Interpretation of the electrons and positron CR spectra

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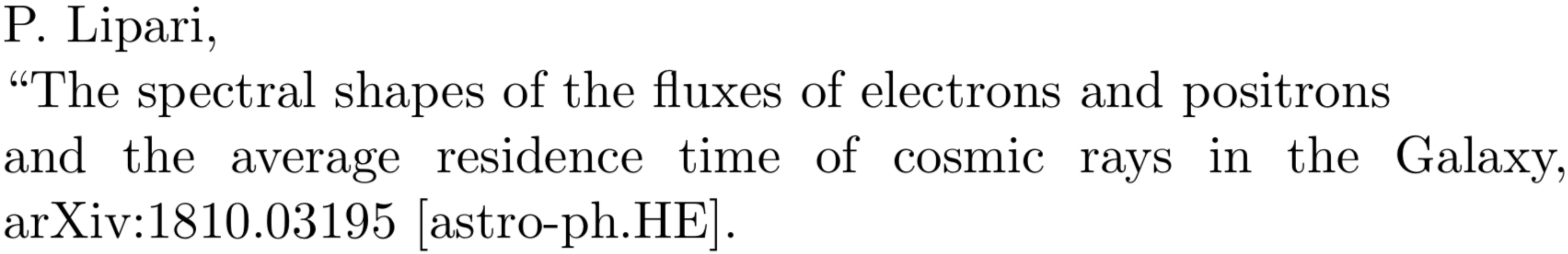
Workshop: Searching for the Sources
of Galactic Cosmic Rays

Paris December 11th 2018

Part of this contribution is based on:



P. Lipari,
“The spectral shapes of the fluxes of electrons and positrons and the average residence time of cosmic rays in the Galaxy,” arXiv:1810.03195 [astro-ph.HE].

Measurements of
at the Earth:

Cosmic Rays

$$\phi_p(E,\Omega)\ ,\quad \phi_{\rm He}(E,\Omega)\ ,\quad \ldots\ ,\quad \phi_{\{\rm A,Z\}}(E,\Omega)$$

protons+ nuclei

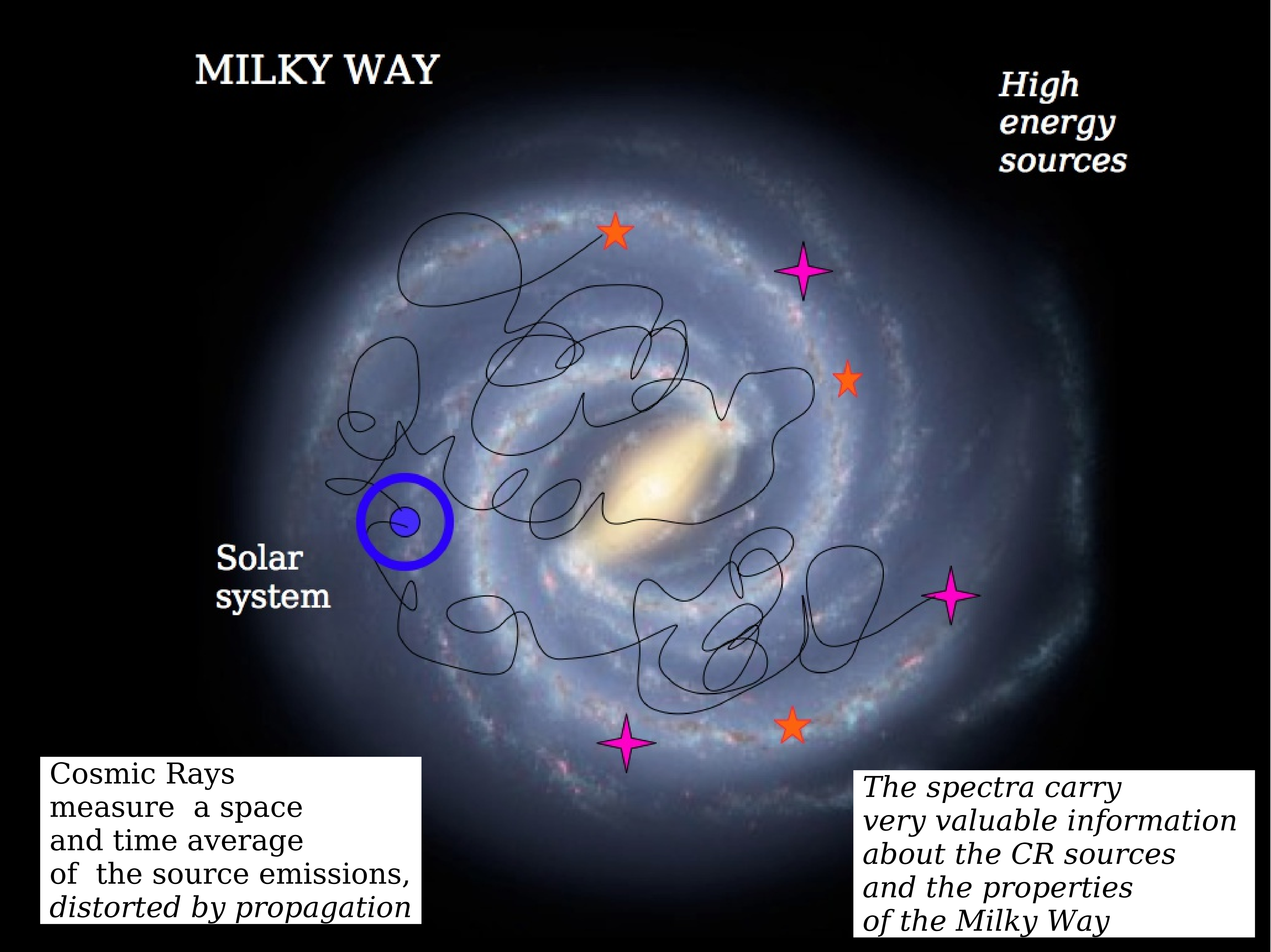
$$\phi_{e^-}(E,\Omega)$$

electrons

$$\phi_{e^+}(E,\Omega)$$

$$\phi_{\overline{p}}(E,\Omega)$$

anti-particles

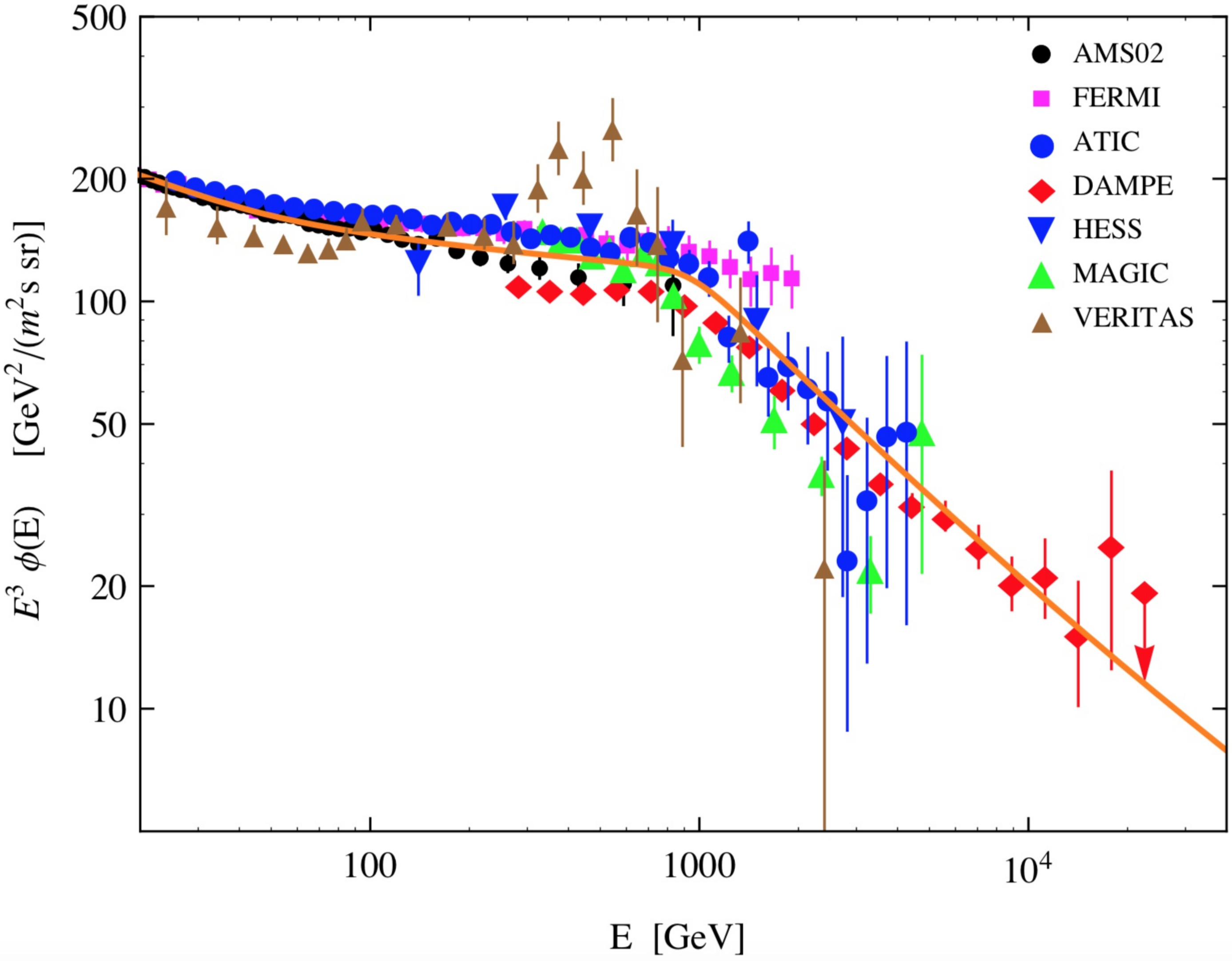


Cosmic Rays
measure a space
and time average
of the source emissions,
distorted by propagation

The spectra carry
very valuable information
about the CR sources
and the properties
of the Milky Way

All electron spectrum $(e^- + e^+)$

Remarkable discovery of Cherenkov telescopes confirmed by satellites

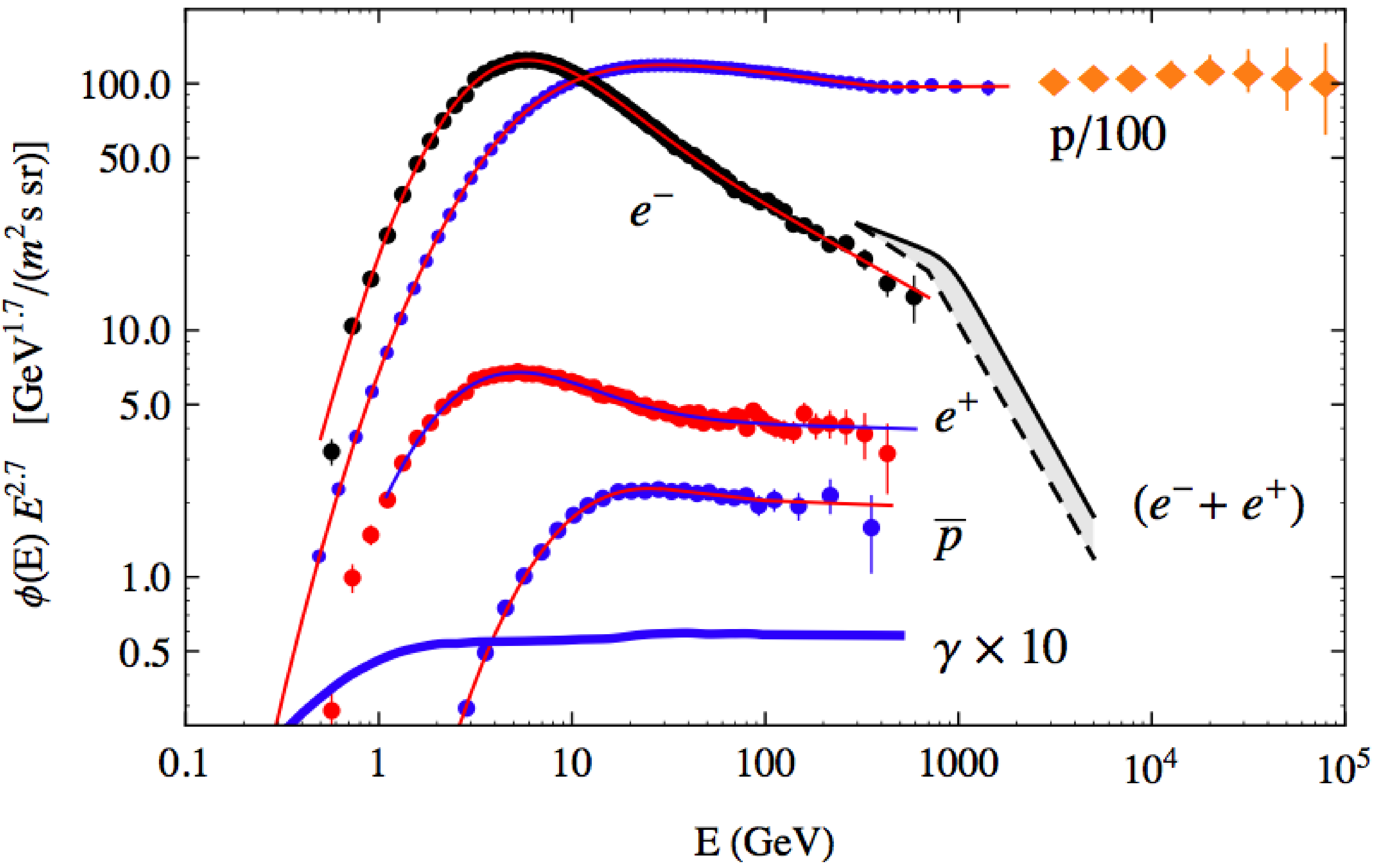


Understanding this spectral structure is *crucial*

Essential to study the electron, and positron spectra together the spectra of other (nuclear) Cosmic Ray particles

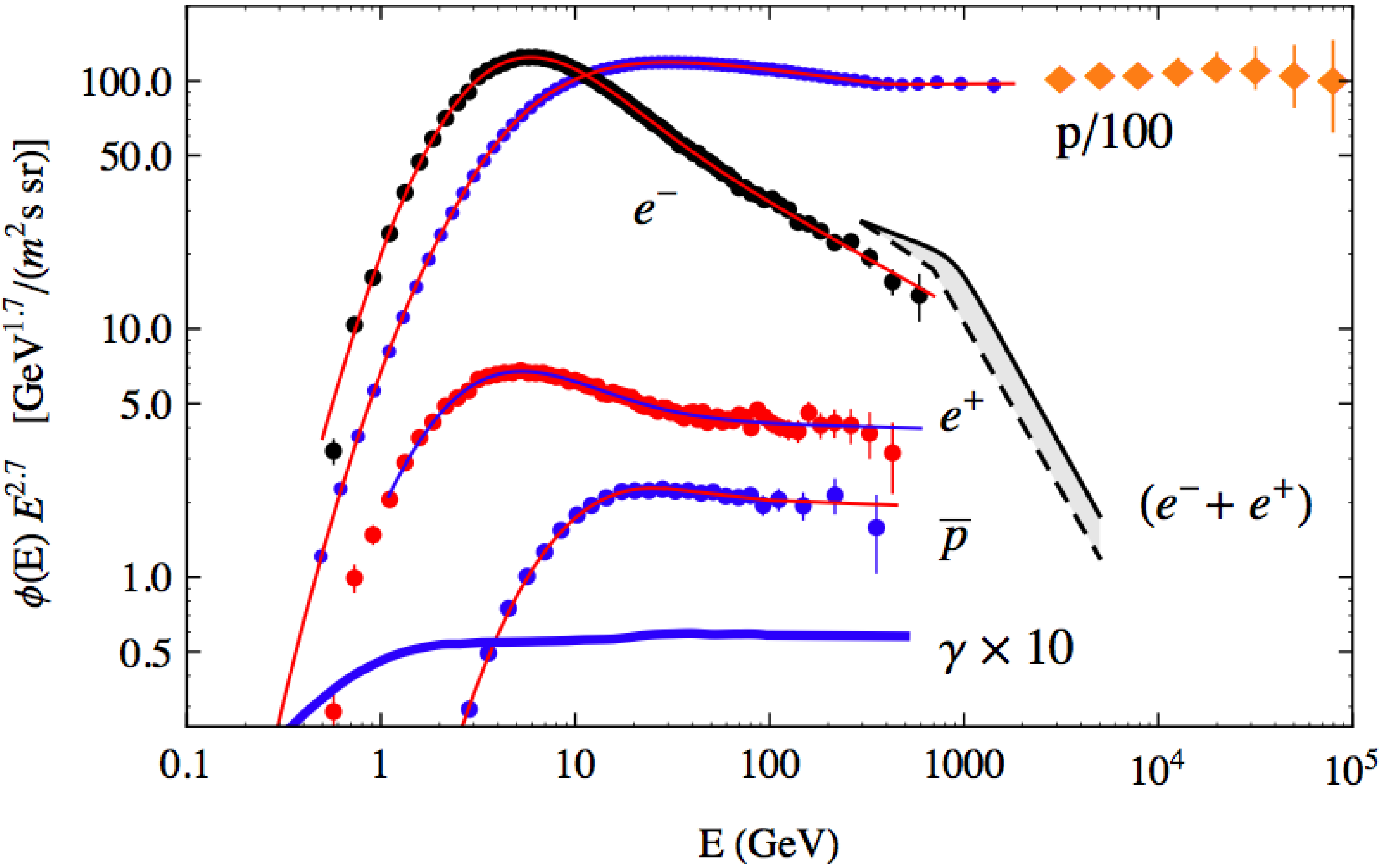
AMS02 $p \quad e^- \quad e^+ \quad \overline{p}$

CREAM p data



angle averaged diffuse Galactic gamma ray flux (Fermi)

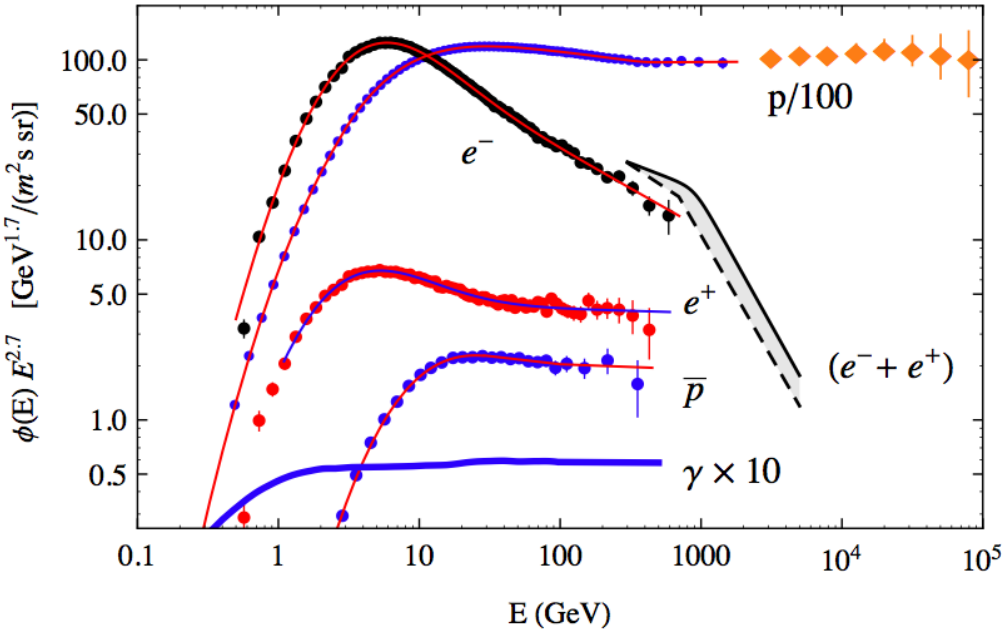
CREAM p data



striking results

soft electron spectrum

4 spectra
have approximately
the same slope



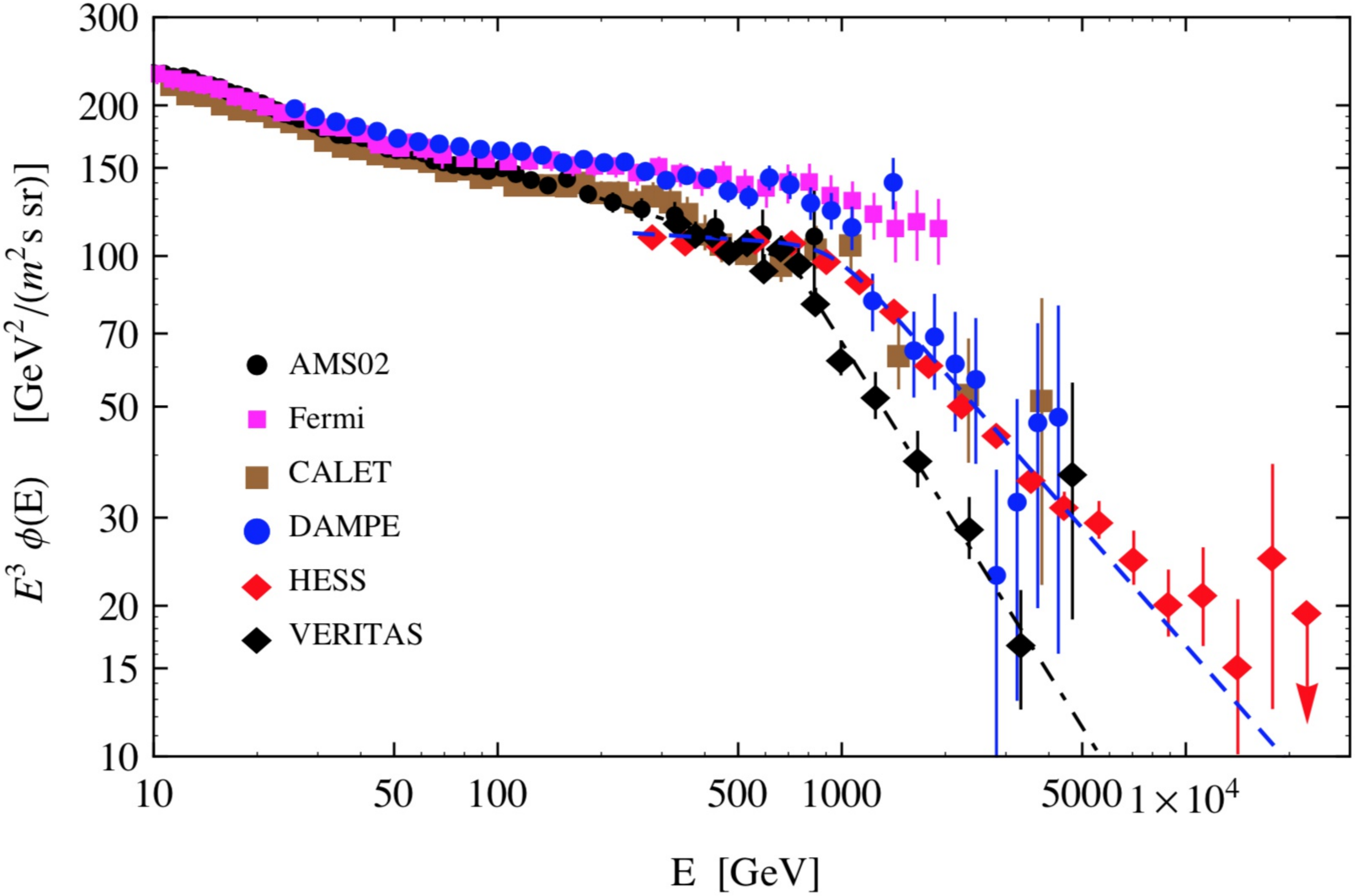
“striking”
qualitative features
that “call out”
for an explanation

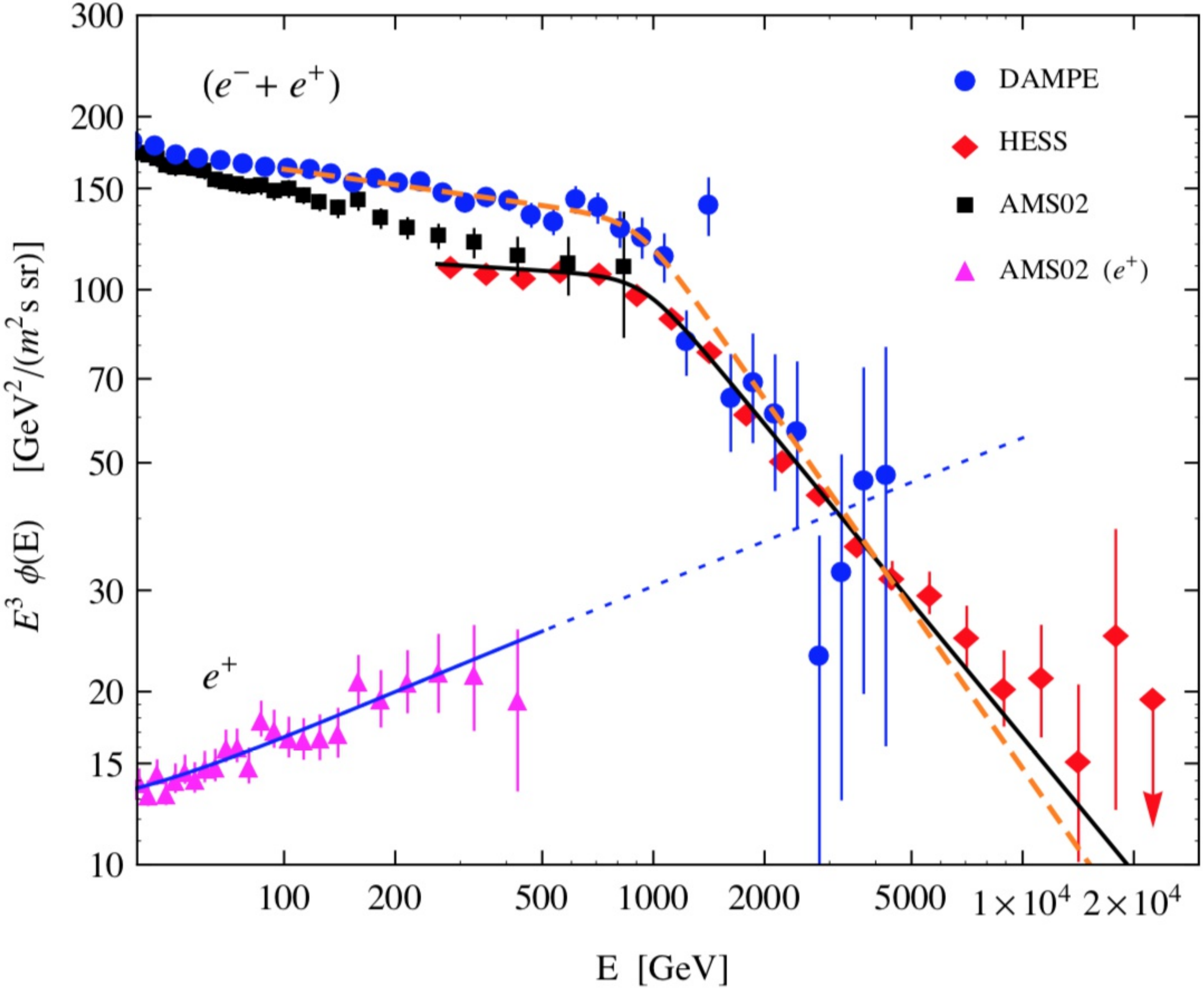
4 spectra
have approximately
the same slope

[A] *Proton* and *electron* spectra are very different.
[a1] much smaller e- flux
[a2] much *softer* electron flux
[a3] evident “break”at 1 TeV in the $(e^+ + e^-)$ spectrum

[B] *positron* and *antiproton* for (E> 30 GeV) have the same power law behavior and differ by a factor 2 (of order unity)

Veritas: break at 710 GeV,
stronger break





Positron component

Crucial to extend the measurement

Energy Loss

main mechanisms

Synchrotron radiation
Compton scattering
strongly depend on the particle mass

$$-\frac{dE}{dt} \propto \frac{q^4}{m^4} E^2$$

quadratic in energy

$$T_{\rm loss}(E) = \frac{E}{|dE/dt|} \simeq \frac{1}{b\,E}$$

Characteristic time
for energy loss

$$T_{\rm loss}(E) \approx \frac{620}{E_{\rm GeV}}\ {\rm Myr}$$

$$\approx \frac{0.62}{E_{\rm TeV}}\ {\rm Myr}$$

Energy losses
can be the main
“sink” for e+/e- CR

or be negligible

depending on the
residence time of the
particles in the Galaxy

Rate of Energy Loss depends on the energy density in magnetic field and radiation (and therefore *is a function of position*)

$$T_{\rm loss}(E) = \frac{E}{|dE/dt|} \simeq \frac{3\, m_e^2}{4\, c\, \sigma_{\rm Th}\, \langle \rho_B + \rho_\gamma^*(E) \rangle \; E}$$

$$\simeq 621.6 \left(\frac{\rm GeV}{E} \right) \left(\frac{0.5 \ {\rm eV/cm^3}}{\rho} \right) \ {\rm Myr}$$

Average value for the particle confinement volume

$$\rho_b = \frac{B^2}{8\,\pi} \simeq 0.22 \ \left(\frac{B}{3 \ \mu{\rm G}} \right)^2 \ \frac{\rm eV}{\rm cm^3}$$

$$\rho_{\rm CMBR} \simeq 0.26 \ \frac{\rm eV}{\rm cm^3}$$

Formation of the Galactic Cosmic Ray spectra

(for each particle type)
three elements are of fundamental importance:

1. Source spectrum

2. Magnetic confinement
   (CR residence (escape) time)

3. Energy losses
   (synchrotron + Compton scattering+ ….)

[4. hadronic + other interactions …..]

Formation of the Cosmic Rays spectra in the Galaxy:

Simplest Model:

LEAKY BOX

[No space variables. The Galaxy is considered as one single homogeneous volume (or point)]

Equation that describe the CR Galactic population

$$\frac{\partial n(E,t)}{\partial t} = q(E,t) - \frac{n(E,t)}{T_{\rm esc}(E)} + \frac{\partial}{\partial E}\left[\beta(E)\, n(E,t)\right]$$

Three functions of energy/rigidity define completely the model for one particle type

$q(E)$: Source spectrum (stationary)

$T_{\rm esc}(E)$ Escape time

$\beta(E) = -\frac{dE}{dt}$ Rate of energy loss $T_{\rm loss}(E) = E/\beta(E)$

$$\frac{\partial n(E,t)}{\partial t} = q(E,t) - \frac{n(E,t)}{T_{\mathrm{esc}}(E)} + \frac{\partial}{\partial E}\left[\beta(E)\, n(E,t)\right]$$

$$q(E,t)$$

Source

spectrum of
cosmic rays

$$T_{\mathrm{esc}}(E)$$

Escape time

$$-\frac{dE}{dt} = \beta(E)$$

Rate of energy Loss

Propagation

$$n(E,t)$$

Observable CR density

$q(E) = q_0 \; E^{-\alpha}$

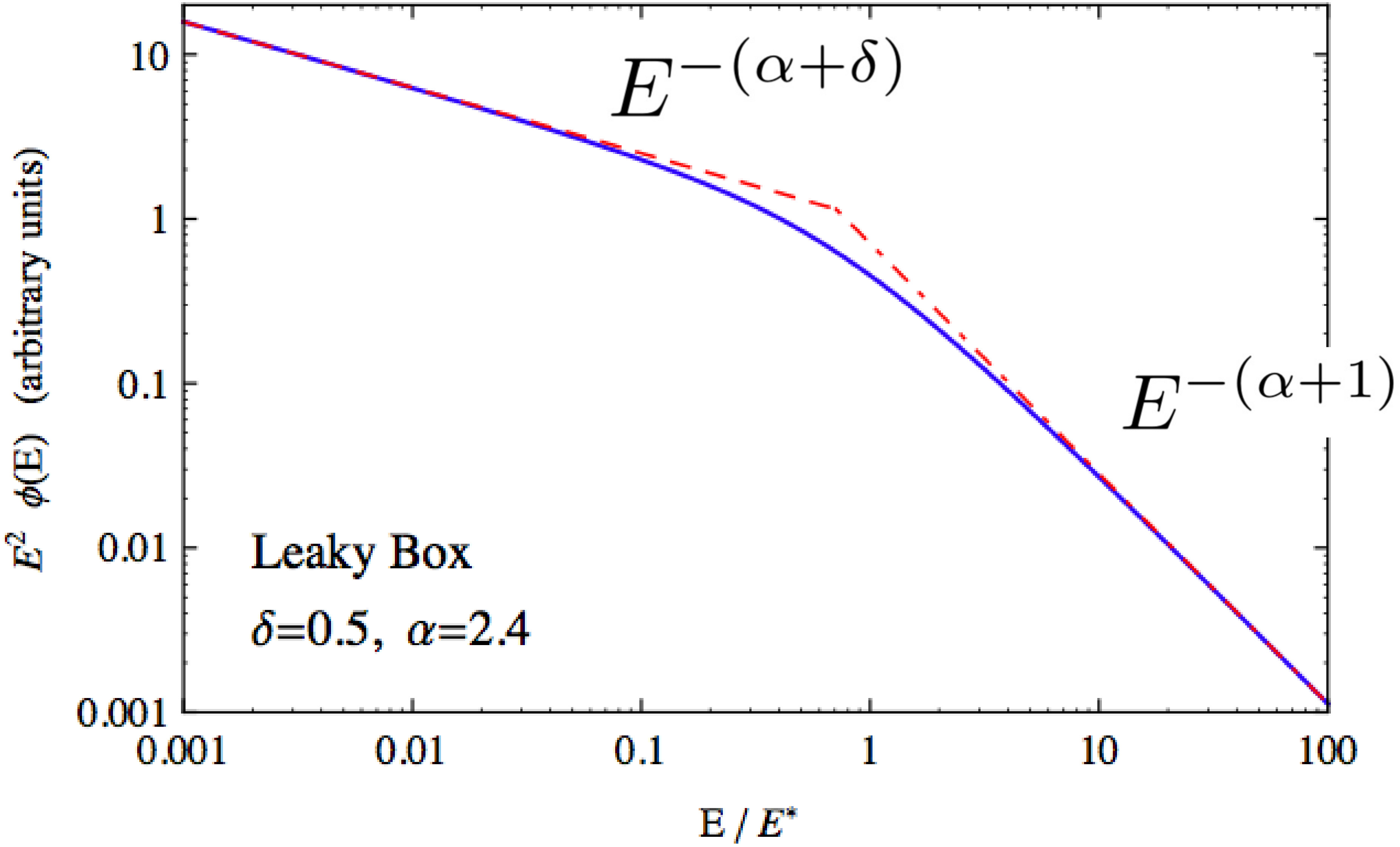
Source

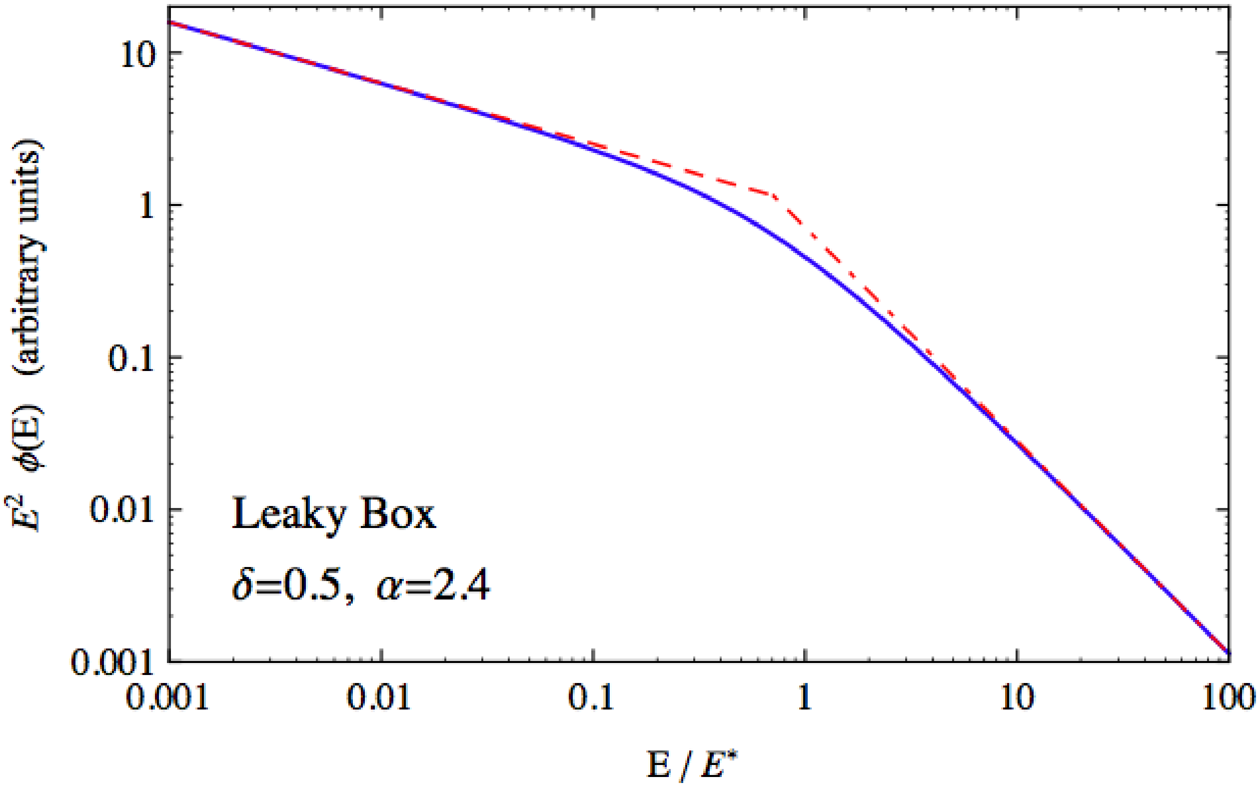
$T_{\rm esc}(E) = T_0 \; E^{-\delta}$

escape

$\beta(E) = b \, E^2$

Energy loss





$$q(E) = q_0 \; E^{-\alpha}$$

$$T_{\rm esc}(E) = T_0 \; E^{-\delta}$$

$$\beta(E) = b\, E^2$$

Spectral "feature"

Softening:

$$\Delta\gamma = 1 - \delta \qquad E_b \approx E^*$$

Critical energy E^*

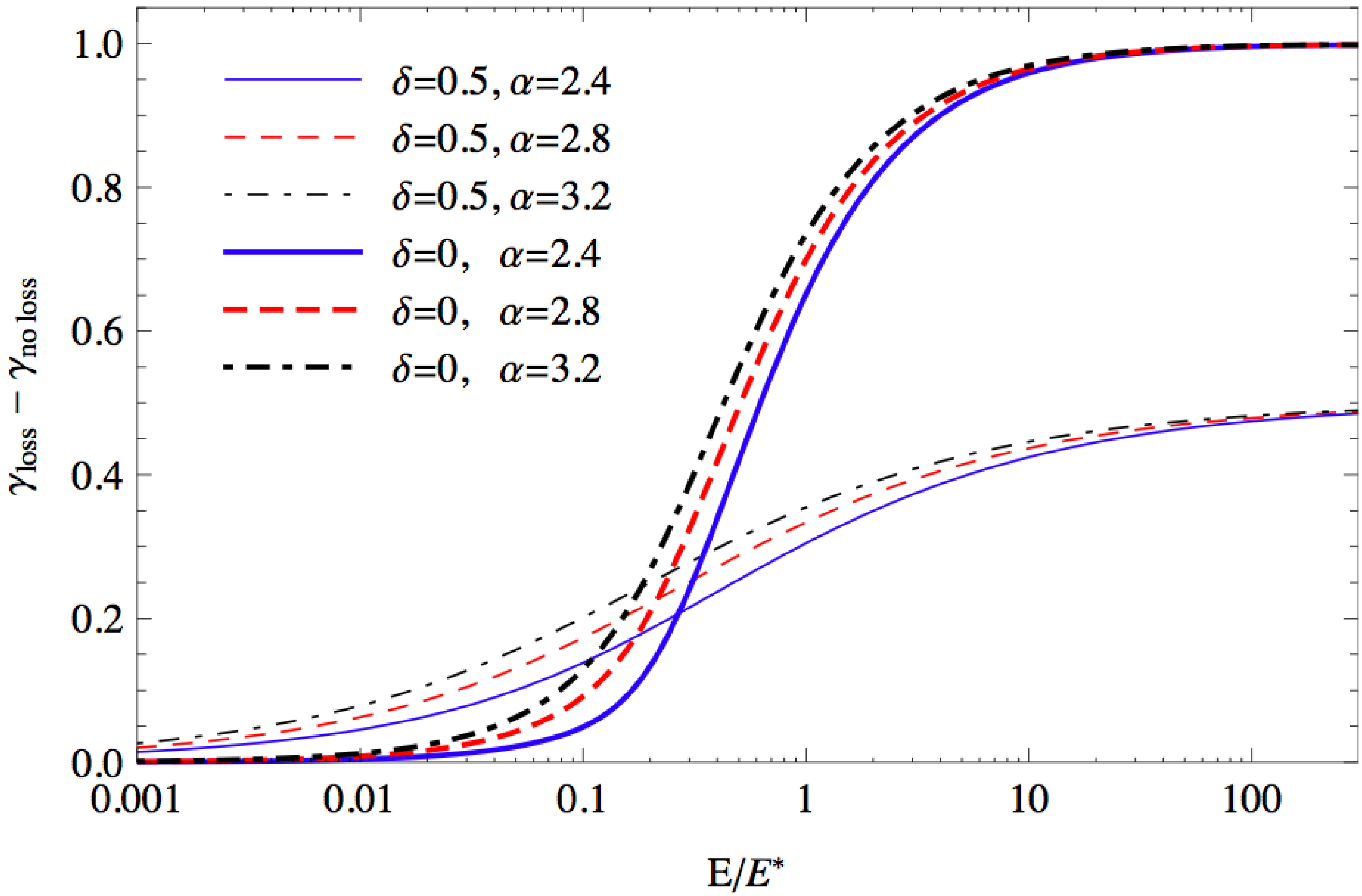
$$T_{\rm loss}(E^*) = T_{\rm esc}(E^*)$$

$$E^* = (T_0\, b)^{1/(\delta-1)}$$

Exact solution:

$$n(E) = q(E)\; T_{\rm esc}(E) \times \int_0^{1/a} d\tau\; (1 - a\,\tau)^{\alpha-2}\; \exp\left[-\frac{1}{a\,(1-\delta)}\left[1 - (1 - a\,\tau)^{1-\delta}\right]\right]$$

$$a = \frac{T_{\rm esc}(E)}{T_{\rm loss}(E)} \simeq (T_0\, b)\; E^{1-\delta} = \left(\frac{E}{E^*}\right)^{1-\delta}$$



Idea of very general validity:

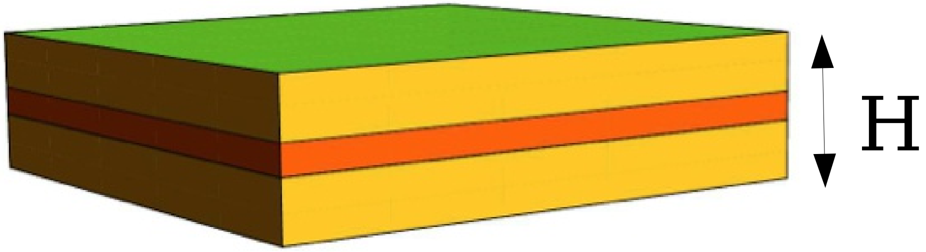
The Spectra of electrons and positrons
should contain a softening "spectral feature"
associated to the energy loss:
at a critical energy *E**

$$T_{\rm esc}(E) \simeq \langle t_{\rm esc}(E) \rangle$$

$$T_{\rm loss}(E) \simeq \frac{E}{\langle |dE/dt| \rangle}$$

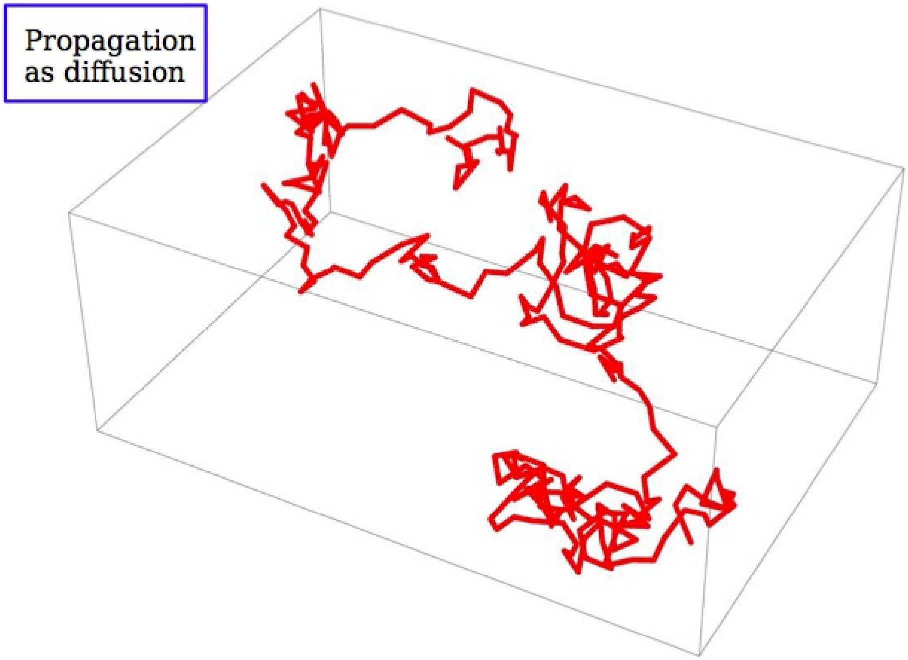
$$\boxed{T_{\rm esc}(E^*) = T_{\rm loss}(E^*)}$$

Diffusion Model ("minimal version")



Galaxy modeled as
a homogeneous slab
of a "diffusive medium"
with 2 absorption surfaces

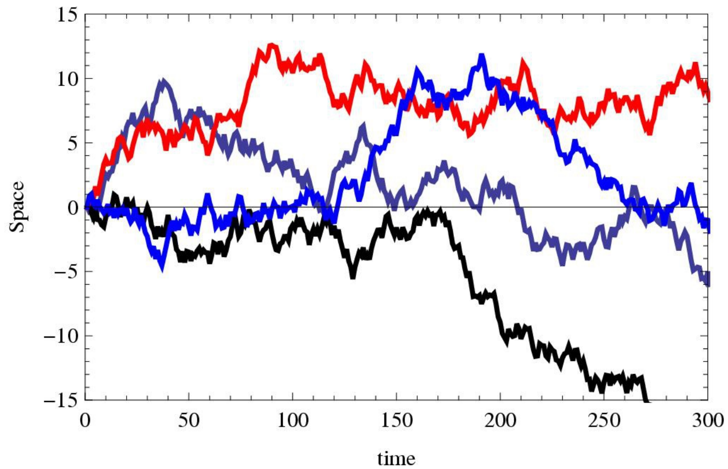
$z = \pm H$ (Halo thickness)



Propagation model
specified by H + 2 functions

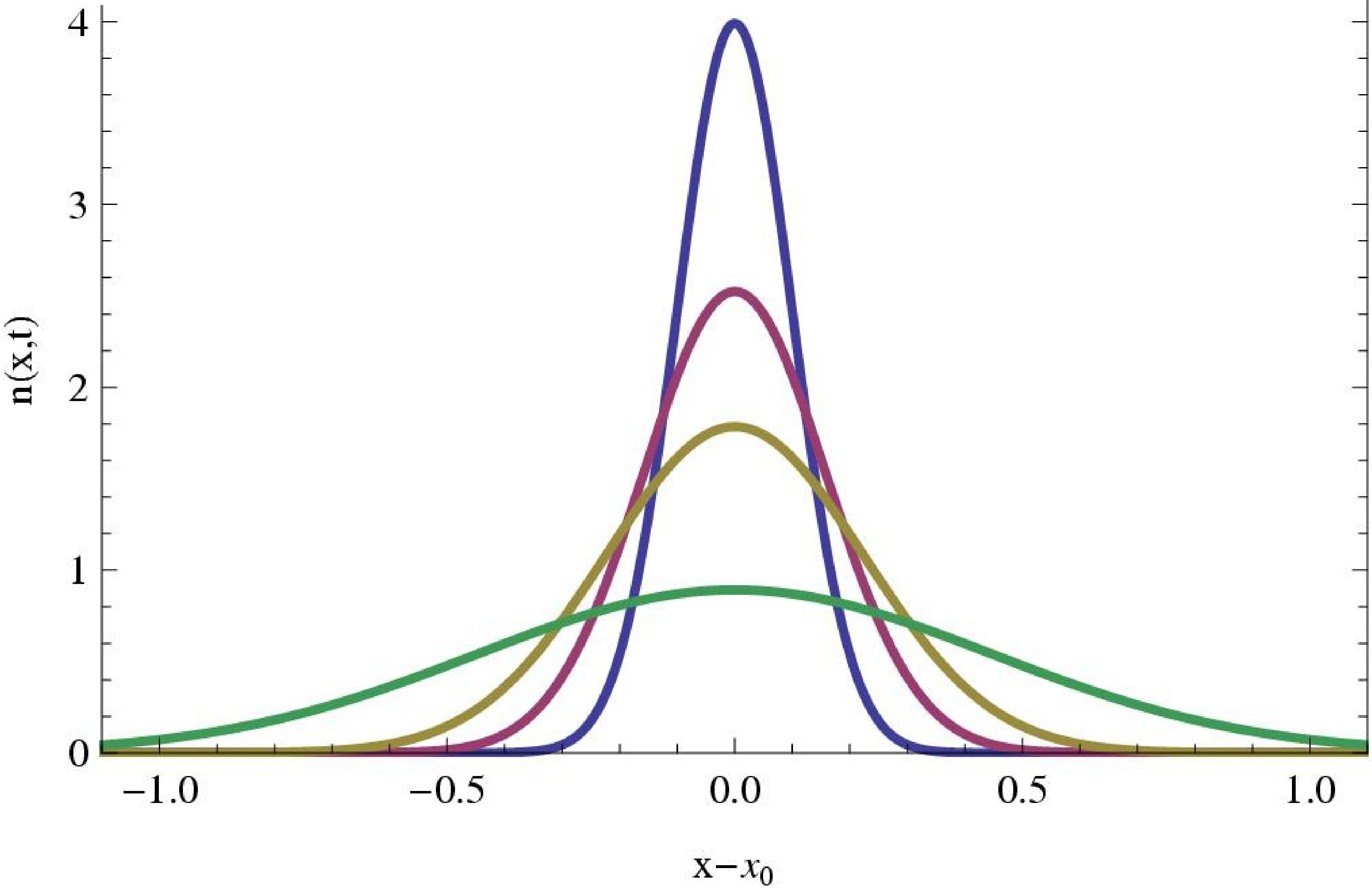
$$D(E) = D_0 \; E^{\delta}$$

$$\beta(E) = b \, E^2$$



Projection in x (or y or z)

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



Average escape time for CR (no energy loss)

$$T_{\rm esc}(E) = \frac{H^2}{2\,D(E)} = \langle t_{\rm esc}(E)\rangle$$

$$T_{\rm esc}(E) = T_0\ E^{-\delta}$$

$$D(E) = D_0\ E^{\delta}$$

$$T_{\rm esc}(E^*) = T_{\rm loss}(E^*)$$

Critical energy

$$E^* = \left(\frac{H^2\,b}{2\,D_0}\right)^{1/(\delta-1)}$$

$$q(E,\vec{x},t) = q_0 \; E^{-\alpha} \; \delta[z]$$

Stationary emission from the Galactic plane

Exact solution:

Energy losses negligible

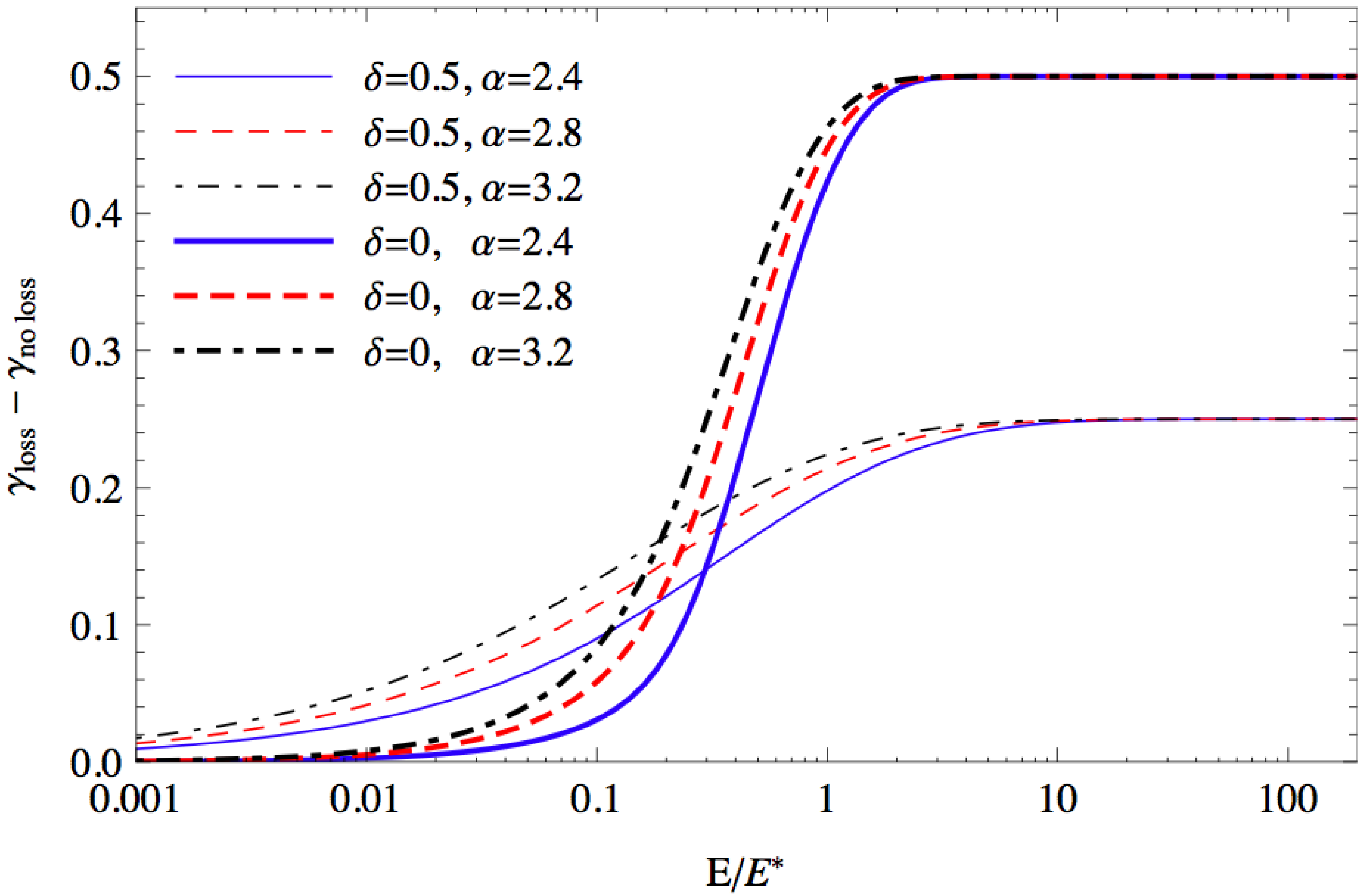
$$n(E) = \begin{cases} \dfrac{q_0 \; H}{2\,D_0} \; E^{-(\alpha+\delta)} & \text{for } E \ll E^* \\[2em] \dfrac{q_0}{\sqrt{2\,D_0\,b}} \; c(\alpha,\delta) \; E^{-[\alpha+(1+\delta)/2]} & \text{for } E \gg E^* \end{cases}$$

Energy losses dominant

$$c(\alpha,\delta) = \sqrt{\frac{1-\delta}{2\pi}} \int_0^1 d\tau \; \frac{(1-\tau)^{\alpha-2}}{\sqrt{1-(1-\tau)^{1-\delta}}}$$

$$\Delta\gamma = \frac{1-\delta}{2}$$

Imprint of the energy losses on the spectral index



$$\Delta\gamma = \frac{1-\delta}{2}$$

$$E_b \approx E^*$$

$$E_b \simeq c(\alpha,\delta)^{2/(\delta-1)}\ E^*$$

The (Model independent) point :

The effects of energy loss during the propagation of electrons and positrons should leave an “imprint” on the spectra: a *softening feature.*

The characteristic energy of the softening has a simple physical meaning: (in good approximation) it is the energy where the Loss-Time is equal to the Escape Time (or age) of the cosmic rays.

$$T_{\rm loss}(E^*) = T_{\rm esc}(E^*)$$

Identification of E^*
corresponds to a measurement of the CR residence time

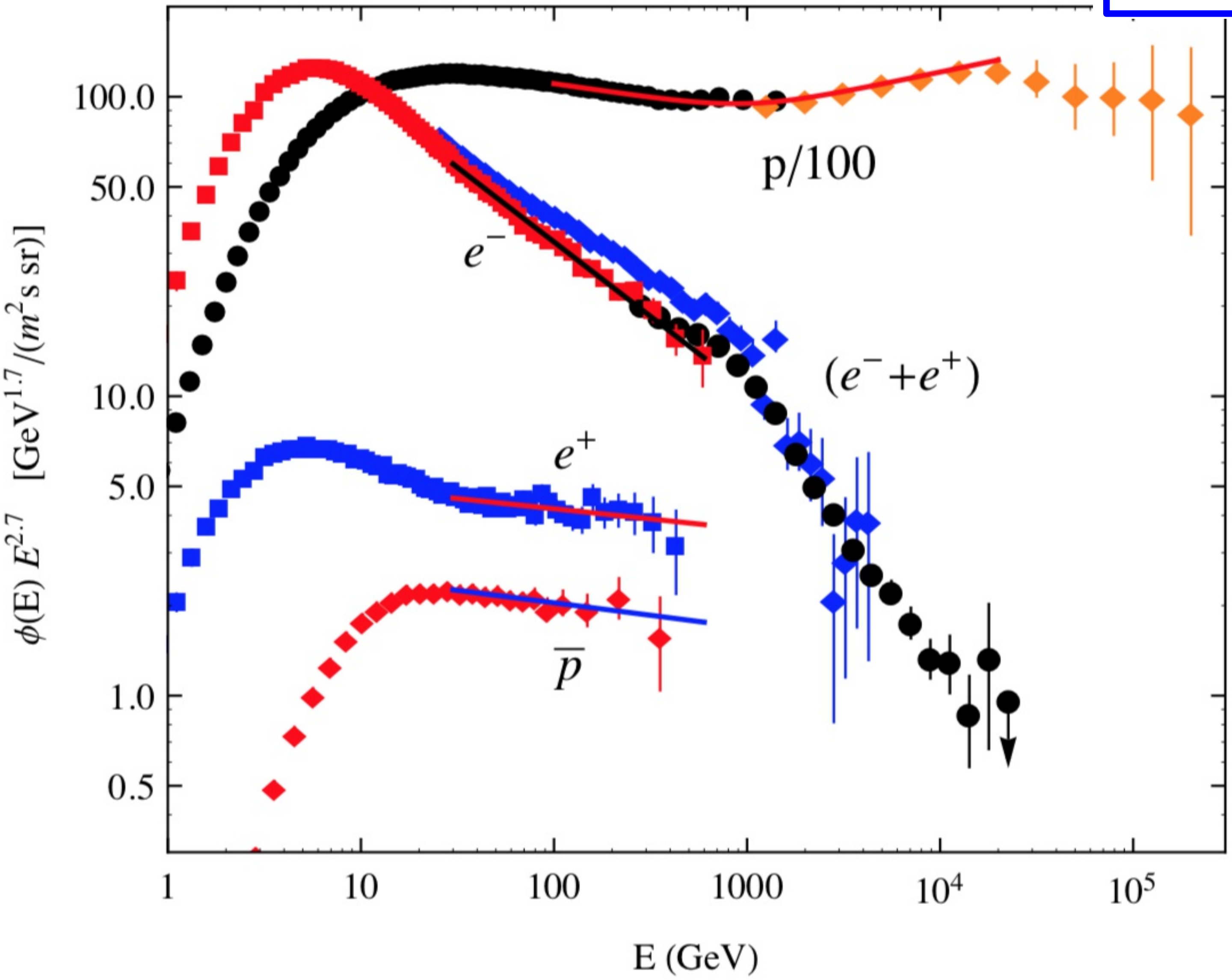
Where is the energy loss softening feature ?

Use the lepton spectra as *“cosmic ray clocks”*

$$E^* \lesssim 3 \text{ GeV}$$

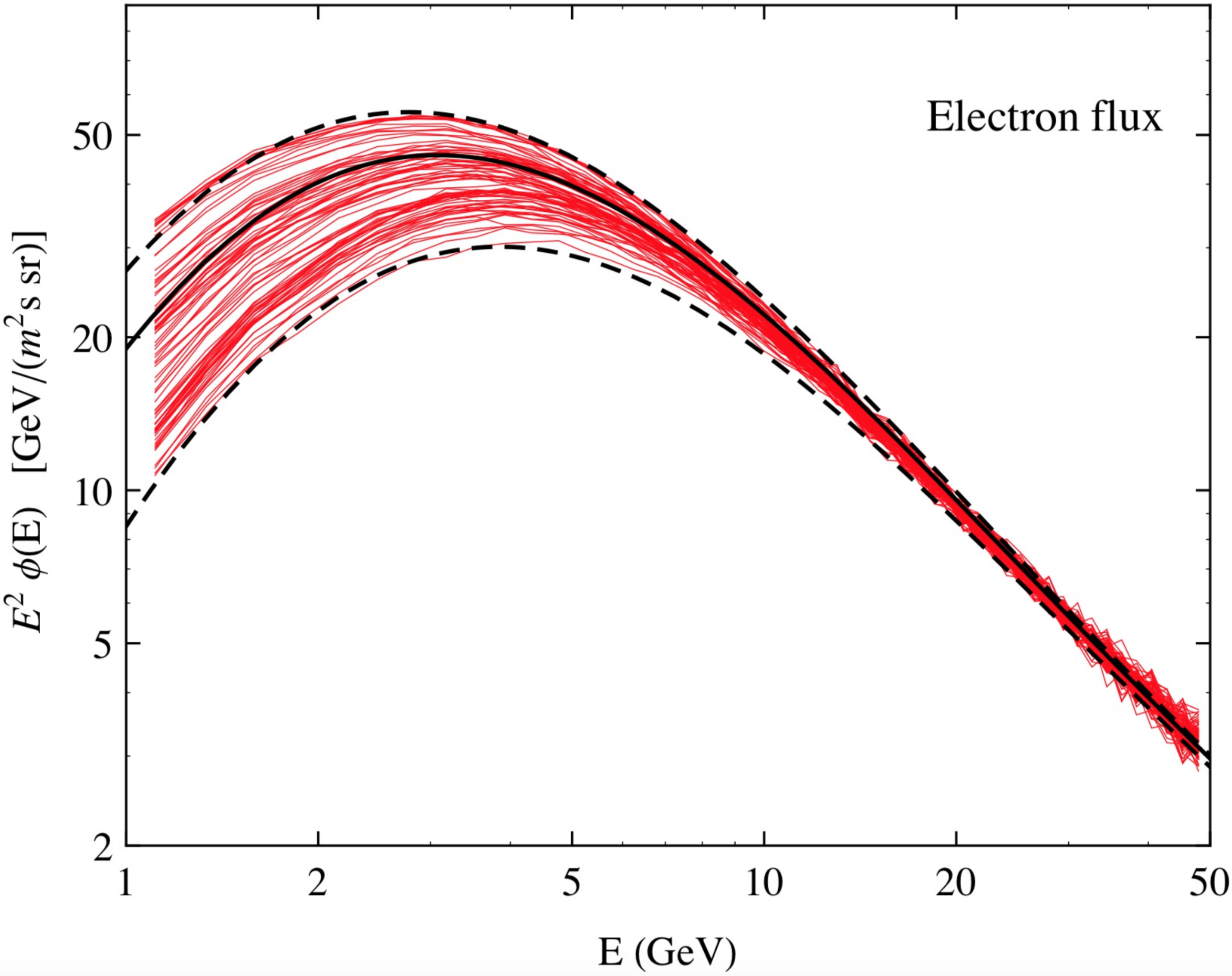
Two possibilities

$$E^* \simeq 900 \text{ GeV}$$



Recent AMS02
[79 spectra of e+ and e-]
[27 days periods]

What is the shape of the interstellar spectrum ?



Fit =

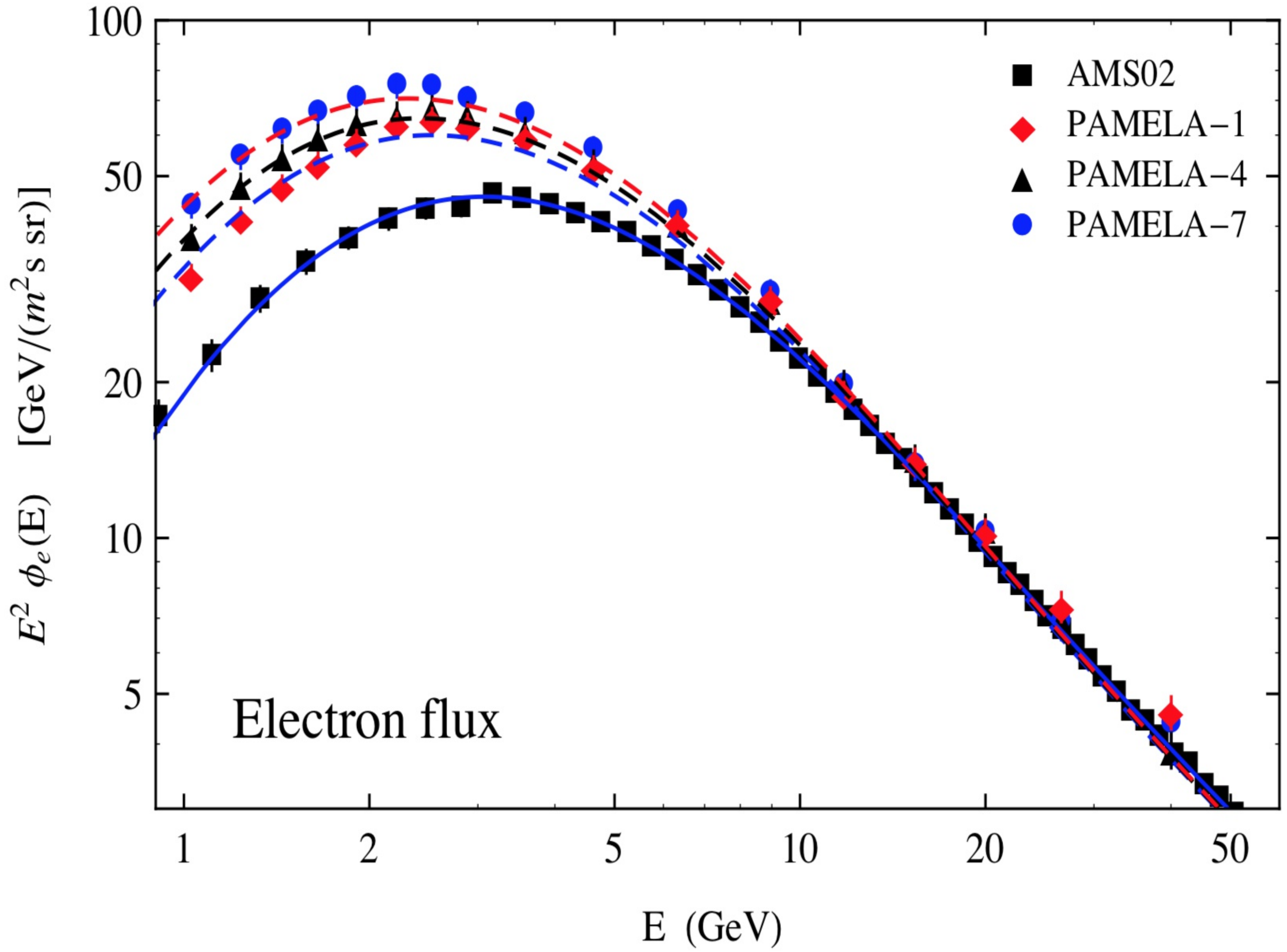
$K\ E^{-3.17}$

$\otimes$

FFA Solar Modulations

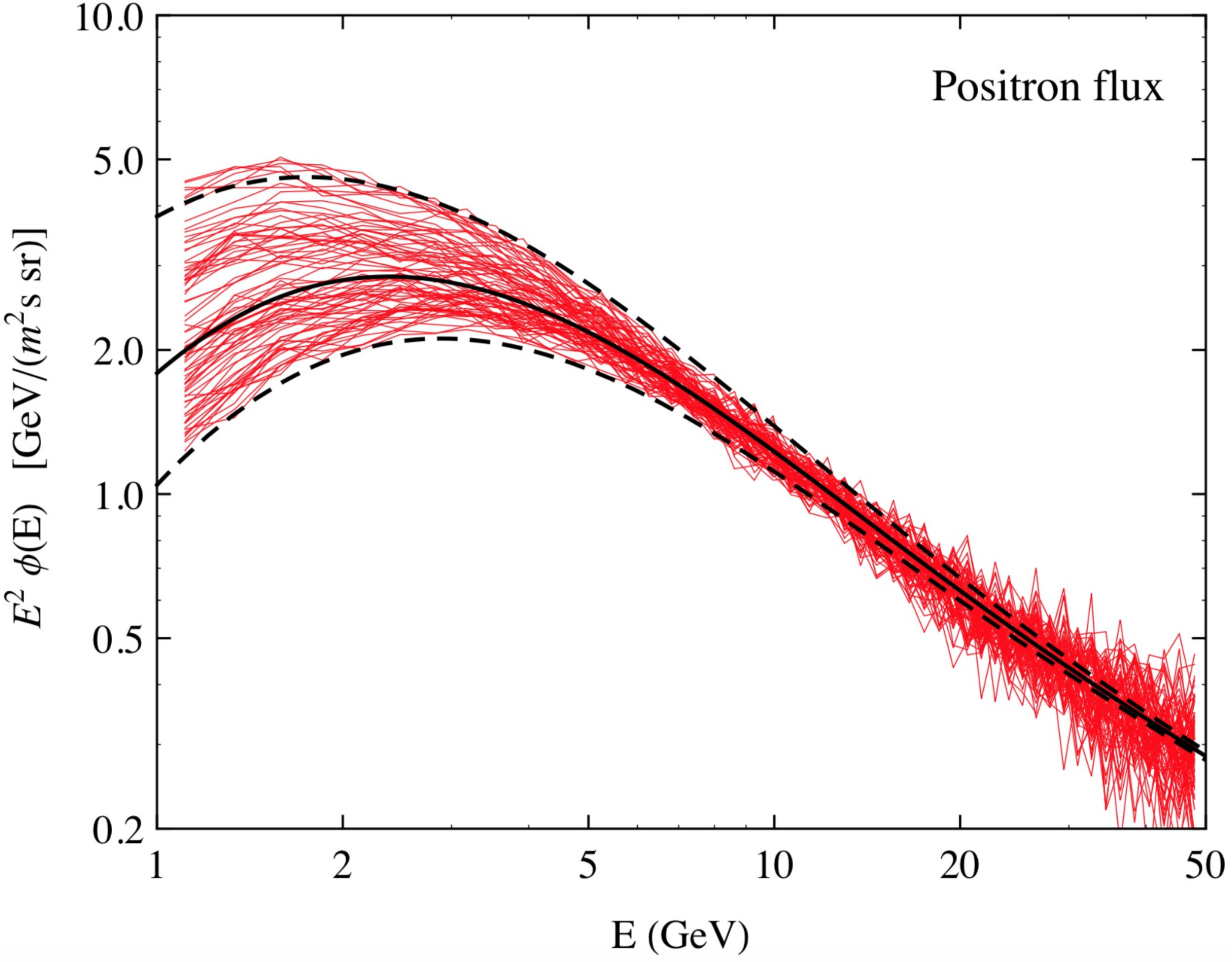
Solar Modulations

Electron spectra
at different times



Positron flux

Unbroken power law
in interstellar space
+ Force Field Approximation
for solar modulations

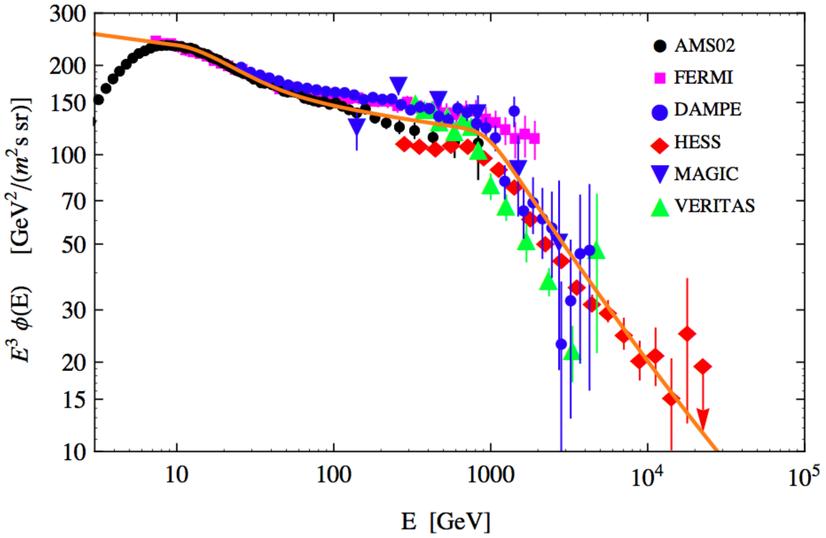


Possible (and "natural") choice: identification of the sharp softening observed by the Cherenkov telescopes in the spectrum of $(e^+ + e^-)$ as the critical energy

$$E^* = E_{\rm HESS} \simeq 900~{\rm GeV}$$

$$T_{\rm confinement}[E \simeq 900~{\rm GeV}] \simeq 0.7 \div 1.3~{\rm Myr}$$

Range depends on volume of confinement



Propagation of positrons and antiprotons is approximately equal for

$$E \lesssim E^* \simeq 900~{\rm GeV}$$

Imprints of the

“*Granular nature*” of the CR sources on the spectra of electrons

Imprints of the

“Granular nature” of the CR sources
on the spectra of electrons

Prediction of large effects
at sufficiently high energy

Large anisotropy

Large deviations
from power law flux

$$E \gtrsim E^{\dagger}$$

“Critical energy for
discrete sources effects”

How many sources contribute to the Cosmic Ray Flux ?

Assumption, for primary CR (p, e^-)

The CR sources are “events”
point-like and “short-lived” (on Galactic scales)
[*Supernova explosions*, Gamma Ray Bursts, Pulsars, ….]

$T_{\rm sources}$

time between events
in the entire Galaxy

$$T_{\rm SNR} \approx 50 \text{ yr}$$

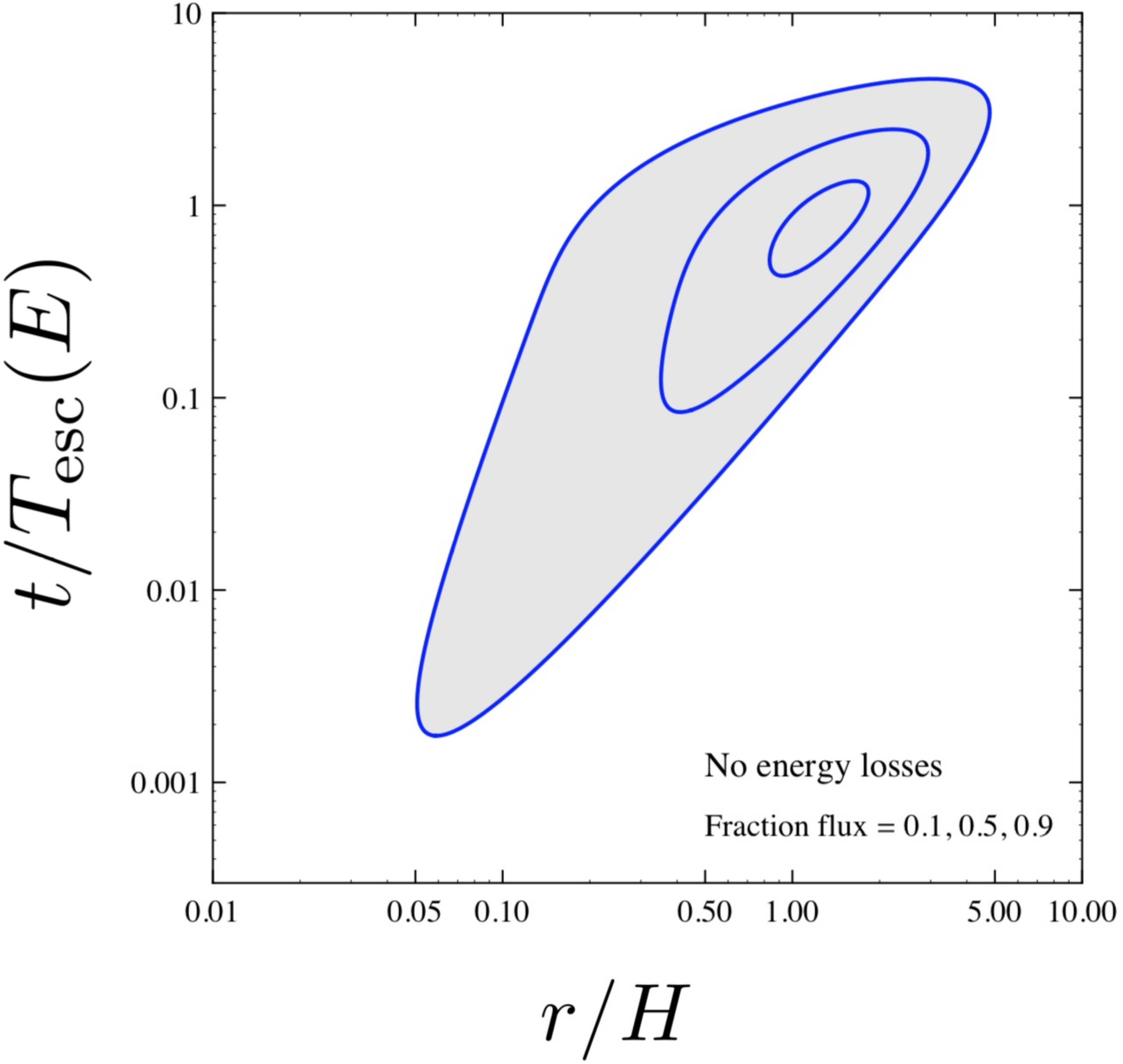
$$n_{\rm sources} \approx \frac{1}{\pi \, R_{\rm disk}^2} \simeq 0.0015 \text{ kpc}^{-2}$$

Number density in the disk

Assume continuous emission of protons

Space-time
origin of the flux

(in Diffusion
Model)



$$\frac{d\phi_p}{d\log r \; d\log t}$$

Protons (Nuclei)

Number of “source-events” that contribute to the flux

$$N^{p}_{\rm sources}(E) \approx \frac{n_s}{T_s} \; H^2 \; T_{\rm esc}(E)$$

All events
at a distance: $r < H$

Age: $t < T_{\rm esc}(E)$

Numerical example: $\delta = 0.4$

$$N_{\rm sources}(E) \simeq 240 \; \left[\frac{T_s}{50 \text{ yr}}\right]^{-1} \; \left[\frac{H}{5 \text{ kpc}}\right]^{2} \; \left[\frac{T_{\rm diff}(10 \text{ GeV})}{10 \text{ Myr}}\right] \; \left(\frac{E}{\rm PeV}\right)^{-0.4}$$

Maximum propagation time for electron and positrons

Evolution of energy with time: $-\frac{dE}{dt} = b\ E^2$

$$E_i(E,t) = \frac{E}{1 - b\,E\,t}$$

Initial energy
(time t in the past)

$$t \to T_{\rm loss}(E) = \frac{1}{b\,E}$$

$$E_i(E,t) \to \infty$$

Maximum age for particle
observed with energy E

$$t_{\rm max}(E) \simeq T_{\rm loss}(E) = \frac{1}{b\,E}$$

Maximum propagation distance

$$R_{\max}(E) = \frac{H}{\sqrt{1-\delta}} \left(\frac{E}{E^*}\right)^{-(1-\delta)/2}$$

Strong dependence on the critical energy

$H = 3$ kpc $\qquad \delta = 0.4$

$E^* = 3$ GeV

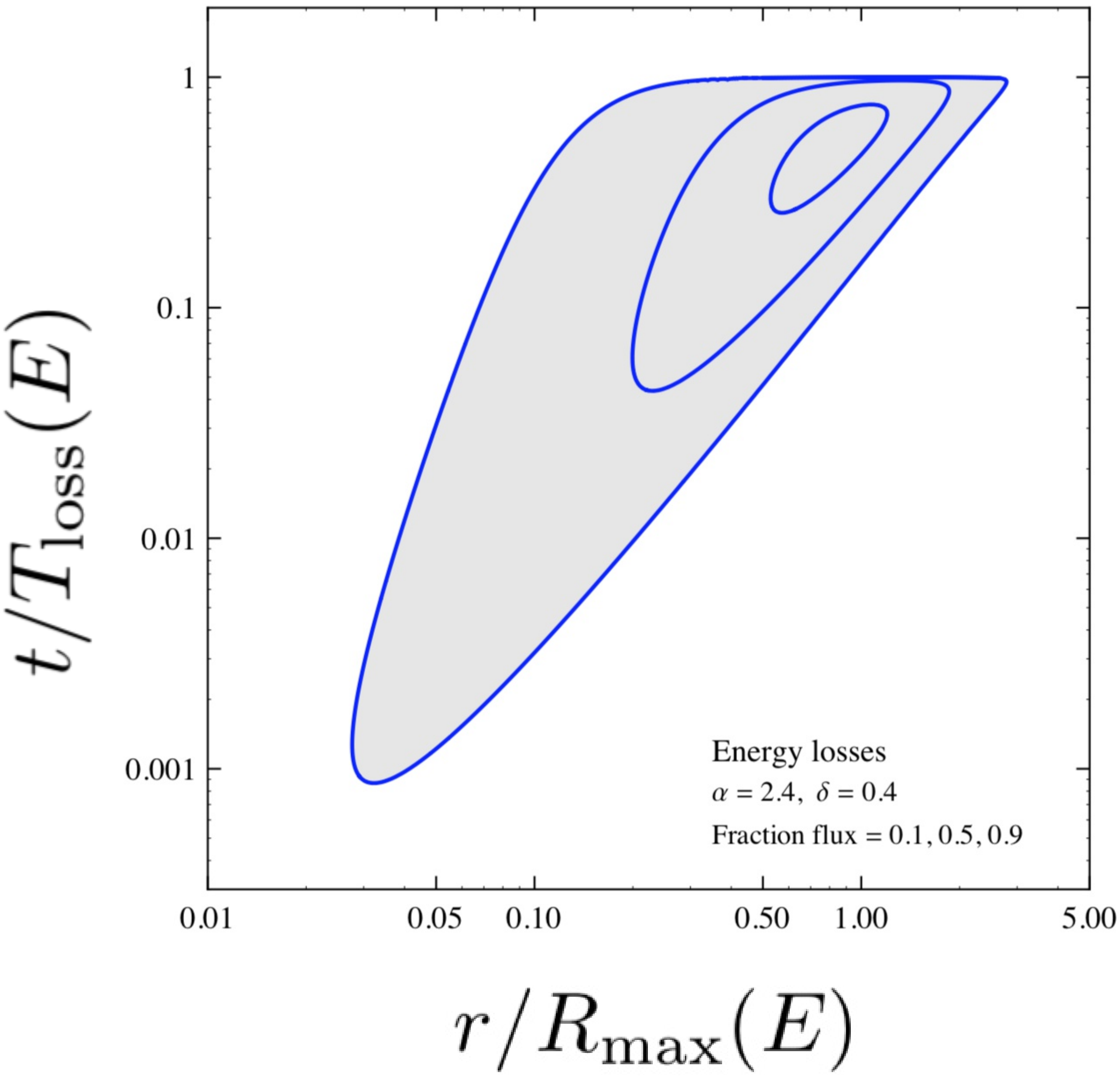
$$R_{\max}(E) = 0.67\ \text{kpc} \left(\frac{E}{\text{TeV}}\right)^{-0.3}$$

$E^* = 940$ GeV

$$R_{\max}(E) = 3.80\ \text{kpc} \left(\frac{E}{\text{TeV}}\right)^{-0.3}$$

Assume continuous emission of electrons

Space-time
origin of the flux



$$\frac{d\phi_{e^\mp}}{d\log r\ d\log t}$$

Electrons

Number of “source-events” that contribute to the flux

$$N^{e^\mp}_{\text{sources}}(E) \approx \frac{n_s}{T_s} \; R^2_{\max}(E) \; T_{\text{loss}}(E)$$

All events
at a distance: $r < H$

Age: $t < T_{\text{esc}}(E)$

Numerical example: $\delta = 0.4$

$$N^{e^\mp}_{\text{sources}}(E) \simeq 8.5 \; \left[\frac{T_s}{50 \text{ yr}}\right]^{-1} \; \left[\frac{H}{3 \text{ kpc}}\right]^{2} \; \left[\frac{E^*}{3 \text{ GeV}}\right]^{0.6} \; \left(\frac{E}{\text{TeV}}\right)^{-1.6}$$

“Stochastic effects critical Energy”: “One single source”

[Brightest source contributes (on average)
½ the expected flux for a continuous source distribution]

$$E^{\dagger} \simeq 1.1 \left[\frac{T_s}{50\ \mathrm{yr}}\right]^{-0.625} \left[\frac{H}{3\ \mathrm{kpc}}\right]^{1.25} \left[\frac{E^*}{3\ \mathrm{GeV}}\right]^{0.375} \mathrm{TeV}$$

If the critical energy is low (GeV Range)
Expect to see the effects of granularity at TeV energy

If the critical energy is high (1 TeV)
expect to see the effects of granularity at 15-20 TeV

Problem of the “Local Sources"

If the CR residence time is long,
and therefore the diffusion coefficient is small:

for $E \gtrsim 1\ \mathrm{TeV}$
one expects that only very near sources
contribute to the flux.

and therefore:

the spectrum should show evidence
for the fact that only very few
sources contribute.

What happens when only few sources contribute to the flux ?

The flux is generated by an ensemble o of discrete “source events” that are localized (“point like”) and last a short time (on Galactic time scales).

$$q_s(E, r, t) = q_0 \; E^{-\alpha} \; \delta[t - t_i] \; \delta[\vec{x} - \vec{r}_s]$$

Each source is defined by two parameters and by its “age” and position

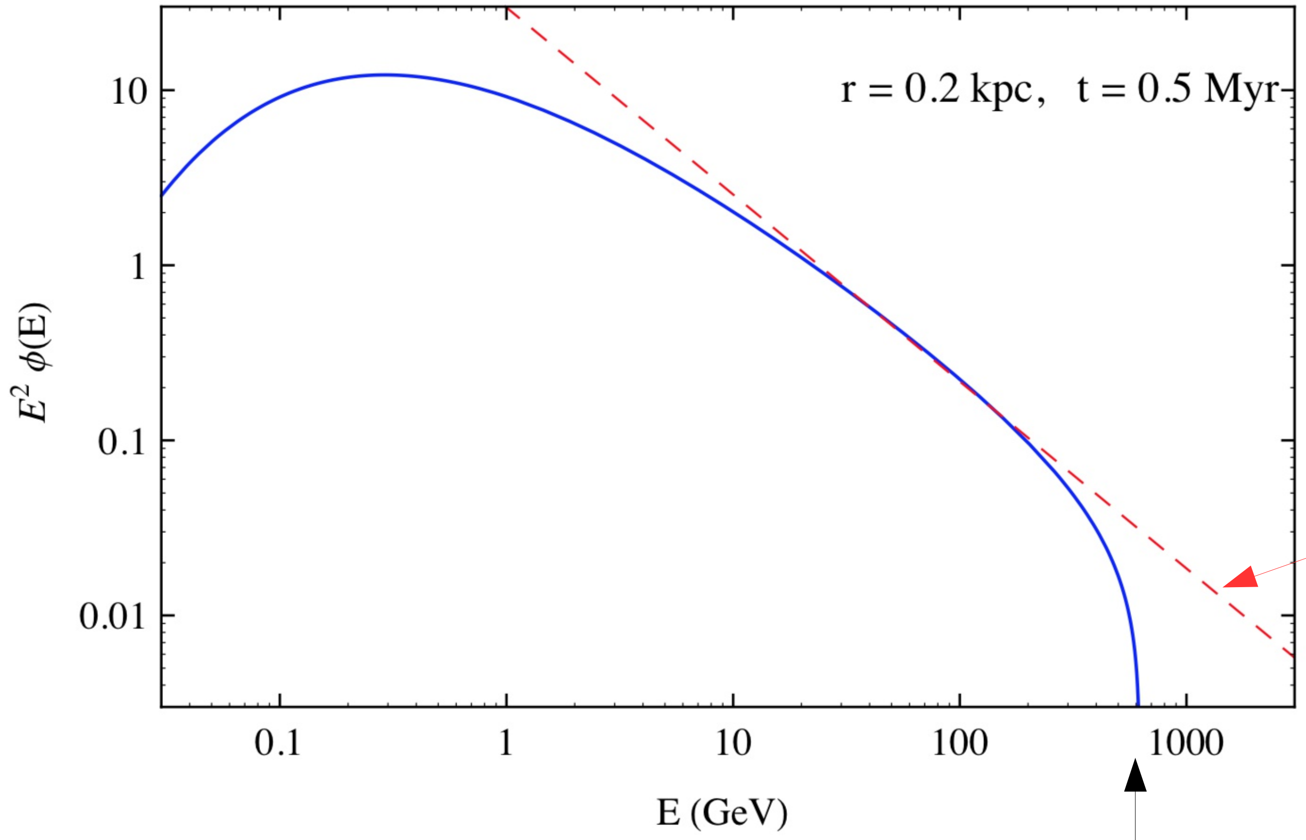
$$\{t_i \; , \quad \vec{r}_s\} \qquad \{\mathcal{E} \; , \quad \alpha\} \qquad q_0 \propto \mathcal{E}$$

Flux from an “ instantaneous explosive) source”

simple diffusive model)

$$\{D_0\ ,\ \delta\ ,\ \ b\ ,\ \ H\}$$

$$q_s(E) = q_0\ E^{-\alpha}\ \delta[t - t_i]$$



$$E^{-\gamma}$$

$$\gamma = \alpha + 3/2\,\delta$$

$$E_{\max} \simeq \frac{1}{b\,t}$$

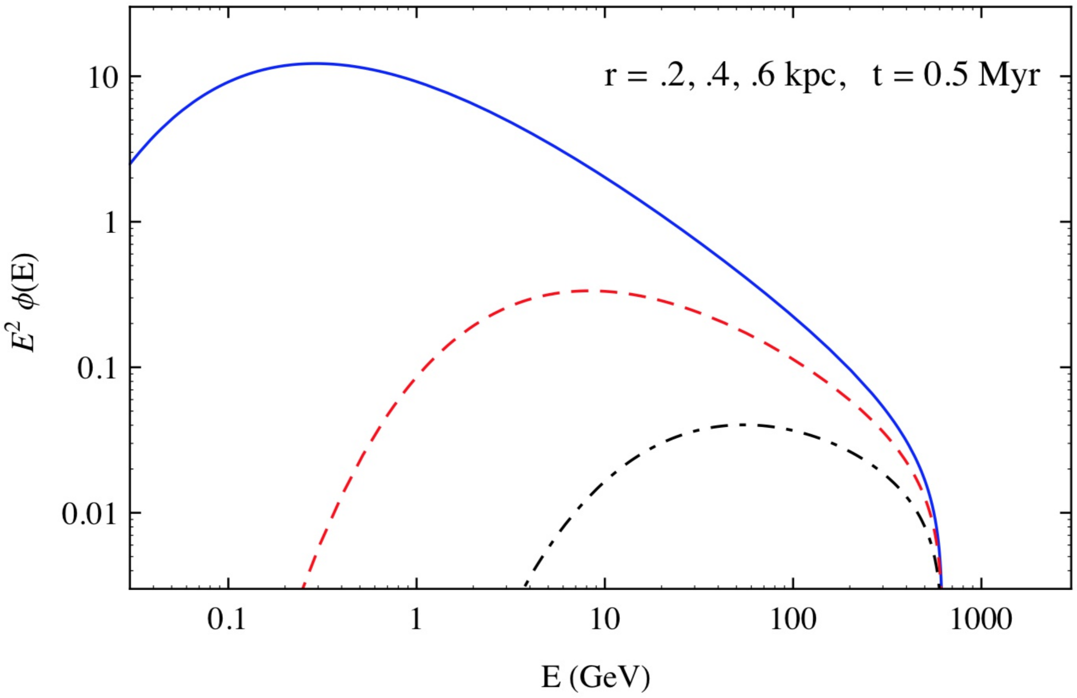
Simple analytic expression
(limit of negligible escape)

$$\phi_s(E, r, t) = \frac{c}{4\pi} \; \frac{q_0 \; E^{-\alpha}}{(2\,\pi)^{3/2} \; R^3(E, t)} \; \exp\left[-\frac{r^2}{2\;R^2(E, t)}\right]$$

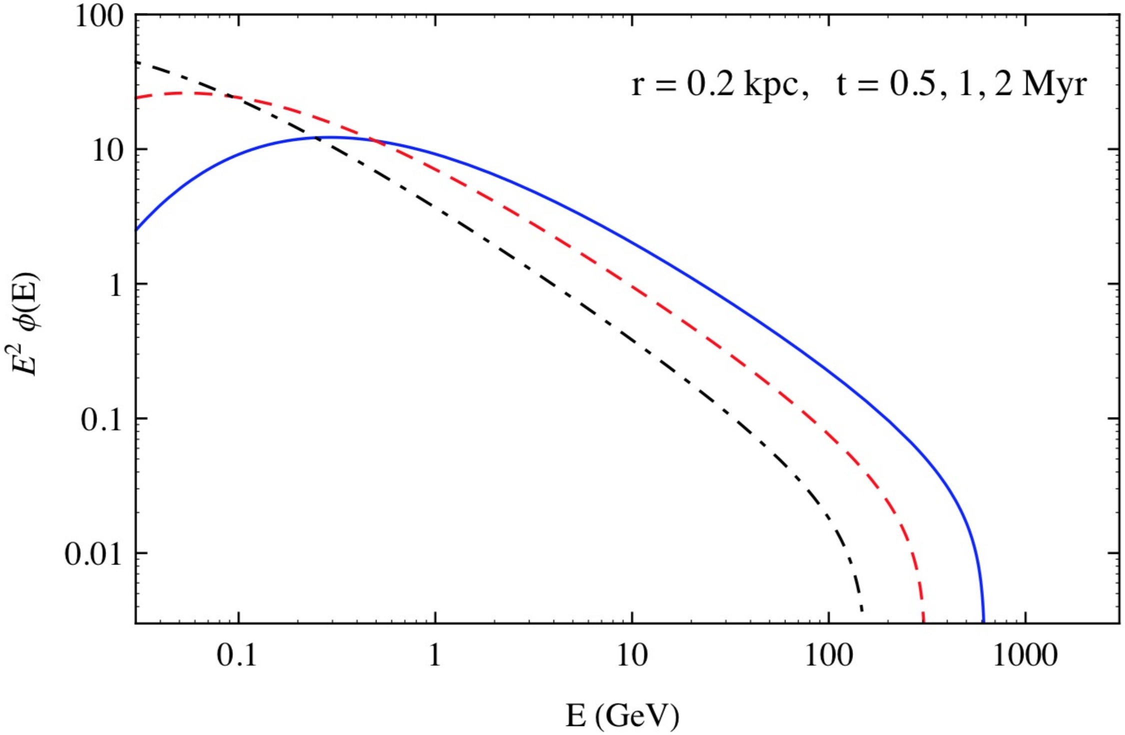
$$R^2(E, t) = 2\;D(E)\;t\;\rho(b\,E\,t)$$

$$\rho(x) = \frac{1-(1-x)^{(1-\delta)}}{(1-\delta)\;x}$$

$$1 \leq \rho(x) \leq (1-\delta)^{-1}$$



Changing r
(same age)



Changing t
(same distance)

An ensemble of many such sources
all equal to each other
uniformly distributed in a thin layer around
the Solar system
with a constant rate $f = 1/T_s$

Result (neglect escape) in a power law flux:

$$\phi(E) = \frac{c}{4\pi} \frac{k(\alpha,\delta)}{\sqrt{4\pi}} \frac{q_0}{T_s} \frac{1}{\sqrt{D_0\, b}} E^{-[\alpha+(1+\delta)/2]}$$

Identical fluxes can be generated by

Many weak sources, or
Few strong sources

But:
"granularity" effects
(discrete sources)

“MonteCarlo study of source configurations

Divide the space time into two regions:

Far, old sources

$$r > r_{\text{cut}}$$

$$t > t_{\text{cut}}$$

Treated as a continuous
“smooth emission”

Near, young sources

$$r < r_{\text{cut}}$$

$$t < t_{\text{cut}}$$

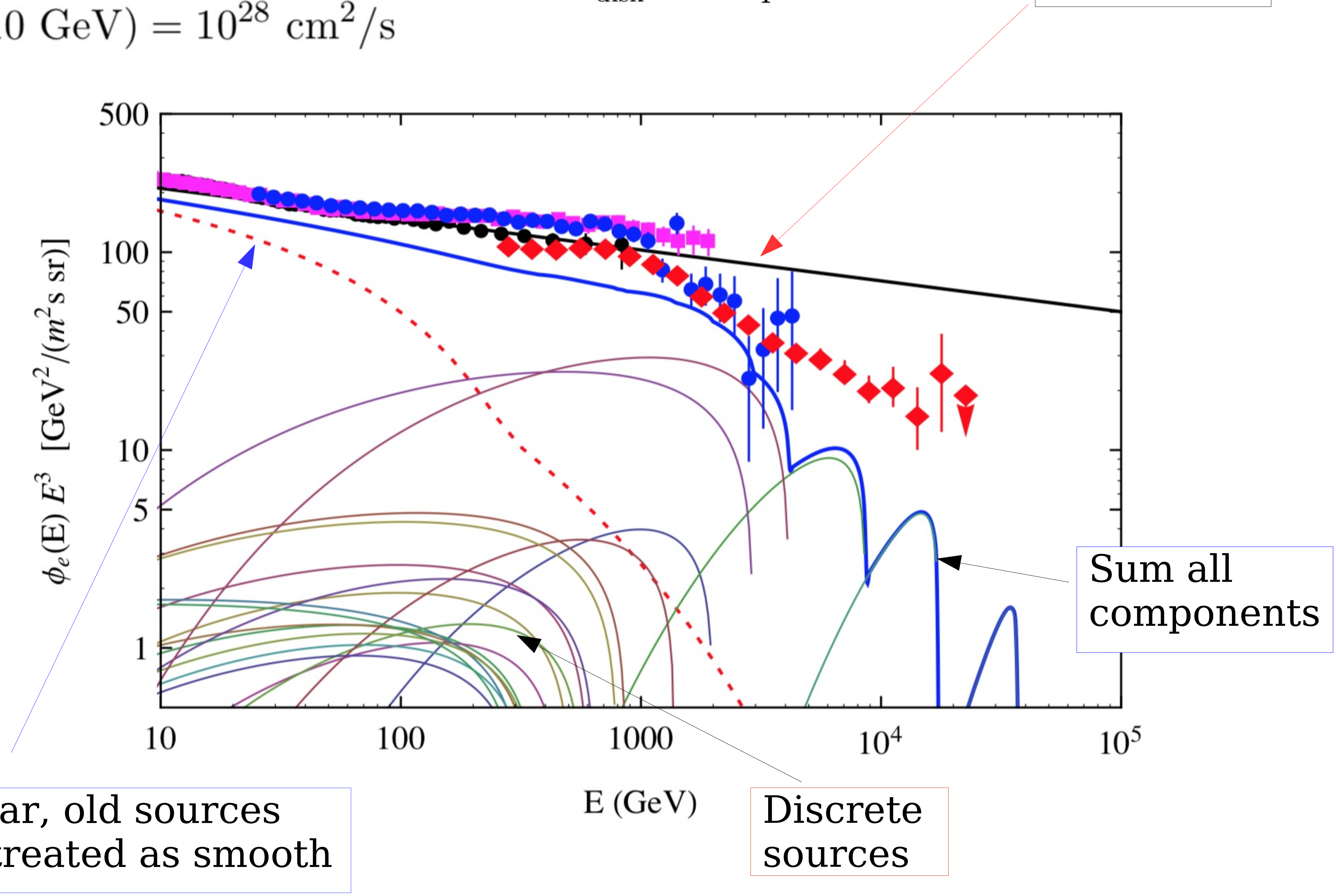
Treated as individual sources
(generating randomly
one configuration)

Randomly generated configuration of sources

$T_s = 50$ yr

$R_{\mathrm{disk}} = 15$ kpc

$D(10 \text{ GeV}) = 10^{28} \text{ cm}^2/\text{s}$



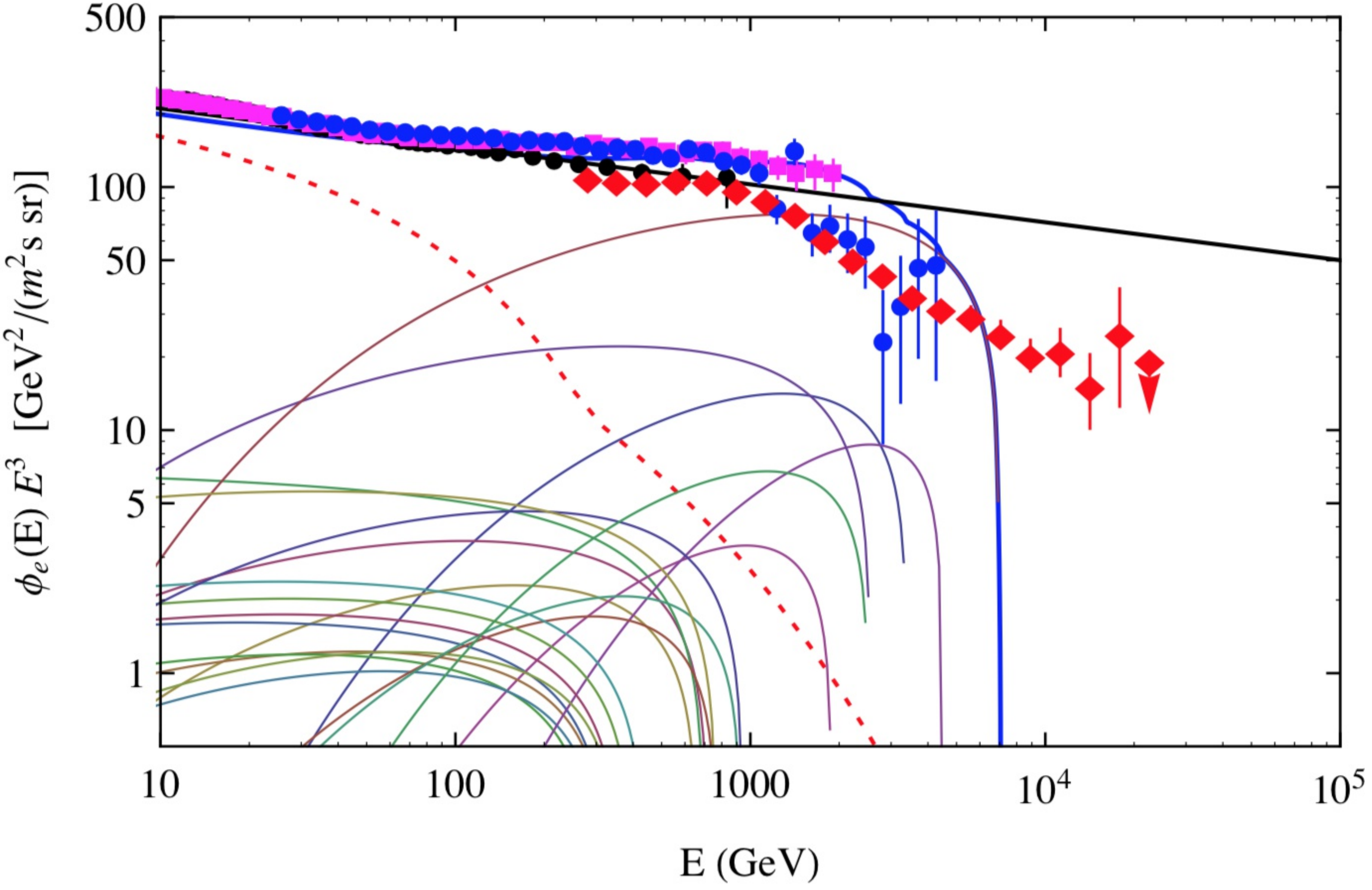
smooth distribution limit

Sum all components

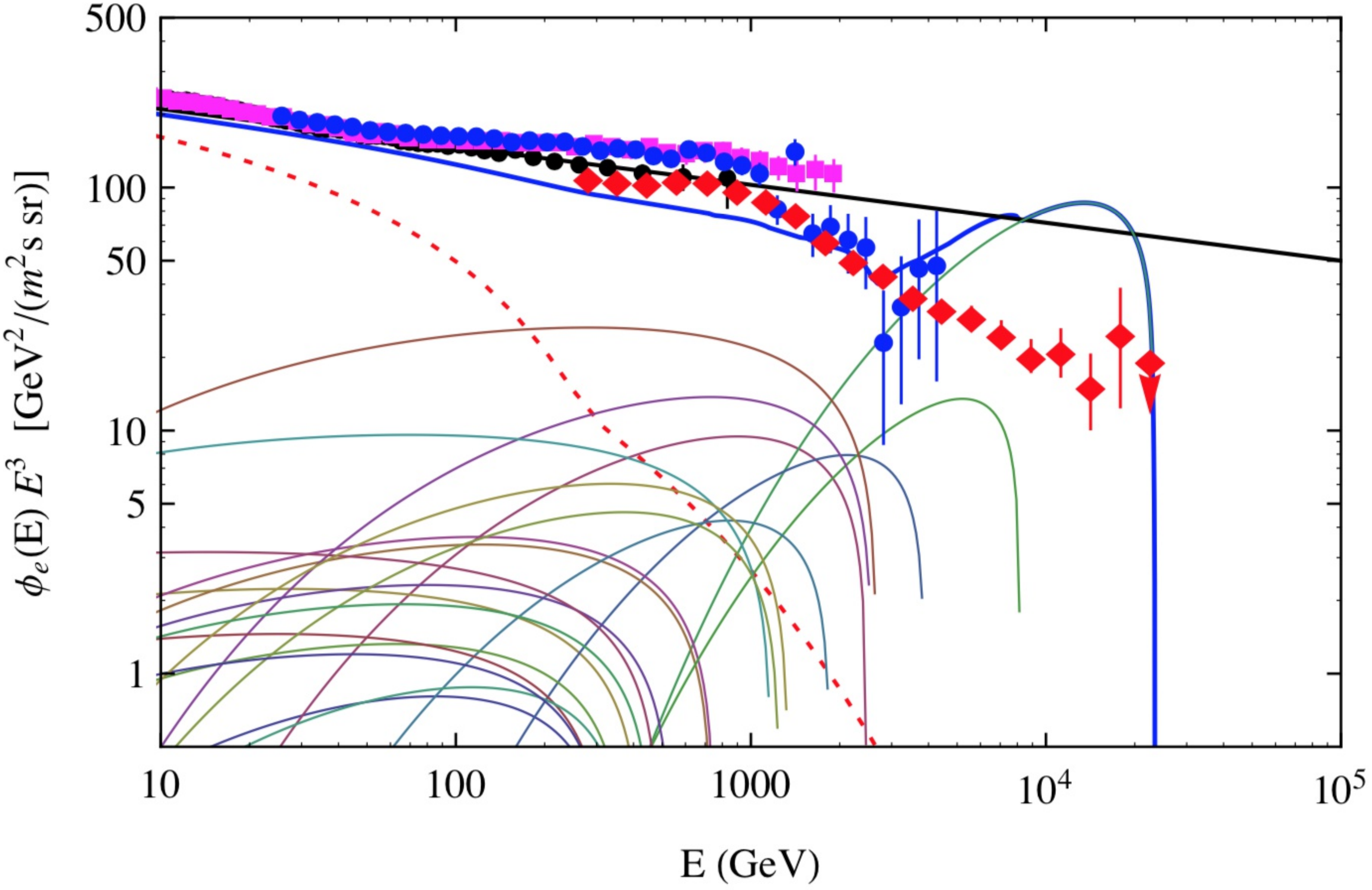
Far, old sources (treated as smooth

Discrete sources

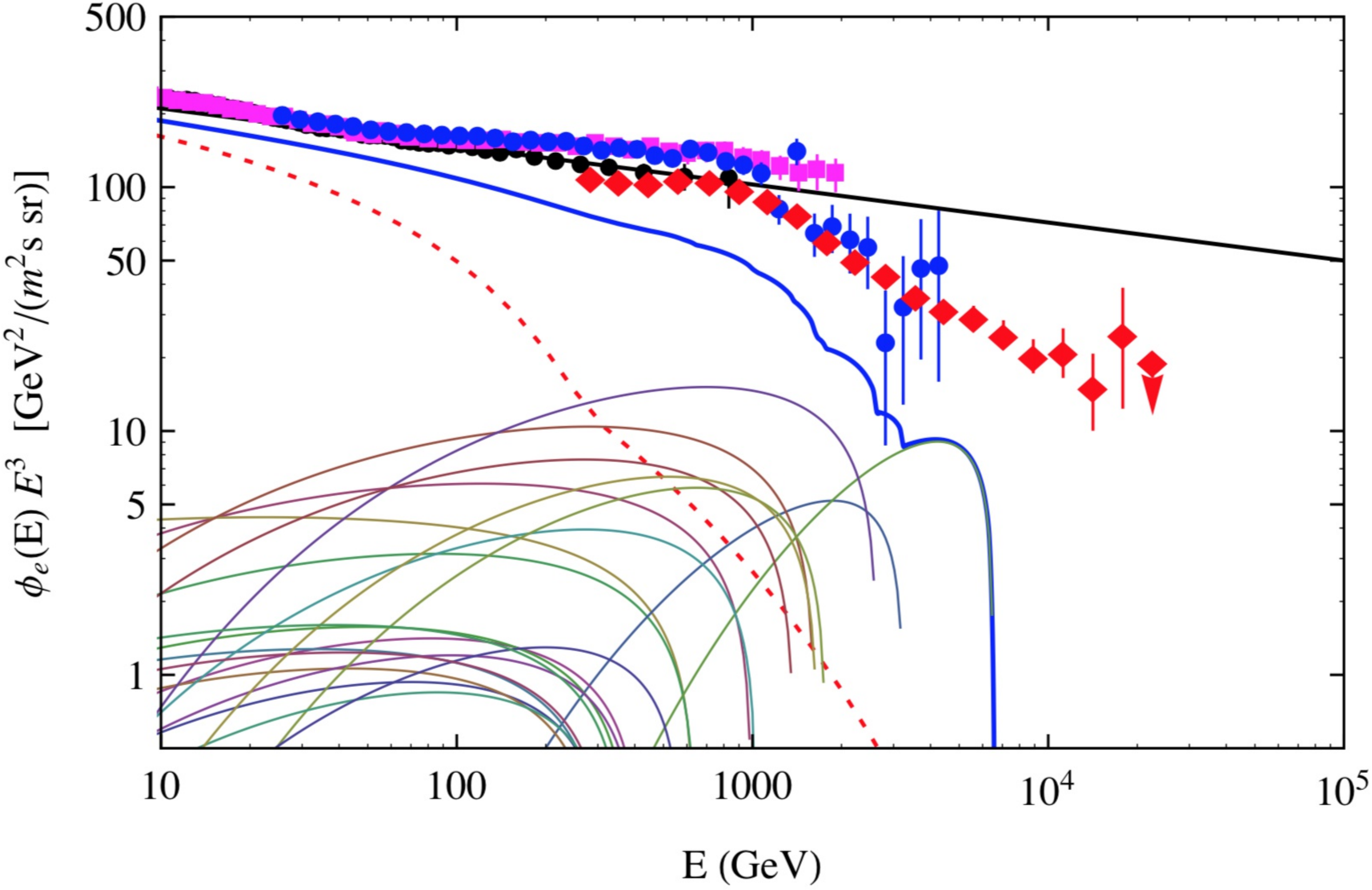
One more randomly generated configuration of sources [2]



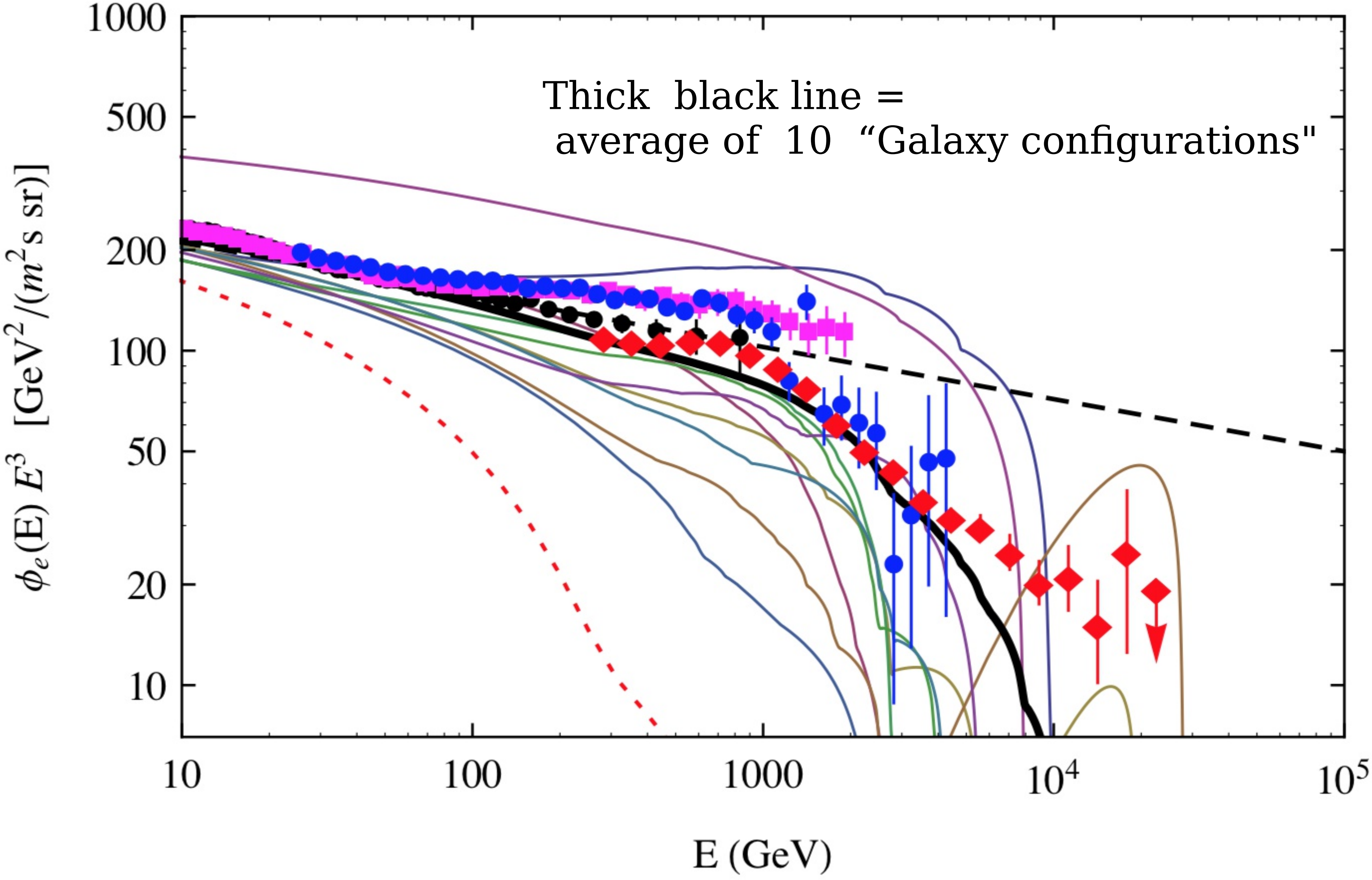
One more randomly generated configuration of sources [3]



One more randomly generated configuration of sources [4]



10 configurations [Sum of all contributions]



Thick black line =
average of 10 “Galaxy configurations"

Conclusion from this numerical study

In the framework of the model described above
(short CR lifetime, explosive sources)

It is *very difficult* to explain the
observed spectral shape
with a sharp break to a steeper power law form

Conclusion from this numerical study

In the framework of the model described above
(short CR lifetime, explosive sources)

It is *very difficult* to explain the
observed spectral shape
with a sharp break to a steeper power law form

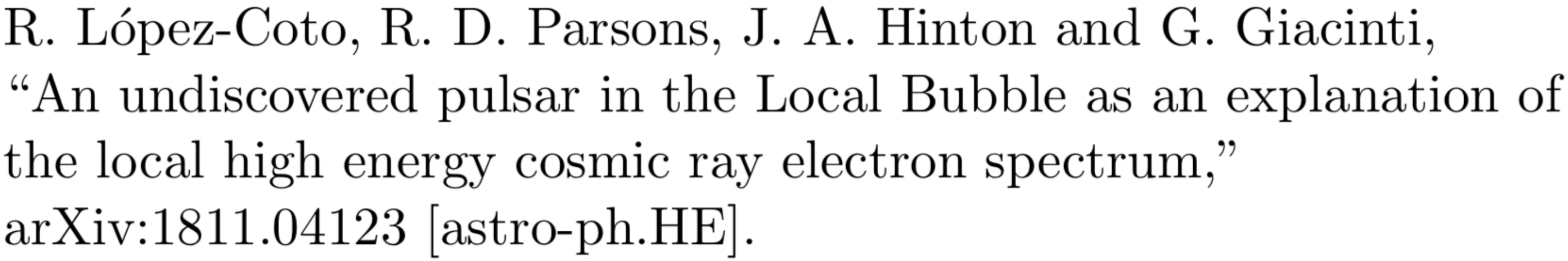
Solutions ….. ?

[1.] High critical energy (large propagation distance)

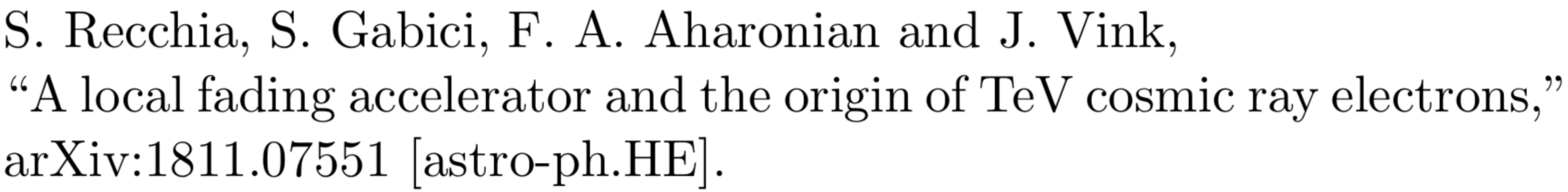
[2.] Modify the source model

The *“Just so”* solution to the *“local sources problem*"

Hypothesis: ONE single log duration source is responsible for the spectral break in the all-electron spectrum



R. López-Coto, R. D. Parsons, J. A. Hinton and G. Giacinti,
“An undiscovered pulsar in the Local Bubble as an explanation of the local high energy cosmic ray electron spectrum,”
arXiv:1811.04123 [astro-ph.HE].



S. Recchia, S. Gabici, F. A. Aharonian and J. Vink,
“A local fading accelerator and the origin of TeV cosmic ray electrons,”
arXiv:1811.07551 [astro-ph.HE].

Emission from a source is extended in time

Simplest hypothesis: a factorized spectrum

$$q_s(E,t) = q_0 \; E^{-\alpha} \; F(t - t_i)$$

Time dependence motivated by
the PULSAR breaking law

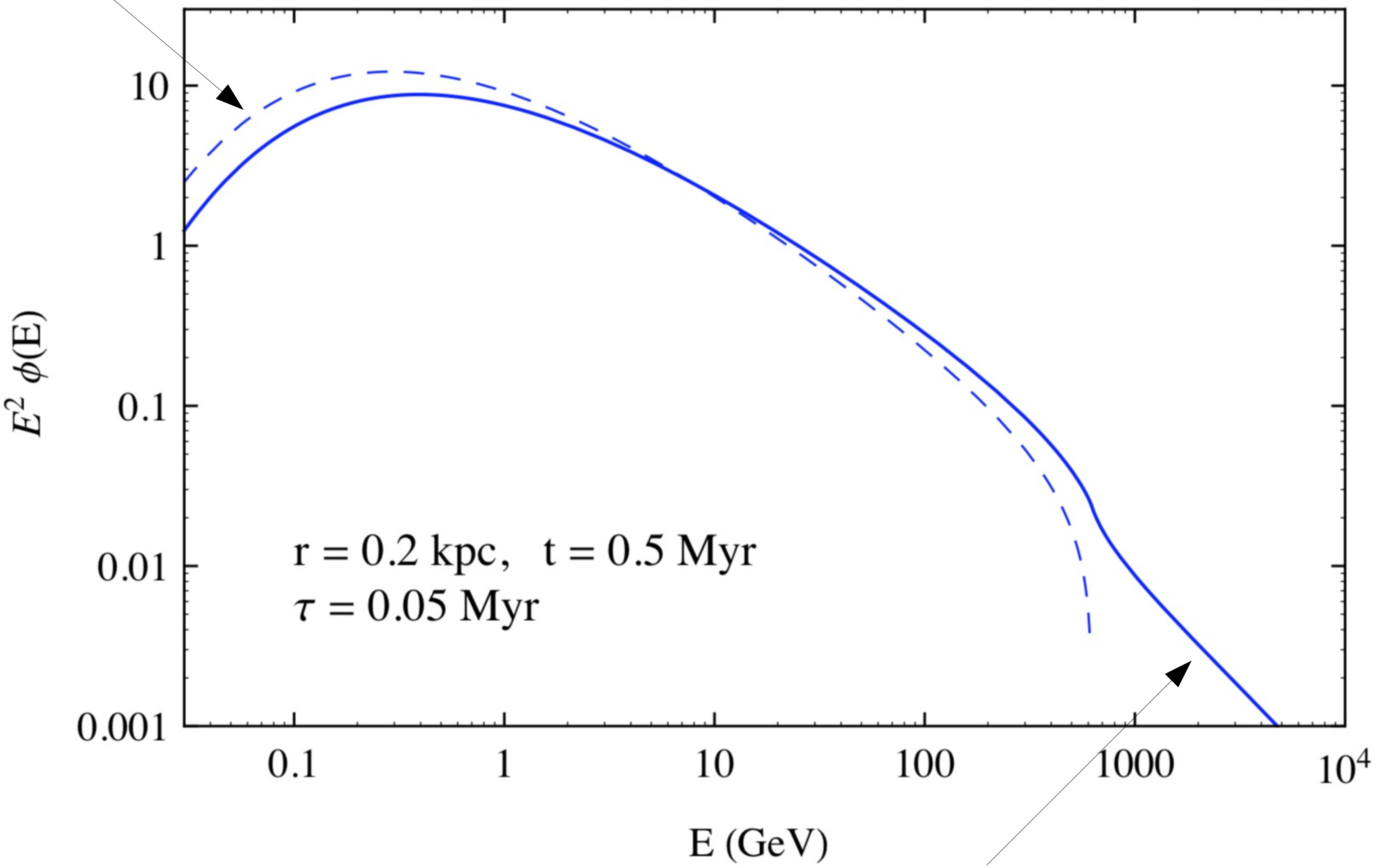
$$q_s(E,t) = q_0 \; E^{-\alpha} \boxed{\frac{(p-1)}{\tau} \; \left[1 + \frac{(t-t_i)}{\tau}\right]^{-p}}$$

$p =$ breaking index

$$\int_0^\infty dt \; F(t) = 1$$

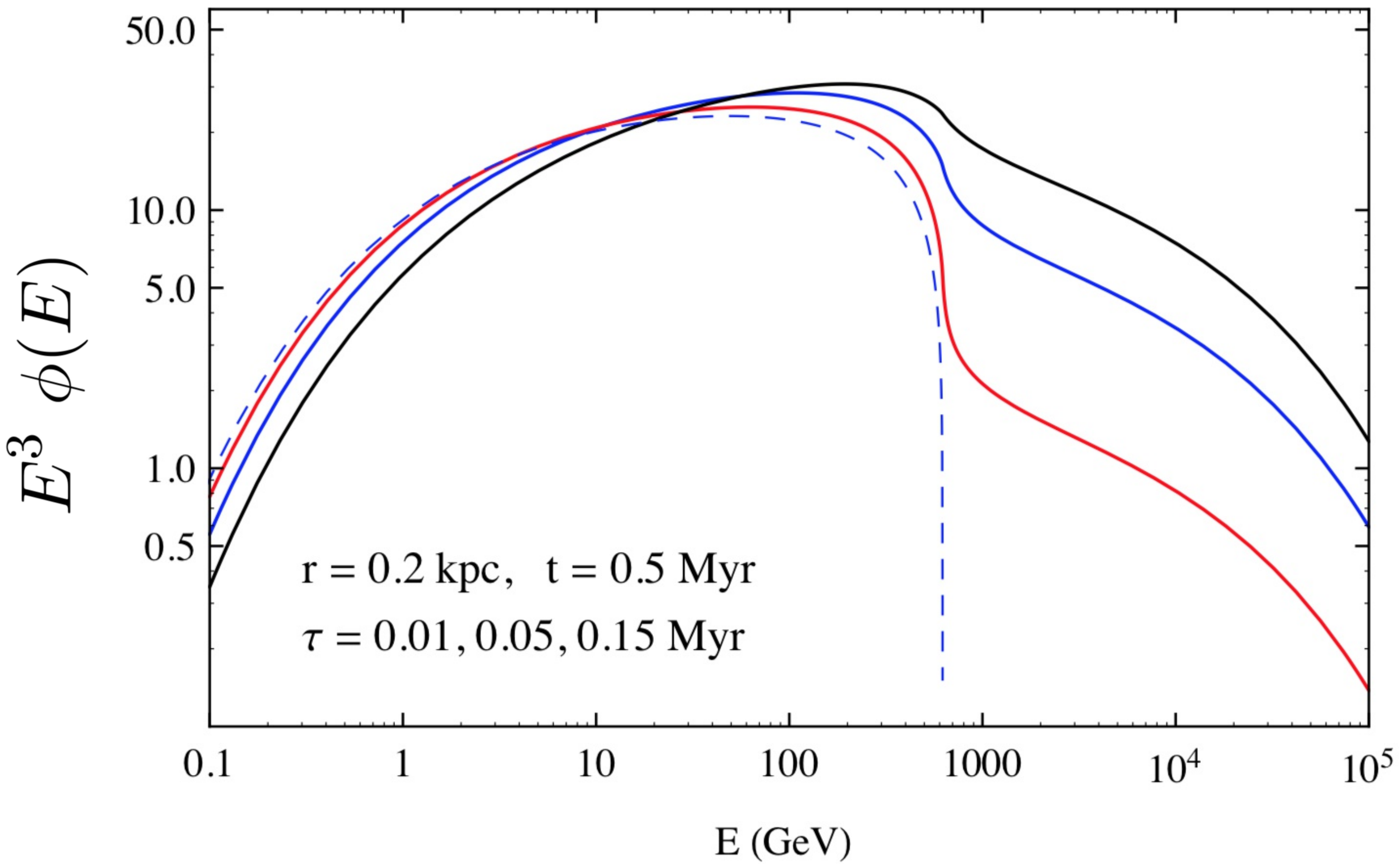
Fading source $p = 2$

Dashed line
Instantaneous source

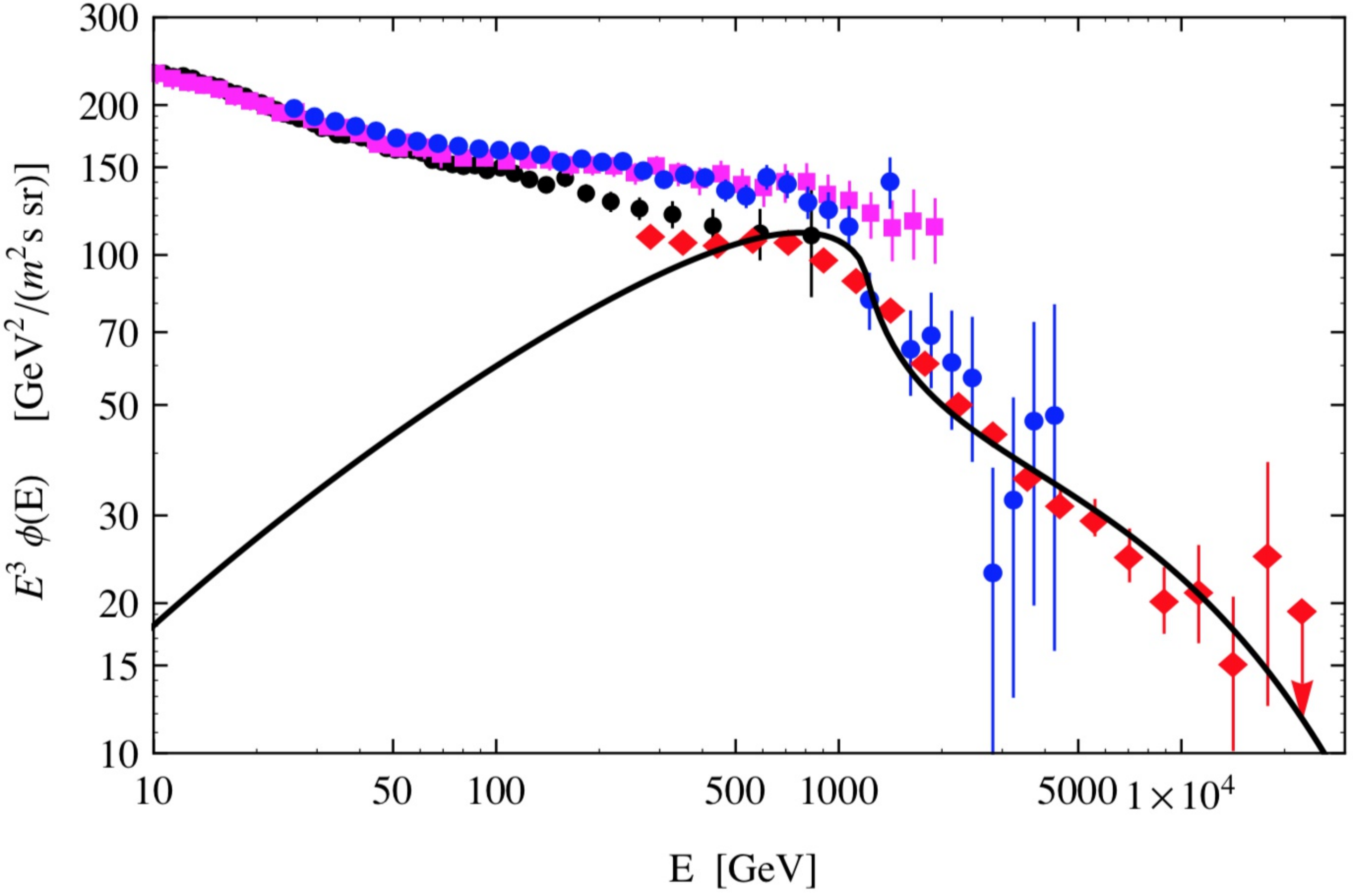


High energy tail

changing source decay time tau:



Matching the spectral break with ONE "fading" source



$r = 157$ kpc

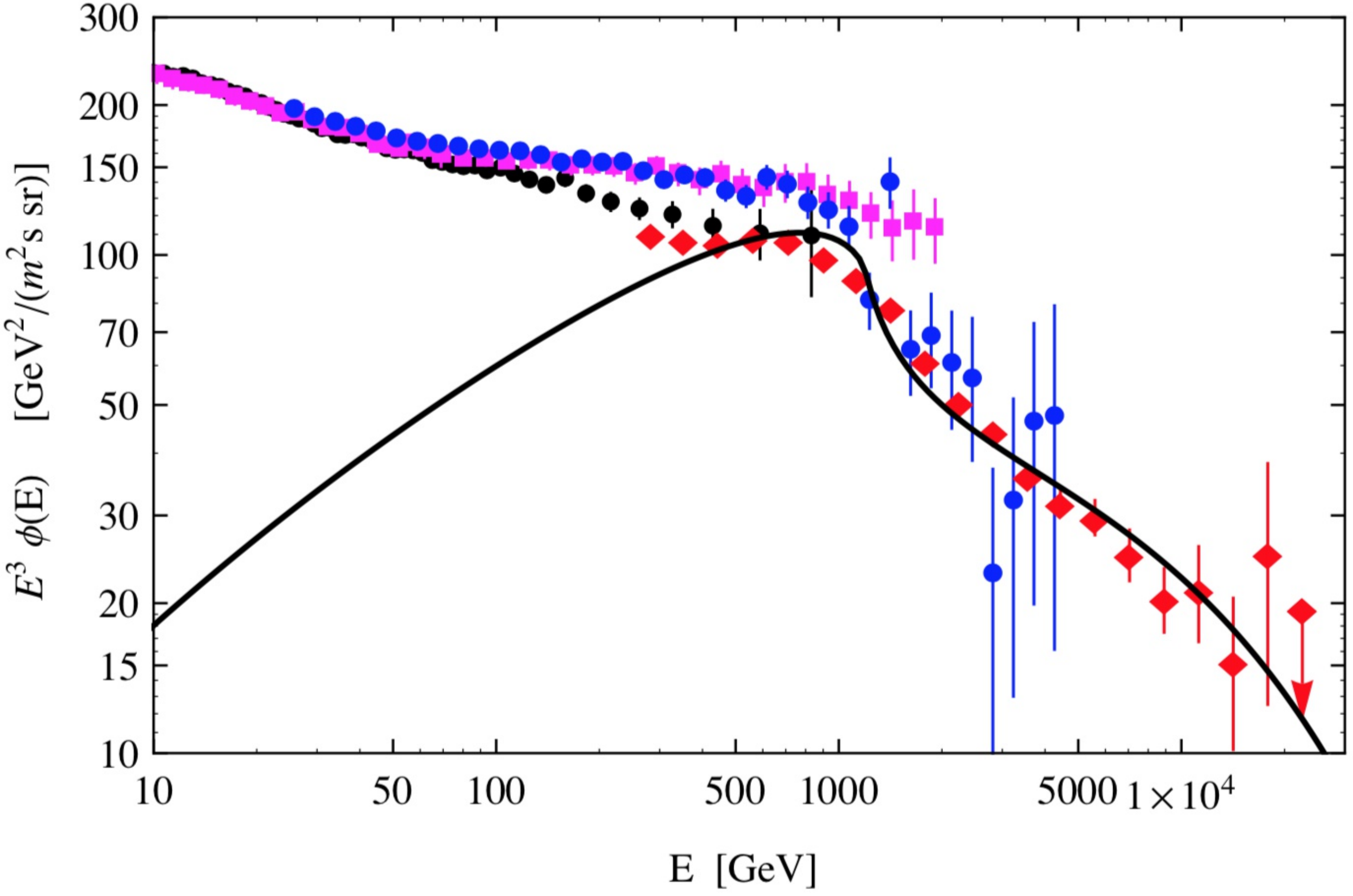
$t = 260$ kyr

$\tau = 40$ kyr

$\mathcal{E} = 1.1\times10^{48}$ erg

Possible to match the break with emission from one source

Matching the spectral break with ONE "fading" source



$r = 157$ kpc

$t = 260$ kyr

$\tau = 40$ kyr

$\mathcal{E} = 1.1 \times 10^{48}$ erg

Possible to match the break with emission from one source

[can one match the entire spectrum ?]

Note on the solution:

The source distance r
enters the flux
In the combination:

$$\frac{r^2}{D(E)\,t}$$

Flux absolute
Normalization

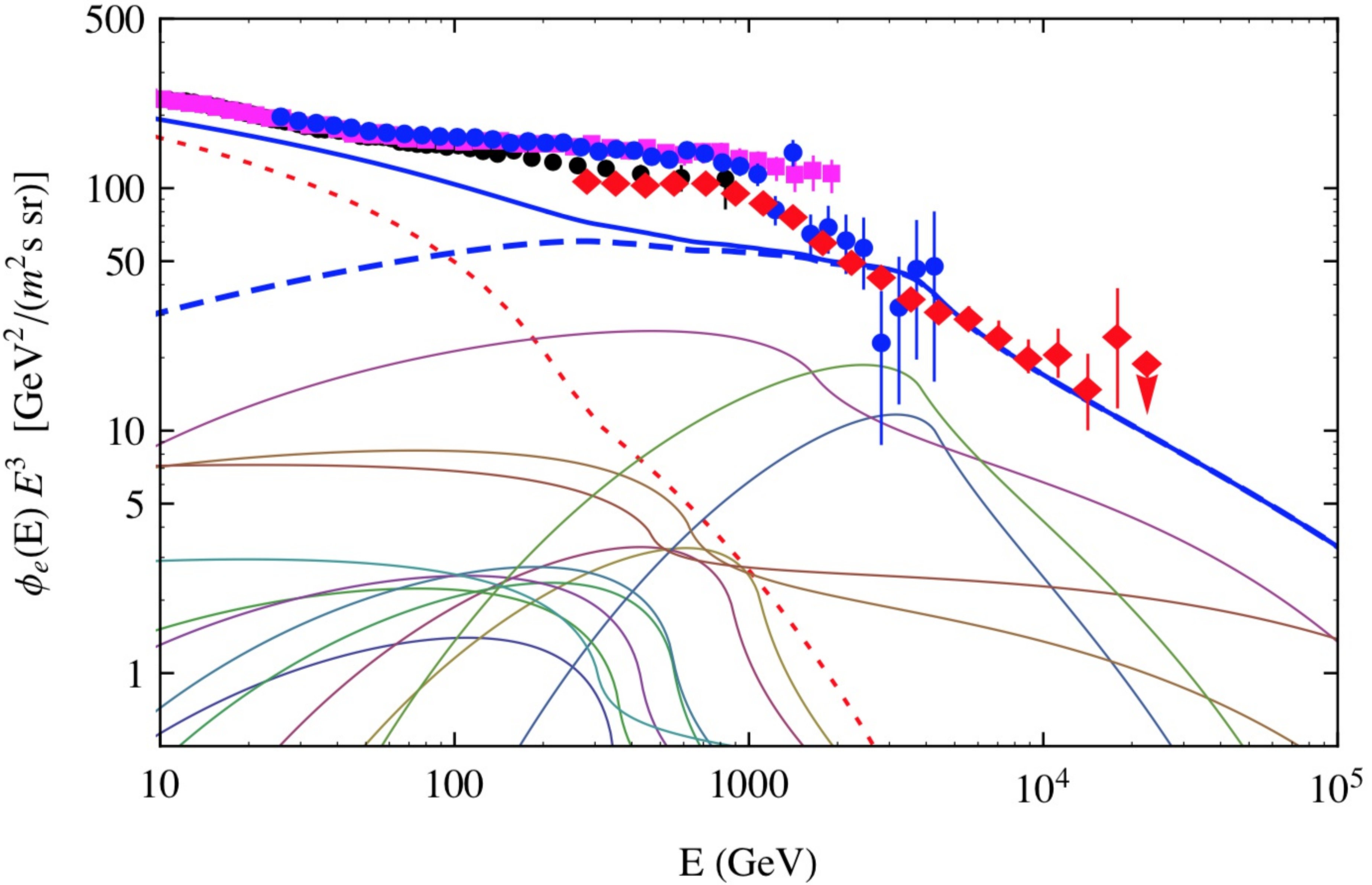
$$\propto \frac{\mathcal{E}}{(D_0)^3}$$

Infinite identical solutions:

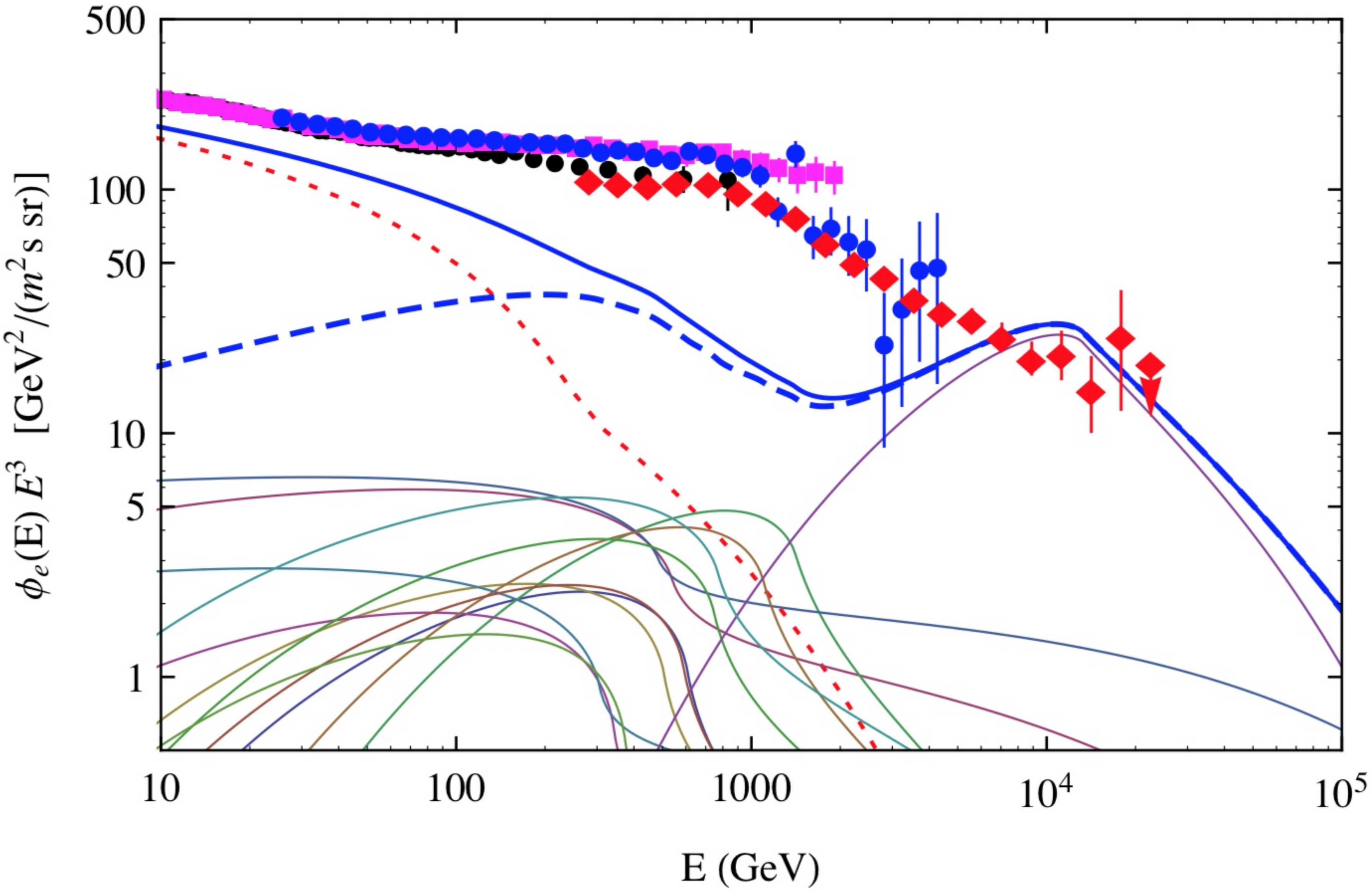
$$\{D_0\ ,\ r,\ \ \mathcal{E},\ \ \ldots\ \}$$

$$\{D_0'\ ,\ r\ (D_0'/D_0)^{1/2},\ \ \mathcal{E}\ (D_0'/D_0)^{3/2},\ \ \ldots\ \ \}$$

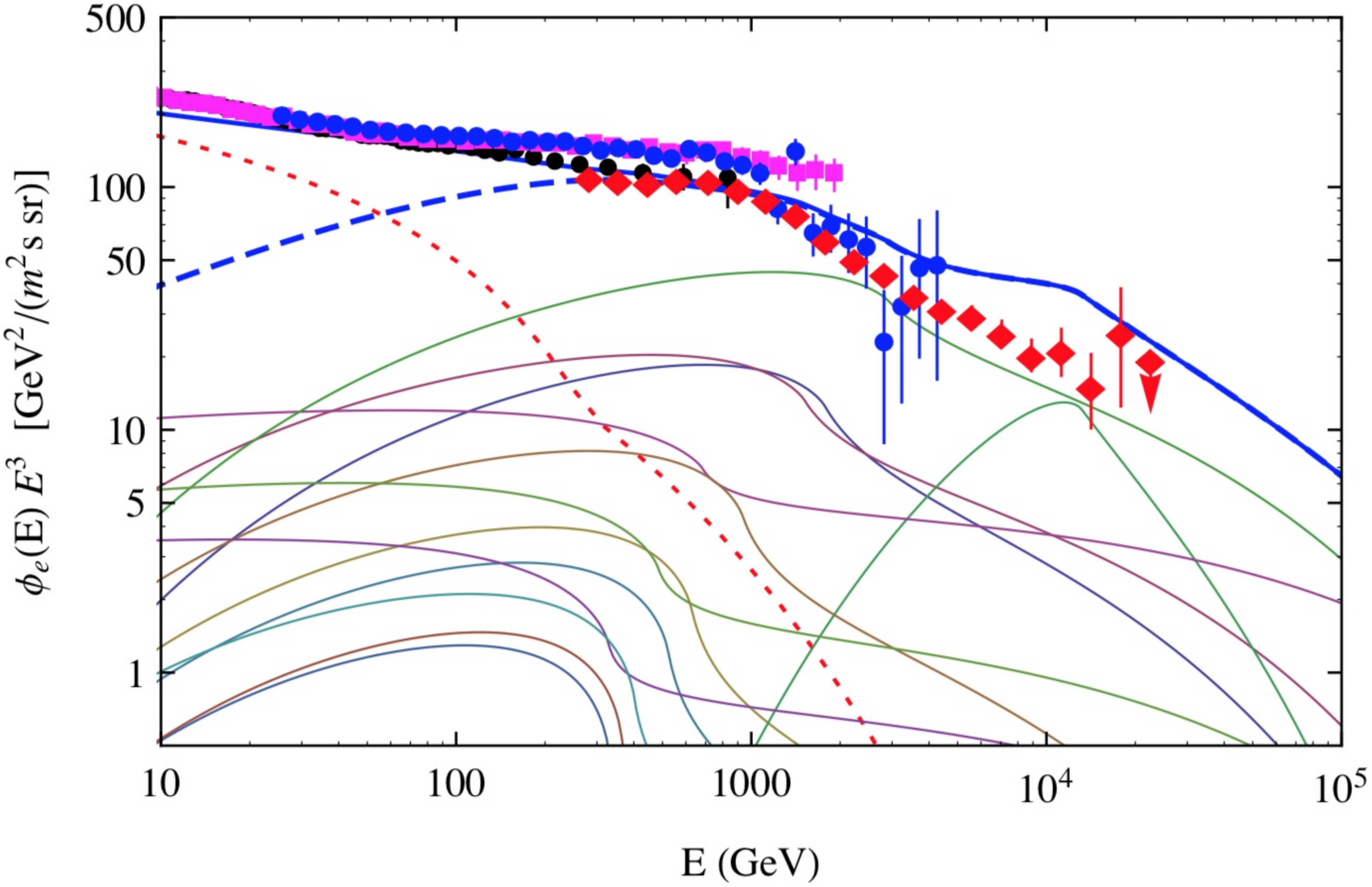
Study ensemble of fading sources



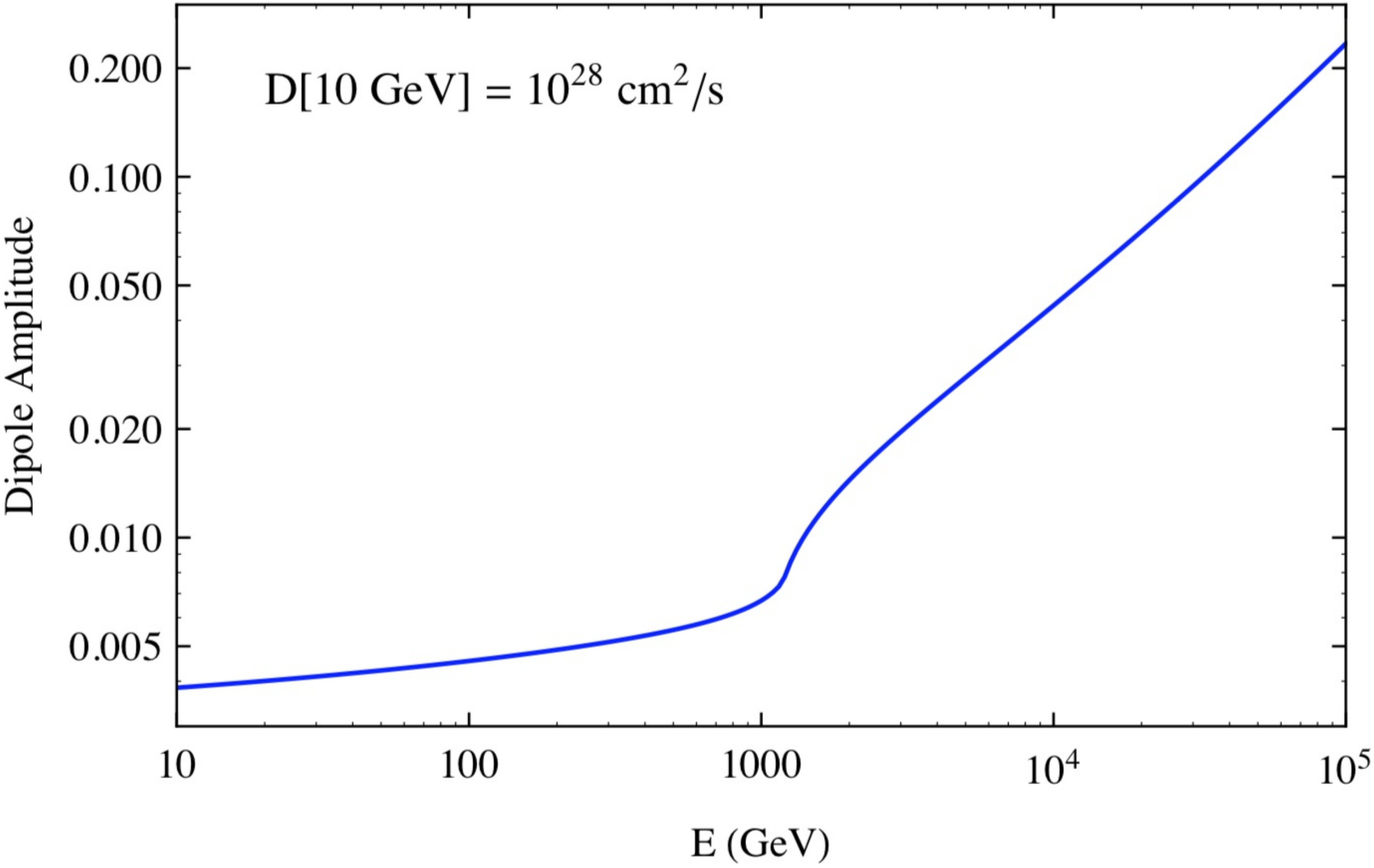
One random Galactic configuration [2]



One random Galactic configuration [e]



Dipole moment of the angular distribution



Comments:

Interesting solution,
But… still requires "significant fine tuning"
to generate a spectrum similar to the observed one
with no additional structure.
[transition many sources → One source]

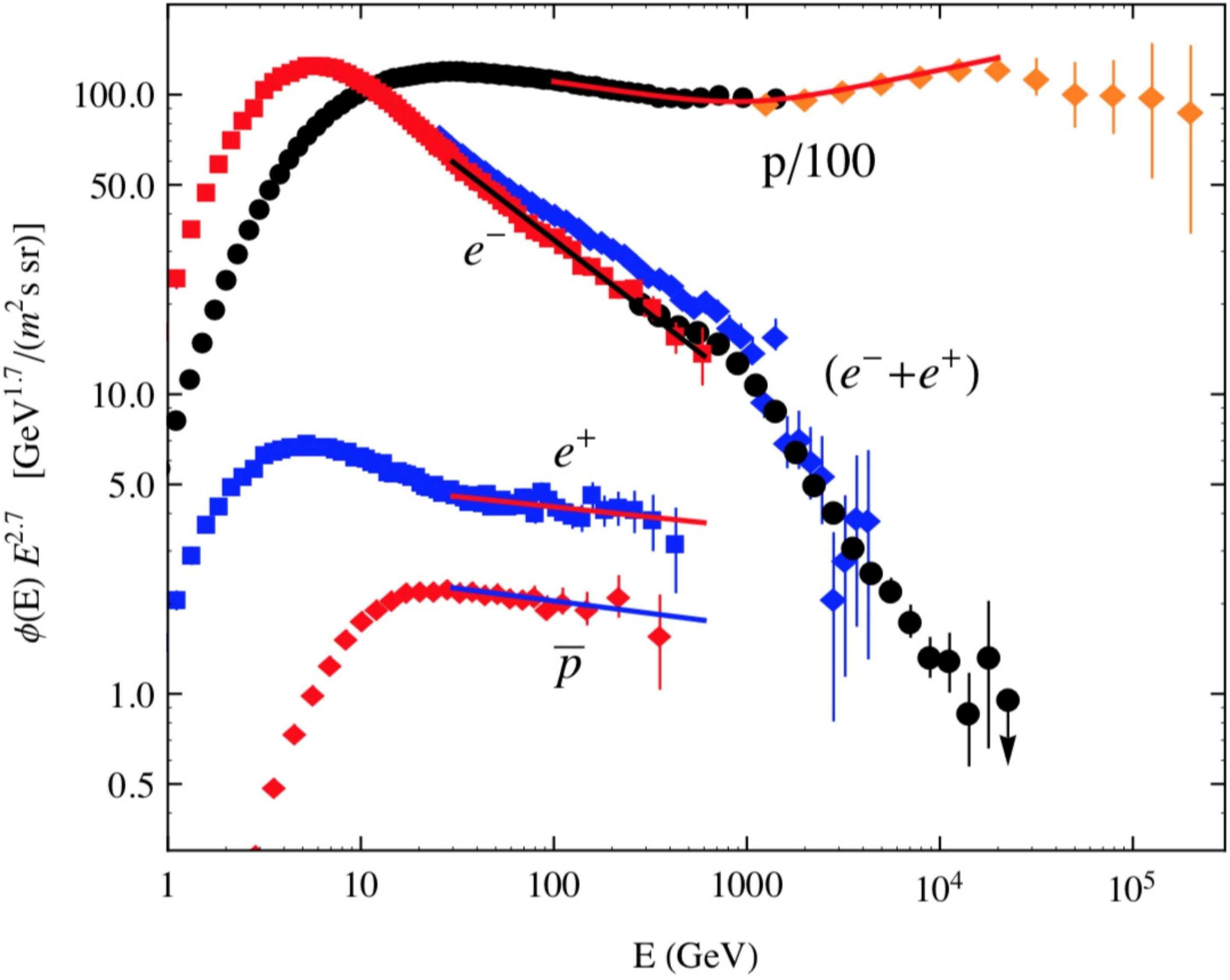
Very important astrophysical implications:

Are Pulsar-like sources the main sources
of electrons ? [and also positrons ?]

Do Pulsars accelerate protons ?

What about Supernovae ?

Profound astrophysical implications of the cosmic ray residence time.



e^- p

e^+ $\overline{p}$

“Conventional mechanism” for the production of positrons and antiprotons:

Creation of secondaries in the inelastic hadronic interactions of cosmic rays in the interstellar medium

$$pp \to \overline{p} + \ldots$$

$$pp \to \pi^+ + \ldots$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_e + \overline{\nu}_\mu$$

$$pp \to \pi^\circ + \ldots$$
$$\hookrightarrow \gamma + \gamma$$

“Standard mechanism” for the generation of positrons and anti-protons

Dominant mechanism for the generation of high energy gamma rays

intimately connected

Straightforward [hadronic physics] exercise:

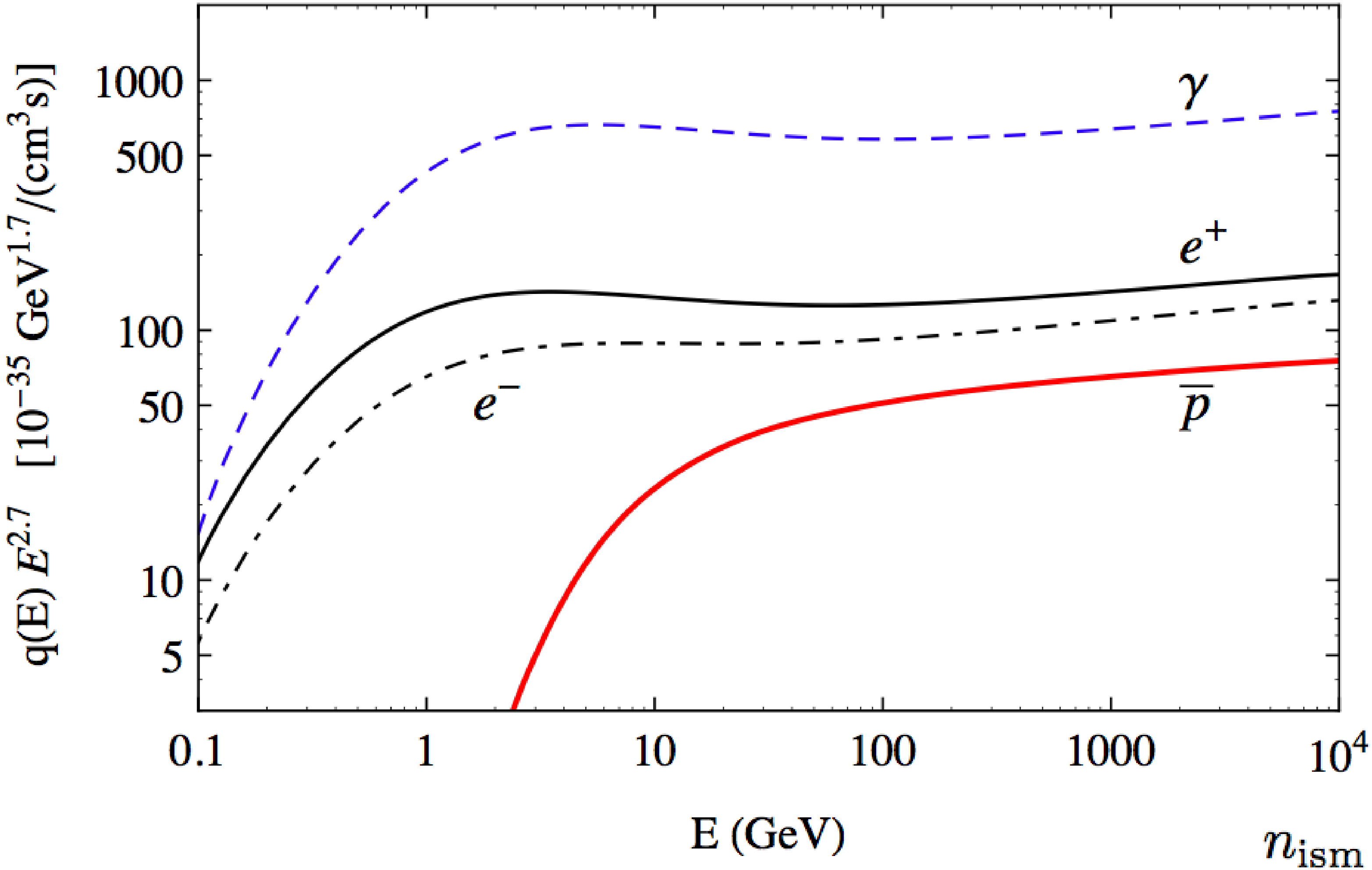
[1] Take spectra of cosmic rays (protons + nuclei) observed at the Earth

[2] Make them interact in the local interstellar medium (pp, p-He, He-p,...)

[3] Compute the rate of production of secondaries

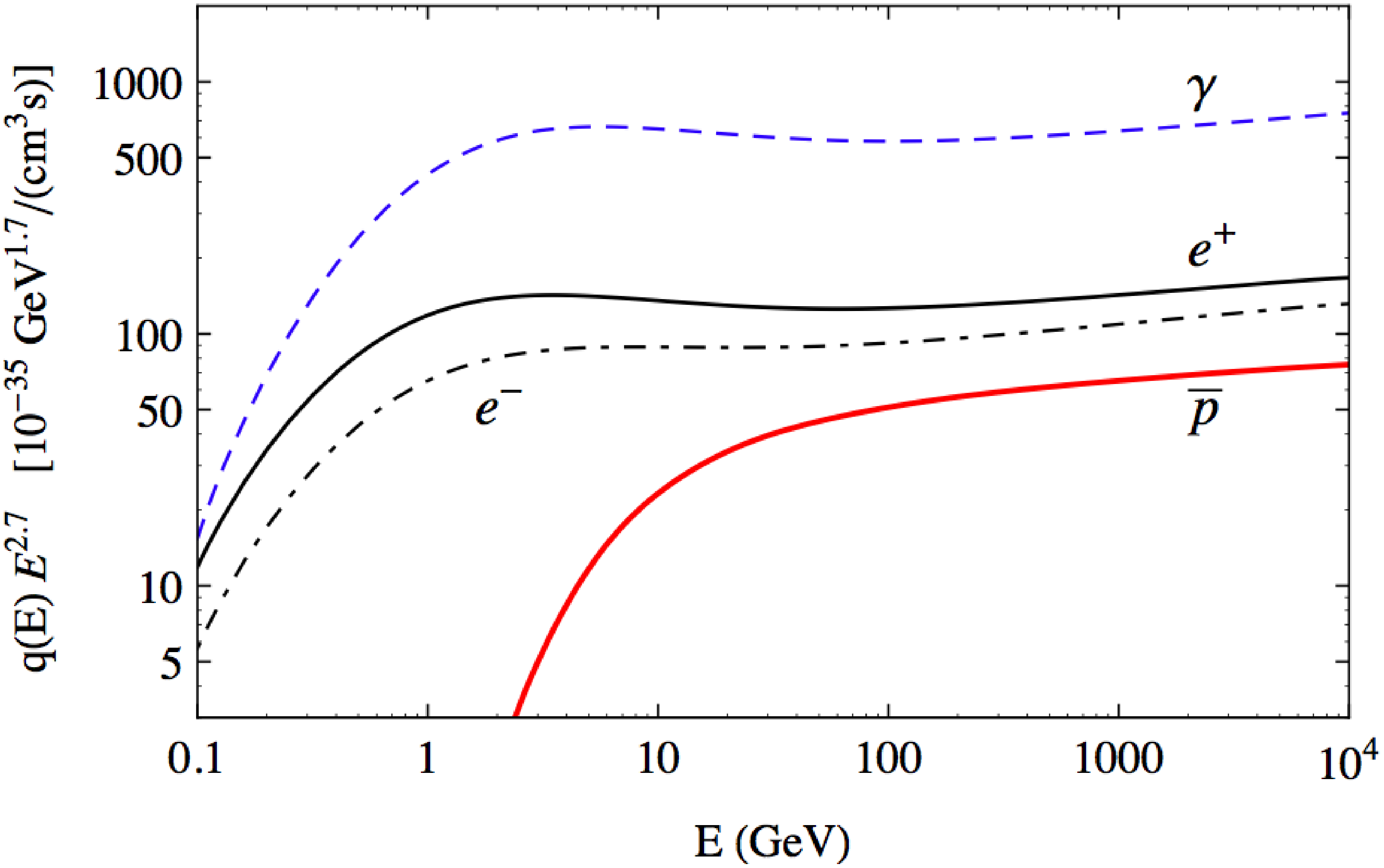
$$q_j(E, \vec{x}_\odot)$$

$[\mathrm{cm}^3 \text{ s GeV}]^{-1}$



$$n_{\mathrm{ism}}(\vec{x}_\odot) = 1\ \mathrm{cm}^{-3}$$

“Local” Rate of production of secondaries



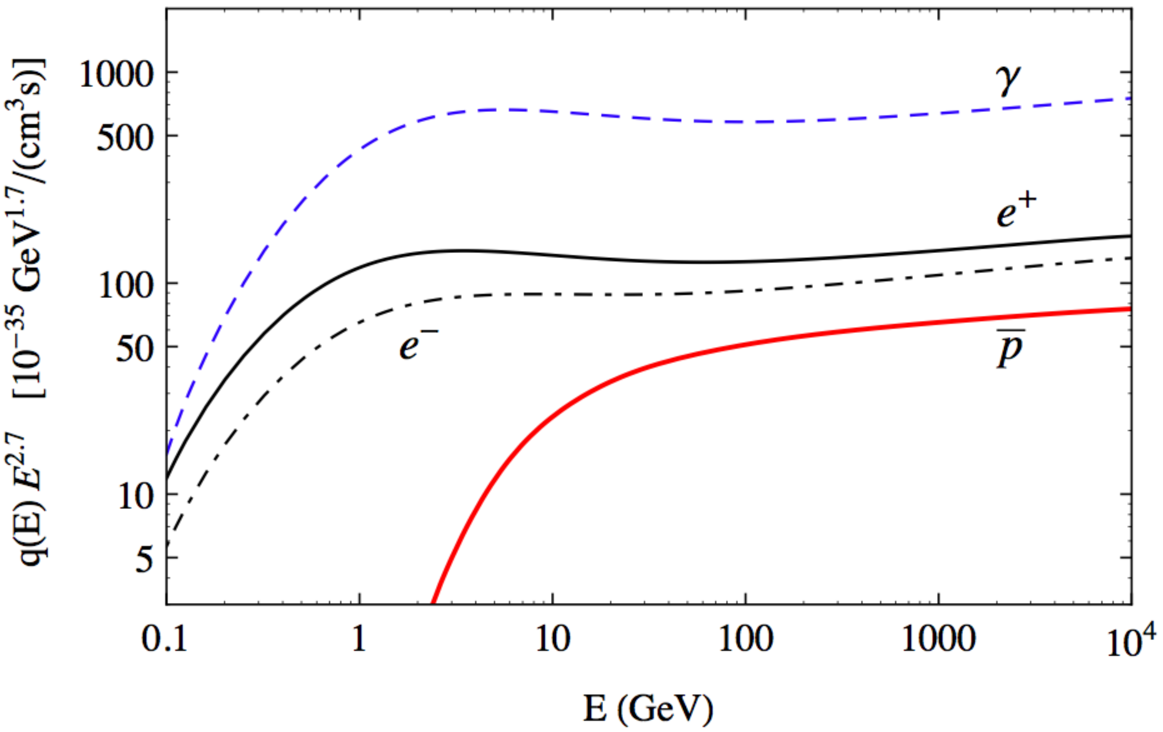
$$\frac{\gamma}{e^+} \approx 5.5$$

$$\frac{e^-}{e^+} \approx 0.8$$

$$\frac{e^+}{\overline{p}} \approx 2.0$$

Different low energy behaviors
(low energy antiproton production suppressed)

Power Law behavior at high energy

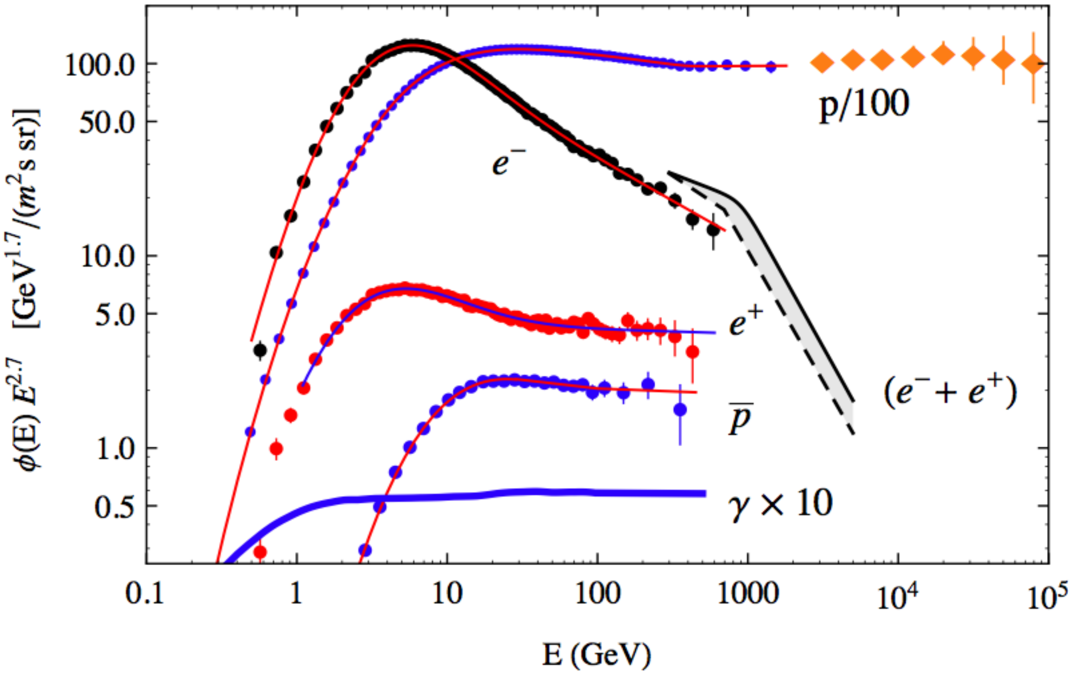


Local production rates of secondaries

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

“striking” similarity

Observed fluxes



$$\boxed{\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} \approx \frac{q^{\rm loc}_{e^+}(E)}{q^{\rm loc}_{\overline{p}}(E)}}$$

The ratio positron/antiproton
Local source (secondary production)
(within systematic uncertainties)
is equal to the ratio of the observed fluxes

Does this result has a
"natural explanation" ?

There is a simple, natural interpretation that
“leaps out of the slide” :

1. The “standard mechanism of secondary production is the main source of the antiparticles (and of the gamma rays)

2. Cosmic rays in the Galaxy (that generate the antiparticles and the photons) have spectra similar to what is observed at the Earth.

3. *The Galactic propagation effects for positrons and antiprotons are approximately equal*

4. The propagation effects have only a weak energy dependence.

The Logic of the discussion on the positron flux:

$$\phi_j(E) = q_j(E)\ \mathcal{P}_j(E)$$

Flux of particle type j is the source spectrum “distorted” by propagation effect.

Apply to positrons:

$$\phi_{e^+}(E) = [q_{e^+}^{\mathrm{sec}}(E) + \boxed{q_{e^+}^{\mathrm{new}}(E)}]\ \mathcal{P}_{e^+}(E)$$

DATA

model

New source
of positrons
(DM, pulsars,...)

model

Phenomenological observation

$$\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} \approx \frac{q^{\rm sec}_{e^+}(E)}{q^{\rm sec}_{\overline{p}}(E)}$$

$$\phi_j(E) = q_j(E)\ \mathcal{P}_j(E)$$

Conventional scenario

Positrons have
an "energy loss sink"

$$\mathcal{P}_{e^+}(E) < \mathcal{P}_{\overline{p}}(E)$$

Meaningless (but strange)
numerical coincidence

$$[q^{\rm sec}_{e^+}(E) + q^{\rm new}_{e^+}(E)]\ \mathcal{P}_{e^+}(E) \approx$$

$$\approx q^{\rm sec}_{e^+}(E)\ \mathcal{P}_{\overline{p}}(E)$$

"Natural" explanation

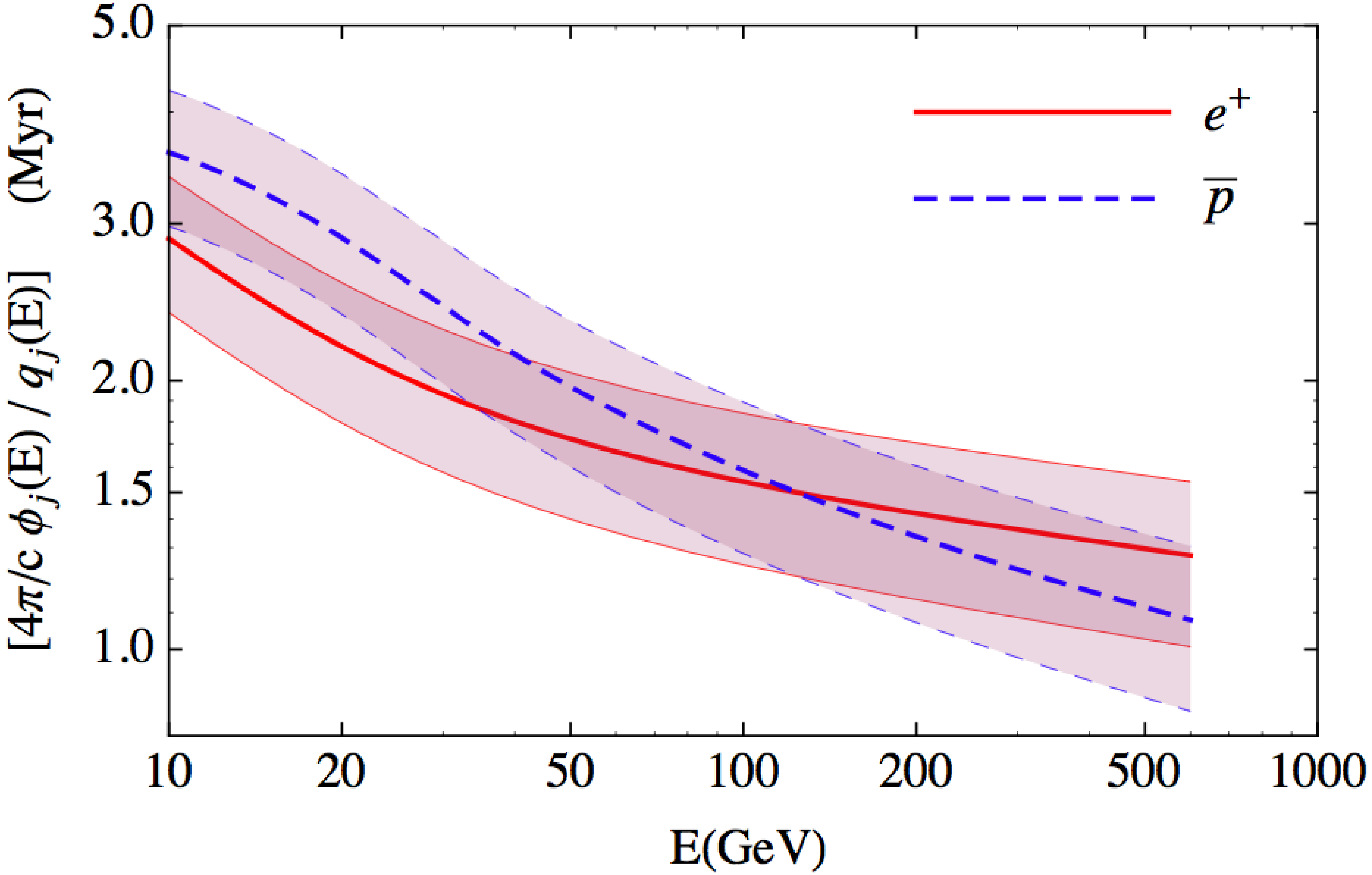
$$\mathcal{P}_{e^+}(E) \approx \mathcal{P}_{\overline{p}}(E)$$

$$q_{e^+}(E) \simeq q^{\rm sec}_{e^+}(E)$$

$$q_{\overline{p}}(E) \simeq q^{\rm sec}_{\overline{p}}(E)$$

$$\frac{\phi_{\overline{p}}(E)}{q^{\rm loc}_{\overline{p}}(E)} \approx \frac{\phi_{e^+}(E)}{q^{\rm loc}_{e^+}(E)}$$

Distortion of the source spectra created by propagation



Weak energy dependence of the propagation effects !

Crucial questions for e+- spectra :

[1.] Where is the critical energy where
(synchrotron + Compton) Energy losses
become dominant in e-/e+ propagation ?

*(what are the spectral features
that show these transitions ?)*

[2.] Are there multiple components in the
electron and positron spectra ?

(Do different sources dominate the spectra
in different energy range ?
Where are these transitions ?)

[3.] Do very local (or just one very local) source(s)
dominate the TeV electron and positron spectra ?

[4.] *What is the origin of the all electron break
at ~1 TeV ?*

The observations of the anti-particle fluxes

brings us to a *“Crossroad”*
in our studies of Cosmic Rays

electrons
positrons

protons
antiprotons

Propagation properties
in the Milky Way

[A] *“Conventional Scenario”*

Different propagation properties for $E \gtrsim 3\ \mathrm{GeV}$

[B] *“Alternative Scenario”*

Equal propagation properties for $E \lesssim 900\ \mathrm{GeV}$

Conventional propagation scenario:

A1. Very long lifetime for cosmic rays

A2. Difference between electron and proton spectra shaped by propagation effects

A3. New hard source of positrons is required

A4. Secondary nuclei generated in interstellar space

Alternative propagation scenario:

B1. Short lifetime for cosmic rays

B2. Difference between electron and proton spectra generated in the accelerators

B3. antiprotons and positrons of secondary origin

B4. Most secondary nuclei generated in/close to accelerators

How can one discriminate between the two scenarios ?

1. Extend measurements of e+- spectra
   Different cutoffs can confirm the conventional picture

2. More precise measuremens of (e+ + e-) spectra
   in the multi-TeV range

3. Extend measurements of secondary nuclei
   [B, Be, Li]. Look for signatures of
   nuclear fragmentation inside/near the accelerators.

4. Study the space and energy distributions
   of the relativistic e+- in the Milky Way
   [from the analysis of diffuse Galactic gamma ray flux]

5. Develop an understanding of the CR sources
   Study the populations of e- and p in young SNR
   (assuming that they are the main sources of CR)

Conclusions:

An understanding of the origin of the
electron, positron and antiproton fluxes
is of central importance for High Energy Astrophysics.

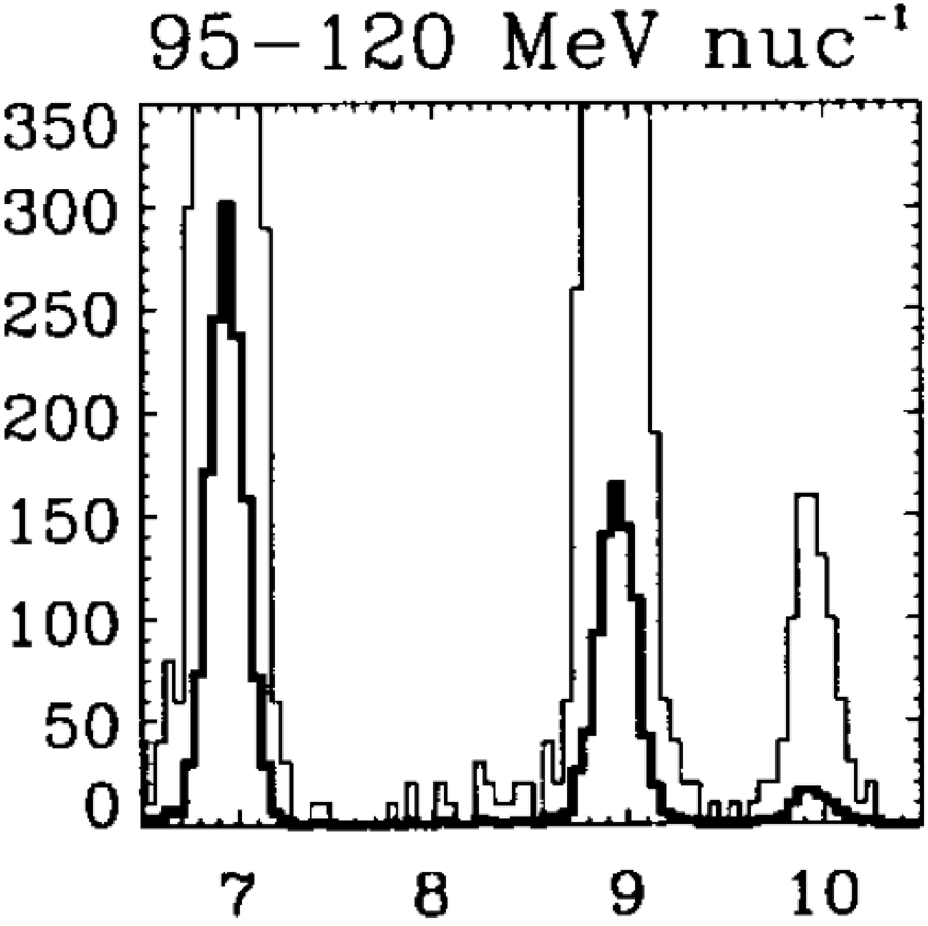
This problem touches the
“cornerstones” of the field
and has profound and broad implications

Discovery of Dark Matter !!?
Possible antiparticle accelerators
Spectra (e and p) released by CR accelerators,
Fundamental properties of CR Galactic propagation

Crucial crossroad for the field.

Additional slides

Direct measurement of the cosmic ray “age” unstable isotope Beryllium-10. ($T_{1/2} \simeq 1.51 \pm 0.04$ Myr)



N.E. Yanasak *et al.* Astrophys. J. **563**, 768 (2001).

Measurements
of Beryllium 10

Compare with
flux of stable isotopes

Decay suppression:
infer residence time

$$\langle P_{\rm surv} \rangle = 0.12 \pm 0.01$$

Estimate of suppression
in original paper

Extracting $\langle t_{\rm age} \rangle$ $\langle P_{\rm surv} \rangle$

is in general *model dependent*
[depends on the distribution of the age]

Single age
for CR:

$$\langle P_{\rm surv} \rangle = e^{-t/\tau}$$

Distribution of ages

$$\langle P_{\rm surv} \rangle = \int_0^\infty dt \, \boxed{F(t, \langle t \rangle)} \, e^{-t/\tau}$$

Work of

N.E. Yanasak *et al.*

Astrophys. J. **563**, 768 (2001).

$E_0 = 70\text{–}145$ MeV/nucleon

$$\langle P_{\rm surv} \rangle = 0.12 \pm 0.01$$

$$\langle t_{\rm age} \rangle \simeq 15.0 \pm 1.6 \text{ Myr}$$

[Leaky Box framework]

Result reinterpreted with longer lifetimes in different frameworks

---

M. Kruskal, S. P. Ahlen and G. Tarlé,

Astrophys. J. **818**, no. 1, 70 (2016)

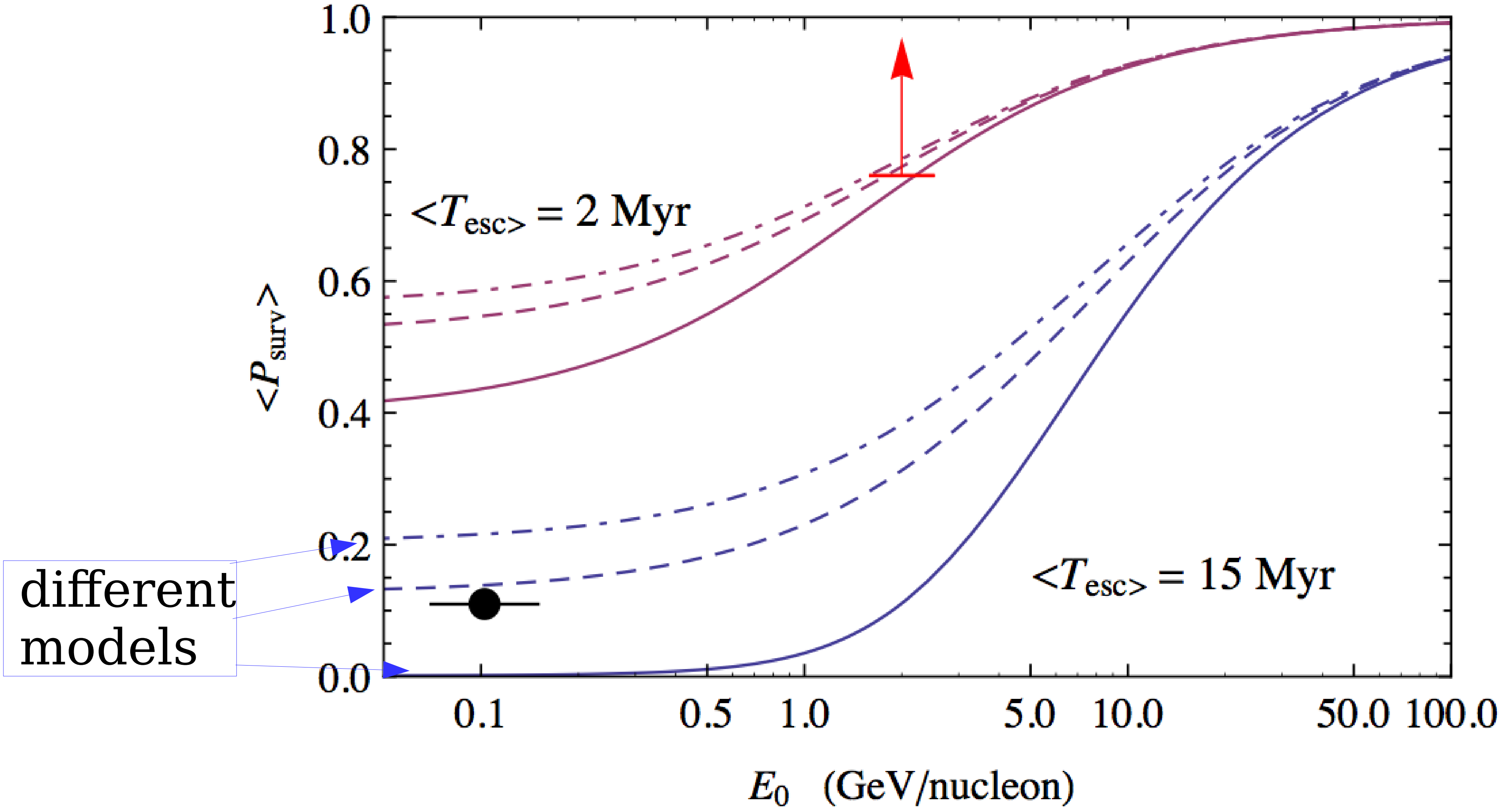
$E_0 = 2$ GeV/nucleon

very important to confirm !

$$\langle P_{\rm surv} \rangle \approx 1$$

$$\langle t_{\rm age} \rangle \leq 2.0 \text{ Myr}$$

Much smaller sensitivity to the modeling “theory”



different models

N.E. Yanasak *et al.*

Astrophys. J. **563**, 768 (2001).

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Proton versus electron

Acceleration in sources

Cosmic Ray generation

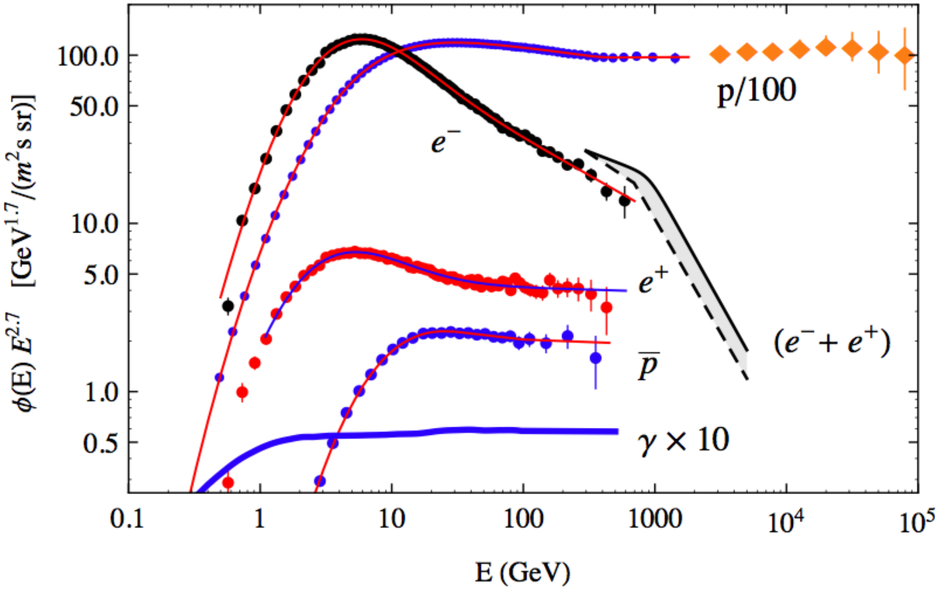
Problem of central importance in High Energy Astrophysics

If: positrons and antiprotons have equal
propagation properties.

Then: also electron and protons have also the same
propagation properties

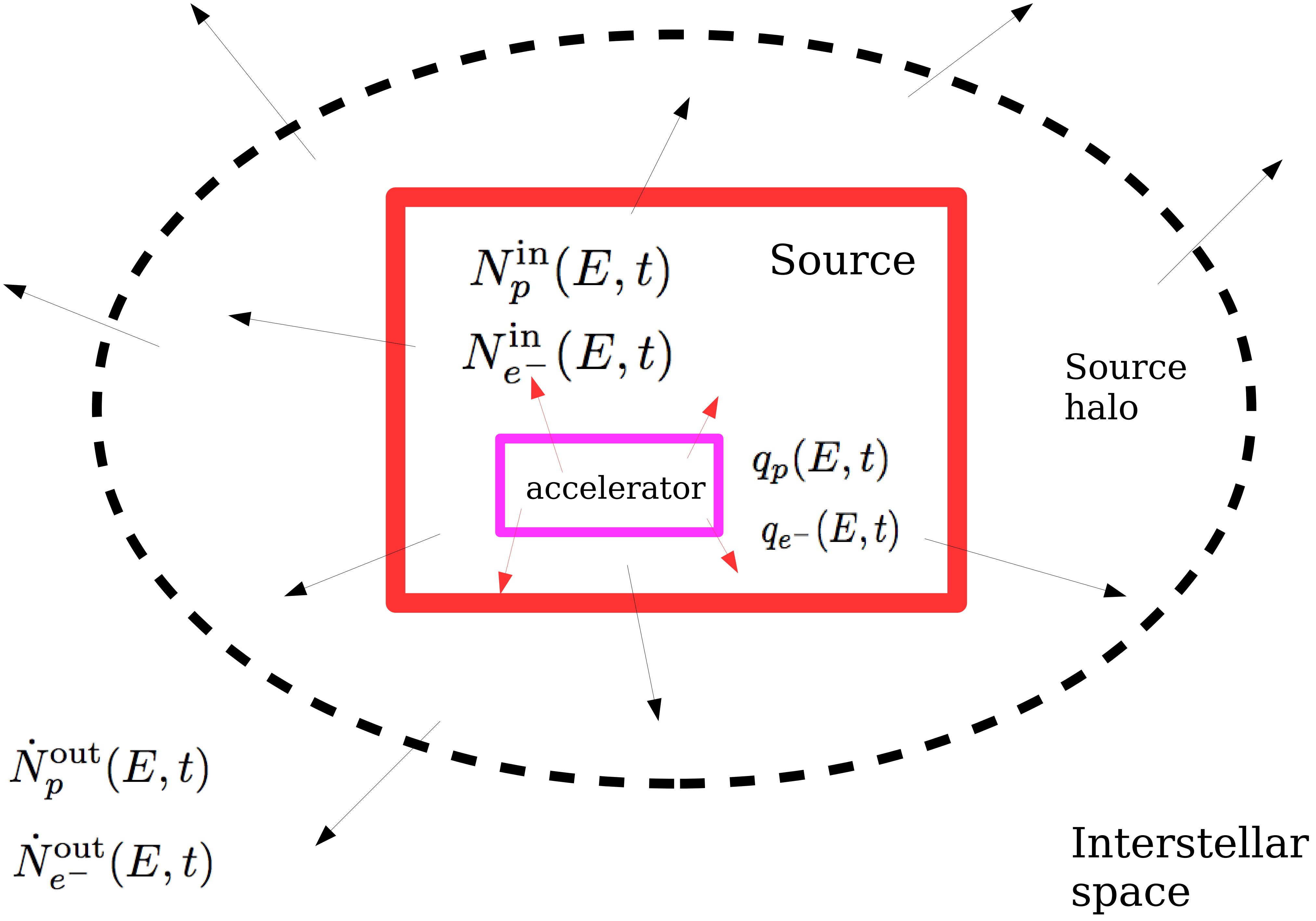
But then:

why are the electron the proton spectra so different from each other ?!



The e/p difference must be generated by the sources

Scheme of a source



$N_p^{\mathrm{in}}(E,t)$

Source

$N_{e^-}^{\mathrm{in}}(E,t)$

Source halo

accelerator

$q_p(E,t)$

$q_{e^-}(E,t)$

$\dot{N}_p^{\mathrm{out}}(E,t)$

$\dot{N}_{e^-}^{\mathrm{out}}(E,t)$

Interstellar space

Primary Cosmic Rays:

understand the Accelerators

Nearly certainly the accelerators are *transients*

A single accelerator

t_i (Accelerator is born)

$t_i + T$ (Accelerator "disappears")

Integrating over its entire lifetime, the Accelerator "releases" in interstellar space populations of relativistic Particles.

$$N_p^{\rm out}(E) \;,\; N_{e^-}^{\rm out}(E) \;,\; N_{\rm He}^{\rm out}(E) \;, \ldots.$$

During its lifetime, $t_i < t < t_i + T$

the accelerator is a gamma ray and neutrino emitter

$$q_\gamma(E,t) \qquad q_\nu(E,t)$$

Infer the populations of relativistic particles
inside (or near) the accelerators:

$$N_p^{\rm in}(E,t) \qquad N_{e^-}^{\rm in}(E,t)$$

Far from trivial to relate this information
to the CR spectra released in interstellar space

$$N_p^{\rm out}(E) \quad , \quad N_{e^-}^{\rm out}(E)$$

“Secondary Nuclei” Li, Be, B

Rare nuclei created in the fragmentation of primary (directly accelerated) more massive nuclei

Some examples:

$$^{12}\mathrm{C} + p \to {}^{10}\mathrm{B} + 2\,p + n$$

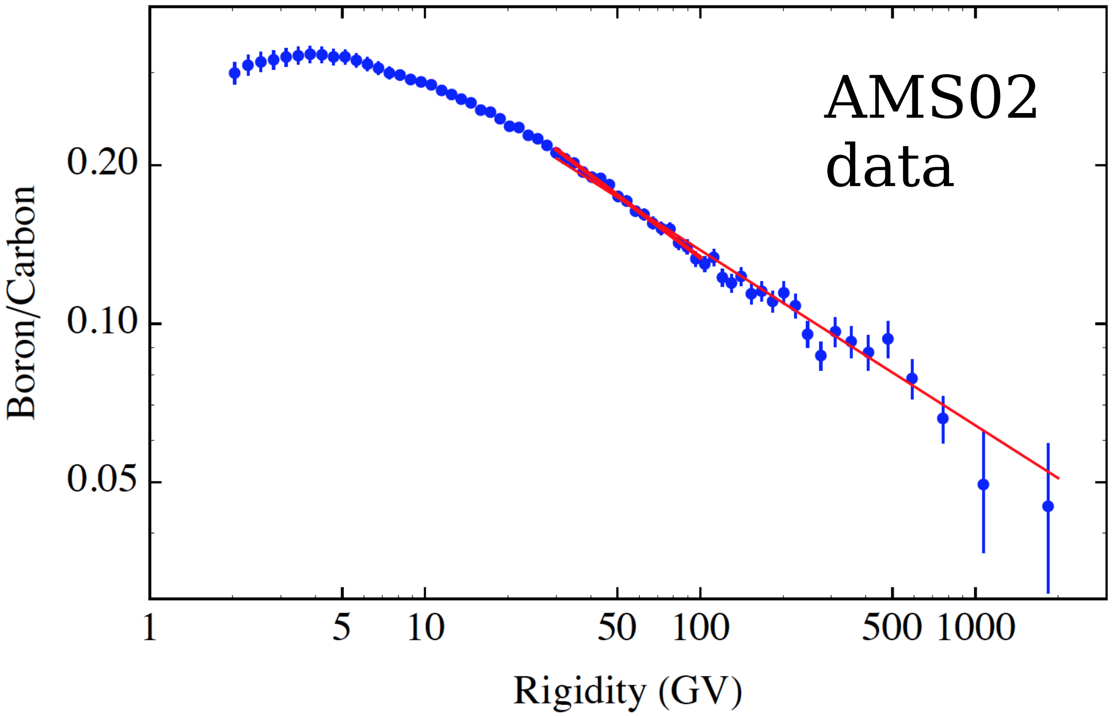
$$^{12}\mathrm{C} + p \to {}^{11}\mathrm{B} + 2\,p$$

$$^{16}\mathrm{O} + p \to {}^{11}\mathrm{B} + {}^{4}\mathrm{He} + 2\,p$$

....

$$\frac{\text{secondary nuclei}}{\text{primary nuclei}} \Longrightarrow$$

“grammage" traversed by the nuclei



$$\frac{\text{Boron}}{\text{Carbon}} \approx 0.21 \left(\frac{p/Z}{30\ \text{GV}}\right)^{-0.33}$$

$$\frac{\text{Boron}}{\text{Carbon}} \approx 0.21 \left(\frac{p/Z}{30\ \text{GV}}\right)^{-0.33}$$

Approximation
of constant fragmentation
cross sections

Interpretation in terms of Column density

$$\langle X \rangle \approx 4.7 \left(\frac{p/Z}{30\ \text{GV}}\right)^{-0.33} \frac{\text{g}}{\text{cm}^2}$$

[Assuming that the column density is accumulated during *propagation in interstellar space*]

$$\langle T_{\text{age}} \rangle \simeq 30\ \text{Myr} \left[\frac{0.1\ \text{g}\,\text{cm}^{-3}}{\langle n_{\text{ism}} \rangle}\right] \left(\frac{|p/Z|}{30\ \text{GV}}\right)^{-0.33}$$

Residence time inferred from B/C ratio
assuming that the column density crossed by the nuclei is accumulated in interstellar space

is *inconsistent* [as it is too long]
with the hypothesis that the energy losses of $e^{\pm}$
are negligibly small.

Possible solutions

1. [Energy dependence of fragmentation Cross sections]

2. Most of the column density inferred from the B/C ratio
   is integrated not in interstellar space
   but inside or in the envelope of the sources
   [Cowsik and collaborators]