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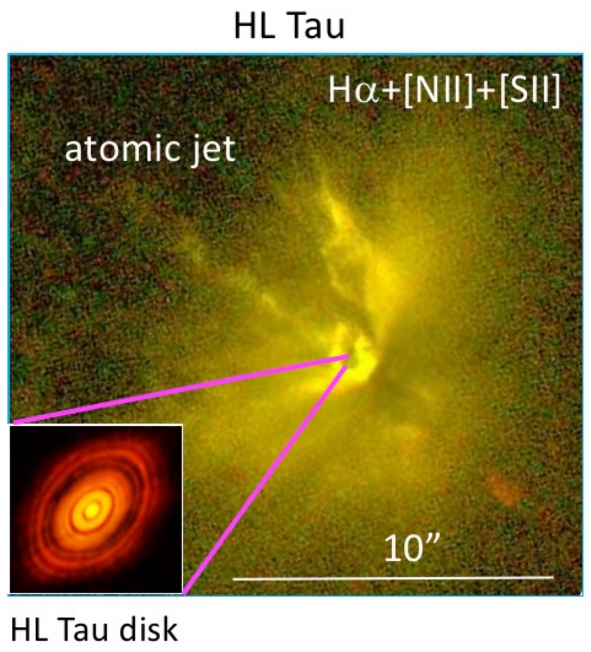
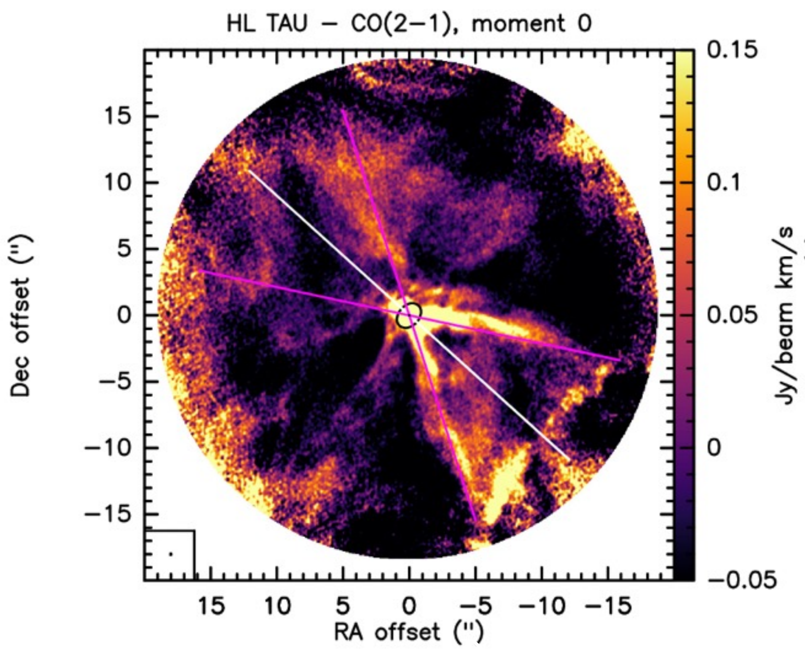
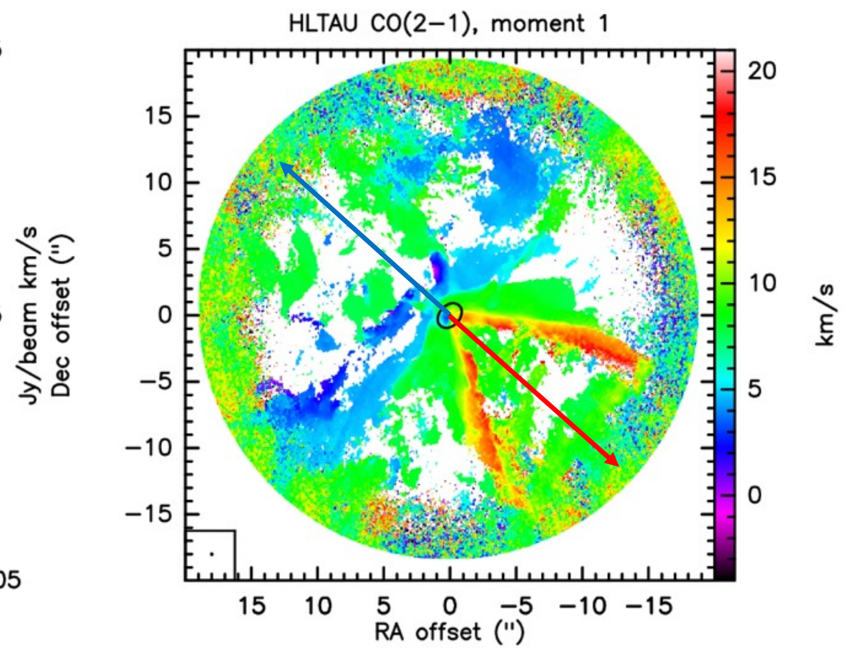
Layered molecular outflows and disk substructures in YSOs: the HL Tau case







HL Tau is a Class I-II young star in Taurus at 147 pc surrounded by a protoplanetary disk (*inset*), the first found to possess concentric rings and gaps (Alma Partnership, 2015). It is associated to a collimated atomic jet seen in optical and IR lines (*left panel*, from Krist et al. 2008), by a warm wind revealed in H2 lines (Takami et al. 2007) and a CO outflow.

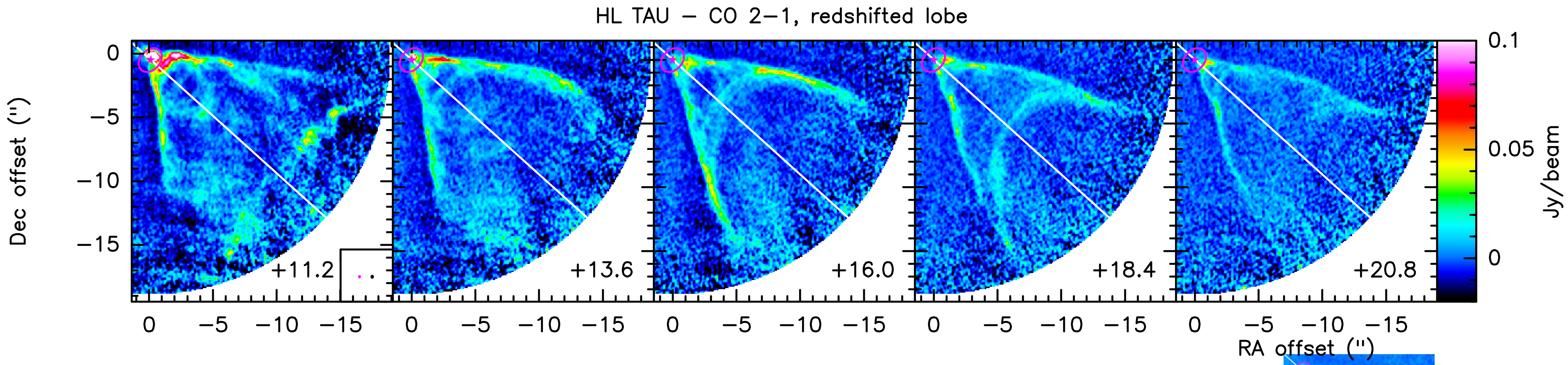
The CO Outflow

The coaxial conical molecular outflow has been investigated within the ALMA-DOT project (Podio et al. 2020) in the CO(2-1) line at 0.”25 resolution **(Bacciotti et al. in prep.)** *The central panel* illustrates the moment 0 map. The black ellipse indicates the disk. The white line has the same PA of the atomic jet and the magenta lines trace an aperture of +-30 deg. *The right panel* shows the moment 1 map.

Projections of the PPV cube

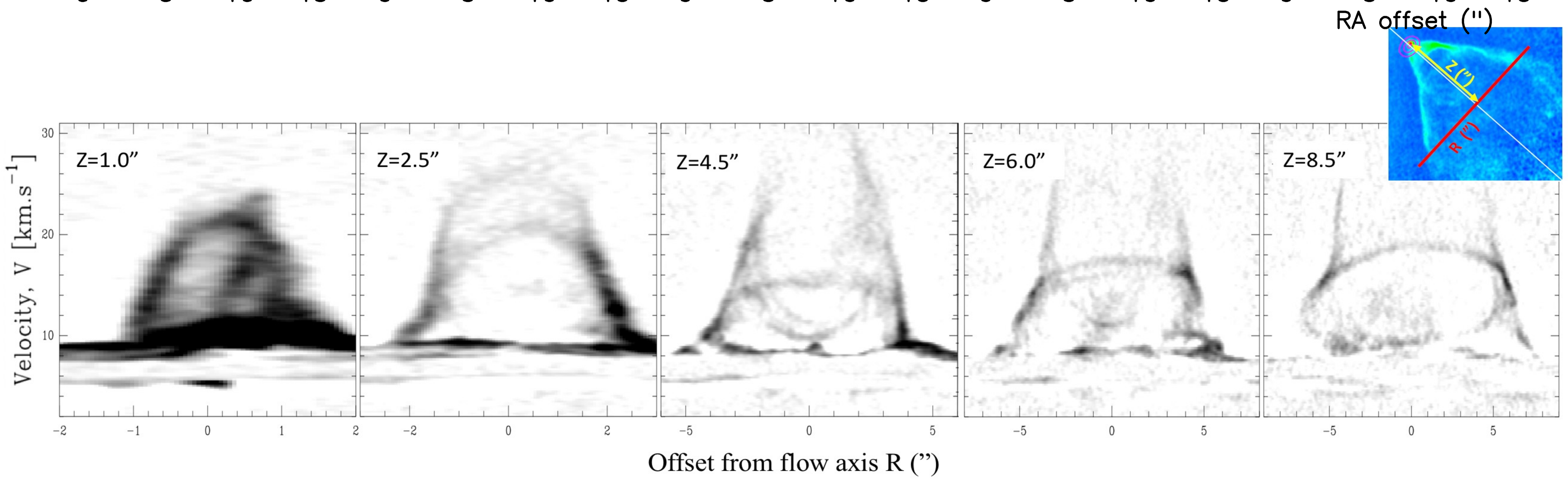
1) Channel maps

When imaged in the single velocity channel maps the SW redshifted lobe of the outflow presents a **system of arcs and bubbles** that change continuously position and size with velocity (Bacciotti et al. in prep)).).



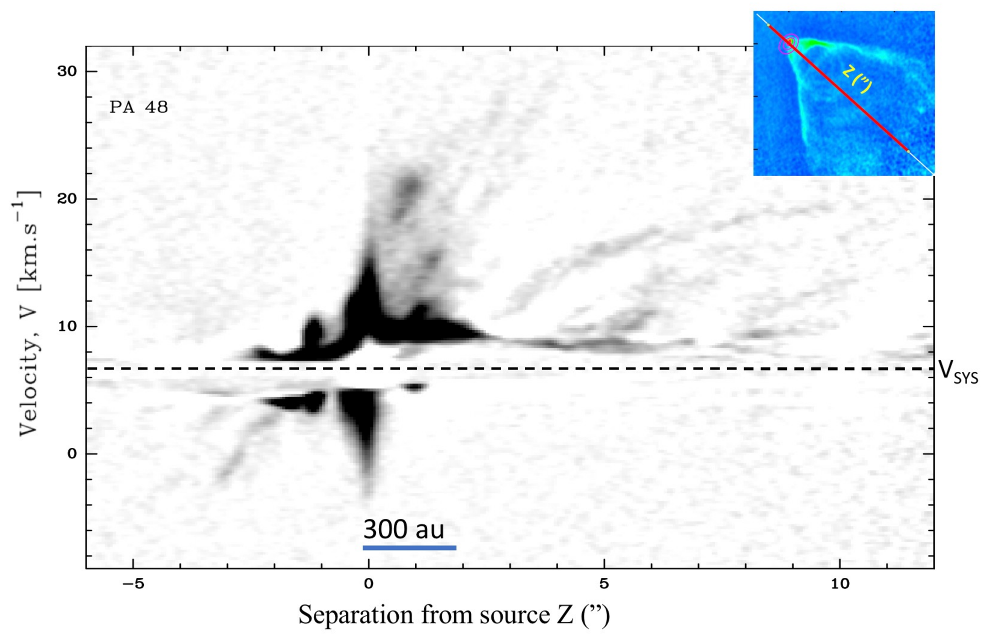
2) PVs across the flow

When imaged in the single PVs across the flow at stepped separations from the source the outflow presents **a system of tilted ellipses** that change continuously position and size as the separation increases.
The tilt in velocity indicates flow rotation.



3) PV along the flow axis

When imaged in the PV along the flow axis (PA=48) the flow presents a **system of lines and parabolas** in both the blue- and red-shifted lobes. An apparent acceleration with separation from the source (Hubble law) is observed.



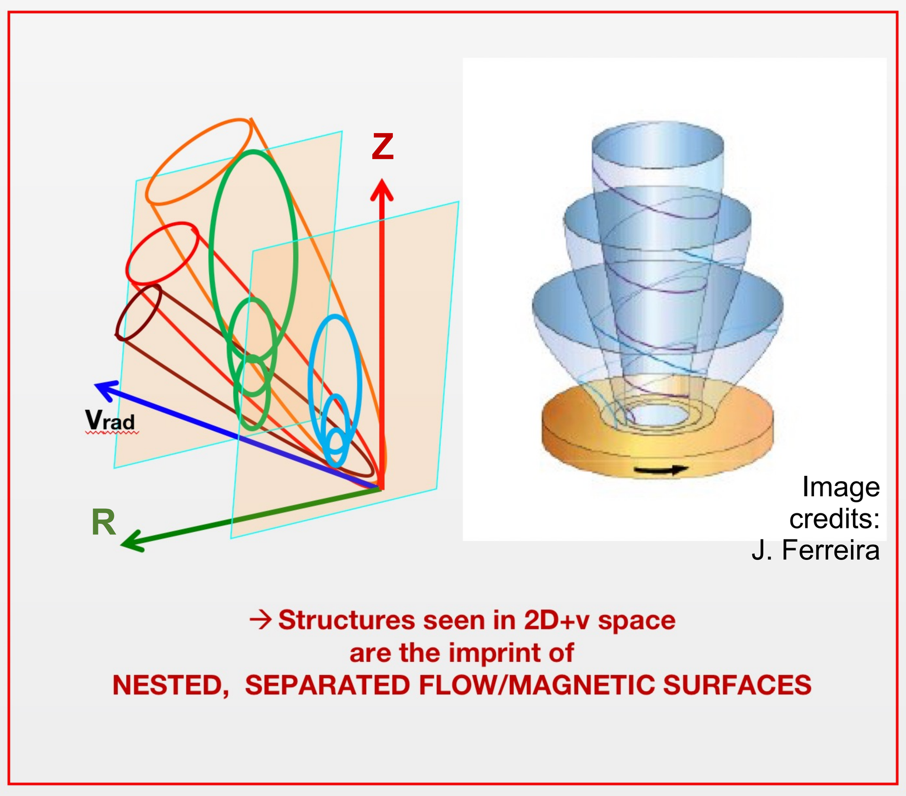
Similarity to other cases

The same system of substructures has been found in other conical outflows (e.g. HH 46/47, Zhang et al. 2019; DG Tau B, de Valon et al. 2020, 2022; HH 30, Louvet et al. 2018, Lopez-Vazquez et al ., subm.; DO Tau (Fernandez et al. 2020). Among them, however, **HL Tau is the only object with a detectable ring / gap structure in the disk ,** allowing us to test the possible relationship between disk and wind substructures.

Interpretation

Substructures in the PPV datacube are the imprint of nested, separated flow layers

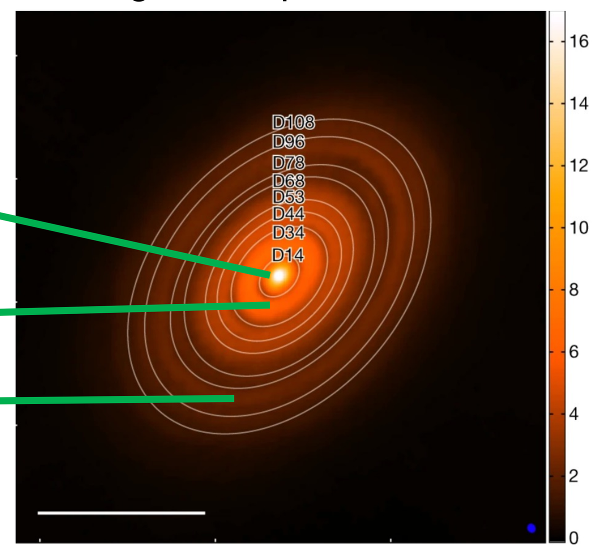
The projections of the ALMA datacube are **consistent with a layered structure of the CO outflow** in physical space, with inner shells faster and more readily accelerated than the outer shells. Such a structure is reminiscent of a magnetically driven disk wind (e.g. Ferreira et al. 2006).
The panel illustrates how such a wind structure would generate, e.g., concatenated bubbles in the channel maps.



Preliminary estimate of footpoint radii in the disk

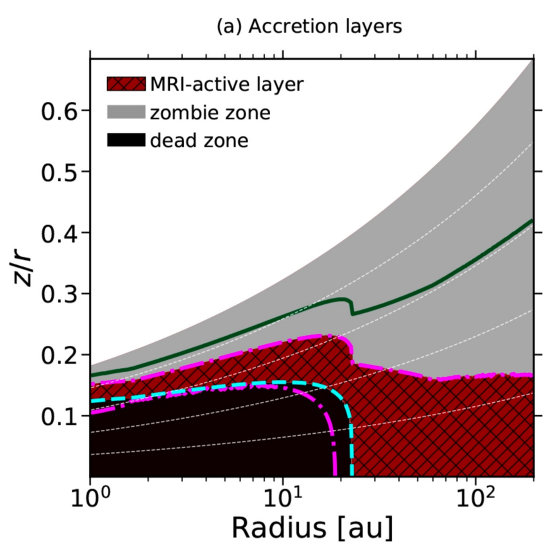
Assuming that the outflow is a magnetocentrifugal cold disk-wind the footpoints in the disk of the nested layers can be found from flow rotation measurements (Bacciotti et al. 2002, Anderson et al 2003, Ferreira et al. 2006). This involves the determination of poloidal and toroidal velocities, plus the flow width. These quantities can be derived from the inspection of the tilted ellipses in the transverse PVs (point 2 above).
Two independent estimates locate the origin of detectable layers between 4 and 20 au from the star, and at about 85 au for the outer envelope (Bacciotti et al. in prep). Interestingly, the origin of the sixth layer and of the outer envelope correspond to the location of rings in the disk as seen in the high resolution image of Stephens et al. 2023.

Layer 1	4 au
Layer 2	5 au
Layer 3	7 au
Layer 4	10 au
Layer 5	11 au
Layer 6	18 au
....	
Outer Layer	85 au



Stephens et al. 2023

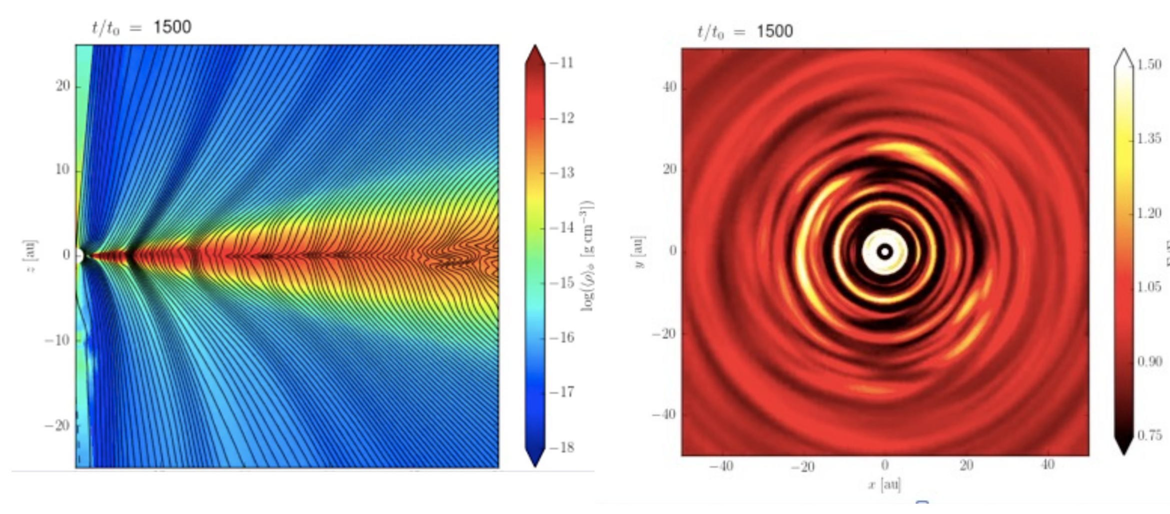
Implication 1 : angular momentum extraction at the dead zone



The origin of the wind between 4 and 20 au from the star is coincident with the location of the so-called ‘dead zone’ where turbulence is suppressed. The excess angular momentum, however, can still be transported away vertically by the magnetically driven wind, allowing accretion to proceed.

From Delage et al. . 2022

Implication 2 : support to MHD instabilities as origin of rings & gaps



The layered structure of the wind and the origin from the rings appear to support recent models in which rings and gaps in the disk are produced by the development of non-ideal MHD instabilities, alternatively to the presence of the yet elusive protoplanets (Suriano et al. 2019, Riols et al. 2020).

from Suriano et al. 2019

References: Bacciotti et al., 2002, ApJ 576, 222; Alma Partnership, 2015, ApJ 808, L3; Anderson et al. 2003, ApJ 590, L107; Delage et al. 2022, A&A 658, A97; De Valon et al. 2020, A&A, 634, L12; De Valon, 2022 A&A 668, 78; Ferreira et al. 2006, 453, 785; Krist et al. 2008, AJ 136, 1980; Podio et al. 2020, A&A 642 L7; Riols et al., 2020, A&A, 639, 95; Stephens et al. 2023, Nature, in press arXiv:2311.08452; Suriano et al., 2019, MNRAS, 484, 107; Takami et al. 2008, ApJ, 670, L33; Zhang et al. 2019 ApJ, 883,1