Possibility of the formation of high-mass close binary systems by magnetic braking

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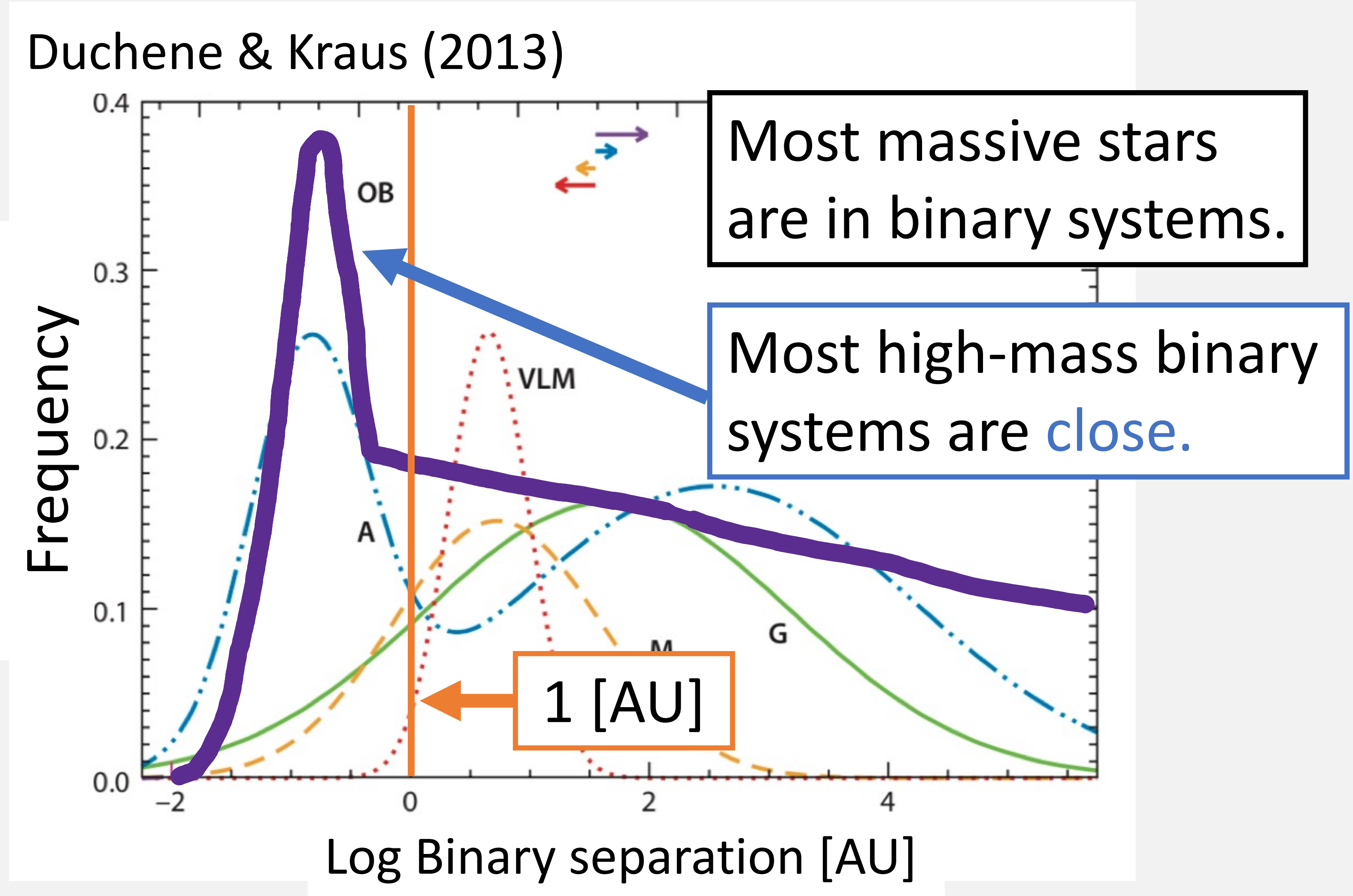
Observations of High-Mass Close Binaries



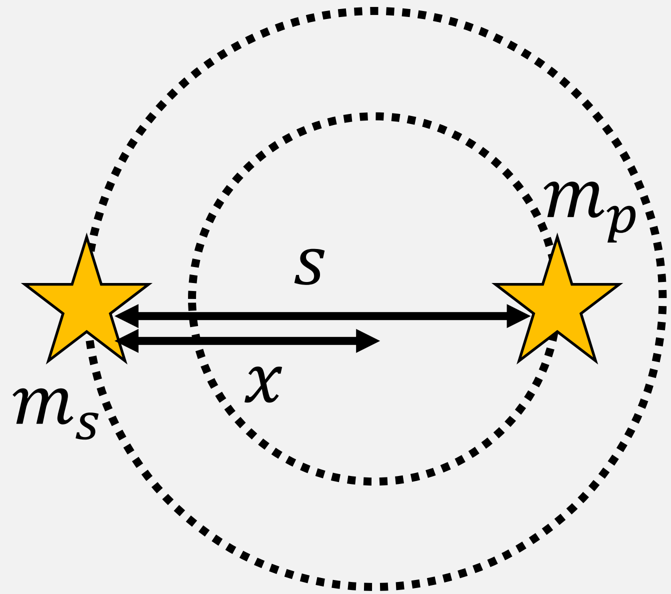
but <u>the mechanism of the formation of HMCB is unclear.</u>

Expression of the separation

- Assume that eccentricity = 0.
- Equation of motion

$$m_\mathrm{p} \cdot (s - x) \cdot \omega^2 = G\frac{m_\mathrm{p} m_\mathrm{s}}{s^2}$$

$$m_\mathrm{s} \cdot x \cdot \omega^2 = G\frac{m_\mathrm{p} m_\mathrm{s}}{s^2}$$



- Orbital angular momentum around the center of gravity

$$J = (s - x) \cdot m_\mathrm{p}(s - x)\omega + x \cdot m_\mathrm{s} x\omega$$

$$\Rightarrow \quad s = \frac{(1+q)^4}{q^2} \frac{J^2}{G(m_p + m_s)^3}$$

$q \equiv m_s/m_p$

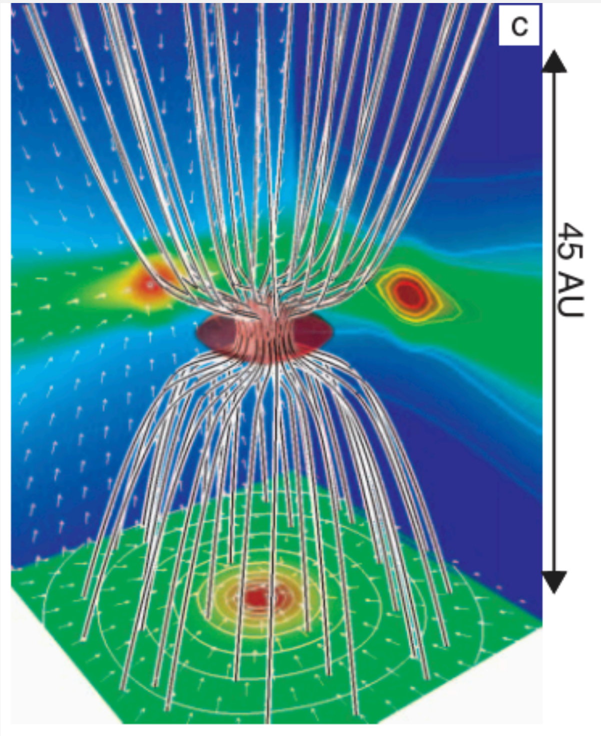
… Bate & Bonnell (1997)

Difficulty of the formation of close systems

- Assume the equal mass binary (q = 1)

$$s = \frac{16}{G}\frac{J^2}{M_{tot}^3}$$

→ Angular Momentum transfer is necessary to form close systems!

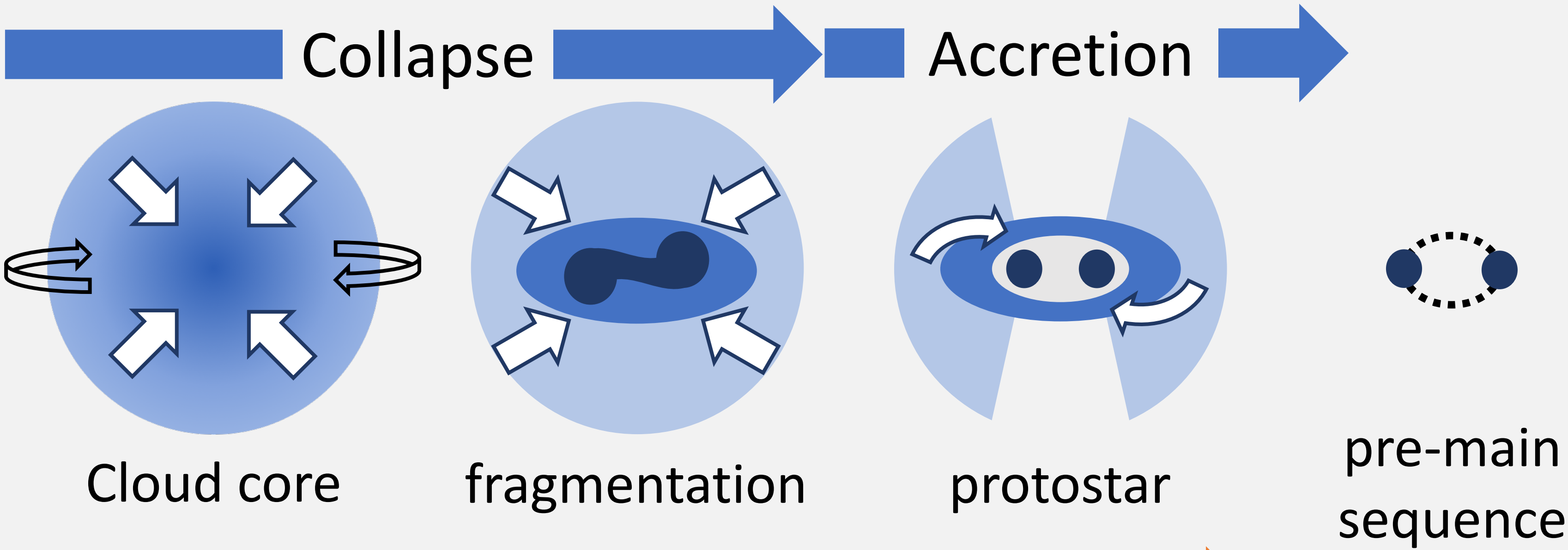


Machida+ 2007

- How to transfer the angular momentum?

We paid attention to magnetic braking during the collapse of a molecular cloud core.

Previous works on the formation of binaries



Simulation

Kuruwita+ (2017) : Ideal MHD, Low-mass, 1 model

3000 yr since sink particle formation

Modeling the magnetic braking effect

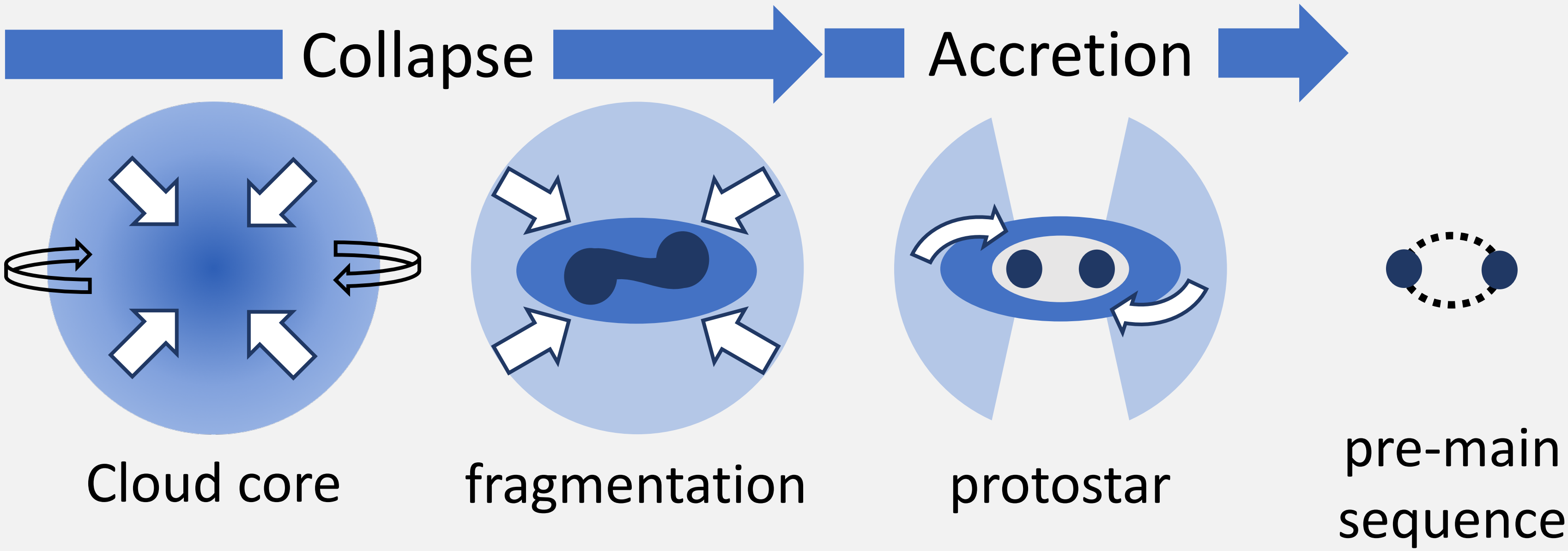
$$\tau = \frac{\boldsymbol{B}_{\mathrm{z}}\boldsymbol{B}_{\phi}R}{2\pi}$$

$$J_{\mathrm{new}} = J - I_f\tau(R)\Delta t$$

Semi Analysis

Lund & Bonnell (2018)

Overview of this work



This work：

3D non-ideal MHD simulation + analytical model, 8 models

$\sim 5\times10^{4}$ yr since sink formation

We investigated the magnetic braking effect on the long-time evolution of the separation!

Methods : Outline of this work

Simulation

Set one sink at the center

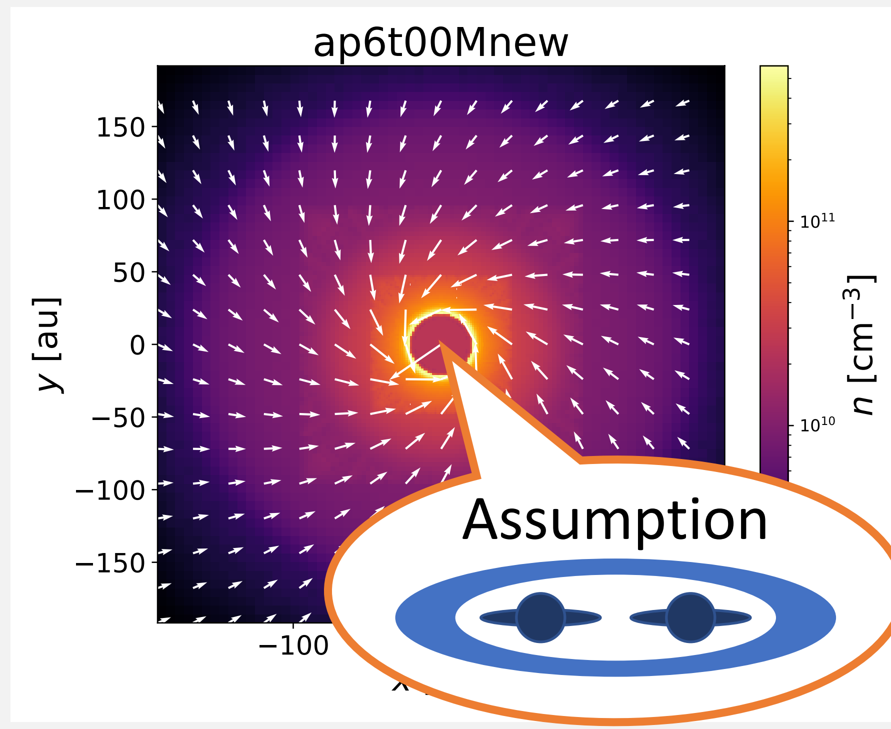
Analysis

Estimate the separation by sink data

Calculate how much M & J are brought into the center with magnetic braking working.

Two sink thresholds

$n_{sink} = 10^{10}\ cm^{-3}, r_{sink} \approx 21\ au$



Simulation set up

- Basic equation

$$
\begin{cases}
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0 \\
\rho \left[\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \nabla) \boldsymbol{v} \right] \\
\quad = -\nabla P - \rho \nabla \Phi - \frac{1}{\mu} \boldsymbol{B} \times (\nabla \times \boldsymbol{B}) \\
\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \eta \nabla^2 \boldsymbol{B} \\
\nabla^2 \Phi = 4\pi G \rho \\
P = P(\rho)
\end{cases}
$$

- Initial condition

~~Critical Bonnor-Ebert sphere~~

$M_{cloud} = 100\ [M_{\odot}]$

$n_{center} = 3.9 \times 10^4\ [cm^{-3}]$

$\beta \equiv E_{rot}/E_{gra} = 0.02$

$\mu \equiv \frac{M/\phi}{(M/\phi)_{crit}} = \infty\ or\ 3$

$\mathrm{T} = 10\ [\mathrm{K}]\ (isothermal)$

$n_{sink} = 10^{10}\ [cm^{-3}]$

- Simulation code

Nested Grid Code (Machida & Hosokawa 2013)

Stellar evolution （Hosokawa+ 2011）

Parameter

We studied α, θ dependence of the separation evolution.

$\alpha \equiv E_{th}/E_{gr}$

=> Accretion rate is depend on α.

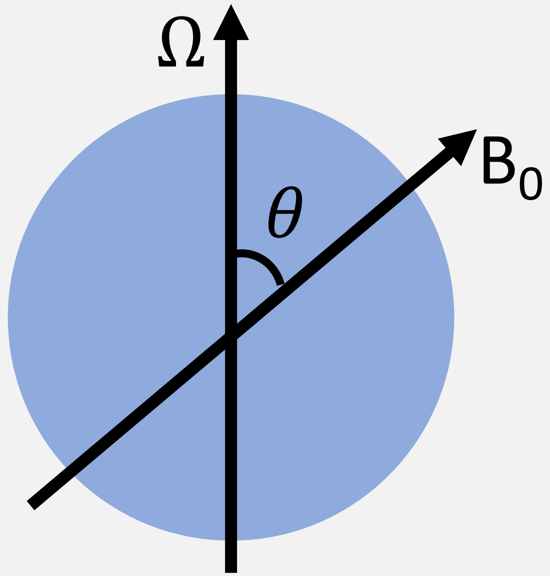
$\theta \equiv$ Inclination b/t B_0 direction & rotation axis

=> Efficiency of angular momentum transfer is depend on θ.

$\alpha = 0.2$
$= 0.6$

×

Non-Mag
$\theta = 00°$
$= 45°$
$= 90°$



Assumption & Analytical model

- Assumption

  Binary system formed in sink region and

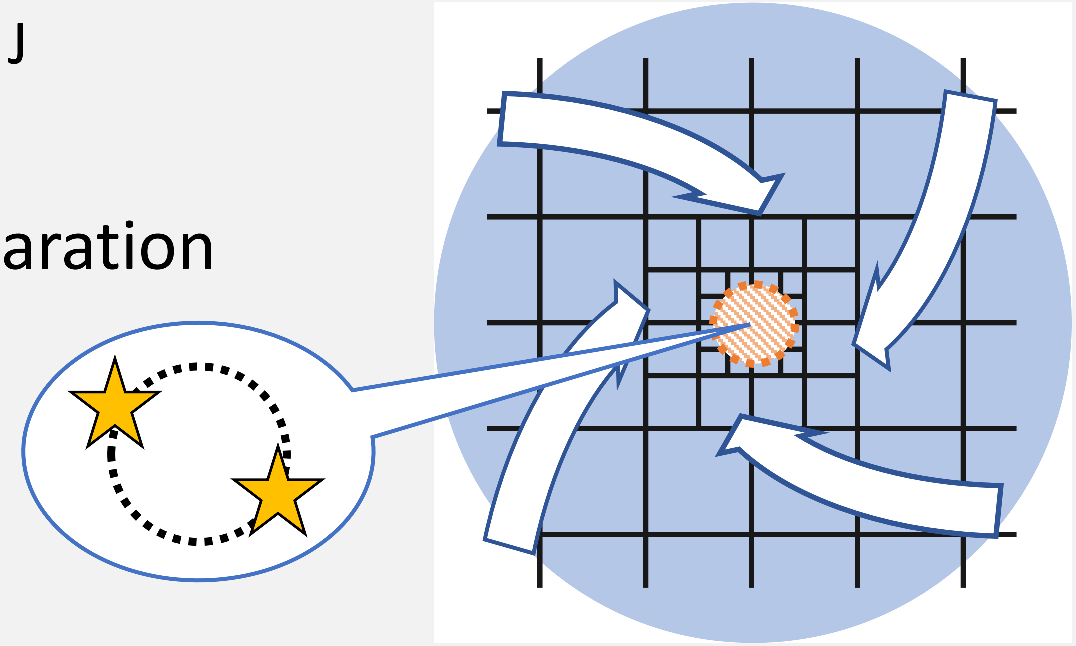
  $M_{tot} = M_{sink}, J_{tot} = J_{sink}$

  M_{tot} : Binary's total mass,

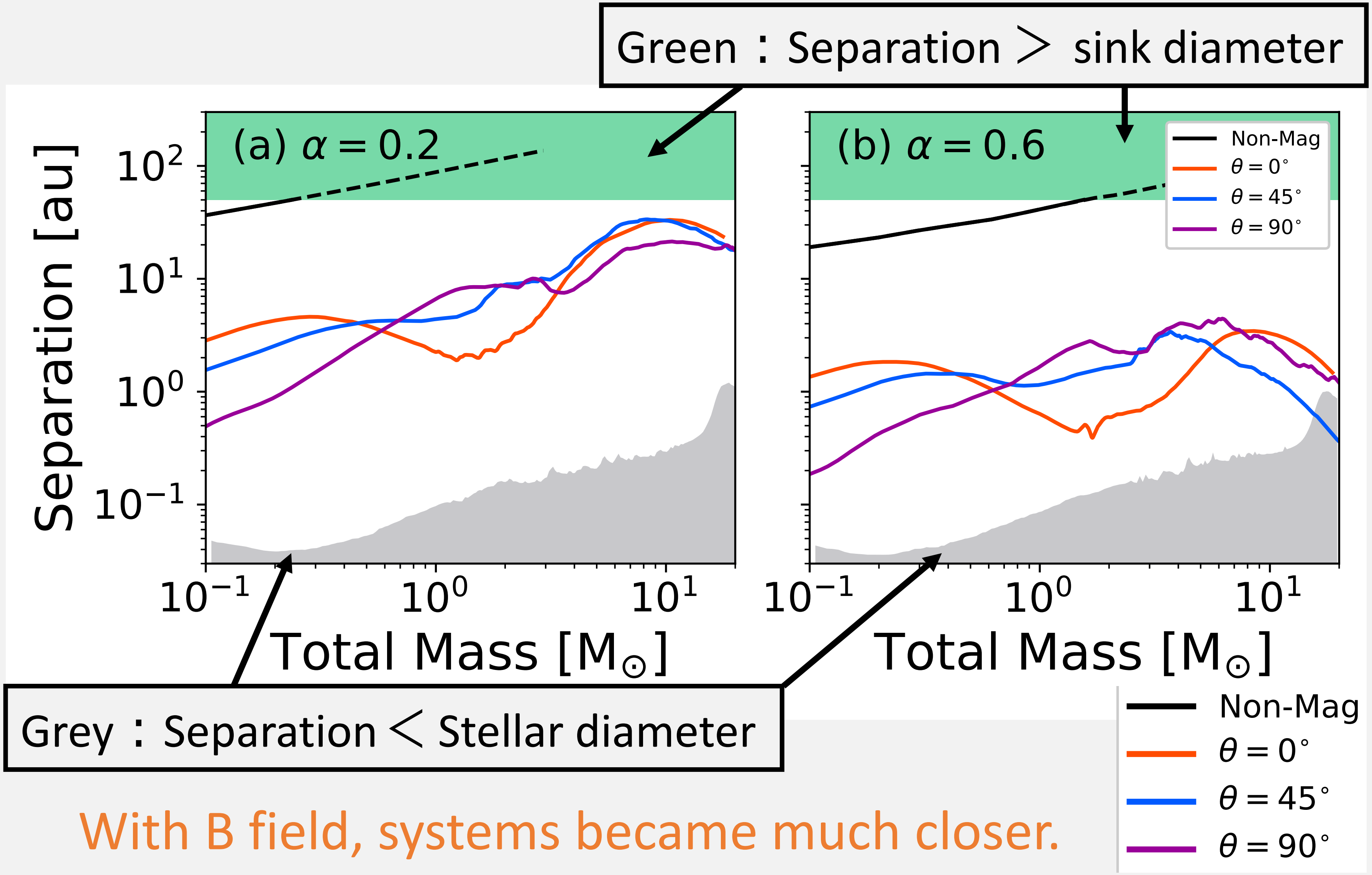
  J_{tot} : Binary's total J

- Calculate the separation

$$s = \frac{16}{G}\frac{J_{tot}^2}{M_{tot}^3}$$

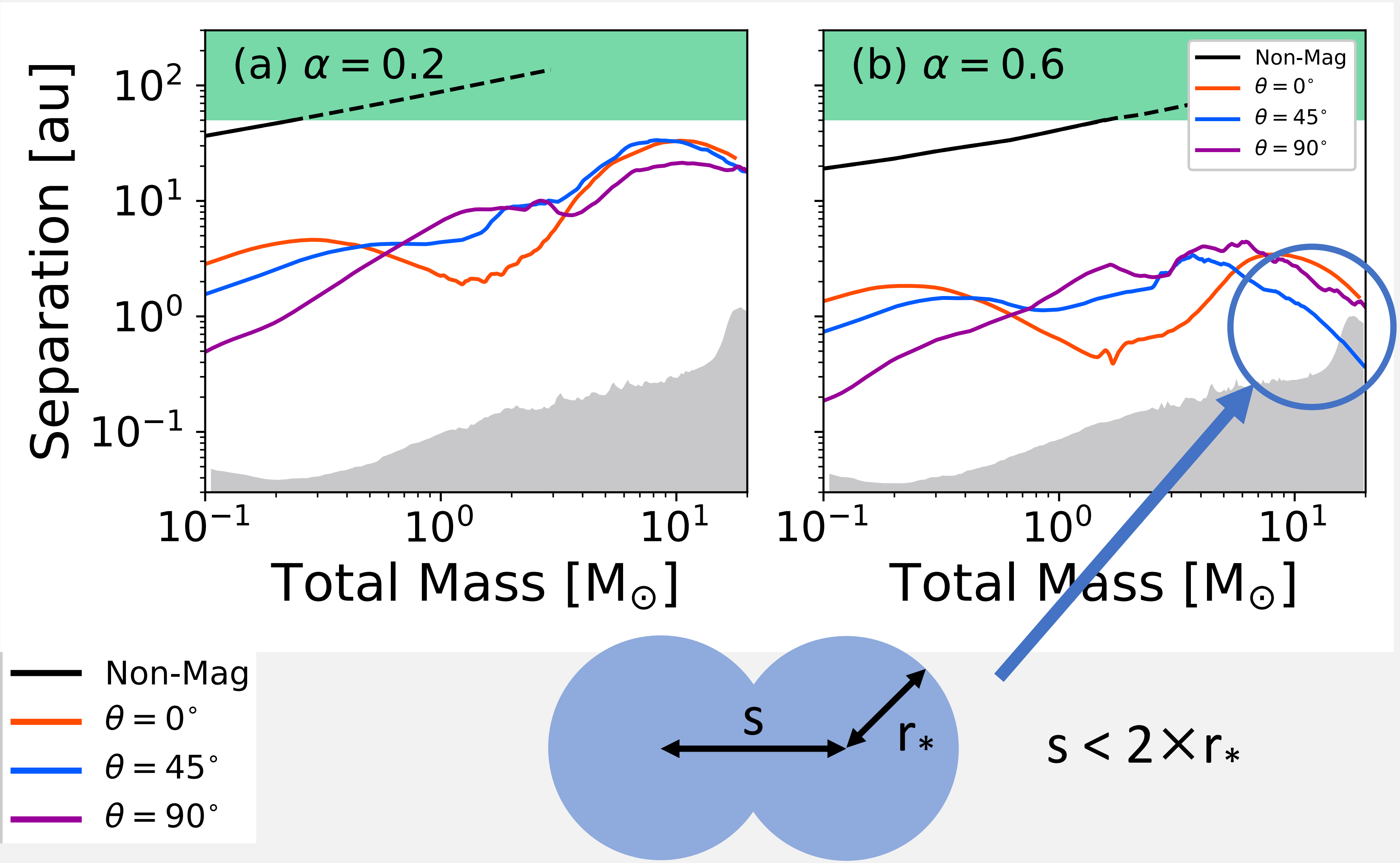


Results：Time evolution of the separation

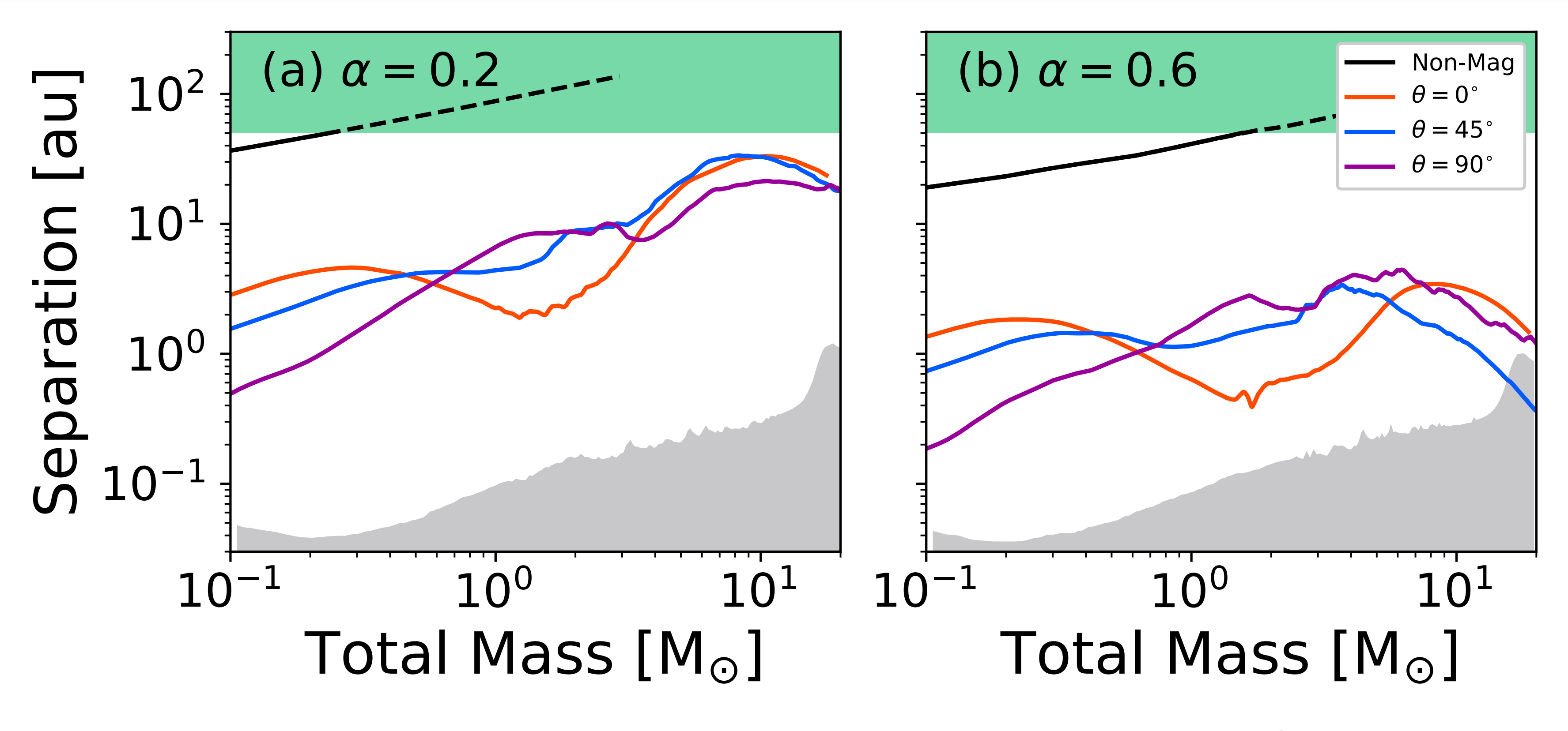


With B field, systems became much closer.

Formation of the Contact Binary

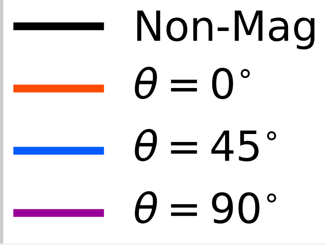


α dependence



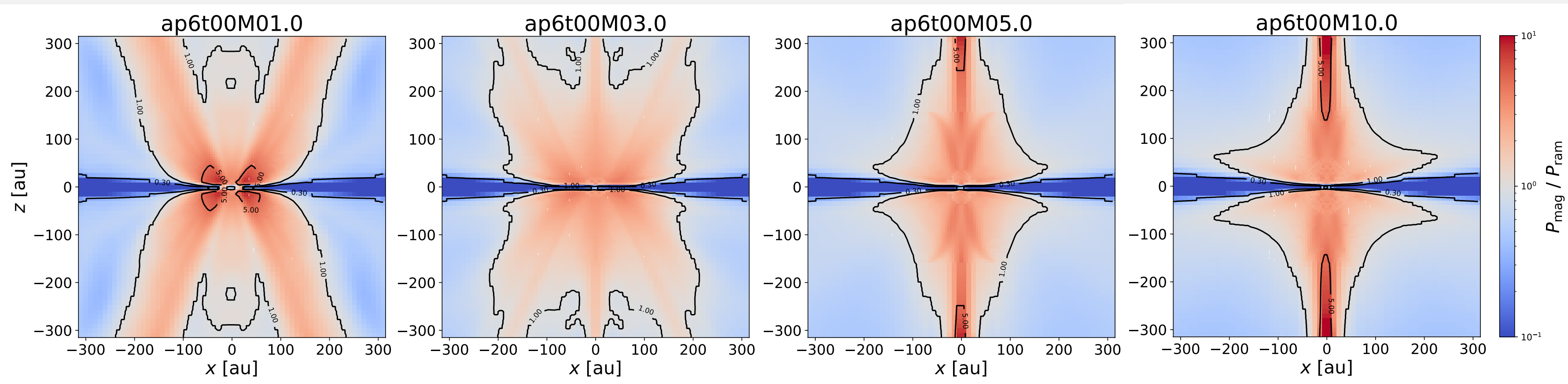
Large α => Close separation

← Angular momentum is more transferred because the collapse time became longer.



Discussion：Why the separation fluctuated?

xz plane of α=0.6, θ=0° at M={1,3,5,10}



Red regions :

$P_{Mag}/P_{ram} > 1$ … $P_{Mag} \equiv B^2/2\mu_0, P_{ram} \equiv \rho v^2$

The change of this configuration caused the separation fluctuations?

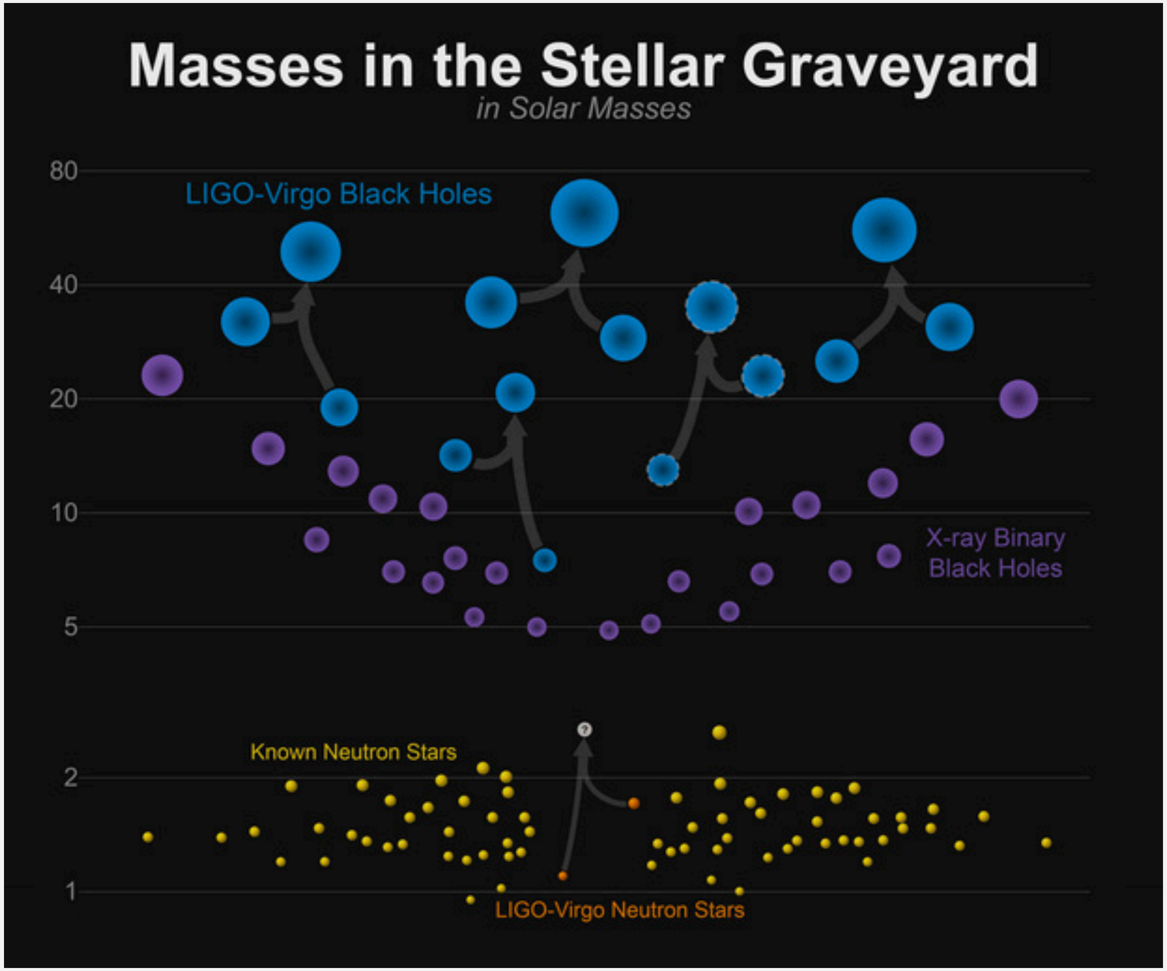
Summary

By MHD simulation + Analytical model,
we investigated long-time evolution of the separation.

- Angular momentum transfer by magnetic braking is necessary to form high-mass close binaries!
- α dependence…
  Larger α model evolved closer system.
- θ dependence…
  The relationship is reversed several times.
- Separation fluctuation
  It is caused by the change of $P_{Mag}/P_{ram} > 1$ region?

Appendix

Origins of Binary-BH, NS



LIGO-Virgo/
Frank Elavsky/
Northwestern
University

High-Mass Close Binary can evolve to Binary-BH or NS.

Sink setting

- Set two thresholds, n_{sink} & r_{sink}.
- Renew the sink parameters every step based on…

$$M_{\rm add} = \int_{r<r_{\rm sink}} {\rm C_{acc}}\, \mu m_{\rm p}(n - n_{\rm sink})\, {\rm dV}$$

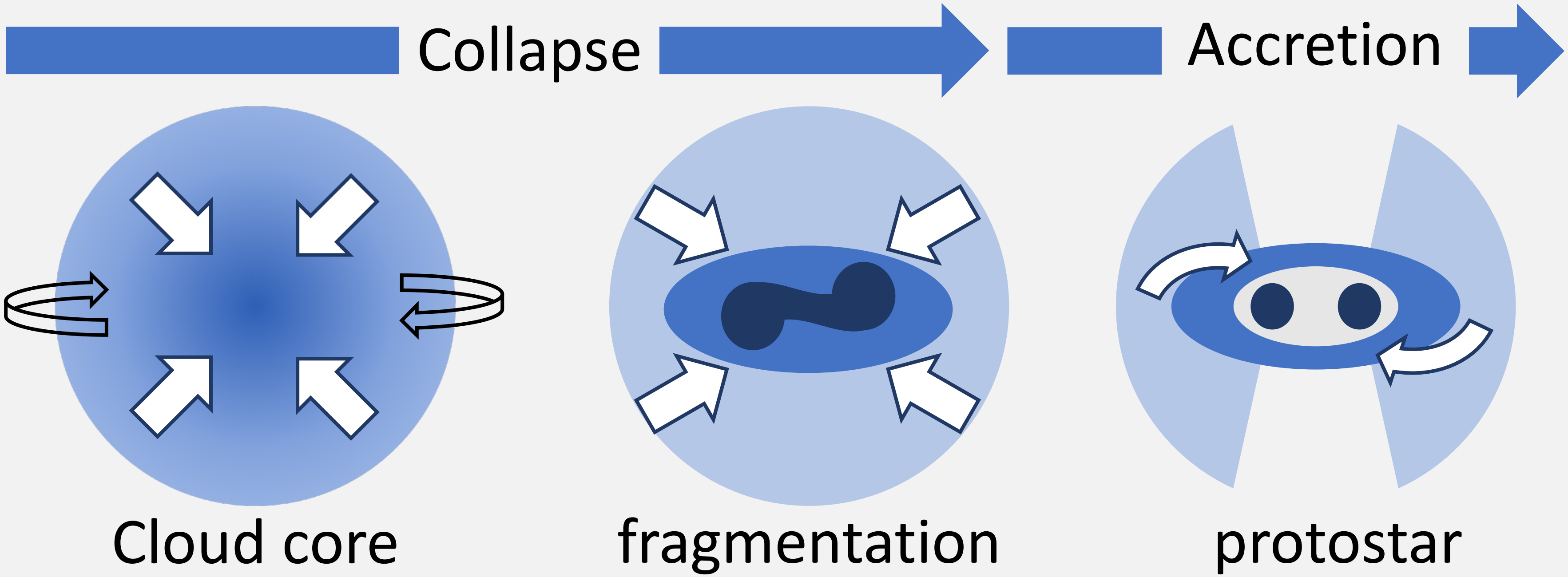
$$\boldsymbol{J}_{\rm add} = \int_{r<r_{\rm sink}} {\rm C_{acc}}\, \mu m_{\rm p}(n - n_{\rm sink})\, \boldsymbol{r} \times \boldsymbol{v}\, {\rm dV}$$

$$M_{\rm sink,new} = M_{\rm sink,old} + M_{\rm add}$$

$$\boldsymbol{J}_{\rm sink,new} = \boldsymbol{J}_{\rm sink,old} + \boldsymbol{J}_{\rm add}$$

- In this work, $C_{acc} = 0.03,\ r_{sink} = \frac{1}{2}\lambda_J = \frac{1}{2}\sqrt{\frac{\pi}{G\mu m_p n_{sink}}}\, c_s$

Previous works on the formation of binaries



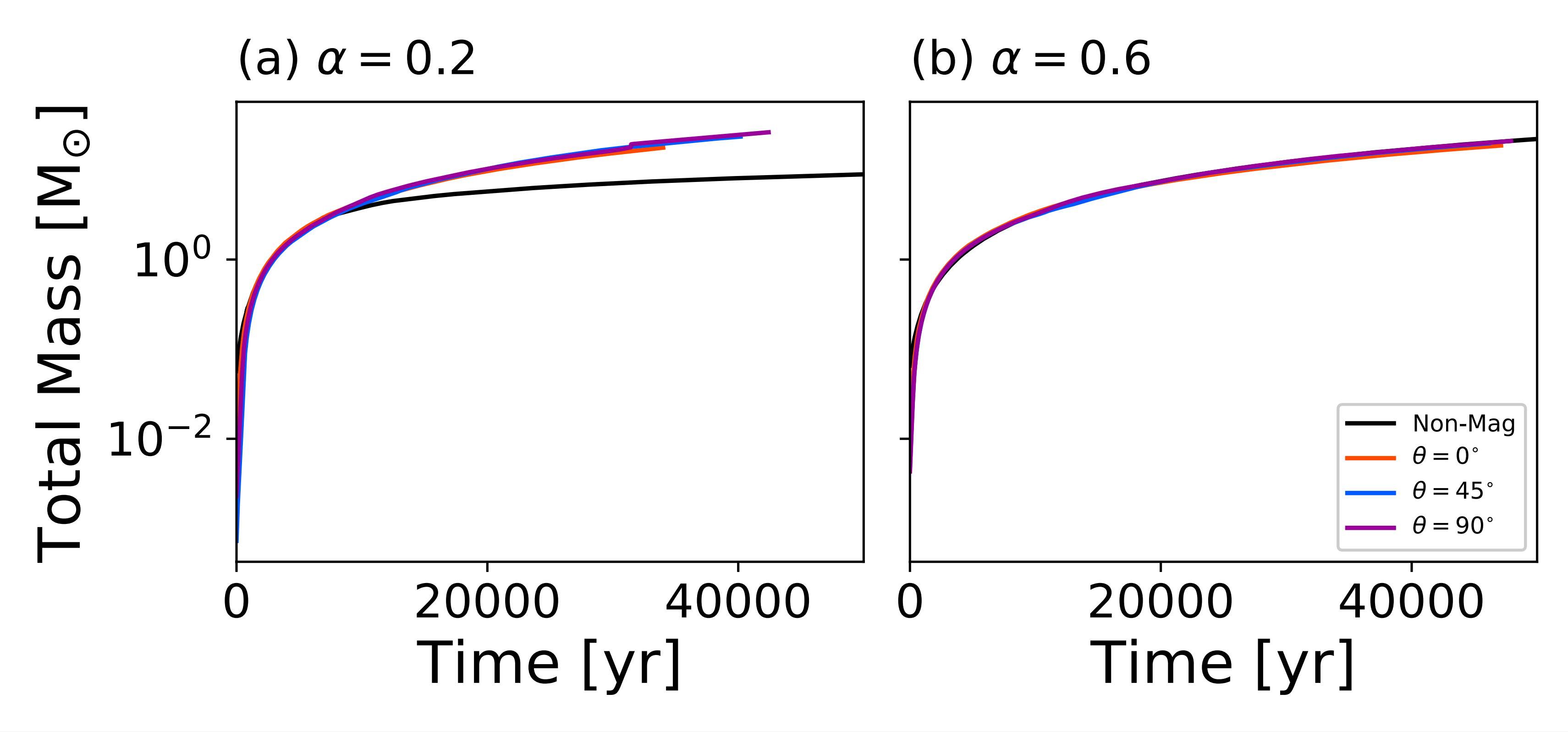
Simulation

Matsumoto & Hanawa (2003)
Machida+ (2008)

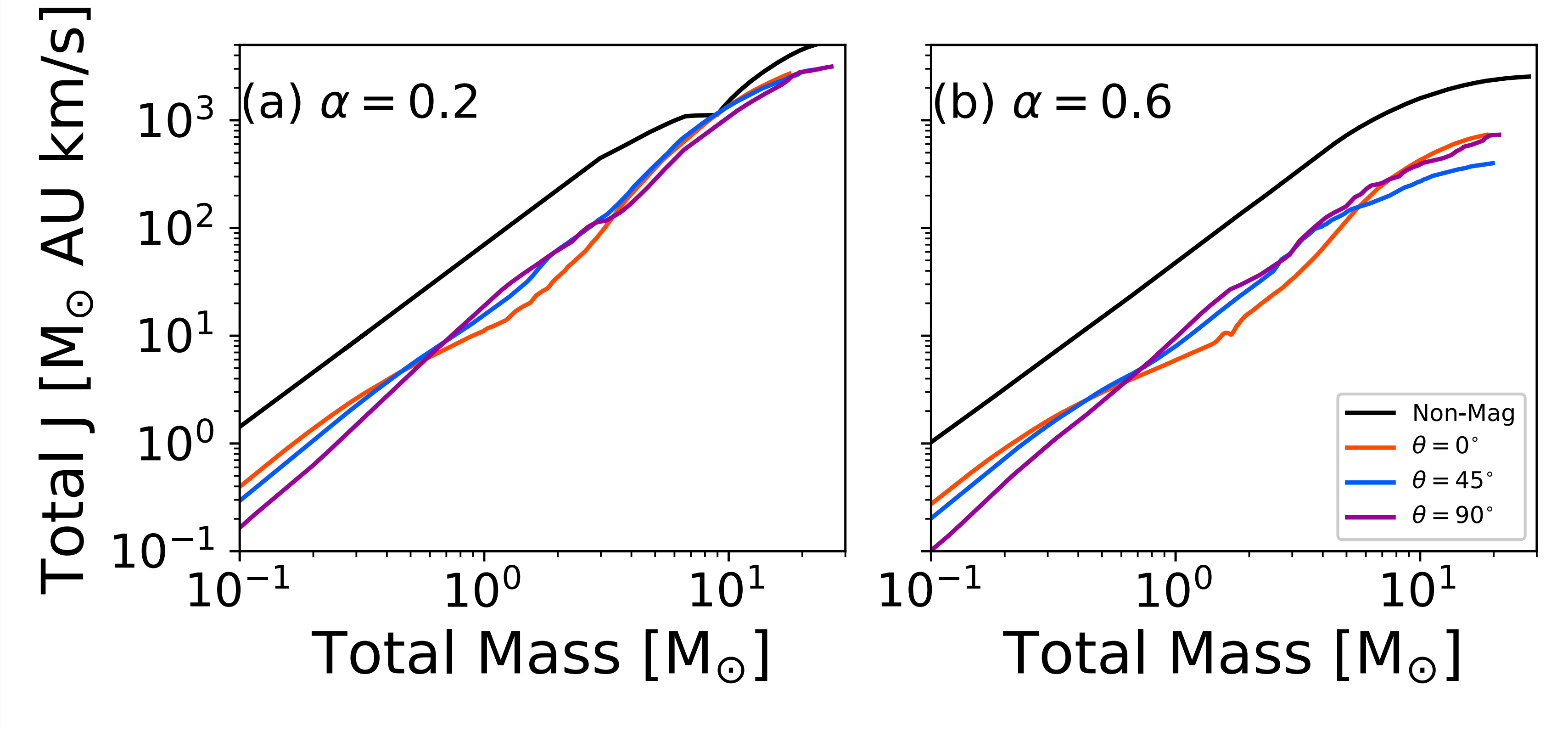
Semi Analysis

Lund & Bonnell (2018)

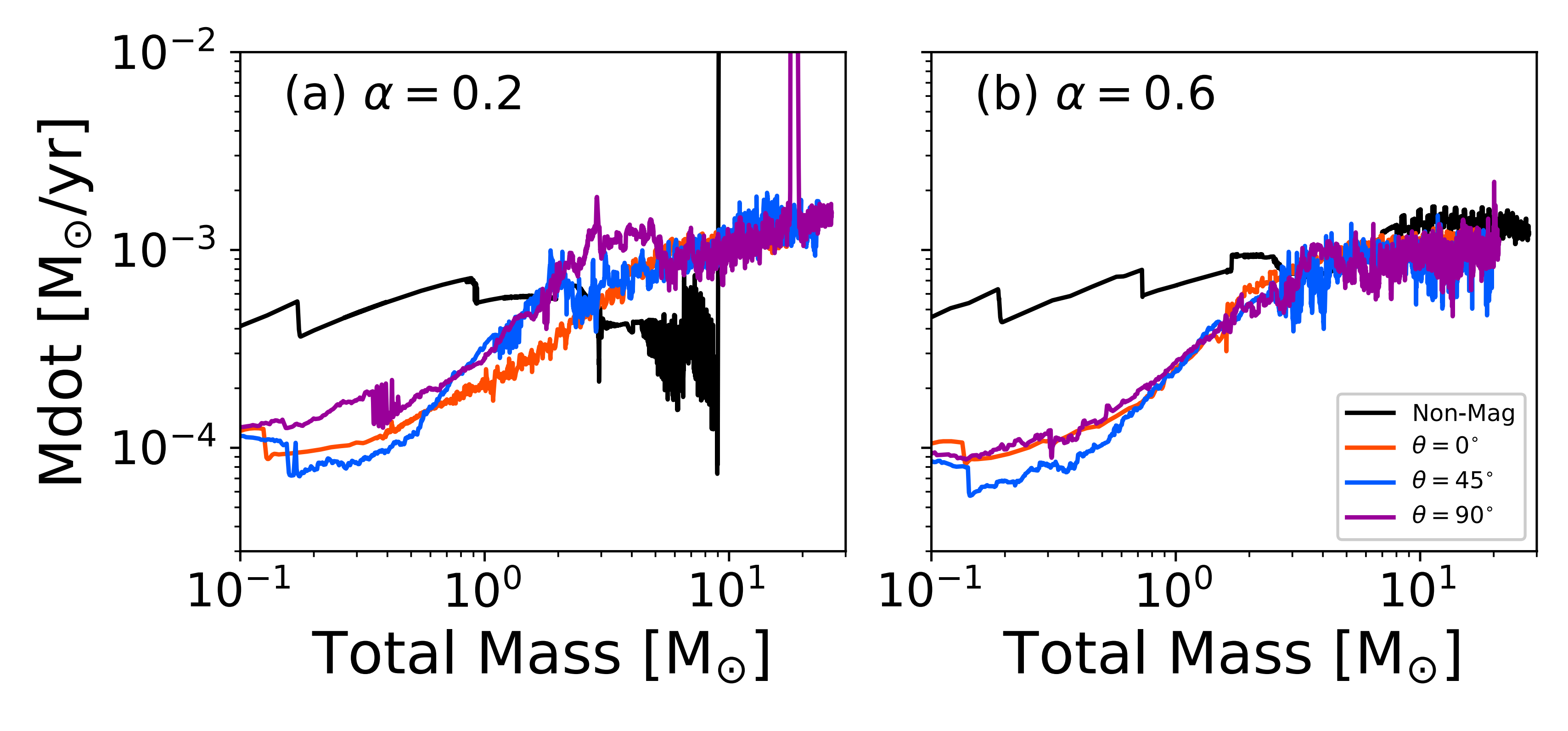
Mass-Time plot



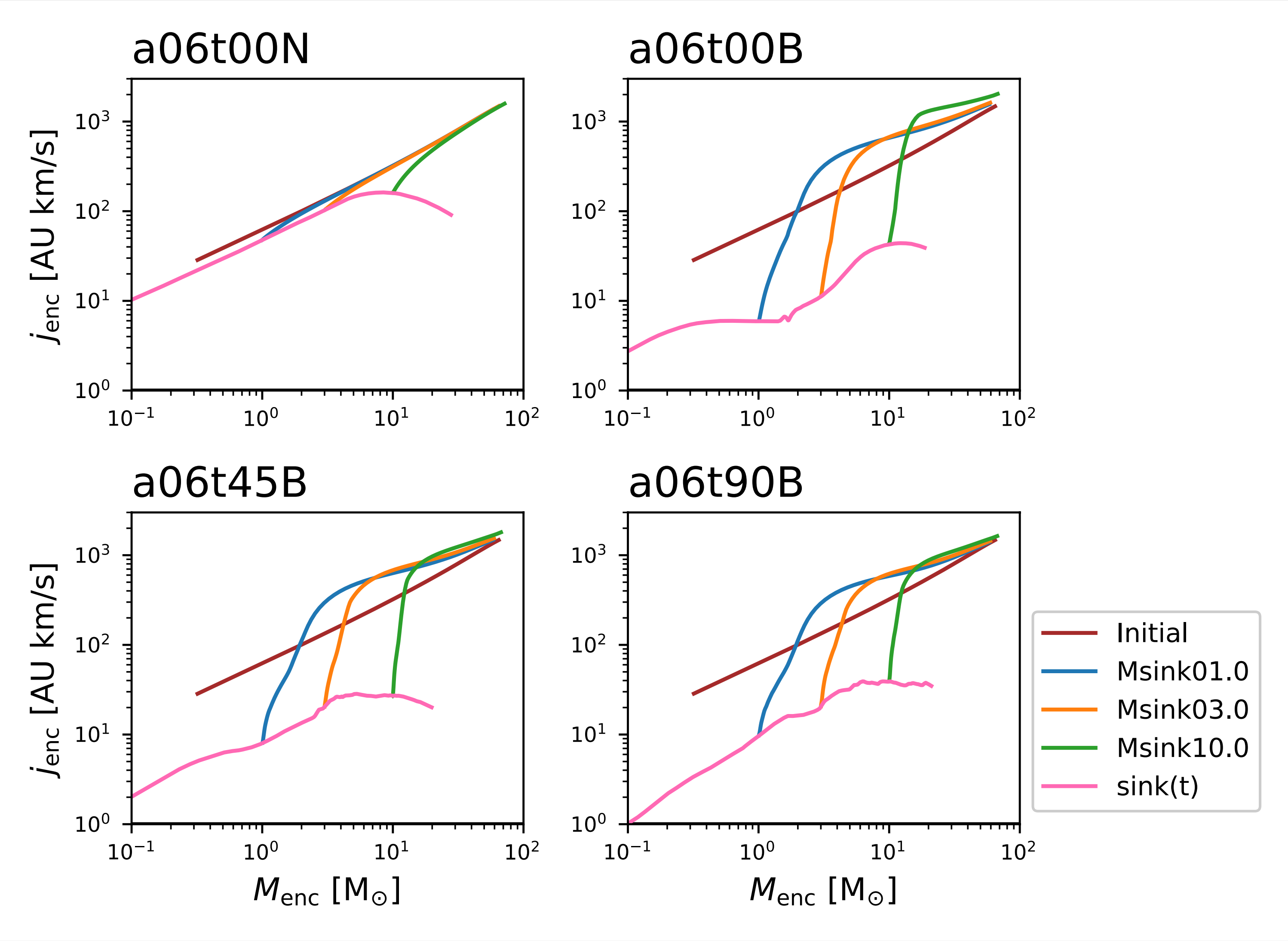
Angular momentum-Mass plot



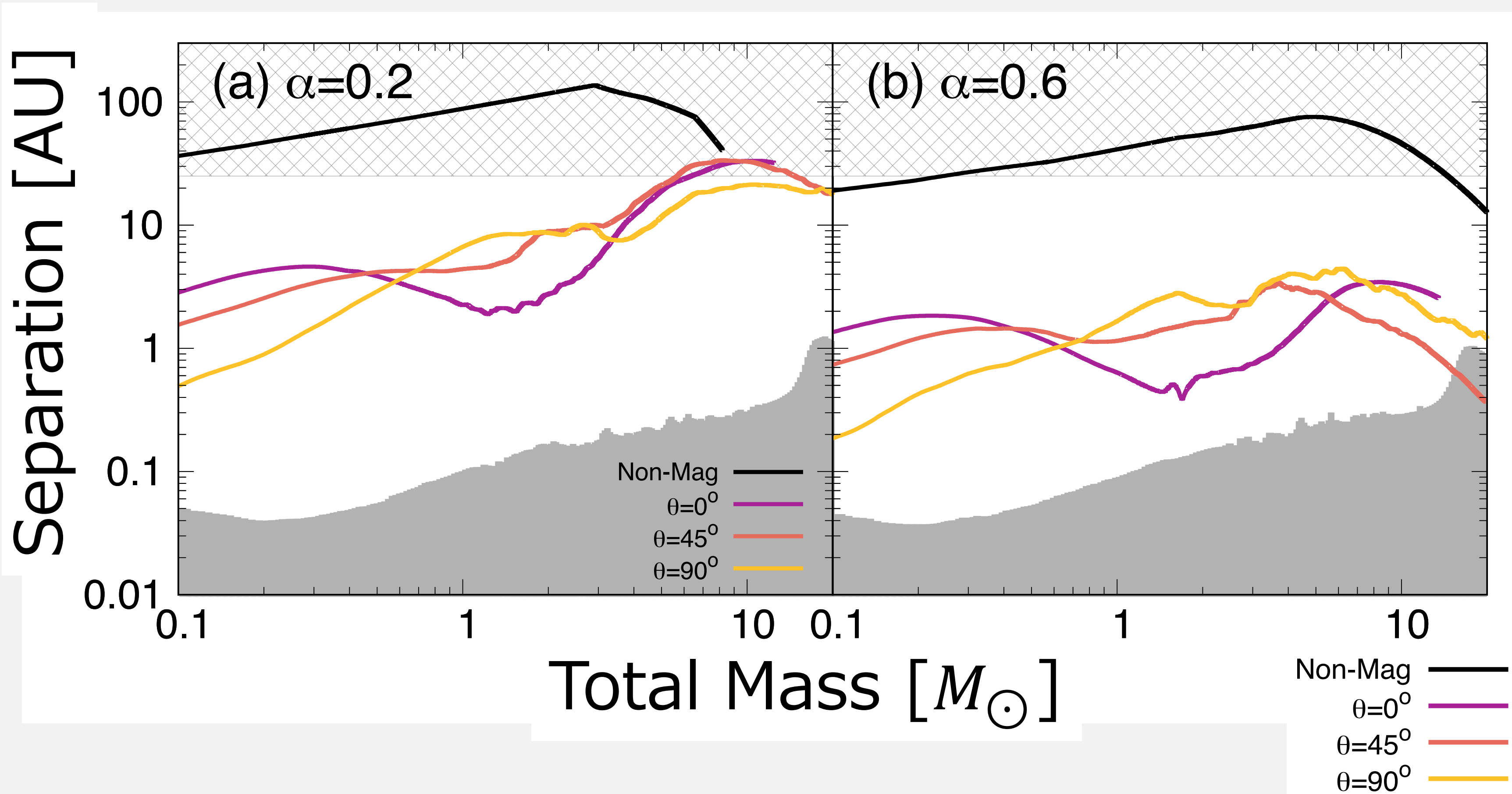
Mdot-Mass plot



Angular momentum transfer



θ dependence



Early stage：The larger θ is, the closer the separation is.

Late stage：The relationship is reversed several times.