Can we explain AMS-02 antiproton and positron excesses simultaneously by nearby supernovae without pulsars nor dark matter?

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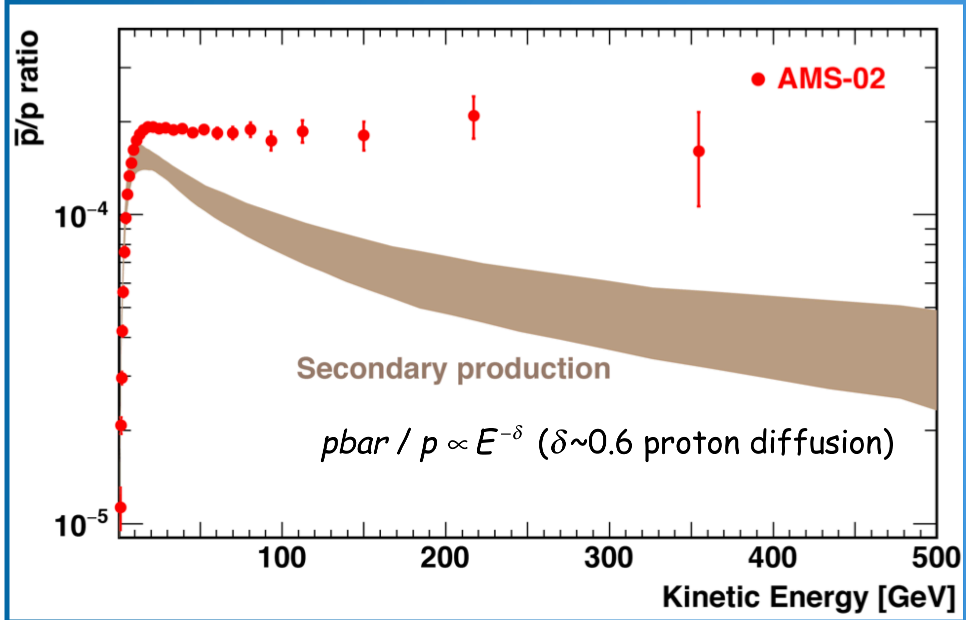
Abstract 1/2

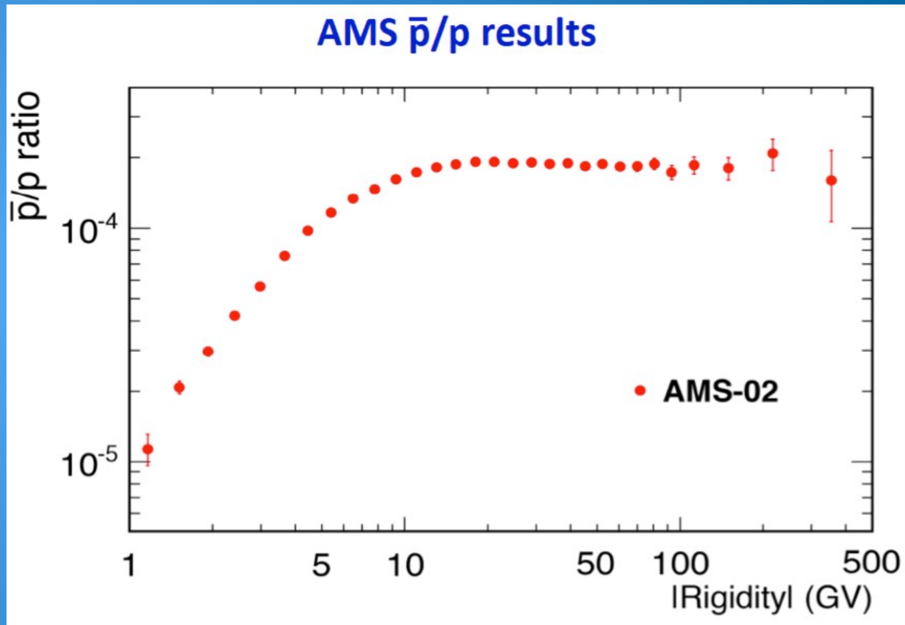
- We explain the excess of the antiproton fraction recently reported by the AMS-02 experiment by considering collisions between cosmic-ray protons accelerated by a local supernova remnant (SNR) and the surrounding dense cloud.
- The same "pp collisions" provide the right branching ratio to fit the observed positron excess simultaneously without a fine tuning.

Abstaract 2/2

- The supernova happened in relatively lower metalicity than the major cosmic-ray sources. The cutoff energy of electrons marks the supernova age of $\sim 10^5$ years, while the antiproton excess may extend to higher energy. Both antiproton and positron fluxes are completely consistent with our predictions done in Fujita, Kohri, Yamazaki and Ioka (2009).

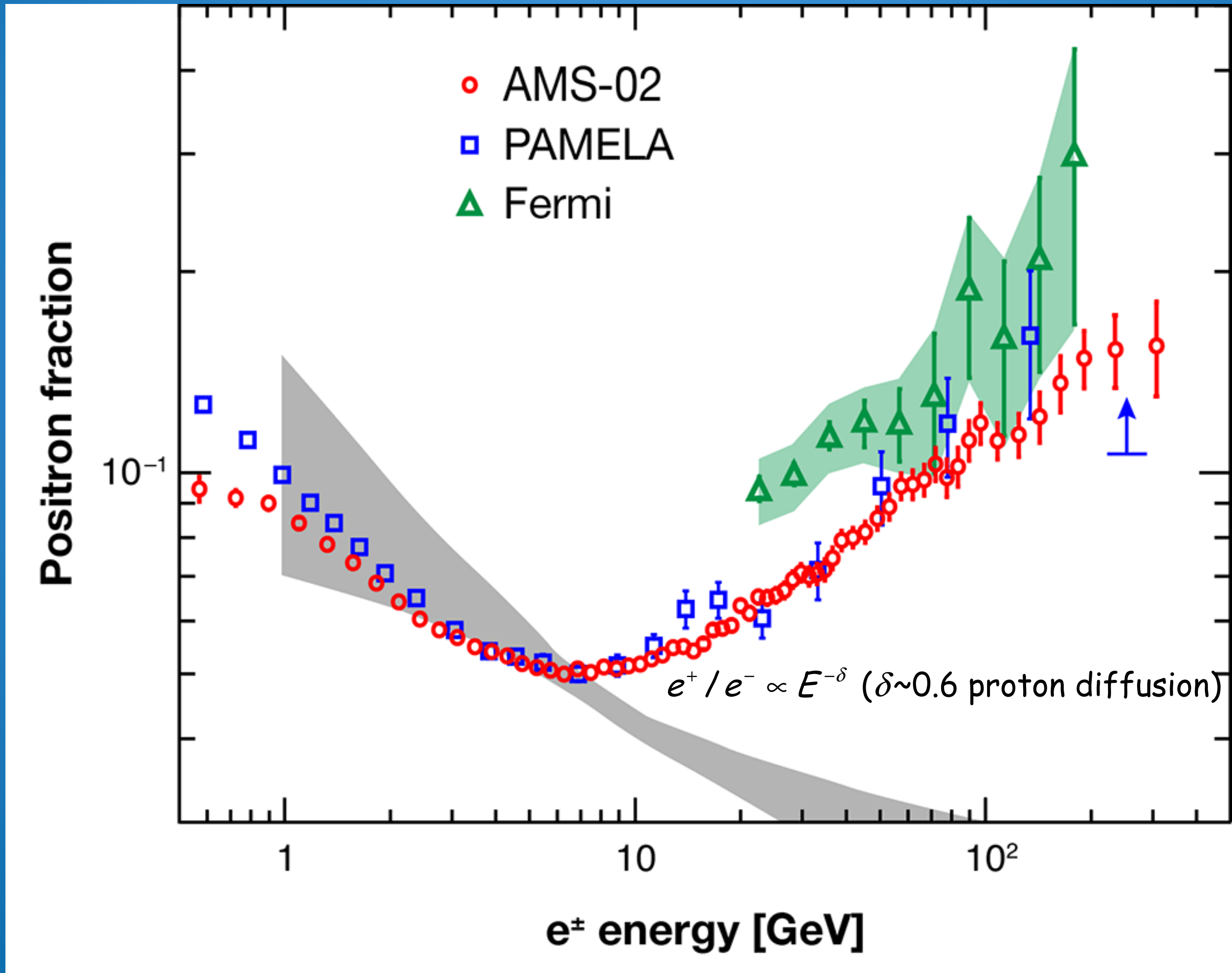
AMS-02 antiproton data





AMS DAYS AT CERN, 15th -17th April, 2015

AMS-02 positron fraction



AMS-02 collaboration, M. Aguilar *et al*. Phys. Rev. Lett. 110, 2013

Diffusion equation

Diffusion model

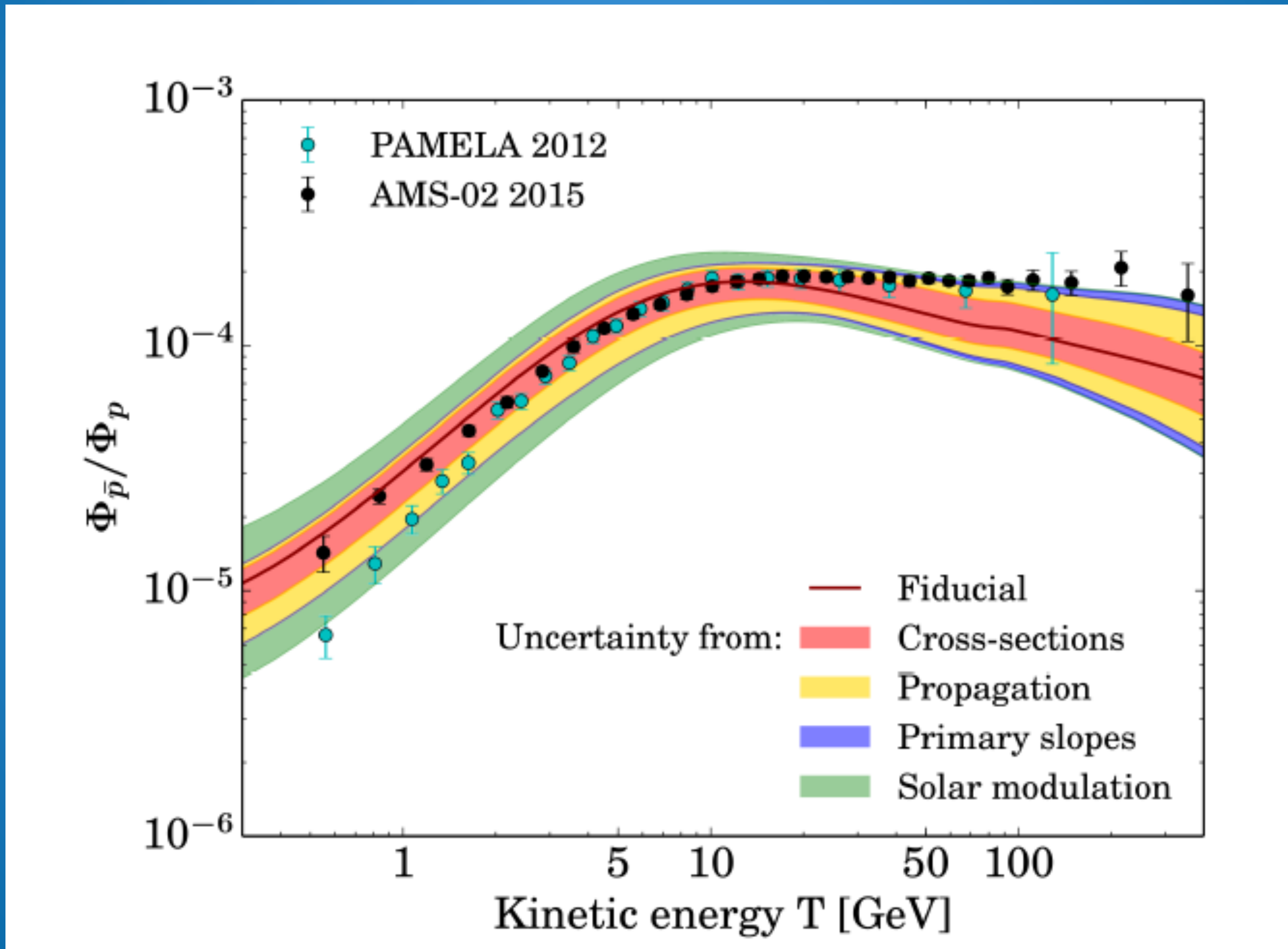
$$\frac{\partial}{\partial t} f(E,\vec{x}) = K(E)\nabla^2 f(E,\vec{x}) + \frac{\partial}{\partial E}[b(E) f(E,\vec{x})] + Q(E,\vec{x})$$

Flux

$$\Phi_{e^+}^{(\mathrm{DM})}(E,\vec{x}_\odot) = (c/4\pi) f(E,\vec{x}_\odot)$$

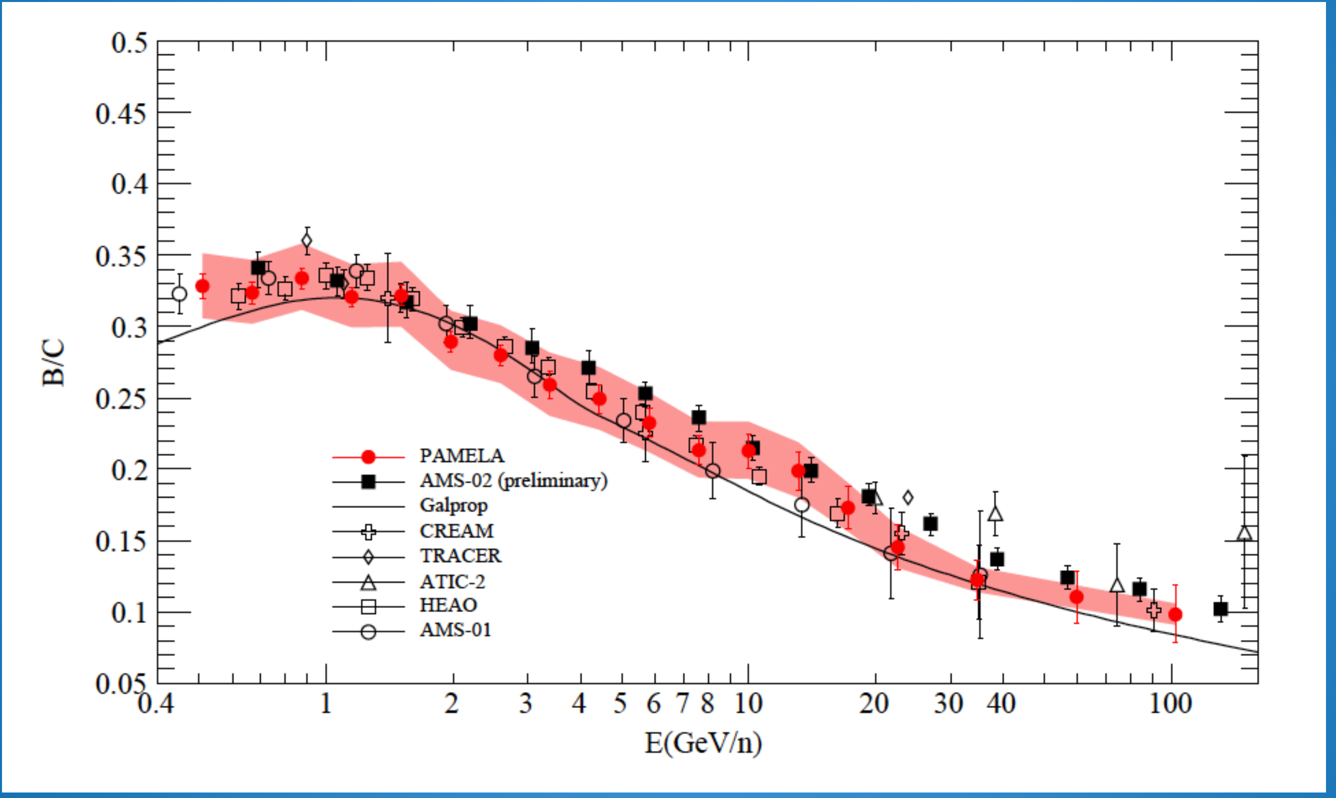
$$r_{\mathrm{propagation}} \sim \sqrt{EK(E)/b(E)} \sim 0.7\,\mathrm{kpc}(E/\mathrm{GeV})^{-0.2}$$

Combined errors?



G. Giesen et al, (2015)

B/C and diffusion coefficient fitting



δ~ 1/3 – 1/2

AMS Collaboration (20140

Astrophysical origin?

- Supernova Remnants (SNRs)
  i. A local and old unknown SNR with $n_s \leqq 2$ in radiative phase

     Fujita, Kohri, Yamazaki, Ioka (2009)(2015)

  ii. Statistically-known SNRs with (re)acceleration of secondary positron

     Ahlers, Mertsch, Sarkar (2009)

- Pulsar

Only for positron and electron, see Hooper, Blasi and Serpico (2008)

Various Scales

- Cooling time (diffusion time)

$$t_{\rm cool} \sim E / b(E) \sim 10^{6}\,{\rm yrs}({\rm E}/10^{2}{\rm GeV})^{-1}$$

$$\text{with } b(E) \sim 10^{-16}\,{\rm GeVs}^{-1}({\rm E}/10^{2}{\rm GeV})^{2}\left[({\rm B}/7\mu{\rm G})^{2}+1\right]$$

- Diffusion length

$$r_{\rm diff} \sim \sqrt{K\ t_{\rm cool}} \sim 1{\rm kpc}({\rm E}/10^{2}{\rm GeV})^{-0.2}$$

$$\text{with } K = 5.8\times10^{28}\,{\rm cm}^{2}s^{-1}(1+E/3{\rm GeV})^{\delta}$$

δ~1/3 – 1/2, actually we adopted 0.5--0.6

An old SNR near the Earth

Fujita, Kohri, Yamazaki, Ioka, arXiv:**0903.5298**

- Proton was accelerated at a local SNR (<200 pc) in a dense gas cloud (n~50/cc) 10^6 years ago

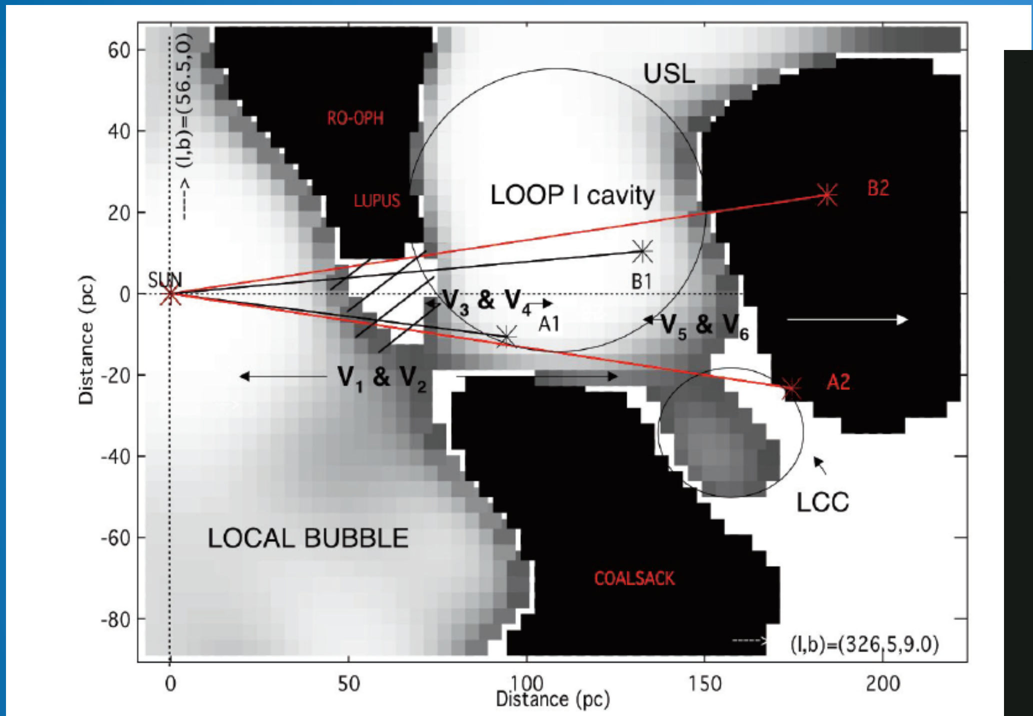
photon index in radiative phase can be

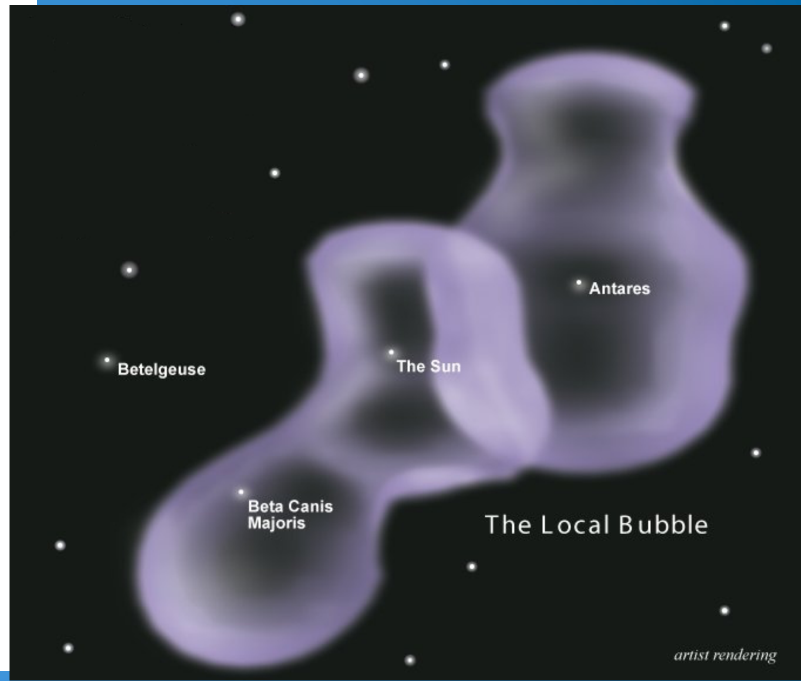
$n_s \sim v_s / v_{A,upp} \leq 2$

- p-p collision produces antiproton and pions (→ electrons and positrons) which propagated for 10^6 years

- The cloud had alrerady disappeared (see Loop I, Local Buble as its vestige)

Candidates of nearby old SNRs





B. Y. Welsh & R. Lallement (2005)

n < ~ 0.05/cc

Evolution of SNRs

- Velocity of the expansion

$$v_s(t_{\rm age}) = \begin{cases} v_i & (t_{\rm age} < t_1) \\ v_i \left(\frac{t_{\rm age}}{t_1}\right)^{-3/5} & (t_1 < t_{\rm age} < t_2) \\ v_i \left(\frac{t_2}{t_1}\right)^{-3/5} \left(\frac{t_{\rm age}}{t_2}\right)^{-2/3} & (t_2 < t_{\rm age}) \end{cases}$$

$t_1 \sim O(100)$yrs

$t_2 \sim O(10^3)$yrs, r=4

$r=\sqrt{2}\, v_s/v_{Au} >> 4$

- Accelerated cosmic-ray spectrum

$$N_p(E) \propto E^{-s} \exp(-E/E_{\rm max,p})$$

$$s = (r+2)/(r-1)$$

- Maximum energy ($t_{acc} = t_{age}$)

$$E_{\rm max,p} = 1.6 \times 10^2\, h^{-1} v_{s,8}^2 \left(\frac{B_{\rm d}}{10\ \mu{\rm G}}\right) \left(\frac{t_{\rm age}}{10^5 {\rm yr}}\right)\ {\rm TeV}$$

$$B_{\rm d} = r B_{\rm DC}$$

Various Scales

- Cooling time (diffusion time)

$$t_{\rm cool} \sim E / b(E) \sim 10^6\,{\rm yrs}({\rm E}/10^2{\rm GeV})^{-1}$$

$$\text{with } b(E) \sim 10^{-16}\,{\rm GeVs}^{-1}({\rm E}/10^2{\rm GeV})^2\left[({\rm B}/7\mu{\rm G})^2 + 1\right]$$

- Diffusion length

$$r_{\rm diff} \sim \sqrt{K\ t_{\rm cool}} \sim 1{\rm kpc}({\rm E}/10^2{\rm GeV})^{-0.2}$$

$$\text{with } K \;=\; 5.8\times 10^{28}\,{\rm cm}^2 s^{-1}(1 + E / 3{\rm GeV})^{\delta}$$

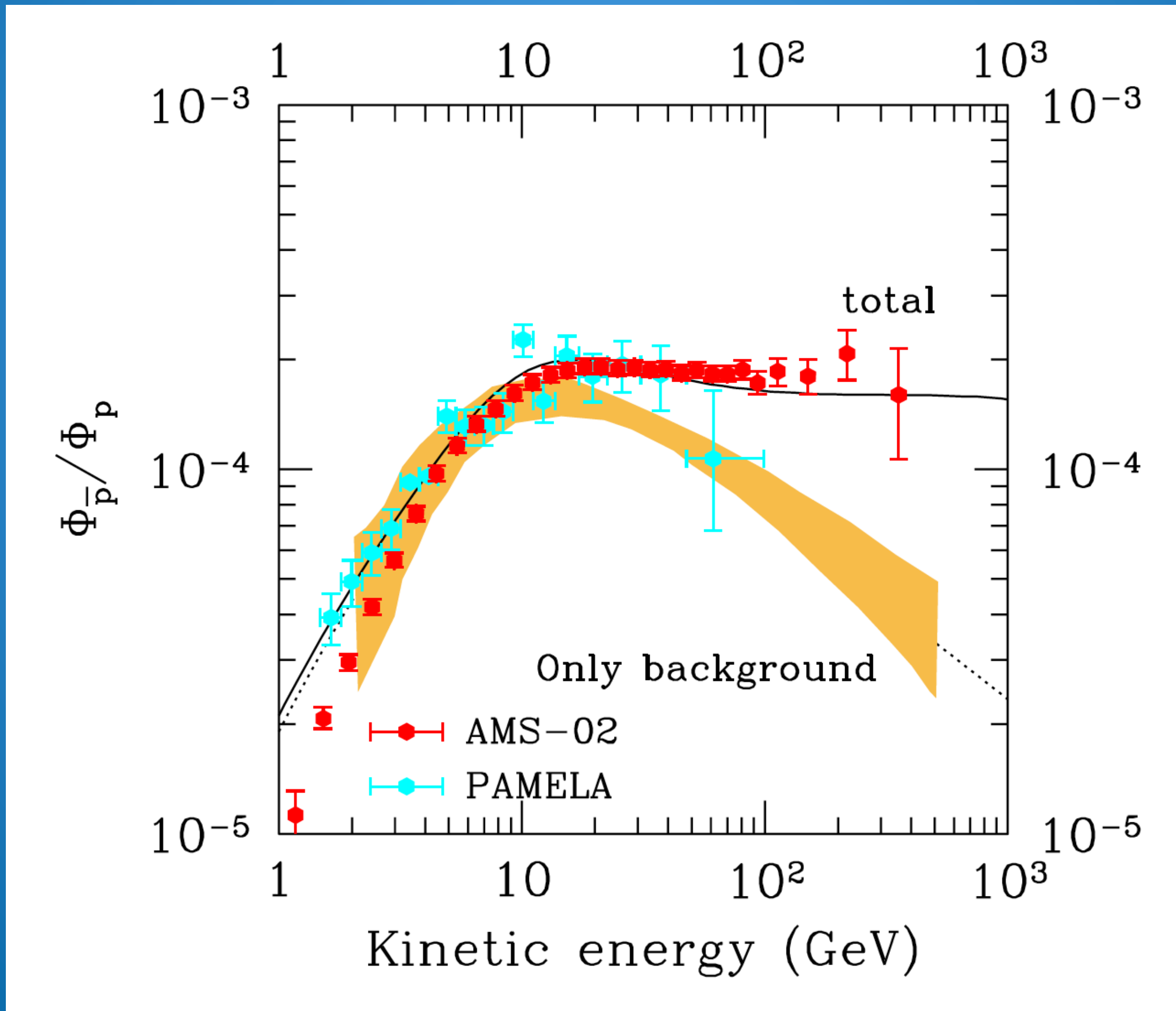
δ~1/3 – 2/3, actually we adopted 0.5 -- 0.6

Natural setup in parameters

Radius of the Dense clould	$R_{\mathrm{DC}} = 40\mathrm{pc}$
Number density of the target	$\mathrm{n}_0 = 50 cm^{-3}$
Spectral index	$s = 1.75$
Collision time and diffusion time	$t_{pp} = t_{\mathrm{diff}} = 2\times 10^5 yr$
Maximum energy	$E_{\mathrm{max}} = 100\mathrm{TeV}$
Total energy in the system	$E_{\mathrm{tot,\,p}} = 3\times 10^{50}\mathrm{erg}$
Distance to the source	d=200 pc
Magnetic field in SNR	$B_{\mathrm{diff}} = 3\mu G$

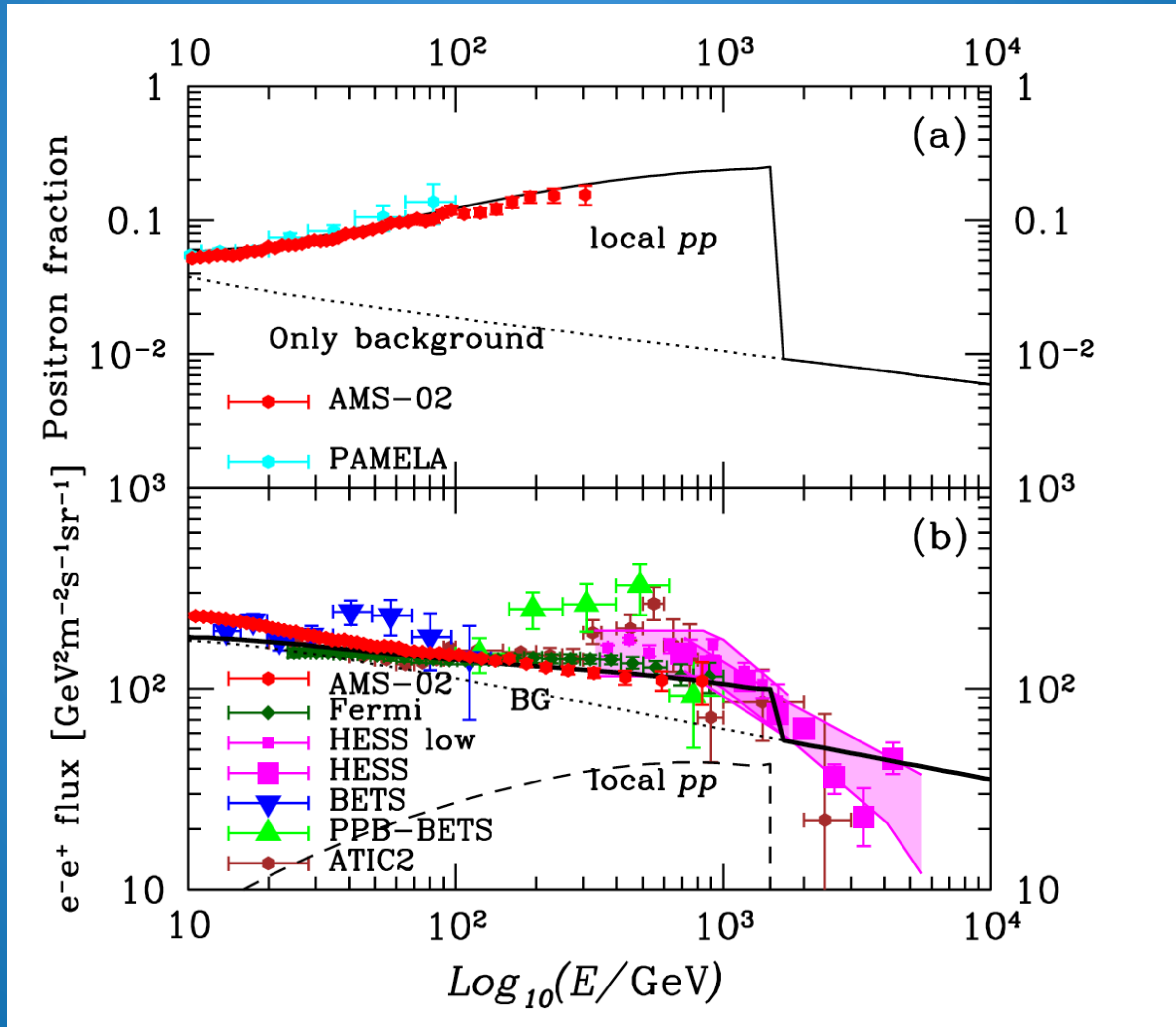
Fitted to antiproton data by local SNR model

Fujita, Kohri, Yamazaki, Ioka, arXiv:0903.5298
Kohri, Ioka, Fujita, Yamazaki, arXiv:1505.01236



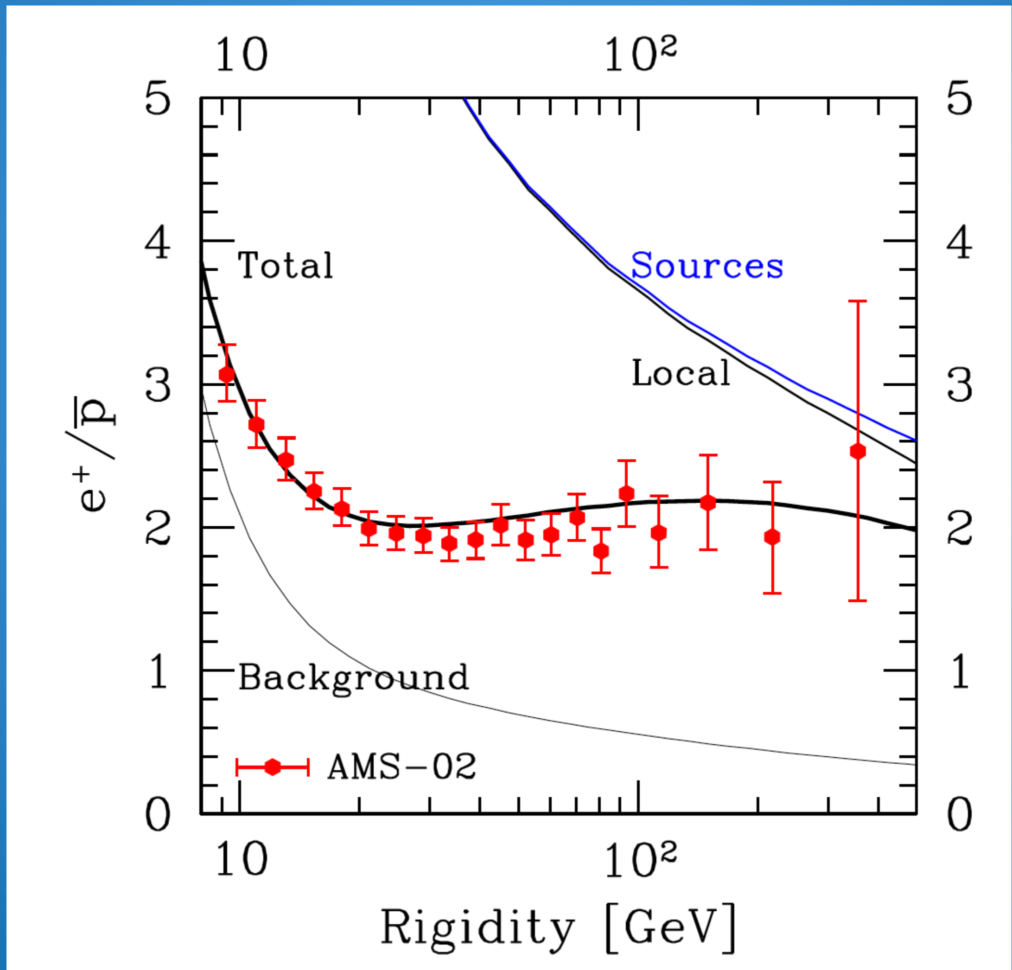
Fitted to positron data by local SNR model

Fujita, Kohri, Yamazaki, Ioka, arXiv:0903.5298
Kohri, Ioka, Fujita, Yamazaki, arXiv:1505.01236



Positron to antiproton ratio

Kohri, Ioka, Fujita, Yamazaki, arXiv:**1505.01236**



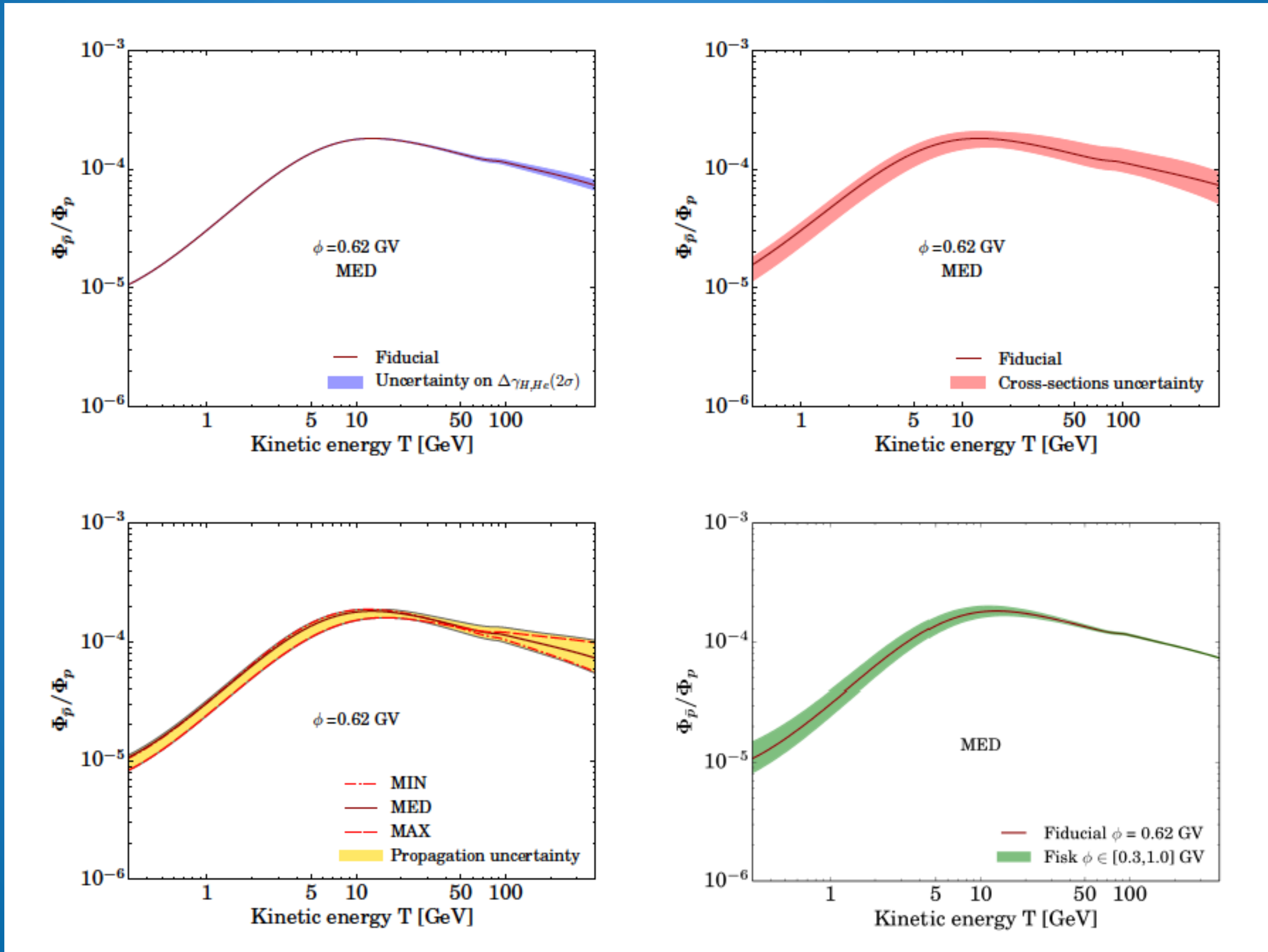
Summary

- Only through the pp collision in dense clouds at a local and old SNR near the solar system, we can simultaneously fit the positron and the antiproton excesses recently-reported by AMS-02

- This features had been already predicted by our previous paper, Fujita, Kohri, Yamazaki, Ioka (2009)

- Pulsars cannot accelerate cosmic-ray protons with O(100) GeV, which fails to explain the observed high-energy antiproton

Possible uncertainties



G. Giesen et al, (2015)

- Source spectrum

$$Q = Q_0 \varepsilon^{-\alpha} \delta(x) \delta(t)$$

$$\alpha \simeq s$$

- Spectrum

$$Q_0 \varepsilon_i^{-\alpha} \sim V_s t_{pp} d^2 n_i / (dt dE_i)$$

$$f_e = \frac{Q_0 \varepsilon_e^{-\alpha}}{\pi^{3/2} d_{\rm diff}^3} \left(1 - \frac{\varepsilon_e}{\varepsilon_{\rm cut}}\right)^{\alpha-2} e^{-(\bar{d}/d_{\rm diff})^2}$$

$$\varepsilon_{\rm cut} = (B t_{\rm diff})^{-1}$$

- Diffusion length

$$d_{\rm diff} = 2\sqrt{K t_{\rm diff} \frac{1 - (1 - \varepsilon_e/\varepsilon_{\rm cut})^{1-\delta}}{(1-\delta)\varepsilon_e/\varepsilon_{\rm cut}}}$$

Here

- Fragmentation function

$$\frac{d^2 n_i}{dt dE_i} = \int dE_p n_0 N_p \sum_j g_j c \frac{d\sigma_j}{dE_i}$$

$$g_j = g_j(E_p, E_i)$$

$$d\sigma_j(E_p, E_i)/dE_i$$

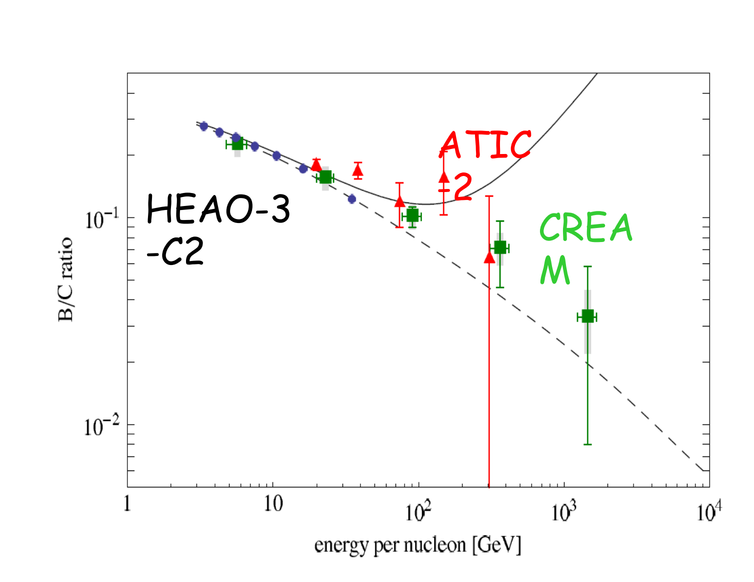
- Normalization

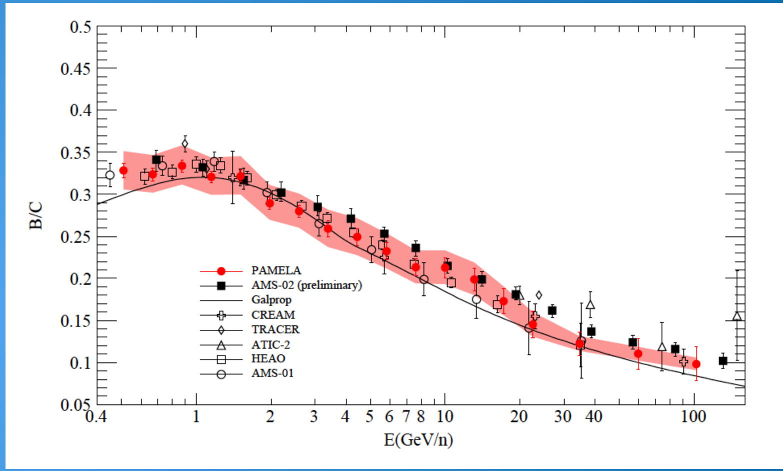
$$V_s \int dE_p N_p(E_p) = E_{\rm tot,p}$$

Another observables in pp collision model

Mertsch and Sarkar, arXiv:0905.3152v3

- B/C is also increasing? No





δ~ 1/3 - 1/2 AMS Collaboration (2014)

- Acceleration sites could be the low-metalicity places, in which the stellar wind is too weak to destroy the dense clouds (consistent with the current setup).

Propagation model

- Flux

$$\Phi_{e^+}(E, \vec{r}_\odot) = \frac{v_{e^+}}{4\pi M_{\rm DM}\tau_{\rm DM}} \int_0^{M_{\rm DM}} dE' \frac{dN_{e^+}}{dE'} G_{e^+}(E, E')$$

- Green function

$$G_{e^+}(E, E') = \frac{10^{16}\mathrm{s}}{\mathrm{cm}^3}\theta(E' - E) \times \frac{e^{a+b\left((E/\mathrm{GeV})^{\delta-1}-(E'/\mathrm{GeV})^{\delta-1}\right)}}{(E/\mathrm{GeV})^2},$$

Propagation model	L(kpc)	a	b	δ
min	1	−0.9716	−10.012	0.55
med	4	−1.0203	−1.4493	0.70
max	15	−0.9809	−1.1456	0.46