Radiation Efficiency and Pair Multiplicity of **MeV Pulsars**

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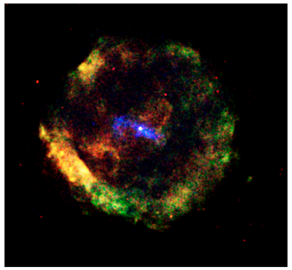
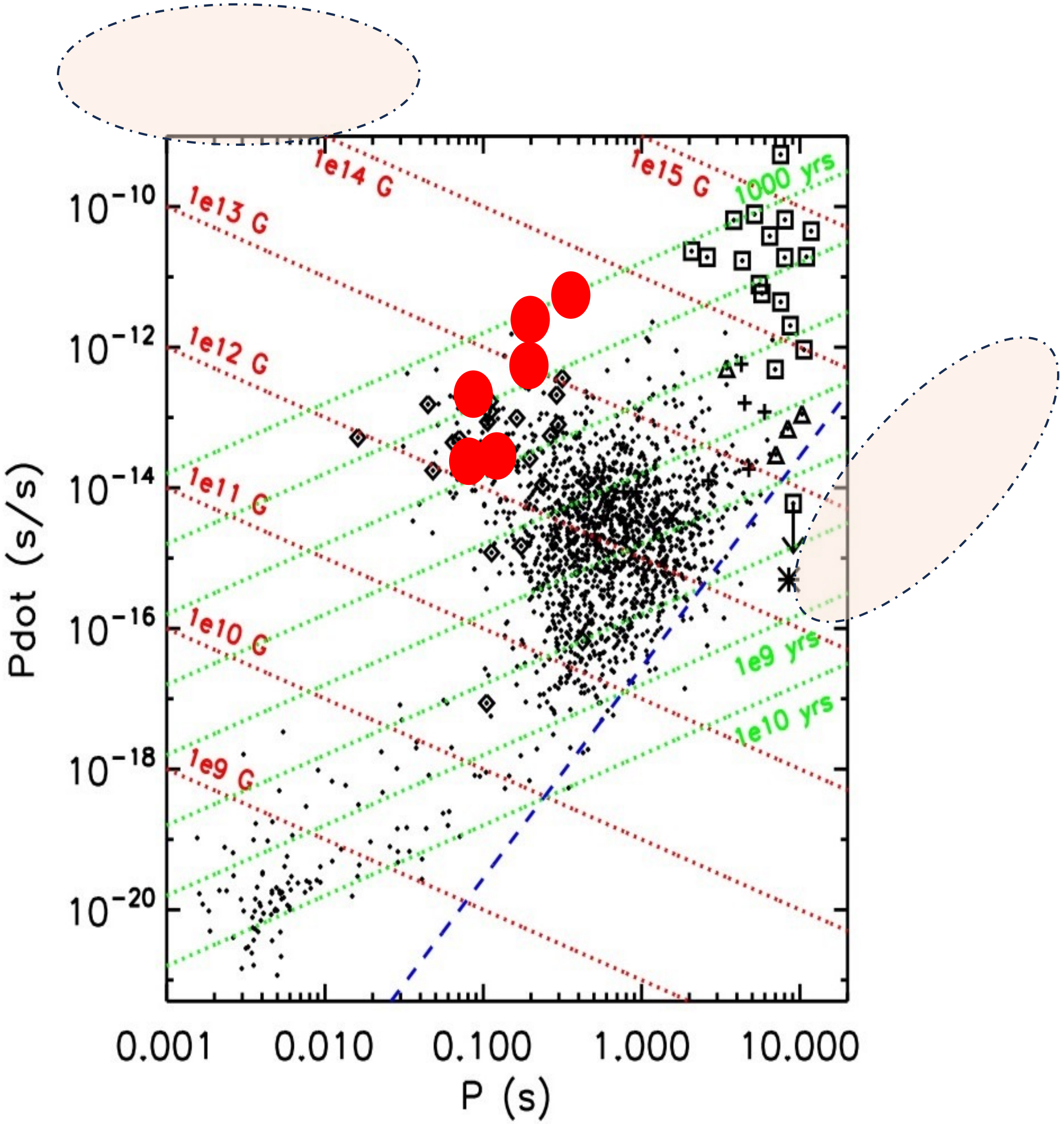
2024, May 11-15 @ Dream field

Pulsar zoo

RCW 103/ PSR B1509-58

G11.2-0.3/PSR J1811-1925





Outline

1. Motivation.

2. New X-ray analysis for eight MeV pulsars.

3. Estimation of the multiplicity of MeV pulsar's emission.

4. Summary.

1. Motivation

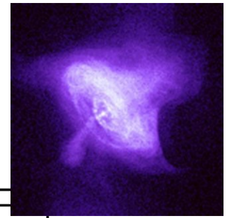
- Pair-creation process in the magnetosphere.
  (i) Magnetic pair-creation process.
  (ii) Photon-photon pair-creation process.

- Multiplicity (κ) = Pair number/ Goldreich-Julian value.
  - How many pairs are created by one electron accelerated in the magnetosphere

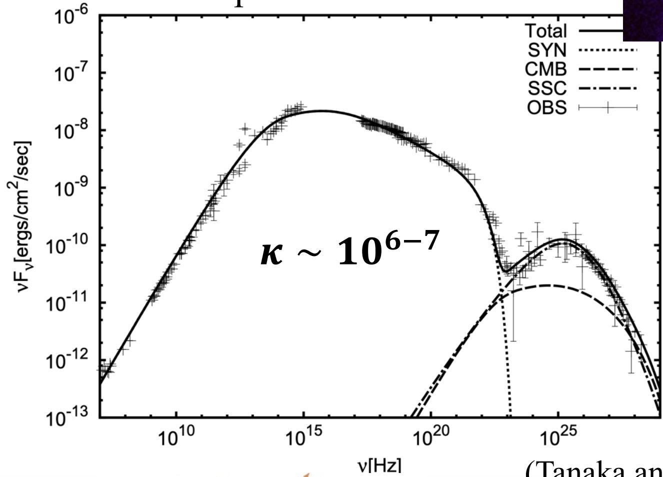
- Pair-creation cascade on **near the stellar surface**.

$$\kappa_{max} \sim \frac{\text{Energy of one accelerated primary } (\sim 10^{13}\text{eV})}{\text{Minimum photon energy of process } (1\sim\text{MeV})} \sim 10^7$$

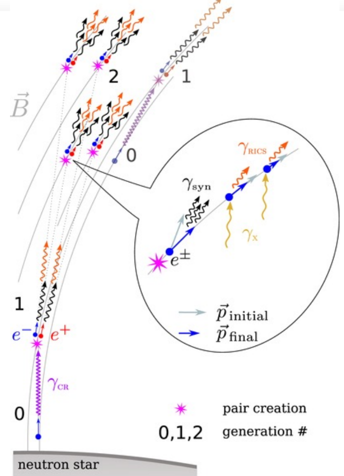
- **Has the high-energy emission from $\boldsymbol{\kappa = 10^{6-7}}$ pairs in "the magnetosphere" been observed ?**



Spectrum of Crab nebula



(Tanaka and Takahara 2010)



(Timokhin and Harding 2019)

1, Motivation:

❑ GeV/TeV emission from magnetosphere

- > 300 *Fermi*-LAT GeV pulsars.
- 2 TeV pulsars (Crab and Vela).

- Emission from the outer magnetosphere (~light cylinder).

- Two radiation models.

(1) Canonical gap model

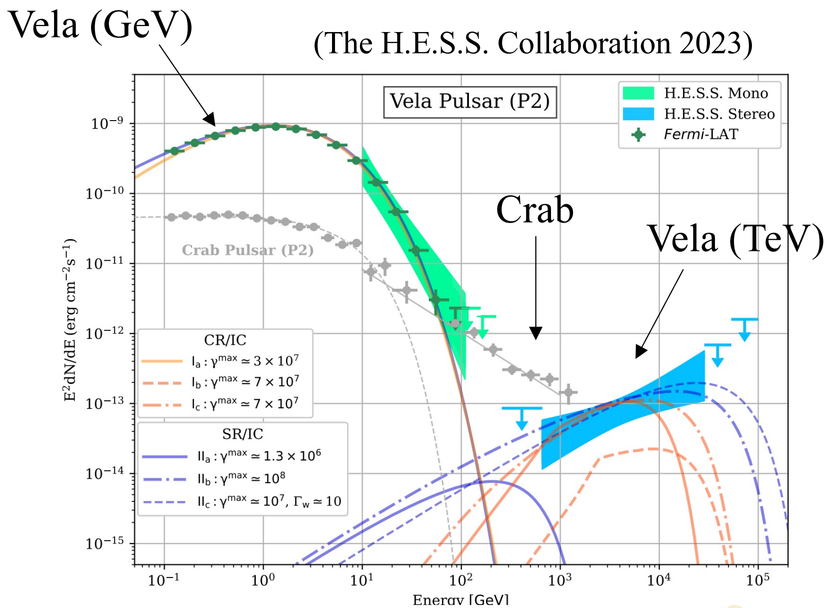
(i) GeV emission:

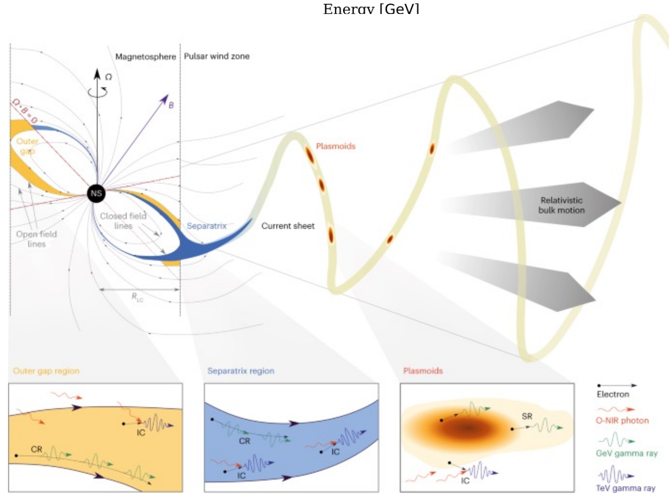
- Curvature radiation of primary particles (energy ~ gap electric potential): $n_p \sim n_{GJ}$ ($\boldsymbol{\kappa}$~1) .

(ii) TeV emission (inverse-Compton process):

- Crab: Secondary pair's ($\boldsymbol{\kappa \sim 10^3}$) .
- Vela: Primary ($\boldsymbol{\kappa}$~1) .

(The H.E.S.S. Collaboration 2023)





1, Motivation:

❑ GeV/TeV emission from magnetosphere

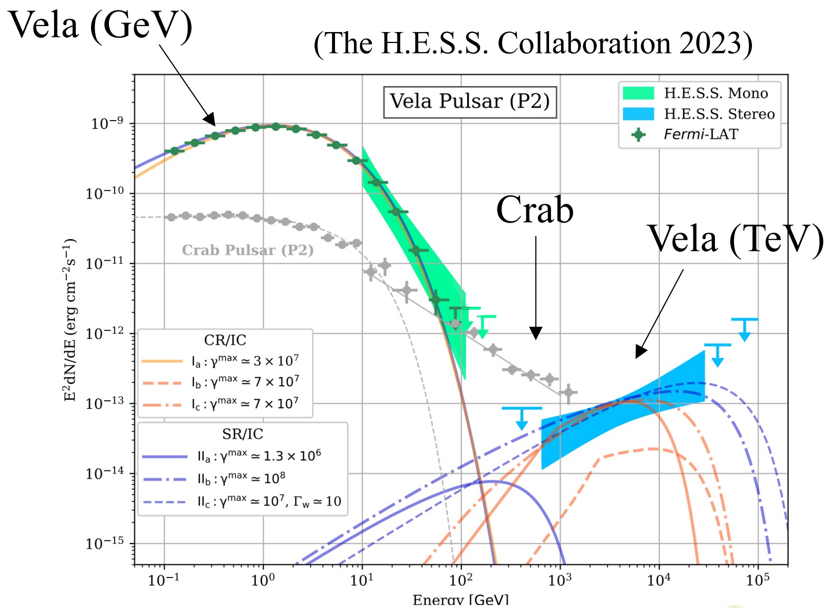
(2) Current sheet model

- Accelerated pair energy density ~ magnetic energy density.

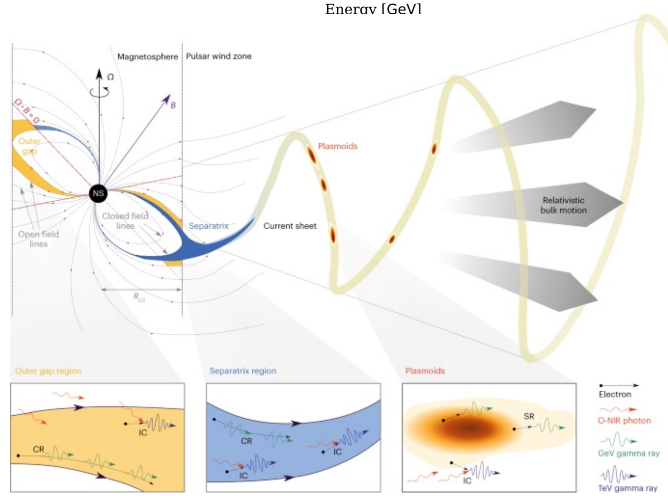
$$\left(\gamma\kappa n_{GJ} m_e c^2 \sim \frac{B^2}{8\pi}\right)$$

- Synchrotron radiation.
- GeV emission: $\boldsymbol{\kappa \sim 10^3}$
- TeV emission: $\boldsymbol{\kappa \sim 100}$

- **Where do the high-energy emissions from new born pairs ($\boldsymbol{\kappa = 10^{6-7}}$) ?**



(The H.E.S.S. Collaboration 2023)



1, Motivation:

❑ MeV pulsar

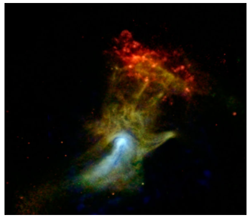
- **Eight young pulsars (isolate).**
  - Represent source is PSR B1509-58

PSR	P_s (ms)	B_s (10^{12}G)	L_{sd} (10^{36}erg s^{-1})	d (kpc)
B1509-58	152	15	17	4.4
J1617-5055	69.4	3.1	16	4.7
J1811-1925	64.7	1.7	6.4	5.0
J1813-1749	44.7	2.4	56	6.1
J1838-0655	70.5	1.9	5.5	6.6
J1846-0258	327	49	8.1	5.8
J1849-0001	38.5	0.75	9.8	7.0^a
J1930+1852	137	10	12	7.0

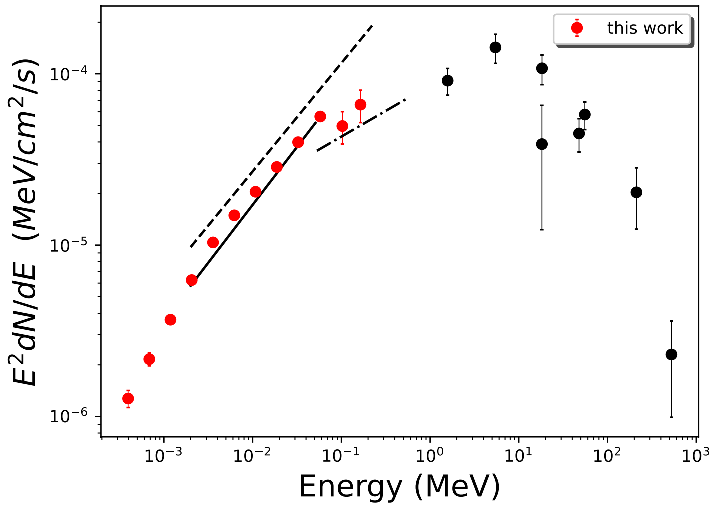
(i) No GeV detection.

(ii) SED peak at 1-10MeV.

(iii) Non-thermal X-ray.
- Thermal emission may be buried under the non-thermal component.



PSR B1509-58



- **What is the emission process?**
  - **Radiation efficiency.**
  - **Required multiplicity.**

2. New X-ray data analysis

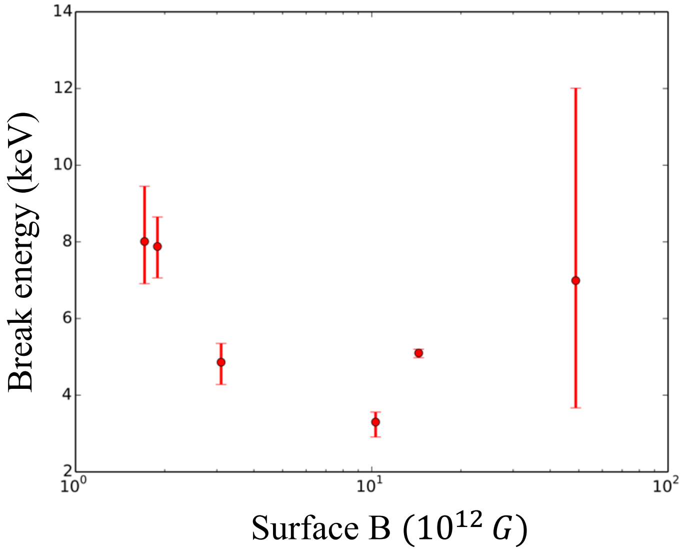
- **XMM-Newton, NICER, NuSTAR and HXMT**
- Eight MeV PSRs share similar spectra and pulse profiles.

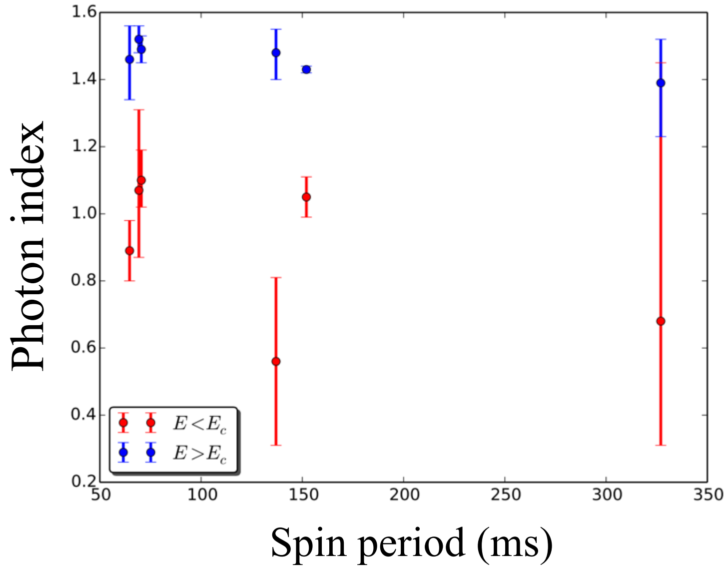
(1) **Broken power law** spectrum (pulsed component)

-Break energy: $E_{break} \sim 5 - 10\text{keV}$.

- Photon index: $\Gamma_1 \sim 1$ for $E < E_{break}$ and $\Gamma_1 \sim 1.5$ for $E > E_{break}$

→ Synchrotron radiation.



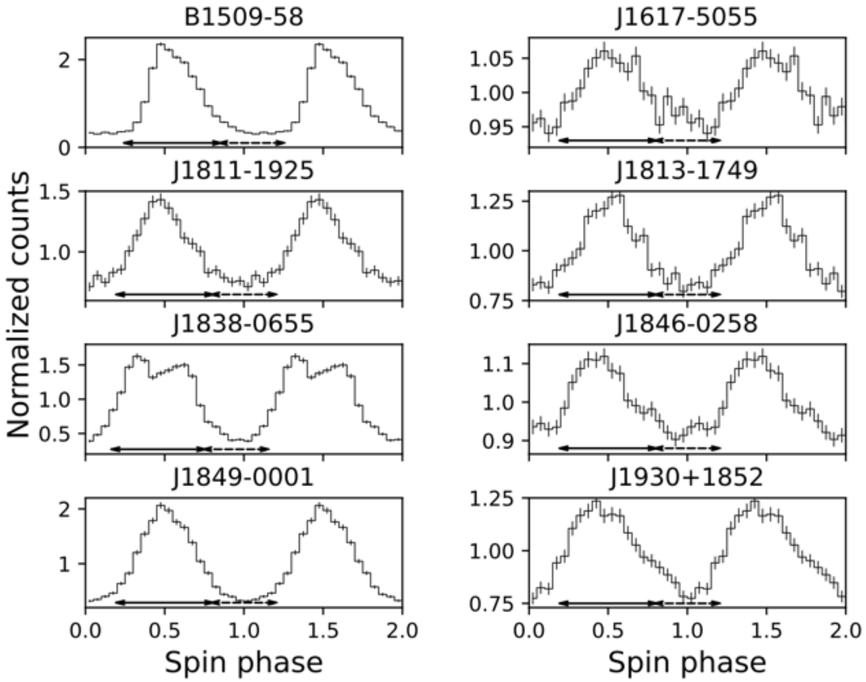


❑ New X-ray data analysis

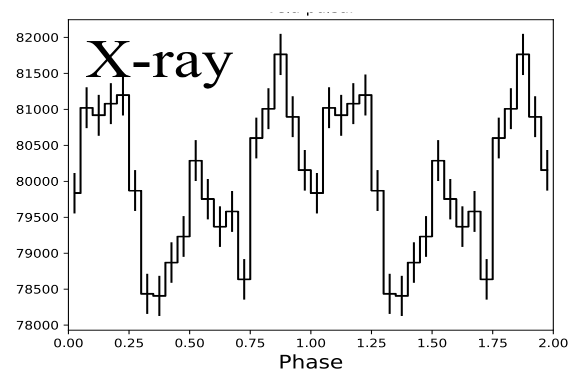
(2) **Singla broad peak of X-ray emission**.

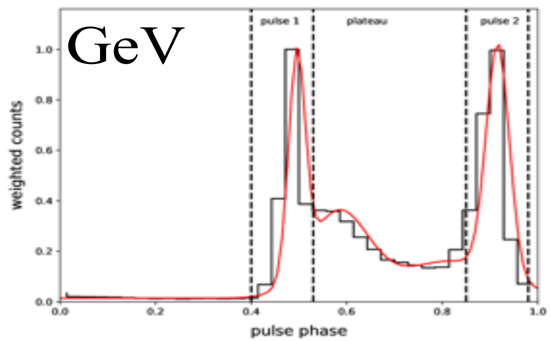
- Emission region may be different from that of GeV pulsars.

MeV pulsar (X-ray)



GeV pulsar (Vela)





(Wang et al. 2024)

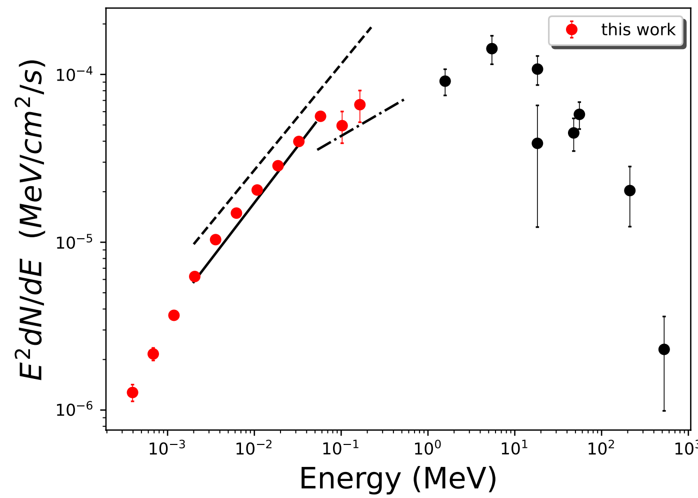
2. New X-ray data analysis

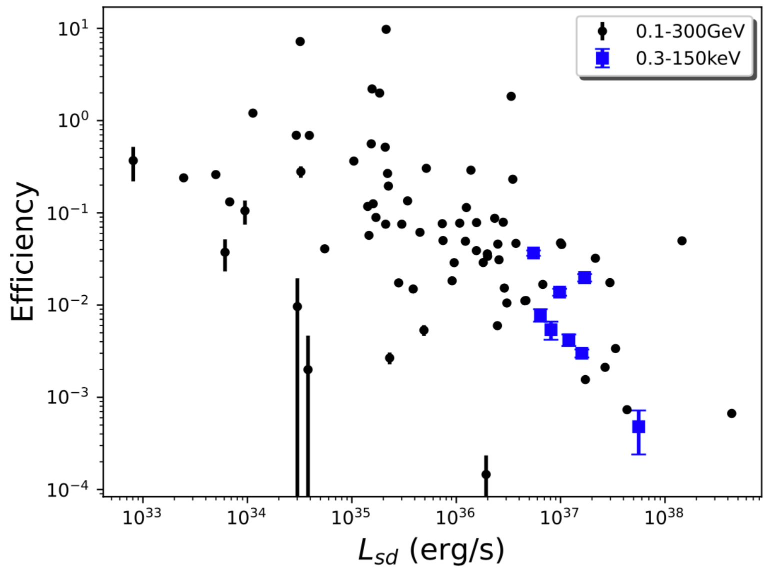
❑ Radiation efficiency of MeV pulsar

- Efficiency (η) = Luminosity / Spin down power
- *Isotropic* radiation efficiency in 0.3-150 keV bands is $\eta \sim 10^{-2} - 10^{-1}$ (most pulsars has no data in 500keV-10 MeV bands).
- The efficiency is on the track of the "GeV" efficiency of Fermi-*LAT* pulsar.
- Two possible interpretations of $\eta_{MeV\ PSR} \sim \eta_{GeV\ PSR}$.

(i) Emission from the secondary pairs, into which most of primary GeV emission is converted.

(ii) The emission region is the same.





3. Multiplicity

❑ Estimation

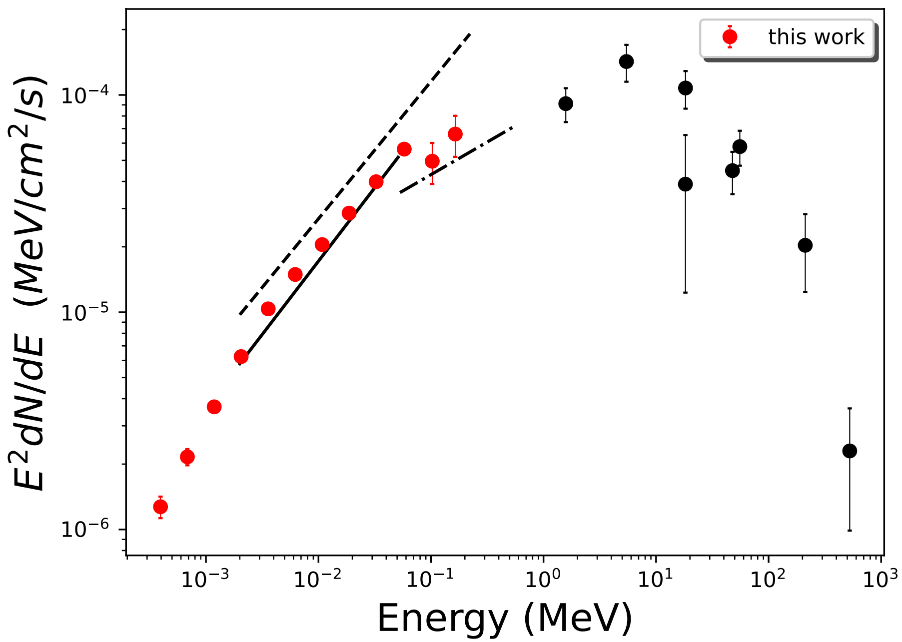
(i) Secondary emission inside light cylinder:

- **Assumption**

(a) Distance to emission region from the star.
(b) All pairs are injected with a Lorentz factor γ_{max}.
(c) Synchrotron radiation.
(d) E_{break} corresponds to the minimum Lorentz factor of the pairs.
  (i) Dynamical time scale = Synchrotron cooling time scale, or
  (ii) The lowest Landau level.

- **Model parameters:**

(1) Efficiency: $\eta = 10^{-3} - 10^{-2}$.
(2) Spectral peak: $E_{peak} \sim$ 1MeV (fixed).
(3) Spectral break energy: $E_{break} \sim$ 5keV (fixed).
(4) Magnetic field (or radial distance) : $B(r) = \left(\frac{R_{NS}}{r}\right)^3 B_{NS}$.

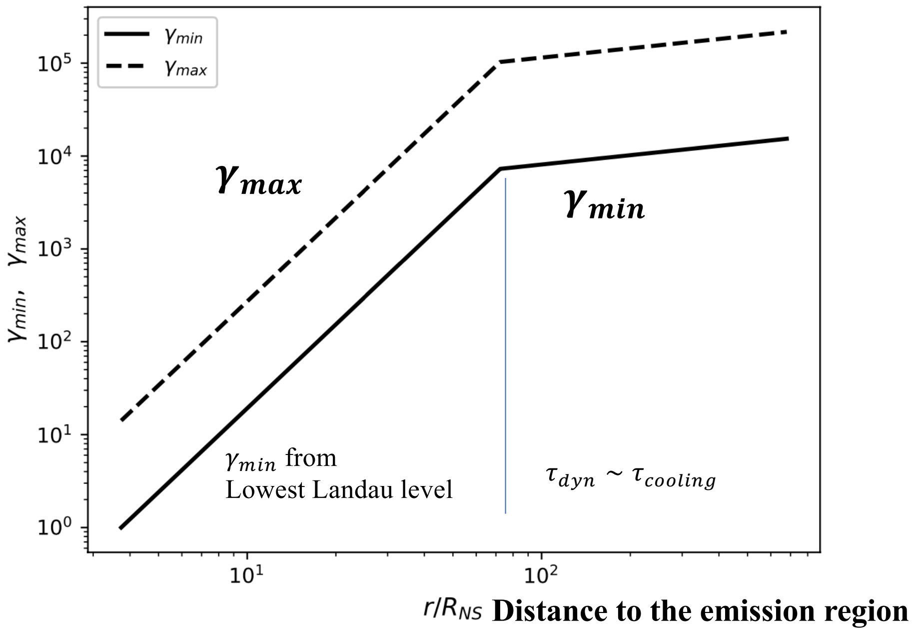


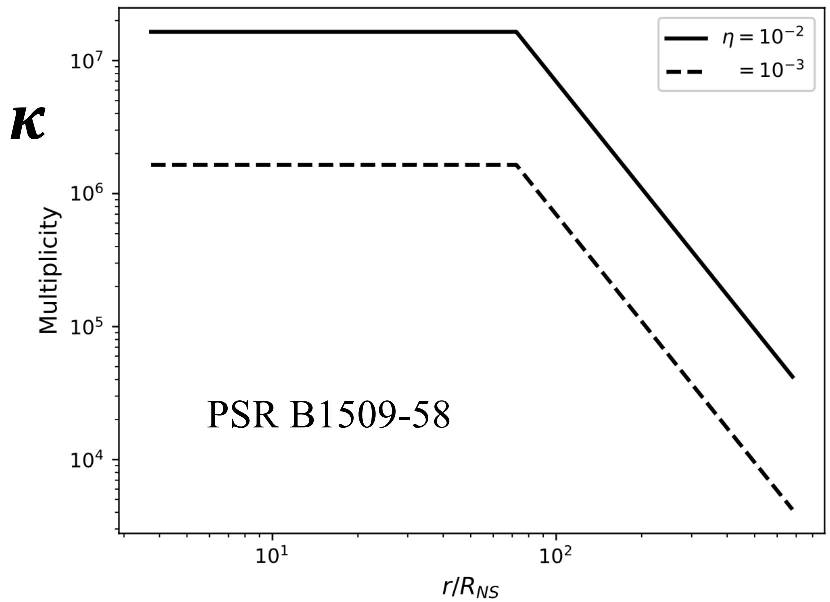
- **Estimated parameters:**

(1) Multiplicity (κ).
(2) Initial Lorentz factor of pair (γ_{max}).
(3) Final Lorentz factor (γ_{min}).
(4) Pitch angle (α).

(i) Secondary emission inside light cylinder (cont'd)

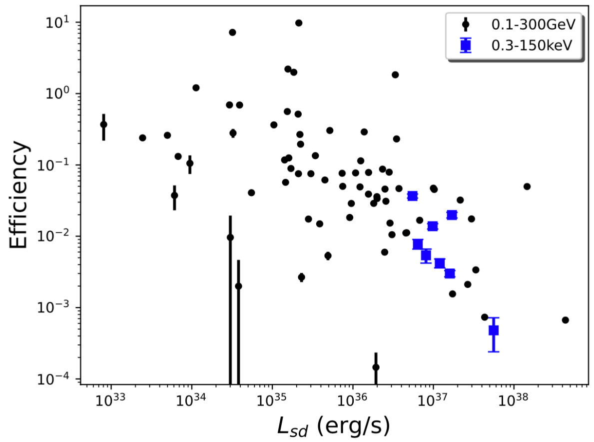
- If the emission region $\frac{r}{R_{NS}} < 80$, $\kappa \sim 10^{6-7}$ is expected.
  - **It is similar to the theoretical prediction of pair cascade near the stellar surface.**
- For outer magnetosphere, the pairs with an injected energy of $\gamma_{max} m_e c^2 \sim 1\text{TeV}$ is required.
  - It may be difficult to create such a high-energy pair with $\kappa \sim 10^{4-5}$.





3. Multiplicity

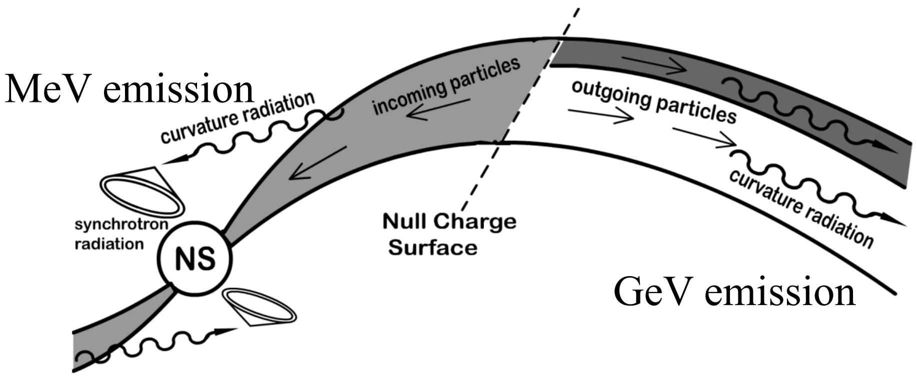
(i) Secondary emission inside light cylinder (cont'd)

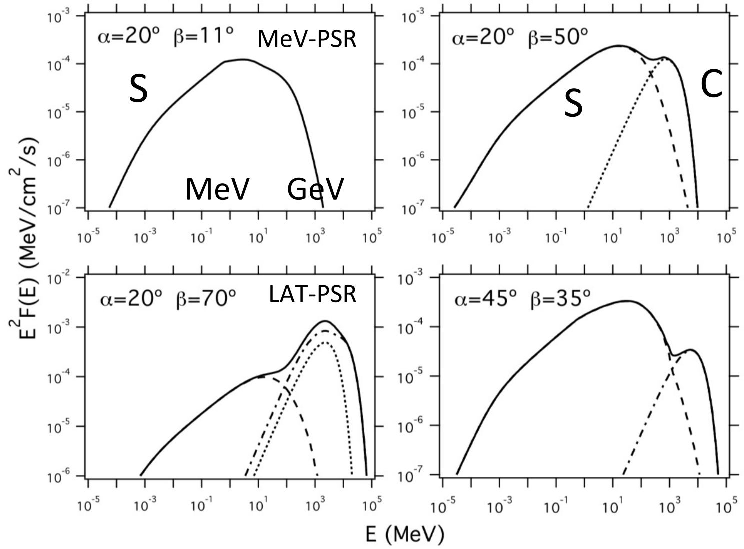


Interpretation

- Efficiency of MeV pulsar emission ~ Efficiency of GeV pulsar emission.

→**Inward GeV emission** from the outer magnetosphere is converted into pairs near the stellar surface.





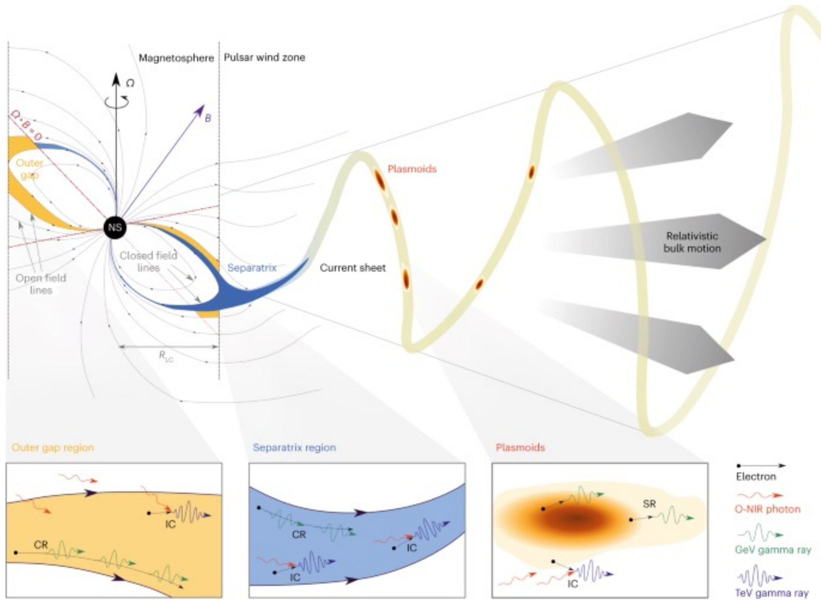
(Wang, Ng Takata et a. 2014).

3. Multiplicity

❑ Estimation

(ii) Current sheet model

- Magnetic reconnection in the current sheet (Lyubarskii 1996; Chernoglazov et al. 2023).



(i) Accelerated pair energy density ~ Magnetic energy density.

$$(\kappa n_{GJ}/\Gamma_{bulk})\times\gamma'_p m_e c^2 \sim \frac{B_{lc}^2}{8\pi}$$

(ii) Peak energy

$$E_{peak} \sim \Gamma_{bulk}\times\left(\frac{3}{2}\right)^{\frac{3}{2}} \gamma'^2_p \frac{heB_{lc}}{2\pi m_e c} \sim 1MeV$$

→ $\kappa\sim4\times10^6$ for $\Gamma_{bulk}\sim10$

- Most of pairs created at the polar cap region is injected into the current sheets.

→ $\kappa\sim10^4$ for GeV pulsar.

Emission of the MeV pulsars is likely produced by the pairs with $\kappa \sim 10^{6-7}$.

❑Resonant Cyclotron Scattering feature?

- Indication of 40keV absorption feature in the spectrum.
  - New NuSTAR observation has been approved.

- If this would be true, the MeV pulsar emission likely originates near the stellar surface.
- Optical depth of RCS.

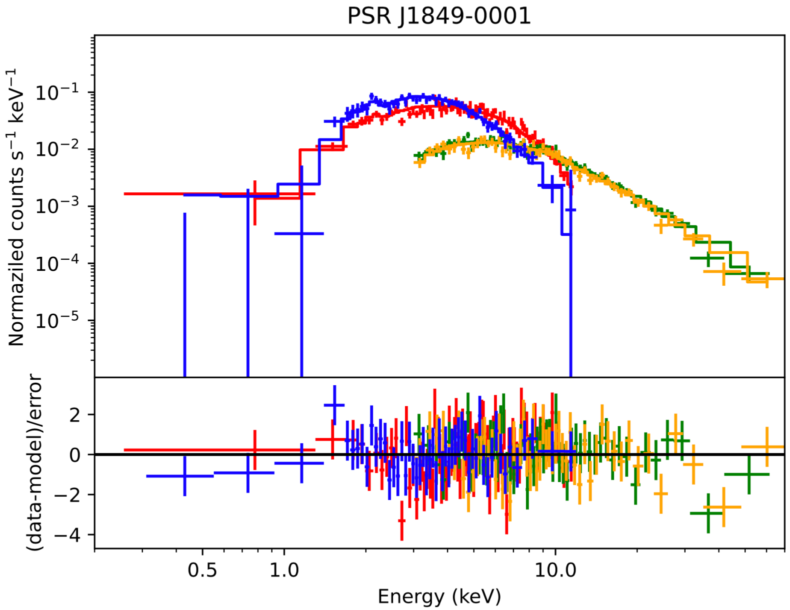
$$\tau_{res} \sim \frac{16}{3}\frac{\pi^2 e^2}{m_e c}\frac{(\kappa n_{GJ})\Delta r_{res}}{\omega_{cyc}}$$

$$\sim 80 \left(\frac{\kappa}{10^6}\right)\left(\frac{B}{10^{12}G}\right)\left(\frac{E_{cyc}}{50keV}\right)^{-1}\left(\frac{\Delta r_{res}}{10^4 cm}\right)$$

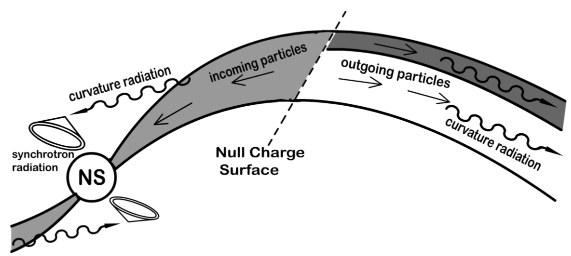
- How is the population of the ***non-relativistic*** pairs created ?

(i) Polar cap accelerator cascade: $\gamma\sim$ several for $\kappa \sim 10^{6-7}$.

(ii) The inward GeV emission creates the pairs with a large pitch angle, $\sin\alpha = \frac{\gamma_\perp}{\gamma_{||}} \sim 1$.



(Takata et al. 2014)



Summary

- Pulsar wind nebulae indicates $\kappa \sim 10^{6-7}$.

- Missing high-energy emission from the pars.

- MeV pulsar's emission from the pairs with $\kappa \sim 10^{6-7}$.

- Resonant Cyclotron Scattering feature ?