“Evolution of magnetic fields in collapsing star-forming clouds under different environments”

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Star formation during collapsing phase in low metallicity environments

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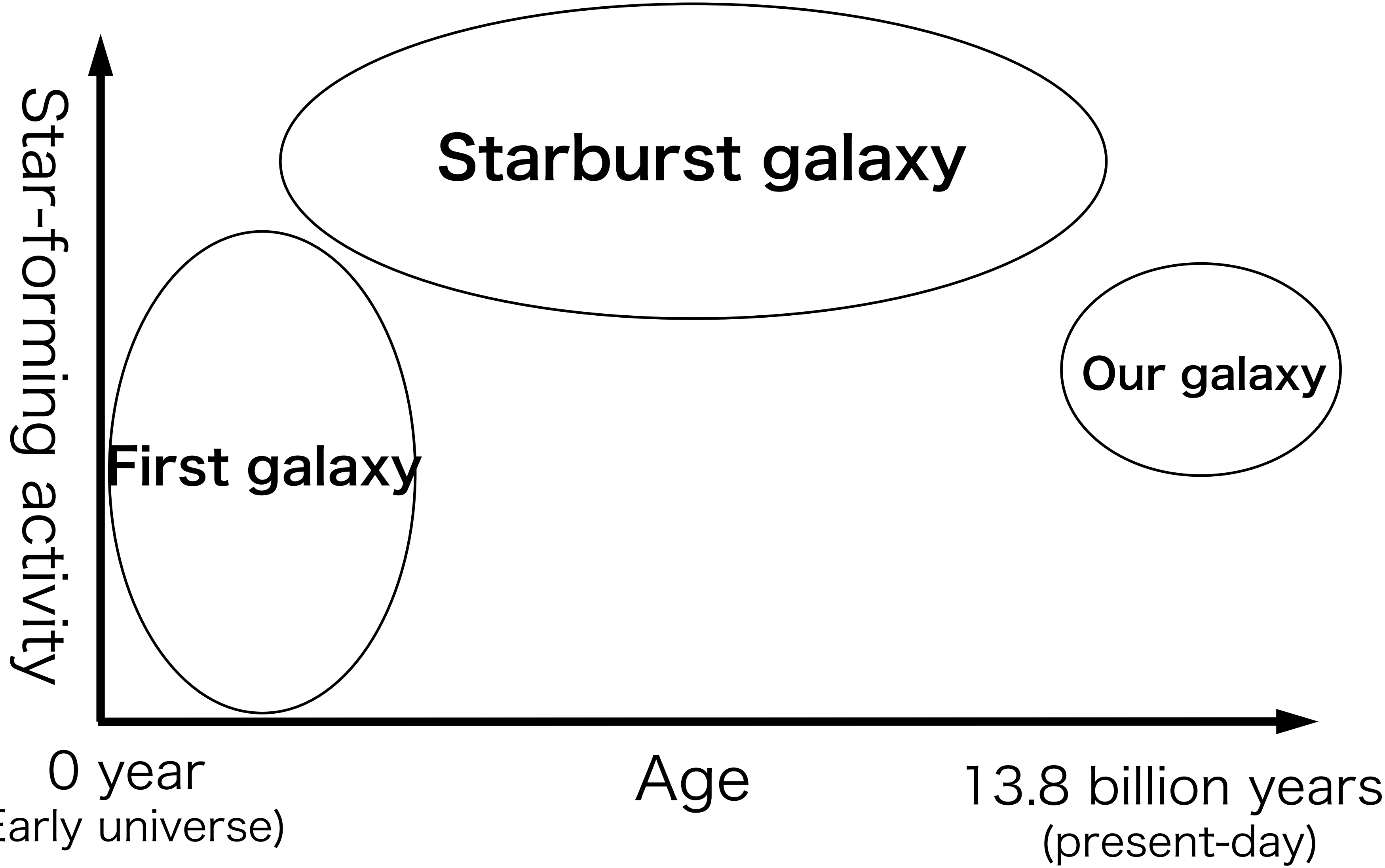
Various star-forming environments



The transition of star formation

FIRST STAR

- IMF composed predominantly of high mass stars (Abel+ 02; Bromm+ 02; O'Shea & Norman 07; Yoshida+ 08; Hosokawa+ 11)

PRESENT-DAY STAR

- IMF composed predominantly of low mass stars (Kroupa 2002; Chabrier 2003)

transition

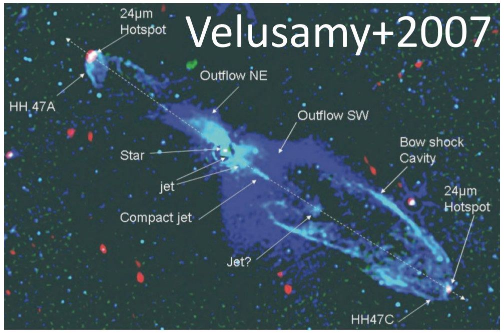
Where is the transition?

This transition Z_{cri} is 10^{-6} - 10^{-3} Z_{sun} ?

(e.g., Bromm+ 01; Bromm & Loeb 03; Omukai+ 05, 10; Santoro & Shull 06; Frebel+ 07; Dopcke+ 11; Schneider+ 06, 12)

Outflow during star formation

- **present-day, Our galaxy**
  - Observation examples （Wu+2004; Zhang+2005）
    -> Theoretical study
    -> Outflow contributes to the star formation



Models

INITIAL CONDITIONS

- 28 clouds have each critical Bonner-Ebert density profiles

Ionization parameter $C_\zeta = 0,\ 0.01,\ 1,\ 10$

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Metallicity $Z/Z_\odot = 0,\ 10^{-5},\ 10^{-4},\ 10^{-3},\ 10^{-2},\ 10^{-1},\ 1$

- Magnetic field strength B_0
  (B is adjusted such that $\mu_0 = 3$)

- rotation $\omega (\equiv \Omega_0 t_{ff}) = 10^{-1}$

Ω_0: initial angular velocity

t_{ff}: free-fall time

BASIC EQUATIONS

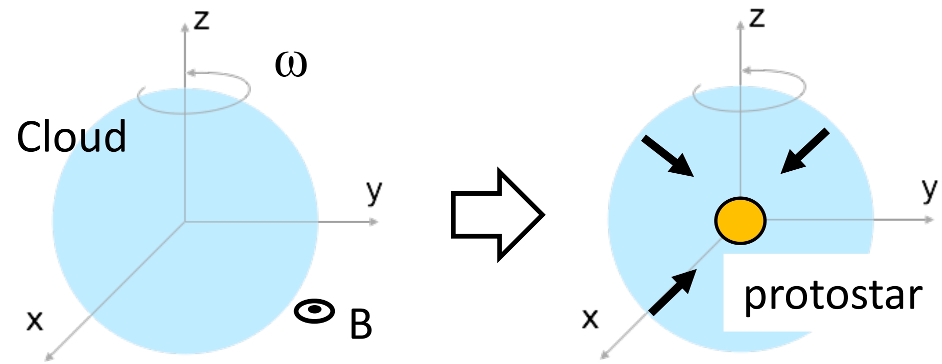
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

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

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left[\boldsymbol{v} \times \mathbf{B} + \frac{\eta_{\mathrm{AD}}}{|B|^2}[(\nabla \times \mathbf{B}) \times \mathbf{B}] \times \mathbf{B} - \eta_{\mathrm{OD}} \nabla \times \mathbf{B} \right]$$

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

$$P = P(\rho)$$



Ionization rate ζ

$$\zeta = \zeta_{\rm CR} + \zeta_{\rm RE,short} + \zeta_{\rm RE,long}$$

- **Radioactivity**
  - Short-lived REs
  - Long-lived REs

$$\zeta_{\rm RE,short} = 7.6 \times 10^{-19}\ {\rm s^{-1}} {\rm C}_\zeta$$

$$\zeta_{\rm RE,long} = 1.4 \times 10^{-22}\ {\rm s^{-1}} \left(\frac{\rm Z}{\rm Z_{sun}}\right)$$

- **Cosmic rays (CR)**

$$\zeta_{\rm CR} = C_\zeta \zeta_{\rm CR,0} {\rm exp}\left(-\frac{\rho {\rm R_J}}{\lambda}\right)$$

C_ζ	Environments
0	Purely primordial environment, no ionization source is included
0.01	Low-metallicity environment, weak ionization sources exist
1	Nearby star-forming environment, the ionization intensity is the same as in nearby star-forming regions ($\zeta_{\rm CR,0} = 1 \times 10^{-17}\ {\rm s^{-1}}$)
10	Starburst galaxy environment: many (or strong) ionization sources exist

$$R_{\rm J} = \sqrt{\frac{\pi k_{\rm B} T}{G \mu m_{\rm p} \rho}}$$

λ: attenuation length ($\lambda = 96\ {\rm g\ cm^{-2}}$)

$R_{\rm J}$: Jeans length

Initial parameters

	Model	C_ζ	Z/Z_{sun}	μ_0	$B_0(\mu G)$	$\Omega_0(s^{-1})$	$M_{cl}(M_\odot)$	$T_{cl}(K)$	$r_{cl}(AU)$
1	I0ZPM3		0		34.1	1.31×10^{-14}	1.08×10^4	198	4.91×10^5
2	I0Z5M3		10^{-5}		33.8	1.31×10^{-14}	1.05×10^4	194	4.87×10^5
3	I0Z4M3		10^{-4}		31.9	1.31×10^{-14}	8.75×10^3	172	4.59×10^5
4	I0Z3M3	0	10^{-3}	3	24.6	1.31×10^{-14}	3.98×10^3	103	3.52×10^5
5	I0Z2M3		10^{-2}		9.83	1.35×10^{-14}	2.27×10^2	16.4	1.33×10^5
6	I0Z1M3		10^{-1}		10.3	1.62×10^{-14}	1.26×10^2	18.1	9.67×10^4
7	I0Z0M3		1		5.76	1.78×10^{-14}	15.2	5.65	4.49×10^4
8	I001ZPM3		0		28.4	1.31×10^{-14}	6.20×10^3	140	4.09×10^5
9	I001Z5M3		10^{-5}		25.1	1.31×10^{-14}	6.03×10^3	136	4.05×10^5
10	I001Z4M3		10^{-4}		26.2	1.31×10^{-14}	4.88×10^3	117	3.77×10^5
11	I001Z3M3	0.01	10^{-3}	3	20.0	1.31×10^{-14}	2.15×10^3	68.0	2.87×10^5
12	I001Z2M3		10^{-2}		9.85	1.35×10^{-14}	2.30×10^2	16.5	1.34×10^5
13	I001Z1M3		10^{-1}		10.4	1.62×10^{-14}	1.28×10^2	18.2	9.72×10^4
14	I001Z0M3		1		5.76	1.78×10^{-14}	15.2	5.64	4.49×10^4
15	I1ZPM3		0		12.1	1.31×10^{-14}	4.79×10^2	24.9	1.74×10^5
16	I1Z5M3		10^{-5}		12.1	1.31×10^{-14}	4.82×10^2	25.1	1.74×10^5
17	I1Z4M3		10^{-4}		12.4	1.31×10^{-14}	5.09×10^2	26.0	1.77×10^5
18	I1Z3M3	1	10^{-3}	3	12.7	1.31×10^{-14}	5.43×10^2	27.3	1.81×10^5
19	I1Z2M3		10^{-2}		12.1	1.34×10^{-14}	4.39×10^2	25.0	1.66×10^5
20	I1Z1M3		10^{-1}		10.9	1.59×10^{-14}	1.58×10^2	20.1	1.06×10^5
21	I1Z0M3		1		6.11	1.78×10^{-14}	18.0	6.34	4.75×10^4
22	I10ZPM3		0		13.5	1.31×10^{-14}	6.56×10^2	31.0	1.93×10^5
23	I10Z5M3		10^{-5}		13.6	1.31×10^{-14}	6.64×10^2	31.2	1.94×10^5
24	I10Z4M3		10^{-4}		14.0	1.32×10^{-14}	7.25×10^2	33.1	1.99×10^5
25	I10Z3M3	10	10^{-3}	3	15.3	1.32×10^{-14}	9.39×10^2	39.6	2.17×10^5
26	I10Z2M3		10^{-2}		15.3	1.34×10^{-14}	8.67×10^2	39.6	2.09×10^5
27	I10Z1M3		10^{-1}		12.6	1.55×10^{-14}	2.74×10^2	26.8	1.29×10^5
28	I10Z0M3		1		8.03	1.78×10^{-14}	40.1	11.0	6.24×10^4

$\omega_0 = 10^{-1}$

$\alpha_0 \left(\equiv \frac{E_t}{E_g}\right) = 0.47$

$\beta_0 \left(\equiv \frac{E_{rot}}{E_g}\right) = 1.84 \times 10^{-2}$

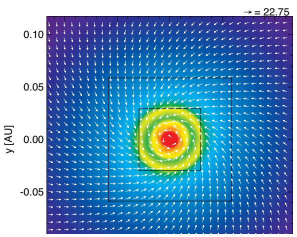
Result: star formation

Present-day star formation
(has Z/Z_{sun} ~ 1)

程を経る
/o outflow)

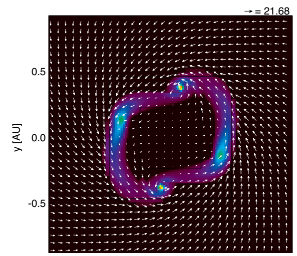
Lower metallicity star formation
(has $Z/Z_{sun} < 10^{-3}$)

First star
(Z/Z_{sun} =0)



Single star
(or Massive close binary)

Lower metallicity star



Multiple stars

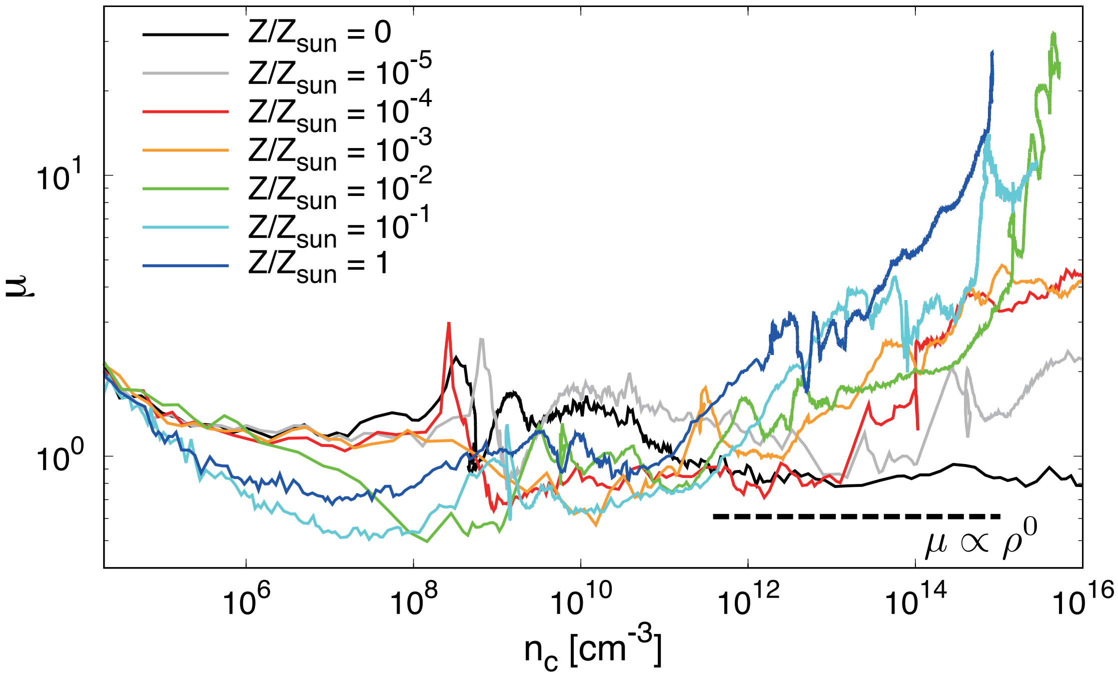
全く異なる星形成

Mass-to-flux ratio evolution: Comparison of metallicities

Definition

$$\mu_0 = \frac{(M/\Phi)}{(M/\Phi)_{\rm cri}}, \quad \left(\frac{M}{\Phi}\right)_{\rm cri} = \frac{1}{2\pi G^{1/2}}.$$

present-day (C_ζ=1)



approximation of the mass-to-flux ratio

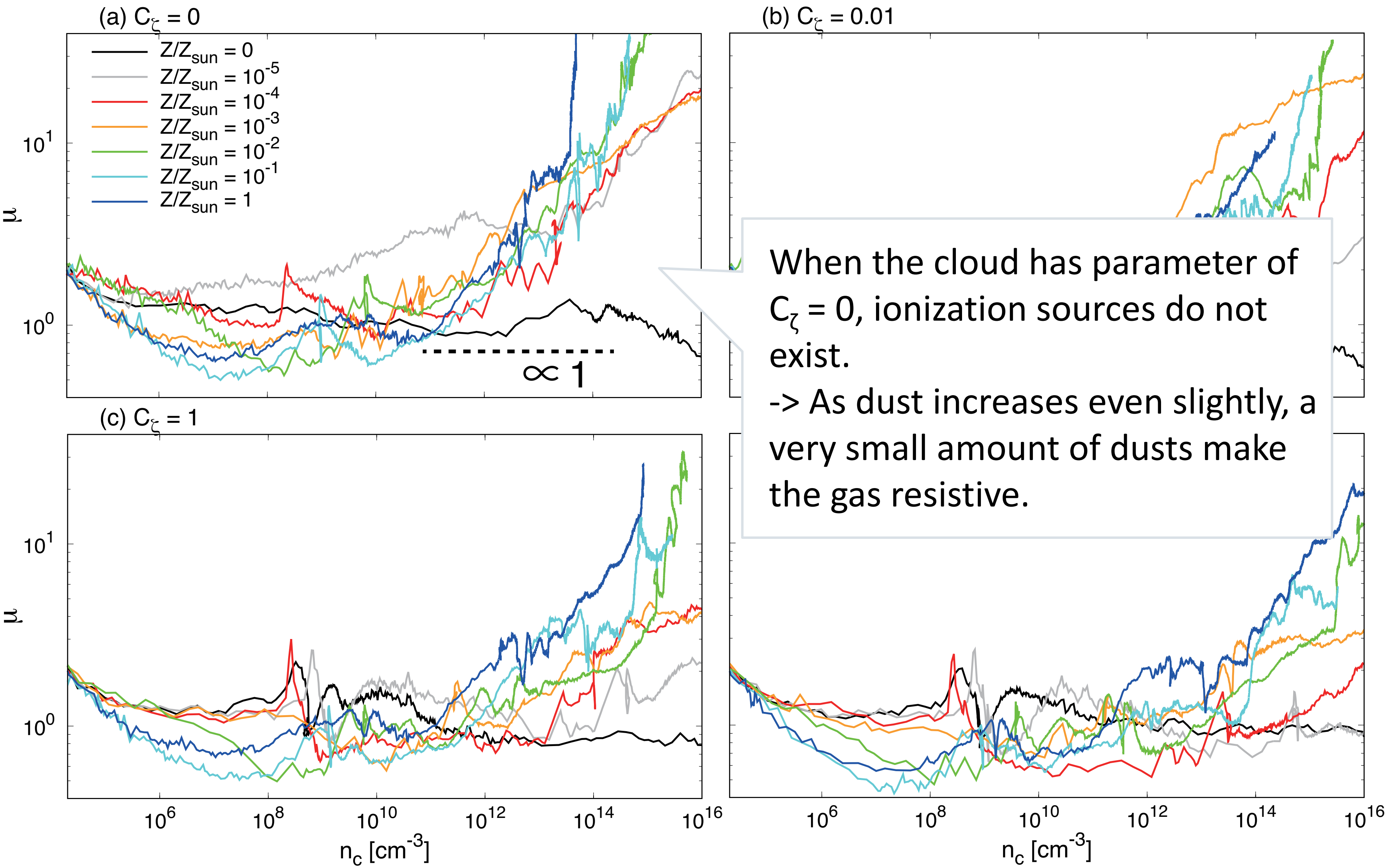
Case of disk-like collapse

$$\mu \approx \frac{M}{BL^2} \begin{cases} R_{\rm J} \propto \rho^{(\gamma-2)/2} \\ M_{\rm J} \propto \rho^{(3\gamma-4)/2} \\ B \propto \rho^{(2\gamma-1)/2} \end{cases}$$

Adopting $\gamma \sim 1$, $\mu \propto \rho^0$

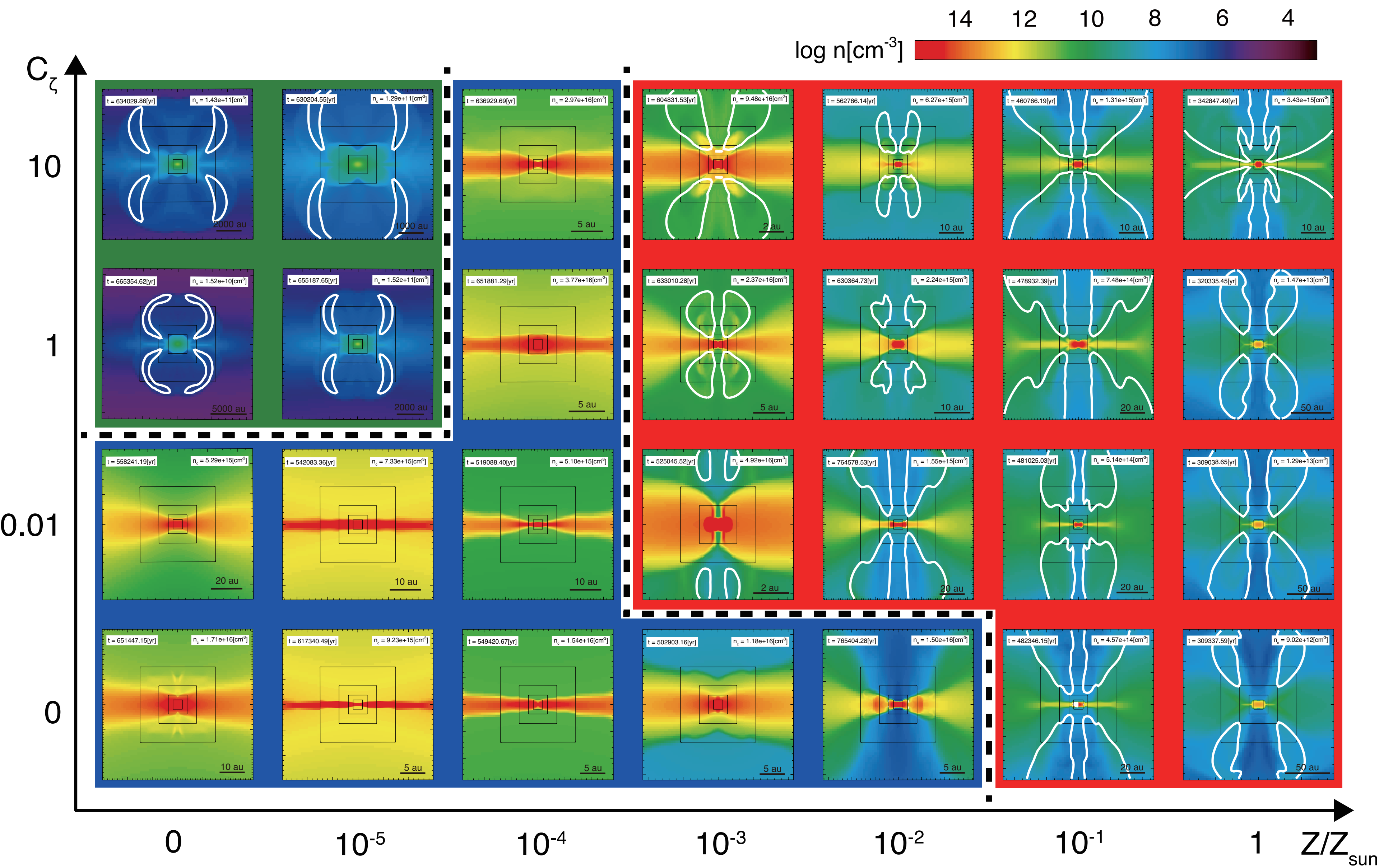
$Z/Z_{sun} \geqq 10^{-5}$
-> μ value is high
(the magnetic dissipation becomes)

Mass-to-flux ratio evolution: Comparison of metallicities



When the cloud has parameter of C_ζ = 0, ionization sources do not exist.
-> As dust increases even slightly, a very small amount of dusts make the gas resistive.

Driving or not outflow in different environments



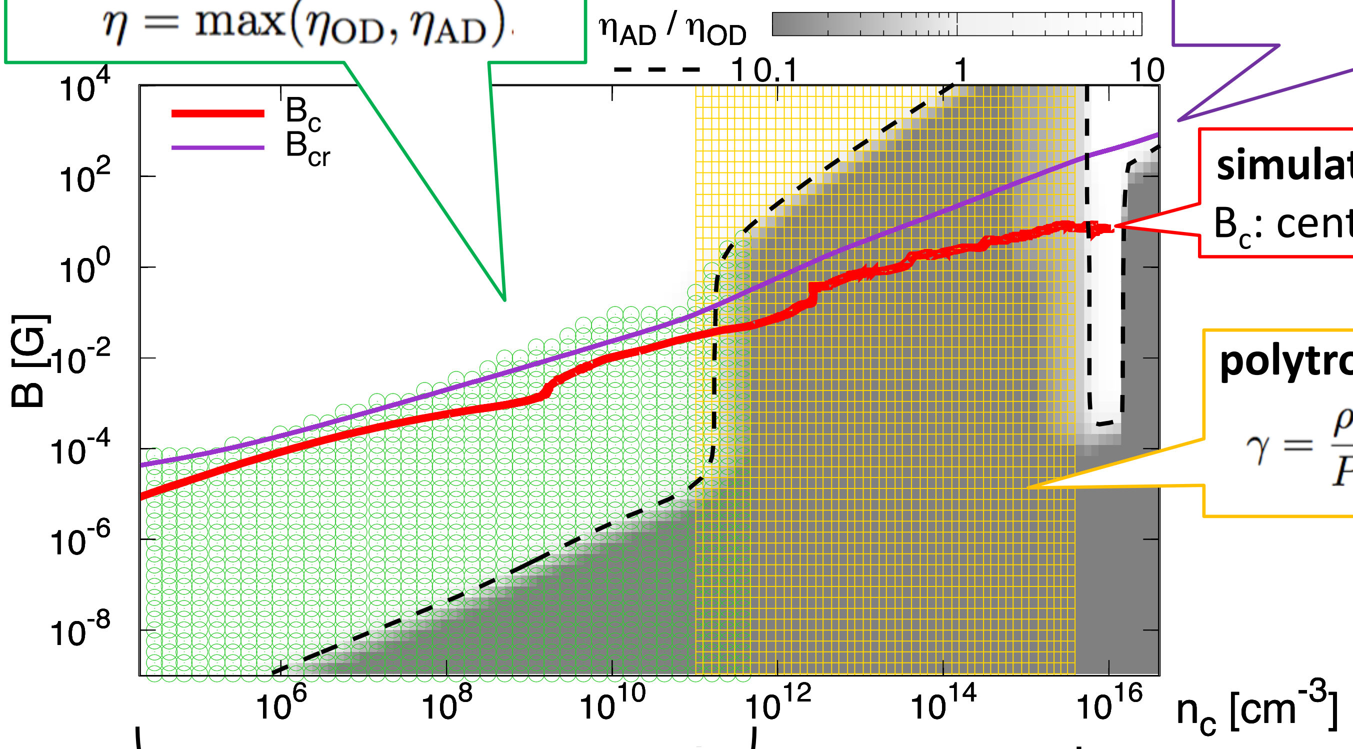
Magnetic field evolution on the n_c – B plane

magnetic Reynolds number

$$R_m \equiv v_f \lambda_J \eta^{-1},$$
$$\lambda_J \equiv (\pi c_s^2 / G\rho_c)^{1/2}$$
$$v_f \equiv [(4/3)\pi G \lambda_J^2 \rho_c]^{1/2}$$
$$\eta = \max(\eta_{OD}, \eta_{AD})$$

critical magnetic field strength

$$B_{cr} = \left(\frac{16\pi^2 G \rho_c^2 \lambda_J^2}{3}\right)^{1/2}$$



simulation result

B_c: central magnetic field strength

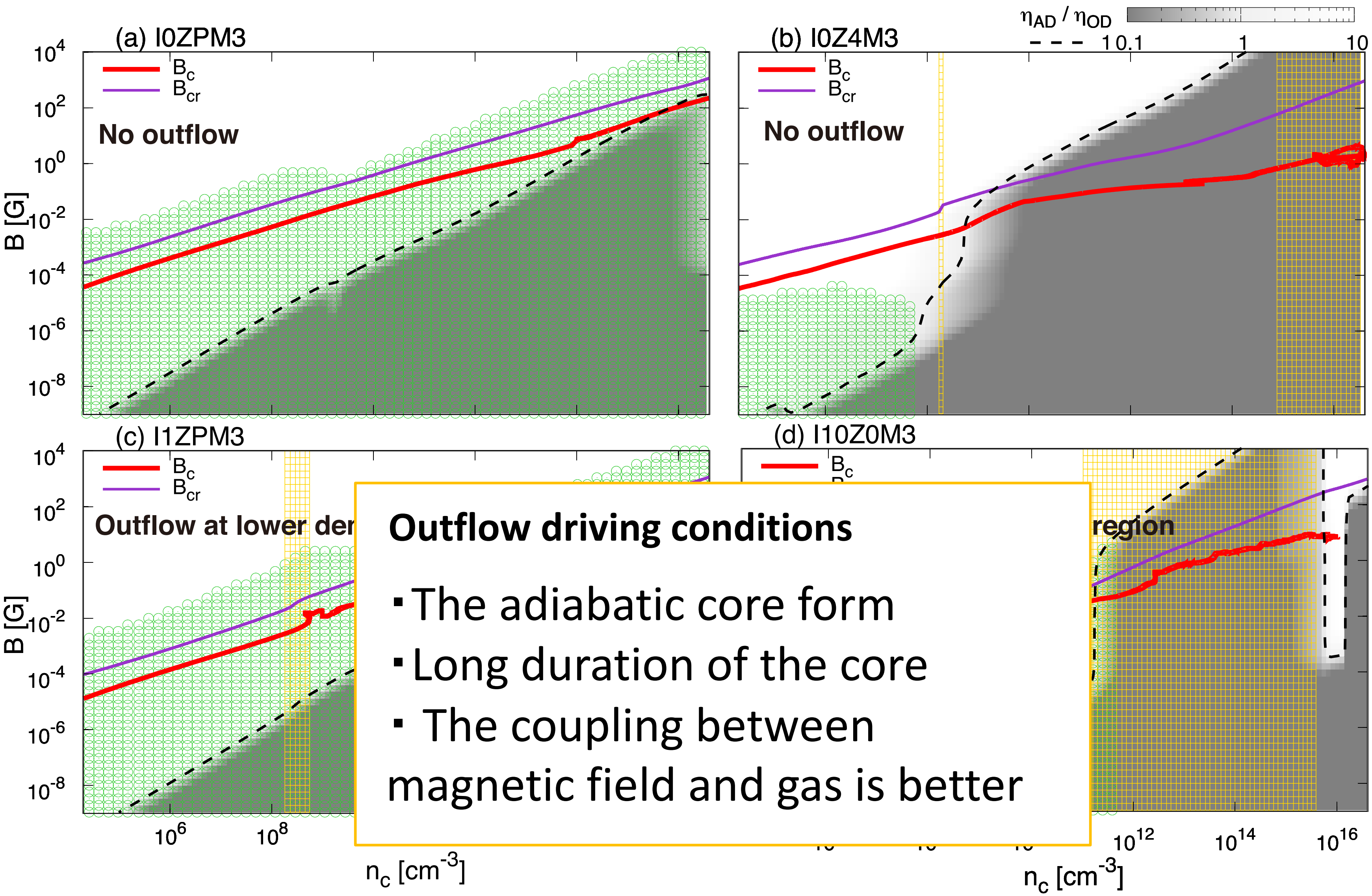
polytropic index

$$\gamma = \frac{\rho_c}{P_c}\left(\frac{dP}{d\rho}\right)_c$$

magnetic field is coupled to the gas ($R_m > 1$)

quasi-hydrostatic core can be formed ($\gamma > 4/3$)

Magnetic field evolution on the n_c – B plane

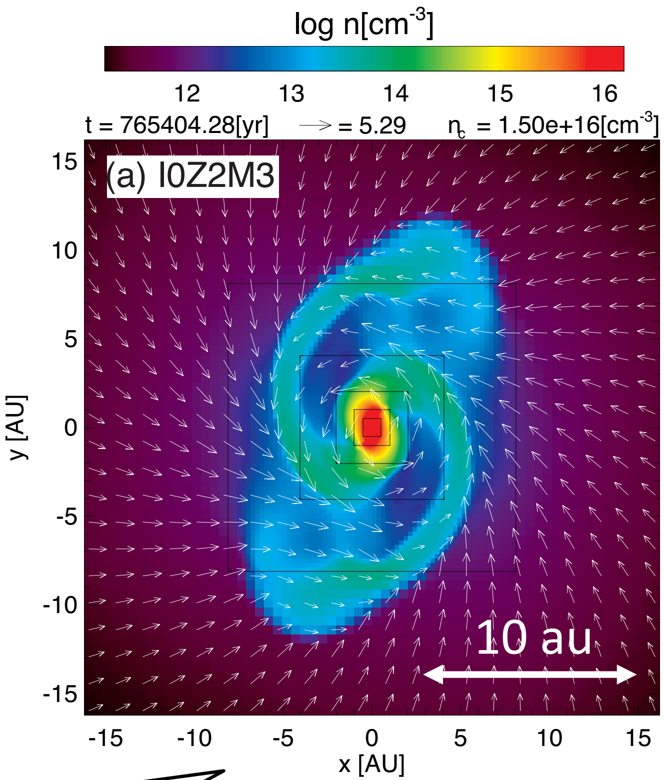


Outflow driving conditions

- The adiabatic core form
- Long duration of the core
- The coupling between magnetic field and gas is better

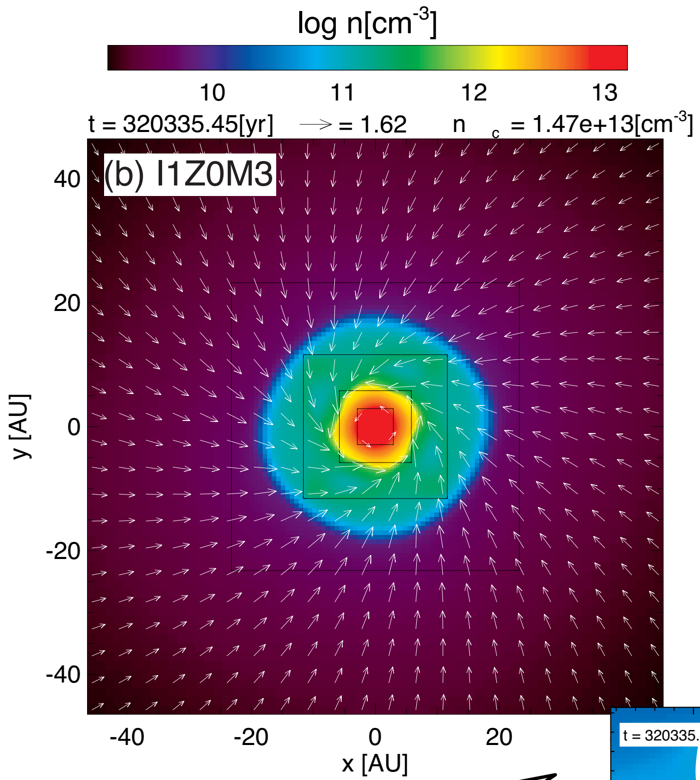
Angular momentum transfer

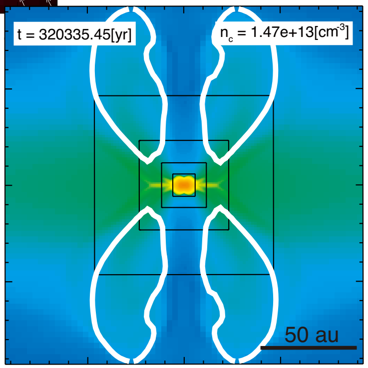
Outflow is not driven



Formation of non-axisymmetric structure of first core scale
-> Angular momentum is transported by gravity torque

Outflow is driven





Angular momentum is transported by outflow

Summary

- In the present conditions($\mu_0 = 3$, $\omega_0 = 10^{-1}$), outflow does not drive in the metallicity range $Z/Z_{sun} < 10^{-3}$ expect $C_\zeta = 1, 10$
- For the case in which $C_\zeta = 0$ and lower metallicities, star formation process is quite different.
- The transition of star formation exist at $Z \sim 10^{-4}$-10^{-3} Z_{sun}.

Result: star formation

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(has Z/Z_{sun} ~ 1)

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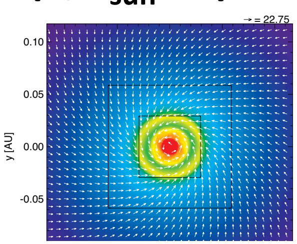

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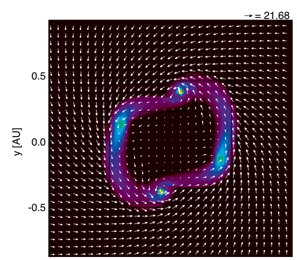

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