White dwarf pulsar as Possible Cosmic Ray Electron-Positron Factories

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http://www.nasa.gov/centers/goddard/news/topstory/2007/whitedwarf_pulsar.html

Background: "Electron-Positron Excess"

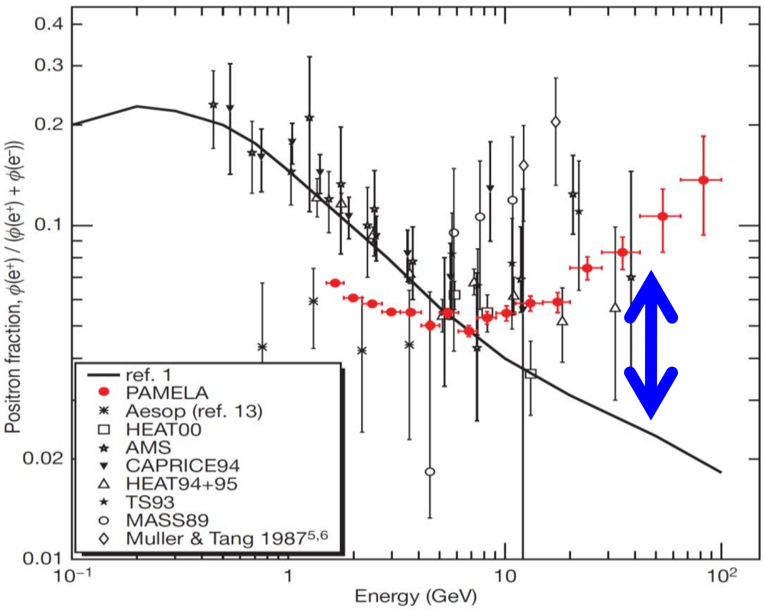
PAMELA

(capable of identifying CR ray charge)

⇩

The positron excess in
the energy range 10-100GeV

(Adriani, et al 2008)

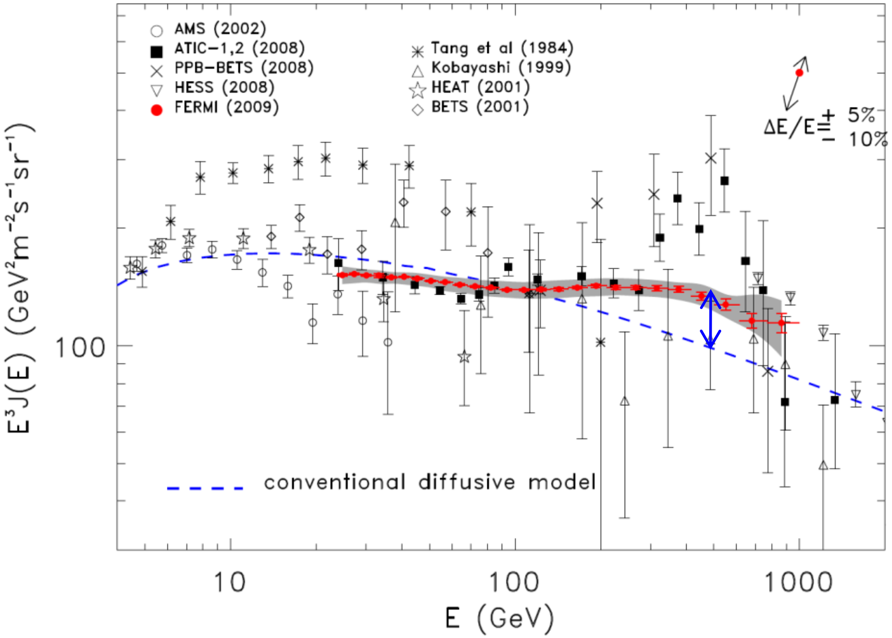


ATIC/PPT-BETS/H.E.S.S/Fermi

⇩

The excess in
the $e^{-}+e^{+}$ flux up to TeV

(Abdo, et al 2009 etc)



What is the source?

- **Neutron star 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; Kawanaka, 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; Stawarz+09; Schlickeiser & Ruppel 09

- **Dark matter decay or annihilation ???** So many references

High accuracy, broadband CR e± observations are coming.
ex） AMS-02, CALET, CTA

Is there any new sources?

Goal

We propose "White Dwarf Pulsars"
as a new candidate for TeV $e^{\pm}$ emitters,
and discuss the possibility of the detection
by PAMELA/Fermi or the future observations
like AMS-02/CALET/CTA.

Candidates of White Dwarf Pulsars

AE Aquarii

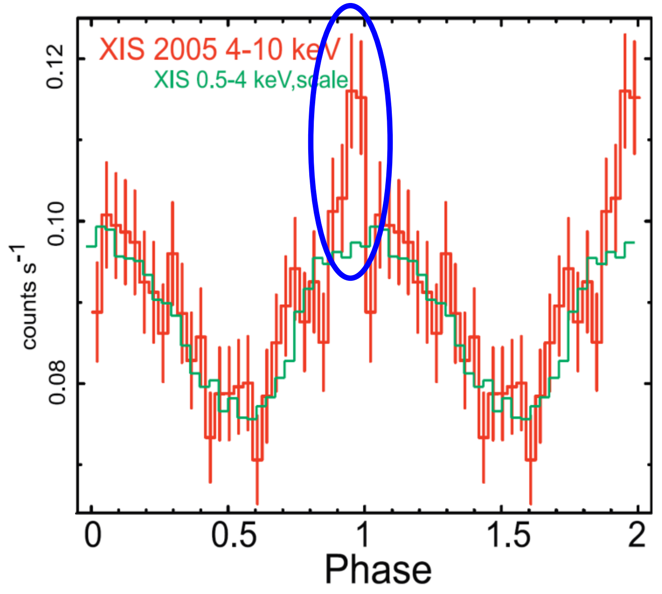
- MCVs
- Long term spin down $\sim 6 \times 10^{-14} \mathrm{s\ s}^{-1}$

→ inferred magnetic field

$B \sim 5 \times 10^7$ Gauss

- Rapid rotation $P \sim 33$ sec
- **Hard X-ray pulsations**

Sharp Pulsation !



(Terada et al 2008)

EUVE J0317-855

- single magnetized white dwarf $B \sim 4.5 \times 10^8$ Gauss
- rapid rotation $P \sim 725$ sec
- large mass $\sim 1.3 M_{\odot}$
- No pulse emission have been reported yet.

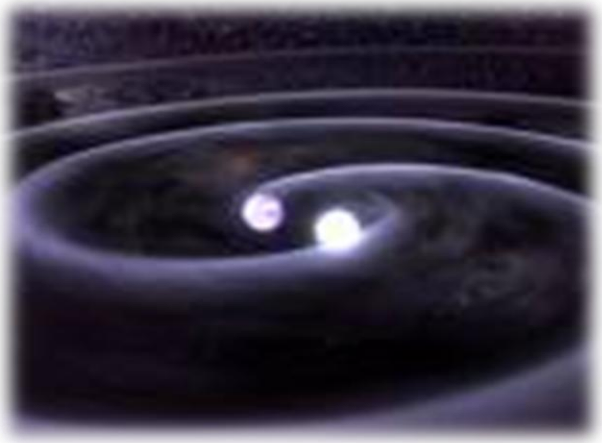
⇒ merger origin ?

White dwarf pulsar model

- formation scenario

  "WD−WD mergers"

  - MCVs may also contribute ?
  - Gravitational wave sources for LISA.



- fiducial parameters

  mass: $M > 1.0 M_\odot$ (typical WD: $0.6 M_{sun}$)

  period: $P \sim 50$ sec (typical : 10^{4-5}[sec])

  magnetic field: $B \sim 10^{7\text{-}9}$ G (typical: less than 10^6[G])

Energetics

· **Energy of a WD pulsar**

Intrinsic energy is its rotational energy

$$\frac{1}{2} I\Omega^2 \approx \frac{1}{2} M_{\mathrm{WD}} V^2 \approx \frac{GM_{\mathrm{WD}}}{R_{\mathrm{WD}}} \approx 10^{50} [\mathrm{erg}]$$

rotational energy just after merger — rotational energy just before merger — gravitational energy just before merger

⇨ comparable to rotational energy of new born NS pulsars

· **Total number of WD pulsars**

WD–WD merger rate in our galaxy ～ 1/100yr

⇨ comparable to birth rate of NS pulsars in our galaxy

Total energy budget is comparable to NS pulsars！

WD pulsar can produce TeV $e^{\pm}$?

- Check point ①

  $e^{\pm}$ pair production can occur？

- Check point ②

  WDs can accelerate $e^{\pm}$ up to TeV？

Point： WD pulsars ≒ NS pulsars

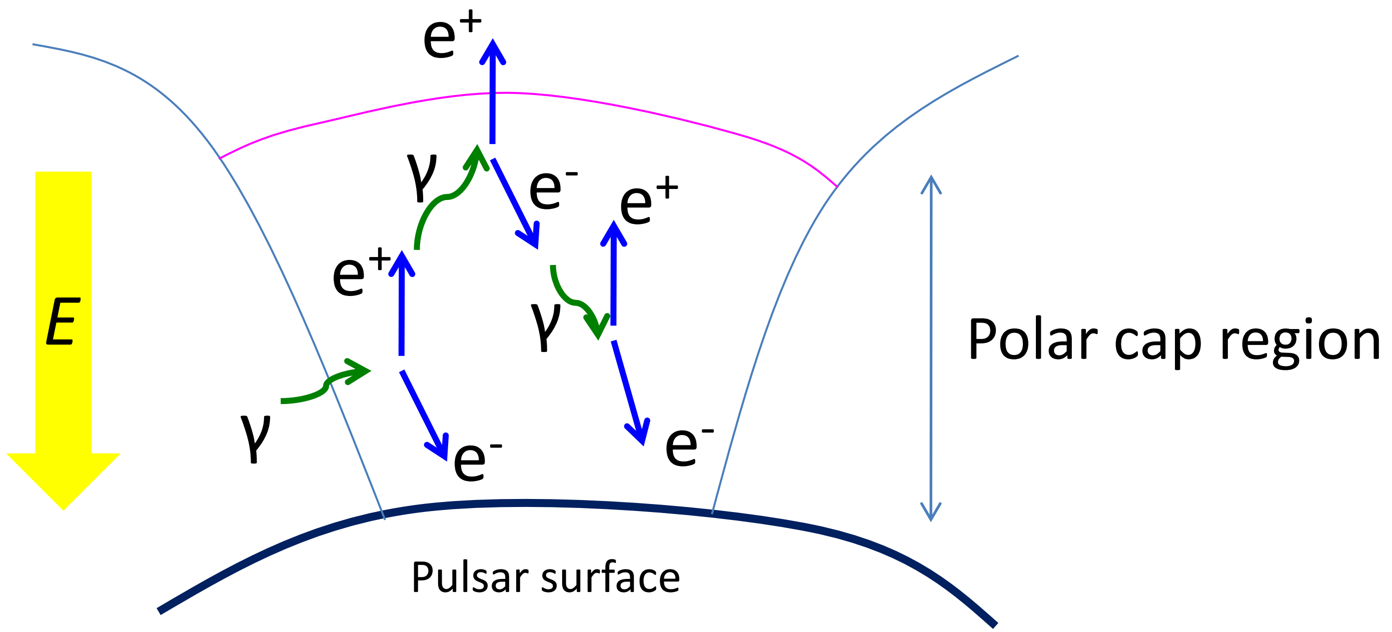
$e^{\pm}$ pair production in pulsar magnetosphere

Polar cap (PC) model

e^{-} acceleration in PC region → γ−ray production by curvature radiation and Inverse Compton scattering

→ γ + B field → $e^{\pm}$

→ Pair production avalanche!



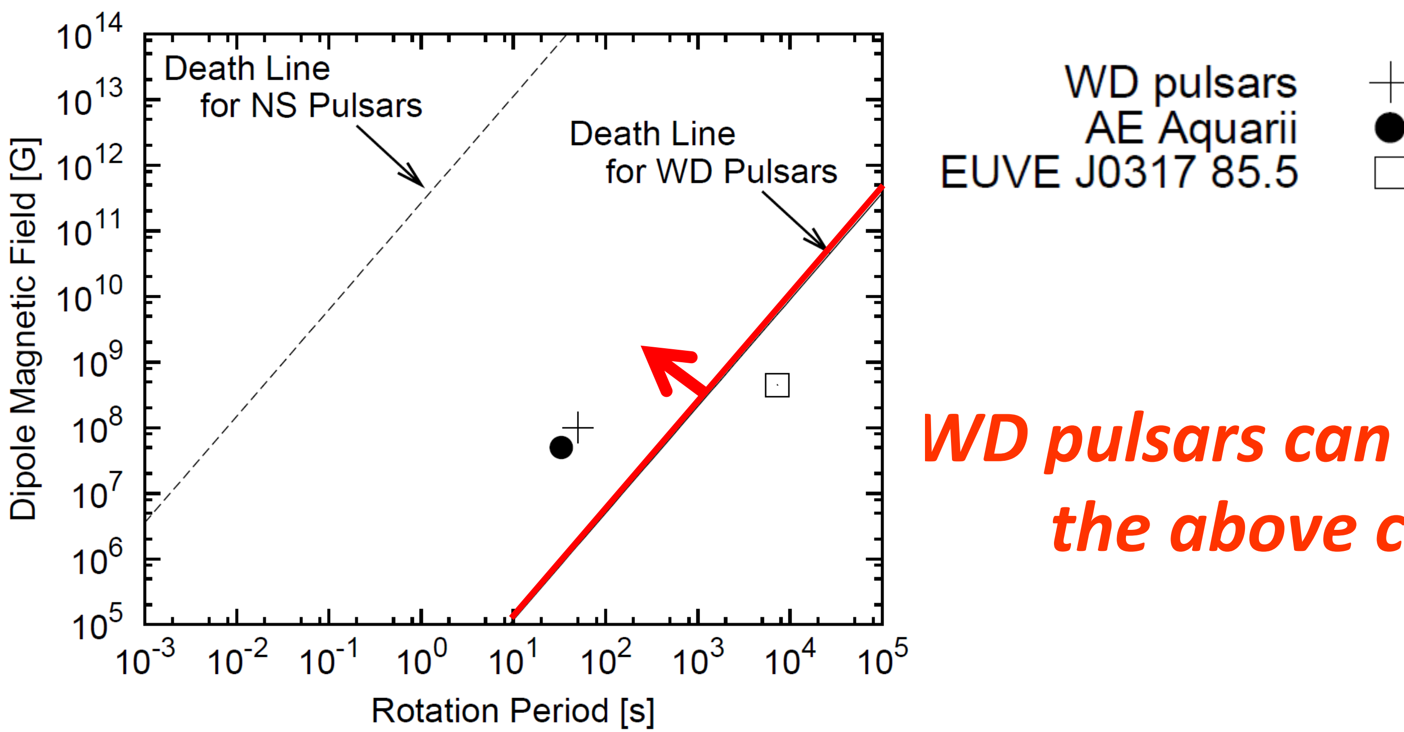
WD pulsar death line

- The condition for $e^{\pm}$ pair creation occurs

"γ-ray emitted by accelerated particle in the gap is energetic enough to produce $e^{\pm}$."

⇕

$$4 \log B - 7.5 \log P + 9.5 \log R \geq 96.7$$ in unit of [Gauss], [sec], [cm]



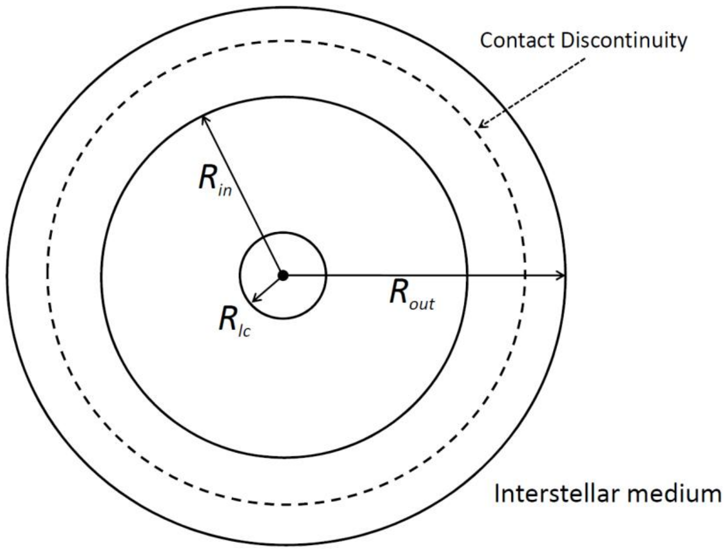
WD pulsars can satisfy the above condition !

$e^{\pm}$ acceleration in the pulsar wind nebula

Assumptions

In the wind region,

- the energy equipartition between B and $e^{\pm}$.
- the flux conservation of B and $e^{\pm}$.



$$\frac{e\Delta V_{max}}{\mathcal{M}} \sim 10\mathcal{M}^{-1}\left(\frac{B_p}{10^8\mathrm{G}}\right)\left(\frac{\Omega}{0.1\mathrm{s}^{-1}}\right)^2\left(\frac{R}{10^{8.7}\mathrm{cm}}\right)^3\mathrm{TeV}$$

$\mathcal{M}$: $e^{\pm}$ multiplicity

WD pulsars can accelerate $e^{\pm}$ up to TeV！

$e^{\pm}$ cooling in the wind nebula

- Adiabatic cooling → negligible!

  ∵ The shocked stops soon since the wind is weak.

- Radiative cooling → at least～10%

  ・Bohm limit
  ・Synchrotron cooling

  ⇒ $$\frac{\Delta\epsilon}{\epsilon} \sim 0.1 \left(\frac{B_{\rm in}}{3 \times 10^{-6} {\rm G}} \right)^3$$

  $B_{\rm in}$: B @ inner edge of the shocked region

TeV $e^{\pm}$ can escape the wind nebula without serious cooling !

Difference between WD pulsars and NS pulsars

- What is the difference?

"Spin down luminosity"

$$L \approx \frac{B^2 \Omega^4 R^6}{c^3} \approx \begin{cases} 10^{38}\ \text{[erg] for NS pulsar} \\ 10^{34}\ \text{[erg] for WD pulsar} \end{cases}$$

NS is 10^4 times powerful!

"life time" = (Total energy)/(spin down luminosity)

$$\tau_{life} \approx \begin{cases} 10^{4}\ \text{[yr] for NS pulsar} \\ 10^{8}\ \text{[yr] for WD pulsar} \end{cases}$$

WD is 10^4 times longer life!

WD pulsars are weak, but active for a long time!!

WDs is better than NSs as TeV $e^{\pm}$ source ?

Point

TeV $e^{\pm}$ can propagate only ～1kpc in our galaxy.

(source number)≒(life time)/(event rate)/(volume of galaxy)

$$\fallingdotseq \begin{cases} 10^{-1}[1/\mathrm{kpc}^3] \text{ for NS} \\ 10^{3}\ [1/\mathrm{kpc}^3] \text{ for WD} \end{cases}$$

NS is uncertain.
WD is a lot !

WD pulsars may be numerous !

Calculation of e$^{\pm}$ flux

Solve diffusion eq. including the KN effect for each WD pulsar.

$$\frac{\partial f}{\partial t} = \frac{D}{r}\frac{\partial}{\partial r}r^2\frac{\partial f}{\partial r} - \frac{\partial}{\partial \epsilon}(Pf) + Q.$$

Cooling Func : $P(\epsilon) = -\frac{d\epsilon}{dt} = \frac{4}{3}\sigma_T c\left(\frac{\epsilon}{m_e c^2}\right)^2\left[\frac{B_{\rm ISM}^2}{8\pi} + \int d\epsilon_{\rm ph} u_{\rm tot}(\epsilon_{\rm ph}) f_{\rm KN}\left(\frac{4\epsilon\epsilon_{\rm ph}}{{m_e}^2c^4}\right)\right].$

Diffusion Co : $D(\epsilon) = D_0\left(1+\frac{\epsilon}{3{\rm GeV}}\right)^\delta.$

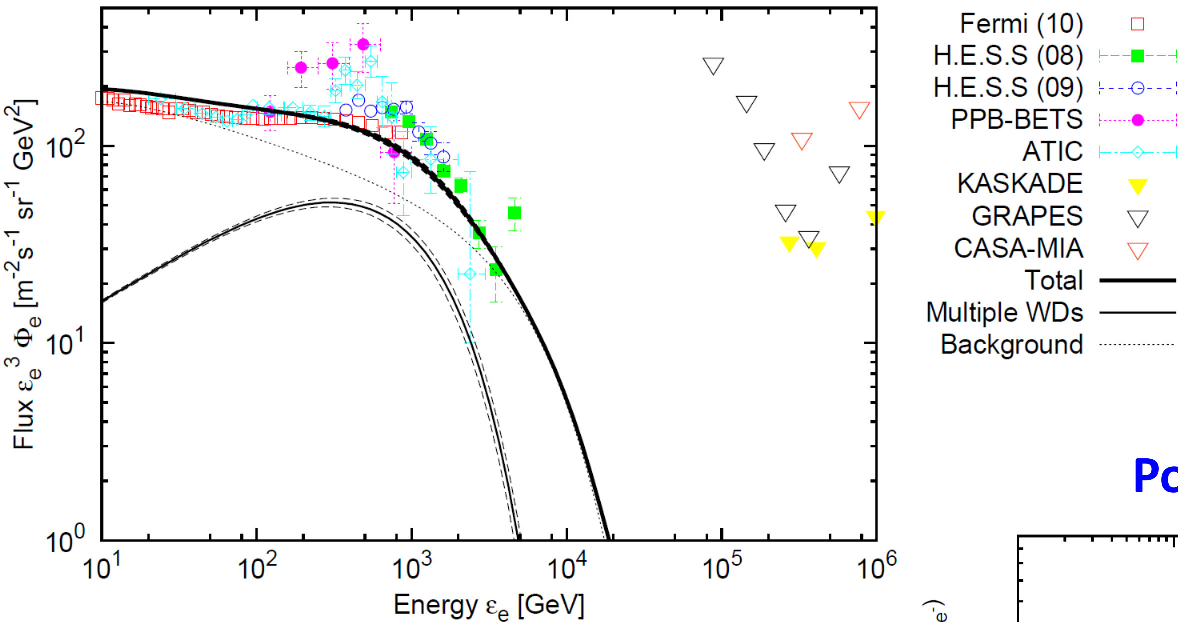
Source Func : $Q(\epsilon, t_0, \hat{t}) = Q_0\epsilon^{-\nu}\exp\left(-\frac{\epsilon}{\epsilon_{\rm cut}}\right)\left(1+\frac{t_0-\hat{t}}{\tau}\right)^{-2}.$

Sum up the multiple contribution.

$$F(\epsilon) = \int_{-\tau_{\rm WD}}^{0} d\hat{t}\int_0^{r_{\rm dif}(\epsilon,\epsilon_{\hat{t}})} 2\pi r dr\cdot\alpha\cdot\eta_{\rm WD} f(\epsilon, r, \hat{t}).$$

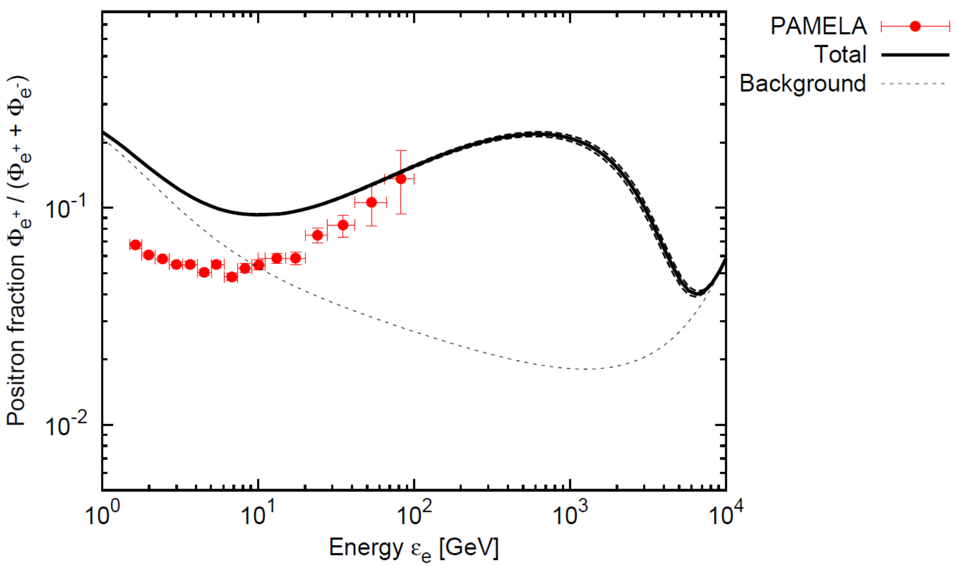
$\alpha\cdot\eta \sim$ "WD pulsar birth rate in our galaxy" [1/yr/kpc^2]

Result 1:WD pulsar dominated model



e± total flux

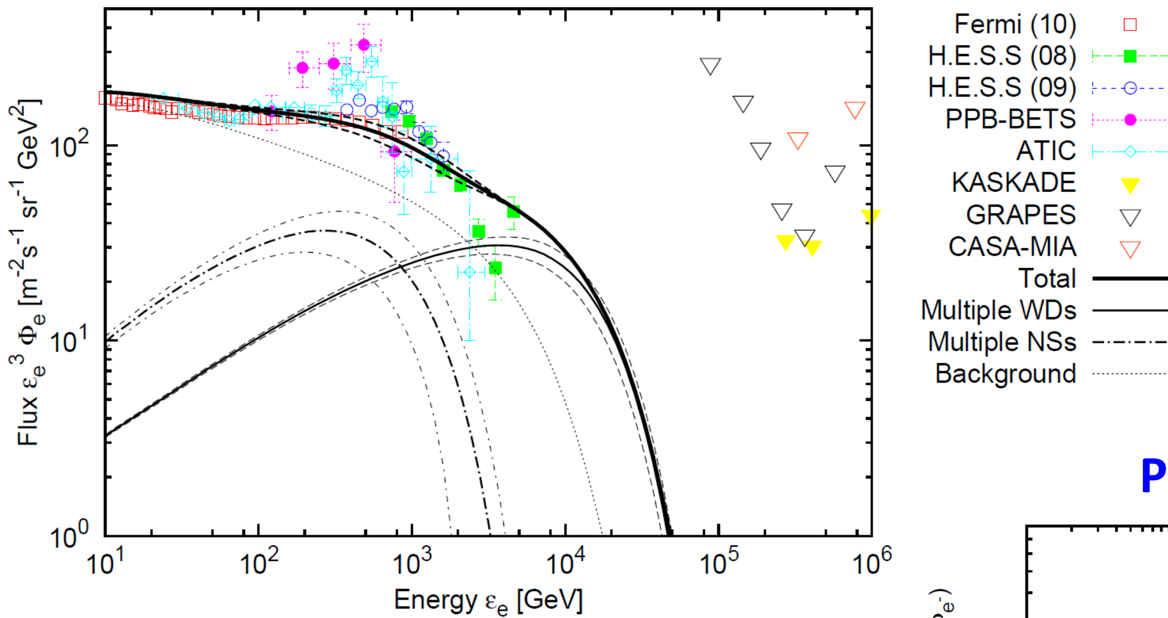
Positron fraction



WD : cut off energy ~ 1 TeV
total energy 10^{49}erg for each

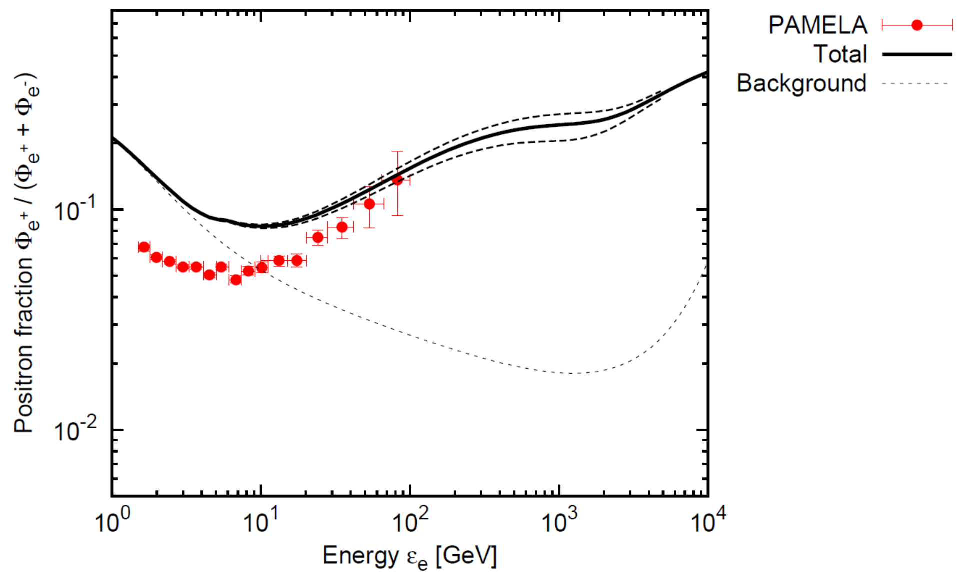
WD pulsars can explain the excess around TeV!

Result 2 :WD + NS pulsar mixed model



e± total flux

Positron fraction



WD : cut off energy ～ 10 TeV
total energy 5×10^{48}erg for each

NS : cut off energy ～ 1 TeV
total energy 10^{49}erg for each

"Bumps" are formed @ TeV and10TeV→ detectable by AMS-02,CALET,CTA!?

Summary

- Recently, excess in observed $e^{\pm}$ flux up to TeV have been presented, and the origin is still under debate.
- There are several observational projects for cosmic ray $e^{\pm}$ above TeV (AMS-02, CALET, CTA).
- Here, we investigate the possibility of WD pulsars to be TeV $e^{\pm}$ sources.
- We show that white dwarf pulsars can produce and accelerate $e^{\pm}$ up to TeV.
- WD pulsars can explain the excess in observed $e^{\pm}$ flux.
- There may be formed the “bumps” in the $e^{\pm}$ spectrum around TeV and 10 TeV, which can be detectable by the future observation.