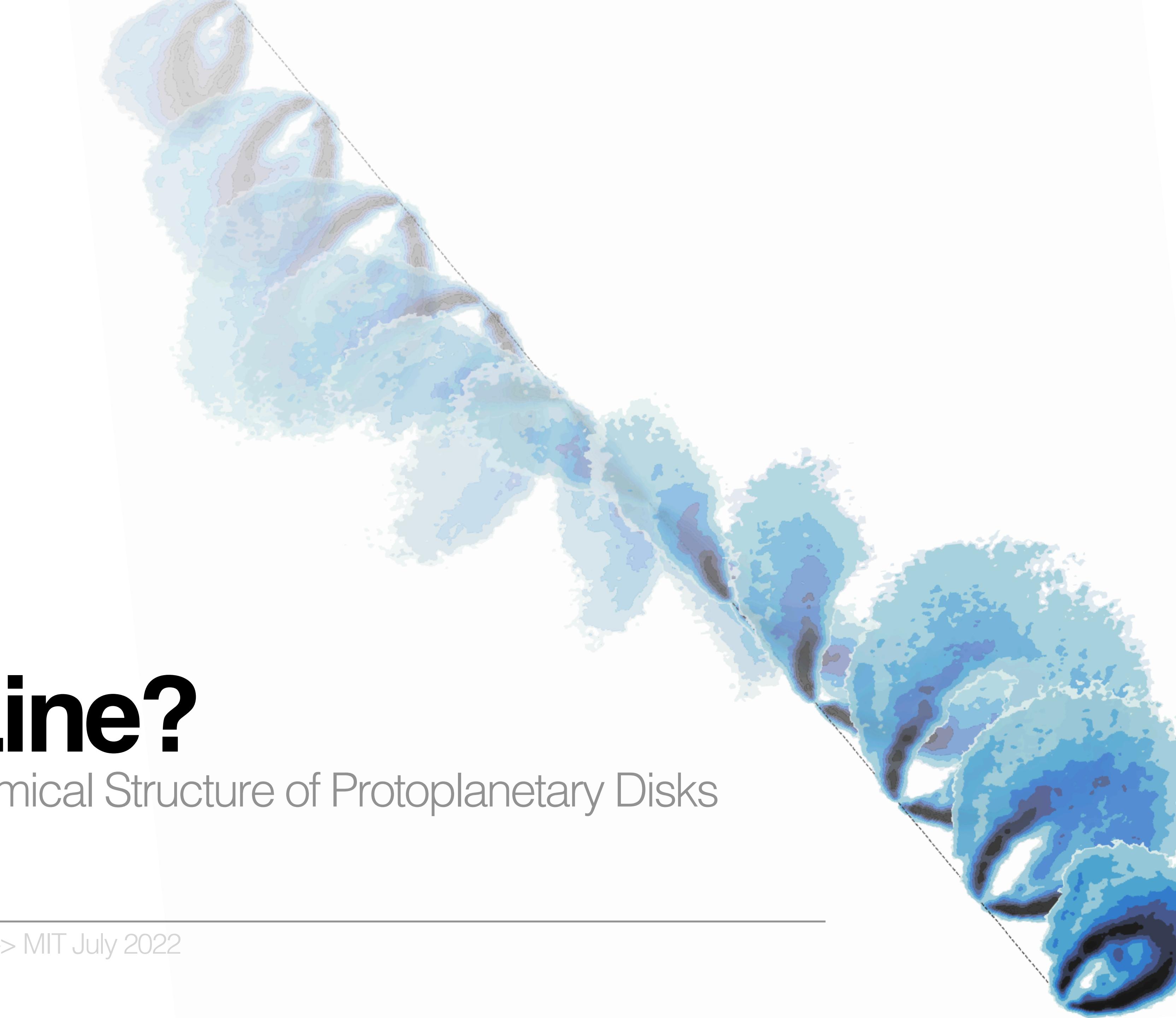


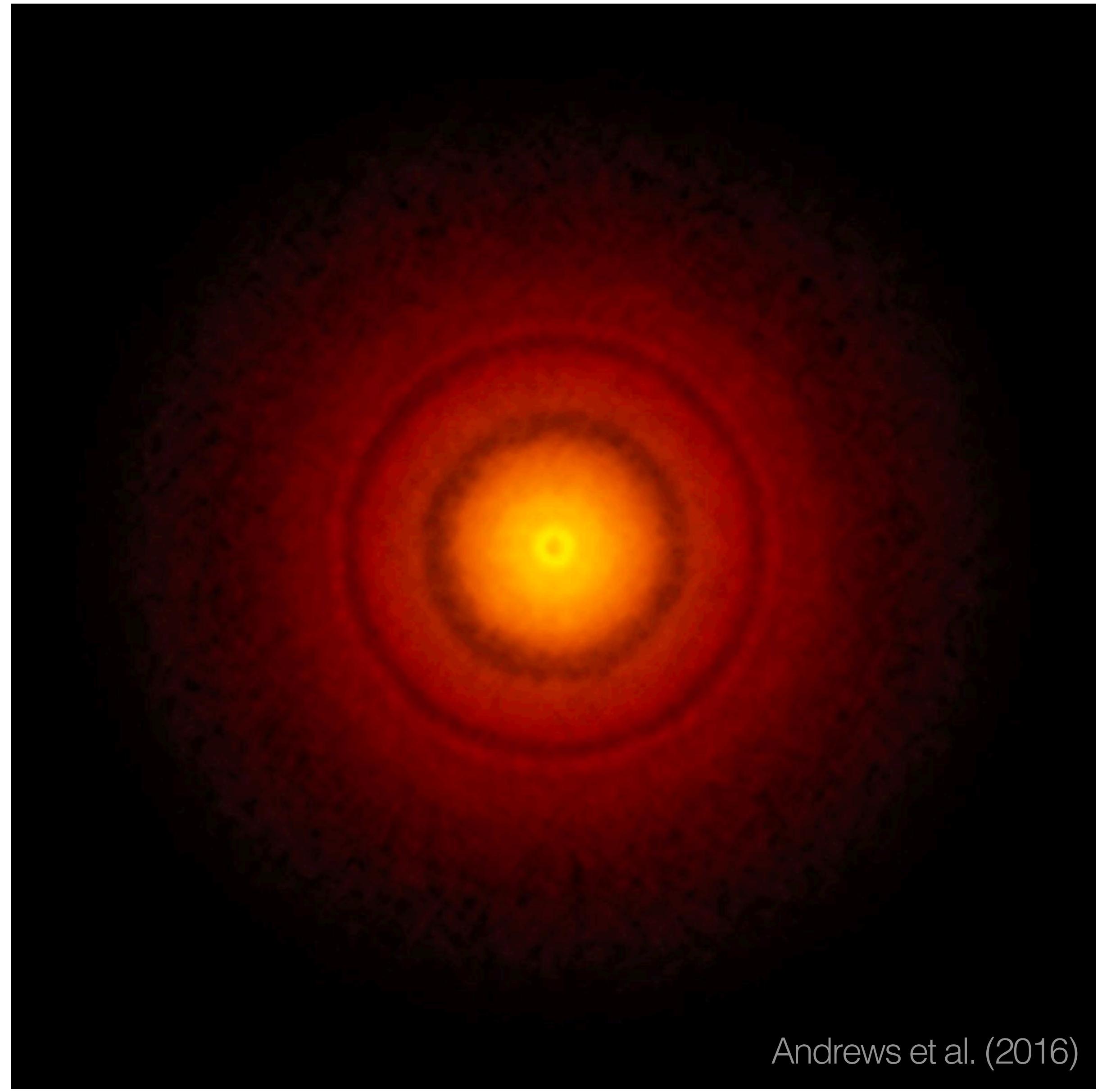
What's In a Line?

How We're Mapping the Dynamical Structure of Protoplanetary Disks

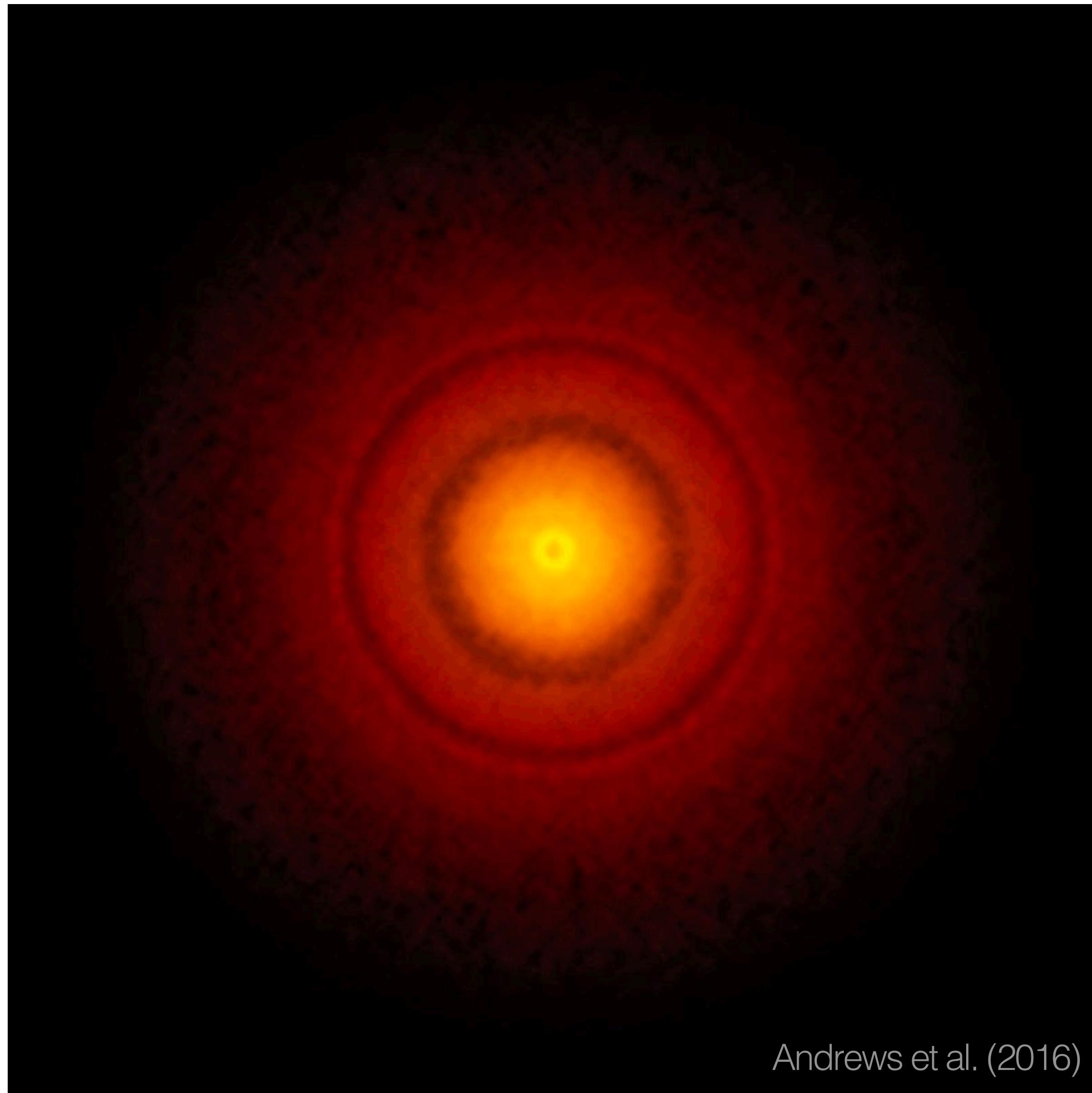
Richard Teague

Harvard & Smithsonian | Center for Astrophysics → MIT July 2022



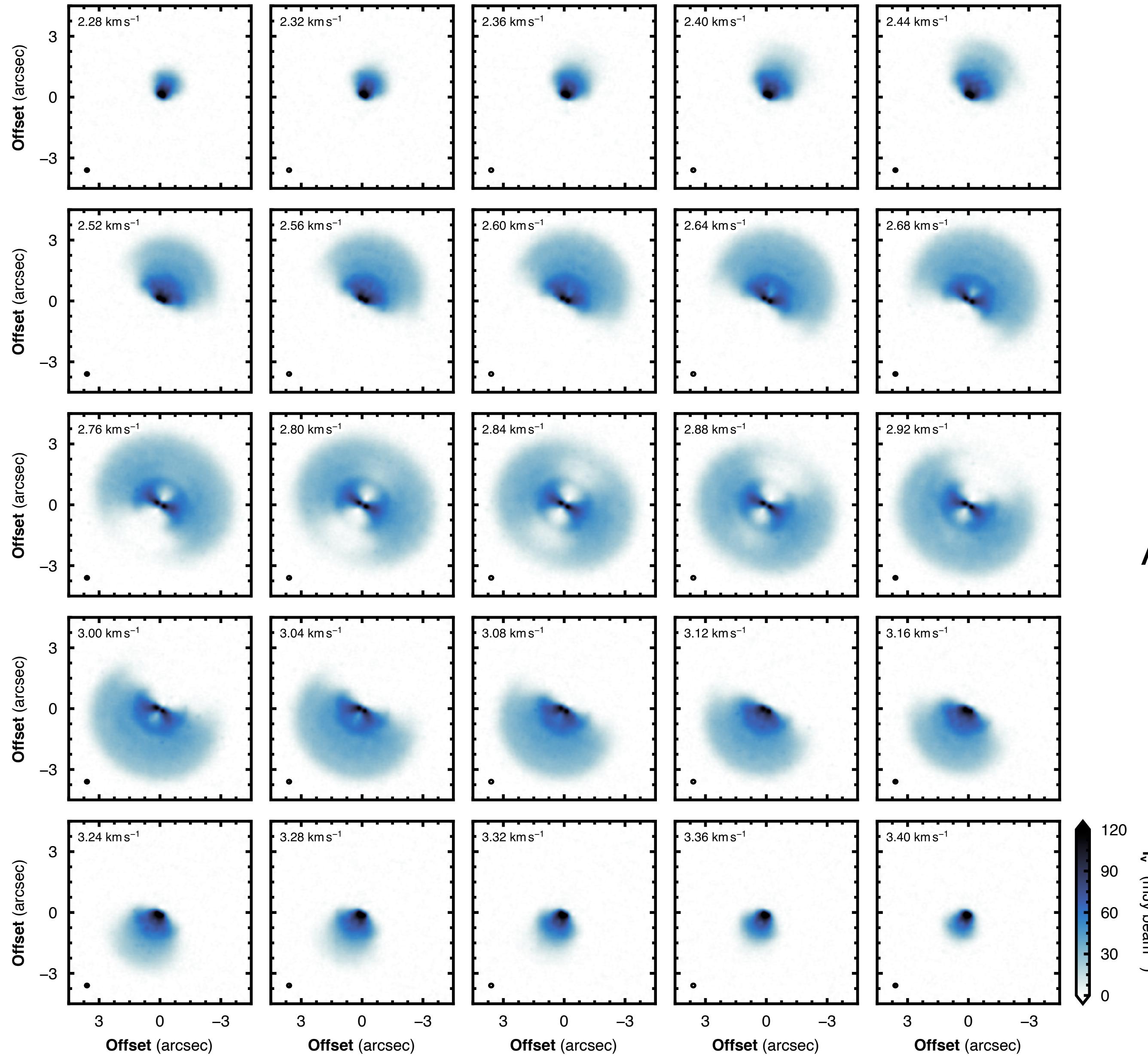


Andrews et al. (2016)

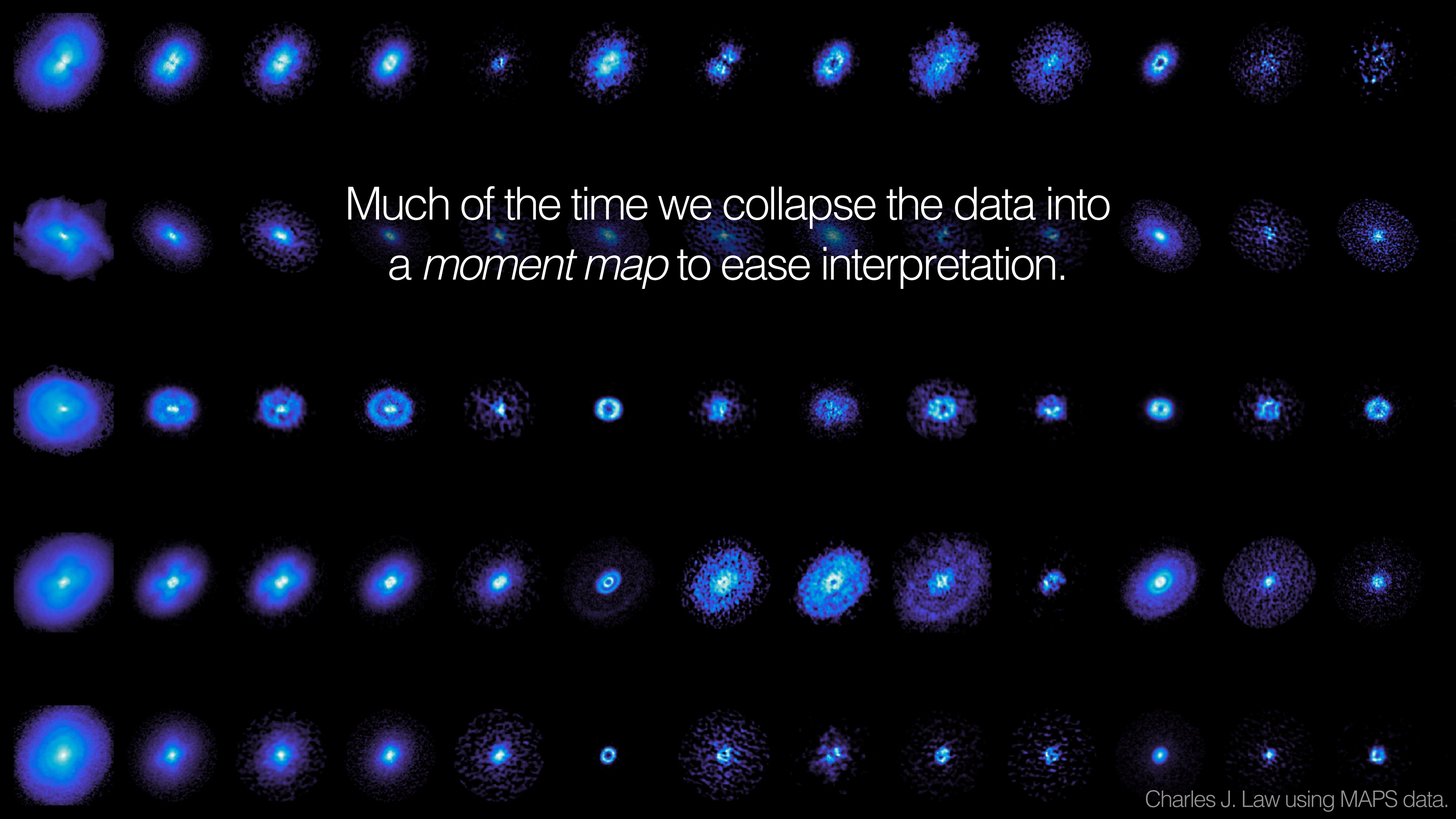


Andrews et al. (2016)

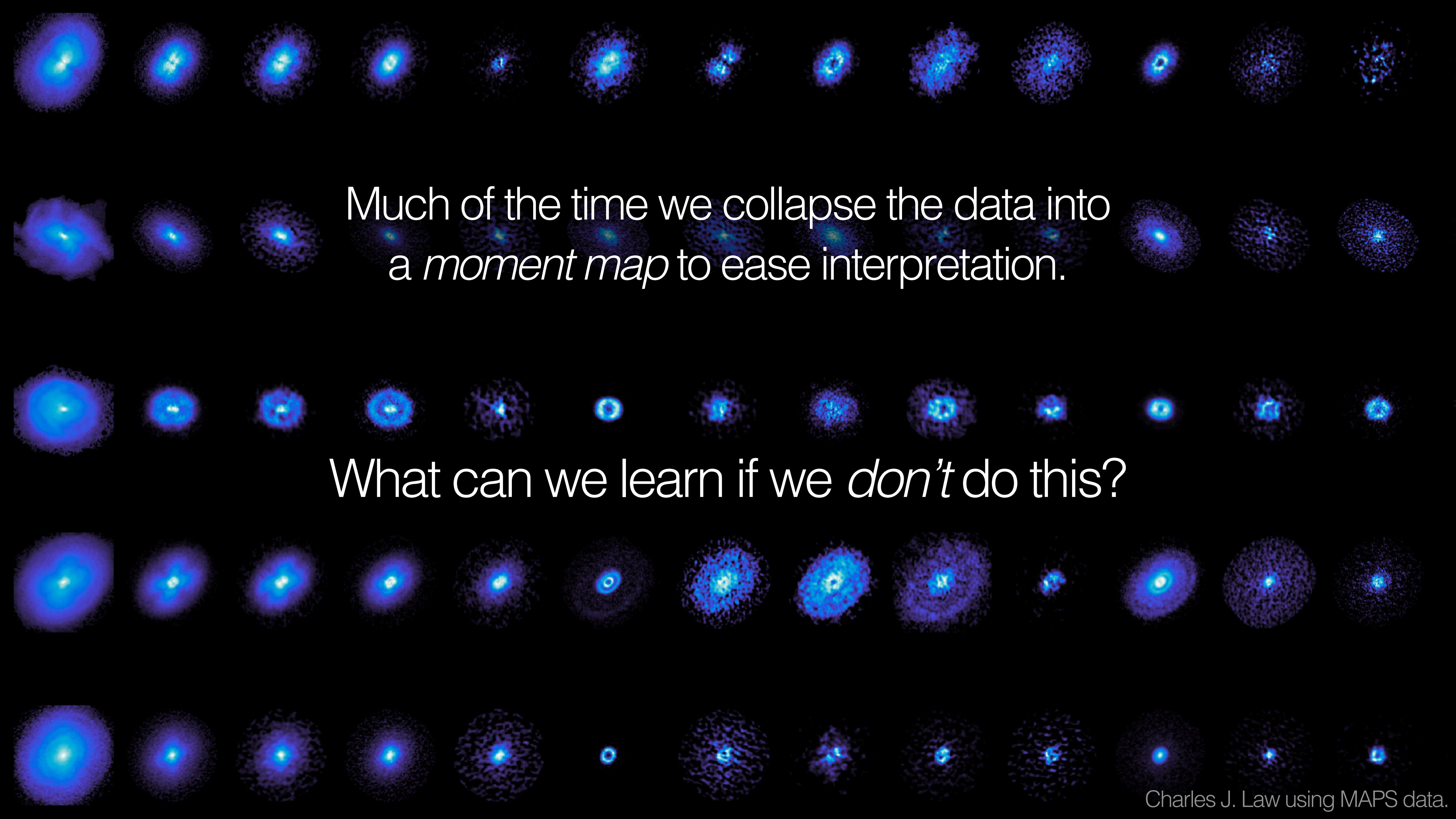
A picture is worth a thousand words.



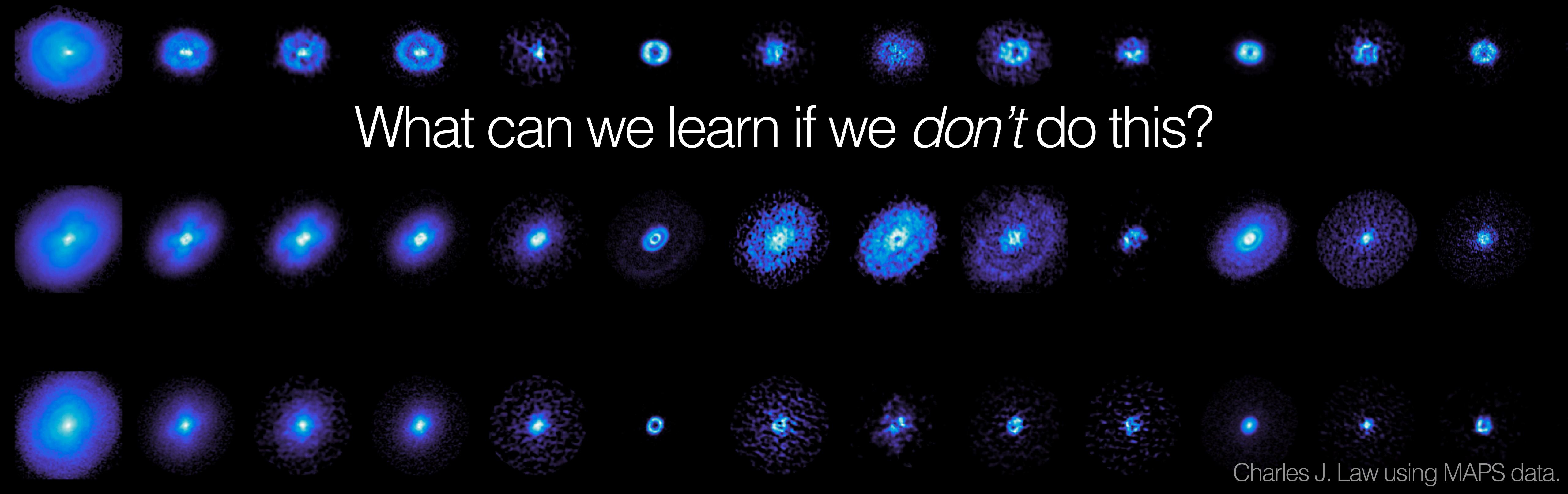
A picture is worth a thousand words.
An ALMA observation is worth **3.8 million**.
(almost 8 copies of War & Peace)



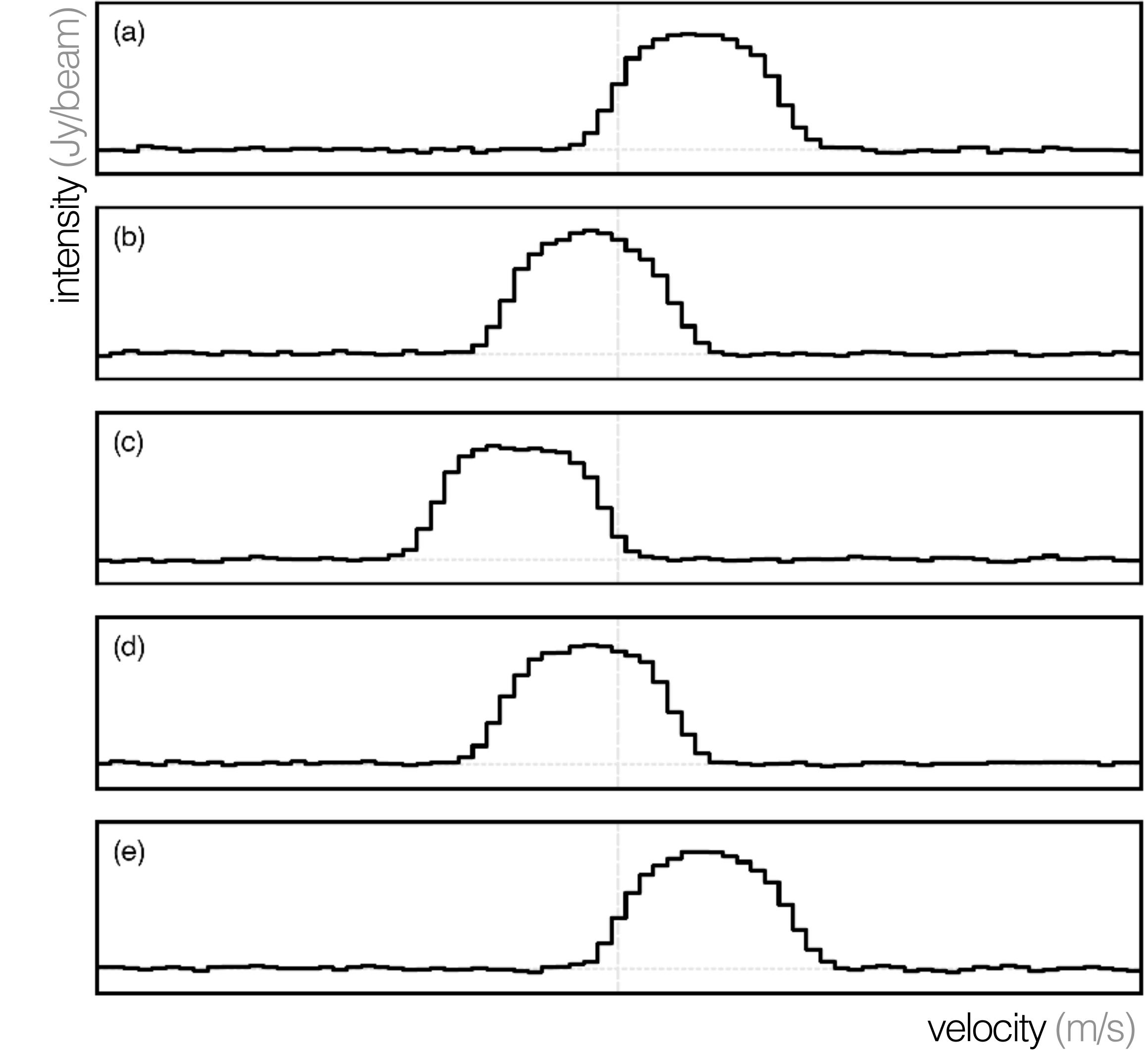
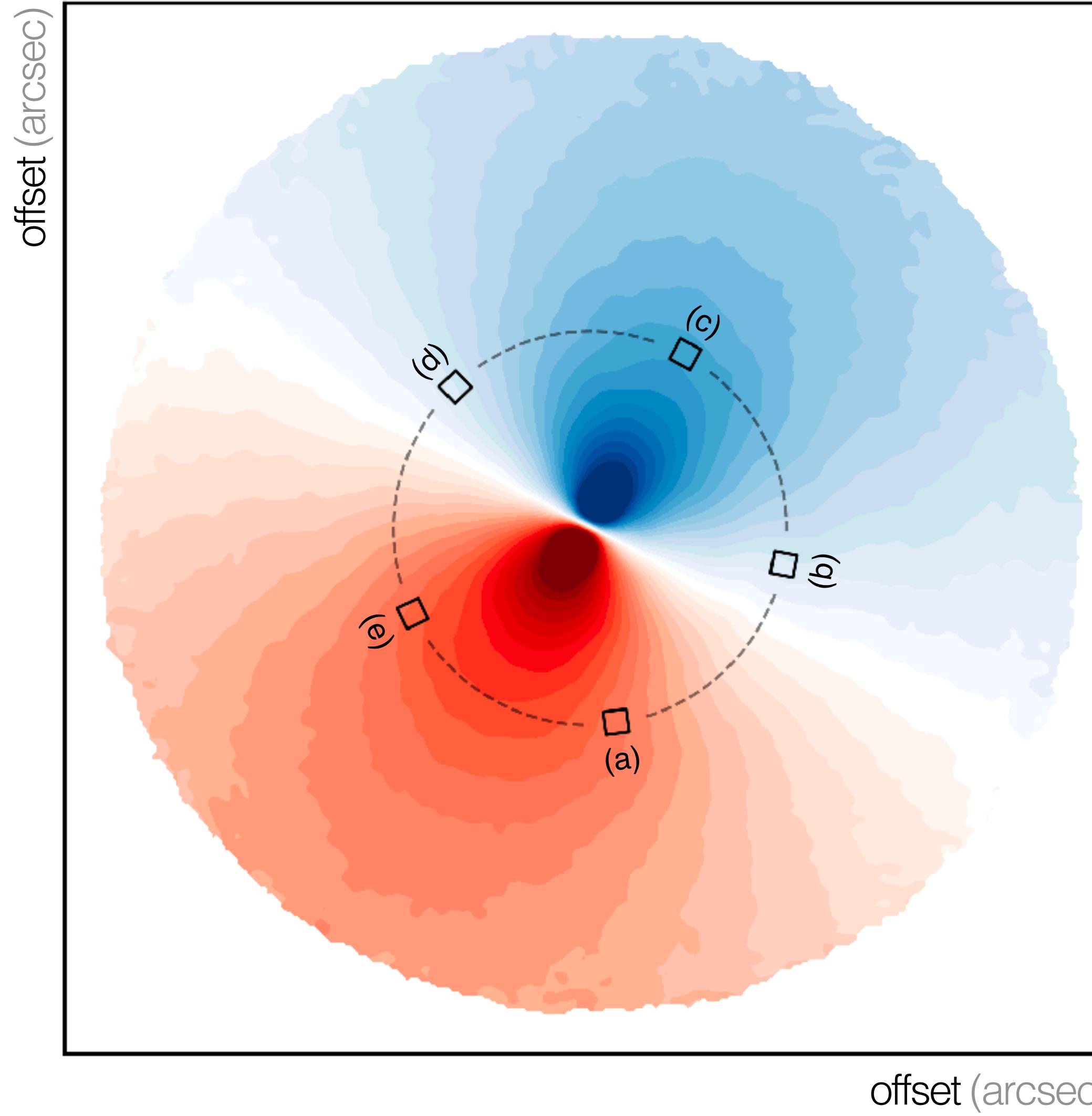
Much of the time we collapse the data into
a moment map to ease interpretation.



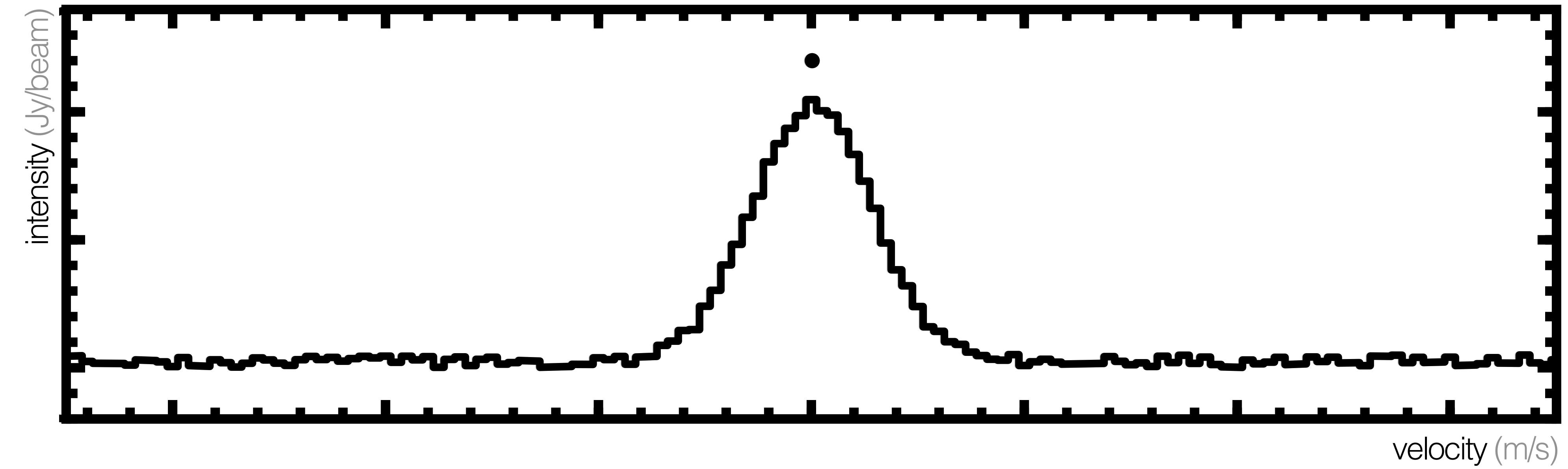
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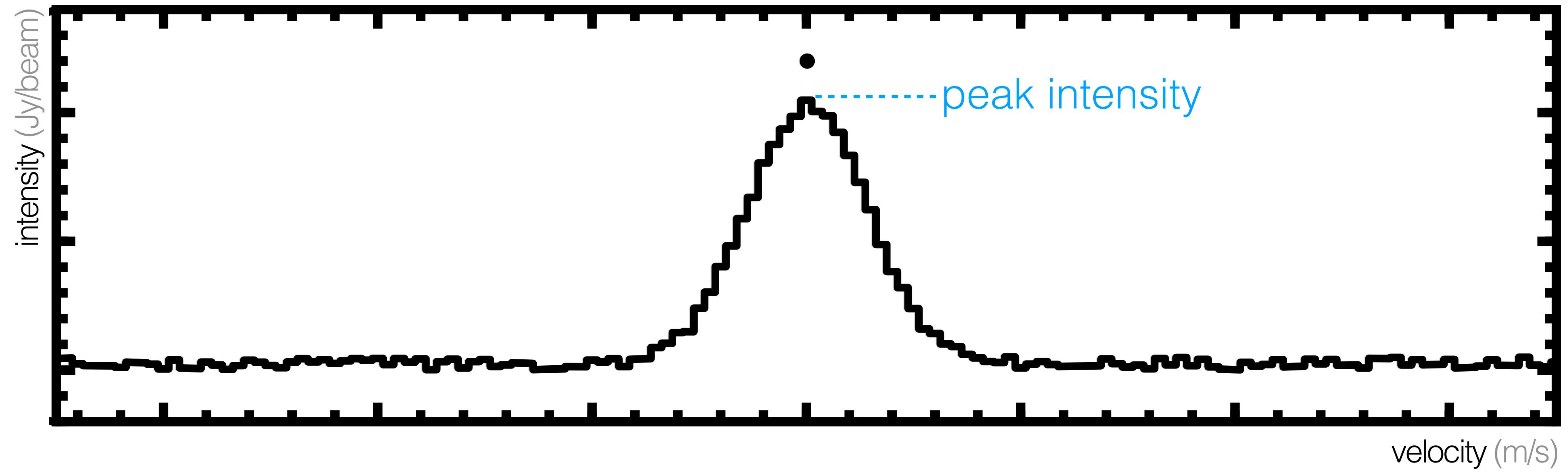


What can we learn if we *don't* do this?

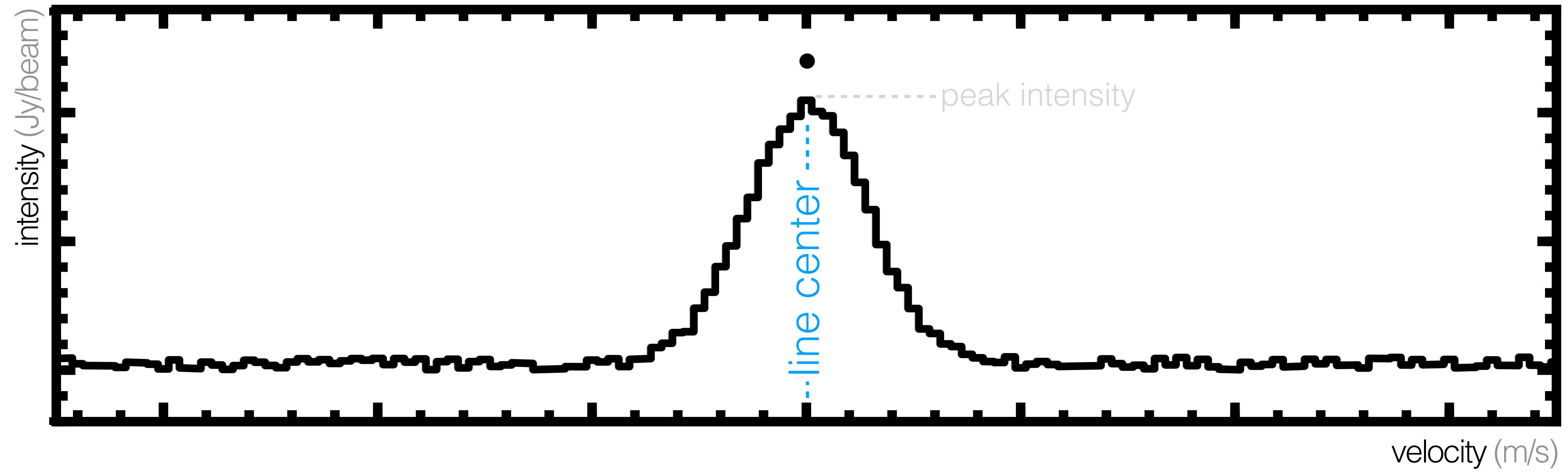


Each pixel is an emission line that has been Doppler shifted relative to the systemic velocity.



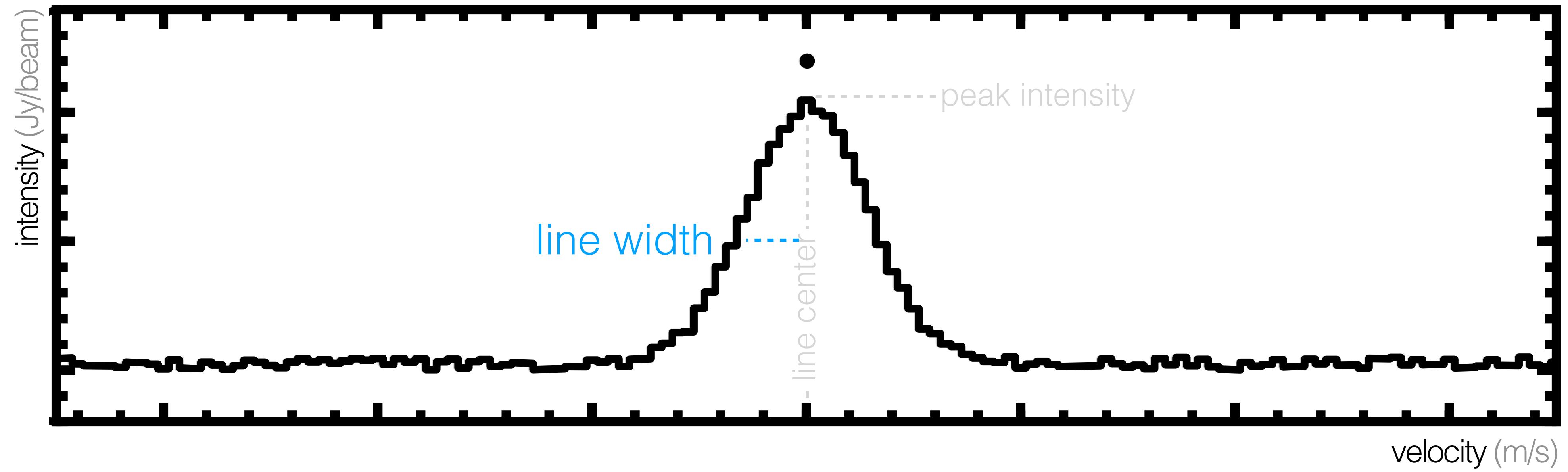


Peak Intensity: gas temperature, molecular column density.



Peak Intensity: gas temperature, molecular column density.

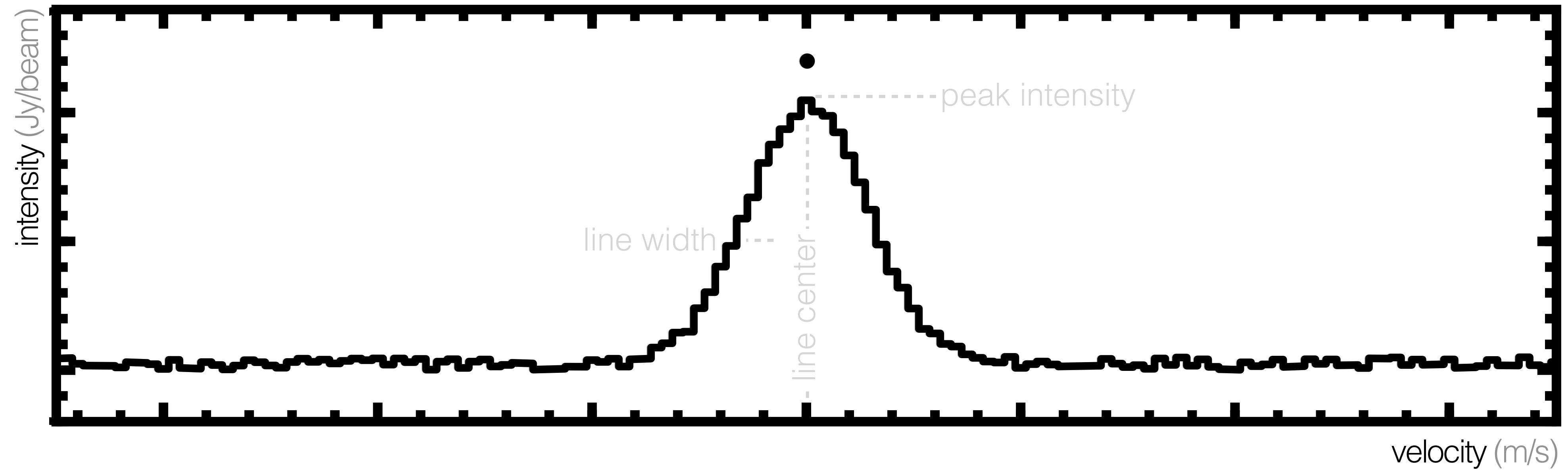
Line Center: (coherent) velocity structure.



Peak Intensity: gas temperature, molecular column density.

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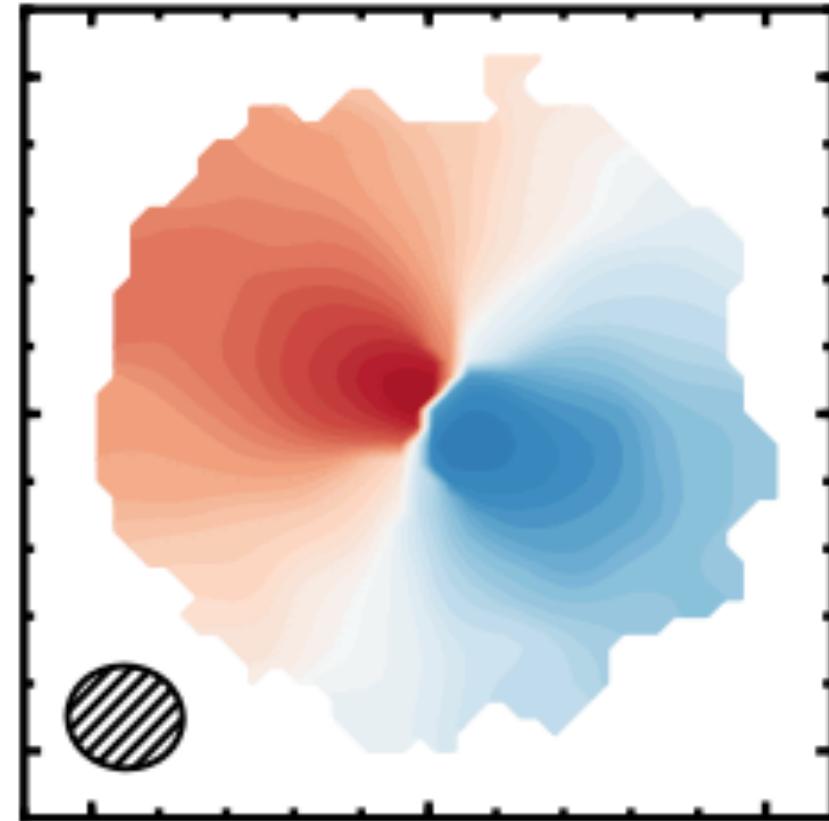
Line Width: velocity dispersions.



Peak Intensity: gas temperature, molecular column density.

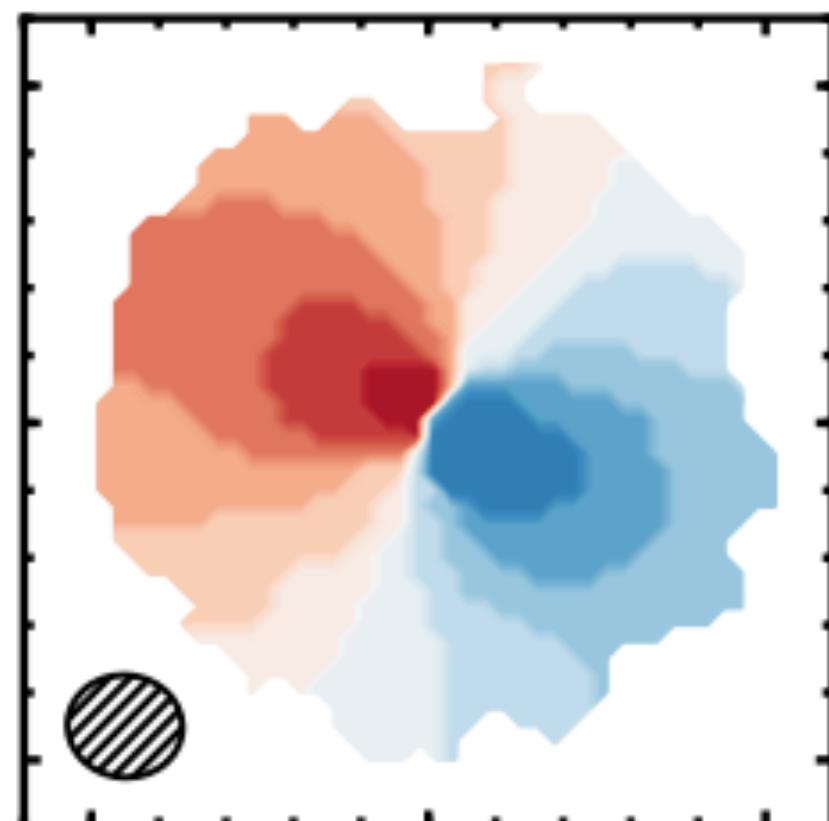
Line Center: (coherent) velocity structure.

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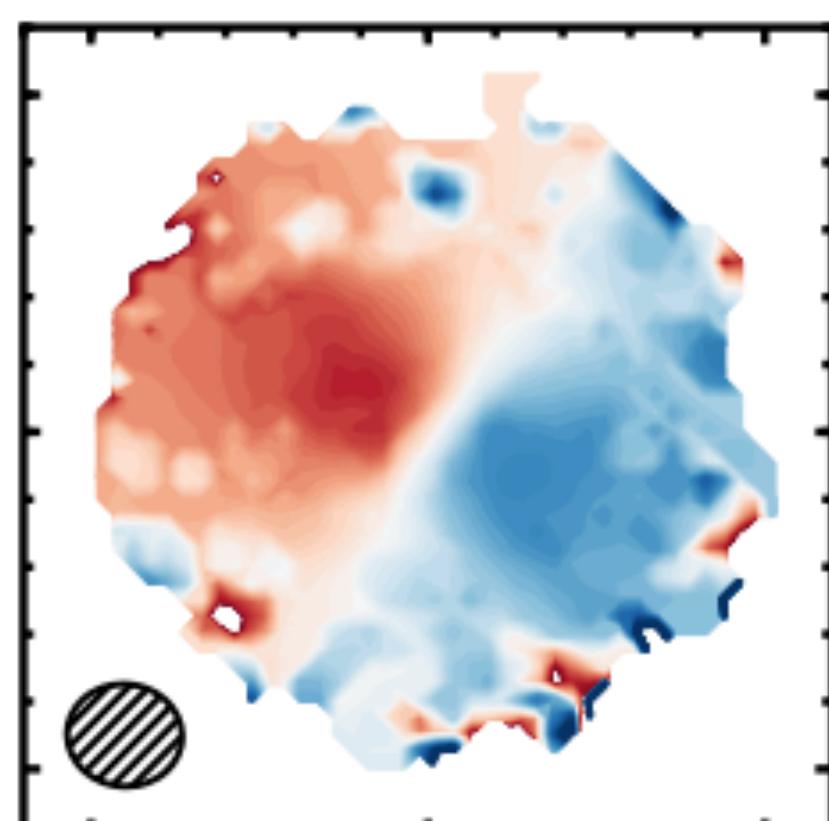
Fit an Analytical Form

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

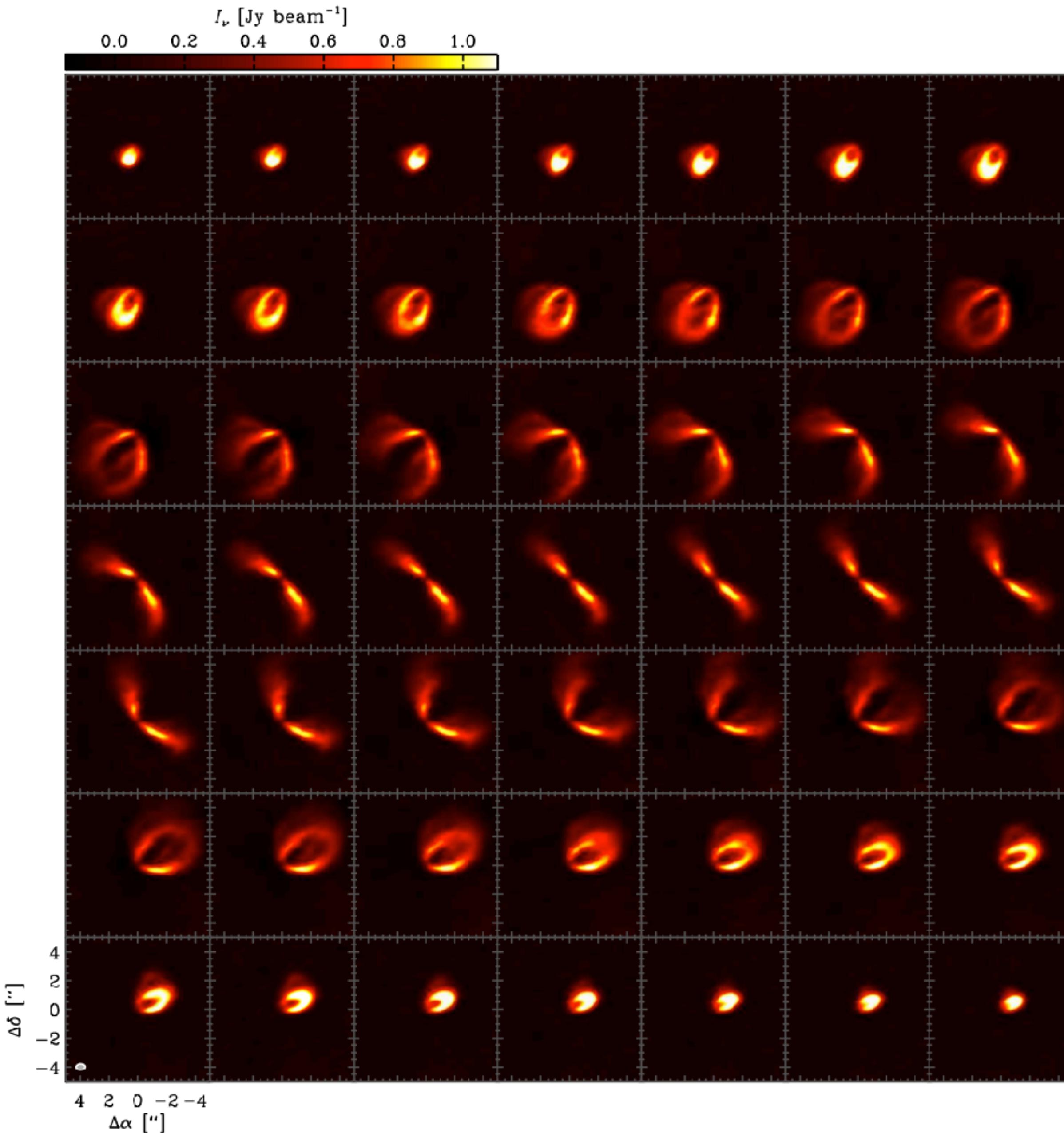


Take Peak Value

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

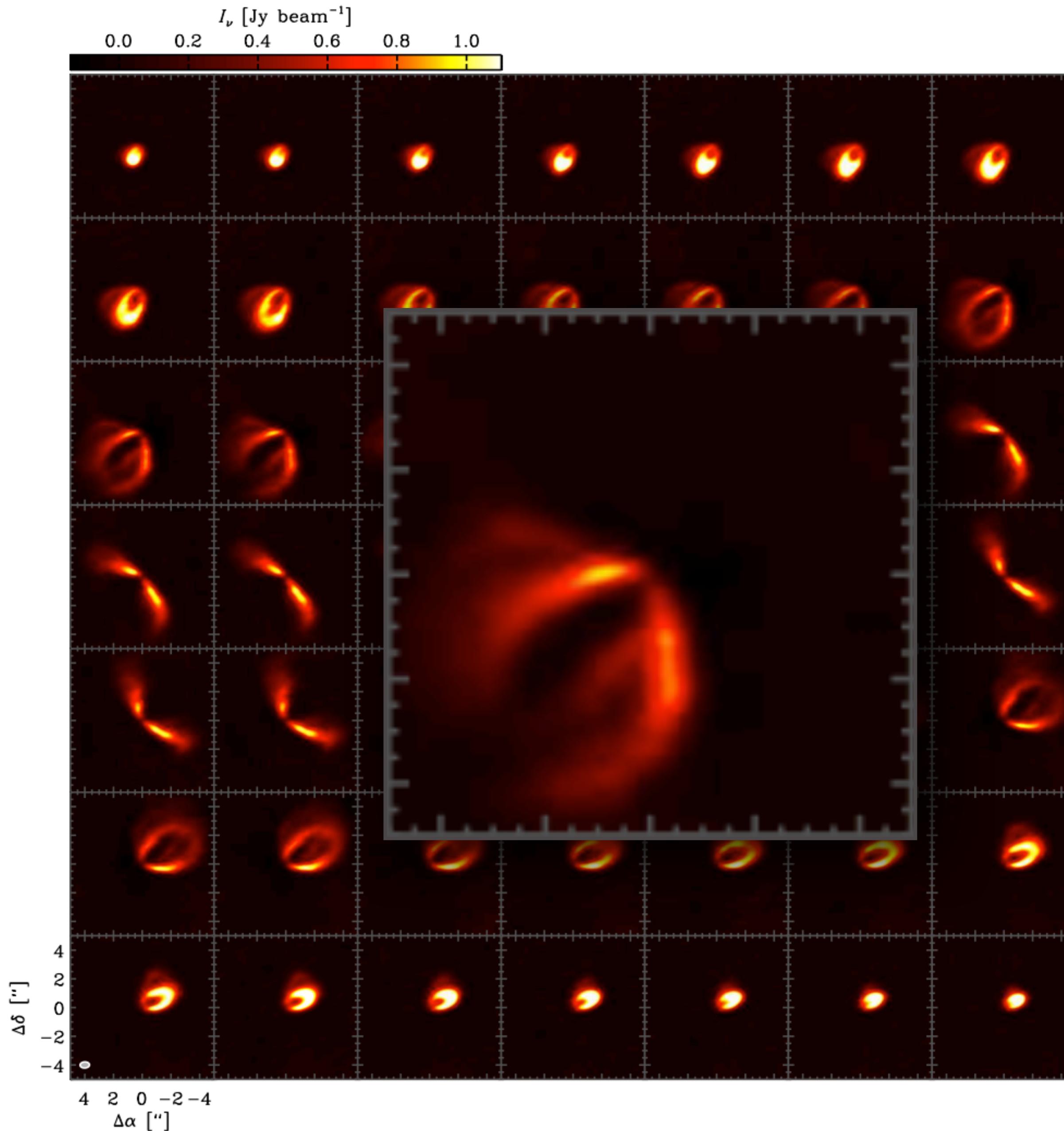
Take Statistical Moments

pro: implemented in CASA
con: horrendously noisy



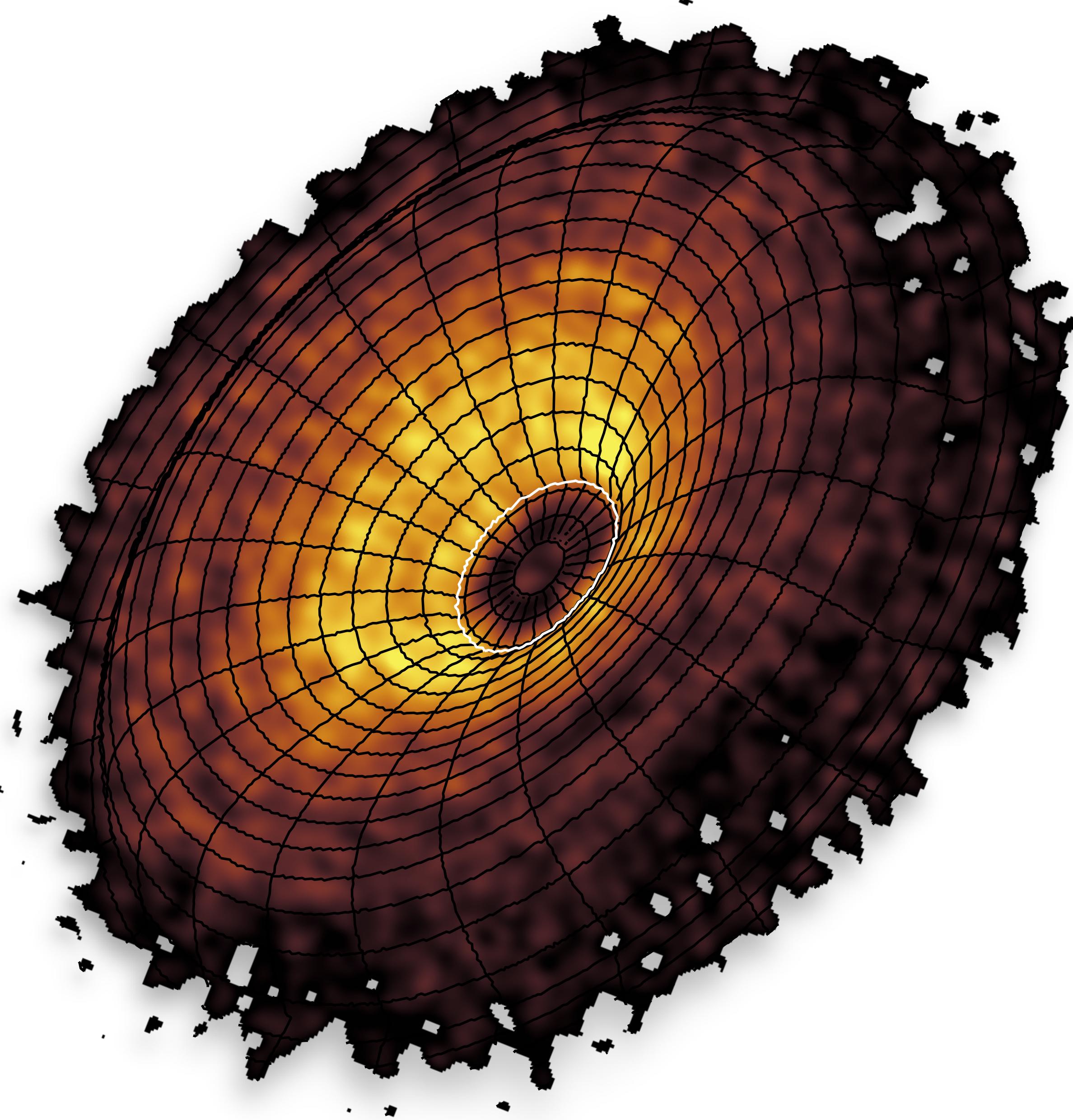
We're actually tracing *two* sides of the disk and we can start to map out the 3D structure of the disk.

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



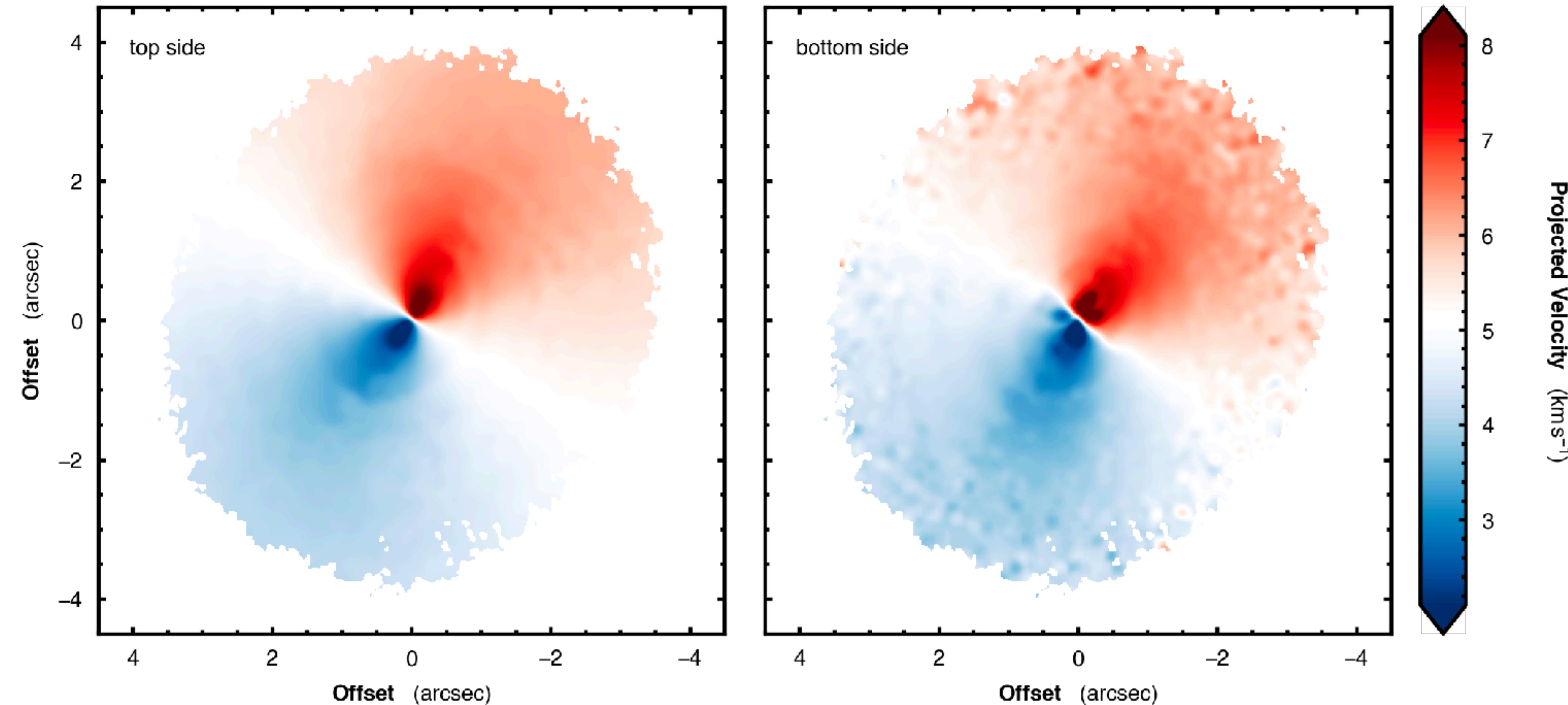
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Rich et al. (2021), Casassus et al. (2021), Law et al. (2021c)



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

The velocity structure of the disk is dominated by rotation.

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

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.

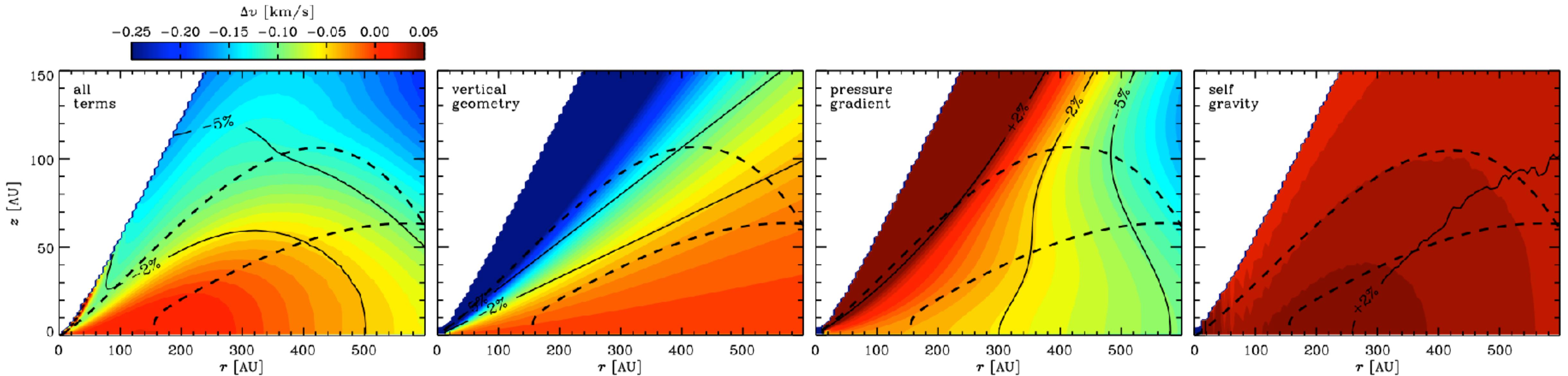
Teague et al. (2018ac, 2019), Dullemond et al. (2020), Rab et al. (2020), Rosotti et al. (2020), Yu et al. (2021)

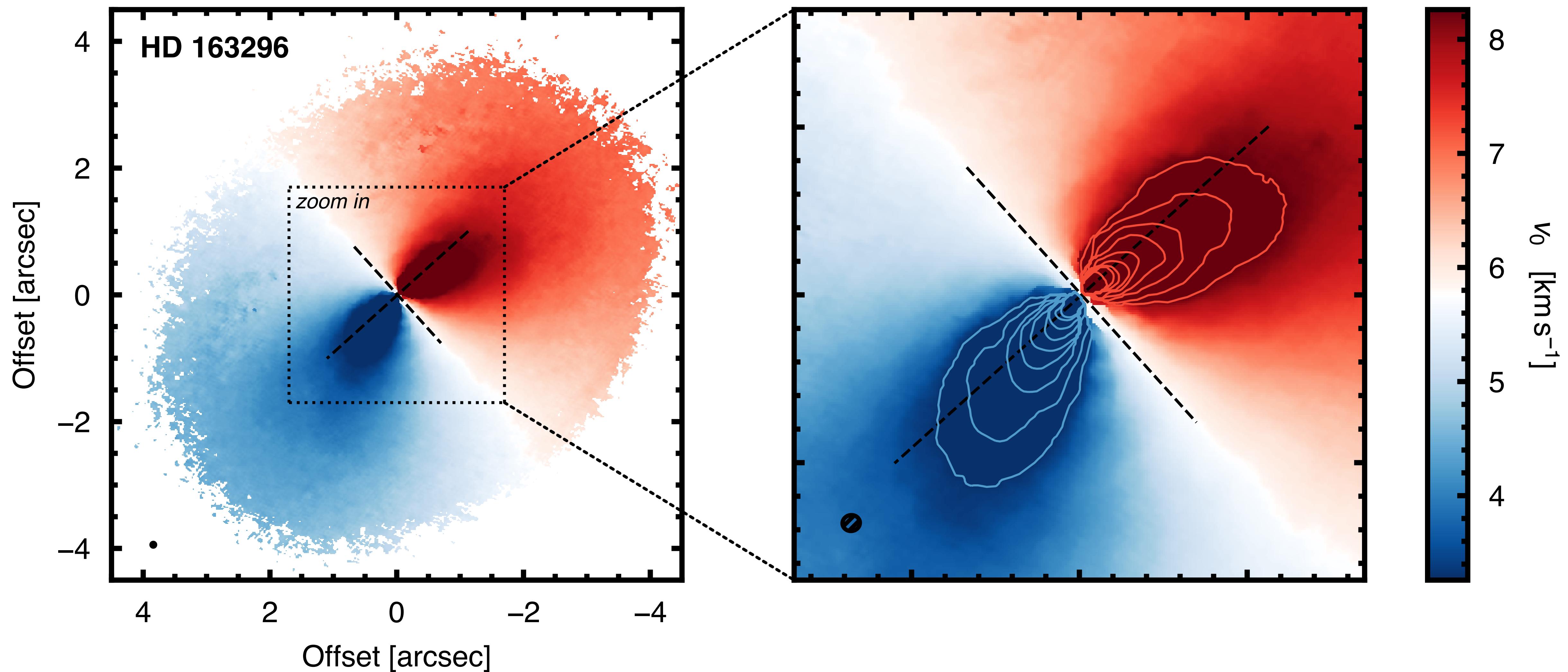
Self-Gravity: Disk surface density.

Veronesi et al. (2021)

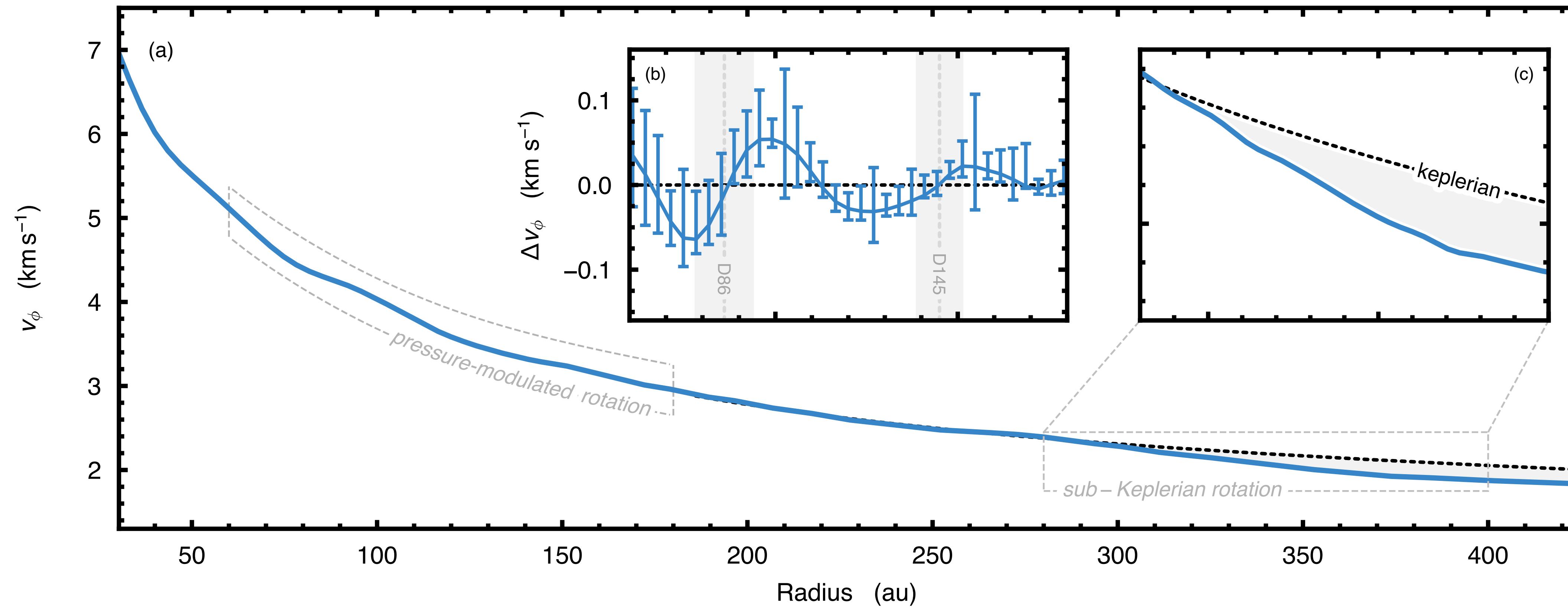
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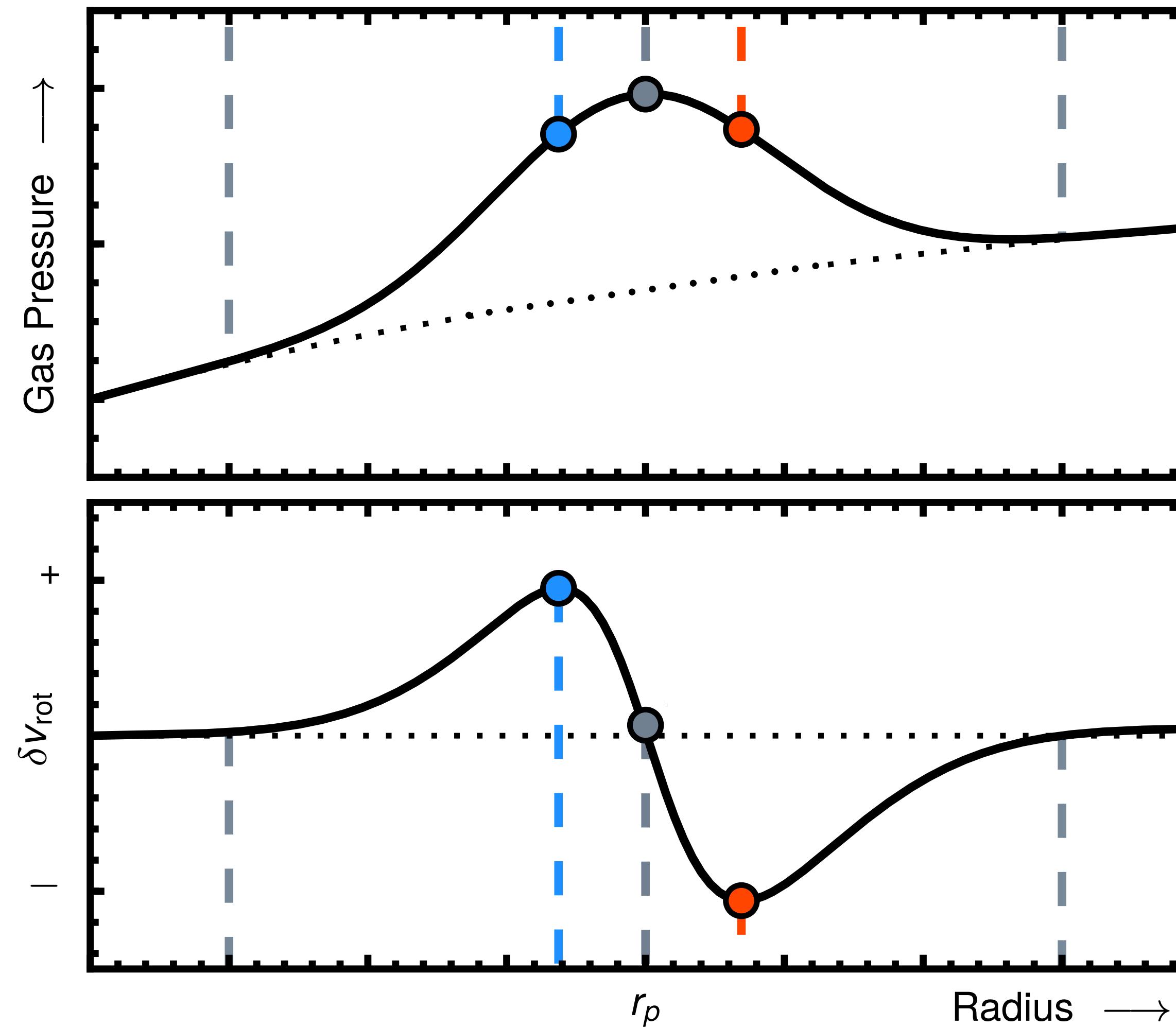
data from DSHARP; Andrews et al. (2018), Isella et al. (2018)



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

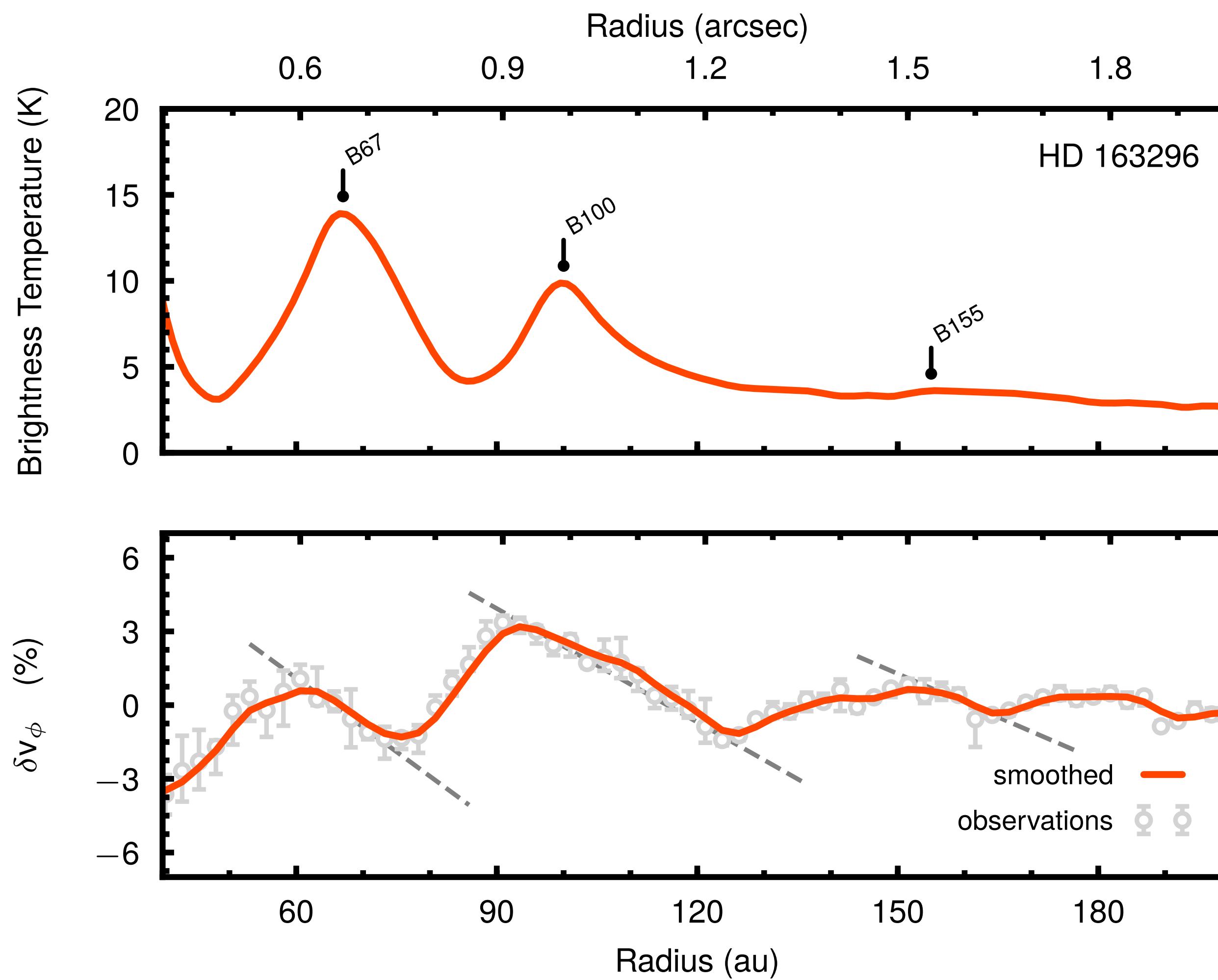
conerot (Casassus et al., 2021) // eddy (Teague 2019)

adapted from Pinte et al. (PPVII Review)



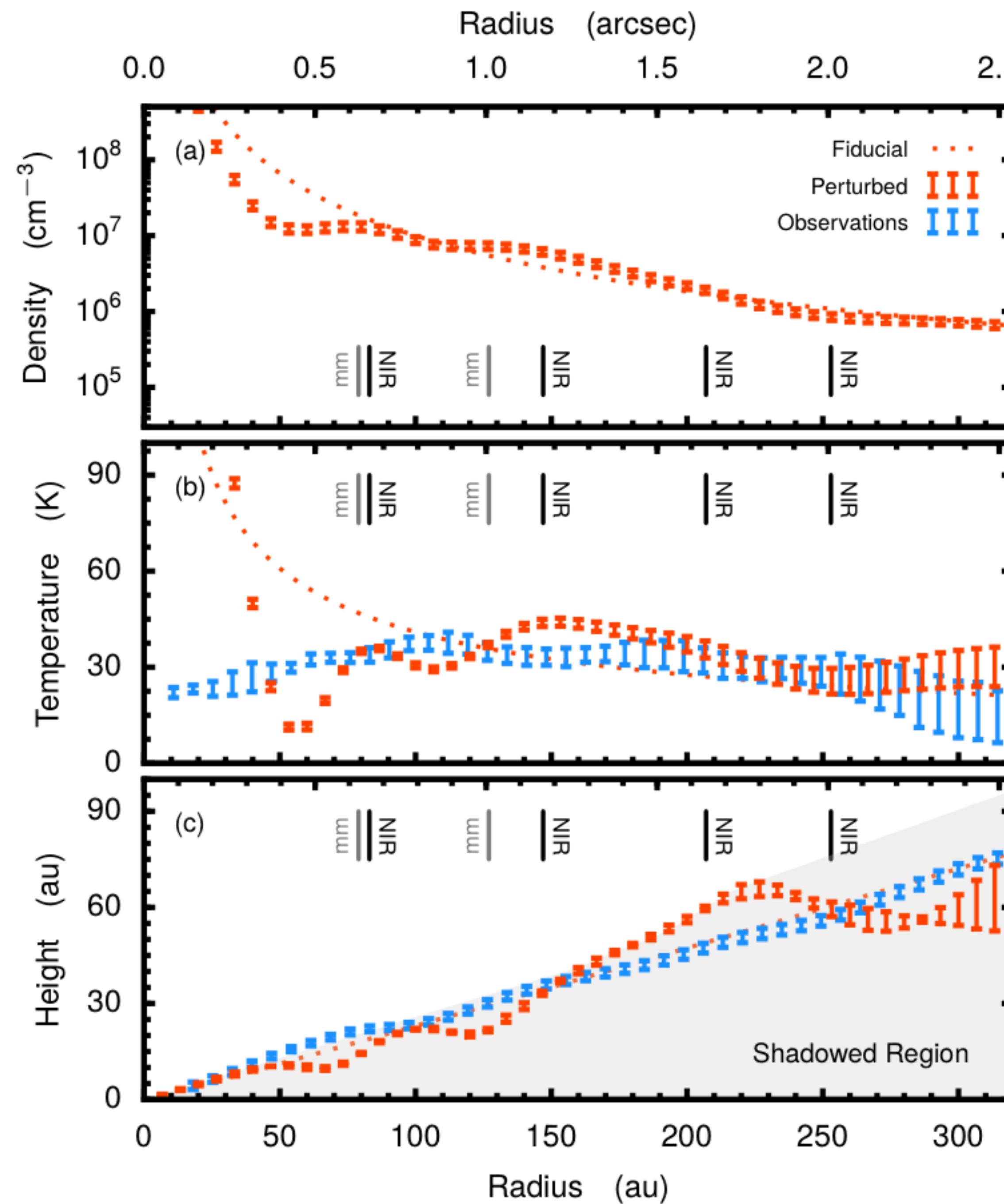
Localized changes in the rotation velocity allow us to infer the presence of substructure in the gas pressure.

see also Kanagawa et al. (2015)



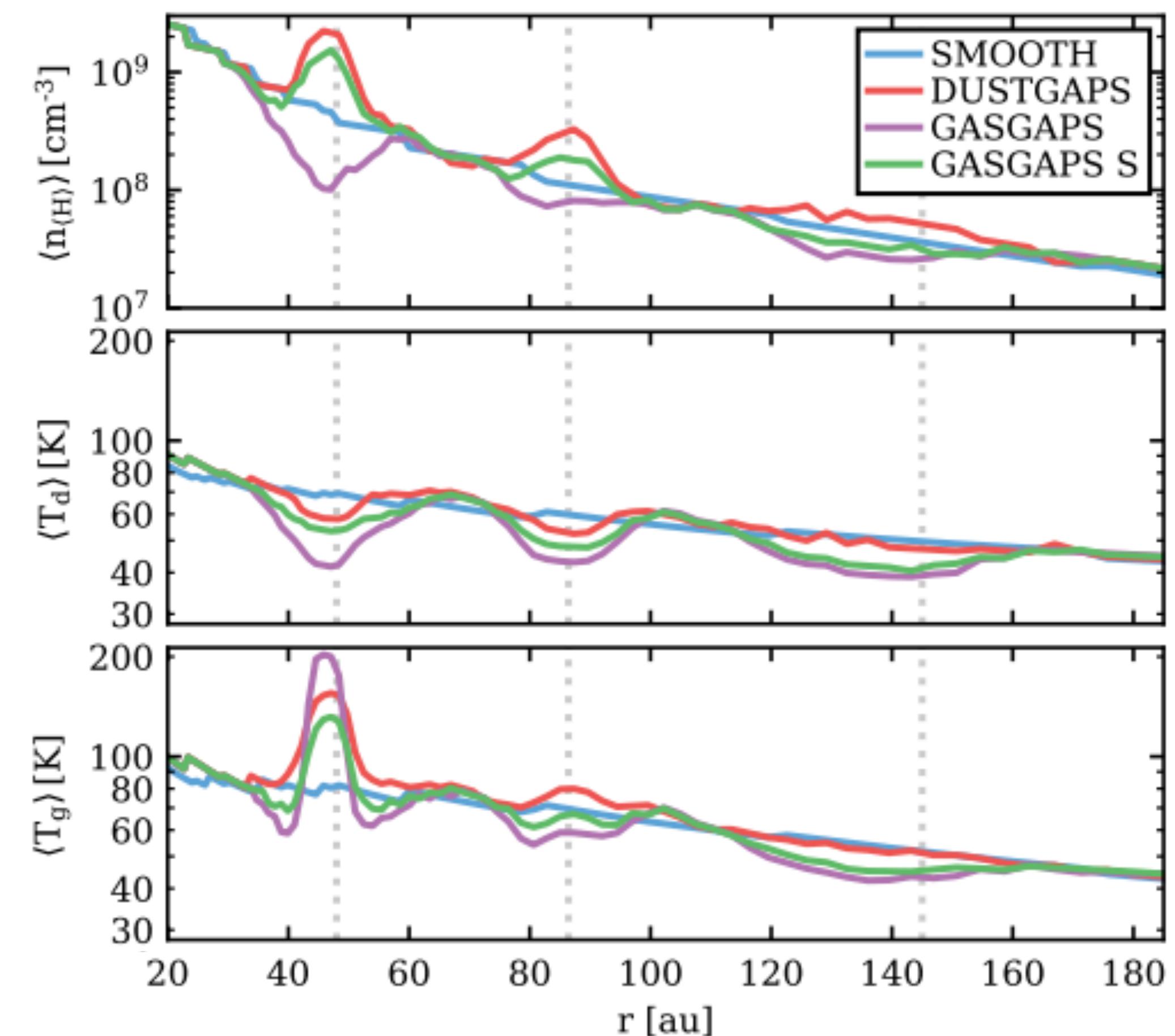
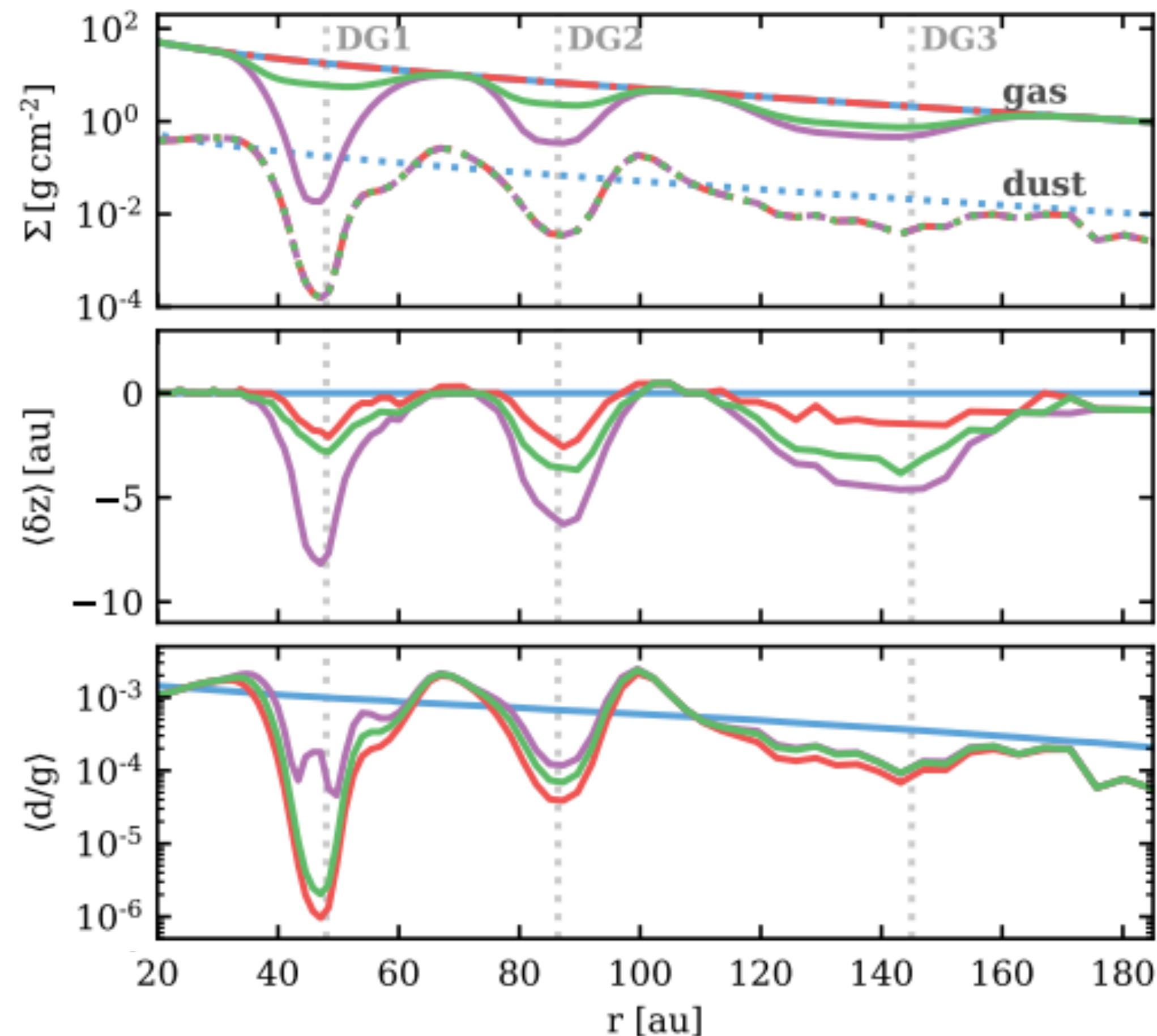
We can also use this to test the efficiency of grain trapping and the coupling between gas and dust.

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

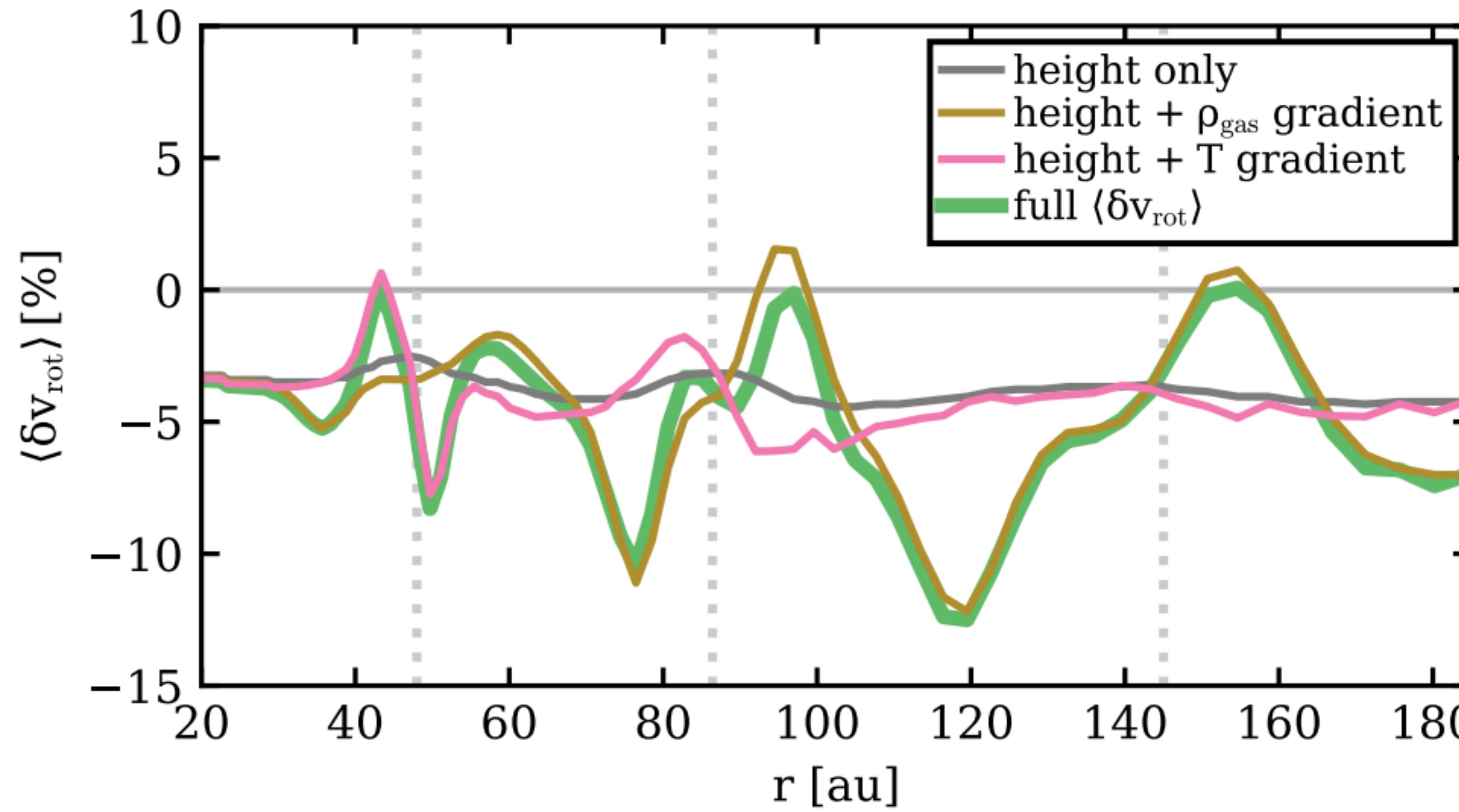


Under certain assumptions we can start to reconstruct the underlying density and temperature profiles.

see also Yu et al. (2021)

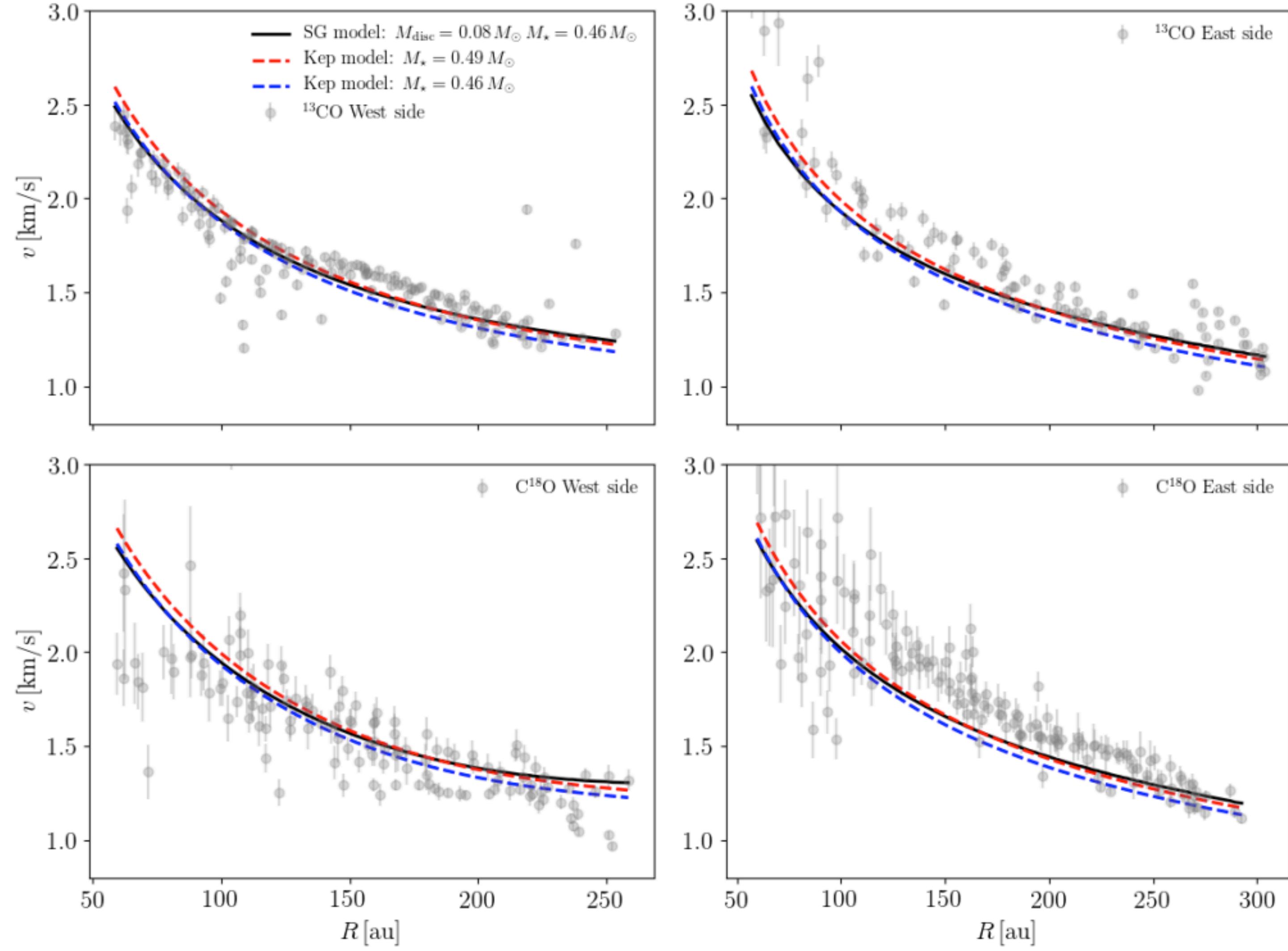


Velocity perturbations sensitive to both temperature *and* density in the gap.



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

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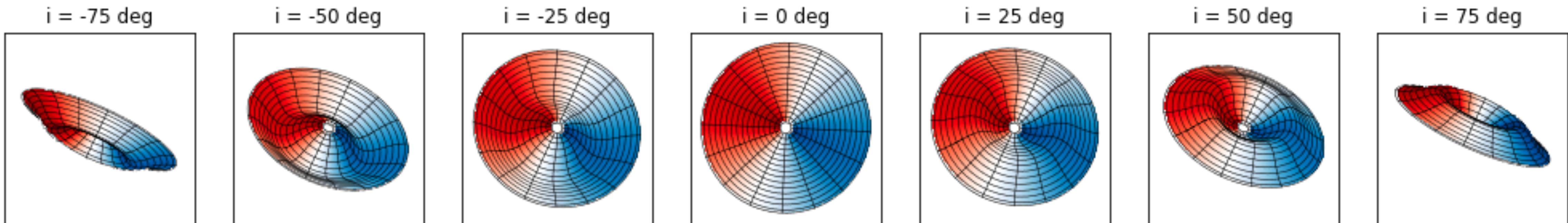
With sufficiently sensitive observations we can search for the imprints of self-gravity.

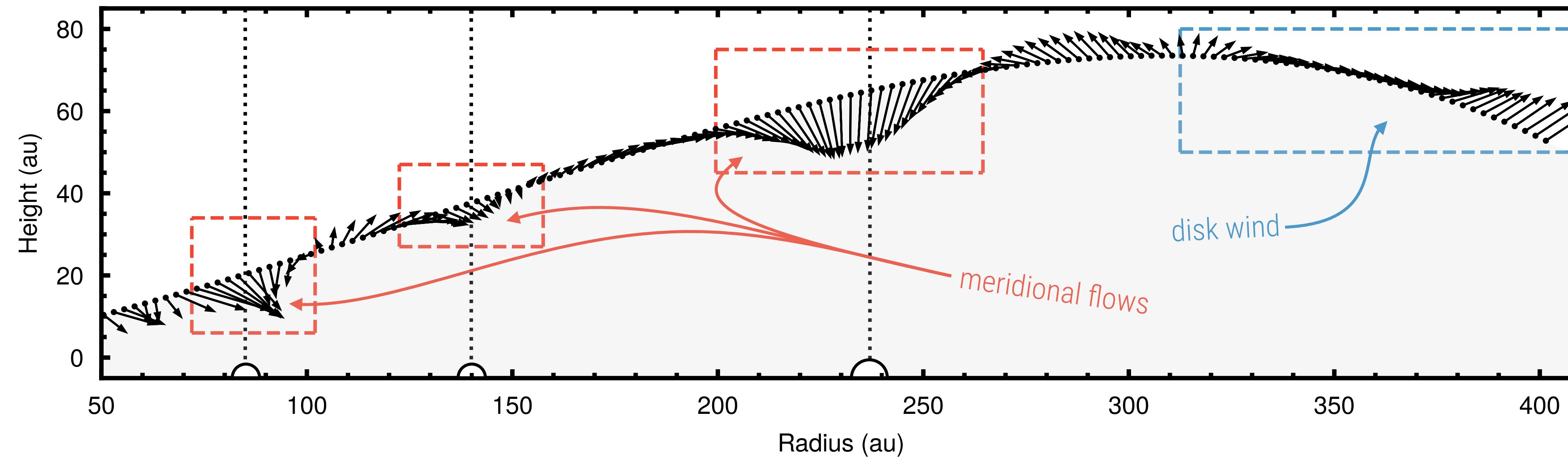
Caveat: Can we disentangle pressure support and self-gravity?

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

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

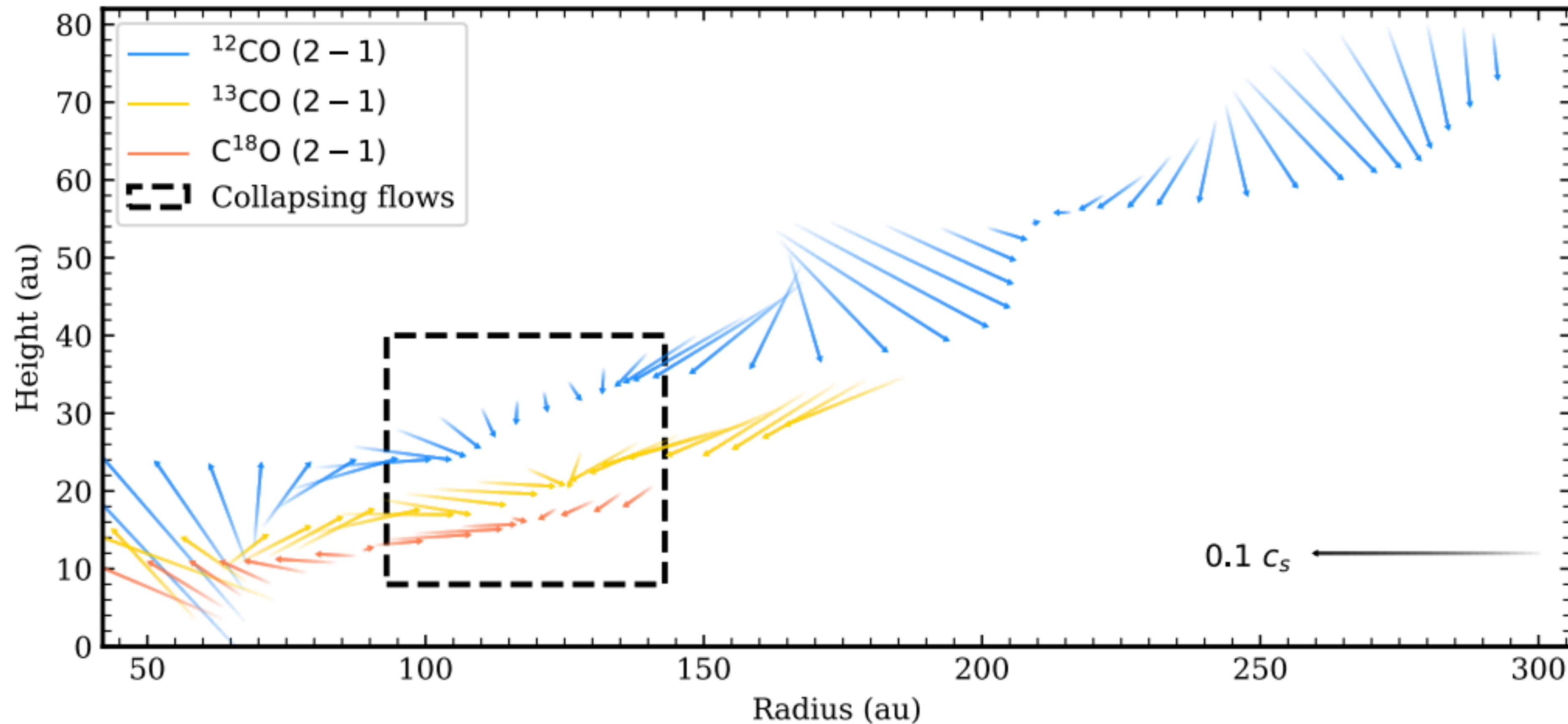
We can leverage our 3D reconstruction to account for that projection.





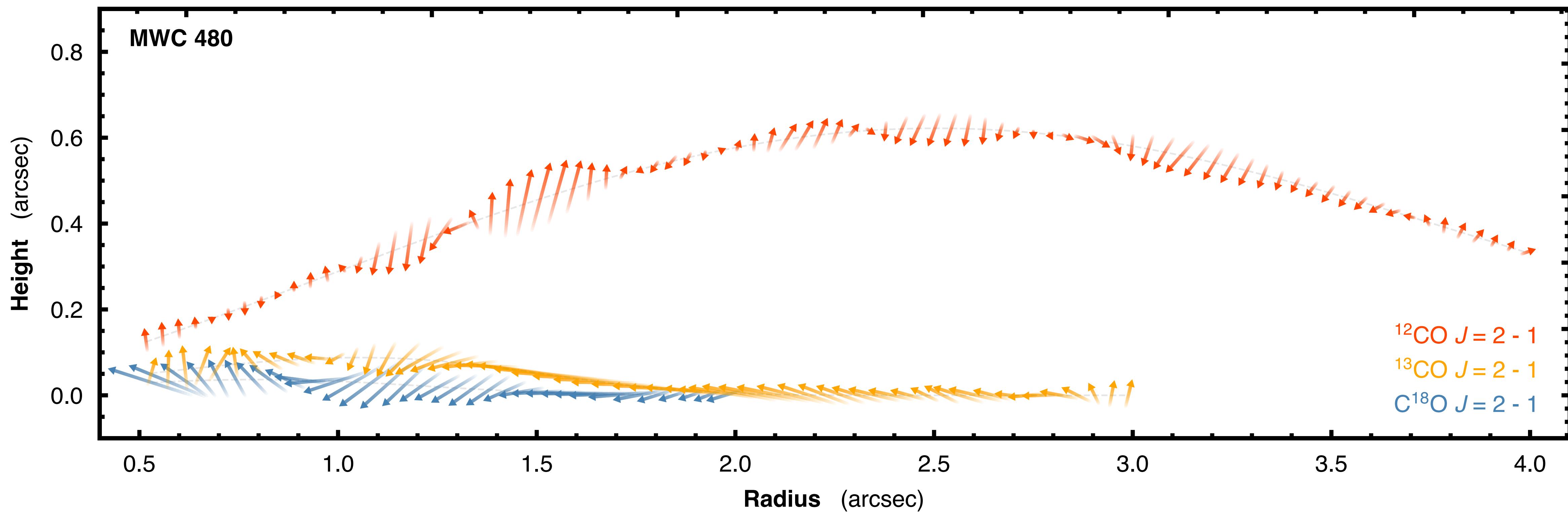
It is now possible to map out the velocity structure in the (r, z) plane allowing for a direct comparison to numerical simulations.

also see Casassus et al. (2021)



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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)

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.

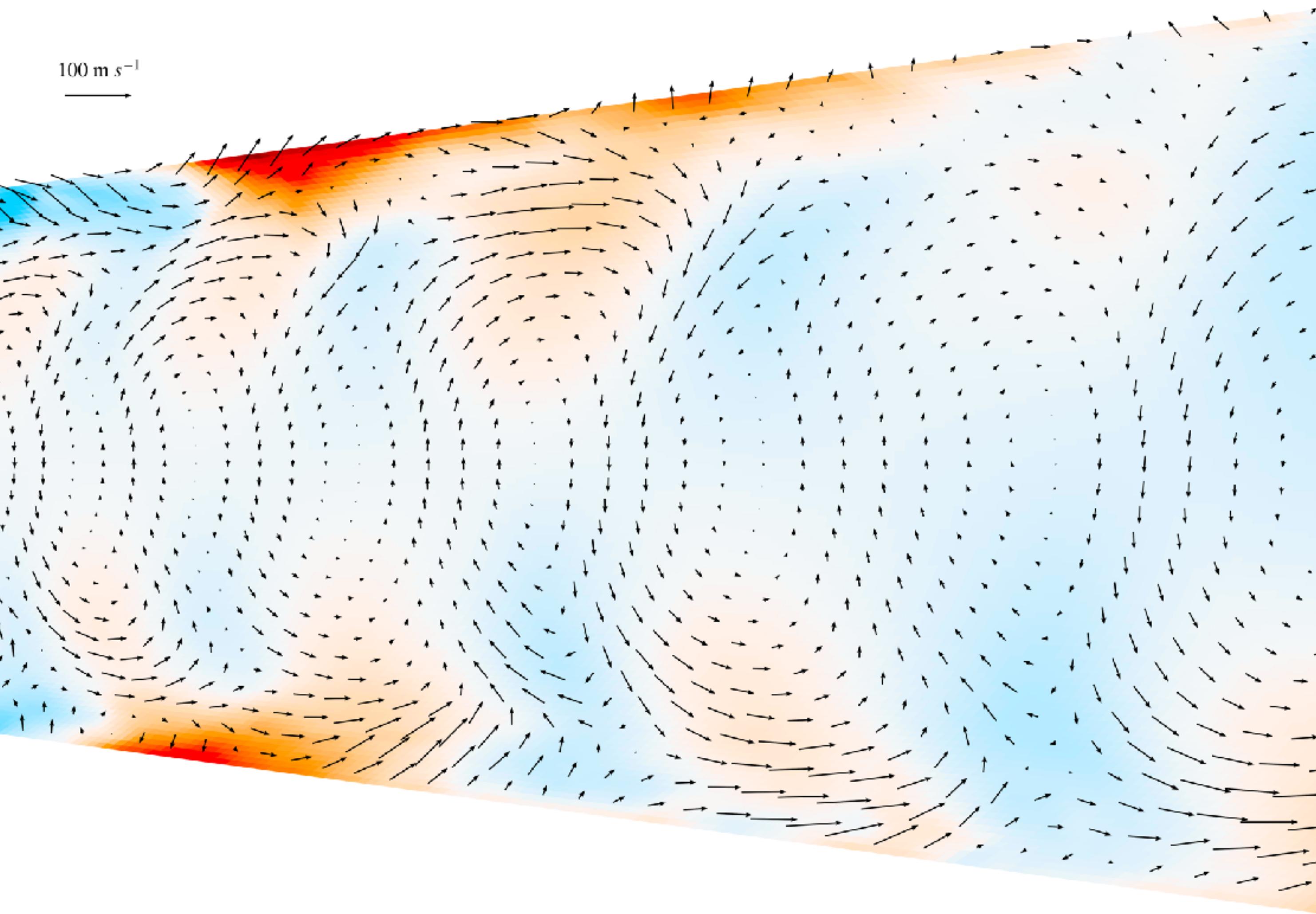
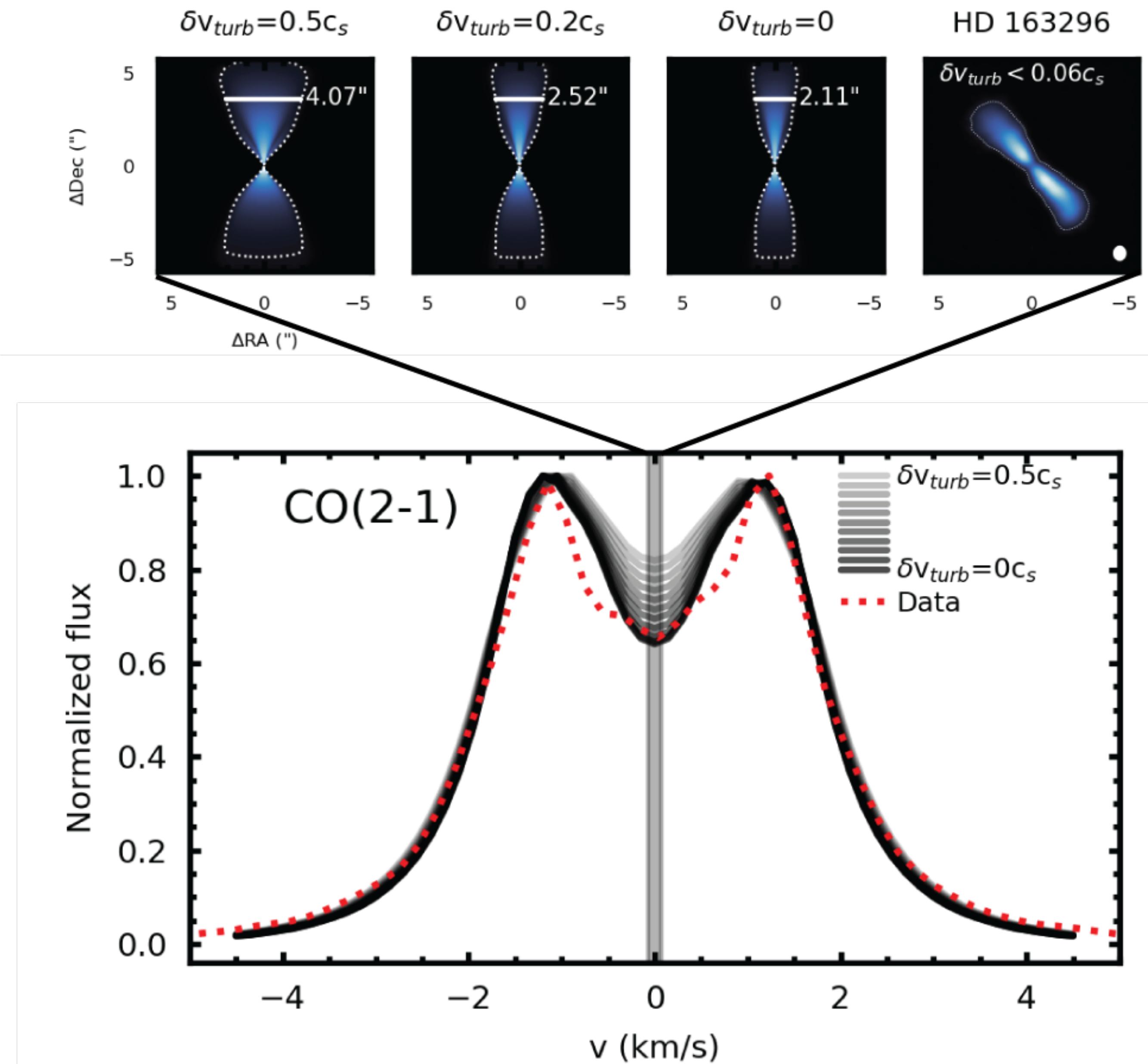
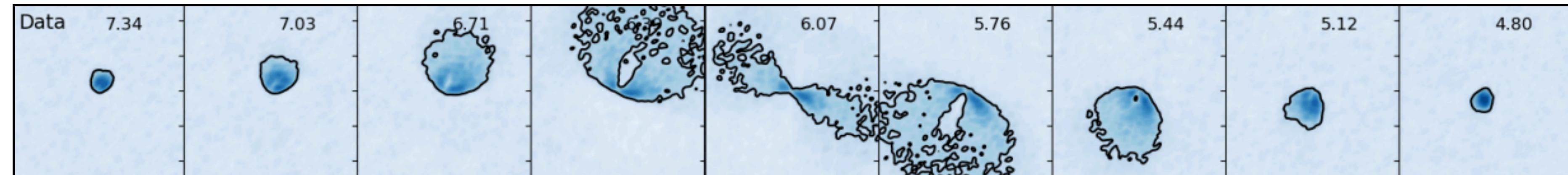


figure courtesy of Marcelo Barraza

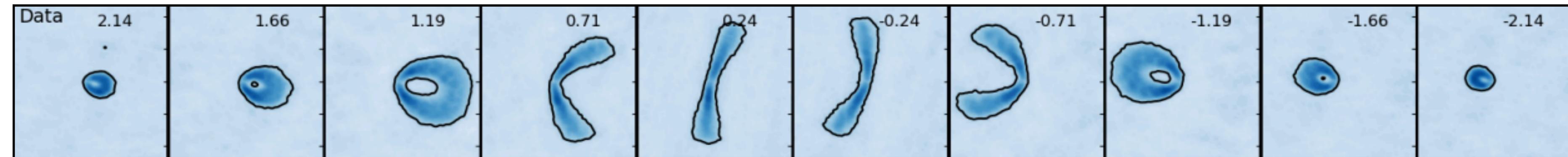
By modeling the resolved line profile we can try and measure any non-thermal contribution to broadening.

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

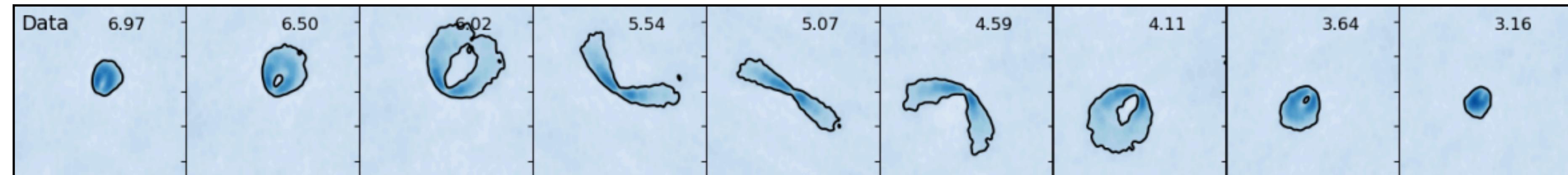




DM Tau
 $\alpha \sim 8 \times 10^{-2}$



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

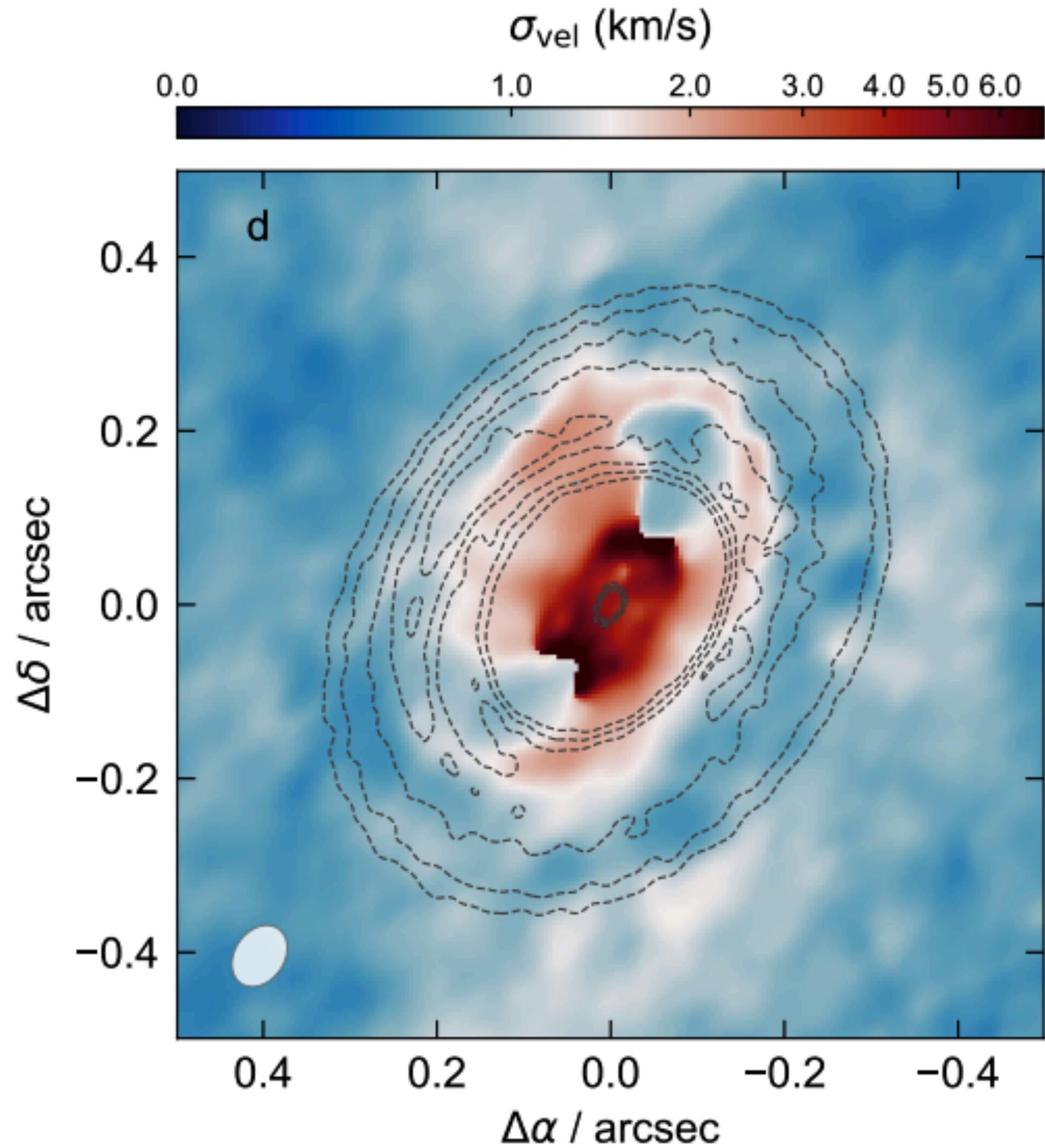


MWC 480
 $\alpha \lesssim 10^{-3}$

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

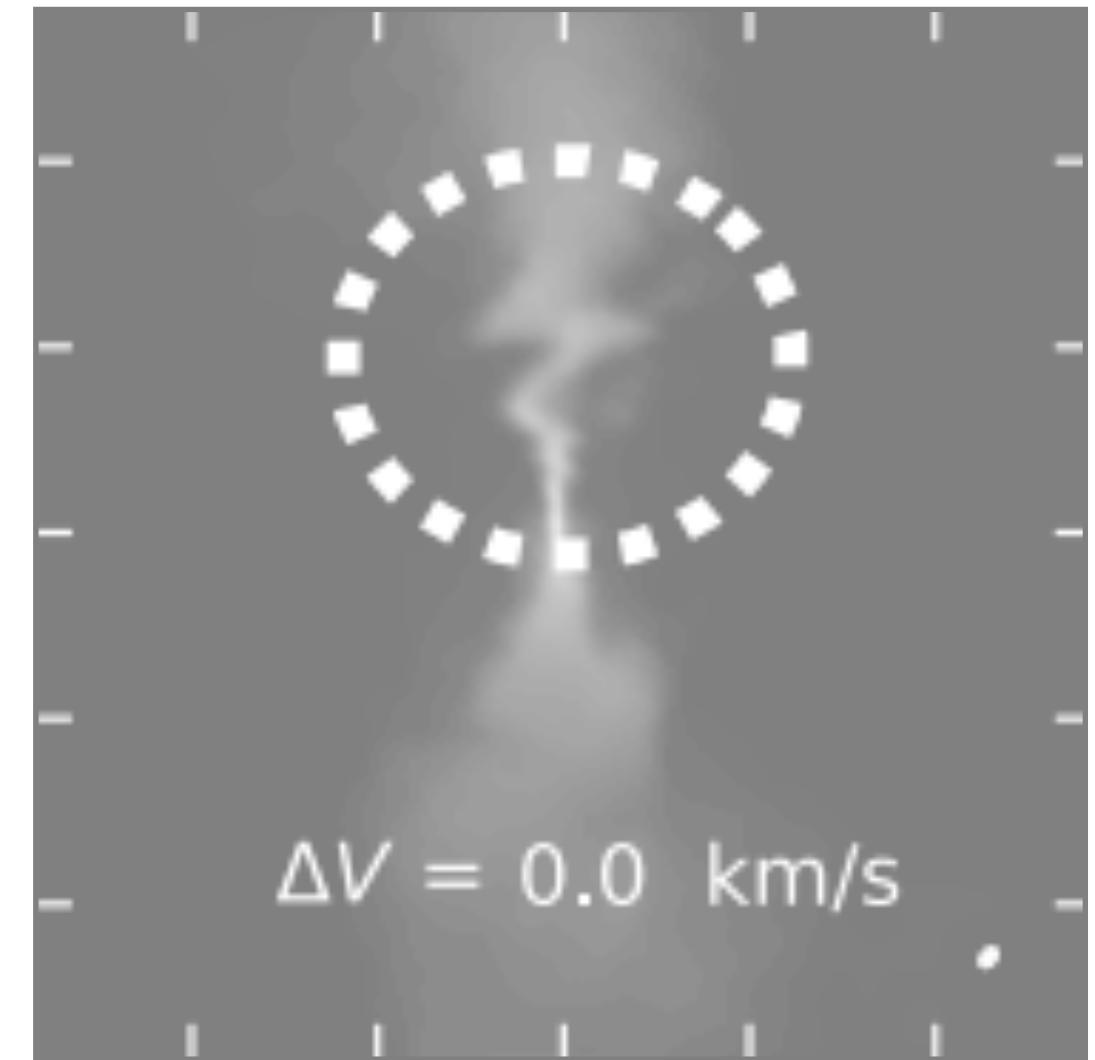
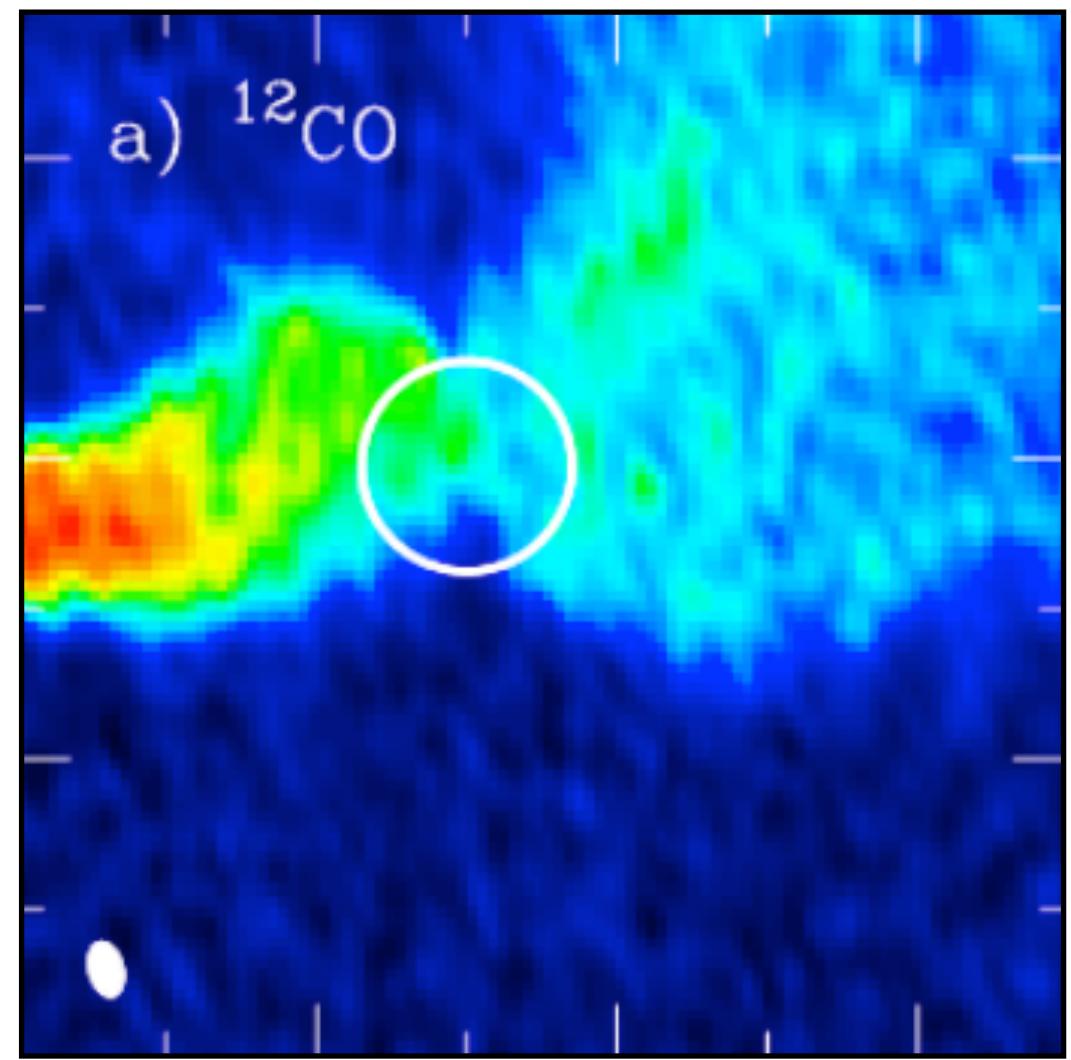
Caveat: Do we know the systematics?

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



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

See also Casassus et al. (2021)



Embedded Planets: 'kinks' around the planet's location.

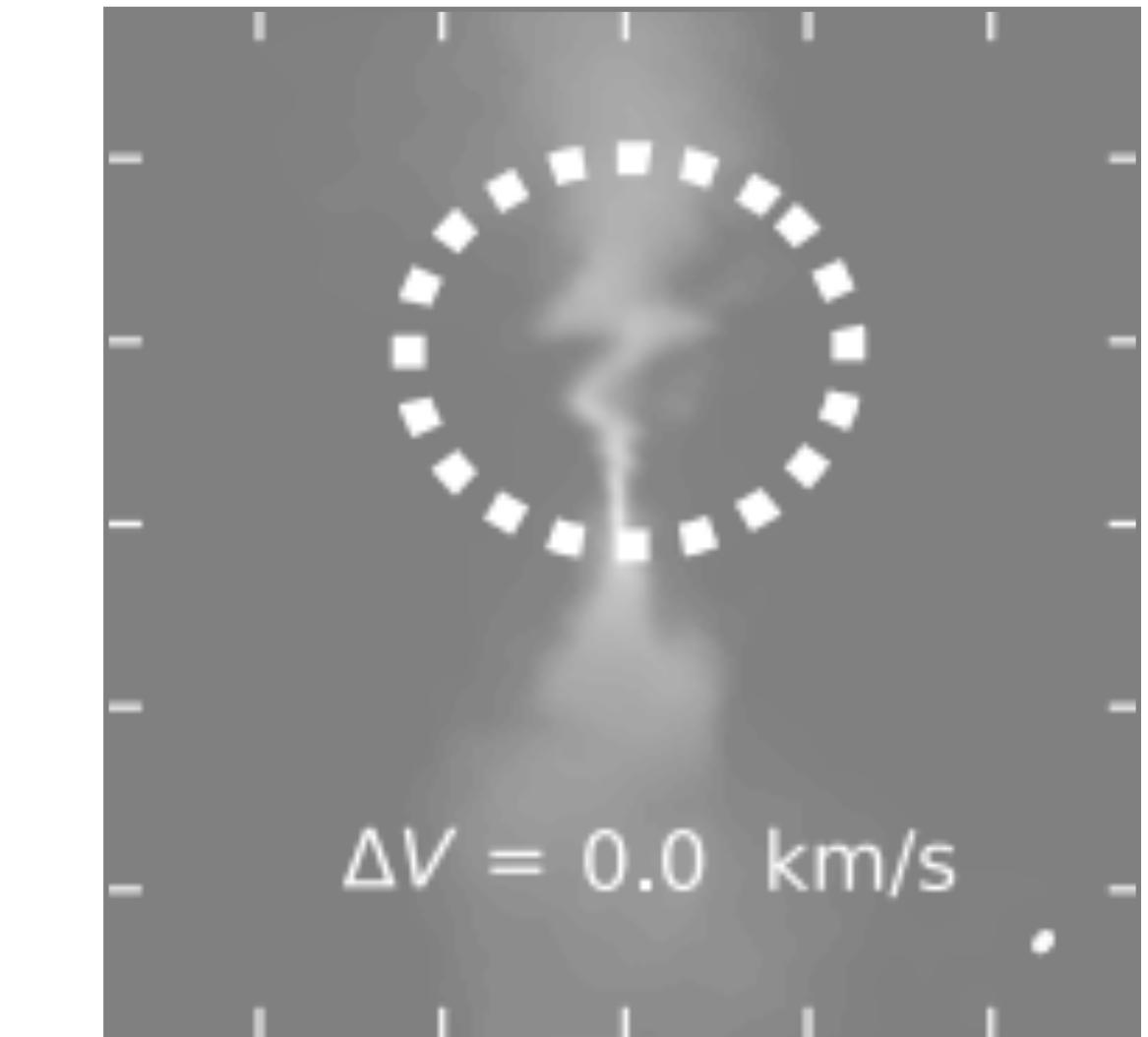
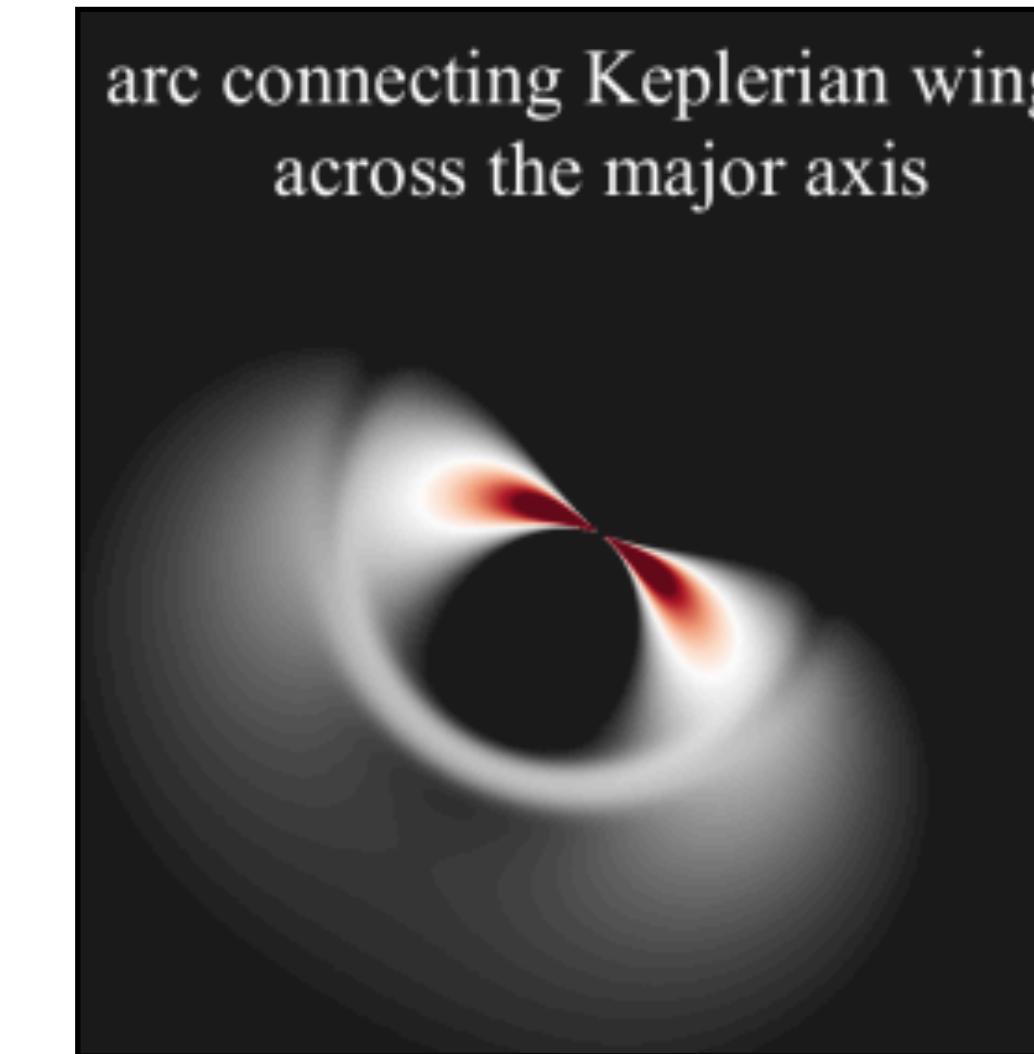
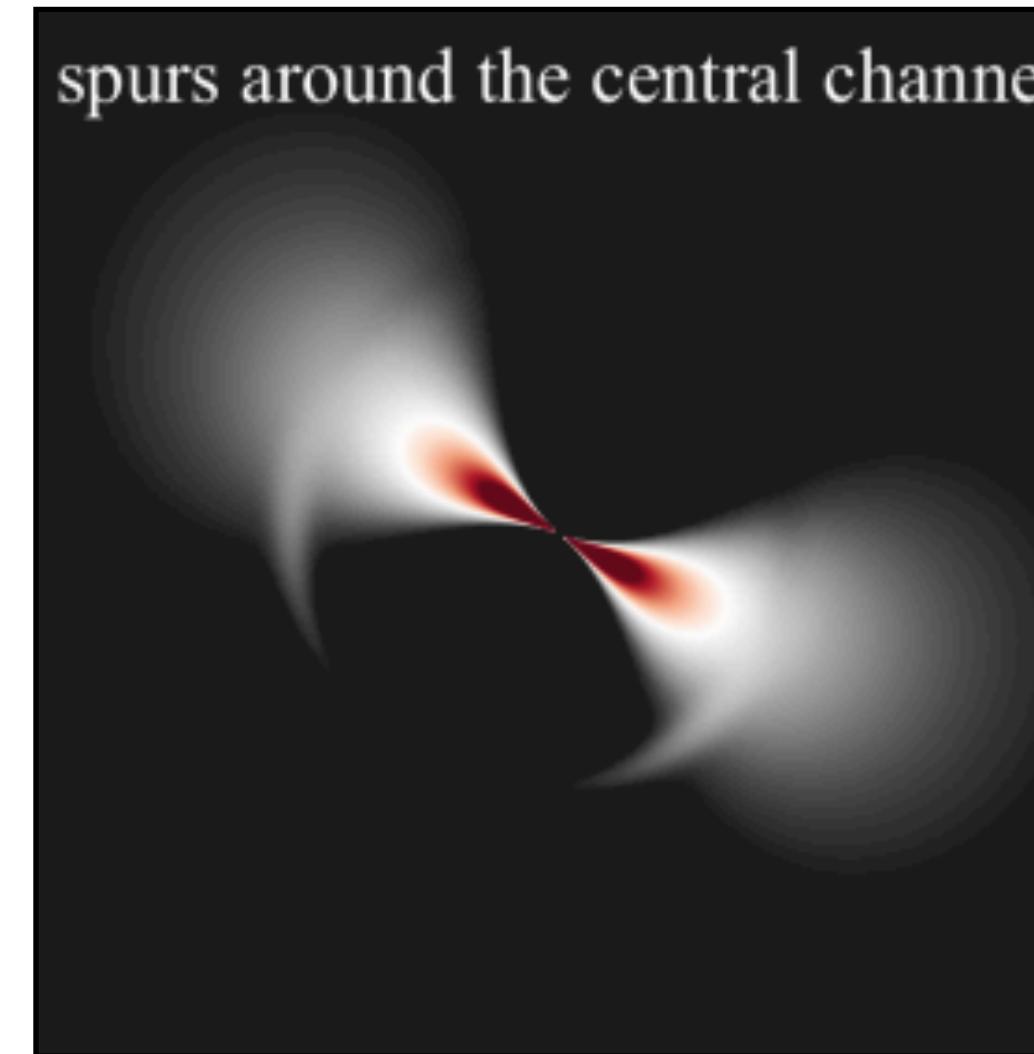
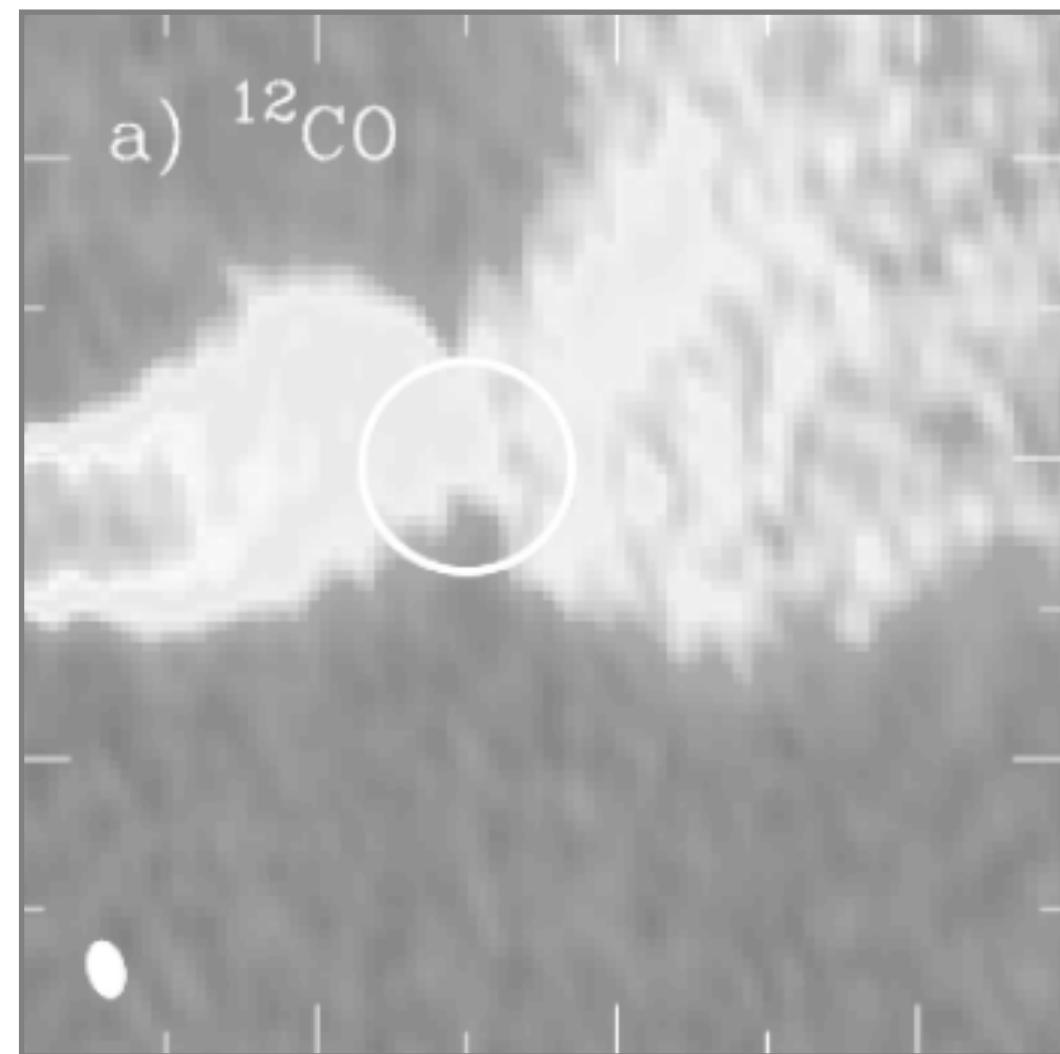
Perez et al. (2015), Pinte et al. (2018, 2019, 2020)

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)



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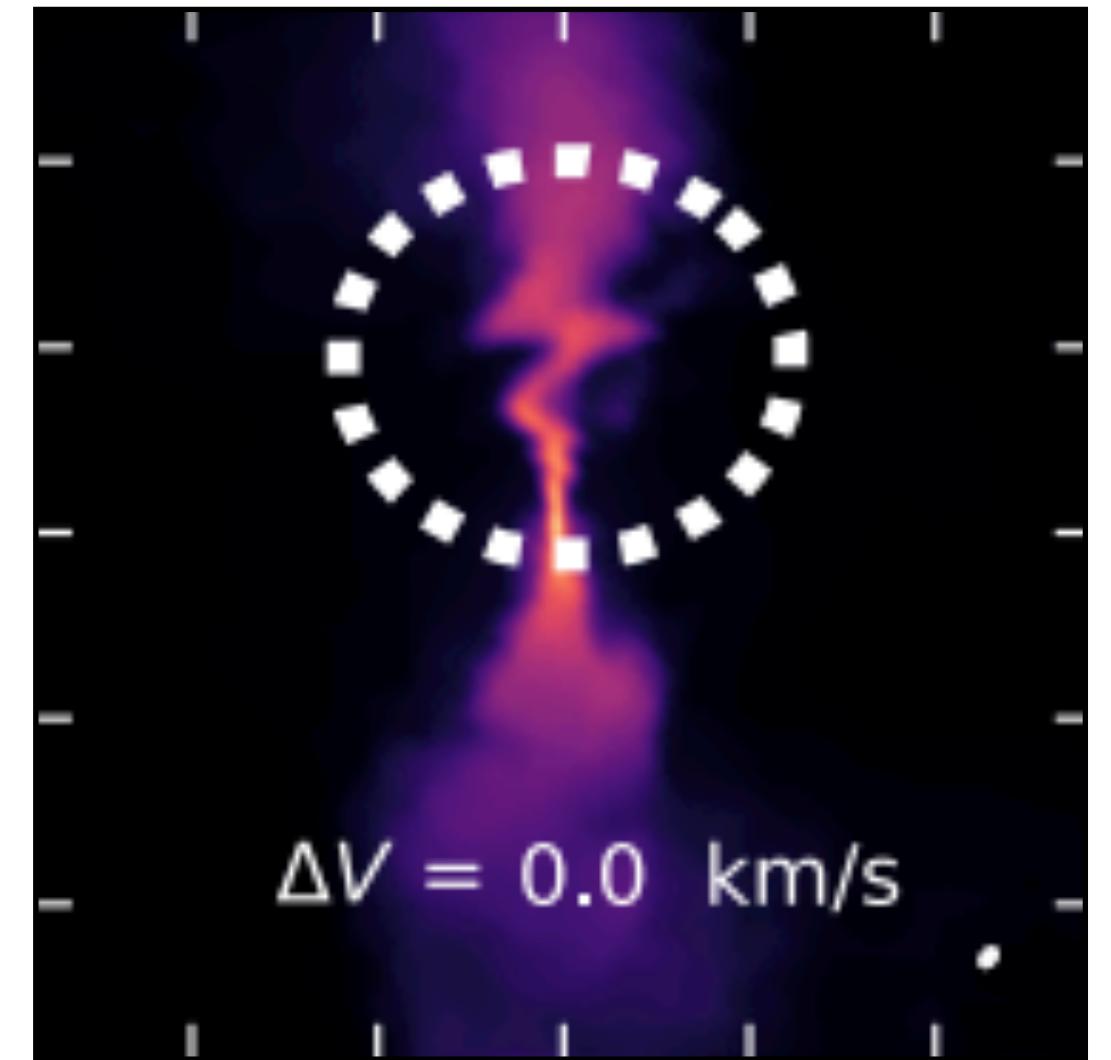
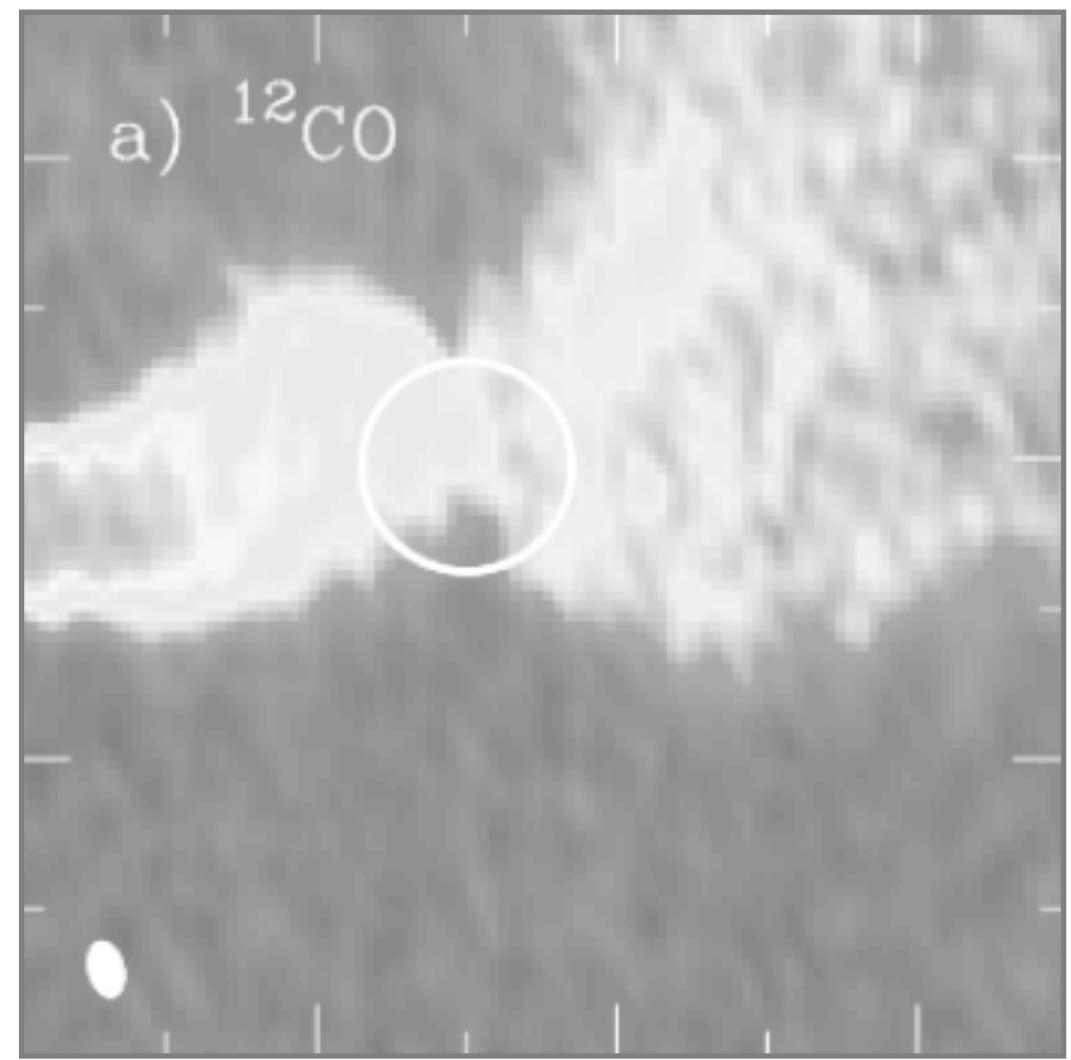
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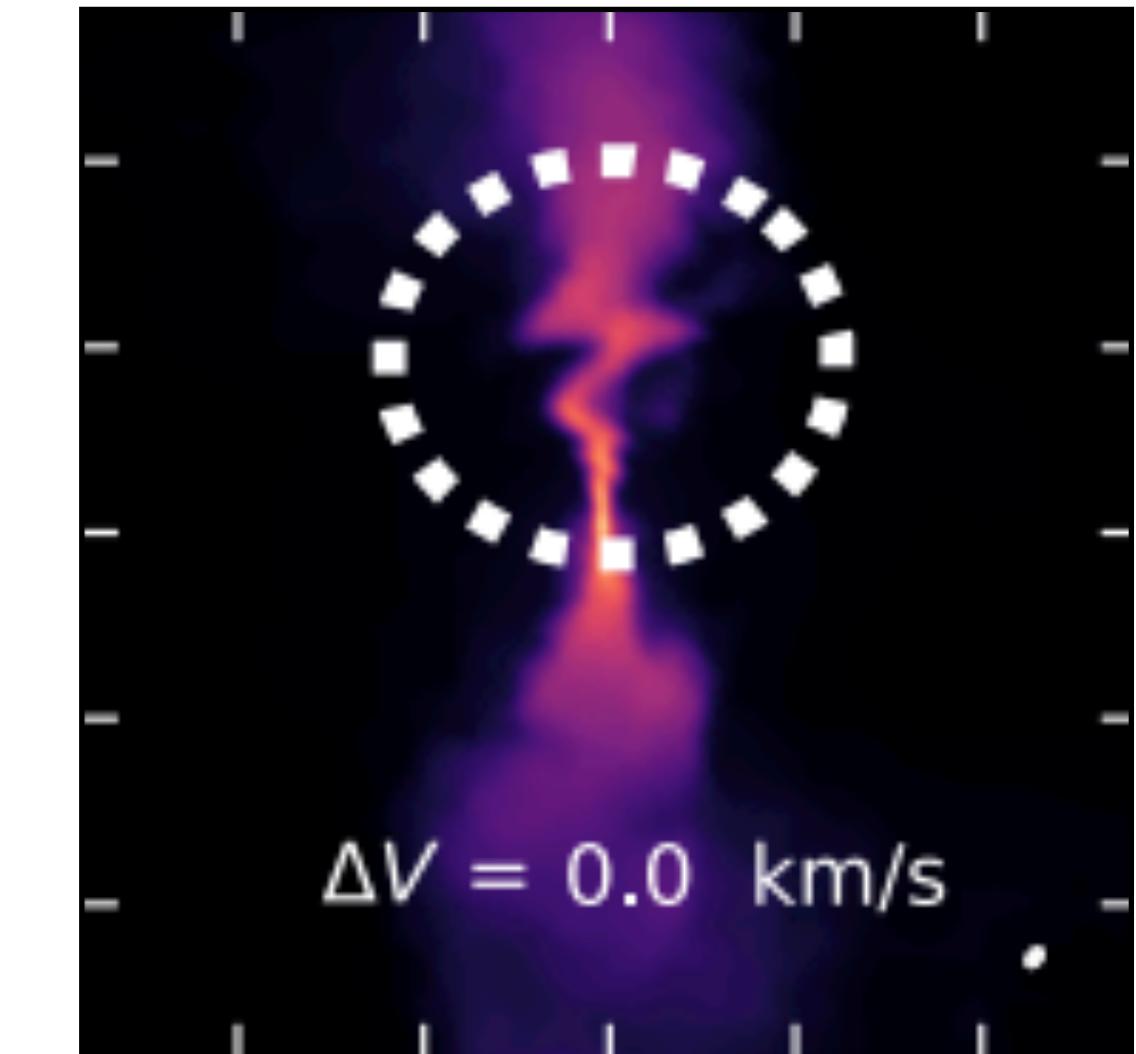
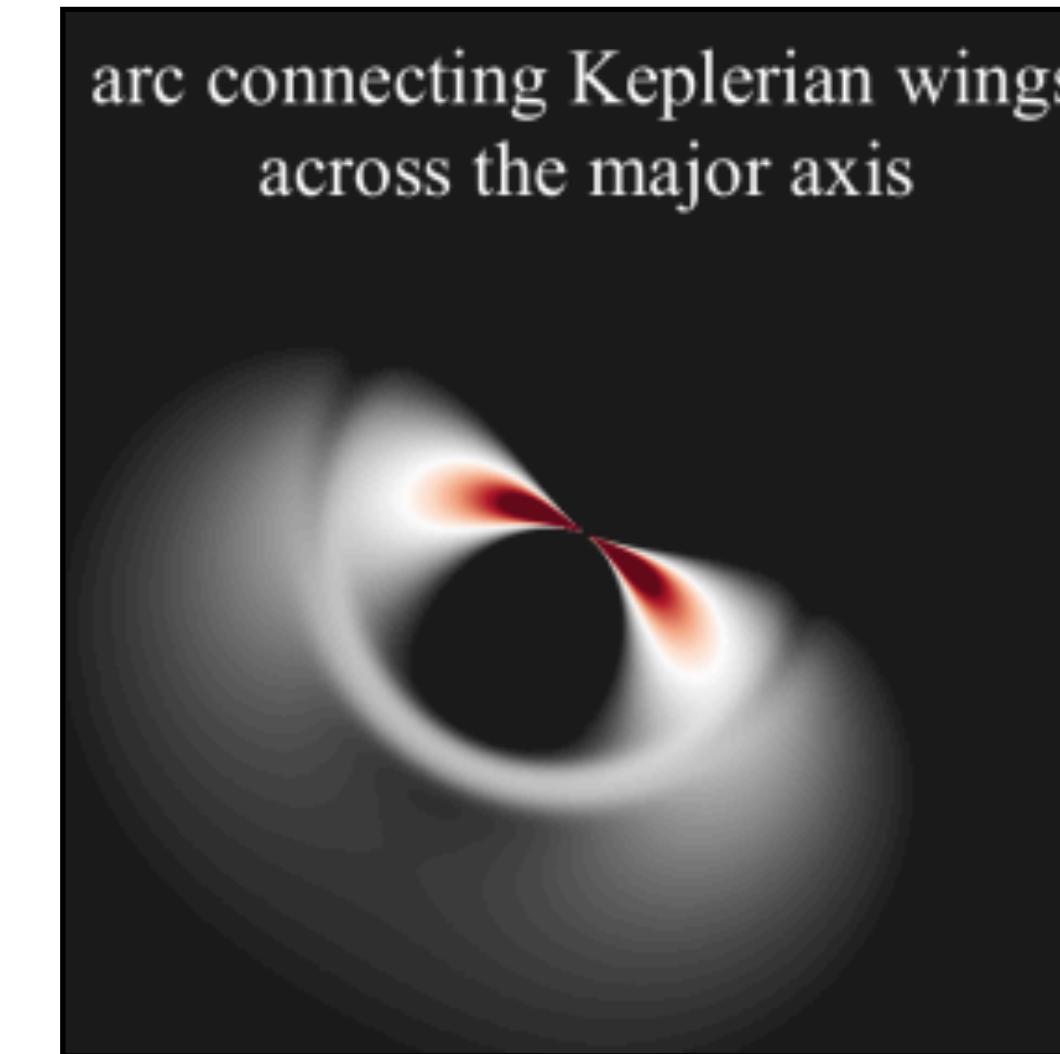
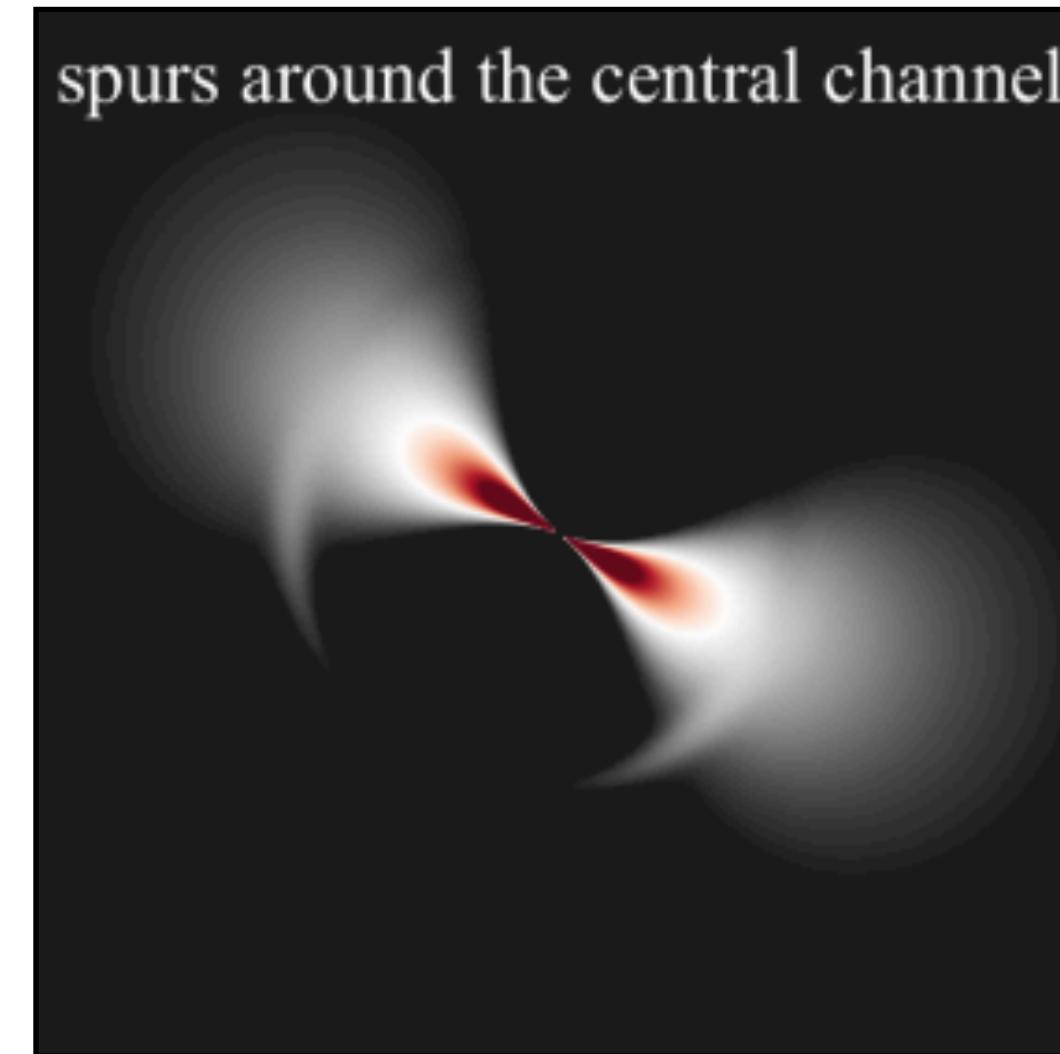
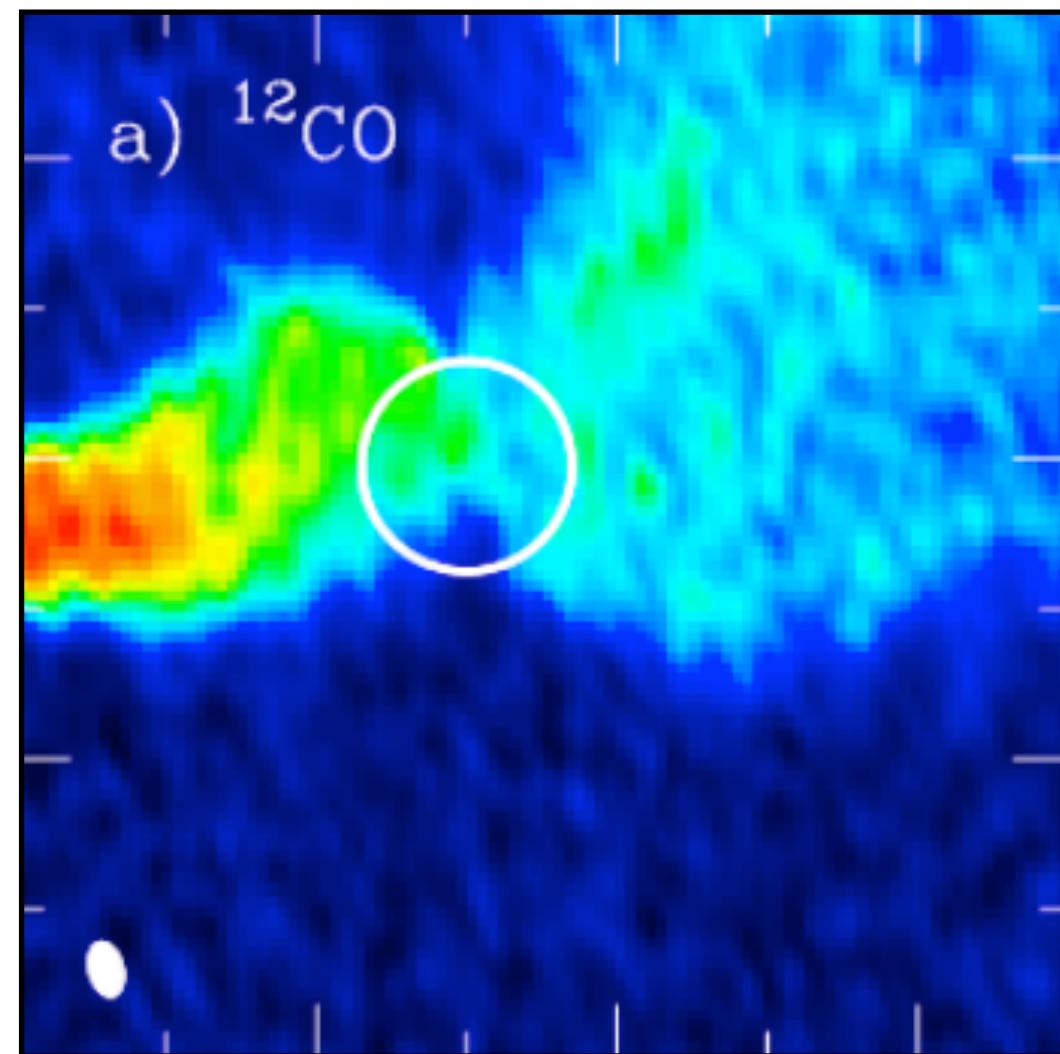
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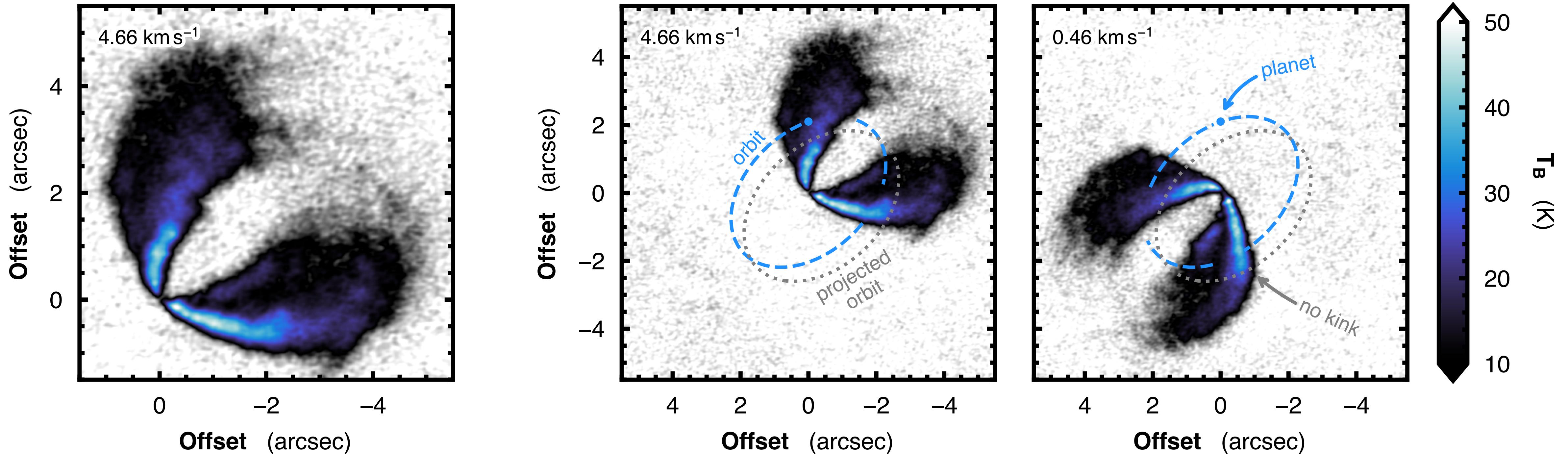
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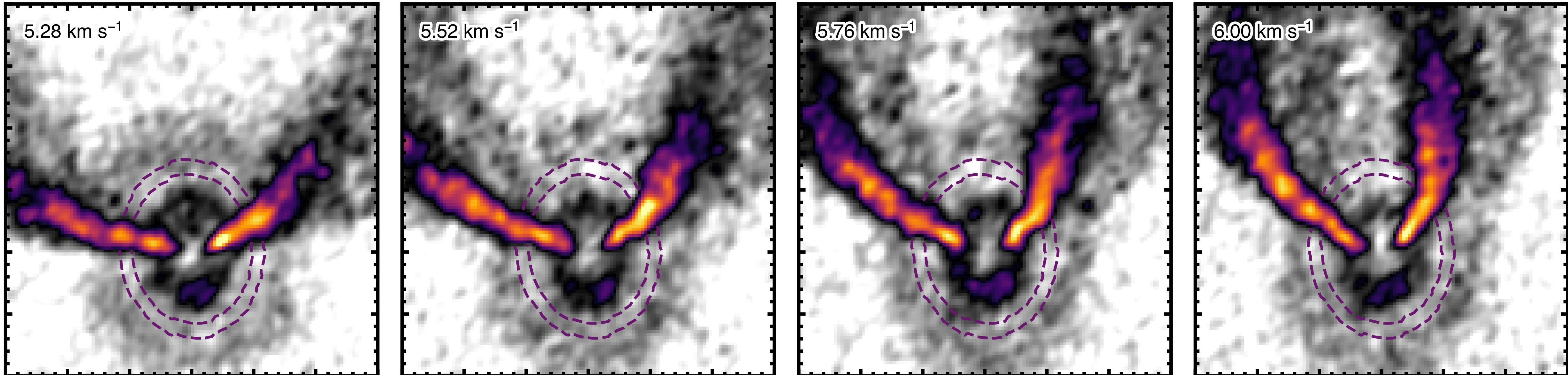


Caveat: The perturbation depends entirely on the inclination
of the disk and the position angle of the planet.

also see Disk Dynamics Collaboration et al. (2009.04345)

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

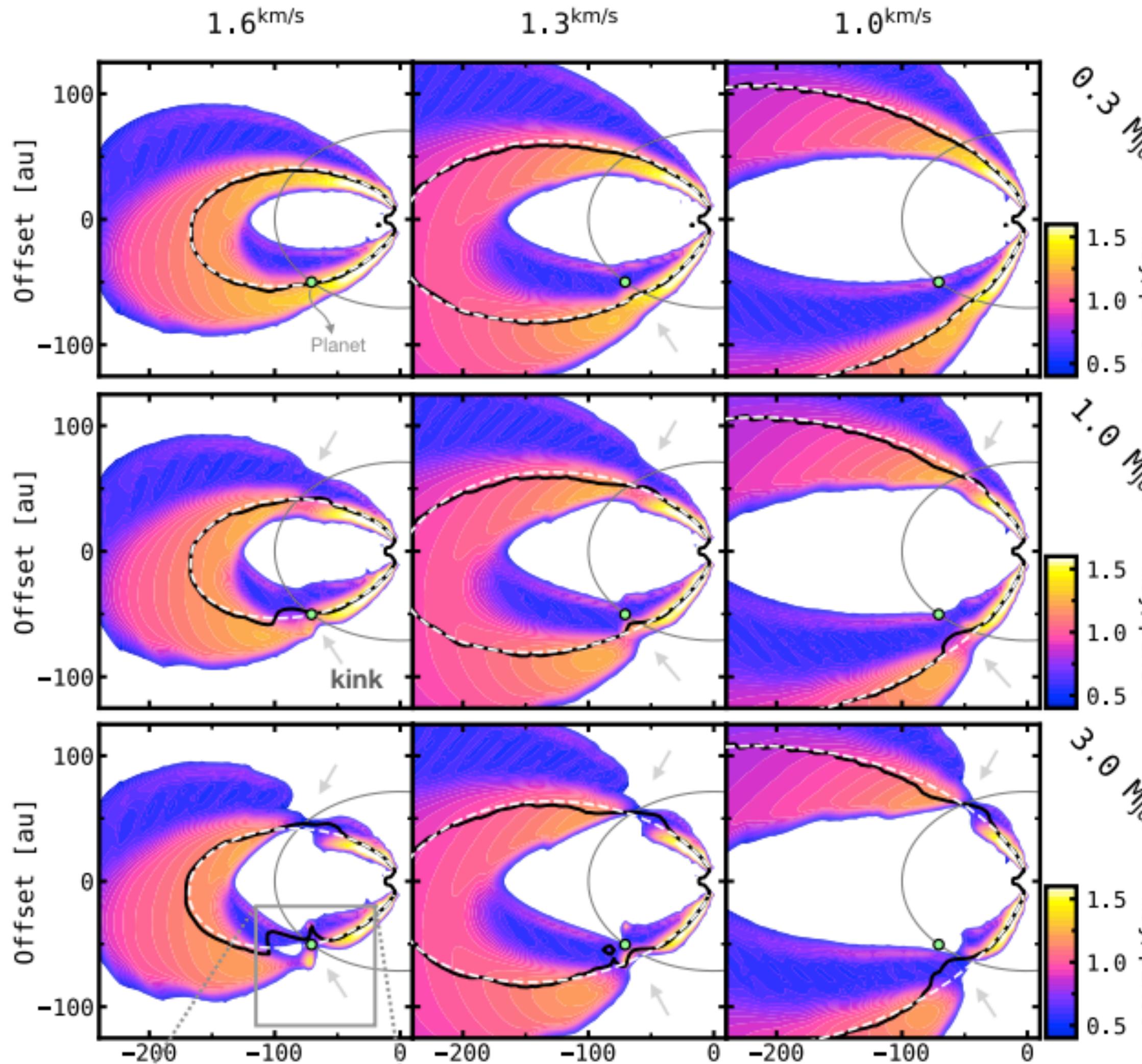
Perez et al. (2015), Pinte et al. (2018, 2019, 2020)



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

Embedded Planets: 'kinks' around the planet's location.

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

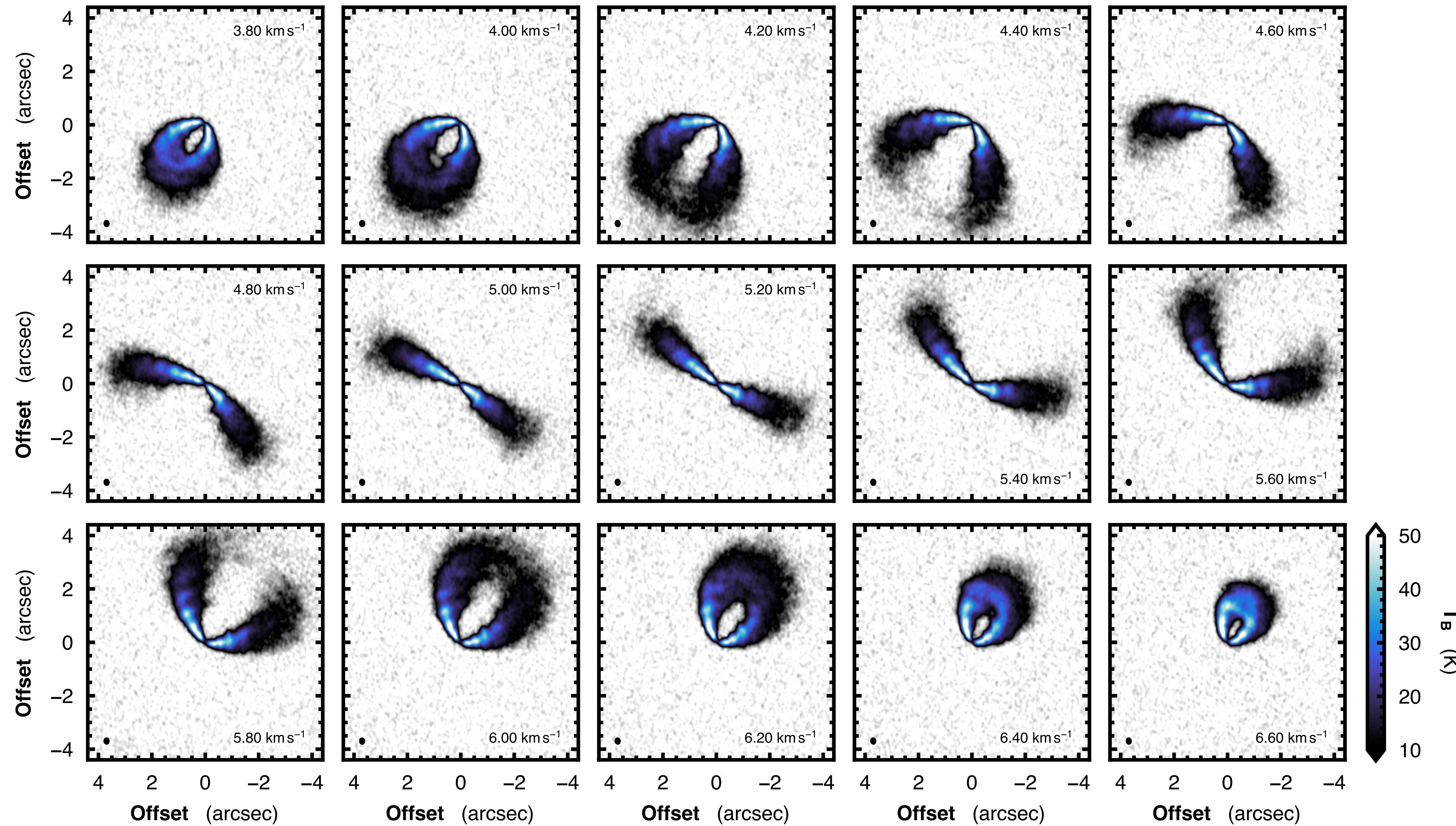


Using an empirical background model
it is possible to search for features in a
more quantitative manner.

see Friday's talk to hear more about discliner.

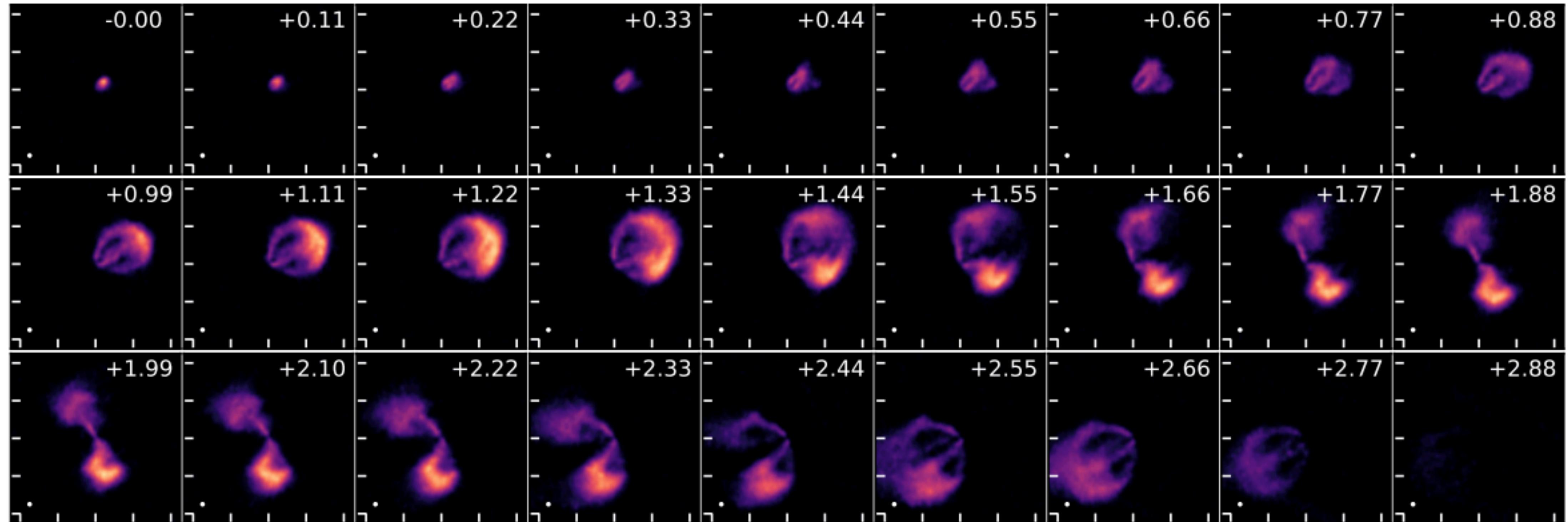
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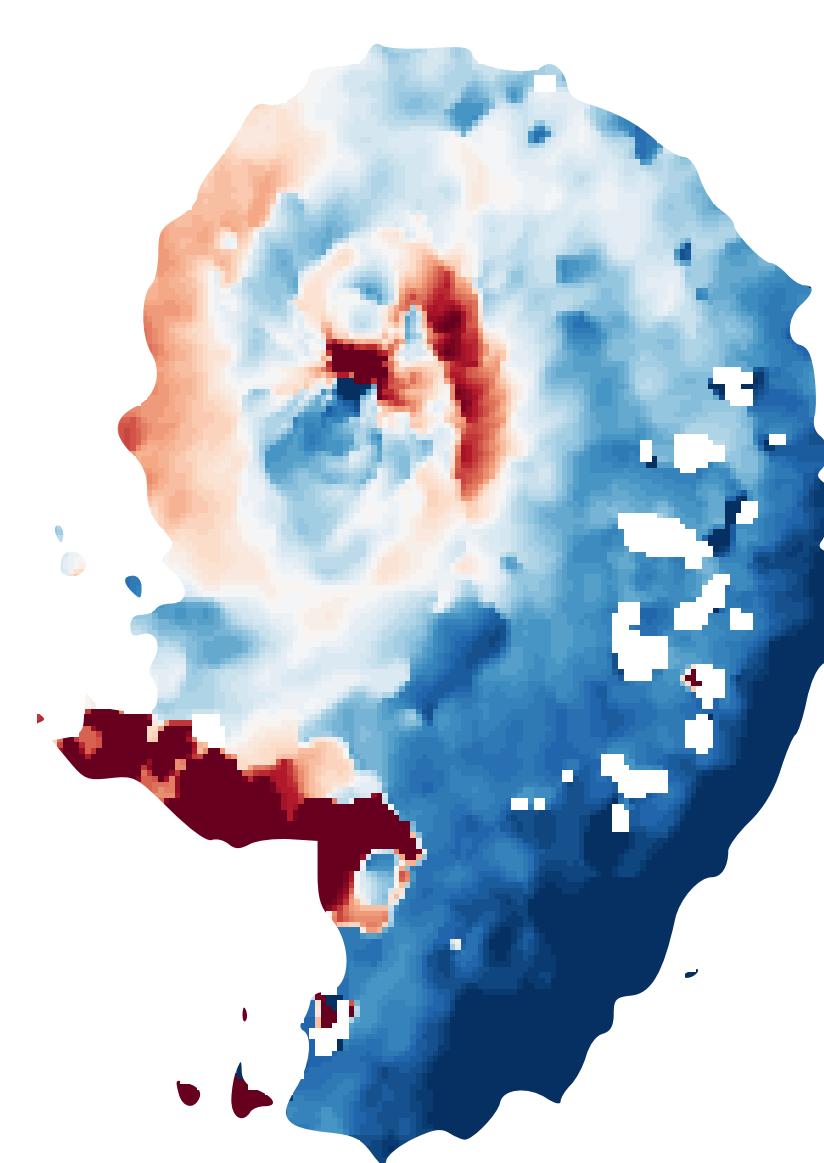
Gravitational Instability: ‘wiggles’ seen in most channels.

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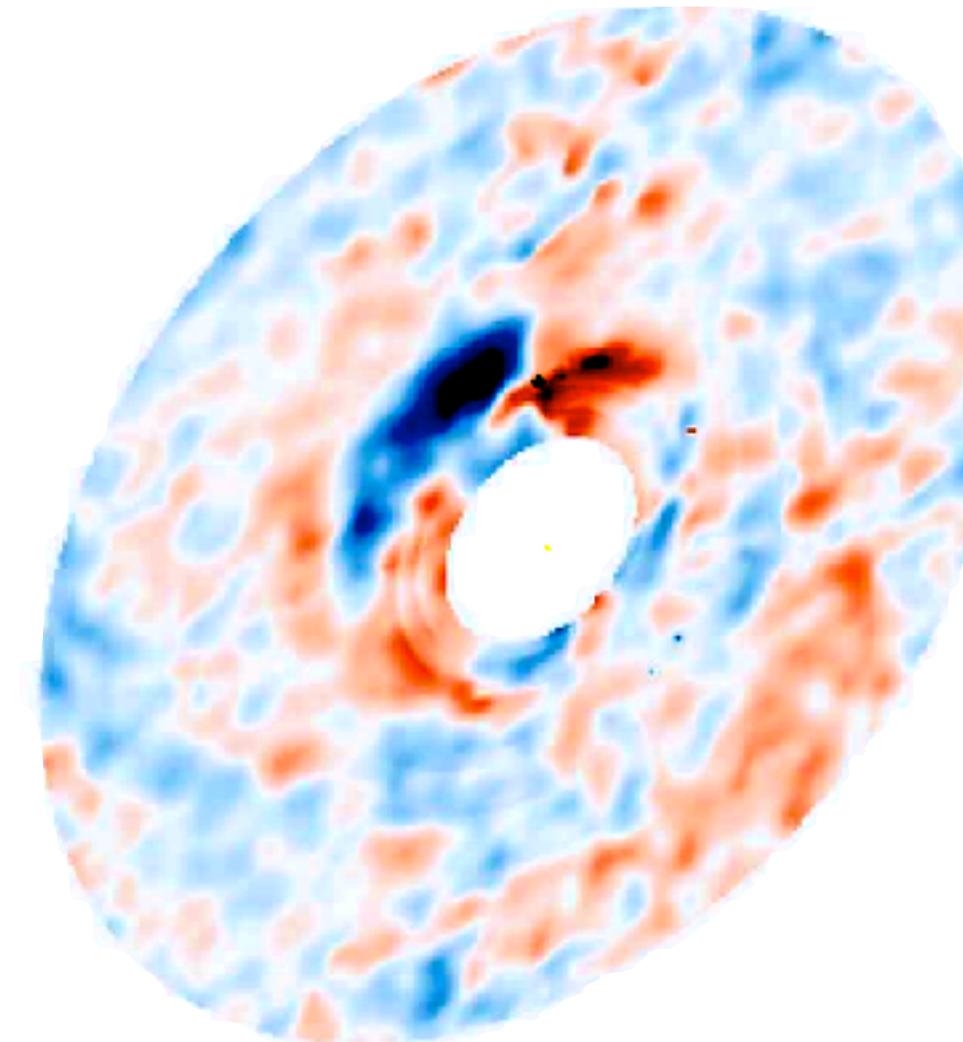


Subtraction of complex continuum emission may hamper interpretation.

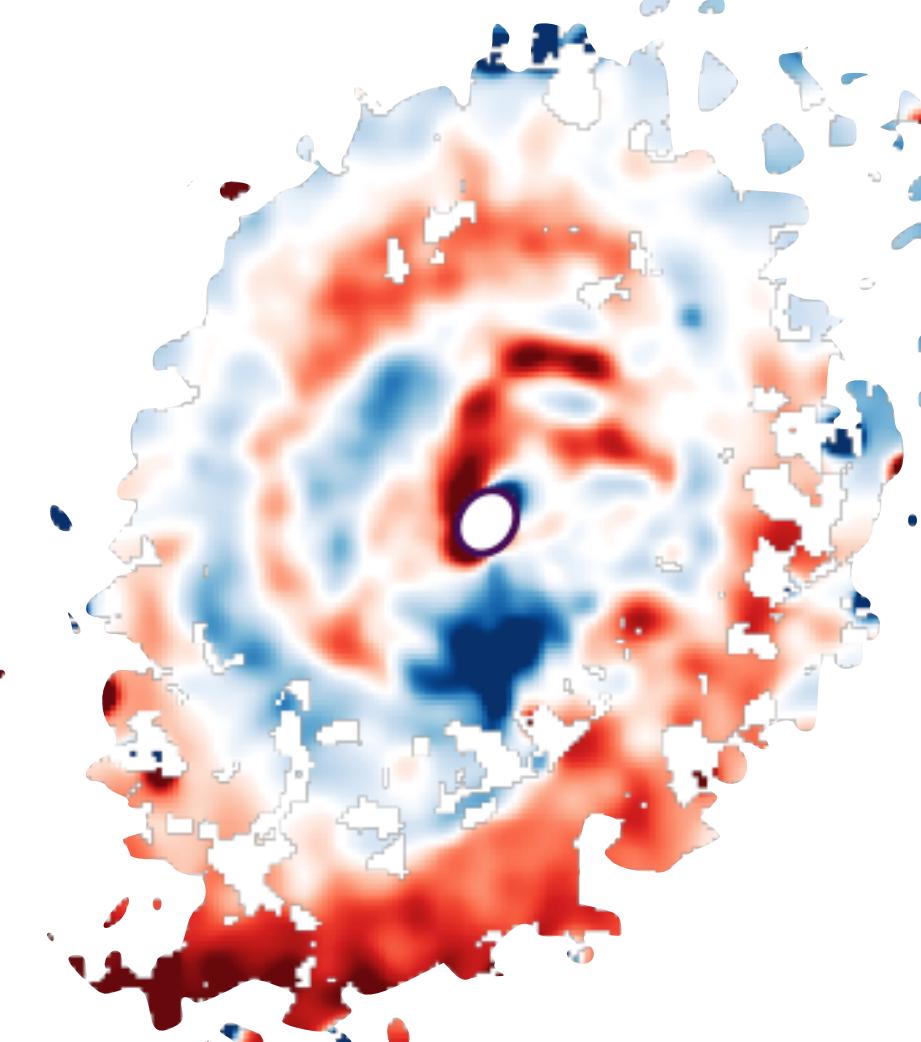
Now we have good models for the background, we are starting to see more structure in the residuals.



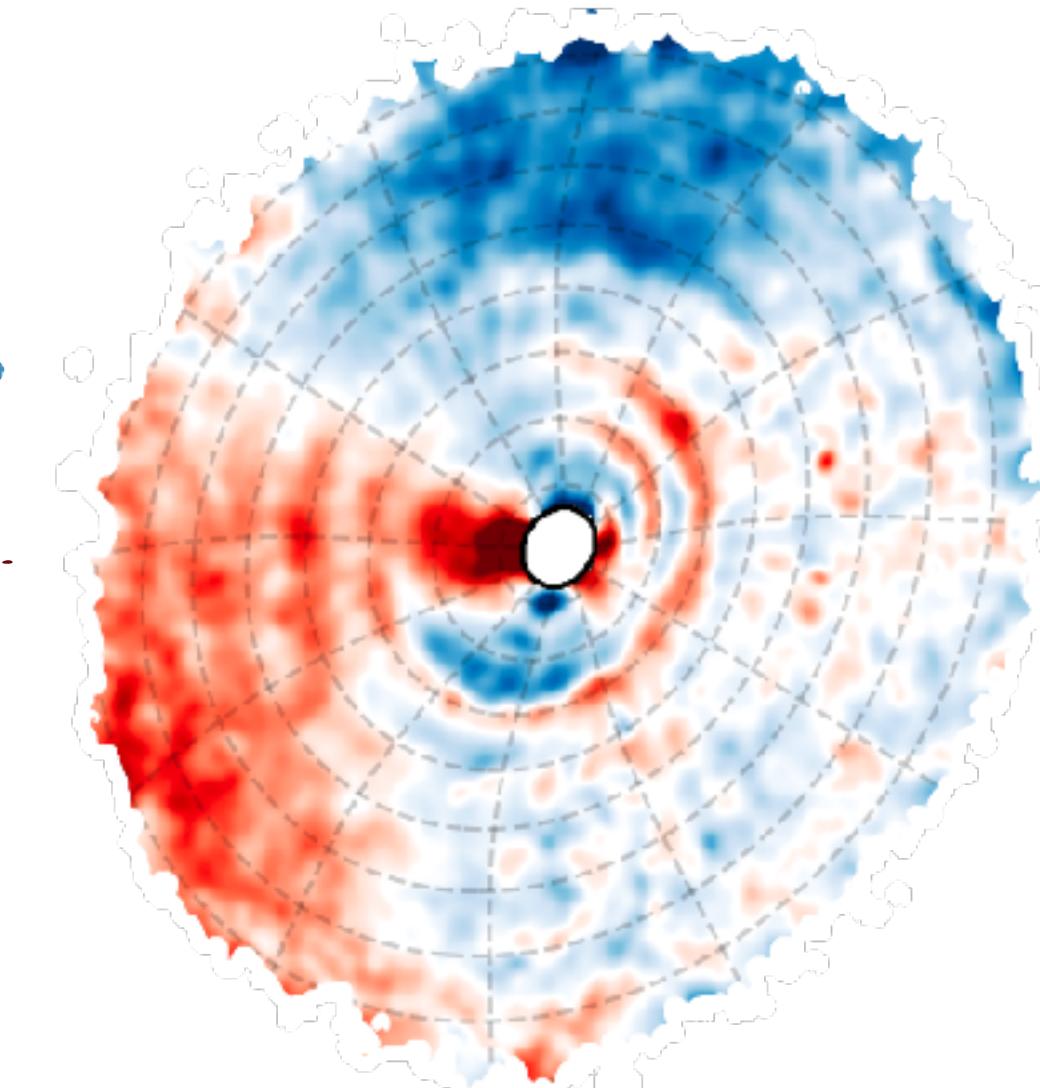
UX Tau a



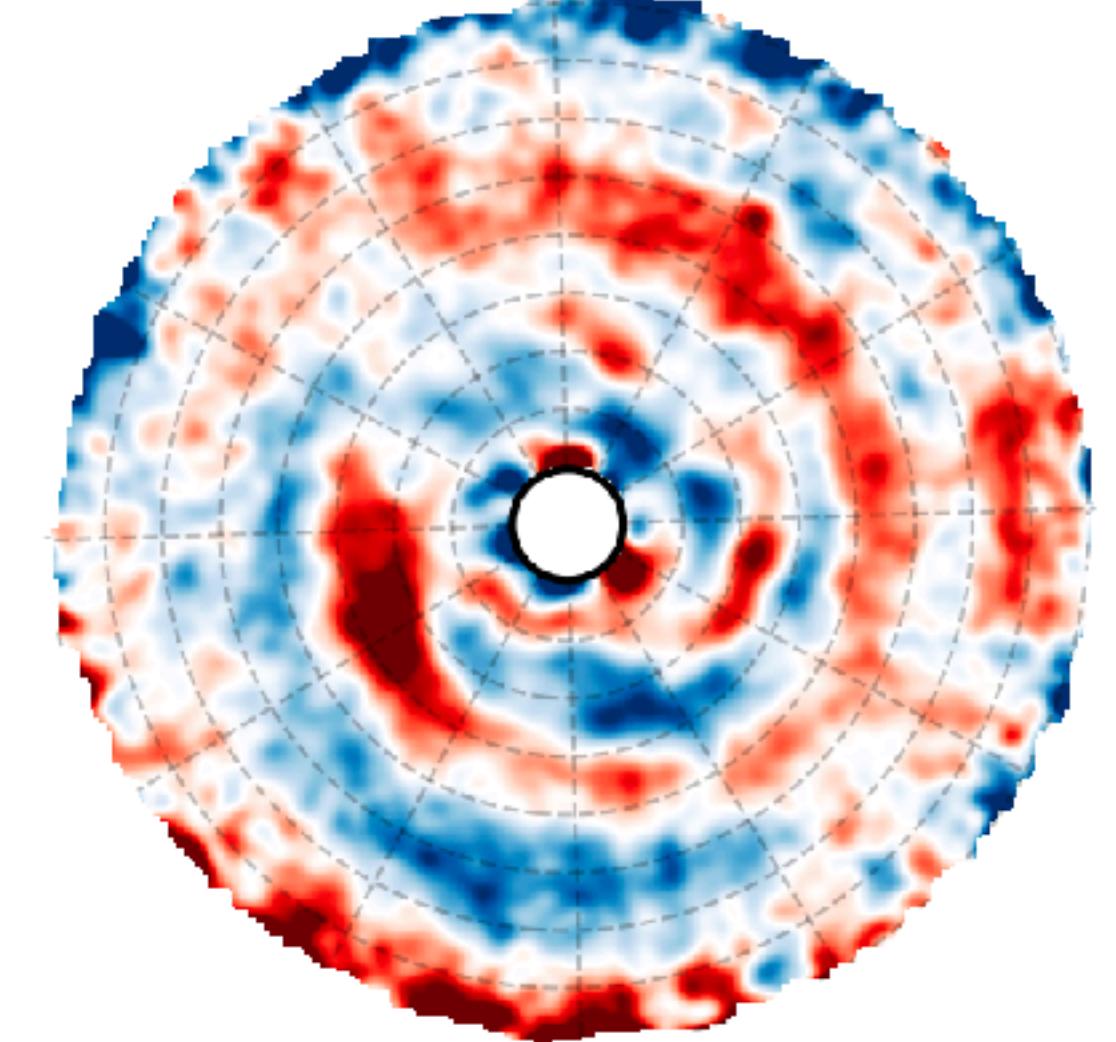
HD 100546



HD 100453

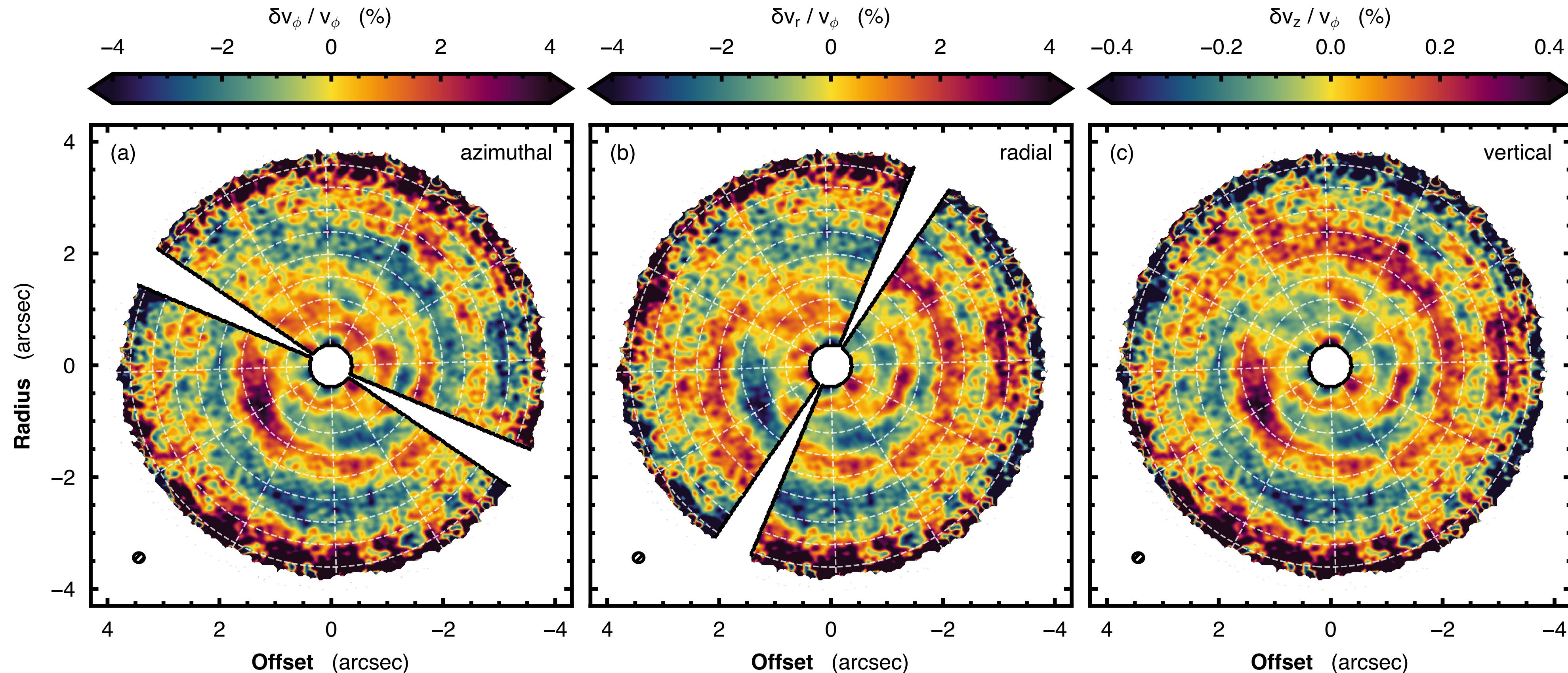


MWC 480



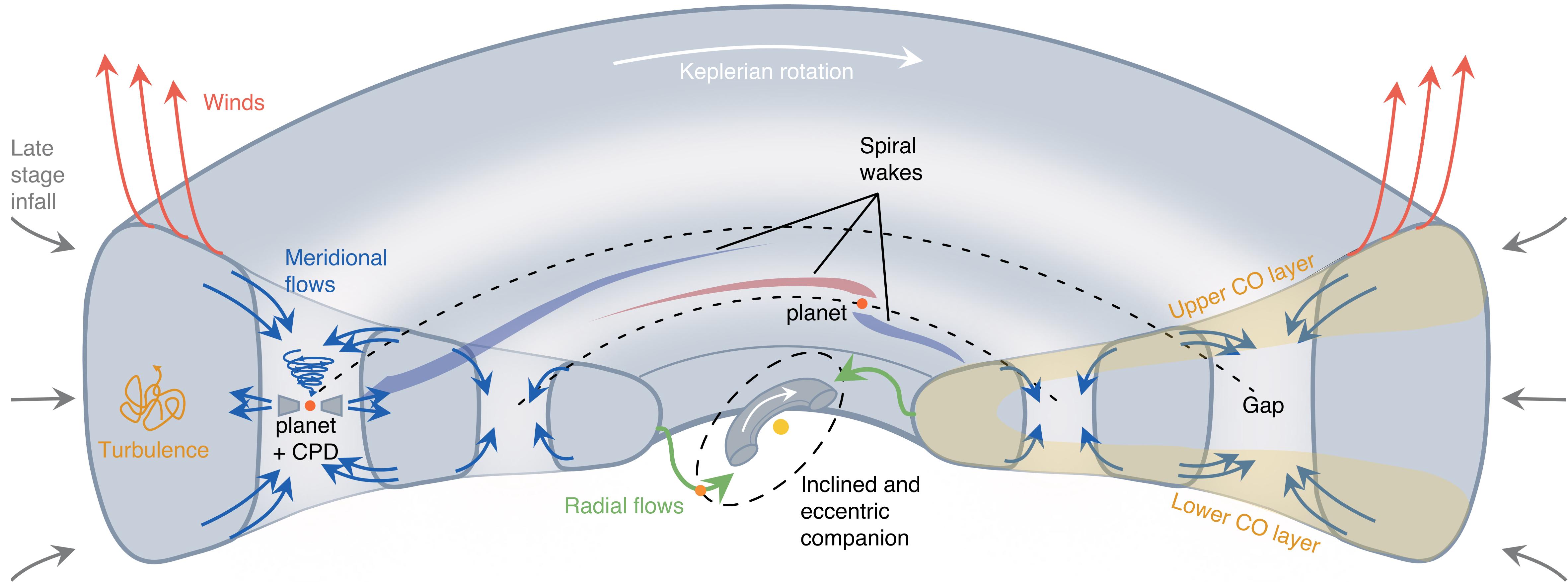
TW Hya

And there are many more coming...



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

Caveat: Are the features azimuthally symmetric?



What's In a Line?

