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Ionization degree & magnetic diffusivities in low-metallicity star-formation

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1. Introduction

Magnetic fields in star-formation

B-field affects the low-Z star-formation even if $B \ll B_{\rm ISM}$.

$B \gtrsim 10^{-11}$ G @ ~ 1 cm^{-3}

→ Outflow decreases the star-formation efficiency.

Machida et al. 2006

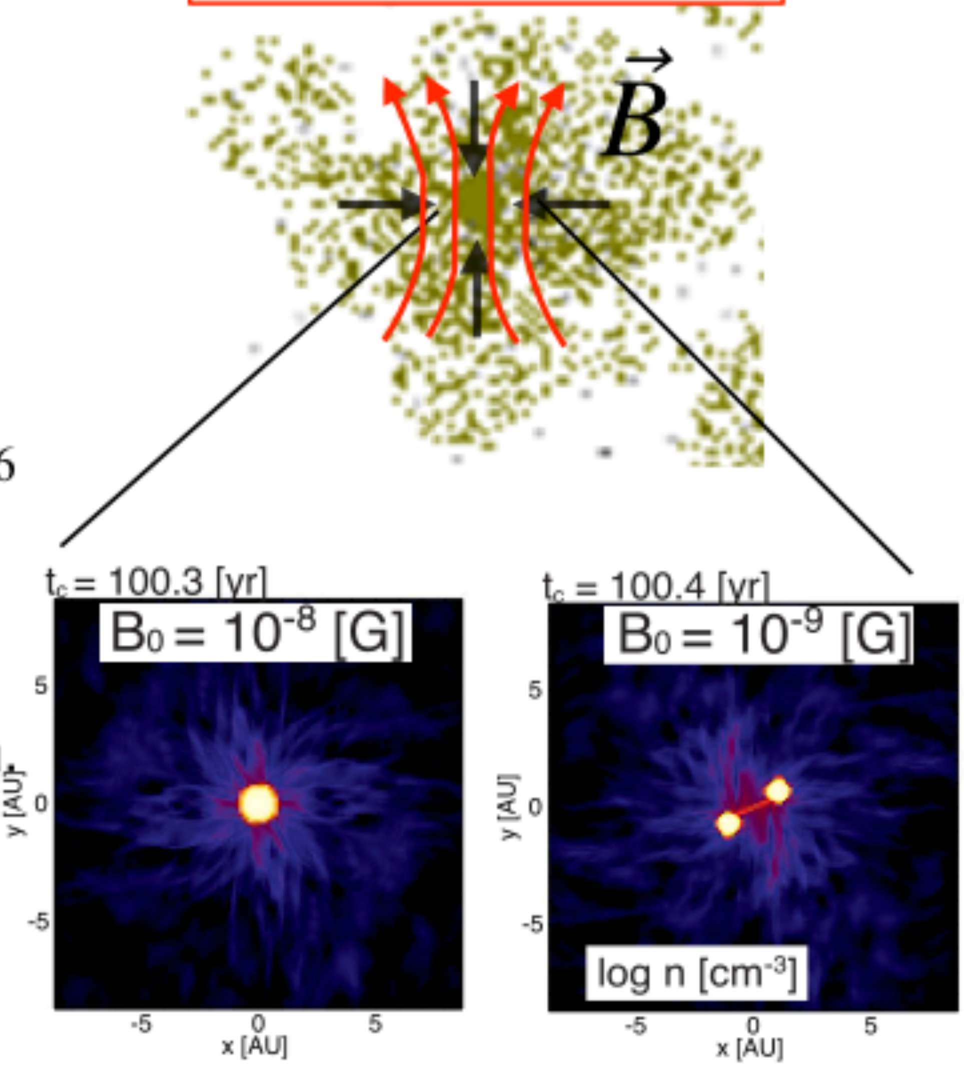
$B \gtrsim 10^{-12}$ G @ ~ 1 cm^{-3}

→ Magnetic braking prevents disc formation & fragmentation.

Machida & Doi 2013

MHD calculation is needed in low-Z star-formation.

star-forming cloud



w/o disk
single star

w/ disk
binary system

Machida & Doi 2013

Non-ideal MHD effects in star-formation

Star-forming gas = weakly ionized plasma
→ Gas decouples from B-field via non-ideal MHD effects.

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{u}_{\rm n} \times \boldsymbol{B}) + \underbrace{\nabla \times [\eta_{\rm ambi}((\nabla \times \boldsymbol{B}) \times \boldsymbol{e}_B) \times \boldsymbol{e}_B]}_{\text{ambipolar diffusion (plasma drift)}}$$

$$- \underbrace{\nabla \times (\eta_{\rm Ohm}(\nabla \times \boldsymbol{B}))}_{\text{Ohmic dissipation}} - \underbrace{\nabla \times [\eta_{\rm Hall}(\nabla \times \boldsymbol{B}) \times \boldsymbol{e}_B]}_{\text{Hall effect}}$$

$\eta_{\rm ambi}$ $\eta_{\rm ohm}$ $\eta_{\rm hall}$ depend on the fractional abundances of charged species y(i).

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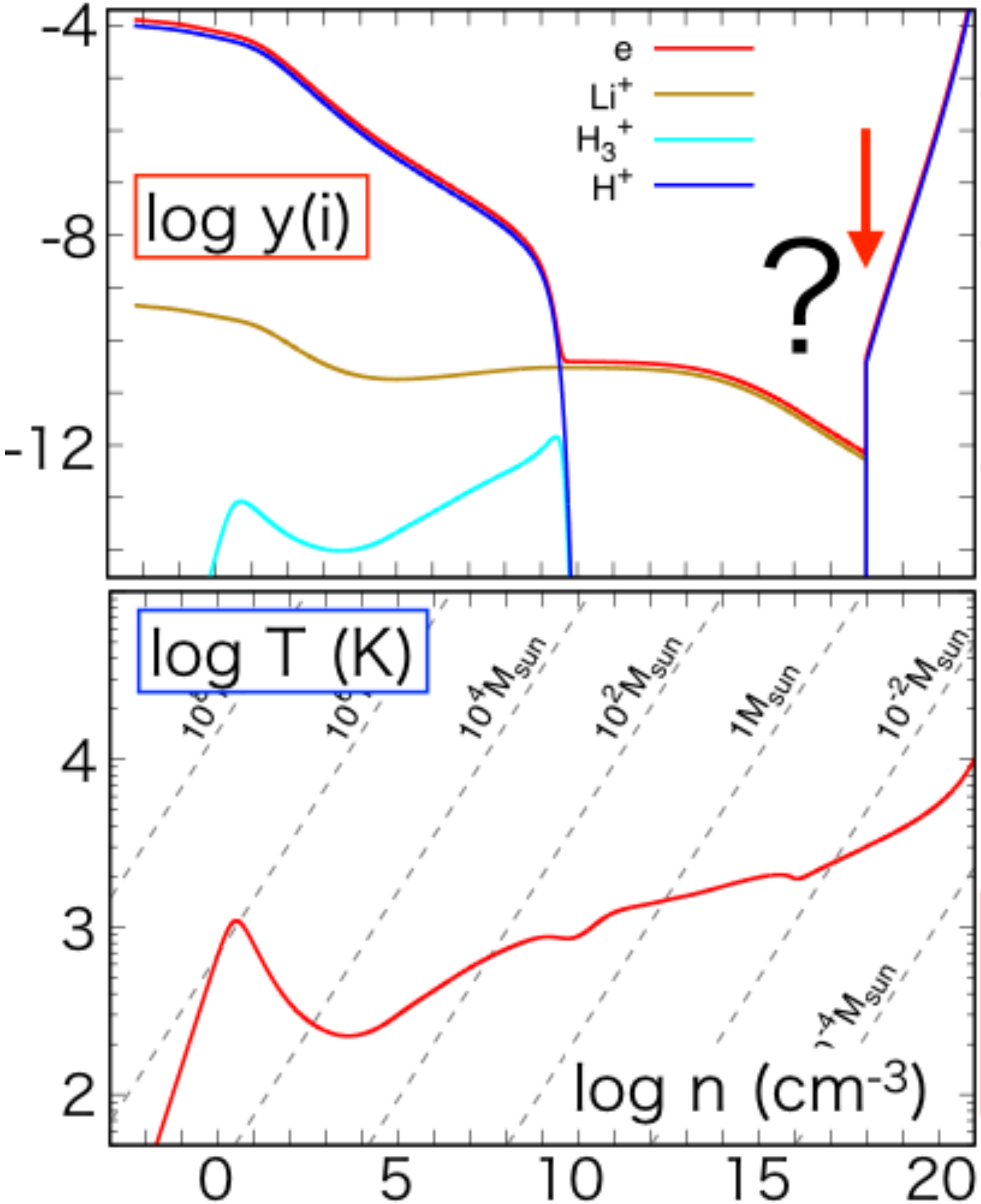
Accurate calculation of y(i) is needed.

Problems in the primordial gas

Omukai 2001
Maki&Susa 2004
2007



- Discontinuity of y(i) @ 10^{18} cm^{-3}.

- y(i) is not calculated accurately until the equilibrium.

- Chemical network:

$$R_1+R_2+\ldots+R_M \rightarrow P_1+P_2+\ldots+P_N$$

For 102 forward reactions, only 21 reverse reactions are considered.

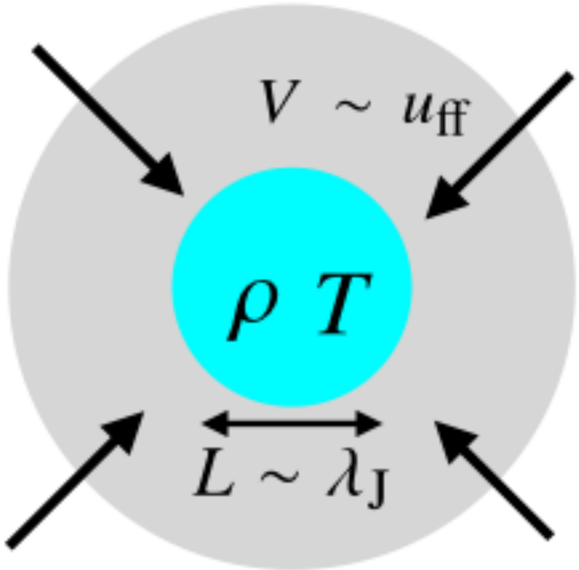
- We calculate T & y(i) evolution by considering all the reverse reactions.

2. Ionization degree of the low-Z gas

Dynamics and Chemistry

Palla et al. 1983
Omukai 2001 etc.

★ One-zone model for a star-forming cloud.



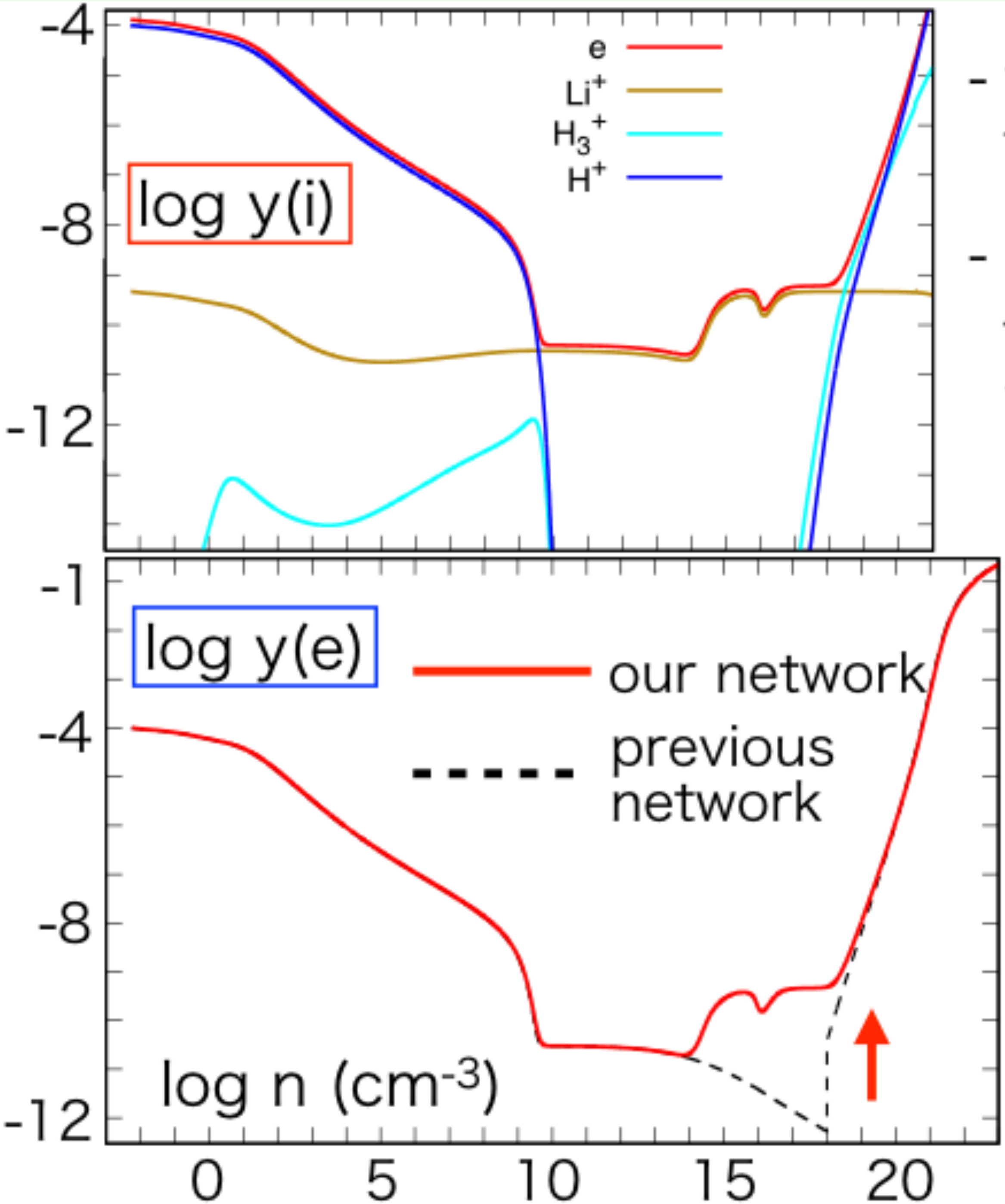
- Dynamics: $\dfrac{d\rho}{dt} = \dfrac{\rho}{t_{\rm col}}$
- Energy: $\dfrac{de}{dt} = -P\dfrac{d}{dt}\left(\dfrac{1}{\rho}\right) - \Lambda_{\rm net},$
- Chemical network:
  102+102=204 reactions among 23 species.
  H, H_2, e^-, H^+, H_2^+, H_3^+, H^-, He, He^+, He^{2+}, HeH^+, D, HD, D^+, HD^+, D^-, Li, LiH, Li^+, Li^-, LiH^+, Li^{2+}, Li^{3+}.

- Reverse reaction rates are calculated from the detailed balance principle.

$$\mathrm{R}_1 + \mathrm{R}_2 + \ldots + \mathrm{R}_M \rightarrow \mathrm{P}_1 + \mathrm{P}_2 + \ldots + \mathrm{P}_N \qquad k_{\rm rev} = k_{\rm fwd} K_{\rm eq}(T)$$

$$K_{\rm eq}(T) = \left(\frac{2\pi k_{\rm B} T}{h_{\rm P}^2}\right)^{3(M-N)/2} \left(\frac{m_{\mathrm{R}_1} \ldots m_{\mathrm{R}_M}}{m_{\mathrm{P}_1} \ldots m_{\mathrm{P}_N}}\right)^{3/2} \left(\frac{z(\mathrm{R}_1) \ldots z(\mathrm{R}_M)}{z(\mathrm{P}_1) \ldots z(\mathrm{P}_N)}\right) e^{-\Delta E / k_{\rm B} T}$$

Ionization degree of the primordial gas

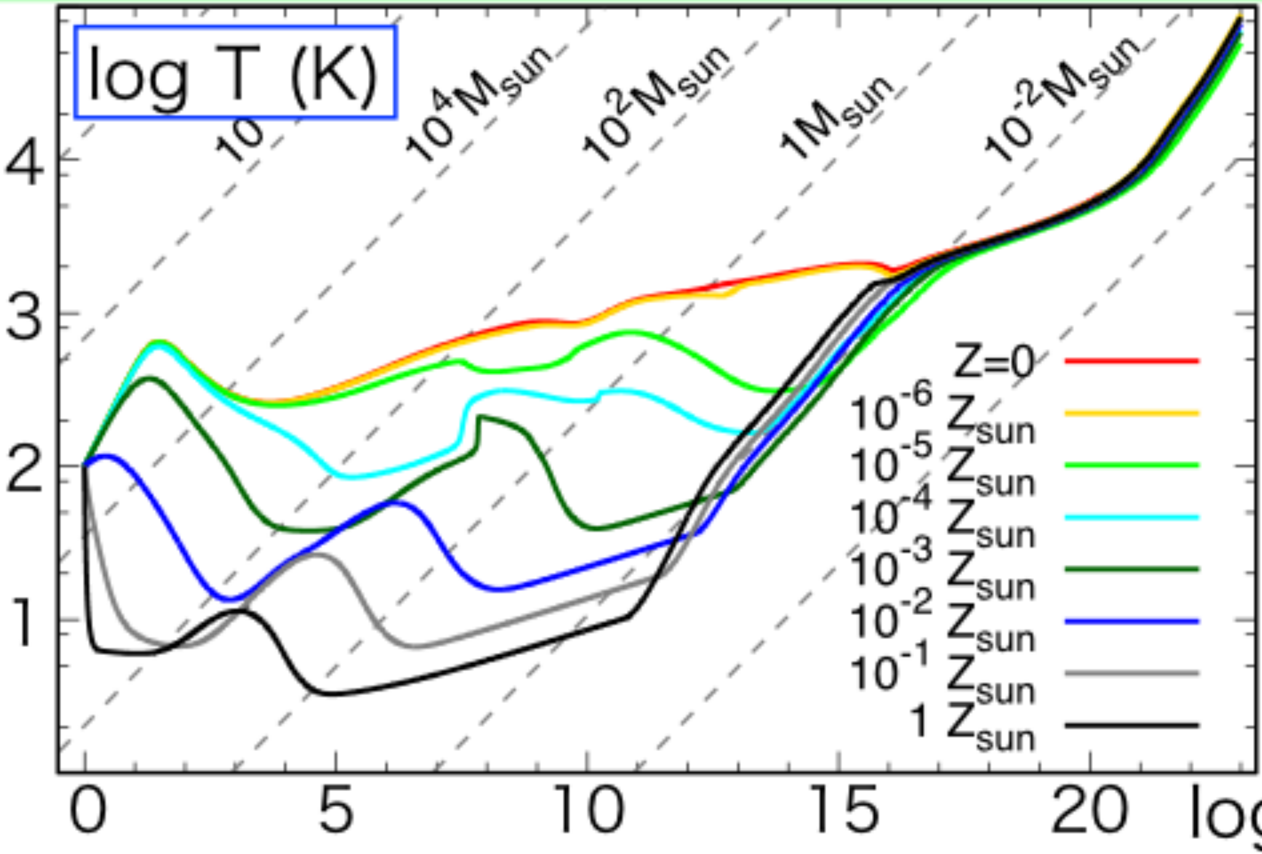


- y(i) evolves smoothly until the equilibrium value.
- major charged species:
  — : electron
  \+ : $H^+ \rightarrow Li^+ \rightarrow H_3^+ \rightarrow H^+$.
- y(e) becomes 100-1000 times higher than before @ 10^{14}-10^{18} cm^{-3}.
- This is due to Li ionization by thermal photons trapped in the cloud.

$$Li^+ + e \rightleftharpoons Li + \gamma$$

Problems in the low-Z gas

Omukai 2000, 2005
Susa et al. 2015

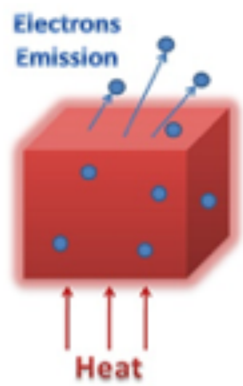


＊Metals & dusts become major charged species.

Only 56 reverse reactions for 570 forward reactions.

＊Alkali metals & dusts become e^- donors at high n & T.

- So far, alkali metal is represented by Mg. How Li, Na, K, Mg work individually?
- e^- can be emitted from a heated dust (thermionic emission).



Chemical network for the low-Z gas

- Gas-phase: 570+570=1140 reactions among 63 species.

  H, H_2, e^-, H^+, H_2^+, H_3^+, H^-, He, He^+, He^{2+}, HeH^+, D, HD, D^+, HD^+, D^-, C, C_2, CH, CH_2, CH_3, CH_4, C^+, C_2^+, CH^+, CH_2^+, CH_3^+, CH_4^+, CH_5^+, O, O_2, OH, CO, H_2O, HCO, O_2H, CO_2, H_2CO, H_2O_2, O^+, O_2^+, OH^+, CO^+, H_2O^+, HCO^+, O_2H^+, H_3O^+, H_2CO^+, HCO_2^+, H_3CO^+, Li, LiH, Li^+, Li^-, LiH^+, Li^{2+}, Li^{3+}, K, K^+, Na, Na^+, Mg, Mg^+

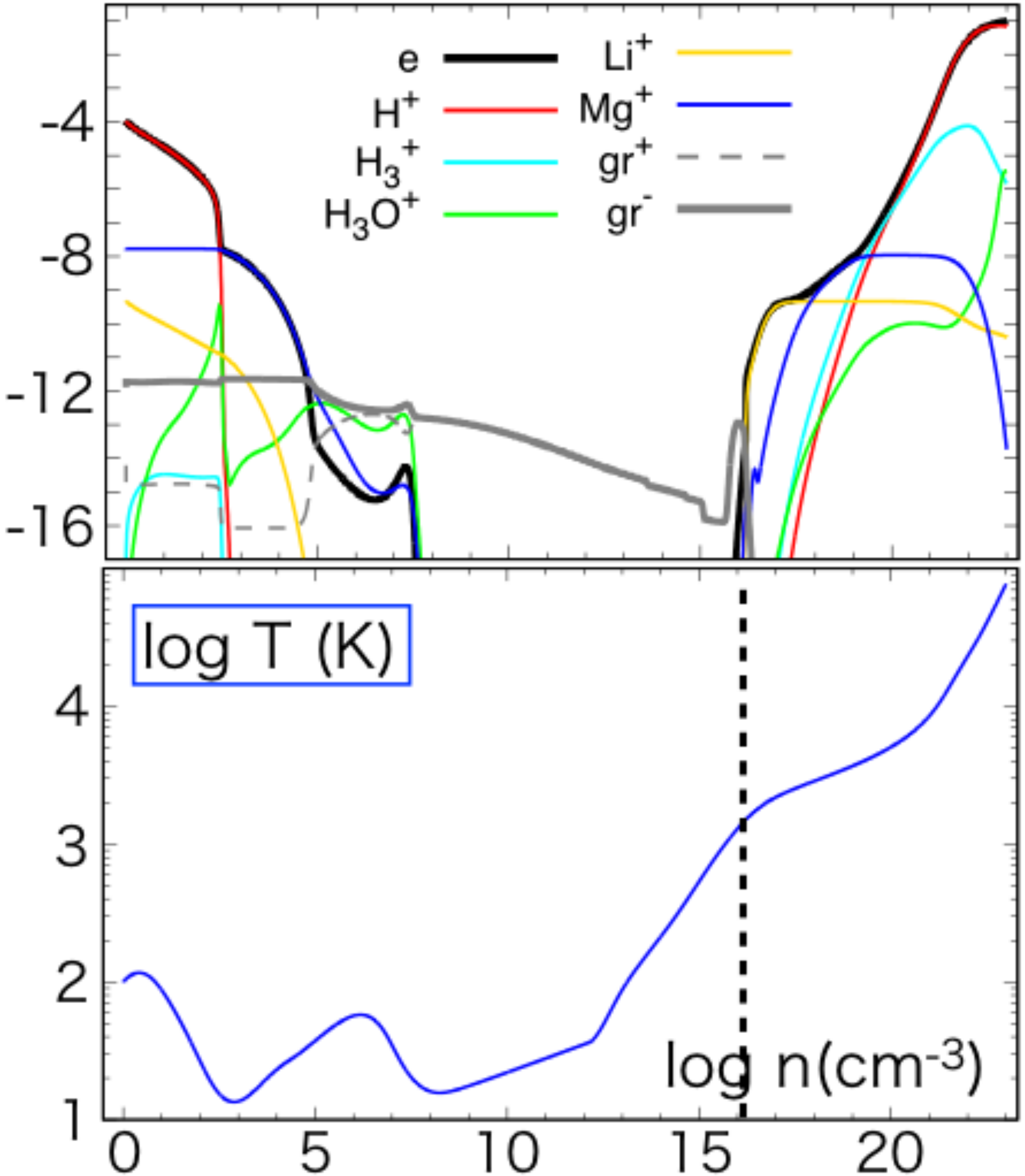
  - Na, K, Mg are treated separately.

- Dust grain: 5 charged states, gr^0, $\mathrm{gr}^{\pm}$, $\mathrm{gr}^{2\pm}$

  - Gas-grain, grain-grain charge transfer: 150 reactions.
  - Thermionic emission: $\mathrm{gr}^n \rightarrow \mathrm{gr}^{n+1} + e^-$

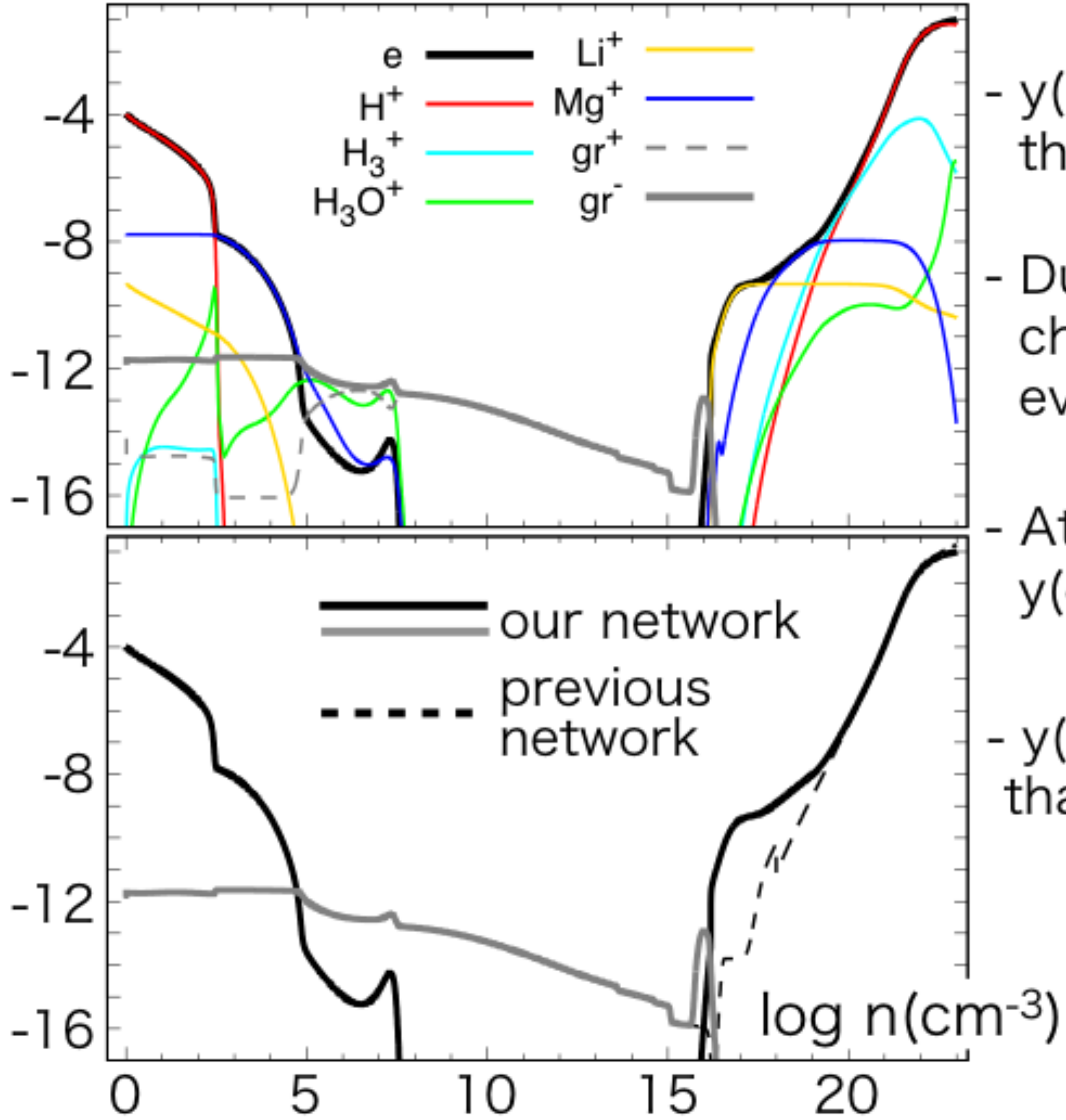
- T & y(i) evolution of low-Z gas is calculated.
- y(i) is used to calculate magnetic diffusivities.

y(i) of a low-Z gas: $10^{-2}\,Z_{sun}$



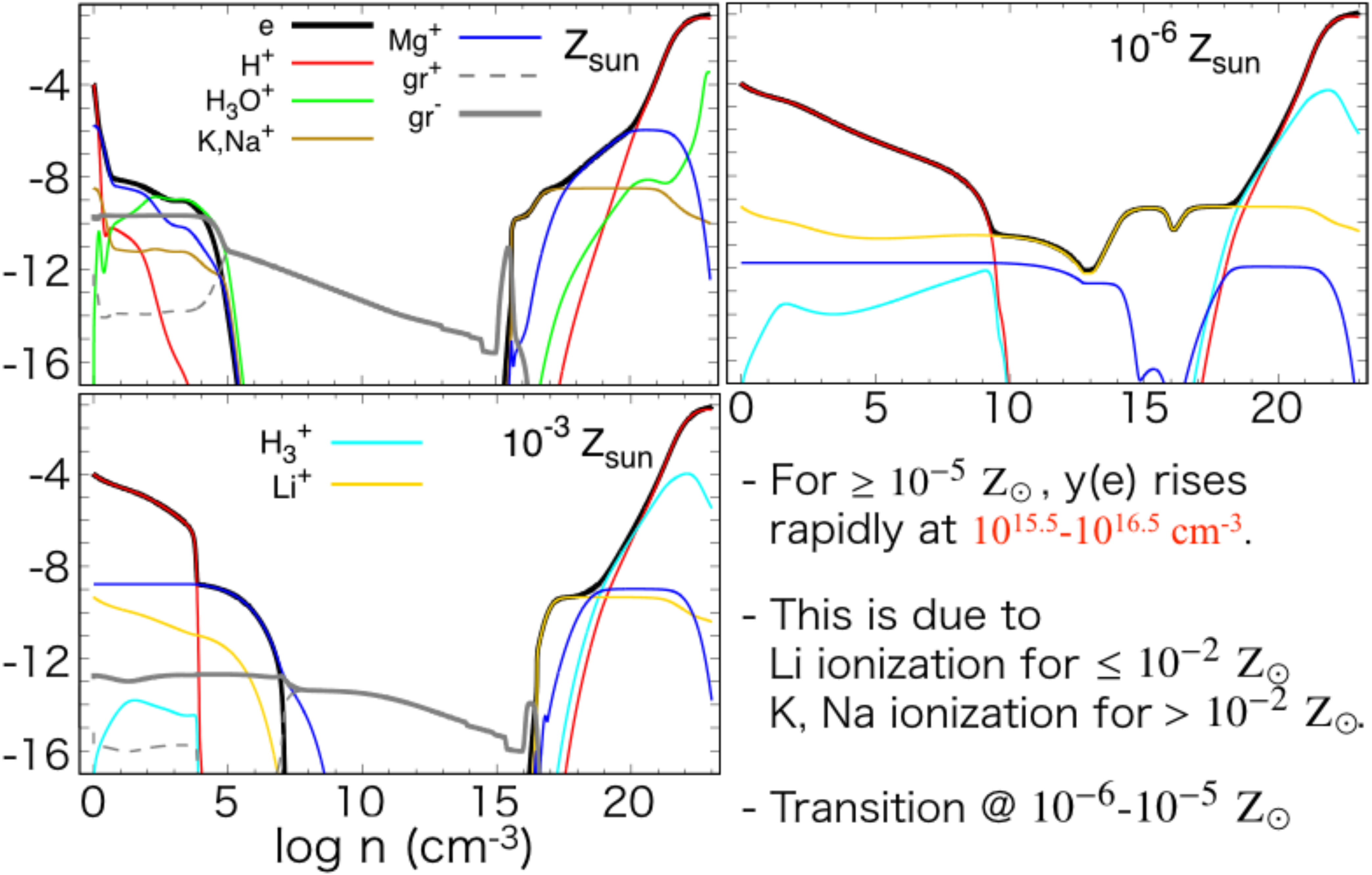
- y(i) evolves smoothly until the equilibrium value.
- Dust grains become major charged species until the evaporation at ~1500 K.
- At 10^{16} cm^{-3}, rapid rise in y(e) is due to Li ionization.

y(i) of a low-Z gas: 10^{-2} Z_{sun}



- y(i) evolves smoothly until the equilibrium value.
- Dust grains become major charged species until the evaporation at ~1500 K.
- At 10^{16} cm^{-3}, rapid rise in y(e) is due to Li ionization.
- y(e) becomes much higher than before at $10^{15.5}$-10^{19} cm^{-3}.

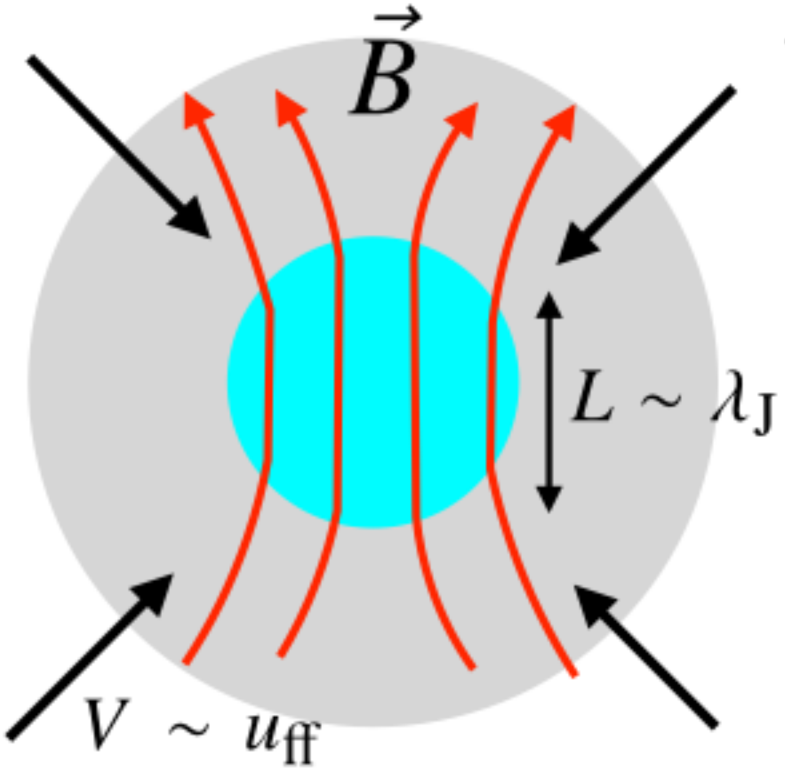
Metallicity dependence of y(i)



- For $\geq 10^{-5}\ Z_\odot$, y(e) rises rapidly at $10^{15.5}$-$10^{16.5}$ cm^{-3}.
- This is due to Li ionization for $\leq 10^{-2}\ Z_\odot$ K, Na ionization for $> 10^{-2}\ Z_\odot$.
- Transition @ 10^{-6}-$10^{-5}\ Z_\odot$

3. Magnetic diffusivities of the low-Z gas

Conditions for B-field dissipation



- Consider B-field dissipation from the center of a contracting cloud.

Magnetic Reynolds number:

$$\mathrm{Rm} \equiv \frac{VL}{\eta_{\rm ambi} + \eta_{\rm Ohm}}$$

$L \sim \lambda_J$: characteristic length scale of B.

$V \sim u_{ff} \sim \lambda_J / 3t_{\rm col}$: fluid velocity

$$\Rightarrow \mathrm{Rm} \sim t_{\rm dis}/t_{\rm col}$$

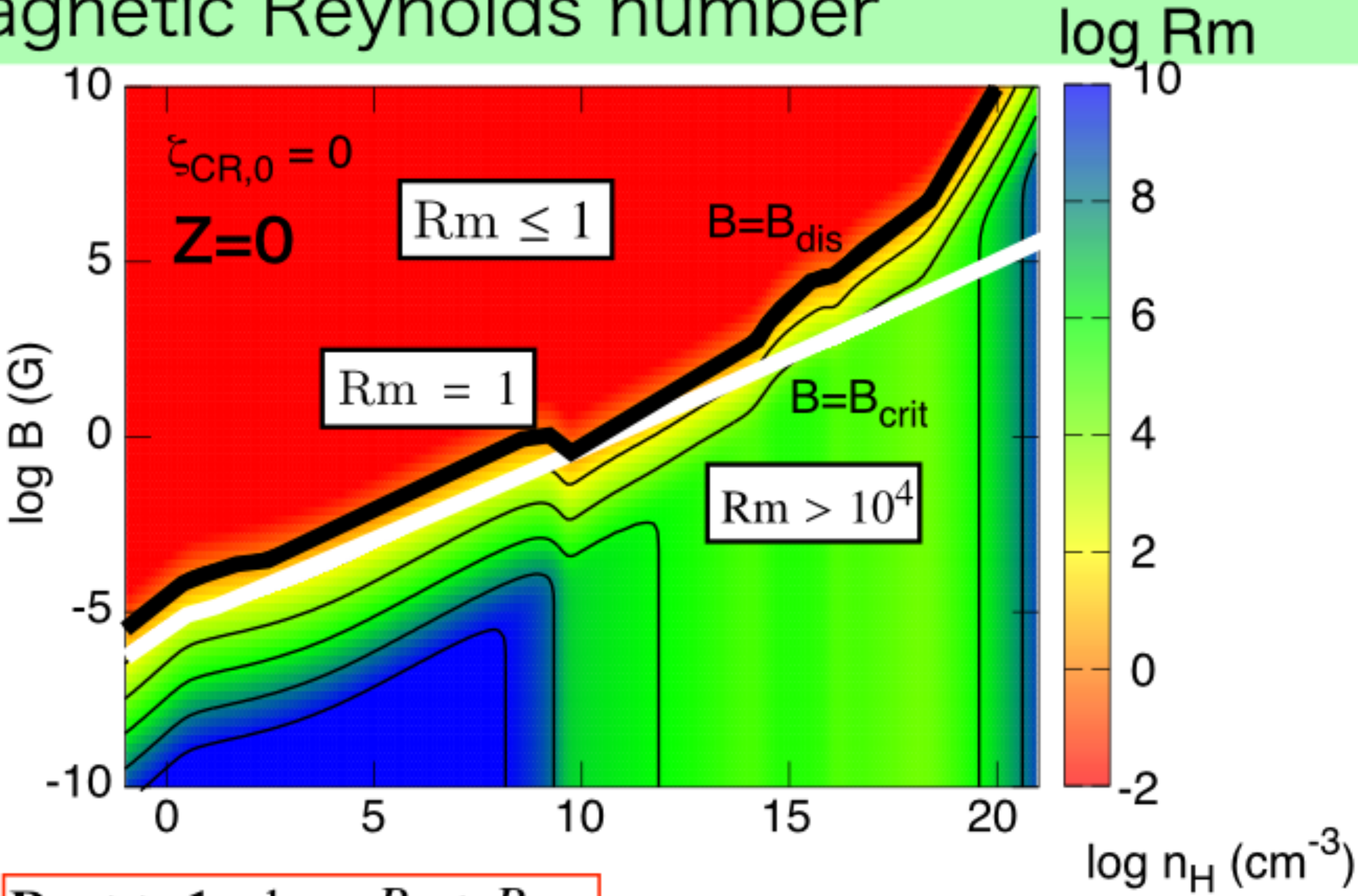
$$t_{\rm dis} \sim L^2/(\eta_{\rm ambi} + \eta_{\rm Ohm})$$

$$\mathrm{Rm} \leq 1 \quad \text{and} \quad B \leq B_{\rm crit}$$

$$B_{\rm crit} = \left(\frac{4\pi G M_J \rho}{\lambda_J}\right)^{1/2}$$

B-field dissipates. Cloud contracts.

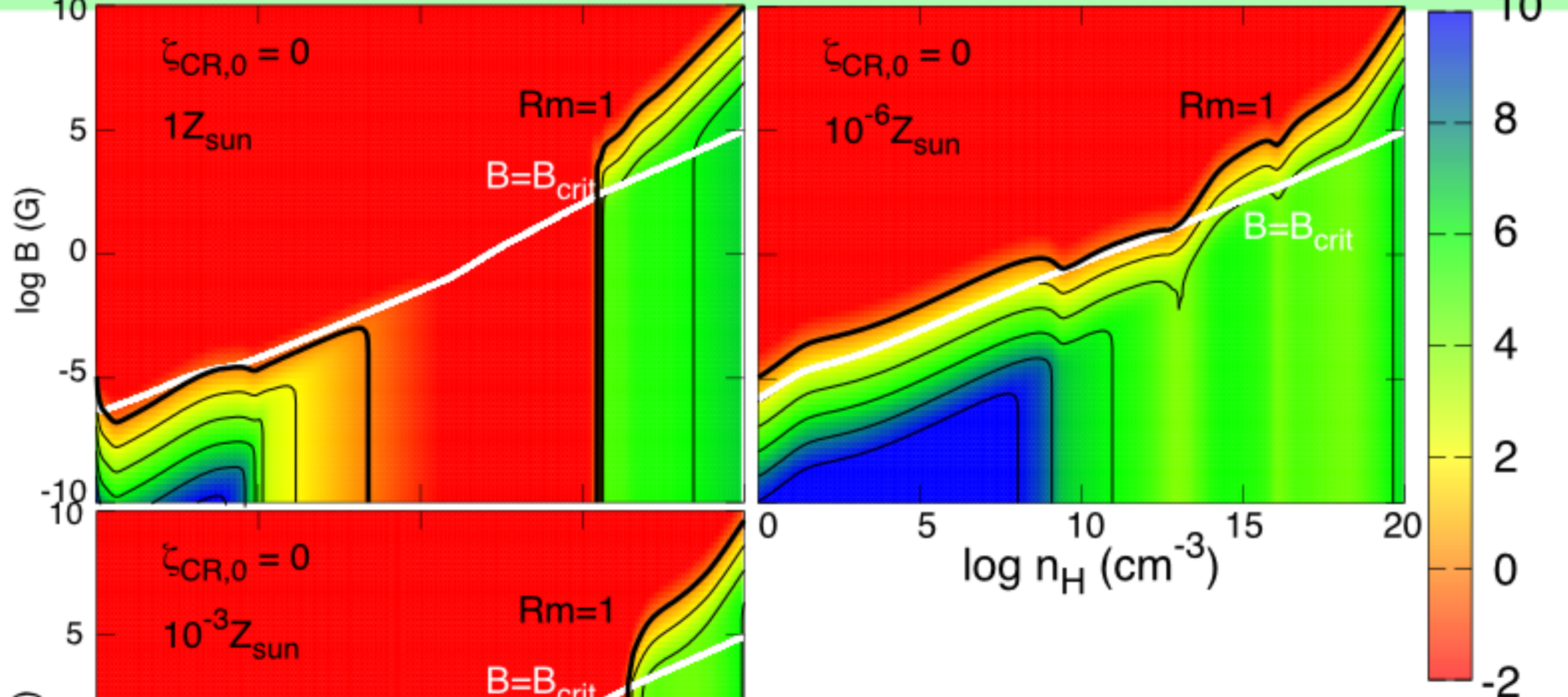
Magnetic Reynolds number

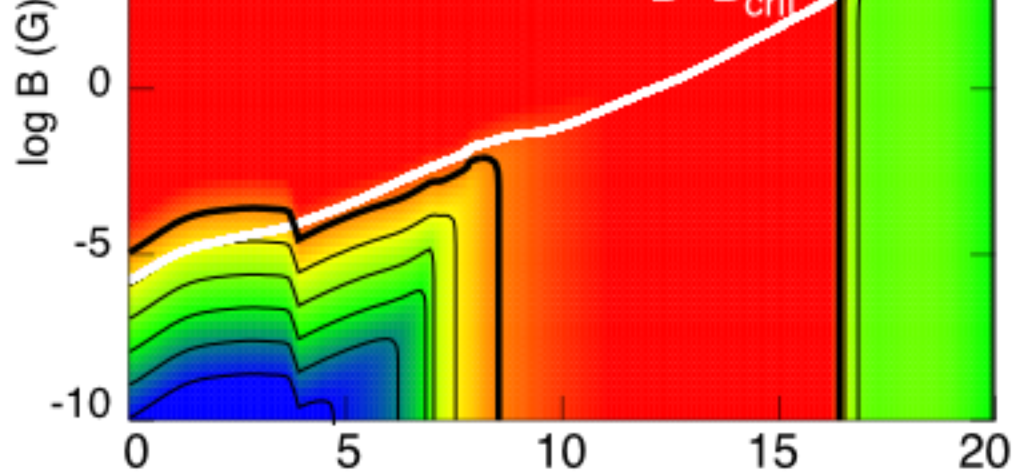


$\mathbf{Rm >> 1}$ when $B < B_{\rm crit}$

In the primordial gas, B-field dissipation becomes (marginally) important only when $B \sim B_{\rm crit}$.

Metallicity dependence of Rm





- Transition @ 10^{-6}-10^{-5} $Z_\odot$
- For $\geq 10^{-5}$ $Z_\odot$,
  Ohmic dissipation is important even when $B \ll B_{crit}$.

4. Summary

∗We calculate the evolution of T & y(i) in the low-Z gas.

∗We make a chemical network in which reverse reactions are considered for all the forward reactions.

∗Ionization degree becomes much higher than before at 10^{14}-10^{19} cm^{-3}, due to the ionization of Li, K, Na.

∗Dust grains become major charged species until the evaporation.

∗For $\geq 10^{-5}\ Z_{\odot}$, B-field is dissipated by Ohmic diffusion.