Efficiency of VHE emission from rotation-powered pulsars

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Energy Conversion

Rotation energy

Dipole B-field ⟶ ↓

Electromagnetic energy (Poynting flux)

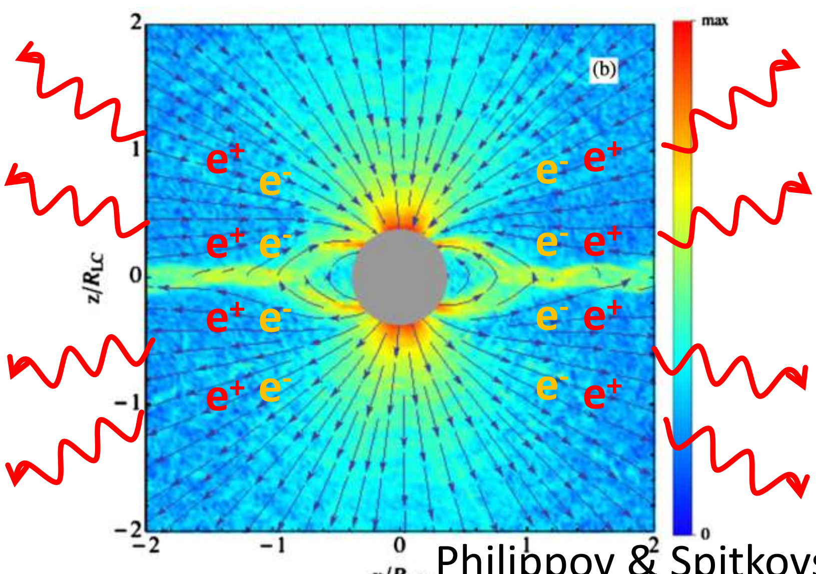
Acceleration, creation ⟶ ↓

Particle energy

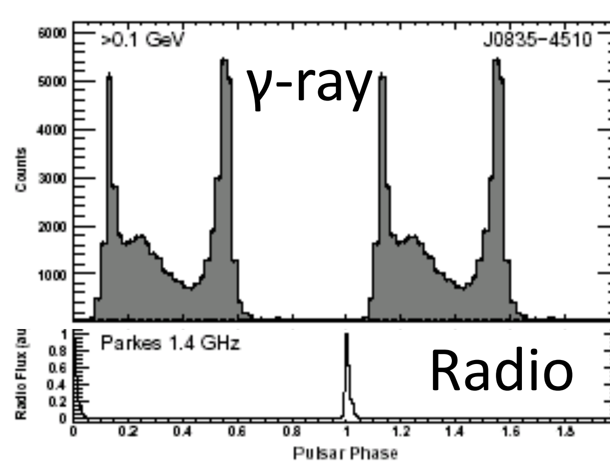
B-field, environment ⟶ ↓

Radiation, cosmic ray, heat

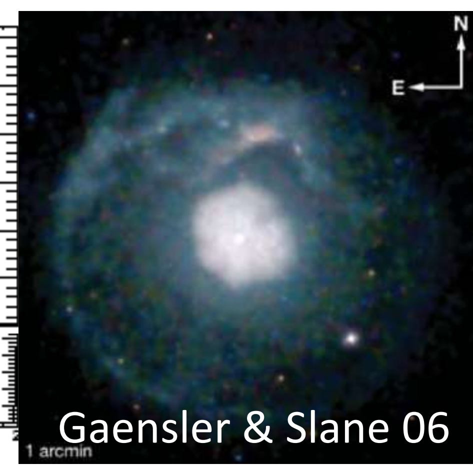
Where?
How efficient?



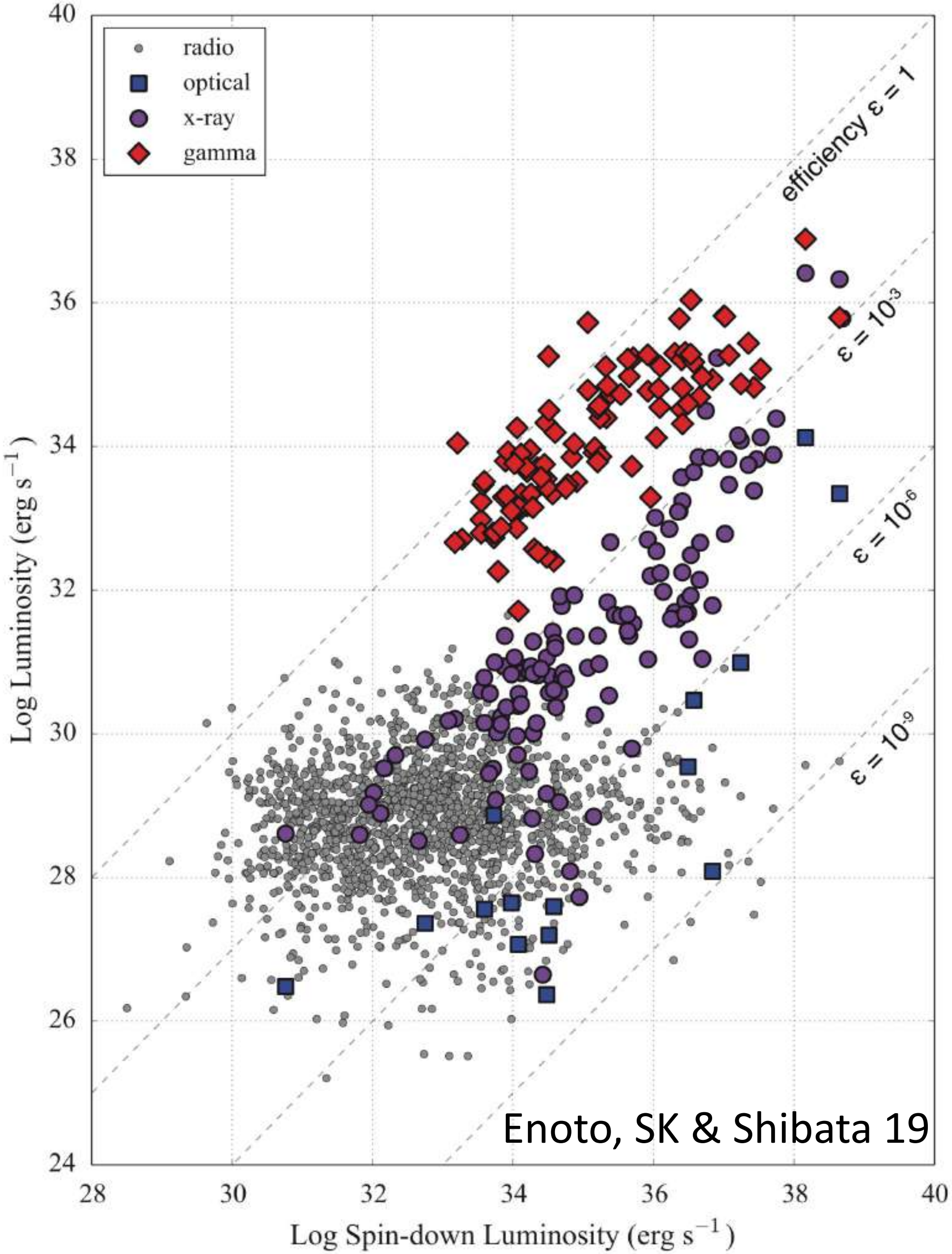
Philippov & Spitkovsky 14



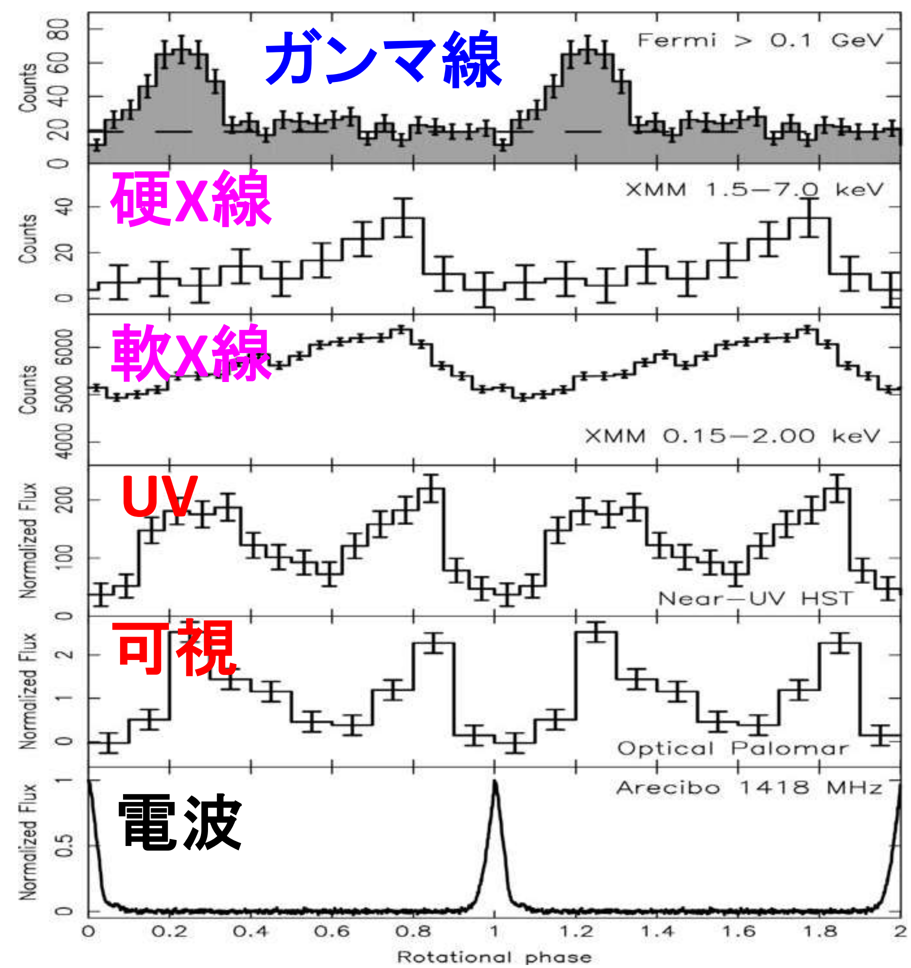
Abdo+ 10



Multiwavelength Pulsed Emission



PSR J0659+1414



Weltevrede+ 10

Multiwavelength Pulsed Emission

Frequency	radio	optical/UV	soft X-ray	hard X-ray	GeV
Detected number	~10^3	~10	~10^2	~10^2	~10^2
Luminosity (L_{sd})	~10^{-4}	~10^{-6}	~10^{-3}	~10^{-3}	~10^{-1}
Radiation mechanism	?	Synchrotron (+ Thermal radiation)	Thermal radiation	Synchrotron (+ IC?)	Curvature Radiation (IC?)
Peak shape	Very sharp (~0.01)	Slightly sharp (~0.1)	sinusoidal	sharp (~0.01-0.1)	sharp (~0.01-0.1)

Multiwavelength Pulsed Emission

Frequency	radio	optical/UV	soft X-ray	hard X-ray	GeV	TeV
Detected number	$\sim 10^3$	~ 10	$\sim 10^2$	$\sim 10^2$	$\sim 10^2$	3
Luminosity (L_{sd})	$\sim 10^{-4}$	$\sim 10^{-6}$	$\sim 10^{-3}$	$\sim 10^{-3}$	$\sim 10^{-1}$	$\sim 10^{-5}$
Radiation mechanism	?	Synchrotron (+ Thermal radiation)	Thermal radiation	Synchrotron (+ IC?)	Curvature Radiation (IC?)	Inverse Compton
Peak shape	Very sharp (~0.01)	Slightly sharp (~0.1)	sinusoidal	sharp (~0.01-0.1)	sharp (~0.01-0.1)	Very sharp (~0.01)

TeV Pulse from the Crab Pulsar

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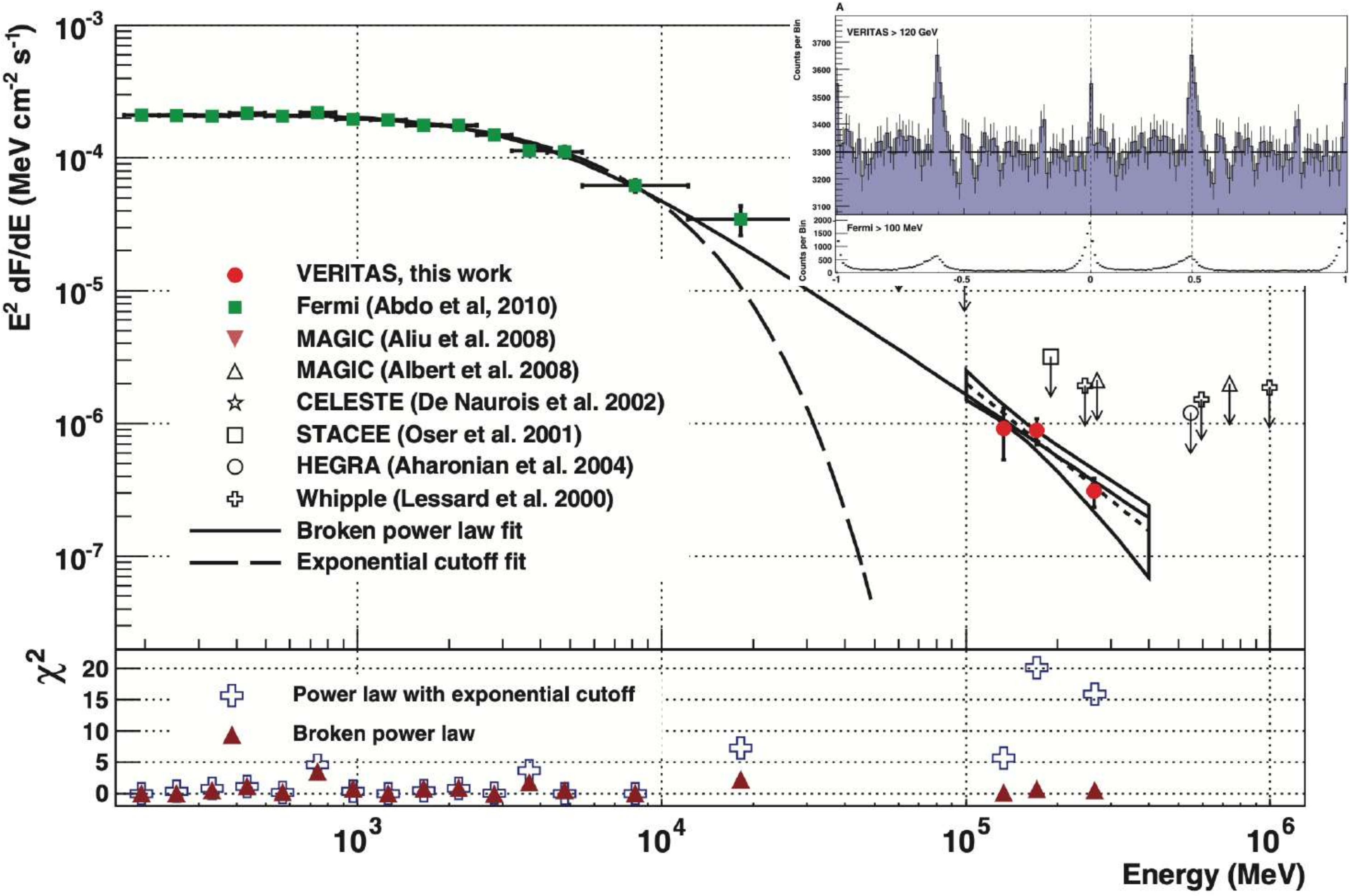

TeV Pulse from the Vela Pulsar

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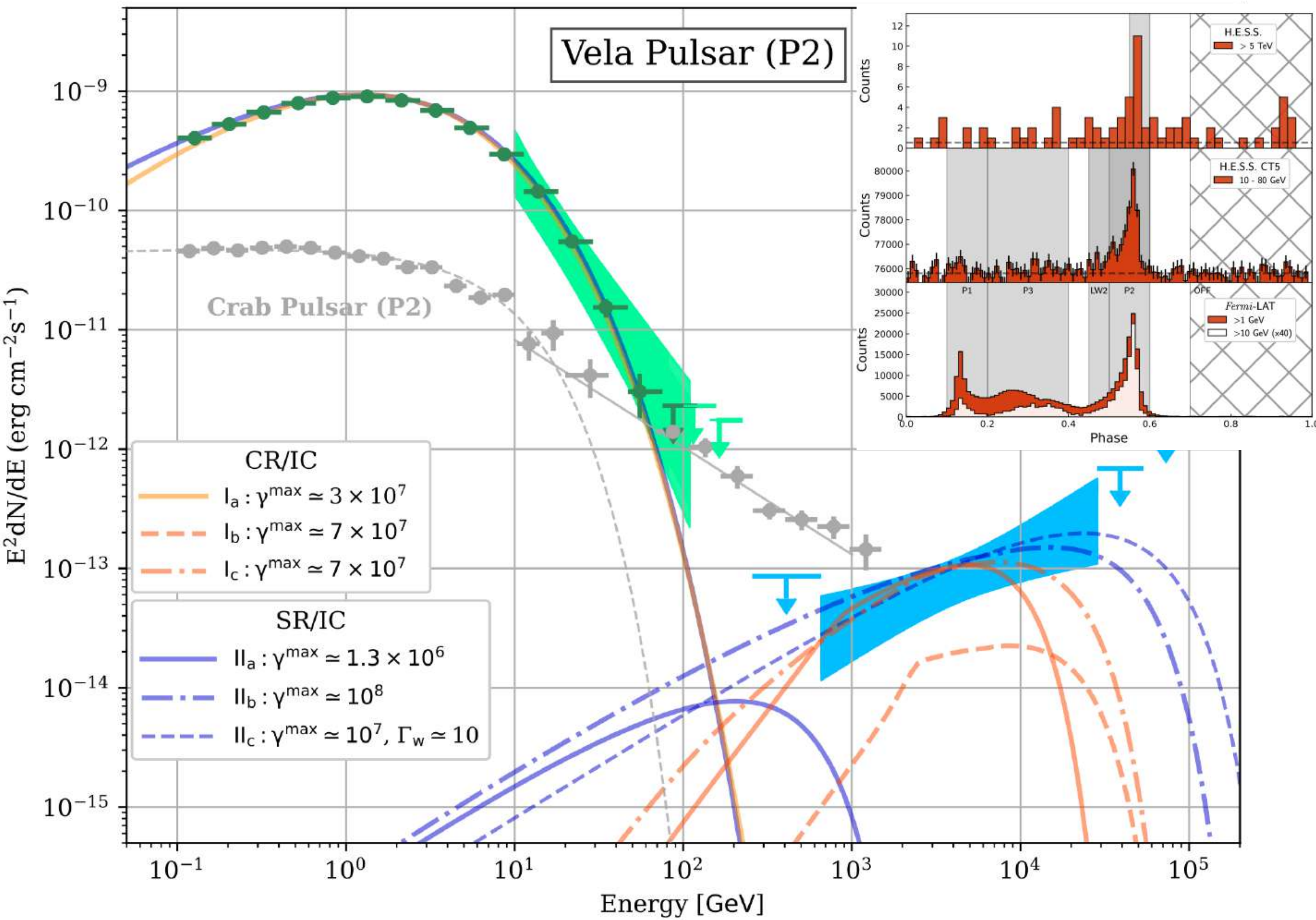
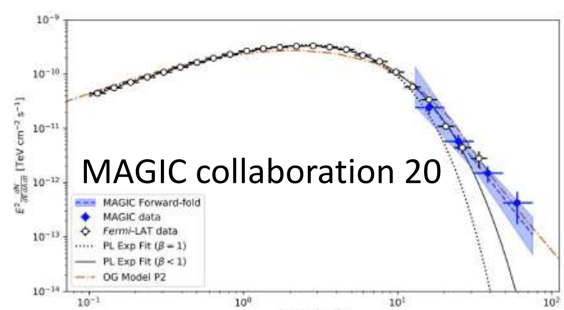
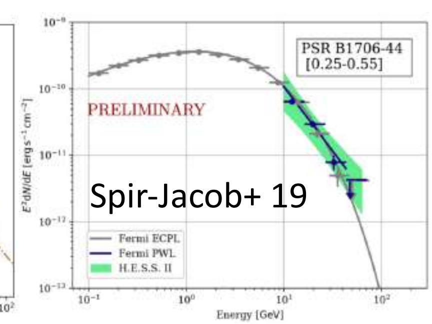


Summary of VHE Pulsars

	Crab	Vela	PSR J1509-5850	Geminga	PSR B1706-44
P [sec]	0.033	0.089	0.089	0.237	0.102
τ [kyr]	1	11	150	340	17
L_{sd} [erg/s]	5e38	7e36	5e35	3e34	3e36
Detected Energy [TeV]	< 1.5	0.7-20	0.5-10	< 0.075	< 0.055
Efficiency	**10^{-4}-10^{-5}**	**10^{-6}**	**10^{-3}**	Consistent with curvature radiation	Consistent with curvature radiation



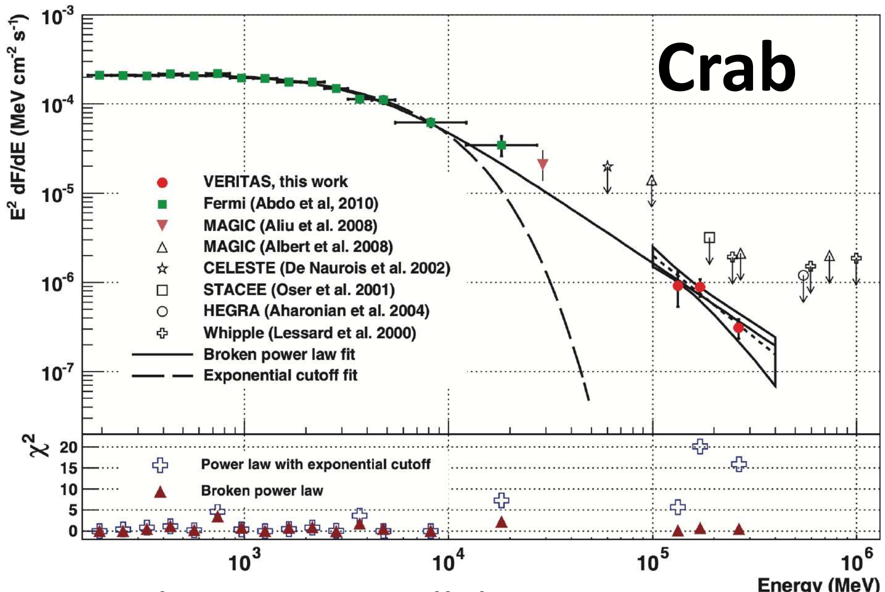


Why VHE pulse is important?

- Emission mechanism
  - → Inverse Compton Scattering
  - → The energy of accelerated particles

Question

- Luminosity can reach to $10^{-3} \times L_{sd}$?
- What causes the difference between Crab-type and Vela-type?



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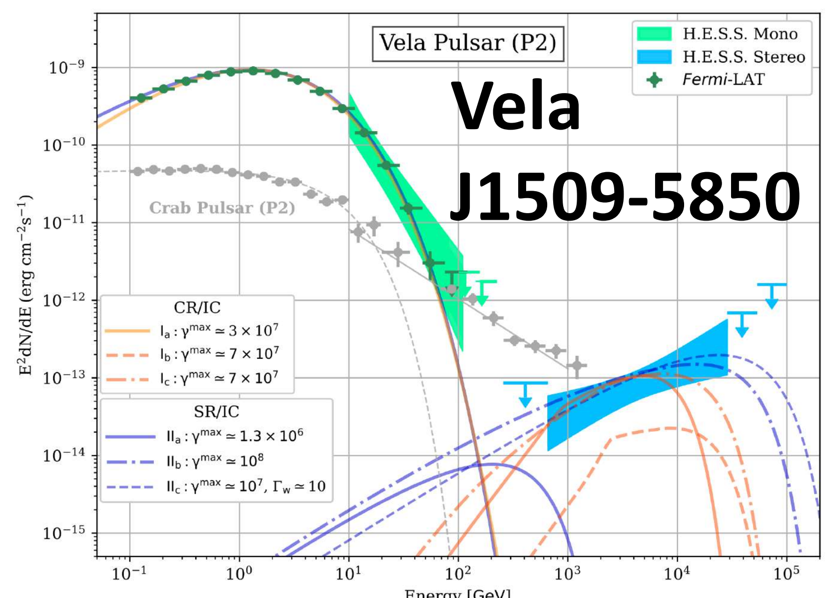

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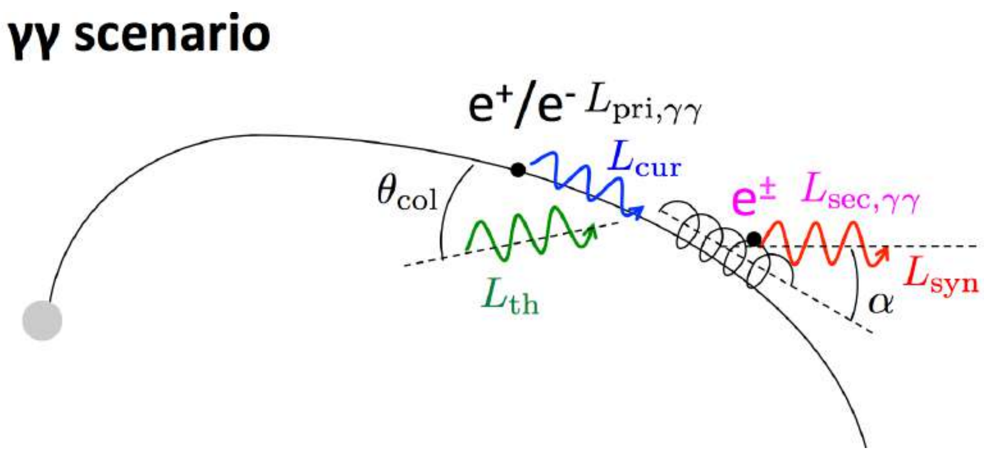
Model

Model

- Primary particles emit curvature radiation (CR) and inverse Compton scattering (IC).
- Synchrotron radiation (SR) is emitted by secondary particles through photon-photon (γγ) pair creation.

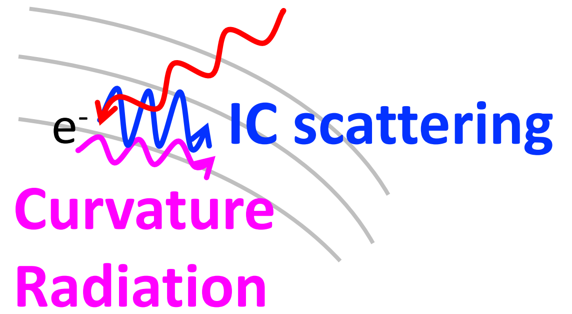


Assumptions

- Physical quantities are described **by a function of radius *r*.**
- Maximum luminosity is limited **by the spin-down luminosity**.
- **Dipole structure** dominates near the light cylinder.

Inverse Compton Luminosity

$$L_{\rm IC} = E_{\rm IC}\dot{N}_{\rm p}\tau_{\rm IC}$$



#-flux of primary e$^{\pm}$

$$\dot{N}_{\rm p} = \frac{\eta L_{\rm sd}}{\gamma_{\rm p} m_{\rm e} c^2}$$

η : Energy conversion efficiency

IC photon energy

$$E_{\rm IC} \sim \begin{cases} \gamma_{\rm p} & (\gamma_{\rm p} E_{\rm seed} \gtrsim m_{\rm e}c^2) \\ \gamma_{\rm p}^2 E_{\rm seed} & (\gamma_{\rm p} E_{\rm seed} \lesssim m_{\rm e}c^2) \end{cases}$$

Lorentz factor of primary e$^{\pm}$

$$\gamma_{\rm p} = \left(\frac{4\pi}{0.87}\frac{E_{\rm cur}}{h}\frac{R_{\rm cur}}{c}\right)^{1/3}$$

IC cross section

$$\sigma_{\rm IC} \sim \begin{cases} \sigma_{\rm T}\left(\frac{\gamma_{\rm p} E_{\rm seed}}{m_{\rm e}c^2}\right)^{-1} & (\gamma_{\rm p} E_{\rm seed} \gtrsim m_{\rm e}c^2) \\ \sigma_{\rm T} & (\gamma_{\rm p} E_{\rm seed} \lesssim m_{\rm e}c^2) \end{cases}$$

IC optical depth

$$\tau_{\rm IC} \sim n_{\rm seed}\sigma_{\rm IC} R_{\rm lc}$$

Inverse Compton Luminosity

$$L_{\rm IC} = E_{\rm IC}\dot{N}_{\rm p}\tau_{\rm IC}$$

$$\tau_{\rm IC} \sim n_{\rm seed}\sigma_{\rm IC}R_{\rm lc}$$

Seed photon : Thermal photons from the NS surface

- Heated polar cap

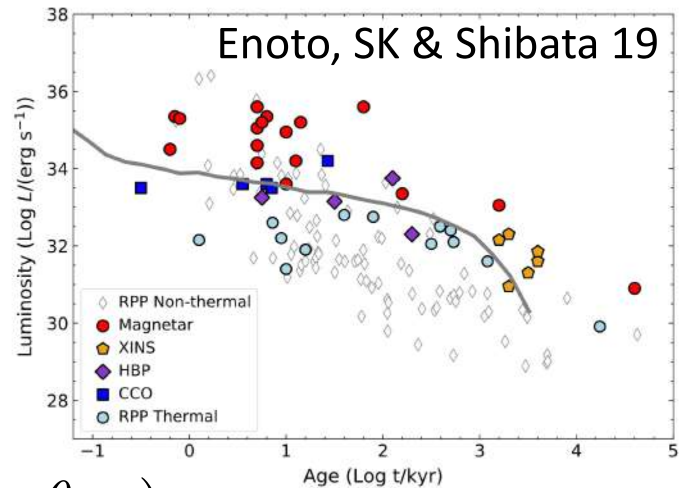
$$L_{\rm pc} \sim 10^{-3}L_{\rm sd}$$

$$T_{\rm pc} \sim 10^{6.5}{\rm K}$$

- Entire surface

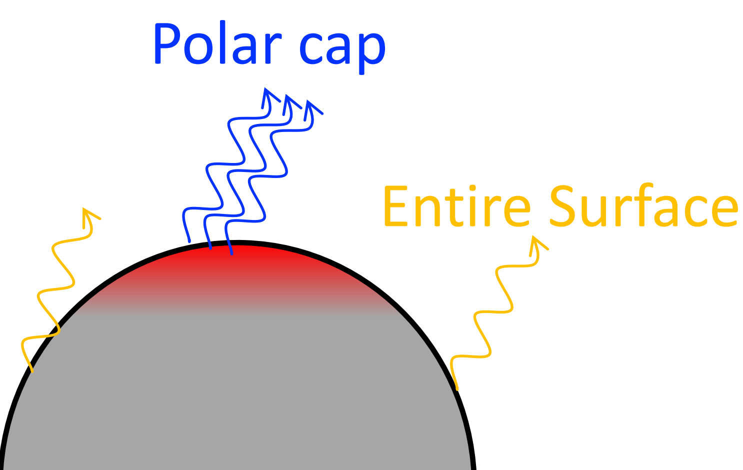
$$L_{\rm sur} \sim 10^{33}{\rm erg\ s^{-1}}$$

$$T_{\rm sur} \sim 10^{6}{\rm K}$$



#-density of seed photons

$$n_{\rm seed} \sim \frac{L_{\rm seed}}{4\pi r^2 c E_{\rm seed}}(1-\cos\theta_{\rm col})$$



IC Efficiency

$$\frac{L_{\rm IC}}{L_{\rm sd}} \sim \eta\tau_{\rm IC} \sim \begin{cases} 10^{-8}\eta L_{\rm sd,36}P_{-1}^{-1}\gamma_{\rm p,8}^{-1} \\ 10^{-7}\eta P_{-1}^{-1}\gamma_{\rm p,8}^{-1} \end{cases}$$

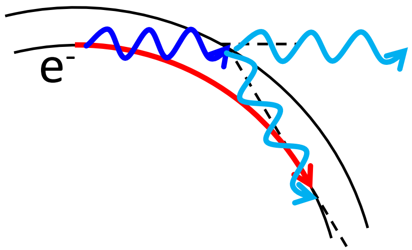
Inverse Compton Luminosity

$$L_{\rm IC} = E_{\rm IC}\dot{N}_{\rm p}\tau_{\rm IC}$$

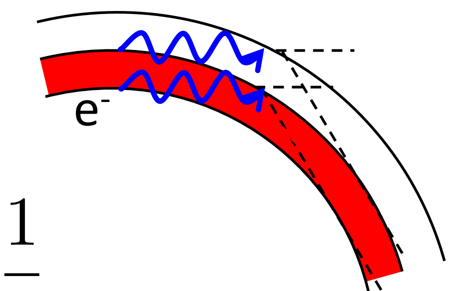
$$\tau_{\rm IC} \sim n_{\rm seed}\sigma_{\rm IC}R_{\rm lc}$$

Seed photon : Synchrotron photons

How fraction of synchrotron photons can be scattered by primary $e^{\pm}$?



$$\frac{1}{\gamma} \lesssim \epsilon \lesssim \frac{1}{4}$$

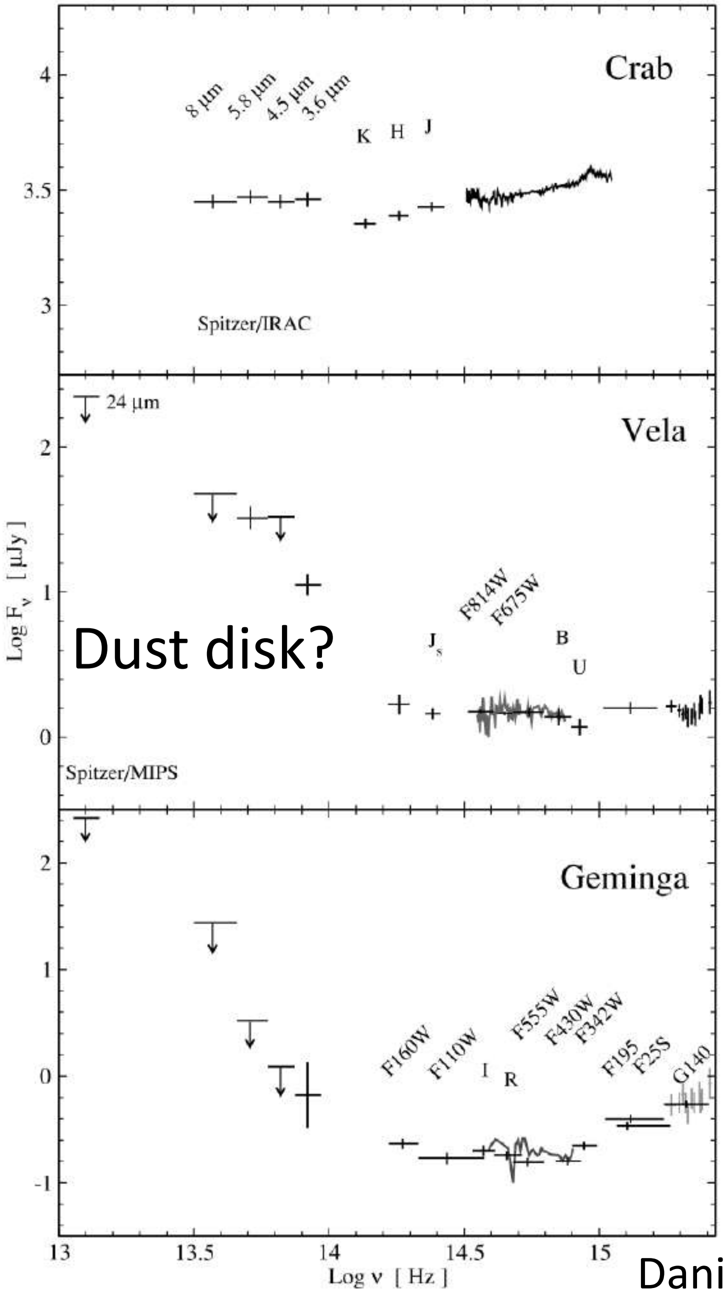


Energy spectrum

$$\nu F_\nu \propto \nu^a \quad (a \sim 1-2)$$

⇒ Synchrotron photons at ~ 10^{13} Hz is dominantly contributed.

Pulsed Emission at Infrared



Dust disk?

Danilenko+ 11

No observation data for pulsed emission at ~10^{13} Hz.

Analytic model

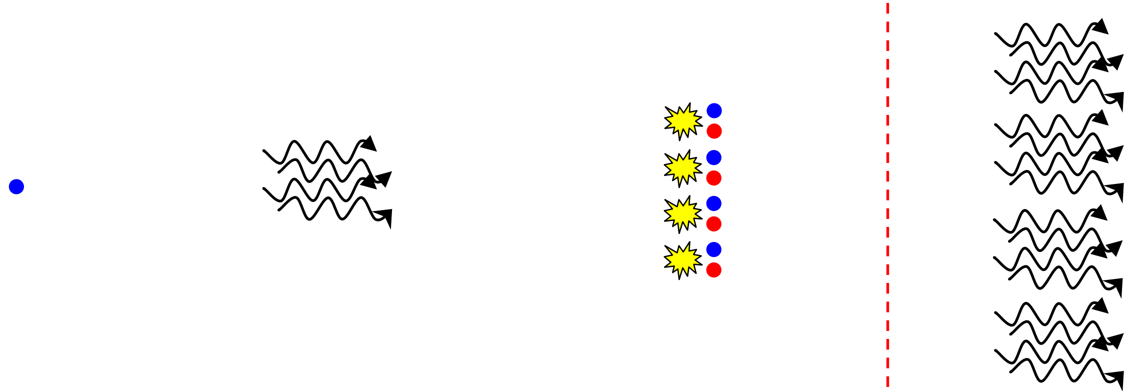
(SK & Tanaka 17)

Synchrotron Luminosity

SK & Tanaka 17

$$L_{\rm syn} = P_{\rm syn}\dot{N}_{\rm s}\min\{t_{\rm ad}, t_{\rm cool,syn}\}$$

Primary e$^{\pm}$ | **CR photons** | **Secondary e$^{\pm}$** | **SR photons**



$\dot{N}_{\rm p}$ | $\dot{N}_{\rm p}N_{\gamma}$ | $\dot{N}_{\rm p}N_{\gamma}\tau \equiv \dot{N}_{\rm s}$

SR power

$$P_{\rm syn} = \frac{2e^4B^2\alpha^2}{3c^3m_{\rm e}^2}\gamma_{\rm s,syn}^2$$

SR cooling timescale

$$t_{\rm cool,syn} \sim \frac{\gamma_{\rm s,syn}\alpha m_{\rm e}c^2}{P_{\rm syn}}$$

Lorentz factor of SR emitting e$^{\pm}$

$$\gamma_{\rm s,syn}(\nu_{\rm obs}) = \sqrt{\frac{4\pi}{0.87}\nu_{\rm obs}\frac{m_{\rm e}c}{eB\alpha}}$$

Advection timescale

$$t_{\rm ad} \sim \frac{r}{c}$$

Summary

- Five VHE pulsars are detected, three of which require components other than curvature radiation. Among the three, the spectra are divided into Crab-type and Vela-type.

- Using an analytical model, we investigated the radiation efficiency of inverse Compton scattering from accelerated particles in the magnetosphere. It was also found that the pair production process due to the magnetic field can be divided into two types, Crab-type and Vela-type.

- PSRs with L_{sd} ~ 10^{35} – 10^{37} erg/s are TeV pulsar candidates. Observations at ~10^{13} Hz are important to determine the seed photon field and Inverse Compton efficiency.