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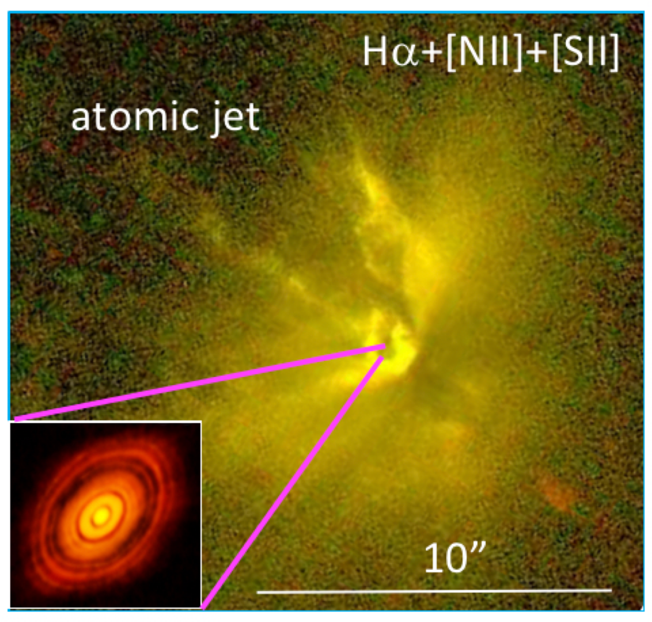
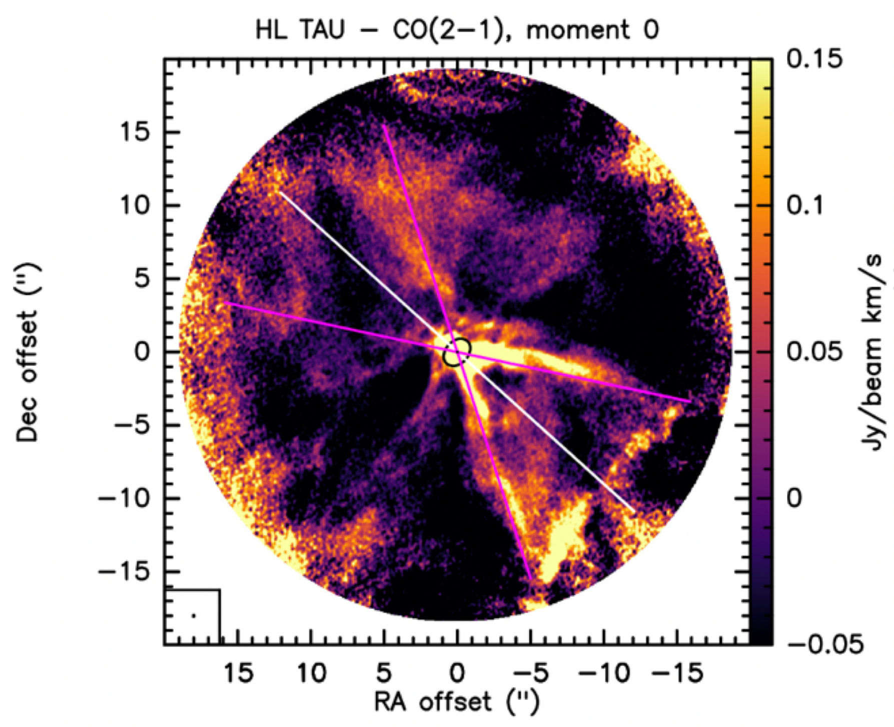
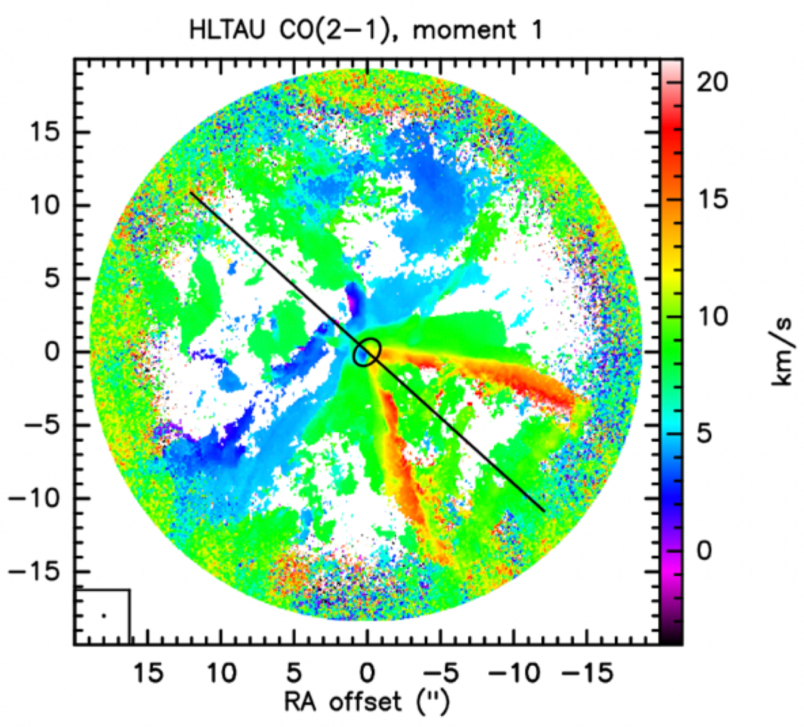
The layered molecular outflow from HL Tau and its relationship with the ringed disk



HL Tau disk
Alma partnership
2015

Krist et al. 2008





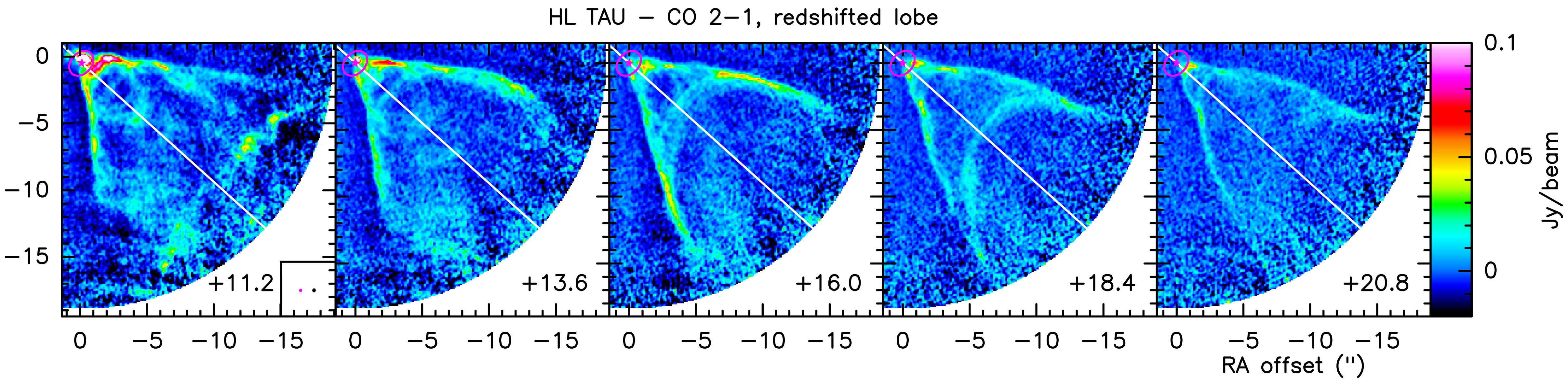
HL Tau is a Class I-II young star in Taurus surrounded by a protoplanetary disk (*inset*), the first found to possess concentric rings and gaps (Alma Partnership, 2015). It is associated to a collimated atomic jet seen in optical and IR lines (*left panel*, from Krist et al. 2008), by a warm wind revealed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

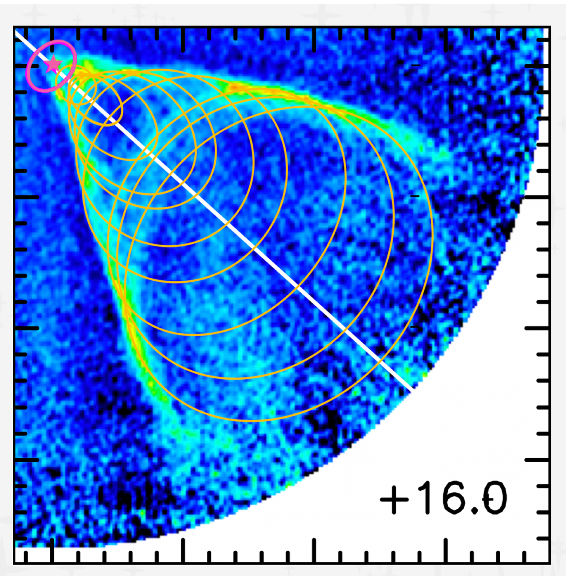
The CO Outflow

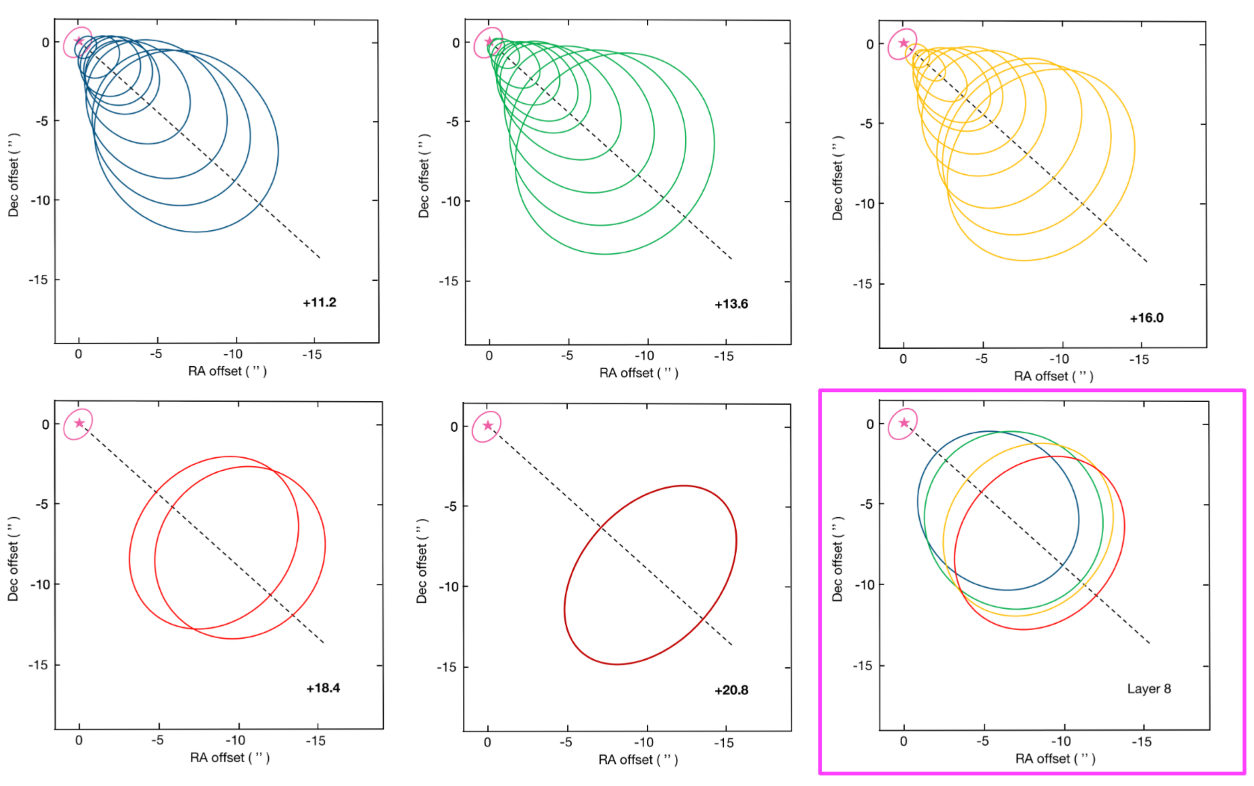
The coaxial conical molecular outflow has been investigated within the ALMA-DOT project (Podio et al. 2020) in the CO(2-1) line at 0."25 resolution (Bacciotti et al. in prep.) *The central panel* illustrates the moment 0 map. The black ellipse indicates the disk. The white line has the same PA of the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

Substructures in the 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). Similar substructures have been found in other conical outflows (e.g. HH 46/47, Zhang et al. 2019; DG Tau B, de Valon et al. 2020, 2021).







Substructures are the imprint of detached flow layers

In each velocity bin the structures can be fitted with a set of ellipses
Interpretation: the ellipses are cuts of multiple layers in 2D+v space at a single radial velocity

Magenta box:
a given ellipse moves away from the source and increases in size from one channel map to the next.
Interpretation: these ellipses are cuts at multiple radial velocities of a single layer in 2D+v space

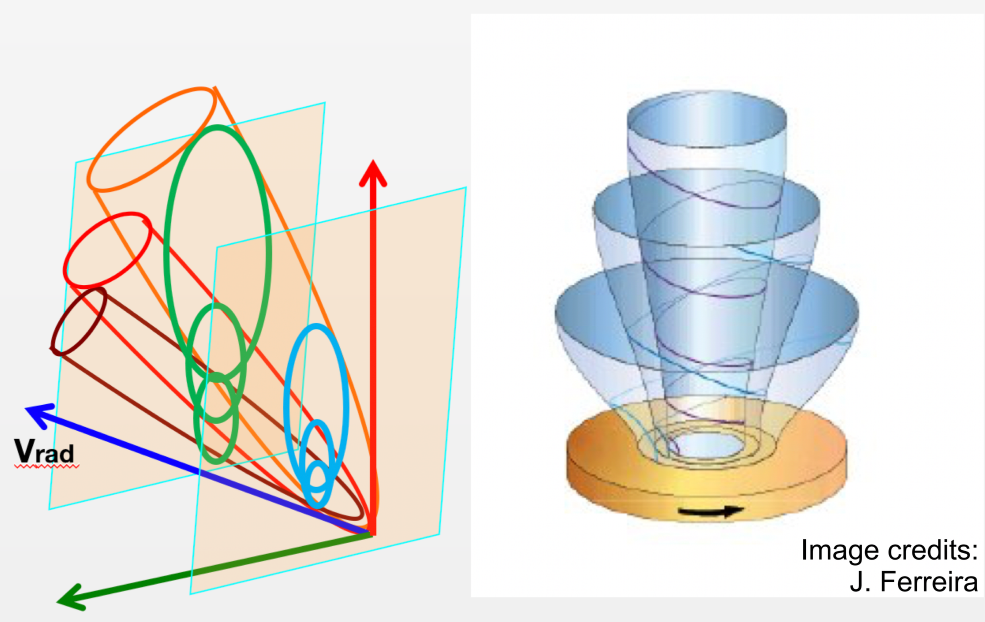


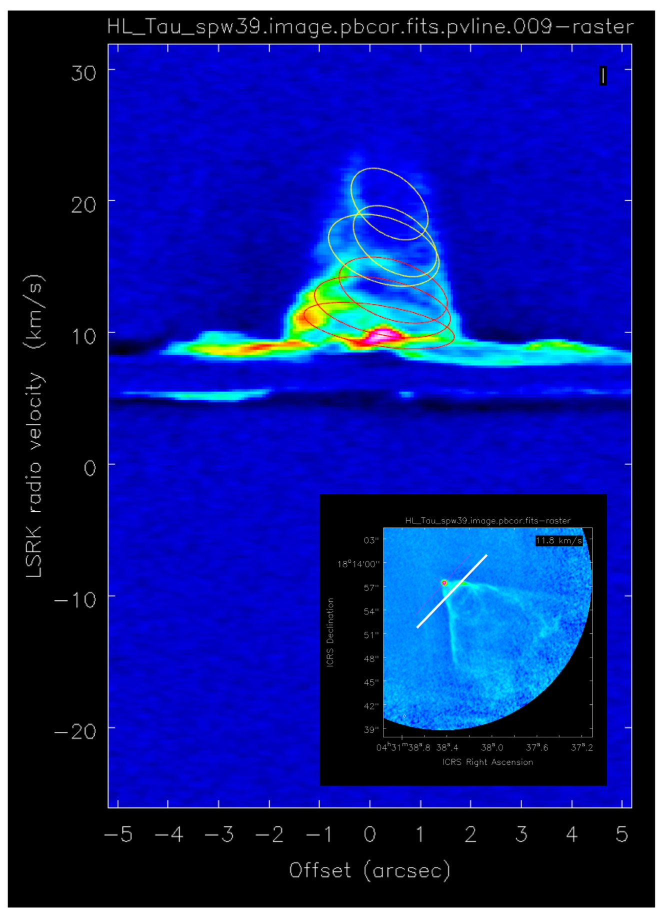
Image credits:
J. Ferreira

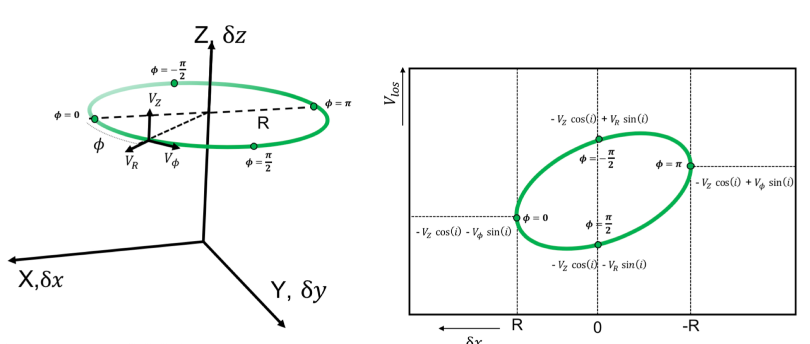
→ **Structures seen in 2D+v space are the imprint of NESTED, SEPARATED FLOW/MAGNETIC SURFACES**

Where is the origin of the layers ?

Assuming that the outflow is a MHD wind the foot point of the nested layers in the disk can be found with flow rotation estimates, measuring for each layer poloidal and toroidal velocities, and corresponding flow width (Bacciotti et al. 2002, Anderson et al 2003, Ferreira et al. 2006).

These quantities are derived from the Position-Velocity diagram taken transversely to the flow axis. In such a diagram each oblique ellipse is a trace of a rotating flow layer.





De Valon 2021

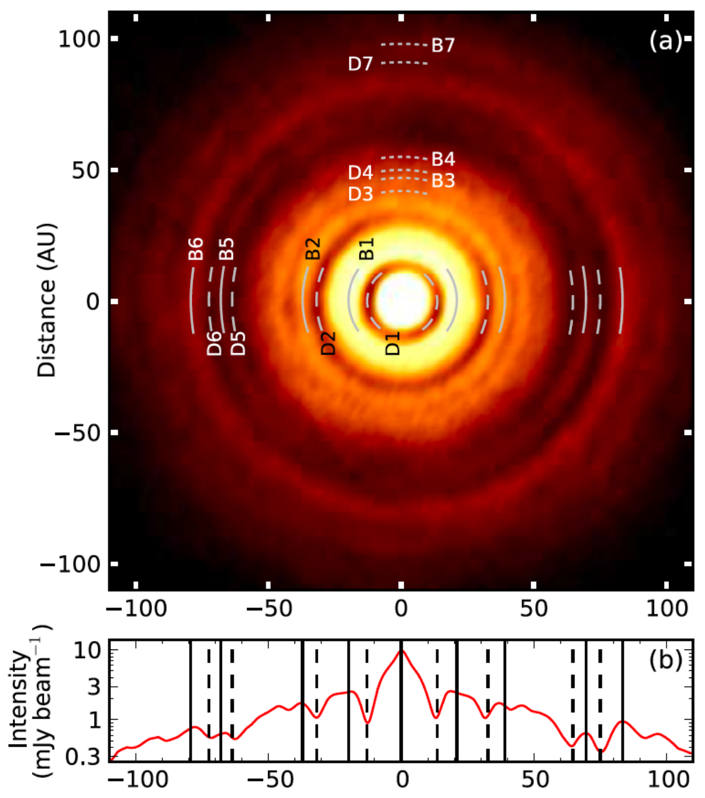
Resulting foot points in the disk

Two independent estimates locate the origin of the layers in selected positions in the disk between 4 and 20 au from the star. Interestingly, the foot point of layer 1 lies beyond the first gap in the disk
(Bacciotti et al., in prep.)

Foot points r_0 :

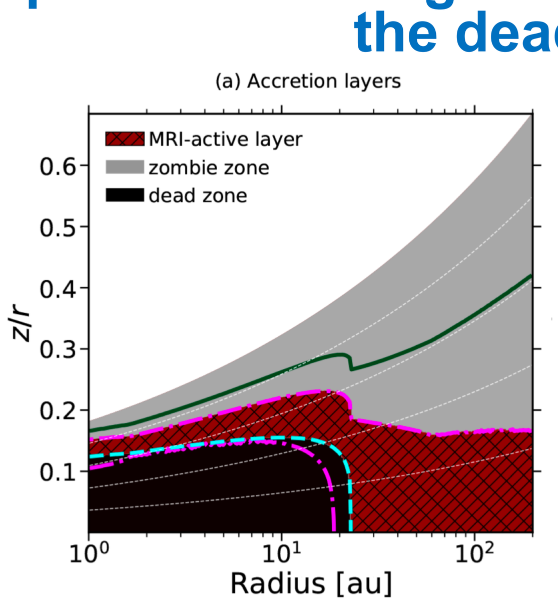
Layer 1	**17.8 au**
Layer 2	**11.0 au**
Layer 3	**9.7 au**
Layer 4	**7.0 au**
Layer 5	**5.4 au**
Layer 6	**4.5 au**

(uncertainty 25%)



ALMA Partnership, 2015

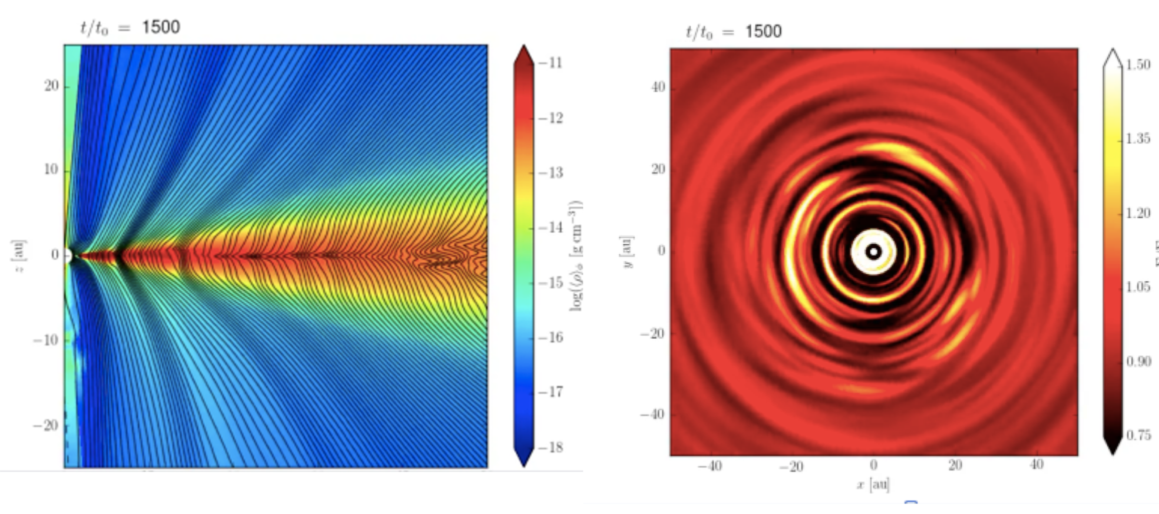
Implication 1 : angular momentum extraction at the dead zone



From Delage et al. . 2022

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 can be, however, transported vertically by the wind allowing accretion to proceed.

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



The layered structure of the wind and the origin from the rings is in agreement with the predictions of models in which the ringed structure of the disk is produced by the development of non-ideal MHD instabilities.

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, 2021 PhDT; Ferreira et al. 2006, 453, 785; Krist et al. 2008, AJ 136, 1980; Podio et al. 2020, A&A 642 L7; Suriano et al., 2019, MNRAS, 484, 107; Takami et al. 2008, ApJ, 670, L33; Zhang et al. 2019 ApJ, 883,1