Necessary Condition for Circumstellar Disk Formation: Effects of Initial Conditions and Sink Treatment

arXiv:1307.1747

Masahiro N. Machida (Kyushu University)
Shu-ichiro Inutsuka (Nagoya University)
Tomoaki Matsumoto (Hosei University)

Abstract

The formation of a circumstellar disk in collapsing cloud cores is investigated with 3D MHD simulations. We prepare four types of initial cloud having different density profiles and calculate their evolution **with or without a sink**. To investigate effects of magnetic dissipation on disk formation, the Ohmic dissipation is considered in some models.

Calculations show that **disk formation is very sensitive to both the initial cloud configuration and the sink treatment**. The disk size considerably differs in clouds with different density profiles even when the initial clouds have almost the same mass-to-flux ratio. Only a very small disk (~10 AU in size) appears in clouds with a uniform density profile, whereas a large disk (~100AU in size) forms in clouds with a Bonnor-Ebert density profile.

In addition, **a large sink accretion radius numerically impedes disk formation** during the main accretion phase and tends to foster the misleading notion that disk formation is completely suppressed by magnetic braking. **The protostellar outflow is also greatly affected by the sink properties**. A sink accretion radius of <1AU and sink threshold density of $>10^{13}$ cm^{-3} are necessary for investigating disk formation during the main accretion phase.

Purpose of This Study

- It had been considered that disk formation is a natural consequence of angular momentum conservation
- Recent studies showed that angular momentum is excessively transferred by **Magnetic Braking** that strongly suppresses disk formation
- Now, disk formation is controversial topic:
  When, Where and How is it formed?
- **Various studies** with different initial conditions and numerical settings **showed different (or conflicting) results**
- In this study, we calculated the disk formation with different initial conditions and sink treatments to discuss necessary numerical conditions for disk formation

Initial Settings, Basic eqs. & Numerical Method

Resistive MHD eqs.

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

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

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

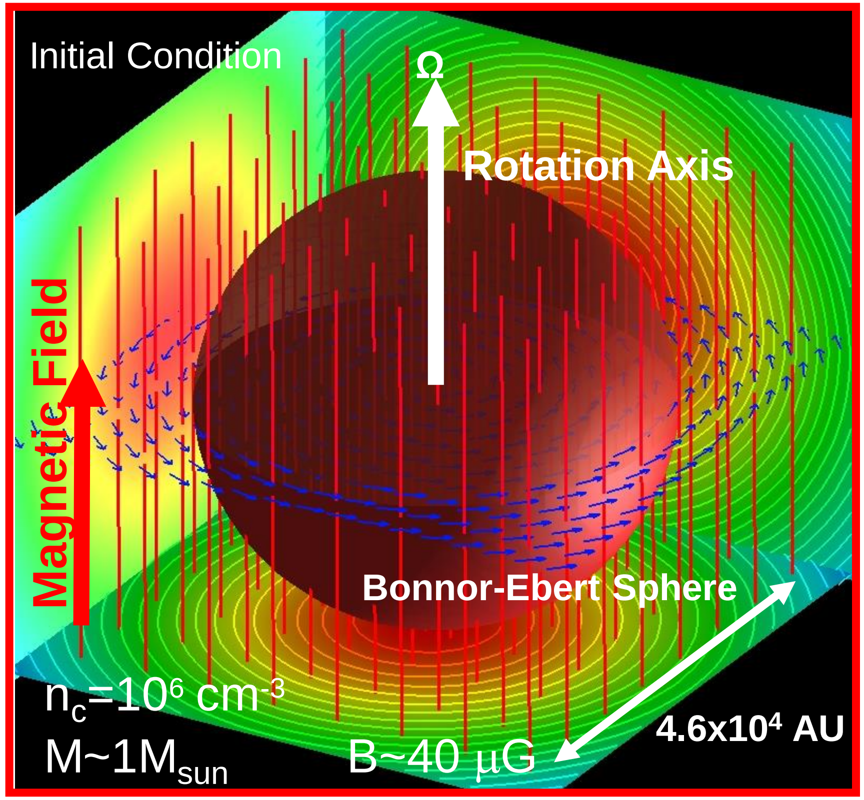
$$P = P(\rho),$$

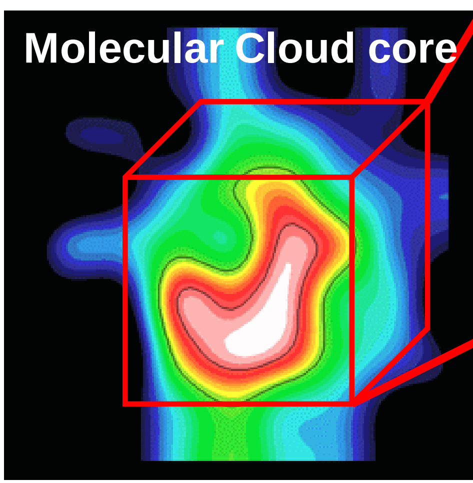
$$\phi = \phi_{gas} + \phi_{ps}, \; \nabla^2 \phi_{gas} = 4\pi G \rho, \; \phi_{ps} = -GM_{ps}/r$$

Sink: Two parameters

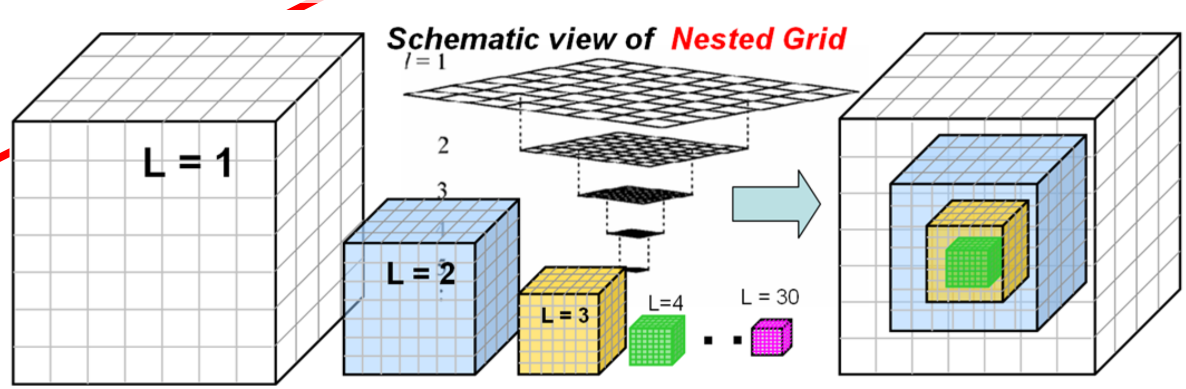
- Threshold density: n_{trh}
- Accretion radius: r_{acc}

➢ Inside $r<r_{acc}$, the gas with $n>n_{trh}$ is removed and added to the protostellar mass





Nested Grid



Models: Parameters and Results

US: Uniform Sphere
BE: Bonnor-Ebert Sphere
RJ: Steep density profile
RS: Massive Cloud

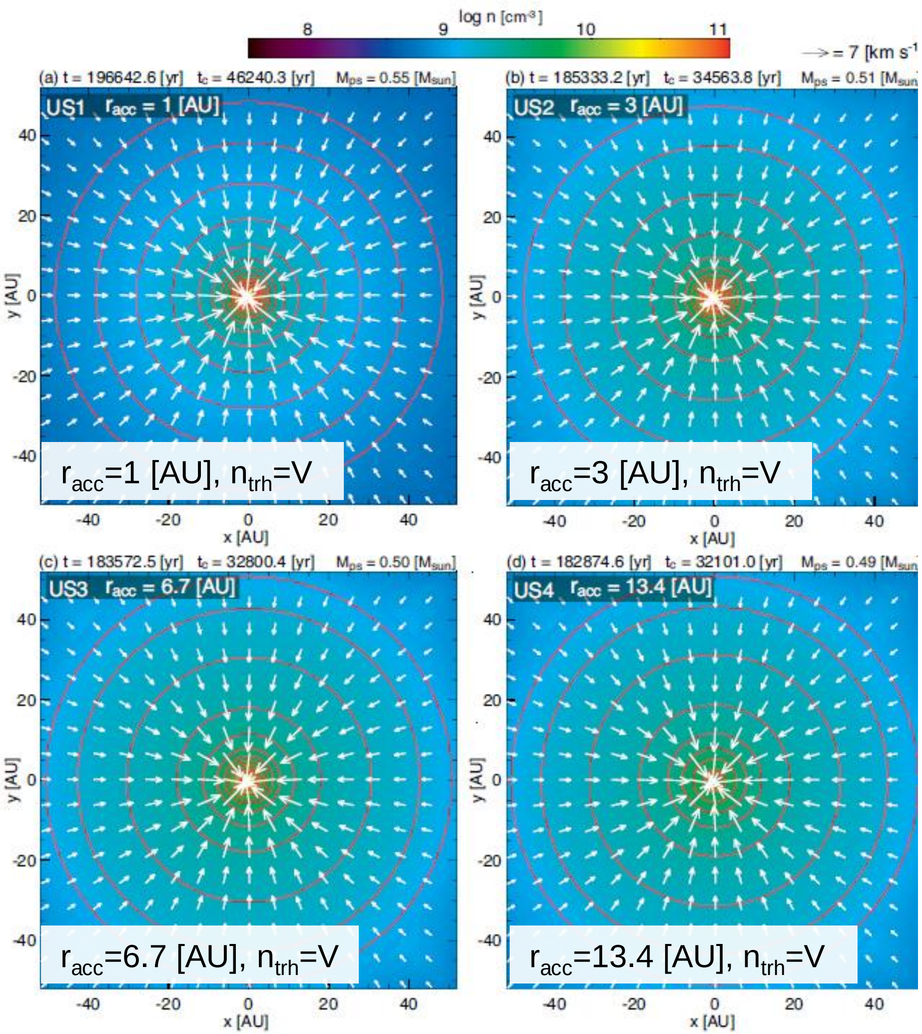
Model	$n_{c,0}$ [cm^{-3}]	M_c [$M_\odot$]	r_c [AU]	B_0 [μ G]	Ω_0 [10^{-13} s^{-1}]	α_0	β_0	γ_0	μ	Sink	r_{acc} [AU]	n_{thr} [cm^{-3}]	h [AU]	O.D.[1]	RSD[2]	Out[3]
US1										Y	1	V	0.4	Y	N	N
US2										Y	3.4	V	0.4	Y	N	N
US3										Y	6.7	V	0.4	Y	N	N
US4										Y	13.4	V	0.4	Y	N	N
US5	10^5	1.0	6.7×10^3	35.4 (U)	1	0.8	0.03	0.13	2.9	Y	1	10^{11}	0.4	Y	N	Y(?)
US6										Y	1	10^{12}	0.4	Y	N	Y(?)
US7										Y	1	10^{13}	0.2	Y	Y	Y
US8										Y	1	10^{14}	0.1	Y	Y	Y
USL										Y	6.7	V	1.6	Y	N	N
BE1	1.4×10^5	2.1		14.3 (U)	0.81	0.6		0.10	3.0	Y	3	V	0.5	Y	Y	Y
BE2	1.7×10^5	2.6		17.2 (U)	0.87	0.5		0.10	3.0	Y	3	V	0.5	Y	Y	Y
BE3	2.1×10^5	3.2		21.5 (U)	0.98	0.4		0.10	3.0	Y	3	V	0.5	Y	Y	Y
BE4	1.7×10^5	2.6	1.5×10^4	17.2 (U)	0.87	0.5	0.02	0.10	3.0	Y	1	10^{12}	0.5	Y	Y	Y
BE5	1.7×10^5	2.6		37.8	0.87	0.5		0.14	3.0	Y	3	V	0.5	Y	Y	Y
BE6	1.7×10^5	2.6		23.2 (U)	0.87	0.5		0.30	1.7	Y	3	V	0.5	Y	Y	Y
BEH	1.7×10^5	2.6		17.2 (U)	0.87	0.5		0.10	3.0	Y	0.2	10^{14}	0.06	Y	Y	Y
RJ1										N	—	—	0.4	N	N(?)	Y
RJ2	8×10^6	1.0	3×10^3	257 (U)	5	0.4	0.03	0.21	3.0	Y	3	—	0.4	N	Y	Y
RJ3										N	—	—	0.4	Y	Y	Y
RJ4										Y	1	10^{13}	0.4	Y	Y	Y
RS1										Y	12.6	3×10^{11}	4.7	N	N	N(?)
RS2	6×10^6	100	2.6×10^4	659	3.16	0.1	0.08	0.06	5.2	Y	1	10^{13}	0.6	N	Y	N
RS3										Y	3	10^{12}	0.6	Y	Y	Y
RS4										Y	1	10^{13}	0.6	Y	Y	Y

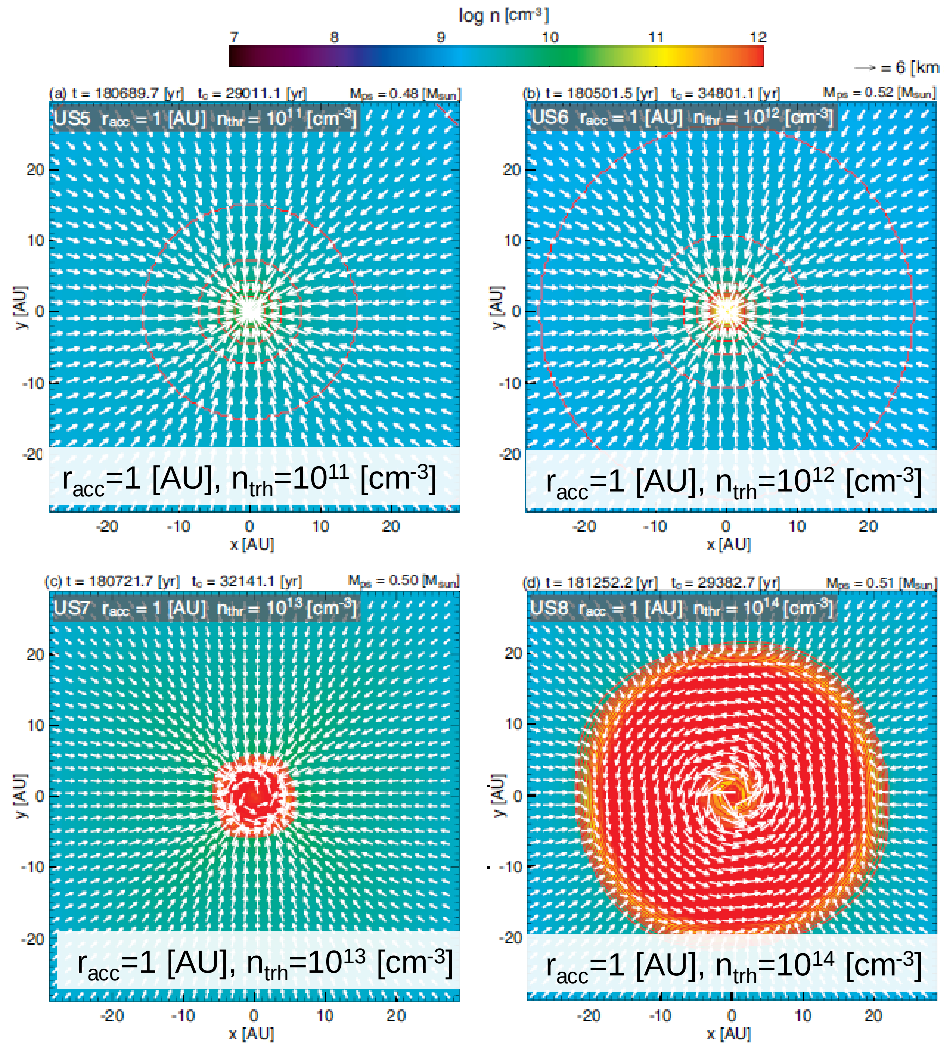
[1] whether or not Ohmic dissipation was included. [2] whether or not the rotation-supported disk formed. [3] whether or not the protostellar outflow appeared.

Uniform Sphere Models

Same initial condition as in Li et al. 2011, but different sink treatments

Disk forms with r_{acc} < 1 AU and $n_{thr} > 10^{13}$ cm^{-3}





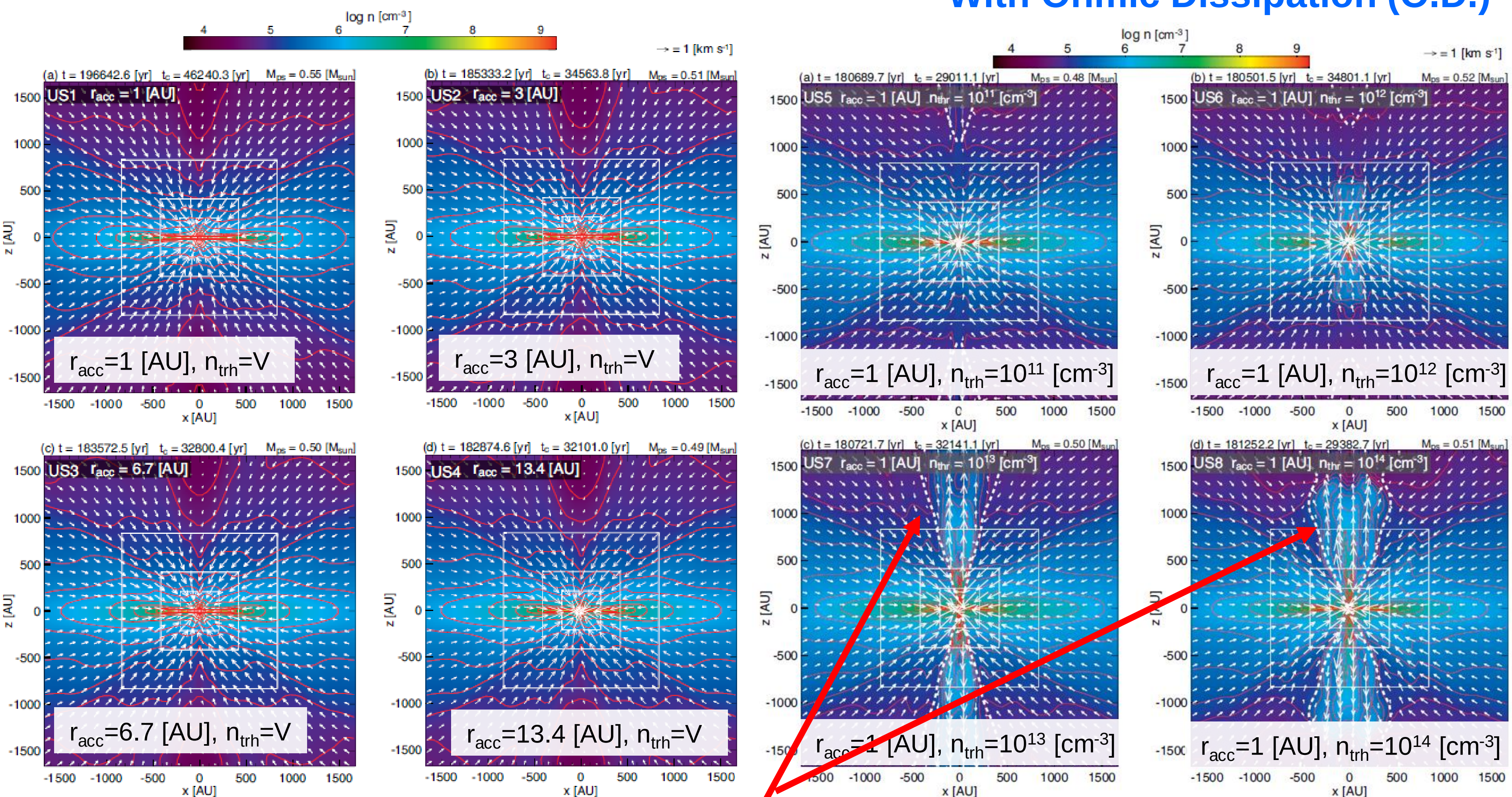
V: variable threshold density

Uniform Sphere Models

Same initial condition as in Li et al. 2011), but different sink treatments

Outflow appears with r_{acc} < 1 AU and $n_{thr} > 10^{13}$ cm^{-3}

With Ohmic Dissipation (O.D.)



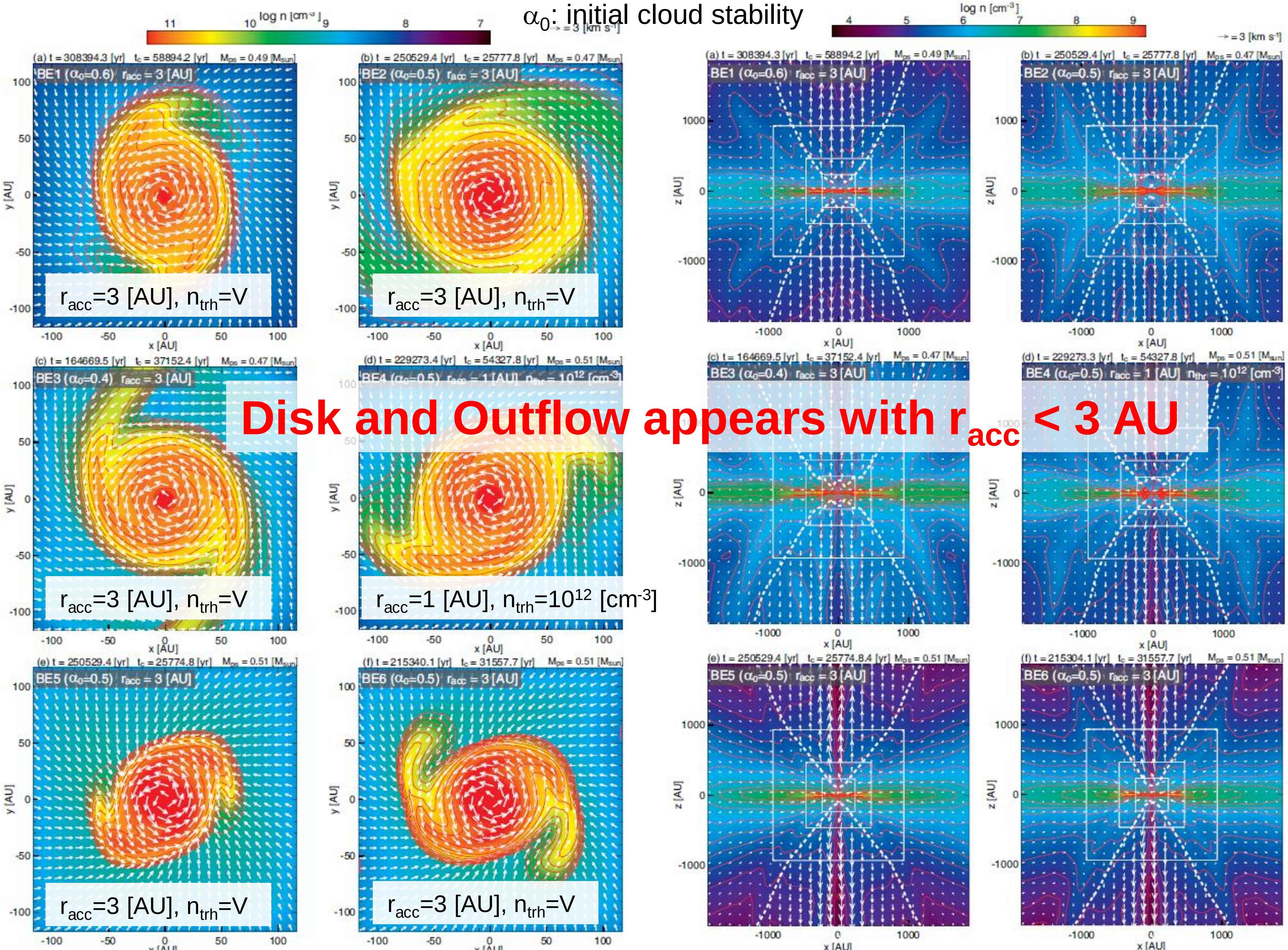
Outflow: inside the white dotted line

Bonnor-Ebert Models

Same initial condition as in Machida et al. 2011), but different sink treatments

With O.D.

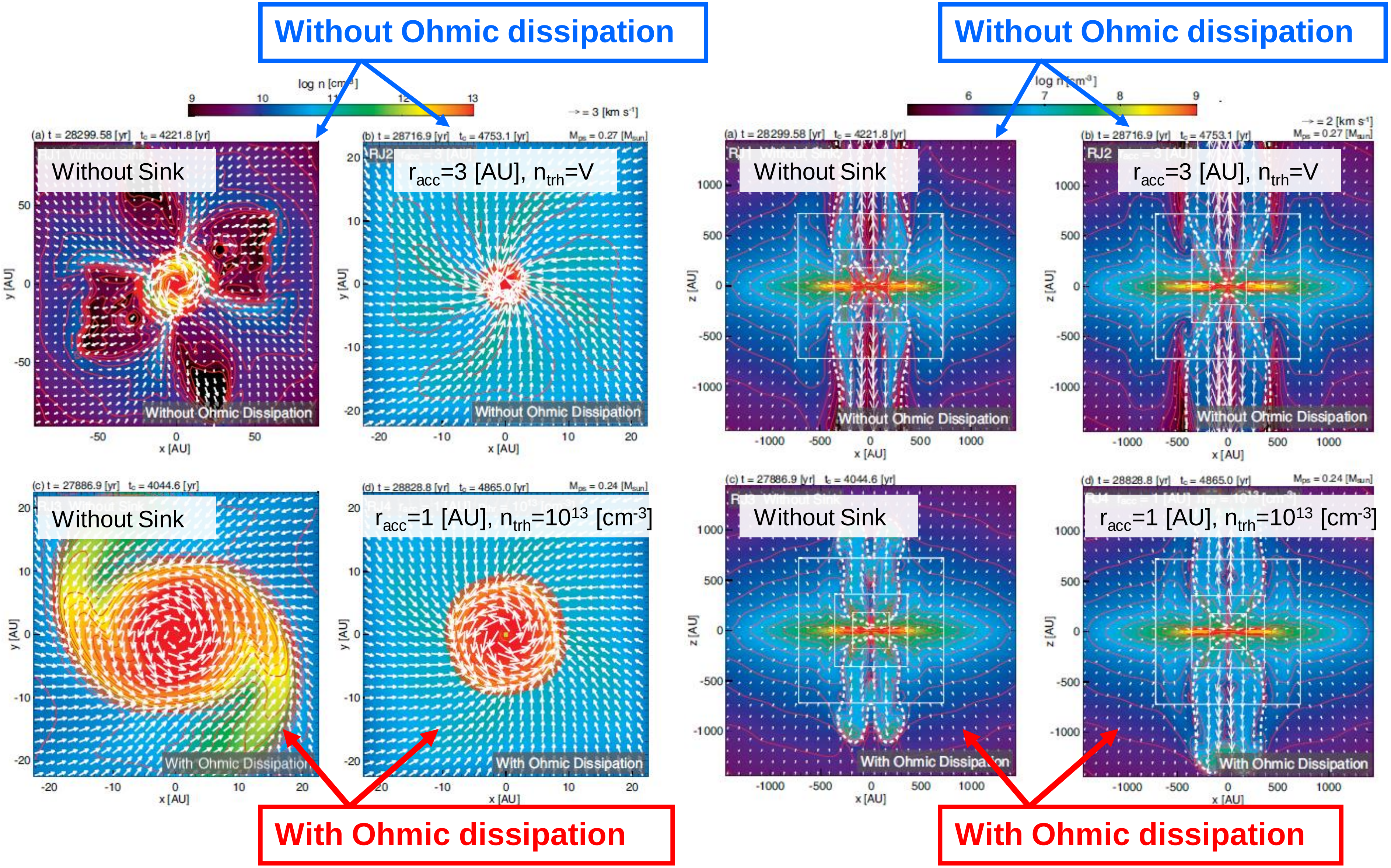
α_0: initial cloud stability



Other Low-mass Cloud Model

Same initial settings as in Joos et al. (2012)

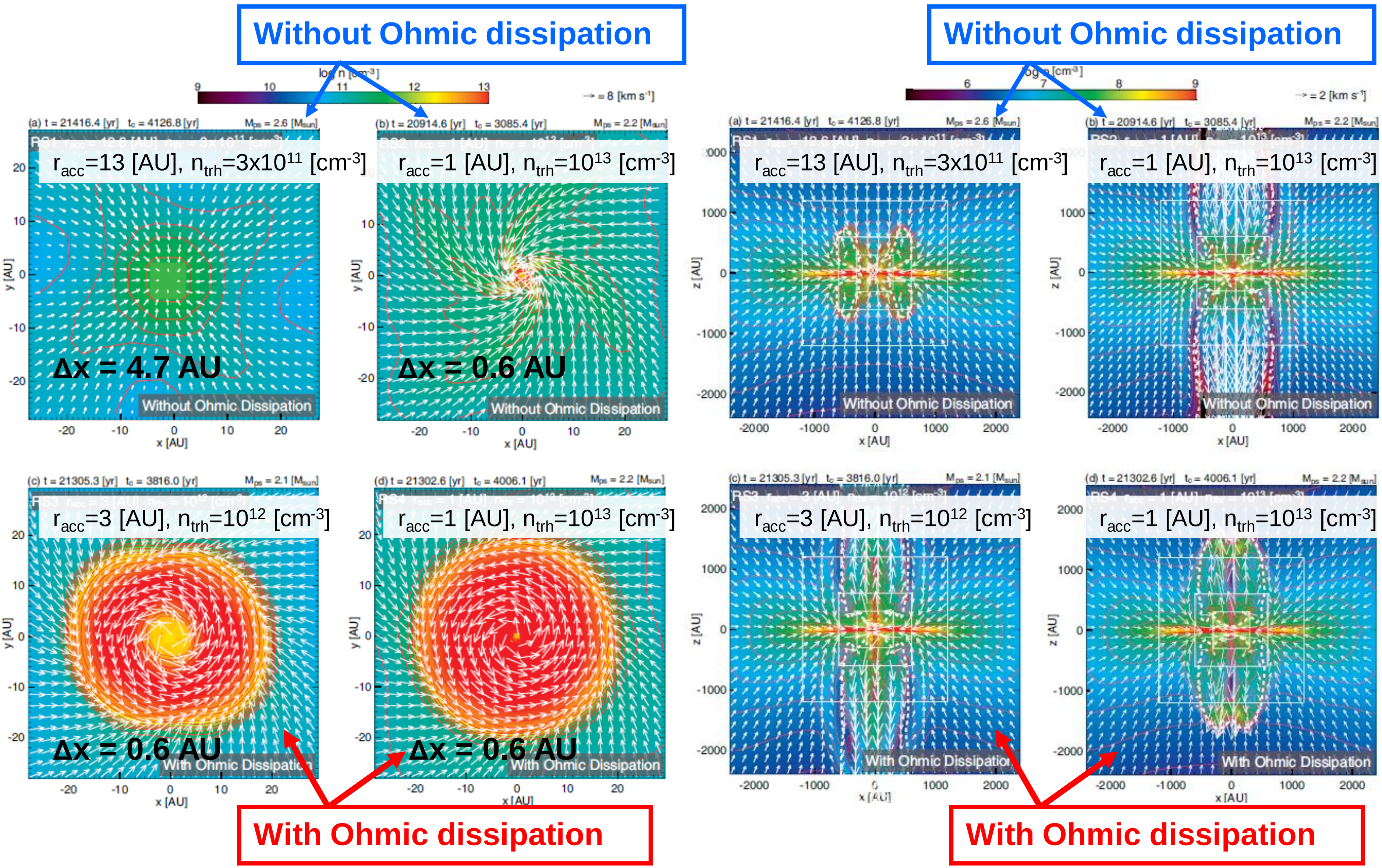
Whether Sink is introduced or not / Whether O.D. is imposed or not



Massive Cloud Model

Same initial settings as in Seifried et al. (2012)

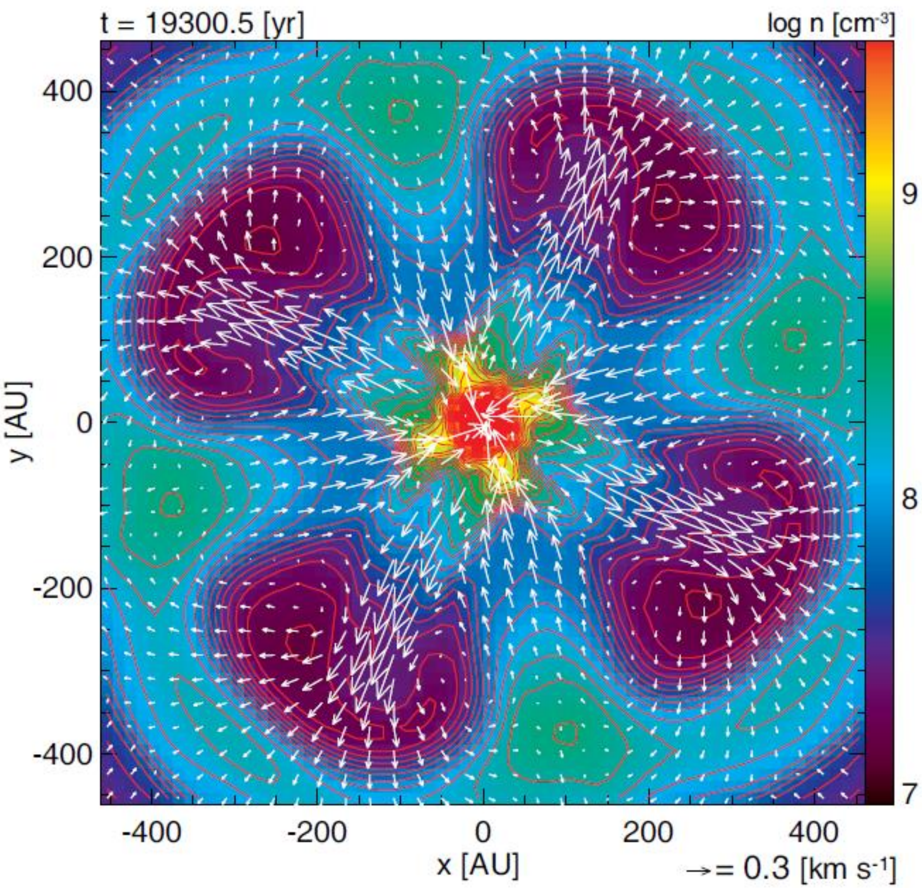
Spatial resolution of <1 AU is necessary



Resolution Dependence

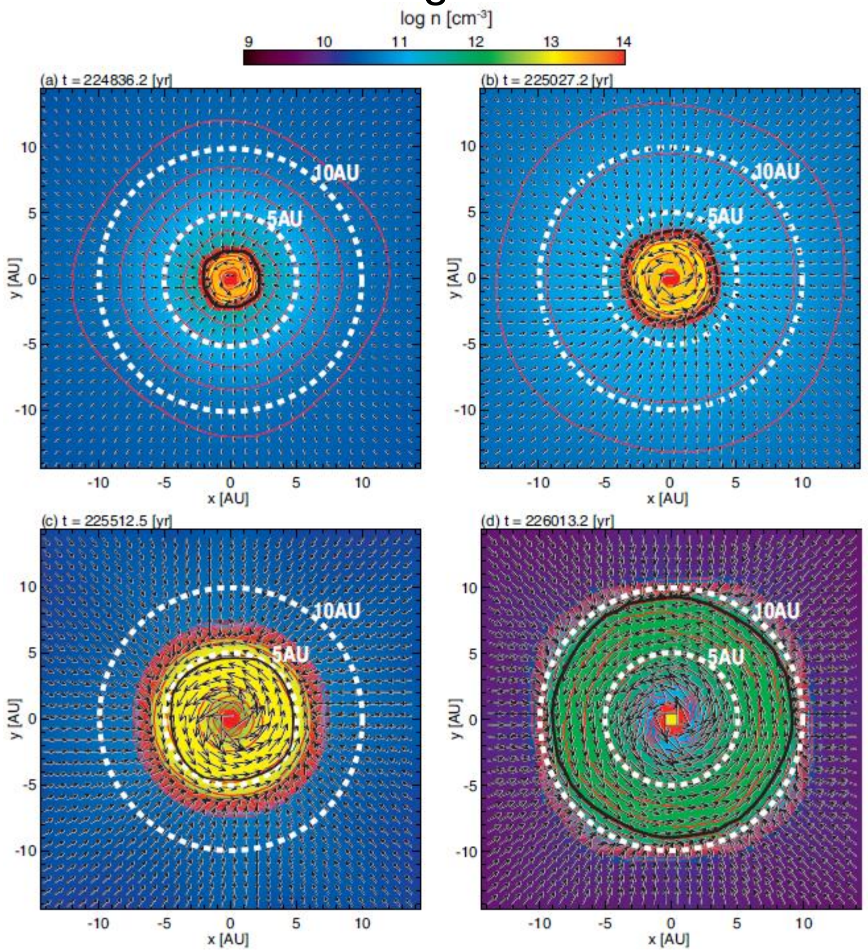
⊗x = 1.6 AU

Numerical reconnection or
Interchange instability?

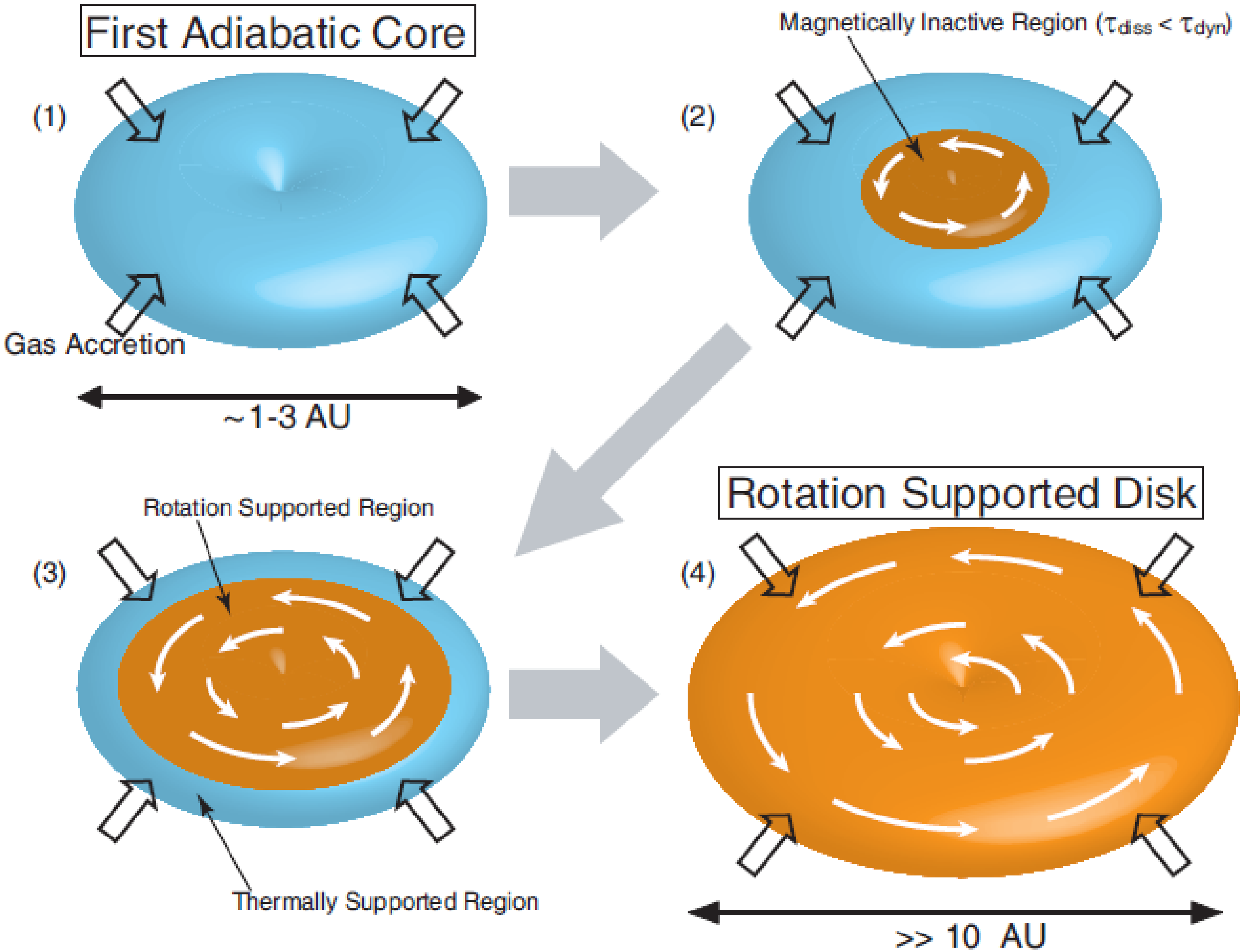


⊗x = 0.06 AU

Tiny disk formation
It evolves into a large-sized disk?



Disk Formation Scenario



Summary

Sink can reproduce any results

- Larger sink accretion radius or lower threshold density
  - can suppress disk formation
  - can weaken or erase outflow
  - can cause interchange instability or numerical reconnection

- For Disk Formation
  - $r_{acc} < 1$ AU and $n_{trh} > 10^{13}$ cm^{-3} are at least necessary
  - Ideally, we should calculate disk formation **WITHOUT SINK**
  - Detailed physical processes such as Magnetic dissipation process and Radiation effects are also essential for disk formation