Title: Arcs, Cavities, and Outflows: The Dynamic Drama of Star Formation

Speakers: Shantanu Basu

Collection/Series: Cosmology and Gravitation

Subject: Cosmology

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Abstract:

We are now firmly within the ALMA-inspired era of star formation studies. We have abundant high sensitivity and resolution observations of star-disk-outflow systems as well as the ability to perform complex high-resolution plasma astrophysics simulations of their formation. I review recent three-dimensional nonideal MHD simulations that reveal surprising new insights into the role of magnetic fields and magnetic field dissipation in creating outflows, arcs, and cavities on scales of hundreds to thousands of au. Magnetic fields are responsible for a complex inflow-outflow structure around a protostar. I end the talk with results that may answer the longstanding big question in star formation studies: what stops the mass infall on to a protostar?

Arcs, Cavities, and Outflows: The Dynamic Drama of Star Formation

- SHANTANU BASU
- Perimeter Institute
- 15 April 2025

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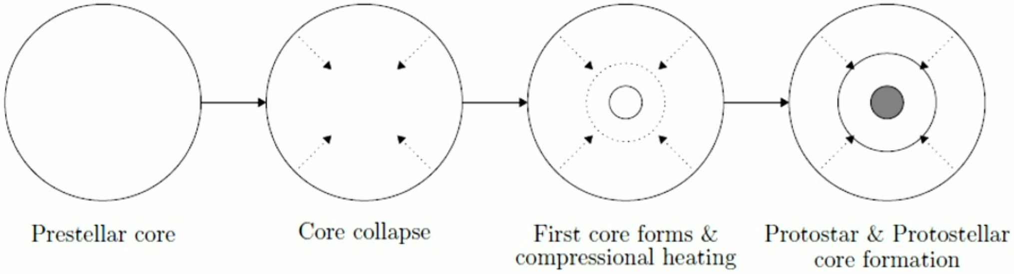
Classical views of Star Formation

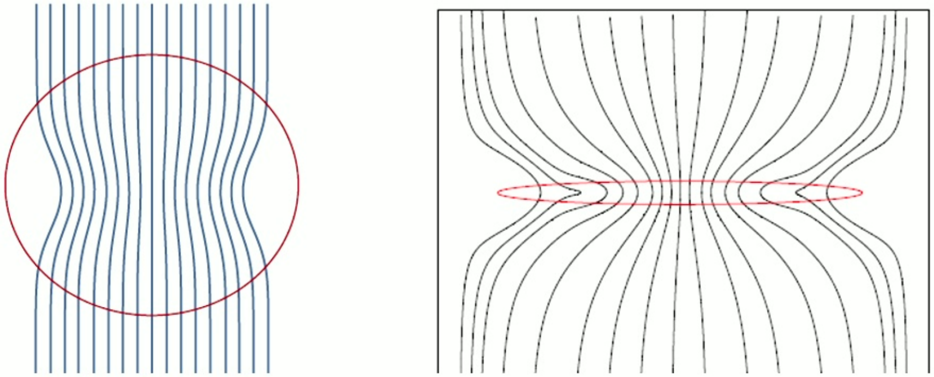


Prestellar core

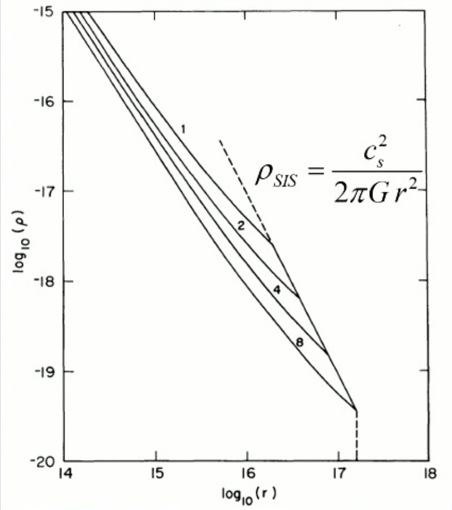
Core collapse

First core forms & compressional heating

Protostar & Protostellar core formation



Star Formation as Accretion Process



Shu (1977) – once a central point mass (protostar) is formed, the layers of gas above fall in successively.

Mass accretion rate to central star is

$$\frac{dM}{dt} \simeq \frac{c_s^3}{G},$$

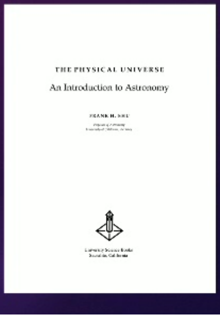
c_s = isothermal sound speed

But when does accretion stop?

"It is clear that the fundamental question of the masses of forming protostars has not been answered by any of the spherical gravitational collapse calculations performed to date - including the present one."

Frank Shu (1943 – 2023)

https://memorial.asiaa.sinica.edu.tw/frankshu/wall.html



THE PHYSICAL UNIVERSE
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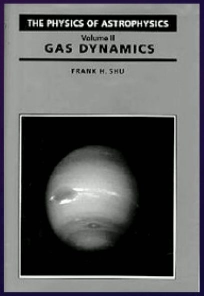

THE PHYSICS OF ASTROPHYSICS
Volume II
GAS DYNAMICS
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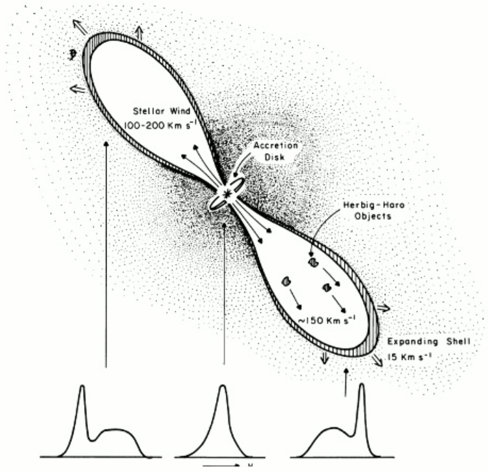

OBSERVATIONS OF CO IN L1551: EVIDENCE FOR STELLAR WIND DRIVEN SHOCKS

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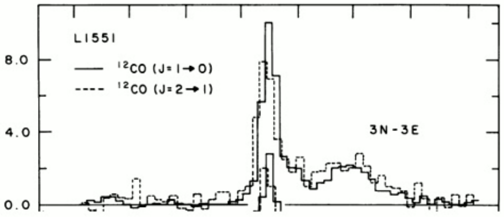
Received 1980 January 17; accepted 1980 March 28

ABSTRACT

CO observations reveal the presence of a remarkable, double-lobed structure in the molecular cloud L1551. The two lobes extend for ~0.5 pc in opposite directions from an infrared source buried within the cloud; one lobe is associated with the Herbig-Haro objects HH28, HH29, and HH102. We suggest that the CO emission in the double-lobed structure arises from a dense shell of material which has been swept up by a strong stellar wind from the infrared source. This wind has a velocity of ~200 km s^{-1}, and evidently is channeled into two oppositely directed streams. The CO observations indicate that the shell has a velocity of ~15 km s^{-1}, a mass of 0.3 $M_\odot$, and a kinetic temperature of 8–35 K. Its age is roughly 3×10^4 years. A stellar mass-loss rate of $\sim 8 \times 10^{-7}\ M_\odot\ yr^{-1}$ would be sufficient to create such a shell.

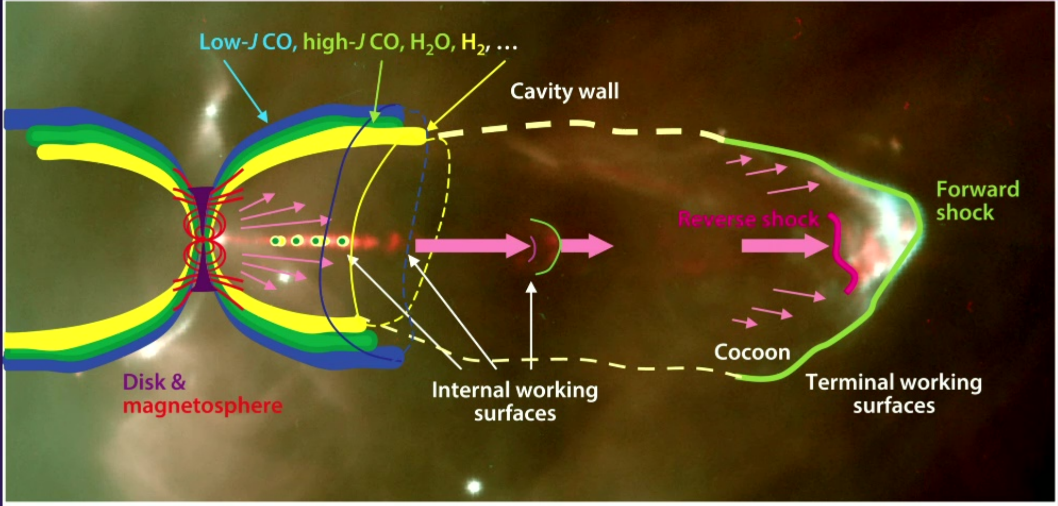
Subject headings: infrared: sources — interstellar: molecules — shock waves — stars: winds



Discovery of Outflows

SNELL, LOREN, PLAMBECK, 1980, APJ, 239, L17

Launch and Collimation



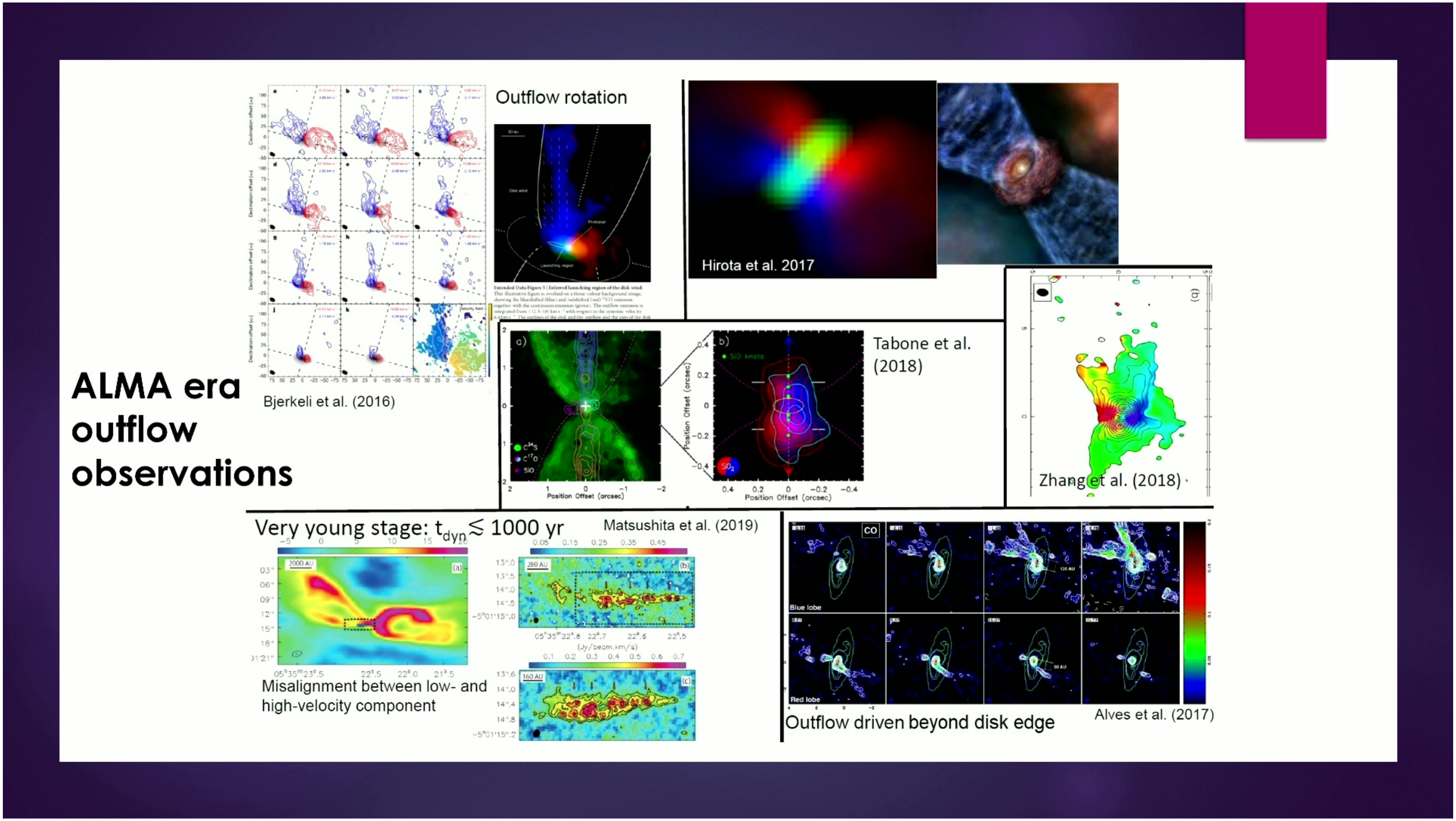
Bally J. 2016.
Annu. Rev. Astron. Astrophys. 54:491–528

The jets and wide-angle winds inflate an ever-widening cavity in the cloud, sweeping up, shocking, and accelerating shells of gas until they break out of their parent cloud envelopes

Propagation to large distances laterally and along axis, > 1000 au

Evidence of a high-speed central jet (~ 100s km/s)

Also a wide-angle wind (~10s km/s)



ALMA era outflow observations

Bjerkeli et al. (2016)

Outflow rotation

Hirota et al. 2017

Tabone et al. (2018)

Zhang et al. (2018)

Very young stage: $t_{dyn} \lesssim 1000$ yr

Matsushita et al. (2019)

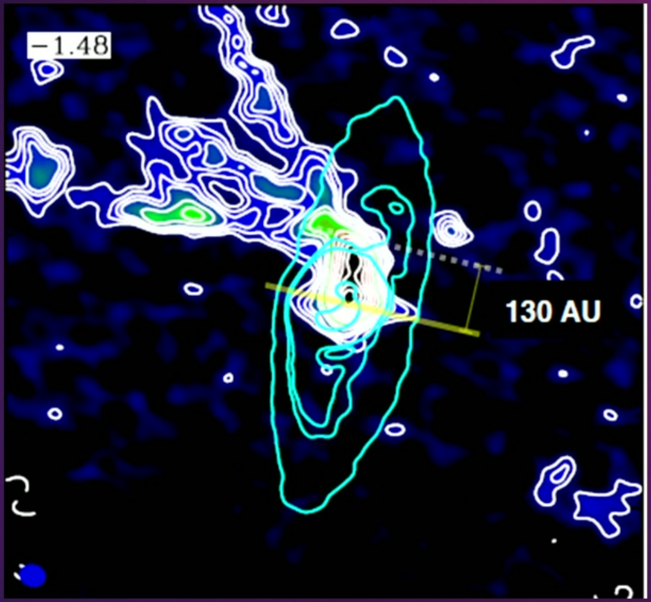
Misalignment between low- and high-velocity component

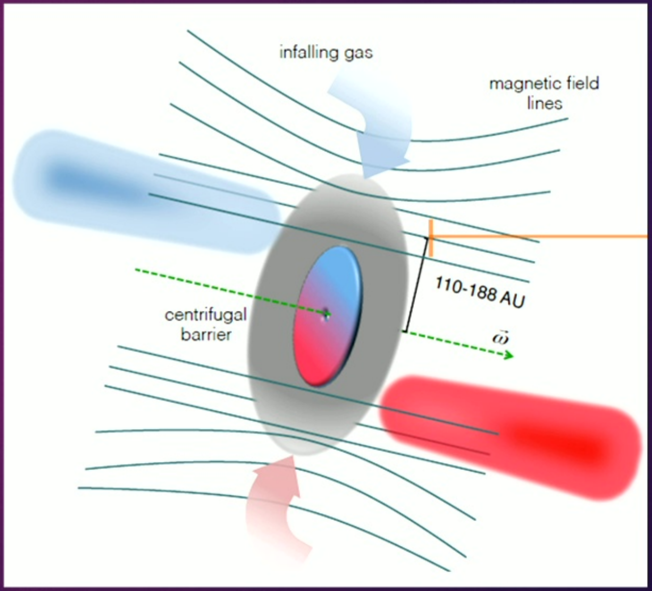
Outflow driven beyond disk edge

Alves et al. (2017)

Molecular outflow launched beyond the disk edge

F. O. Alves[1], J. M. Girart[2], P. Caselli[1], G. A. P. Franco[3], B. Zhao[1], W. H. T. Vlemmings[4], M. G. Evans[5], and L. Ricci[6]

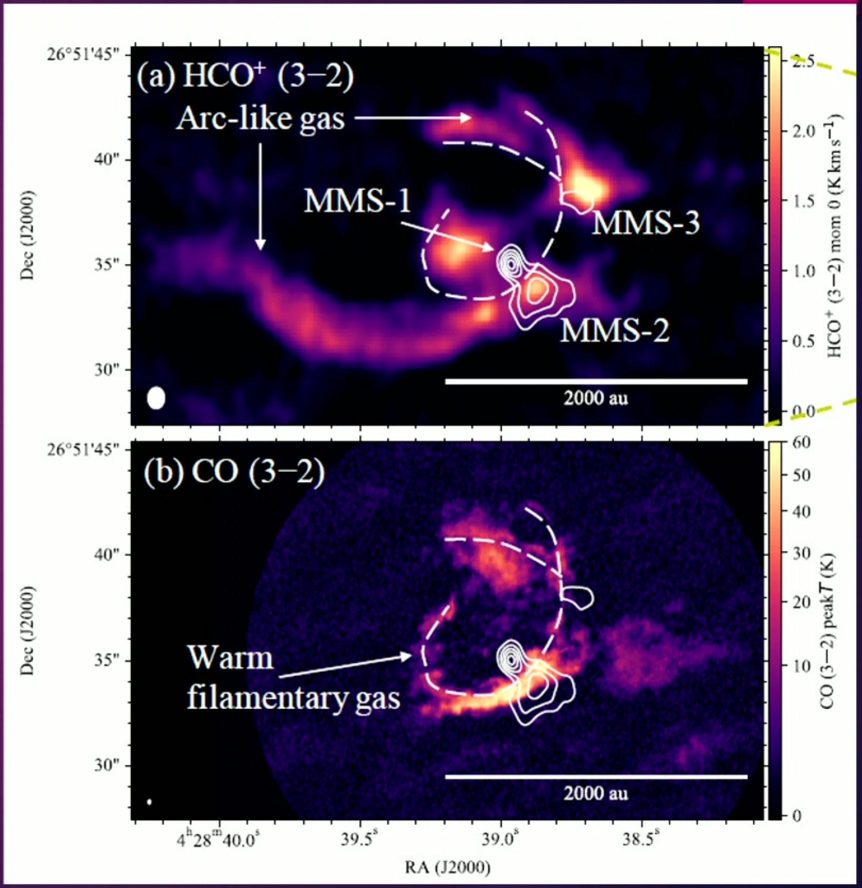




Alves et al. (2017)

Arcs and Rings

- ➢ Seen on ~ 1000 au scales (Tokuda et al. 2018, 2023, 2024; Pineda et al. 2022)
- ➢ Evidence for turbulent initial conditions?



Tokuda et al. (2024)

Why does accretion end?

Finite mass reservoir? BUT…

- Star formation efficiency ~ 1% in molecular clouds
- Dense core masses several to tens M_{sun}
- Core boundaries hard to identify

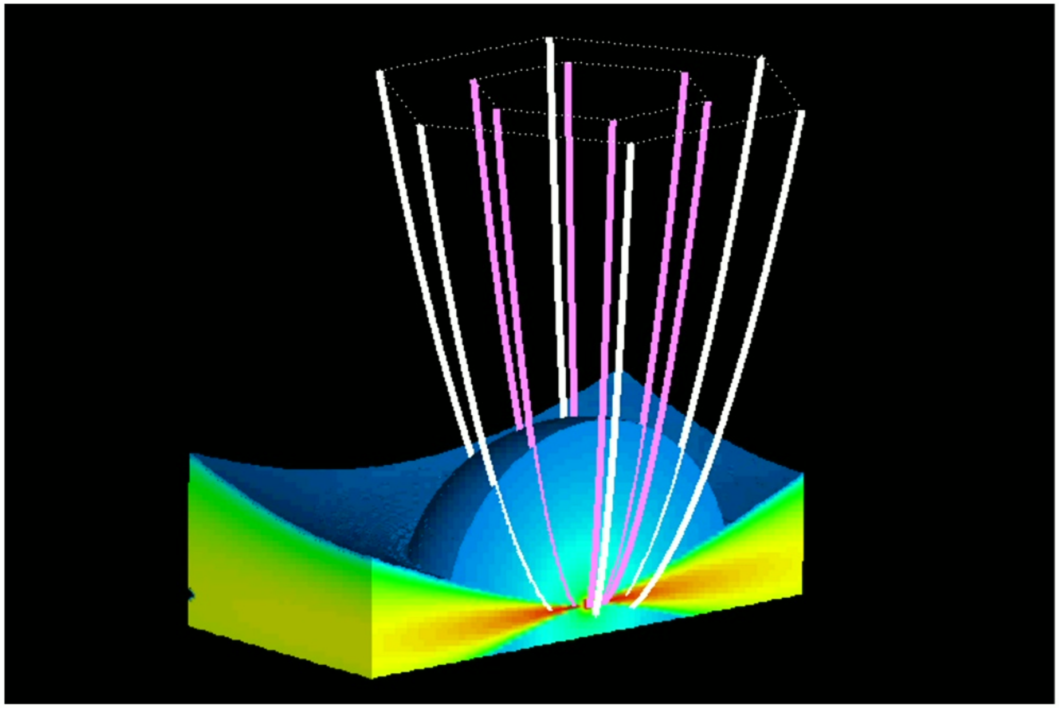
Why does accretion end?

Wide angle winds? But can they

- Carry away significant mass and angular momentum?
- Stop accretion across all 4 π steradians?

Magnetic Launching

- Rotation plus magnetic field leads to outflow launch
- Driven by pressure of twisted magnetic field lines (**tower flow – low signal speed**), **OR**
- Driven by flinging outward along FLs (**magnetocentrifugal flow – high signal speed**)



Simulation by Kudoh, Matsumoto, & Shibata

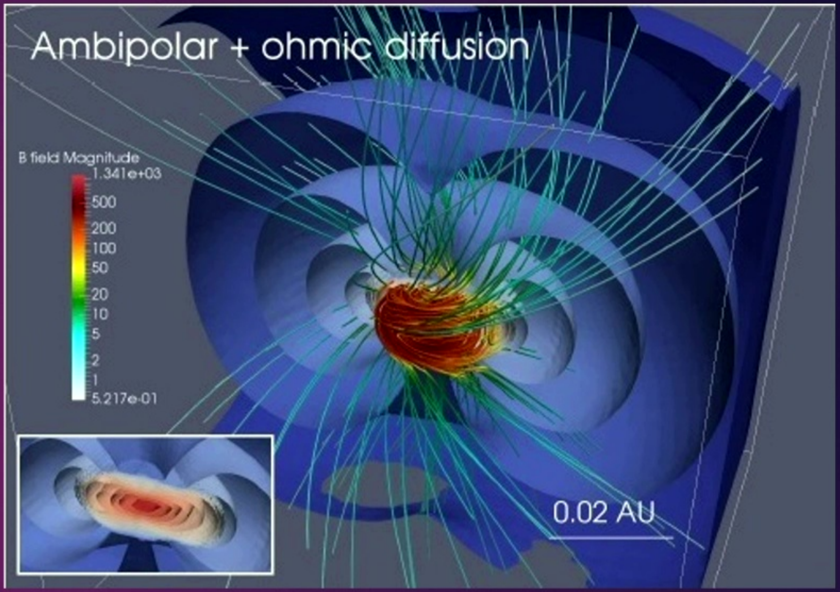
Signal speed is Alfvén speed

$$v_A = \frac{B}{\sqrt{4\pi\rho}}$$

Computational Challenges

- ➢ In principle, need to resolve the protostar itself
- ➢ But the time step of calculation becomes very short as the spatial resolution improves
- ➢ Current simulations can only get a short time past protostar formation

Vaytet et al. (2018)

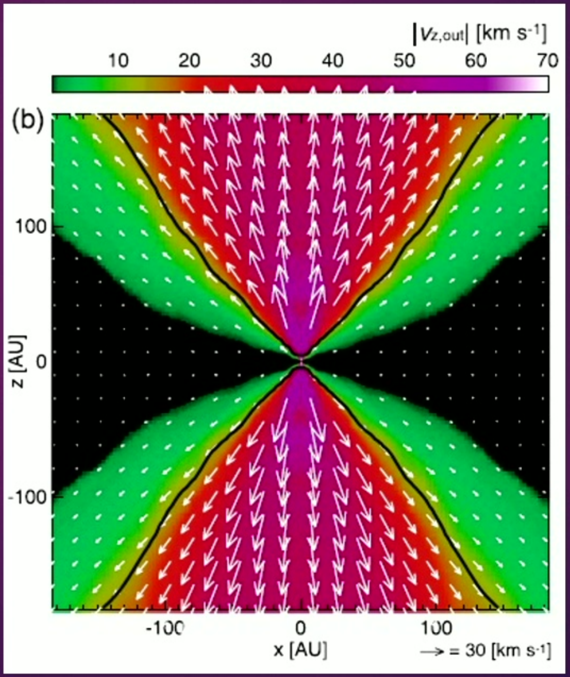


This calculation stops only ~ 1 month after protostar formation.

Longest calculation with no sink

Resolve protostar formation, progress as far as 2000 yr past its formation.

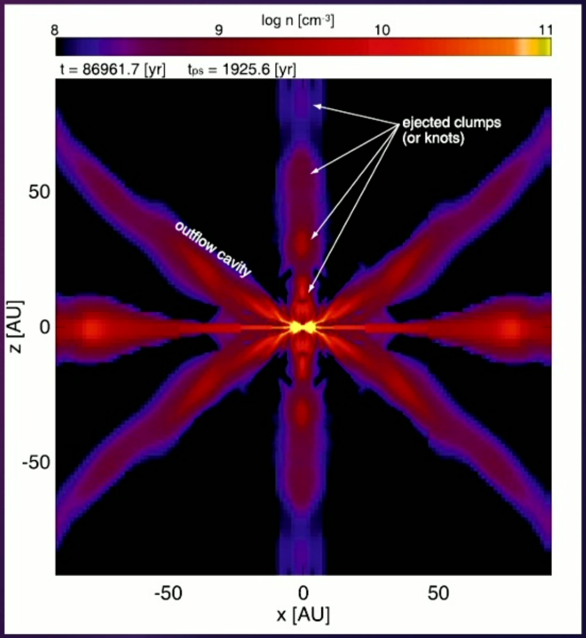
- A weak outflow < 10 km s^{-1} from outer disk region
- A strong jet 10 – 100 km s^{-1} from inner region near protostar
- Variability in accretion rate → knots in outflow

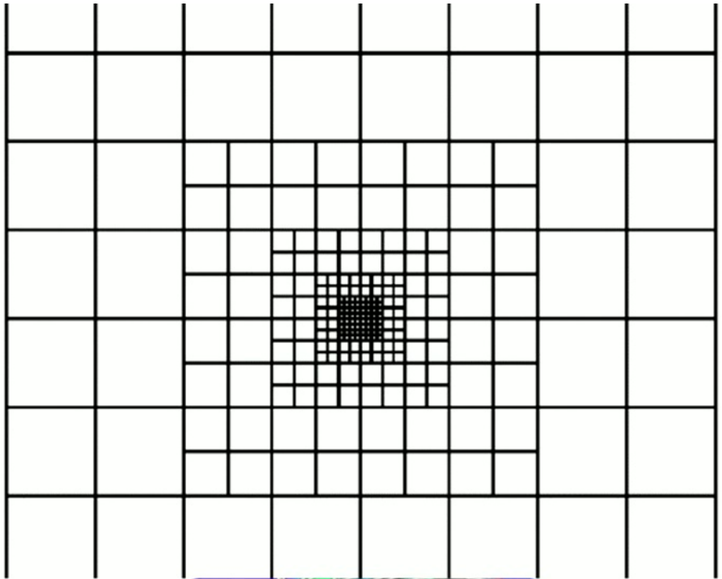


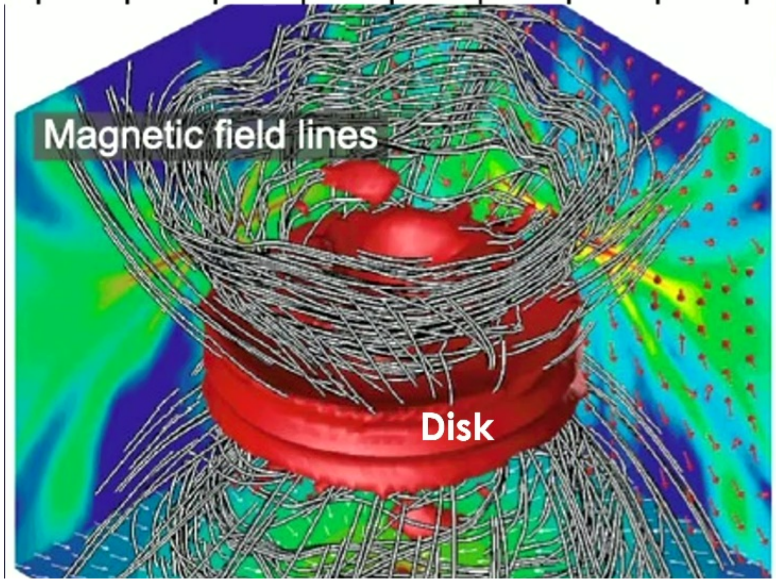
Machida & Basu (2019)

$t_{ps} \simeq 2000$ yr

$M_{star} \simeq 0.04\, M_{sun}$





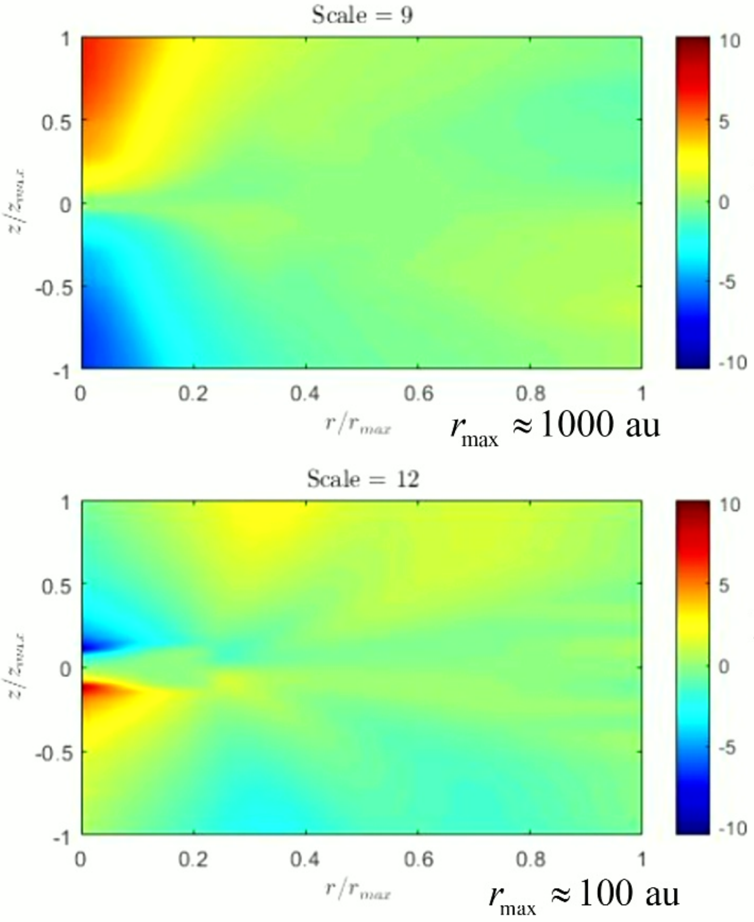


Nested Grid Nonideal MHD

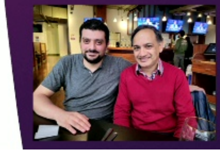
- Code introduced by Machida, Inutsuka, Matsumoto (2006, 2008). Up to 21 levels of refinement and 64^3 in each level
- Initially an isothermal sphere at level L5 embedded in a uniform medium. Typically run with initial solid body rotation and uniform magnetic field
- Central sink cell. Assign mass within a central cell of size 2 au to a central point mass. Allows long-term calculation
- Resolve the disk and outflow zone
- Investigate launch mechanism of the wide-angle low velocity wind
- Inner jet launching not resolved

First Look at Results

Heat maps of v_z, km/s



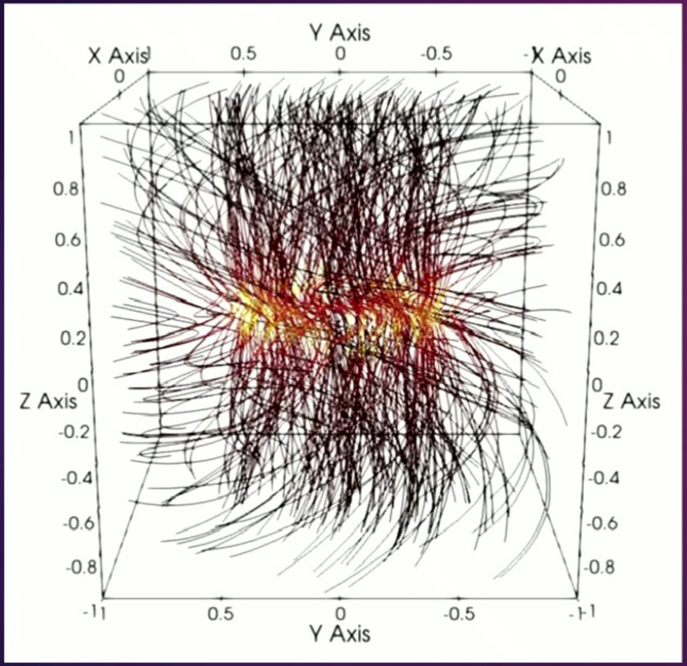
- Time 26 kyr after protostar formation – Class 0 phase
- Inflow-outflow conundrum above the central protostar
- Upward motion at large heights above protostar, but downward motion at low heights



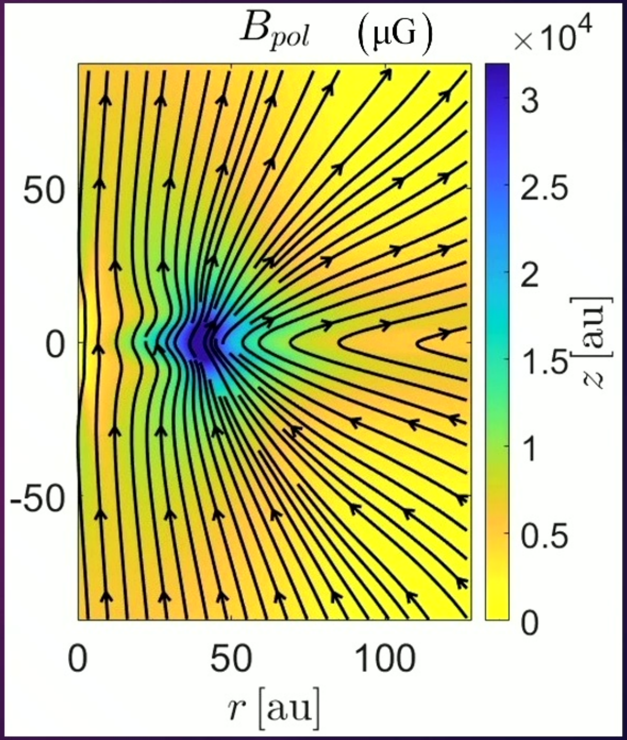
Simplify the Analysis

3D Cartesian → cylindrical azimuthal average

Full magnetic field

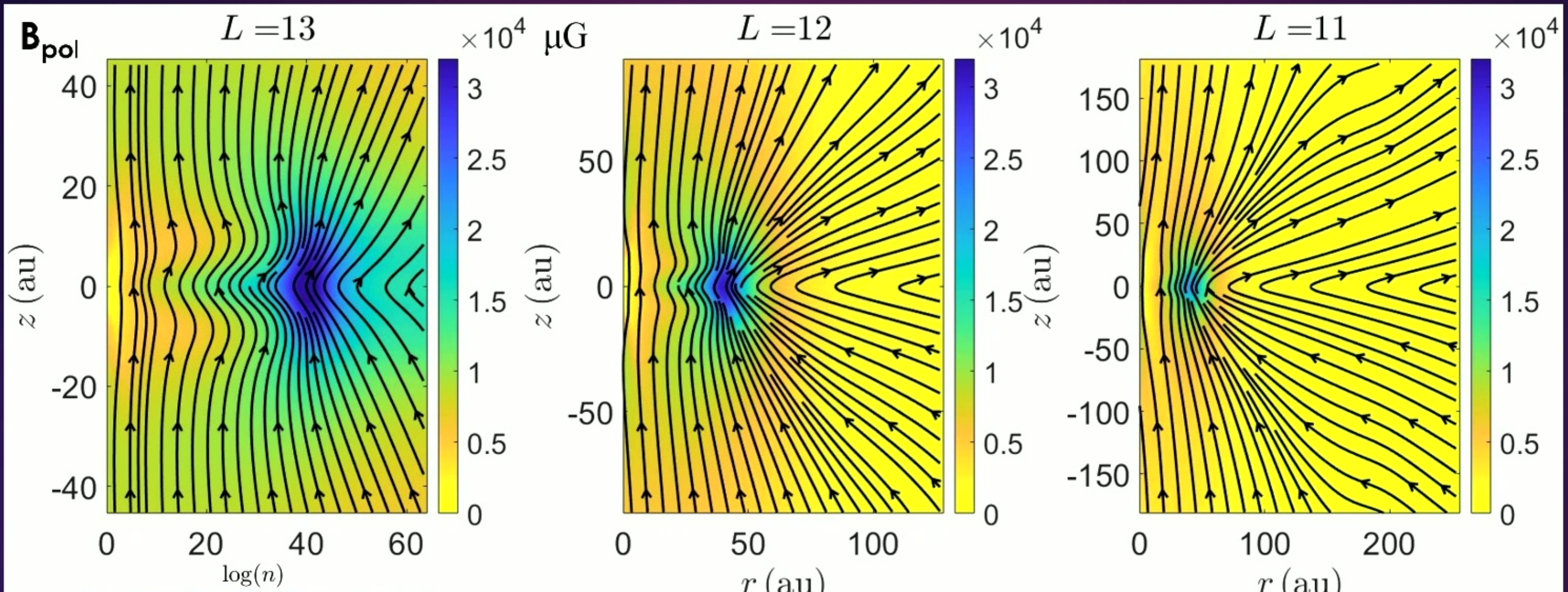


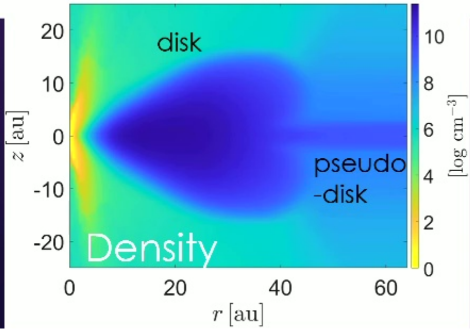
Angle averaged poloidal field



Basu, Sharkawi, Machida (2024)

Magnetic Field (poloidal: B_r, B_z)



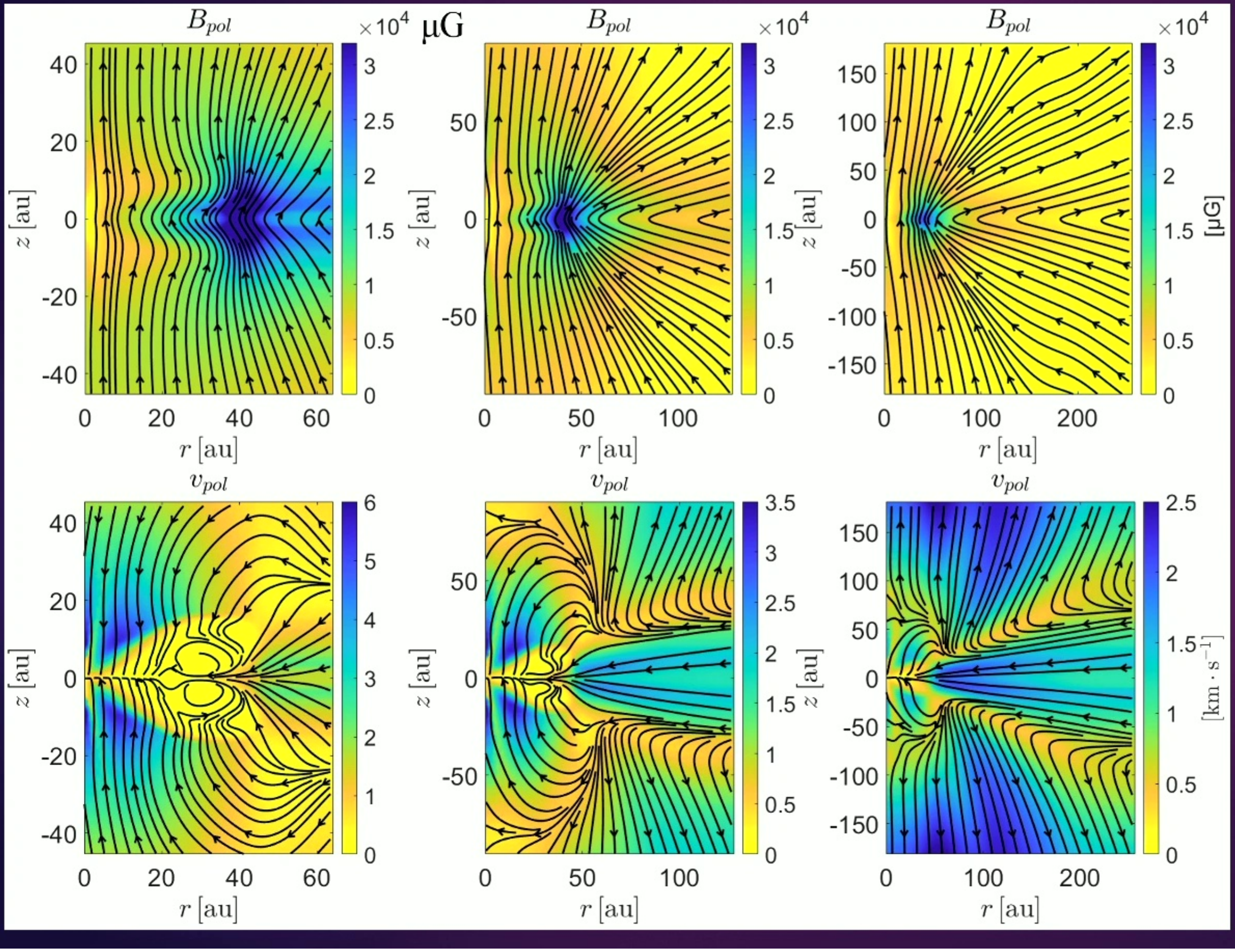


Poloidal magnetic field heat map and vectors.

The field diffuses outward in the disk.

Field strength peaks at disk edge. Sharply flared poloidal field just outside. Straighter field lines inside disk – due to Ohmic dissipation, i.e., resistivity.

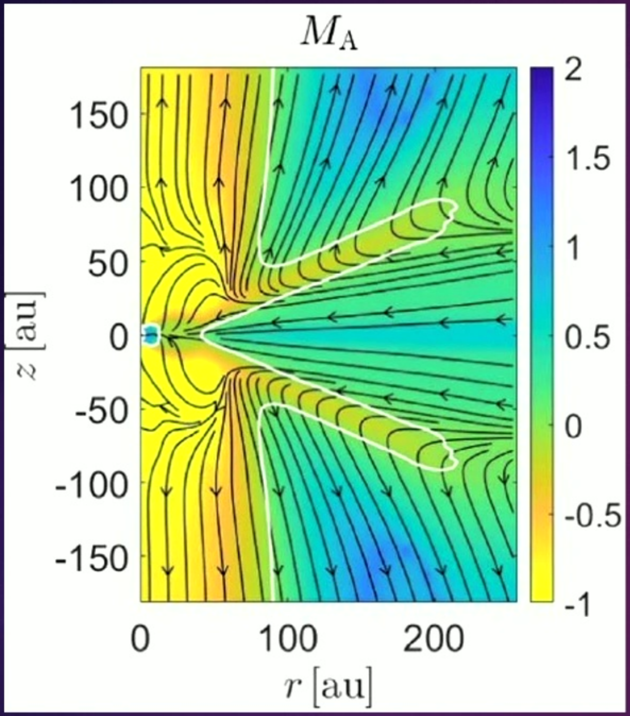
It’s a Pseudodisk-wind!

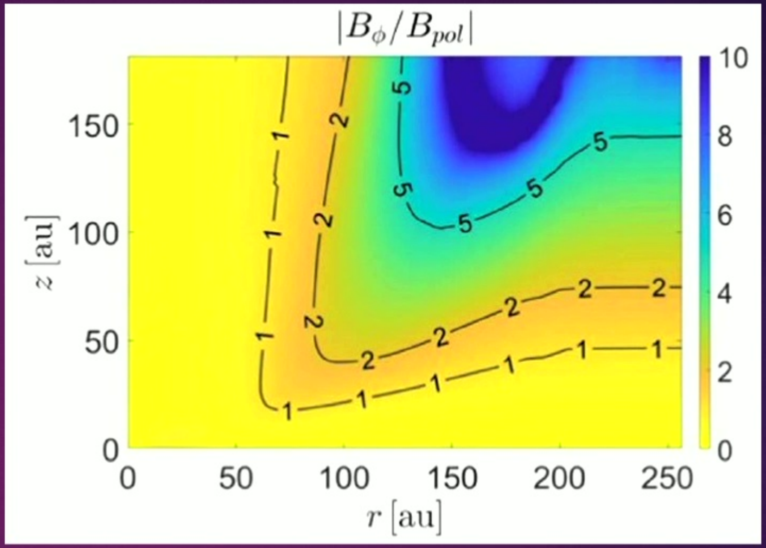


Poloidal magnetic field B_{pol} is diffused inside the disk; does not launch an outflow.

Poloidal velocity field. Wind launched from outside the disk, removes ~ 1/3 infalling mass. The disk itself experiences mass infall.

Elements of tower and magnetocentrifugal flows



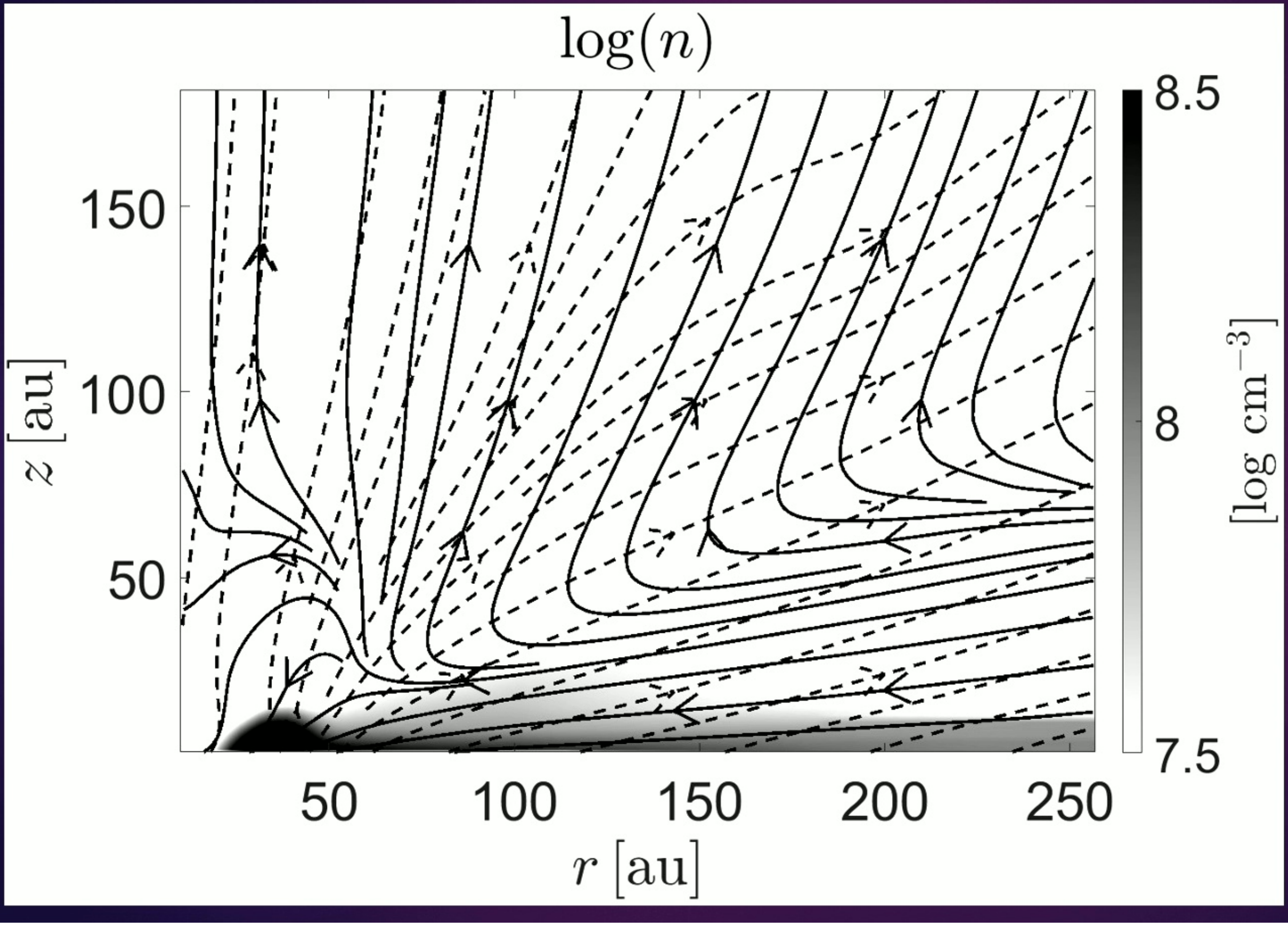


B_ϕ/B_z increases rapidly above Alfvén surface.

Alfvén surface shown by white line.

Launch angle can be greater than the canonical 60° from horizontal if launched from pseudodisk (see Basu et al. 2024 for proof).

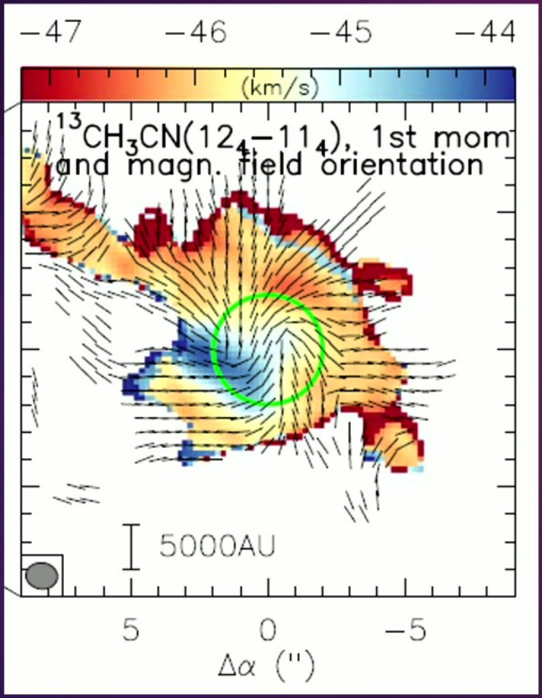
Misalignment of v and B



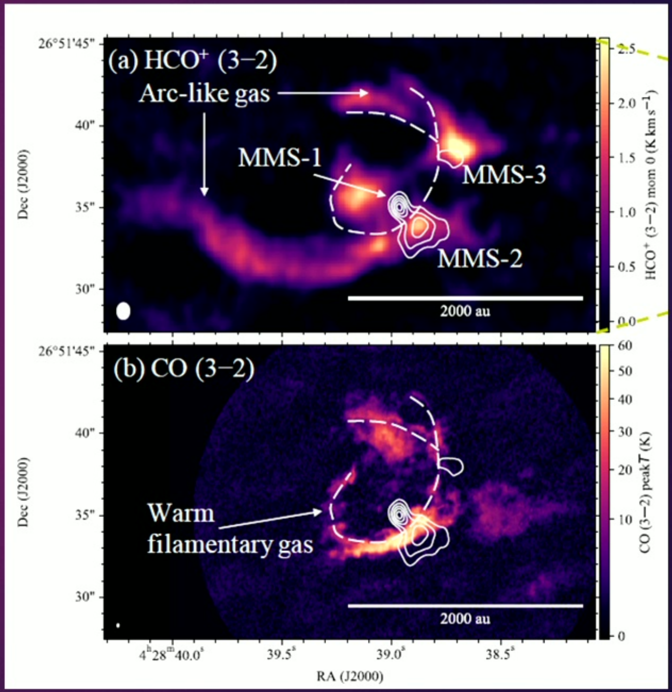
Poloidal velocity field (solid) and poloidal magnetic field (dashed) do NOT align.

Infall motion contributes to misalignment.

What about the complex observed structures?



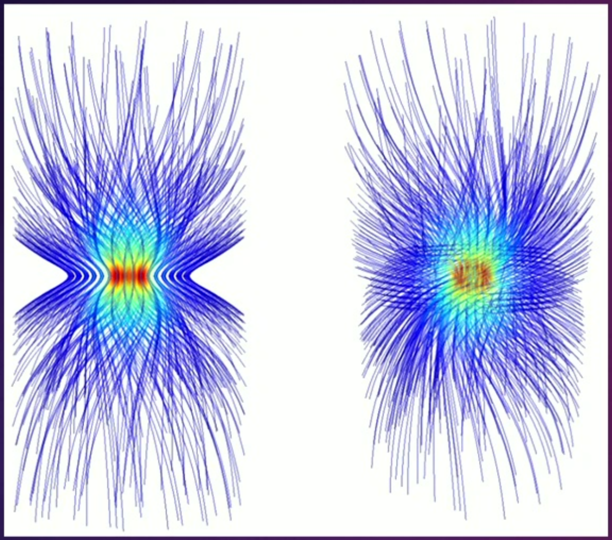
Beuther et al. (2020)



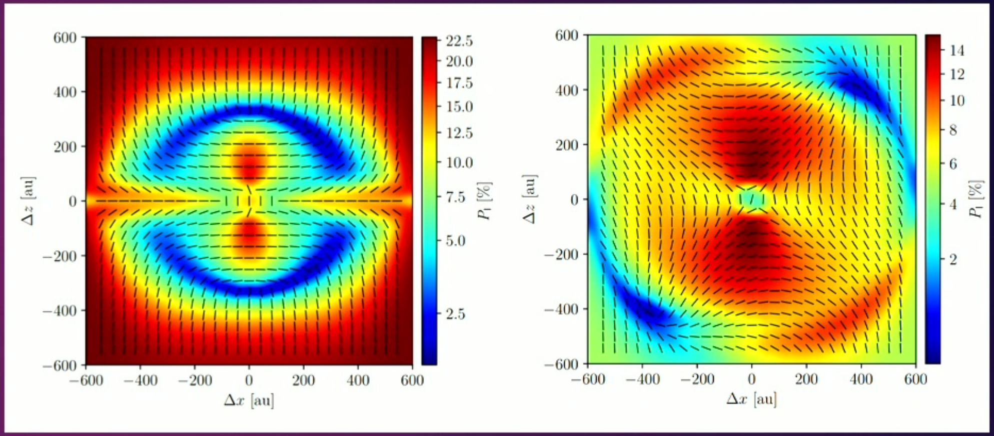
Tokuda et al. (2024)

“Observed” B field can be complex

Analytic model of 3D protostellar magnetic field viewed through emergent polarized mm emission using POLARIS code (Reissl et al. 2016).

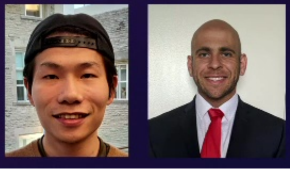


$\theta = \pi/2$ $\theta = \pi/3$

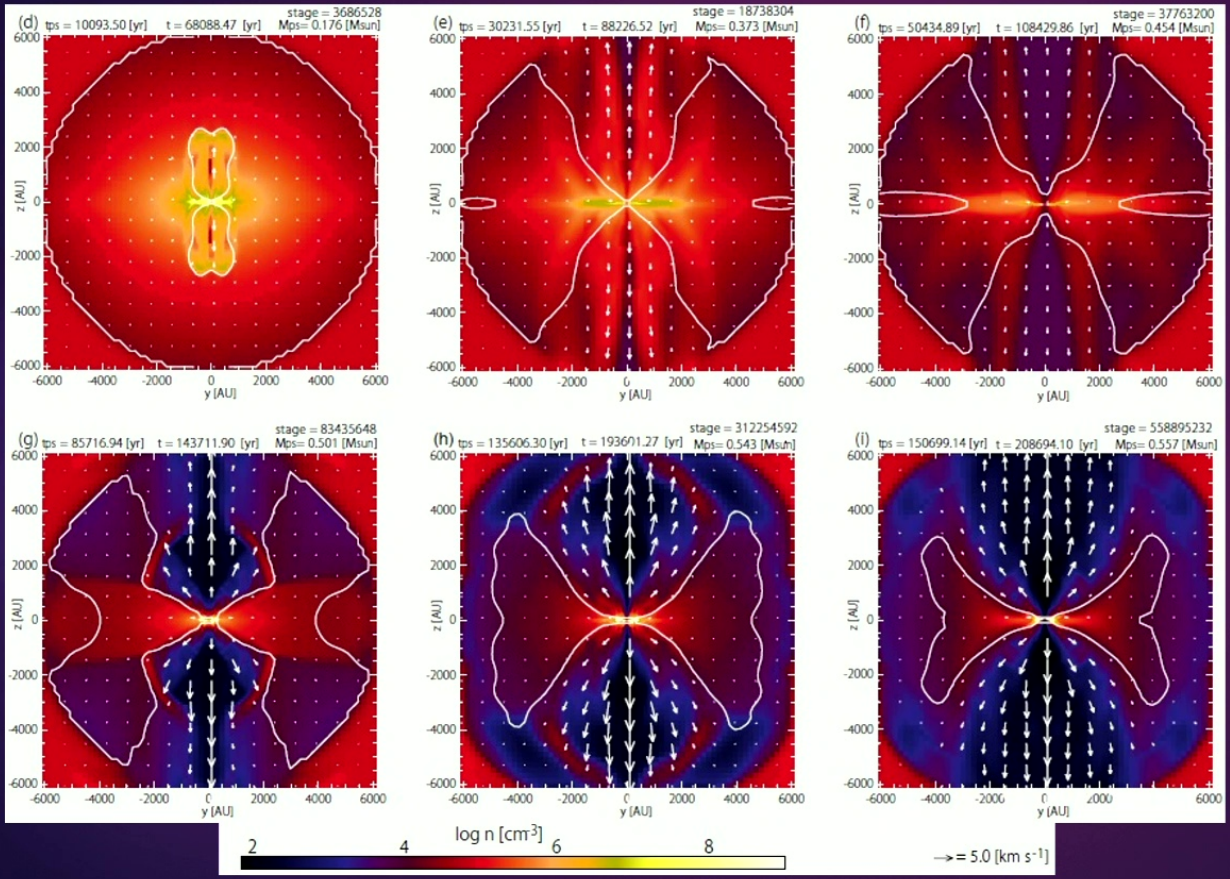


$\theta = \pi/2$ $\theta = \pi/3$

Basu, Li, Bino (2024)



Extend to later times, ~ 1.5 x 10^5 yr

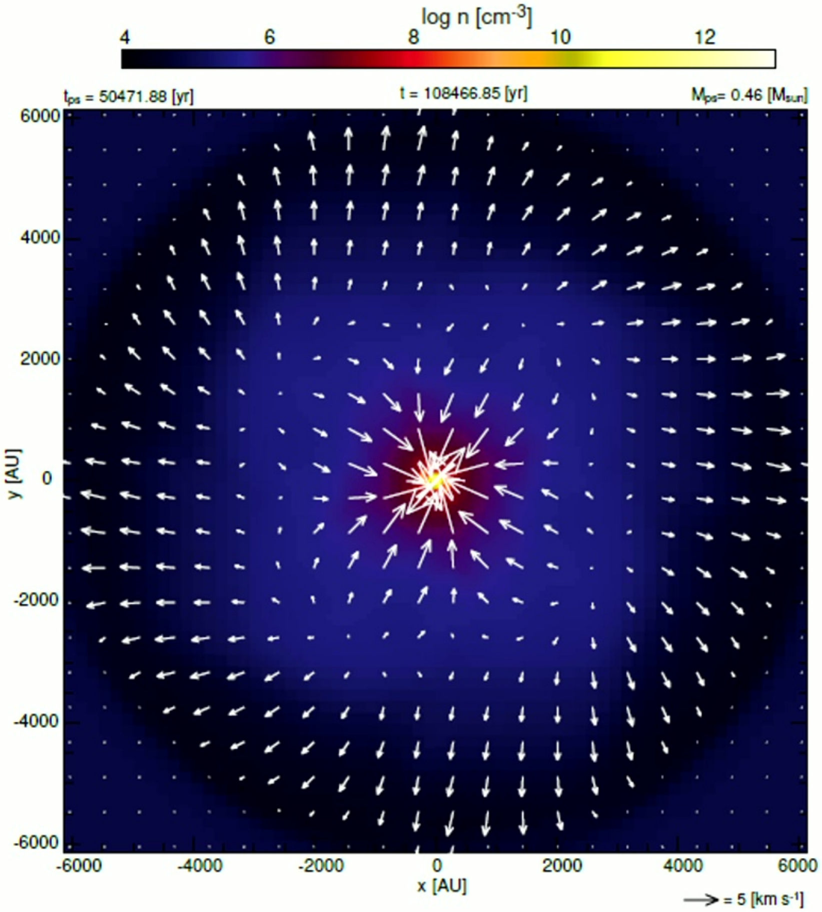


Early times, up to t_{ps}=50 kyr. Pseudodisk wind.

Later times, after 70 kyr. Disk wind finally appears after cavity is created. Ablation, not entrainment.

White lines enclose region of infall.

Machida & Basu (2024)



Equatorial plane

How does accretion end?

- The equatorial flow at t_{ps} = 50 kyr and beyond
- A reversal of flow in the equatorial plane!
- Outer layers moving outward – **outflow has eliminated gravitational binding**

Machida & Basu (2024)

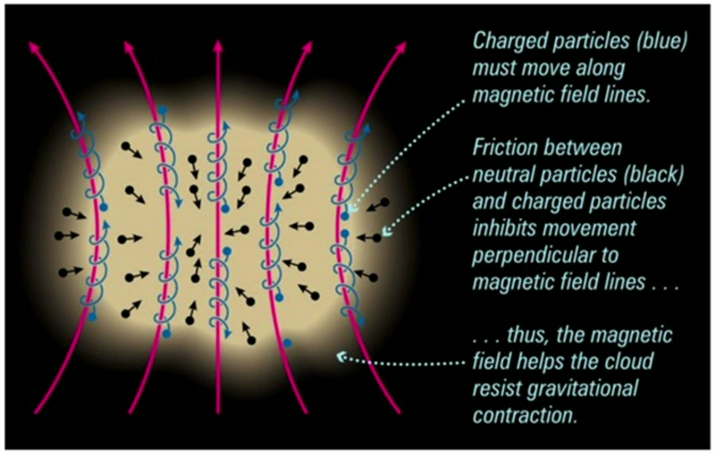
Run a model with additional B support

Machida & Basu (2025)

- ➢ Transcritical case - initial mass-to-flux ratio

$$\mu \equiv \frac{M}{\Phi}\left(2\pi G^{1/2}\right) = 1$$

- ➢ Neutral-ion slip (ambipolar diffusion) initiates collapse



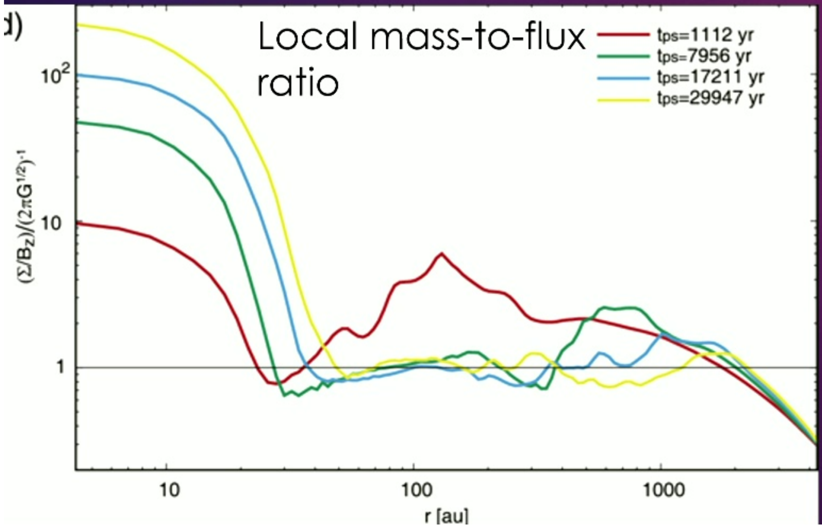
Charged particles (blue) must move along magnetic field lines.

Friction between neutral particles (black) and charged particles inhibits movement perpendicular to magnetic field lines . . .

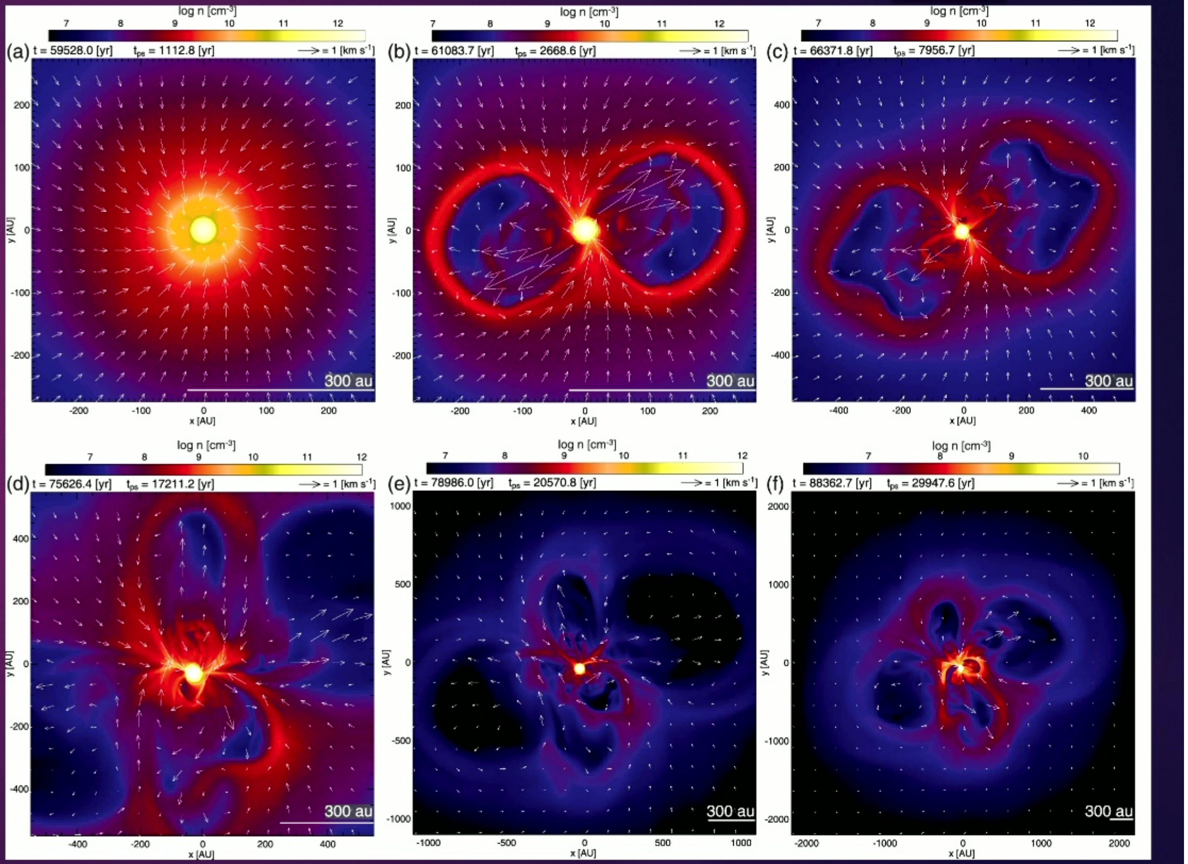
. . . thus, the magnetic field helps the cloud resist gravitational contraction.

Interchange Instability

- Radial inversion of mass-to-flux ratio leads to outgoing cavities and ring structures → a redistribution of magnetic flux

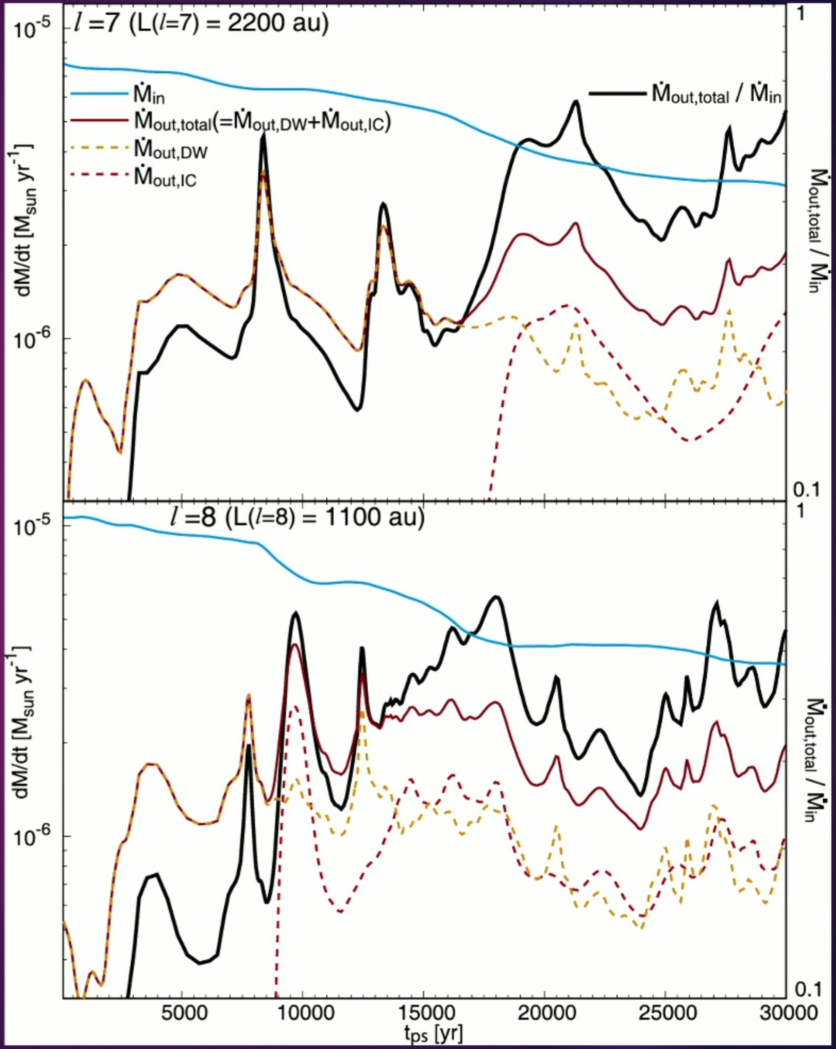


Local mass-to-flux ratio



Wind outflow vs. Interchange outflow

- Have comparable strength during the early embedded (class 0) phase



Summary / Key Takeaways

- ➢ High-resolution 3D simulations are revealing new physical phenomena in star-disk-outflow systems
- ➢ Complex structures may correspond to some of the ALMA observed arcs, shells, etc.
- ➢ Newest results yield equatorial outflows -- leading us to answer the longstanding issue of accretion termination

Thank you!