Stellar Archaeology as a Time Machine to the First Stars

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

Daisuke Nakauchi, Kazu Omukai
(Tohoku Univ.)
Hajime Susa
(Konan Univ.)

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TOHOKU UNIVERSITY

Theoretical Astrophysics Tohoku University

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1. Introduction

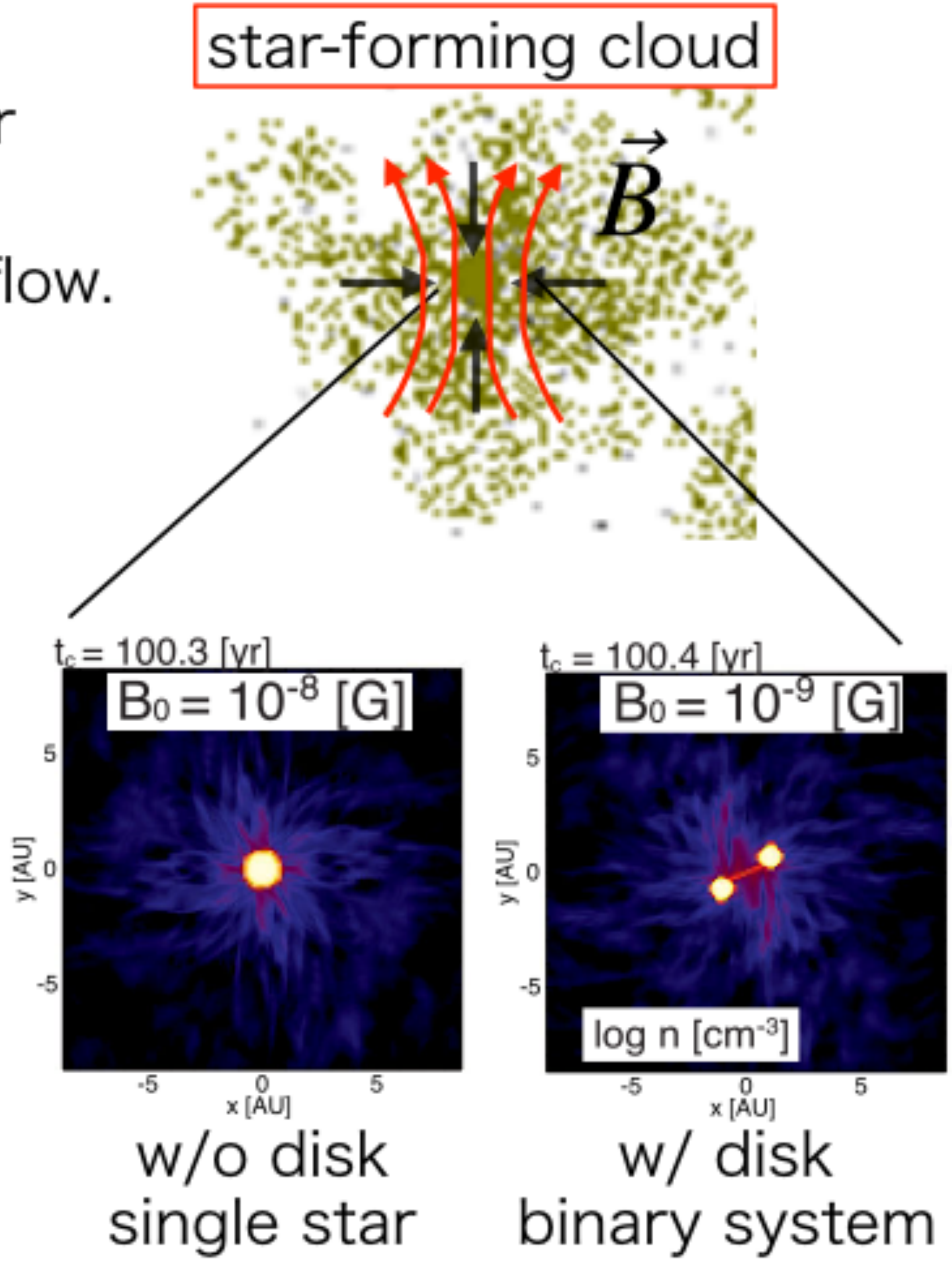
Magnetic field in star-formation

∗B-fields change mass & angular momentum of a cloud by magnetic braking & driving outflow.

∗B-fields control final mass & spin of a star, as well as formation rate of binaries.

∗They work even if $B \ll B_{\rm ISM}$.

∗B-field should be considered in low-Z star-formation.



Machida & Doi 2013

Magnetic diffusivity & ionization degree

Ionization degree of star-forming cloud can be very low.
→ B-field is dissipated by non-ideal MHD effects.

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

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

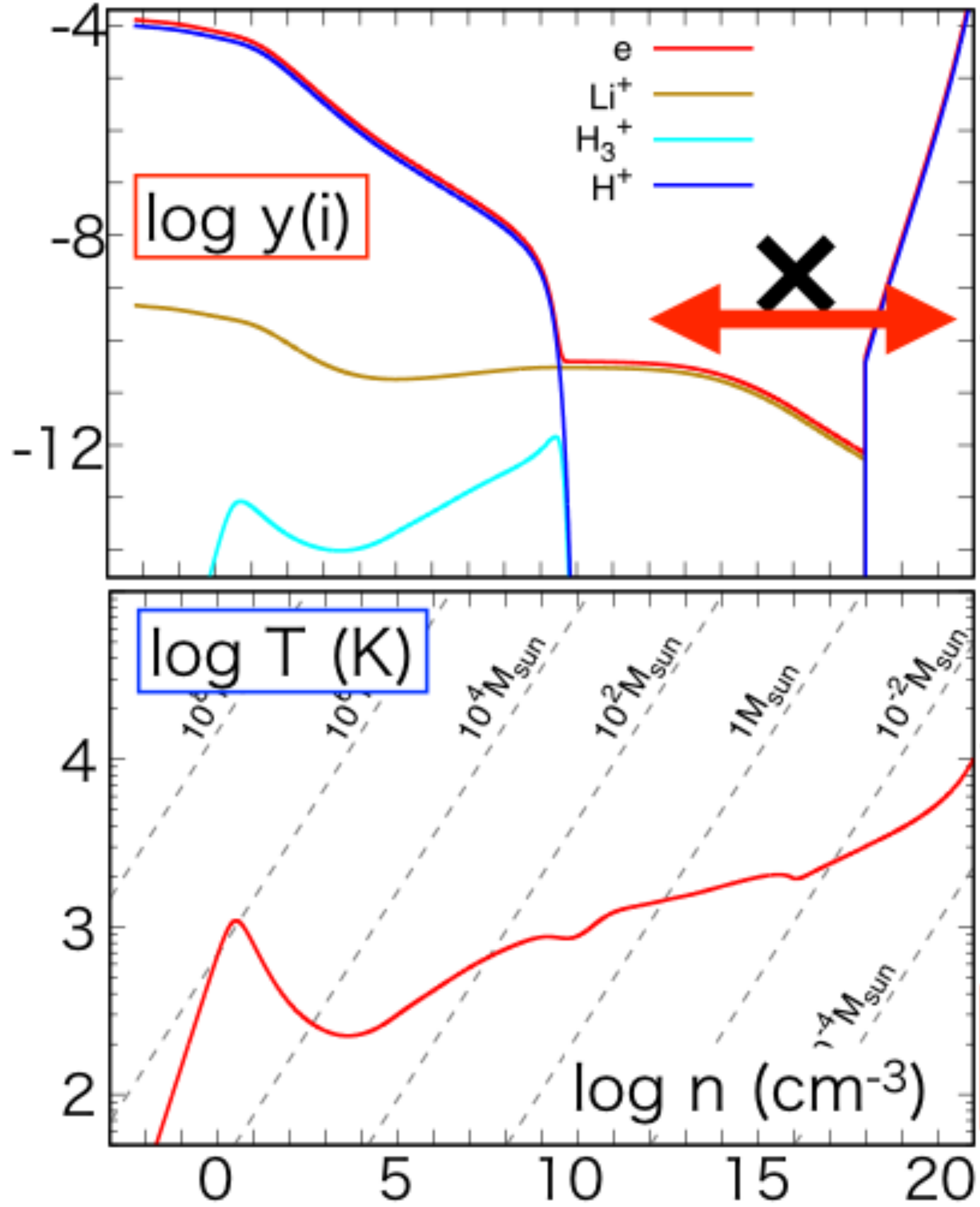
$\eta_{\rm ambi}$ $\eta_{\rm ohm}$ $\eta_{\rm hall}$ depend on the ionization degree y(i).

↓

MHD calculation requires accurate calculation of chemical reactions.

Problems in the chemical model

Omukai 2001
Maki&Susa 2004
2007



- Existing chemical models are unsatisfactory at high density where B-field will dissipate.
- At high density, y(i) takes equilibrium value, as a result of the balance between forward & reverse reactions:

$$R_1 + R_2 \rightleftarrows P_1 + P_2$$

- Any chemical model does not give correct equilibrium value without reverse reactions.

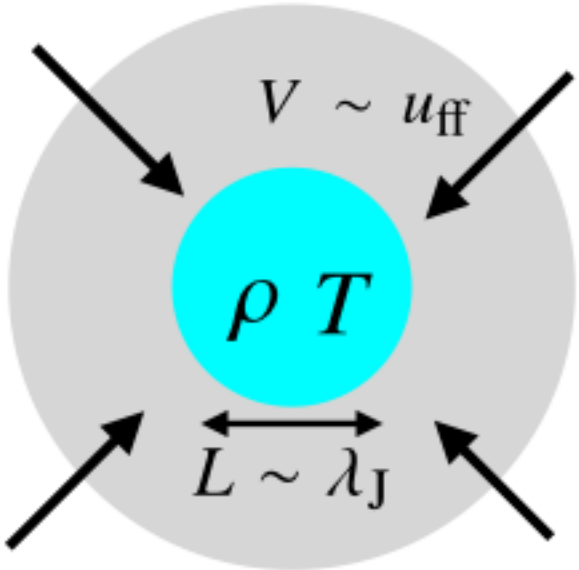
- We calculate y(i), considering all the reverse reactions.

2. Ionization degree of low-Z gas

Dynamics and Chemistry

Palla et al. 1983
Omukai 2001 etc.

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



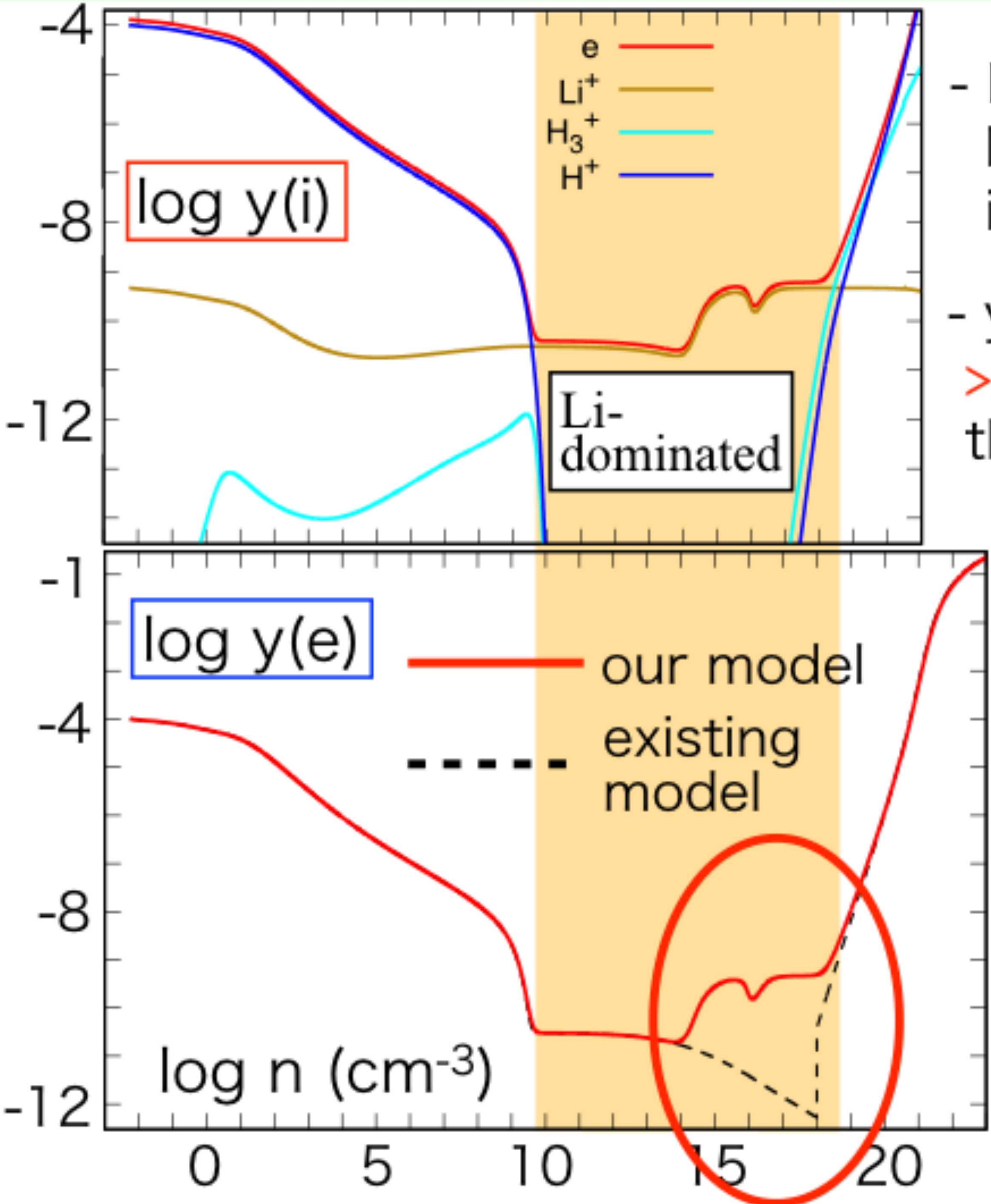
- Dynamics: $\frac{d\rho}{dt} = \frac{\rho}{t_{\rm col}}$
- Energy: $\frac{de}{dt} = -P\frac{d}{dt}\left(\frac{1}{\rho}\right) - \Lambda_{\rm net},$
- Chemical model:
  107+107=214 reactions among 23 species.
  H, H_2, e^-, H^+, H_2^+, H_3^+, H^-, He, He^+, He^{2+}, HeH^+, D, HD, D^+, HD^+, D^-, Li, LiH, Li^+, Li^-, LiH^+, Li^{2+}, Li^{3+}.

- For reverse reactions, rate coefficients are calculated from the detailed balance principle.

$$R_1 + R_2 \rightleftarrows P_1 + P_2 \qquad k_{\rm rev} = k_{\rm fwd} K_{\rm eq}(T)$$

$$K_{\rm eq}(T) = \left(\frac{2\pi k_{\rm B} T}{h_{\rm P}^2}\right)^{3(M-N)/2} \left(\frac{m_{\rm R_1}\ldots m_{\rm R_M}}{m_{\rm P_1}\ldots m_{\rm P_N}}\right)^{3/2} \left(\frac{z(\rm R_1)\ldots z(\rm R_M)}{z(\rm P_1)\ldots z(\rm P_N)}\right) e^{-\Delta E/k_{\rm B}T}$$

Ionization degree of primordial gas



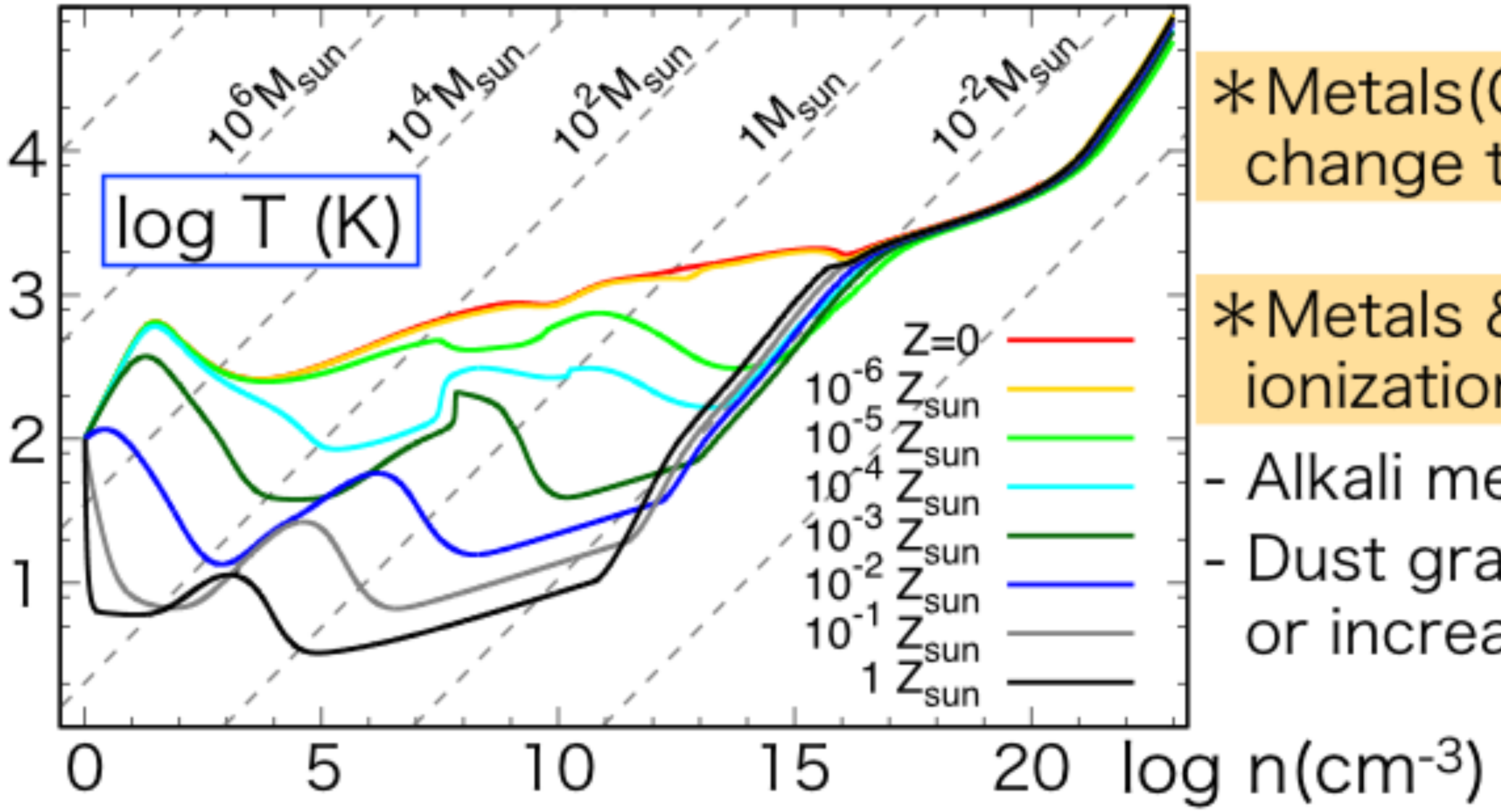
- Negative charge is carried by e, while positive charge is carried by H & Li.
- y(e) becomes > 100 times higher than before @ 10^{14}-10^{18} cm^{-3}.
- The reason is that Li is ionized almost completely by thermal photons trapped in the cloud.

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

- Existing model does not consider this process and is not valid @ > 10^{14}cm^{-3}.

Chemical model in low-Z gas

Omukai 2000, 2005
Susa et al. 2015



＊Metals(C, O) & dusts change thermal evolution.

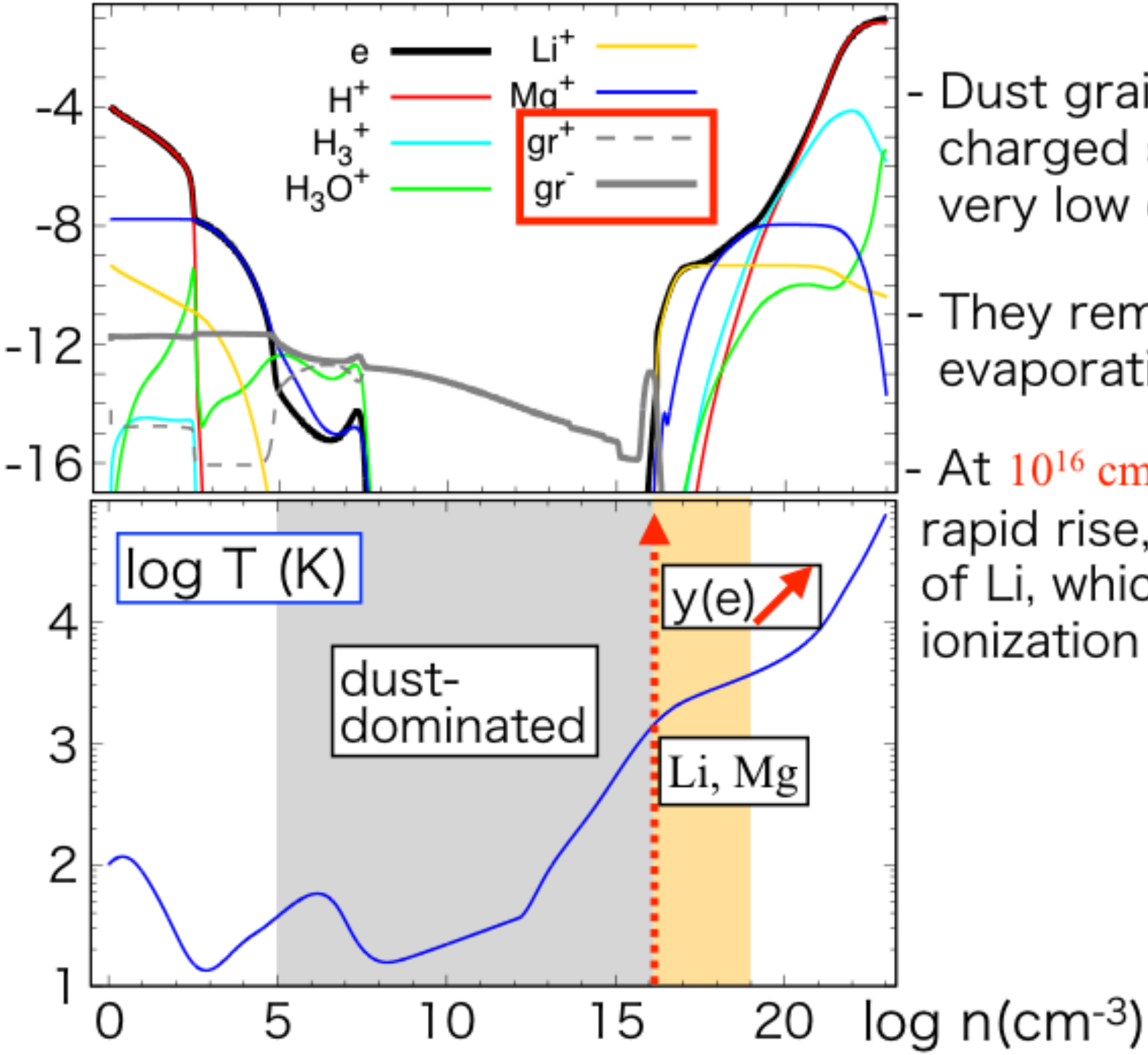
＊Metals & dusts control ionization degree y(i).

- Alkali metals increase y(i).
- Dust grains decrease or increase y(i).

＊T & y(i) are calculated using a chemical model which takes all the effects into account.

- Gas-phase 570+570=1140 reactions among 63 species, including alkali metals, Li, Na, K, Mg.
- Dust-related 154 reactions, including gr^0, $gr^{\pm}$, $gr^{2\pm}$.

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



- Dust grains become major charged species from a very low density.
- They remain major until evaporation at ~1500 K.
- At 10^{16} cm^{-3}, y(e) shows rapid rise, due to ionization of Li, which is followed by ionization of Mg & H.

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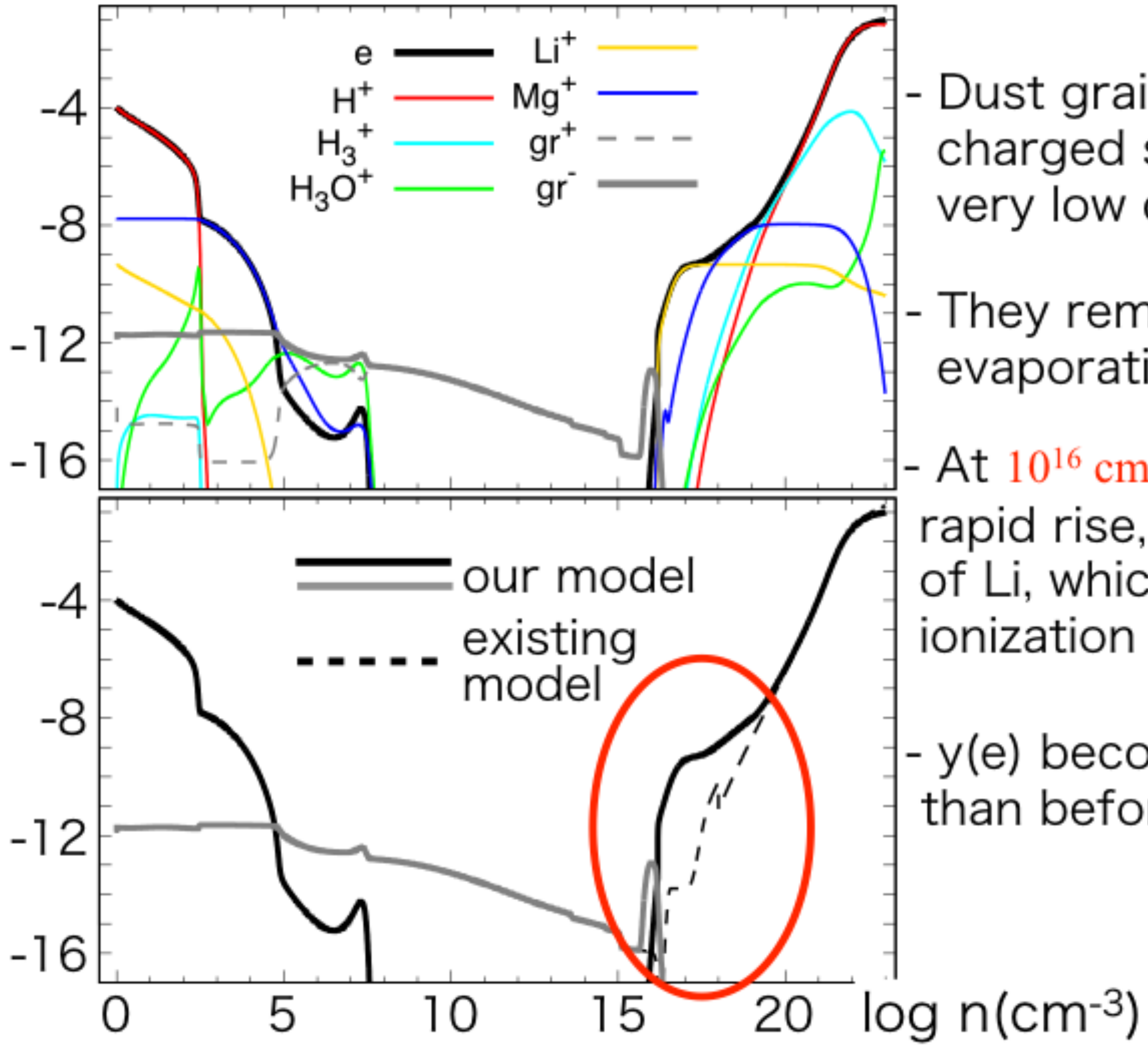
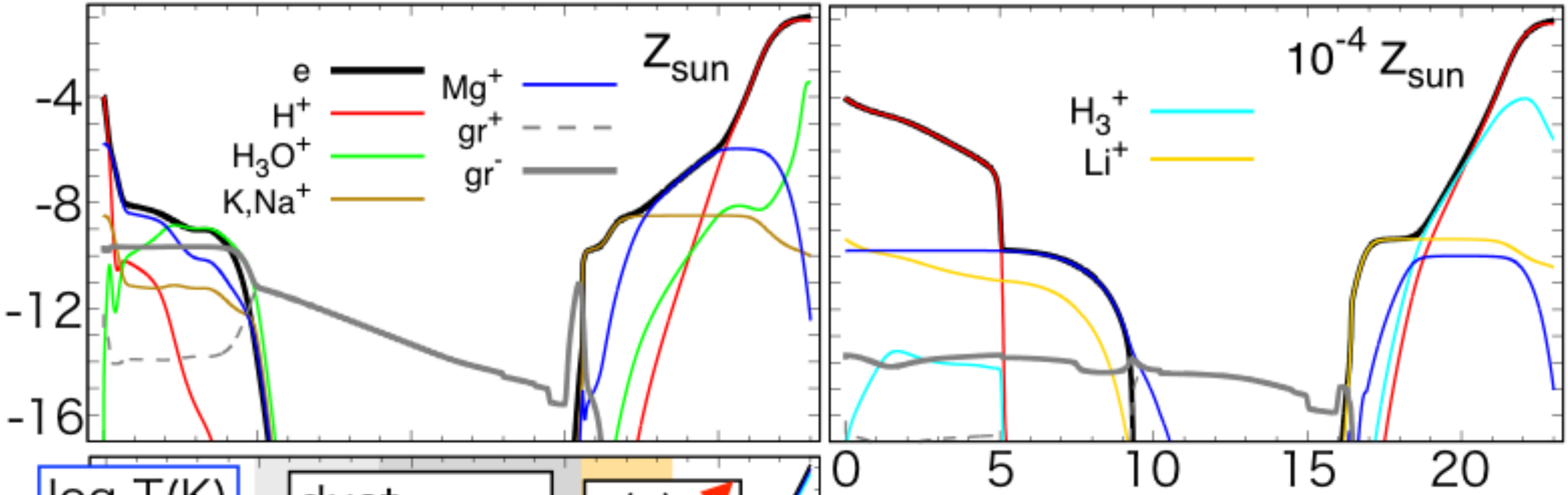
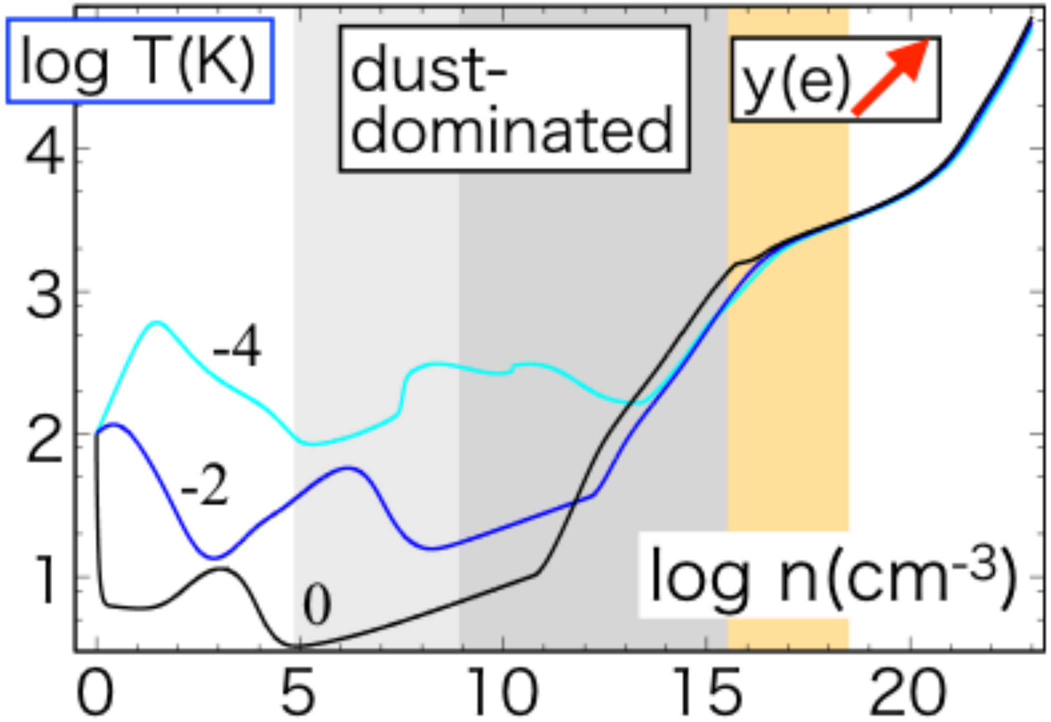


- Dust grains become major charged species from a very low density.
- They remain major until evaporation at ~1500 K.
- At 10^{16} cm^{-3}, y(e) shows rapid rise, due to ionization of Li, which is followed by ionization of Mg & H.
- y(e) becomes much higher than before at $10^{15.5}$-10^{19} cm^{-3}.

Metallicity dependence of y(i)

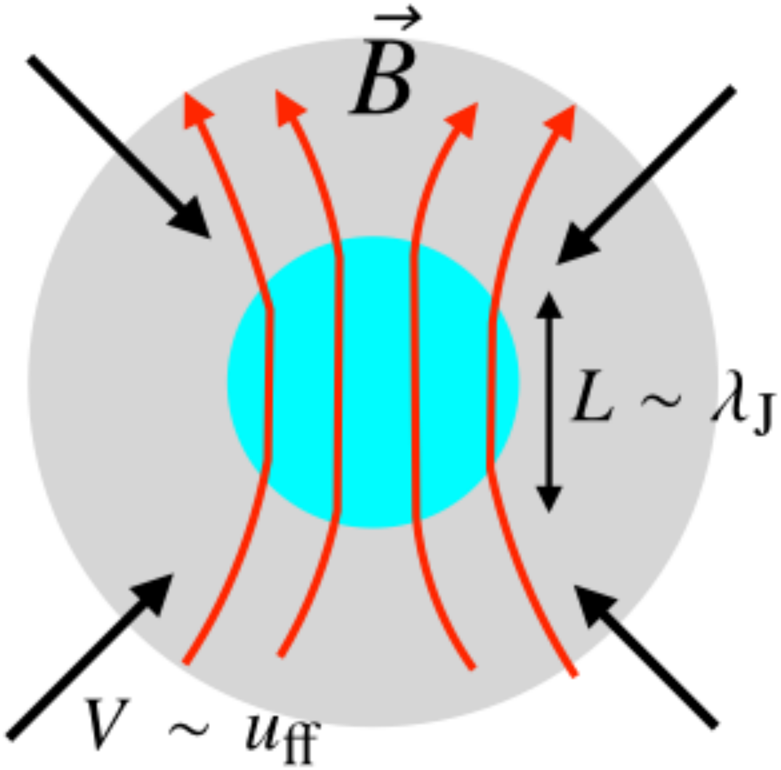




- For each Z, y(e) becomes much higher than before @$10^{15.5}$-10^{19} cm^{-3}.
- This is due to ionization of alkali metals, Li, K, Na.

3. Magnetic diffusivities

B-field dissipation from collapsing cloud



Magnetic Reynolds number:

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

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

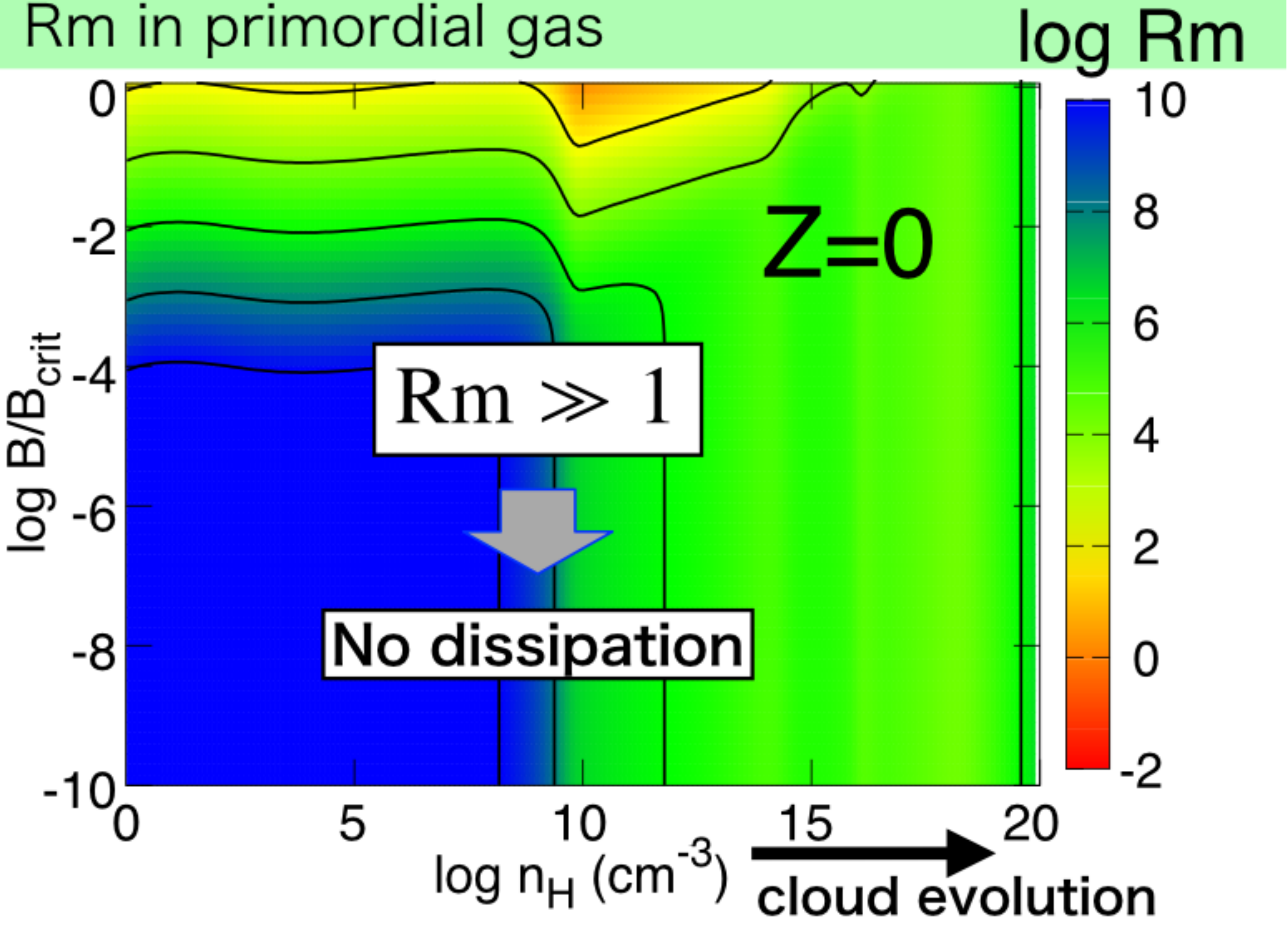
$V \sim u_{ff} \sim \lambda_J / 3t_{col}$: fluid velocity

⇨ $\mathrm{Rm} \sim t_{\mathrm{dis}}/t_{\mathrm{col}}$ $\quad t_{\mathrm{dis}} \sim L^2/(\eta_{\mathrm{ambi}} + \eta_{\mathrm{Ohm}})$

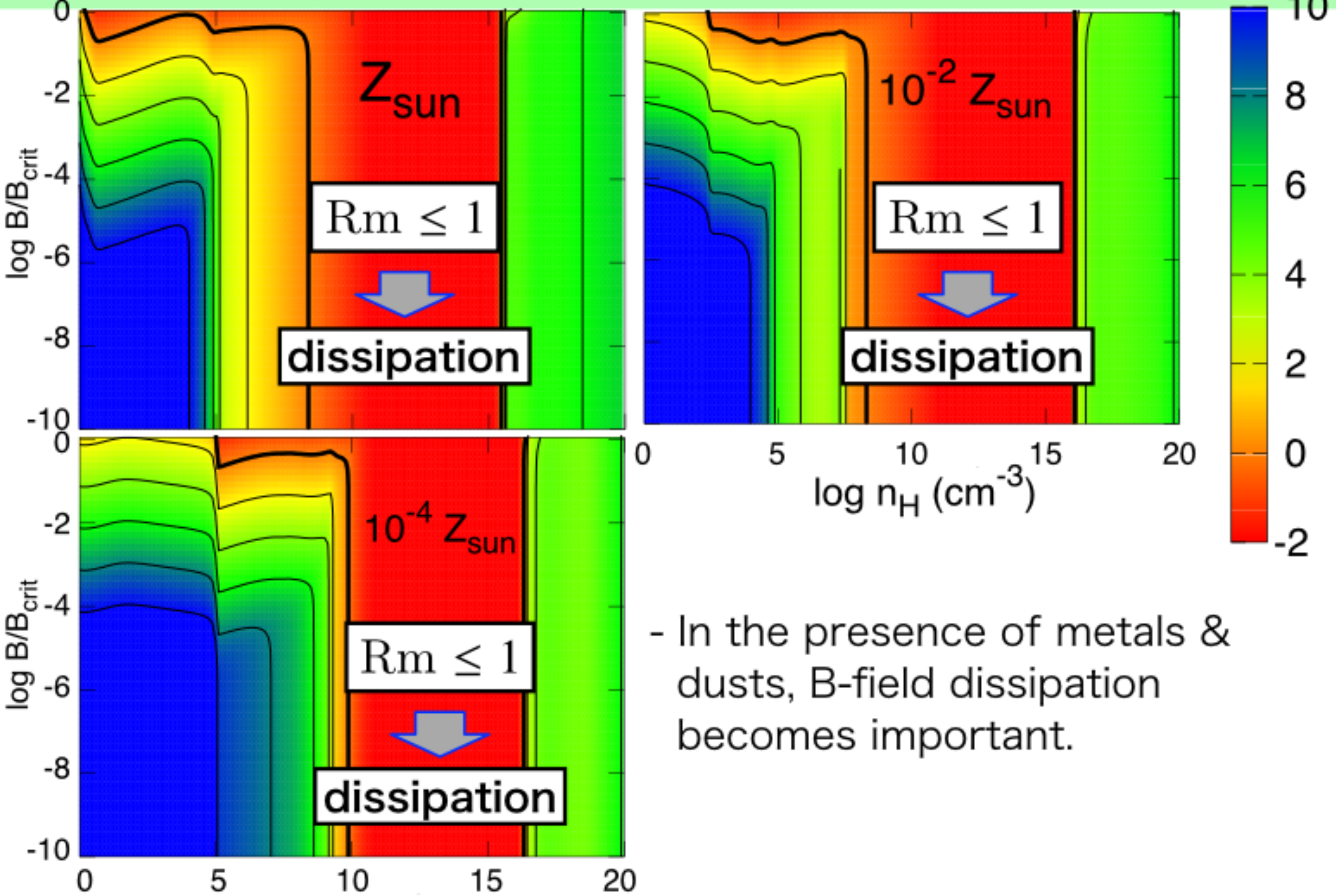
Rm = dissipation time / collapse time

$\mathrm{Rm} \leq 1$ ⇨ B-field is dissipated from the collapsing cloud.

Rm in primordial gas



Metallicity dependence of Rm



- In the presence of metals & dusts, B-field dissipation becomes important.

4. Summary

＊We calculate ionization degree of low-Z gas until high density.

＊We use a detailed chemical model which considers the reverse reactions, & chemistry of alkali metals & dust grains.

＊Ionization degree becomes much higher than before @10^{14}-10^{19} cm^{-3}.

＊This is due to the ionization of alkali metals, Li, K, Na, which are missed in the existing models.

＊B-field dissipation is negligible in primordial gas.