銀河進化の解明に向けた磁場・宇宙線が駆動する銀河風についての理論研究

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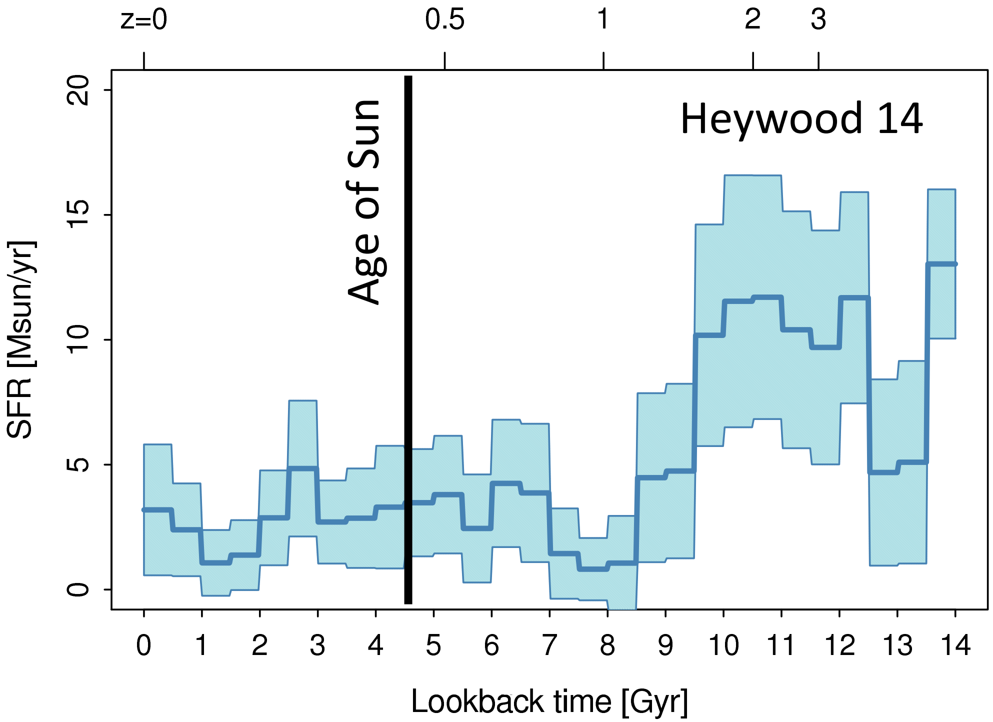
Star Formation Rate of MW

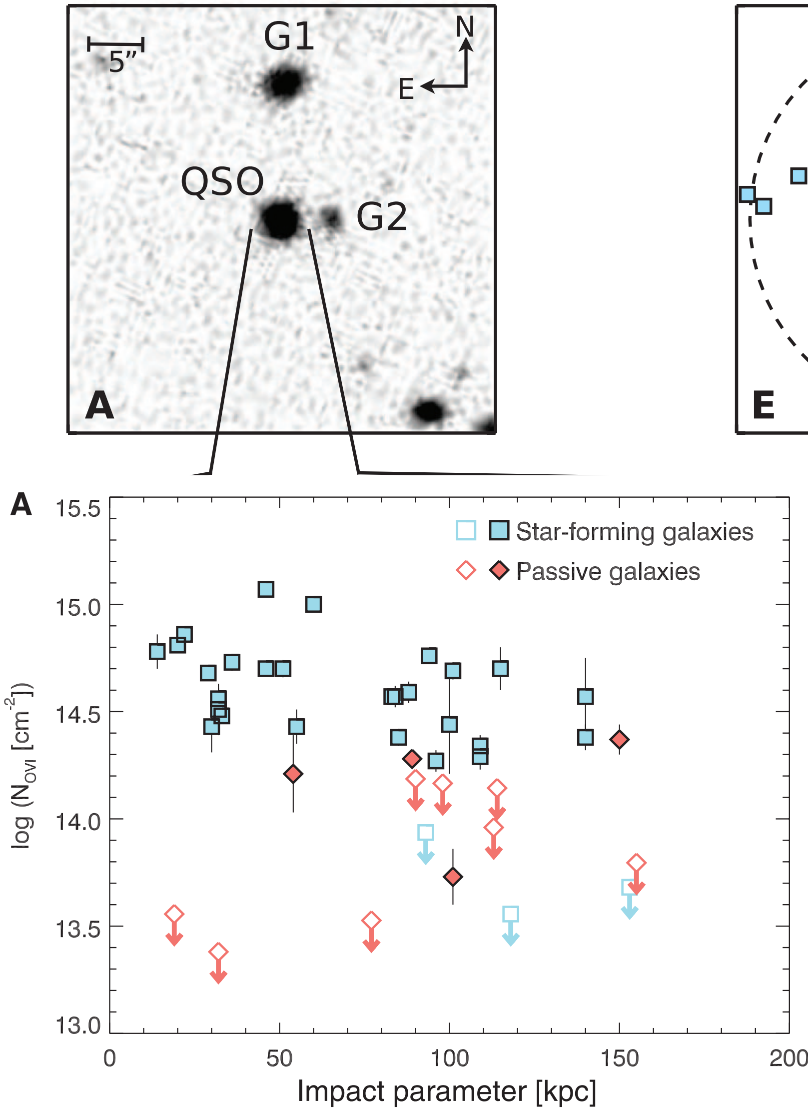


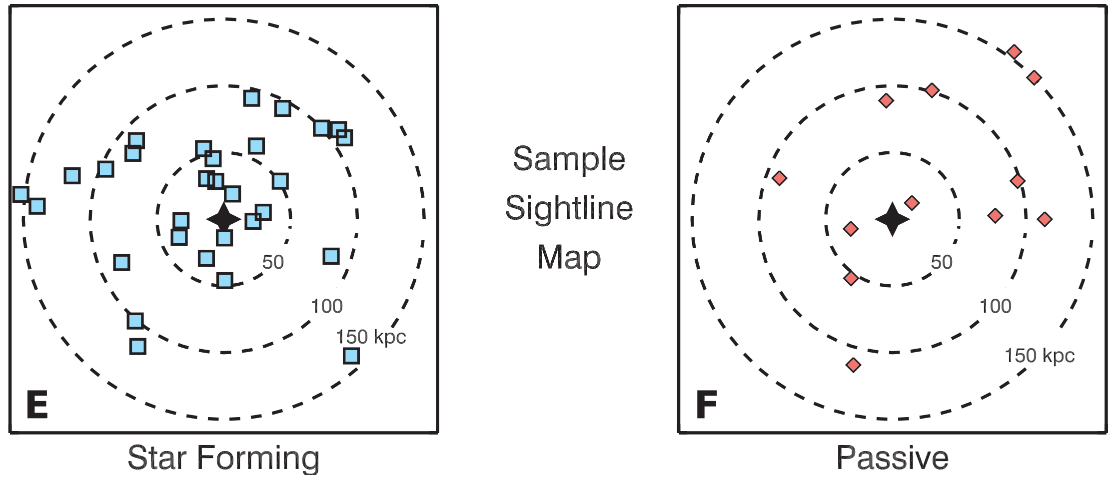
Current SFR: $\sim 1\ M_{sun}/yr$

Total gas mass: $\sim 10^9\ M_{sun}$

1. The gas should be depleted within ~ 1 Gyr !
2. Replenishment of gas is required.
3. Galactic halo (CGM) may be a dominant gas reservoir.

Circum-Galactic Medium (CGM)



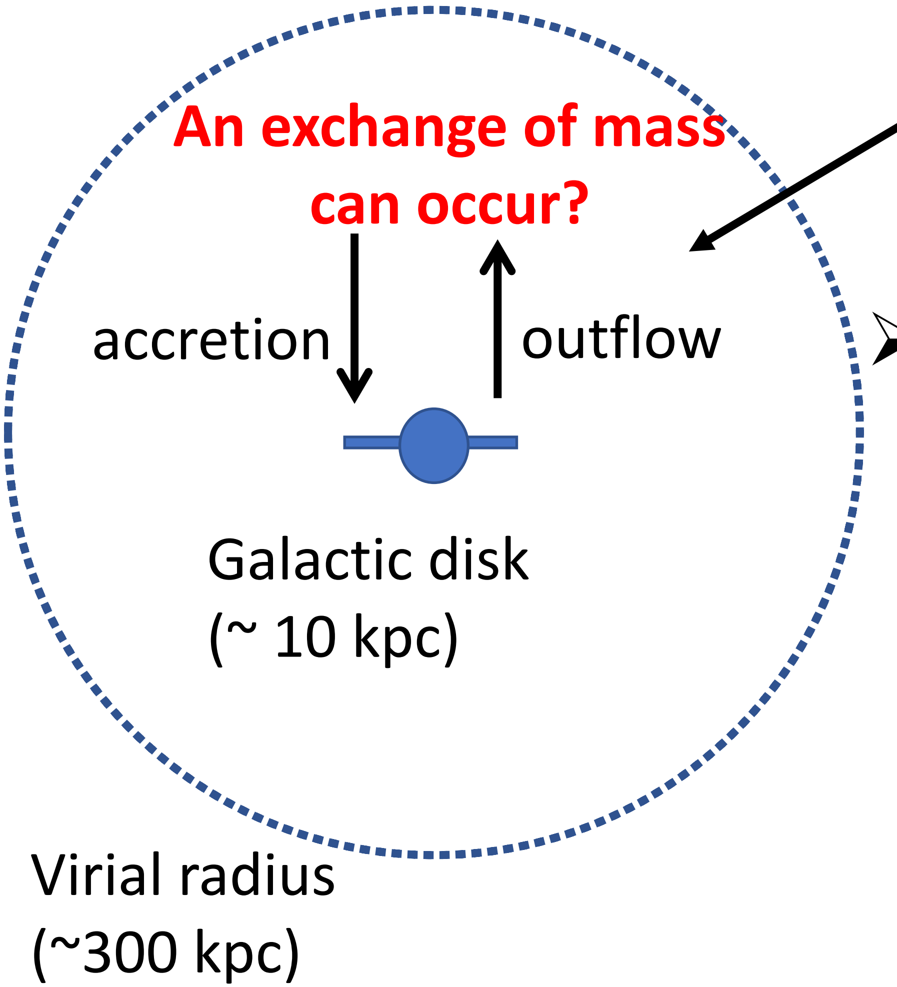


“Discovery” of hot, highly ionized medium around galaxies (Tumlinson+11, 17).

- O_{VI} absorption line
  - → $T_{ionized}$ ~ 3 x 10^5 K, N_{OVI} ~ 10^{14} cm^{-2}
  - → Estimated total gas mass

~ 10^{10}–10^{12} M_{sun}

Circum-Galactic Medium (CGM)

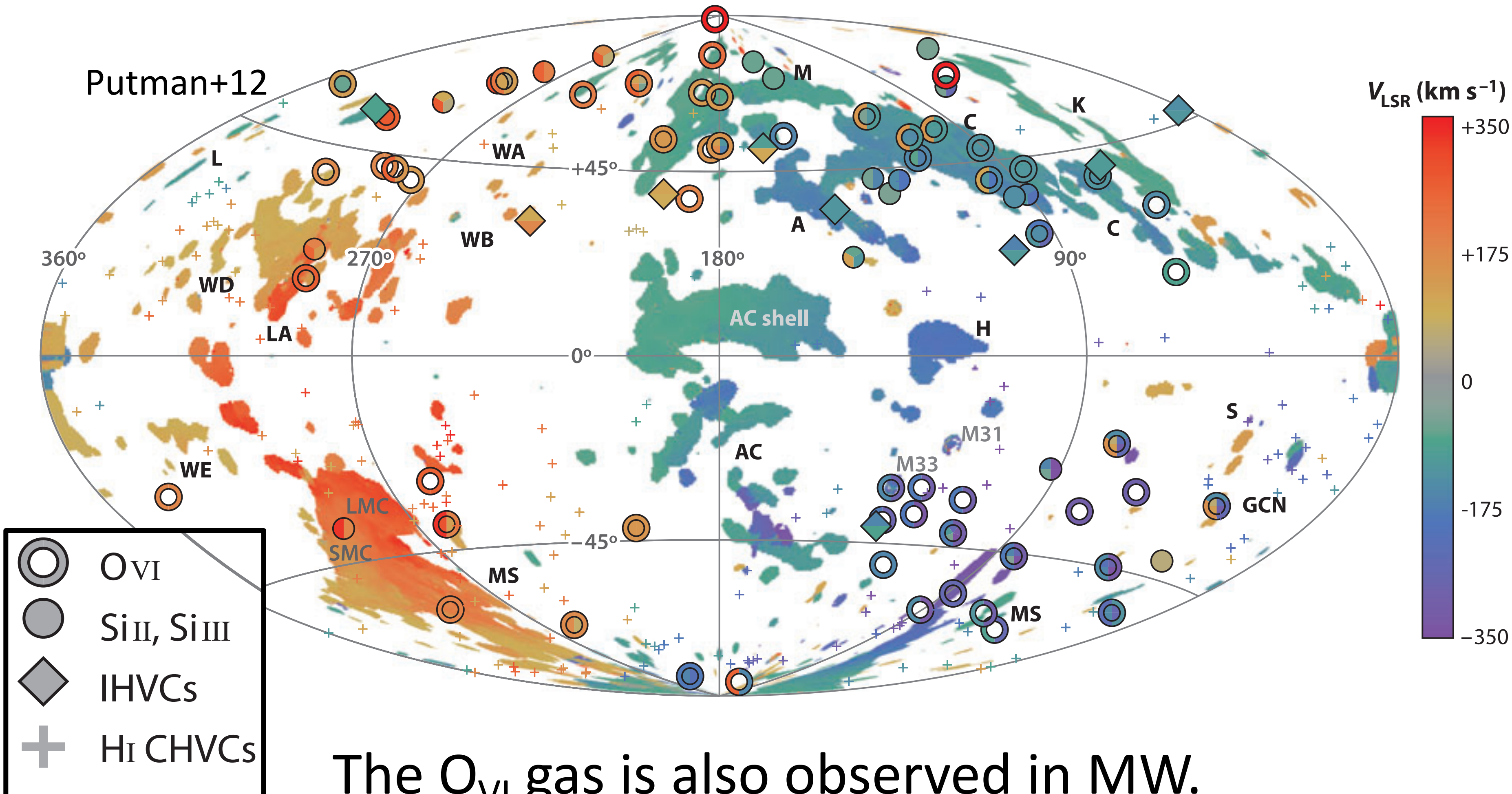


How much does CGM contain available gas?

- The CGM contains hot, highly ionized gas with a mass of $\sim 10^{10} - 10^{12}$ M_{sun} !

CGM of Milky Way

Putman+12

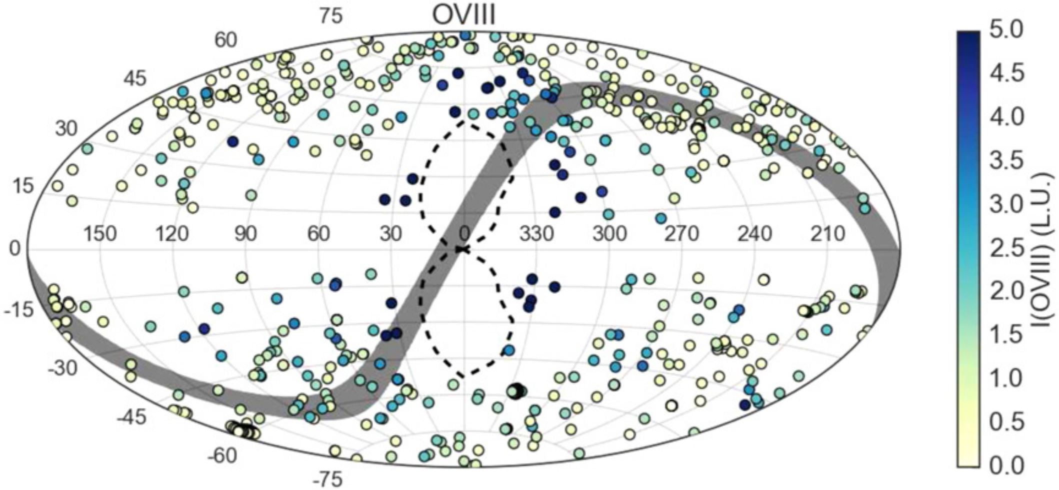


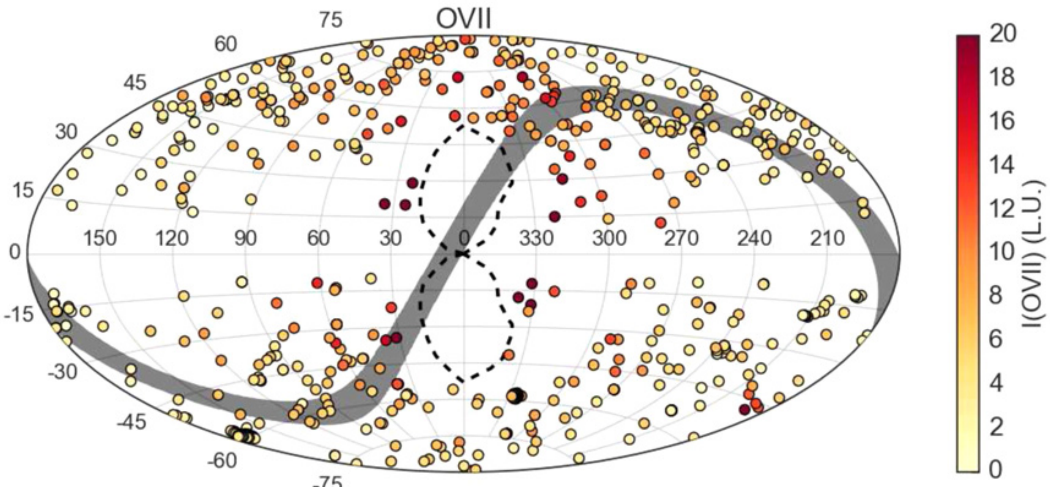
The O_{VI} gas is also observed in MW.

(Bregman & Lloyd-Davies 07; Miller & Bregman 13, 15; Faerman+ 17, 19; Nakashima+18, etc…)

CGM of Milky Way

Miller & Bregman 15





OVII & O VIII emission lines are also observed.

Problems of CGM

- **Metal transfer** to the CGM

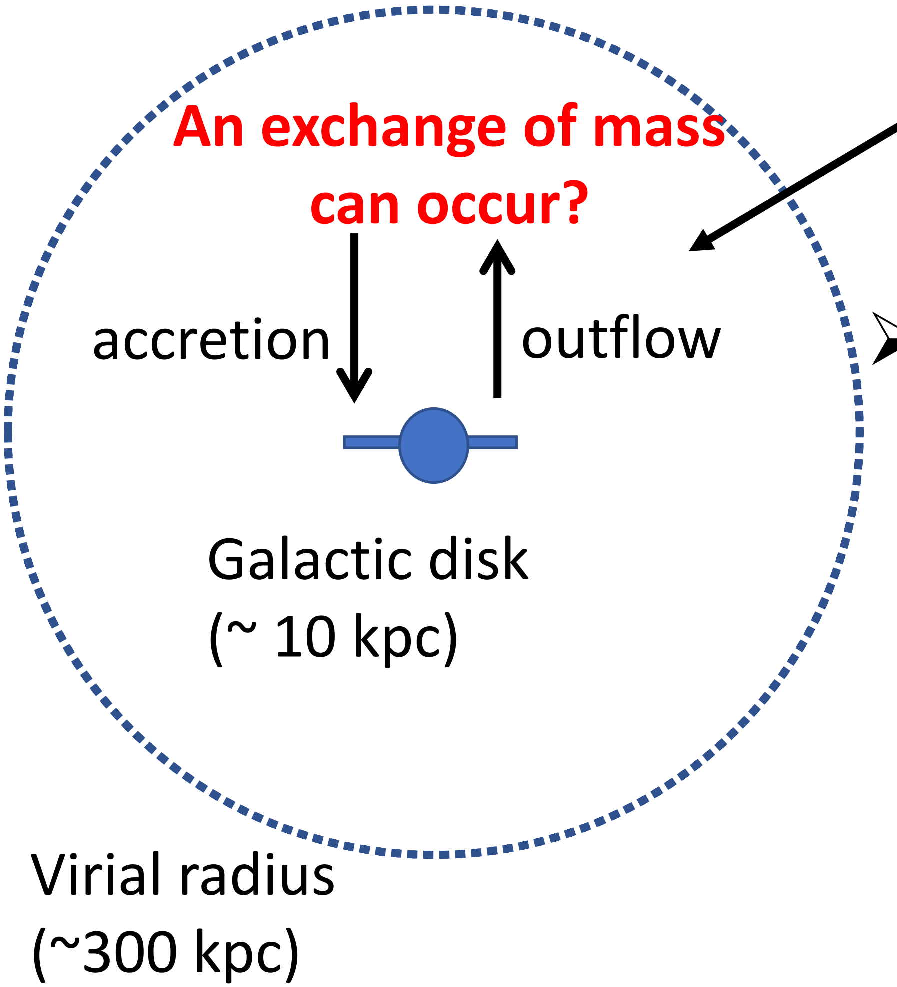
  How the metals are transferred to a scale height of > 100 kpc? (Supernovae make a fountain flow with a scale height of $\sim$ kpc, Shapiro & Field 76)

  → **Galactic wind may be required.**

- **Cooling time** of O_{VI} gas < 0.1 Gyr (e.g. Faerman+17, 19)

  If the gas is really cooled, our galaxy would suffer a drastic mass accretion (like a galactic fountain flow).

Circum-Galactic Medium (CGM)



How much does CGM contain available gas?

- The CGM contains hot, highly ionized gas with a mass of $\sim 10^{10} - 10^{12}$ M_{sun} !

Circum-Galactic Medium (CGM)

1. Observations suggest that the CGM contains a sufficient gas to maintain the Galactic star formation.

2. From the cooling time of gas, we expect an accretion flow of the CGM gas , but it is in conflict to the current picture of MW.

3. We should study what mechanisms control the mass exchange between the galactic disk and CGM.

As a first step, we study the Galactic wind properties.

Galactic Wind: Previous studies

author	method	CR spatial diffusion	Wave generation	Wave damping	gas cooling	galaxy rotation	Notes
Breitschwerdt+91	analytic	No	Yes	No	No	No	Standard model
Zirakashvili+96	analytic	Yes	Yes	Yes	No	Yes	w B-field high T
Everett+08	analytic	No	Yes	Yes	No	No	Compared with X-ray obs.
Recchia+16	analytic	Yes	Yes	Yes	No	No	w CR spectra
Girichidis+18	Numerical	Yes	No	No	Yes	No	local box <B> = 0
Dashyan & Dubois 20	Numerical	Yes	Yes	No	Yes	Yes	Global <B> ≠ 0
Hopkins+ 20	Numerical	Yes	Yes	Yes	Yes	Yes	FIRE simulation

analytic：
- Only Z > 1 kpc considered
- $10^5 - 10^6$ K gas at ~ 100 kpc scale due to the wave dissipation

Numerical：
- Solve within a scale height of ~ kpc, simulation time is ~ 0.1 Gyr

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Hopkins+ 20	Numerical	Yes	Yes	Yes	Yes	Yes	FIRE simulation

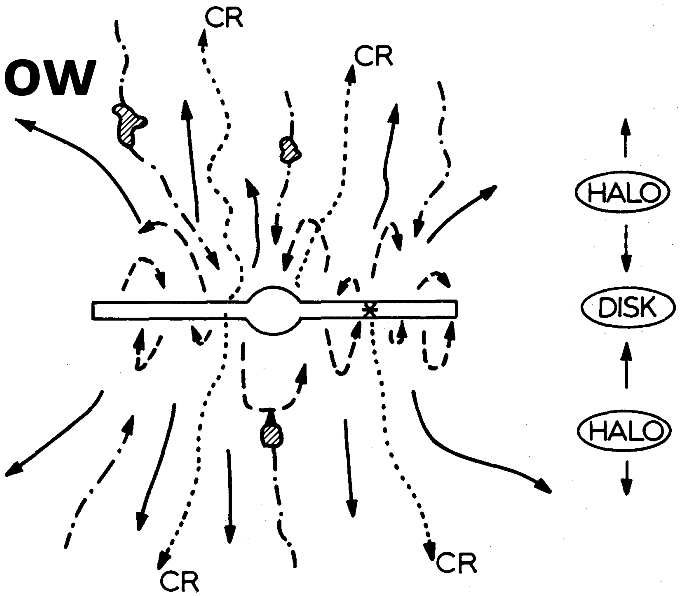
We study the galactic wind with radiative cooling.

analytic：
- Only Z > 1 kpc considered
- $10^5 - 10^6$ K gas at ~ 100 kpc scale due to the wave dissipation

Numerical：
- Solve within a scale height of ~ kpc, simulation time is ~ 0.1 Gyr

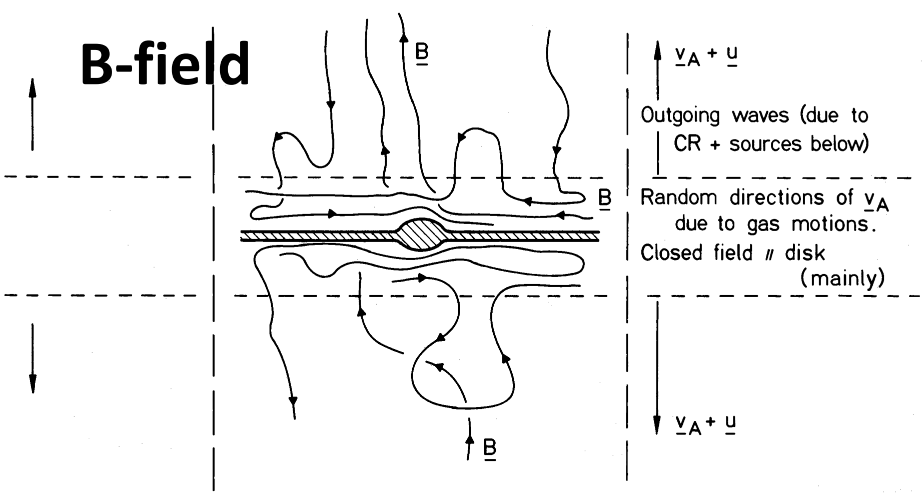
Standard Model (Breitschwerdt+91)

flow



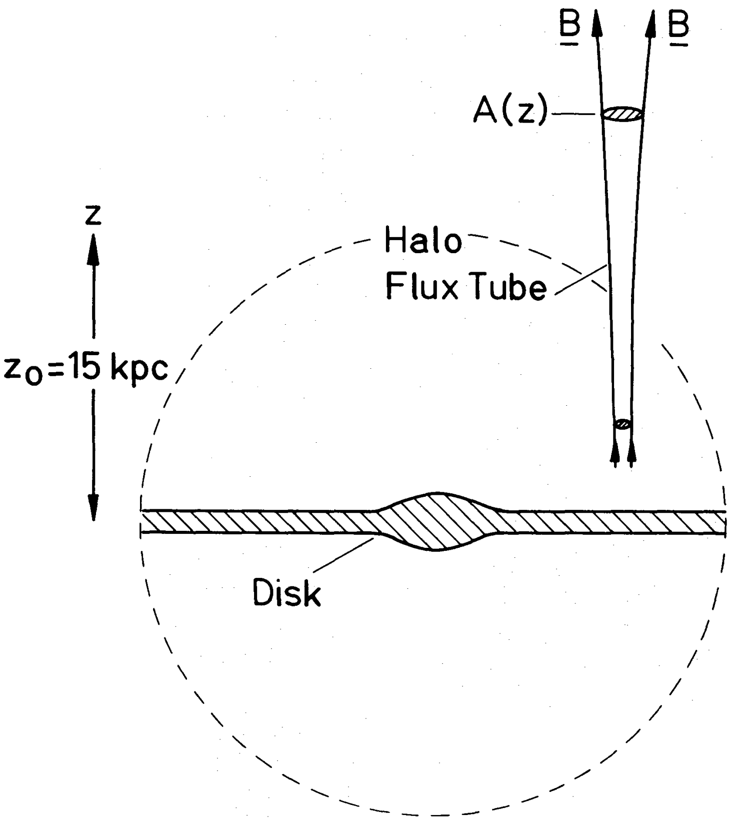
Model description：
　The galactic fountain flow is driven at a scale height of several kpc.
　The hot, tenuous gas is pushed by cosmic-rays, and eventually escaping as a galactic wind.

B-field



*Breitschwerdt+91 extended the pioneering work by Ipavich 75, and estimated that the mass loss rate due to the wind is $\sim 1\ \mathrm{M_{sun}/yr}$.

Standard Model (Breitschwerdt+91)



B-field geometry

$$A(z) = A_0 \left[1 + \left(\frac{z}{Z_0} \right)^2 \right]$$

We follow this model description and B-field geometry.

Basic Equations

$$\frac{d}{dz}(\rho u A) = 0$$

$$\rho u \frac{du}{dz} = -\frac{d}{dz}(p_g + p_{cr} + p_w) - \rho \frac{d\Phi}{dz}$$

$$\frac{1}{A}\frac{d}{dz}\left[A\left\{\rho u\left(\frac{1}{2}u^2 + h_g\right)\right\}\right] = -\rho u \frac{d\Phi}{dz} - u\frac{dp_{cr}}{dz} - u\frac{dp_w}{dz} + n^2(\Gamma - \Lambda) - L_w$$

$$\frac{1}{A}\frac{d}{dz}\left[A\left\{\frac{\gamma_c}{\gamma_c - 1}(u + V_A)p_{cr} - \frac{1}{\gamma_c - 1}\kappa\frac{dp_{cr}}{ds}\right\}\right] = (u + V_A)\frac{dp_{cr}}{dz}$$

CR transport eq.

$$\frac{1}{A}\frac{d}{dz}\left[A\left\{\left(\frac{3}{2}u + V_A\right)2p_w\right\}\right] = u\frac{dp_w}{dz} - V_A\frac{dp_{cr}}{dz} + L_w$$

Wave energy eq. (Dewar 70)

$$BA = \text{const}$$

$$p_w \equiv \frac{\langle(\delta B)^2\rangle}{8\pi},\ L_w \equiv V_A\frac{dp_{cr}}{dz},\ \kappa = 3\times 10^{28}\ \text{cm}^2/\text{s}\left(\frac{p_M/p_w}{10^6}\right)\left(\frac{B}{1\ \mu\text{G}}\right)^{-1},\ p_M \equiv \frac{B^2}{8\pi}$$

$$\frac{d^2 \ln p_{cr}}{dz^2} = \left(\frac{d\ln p_{cr}}{dz}\right)^2 + \left(\frac{u + V_A}{\kappa} - \frac{A'}{A} - \frac{\kappa'}{\kappa}\right)\frac{d\ln p_{cr}}{dz} + \frac{\gamma_c(u + V_A/2)}{\kappa}\left(\frac{u'}{u} + \frac{A'}{A}\right)$$

Basic equations: (MHD) + (cosmic-ray) + (Alfven wave excited by CRs)

*Contributions of mean B-field are vanished because we consider a flow along the mean field.

Wind Equation

$$\frac{u'}{u} = \frac{A'}{A} \frac{{C_*}^2 - {V_G}^2}{u^2 - {C_*}^2}$$

(effective) Trans-sonic point: $u^2 = {C_*}^2 = {V_G}^2$

$${C_*}^2 \equiv {C_g}^2 + \frac{M_A + 1}{M_A + 1 - \mathcal{D}/V_A} {C_{cr}}^2 + {C_w}^2$$

$${V_G}^2 \equiv \frac{A}{A'} \left[\frac{d\Phi}{dz} + \frac{\gamma_g - 1}{\rho u} n^2 (\Gamma - \Lambda) + \frac{1}{2(u + V_A)} \frac{L_w}{\rho} \right]$$

$${C_g}^2 \equiv \frac{\gamma_g p_g}{\rho}$$

$${C_{cr}}^2 \equiv \left(\frac{M_A + 1/2}{M_A + 1} \right)^2 \frac{\gamma_{cr} p_{cr}}{\rho}$$

$${C_w}^2 \equiv \frac{3M_A + 1}{2(M_A + 1)} \frac{p_w}{\rho}$$

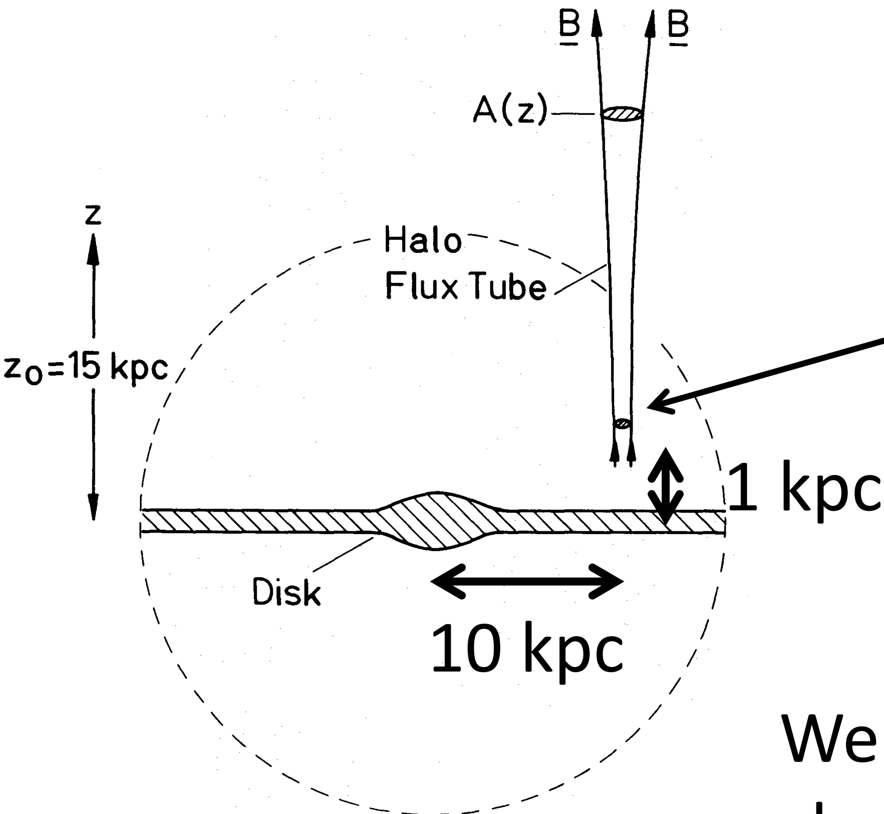
$$\mathcal{D} \equiv \frac{1}{p'_{cr}} \frac{1}{A} \frac{d}{dz} \left(A \kappa p'_{cr} \right)$$

$$A(z) = A_0 \left[1 + \left(\frac{z}{Z_0} \right)^2 \right]$$

Stational Out Flow Solution:

1. Initially, $u^2 < {C_*}^2 < {V_G}^2$
2. Pass through the trans-sonic point at which $u^2 = {C_*}^2 = {V_G}^2$

Boundary Condition



$$\rho_0 = 1.67 \times 10^{-27}\ \mathrm{g\ cm^{-3}}$$
$$p_{g0} = 2.8 \times 10^{-13}\ \mathrm{dyne\ cm^{-2}}$$
$$p_{cr0} = 1.0 \times 10^{-13}\ \mathrm{dyne\ cm^{-2}}$$
$$p_{w0} = 4.0 \times 10^{-16}\ \mathrm{dyne\ cm^{-2}}$$
$$B_0 = 10^{-6}\ \mathrm{G}$$

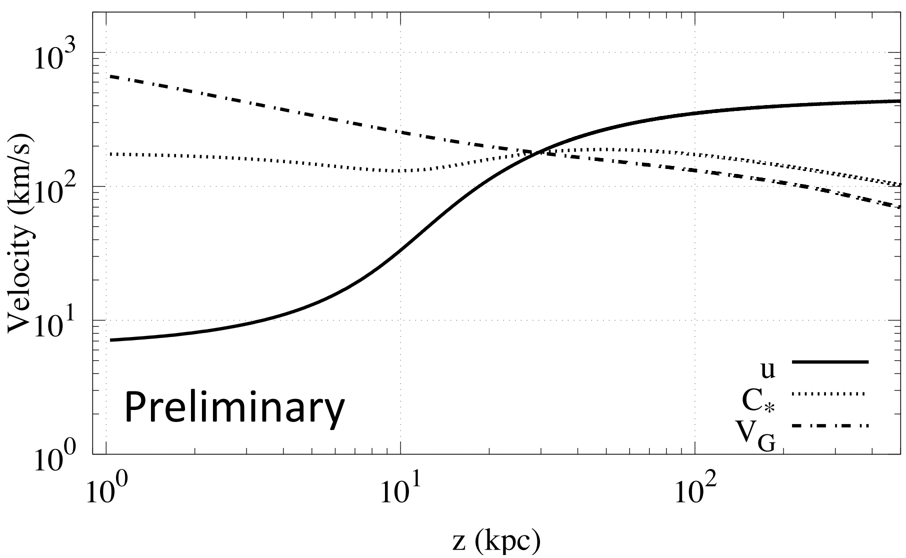
We seek the wind solution by changing the initial velocity u_0.

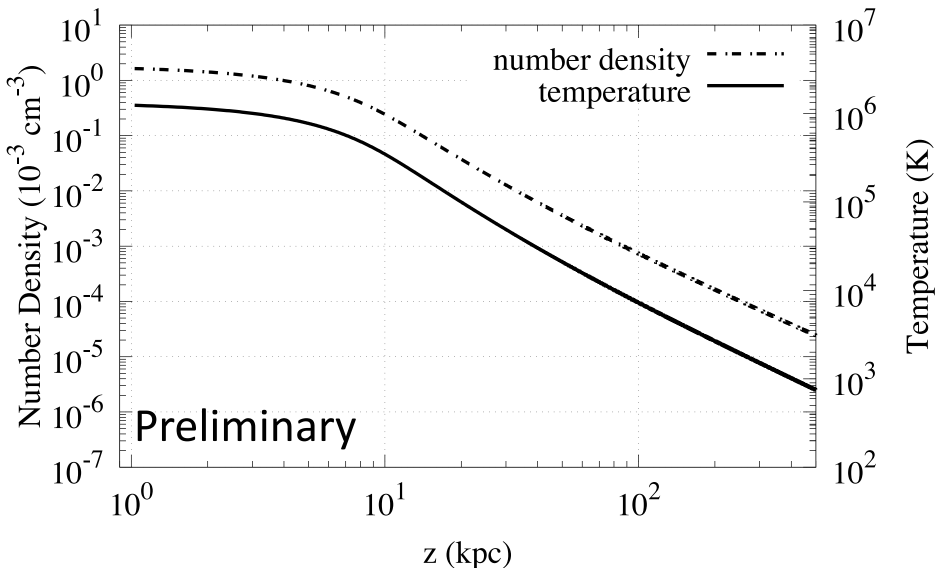
※ The CR diffusion is omitted for simplicity (κ = 0).

Adiabatic Wind

Wave dissipation: $L_w = 0$

Radiative cooling: $n^2(\Gamma\text{-}\Lambda) = 0$





The gas temperature is too low to exist O_{VI}.

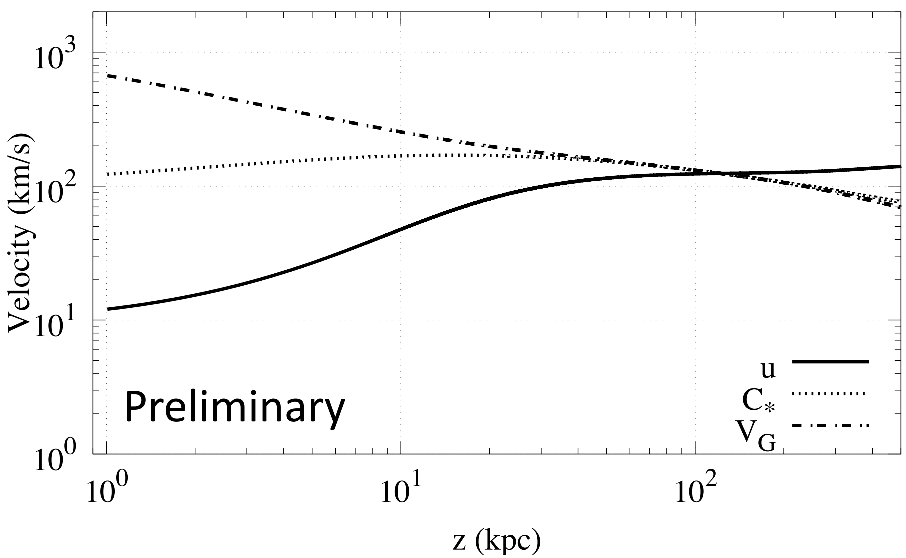
O_{VI} absorption line

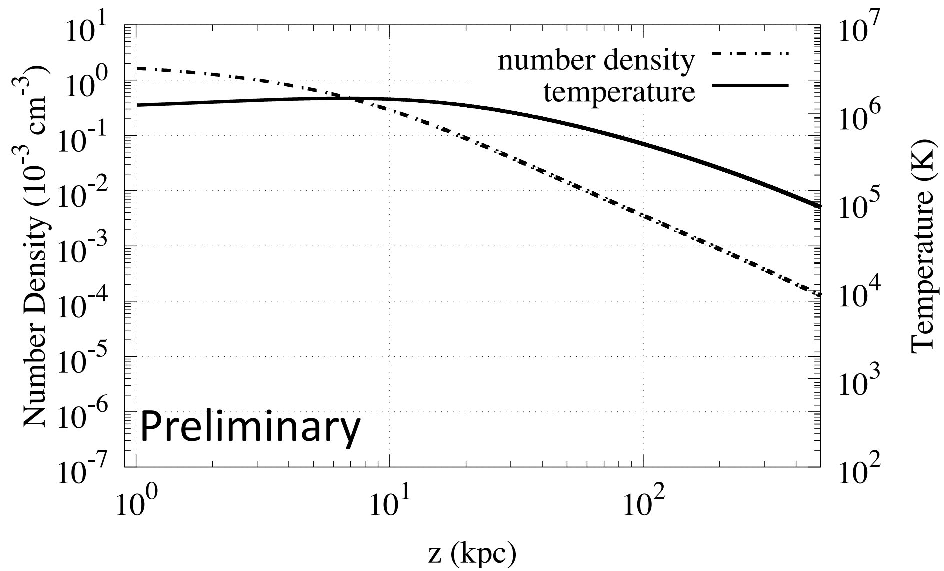
→ $T_{ionized} \sim 3 \times 10^5$ K, $N_{OVI} \sim 10^{14}$ cm^{-2}

Effects of Wave dissipation

Wave dissipation: $L_w = V_A(dp_{cr}/dz)$

Radiative cooling: $n^2(\Gamma - \Lambda) = 0$





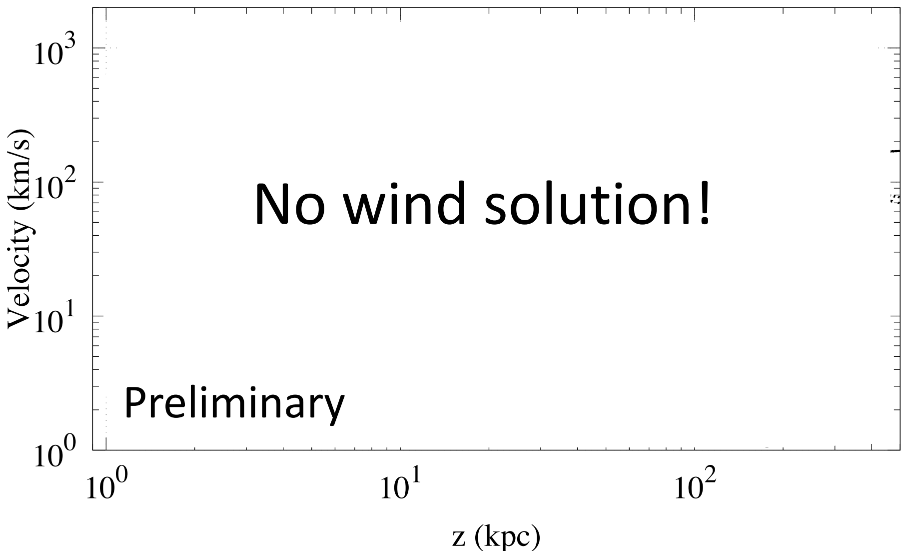
The wave dissipation leads to a high temperature gas to allow existing of O_{VI}.

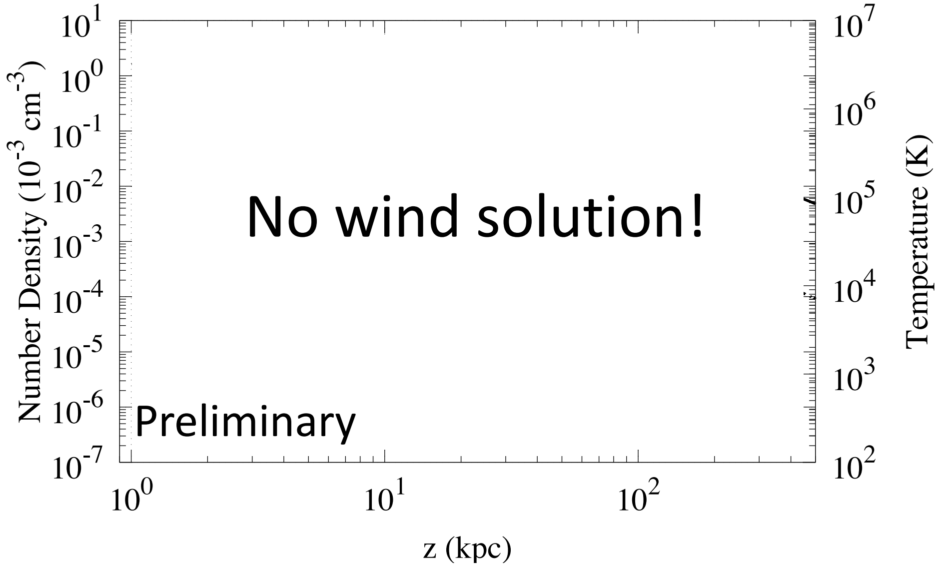
O_{VI} absorption line

→ $T_{ionized} \sim 3 \times 10^5$ K, $N_{OVI} \sim 10^{14}$ cm^{-2}

Effects of radiative cooling

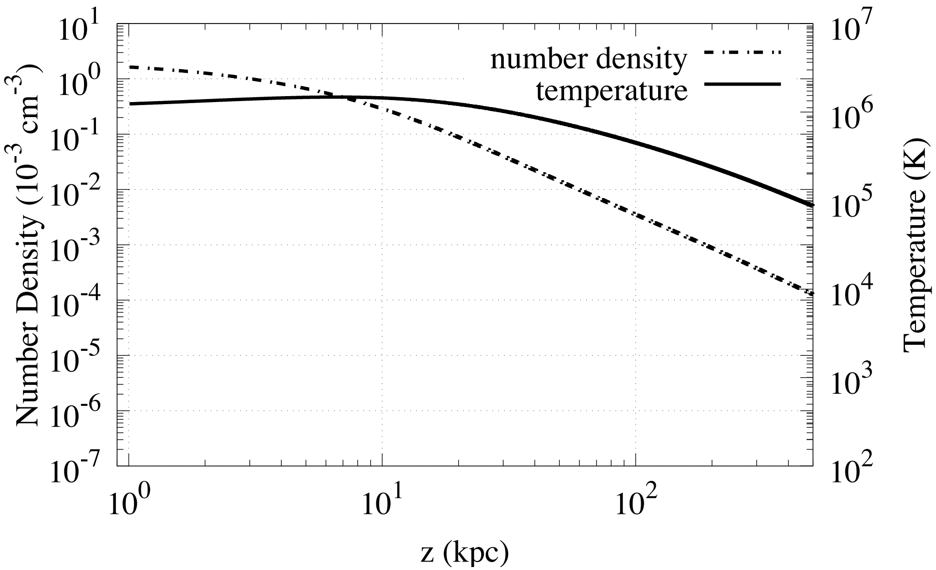
Wave dissipation: $L_w = V_A(dp_{cr}/dz)$
Radiative cooling: $n^2(\Gamma\text{-}\Lambda)$ = (collisional ionization equilibrium)





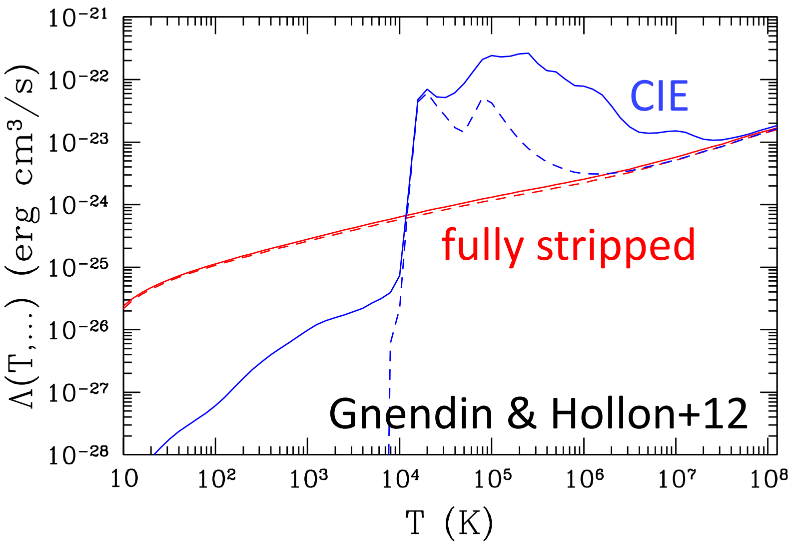
If we consider the collisional ionization equilibrium cooling function, there is no wind solution.

On Radiative Cooling Function



The wind is tenuous (~10^{-3} /cc) gas.

We should consider the photoionization and delayed recombination that may suppress the cooling rate.



We should explain the observed $N_{OVI} \sim 10^{14}$ cm^{-2} simultaneously.

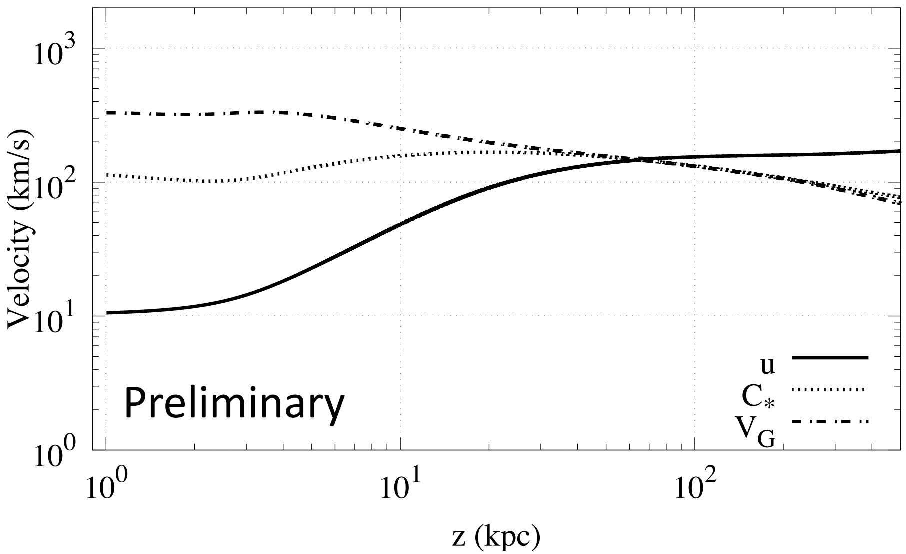
$$t_{\rm rec} \sim \frac{1}{nR_{\rm rec}} \sim 0.1\ {\rm Gyr} \left(\frac{n}{10^{-3}\ {\rm cm}^{-3}}\right)^{-1} \left(\frac{R_{\rm rec}}{10^{-13}\ {\rm cm}^3\ {\rm s}^{-1}}\right)^{-1}$$

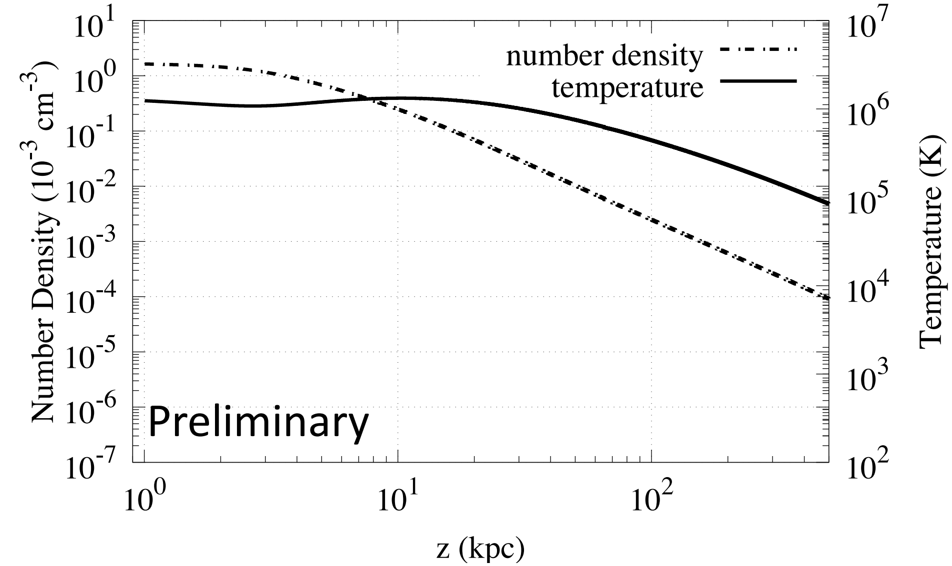
$$t_{\rm dyn} \sim \frac{L}{u} \sim 0.1\ {\rm Gyr} \left(\frac{u}{10\ {\rm km/s}}\right)^{-1} \left(\frac{L}{1\ {\rm kpc}}\right)$$

Effects of radiative cooling

Wave dissipation: $L_w = V_A(dp_{cr}/dz)$

Radiative cooling: $n^2(\Gamma\text{-}\Lambda)$ = (collisional equilibrium) **× 0.1**



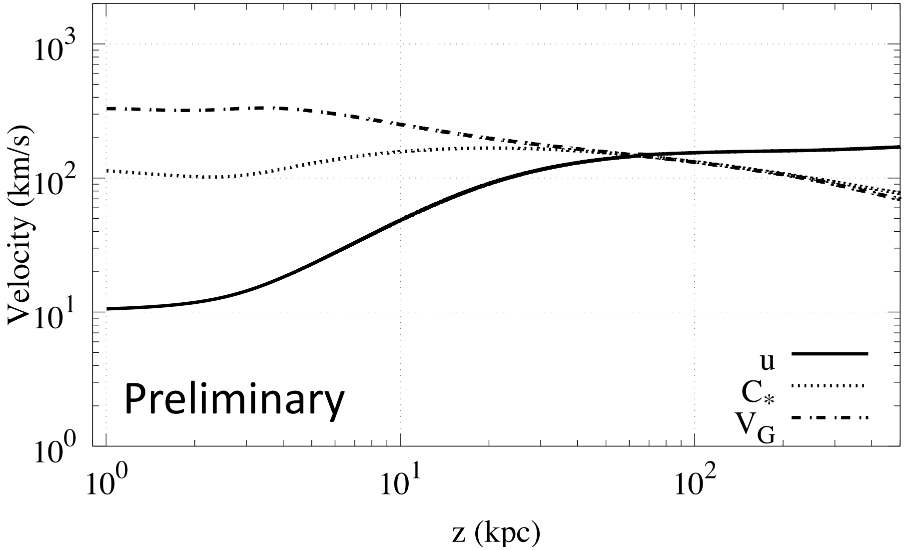


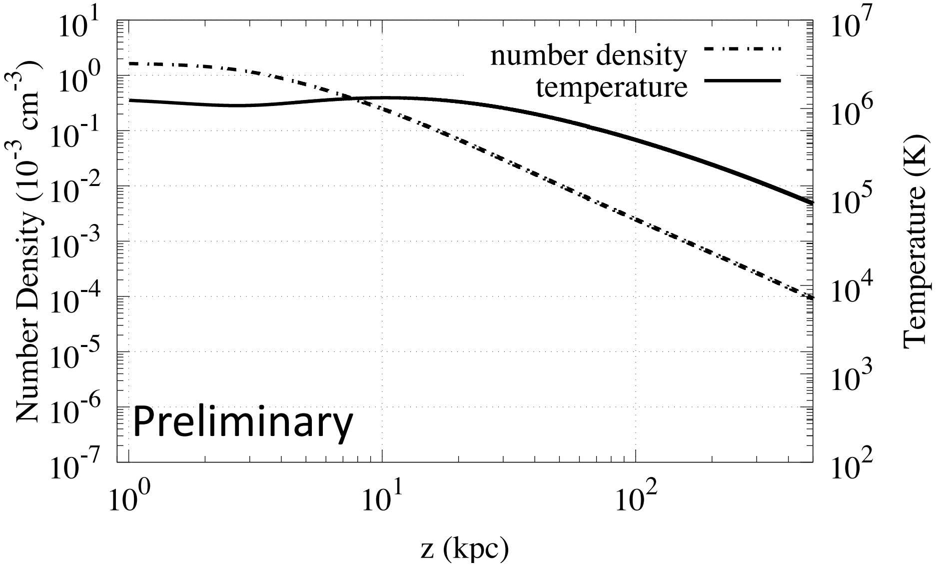
If we suppress the cooling function by a tenth, there is wind solution.

Effects of radiative cooling

Wave dissipation: $L_w = V_A(dp_{cr}/dz)$

Radiative cooling: $n^2(\Gamma\text{-}\Lambda)$ = (collisional equilibrium) $\times$ **0.1**



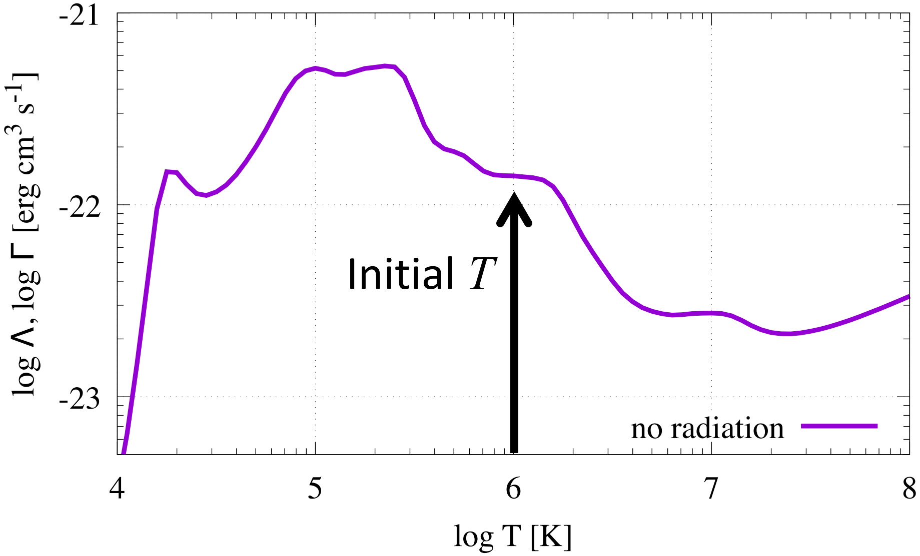


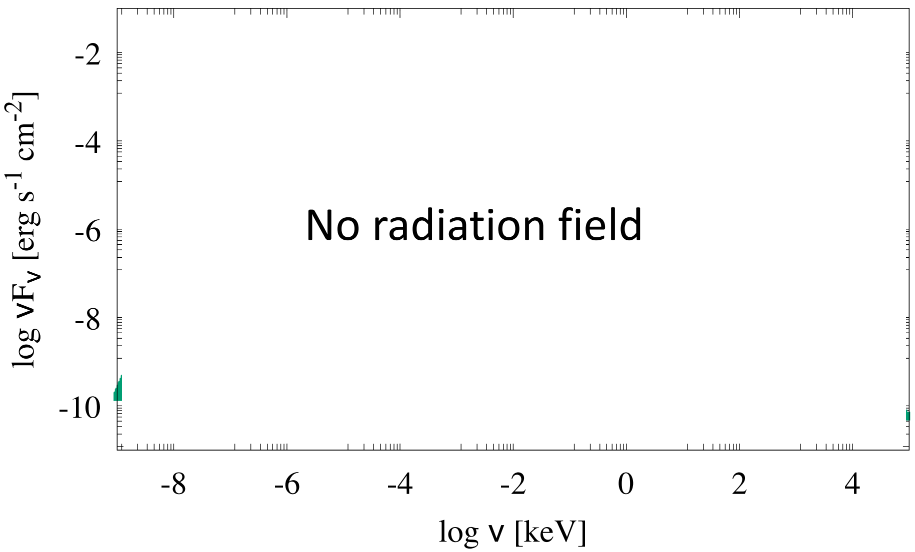
$$t_{\rm dyn} \sim \frac{L}{u} \sim 0.1\ {\rm Gyr} \left(\frac{u}{10\ {\rm km/s}}\right)^{-1} \left(\frac{L}{1\ {\rm kpc}}\right)$$

$\Lambda \sim 0.1\Lambda_{\rm CIE}$ may be required.

$$t_{\rm cool} \sim \frac{nkT}{n^2\Lambda} \sim 0.03\ {\rm Gyr} \left(\frac{n}{10^{-3}\ {\rm cm}^{-3}}\right)^{-1} \left(\frac{T}{10^6\ {\rm K}}\right) \left(\frac{\Lambda}{\Lambda_{\rm CIE}}\right)^{-1}$$

On Radiative Cooling Function



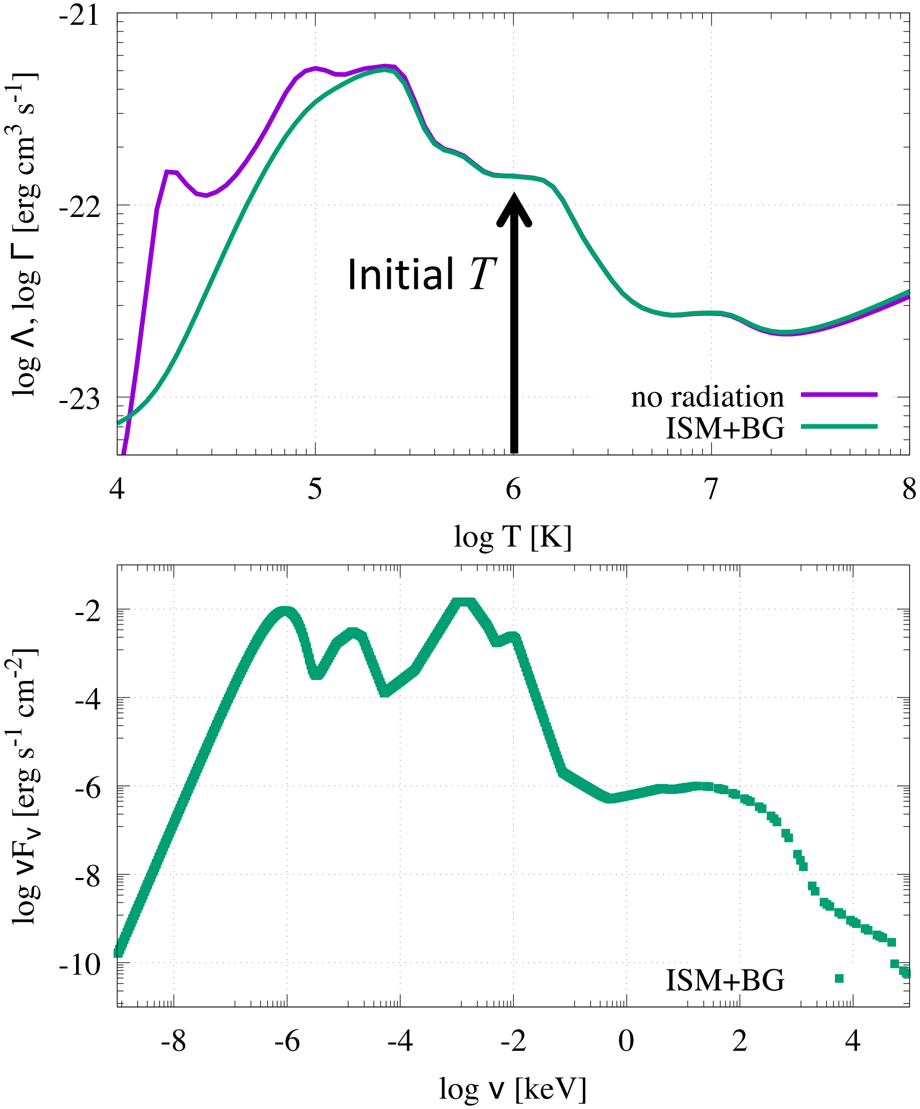


Radiation field: N/A

The cooling function corresponds to the CIE case.

The more gas cools, the more cooling function increases.

On Radiative Cooling Function

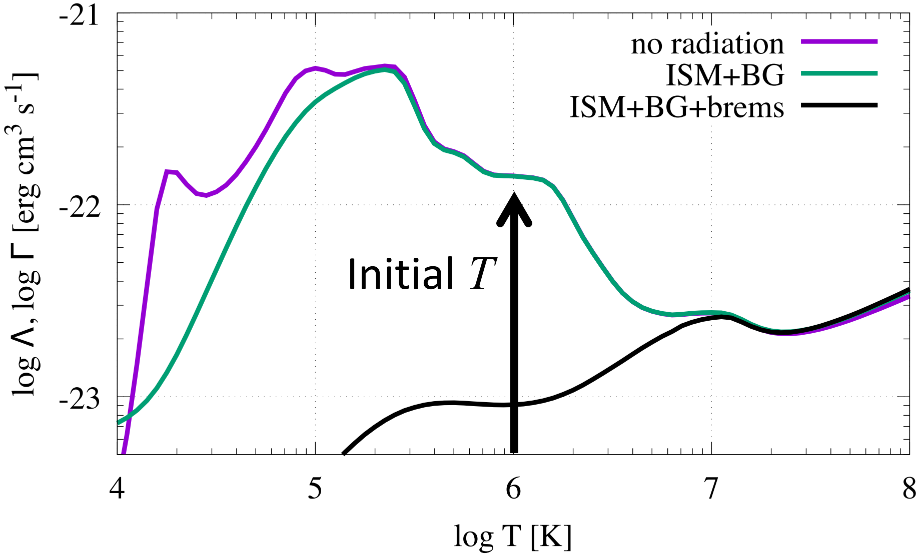


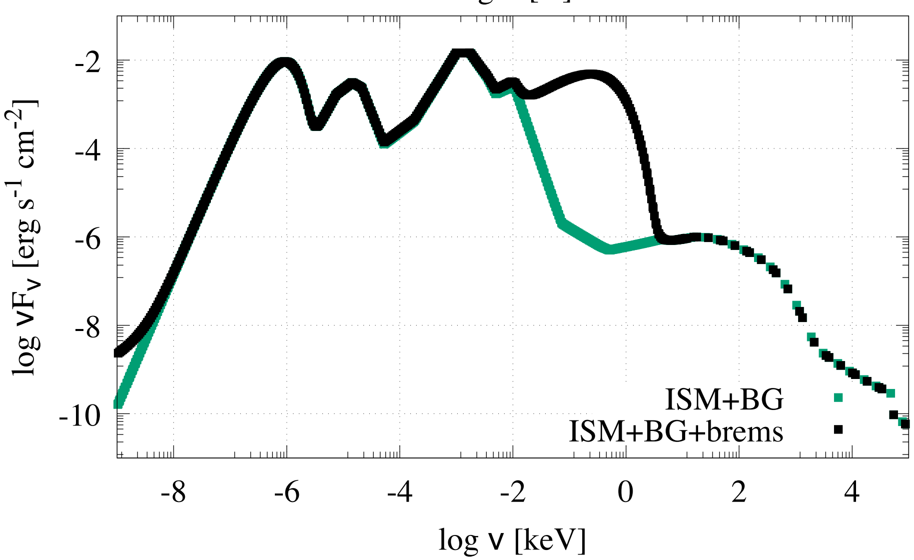
Radiation field:
ISM (Black 1987)
BG (Haardt & Madau 12)

The cooling function does not change at $T \sim 10^6$ K because of a lack of soft X-ray photons.

How many photons are required?

On Radiative Cooling Function





Radiation field:
ISM (Black 1987)
BG (Haardt & Madau 12)

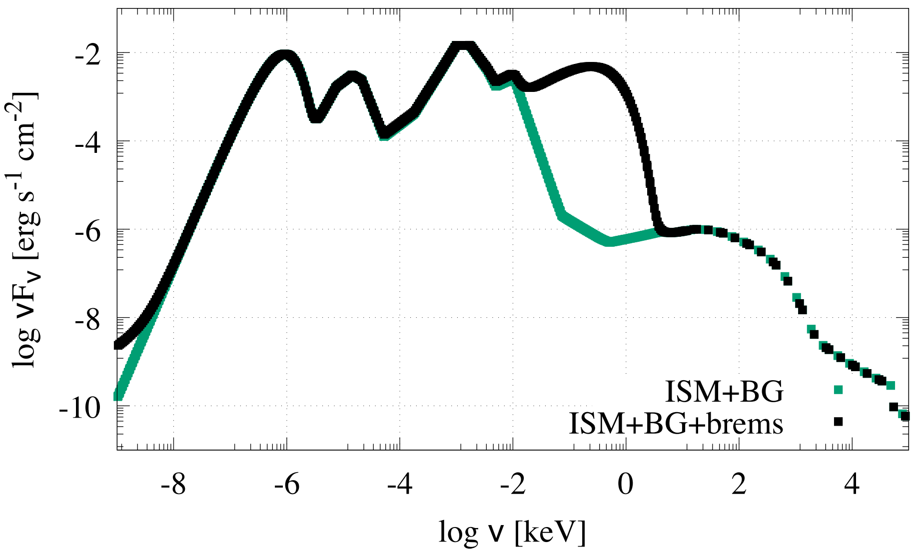
We require ~ 10^{-2} erg/s/cm^2 photons to suppress the cooling function.
→ supernovae?

On Radiative Cooling Function

$$L_{\mathrm{SN}} \sim 10^{42}\ \mathrm{erg/s}$$

$$V_{\mathrm{disk}} \sim 2\pi {R_{\mathrm{disk}}}^2 H_{\mathrm{disk}}$$

$$\nu F_\nu \sim \frac{\eta_X L_{\mathrm{SN}}}{V_{\mathrm{disk}}} H_{\mathrm{disk}} \lesssim 10^{-4} \eta_X\ \mathrm{erg/s/cm^{-2}} \left(\frac{R_{\mathrm{disk}}}{10\ \mathrm{kpc}}\right)^2 \left(\frac{H_{\mathrm{disk}}}{500\ \mathrm{pc}}\right)$$



The supernovae may not provide the required ionizing photons.

We are now studying other possibilities (other soft X-ray sources, effects of delayed recombination, etc…)

Summary

- Recent observations suggest that the CGM is main reservoir of gas.
- The mass exchange between the CGM and Galactic disk is invoked to maintain the star formation in MW.
- The Galactic wind may be responsible for the metal polluted gas of CGM with a scale height of 100 kpc.
- **We must derive how the gas cooling function is suppressed by a tenth compared with the case of CIE.**