原始ガス雲内部から放出される Lyα光子によるH_2形成抑制効果

Effect of Lyman α (Lyα) photon radiated from primordial cloud to H_2 formation

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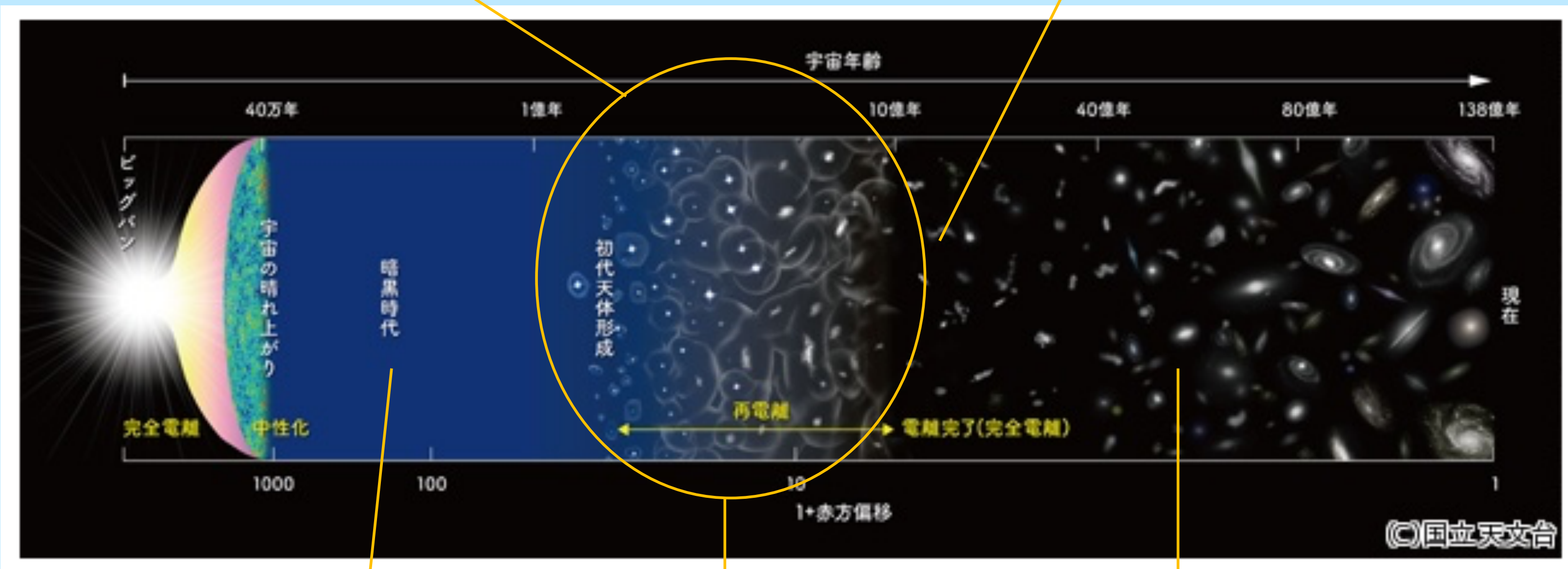
• Introduction

- First object (初代天体)
  - ➢ First star and first galaxy made from primordial gas cloud
- History of universe

Observation of super massive black hole (SMBH) at z~7 ($M \sim 10^9 M_{\odot}$)

First object -> seed BH

reionization



Without metal → Metal formation → With metal

(primordial gas cloud)

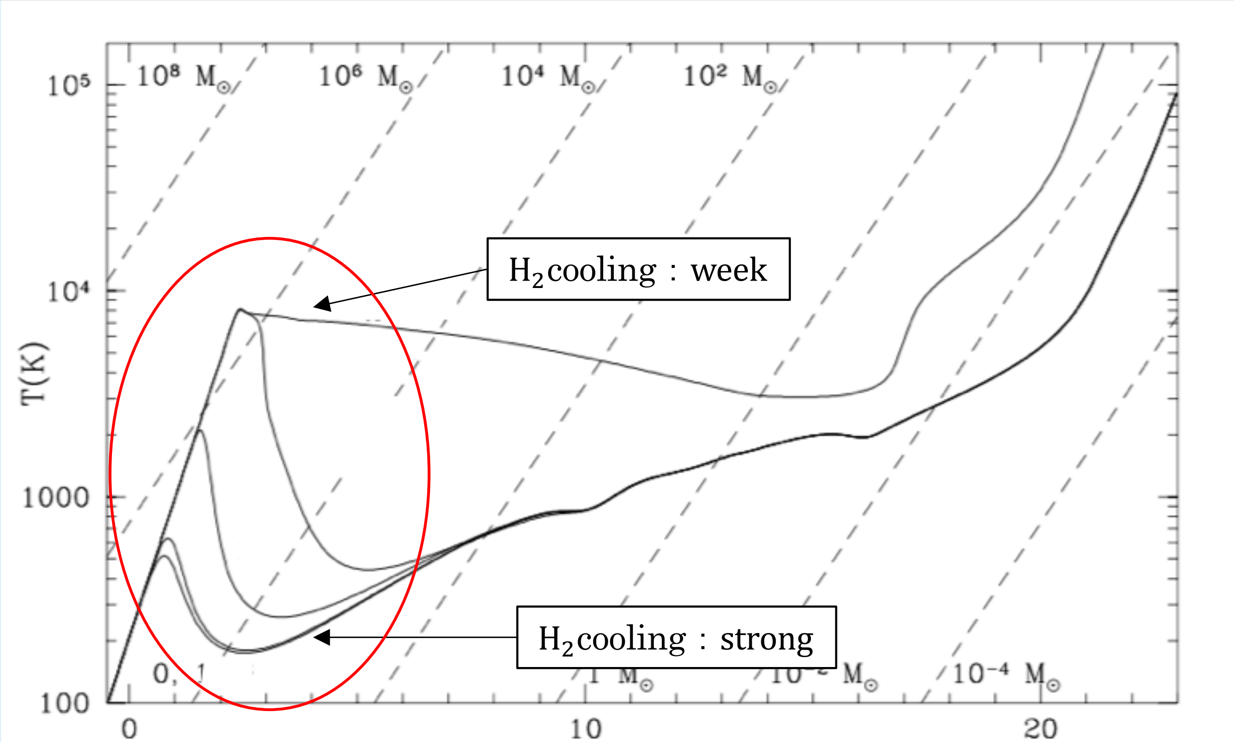
• Introduction

- First object formation scenario

collapse of a cloud of primordial gas ⟸ <u>Without metal</u>

➡ Available cooling is only H and H_2

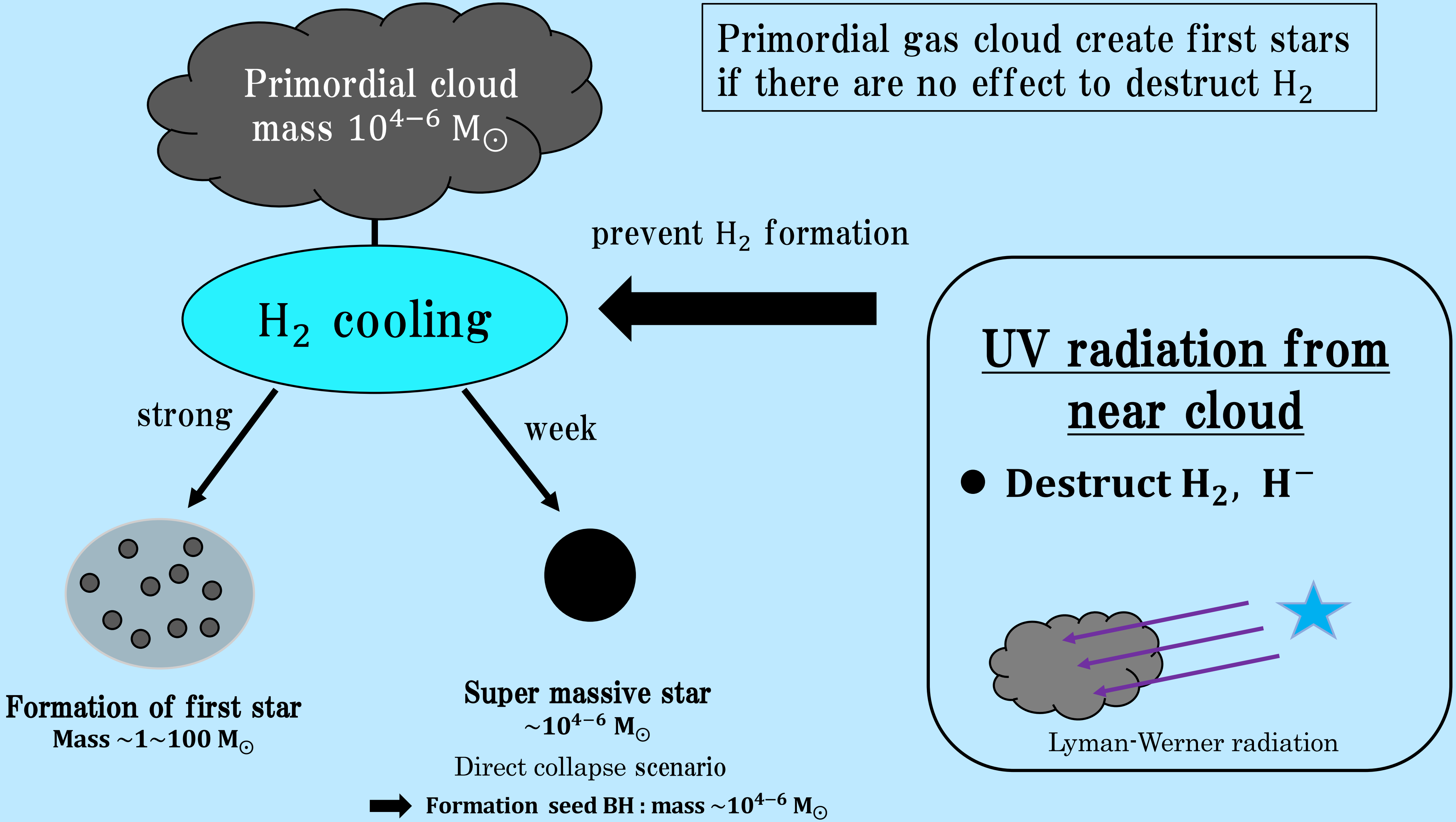
- H cooling → $T_{gas} \sim 8{,}000$ K
- H_2 cooling → $T_{gas} \sim 200$ K



(Omukai 2001)

• Introduction

- The relation between cooling of primordial gas and first object (direct collapse scenario)



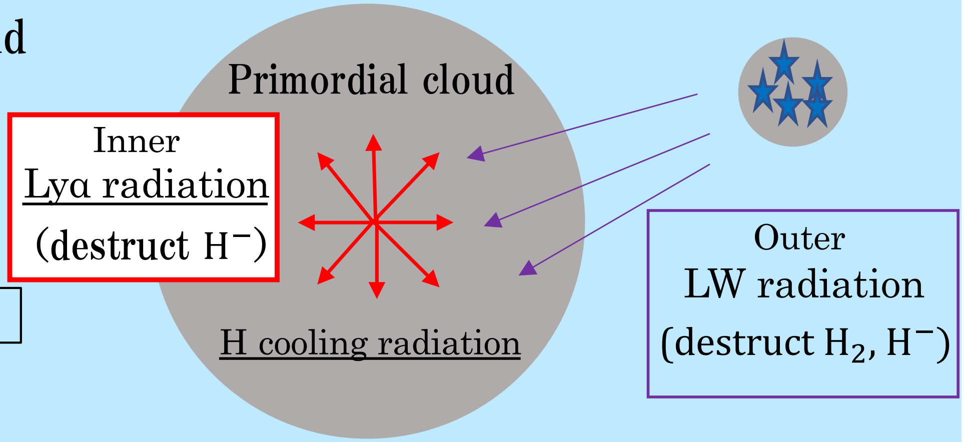
• Introduction

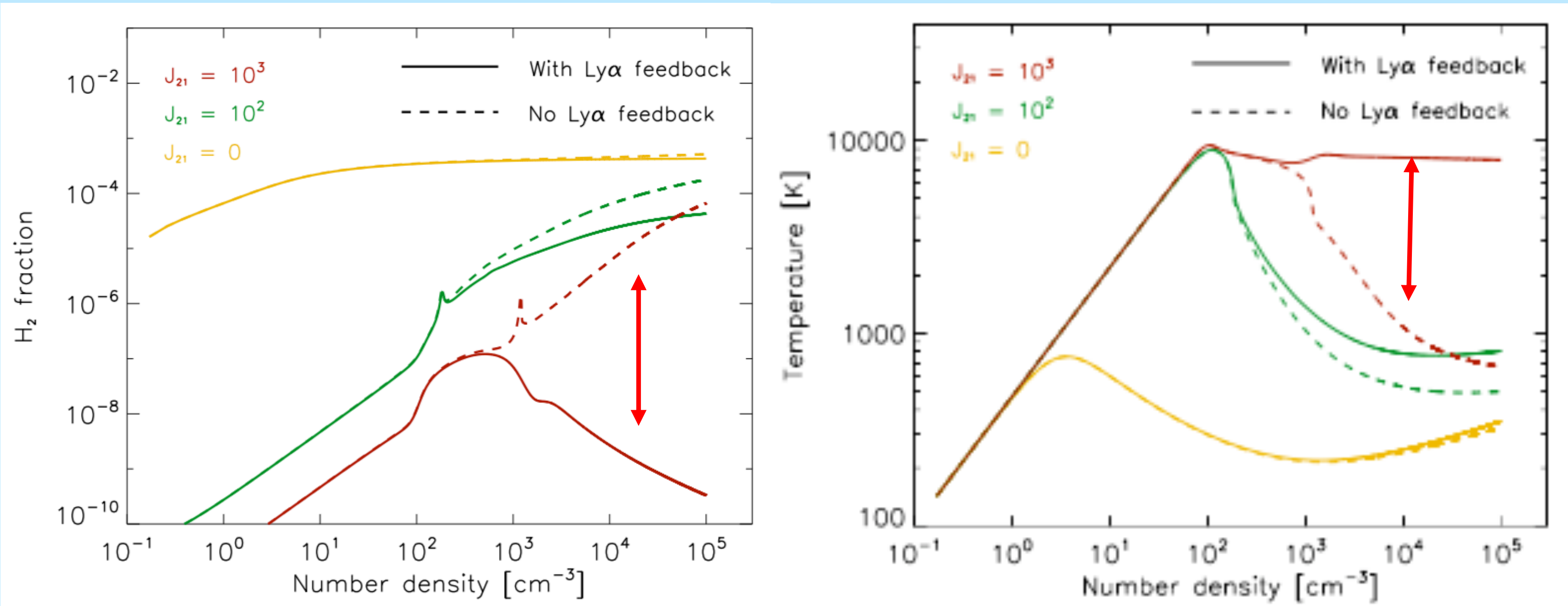
- Effect of Ly α photon to prevent H_2 formation (Johnson & Dijkstra 2017)
  - Main reaction to formation H_2 in primordial cloud

$$\begin{cases} \mathbf{H} + \mathbf{e}^- \rightarrow \mathbf{H}^- + \gamma \\ \mathbf{H}^- + \mathbf{H} \rightarrow \mathbf{H_2} + \mathbf{e}^- \end{cases}$$

Photodetachment energy : >0.76 eV

Lyα photon : 10.2 eV





At high density region, it can not prevent H_2 formation only outer UV radiation,
But include inner Ly α radiation can prevent H_2 formation.

• Introduction

- Problem of Ly α transfer in Johnson & Dijkstra 2017

  Effect of multiple scattering and trapping → use parameter

Luminosity of Lyα : gravitational potential energy

$$L_{\mathrm{Ly}\alpha} = \frac{GM_{\mathrm{cloud}}^2}{r_{\mathrm{cloud}}}\frac{1}{t_{\mathrm{ff}}}$$

Energy density of Lyα

$$u_\alpha = \frac{L_{\mathrm{Lya}} \cdot \frac{r_{\mathrm{cloud}}}{c} M_F}{V_{\mathrm{cloud}}}$$

(M_F: increase length to escape primordial cloud)

$$\Rightarrow \quad R_{\mathrm{detach}} = \sigma_{\mathrm{H^-}} \frac{u_\alpha}{\mathrm{E_{Lya}}} c \cdot B$$

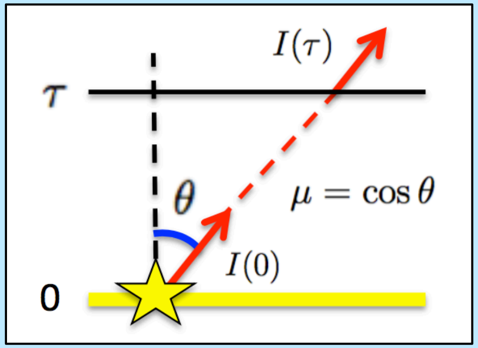
B : effect of non-uniform energy density

B = 1 ~ 10

<u>We think it need to treat Ly α transfer more exactly</u>

• Method

- Radiative transfer of Lyα → radiative diffusion eq.
  - One-dimension plane parallel



$$\mu \frac{dI_\nu}{dz} = \underbrace{-\alpha_\nu I_\nu}_{\text{decrease}} + \underbrace{\alpha_\nu S_\nu}_{\text{increase}}$$

I_ν : intensity, α_ν : extinction coefficient,
S_ν : source term, $\mu = \cos\theta$

➡ Moment equation (average of solid angle)

- first, second moment eq. + Eddington approximation (isotropic radiation)

$$\frac{1}{3\alpha_\nu}\frac{d^2 J_\nu}{dz^2} = \alpha_\nu (J_\nu - S_\nu)$$

Radiative diffusion equation

- Source term : approximation of redistribution (Rybicki & dell' Antonio 1994)

$$S(x) = \frac{1}{\phi(x)}\int R(x;x')J_{x'}dx' \approx J(x) + \frac{1}{2\phi(x)}\frac{\partial}{\partial x}\left(\phi(x)\frac{\partial J(x)}{\partial x}\right)$$

Normalize frequency

$$x = \frac{\nu - \nu_0}{\Delta\nu_D}$$

ν_0 : line center frequency,
$\Delta\nu_D = \frac{V_{th}}{c}\nu_0$: Doppler width

➡

$$\frac{\partial^2 J(\tau,x)}{\partial \tau^2} + \frac{3\phi(x)}{2}\frac{\partial}{\partial x}\left(\phi(x)\frac{\partial J(\tau,x)}{\partial x}\right) = \underbrace{-3\phi^2(x)G(\tau,x)}_{\text{Radiation source}}$$

We solve this equation using numerical simulation

• Method

- Boundary condition
  - ➢ Radiation source：

    Only cloud center ($\tau = 0$)and frequency line center (x=0)

$$\frac{\partial^2 J(\tau,x)}{\partial\tau^2} + \frac{3\phi(x)}{2}\frac{\partial}{\partial x}\left(\phi(x)\frac{\partial J(\tau,x)}{\partial x}\right) = -3\phi^2(x)\underline{G(\tau,x)}$$

$$= \delta(\tau)\,\delta(x)$$

  - ➢ frequency (x) ：boundary = 0

$$J(\tau,\pm\infty) = 0$$

  - ➢ Surface of cloud (τ) ：

    radiation is isotropic and only escape radiation

$$J(\tau_{\max},x) = 2H(\tau_{\max},x) = \frac{2}{3\phi(x)}\left(\frac{\partial J(\tau,x)}{\partial\tau}\right)_{\tau=\tau_{\max}}$$

  - ➢ Symmetry at $\tau = 0$

$$\frac{\partial J(\tau=0,x)}{\partial\tau} = 0$$

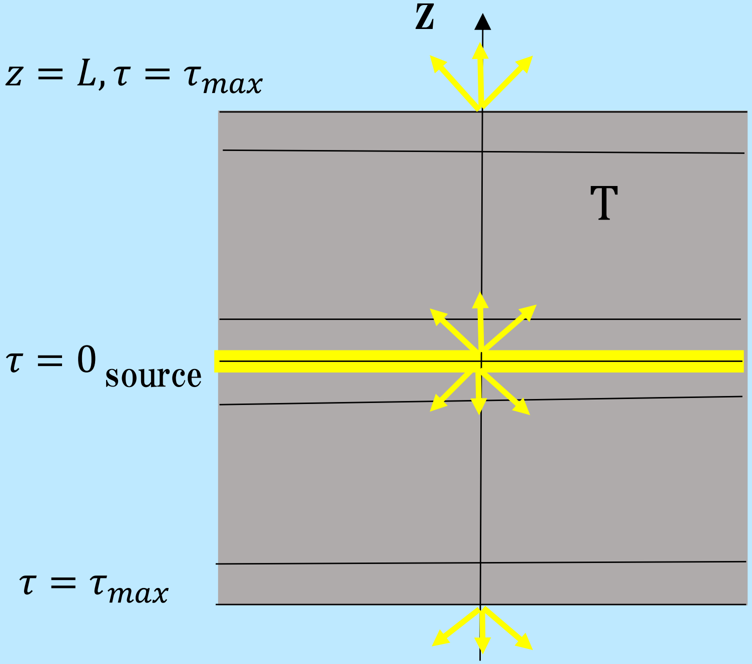
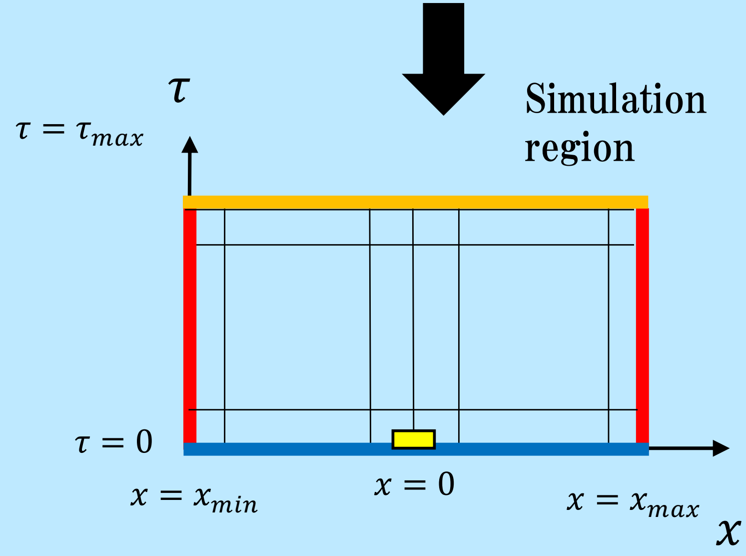


図. Plane parallel, optical depth τ



• Method

- Environment of gas cloud
  - ➢ Isotropic gas cloud
  - ➢ Parameter of simulation
    - Gas temperature T
    - Optical depth at Lyα line center ($\tau_{\text{line center}}$)

- Estimate of optical depth

$$\tau_{\text{line center}} = n\,\sigma\,L = N_H\,\sigma$$ (cloud radius L)

$$\sigma = f_{12}\frac{\pi\,e^2}{m_e\,c}\frac{1}{\Delta\nu_D} = 5.89\times10^{-14}\left(\frac{T}{10^4}\right)^{-\frac{1}{2}}$$

Total mass of gas cloud：$M_{gas} = 10^6 M_{\odot}$

density：$n = 0.1 \sim 10^5$

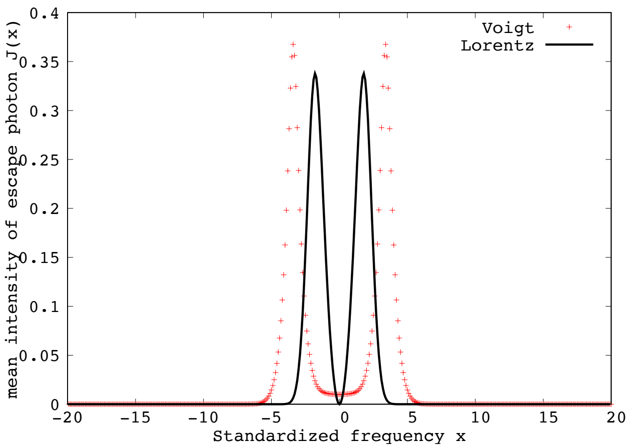
➡ $\tau_{\text{line center}}$：$10^6 \sim 10^{12}$ (assume isotropic spherical cloud)

• Result

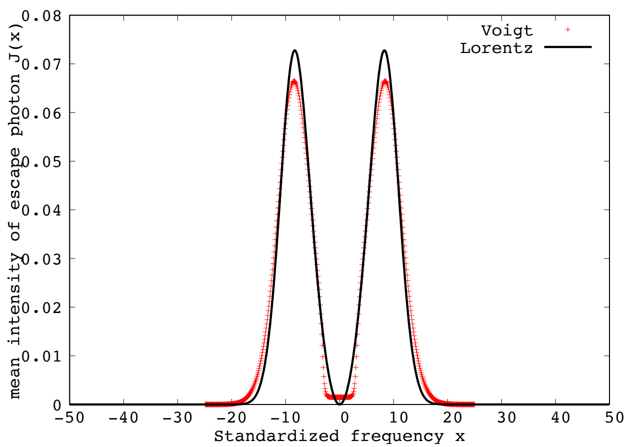
- Spectral of escape photon

$T = 10^4$ K

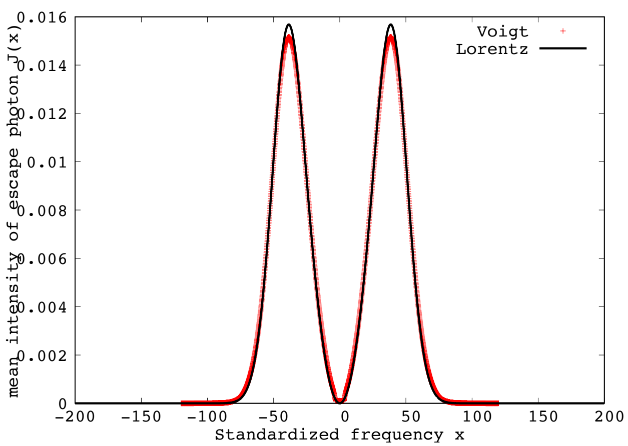
red : Voigt profile : numerical (this work)
black : Lorentz profile :analytical



tau= 10^4



tau= 10^6



tau= 10^8

At high optical depth
Agree with Harrington-Neufeld solution (Lorentz profile analytical solution)

Harrington-Neufeld solution

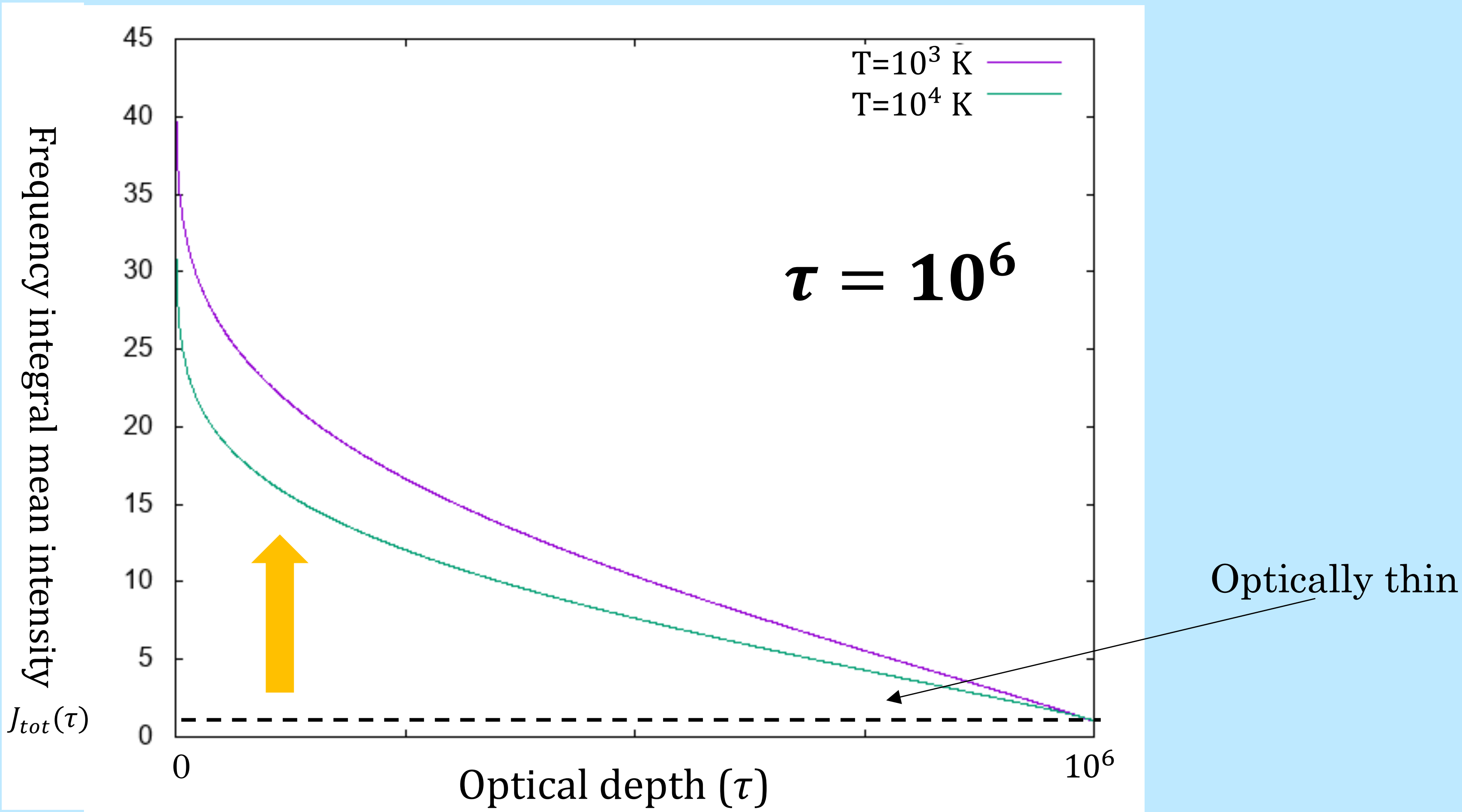
(Harrington 1973, Neufeld 1990)

$$J(x) = \frac{\sqrt{6}}{24 a \tau_{\mathrm{L}}} \frac{x^2}{\cosh[\sqrt{\frac{\pi^4}{54}}(|x^3|/a\tau_{\mathrm{L}})]}$$

• Result

- Frequency average mean intensity (incidence intensity = 1)

$$J_{\rm tot}(\tau) = \int J(\tau, x)dx$$



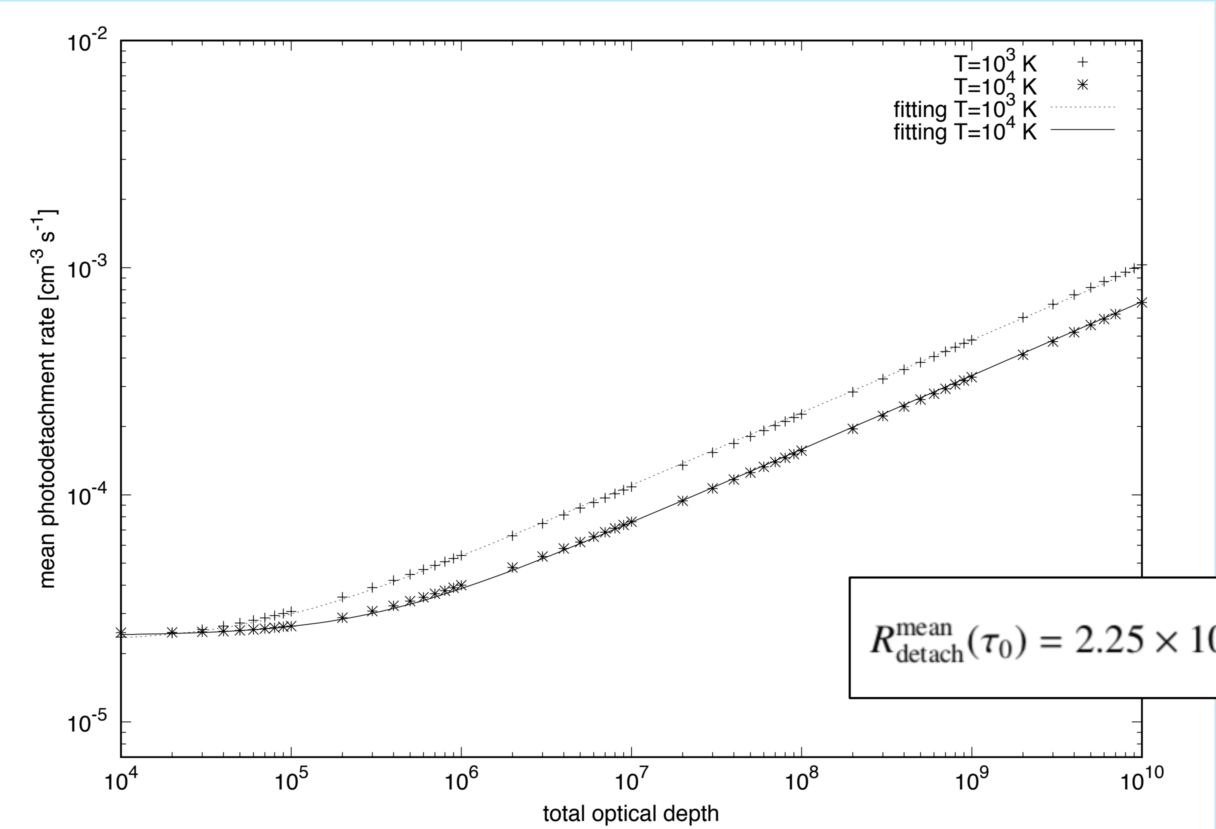
Increase mean intensity at cloud center ← effect of multiple scattering。

• Result

- H^- photodetachment rate of Lyα radiation

$$R_{\rm detach}(\tau) = 4\pi \int_{\nu_{\rm min}}^{\nu_{\rm max}} \frac{J(\tau,\nu)}{h\nu} \sigma_{\rm H^-}(\nu) d\nu$$

➢ Average rate in gas cloud $R_{\rm detach}^{\rm mean}$ $(\tau_{\rm line\ center})$: $\tau_{\rm line\ center} = 10^4 \sim 10^{10}$



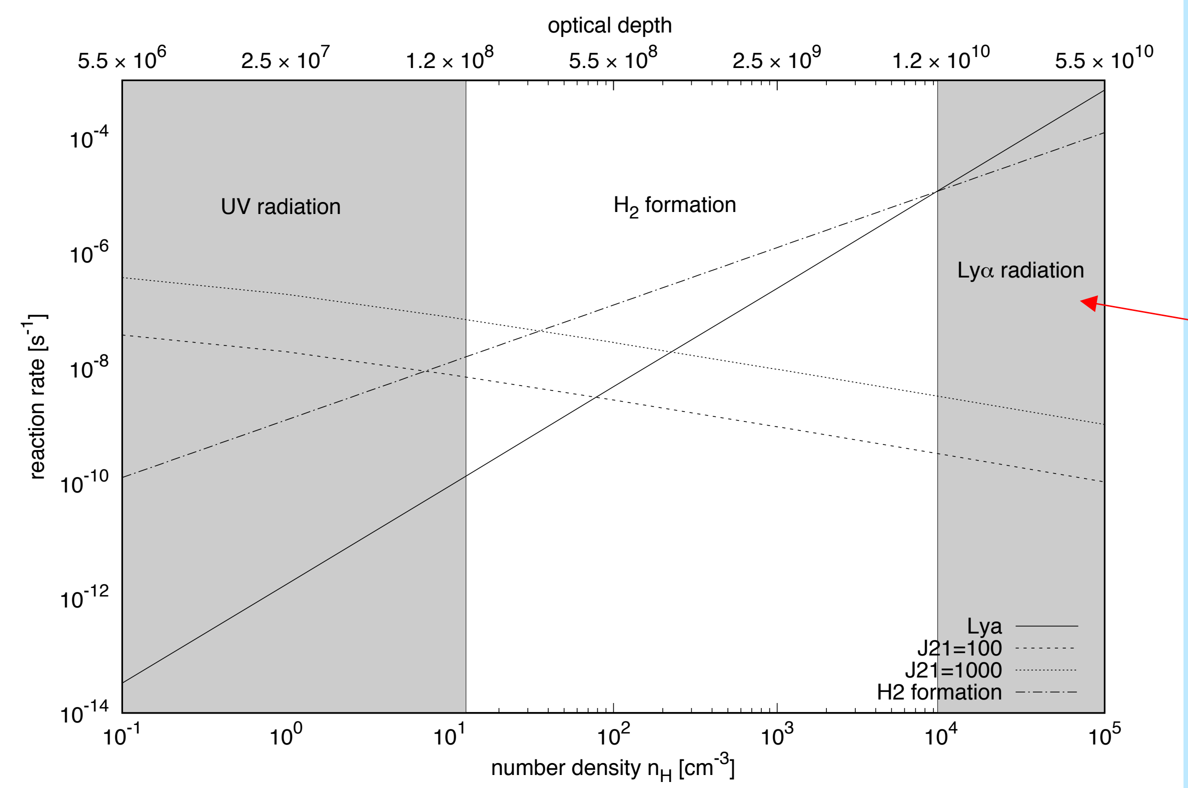
Fitting function at T= 10^4 K

$$R_{\rm detach}^{\rm mean}(\tau_0) = 2.25 \times 10^{-5} \times \left(1 + \left(\frac{\tau_0}{7 \times 10^4}\right)\right)^{0.320} \times \left(\frac{F_0}{[{\rm erg \cdot cm^{-2} \cdot s^{-1}}]}\right)$$

• Result

- Compare with H_2 formation and destruction
  - Lyα radiation : H^- destruction
  - Outer UV radiation : H_2 destruction
  - H_2 formation form H^-

$M_{gas} = 10^6 M_\odot$, $T_{gas} = 10^4$ K



- **Main reaction**

$$\begin{cases} \mathbf{H} + \mathbf{e}^- \rightarrow \mathbf{H}^- + \gamma \\ \mathbf{H}^- + \mathbf{H} \rightarrow \mathbf{H_2} + \mathbf{e}^- \end{cases}$$

- H_2 formation rate

$H^- + H \rightarrow H_2 + e^-$

$R_{H_2\,form} = 4.0 \times 10^{-9} \times T^{-0.17} \times n_H\ [s^{-1}]$

(Galli & Palla 1998)

Restrict H_2 formation only Lyα radiation

• Conclusion

- H⁻ photodetachment rate by Ly α describe below formula in plane parallel primordial gas cloud

$$R_{\mathrm{detach}}^{\mathrm{mean}}(\tau_0) = 2.25 \times 10^{-5} \times \left(1 + \left(\frac{\tau_0}{7 \times 10^4}\right)\right)^{0.320} \times \left(\frac{F_0}{[\mathrm{erg} \cdot \mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}]}\right)$$

- At high density, prevent H_2 formation only by inner Ly α radiation
- But at low density, need to outer UV radiation