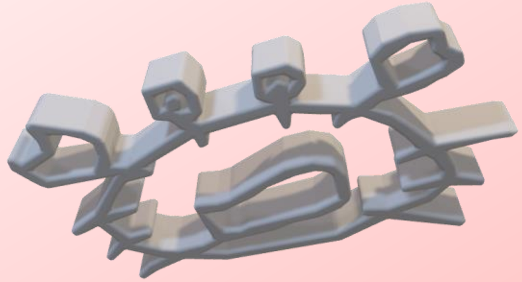
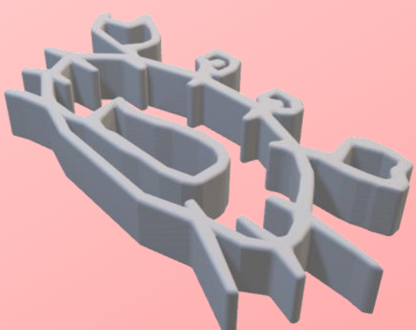
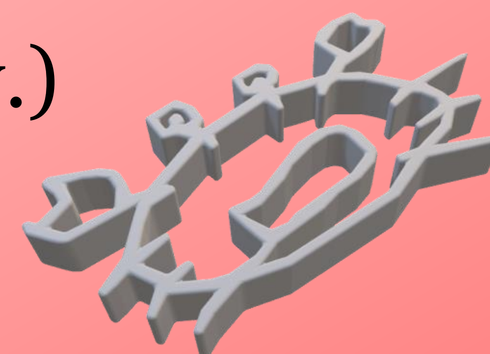
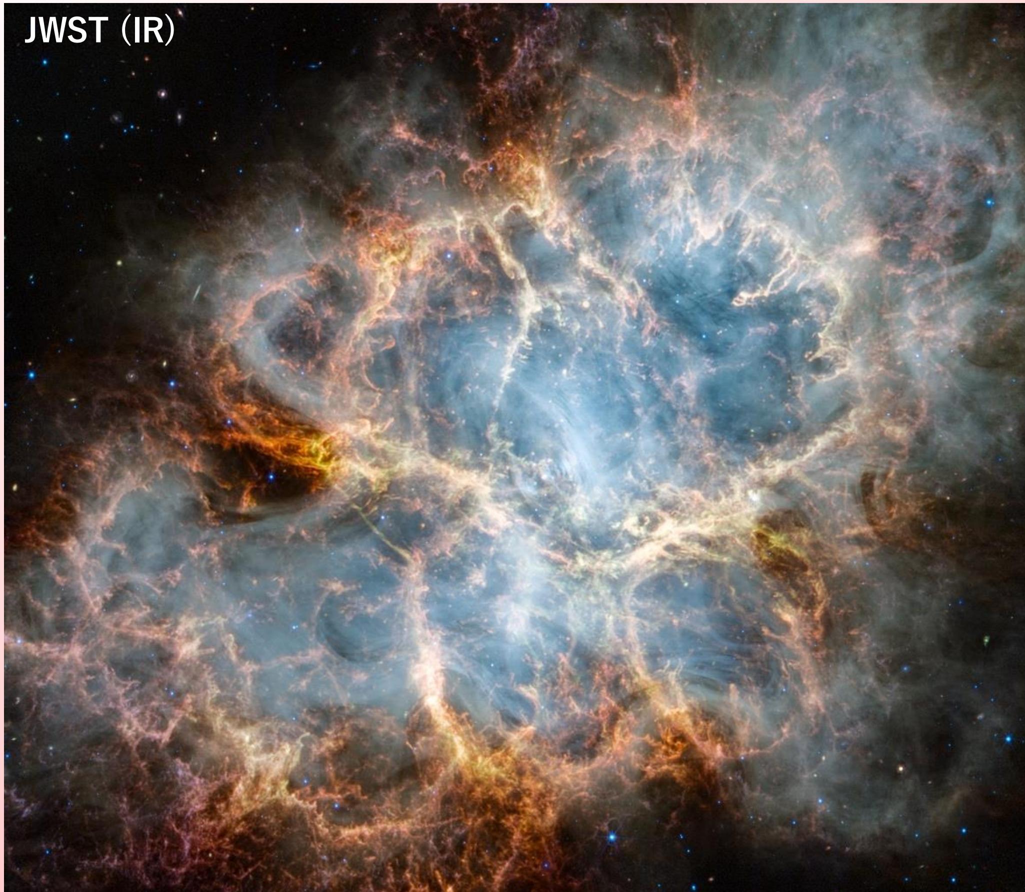


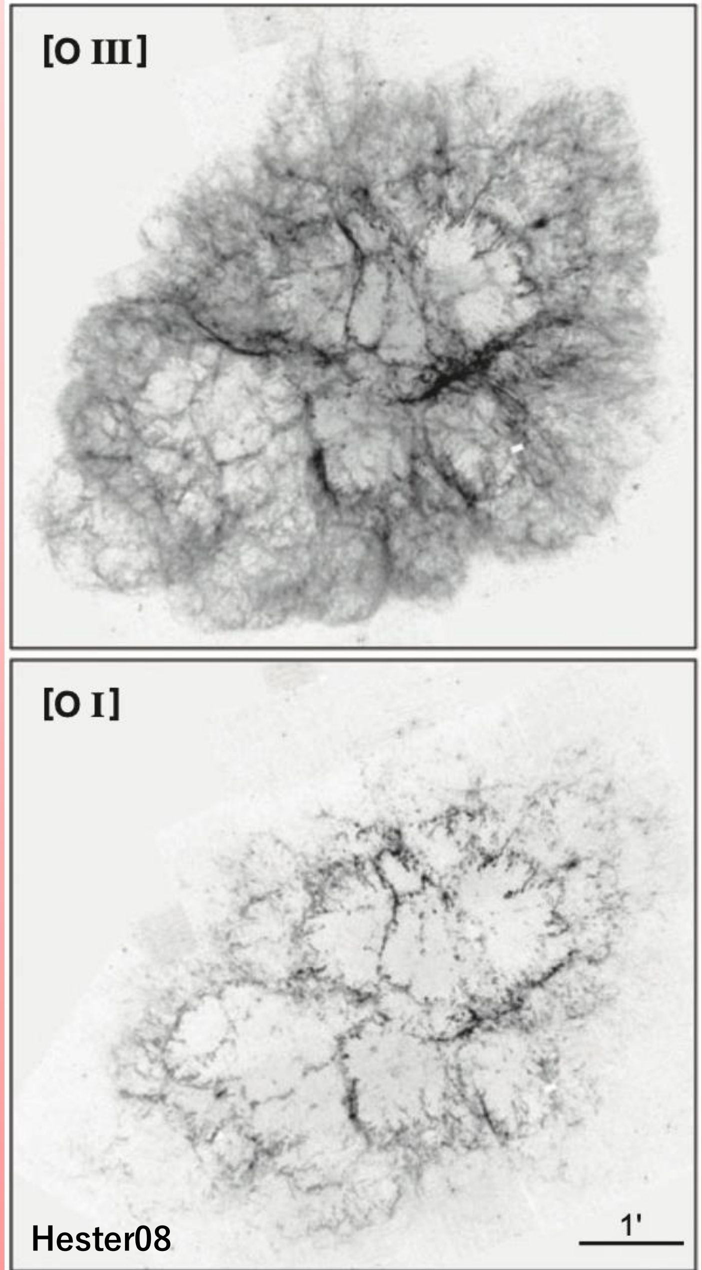
Testing a Stochastic Acceleration Model of Pulsar Wind Nebulae: High-Energy Neutrinos from the Crab Nebula

Shuta J. Tanaka
(Aoyama Gakuin Univ.)
with
Wataru Ishizaki

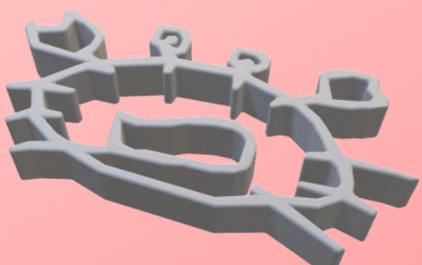


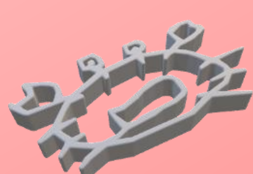


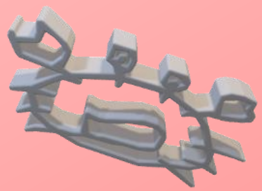




Introduction

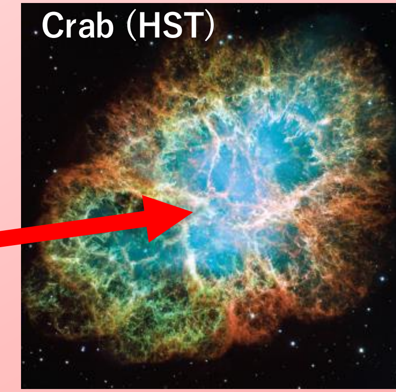






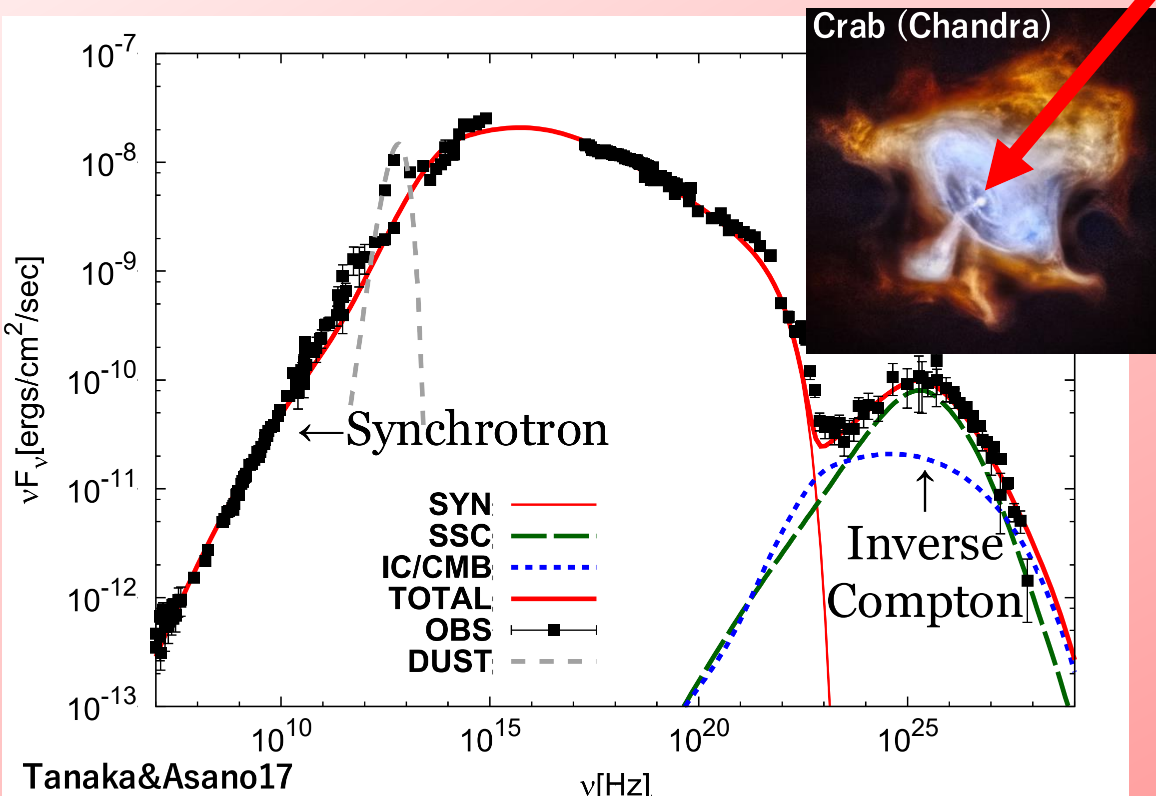
PWN as Particle Accelerator

pulsar wind nebula



Crab Pulsar

Broadband spectrum from sub-μeV through PeV



- PeV photons from the Crab

LHAASO Collab. 21 Sci

Particle accelerator > PeV

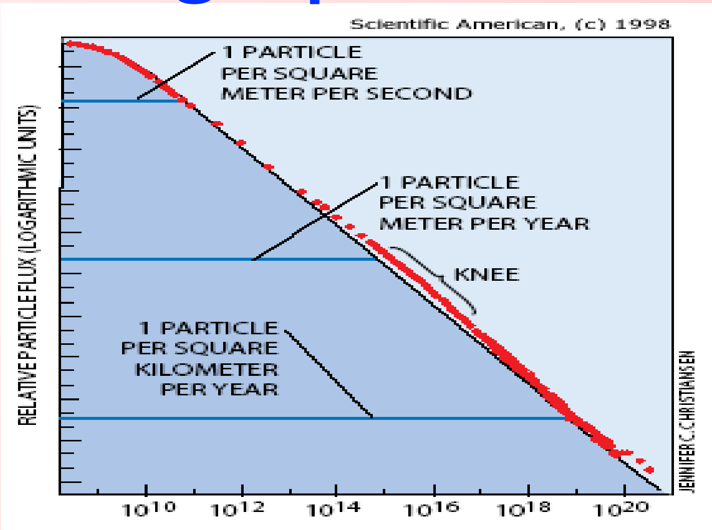
- Optical peak ← synchrotron from TeV particles.

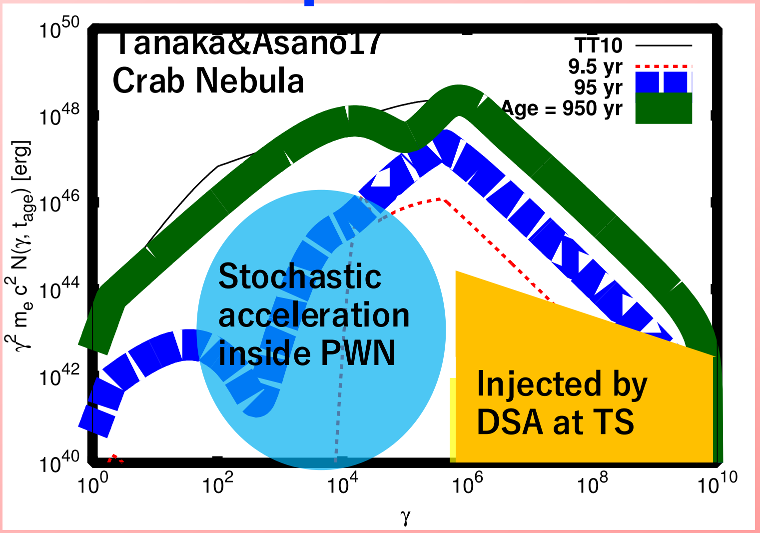
Relativistic (T_{PWN}~TeV) and rarefied (n_{PWN}< 10^{-6} cm^{-3}) magnetized plasma cloud

Closest relativistic object

Origin of Radio Emission

single power-law vs. broken power-law





Particle distribution in Crab Nebula is
- Not single power-law
- Harder than DSA prediction at low-energy
- Dominant in number at low-energy (κ-problem) c.f. Timokhin&Harding15,18

Two different accel. mechanisms.

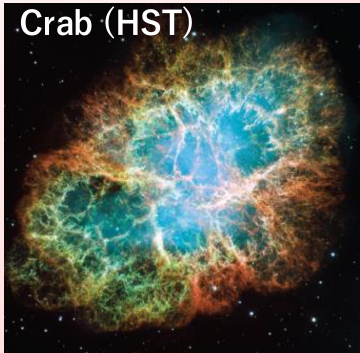
+

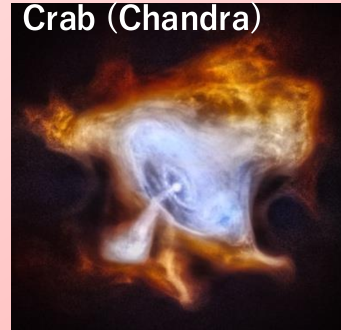
Particles supply other than pulsar

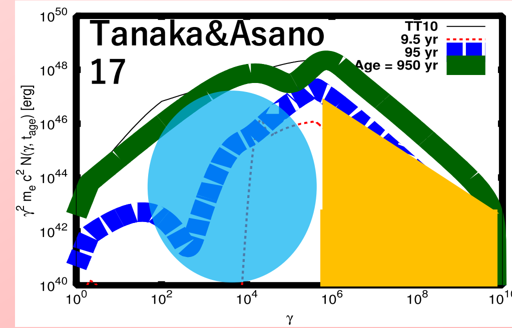
Tanaka&Asano 17

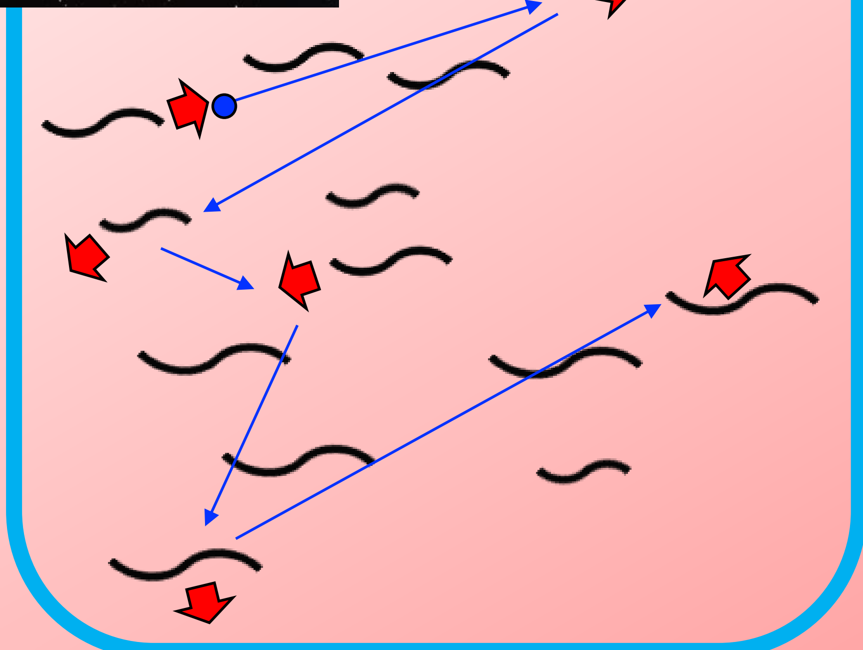
Model

Two Accel. Mechanism

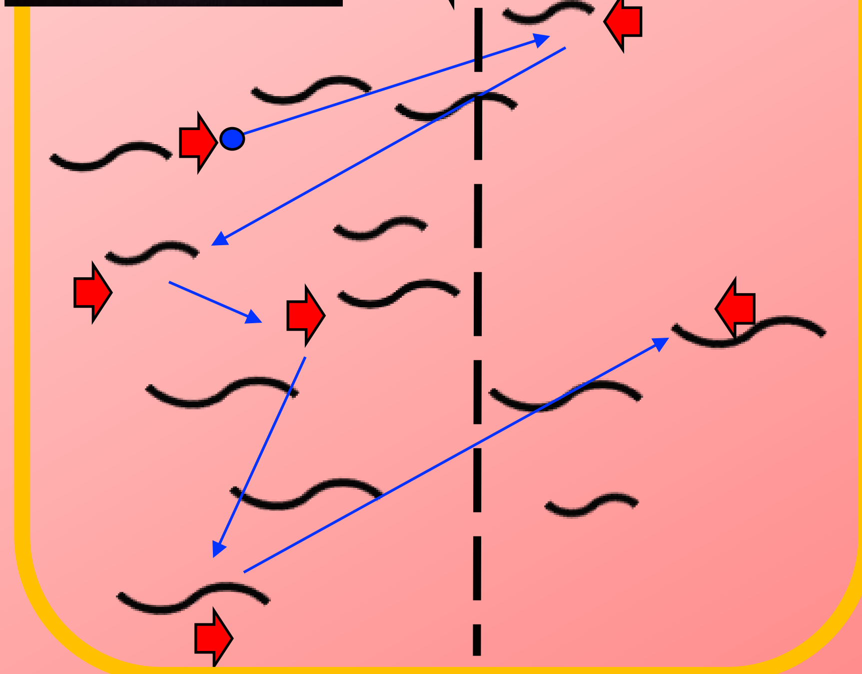








Stochastic Acceleration
by random waves (turbulence)
2nd order Fermi Acceleration



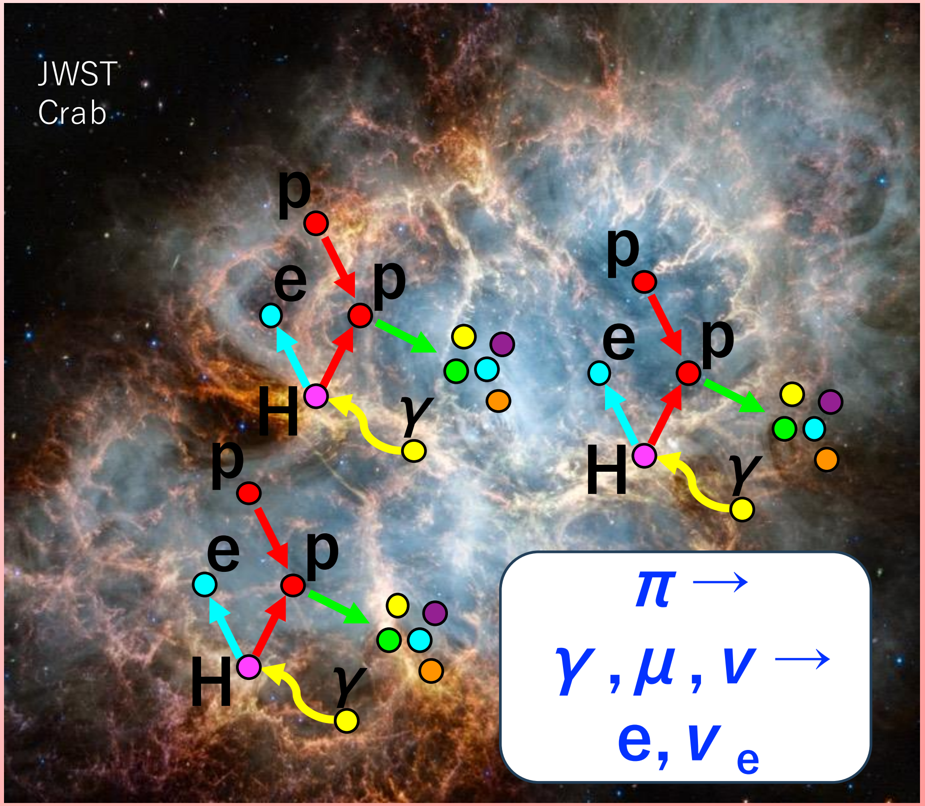
Diffusive Shock Acceleration
by conversing flow (shock)
1st order Fermi Acceleration

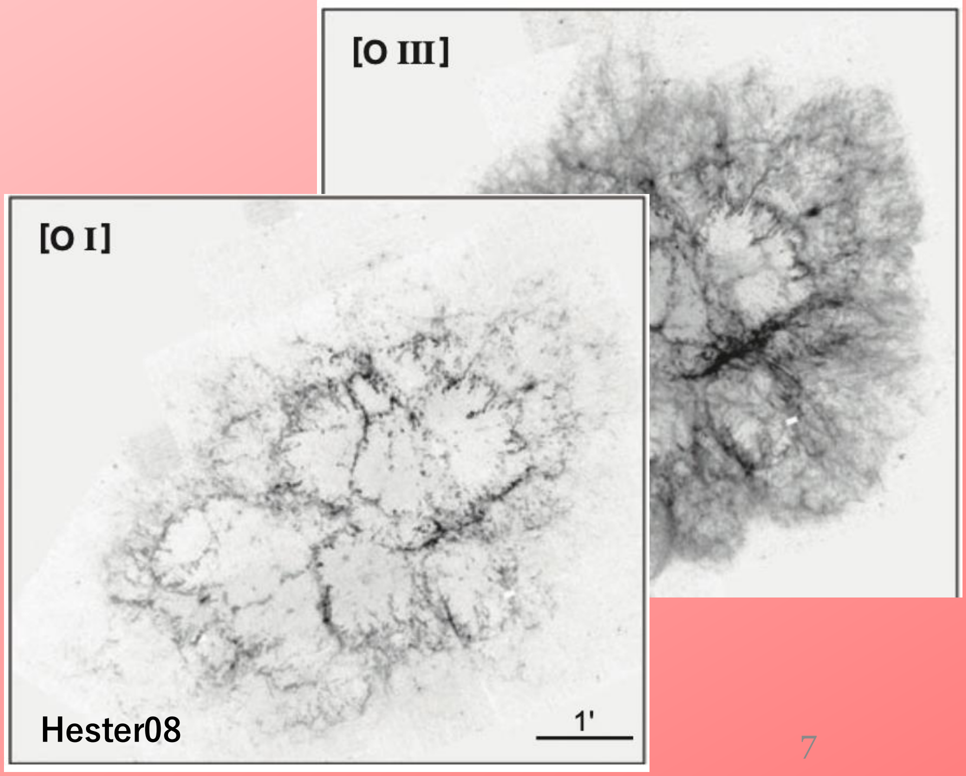
Injection from Ejecta Filaments

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}

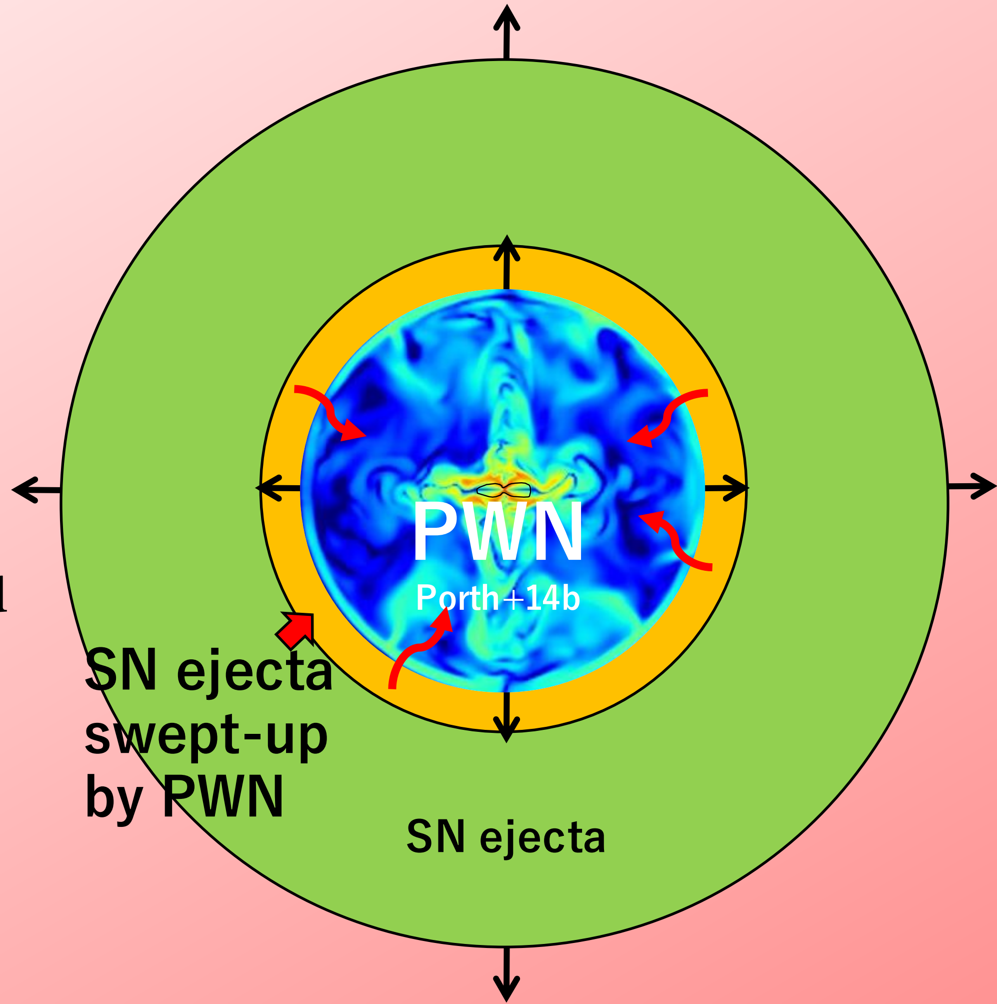




One-zone Model

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&Kashiya

Stochastic Acceleration

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

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

- τ_{acc}: initial acceleration time
- t_{acc}: accel. time increases with decaying of turbulence
- $E_T(t)$: energy of turbulence

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

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

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

Injection of hadrons!!

Neutrino Emission

$$t_{pp} = \frac{1}{\xi_{pp} n \sigma_{pp} c} \approx 10^7 \mathrm{yr} \left(\underline{\frac{n}{10\mathrm{cm}^{-3}}}\right)^{-1} \left(\frac{\xi_{pp}}{0.2}\right)^{-1}$$

target hadrons

inelasticity

$$n_{\rm ej} = 0.74\ \mathrm{cm}^{-3} \left(\frac{M_{\rm ej}}{9.5 M_\odot}\right) \left(\frac{R_{\rm SNR}}{5\mathrm{pc}}\right)^{-3}$$

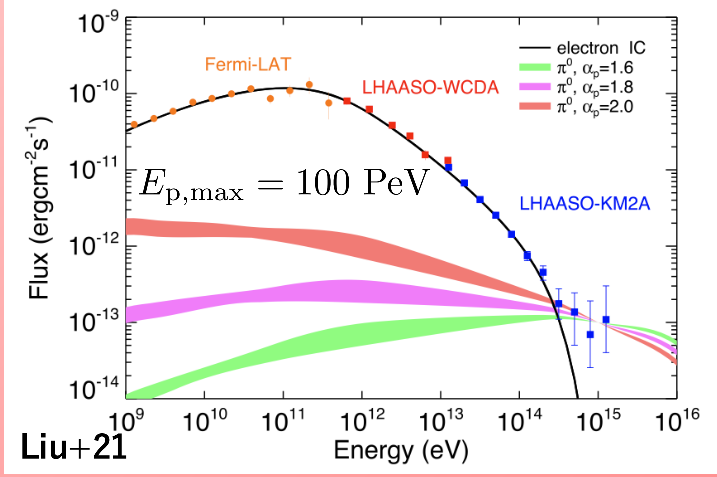
ejecta of SN 1054 condensate as filaments inside the Crab.

Owen&Barlow15

$$n_{\rm ej} = 17.2\ \mathrm{cm}^{-3} \left(\frac{M_{\rm ej}}{7.2 M_\odot}\right) \left(\frac{R_{\rm SNR}}{1.6\mathrm{pc}}\right)^{-3}$$

$$\epsilon_\nu^2 \frac{dN_\nu}{dt} \approx \gamma^2 m_{\rm e} c^2 \frac{dN_{\rm e}}{d\gamma} \frac{1}{t_{pp}} \bigg|_{\epsilon_\nu = 0.1 \gamma m_{\rm e} c^2}$$

Past studies (PSR injection)



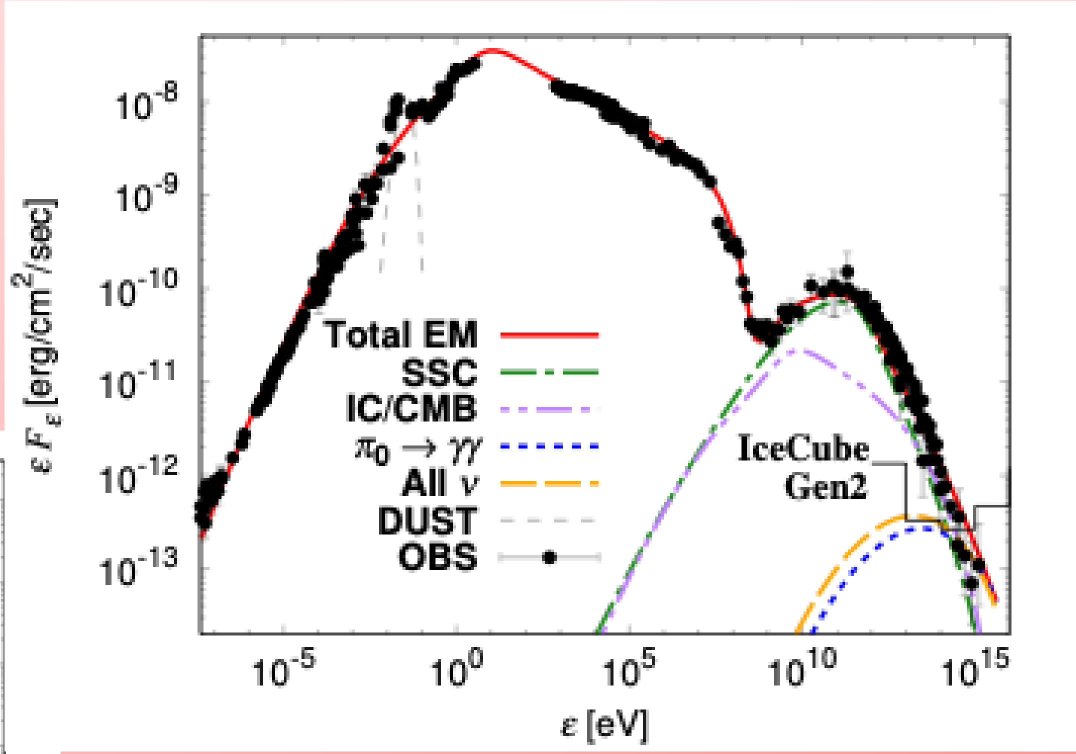
$$\frac{dN_p}{dE_p} = N_0 E_p^{\alpha_p} \exp\left(-\frac{E_p}{E_{p,\max}}\right)$$

$$\int E_p \frac{dN_p}{dE_p} dE_p = \eta_p \int dt L(t)$$

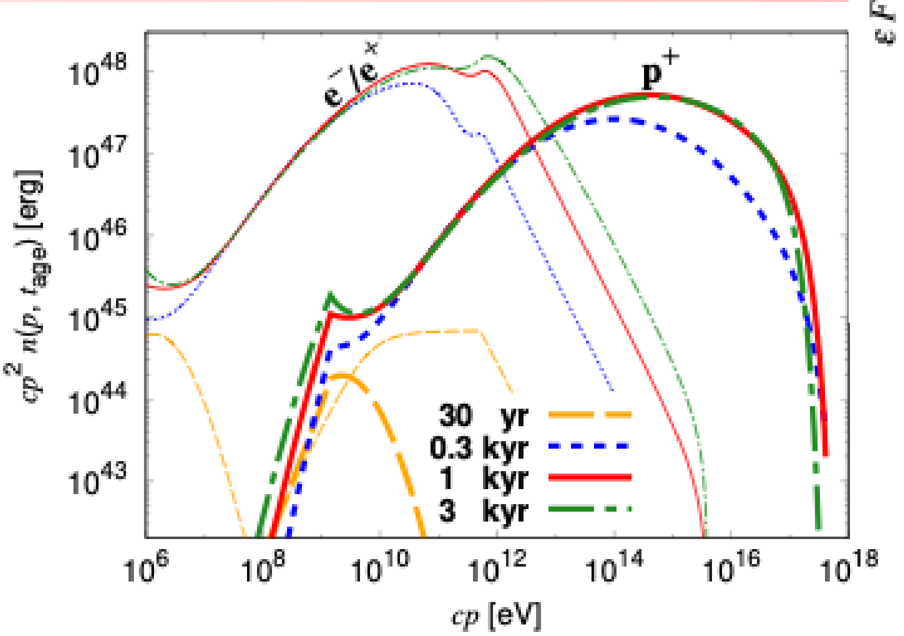
η_p ~ 20 %

Results

Results: Broadband Spectrum



Electron Energy Spectrum↓



Tanaka&Ishizaki in prep.

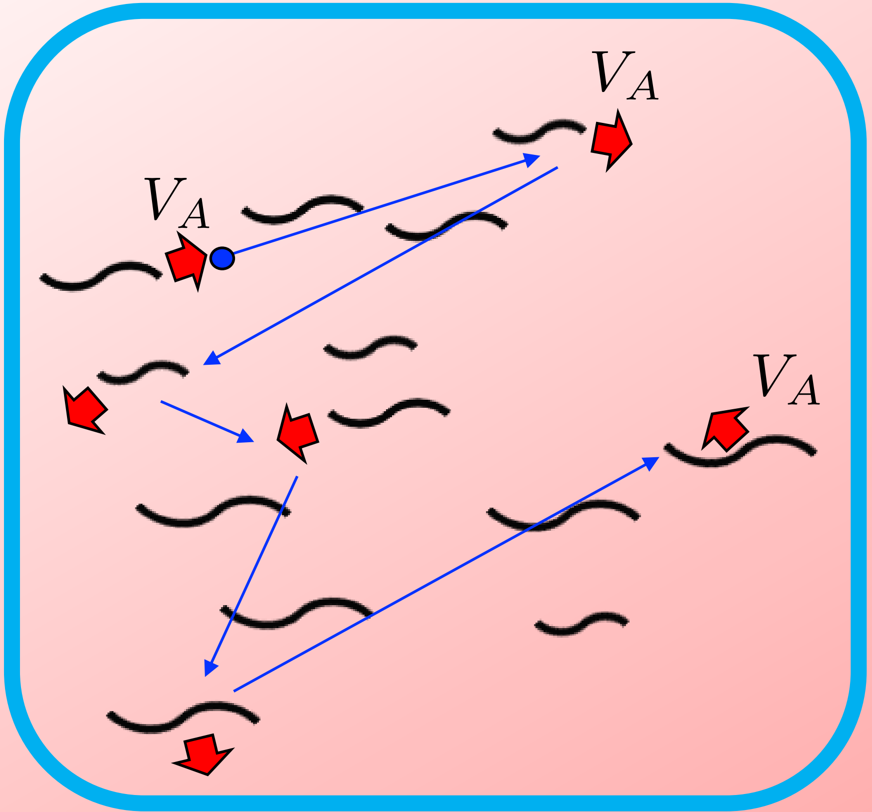
$$\frac{\partial}{\partial t}N(\gamma,t)+\frac{\partial}{\partial\gamma}\left[\left(\dot{\gamma}_{\rm cool}(\gamma,t)-\gamma^2 D_{\gamma\gamma}(\gamma,t)\frac{\partial}{\partial\gamma}\frac{1}{\gamma^2}\right)N(\gamma,t)\right]=Q_{\rm PSR}(\gamma,t)+Q_{\rm ext}(t)$$

Conclusions

Applying stochastic accel. model to young PWNe

- **Predicts the hadronic ν and γ from PWNe for the test of our turbulent acceleration and particle injection model.**
- **Stochastic acceleration model resolves the *κ*-problem of PWNe.**
- **Different radio spectral indices for different PWNe can be explained by stochastic acceleration model.**

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

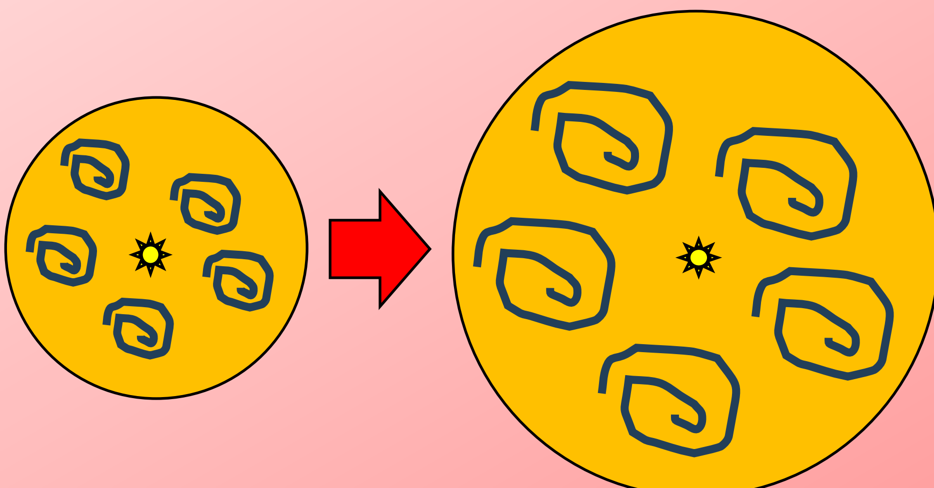
Evolution of Turbulence

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

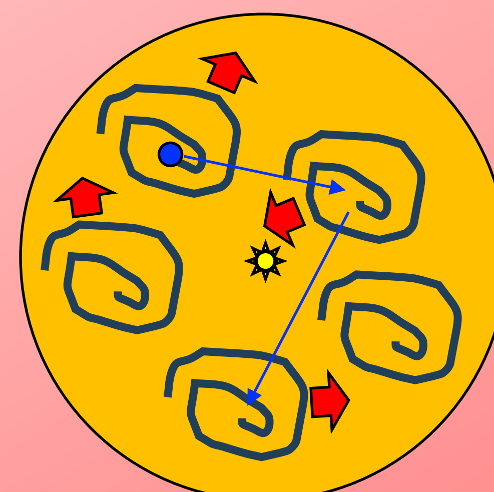
$$\eta_{\mathrm{T}} \sim 0.5$$

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