パルサー星雲電波放射の乱流加速モデル

Shuta J. Tanaka
Aoyama Gakuin Univ.

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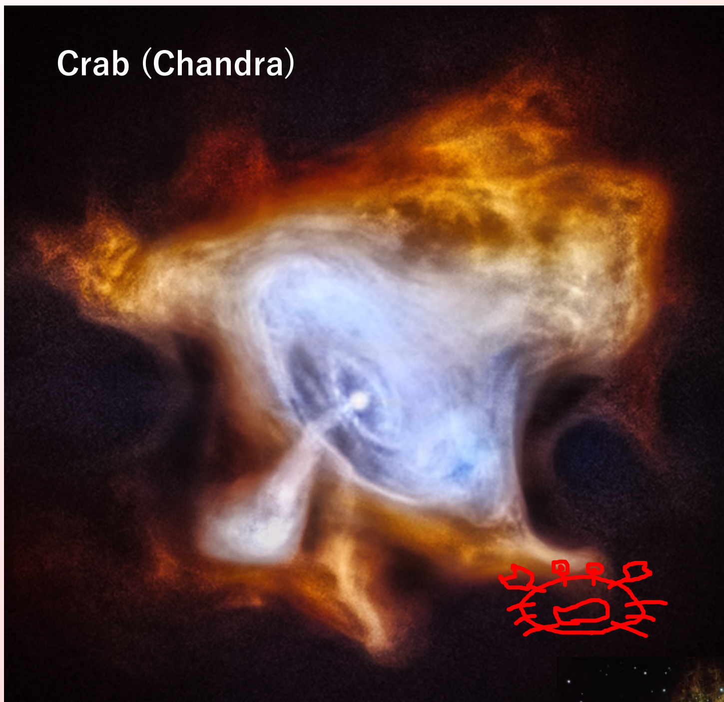
Introduction

PSR/PWN/SNR systems

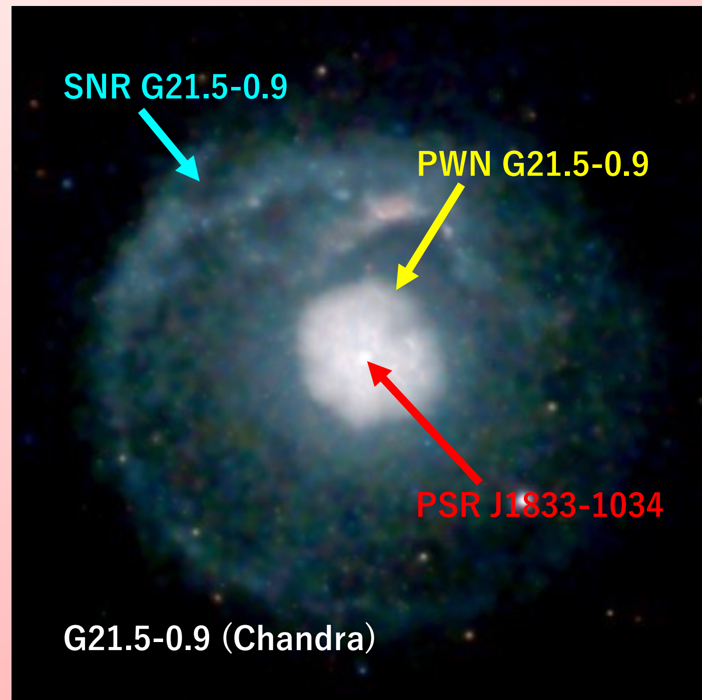
pulsars

pulsar wind nebula

supernova remnant



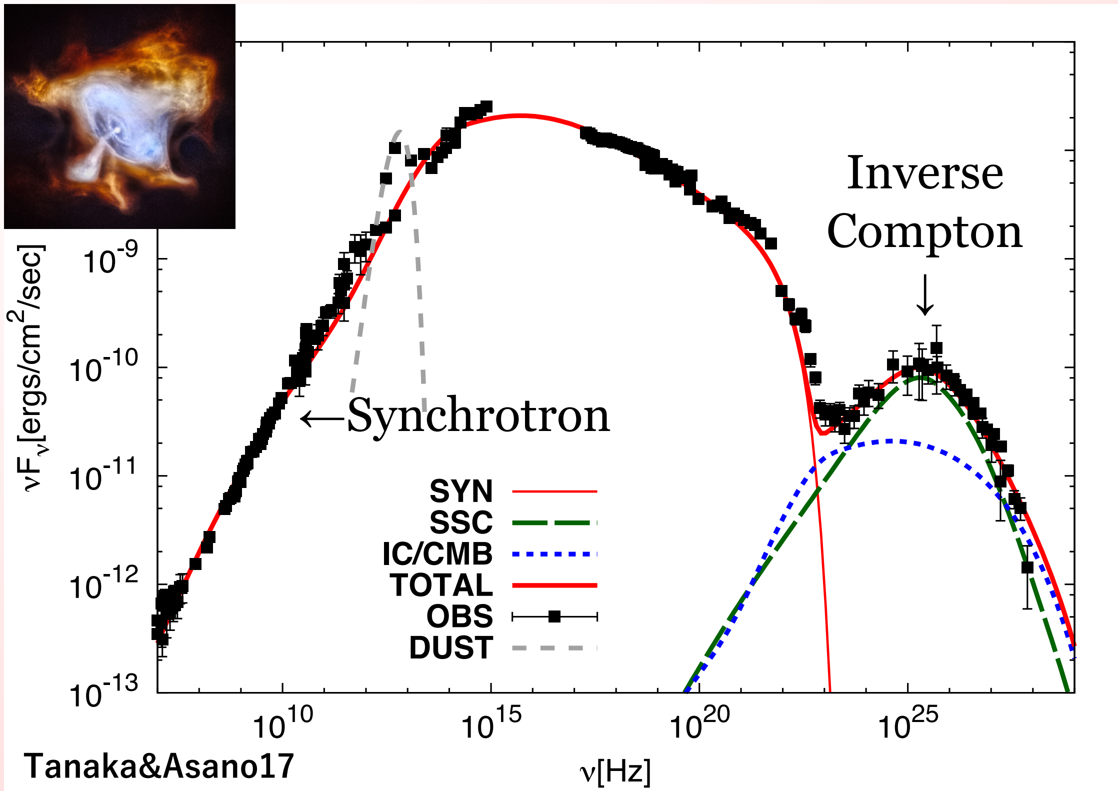
powered by pulsars

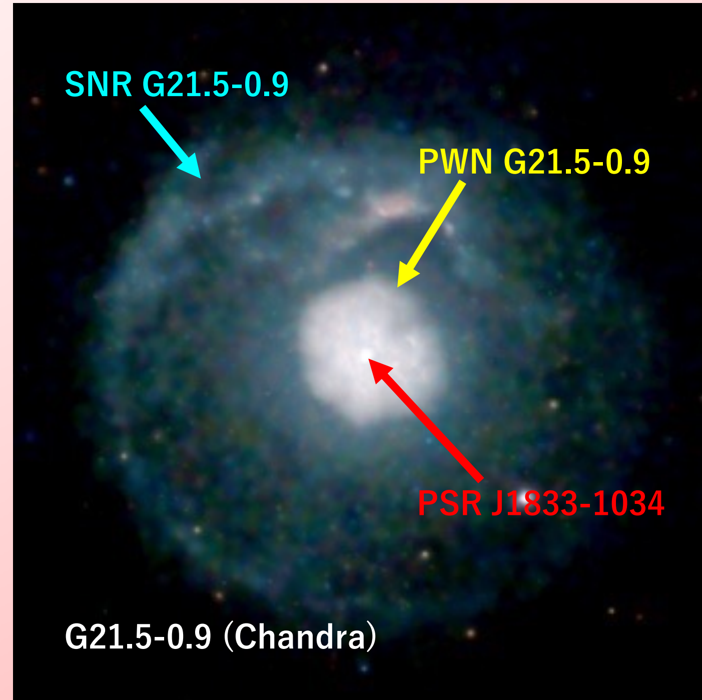


confined by SNR

PWN as Particle Accelerator

Broadband emission from radio to TeV.





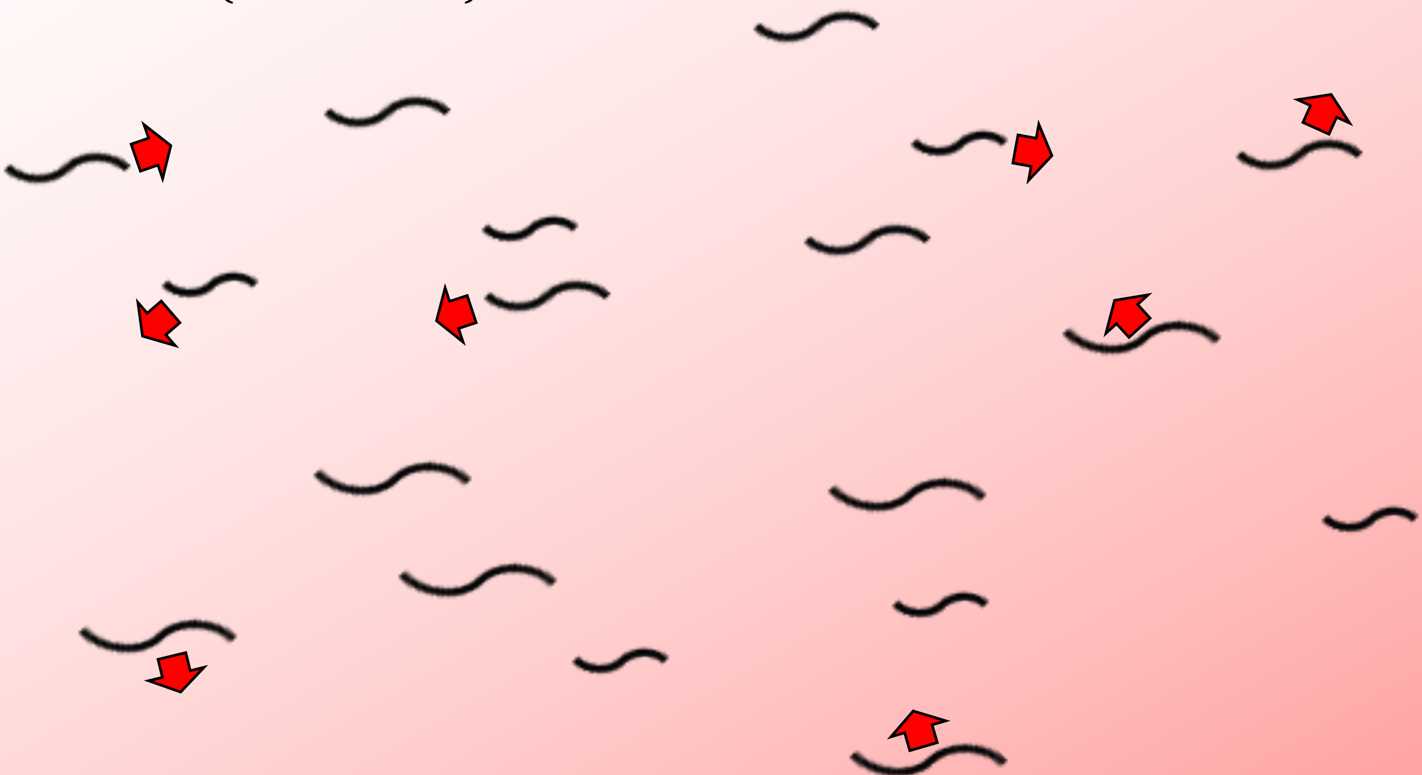
Typical electron energy @ optical peak is ~ TeV

extremely hot (energetic) and rarefied plasma cloud ($n_{\rm PWN} < 10^{-6}$ cm^{-3})

Closest relativistic object

Particle Acceleration = Mechanism to form non-thermal particle distribution

Stochastic Acceleration
(2nd order Fermi acceleration)
by random waves (turbulence)



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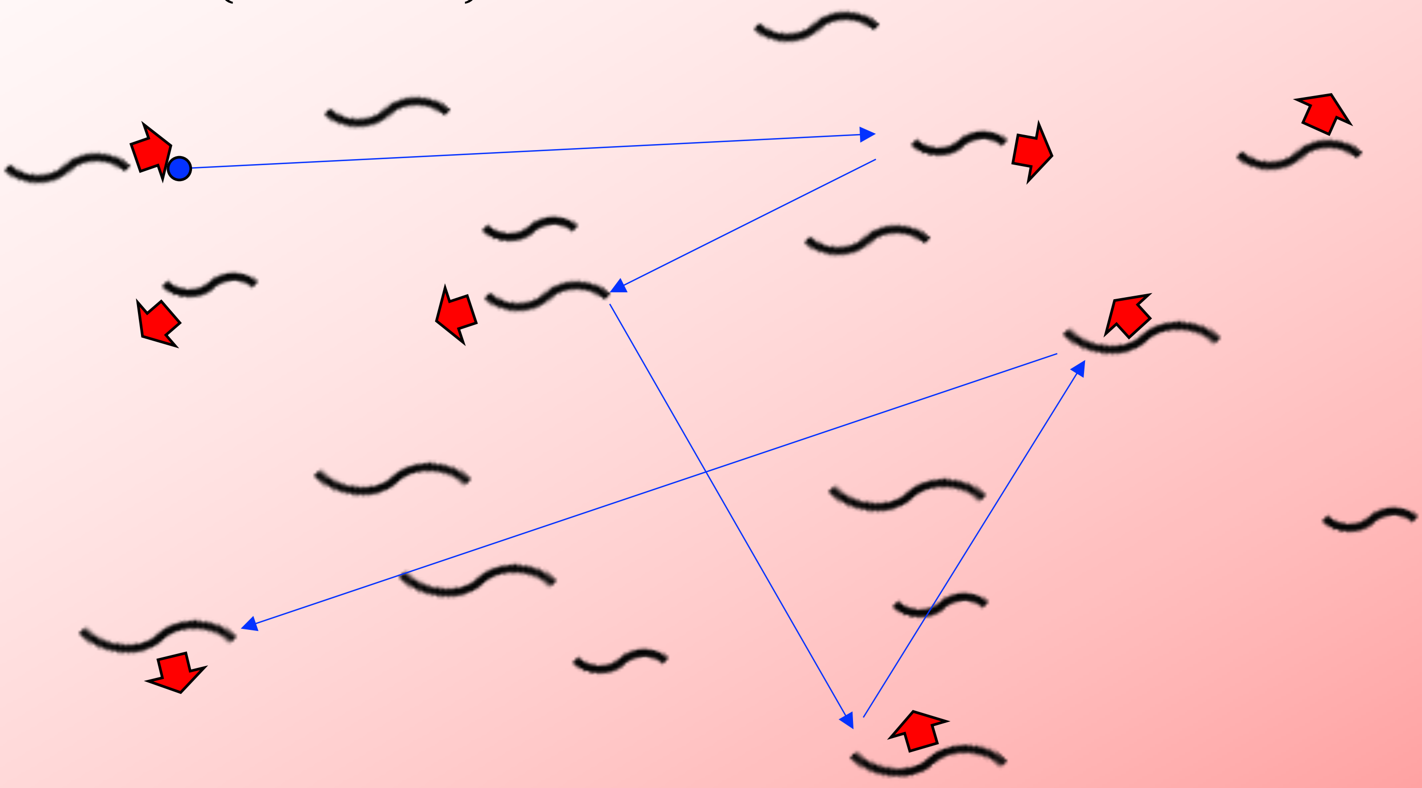
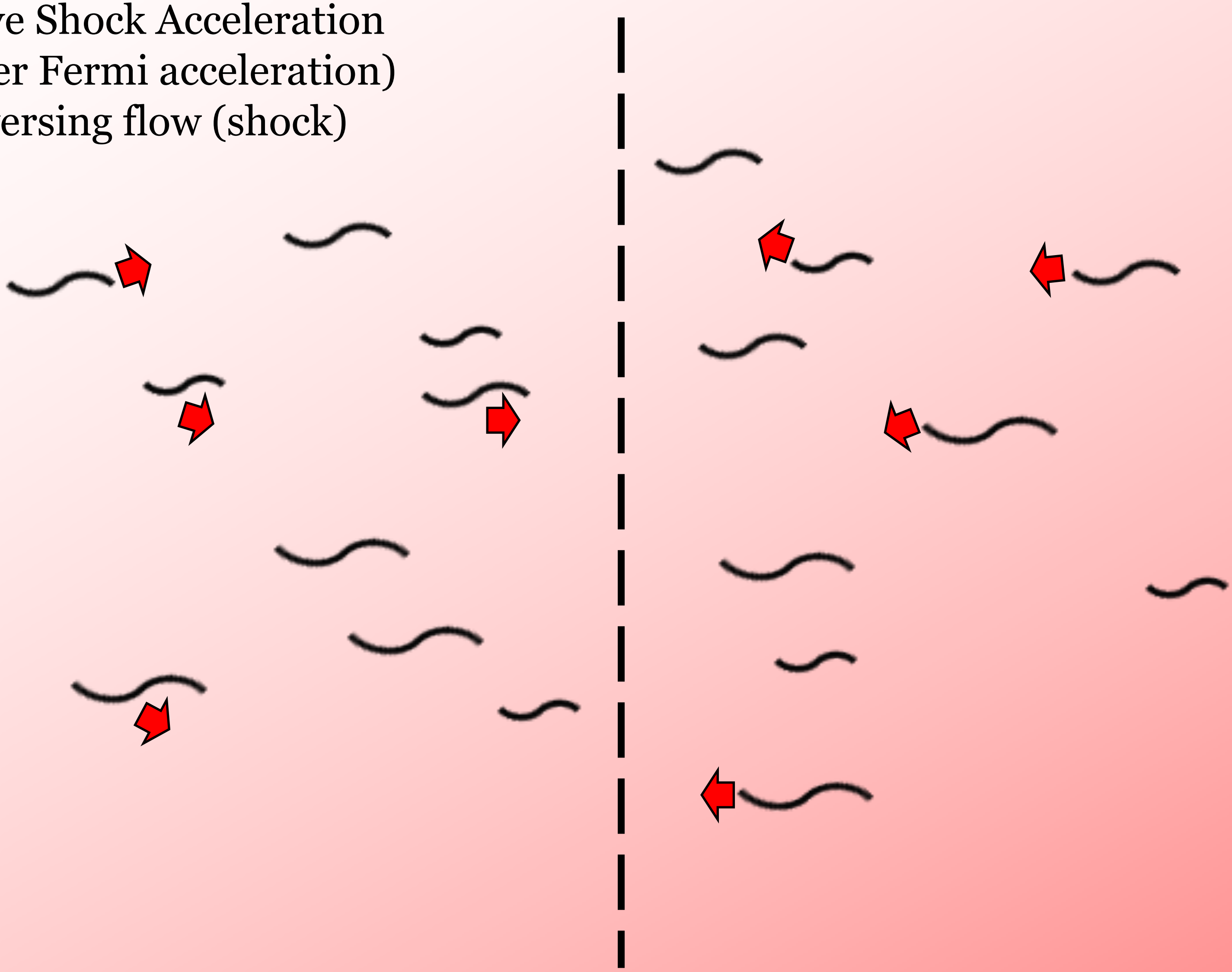


Particle Acceleration

Diffusive Shock Acceleration
(1st order Fermi acceleration)
by conversing flow (shock)



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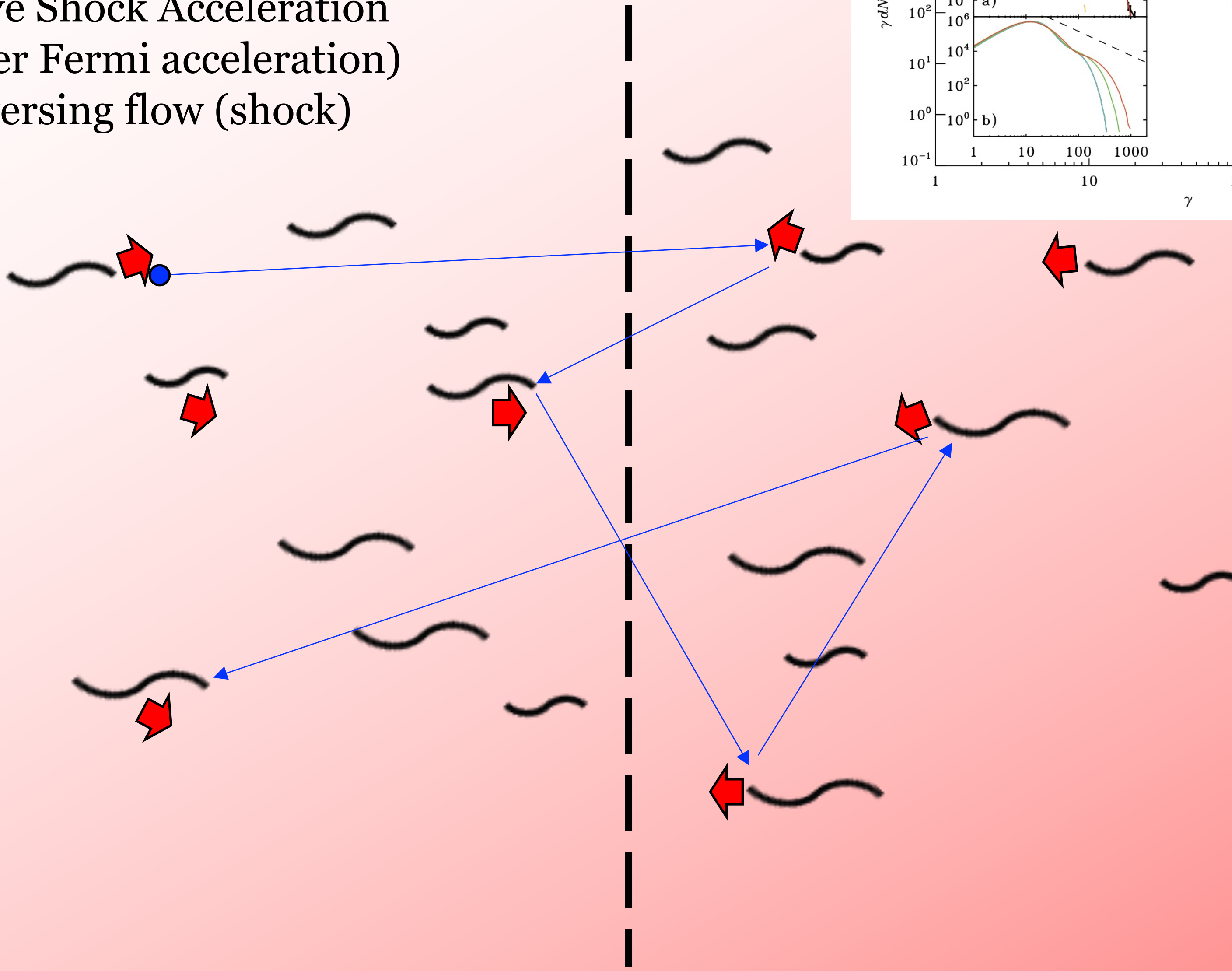
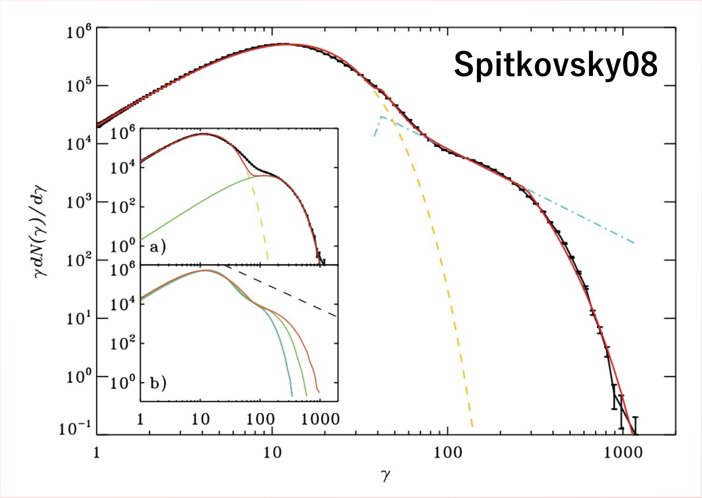
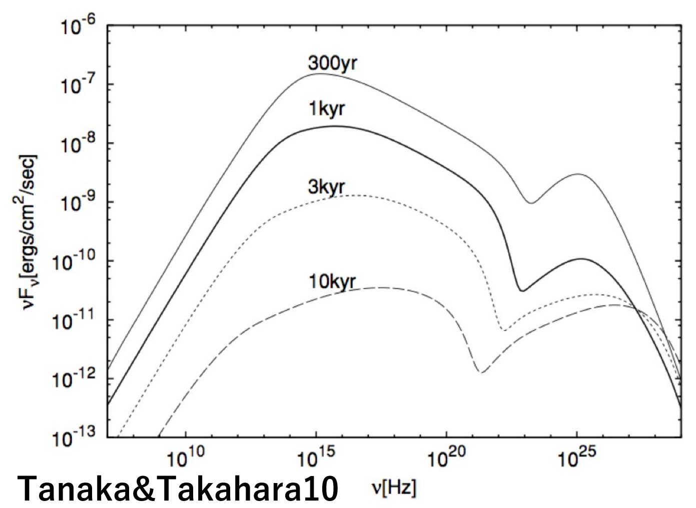




Origin of Radio Emission



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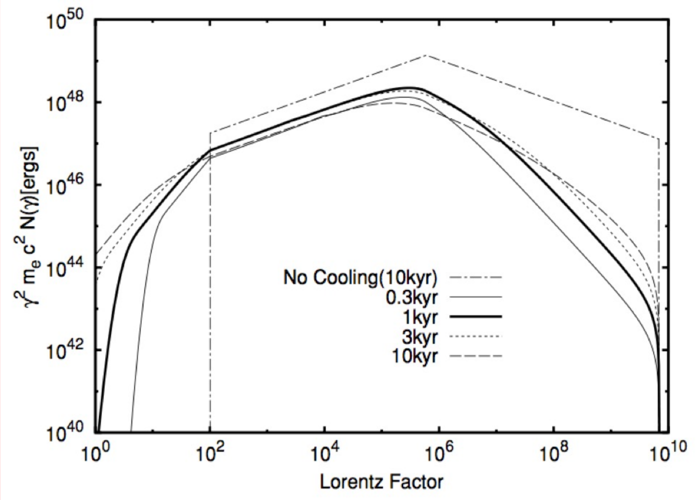


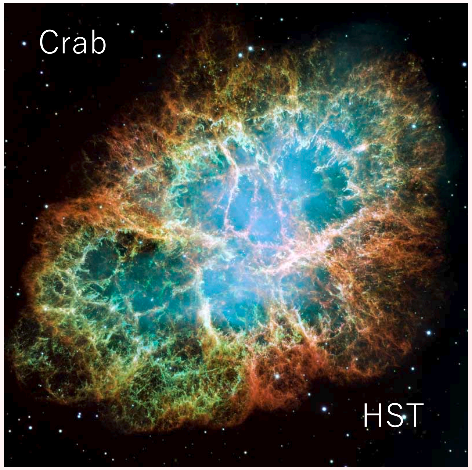
- Standard acceleration model (e.g., shock accel.) forms single power-law distribution.
- Radio obs. indicate very hard spectrum.
- Radio emitting particle dominate in # (κ-problem)
- PWNe are in turbulent state.

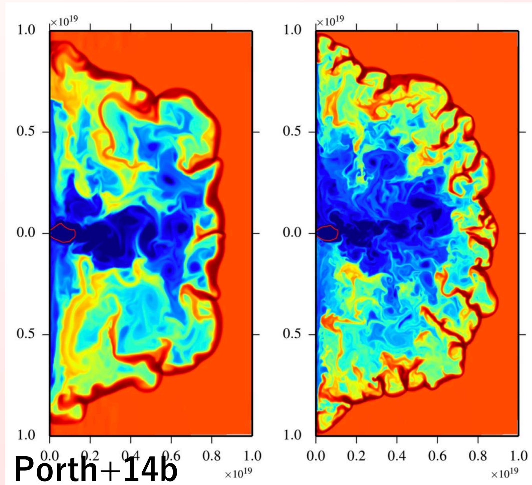
Single power-law injection from central pulsar @ high energy & **external particle injection** + stochastic accel.

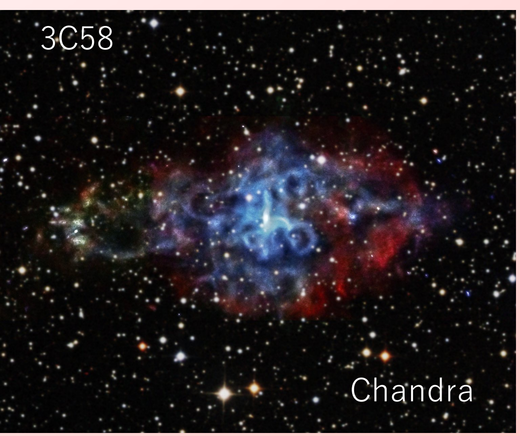
Tanaka&Asano17

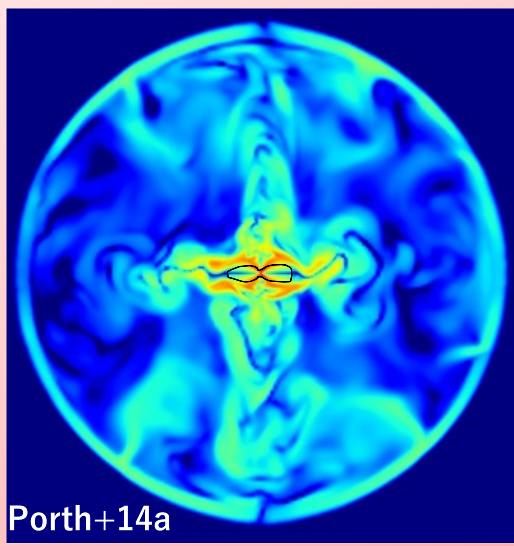
Model

Turbulence in PWNe

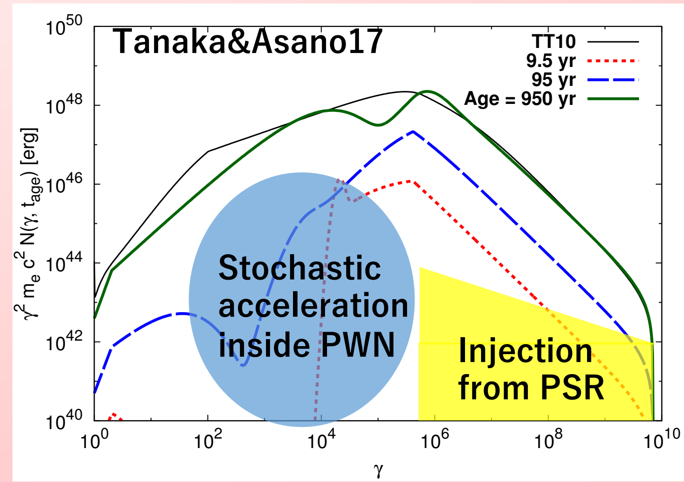








Stochastic acceleration model

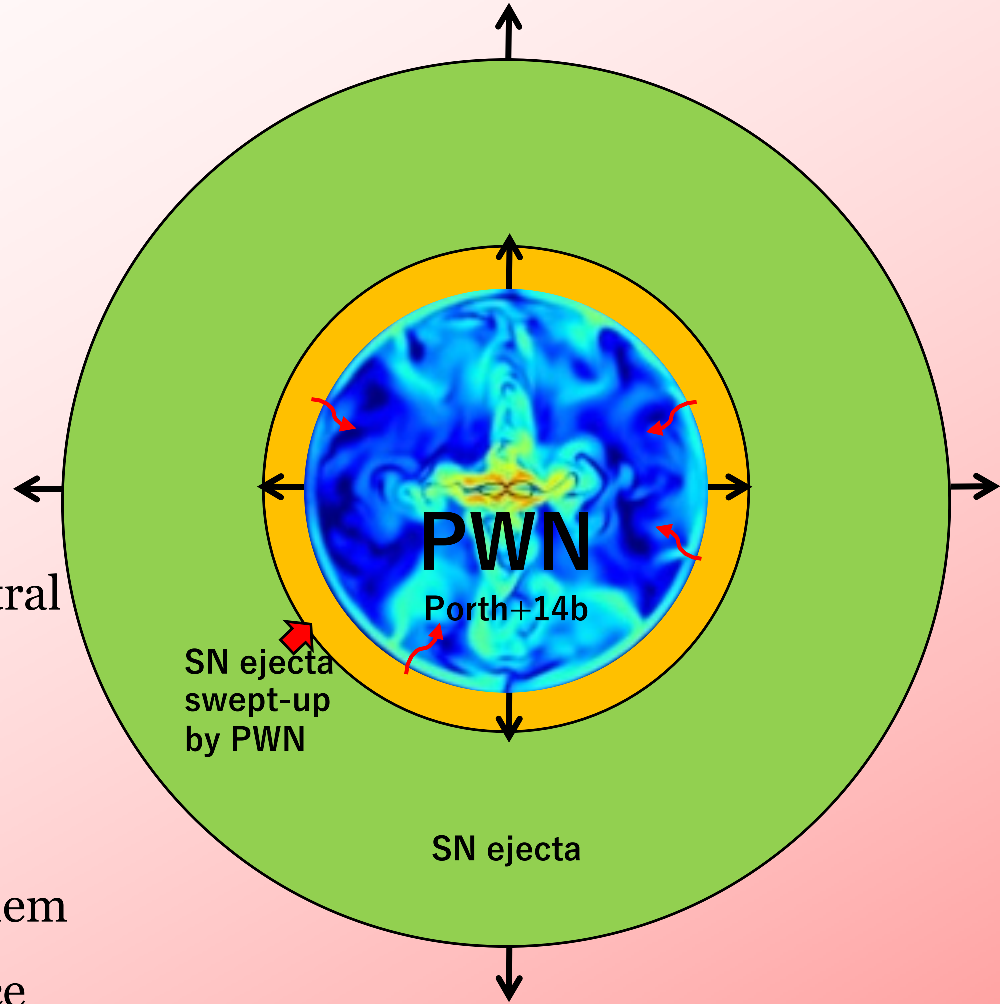


- Standard single PL injection + stochastic acceleration
- Radio-emitting particles increase more rapidly than broken PL model

One-zone Model

One-zone approx. for PWN

- Expanding PWN inside expanding SN ejecta e.g., Gelfand+09, Bandiera+20
- Supplying accelerated $e^{\pm}$ & B from central PSR e.g., Pacini&Salvati73, Kennel&Coroniti84
- Seeding low-energy electrons from SN ejecta and stochastically accelerating them to radio-emitting particles by turbulence Tanaka&Asano17



- B-field evolution of $\frac{4\pi}{3} R_{\rm PWN}^3(t) \frac{B^2(t)}{8\pi} = \eta_{\rm B} \int_0^t L_{\rm spin}(t') dt'$ Tanaka&Takahara10

$$L_{\rm spin} = (\eta_{\rm e} + \eta_{\rm B} + \eta_{\rm turb}) L_{\rm spin}$$

Stochastic Acceleration

$$\frac{\partial}{\partial t}N(\gamma,t)+\frac{\partial}{\partial\gamma}\left[\left(\underline{\dot{\gamma}_{\rm cool}(\gamma,t)}-\underline{\gamma^2 D_{\gamma\gamma}(\gamma,t)\frac{\partial}{\partial\gamma}\frac{1}{\gamma^2}}\right)N(\gamma,t)\right]=\underline{Q_{\rm PSR}}(\gamma,t)+\underline{Q_{\rm ext}}(t)$$

cooling effects

stochastic accel.

from pulsar

Extra injection

$$D_{\gamma\gamma}=\frac{\gamma_{\rm min}^2}{2\tau_{\rm acc,m}}\left(\frac{\gamma}{\gamma_{\rm min}}\right)^2\exp\left(-\frac{t}{\tau_{\rm turb}}\right)$$

Tanaka&Asano17

- $\tau_{\rm acc,m}$: acceleration time normalized at $\gamma_{\rm min}$
- $\tau_{\rm turb}$: decay time-scale of turbulence

$$Q_{\rm ext}(\gamma,t)=f_{\rm inj}4\pi R_{\rm PWN}^2(t)v_{\rm PWN}(t)\,n_{\rm ej}(R_{\rm PWN}(t))\delta(\gamma-\gamma_{\rm inj})$$

- $f_{\rm inj}$: injection efficiency
  $f_{\rm inj} \ll 1$ ($O(10^{-5})$)
- $\gamma_{\rm inj}$: injection energy
  $\gamma_{\rm inj} \sim 1$

Stochastic Acceleration

$$\frac{\partial}{\partial t}N(\gamma,t)+\frac{\partial}{\partial\gamma}\left[\left(\dot{\gamma}_{\rm cool}(\gamma,t)-\gamma^2D_{\gamma\gamma}(\gamma,t)\frac{\partial}{\partial\gamma}\frac{1}{\gamma^2}\right)N(\gamma,t)\right]=Q_{\rm PSR}(\gamma,t)+Q_{\rm ext}(t)$$

cooling effects — stochastic accel. — from pulsar — Extra injection

$$D_{\gamma\gamma}=\frac{\gamma^2}{\tau_{\rm acc}}\left(\frac{E_\delta}{E_{\rm rot}}\right)$$

This study

- τ_{acc}: parameter determines time-scale
- E_{rot}: total spin-down energy
- E_δ: energy of turbulence injection from spin-down & decreasing for stochastic accel.

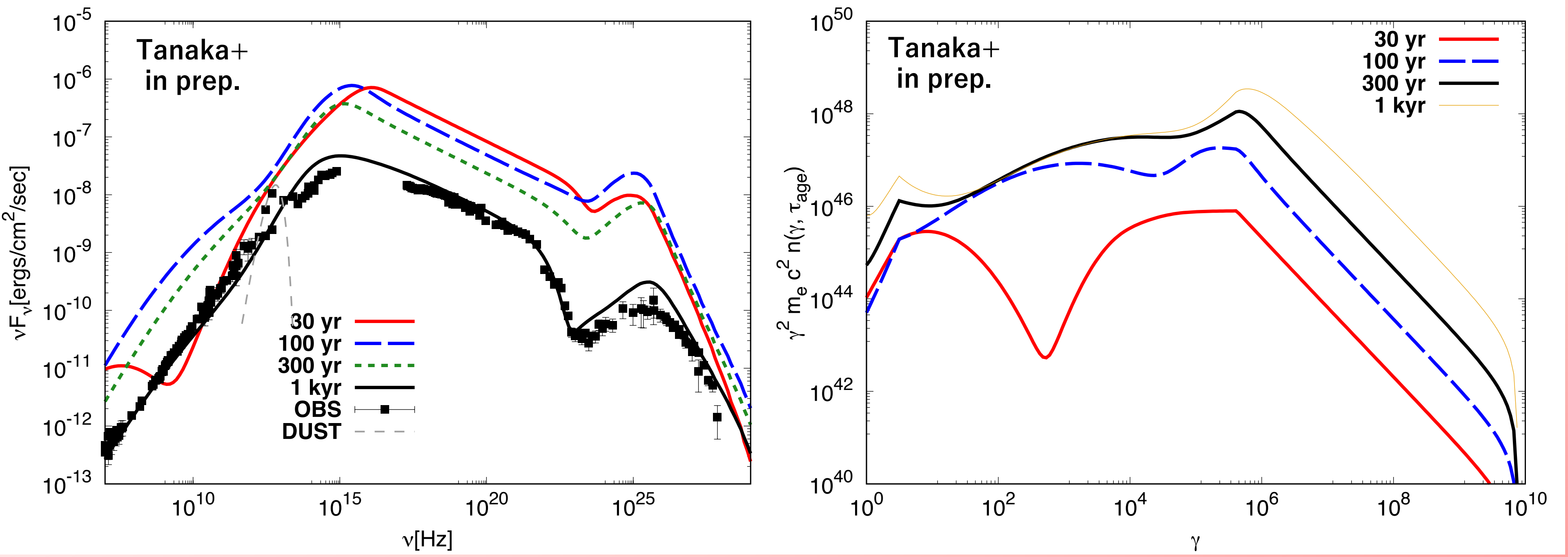
$$Q_{\rm ext}(\gamma,t)=f_{\rm inj}4\pi R_{\rm PWN}^2(t)v_{\rm PWN}(t)\, n_{\rm ej}(R_{\rm PWN}(t))\delta(\gamma-\gamma_{\rm inj})$$

- f_{inj}: injection efficiency
  $f_{inj} \ll 1$ ($O(10^{-5})$)
- γ_{inj}: injection energy
  $\gamma_{inj} \sim 1$

Results & Conclusion

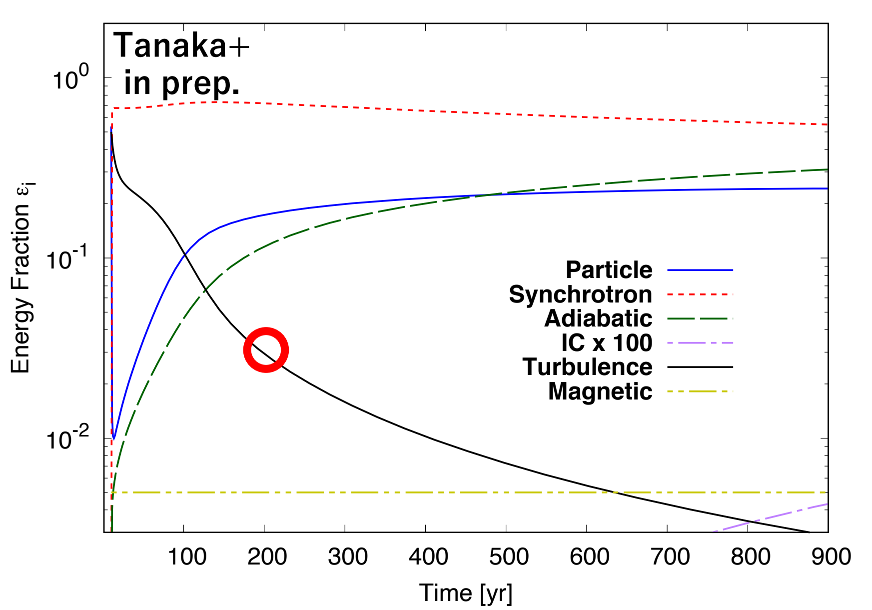
Results

Application to the Crab Nebula ($\tau_{acc} \sim 1$ yr)



A preliminary result shows that the hard radio spectrum can be reproduced with the current model

Conclusions



Stochastic acceleration model of radio emission from the Crab Nebula is improved considering the evolution of turbulent energy.

- Origin of the radio-emitting particles of PWNe is unknown.
- Studied the external particle origin scenario with stochastic acceleration model by Tanaka & Asano (2017) improved by excluding artificial decaying behavior of the turbulent.
- The radio spectrum of the Crab Nebula is reproduced with the current model which has no artificial decaying term.