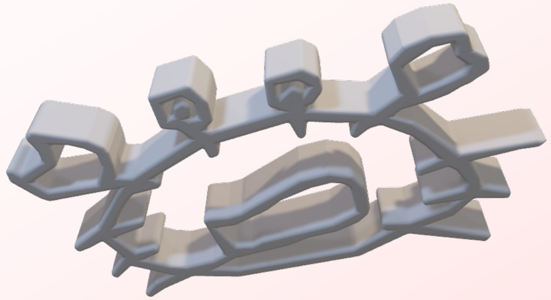
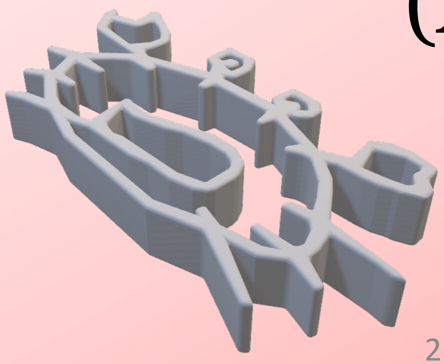
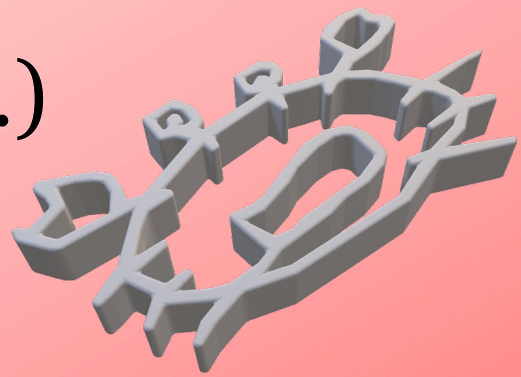


パルサー星雲の乱流加速モデル: 若いパルサー星雲への適用

Shuta J. Tanaka
(Aoyama Gakuin Univ.)





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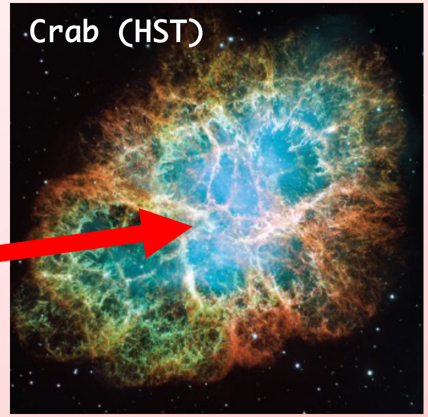
Introduction

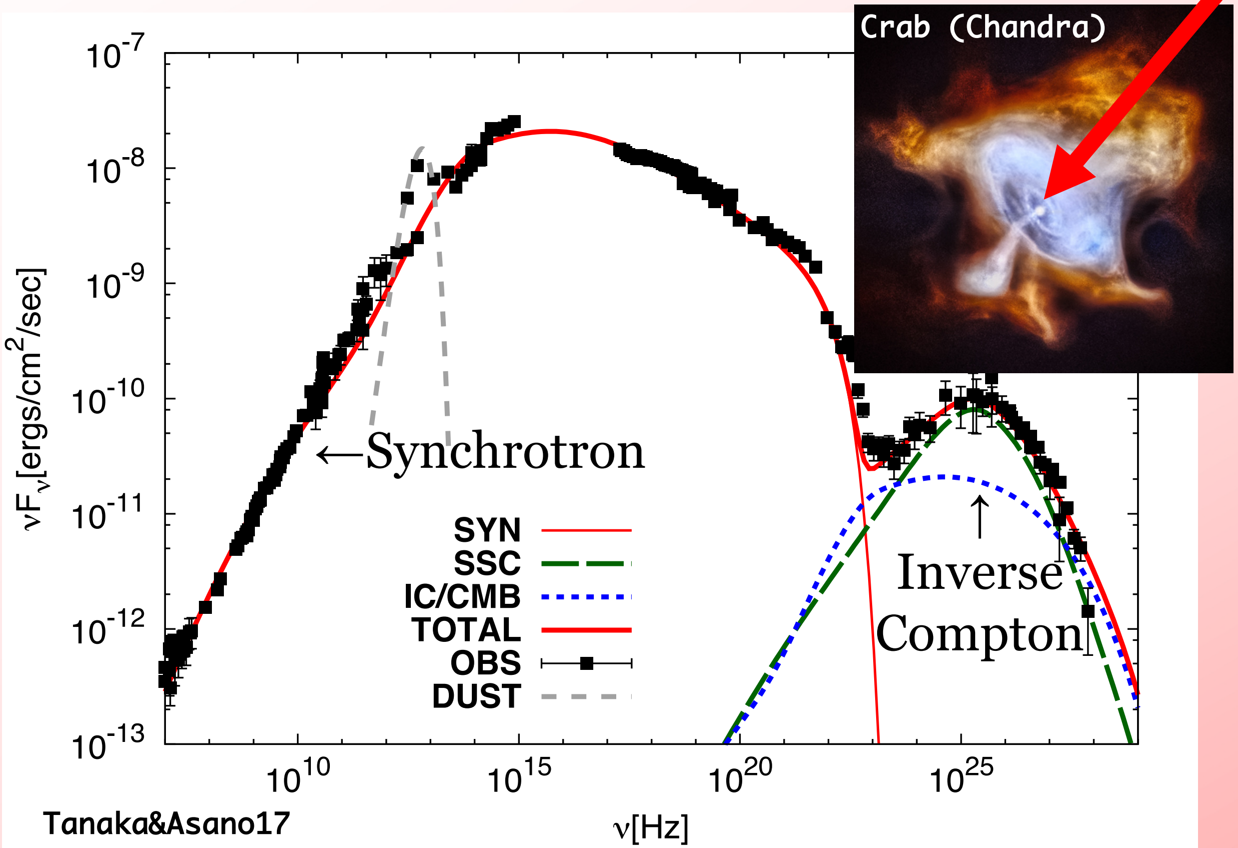
PWN as Particle Accelerator

pulsar wind nebula



Crab Pulsar

Broadband spectrum from sub-μeV through PeV



- PeV photons from the Crab

LHAASO Collab. 21 Sci

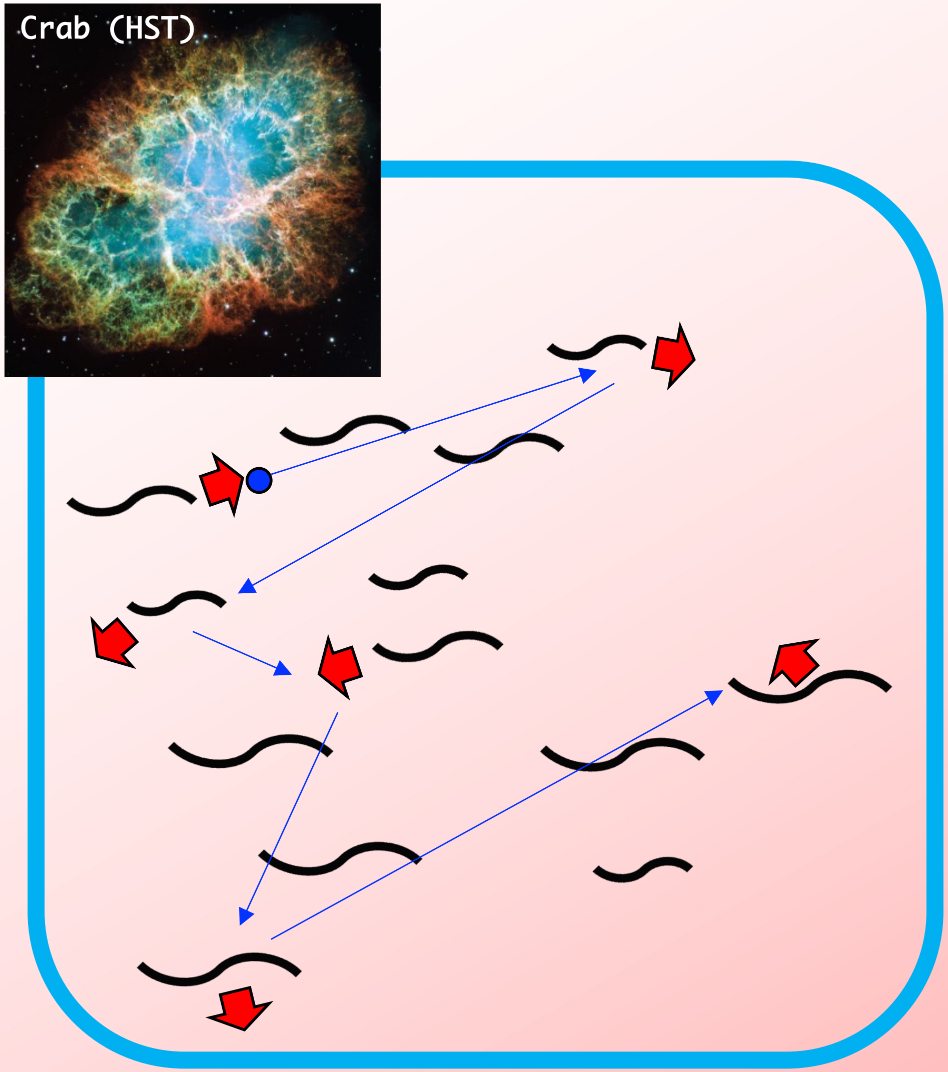
Particle accelerator > PeV

- Optical peak ← synchrotron from TeV particles.

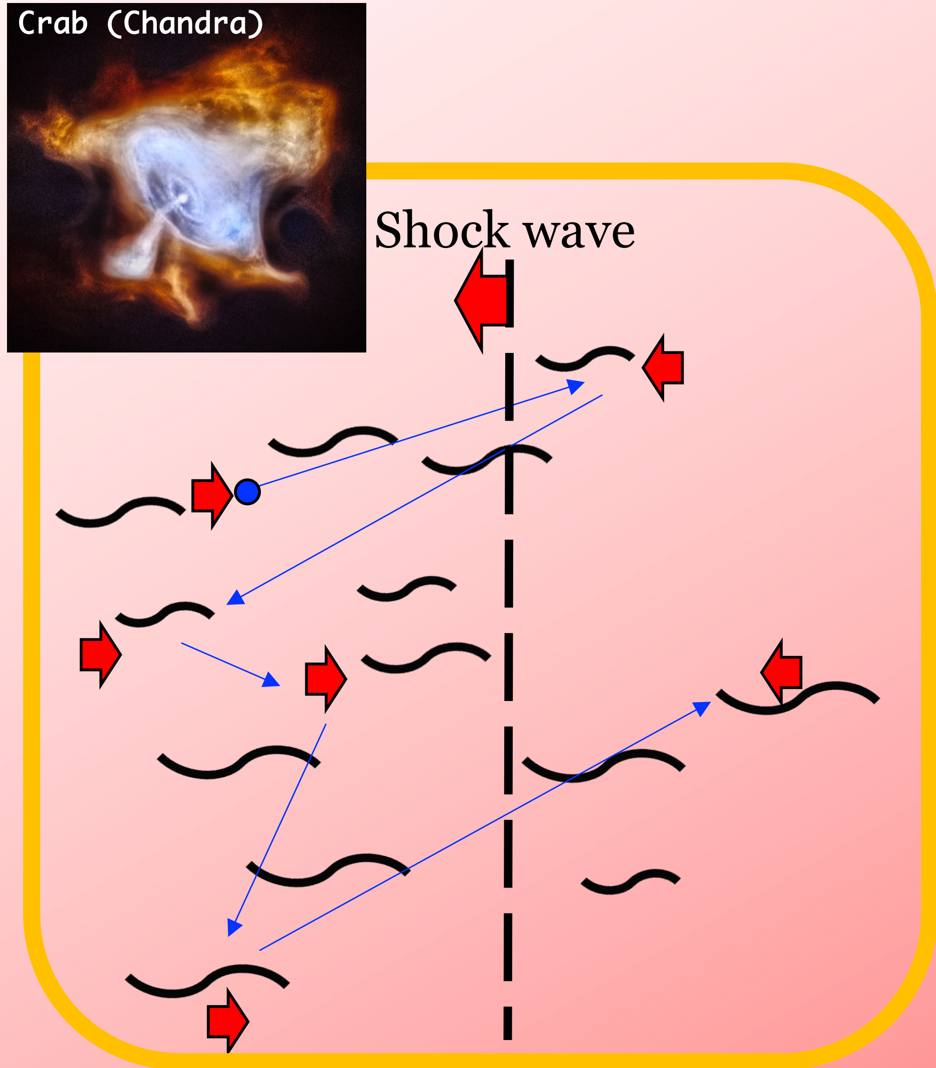
Relativistic (T_{PWN}~TeV) and rarefied (n_{PWN}< 10^{-6} cm^{-3}) magnetized plasma cloud

Closest relativistic object

Particle Acceleration = Mechanism to form non-Maxwellian distribution

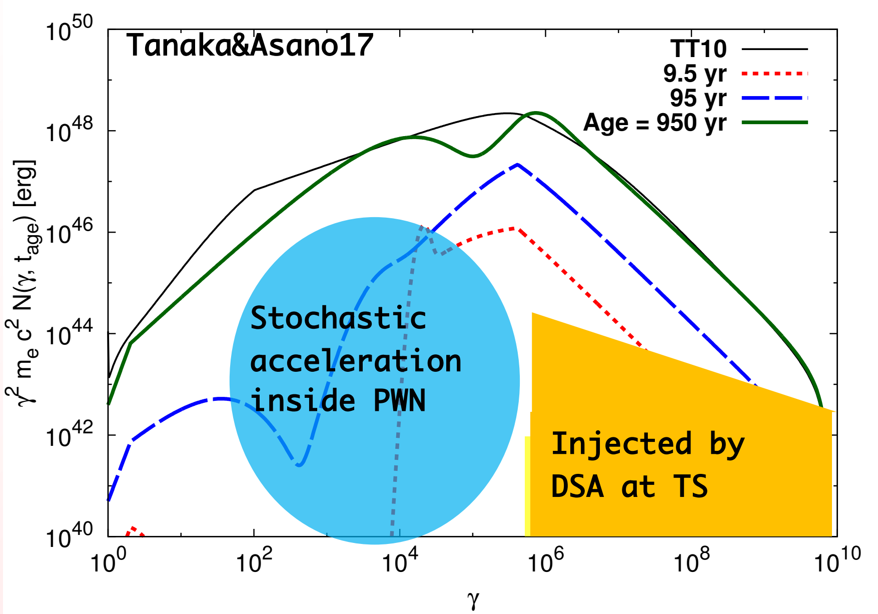


Stochastic Acceleration
by random waves (turbulence)
2^{nd} order Fermi Acceleration

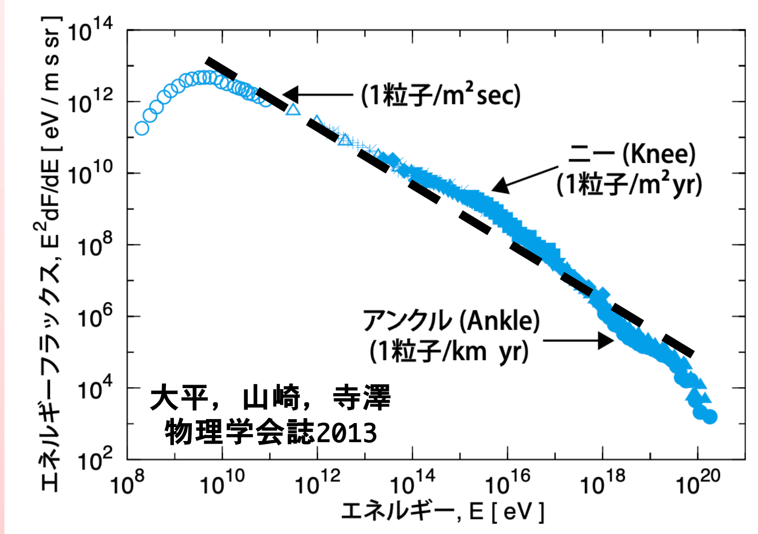


Diffusive Shock Acceleration
by conversing flow (shock)
1^{st} order Fermi Acceleration

Origin of Radio Emission



Cosmic-ray energy spectrum ~ single power-law



- A single power-law particle distribution is predicted from particle acceleration theory.

our stochastic accel. model Tanaka&Asano17

- Low energy component has a harder spectrum than diffusive shock acceleration
- Low energy component is dominant in total particle number. (κ-problem)

Two different accel. mechanisms.

\+

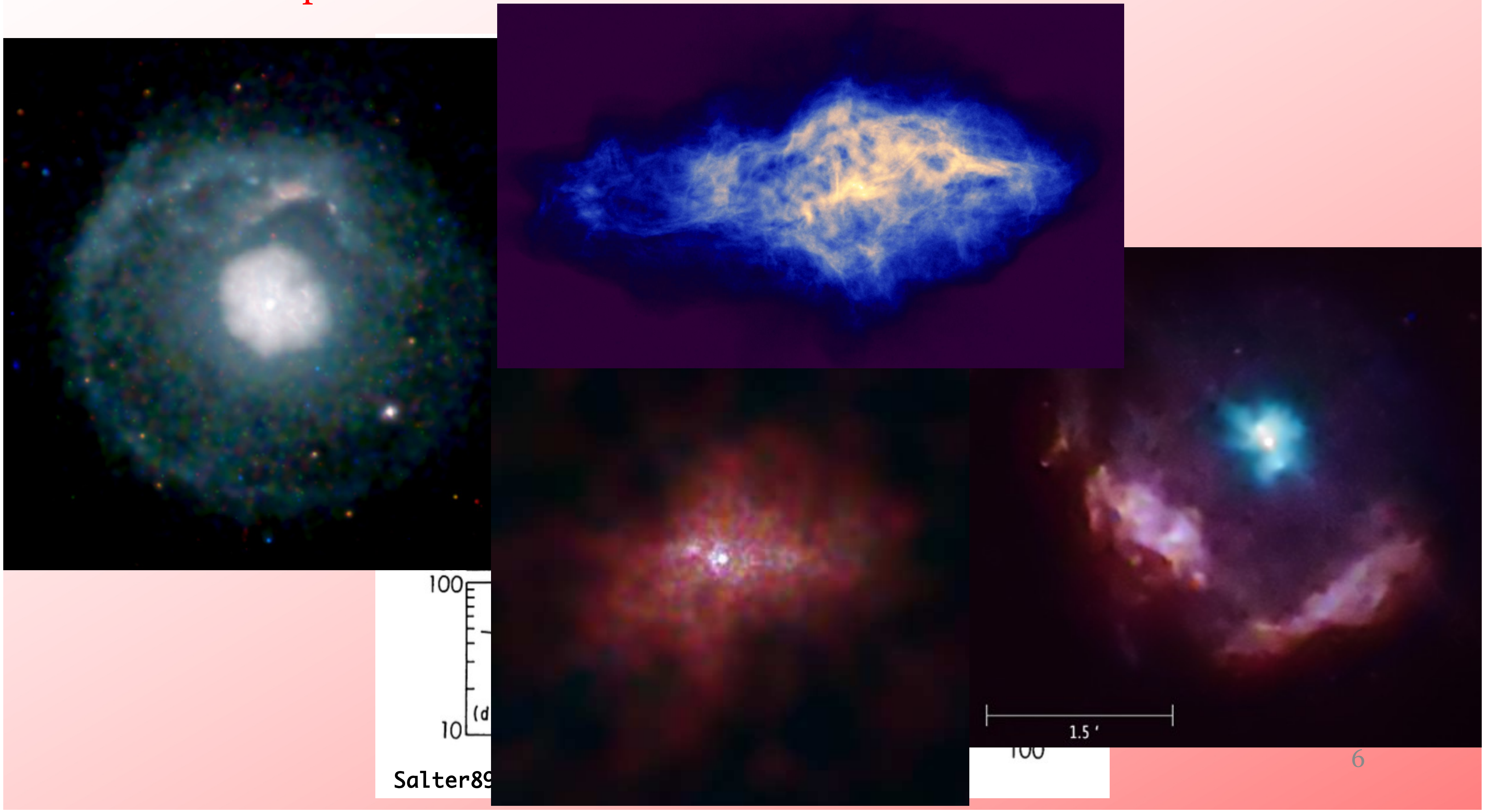
Paticles supplied from outside PWNe

c.f. Timokhin&Harding15,18

Variation of Radio Indices

Pulsar wind nebulae (PWNe) are a kind of supernova remnant characterized by

- a “filled-center morphology”
- a “flat radio spectrum with different indices for different sources”

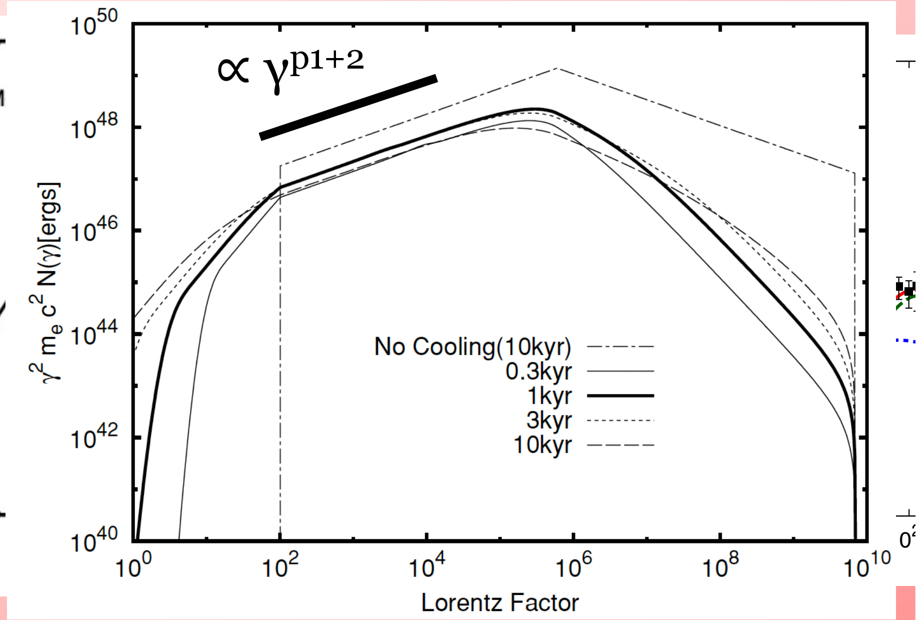


Variation of Radio Indices

Pulsar wind nebulae (PWNe) are a kind of supernova remnant characterized by

- a “filled-center morphology”
- a “flat radio spectrum with different indices for different sources”

Object Name	Low index	Pair Multiplicity
Crab	1.5	$> 4.2 \times 10^6$
G21.5-0.9	1.0	$> 1.3 \times 10^5$
3C58	1.0	$> 4.5 \times 10^5$
G54.1+0.3	1.2	$> 3.7 \times 10^4$
Kes 75	1.6	$> 2.8 \times 10^4$
G0.9+0.1	N/A	8.3×10^4



Model

One-zone Model

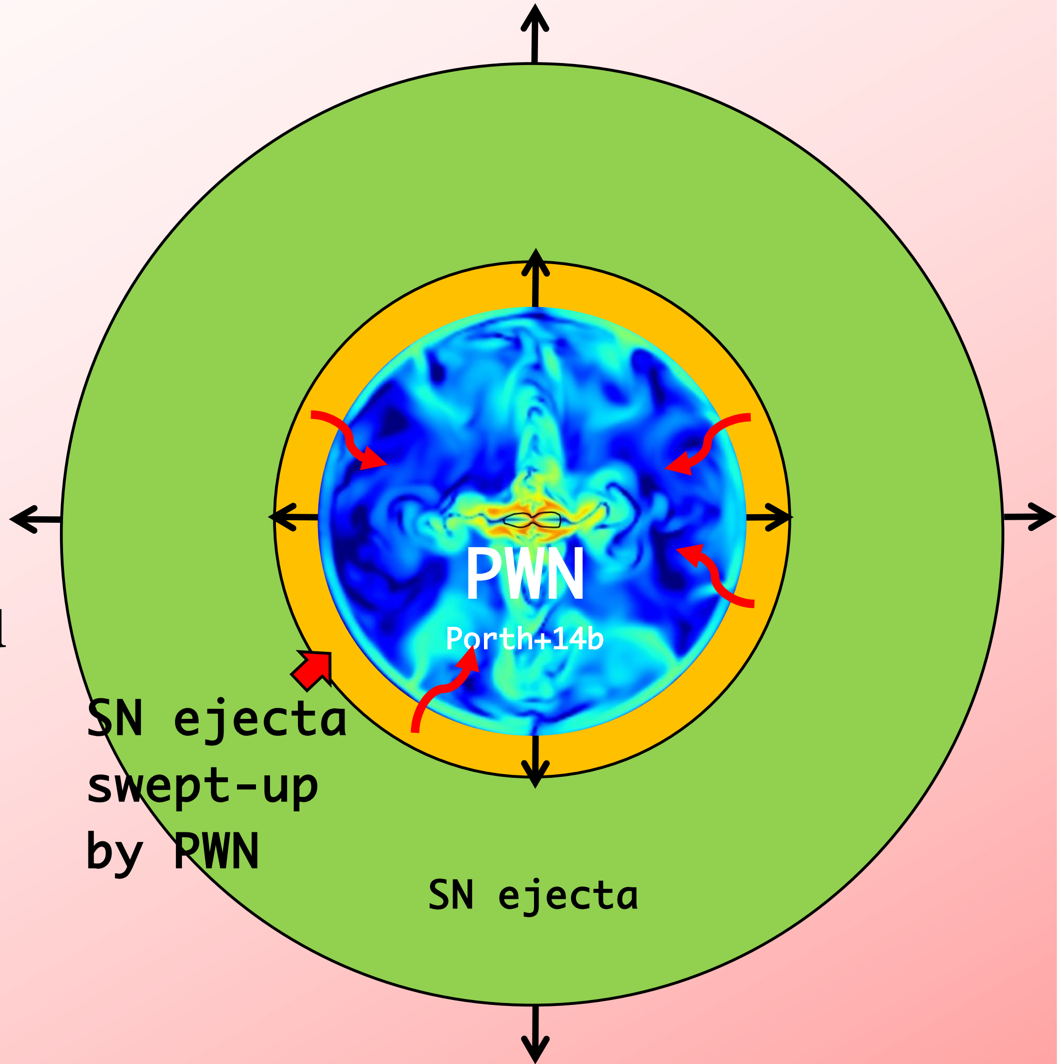
One-zone approx. for PWN

- Uniform PWN expanding inside SN ejecta. e.g., Gelfand+09, Bandiera+20

- Rela. particles ($e^{\pm}$) and B-field supplied from PSR e.g., Pacini&Salvati73, Kennel&Coroniti84

- Non-rela. particles supplied from SN ejecta (photoionization) Tanaka&Asano17

- Turbulent energy for stochastic accel. is supplied from PSR and decreases by accelerating particles (backreaction).



$$\frac{4\pi}{3} R_{\rm PWN}^{3}(t) \frac{B^{2}(t)}{8\pi} = \eta_{\rm B} \int_{0}^{t} L_{\rm spin}(t') dt'$$

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

Tanaka&Takahara10, Tanaka&Asano17, Tanaka&Kashiyama23

Stochastic Acceleration

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

cooling effects — stochastic accel. — from pulsar (shock accel.) — Extra injection

$$D_{\gamma\gamma}=\frac{\gamma^2}{2t_{\rm acc}},\ \ t_{\rm acc}(t)=\tau_{\rm acc}\frac{\eta_{\rm T}E_{\rm rot}}{E_{\rm T}(t)}$$

- τ_{acc}: initial acceleration time
- t_{acc}: accel. time increases with decaying of turbulence

- $E_T(t)$: energy of turbulence

$$\frac{dE_{\rm T}}{dt}=\eta_{\rm T}L_{\rm spin}-\frac{E_{\rm T}}{t_{\rm adi}(t)}-\left(\frac{\delta E_{\rm T}}{\delta t}\right)_{\rm damp}$$

decay by expansion — decay by particle accel.

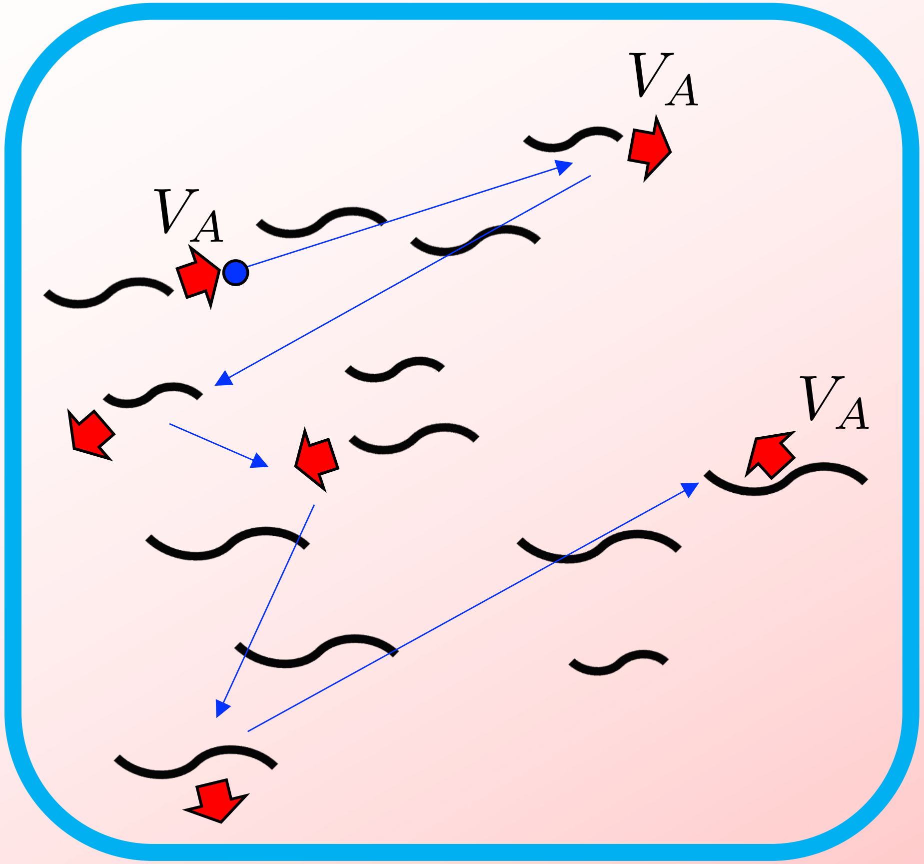
$$Q_{\rm ext}(\gamma,t)=f_{\rm inj}4\pi R_{\rm PWN}^2(t)v_{\rm PWN}(t)\, n_{\rm ej}(R_{\rm PWN}(t))\delta(\gamma-\gamma_{\rm inj})$$

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

- γ_{inj}: injection energy
  $\gamma_{inj} \sim 1$

Injection of hadrons!!

Acceleration Time-scale



Original

$$\tau_{\rm acc} = t_{\rm coll} \left(\frac{V_A}{c} \right)^{-2}$$

$$= t_{\rm coll} \frac{\rho c^2}{u_B}$$ Fermi49PR

Resonant scattering

$$\tau_{\rm acc} = t_{\rm coll} \left(\frac{V_A}{c} \right)^{-2} \frac{B^2}{\delta B^2}$$

$$= t_{\rm coll} \frac{\rho c^2}{u_{\rm T}}$$ e.g., Mertsch11

$$D_{pp} = \frac{\zeta \beta_{\rm A}^2 p^2 c}{r_g^{2-q} \lambda_2^{q-1}}$$

$$\zeta = (\delta B)^2 / B^2$$

$$(\delta B)^2 = \int_{k_1}^{k_2} {\rm d}k' \mathcal{W}(k')$$

e.g., Mertsch11

Alfven velocity ⇔ Plasma density

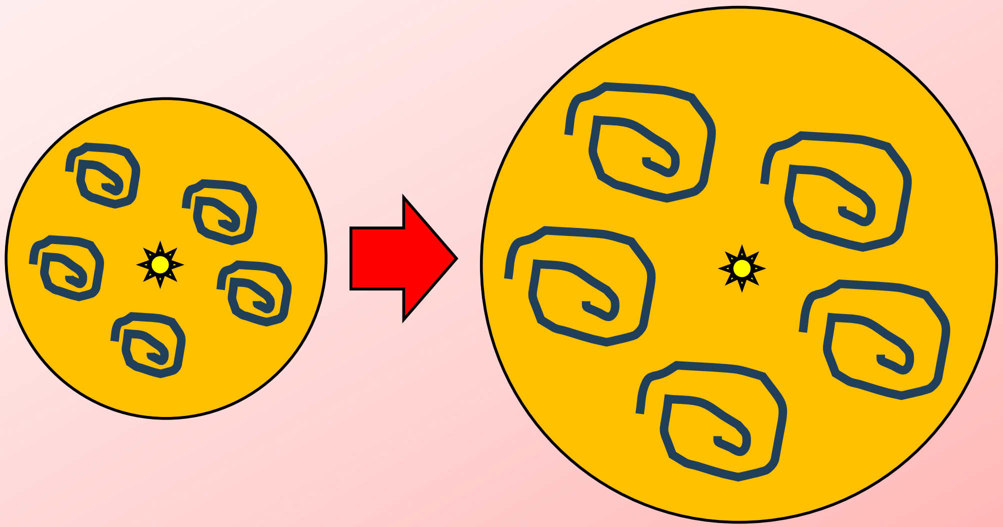
Evolution of Turbulence

$$\frac{dE_{\mathrm{T}}}{dt} = \eta_{\mathrm{T}} L_{\mathrm{spin}} - \frac{E_{\mathrm{T}}}{t_{\mathrm{adi}}(t)} - \left(\frac{\delta E_{\mathrm{T}}}{\delta t}\right)_{\mathrm{damp}}$$

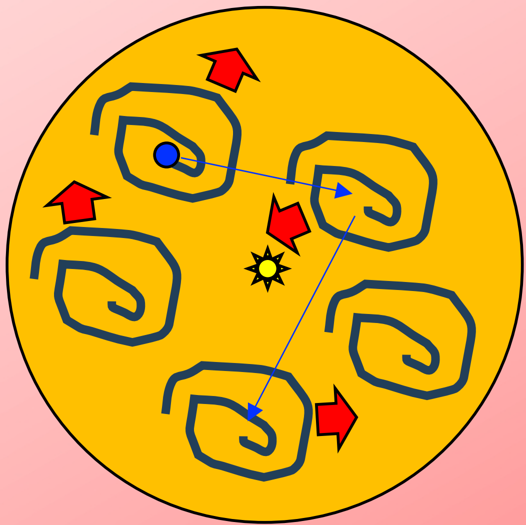
$$\eta_{\mathrm{T}} \sim 0.5$$

Total energy of radio-emitting particles close to X-ray-emitting ones.

$$\equiv \int d\gamma \gamma m_{\mathrm{e}} c^2 \frac{\partial}{\partial \gamma} \left(-\gamma^2 D_\gamma \frac{\partial}{\partial \gamma} \frac{N}{\gamma^2} \right)$$



Adiabatic expansion



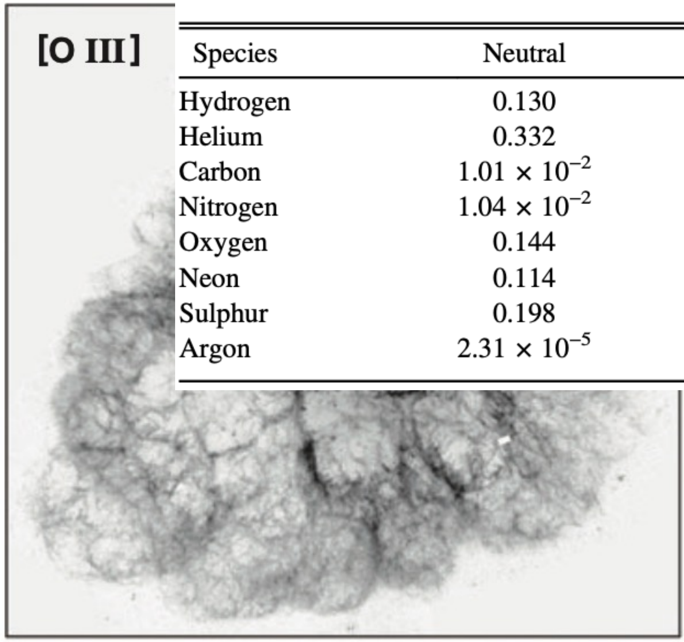
Backreaction

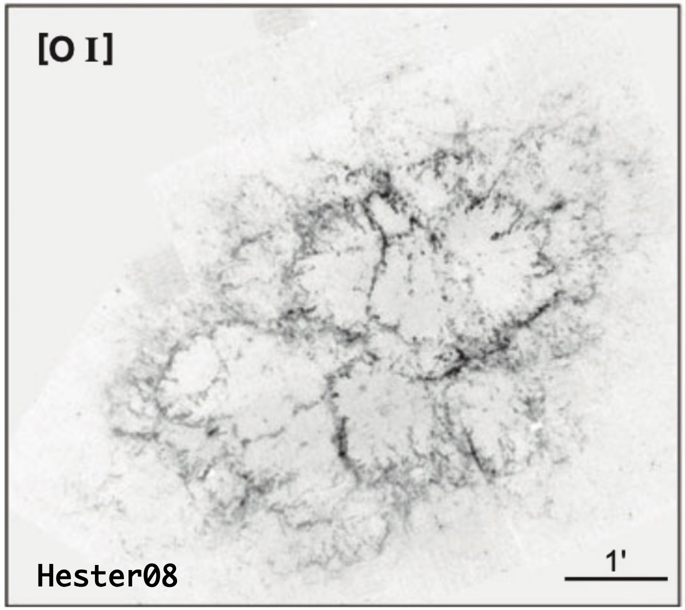
Injection from Ejecta Filaments

Table 4
Gas-phase Elemental Ion Fractions for the Best-fit Clumpy Model VI

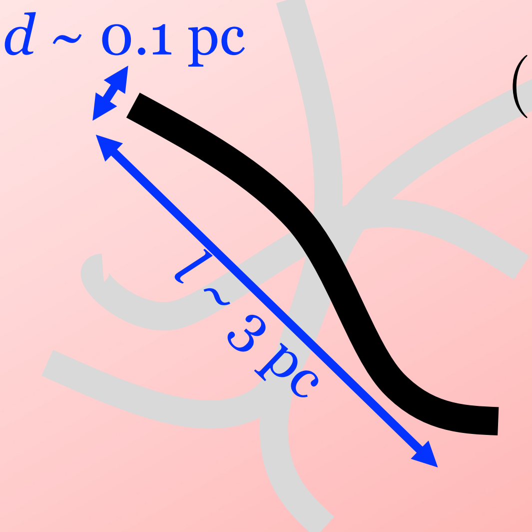
Owen&Barlow15

Species	Neutral	1^+	2^+	3^+	4^+	5^+
Hydrogen	0.130	0.870	?	?	?	?
Helium	0.332	0.630	3.77×10^{-2}	?	?	?
Carbon	1.01×10^{-2}	0.730	0.248	2.08×10^{-2}	2.01×10^{-6}	1.04×10^{-10}
Nitrogen	1.04×10^{-2}	0.708	0.237	5.39×10^{-3}	1.17×10^{-6}	2.34×10^{-9}
Oxygen	0.144	0.721	0.107	2.75×10^{-3}	1.05×10^{-6}	7.37×10^{-8}
Neon	0.114	0.772	0.113	3.72×10^{-4}	4.10×10^{-6}	9.93×10^{-9}
Sulphur	0.198	0.440	0.299	7.05×10^{-3}	3.34×10^{-5}	5.66×10^{-8}
Argon	2.31×10^{-5}	0.116	0.702	0.178	2.31×10^{-3}	4.25×10^{-5}





Photoionization of neutrals in filaments



$$(n_{\rm fil}, T_{\rm fil}) \sim (10^3~{\rm cm}^{-3}, 10^3~{\rm K})$$

Graham+90

$$\dot{N}_{\rm fil} \lesssim \pi d l c_s n_{\rm fil}$$
$$\approx 10^{46}~{\rm s}^{-1}$$

Only a tiny (~10^{-5}) fraction to be accelerated.

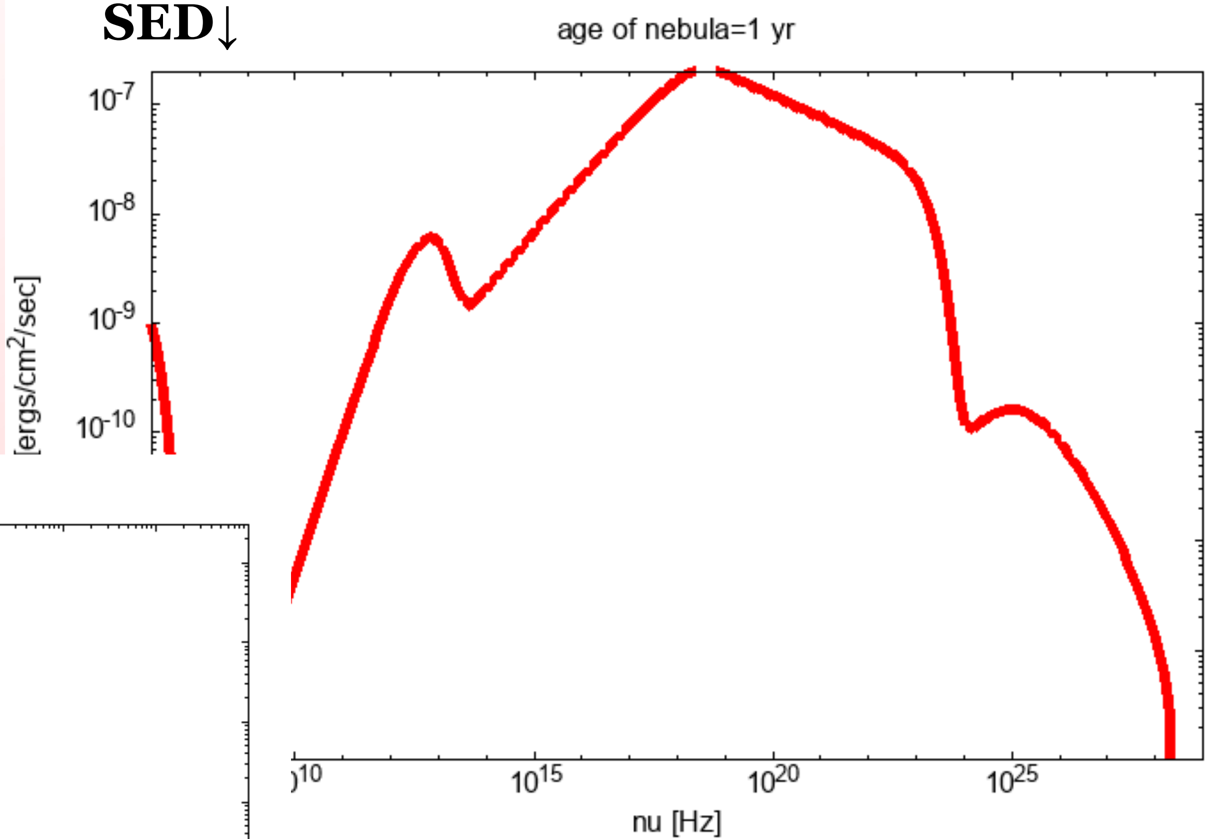
c.f. $\dot{N}_{\rm GJ} \approx 10^{34}~{\rm s}^{-1} L_{\rm spin,38}^{1/2}$

Results

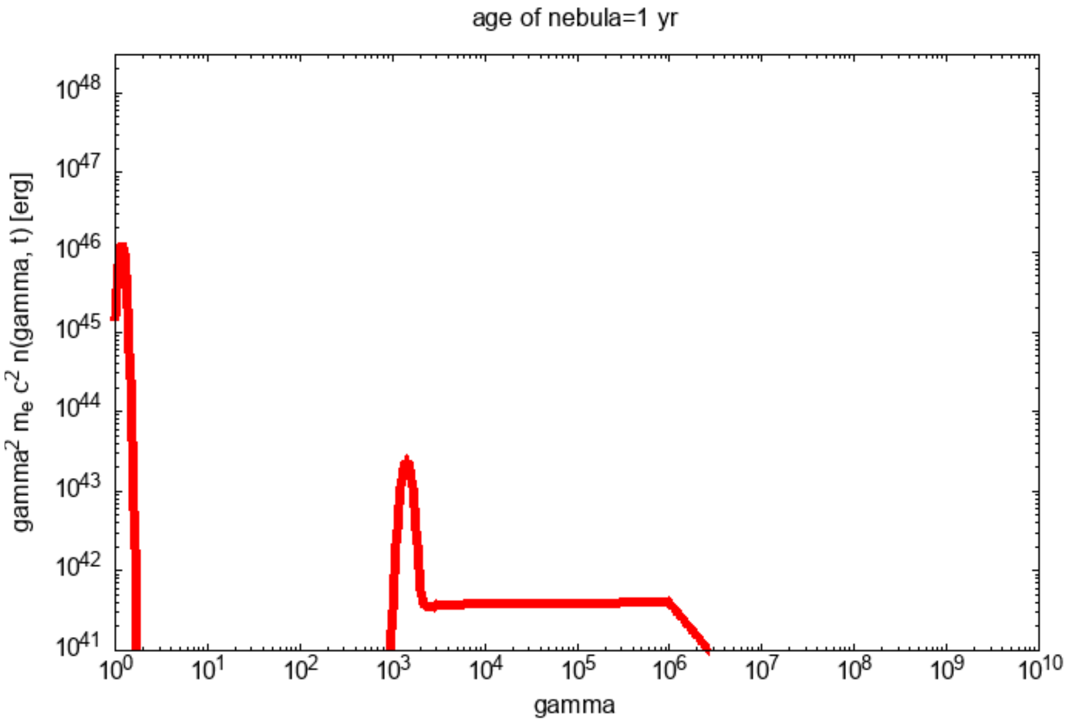
Results: Broadband Spectrum

$$\tau_{\mathrm{acc},0} = 10\ \mathrm{yr}$$

SED↓



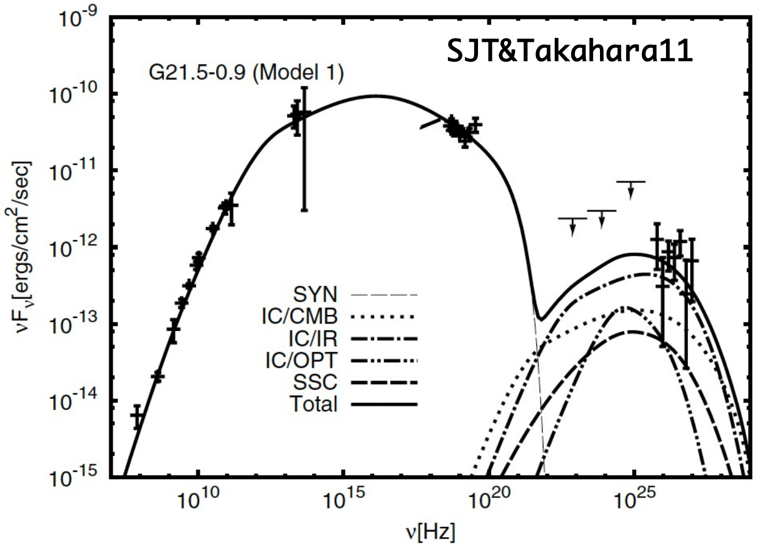
Electron Energy Spectrum↓

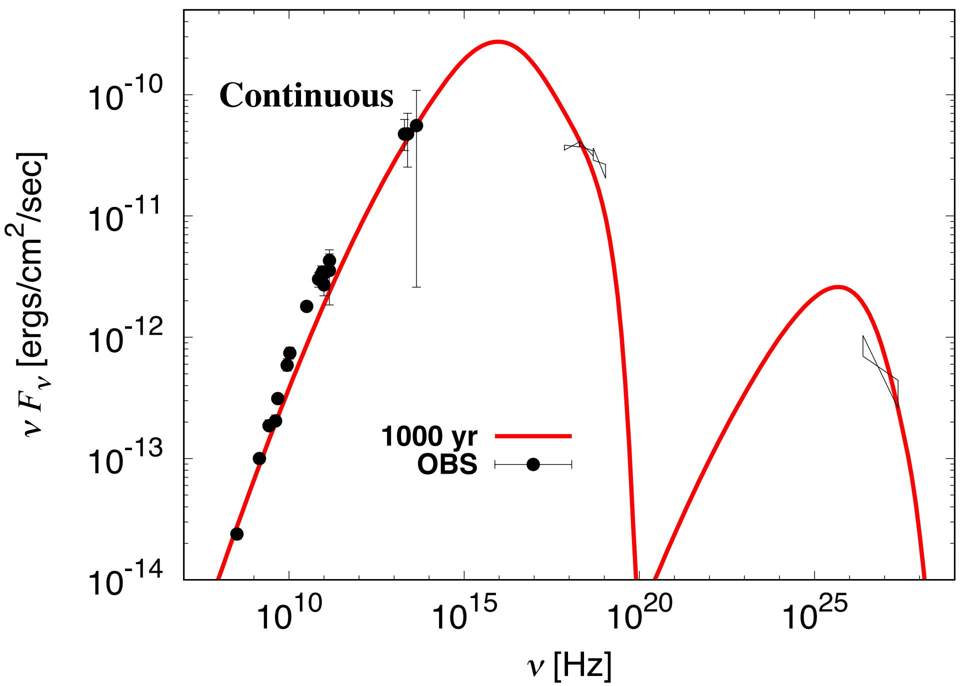


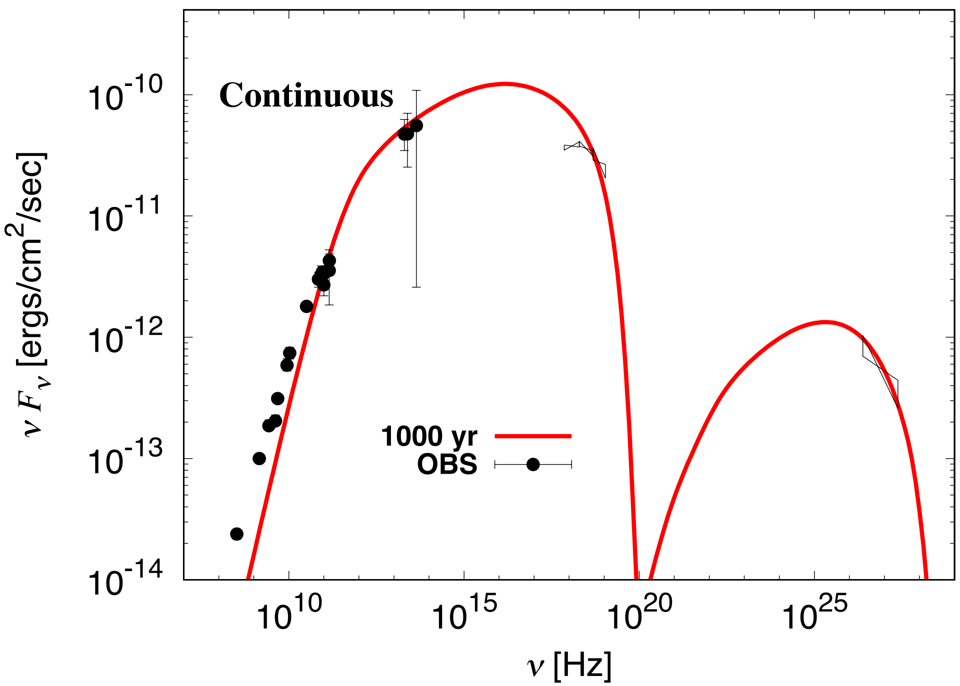
$$\frac{\partial}{\partial t}N(\gamma,t) + \frac{\partial}{\partial \gamma}\left[\left(\dot{\gamma}_{\mathrm{cool}}(\gamma,t) - \gamma^2 D_{\gamma\gamma}(\gamma,t)\frac{\partial}{\partial \gamma}\frac{1}{\gamma^2}\right)N(\gamma,t)\right] = Q_{\mathrm{PSR}}(\gamma,t) + Q_{\mathrm{ext}}(t)$$

Results: G21.5-0.9

Preliminary







Stochastic Acceleration Model

Single Power-law Model

Conclusions

Applying stochastic accel. model to young PWNe

- **Different radio spectral indices can be explained by stochastic acceleration model (different injection rate, acceleration time-scale etc.).**

- **Comprehensive study by applying other young PWNe with broadband fitting is required to comfirm the validity of stochastic acceleration model.**