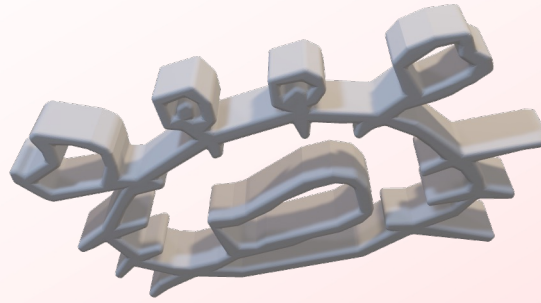
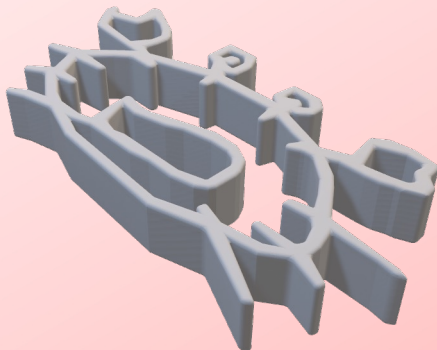


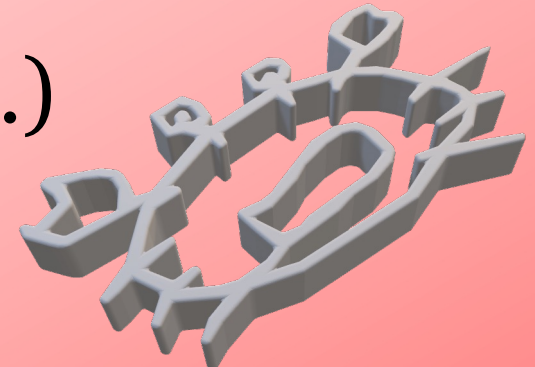


Applying a Stochastic Acceleration Model to Young Pulsar Wind Nebulae

Shuta J. Tanaka
(Aoyama Gakuin Univ.)



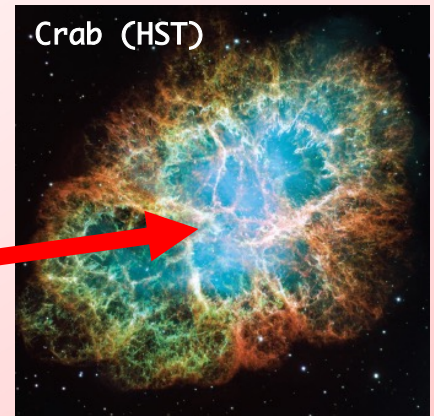
24H01816



Introduction

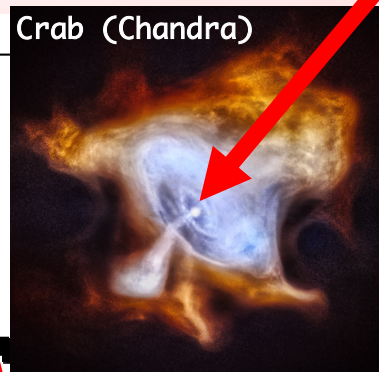
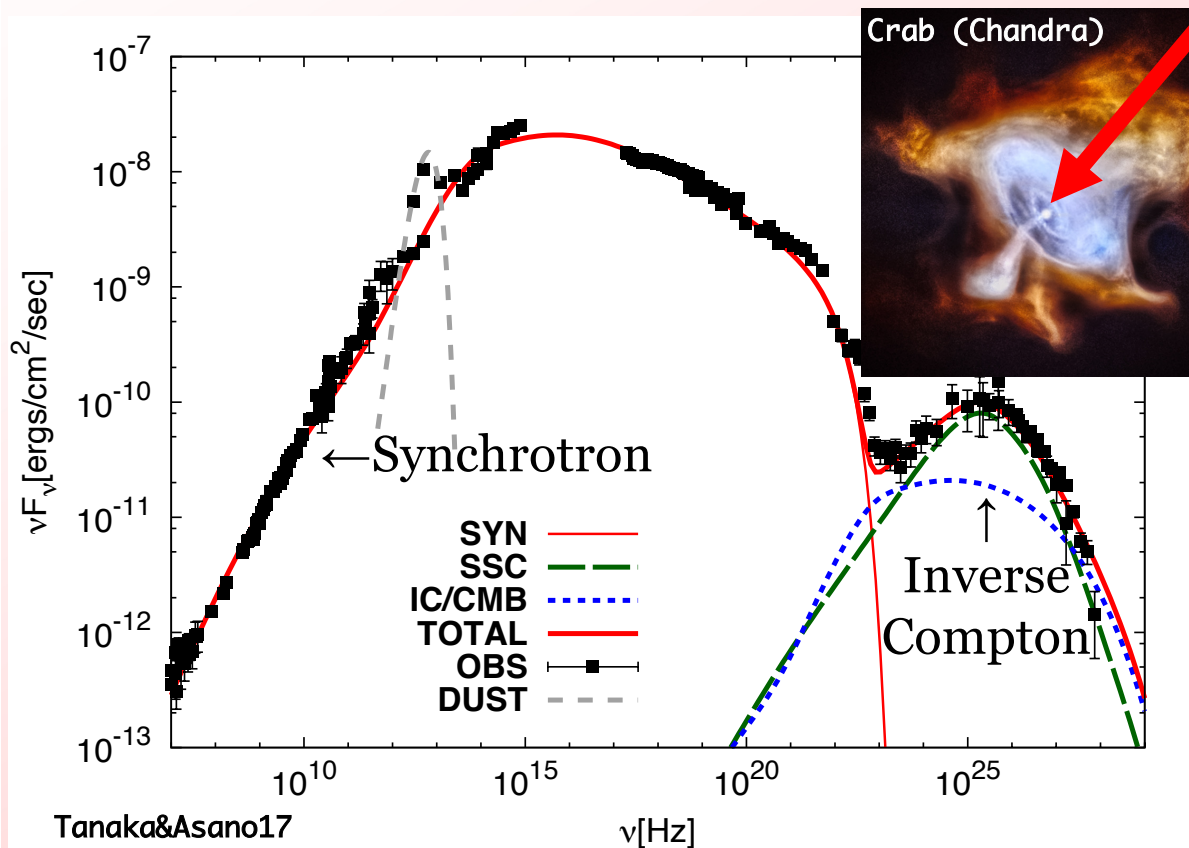
PWN as Particle Accelerator

pulsar wind nebula



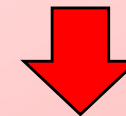
Crab Pulsar

Broadband spectrum from sub- μeV through PeV



- PeV photons from the Crab

LHAASO Collab. 21 Sci



Particle accelerator $> \text{PeV}$

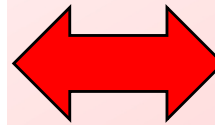
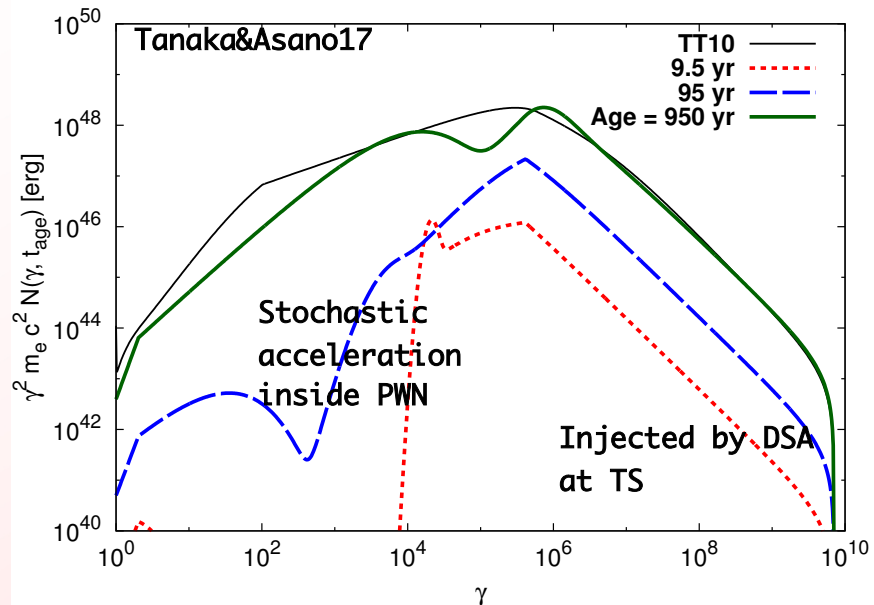
- Optical peak $\leftarrow$ synchrotron from TeV particles.



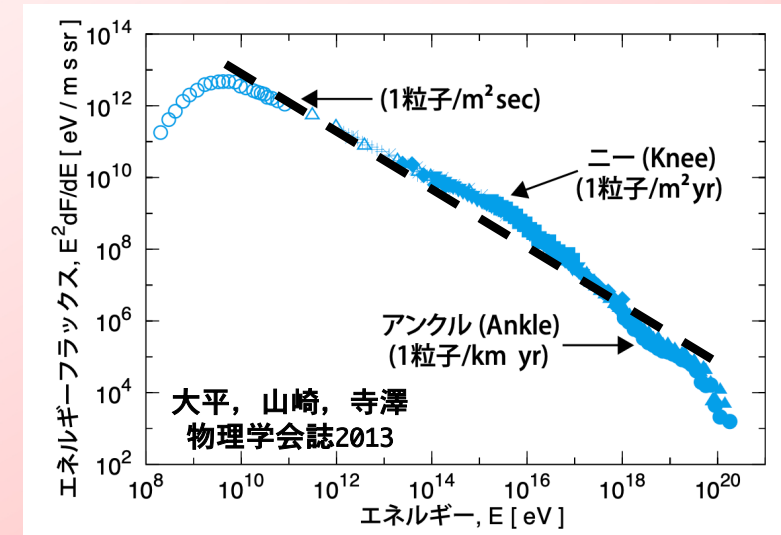
Relativistic ($T_{\text{PWN}} \sim \text{TeV}$) and rarefied ($n_{\text{PWN}} < 10^{-6} \text{ cm}^{-3}$) magnetized plasma cloud

Closest relativistic object

Stochastic Acceleration Model

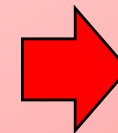


Cosmic-ray energy spectrum ~ single power-law



- A single power-law particle distribution is predicted from particle acceleration theory.
- Low energy component has a harder spectrum than diffusive shock acceleration
- Low energy component is dominant in total particle number. (κ -problem)

our stochastic accel.
model Tanaka&Asano17



Two different accel.
mechanisms.

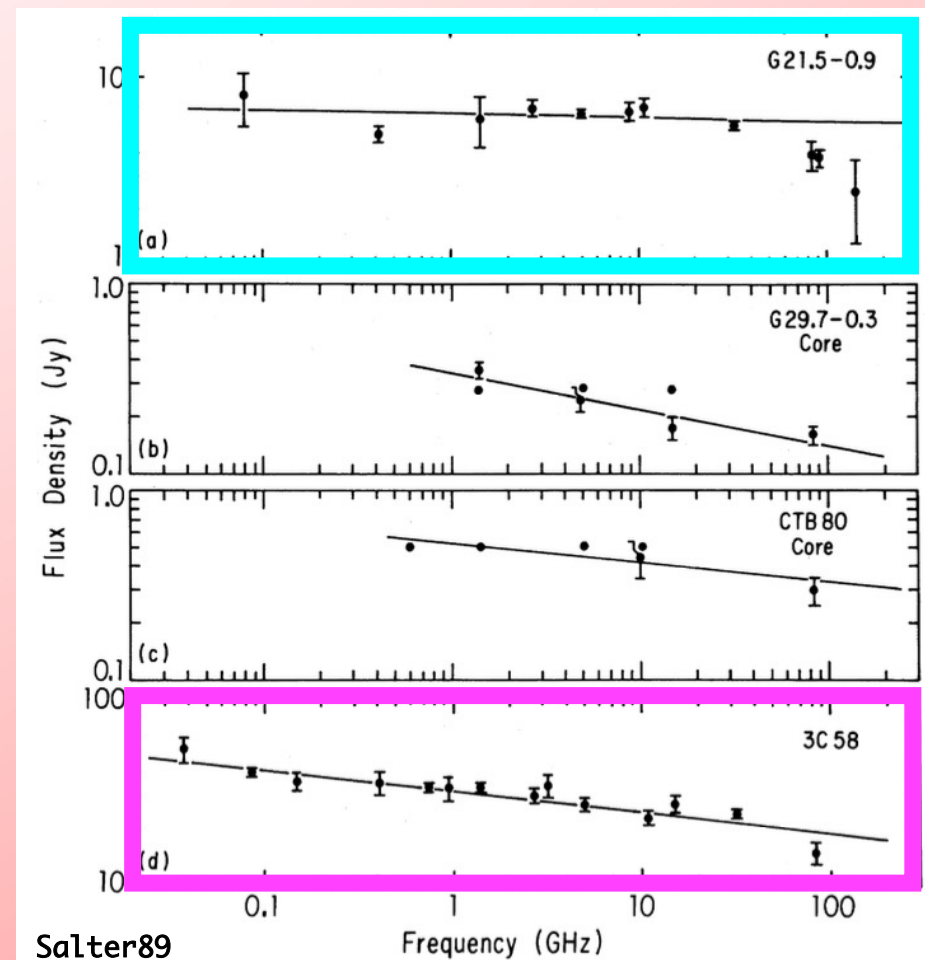
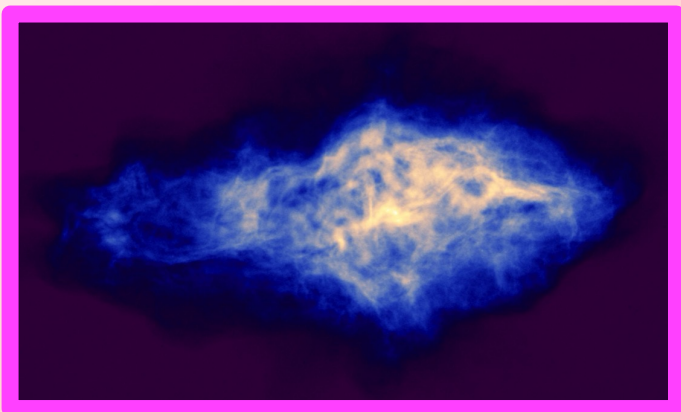
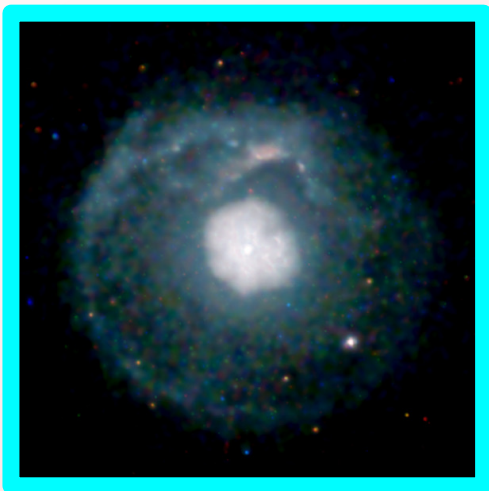
+

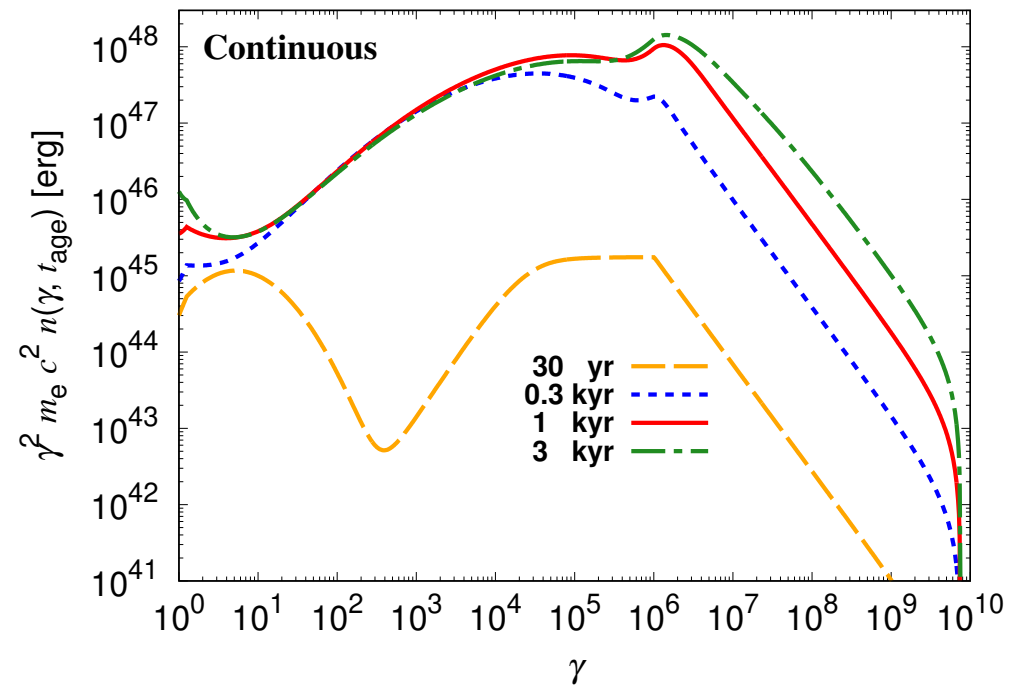
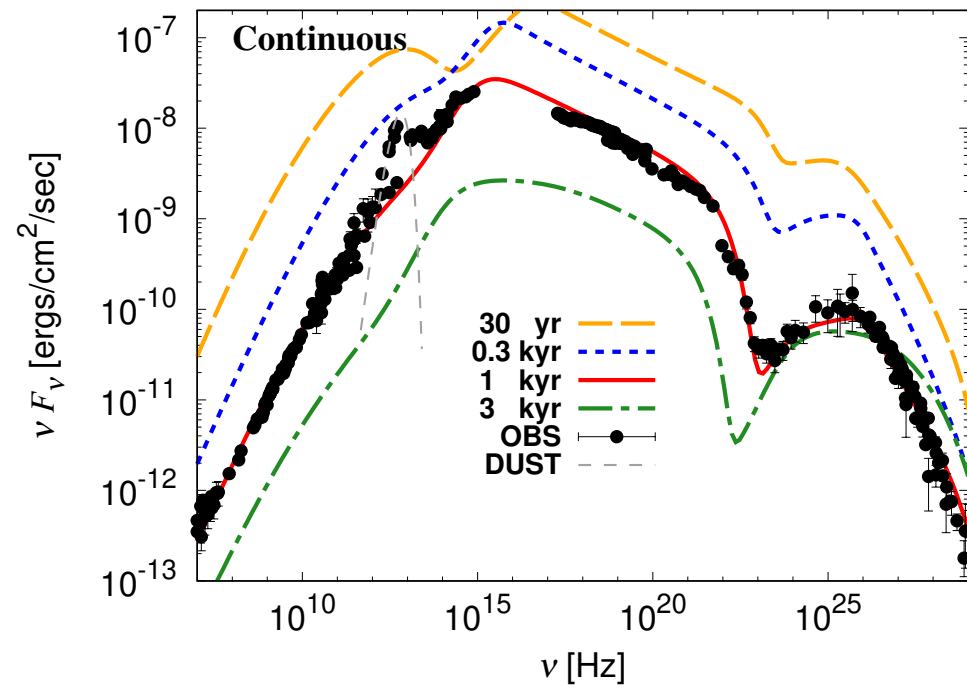
Particles supplied from
outside PWNe

Variation of Radio Indices

PWNe are a kind of supernova remnant characterized by

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



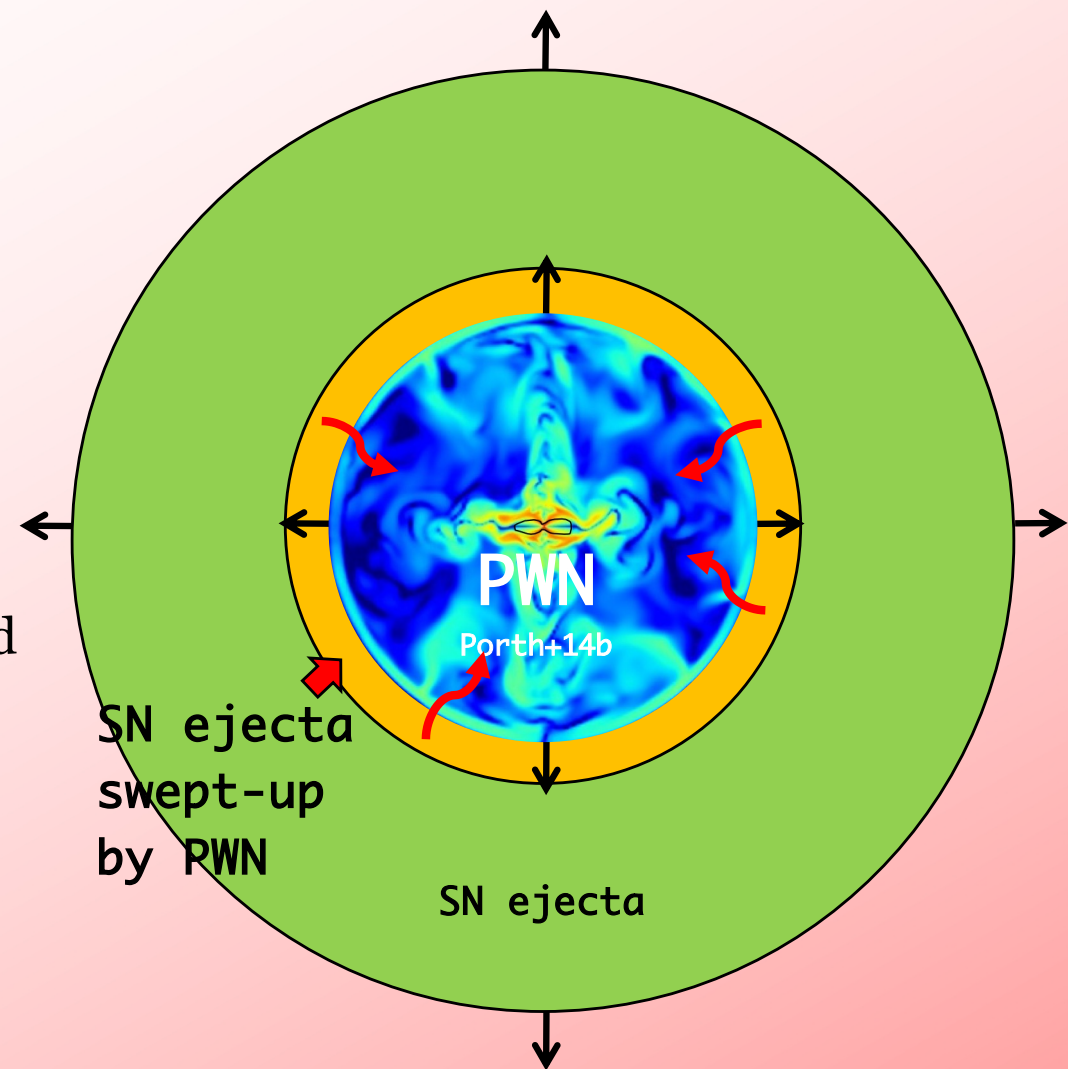


Model

One-zone Model

One-zone approx. for PWN

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



$$\frac{4\pi}{3} R_{\text{PWN}}^3(t) \frac{B^2(t)}{8\pi} = \eta_B \int_0^t L_{\text{spin}}(t') dt'$$

$$L_{\text{spin}} = (\eta_e + \eta_B + \eta_{\text{turb}}) L_{\text{spin}}$$

Tanaka&Takahara10, Tanaka&Asano17, Tanaka&Kashiyama23

Stochastic Acceleration

$$\frac{\partial}{\partial t} N(\gamma, t) + \frac{\partial}{\partial \gamma} \left[\underbrace{\dot{\gamma}_{\text{cool}}(\gamma, t)}_{\text{cooling effects}} - \underbrace{\gamma^2 D_{\gamma\gamma}(\gamma, t) \frac{\partial}{\partial \gamma} \frac{1}{\gamma^2}}_{\text{stochastic accel.}} N(\gamma, t) \right] = \underbrace{Q_{\text{PSR}}(\gamma, t)}_{\text{from pulsar (shock accel.)}} + \underbrace{Q_{\text{ext}}(t)}_{\text{Extra injection}}$$

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

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

- $E_{\text{T}}(t)$: energy of turbulence

$$\frac{dE_{\text{T}}}{dt} = \eta_{\text{T}} L_{\text{spin}} - \underbrace{\frac{E_{\text{T}}}{t_{\text{adi}}(t)}}_{\text{decay by expansion}} - \underbrace{\left(\frac{\delta E_{\text{T}}}{\delta t} \right)_{\text{damp}}}_{\text{decay by particle accel.}}$$

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

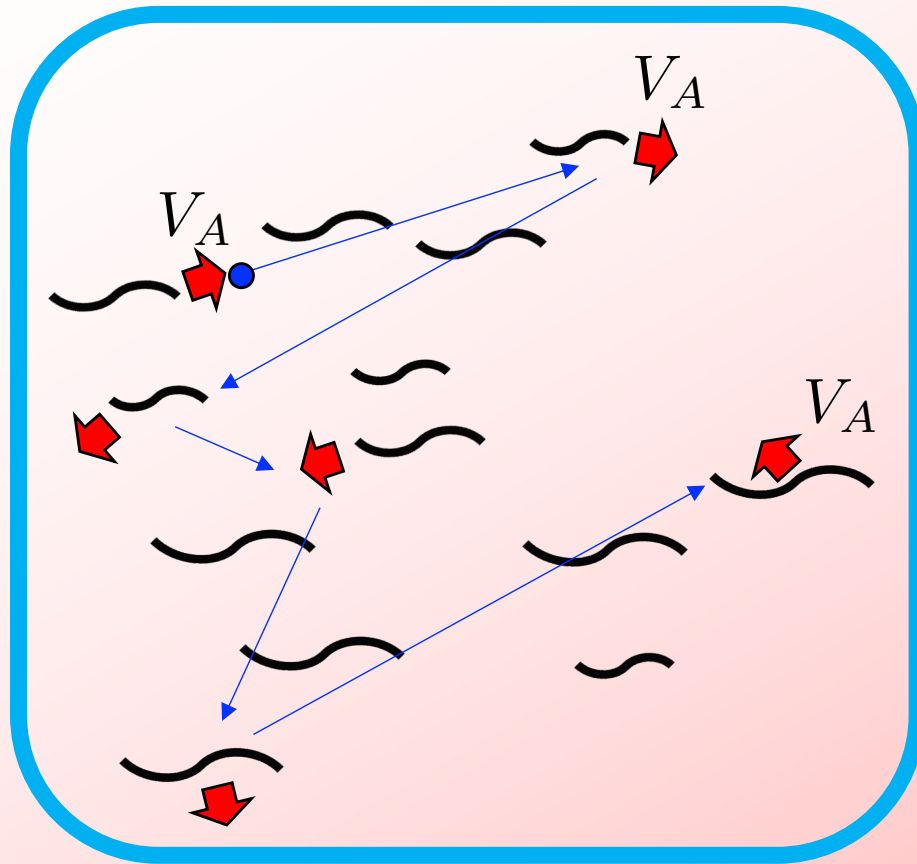
- f_{inj} : injection efficiency
 $f_{\text{inj}} \ll 1$ ($O(10^{-5})$)

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



Injection of hadrons!!

Acceleration Time-scale



Original

$$\begin{aligned}\tau_{\text{acc}} &= t_{\text{coll}} \left(\frac{V_A}{c} \right)^{-2} \\ &= t_{\text{coll}} \frac{\rho c^2}{u_B} \quad \text{Fermi49PR}\end{aligned}$$

Resonant scattering

$$\begin{aligned}\tau_{\text{acc}} &= t_{\text{coll}} \left(\frac{V_A}{c} \right)^{-2} \frac{B^2}{\delta B^2} \\ &= t_{\text{coll}} \frac{\rho c^2}{u_T} \quad \text{e.g., Mertsch11}\end{aligned}$$

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

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

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

e.g., Mertsch11

Alfven velocity $\Leftrightarrow$ Plasma density

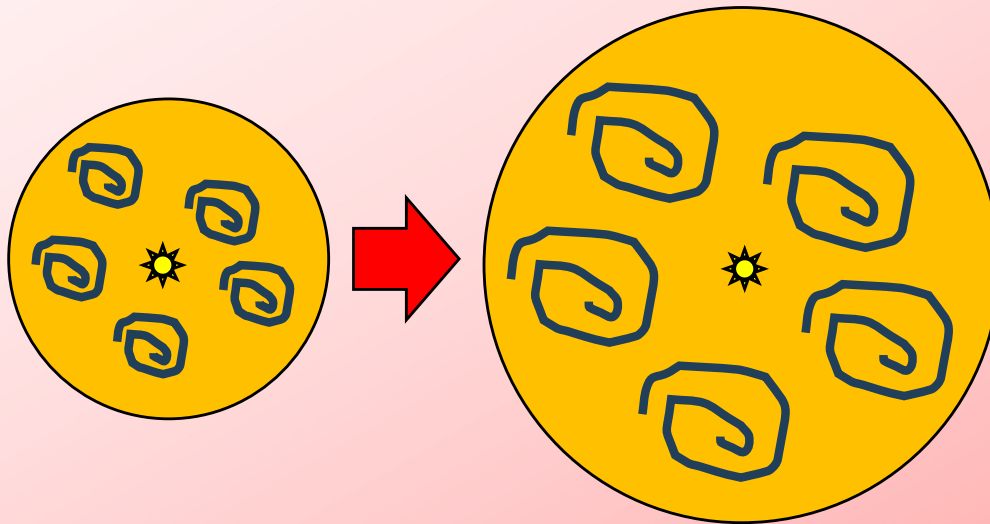
Evolution of Turbulence

$$\frac{dE_T}{dt} = \eta_T L_{\text{spin}} - \frac{E_T}{t_{\text{adi}}(t)} - \left(\frac{\delta E_T}{\delta t} \right)_{\text{damp}}$$

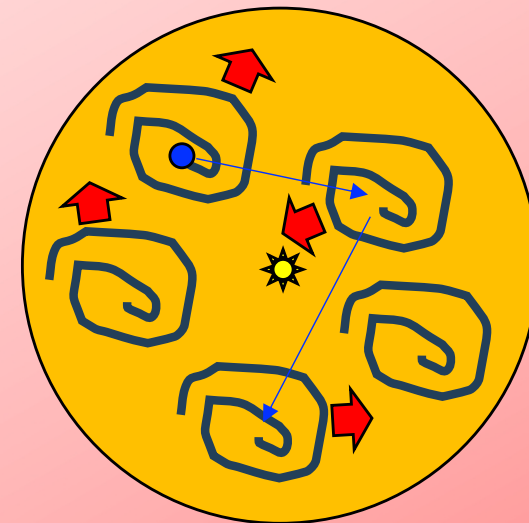
$$\eta_T \sim 0.5$$

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

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



Adiabatic expansion



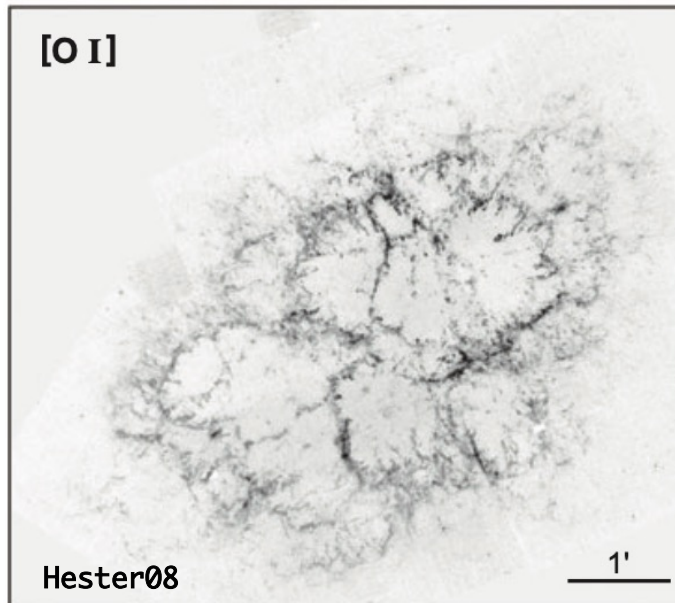
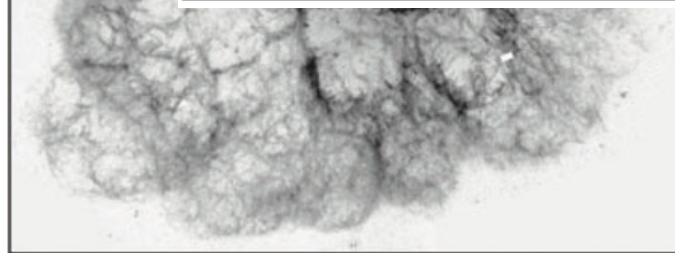
Backreaction

Injection from Ejecta Filaments

Table 4
Gas-phase Elemental Ion Fractions for the Best-fit Clumpy Model v1

Owen&Barlow15

[O III]	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}



Hester08

Photoionization of neutrals in filaments

$d \sim 0.1 \text{ pc}$

$(n_{\text{fil}}, T_{\text{fil}}) \sim (10^3 \text{ cm}^{-3}, 10^3 \text{ K})$
Graham+90

$$\dot{N}_{\text{fil}} \lesssim \pi d l c_s n_{\text{fil}}$$

$$\approx 10^{46} \text{ s}^{-1}$$

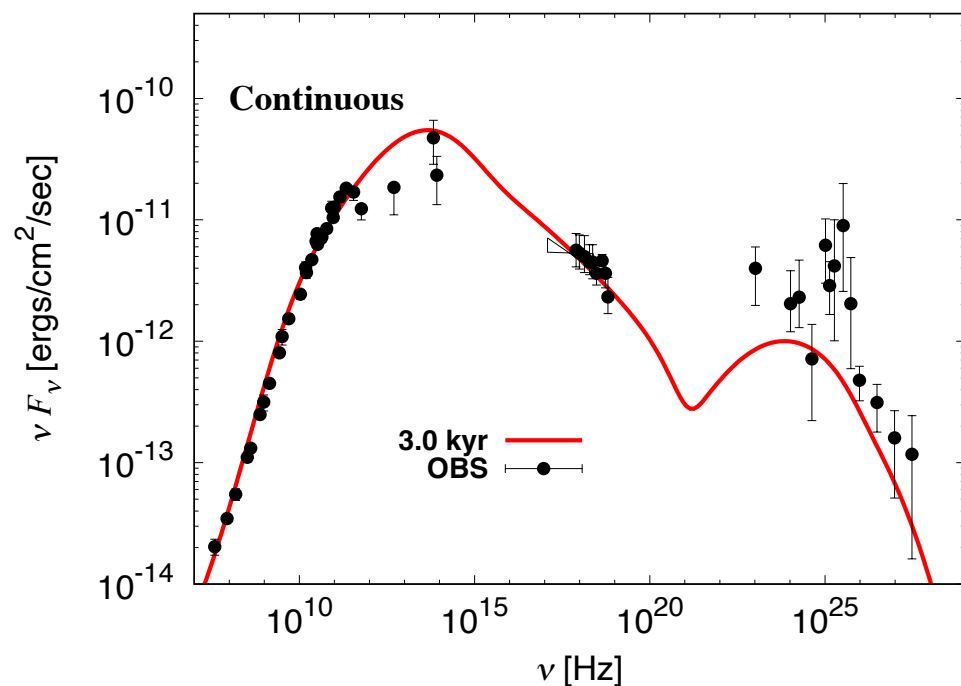
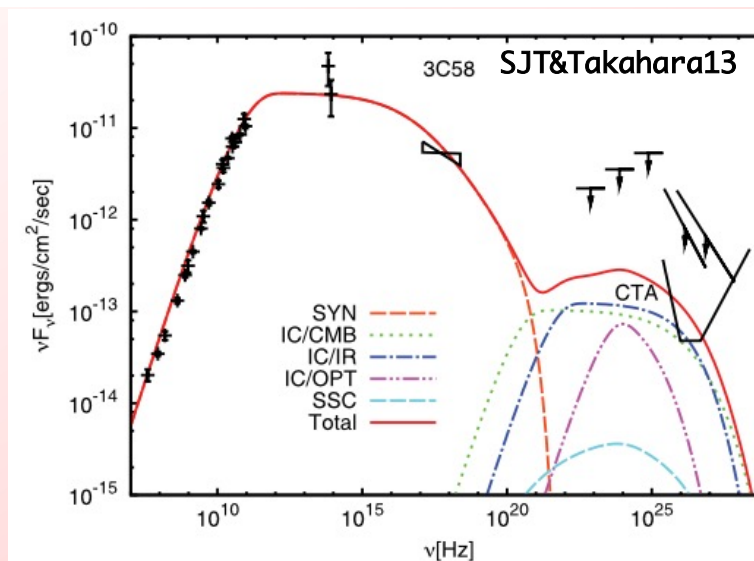
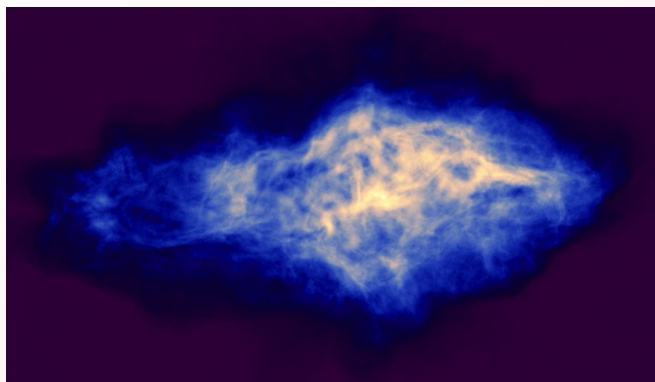
$l \sim 3 \text{ pc}$

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

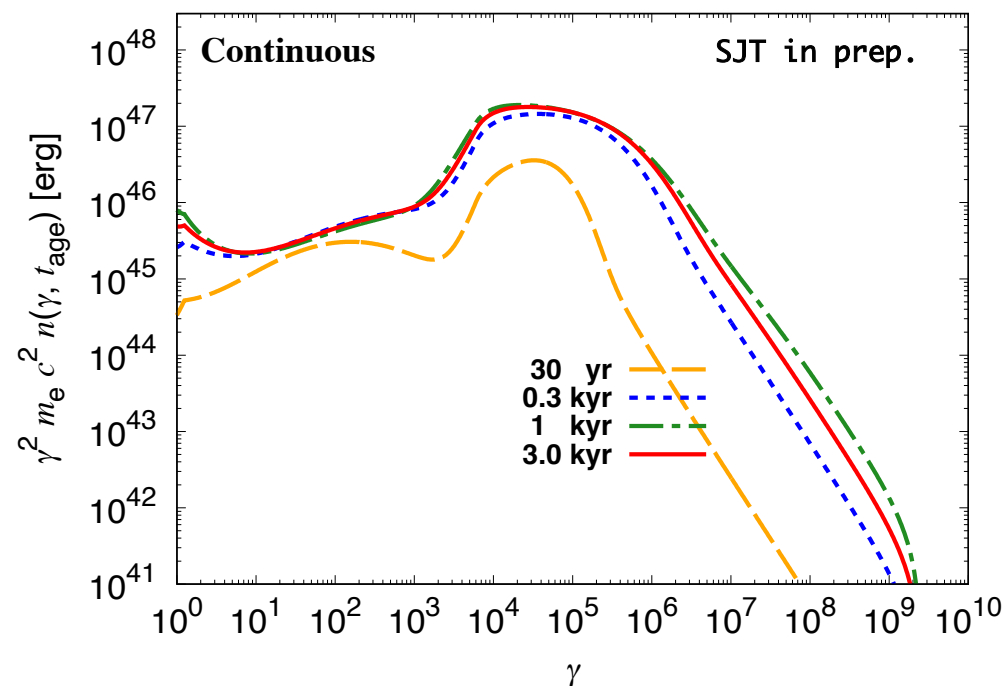
c.f. $\dot{N}_{\text{GJ}} \approx 10^{34} \text{ s}^{-1} L_{\text{spin},38}^{1/2}$

Results

Results: 3C 58

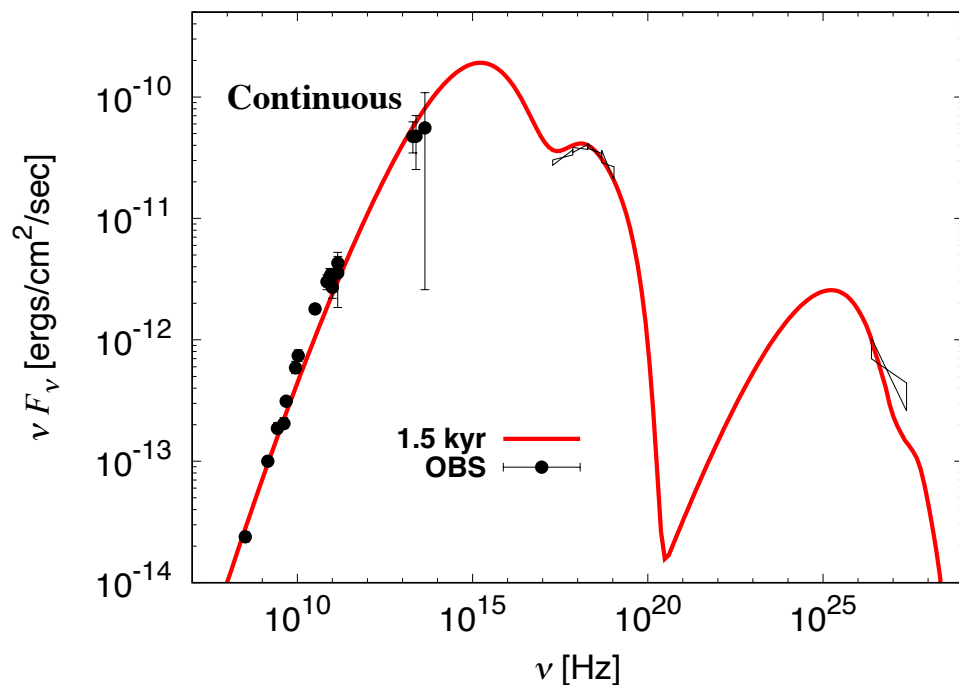
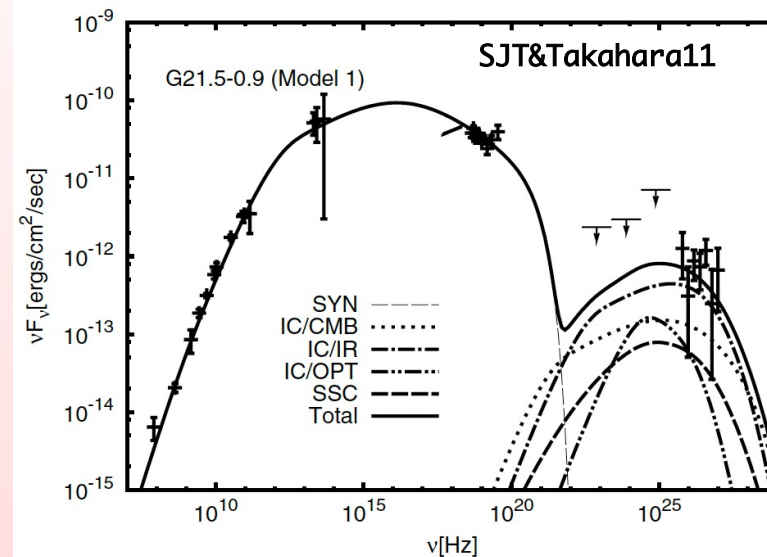
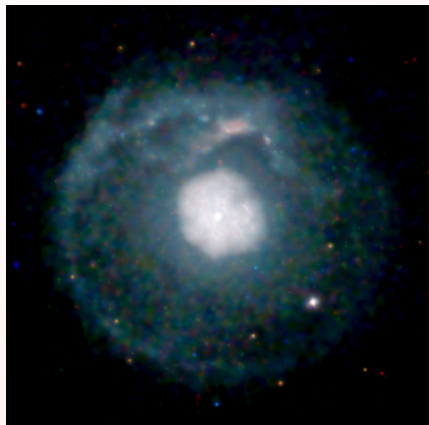


Photon
Spectrum

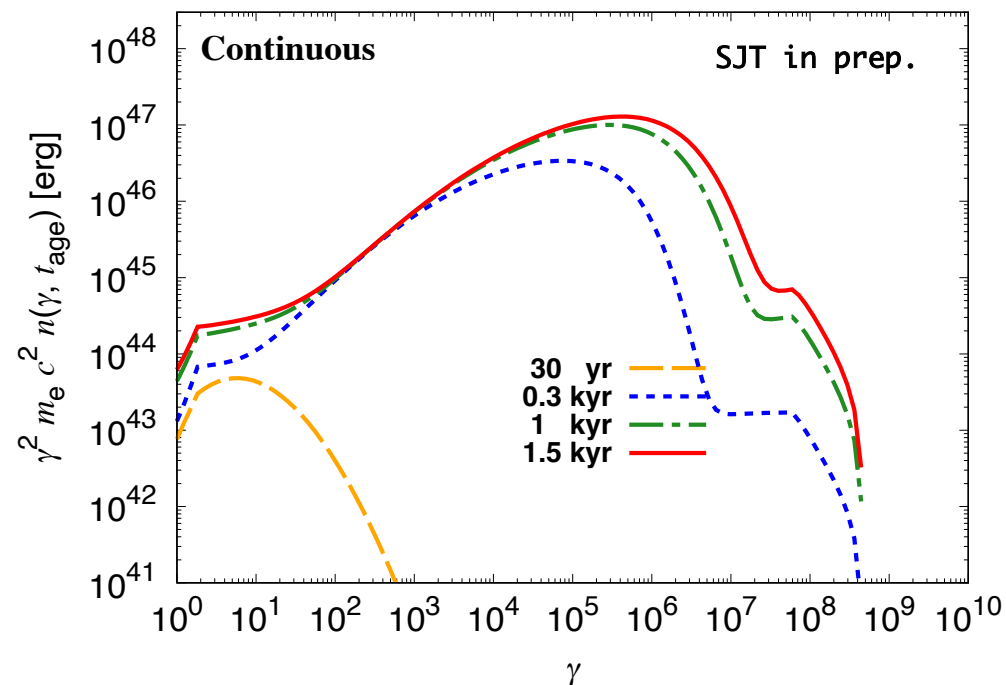


Electron
Spectrum

Results: G21.5-0.9



Photon
Spectrum



Electron
Spectrum

Conclusions

Applying stochastic accel. model to young PWNe

- **Stochastic acceleration model resolves the κ -problem of PWNe.**
- **Different radio spectral indices can be explained by stochastic acceleration model.**
- **Time-scales and electron injection rates for stochastic acceleration can be similar values.**