Understanding the origin of Cosmic Rays and high energy particles in the Milky Way and in the Universe

Paolo Lipari, INFN Roma

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1. General Considerations.

2. Propagation of Cosmic Rays
in the Heliosphere

3. Structure of the Magnetic Field
in the Milky Way

(my personal work in progress)

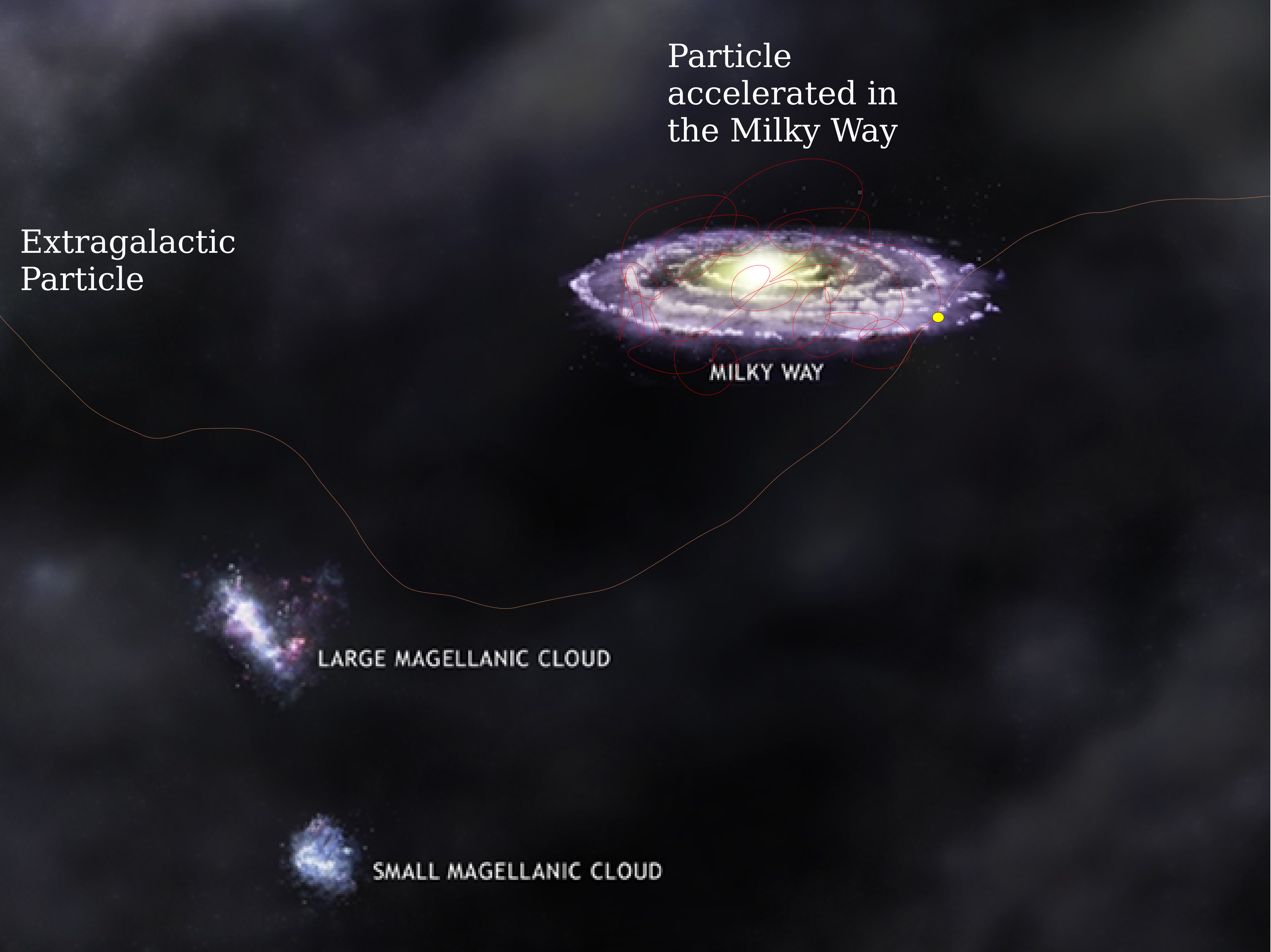
1. General Considerations.

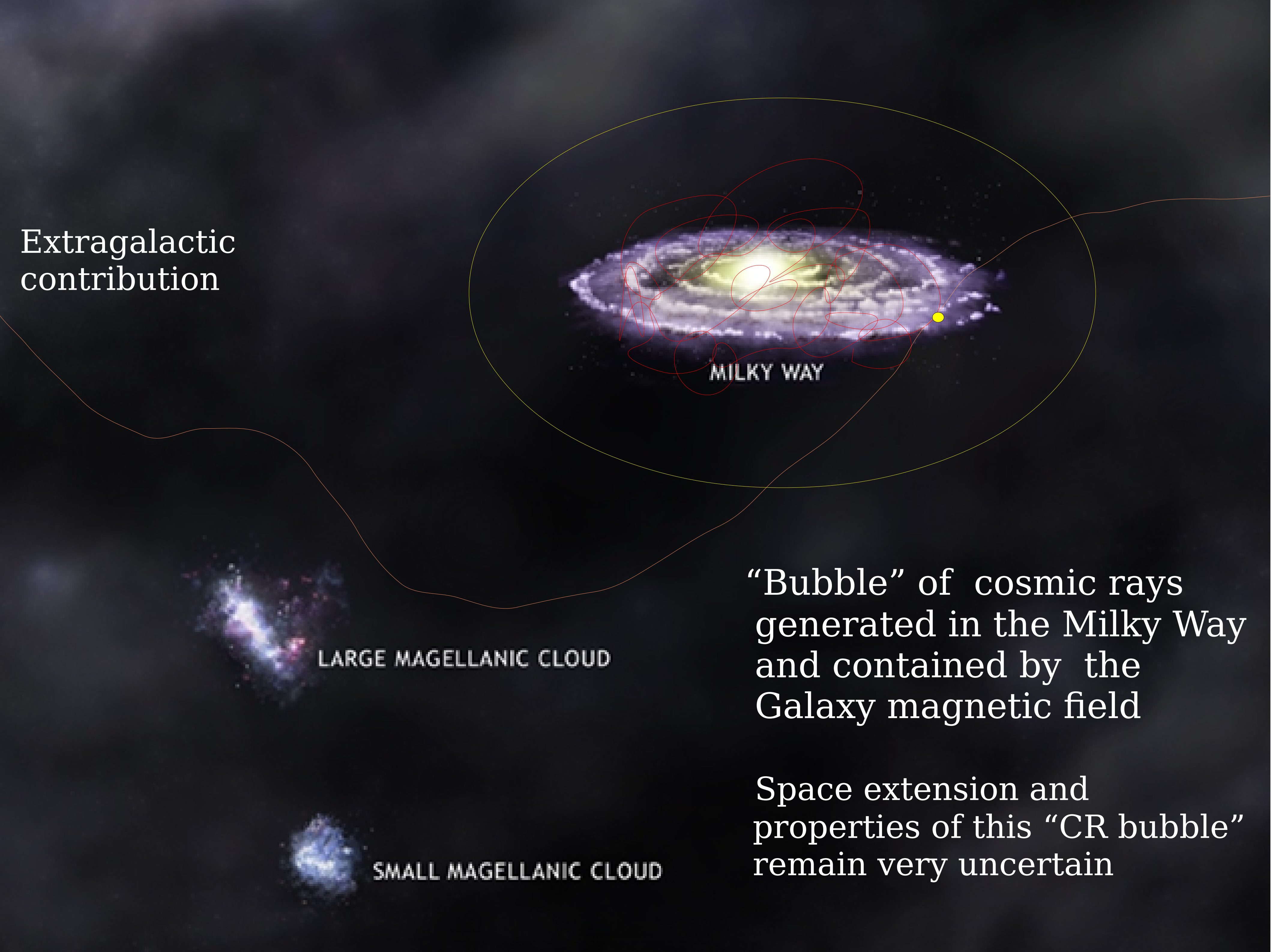
Three main sources of cosmic rays
[high energy (relativistic) charged particles] :

[1. The sun (E < 10-100 GeV)]

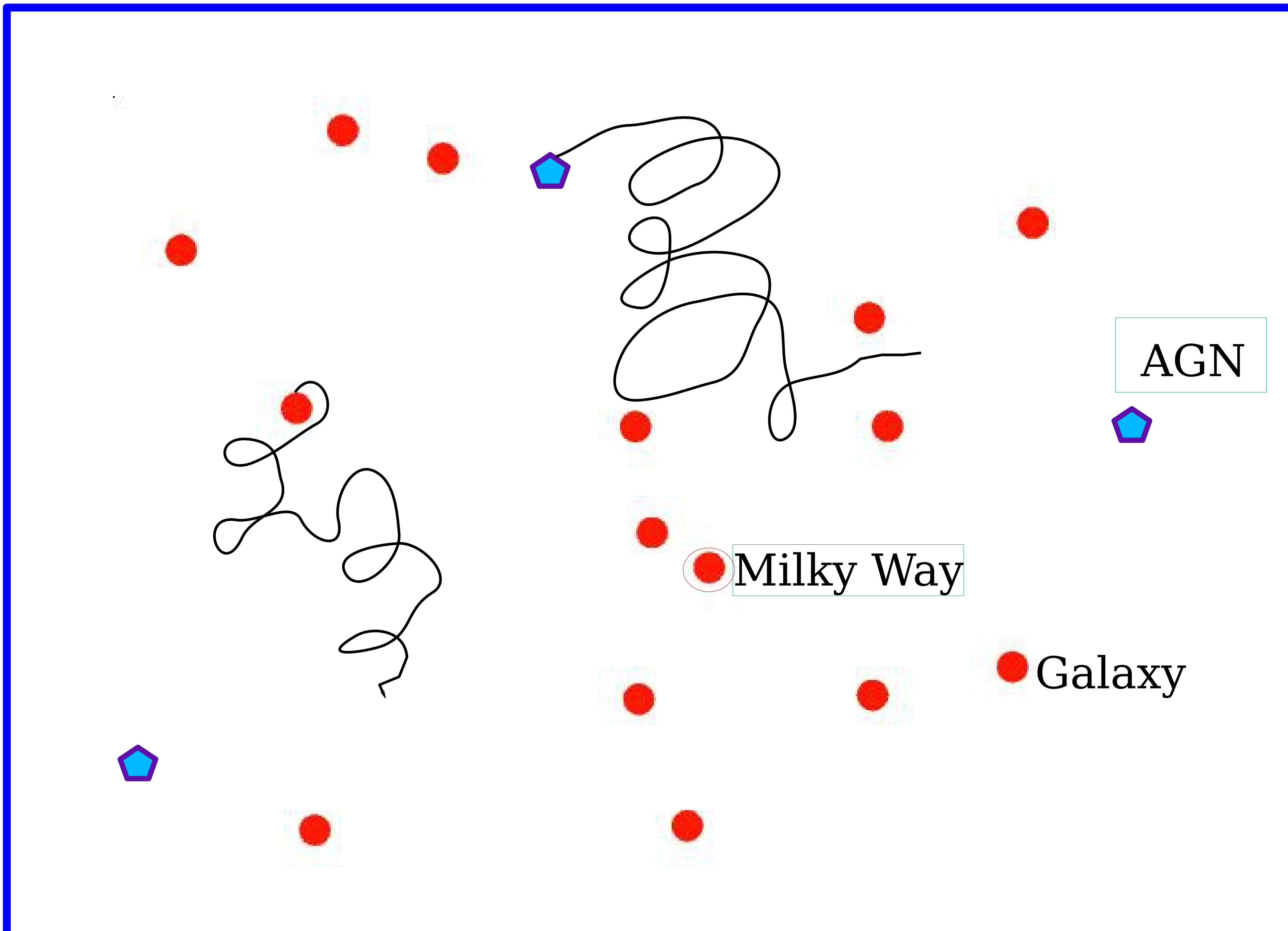
2. Galactic Sources

3. Extragalactic Sources

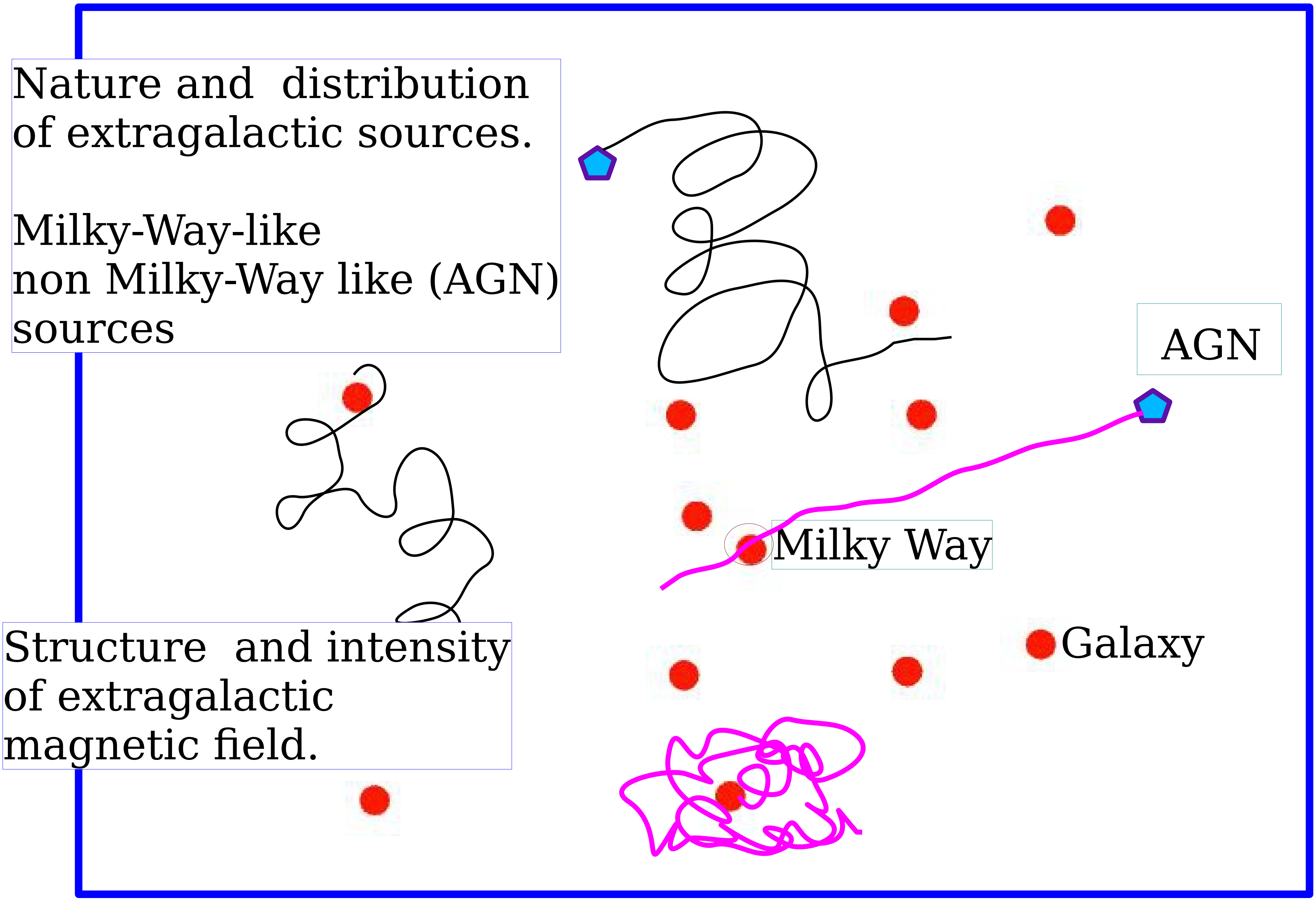

Particle accelerated in the Milky Way
Extragalactic Particle
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD

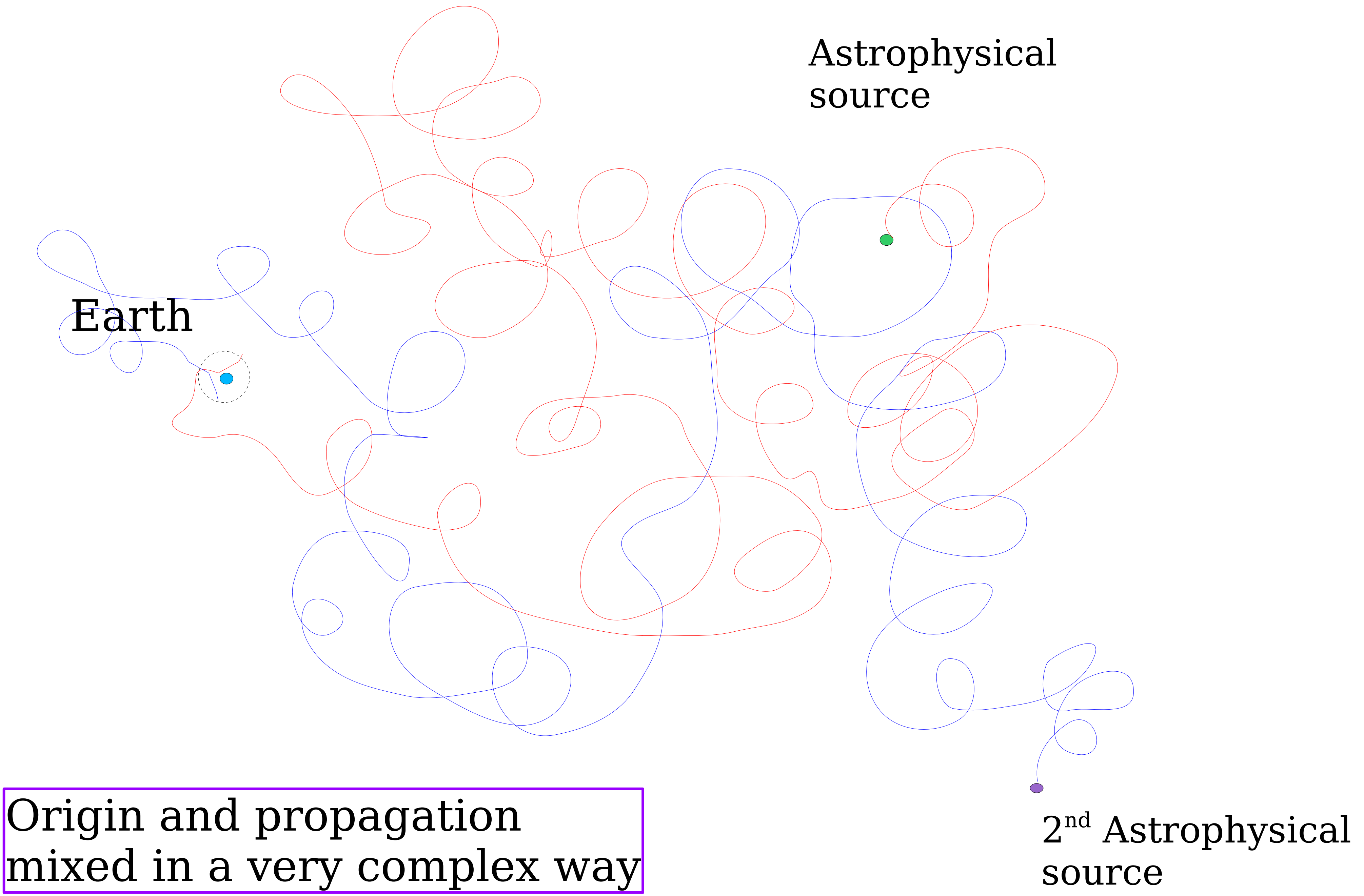

Extragalactic
contribution
MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
“Bubble” of cosmic rays
generated in the Milky Way
and contained by the
Galaxy magnetic field
Space extension and
properties of this “CR bubble”
remain very uncertain

Piece of extragalactic space: Non MilkyWay-like sources



Piece of extragalactic space:




Astrophysical source
Earth
2nd Astrophysical source
Origin and propagation mixed in a very complex way

Flux of Cosmic Rays
Integration over Volume and over Time
from sources of an unknown nature and position.

$$n(E, \vec{r}_\odot) = \frac{4\pi}{\beta\, c} \int d\Omega\; \phi(E, \Omega; \vec{r}_\odot)$$

number
density of CR

flux of CR

$$n(E, \vec{r}_\odot) = \int d^3 r \int dt\; q(E, \vec{r}, t)\; P(\vec{r}_\odot;\; E, \vec{r}, t)$$

Integration over space and time
[sum over all sources in the Galaxy
and in the universe]

Propagation function
[probability that the particle
is a volume $d^3 r$ around the sun]

Cosmic Ray injection

$$Q(E) = \int d^3x \; q(E, \vec{x})$$

$$Q(E,t) = \sum_j q(E, \vec{x}_j, t)$$

$$n(E) = Q(E) \times F_{\rm prop}(E)$$

$$[n(E)] = L^{-3} \; E^{-1}$$

$$[Q(E)] = T^{-1} \; E^{-1}$$

$$[F_{\rm prop}(E)] = T \; L^{-3}$$

$$n(E) = Q(E) \times \frac{T(E)}{V(E)}$$

$$n(E) = Q(E) \times \frac{T_{\mathrm{diff}}(E)}{V_{\mathrm{confinement}}}$$

Standard discussion.
one confinement volume
“Residence time” (function of energy)

Galactic Cosmic Rays

$$N_j(E) = Q_j(E) \times T_j(E)$$

Different particles

$p, \quad \text{nuclei}(Z, A)$

$\overline{p}, \quad e^-, \quad e^+$

Injection
of cosmic rays

Containment
time

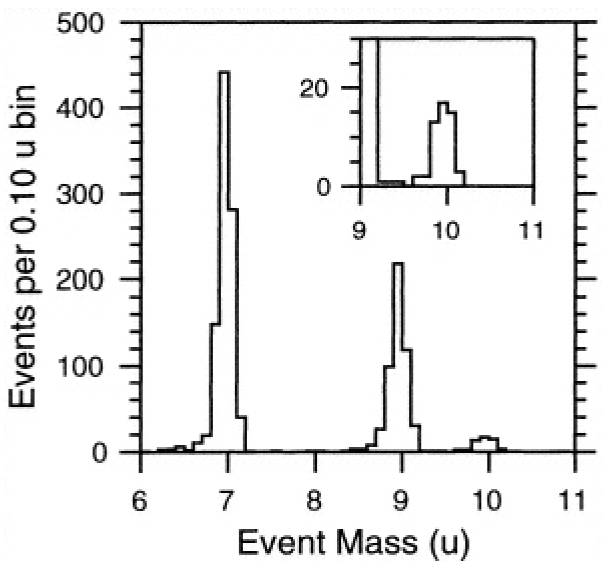
$$N_j(E) = \int d^3x \; n_j(E, \vec{x})$$

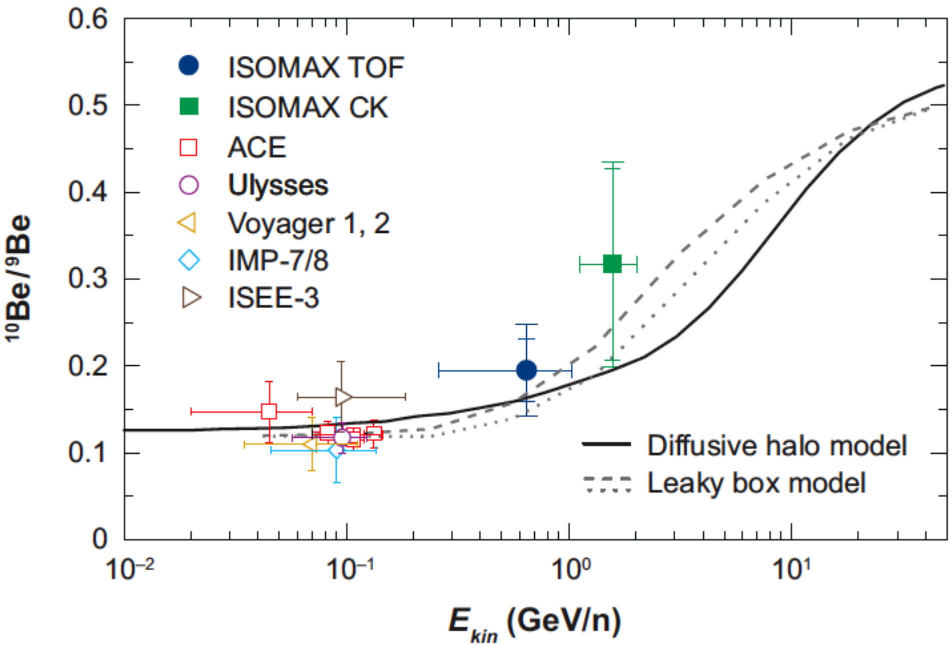
$$\phi_j(E) = \frac{c}{4\pi} \, n_j(E)$$

Determination of the "confinement time" $T(p/Z)$

"Cosmic clock" (Beryllium-10)

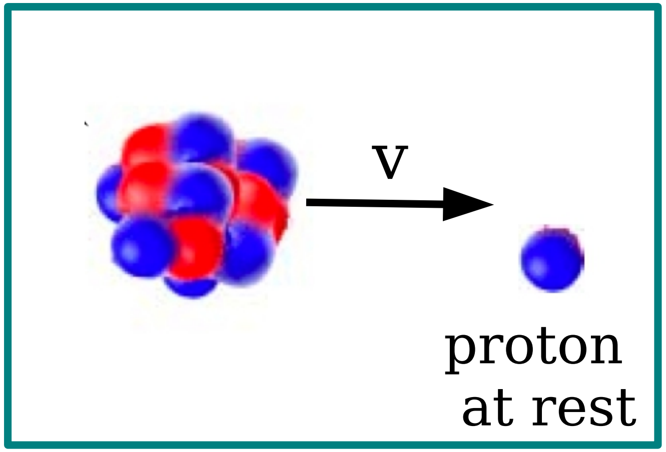
$$T_{1/2}\left[{}^{10}\mathrm{Be}\right] = 1.39 \times 10^6 \text{ years}$$

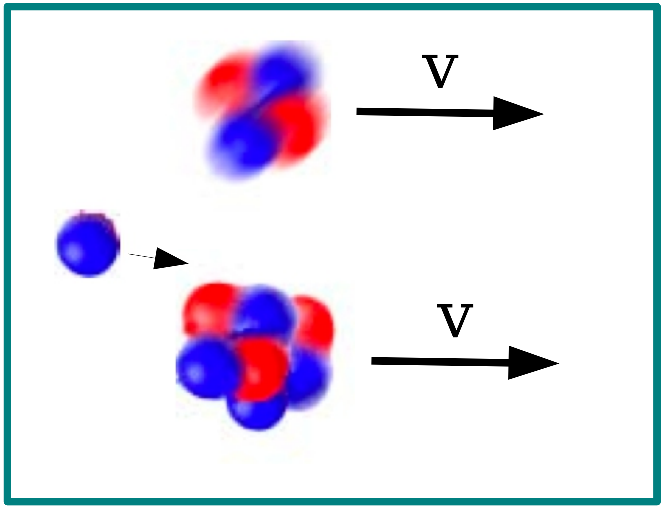


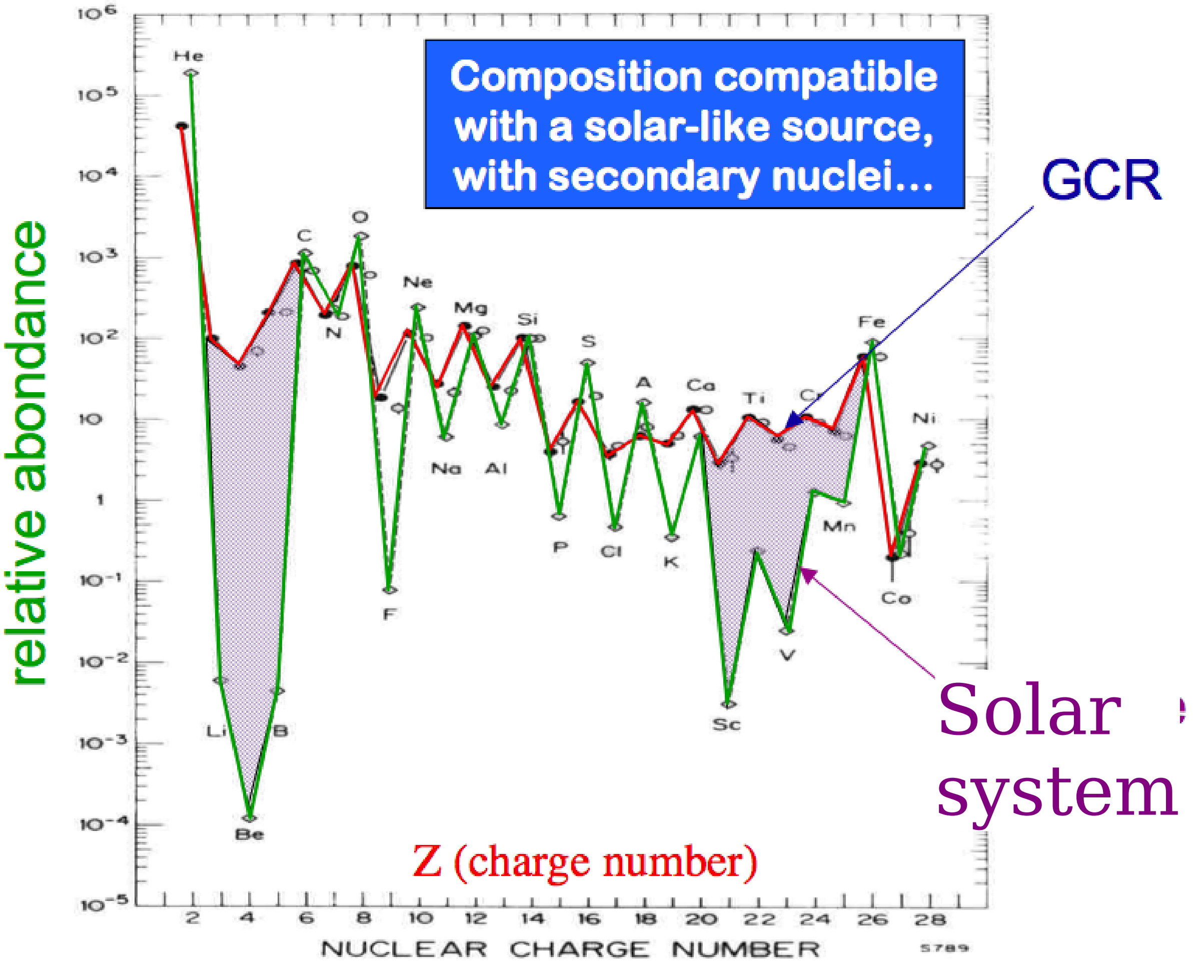


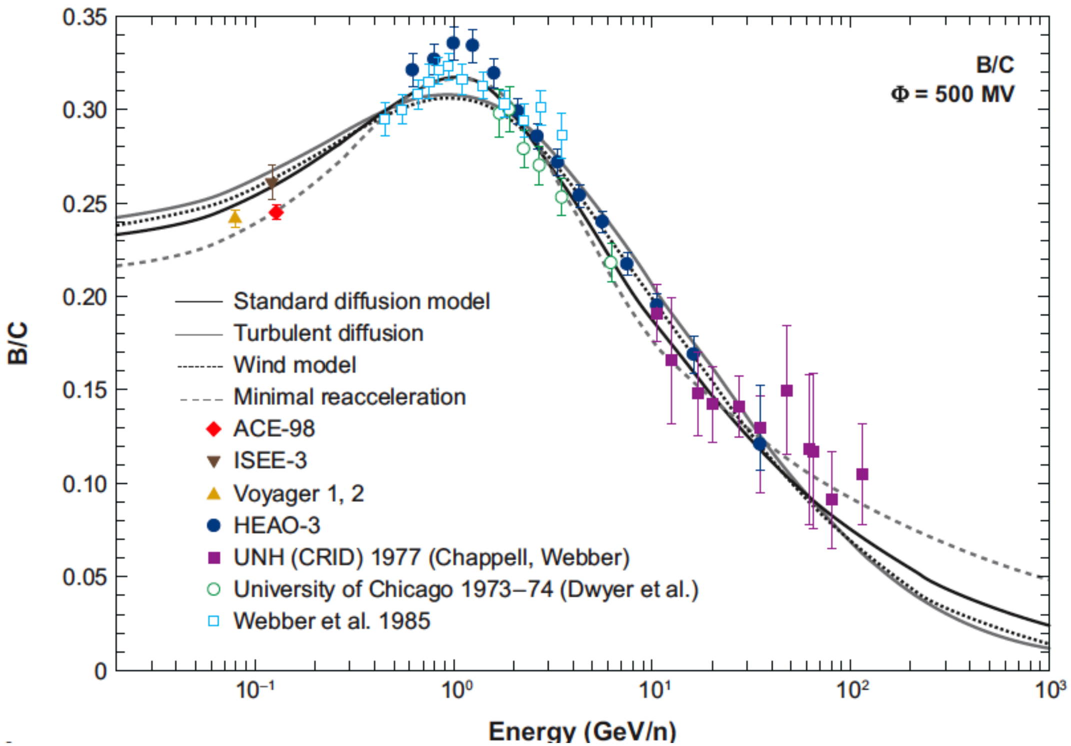
$$T \simeq 10 \text{ Myr}$$

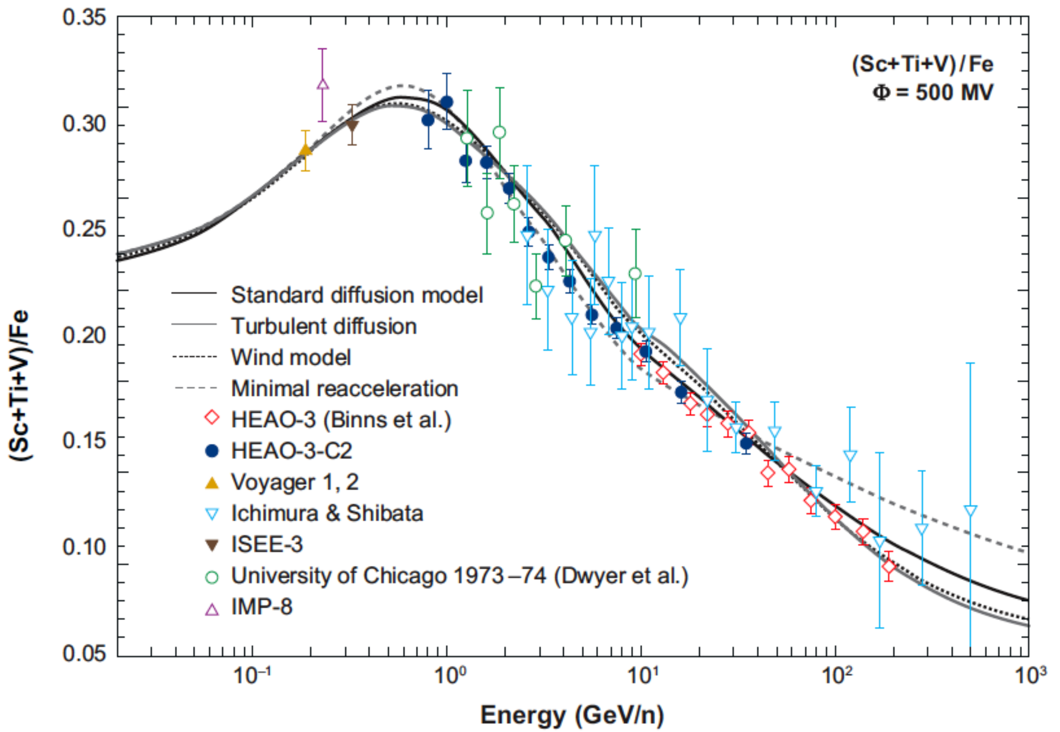
Nuclear Fragmentation
(collisions with the Inter Stellar Medium)











Column density

$$X(E) = \langle \rho \rangle \, T(E)$$

Escape faster at higher E

$$X(E) \propto E^{-\delta}$$

$$\delta \simeq 0.4 \div 0.6$$

$$\frac{\langle \rho \rangle}{m_p} \simeq 0.2 \text{ cm}^{-3}$$

(extended halo)

Injection of cosmic rays

Containment time

$$N_j(E) = Q_j(E) \times T_j(E)$$

$$L_j = \int dE \; E \; Q_j(E)$$

LARGE Power Requirement

Spectral Shape [Dynamics of acceleration process]

$$L_{\rm cr}(\text{Milky Way}) \simeq 2 \times 10^{41} \text{ erg/s}$$

$$\simeq 5 \times 10^{7} \; L_{\odot}$$

Source Identification

Understanding the “confinement properties”
for Cosmic Rays in the Milky Way at
very high energy is of critical importance.

Turbulence power spectrum

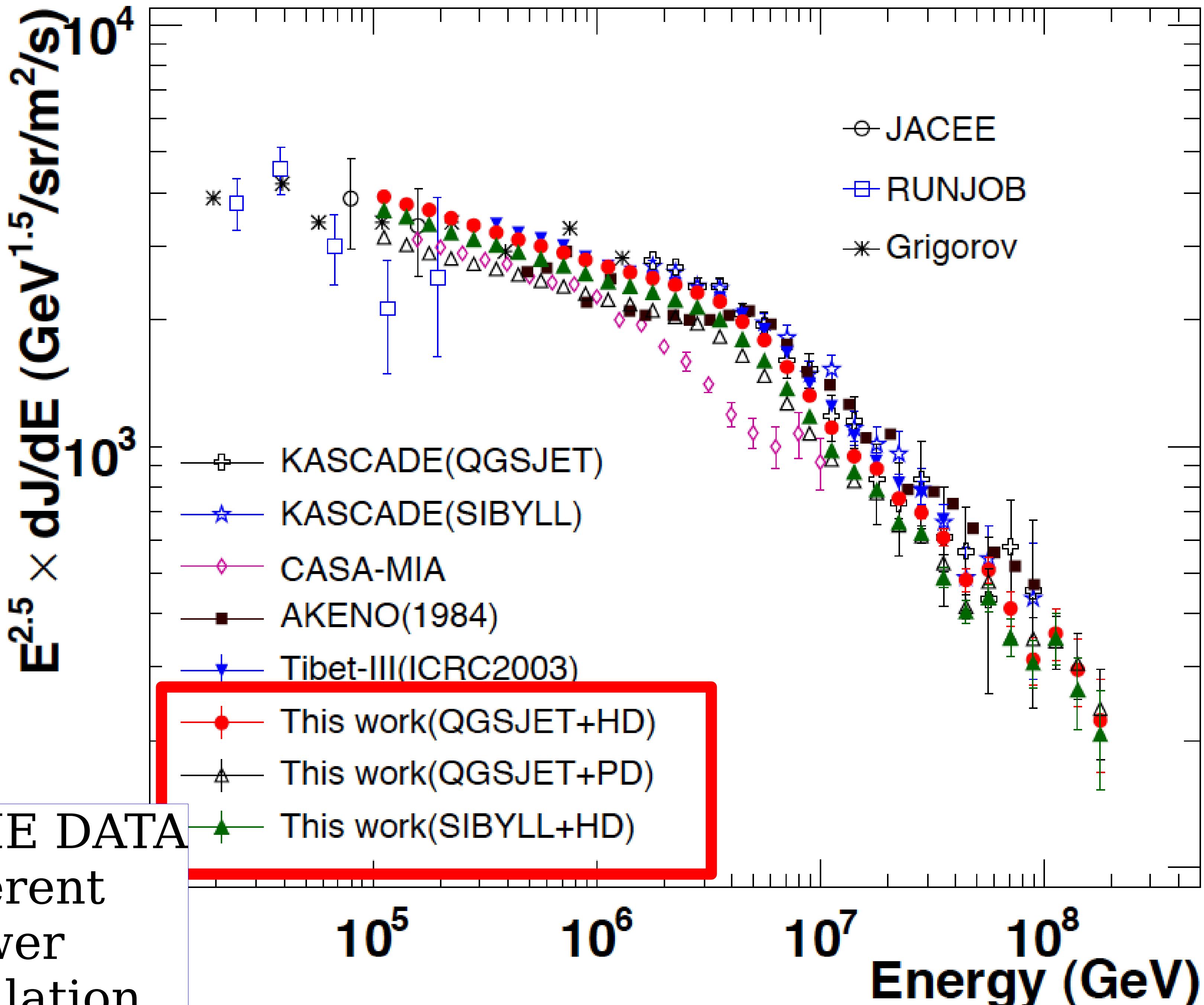
Global Structure of the Milky Way
Magnetic Field

Galactic Wind ?

$$n(E) = Q(E) \times F_{\mathrm{prop}}(E)$$

Ambiguity in the origin of the features
Present in the cosmic ray energy spectrum

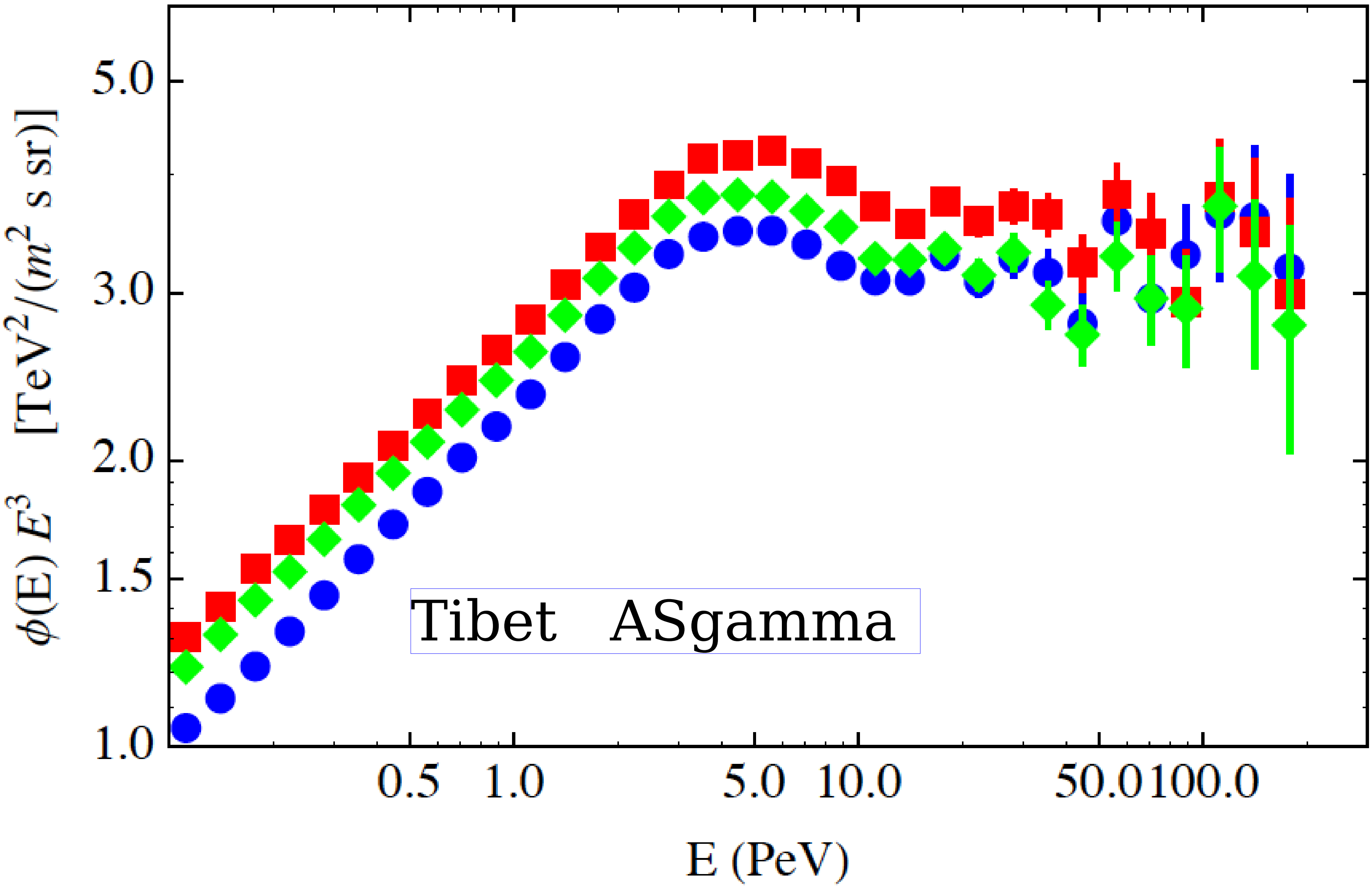
Tibet Air Shower Energy Spectrum

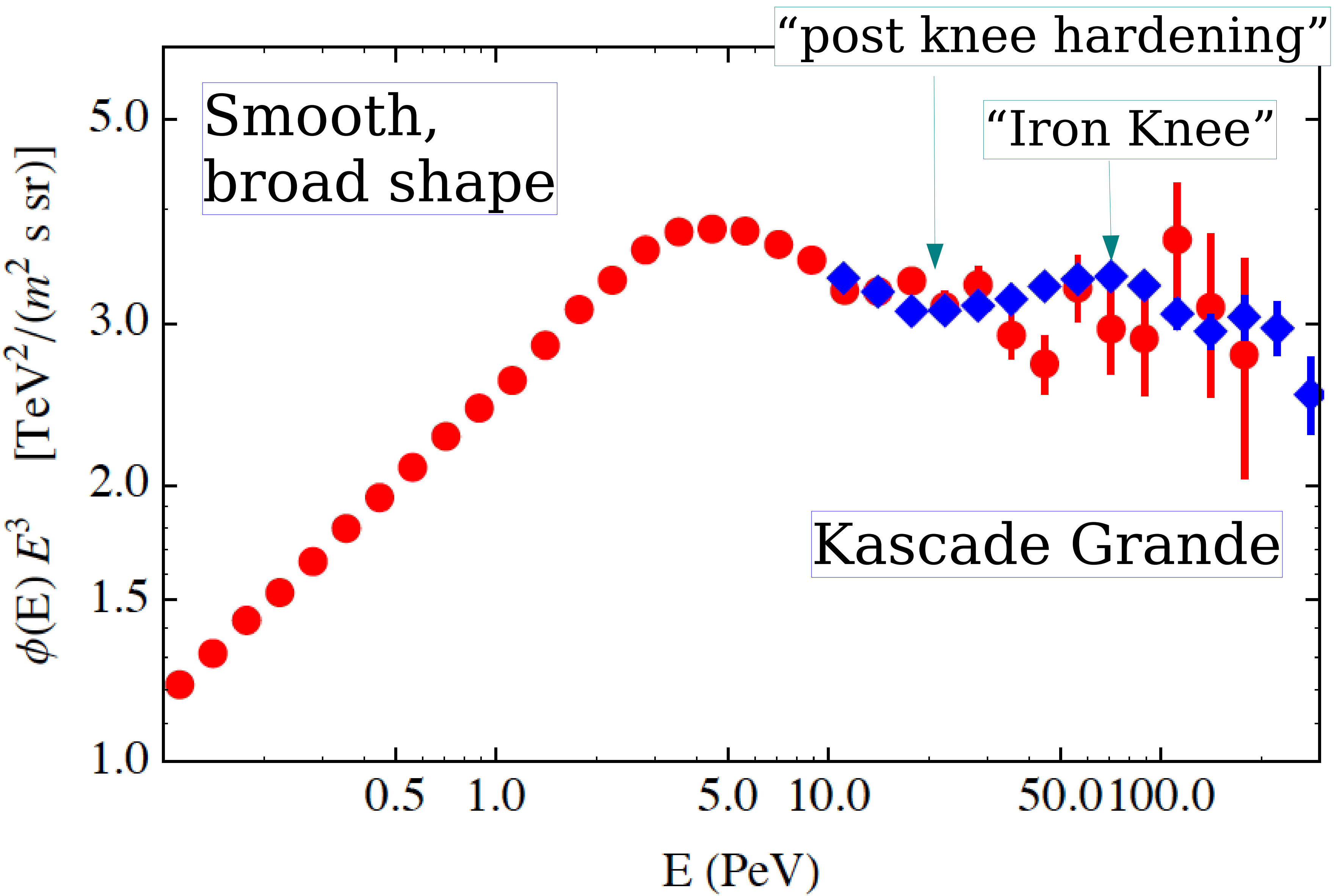


SAME DATA
Different
shower
simulation

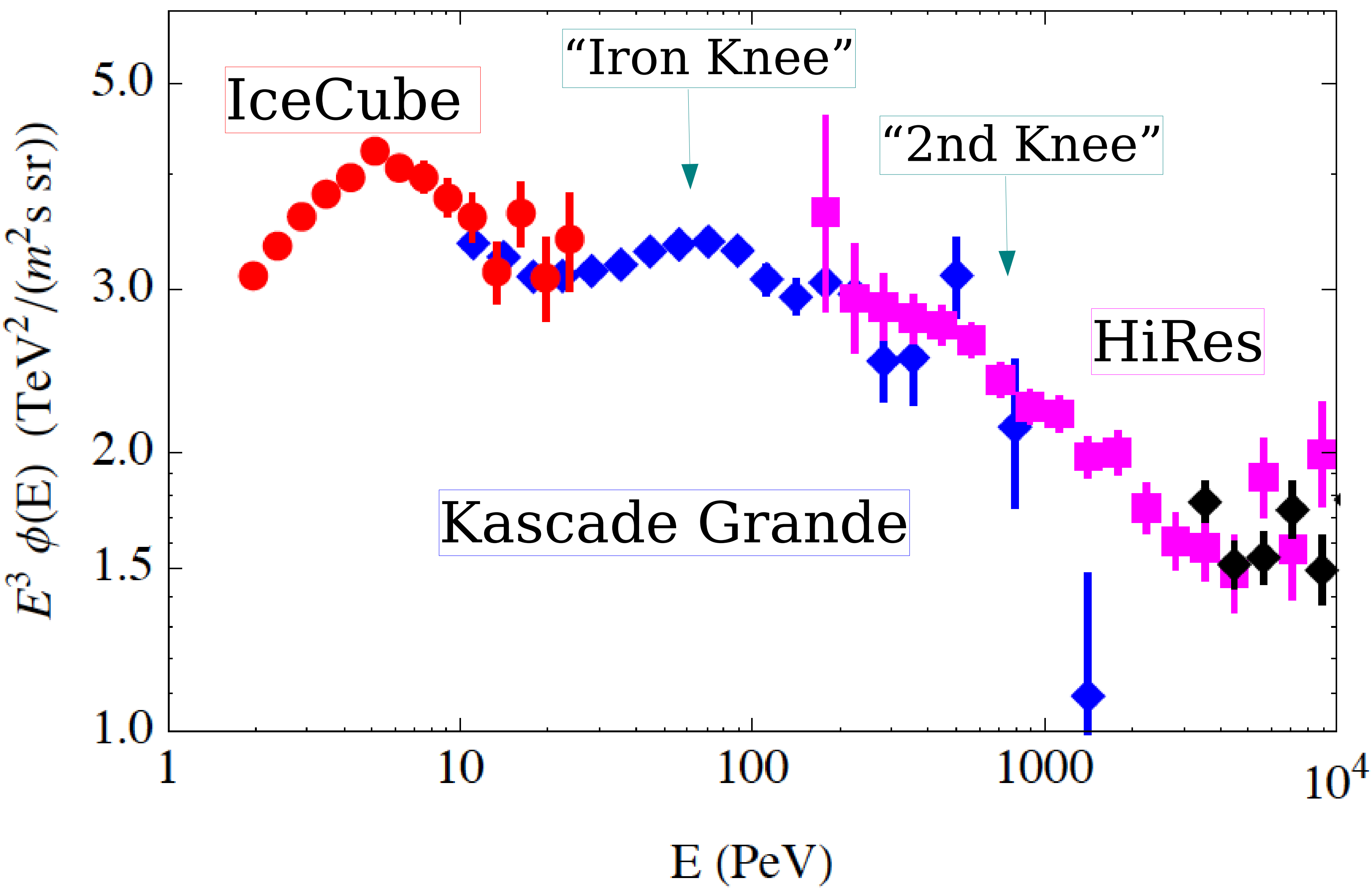
The “Shape of the KNEE”

$$E^3\ \phi(E)$$

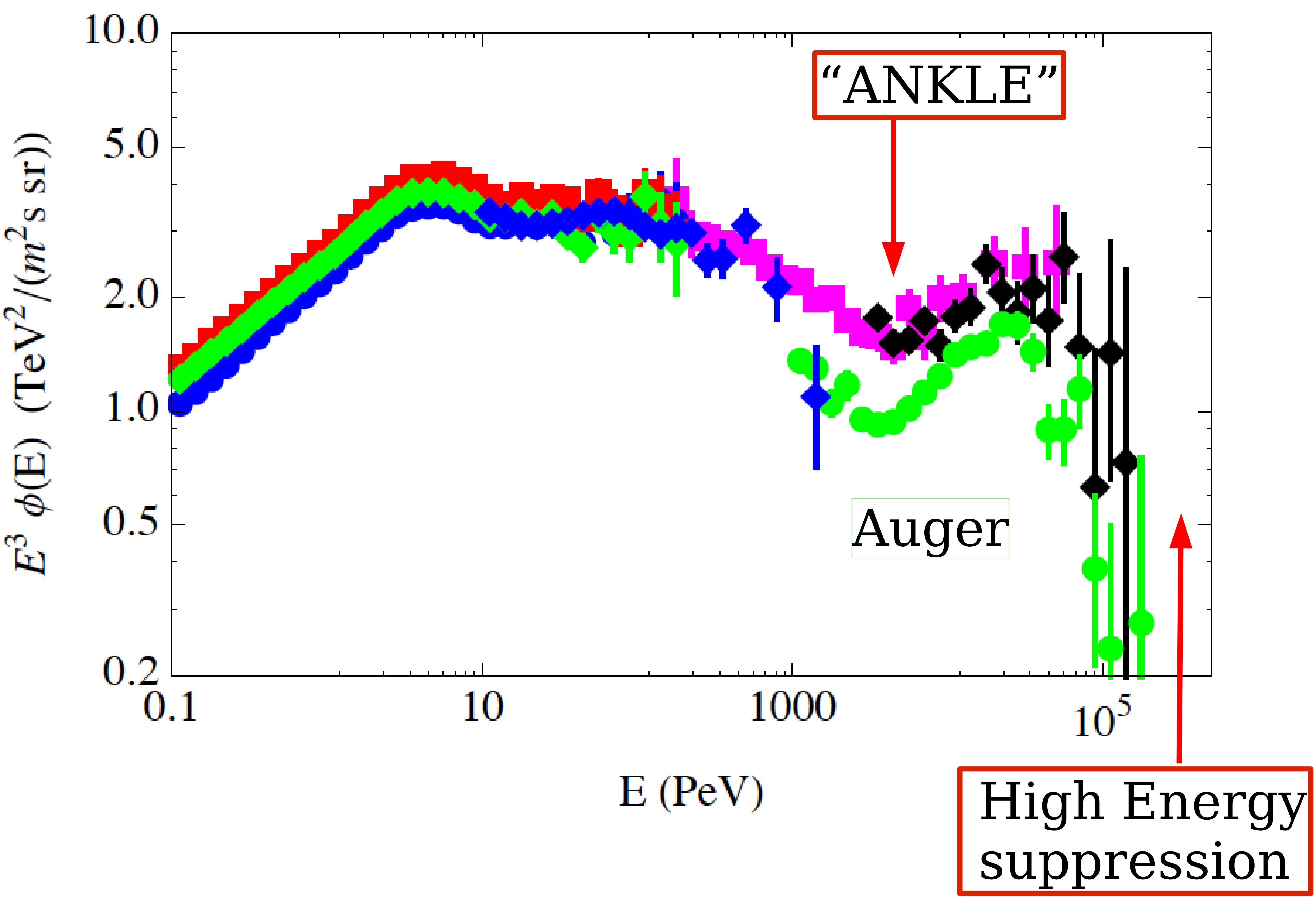




"post knee hardening"
"Iron Knee"
Smooth,
broad shape
Kascade Grande
$\phi(E)\, E^3$ [TeV^2/(m^2 s sr)]
5.0
3.0
2.0
1.5
1.0
0.5
1.0
5.0
10.0
50.0
100.0
E (PeV)



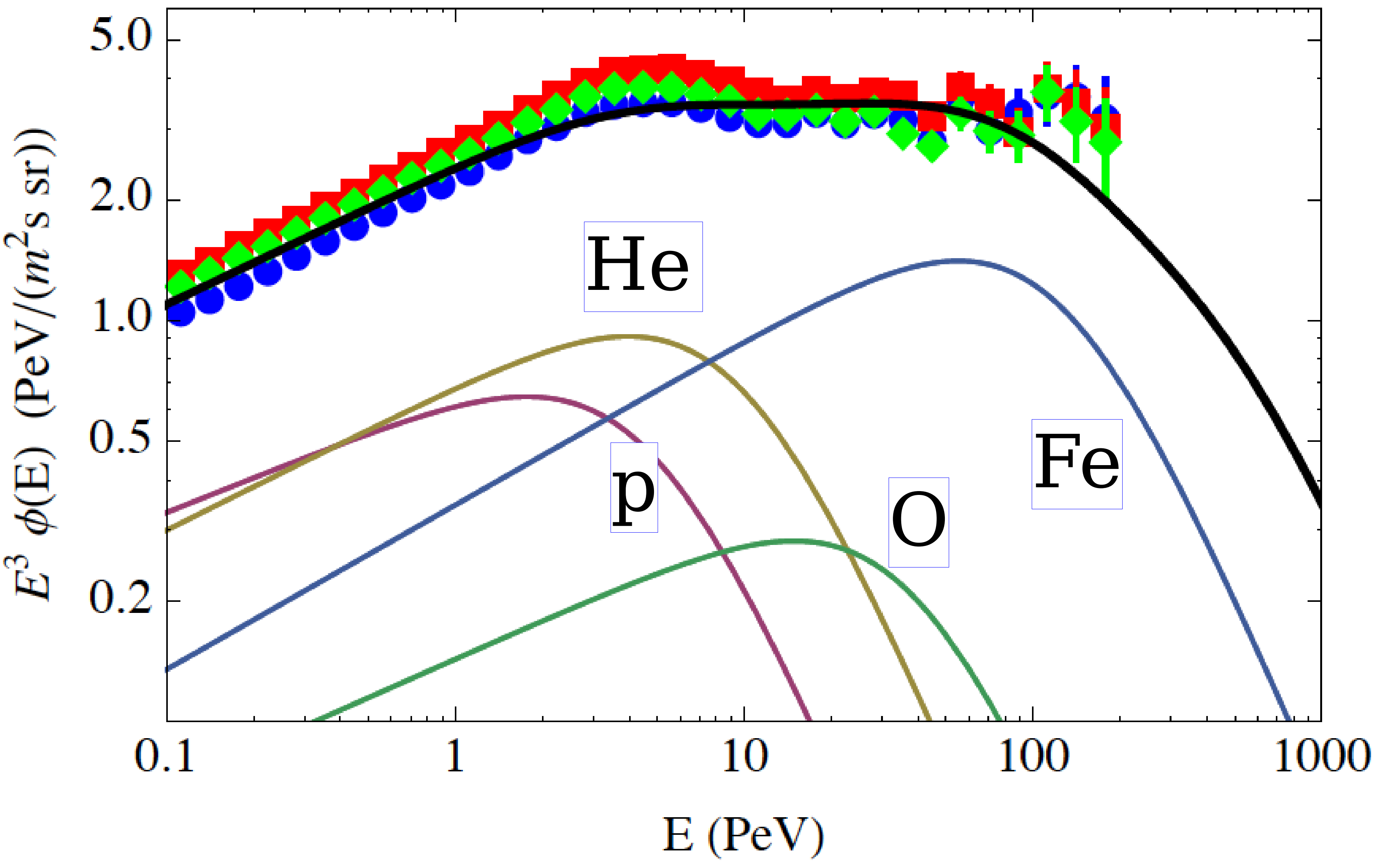
IceCube
"Iron Knee"
"2nd Knee"
HiRes
Kascade Grande
5.0
3.0
2.0
1.5
1.0
1
10
100
1000
10^4
$E^3\ \phi(E)\ \ (TeV^2/(m^2 s\ sr))$
E (PeV)



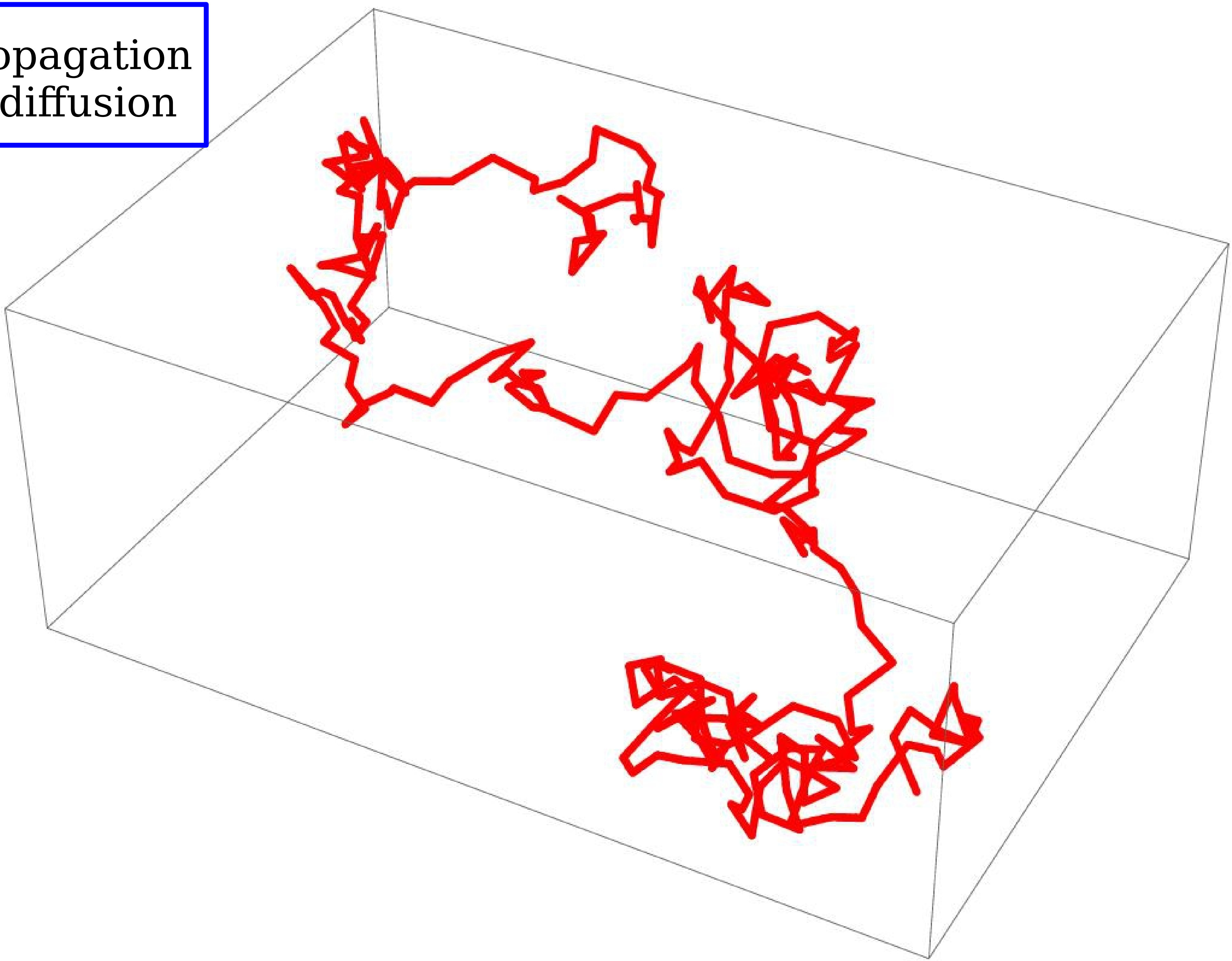
"ANKLE"
Auger
High Energy suppression
$E^3\ \phi(E)\ (\mathrm{TeV}^2/(m^2\,\mathrm{s\,sr}))$
E (PeV)
10.0
5.0
2.0
1.0
0.5
0.2
0.1
10
1000
10^5

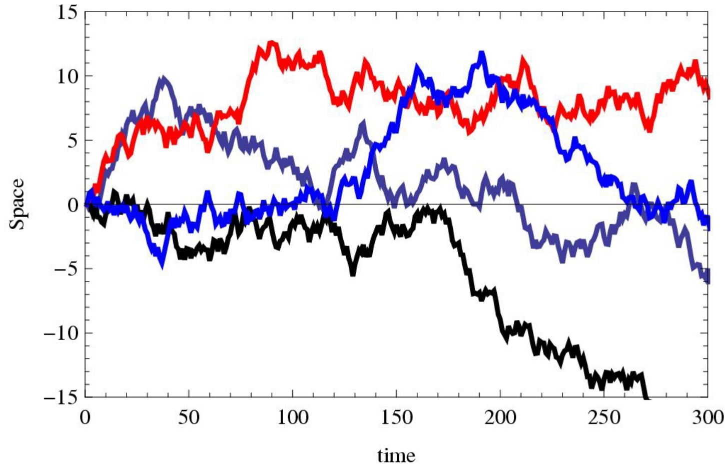
“Standard idea”

Same structure repeated “rescaled in Z”



Propagation
as diffusion

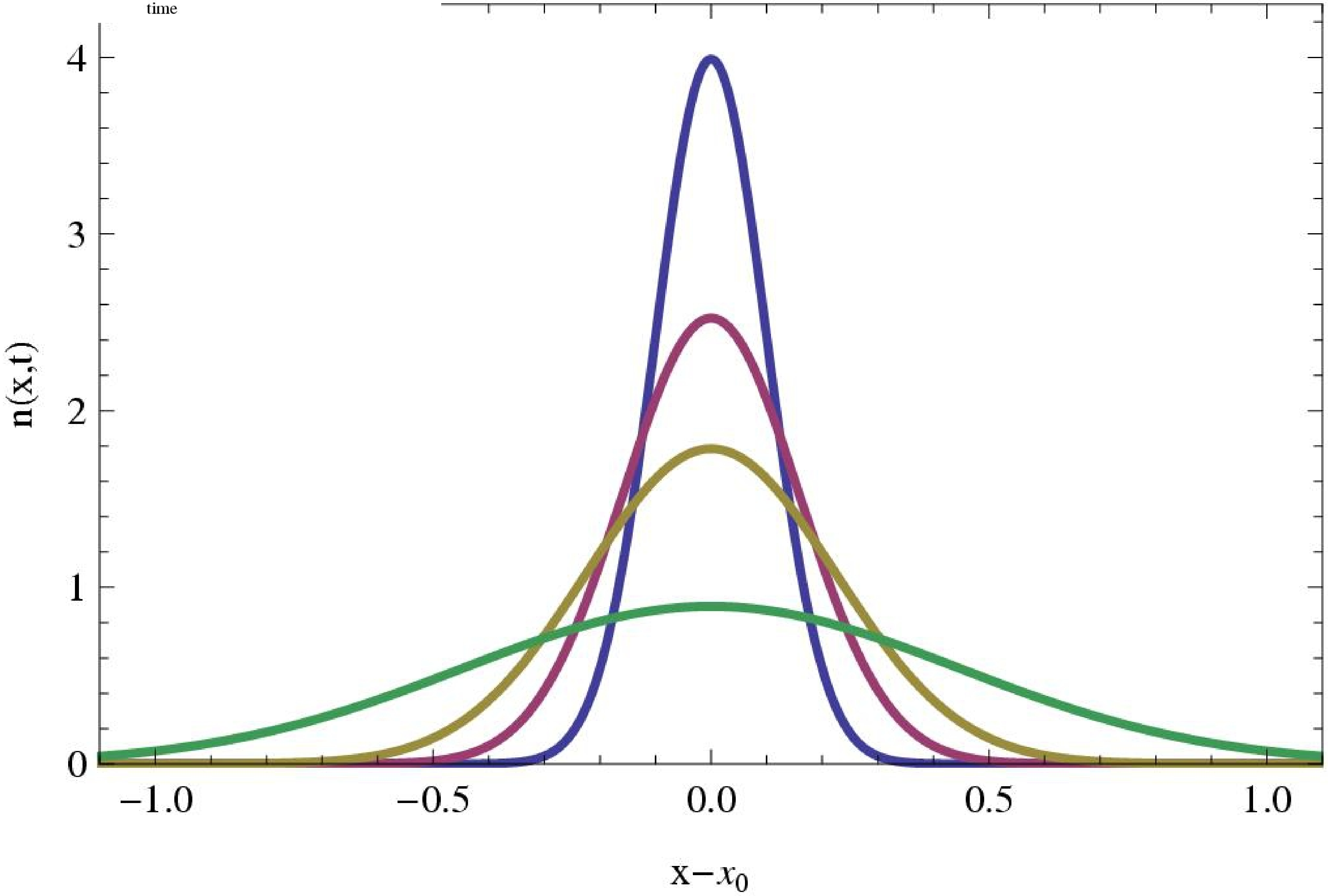




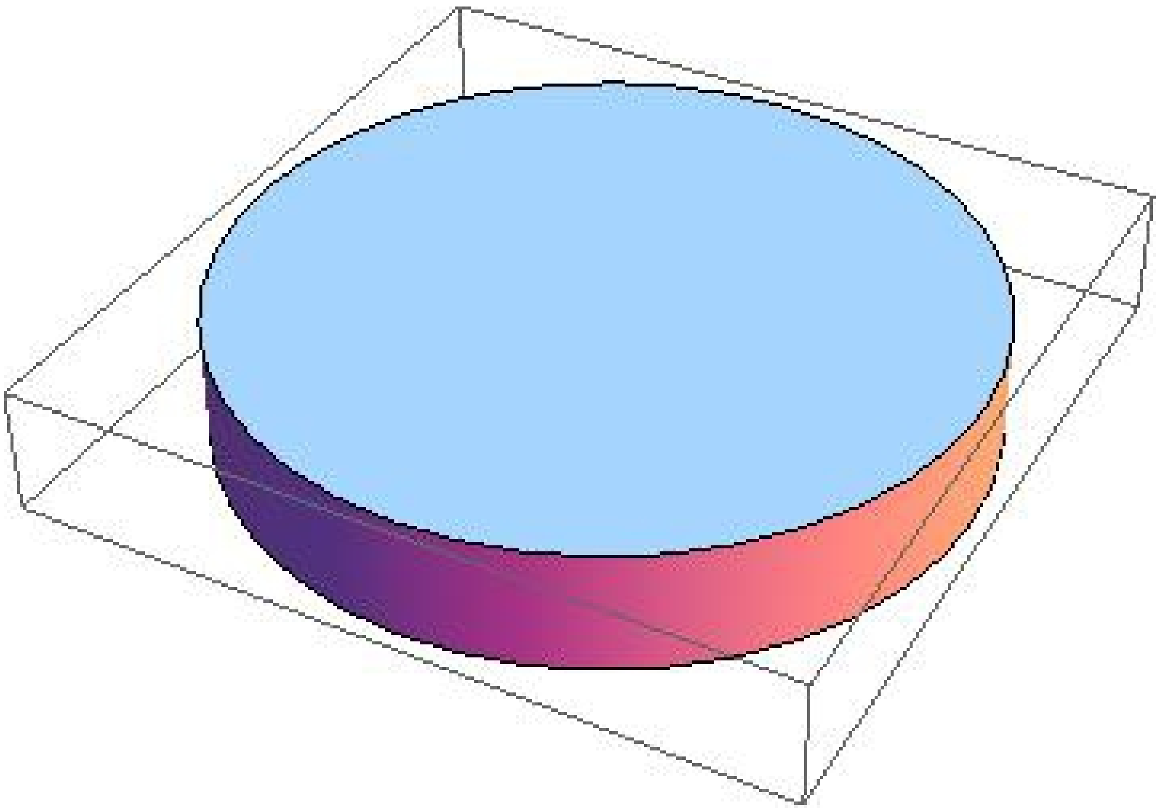
One dimensional diffusion

$$\sigma_x^2 = 2\,D\,t$$

Diffusion coefficient D



Escape as "absorbing boundary condition"
The diffusion coefficient become infinity at the boundary



Galaxy as a cylinder

Stationary sources
(no time dependence)

Isotropic Diffusion description
Good approximation:

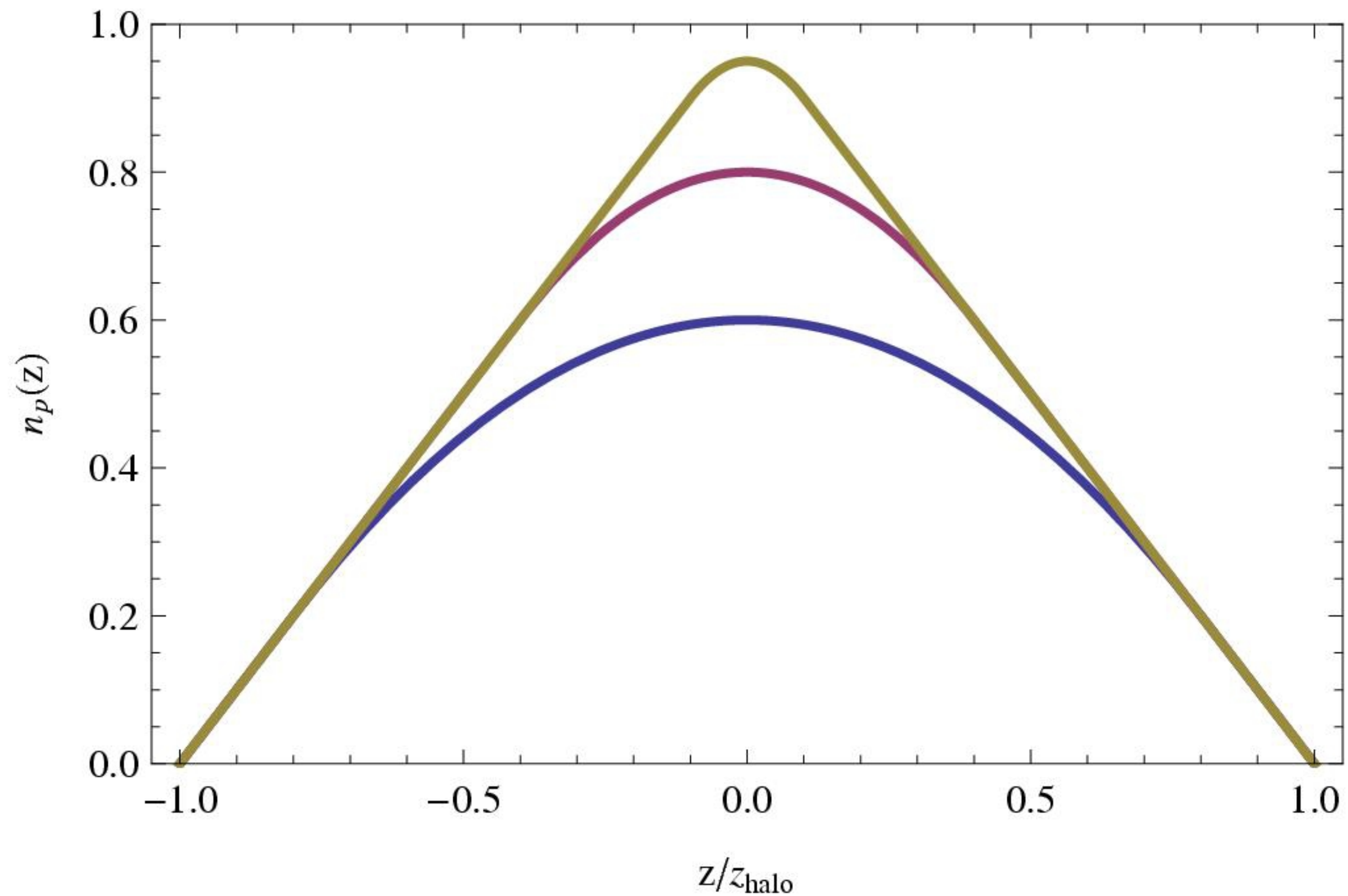
Factorization
of the energy dependence:
For the source.
For the diffusion coefficient

$$q(E, \vec{r}) = q(E) \; q_{\rm space}(\vec{r})$$

$$D(E, \vec{r}) = D(E) \; D_{\rm space}(\vec{r})$$

$$n(E, \vec{r}) = n(E) \; n_{\rm space}(\vec{r}) = \frac{q(E)}{D(E)} \; n_{\rm space}(\vec{r})$$

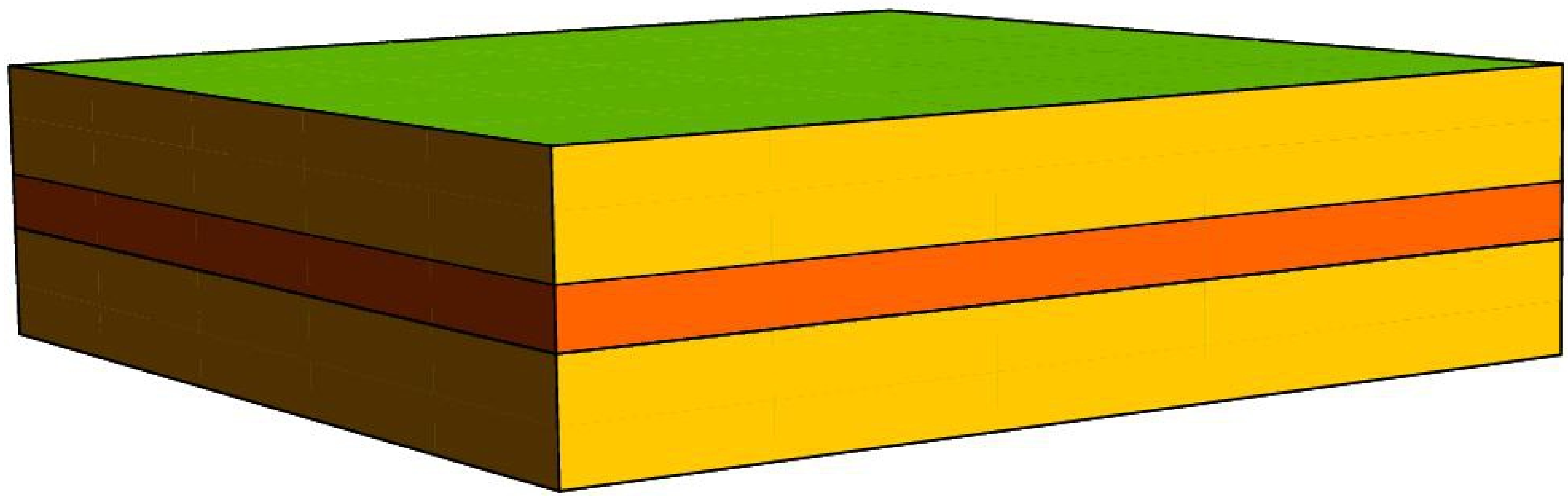
$$n(E,\vec{r}) = \frac{q(E)}{2\,D(E)}\; z_{\rm disk}\; z_{\rm halo} \quad \times \begin{cases} 1 - \frac{1}{2}\frac{z_{\rm disk}}{z_{\rm halo}} - \frac{1}{2}\frac{z^2}{z_{\rm disk}\; z_{\rm halo}} & \text{for} \quad |z| \le z_{\rm disk} \\ 1 - \frac{1}{2}\frac{|z|}{z_{\rm halo}} & \text{for} \quad |z| > z_{\rm disk} \end{cases}$$



“Slab Galaxy”

Galaxy modeled
as an infinite “slab”

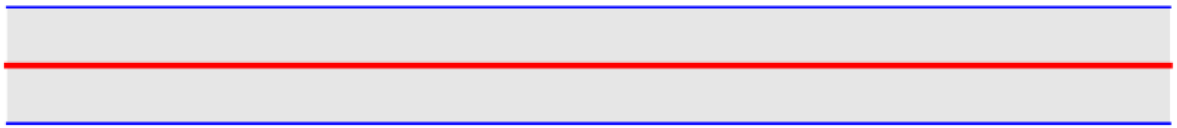
1-D problem

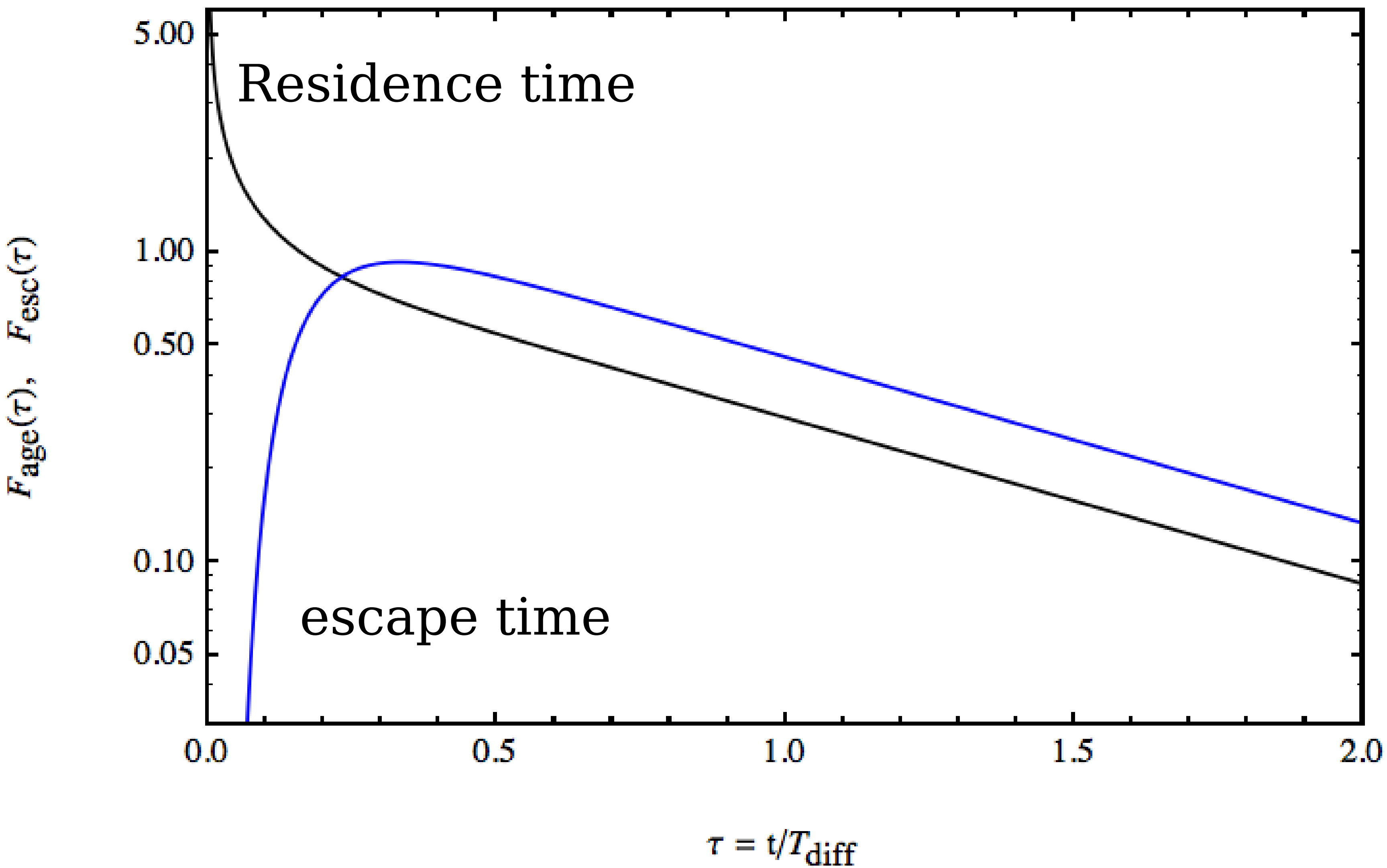


$$T_{\mathrm{diff}}(E) = \frac{z_h^2}{2\,D(E)}$$

$$D(E/Z) \simeq D_0 \ \left[\frac{E}{Z\,E_0}\right]^{\delta}$$

$$T_{\mathrm{diff}}(E/Z) \simeq T_0 \ \left[\frac{E}{Z\,E_0}\right]^{-\delta}$$




Residence time
escape time
5.00
1.00
0.50
0.10
0.05
0.0
0.5
1.0
1.5
2.0
$F_{\rm age}(\tau), \quad F_{\rm esc}(\tau)$
$\tau = t/T_{\rm diff}$

$$q(E) \propto E^{-\alpha}$$

$$D(E) \propto E^{\delta}$$

$$n(E) \propto \frac{q(E)}{D(E)} \propto E^{-(\alpha+\delta)}$$

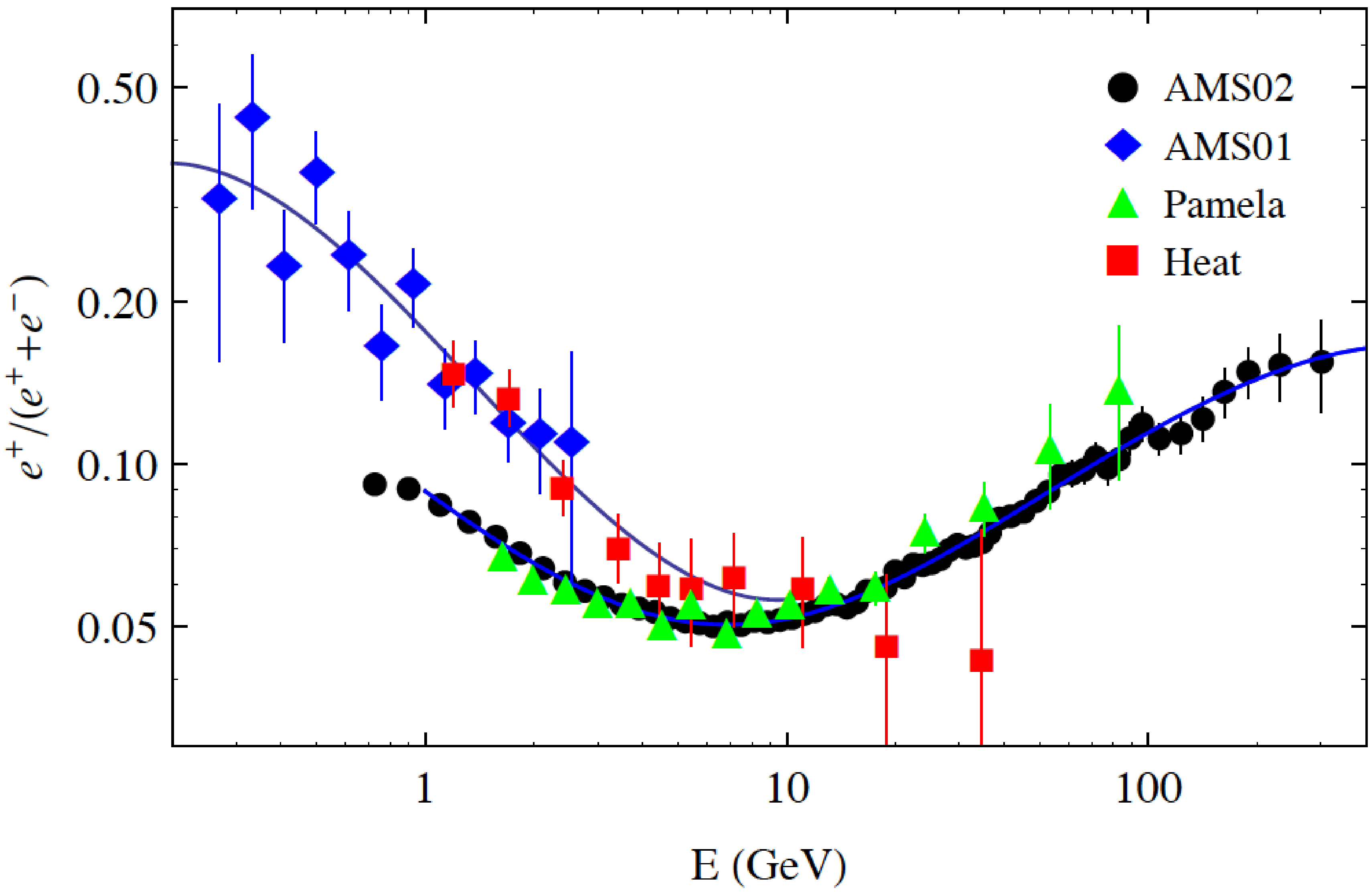
1. General Considerations.

2. Propagation of Cosmic Rays in the Heliosphere

The heliosphere as a "laboratory"
to study the propagation of cosmic rays

Recent measurement of the of the positron/electron ratio by AMS02.

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



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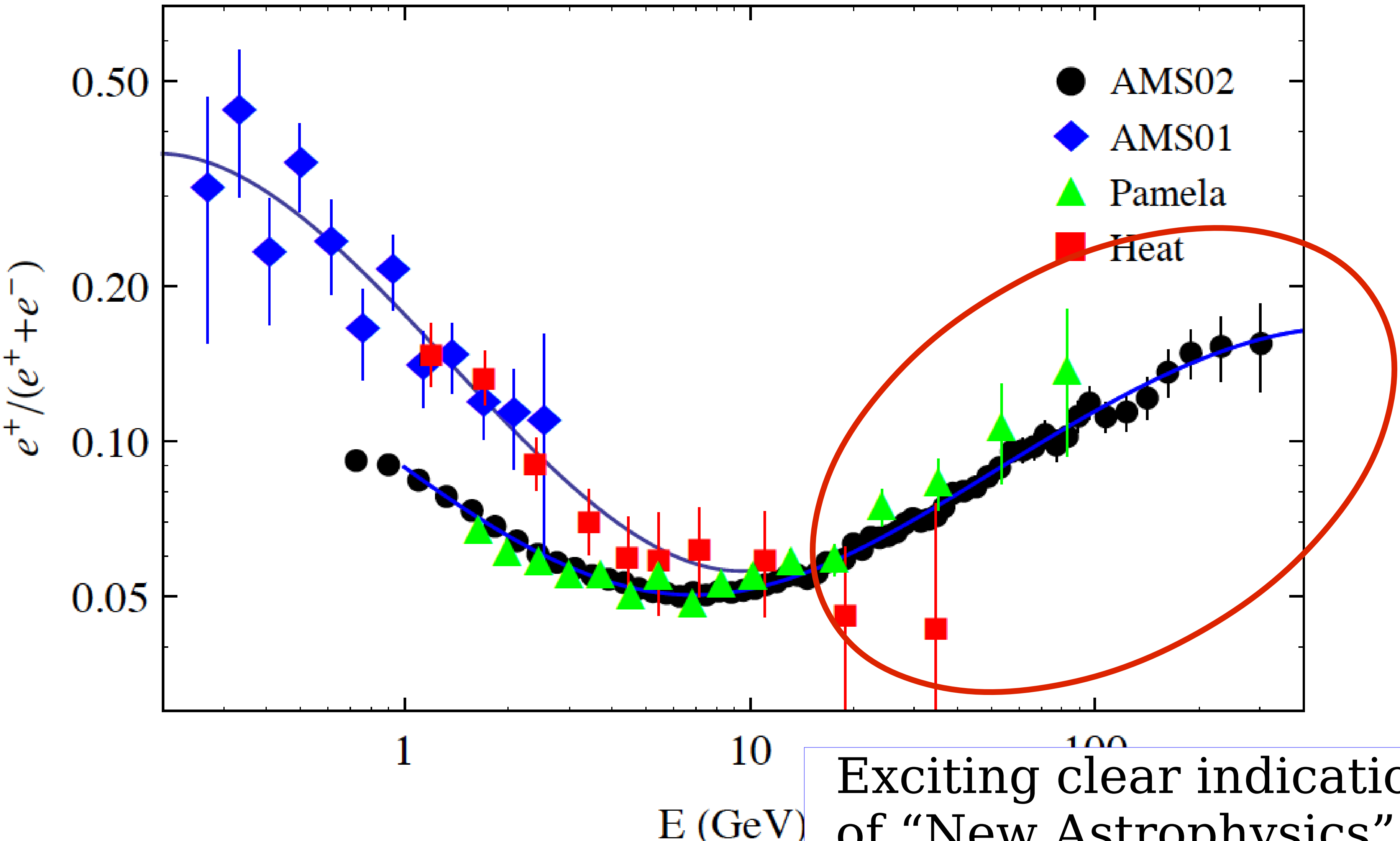

Exciting clear indication of “New Astrophysics” or “New Physics” (DM)

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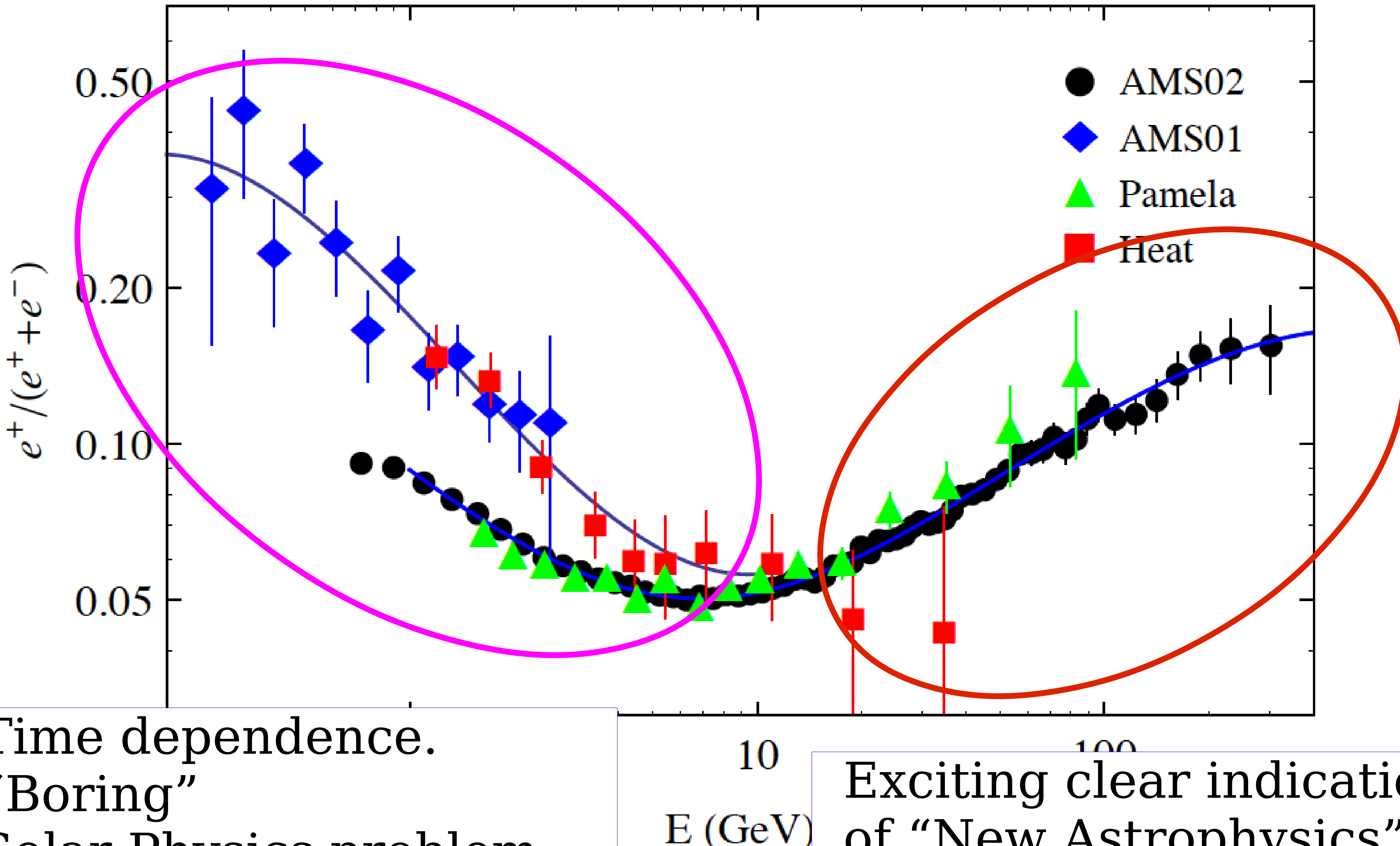
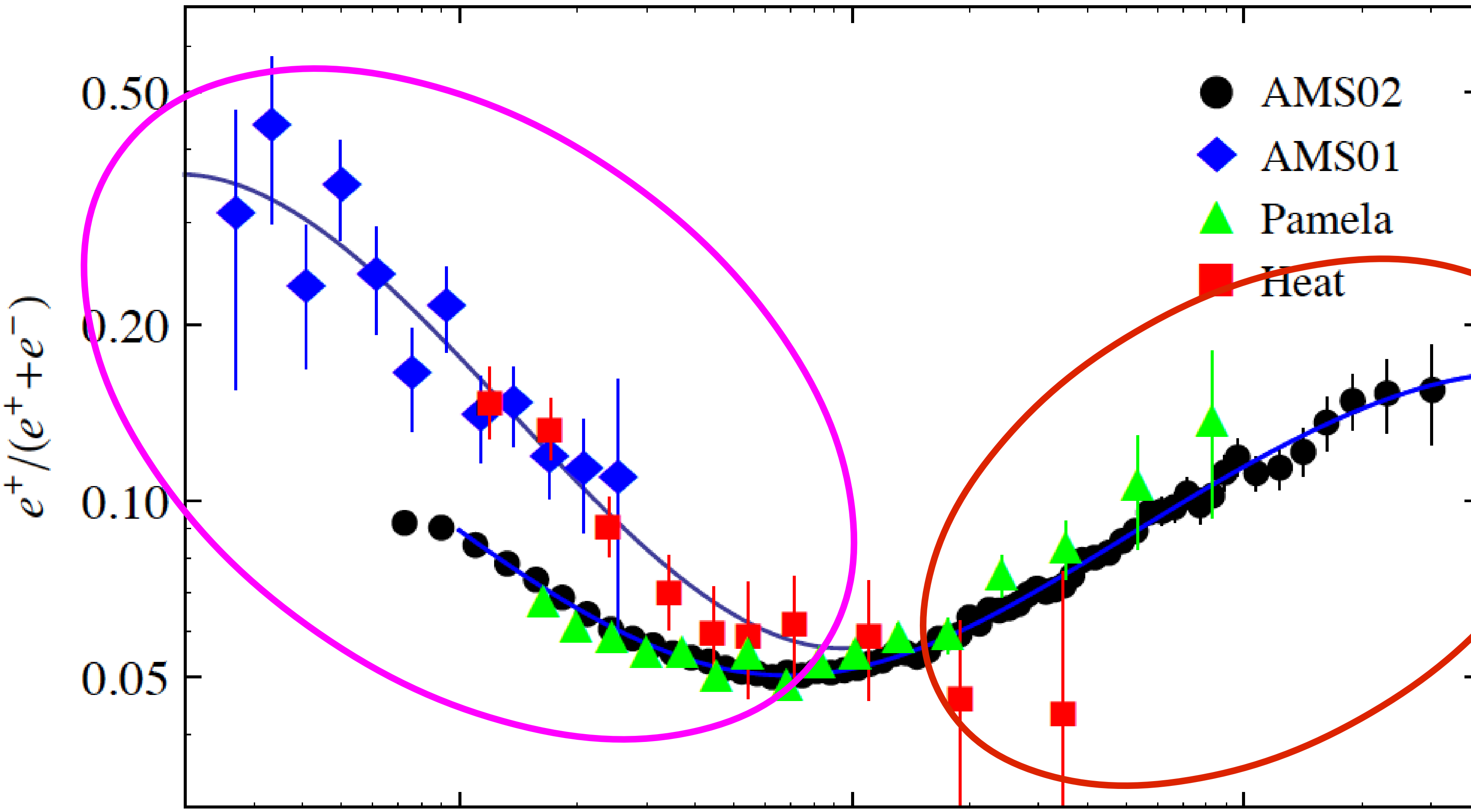


Time dependence.
“Boring”
Solar Physics problem…..

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

Recent Measurement of the of the ratio by AMS02.

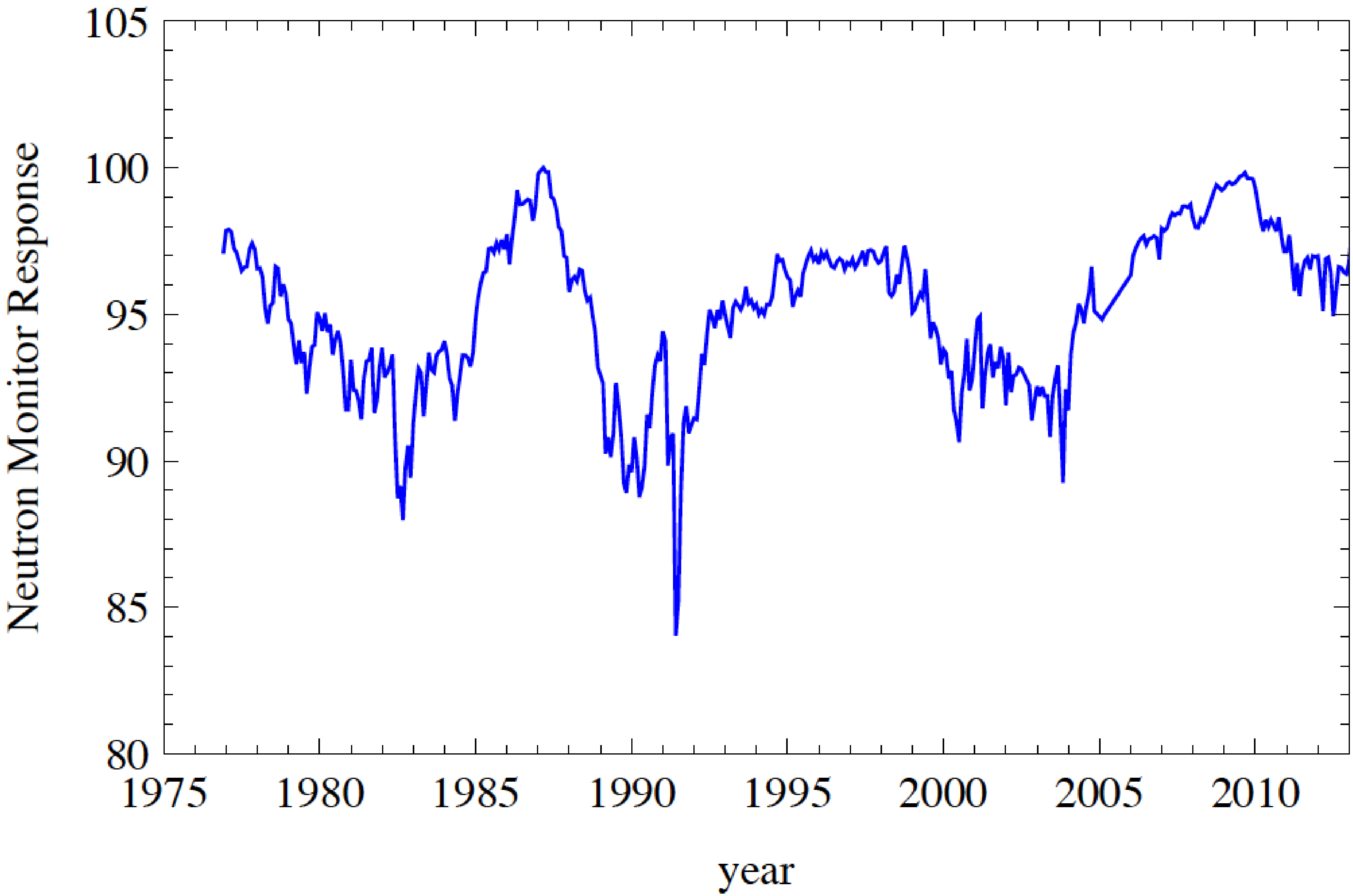
$$\frac{e^+}{e^+ + e^-}$$



Important Laboratory for the study of Cosmic Ray Propagation!

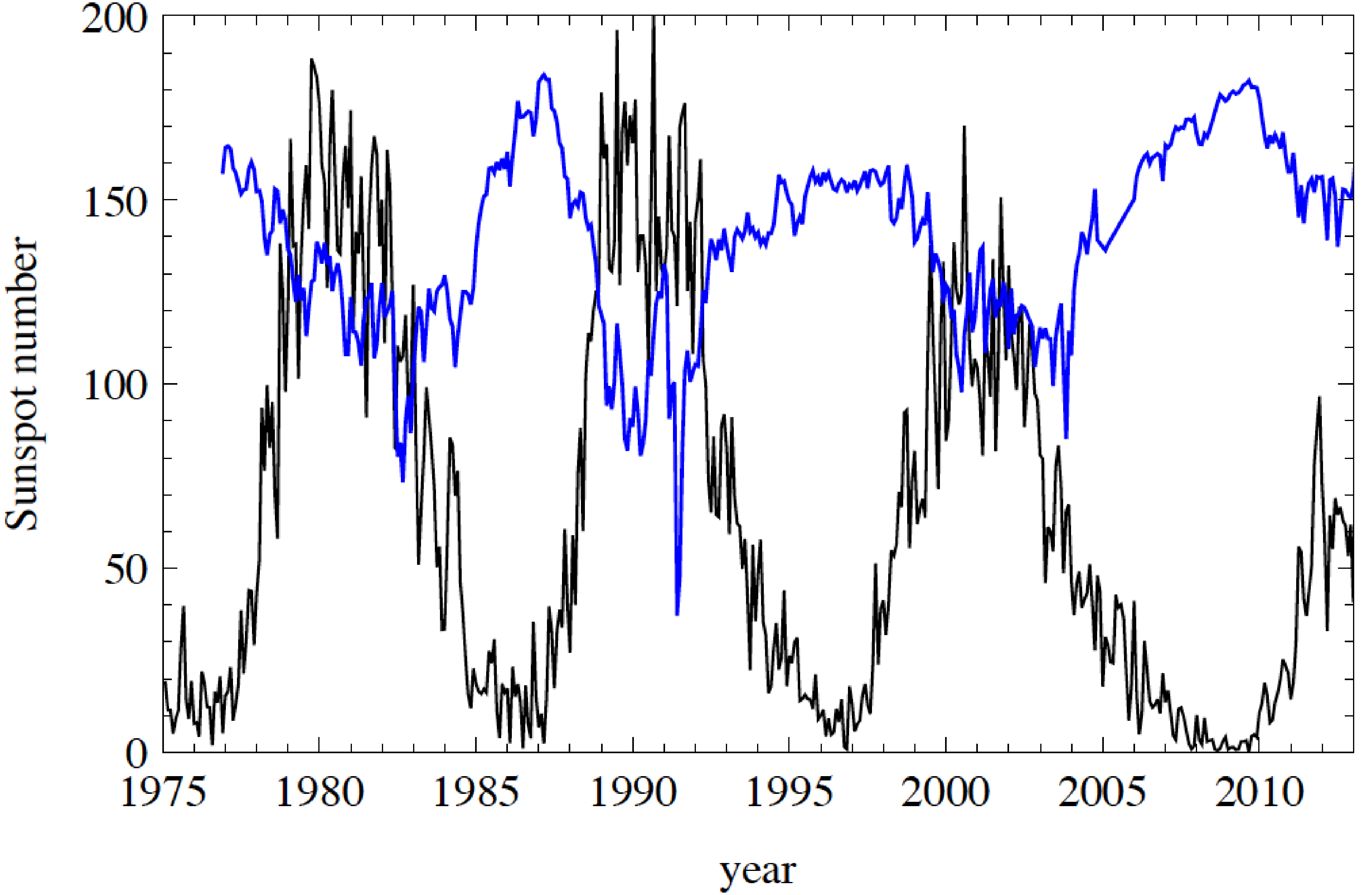
Exciting clear indication of “New Astrophysics” or “New Physics” (DM)

Time dependence of the Cosmic Ray Flux:

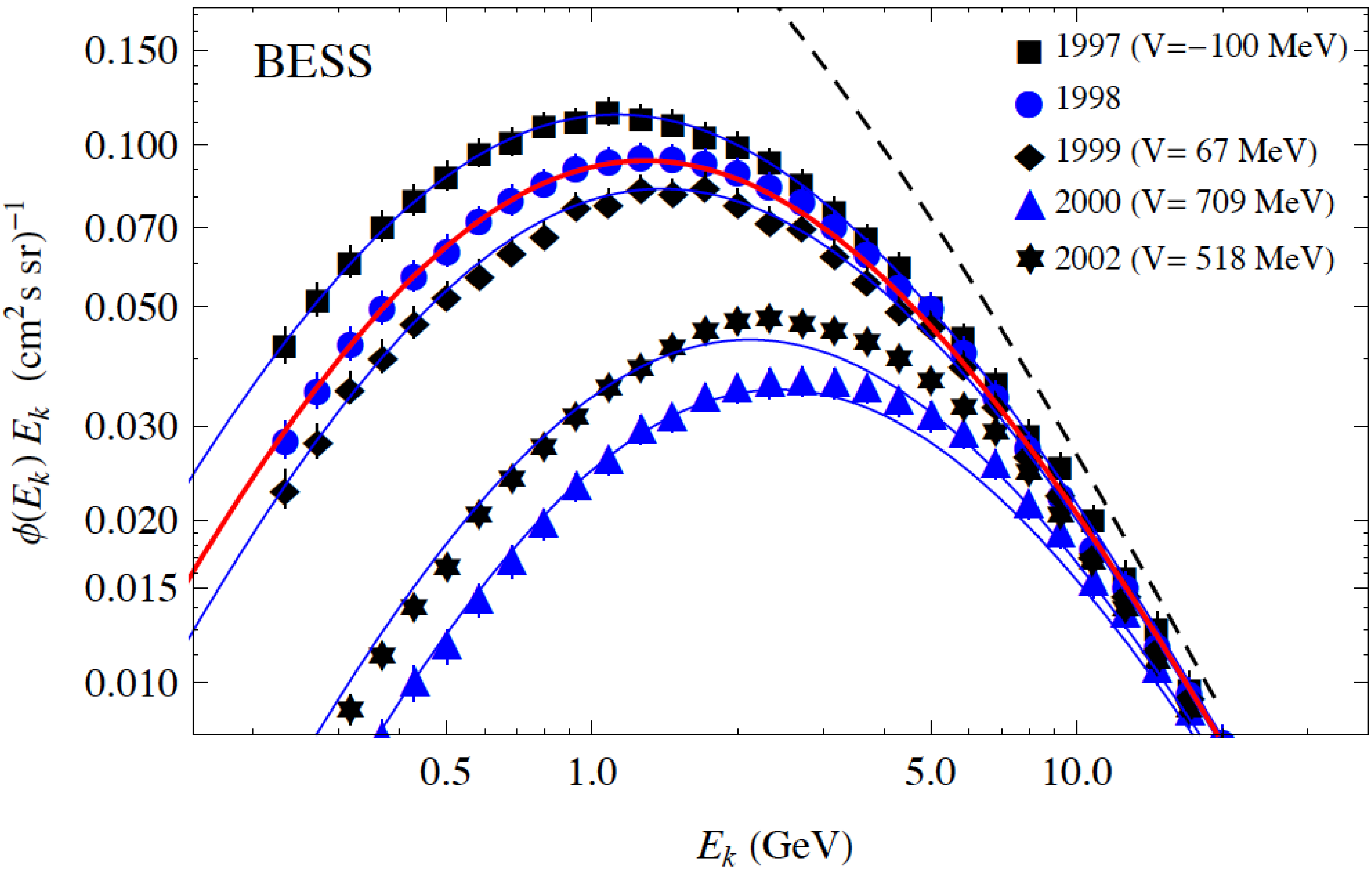


Hermanus (South Africa) Neutron Monitor

Correlation with Solar Activity (Sunspot Number)



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



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

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

Flux at the Earth at time t

$$\phi(E, t)$$

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"

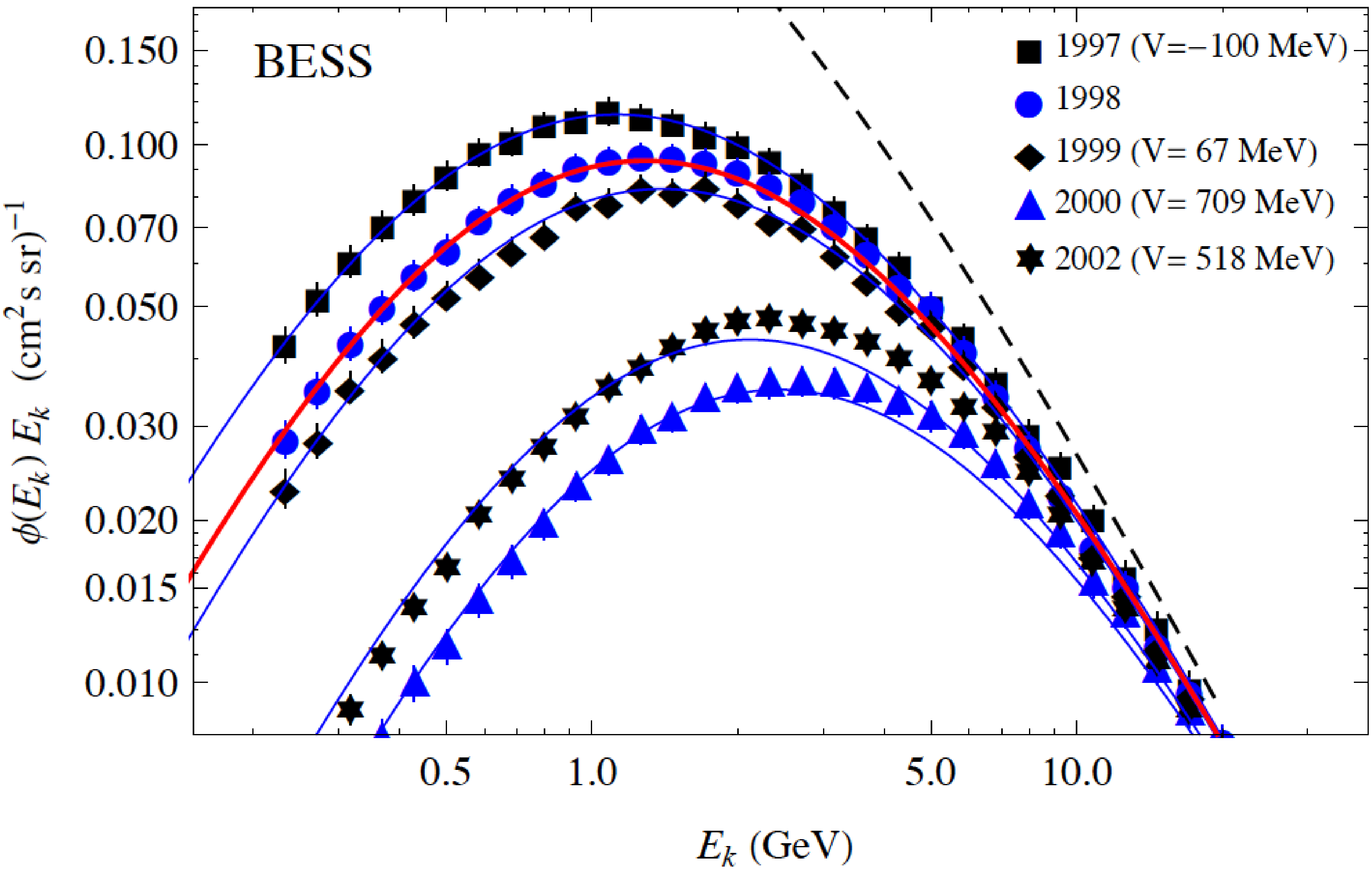
$$\phi(E, t_2) = \phi(E + V_{21}, t_1) \, \frac{E^2 - m^2}{(E + V_{21})^2 - m^2}$$

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

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

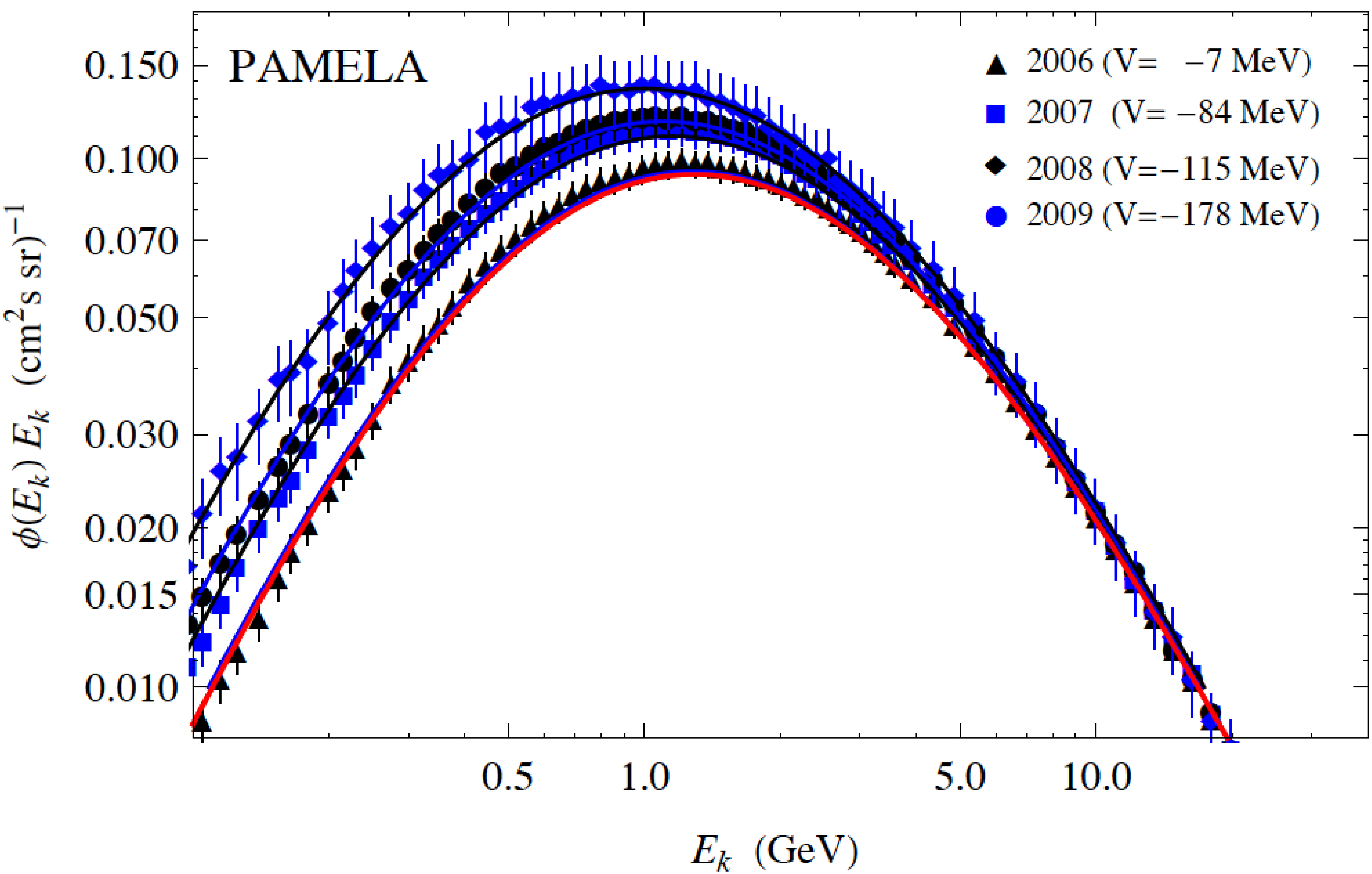
Algorithm is not perfect but phenomenologically quite successful.

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

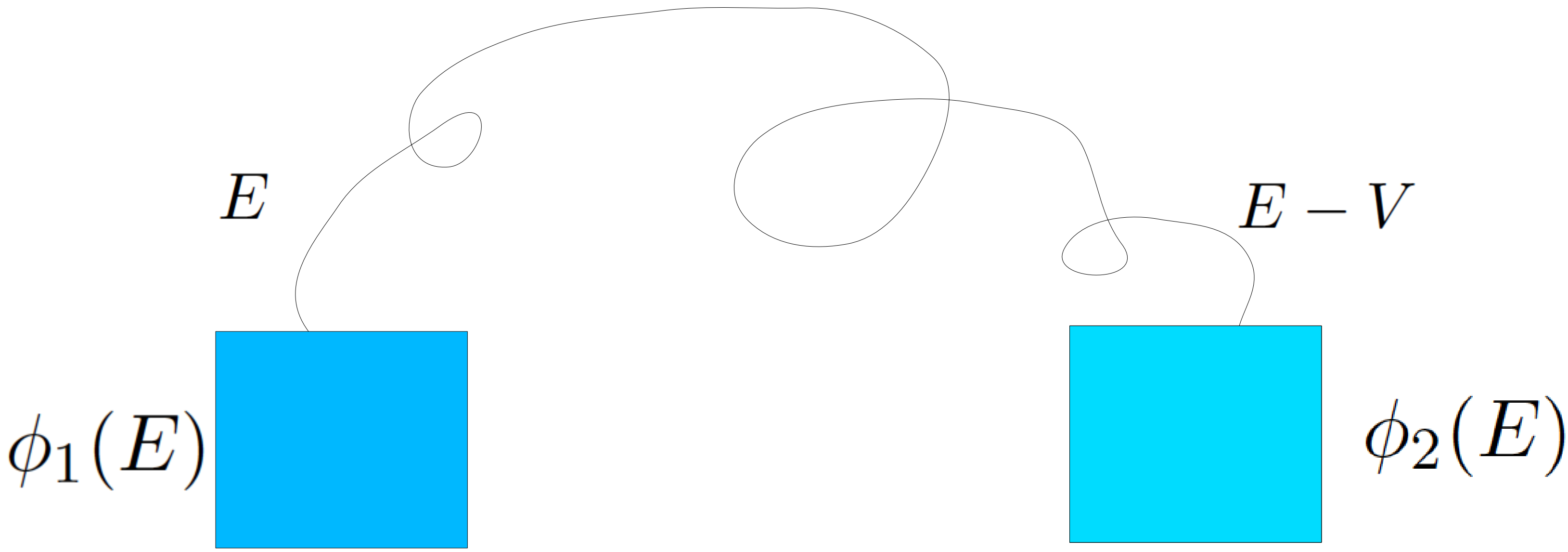


Pamela data: (proton spectrum)

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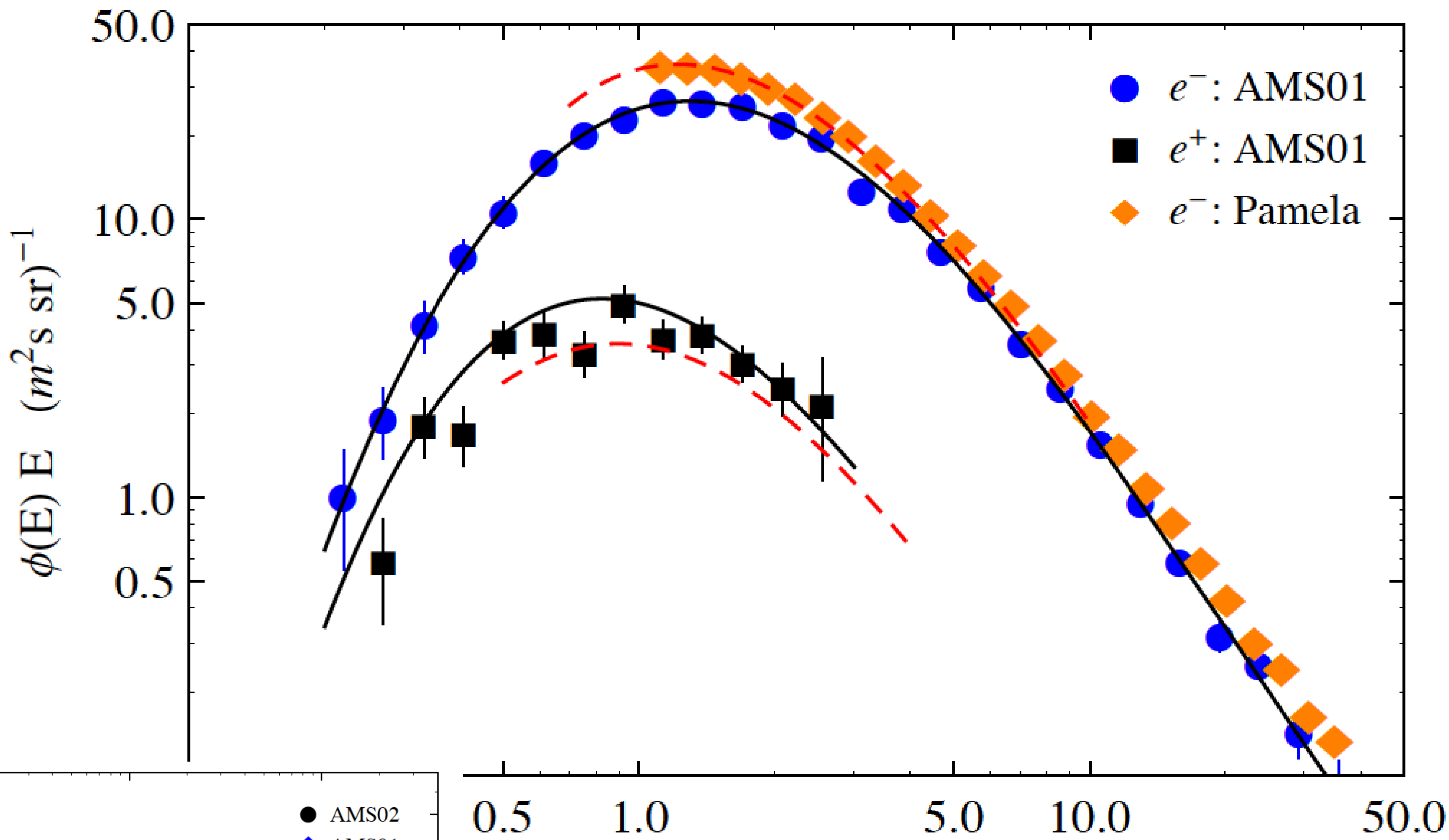
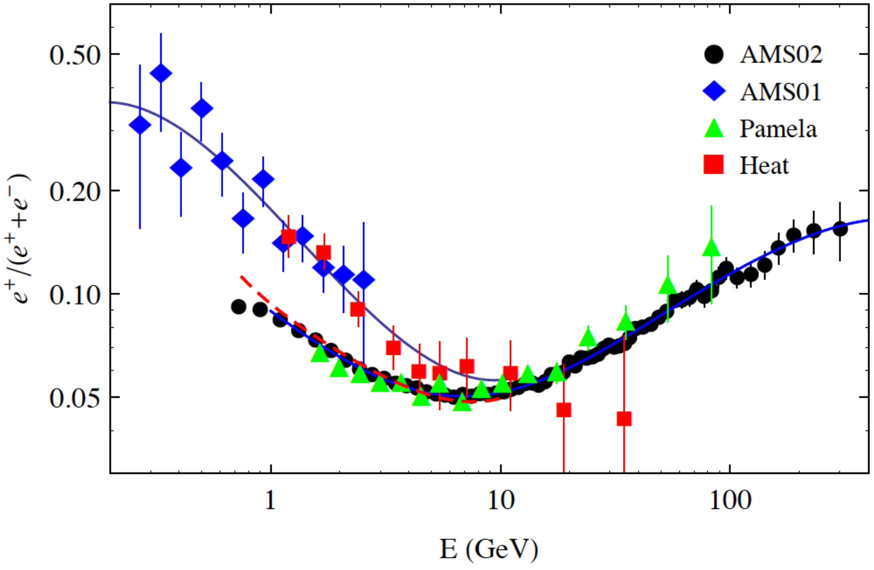
$$V(t) = \Delta E(t)$$

Particles of opposite electric charge
lose a different amount of energy





Fit AMS01 data, apply FF alg.

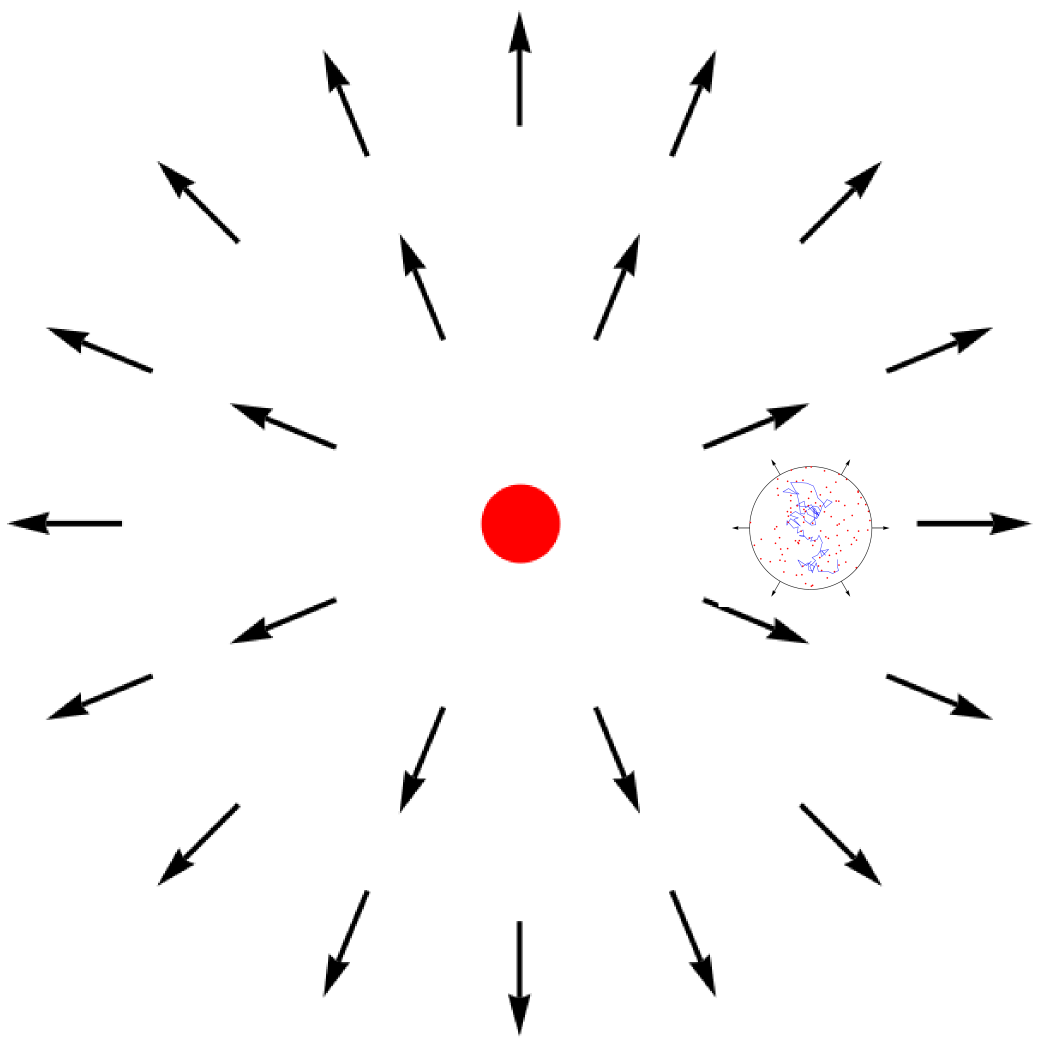
$$\Delta V_{e^-} = -127\ \text{MeV}$$

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

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

Parker's (1965) original idea for Solar Modulations

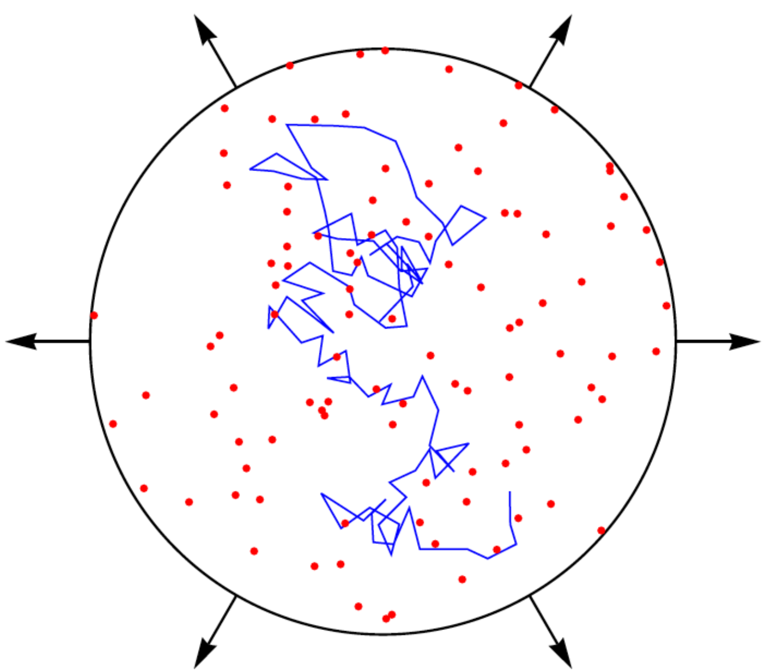
Radial Solar Wind (400 Km/s)



"adiabatic energy losses"
In expanding medium

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

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



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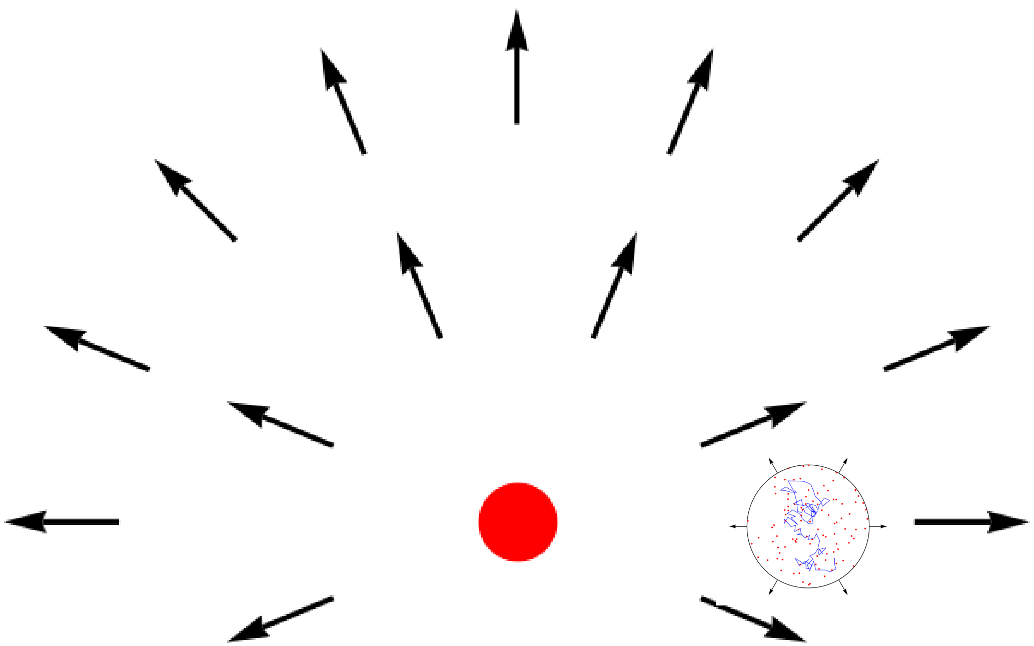
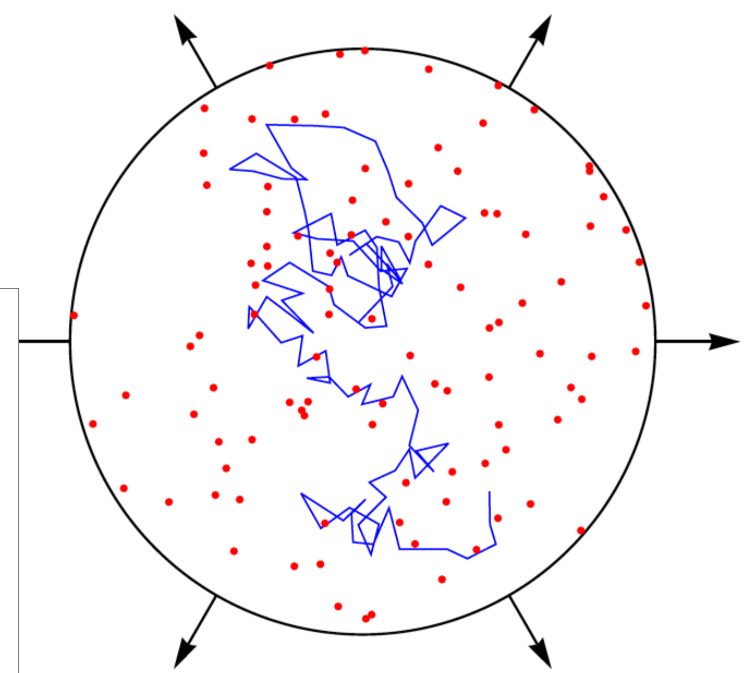
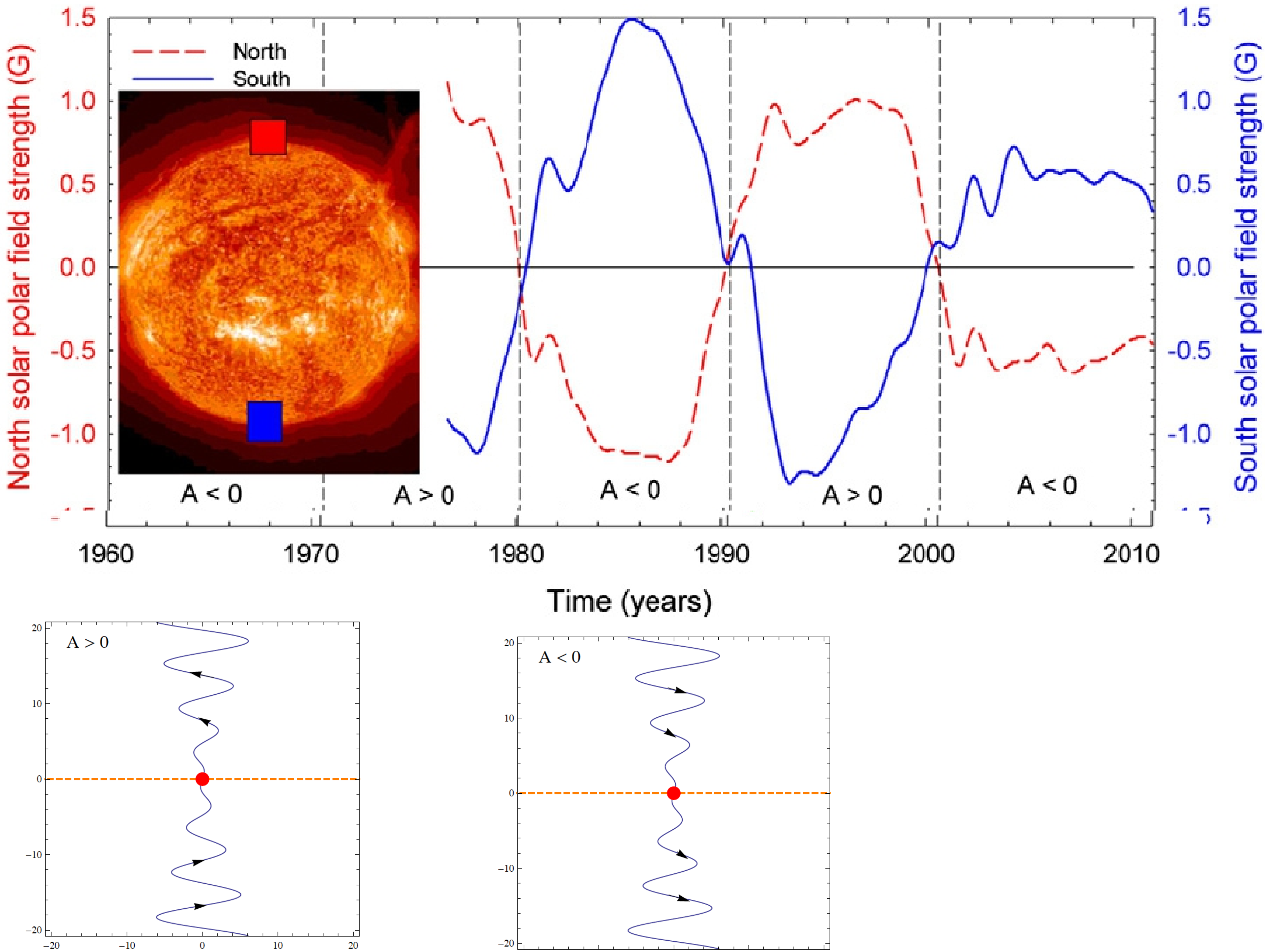




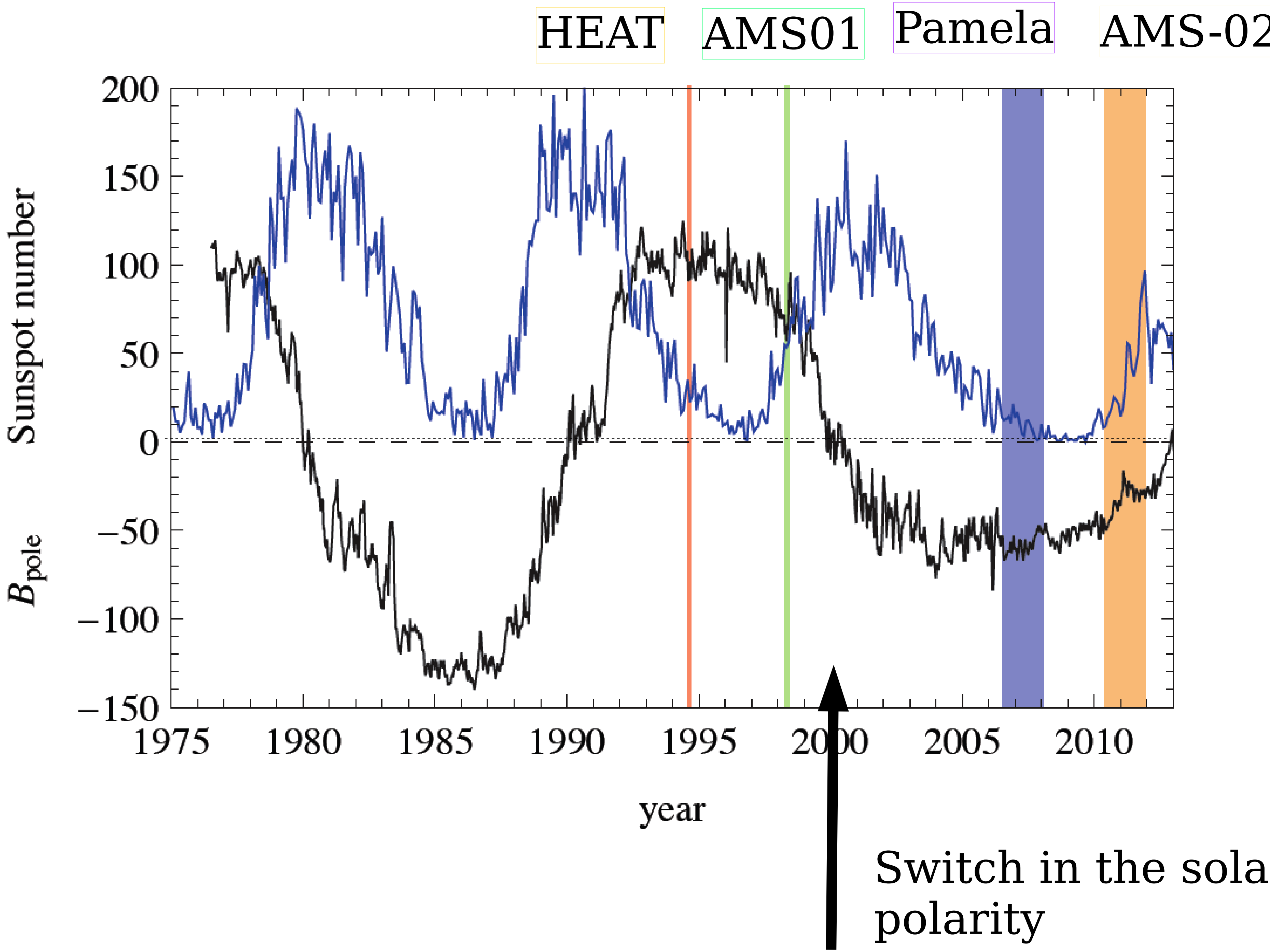
$$\Delta E = \text{const}$$

$$D(E) \propto E$$

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



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
A < 0

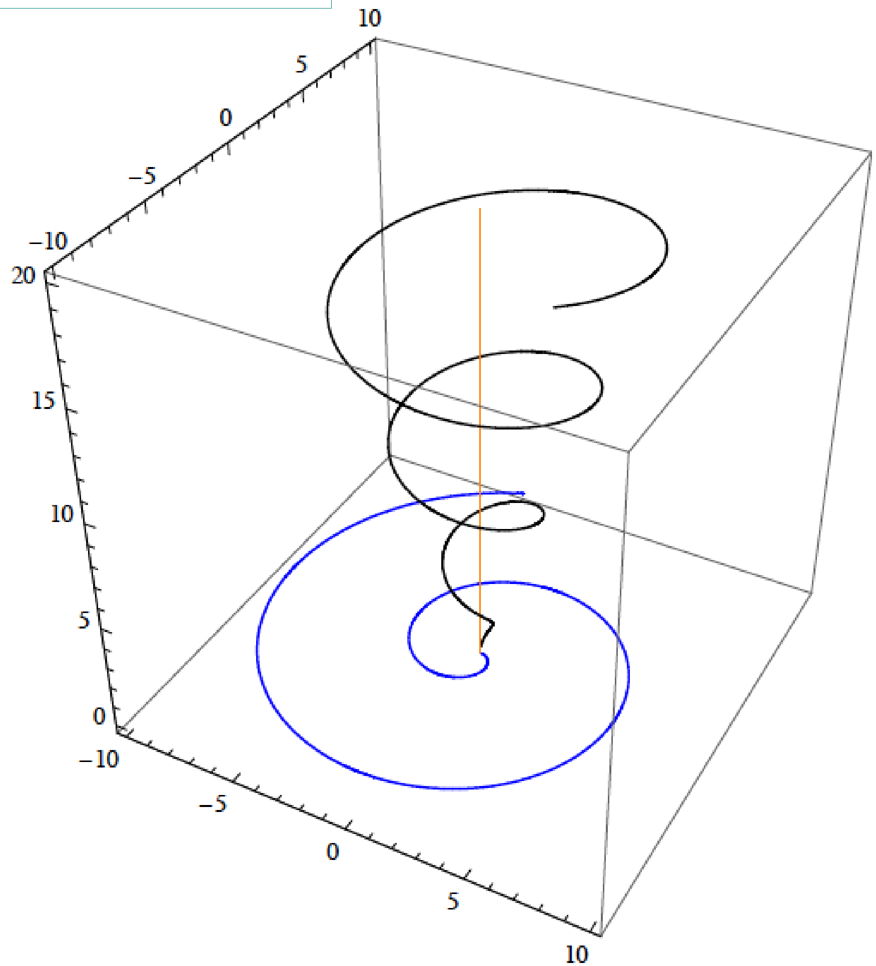


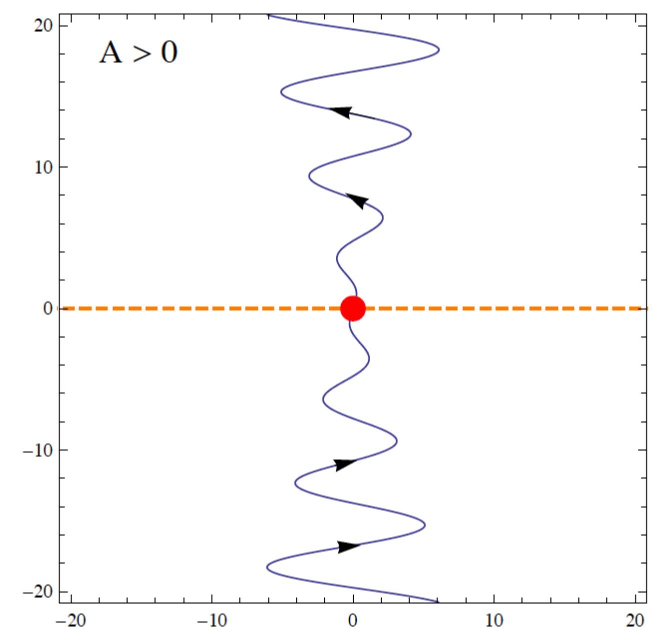
HEAT
AMS01
Pamela
AMS-02
Sunspot number
B_{pole}
200
150
100
50
0
−50
−100
−150
1975
1980
1985
1990
1995
2000
2005
2010
year
Switch in the solar polarity

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

$A = \pm 1$

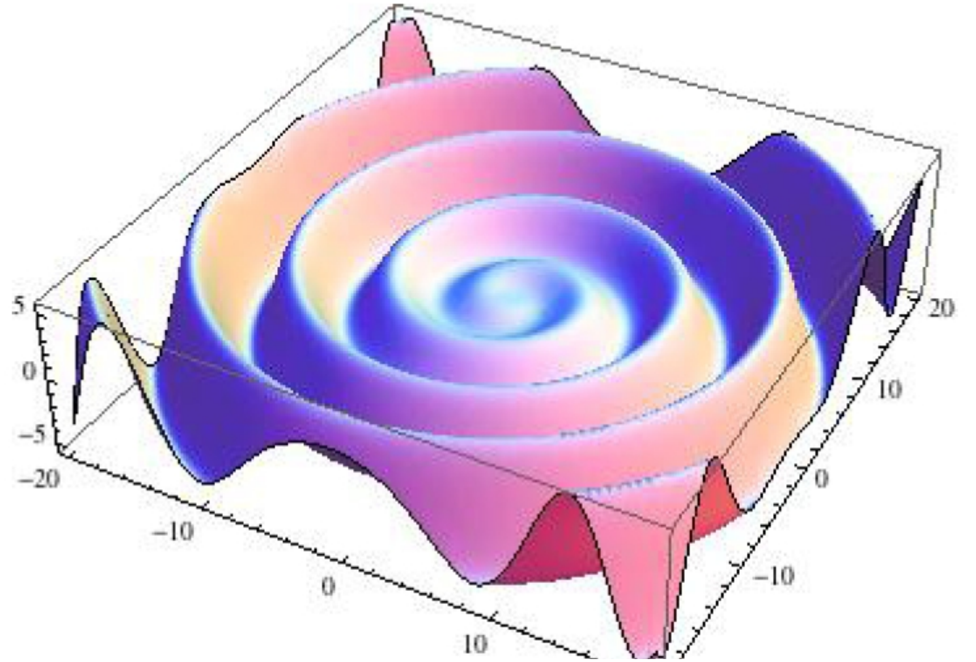
$S(\vec{r}) = \pm 1$

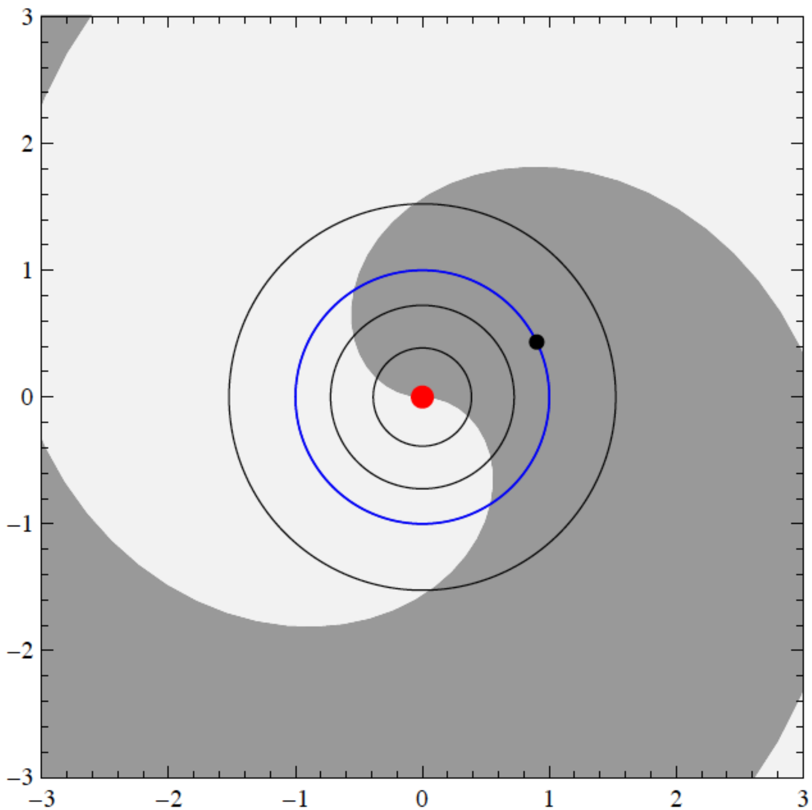


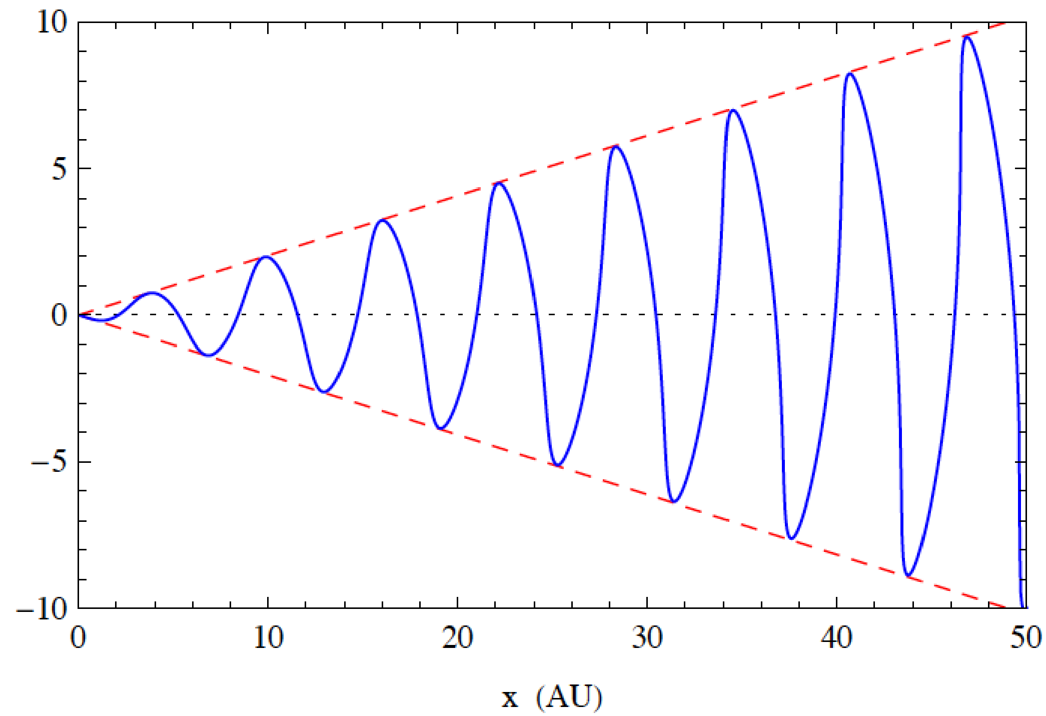


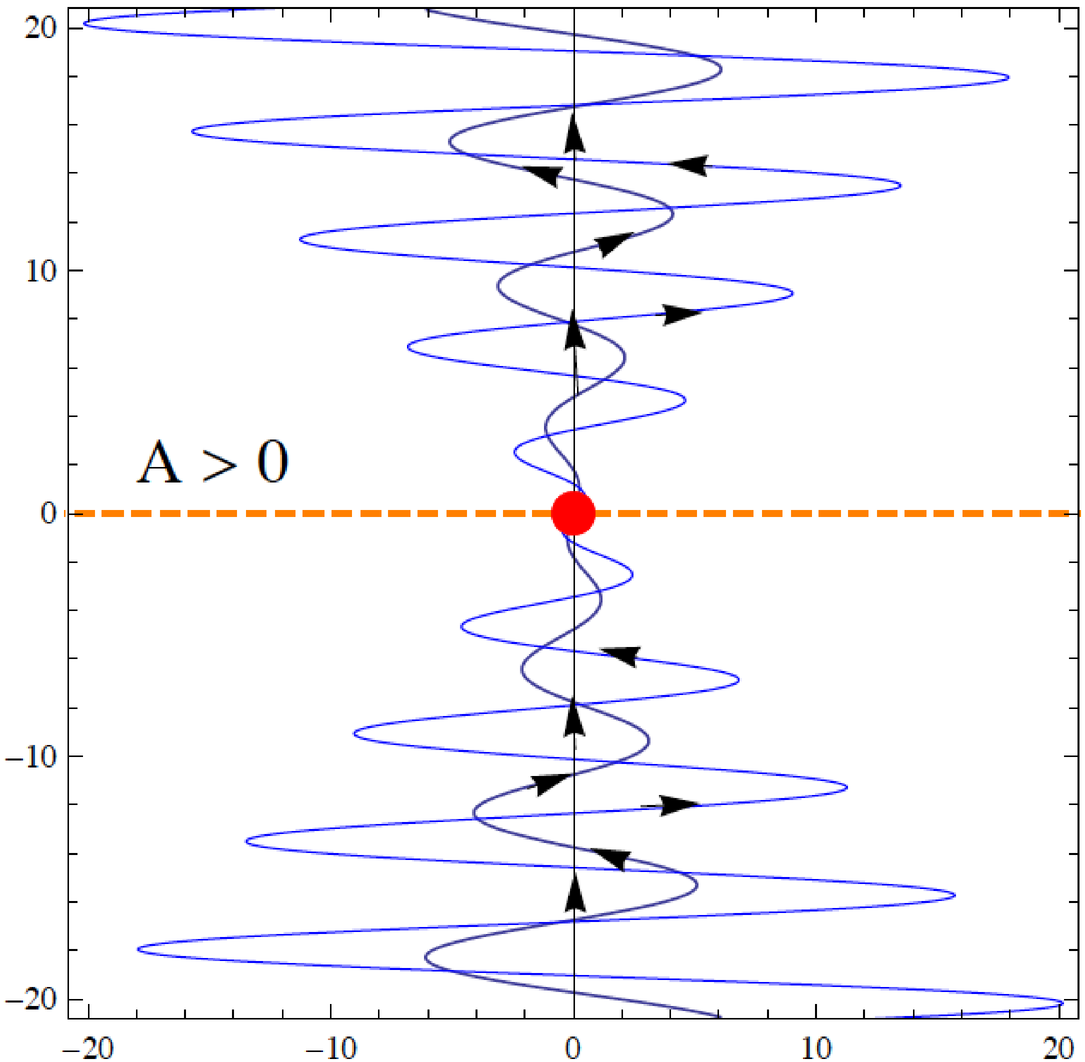
Heliospheric Current Sheet

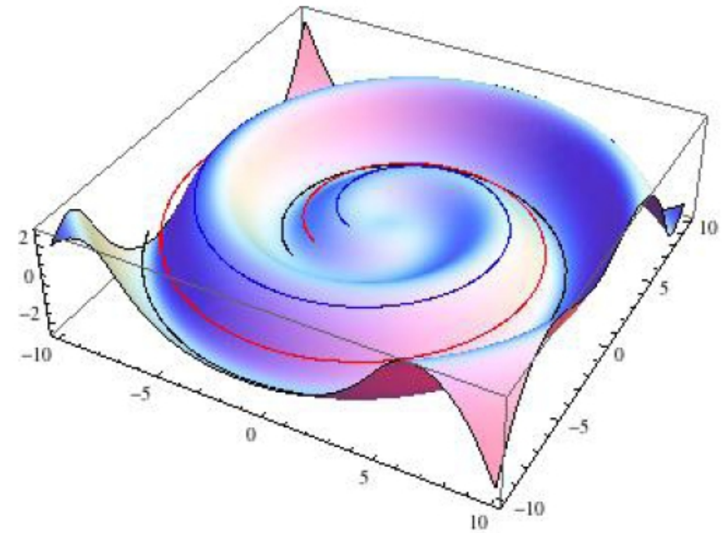
("Ballerina skirt")








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

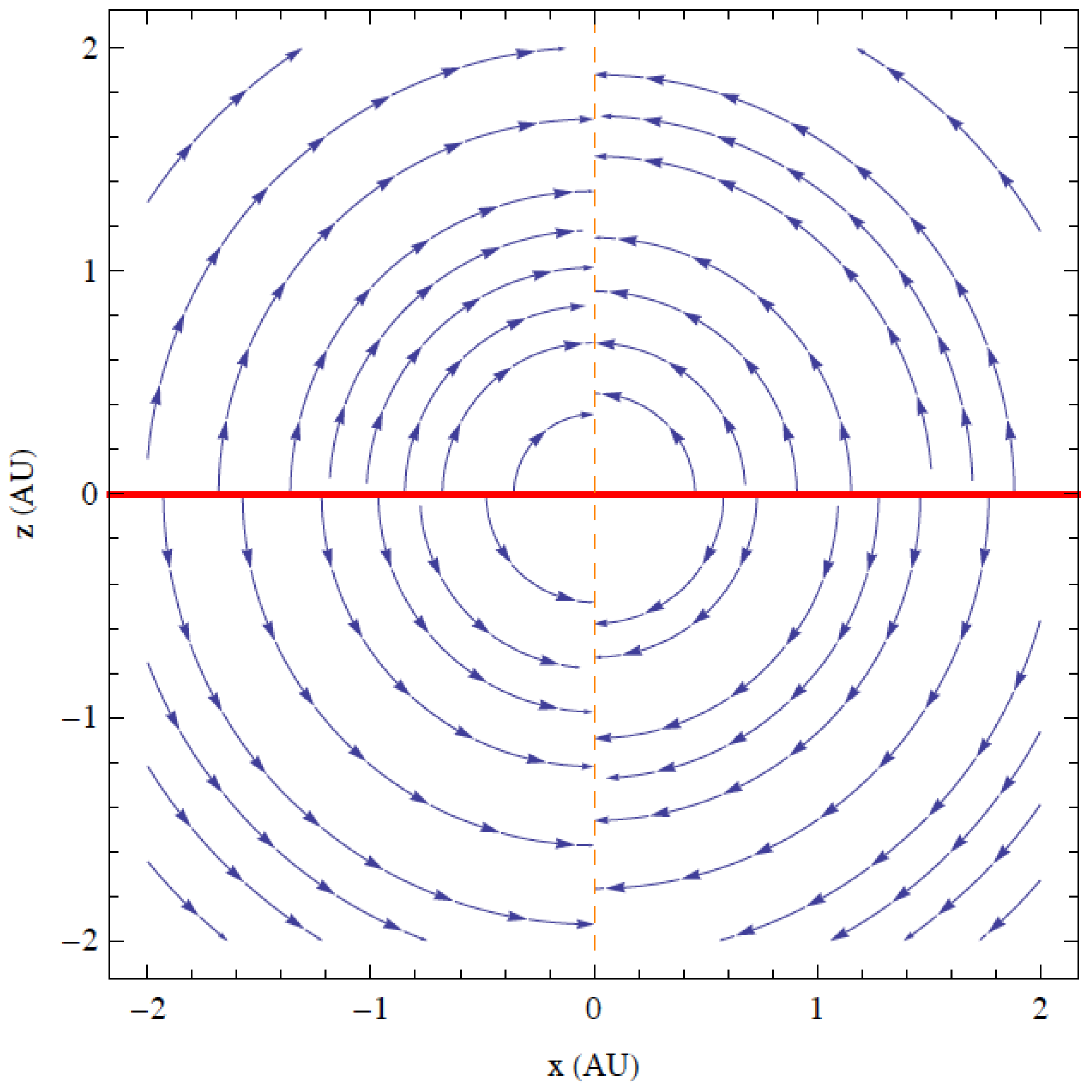
$$\vec{E}(\vec{x}) = -\frac{\vec{v}_w(\vec{x})}{c} \wedge \vec{B}(\vec{x})$$

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.

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

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

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

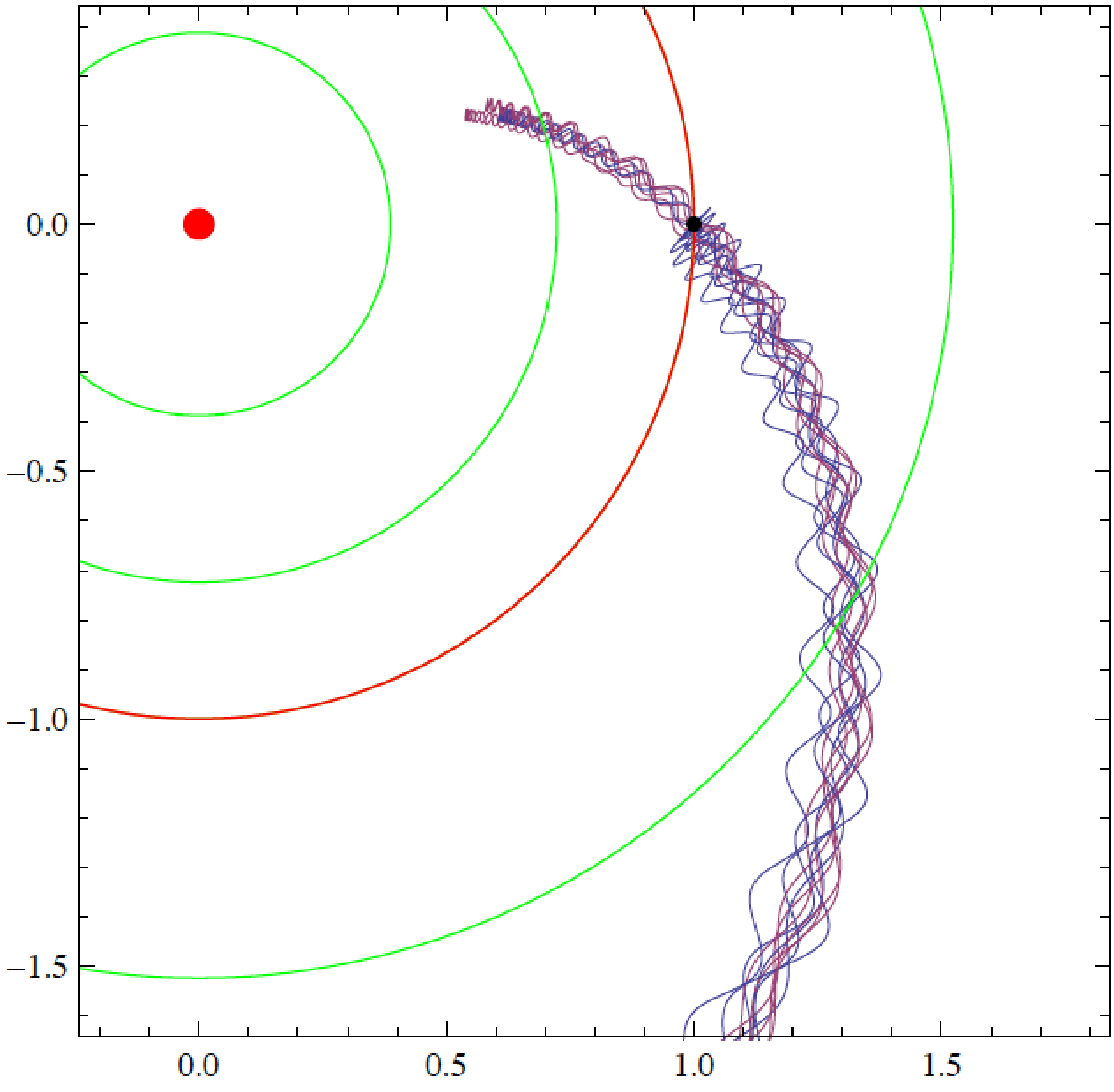
“Back-tracing” of particles observed at the Earth.
[Neglect random, turbulent field]

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

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

Small perturbation

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



“Backtracing” of particles

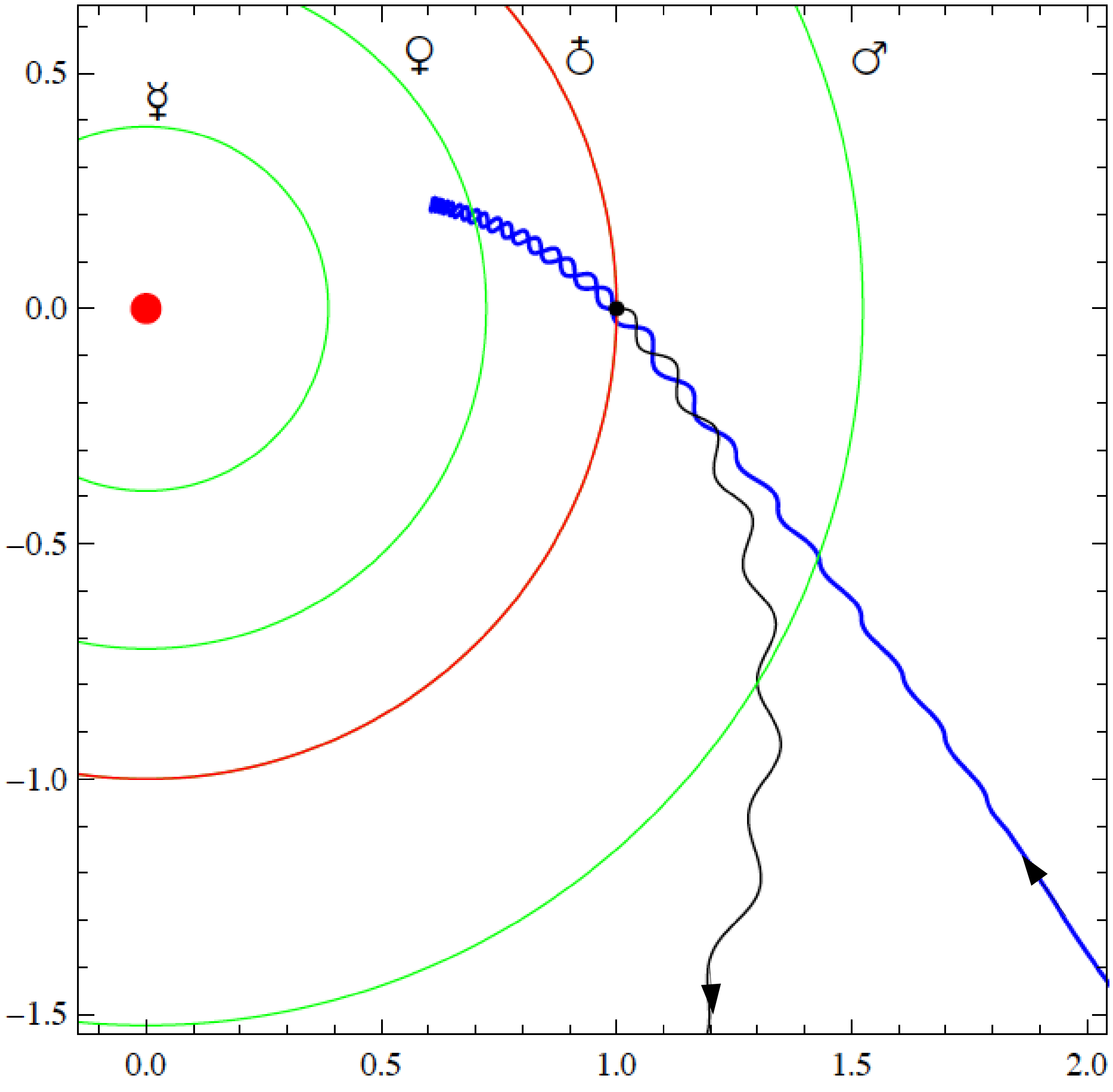
e+ (12 GeV)

12 directions

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

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

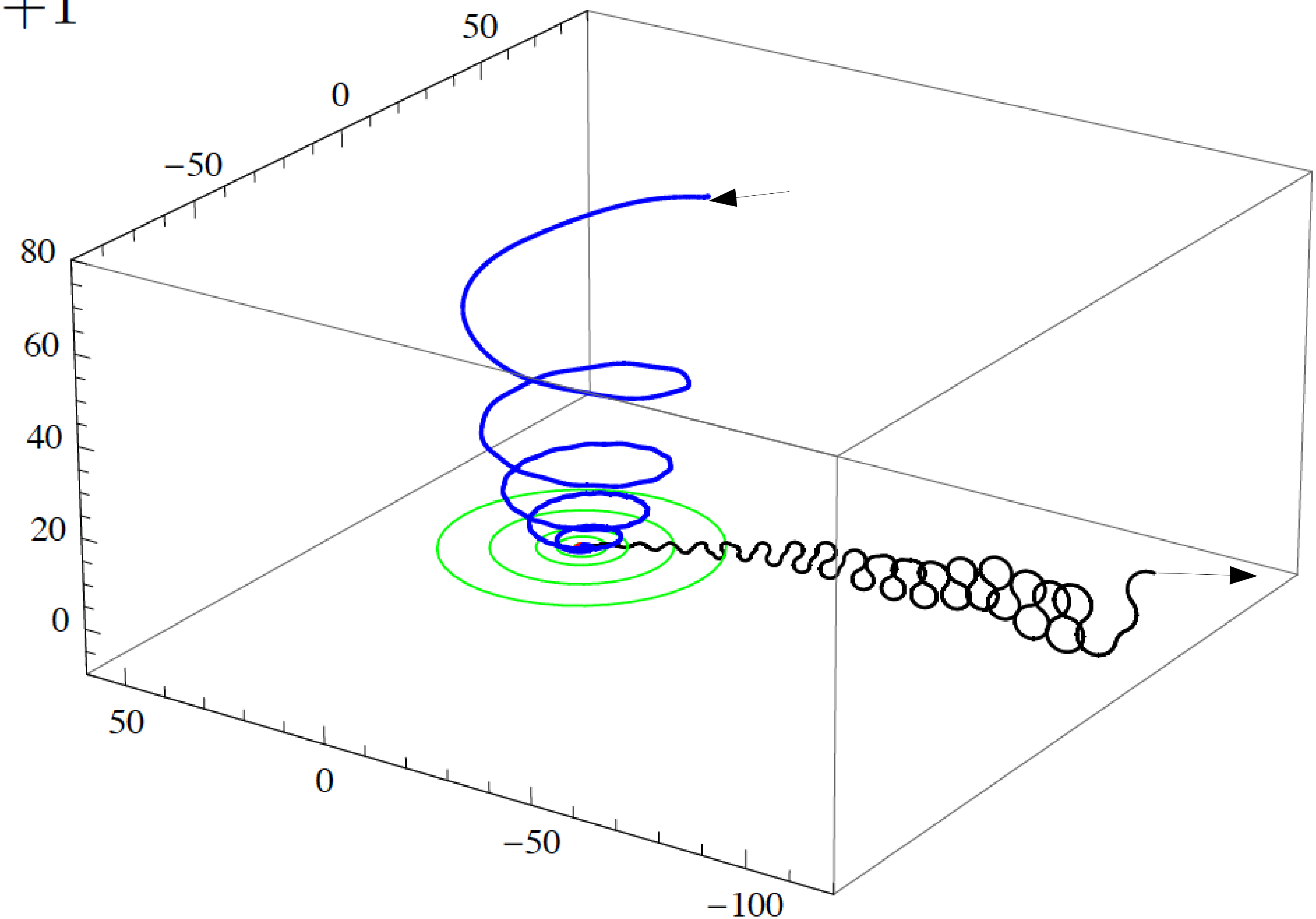
$$\sin\alpha = 0.05$$

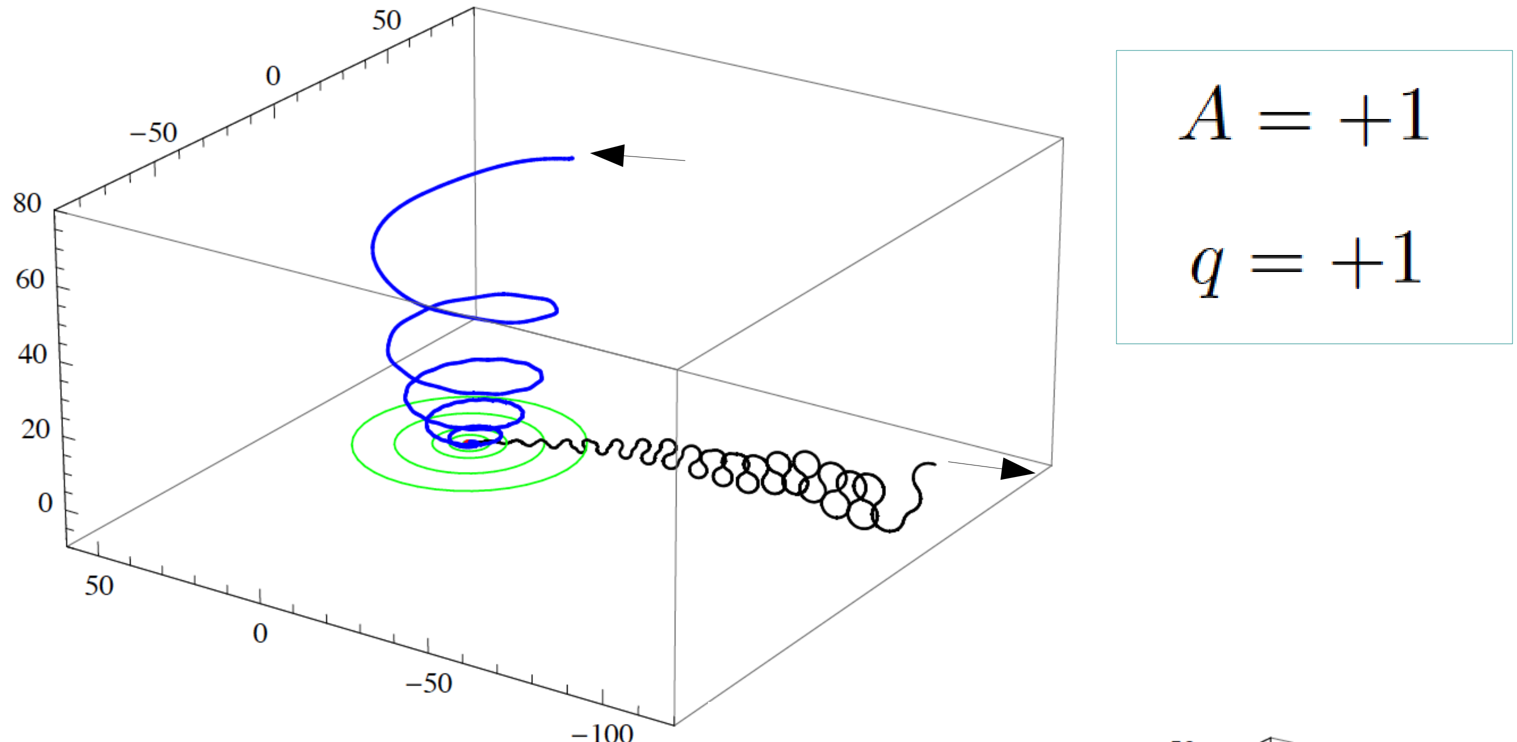


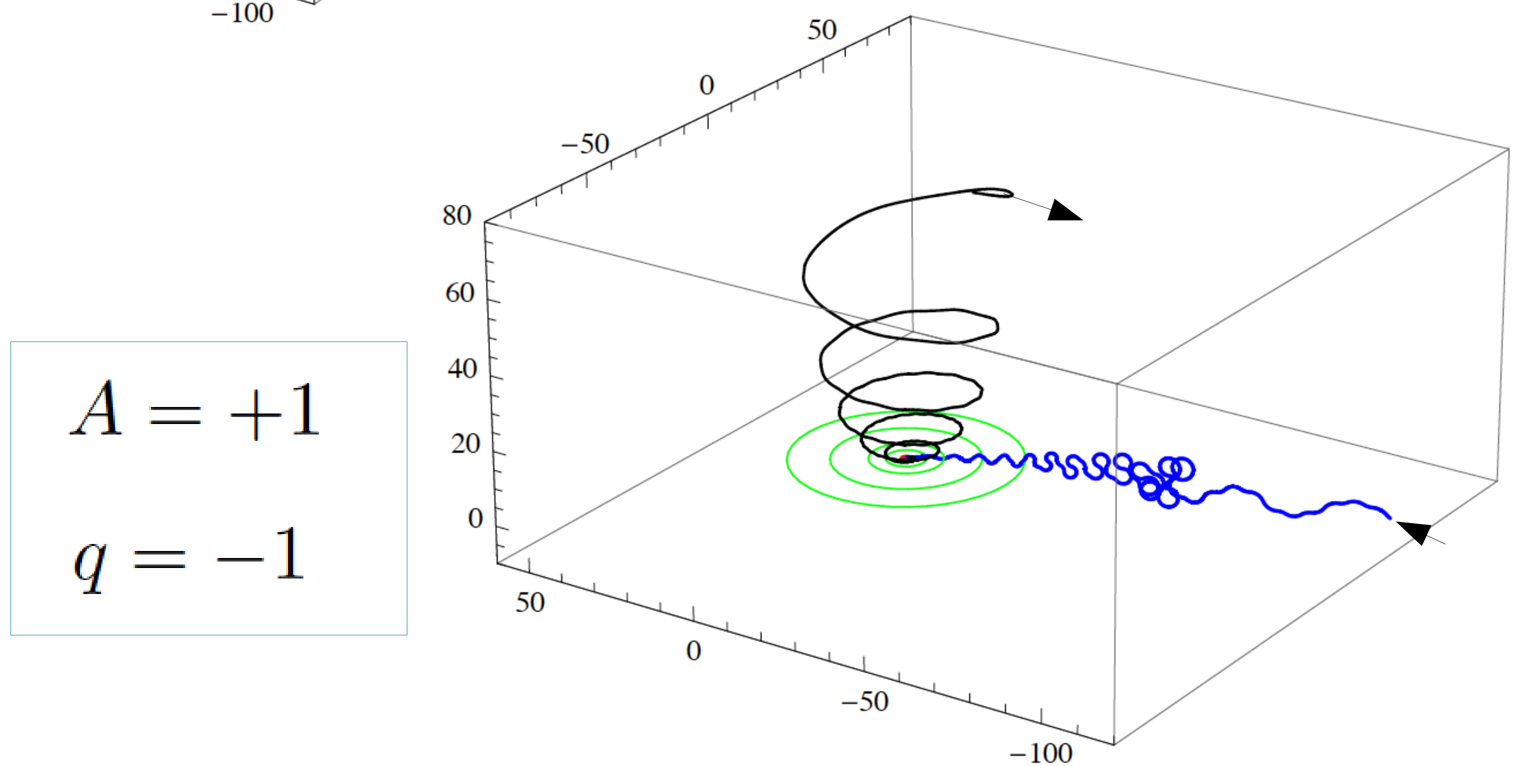
12 GeV
e-

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

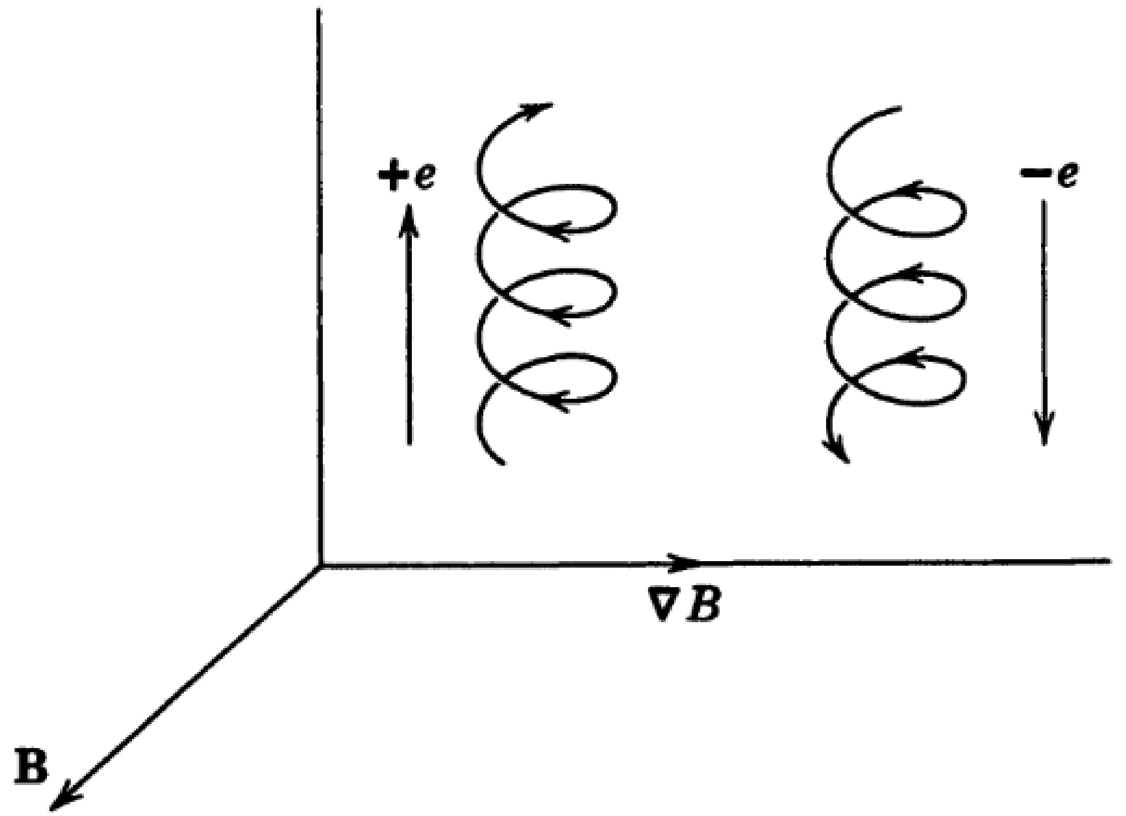
$q = +1$



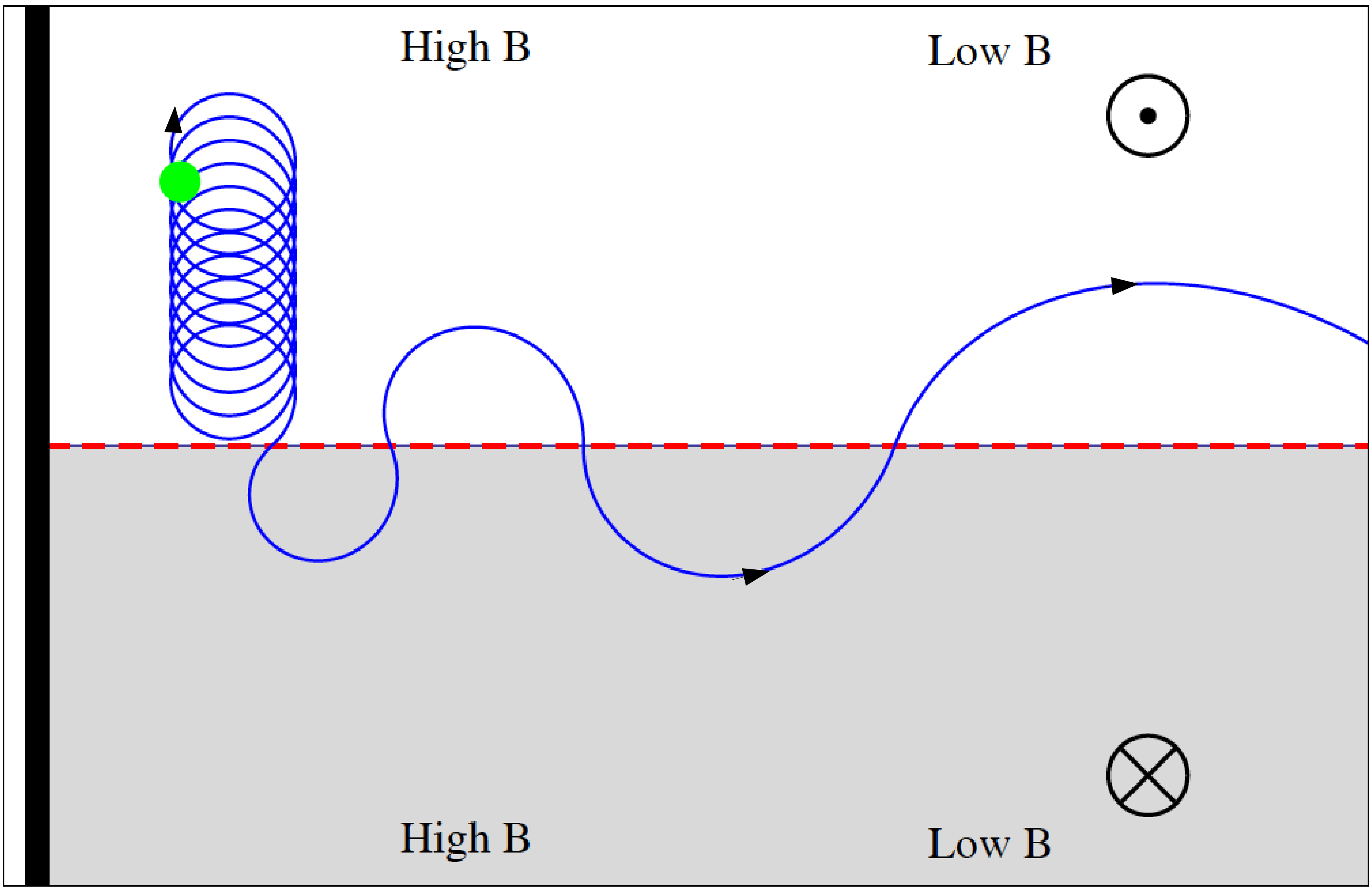

A = +1
q = +1
50
0
−50
80
60
40
20
0
50
0
−50
−100


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

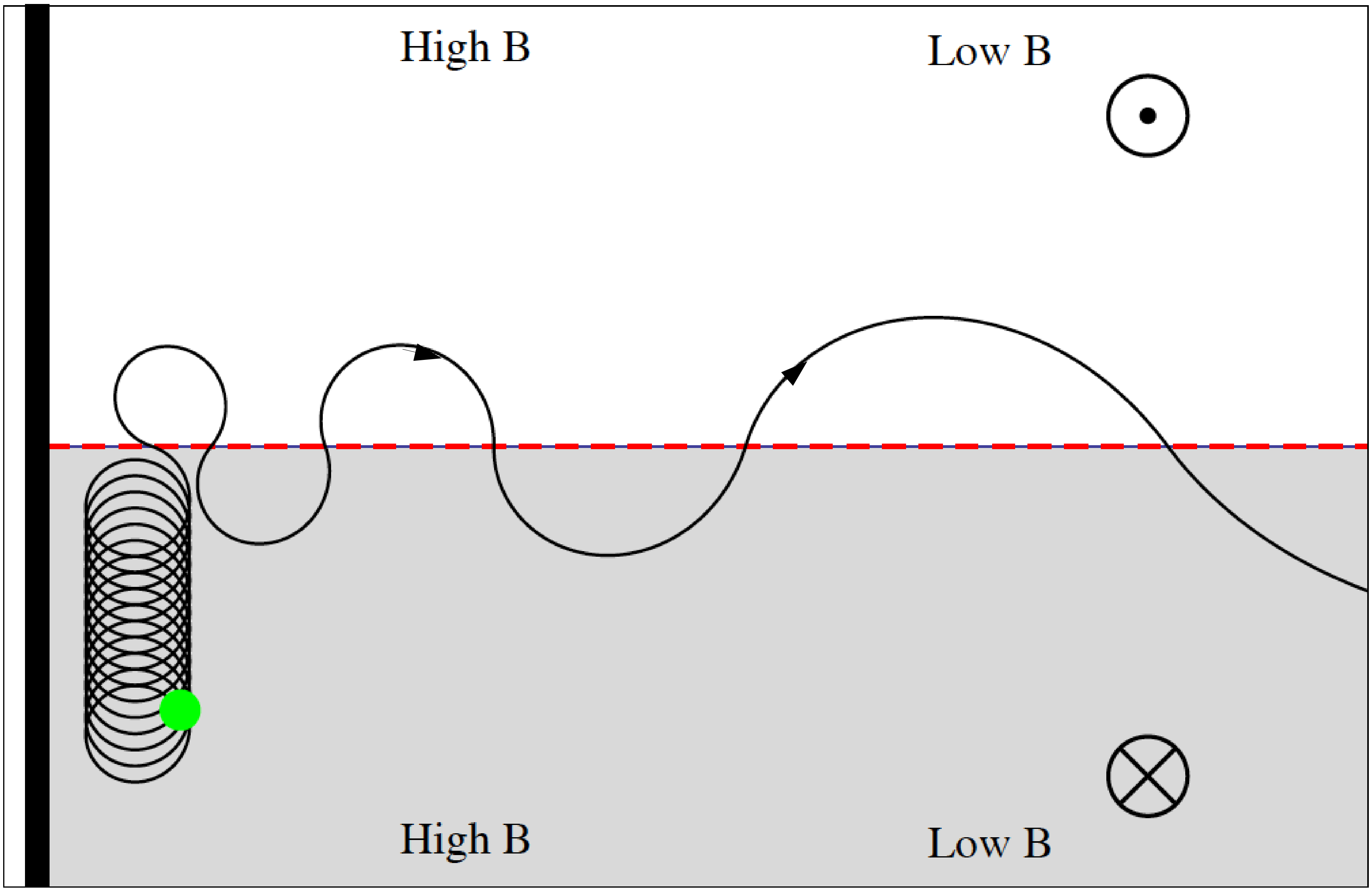
“Drift” of the guiding center of the particle gyration



$q = +1$

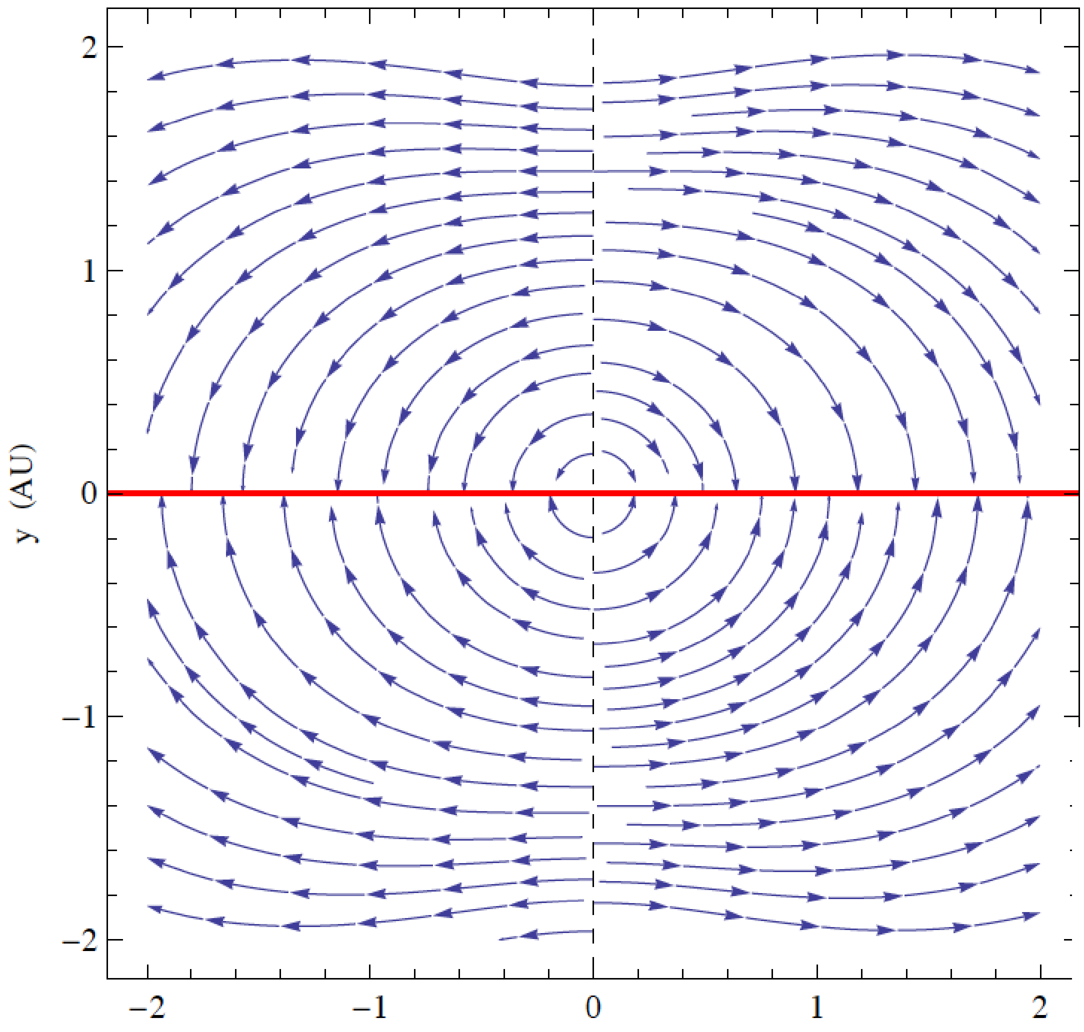


$q = +1$

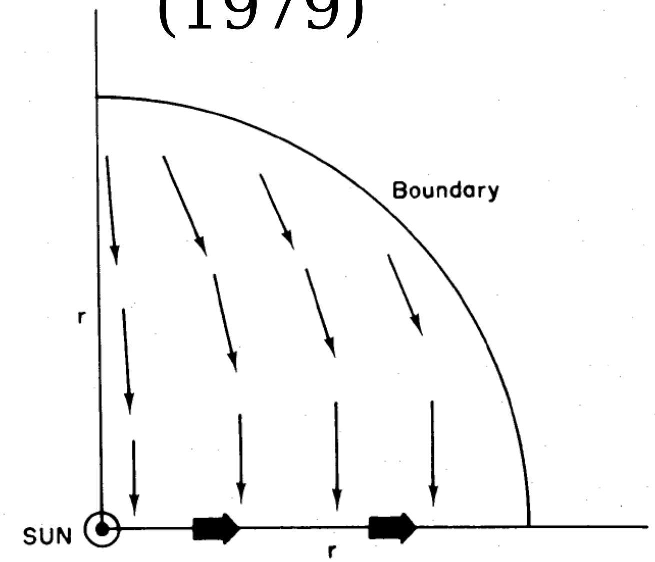


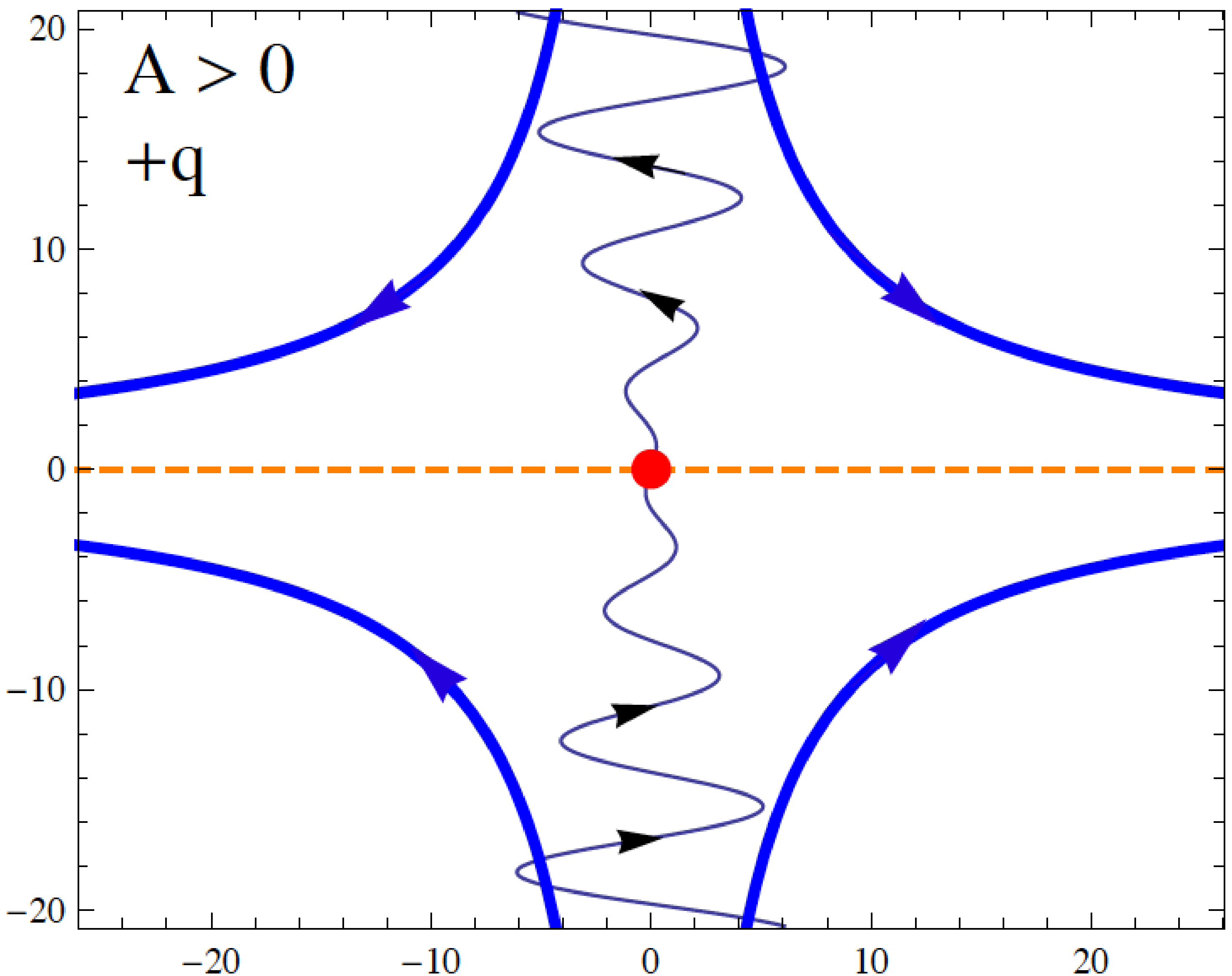
Stream lines of the drift velocity

$$q\,A > 0$$

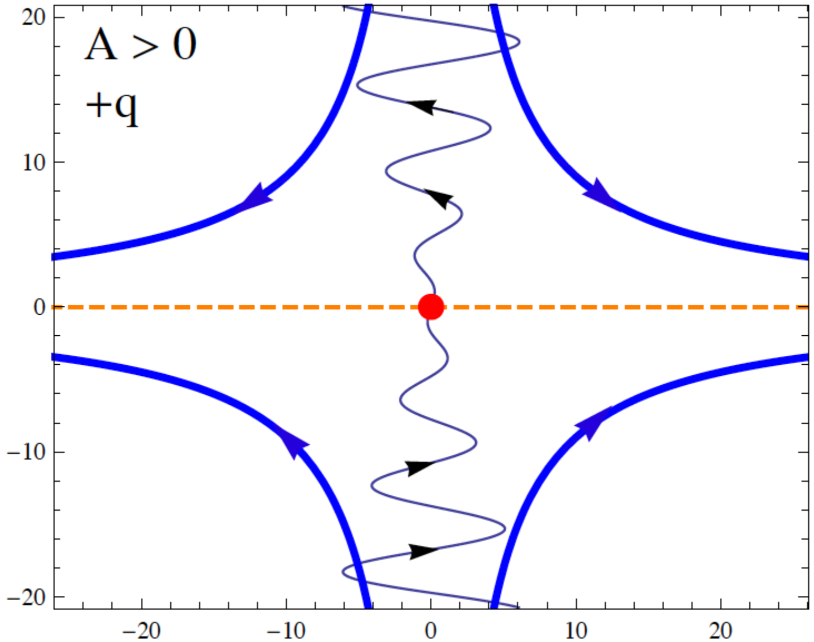


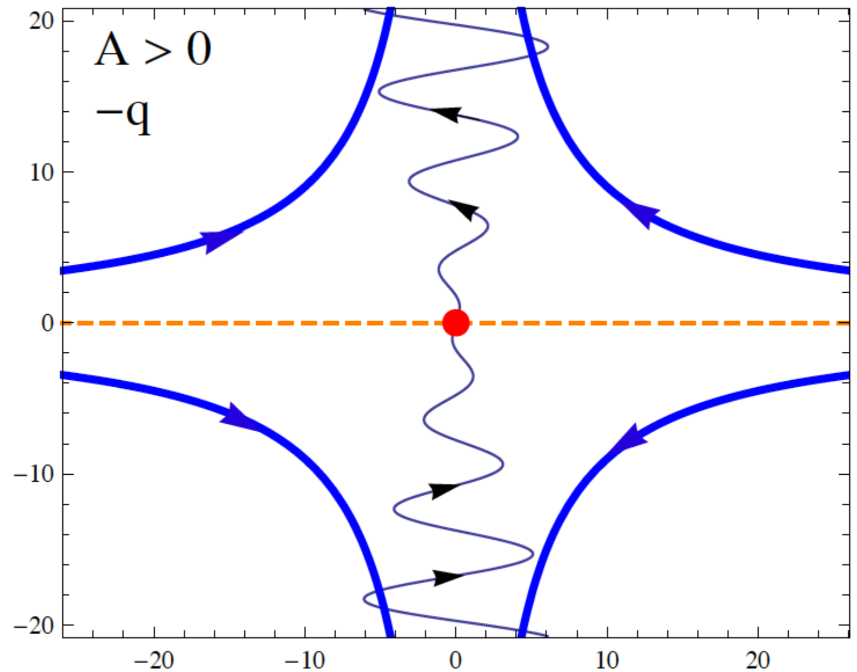
Jokipii + Kopriva (1979)



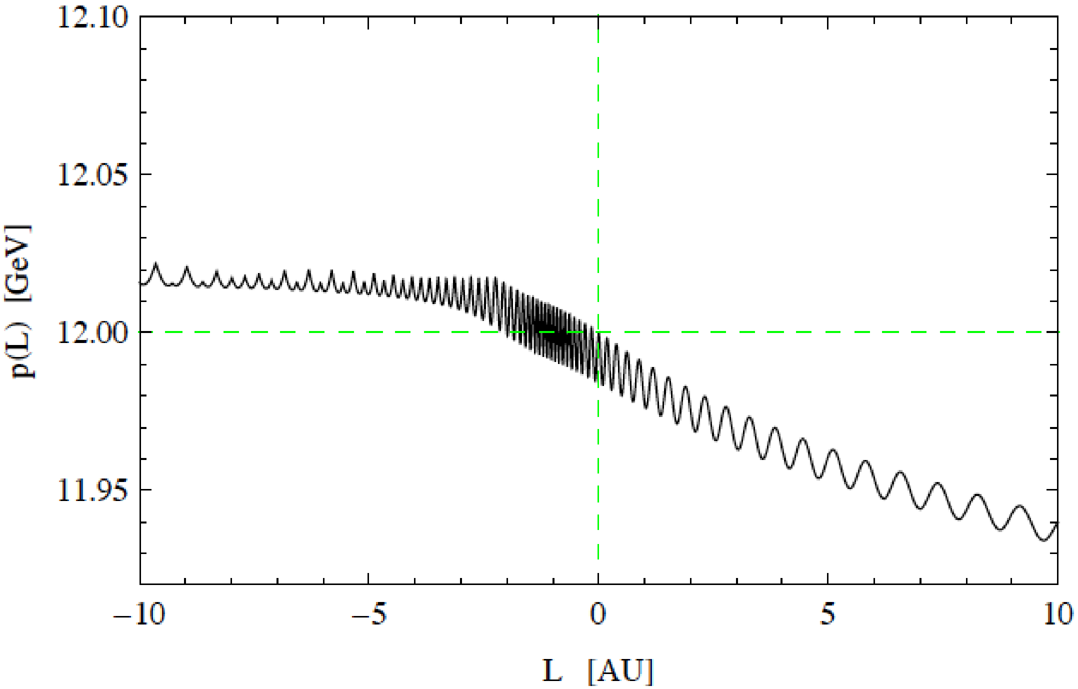


A > 0
+q
20
10
0
−10
−20
−20
−10
0
10
20


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

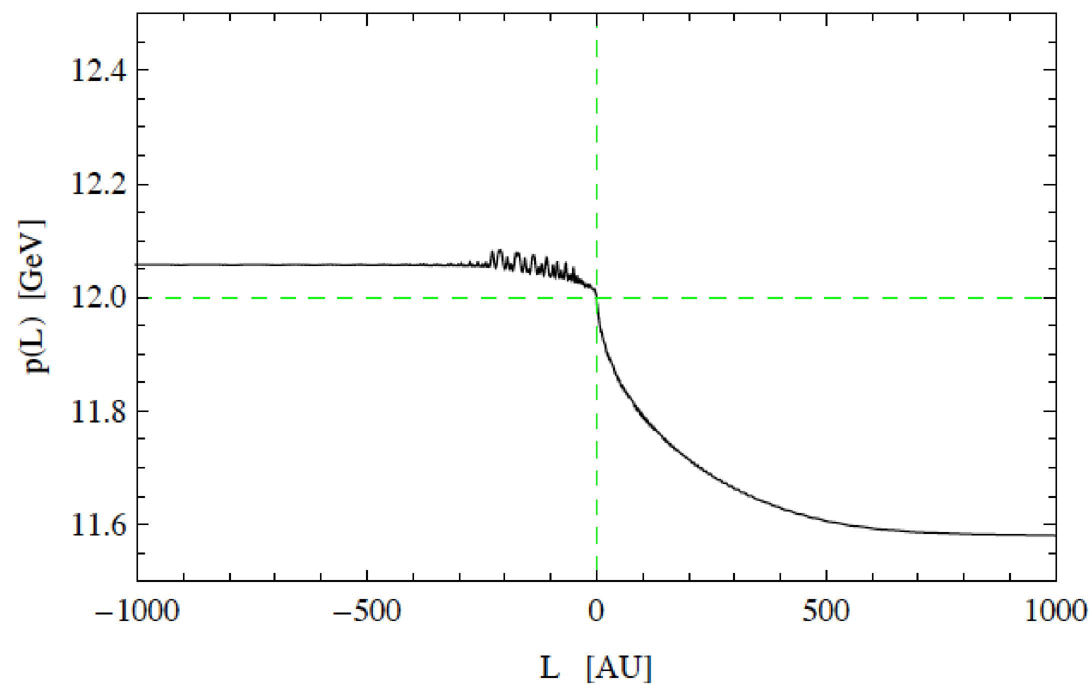

A > 0
−q
20
10
0
−10
−20
−20
−10
0
10
20

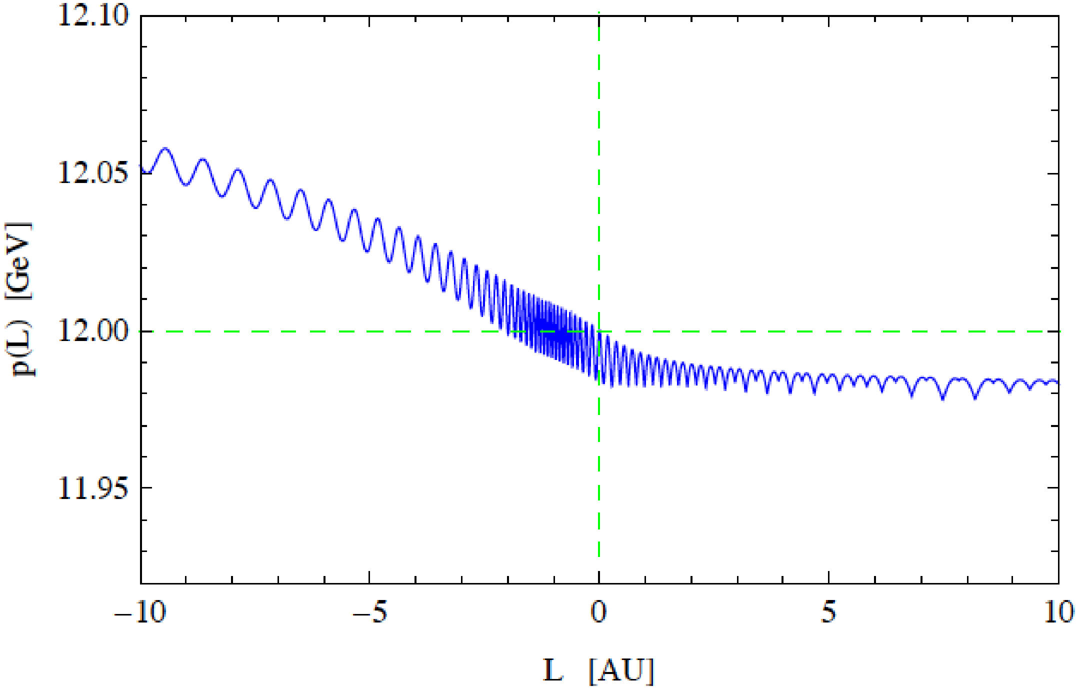
Energy Evolution



$$A = +1$$

$$q = +1$$

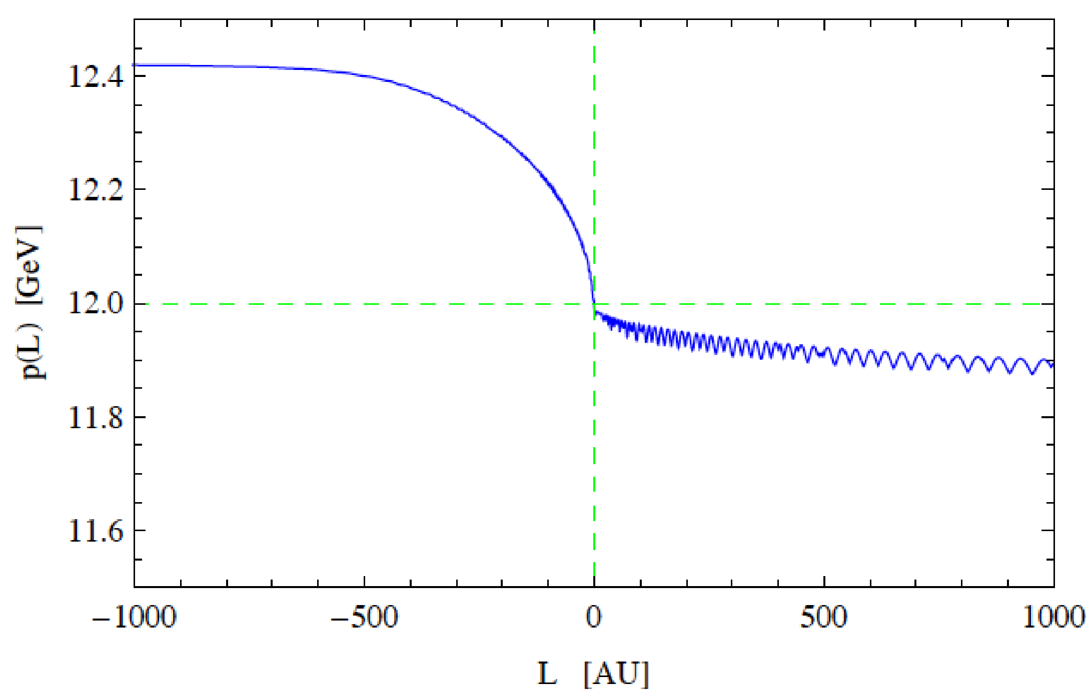




Energy Evolution

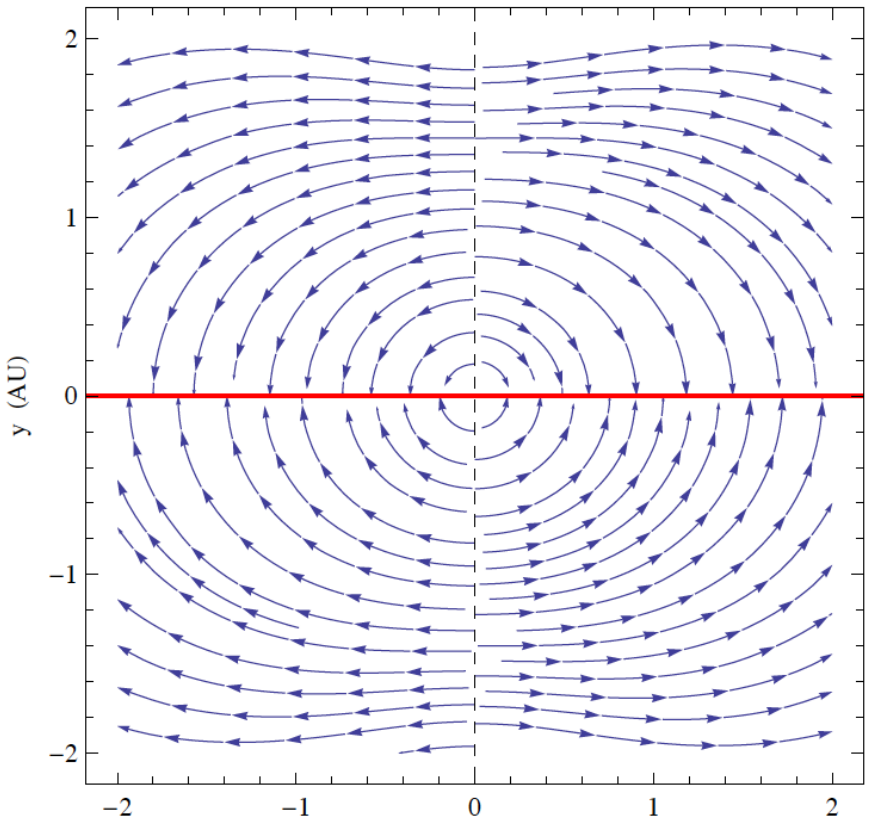
$$A = +1$$

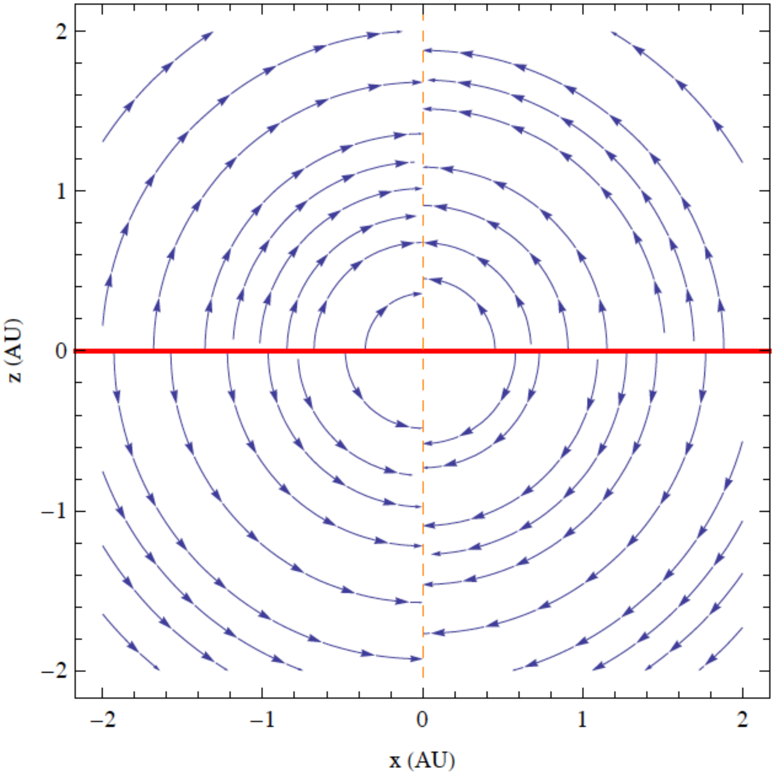
$$q = -1$$



Stream lines of the drift velocity

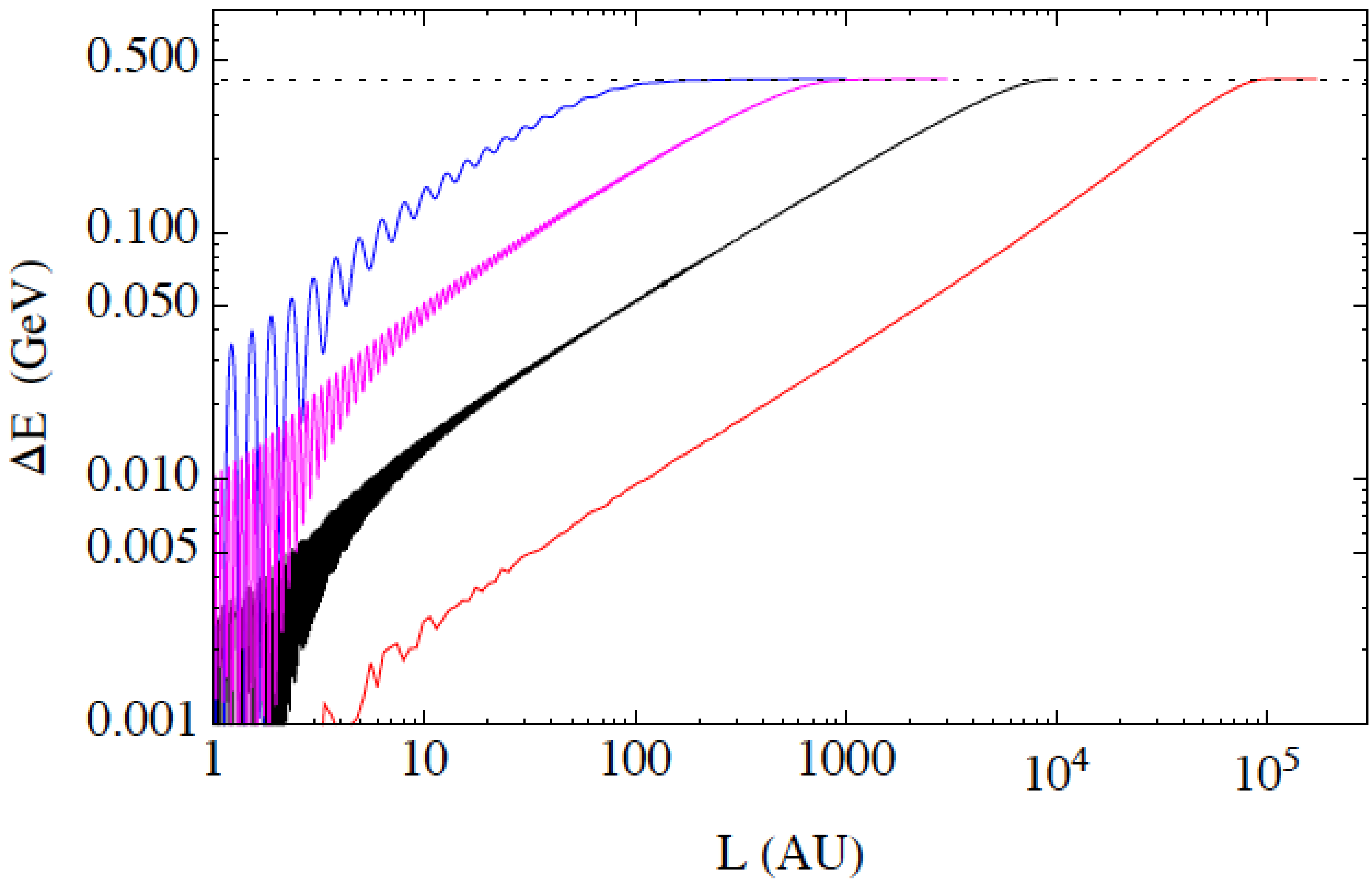
$$q\,A > 0$$





Stream-lines of the
“regular' Electric Field

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



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

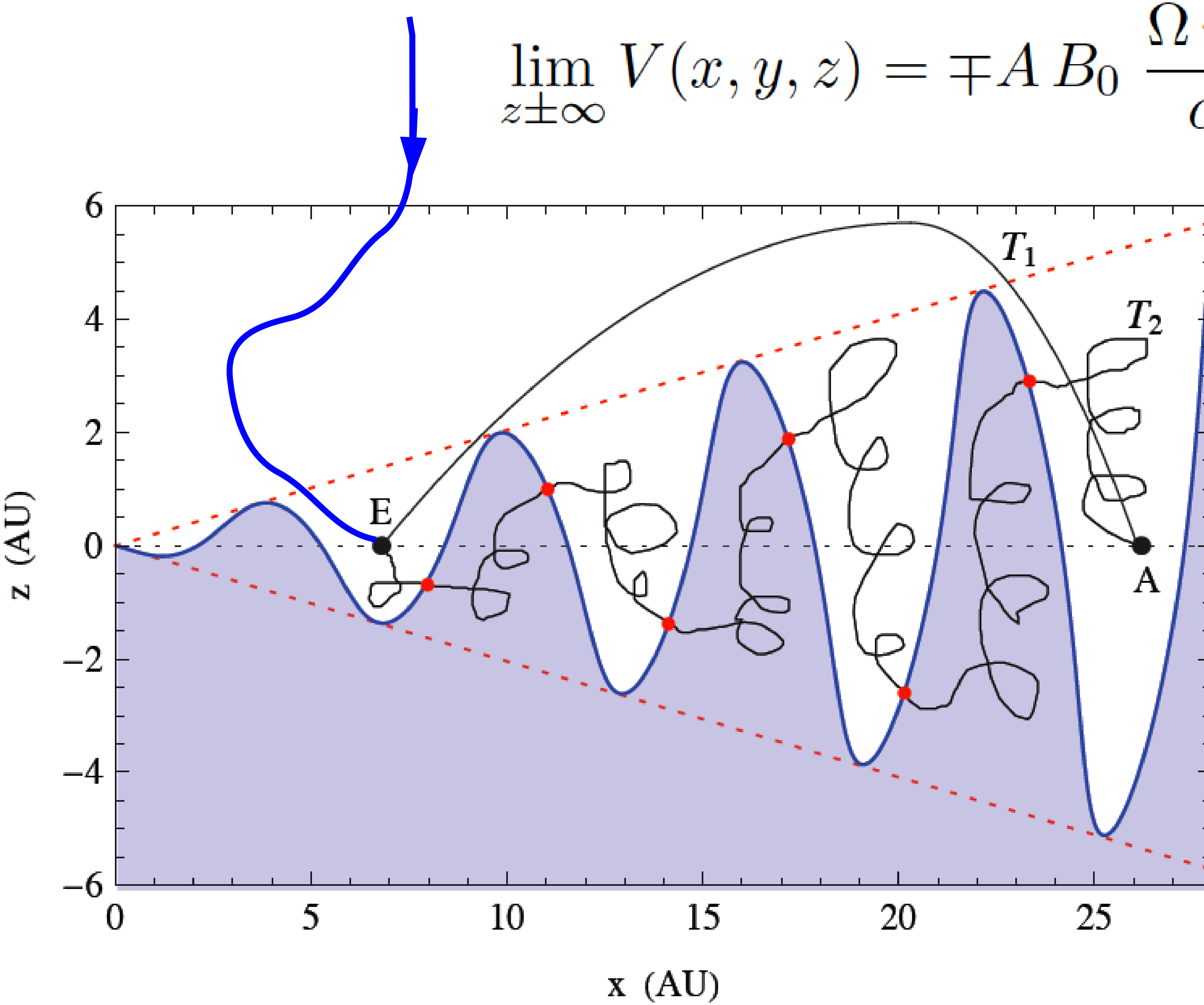
$$\vec{E}(x,y,z) = -\nabla V(x,y,z)$$

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

Trajectory that does not cross
the Heliospheric Current Sheet

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

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

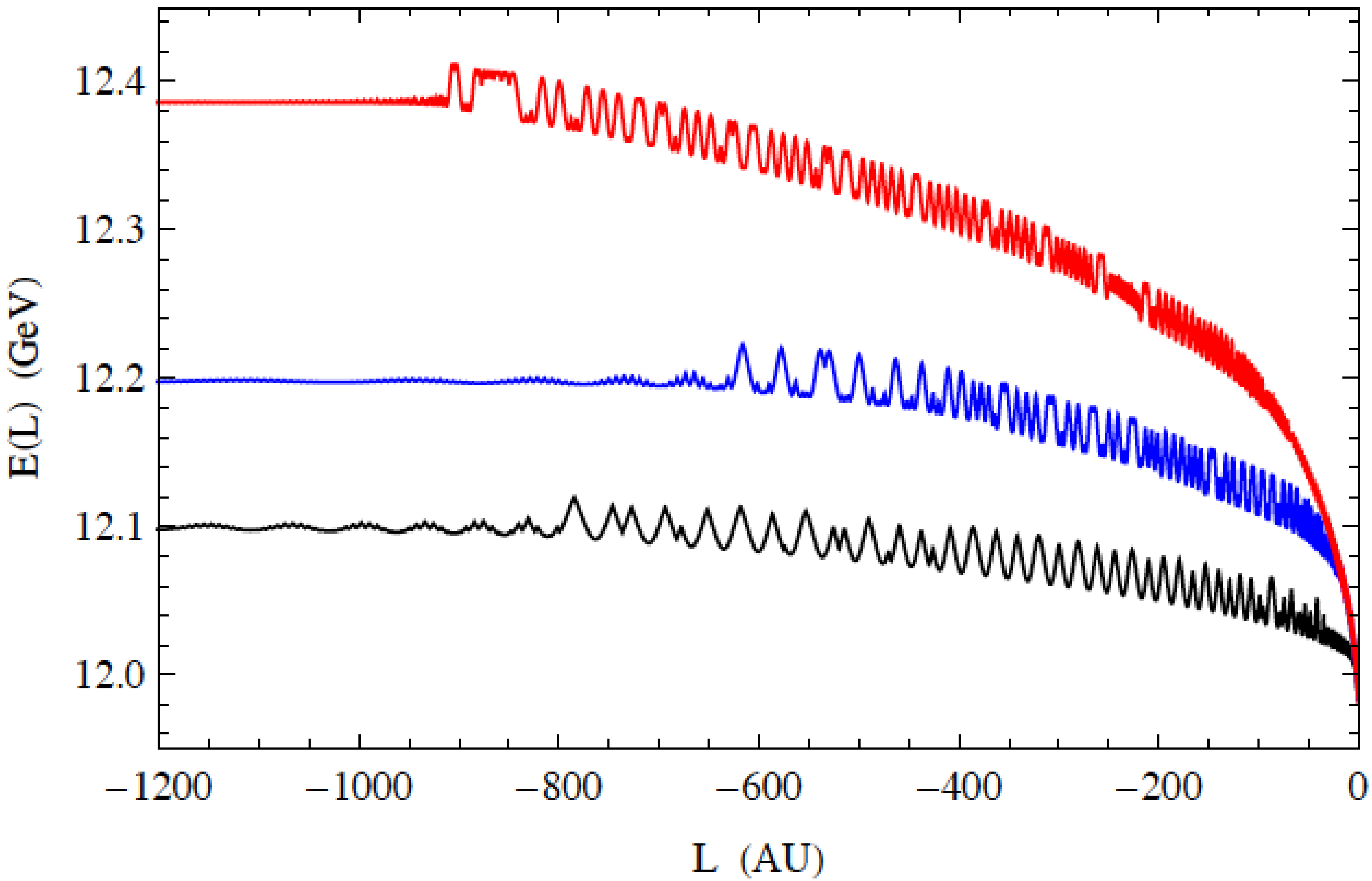


$$V(x,y,z=0) = 0$$

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

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

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)

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.

1. General Considerations.

2. Propagation of Cosmic Rays
   in the Heliosphere

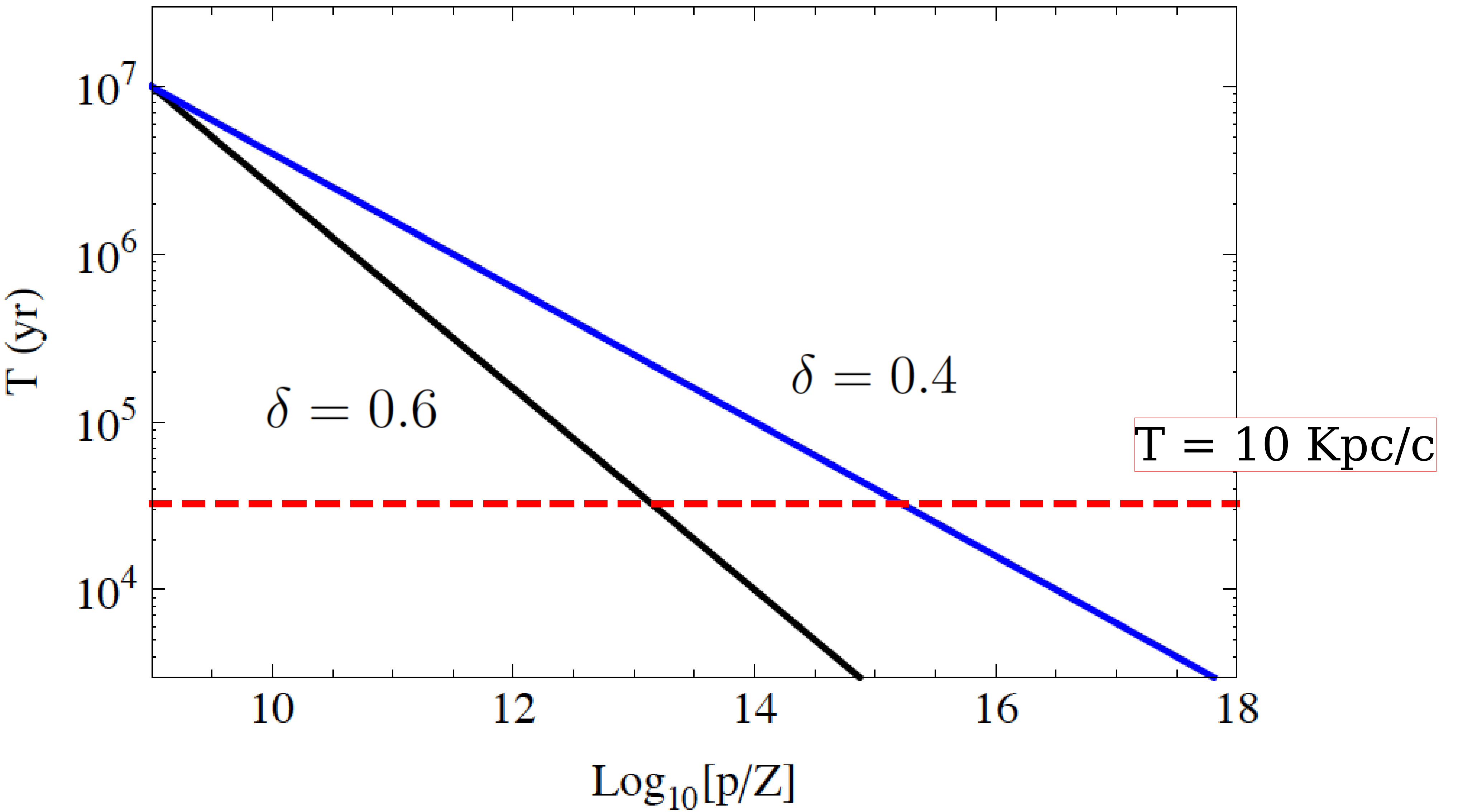
3. Structure of the Magnetic Field in the Milky Way

Difficulties of "diffusive models"
and a possible (very speculative) solution.

Confinement time as a function of rigidity (p/Ze)

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

Failure of a simple diffusion modeling for CR confinement and escape



$$E^* \simeq E_0\, Z \left(\frac{c\, z_h}{2\, D_0}\right)^{1/\delta}$$

$$E^* \simeq E_0\, Z \left(\frac{c\, T_0}{z_h}\right)^{1/\delta}$$

Energy where
The calculated escape time
is equal to the linear propagation
Time (at the speed of light)

$$E^* \simeq 3.7 \times 10^{15}\ Z \left[\frac{T(10\ \mathrm{GV})}{10\ \mathrm{Myr}}\right]^{\frac{1}{\delta}-\frac{1}{0.5}} \left[\frac{z_h}{5\ \mathrm{kpc}}\right]^{-\frac{1}{\delta}+\frac{1}{0.5}}\ \mathrm{eV}$$

$$E^* \simeq 3.7 \times 10^{15}\ Z \left[\frac{D(10\ \mathrm{GV})}{1.25\ \mathrm{kpc}^2\ \mathrm{Myr}^{-1}}\right]^{-\frac{1}{\delta}+\frac{1}{0.5}} \left[\frac{z_h}{5\ \mathrm{kpc}}\right]^{\frac{1}{\delta}-\frac{1}{0.5}}\ \mathrm{eV}$$

Anisotropies

“Dipole moment” of the angular distribution

$$\phi(E,\Omega) \simeq \phi_0(E) + \phi_1(E) \times cos\theta_{\hat{n}}$$

$$\Delta = \frac{\phi_{\rm max} - \phi_{\rm min}}{\phi_{\rm max} + \phi_{\rm min}} \simeq \frac{\phi_1}{\phi_0}$$

Homogeneous diffusion.
In the presence of a gradient of the particles there is a a net flux of particles across a surface:

$$\mathrm{flux}(\hat{u}, E) = -D(E)\, \vec{\nabla} n(E, \vec{x}) \cdot \hat{u}$$

$$\phi(\hat{u}) = \phi_0 + \phi_1 \; \hat{u} \cdot \hat{d}$$

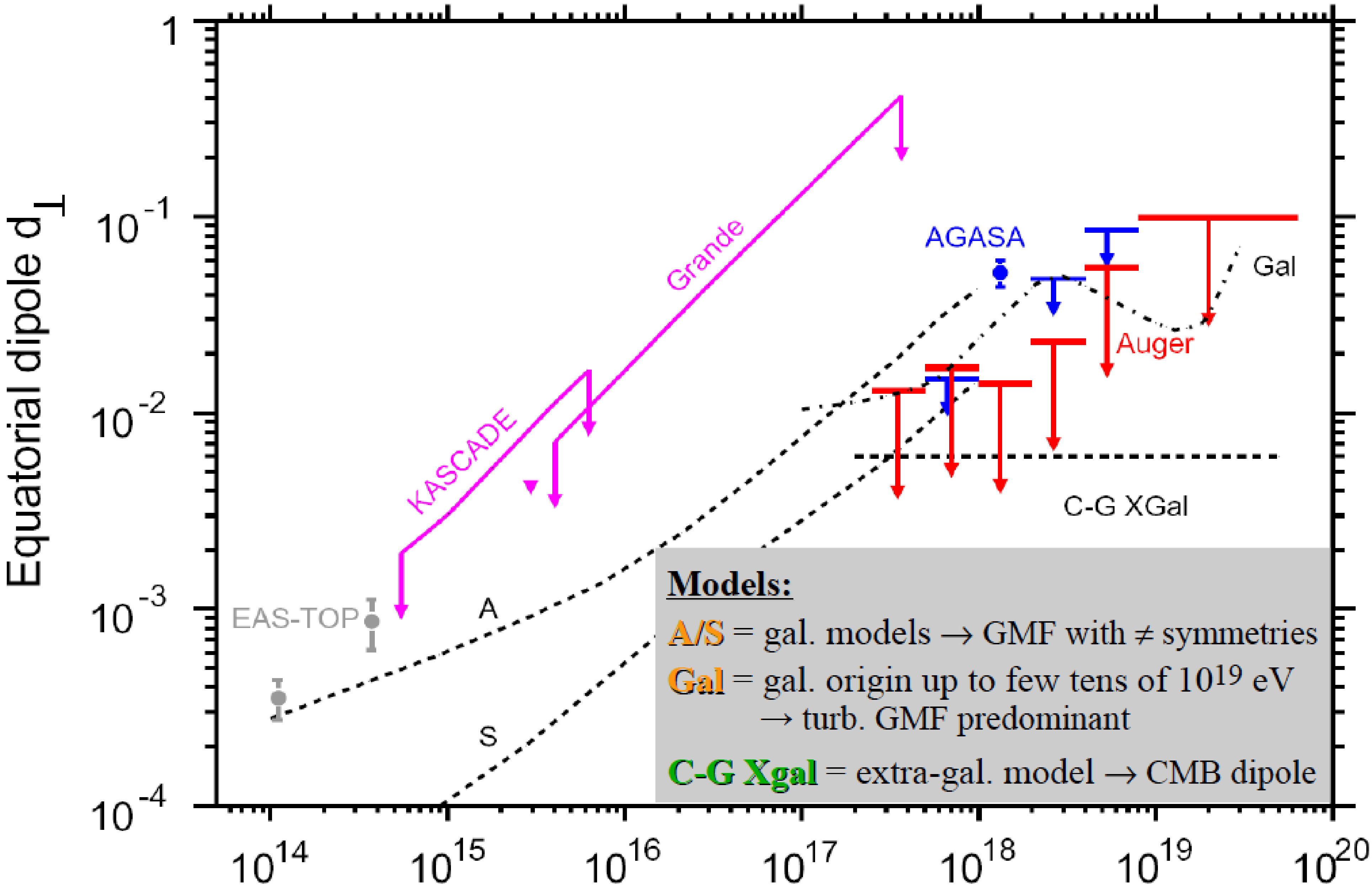
Isotropic component

Dipole component

$$\frac{\phi_1}{\phi_0} = \frac{3\, D(E, \vec{x})}{\beta\, c} \; \frac{|\nabla n(E, \vec{x}|}{n(E, \vec{x})}$$

AUGER

Upper limits



Magnetic Field of the Milky Way

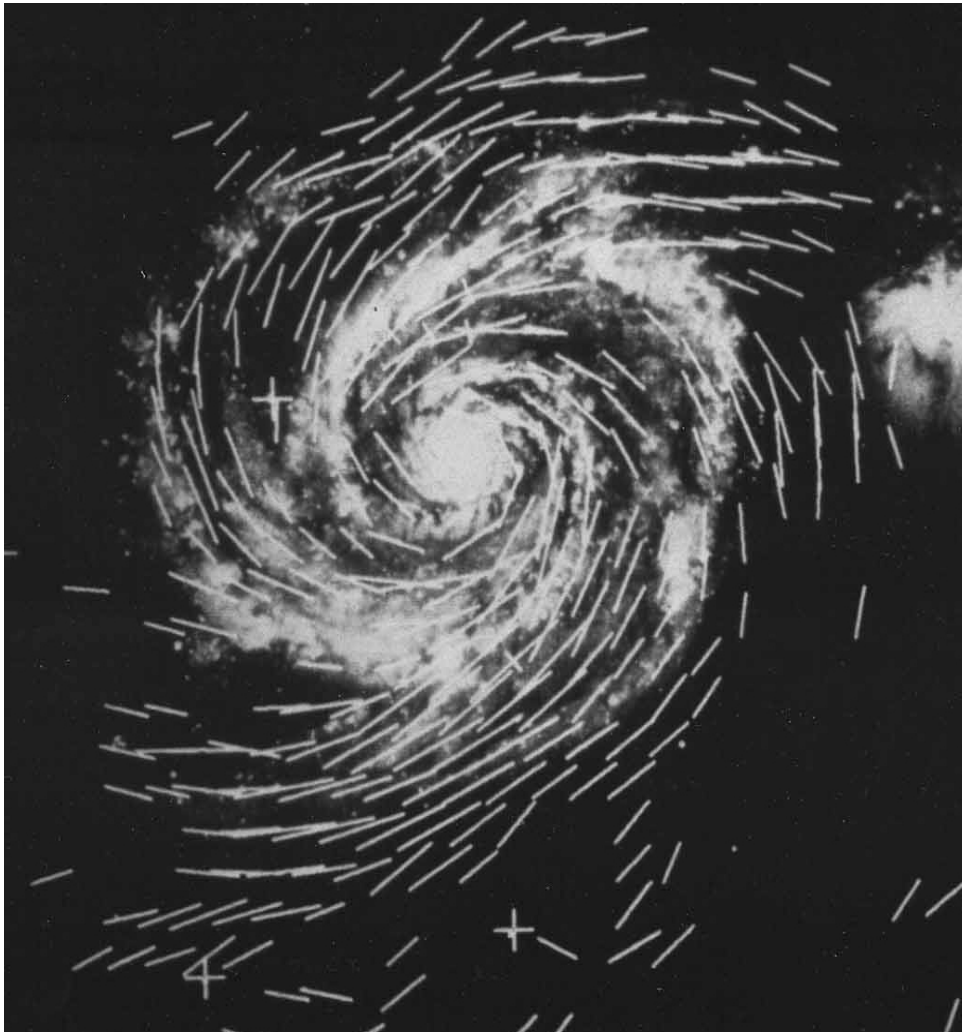
$$\vec{B} = \vec{B}_{\rm regular} + \vec{B}_{\rm random}$$

"Regular Field"

(Global structure)

"Random Field"

(associated with turbulent motions
in the interstellar plasma)



Magnetic fields of different galaxies

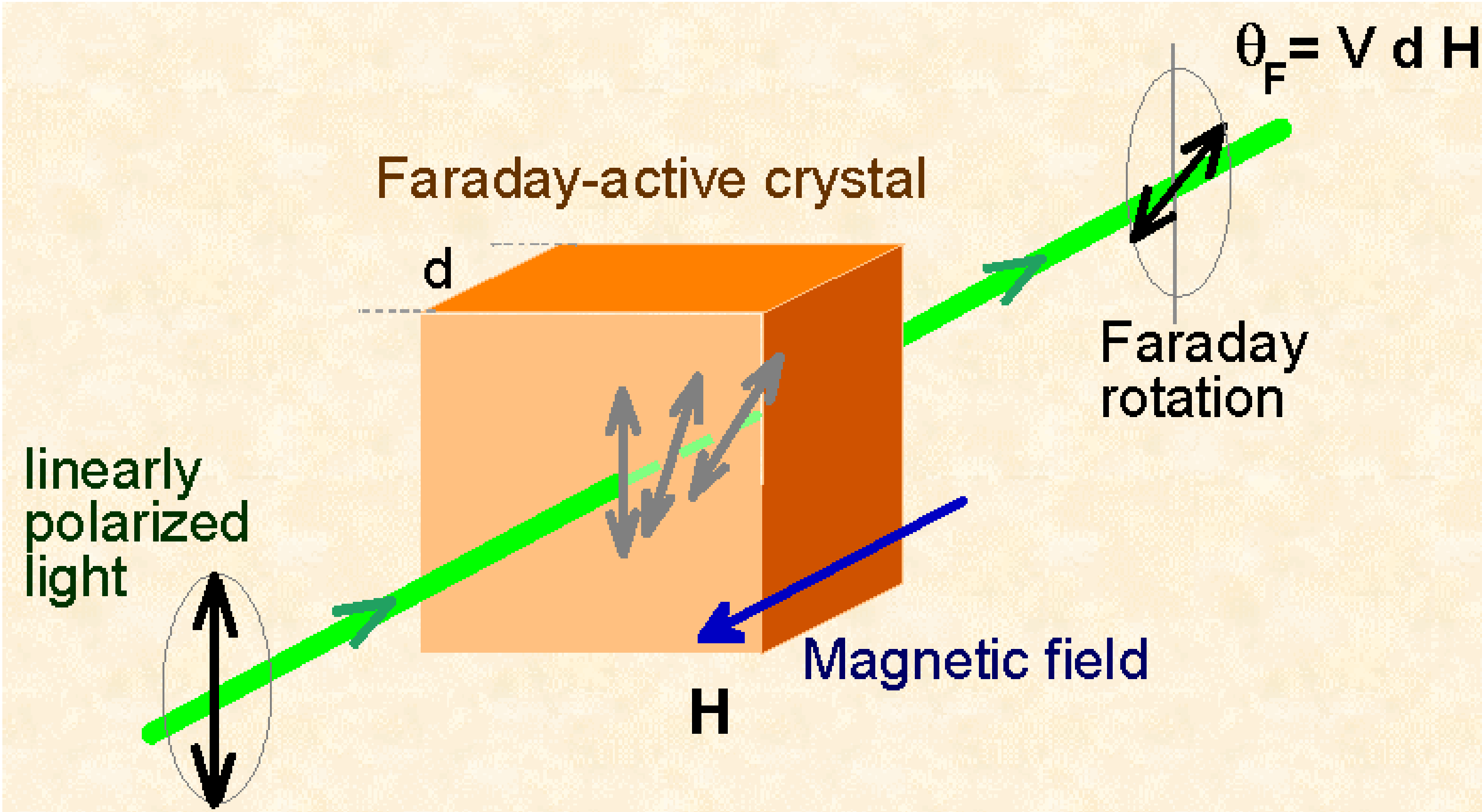
Measurements Methods for the magnetic field in Astronomy:

Zeeman effect

Faraday Rotation

Stellar Polarimetry

Synchrotron Radiation



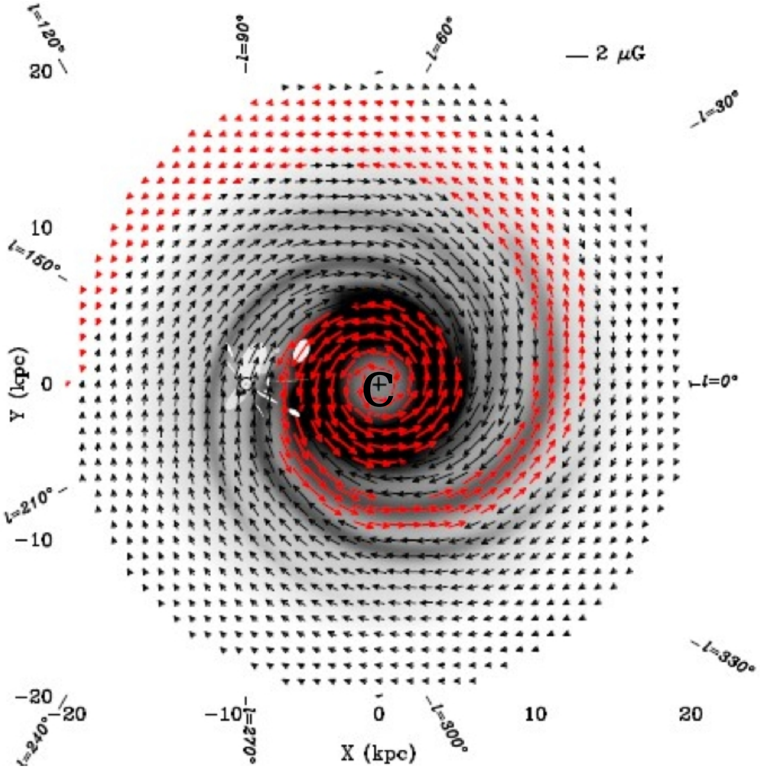
$$\varphi = \frac{e^3 \lambda^2}{2\pi m_e^2 c^4} \int_0^{\ell} d\ell' \; n_e(\ell') \; B_{||}(\ell')$$

Magnetic field in the galactic plane is of order
<B> = few (5-10) microGauss,
with approximate equal contributions of the
Regular and Random fields.

The regular field in the galactic plane
has a spiral pattern with a pitch angle
similar to what is seen in optical observations.

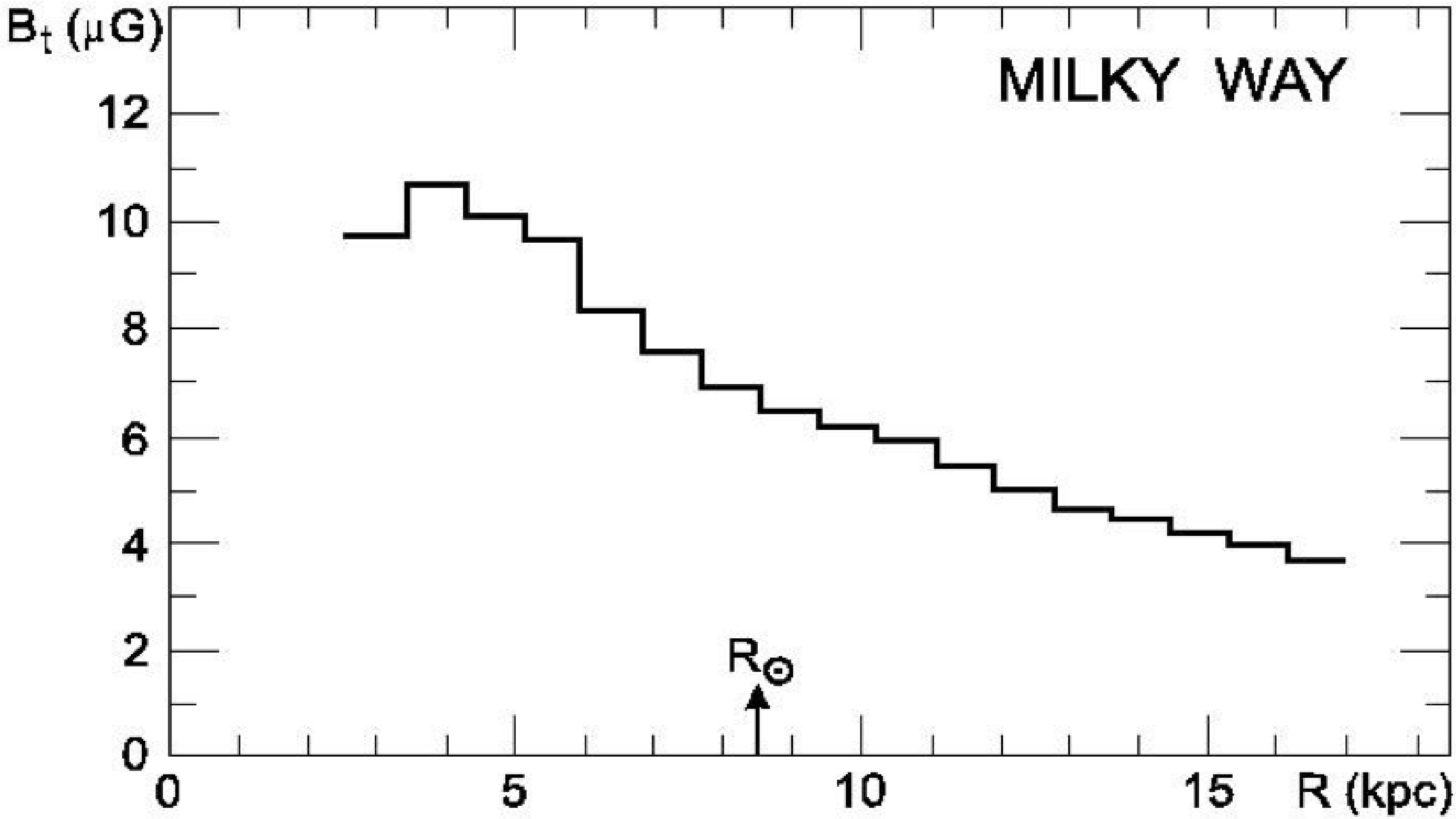
The Field direction reverses
with regions where
the field is "in" and "out"

Extended halo with
very poorly known properties.



Equipartition field in the Milky Way

(Berkhuijsen, in Wielebinski & Beck 2005)

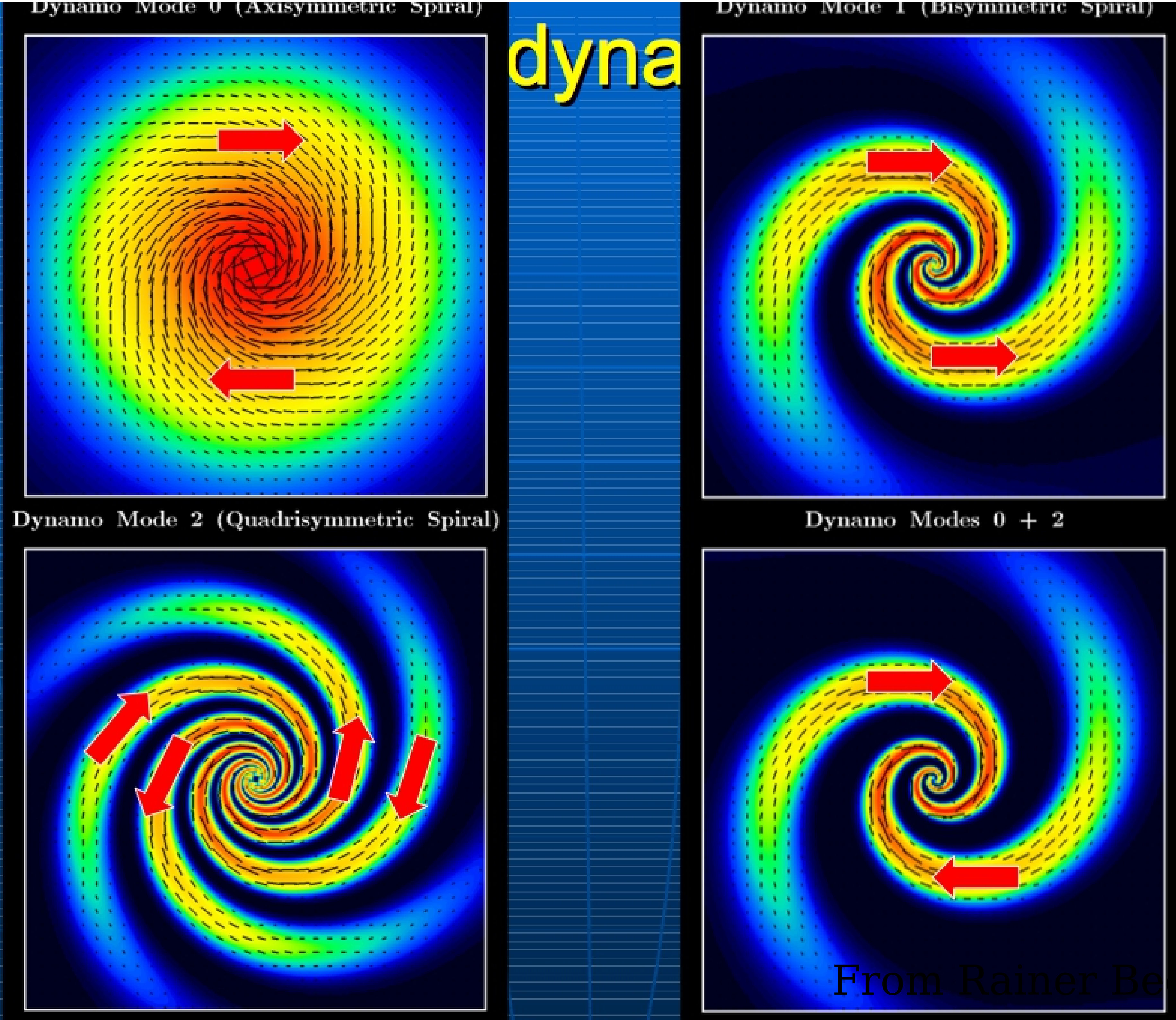


Consistent with estimates from γ rays

(Strong et al. 2000)

From Rainer Beck

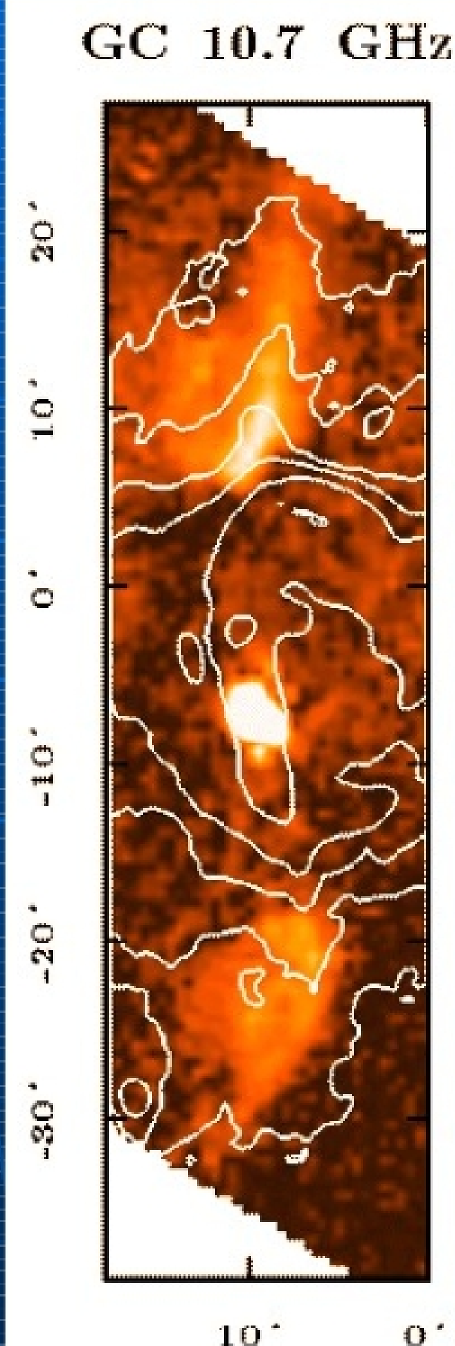
dyna

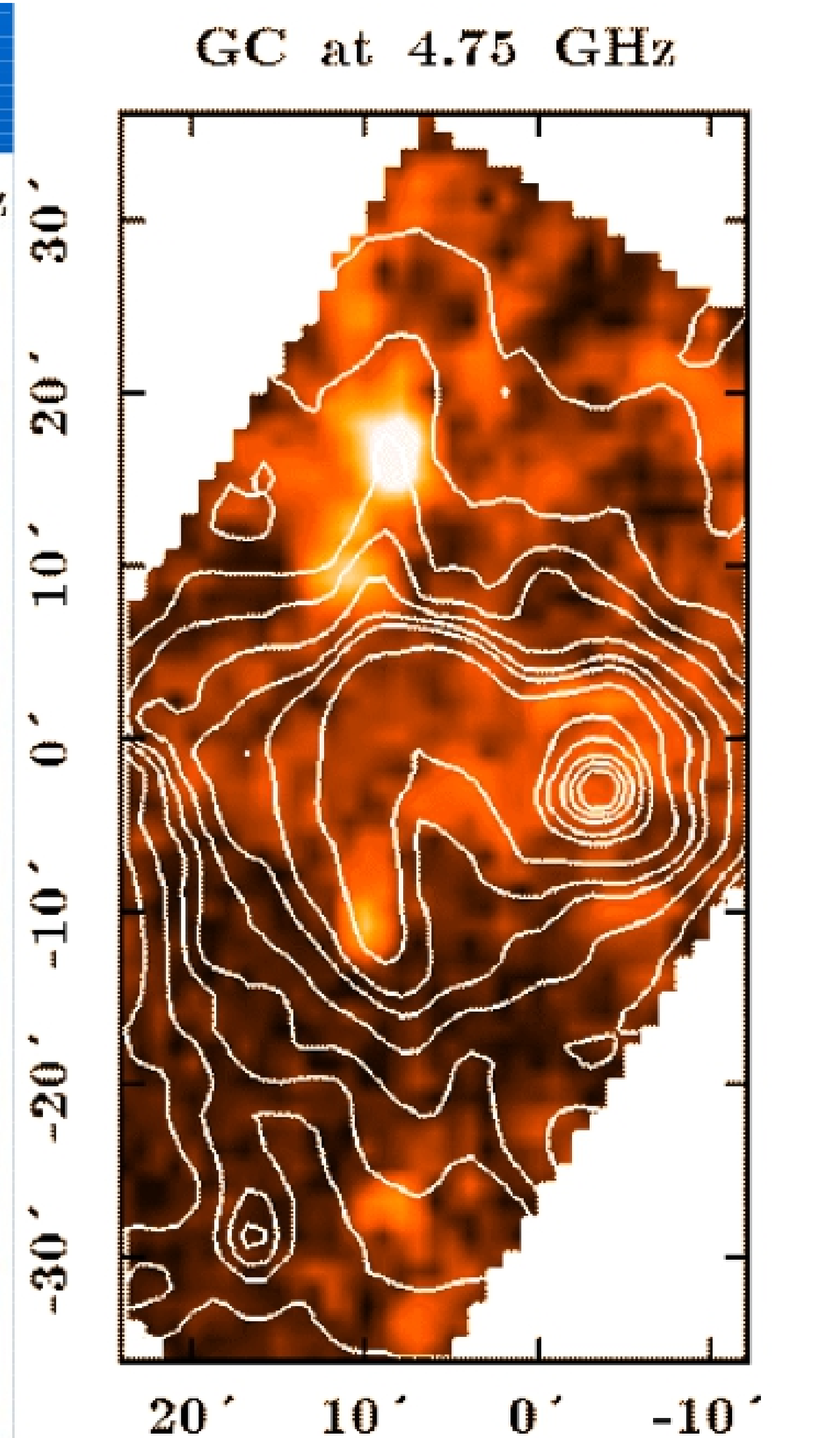


From Rainer Beck

Galactic center

Effelsberg
2.8 + 6cm
(Reich, priv. comm.)



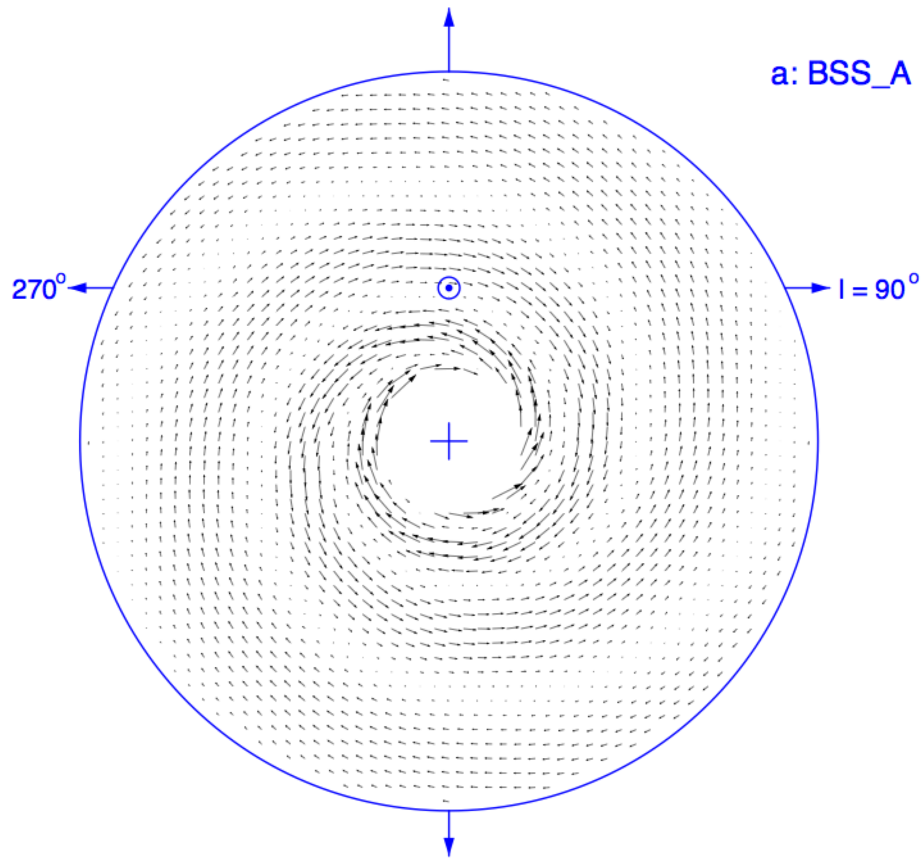


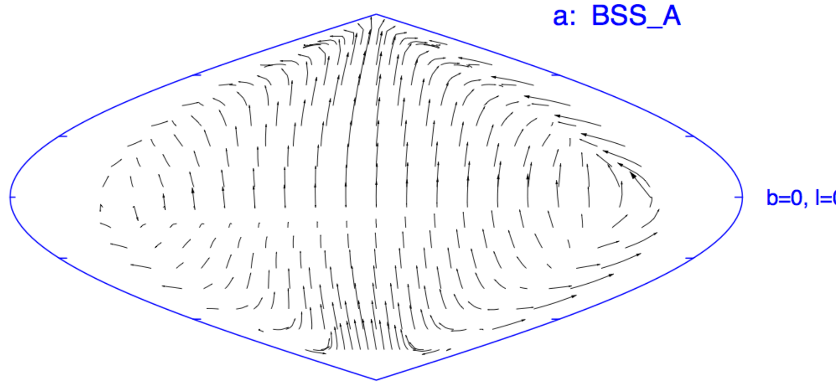
RMs of +/- several 1000 rad/m² :

Regular fields of several 100 μG !

Ultra High Energy Cosmic Rays and the Large Scale Structure of the Galactic Magnetic Field (ApJ 1996)

Todor Stanev





Deviation map

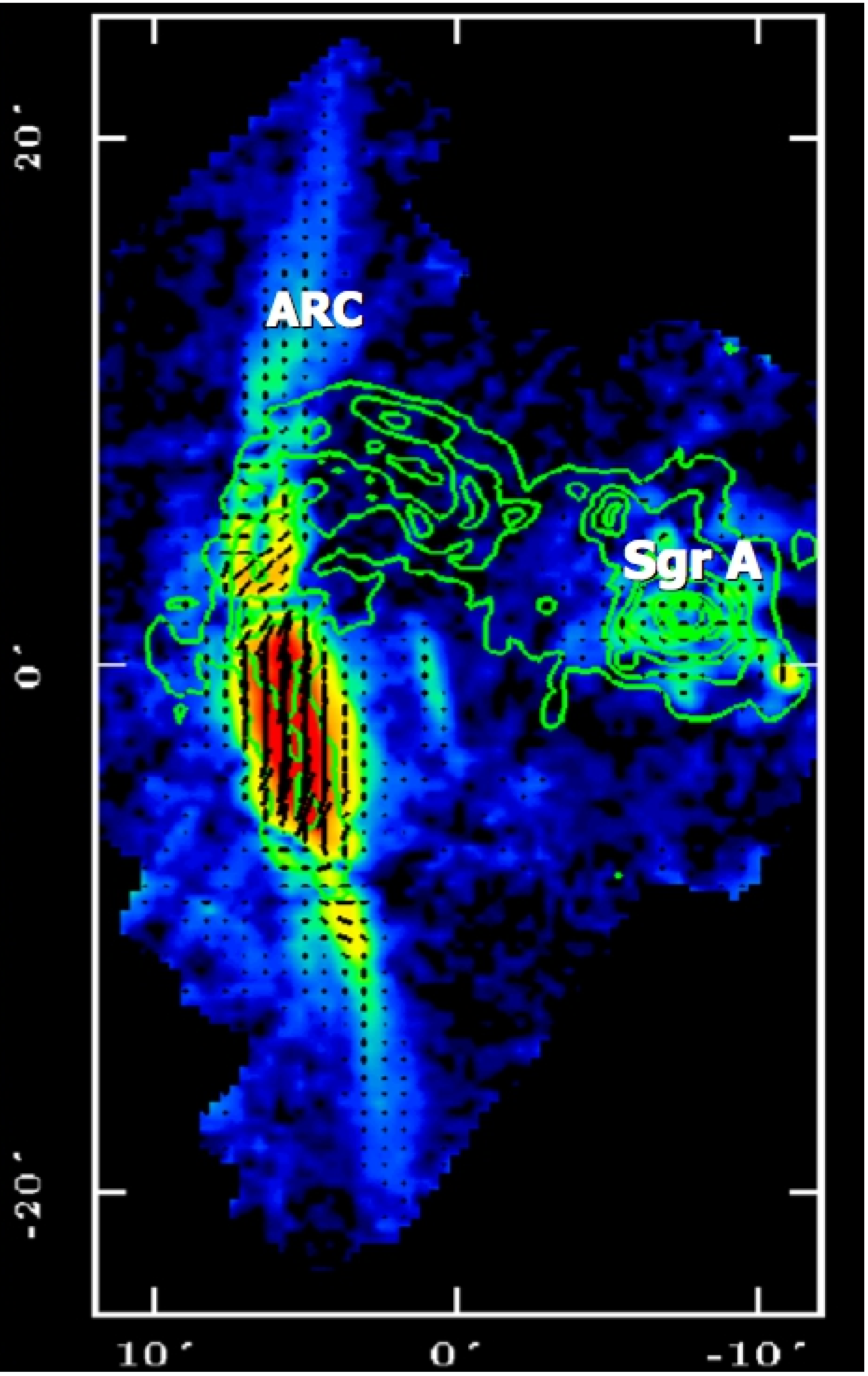
$$B(r,\theta) = B_0(r)\cos(\theta - \beta \ln \frac{r}{r_0})$$

Galactic center

Effelsberg 9mm
Total + pol. int.
(Reich, priv. comm.)

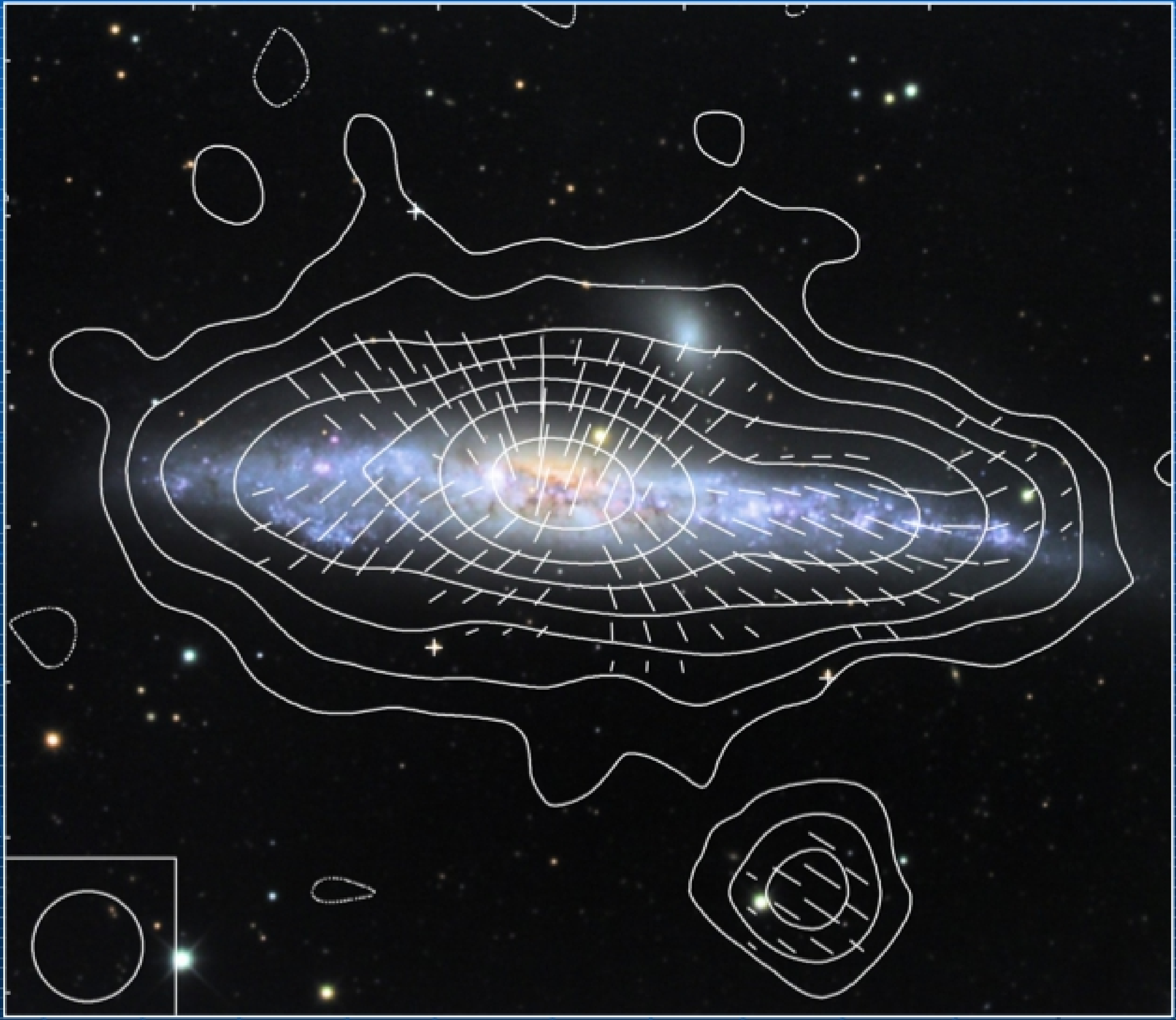
Percentage polarization up to ~60% :

Almost totally aligned field, perpendicular to plane



NGC 4631

Effelsberg 3.6cm
Total intensity
+ B-vectors
(Krause & Dumke)

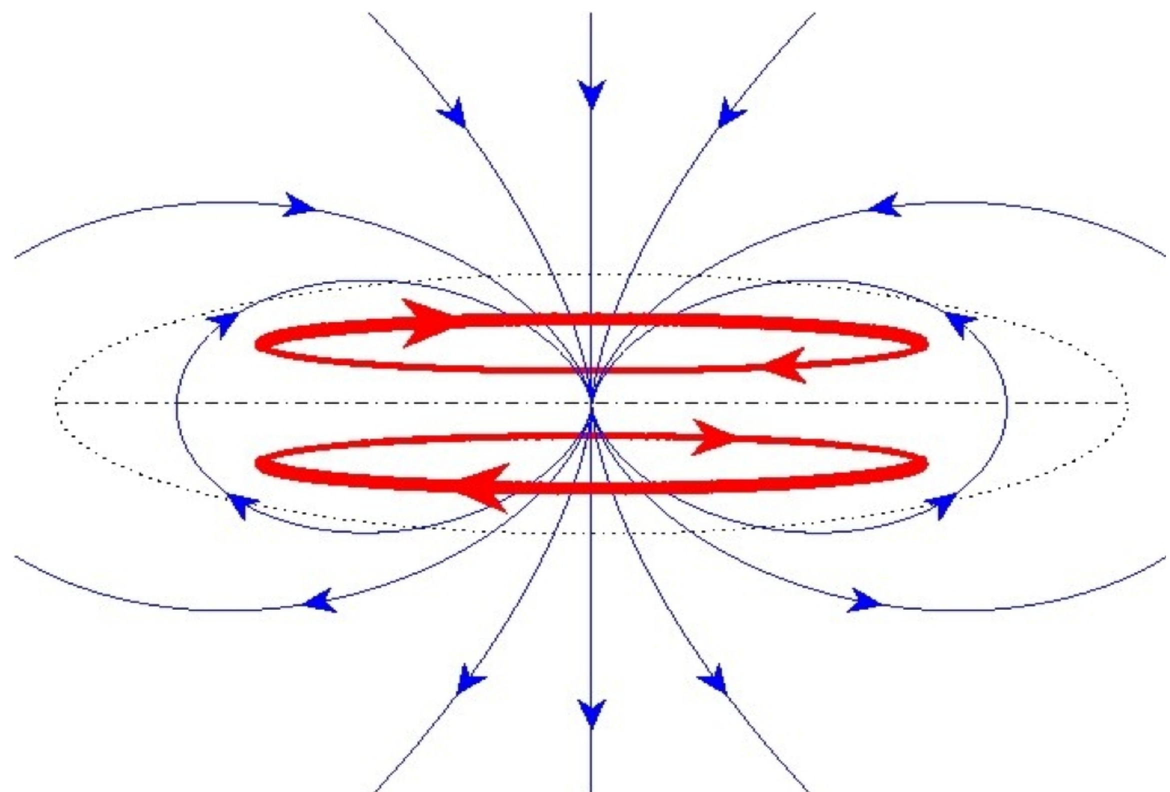


Huge halo with exceptionally large scale height and strong vertical field

J. L. Han, R. N. Manchester and G. J. Qiao, "Pulsar rotation measures and the magnetic structure of our galaxy," MNRAS **306**, 371, (1999), [astro-ph/9903101].

The galactic vertical magnetic field in the vicinity of the Solar System is of order 0.2-0.3 microGauss, and directed from the South galactic Pole to the North Galactic Pole.

"This field could be the manifestation of a global dipolar field"

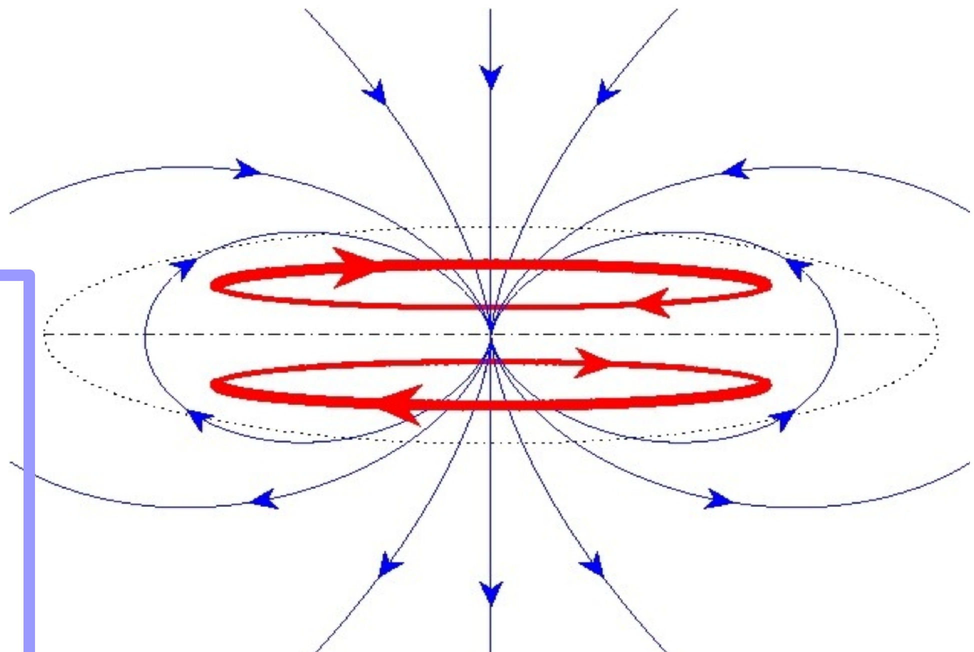


J. L. Han, R. N. Manchester and G. J. Qiao, "Pulsar rotation measures and the magnetic structure of our galaxy," MNRAS **306**, 371, (1999), [astro-ph/9903101].

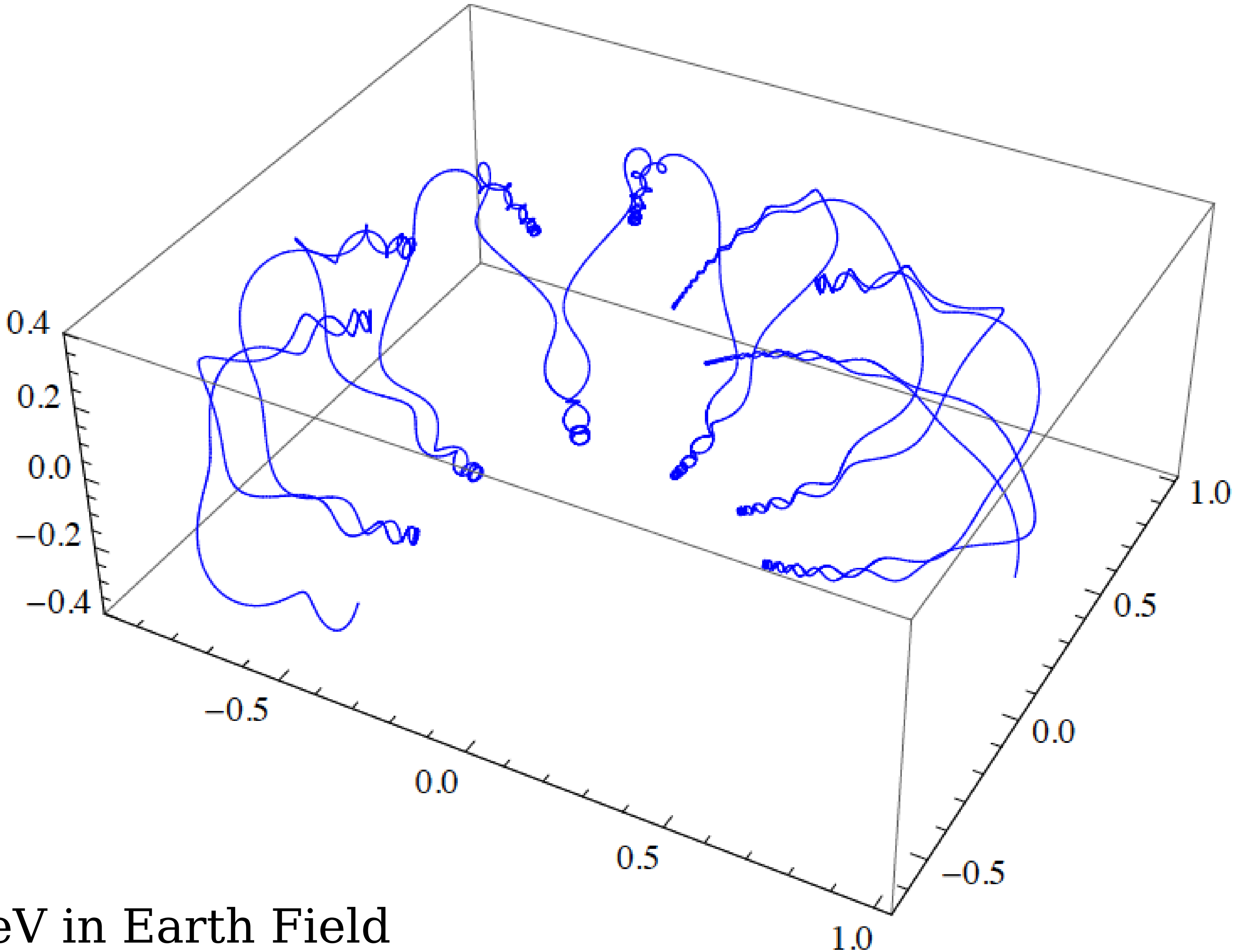
The galactic vertical magnetic field in the vicinity of the Solar System is of order 0.2-0.3 microGauss, and directed from the South galactic Pole to the North Galactic Pole.

"This field could be the manifestation of a global dipolar field"

IF the Milky Way
Magnetic field has a dipole
As large as suggested above
What are the consequences ?

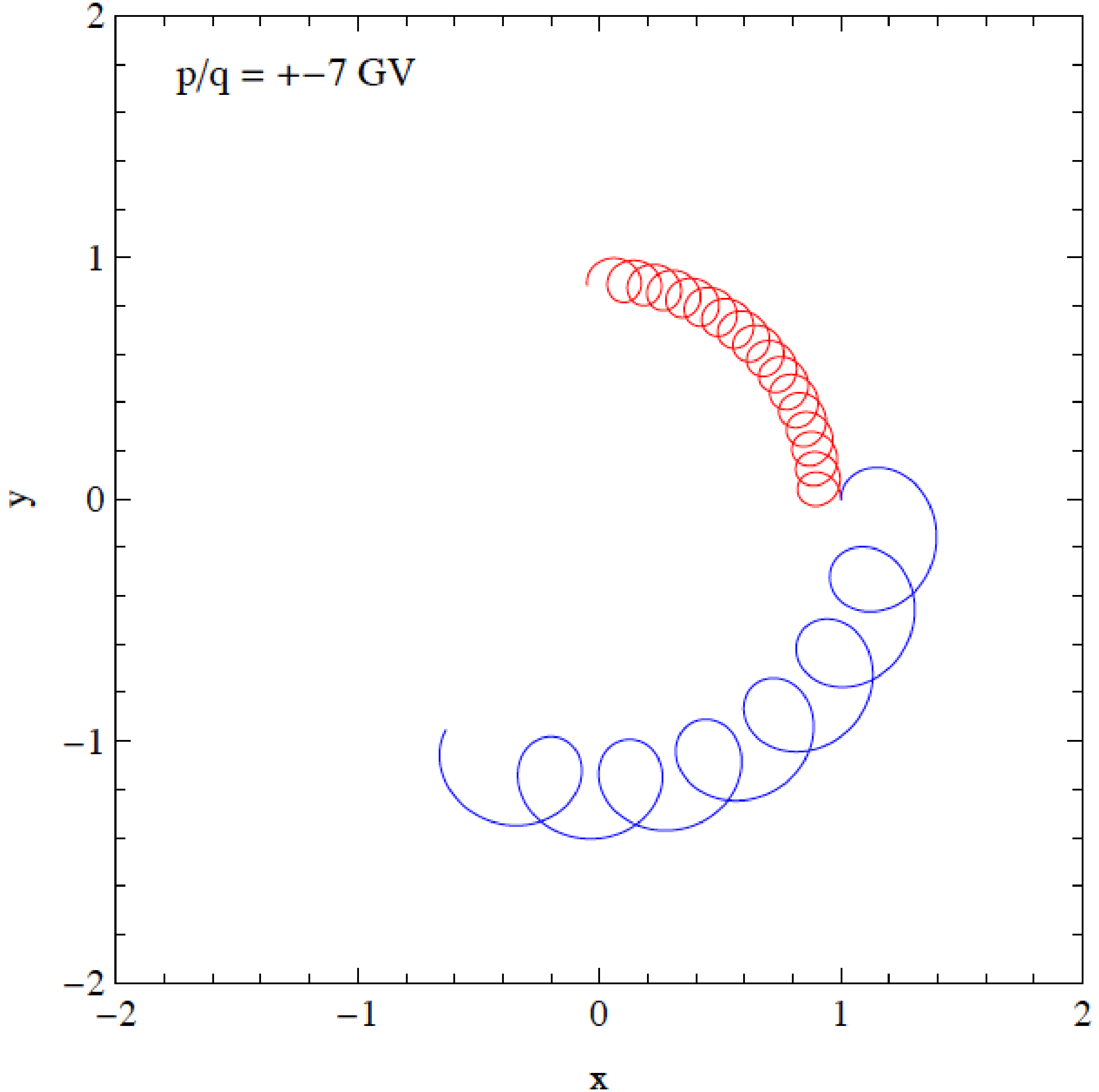


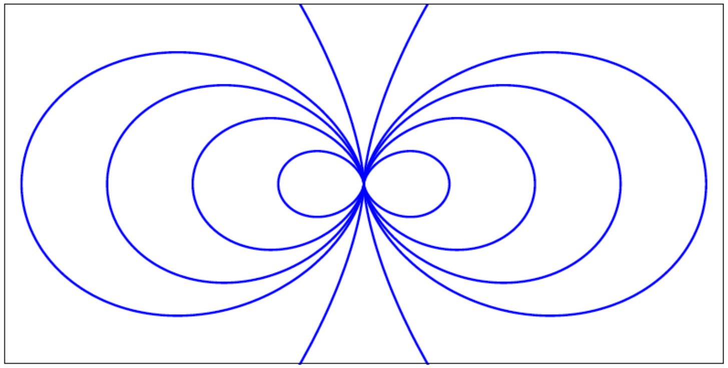
Confinement of cosmic rays in the Earth dipole.

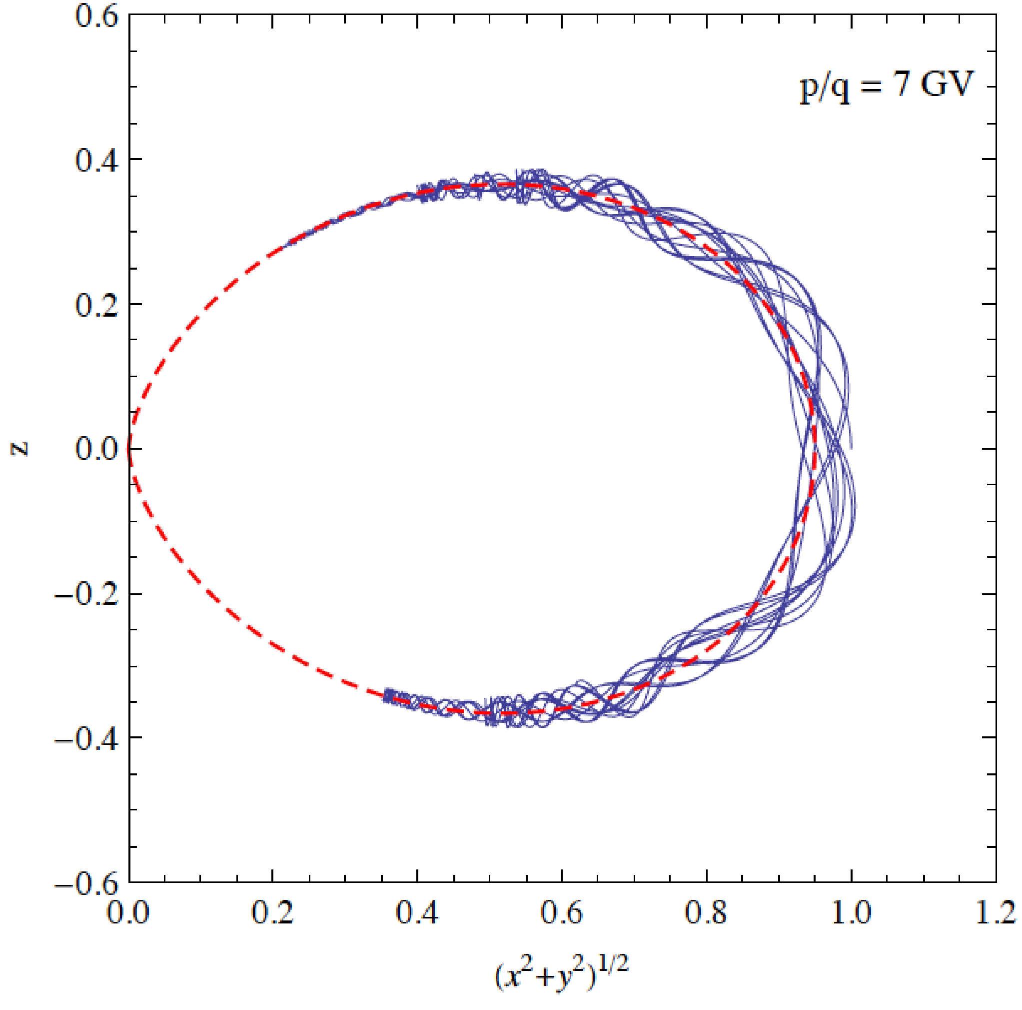


7 GeV in Earth Field

Equatorial plane of a dipole field

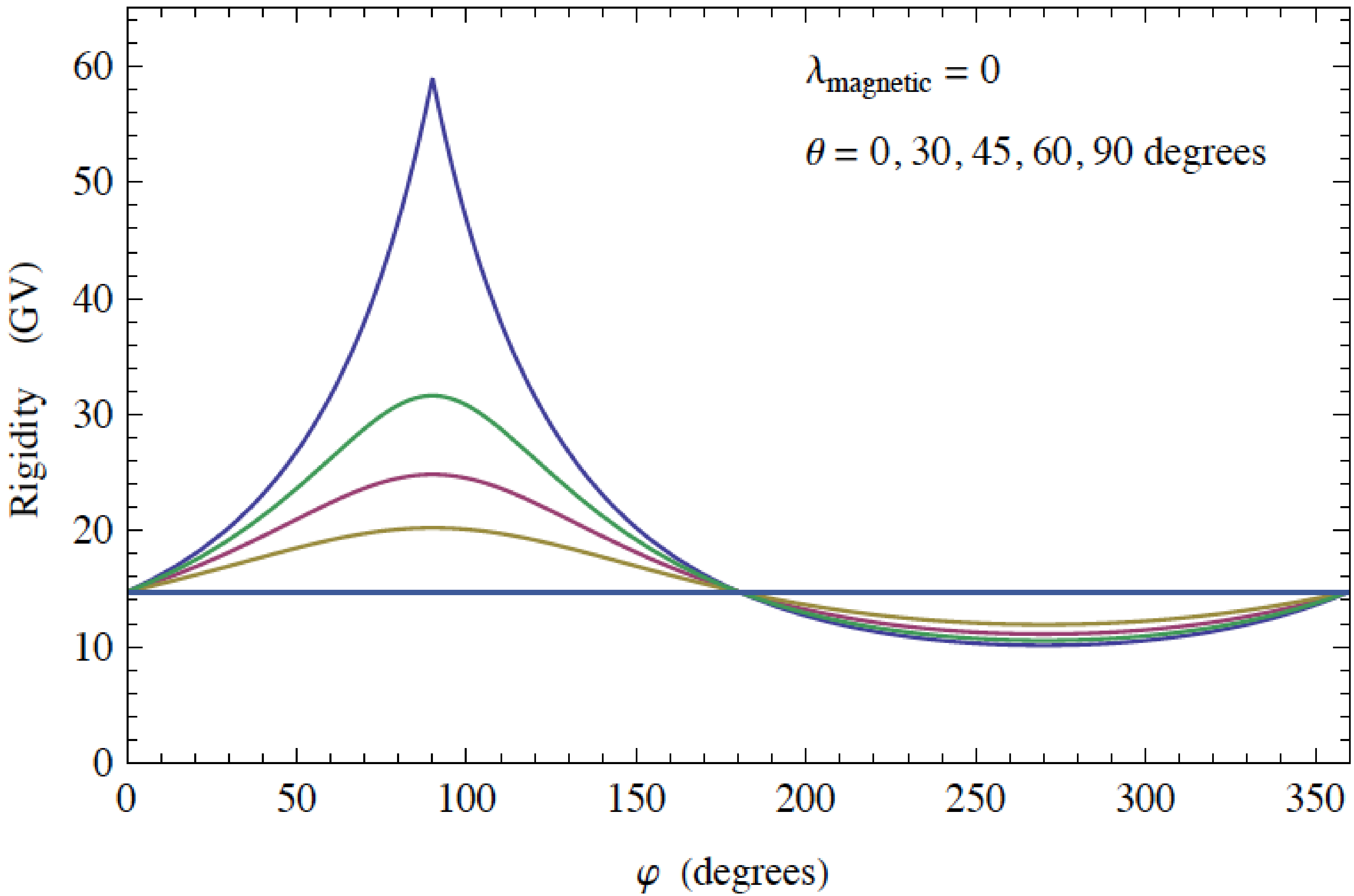






p/q = 7 GV
z
$(x^2+y^2)^{1/2}$
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
0.0
0.2
0.4
0.6
0.8
1.0
1.2

$$\left(\frac{p}{q}\right)^* = \frac{M}{r^2}\left[\frac{\cos^4\lambda}{(1+\sqrt{1-\cos^3\lambda\cos b\sin\ell})^2}\right]$$



$$M = B_{\odot z}\, r_\odot^3$$

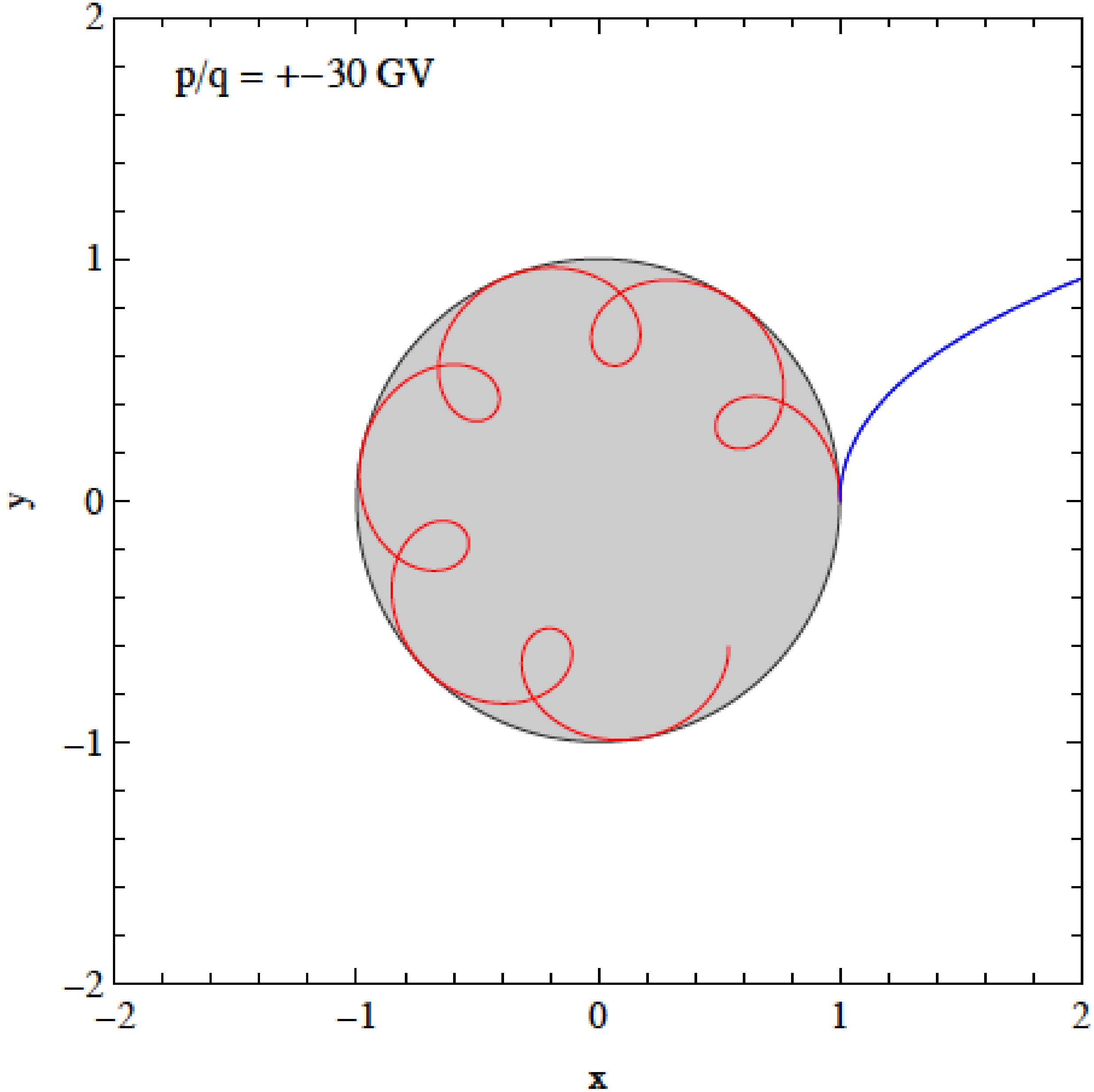
Dipole Magnetic Moment

$$E^* = q_e\, B_{\odot z}\, r_\odot = q_e \frac{M}{r_\odot^2} \simeq 1.57 \times 10^{18} \left(\frac{B_{\odot,z}}{0.2\ \mu\text{G}} \right) \text{ eV}$$

$$e\, B_{\oplus,\text{eq}}\, R_\oplus \simeq 59 \text{ GeV}$$

$$e\, B_{\odot,z}\, r_\odot \sim 1.5 \times 10^{18} \text{ eV}$$

On the Earth, strong anisotropy due to the dipole field (East-West effect)



$$\Omega_{\rm bounce} = \frac{3}{\sqrt{2}} \frac{\beta\, c}{r}$$

Main component of motion for trapped Particles

$$\Omega_{\rm drift} = \frac{3}{2} \frac{\beta\, c\, p\, r}{Z\, e\, B_{\odot,z}\, r_{\odot}^{3}}$$

Bounce + Azimuthal drift

$$T_{\rm bounce} = \frac{2\pi}{\Omega_{\rm drift}} \simeq 0.08 \ {\rm Myr}$$

$$T_{\rm drift} = \frac{2\pi}{\Omega_{\rm drift}} \simeq 180 \ Z \ \left(\frac{10^{15} \ {\rm eV}}{E}\right) \ \left(\frac{B_{\odot z}}{0.2 \ \mu \ {\rm G}}\right) \ {\rm Myr}$$

Can the global structure of the Milky Way magnetic field play (especially dipole, and quadrupole component) Play a significant role in the confinement of the highest energy cosmic rays ?

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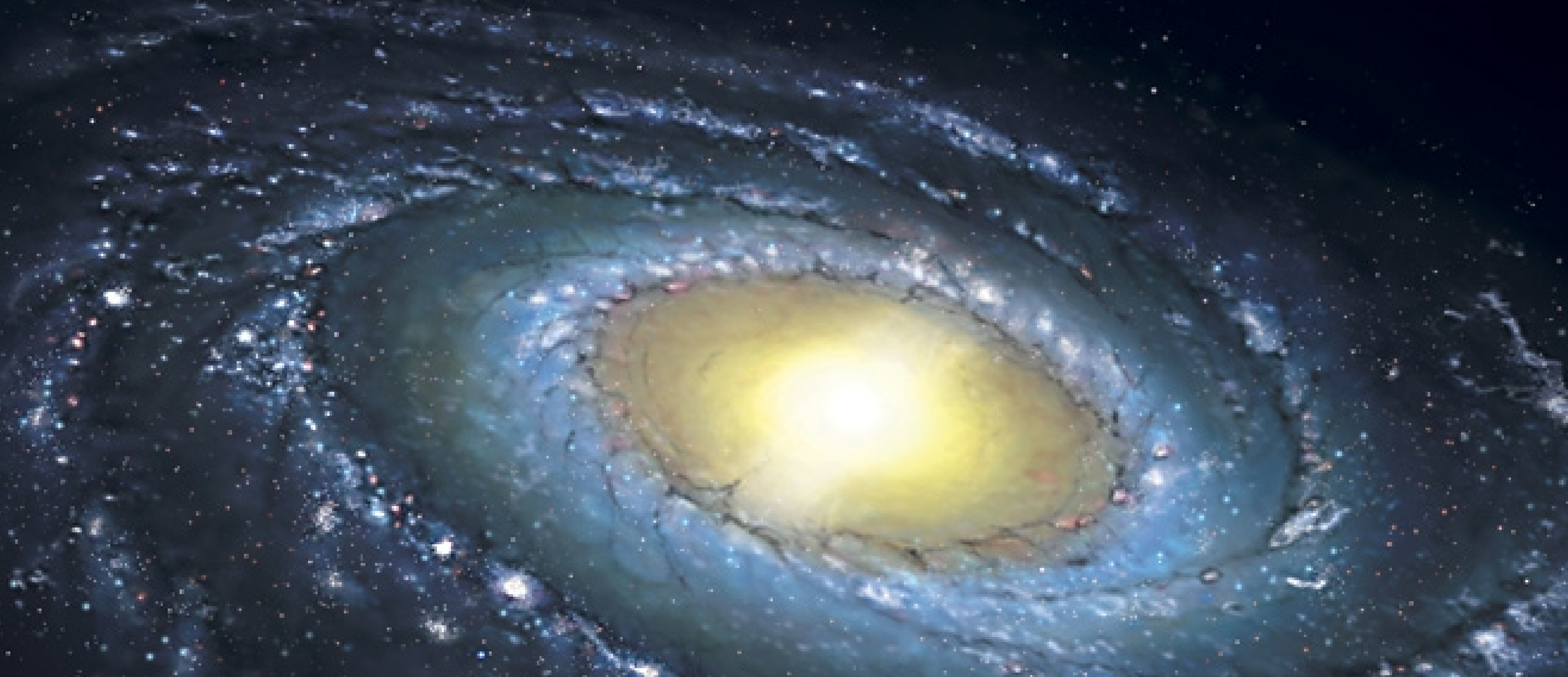
One could speculate that the spectral features of the Cosmic Ray energy spectrum are the imprints of propagation on an injection spectrum a smooth (approximate) power law.

[“wild speculation”]
The KNEE could be the manifestation of the transition of a propagation controlled by diffusion (at low rigidity), and propagation controlled by the global structure of the magnetic field (at high rigidity)

High Energy Astrophysics is a vibrant field with exciting perspectives.



Thanks for the possibility to discuss
These perspectives with you
in this beautifil place