

パルサー星雲の 非熱的MeVガンマ線放射

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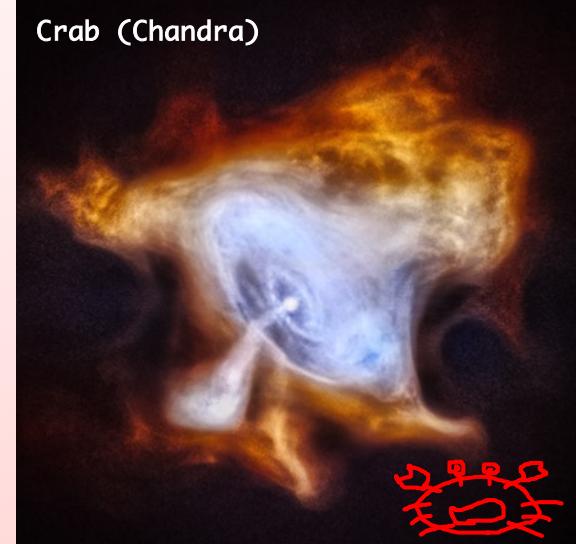
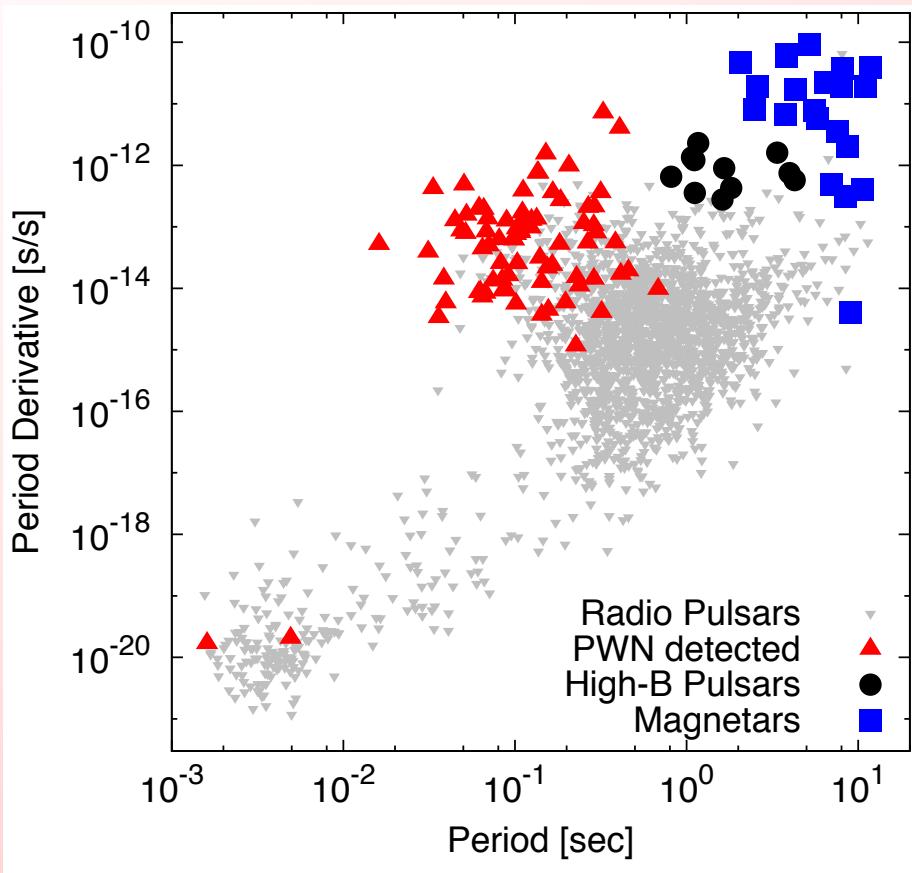


Introduction

PSRs & PWNe

Pulsar Wind Nebulae (PWNe) are powered by pulsars (PSRs)

$$L_{\text{spin}} \equiv I\Omega\dot{\Omega}, \quad I \approx 10^{45} \text{ g cm}^2$$

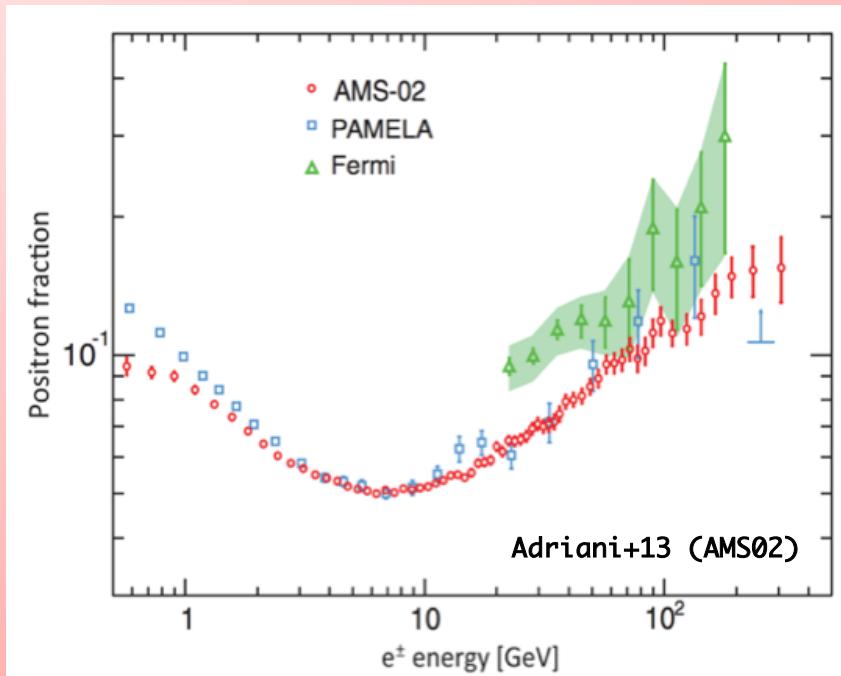
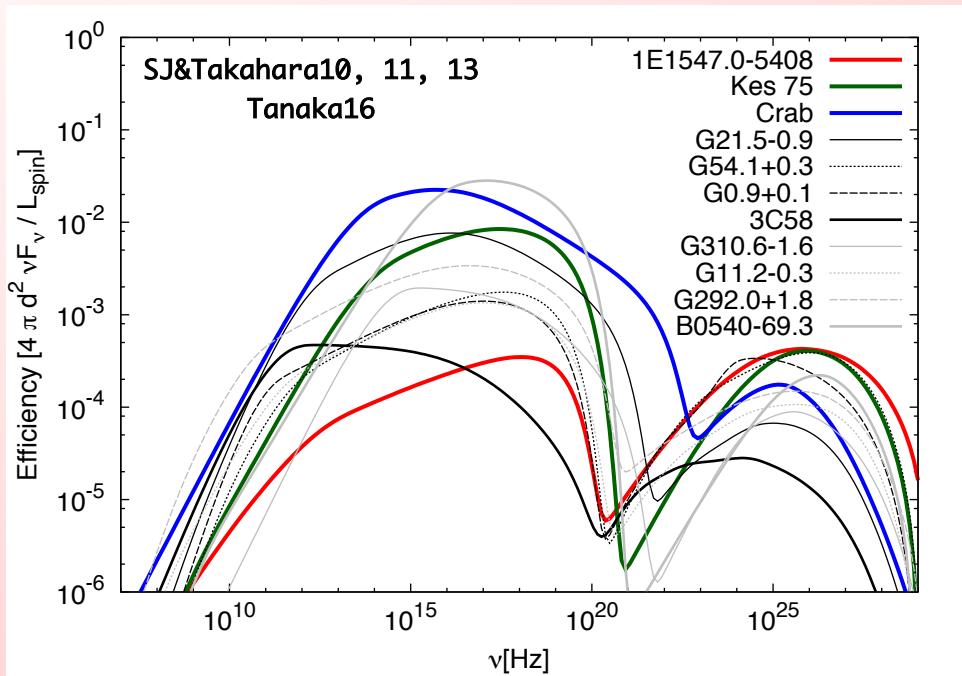
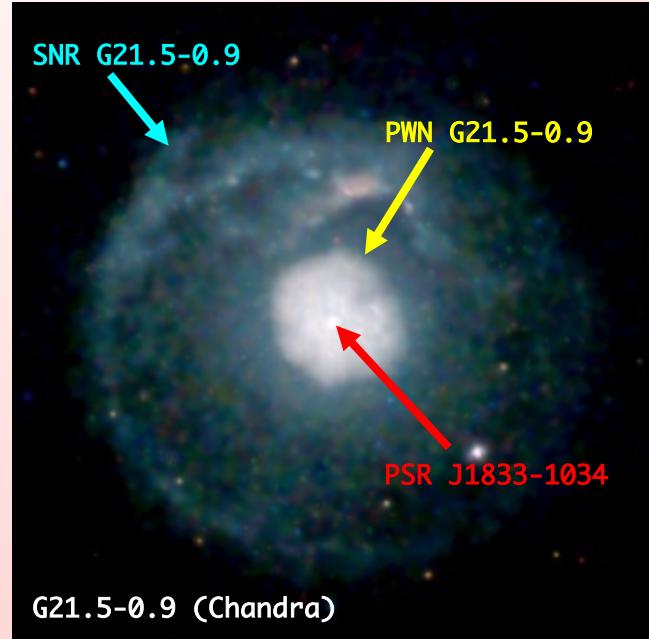


- Pulsed emission \sim a few % of L_{spin} .
- => Most of L_{spin} release as pulsar winds.
- ~ 70 of 2500 pulsars have observable PWNe.
 - Some low L_{spin} pulsars also have PWNe bow shock nebulae

Pulsar wind brakes pulsar spin!

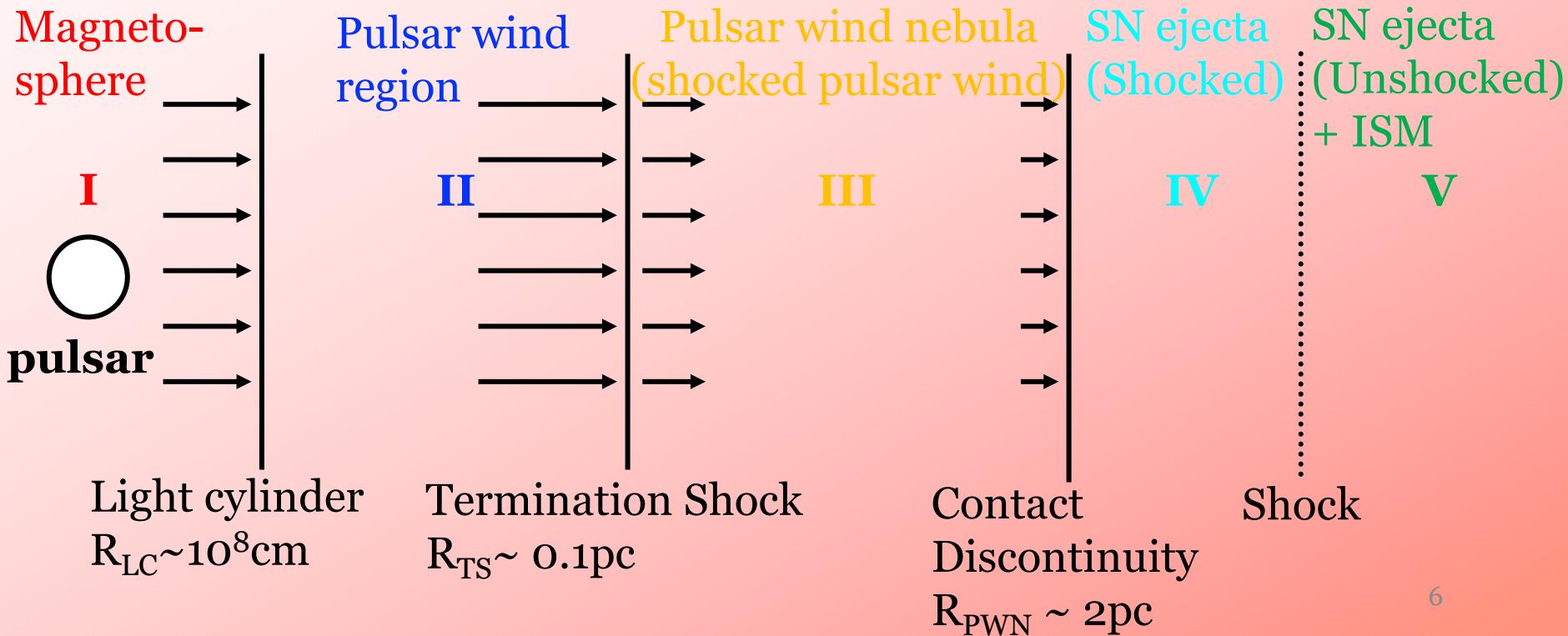
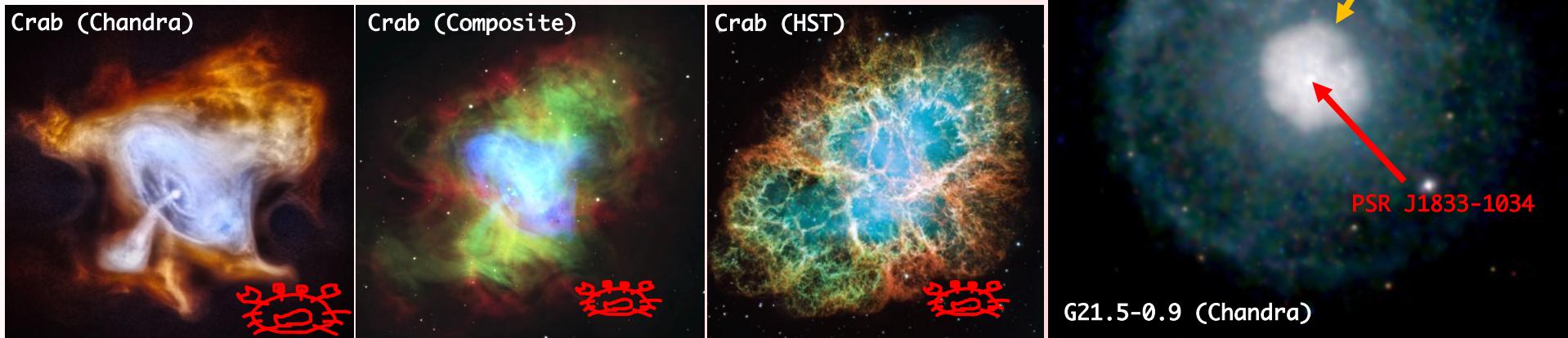
PWN & CR

- Confined by progenitor supernova remnant (SNR)
- Broadband emission from radio to TeV
- More efficient γ -ray emitter than SNR
- Leptonic cosmic-rays (CRs) rather than hadronic ones



PWN as a CR Accelerator

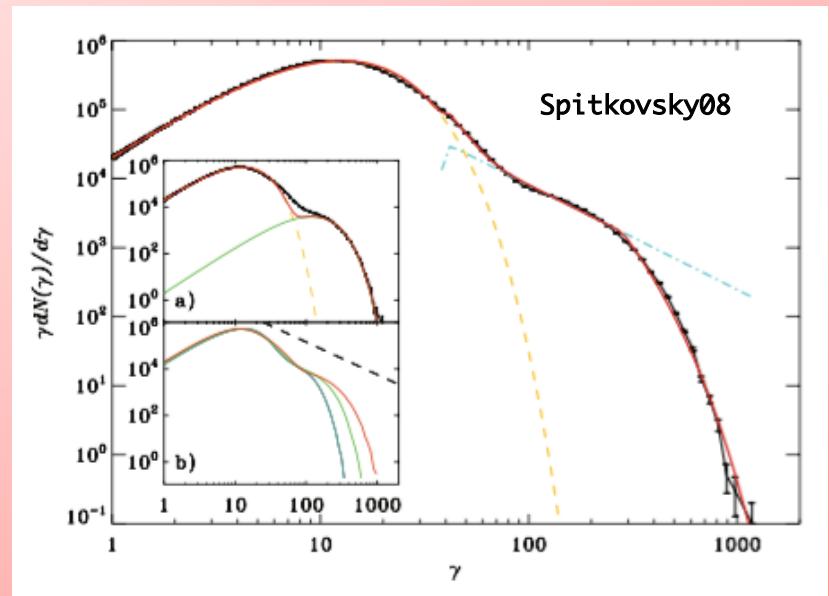
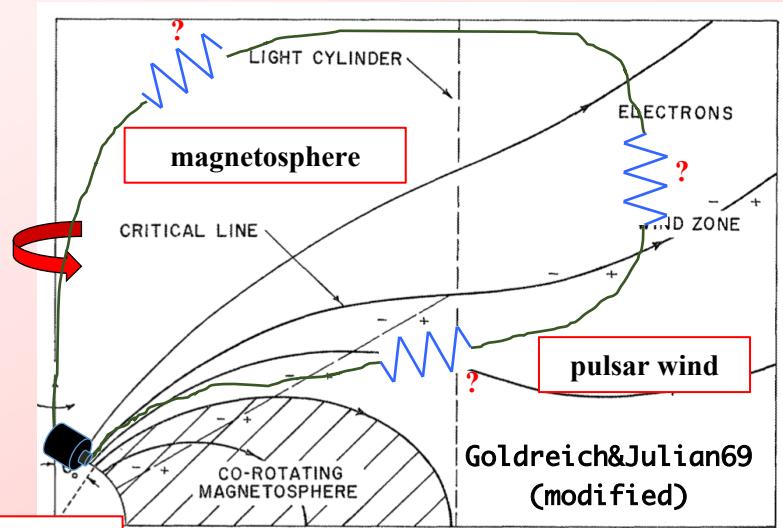
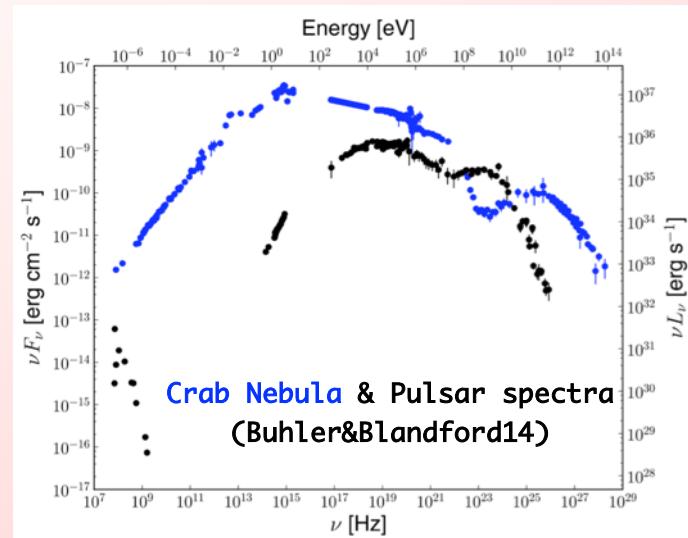
PWN Structure



Acceleration Sites

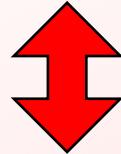
- PSRのパルス放射 + PWNの定常放射
- エネルギー源は同じ、PWNの方が明るい
- PSR magnetosphere = 電場加速
- PWN = 衝撃波加速 and/or 乱流加速

SJT&Asano in prep.



Hillas Condition

$$E_{\max} = eBR$$



$$\gamma_{\max} m_e c^2 = eB(r)r$$

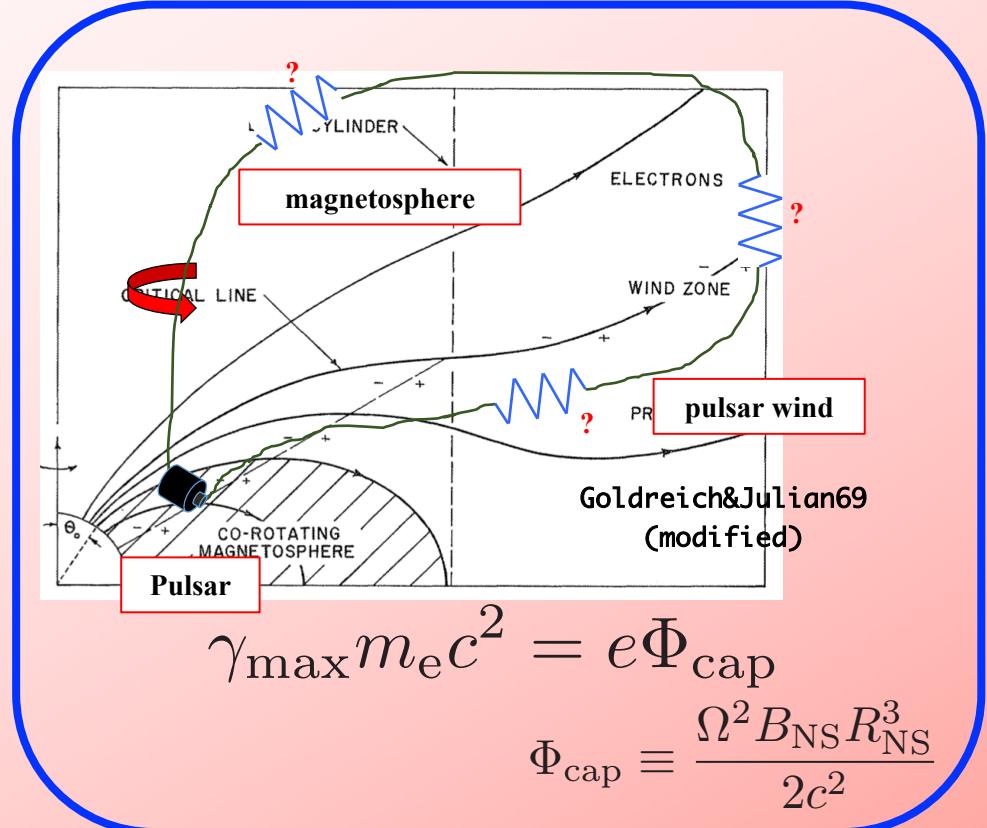
$$B(r) = B_{\text{NS}} \left(\frac{R_{\text{NS}}}{R_{\text{LC}}} \right)^3 \left(\frac{R_{\text{LC}}}{r} \right)$$

$$R_{\text{LC}} = \frac{c}{\Omega}$$

MHDを大きく破らない限り、accelerated particleの最大エネルギーはパルサー周辺のどの領域で考えても同じ

$$\gamma_{\max, \text{cap}} \approx 1.3 \times 10^{10} \left(\frac{P}{0.1 \text{ sec}} \right)^{-2} \left(\frac{B_{\text{NS}}}{10^{13} \text{ G}} \right)$$

系のサイズと磁場の大きさ => max. energy



$$\gamma_{\max} m_e c^2 = e \Phi_{\text{cap}}$$

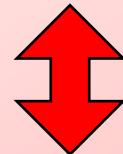
$$\Phi_{\text{cap}} \equiv \frac{\Omega^2 B_{\text{NS}} R_{\text{NS}}^3}{2c^2}$$

σ -problem

MHDを大きく破らない限り、accelerated particleの最大エネルギーはパルサー周辺のどの領域で考えても同じ

$$B(r) = B_{\text{NS}} \left(\frac{R_{\text{NS}}}{R_{\text{LC}}} \right)^3 \left(\frac{R_{\text{LC}}}{r} \right) = 142 \text{ } \mu\text{G} \left(\frac{B_{\text{NS}}}{10^{13} \text{ G}} \right) \left(\frac{P}{0.1 \text{ s}} \right)^{-2} \left(\frac{r}{0.1 \text{ pc}} \right)^{-1}$$

$$B(r_{\text{TS}}) = 485 \text{ } \mu\text{G} \text{ for Crab!!}$$



$$B_{\text{Crab}} \sim 85 \text{ } \mu\text{G} \text{ from broadband spectrum}$$
$$\sigma \sim (B_{\text{Crab}} / B(r_{\text{TS}}))^2 \sim 0.031$$

磁場のエネルギーを粒子に渡しているはず!!
粒子の平均エネルギーは上がるが粒子加速にはマイナス効果!!

Time-scales

- Acceleration time

$$t_{\text{acc}} \approx \frac{D}{V_{\text{shock}}^2} = \frac{\eta}{3} r_g v V_{\text{shock}}^{-2}$$

$$\approx 0.60 \text{ yrs} \left(\frac{\eta}{1} \right) \left(\frac{\gamma}{10^{10}} \right) \left(\frac{B}{10 \mu\text{G}} \right)^{-1} \left(\frac{c}{V_{\text{shock}}} \right)^2$$

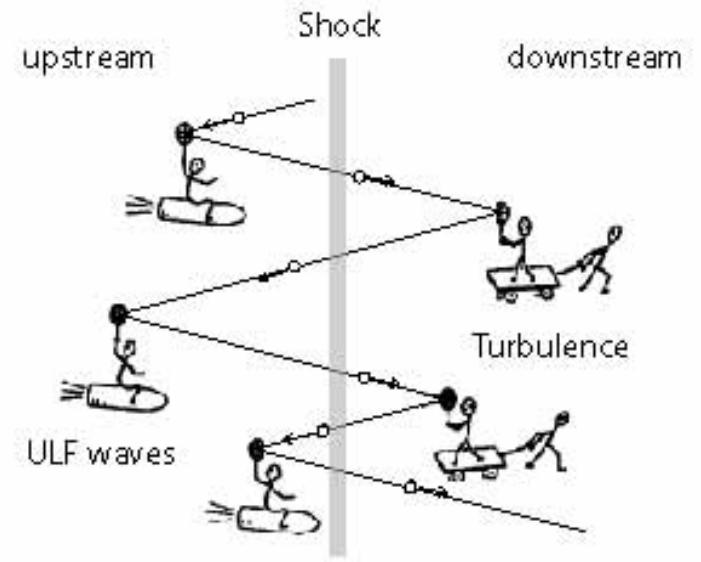
- synchrotron cooling time

$$t_{\text{syn}} \approx \frac{\gamma m_e c^2}{p_{\text{syn}}} = \frac{6\pi m_e c^2}{\sigma_T \gamma B}$$

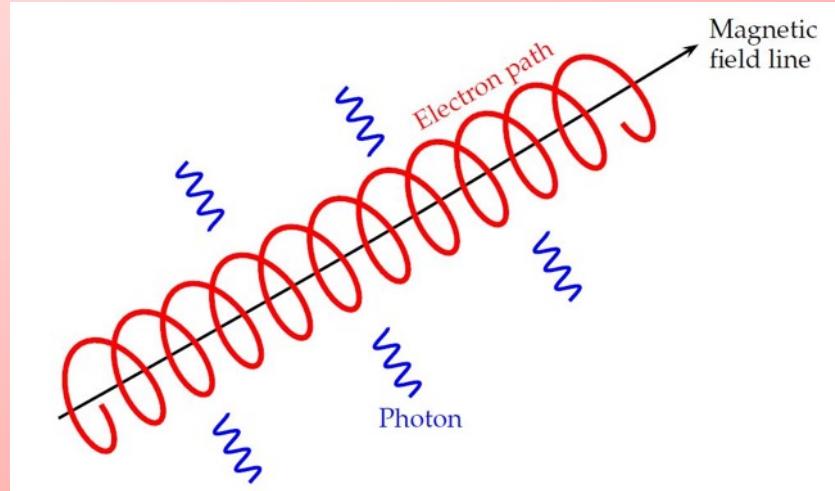
$$\approx 25 \text{ yrs} \left(\frac{\gamma}{10^{10}} \right)^{-1} \left(\frac{B}{10 \mu\text{G}} \right)^{-2}$$

- Age of system

kyr $\lesssim t_{\text{age}} \lesssim$ a few $\times 10$ kyr



Diffusive acceleration
sketched by Scholer



Maximum Energies

- Hillas condition

$$\gamma_{\max, \text{cap}} \approx 1.3 \times 10^{10} \left(\frac{P}{0.1 \text{ sec}} \right)^{-2} \left(\frac{B_{\text{NS}}}{10^{13} \text{ G}} \right)$$

- Size limited

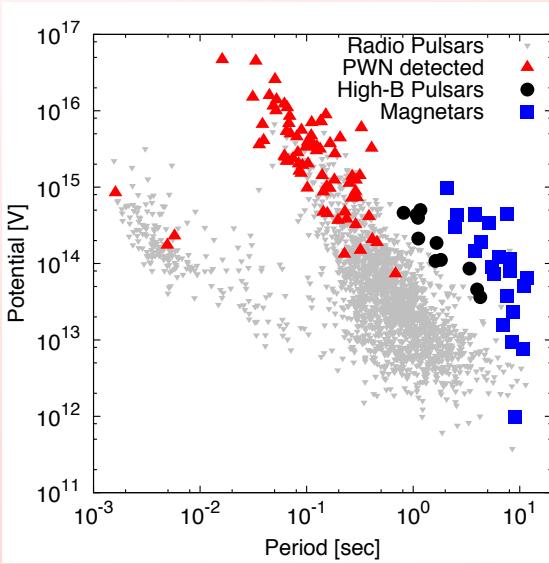
$$\gamma_{\max, \text{size}} \approx 1.8 \times 10^9 \left(\frac{B}{10 \text{ } \mu\text{G}} \right) \left(\frac{r_{\text{TS}}}{0.1 \text{ pc}} \right)$$

- Cooling limited ($t_{\text{acc}} = t_{\text{syn}}$)

$$\gamma_{\max, \text{cool}} \approx 6.4 \times 10^{10} \left(\frac{\eta}{1} \right)^{-1/2} \left(\frac{B}{10 \text{ } \mu\text{G}} \right)^{-1/2} \left(\frac{V_{\text{shock}}}{c} \right)$$

- Age limited ($t_{\text{acc}} = t_{\text{age}}$)

$$\gamma_{\max, \text{age}} \approx 1.7 \times 10^{13} \left(\frac{\eta}{1} \right)^{-1} \left(\frac{B}{10 \text{ } \mu\text{G}} \right) \left(\frac{V_{\text{shock}}}{c} \right)^2 \left(\frac{t_{\text{age}}}{1 \text{ kyr}} \right)$$



Maximum Synchrotron Frequency

- Hillas condition

$$\epsilon_{\text{cap}} \approx 8.4 \text{ MeV} \left(\frac{B_{\text{NS}}}{10^{13} \text{ G}} \right)^2 \left(\frac{P}{0.1 \text{ sec}} \right)^{-4} \left(\frac{B}{10 \text{ } \mu\text{G}} \right)^2$$

- Size limited

$$\epsilon_{\text{size}} \approx 161 \text{ keV} \left(\frac{B}{10 \text{ } \mu\text{G}} \right)^3 \left(\frac{r_{\text{TS}}}{0.1 \text{ pc}} \right)^2$$

- Cooling limited ($t_{\text{acc}} = t_{\text{syn}}$)

$$\epsilon_{\text{cool}} \approx 203 \text{ MeV} \left(\frac{\eta}{1} \right)^{-1} \left(\frac{v_{\text{shock}}}{c} \right)^2$$

The limit written in the physical constants $\sim \alpha_f^{-1} m_e c^2$

- Age limited ($t_{\text{acc}} = t_{\text{age}}$)

$$\epsilon_{\text{age}} \approx 14 \text{ TeV} \left(\frac{\eta}{1} \right)^{-2} \left(\frac{B}{10 \text{ } \mu\text{G}} \right)^3 \left(\frac{v_{\text{shock}}}{c} \right)^4 \left(\frac{t_{\text{age}}}{\text{kyr}} \right)^{\frac{1}{2}}$$

Too big for PWNe because $v_{\text{shock}} \sim c$

Maximum Synchrotron Frequency

ST&Takahara 10, 11, 13↓

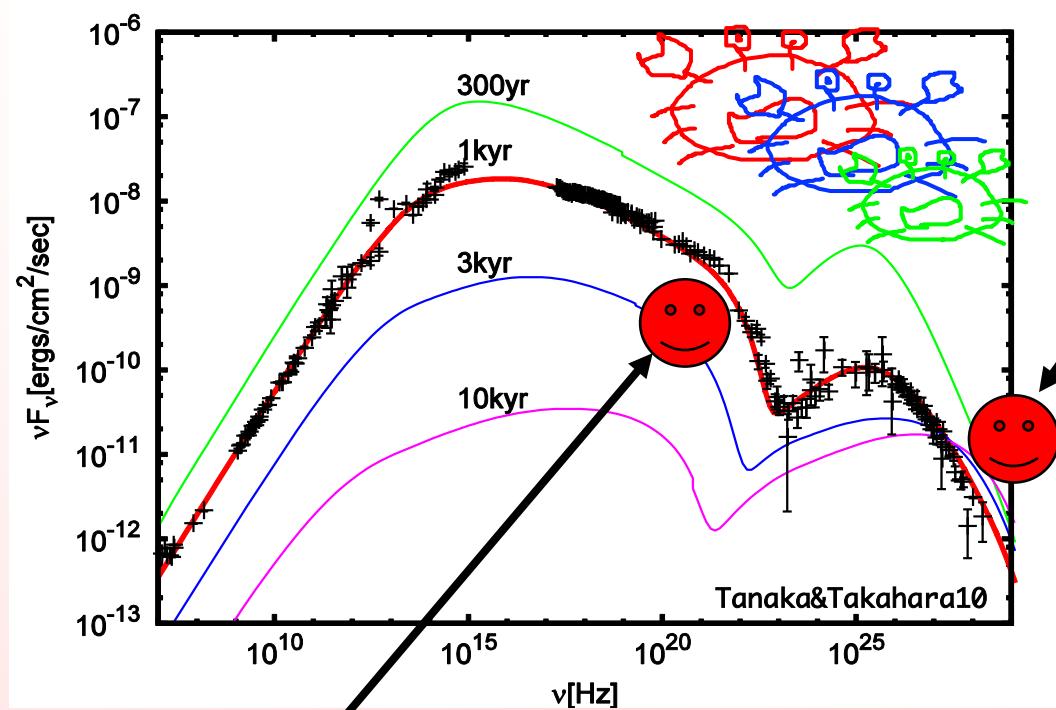
$r_{\text{TS}} = 0.1 \text{ pc}$

$$\epsilon_{\text{cool}} \approx 203 \text{ MeV} \left(\frac{\eta}{1} \right)^{-1} \left(\frac{v_{\text{shock}}}{c} \right)^2$$

Name	B_{PWN}	B_{MHD}	σ_{PWN}	ϵ_{size}	ϵ_{cap}
Crab	85 μG	485 μG	0.031	99 MeV	18.7 GeV
G21.5-0.9	64 μG	133 μG	0.233	42 MeV	839 MeV
G54.1+0.3	10 μG	76 μG	0.018	0.161 MeV	2.32 MeV
Kes 75	20 μG	65 μG	0.095	1.29 MeV	1.43 MeV
G0.9+0.1	15 μG	150 μG	0.010	0.542 MeV	73 MeV
3C58	17 μG	119 μG	0.021	0.791 MeV	47 MeV
MSH15-52	17 μG	96 μG	0.031	0.791 MeV	7.2 MeV
Vela X	5 μG	60 μG	0.0069	0.020 MeV	1.2 MeV

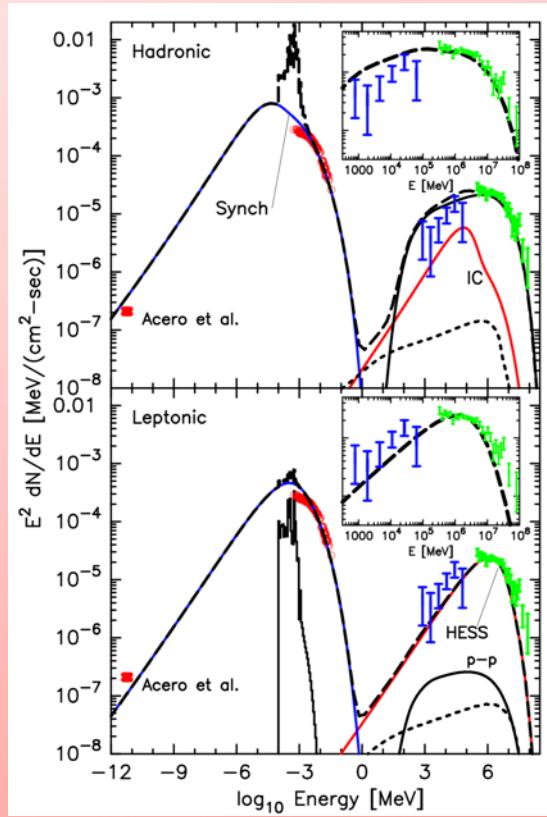
One-zone Model of PWNe

Obs. of Max. Energy



Cooling limitedなら~100MeVでそうでない場合はそれ以下。~MeVの観測は大変でcut-offがちゃんと見えている天体はCrab以外にほほない。
SNRのX-rayで一応見えているけど、low-freq.過ぎるのが問題。

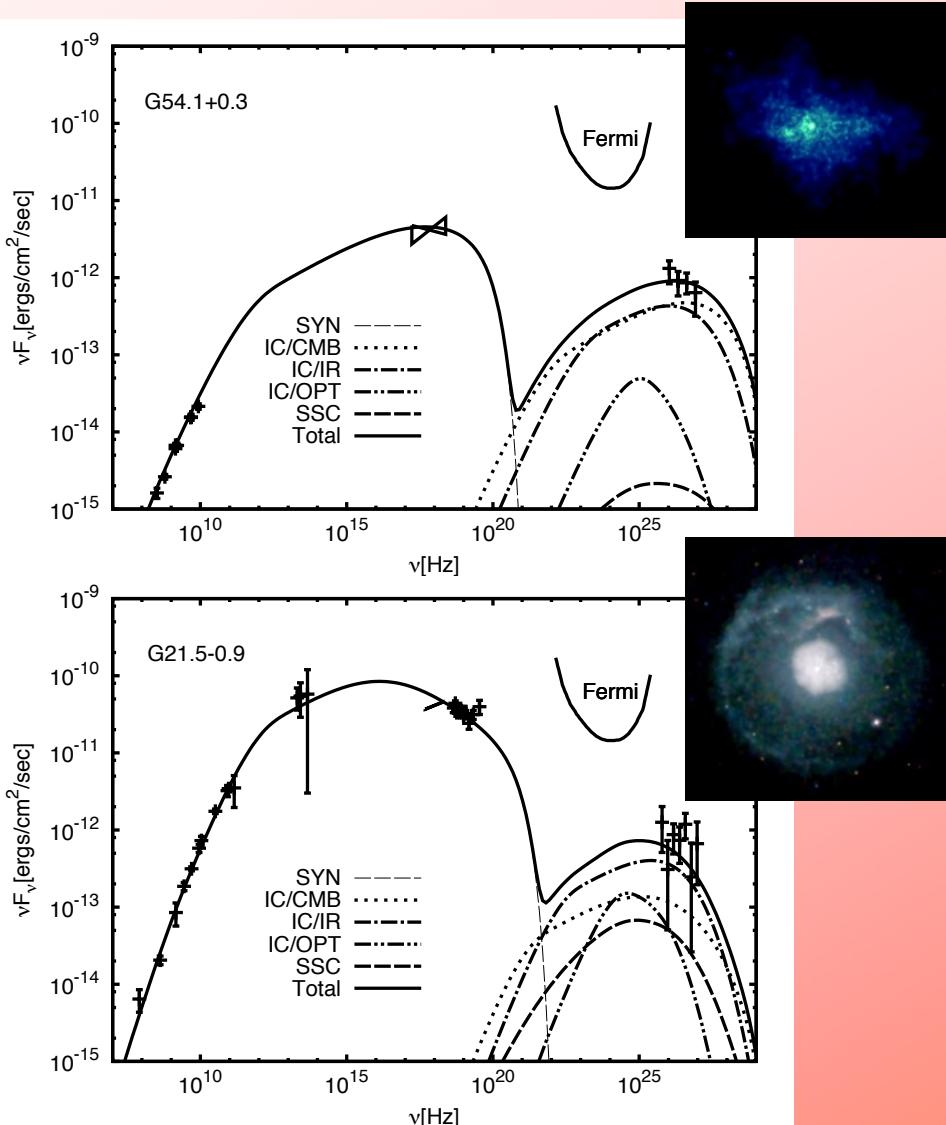
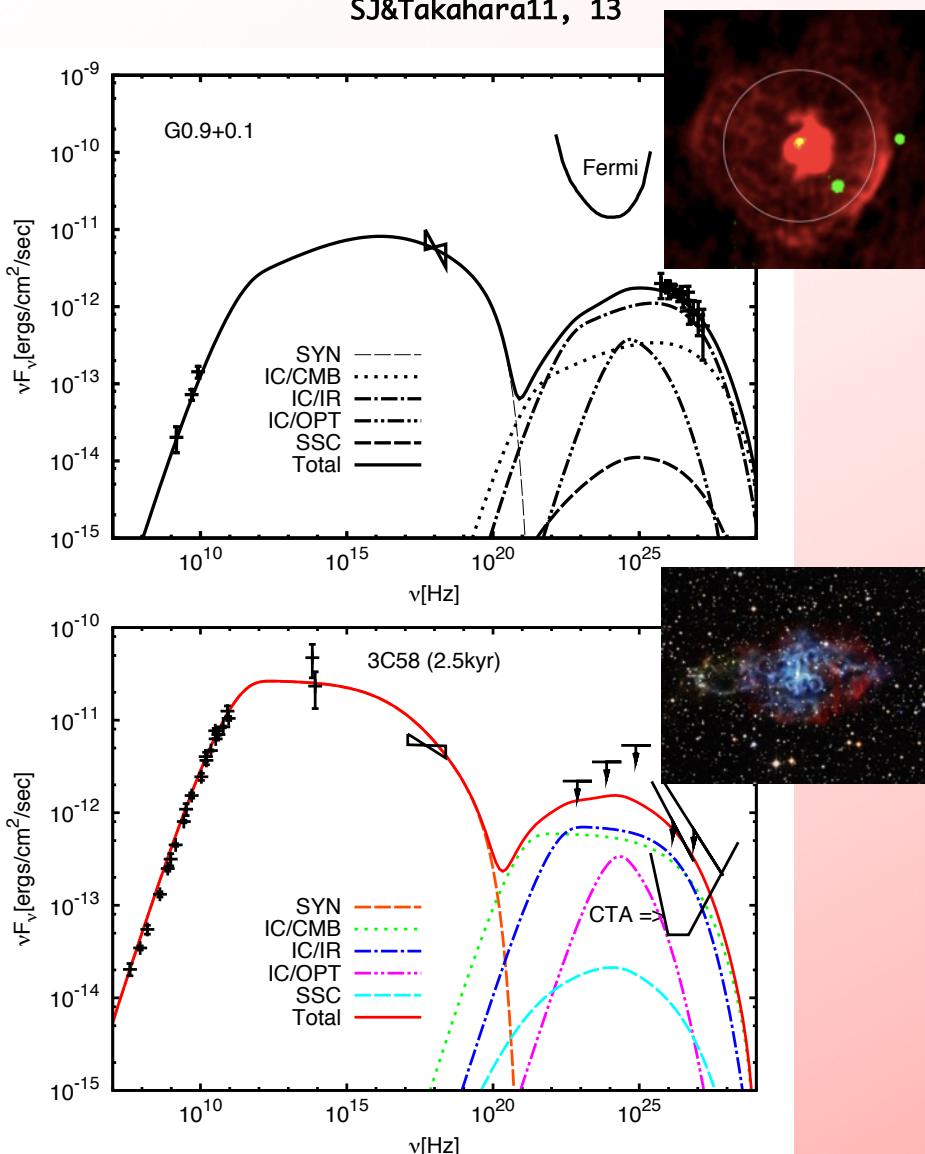
今回注目するところ。Crabの場合はSSCなので少し振る舞いが違うが、基本的にはcut-offは見えていない。TeV blazarで見えているのはmax. energyのcut-offではなくて、 $\gamma\gamma$ -abs.でのcut-off。



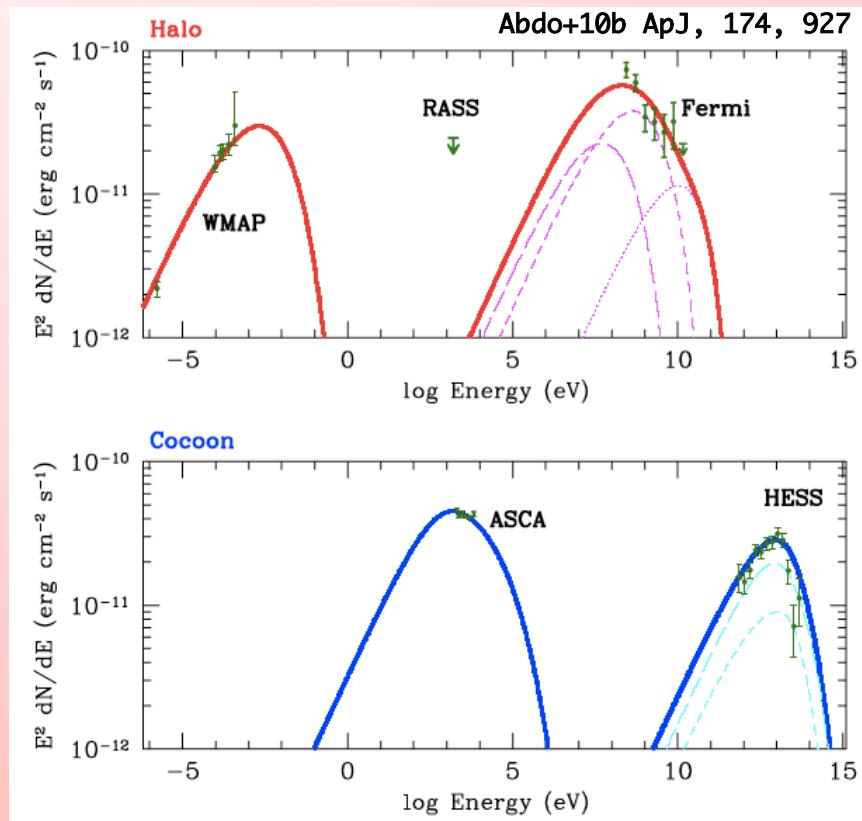
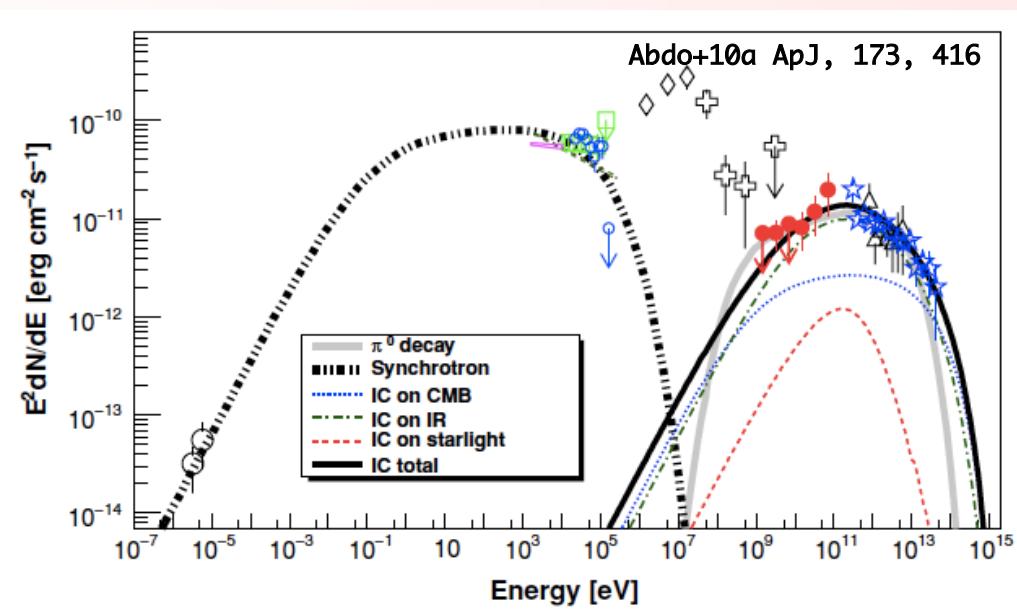
Ellison+10 (RX J1713.7-3946)

Past studies

SJ&Takahara11, 13



Other studies



Summary

- PWNは潜在的にはPeV acceleratorで、パルサー磁気圏における磁力線の開き方で決まっている(old PSRも同じ)。
- パルサー風の磁場はほとんど粒子のエネルギーに変換されている(σ -problem)ため、粒子の最高エネルギーやそのシンクロトロン放射のエネルギーは小さくなる。
- Crabはsize limited, cooling limitedのエネルギーが同程度になる特殊な天体、maximum synchrotron frequencyが磁場を測るツールとして使えない。
- 他の天体ではMeV付近のsynchrotronの観測がこれまでと独立に磁場を観測する手段になり得て、 σ -problemにも新しい示唆を与えることが可能。
- G21.5-0.9, 3C58くらいが狙い目だが、時間分解は必須。 18