銀河系ヘイズのプラズマ運動論的不安定性モードにより生成された 銀河乱流磁場起源のジッター放射モデル

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- Brief introduction of proposed models; warm gas halo around Our Galaxy, magnetic turbulence derived by plasma kinetic instability when significant the temperature fluctuation exists in the plasma.
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- Effect of background magnetic field.
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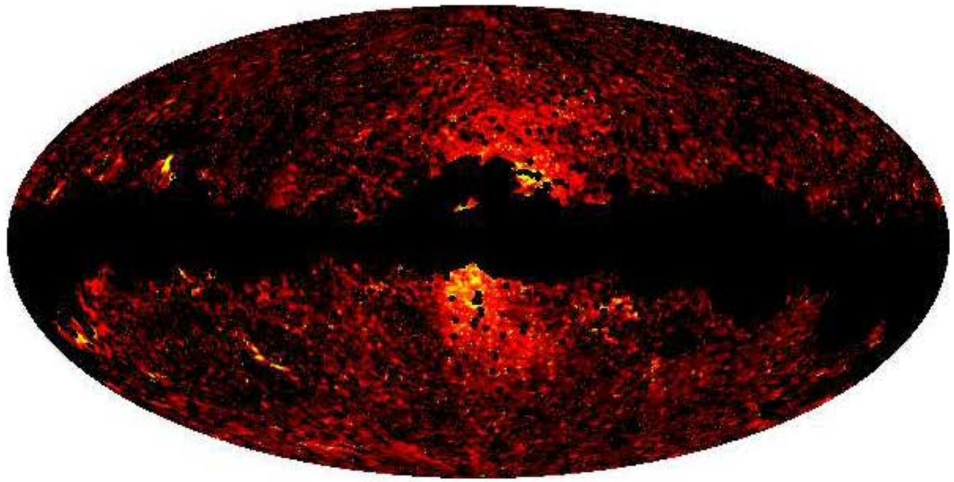
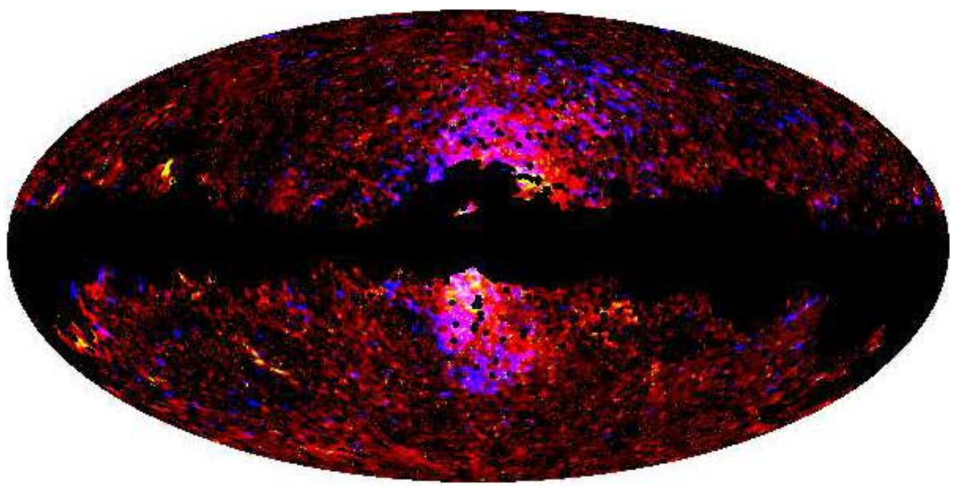
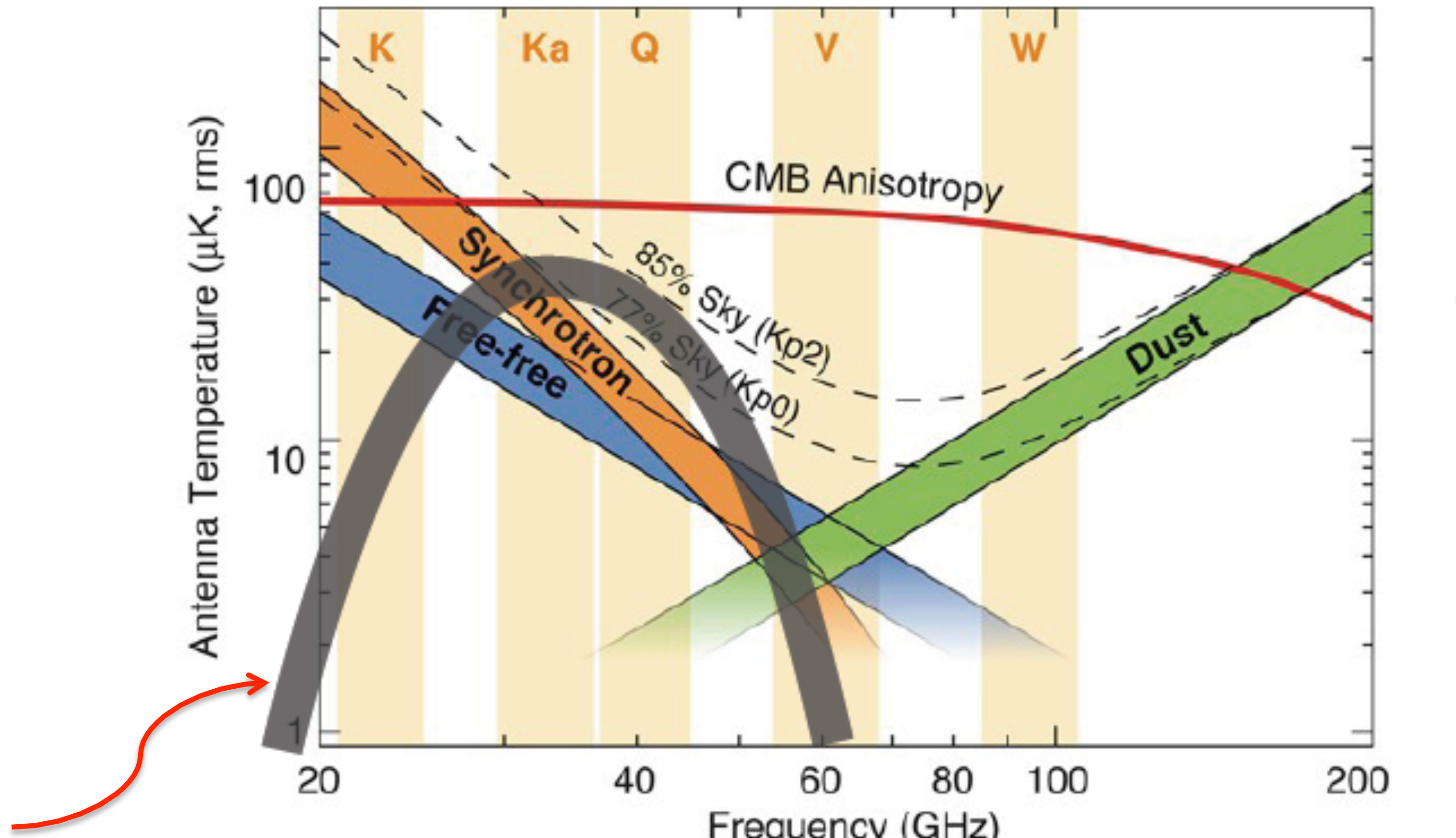
Microwave Galactic Haze





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

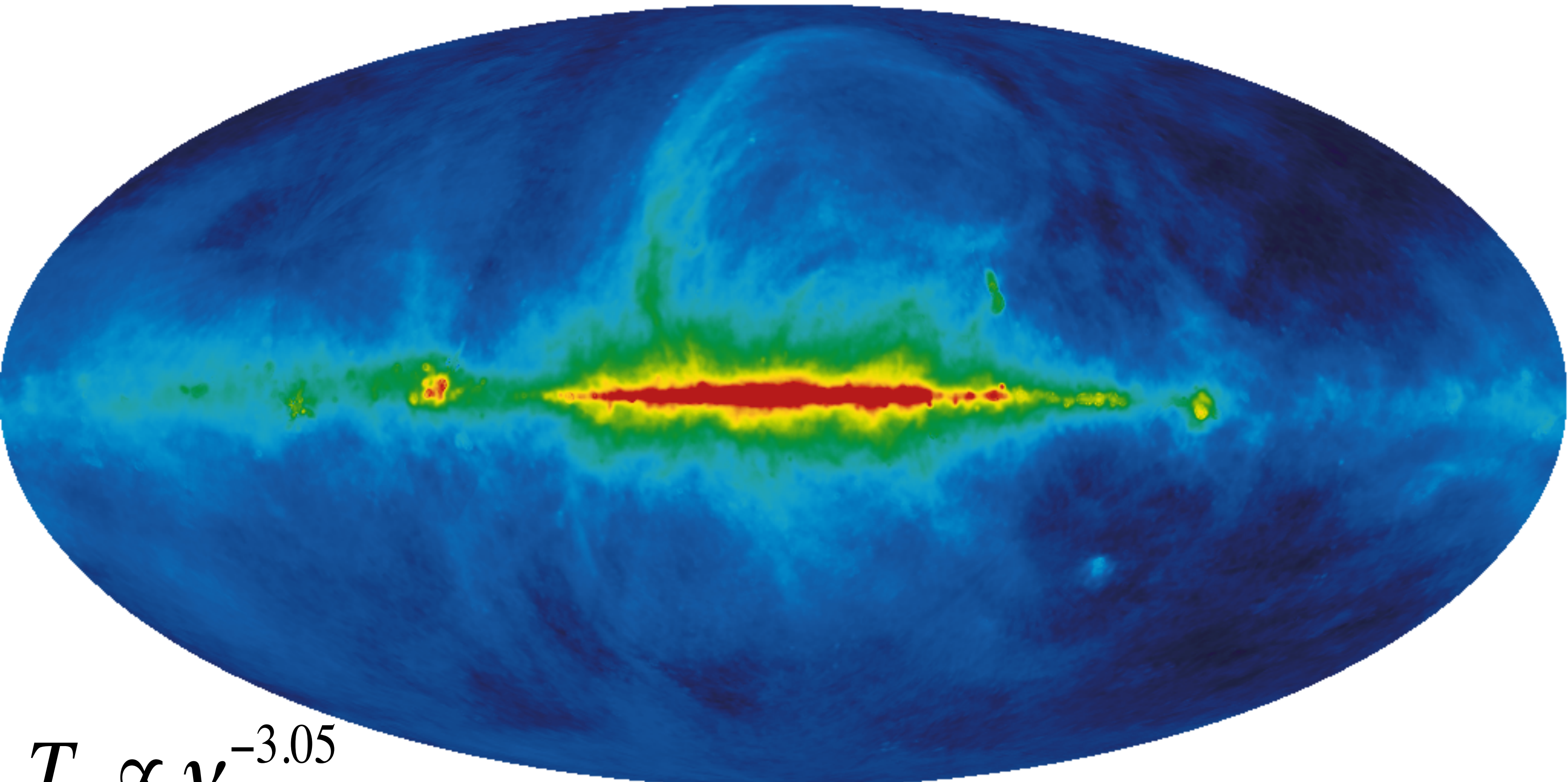
Galactic microwave emissions



Anomalous Microwave Emission (AME)

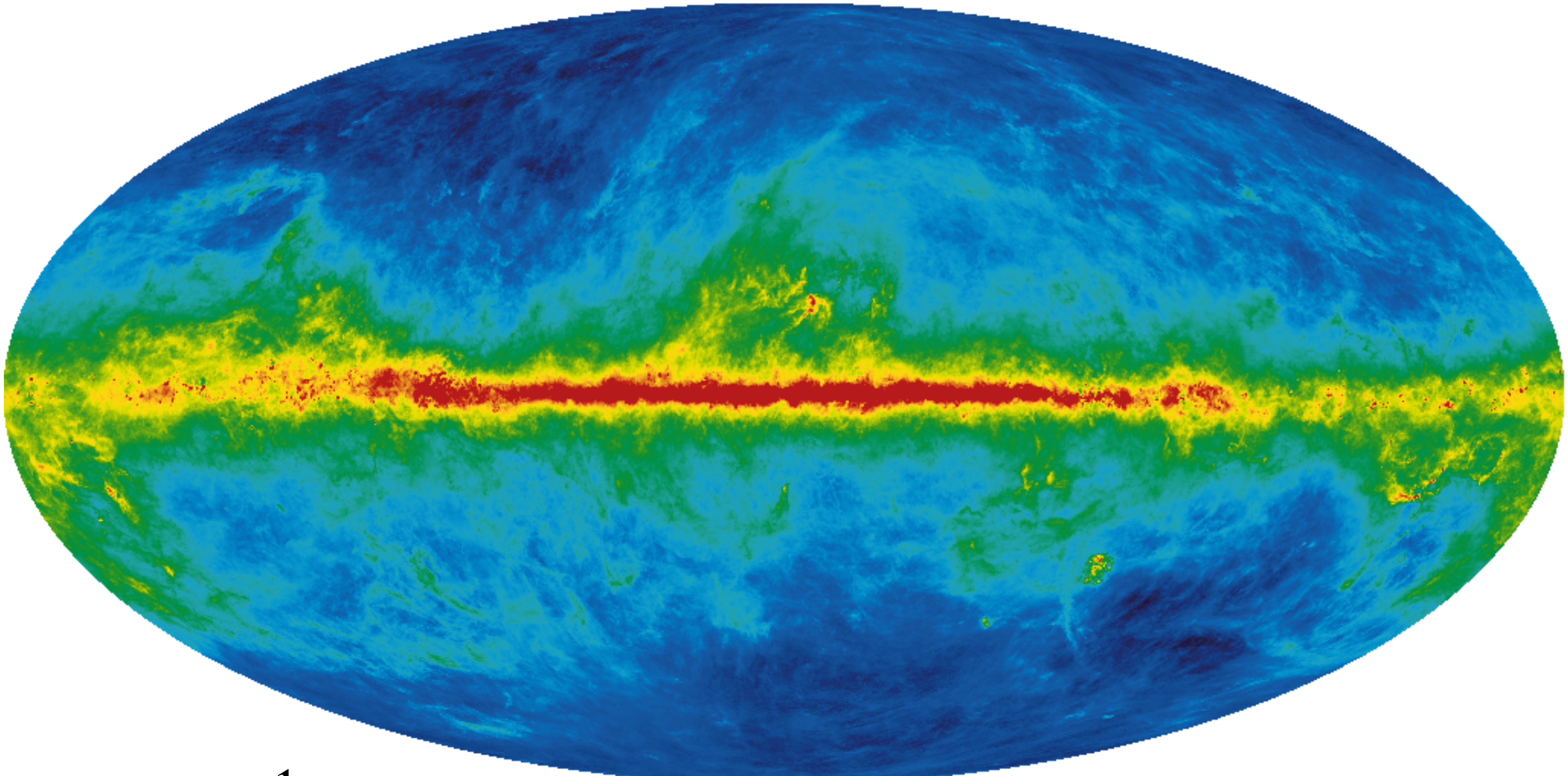
Spinning dust grains

Synchrotron template
Haslam 408MHz map



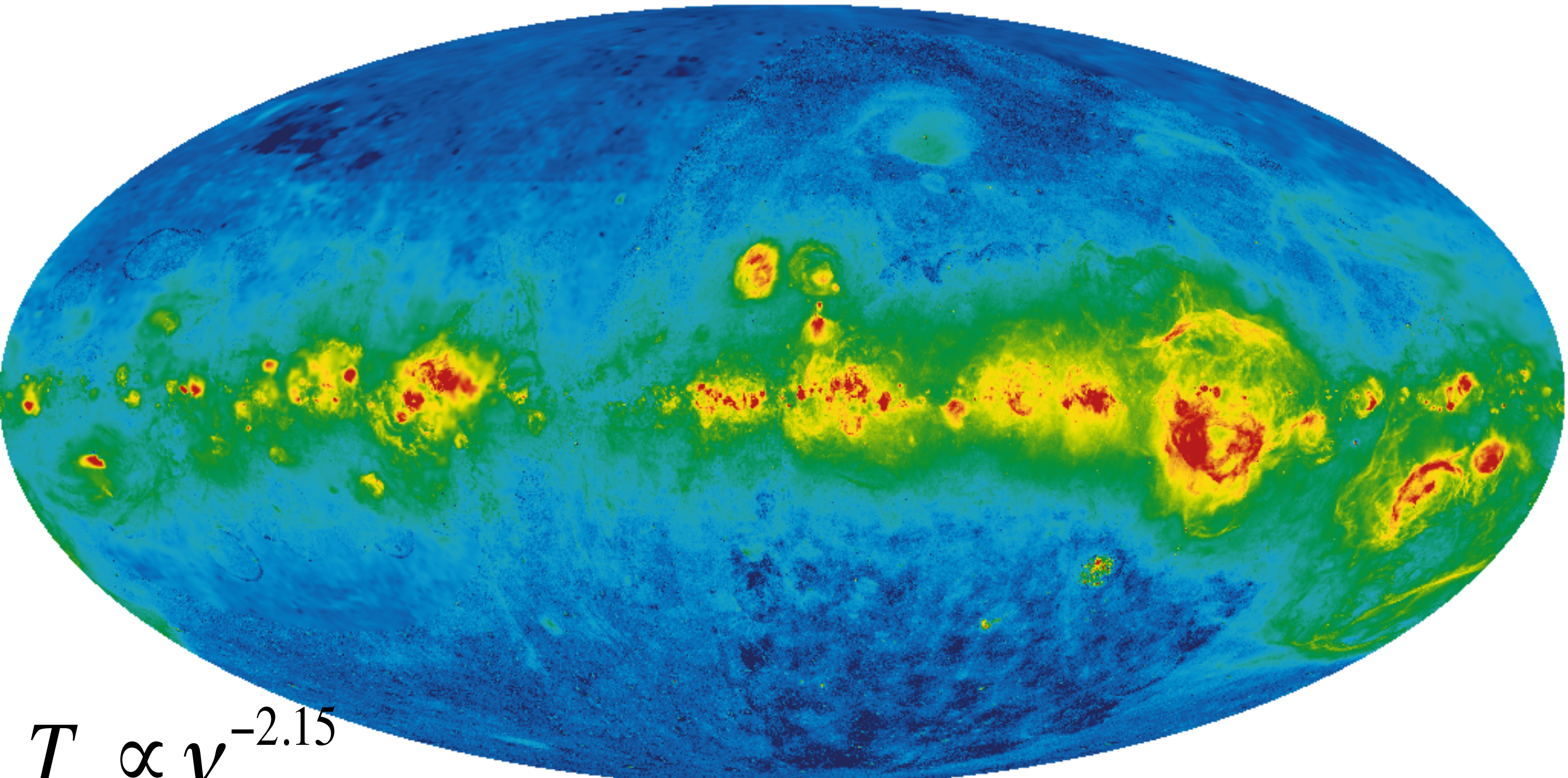
$T_\nu \propto \nu^{-3.05}$

Dust template(spinning dust)
FDS model 8



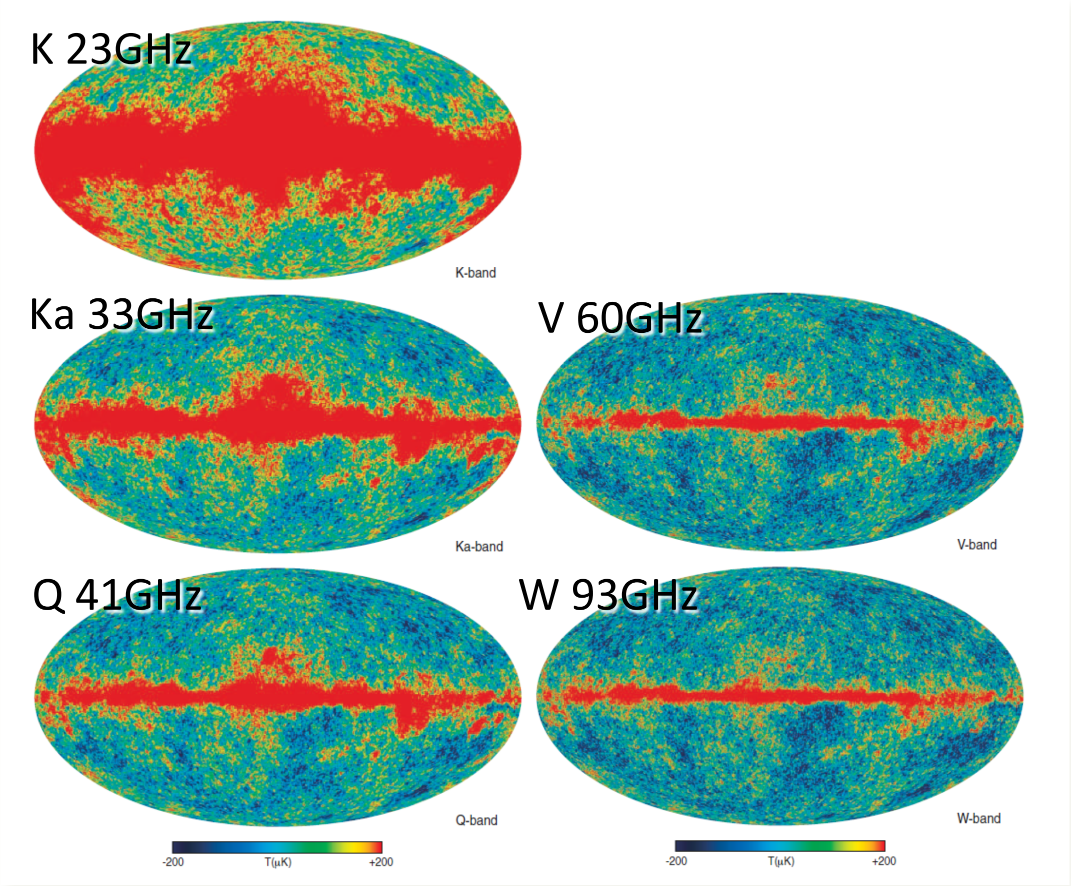
$$I_\nu \propto \left(\frac{\nu}{\nu_0}\right)^{1+\varepsilon} \frac{B(\nu,T)}{B(\nu_0,T)} + e^{\alpha} e^{-[(\nu-\nu_1)/b]^2/2}$$

Free-Free template
Hα map

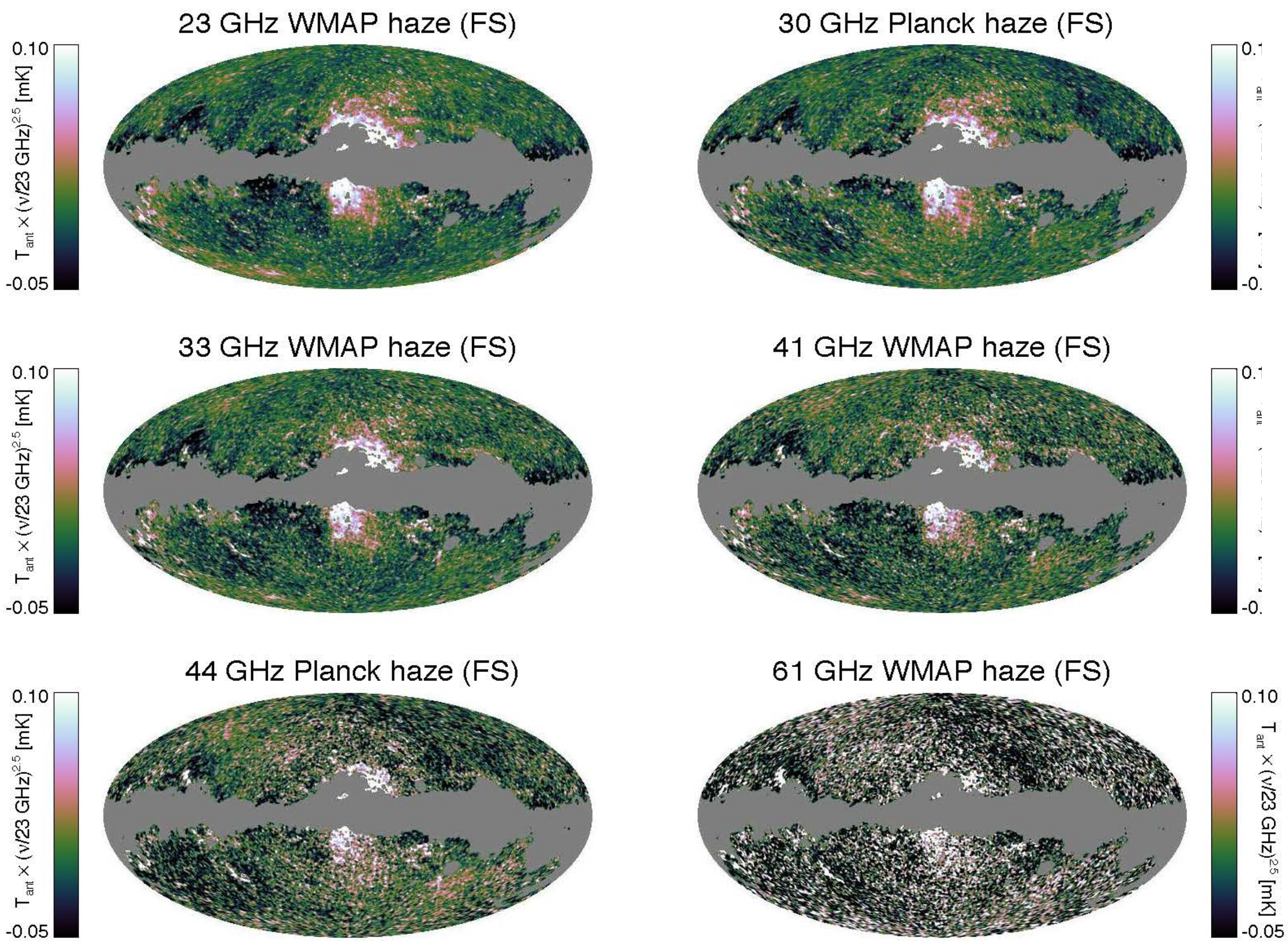


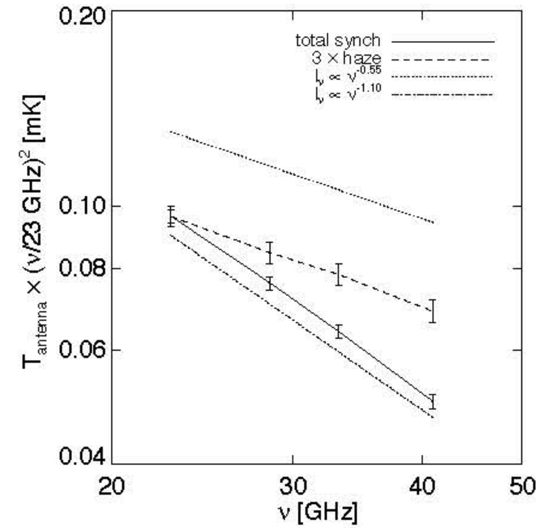
$$T_\nu \propto \nu^{-2.15}$$

WMAP intensity maps



Microwave Haze





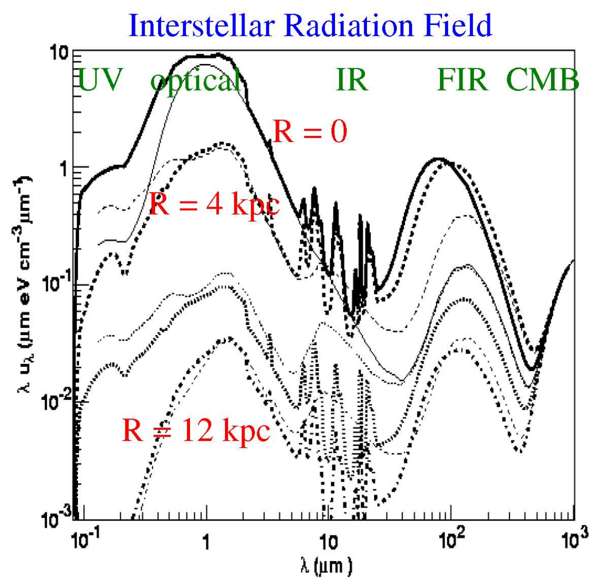
$$T_\nu \propto \nu^{-2.5}$$

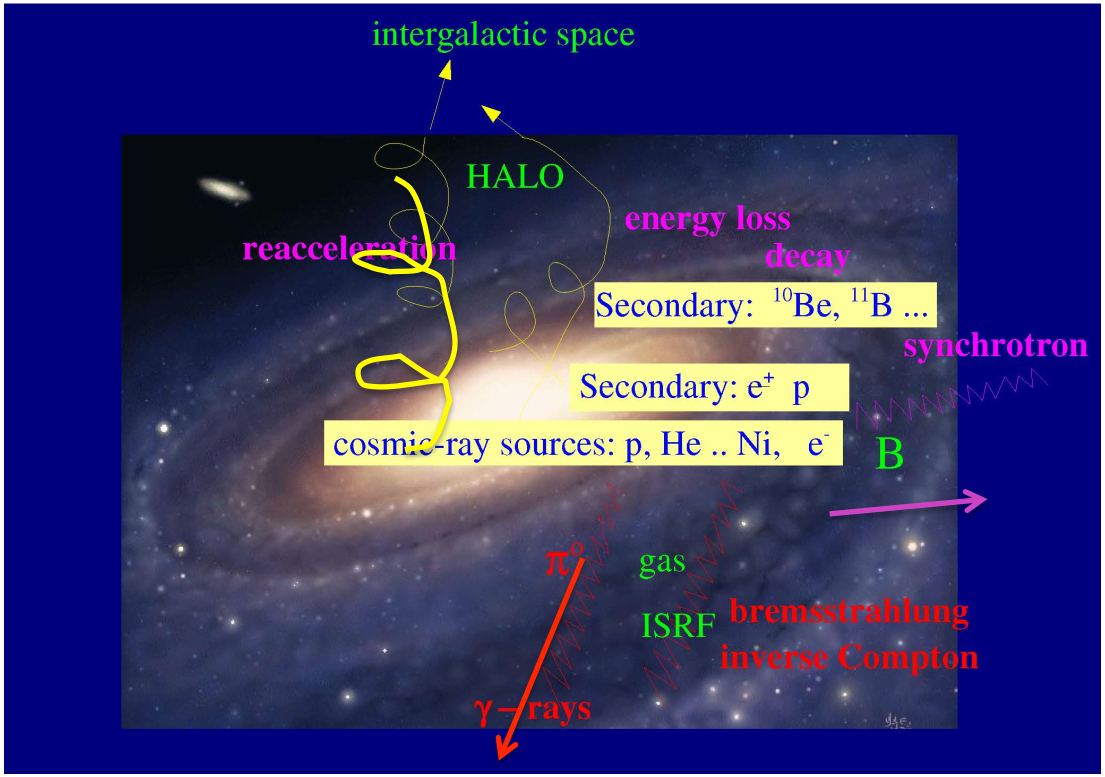
Flat spectrum residual in the Galactic centeral region

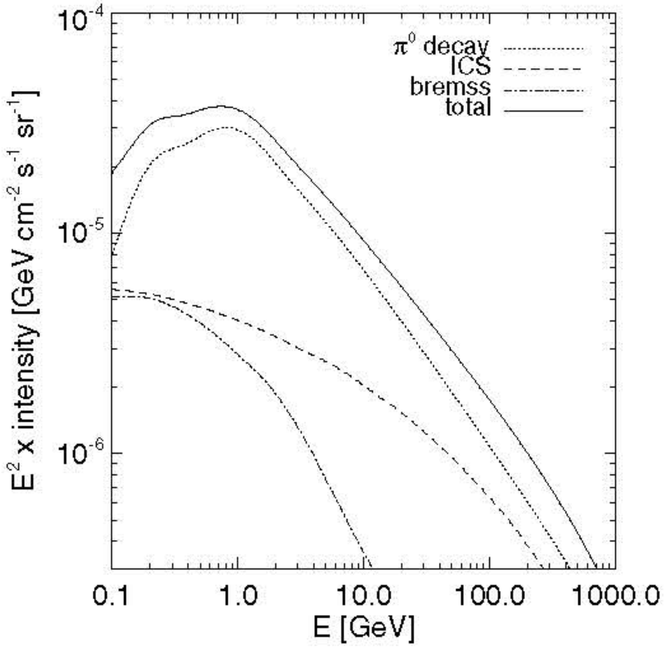
$$I_\nu \approx \nu^2 T_\nu$$

The Fermi Haze

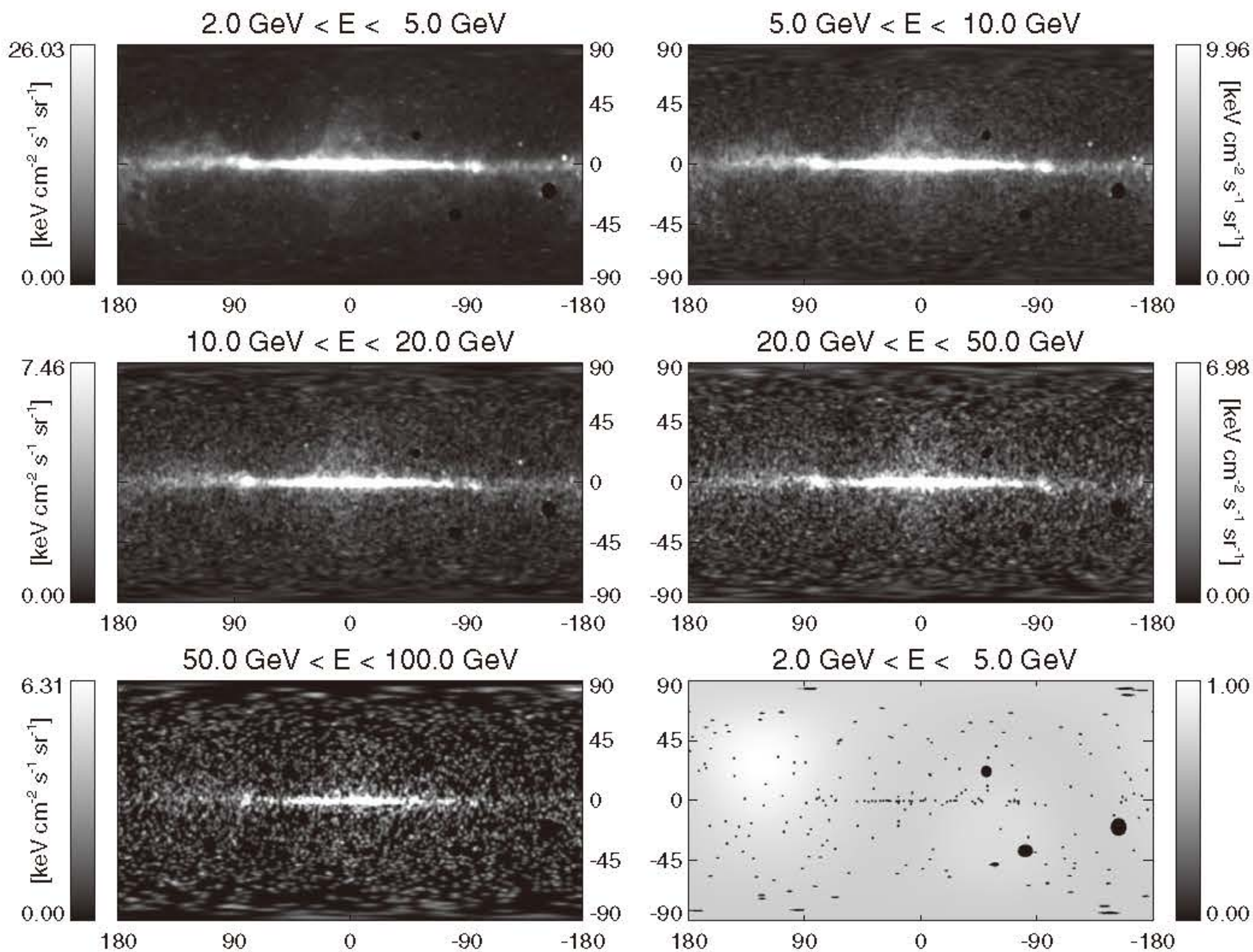
Dobler etal. ApJ, 717, 825-842 (2010)
Strong et al. , ApJ, 537, 763 (2000)



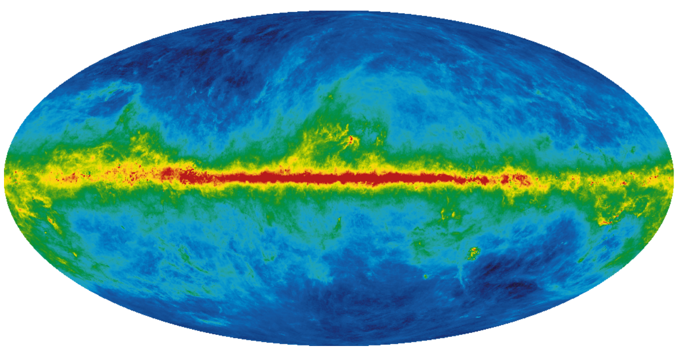




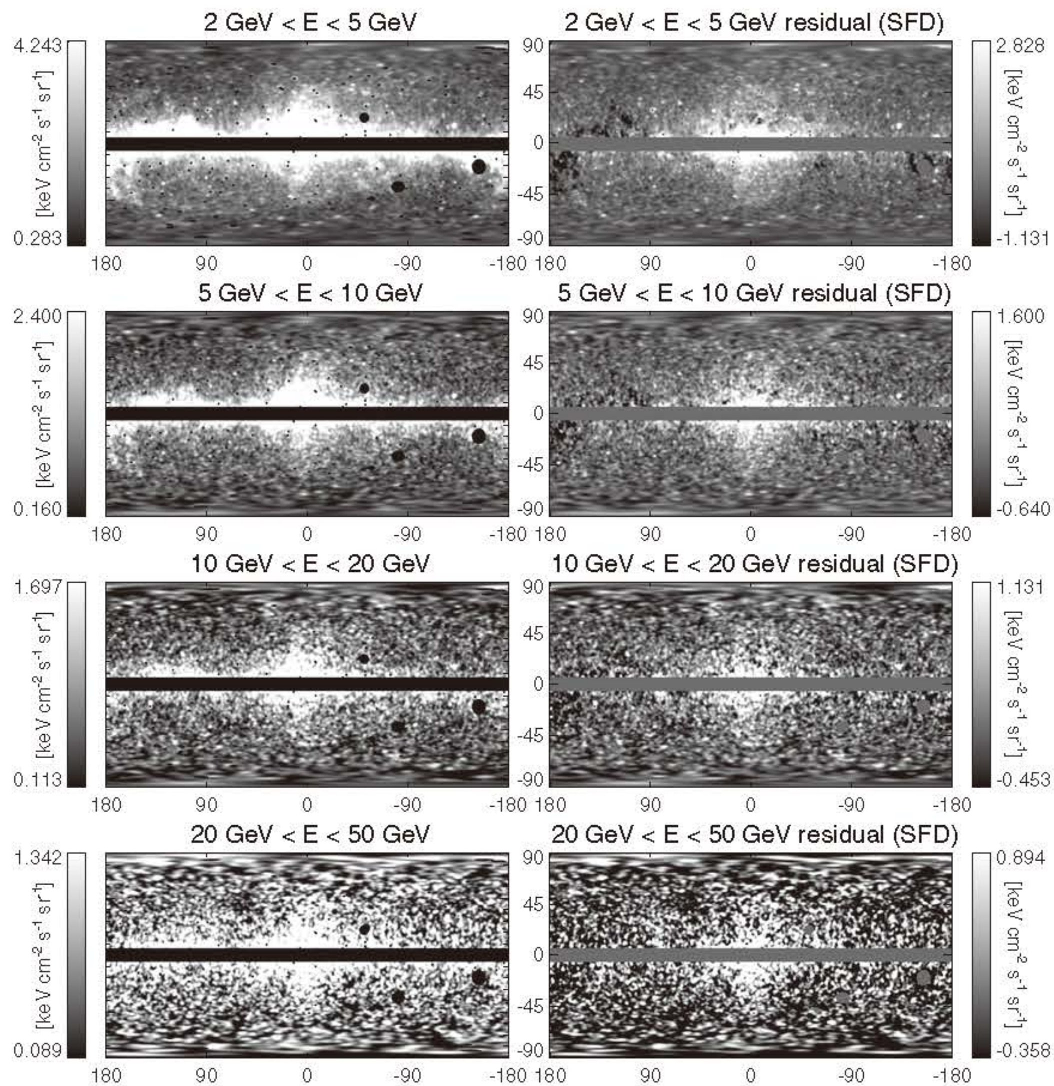
Fermi gamma-ray maps



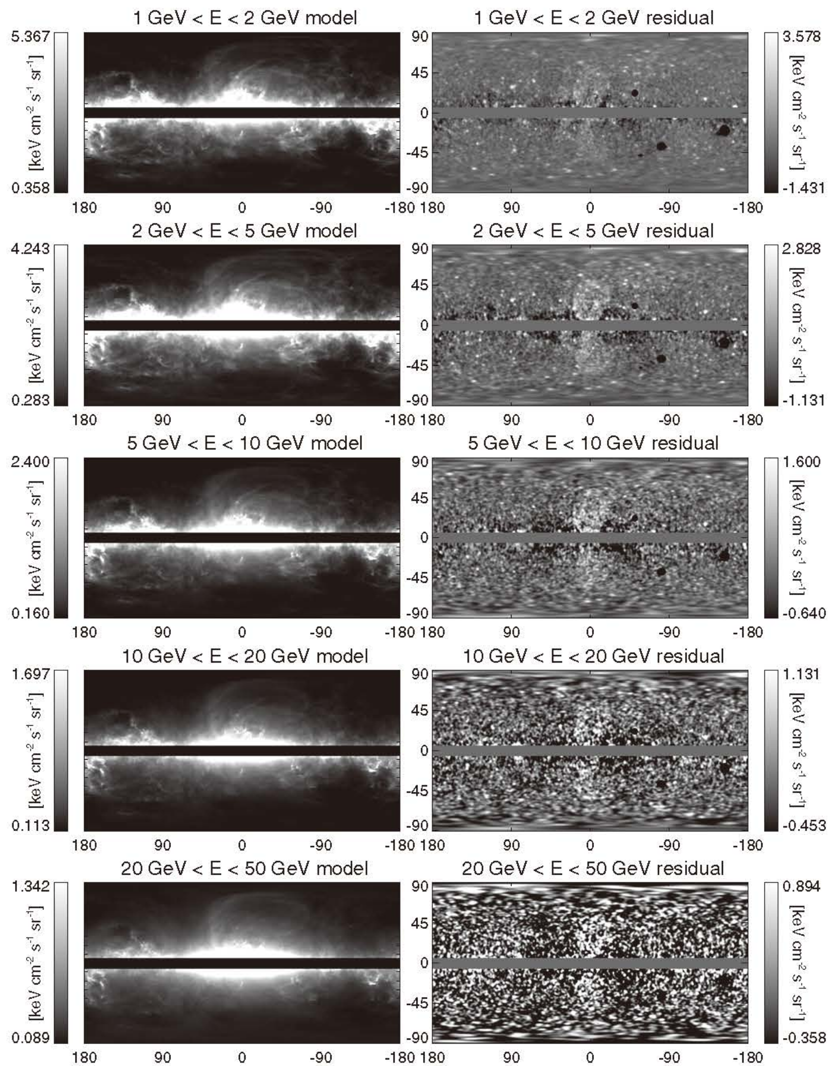
Residual maps after subtracting the SFD dust template from Fermi maps



Flat spectrum residual in the Galactic centeral region

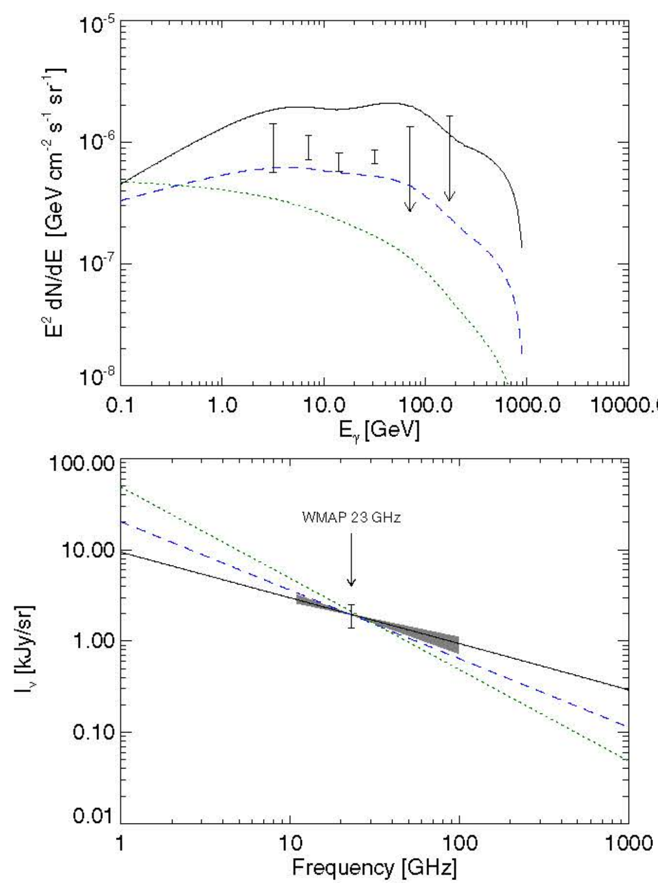


Residual after subtracting the official Fermi team Galactic diffuse model



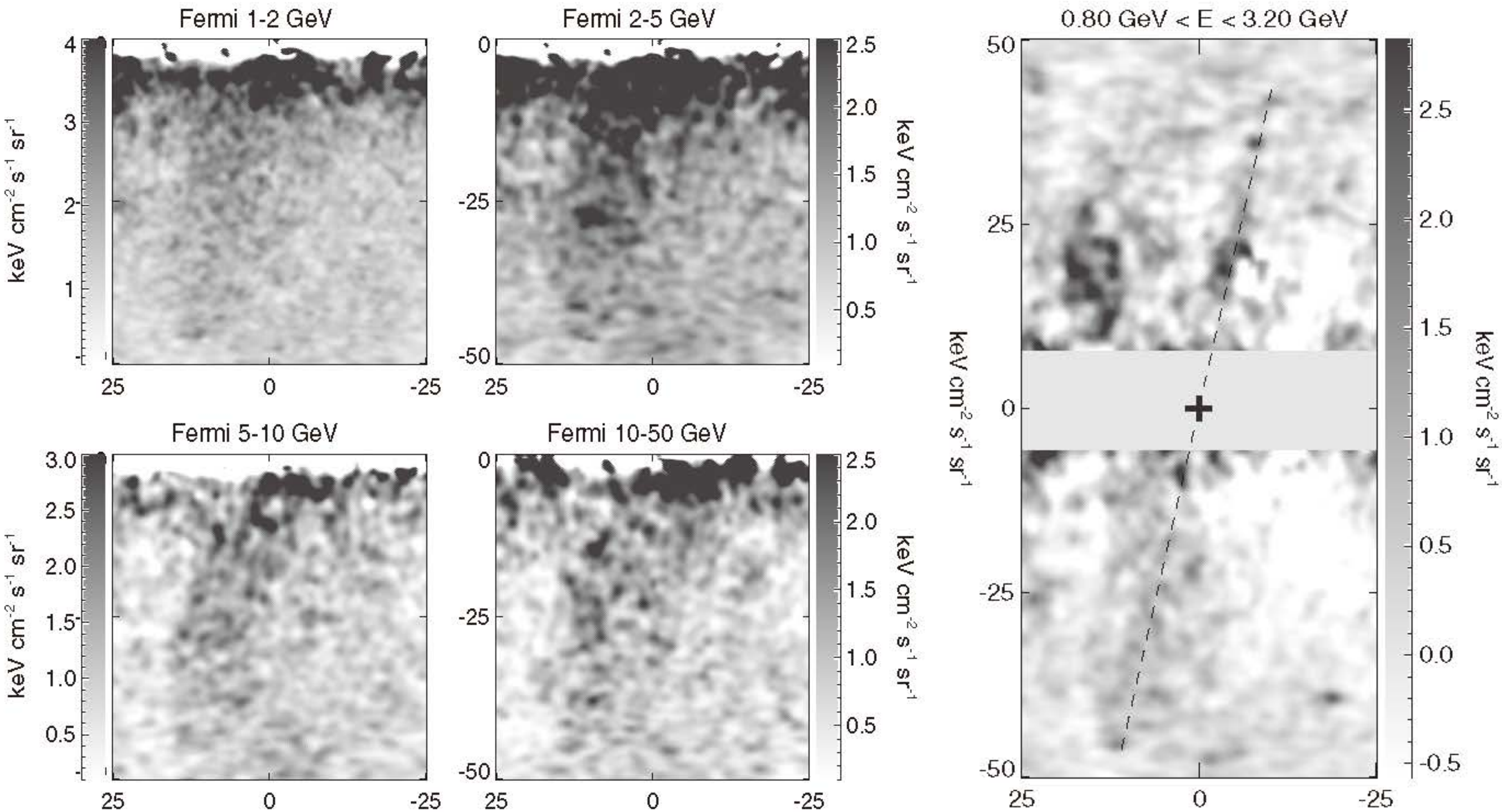
Fermi bubble

Spetcrum of the Haze

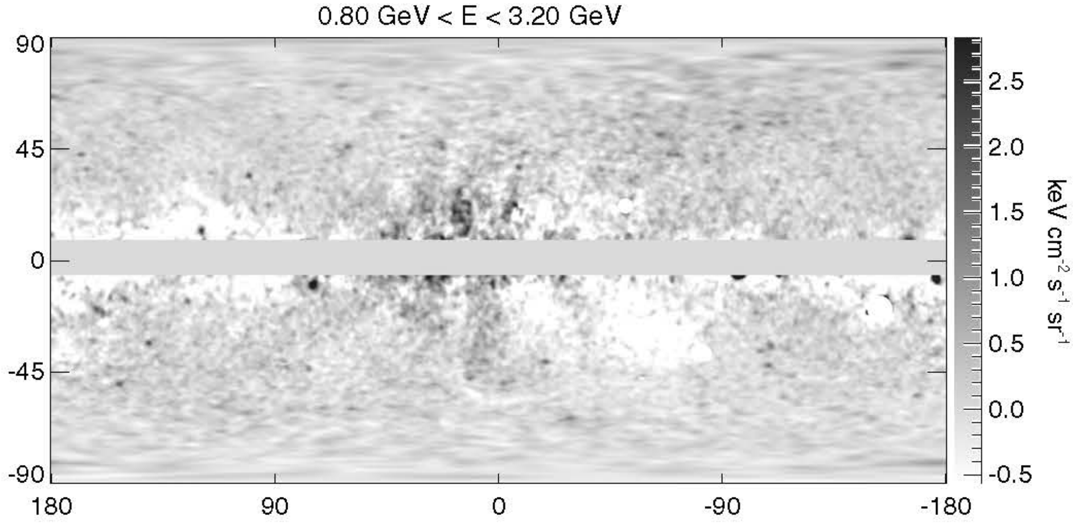


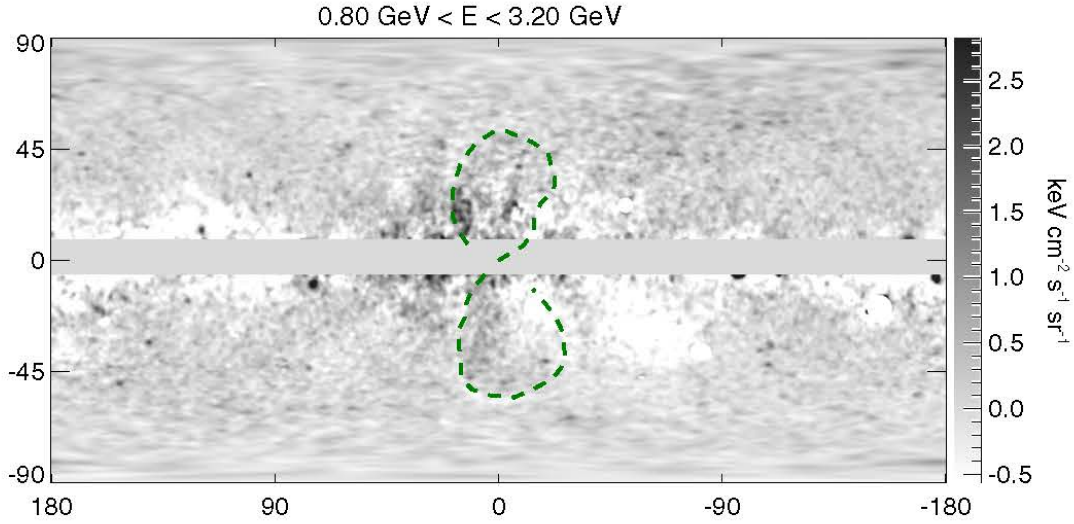
Gamma-ray jets?

Su, Finkbeiner, ApJ, 753, 61 (2012)



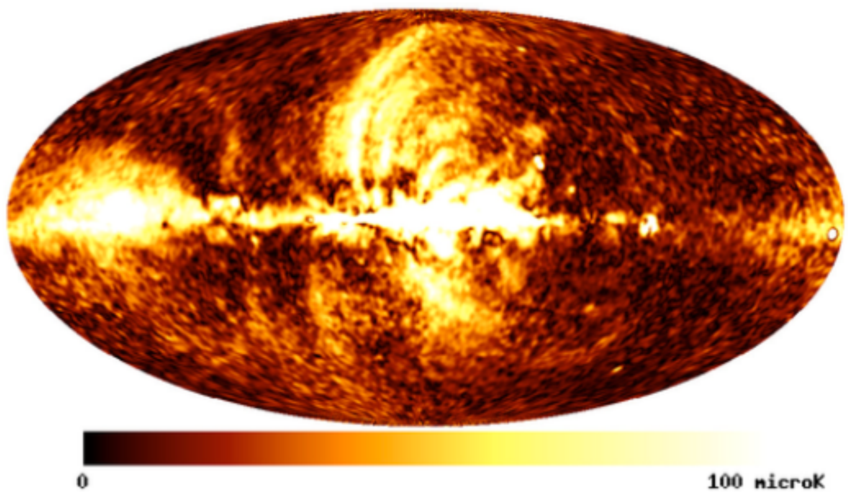
The Fermi bubble and jets



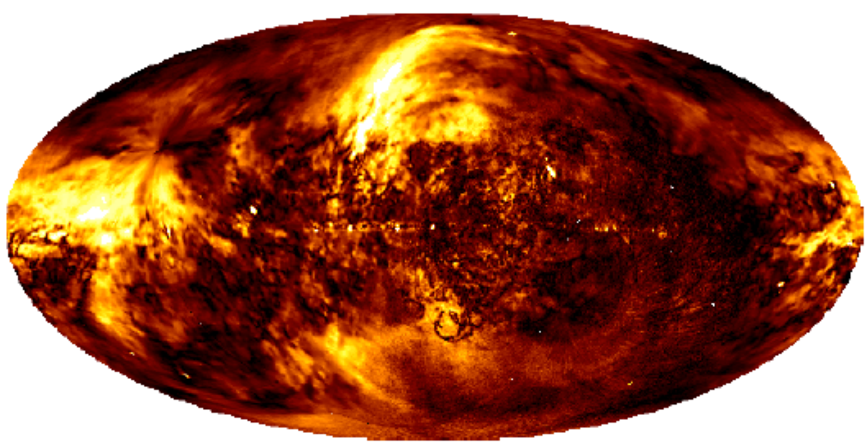


S-PASS bubble

S-PASS: Parks s-band (2.3GHz) polarization survey

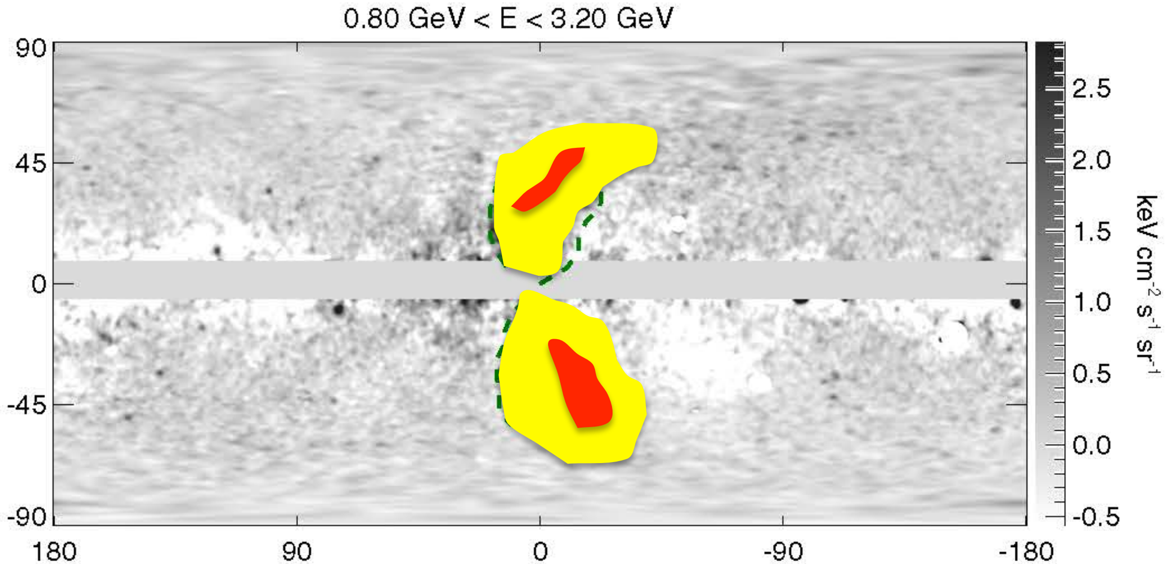


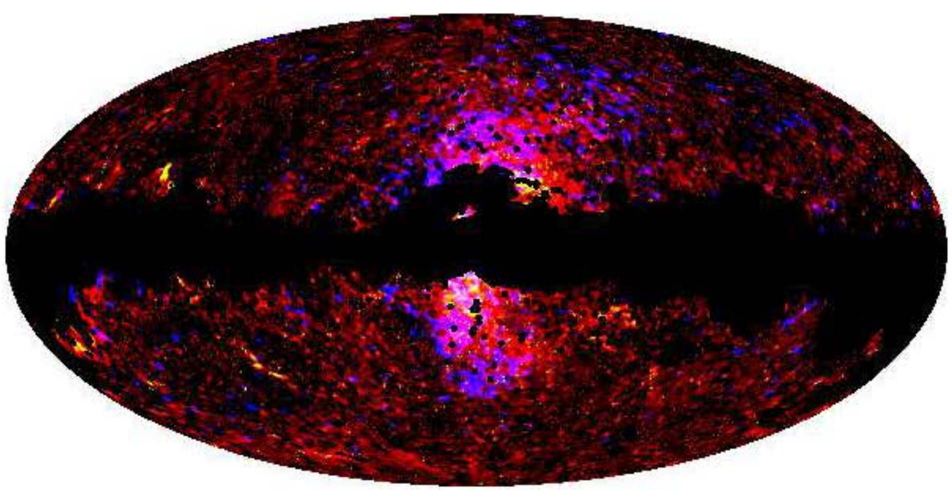
K-band (23GHz) polarization intensity maps



1.4GHz polarization intensity maps: Faraday depolarization

The S-PASS bubble





Polarization degree
=25-30%
B(lobe)=2-12 μG
B(ridge)=15μG
Twisted structure =>
Not AGN origin
10^5 stars bursts

Appear in Nature soon

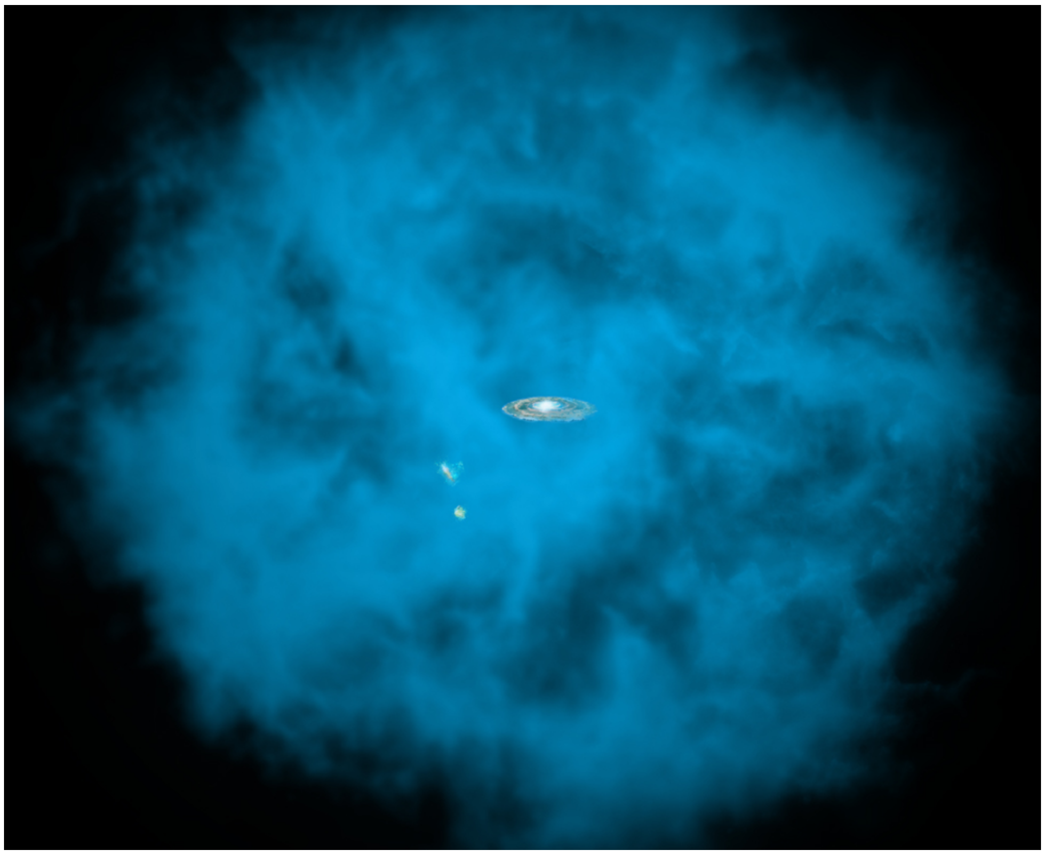
Proposed model for origin of turbulent B field and microwave Haze emission

- Existence of Temperature fluctuation in warm Galactic halo
- Magnetic waves are excited by plasma kinetic instability
- Interaction of relativistic electrons with excited magnetic waves result in Jitter radiation=> Microwave Haze ?

Galactic warm gaseous halo

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

140kpc



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

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

Chandra search for OVII (21.602Å) and OVIII(18.9767Å) absorption lines at z=0 along LOS of extragalactic X-ray sources

OVII Kα detections:
21/50 => saturated

OVIII Kα detections:
15/50

8/50 both OVII and OVIII Kα are confidently detected

Table 1
Summary of the Targets Used in This Investigation

Target	l (deg)	b (deg)	Redshift z	Exposure (ks)
Mrk290	91.48	47.95	0.0304	250
PKS2155-304	17.73	−52.24	0.1160	530
Mrk421	179.83	65.03	0.0300	720
Mrk509	35.97	−29.86	0.0344	460
3C382	61.30	17.44	0.0579	120
Ark564	92.13	−25.33	0.0247	250
NGC 3783	287.45	22.94	0.0097	905
H2106-099	40.26	−34.93	0.0265	100

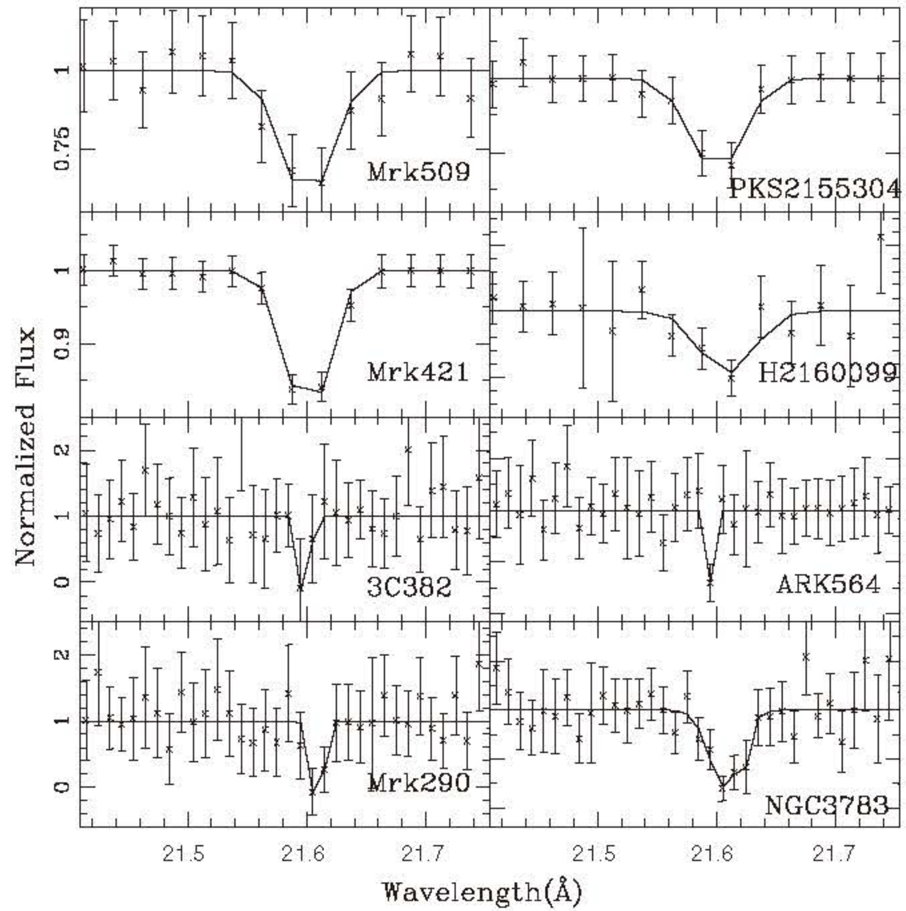


Figure 1. Normalized flux at the location of the O VII line at 21.602 Å.

For 6/8, OVII Kβ@18.67Å is detected

Chandra gratings FWHM=0.05Å for LEG and FWHM=0.023Å for MEG

Column density measurement

Table 2
The O VII and O VIII Absorption Line Measurement

Target	EW (O $\text{VII}_{K\alpha}$) (mÅ)	EW (O $\text{VII}_{K\beta}$) (mÅ)	EW (O $\text{VIII}_{K\alpha}$) (mÅ)	O VII($\frac{EW(K\beta)}{EW(K\alpha)}$)	b (km s^{-1})	log(NO VII) (cm^{-2})
Mrk290	18.9 ± 4.5	5.1 ± 3.7	8.4 ± 2.9	0.27 ± 0.21	>55	16.14 ± 0.32[a]
PKS2155-304	11.6 ± 1.6	4.2 ± 1.3	6.7 ± 1.4	0.36 ± 0.12	35–94	16.09 ± 0.19
Mrk421	9.4 ± 1.1	4.6 ± 0.7	1.8 ± 0.9	0.49 ± 0.09	24–55	16.22 ± 0.23
Mrk509	23.9 ± 5.0	11.7 ± 4.1	10.3 ± 4.3	0.49 ± 0.20	70–200	16.7 ± 0.27
3C382	17.3 ± 5.0	7.8 ± 3.0	6.8 ± 3.8	0.45 ± 0.22	>40	16.50 ± 0.49[a]
Ark564	12.0 ± 1.9	<3.8	9.5 ± 4.1	...	>20	15.82 ± 0.20[a]
NGC 3783	14.4 ± 2.5	5.6 ± 1.6	4.5 ± 2.9	0.39 ± 0.13	50–130	16.30 ± 0.25
H2106-099	48.3 ± 18.0	<34.2	28.8 ± 13.8	...	>70	16.23 ± 0.16[a]

Note. [a] The lower limits on O VII column densities are calculated using the curve-of-growth analysis.

$$\frac{EW(K\alpha)}{EW(K\beta)} = \frac{f(K\alpha)\lambda^2(K\alpha)}{f(K\beta)\lambda^2(K\beta)} = 0.156$$

$$\log N(OVII) = 15.82 - 16.50\text{cm}^{-2}$$

$$\text{weighted mean } = 16.19 \pm 0.08\text{cm}^{-2}$$

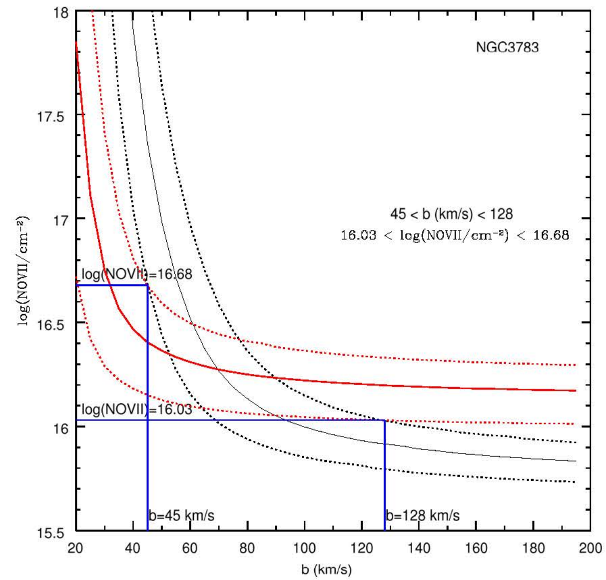
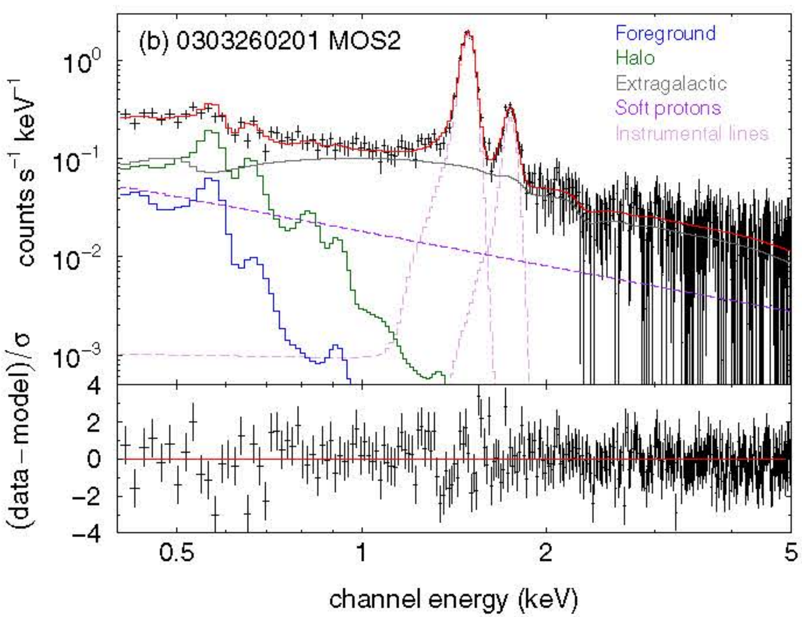


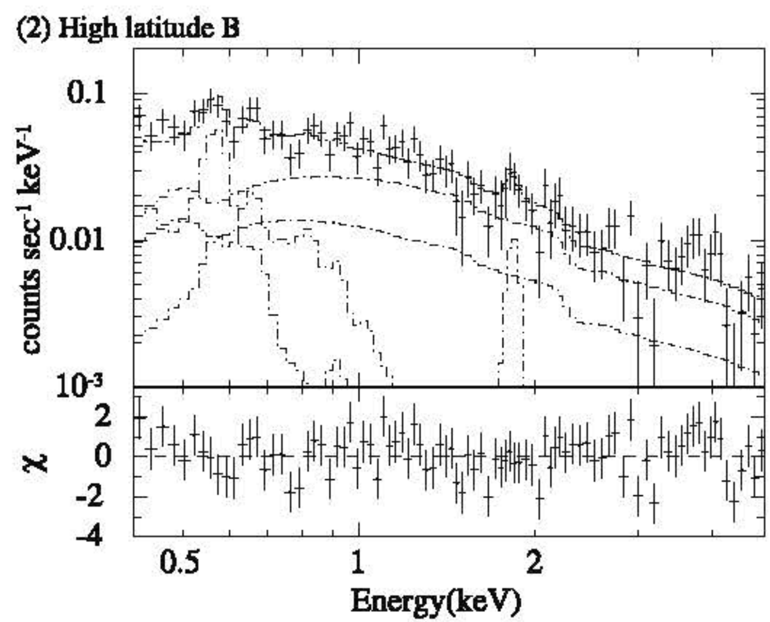
Figure 2. Contours of allowed column densities N(O VII) and Doppler parameters b for the O $\text{VII}_{K\alpha}$ (black) and O $\text{VII}_{K\beta}$ (red).
(A color version of this figure is available in the online journal.)

OVII and OVII emissions detected by XMM-Newton (Henley et al. ApJ, 723, 935(2010)) and Suzaku (Yoshino etal. PASJ, 61, 805(2009))

Solar wind charge exchenge (SWCX), local hot bubble (LHB) contaminations

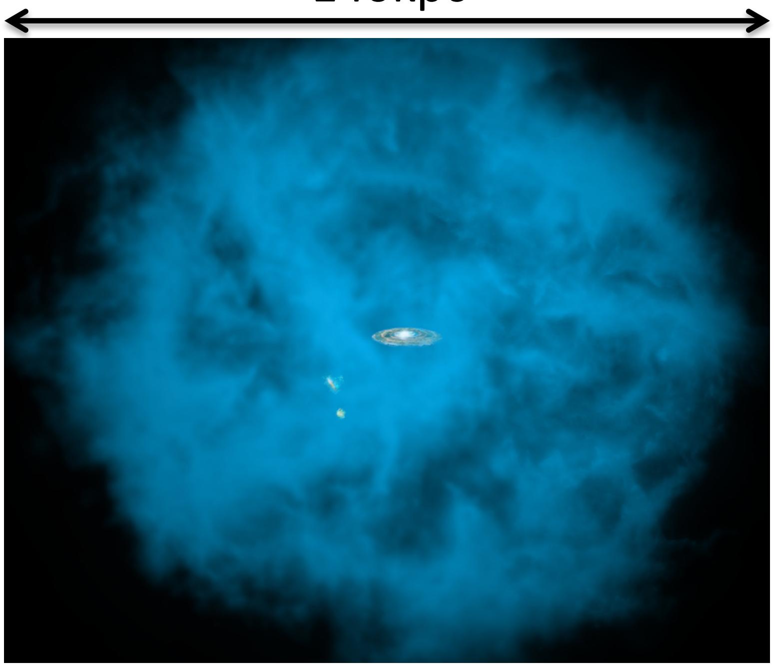
Transabsorption emission (TAE)





Galactic warm gaseous halo

140kpc



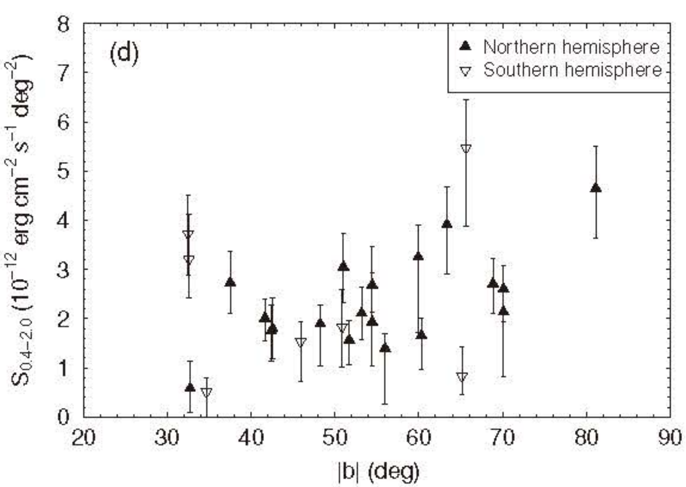
$$n_e = 0.0002\mathrm{cm}^{-3} @ Z = Z_\Theta$$

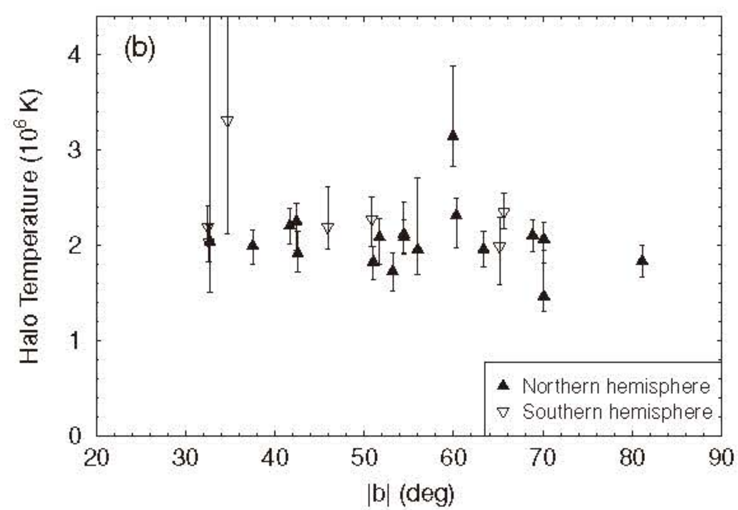
From detection of OVII and OVIII lines

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

if in collisional ionization equilibrium

$$M_{gas} \approx 2 \times 10^{11} M_\Theta$$





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

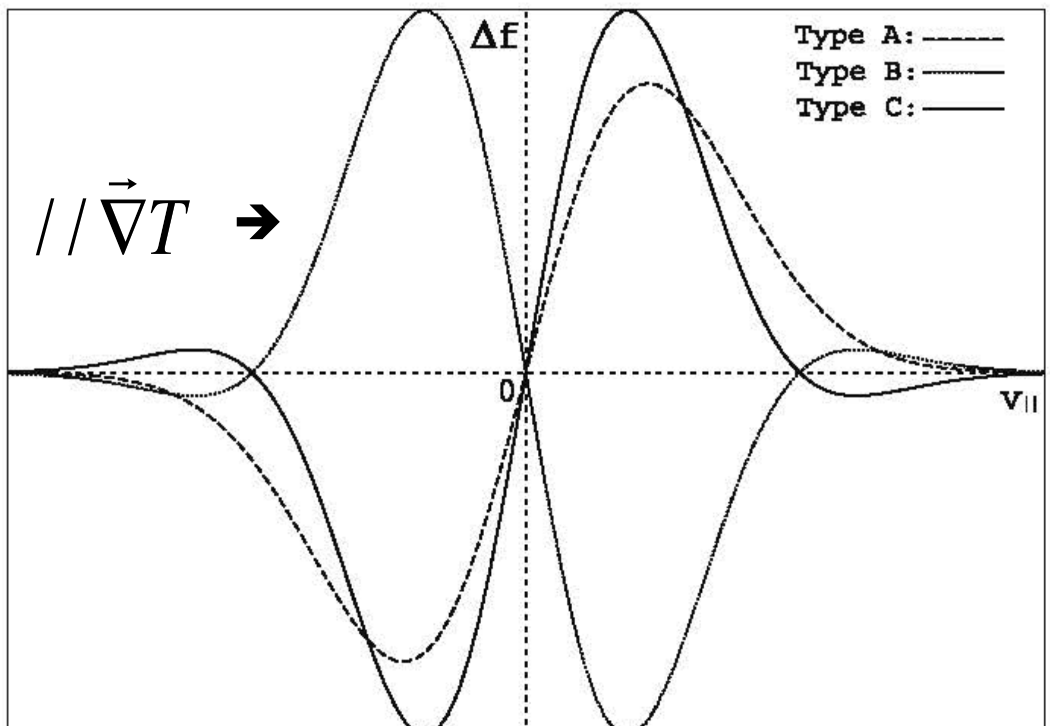
Estimation of Δf: physical approach

$\langle \Delta f \rangle = 0$: 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

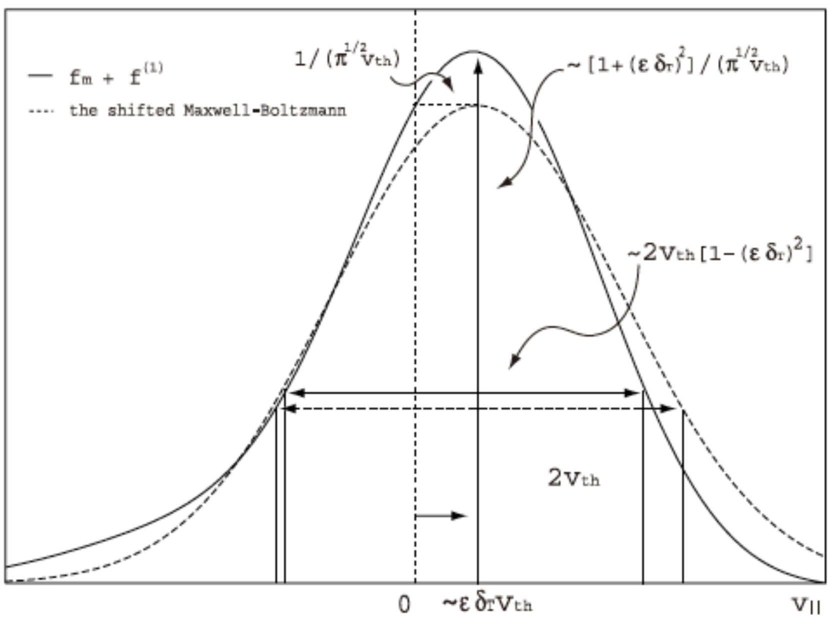
$\langle \frac{1}{2} m v^2 v_z \rangle < 0$ when $dT/dz > 0$ ➔ Type C is remained



Mechanism of the instability

Total velocity distribution function

direction of the grad T : ➔



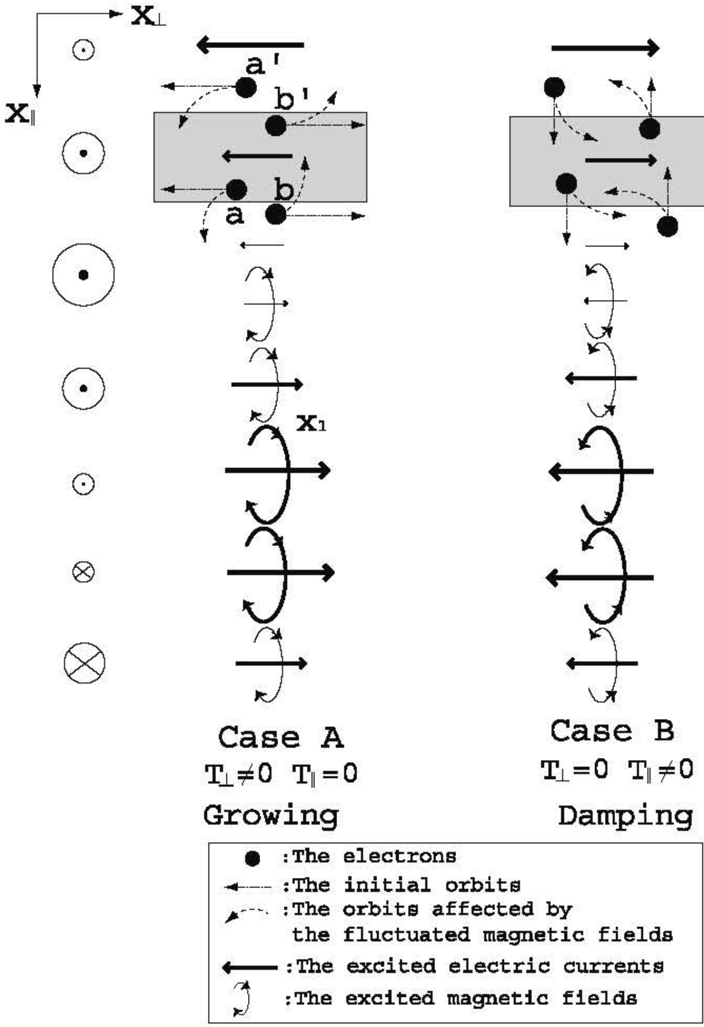
- the peak position shift by $\varepsilon\delta_T\, V_{th}$
- The peak value is increased by $(1+(\varepsilon\delta_T)^2)$
- Width in the grad T direction becomes thinner by $(1-(\varepsilon\delta_T)^2)$

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

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

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

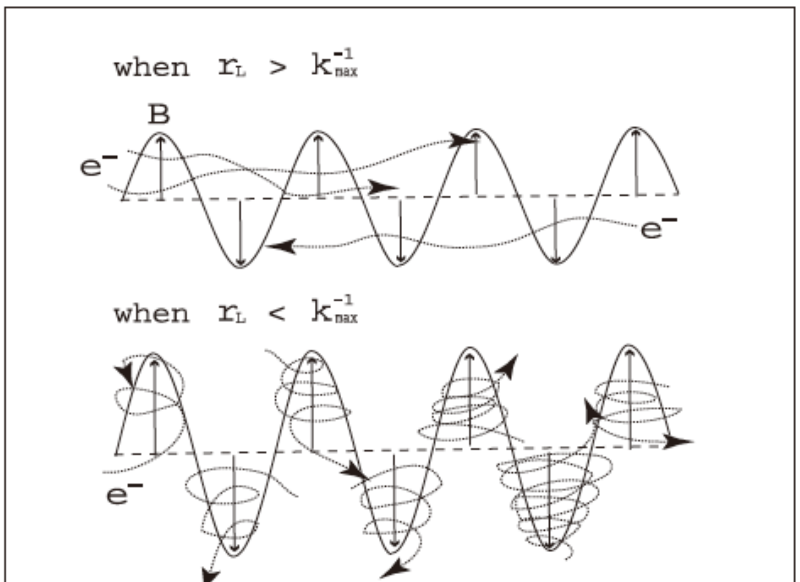
$$\approx 1.5\times10^7\,\text{cm}\left(\frac{n_e}{0.01\text{cm}^{-3}}\right)^{-0.5}\left(\frac{\varepsilon\delta_T}{1.0}\right)^{-1} << \lambda_e$$

The growth time of the fastest growing mode

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

Nonlinear saturation level

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



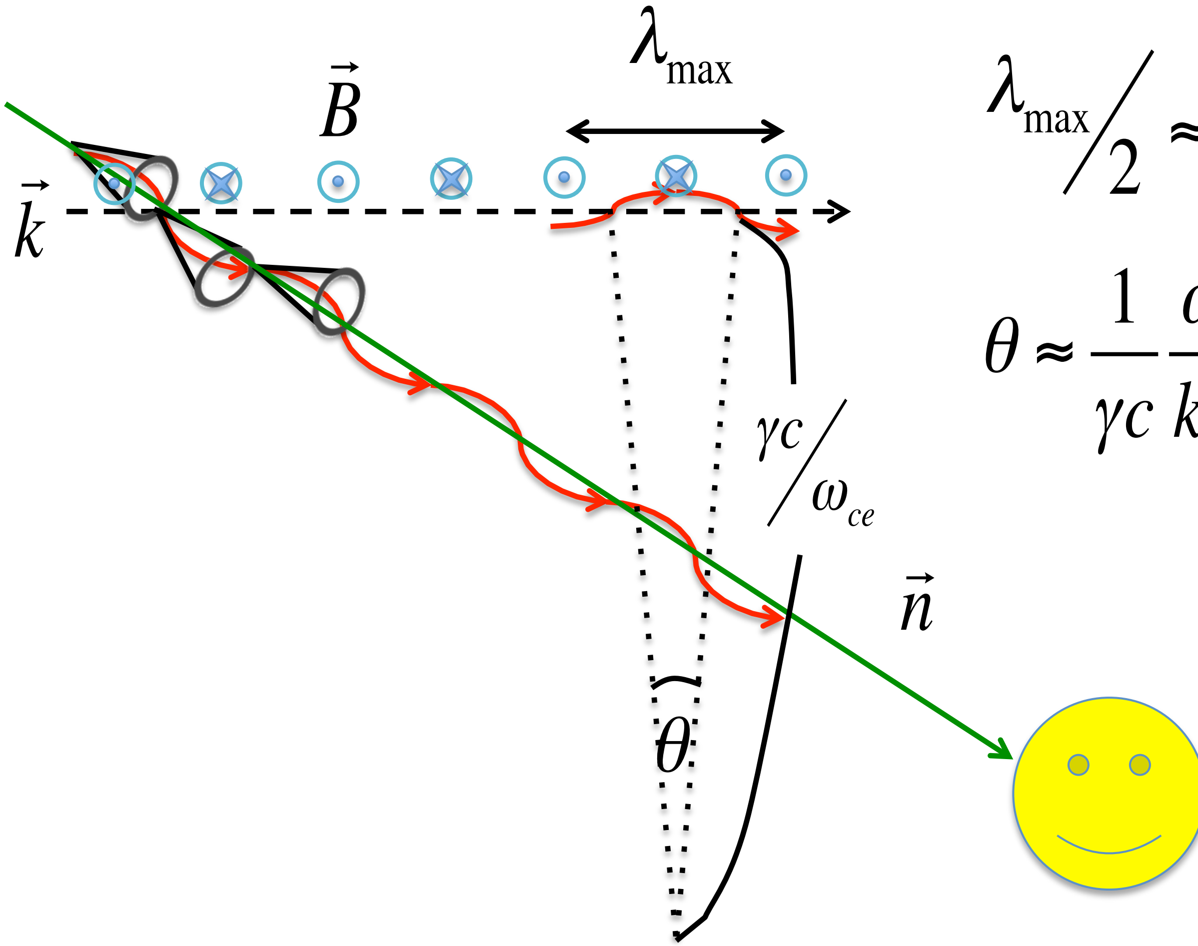
$$\frac{V_{th}}{\omega_{ce}} \approx \frac{1}{k_{max}}$$

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

: 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

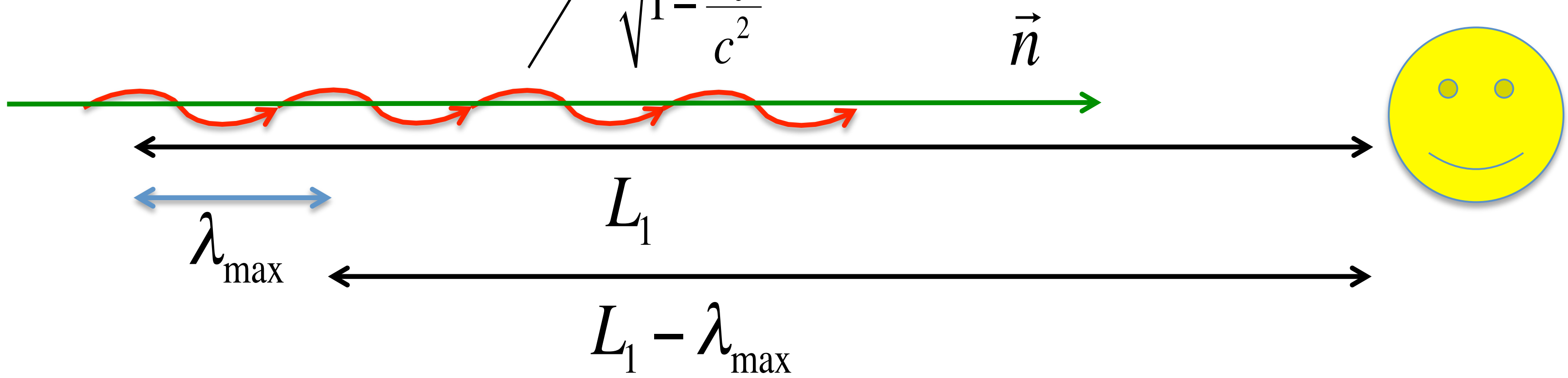


$$\lambda_{\max}/2 \approx \left(\gamma c / \omega_{ce}\right)\theta,$$

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

Jitter radiation from the Weibel turbulence

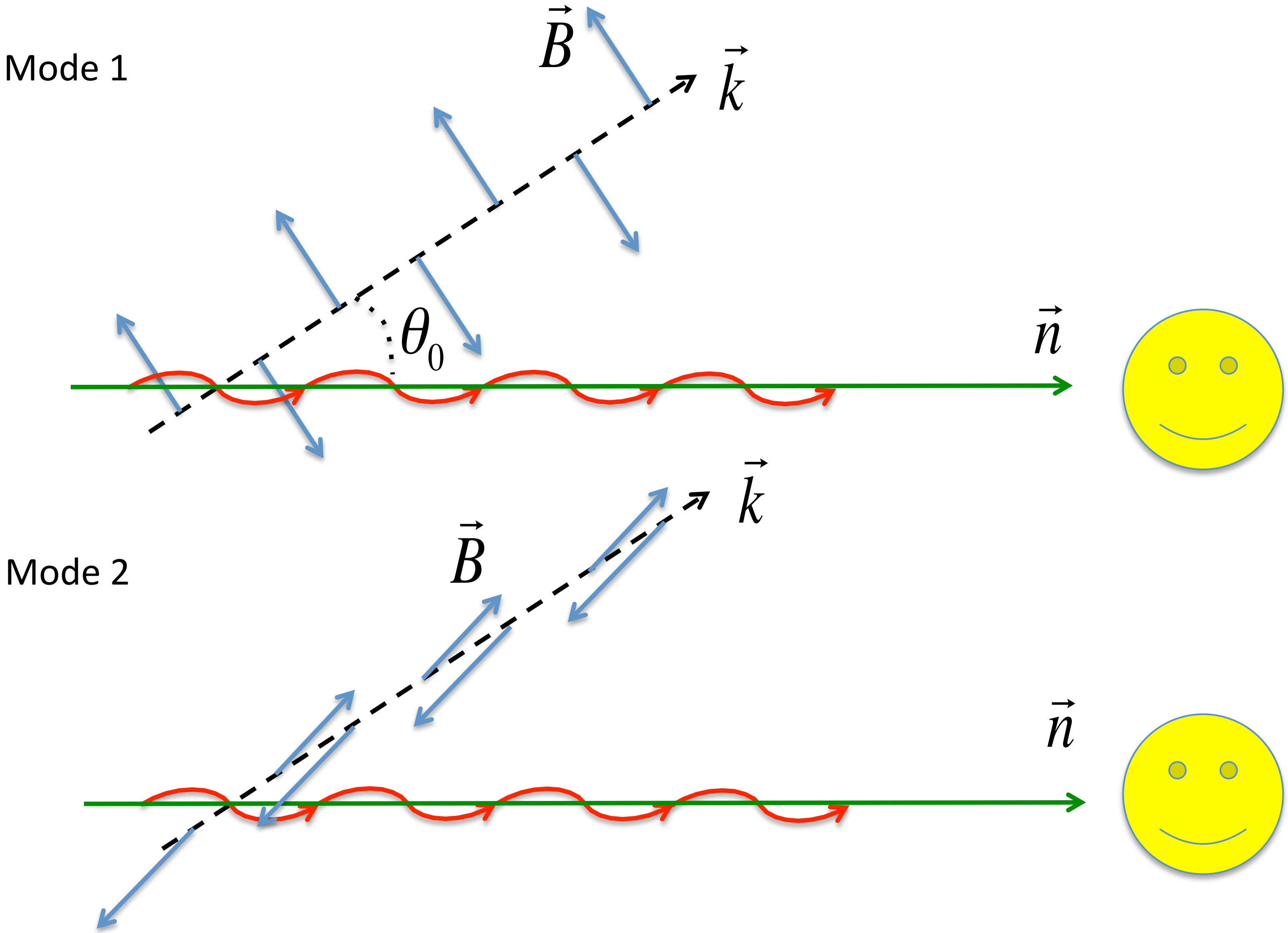
V_0 : electron velocity, $\gamma = 1 \Big/ \sqrt{1 - \frac{V_0^2}{c^2}}$



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

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

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

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

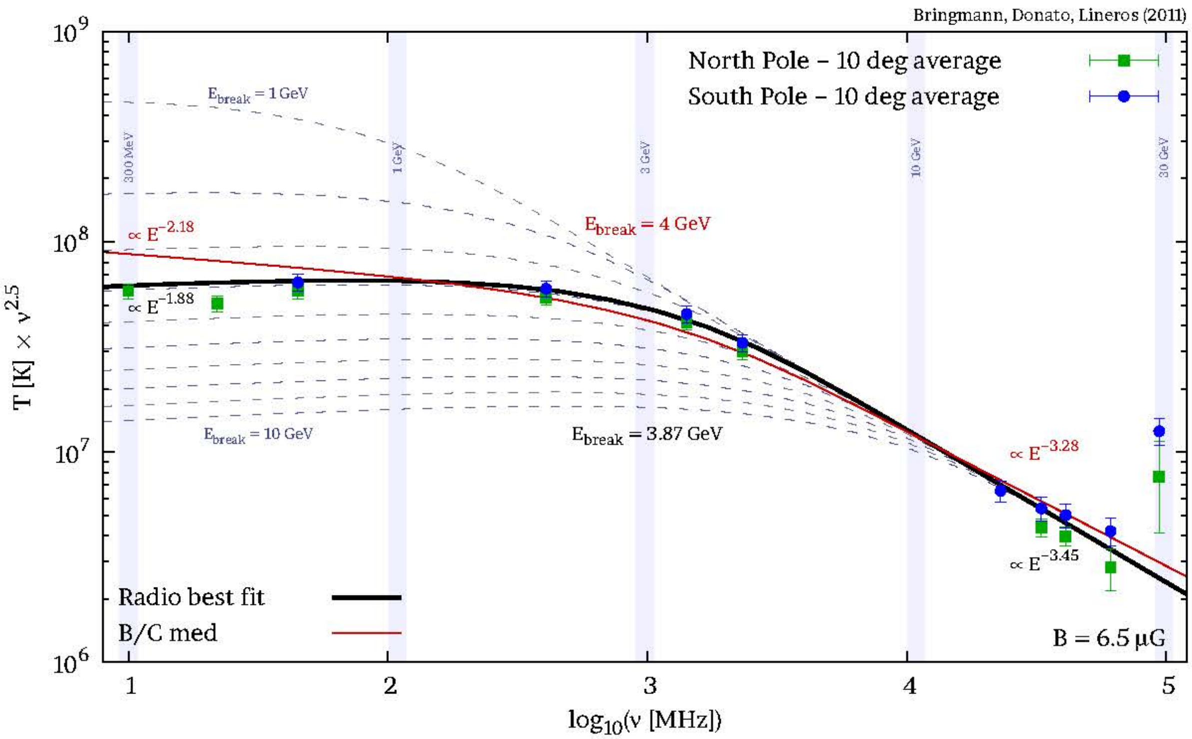
The plasma beta of the back ground plasma.
← Magnetic energy of the ordered magnetic field.

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

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

Galactic relativistic electron energy spectrum model

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



Broken spectrum:

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

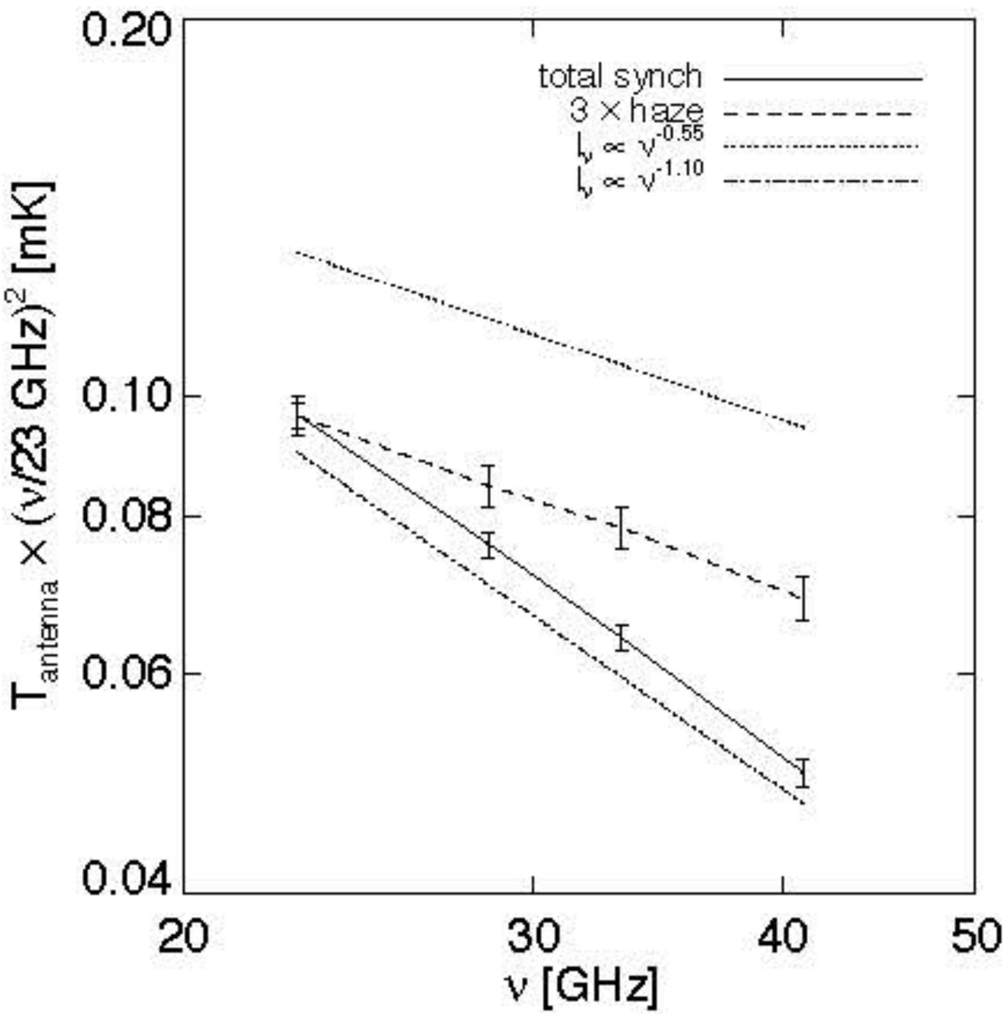
$$= C_q \gamma^{-q}:\ \gamma_2 < \gamma < \gamma_3$$

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

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

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

Galactic relativistic electron energy spectrum model

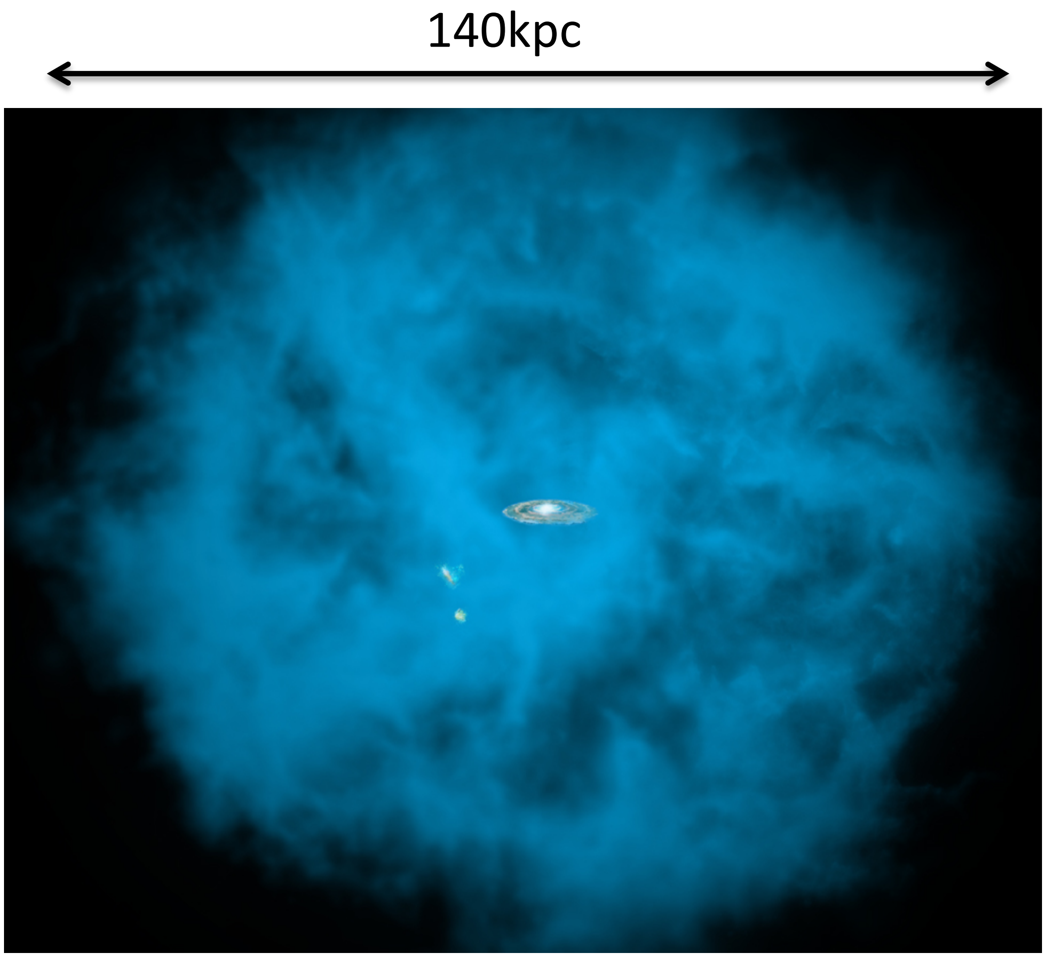


$$T_{Sync}(23\mathrm{GHz}) = 0.098\mathrm{mK}$$

'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)



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

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

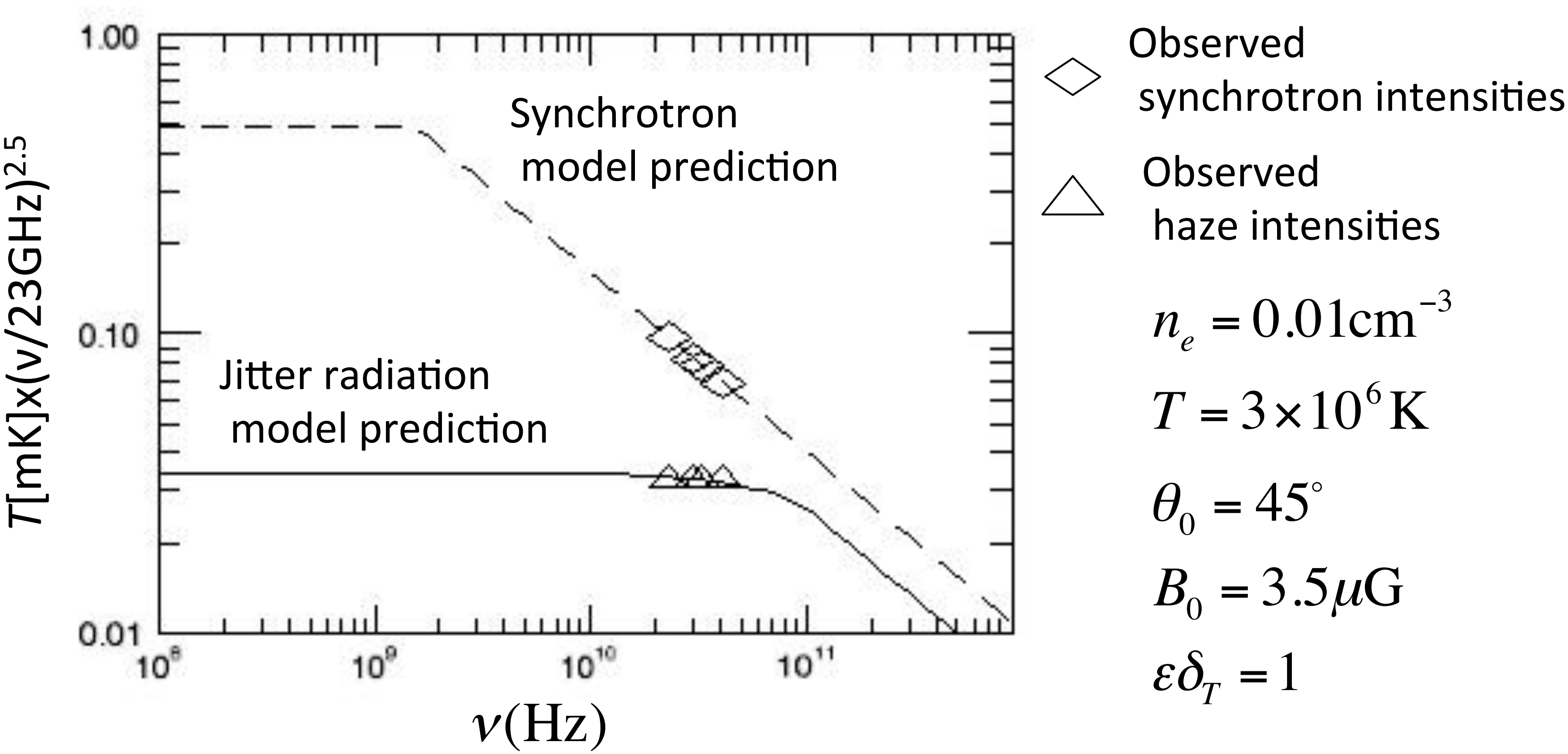
$$\lambda_e \approx 50\mathrm{pc}$$

$$\varepsilon\delta_T \approx 1 \rightarrow$$

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



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

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

$\theta_0 = 45^\circ$

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

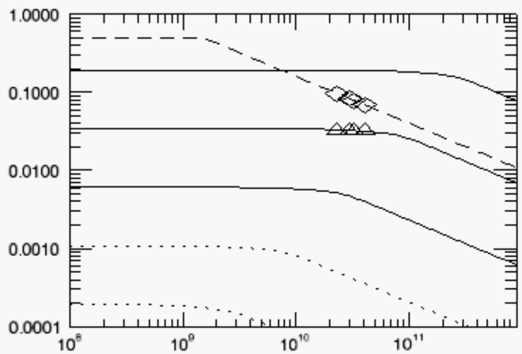
$\varepsilon\delta_T = 1$

Dependences on parameters

—— $\varepsilon\delta_T = 1$

· · · · · $= 0.1$

B=3.5μG

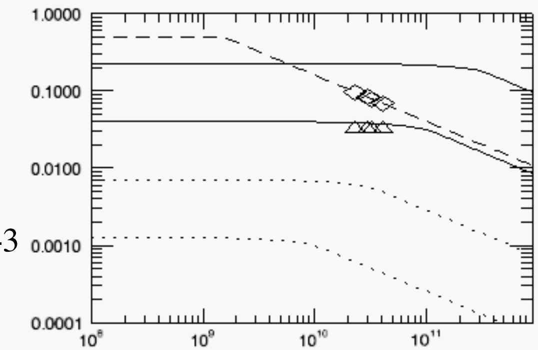


$n_e = 0.1\mathrm{cm}^{-3}$

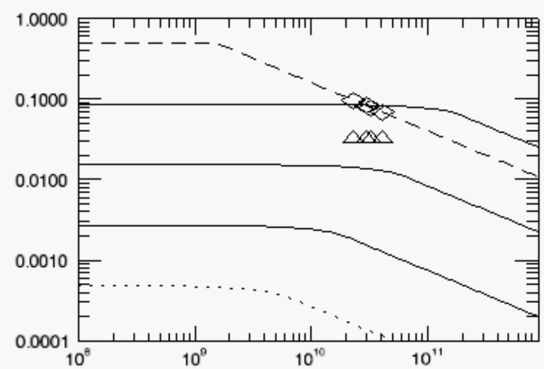
$n_e = 0.01\mathrm{cm}^{-3}$

$n_e = 0.001\mathrm{cm}^{-3}$

B=1μG



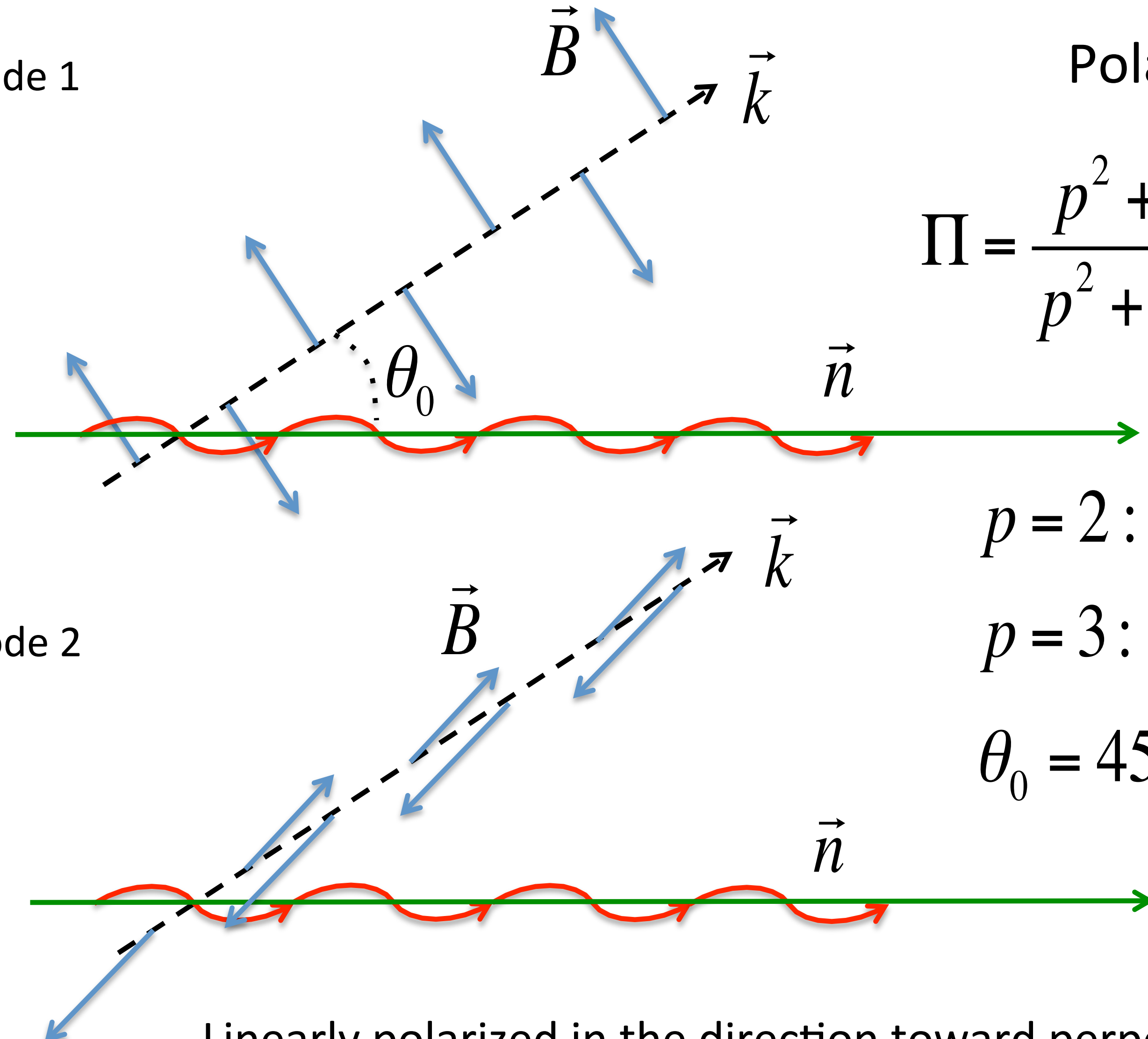
B=6μG



Polarization of the Jitter radiation

Mode 1

Mode 2



Polarization degree

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

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

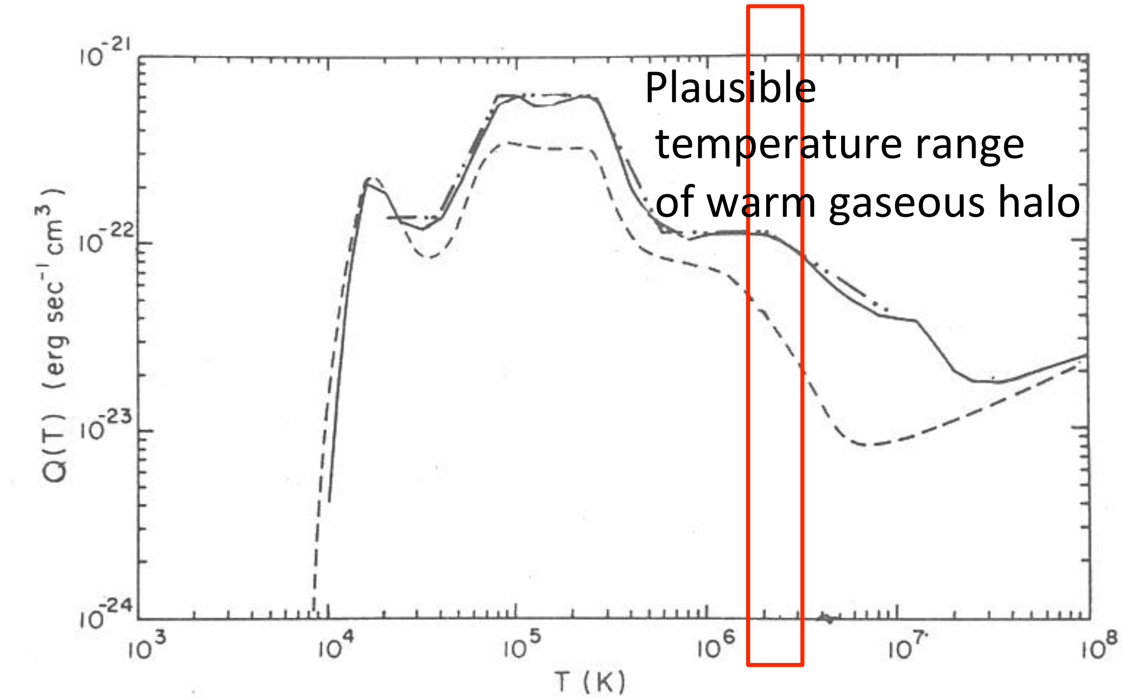
$$p=3:\ \Pi=0.21$$

$$\theta_0=45^\circ$$

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

Physical conditions of gaseous halo

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



$$t_{cool} \approx 3.5\times10^7\,\mathrm{yr}\left(\frac{n_e}{0.01\mathrm{cm}^{-3}}\right)^{-1}$$

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

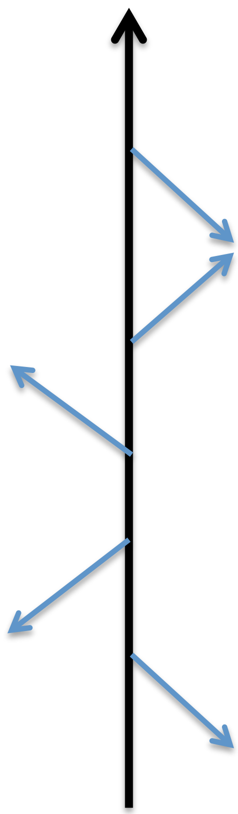
$$\times\left(\frac{n_e}{0.01\mathrm{cm}^{-3}}\right)\left(\frac{T}{3\times10^6\,\mathrm{K}}\right)^{-2.5}\left(\frac{L}{1\mathrm{pc}}\right)^2$$

$$t_{heat\_cond\_\perp\vec{B}} \approx 10^{47}\left(\frac{n_e}{0.01\mathrm{cm}^{-3}}\right)^{-2}\left(\frac{T}{3\times10^6\,\mathrm{K}}\right)^3\left(\frac{B_W}{3\mu\mathrm{G}}\right)^2 t_{heat\_conduction}$$

$$\gamma_{\max}^{-1} \approx 0.2\,\mathrm{sec}\left(\frac{n_e}{0.01\mathrm{cm}^{-3}}\right)^{-0.5}\left(\frac{T_e}{3\times10^6\,K}\right)^{-0.5}\left(\frac{\varepsilon\delta_T}{1.0}\right)^{-3}$$

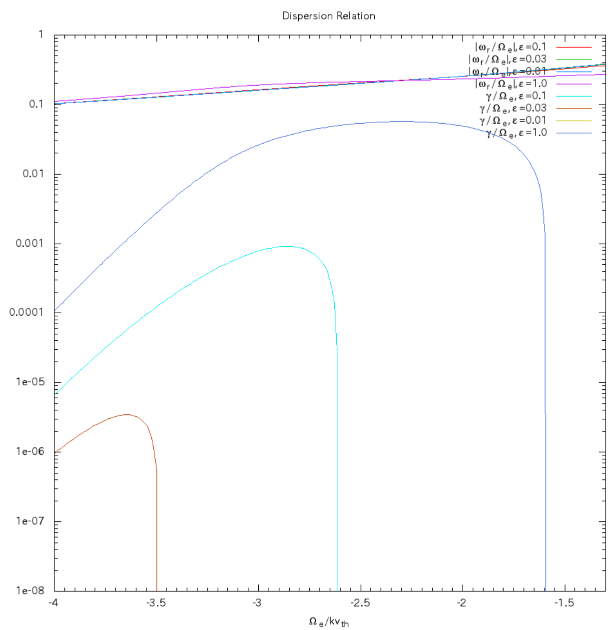
Effect of background magnetic field dispersion relation

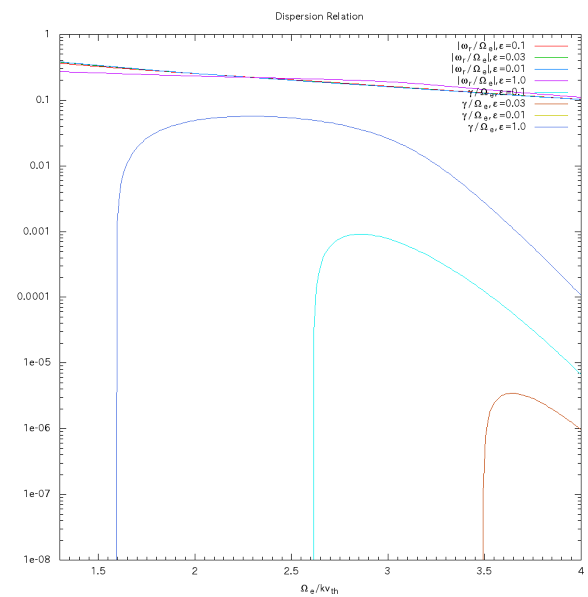
B//k//grad T



Helical mode:

left handed n=+ 1 right handed n=-1

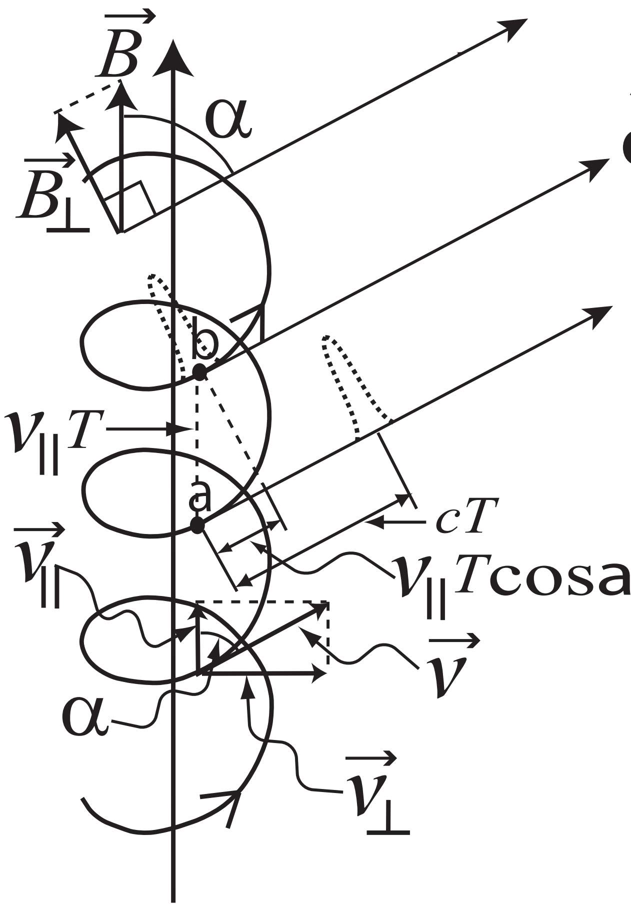


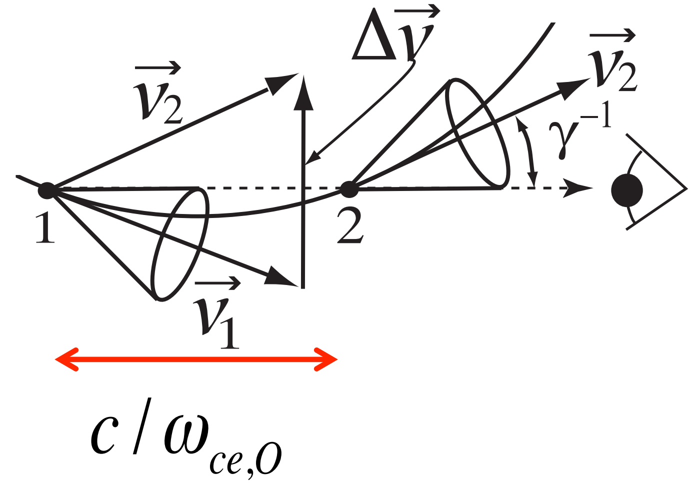


$$\omega_{ce} / kV_{th} \approx 1 \Rightarrow kc \approx \omega_{ce} c / V_{th} \approx \sqrt{2}\beta^{-0.5}\omega_{pe}$$

$$\omega_{Jitter} \approx 2\gamma^2 kc \approx \gamma^2 \omega_{pe}$$

Effect of background magnetic field
Jitter radiation



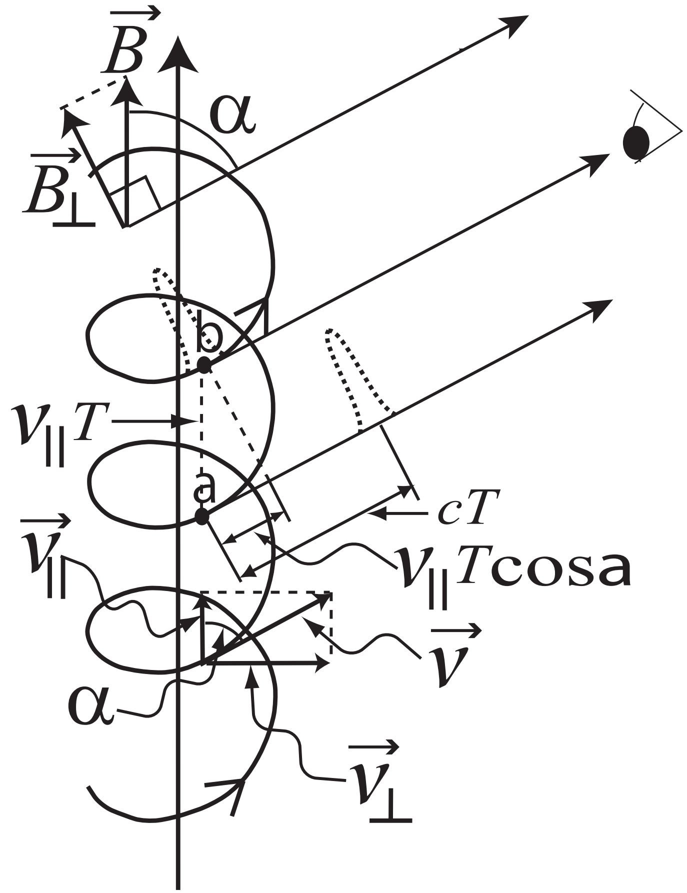


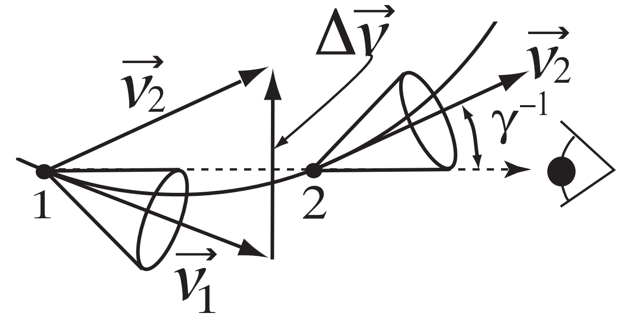
$$\frac{c}{\omega_{ce,O}} k_{\max} \approx \frac{\omega_{ce,W}}{\omega_{ce,O}} \frac{k_{\max}}{\omega_{ce,W}} c$$

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

Jitter radiation is superposed onto the synchrotron emission

Effect of background magnetic field Jitter radiation





$$\omega_{se} = \frac{\omega_{ce}}{\gamma}$$

$$T_0\omega_{se} = 2\pi, \quad T'\omega_{se} = 2/\gamma \Rightarrow \frac{T'}{T_0} = \frac{1}{\pi\gamma}$$

Jitter radiation power from a single electron

$$P_{Jitter-with-B} = \frac{1}{\pi\gamma} P_{Jitter-no-B}$$

Effect of background magnetic field Jitter radiation

$$I_{Jitter-B}(\nu) = \frac{1}{2\pi}\frac{e^2}{c}\frac{\omega_{ce,W}^2}{\omega_0} C_e \left(\frac{2\pi\nu}{\omega_0}\right)^{-\frac{p}{2}} f(p)$$

$$\frac{I_{Jitter-B}}{I_{Jitter-no-B}} \approx \left(\frac{2\pi\nu}{\omega_0}\right)^{-\frac{1}{2}} \approx 10^{-4}\left(\frac{\nu}{100GHz}\right)^{-0.5}\left(\frac{n_e}{0.01cm^{-3}}\right)^{0.5}$$

Far from Haze spectrum:

too small amplitude & steeper spectrum shape

Polarization:

Weakly circularly polarized

Discussion

- Plasma kinetic instability could be another route to excite Galactic turbulent magnetic field
- If 50% of the volume of the halo is occupied by non magnetized gas, Jitter radiation due to Weibel turbulence in warm gaseous halo could fit the Galactic Haze spectrum in microwave but requires. Could it be?
- Warm gaseous halo is dominated by Weibel turbulent magnetic field and is occupied by relativistic electron which has the similar characteristics as the Galactic central region.
- If 100% of the halo gas is magnetized, spectrum shape of the Jitter radiation is far from that of the micro wave Haze. Amplitude is too small and spectrum shape is too steep compared with that of Micro wave Haze.
- Gamma ray Haze: IC by $\gamma=10^4$ source photon $h\nu=10\mathrm{GeV}/\gamma^2$ =0.1keV; free-free from warm halo but amplitude is 10^{-4} times smaller. A small fraction of the Gamma ray Haze could be this origin.