Features in the Galactic Cosmic Ray Spectra and their interpretation

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LHAASO Scientific Observation
and Multi-messenger Astronomy
Workshop

Chengdu, april 25-27 2019

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

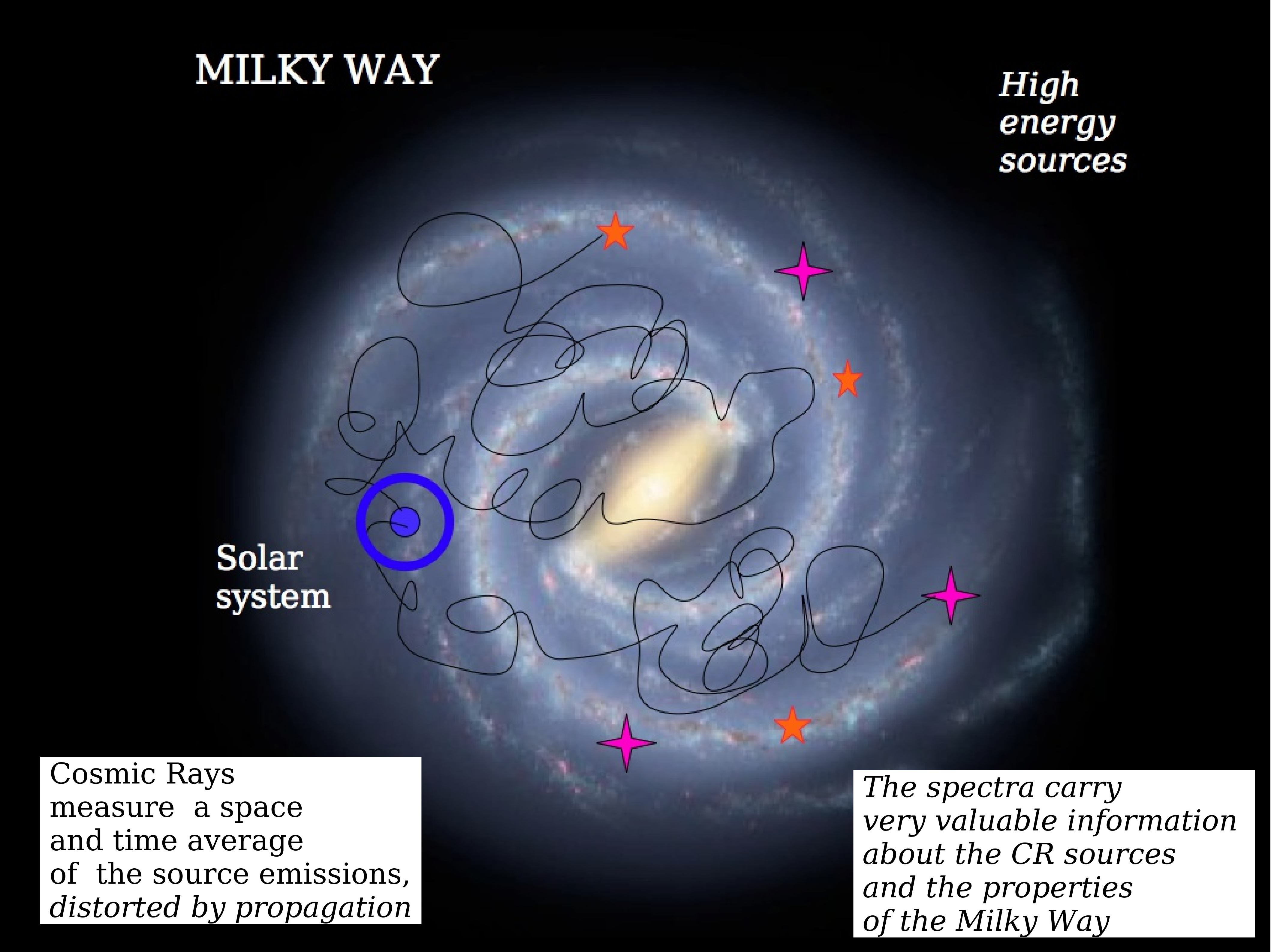
$$\phi_{e^-}(E,\Omega)$$

electrons

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

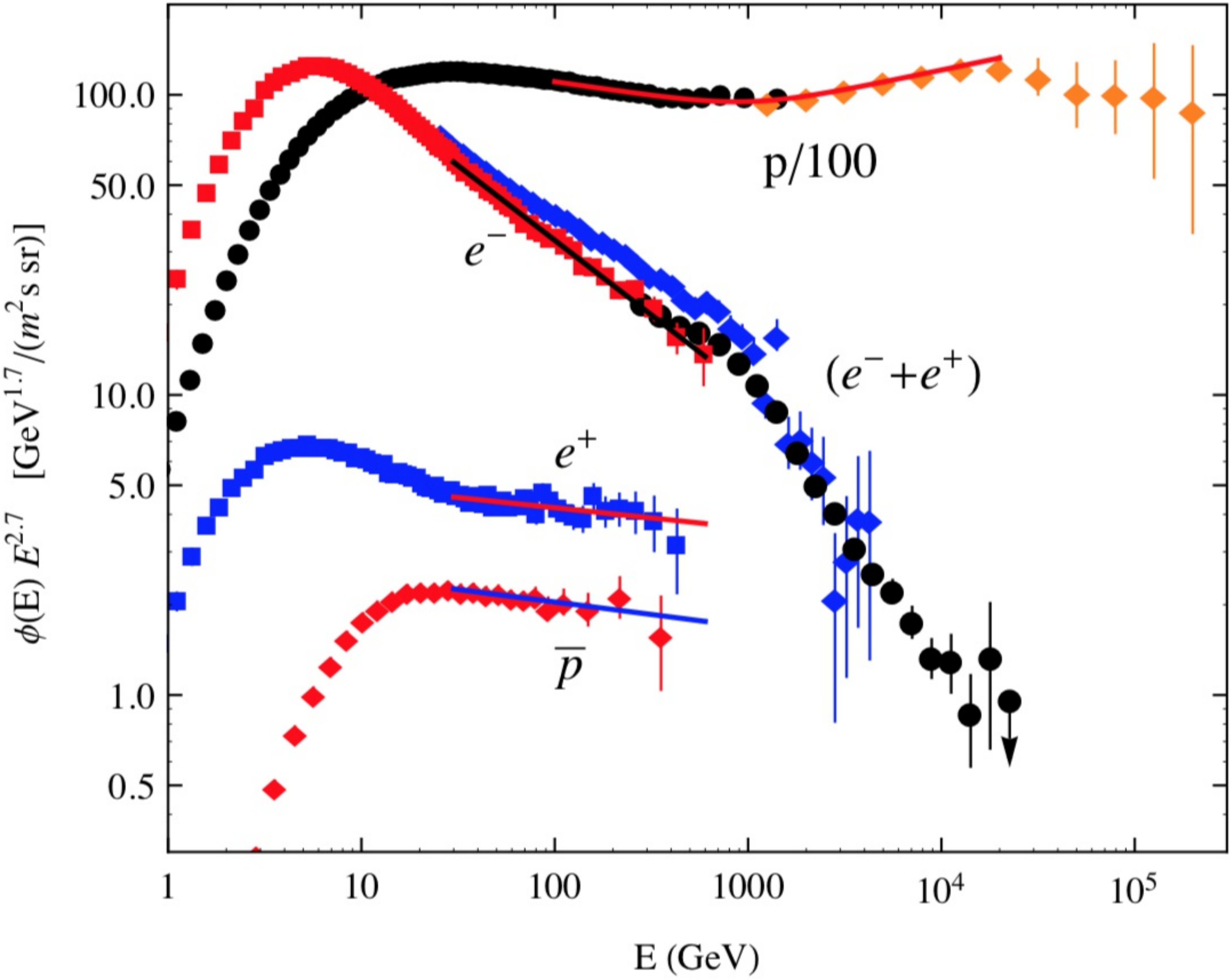
$$\phi_{\overline{p}}(E,\Omega)$$

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

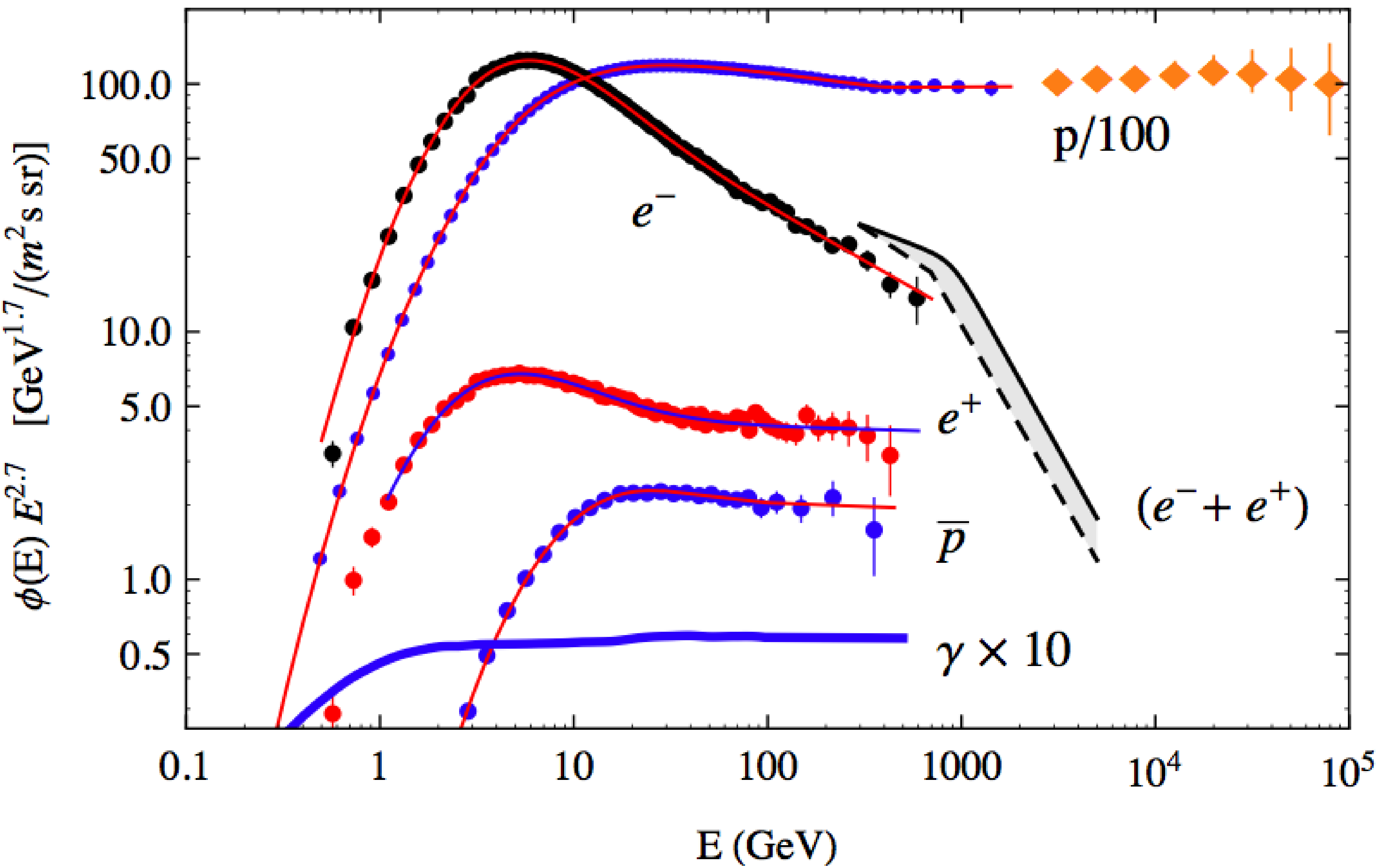


e^- p

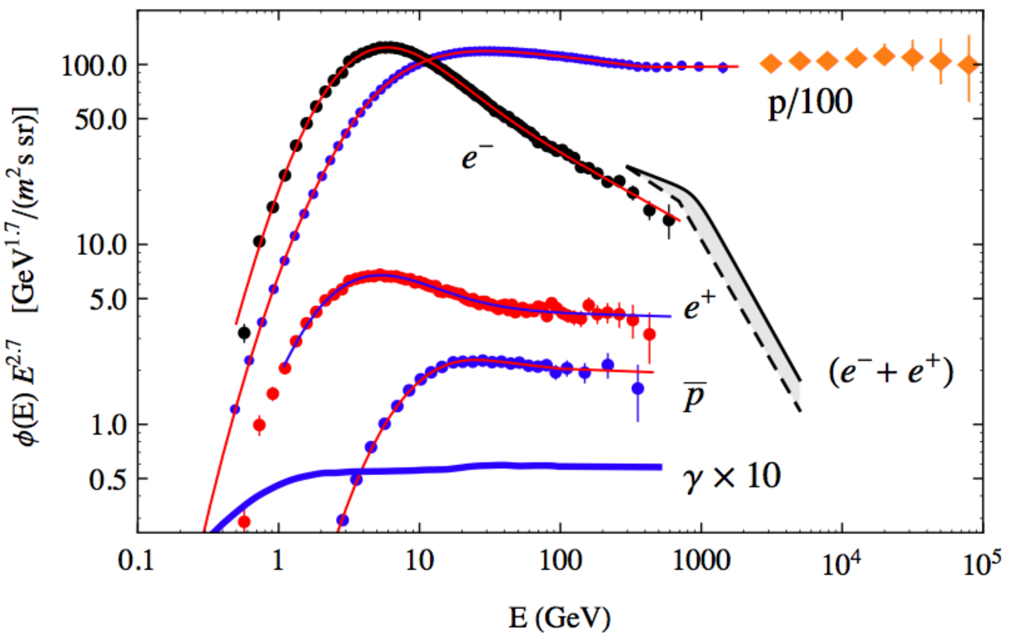
e^+ $\overline{p}$

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

CREAM p data



angle averaged diffuse Galactic gamma ray flux (Fermi)



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

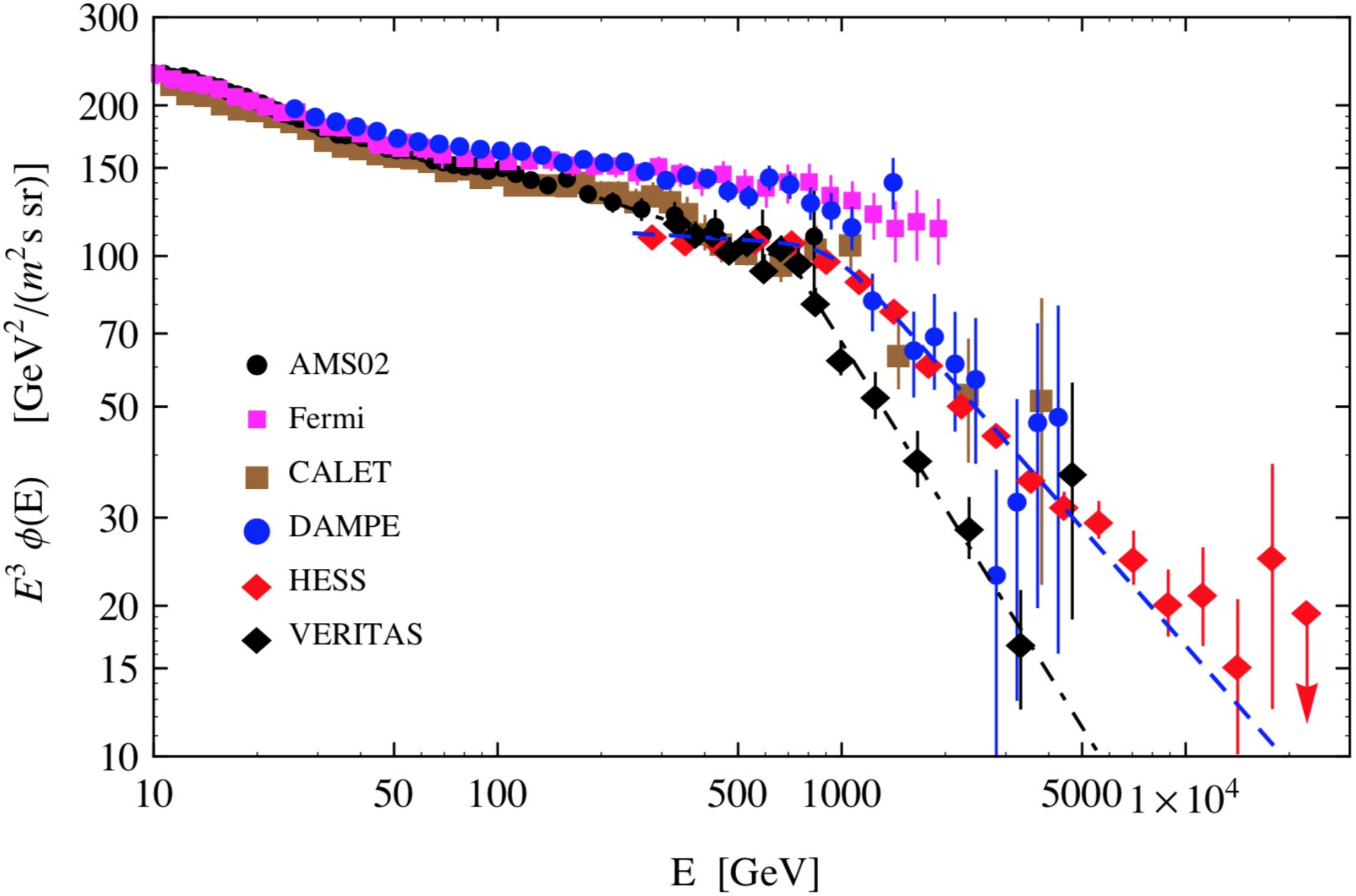
4 spectra
have approximately
the same slope

[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

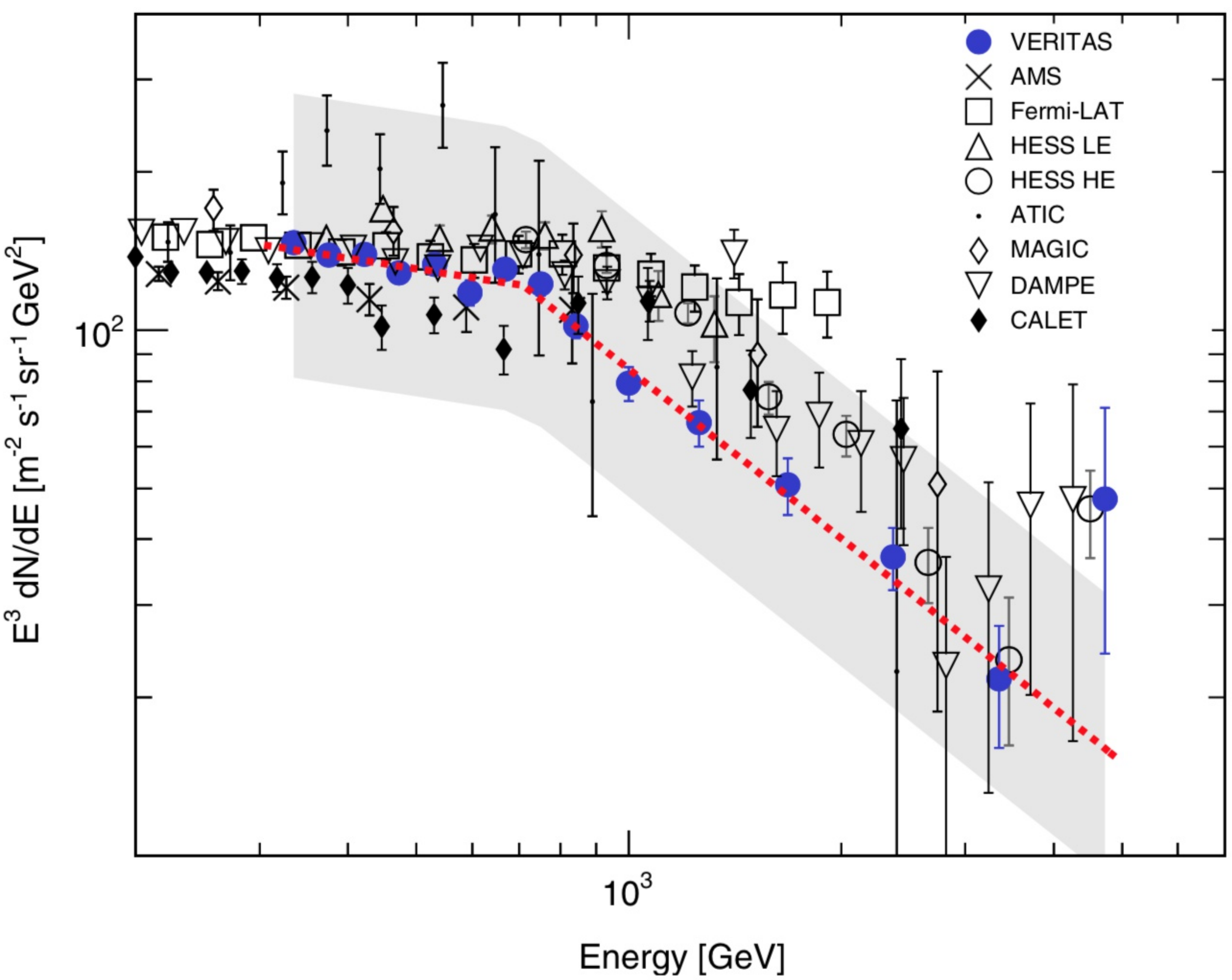
[B] *positron* and *antiproton* for (E> 30 GeV)
have the same power law behavior
and differ by a factor 2 (of order unity)

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

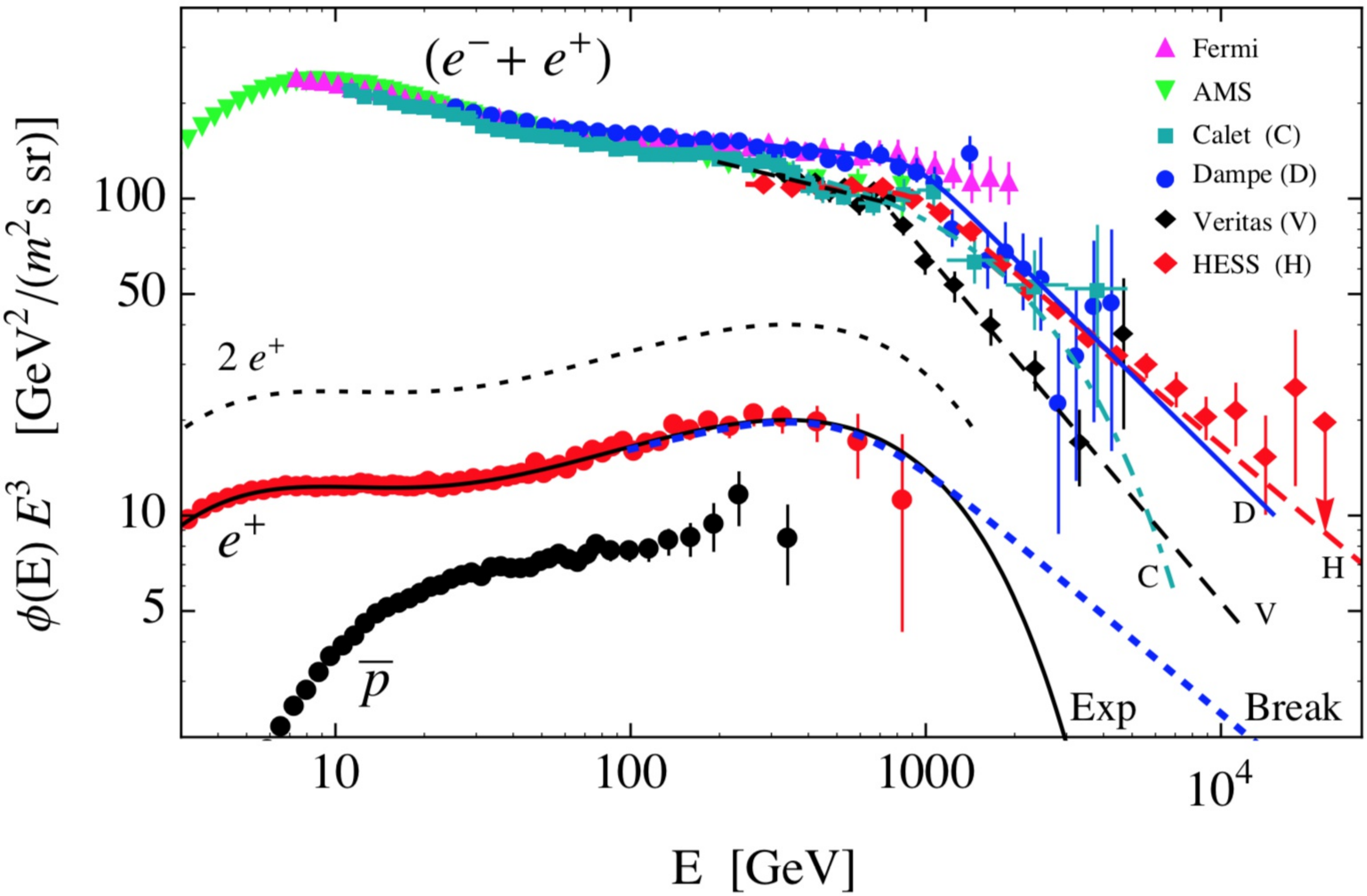
Remarkable discovery of Cherenkov telescopes confirmed by satellites



Systematic uncertainties in VERITAS data

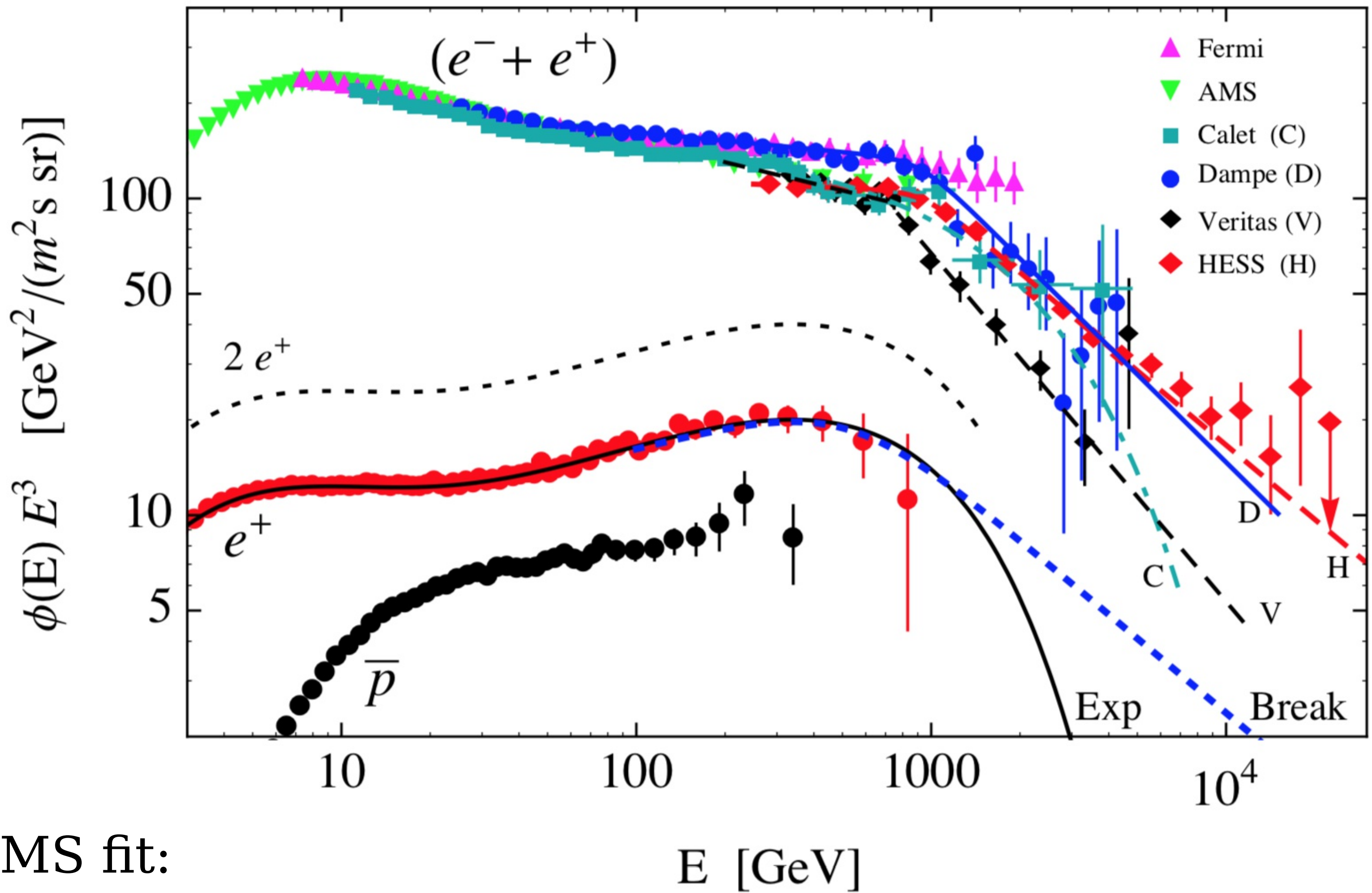


Detection of a “softening feature” in the positron spectrum



AMS02 Collaboration
“Towards Understanding the Origin of Cosmic-Ray Positrons,”
Phys. Rev. Lett. **122**, no. 4, 041102 (2019).

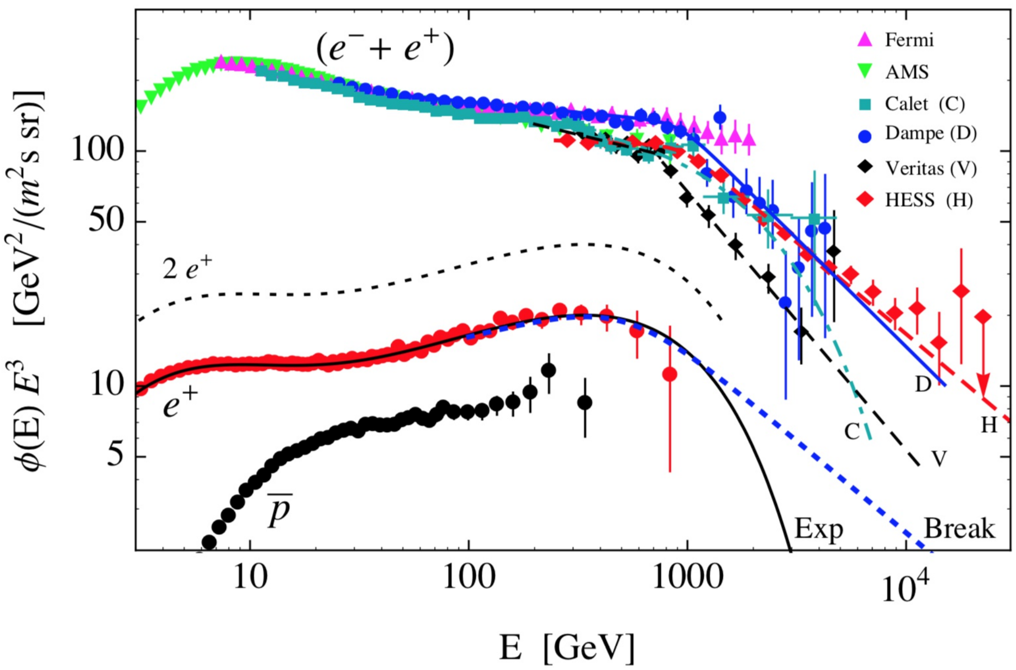
Detection of a “break” in the positron spectrum



AMS fit:
Exponential cutoff

$$E^{-\alpha}\ e^{-E/E_s} \qquad E_s = 810^{+310}_{-180}\ \text{GeV}$$

Detection of a “softening feature” in the positron spectrum



Note : *Main source of TeV electrons is not equal to the positrons source*

Questions:

(1) Is the e+ suppression an exponential cutoff ?

(2) Are the spectral structures for e- and e+ related or independent ?

Energy Loss

Important for e+- at high energy

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

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

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

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 $T_{\rm loss}(E) = E/\beta(E)$

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

$$q(E,t)$$

Source

spectrum of
cosmic rays

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

Escape time

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

Rate of energy Loss

Propagation

$$n(E,t)$$

Observable CR density

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

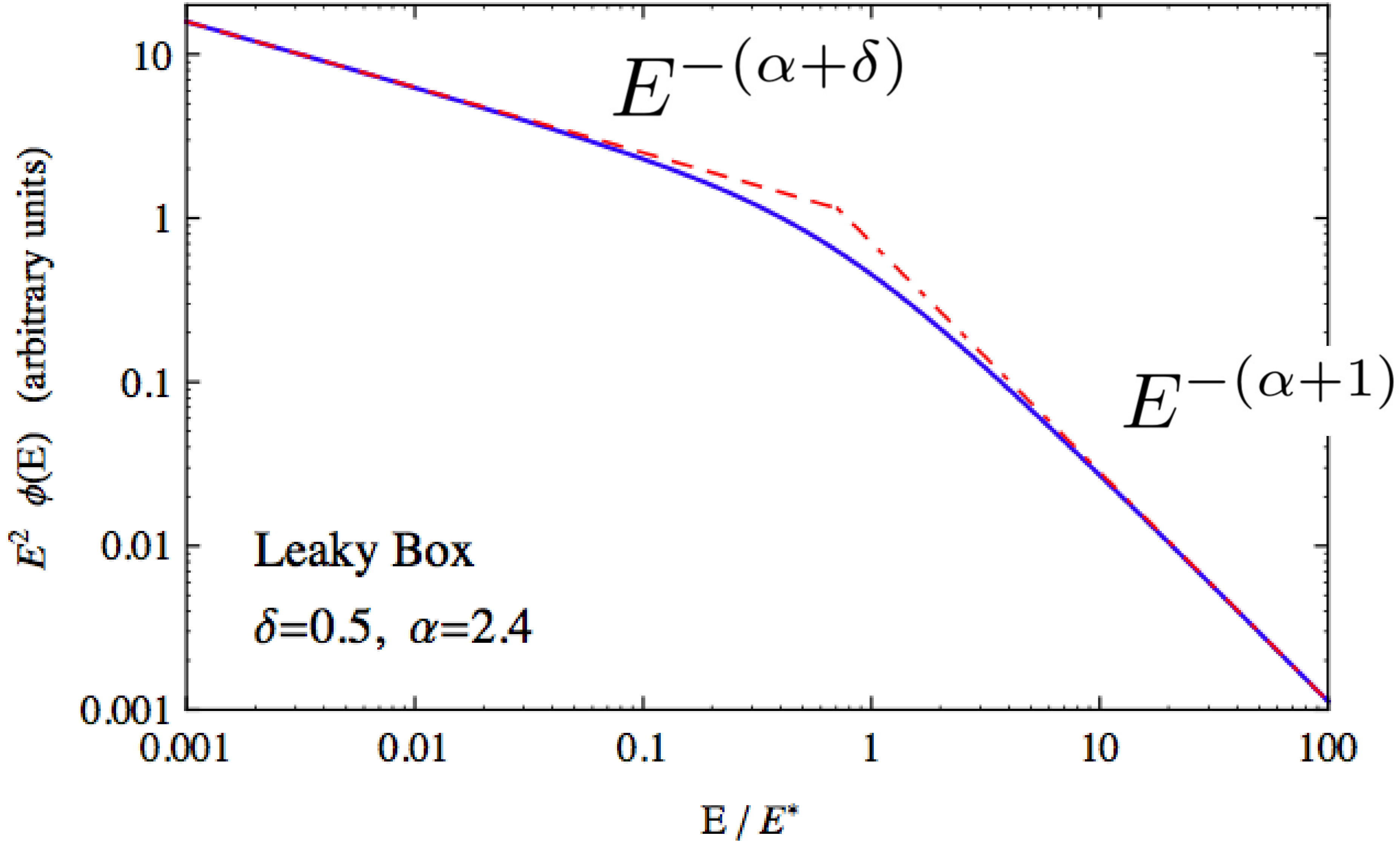
Source

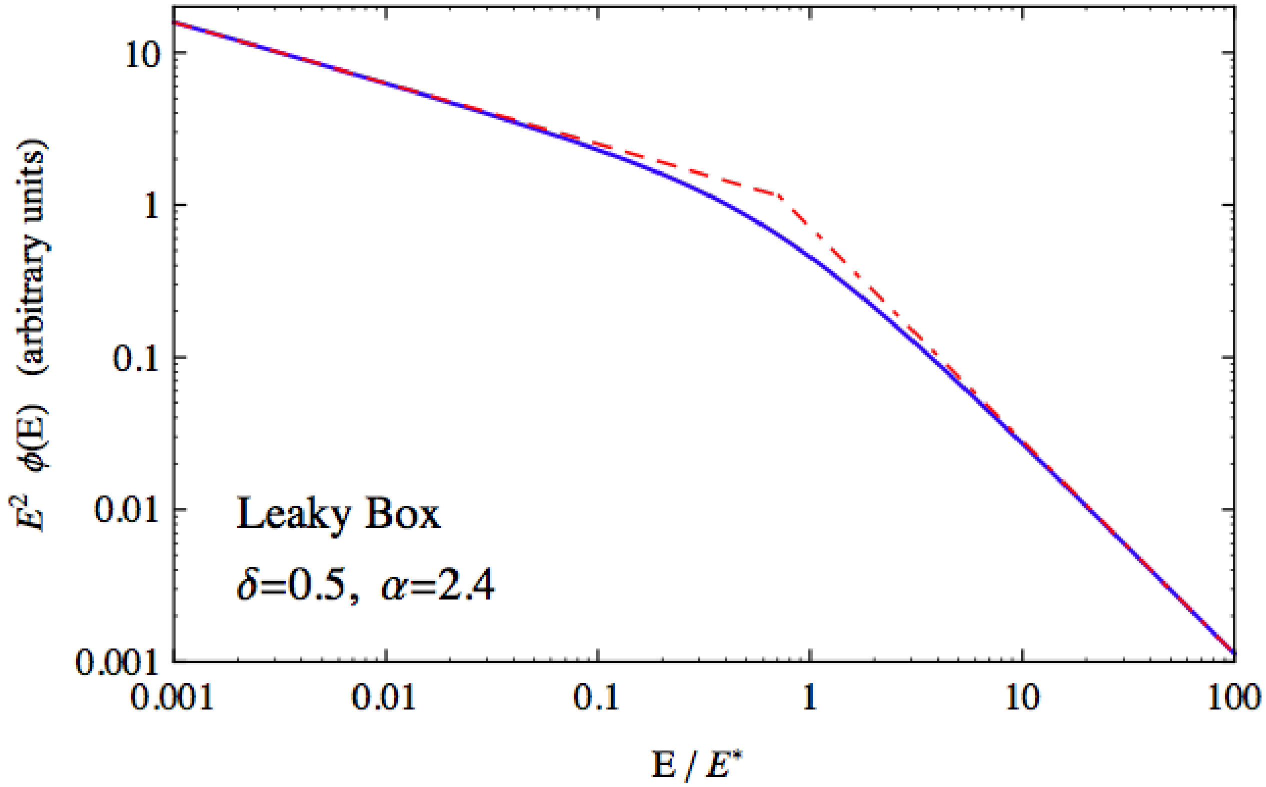
$$T_{\rm esc}(E) = T_0 \; E^{-\delta}$$

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^*

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

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

Idea of very general validity:

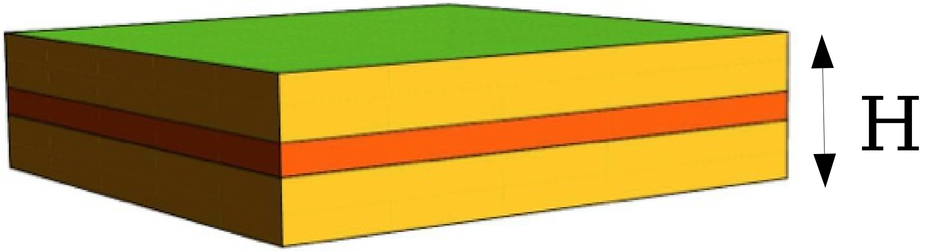
The Spectra of electrons and positrons
should contain a softening "spectral feature"
associated to the energy loss:
at a critical energy *E**

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

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

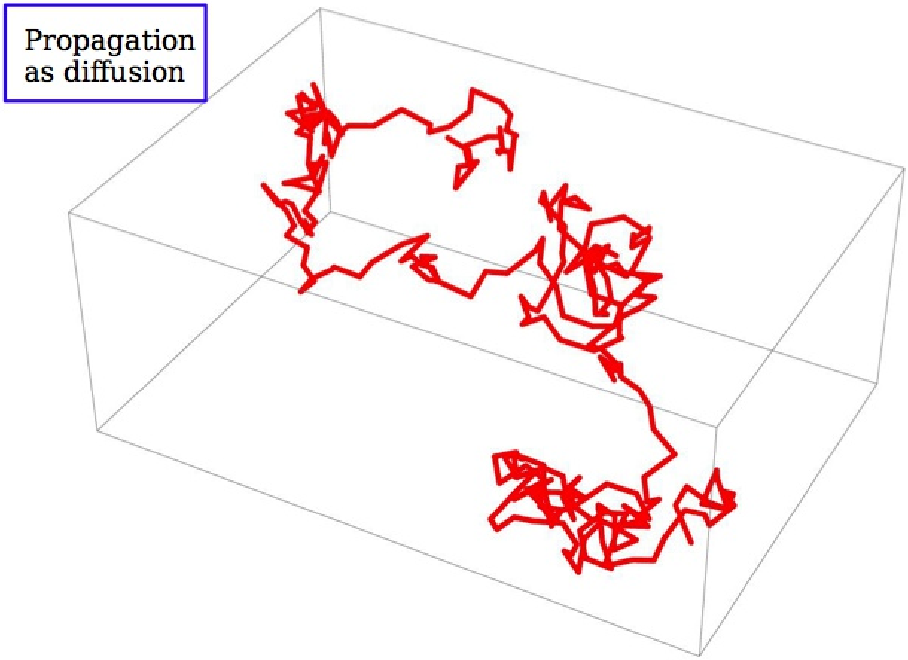
$$\boxed{T_{\rm esc}(E^*) = T_{\rm loss}(E^*)}$$

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

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

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

Average escape time for CR (no energy loss)

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

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

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

Critical energy

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

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

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

Stationary emission from the Galactic plane

Exact solution:

Energy losses negligible

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

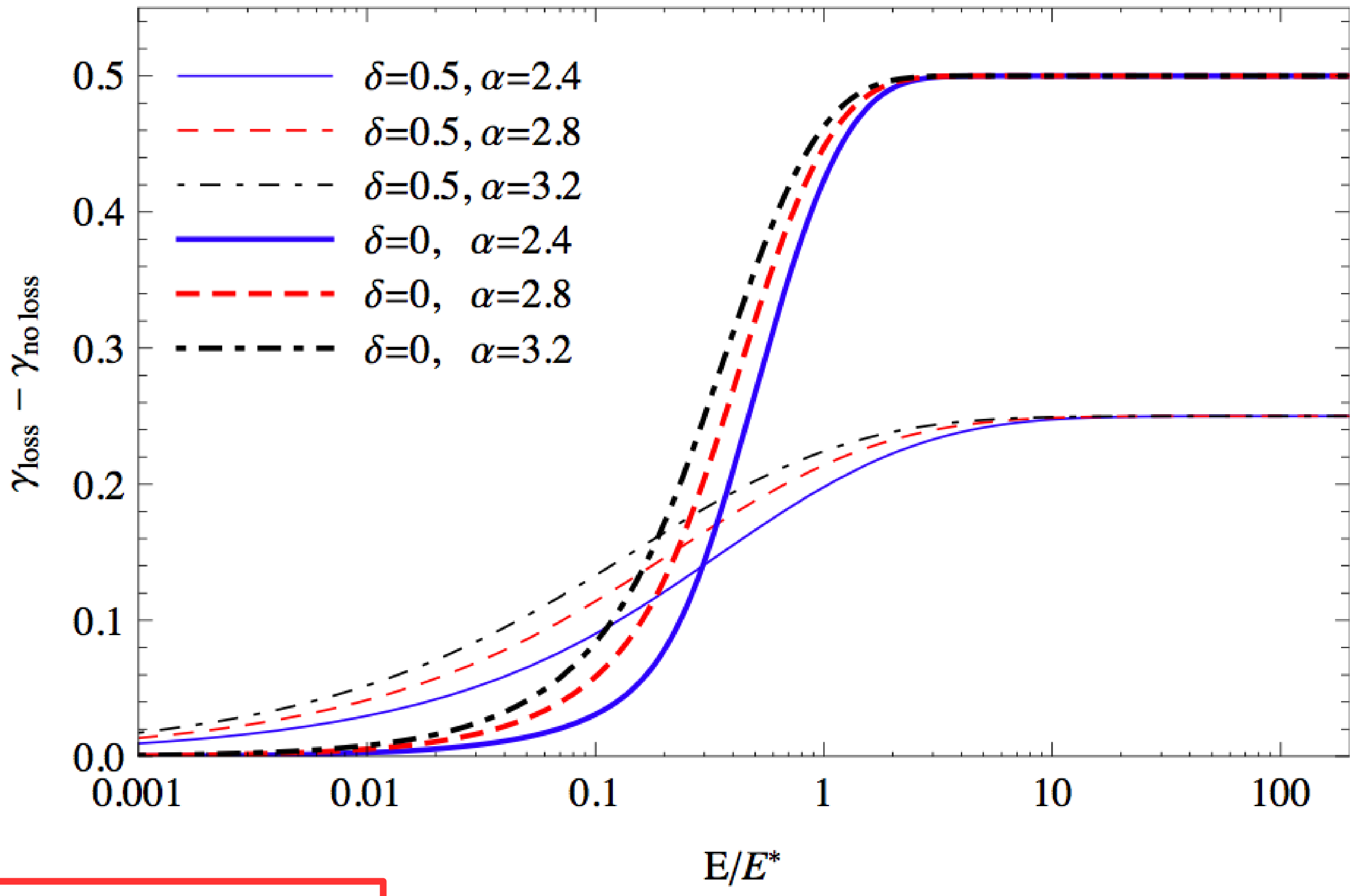
Energy losses dominant

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

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

Softening break due to propagation

Imprint of the energy losses on the spectral index



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

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

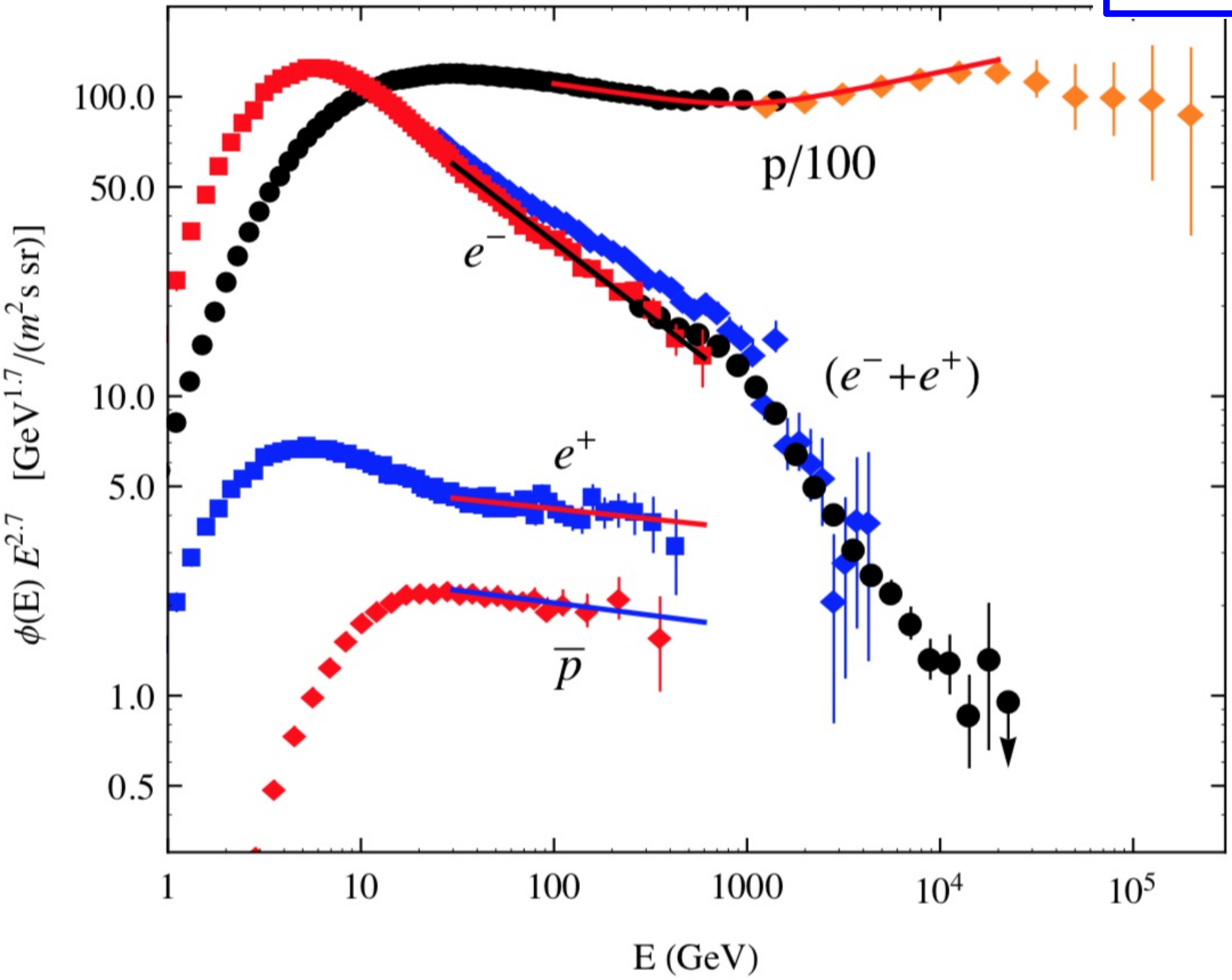
Where is the energy loss softening feature ?

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

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

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

Two possibilities



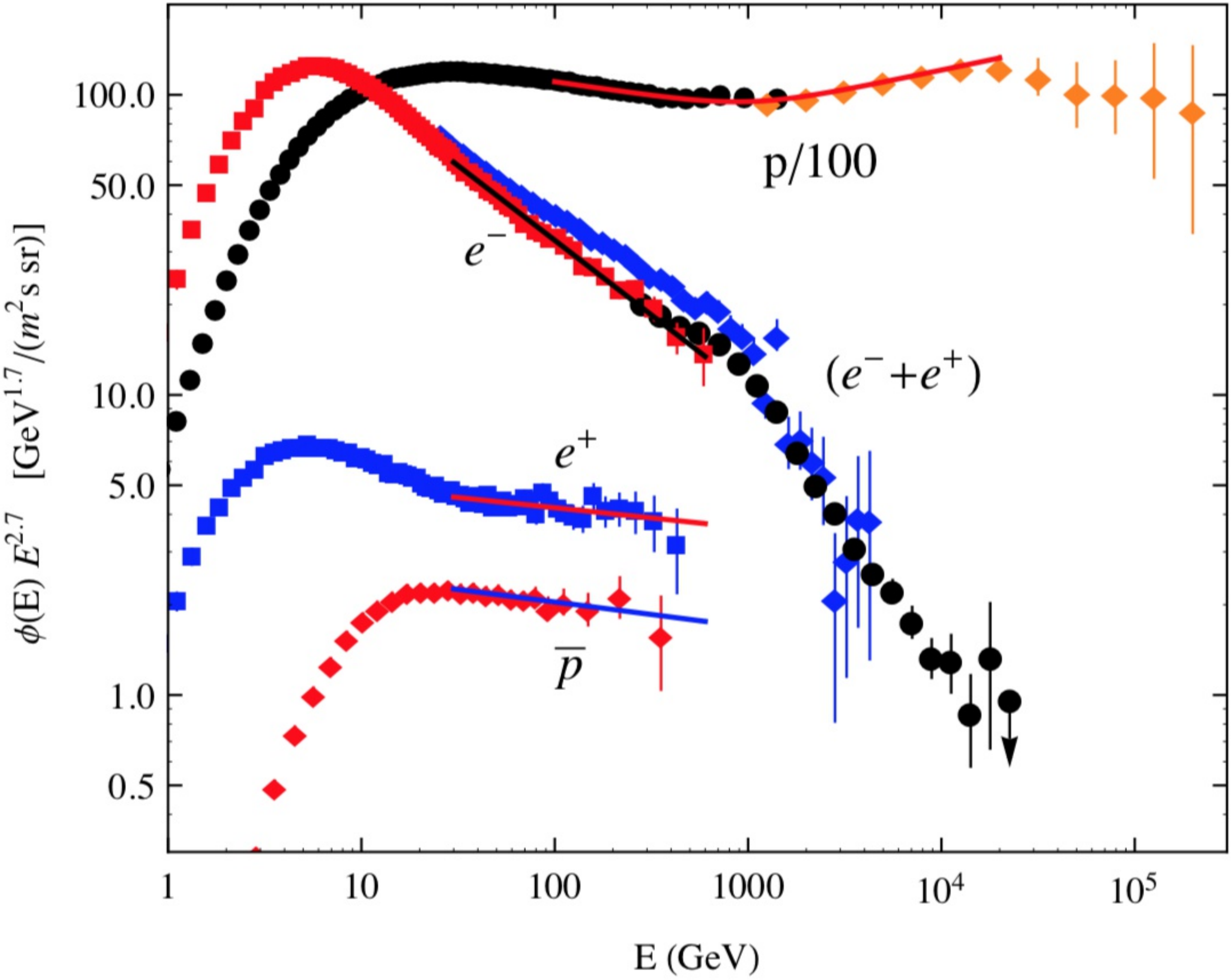
Use the lepton spectra as *“cosmic ray clocks”*

Standard assumption

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

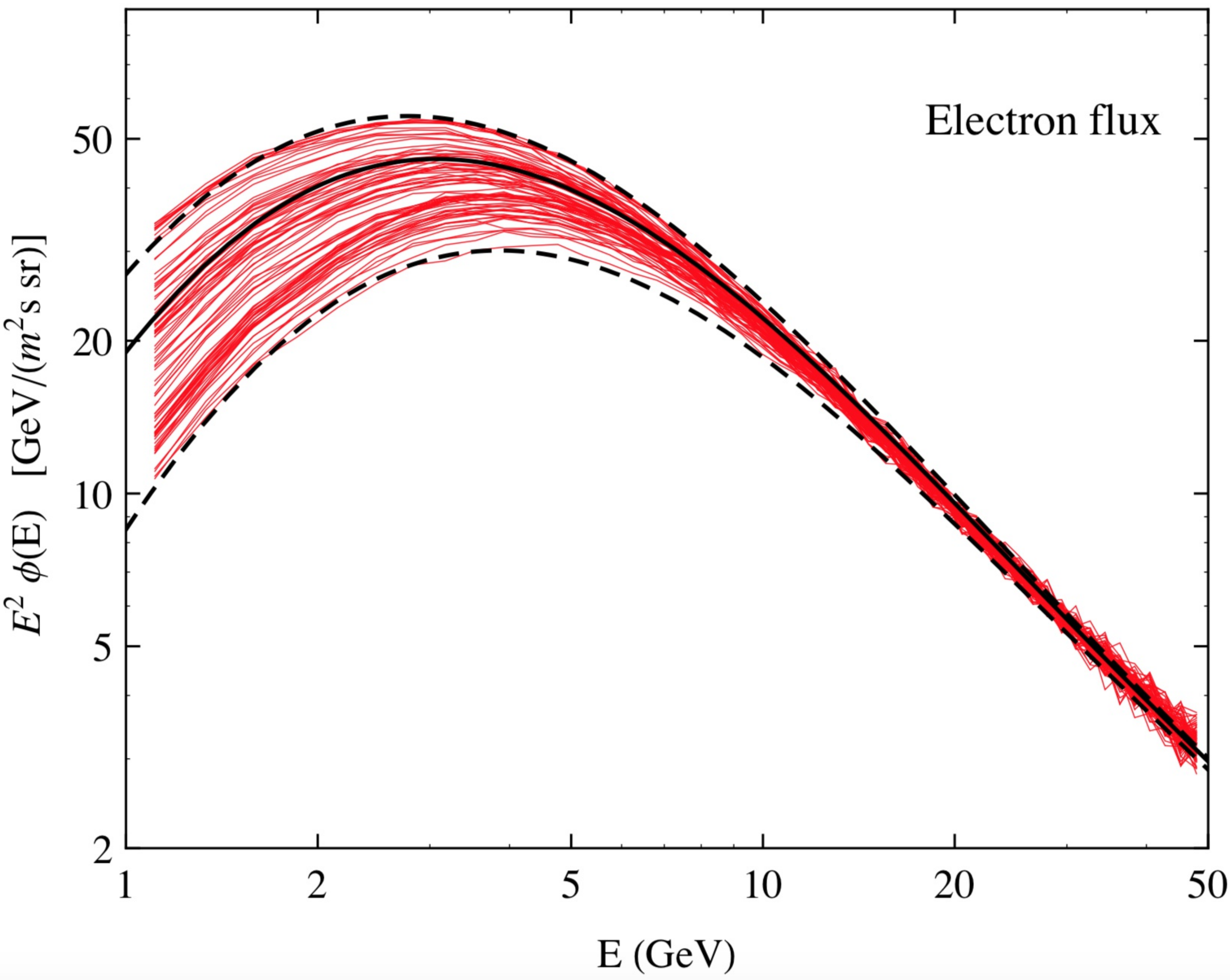
Two possibilities

Imply New source of positrons



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

What is the shape of the interstellar spectrum ?



Fit =

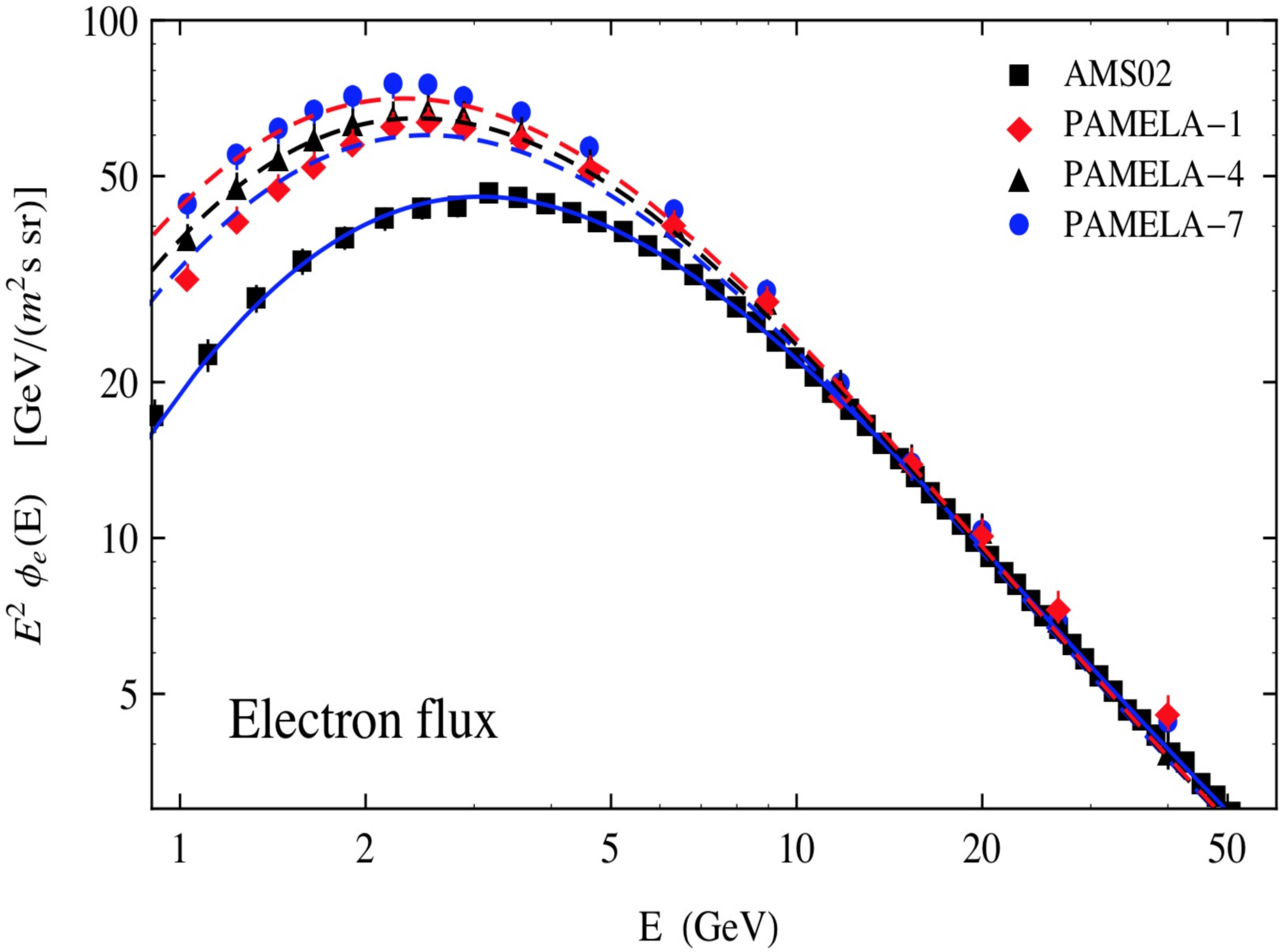
$$K\ E^{-3.17}$$

$$\otimes$$

FFA Solar Modulations

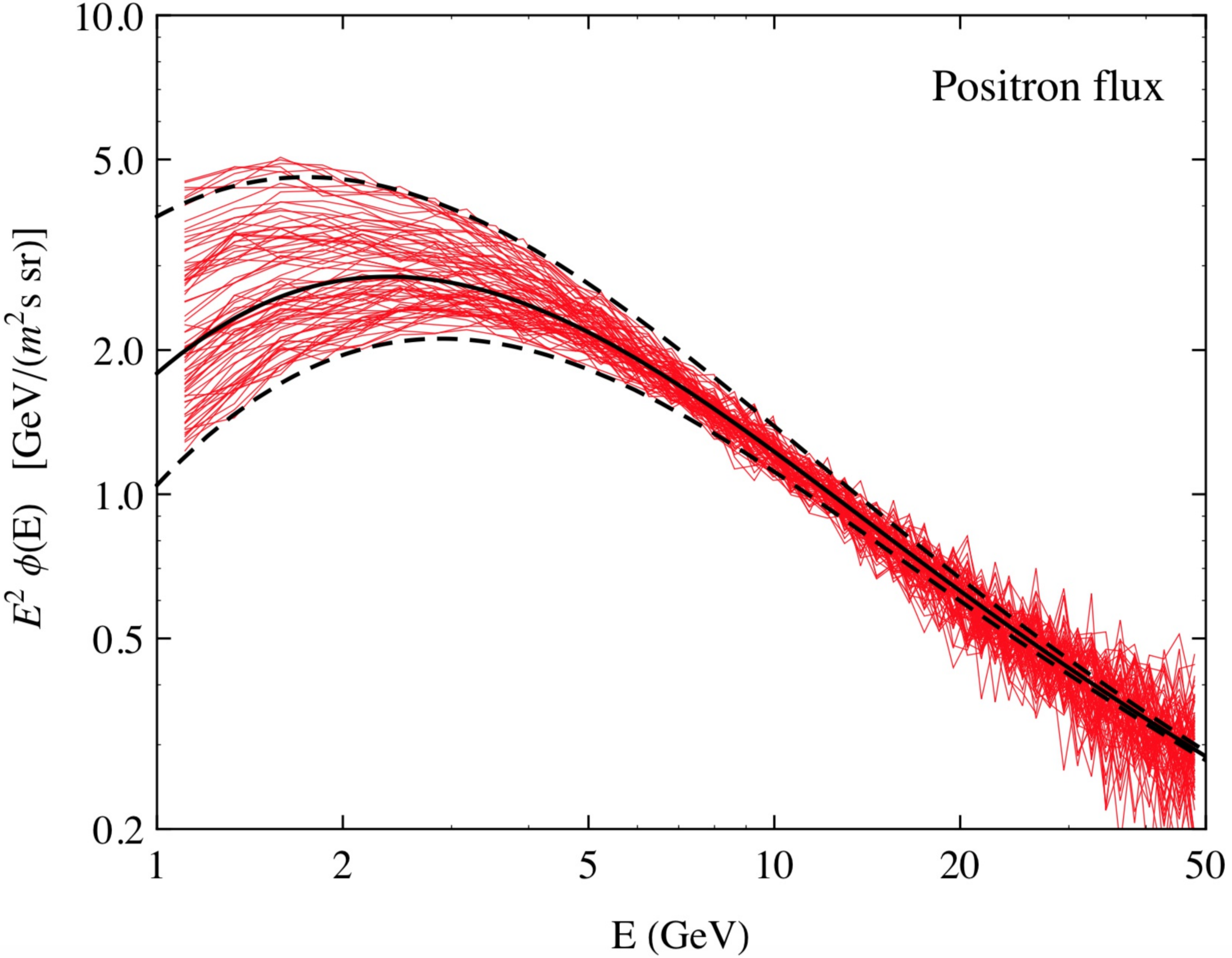
Solar Modulations

Electron spectra
at different times



Positron flux

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

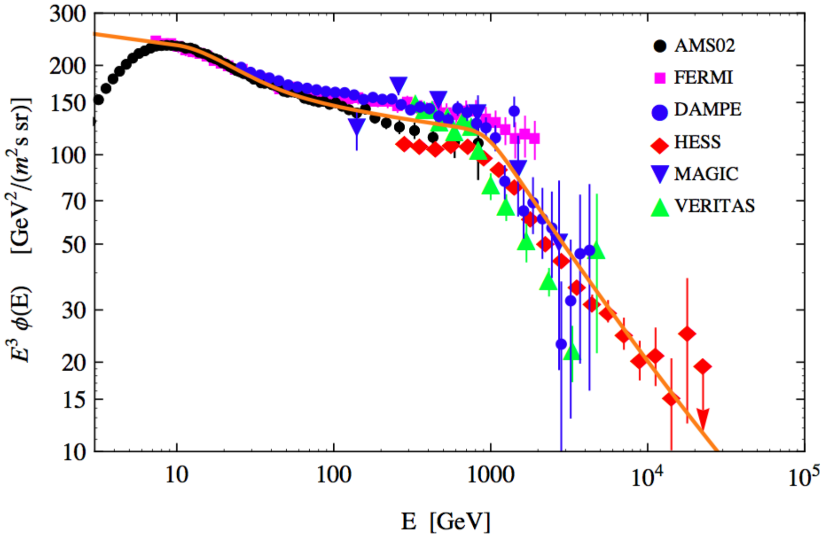


Possible (and "natural") choice: identification of the sharp softening observed by the Cherenkov telescopes in the spectrum of $(e^+ + e^-)$ as the critical energy

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

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

Range depends on volume of confinement



Propagation of positrons and antiprotons is approximately equal for

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

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

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

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

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

Number density in the disk

The source-events that contribute to the CR flux (at the Earth) are those in an energy dependent:

Time interval $T(E)$ and

Galactic Volume $V(E)$

Main time scales relevant for Cosmic Ray propagation

$T_{\rm esc}(E)$ $T_{\rm loss}(E)$ [relevant for e+-]

$$T(E) \simeq \min\left[T_{\rm esc}(E), T_{\rm loss}(E)\right]$$

$$\text{Volume}(E) \simeq \pi\, R^2(E)\, h_{\rm disk}$$

Propagation radius

$$R^2(E) \approx 2\ D(E)\ T(E)$$

The diffusion coefficient is related to the escape time:

$$H^2 = 2\ D(E)\ T_{\rm esc}(E)$$

H	Size of the Cosmic Ray Halo

Energy losses are negligible (e.g. for *protons*)

$$R^2(E) \approx H^2$$

$$N_s^p(E) \propto H^2\ T_{\rm esc}(E) \propto (E^*)^{-(1-\delta)}\ E^{-\delta}$$

Energy losses are dominant "sink" of particles
(*electrons* at sufficiently high energy)

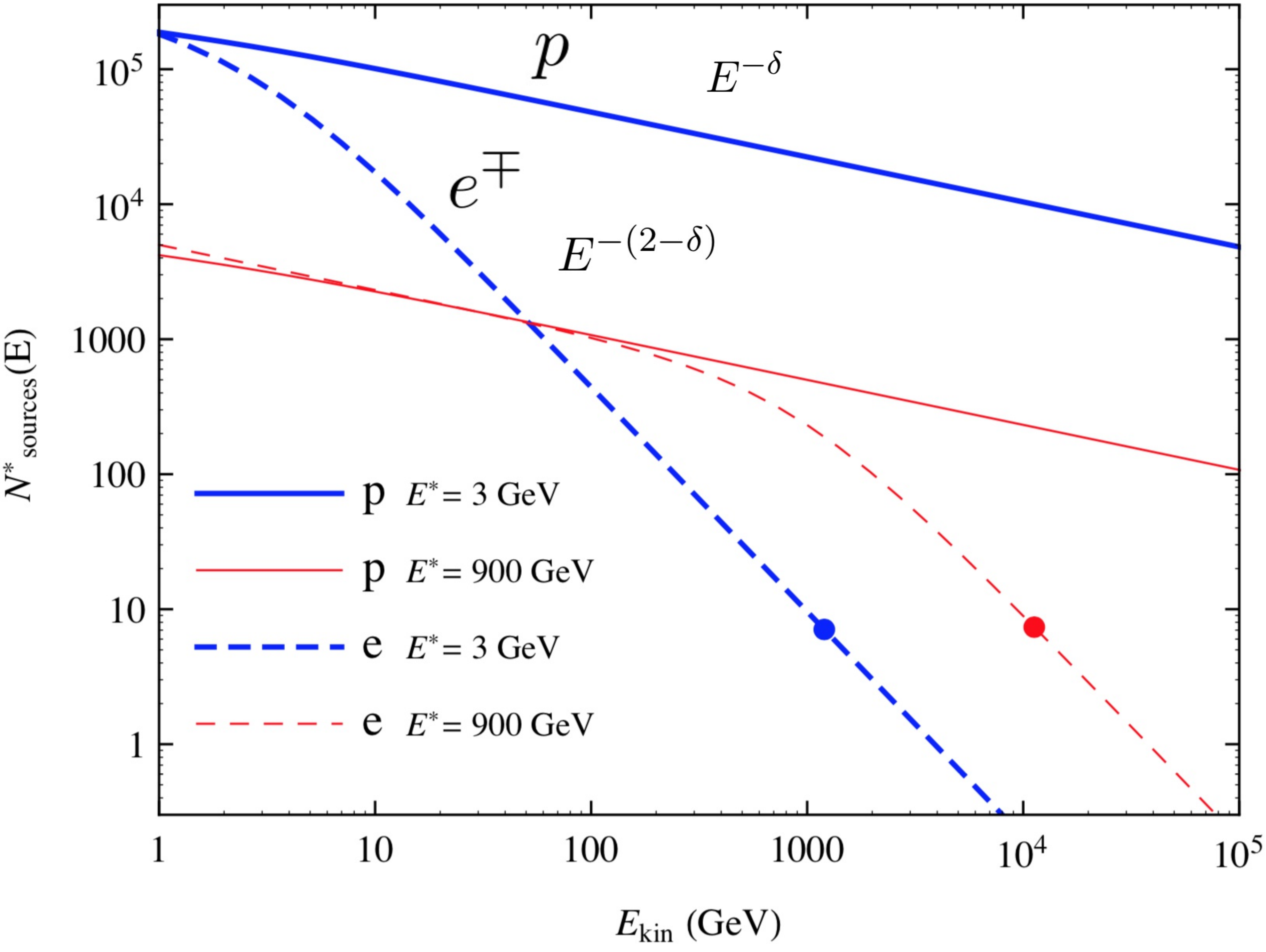
$$R^2(E) \simeq 2\, D(E)\, T_{\rm loss}(E)$$

$$\simeq H^2 \; \frac{T_{\rm loss}(E)}{T_{\rm esc}(E)}$$

$$N_s^e(E) \propto R^2(E)\; T_{\rm loss}(E)$$

$$\propto H^2 \; \frac{T^2_{\rm loss}(E)}{T_{\rm esc}(E)}$$

$$\propto (E^*)^{1-\delta}\; E^{-(2-\delta)}$$



p
$E^{-\delta}$
$e^{\mp}$
$E^{-(2-\delta)}$
10^5
10^4
1000
100
10
1
$N^*_{\mathrm{sources}}(\mathrm{E})$
p E^* = 3 GeV
p E^* = 900 GeV
e E^* = 3 GeV
e E^* = 900 GeV
1
10
100
1000
10^4
10^5
E_{kin} (GeV)

Protons (Nuclei)

Numerical example: $\delta = 0.4$

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

Electrons

Numerical example: $\delta = 0.4$

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

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

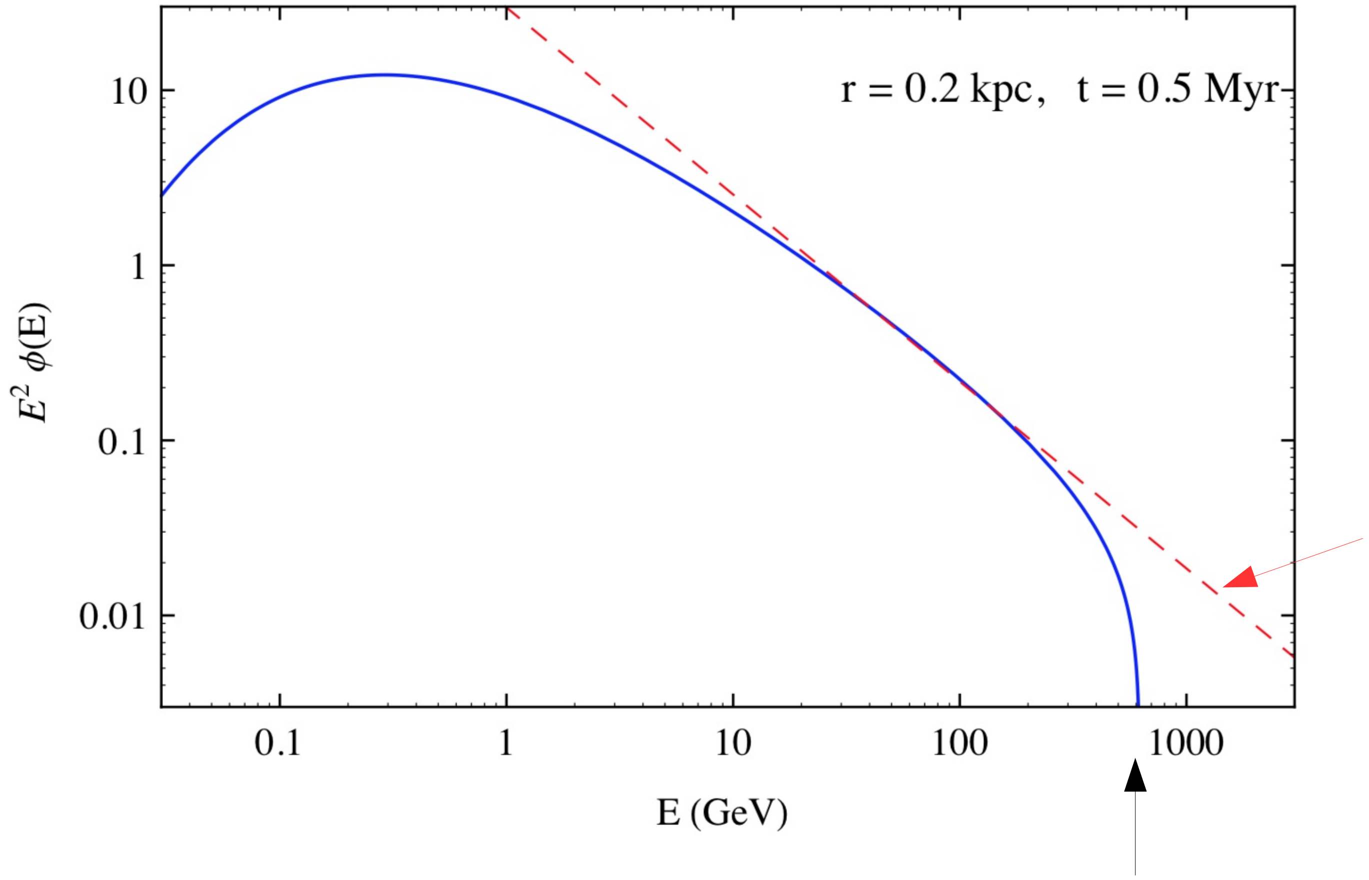
$$\{t_i \ , \quad \vec{r}_s\} \qquad \{\mathcal{E} \ , \quad \alpha\} \qquad q_0 \propto \mathcal{E}$$

Flux from an “ instantaneous explosive) source”

simple diffusive model)

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

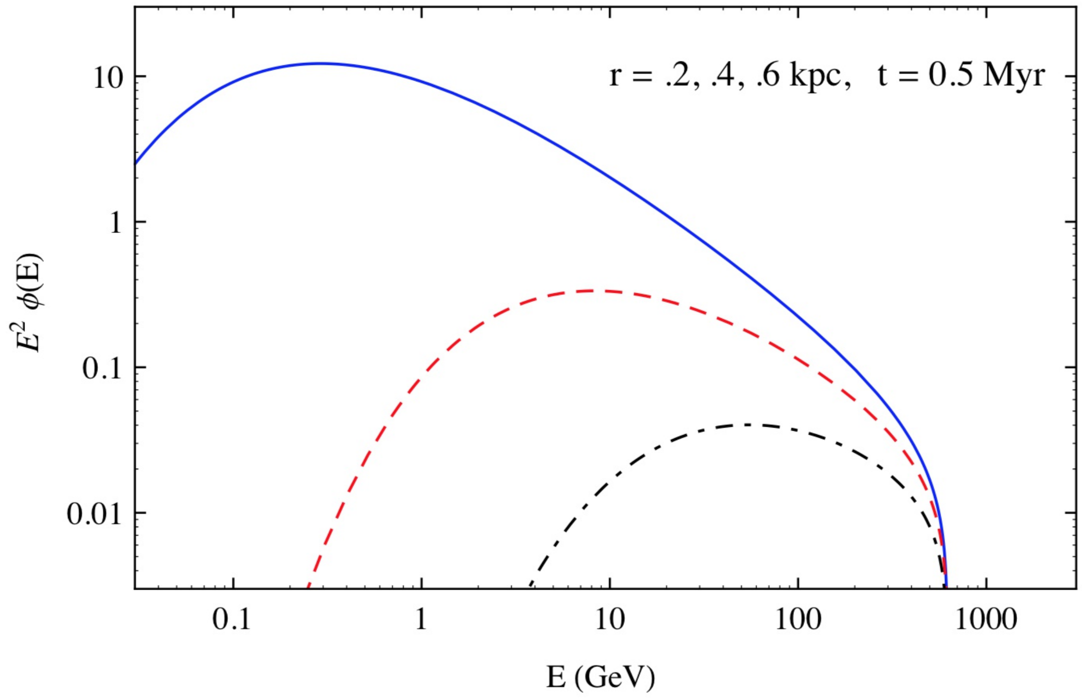
$$q_s(E) = q_0\ E^{-\alpha}\ \delta[t - t_i]$$



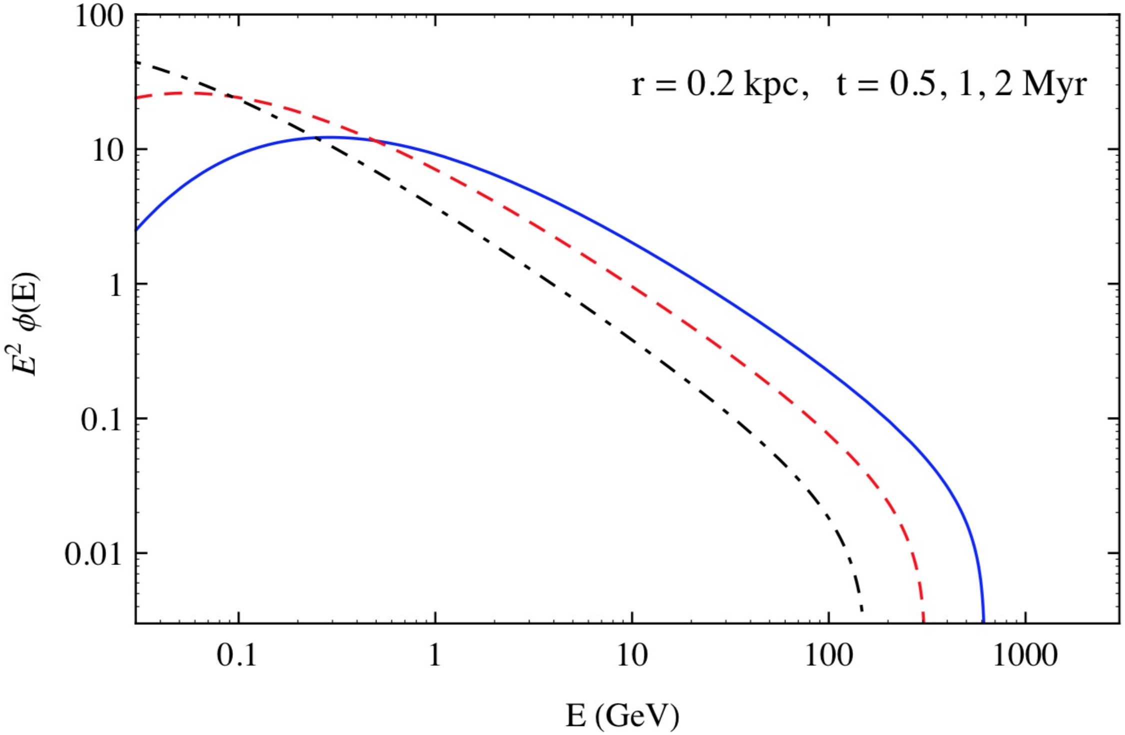
$$E^{-\gamma}$$

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

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



Changing **r**
(same age)



Changing **t**
(same distance)

Simple analytic expression (limit of negligible escape)

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

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

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

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

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

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

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

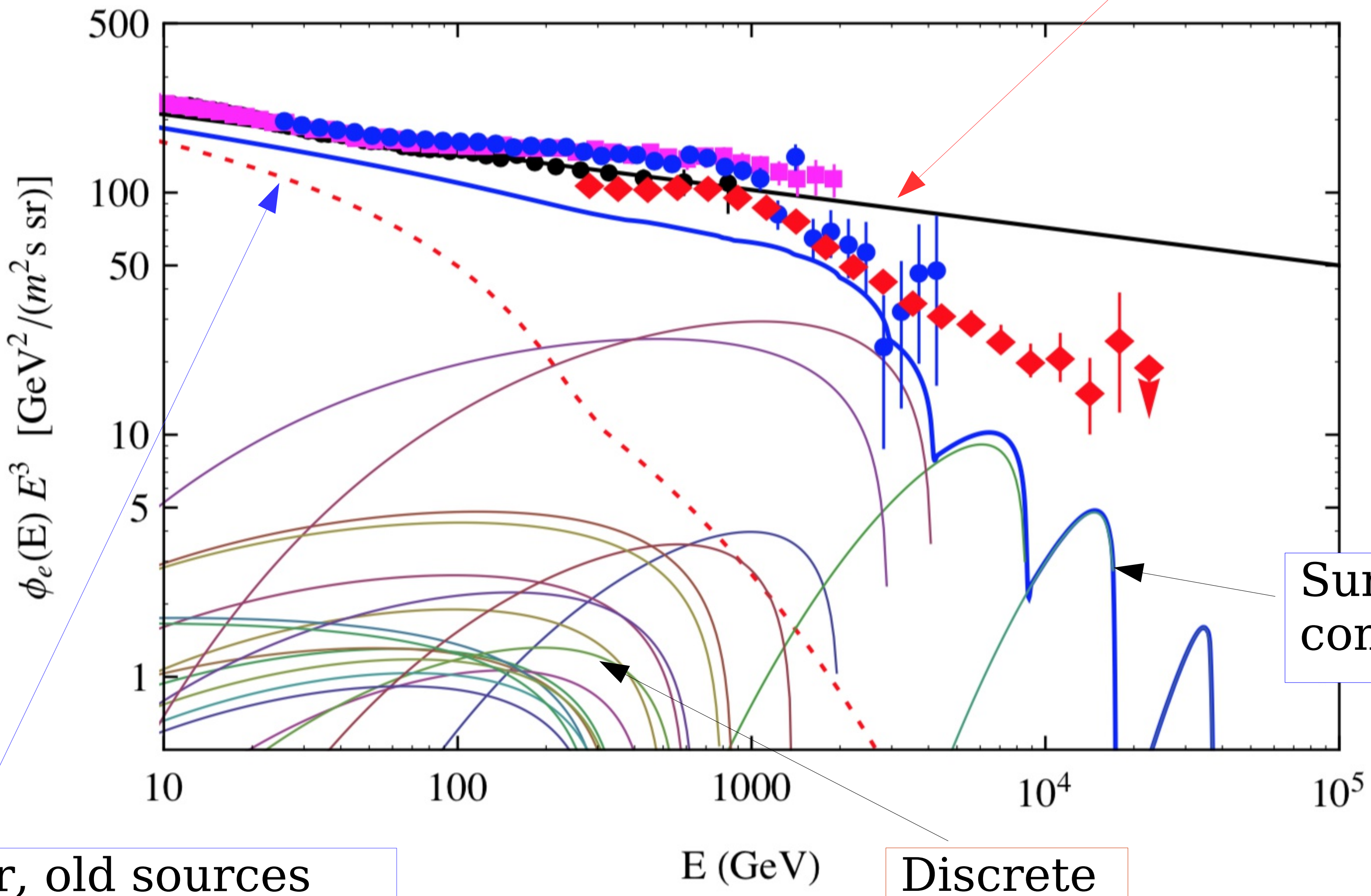
Treated as individual sources
(generating randomly
one configuration)

Randomly generated configuration of sources

$$T_s = 50 \text{ yr}$$

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

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



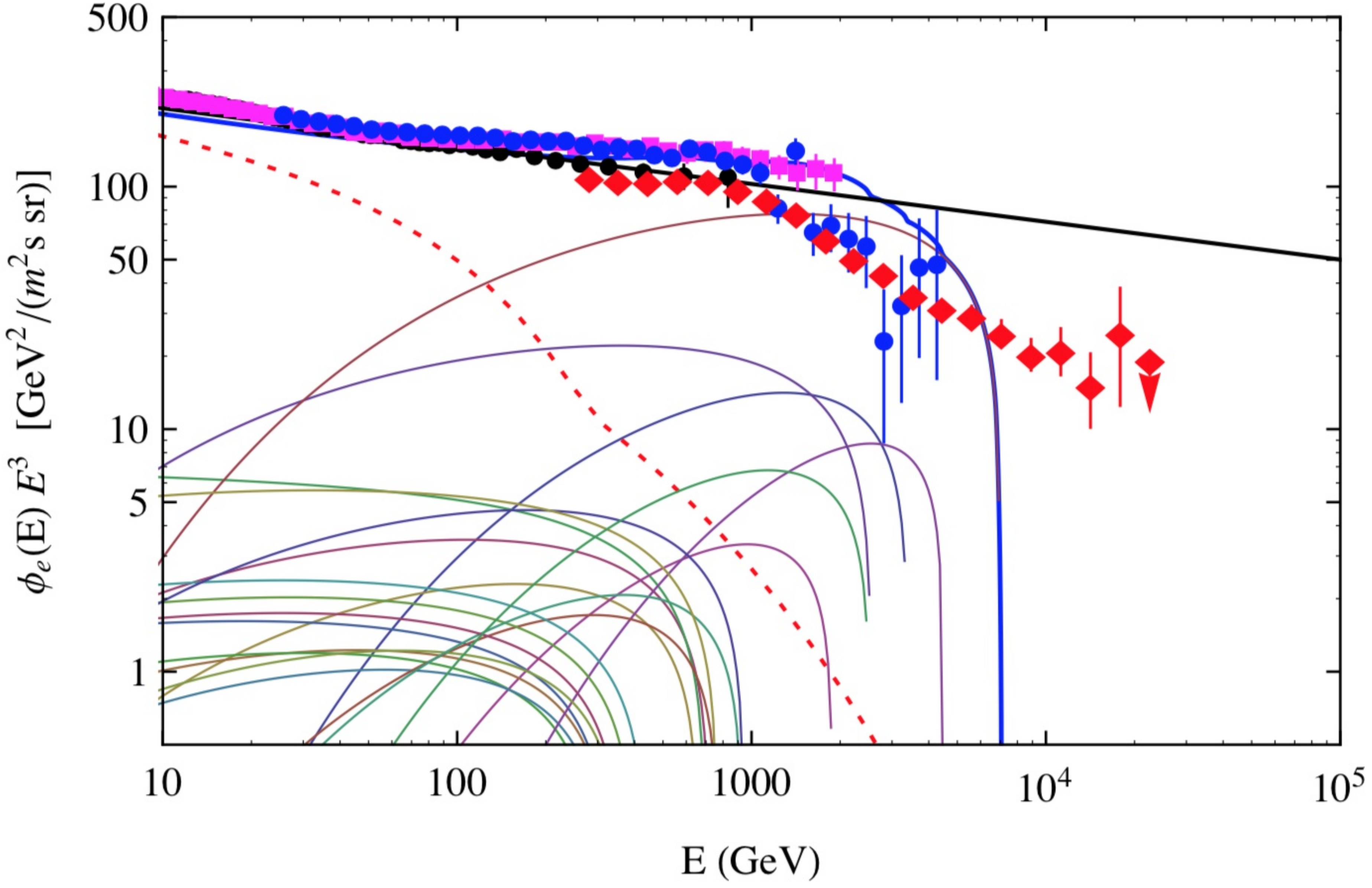
smooth distribution limit

Sum all components

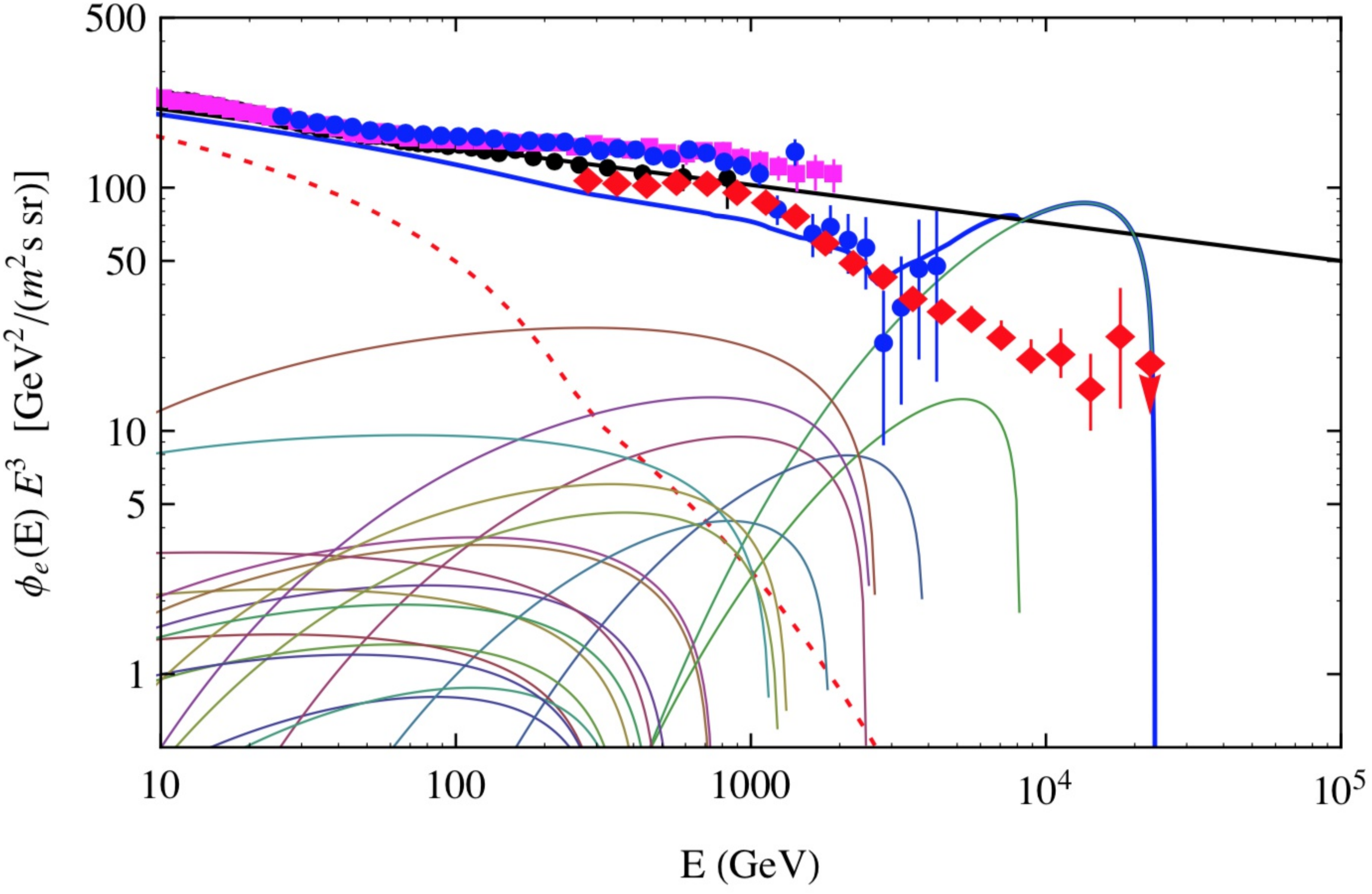
Far, old sources (treated as smooth

Discrete sources

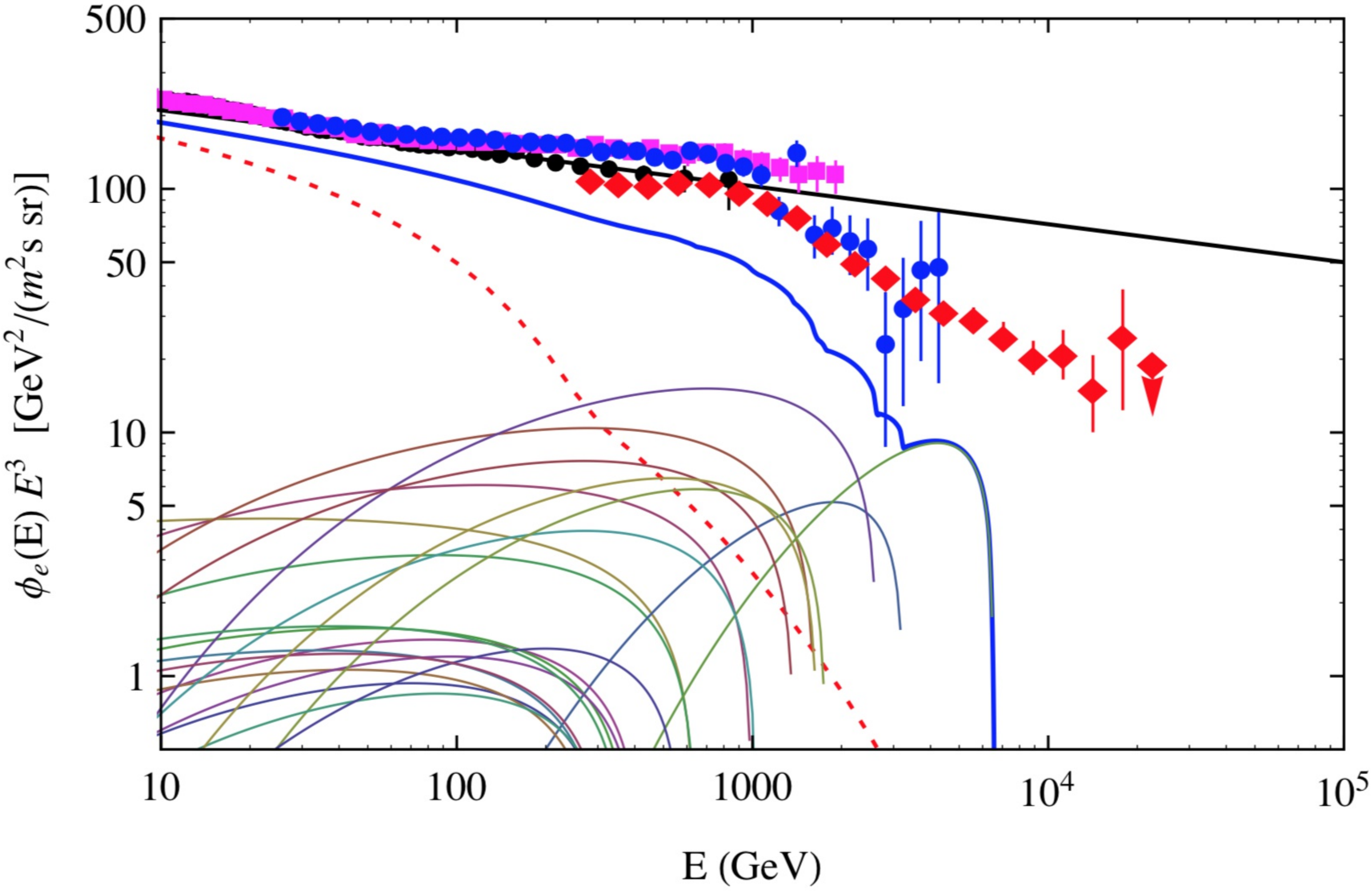
One more randomly generated configuration of sources [2]



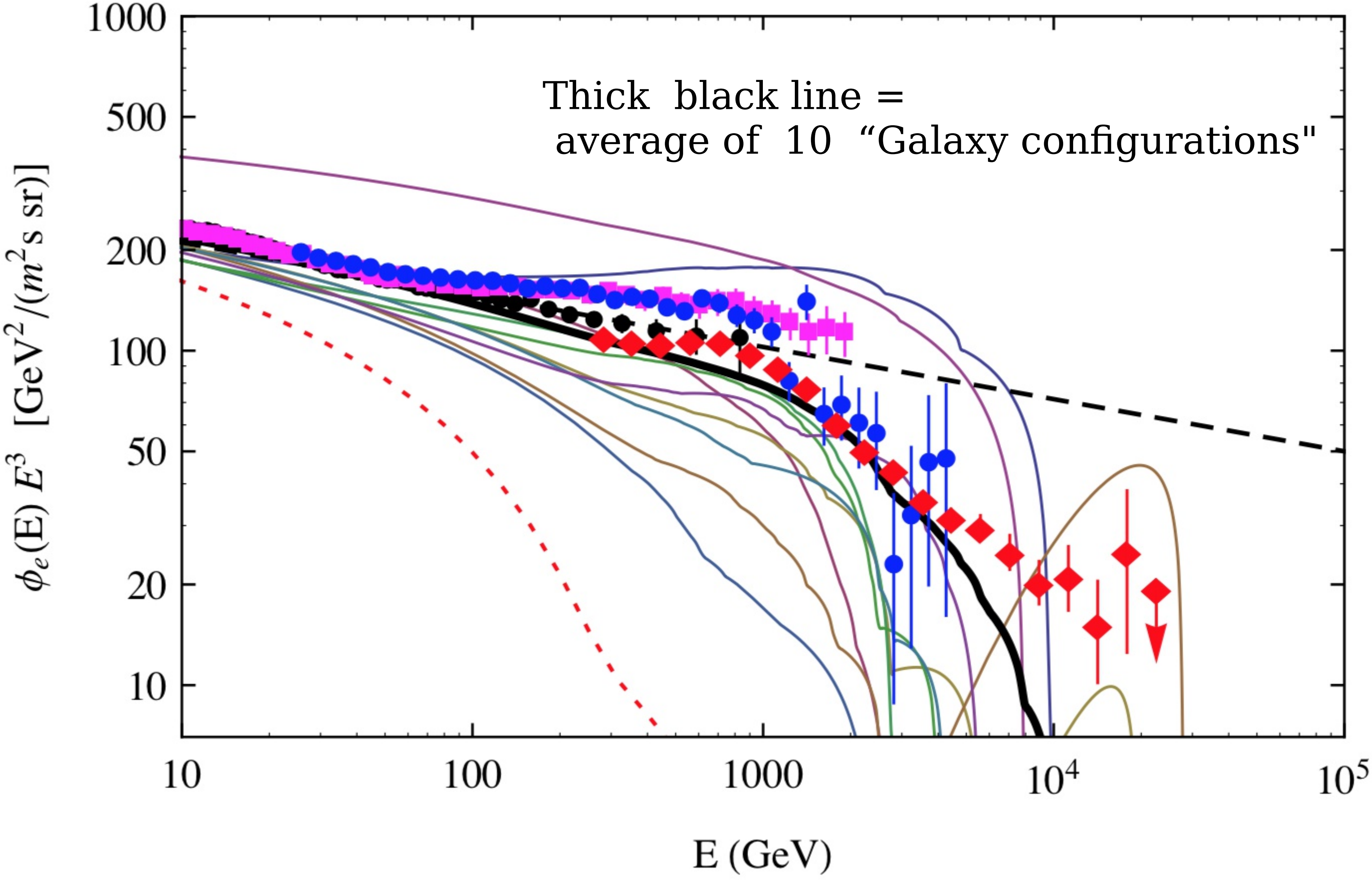
One more randomly generated configuration of sources [3]



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

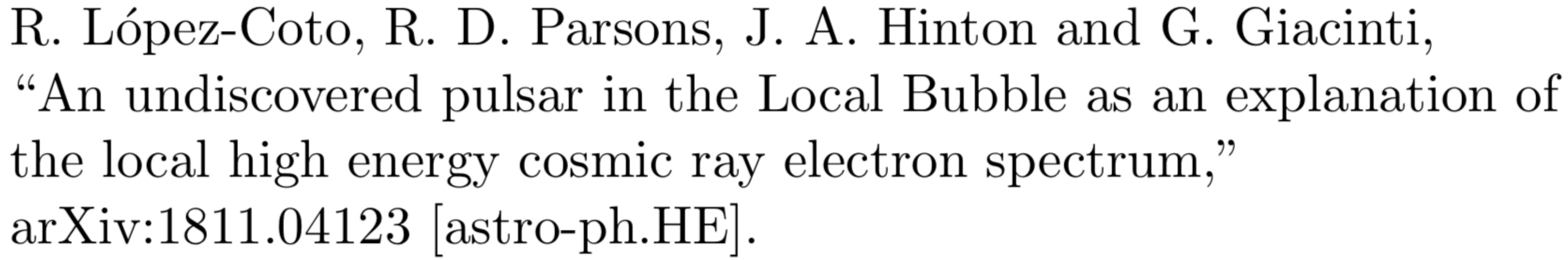
Solutions ….. ?

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

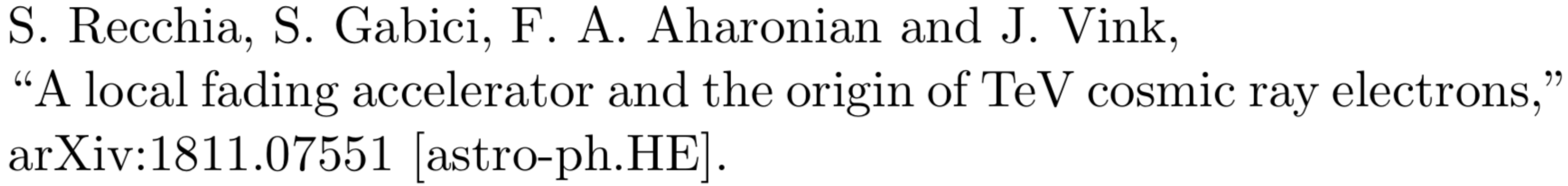
[2.] Modify the source model

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

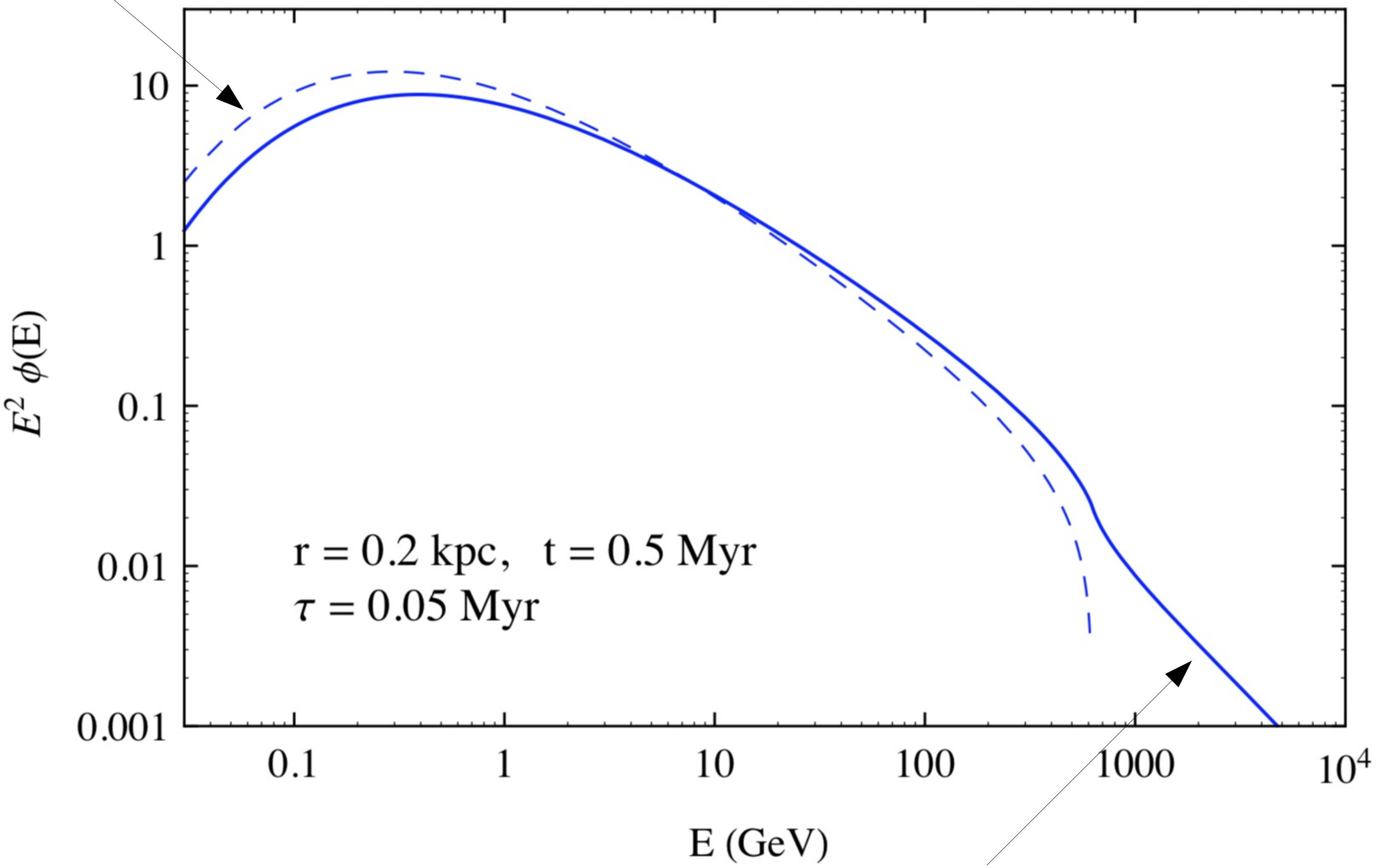
$$q_s(E,t) = q_0 \; E^{-\alpha} \boxed{\frac{(p-1)}{\tau} \; \left[1 + \frac{(t-t_i)}{\tau}\right]^{-p}}$$

$p = \text{breaking index}$

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

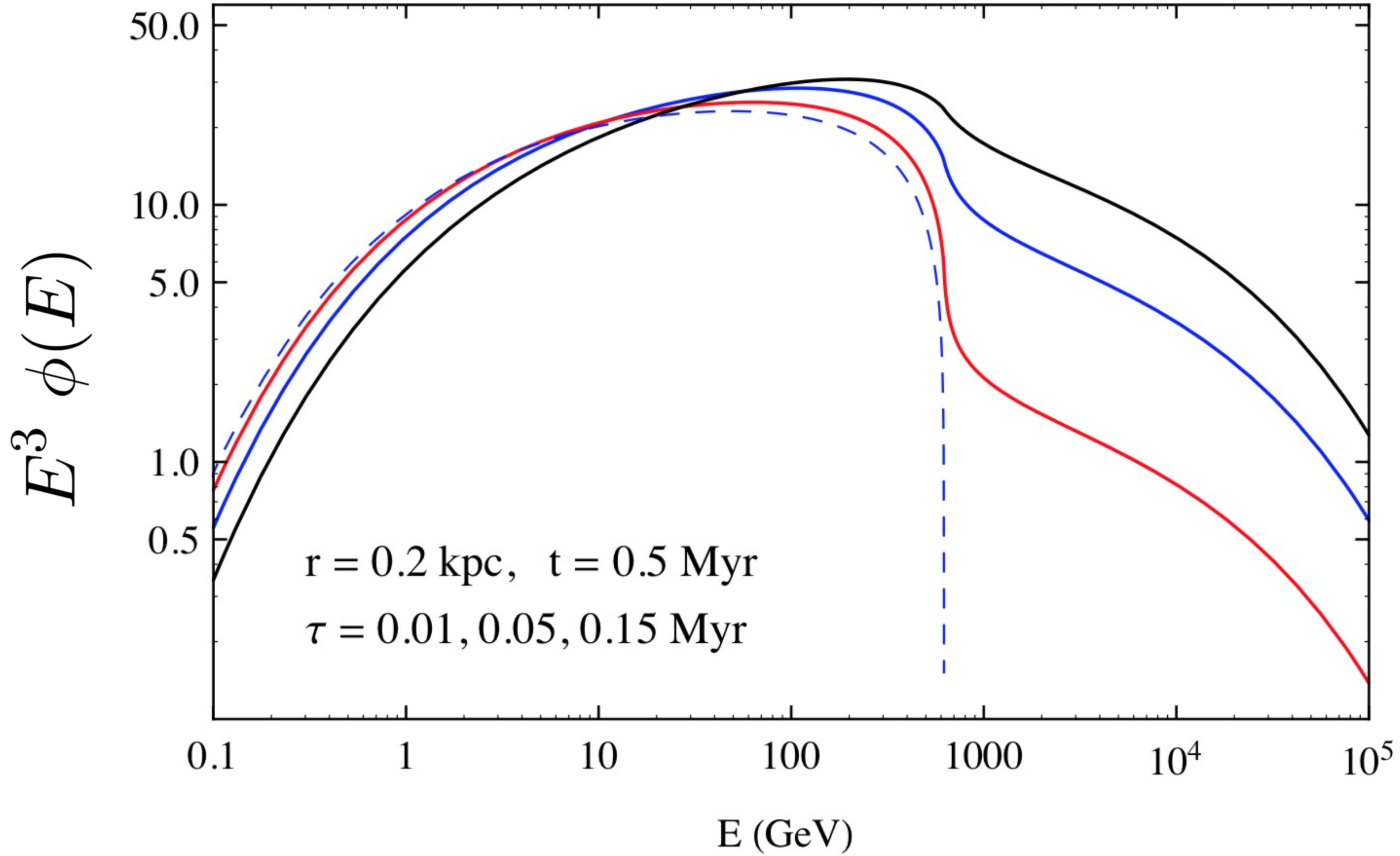
Fading source $p = 2$

Dashed line
Instantaneous source

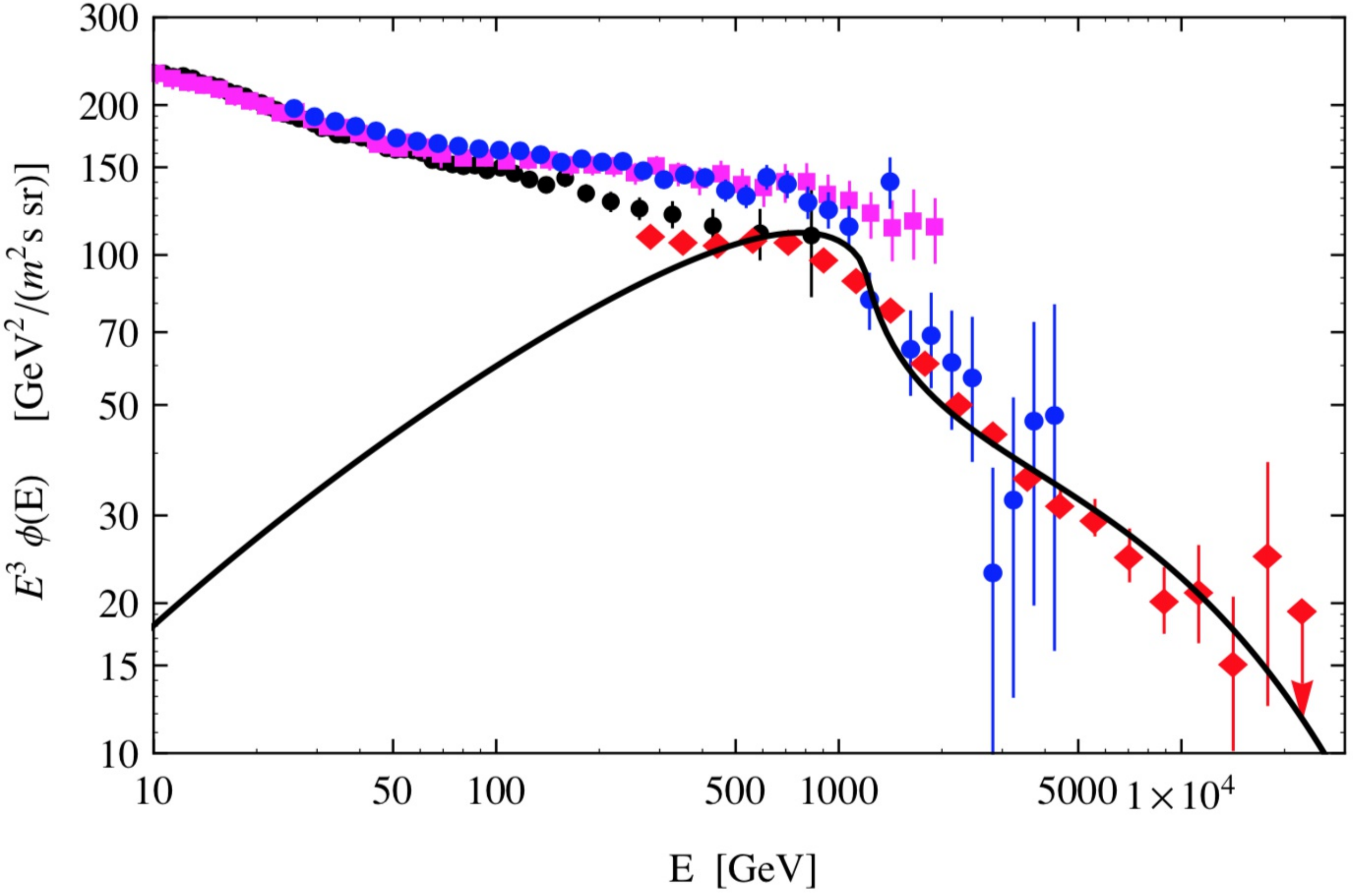


High energy tail

changing source decay time tau:



Matching the spectral break with ONE “fading” source



$r = 157$ kpc

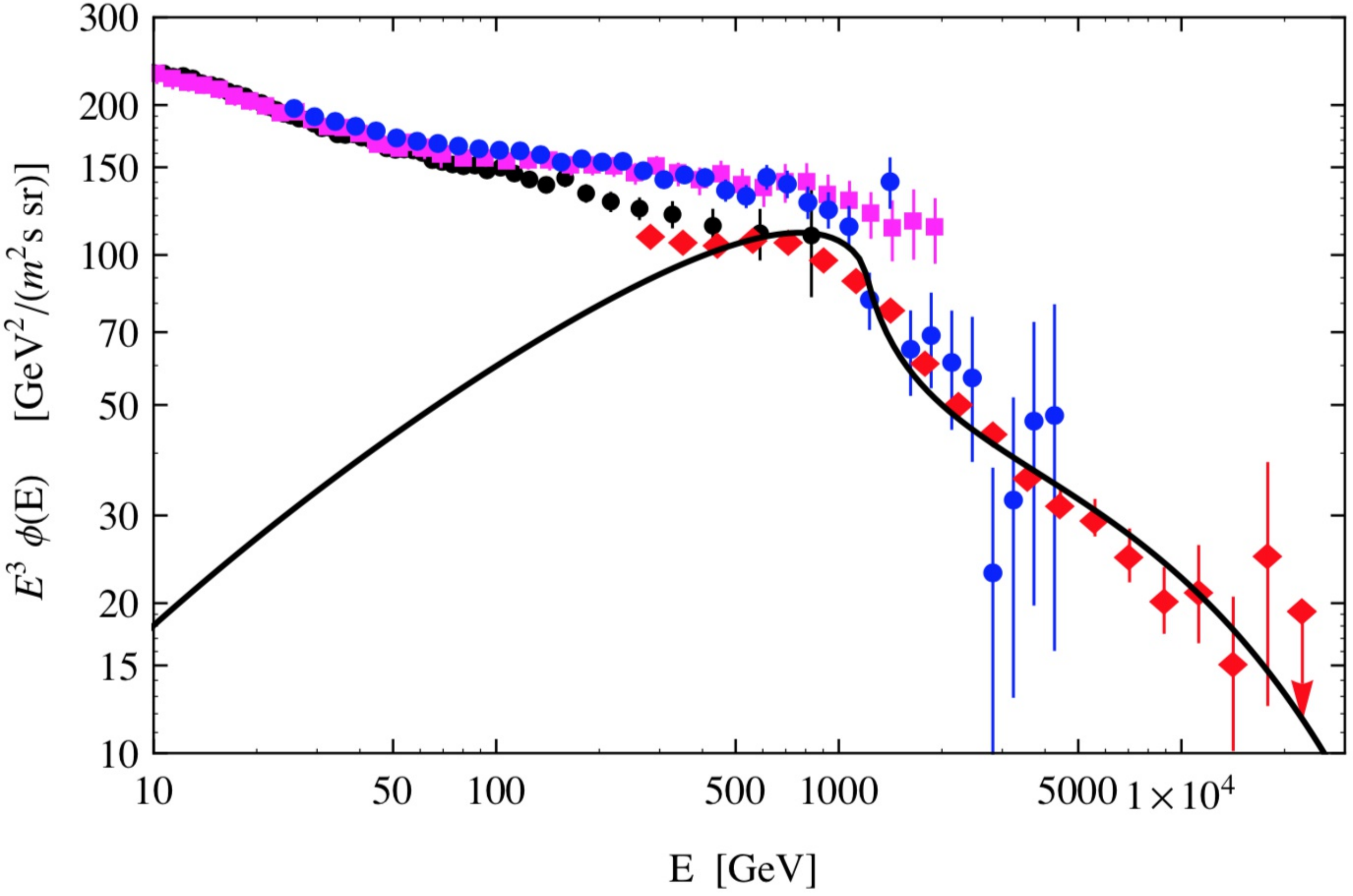
$t = 260$ kyr

$\tau = 40$ kyr

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

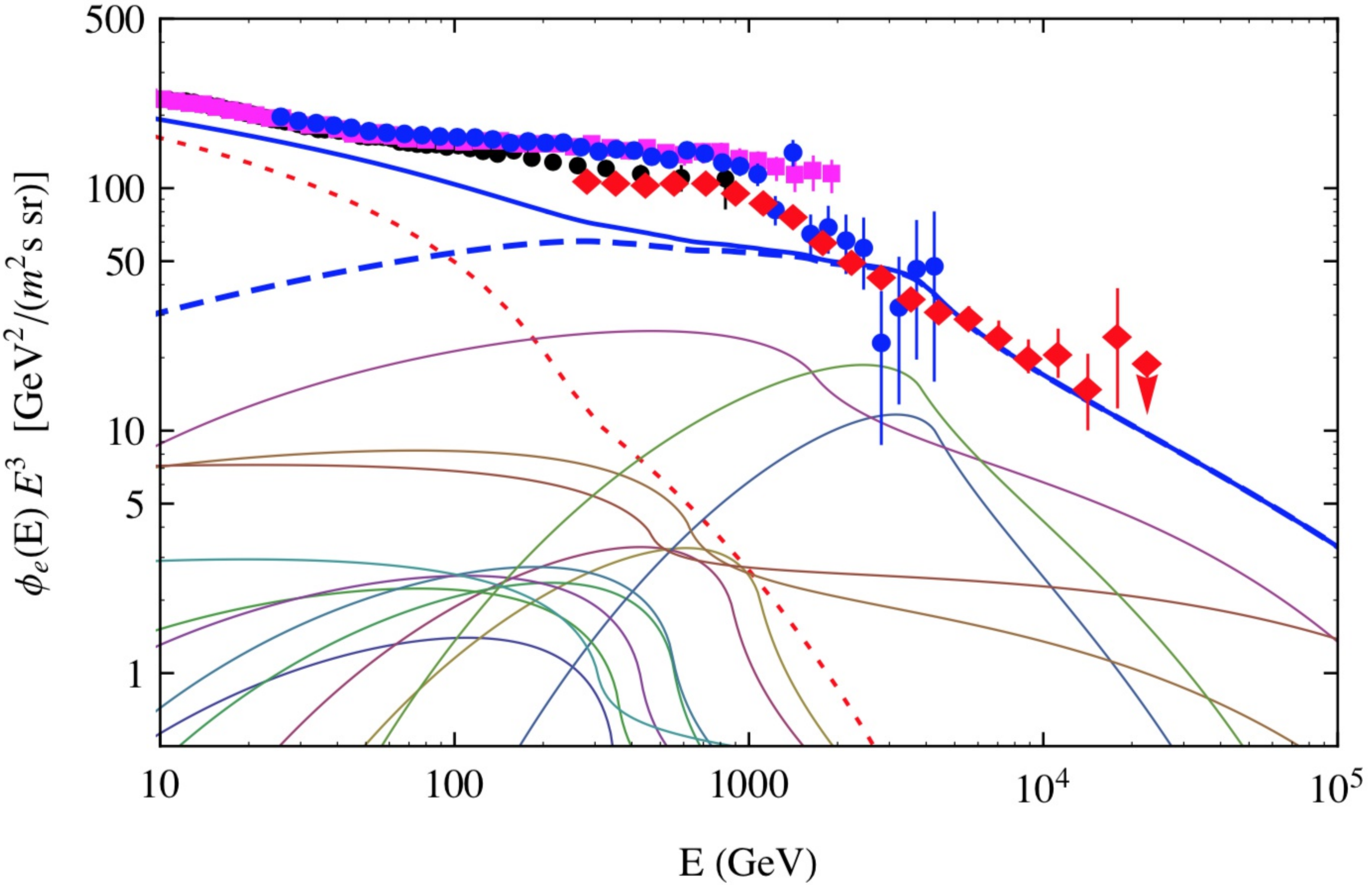
$$\propto \frac{\mathcal{E}}{(D_0)^3}$$

Infinite identical solutions:

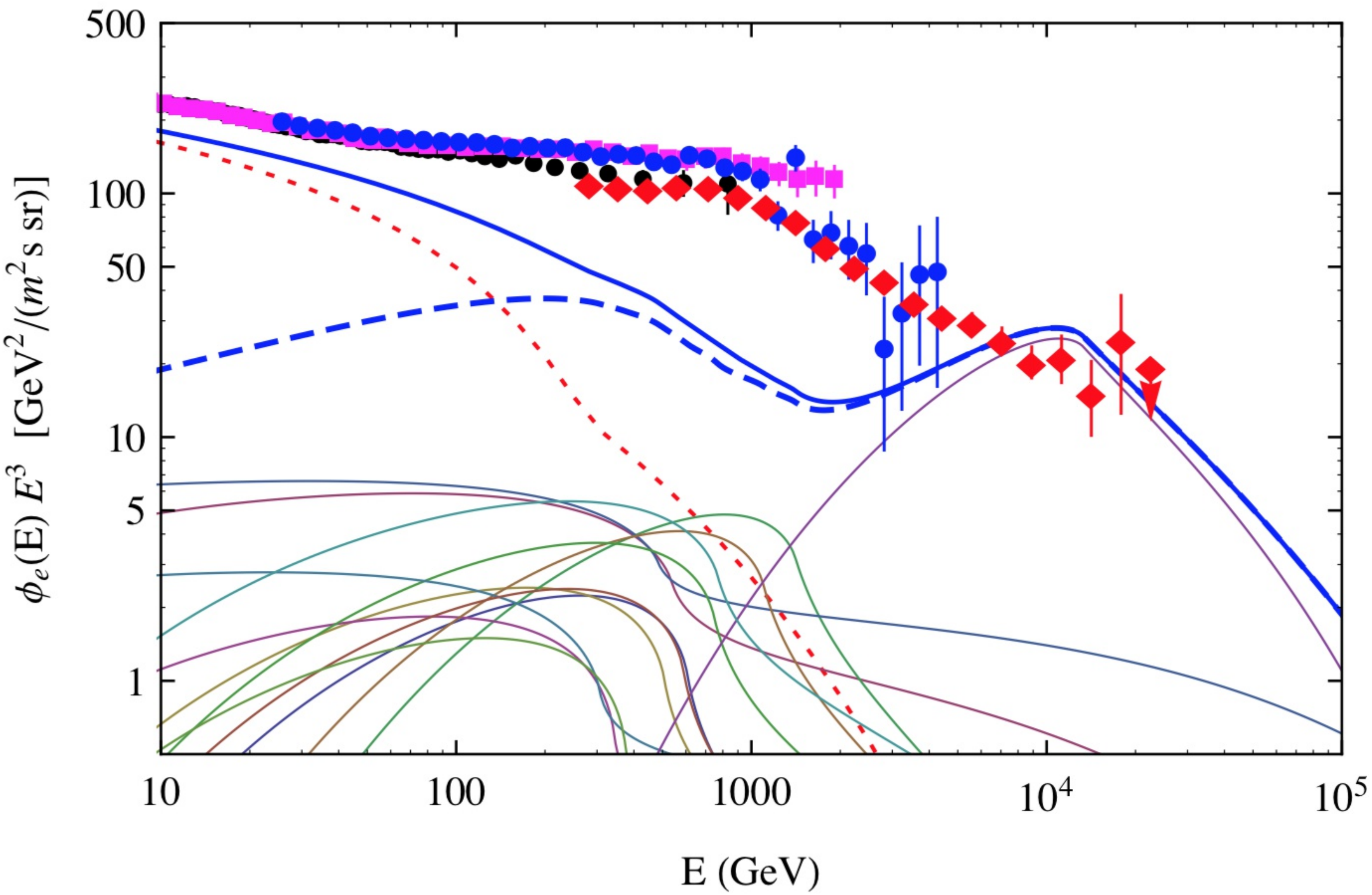
$$\{D_0\ ,\ r,\ \ \mathcal{E},\ \ \ \ldots\ \}$$

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

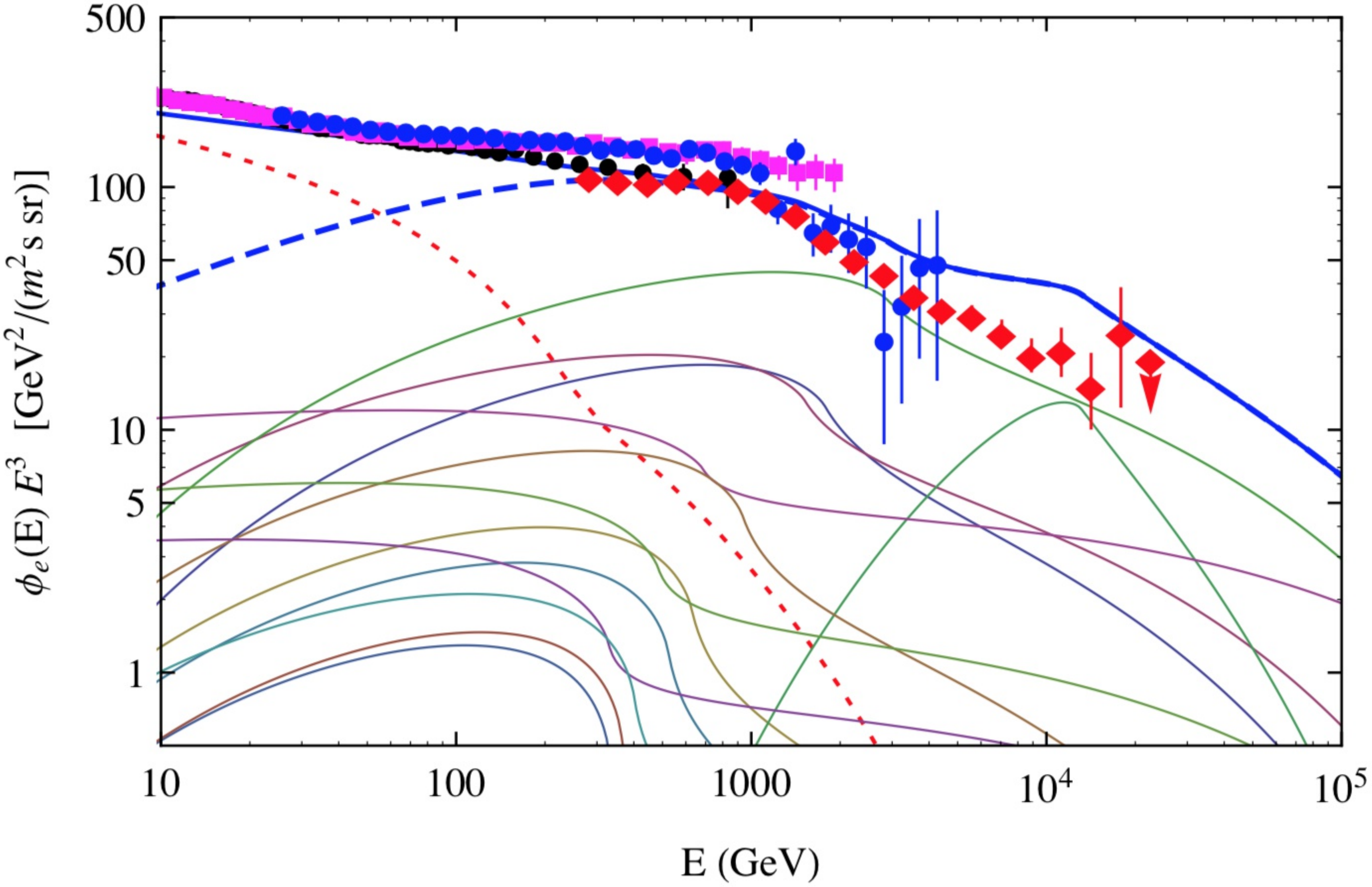
Study ensemble of fading sources



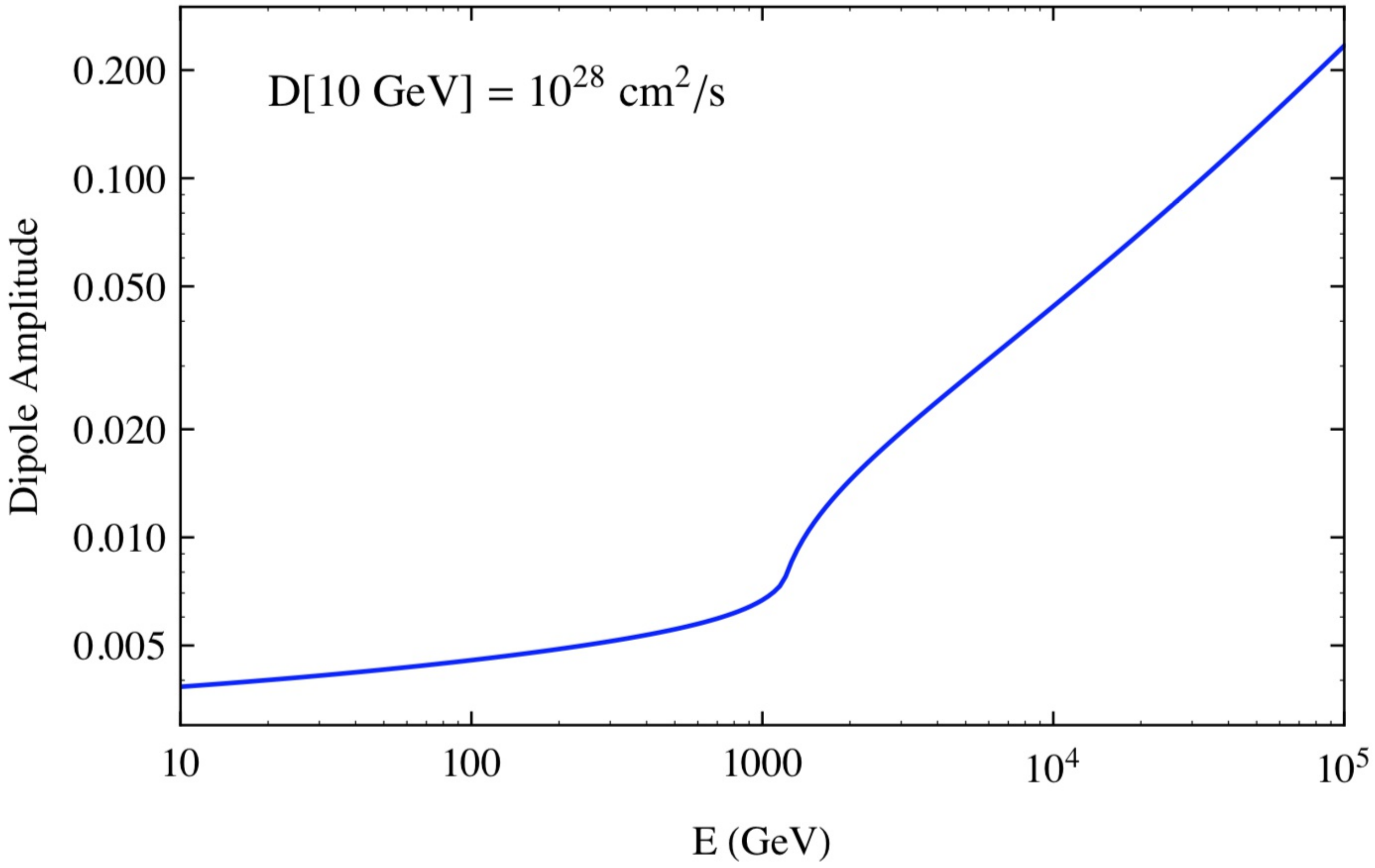
One random Galactic configuration [2]



One random Galactic configuration [e]



Dipole moment of the angular distribution



Comments:

The “single fading source” is an interesting solution,
… but… 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 ?

Do Pulsars accelerate different spectra of e+ and e- ?

What about Supernovae ?

Alternative solution:

Interpret the softening structures in the electron and positron spectra as the signatures of energy losses

Solution allows to “solve” the problem
of the “positron excess”
[with positrons purely secondary]

But runs in several difficulties

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

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

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

$$\begin{tikzcd}[column sep=small] pp \to \pi^+ + \ldots \arrow[d, hook] & & \\ & \mu^+ + \nu_\mu \arrow[d, hook] & \\ & & e^+ + \nu_e + \overline{\nu}_\mu \end{tikzcd}$$

$$\begin{tikzcd}[column sep=small] pp \to \pi^\circ + \ldots \arrow[d, hook] & \\ & \gamma + \gamma \end{tikzcd}$$

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

Dominant mechanism for the generation of high energy gamma rays

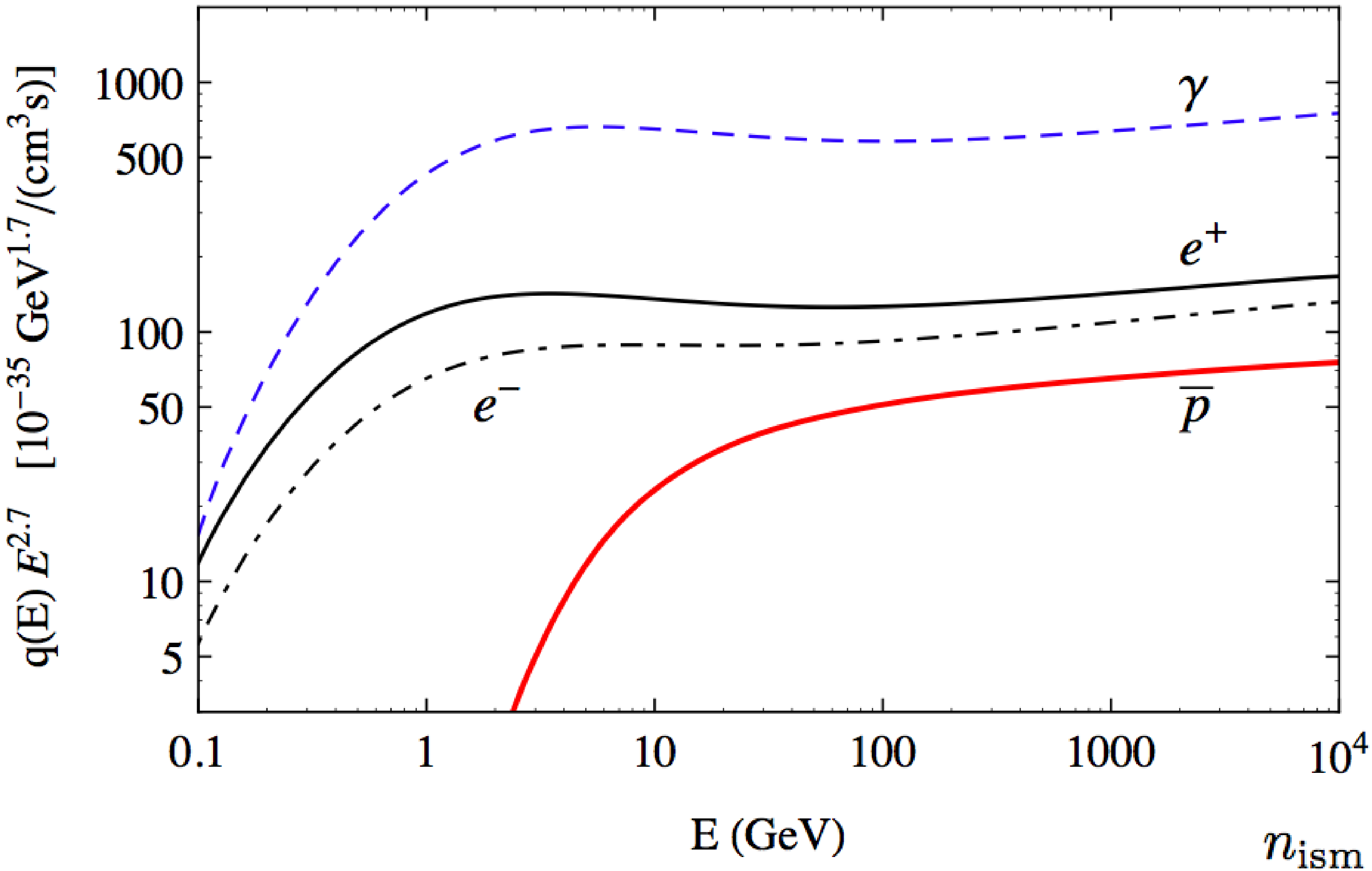
intimately connected

Straightforward [hadronic physics] exercise: $q_j(E, \vec{x}_\odot)$

[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

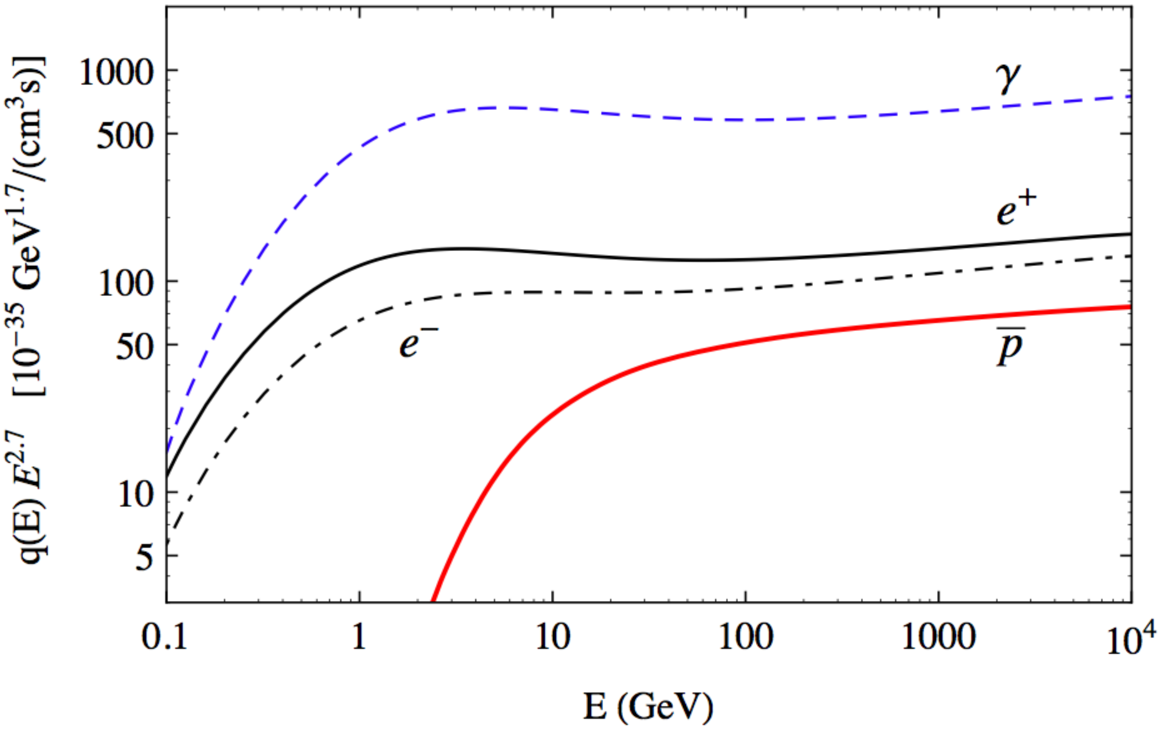


$$\frac{\gamma}{\perp} \approx 5.5$$

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

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

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

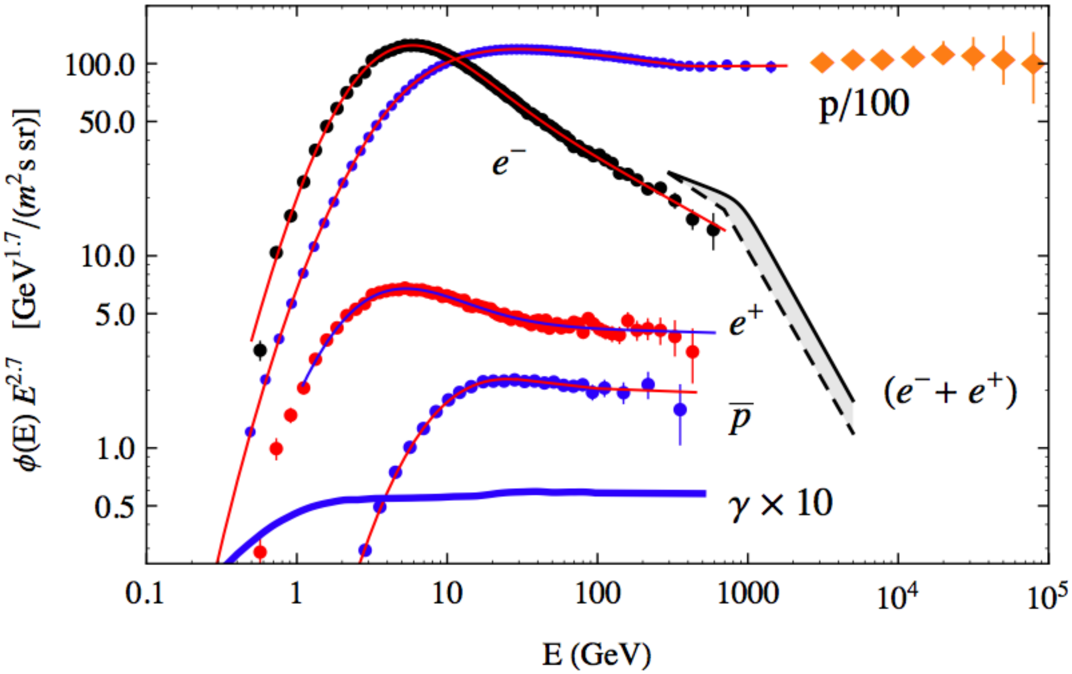


Local production rates of secondaries

e^+ $\overline{p}$

“striking” similarity

Observed fluxes



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)

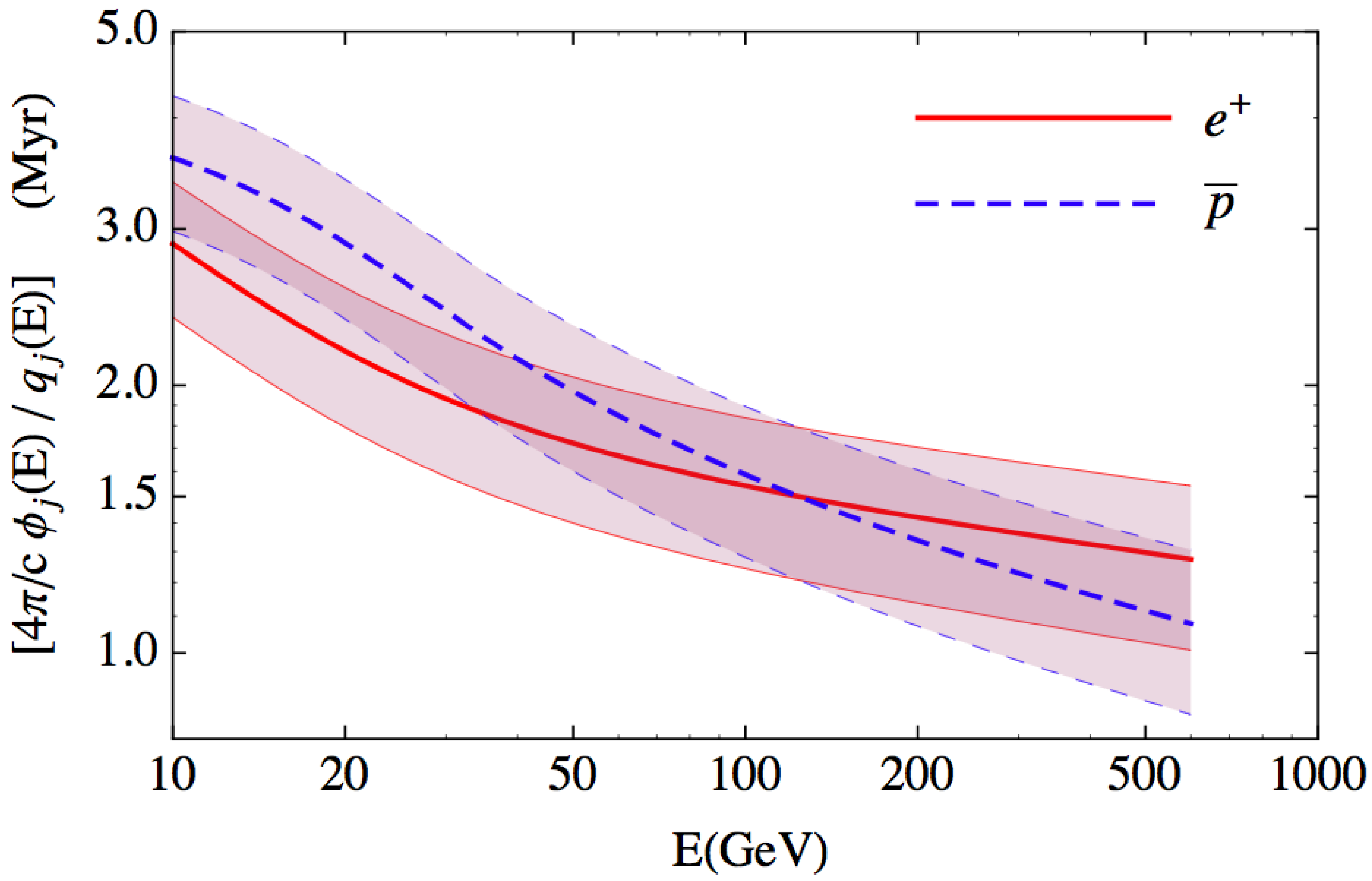
2. Cosmic rays in the Galaxy (that generate the antiparticles and the photons) have spectra similar to what is observed at the Earth.

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

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

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

Distortion of the source spectra created by propagation



Weak energy dependence of the propagation effects !

“Standard Scenario” (Long residence time) for CR prop.

1. *New source of Positrons*
2. e- and p source spectra have similar shape
3. High energy positron suppression (800 GeV)
   associated to maximum energy of the source [?]
4. High energy electron suppression (1000 GeV).
   Closest source [?]

“Alternative Scenario” (Short residence time) for CR prop.

1. *Positrons are explained as secondaries*
2. e- source spectrum softer than the proton one
3. High energy supporessions of e- and e+_
   Explained as a propagation effect.

How can one discriminate between the two scenarios ?

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

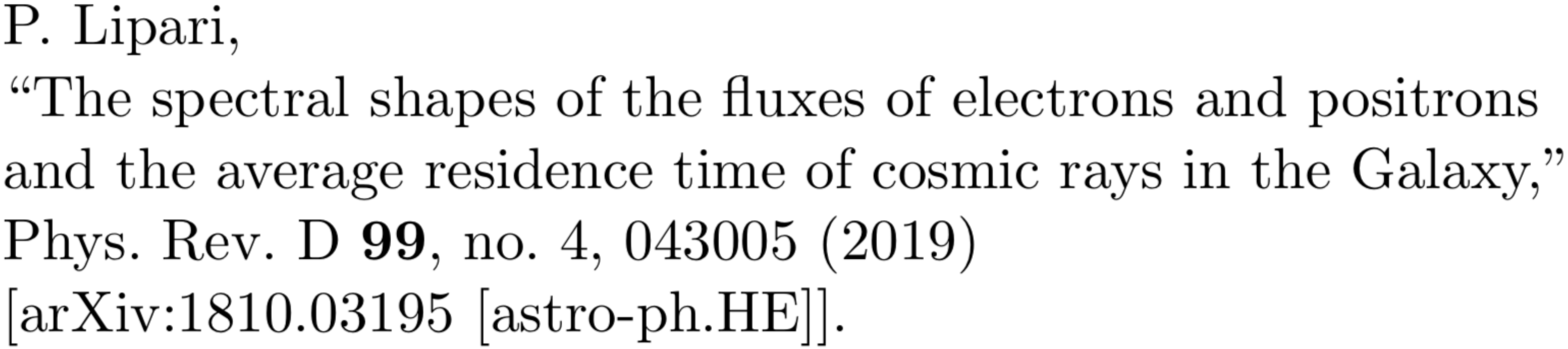
2. More precise measuremens of (e+ + e-) spectra
   in the multi-TeV range

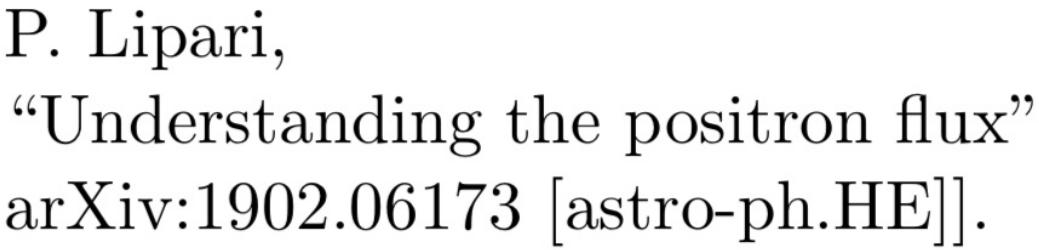
3. Extend measurements of secondary nuclei
   [B, Be, Li]. Look for signatures of
   nuclear fragmentation inside/near the accelerators.

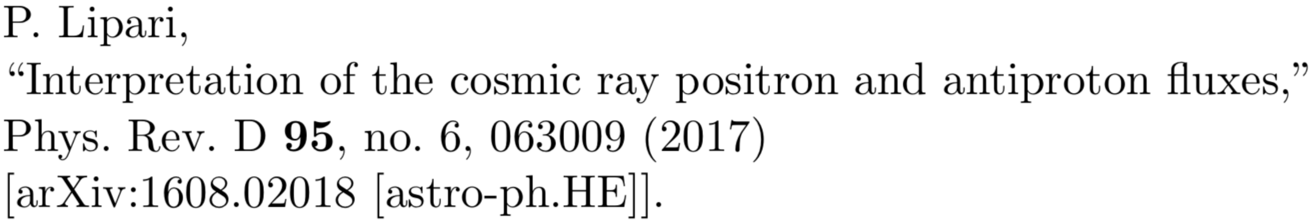
4. Study the space and energy distributions
   of the relativistic e+- in the Milky Way
   [from the analysis of diffuse Galactic gamma ray flux]

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)

Based in part on:


P. Lipari,
"The spectral shapes of the fluxes of electrons and positrons
and the average residence time of cosmic rays in the Galaxy,"
Phys. Rev. D **99**, no. 4, 043005 (2019)
[arXiv:1810.03195 [astro-ph.HE]].


P. Lipari,
"Understanding the positron flux"
arXiv:1902.06173 [astro-ph.HE]].


P. Lipari,
"Interpretation of the cosmic ray positron and antiproton fluxes,"
Phys. Rev. D **95**, no. 6, 063009 (2017)
[arXiv:1608.02018 [astro-ph.HE]].

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

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:

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

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

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

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

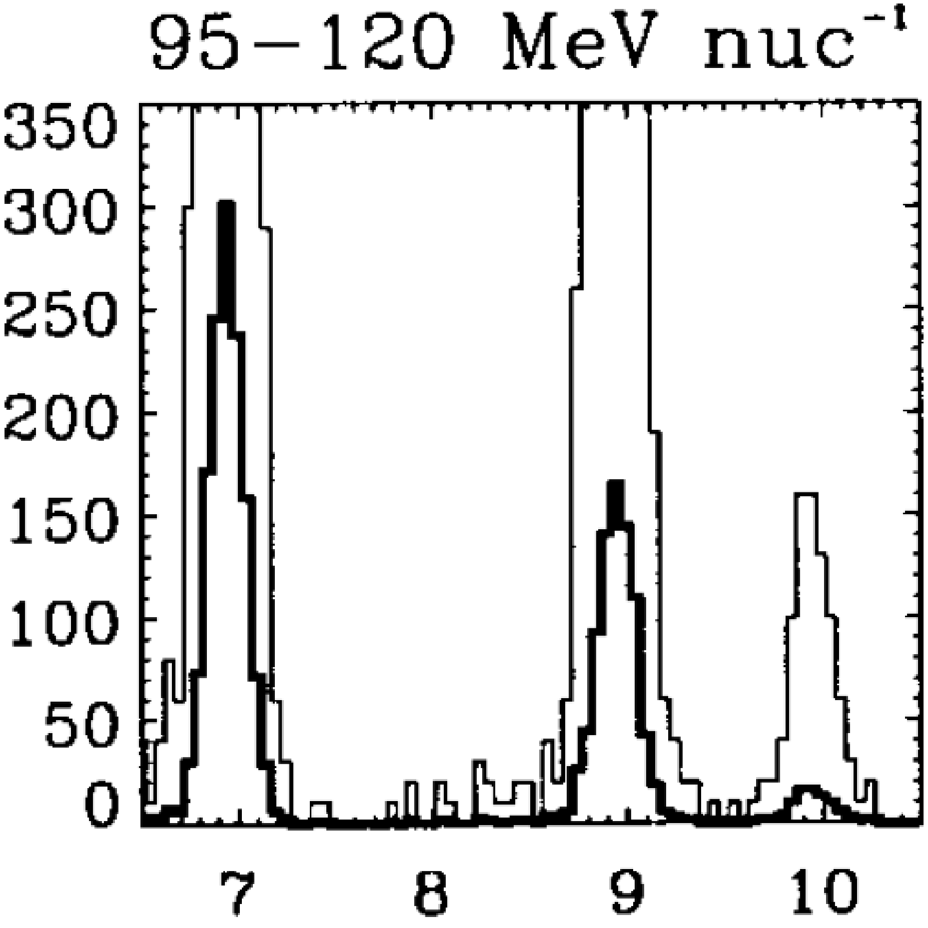
“Natural” explanation

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

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

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

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).

$E_0 = 70\text{–}145 \text{ MeV/nucleon}$

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

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

[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)

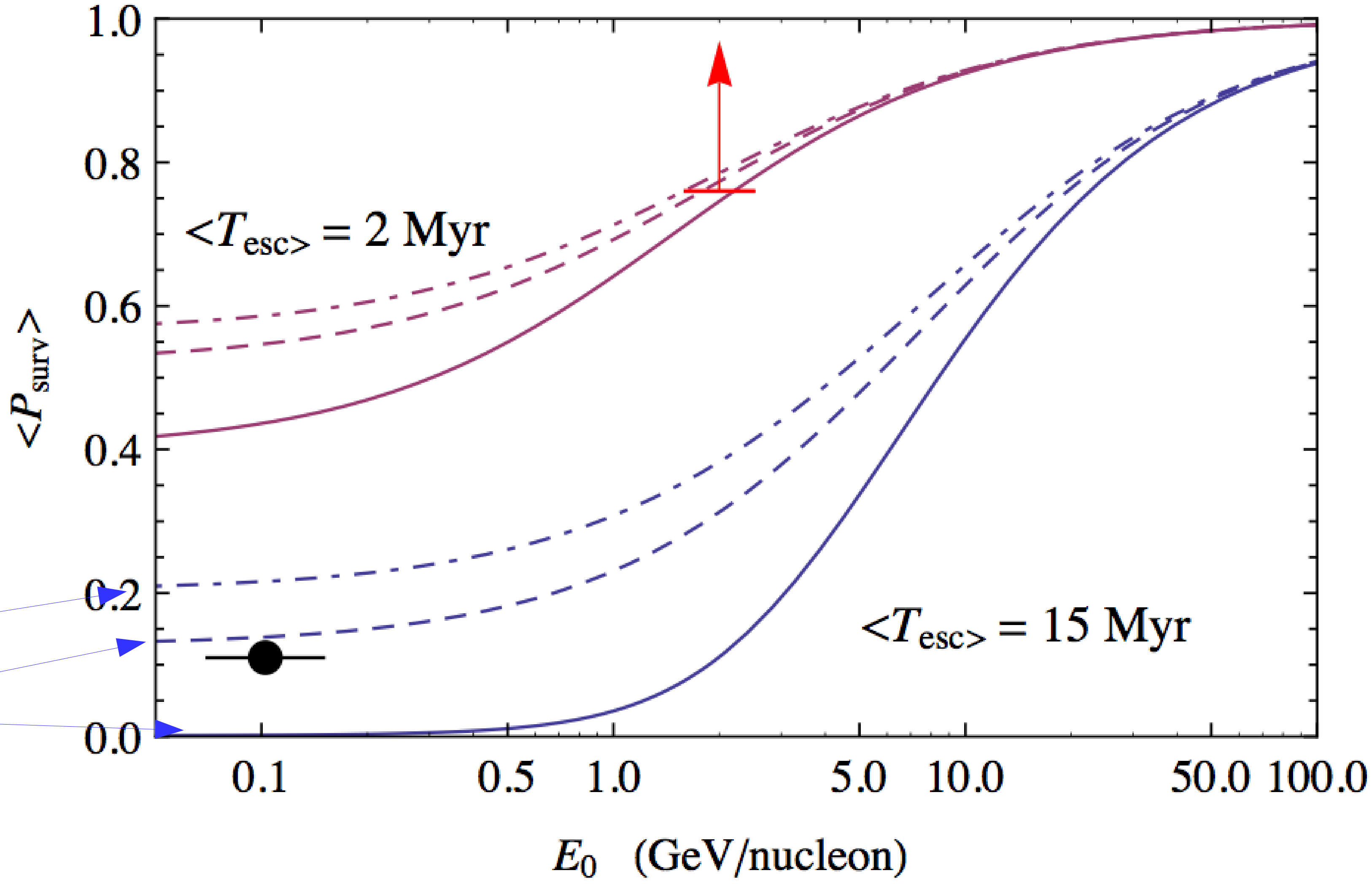
$E_0 = 2 \text{ GeV/nucleon}$

*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).

M. Kruskal, S. P. Ahlen and G. Tarlé,

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

Proton versus electron

Acceleration in sources

Cosmic Ray generation

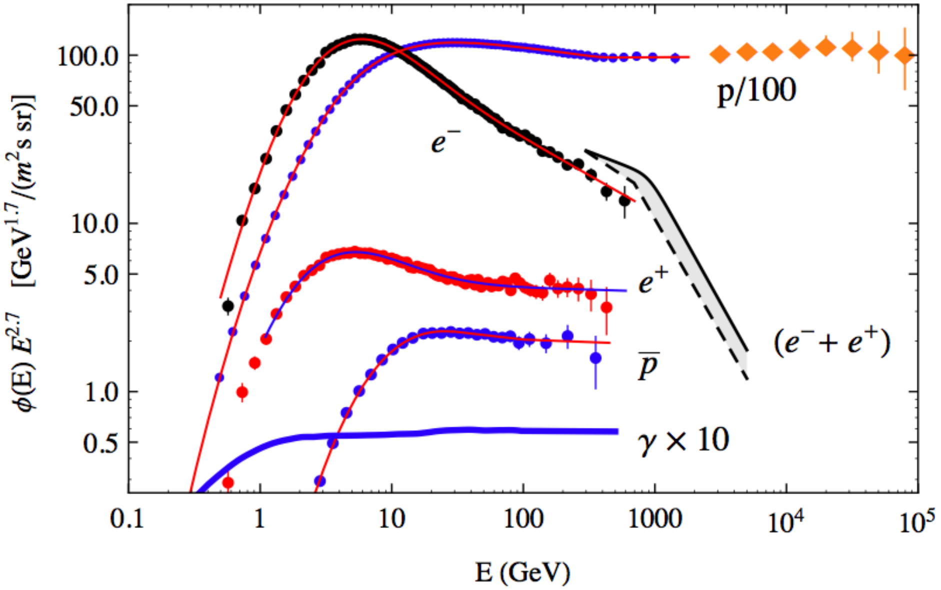
Problem of central importance in High Energy Astrophysics

If: positrons and antiprotons have equal propagation properties.

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

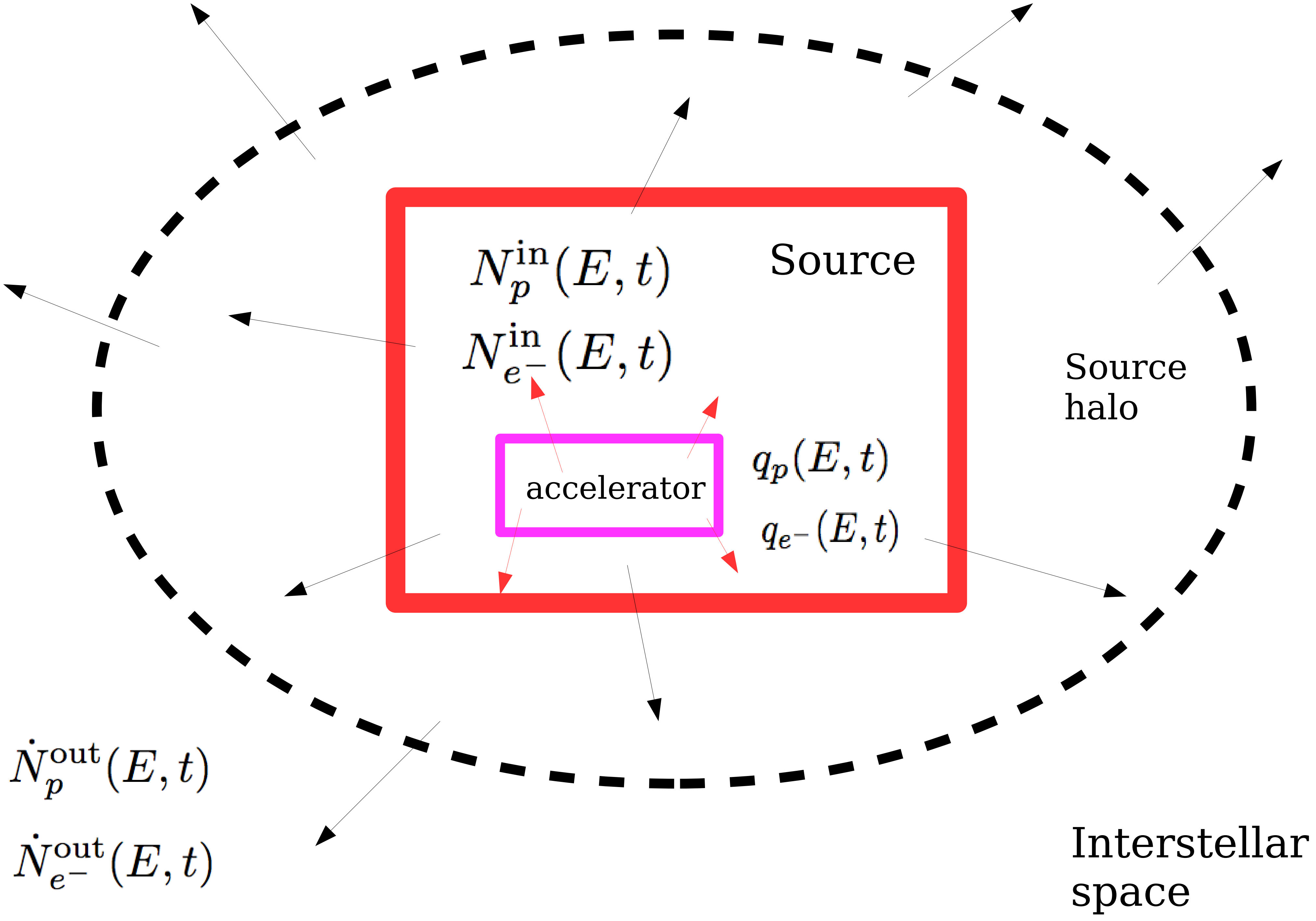
But then:

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



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.

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

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:

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

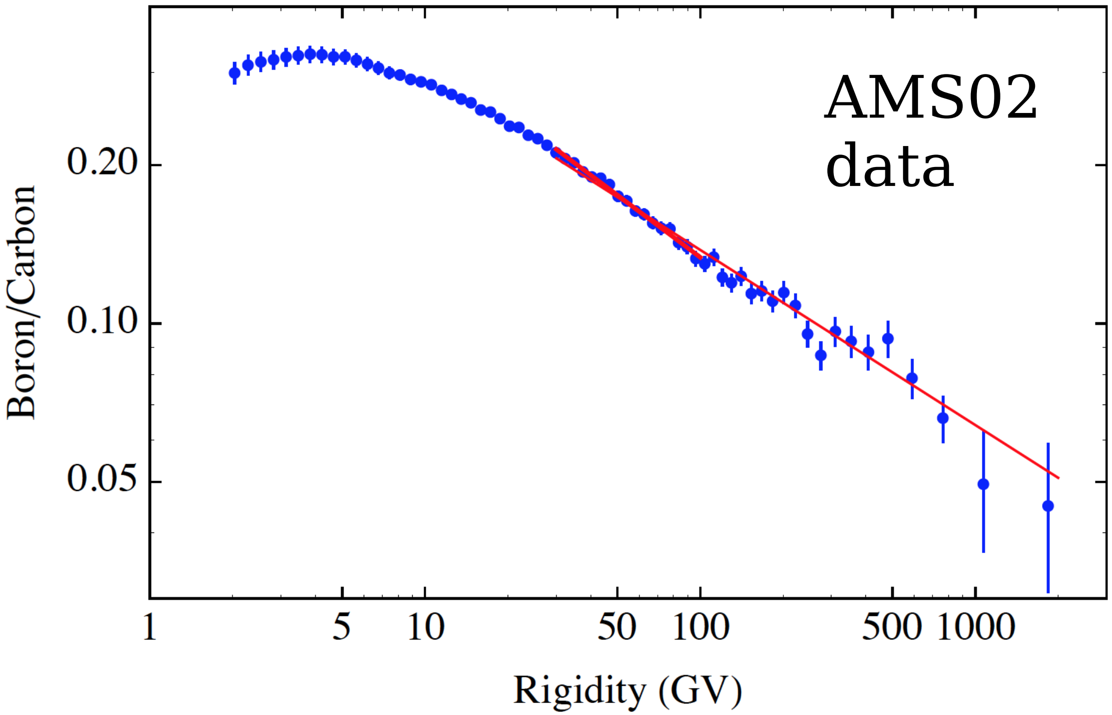
$$^{12}\mathrm{C} + p \to {}^{11}\mathrm{B} + 2\,p$$

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

....

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

“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*]

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

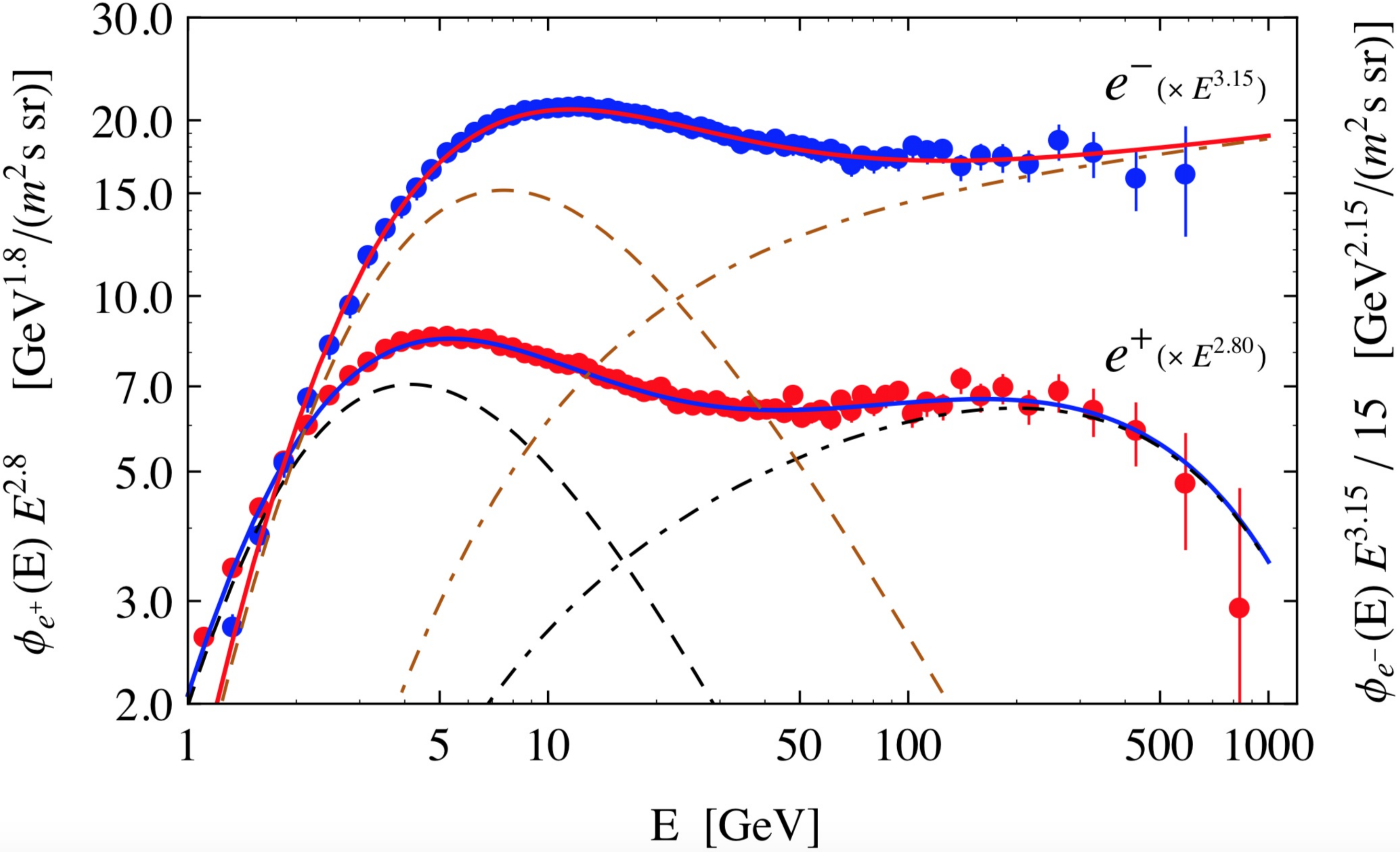
Residence time inferred from B/C ratio
assuming that the column density crossed by
the nuclei is accumulated in interstellar space

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]


30.0
20.0
15.0
10.0
7.0
5.0
3.0
2.0
$[\mathrm{GeV}^{1.8}/(m^2\,\mathrm{s\ sr})]$
$\phi_{e^+}(\mathrm{E})\ E^{2.8}$
$e^-{}_{(\times E^{3.15})}$
$e^+{}_{(\times E^{2.80})}$
$[\mathrm{GeV}^{2.15}/(m^2\mathrm{s\ sr})]$
$\phi_{e^-}(\mathrm{E})\ E^{3.15}\ /\ 15$
1
5
10
50
100
500
1000
E [GeV]