Outflow Launching and Protostellar Evolution with Episodic Mass Accretion Histories

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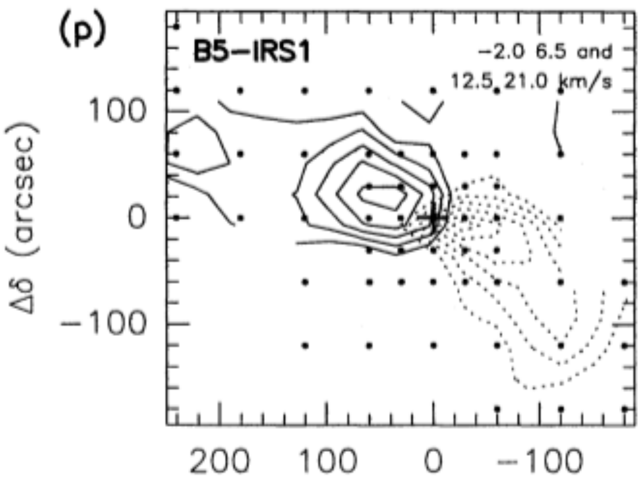
Ref) Machida & Hosokawa, 2013, MNRAS, 431, 1719

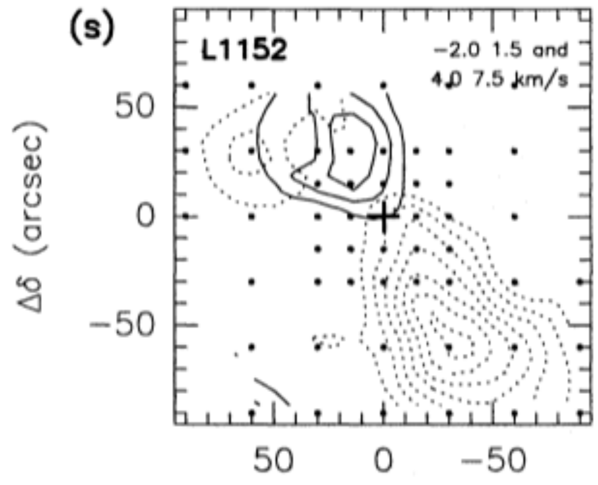
Protostars & Planets VI @ Heidelberg

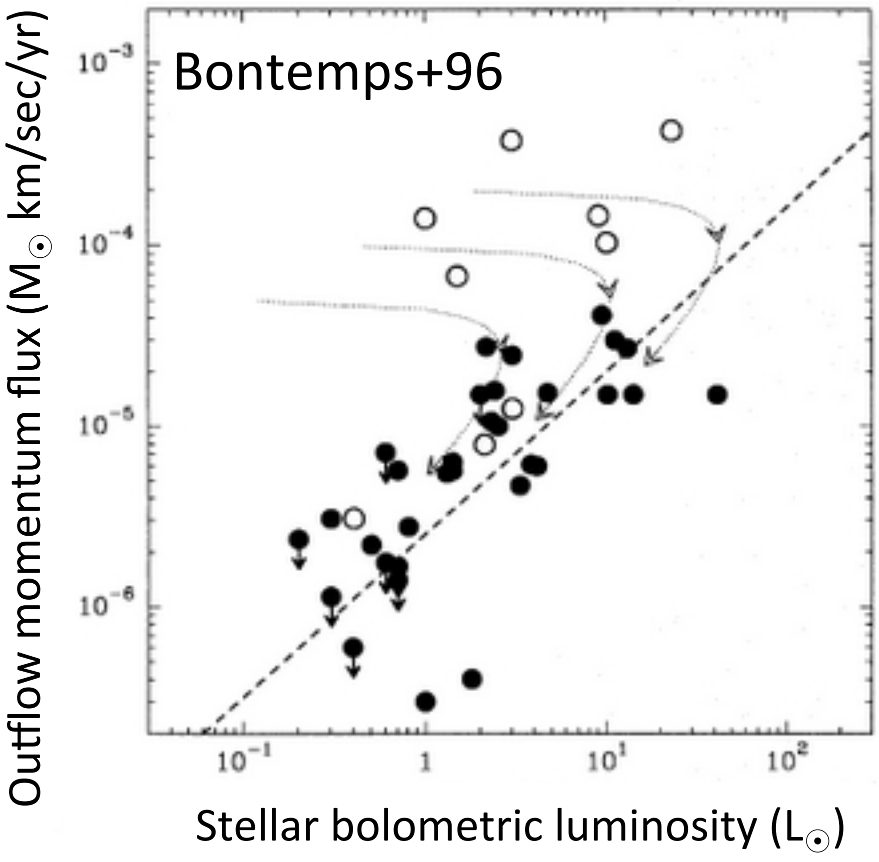
ABSTRACT

The evolution of the outflow is followed with resistive magnetohydrodynamic nested-grid simulations that cover a wide range of spatial scale (1 AU -- 1 pc). We follow the cloud evolution from the prestellar core stage until the infalling envelope dissipates long after the protostar formation. We also calculate the protostellar evolution to derive the protostellar luminosity with time-dependent mass accretion through a circumstellar disk. The protostellar outflow is driven by the first core before the protostar formation, and directly driven by the circumstellar disk after the protostar formation. The opening angle of the outflow is large in Class 0 stage. A large fraction of the cloud mass is ejected in this stage, which reduces the star formation efficiency down to < 50 %. After the outflow breaks out of the natal cloud, the outflow collimation is gradually improved in Class I stage. The head of the outflow travels over 10^5 AU in 10^5 yr. The outflow momentum, energy, and mass derived in our calculations agree well with observations. Our simulations also show the same correlations between the outflow momentum flux, protostellar luminosity, and envelope mass as seen in observations. These correlations differ between Class 0 and I stages, which is explained by different evolutionary stages of the outflow; in Class 0 stage the outflow is powered by the accreting mass and acquires its momentum from the infalling envelope, and in Class I stage the outflow enters the momentum-driven snow-plow phase. Our results suggest that the protostellar outflow should determine the final stellar mass and significantly affect the early evolution of the low-mass protostars.

Protostellar Evolution *v.s.* Outflow





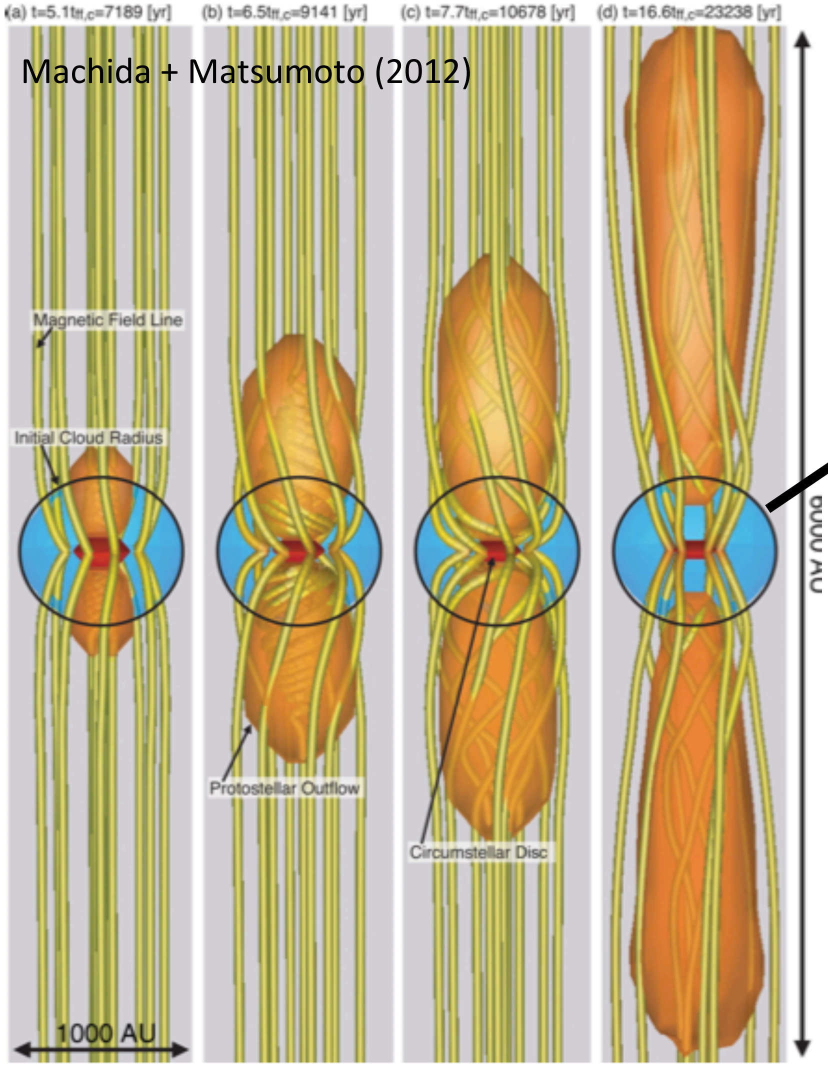


Correlation between the stellar luminosity and outflow momentum flux

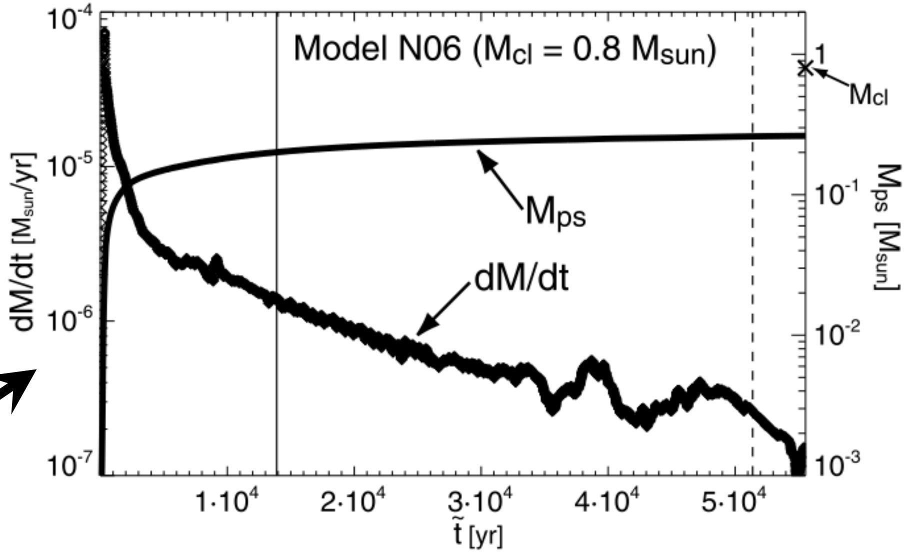
Theoretical tracks?

MHD Simulations

State-of-the-art MHD simulations now follow the launching and long-term evolution of the protostellar outflows.



Machida + Matsumoto (2012)



stellar mass increases with the time-dependent mass accretion rates

How is this related to the protostellar evolution?

Let's see it combining the MHD simulations and stellar evolution calculations!

Stellar Evolution Calculations

Basic eq. :
4 stellar structure eqs.

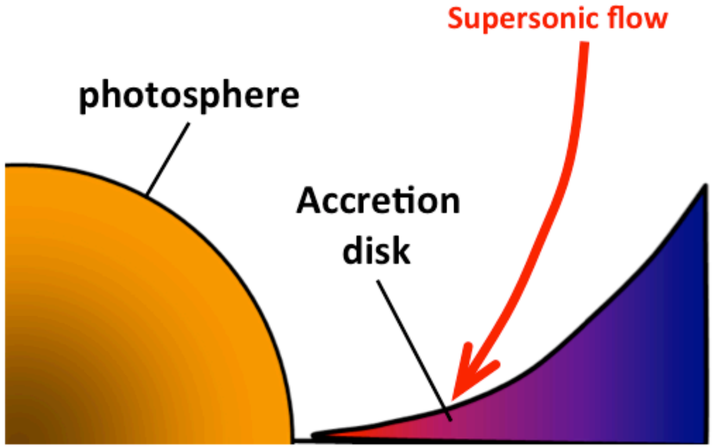
Continuity : $\frac{\partial r}{\partial m} = \frac{1}{4\pi \rho r^2}$

Energy : $\frac{\partial l}{\partial m} = \epsilon_{\mathrm{nuc}} + T\left(\frac{\partial s}{\partial t}\right)_m$

Momentum : $\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4}$

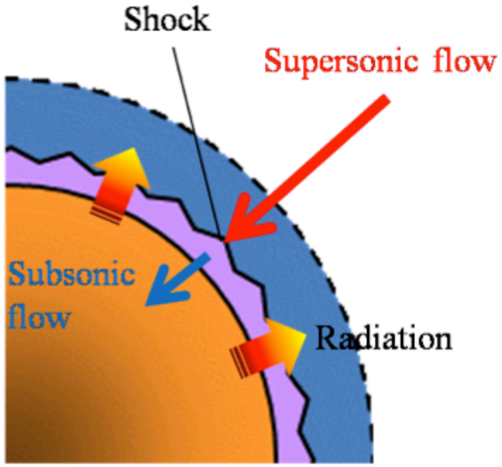
Heat transport : $\frac{\partial T}{\partial m} = -\frac{T}{P}\frac{Gm}{4\pi r^4}\nabla$

"COLD" mass accretion



Gas softly accretes to the protostar through the disk. Accreting materials join the star with the same entropy as in the stellar atmosphere.

"HOT" mass accretion



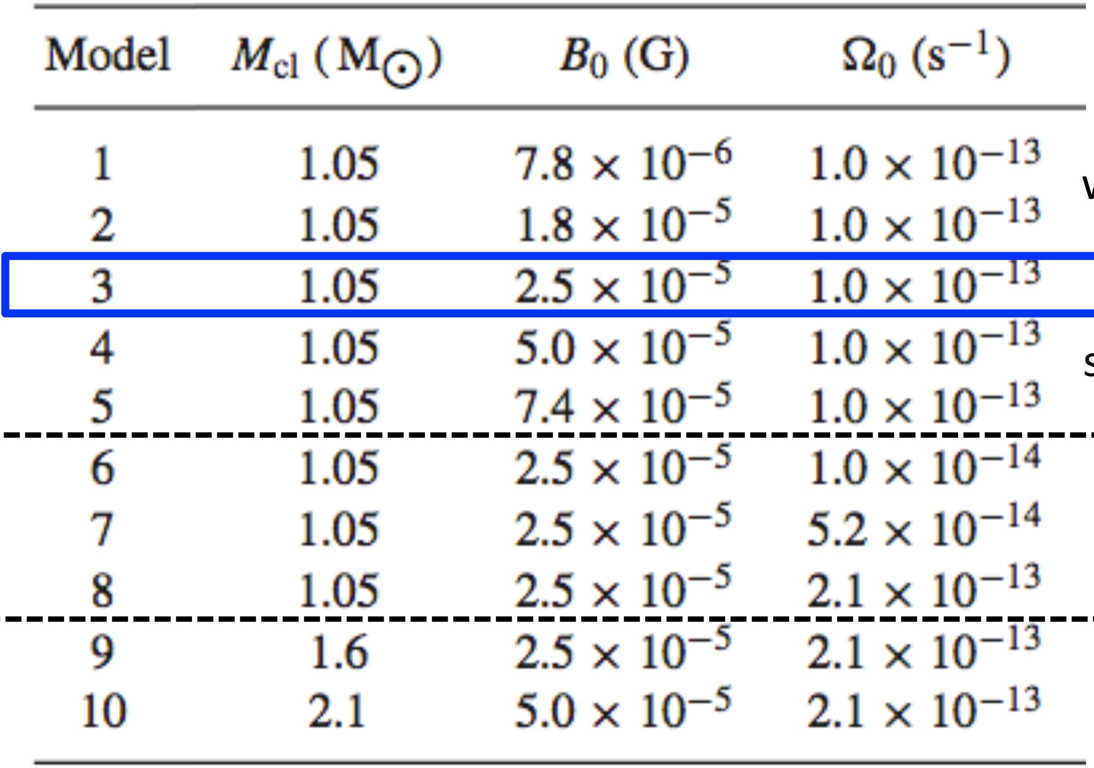
Accretion flow directly hits the stellar surface. A part of the entropy generated at the shock front is taken into the stellar interior.

The evolution doesn't depend on initial models.

(also see, e.g., Hosokawa, Offner & Krumholz 2011)

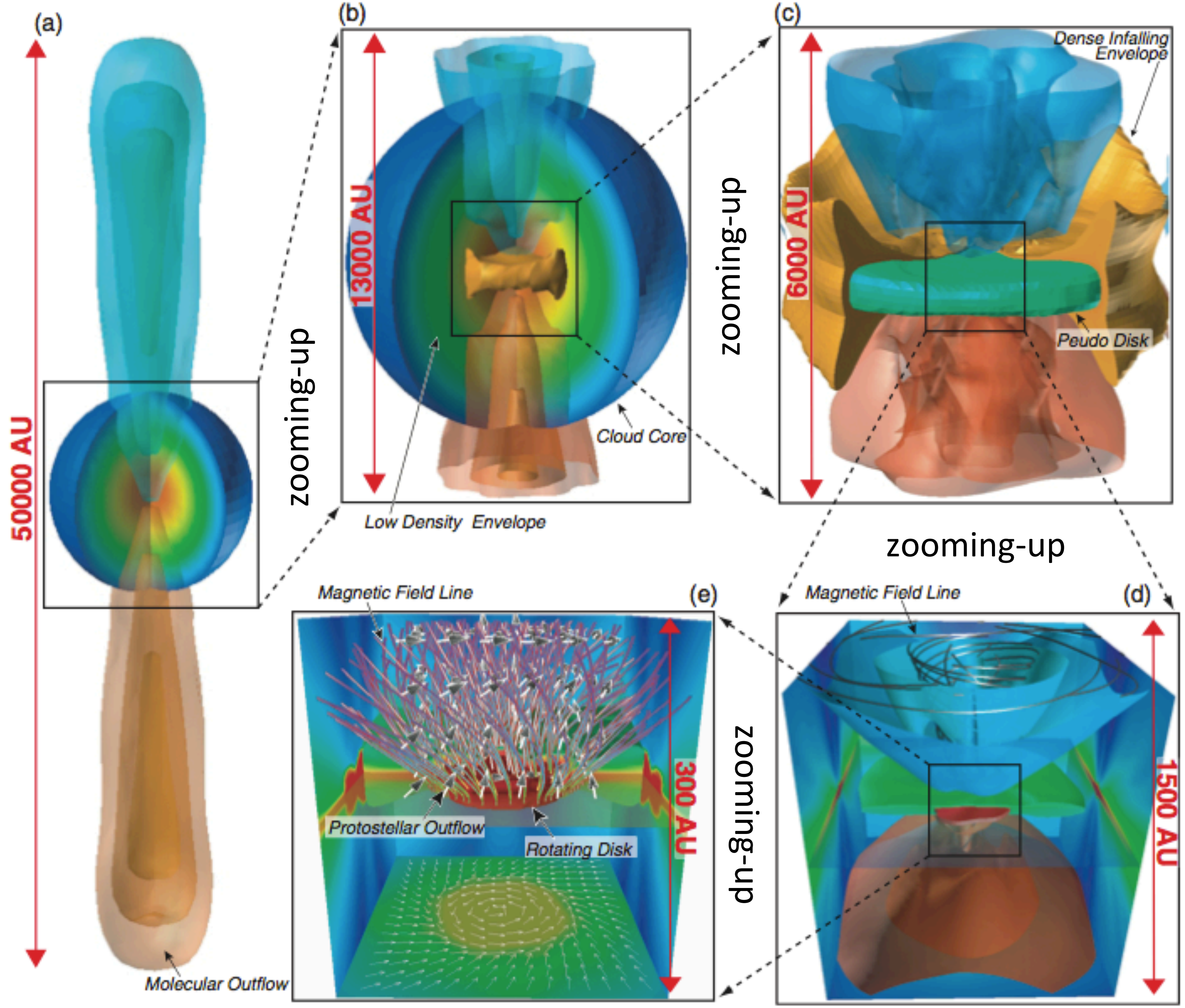
Cases Considered

Follow the collapse and subsequent accretion stage beginning with various settings of molecular cloud cores, e.g., with different magnetic fields, rotation, and core masses



Model	$M_{\rm cl}$ ($M_\odot$)	B_0 (G)	Ω_0 (s^{-1})	
1	1.05	7.8×10^{-6}	1.0×10^{-13}	weaker B-fields
2	1.05	1.8×10^{-5}	1.0×10^{-13}	
3	1.05	2.5×10^{-5}	1.0×10^{-13}	fiducial case
4	1.05	5.0×10^{-5}	1.0×10^{-13}	stronger B-fields
5	1.05	7.4×10^{-5}	1.0×10^{-13}	
6	1.05	2.5×10^{-5}	1.0×10^{-14}	slower rotation
7	1.05	2.5×10^{-5}	5.2×10^{-14}	
8	1.05	2.5×10^{-5}	2.1×10^{-13}	faster rotation
9	1.6	2.5×10^{-5}	2.1×10^{-13}	more massive cores
10	2.1	5.0×10^{-5}	2.1×10^{-13}	

snapshots in model #3 (0.15 Myr after the birth of the protostar)

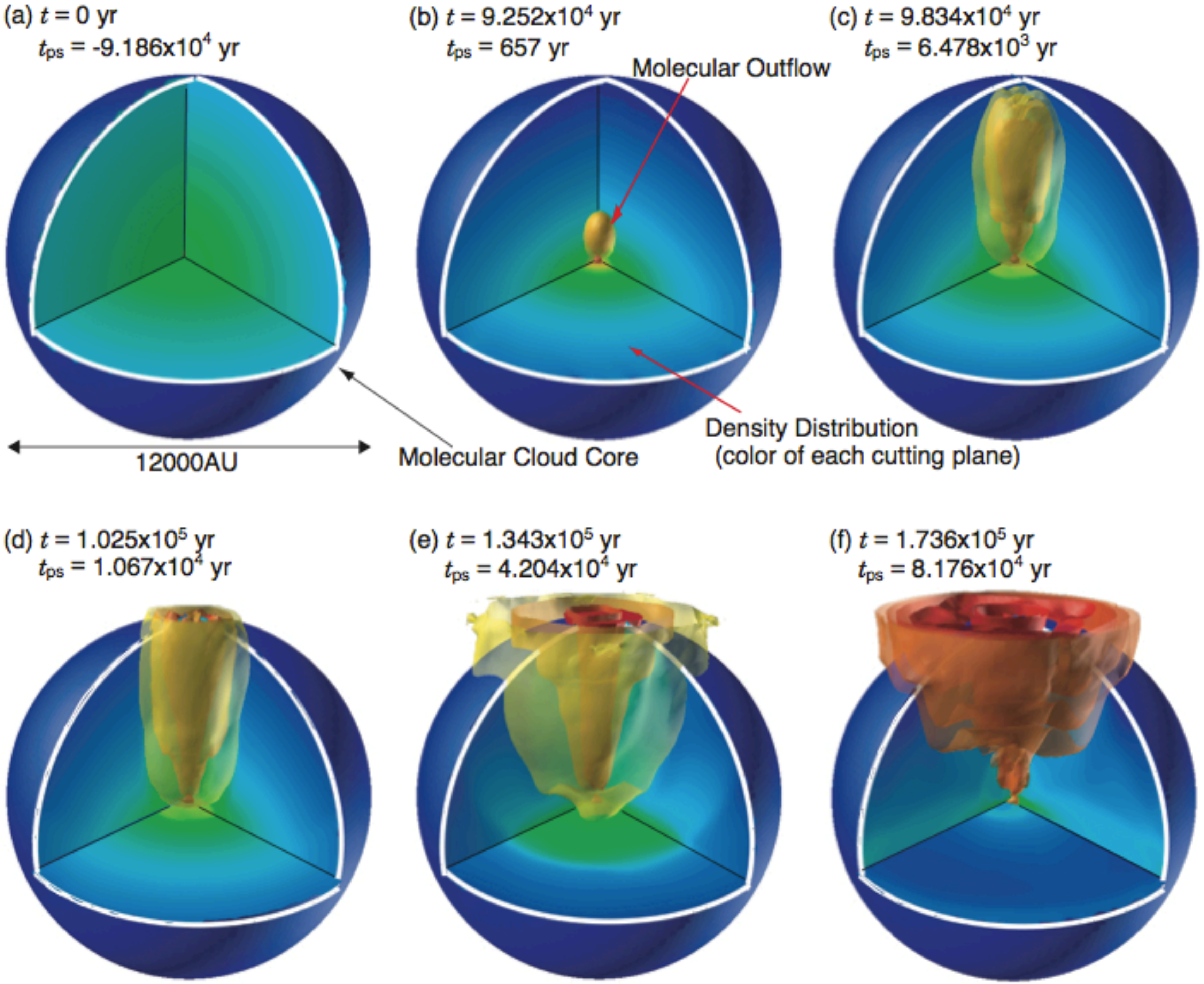


zooming-up

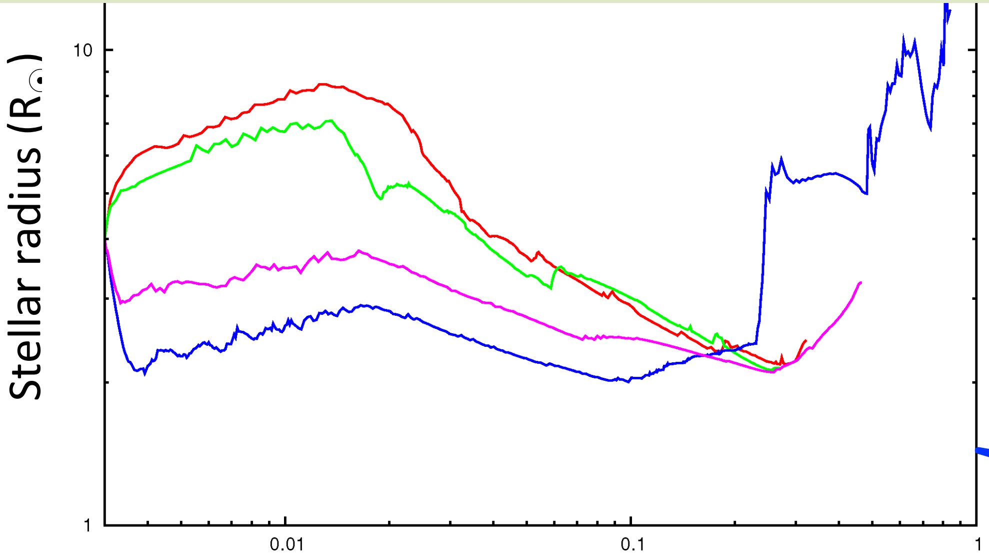
zooming-up

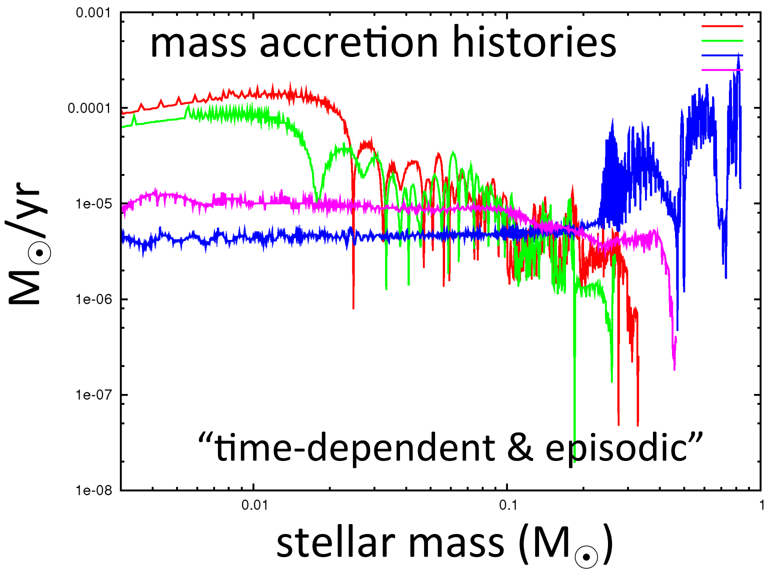
zooming-up

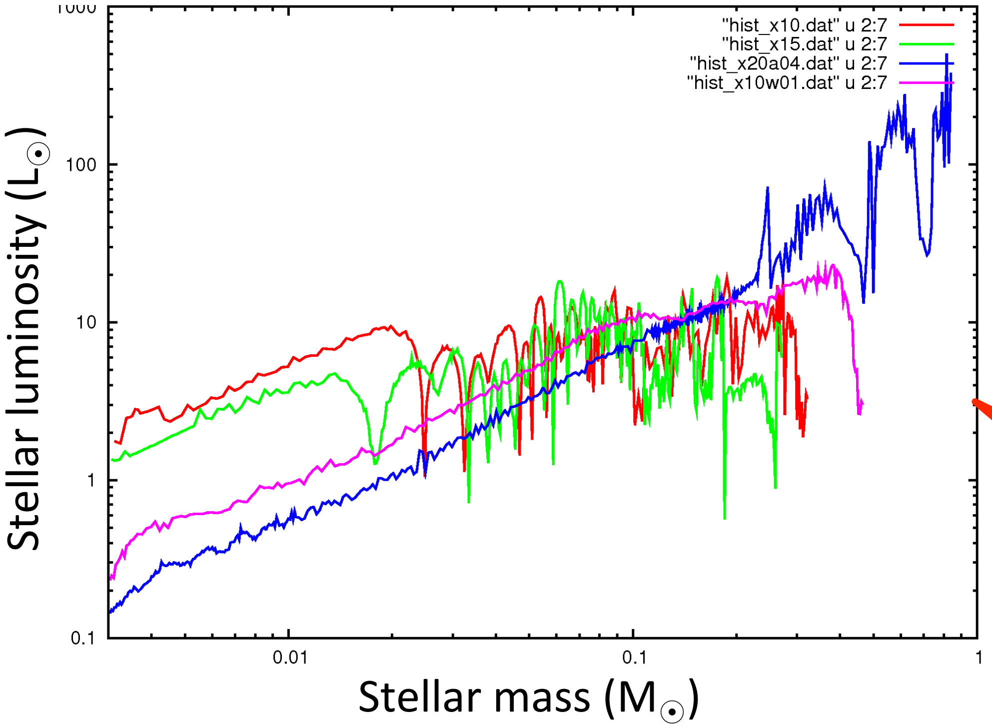
zooming-up


(a) $t = 0$ yr
$t_{ps} = -9.186\text{x}10^4$ yr
(b) $t = 9.252\text{x}10^4$ yr
$t_{ps} = 657$ yr
(c) $t = 9.834\text{x}10^4$ yr
$t_{ps} = 6.478\text{x}10^3$ yr
Molecular Outflow
12000AU
Molecular Cloud Core
Density Distribution
(color of each cutting plane)
(d) $t = 1.025\text{x}10^5$ yr
$t_{ps} = 1.067\text{x}10^4$ yr
(e) $t = 1.343\text{x}10^5$ yr
$t_{ps} = 4.204\text{x}10^4$ yr
(f) $t = 1.736\text{x}10^5$ yr
$t_{ps} = 8.176\text{x}10^4$ yr

Protostellar Evolution







Evolution of stellar radius

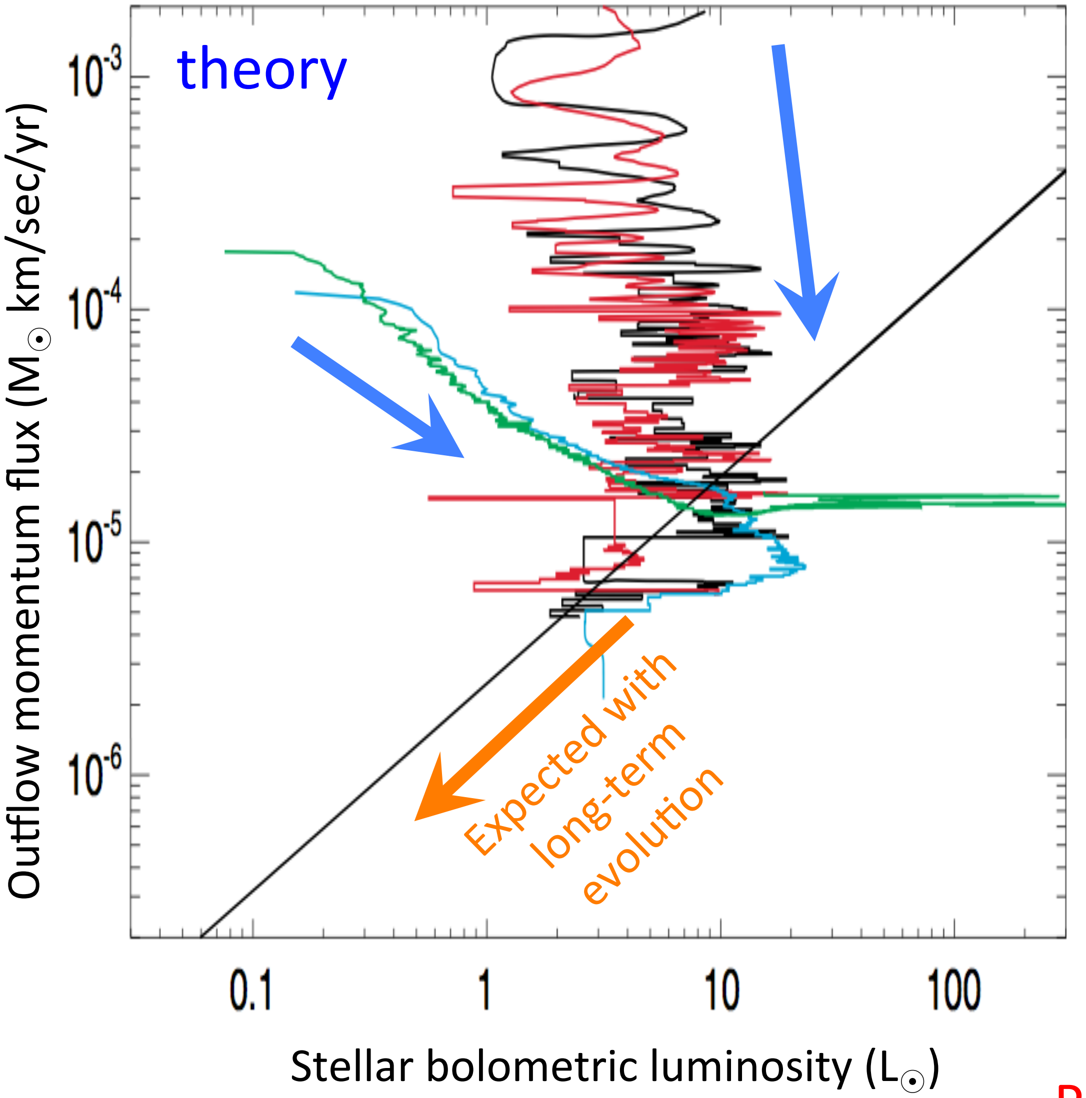
- Initial model : 0.003M⊙, 4R⊙ (e.g., Masunaga & Inutsuka 00)

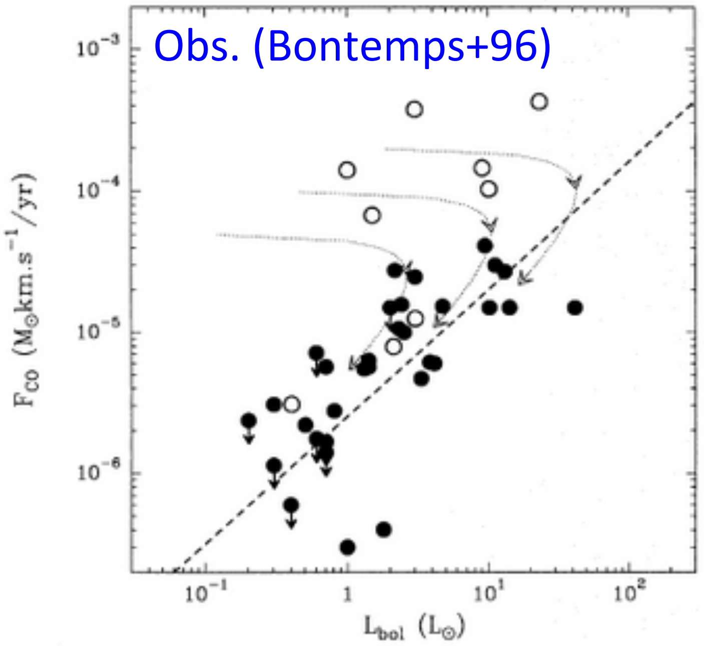
  But initial model doesn't matter
- Low acc. rates → smaller radii

Evolution of stellar lum.

$$L \simeq L_{\rm acc} \simeq G M_* \dot{M}_* / R_*$$

Theoretical Tracks *v.s.* Obs.

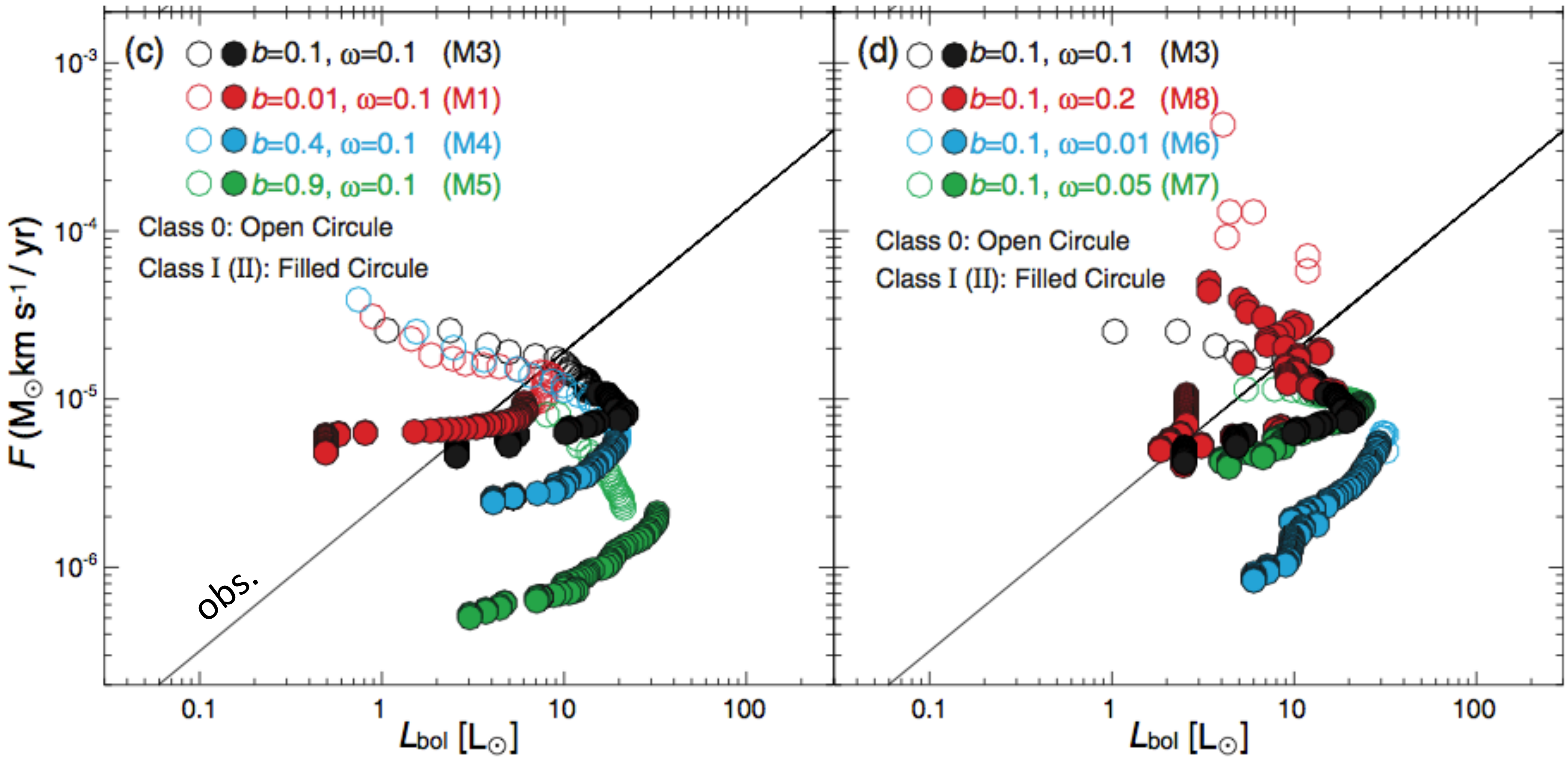




- ➢ Tracks go down with increasing the stellar mass
- ➢ longer-term evolution
  → tracks will extend toward the lower-left corner

Pretty good agreement with obs.!

Dependence on different B-fields & spins



with different B-fields

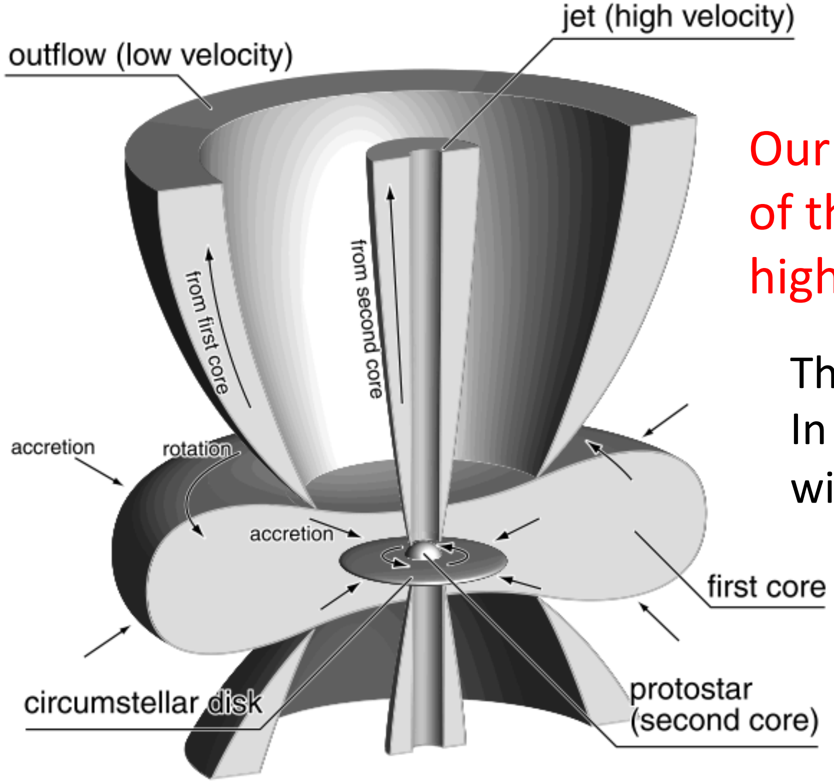
with different spins

+ plotted every 1000 yesars (○: class 0 / ●: class I).
  the distributions of class 0/I sources also agree with the observations

+ scatters depending on the different magnetic fields and cloud rotation
  given for the initial conditions

Summary

We have obtained theoretical tracks which connect the protostellar evolution and outflow activity, combining the MHD simulations and stellar evolution calculations. Our theoretical tracks agree well with the observations.



Machida, Inutsuka & Matsumoto (2008)

※ Note ※

Our results do not stands on the classical picture of the entrainment of molecular outflows by high-speed jets (optical jets).

The outflow is driven from the circumstellar disk.
In the current simulations, the jet does NOT appear without resolving the very vicinity of the protostar.

The observational properties of the molecular outflow are explained without any effects of the jet.