Star Formation in Different Environments

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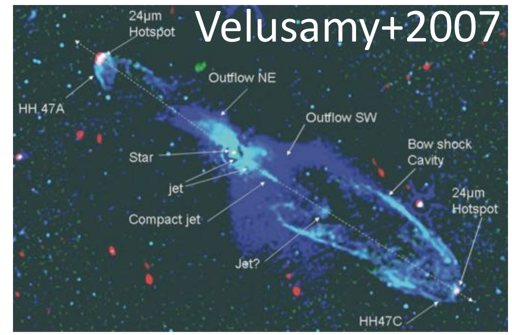
Outflow during star formation

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



- **Excepting present-day, Our galaxy**
  - Not observation
    -> Theoretical study is not performed

Contents

- Estimation of the magnetic dissipation in different environments
- Whether outflow occur or not in different environments

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The factor of changing star forming environment

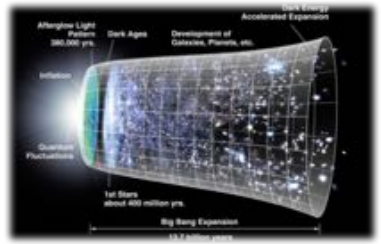
Metallicity

HIGH

Cooling efficiency ↗

LOW

Cooling efficiency ↘



Transition

Star forming environment

Star forming activity

(Ionization rate)

HIGH

Coupling between magnetic field and gas ↗

LOW

Coupling between magnetic field and gas ↘

Ionization rate ζ $\zeta = \zeta_{\mathrm{CR}} + \zeta_{\mathrm{RE,short}} + \zeta_{\mathrm{RE,long}}$

- **Radioactivity**
  - Short-lived REs $\zeta_{\mathrm{RE,short}} = 7.6 \times 10^{-19}\ \mathrm{s}^{-1} \mathrm{C}_{\zeta}$
  - Long-lived REs $\zeta_{\mathrm{RE,long}} = 1.4 \times 10^{-22}\ \mathrm{s}^{-1} \left(\frac{\mathrm{Z}}{\mathrm{Z_{sun}}}\right)$
- **Cosmic rays (CR)** $\zeta_{\mathrm{CR}} = C_{\zeta} \zeta_{\mathrm{CR,0}} \exp\left(-\frac{\rho \mathrm{R_J}}{\lambda}\right)$

C_{ζ}	Environments
0	Primordial (w/o ionization either by CR or short-lived REs)
0.01	100 times smaller ionization rate than the local value
1	Our galaxy (CR intensity : $\zeta_{\mathrm{CR,0}} = 1 \times 10^{-19}\ \mathrm{s}^{-1}$)
10	Starburst galaxies

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

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

$\mathrm{R_J}$: Jeans length

Model（Initial conditions）

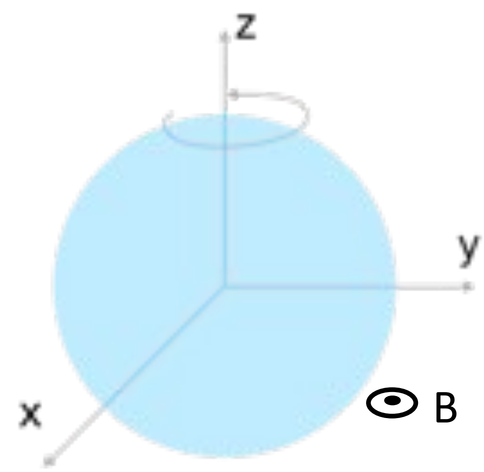
- Assumption of different environments
  ->metallicity（Z/Z_{sun}） × ionization parameter（C_ζ）

$$Z/Z_{\rm sun} = 0,\ 10^{-7},\ 10^{-6},\ 10^{-5},\ 10^{-4},\ 10^{-3},\ 10^{-2},\ 10^{-1}, 1$$

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

- Bonner-Ebert sphere
- Magnetic field :

  B for coping with $\mu = 100$



- Rotation : $\omega(\equiv \Omega_0 t_{\rm ff}) = 10^{-4}$

$$\mu \equiv \left(\frac{{\rm M}/\Phi}{({\rm M}/\Phi)_{\rm cri}}\right)$$

Model	μ	ω	f	$B_0(\mu G)$	$M_{cl}(M_\odot)$	$T_{cl}(K)$	$r_{cl}(AU)$	$c_s(km\ s^{-1})$
$C_\zeta = 0\ Z/Z_{sun} = 0$	100	10^{-4}	1.8	1.02	1.08×10^4	198	4.91×10^5	1.49
$C_\zeta = 0\ Z/Z_{sun} = 10^{-7}$	100	10^{-4}	1.8	1.02	1.08×10^4	198	4.91×10^5	1.49
$C_\zeta = 0\ Z/Z_{sun} = 10^{-6}$	100	10^{-4}	1.8	1.02	1.07×10^4	198	4.91×10^5	1.49
$C_\zeta = 0\ Z/Z_{sun} = 10^{-5}$	100	10^{-4}	1.8	1.01	1.05×10^4	194	4.87×10^5	1.48
$C_\zeta = 0\ Z/Z_{sun} = 10^{-4}$	100	10^{-4}	1.8	0.96	8.75×10^3	172	4.59×10^5	1.39
$C_\zeta = 0\ Z/Z_{sun} = 10^{-3}$	100	10^{-4}	1.8	0.74	3.98×10^3	103	3.52×10^5	1.07
$C_\zeta = 0\ Z/Z_{sun} = 10^{-2}$	100	10^{-4}	1.8	0.30	2.27×10^2	16.4	1.33×10^5	0.42
$C_\zeta = 0\ Z/Z_{sun} = 10^{-1}$	100	10^{-4}	1.8	0.31	1.26×10^2	18.1	9.67×10^4	0.36
$C_\zeta = 0\ Z/Z_{sun} = 1$	100	10^{-4}	1.8	0.17	15.2	5.65	4.49×10^4	0.19
$C_\zeta = 0.01\ Z/Z_{sun} = 0$	100	10^{-4}	1.8	0.86	6.20×10^3	137	4.09×10^5	1.24
$C_\zeta = 0.01\ Z/Z_{sun} = 10^{-7}$	100	10^{-4}	1.8	0.85	6.19×10^3	137	4.09×10^5	1.24
$C_\zeta = 0.01\ Z/Z_{sun} = 10^{-6}$	100	10^{-4}	1.8	0.85	6.18×10^3	137	4.08×10^5	1.24
$C_\zeta = 0.01\ Z/Z_{sun} = 10^{-5}$	100	10^{-4}	1.8	0.84	6.03×10^3	135	4.05×10^5	1.23
$C_\zeta = 0.01\ Z/Z_{sun} = 10^{-4}$	100	10^{-4}	1.8	0.79	4.88×10^3	117	3.77×10^5	1.15
$C_\zeta = 0.01\ Z/Z_{sun} = 10^{-3}$	100	10^{-4}	1.8	0.60	2.15×10^3	68.0	2.87×10^5	0.87
$C_\zeta = 0.01\ Z/Z_{sun} = 10^{-2}$	100	10^{-4}	1.8	0.30	2.30×10^2	16.5	1.34×10^5	0.42
$C_\zeta = 0.01\ Z/Z_{sun} = 10^{-1}$	100	10^{-4}	1.8	0.31	1.28×10^2	18.2	9.72×10^4	0.37
$C_\zeta = 0.01\ Z/Z_{sun} = 1$	100	10^{-4}	1.8	0.17	15.2	5.64	4.49×10^4	0.19
$C_\zeta = 1\ Z/Z_{sun} = 0$	100	10^{-4}	1.8	0.36	4.79×10^2	24.9	1.74×10^5	0.53
$C_\zeta = 1\ Z/Z_{sun} = 10^{-7}$	100	10^{-4}	1.8	0.36	4.79×10^2	24.9	1.74×10^5	0.53
$C_\zeta = 1\ Z/Z_{sun} = 10^{-6}$	100	10^{-4}	1.8	0.36	4.79×10^2	24.9	1.74×10^5	0.53
$C_\zeta = 1\ Z/Z_{sun} = 10^{-5}$	100	10^{-4}	1.8	0.36	4.82×10^2	25.1	1.74×10^5	0.53
$C_\zeta = 1\ Z/Z_{sun} = 10^{-4}$	100	10^{-4}	1.8	0.37	5.09×10^2	26.0	1.77×10^5	0.54
$C_\zeta = 1\ Z/Z_{sun} = 10^{-3}$	100	10^{-4}	1.8	0.38	5.43×10^2	27.3	1.81×10^5	0.55
$C_\zeta = 1\ Z/Z_{sun} = 10^{-2}$	100	10^{-4}	1.8	0.36	4.39×10^2	25.0	1.66×10^5	0.52
$C_\zeta = 1\ Z/Z_{sun} = 10^{-1}$	100	10^{-4}	1.8	0.33	1.58×10^2	20.1	1.06×10^5	0.39
$C_\zeta = 1\ Z/Z_{sun} = 1$	100	10^{-4}	1.8	0.18	18.0	6.34	4.75×10^4	0.20
$C_\zeta = 10\ Z/Z_{sun} = 0$	100	10^{-4}	1.8	0.41	6.56×10^2	31.0	1.93×10^5	0.59
$C_\zeta = 10\ Z/Z_{sun} = 10^{-7}$	100	10^{-4}	1.8	0.41	6.57×10^2	31.0	1.93×10^5	0.59
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$C_\zeta = 10\ Z/Z_{sun} = 10^{-4}$	100	10^{-4}	1.8	0.42	7.25×10^2	33.1	1.99×10^5	0.61
$C_\zeta = 10\ Z/Z_{sun} = 10^{-3}$	100	10^{-4}	1.8	0.46	9.39×10^2	39.6	2.17×10^5	0.66
$C_\zeta = 10\ Z/Z_{sun} = 10^{-2}$	100	10^{-4}	1.8	0.46	8.67×10^2	39.6	2.09×10^5	0.65
$C_\zeta = 10\ Z/Z_{sun} = 10^{-1}$	100	10^{-4}	1.8	0.38	2.74×10^2	26.8	1.29×10^5	0.46
$C_\zeta = 10\ Z/Z_{sun} = 1$	100	10^{-4}	1.8	0.24	40.1	11.0	6.24×10^4	0.26

36 parameters × 4

Basic equations

3 dimensional non-Ideal MHD nested grid code

① Ideal
② Ohmic dissipation（OD）
③ Ambipolar diffusion（AD）
④ non-Ideal (OD and AD)

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

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

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

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

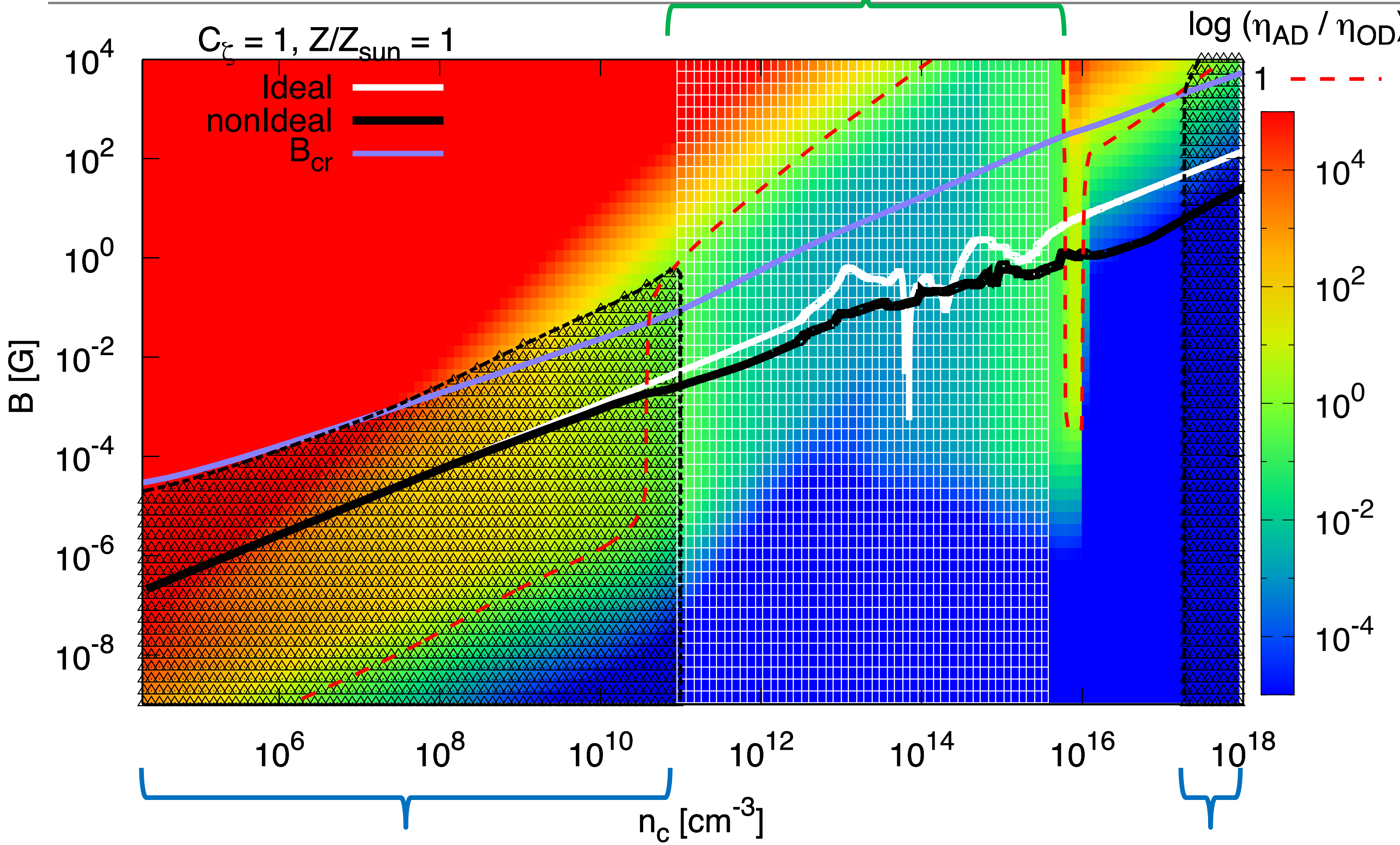
$$P = P(\rho)$$

Calculation of chemical evolution during collapsing cloud
(η_{AD}, η_{OD} 、thermal evolution)
-> 1-zone calculation Nakano+2002

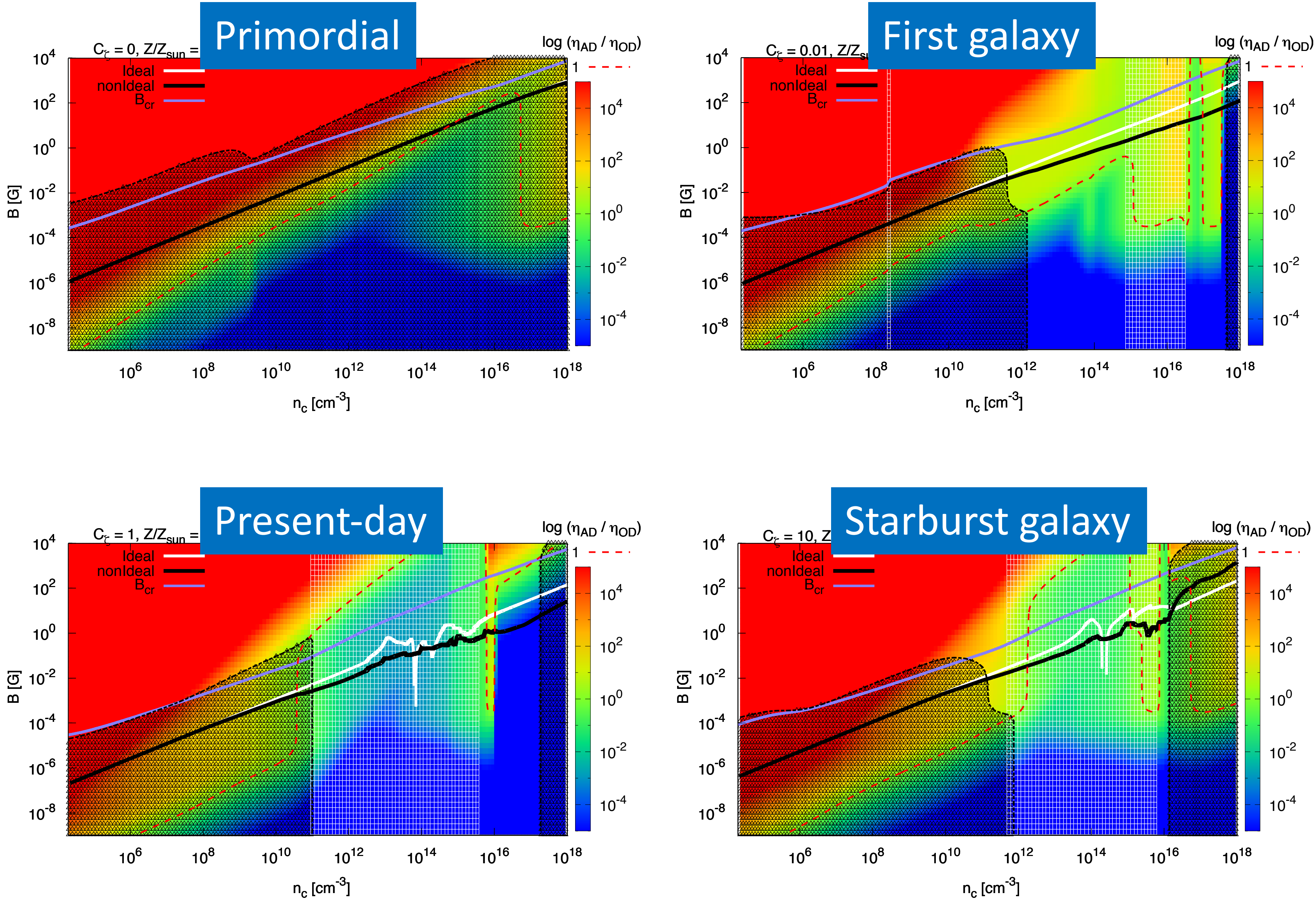
$C_\zeta = 1,\ Z/Z_{sun} = 1$

results

$\gamma \geqq 4/3$



Coupled zone Coupled zone



Black shadow : coupled region

White shadow ：$\gamma \geqq 4/3$

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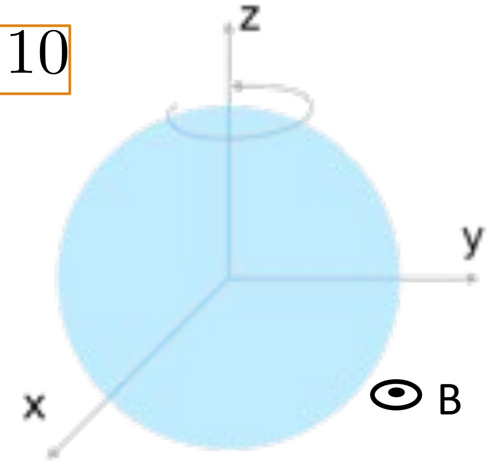
  ->metallicity（Z/Z_{sun}） × ionization parameter（C_ζ）

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

×

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



- Bonner-Ebert sphere
- Magnetic field：

  B for coping with $\mu = 3$

- Rotation： $\omega(\equiv \Omega_0 t_{\mathrm{ff}}) = 0.1$

$$\mu \equiv \left(\frac{\mathrm{M}/\Phi}{(\mathrm{M}/\Phi)_{\mathrm{cri}}}\right)$$

Initial parameters

Model	μ	ω	f	$B_0(\mu G)$	$M_{cl}(M_\odot)$	$T_{cl}(K)$	$r_{cl}(AU)$	c_s(km s^{-1})
$C_\zeta = 0$ $Z/Z_{sun} = 0$	3	0.1	1.8	34.1	1.08×10^4	198	4.91×10^5	1.49
$C_\zeta = 0$ $Z/Z_{sun} = 10^{-5}$	3	0.1	1.8	33.8	1.05×10^4	194	4.87×10^5	1.48
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$C_\zeta = 0$ $Z/Z_{sun} = 1$	3	0.1	1.8	5.76	15.2	5.65	4.49×10^4	0.19
$C_\zeta = 001$ $Z/Z_{sun} = 0$	3	0.1	1.8	28.4	6.20×10^3	140	4.09×10^5	1.24
$C_\zeta = 001$ $Z/Z_{sun} = 10^{-5}$	3	0.1	1.8	25.1	6.03×10^3	136	4.05×10^5	1.23
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$C_\zeta = 10$ $Z/Z_{sun} = 0$	3	0.1	1.8	13.5	6.56×10^2	31.0	1.93×10^5	0.59
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Basic equations

<u>3 dimensional non-Ideal MHD nested grid code</u>

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

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

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

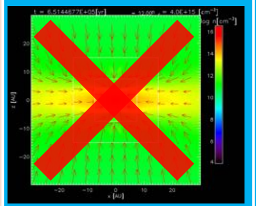
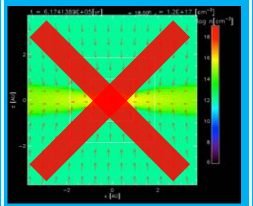
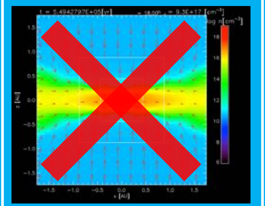
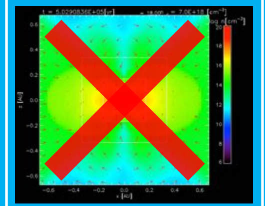
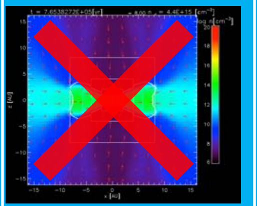
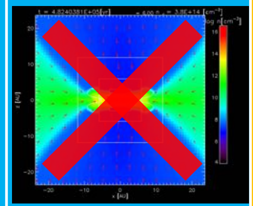
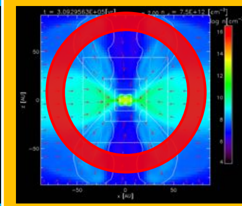
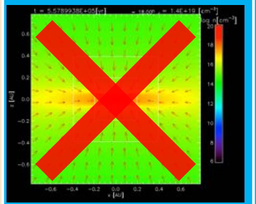
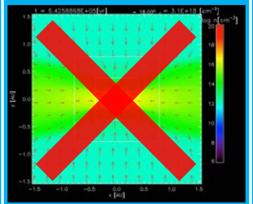
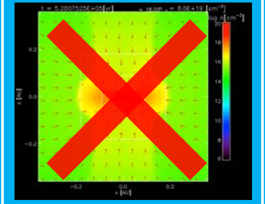
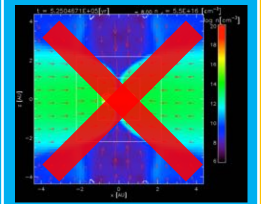
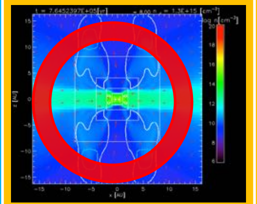
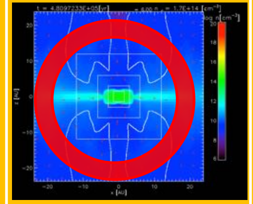
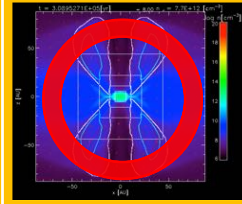
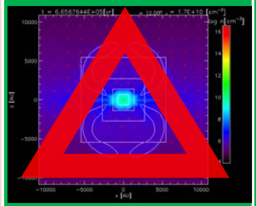
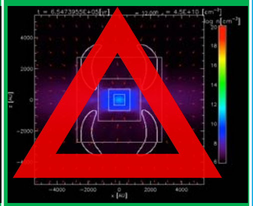
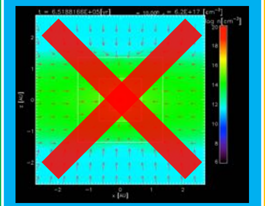
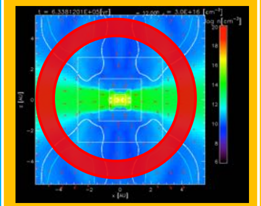
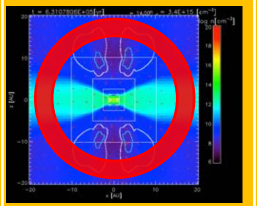
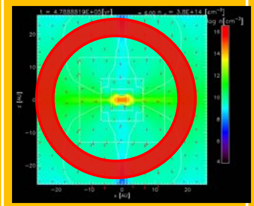
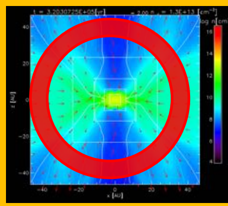
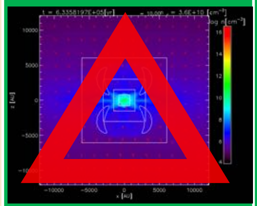
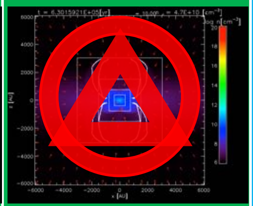
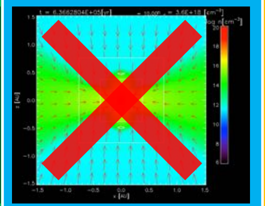
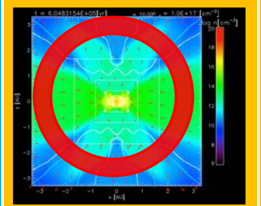
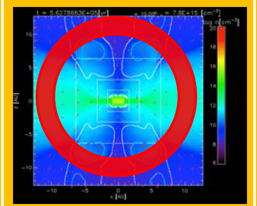
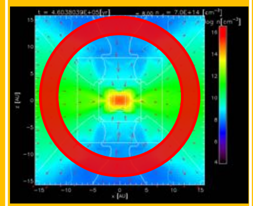
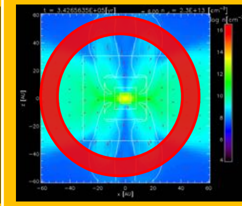
$$\nabla^2 \phi = 4\pi G \rho$$

$$P = P(\rho)$$

Calculation of chemical evolution during collapsing cloud

($\eta_{\rm AD}$, $\eta_{\rm OD}$ 、thermal evolution)

-> 1-zone calculation Nakano+2002

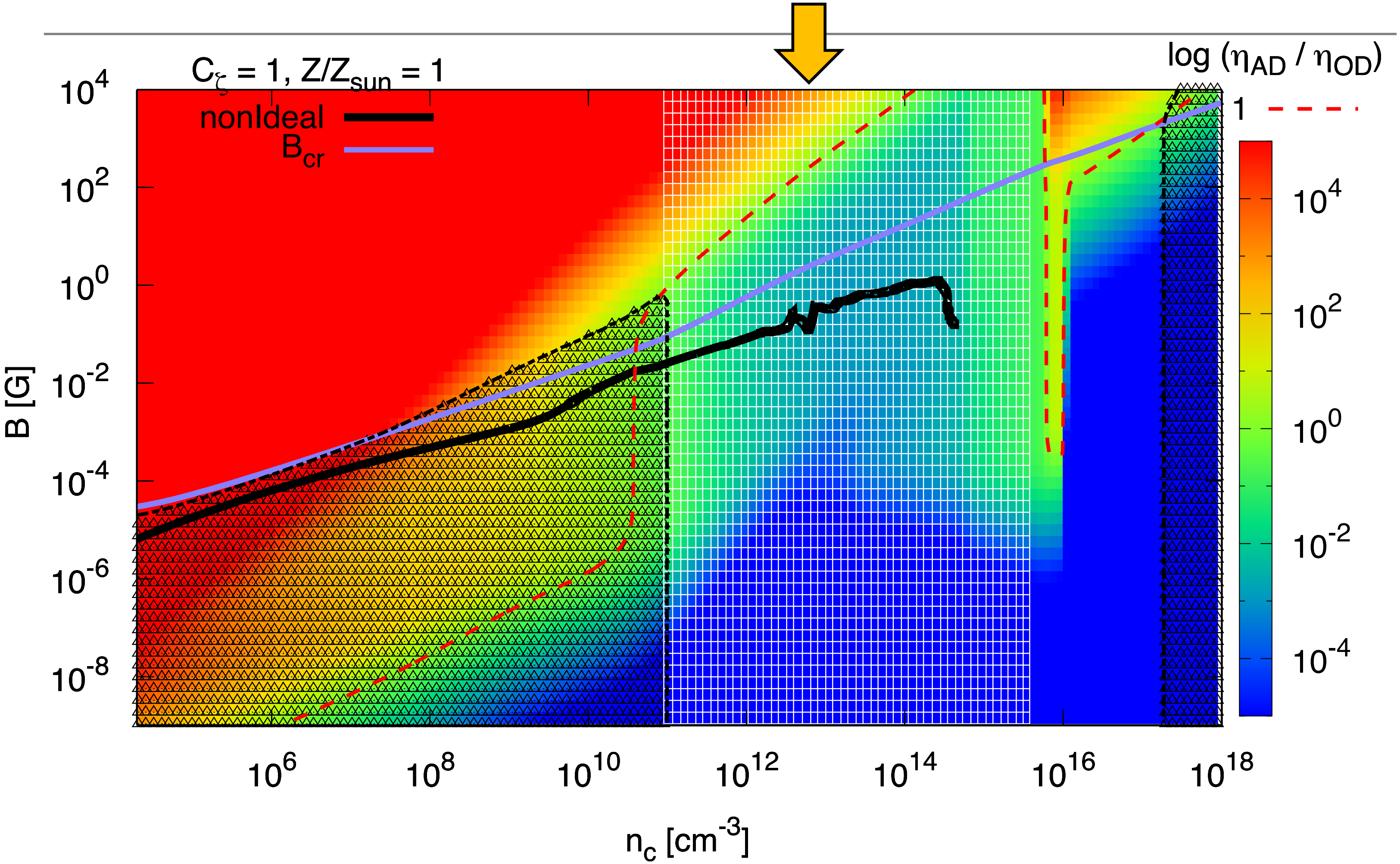
C_ζ \ $Z/Z_{\rm sun}$	0	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}	1
0							
0.01							
1							
10							

* Grav. Collapsing Phase

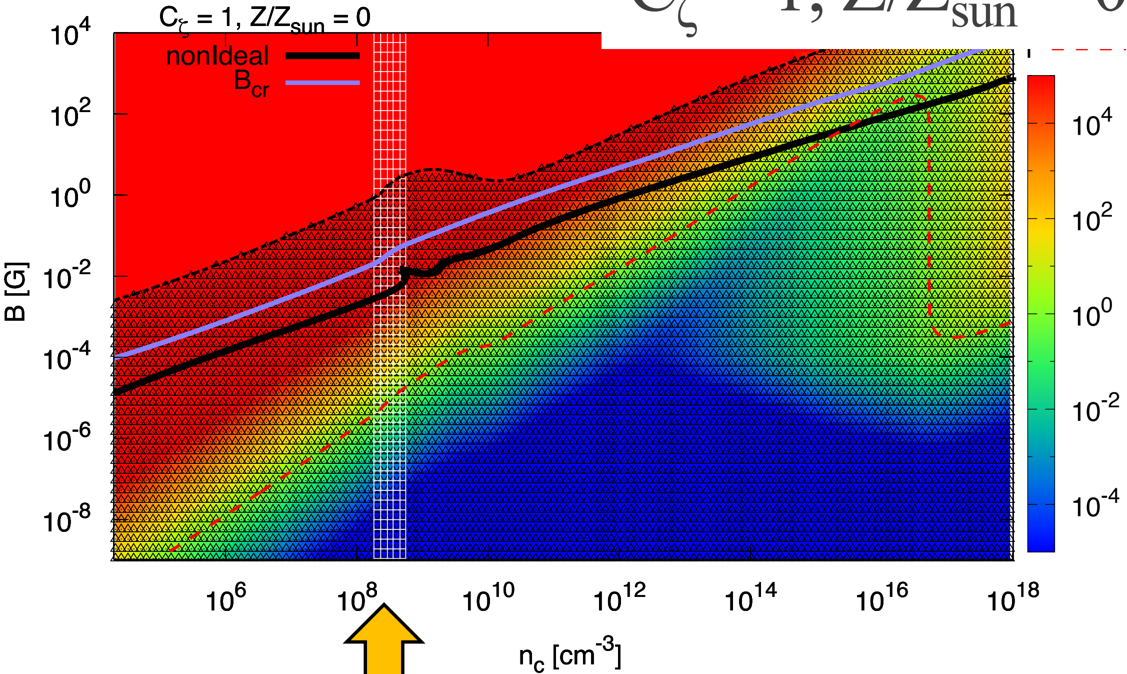
$C_\zeta = 1, \ Z/Z_{sun} = 1$

results

outflow



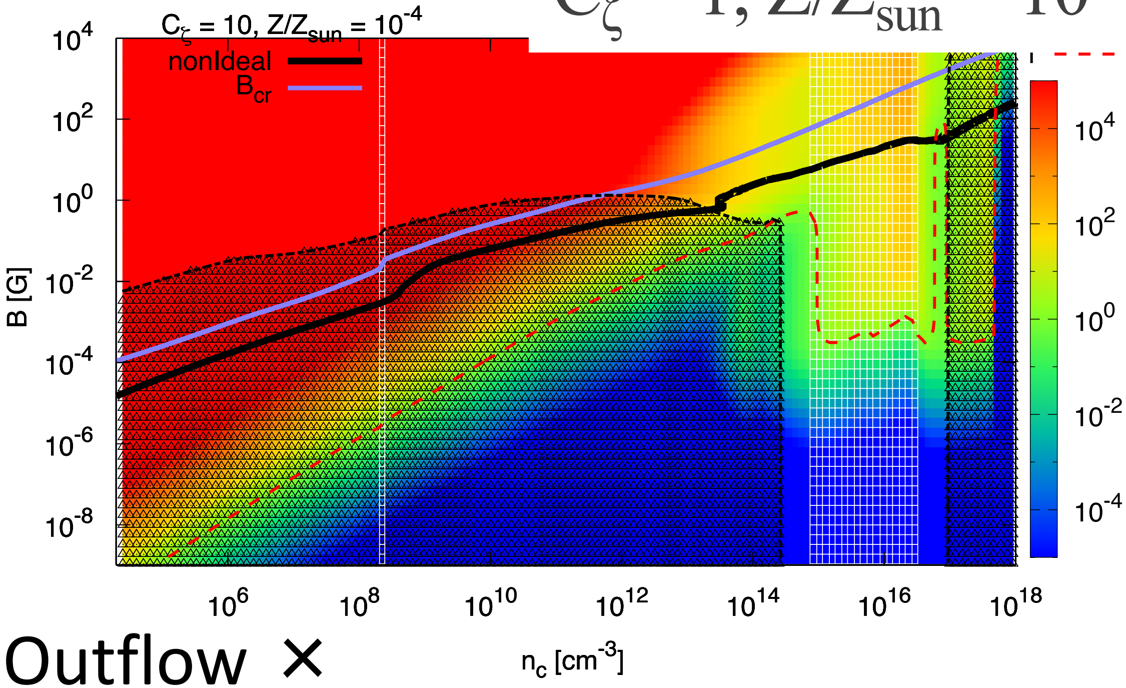
$C_\zeta = 1, Z/Z_{sun} = 0$



Black shadow : coupled region
White shadow : $\gamma \geqq 4/3$
Purple line : critical magnetic flux
Black line : magnetic evolution

outflow

$C_\zeta = 1, Z/Z_{sun} = 10^{-4}$



Outflow ×

Summary

・With non-Ideal MHD simulation,
"Estimation of dissipation" and "Whether outflow is driven or not" in different environments (Metallicity & Ionization rate)

-> By different environments,
whether Outflow is driven or not

-> star formation is different depending on environments