Massive Outflows Driven by Magnetic Effects in Star Forming Clouds with High Mass Accretion Rates

---

YUKO MATSUSHITA / Masahiro Machida
: Kyushu University
Yuya Sakurai / Takashi Hosokawa
: The University of Tokyo / Kyoto University

DTA 2016/11/24-25@Mitaka

Motivation

- Massive stars (> $8M_{sun}$) formation process is no clearly understand
- Massive stars significantly affect the evolution of the universe
  - stellar radiation feedback
  - inject kinetic energy, thermal energy
  - polluted gas into interstellar space / stellar wind / supernova explosion

http://www.nao.ac.jp/gallery/weekly/2014/20141216-w3-main.html

Clarifying Massive stars formation process is important in astrophysical study !!!

Previous Works

- Krumholz / Kuiper
  - → stellar radiation feedback ○
  - → magnetic outflow ✕
- Hennebelle, Commercon
- Seifried

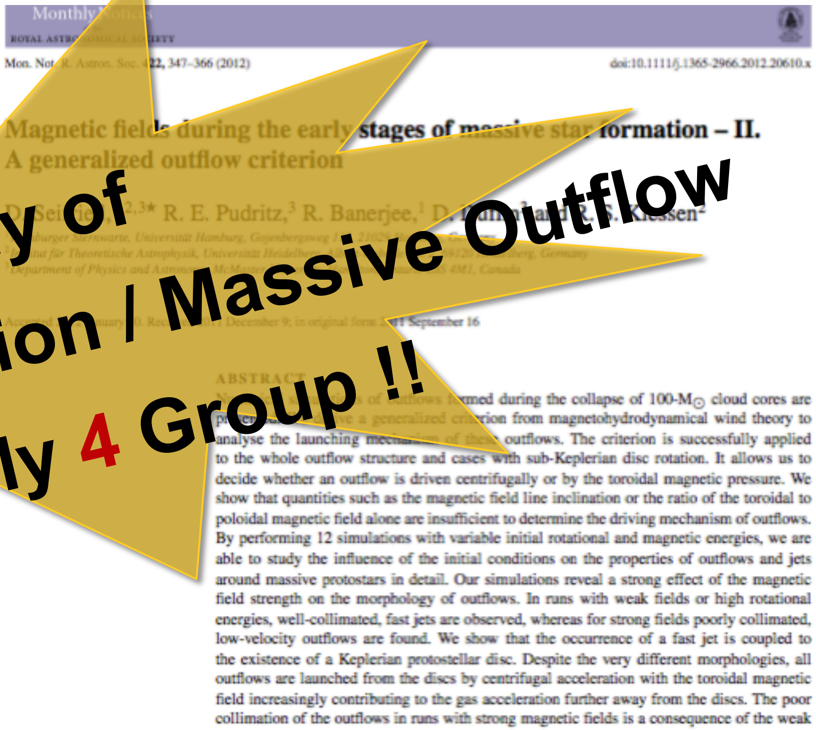
→ stellar radiation feedback ✕
→ magnetic outfow ○


REPORTS

The Formation of Massive Star Systems by Accretion

Mark R. Krumholz,[1*] Richard I. Klein,[2,3] Christopher F. McKee,[2,4] Stella S. R. Offner,[4] Andrew J. Cunningham[3]

Massive stars produce so much light that the radiation pressure they exert on the gas and dust around them is stronger than their gravitational attraction, a condition that has long been expected to prevent them from growing by accretion. We present three-dimensional radiation-hydrodynamic simulations of the collapse of a massive prestellar core and find that radiation pressure does not halt accretion. Instead, gravitational and Rayleigh-Taylor instabilities channel gas onto the star system through nonaxisymmetric disks and filaments that self-shield against radiation while allowing radiation to escape through optically thin bubbles. Gravitational instabilities cause the disk to fragment and form a massive companion to the primary star. Radiation pressure does not limit stellar masses, but the instabilities that allow accretion to continue lead to small multiple systems.


Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. 422, 347–366 (2012) doi:10.1111/j.1365-2966.2012.20610.x

Magnetic fields during the early stages of massive star formation – II. A generalized outflow criterion

D. Seifried,[1,2,3*] R. E. Pudritz,[3] R. Banerjee,[1] D. Duffin[3] and R. S. Klessen[2]

Accepted 2012 January 20. Received 2011 December 9; in original form 2011 September 16

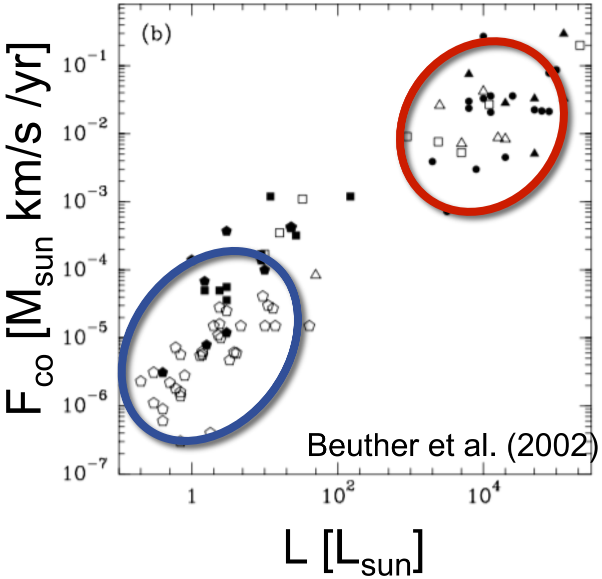
ABSTRACT

Numerical simulations of outflows formed during the collapse of 100-$M_\odot$ cloud cores are presented. We derive a generalized criterion from magnetohydrodynamical wind theory to analyse the launching mechanism of these outflows. The criterion is successfully applied to the whole outflow structure and cases with sub-Keplerian disc rotation. It allows us to decide whether an outflow is driven centrifugally or by the toroidal magnetic pressure. We show that quantities such as the magnetic field line inclination or the ratio of the toroidal to poloidal magnetic field alone are insufficient to determine the driving mechanism of outflows. By performing 12 simulations with variable initial rotational and magnetic energies, we are able to study the influence of the initial conditions on the properties of outflows and jets around massive protostars in detail. Our simulations reveal a strong effect of the magnetic field strength on the morphology of outflows. In runs with weak fields or high rotational energies, well-collimated, fast jets are observed, whereas for strong fields poorly collimated, low-velocity outflows are found. We show that the occurrence of a fast jet is coupled to the existence of a Keplerian protostellar disc. Despite the very different morphologies, all outflows are launched from the discs by centrifugal acceleration with the toroidal magnetic field increasingly contributing to the gas acceleration further away from the discs. The poor collimation of the outflows in runs with strong magnetic fields is a consequence of the weak

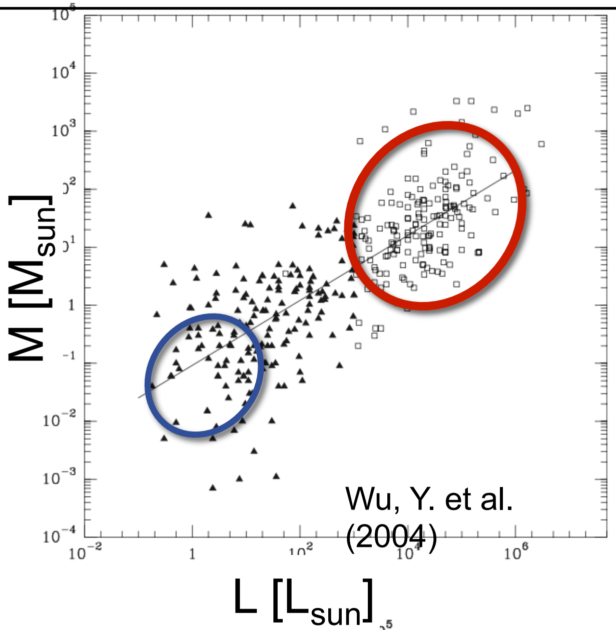
Study of Massive star Formation / Massive Outflow

Mainly Only 4 Group !!

Introduction

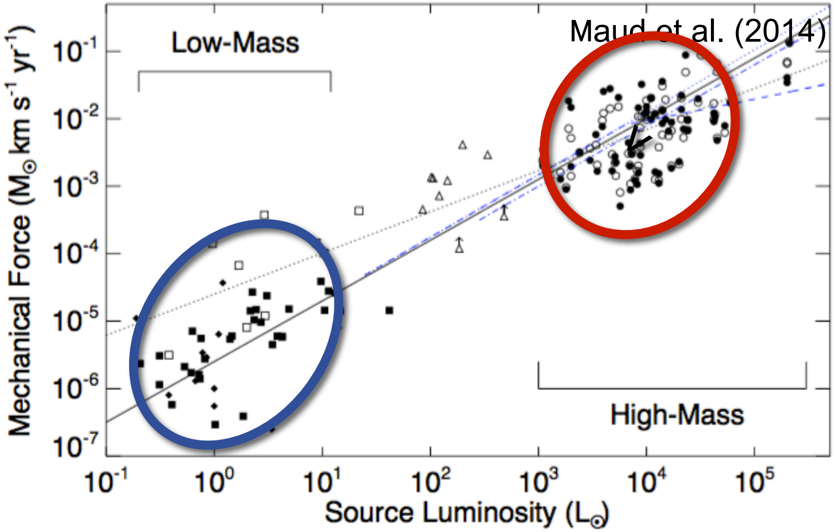


Beuther et al. (2002)

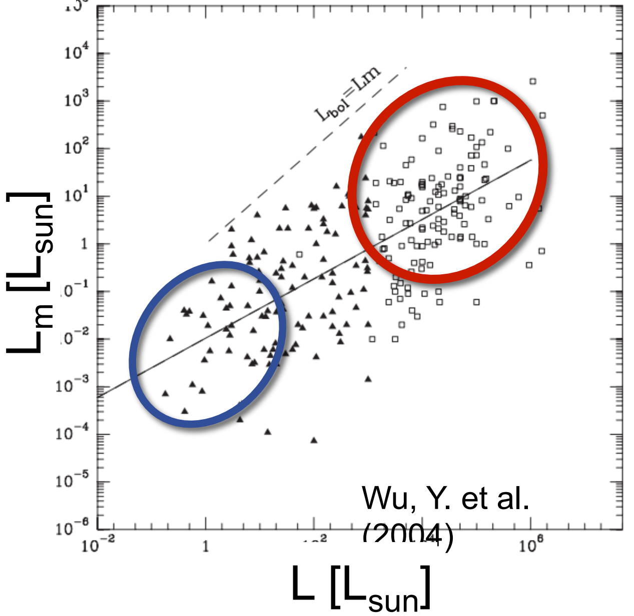


Wu, Y. et al. (2004)

Massive outflows are **scaled-up versions** of low-mass outflow ?



Maud et al. (2014)

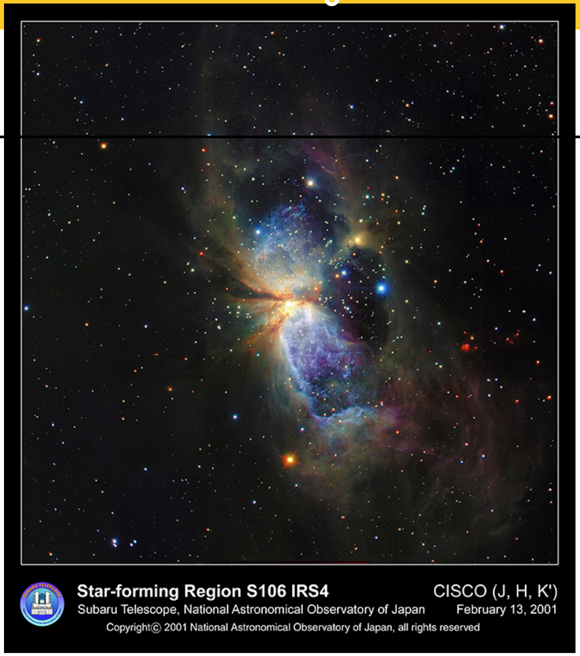


Wu, Y. et al. (2004)

Introduction

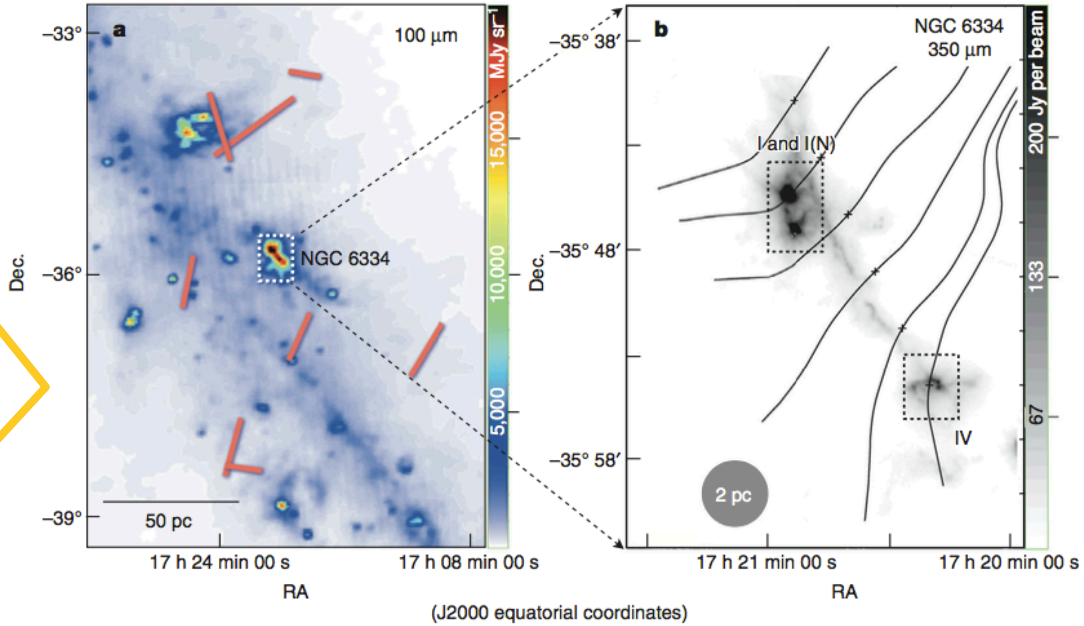
What's the Magnetic Outflow ?

→ transfer **angular momentum** by magnetic and rotation effects



Strong magnetic field observed in massive star forming regions

(Li et al. 2015 / Falgarane et al. 2008)



Li et al. (2015)

Introduction

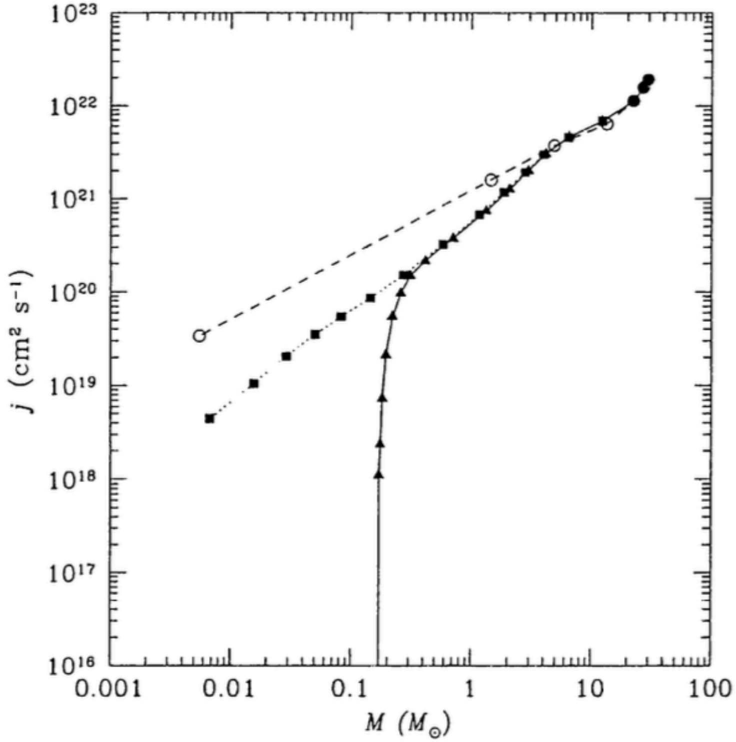
Angular momentum problem

Objects	$J/M(\mathrm{cm}^2/\mathrm{s})$
Molecular Cloud Core	10^{21-22}
Circumstellar Disk	10^{19-21}
Protostar	10^{16-17}

Goodman et al. (1993), Williams &Cieza (2011), Mathieu (2004)

specific angular momentum

should **decrease** a factor of **10^{-5}**



Low-mass Stars

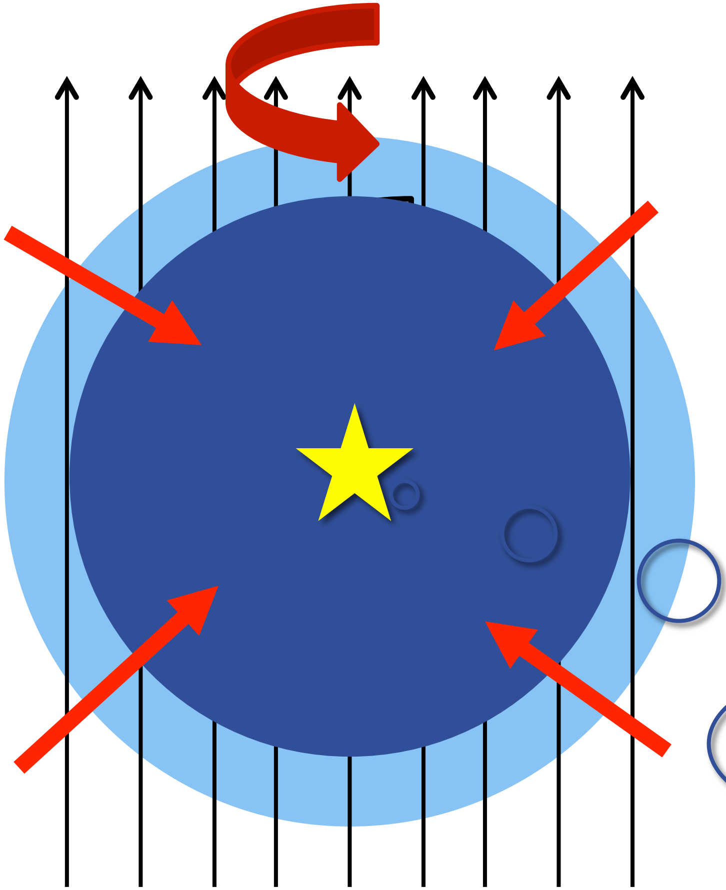
: Jet, Outflow can transfer angular momentum ~99.9%

(Tomisaka 2000)

→ How are massive stars ?

Methods

Bonnor-Ebert density profile



central density : $3.8 \times 10^{-19} \mathrm{gcm}^{-3}$

isothermal temperature : 40K

Resistive-MHD eq

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

$$\rho \frac{\partial \boldsymbol{v}}{\partial t} + \rho(\boldsymbol{v} \cdot \nabla)\boldsymbol{v} = -\nabla P - \frac{1}{4\pi}\boldsymbol{B} \times (\nabla \times \boldsymbol{B}) - \rho \nabla \phi$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B}$$

$$\nabla^2 \phi = 4\pi G \rho$$

barotropic eq : $p = p(\rho)$

Protostar is formed

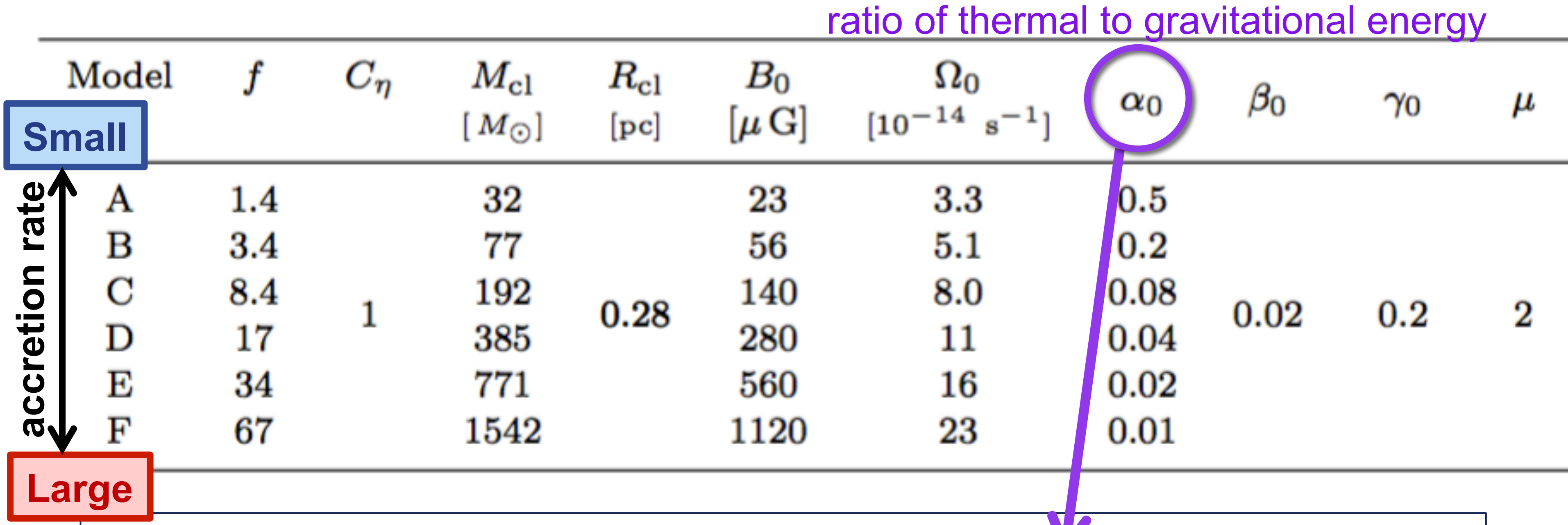
→ remove the gas $n > n_{thr}$

in $r < r_{sink}$

sink radius : 1AU

(Machida & Hosokawa. 2013)

Methods



ratio of thermal to gravitational energy

Small

accretion rate

Large

Model	f	C_η	$M_{\rm cl}$ $[M_\odot]$	$R_{\rm cl}$ [pc]	B_0 [μG]	Ω_0 [10^{-14} s^{-1}]	α_0	β_0	γ_0	μ
A	1.4	1	32	0.28	23	3.3	0.5	0.02	0.2	2
B	3.4		77		56	5.1	0.2			
C	8.4		192		140	8.0	0.08			
D	17		385		280	11	0.04			
E	34		771		560	16	0.02			
F	67		1542		1120	23	0.01			

prepared **6** model

controls **the cloud mass**, **initial cloud stability**

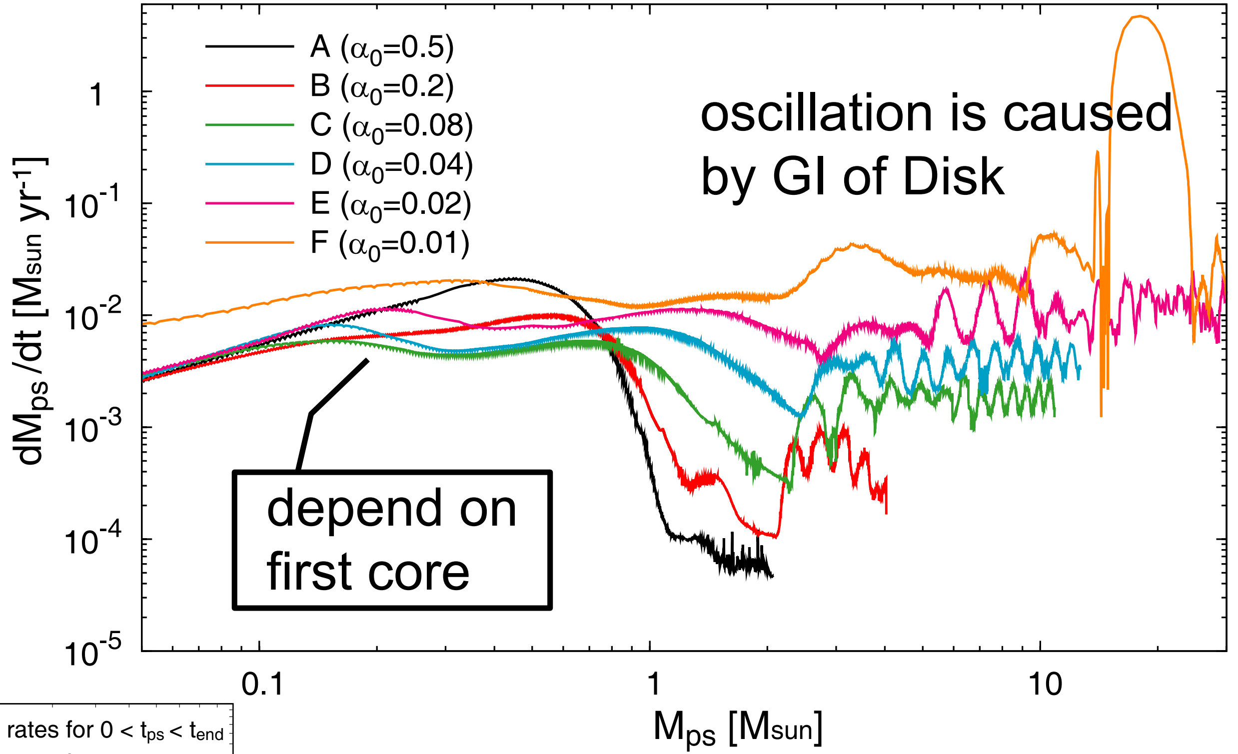
- mass accretion rate is large in an initially thermally unstable cloud
- magnetic field strength : B_0 is adjusted to $\mu = 2$

→each model has different magnetic field strengths

Results : Mass accretion rate against protostellar mass

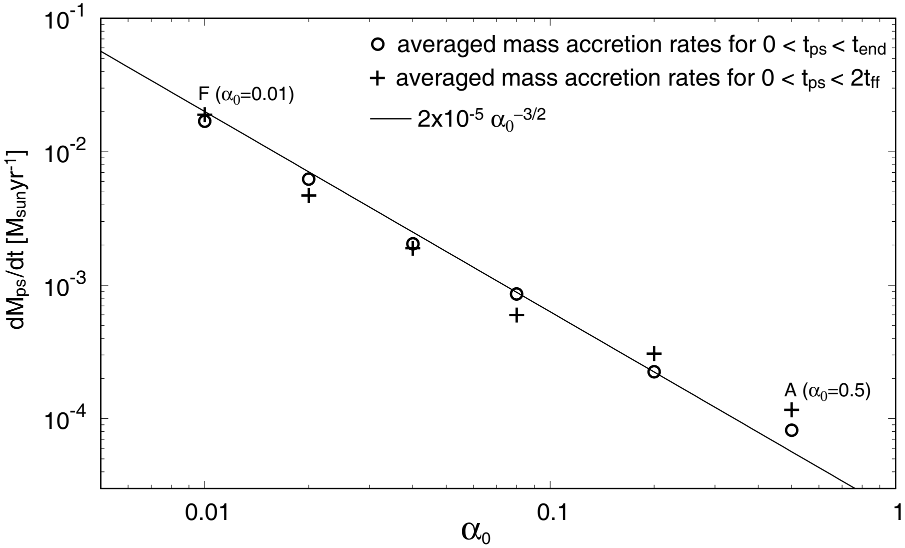
initially more **unstable** cloud

→ **higher accretion rate**



oscillation is caused by GI of Disk

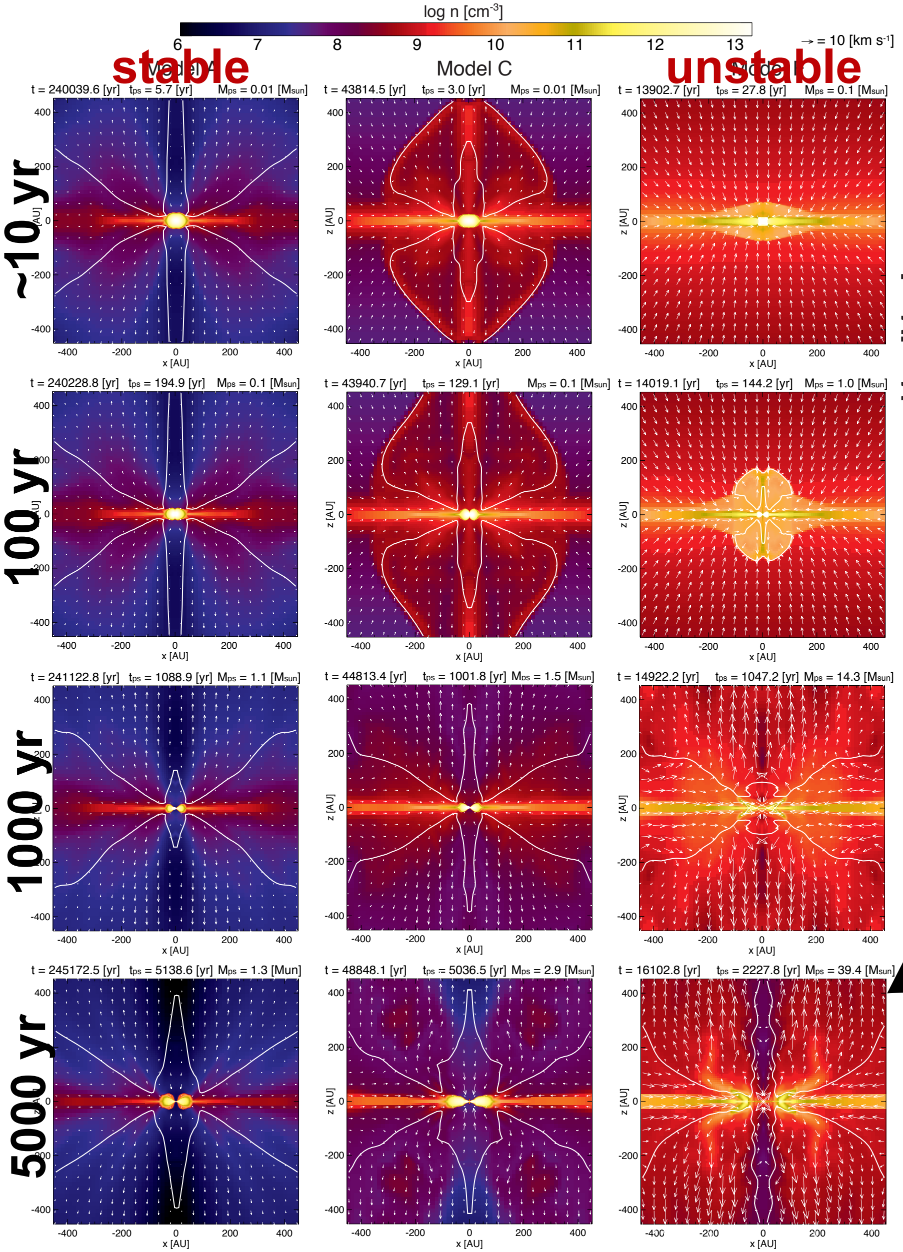
depend on first core

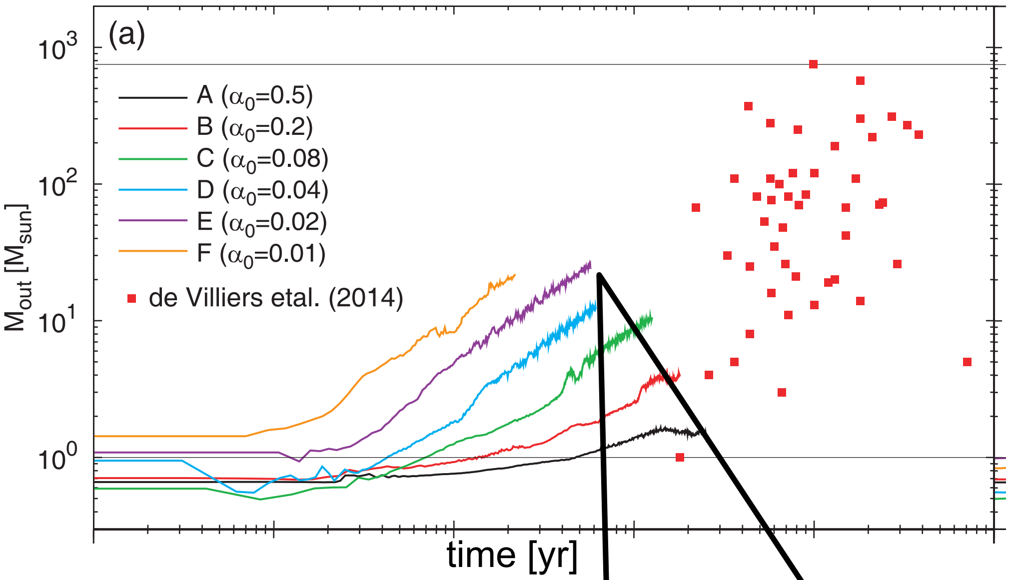


averaged mass accretion rate in each model corresponds to the theoretical prediction

$$\sim \alpha_0^{-3/2}\,(c_s^3/G)$$

Results : Outflow of each model





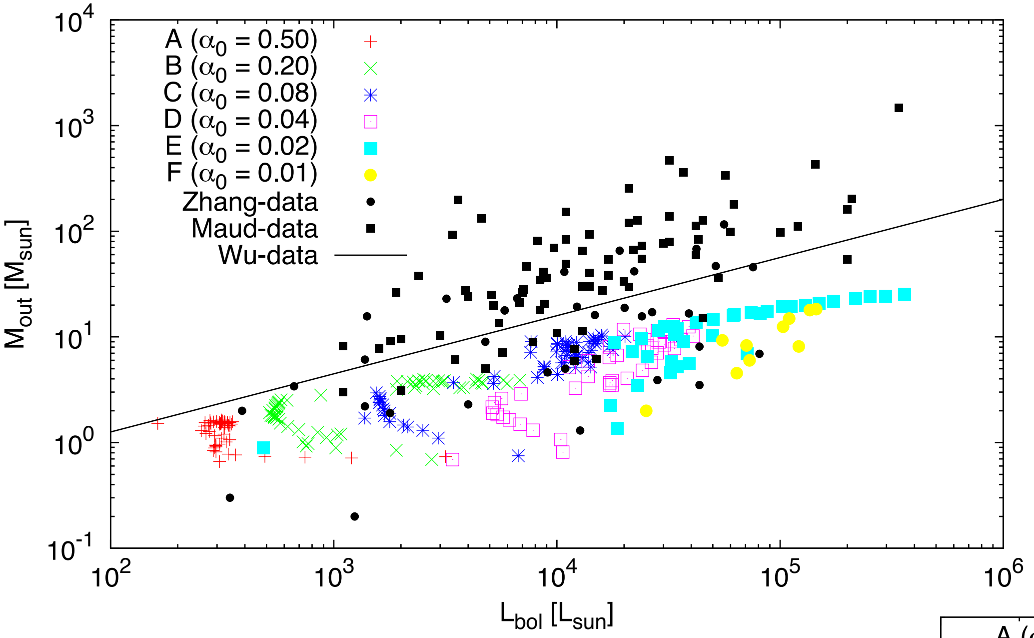
Massive outflow !

> 20 M_{sun} : Outflow mass

higher accretion rate shortens the lifetime of first core

color : density
arrows : velocity

Discussion : Comparison with Observations



← **M_{out} - L_{bol}**

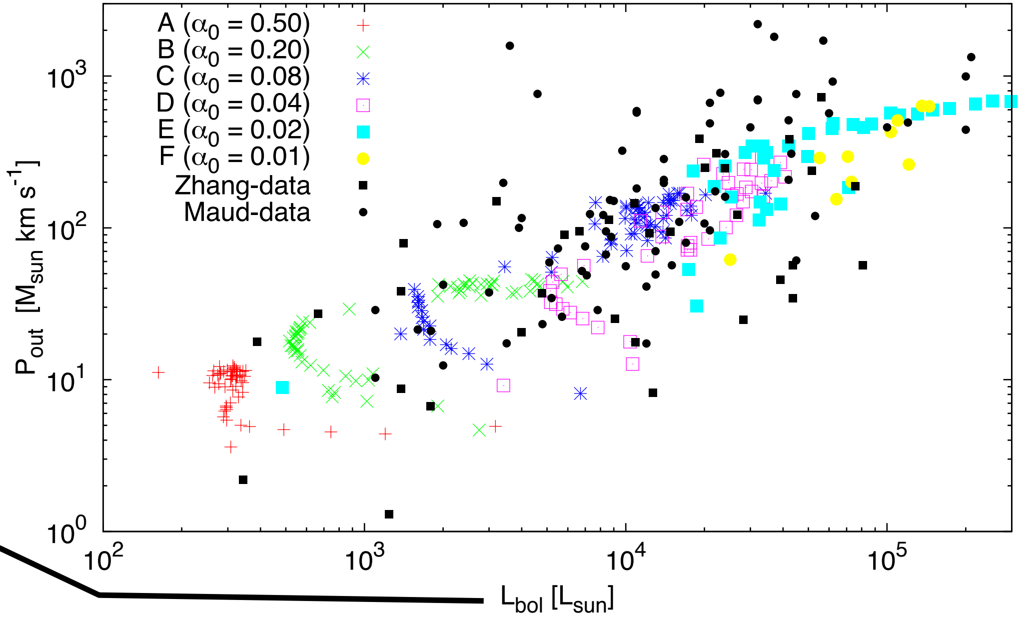
Beuther+02
Zhang+05
Wu+08
Maud+15

Observation data is a little high

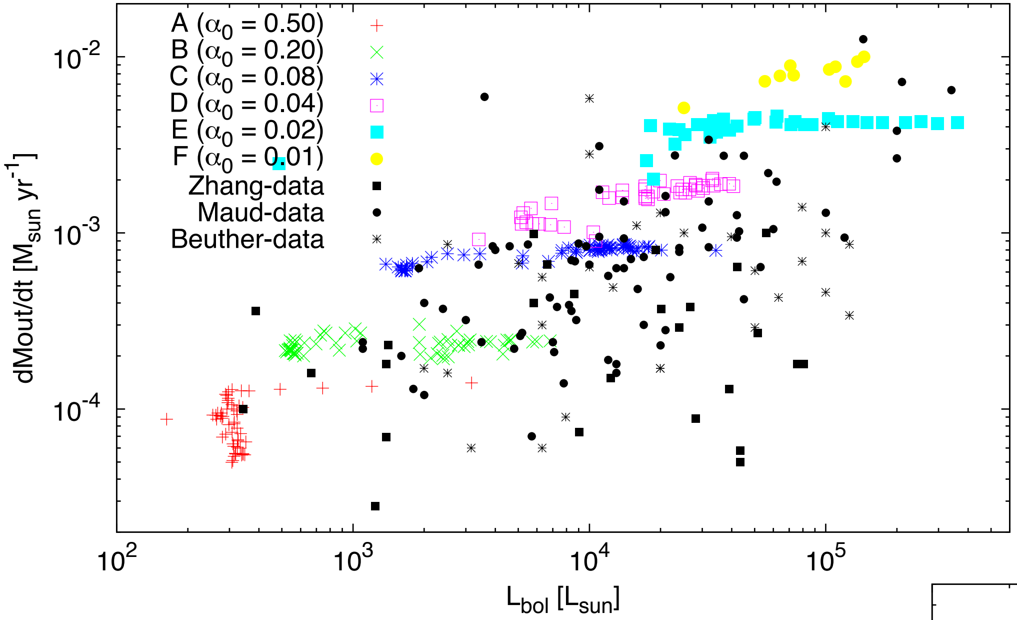
P_{out} – L_{bol} →

Simulation data agree with Observations

$$L_{bol} = L + G\frac{M\dot{M}}{R}$$



Discussion : Comparison with Observations

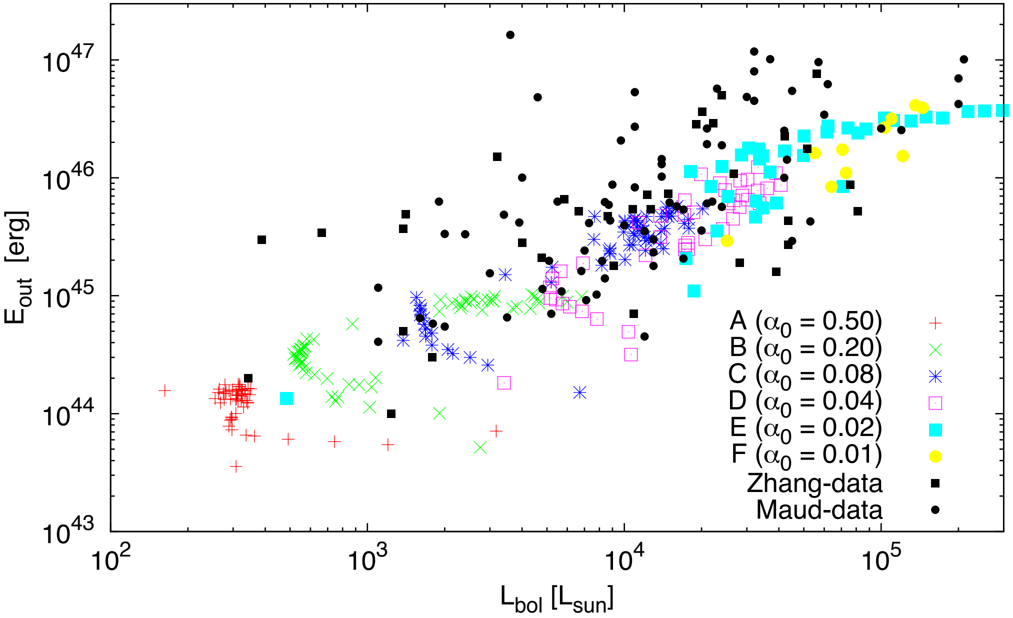


← **Outflow rate – L_{bol}**

Simulation data almost agree with Observation. Observation is a little low.

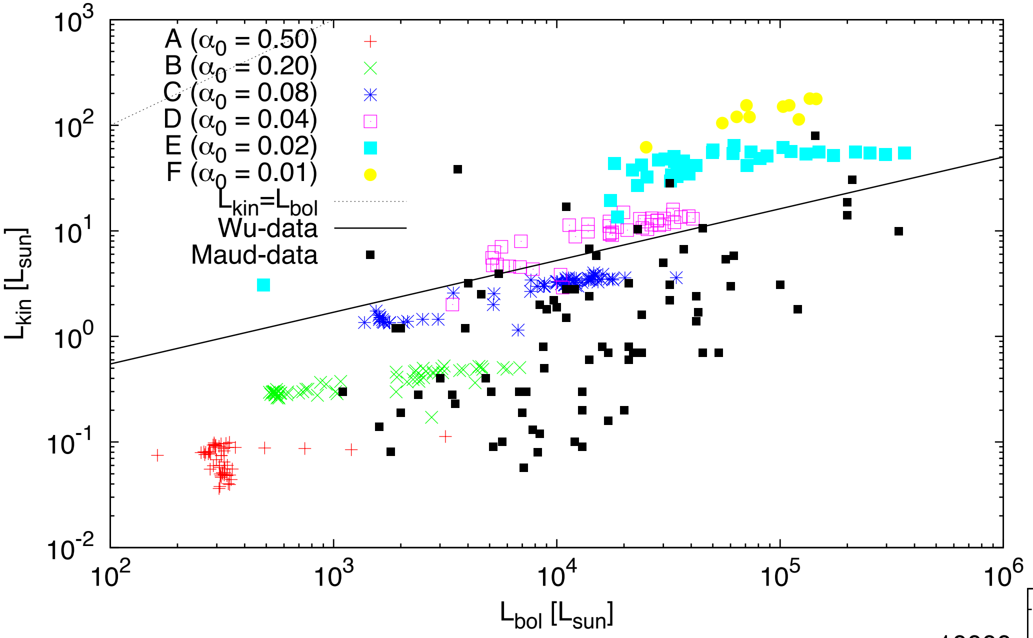
E_{out} – L_{bol} →

Simulation agree with Observation



Beuther+02
Zhang+05
Wu+08
Maud+15

Discussion : Comparison with Observations



← L_{kin} – L_{bol}

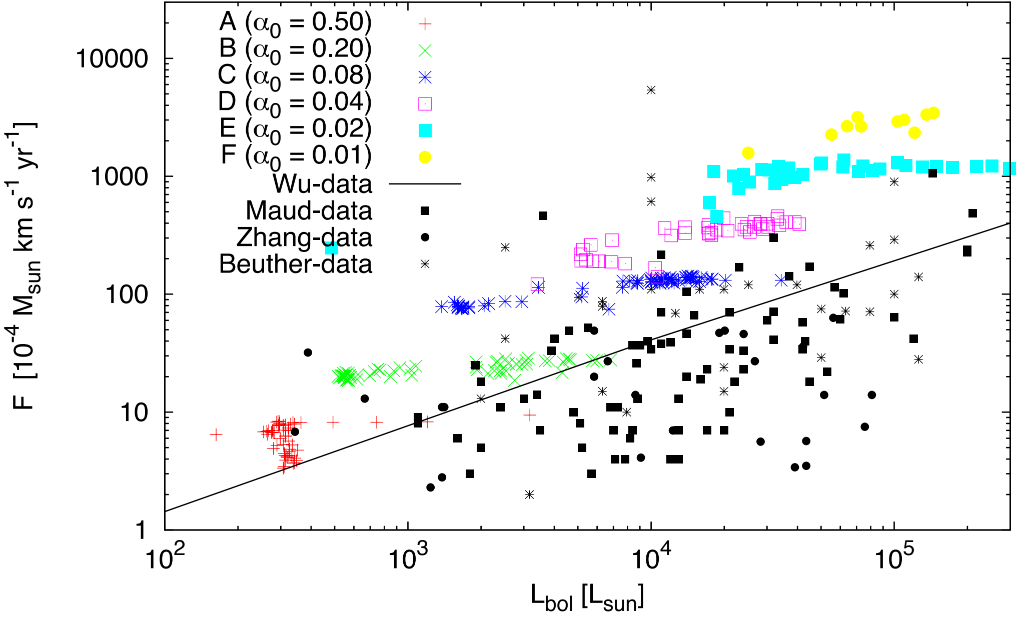
Beuther+02
Zhang+05
Wu+08
Maud+15

Simulation and Observation are almost the same

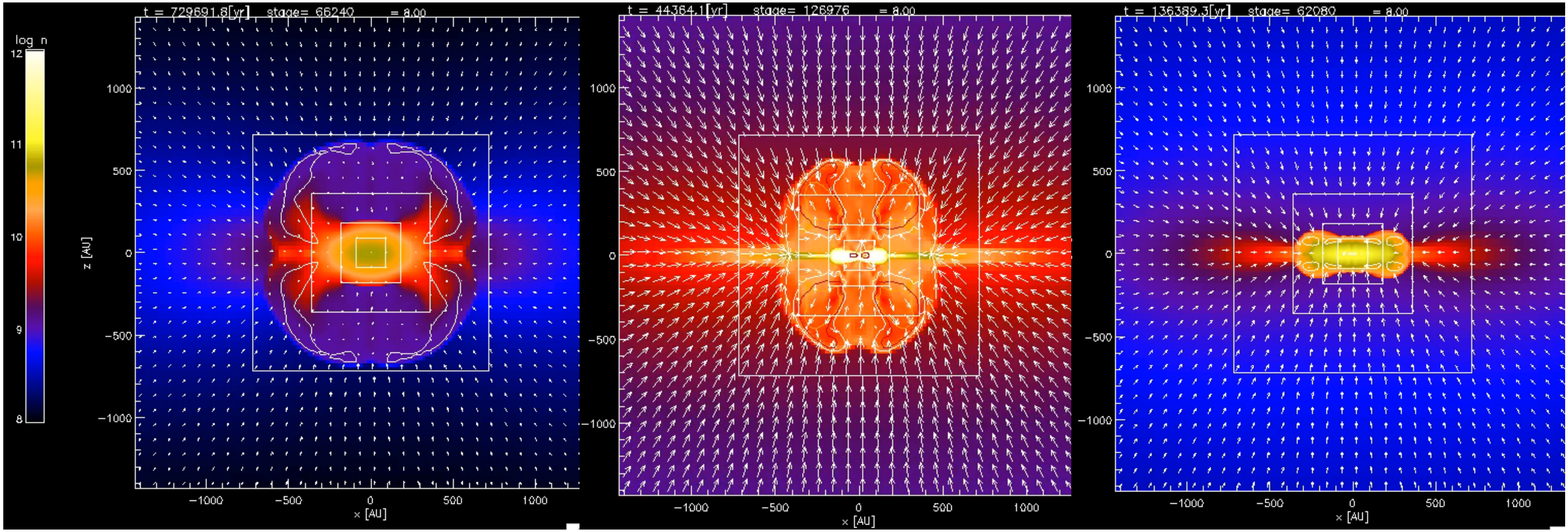
F – L_{bol} →

Simulation date is high.

Caused by estimate of t_{dyn} ?



Now analyzing… “ Failed Outflow”



↑ Drive ↑ Fail ↑ No Drive

prepared **6** model controls
initial cloud stability

central density : 3.8×10^{-19}gcm^{-3}
isothermal temperature : 20K

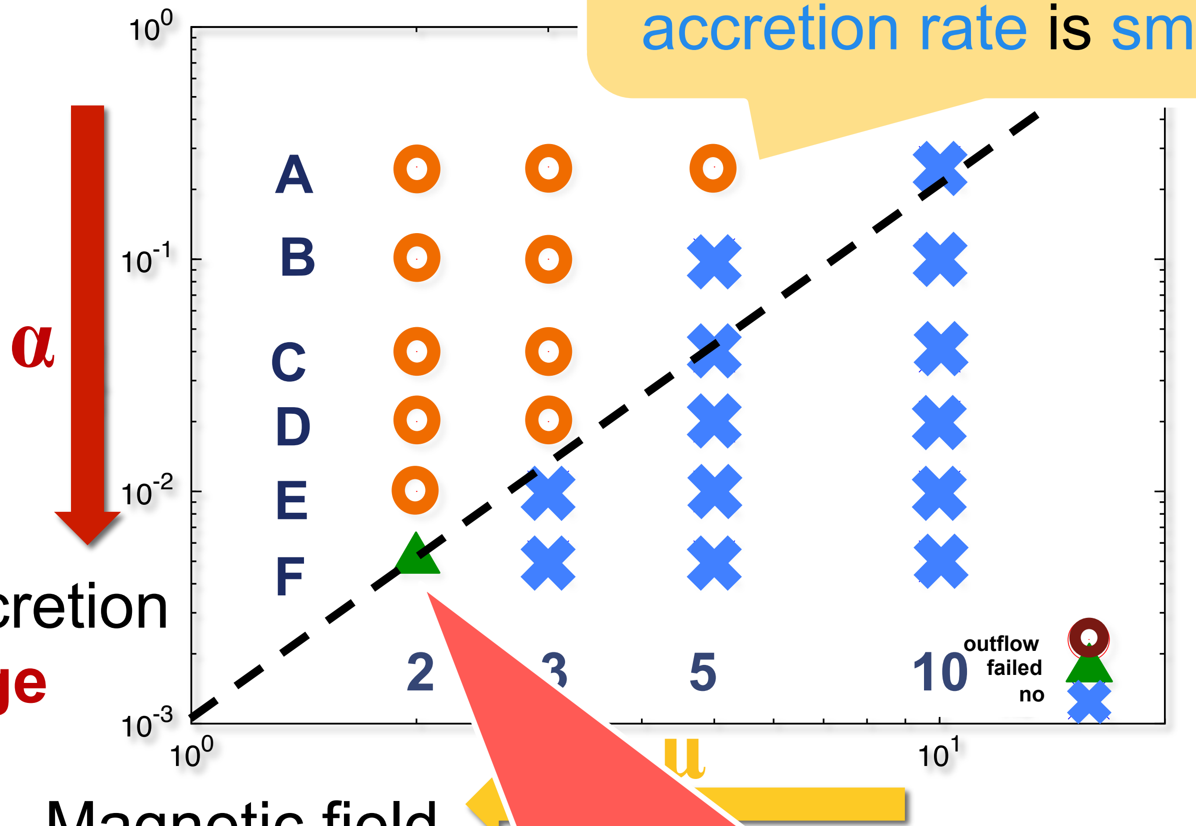
+

set up **Mass-to-Flux ratio**

$$\mu = \left(\frac{M}{\Phi}\right) \Big/ \left(\frac{M}{\Phi}\right)_{cri}$$ 2, 3, 5, 10

change Magnetic strength

Results



mass accretion rate **Large**

Magnetic field **Strong**

Even if magnetic field is weak, Outflow can drive when accretion rate is small.

Even if magnetic field is strong, Outflow **cannot** drive when accretion rate is extremely Large.

Conclusion & Future Works

- ✓ investigate the relation between mass accretion onto the protostar and the magnetically driven outflow

- ✓ When the initial prestellar cloud has a strong magnetic field, the outflow is powerful at any accretion rate

- ✓ The physical quantities derived from our simulations favorably agree with observation in massive outflow.
  outflow mass / momentum / kinetic energy /
  outflow rate / kinetic luminosity / momentum flux /

- ✓ Both low- and high-mass stars form by a common fundamental mechanism
  → must ultimately consider various physical effects.
  turbulence / radiation effects / etc…

Conclusion & Future Works

Change mass accretion rate and magnetic strength

→ Even if magnetic field is weak, Outflow can drive when accretion rate is small.

Like low-mass stars.

→Even if magnetic field is strong,
Outflow cannot drive when accretion rate is extremely Large.

✓ Compare magnetic pressure to ram pressure

→ if magnetic pressure strong, outflow driven?

✓ angular momentum transfer

→ What is the most efficient ?

Methods : “ Failed Outflow”

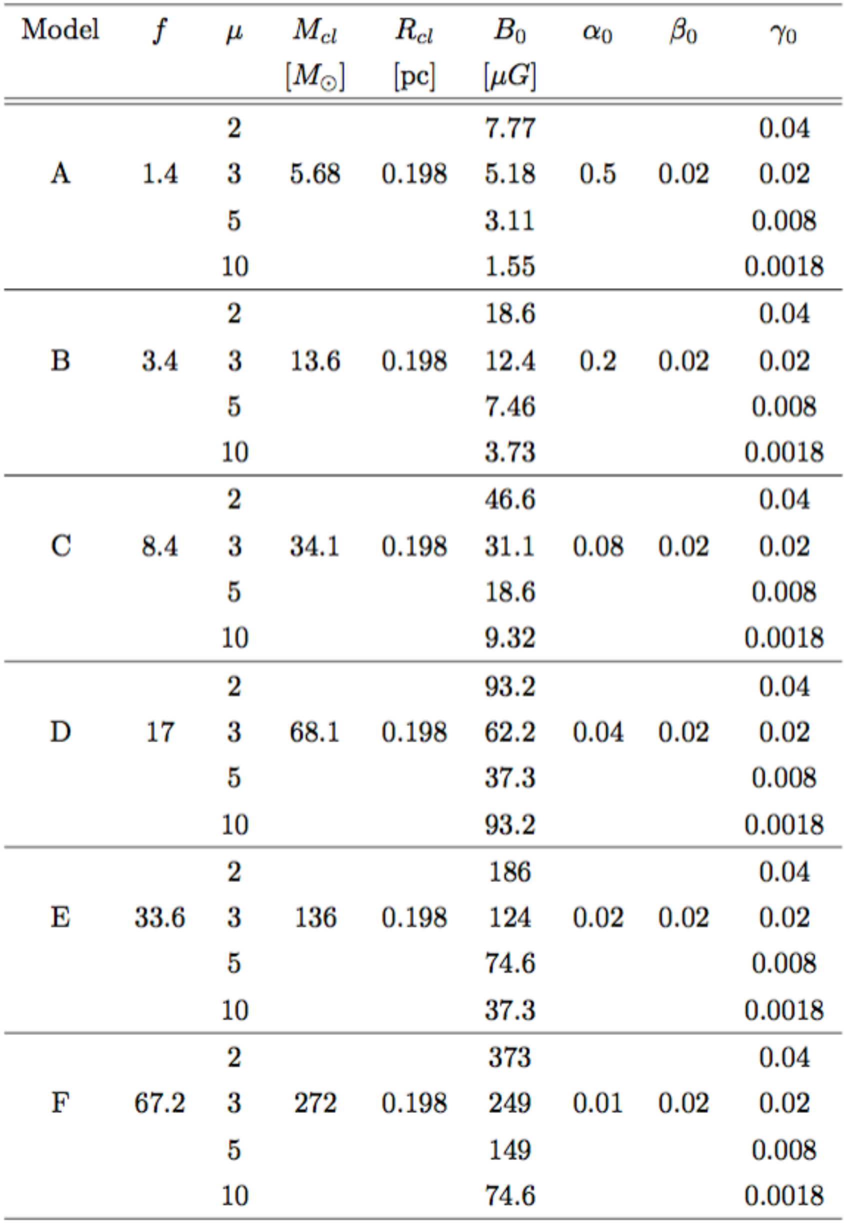
prepared **6** model controls
initial cloud stability

+

set up **Mass-to-Flux ratio**

$$\mu = \left(\frac{\mathrm{M}}{\Phi}\right) \Big/ \left(\frac{\mathrm{M}}{\Phi}\right)_{cri}$$ 2, 3, 5, 10

change Magnetic strength



Model	f	μ	M_{cl} $[M_\odot]$	R_{cl} [pc]	B_0 $[\mu G]$	α_0	β_0	γ_0
A	1.4	2	5.68	0.198	7.77	0.5	0.02	0.04
		3			5.18			0.02
		5			3.11			0.008
		10			1.55			0.0018
B	3.4	2	13.6	0.198	18.6	0.2	0.02	0.04
		3			12.4			0.02
		5			7.46			0.008
		10			3.73			0.0018
C	8.4	2	34.1	0.198	46.6	0.08	0.02	0.04
		3			31.1			0.02
		5			18.6			0.008
		10			9.32			0.0018
D	17	2	68.1	0.198	93.2	0.04	0.02	0.04
		3			62.2			0.02
		5			37.3			0.008
		10			93.2			0.0018
E	33.6	2	136	0.198	186	0.02	0.02	0.04
		3			124			0.02
		5			74.6			0.008
		10			37.3			0.0018
F	67.2	2	272	0.198	373	0.01	0.02	0.04
		3			249			0.02
		5			149			0.008
		10			74.6			0.0018