Astrophysical Electron-Positron Factories and their Spectral Features

Ref.)
NK, Ioka & Nojiri 2010, ApJ, 710, 958
NK, Ioka, Ohira & Kashiyama 2011, ApJ, 729, 93
Kashiyama, Ioka & NK, 2011, Phys. Rev. D
NK arXiv:1207.0010
Kisaka & NK, 2012, MNRAS, 421, 3543
Ohira, Yamazaki, NK & Ioka 2012, MNRAS, 427, 91
Ohira, NK & Ioka, 2016, Phys. Rev. D 93, 083001
NK, Kashiyama & Murase 2016 in prep.

Norita Kawanaka (Univ. of Tokyo)

MACROS 2016 at Penn State Univ. 6/20-22/2016

Contents

- Why are CR electrons/positrons interesting?
- What is the difference between CR $e^{\pm}$ and CR nuclei?
- What is the candidate of CR $e^{\pm}$ sources (other than DM particles)?
- What will the future experiments tell us about CR $e^{\pm}$ sources?

Cosmic-ray Electrons (e^-)

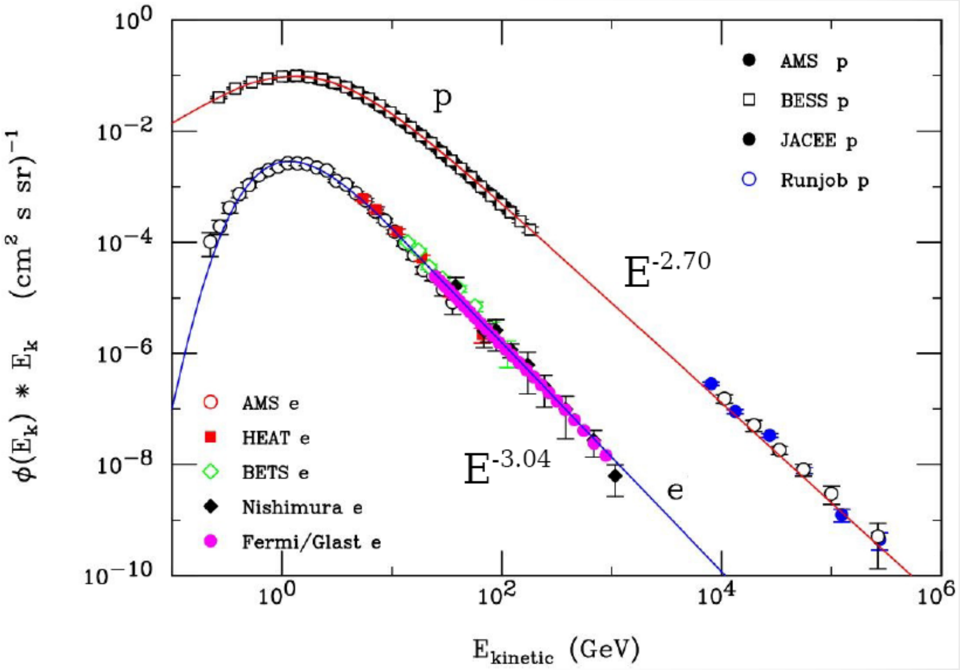
- flux ~ 1% of p

- (partly) accelerated in SNRs

- significant energy loss during propagation (synchrotron & inverse Compton scattering)

- the spectrum is softer than that of nuclei

- cannot propagate farther than ~ 1-2 kpc due to the energy loss



Cosmic-ray Positrons (e^+)

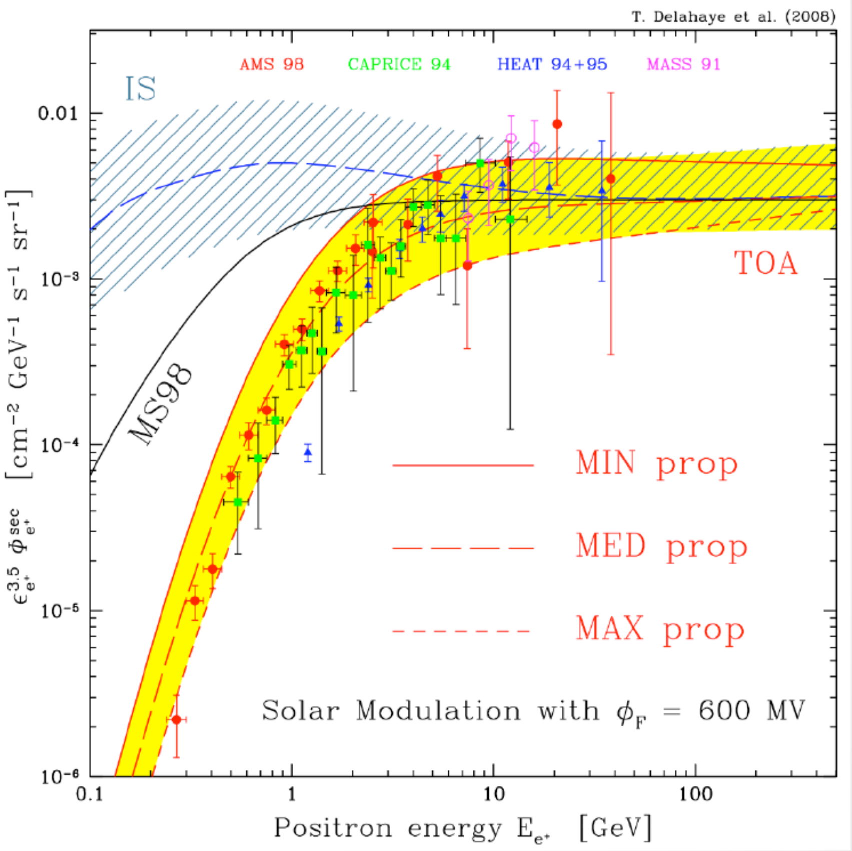
- flux ~ 10% of e^- (~ 0.1% of p)
- Lose their energy during propagation in the same way as e^-
- “standard” model
  produced via interactions
  between CR p and ISM p

$$p + p \rightarrow \pi^+ \rightarrow \mu^+ \rightarrow \boldsymbol{e^+}$$

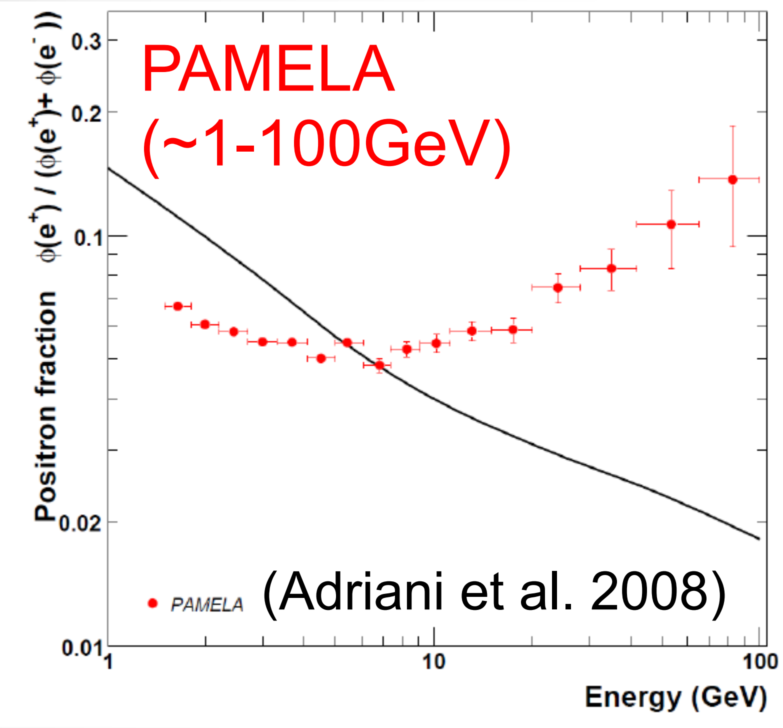
… secondary origin

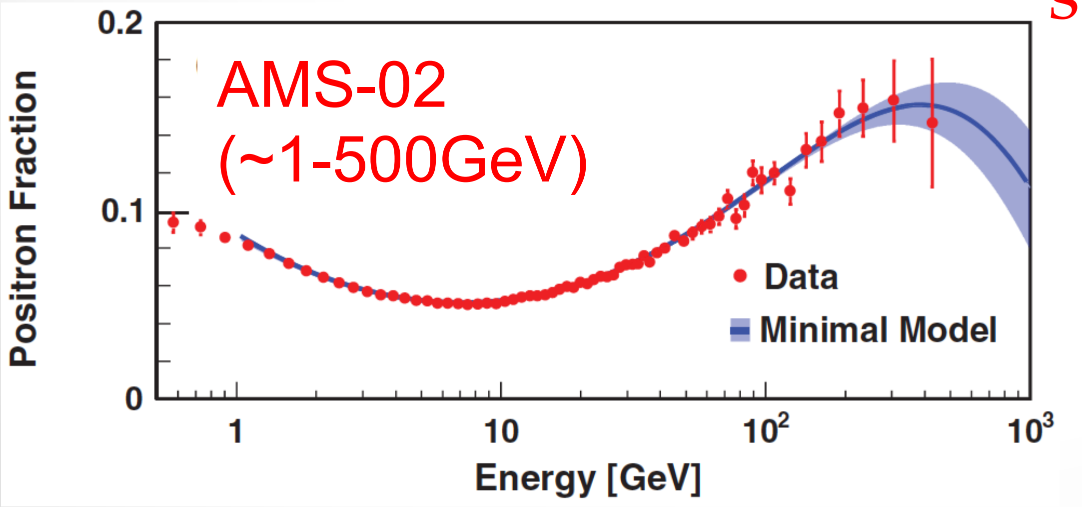
- # of produced e^+
  $\propto$ p trapping time in the Galaxy
  … shorter for higher energy p

∴ The spectrum of secondary e^+ should be <u>softer</u> than that of primary CRs (p, e^-,…)



“positron excess”





Observed CR e^+ flux seems to exceed that expected from the standard secondary production model, and rises with the energy.

Some primary positron sources are needed!

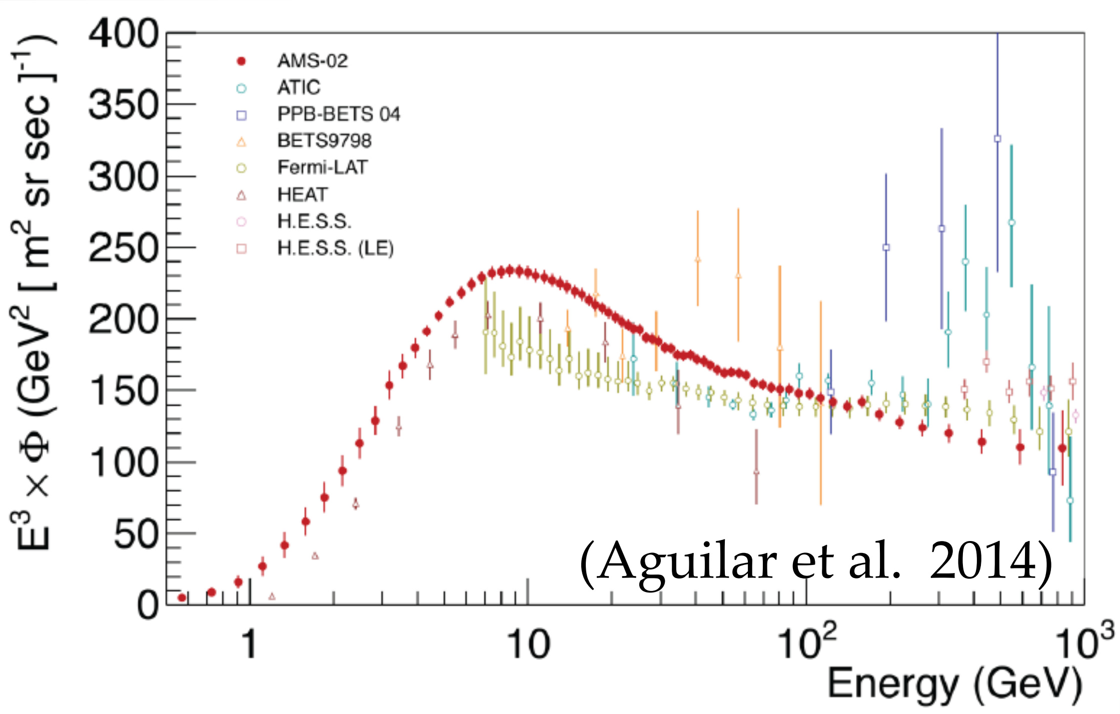
← Drop above ~200 GeV?

Electron + Positron Flux

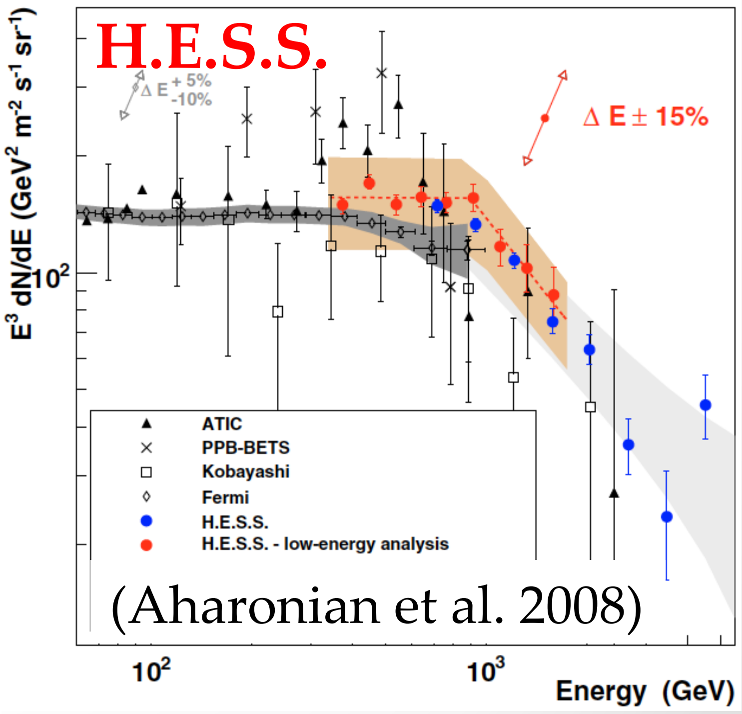
- Excess from the conventional model?

→ Primary CR $e^{\pm}$ sources?

- Bumpy structure and sharp cutoff at ~500 GeV? (ATIC/PPB-BETS)
- drop above ~TeV? (HESS)



(Aguilar et al. 2014)



(Aharonian et al. 2008)

Astrophysical Origin

- Pulsars (including MSPs)

Atoyan et al. 95; Chi+ 96; Zhang & Cheng 01; Yuksel+ 08; Buesching+ 08; Hooper+ 08; Profumo 08; Malyshev+09; Grasso+ 09; NK, Ioka & Nojiri 10; NK, Ioka, Ohira & Kashiyama 11; Kisaka & NK 12 etc.

- Supernova Remnants

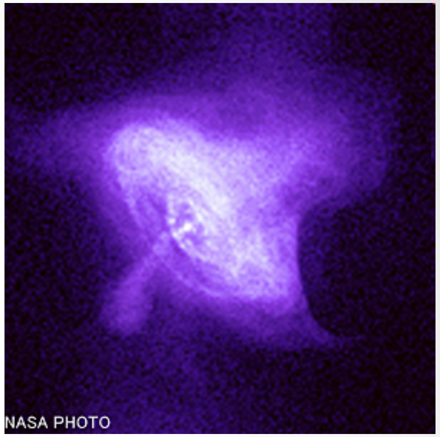
Pohl & Esposito 98; Kobayashi+ 04; Shaviv + 09; Hu+ 09; Fujita+ 09; Blasi 09; Blasi & Serpico 09; Mertsch & Sarkar 09; Biermann + 09; Ahlers+ 09; NK 12 etc.

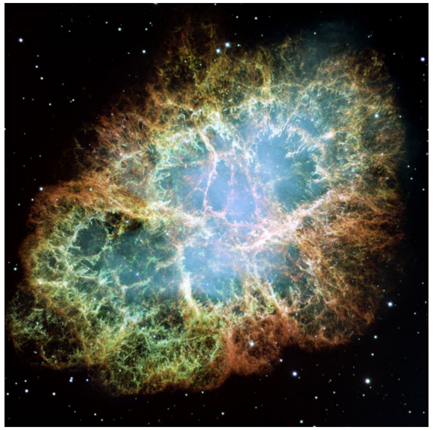
- Microquasars (Galactic BHs)

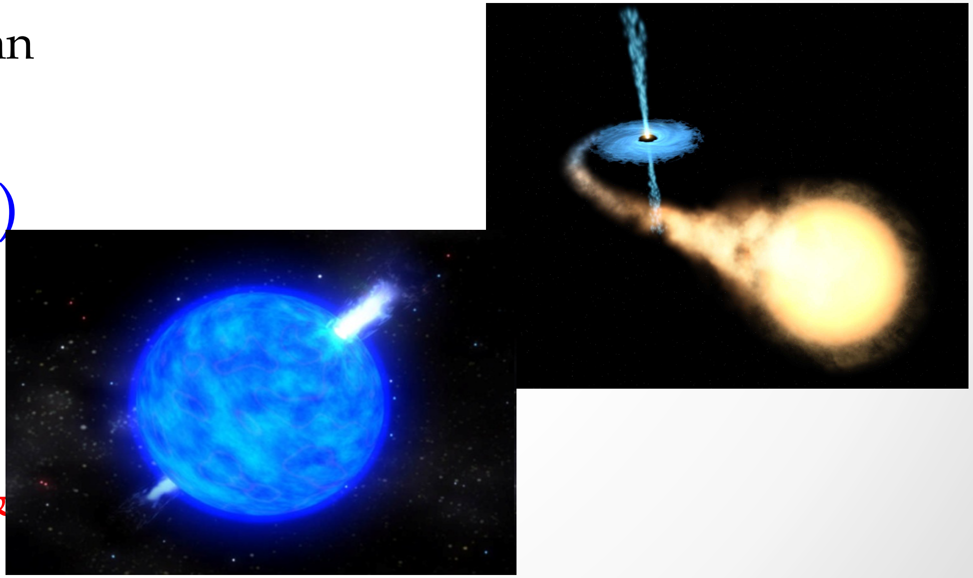
Heinz & Sunyaev 02

- Gamma-Ray Burst Ioka 10

- White Dwarfs Kashiyama, Ioka & NK 11







CR $e^{\pm}$ propagation equation

Diffusion equation for CR $e^{\pm}$ distribution function, f:

$$\frac{\partial}{\partial t} f(t,\vec{r},\varepsilon_e) = \underbrace{K(\varepsilon_e)\nabla^2 f}_{\text{diffusion}} + \underbrace{\frac{\partial}{\partial \varepsilon_e}\left[P(\varepsilon_e) f\right]}_{\text{energy loss (not negligible)}} + \underbrace{Q(t,\vec{r},\varepsilon_e)}_{\text{injection}}$$

diffusion coefficient: $K(\varepsilon_e) \sim 5.8\times10^{28}\mathrm{cm}^2\mathrm{s}^{-1}(\varepsilon_e/3\mathrm{GeV})^{\delta}$, $\delta = 1/3$

energy loss rate: $\boldsymbol{P(\varepsilon_e) = P_{\mathrm{syn}}(\varepsilon_e) + P_{\mathrm{IC}}(\varepsilon_e)}$

- $\boldsymbol{P_{\mathrm{syn}}}$: synchrotron cooling (Galactic magnetic field ~1-3 μG)
- $\boldsymbol{P_{\mathrm{IC}}}$: inverse Compton scattering (starlight, dust, CMB)
- Thomson approx. $\boldsymbol{P(\varepsilon_e) \sim b\varepsilon_e^2}$, $\boldsymbol{b \sim 10^{-16}\ \mathrm{GeV}^{-1}\mathrm{s}^{-1}}$
- $t_{\mathrm{cool}} \sim 1/b\varepsilon_e \sim 10^6\ \mathrm{yr}\ (\varepsilon_e/300\mathrm{GeV})^{-1}$

Simplest Solution

Atoyan+ 1995

Point-like, instantaneous injection $Q \propto \delta(r)\,\delta(t - t_0)$

$$f = G(t,\vec{r},\varepsilon_e;t_0) = \frac{N_e\left(\varepsilon_{e,0},t_0\right)P\left(\varepsilon_{e,0}\right)}{\pi^{3/2}d_{diff}^3 P\left(\varepsilon_e\right)}\exp\left(-\frac{r^2}{d_{diff}^2}\right)$$

$N_e(\varepsilon_e, t)$: total number of injected particles

$\varepsilon_{e,0}$:energy of a particle at its injection

$d_{diff} \approx 2\sqrt{K(\varepsilon_e)t}$: diffusion length

Thomson approx. $P\left(\varepsilon_e\right) \approx -b\varepsilon_e^2,\ b = 10^{-16}\,\mathrm{GeV^{-1}s^{-1}}$

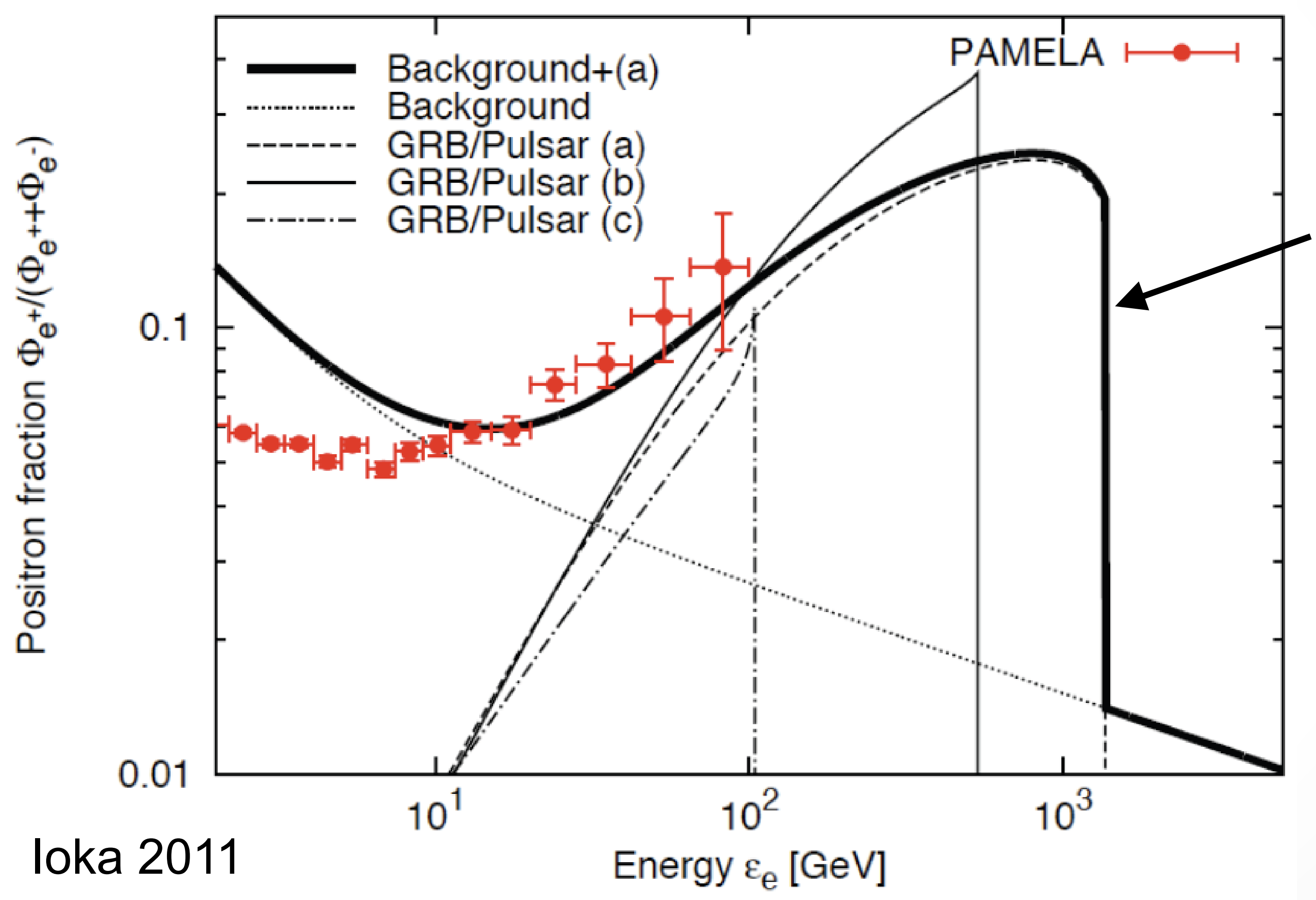
$$G(t,\vec{r},\varepsilon_e;t_0) = \frac{N_e(\varepsilon_e,t_0)}{\pi^{3/2}d_{diff}^3}\left(1 - bt\varepsilon_e\right)^{\alpha-2}\exp\left(-\frac{r^2}{d_{diff}^2}\right)$$

cutoff:
$\varepsilon_e \sim 1/bt_{age}$

(α: spectral index of e±)

The case of transient source: e^+ fraction

The cutoff energy corresponds to the age of the source.



Ioka 2011

d=1kpc

(a)
E=0.9×10^{50}erg
age=2×10^5yr
α=2.5

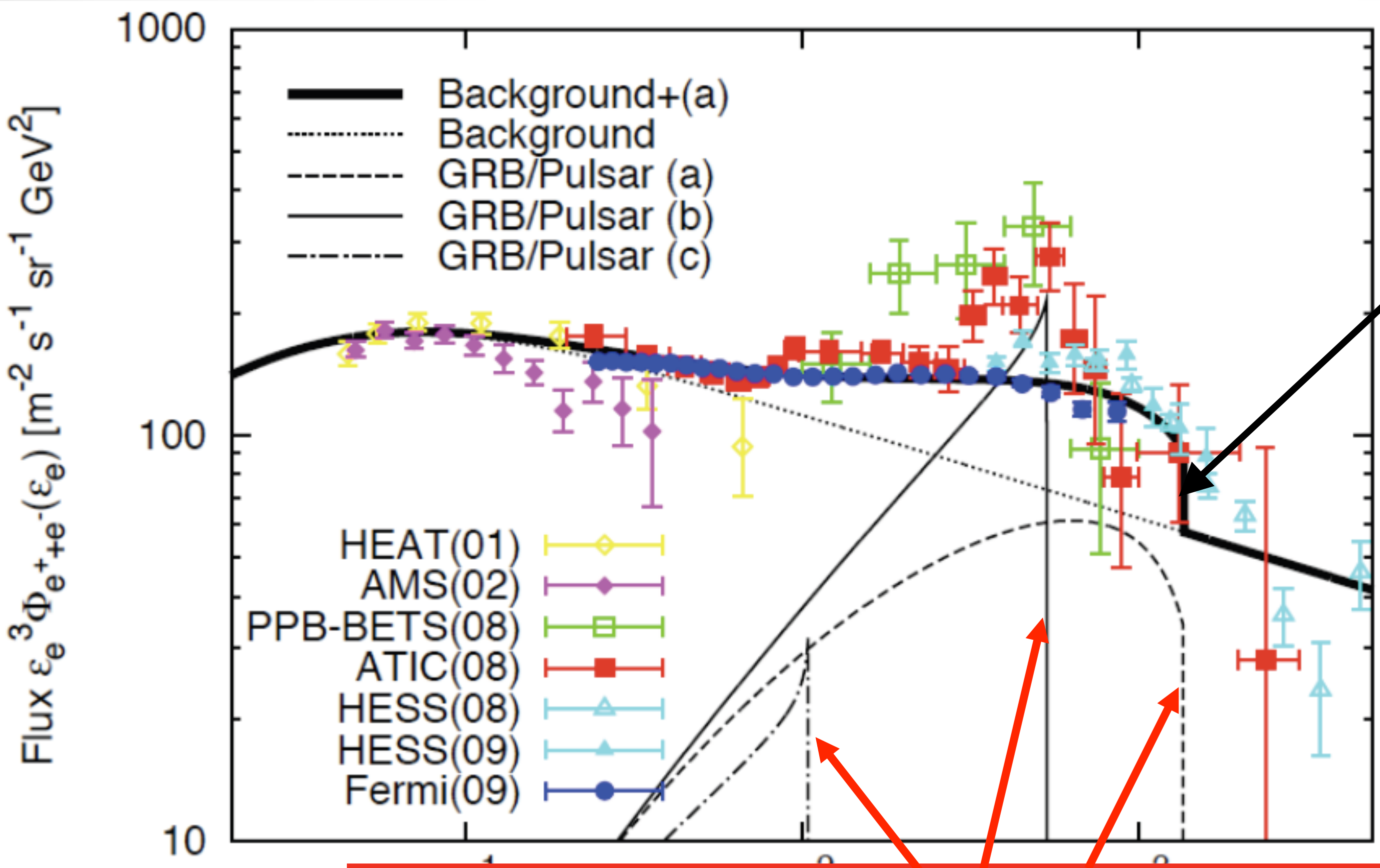
(b)
E=0.8×10^{50}erg
age=5.6×10^5yr
α=1.8

(c)
E=3×10^{50}erg
age=3×10^6yr
α=1.8

At the source, $\dot{N}_{e^+} = \dot{N}_{e^-}$ is assumed.

The case of transient source: $e^{\pm}$ spectrum

The cutoff energy corresponds to the age of the source.



Ioka 2011

d=1kpc

(a)
E=0.9x10^{50}erg
age=2x10^5yr
α=2.5

(b)
E=0.8x10^{50}erg
age=5.6x10^5yr
α=1.8

(c)
3x10^{50}erg
e=3x10^6yr
1.8

$$\varepsilon_{\rm cut} = \frac{1}{bt} \simeq 300 \left(\frac{10^6{\rm yr}}{t_{\rm age}}\right) {\rm GeV}$$

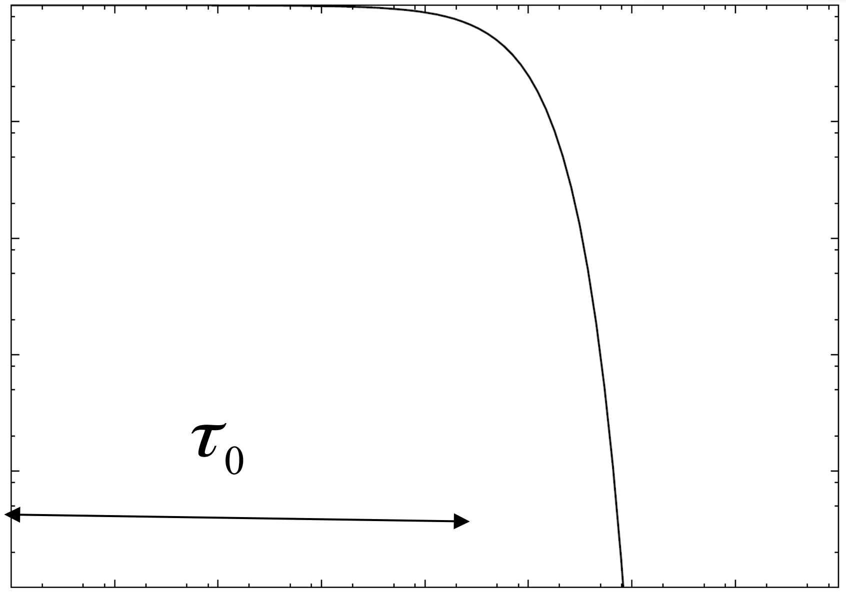
Continuous injection (expected in pulsars, SNRs, etc.)

The spectral bump around $E_e \sim 1/bt$ will be broadened!

$$\boxed{F(t,\varepsilon_e) = \int_0^t dt' \frac{Q_0(t-t')\,\varepsilon_e^{-\alpha}}{\pi^{3/2} r_{\mathrm{diff}}^3} \left(1 - bt'\varepsilon_e\right)^{\alpha-2} \exp\left(-\frac{r^2}{r_{\mathrm{diff}}^2}\right)}$$

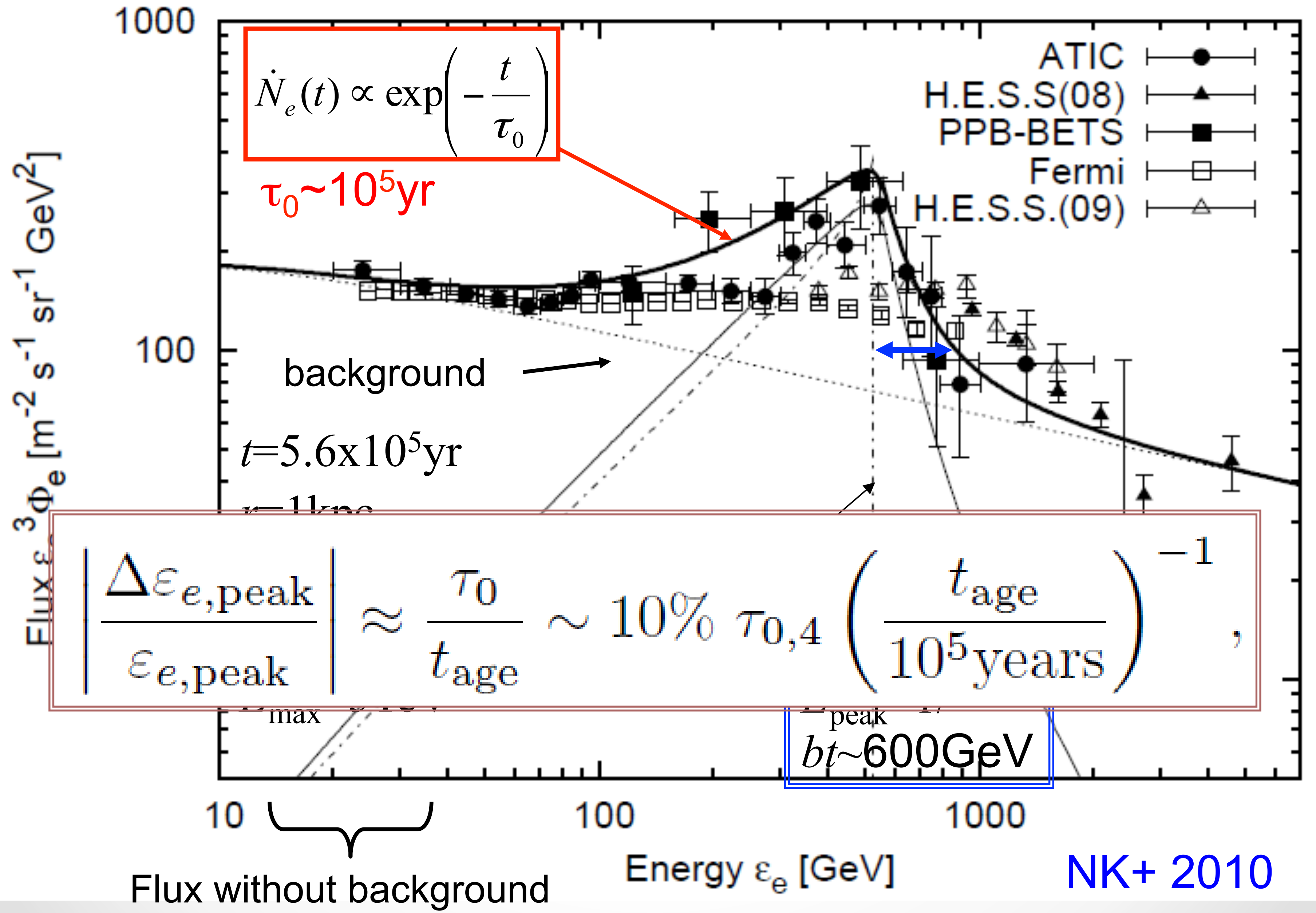
simple example: exponential decay

$$Q_0(t) \propto \frac{E_{tot}}{\tau_0} \exp\left(-\frac{t}{\tau_0}\right)$$



cf. spindown timescale for typical pulsars ~ $10^{3\text{-}5}$yrs

Continuous Injection: Broadened Peak



$$\dot{N}_e(t) \propto \exp\left(-\frac{t}{\tau_0}\right)$$

τ_0~10^5yr

background

t=5.6x10^5yr

$$\left|\frac{\Delta\varepsilon_{e,\mathrm{peak}}}{\varepsilon_{e,\mathrm{peak}}}\right| \approx \frac{\tau_0}{t_{\mathrm{age}}} \sim 10\%\ \tau_{0,4}\left(\frac{t_{\mathrm{age}}}{10^5\mathrm{years}}\right)^{-1},$$

bt~600GeV

Flux without background

NK+ 2010

Summary of the case with a Single e± source

- A high energy cutoff expected in the dark matter model can be reproduced also in the astrophysical source model.
- Older (Younger) sources contribute to the lower (higher) energy range of the e± flux because of the energy loss during propagation
- Continuous *e*± injection → broadened cutoff

$e^{\pm}$ Injection from Multiple Sources

- Total injection energy required to account for the CR electron/positron flux **~ $10^{50\text{-}51}$ erg**

  ~ Rotation energy of a pulsar with P_0~10msec

  Too efficient for a single pulsar?

- Local pulsar birth rate ~10^{-5} yr^{-1} kpc^{-2}

  Some young pulsars (age < 5×10^5yr) may exist in the vicinity of the Earth.

- It is natural to consider the contribution of multiple pulsars to CR $e^{\pm}$.

- ***Let us evaluate the average spectrum and its dispersion expected from nearby pulsars***

Average $e^{\pm}$ Spectrum and Its Dispersion

NK+ 2010; Kashiyama, Ioka & NK 2011

Average flux from nearby sources with a birth rate of R:

$$f_{\rm ave}(\varepsilon_e) = \int_0^{1/(b\varepsilon_e)} dt \int_0^{d_{\rm diff}} 2\pi r dr \underline{f(t,r,\varepsilon)} R$$

Flux per source

Number of sources which contribute to the energy bin of ε_e

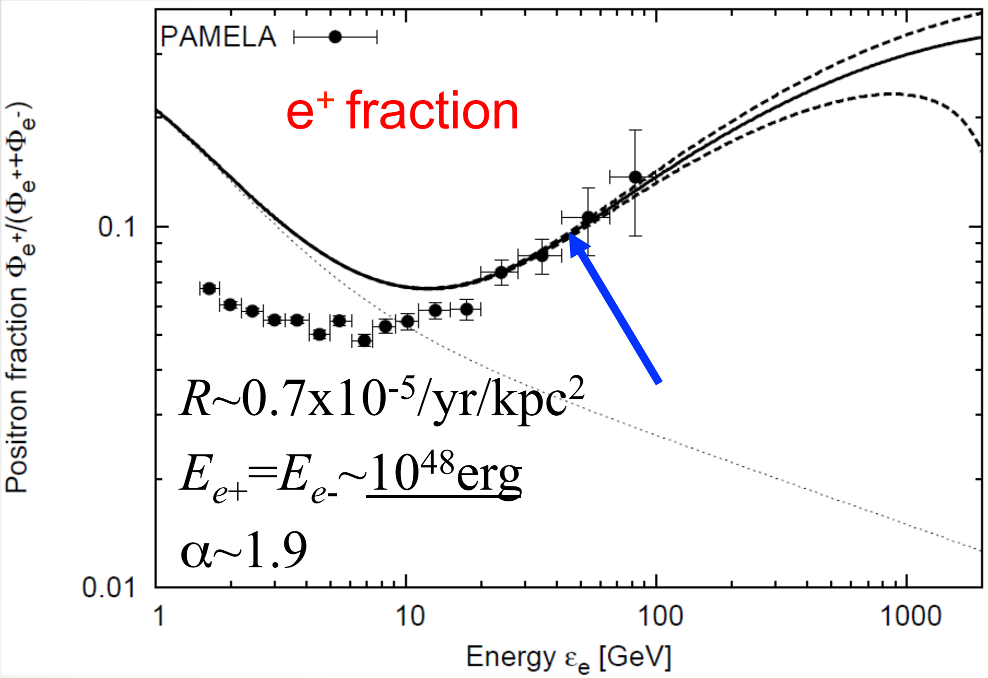
$$N(\varepsilon_e) = \int_0^{(b\varepsilon_e)^{-1}} dt \int_0^{d_{\rm diff}} dr 2\pi r R \sim \frac{2\pi K(\varepsilon_e) R}{(b\varepsilon_e)^2}$$

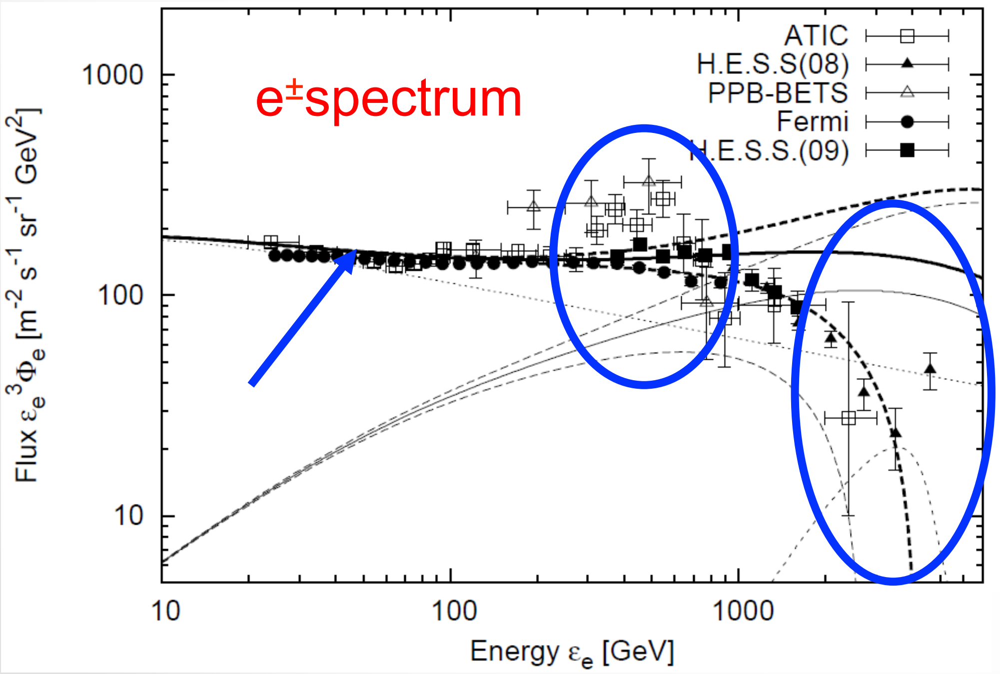
$$\sim 6 \left(\frac{\varepsilon_e}{\rm TeV}\right)^{-5/3} \left(\frac{R}{0.7\times10^{-5}\,{\rm yr}^{-1}{\rm kpc}^{-2}}\right)$$

Assuming the Poisson statistics of the source distribution,

$$\Delta f_{\rm ave}(\varepsilon_e) = f_{\rm ave}(\varepsilon_e)/\sqrt{N(\varepsilon_e)}$$

$\varepsilon_e \uparrow$ or $R \downarrow \Rightarrow \Delta f/f \uparrow$ i.e. higher energy/lower birth rate would make the spectrum wiggled



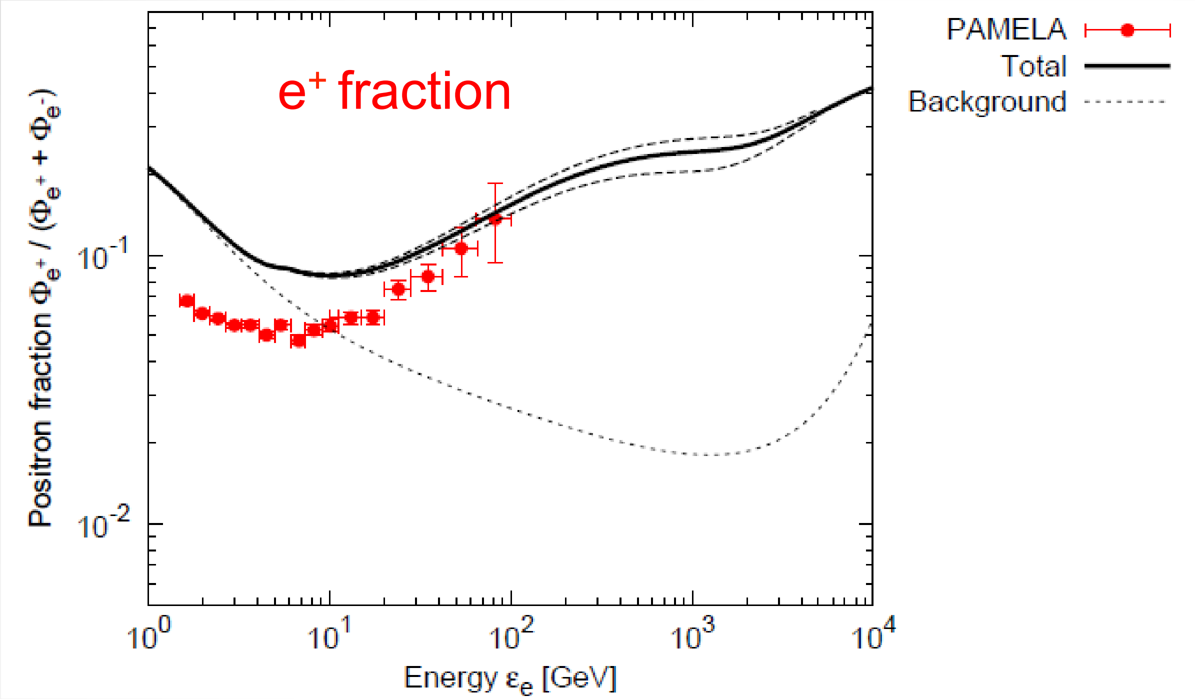


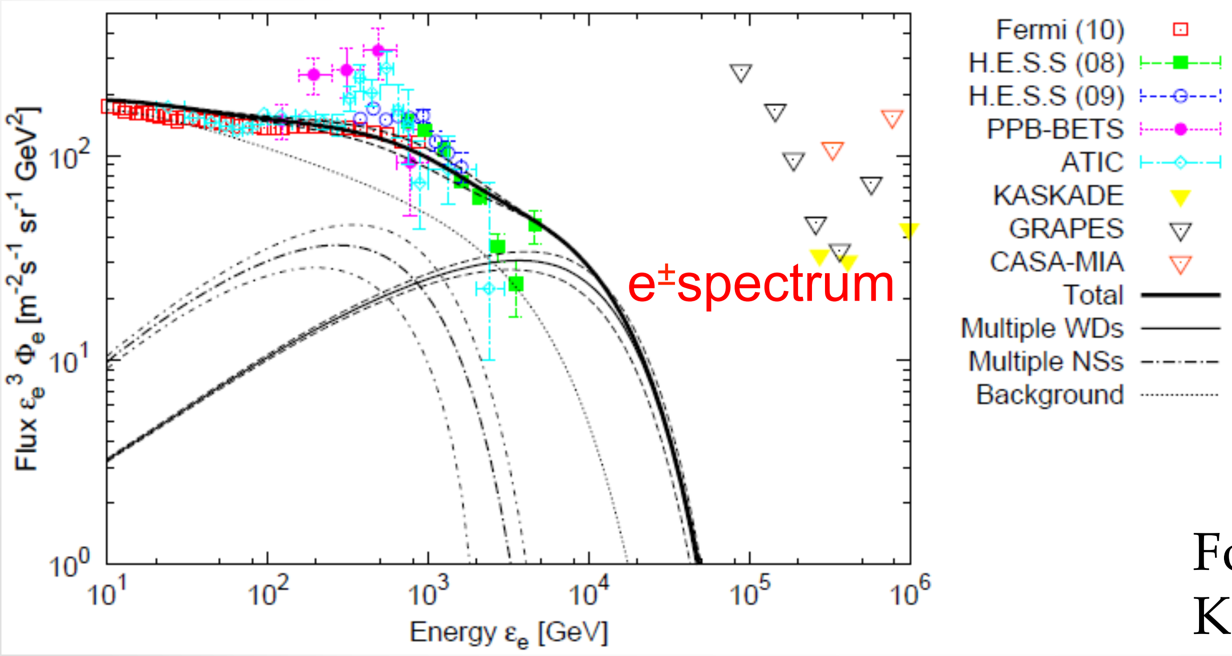
solid lines: $f_{\rm ave}(\varepsilon_e)$

dashed lines: $f_{\rm ave}(\varepsilon_e) \pm \Delta f_{\rm ave}$

1. Average spectra are consistent with PAMELA, Fermi & H.E.S.S.
2. ATIC/PPB-BETS peak is largely separated from the average flux. → Such a peak is hard to produce by the sum of multiple pulsars.
3. Large dispersion in the TeV range due to the small $N(\varepsilon_e)$ → possible explanation for the cutoff inferred by H.E.S.S.

Contributions from White Dwarfs





WDs with >~$10^{7\text{-}9}$G have been discovered (e.g. AE Aquarii; Terada+08).

→ Can be CR $e^{\pm}$ factories!

The lifetime is much longer than NS.

→ can be dominant in ~1-10TeV

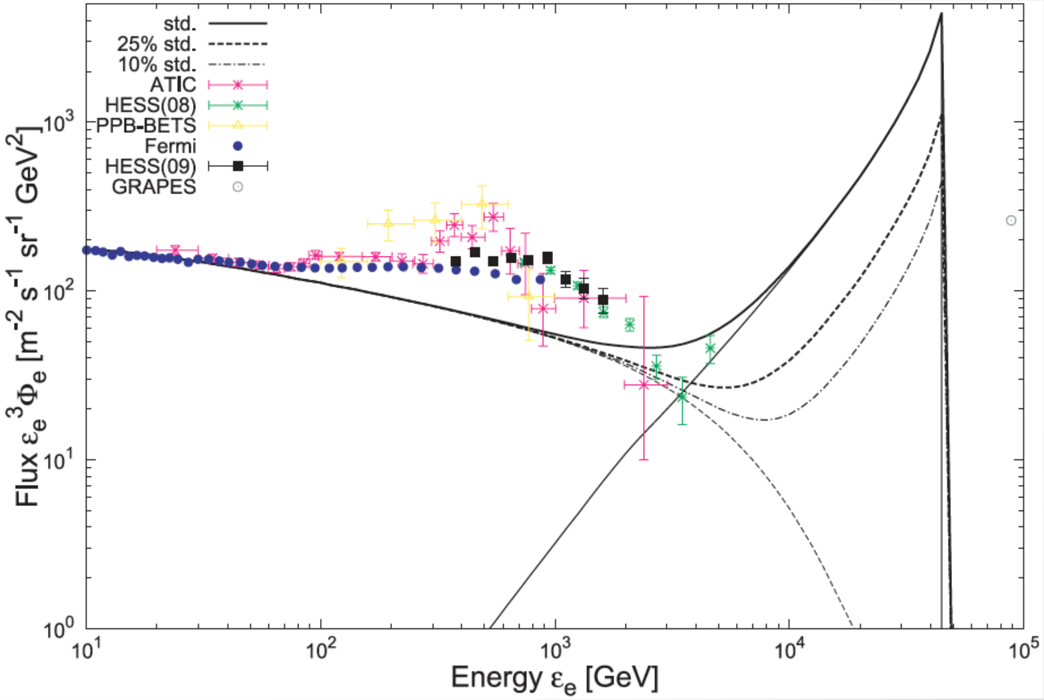
For the detail, see Kashiyama, Ioka & NK 2011

TeV Electrons from Millisecond Pulsars

Kisaka & NK 2012

Weak magnetic field (~$10^{8\text{-}9}$G) → long spindown time (~Gyr)
→ Many MSPs may exist in the vicinity of the Earth.
Fermi detected gamma-ray emissions from MSPs
→ Evidence that $e^{\pm}$ are accelerated up to ~TeV
→They may contribute to the CR $e^{\pm}$ spectrum!

MSPs are pair-starved?
(Muslimov & Harding 2004)
→ They may emit $e^{\pm}$ only in a narrow energy range (~50TeV)
→A large peak would appear in TeV range.

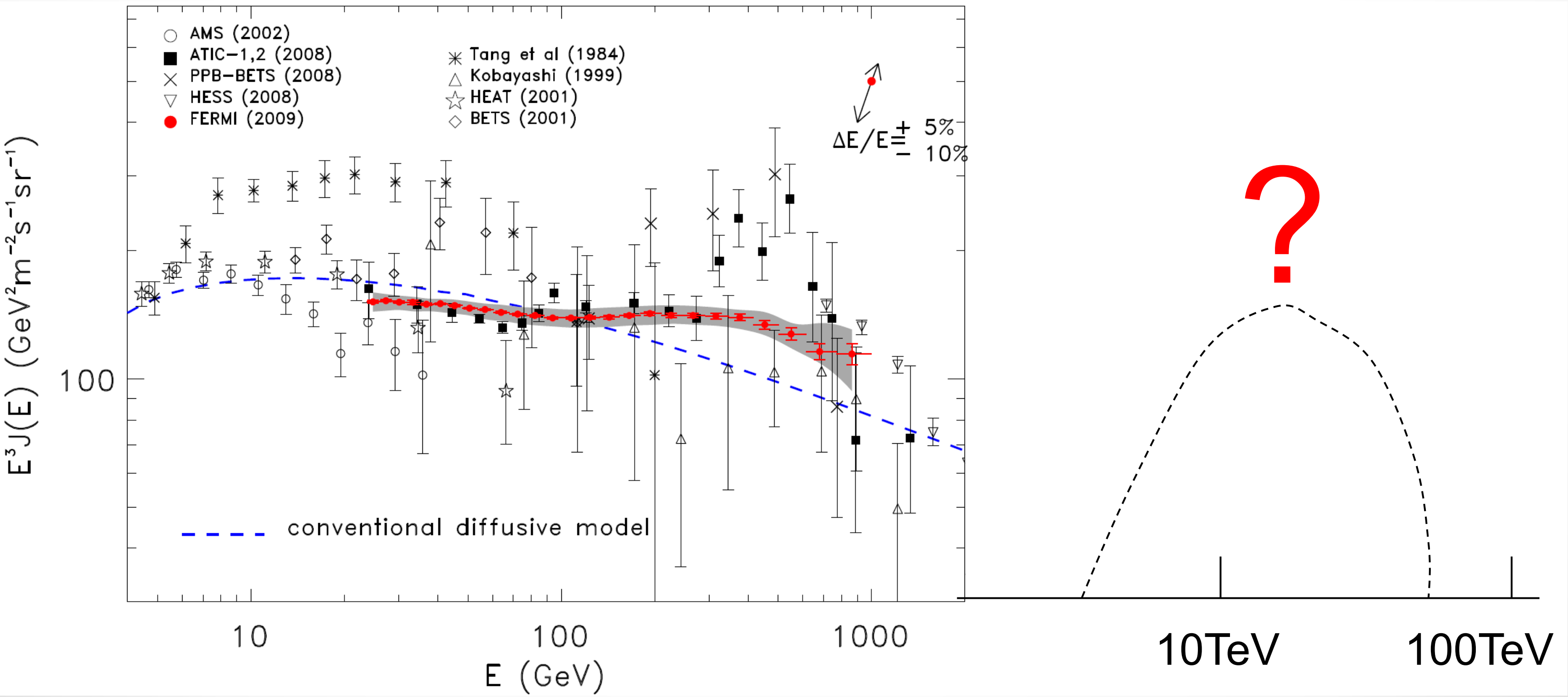


ε_e>TeV spectrum is interesting!

Will be explored by CALET, DAMPE, ISS-CREAM, etc.

Large theoretical dispersion → We can expect to observe the contributions from a single young and nearby source.

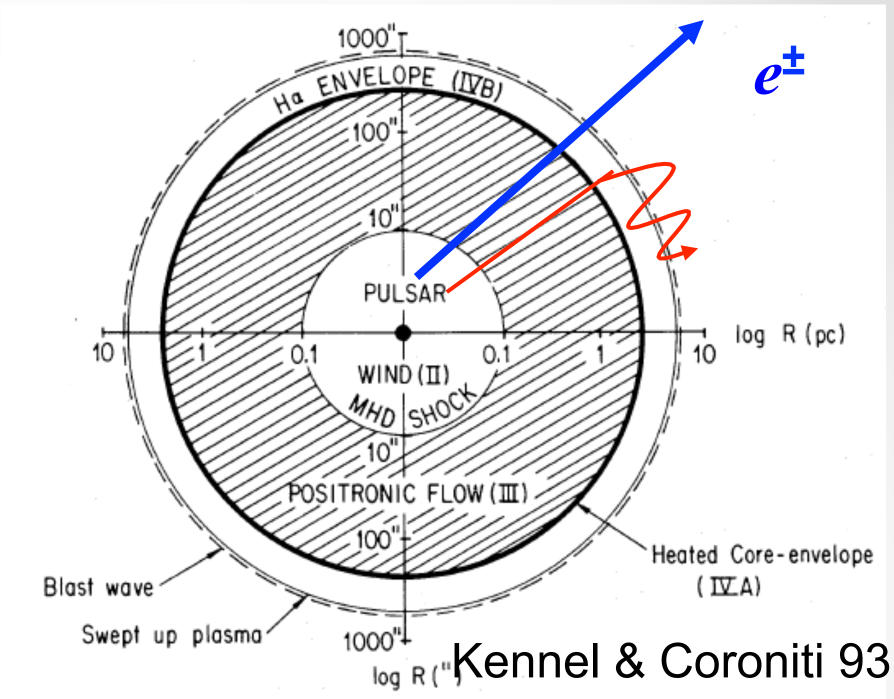
Vela pulsar (age~10^4year, distance~290pc), Cygnus loop, or undiscovered compact objects



A young PSR/PWN is surrounded by a SNR.

→ CR $e^{\pm}$ from a PWN should go through the SNR shock without trapped by the magnetic field around the shock

The escape from a PWN is also important (NK, Kahiyama & Murase in prep.)



Kennel & Coroniti 93

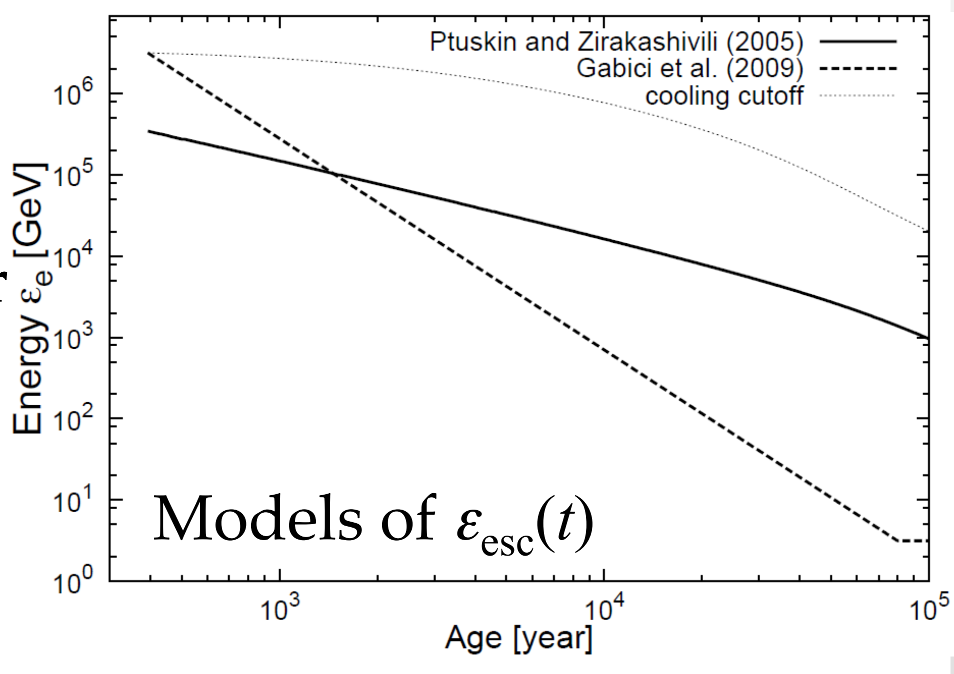
Escape condition: $\varepsilon_e > \varepsilon_{\rm esc}(t)$

$\varepsilon_{\rm esc}(t)$: given by models

e± spectrum from a young pulsar should have a low energy cutoff

→ Probe of the energy-dependent escape scenario

(Ohira+ 2010; Ohira, Yamazaki, NK & Ioka 2012; Ohira, NK & Ioka 2016)



Models of $\varepsilon_{\rm esc}(t)$

TeV $e^{\pm}$ spectrum can prove the CR escape!

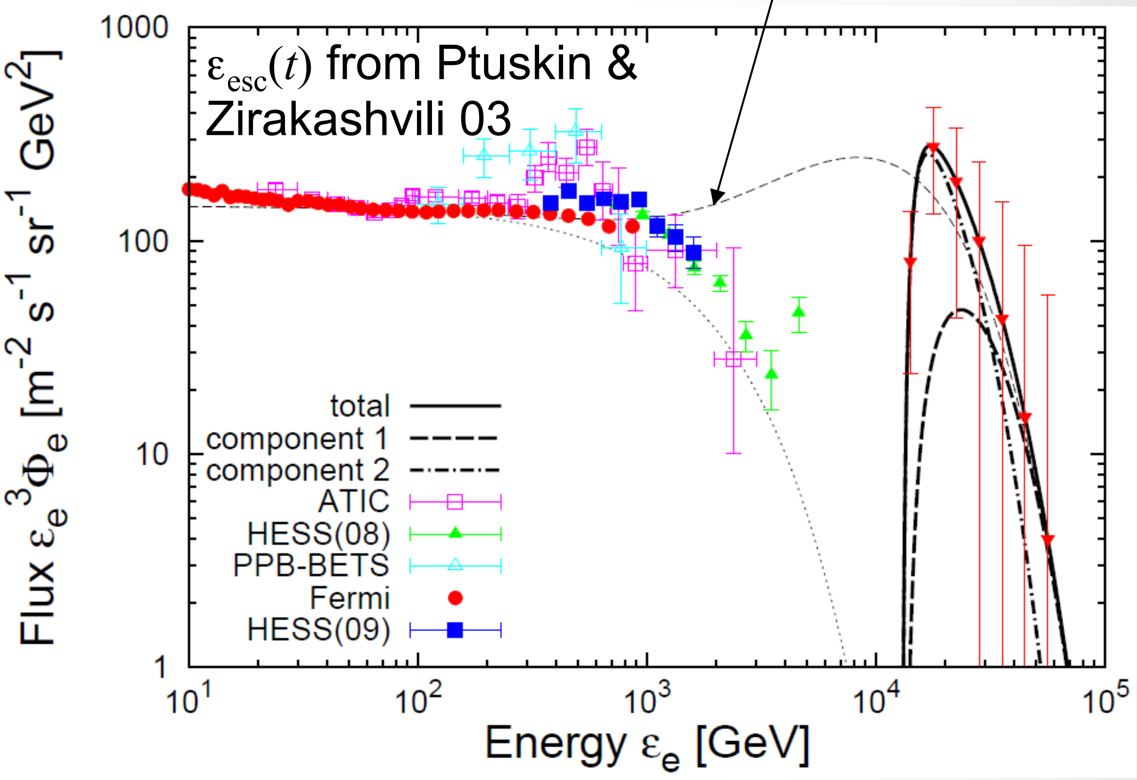
- Electron spectrum from Vela SNR/PSR (d=290pc, $t_{\rm age}$~10^4yr, $E_{\rm tot}$=10^{48}erg)

- Only $e^{\pm}$ with $\varepsilon_e > \varepsilon_{\rm esc}(t_{\rm age})$ can run away from the SNR.

→ Low Energy Cutoff

- 5yr obs. by CALET ($S\Omega T$=220m^{2}sr days; see next slide) may detect it.

Without energy-dependent escape

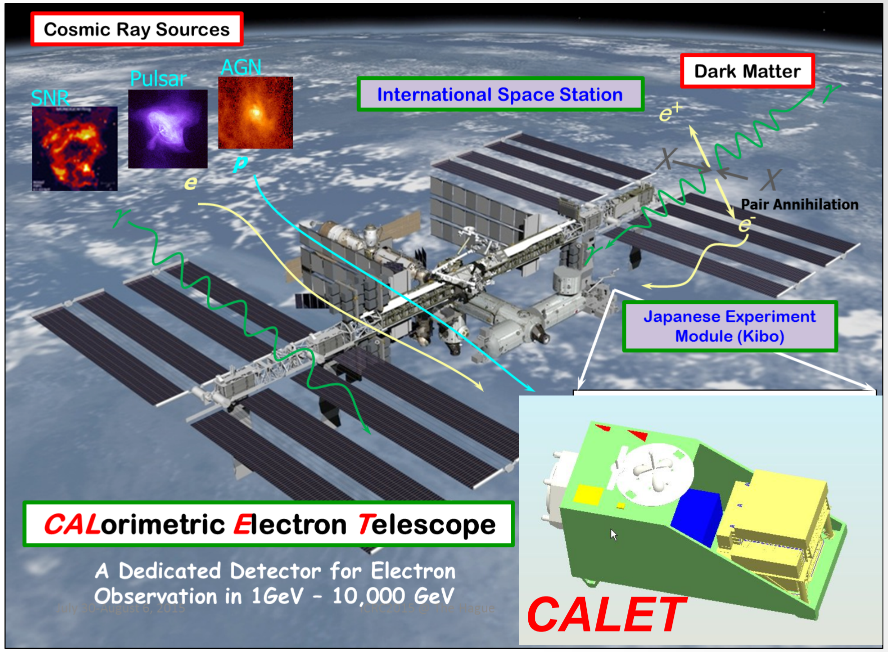


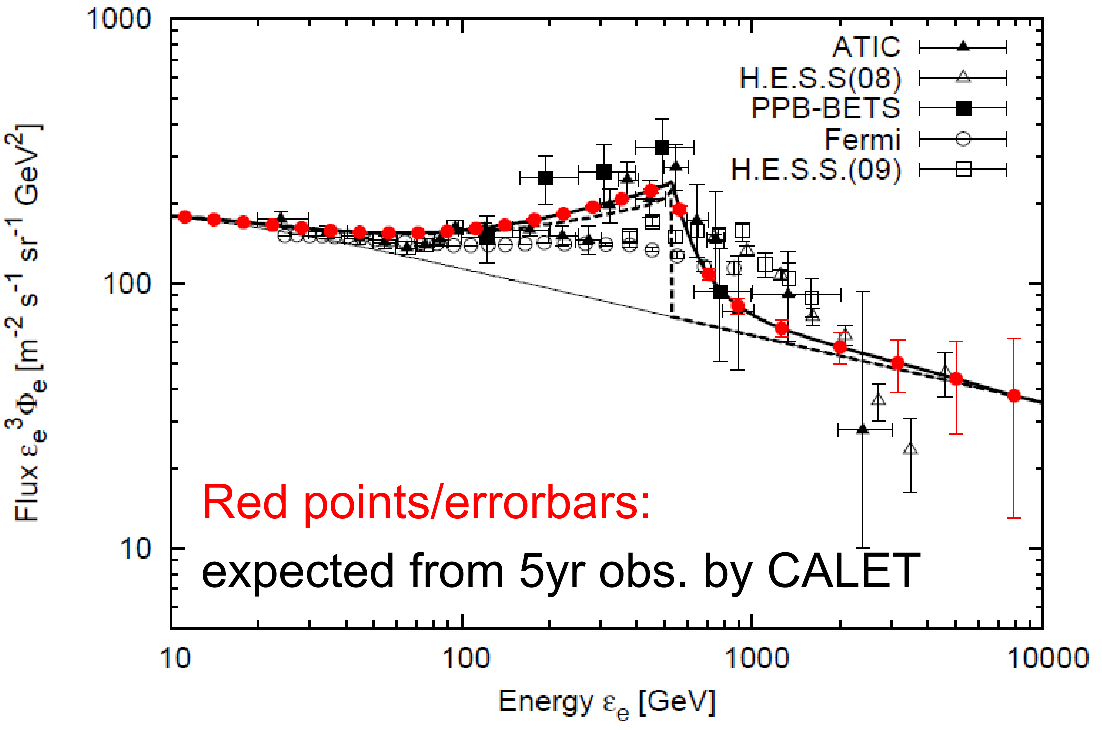
NK+ 2011

→ Direct Evidence of Escape-Limited Model for CR accelerators (=SNR)!

CALorimetric Electron Telescope

- **A dedicated detector for CR electrons on ISS**
- **Japan/Italy/USA**
- **Launched on Aug. 19th, 2015**
- **Energy range: 1 GeV – >~10 TeV**
- **Energy resolution: ~2% (>100GeV)**





Red points/errorbars:
expected from 5yr obs. by CALET

High energy resolution

→ Duration of a source, wiggle in the spectrum

>~ TeV range

→ cutoff, the contribution from young sources

CALET Collaboration

O. Adriani[19], Y. Akaike[3], K. Asano[17], Y. Asaoka[23], M.G. Bagliesi[22], G. Bigongiari[22], W.R. Binns[24], S. Bonechi[22], M. Bongi[19], J.H. Buckley[24], A. Cassese[19], G. Castellini[19], M.L. Cherry[9], G. Collazuol[26], K. Ebisawa[5], V. Di Felice[21], H. Fuke[5], T.G. Guzik[9], T. Hams[30], N. Hasebe[23], M. Hareyama[6], K. Hibino[7], M. Ichimura[2], K. Ioka[8], M.H. Israel[24], A. Javaid[9], E. Kamioka[15], K. Kasahara[23], Y. Katayose[25], J. Kataoka[23], R. Kataoka[32], N. Kawanaka[33], H. Kitamura[11], T. Kotani[23], H.S. Krawczynski[24], J.F. Krizmanic[31], A. Kubota[15], S. Kuramata[2], T. Lomtadze[20], P. Maestro[22], L. Marcelli[21], P.S. Marrocchesi[22], J.W. Mitchell[10], S. Miyake[28], K. Mizutani[14], A.A. Moiseev[30], K. Mori[5,23], M. Mori[13], N. Mori[19], H.M. Motz[23], K. Munakata[16], H. Murakami[23], Y.E. Nakagawa[5], S. Nakahira[5], J. Nishimura[5], S. Okuno[7], J.F. Ormes[18], S. Ozawa[23], F. Palma[21], P. Papini[19], B.F. Rauch[24], S. Ricciarini[19], T. Sakamoto[1], M. Sasaki[30], M. Shibata[25], Y. Shimizu[4], A. Shiomi[12], R. Sparvoli[21], P. Spillantini[19], I. Takahashi[1], M. Takayanagi[5], M. Takita[3], T. Tamura[4,7], N. Tateyama[7], T. Terasawa[3], H. Tomida[5], S. Torii[4,23], Y. Tunesada[17], Y. Uchihori[11], S. Ueno[5], E. Vannuccini[19], J.P. Wefel[9], K. Yamaoka[29], S. Yanagita[27], A. Yoshida[1], K. Yoshida[15], and T. Yuda[3]

1) Aoyama Gakuin University, Japan
2) Hirosaki University, Japan
3) ICRR, University of Tokyo, Japan
4) JAXA/SEUC, Japan
5) JAXA/ISAS, Japan
6) St. Manianna University School of Medicine, Japan
7) Kanagawa University, Japan
8) KEK, Japan
9) Louisiana State University, USA
10) NASA/GSFC, USA
11) National Inst. of Radiological Sciences, Japan
12) Nihon University, Japan
13) Ritsumeikan University, Japan
14) Saitama University, Japan
15) Shibaura Institute of Technology, Japan
16) Shinshu University, Japan
17) Tokyo Institute of Technology, Japan
18) University of Denver, USA
19) University of Florence, IFAC (CNR) and INFN, Italy
20) University of Pisa and INFN, Italy
21) University of Rome Tor Vergata and INFN, Italy
22) University of Siena and INFN, Italy
23) Waseda University, Japan
24) Washington University-St. Louis, USA
25) Yokohama National University, Japan
26) University of Padova and INFN, Italy
27) Ibaraki University, Japan
28) Ibaraki National College of Technology, Japan
29) Nagoya University, Japan
30) CRESST/NASA/GSFC and University of Maryland, USA
31) CRESST/NASA/GSFC and Universities Space Research Association, USA
32) National Institute of Polar Research, Japan
33) The University of Tokyo, Japan

Summary

- Why are CR electrons/positrons interesting?

→ Their excesses have been reported by PAMELA/AMS-02 (e^+) and Fermi/ATIC/PPB-BETS ($e^\pm$)

- What is the difference between CR $e^\pm$ and CR nuclei?

→ Younger (Older) sources can contribute to the higher (lower) energy range of the CR $e^\pm$ flux due to their fast energy loss during the propagation

- What is the candidate of CR $e^\pm$ sources?

→ Pulsars, SNRs, GRBs, Galactic BHs, WDs, MSPs,…

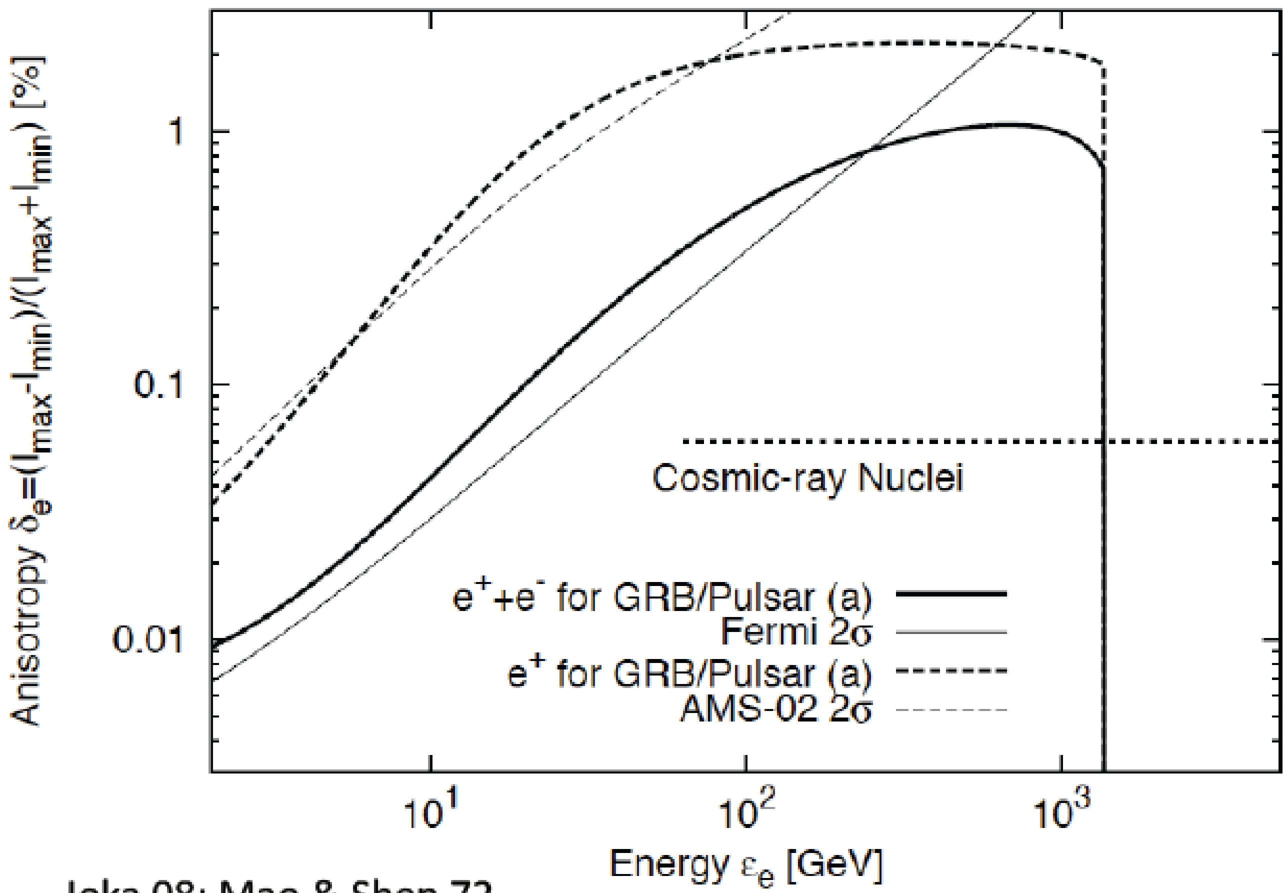
- What will the future experiments tell us about CR $e^\pm$ source?

→ Cutoff and its shape (age and duration), wiggleness (number of sources), contribution from a single, young CR source in the high energy range (>~TeV)

Backup Slides

anisotropy

predicted in the case of a single energetic source



Ioka 08; Mao & Shen 72

$$\delta = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}}$$

$$= \frac{3K|\nabla f|}{cf}$$

$$\sim \frac{3d}{2ct} @ \varepsilon_e \sim \varepsilon_{\max}$$

Why are the PAMELA/AMS-02 results "anomaly"?

Positrons are generated from CR protons (secondary origin)

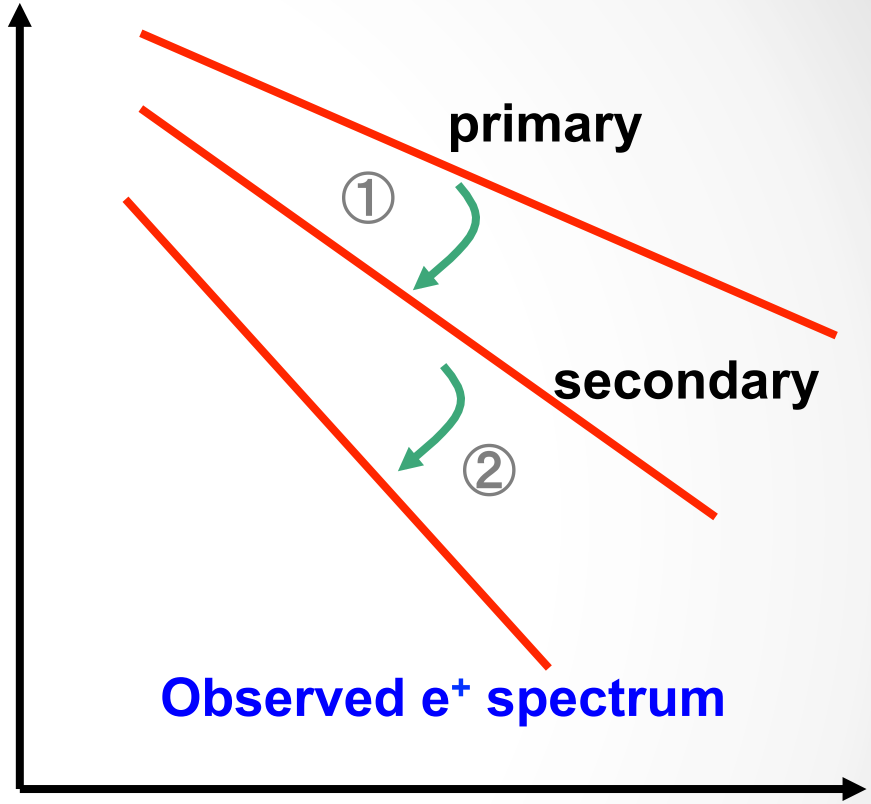
Higher energy protons can escape the Galaxy earlier

→ Higher energy positrons are less produced: ①

→ Observed positron spectrum becomes softer because of the escape and energy loss: ②

Electrons: primary origin

→ Spectral change should be only from ②



CR e^+ spectrum should be softer than that of e^-

Diffusion coefficient: secondary CRs

primary : accelerated at the sources such as SNRs (p, e^-, C, N, O, Fe etc.)

secondary : produced during the propagation of primary CRs (e^+, $\bar{p}$, Li, Be, B, Ti etc.)

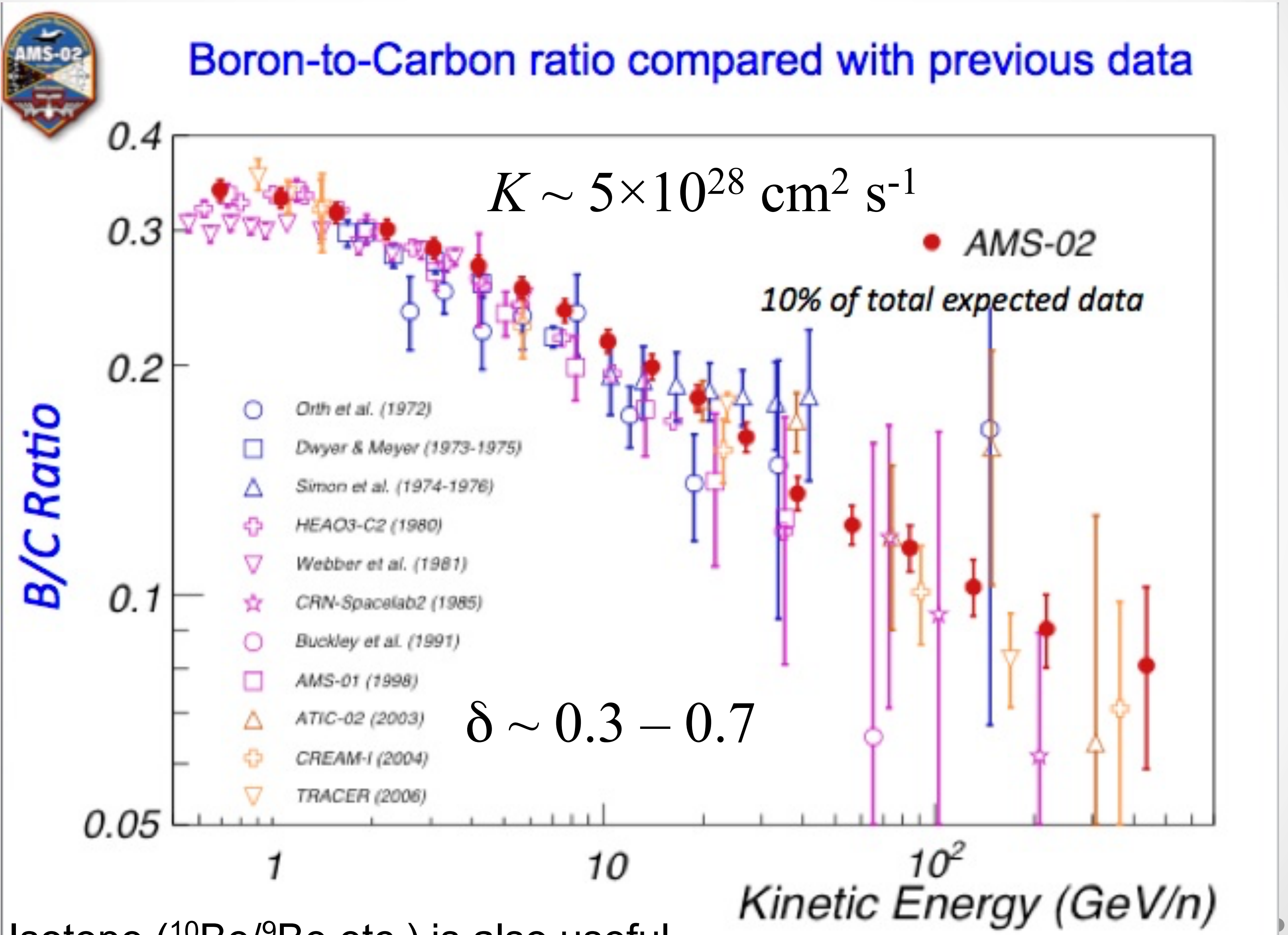
Created as fragmentation products of the interactions of heavier CR nuclei with ISM

energy dependence of (secondary) / (primary)

→ t_{trap} and its energy dependence

→ diffusion coefficient $K(\varepsilon)$

Recent results (AMS-02)



$K \sim 5\times10^{28}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$

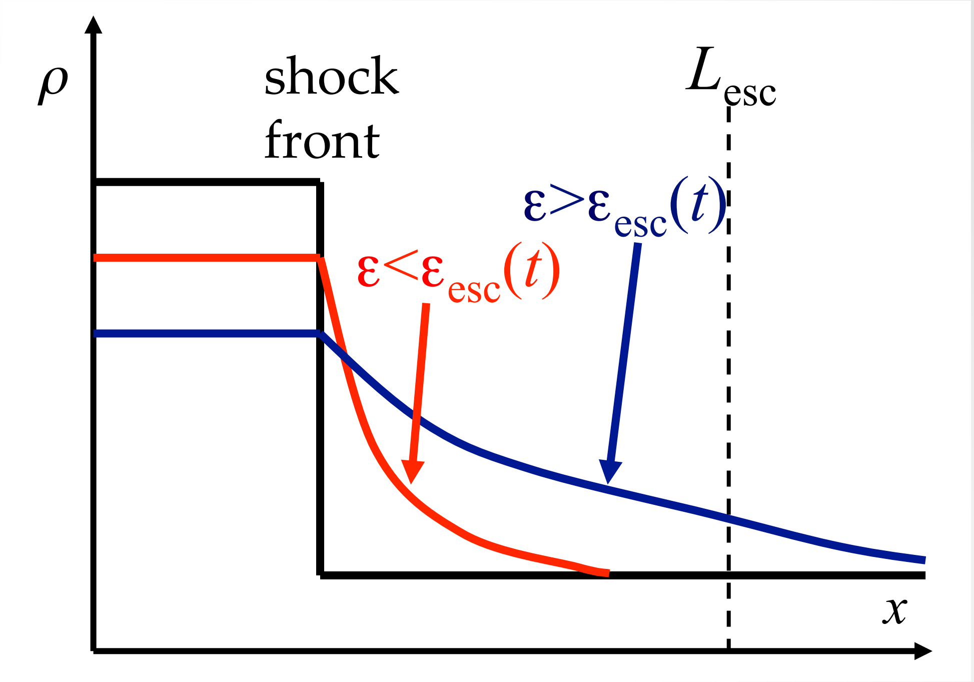
$\delta \sim 0.3 - 0.7$

- Isotope (^{10}Be/^{9}Be etc.) is also useful.

CR escape from SNRs

(Ptuskin & Zirakashvili 05; Caprioli+ 09; Gabici+ 09; Ohira+ 10 etc.)

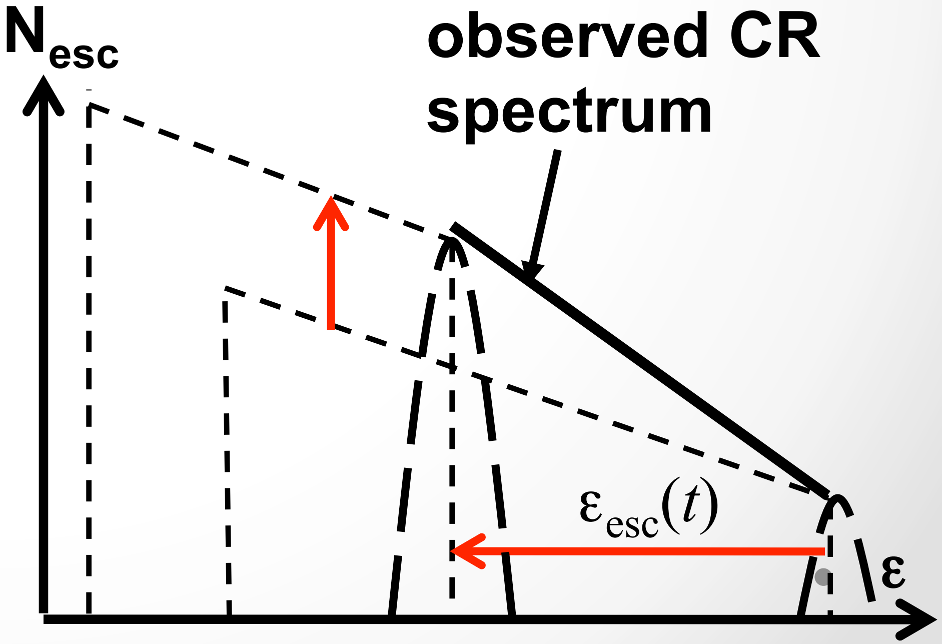
- The particles with highest energy can escape the SNR shock at the beginning of the Sedov phase
- As the shock decelerates, lower energy particles become able to escape the shock

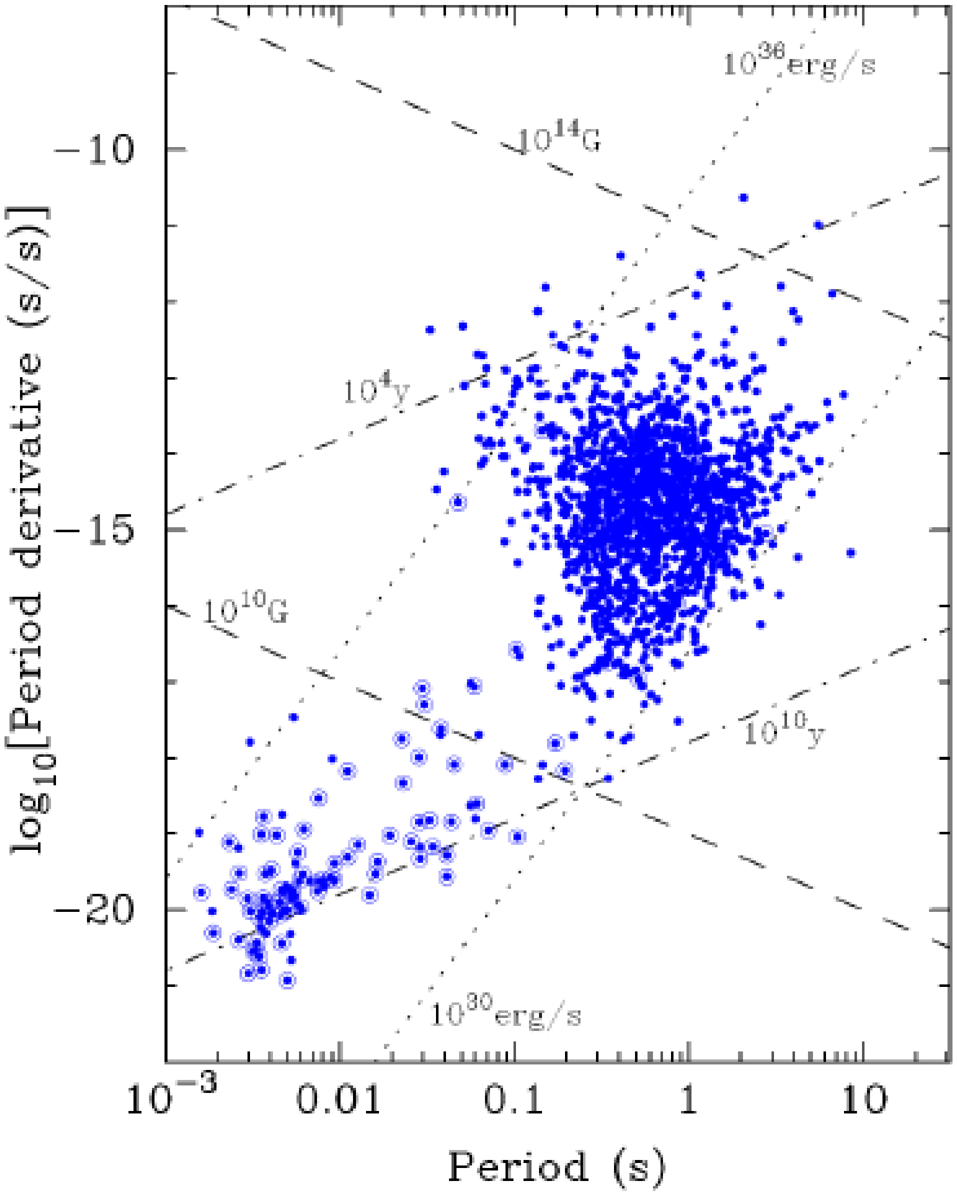


If the CR injection rate increases with time, the observed CR spectrum would become softer

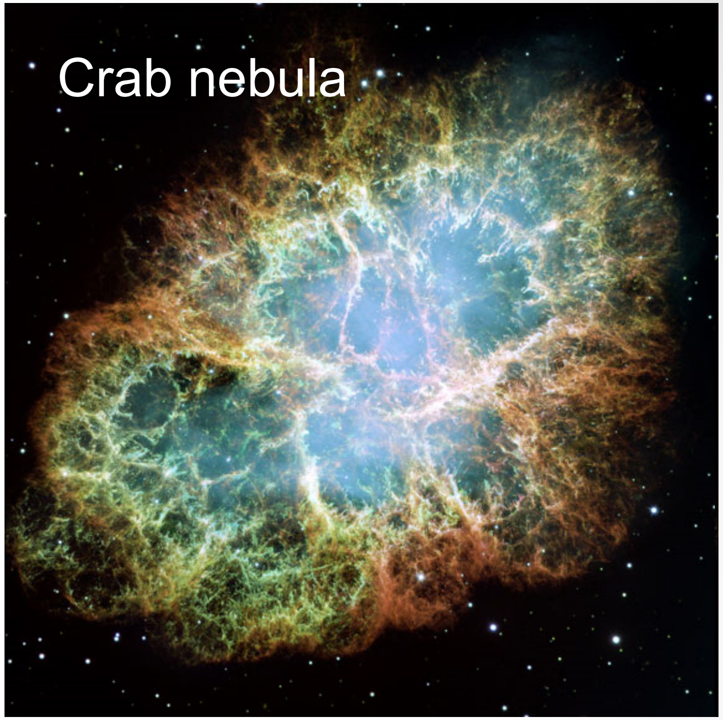
→ consistent with observations (CR spectrum $\propto \varepsilon^{-2.7}$)

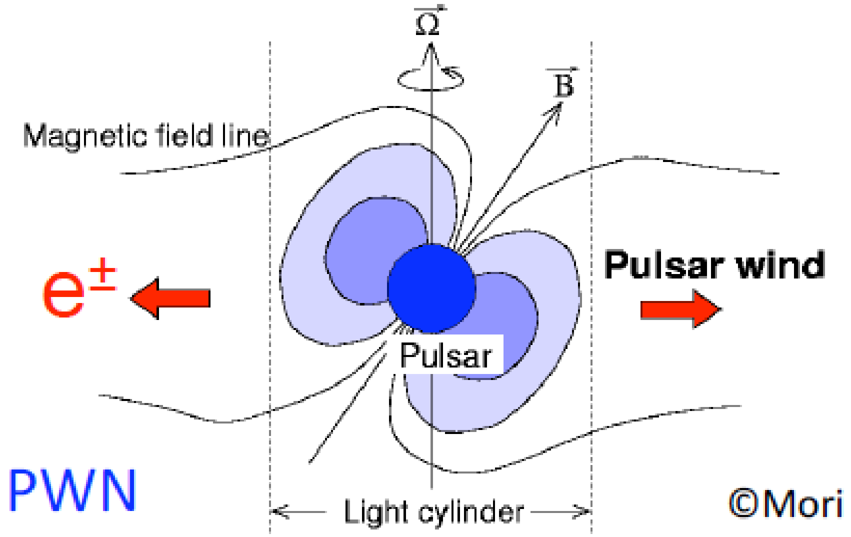
γ-ray spectra of SNRs (Ohira+ 10), CR helium hardening (Ohira, NK+ 16)





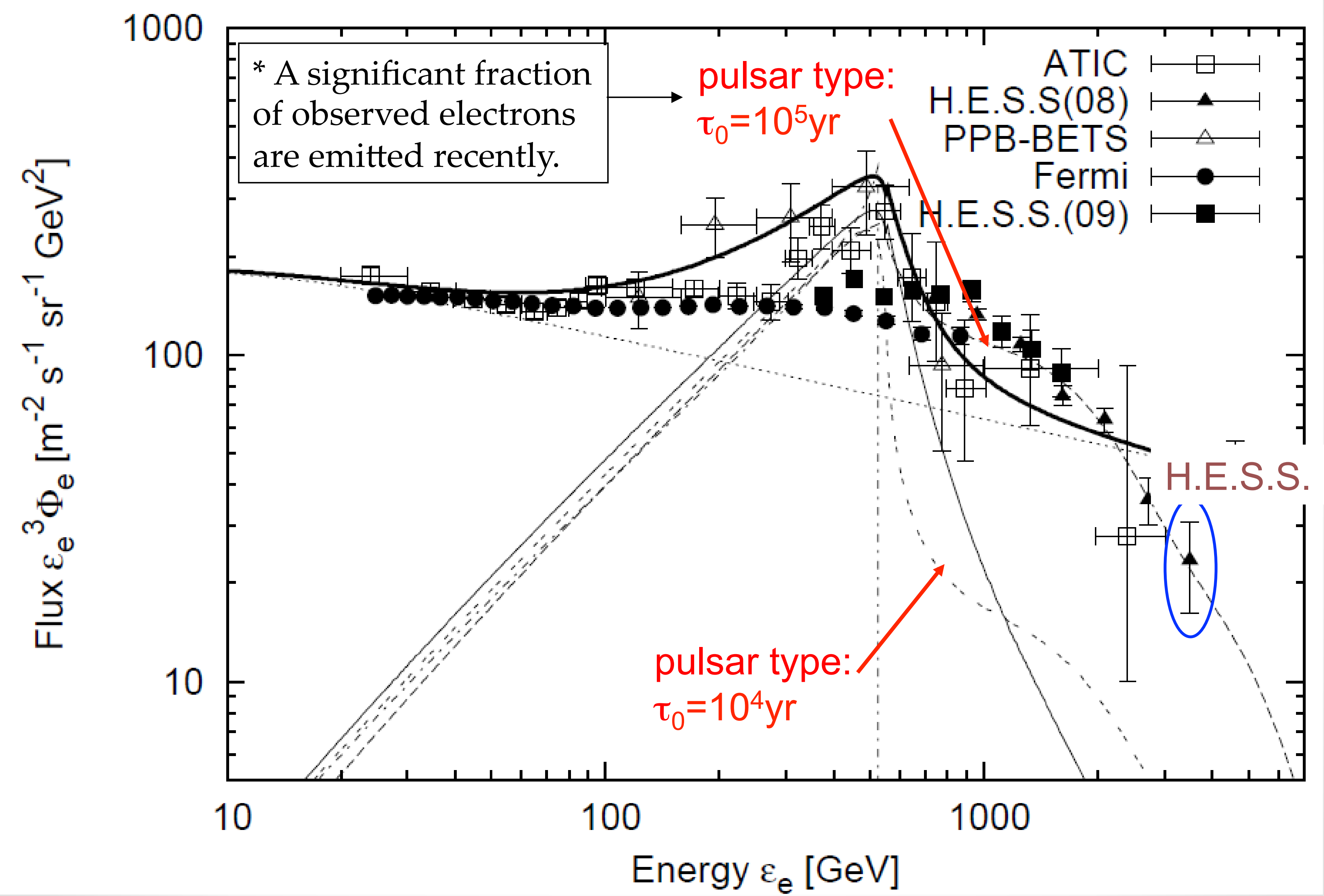
Lorimer 08





©Mori

Constraints on pulsar-type decay time



* A significant fraction of observed electrons are emitted recently.

pulsar type: $\tau_0=10^5$yr

pulsar type: $\tau_0=10^4$yr

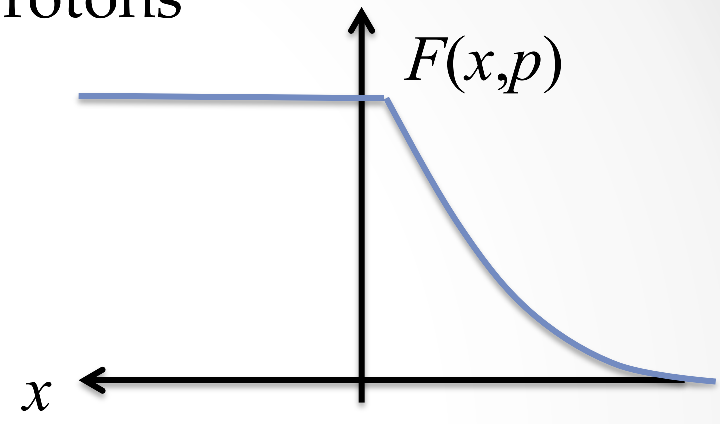
H.E.S.S.

Positron excess by SNRs

Blasi (2009) etc.

distribution function of accelerated protons

$$f_1(x,p) \propto p^{-\gamma} F(x,p)$$



$$F(x,p) = \begin{cases} 1 & \text{for } x>0 \\ \exp[ux/D(p)] & \text{for } x<0 \end{cases}$$

u: upstream velocity (=shock velocity)
$D(p)$: diffusion coefficient
γ~4（non-relativistic shock）

e^+ injection at the shock being proportional to $F(x,p)$: $Q_2(x,p)$

diffusion-convection eq. $$u\frac{\partial f_2}{\partial x} = D(p)\frac{\partial^2 f_2}{\partial x^2} + \frac{1}{3}\frac{du}{dx}p\frac{\partial f_2}{\partial p} + Q_2(x,p)$$

Solution at the shock: $$f_2(0,p) \propto \int_0^p \frac{dp'}{p'}\left(\frac{p'}{p}\right)^{\gamma}\frac{D(p')}{u^2}Q_2(p')$$

∴ $D(p) \propto p^{\alpha}(\alpha>0)$ → $f_2(0,p) \sim p^{-\gamma+\alpha}$: harder than protons

Qualitative interpretation

Protons are Shock-accelerated

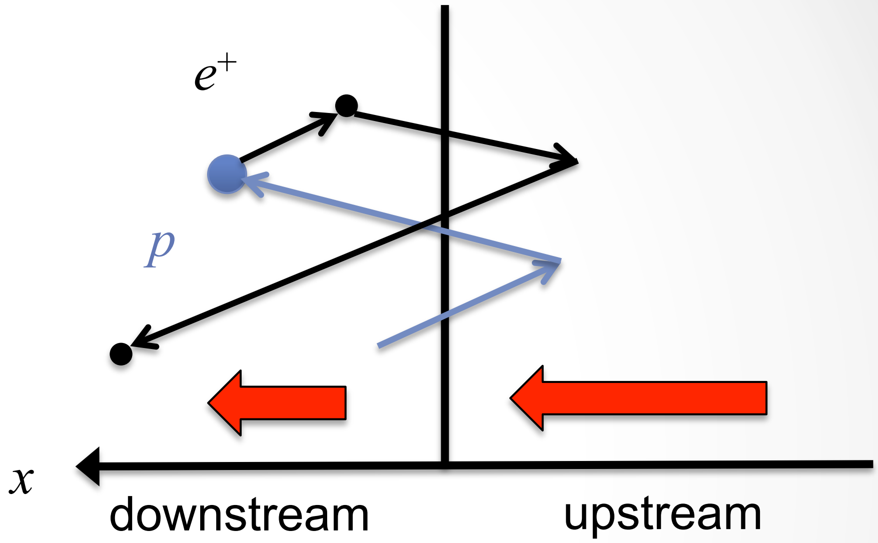
→ Interactions with surrounding medium

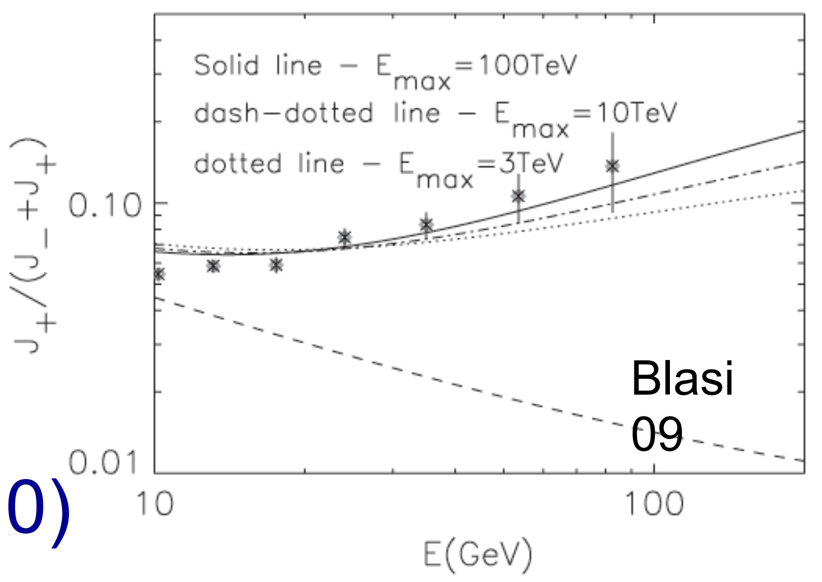
→ e^+ production via *pp* collisions

→ e^+ are also shock-accelerated

→ Higher energy e^+ are accelerated for a longer time

→ rising e^+ fraction





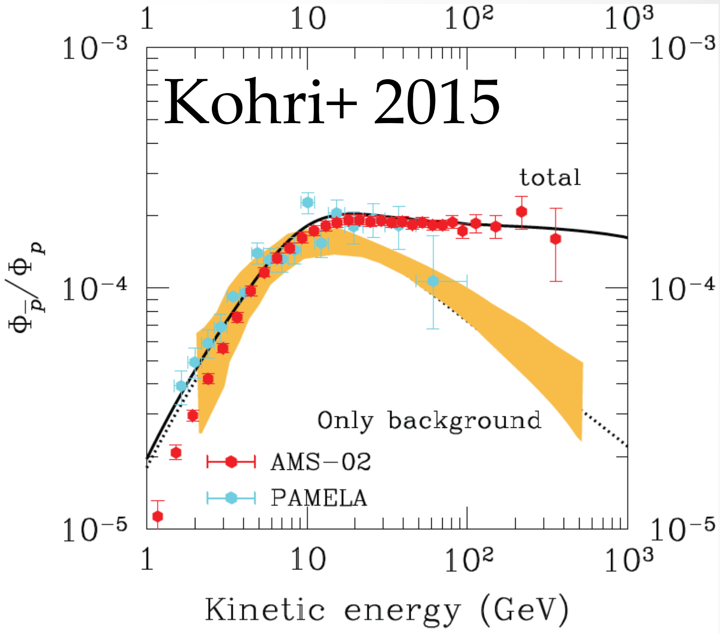
However, see NK 12 (1207.0010)

How to test the hadronic scenarios

1. Antiproton spectrum

pp interactions would produce not only positrons but also antiproton

→ Excess from the standard prediction



2. The ratio of secondary-to-primary nuclei

Heavy nuclei are also accelerated

→ Excess of secondary-to-primary ratio (B/C, Ti/Fe etc.) due to spallations