Formation Process of the Outer Radiation Belt Through Nonlinear Interaction with Chorus Emissions Localized in Longitude

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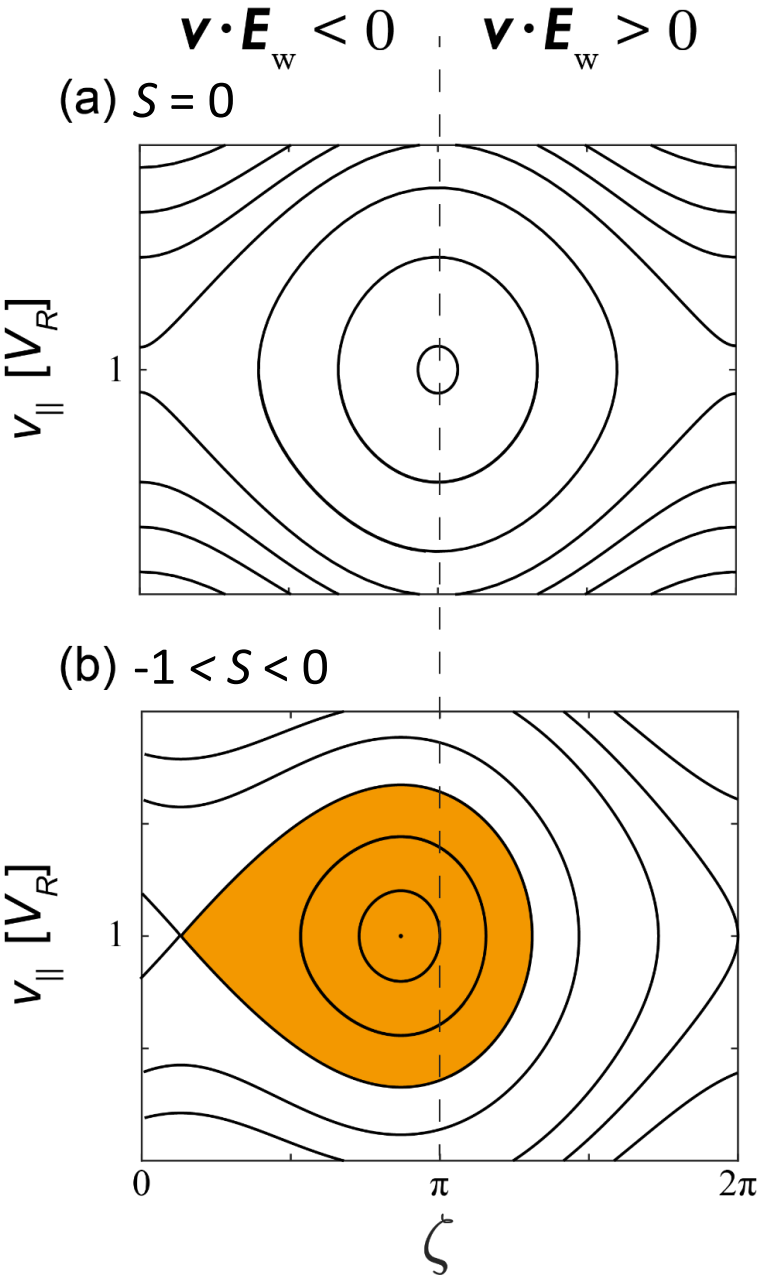
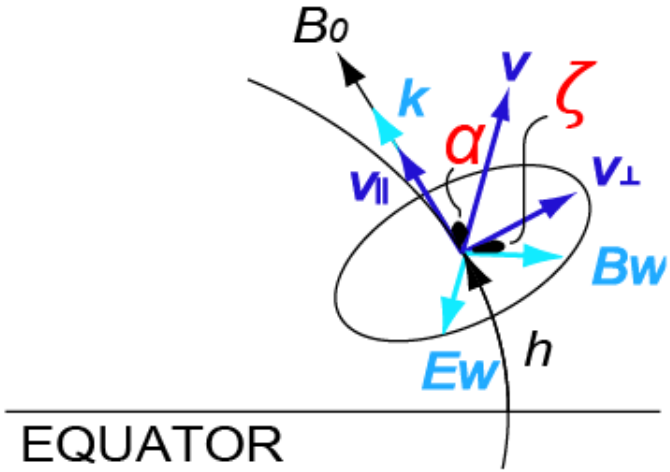
Electron Acceleration by Chorus Emissions





$$\frac{\mathrm{d}\zeta}{\mathrm{d}t} = \theta$$

$$\frac{d\theta}{dt} = \omega_{tr}^2 \left(\sin\zeta + S\right)$$

$$\theta = k(v_{\parallel} - V_R)$$

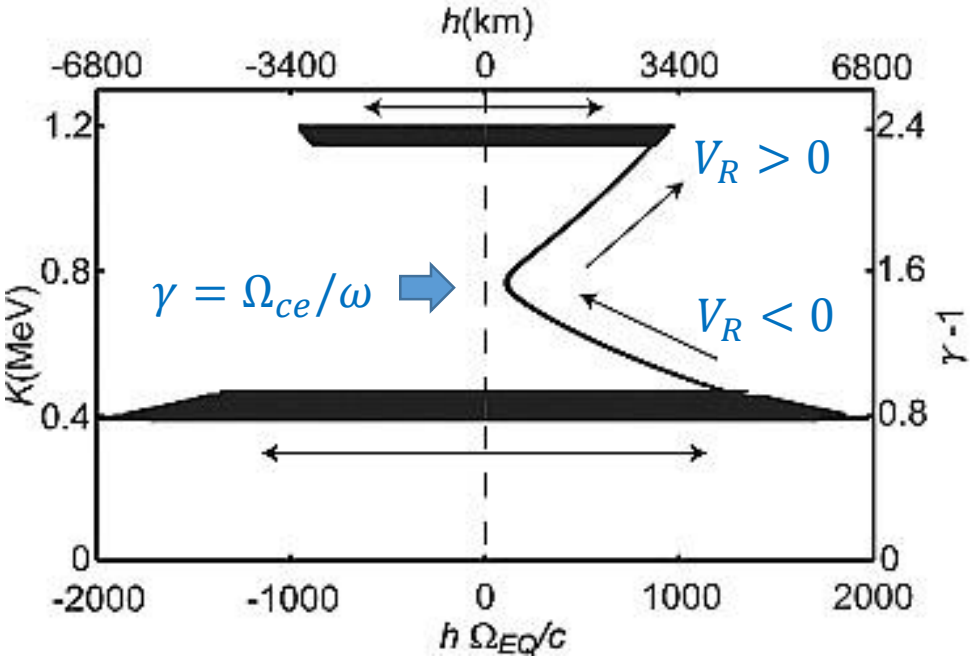
$$S = -\frac{1}{s_0 \omega \Omega_w}\left(s_1 \frac{\partial \omega}{\partial t} + c s_2 \frac{\partial \Omega_{ce}}{\partial h}\right)$$

[*Omura et al., JGR, 2007,* 2008]

Two Nonlinear Acceleration Processes

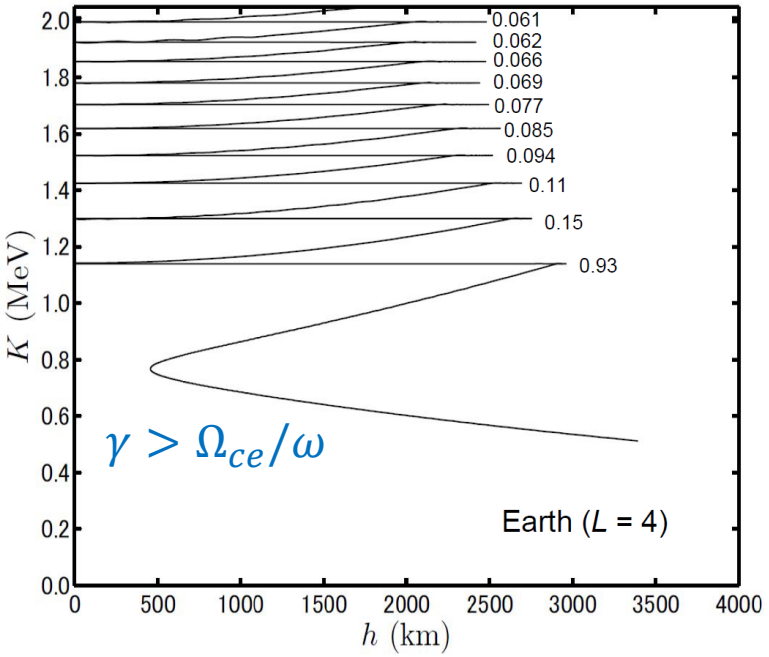
$$V_R = \frac{\omega - \Omega_{ce}/\gamma}{k} \qquad \gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$

Relativistic Turning Acceleration（RTA）



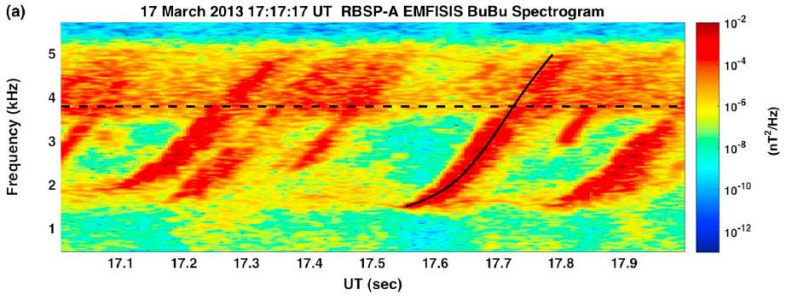
[*Omura,et al., 2007*]

Ultra-Relativistic Acceleration (URA)

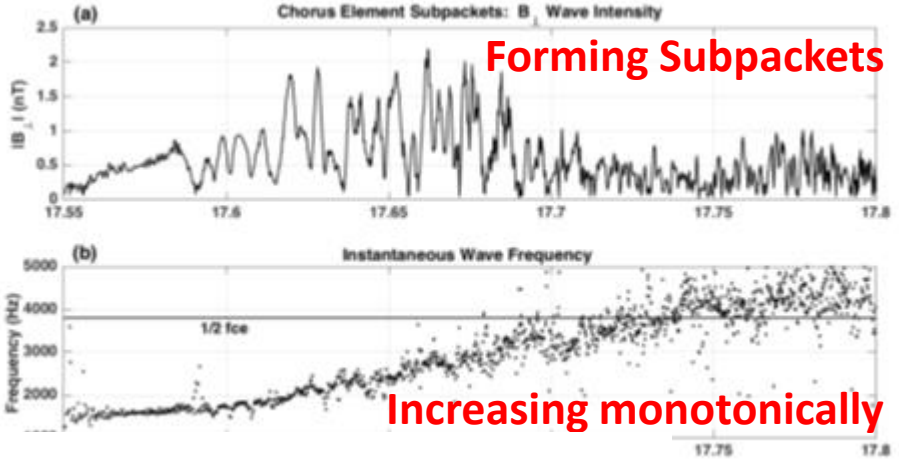


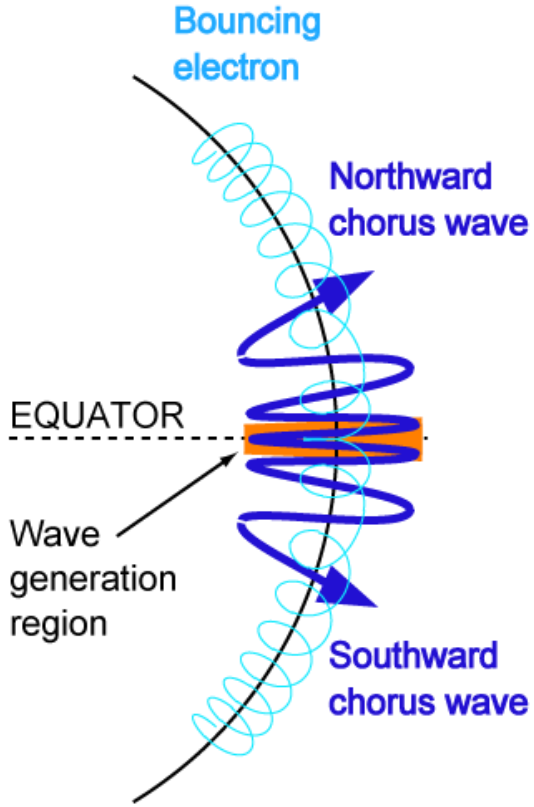
[*Summers and Omura, 2007*]

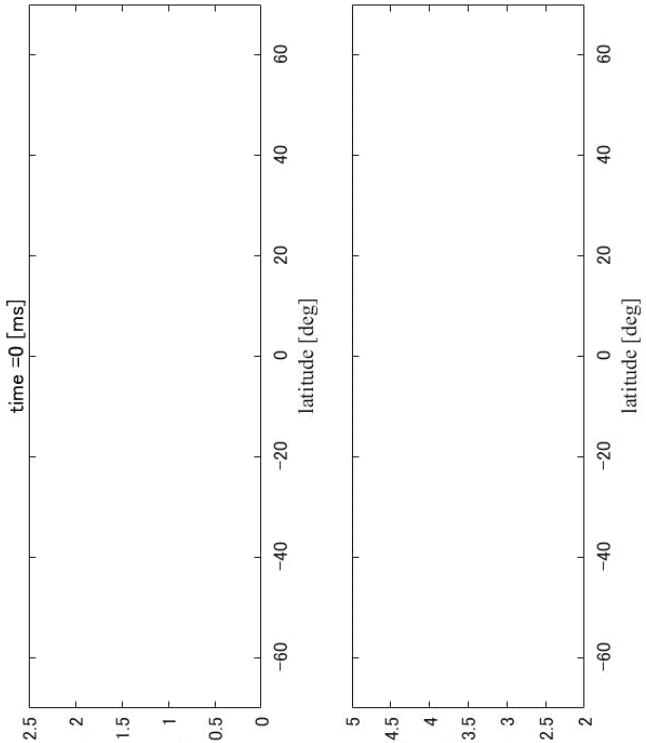
Chorus Waves



[*Foster et al.*, 2017]

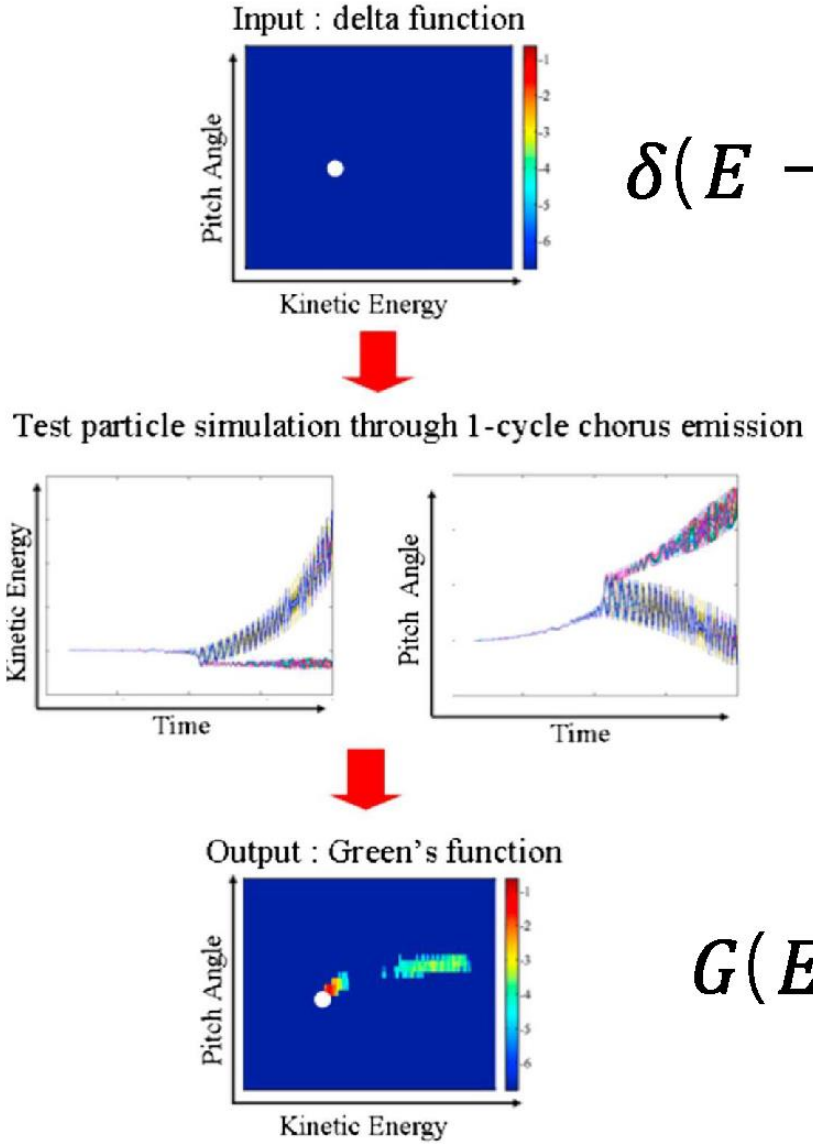






B_w [nT] f [kHz]

Numerical Green's Functions



$$\delta(E - E_0, \alpha - \alpha_0)$$

$$\times$$

$$C$$

$$m_e \frac{d(\gamma \boldsymbol{v})}{dt} = -e\left[\boldsymbol{E}_w + \boldsymbol{v} \times (\boldsymbol{B}_0 + \boldsymbol{B}_w)\right]$$

$$||$$

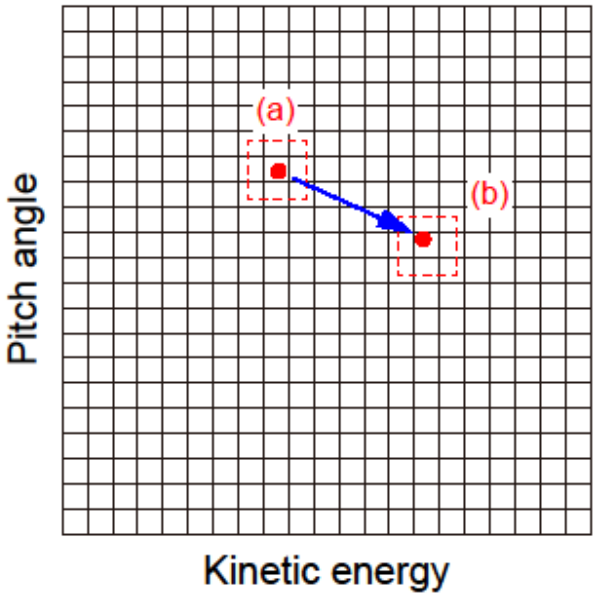
$$G(E, E_0, \alpha, \alpha_0)$$

[*Omura et al.*, 2015]

Numerical Green's Functions

$$G(E,E_0,\alpha,\alpha_0)=\frac{\tilde{A}(E_0,\alpha_0)}{\tilde{A}(E,\alpha)}\times\frac{N_p(E,E_0,\alpha,\alpha_0)}{N_{p0}(E_0,\alpha_0)\Delta E\Delta\alpha}$$

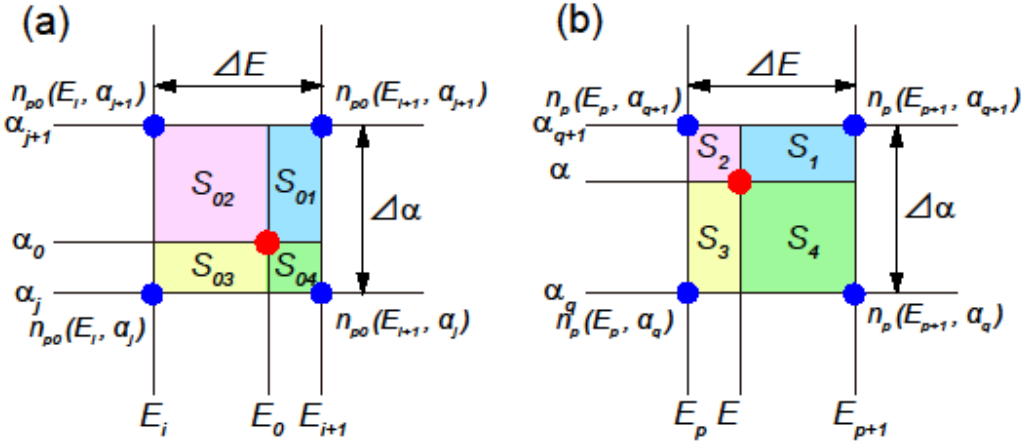
$$N_{p0}(E_i,\alpha_j)=\sum_{E_k}\sum_{\alpha_l}N_p(E_k,E_i,\alpha_l,\alpha_j)\ .$$



$$\int_\alpha\int_E\frac{N_p(E,E_0,\alpha,\alpha_0)}{N_{p0}\,(E_0,\alpha_0)\Delta E\Delta\alpha}dEd\alpha$$

$$=\sum_\alpha\sum_E\frac{N_p(E,E_0,\alpha,\alpha_0)}{N_{p0}\,(E_0,\alpha_0)\Delta E\Delta\alpha}\Delta E\Delta\alpha=1$$

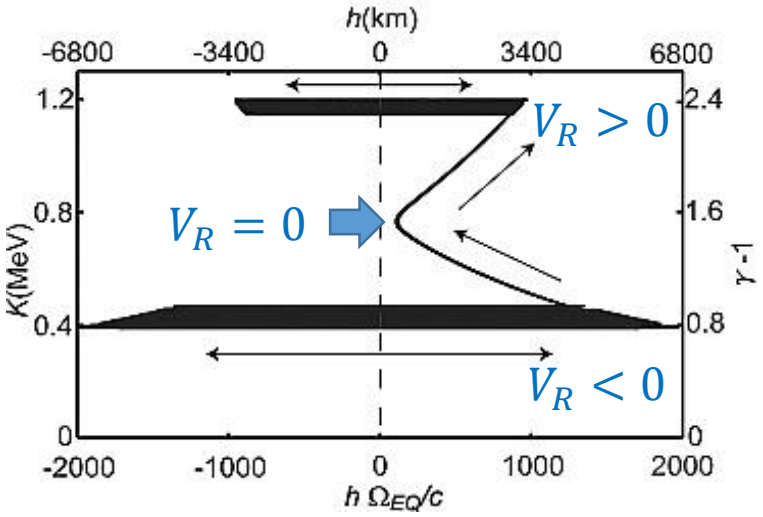
$$\int_\alpha\int_E\delta(E-E_0,\alpha-\alpha_0)dEd\alpha=1$$



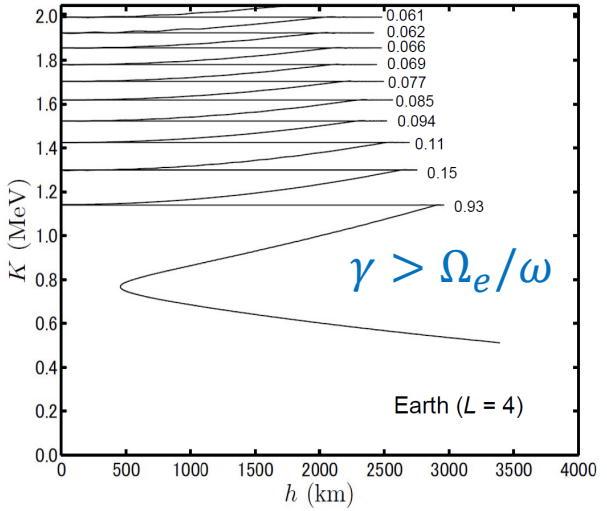
Relativistic Turning Acceleration（RTA）

Ultra-Relativistic Acceleration (URA)

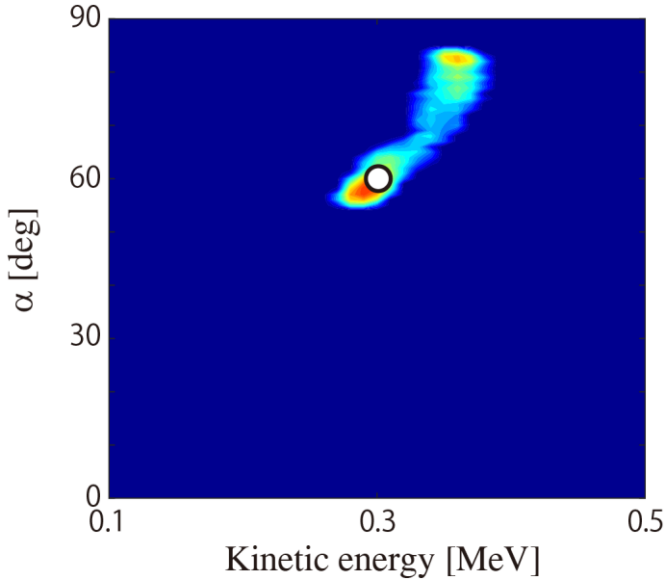
$$V_R = \frac{\omega - \Omega_{ce}/\gamma}{k}$$

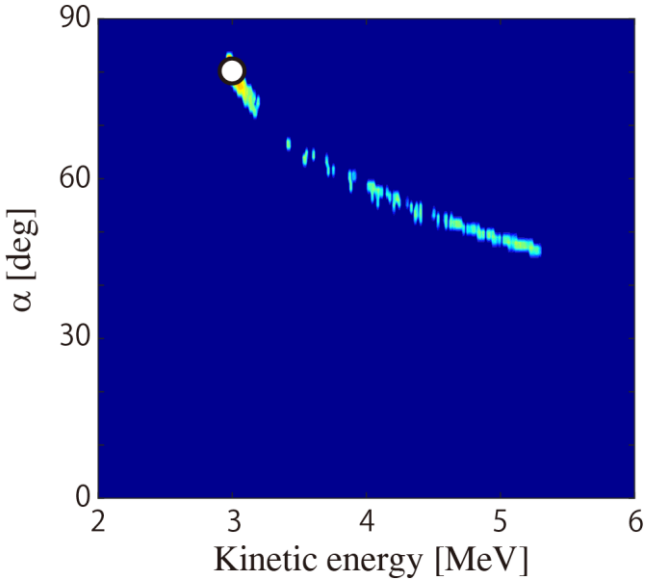


[*Omura,et al, JGR, 2007*]



[*Summers and Omura, GRL, 2007*]





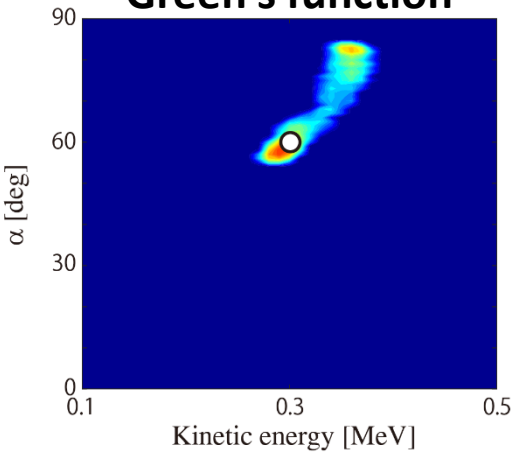
Numerical Green's Function Method

Test particle simulation: Linearity

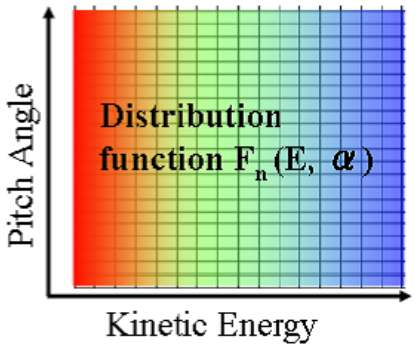
$$C[f_a + f_b] = C[f_a] + C[f_b]$$

$$wC[f_a] = C[wf_a]$$

Green's function



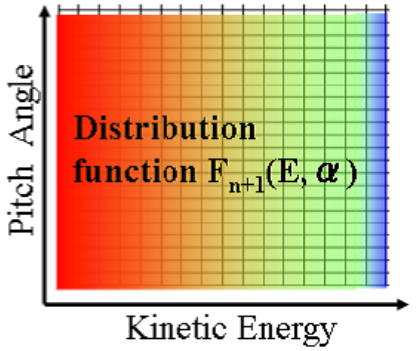
Input : Electron distribution function at n cycles



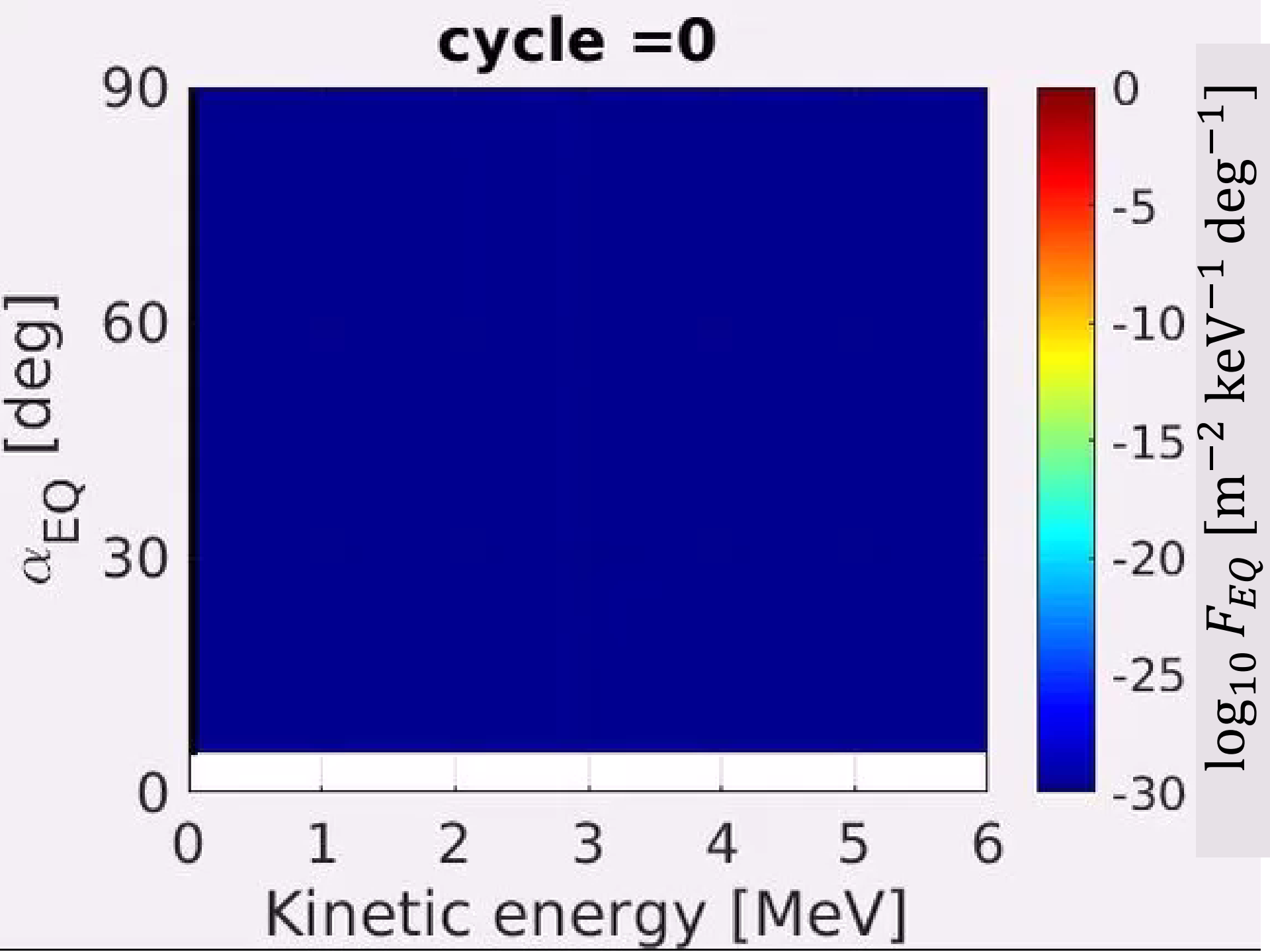
Convolution integral

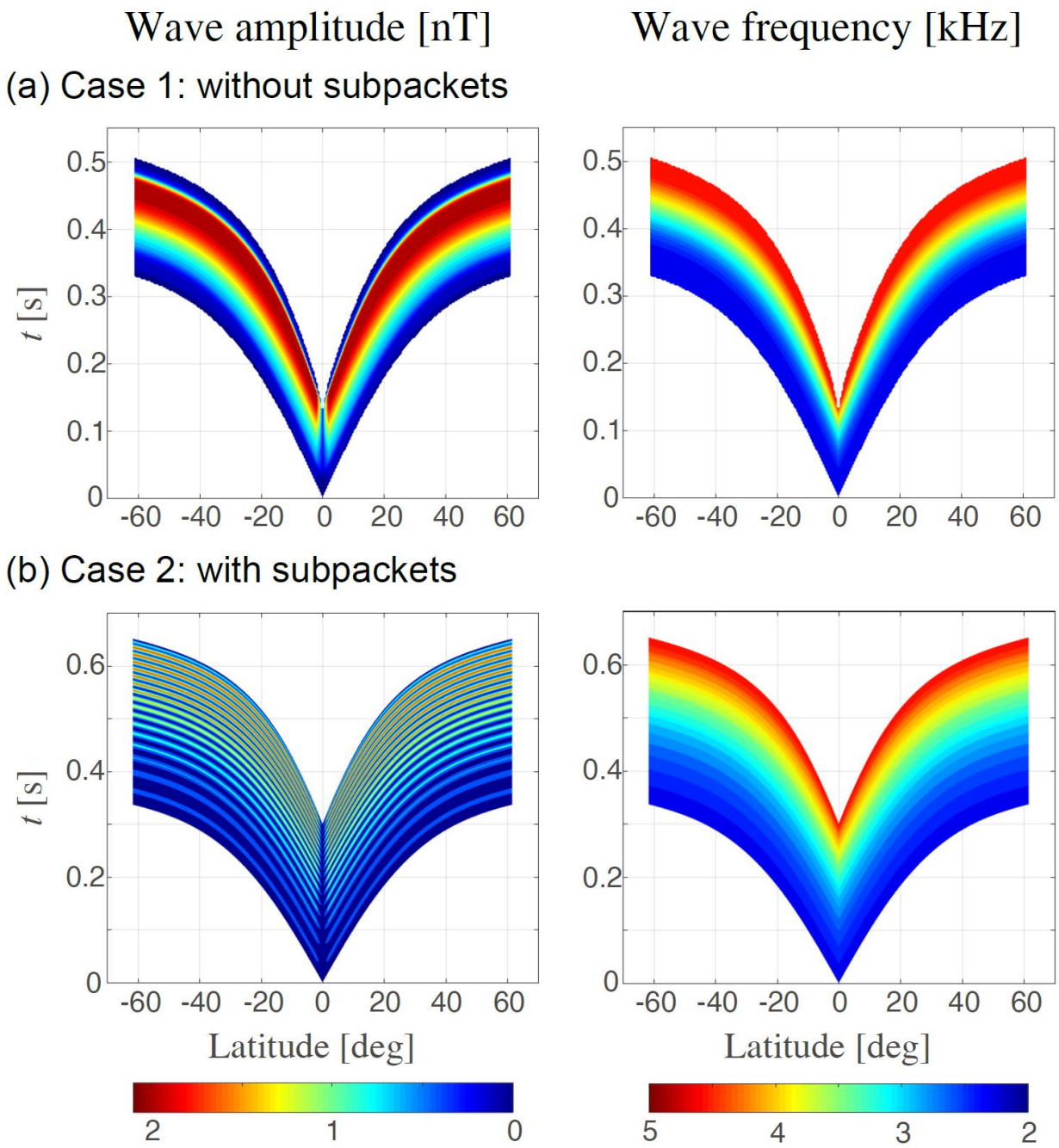
$$f_n(E,\alpha) = \sum_{a_0}\sum_{E_0} f_{n-1}(E_0,\alpha_0)G(E,E_0,\alpha,\alpha_0)\Delta E\Delta\alpha$$

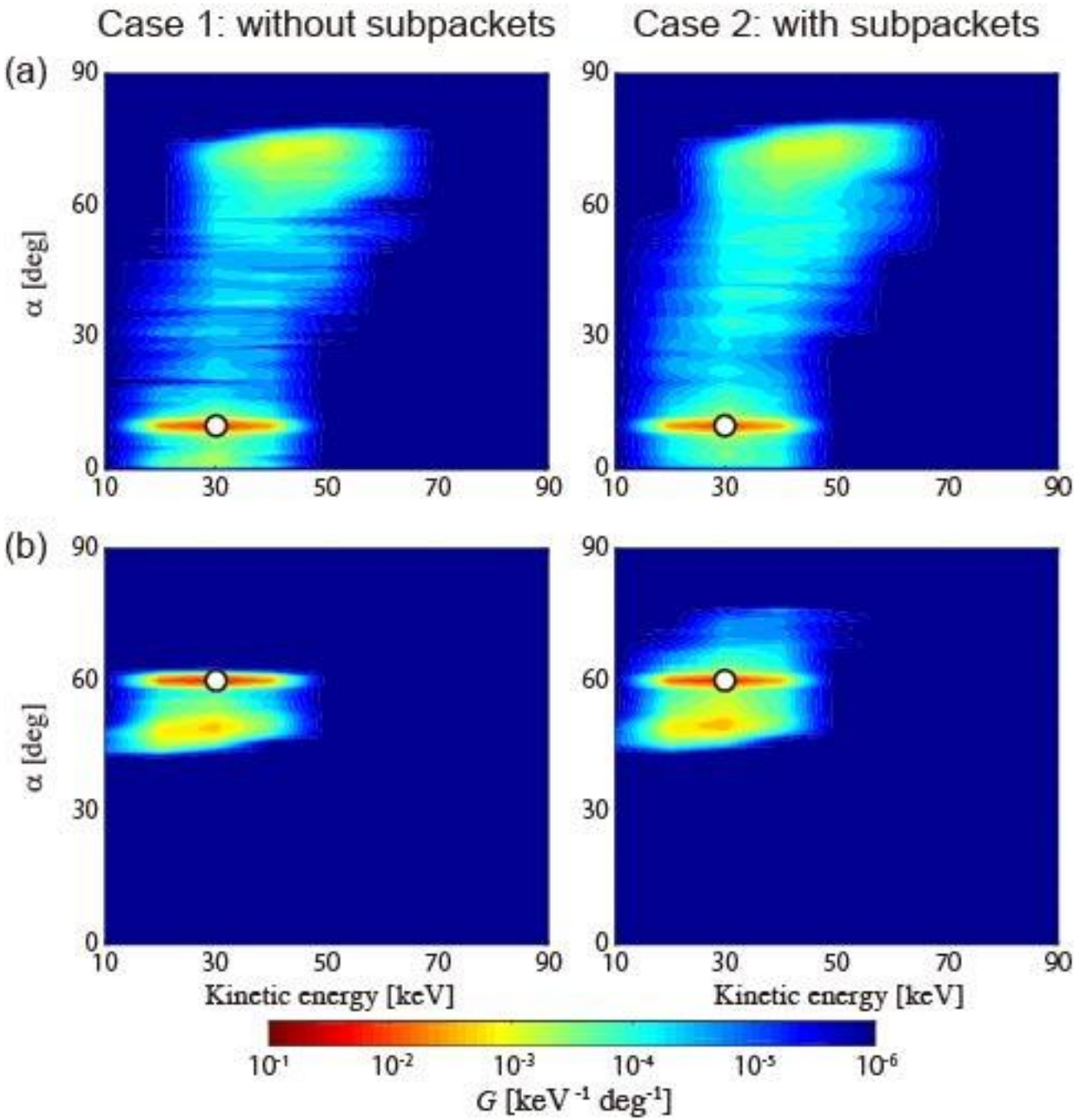
Output : Distribution after n+1 cycle chorus emission

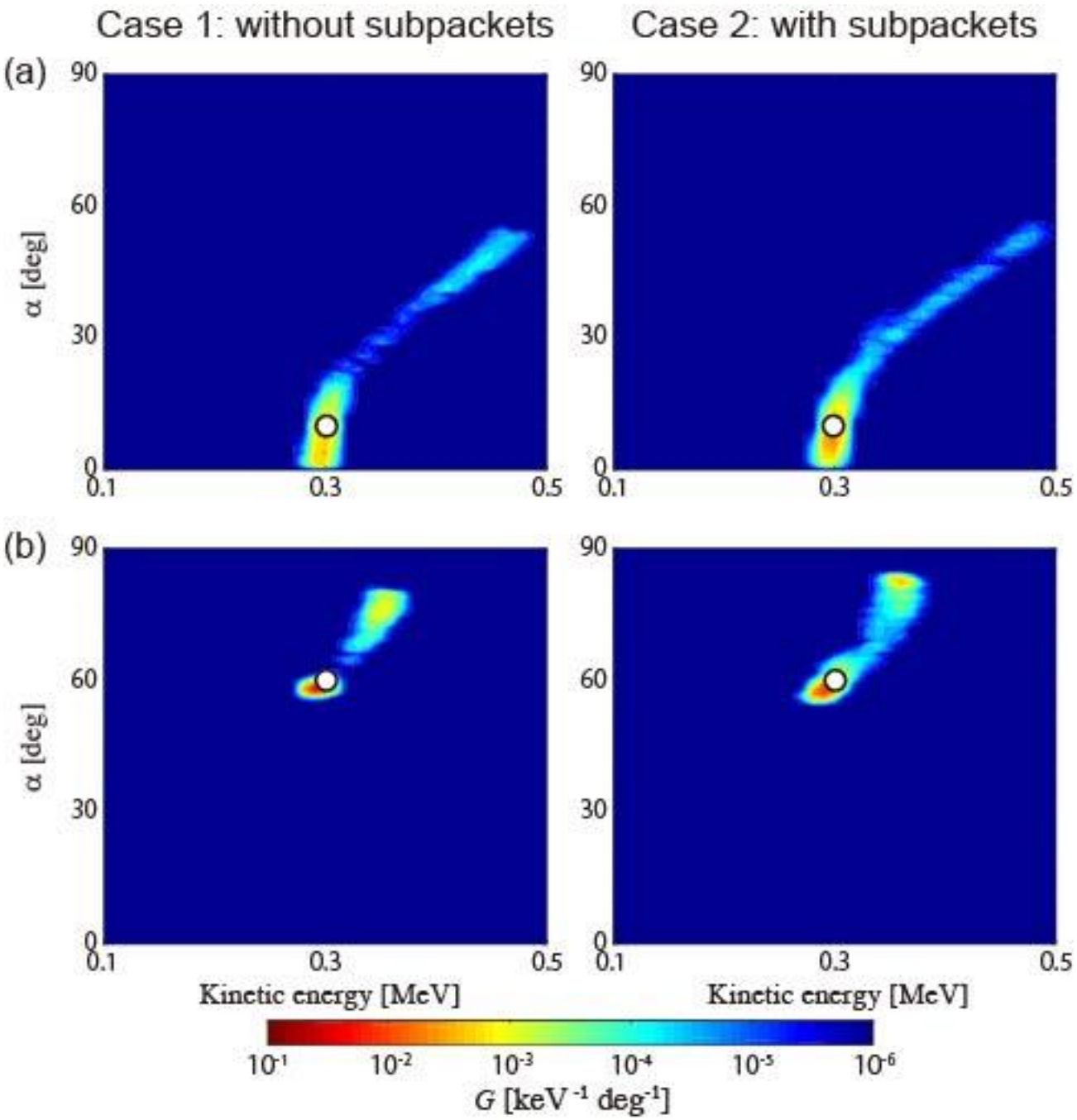


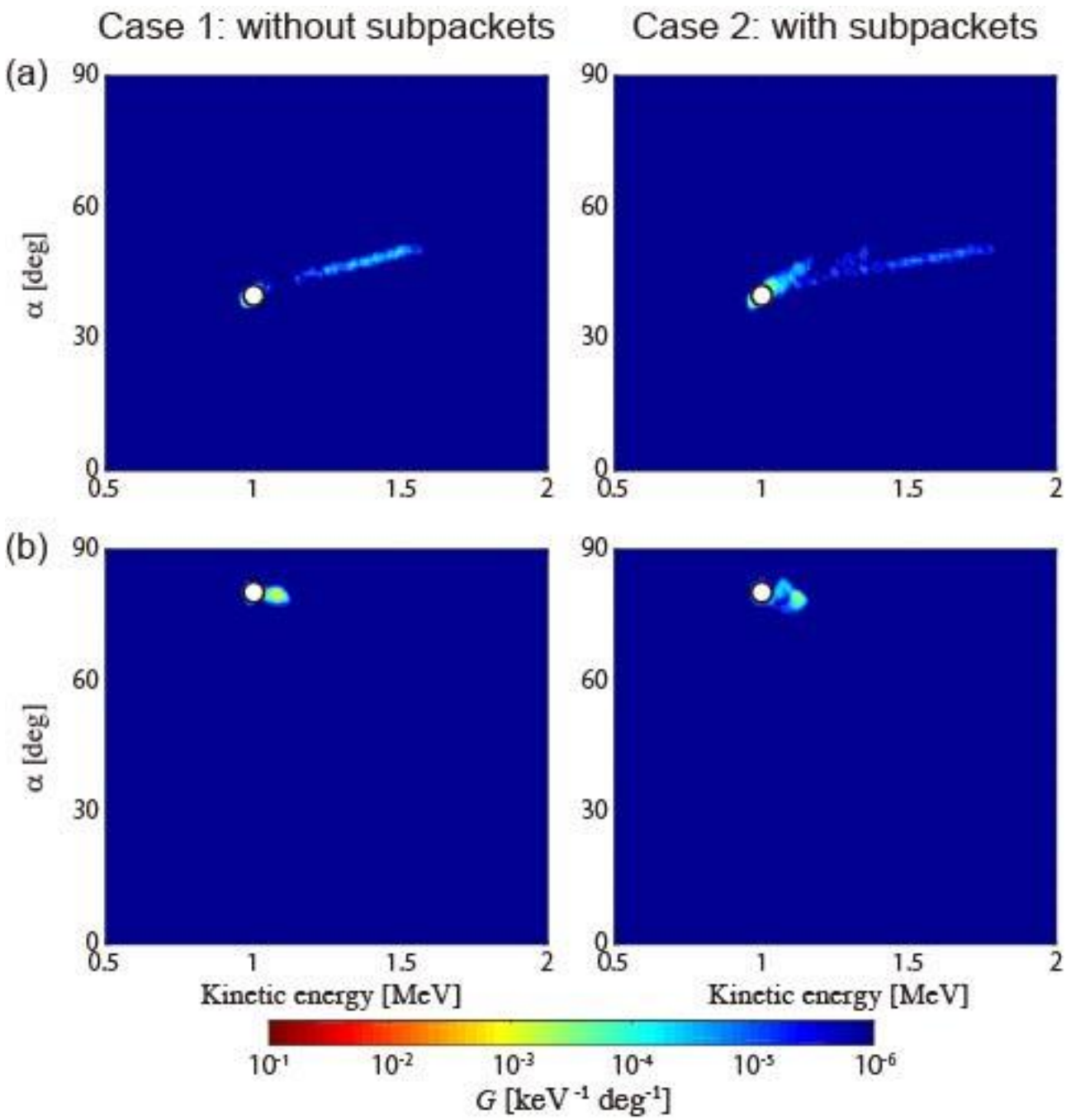
[*Omura et al.*, 2015]

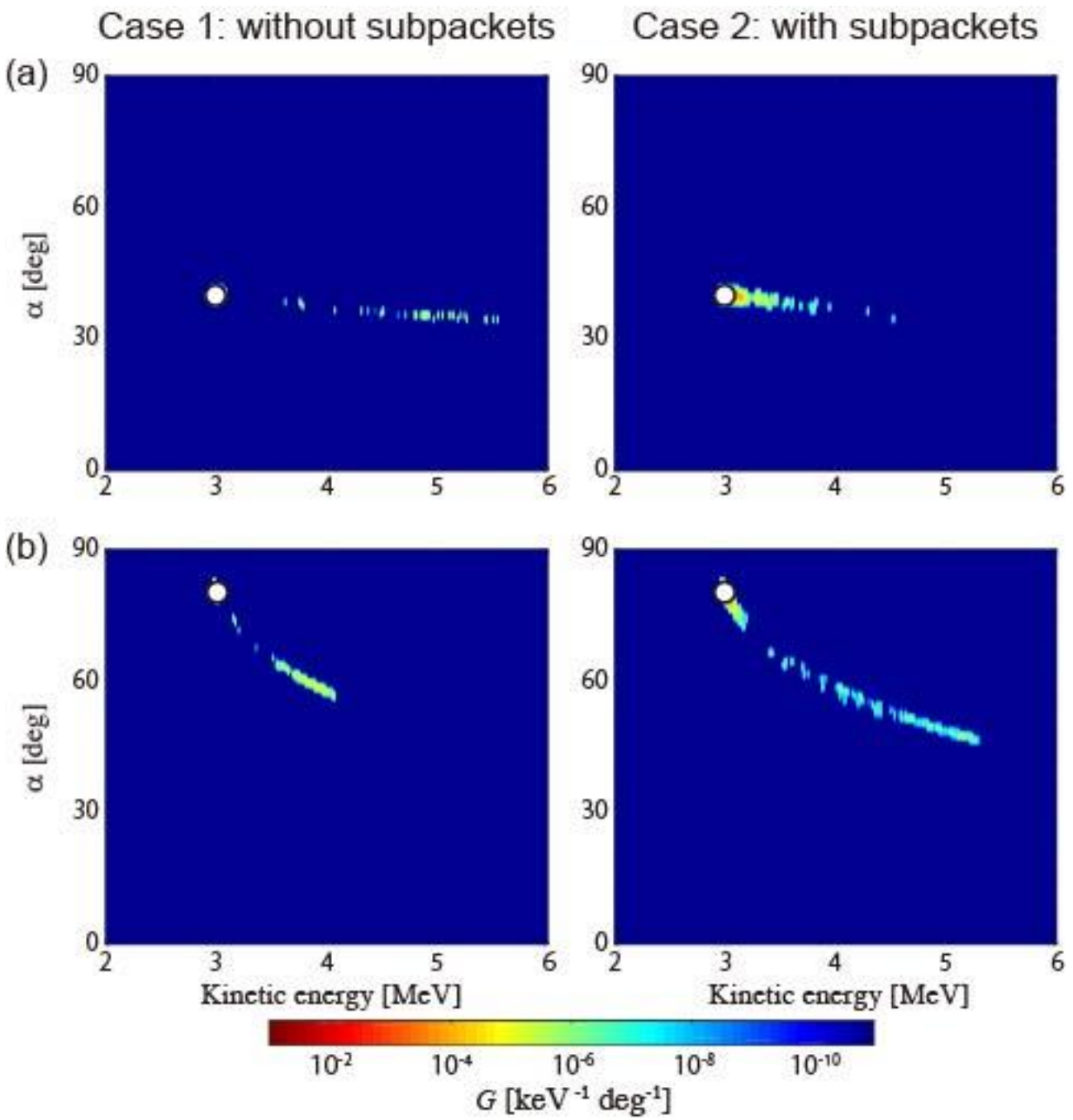

cycle =0
90
60
30
0
α_{EQ} [deg]
0
1
2
3
4
5
6
Kinetic energy [MeV]
0
-5
-10
-15
-20
-25
-30
$\log_{10} F_{EQ}$ [m^{-2} keV^{-1} deg^{-1}]

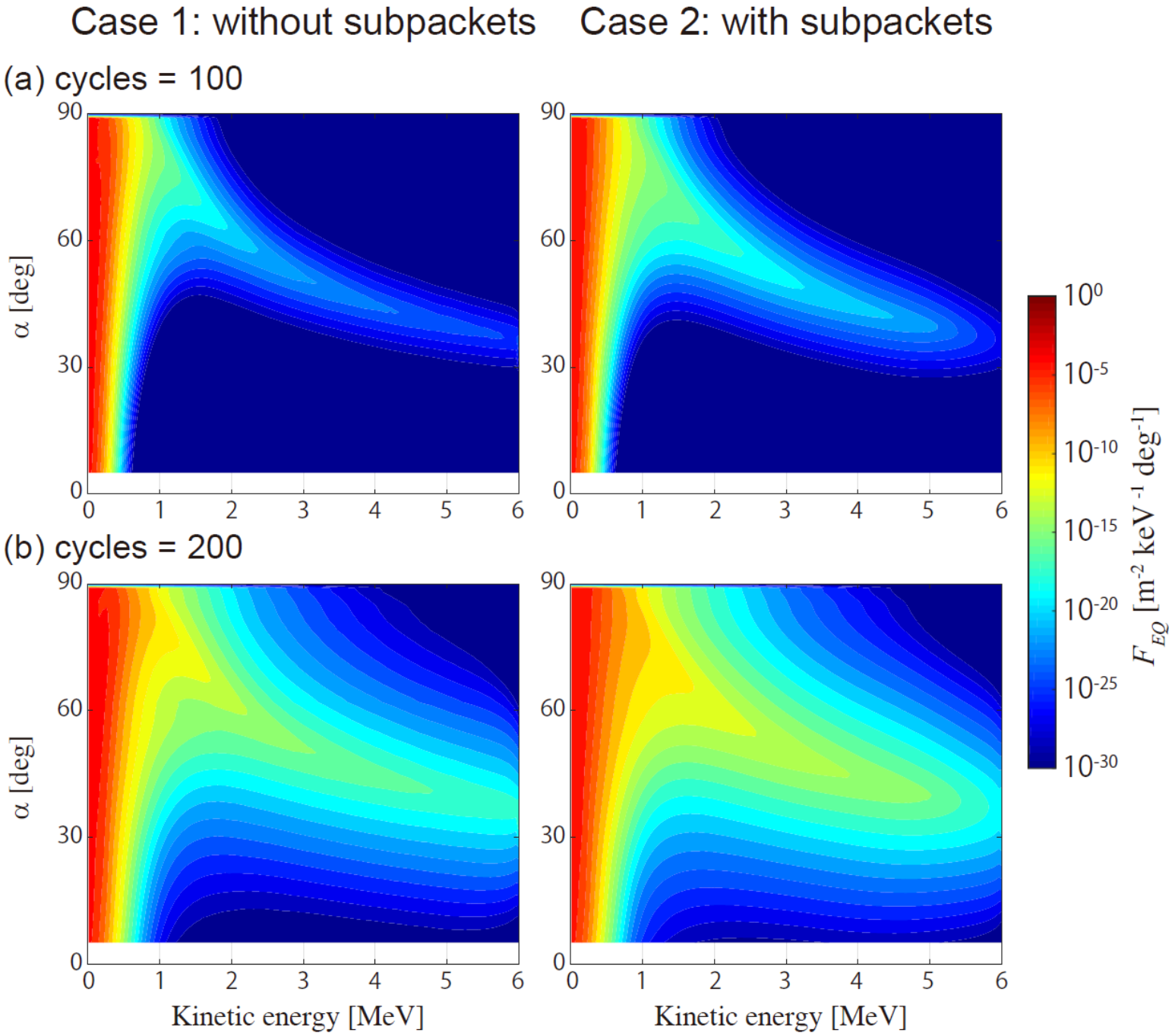

Wave amplitude [nT]
Wave frequency [kHz]
(a) Case 1: without subpackets
(b) Case 2: with subpackets
t [s]
Latitude [deg]
0.5
0.4
0.3
0.2
0.1
0
0.6
-60 -40 -20 0 20 40 60
2 1 0
5 4 3 2

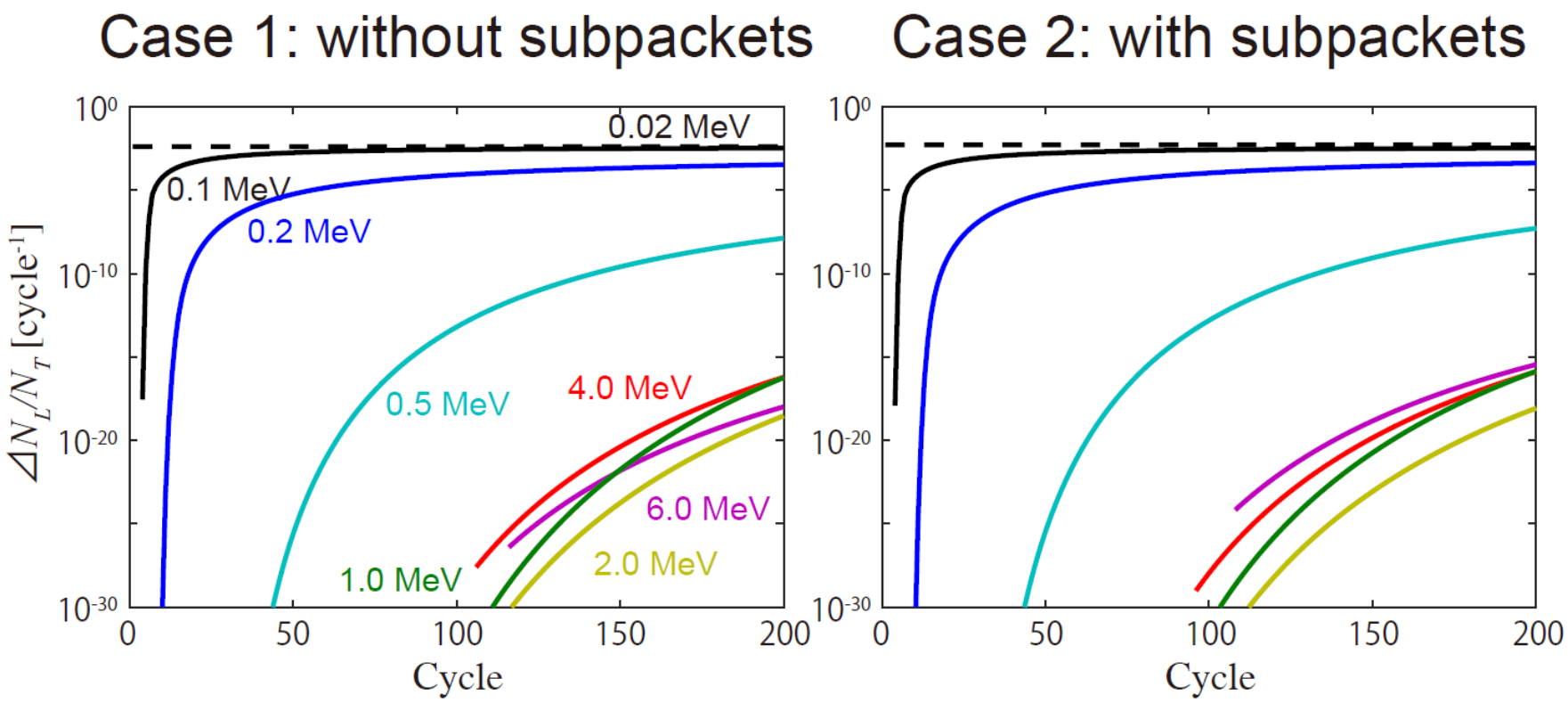

Case 1: without subpackets
Case 2: with subpackets
(a)
(b)
α [deg]
0
30
60
90
10
30
50
70
90
Kinetic energy [keV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
G [keV^{-1} deg^{-1}]


Case 1: without subpackets
Case 2: with subpackets
(a)
(b)
α [deg]
90
60
30
0
0.1
0.3
0.5
Kinetic energy [MeV]
10-1
10-2
10-3
10-4
10-5
10-6
G [keV-1 deg-1]

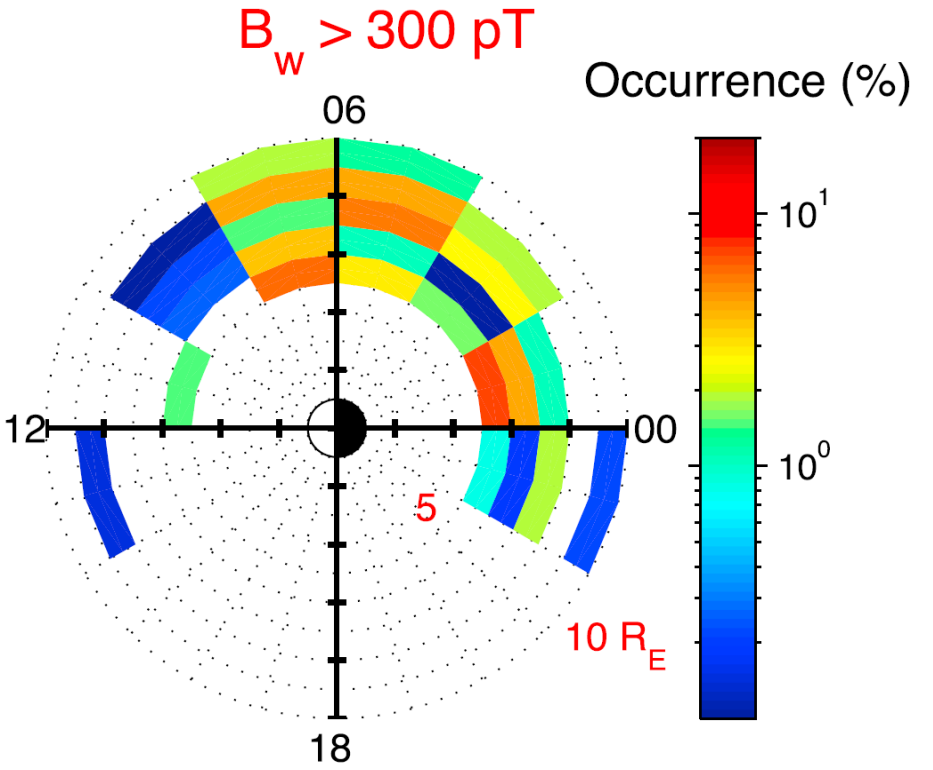

Case 1: without subpackets
Case 2: with subpackets
(a)
(b)
α [deg]
90
60
30
0
0.5
1
1.5
2
Kinetic energy [MeV]
10-1
10-2
10-3
10-4
10-5
10-6
G [keV-1 deg-1]


Case 1: without subpackets
Case 2: with subpackets
(a)
(b)
α [deg]
Kinetic energy [MeV]
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
G [keV^{-1} deg^{-1}]

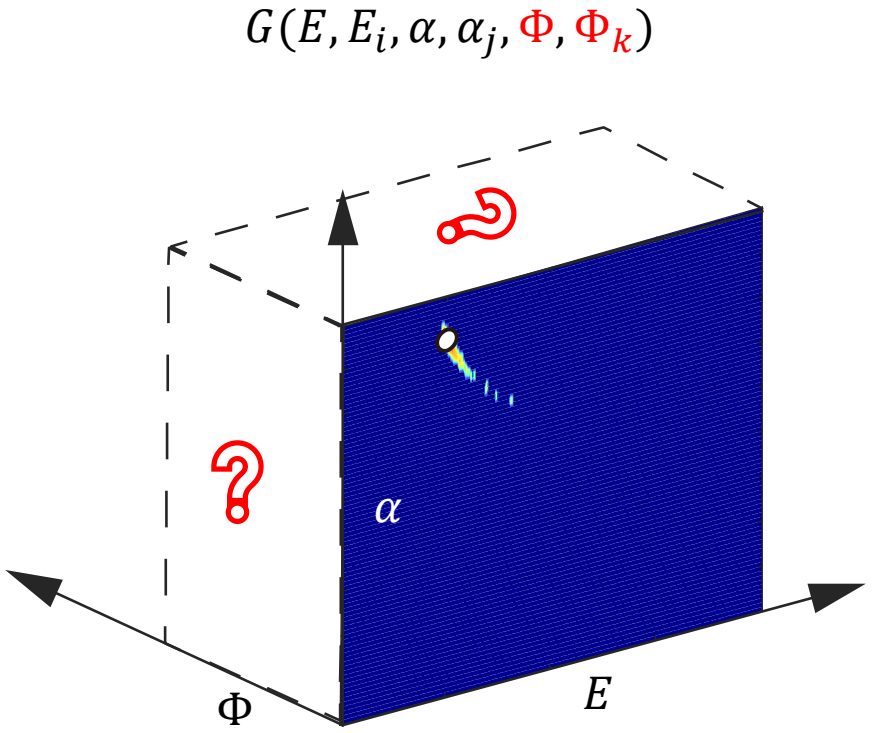

Case 1: without subpackets
Case 2: with subpackets
(a) cycles = 100
(b) cycles = 200
α [deg]
Kinetic energy [MeV]
F_{EQ} [m^{-2} keV^{-1} deg^{-1}]
10^{0}
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}


Case 1: without subpackets
Case 2: with subpackets
$\Delta N_L/N_T$ [cycle^{-1}]
10^{0}
10^{-10}
10^{-20}
10^{-30}
0.02 MeV
0.1 MeV
0.2 MeV
0.5 MeV
4.0 MeV
6.0 MeV
1.0 MeV
2.0 MeV
0
50
100
150
200
Cycle

Longitudinal Dependency



[*Li et al., JGR,* 2011]

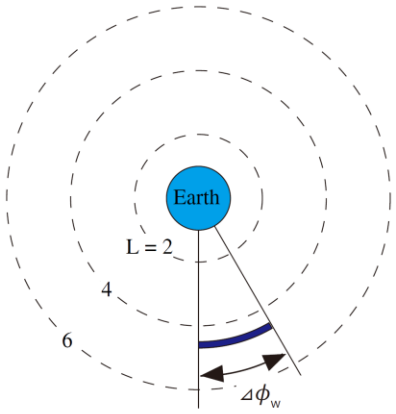


Modified Numerical Green's Function Method

※ Assuming dipole geomagnetic field

※ $\Delta\Phi \leq 3^\circ$ at $E \leq 6$ MeV and $\alpha \leq 90^\circ$

$$f_n^{\phi}(E,\alpha,\phi) = \sum_{a_0}\sum_{E_0}\sum_{\phi_w} f_{n-1}^{\phi}(E_0,\alpha_0,\phi_w)G^{\phi}(E,E_0,\alpha,\alpha_0,\phi-\phi_w)\Delta\phi\Delta E\Delta\alpha$$
$$+\sum_{\overline{\phi}_w} f_{n-1}^{\phi}(E,\alpha,\overline{\phi}_w)G_0^{\phi}(E,\alpha,\phi-\overline{\phi}_w)\Delta\phi \ ,$$



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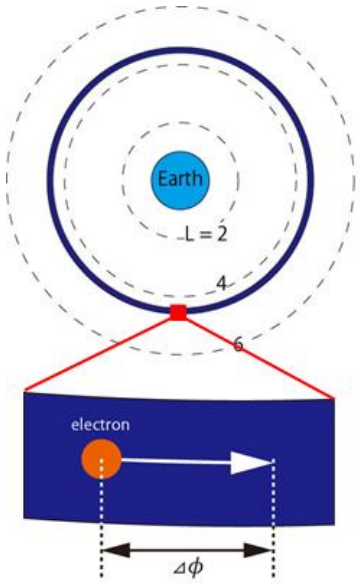
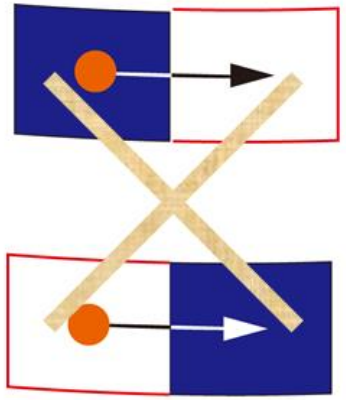


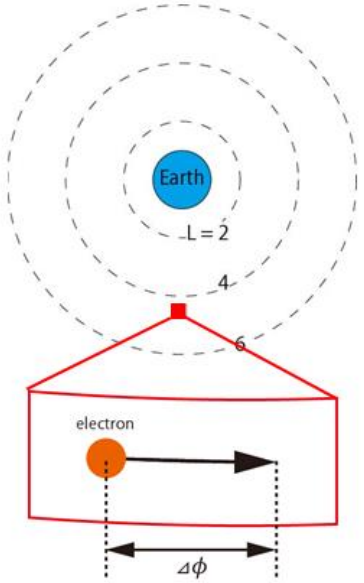
$G^{\phi}(E,E_0,\alpha,\alpha_0,\Delta\phi_d)$

+

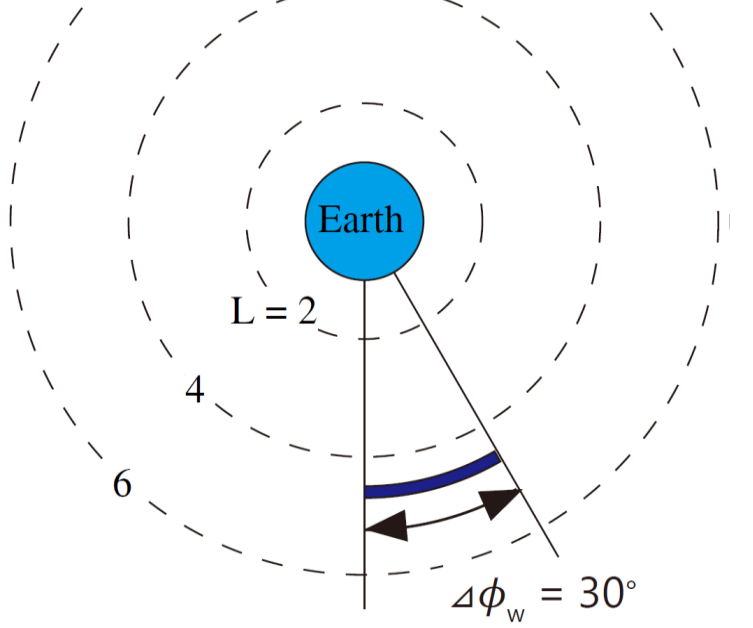


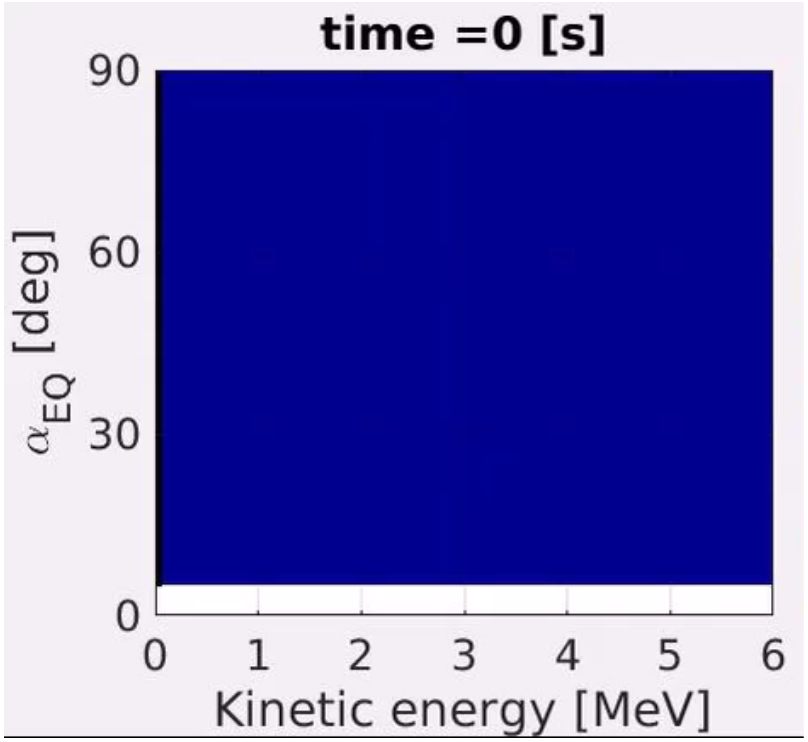
Neglected

+

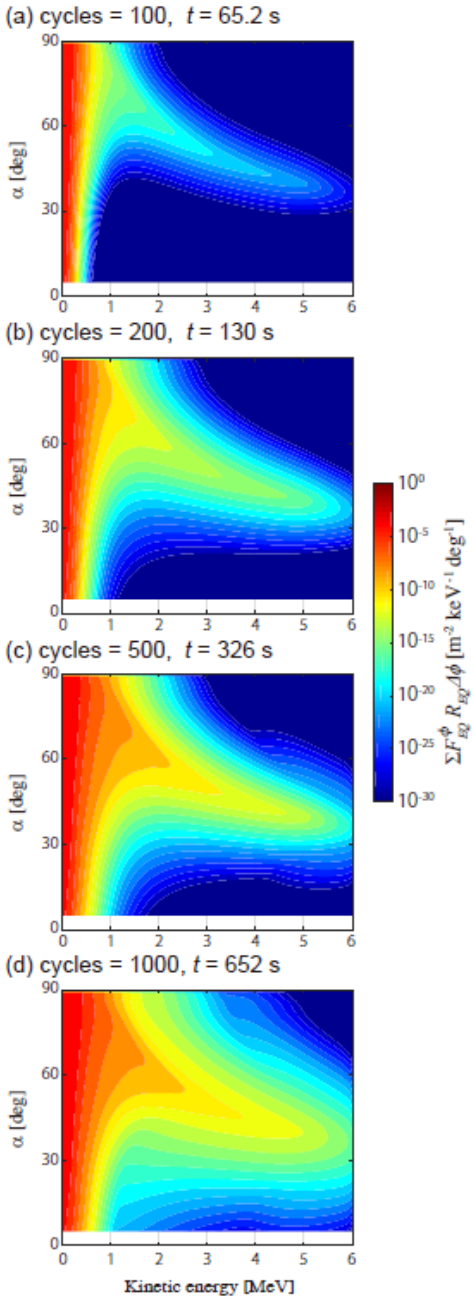


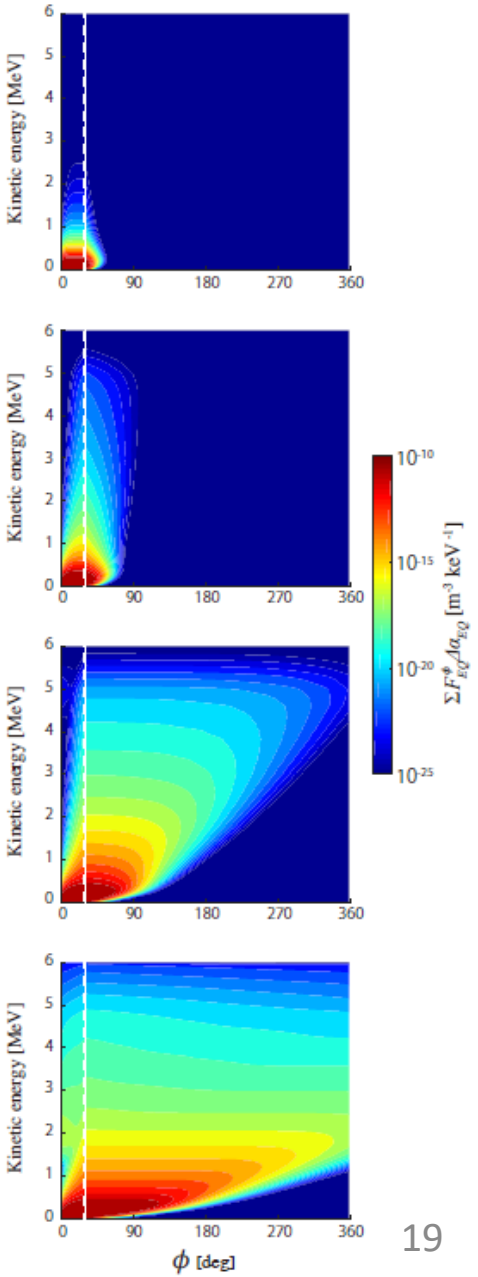
$G_0^{\phi}(E,\alpha,\Delta\phi_d)$

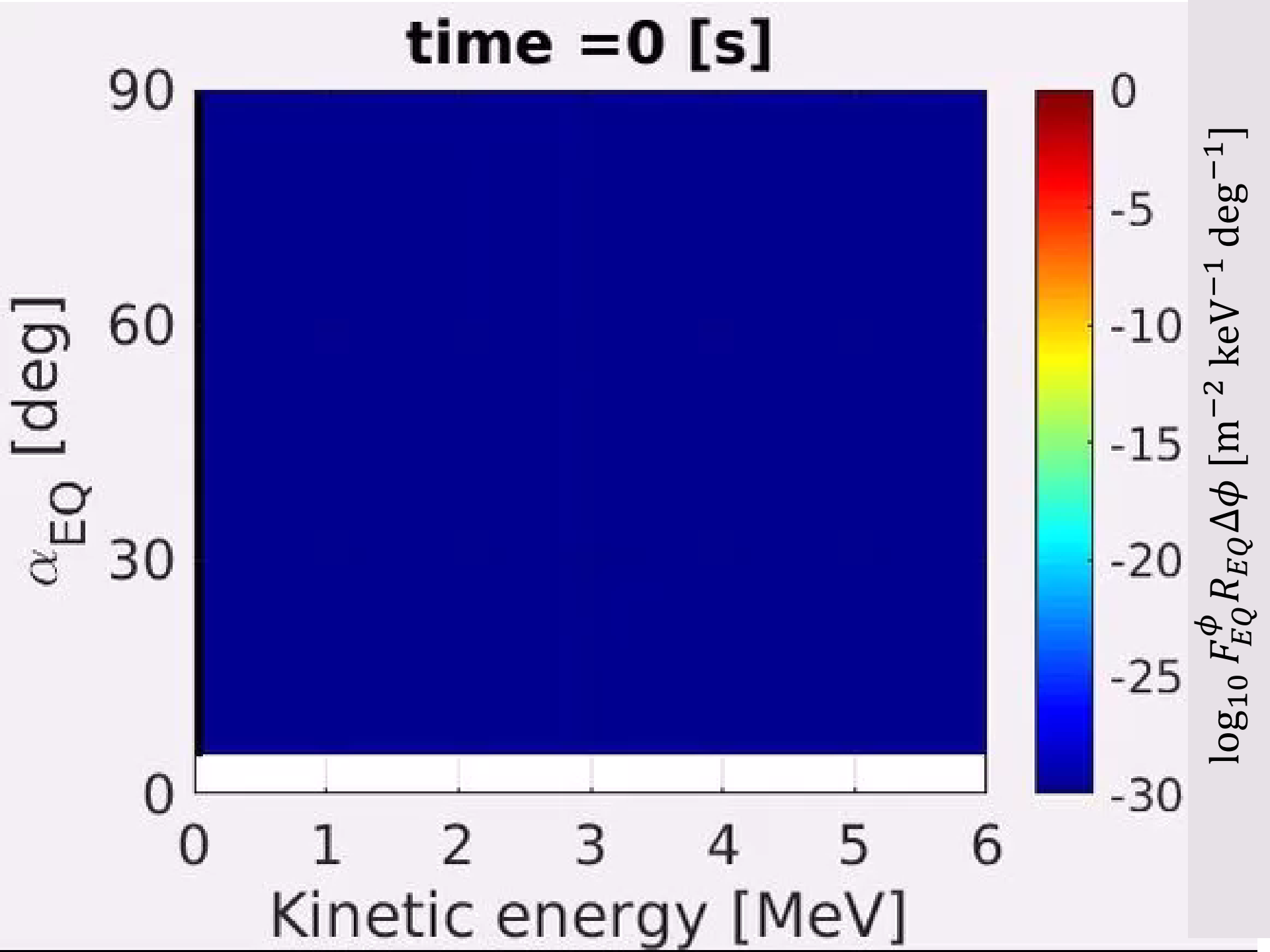


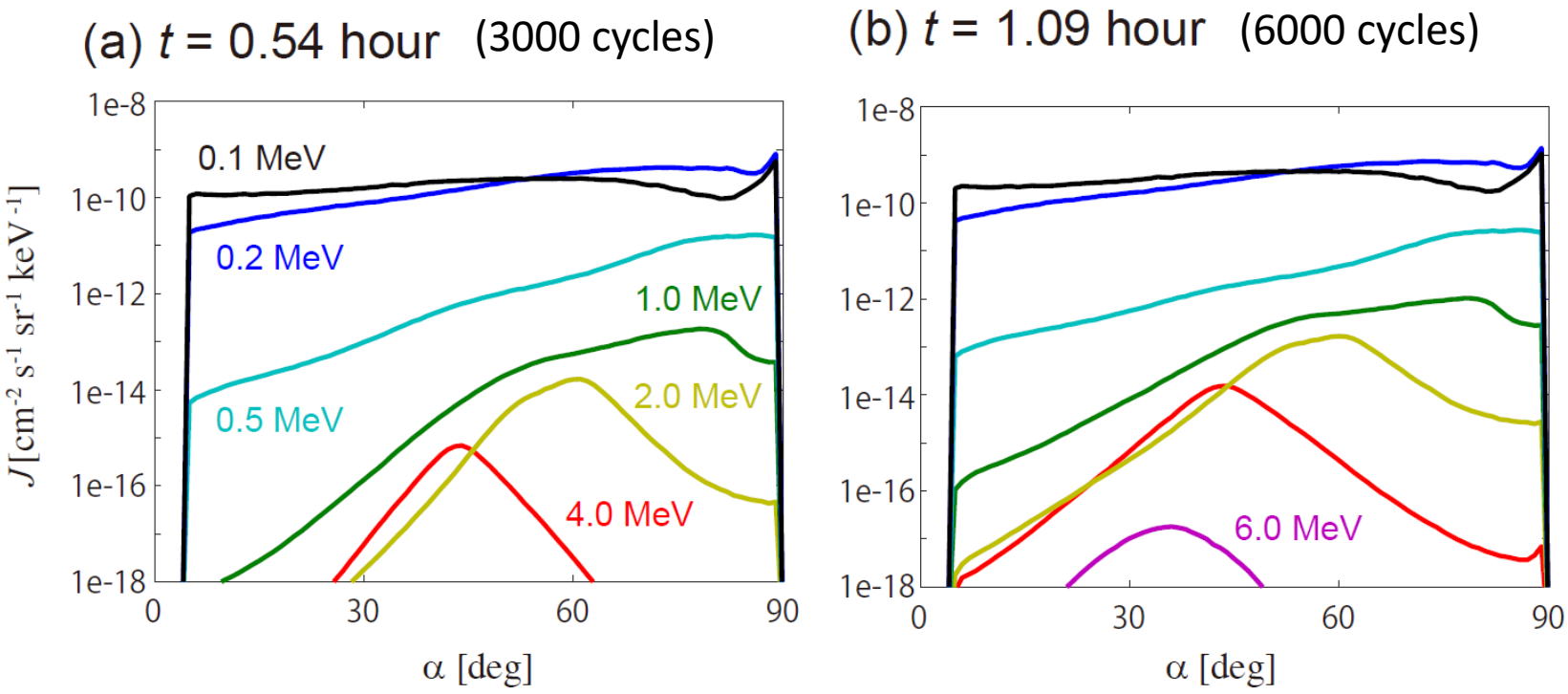


Constant influx: 10 – 30 keV electrons






time =0 [s]
90
60
30
0
α_{EQ} [deg]
0
1
2
3
4
5
6
Kinetic energy [MeV]
0
-5
-10
-15
-20
-25
-30
$\log_{10} F_{EQ}^{\phi} R_{EQ} \Delta\phi$ [m^{-2} keV^{-1} deg^{-1}]

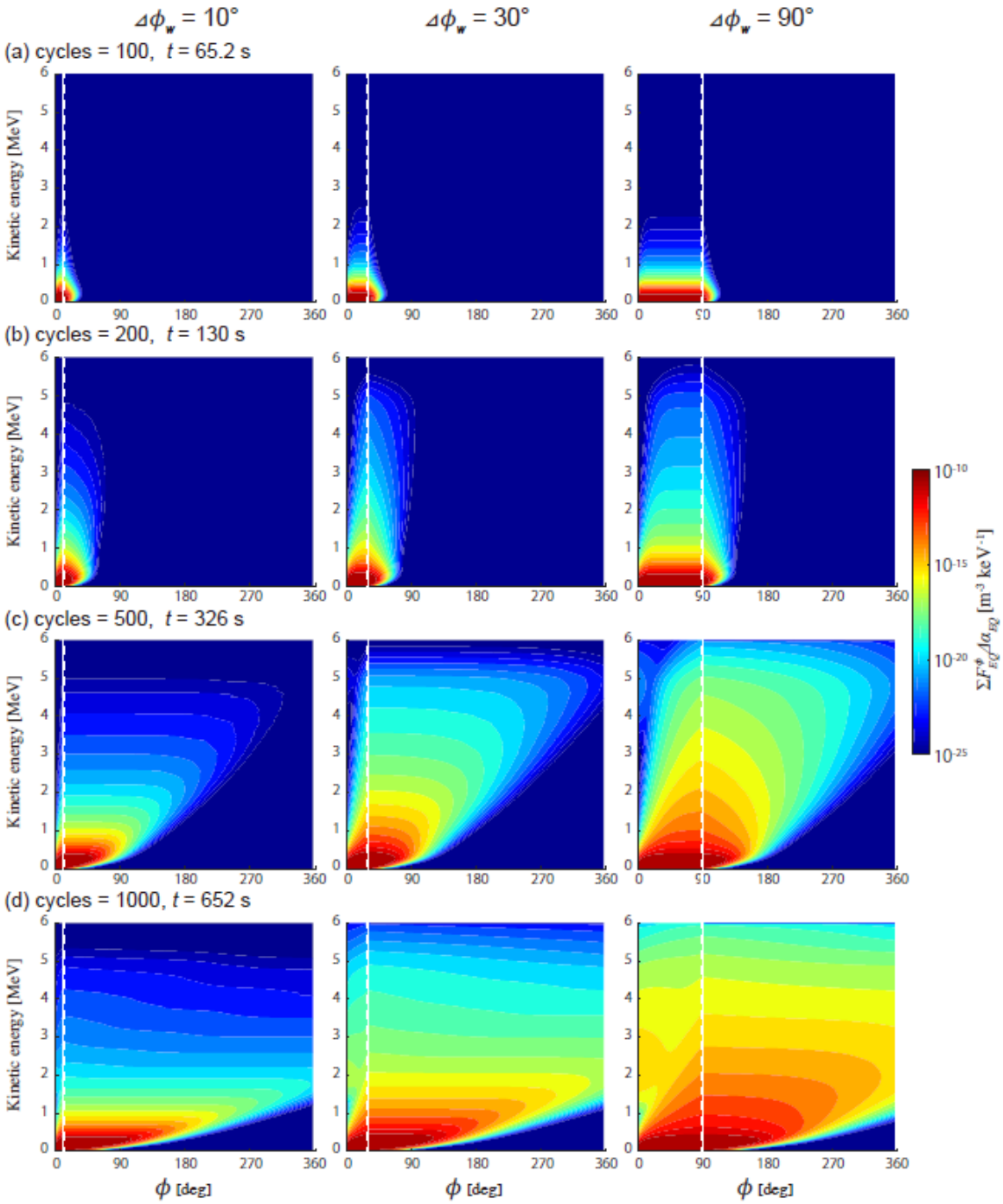

(a) t = 0.54 hour (3000 cycles)
(b) t = 1.09 hour (6000 cycles)
J [cm-2 s-1 sr-1 keV-1]
1e-8
1e-10
1e-12
1e-14
1e-16
1e-18
0
30
60
90
α [deg]
0.1 MeV
0.2 MeV
0.5 MeV
1.0 MeV
2.0 MeV
4.0 MeV
6.0 MeV

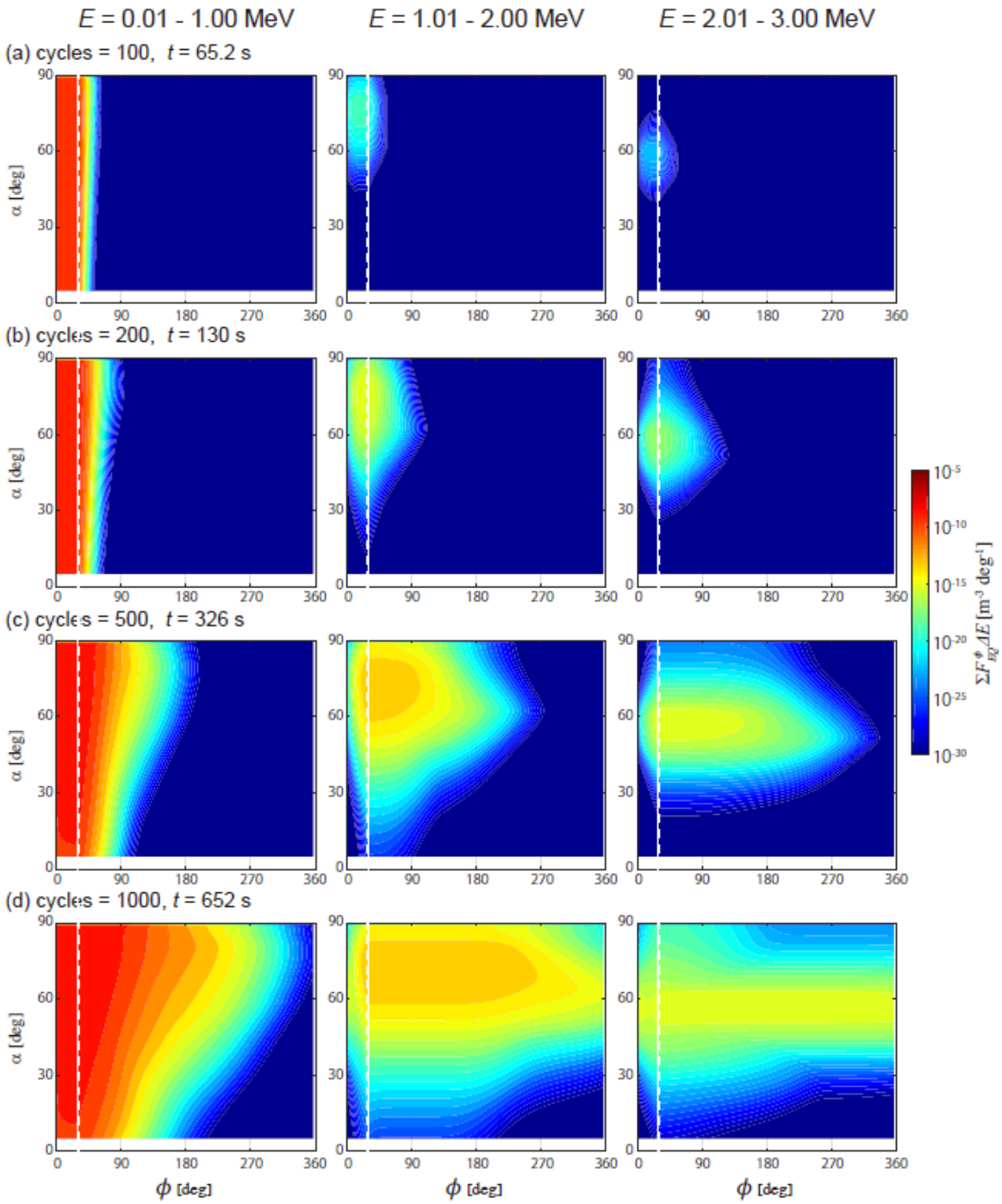
Summary

1. We have modified the numerical Green's function method including longitudinal dependency of chorus emissions.
2. Chorus emissions localized in longitude result in rapid formation of the outer radiation belt.

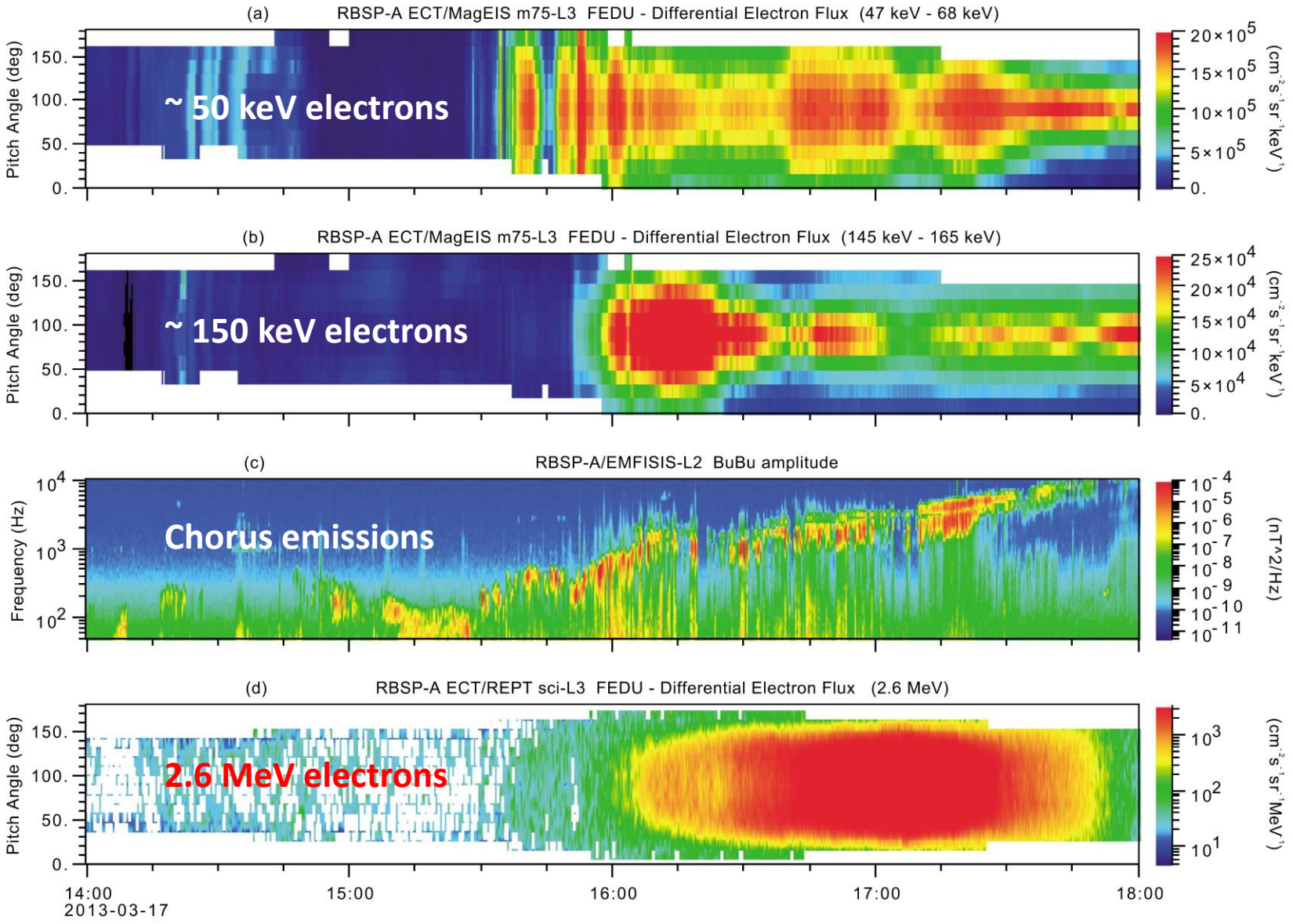
References

1. Kubota, Y., and Y. Omura, Nonlinear dynamics of radiation belt electrons interacting with chorus emissions localized in longitude, submitted to *J. Geophys. Res.*
2. Omura, Y. et al., Formation process of relativistic electron flux through interaction with chorus emissions in the Earth's inner magnetosphere, *J Geophys. Res. Space Physics, 120, 9545-9562, 2015.*


$\Delta\phi_w$ = 10°
$\Delta\phi_w$ = 30°
$\Delta\phi_w$ = 90°
(a) cycles = 100, t = 65.2 s
(b) cycles = 200, t = 130 s
(c) cycles = 500, t = 326 s
(d) cycles = 1000, t = 652 s
Kinetic energy [MeV]
ϕ [deg]
$\Sigma F^{\Phi}_{EQ} \Delta\alpha_{EQ}$ [m^{-3} keV^{-1}]
10^{-10}
10^{-15}
10^{-20}
10^{-25}


E = 0.01 - 1.00 MeV
E = 1.01 - 2.00 MeV
E = 2.01 - 3.00 MeV
(a) cycles = 100, t = 65.2 s
(b) cycles = 200, t = 130 s
(c) cycles = 500, t = 326 s
(d) cycles = 1000, t = 652 s
α [deg]
ϕ [deg]
0
30
60
90
180
270
360
10-5
10-10
10-15
10-20
10-25
10-30
ΣF_EJ^ϕ ΔE [m-3 deg-1]

Rapid-acceleration of MeV Electrons



[*Foster et al.*, 2017]