Propagation of Cosmic Ray in the Heliosphere

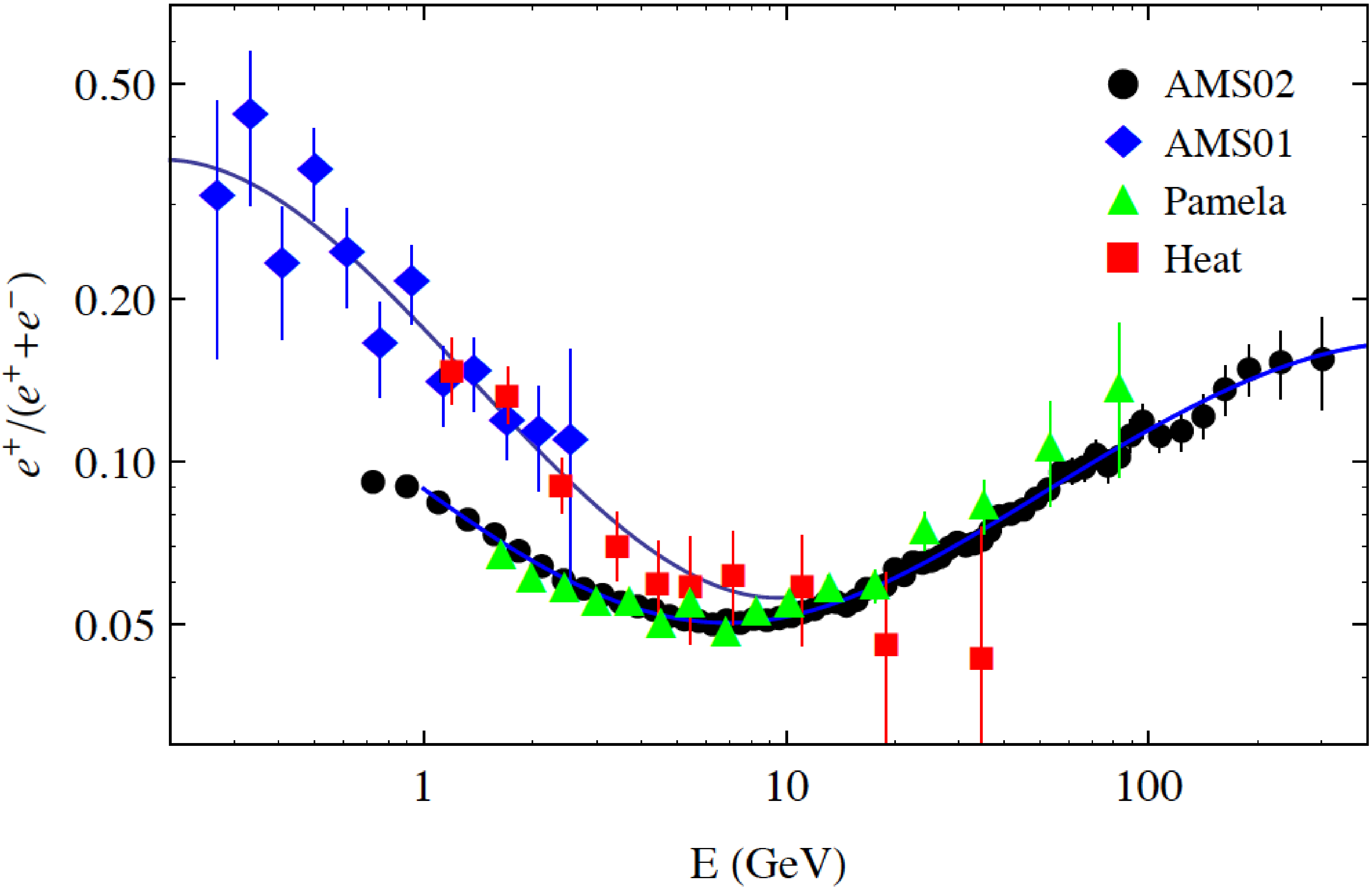
Paolo Lipari, INFN Roma

RICAP 2013

Roma, 23rd may 2013

Recent Measurement of the of the ratio by AMS02.

$$\boxed{\frac{e^+}{e^+ + e^-}}$$



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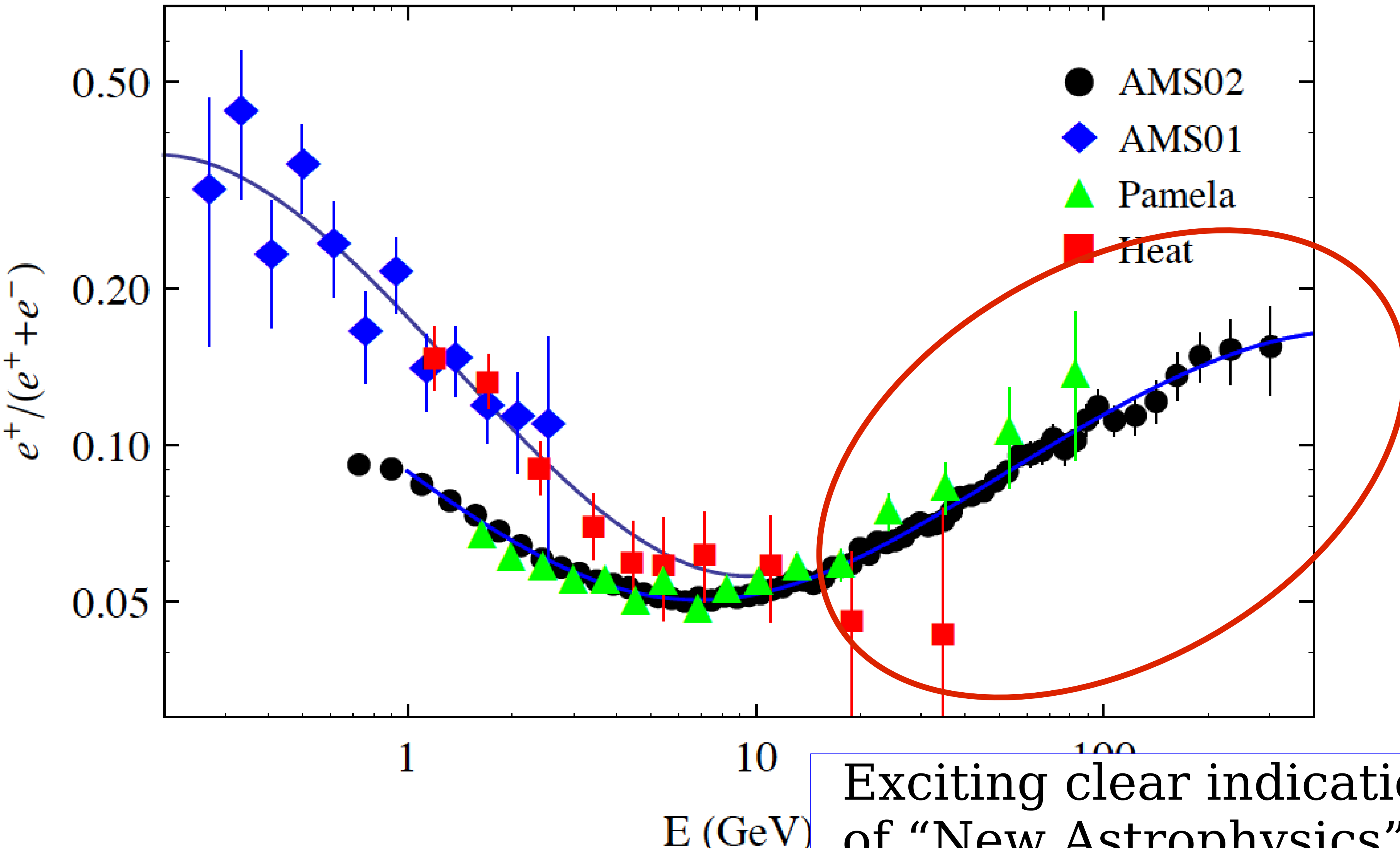

Exciting clear indication of “New Astrophysics” or “New Physics” (DM)

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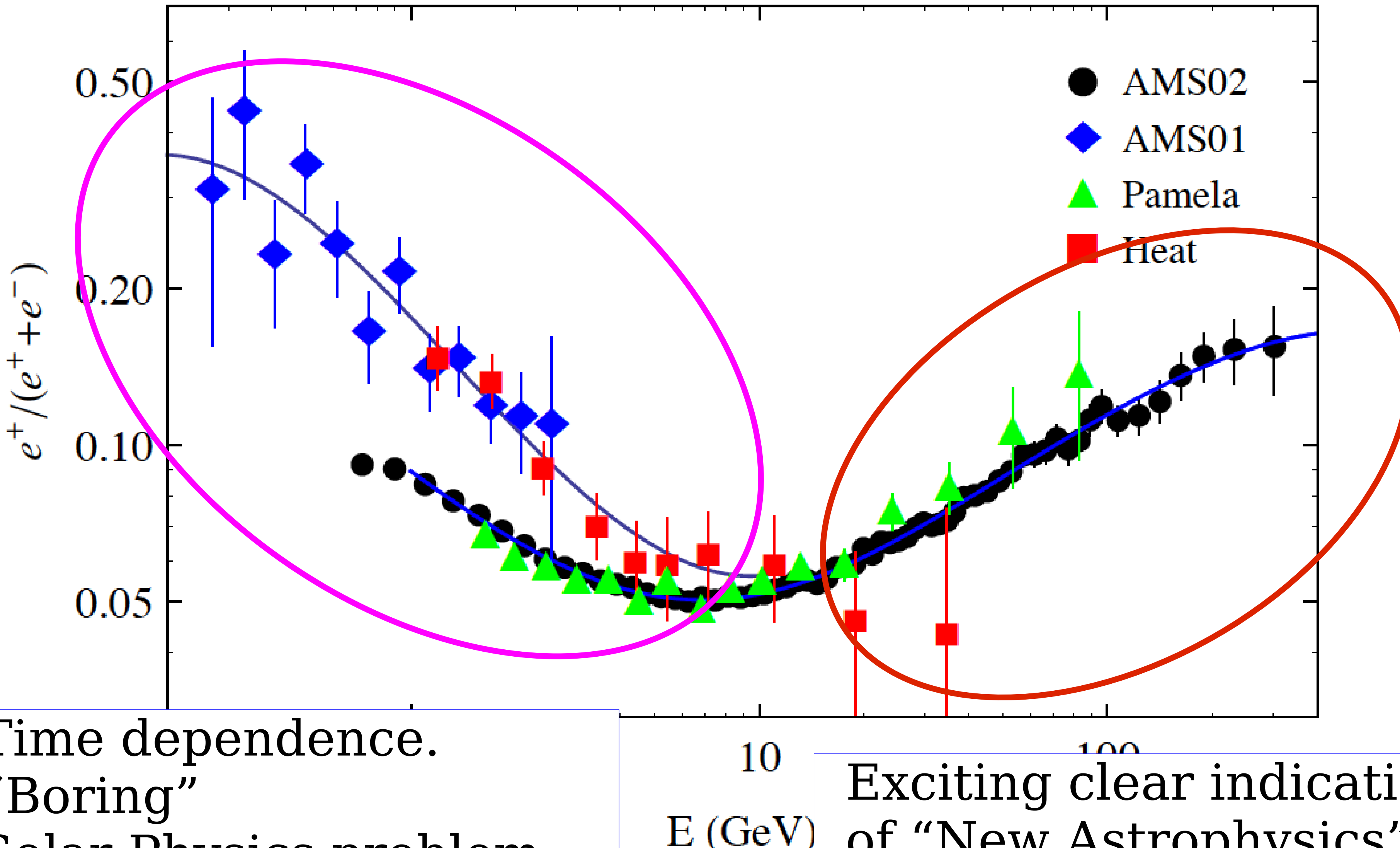

Time dependence.
“Boring”
Solar Physics problem…..

Exciting clear indication of “New Astrophysics” or “New Physics” (DM)

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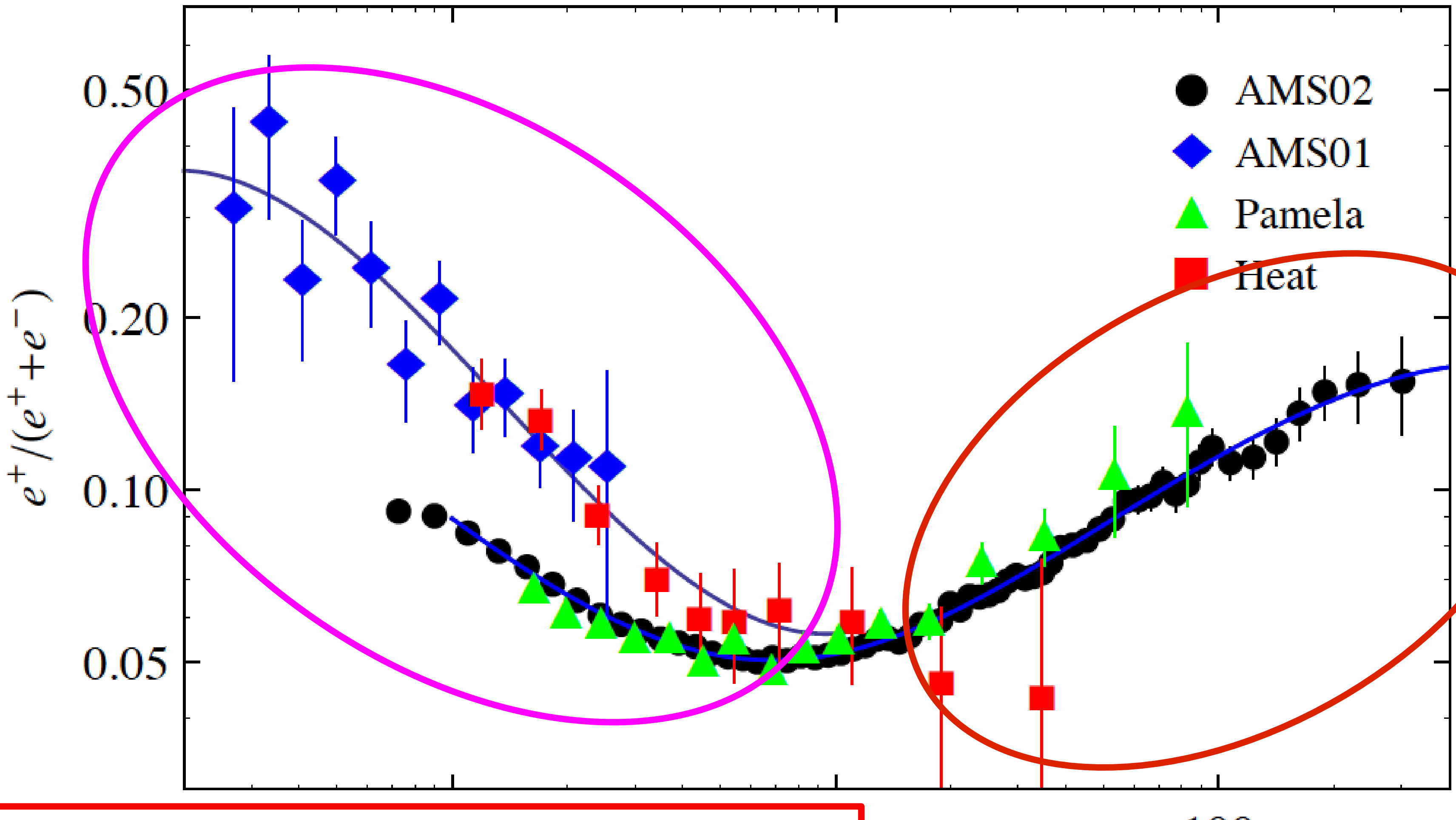


Important Laboratory
for the study
of Cosmic Ray Propagation!

Exciting clear indication
of “New Astrophysics”
or “New Physics” (DM)

Propagation in the Heliosphere

Propagation in the Milky Way

$$n(E) = \frac{1}{\beta\, c} \int d\Omega \; \phi(E, \Omega)$$

$$n(E) = q(E) \times T(E)$$

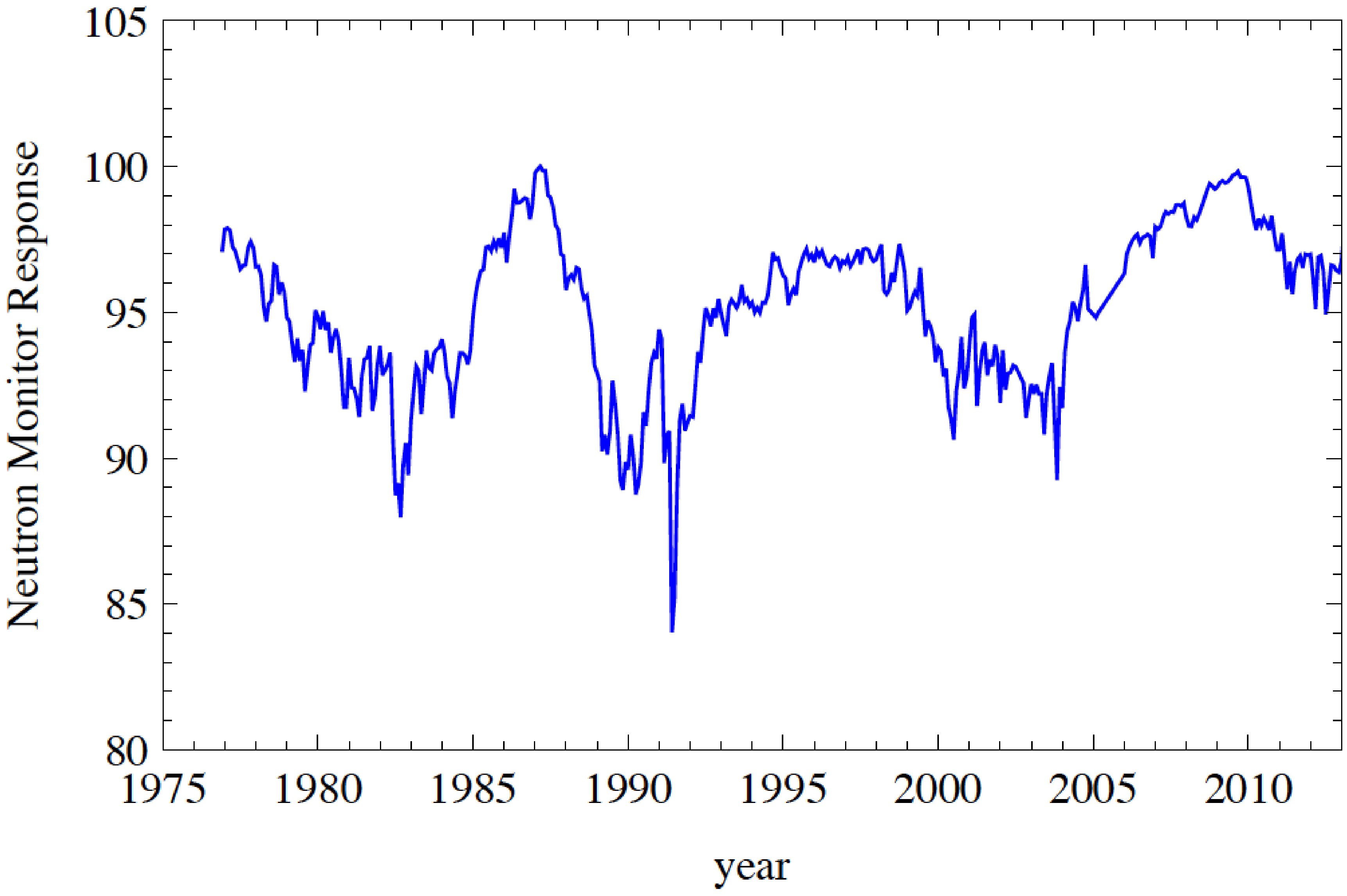
$$n(E) = q(E) \times \frac{L^2}{2\, D(E)}$$

$$D(E) \simeq D_0 \; E^{\delta}$$

$$D_{\perp}(E)$$

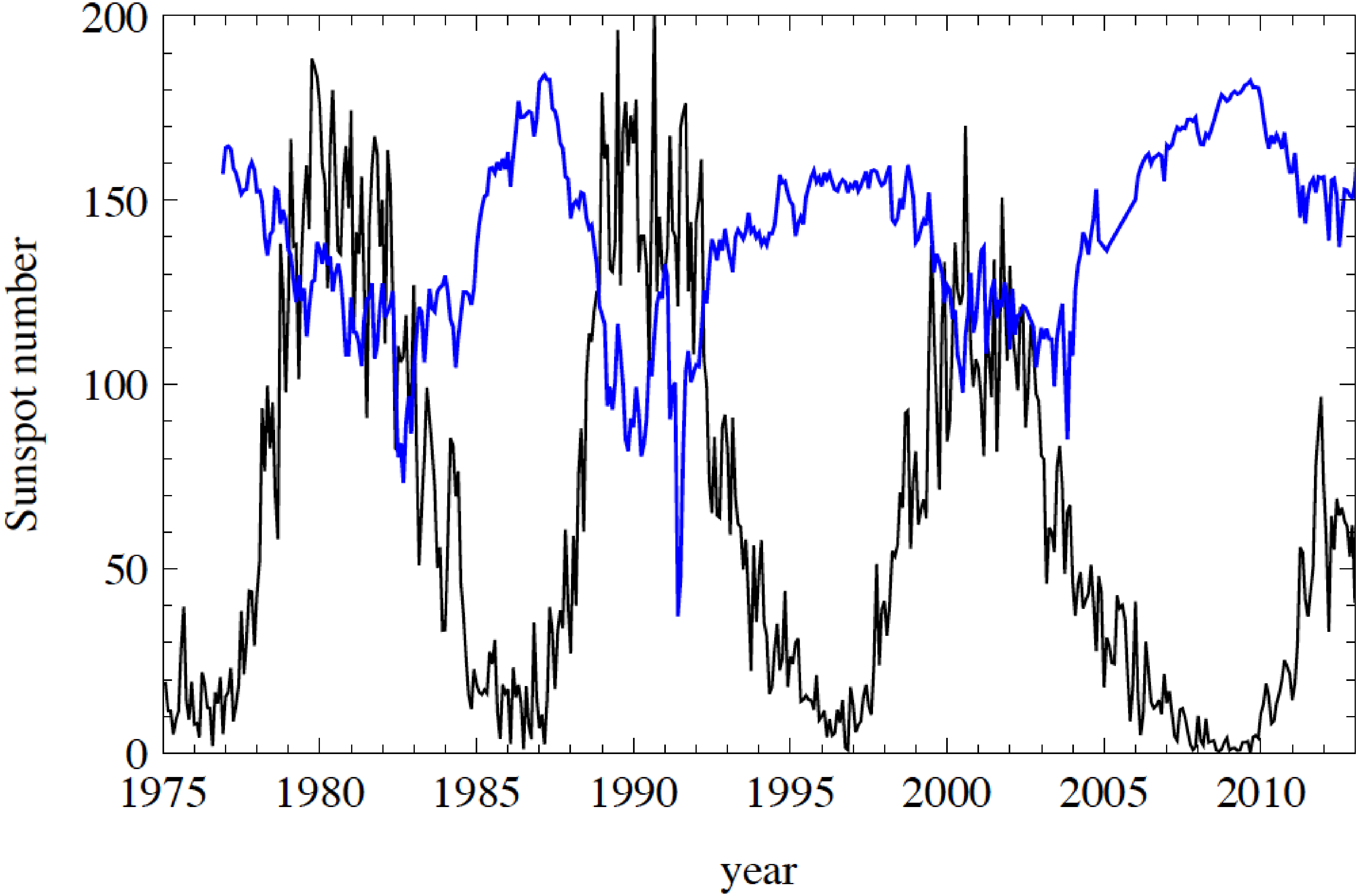
$$D_{||}(E)$$

Time dependence of the Cosmic Ray Flux:

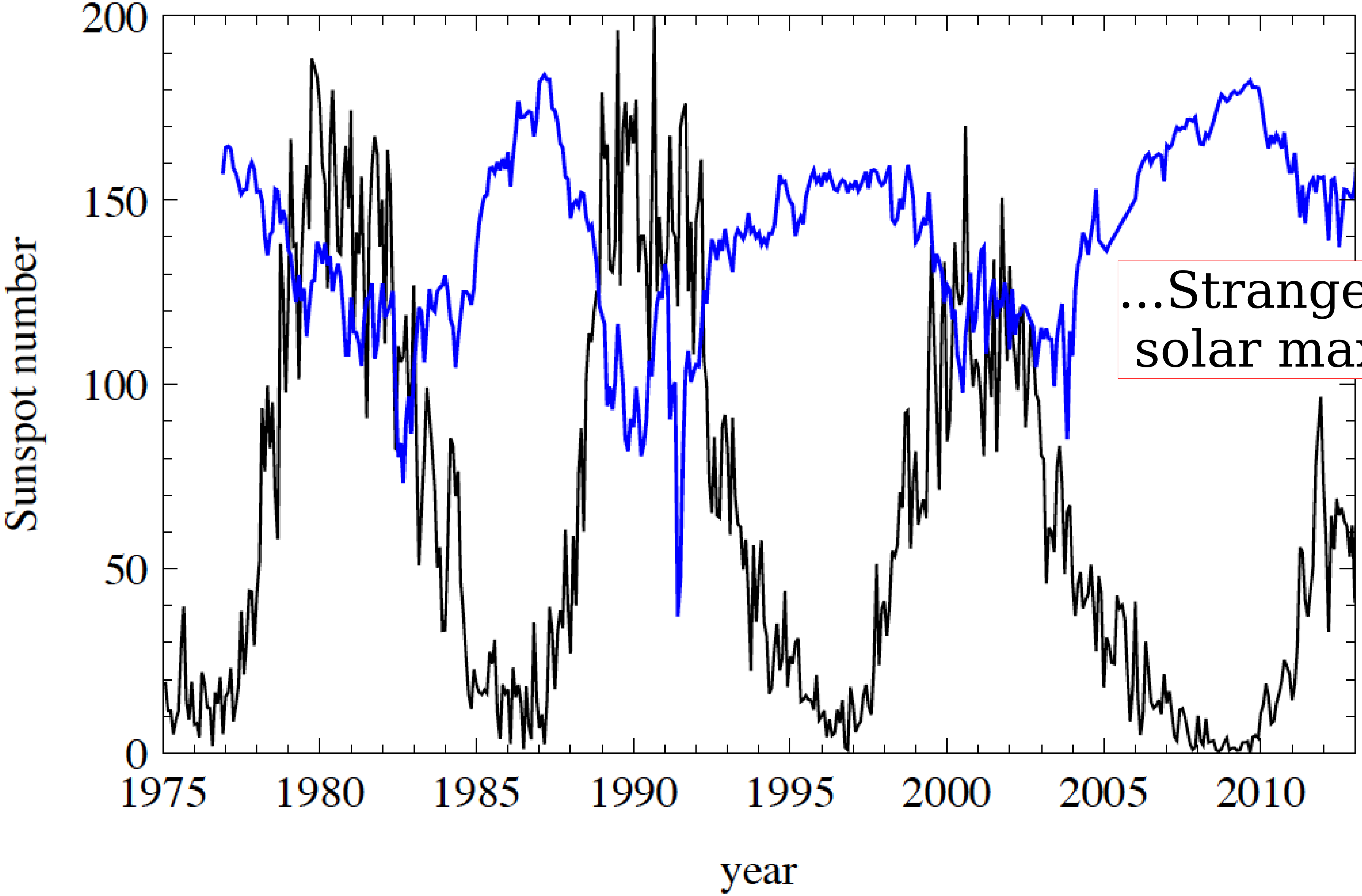


Hermanus (South Africa) Neutron Monitor

Correlation with Solar Activity (Sunspot Number)

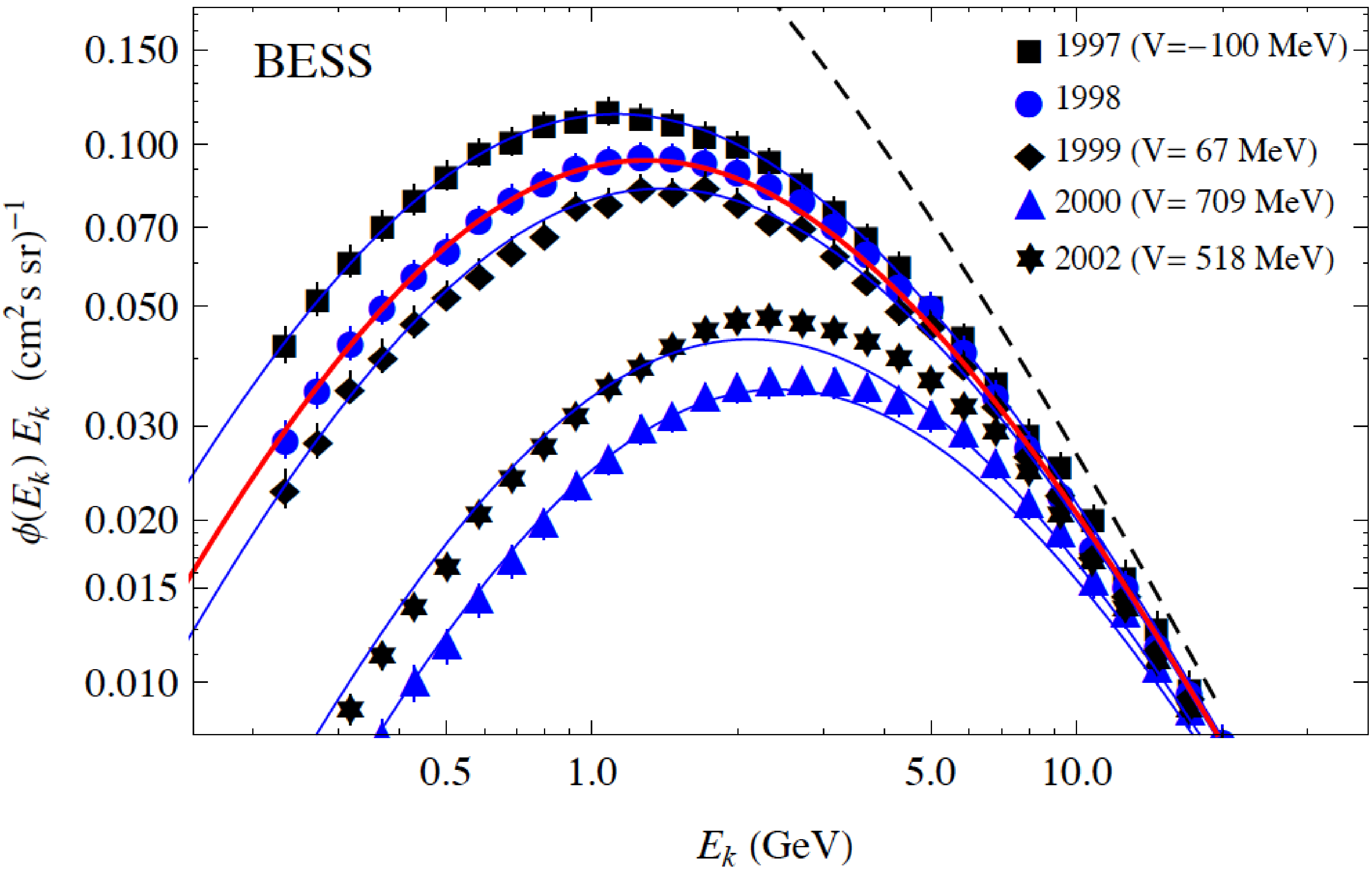


Correlation with Solar Activity (Sunspot Number)



...Strange
solar maximum. ?

Precision Measurements of CR (proton spectra) at different times [BESS]



Flux in the “Local Interstellar Space” (LIS)
(outside the heliosphere)

$$\boxed{\phi_{\mathrm{LIS}}(E)}$$

Flux at the Earth at time t

$$\boxed{\phi(E,t)}$$

Flux in the "Local Interstellar Space" (LIS)
(outside the heliosphere)

$\phi_{\rm LIS}(E)$

Flux at the Earth at time t

$\phi(E, t)$

Phenomenological analysis.
Relation between 2 fluxes:

$\phi(E, t_1)$ $\phi(E, t_2)$

$$\phi(E, t_2) = \phi(E + V_{21}, t_1) \; \frac{E^2 - m^2}{(E + V_{21})^2 - m^2}$$

One parameter transformation.

Transformation: "Force – Field algorithm"

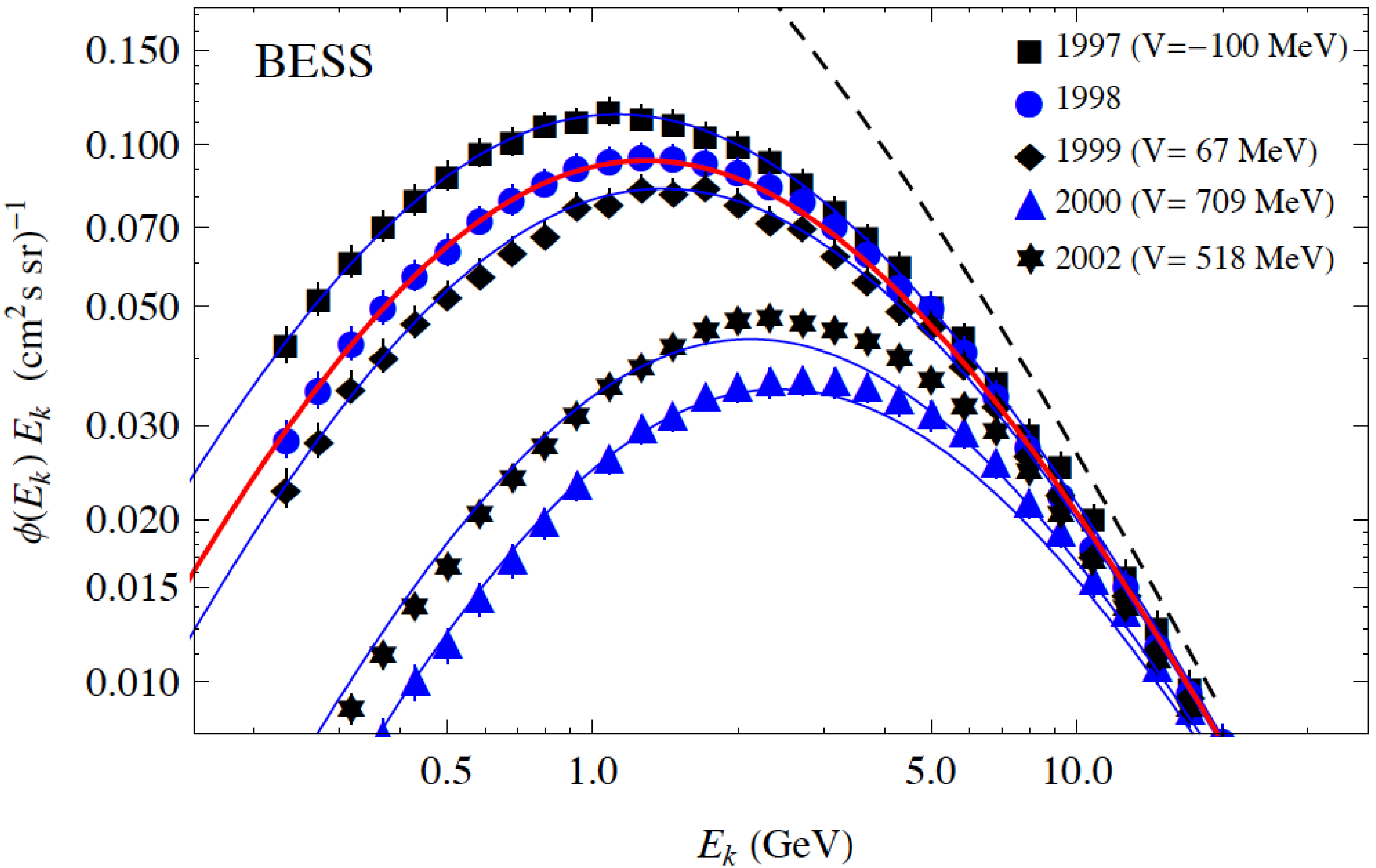
$$\phi(E,t_2) = \phi(E+V_{21},t_1)\ \frac{E^2-m^2}{(E+V_{21})^2-m^2}$$

inversion: $V_{12} = -V_{21}$

$$\phi(E,t_1) = \phi(E+V_{12},t_2)\ \frac{E^2-m^2}{(E+V_{12})^2-m^2}$$

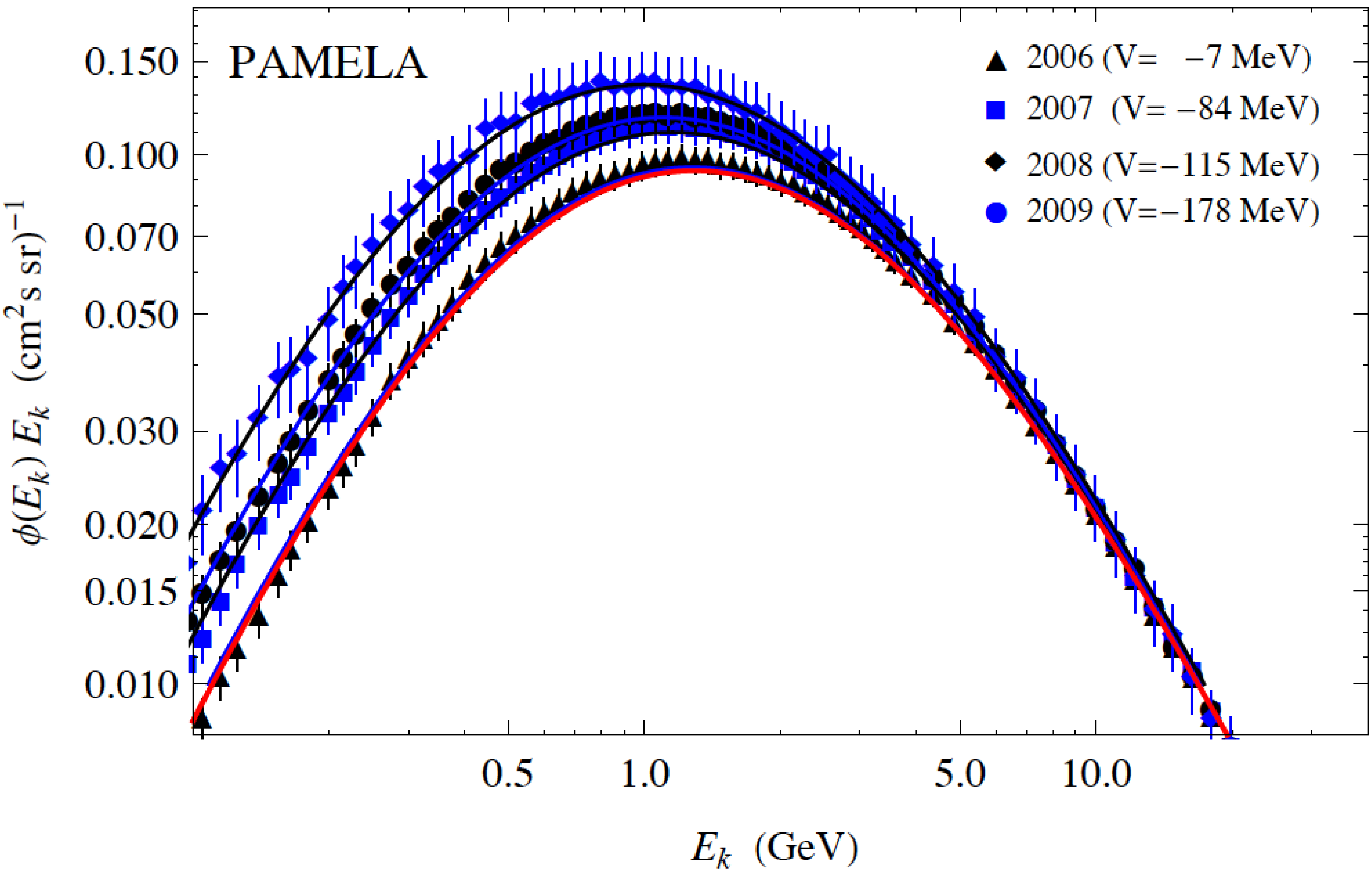
Algorithm is not perfect but
phenomenologically quite successful.

Precision Measurements of CR (proton spectra)
at different times.   BESS instrument.
Fit 1998 + use Force-FIeld algorithm.

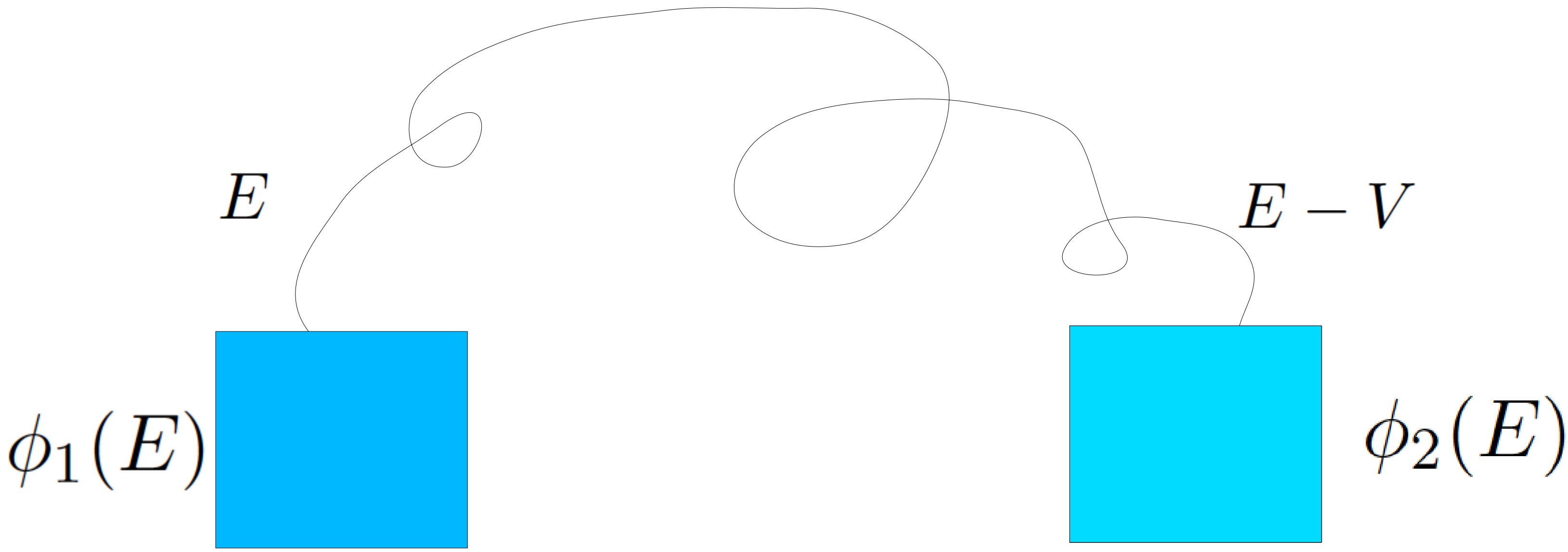


Pamela data: (proton spectrum)

[Compare with BESS-1998 fit (red line)
+ ForceField algorithm]



Physical Meaning of the success of the Force Field Algorithm:



$$\phi_1(E) = \phi_2(E+V)\,\frac{E^2 - m^2}{(E+V)^2 - m^2}$$

Relation between Flux and phase space density

$$\phi(E, \hat{p}, \vec{x}, t) = p^2\ \rho(\vec{x}, \vec{p}, t)$$

$$\rho(\vec{x}, \vec{p}, t) = \frac{d^6 N}{d^3x\, d^3p}$$

Liouville Theorem

$$\rho[\vec{x}(t_0), \vec{p}(t_0), t_0] = \rho[\vec{x}(t), \vec{p}(t), t]$$

Physical Meaning of the phenomenological success of the Force Field Algorithm:

ALL particles of the same type (*independently from their energy and direction of arrival)* lose approximately the same amount of energy penetrating the heliosphere.

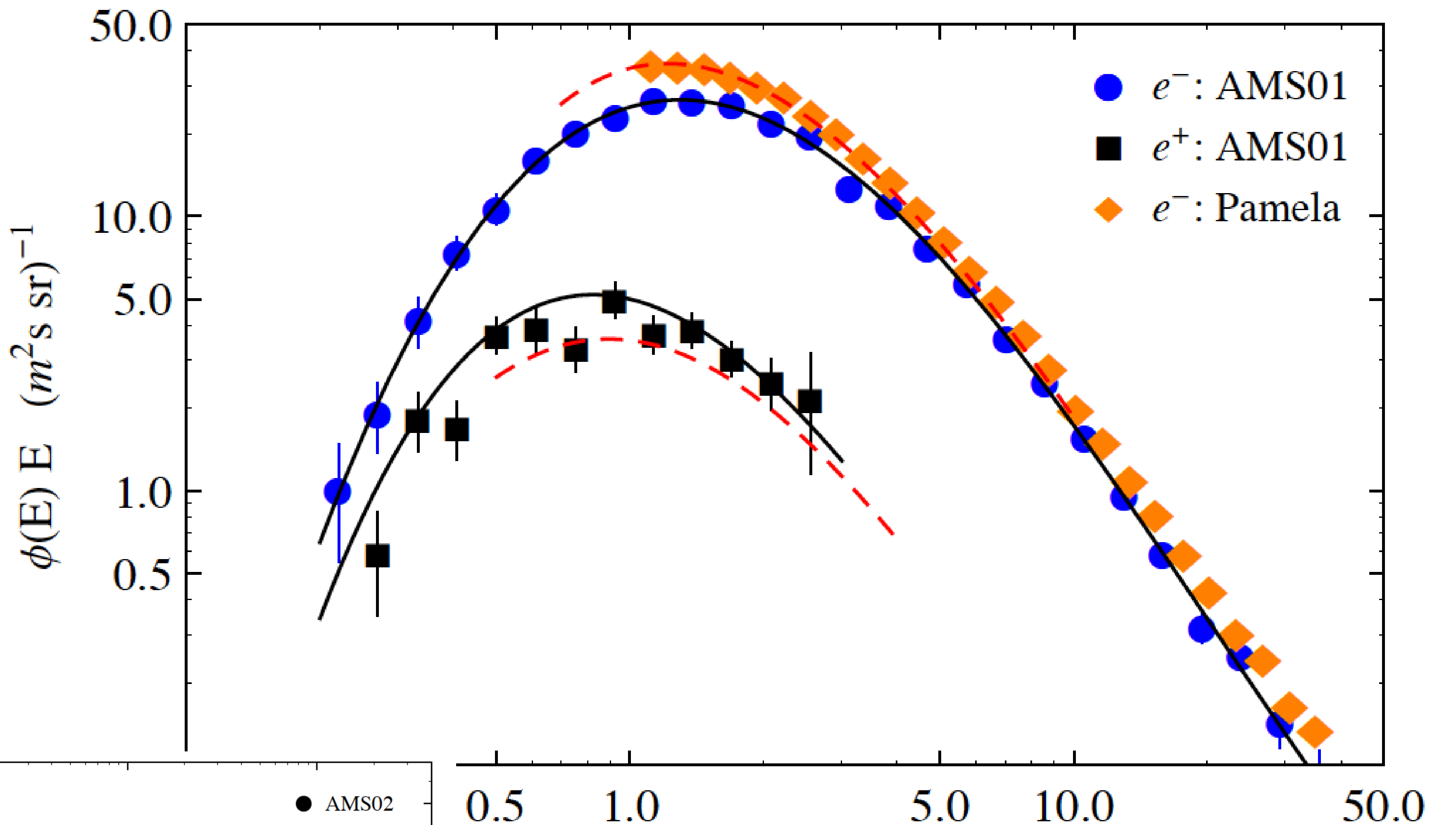
$$V(t) = \Delta E(t)$$

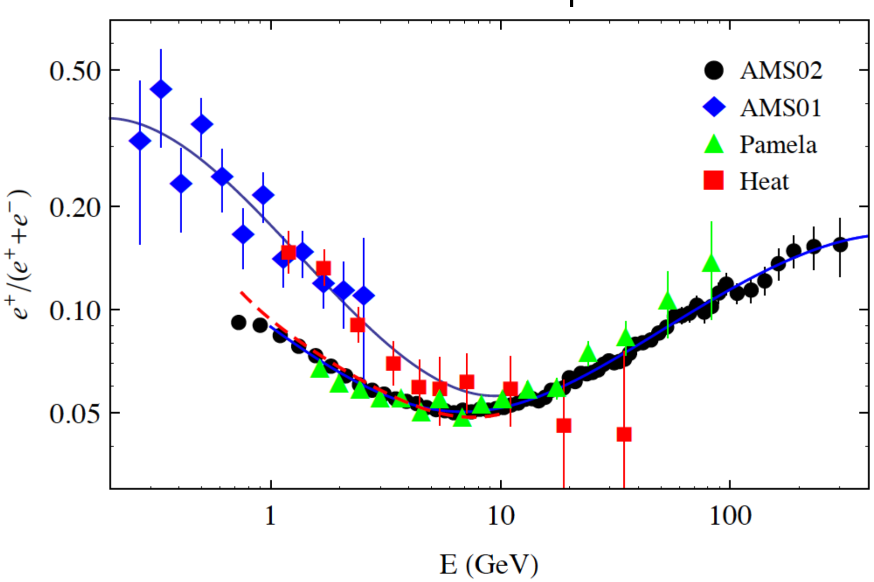
Physical Meaning of the
phenomenological success of the Force Field Algorithm:

ALL particles of the same type (*independently from their energy and direction of arrival)* lose approximately the same amount of energy penetrating the heliosphere.

$$V(t) = \Delta E(t)$$

Particles of opposite electric charge lose a different amount of energy





Fit AMS01 data, apply FF alg.

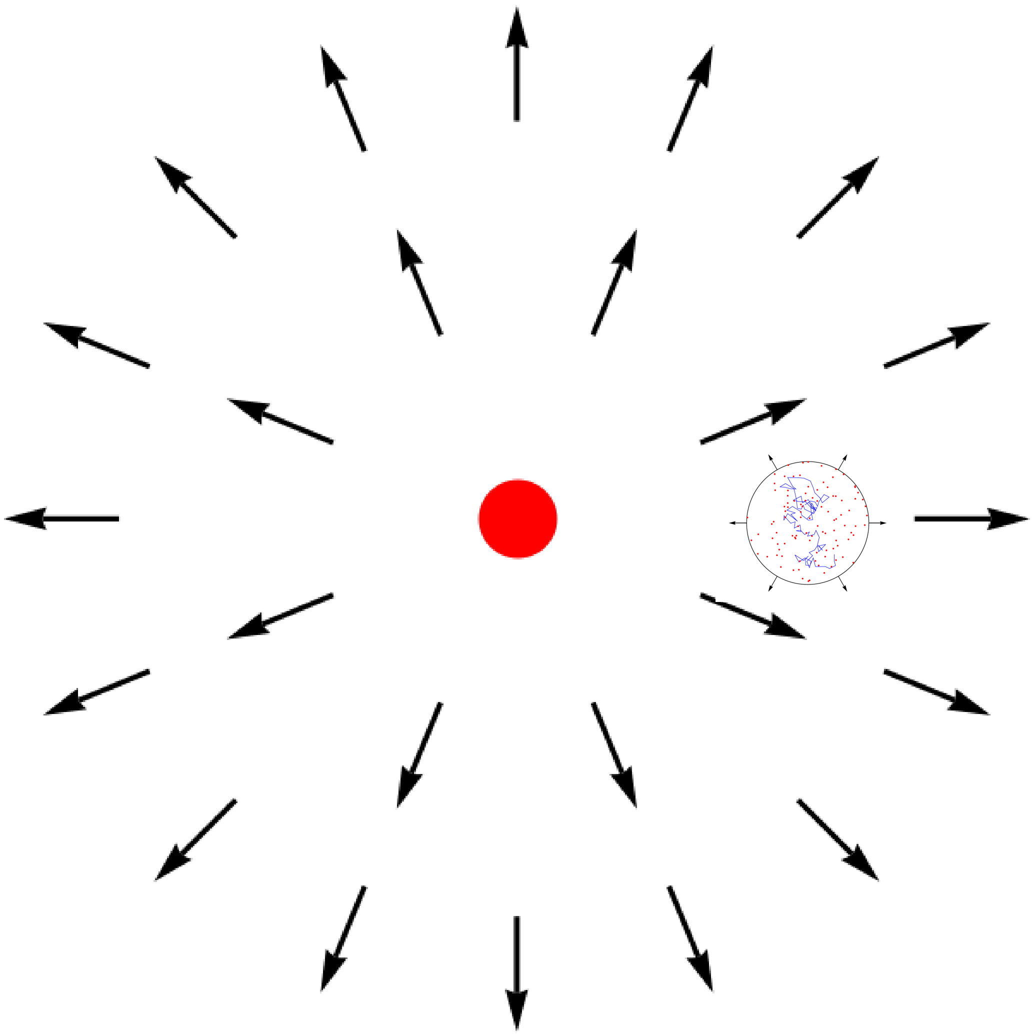
$$\Delta V_{e^-} = -127 \text{ MeV}$$

$$\Delta V_{e^+} = +127 \text{ MeV}$$

$$\boxed{V_{e^-} \leftrightarrow V_{e^+}}$$

Parker's (1965) original idea for Solar Modulations

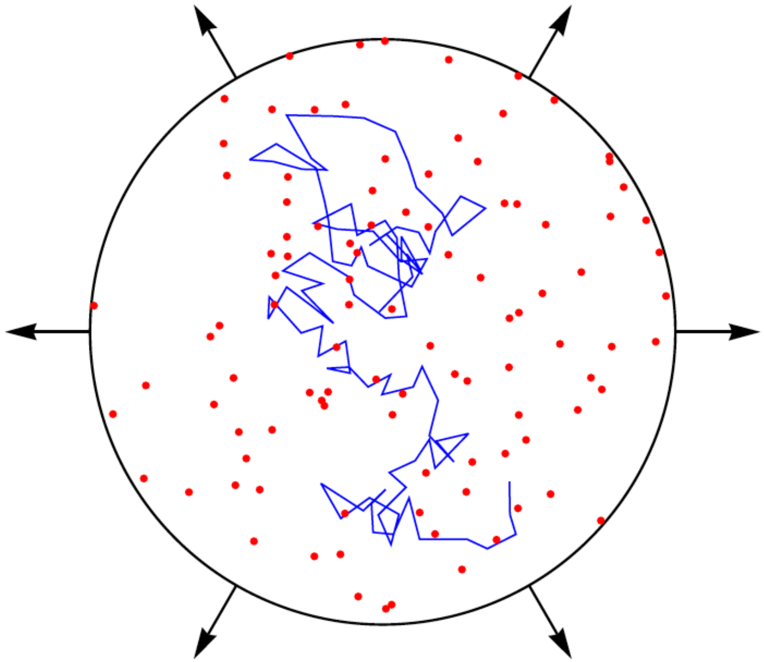
Radial Solar Wind (400 Km/s)



“adiabatic energy losses”
In expanding medium

$$\left\langle \frac{dp}{dt} \right\rangle = -\left[\nabla \cdot \vec{v}_{\text{wind}}\right] \frac{p}{3}$$

$$\nabla \cdot \hat{r} = \frac{2}{r}$$



Parker's (1965) original idea for Solar Modulations

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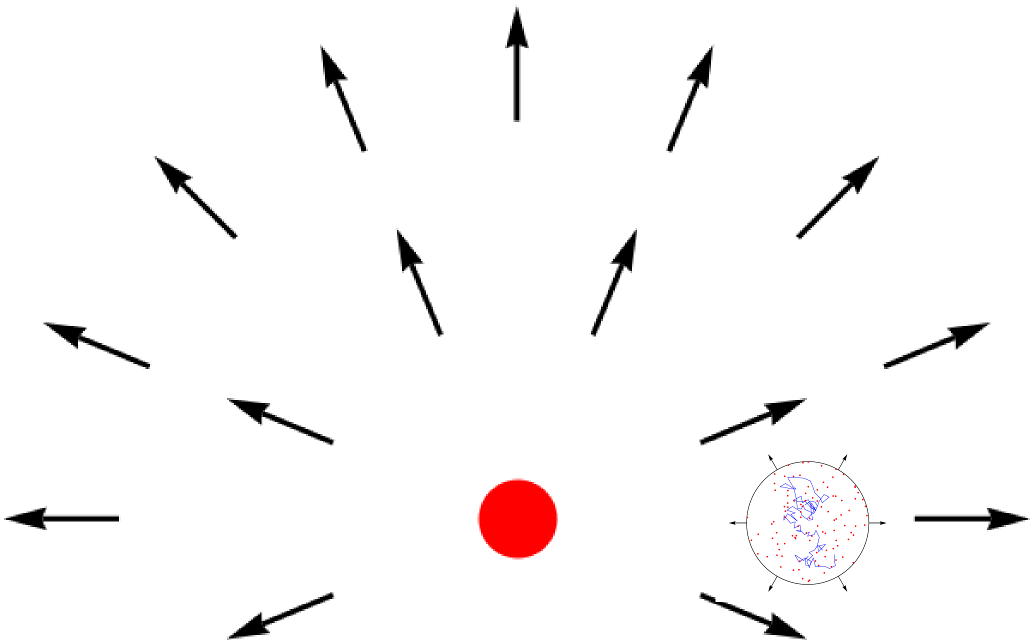
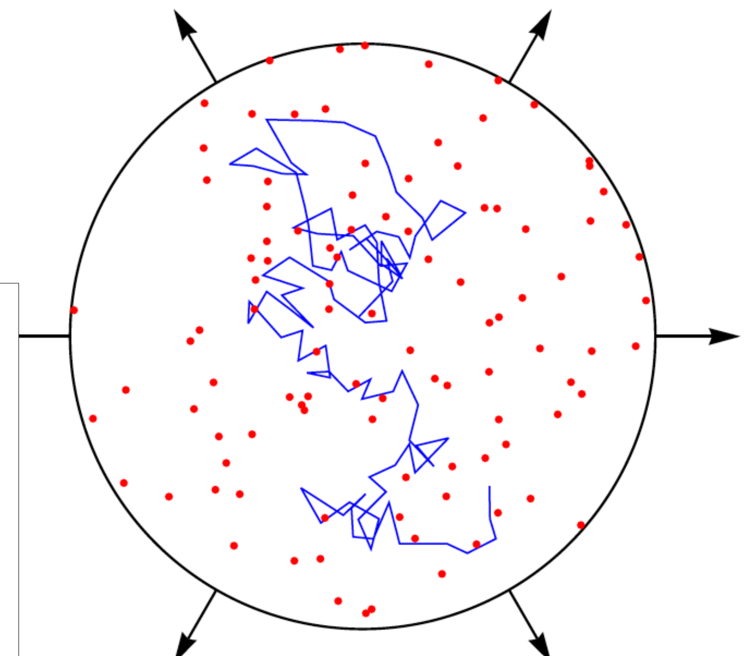
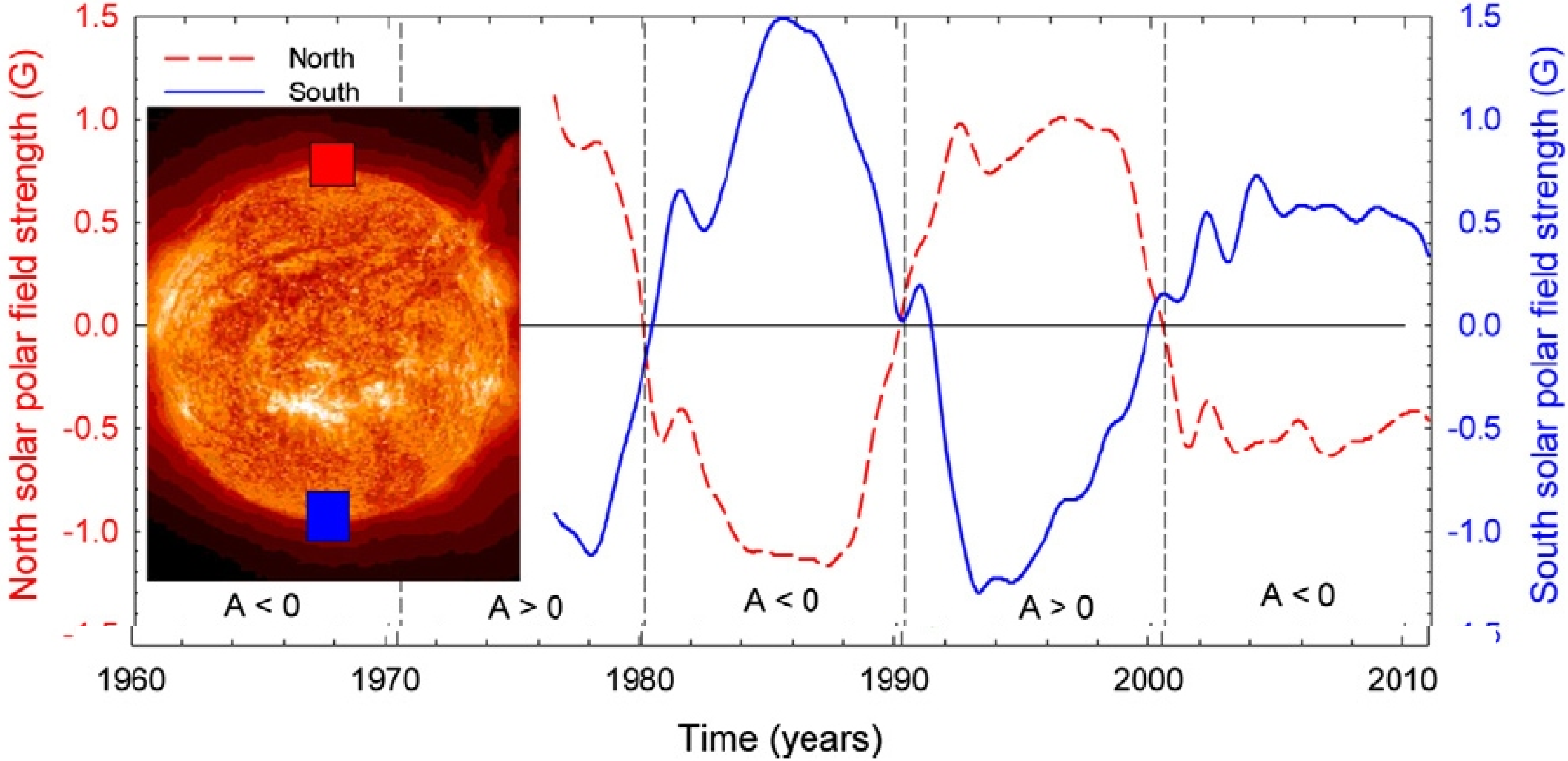


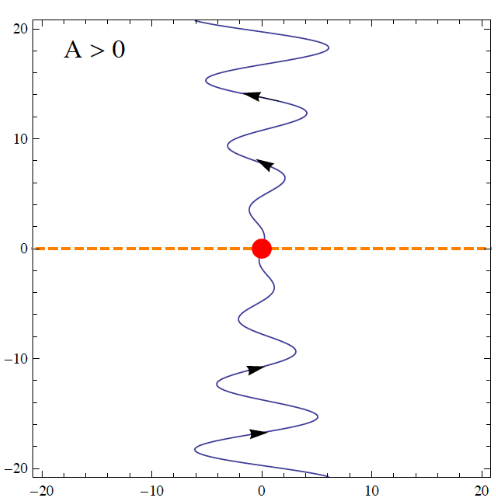


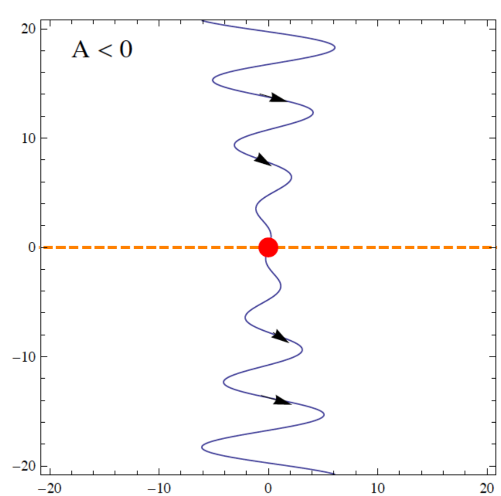
$$\Delta E = \text{const}$$

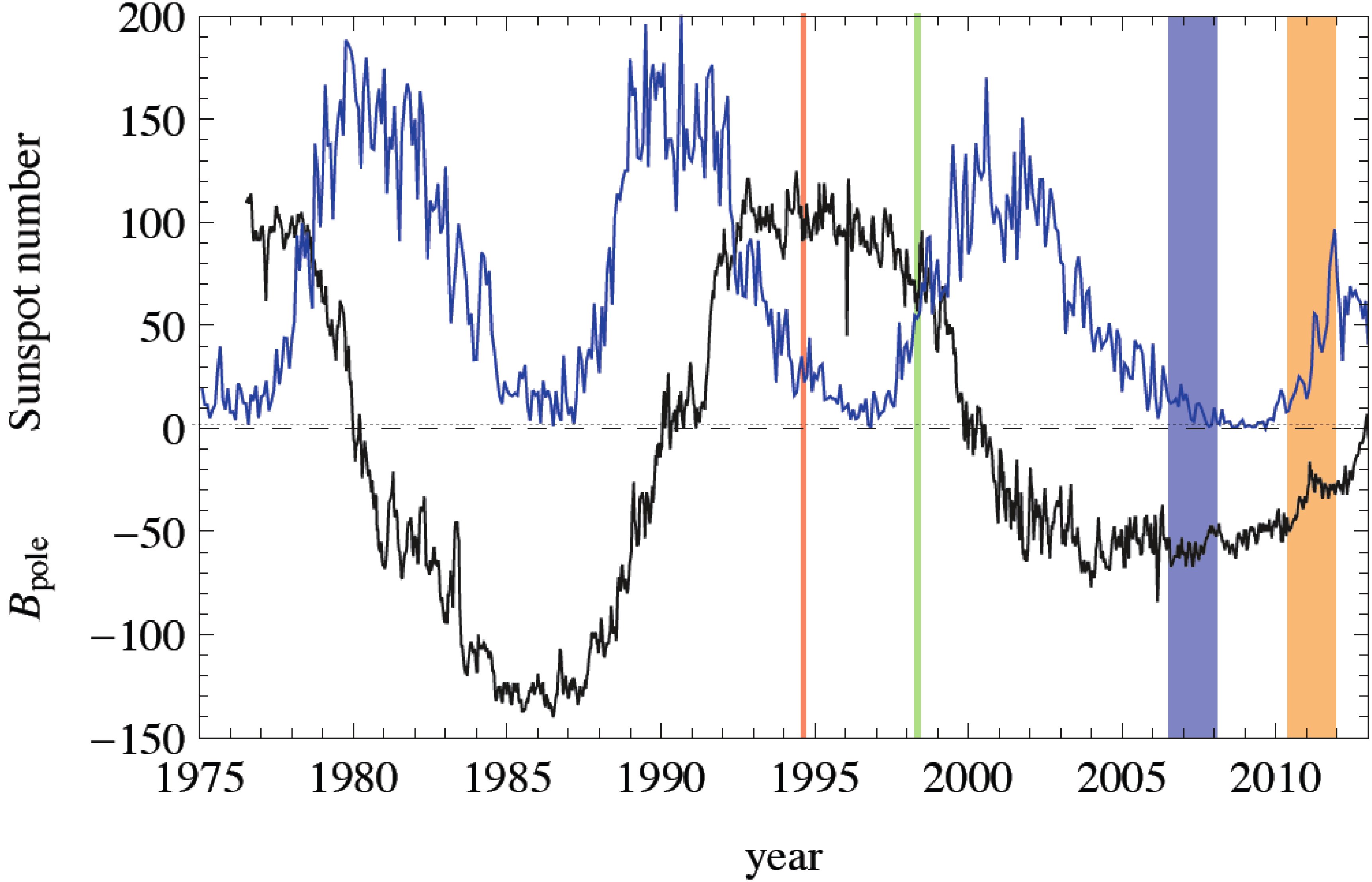
$$D(E) \propto E$$

$$T(E) \propto E^{-1}$$


North
South
North solar polar field strength (G)
South solar polar field strength (G)
1.5
1.0
0.5
0.0
-0.5
-1.0
A < 0
A > 0
A < 0
A > 0
A < 0
1960
1970
1980
1990
2000
2010
Time (years)


A > 0
20
10
0
−10
−20

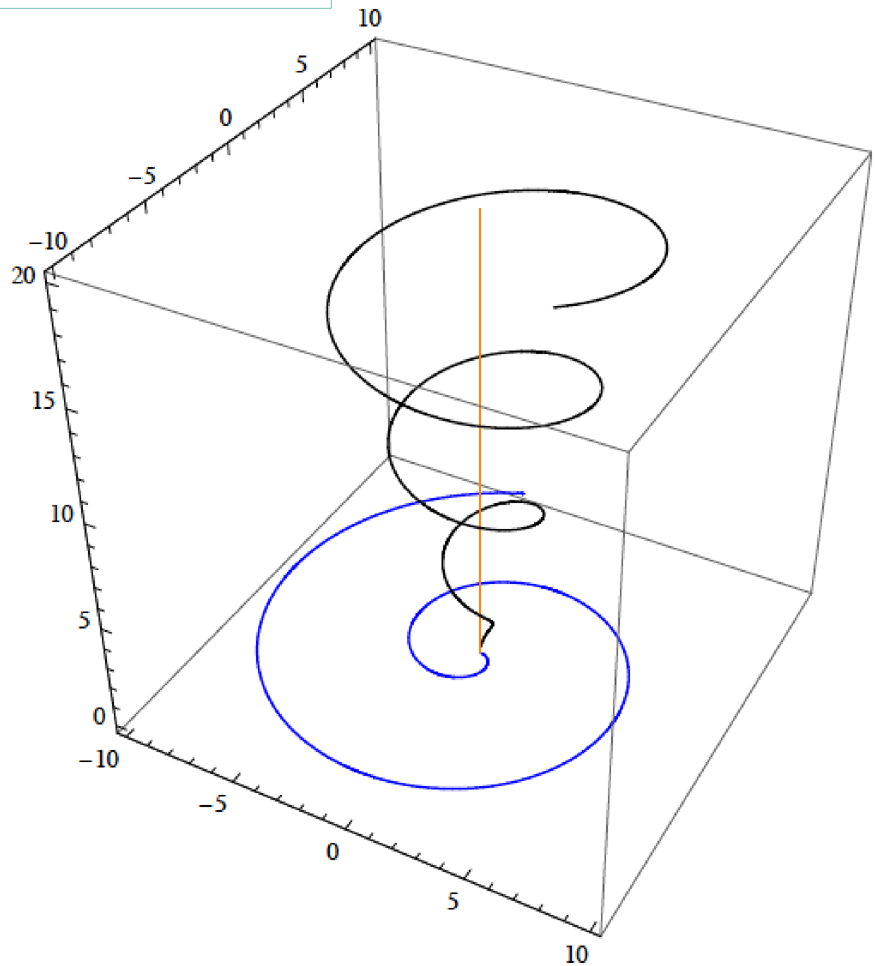

A < 0
20
10
0
−10
−20

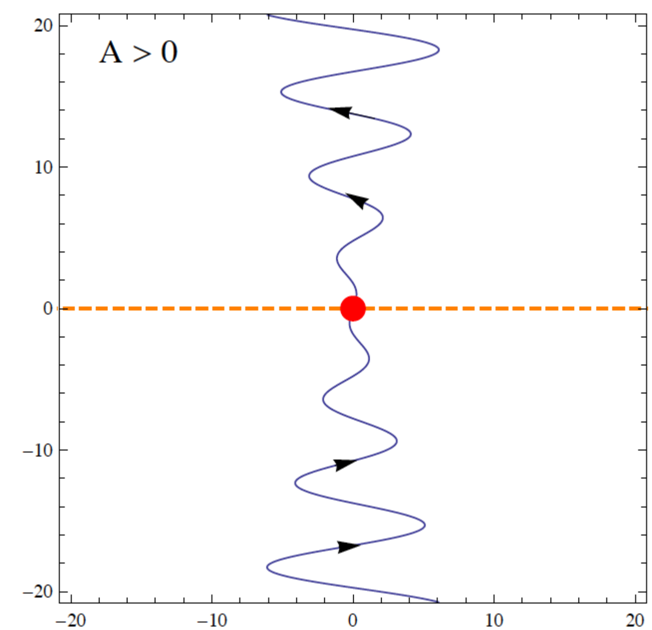

200
150
100
50
0
−50
−100
−150
Sunspot number
B_{pole}
1975
1980
1985
1990
1995
2000
2005
2010
year

$$\vec{B} = A\ B_0\ \left(\frac{r}{r_0}\right)^2\ \left[\hat{r} - \frac{\Omega}{v_w} r\ \sin\theta\ \hat{\varphi}\right]\ S(\vec{r})$$

$A = \pm 1$

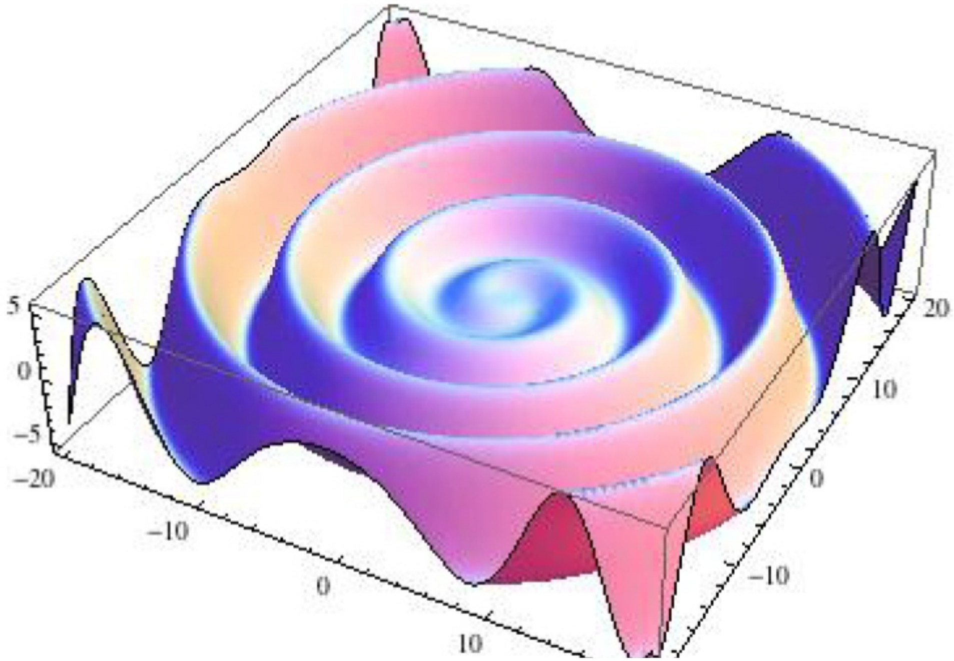
$S(\vec{r}) = \pm 1$

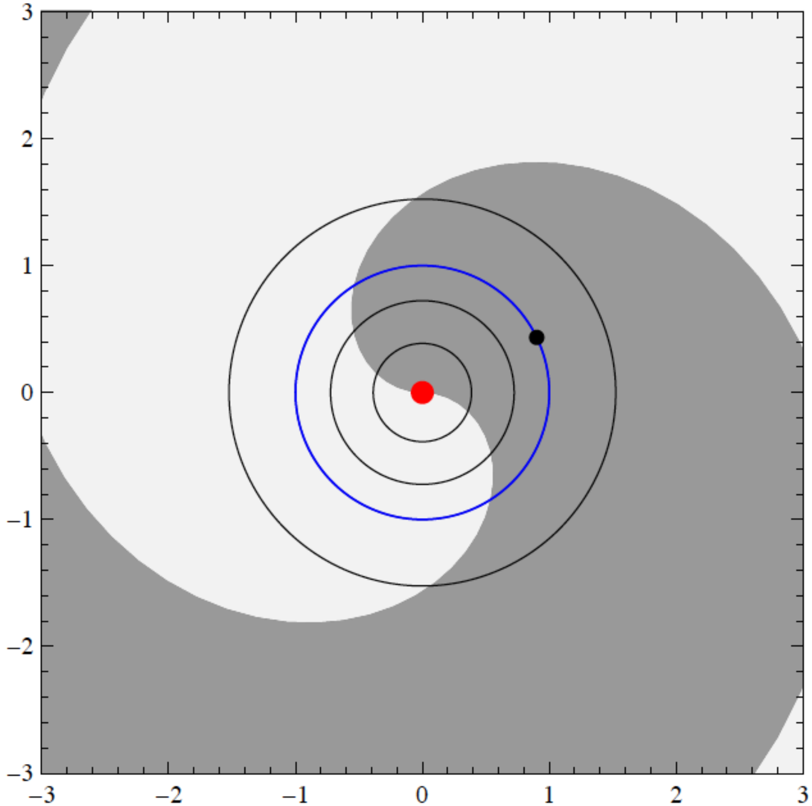


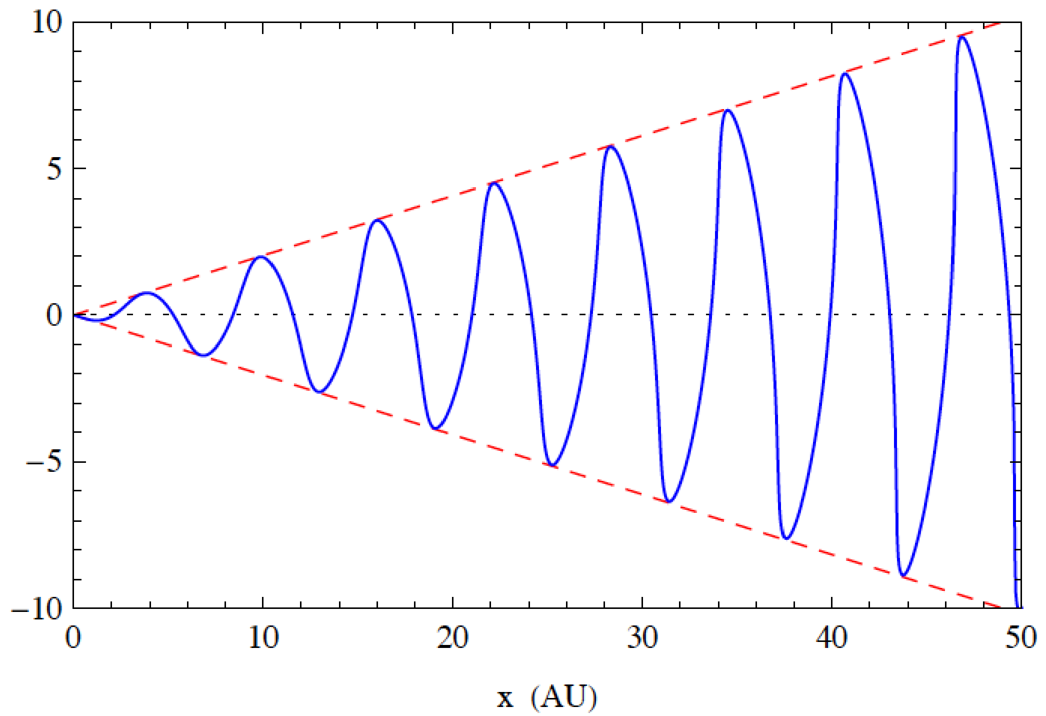


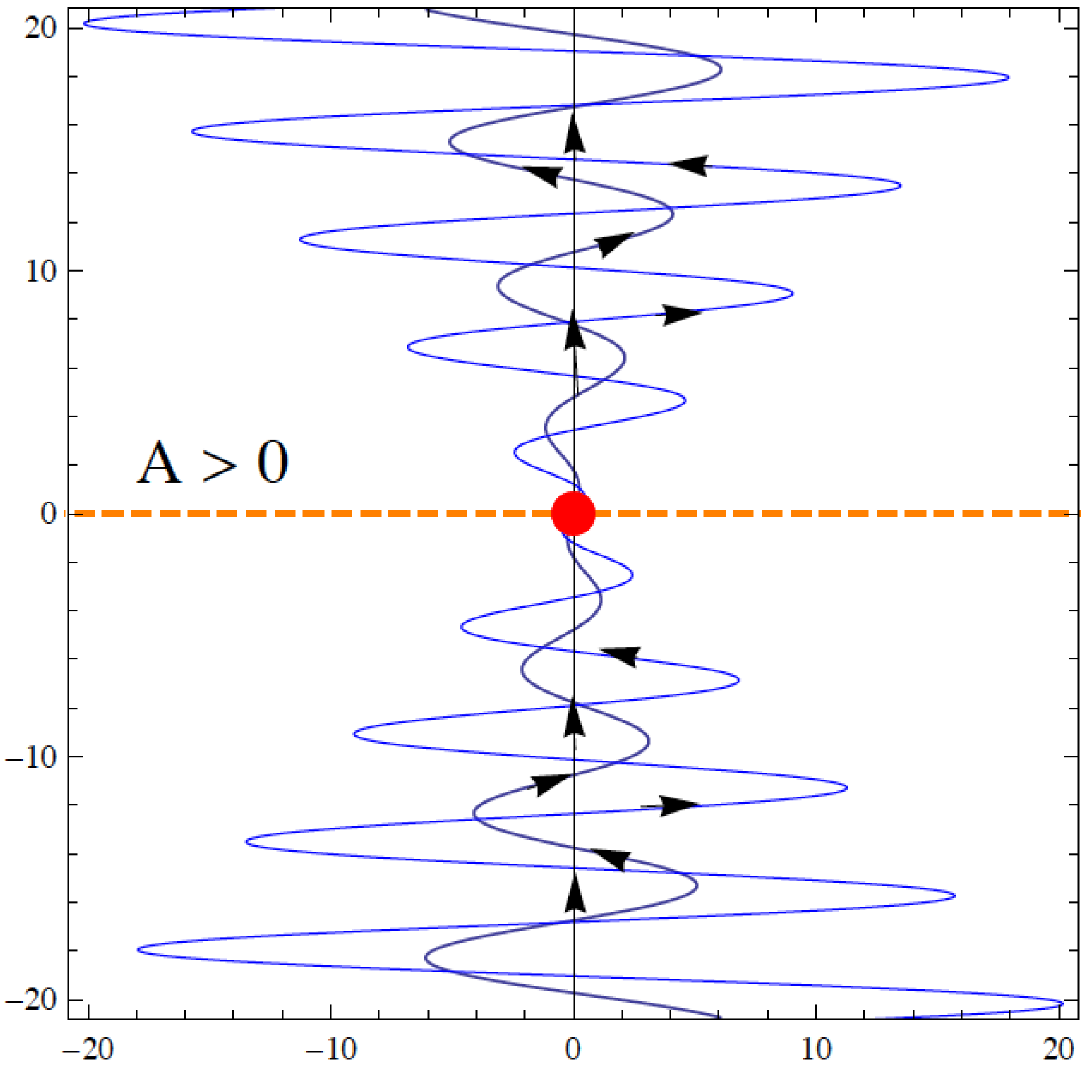
Heliospheric Current Sheet

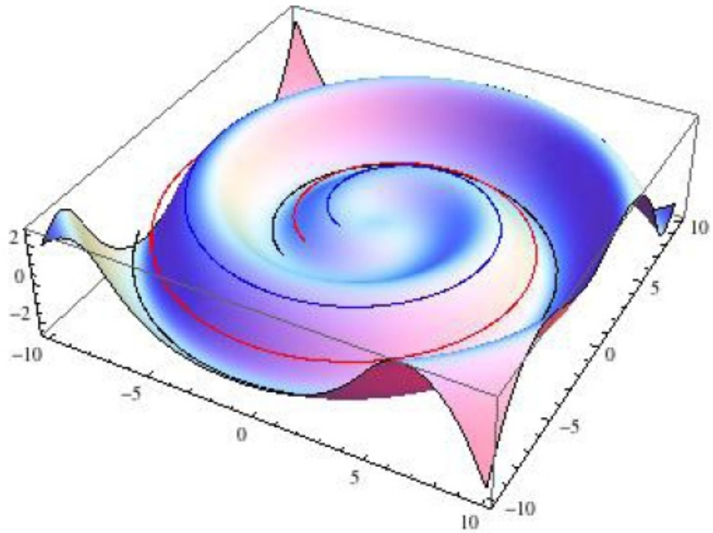
("Ballerina skirt")








A > 0
20
10
0
−10
−20
−20
−10
0
10
20


2
0
−2
−10
−5
0
5
10
10
5
0
−5
−10

Electric Field Associated to the "regular" Magnetic Field

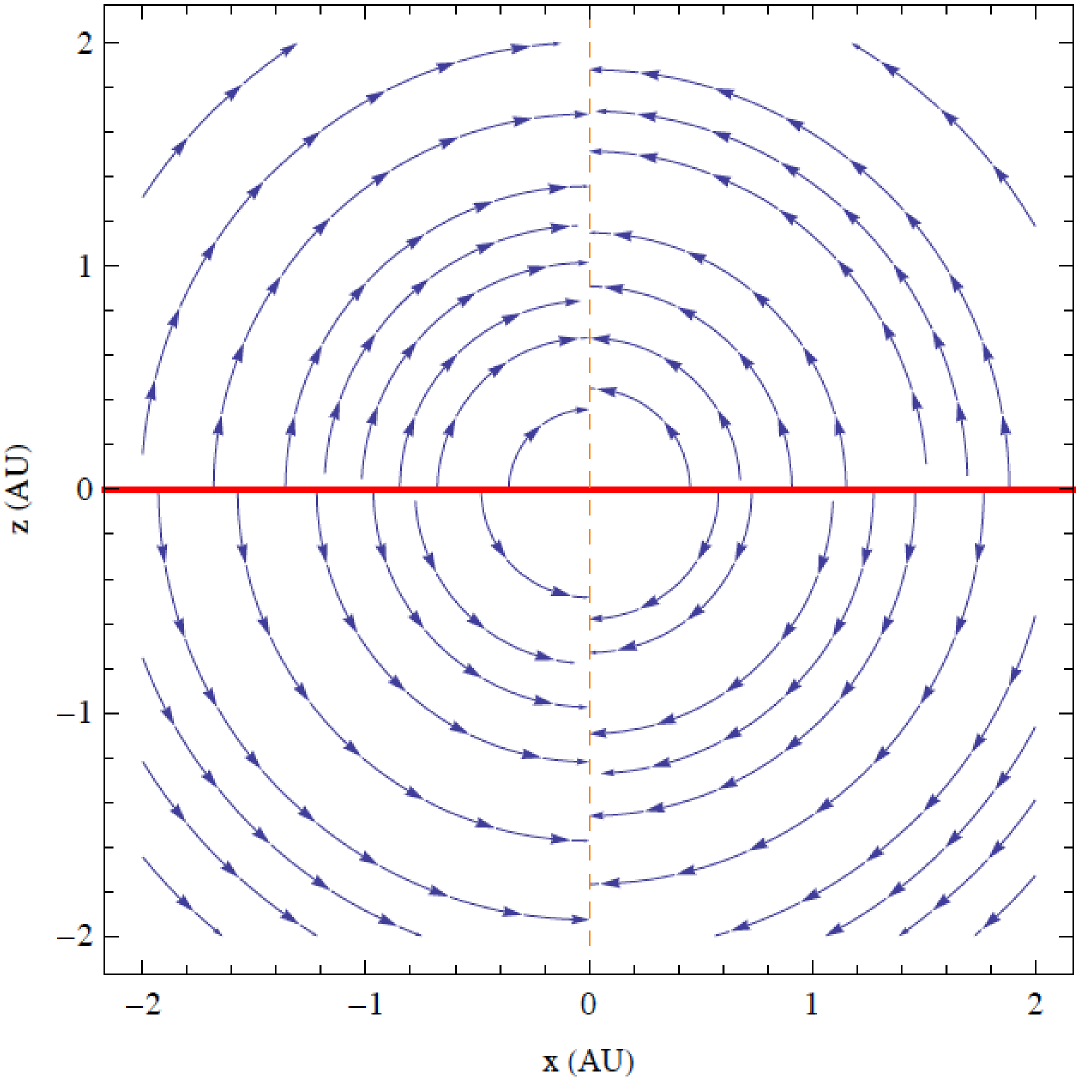
$$\boxed{\vec{E}(\vec{x}) = -\frac{\vec{v}_w(\vec{x})}{c} \wedge \vec{B}(\vec{x})}$$

Equivalent motivations for expression for electric field:

1. Net force on particle moving with the wind vanishes.

2. Field in wind frame is purely magnetic

$$\vec{E}(x,y,z) = \pm A\, B_0\, \frac{\Omega\, r_0^2}{c\, r^3}\, \{x\, z, y\, z, -(x^2+y^2)\}$$



Field with
Cylindrical symmetry

Stream-lines of the
“regular' Electric Field

“Back-tracing” of particles observed at the Earth.

$$\frac{d\vec{x}}{dt} = \vec{v} = \frac{\vec{p}}{\sqrt{p^2 + m^2}}$$

$$\frac{d\vec{p}}{dt} = q \left(\vec{E} + \frac{\vec{v}}{c} \wedge \vec{B} \right)$$

$$\vec{E}(\vec{x}) = -\frac{\vec{v}_w(\vec{x})}{c} \wedge \vec{B}(\vec{x})$$

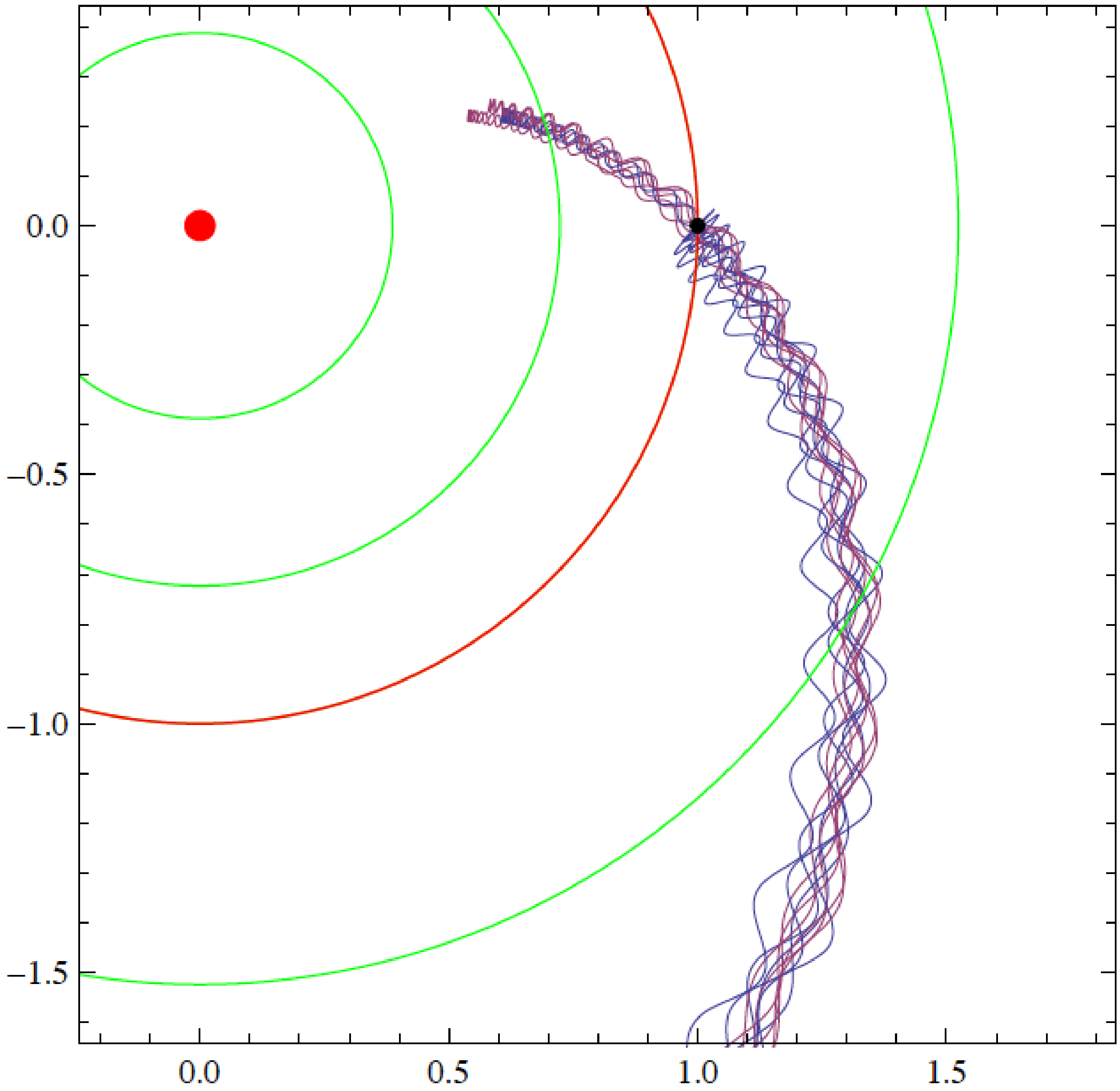
“Back-tracing” of particles observed at the Earth.
[Neglect random, turbulent field]

$$\frac{d\vec{x}}{dt} = \vec{v} = \frac{\vec{p}}{\sqrt{p^2 + m^2}}$$

$$\frac{d\vec{p}}{dt} = q \left(\boxed{\vec{E}} + \frac{\vec{v}}{c} \wedge \vec{B} \right)$$

Small perturbation

$$\vec{E}(\vec{x}) = -\frac{\vec{v}_w(\vec{x})}{c} \wedge \vec{B}(\vec{x})$$



“Backtracing” of particles

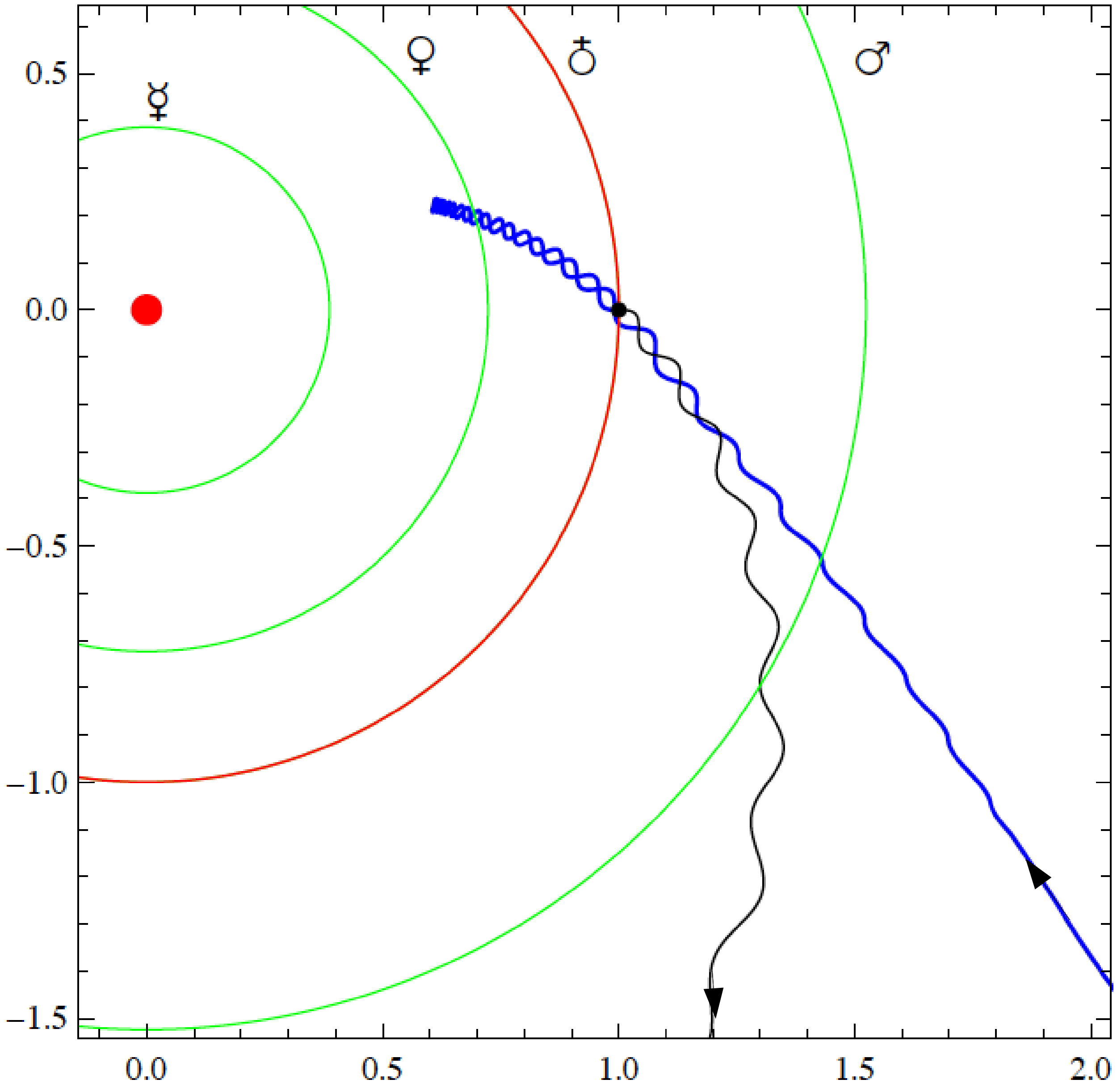
e+ (12 GeV)

12 directions

$$B_0 = 10^{-4}\ \mathrm{G}$$

$$v_w = 400\ \mathrm{km/s}$$

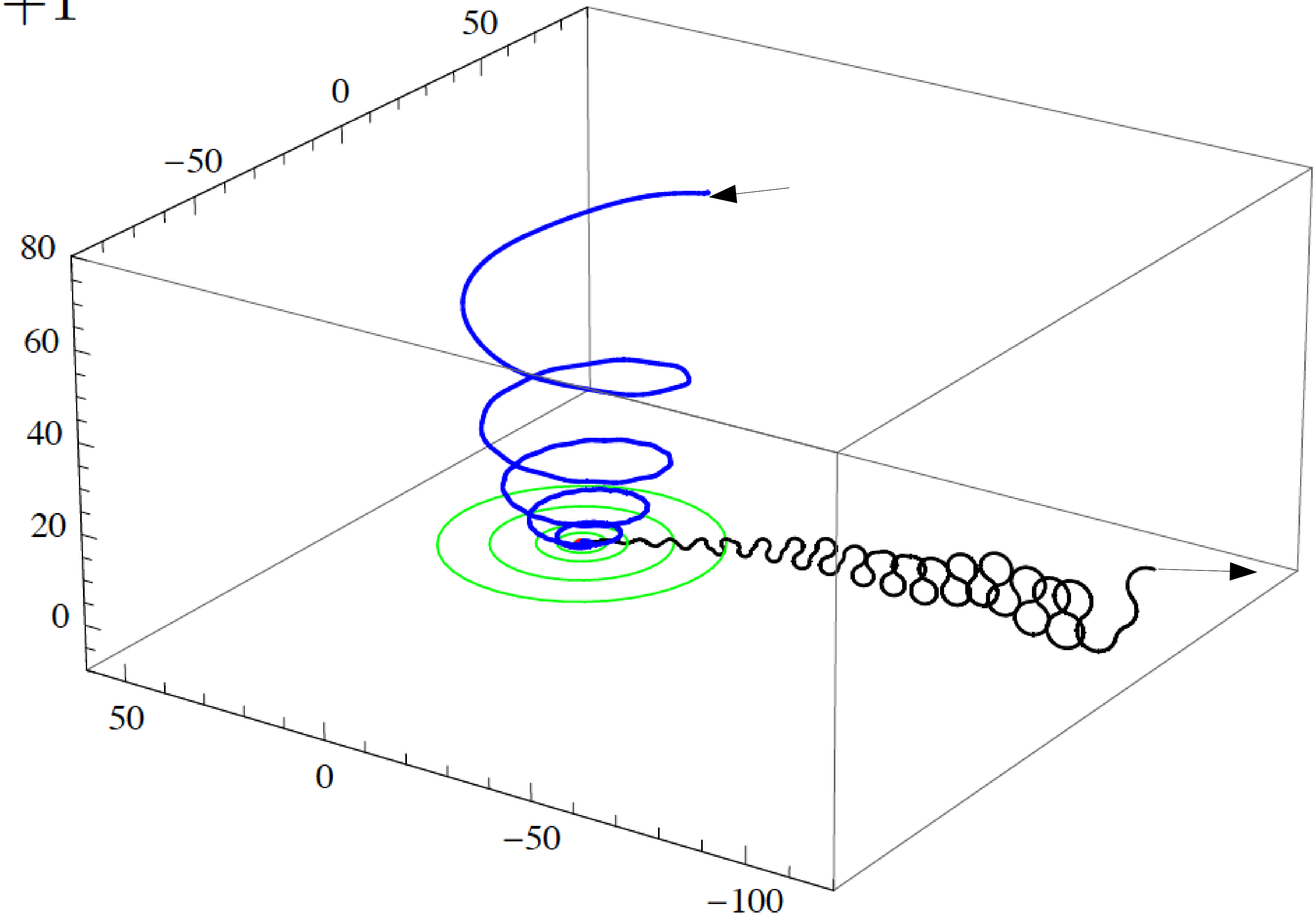
$$\sin\alpha = 0.05$$

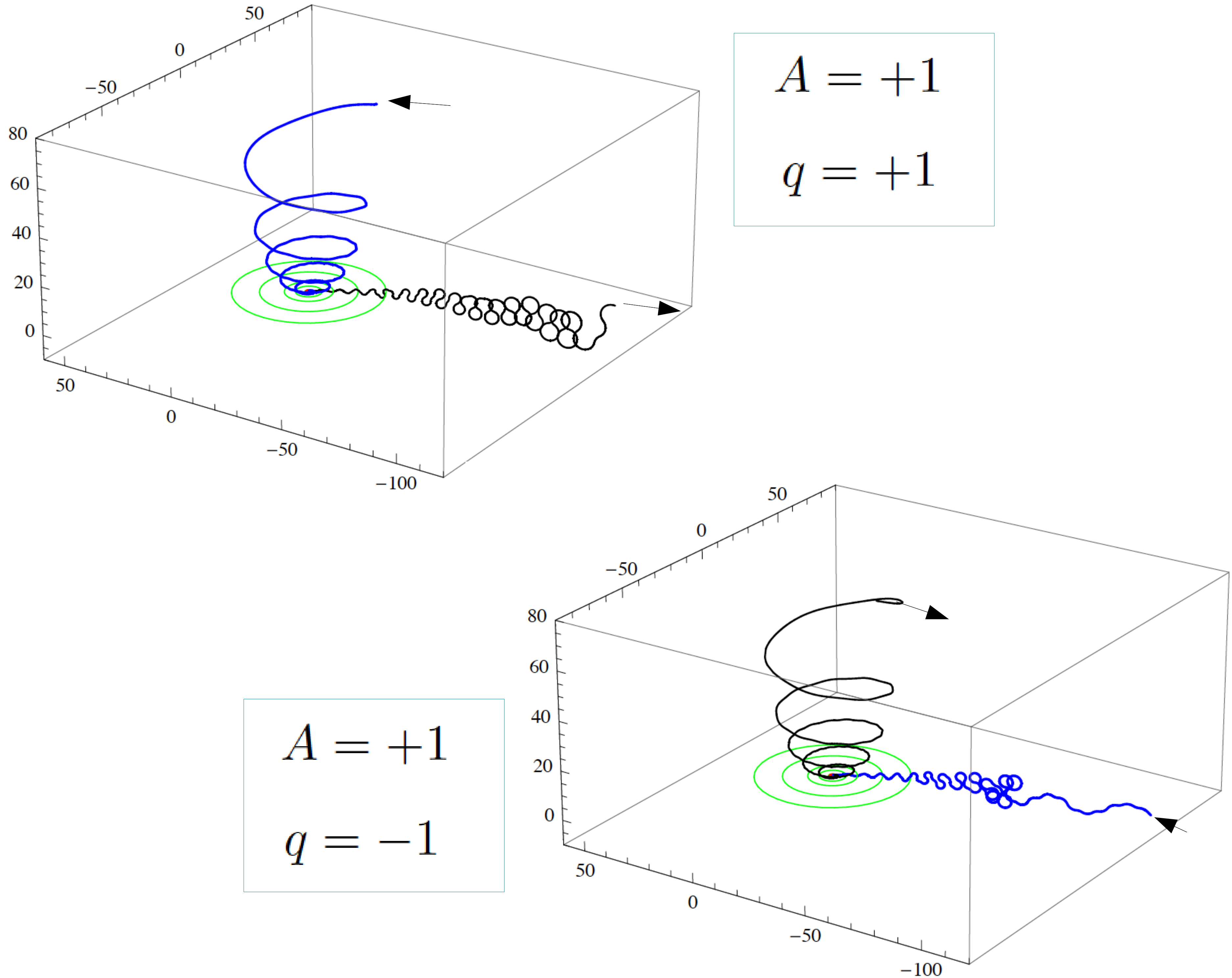


12 GeV
e-

$A = +1$ $E_{\mathrm{obs}} = 12\ \mathrm{GeV}$

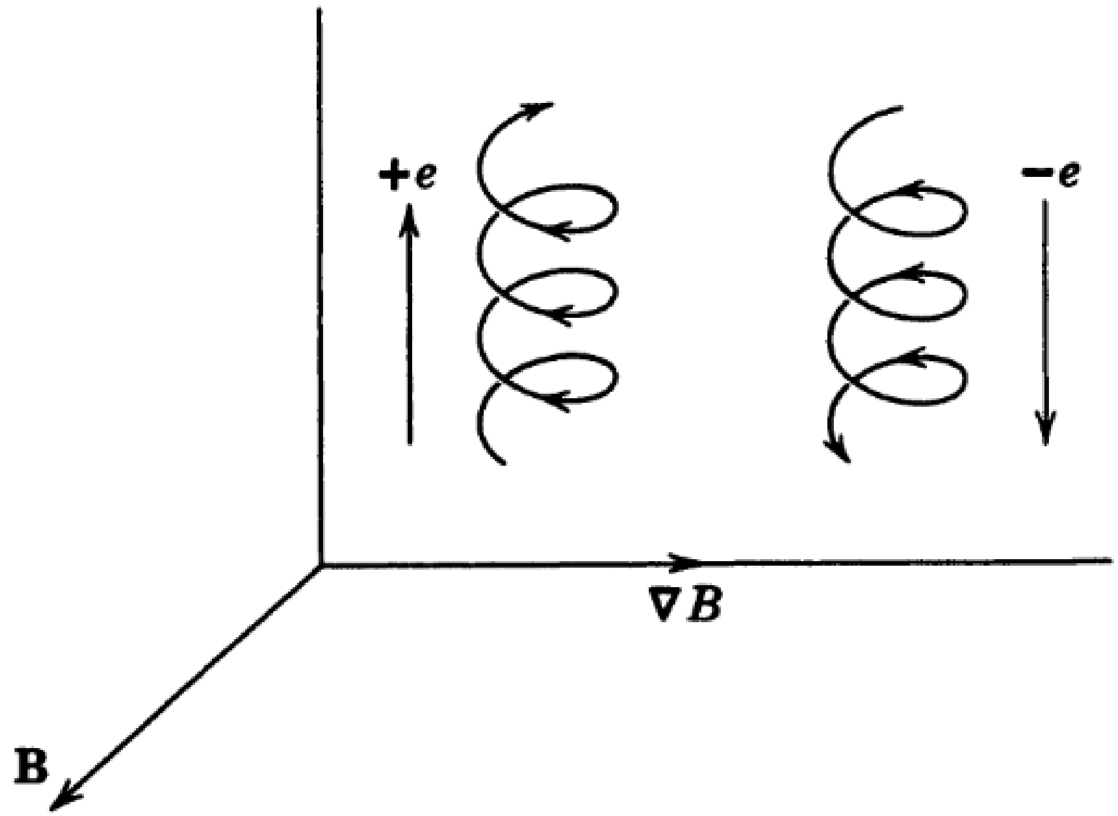
$q = +1$



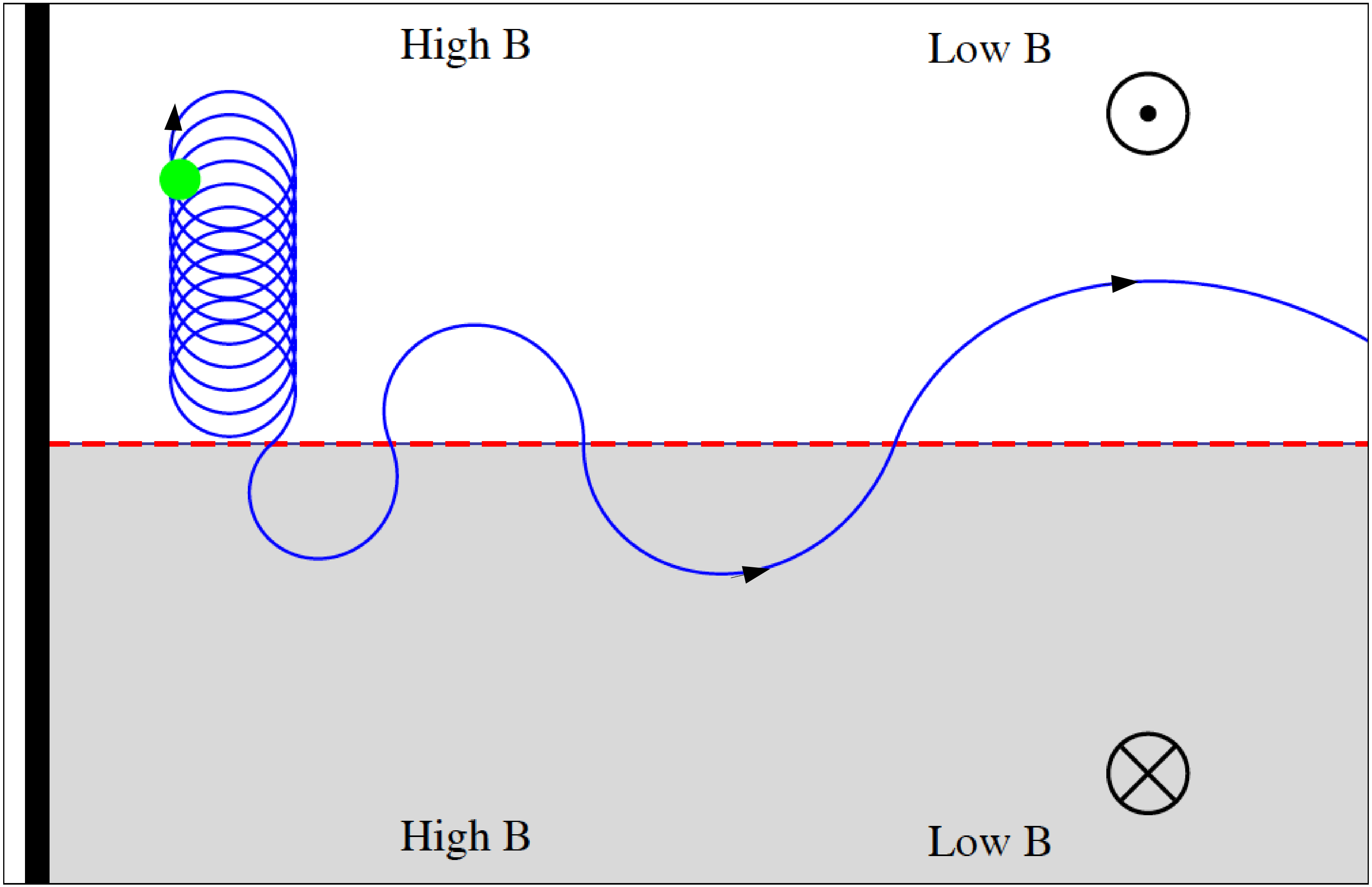


A = +1
q = +1
80
60
40
20
0
50
0
−50
−100
50
0
−50
A = +1
q = −1

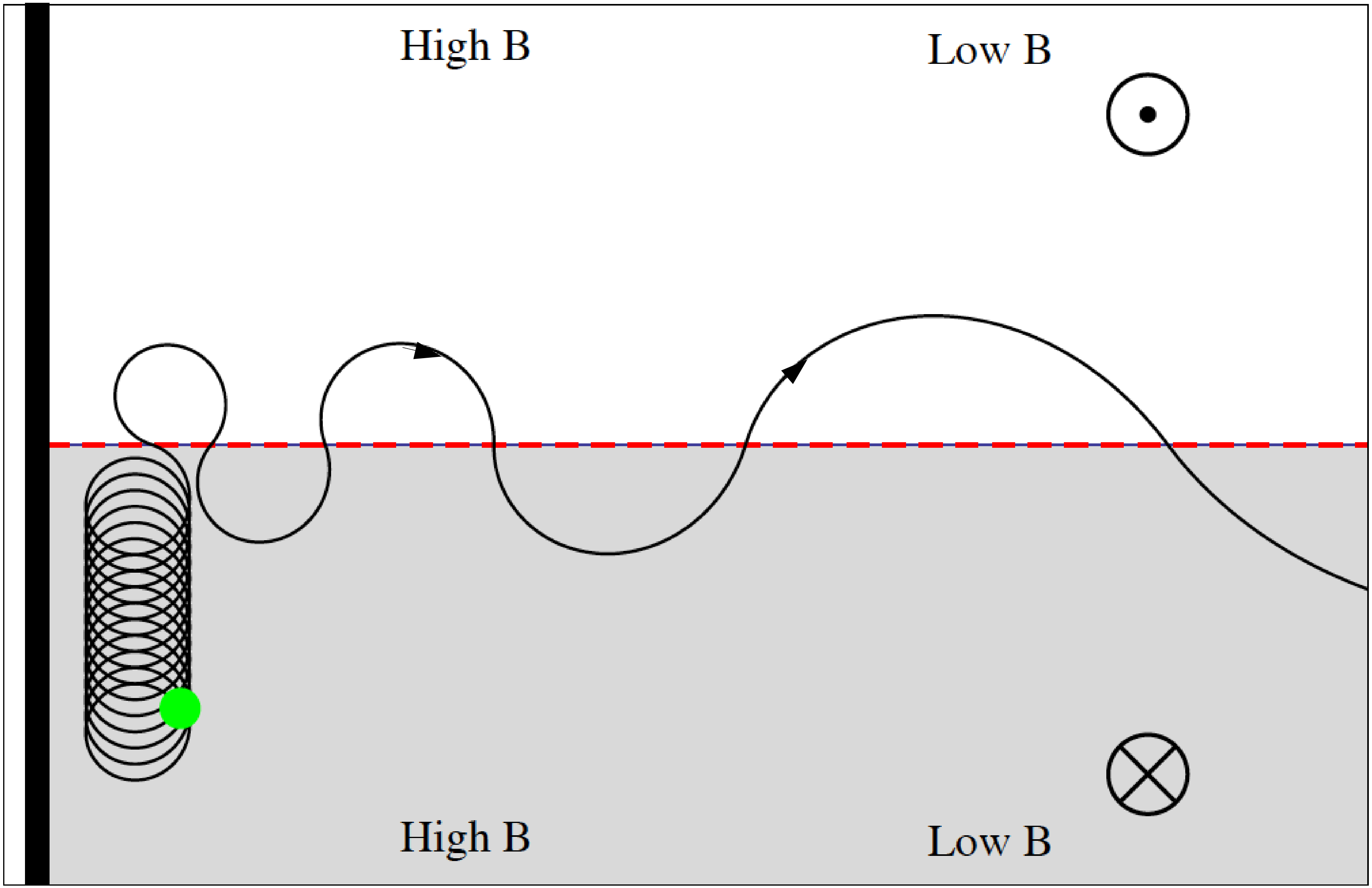
“Drift” of the guiding center of the particle gyration



$q = +1$

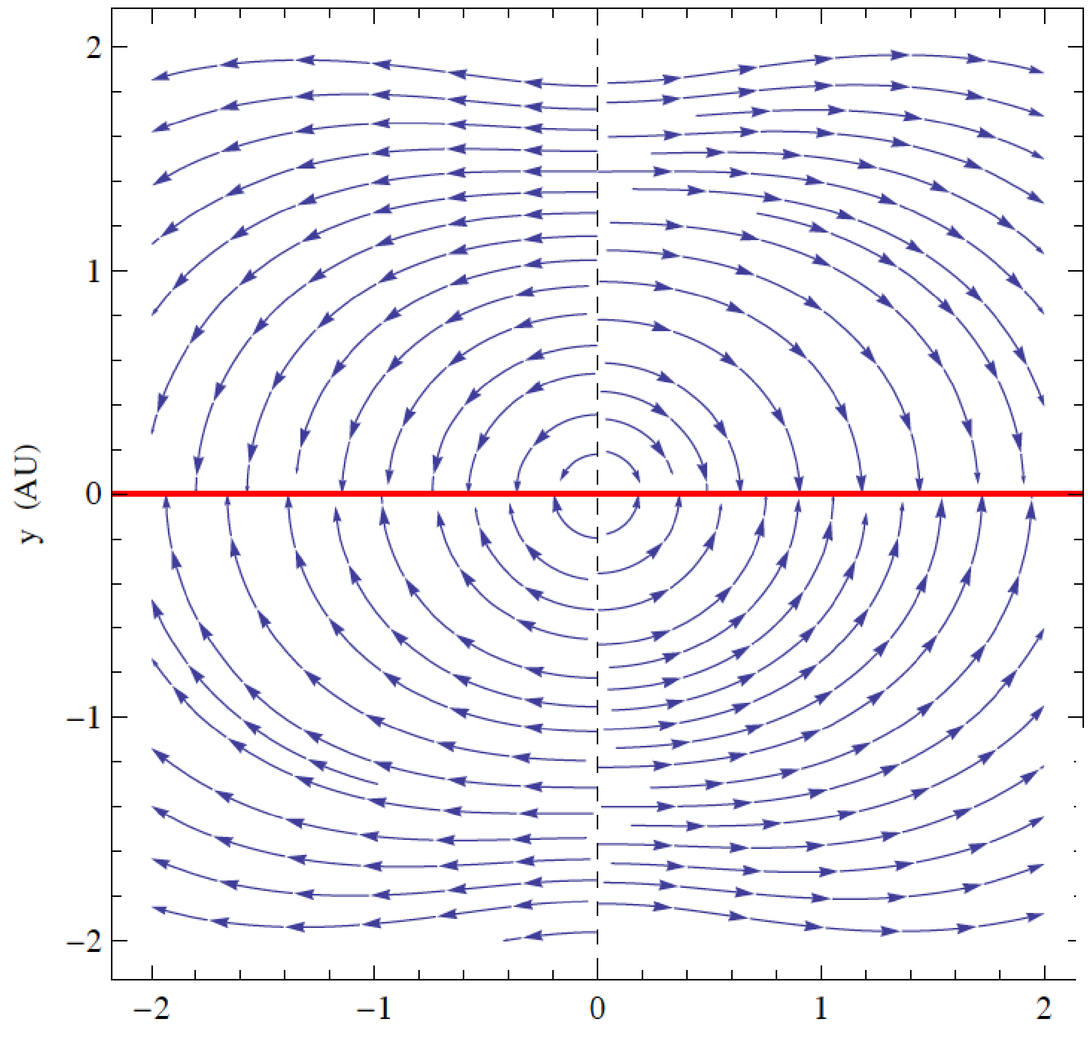


$q = +1$

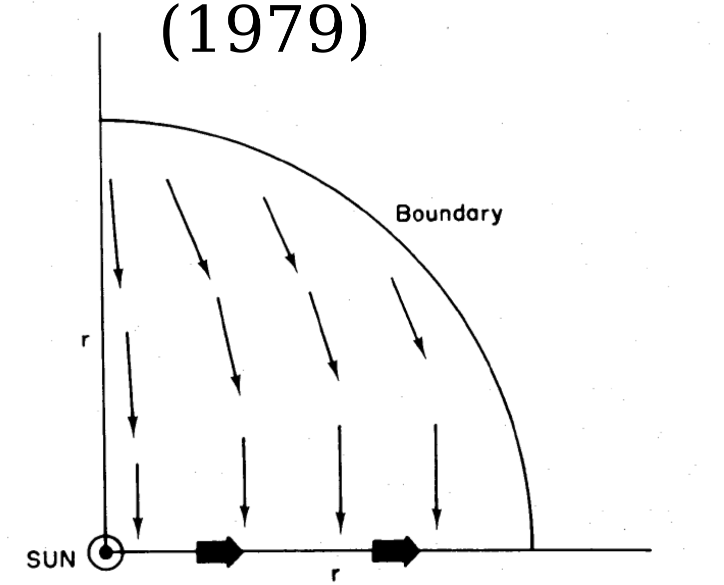


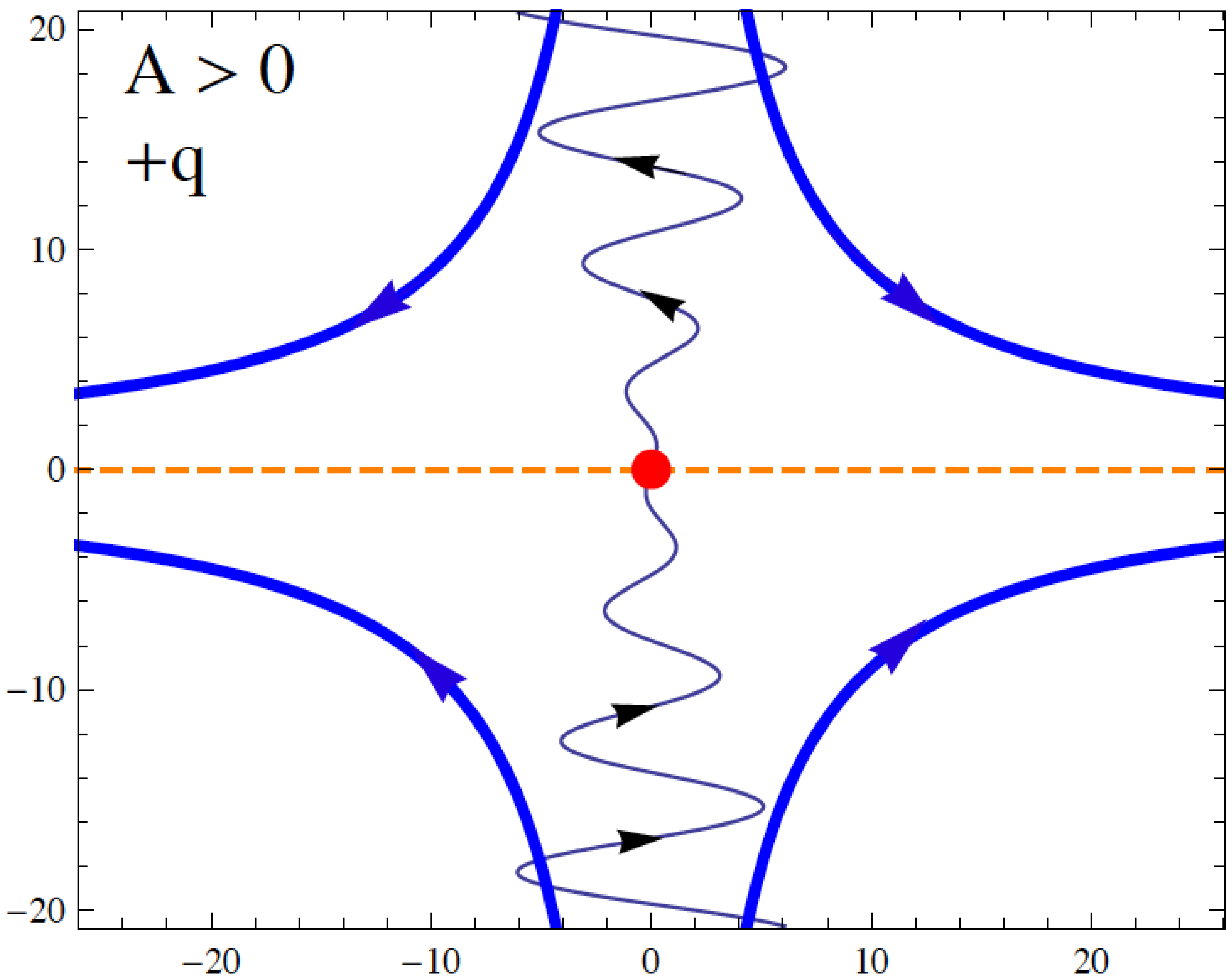
Stream lines of the drift velocity

$$q\,A > 0$$

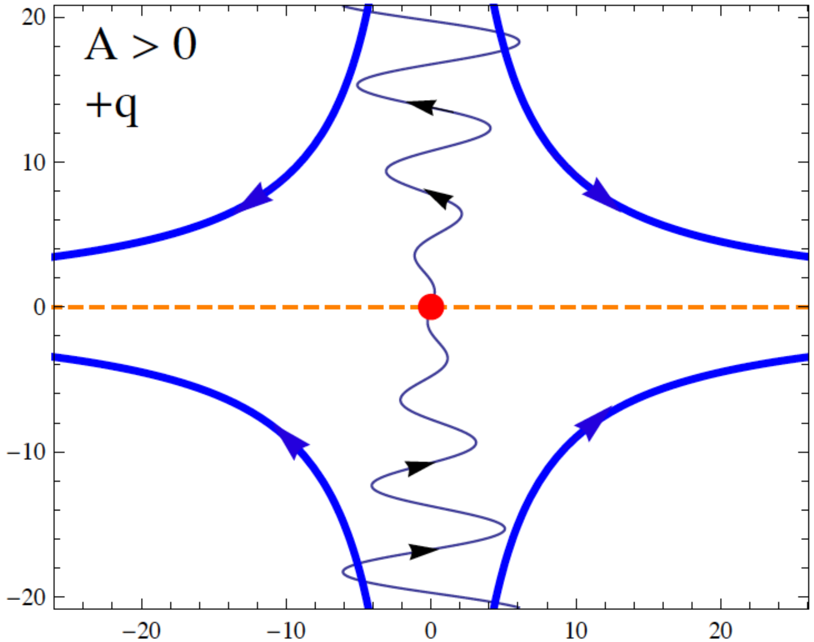


Jokipii + Kopriva (1979)

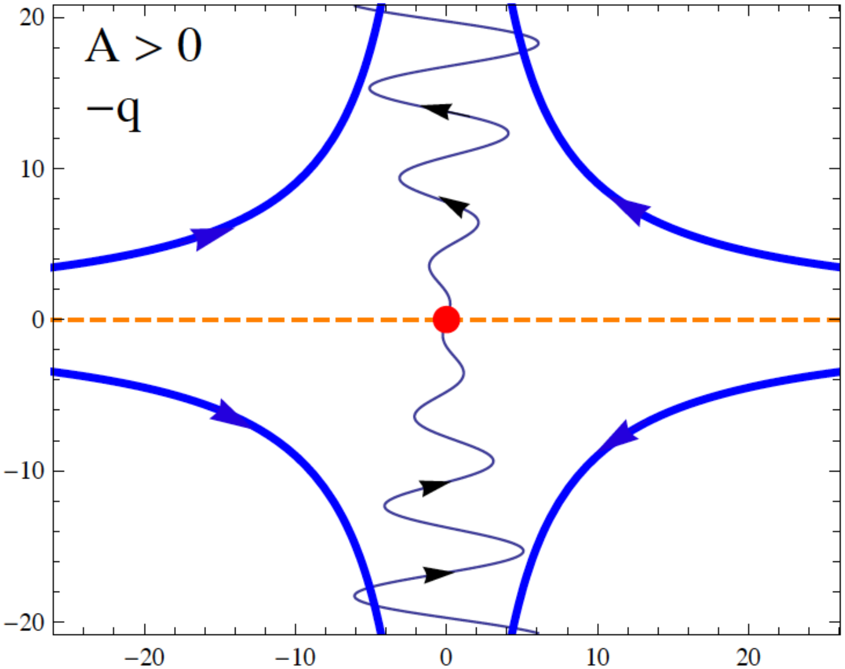




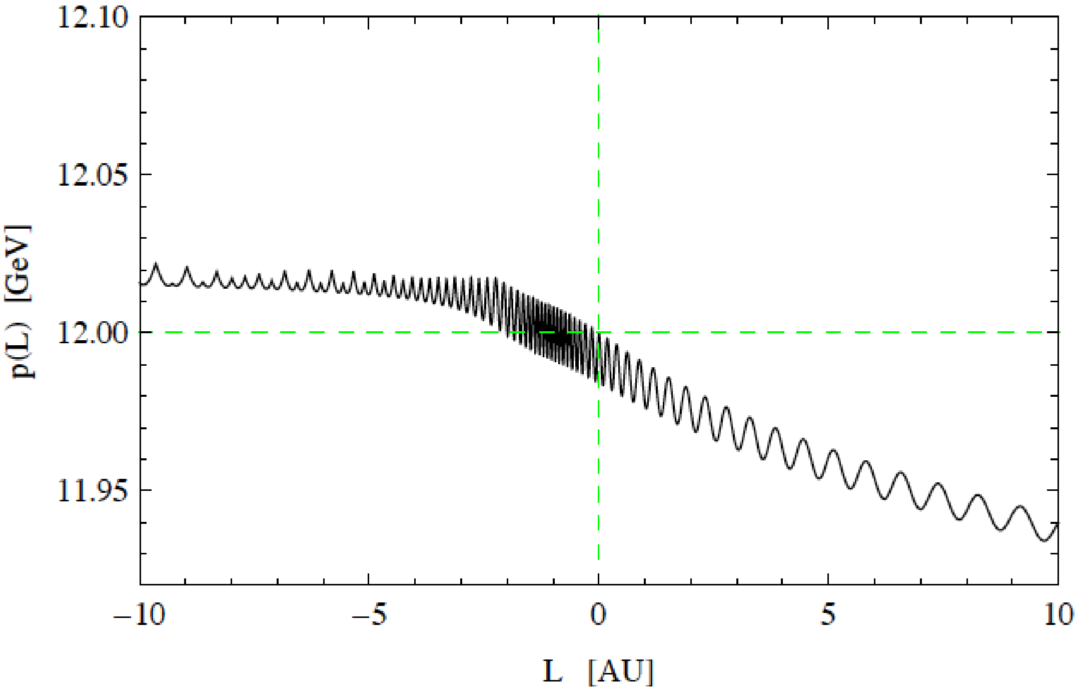
A > 0
+q
20
10
0
−10
−20
−20
−10
0
10
20



A > 0
+q
20
10
0
−10
−20
−20
−10
0
10
20



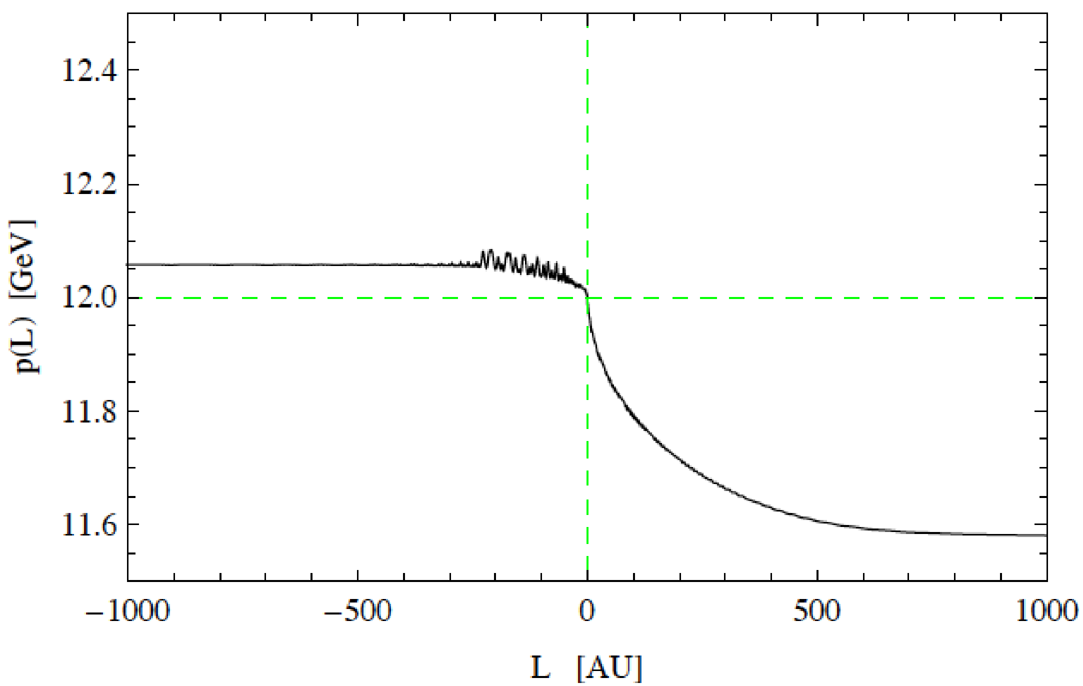
A > 0
−q
20
10
0
−10
−20
−20
−10
0
10
20



Energy Evolution

$$A = +1$$

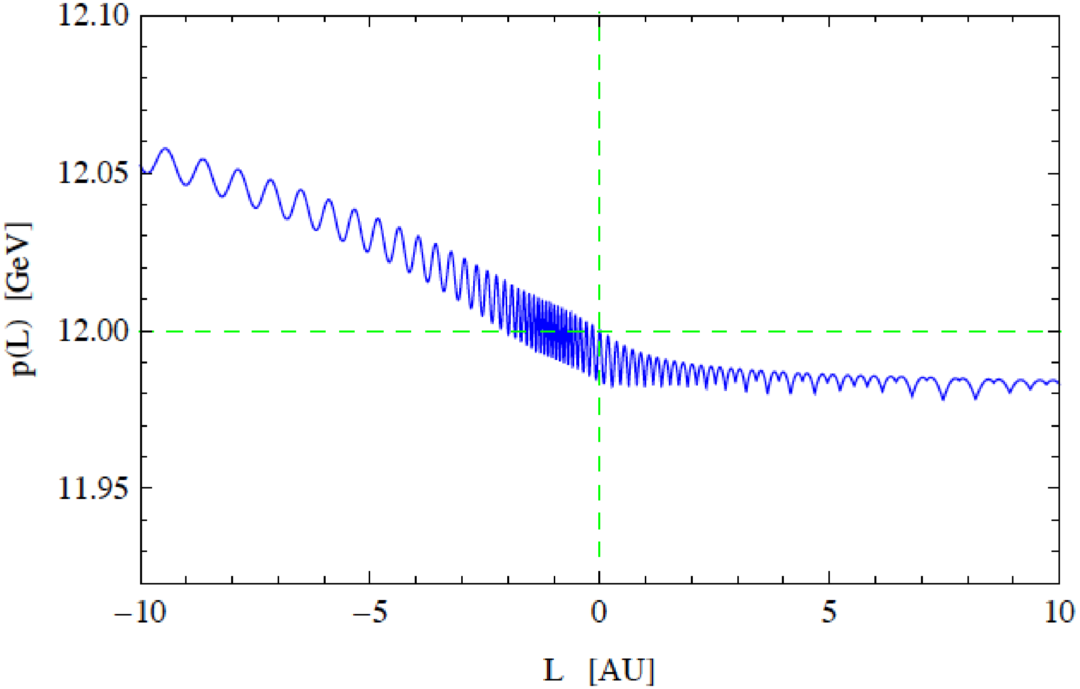
$$q = +1$$

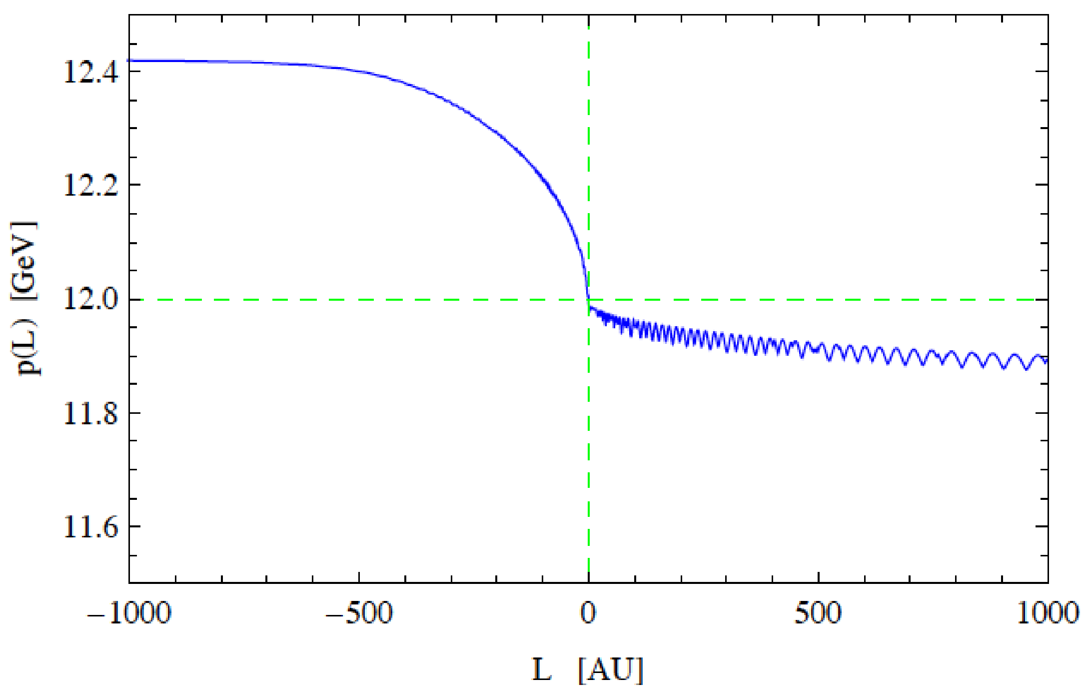


Energy Evolution

$$A = +1$$

$$q = -1$$





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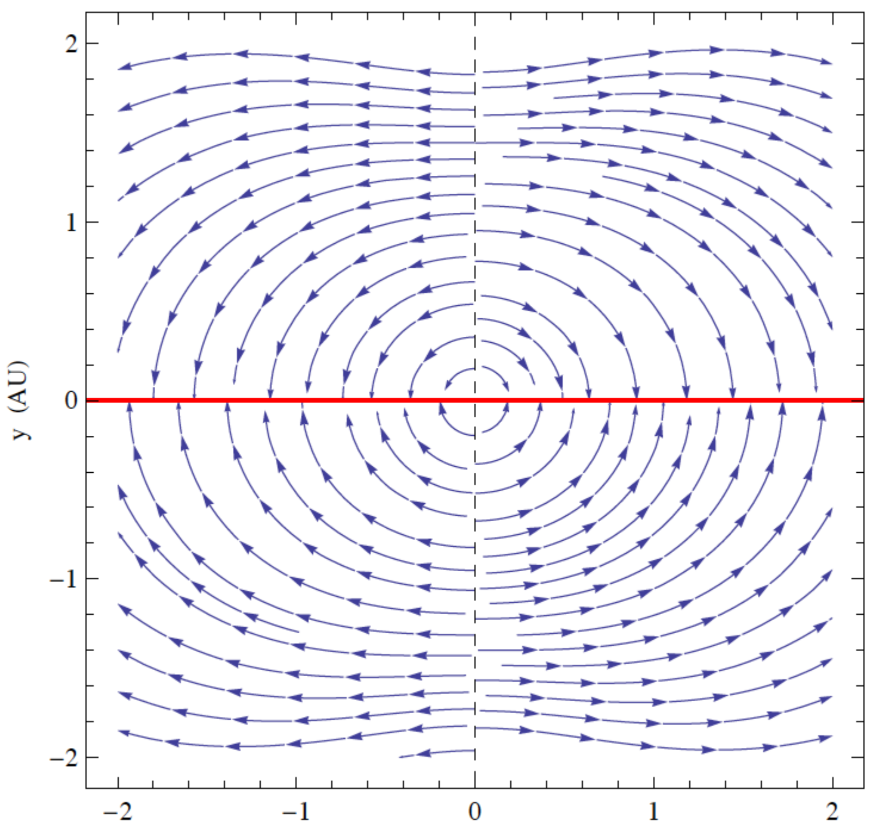
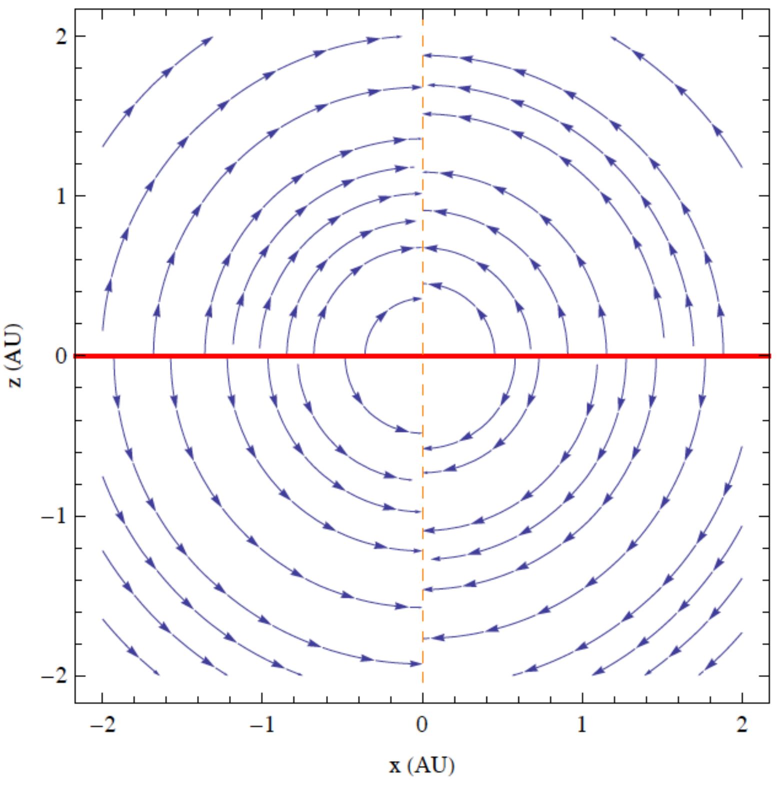
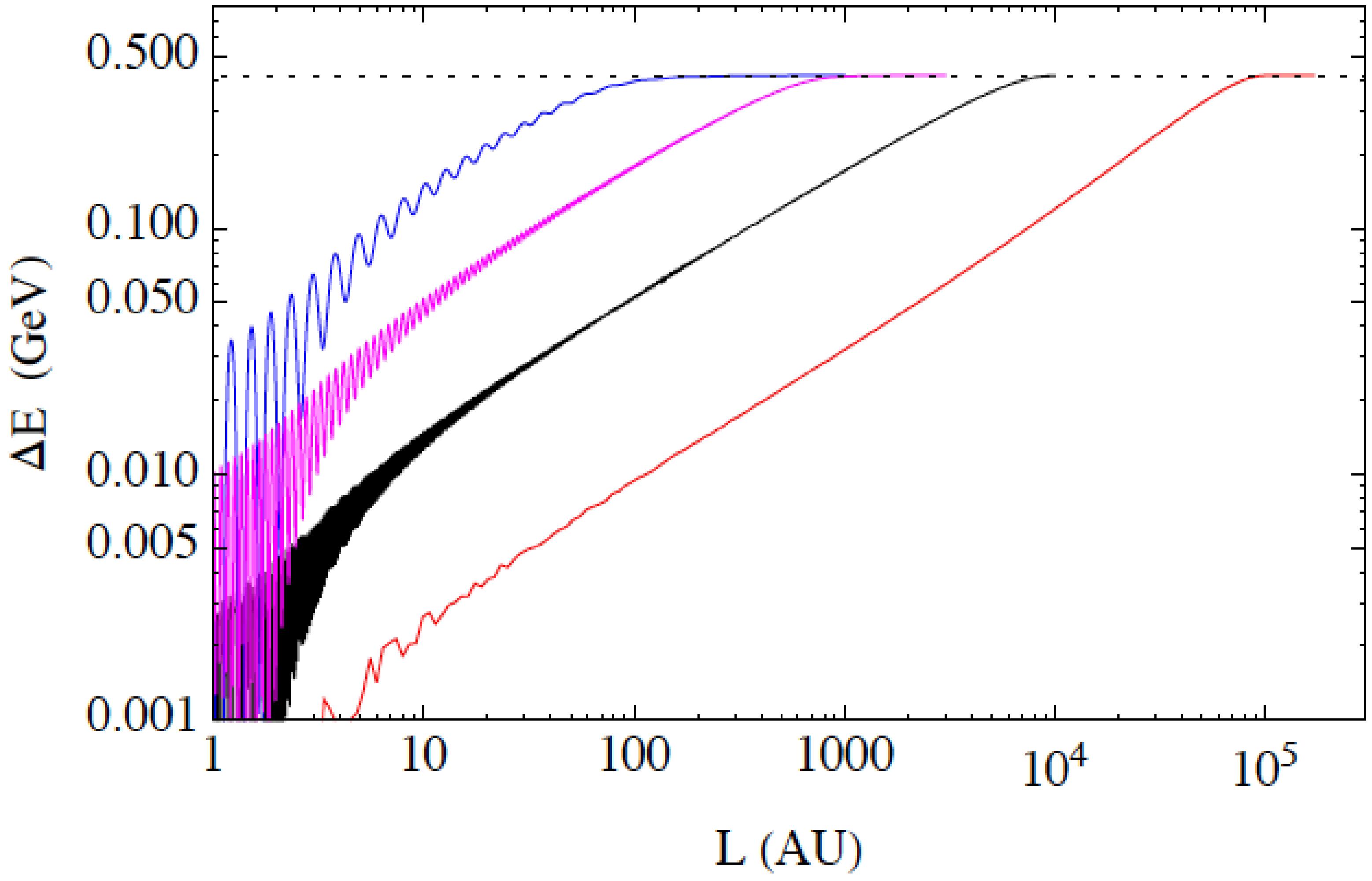




Stream-lines of the
“regular' Electric Field

Back-Tracing e+ (A=+1) 1,3,10,20 GeV



$$\vec{E}(x,y,z) = \pm A\, B_0\, \frac{\Omega\, r_0^2}{c\, r^3}\, \{x\, z, y\, z, -(x^2+y^2)\}$$

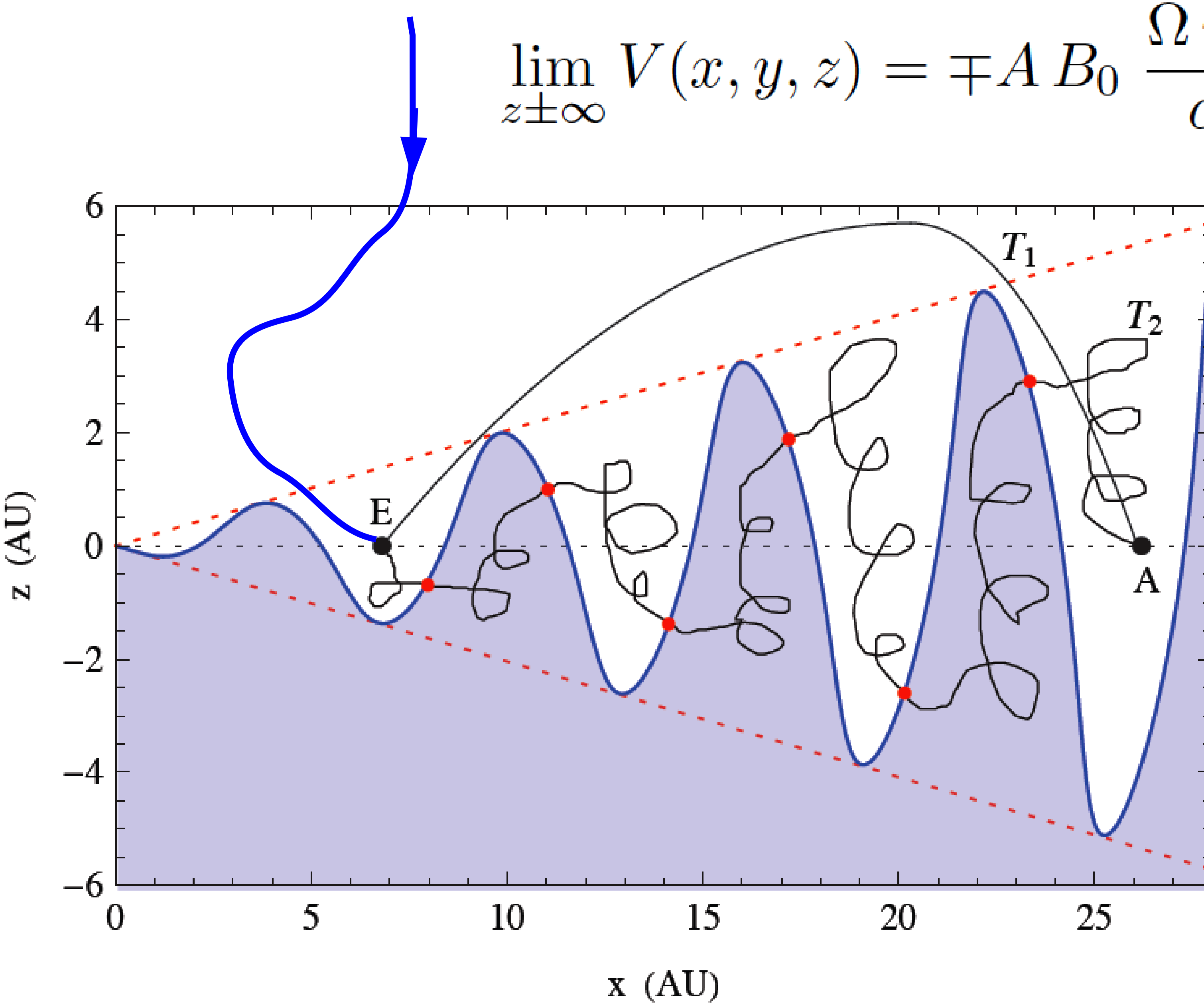
$$\vec{E}(x,y,z) = -\nabla V(x,y,z)$$

$$V(x,y,z) = \mp A\, B_0\, \frac{\Omega\, r_0^2}{c}\, \frac{z}{r}$$

Trajectory that does not cross
the Heliospheric Current Sheet

$$\boxed{\int_T d\vec{s}\cdot \vec{E}(s) = V(\vec{x}_f) - V(\vec{x}_i)}$$

$$\lim_{z \pm\infty} V(x,y,z) = \mp A\, B_0\, \frac{\Omega\, r_0^2}{c}$$

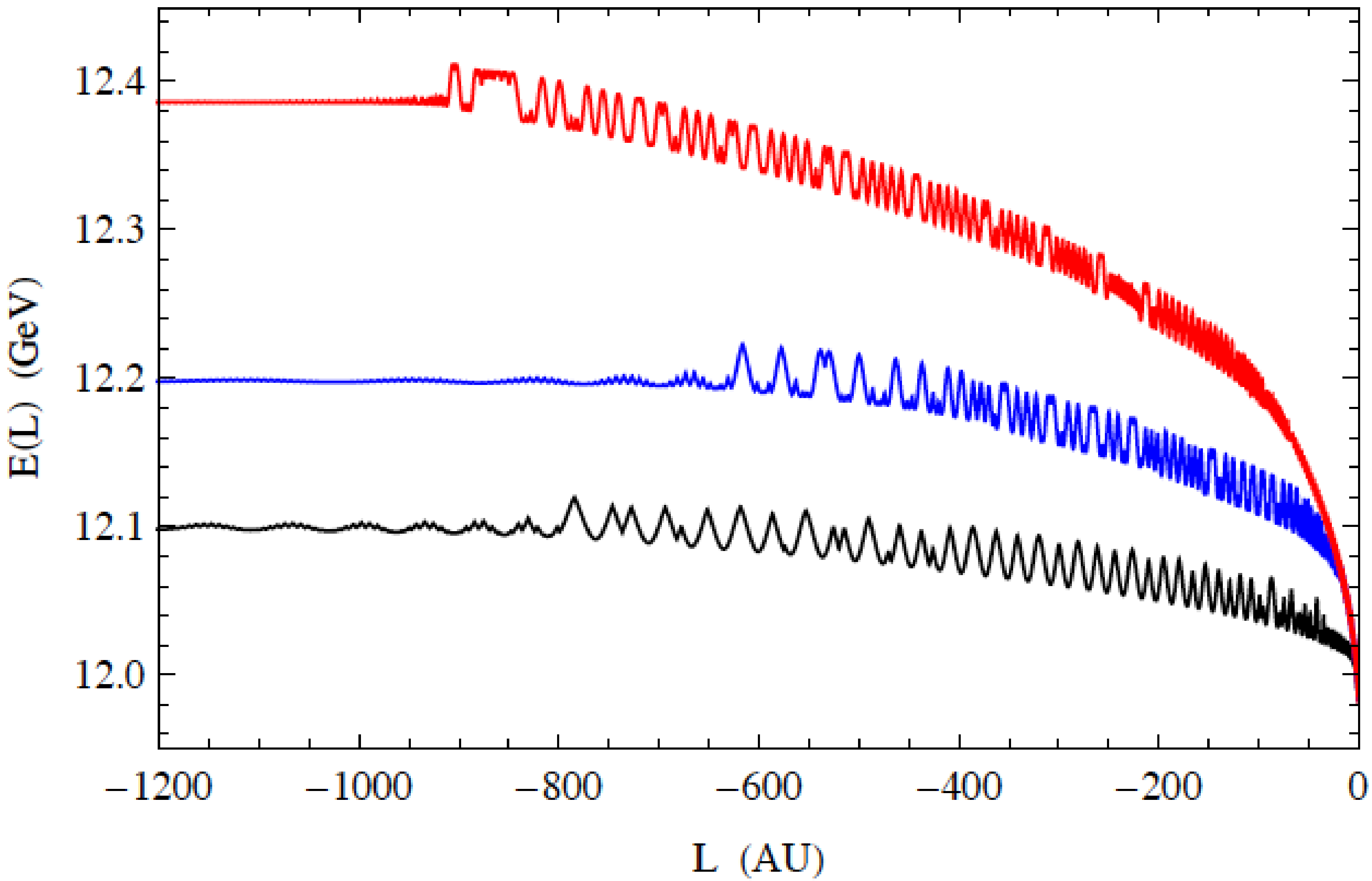


$$V(x,y,z=0) = 0$$

$$\Delta E|_{qA>0} = |q_e|\ B_0\,\frac{\Omega\, r_0^2}{c} \simeq 0.422\ \left(\frac{B_0}{10^{-4}\ \mathrm{Gauss}}\right)\ \mathrm{GeV}$$

$$\Delta E|_{qA<0} \simeq 2\ \sin\alpha\ \ \Delta E|_{qA>0}$$

Energy Losses attributable to
the regular heliospheric electric field



12.4
12.3
12.2
12.1
12.0
E(L) (GeV)
−1200
−1000
−800
−600
−400
−200
0
L (AU)

Concluding Remarks:

The Heliosphere is a fundamental "Laboratory"
to study the propagation of relativistic particles.
Many problems relevant for Milky Way propagation
can be studied in detail.

The AMS02 data with their high statistics
(together with various measurement of the (time varying)
properties of the heliospheric environment) can provide
very important information.

The "regular" Heliospheric Magnetic Field
has associated a regular electric field that is very
important in the energy evolution of the particles
that penetrates the heliosphere.