The positron and antiproton fluxes in Cosmic Rays

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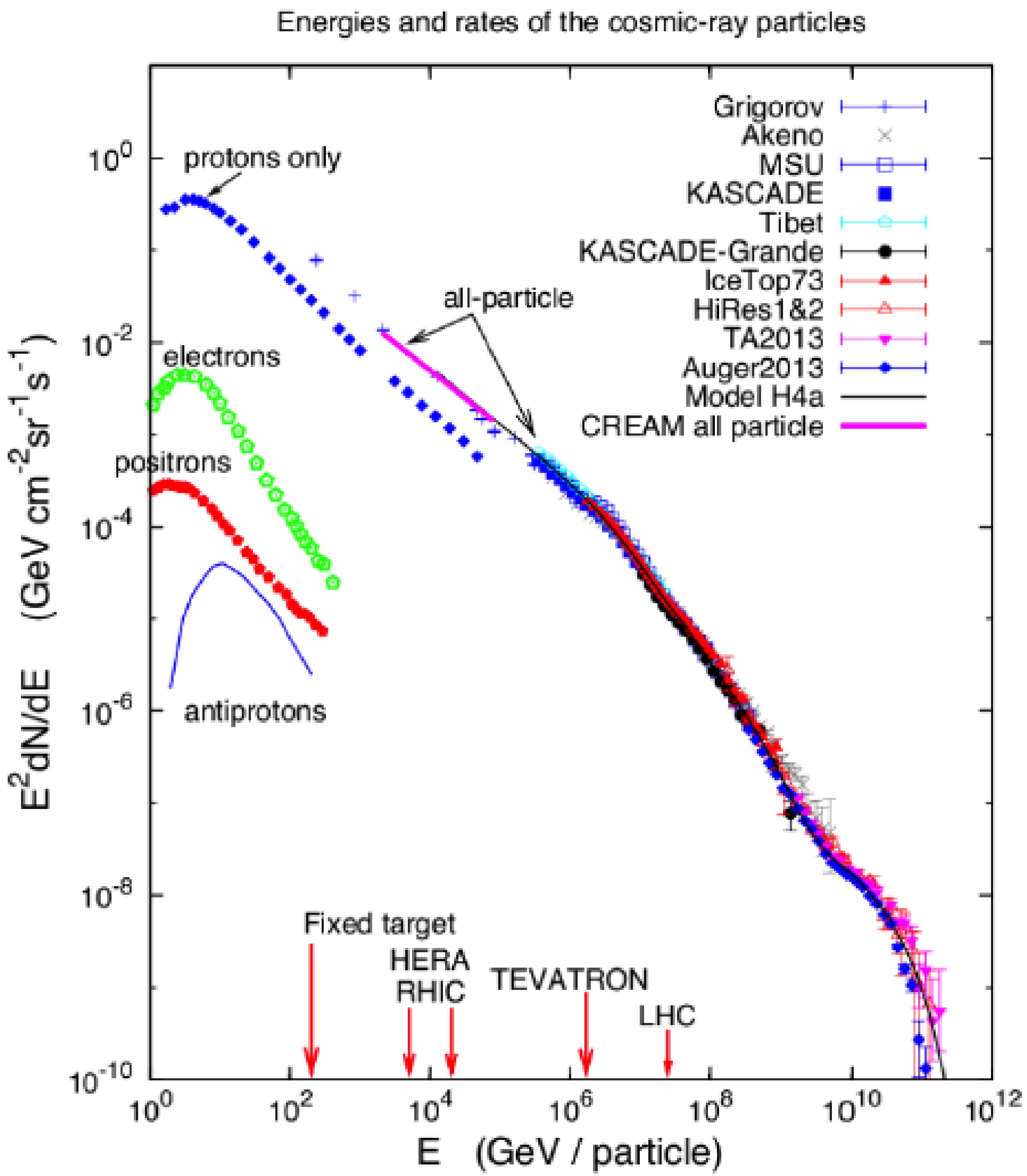
“Interpretation of the cosmic ray positron and antiproton fluxes”

Recently accepted in Phys.Rev. D



Fluxes of

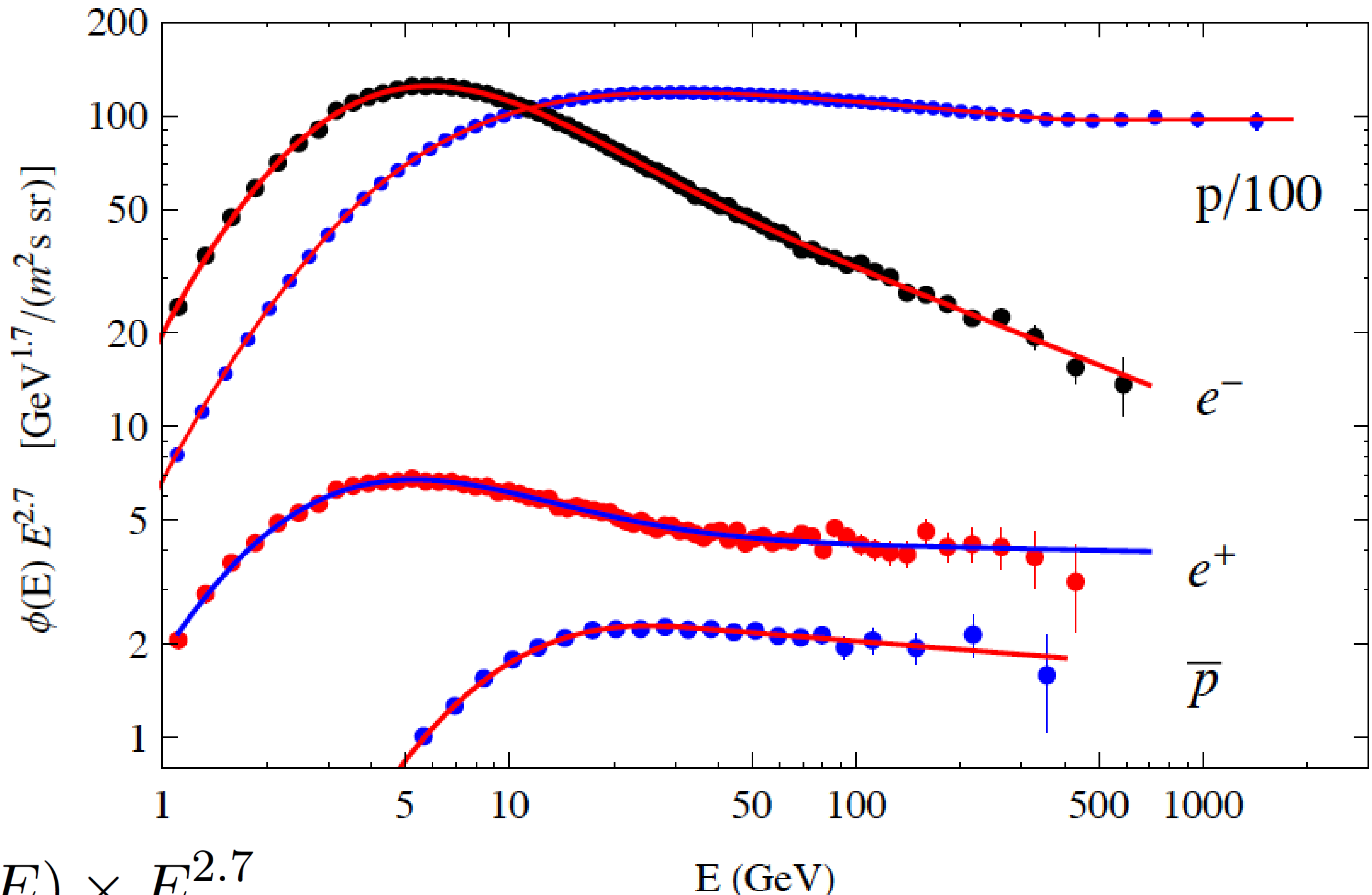
protons
electrons
positrons
antiprotons

$$\phi(E) \times E^2$$

Figure from Tom Gaisser

AMS02 measurements: $p \quad e^- \quad e^+ \quad \bar{p}$

(antiprotons from AMS days)



$\phi(E) \times E^{2.7}$

Scientific motivations

for the study of the fluxes of antiparticles
(positrons and antiprotons) in cosmic rays:

Indirect Search for *Dark Matter* in the form
of Weakly Interacting Massive Particles [WIMP's]

Understanding the *“High Energy Universe”*
[The ensemble of astrophysical object, environments
and mechanisms that generates very high energy
relativistic particles in the Milky Way and in the
entire universe.]

1. **An anomalous positron abundance in cosmic rays with energies 1.5-100 GeV**

PAMELA Collaboration (Oscar Adriani (Florence U. & INFN, Florence) *et al.*). Oct 2008. 20 pp.

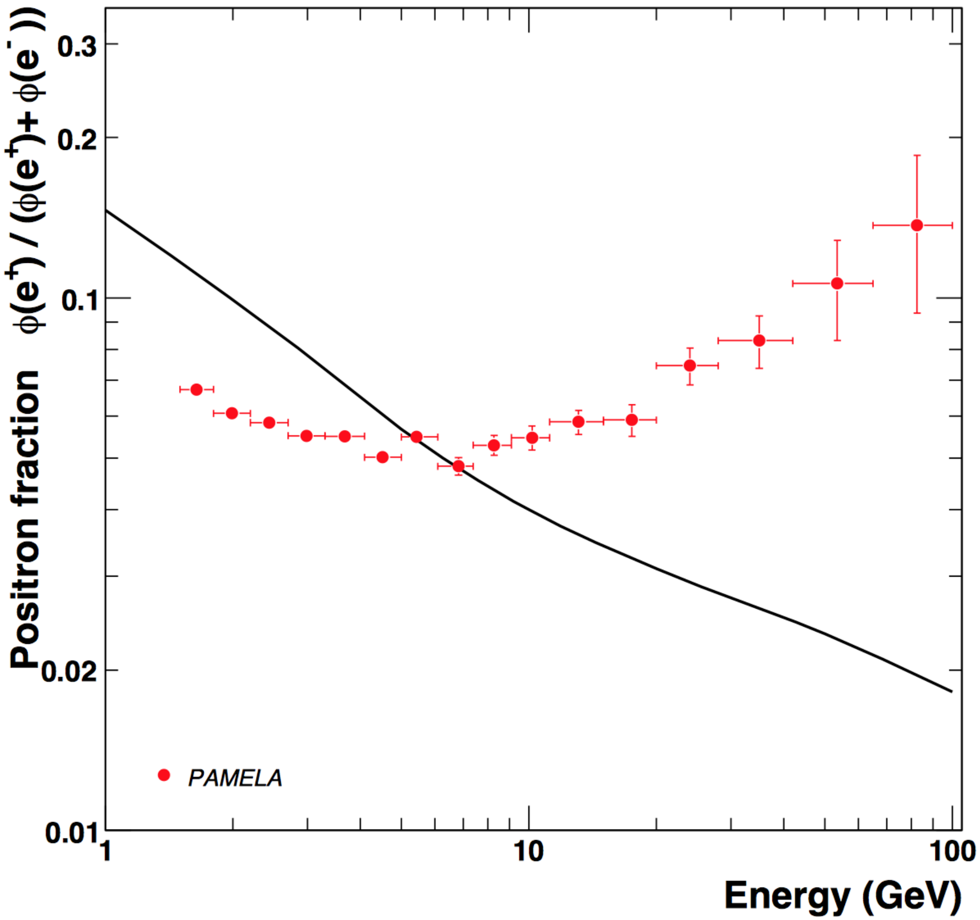
Published in **Nature 458 (2009) 607-609**

DOI: 10.1038/nature07942

e-Print: **arXiv:0810.4995 [astro-ph] | PDF**

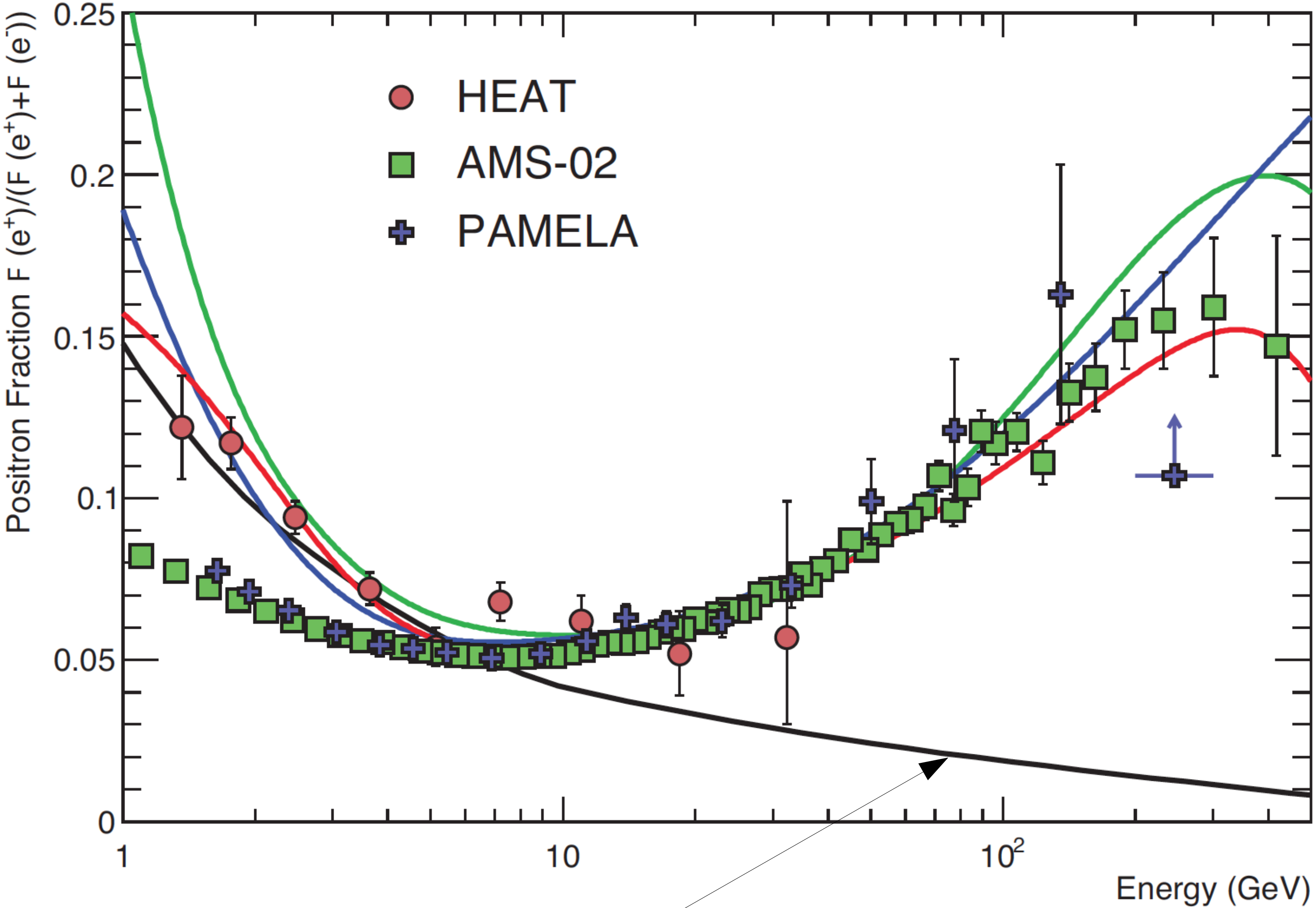
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote

ADS Abstract Service



Electron/Positron Ratio

PDG Review



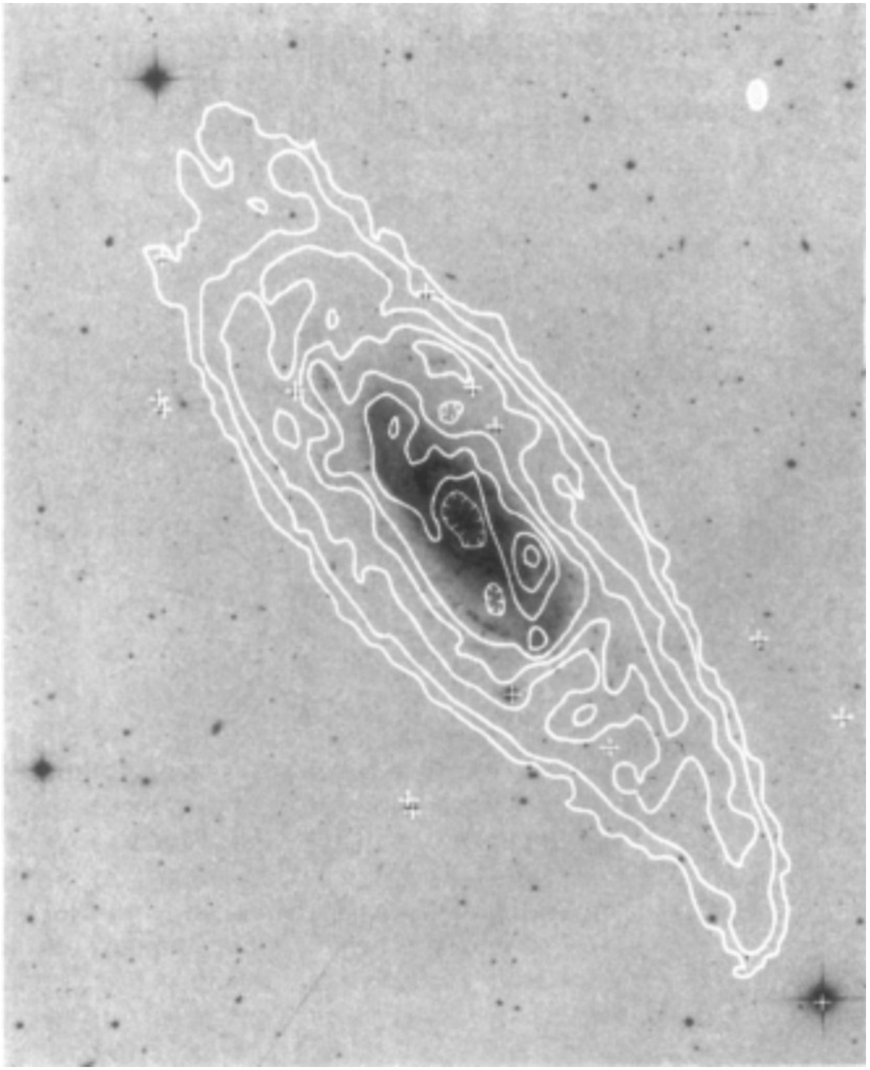
Standard mechanism of positron production

Dynamical evidence
for Dark Matter
at different length-scales
[Galaxies,
Clusters of Galaxies,
the entire universe]

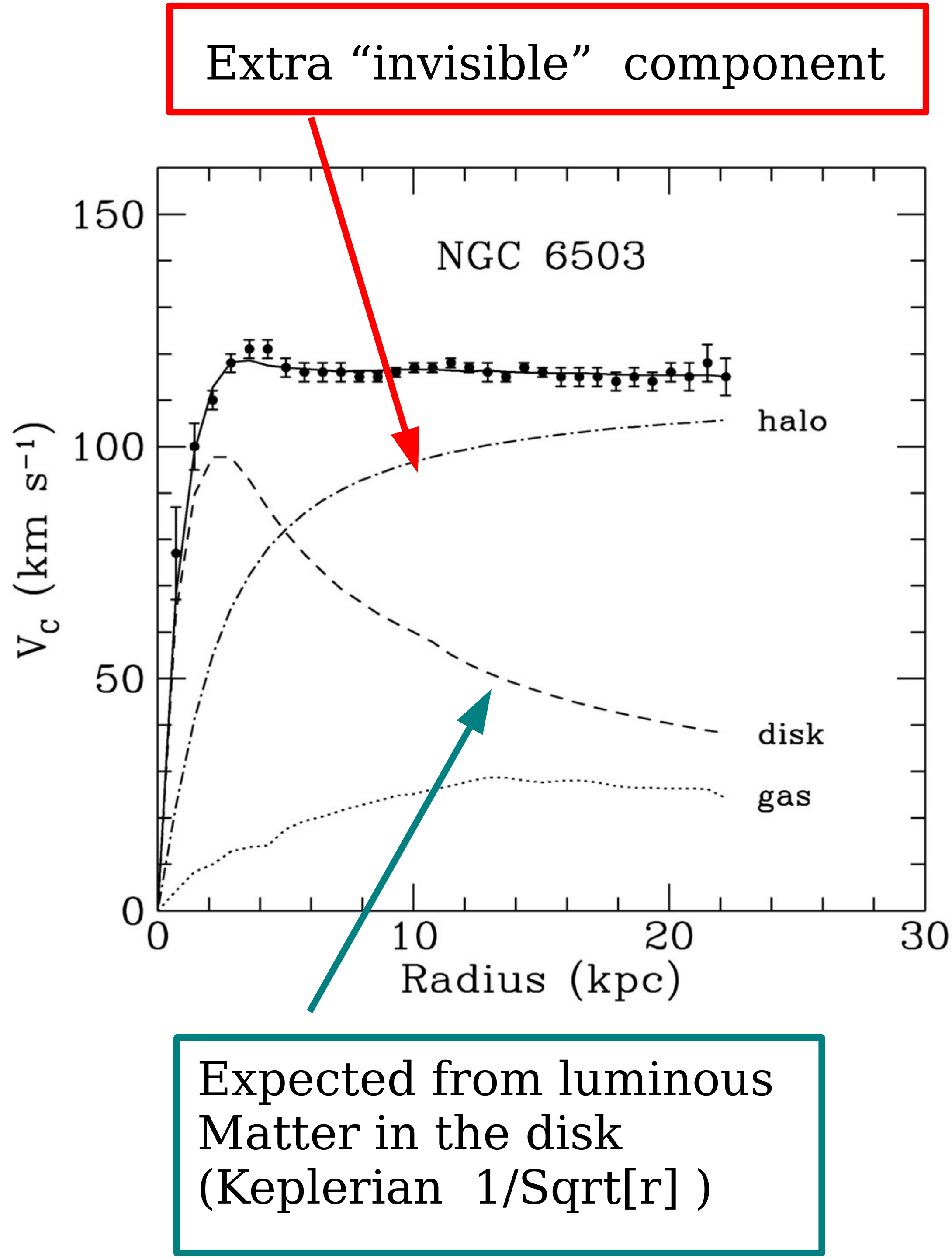
Cold Dark Matter
Cornelia Parker. (Tate Gallery, London)

What is the nature
of the Dark Matter ?

Dark Matter Halo in spiral Galaxies



Spiral galaxy NGC 3198
overlaid with hydrogen
column density [21 cm]
[ApJ 295 (1995) 305



The “thermal relic” or *WIMP paradigm* for Dark Matter

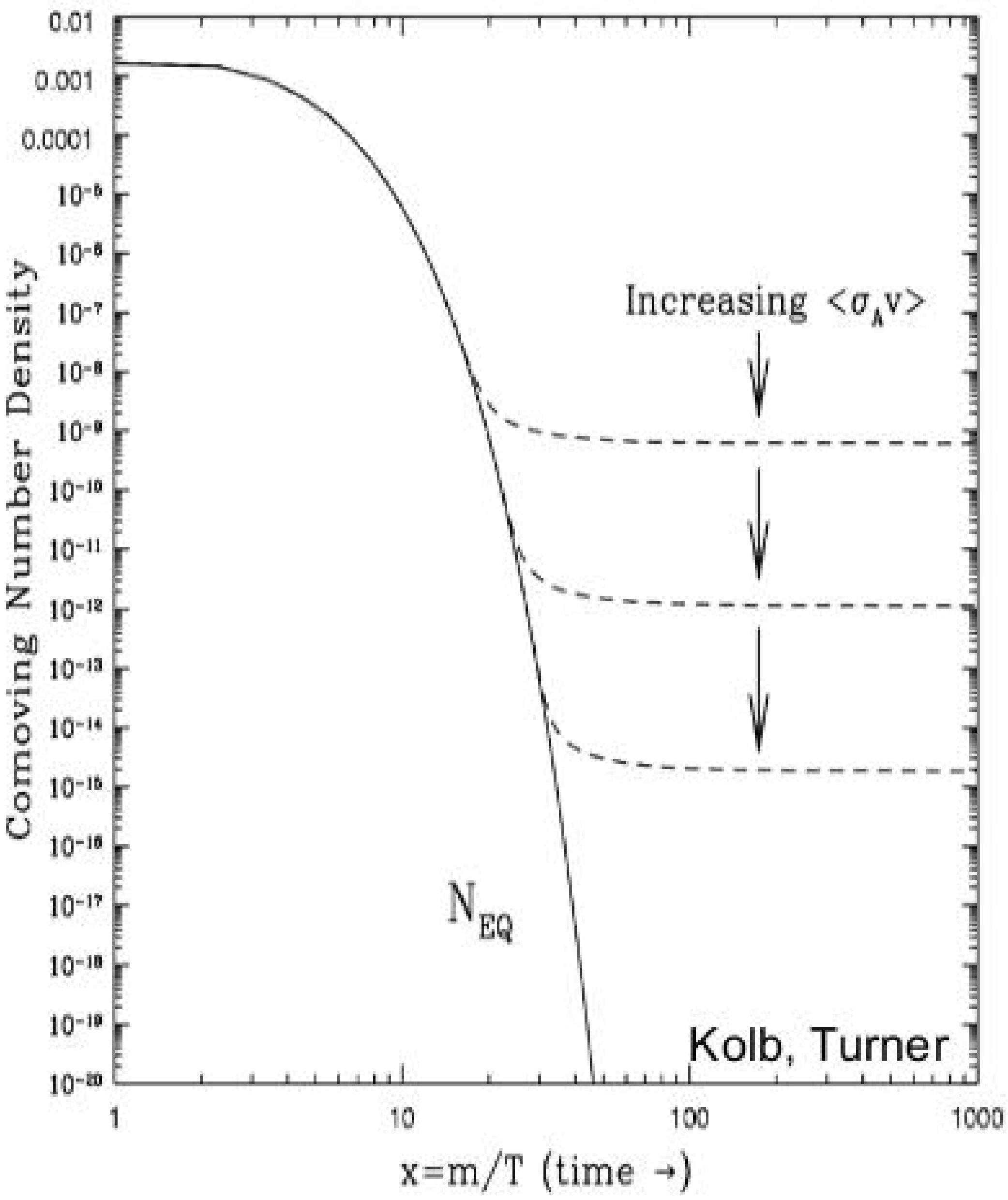
Hypothesis that the Dark Matter is formed by a (yet undiscovered) *elementary particle*

This particle was in thermal equilibrium in the early universe when the temperature was $T \gg m_\chi$

The “relic abundance” of this particle is determined by (and is inversely proportional to) its (velocity averaged) annihilation cross section.

$$\rho_\chi \propto \frac{1}{\langle \sigma v \rangle}$$

Concept of thermal relic [WIMP] :



$$\chi + \chi \leftarrow f + \overline{f}$$

$$\chi + \chi \rightarrow f + \overline{f}$$

Annihilation cross section
Determines the
"relic abundance"

$$\Omega_j^0 \simeq 0.2 \left[\frac{3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle \sigma \, v \rangle} \right]$$

“Relic abundance” estimate in standard Cosmology
(simplest treatment)

$$\Omega_\chi \simeq \left(\frac{16\,\pi^{5/2}}{9\,\sqrt{\pi}}\right)\;\frac{G^{3/2}\,T_0^3}{H_0^2\,(\hbar c)^{3/2}\,c^3}\;\frac{\sqrt{g^*}}{\langle\sigma\,v\rangle}$$

$$\Omega_\chi \simeq 0.2$$

$$\langle\sigma\,v\rangle \simeq 3\times 10^{-26}\;\frac{\mathrm{cm}^3}{\mathrm{sec}}$$

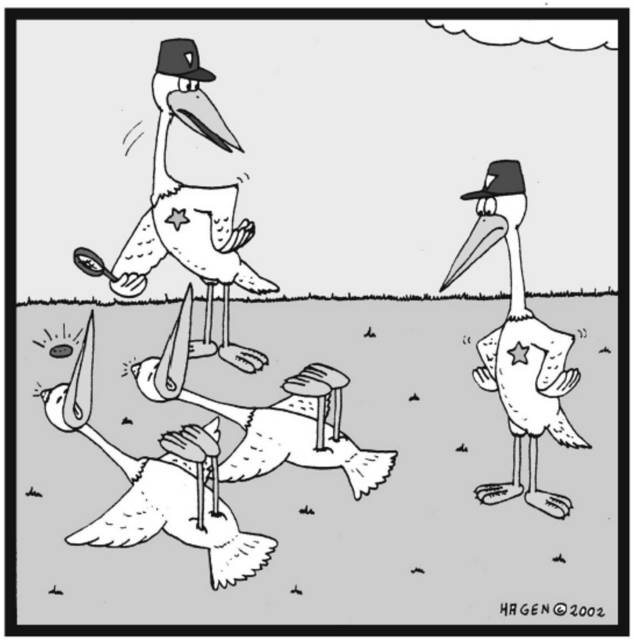
$$\sigma \simeq \frac{\alpha^2}{M^2}$$

$$M \simeq \frac{\hbar\,c}{\sqrt{\sigma/\alpha^2}} \simeq 140\;\mathrm{GeV}$$

Connection with
Weak (Fermi) scale ?!
[and perhaps supersymmetry]

The *“WIMP's Miracle”*

the WIMP's "miracle"



Unbelievable! It looks like they've
both been killed by the same stone...

"Killing two birds
with a single stone"

"Dark Matter Particle"

Direct observational puzzle

New particles are predicted in "beyond the Standard Model" theories, (in particular Supersymmetry) that have the DM particle properties.

Theoretical motivations (hierarchy problem)

Supersymmetry

Fermionic degrees of freedom

Bosonic degrees Of freedom

All “internal quantum numbers” (charge, color,...) must be identical

q $\tilde{q}$ squark

$e^{\pm}$ $\tilde{e}^{\pm}$ selectron

g $\tilde{g}$ gluino

....

	Standard Model fields	Super-symmetric extension	
fermions	quarks	Squarks	New bosons (scalar) spin 0 S-
	leptons	Sleptons	
	neutrinos	Sneutrinos	
bosons	photon	photino	New fermions spin 1/2 -ino
	W	Wino	
	Z	Zino	
	gluons	gluinos	
	Higgs	Higgsino	
2 Higgs →	H h	$\tilde{H}$ $\tilde{h}$	

Weak (~100 GeV) Mass scale ?

1 stable new particle (R-parity conserved)

$$|\chi\rangle = c_1 \, |\tilde{\gamma}\rangle + c_2 \, |\tilde{z}\rangle + c_3 \, |\tilde{H}\rangle + c_4 \, |\tilde{h}\rangle$$

Three roads to the discovery of DM
in the form of thermal relics (WIMP's)

$$\chi + \chi \to q + \overline{q}$$

Annihilation

$$q + \overline{q} \to \chi + \chi$$

Creation

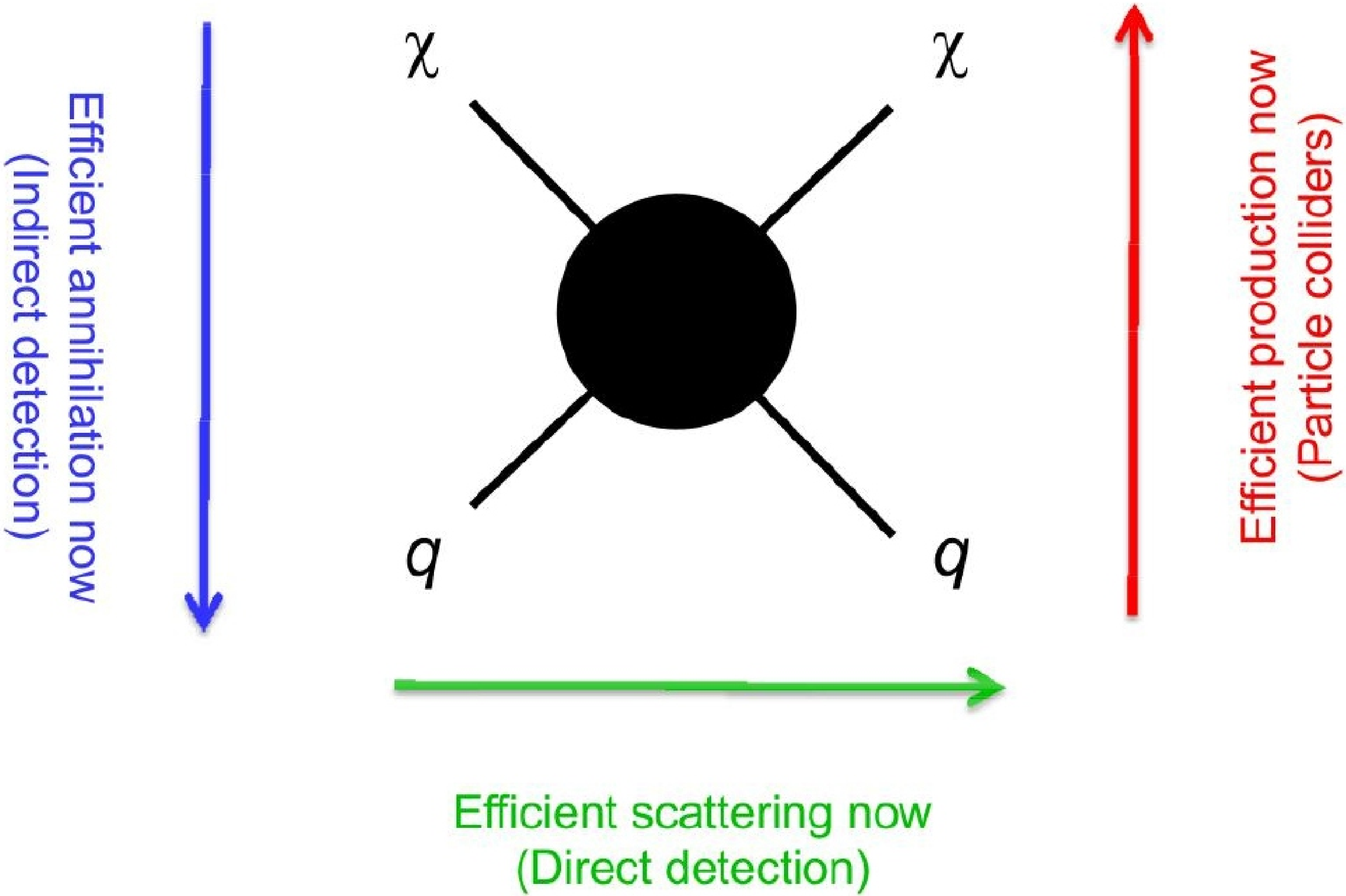
Time reversal

$$\chi + q \to \chi + q$$

Elastic

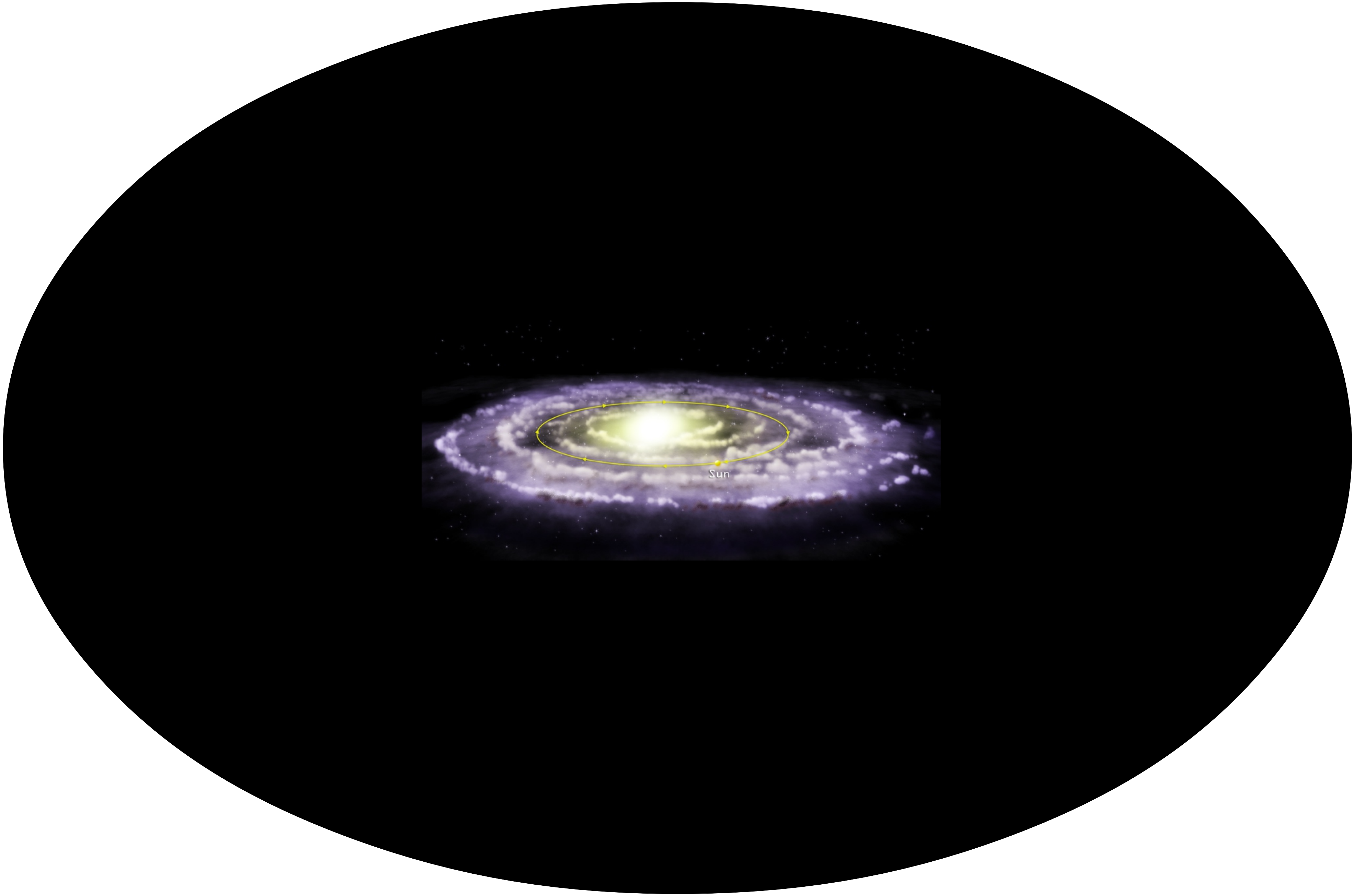
Crossing symmetry

Three roads to the discovery of DM
in the form of thermal relics (WIMP's)



Indirect searches for DARK MATTER

Dark Matter Halo in our Galaxy.



In the “WIMP paradigm” Dark Matter is NOT really dark

Self-annihilation of the DM particles that form the halo

$$n_\chi(\vec{x}) = \frac{\rho_\chi(\vec{x})}{m_\chi}$$

Number density of Dark Matter particles

$$\frac{dN_{\chi\chi\to X}}{d^3x\,dt} = \frac{1}{2}\, n_\chi^2(\vec{x}) \;\; \langle \sigma\, v \rangle$$

Number of annihilations
per unit time and unit volume

$$\frac{dL_{\rm DM}}{d^3x}(\vec{x}) = \frac{\rho^2(\vec{x})}{m_\chi}\; \langle \sigma\, v \rangle$$

Luminosity
per unit volume

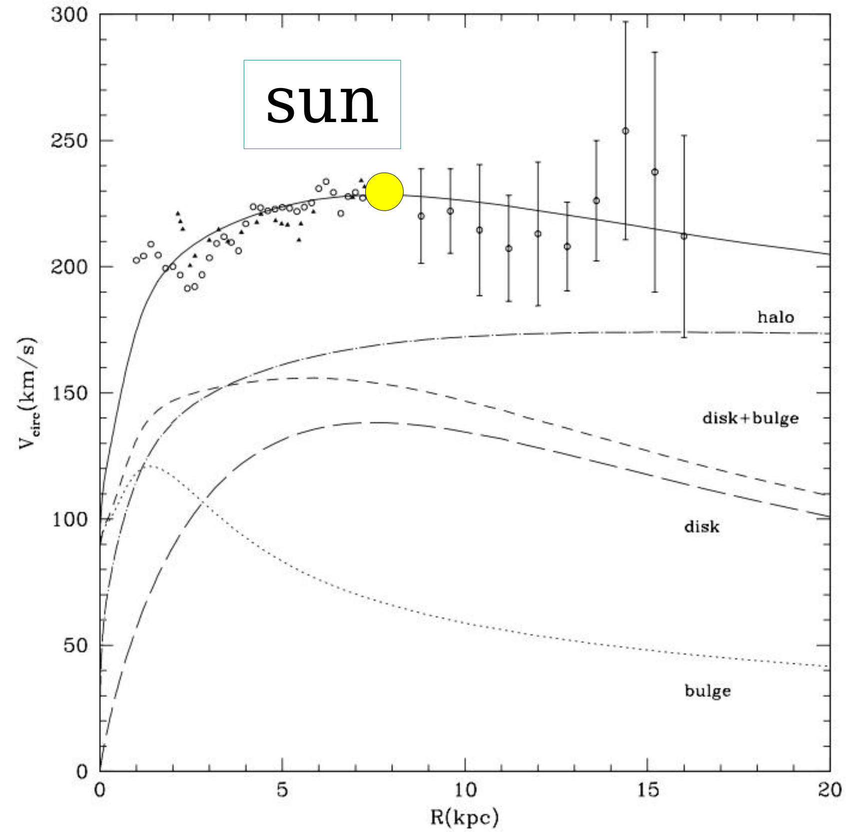
What is the energy output of the Milky Way in DM annihilations?

$$\frac{dL_{\rm DM}}{d^3x}(\vec{x}) = \frac{\rho^2(\vec{x})}{m_\chi} \langle \sigma\, v \rangle$$

We know
(at least approximately)
from cosmology

Astrophysical observations
(rotation velocity)
+ Modeling of galaxy formation
for the central part of the Galaxy

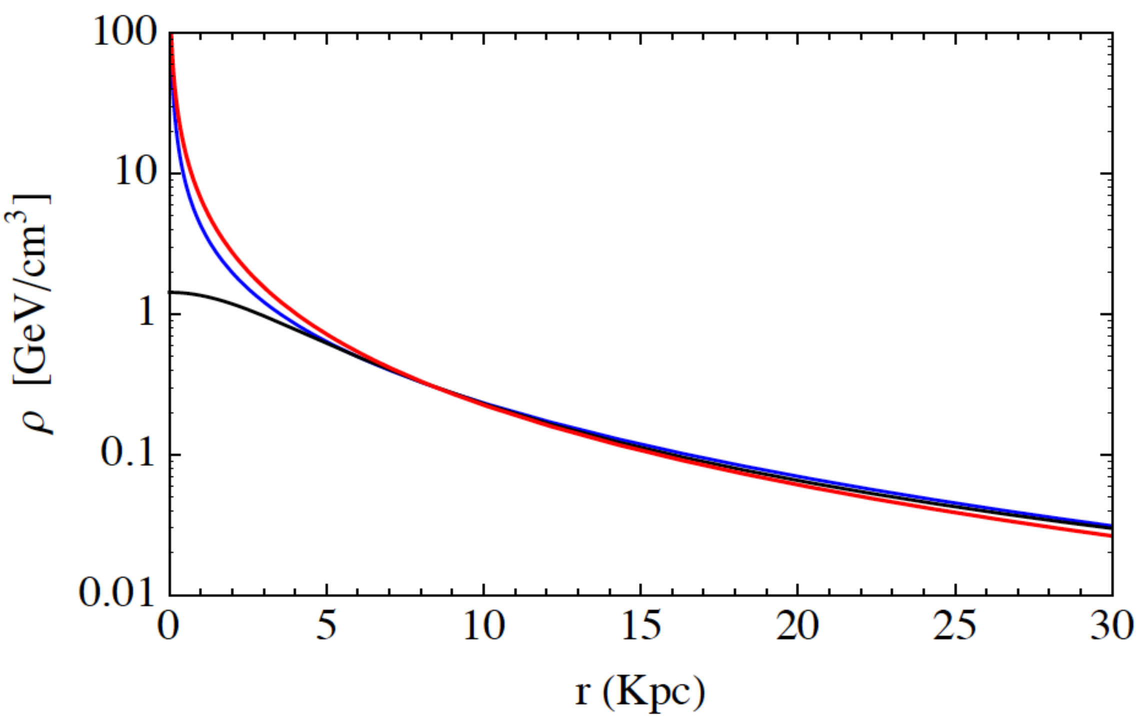
DM in the Milky Way



$$\rho_{\text{isothermal}}(r) = \frac{\rho_s}{1 + (r/r_s)^2}$$

$$\rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

$$\rho_{\text{Einasto}}(r) = \rho_s \exp\{-(2/\alpha)[(r/r_s)^\alpha - 1]\}$$



Density distribution
determined by
Rotation velocity measurements

"Cusp" at GC
derived by N-body simulations

DM in the Milky Way

$$\rho_{\text{isothermal}}(r) = \frac{\rho_s}{1+(r/r_s)^2}$$

$$\rho_{\text{NFW}}(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

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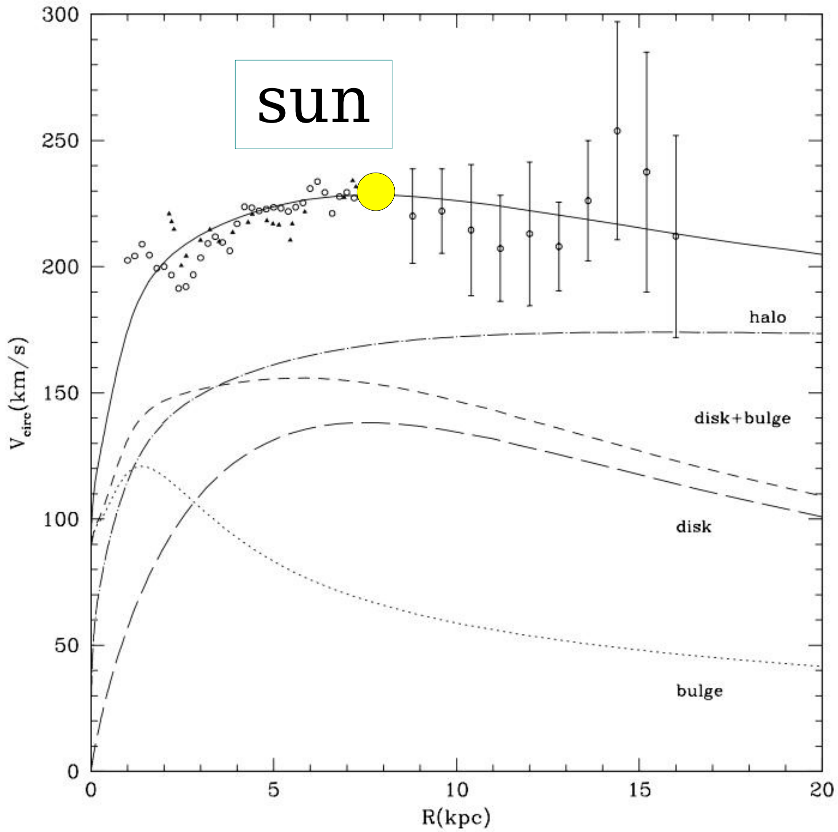
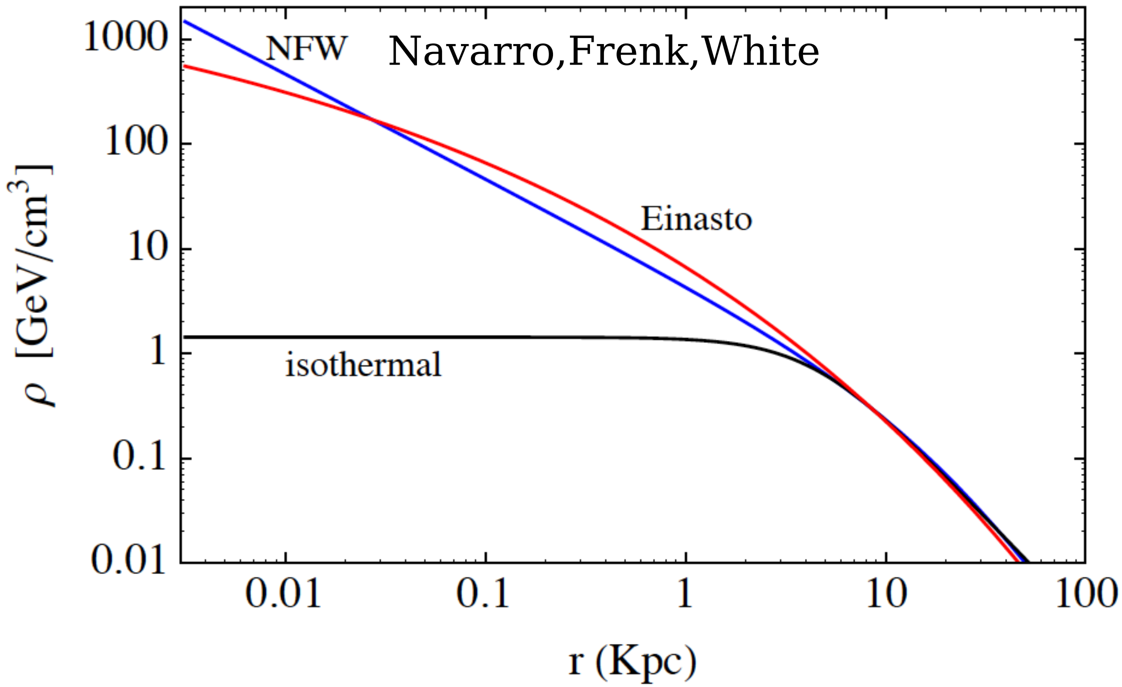




Density distribution
determined by
Rotation velocity measurements

"Cusp" at GC
derived by N-body simulations

Power generated by DM annihilations in the Milky Way halo

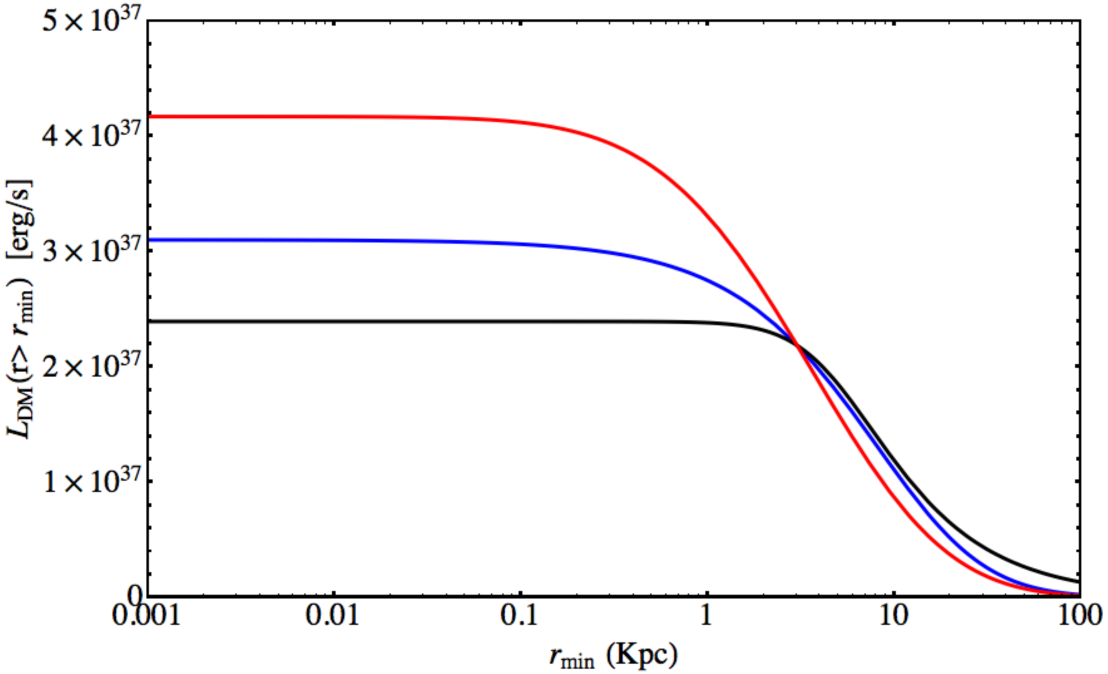
$$\frac{dN_{\chi\chi\to X}}{d^3x\,dt} = \frac{1}{2}\, n_\chi^2(\vec{x})\ \langle\sigma\, v\rangle$$

$$\frac{dL_{\rm DM}}{d^3x}(\vec{x}) = \frac{\rho^2(\vec{x})}{m_\chi}\ \langle\sigma\, v\rangle$$

$$L_{\rm DM} \propto \frac{\langle\sigma\, v\rangle}{m_\chi}$$

$$L_{\rm DM} \simeq 3\times 10^{37}\ {\rm erg\ s^{-1}}\ \left[\frac{\langle\sigma\, v\rangle}{3\times 10^{-26}\ ({\rm cm^3 s})^{-1}}\right]\ \left[\frac{100\ {\rm GeV}}{m_\chi}\right]$$

[Majorana particle]



small effect of
"Cusp" on total luminosity

For comparison:
Power of the
Cosmic Ray Accelerators
in the Milky Way:

$$L_p \simeq 10^{41}\ \frac{\rm erg}{\rm s}$$

What is the final state of DM annihilations ?

... well we do not know, we have to build a model (for example supersymmetry).

But it is plausible that the Dark Matter particle will (or could) produce all particles (and anti-particles) that we know.

Most promising for detection:

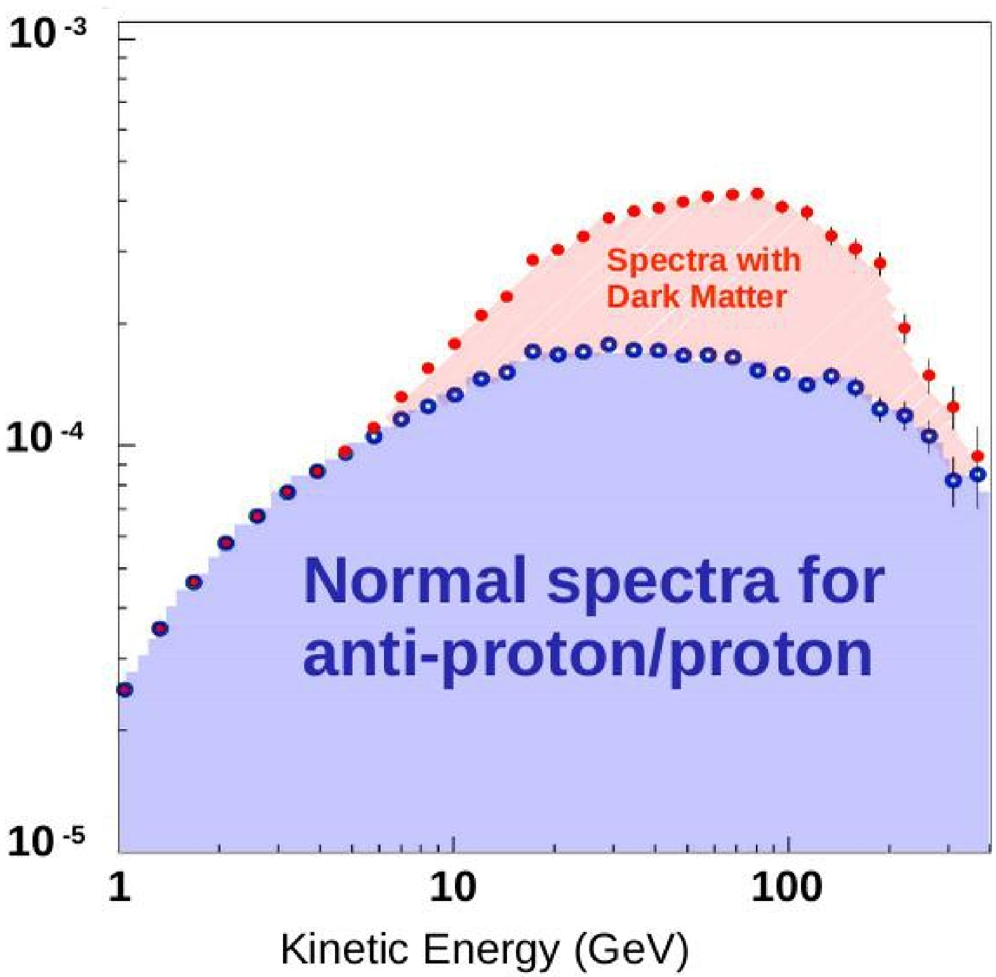
$$\chi + \chi \rightarrow \gamma \quad e^+ \quad \bar{p} \quad \nu_\alpha$$

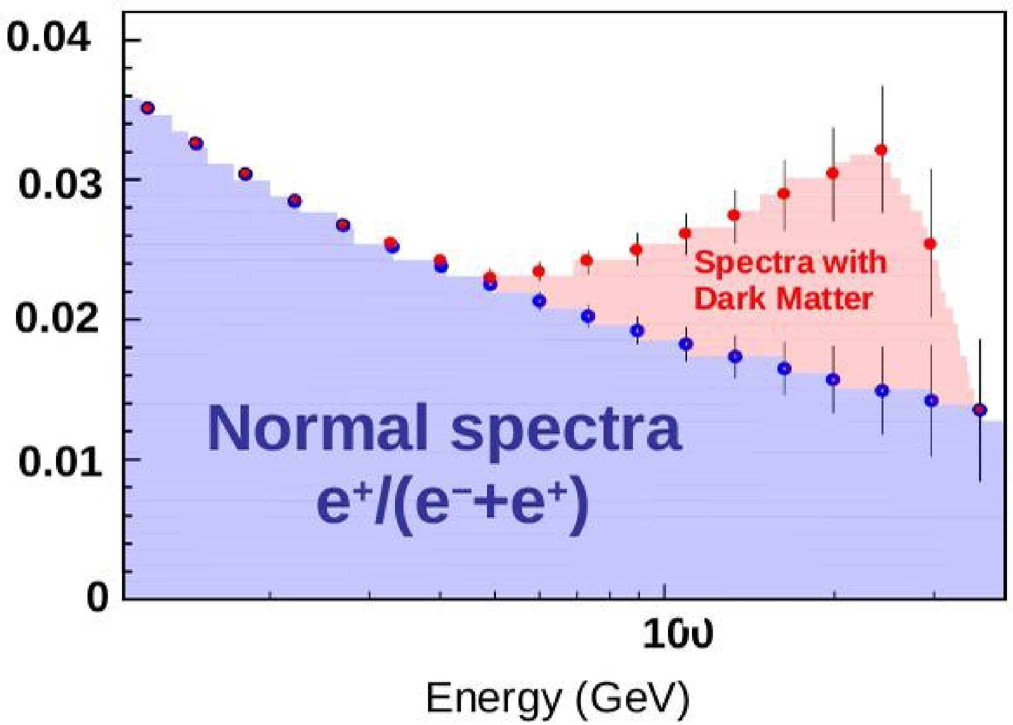
photons | Charged (anti)particles | Neutrinos

Charged particles:
positrons and
anti-protons

Trapped by the
Galactic magnetic field

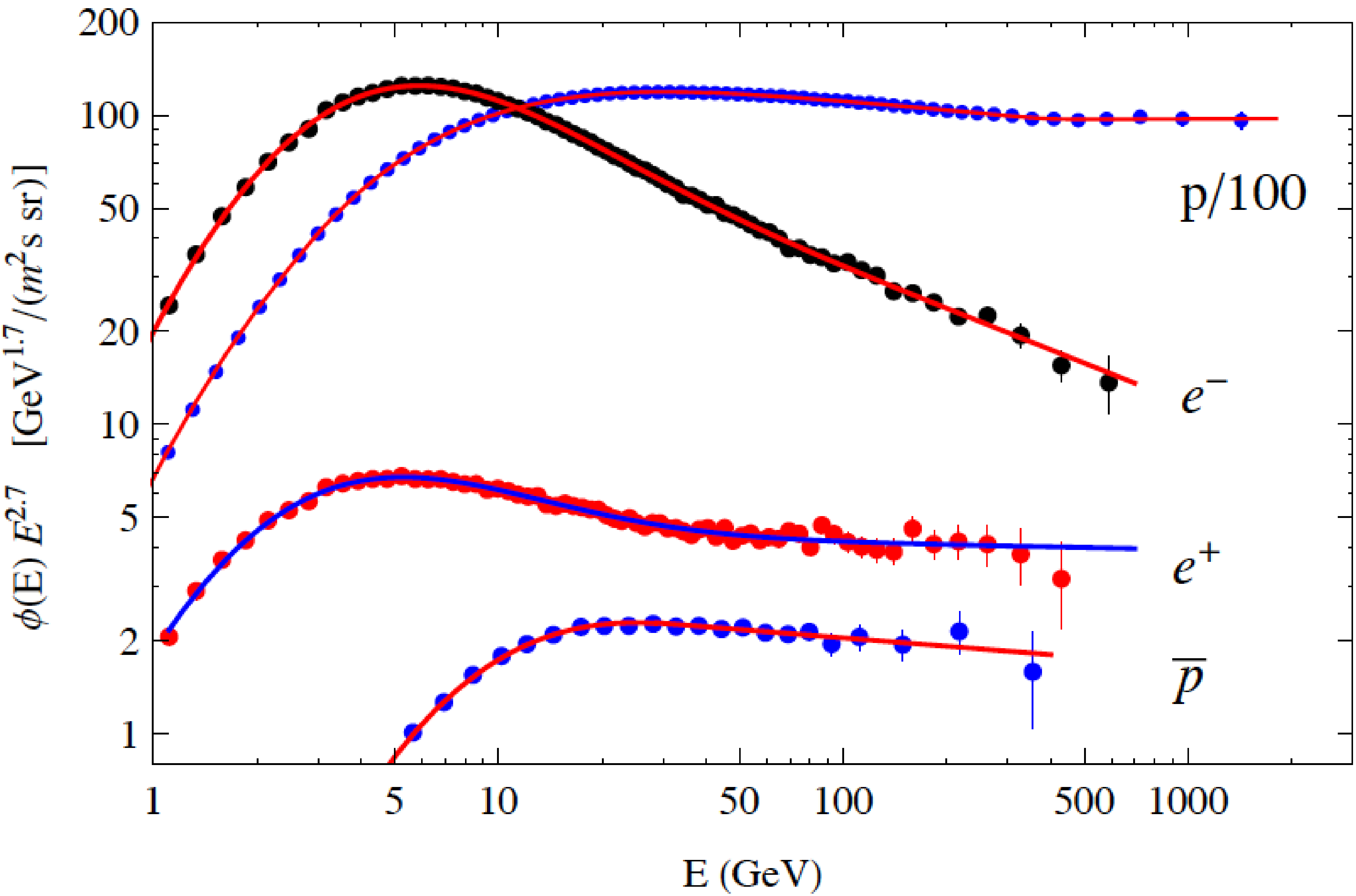
Extra contribution to
the cosmic ray fluxes





AMS02 measurements:
(antiprotons from AMS days)

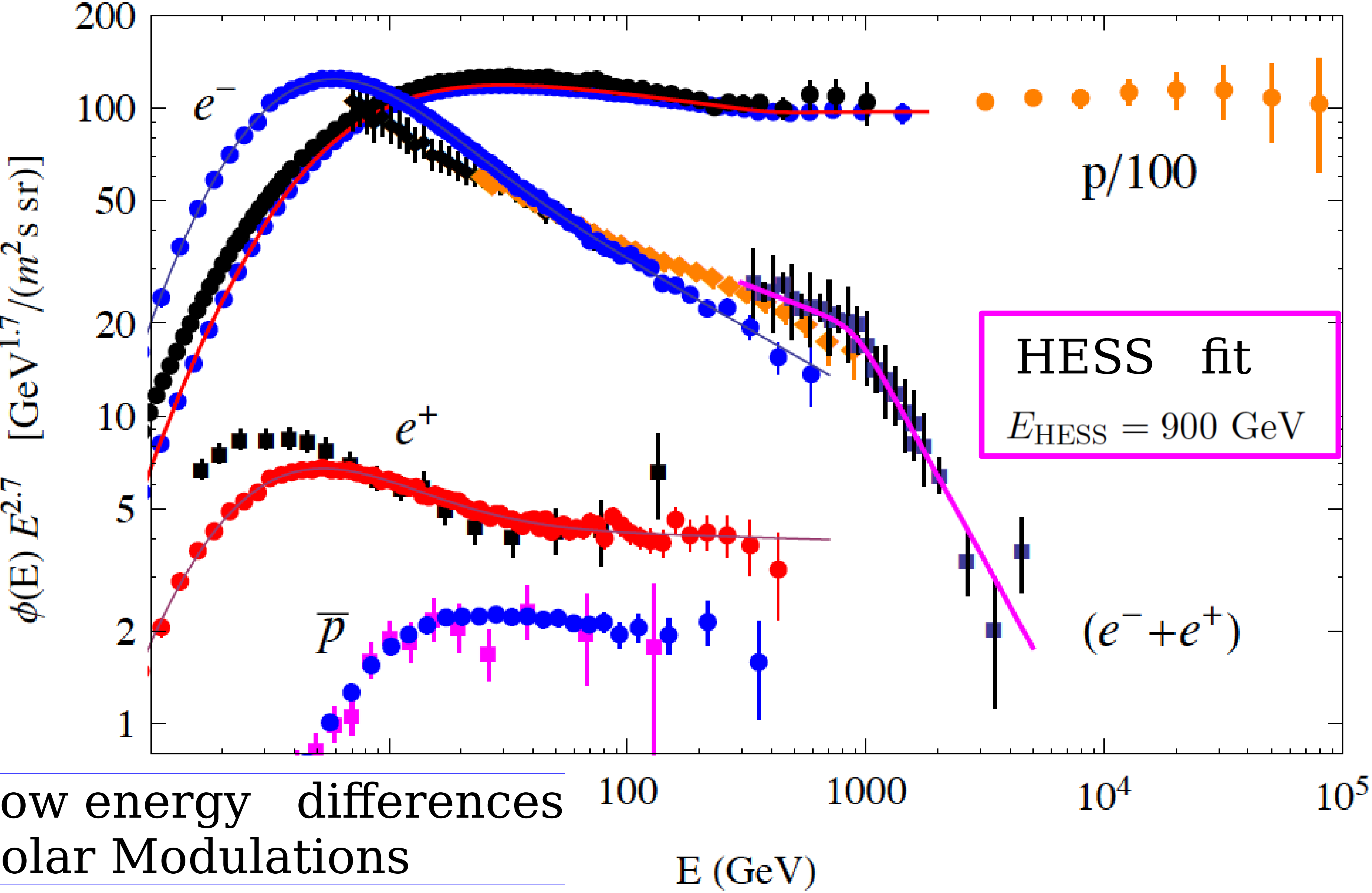
$p \quad e^- \quad e^+ \quad \bar{p}$



AMS02, PAMELA, CREAM, FERMI, HESS

$p \quad e^- \quad e^+ \quad \bar{p}$

Different shapes of the spectra



Low energy differences
Solar Modulations

- Why the proton flux has its shape ?
- Why the electron flux has its shape ?
- Why the positron flux has its shape ?
- Why the $\overline{p}$ flux has its shape ?

Scientific motivations

for the study of the fluxes of antiparticles (positrons and antiprotons) in cosmic rays:

Indirect Search for *Dark Matter* in the form of Weakly Interacting Massive Particles [WIMP's]

Understanding the *"High Energy Universe"* [The ensemble of astrophysical object, environments and mechanisms that generates very high energy relativistic particles in the Milky Way and in the entire universe.]

Formation of the Cosmic Ray Spectra

$$n(E) = \frac{4\pi}{\beta c}\,\phi(E)$$

Cosmic Ray Density
at the Sun position

=

Generation
[“release” in interstellar space]

$\otimes$

Propagation
from source to Sun

$$\phi_j(E, \vec{x}, t)$$

FLUX (isotropic)
at position x, time t
of particles of type j and energy E

$$\phi_j(E, \vec{x}_\odot, t_{\rm now})$$

Flux directly measurable at the Earth
(correcting for solar modulations)

$$q_j(E, \vec{x}, t)$$

Generation Rate
(per unit volume)
at position x, time t
of particles of type j and energy E

Generation Rate

Flux at position x

$$q_j(E, \vec{x}, t) \quad \Longleftrightarrow \quad \phi_j(E, \vec{x}, t)$$

Propagation

Formation of the (proton) Cosmic Ray Spectrum

$$n_p(E, \vec{x}_\odot, t_{\rm now}) =$$

Instellar generation (or "release") function

$$\int_{-\infty}^{t_{\rm now}} dt \int d^3x \int dE_i \quad q_p(E_i, \vec{x}, t) \times$$

$$P_p(E, \vec{x}_\odot, t_{\rm now};\ E_i, \vec{x}, t)$$

Propagation effects

[*General*, explicit (but "formal") expression]

Primary particles:
(protons, electrons, Helium nuclei, ...)

Accelerated in Astrophysical Sources
(such as Supernovae, GRB's, Pulsars)

"Generation" =

Injection in the acceleration process

$\otimes$

Acceleration

$\otimes$

source Ejection

(escape from accelerator)

Primary Particles

Sources are (very likely) "stochastic" (localized and transients)

$$q_j(E, \vec{x}, t) \approx \sum_k Q_j^{(k)}(E)\ \delta[\vec{x} - \vec{x}_k]\ \delta[t - t_k]$$

"Smoothing out" in time and space to have an (approximately) stationary and continuous generation

$$\langle q_j(E, \vec{x}) \rangle = \frac{1}{\Delta T} \int_t^{t+\Delta t} dt' \frac{1}{\Delta V} \int_{\Delta V} d^3x' \ q_j(E, \vec{x} + \vec{x}', t')$$

Secondary particles:

positrons, antiprotons

[in the "conventional picture" :
no DM, no antimatter accelerators)]

rare nuclei (Li, Be, B, ...) [Z=3,4,5]

"born relativistic"

"Generation" = Creation in the interaction of a higher energy particle

Integration over volume to obtain
The total Milky Way *Generation Rate* of particles of energy E:

$$\langle Q_j(E) \rangle = \int d^3x \; \langle q_j(E, \vec{x}) \rangle$$

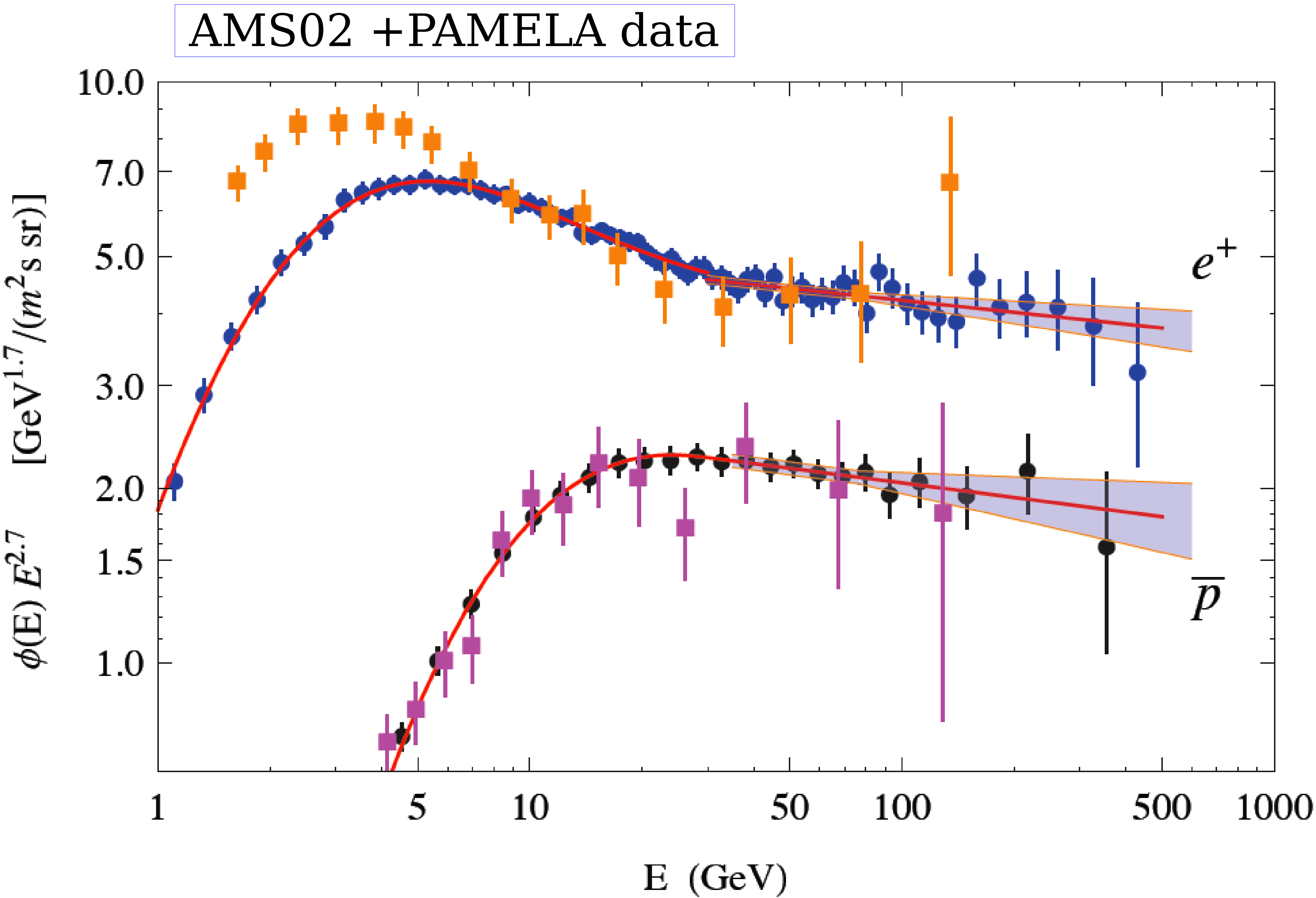
Spectral shape of flux determined by
Generation * Propagation

$$[P_j(E, \vec{x}_\odot, t)]] = \frac{[T]}{[L^3]}$$

$$\phi_j(E) = \frac{\beta\, c}{4\pi} \; \langle Q_j(E) \rangle \; P_j(E)$$

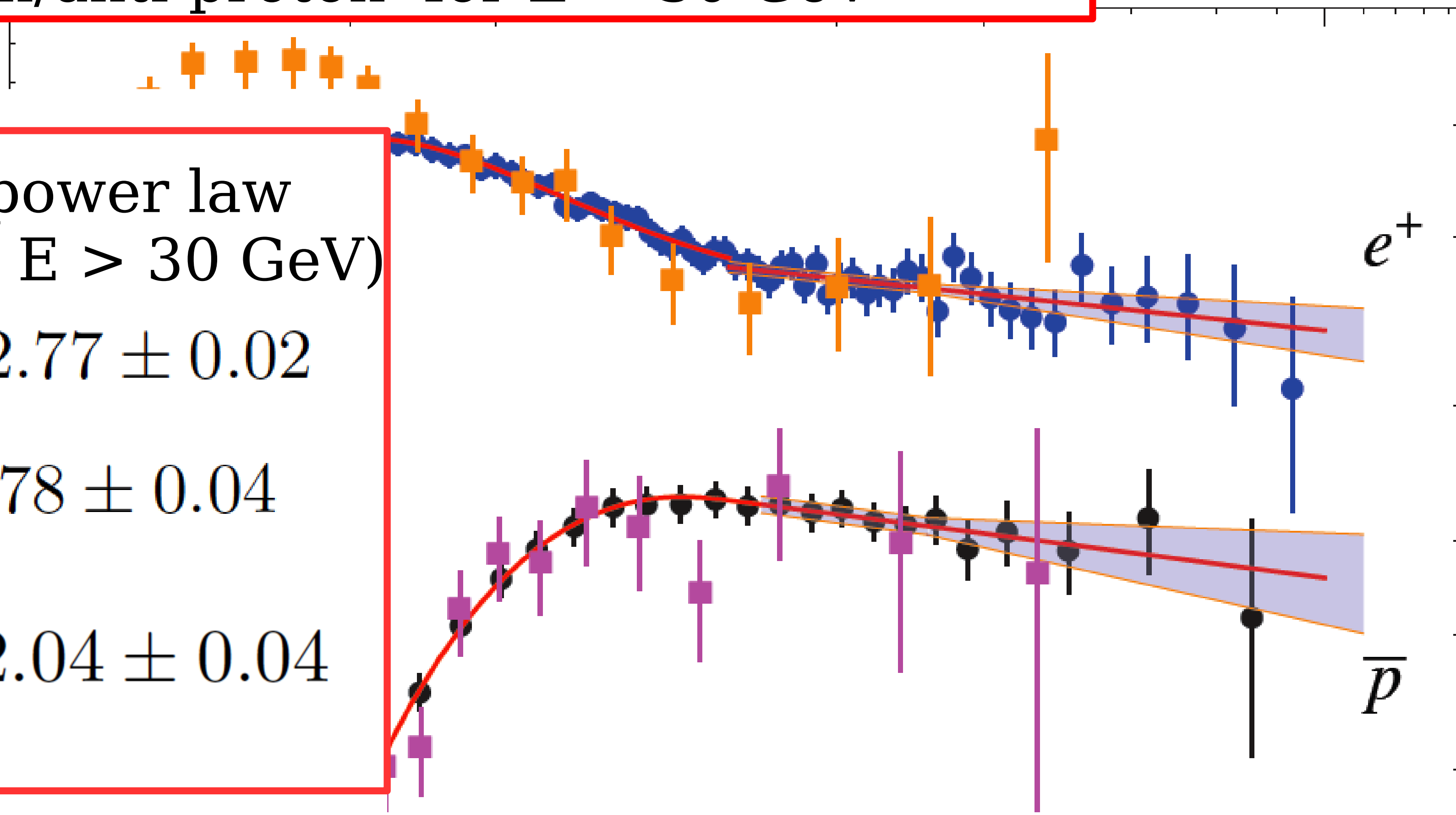
$$\phi_j(E, \vec{x}_\odot, t_{\rm now}) = \frac{\beta\, c}{4\pi} \; \langle Q_j(E) \rangle \; P_j(E, \vec{x}_\odot, t_{\rm now})$$

New precision measurements (by AMS02) of anti-matter Cosmic Rays. e^+ $\overline{p}$



New precision measurements (by AMS02) of anti-matter Cosmic Rays. e^+ $\overline{p}$

Approximately constant value for the ratio positron/anti-proton for E > 30 GeV



Simple power law Fits (for E > 30 GeV)

$$\gamma_{e^+} = 2.77 \pm 0.02$$

$$\gamma_{\overline{p}} = 2.78 \pm 0.04$$

$$\frac{e^+}{\overline{p}} \simeq 2.04 \pm 0.04$$

$$\left.\frac{\phi_{e+}(E)}{\phi_{\overline{p}}(E)}\right|_{E\in[30,400]\ \mathrm{GeV}} \simeq (2.04 \pm 0.04) \times \left(\frac{E}{50\ \mathrm{GeV}}\right)^{0.015\pm0.045}$$

Simple Power Law Fits [E > 30 GeV]

$$\phi_j(E) = K_j \left(\frac{E}{50\ \text{GeV}} \right)^{-\gamma_j}$$

$$\chi^2_{\text{min}} = 12.0 \qquad \text{(27 d.o.f.)}$$

$$K_{e^+} = (11.4 \pm 0.1) \times 10^{-5}\ (\text{m}^2\text{s}\,\text{sr}\,\text{GeV})^{-1}$$

$$\gamma_{e^+} = 2.77 \pm 0.02$$

e^+

$$\chi^2_{\text{min}} = 1.56 \qquad \text{(10 d.o.f.)}$$

$$K_{\overline{p}} = (5.6 \pm 0.1) \times 10^{-5}\ (\text{m}^2\text{s}\,\text{sr}\,\text{GeV})^{-1}$$

$$\gamma_{\overline{p}} = 2.78 \pm 0.04$$

$\overline{p}$

$$\gamma_{e^+} = 2.77 \pm 0.02$$

Fitted slopes:

E > 30 GeV

$$\gamma_{\overline{p}} = 2.78 \pm 0.04$$

Protons

$$\gamma_p = 2.85 \pm 0.01$$

$$\gamma_p = 2.72 \pm 0.05$$

$$E_{\rm break} \simeq 330 \text{ GeV}$$

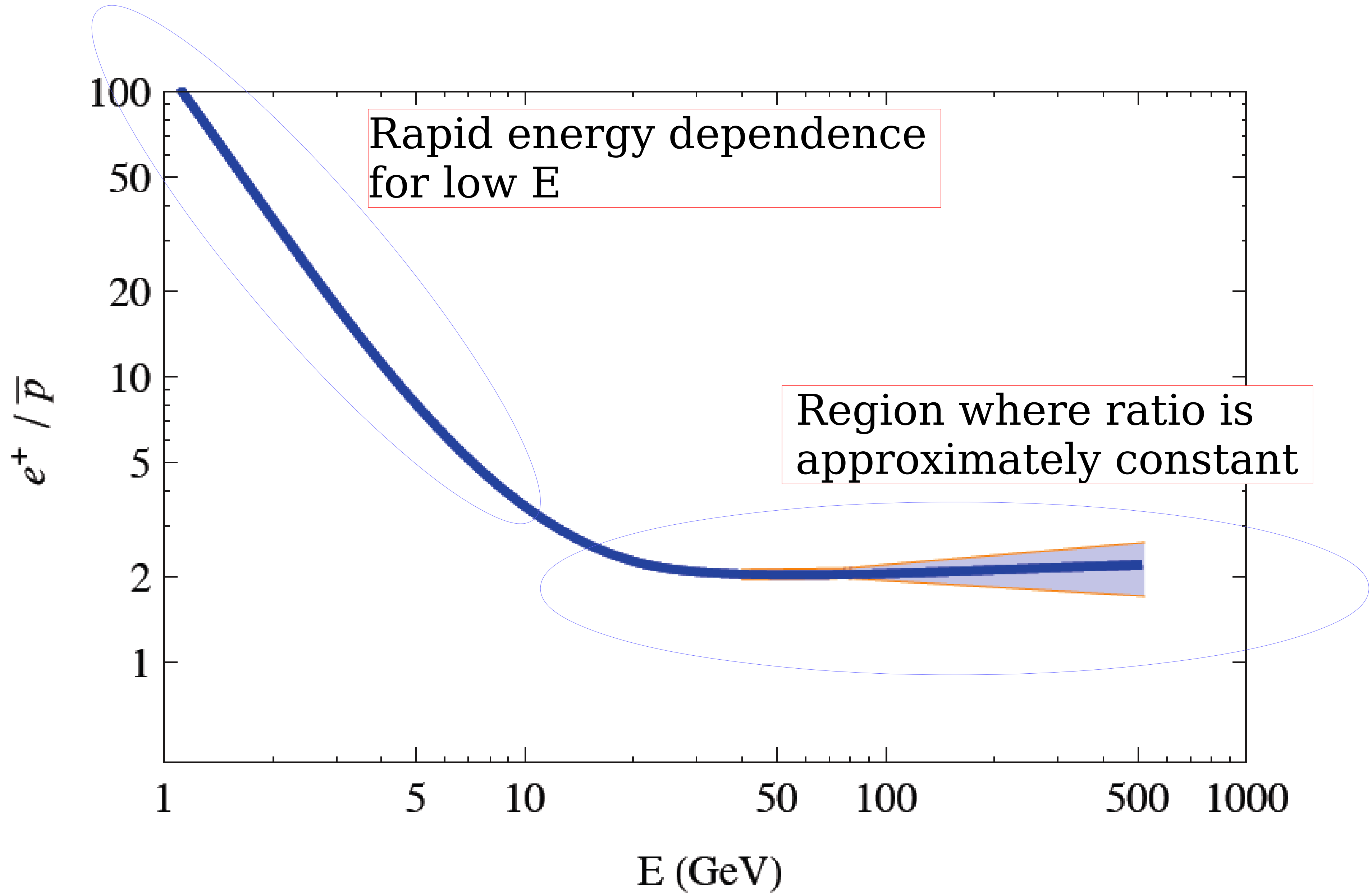
$$\frac{e^+}{\overline{p}} \simeq 2.04 \pm 0.04$$

$$\left.\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)}\right|_{E\in[30,400]\ \text{GeV}} \simeq (2.04 \pm 0.04) \times \left(\frac{E}{50\ \text{GeV}}\right)^{0.015\pm0.045}$$

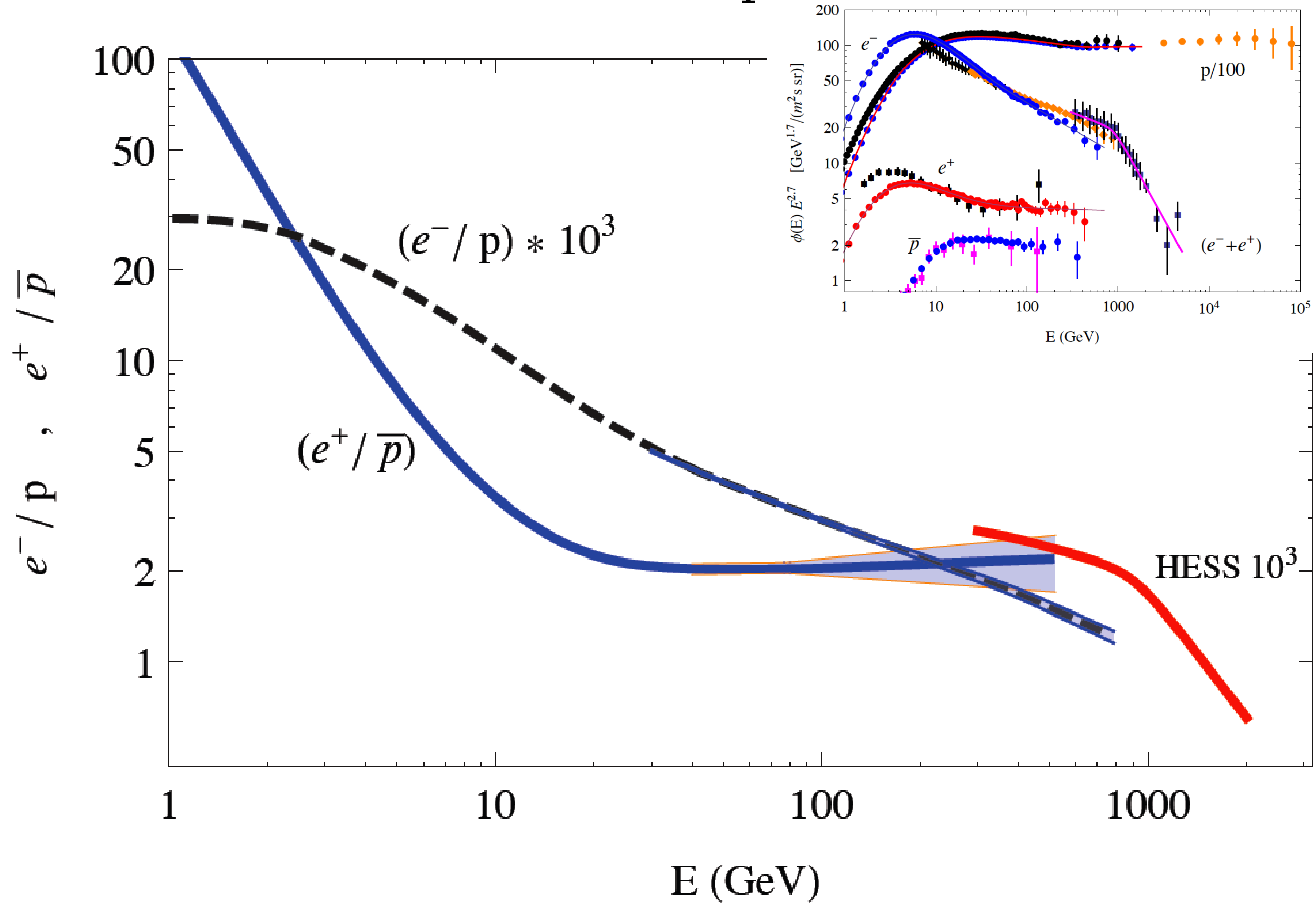
Approximately constant value
for the ratio positron/anti-proton

Does this
"mean" something ?

Ratio positron/anti-proton [Energy dependence]



Different behavior: positron/anti-proton
electron/proton



Very different behavior (high energy) $E > 30$ GeV

$e^+/\overline{p}$ Approximately flat

$$\left.\frac{\phi_{e+}(E)}{\phi_{\overline{p}}(E)}\right|_{E\in[30,400]\ \mathrm{GeV}} \simeq (2.04 \pm 0.04) \times \left(\frac{E}{50\ \mathrm{GeV}}\right)^{0.015\pm0.045}$$

e^-/p Falling rapidly with energy

$$\left.\frac{\phi_{e-}(E)}{\phi_{p}(E)}\right|_{E\in[30,300]\ \mathrm{GeV}} \simeq (3.95 \pm 0.10) \times 10^{-3} \left(\frac{E}{50\ \mathrm{GeV}}\right)^{-0.41\pm0.02}$$

Why ? (for E > 20-30 GeV)

$$\gamma_{e^+} \simeq \gamma_{\overline{p}}$$

$$\gamma_{e^+} \simeq \gamma_{\overline{p}} \approx \gamma_p$$

$$\gamma_{e^-} \simeq \gamma_p + (0.41 \pm 0.02)$$

Why ?

(for E > 20-30 GeV)

$$\gamma_{e^+} \simeq \gamma_{\overline{p}}$$

$$\gamma_{e^+} \simeq \gamma_{\overline{p}} \approx \gamma_p$$

Is there a
"physical reason",
or it is
"just a coincidence" ?

$$\gamma_{e^-} \simeq \gamma_p + (0.41 \pm 0.02)$$

Question :

Why the electron and proton CR spectra have different shapes ?

$$\gamma_{e^-} \simeq \gamma_p + (0.41 \pm 0.02)$$

[Commonly accepted] ANSWER:

[1.] The electron and proton spectra have the same shape at injection.

[2.] The propagation effects are different, because electrons have a much larger energy loss rate

Electron/Proton Ratio (E > 30 GeV)

$$\frac{\phi_{e^-}(E)}{\phi_p(E)} = \frac{Q_{e^-}(E)\ P_{e^-}(E)}{Q_p(E)\ P_p(E)} \approx E^{-0.4}$$

Propagation effect

$$\frac{Q_{e^-}(E)}{Q_p(E)} \approx \text{constant}$$

$$\frac{P_{e^-}(E)}{P_p(E)} \approx E^{-0.4}$$

Source properties

$$\frac{Q_{e^-}(E)}{Q_p(E)} \approx E^{-0.4}$$

$$\frac{P_{e^-}(E)}{P_p(E)} \approx \text{constant}$$

Energy losses

[synchrotron, Compton scattering]
strongly depend on the particle mass

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

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

Characteristic time
for energy loss

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

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

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

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

Assumption that the difference in shape between Electrons and protons is a propagation effect:

$$E \gtrsim 30 \text{ GeV}$$

$$\frac{T_{\rm loss}(E)}{T_{\rm escape}(E)} \propto \frac{\phi_{e^-}(E)}{\phi_p(E)} \propto E^{-0.41}$$

$$T_{\rm escape}(30 \text{ GeV}) \gtrsim T_{\rm loss}(30 \text{ GeV}) \simeq 30 \text{ Myr}$$

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

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

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

Injections of positrons and anti-protons are intimately connected

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

Dominant source of positrons:

$$\pi^+ \to \mu^+ + \nu_\mu \to [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu$$

Additional sources [kaon decay]

$$K^+ \to e^+ + \nu_e + \pi^\circ$$

$$K^+ \to \mu^+ + \nu_\mu \to [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu$$

$$K^+ \to \mu^+ + \nu_\mu + \pi^\circ \to [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu + \pi^\circ$$

$$K^+ \to \pi^+ + \pi^\circ \to \nu_\mu \to e^+$$

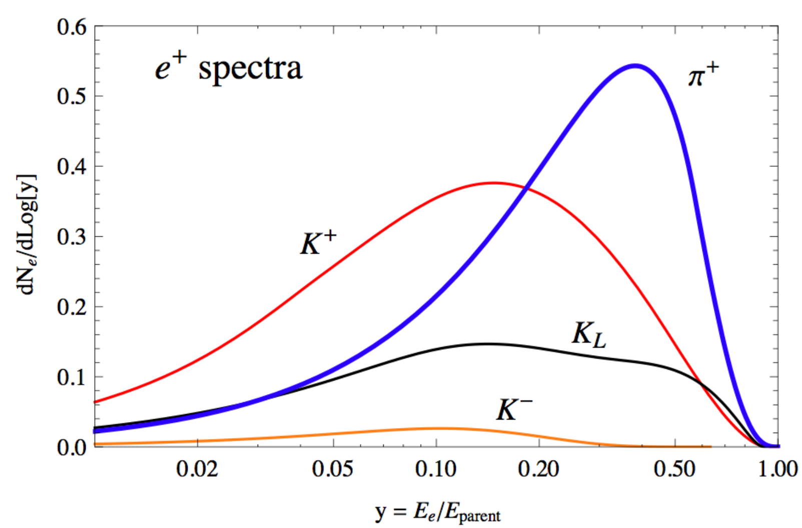
$$K^+ \to \pi^+ + \pi^\circ + \pi^\circ \to e^+ + \ldots$$

$$K^+ \to \pi^+ + \pi^+ + \pi^- \to e^+ + \ldots$$

$$K_L \to \pi^- + e^+ + \nu_e$$

$$K_L \to \pi^- + \mu^+ + \nu_\mu \to \pi^- + [e^+ \; \nu_e \; \overline{\nu}_\mu] + \nu_\mu$$

$$K_L \to \pi^+ + \pi^\circ + \pi^\circ \to e^+ + \ldots$$



Calculation of the "Local injection" of secondaries by the *"conventional mechanism"*

$$q_{\overline{p}}^{\rm loc}(E) = \phi_p(E) \otimes n_{\rm ism}(\vec{x}_\odot) \otimes \sigma_{\rm hadronic}[pp \to \overline{p} + \ldots]$$

$$q_{e^+}^{\rm loc}(E) = \phi_p(E) \otimes n_{\rm ism}(\vec{x}_\odot) \otimes \sigma_{\rm hadronic}[pp \to e^+ + \ldots]$$

Step 1: Measure the spectra of CR near the Earth.

Step 2: Correct for Solar Modulation effects to obtain the spectra in interstellar space

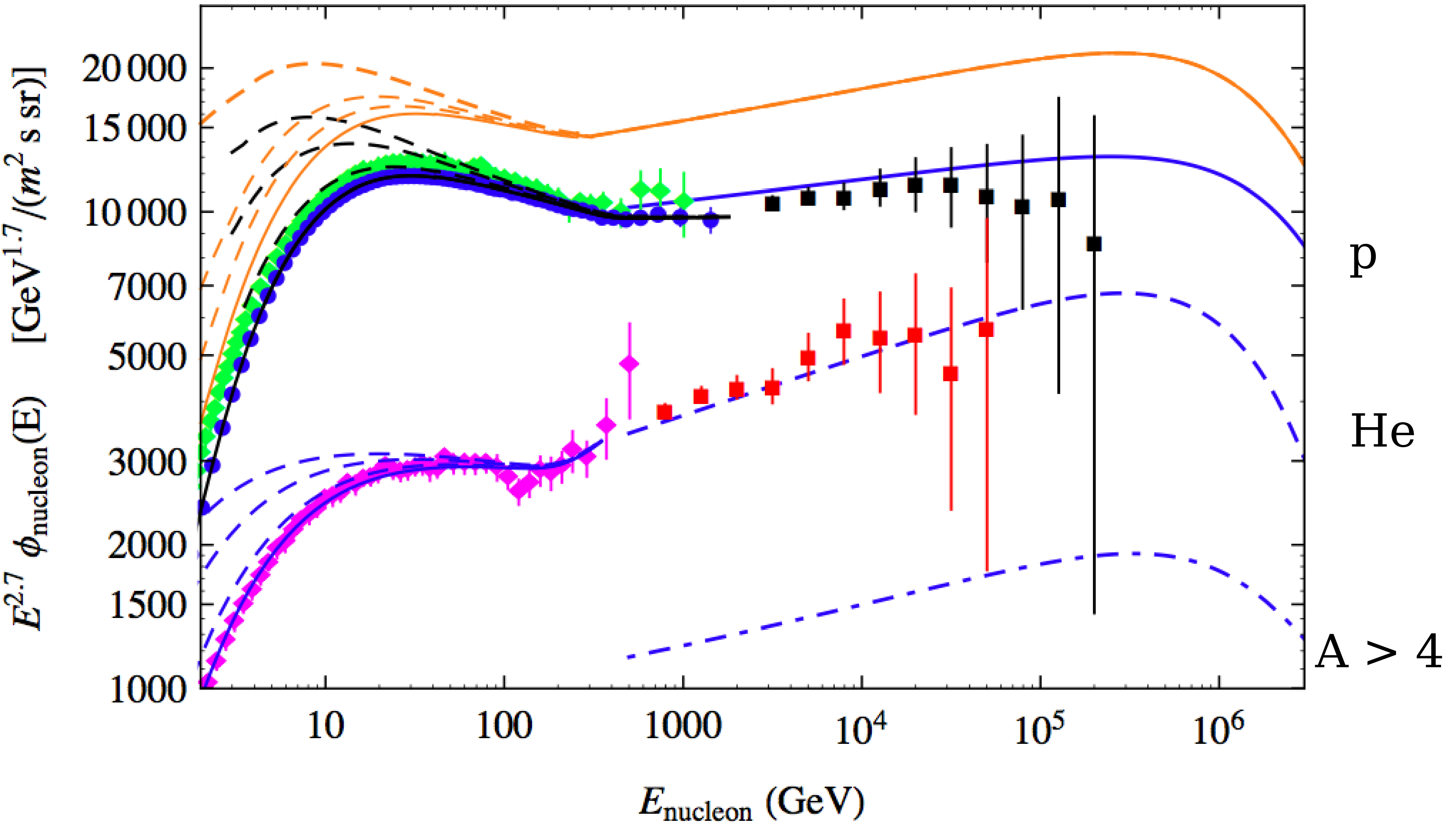
Step 4: Model the interaction to compute injection spectra of positrons + anti-protons.

$$q_j^{\rm loc}(E) = n_{\rm ism}\,(\vec{x}_\odot)\, f_p \int dE_0\; n_p^{\rm loc}(E_0)\;(\beta\, c)\;\sigma_{pp}(E_0)\;\frac{dN_{pp\to j}}{dE}(E, E_0)$$

$$+ (p + {\rm He}) + ({\rm He} + p) + ({\rm He} + {\rm He}) + \ldots$$

Nucleon Fluxes

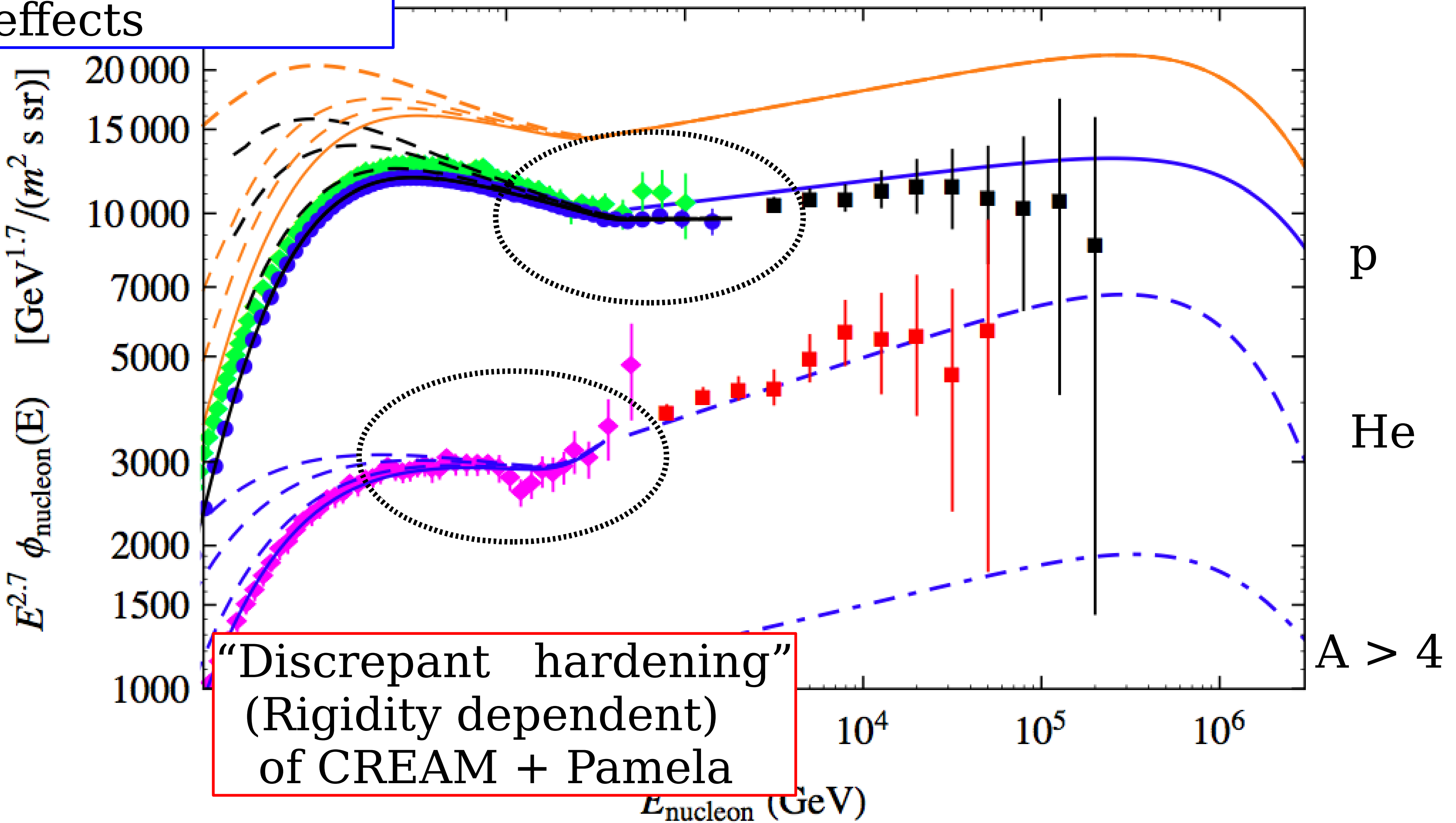
Pamela, AMS02, CREAM
HEA0 (for nuclei)



Nucleon Fluxes

Pamela, AMS02, CREAM
HEA0 (for nuclei)

“unfold”
Solar Modulation
effects



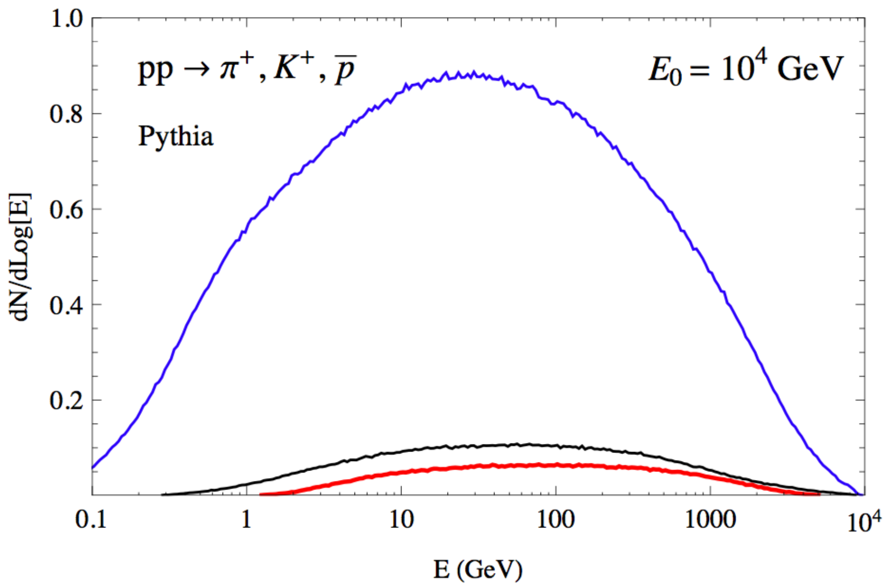
“Discrepant hardening”
(Rigidity dependent)
of CREAM + Pamela

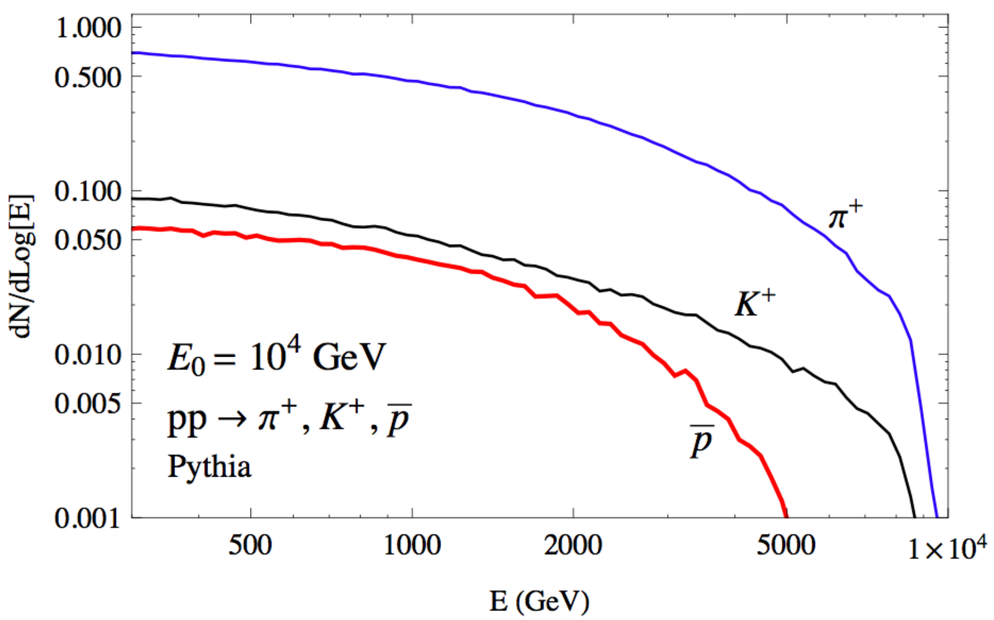
Particle production in hadronic collisions

$$pp \to \pi^+, \quad K^+, \quad \overline{p}, \quad \ldots$$

$$E_0 = 10^4 \text{ GeV}$$

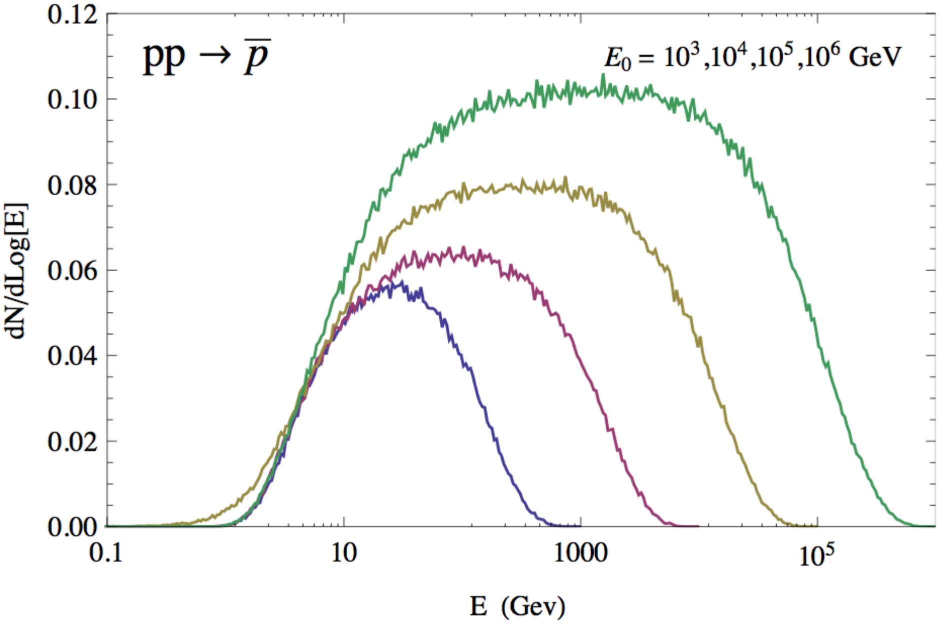
Example of a Montecarlo calculation with Pythia

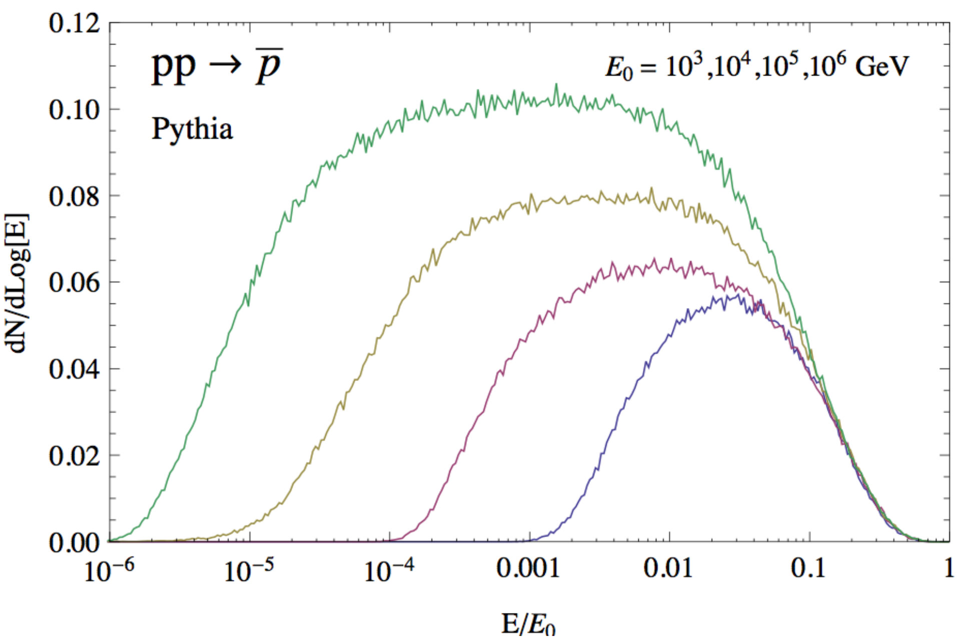


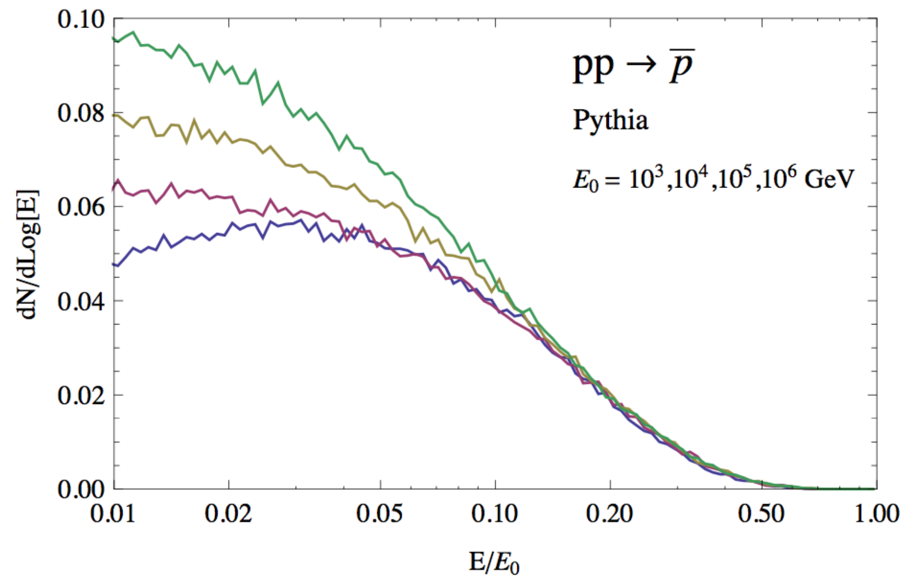


Pythia Montecarlo

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



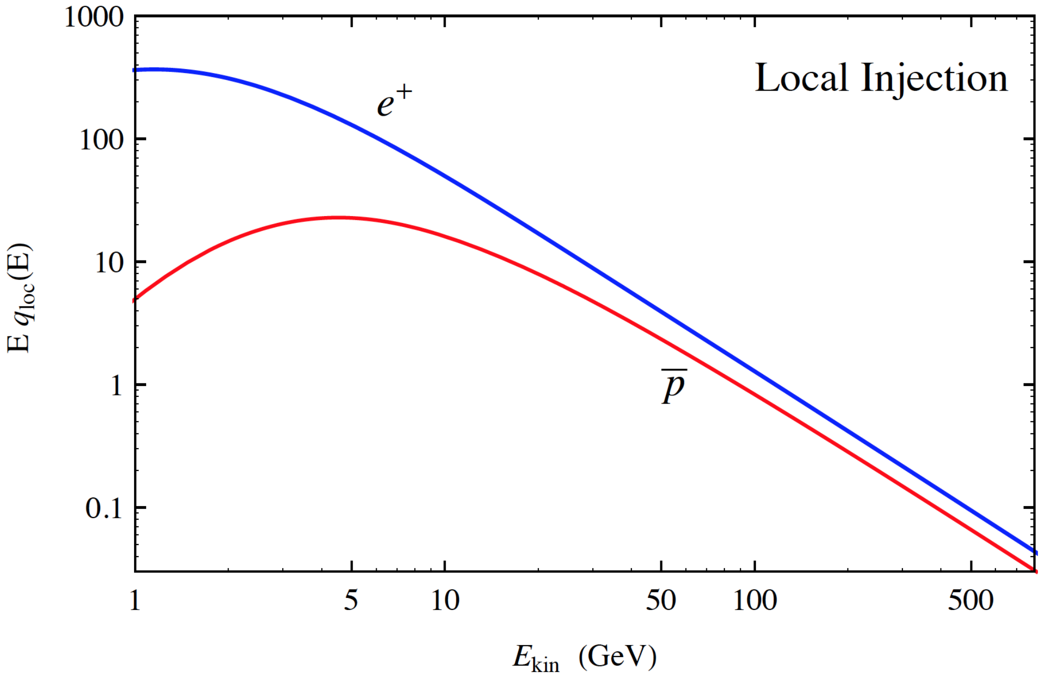




Note: approximate "scaling" of cross section

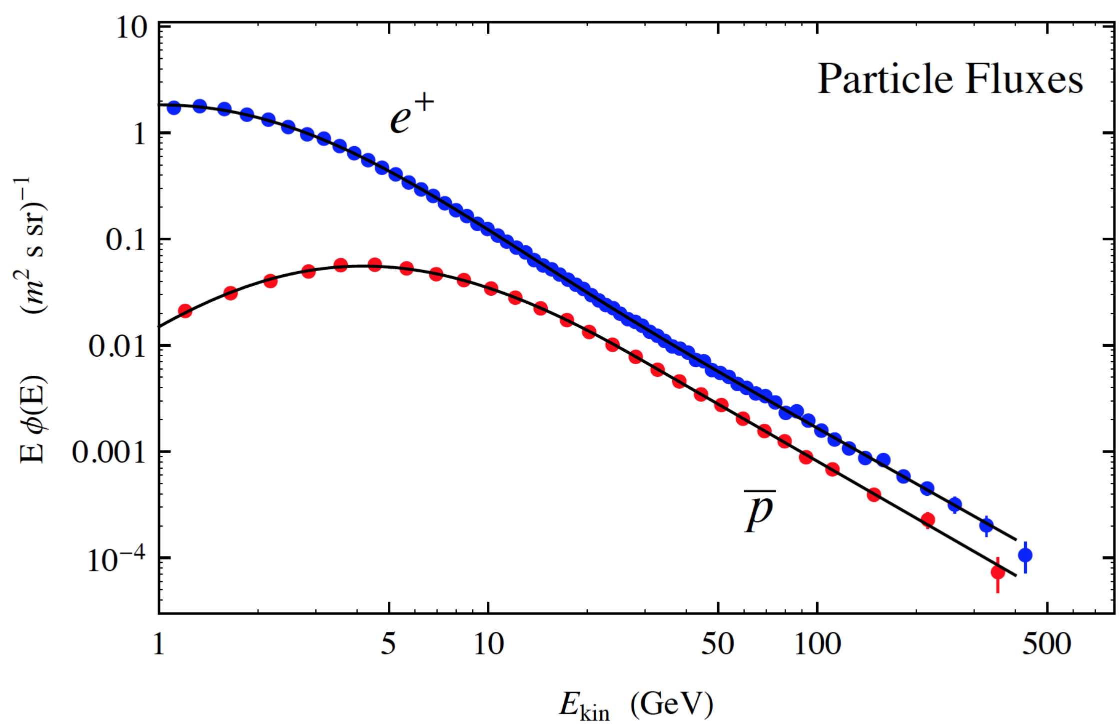
Power Law for projectiles

Power law for secondaries

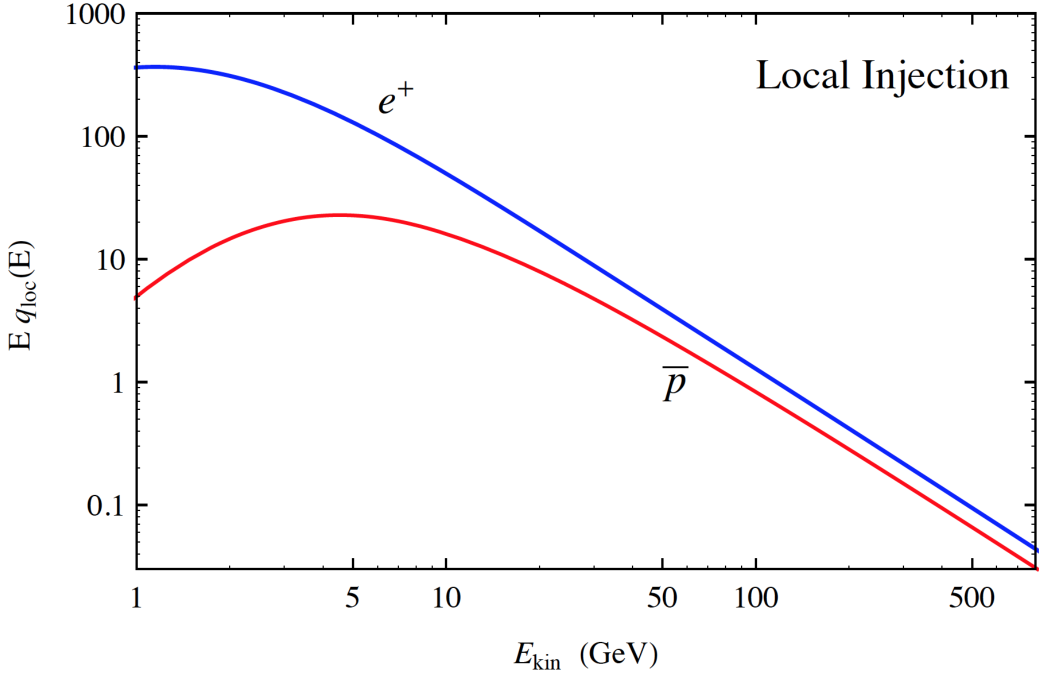


Injection

Observed Fluxes



"Striking" similarity



Injection of positrons and antiprotons

At *high energy*
approximately constant ratio
(consequence of scaling)

$$\frac{q_{\overline{p}}}{q_{e^+}} \simeq 1.80 \pm 0.5$$

$$\left.\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)}\right|_{E\in[30,350]\ \text{GeV}} \simeq 2.04 \pm 0.04$$

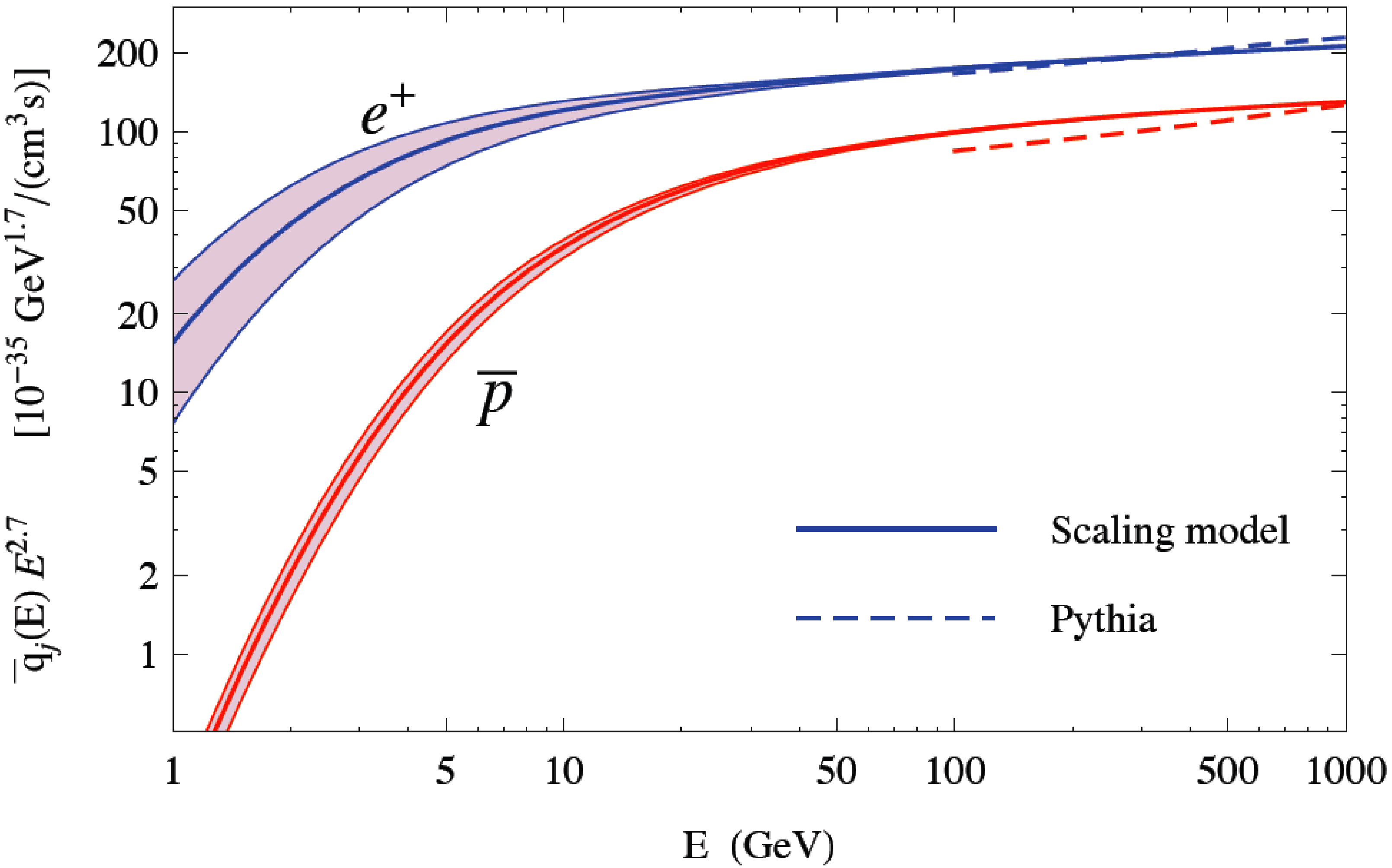
$$p + p \to p + p + p + \overline{p}$$

$$E_{i,\text{threshold}} = 7\ m_p$$

$$E_{f,\text{threshold}} = 2\ m_p$$

Low energy:
kinematical suppression of
antiproton production

“Local injection” for positrons and antiprotons

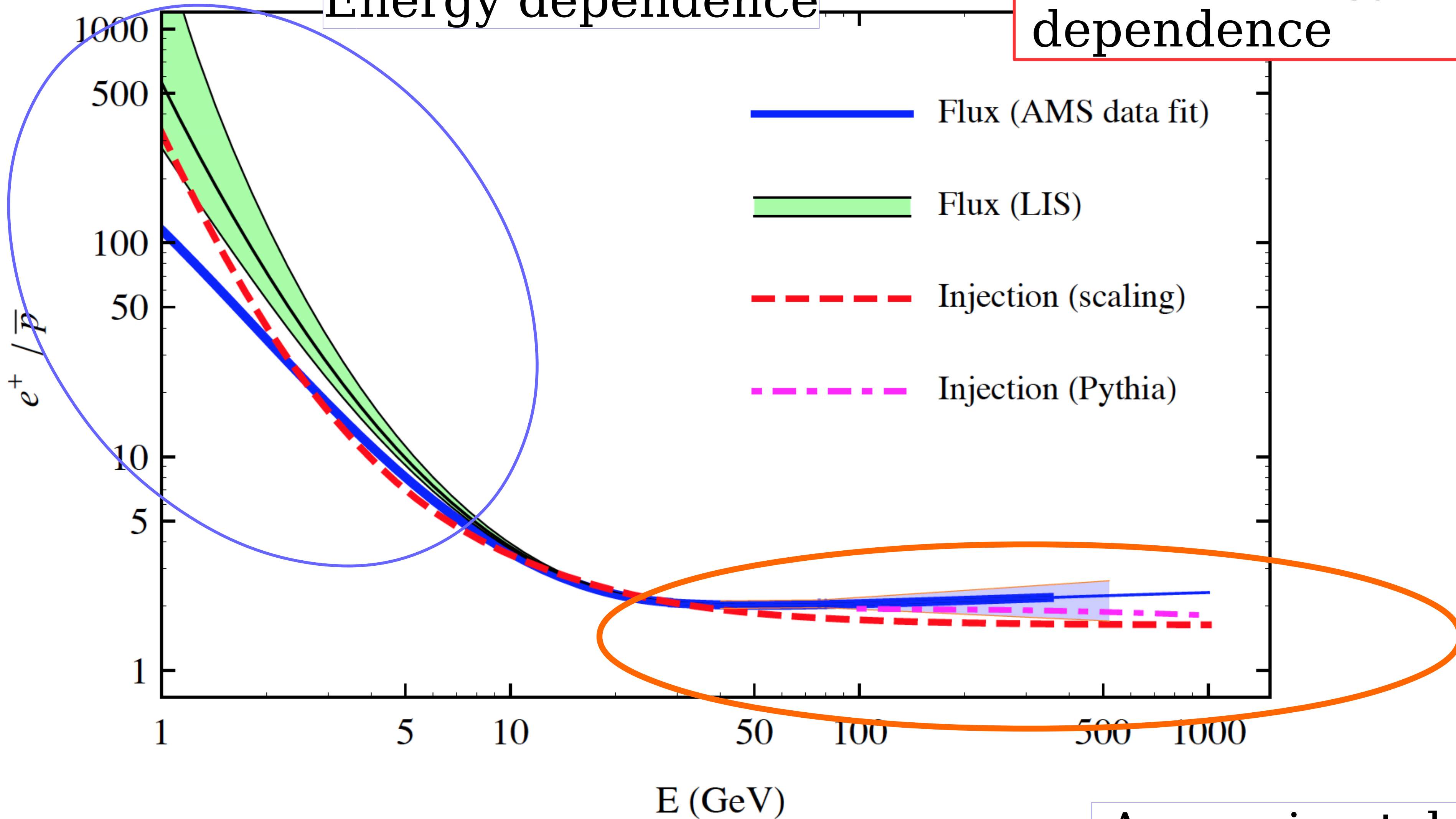


Ratios positrons/antiprotons

Ratio of Injections
Ratio of Fluxes

Similar energy
dependence

Rapid
Energy dependence



Approximately
constant value

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

The ratio positron/antiproton of
the injection is *(within errors)*
equal to the ratio of the observed fluxes

Does this result has a
"natural explanation" ?

$$\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} = \frac{\langle Q_{e^+}(E)\rangle \;\; P_{e^+}(E)}{\langle Q_{\overline{p}}(E)\rangle \;\; P_{\overline{p}}(E)}$$

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

"Natural Interpretation"

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

Secondary production
("local" production
spectrum)

$$\frac{P_{e^+}(E)}{P_{\overline{p}}(E)} \simeq 1$$

Equal propagation for antiprotons and positrons

$$\frac{P_{e^+}(E)}{P_{\overline{p}}(E)} \simeq 1$$

Equal propagation for antiprotons and positrons

Lifetime of positrons (and electrons) must be sufficiently short

$$T_{\rm age}(E = 400 \text{ GeV}) \lesssim 1 \text{ Myr}$$

The estimate of the residence time of cosmic rays is crucial

Alternative explanation:

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

is simply a (rather extraordinary) coincidence

$$Q_{e^+}(E) = Q_{e^+}^{\rm secondary}(E) + Q_{e^+}^{\rm new}(E)$$

$$Q_{\overline{p}}(E) = Q_{\overline{p}}^{\rm secondary}(E)$$

Example of High energy

"cancellation effect"

$$\frac{Q_{e^+}^{\rm extra}(E)\ P_{e^+}(E)}{Q_{\overline{p}}(E)\ P_{\overline{p}}(E)} \approx 2.0$$

Two “scenarios” seem to emerge:

Scenario 1 (“Conventional picture”)

1a. We assume (from the study of e-, p spectra) that propagation effects suppress electrons versus protons [with a marked energy dependence].

1b. If both positrons and antiprotons have a secondary origin, their ratio must strongly depend on energy

1c. The ratio e+/pbar is constant, therefore, A NEW POSITRON SOURCE is required to compensate for the suppression of positrons (due to energy losses)

[the equality $\frac{\phi_{e^+}(E)}{\phi_{\overline{p}}(E)} \approx \frac{q_{e^+}(E)}{q_{\overline{p}}(E)}$ is “just a coincidence”.]

Alternative possibility

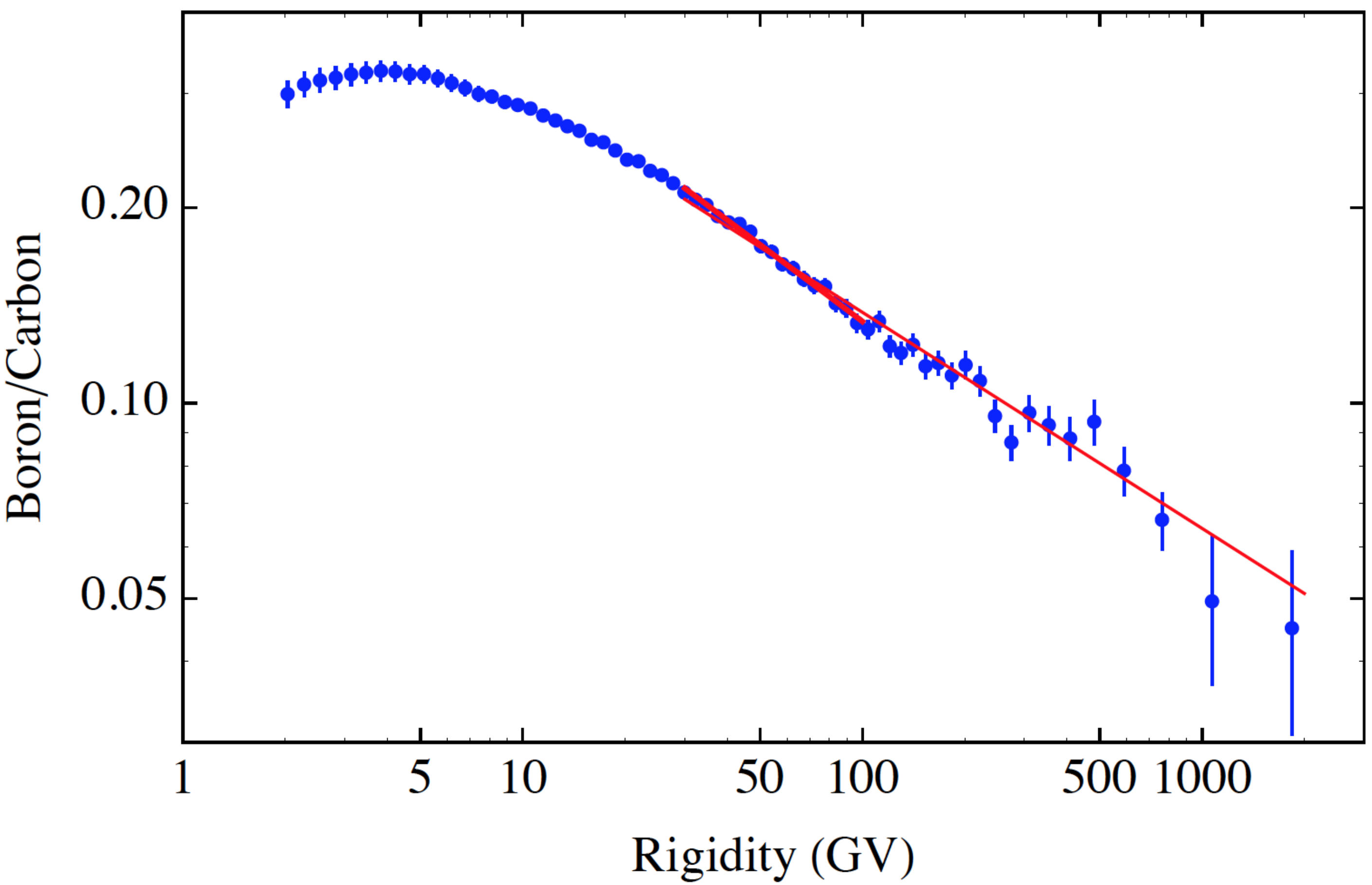
Scenario 2.

2a. Positrons and antiprotons are both of secondary origin.

2b. The observed positron/anti-proton ratio is approximately equal to the ratio at source.
Therefore positrons and anti-protons propagate in approximately the same way.
Escape is rapid, and energy losses negligible.

2c. The energy dependence of the e-/p fluxes is NOT the effect of propagation, but is formed at injection, in the CR accelerators.
[Perhaps because of energy losses inside the accelerators]

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



AMS02
data

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

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]

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

Compare the Loss time with the age inferred from the data on Boron/Carbon.

Determine the critical energy E^*

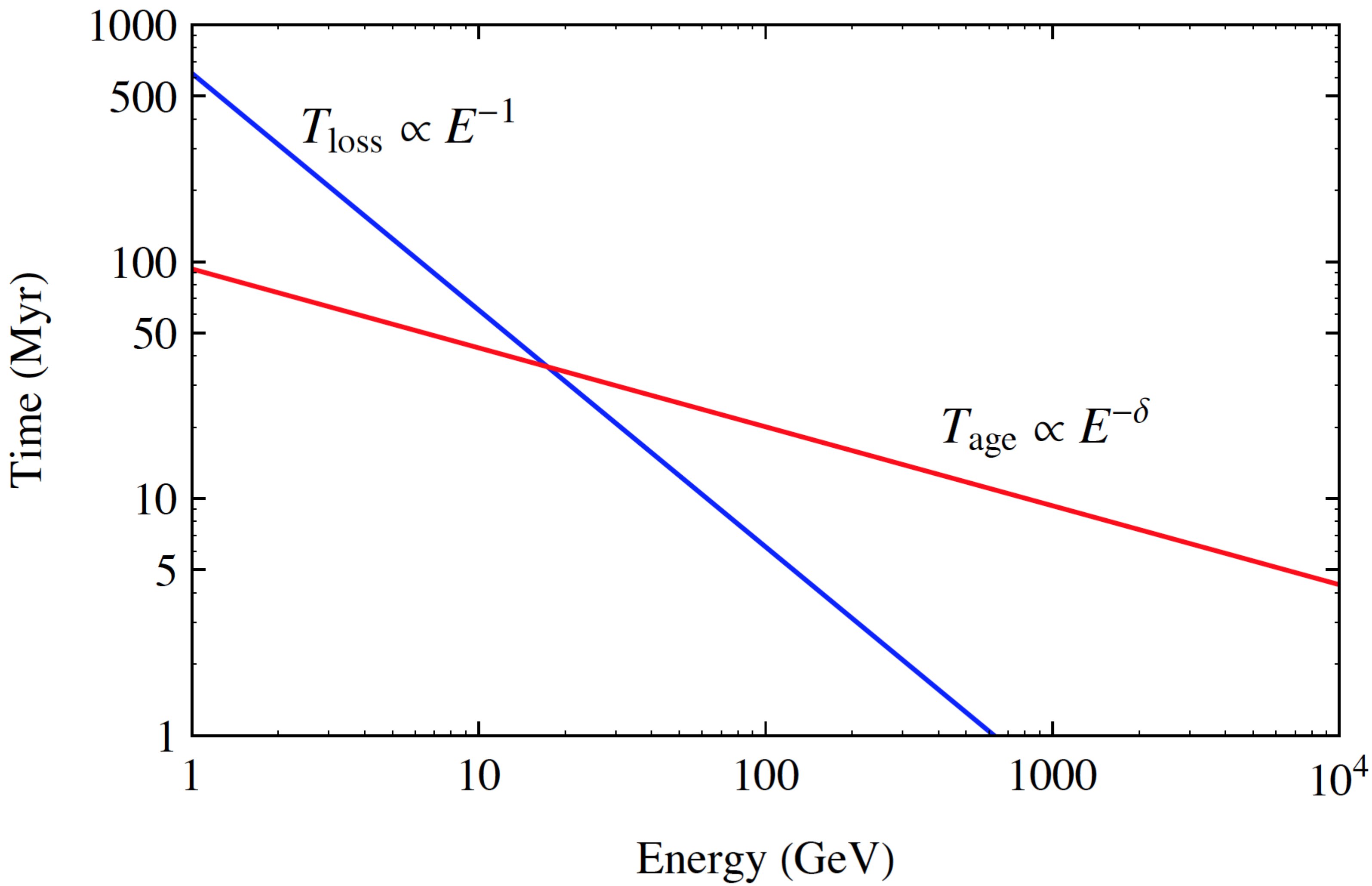
$$T_{\rm loss}(E^*) \simeq T_{\rm age}(E^*)$$

$E \lesssim E^*$ Energy losses are negligible

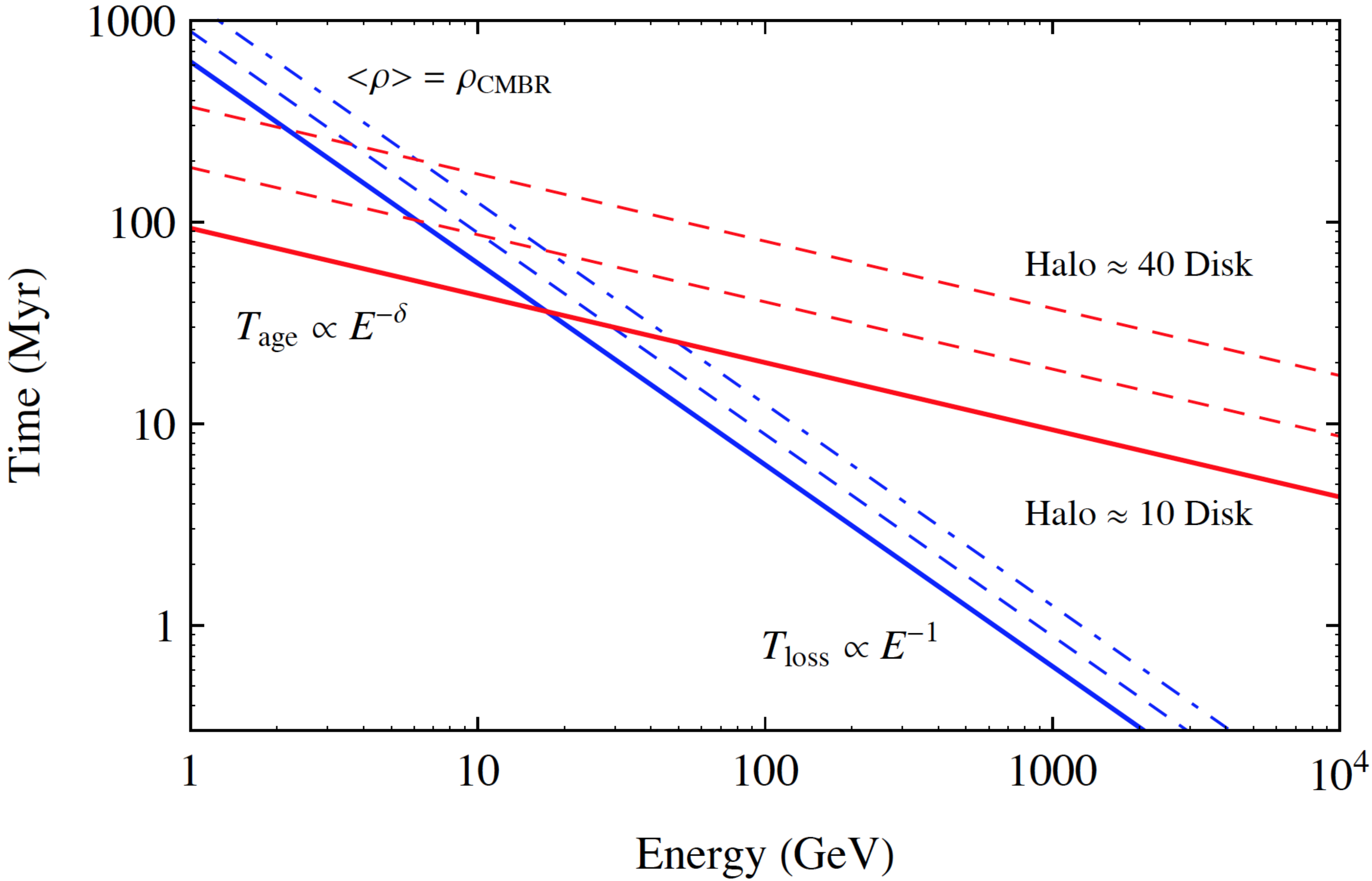
$E \gtrsim E^*$ Energy losses significant

Compare the electron Loss-time with the Age inferred from the Boron/Carbon Ratio:

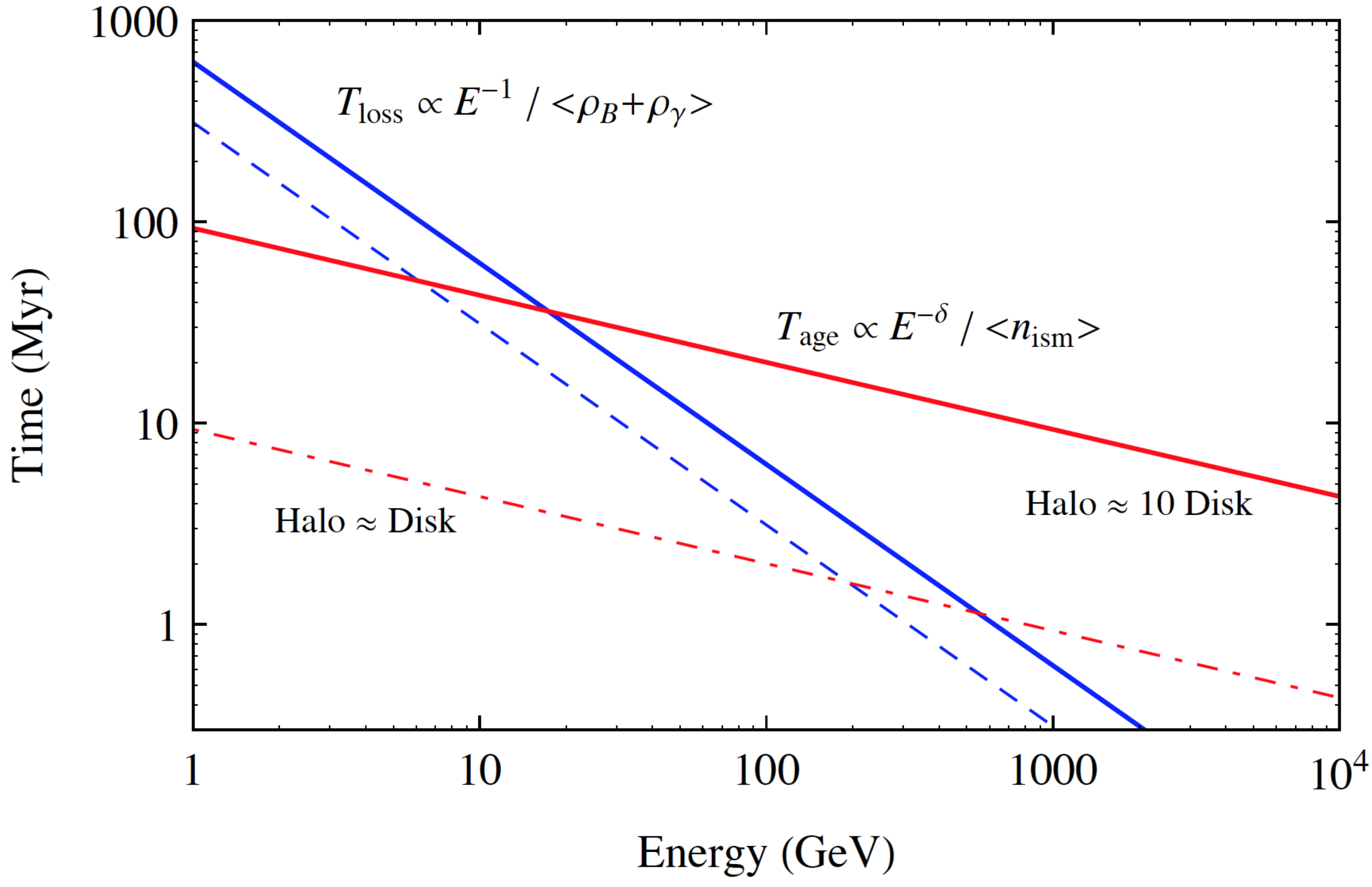
$$E^* \simeq 18\ \mathrm{GeV}\ \left[\left(\frac{\langle n_{\rm ism}\rangle}{0.1\ \mathrm{cm}^{-3}\rangle}\right)\ \left(\frac{0.5\ \mathrm{eV/cm}^3\rangle}{\langle \rho_B + \rho_\gamma^*\rangle}\right)\right]^{1/(1-\delta)}$$

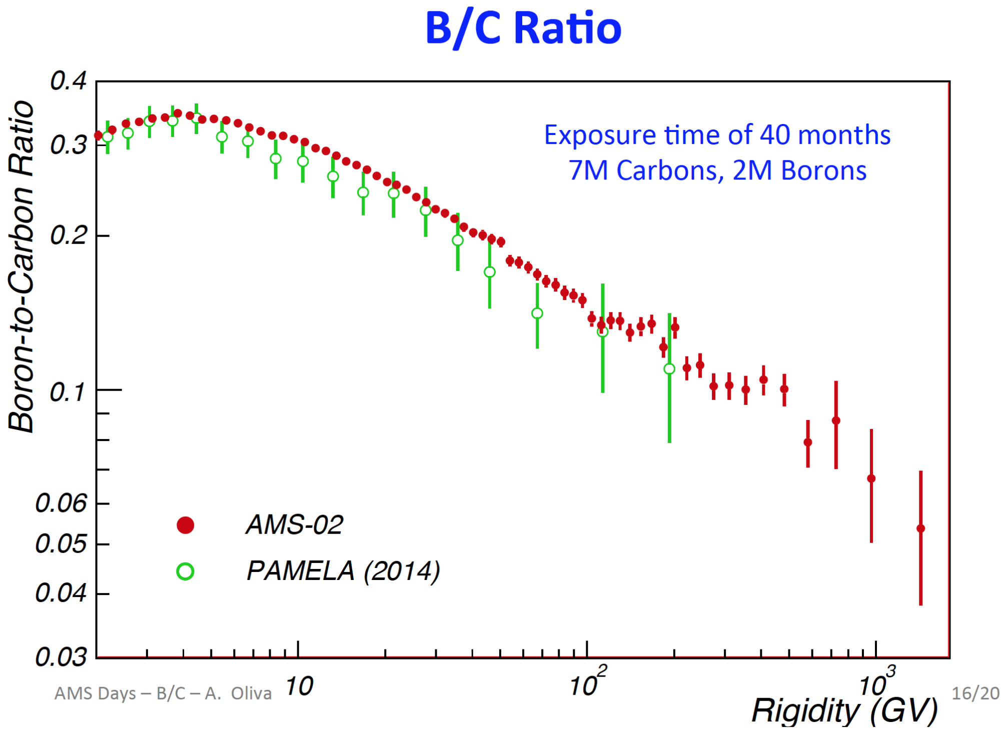


Making the containment volume of cosmic rays larger pushes the critical energy to lower values



Making the containment volume small
makes a high transition energy. But not easy.



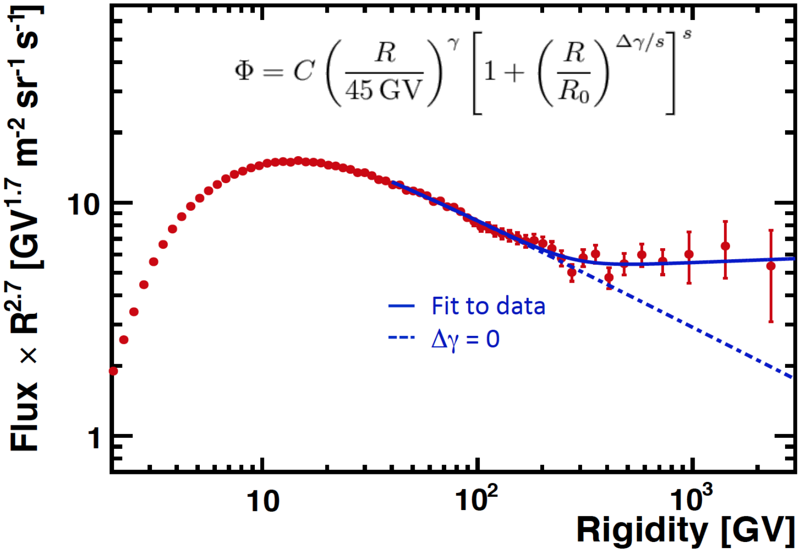


Secondary nuclei: Li, Be,

AMS02 preliminary data on Lithium

Fit of Lithium flux

Same model as the one used for proton and helium (double power law with smooth transition) between 45 GV and 3 TV:



→ Change of slope at the same range than for the one found for Proton and Helium.

A complex scenario is emerging

Probably production in sources is important

Antiproton Energy Spectrum

$$\phi_{\overline{p}}(E) \propto q_{\overline{p}}(E) \times T_{\mathrm{confinement}}(E)$$

$$T_{\mathrm{confinement}}(E) \propto E^{-\delta}$$

From secondary
to primary nuclei
B, Li

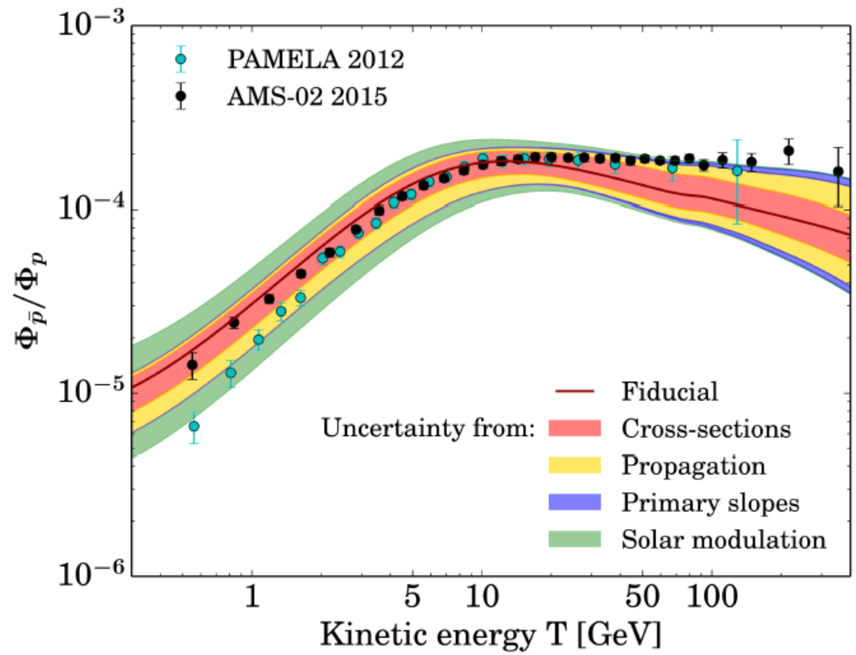
$$q_{\overline{p}}(E) \propto E^{-\gamma_0' + (\mathrm{small\ \ correction})}$$

$$\gamma_0'(E) \approx \gamma_0(10 \times E)$$

All models have predicted
an antiproton spectrum
softer than the observations

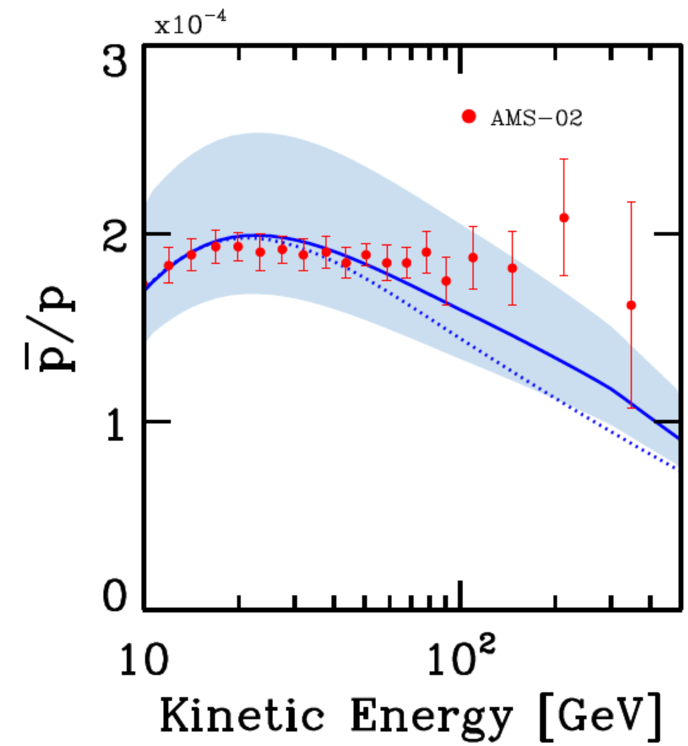
Antiproton/proton ratio

Claims in the recent literature that the recent data AMS02 data is consistent with the “standard scenario”



AMS-02 antiprotons, at last!
Secondary astrophysical component and immediate implications for Dark Matter

Gaëlle Giesen[a*], Mathieu Boudaud[b], Yoann Génolini[b], Vivian Poulin[b,c], Marco Cirelli[a], Pierre Salati[b], Pasquale D. Serpico[b]



Secondary antiprotons as a Galactic Dark Matter probe

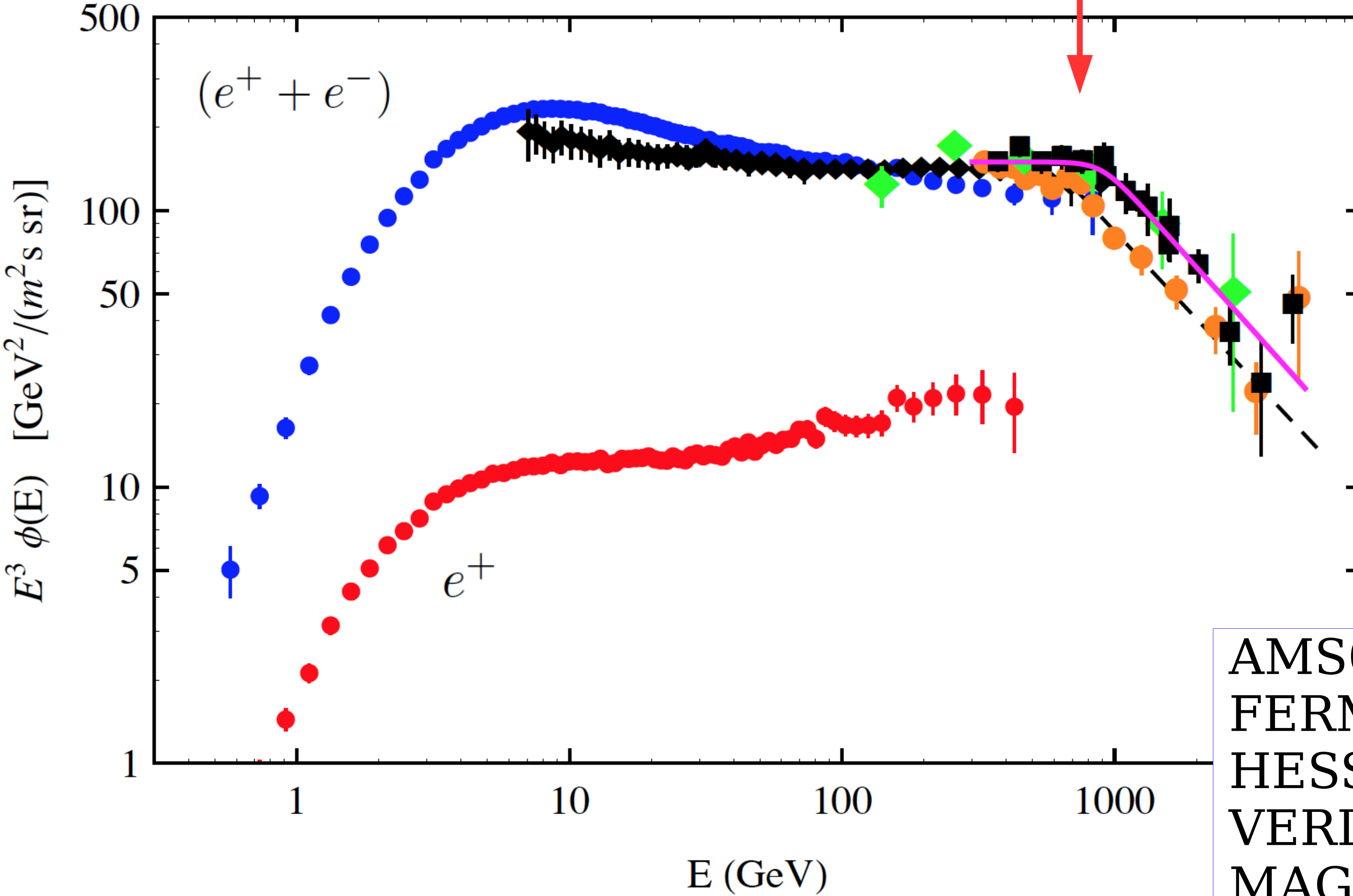
Carmelo Evoli[a] Daniele Gaggero[b] Dario Grasso[c]

Significant tension between data and models

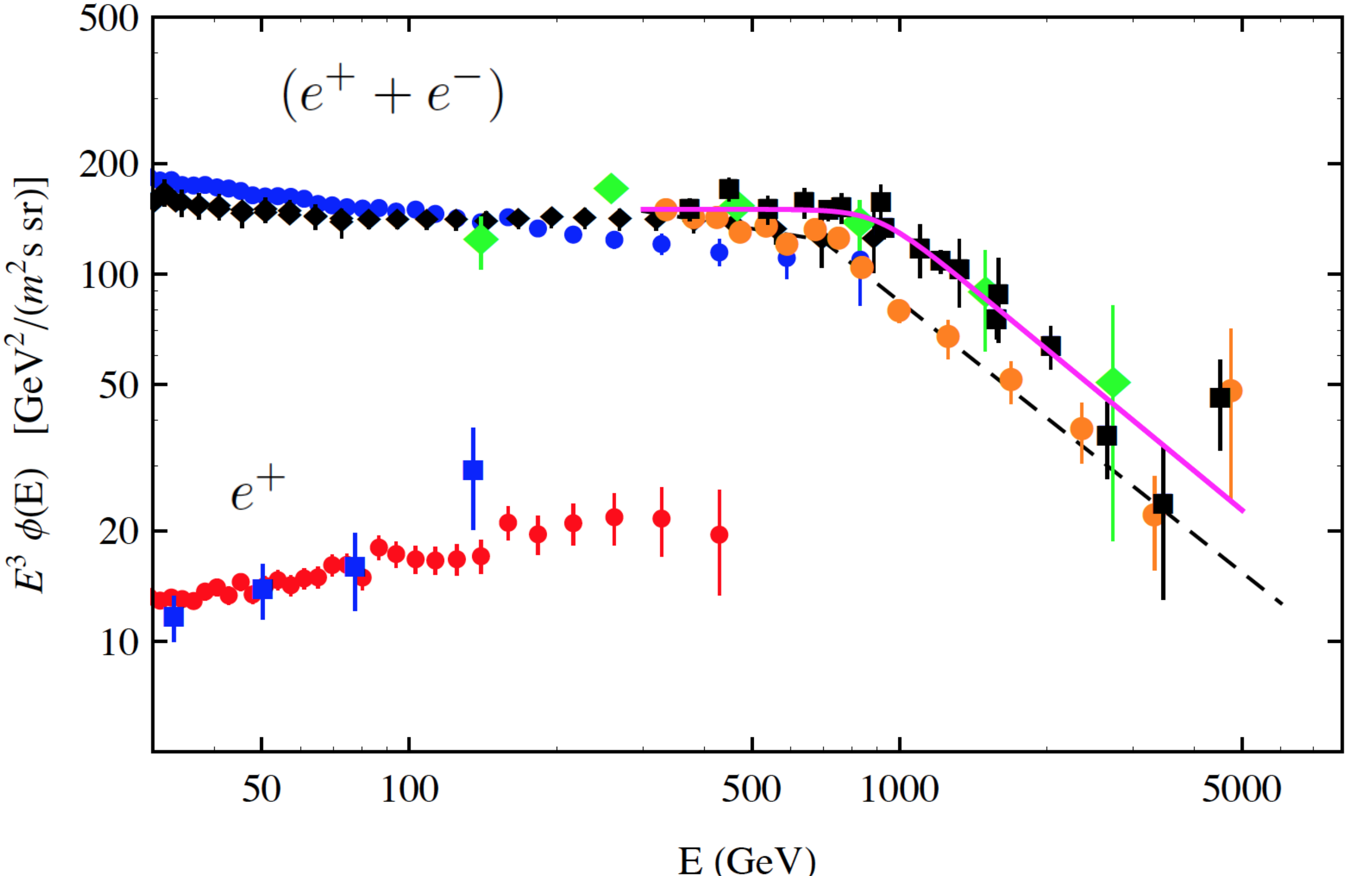
Tentative identification of the
transition energy as the energy that marks the
sharp softening identified by the Cherenkov telescopes

All electrons , Positron Spectra

Very Prominent spectral structure



AMS02
FERMI-LAT
HESS
VERITAS
MAGIC



AMS02
FERMI-LAT
HESS
VERITAS
MAGIC

HESS fit

$\gamma_1 \simeq 3.0$

$\gamma_2 \simeq 4.1$

$E_{\rm break} = 900$ GeV

MAGIC fit

$\gamma_1 \simeq 3.2 \pm 0.01$

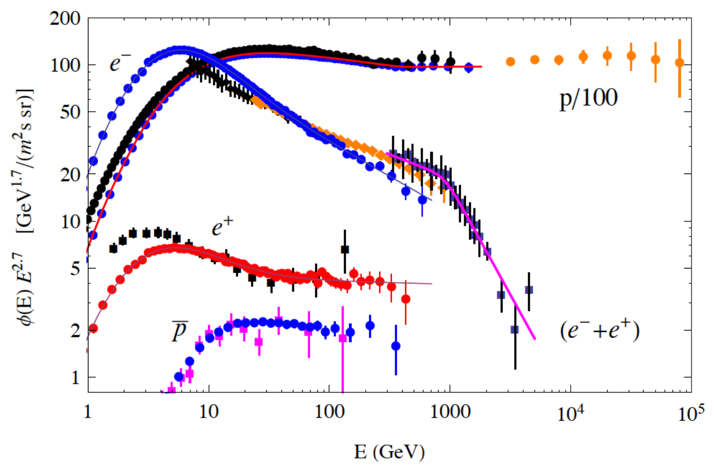
$\gamma_2 \simeq 4.1 \pm 0.01$

$E_{\rm break} = 710 \pm 40$ GeV

Critical Energy E^*

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

[For electrons with $E > E^*$
energy losses are important]



Identify the softening in the all electron spectrum
and the critical energy

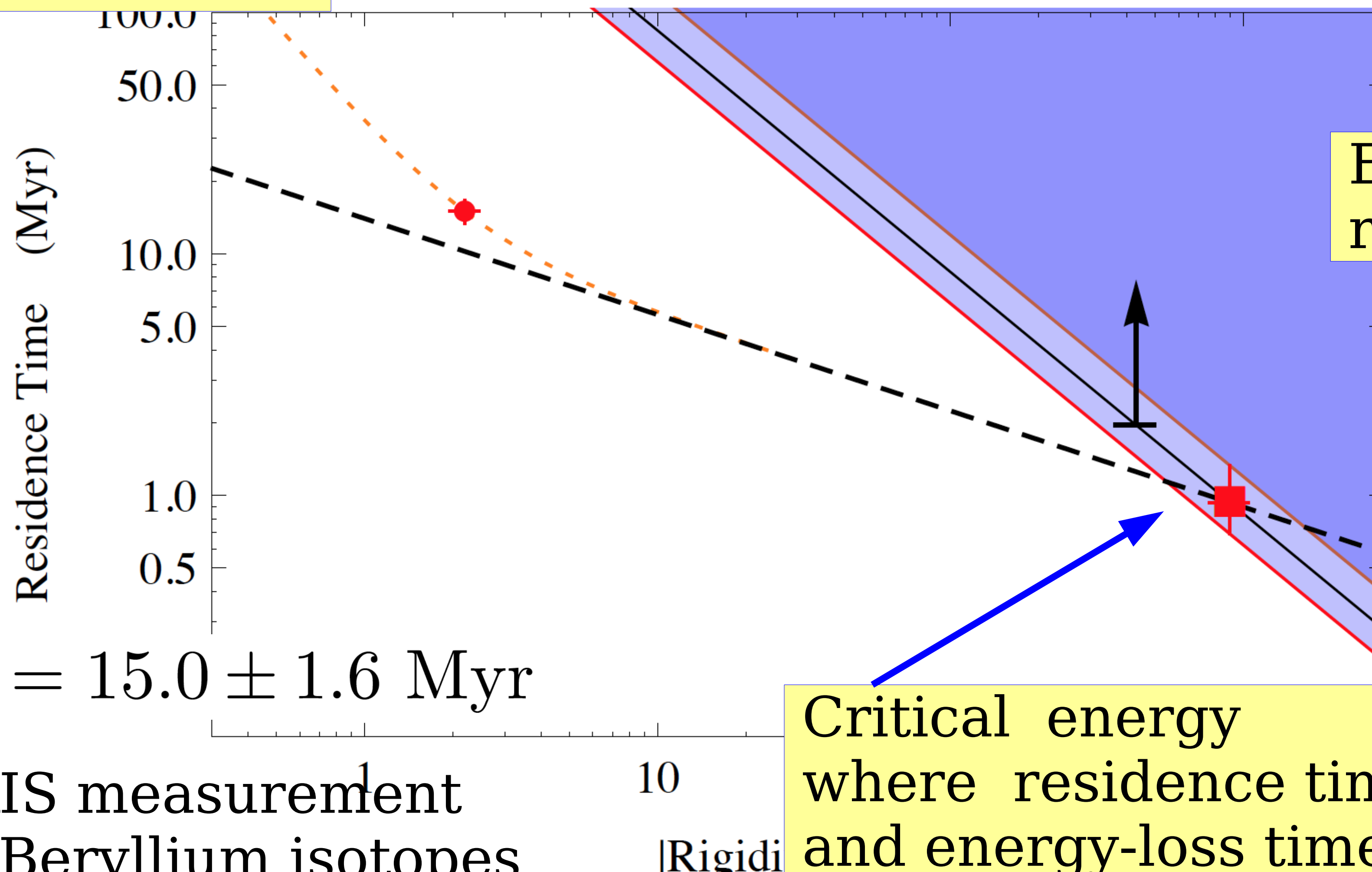
$$E^* = E_{\rm HESS} \simeq 900 \text{ GeV}$$

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

Range depends on volume
of confinement

Constraints on the residence time of $e^{\pm}$

Beryllium-10 Measurement



Excluded region

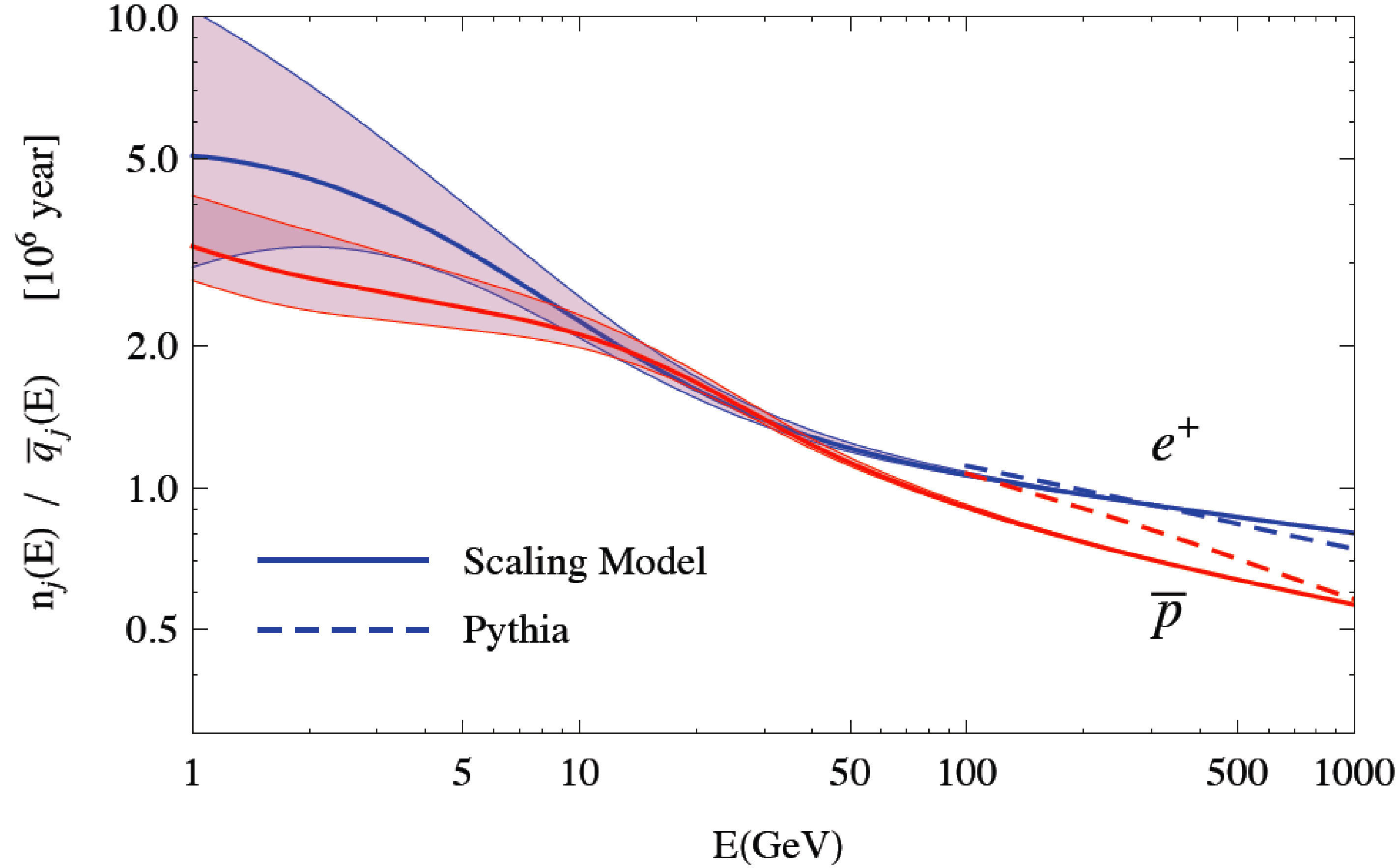
$$\tau_{\text{esc}} = 15.0 \pm 1.6 \text{ Myr}$$

Critical energy where residence time and energy-loss time are equal

CRIS measurement Of Beryllium isotopes

S.P. Ahlen *et al.* "Measurement of the Isotopic Composition of Cosmic-Ray Helium, Lithium, Beryllium, and Boron up to 1700 MEV per Atomic Mass Unit" Astrophys. J. **534**, 757 (2000).

$$\frac{n_{\overline{p}}^{\rm loc}(E)}{q_{\overline{p}}^{\rm loc}(E)} = \tau_{\overline{p}}(E) \qquad \frac{n_{e^+}^{\rm loc}(E)}{q_{e^+}^{\rm loc}(E)} = \tau_{e^+}(E)$$



Characteristic time for antiprotons and positrons: of order of a few Million years

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Report of Referee A -- DV11636/Lipari

This is a very interesting and provocative paper which definitely deserves publication. I have a few minor comments, listed below, but I think the key point is that the author forces us to think again about the interpretation of the cosmic ray data on antiparticles and makes some very interesting observations. It will certainly not be universally accepted, but the work is scientifically sound and will stimulate a welcome debate. I have no hesitation in recommending publication in PRD.

Report of Referee B -- DV11636/Lipari

The manuscript points out that the spectra of positrons and antiprotons are curiously similar, and both are similar to the proton spectrum, at least at high energies. This argument is then used to toy with the idea that both positrons and antiprotons may be secondary products of cosmic ray interactions. In this scenario, no additional source of positrons would be required.

[....]

although it is legitimate to noticing a numerical coincidence, in order to transform it into a physical model one needs to propose at least one scenario in which the alternative model in question can be implemented and possibly ruled out. This is not the case in this manuscript, as I discuss below. In order to make the manuscript suitable for publication, the author should elaborate on possible avenues in which not only the positrons and antiprotons, but also secondary-to-primary ratios (e.g. B/C) are or can be accommodated.

[....]

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------------------------------------------------------------------
Second  Report of Referee B -- DV11636/Lipari
------------------------------------------------------------------
[...]
The fact that the spectra of electrons and protons are required to
be different is an implication of the view proposed in this
manuscript, but it is rather puzzling for any rigidity dependent
electromagnetic model of acceleration. Can the author think of any
practical way that the difference in the spectra could be
accomplished?
[...]
```

Third Report of Referee B -- DV11636/Lipari

The author addressed all my comments and I think that the paper should now be published in Phys. Rev. D.

[...]

I think that this paper is a well written, fair insight into the problem of CR transport, and will hopefully stimulate the community to question the bases of the so-called standard model, either to make it stronger or to come up with equally strong alternatives.

How can one discriminate between these two scenarios ?

1. Different cutoffs in the spectra of positrons and electrons would falsify scenario 1.

2. Study the space and energy distributions of the e+- component of cosmic ray in the Galaxy With gamma astronomy

3. Study the mechanisms in the CR sources (assuming that they are SuperNovae)

Conclusions:

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

Crucial crossroad for the field.

Most commonly accepted view:
The hard positron flux requires an "extra component"
Sources of relativistic positrons [Pulsars, DM annihilation] exist.

The similarity of the antiproton and positron fluxes:

[Constant ratio $e^+/\overline{p} \approx 2$ at high energy (E > 30 GeV]
[Kinematical suppression of antiprotons at low energy]
suggests a secondary origin for both fluxes.
Viable solution, but the implications are profound.

It is very important to clarify what is the correct explanation

Preprint: astro-ph/1608.02018

Author: Paolo Lipari

"Interpretation of the cosmic ray positron and antiproton fluxes"

Recently accepted in Phys.Rev. D

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