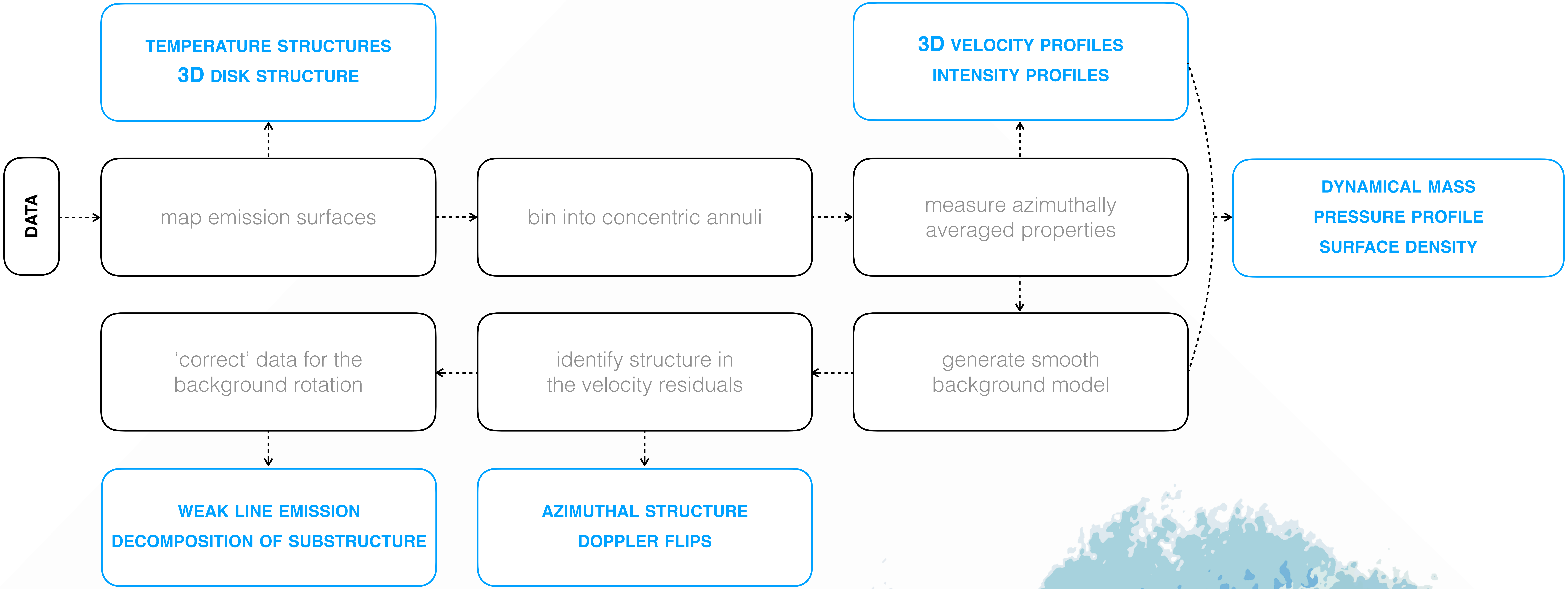
Myriam Benisty, Stefano Facchini, Misato Fukagawa, Christophe Pinte, Richard Teague

Targeting 15 disks at 100 mas spatial resolution and 26 ms^{-1} spectral resolution.



Pinte et al. (PPVII Review)

What's In a Line?



TEMPERATURE STRUCTURES
3D DISK STRUCTURE

3D VELOCITY PROFILES
INTENSITY PROFILES

DATA

map emission surfaces

bin into concentric annuli

measure azimuthally averaged properties

DYNAMICAL MASS
PRESSURE PROFILE
SURFACE DENSITY

'correct' data for the background rotation

identify structure in the velocity residuals

generate smooth background model

WEAK LINE EMISSION
DECOMPOSITION OF SUBSTRUCTURE

AZIMUTHAL STRUCTURE
DOPPLER FLIPS