Proposal of new Galactic magnetic field models and their observational test

Makoto Hattori
Astronomical Institute
Tohoku University
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Try to improve the accuracy of the component separation by maximally incorpolating physical understandings of foreground emission

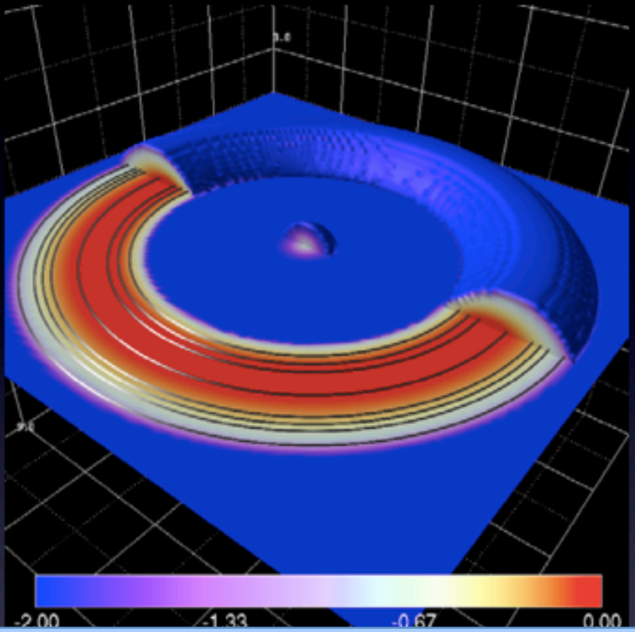
- Development of component separation scheme which is able to evaluate quantitatively on the systematics introduced by incorpolating the physics of the foregrounds (Morishima, Hattori)
- Theoretical modeling of the Galactic magnetic field
  - ◆Global MHD simulation (Nakamura, Hattori)
  - ◆Plasma kinetic approach of Galactic turbulent field modeling (Hattori, Fujiki)
- Revise the Galactic dust temperature and column density all sky map using AKARI FIR all sky survey data (Doi, Ootsubo, Morishima, Hattori et al.)

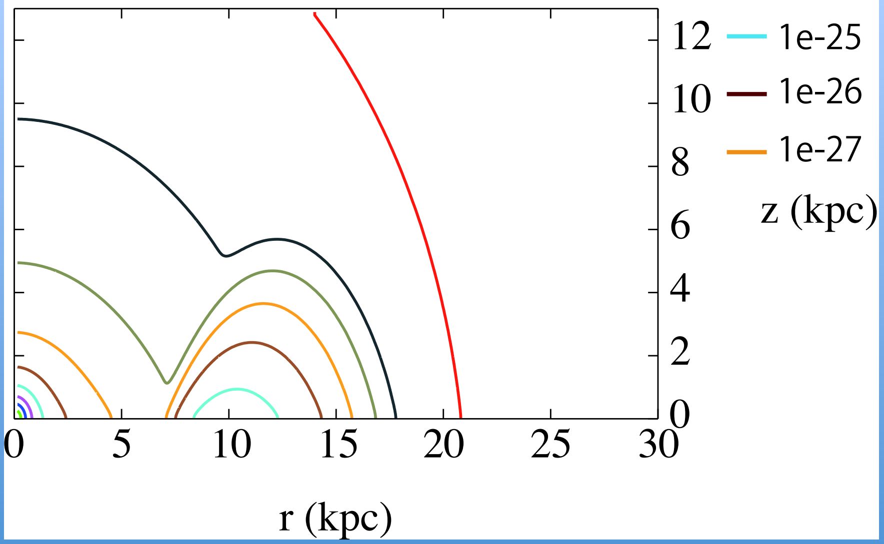
Start the calculation from Magneto-Hydrostatic equilibrium rotating gas disk which is solved stablely when no perturbation is set.

$$P_{\rm gas} = K\rho^{\Gamma}$$

$$\Psi_b \equiv \Phi(r_b) + \frac{C_{sb}^2}{\Gamma-1} + \frac{\Gamma}{2(\Gamma-1)} v_{Ab}^2 + \frac{L_z^2}{2r_b^2}$$

$$\rho = \left[\frac{\max\left(\Psi_b - \Phi - \frac{L_z^2}{2r^2},\ 0\right)}{\frac{\Gamma}{\Gamma-1}K\left\{1+\beta_b^{-1}(r/r_b)^{2(\Gamma-1)}\right\}}\right]^{\frac{1}{\Gamma-1}}$$

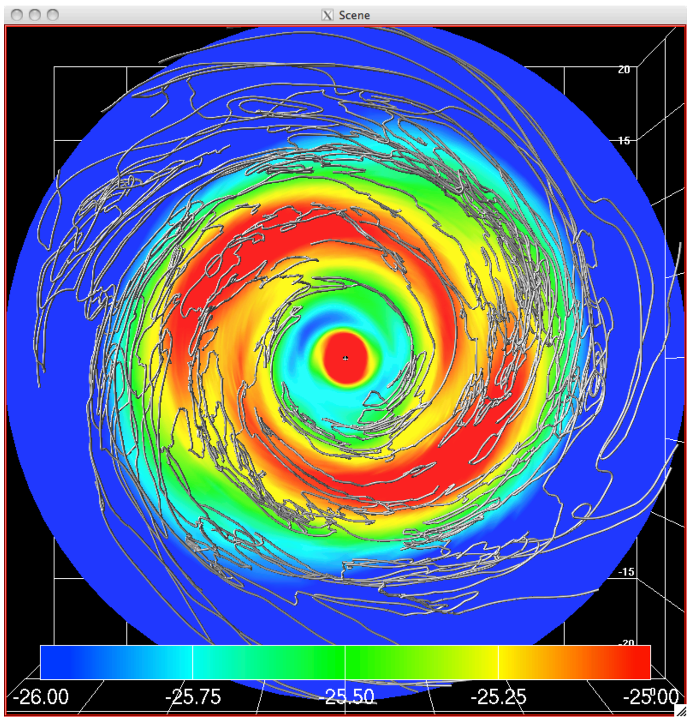


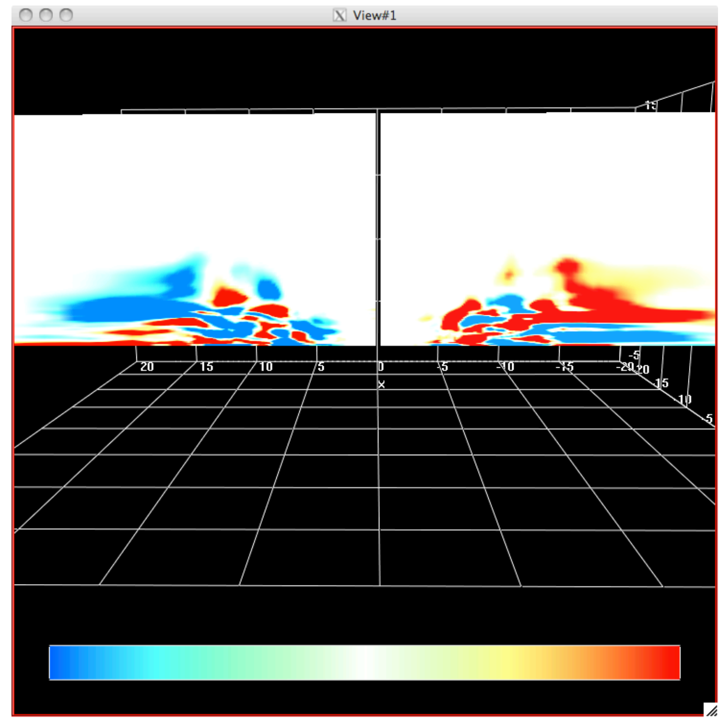


Initially Magneto-Hydrostatic equilibrium rotating gas disk stays initial states for 4Gyr (Nakamura, Hattori)

Results

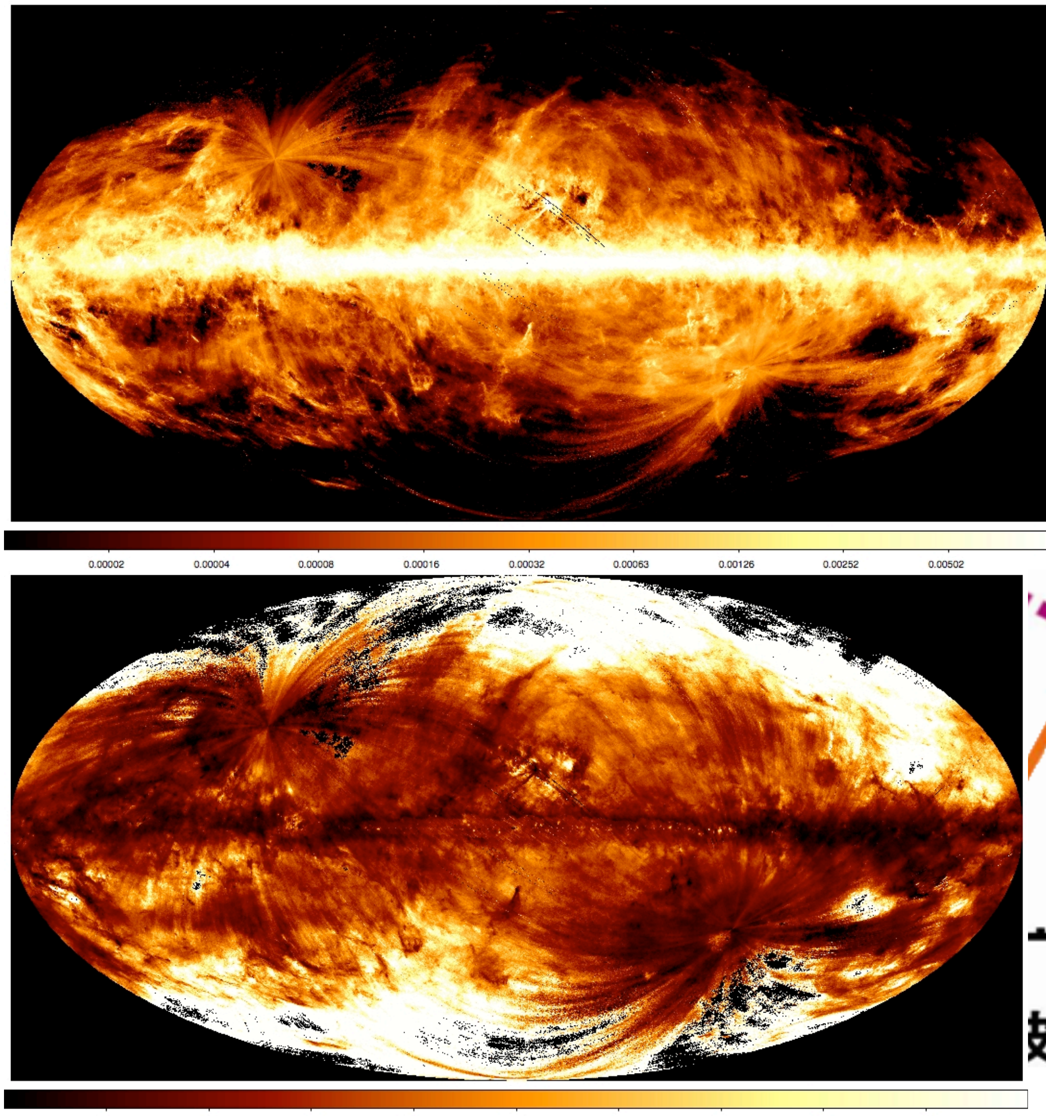
Results when the spiral potential with relative amplitude of 0.04 to disk potential is inserted as perturbation.





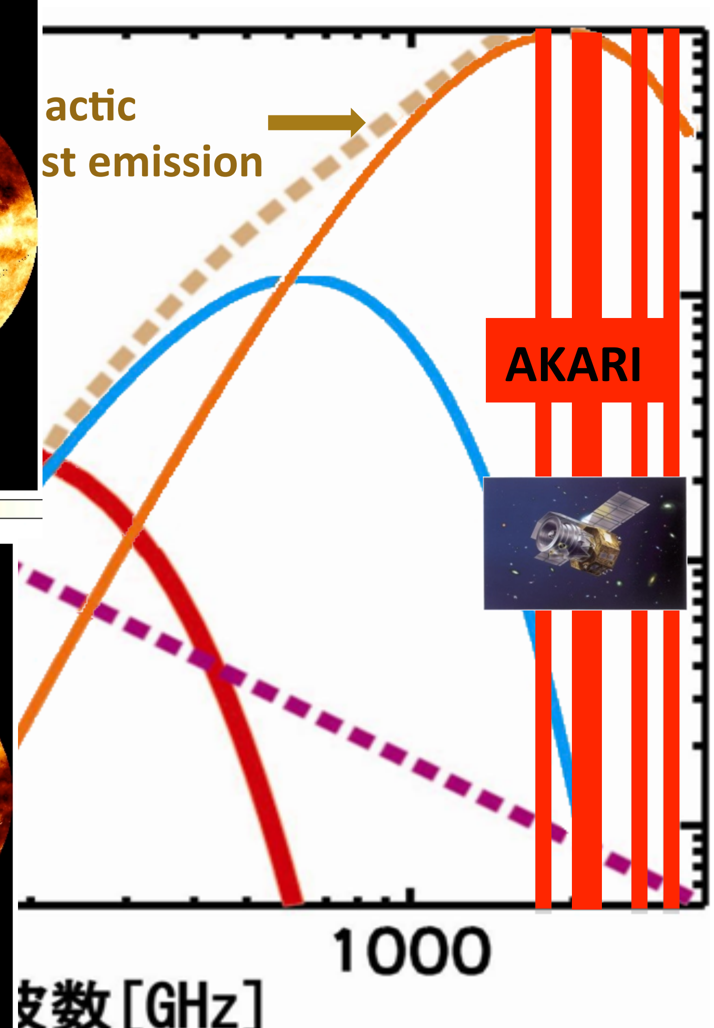
Now the radiative cooling is trying to taken into account in the simulation.
It is difficult to prevent the cooling infall of the halo gas.

Dust map made from AKARI all sky survey data

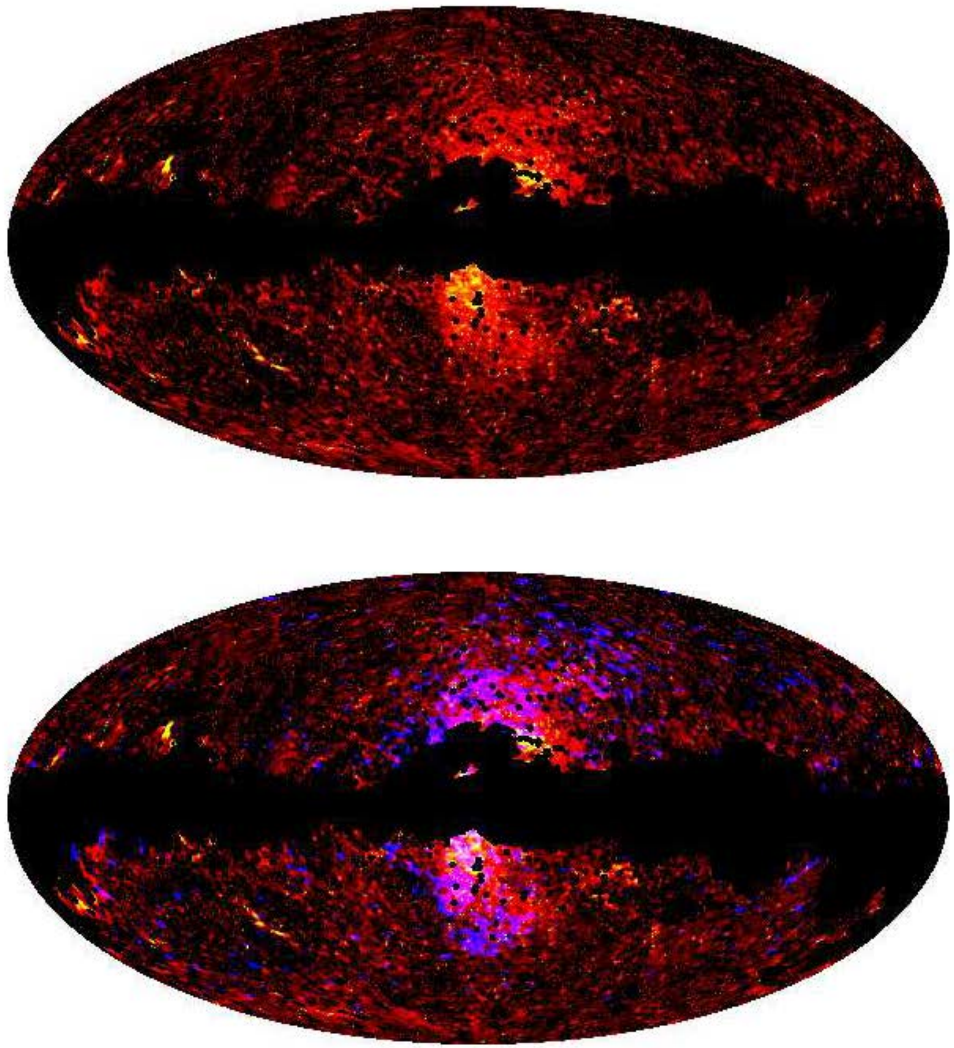


Doi, Ootsubo, et al. 2012

In µm 160, 140, 90, 60



Microwave Galactic Haze

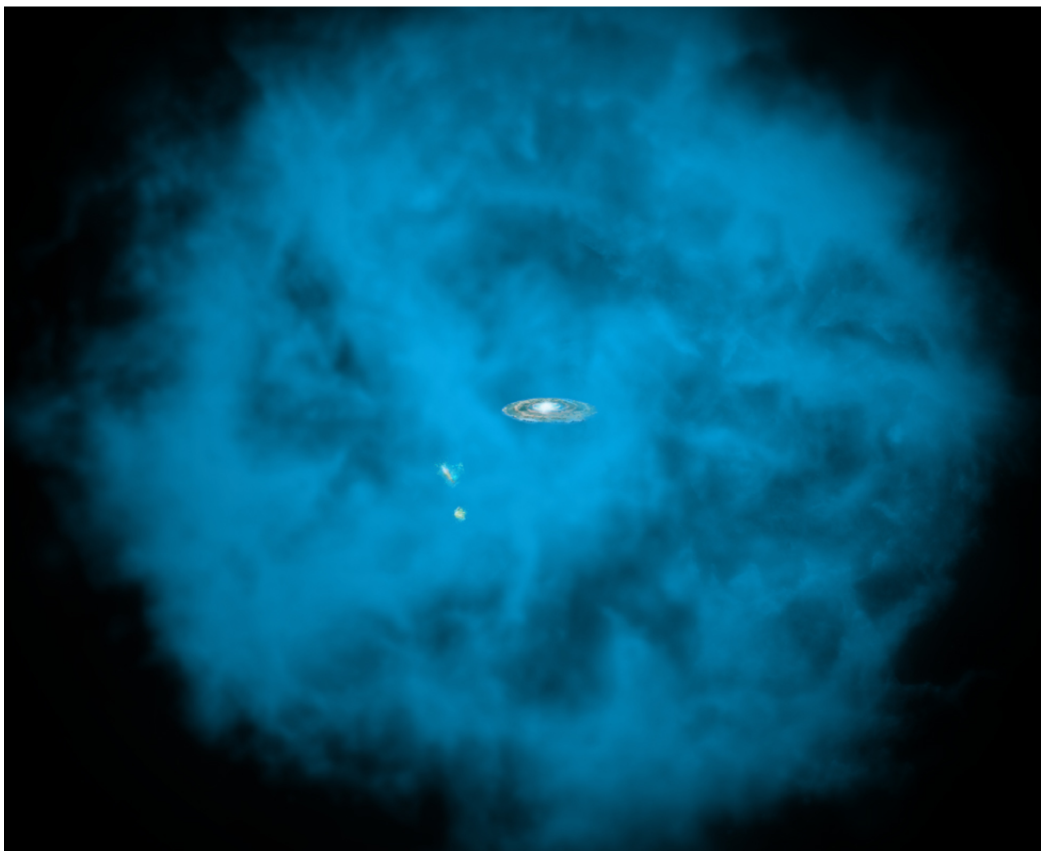


‘Planck intermediate results. IX. Detection of the Galactic haze with Planck’
Planck Collaboration (2012)

Galactic warm gaseous halo

Gupta,A., Mathur,S., Krongold,Y., Nicastro,F., Galeazzi,M., ApJ Lett., 756,L8(2012)

140kpc



$$n_e = 0.0002\mathrm{cm}^{-3}$$

$$T = (1.8 - 2.4) \times 10^6\,\mathrm{K}$$

Outline

- Existence of Temperature fluctuation in warm Galactic halo
- Magnetic waves are excited by plasma kinetic instability
- Interaction between relativistic electrons which cause Galactic synchrotron emission and excited magnetic waves result in Jitter radiation
- The spectrum of the Jitter radiation is possible to fit the spectrum of the Galactic Microwave Haze emission

Plasma kinetic instability in the plasma with temperature gradient

- grad T => finite heat conduction
- Heat conduction= electron kinetic energy flux

$$\langle \tfrac{1}{2}\, m\, v^2\, v \rangle \neq 0$$

➔ $\Delta f_e(v) = f_e(v) - f_m(v) \neq 0$;

$f_m(v)$ Maxwell-Boltzmann distribution

$$\frac{\partial f_e}{\partial t} + \vec{V} \cdot \vec{\nabla} f_e = -\nu (f_e - f_m); \qquad \nu = \frac{V_{the}}{\lambda_e}$$

Okabe, Hattori, ApJ, 599, 964(2003)

Basic elements

Boltzmann equation of electron velocity distribution

$$\frac{\partial f_e}{\partial t} + \vec{V} \cdot \vec{\nabla} f_e = -\nu (f_e - f_m);$$

Electron collision frequency

$$\nu = \frac{V_{th}}{\lambda_e}$$

V_{th} :Electron thermal velocity

λ_e :Electron collision mean free path

We consider the scale much less than the mean free path in the following discussion

$$\lambda_e = 2\mathrm{pc} \left(\frac{T_e}{3 \times 10^6 \mathrm{K}} \right)^2 \left(\frac{n_e}{10^{-2} \mathrm{cm}^{-3}} \right)^{-1}$$

Estimation of Δf: Chapman-Enskog expansion

$$\varepsilon = \frac{\lambda_e}{L}, \qquad L = \left|\frac{T}{\nabla T}\right|, \qquad \delta_T = \frac{\Delta T}{T}; \quad \varepsilon\delta_T$$ expansion coefficient

The first order in $\varepsilon\delta_T$

$$\Delta f_e = \varepsilon\delta_T \frac{V_\parallel}{V_{th}}\left(\frac{5}{2} - \frac{V^2}{V_{th}^2}\right),$$ $V_\parallel$;electron velocity component along temperature gradient

Estimation of Δf: physical approach

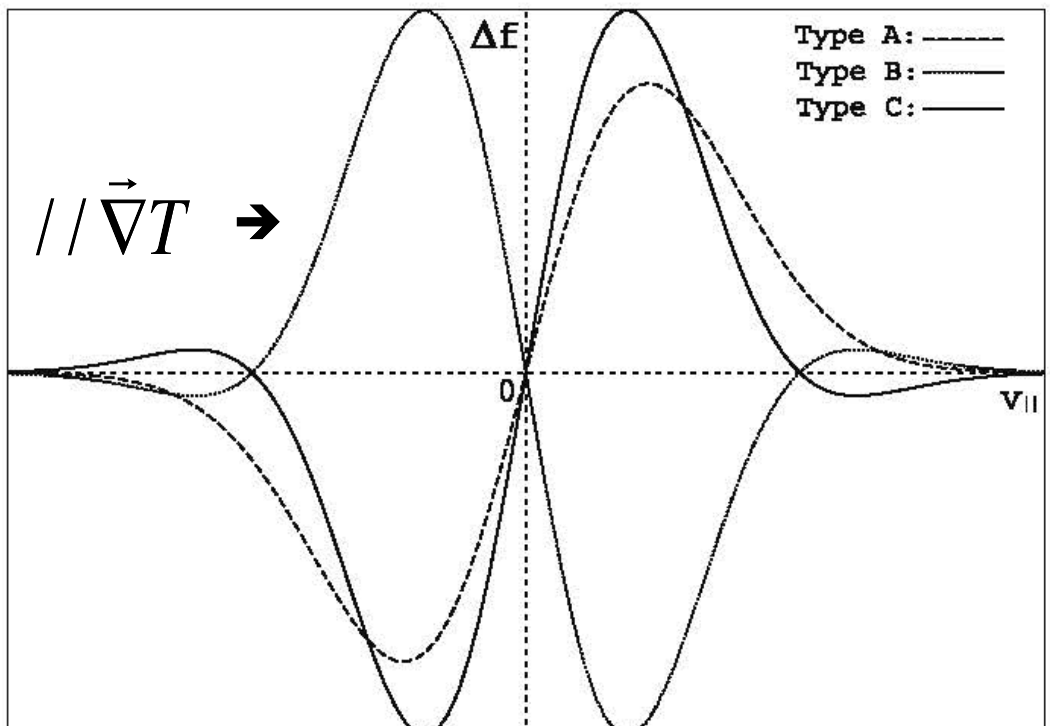
$\langle \Delta f \rangle = 0$: conservation of electron number ➔ odd function of V

$\langle \frac{1}{2} m v^2 \ \Delta f \rangle = 0$: energy conservation ➚

$\langle V \Delta f \rangle = 0$: zero electric current condition ➔ Type A is rejected

$\langle \frac{1}{2} m v^2 v_z \rangle < 0$ when $dT/dz > 0$ ➔ Type C is remained

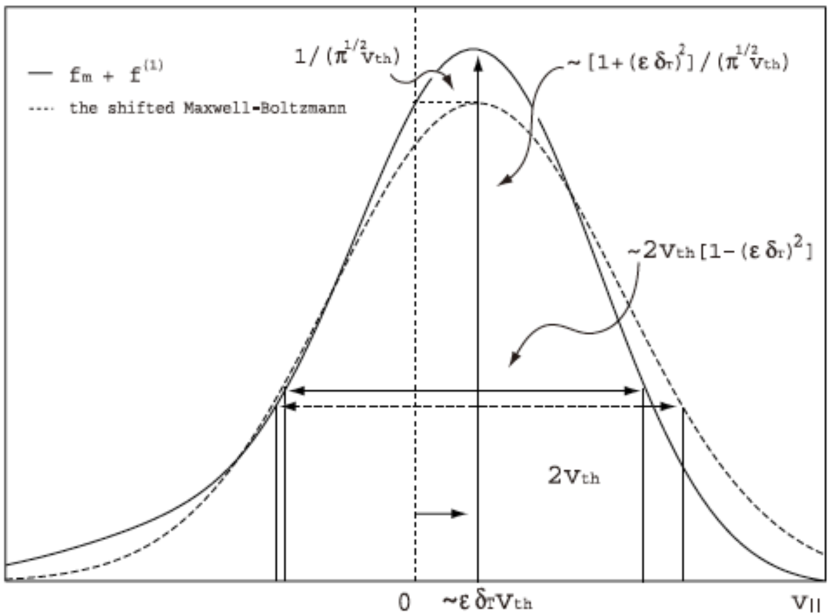
$// \vec{\nabla} T$ ➔



Mechanism of the instability

Total velocity distribution function

direction of the grad T : ➔



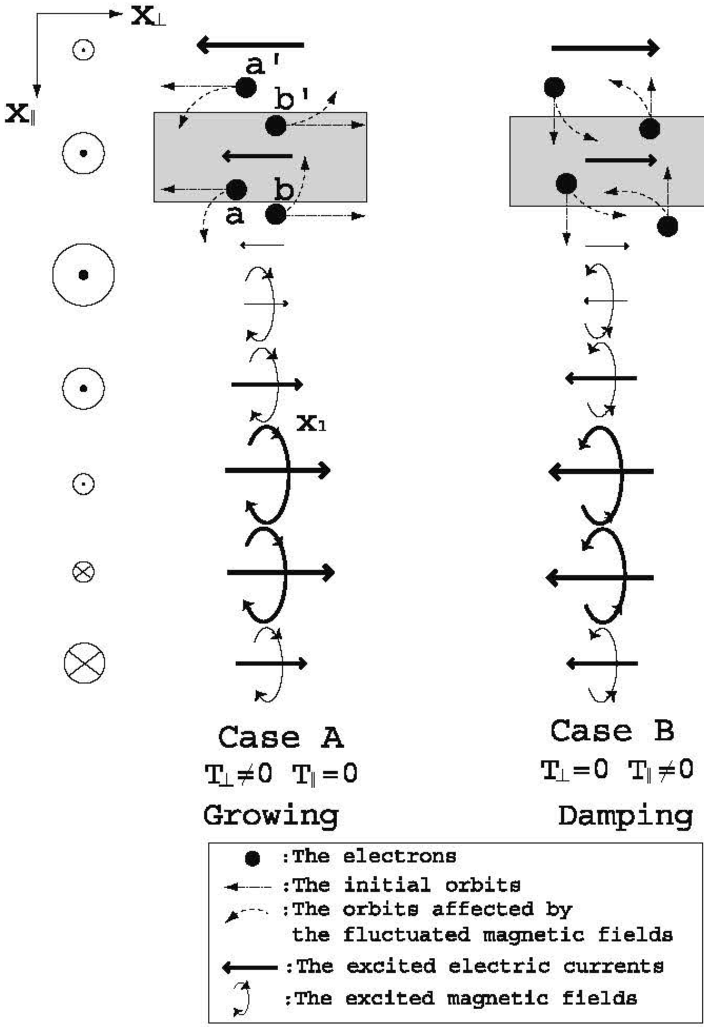
- the peak position shift by $\varepsilon\delta_T V_{th}$
- The peak value is increased by $(1+(\varepsilon\delta_T)^2)$
- Width in the grad T direction becomes thinner by $(1-(\varepsilon\delta_T)^2)$

The effective temperature in the grad T direction becomes lower by a factor of $(1-(\varepsilon\delta_T)^2)$ relative to the temperature of other directions :
anisotropic temperature distribution

For the comoving observer with the wave propagate in the direction of grad T with the phase velocity of $\varepsilon\delta_T V_{th},$ the plasma is observed as temperature anisotropy plasma.

The dispersion relation; $$\omega_r = \frac{\varepsilon\delta_T}{4}kV_{th}; \quad \omega_i = \frac{\varepsilon^2\delta_T^2}{8\sqrt{\pi}}kV_{th} - \frac{1}{\sqrt{\pi}}\left(\frac{c}{\omega_{pe}}\right)^2 k^3 V_{th}$$

Mechanism of the instability



The growth rate of the Weibel instability

$$\gamma \approx V_{th}\left[\left(\frac{T_\perp}{T_\parallel}-1\right)k-\left(\frac{c}{\omega_{pe}}\right)^2 k^3\right];$$

$T_\parallel$: temperature // to $\vec{k}$;

$T_\perp$: temperature $\perp$ to $\vec{k}$

$\vec{k} \perp \vec{\nabla} T : T_\parallel > T_\perp$ Stable; damping mode

$\vec{k} \,//\, \vec{\nabla} T : T_\parallel < T_\perp$ Unstable; the fastest growing mode

The wavelength of the fastest growing mode

$$k_{\max}^{-1} = \left[\frac{\varepsilon\delta_T}{2\sqrt{2}}\left(\frac{\omega_{pe}}{c}\right)\right]^{-1}$$

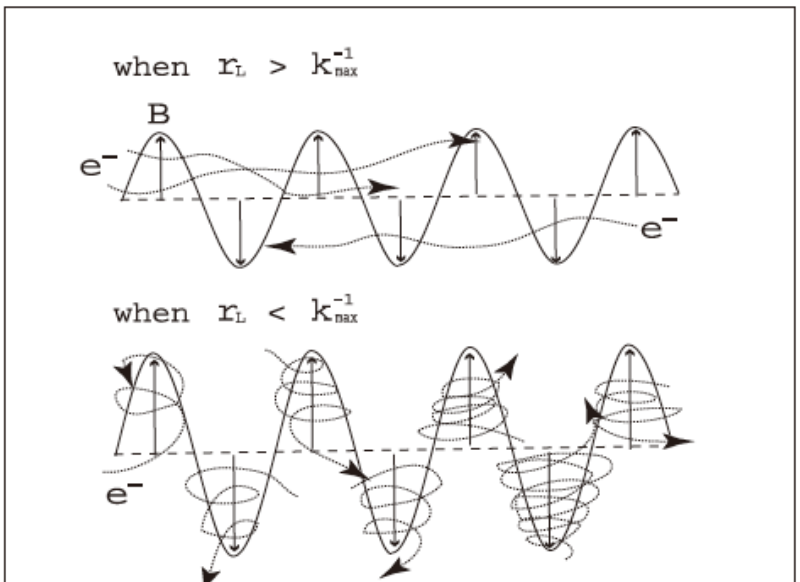
$$\approx 1.5\times10^7\,\mathrm{cm}\left(\frac{n_e}{0.01\mathrm{cm}^{-3}}\right)^{-0.5}\left(\frac{\varepsilon\delta_T}{1.0}\right)^{-1} << \lambda_e$$

The growth time of the fastest growing mode

$$\gamma_{\max}^{-1} = \left[\frac{(\varepsilon\delta_T)^3}{8\sqrt{2\pi}}\left(\frac{\omega_{pe}}{c}\right)V_{th}\right]^{-1} \approx 0.2\sec\left(\frac{n_e}{0.01\mathrm{cm}^{-3}}\right)^{-0.5}\left(\frac{T_e}{3\times10^6 K}\right)^{-0.5}\left(\frac{\varepsilon\delta_T}{1.0}\right)^{-3}$$

Nonlinear saturation level

When thermal electrons are trapped by excited magnetic field, the growth of the waves could be stopped



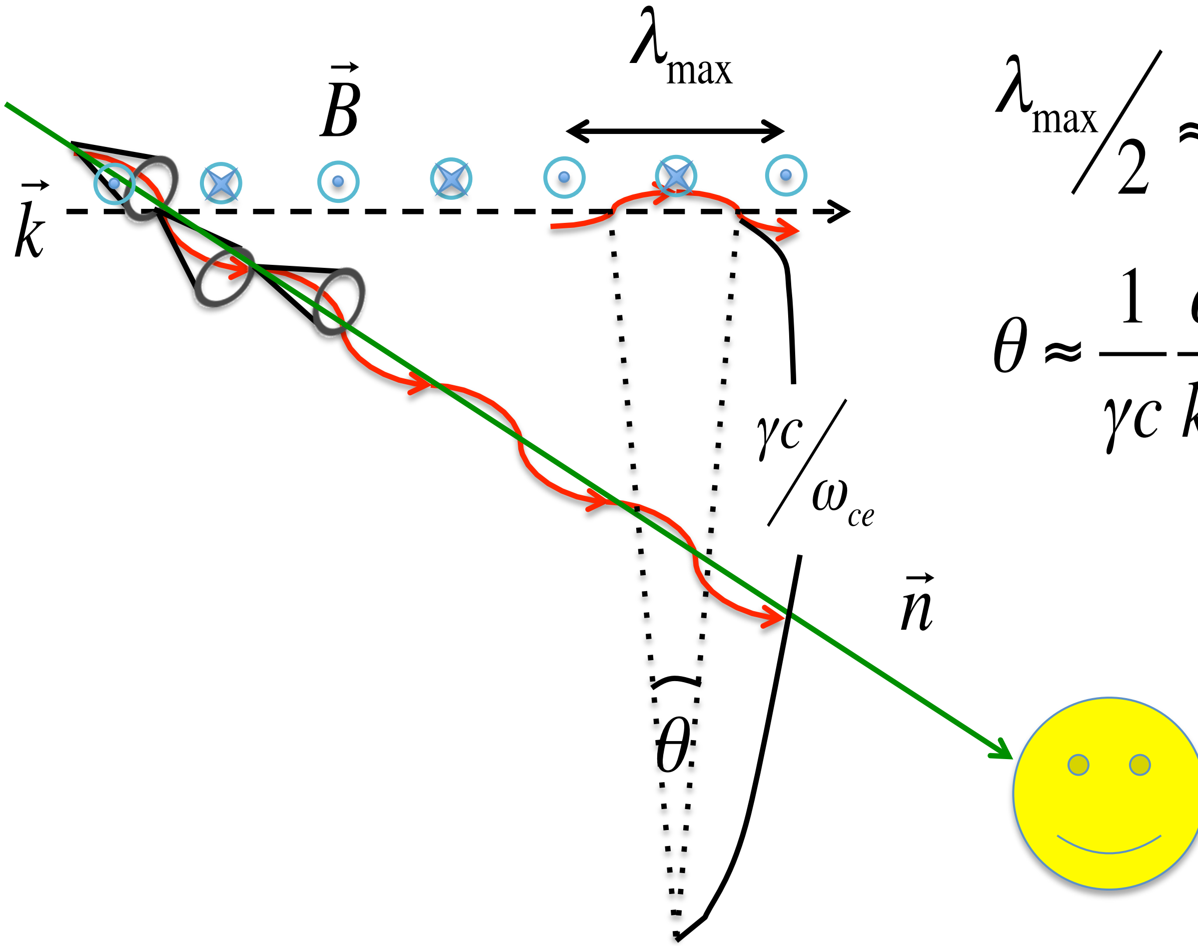
$$\frac{V_{th}}{\omega_{ce}} \approx \frac{1}{k_{max}}$$

$$\omega_{ce} = 54\mathrm{Hz}\left(\frac{B_{satu}}{3\mu\mathrm{G}}\right)$$

: electron cycrotron frequency

$$\beta_{satu} = \left(\frac{3n_e k_B T}{B_{satu}^2 / 8\pi}\right) = 50\left(\frac{\varepsilon\delta_T}{1.0}\right)^{-2}$$

Jitter radiation from the Weibel turbulence

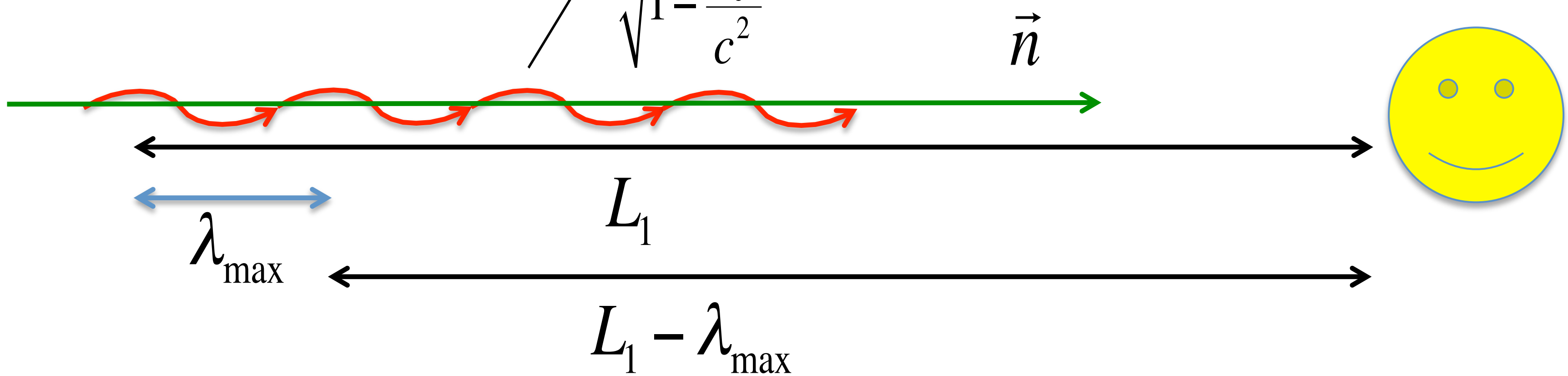


$$\lambda_{\max}/2 \approx \left(\gamma c / \omega_{ce}\right)\theta,$$

$$\theta \approx \frac{1}{\gamma c}\frac{\omega_{ce}}{k_{\max}} \approx \frac{1}{\gamma}\frac{V_{th}}{c} << 1$$

Jitter radiation from the Weibel turbulence

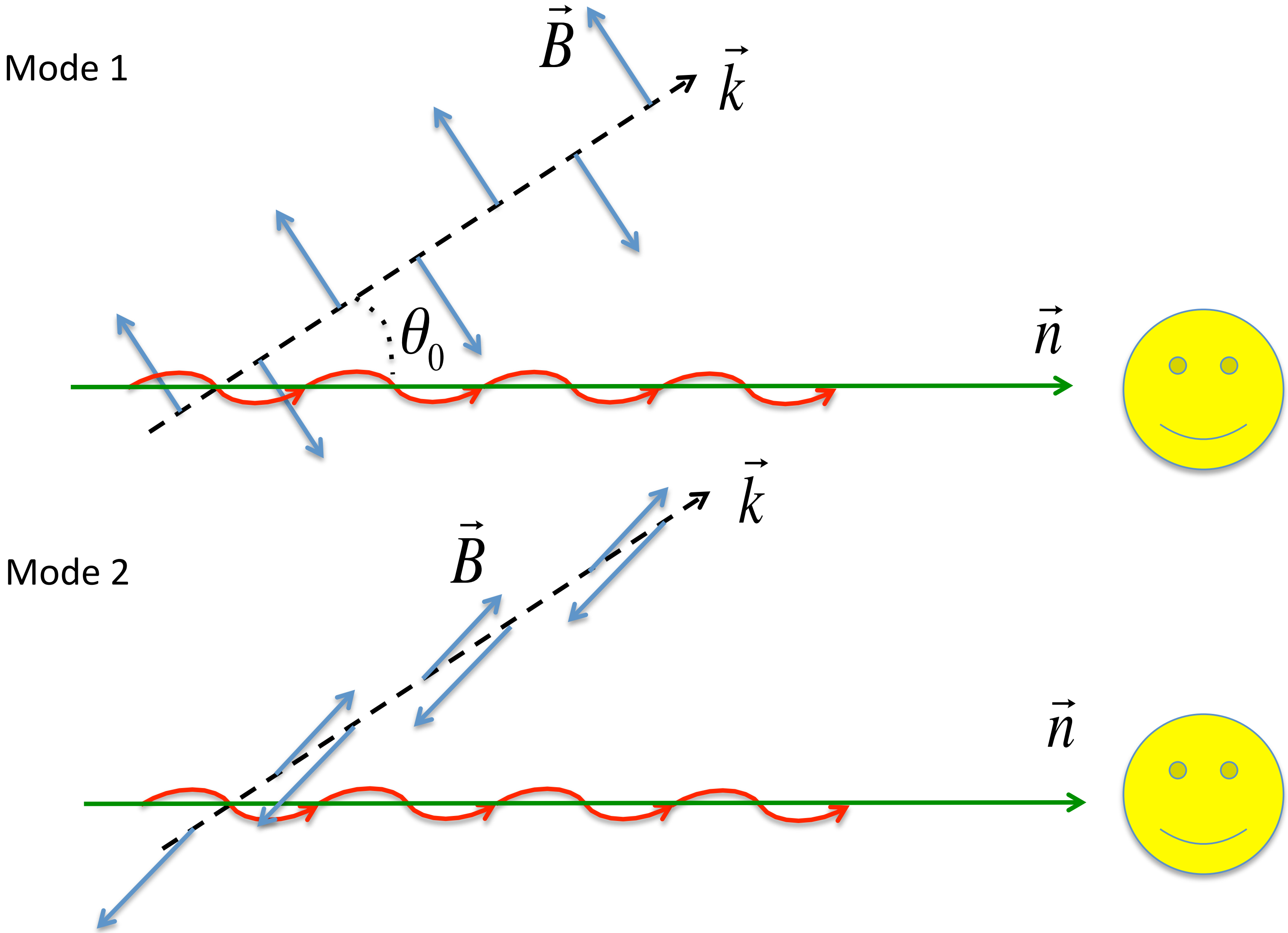
V_0 : electron velocity, $\gamma = 1 \Big/ \sqrt{1 - \frac{V_0^2}{c^2}}$



$$\nu_{obs} \approx 2\gamma^2 k_{\max} c / 2\pi \approx \gamma^2 \varepsilon \delta_T \omega_{pe} / 2\pi \approx 1000\mathrm{Hz}\ \gamma^2 \left(\frac{n_e}{0.01\mathrm{cm}^{-3}} \right)^{0.5} \left(\frac{\varepsilon \delta_T}{1.0} \right)$$

$$\nu_{sync} \approx 0.45 \gamma^2 \omega_{ce} / 2\pi \approx 4\mathrm{Hz}\ \gamma^2 \left(\frac{B}{3\mu\mathrm{G}} \right)$$

Jitter radiation from two independent modes



The spectrum of the Jitter radiation

$N_e(\gamma) = C_p \gamma^{-p}$: number density of the electron with Lorentz factor of γ

$$I_{Jitter}(\nu) = \frac{1}{2}\frac{e^2}{c}\frac{\omega_{ce,W}^2}{\omega_0} C_e \left(\frac{2\pi\nu}{\omega_0}\right)^{-\frac{p-1}{2}} \frac{2(p^2+4p+11)}{(p+1)(p+3)(p+5)}; \quad \omega_0 = 2\vec{k}_{\max}\cdot\vec{V}_0$$

$\omega_{ce,W}$: cycrotron frequency due to the magnetic field excited by the Weibel instability

$I_{Sync}(\nu)$: specific intensity of the synchrotron emission due to ordered magnetic field

$$\frac{I_{Jitter}}{I_{Sync}} \approx \varepsilon\delta_T \left(\frac{\beta_0}{6}\right)^{0.5} \left(\frac{V_{th}}{c}\right)^{\frac{3-p}{2}} O(1) \qquad \beta_0 = \frac{3n_e k_B T}{B_0^2/8\pi}$$

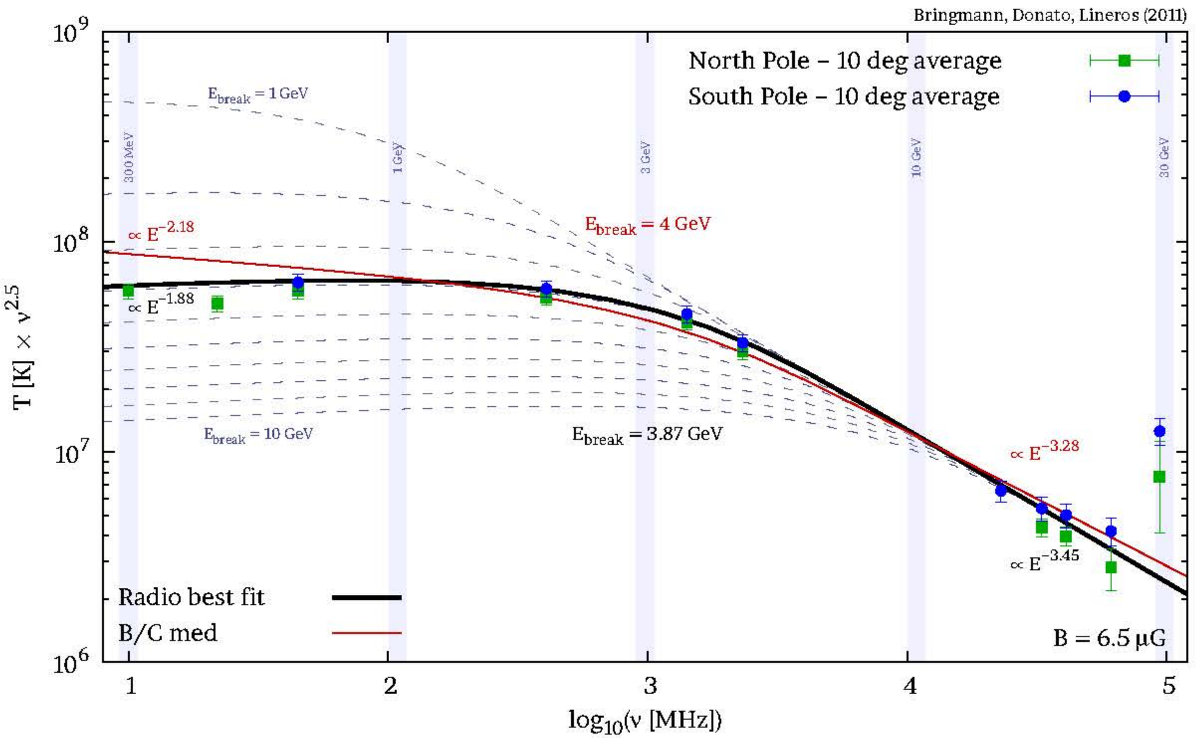
The plasma beta of the back ground plasma.
← Magnetic energy of the ordered magnetic field.

$$p<3:\ I_{Jitter}(\nu) < I_{Sync}(\nu),$$

$$p>3:\ I_{Jitter}(\nu) > I_{Sync}(\nu) \quad \text{when } \varepsilon\delta_T \approx 1$$

Galactic relativistic electron energy spectrum model

Bringmann, Donato, Lineros arXiv:1106.4821v2 (2012)
de Oliveira-Costa etal., MNRAS, 388, 247-260 (2008)



Broken spectrum:

$$N_e(\gamma) = C_p \gamma^{-p} : \gamma_1 < \gamma < \gamma_2$$

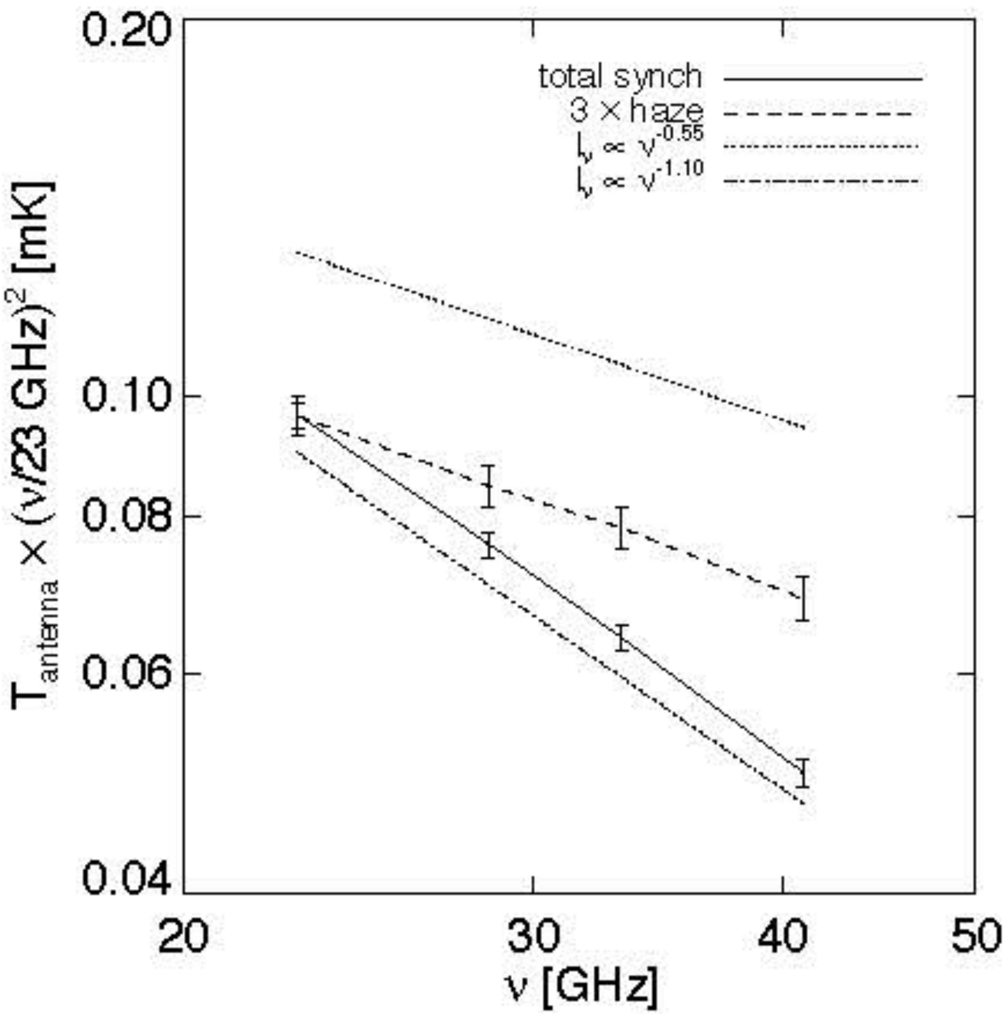
$$= C_q \gamma^{-q} : \gamma_2 < \gamma < \gamma_3$$

where $C_q = C_p \gamma_2^{q-p}$,

$q \approx 3.2$ and $p \approx 2$.

$$T_{Sync}(100\mathrm{MHz}) = 5 \times T_{Sync}(23\mathrm{GHz}) \left(\frac{0.1\mathrm{GHz}}{23\mathrm{GHz}} \right)^{\frac{p+3}{2}}$$

Galactic relativistic electron energy spectrum model



$$T_{Sync}(23\mathrm{GHz}) = 0.098\mathrm{mK}$$

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Galactic warm gaseous halo

Gupta,A., Mathur,S., Krongold,Y., Nicastro,F., Galeazzi,M., ApJ Lett., 756,L8(2012)

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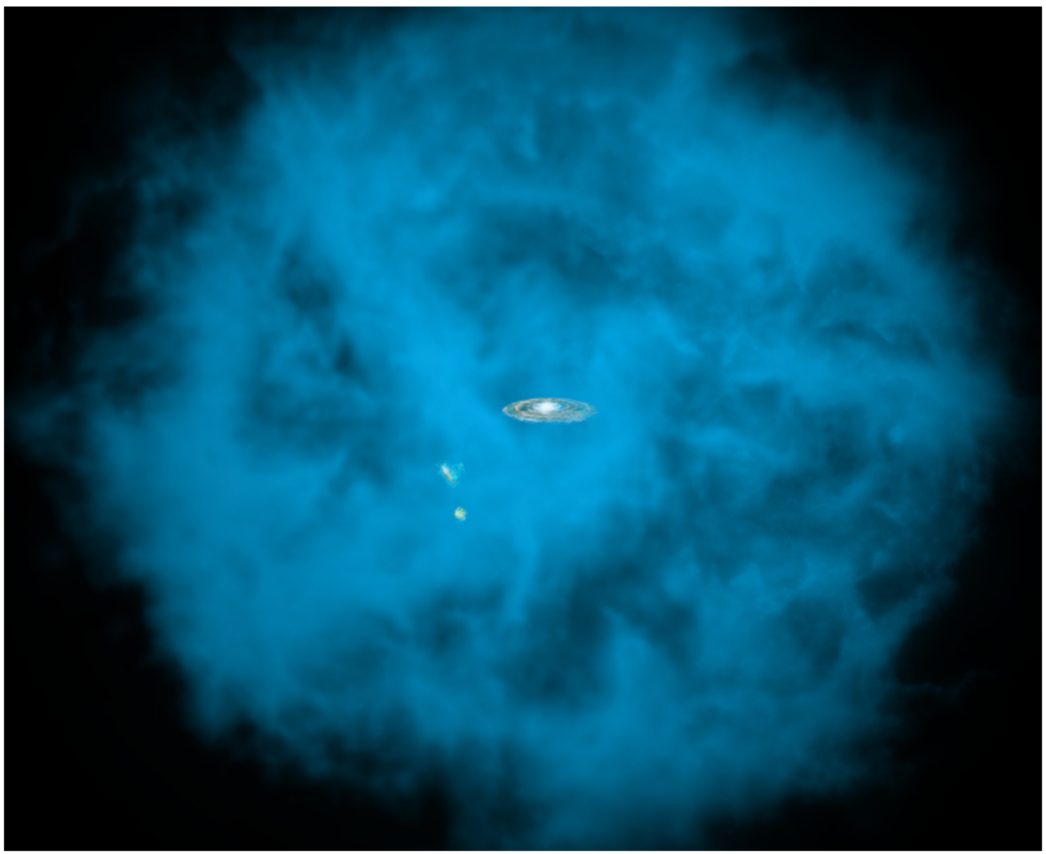


$n_e = 0.0002\mathrm{cm}^{-3}$

$T = (1.8 - 2.4) \times 10^6\,\mathrm{K}$

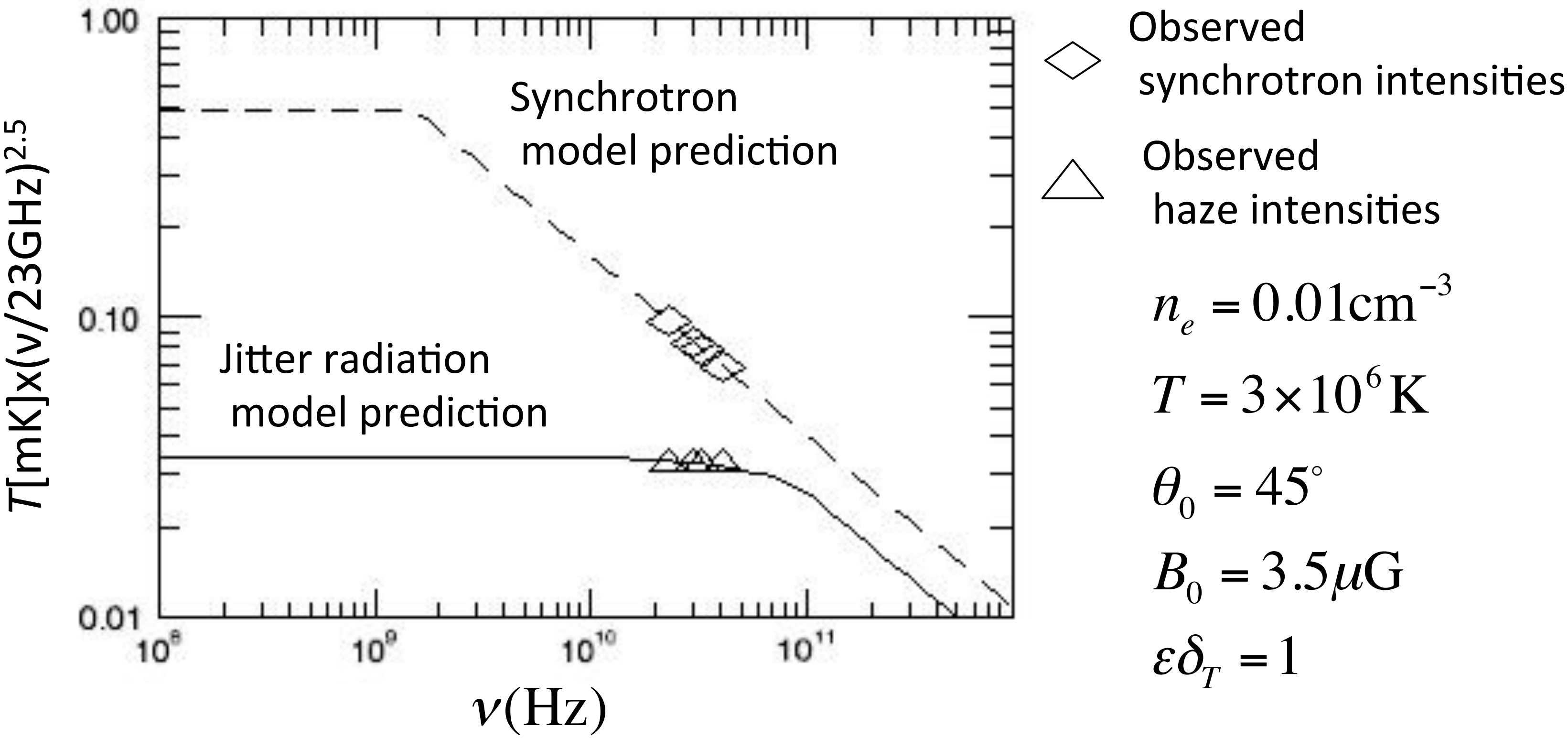
$\lambda_e \approx 50\mathrm{pc}$

$\varepsilon\delta_T \approx 1 \rightarrow$

temperature fluctuation in the scale less than λ_e with 100% volume filling factor

Concentration of the warm gas at the central region of the Galaxy is plausible.
So we assume n_e=0.01cm^{-3} at the central region, that is haze region, of the Galaxy.

Predicted spectrum of the Jitter radiation from the Weibel turbulence



$$n_e = 0.01\mathrm{cm}^{-3}$$

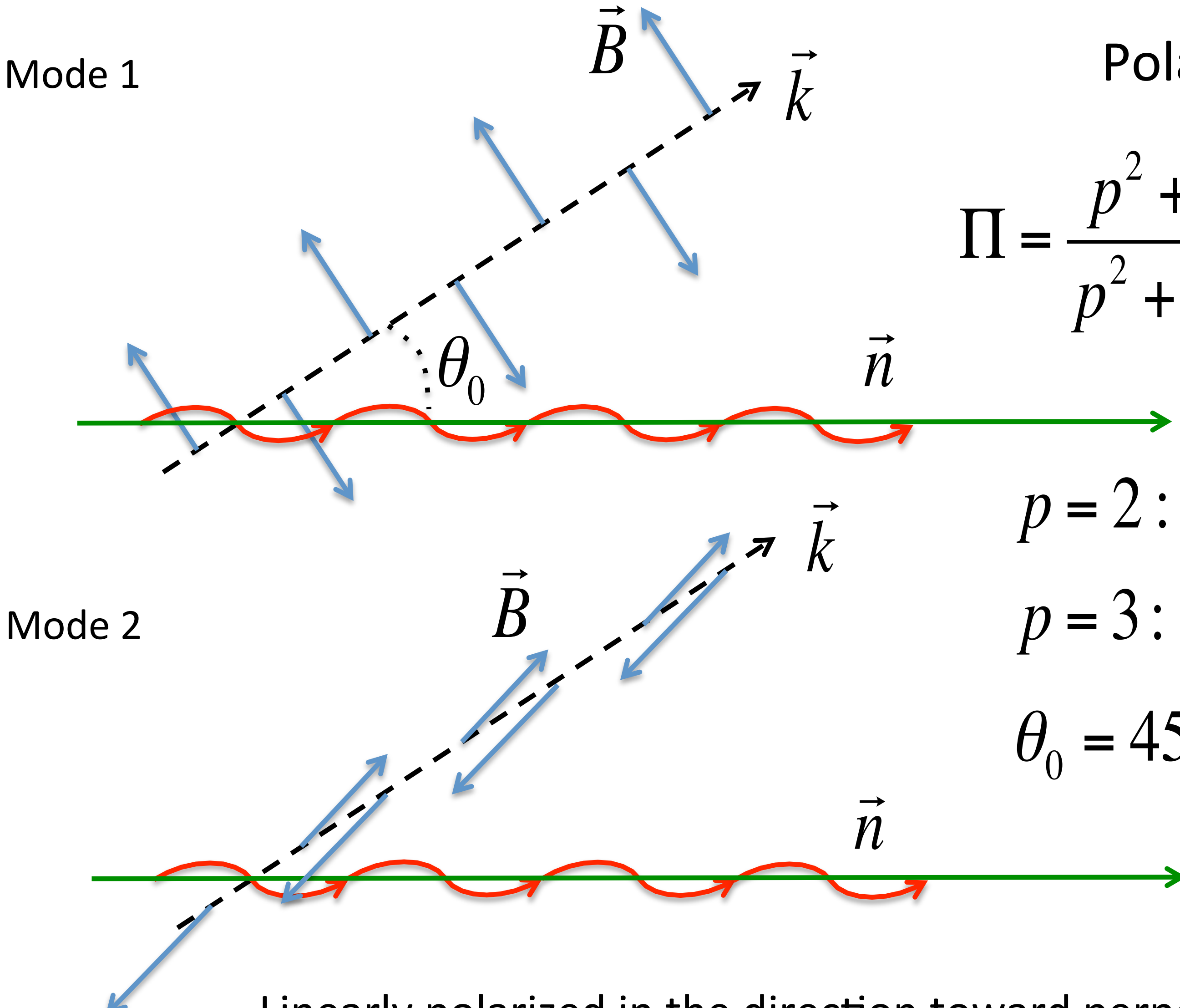
$$T = 3\times10^6\mathrm{K}$$

$$\theta_0 = 45^\circ$$

$$B_0 = 3.5\mu\mathrm{G}$$

$$\varepsilon\delta_T = 1$$

Polarization of the Jitter radiation



Polarization degree

$$\Pi = \frac{p^2+4p-1}{p^2+4p+11}\frac{1-\cos^2\theta_0}{1+\cos^2\theta_0}$$

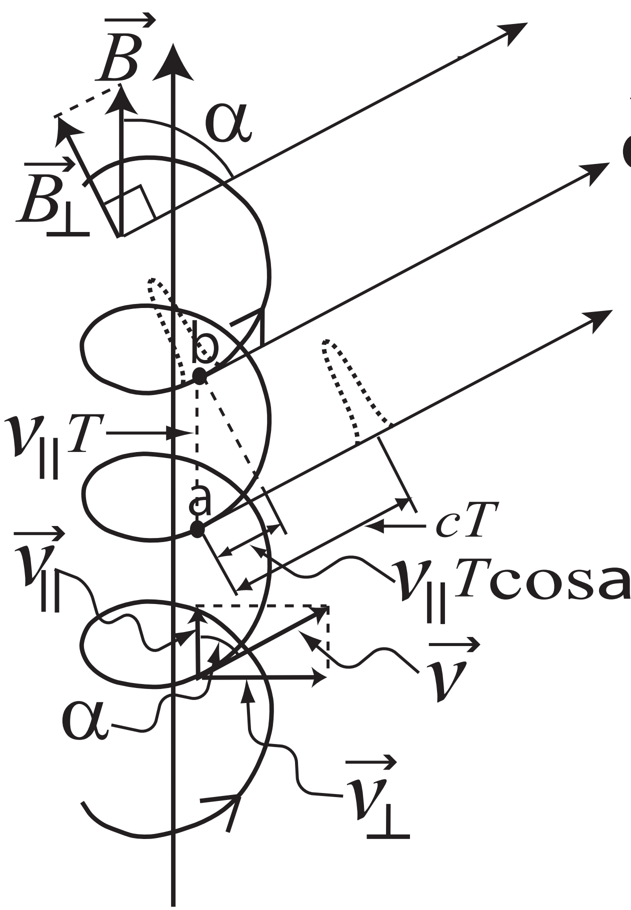
$$p=2:\ \Pi=0.16$$

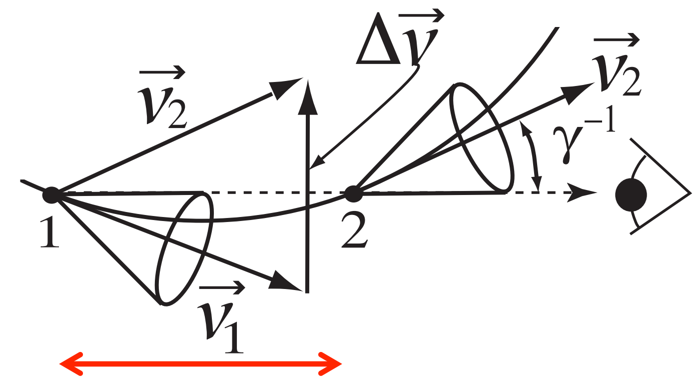
$$p=3:\ \Pi=0.21$$

$$\theta_0=45^\circ$$

Linearly polarized in the direction toward perpendicular to the plane spanned by line-of-sight and grad T.

Effect of ordered magnetic field





$c/\omega_{ce,O}$

$$\frac{c}{\omega_{ce,O}}\,k_{\max} \approx \frac{\omega_{ce,W}}{\omega_{ce,O}}\frac{k_{\max}}{\omega_{ce,W}}c$$

$$\approx \frac{c}{V_{th}}\frac{B_W}{B_O} >> 1$$

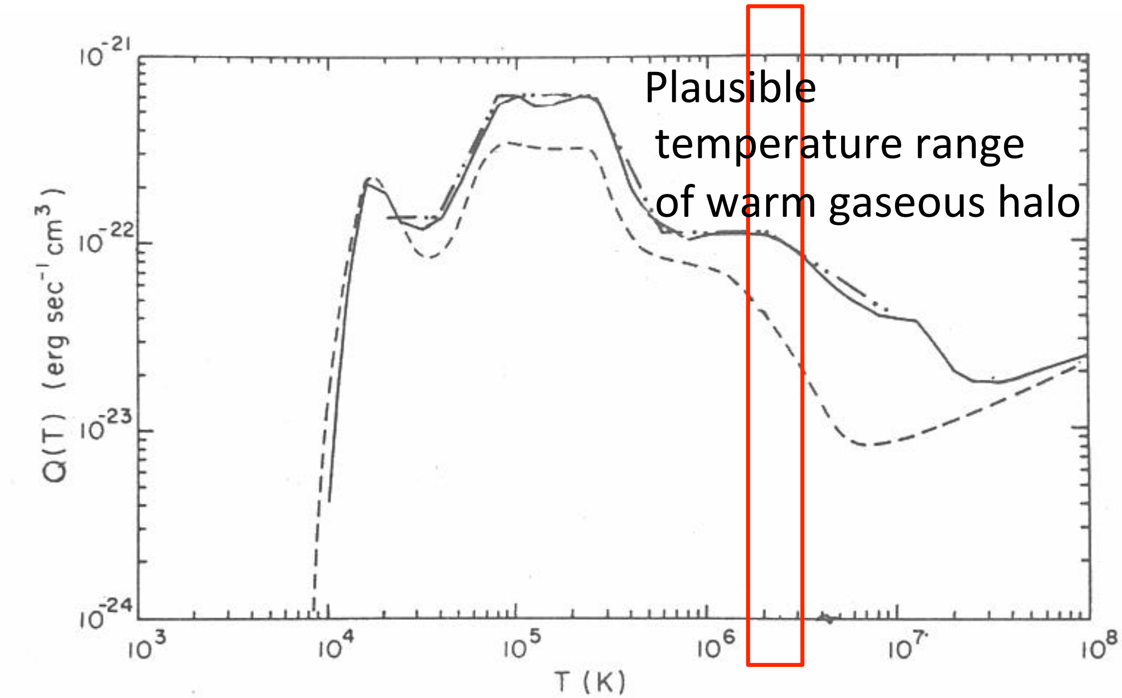
Jitter radiation is superposed onto the synchrotron emission

Discussion

- Plasma kinetic instability could be another route to excite Galactic turbulent magnetic field
- Jitter radiation due to Weibel turbulence in warm gaseous halo could fit the Galactic Haze spectrum in microwave
- Gamma ray Haze: IC by $\gamma=10^4$ source photon $h\nu=10\mathrm{GeV}/\gamma^2=0.1\mathrm{keV}$; free-free from warm halo
- Studies of the effect of the Weibel turbulence based on more realistic models are required

Physical conditions of gaseous halo

Radiative cooling curve: Raymond & Smith, ApJS, 35, 419 (1977)



$$t_{cool} \approx 3.5 \times 10^7 \mathrm{yr} \left(\frac{n_e}{0.01\mathrm{cm}^{-3}} \right)^{-1}$$

$$t_{heat\_conduction} \approx 300\mathrm{yr}$$

$$\times \left(\frac{n_e}{0.01\mathrm{cm}^{-3}} \right) \left(\frac{T}{3 \times 10^6 \mathrm{K}} \right)^{-2.5} \left(\frac{L}{1\mathrm{pc}} \right)^2$$

$$t_{heat\_cond\_\perp\vec{B}} \approx 10^{47} \left(\frac{n_e}{0.01\mathrm{cm}^{-3}} \right)^{-2} \left(\frac{T}{3 \times 10^6 \mathrm{K}} \right)^3 \left(\frac{B_W}{3\mu\mathrm{G}} \right)^2 t_{heat\_conduction}$$

$$\gamma_{\max}^{-1} \approx 0.2\,\mathrm{sec} \left(\frac{n_e}{0.01\mathrm{cm}^{-3}} \right)^{-0.5} \left(\frac{T_e}{3 \times 10^6 K} \right)^{-0.5} \left(\frac{\varepsilon \delta_T}{1.0} \right)^{-3}$$