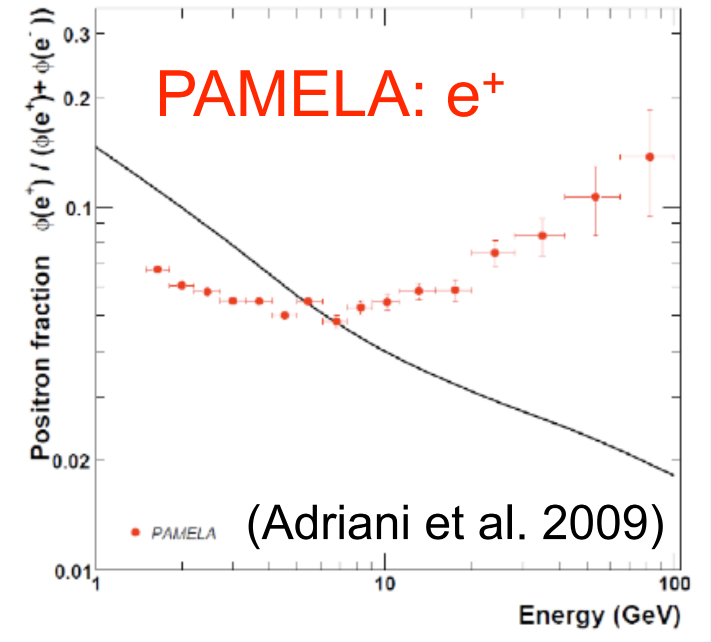
Injections of $e^{\pm}$ from Nearby Pulsars and their GeV/TeV Spectral Features

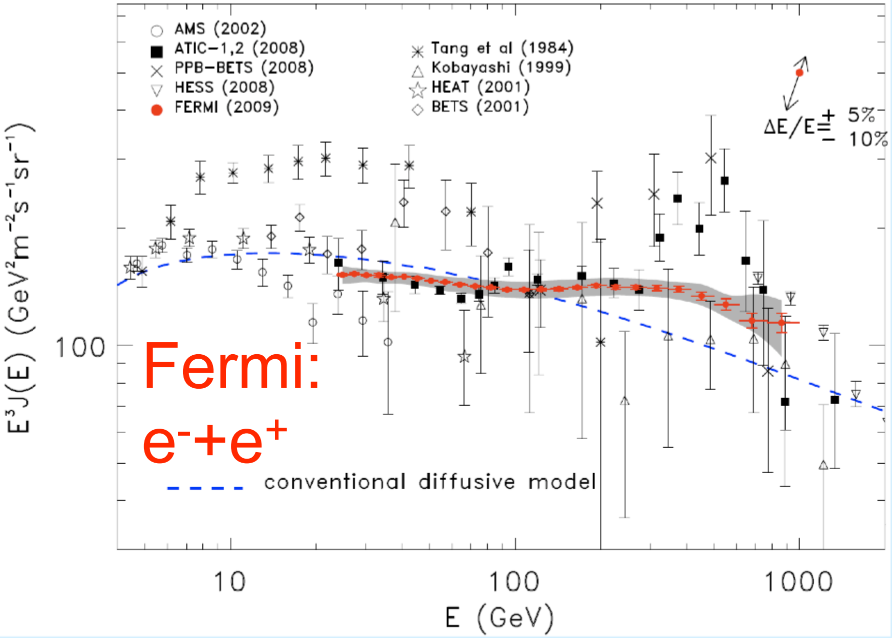
(NK, Ioka & Nojiri 2010, ApJ, **710**, 958)
(NK, Ioka, Ohira & Kashiyama 2010 in prep.)

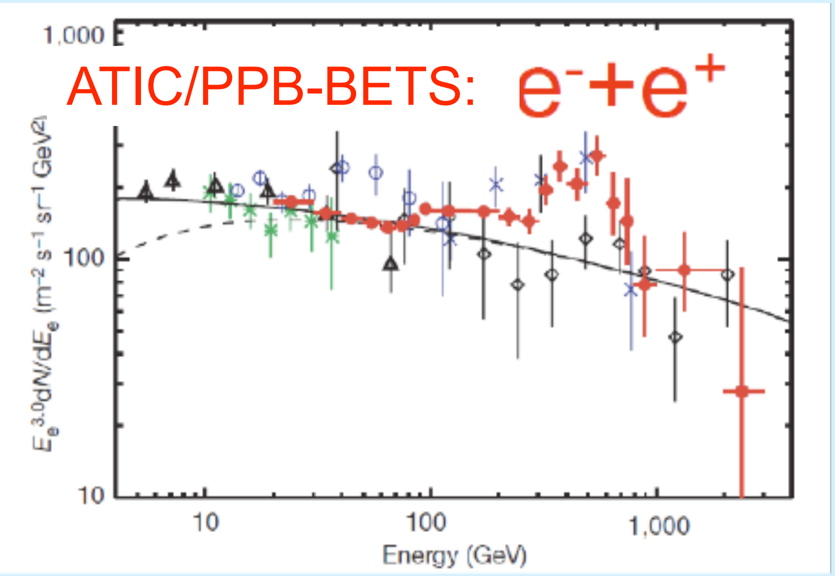
Norita Kawanaka (KEK, Japan)

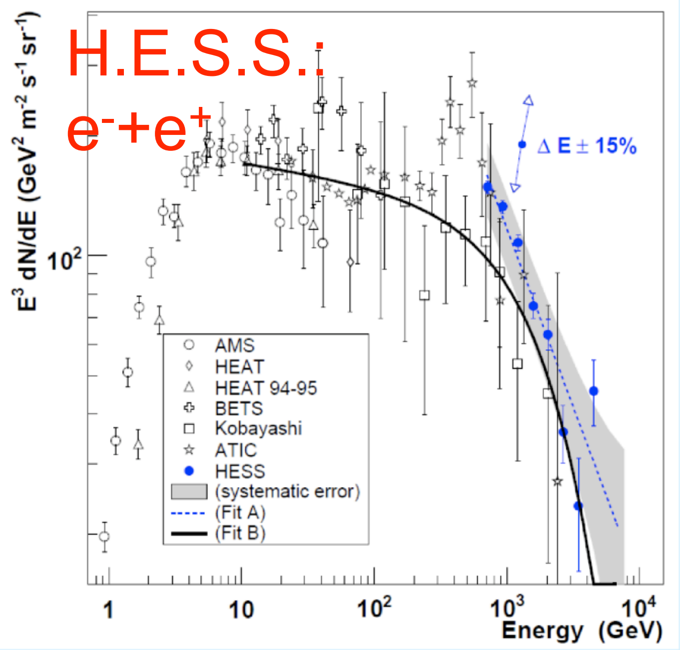
TeV Particle Astrophysics@Paris 2010/7/22

Electron/Positron Excess





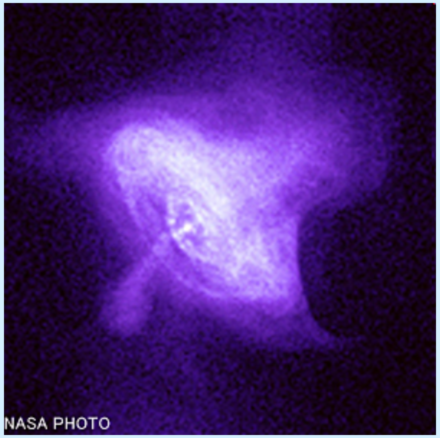


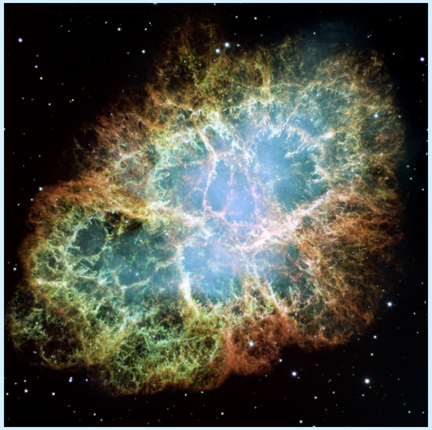


Astrophysical Origin

- Pulsar

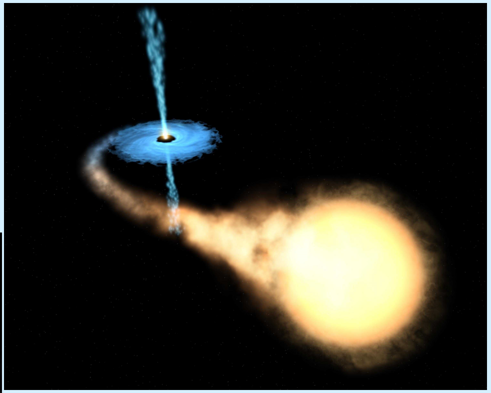
Shen 70; Aharonian+ 95; Atoyan et al. 95; Chi+ 96; Zhang & Cheng 01; Grimani 07; Yuksel+ 08; Buesching+ 08; Hooper+ 08; Profumo 08; Malyshev+09; Grasso+ 09; NK, Ioka & Nojiri 10





- Supernova Remnant

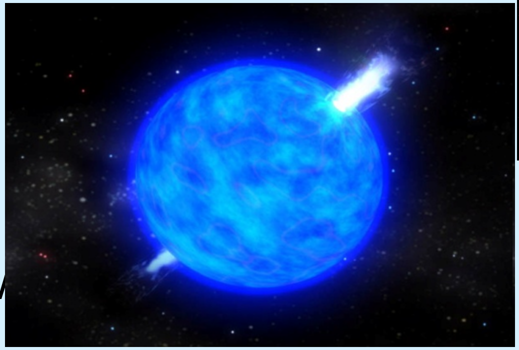
Shen & Berkey 68; Pohl & Esposito 98; Kobayashi+ 04; Shaviv+ 09; Hu+ 09; Fujita, Kohri, Yamazaki & Ioka 09; Blasi 09; Blasi & Serpico 09; Mertsch&Sarkar 09; Biermann+ 09; Ahlers, Mertsch & Sarkar 09



- Microquasar (Galactic BH)

Heinz & Sunyaev 02

- Gamma-Ray Burst Ioka 10



- Propagation Effect

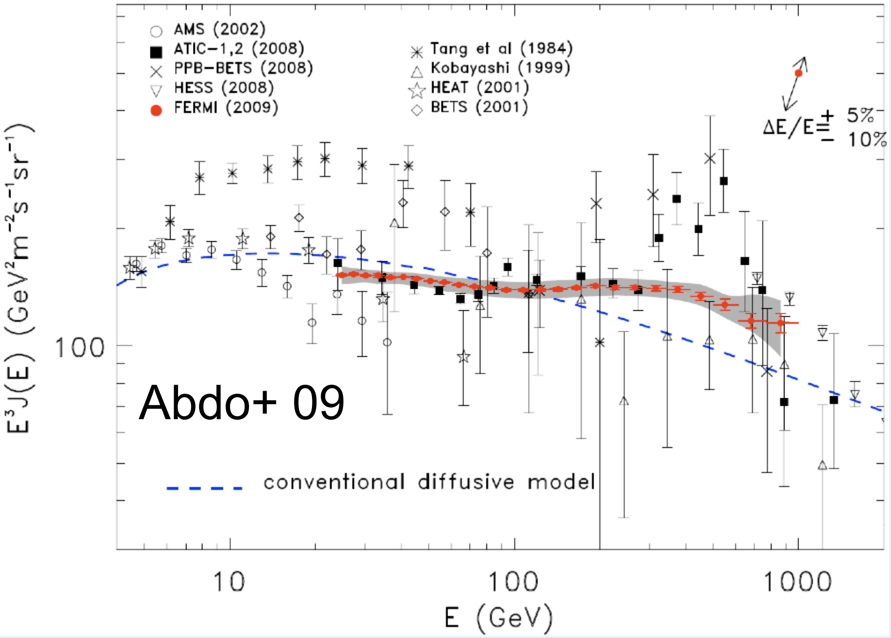
Delahaye+ 08; Cowsik & Burch 09; Staw +09; Schlickeiser & Ruppel 09

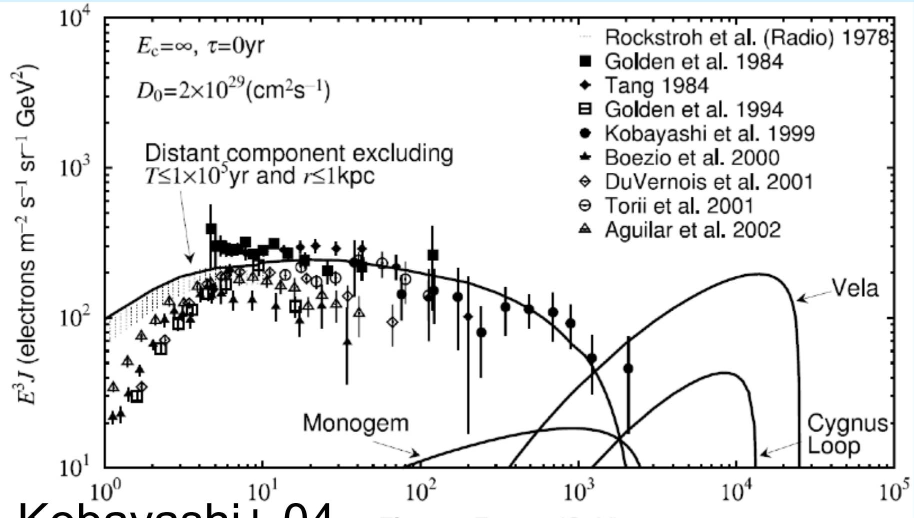
GeV/TeV Spectral Features of $e^- + e^+$

ATIC/PPB-BETS: sharp peak and (possibly) gradual decline ~600GeV

Fermi/H.E.S.S.: ~ε_e^{-3} spectrum with a cutoff ~ a few TeV

Future Observations (AMS-02/ CALET etc.): contributions from young sources are expected above ~1-10TeV





Kobayashi+ 04

CR Propagation Equation and Solution

- diffusion equation

$$\frac{\partial}{\partial t} f(t,\vec{r},\varepsilon_e) = \underbrace{K(\varepsilon_e)\nabla^2 f}_{\text{diffusion}} + \underbrace{\frac{\partial}{\partial \varepsilon_e}\left[P(\varepsilon_e) f\right]}_{\text{energy loss}} + \underbrace{Q(t,\vec{r},\varepsilon_e)}_{\text{injection}}$$

diffusion

injection

energy loss (synchrotron, inverse Compton scattering)

B/C ratio

$$K(\varepsilon_e) = K_0(1+\varepsilon_e/3\mathrm{GeV})^\delta,\ K_0 = 5.8\times10^{28}\,\mathrm{cm^2 s^{-1}}, \delta = 1/3$$

$$P(\varepsilon_e) \approx -b\varepsilon_e^2, b = 10^{-16}\,\mathrm{GeV^{-3} s^{-1}}$$

Galactic Magnetic Fields & Radiation Fields (Thomson limit)

→ Spectrum from instantaneous injection from a point source (Atoyan+ 1995)

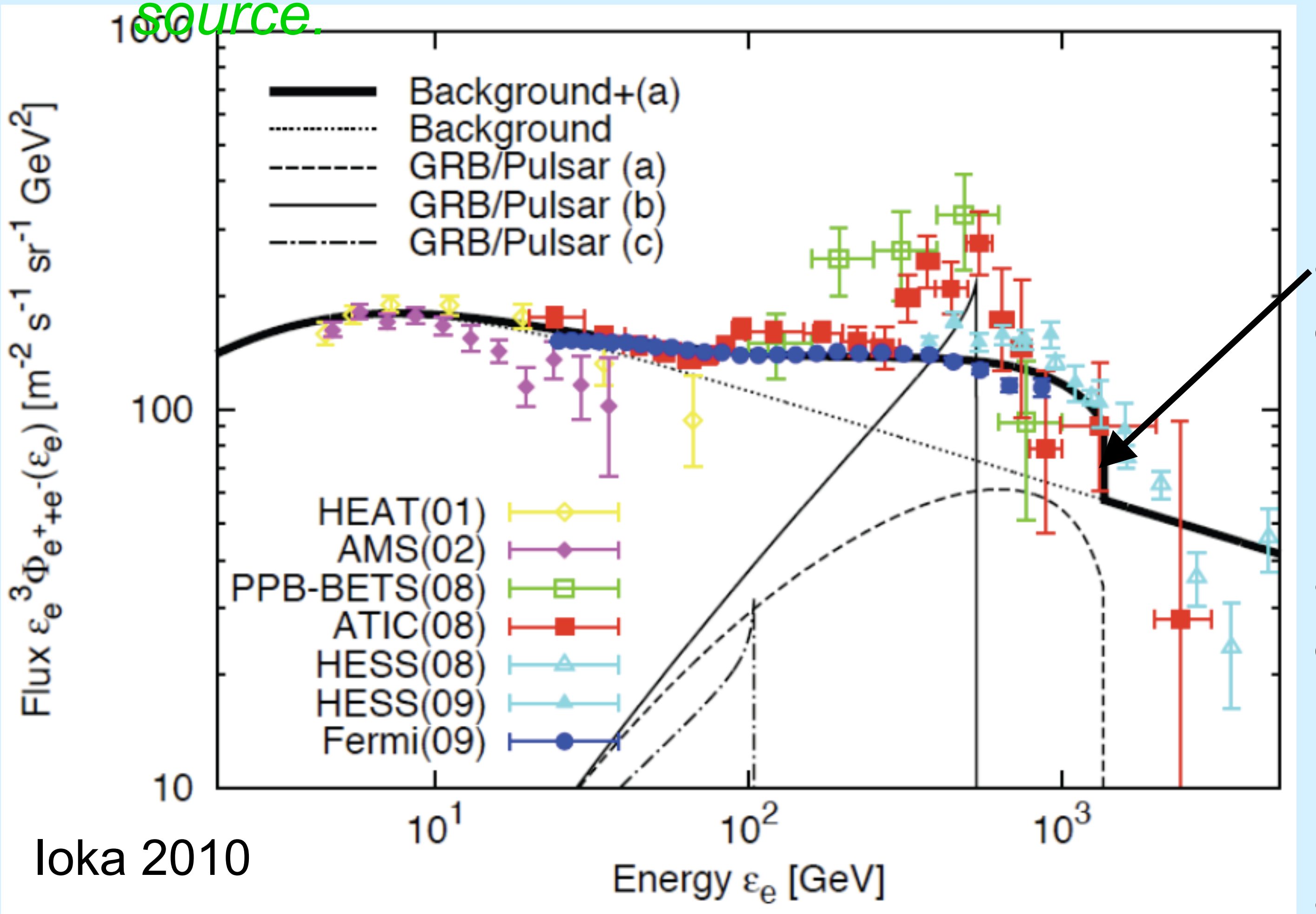
$$G(t,\vec{r},\varepsilon_e;t_0) = \frac{\dot{N}_e(\varepsilon_{e,0},t)P(\varepsilon_{e,0})}{\pi^{3/2} r_{diff}^3 P(\varepsilon_e)} \exp\left(-\frac{r^2}{r_{diff}^2}\right)$$

$\varepsilon_{e,0}$: electron energy at t_0

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

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

The cutoff energy corresponds to the age of the source.



d=1kpc

(a)
$E=0.9\times10^{50}$erg
age=2×10^5yr
$\alpha=2.5$

(b)
$E=0.8\times10^{50}$erg
age=5.6×10^5yr
$\alpha=1.8$

(c)
$E=3\times10^{50}$erg
age=3×10^6yr
$\alpha=1.8$

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

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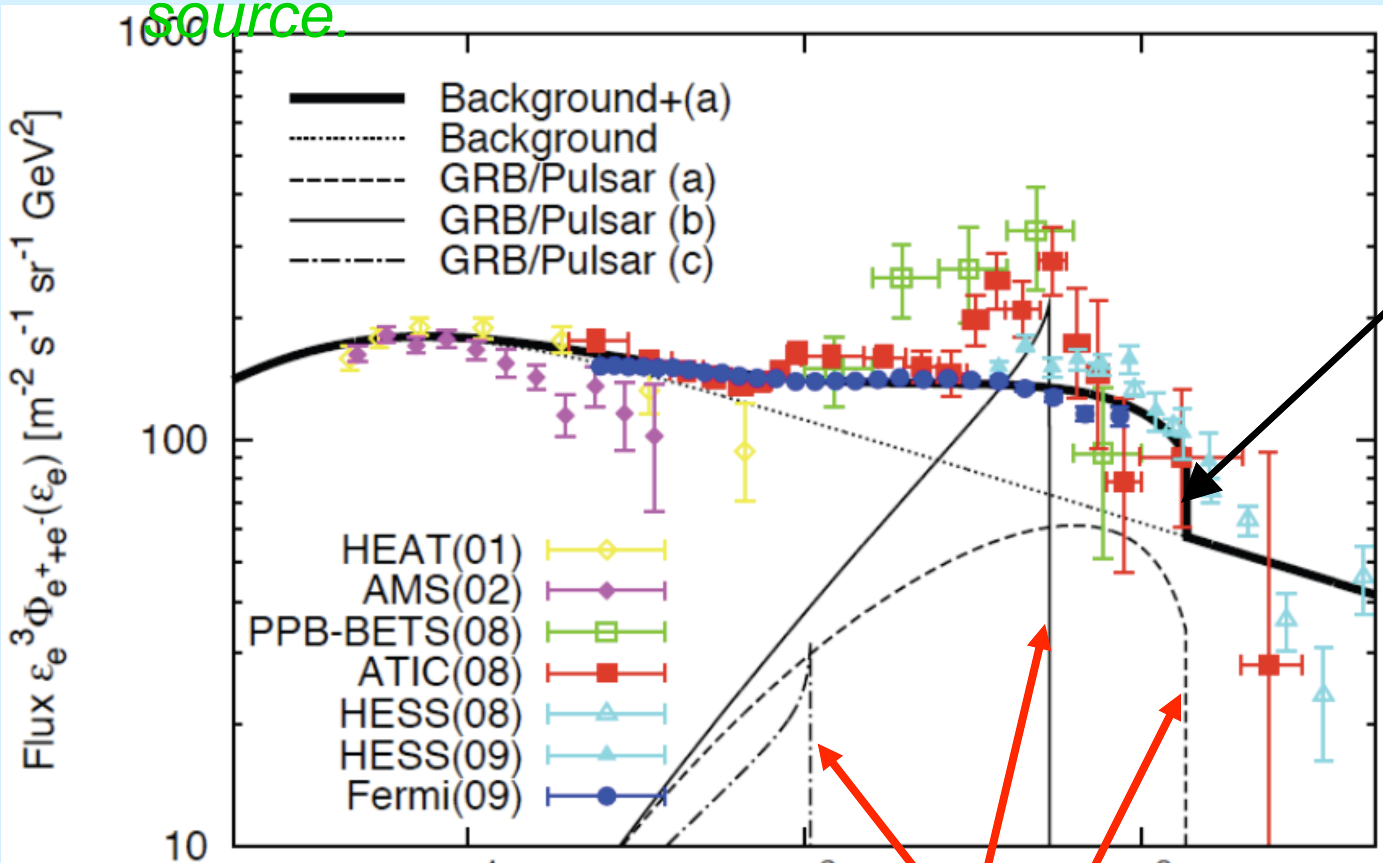

Ioka 2010

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

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

Instantaneous injection → sharp cutoff at $\varepsilon_e \sim 1/bt$

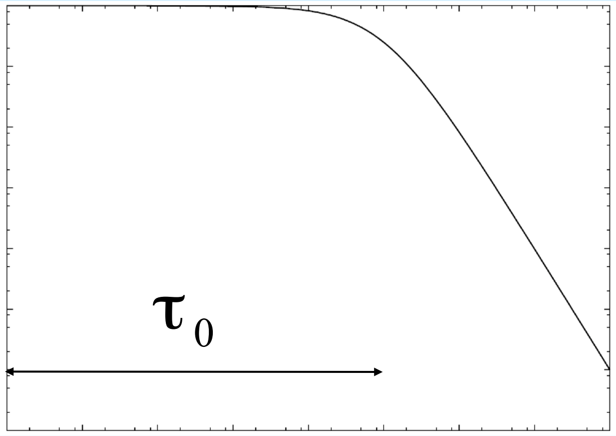
ATIC/PPB-BETS peak may be broadened.

→ Continuous $e^+ + e^-$ injection?

Case 1: pulsar-type decay

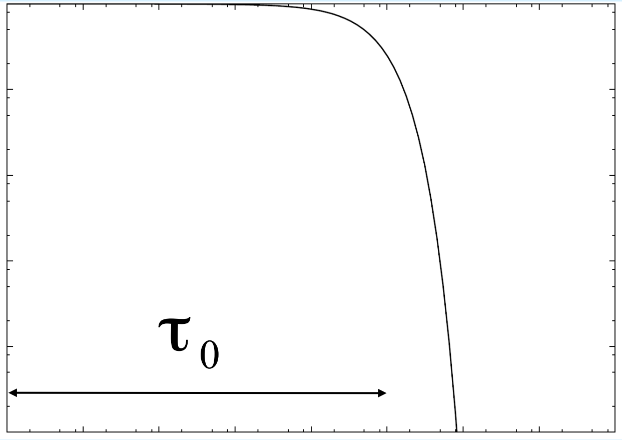
$$Q_0(t) \propto L_{\rm spindown} = \frac{E_{tot}}{\tau_0 (1 + t/\tau_0)^2}$$

cf.) $\tau_0 = 7.4 \times 10^3 (B/10^{12}\,{\rm G})^{-2} P_{10{\rm ms}}^2$ years

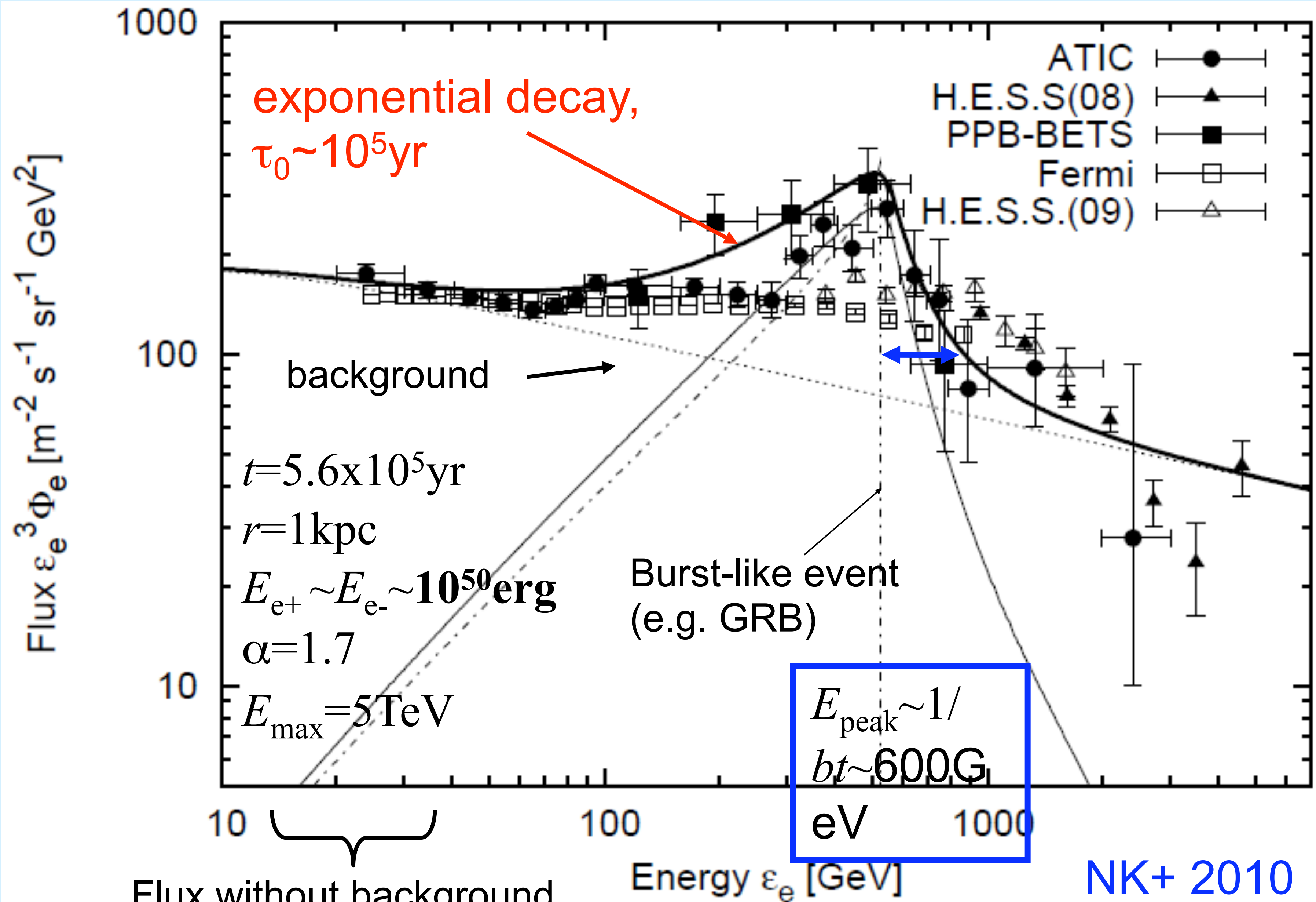


Case 2: exponential decay

$$Q_0(t) \propto \frac{E_{tot} \ln 4}{\tau_0} \exp\left(-\frac{t \ln 4}{\tau_0}\right)$$



Broadened Peak



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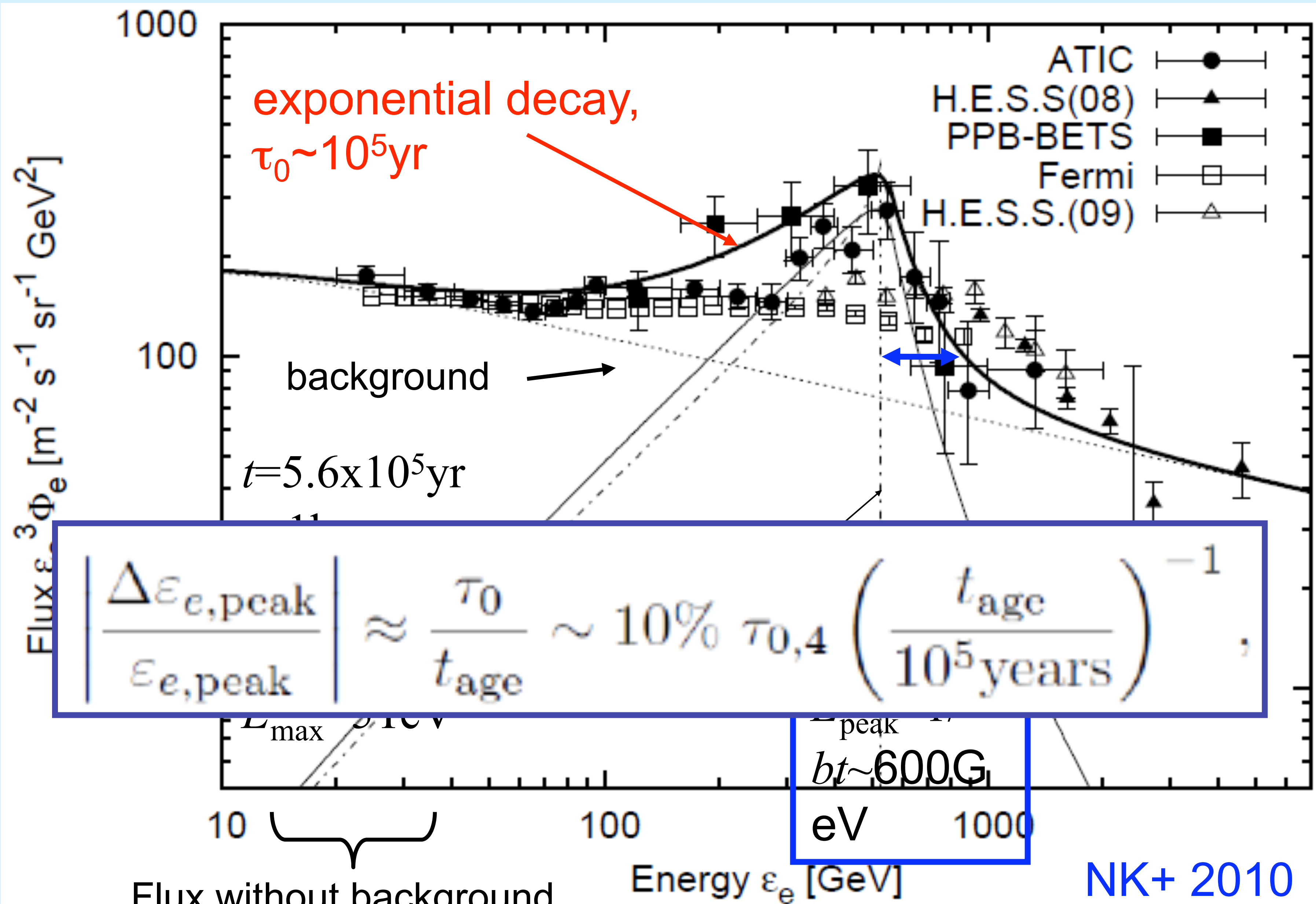
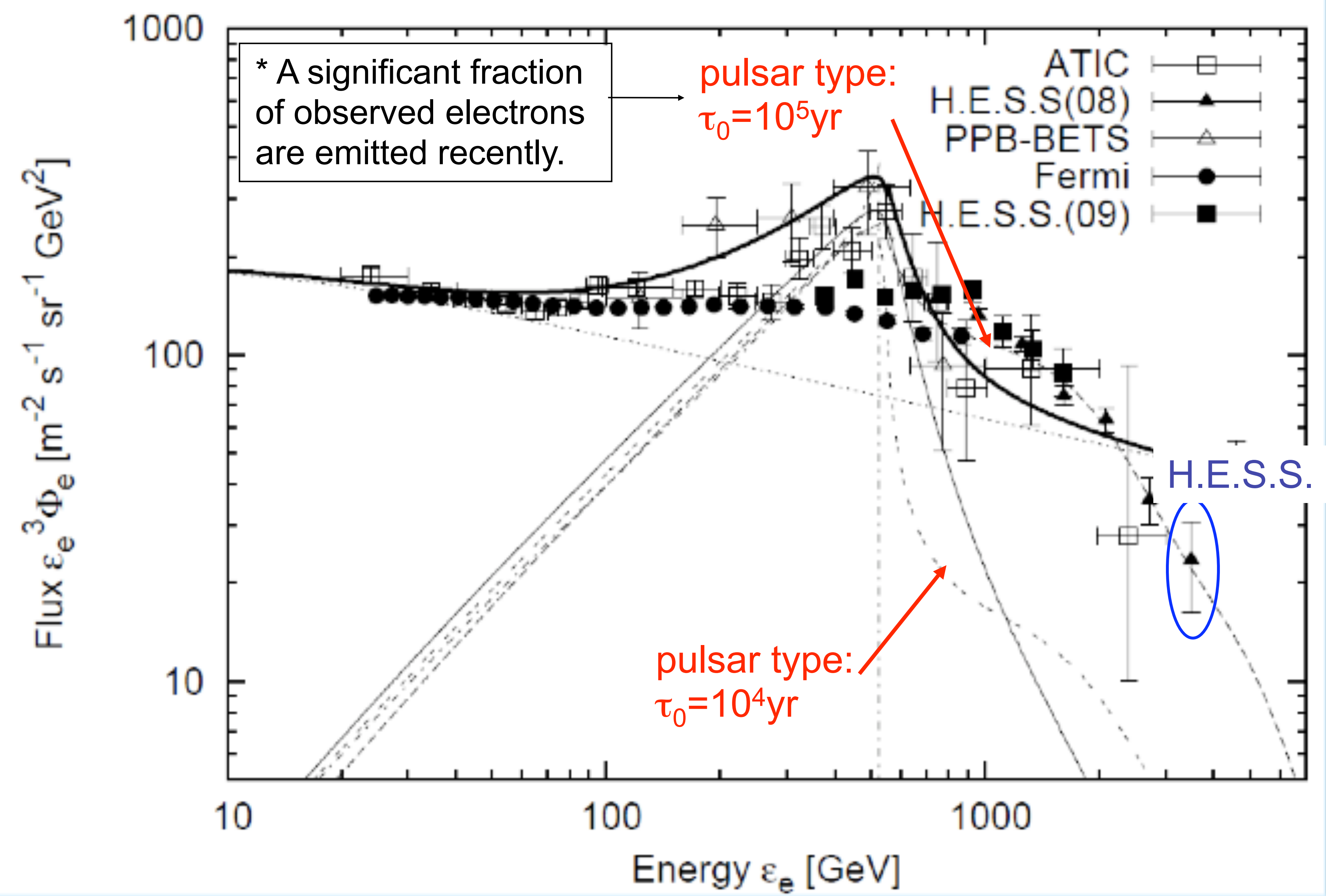


$$\left|\frac{\Delta\varepsilon_{e,\mathrm{peak}}}{\varepsilon_{e,\mathrm{peak}}}\right| \approx \frac{\tau_0}{t_{\mathrm{age}}} \sim 10\%\ \tau_{0,4}\left(\frac{t_{\mathrm{age}}}{10^5\mathrm{years}}\right)^{-1},$$

Constraints on pulsar-type decay time



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

- Total injection energy required to account for the peak of ATIC/PPB-BETS ~ **10^{50}erg**

  ~ Rotation energy of a pulsar with $P_0 \sim 10$msec

  Too efficient?

- Local pulsar birth rate $\sim 10^{-5}\ \mathrm{yr}^{-1}\ \mathrm{kpc}^{-2}$ (Narayan 1985; Lorimer+1994)

  Pulsars which have not observed (e.g. off-beam) should contribute significantly.

  Young pulsars (age<5×10^5yr) should exist.

- The peak might be made by a pulsar with an extraordinary large amount of energy.

- ***Then, what is the spectrum like <u>on average?</u>***

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

NK+ 2010

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

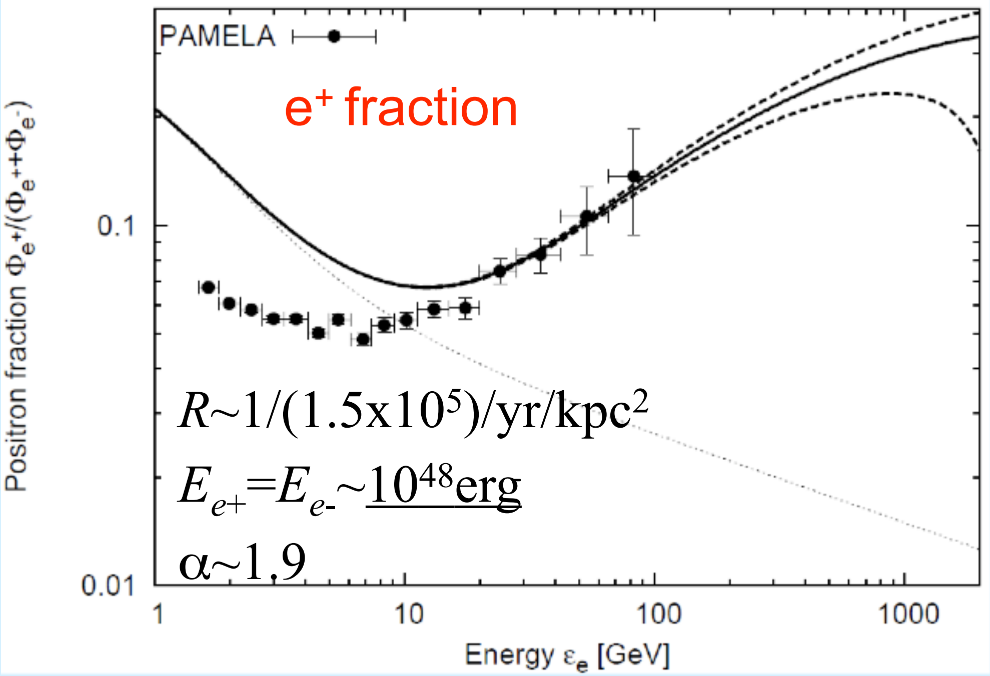
Number of sources which contribute to the energy bin of ε_e

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

$$\sim 6\left(\frac{\varepsilon_e}{\rm TeV}\right)^{-5/3}\left(\frac{R}{1/(1.5\times 10^5)\,{\rm yr}^{-1}{\rm kpc}^{-2}}\right)$$

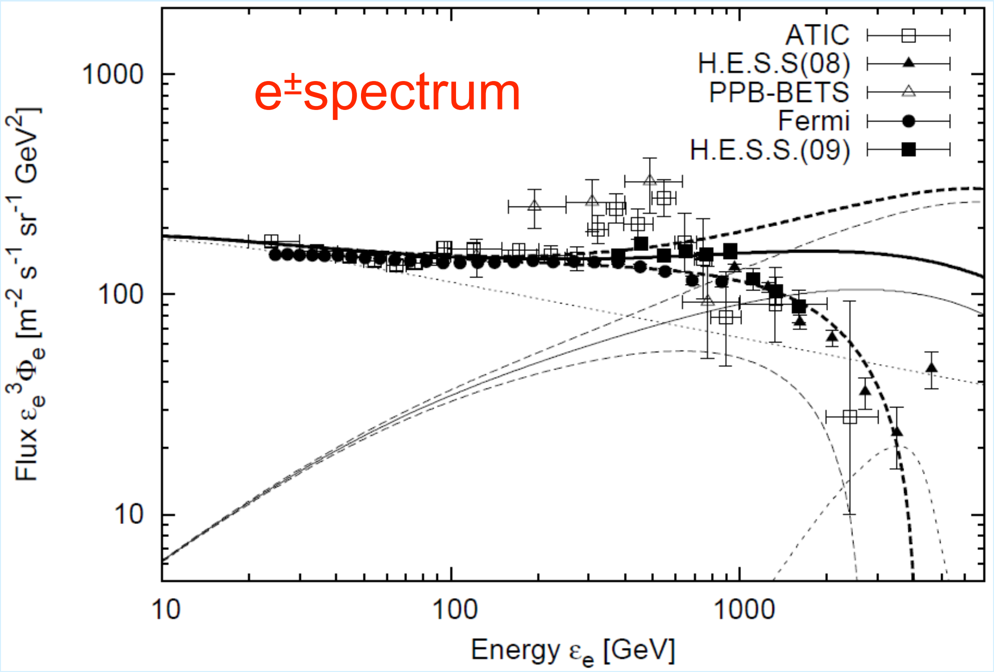
Assuming the Poisson statistics of the source distribution,

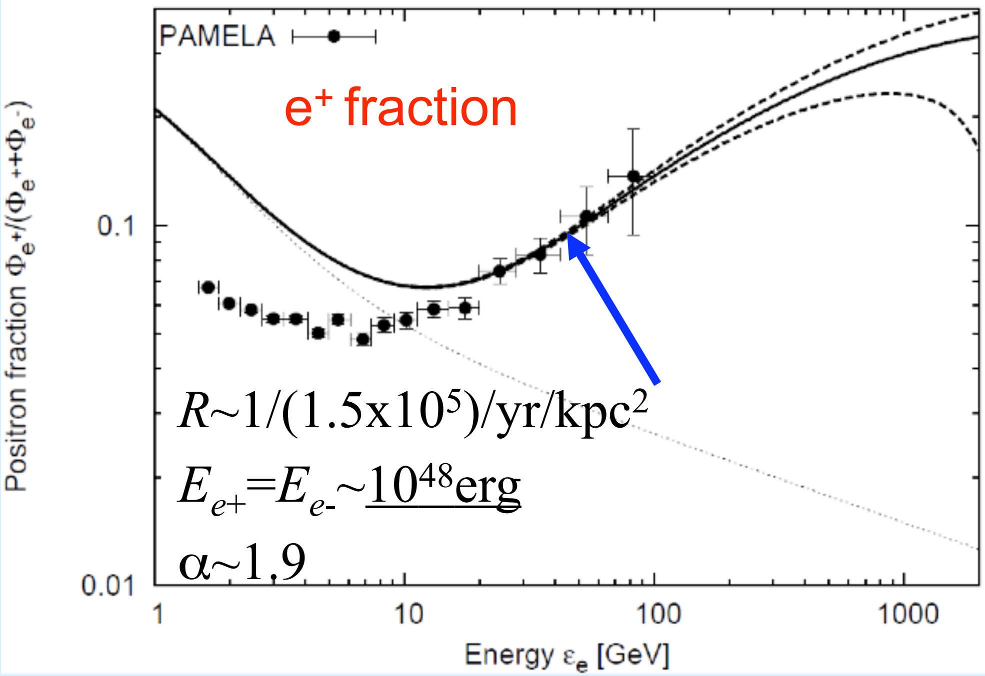
$$\Delta f_{\rm ave}(\varepsilon_e) = f_{\rm ave}(\varepsilon_e)/\sqrt{N(\varepsilon_e)}$$



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

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





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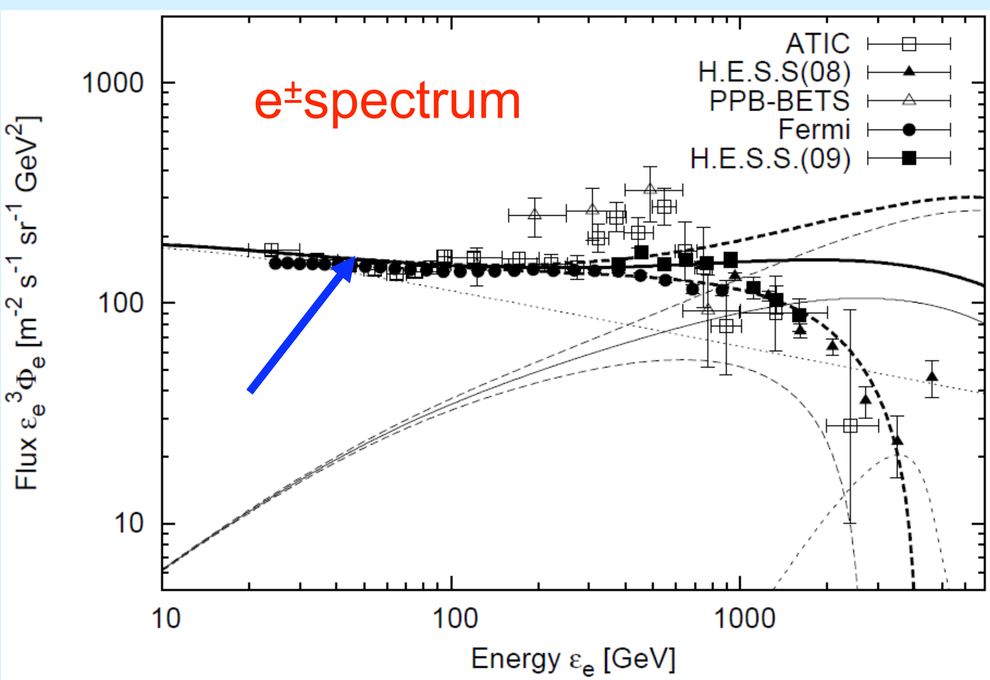
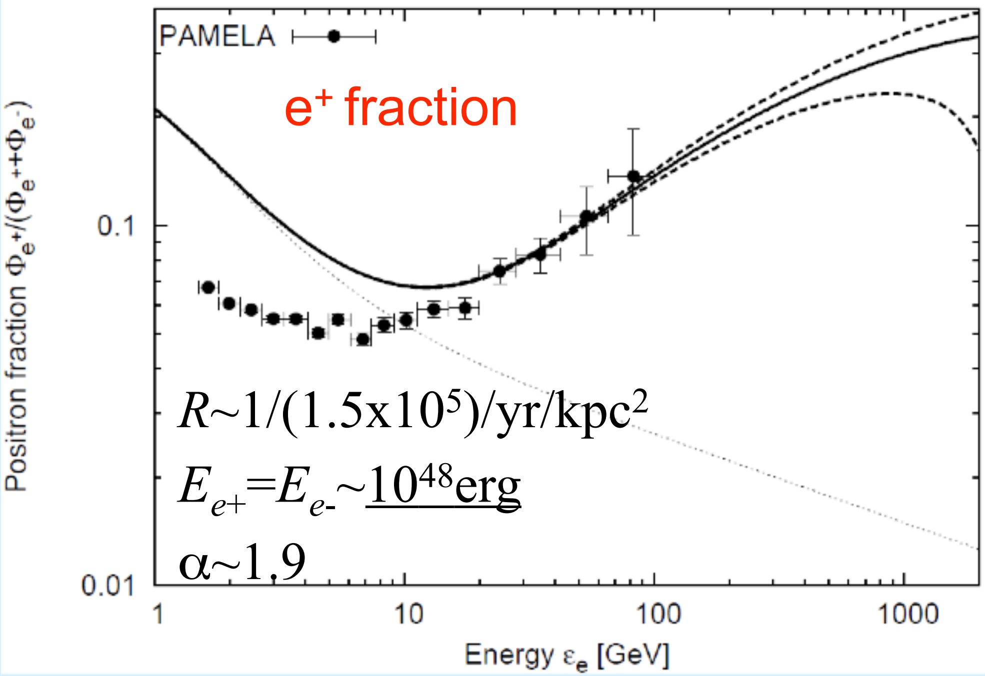
1. Average spectra are consistent with PAMELA, Fermi & H.E.S.S.





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

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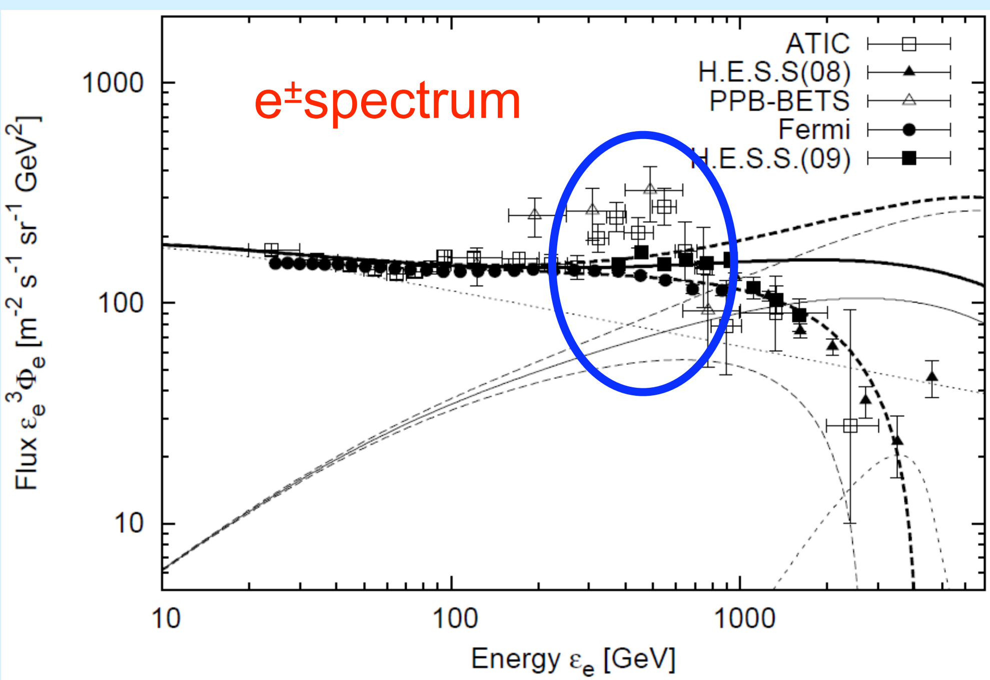
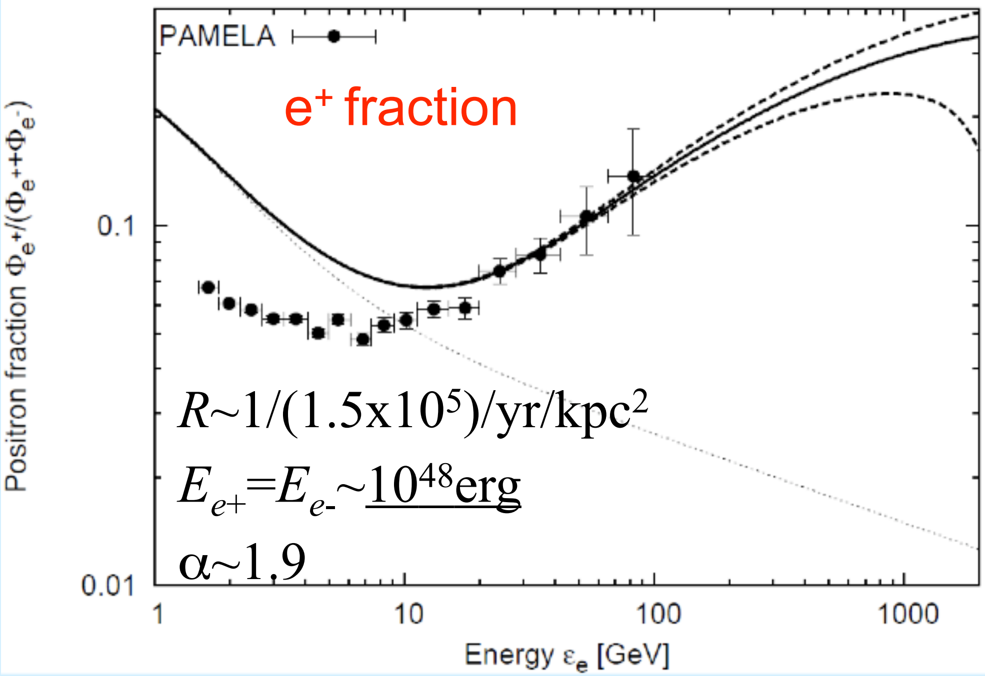
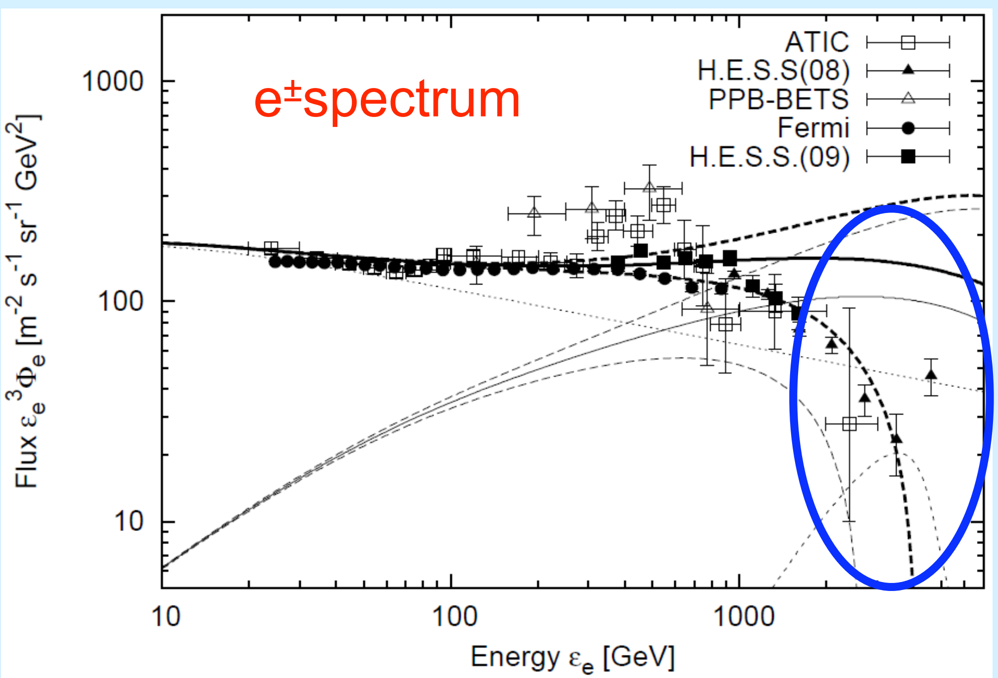
1. Average spectra are consistent with PAMELA, Fermi & H.E.S.S.
2. ATIC/PPB-BETS peak is largely separated from the average flux to the 10σ level. → Such a peak is hardly to produce by the sum of multiple pulsars.







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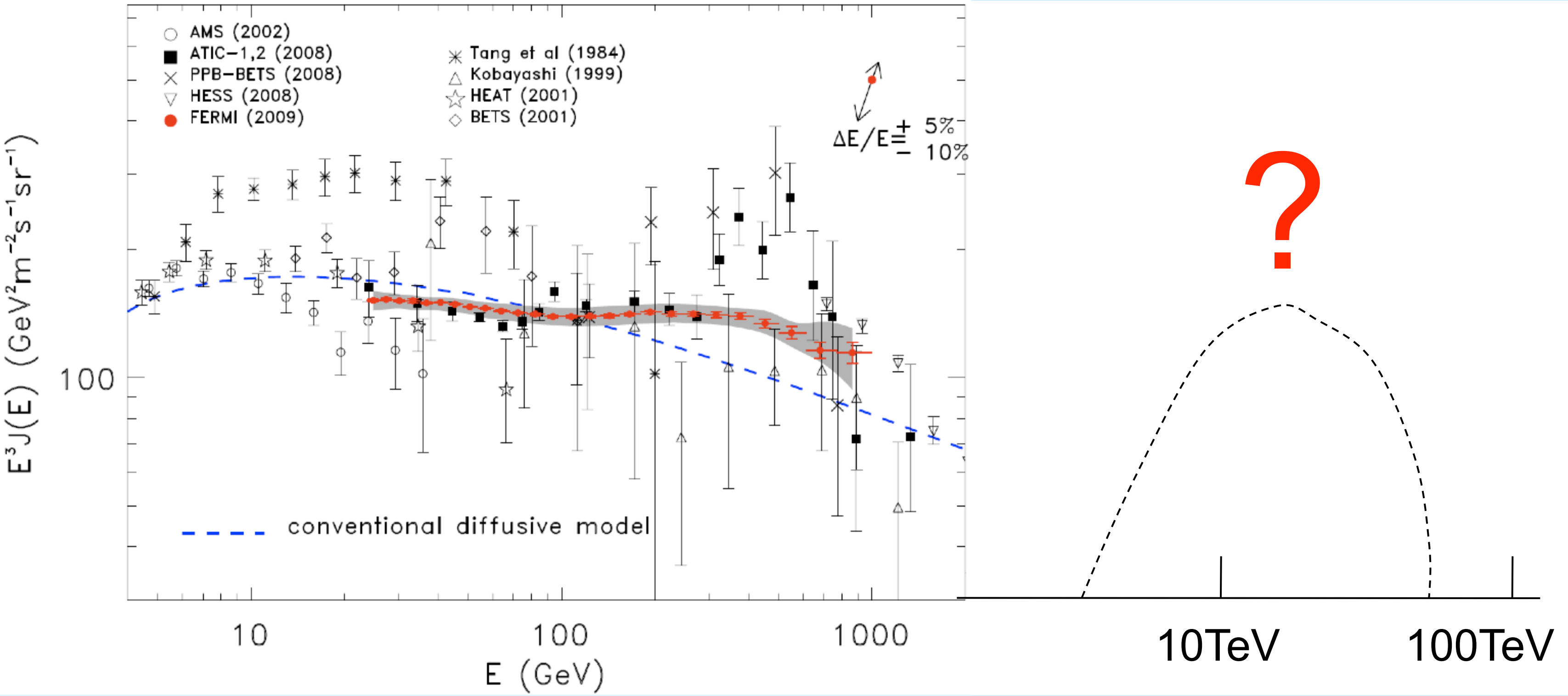
1. Average spectra are consistent with PAMELA, Fermi & H.E.S.S.
2. ATIC/PPB-BETS peak is largely separated from the average flux to the 10σ level.
   → Such a peak is hardly to produce by the sum of multiple pulsars.
3. Large dispersion in the TeV range due to the small $N(\varepsilon_e)$
   → possible explanation for the cutoff inferred by H.E.S.S.

Spectral Features in >TeV Band

Will be explored by CALET (Torii+ 08) etc.

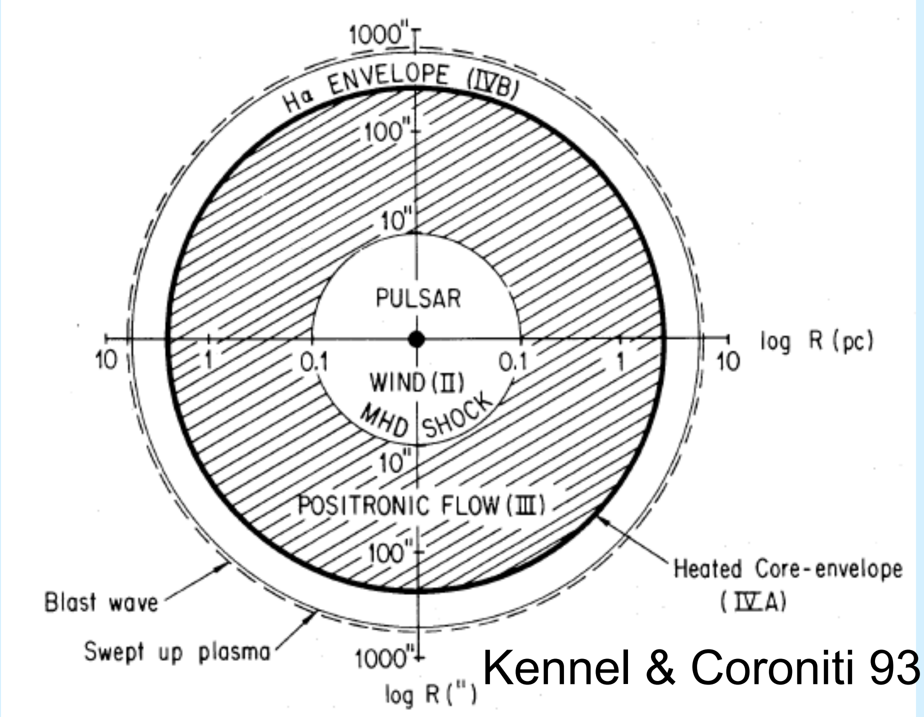
Large dispersion in flux → contributions from a few young and nearby sources are expected

Vela pulsar (age~10^4year, distance~270pc), Cygnus loop, or undiscovered compact objects



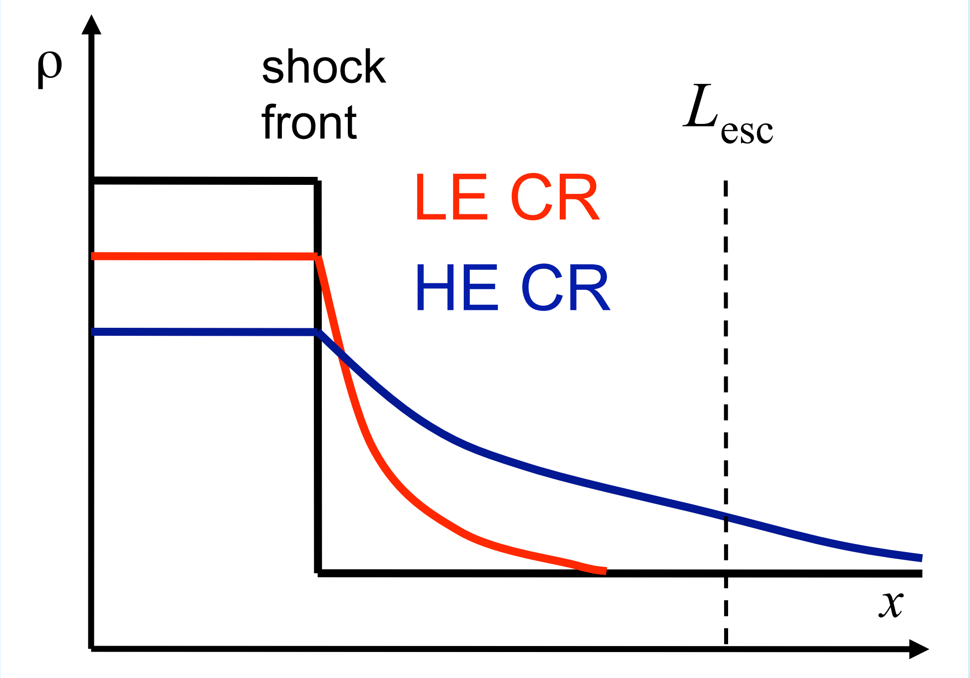
A young PSR/PWN is surrounded by a SNR.

→ CR electrons/positrons from a pulsar should go through the SNR shock.



Kennel & Coroniti 93

Low energy particles are trapped around the shock (i.e. have a smaller diffusion length).



Escape condition: $L_{diff} > L_{esc}$

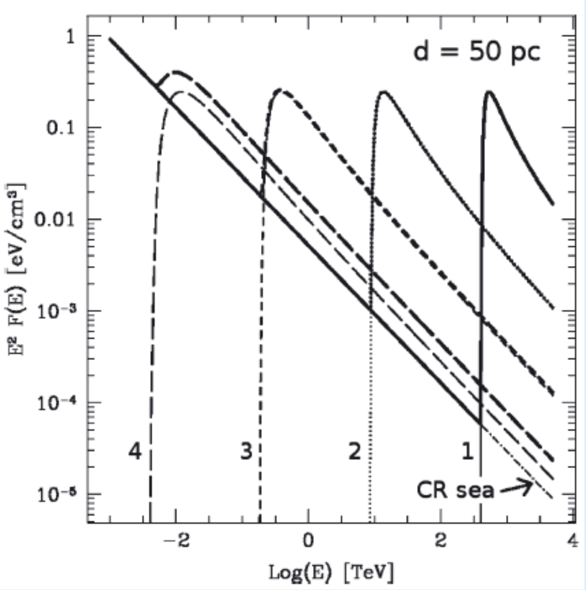
$L_{diff} = D(p)/u_{sh}$

L_{esc}: escape boundary (fixed)

“Escape-Limited” Model

In Sedov phase, higher energy particles escape the SNR shock earlier (Ptuskin & Zirakashivili 03, 05; Caprioli+ 09; Gabici+ 09; Ohira+ 10; Casanova’s talk;Caprioli’s talk)

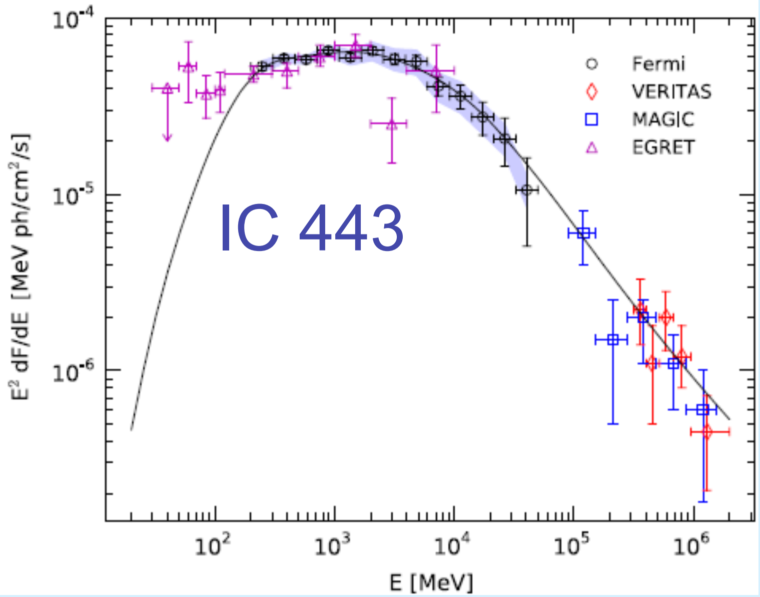
←→ “Age-limited” model (Higher energy particles require a longer time for acceleration)



Gabici+ 2009

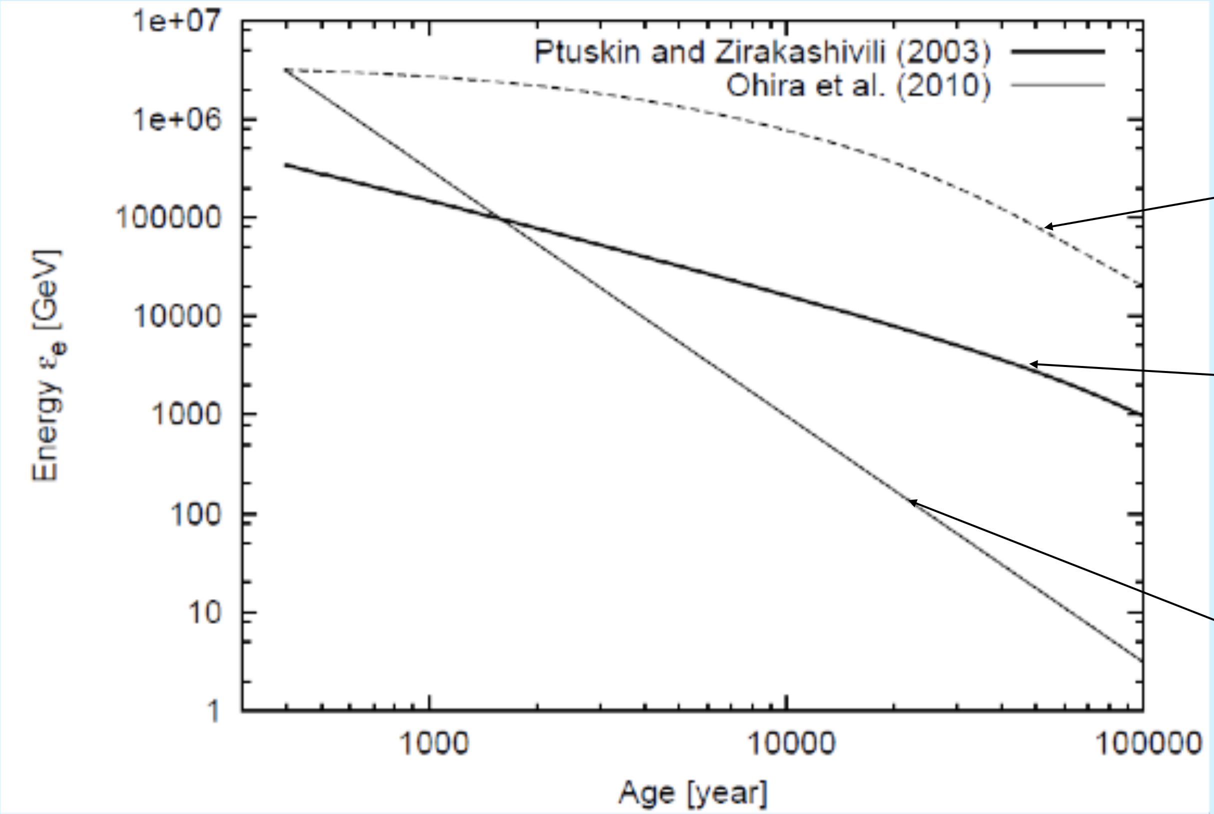
Predict (1) the softening of the CR spectrum from the injection and (2) the spectral break in the γ-ray spectrum

→ consistent with observations



Abdo+ 2009

Models for $\varepsilon_{esc}(t)$



(cooling cutoff)

Taking into account the magnetic field amplified by CR streaming (Ptuskin & Zirakashivili 03, 05)

Phenomenological model for explaining from “knee” down to 1GeV by SNR (Ohira+ 10)

Then how would the electron/positron spectrum be?

… It would have <u>a low energy cutoff</u> corresponding to $\varepsilon_{esc}(t_{age})$, as well as a high energy cutoff due to the energy loss.

$$\dot{N}_{e,\mathrm{esc}}(\varepsilon_e) = \dot{N}_{e,\mathrm{esc},1}(\varepsilon_e) + \dot{N}_{e,\mathrm{esc},2}(\varepsilon_e).$$

$$\dot{N}_{e,\mathrm{esc},1}(\varepsilon_e, t) = \dot{N}_{e,\mathrm{pr}}(\varepsilon_e, t)\underline{\Theta(\varepsilon_e - \varepsilon_{\mathrm{esc}})},$$

step function

$$\dot{N}_{e,\mathrm{esc},2}(\varepsilon_e, t) = -\delta\left(\varepsilon_e - \varepsilon_{\mathrm{esc}}(t)\right)\times\left(\frac{\partial\varepsilon_{\mathrm{esc}}}{\partial t} - \left.\frac{\partial\varepsilon_e}{\partial t}\right|_{\mathrm{ad}}\right)N_{e,\mathrm{conf}}(\varepsilon_e, t)$$

$$\dot{N}_{e,\mathrm{pr}}(\varepsilon_e, t) = K_e(t)\varepsilon_e^{-\alpha}\exp\left(-\frac{\varepsilon_e}{\varepsilon_{e,\mathrm{cut}}}\right)$$

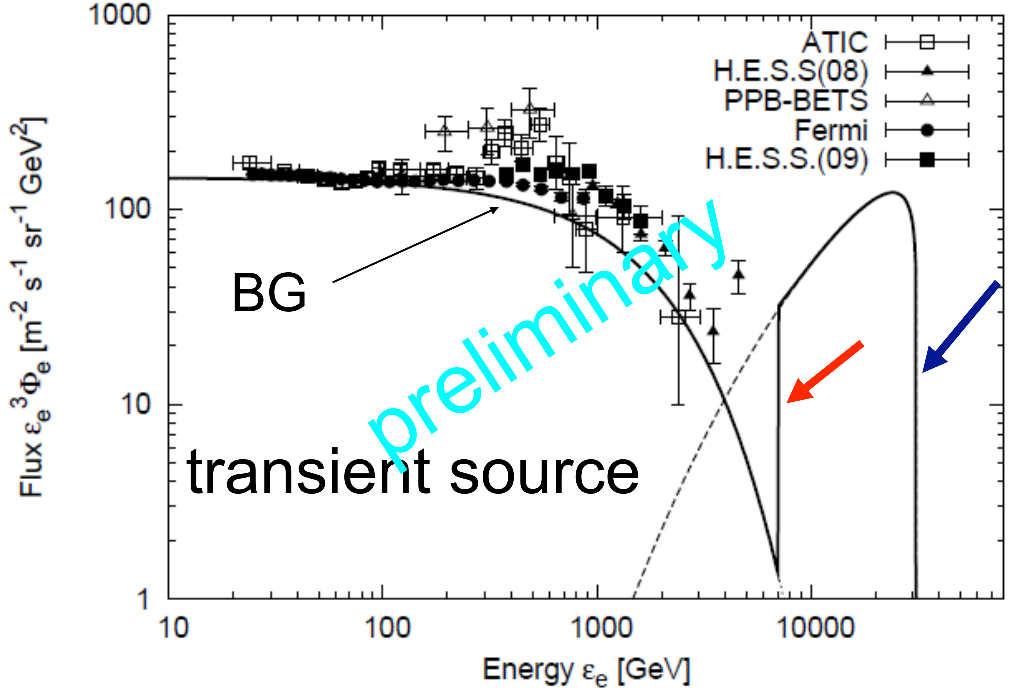
: $e^{\pm}$ production rate from a pulsar

$$N_{e,\mathrm{conf}}(\varepsilon_e, t) = \int_{t_{\mathrm{Sedov}}}^{t} dt' \dot{N}_{e,\mathrm{pr}}(\varepsilon_e', t')\frac{d\varepsilon_e'}{d\varepsilon_e} \times\Theta\left(\varepsilon_{\max}(t') - \varepsilon_e'\right),$$

: $e^{\pm}$ confined inside the SNR

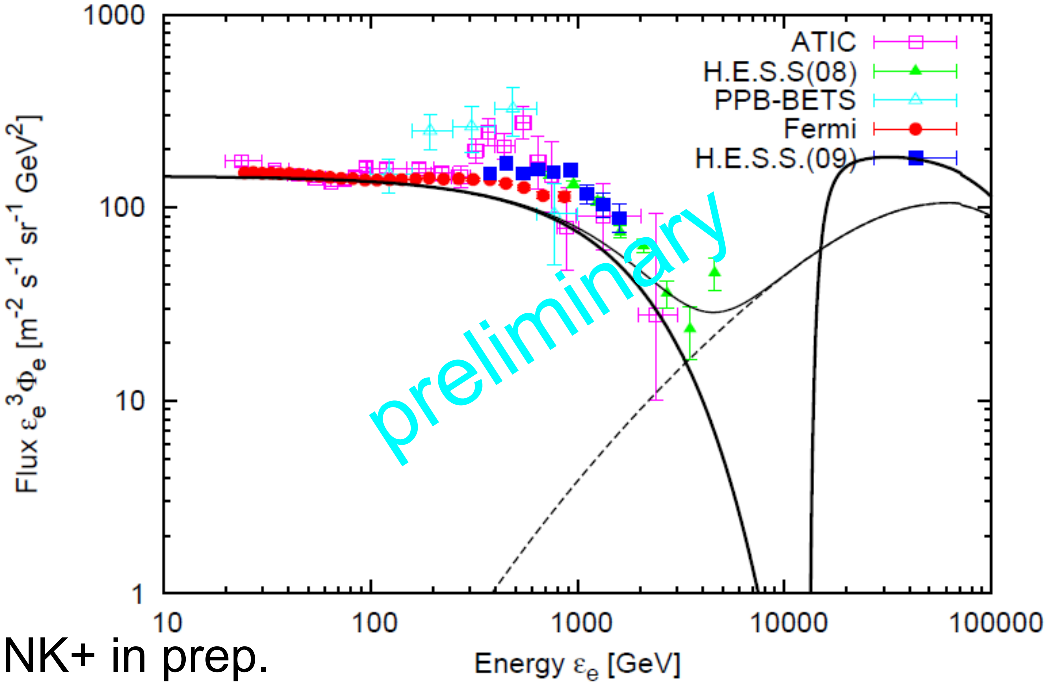
During the confinement, $e^{\pm}$s are adiabatically cooled ($\varepsilon_e' \rightarrow \varepsilon_e$).

$$f(\varepsilon_e, t, r) = \int dt_0 \frac{\dot{N}_{e,\mathrm{esc}}(\varepsilon_{e,0}, t_0)P(\varepsilon_{e,0})}{\pi^{3/2} r_{diff}^3 P(\varepsilon_e)}\exp\left(-\frac{r^2}{r_{diff}^2}\right)$$



Observed electron spectrum can have both **high energy cutoff** due to the energy loss and **low energy cutoff** due to $\varepsilon_{esc}(t)$!

→ **The effect of CR escape-limited scenario can be seen directly.**



NK+ in prep.

Vela pulsar (with a certain duration of $e^{\pm}$ injection)

age ~ 10^4year, distance ~ 270pc, total energy ~ 10^{48}erg

Sharp LE cutoff ~ a few x 10TeV??

CALET may detect it.

Summary

- GeV/TeV spectral features of CR $e^{\pm}$ from pulsars.
- Continuous injection from a single source

  comparison with the ATIC/PPB-BETS data

  → peak width, TeV tail : duration of the source

  → may be measured by AMS-02, CALET
- Multiple injections: average flux and its dispersion

  average $e^{\pm}$ spectrum ← seen in the Fermi data

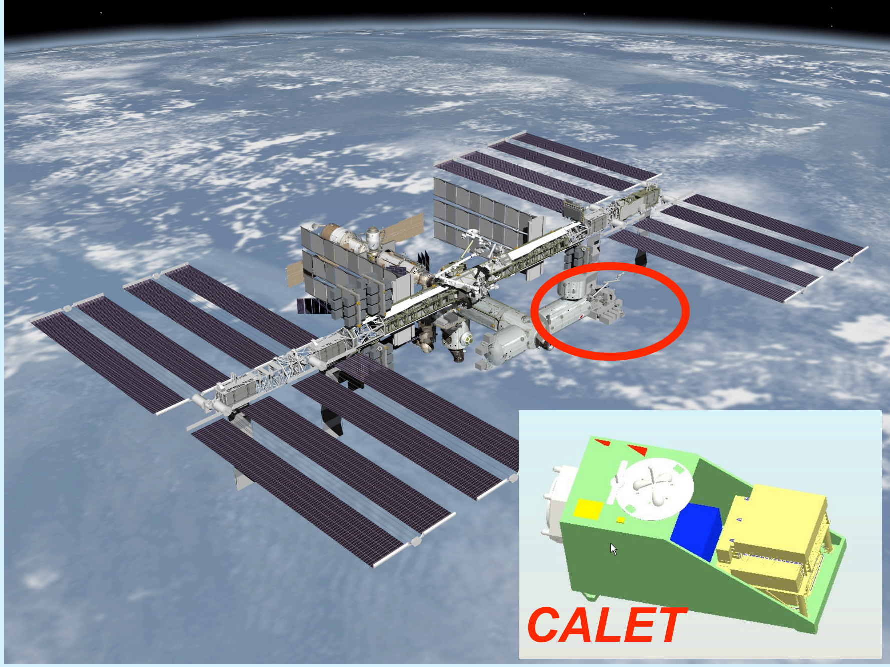
  ATIC/PPB-BETS peak is hardly to produce by multiple pulsars, and requires a single (or a few) energetic source(s).

  spectral cutoff at ~a few TeV seen in the H.E.S.S. data : due to the small number of young and nearby sources
- CR escape from the SNR shock, which is the most important process in determining the CR spectrum, has been never probed directly from observations.

→ The electron flux from a young pulsar may have the low energy cutoff in >~TeV band, which can be the probe of CR escape.

Backup Slides

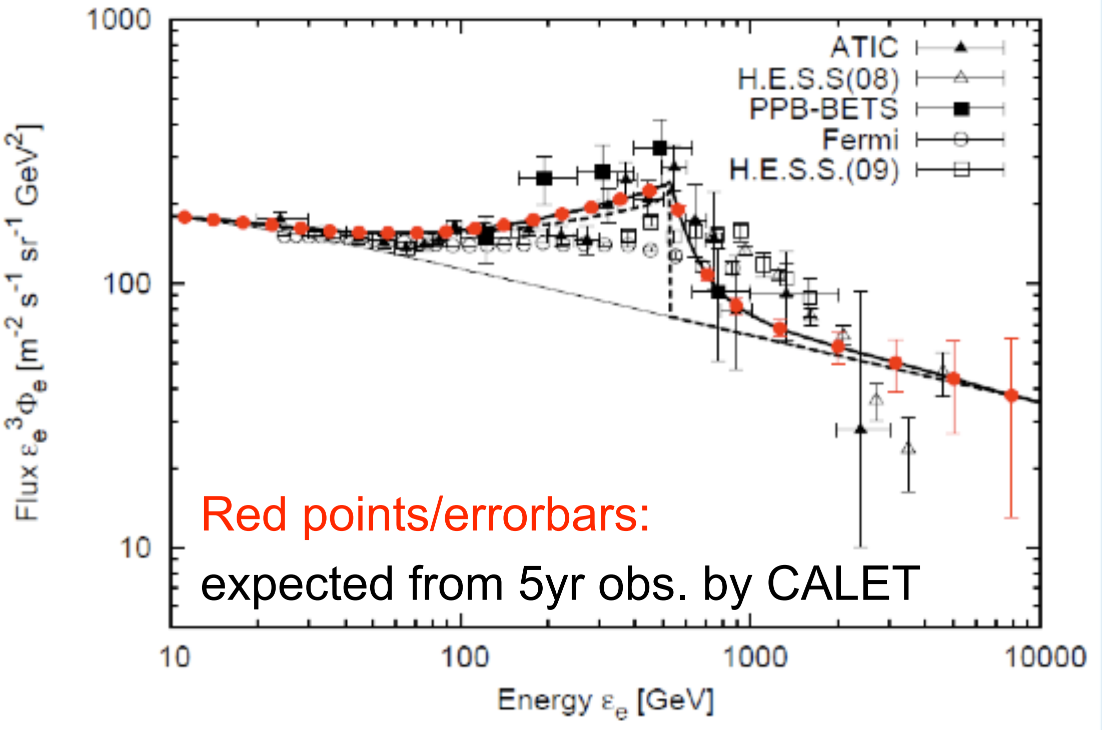
*CAL*orimetric *E*lectron *T*elescope



A Dedicated Detector for Electron Observation in 1GeV – 20,000 GeV

Energy resolution: ~2% (>100GeV)

e/p selection power: ~10^5



With the high energy resolution and statistics of the CALET observations, we will be able to discriminate models of injection.

(duration, the functional form of $Q_0(t)$, etc.)