TeV cosmic ray electrons from millisecond pulsars

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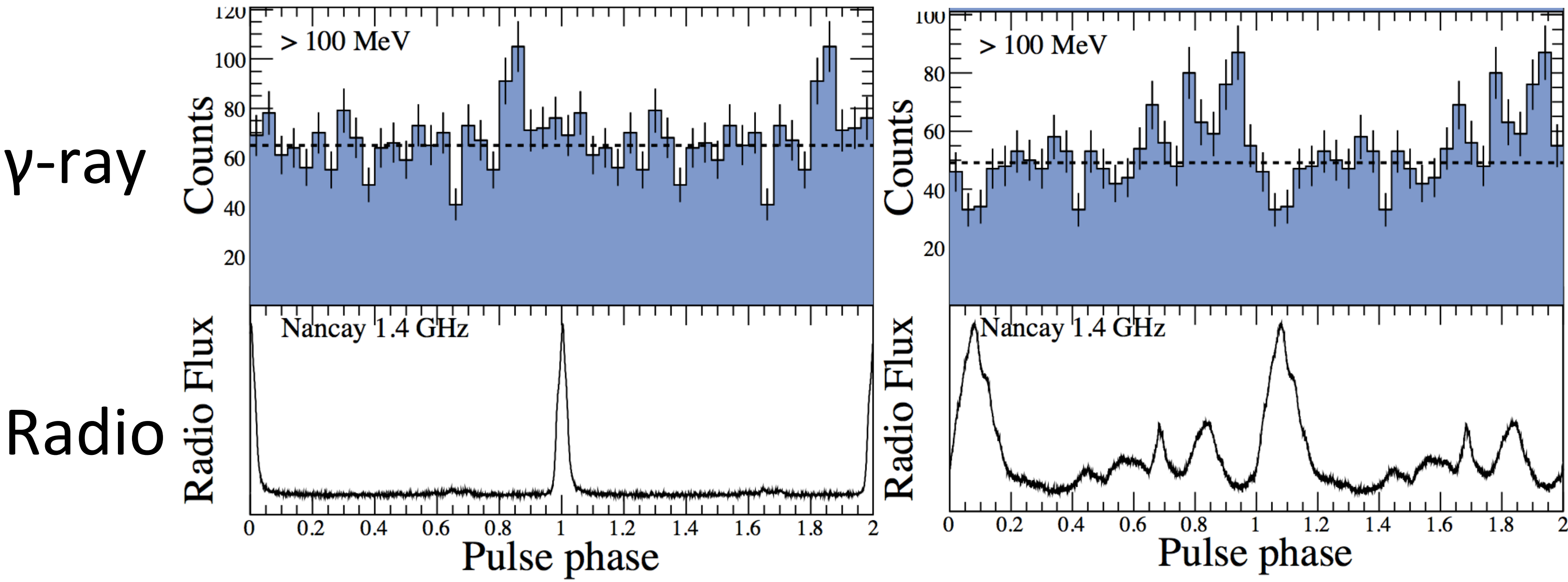
ABSTRACT

Recent γ-ray observations suggest that some γ-ray millisecond pulsars (MSPs) have pair number density less than Goldreich-Julian one. Here, we calculate the cosmic-ray electron/positron spectra from these MSPs. Based on the assumption of equipartition in the pulsar-wind region, the typical energy of electrons/positrons ejected by a pair-starved MSP is ~ 50 TeV. We find that a large peak in the 10 - 50 TeV energy range would be observed in the cosmic-ray electron/positron spectrum. Even if the fraction of pair-starved MSPs is 10 per cent, a large peak would be detectable in future observations.

Unusual γ-ray light curve

Two MSPs show unusual light curves that the γ-ray peak leads the radio peak. Young γ-ray pulsars do not show such light curves.

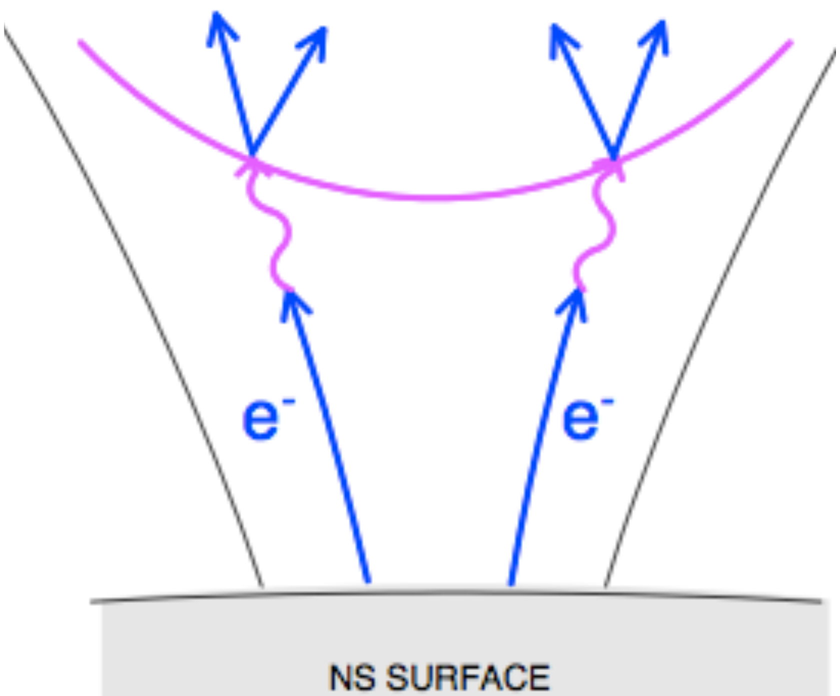


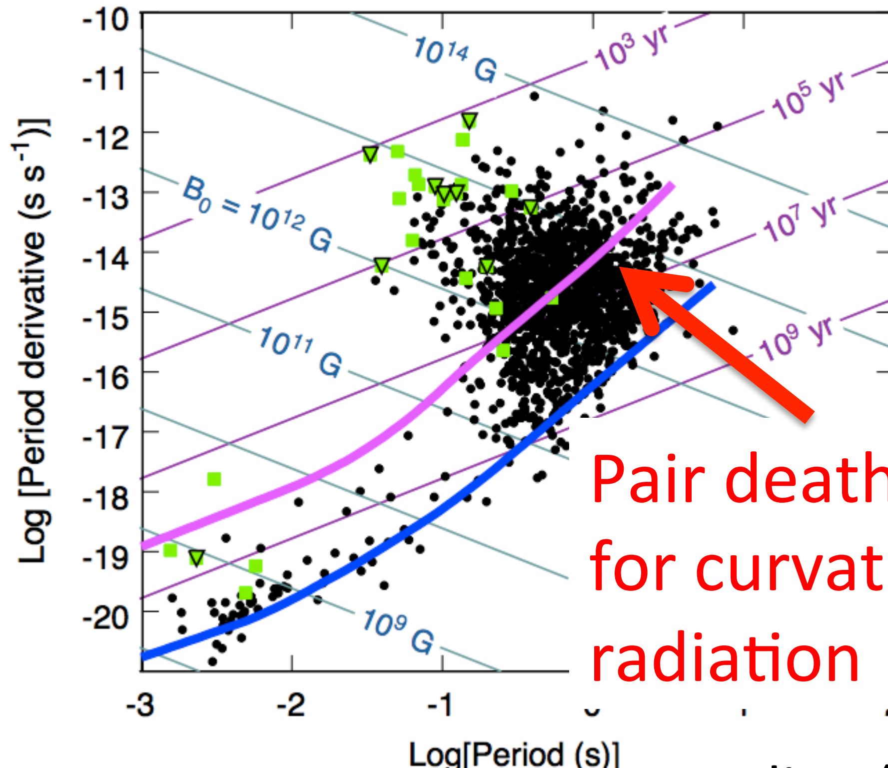
Guillemot (2009)

Pair-Starved Polar Cap (1/2)

Muslimov & Harding (2004) suggest that most MSPs can not produce pairs through curvature radiation.

In this case, particle acceleration can occur in almost open field volume (Pair-Starved Polar Cap model).



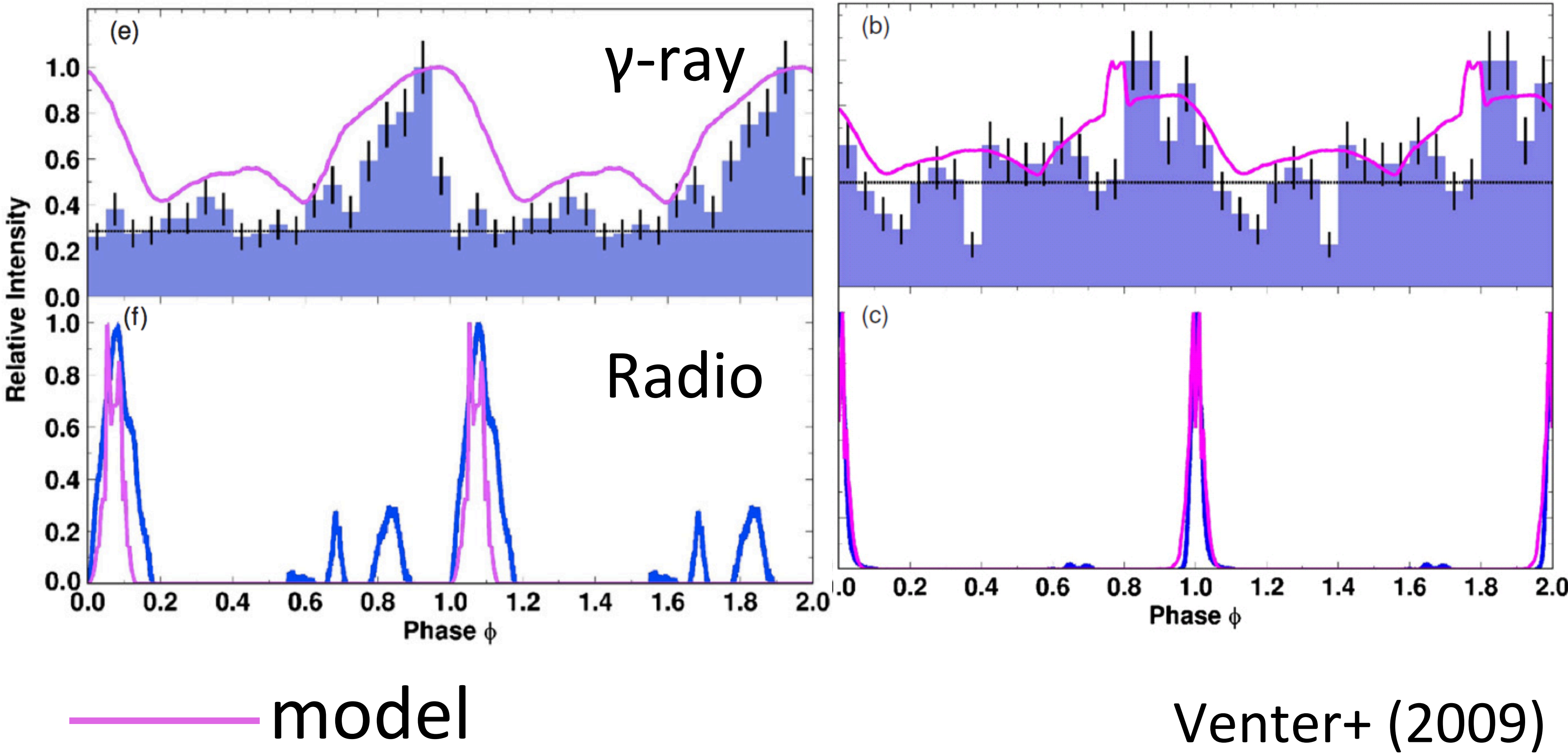


Pair death line for curvature radiation

Harding (2009)

Pair-Starved Polar Cap (2/2)

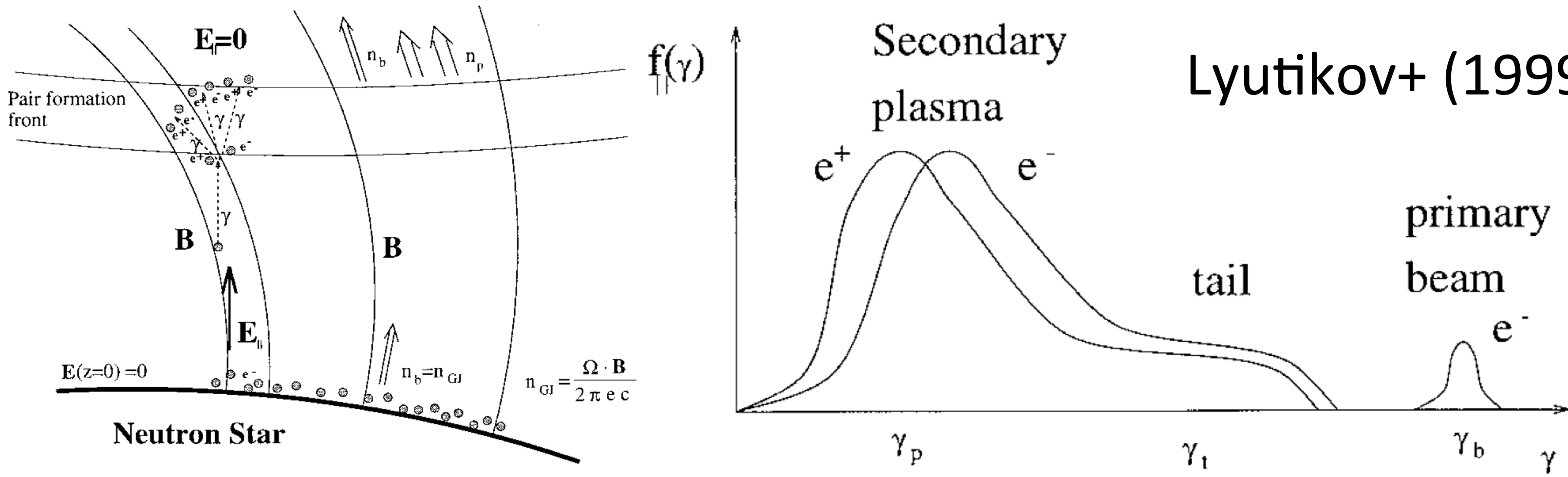
The pair-starved polar cap model can explain observed light curves.



Venter+ (2009)

Conditions for radio-emitting region

In general, people have believed the conditions of a primary beam with γ_b~10^7 and n_b~n_{GJ}, and a secondary $e^{\pm}$ with γ_p~10-10^3 and n_p~10^3-$10^5 n_{GJ}$ in the radio-emitting region.



Lyutikov+ (1999)

However, the existence of pair-starved MSPs suggest that radio emission mechanisms should be insensitive to the particle number density down to sub-GJ one.

Therefore, further verification is important.

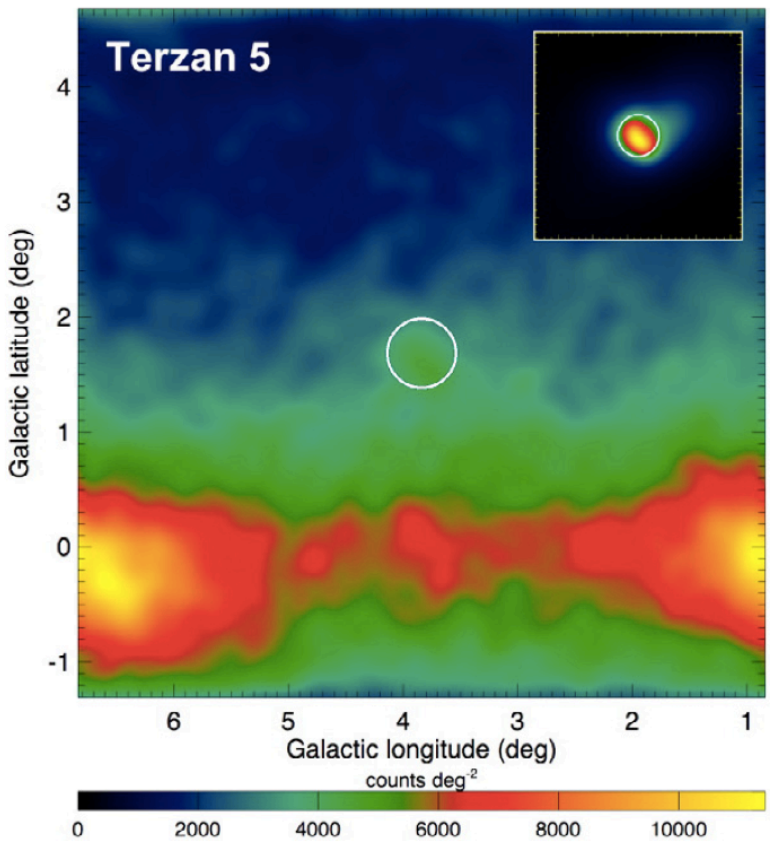
γ-ray from globular cluster

Proposed origin (e.g., Venter+ 2009, Bednarek & Sitarek 2007)

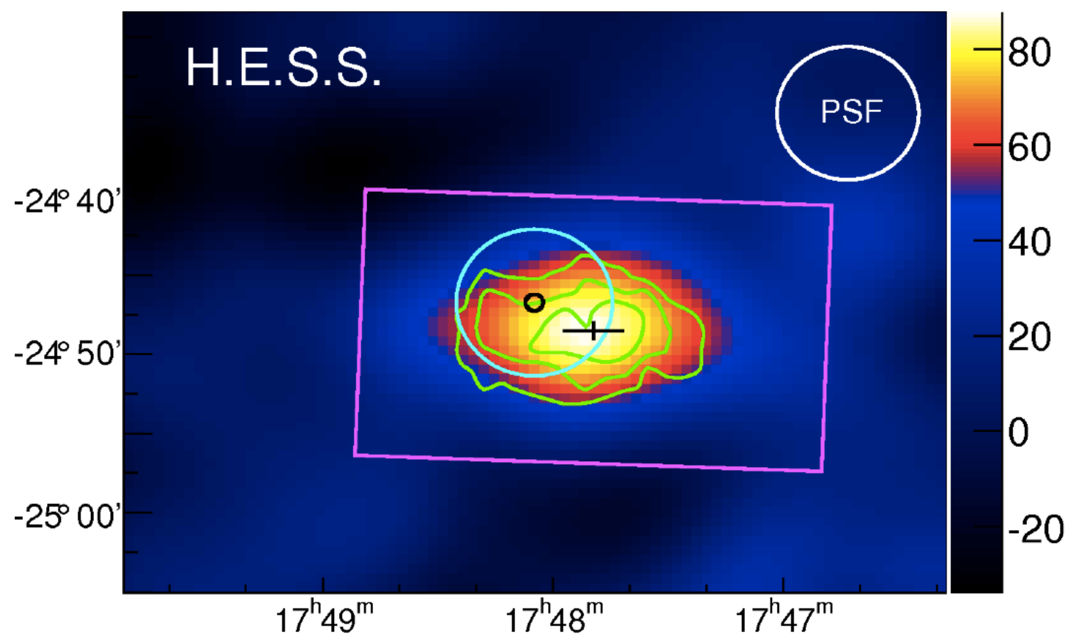
GeV : Curvature radiation from MSPs.

TeV : Inverse Compton of $e^{\pm}$ ejected from MSPs.

This suggests that $e^{\pm}$'s are ejected from MSPs to ISM.



Abdo+ (2011)



Abramowski+ (2011)

Acceleration

Assumptions

In the wind region,

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

Typical energy is related to the number of particles.

$$\varepsilon_e = e\Delta V_{\max}\kappa^{-1} \sim 50\kappa^{-1}\mathrm{TeV}$$

κ : multiplicity

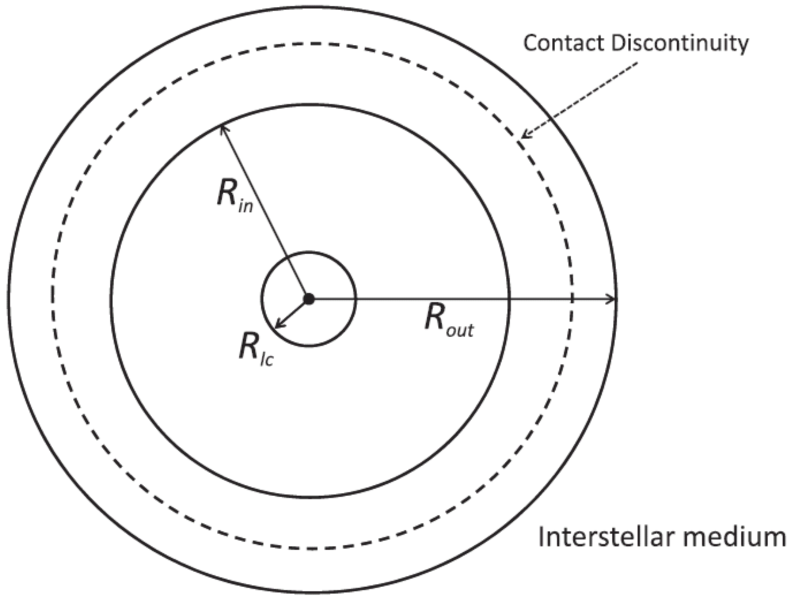
Ω : angular velocity

Cooling (adiabatic expansion)

(See also Kashiyama et al. 2011)

The time when outer shock decays

$$t_{\rm dec} \sim 10^6 \left(\frac{T}{10^3\ {\rm K}}\right)^{5/4}\ {\rm yr}$$

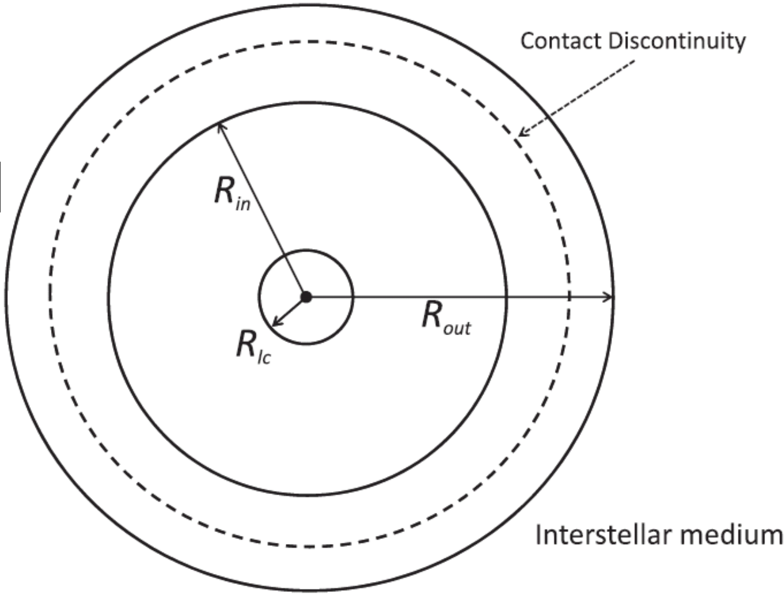


Because lifetime of MSPs is much long (~10^{10}yrs), the outer shock decays at a very early stage of the lifetime of MSPs. Therefore, we can neglect the adiabatic cooling.

Cooling (synchrotron radioation)

(See also Kashiyama et al. 2011)

When particles propagate in shocked region, particle lose energy by synchrotron radiation.
We take the Bohm limit.



$$\frac{\Delta\epsilon}{\epsilon} \sim 0.3\left(\frac{B_0}{10^{8.5}\mathrm{G}}\right)^2\left(\frac{\Omega}{10^3\mathrm{s}^{-1}}\right)^4\left(\frac{R}{10^6\mathrm{cm}}\right)^6$$

$e^{\pm}$ injected into the shocked region lose ~30% of the energy by the synchrotron radiation.

Propagation in ISM

$$\frac{\partial}{\partial t} f(t, r, \epsilon_e) = D(\epsilon_e)\nabla^2 f + \frac{\partial}{\partial \epsilon_e}(P(\epsilon_e) f) + Q(t, r, \epsilon_e)$$

Diffusion coefficient $D(\varepsilon_e) = D_0(1+\varepsilon_e/3\mathrm{GeV})^\delta$

Cooling function $P(\varepsilon_e) = \frac{4\sigma_T \varepsilon_e^2}{3m_e^2c^3}\left[\frac{B^2}{8\pi} + \int d\varepsilon_\gamma u_{\mathrm{tot}}(\varepsilon_\gamma) f_{\mathrm{KN}}\left(\frac{4\varepsilon_e\varepsilon_\gamma}{m_e^2c^4}\right)\right]$

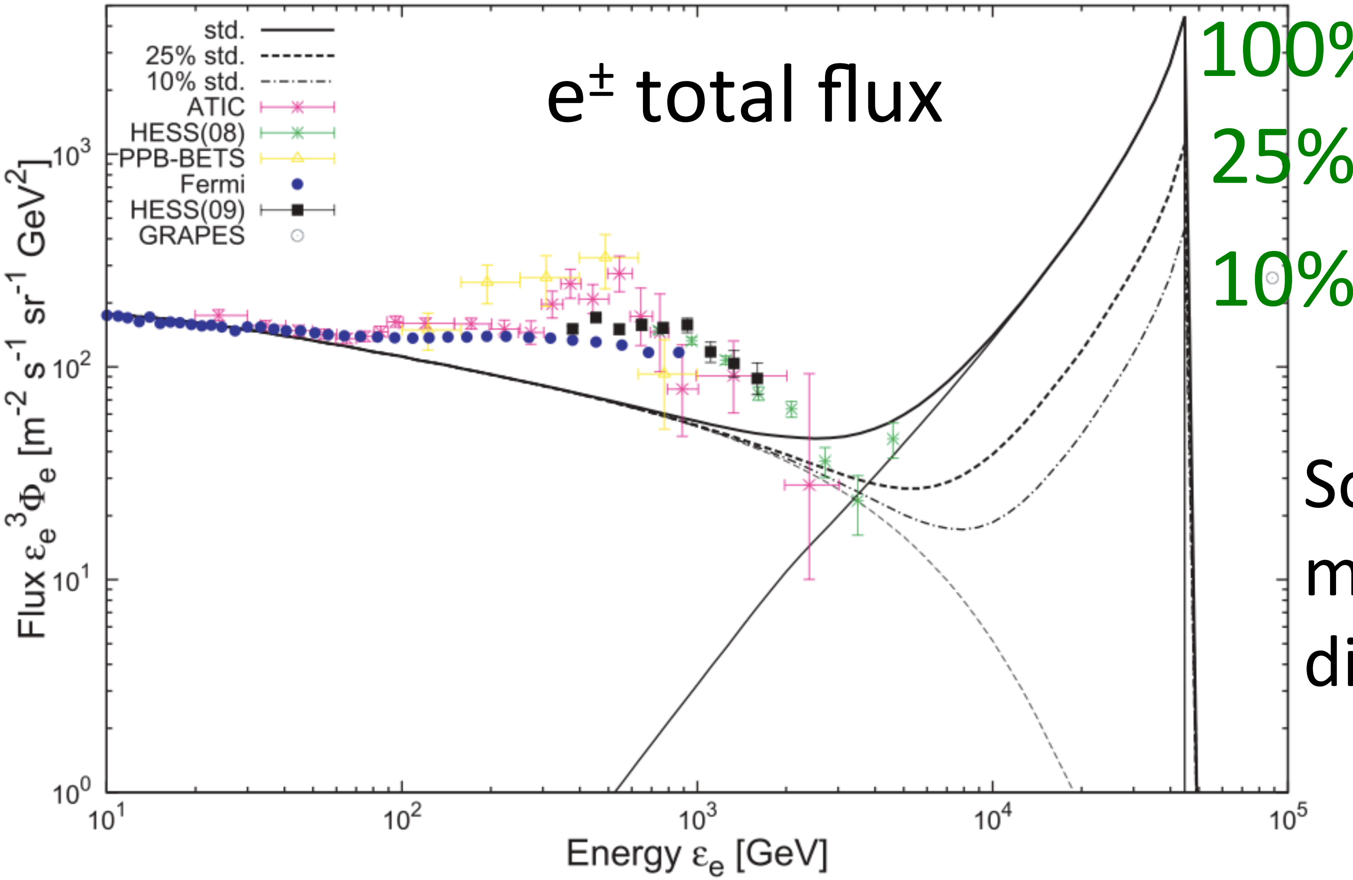
Source function $Q_0(\varepsilon_e, \tilde{t}) \propto \varepsilon_e^{-\alpha} \exp\left(-\frac{\varepsilon_e}{\varepsilon_{\mathrm{cut}}}\right)\left(1 + \frac{\tilde{t} - t_i}{\tau}\right)^{-2}$

Spectrum

$$f_{\mathrm{ave}}(\varepsilon_e) = \int_0^{t_0} dt_i \int_0^{d_{\mathrm{diff}}(\varepsilon_e, \varepsilon_{e,i})} 2\pi r dr f(t_0, r, \varepsilon_e; t_i) R$$

R ~ 3×10^{-9} $\mathrm{kpc}^{-2}\mathrm{yr}^{-1}$: local birth rate

Result for κ=1 (ε_e=50TeV)



Fraction of pair-starved MSPs

Source function is mono-energetic distribution.

Large peak forms in 10-50 TeV range and may be detectable by future observations such as CALET and CTA.

Summary

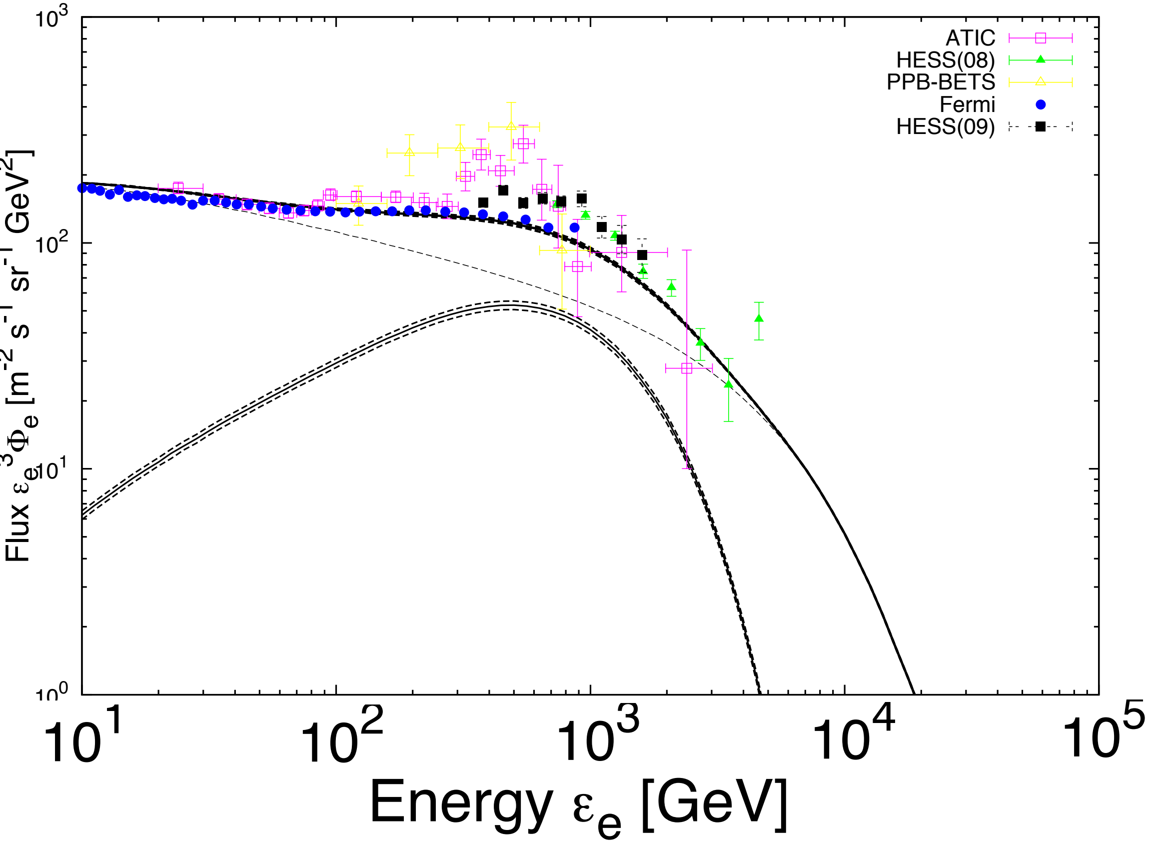
- We calculate $e^{\pm}$ cosmic ray spectra from MSPs based on equipartition in pulsar wind region.

- We propose the possibility that $e^{\pm}$ cosmic rays from MSPs significantly contribute to the observed spectrum.

- In the case ε_e=50TeV and κ ~1, large peak form in 10-50 TeV range and may be detectable by CALET and CTA.

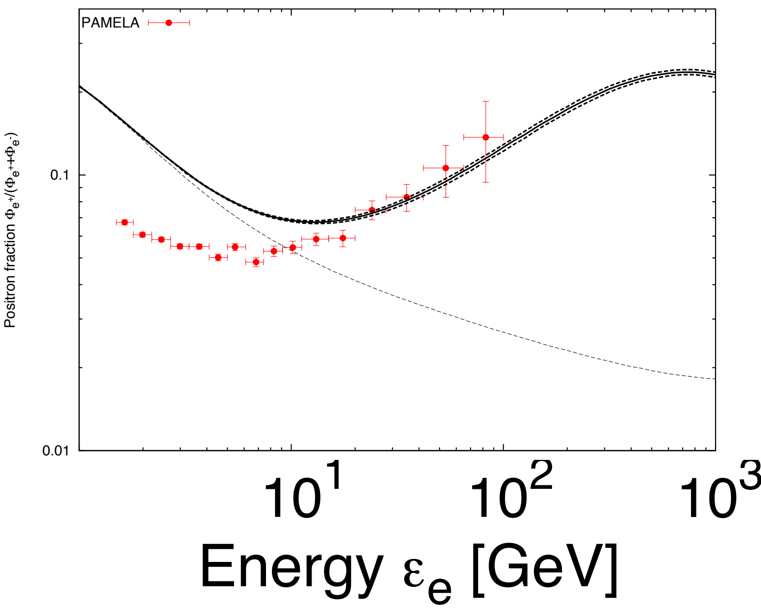
Appendix: Result for $\kappa=10^3$ (ε_e=1TeV)

$e^{\pm}$ total flux



Source function is power-law with α=2.

e^+ fraction



MSPs can also explain the results of PAMELA, Fermi and HESS.