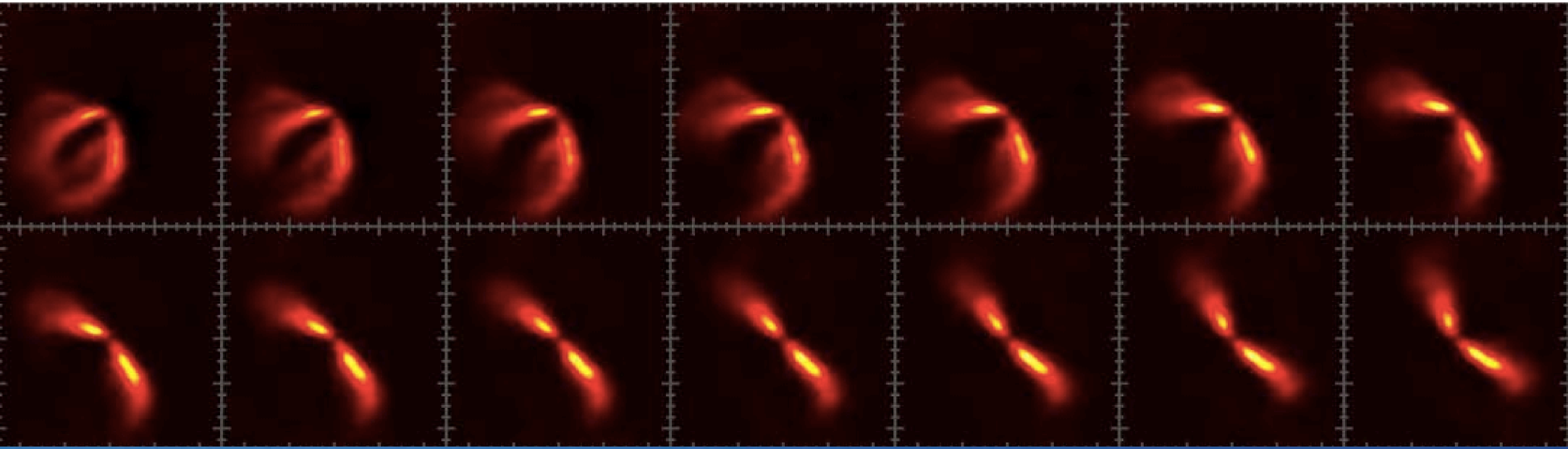
Observational Constraints on Turbulence in Protoplanetary Disks



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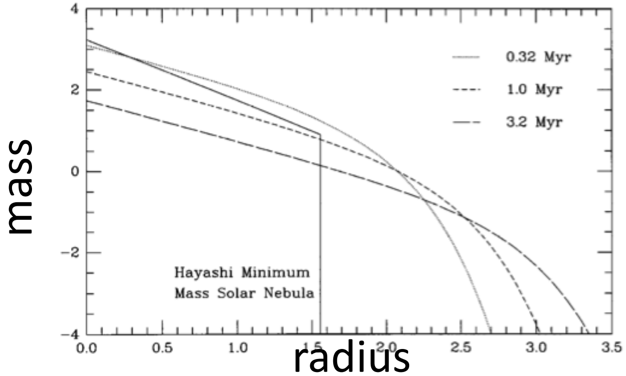
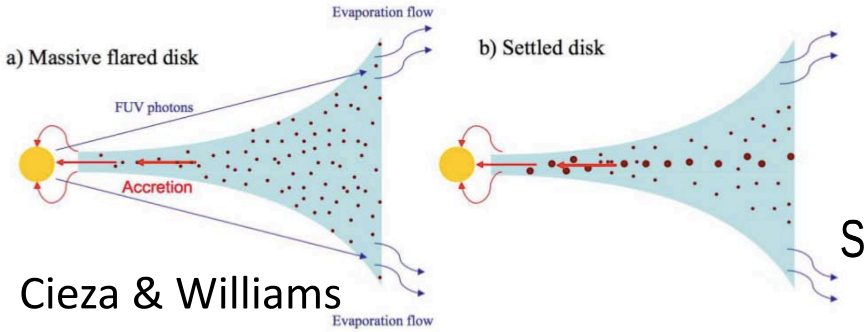
Motivation: Turbulence Influences Planet Formation and Evolution

Evolution of disk mass distribution

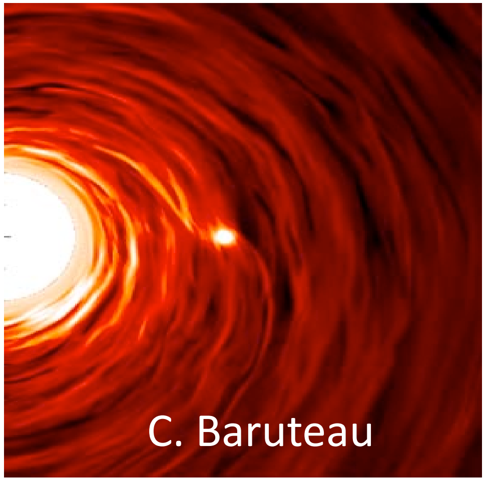


Slows solids settling to disk midplane



Cieza & Williams

Allows solids to collect in pressure peaks



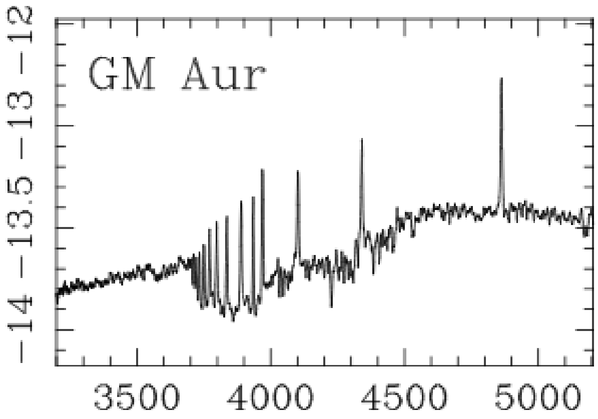
C. Baruteau

Changes rate and direction of planet migration

etc.

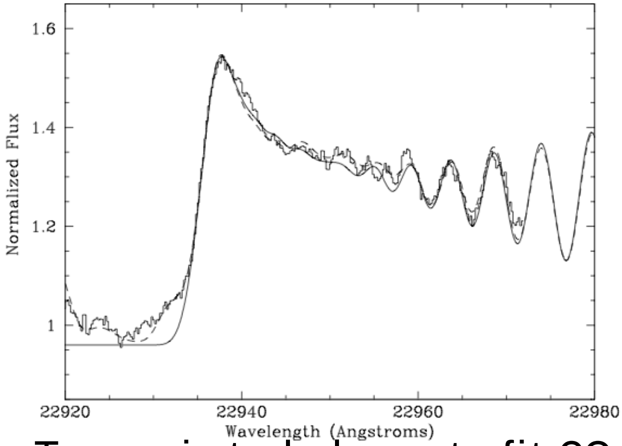
Overview of Efforts to Constrain Turbulence via Disk Observations

Accretion rate measurements



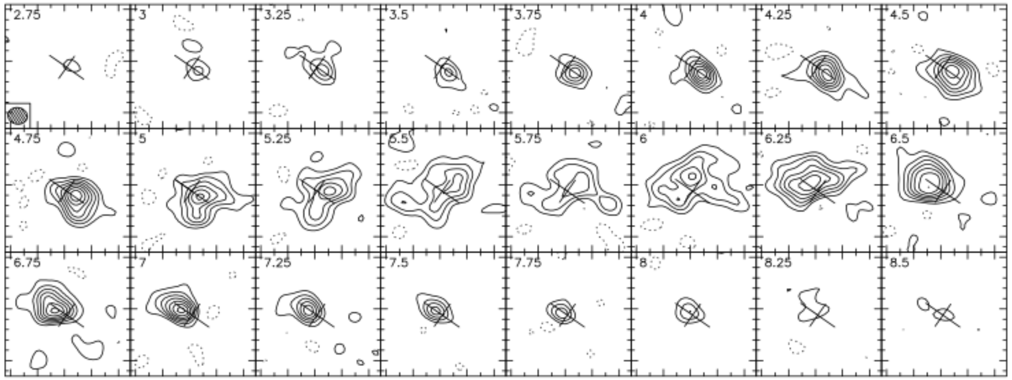
UV continuum excess
Gullbring et al. (1998)

Rovibrational lines



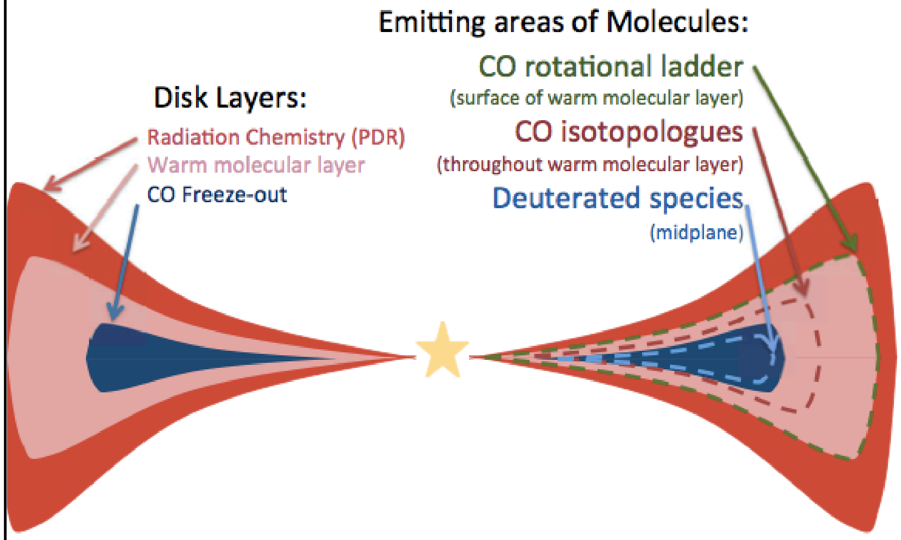
Transonic turbulence to fit CO band head
Carr et al. (2004)

Fitting models to low-res CO spectra
Dutrey et al. (1998)



Millimeter observations

Why Spatially Resolved Molecular Spectroscopy?



Emitting areas of Molecules:

CO rotational ladder
(surface of warm molecular layer)

CO isotopologues
(throughout warm molecular layer)

Deuterated species
(midplane)

Disk Layers:

Radiation Chemistry (PDR)

Warm molecular layer

CO Freeze-out

High spectral (~10m/s) and spatial (~H) resolution BOTH are critical for constraining turbulence

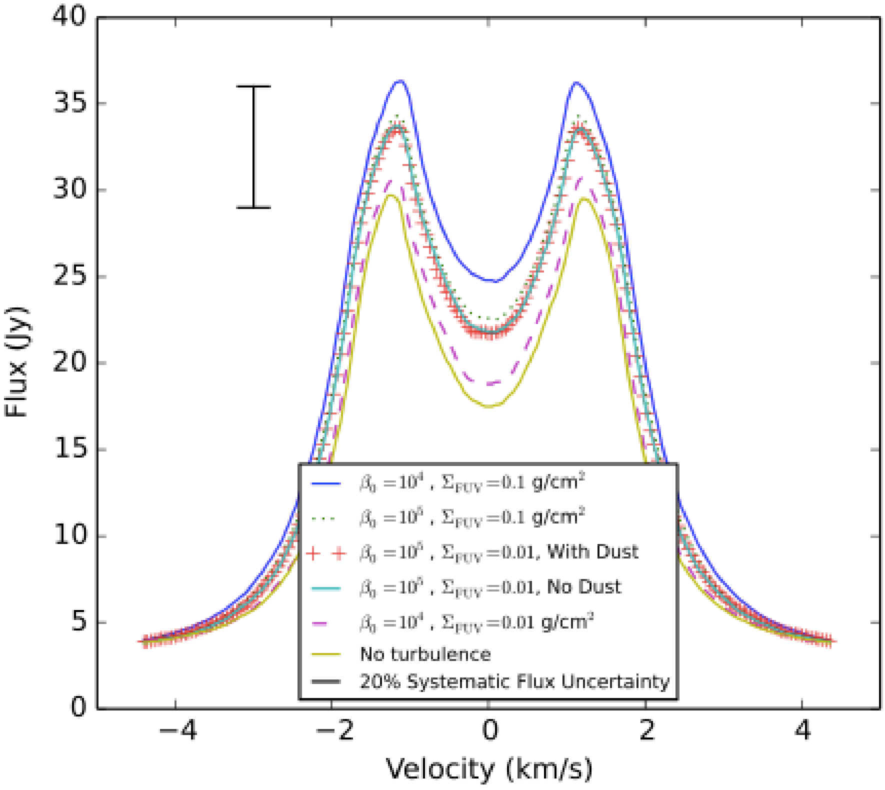
Layered disk structure provides potential for 3-D characterization of turbulence

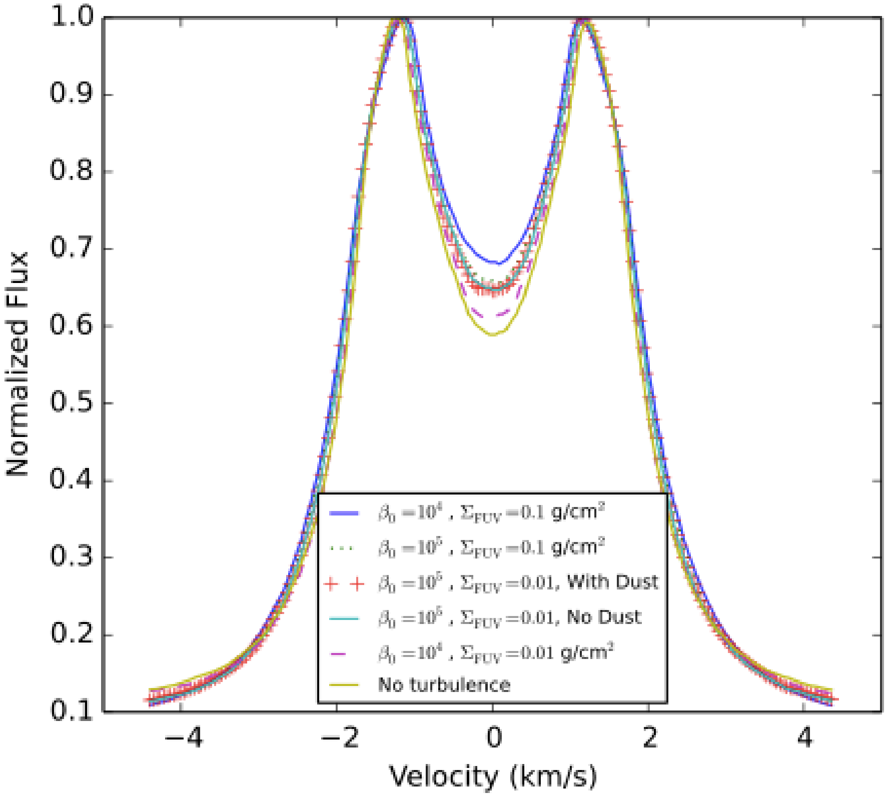
Theoretical Predictions of Observational Signatures

- Shearing box simulations at 10, 30, and 100au
- Variable β_0, Σ_{uv}
- Grafted onto realistic temperature and density structure
- Radiative transfer, simulated observations

Simon, Hughes, Flaherty et al. (2015)

Theoretical Predictions of Observational Signatures

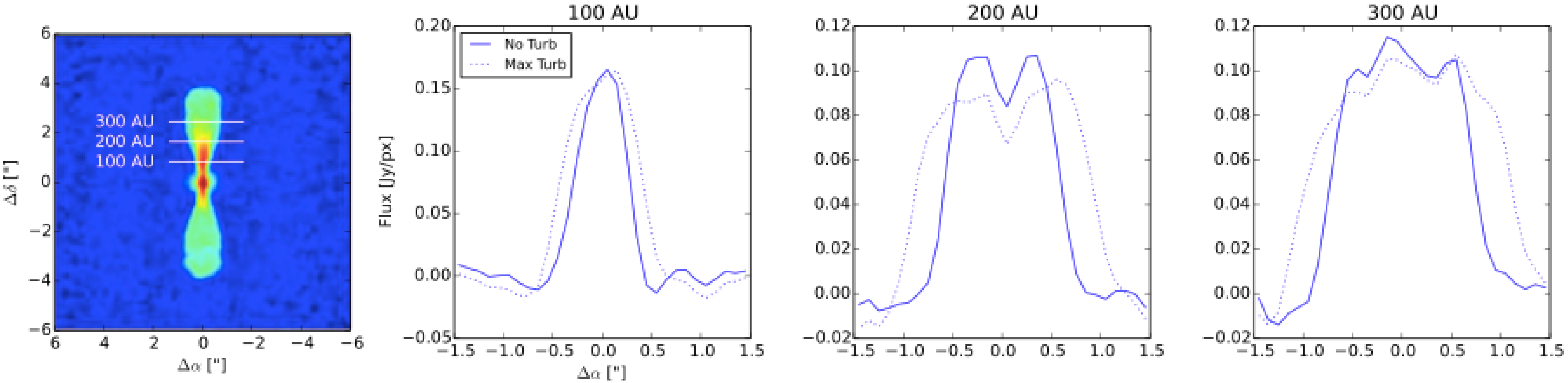




Spectral domain: absolute flux scale is a problem, but temperature and turbulence have different effects on line shape

Simon, Hughes, Flaherty et al. (2015)

Theoretical Predictions of Observational Signatures

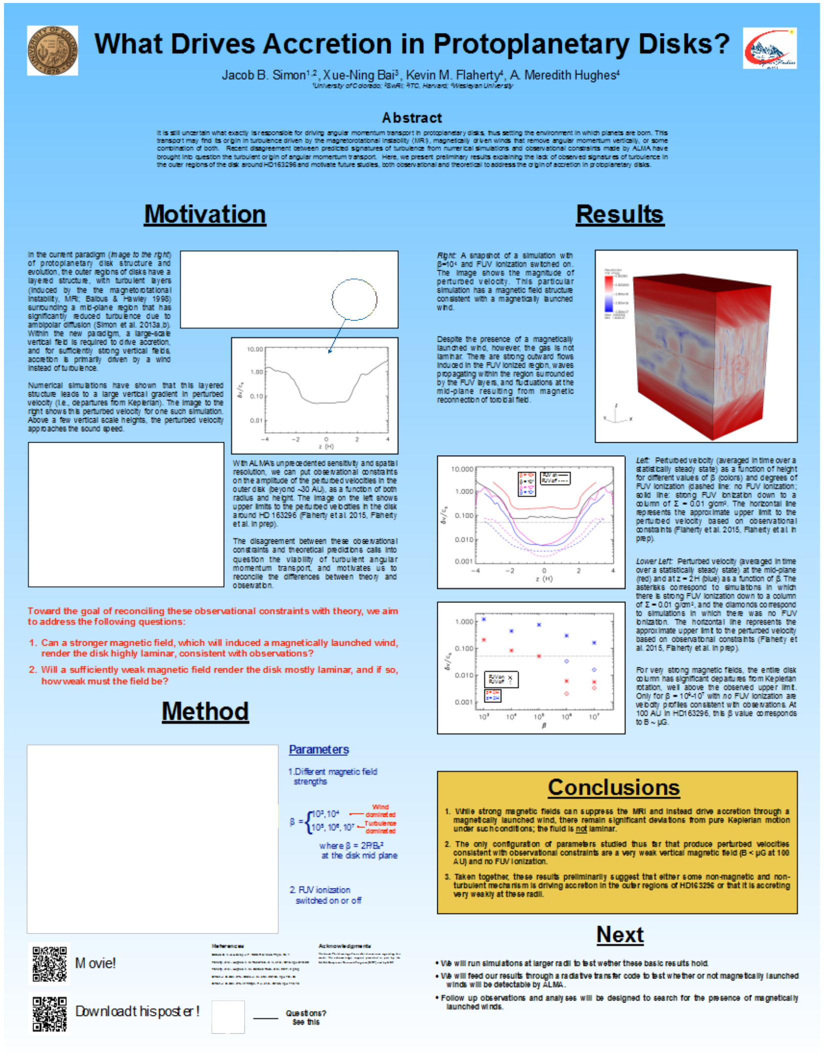


Spatial domain: Unlike temperature, turbulence broadens spatially.
Detectable in 3 hours with ALMA!

Keep in mind: ALMA data are 3-D position-position-velocity cubes. Parametric approach utilizes all three dimensions simultaneously, increasing the strength of the signal.

Simon, Hughes, Flaherty et al. (2015)

For More Information:
Visit Jacob Simon’s Poster!



What Drives Accretion in Protoplanetary Disks?

Jacob B. Simon[1,2], Xue-Ning Bai[3], Kevin M. Flaherty[4], A. Meredith Hughes[4]
[1]University of Colorado; [2]SwRI; [3]ITC, Harvard; [4]Wesleyan University

Abstract

It is still uncertain what exactly is responsible for driving angular momentum transport in protoplanetary disks, thus setting the environment in which planets are born. This transport may find its origin in turbulence driven by the magnetorotational instability (MRI), magnetically driven winds that remove angular momentum vertically, or some combination of both. Recent disagreement between predicted signatures of turbulence from numerical simulations and observational constraints made by ALMA have brought into question the turbulent origin of angular momentum transport. Here, we present preliminary results explaining the lack of observed signatures of turbulence in the outer regions of the disk around HD163296 and motivate future studies, both observational and theoretical to address the origin of accretion in protoplanetary disks.

Motivation

In the current paradigm (*Image to the right*) of protoplanetary disk structure and evolution, the outer regions of disks have a layered structure, with turbulent layers (induced by the the magnetorotational instability, MRI; Balbus & Hawley 1998) surrounding a mid-plane region that has significantly reduced turbulence due to ambipolar diffusion (Simon et al. 2013a,b). Within the new paradigm, a large-scale vertical field is required to drive accretion, and for sufficiently strong vertical fields, accretion is primarily driven by a wind instead of turbulence.

Numerical simulations have shown that this layered structure leads to a large vertical gradient in perturbed velocity (i.e., departures from Keplerian). The image to the right shows this perturbed velocity for one such simulation. Above a few vertical scale heights, the perturbed velocity approaches the sound speed.

With ALMA's unprecedented sensitivity and spatial resolution, we can put observational constraints on the amplitude of the perturbed velocities in the outer disk (beyond ~30 AU), as a function of both radius and height. The image on the left shows upper limits to the perturbed velocities in the disk around HD 163296 (Flaherty et al. 2015, Flaherty et al. in prep).

The disagreement between these observational constraints and theoretical predictions calls into question the viability of turbulent angular momentum transport, and motivates us to reconcile the differences between theory and observation.

Toward the goal of reconciling these observational constraints with theory, we aim to address the following questions:

1. **Can a stronger magnetic field, which will induced a magnetically launched wind, render the disk highly laminar, consistent with observations?**
2. **Will a sufficiently weak magnetic field render the disk mostly laminar, and if so, how weak must the field be?**

Method

Parameters

1. Different magnetic field strengths

$$\beta = \begin{cases} 10^3, 10^4 & \leftarrow \text{Wind dominated} \\ 10^5, 10^6, 10^7 & \leftarrow \text{Turbulence dominated} \end{cases}$$

where $\beta = 2P/B_z^2$ at the disk mid plane

2. FUV ionization switched on or off

Movie!

Download this poster!

References

Acknowledgments

Questions? See this

Results

Right: A snapshot of a simulation with $\beta = 10^4$ and FUV ionization switched on. The image shows the magnitude of perturbed velocity. This particular simulation has a magnetic field structure consistent with a magnetically launched wind.

Despite the presence of a magnetically launched wind, however, the gas is not laminar. There are strong outward flows induced in the FUV ionized region, waves propagating within the region surrounded by the FUV layers, and fluctuations at the mid-plane resulting from magnetic reconnection of toroidal field.

Left: Perturbed velocity (averaged in time over a statistically steady state) as a function of height for different values of β (colors) and degrees of FUV ionization (dashed line: no FUV ionization; solid line: strong FUV ionization down to a column of $\Sigma = 0.01$ g/cm². The horizontal line represents the approximate upper limit to the perturbed velocity based on observational constraints (Flaherty et al. 2015, Flaherty et al. in prep).

Lower Left: Perturbed velocity (averaged in time over a statistically steady state) at the mid-plane (red) and at $z = 2H$ (blue) as a function of β. The asterisks correspond to simulations in which there is strong FUV ionization down to a column of $\Sigma = 0.01$ g/cm², and the diamonds correspond to simulations in which there was no FUV ionization. The horizontal line represents the approximate upper limit to the perturbed velocity based on observational constraints (Flaherty et al. 2015, Flaherty et al. in prep).

For very strong magnetic fields, the entire disk column has significant departures from Keplerian rotation, well above the observed upper limit. Only for $\beta = 10^6$-10^7 with *no* FUV ionization are velocity profiles consistent with observations. At 100 AU in HD163296, this β value corresponds to B ~ μG.

Conclusions

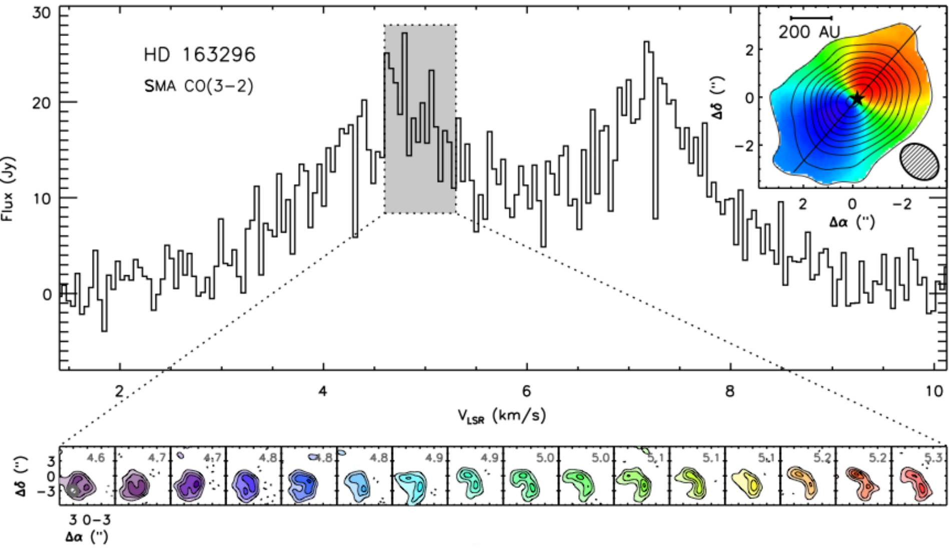
1. **While strong magnetic fields can suppress the MRI and instead drive accretion through a magnetically launched wind, there remain significant deviations from pure Keplerian motion under such conditions; the fluid is not laminar.**
2. **The only configuration of parameters studied thus far that produce perturbed velocities consistent with observational constraints are a very weak vertical magnetic field (B < μG at 100 AU) and no FUV ionization.**
3. **Taken together, these results preliminarily suggest that either some non-magnetic and non-turbulent mechanism is driving accretion in the outer regions of HD163296 or that it is accreting very weakly at these radii.**

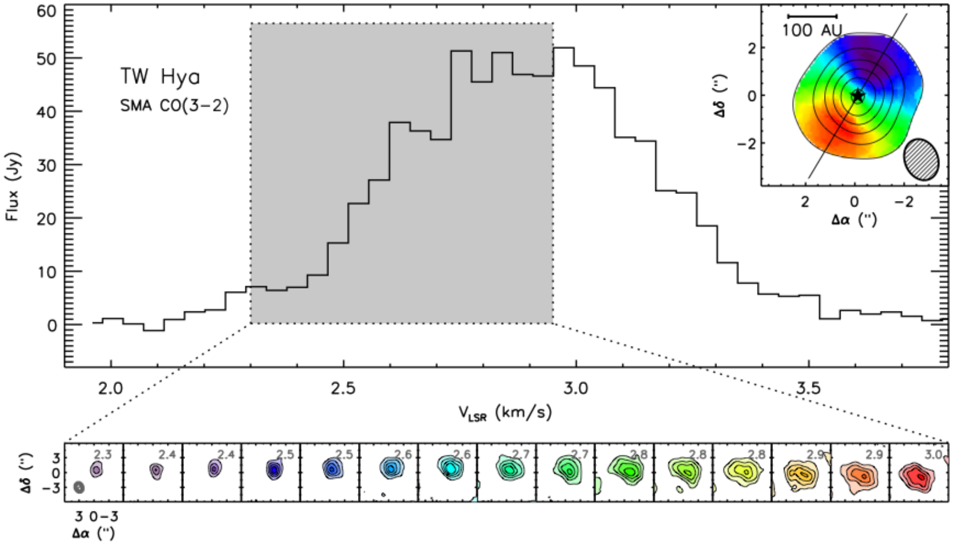
Next

- **We will run simulations at larger radii to test wether these basic results hold.**
- **We will feed our results through a radiative transfer code to test whether or not magnetically launched winds will be detectable by ALMA.**
- **Follow up observations and analyses will be designed to search for the presence of magnetically launched winds.**

Review of Results to Date: Pre-ALMA

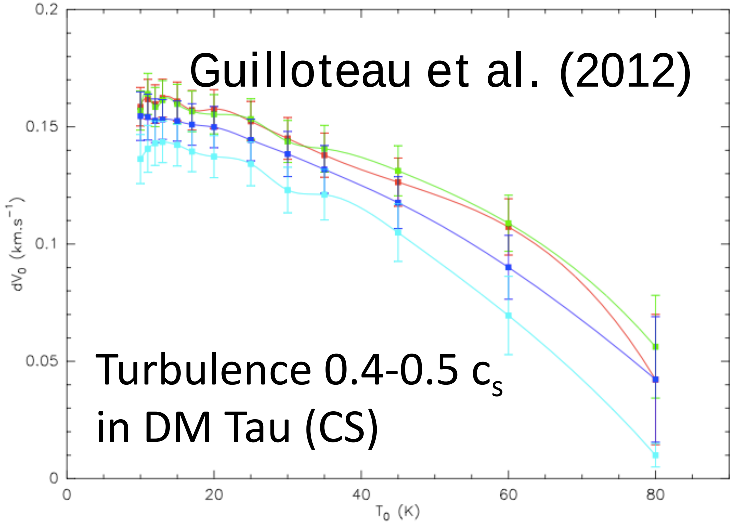
Hughes et al. (2011)





Turbulence ~0.4 c_s (CO)

Turbulence <0.1 c_s (CO)

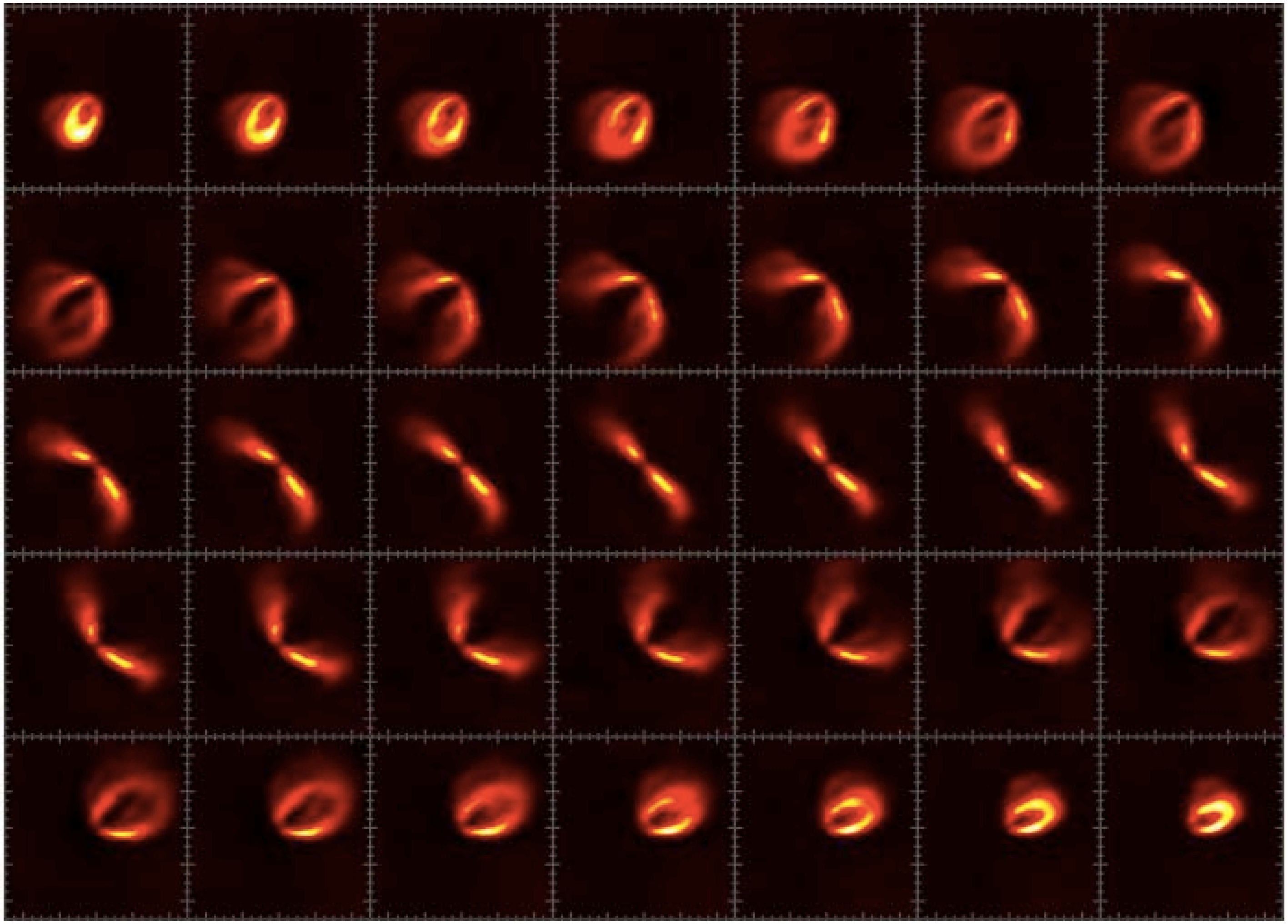


Guilloteau et al. (2012)

Turbulence 0.4-0.5 c_s in DM Tau (CS)

Challenge is to disentangle turbulence from other broadening (rotational, thermal, τ, …)

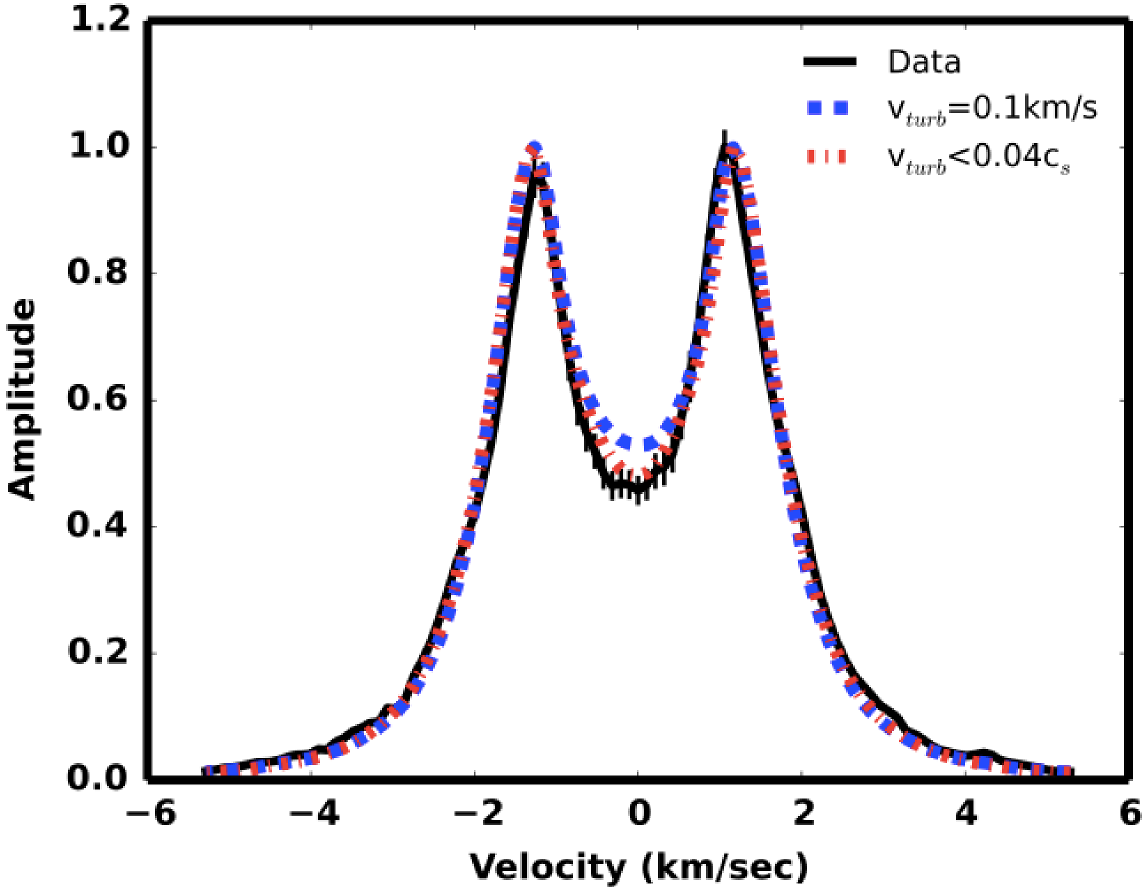
Review of Results to Date: ALMA Era



Rosenfeld et al. (2013)

Rosenfeld et al. (2013) assume constant turbulent linewidth 10 m/s, de Gregorio-Monsalvo et al. (2013) find best fit at 100 m/s

Review of Results to Date: ALMA Era



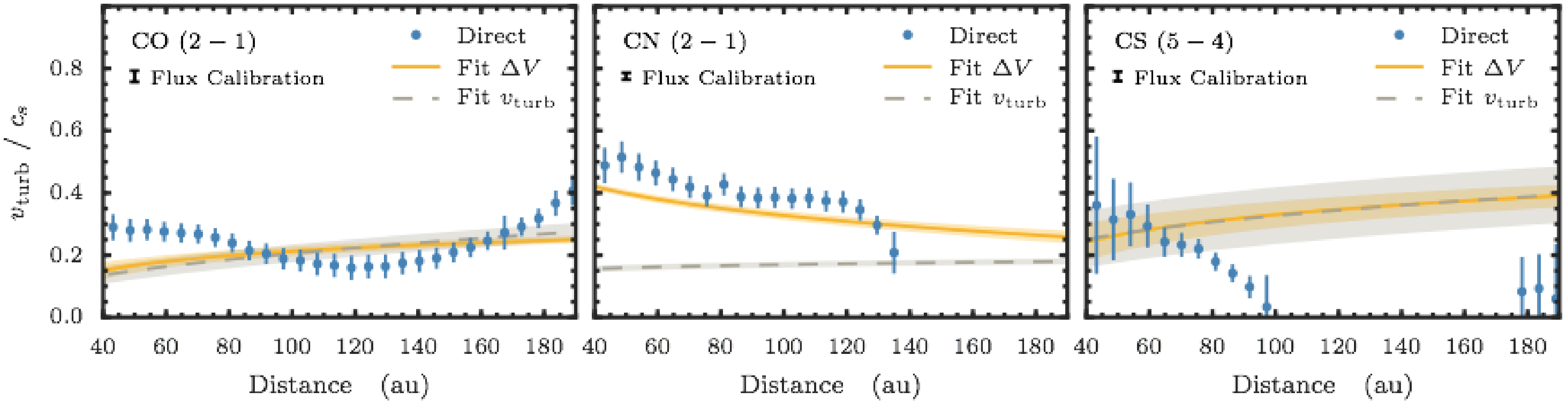
Low turbulence in HD 163296 <$0.04c_s$ (9-19m/s, $\alpha<10^{-3}$).

Constraint comes from four lines of CO, ^{13}CO, and C^{18}O

Limited to radii >~30au, and constraints strongest at large vertical height

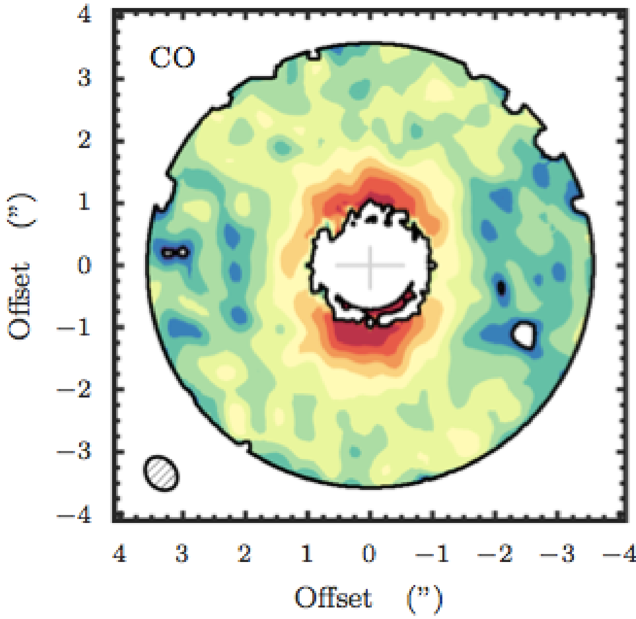
Flaherty, Hughes et al. (2015)

Review of Results to Date: ALMA Era



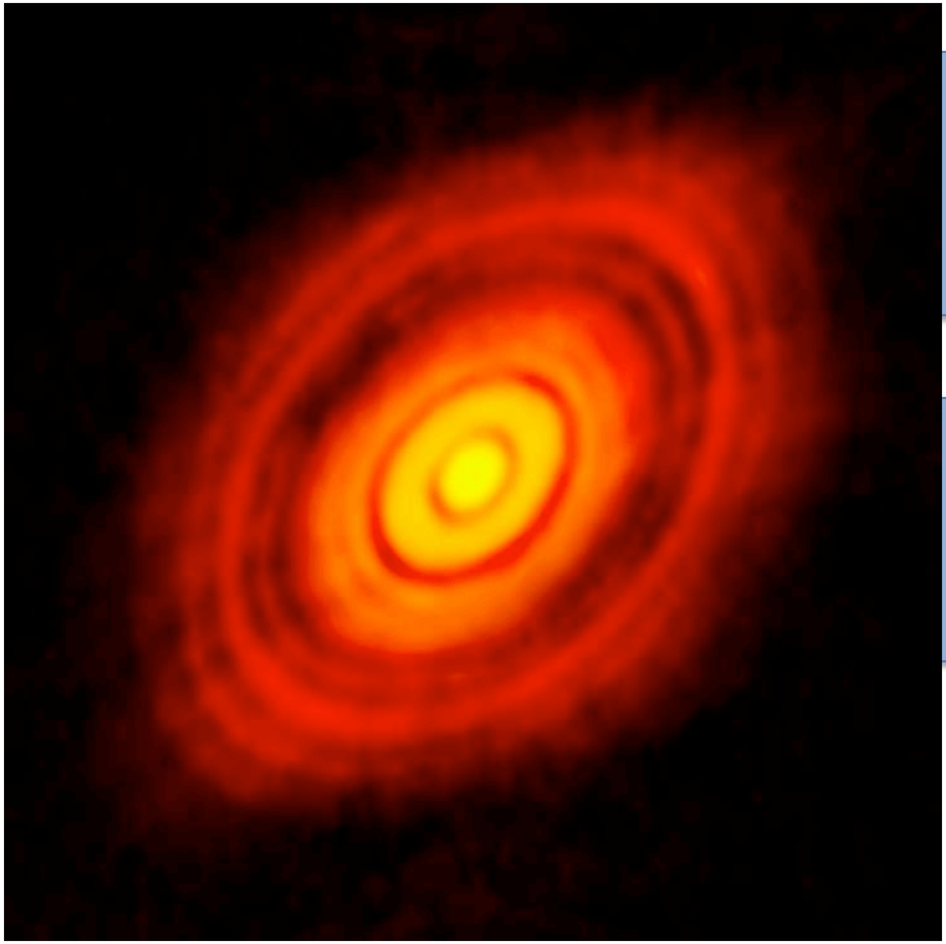
V_{turb} = 0.2-0.4 c_s in the disk around TW Hya using three lines (CO, CN, CS).

Should be considered an upper limit due to absolute flux calibration uncertainties



Teague et al. (2016)

Review of Results to Date: ALMA Era



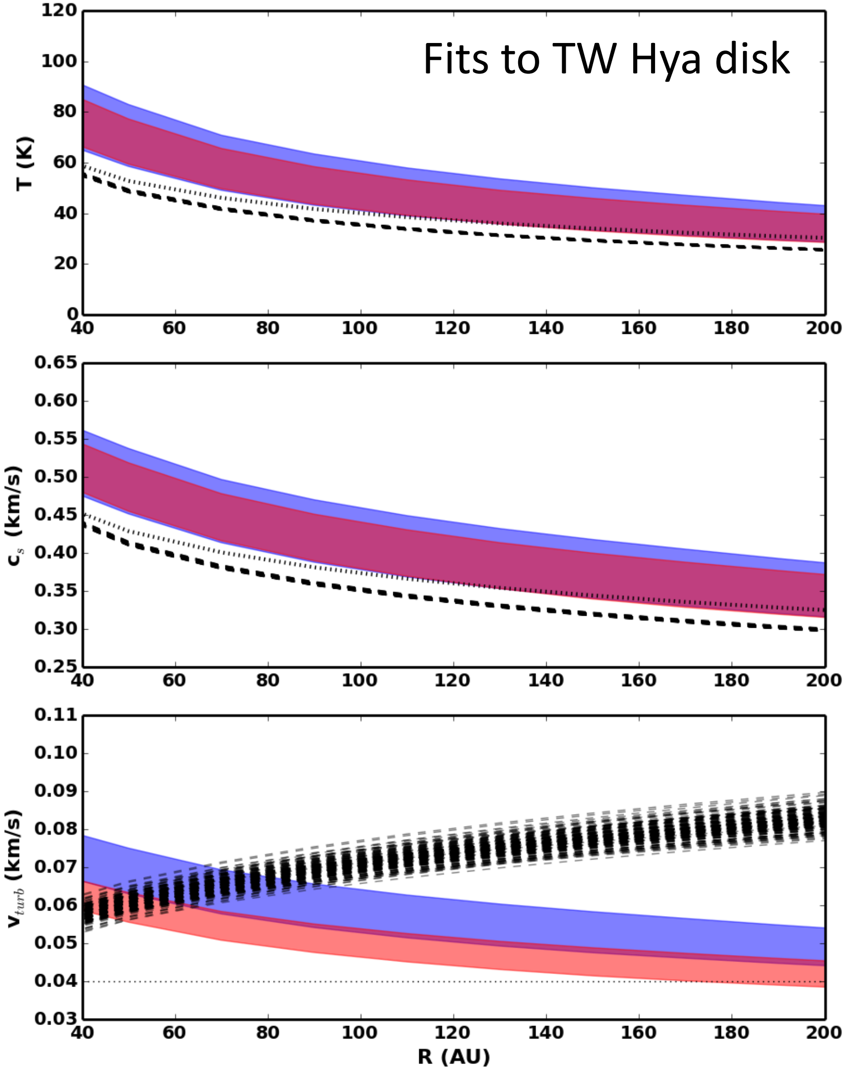
ALMA Partnership et al. (2015)

Well-separated, high-contrast rings indicate a high degree of settling that constrains α to be ~few times 10^{-4} (Pinte et al. 2016)

If rings are due to aggregate sintering outside of ice lines, then low turbulence ($10^{-4}<\alpha<10^{-3}$) is implied (Okuzumi et al. 2016)

Why the Differences???

Temperature and Turbulence are Degenerate (to some extent)

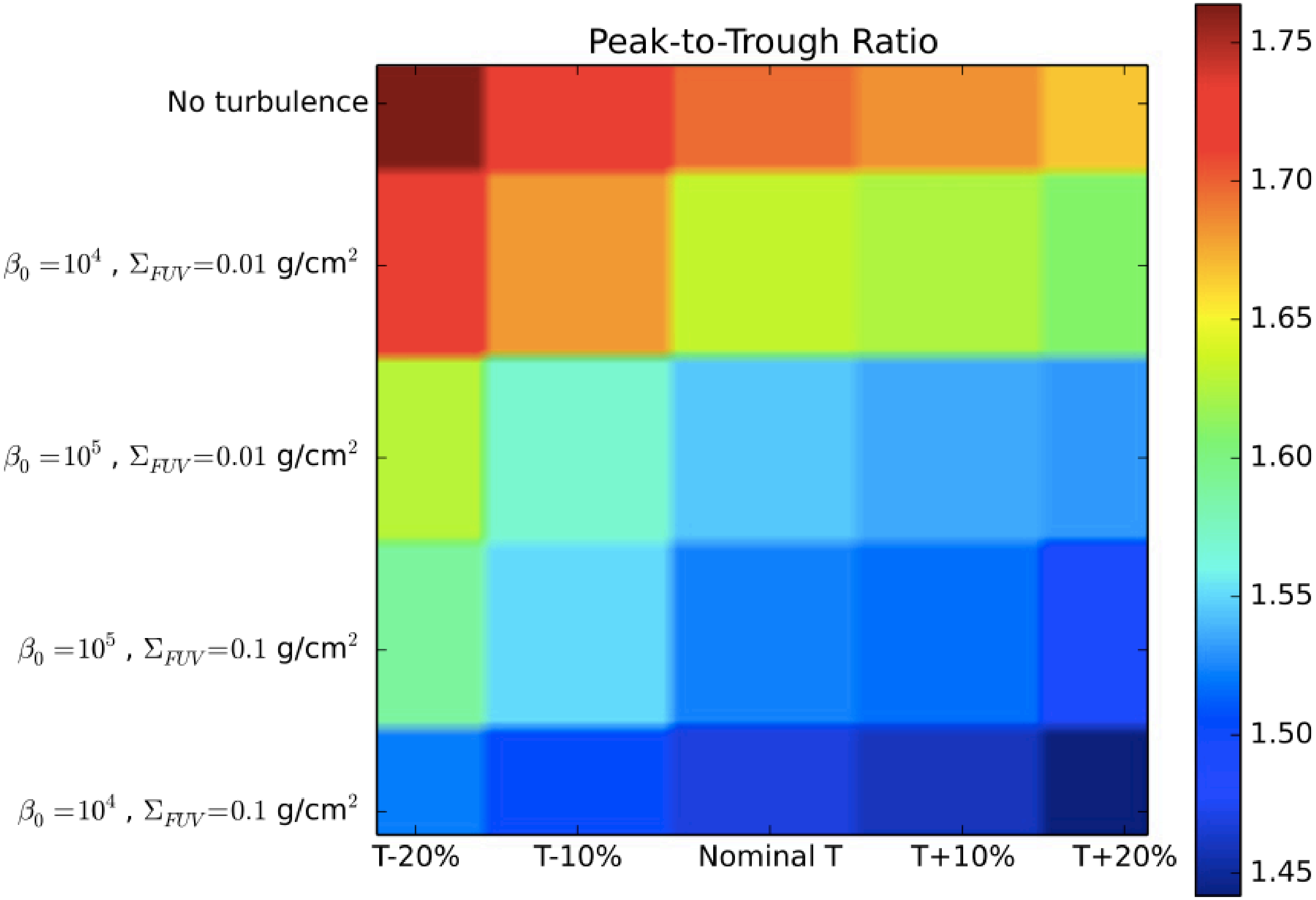


Fits to TW Hya disk

Courtesy Kevin Flaherty

Blue = single-line fit
Red = multi-line fit
Dashed = Teague parametric
Dotted = Hughes 2011 (SMA)

Temperature and Turbulence are Degenerate (to some extent)



Simon, Hughes, Flaherty, et al. (2015)

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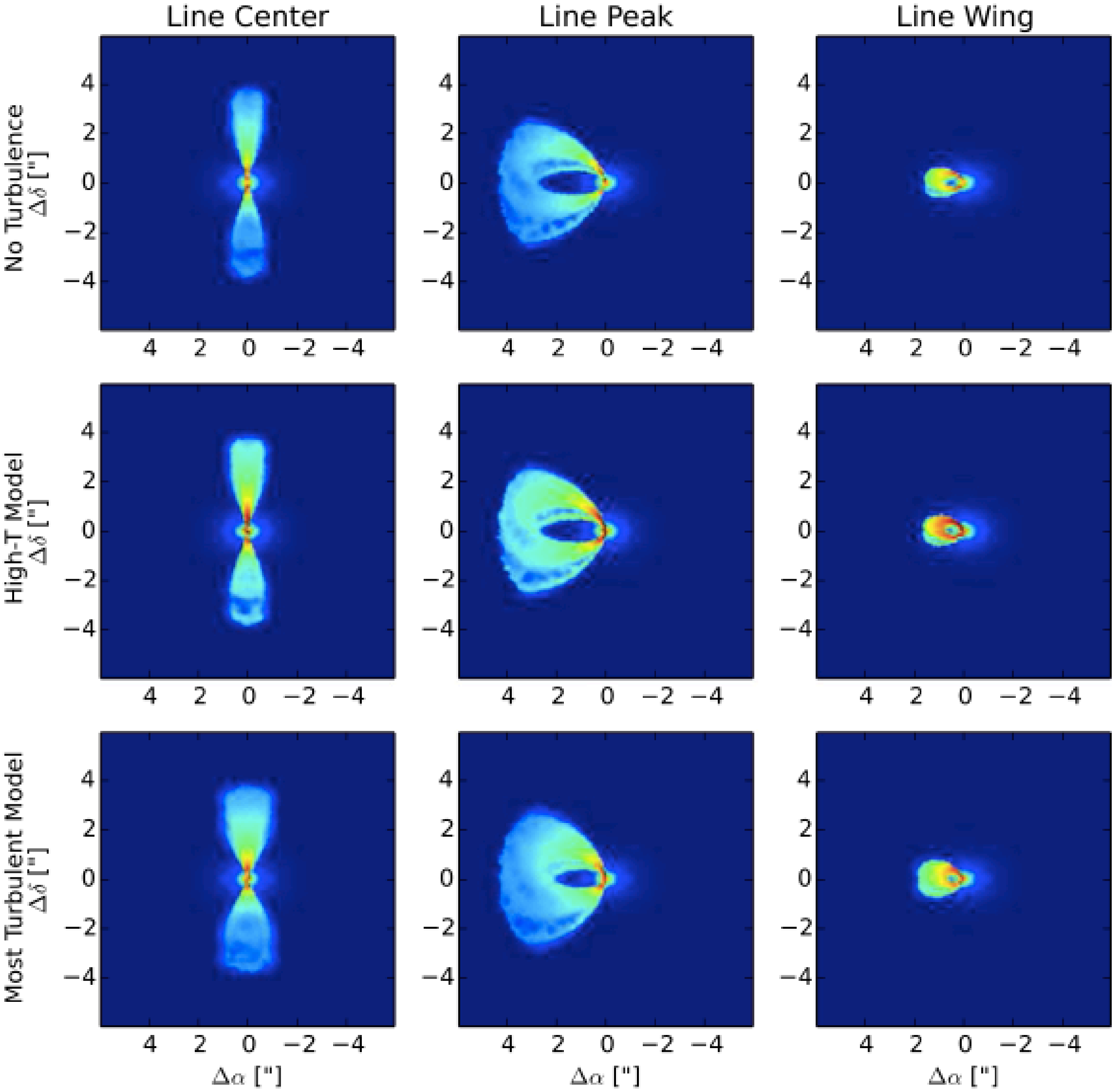
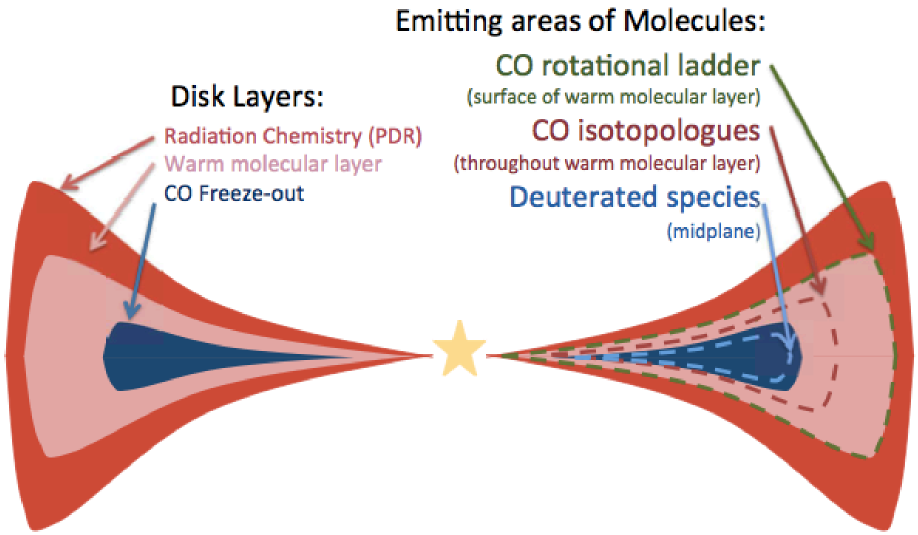


Simon, Hughes, Flaherty, et al. (2015)

Different Tracers (CO, CS, DCO+) and the Role of Optical Depth

Strengths:

- Different molecules probe different disk regions
- Heavier molecules have lower thermal linewidths
- Potential to characterize ions vs. neutrals



Emitting areas of Molecules:

CO rotational ladder
(surface of warm molecular layer)

CO isotopologues
(throughout warm molecular layer)

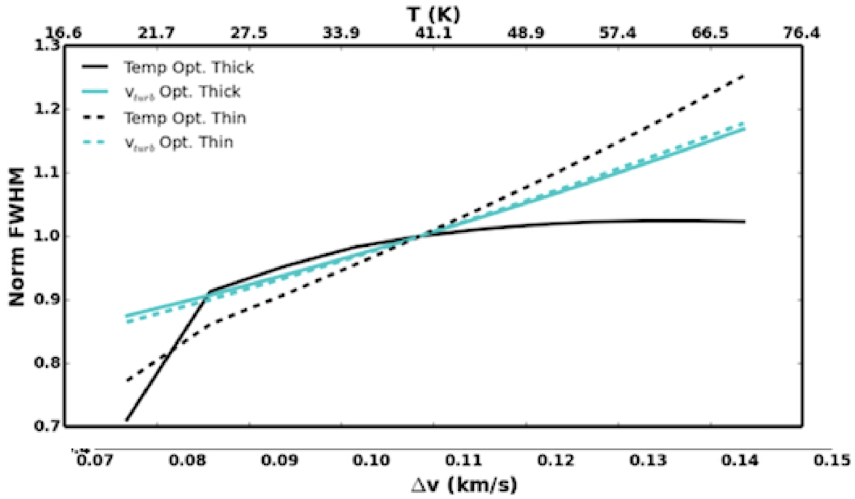
Deuterated species
(midplane)

Disk Layers:

Radiation Chemistry (PDR)

Warm molecular layer

CO Freeze-out



Weaknesses:

- Optically thin lines exhibit more degeneracy between temperature and turbulence
- Chemistry may not be as well understood

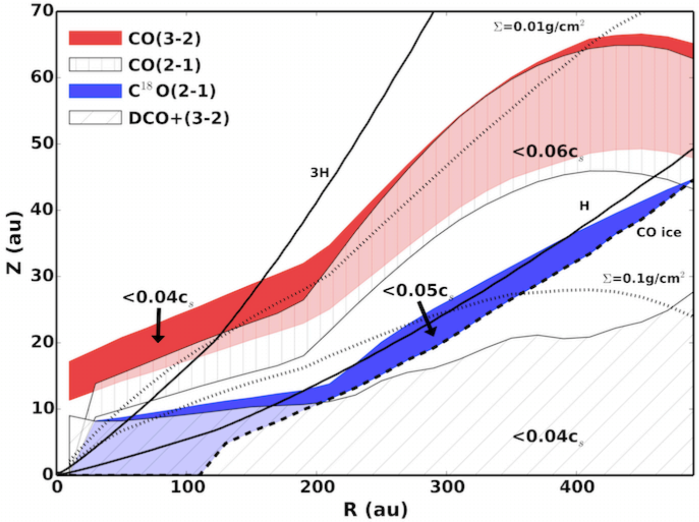
Methods: 2-D Parametric vs. line-of-sight spectrum

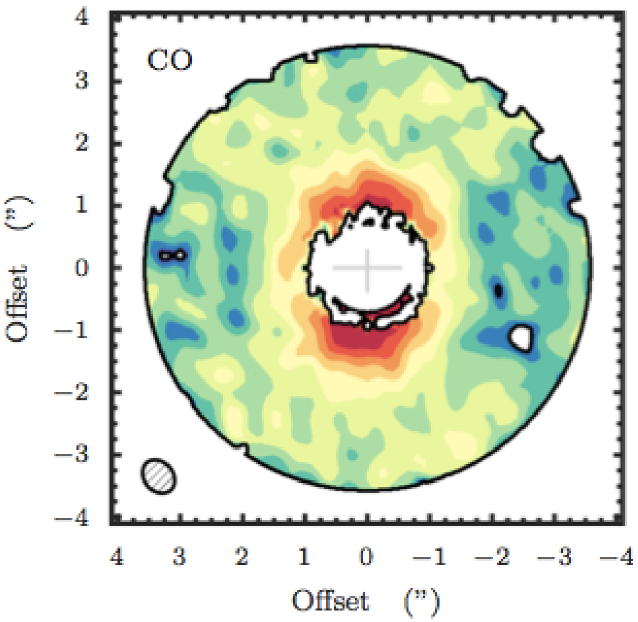
Parametric:

- Utilizes all 3-D data
- Consistently implements radiative transfer

BUT

- Assumes underlying disk structure; may bias results
- Cannot account for local variations





Teague et al. (2016)

Line-of-sight spectrum:

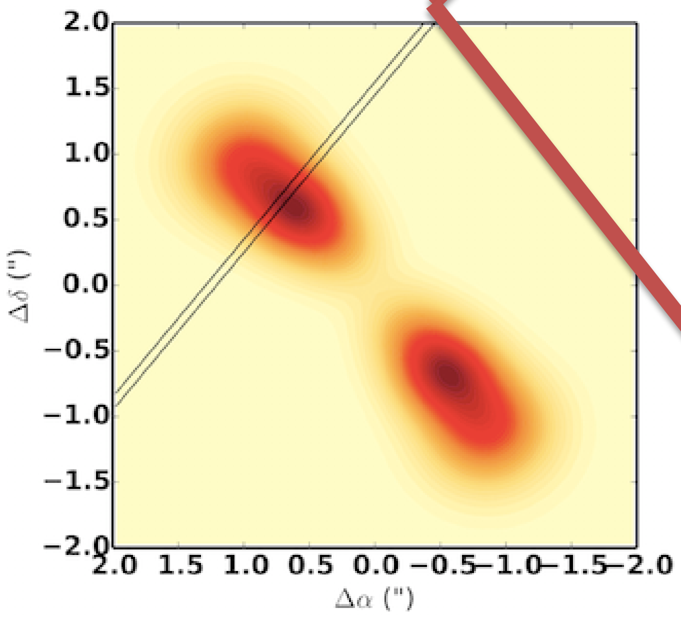
- Sensitive to local variations in turbulence
- Model-independent

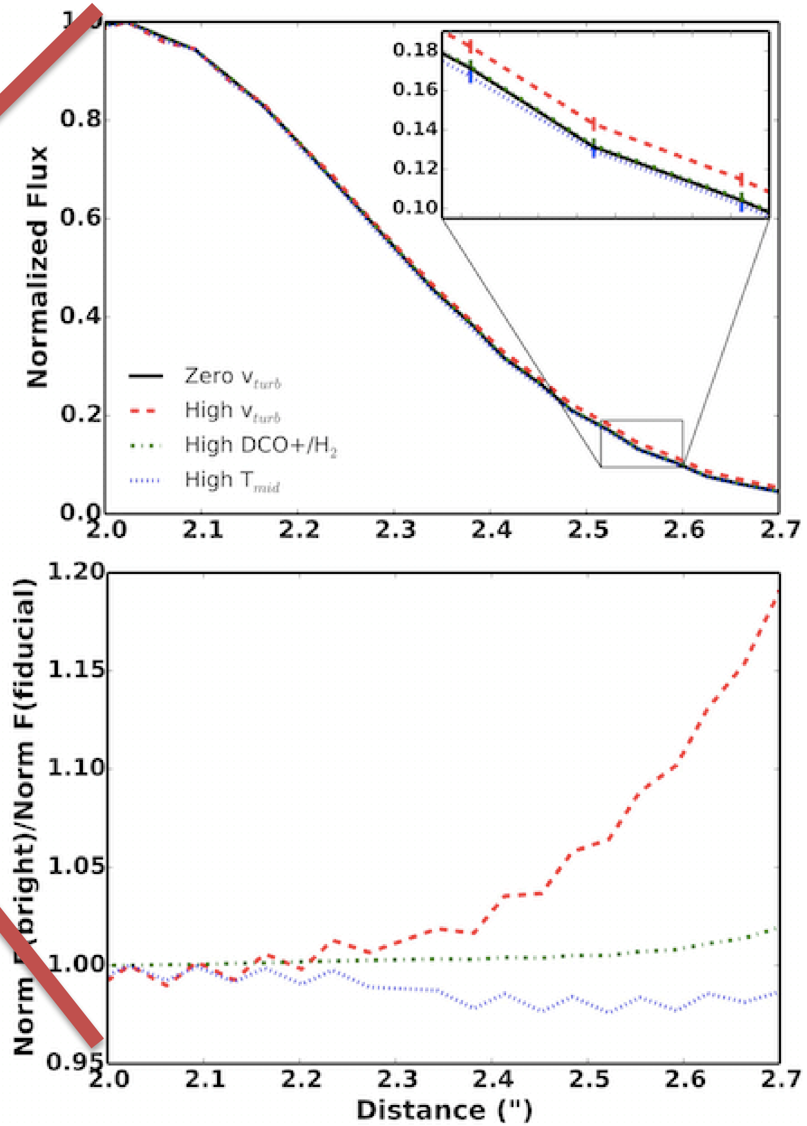
BUT

- Spatial domain cannot be used to distinguish between temp and turbulence
- Assumes single T_{ex} and/or T_{kin}
- Keplerian shear makes it impractical in inclined disks or too close to star
- Radiative transfer not implemented

Absolute Flux Calibration: How Bad is the Problem?

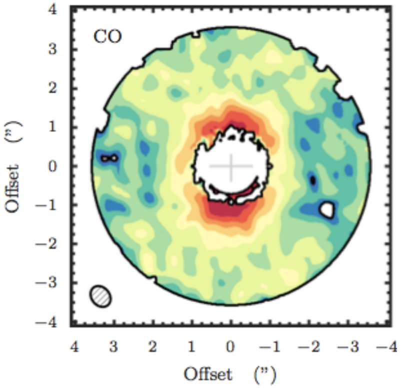
Answer: It’s a problem… but the spatial domain helps!

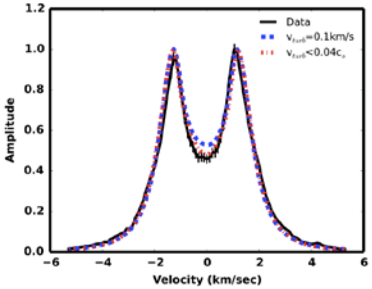




Courtesy Kevin Flaherty

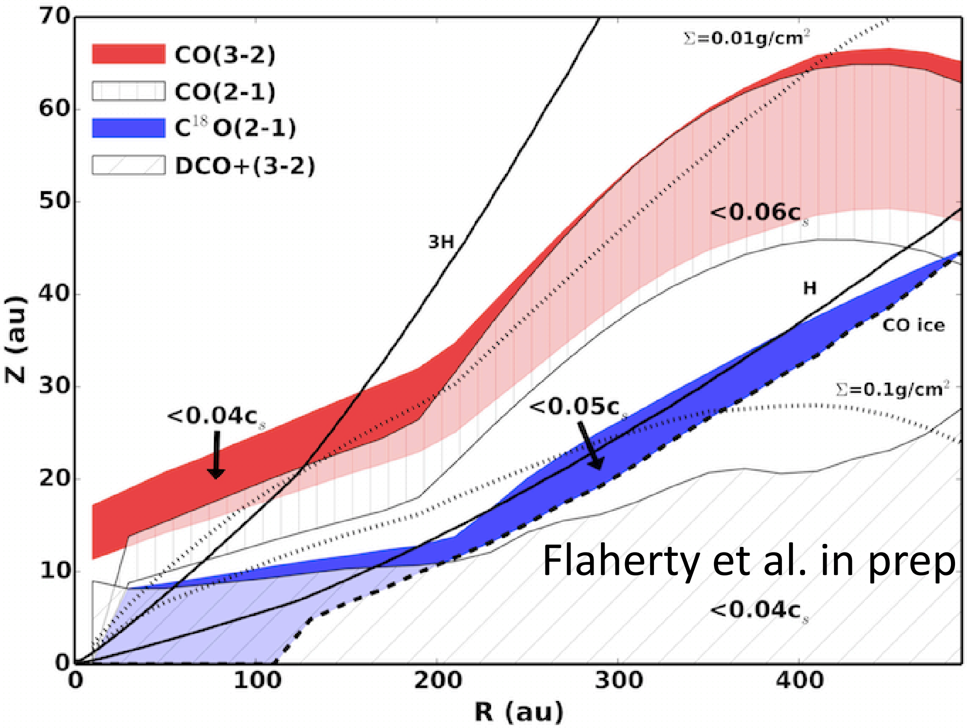
Bottom Line: What to Look For in Evaluating a Result





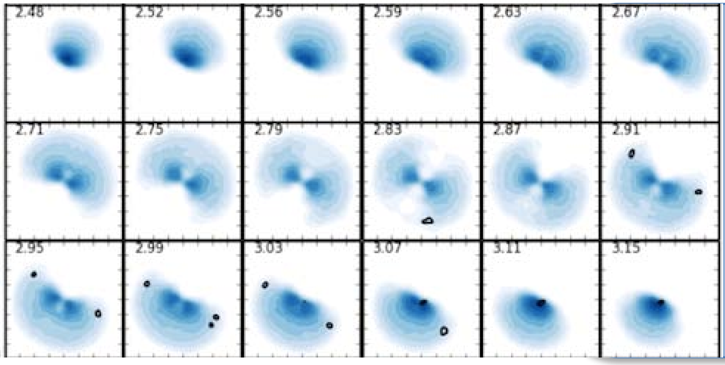
- Parametric approach has strengths over line-of-sight (spatial dimension, radiative transfer), but *only* if residuals are small. Systematic uncertainties affect both approaches.
- It is easy to fit an anomalously large turbulent linewidth to compensate for some other parameter that fits poorly. If you’re adequately fitting the data without turbulence, then you don’t need turbulence!

Summary and Ongoing Work



Flaherty et al. in prep

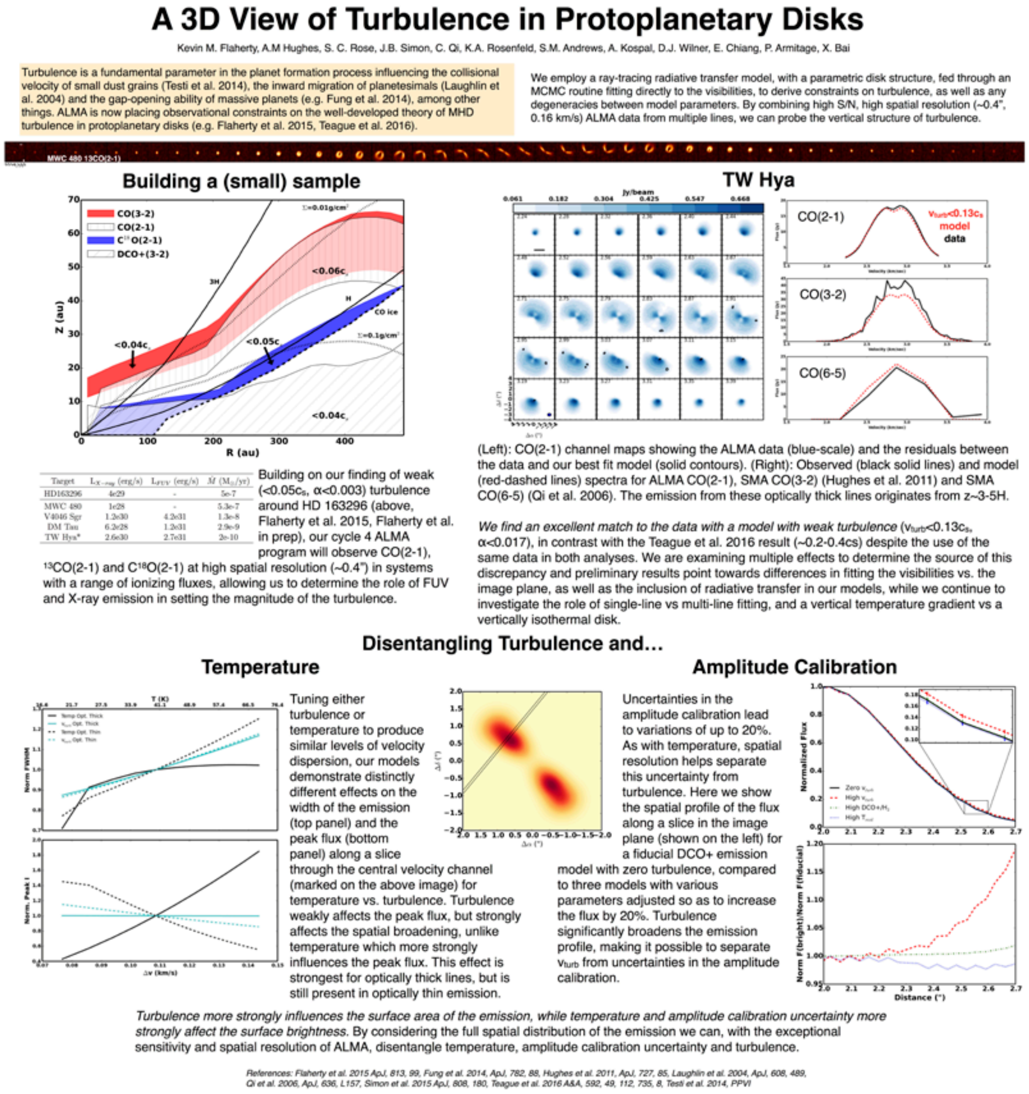
We obtain consistently low limits on the amount of turbulence in the outer (100s of au) disk around HD 163296, using a variety of tracers that probe different vertical layers, via parametric modeling.



Ongoing work:

- Fitting TW Hya ALMA data, comparison of methods (vs. Teague et al.)
- Small sample with various stellar X-ray and FUV fluxes – is low turbulence common?

For More Information:
Visit Kevin Flaherty's Poster!



A 3D View of Turbulence in Protoplanetary Disks

Kevin M. Flaherty, A.M Hughes, S. C. Rose, J.B. Simon, C. Qi, K.A. Rosenfeld, S.M. Andrews, A. Kospal, D.J. Wilner, E. Chiang, P. Armitage, X. Bai

Turbulence is a fundamental parameter in the planet formation process influencing the collisional velocity of small dust grains (Testi et al. 2014), the inward migration of planetesimals (Laughlin et al. 2004) and the gap-opening ability of massive planets (e.g. Fung et al. 2014), among other things. ALMA is now placing observational constraints on the well-developed theory of MHD turbulence in protoplanetary disks (e.g. Flaherty et al. 2015, Teague et al. 2016).

We employ a ray-tracing radiative transfer model, with a parametric disk structure, fed through an MCMC routine fitting directly to the visibilities, to derive constraints on turbulence, as well as any degeneracies between model parameters. By combining high S/N, high spatial resolution (~0.4", 0.16 km/s) ALMA data from multiple lines, we can probe the vertical structure of turbulence.

Building a (small) sample

Target	L_{X-ray} (erg/s)	L_{FUV} (erg/s)	$\dot{M}$ ($M_\odot$/yr)
HD163296	4e29	-	5e-7
MWC 480	1e28	-	5.3e-7
V4046 Sgr	1.2e30	4.2e31	1.3e-8
DM Tau	6.2e28	1.2e31	2.9e-9
TW Hya*	2.6e30	2.7e31	2e-10

Building on our finding of weak (<0.05c_s, α<0.003) turbulence around HD 163296 (above, Flaherty et al. 2015, Flaherty et al. in prep), our cycle 4 ALMA program will observe CO(2-1), ^{13}CO(2-1) and $C^{18}O$(2-1) at high spatial resolution (~0.4") in systems with a range of ionizing fluxes, allowing us to determine the role of FUV and X-ray emission in setting the magnitude of the turbulence.

TW Hya

(Left): CO(2-1) channel maps showing the ALMA data (blue-scale) and the residuals between the data and our best fit model (solid contours). (Right): Observed (black solid lines) and model (red-dashed lines) spectra for ALMA CO(2-1), SMA CO(3-2) (Hughes et al. 2011) and SMA CO(6-5) (Qi et al. 2006). The emission from these optically thick lines originates from z~3-5H.

We find an excellent match to the data with a model with weak turbulence (v_{turb}<0.13c_s, α<0.017), in contrast with the Teague et al. 2016 result (~0.2-0.4cs) despite the use of the same data in both analyses. We are examining multiple effects to determine the source of this discrepancy and preliminary results point towards differences in fitting the visibilities vs. the image plane, as well as the inclusion of radiative transfer in our models, while we continue to investigate the role of single-line vs multi-line fitting, and a vertical temperature gradient vs a vertically isothermal disk.

Disentangling Turbulence and…

Temperature

Tuning either turbulence or temperature to produce similar levels of velocity dispersion, our models demonstrate distinctly different effects on the width of the emission (top panel) and the peak flux (bottom panel) along a slice through the central velocity channel (marked on the above image) for temperature vs. turbulence. Turbulence weakly affects the peak flux, but strongly affects the spatial broadening, unlike temperature which more strongly influences the peak flux. This effect is strongest for optically thick lines, but is still present in optically thin emission.

Amplitude Calibration

Uncertainties in the amplitude calibration lead to variations of up to 20%. As with temperature, spatial resolution helps separate this uncertainty from turbulence. Here we show the spatial profile of the flux along a slice in the image plane (shown on the left) for a fiducial DCO+ emission model with zero turbulence, compared to three models with various parameters adjusted so as to increase the flux by 20%. Turbulence significantly broadens the emission profile, making it possible to separate v_{turb} from uncertainties in the amplitude calibration.

Turbulence more strongly influences the surface area of the emission, while temperature and amplitude calibration uncertainty more strongly affect the surface brightness. By considering the full spatial distribution of the emission we can, with the exceptional sensitivity and spatial resolution of ALMA, disentangle temperature, amplitude calibration uncertainty and turbulence.

References: Flaherty et al. 2015 ApJ, 813, 99, Fung et al. 2014, ApJ, 782, 88, Hughes et al. 2011, ApJ, 727, 85, Laughlin et al. 2004, ApJ, 608, 489, Qi et al. 2006, ApJ, 636, L157, Simon et al. 2015 ApJ, 808, 180, Teague et al. 2016 A&A, 592, 49, 112, 735, 8, Testi et al. 2014, PPVI