The spectral shape of the fluxes of electrons and positrons

and the propagation of cosmic rays in the Galaxy

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Workshop: WASDHA201
Air Shower Detection at High Altitude

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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

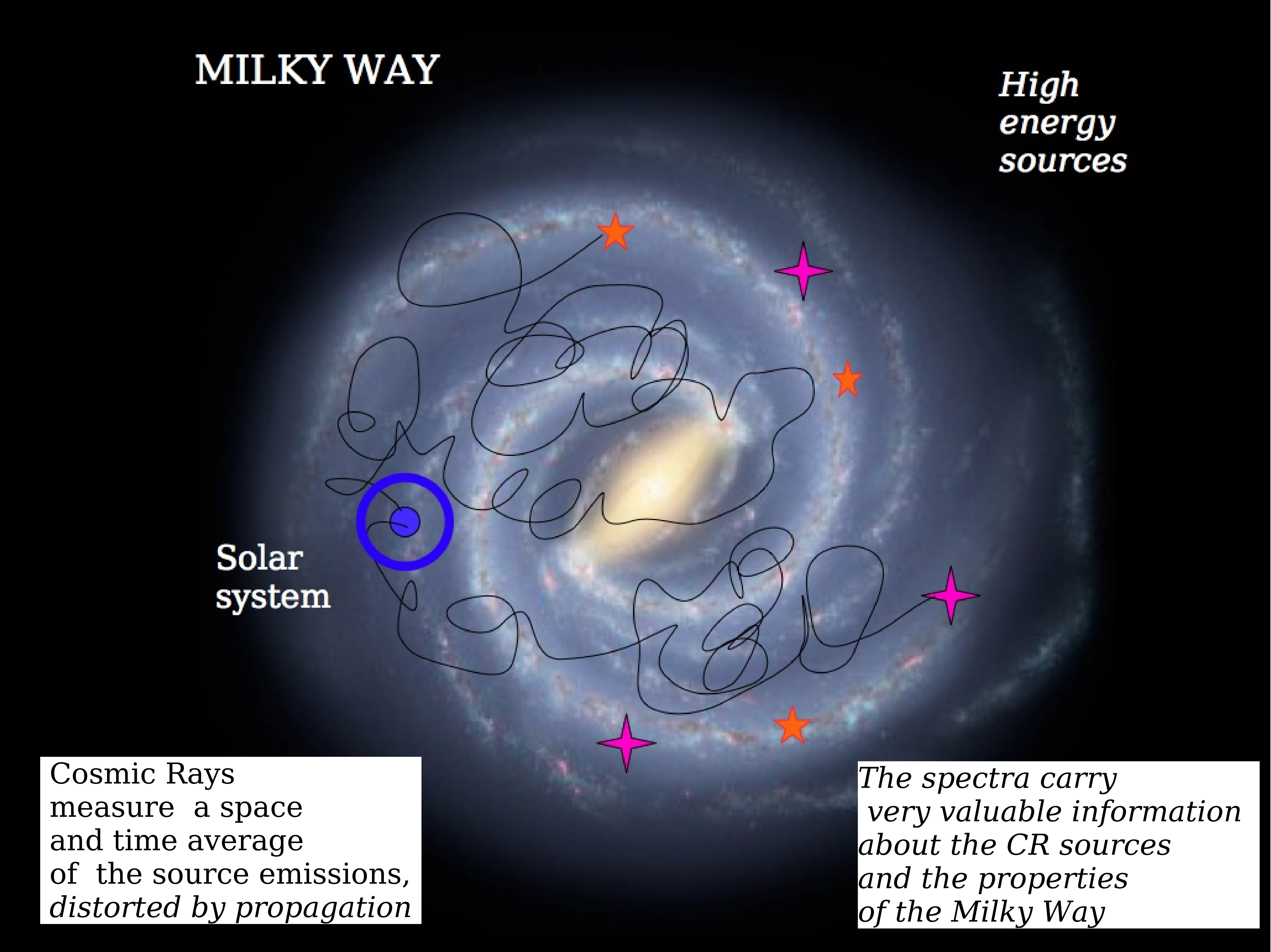
$$\phi_{e^-}(E,\Omega)$$

electrons

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

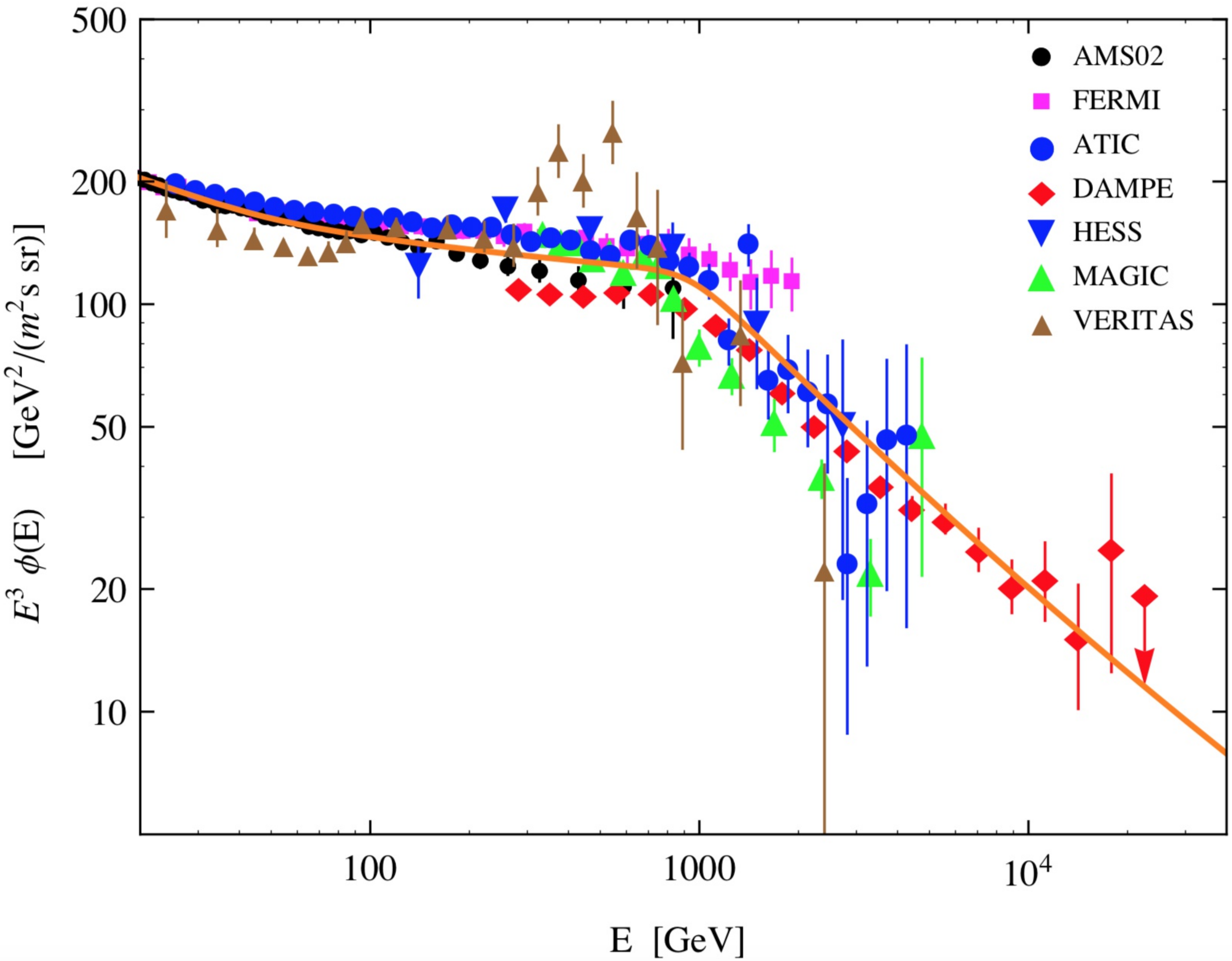
$$\phi_{\overline{p}}(E,\Omega)$$

anti-particles


MILKY WAY
High energy sources
Solar system
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 $(e^- + e^+)$

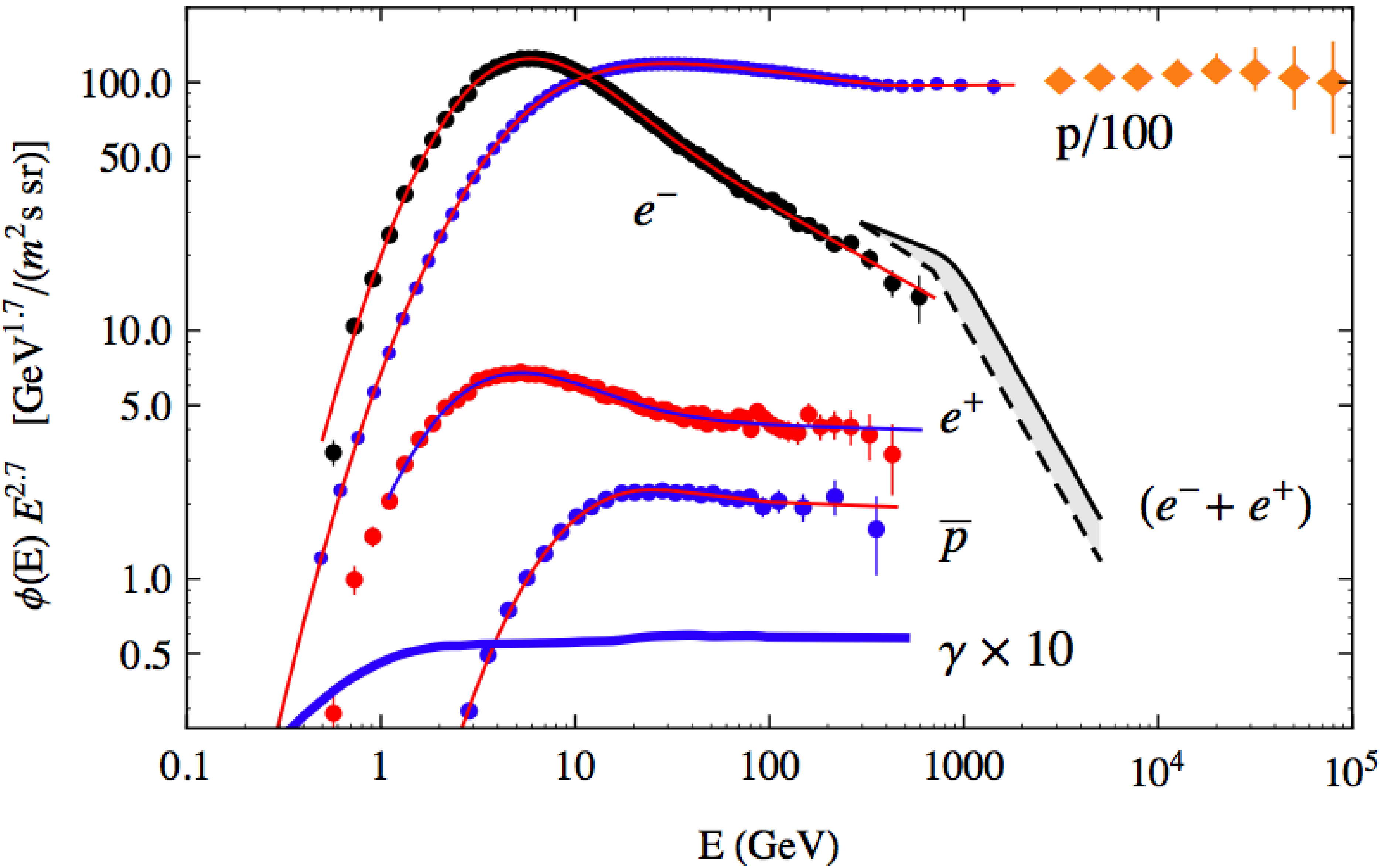
Remarkable discovery of Cherenkov telescopes



Understanding this spectral structure is *crucial*

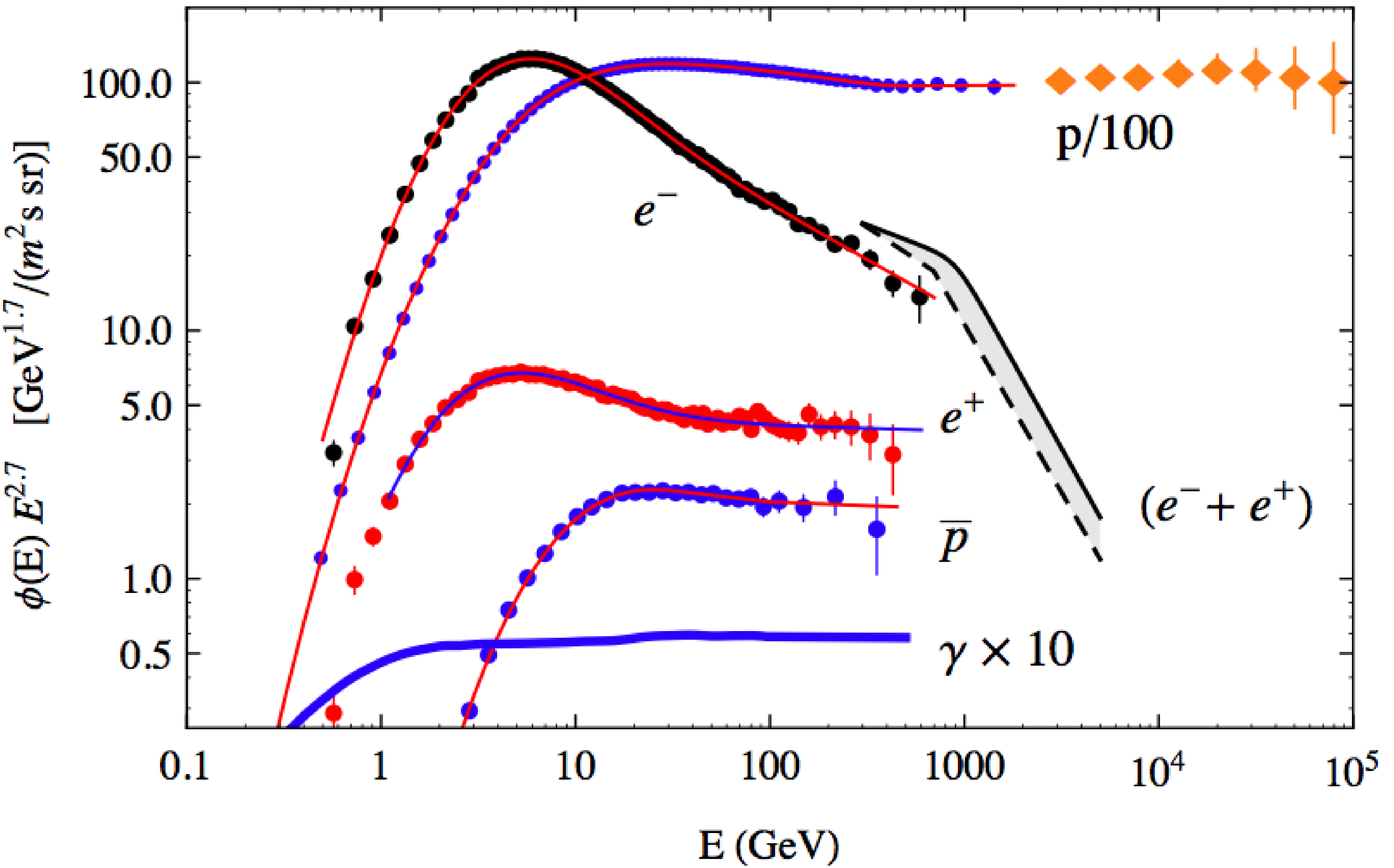
AMS02 p e^- e^+ $\overline{p}$

CREAM p data



angle averaged diffuse Galactic gamma ray flux (Fermi)

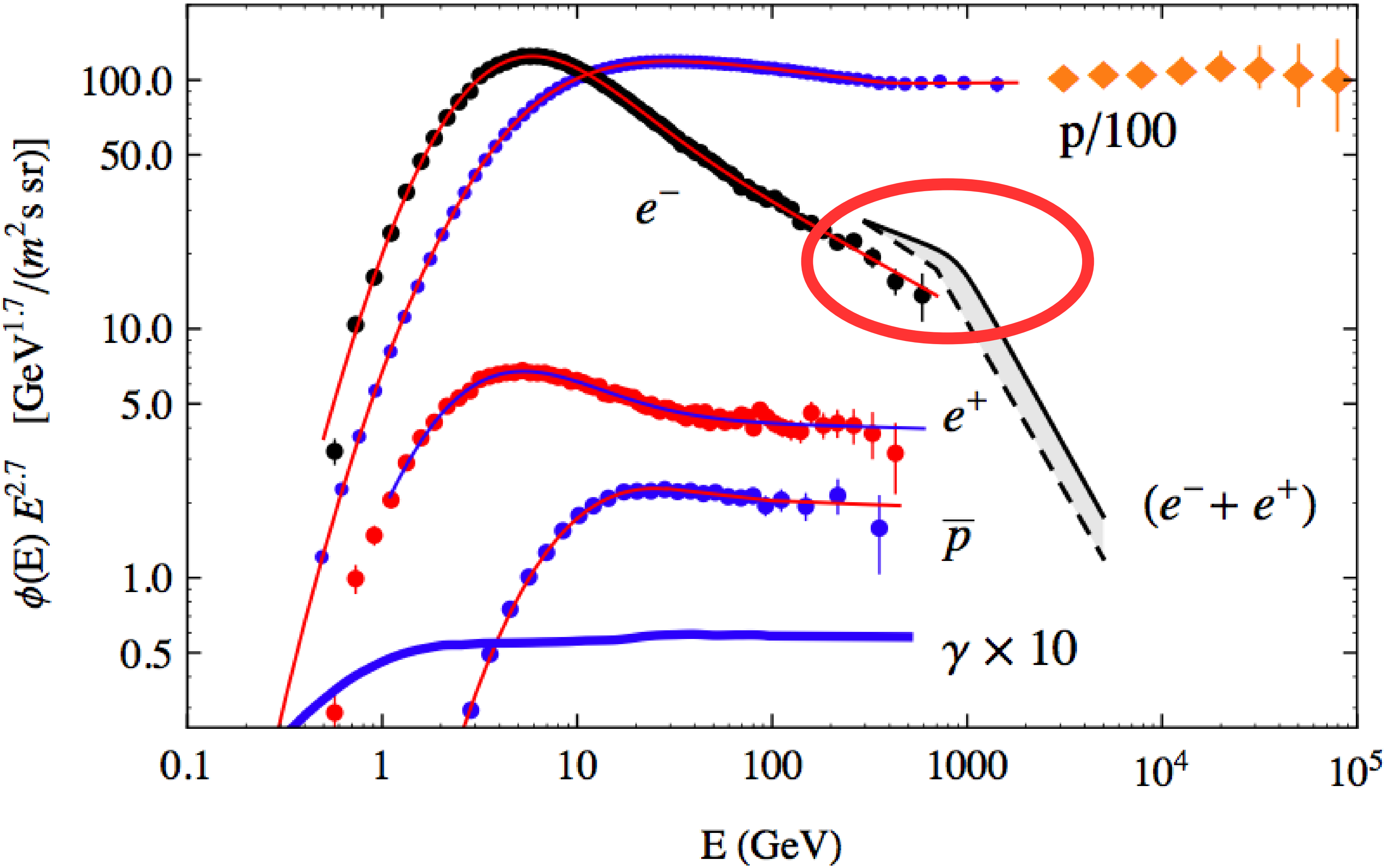
CREAM p data



striking results

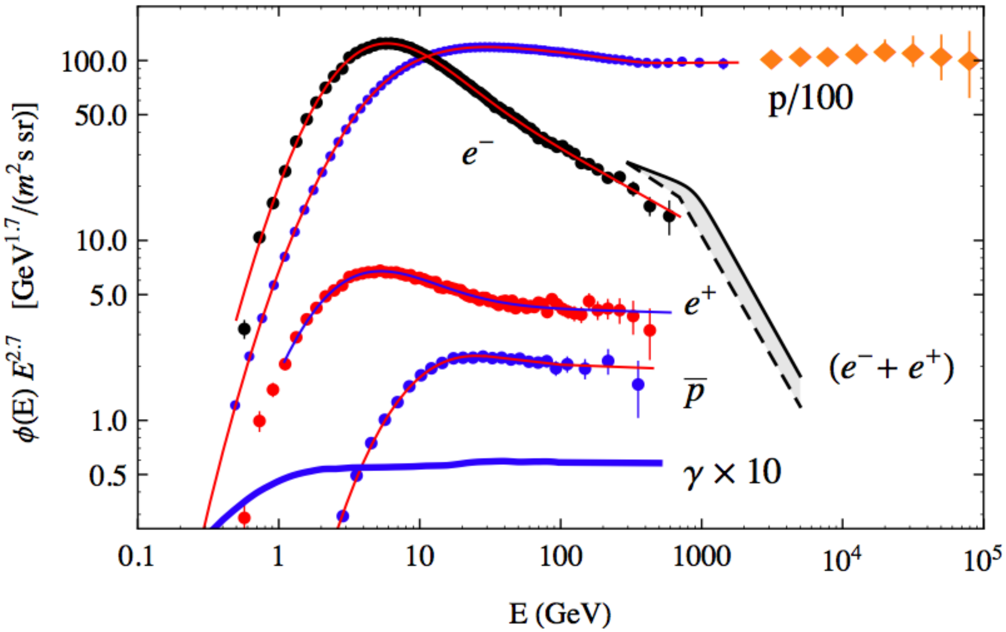
Soft electron spectrum

4 spectra
have approximately
the same slope



Spectral feature
(need explanation)

4 spectra
have approximately
the same slope



"striking"
qualitative features
that "call out"
for an explanation

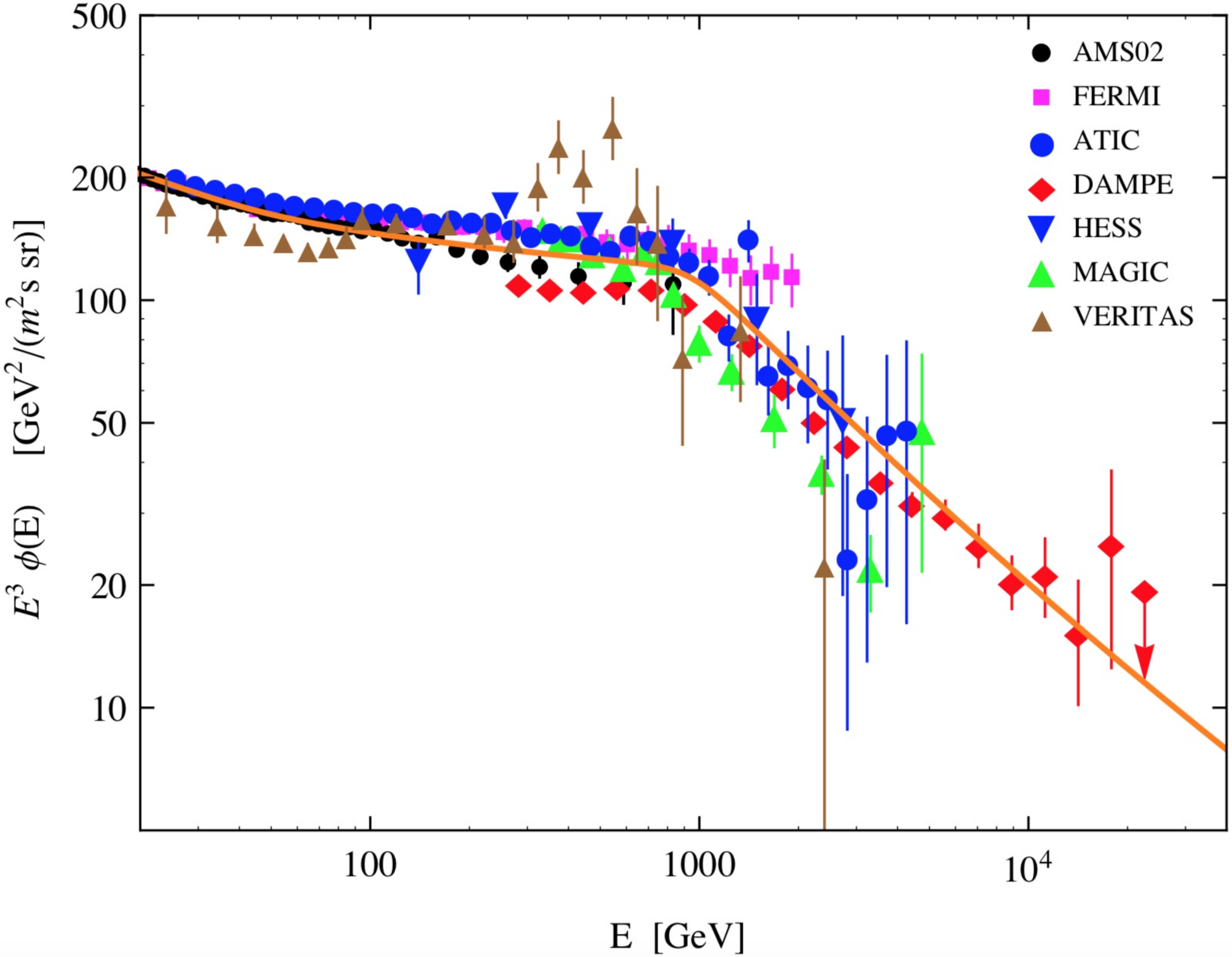
4 spectra
have approximately
the same slope

[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

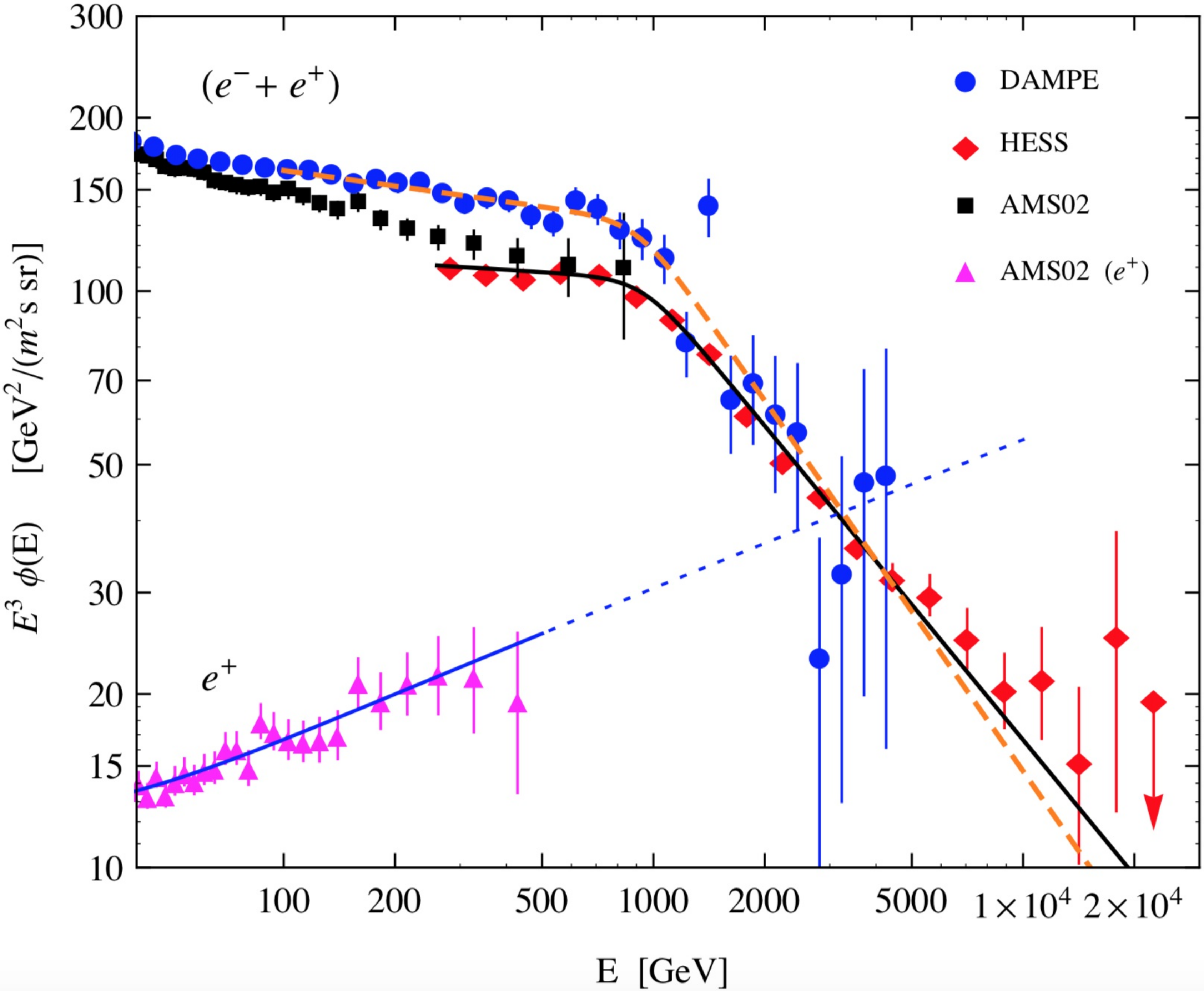
[B] *positron* and *antiproton* for (E> 30 GeV) have the same power law behavior and differ by a factor 2 (of order unity)

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

Remarkable discovery of Cherenkov telescopes



Understanding this spectral structure is *crucial*



$(e^- + e^+)$
e^+
DAMPE
HESS
AMS02
AMS02 (e^+)
$E^3\ \phi(E)$ [GeV^2/(m^2s sr)]
E [GeV]
300
200
150
100
70
50
30
20
15
10
100
200
500
1000
2000
5000
1×10^4
2×10^4

Energy Loss

main mechanisms

Synchrotron radiation
Compton scattering
strongly depend on the particle mass

quadratic in energy

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

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

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

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

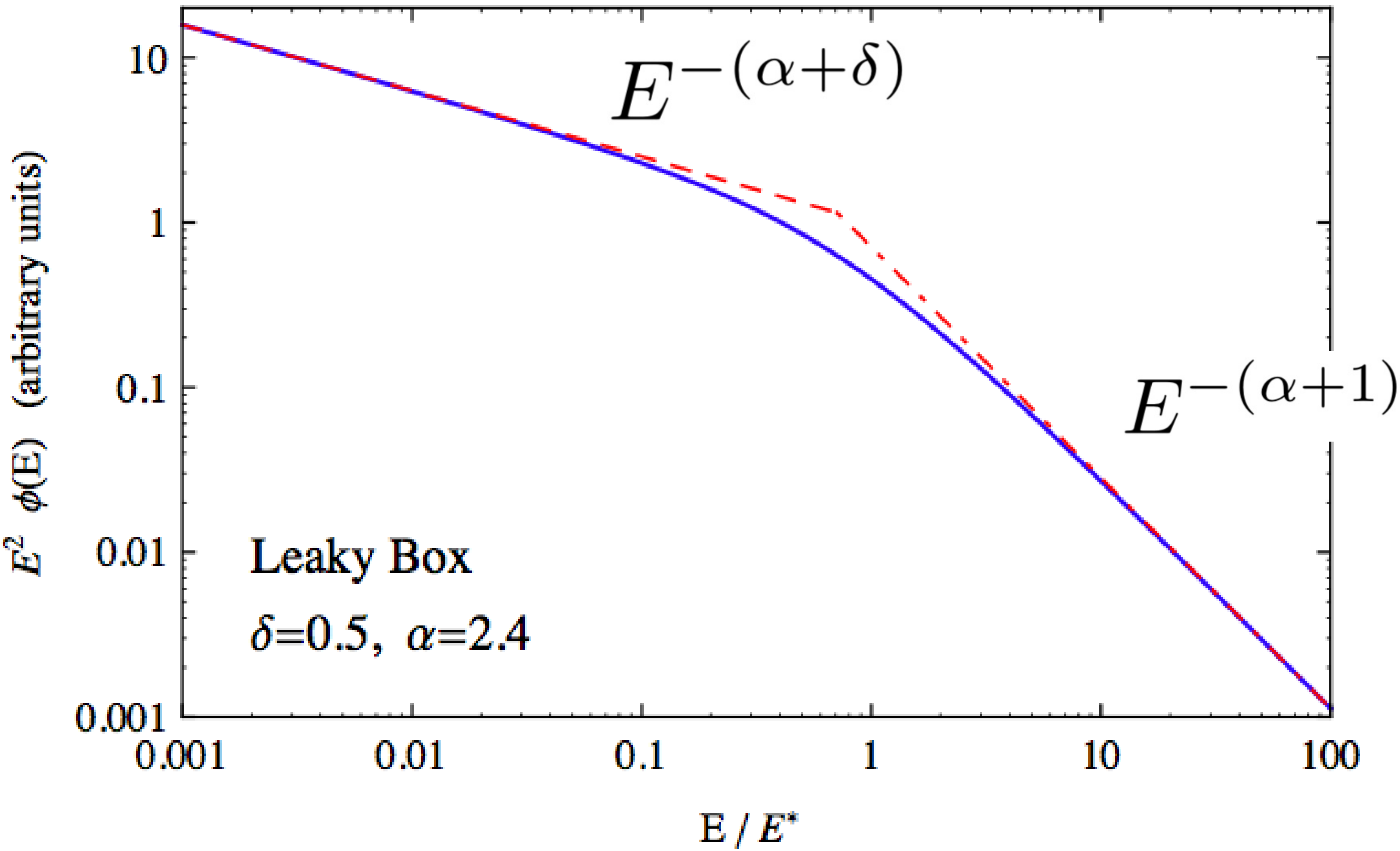
Source

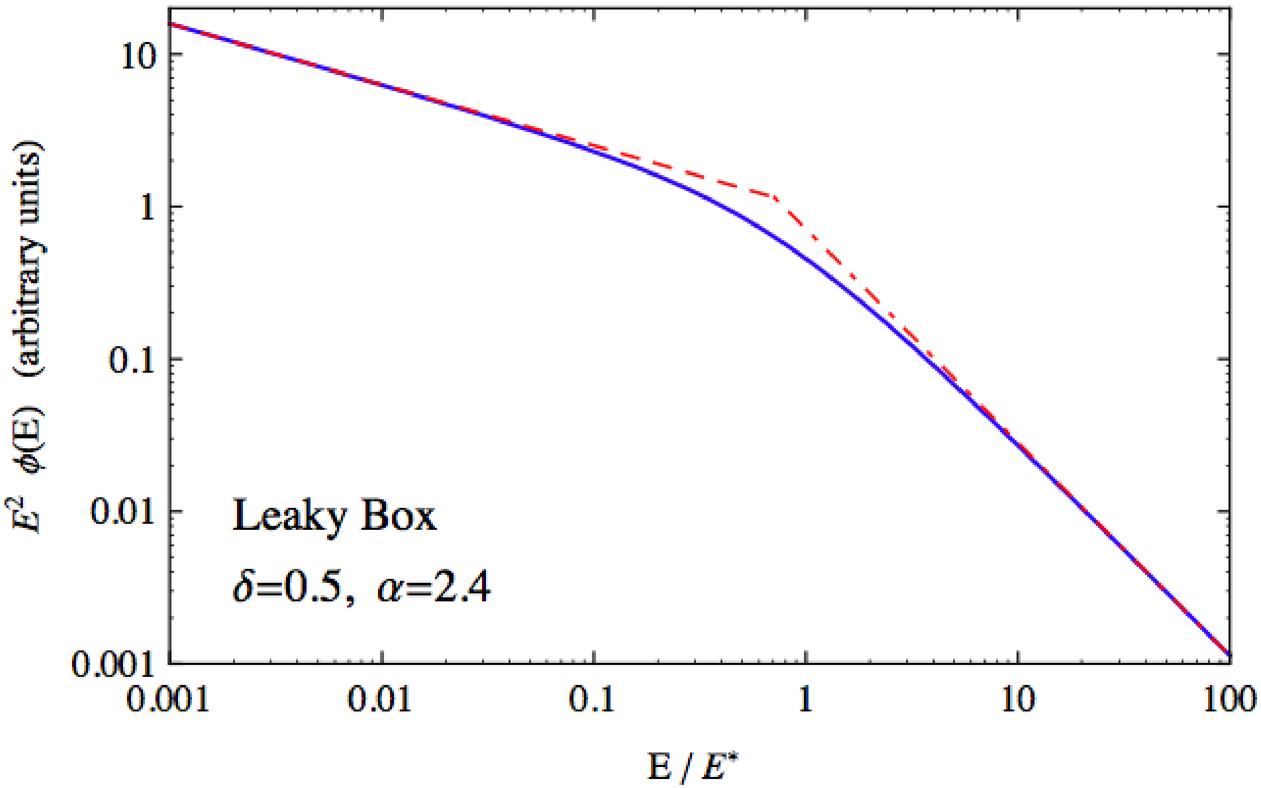
$$T_{\rm esc}(E) = T_0 \; E^{-\delta}$$

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^*

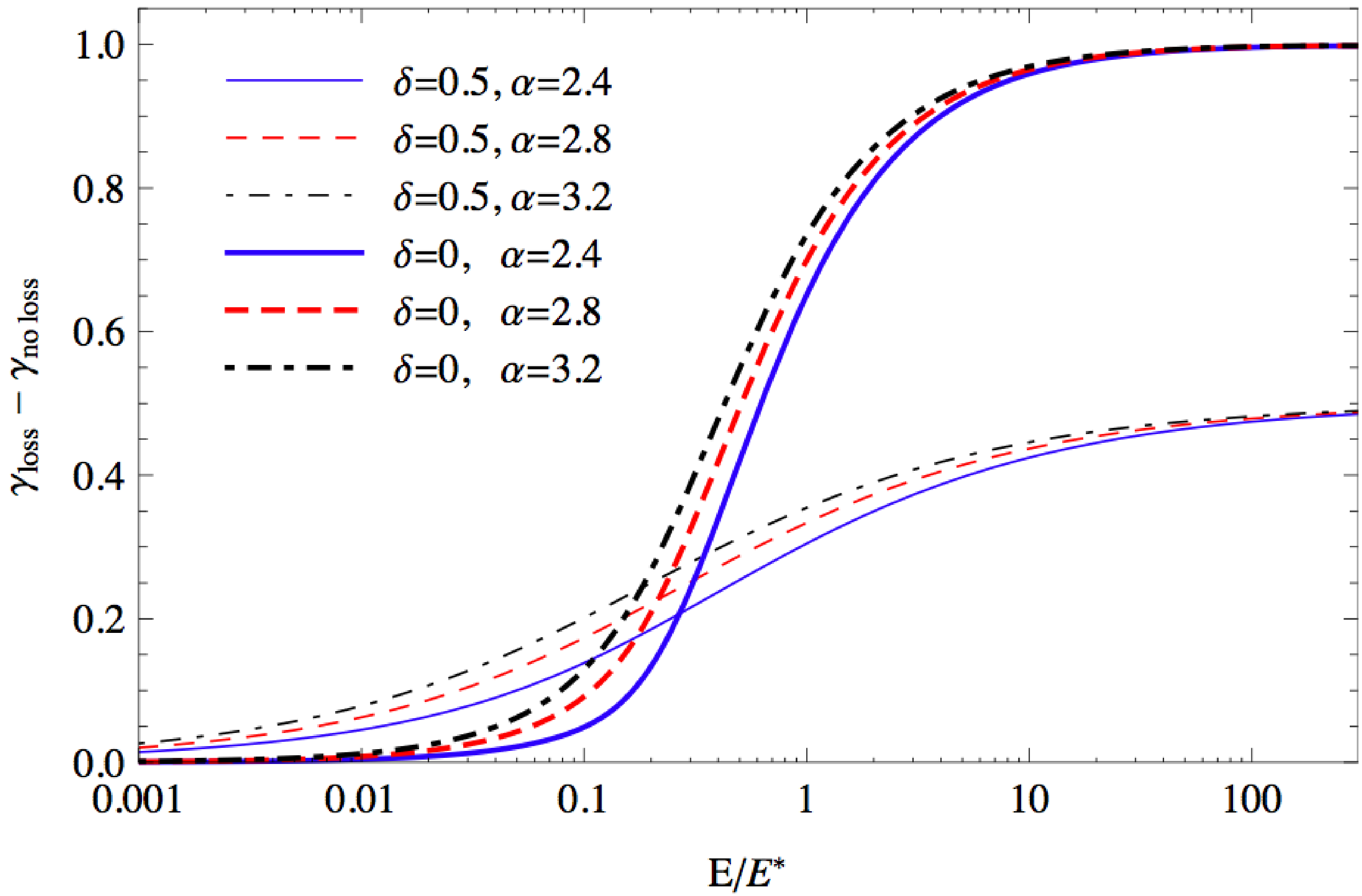
$$T_{\rm loss}(E^*) = T_{\rm esc}(E^*)$$

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

Exact solution:

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

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



Idea of very general validity:

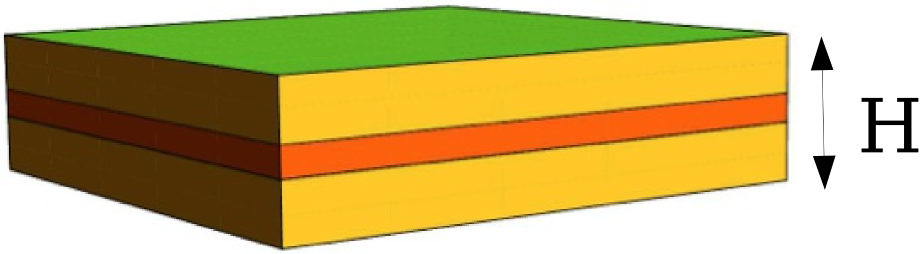
The Spectra of electrons and positrons should contain a softening "spectral feature" associated to the energy loss:
at a critical energy E^*

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

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

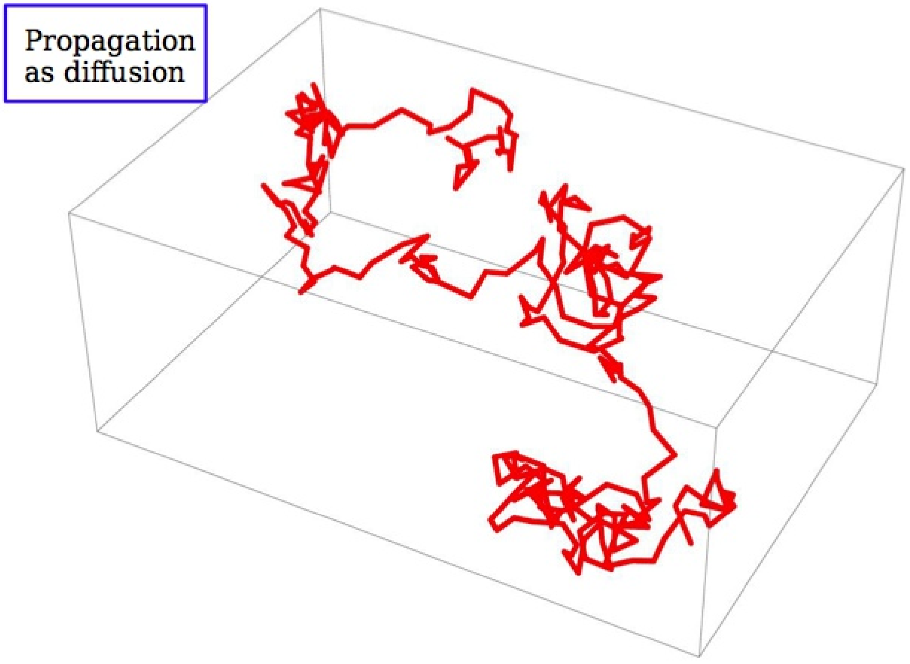
$$T_{\rm esc}(E^*) = T_{\rm loss}(E^*)$$

Diffusion Model ("minimal version")



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

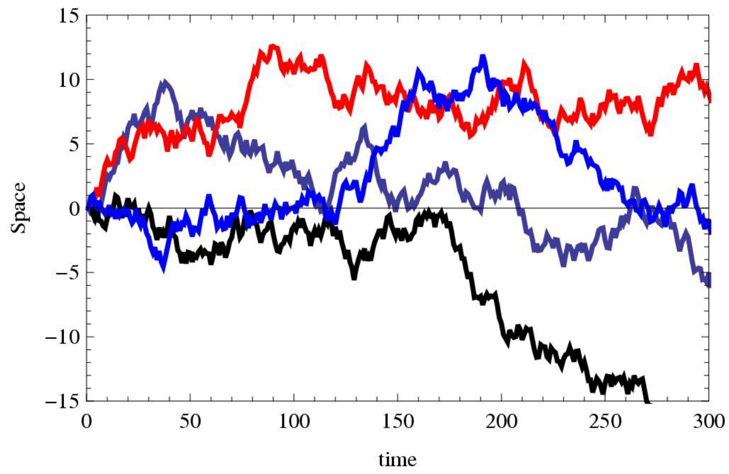
$$z = \pm H$$ (Halo thickness)



Propagation model
specified by H + 2 functions

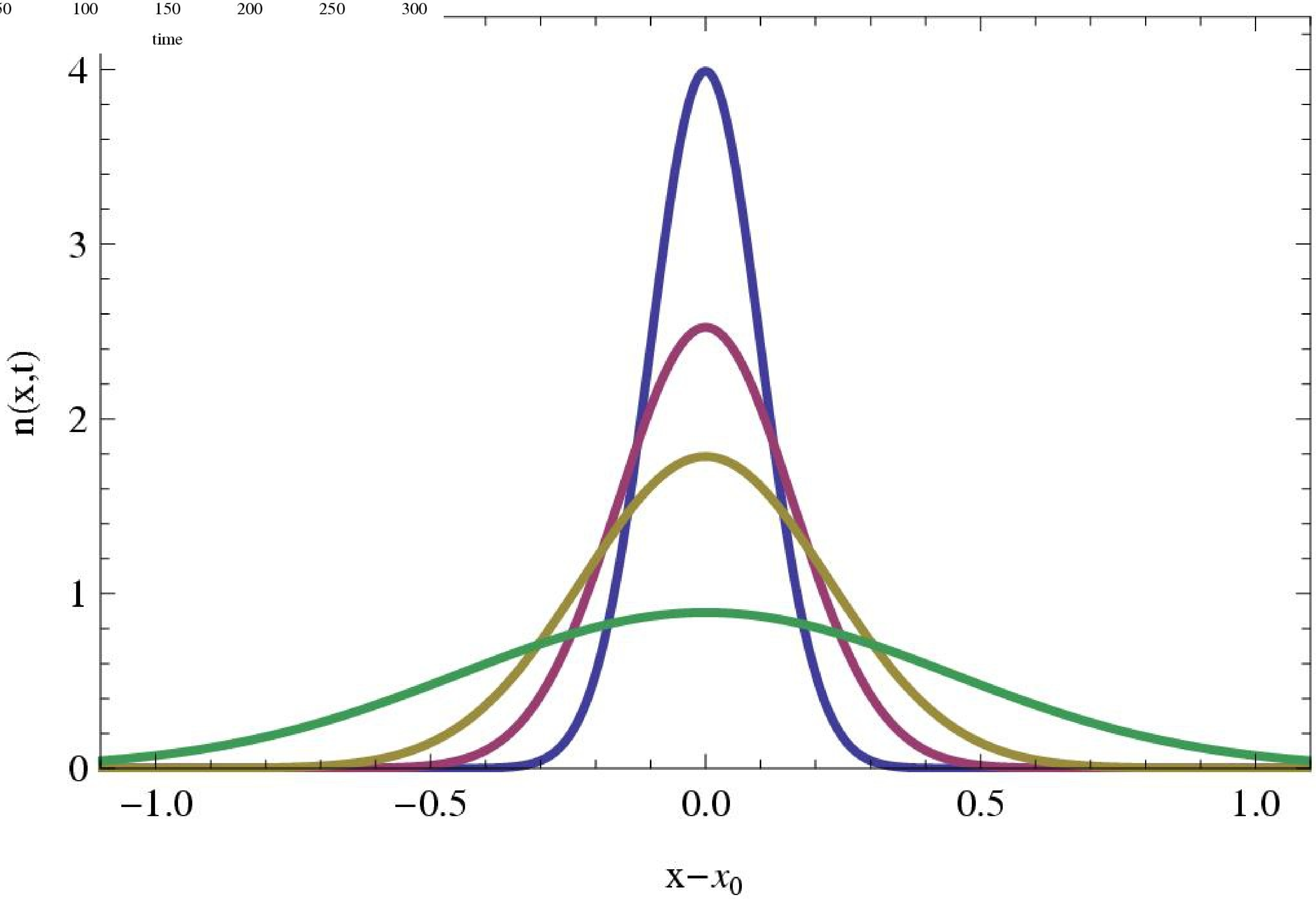
$$D(E) = D_0 \; E^{\delta}$$

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



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

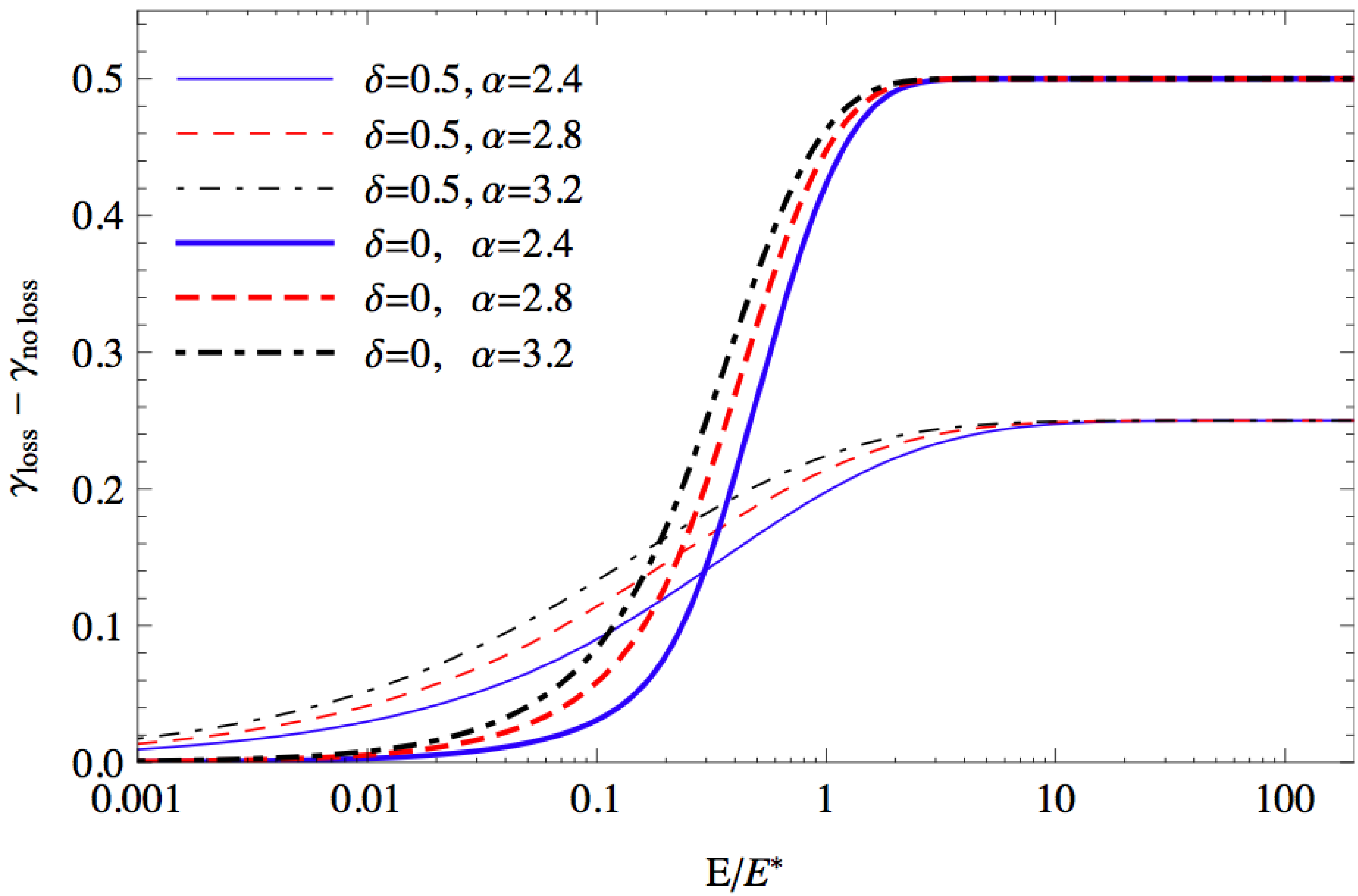
$$n(E) = \begin{cases} \dfrac{q_0 \; H}{2 \, D_0} \; E^{-(\alpha+\delta)} & \text{for } E \ll E^* \\[2em] \dfrac{q_0}{\sqrt{2 \, D_0 \, b}} \; c(\alpha, \delta) \; E^{-[\alpha + (1+\delta)/2]} & \text{for } E \gg E^* \end{cases}$$

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

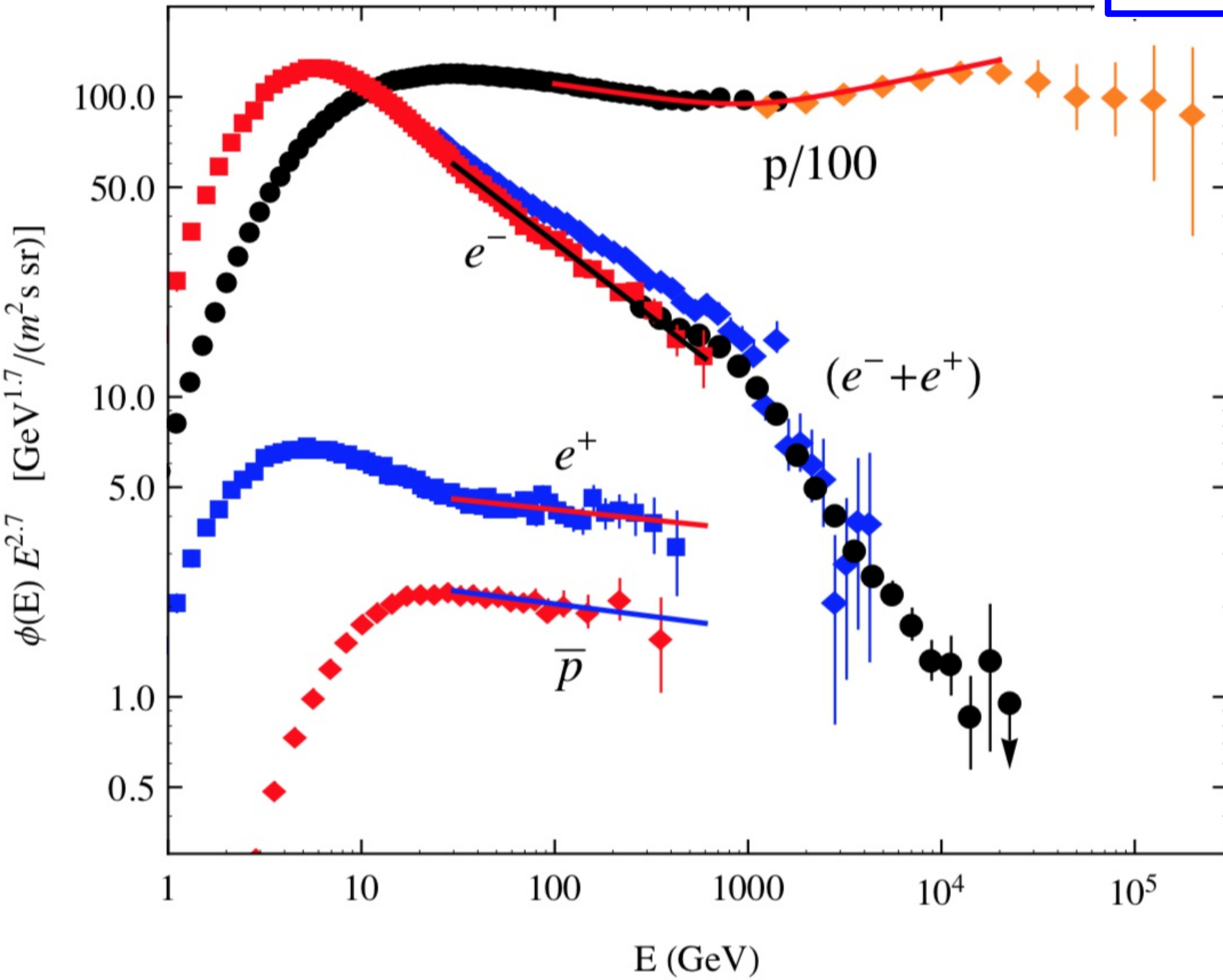
Where is the energy loss softening feature ?

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

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

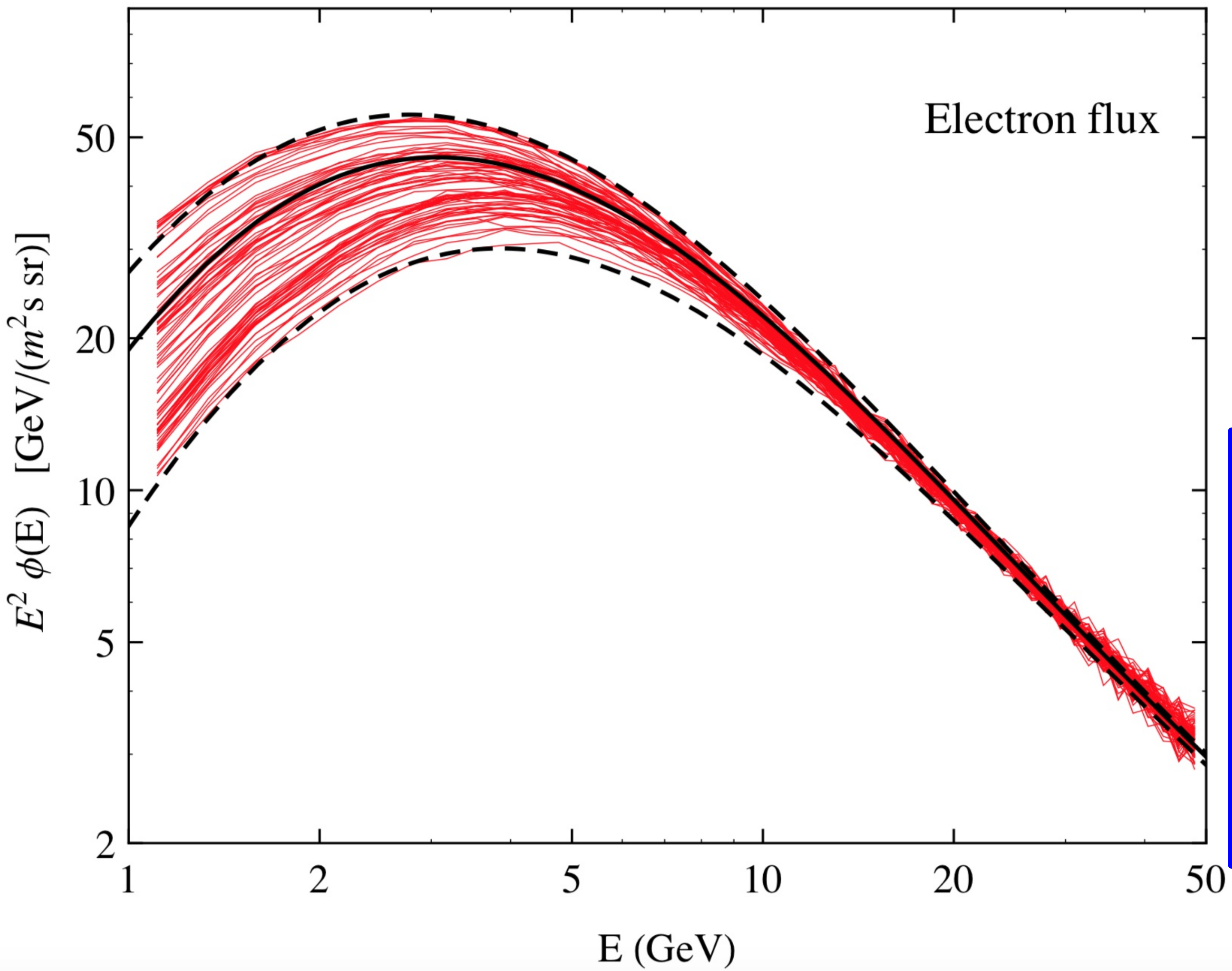
$E^* \simeq 900 \text{ GeV}$

Two possibilities



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

What is the shape of the interstellar spectrum ?

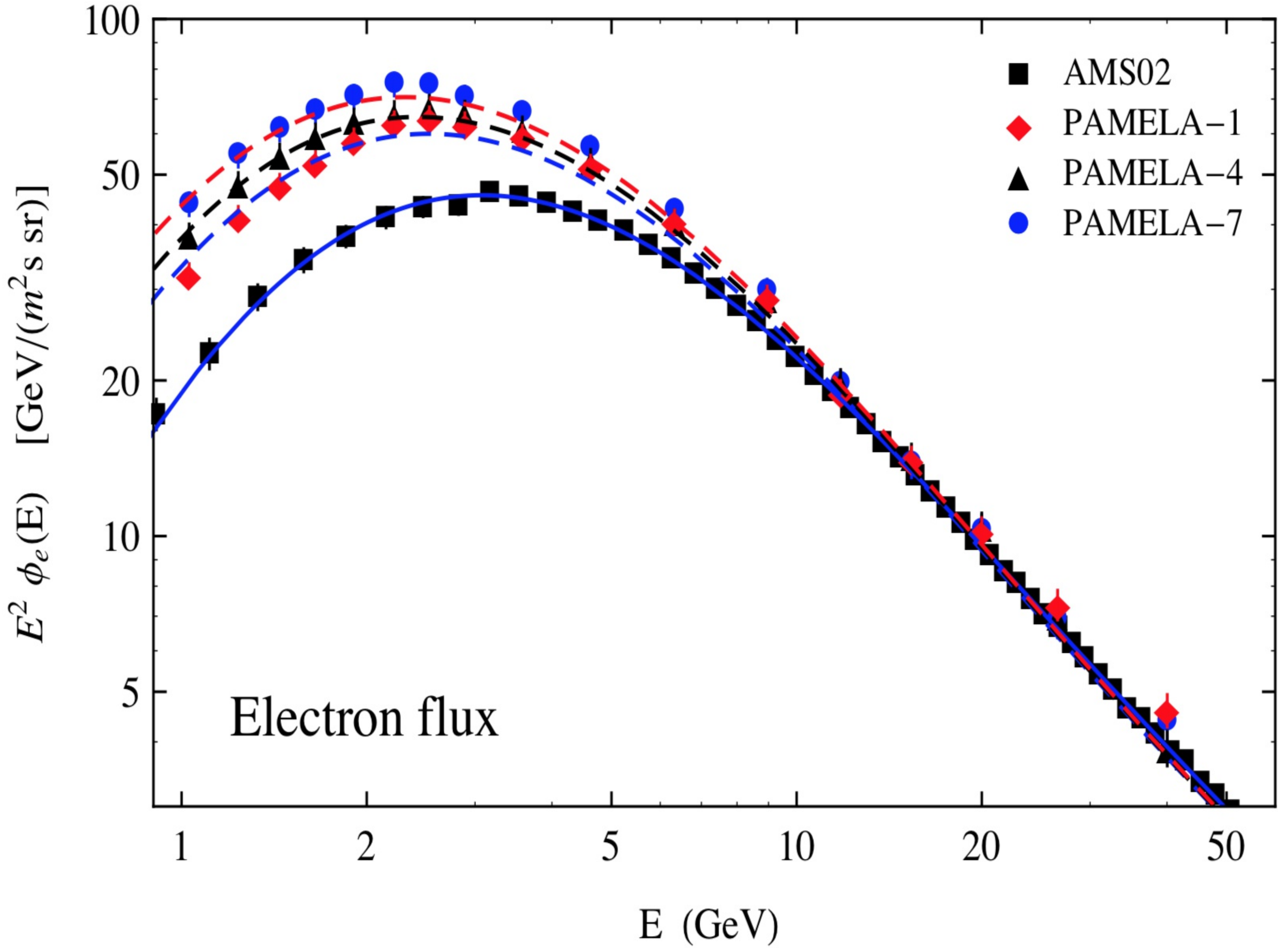


Fit =

$K\ E^{-3.17}$
$\otimes$
FFA Solar Modulations

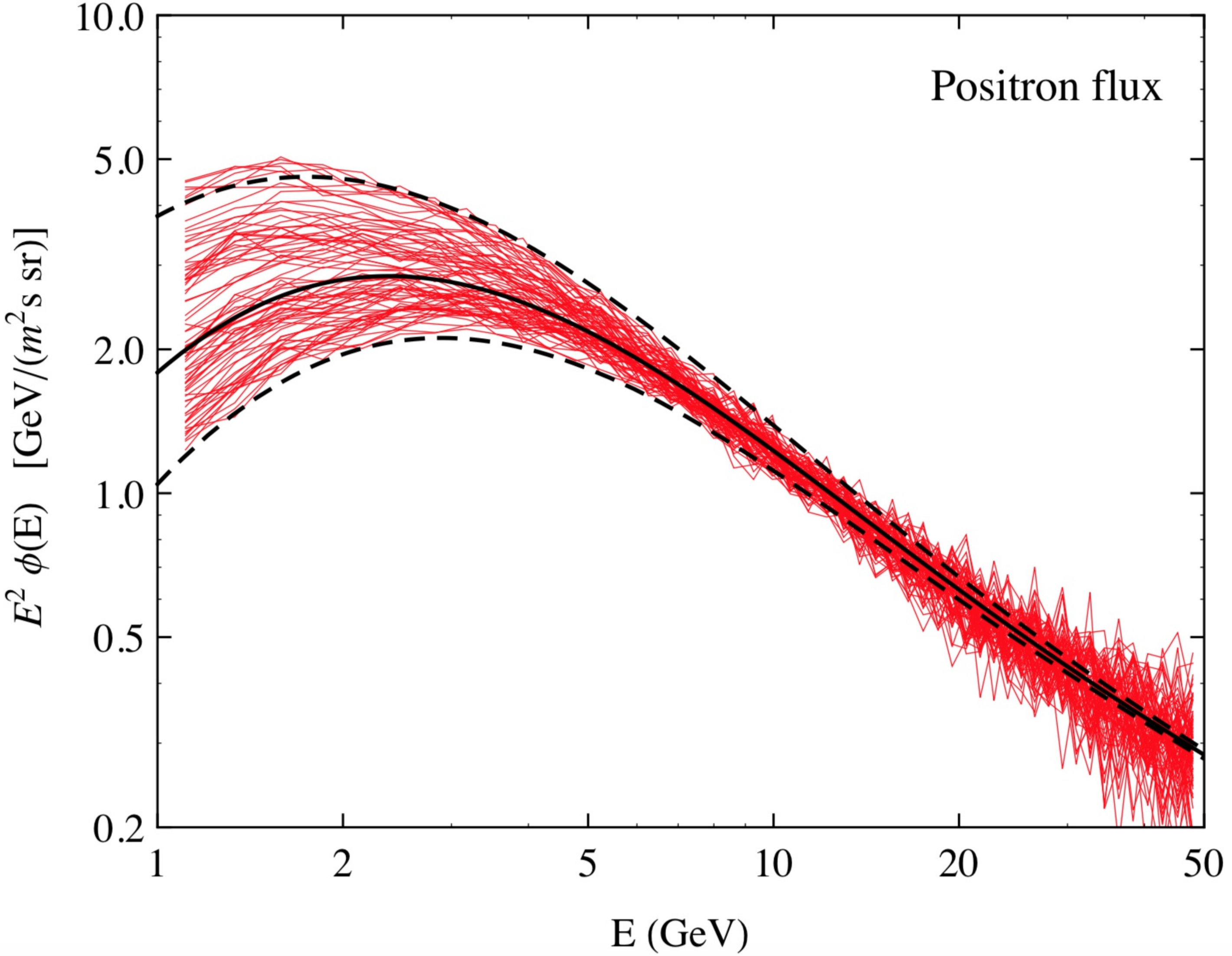
Solar Modulations

Electron spectra
at different times



Positron flux

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

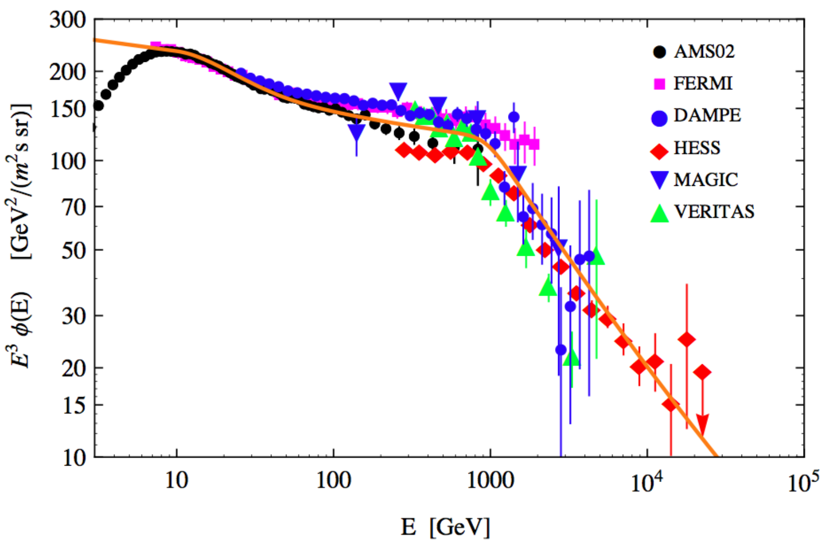


Possible (and "natural") choice: identification of the sharp softening observed by the Cherenkov telescopes in the spectrum of $(e^+ + e^-)$ as the critical energy

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

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

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

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

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

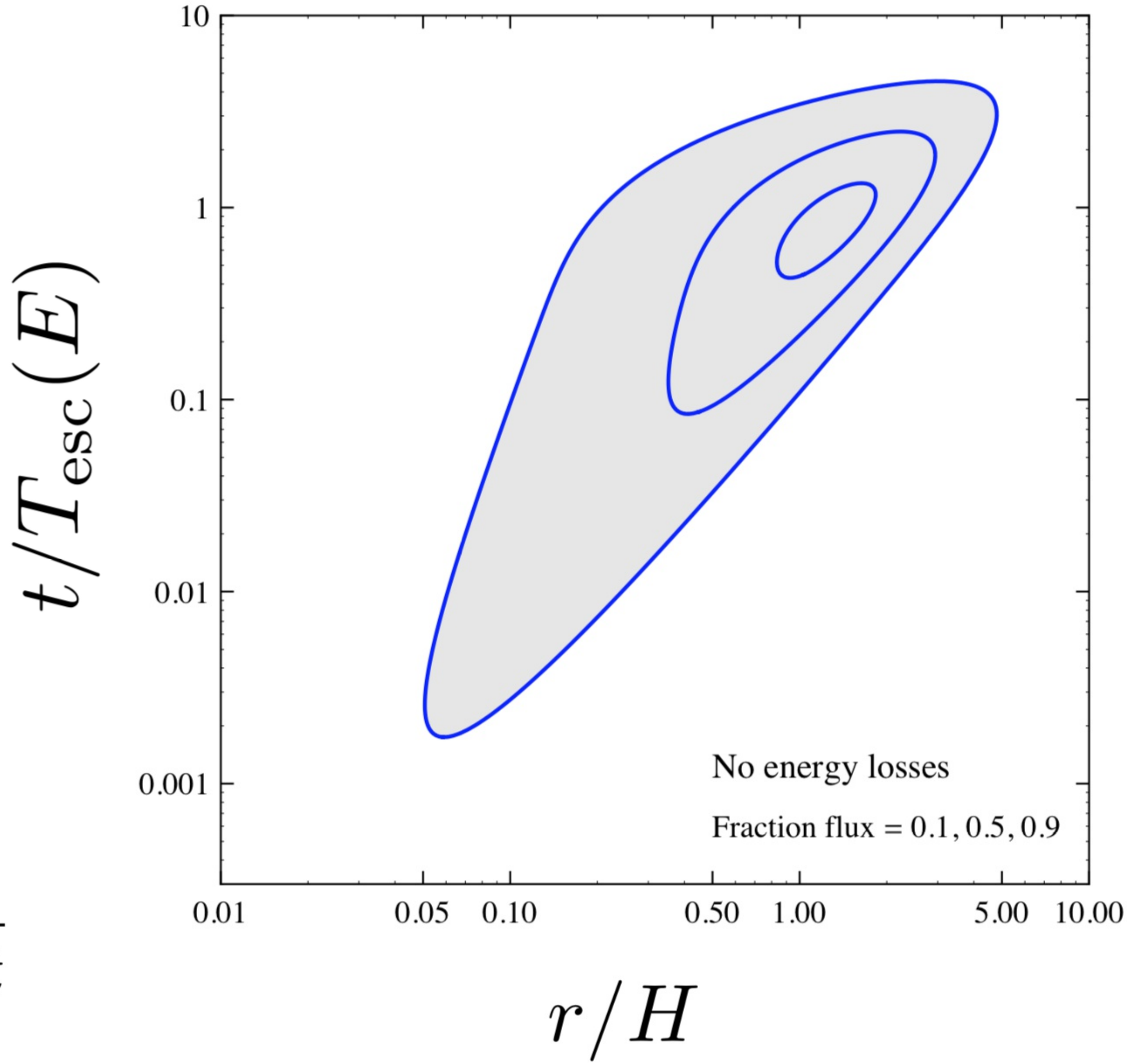
$$n_{\rm sources} \approx \frac{1}{\pi \, R_{\rm disk}^2} \simeq 0.0015 \text{ kpc}^{-2}$$

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: $\delta = 0.4$

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

Prediction of an *exponential cutoff* for the **Electron flux** above a critical energy associated to the maximum distance of propagation

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 distance of propagation (in the past)
for a particle (e+ or e-) observed with energy E

$$\langle x^2(t,E)\rangle = 2\ D(E)\ t$$

Constant energy

$$\langle x^2(t,E)\rangle = 2\int_0^t dt' D[E_i(E,t)]$$

Energy loss

$$R^2_{\rm max}(E) = 2\int_0^{t_{\rm max}(E)} dt'\ D[E_i(E,t')]$$

Maximum Propagation distance

$$R^2_{\rm max}(E) = 2\ D(E)\ t_{\rm max}(E)\ \frac{1}{1-\delta}$$

Analytic solution

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

$$R^2_{\max}(E) = 2\ D(E)\ T_{\rm loss}(E)\ \frac{1}{1-\delta}$$

$$R^2_{\max}(E) = H^2\ \frac{2\ D(E)}{H^2}\ T_{\rm loss}(E)\ \frac{1}{1-\delta}$$

$$R^2_{\max}(E) = \frac{H^2}{1-\delta}\ \frac{T_{\rm loss}(E)}{T_{\rm esc}(E)}$$

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

$$H = 3 \text{ kpc} \qquad \delta = 0.4$$

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

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

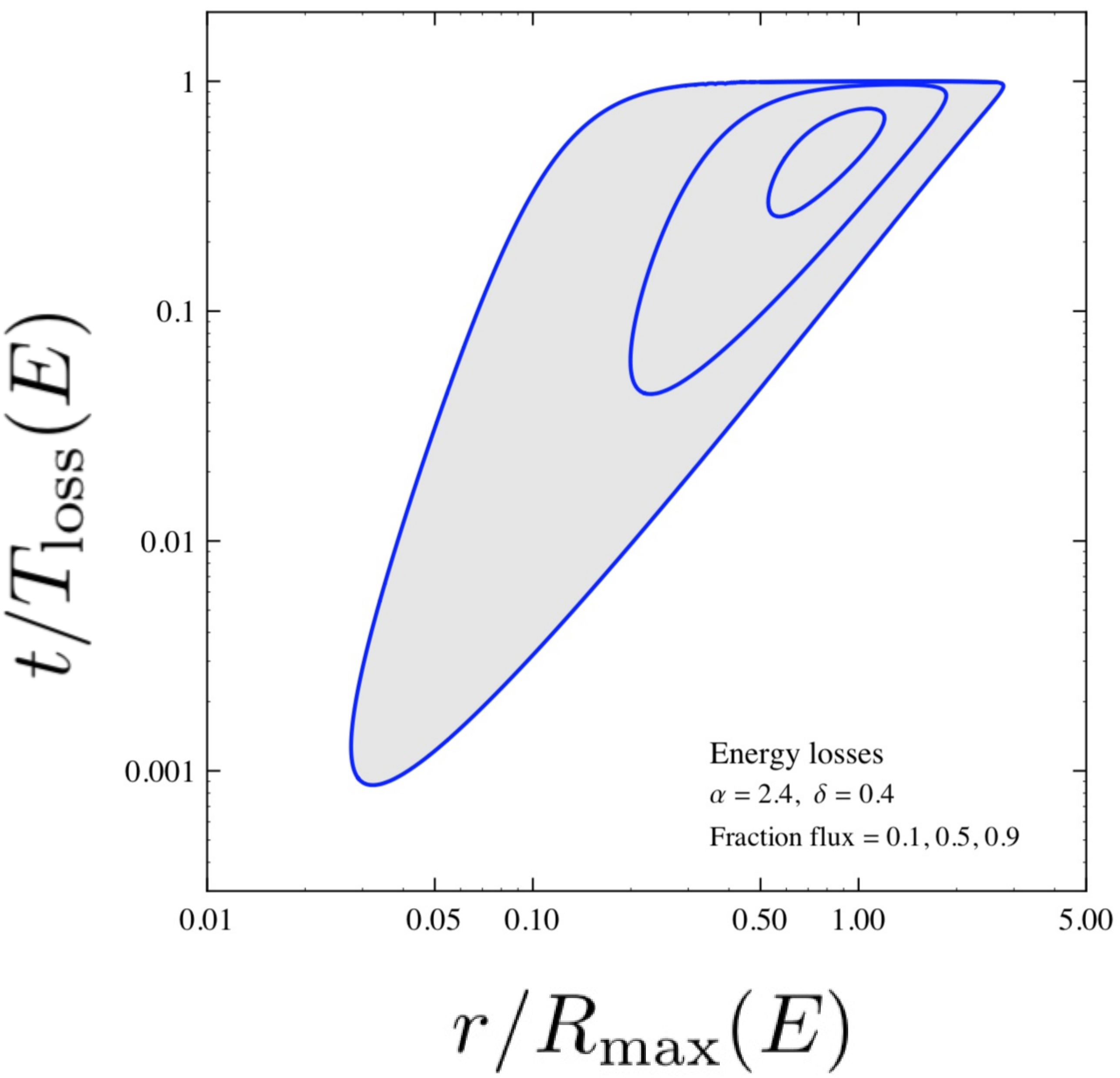
$$R_{\max}(E) = 0.67 \text{ kpc} \left(\frac{E}{\text{TeV}}\right)^{-0.3}$$

$$E^* = 940 \text{ GeV}$$

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

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

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

All events
at a distance: $r < H$

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

Numerical example: $\delta = 0.4$

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

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

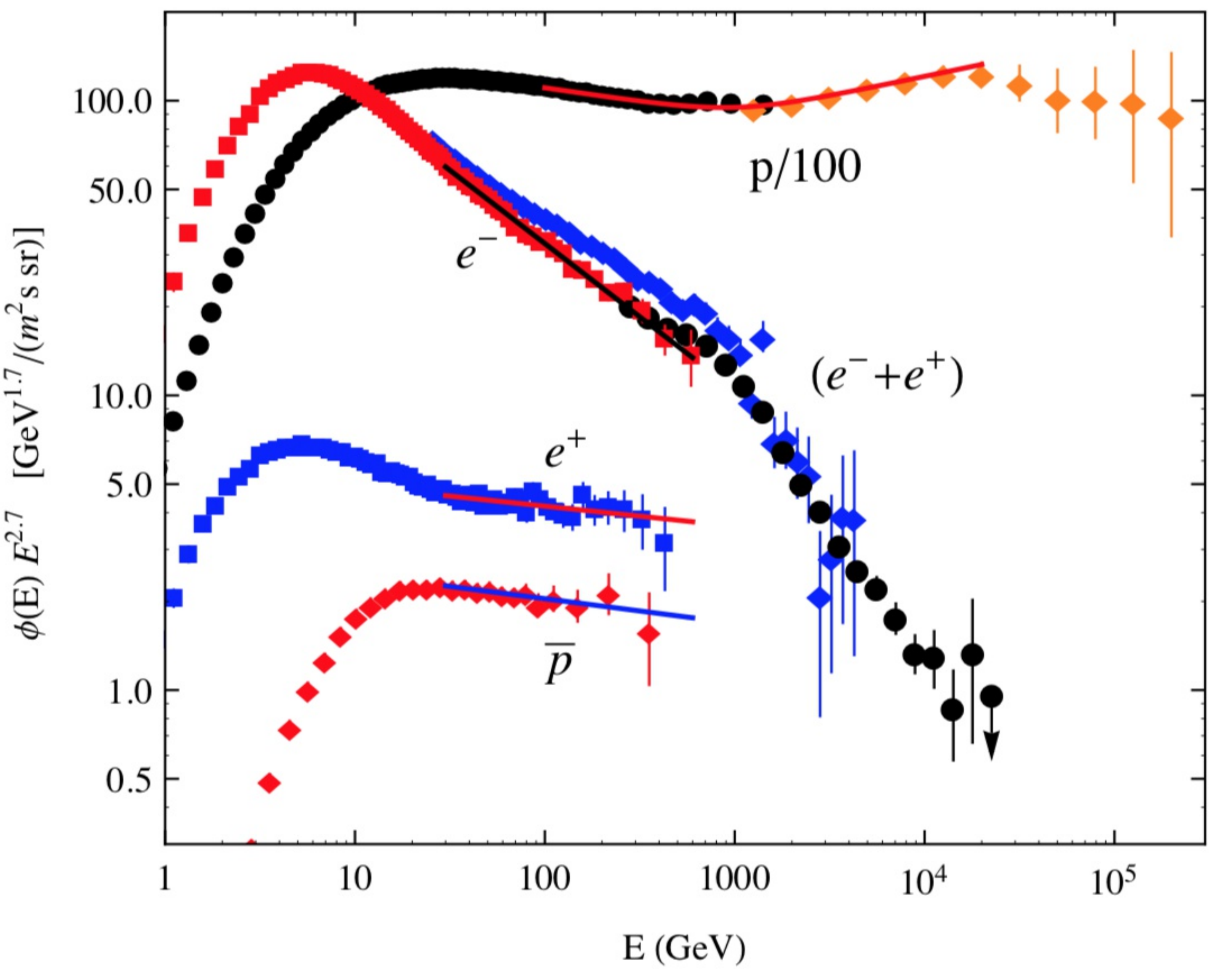
[Brightest source contributes (on average)
½ the expected flux for a continuous source distribution]

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

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

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:

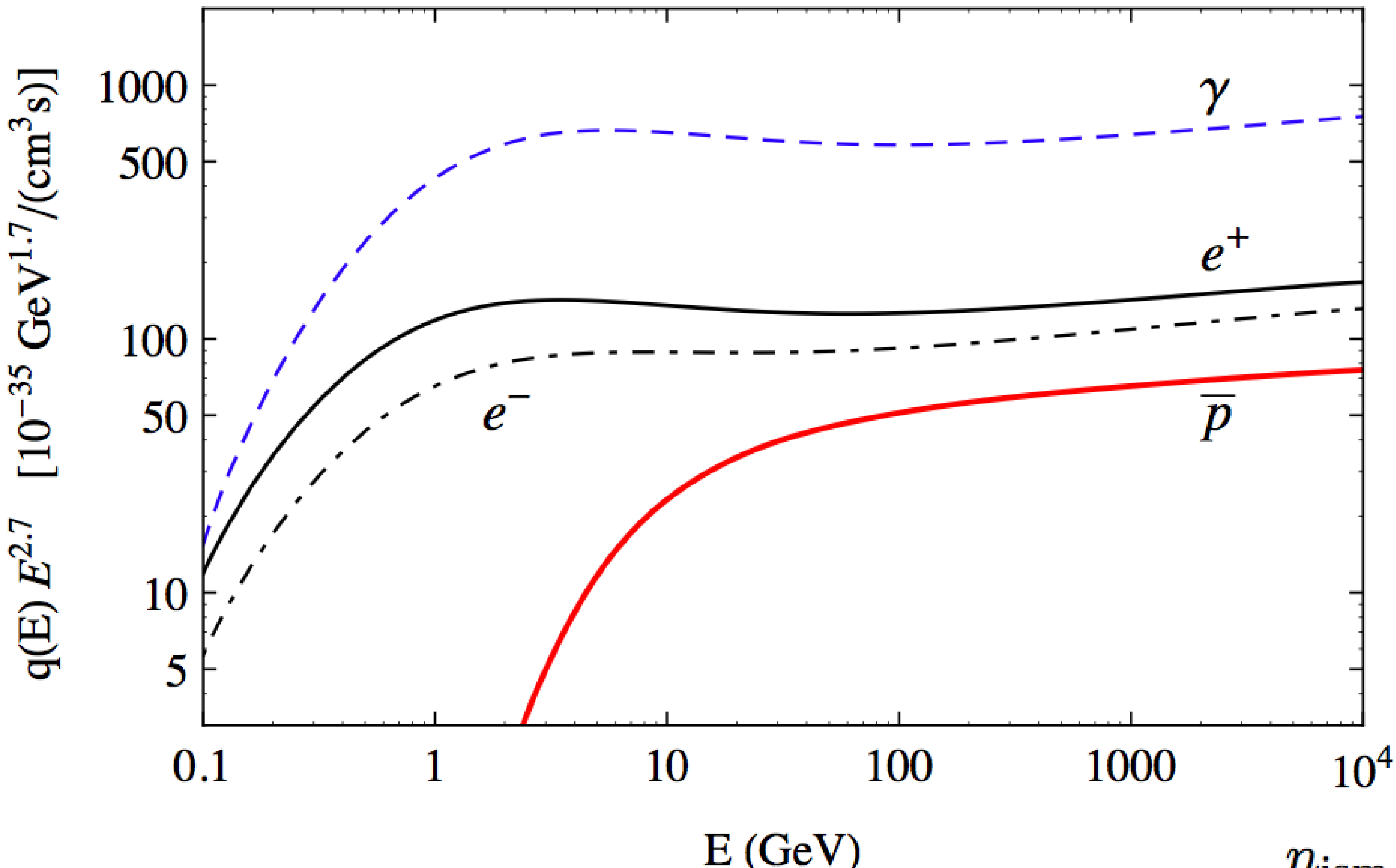
[1] Take spectra of cosmic rays (protons + nuclei) observed at the Earth

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

[3] Compute the rate of production of secondaries

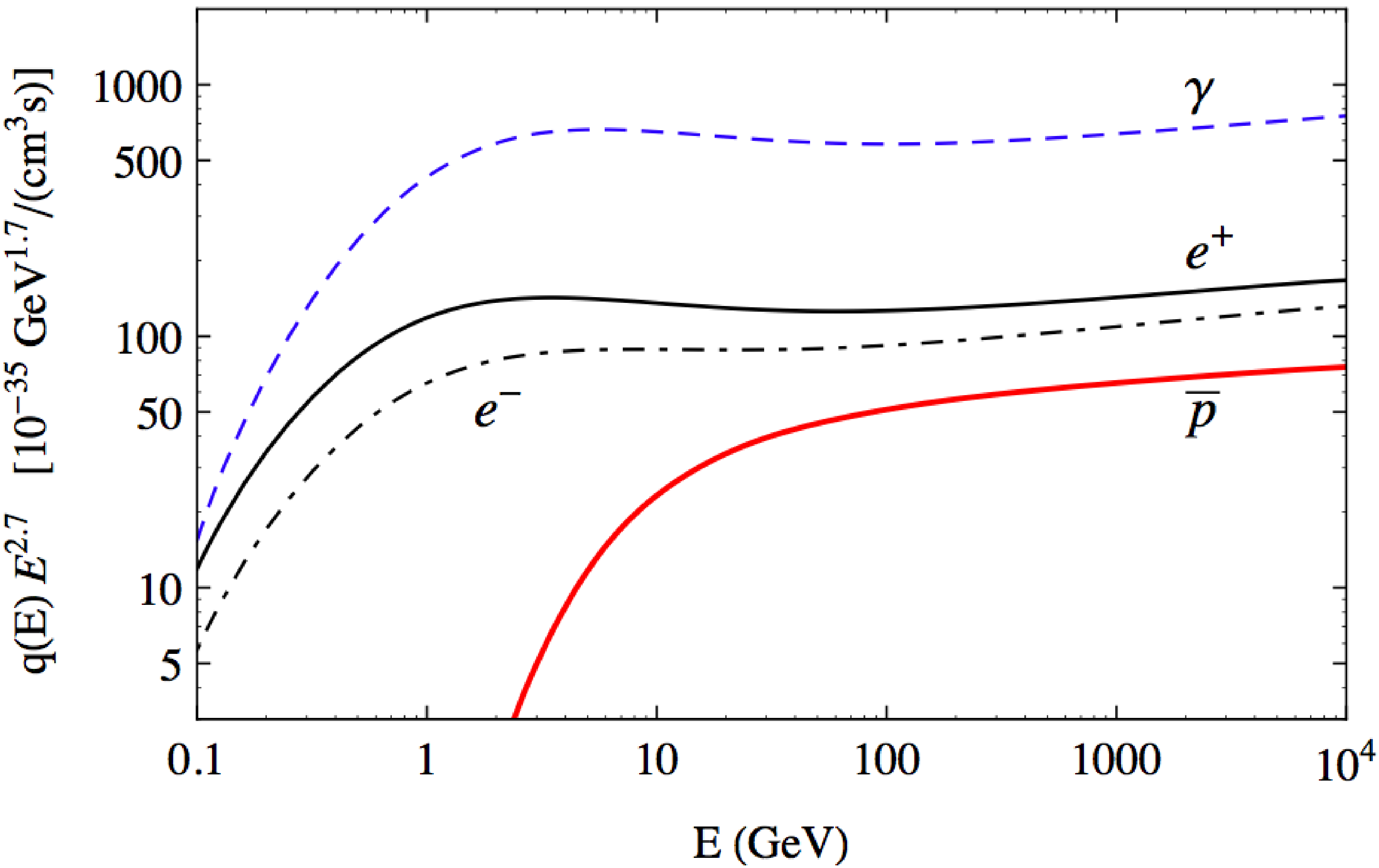
$$q_j(E, \vec{x}_\odot)$$

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



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

“Local” Rate of production of secondaries



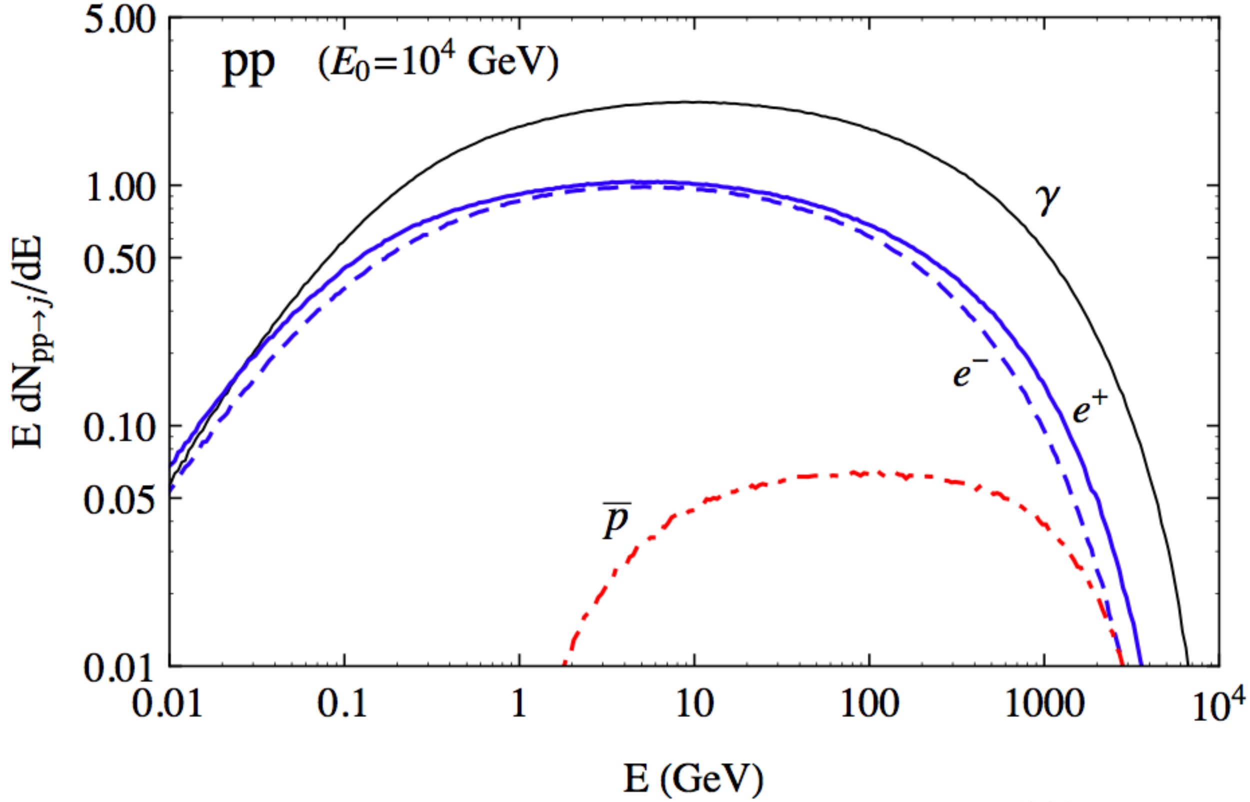
$$\frac{\gamma}{e^+} \approx 5.5$$

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

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

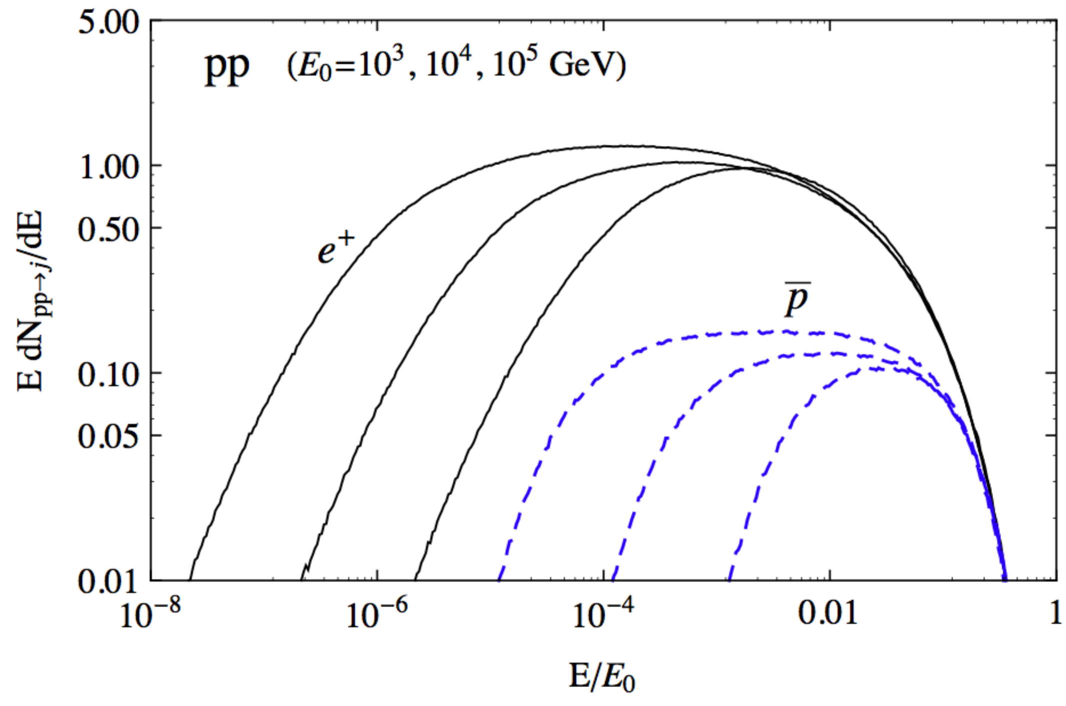
Different low energy behaviors
(low energy antiproton production suppressed)

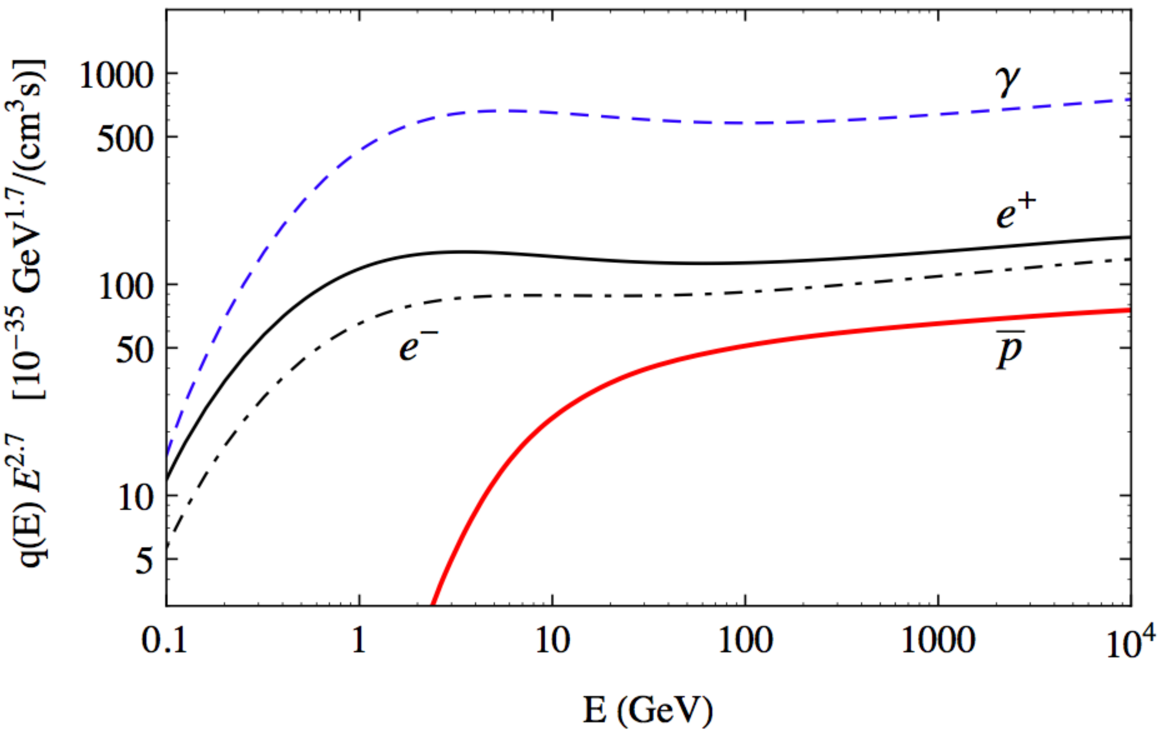
Power Law behavior at high energy



Secondary spectra

Scaling behavior

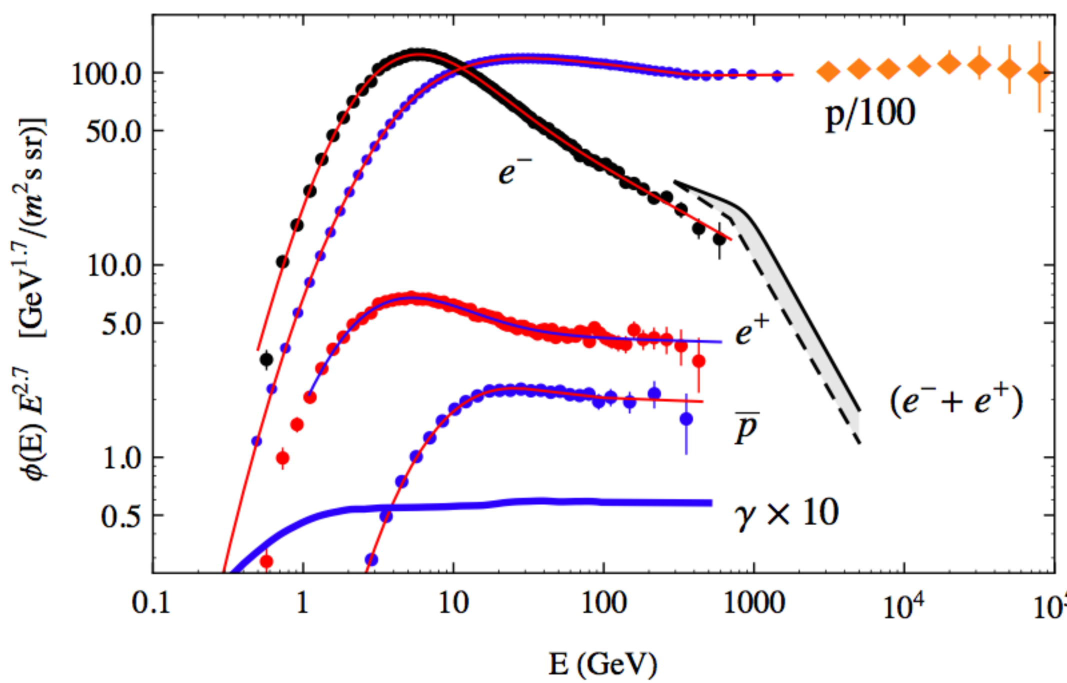




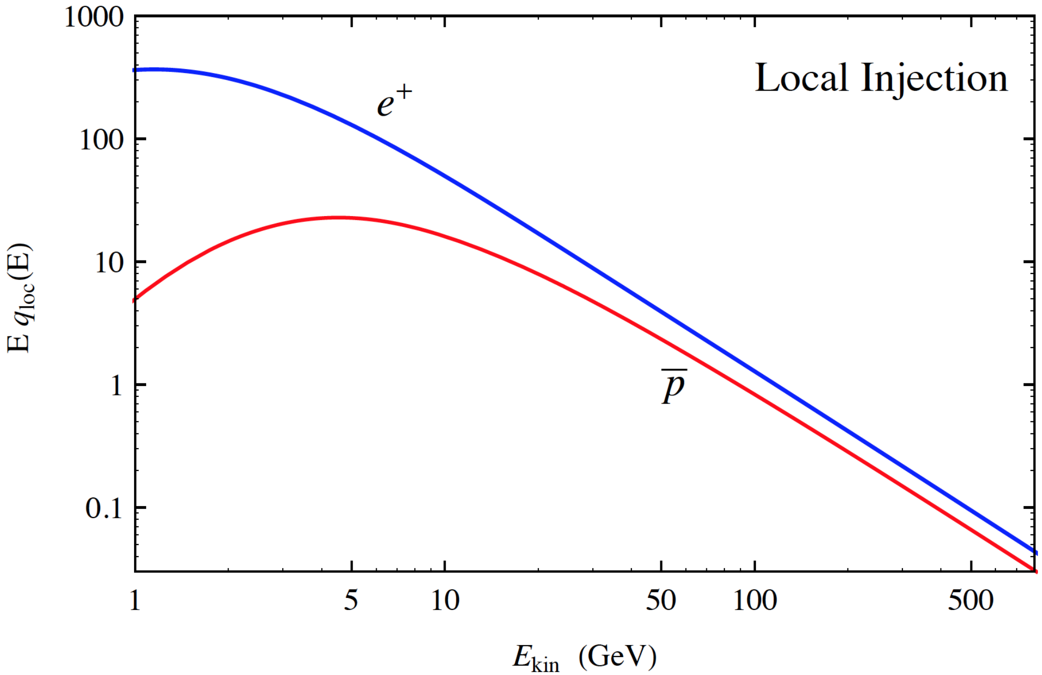
Local production rates of secondaries

e^+ $\overline{p}$

"striking" similarity



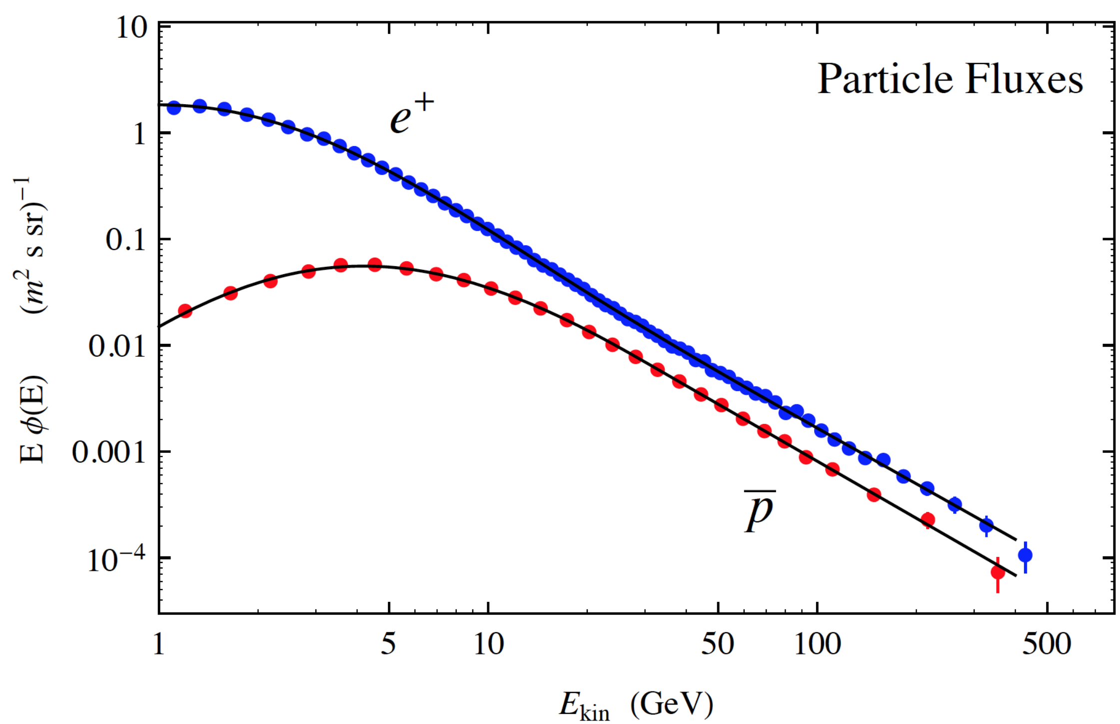
Observed fluxes



Local production rates of secondaries

"striking" similarity

Observed fluxes



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

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:

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

DATA

model

model

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

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

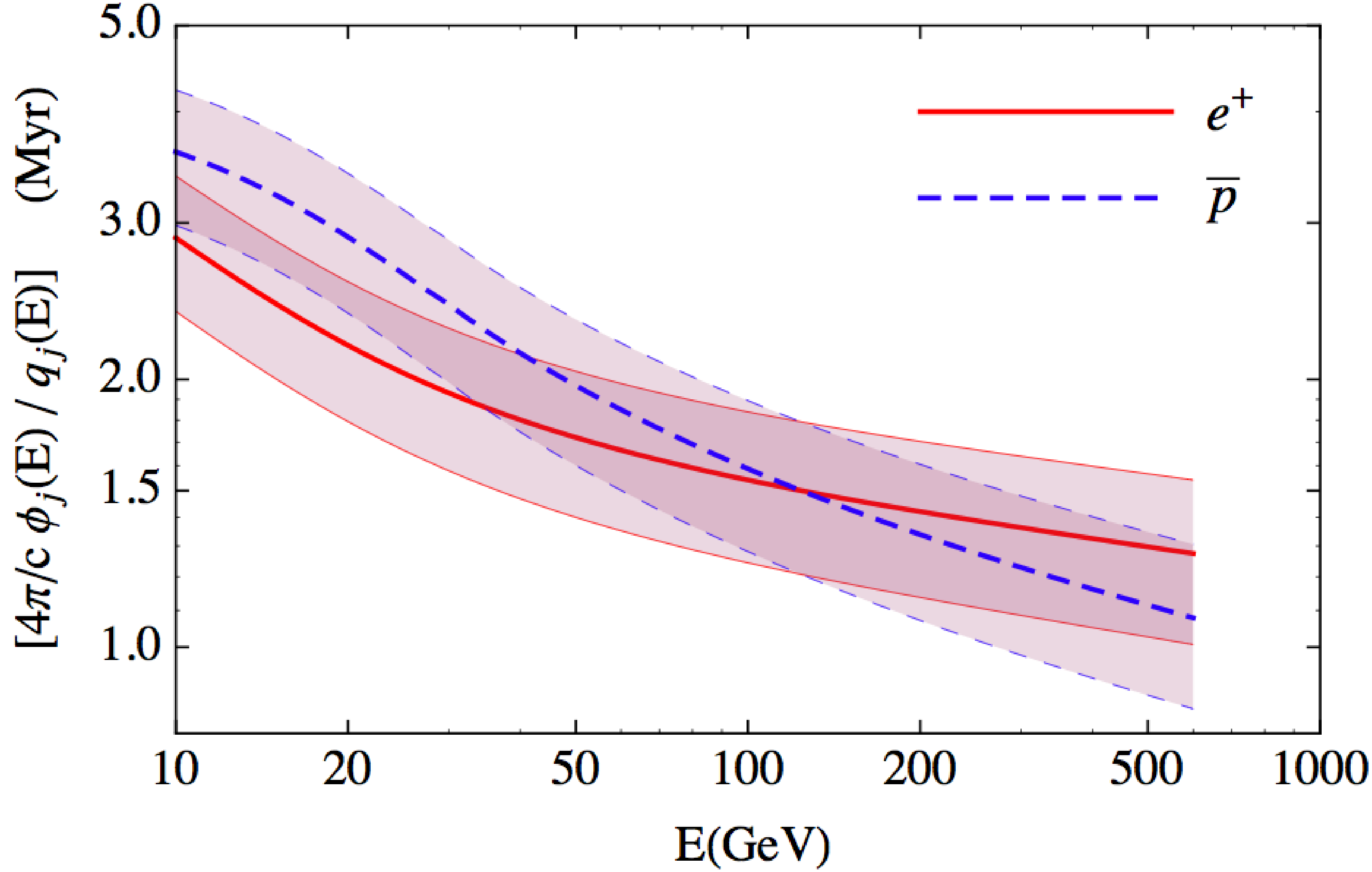
$$\mathcal{P}_{e^+}(E) \approx \mathcal{P}_{\overline{p}}(E)$$

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

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

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

Distortion of the source spectra created by propagation



Weak energy dependence of the propagation effects !

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 $E \gtrsim 3 \text{ GeV}$

[B] *"Alternative Scenario"*

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

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
positron and antiproton fluxes
is of central importance for High Energy Astrophysics.

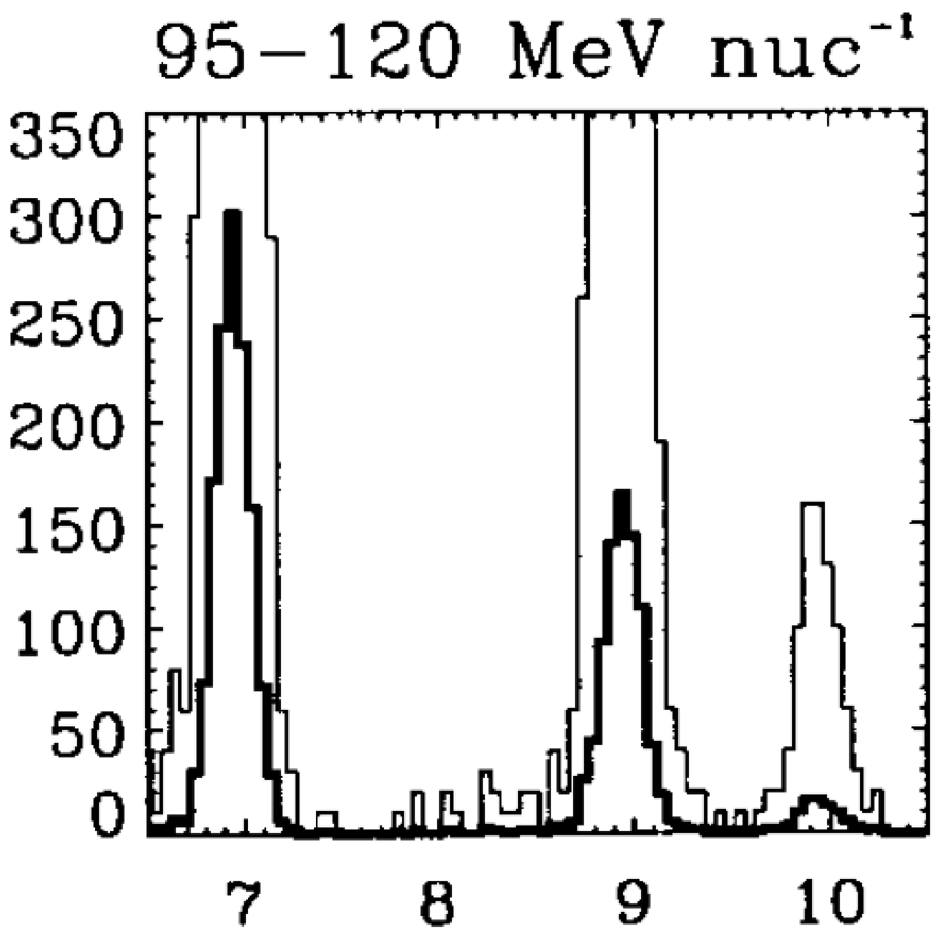
This problem touches the
"cornerstones" of the field
and it has profound and broad implications

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. $(T_{1/2} \simeq 1.51 \pm 0.04 \text{ Myr})$



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

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

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).

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

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

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

[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)

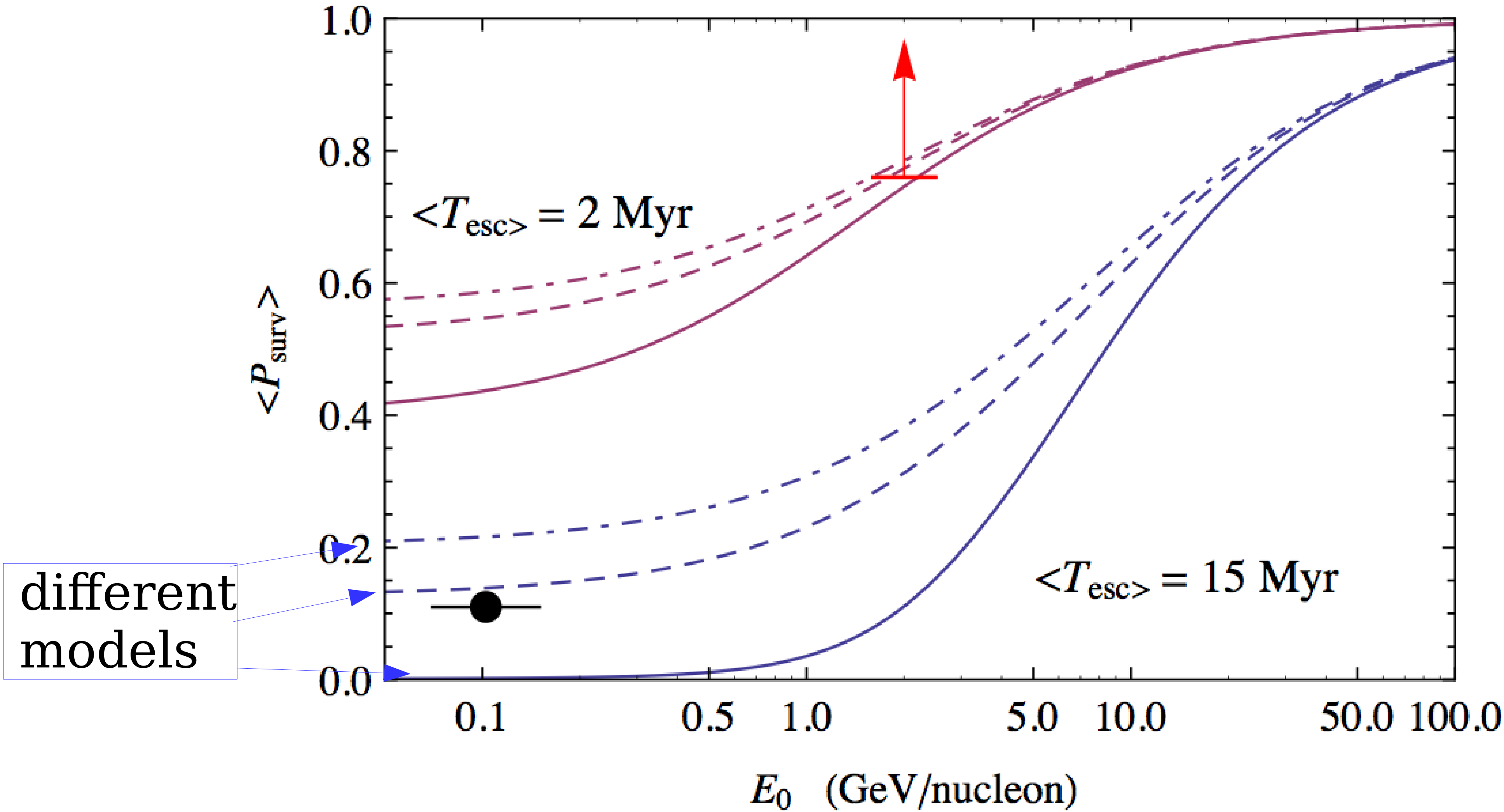
$E_0 = 2\ \mathrm{GeV/nucleon}$

very important to confirm !

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

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

Much smaller sensitivity to the modeling "theory"



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Proton versus electron

Acceleration in sources

Cosmic Ray generation

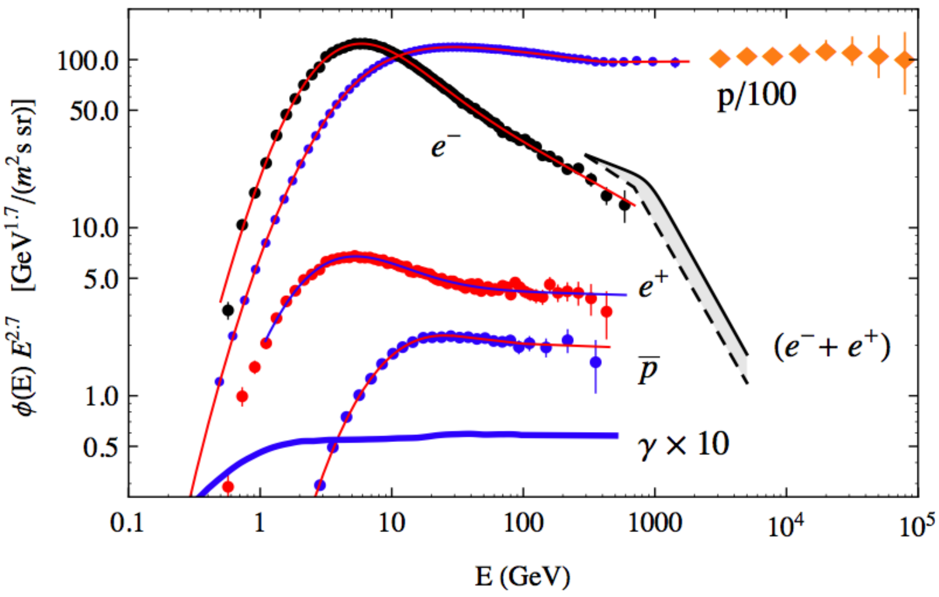
Problem of central importance in High Energy Astrophysics

If: positrons and antiprotons have equal
propagation properties.

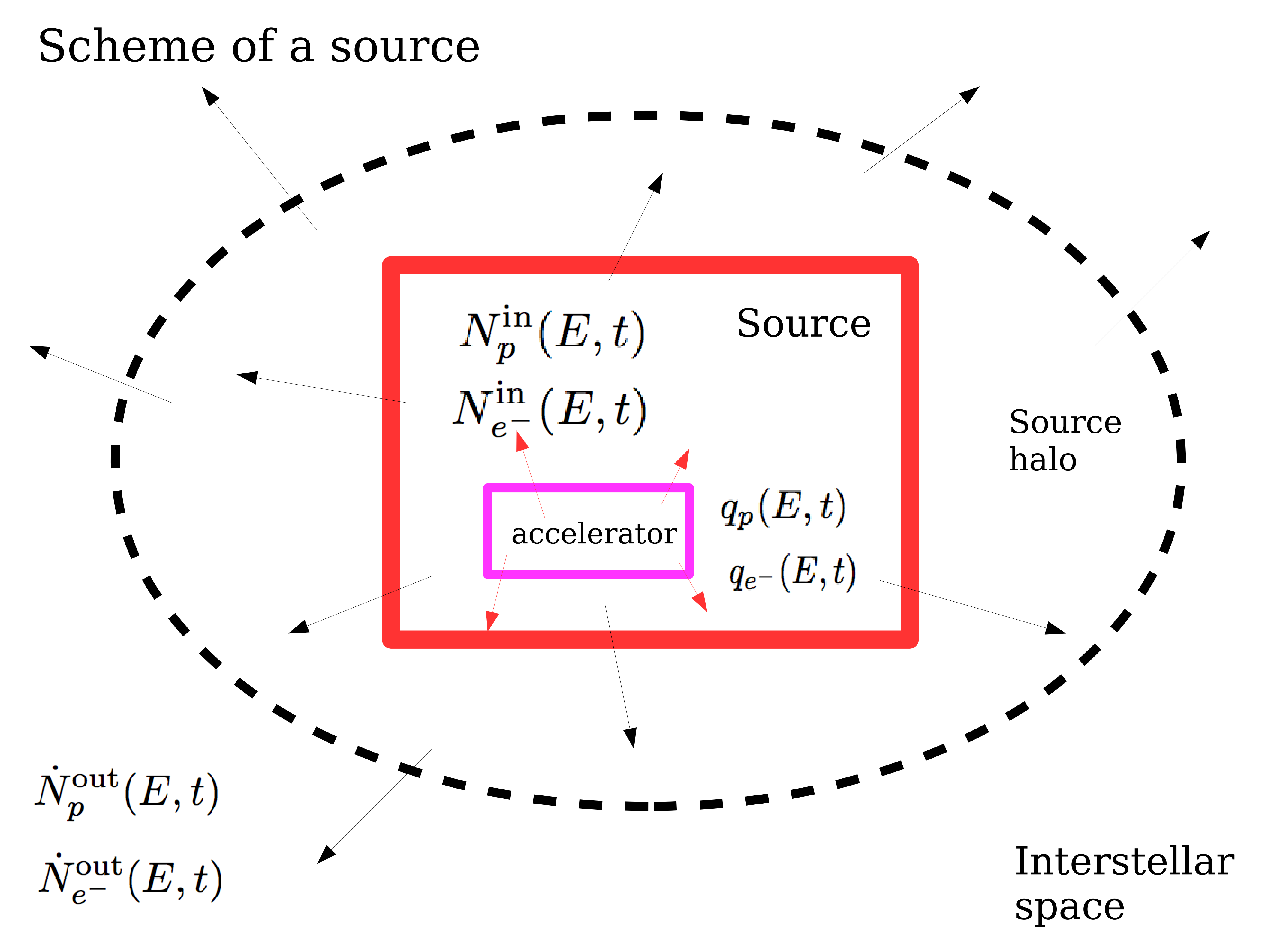
Then: also electron and protons have also the same
propagation properties

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
$N_p^{\rm in}(E,t)$
Source
$N_{e^-}^{\rm in}(E,t)$
Source halo
accelerator
$q_p(E,t)$
$q_{e^-}(E,t)$
$\dot{N}_p^{\rm out}(E,t)$
$\dot{N}_{e^-}^{\rm out}(E,t)$
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.

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

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

the accelerator is a gamma ray and neutrino emitter

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

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:

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

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

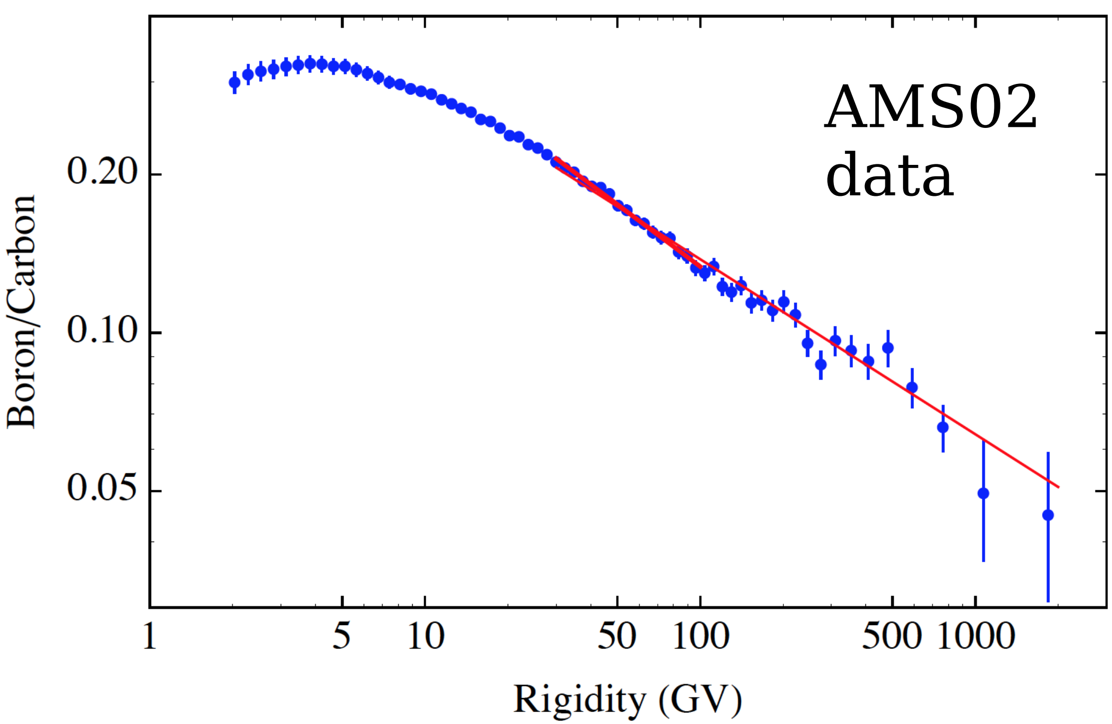
$$^{16}\mathrm{O} + p \to {}^{11}\mathrm{B} + {}^{4}\mathrm{He} + 2\,p$$

....

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

"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*]

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

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]*