



Magnetic-Field-Driven Orbital Decay in Accreting Binary Systems

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Introduction: binary statistics

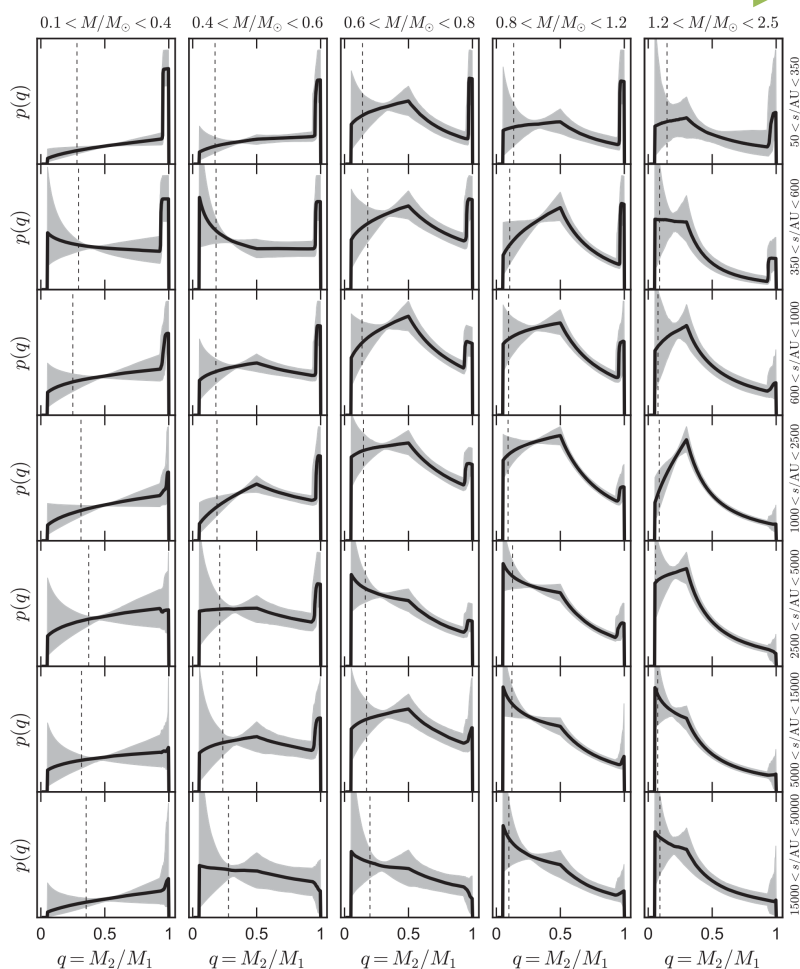
Equal-mass binaries are frequent across a wide parameter range

(mass $> 0.1 M_{\odot}$, separation 0.01–10,000 au)

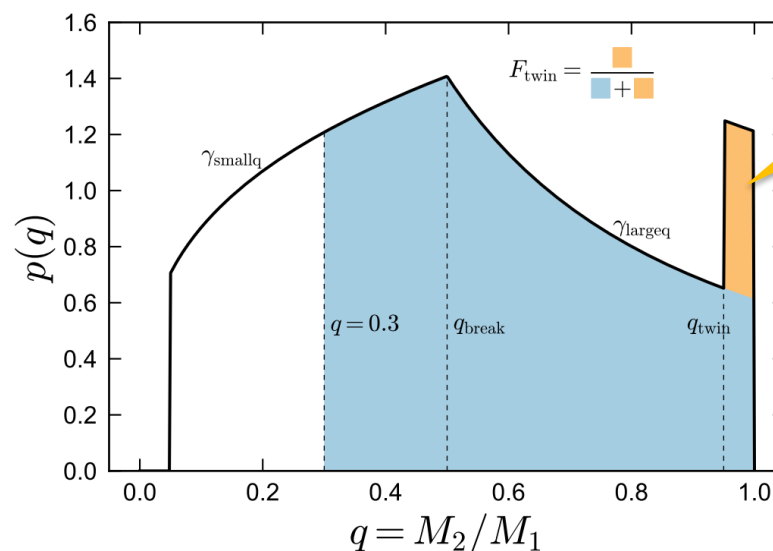
(El-Badry+ 2019, Gaia DR2)

Low-mass

Massive



Mass-ratio distribution



Twin excess

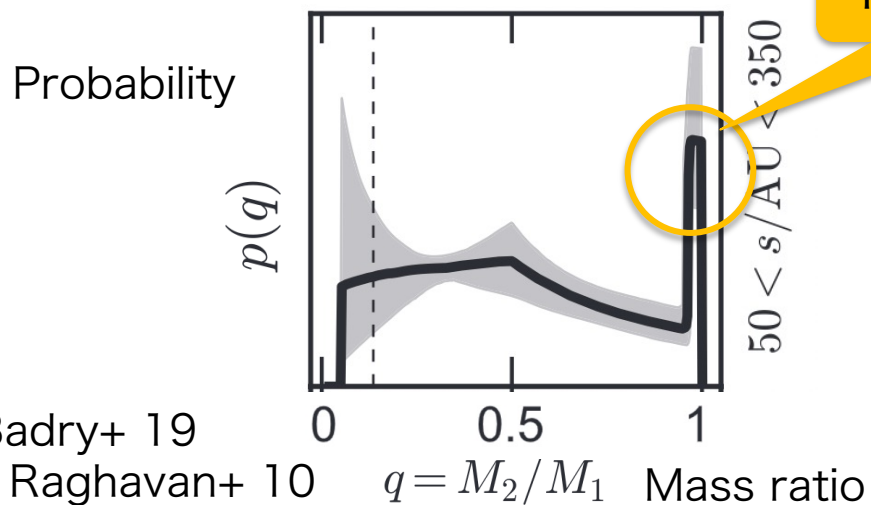
Twin binaries
 ↑
 Accretion in CBD
 ↑
 Disk fragmentation

For OB stars (Moe+ 17)

For close binaries, $s < 0.01$ au (Raghavan+ 10)

Problem: Magnetic field can form close binaries?

- ① **Twin excess** is common for $s = 0.01 - 10,000$ au

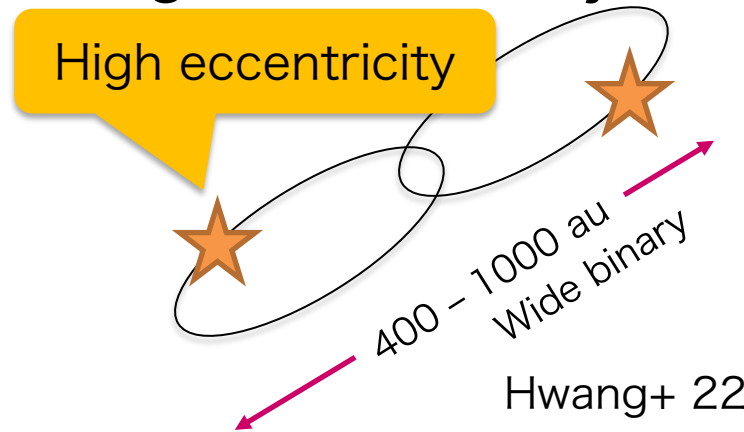


Twin excess

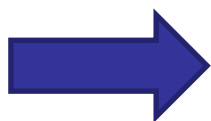
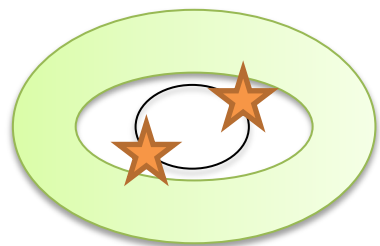
- ✓ Disk fragmentation
- Turbulent fragmentation

El-Badry+ 19
c.f., Raghavan+ 10

- ② **Wide** twin binaries tend to have high eccentricity



Formation scenario of **wide** twin binaries



① Twins form in circumbinary disk ~ 100 au

② Scattered via dynamical interaction

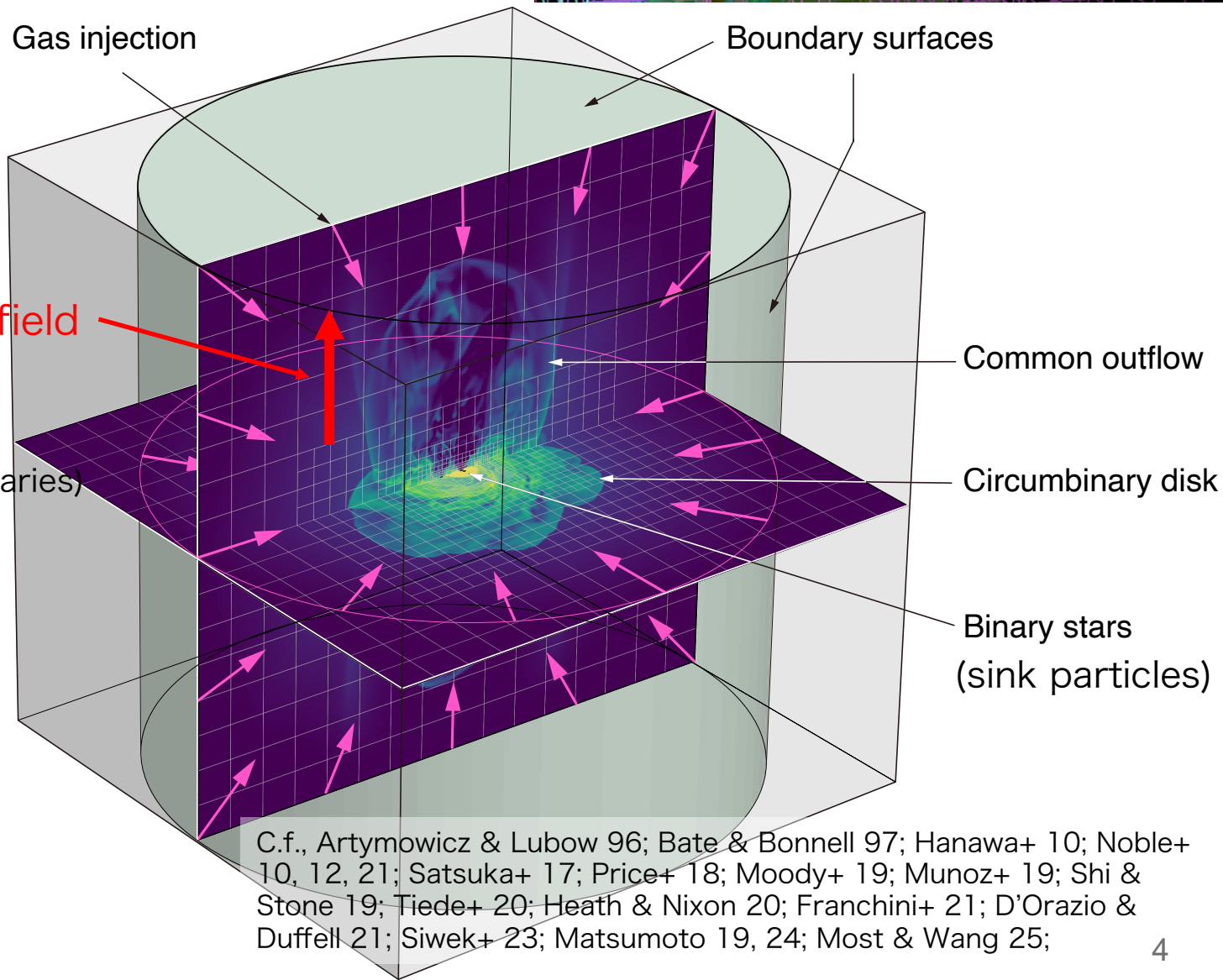
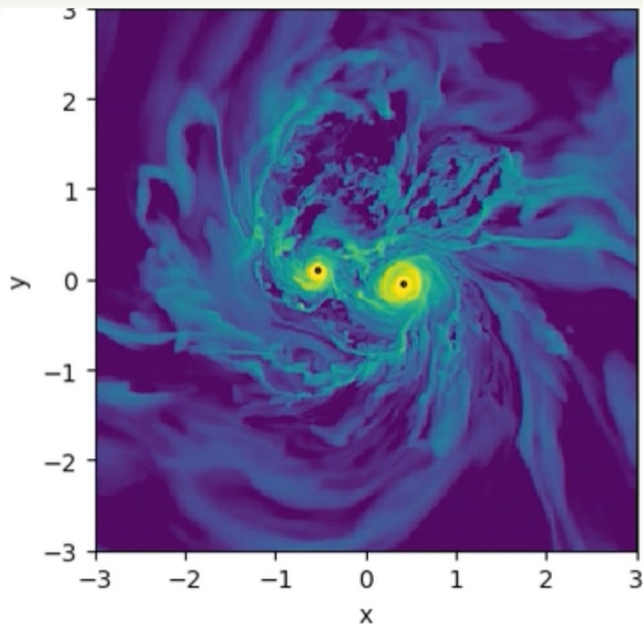
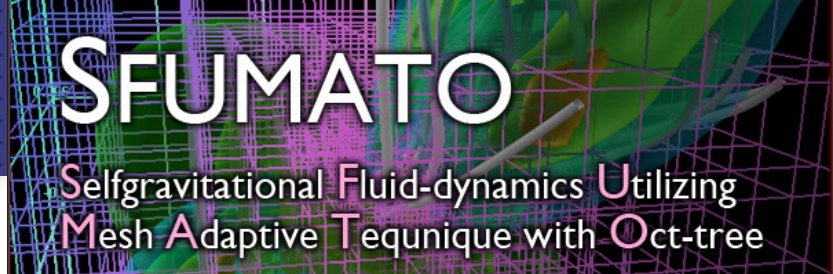
Remaining problem

How are **close** twin binaries formed?

Simple idea:

Magnetic fields transfer angular momentum.
→ binary orbit shrink?

Model & Method



Infalling envelope with rotation (gas injection on boundaries)

Vertical uniform magnetic fields at initial stage

Sink particles accretes gas

Initial circular orbits; follow stellar orbital evolution

Gravitational back-reaction from gas included

Mass ratio $q = 1$ (twin binaries)

Ideal MHD, isothermal EOS.

Code: SFUMATO with SMR

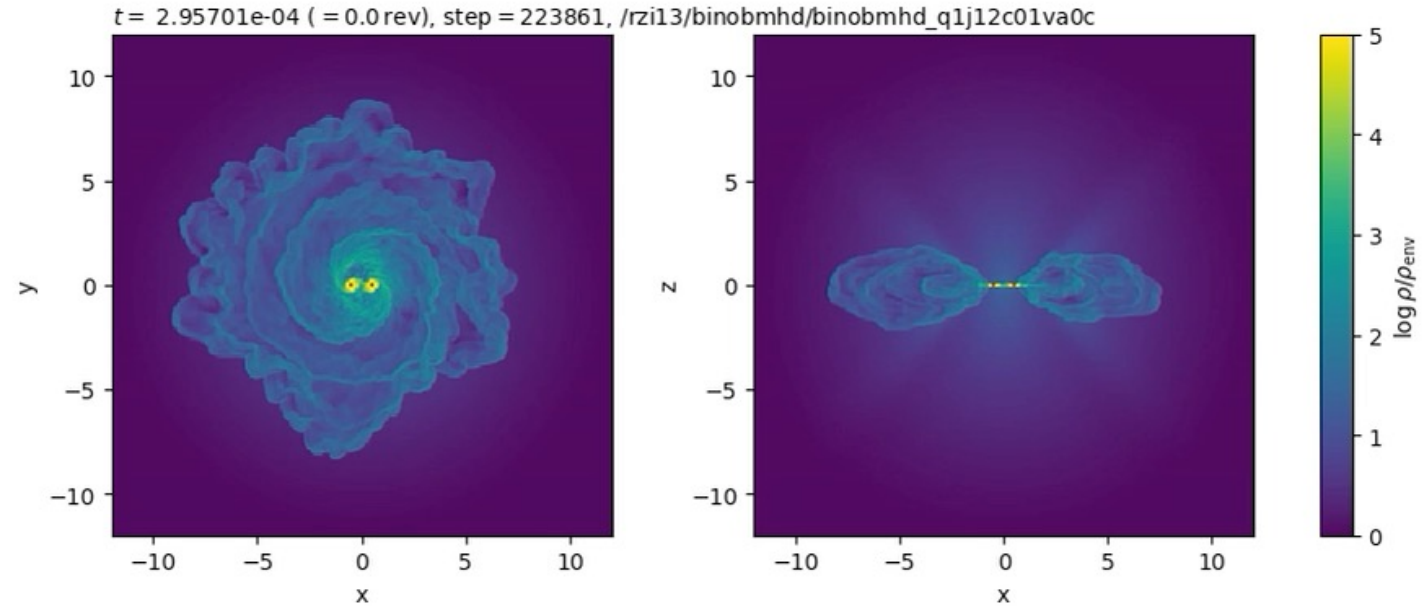
Computation: Cray XC50 @ CfCA, NAOJ (Category A)

C.f., Artymowicz & Lubow 96; Bate & Bonnell 97; Hanawa+ 10; Noble+ 10, 12, 21; Satsuka+ 17; Price+ 18; Moody+ 19; Munoz+ 19; Shi & Stone 19; Tiede+ 20; Heath & Nixon 20; Franchini+ 21; D'Orazio & Duffell 21; Siwek+ 23; Matsumoto 19, 24; Most & Wang 25;

Results: Overview ($q=1, c=0.1$)

HD model

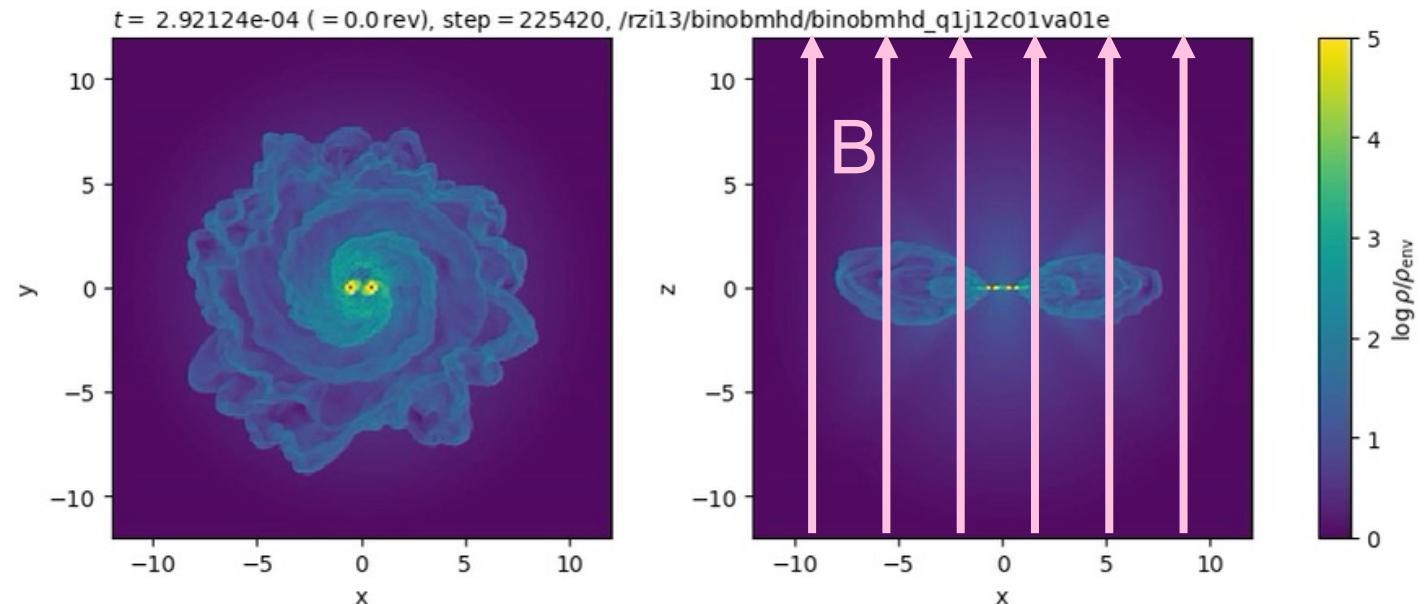
Asymmetry in CBD



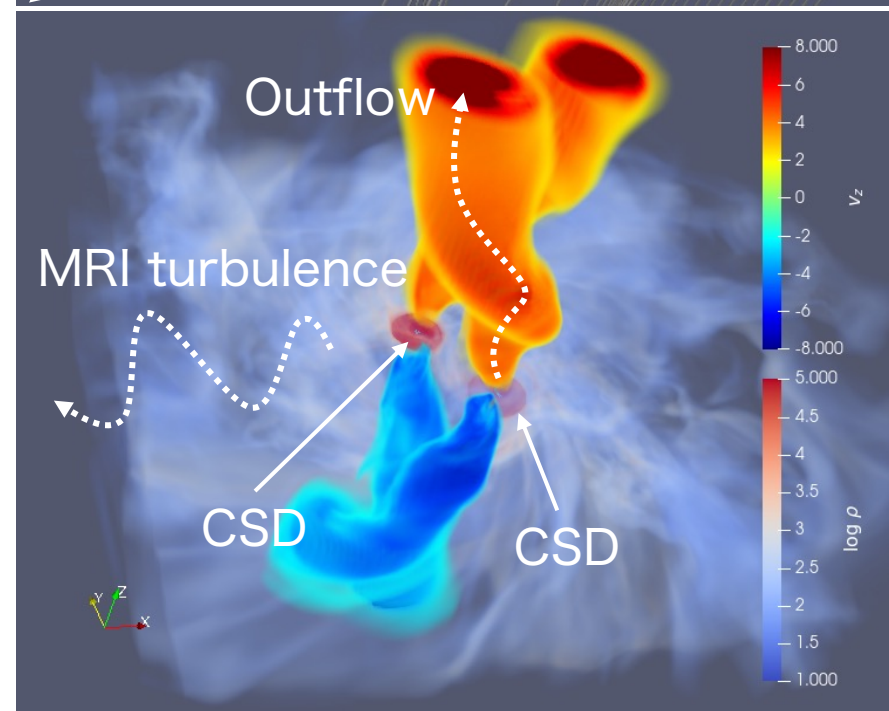
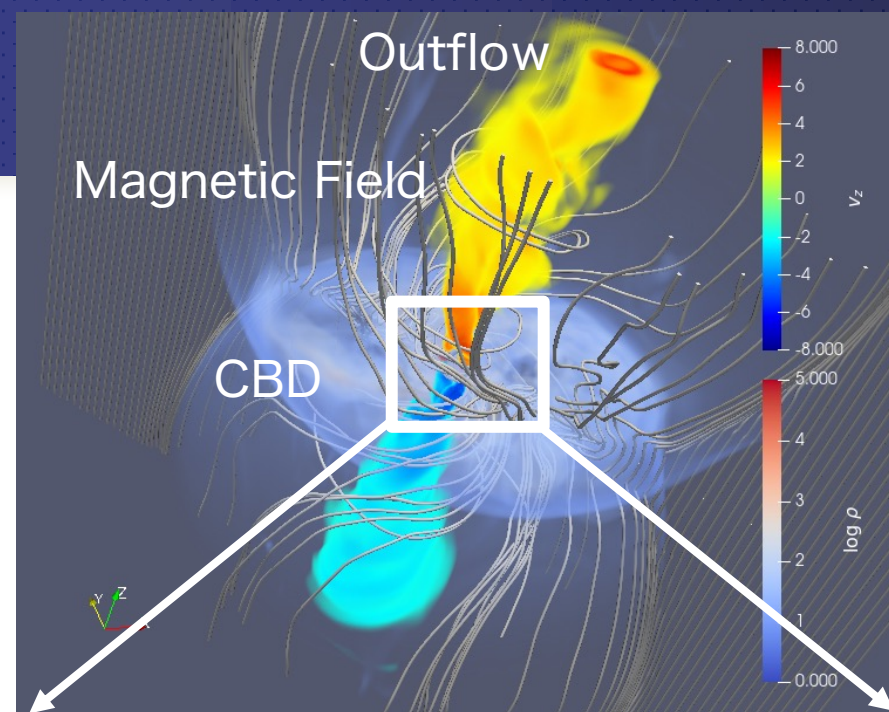
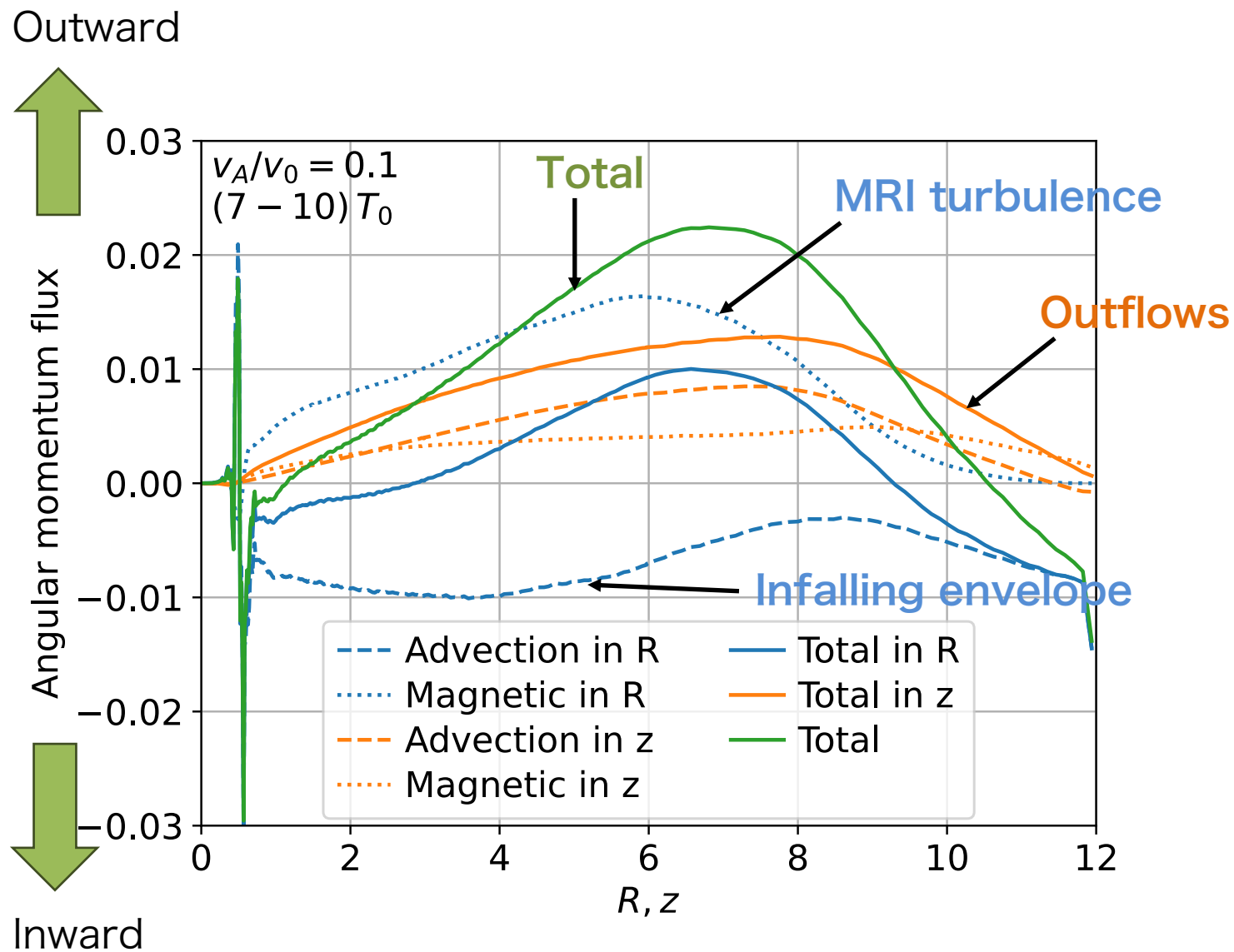
MHD model

Extended CBD with MRI
Two types of outflows:
From CSDs
From CBD

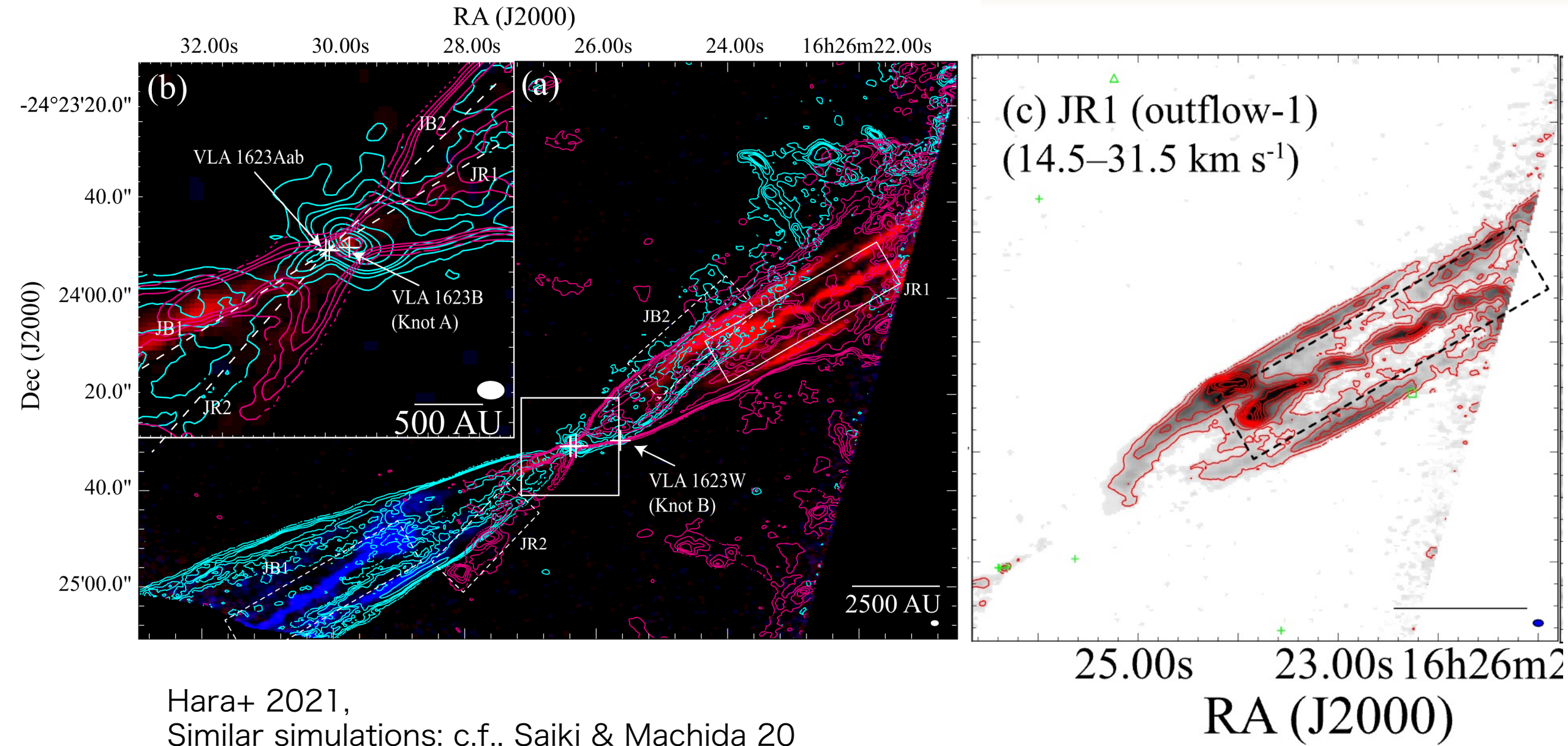
Double-helical outflows



Angular mon. transfer

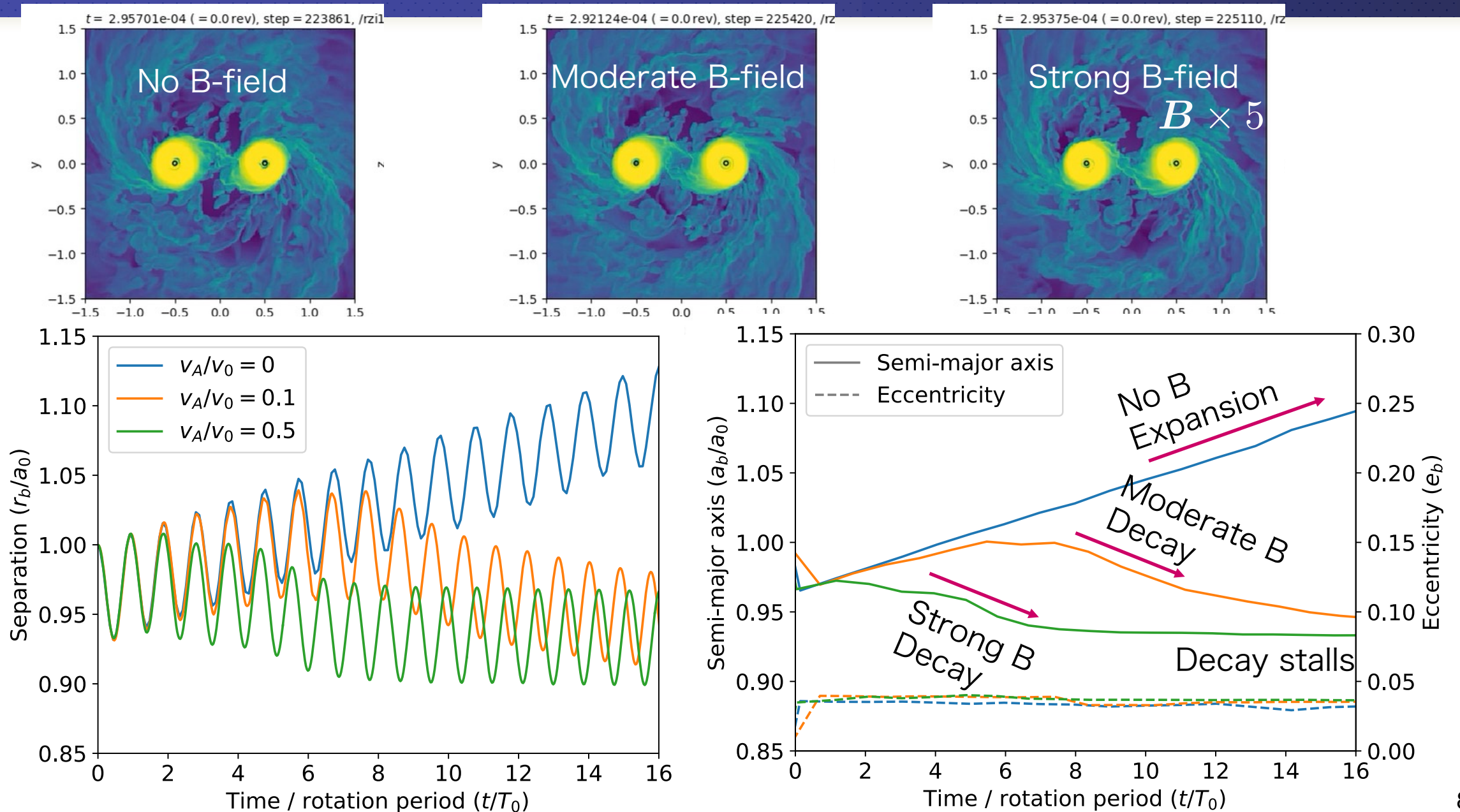


Twin helical outflows observed by ALMA

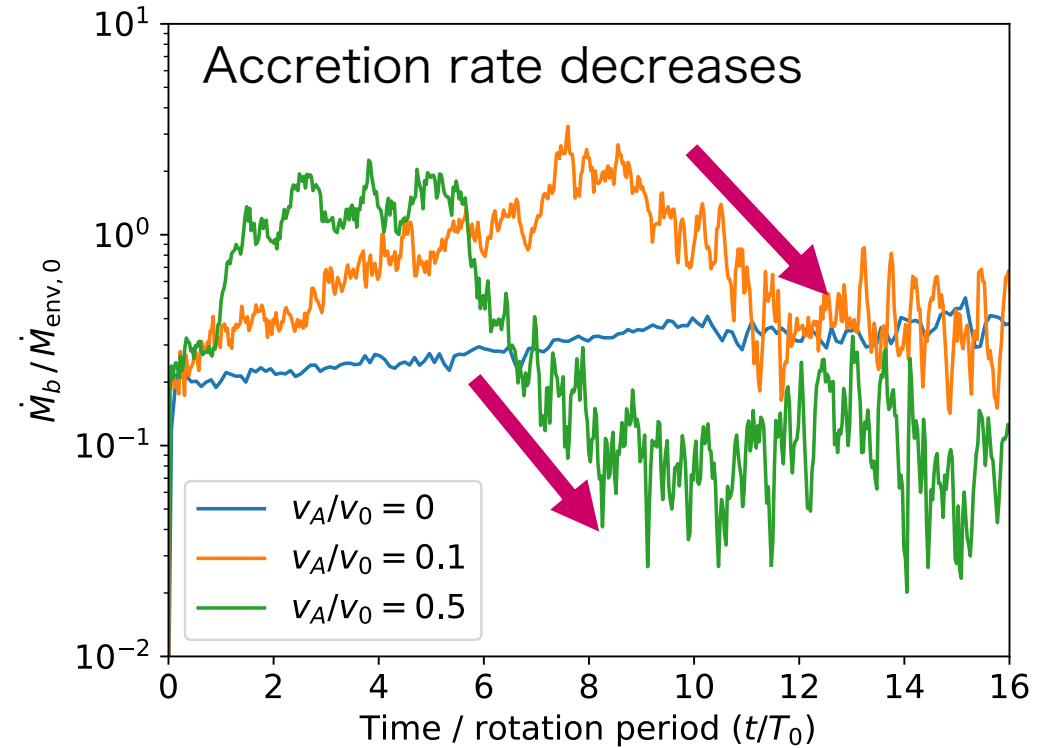
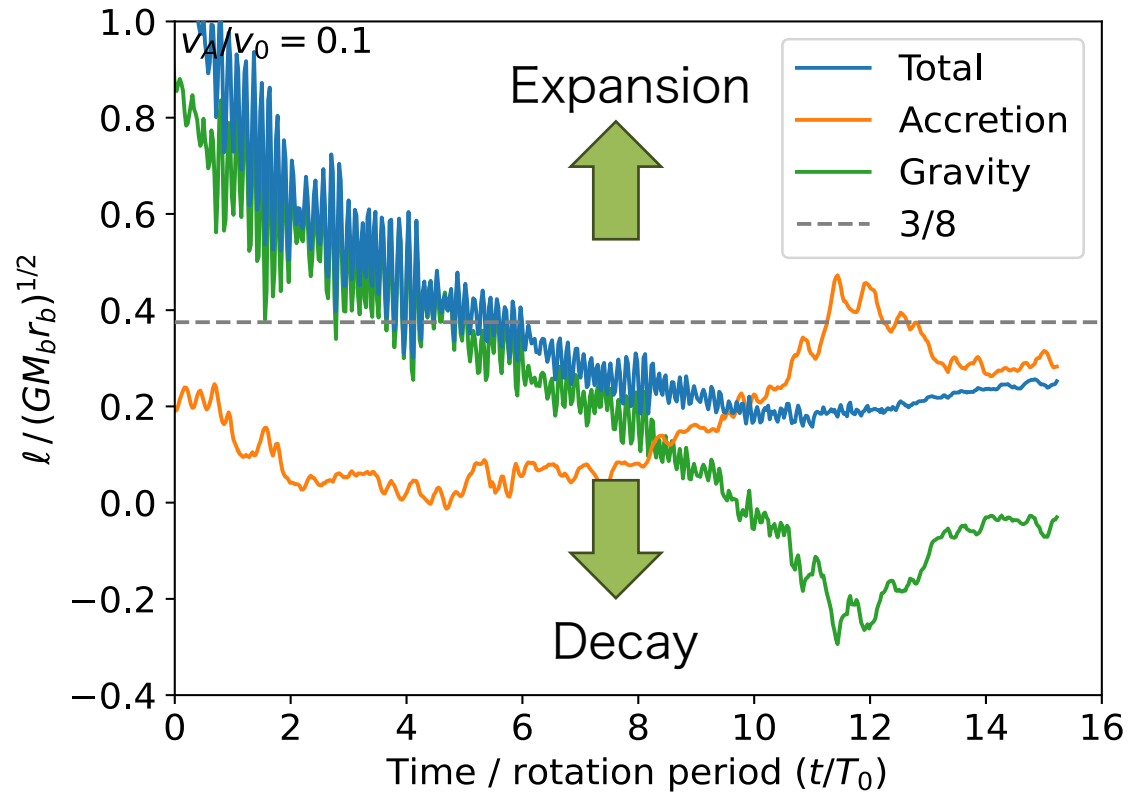


Hara+ 2021,
Similar simulations: c.f., Saiki & Machida 20

Results : binary separation shrinks for B-field models



Eigen value ℓ (specific AM of accreting gas)



$$\frac{\dot{a}_b}{a_b} = 8 \left(\frac{\ell}{a_b^2 \Omega_b} - \frac{3}{8} \right) \frac{\langle \dot{M}_b \rangle}{M_b}, \quad \ell \equiv \frac{\langle \dot{J}_b \rangle}{\langle \dot{M}_b \rangle}$$

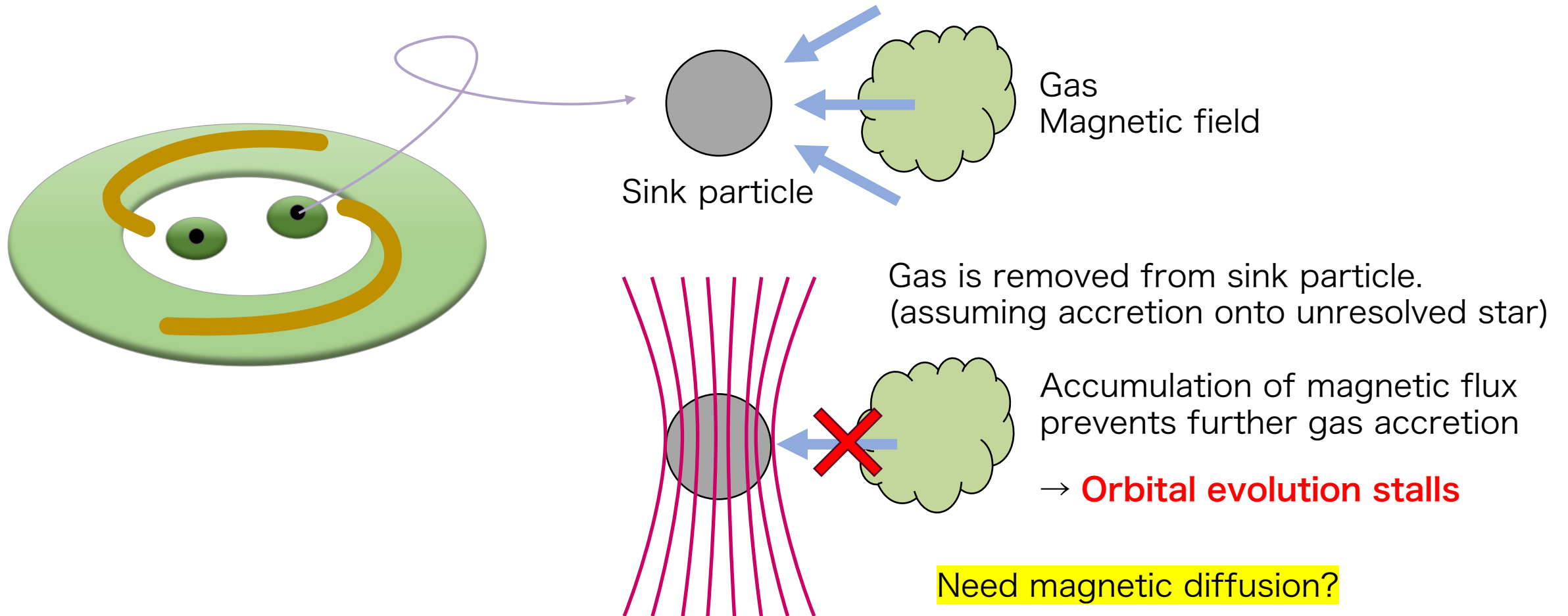
If $\ell < \frac{3}{8} a_b^2 \Omega_b$ then orbital decay

Orbital evolution is driven by accretion

Lai & Munoz (2022)

Discussion: why does orbital evolution stall?

Sink particles (binary stars) accrete both gas and magnetic field.



Summary

- We investigate **orbital decay** driven by **magnetic fields** using SMR simulations.
- Outflows and MRI turbulence **transport angular momentum outward**.
 - Double-helical outflows and a turbulent circumbinary disk (CBD) are reproduced.
 - Magnetic-field models show orbital decay, while the HD model shows orbital expansion.
- **Orbital decay occurs by magnetic fields**, but it **stalls** as the accretion rate decreases.
 - Magnetic dissipation processes (e.g., Ohmic dissipation and ambipolar diffusion) may be required for more realistic modeling.

Backup Slides

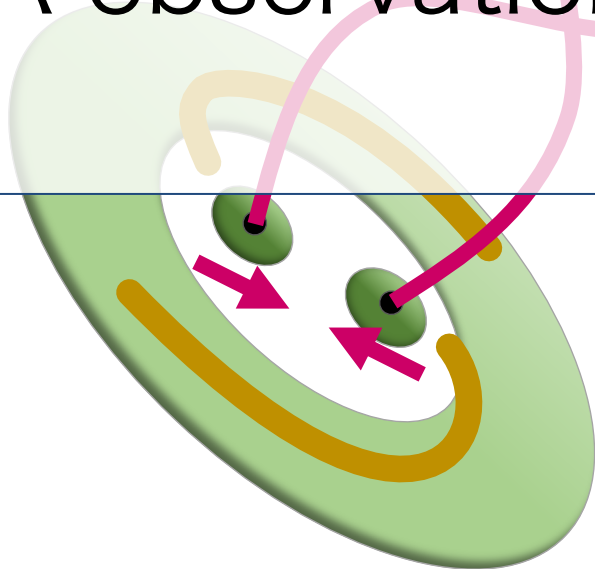
Conclusion at first

Objective: formation of close twin binaries

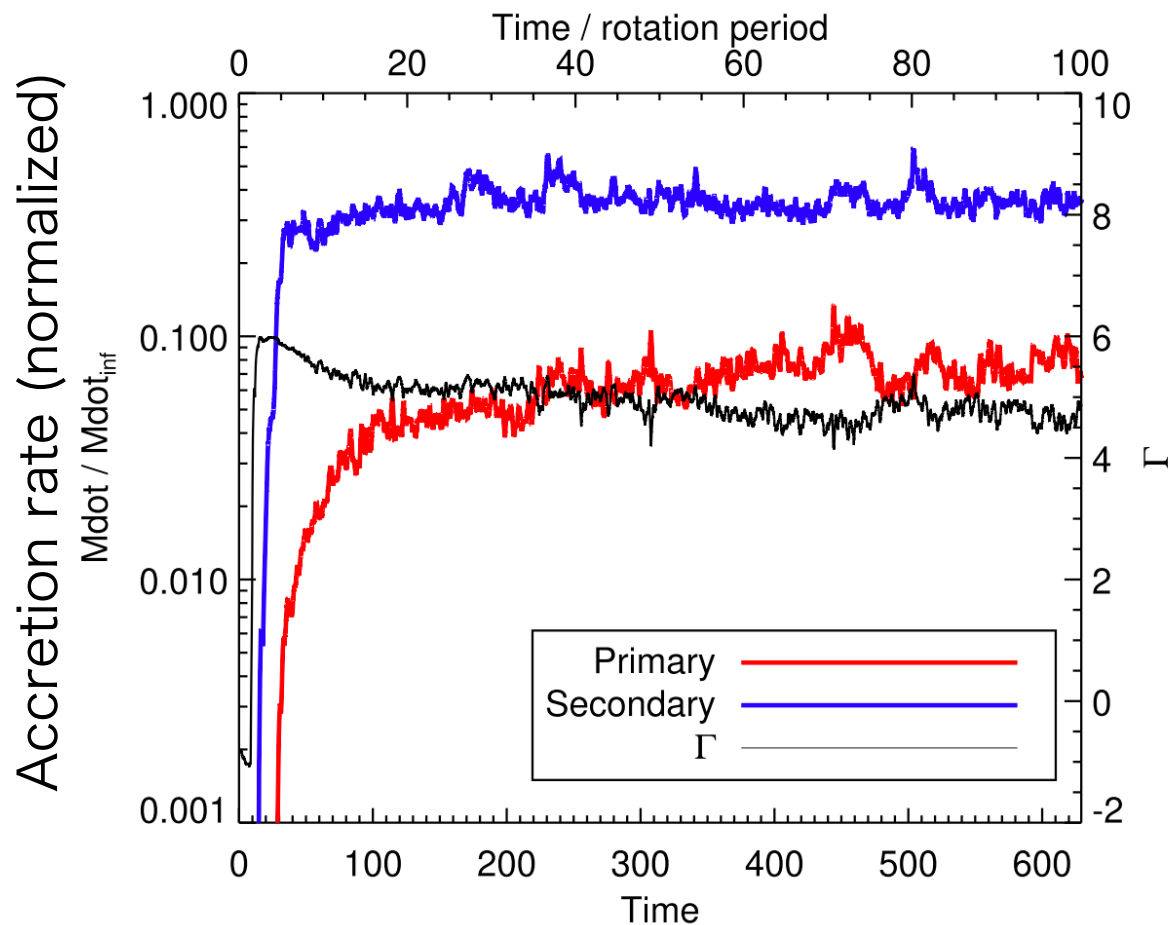
Methods: MHD + AMR simulations

Helical outflows
c.f., ALMA observation

Orbital decay
occurs with B-field,
but stalls in late stage



Twin binaries tend to form in circumbinary disks



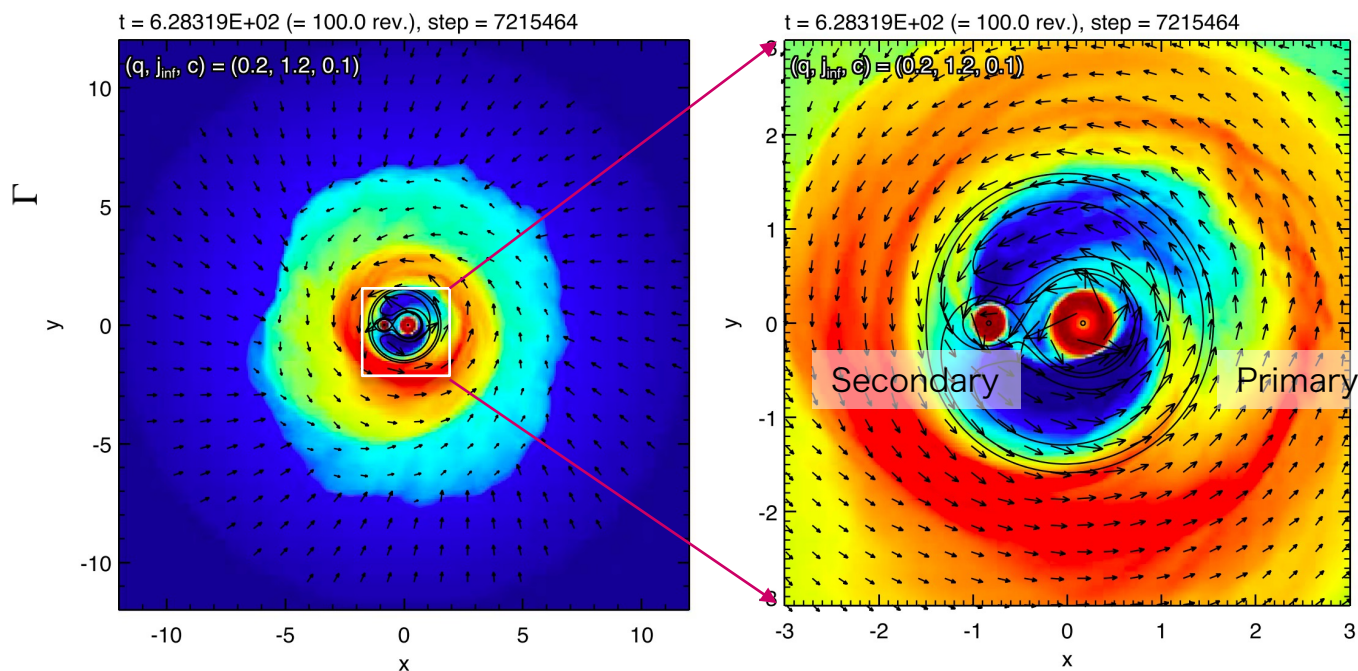
$$\Gamma = \frac{\dot{q}/q}{\dot{M}_{\text{tot}}/M_{\text{tot}}} = \frac{(1+q)(\dot{M}_2 - q\dot{M}_1)}{q(\dot{M}_1 + \dot{M}_2)}, \quad q = \frac{M_2}{M_1}$$

$\Gamma > 0 \rightarrow \dot{q} > 0 \rightarrow$ **Twin binaries**

Supported by hydrodynamical models

TM, Saigo, Takakuwa 19

c.f., Bate & Bonnell 97, Young+ 15



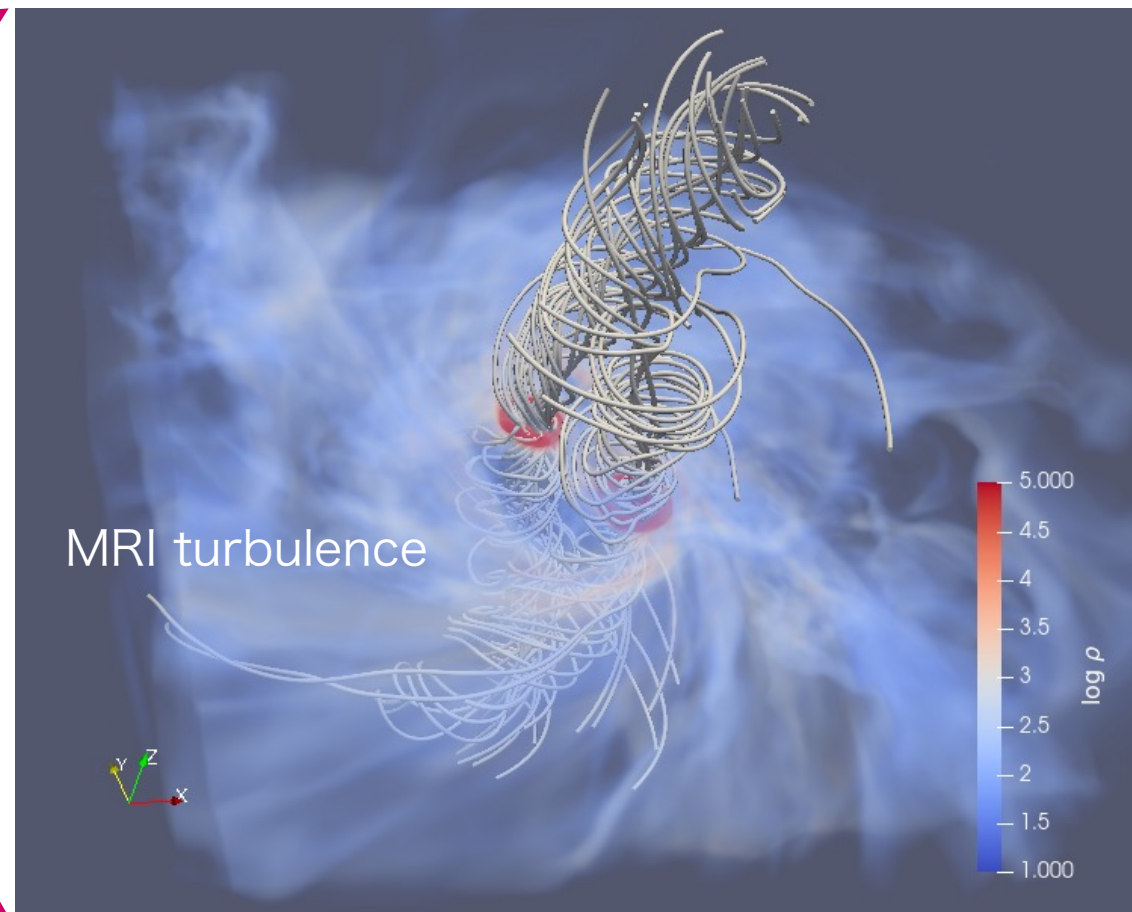
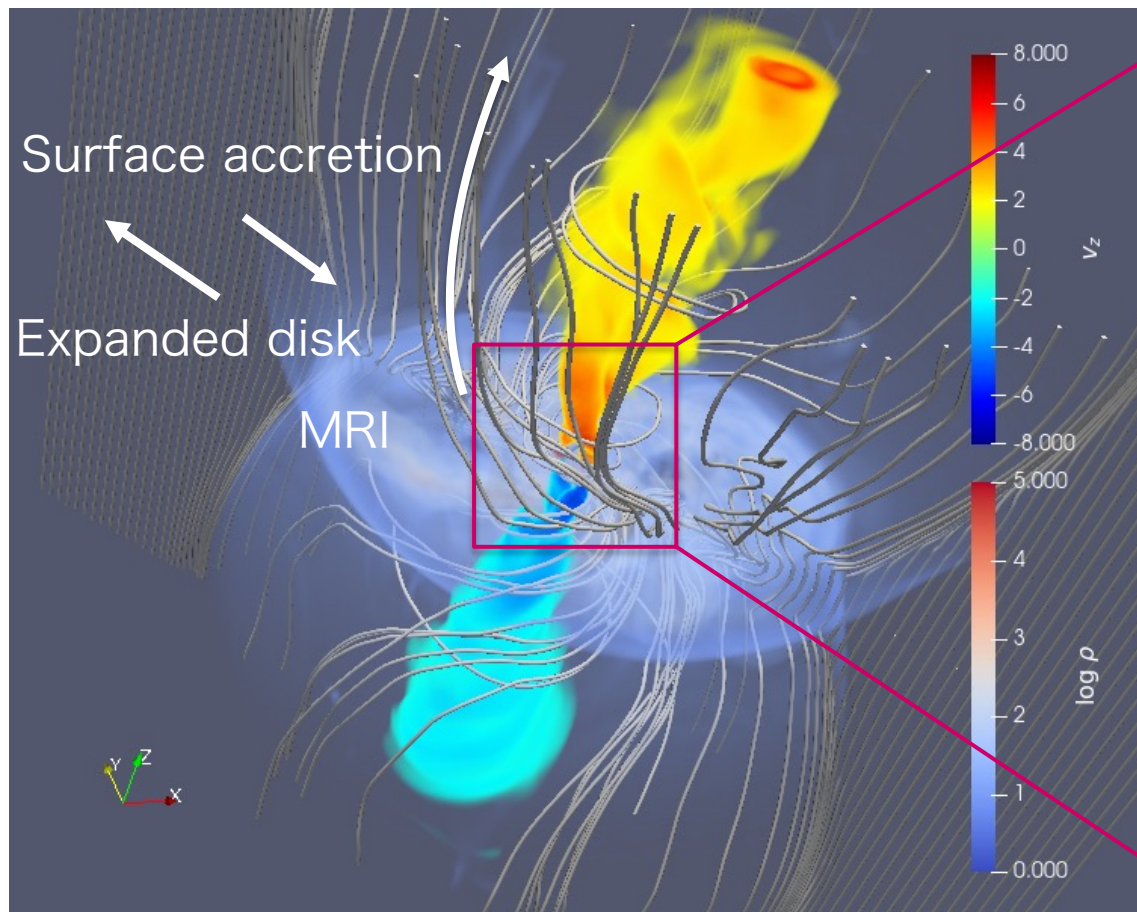
Consistency with recent Gaia observations

Results: Double-helical outflows

Slow outflow
from CBD

Fast outflows
from CSDs

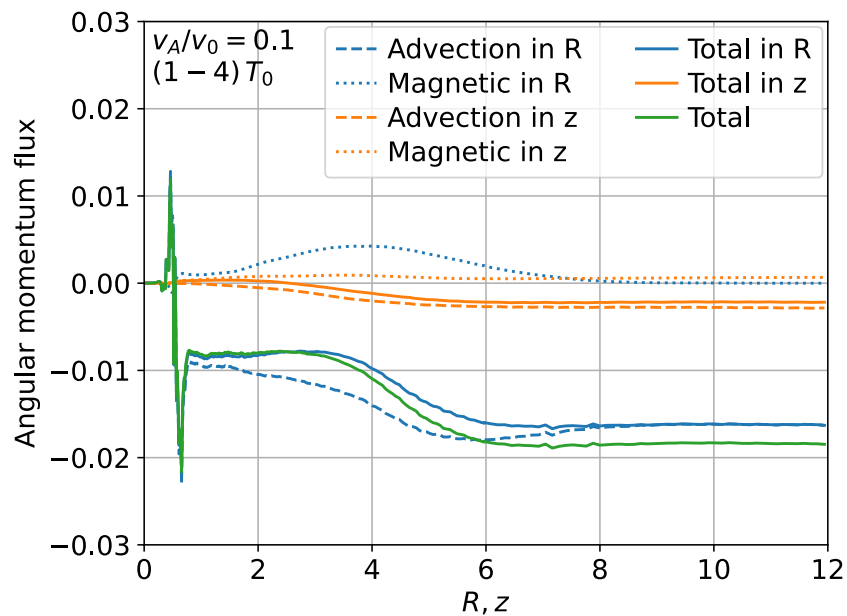
Magnetic-pressure-driven outflows



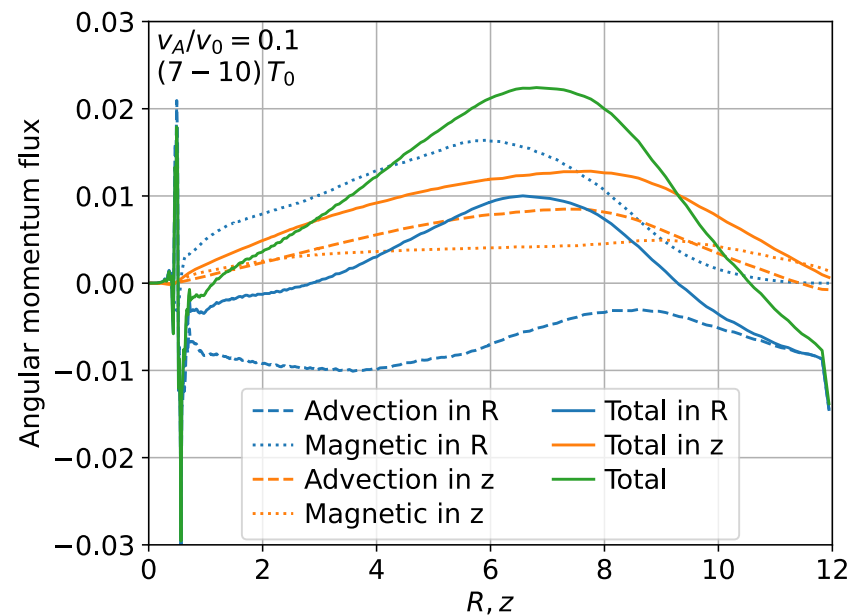
$t = 7 T_b$

C.f., Saiki & Machida 20

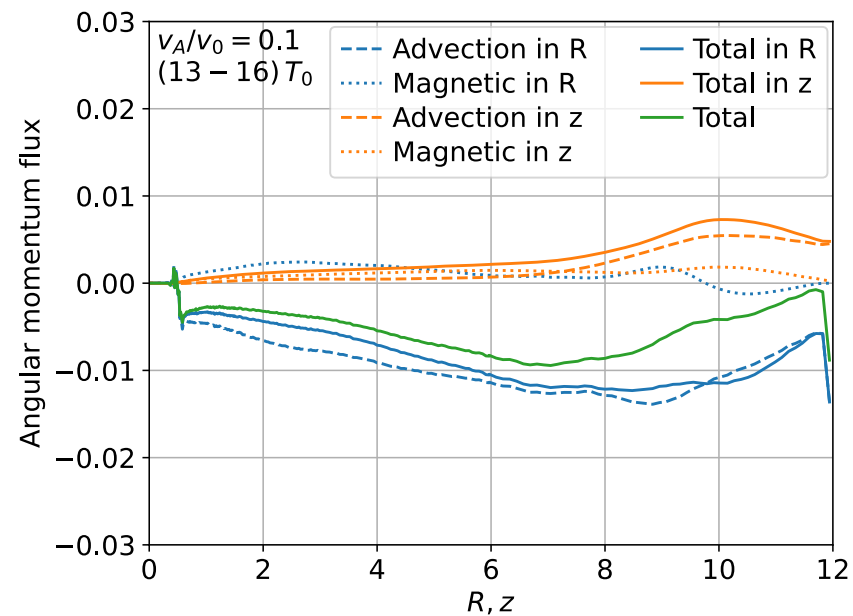
AM transfer



Orbital expansion



Orbital decay



Decay slowdown

Derivation of eigen value

Assumptions:

$$\frac{dJ_d}{dt} = \langle \dot{M}_d \rangle \ell_0,$$

Specific angular momentum

$$J_d = \mu_b a_b \Omega_b,$$

$$q_b = 1,$$

Angular momentum conservation

$$\frac{\dot{a}_b}{a_b} = 8 \left(\frac{\ell_0}{a_b^2 \Omega_b} - \frac{3}{8} \right) \frac{\langle \dot{M}_b \rangle}{M_b}, \quad \ell_0 \equiv \frac{\langle \dot{J}_b \rangle}{\langle \dot{M}_b \rangle}$$

If $\ell_0 < \frac{3}{8} a_b^2 \Omega_b$ then orbital decay

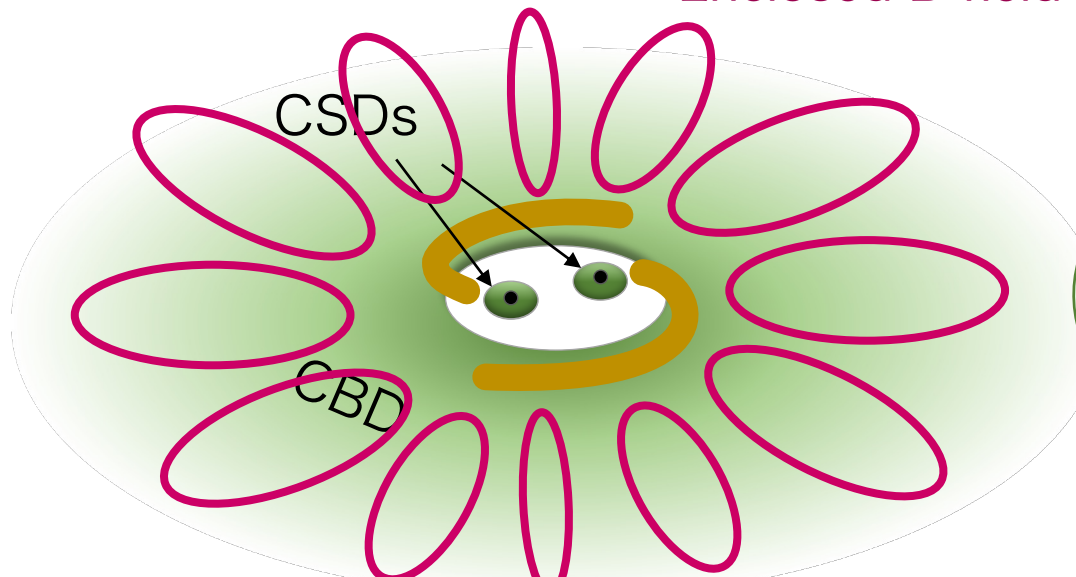
Lai & Munoz (2022)

Previous works vs. this study

Previous works

Extended CBD
“Standard model”

Enclosed B-field

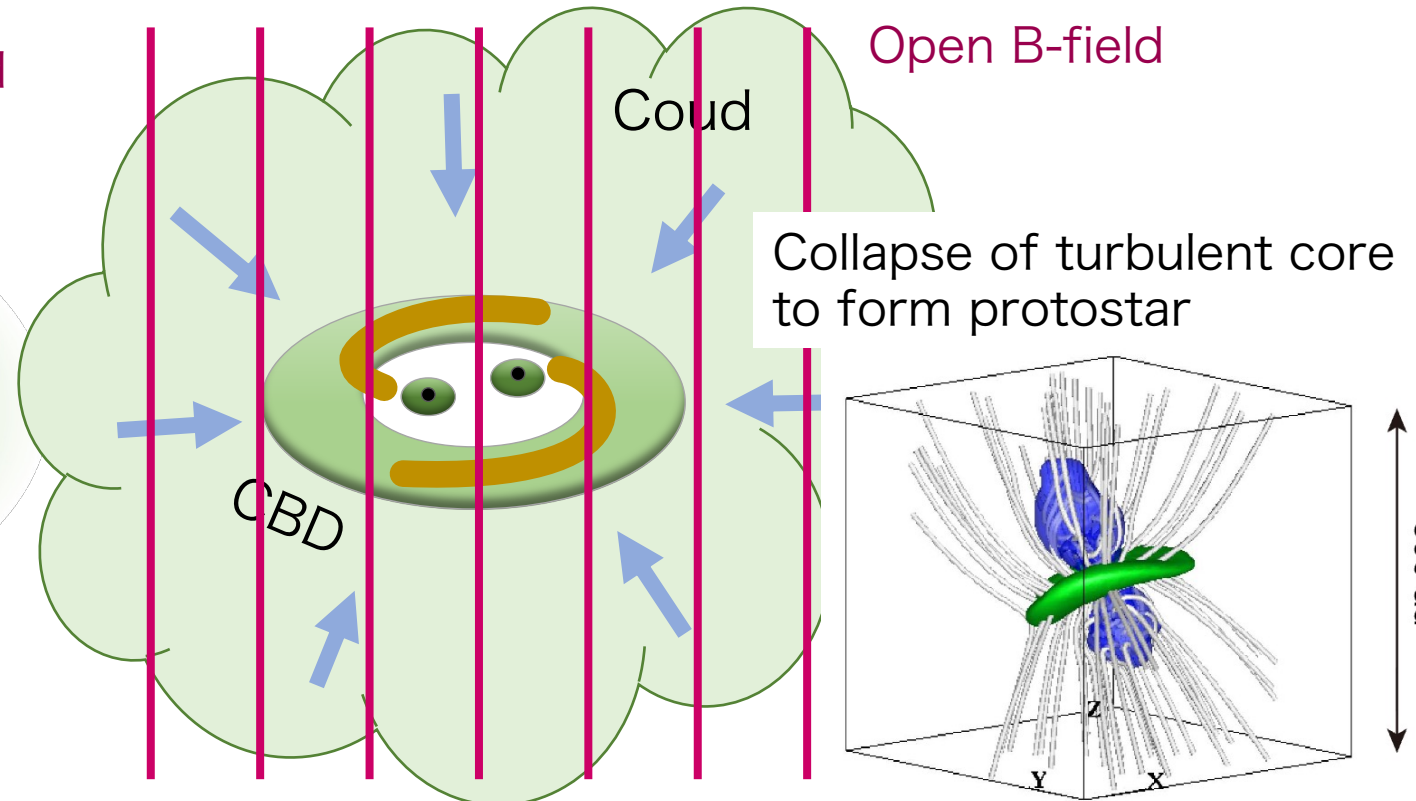


E.g., Artymowicz & Lubow 96; Hanawa+ 10; Noble+ 10, 12, 21; Price+ 18; Moody+ 19; Munoz+ 19; Shi & Stone 19; Tiede+ 20; Heath & Nixon 20; Franchini+ 21; D’Orazio & Duffell 21; Siwek+ 23; Most & Wang 25;

This work

Accretion of gas onto CBD with magnetic fields

Open B-field



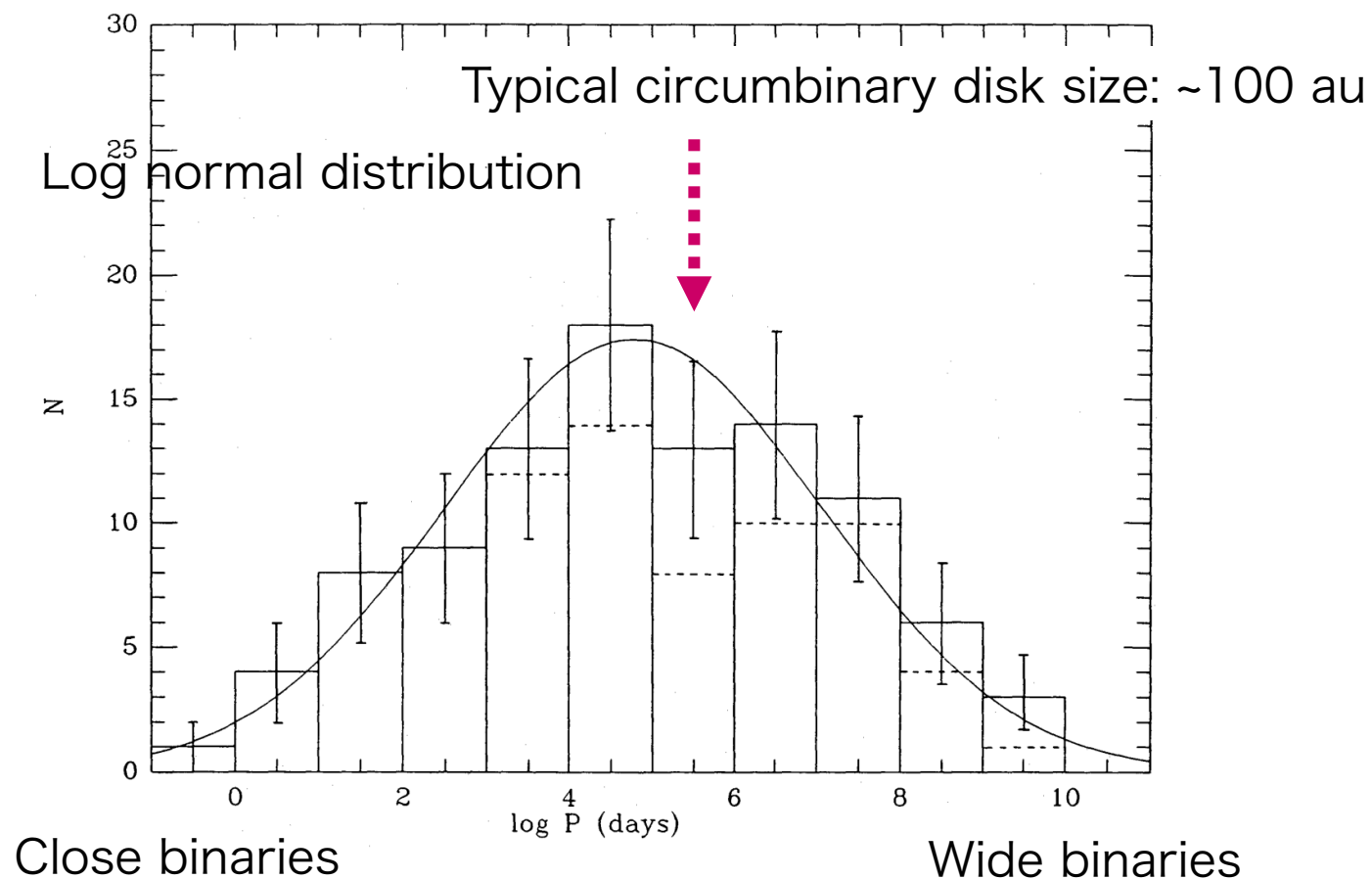
Bate & Bonnell 97; Satsuka+ 17; Matsumoto+ 19; Matsumoto 24

Matsumoto+ 17

Introduction: observation

Histogram of binary separations for solar-type stars

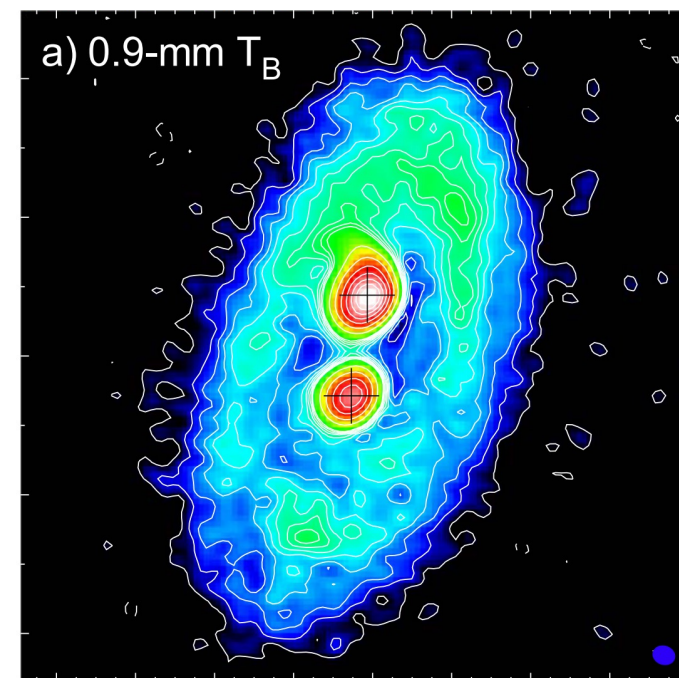
(Duquennoy & Mayor 1991)



Samples : nearby solar type stars (G-dwarf)
Broken lines : w/o correction
Real lines : w/ correction

Binary formation scenarios

- Disk fragmentation
- Turbulent fragmentation
- Hybrid



Example: L1551 IRS 5
(Takakuwa+ 2020, ALMA Cycle 4)

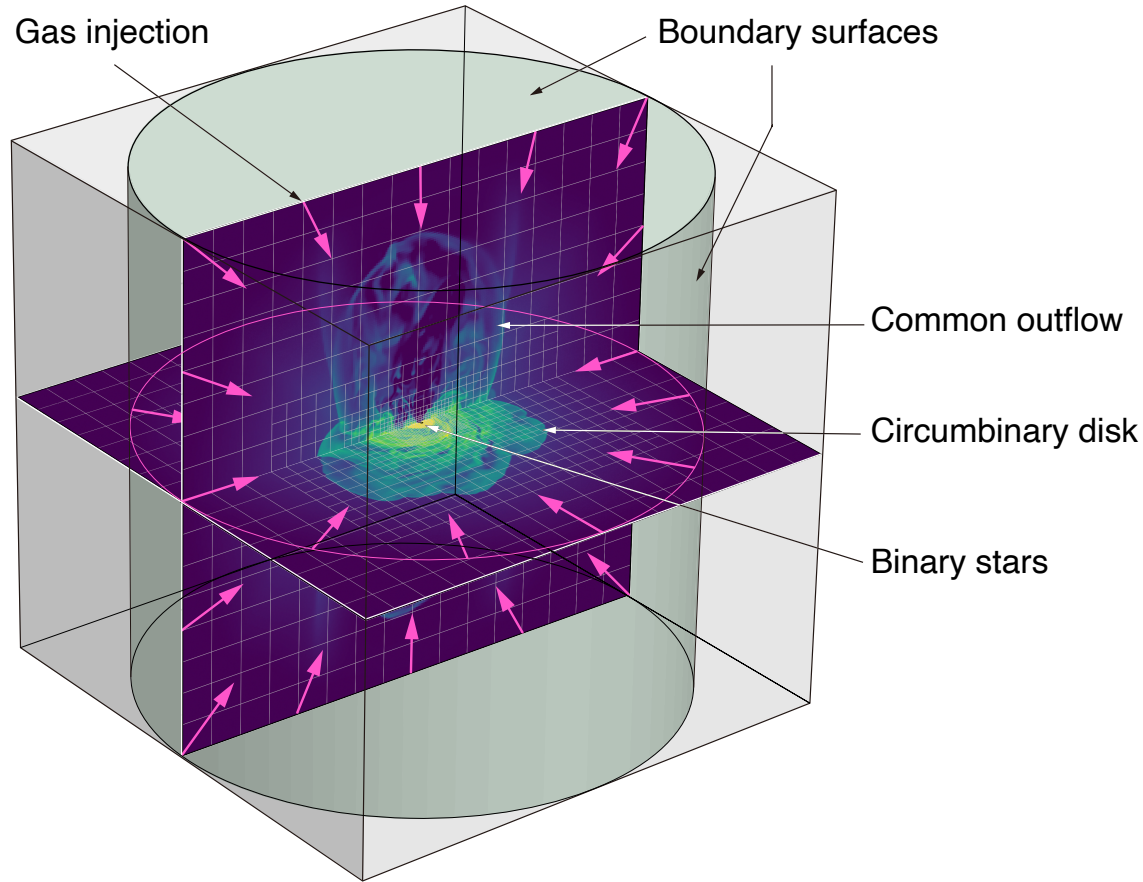


Table 1. Model parameters

q	$B_{z,0}$	Infall	Comments
0.2	0.1	Y	Fiducial model
0.2	0.4	Y	Strong field model
0.2	0.025	Y	Weak field model
0.2	0.01	Y	Very weak field model
0.2	0	Y	HD model
0.2	0.1	N	Fiducial model w/o infall envelope
0.2	0	N	HD model w/o infalling envelope
0	0.1	Y	Single star model
0	0	Y	Single star HD model
0	0.1	N	Single star w/o infall envelope
0	0	N	Single star HD model w/o infall envelope

FMR, w/o self-gravity, ideal MHD (Boris HLLD, Alfven velocity suppressed)
 Sink particles (circular orbit, accretion of gas), Gas injection on boundaries (model of infalling envelope)

Fiducial Model

Density distribution

Circumbinary disk

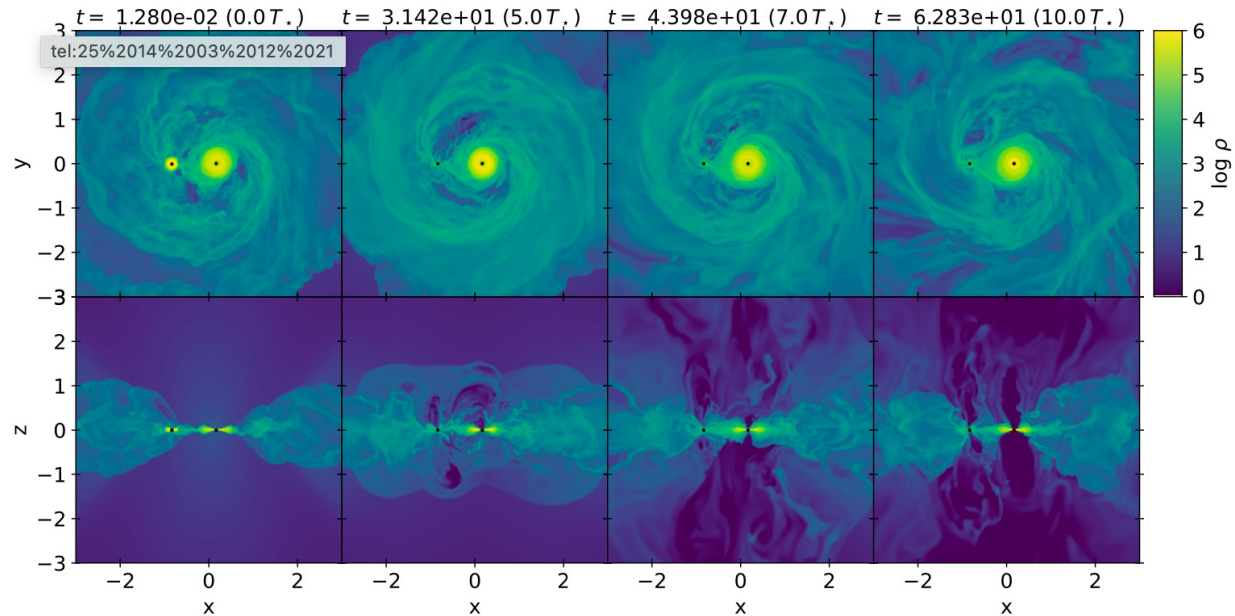
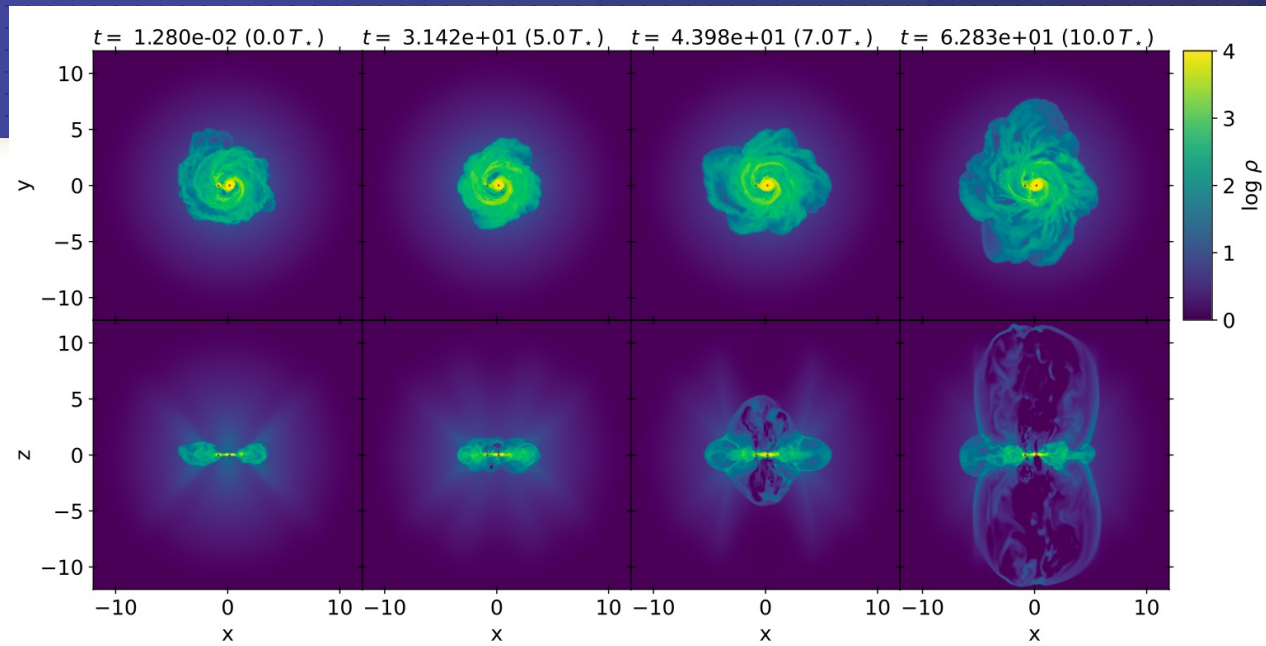
Spiral arms

Outflows

MRI turbulence

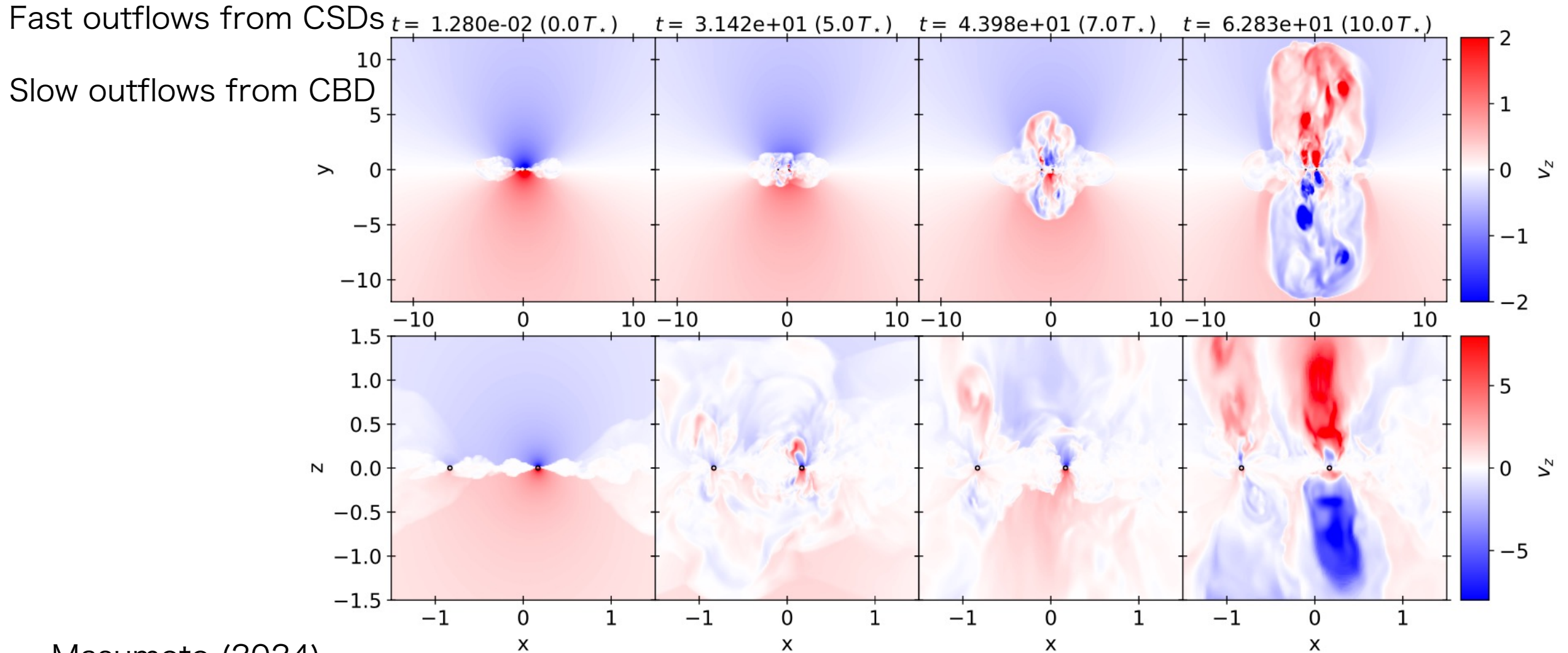
Angular momentum redistribution

Expanding CBD



Masumoto (2024)

Outflows

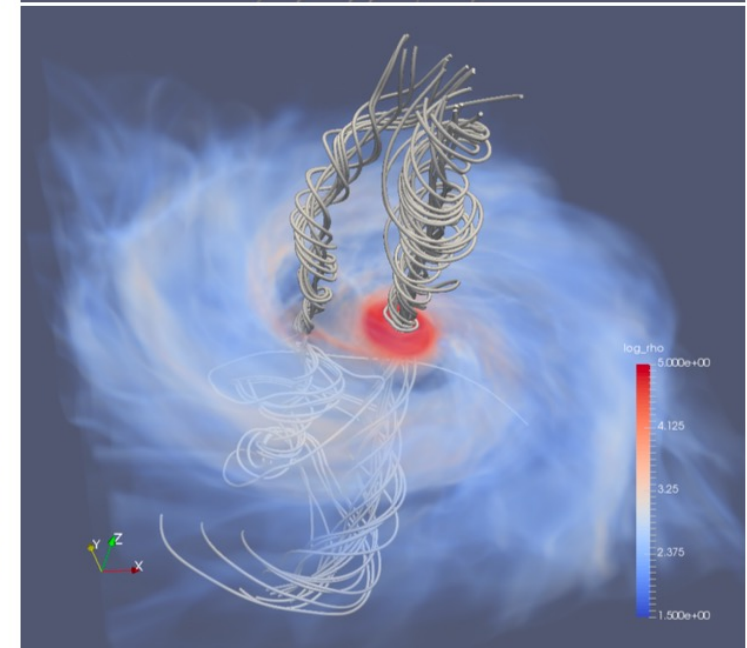
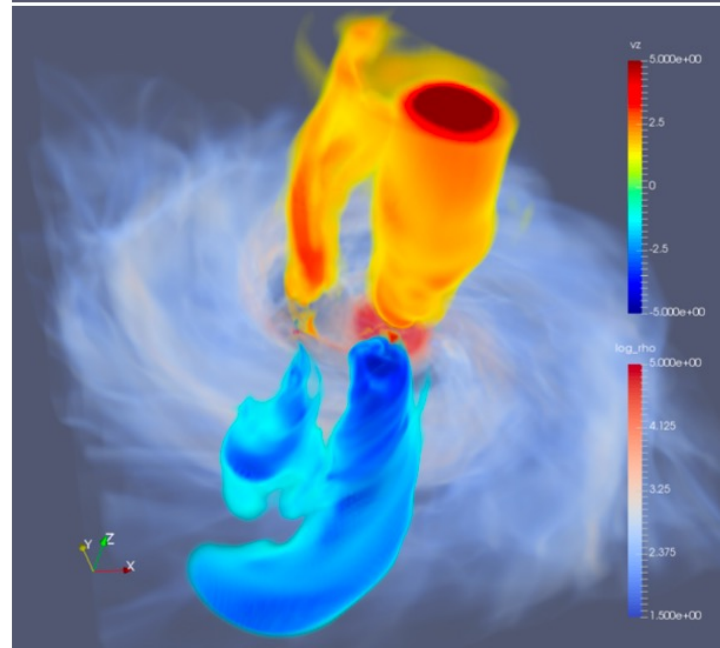
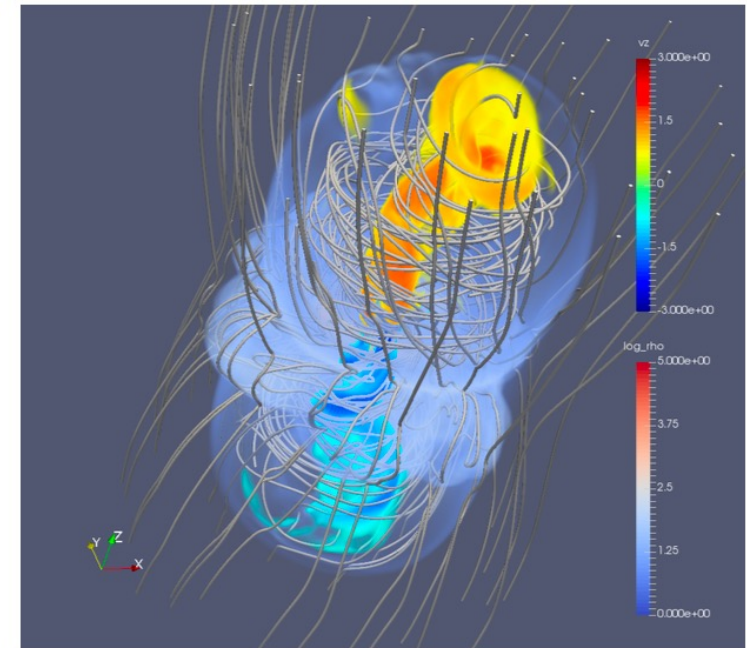
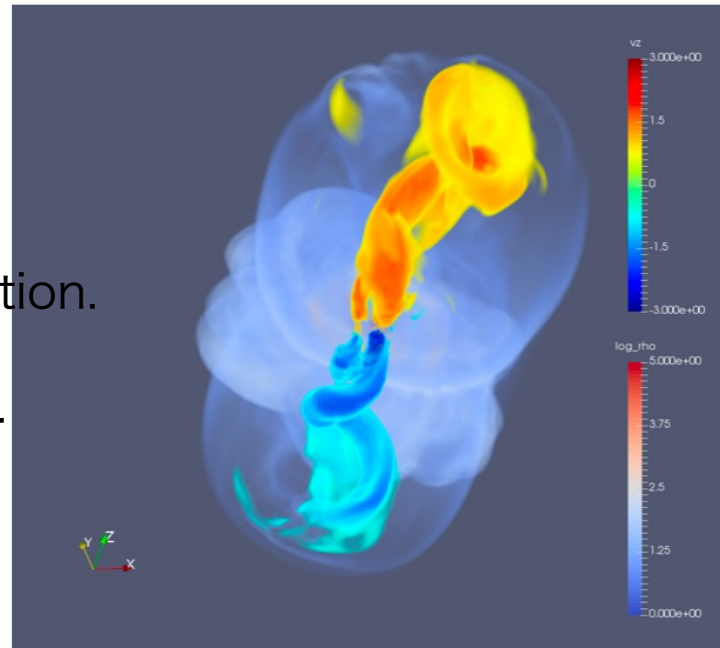


Masumoto (2024)

Outflows

Fast outflows from CSDs
Helical structure due to orbital motion.

Acceleration by magnetic pressure.



Masumoto (2024)

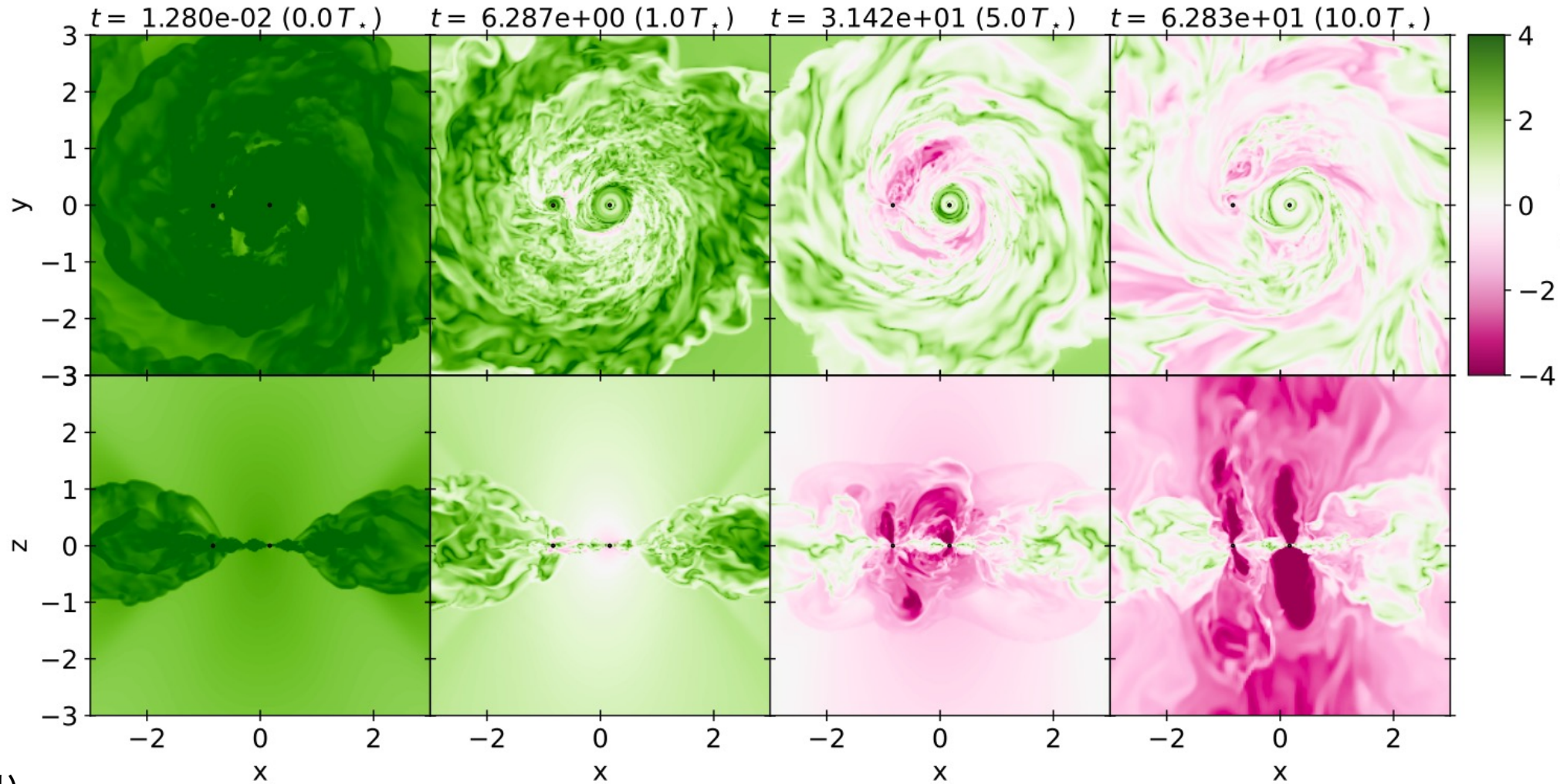
Plasma β

Magnetic field strength increases

Accretion of magnetic flux

Growth by rotation

MRI



Masumoto (2024)

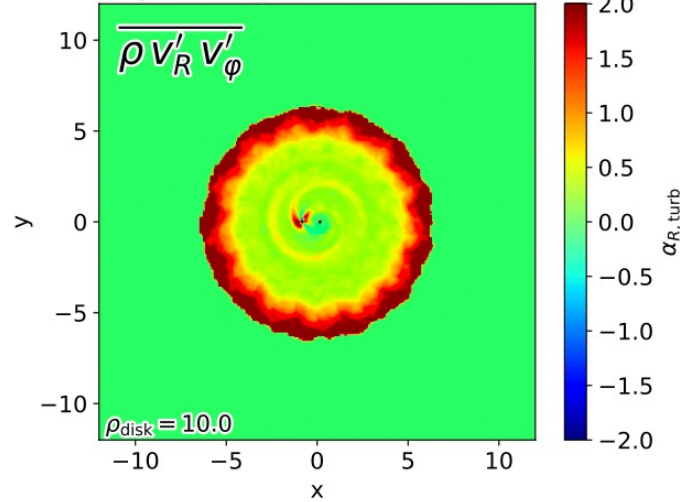
α -parameter (turbulent components)

Disk edge has high α

Overall

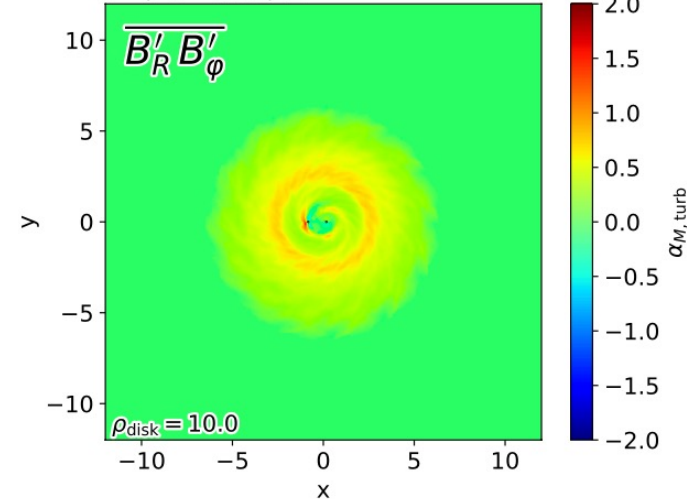
Reynolds stress

$q = 0.2, B_{z,0} = 0.1, w/ \text{infall}$
 $t = (7.0 - 10.0)T.$



Maxwell stress

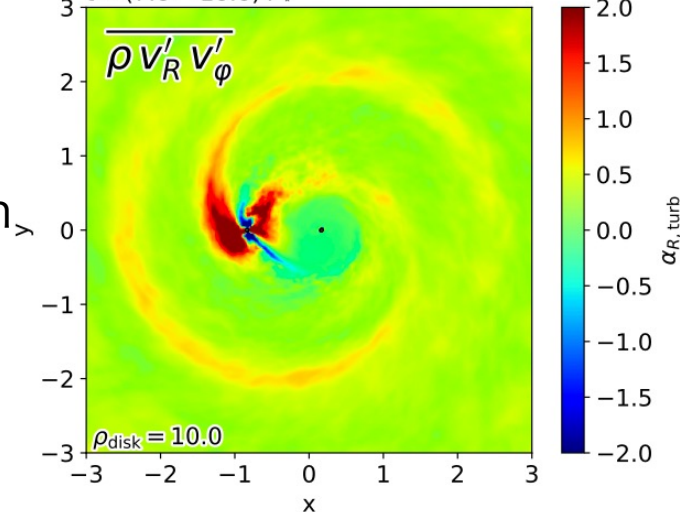
$q = 0.2, B_{z,0} = 0.1, w/ \text{infall}$
 $t = (7.0 - 10.0)T.$



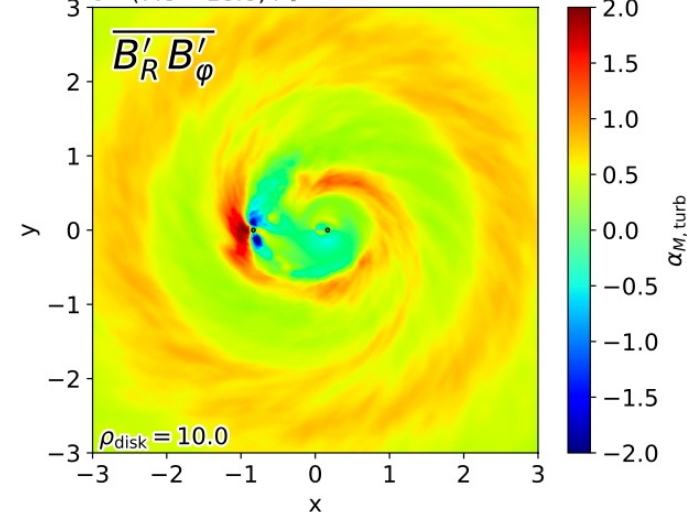
High α along spiral arms

Central region

$q = 0.2, B_{z,0} = 0.1, w/ \text{infall}$
 $t = (7.0 - 10.0)T.$



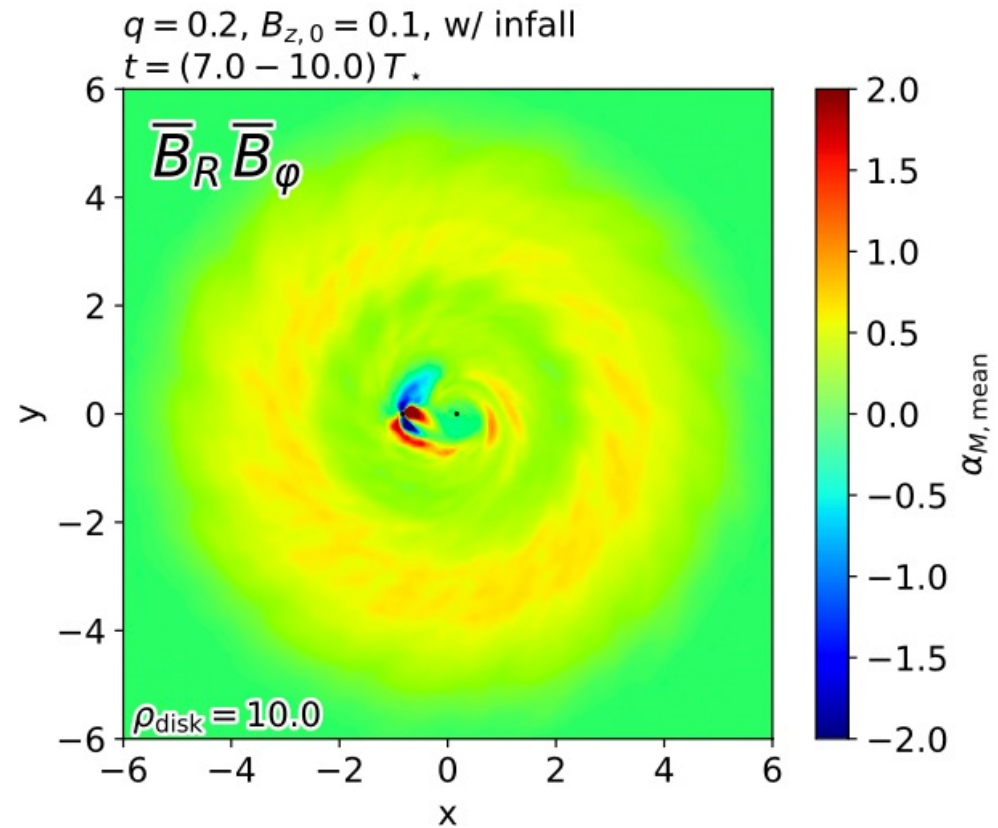
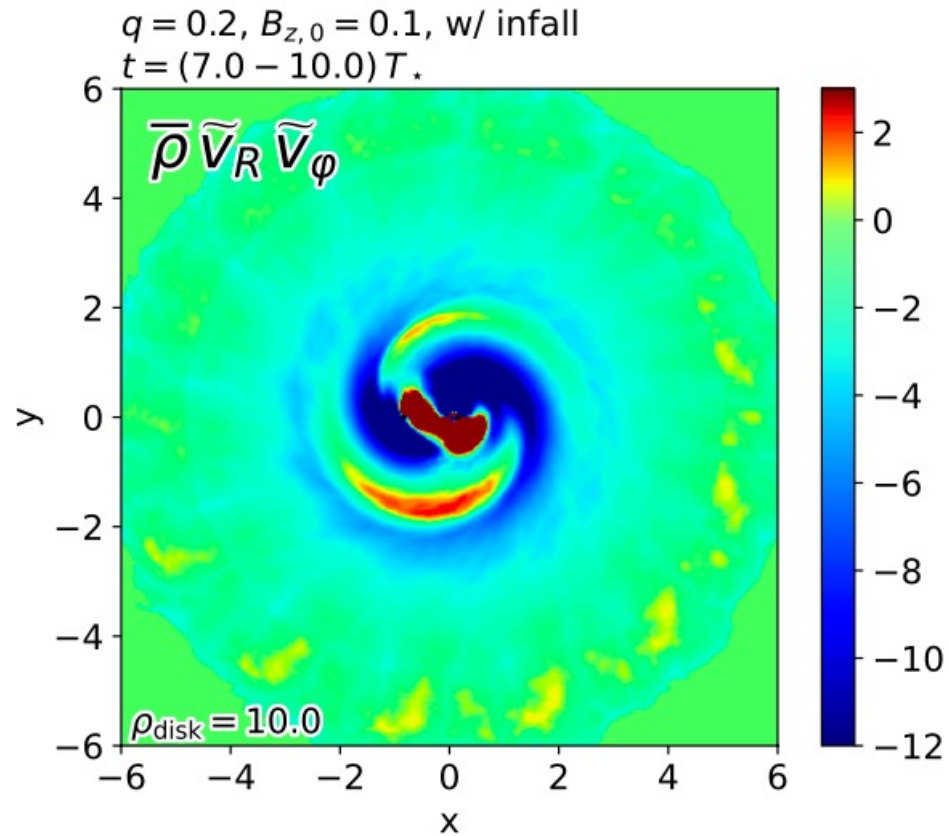
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 $t = (7.0 - 10.0)T.$



Masumoto (2024)

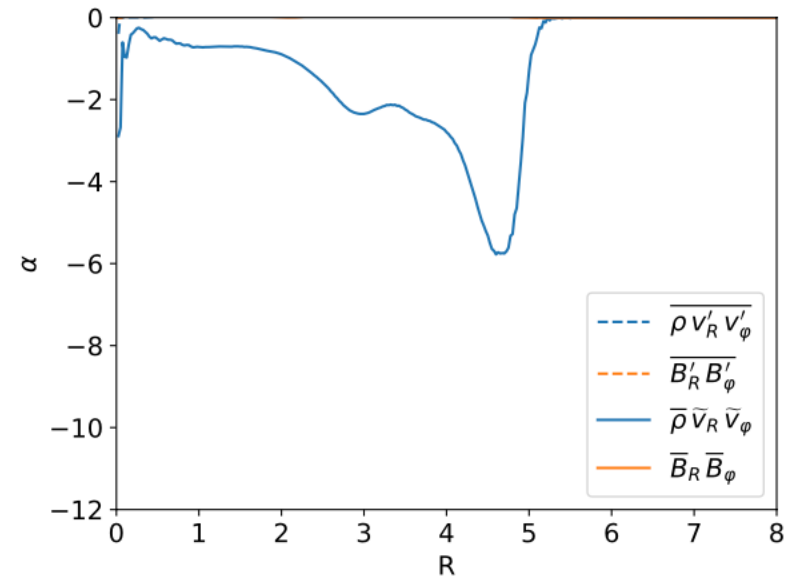
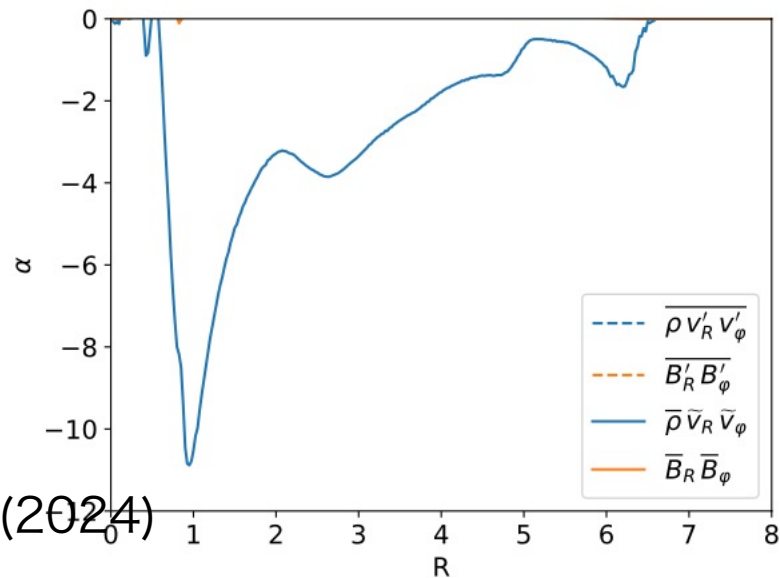
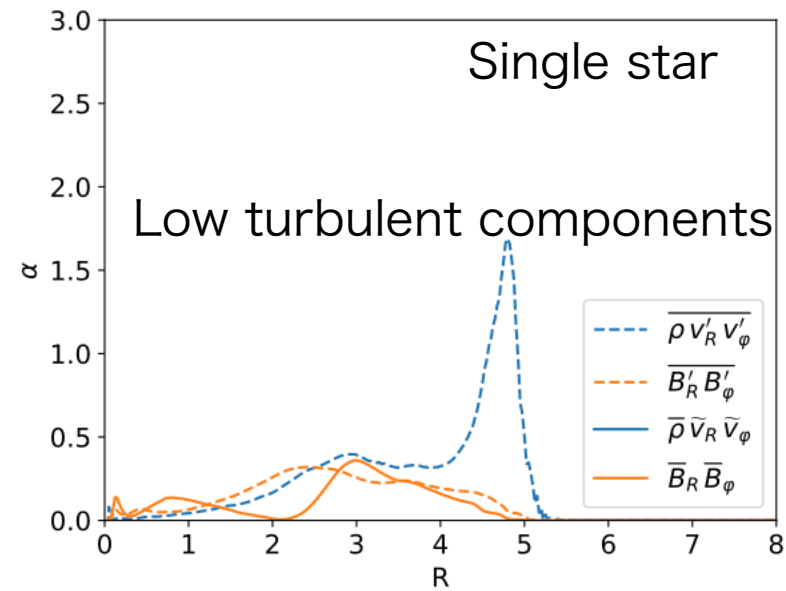
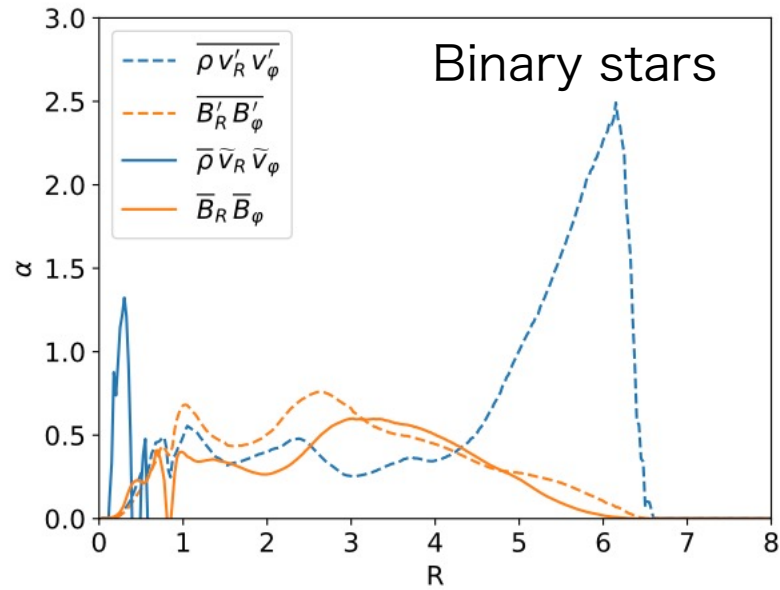
α -parameter (coherent components)

Disturbance by spiral arms



Masumoto (2024)

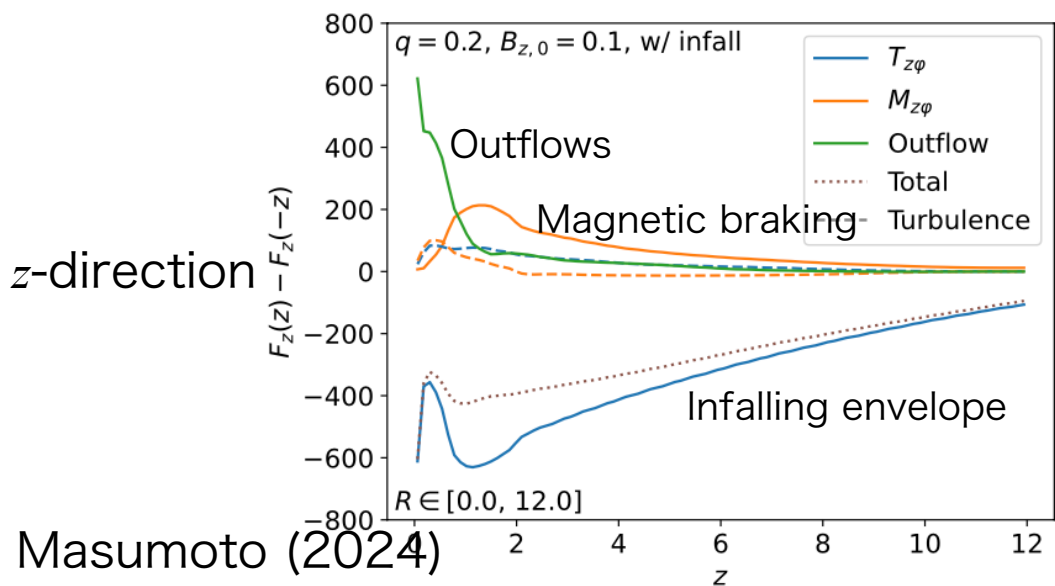
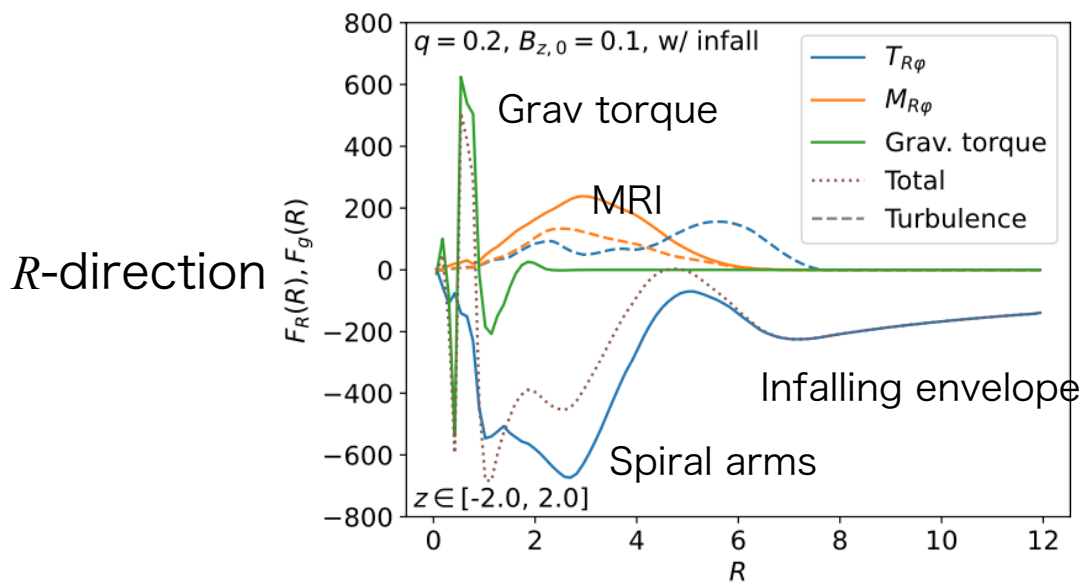
α -parameter, radial distribution



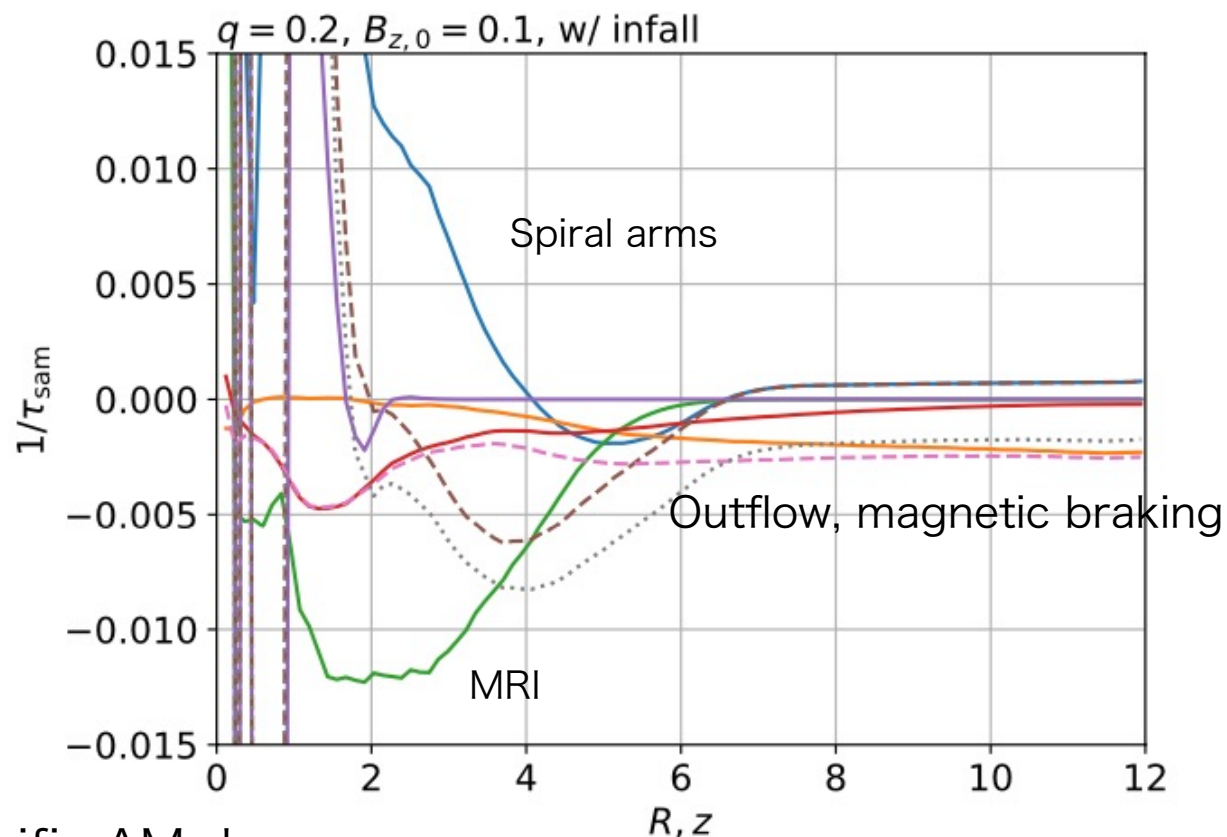
Masumoto (2024)

AM flux (Fiducial model)

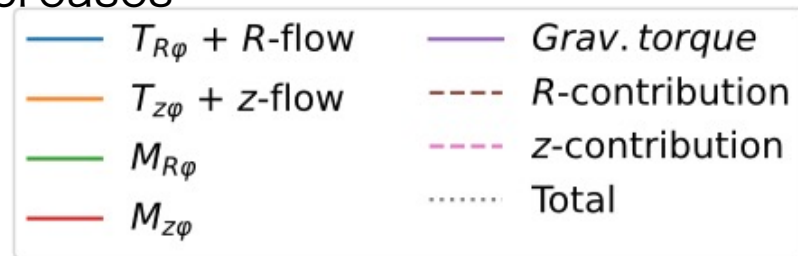
$$\frac{1}{\tau_{\text{sam}}} = \frac{M}{J} \frac{\partial}{\partial t} \left(\frac{J}{M} \right) = \frac{1}{J} \frac{\partial J}{\partial t} - \frac{1}{M} \frac{\partial M}{\partial t}$$



Specific AM increases



Specific AM decreases



Inspiral or Outspiral

Change in semi-major axis

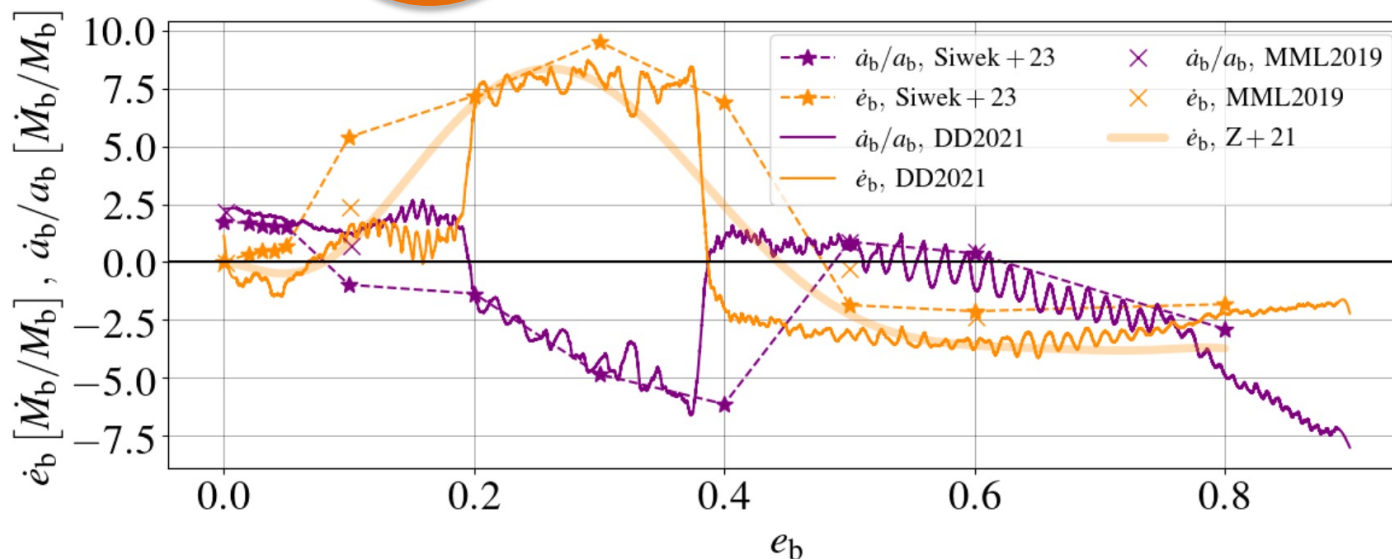
$\dot{a}_b/a_b [\dot{M}_b/M_b], g + a$ Eccentricity

Mass ratio	$\dot{a}_b/a_b [\dot{M}_b/M_b], g + a$							
	$e_b = 0.0$	$e_b = 0.1$	$e_b = 0.2$	$e_b = 0.3$	$e_b = 0.4$	$e_b = 0.5$	$e_b = 0.6$	$e_b = 0.8$
$q_b = 0.1$	-1.28	-5.06	1.03	3.43	3.74	4.0	3.0	-6.32
$q_b = 0.2$	-0.77	-1.51	-0.16	0.92	2.87	2.59	-1.3	-7.09
$q_b = 0.3$	1.15	-2.05	-1.89	-0.19	-1.44	-0.93	-2.34	-3.49
$q_b = 0.4$	1.29	-1.3	-0.65	-2.41	-2.5	-2.93	-1.48	-3.61
$q_b = 0.5$	1.43	-0.69	-0.15	-2.43	-2.1	-3.73	-1.26	-3.52
$q_b = 0.6$	1.58	-0.69	-0.42	-2.37	-2.96	-4.33	-0.3	-2.73
$q_b = 0.7$	1.67	-0.75	-0.46	-2.38	-5.16	-4.36	0.28	-2.85
$q_b = 0.8$	1.72	-0.94	-0.67	-2.52	-6.23	-0.28	0.52	-3.0
$q_b = 0.9$	1.74	-0.88	-1.02	-4.15	-6.23	0.86	0.47	-2.89
$q_b = 1.0$	1.76	-0.95	-1.31	-4.79	-6.1	0.6	0.38	-2.74

Change in eccentricity

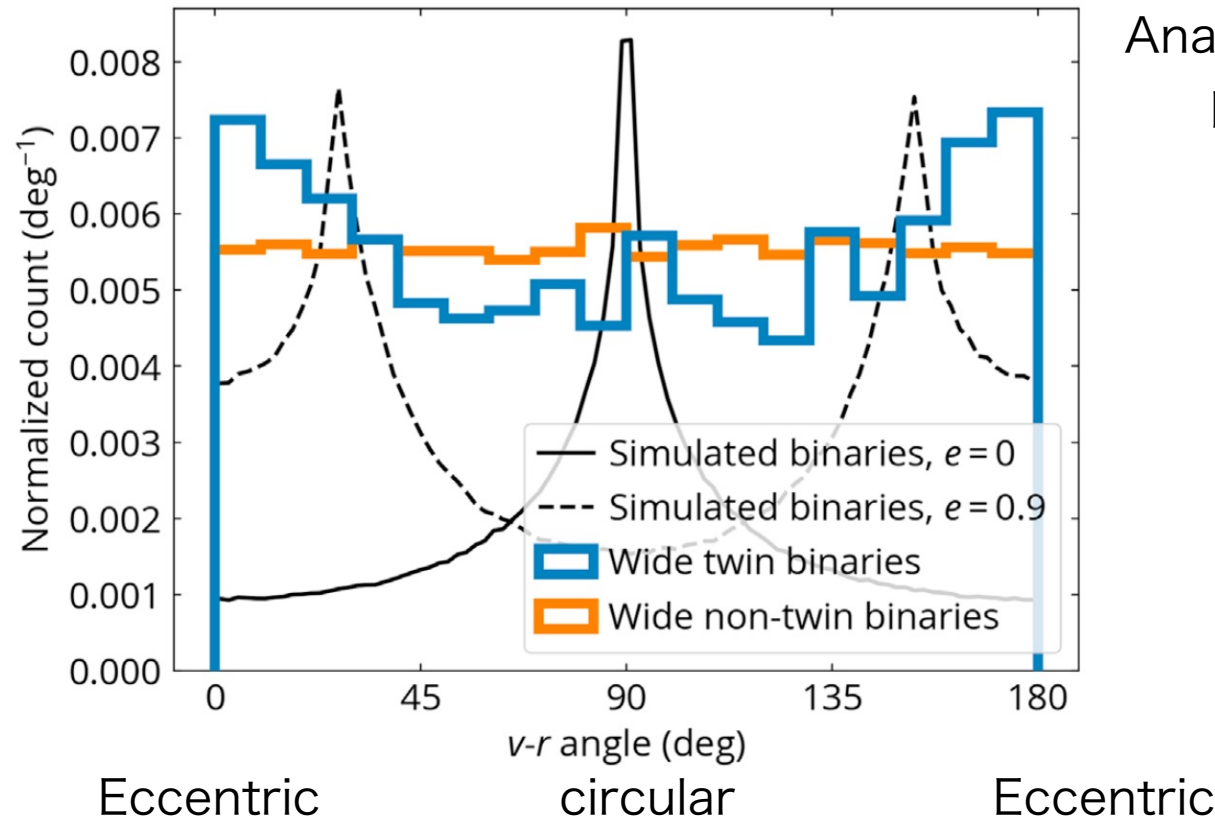
$\dot{e}_b [\dot{M}_b/M_b], g + a$

Mass ratio	$\dot{e}_b [\dot{M}_b/M_b], g + a$							
	$e_b = 0.0$	$e_b = 0.1$	$e_b = 0.2$	$e_b = 0.3$	$e_b = 0.4$	$e_b = 0.5$	$e_b = 0.6$	$e_b = 0.8$
$q_b = 0.1$	0.0	1.55	0.78	-1.84	-4.15	-4.78	-5.95	-7.7
$q_b = 0.2$	0.0	1.32	2.14	0.16	-2.02	-3.96	-4.62	-5.47
$q_b = 0.3$	0.0	3.73	5.59	0.23	-0.4	-2.73	-3.95	-3.46
$q_b = 0.4$	0.0	4.29	3.5	2.52	0.23	-1.64	-2.81	-2.61
$q_b = 0.5$	-0.0	4.33	3.75	3.38	1.33	-1.82	-2.37	-2.15
$q_b = 0.6$	0.0	4.73	4.9	4.52	3.33	-0.04	-2.11	-1.96
$q_b = 0.7$	0.0	5.28	5.95	5.26	5.6	0.58	-2.61	-1.5
$q_b = 0.8$	-0.0	5.28	5.95	5.97	6.48	-1.15	-2.61	-1.7
$q_b = 0.9$	-0.0	5.16	6.6	8.33	7.02	-1.83	-2.12	-1.69
$q_b = 1.0$	0.0	5.33	7.07	9.43	6.91	-1.67	-2.11	-1.85



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Wide Twin Binaries are Extremely Eccentric



Proposed scenario:

- Twin binaries form within circumbinary disk w/ sep = 100 au.
- > scattered by dynamical interaction
- > wide orbit w/ high eccentricity

How about close binaries?