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Multi-epoch Spectroimaging of the DG Tauri Outflows with NIFS

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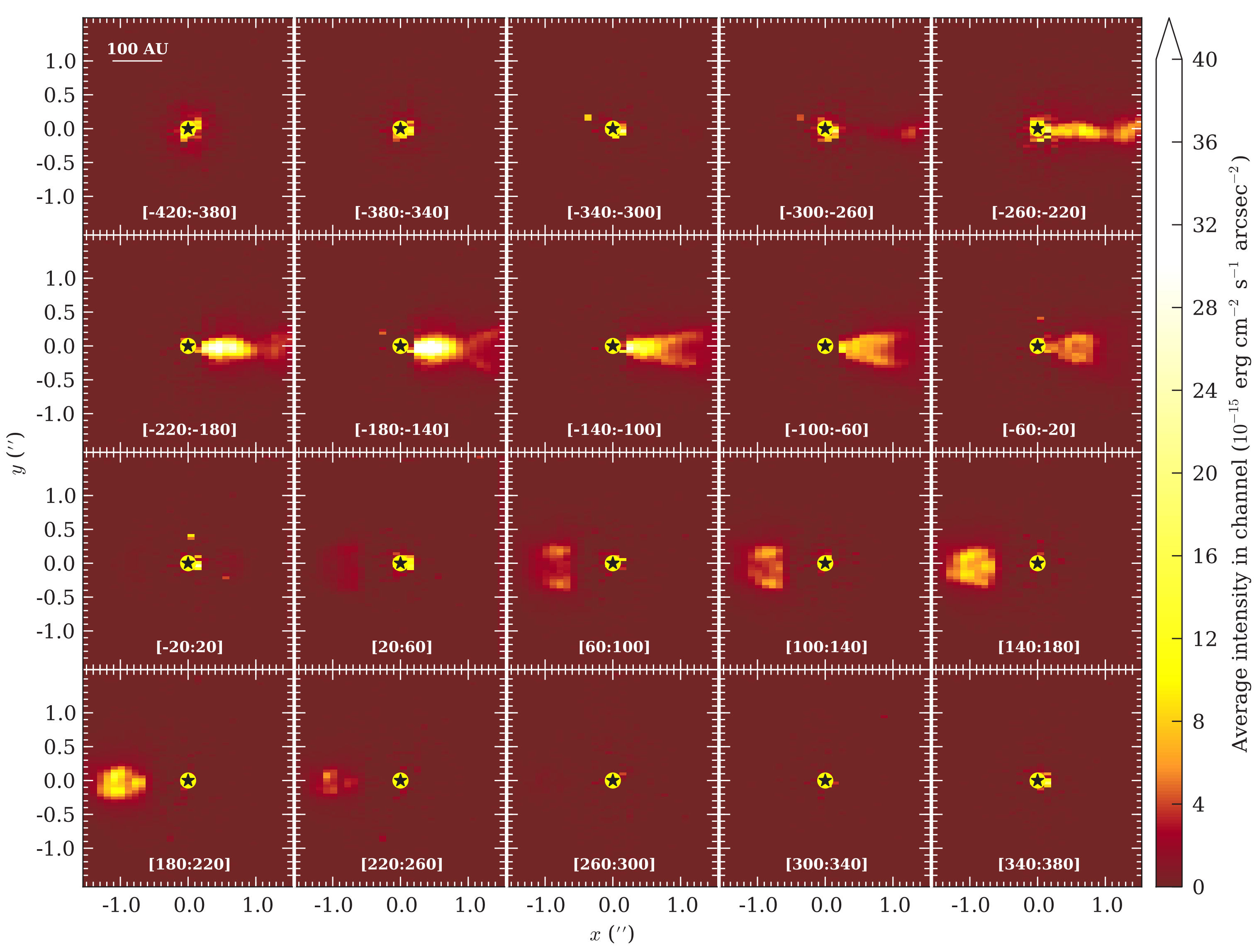
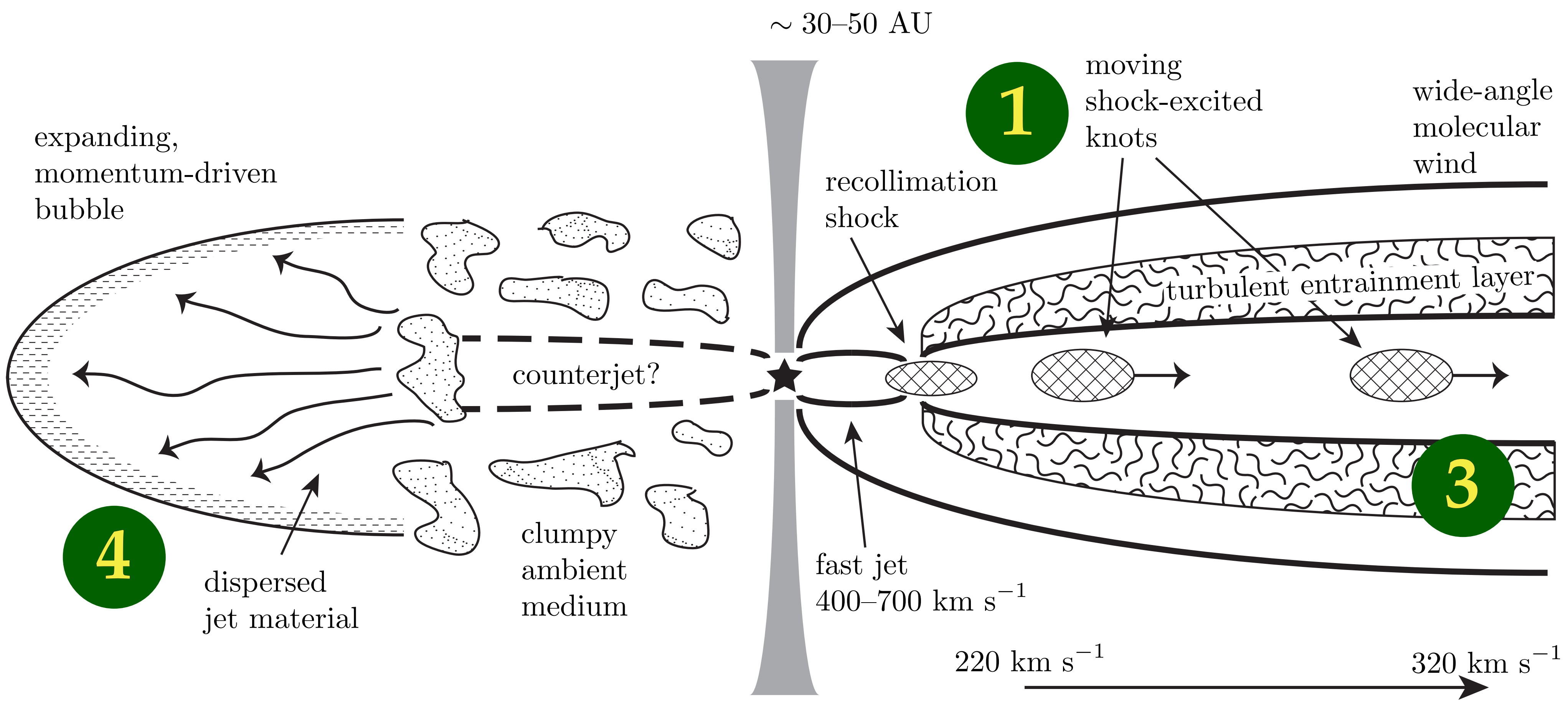
The outflows from young stellar objects provide important clues to the nature of the underlying accretion-ejection mechanism. We present unique high-resolution multi-epoch spectroimaging data of the outflows from the young stellar object DG Tauri, obtained using the Near-infrared Integral Field Spectrograph (NIFS) on Gemini North. These data reveal the presence of recollimation shocks, jet acceleration, entrainment, and bipolar outflow asymmetry, which we model to create a picture of the DG Tau system.

Observations

Stellar-subtracted extended [Fe II] 1.644 μm line emission, binned into 40 km s^{-1}-slices, velocity range indicated in white, occulting disc over central star, 2005 observing epoch



Model



220 km s^{-1} 320 km s^{-1}

coupled jet expansion-acceleration

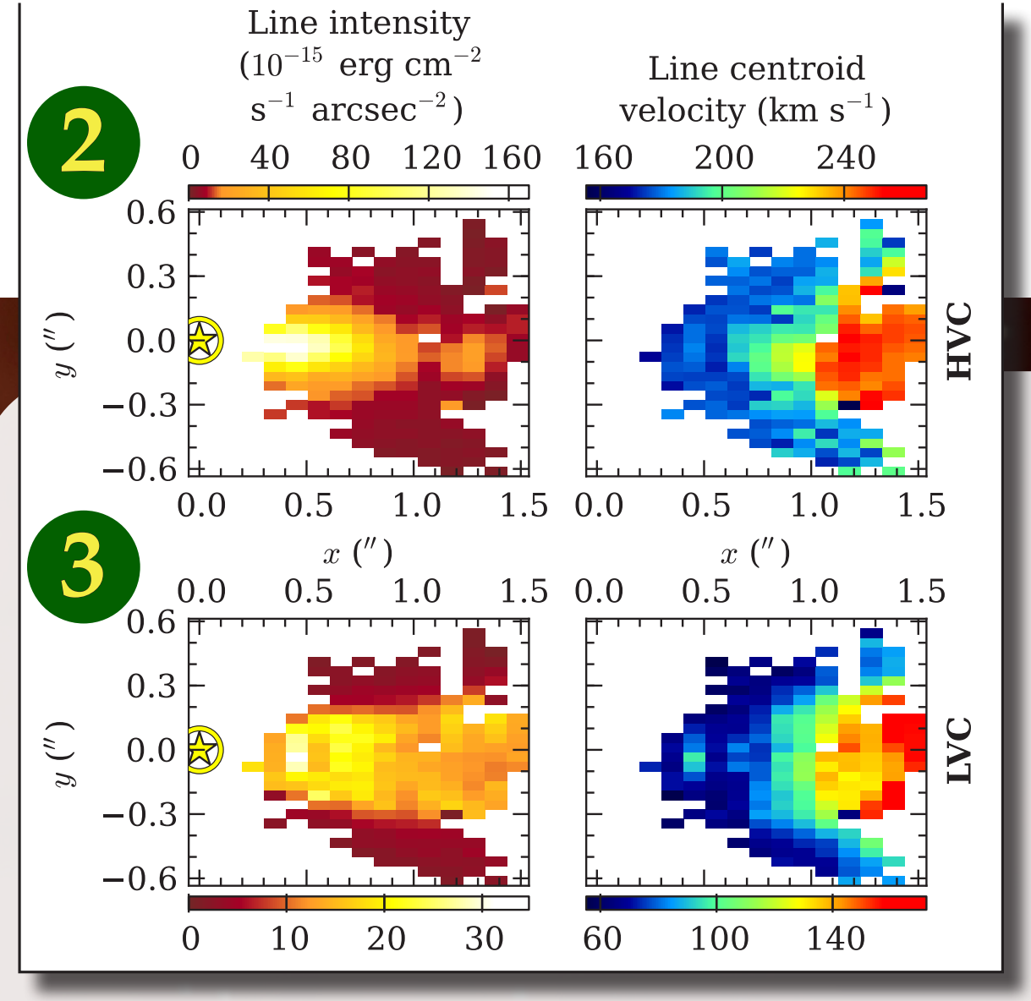
circumstellar disc

2

observer

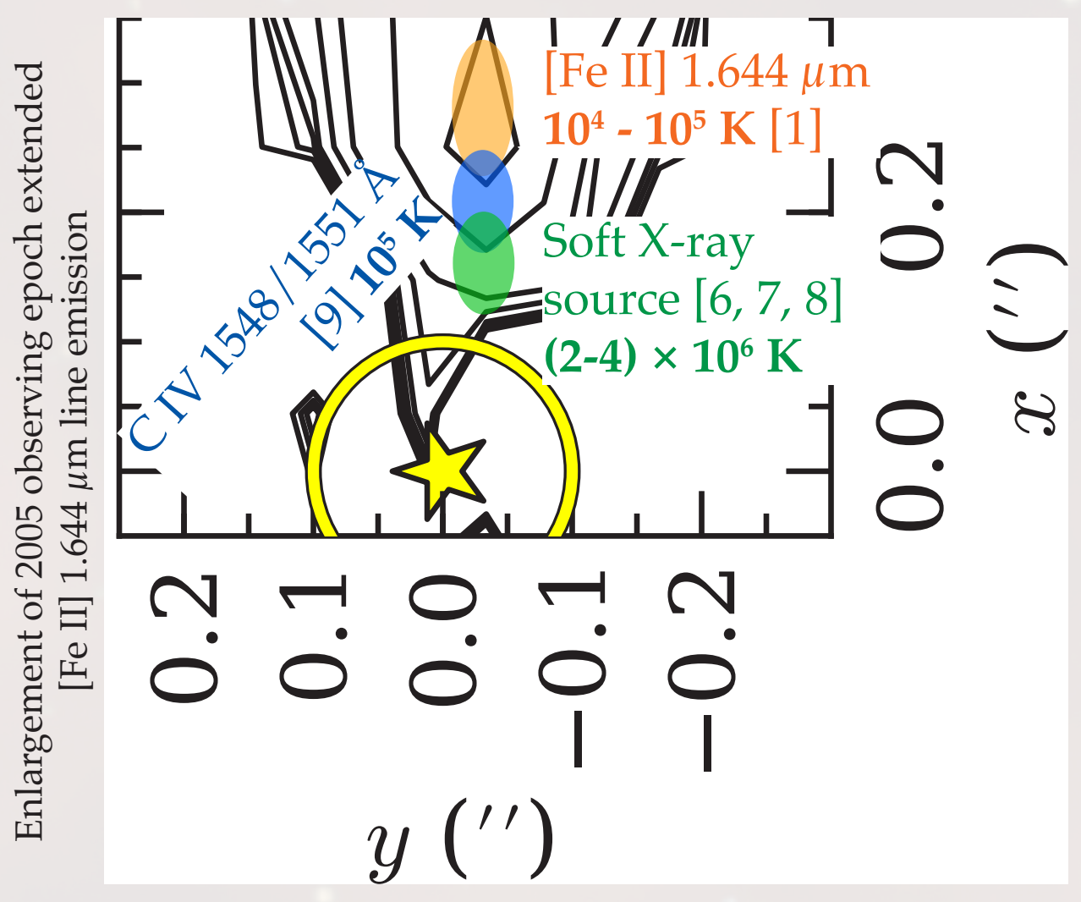
not to scale

Fits to approaching outflow components, showing jet (HVC) and entrainment layer (LVC)

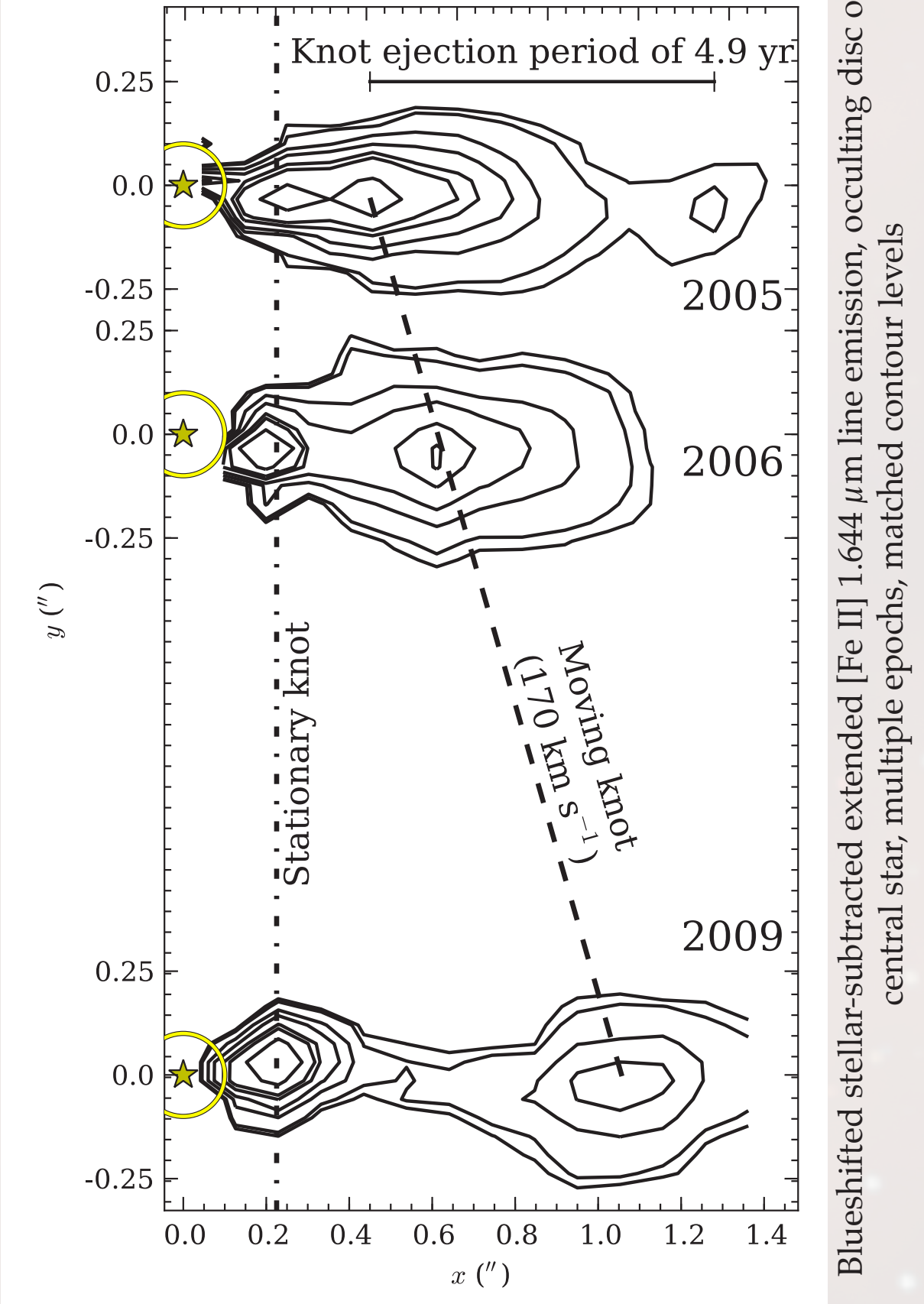


1 Stationary recollimation shock

The approaching outflow is dominated by shock-excited 'knots'. In addition, we detect the presence of a stationary knot ~ 50 AU from the central star, which we intepret to be a **jet recollimation shock** [1].



- Stationary shock feature, occurs in sufficiently fast MHD winds [4, 5]
- Magnetic collimation force exceeds centrifugal force of expanding, rotating outflow material, causing recollimation into a 'diamond shock'
- Analogous to Mach disks observed in jet engines



- X-ray [6, 7, 8] and FUV [9] observations show a stationary feature with peak temperature ≥ 10^6 K, followed by cooling over 10 - 20 AU

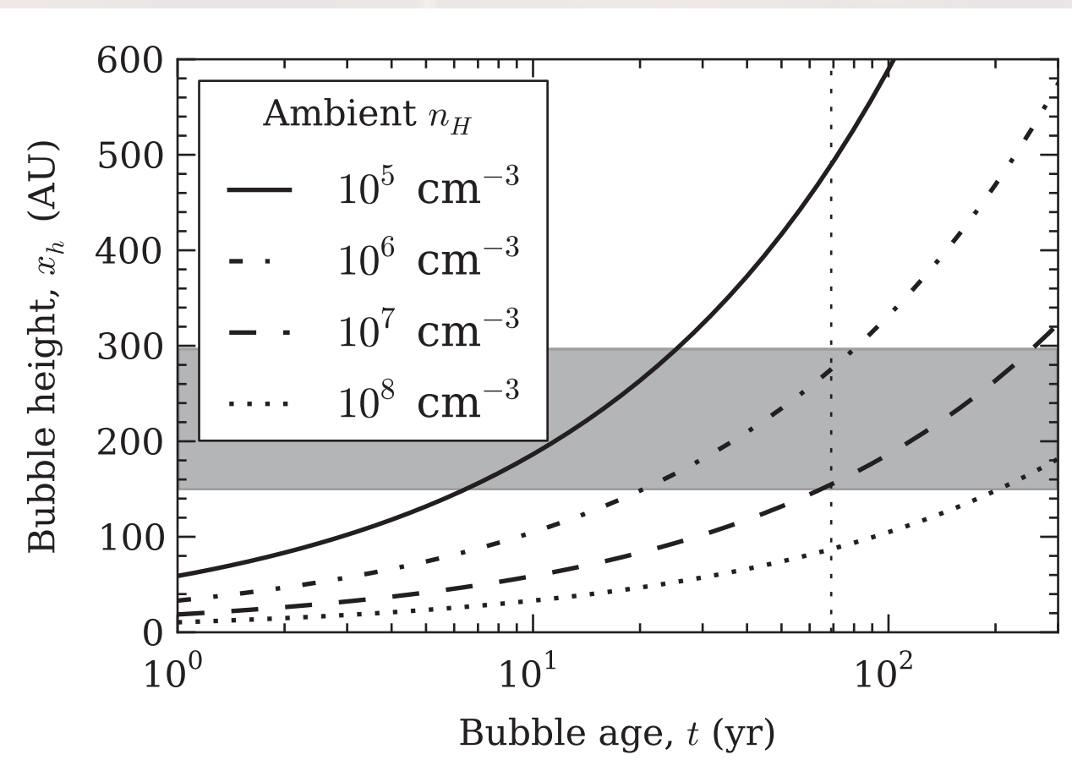
X-ray temperature implies a pre-shock gas velocity **~ 400 - 700 km s^{-1}** → Assuming an MHD wind, **high-velocity jet launched from radius 0.02 - 0.07 AU from star!** [1]

4 Receding outflow bubble

We have modeled this structure as a receding counterjet being obstructed by the flattened, clumpy molecular envelope around DG Tau [16]. The jet then creates a momentum-driven bubble [2].

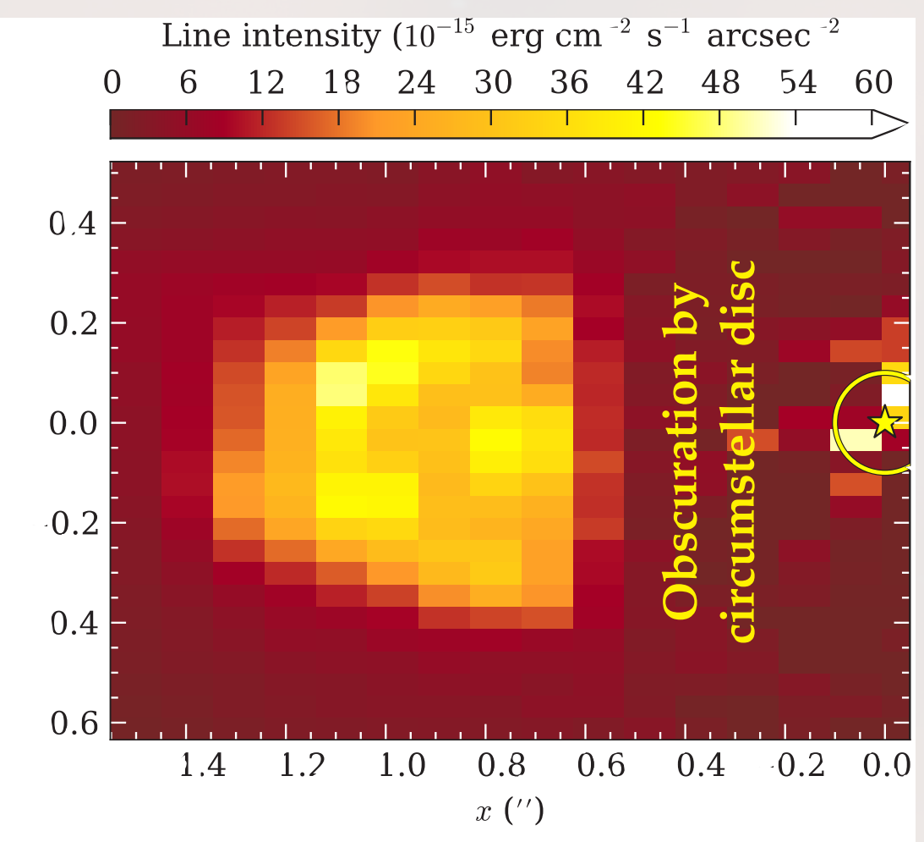
- No mixed blue/redshifted emission → cannot be a bow shock
- The jet drives a momentum-driven bubble as it searches for an 'escape path', similar to the propagation of AGN jets [17,18]
- We modify a previous momentum-driven bubble model [19]. We assume the **DG Tau system drives symmetric jets** with equal age, t, mass loss rate, $\dot{M}_j$, and velocity, v_j, and that the bubble has elongation f:

$$x_h(t) = \left(\frac{3 f^{4/3}}{\pi \sqrt[3]{2}} \sqrt{\frac{\dot{M}_j v_j}{\rho_a}} t \right)^{1/2}$$

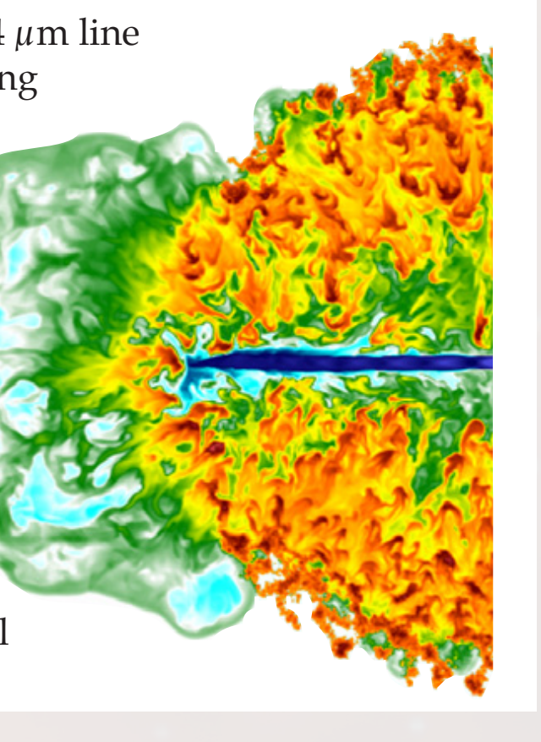


Vertical line: outflow event age as at 2005 [20]. Grey box: Range of possible bubble heights [2]

Model predicts an ambient density, ρ_A, equivalent to n_H ~ 10^6 cm^{-3} ≈ density of the extended DG Tau molecular envelope [2, 15]



Redshifted [Fe II] 1.644 μm line emission, 2005 observing epoch



Simulation of light AGN jet (blue) penetrating a warm, clumpy distribution of material (orange) [18]

Model is consistent with observations [2].
This model explains *structural* bipolar outflow asymmetries in YSOs.

Approaching outflow components were separated using multi-component Gaussian fitting. This separates the **jet** (HVC) emission from the low-velocity component (LVC), which we interpret to be a **turbulent entrainment layer**.

2 Jet kinematics and rotation

Jet shows coupled expansion-acceleration [1]

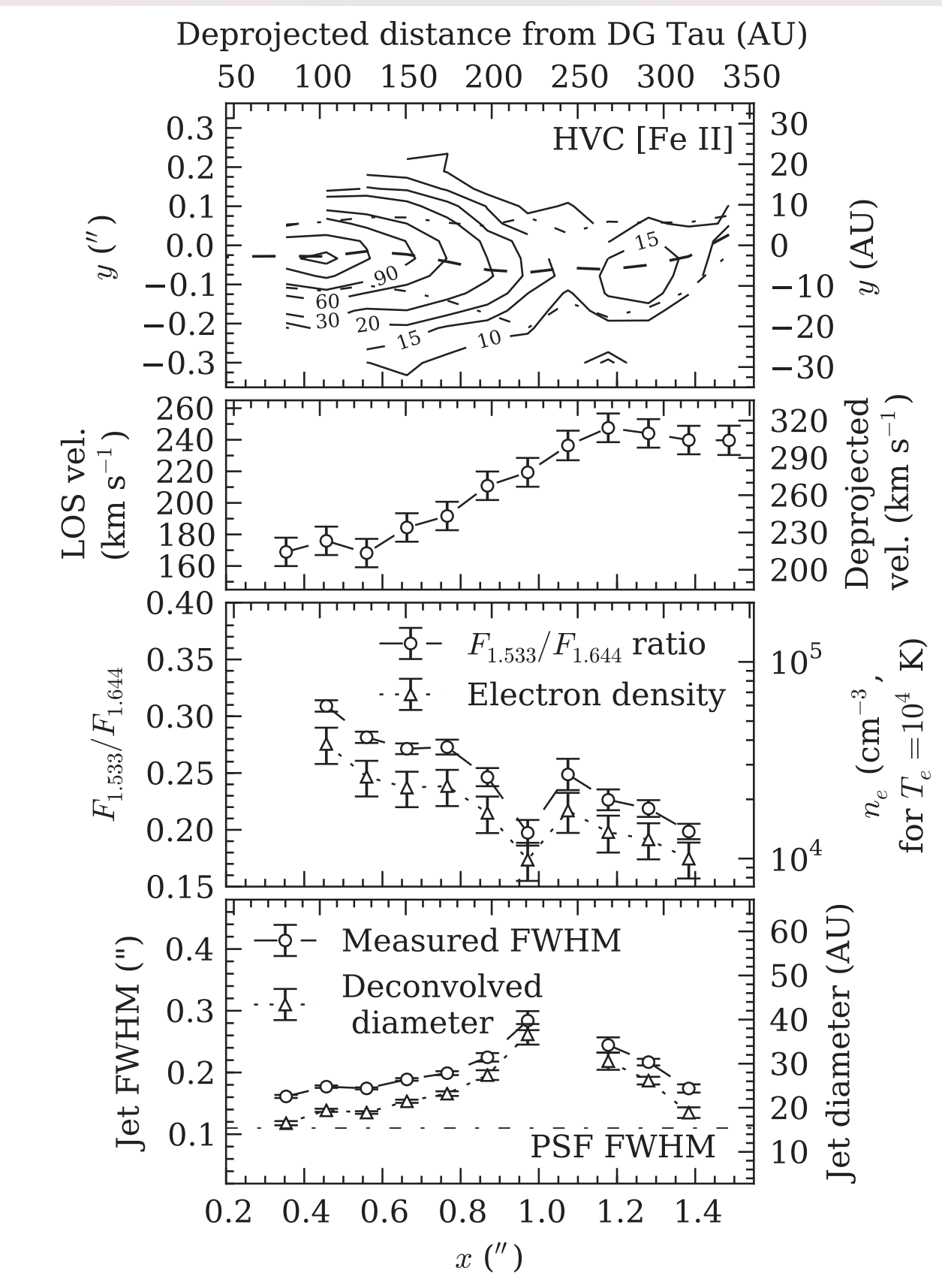
- Jet velocities inconsistent with being intrinsic variations that cause moving knots → steady-state acceleration model required
- Assuming constant jet total power L_{jet} and mass flux $\dot{M}$ (as observed), we form a magnetised Bernoulli-type equation:

$$\left(\frac{1}{2}v^2 + h + \phi\right) + \frac{B^2}{4\pi\rho}\left(1 - (\hat{\boldsymbol{v}} \cdot \hat{\boldsymbol{B}})^2\right) = \frac{L_{\rm jet}}{\dot{M}} = {\rm const.}$$

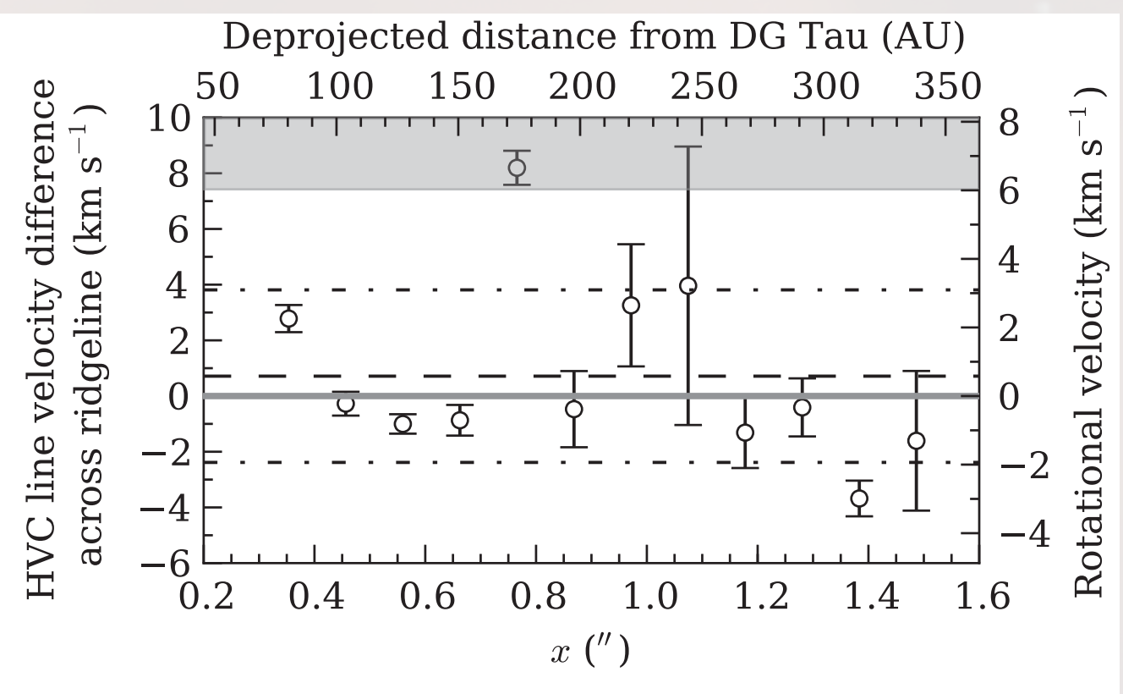
- Assume a tangled jet magnetic field $\boldsymbol{B}$, and neglect enthalpy (h) and gravity (ϕ). For the observed parameters of the DG Tau jet:

Distance from star	Jet velocity v	e^- no. density n_e ($\rho = 1.4(n_e/\chi_e) \times$ amu)	Jet diameter	Jet magnetic field $\boldsymbol{B}$
125 AU	220 km s^{-1}	2×10^4 cm^{-3}	18 AU	**46 mG**
275 AU	320 km s^{-1}	1×10^4 cm^{-3}	30 AU	**29 mG**

Magnetic field strength agrees with previous estimates of magnetic fields in protostellar outflows [1, 10]



Structure & kinematics of the approaching jet. Top panel, dashed line: jet ridgeline.



Grey box: Previous rotation claims [12]. Dashed & dot-dashed lines: average velocity difference and $\pm1\sigma$

No jet rotation observed [1]

- Jets launched from a small radius (< 0.1 AU) around the central star are not expected to show significant rotation [11]
- Passage through recollimation shock is likely to mask any rotation signal present
- Changing position of the jet centre (ridgeline) must be taken into account

3 Turbulent entrainment by the jet

- Wide-angle molecular wind provides material for jet to entrain [13]
- Toroidal magnetic field which collimates the jet destabilises the jet-wind interface to the Kelvin-Helmholtz instability [1, 14, 15]. Leads to the formation of a turbulent, shock-excited entrainment layer, producing shock-excited [Fe II] emission.
- **We have successfully modeled this entrainment process using an analytical two-dimensional 'slab' model and turbulent MHD - stay tuned!** [3]

We have modeled **coupled jet expansion-acceleration** [1] and **entrainment** [3] in the DG Tau approaching outflow. **No jet rotation** is observed [1]. Passage through the recollimation shock **slows** the jet and **concentrates** the magnetic field, leaving the jet susceptible to these processes [1].

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