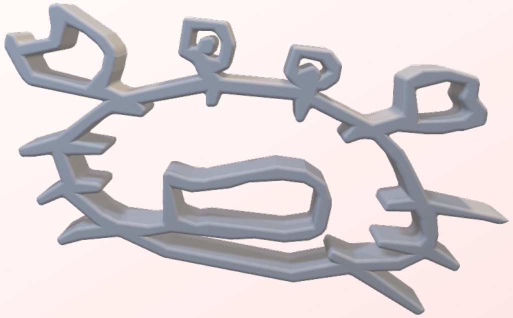

A Self-regulating Stochastic Acceleration Model of Pulsar Wind Nebulae

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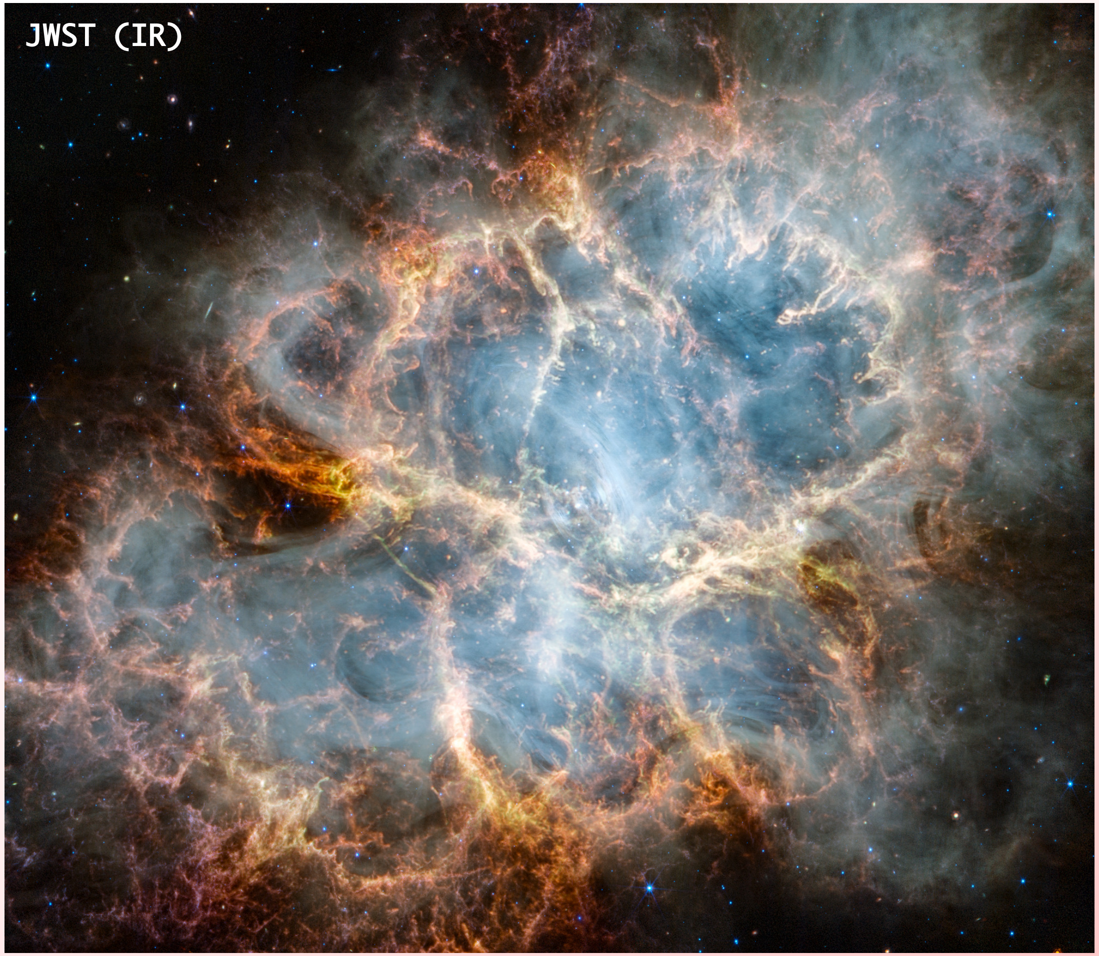
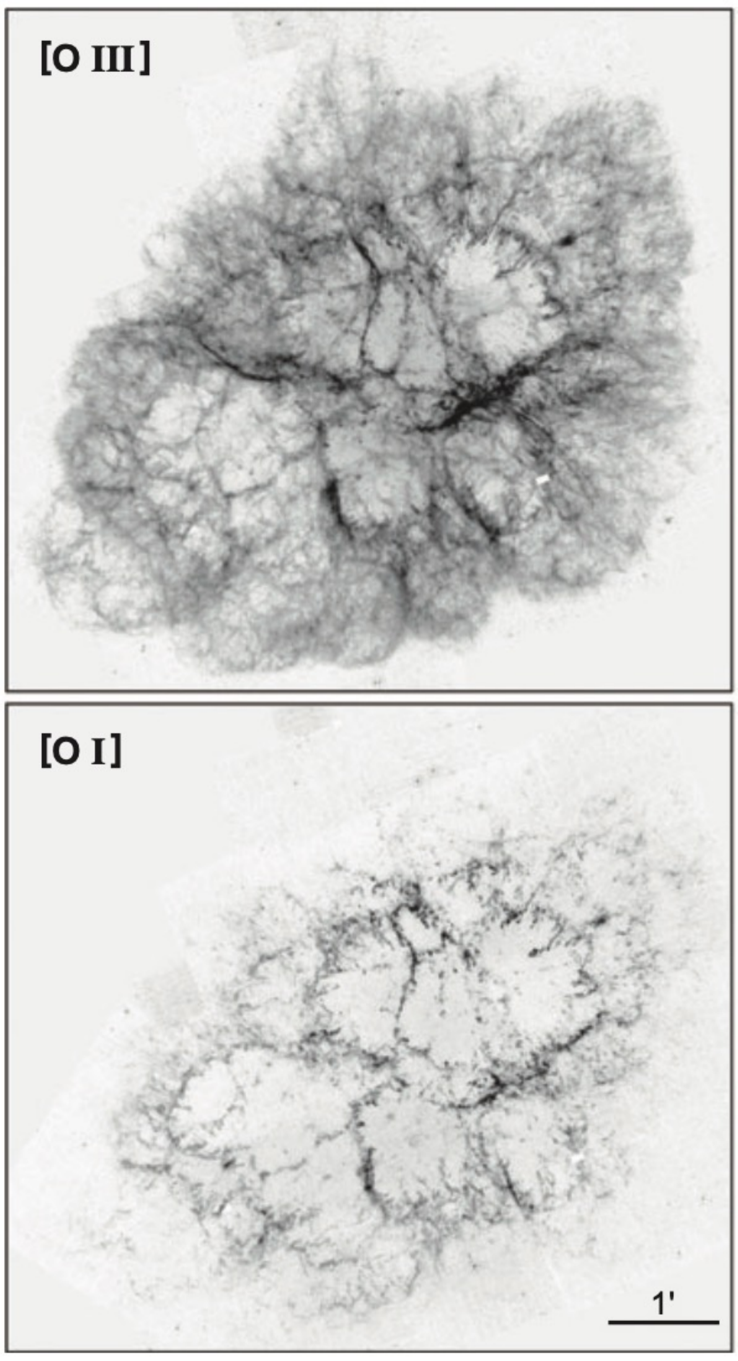
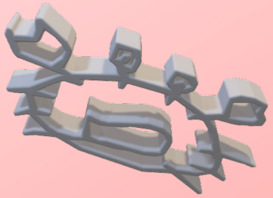
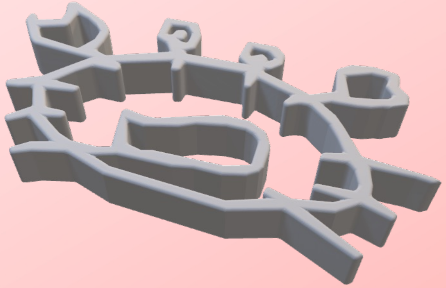
with Wataru Ishizaki

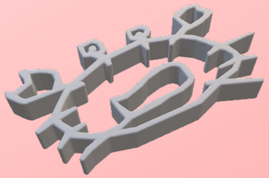




Introduction

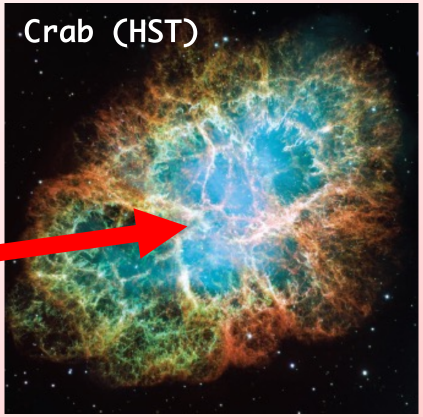






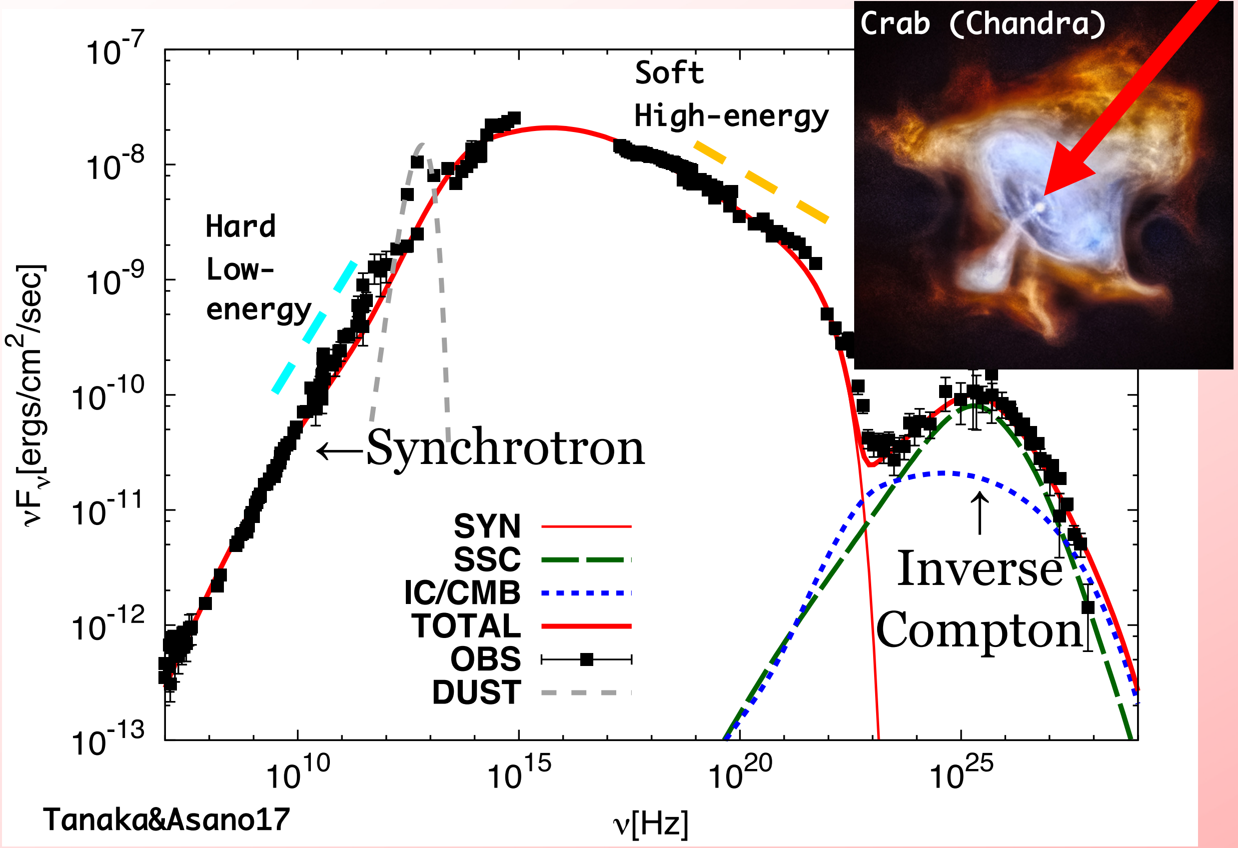
PWN as Particle Accelerator

pulsar wind nebula



Crab Pulsar

Broadband spectrum from sub-μeV through PeV



Tanaka&Asano17

- PeV photons from the Crab

`LHAASO Collab. 21 Sci`

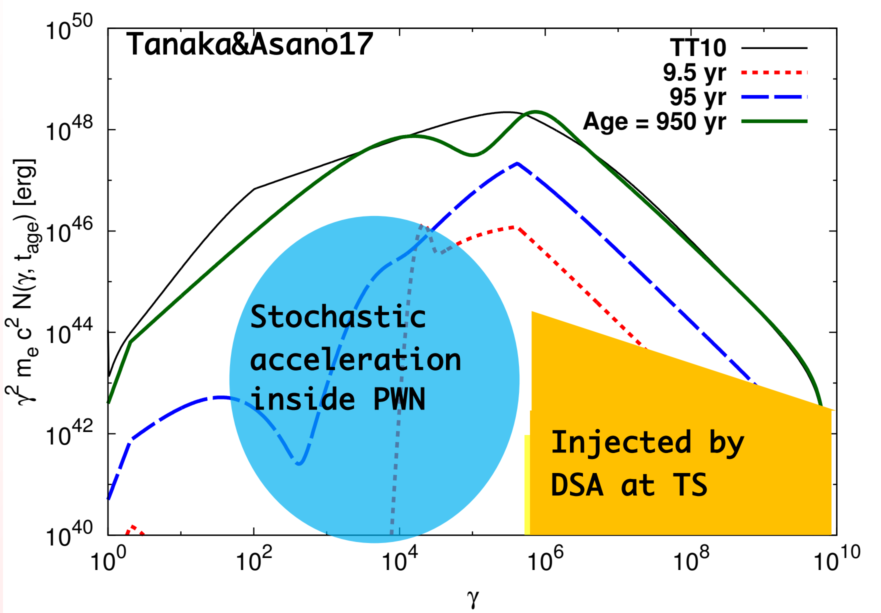
Particle accelerator > PeV

- Optical peak ← synchrotron from TeV particles.

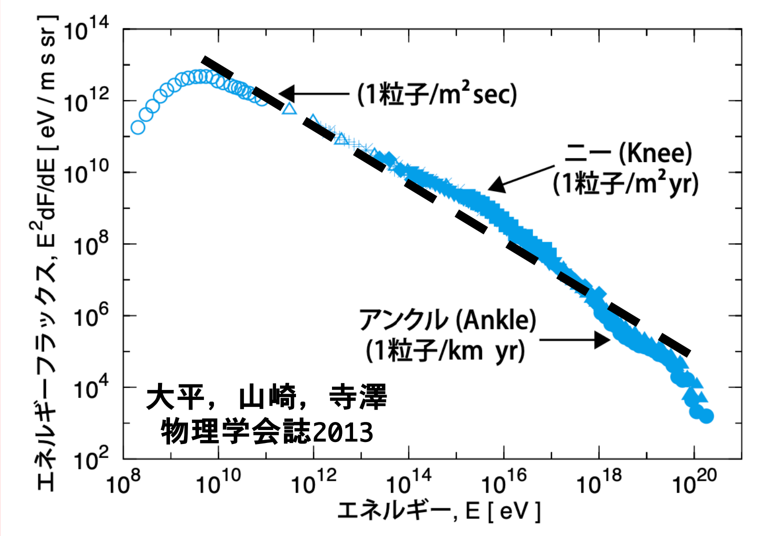
Relativistic (T_{PWN}~TeV) and rarefied ($n_{\mathrm{PWN}} < 10^{-6}$ cm^{-3}) magnetized plasma cloud

Closest relativistic object

Origin of Radio Emission



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)

c.f. Timokhin&Harding15,18

our stochastic accel. model Tanaka&Asano17

Two different accel. mechanisms.

+

Paticles supplied from outside PWNe

Injection from Ejecta Filaments

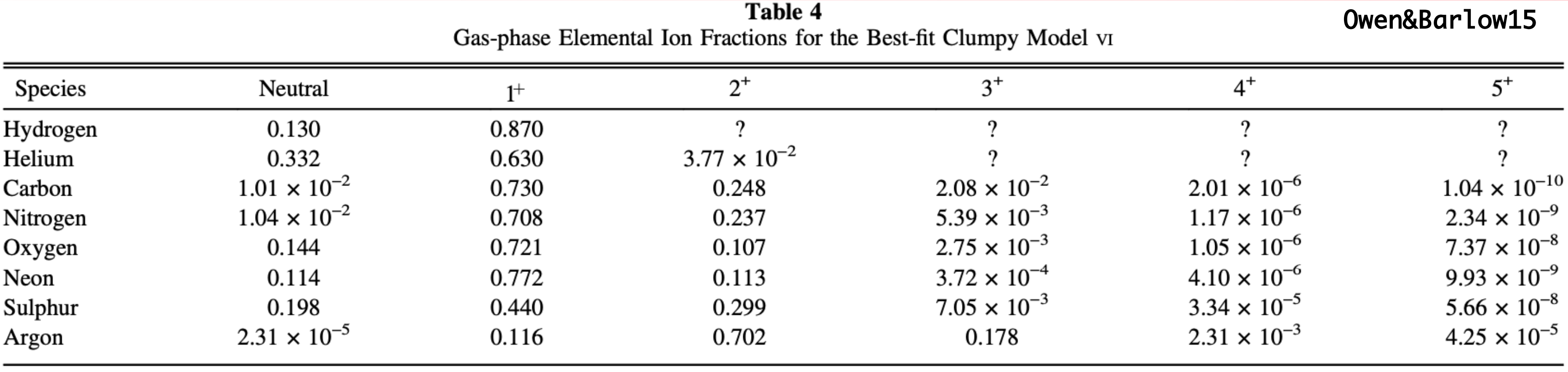
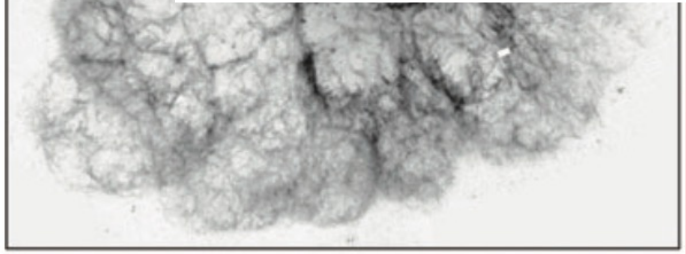


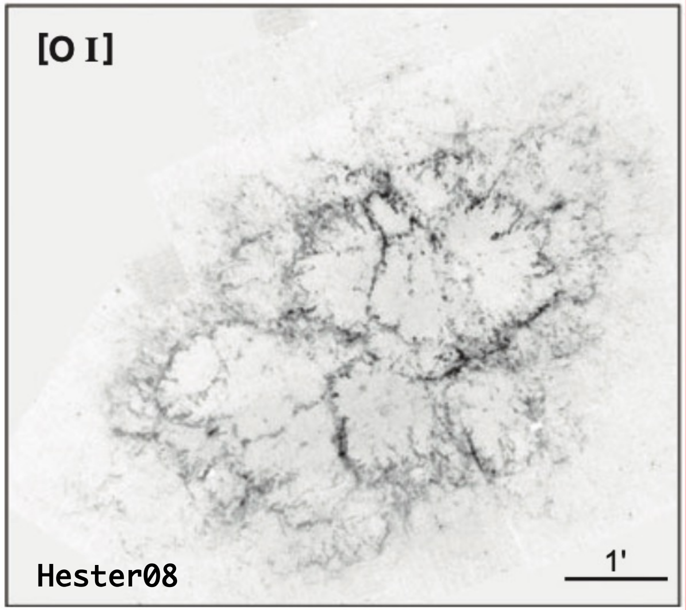
Table 4

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

Owen&Barlow15

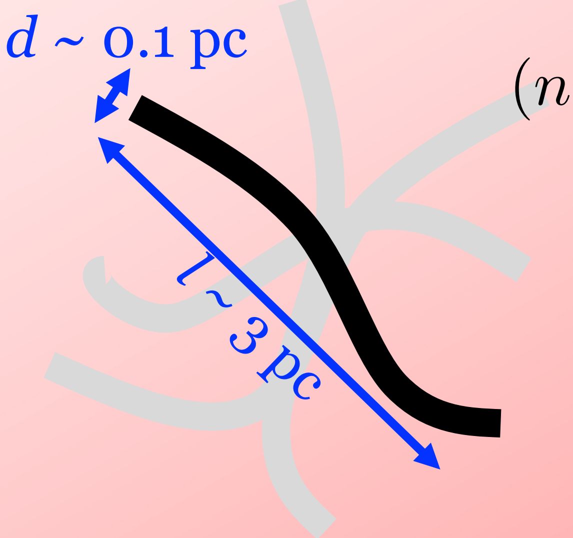
Species	Neutral	1^+	2^+	3^+	4^+	5^+
Hydrogen	0.130	0.870	?	?	?	?
Helium	0.332	0.630	3.77×10^{-2}	?	?	?
Carbon	1.01×10^{-2}	0.730	0.248	2.08×10^{-2}	2.01×10^{-6}	1.04×10^{-10}
Nitrogen	1.04×10^{-2}	0.708	0.237	5.39×10^{-3}	1.17×10^{-6}	2.34×10^{-9}
Oxygen	0.144	0.721	0.107	2.75×10^{-3}	1.05×10^{-6}	7.37×10^{-8}
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}





Hester08

Photoionization of neutrals in filaments



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

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

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

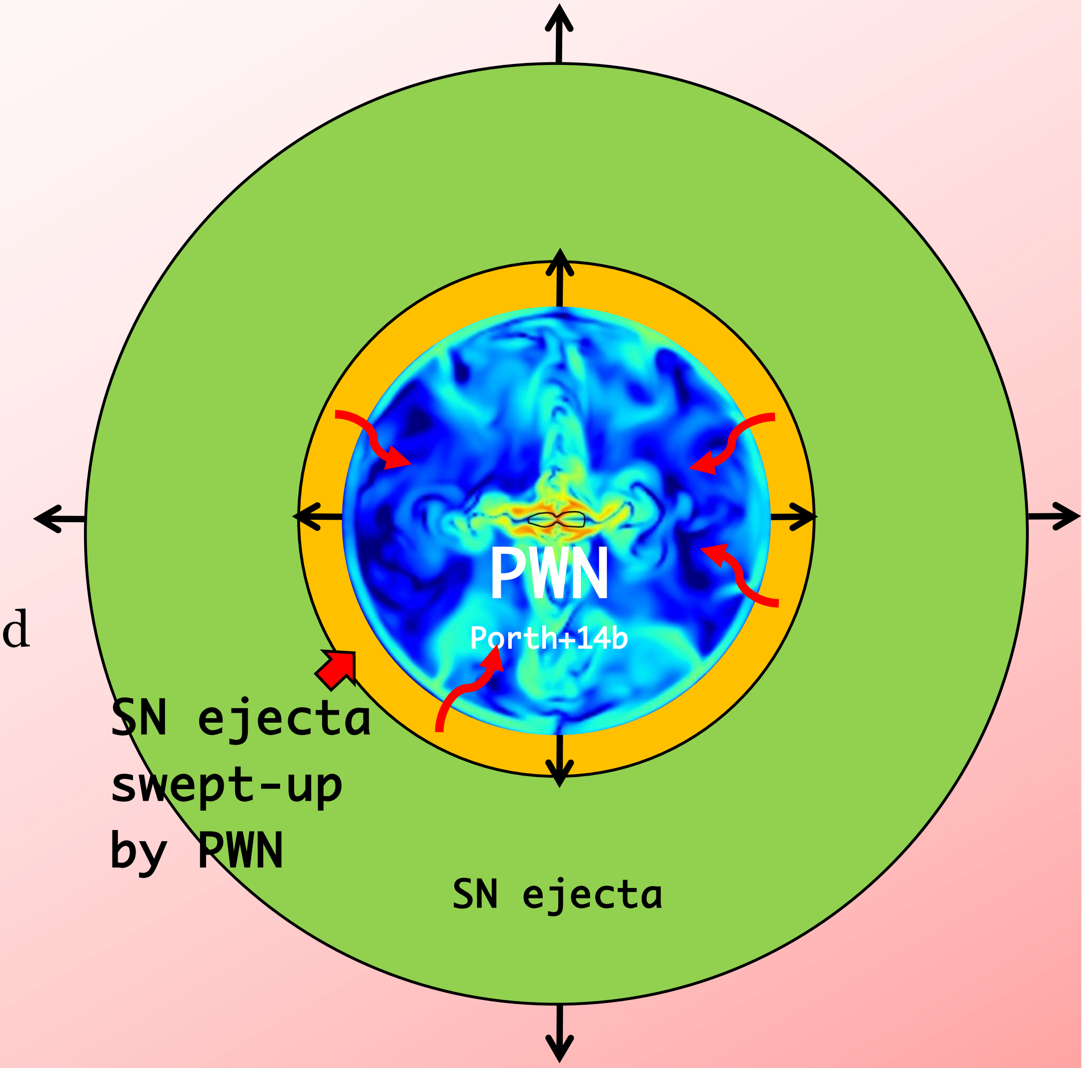
c.f. $\dot{N}_{\rm GJ} \approx 10^{34}~{\rm s}^{-1} L_{\rm spin,38}^{1/2}$

Model

Energetics

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

Particle Distribution

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

Tanaka&Ishizaki24

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

- $\tau_{\rm acc}$: initial acceleration time
- $t_{\rm acc}$: accel. time increases with decaying of turbulence

- $E_T(t)$: energy of turbulence

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

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

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

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

⇓

Injection of hadrons!!

Neutrino Emission

$$t_{pp}=\frac{1}{\xi_{pp}n\sigma_{pp}c}\approx 10^7\mathrm{yr}\underbrace{\left(\frac{n}{10\mathrm{cm}^{-3}}\right)^{-1}}_{\text{target hadrons}}\underbrace{\left(\frac{\xi_{pp}}{0.2}\right)^{-1}}_{\text{inelasticity}}$$

target hadrons

inelasticity

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

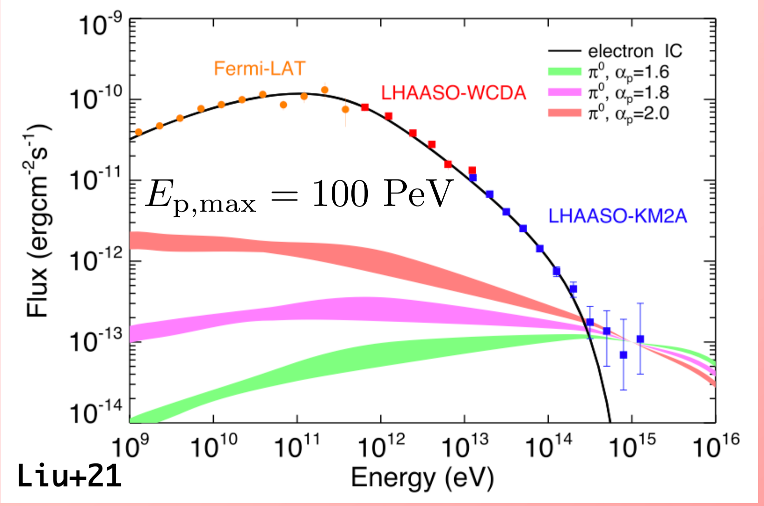
ejecta of SN 1054 condensate as filaments inside the Crab.

Owen&Barlow15

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

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

Past studies (PSR injection)



Liu+21

$$\frac{dN_p}{dE_p}=N_0E_p^{\alpha_p}\exp\left(-\frac{E_p}{E_{p,\max}}\right)$$

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

η_p ~ 20 %

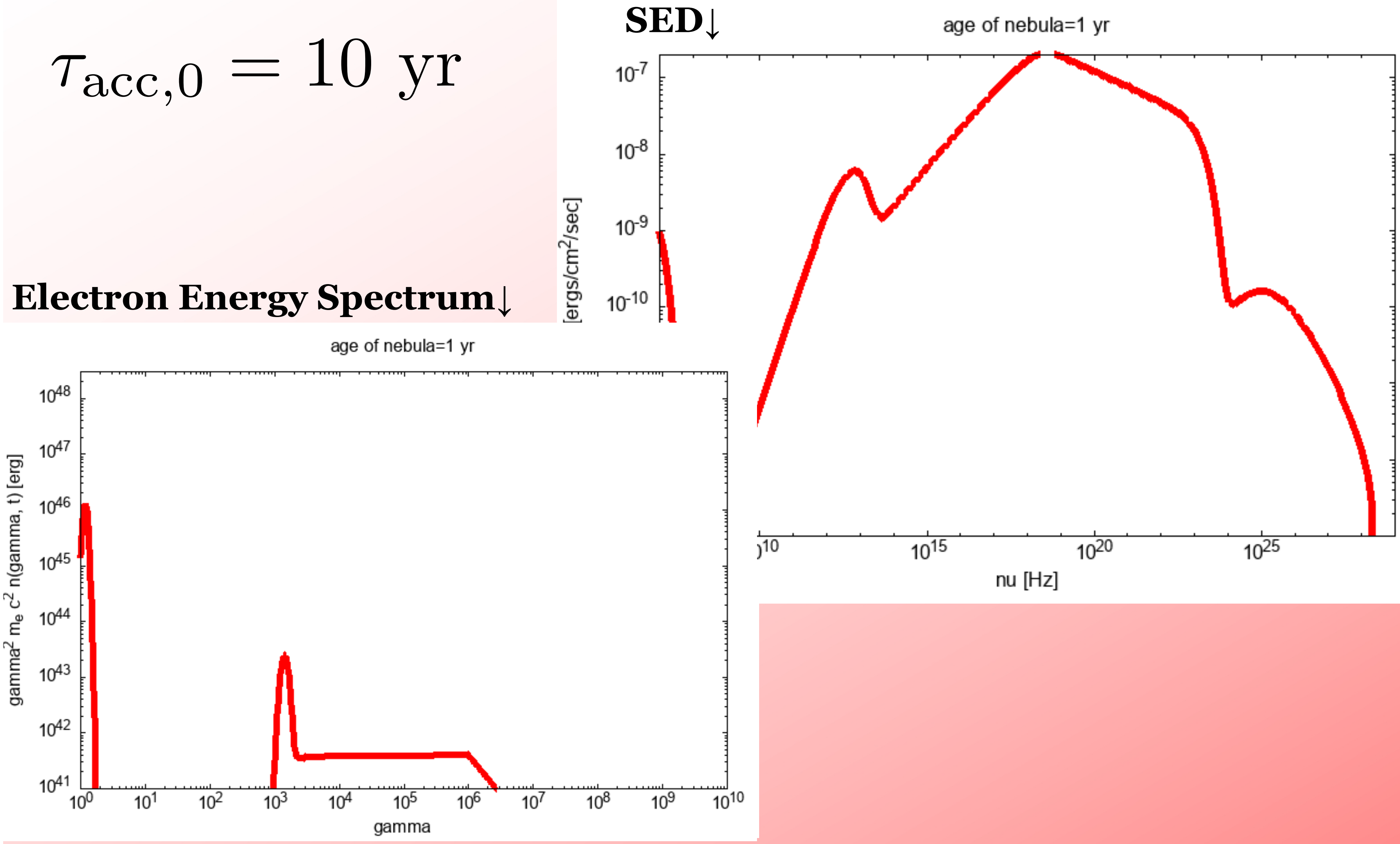
Results

Results: Broadband Spectrum

$$\tau_{\rm acc,0} = 10 \text{ yr}$$

SED↓

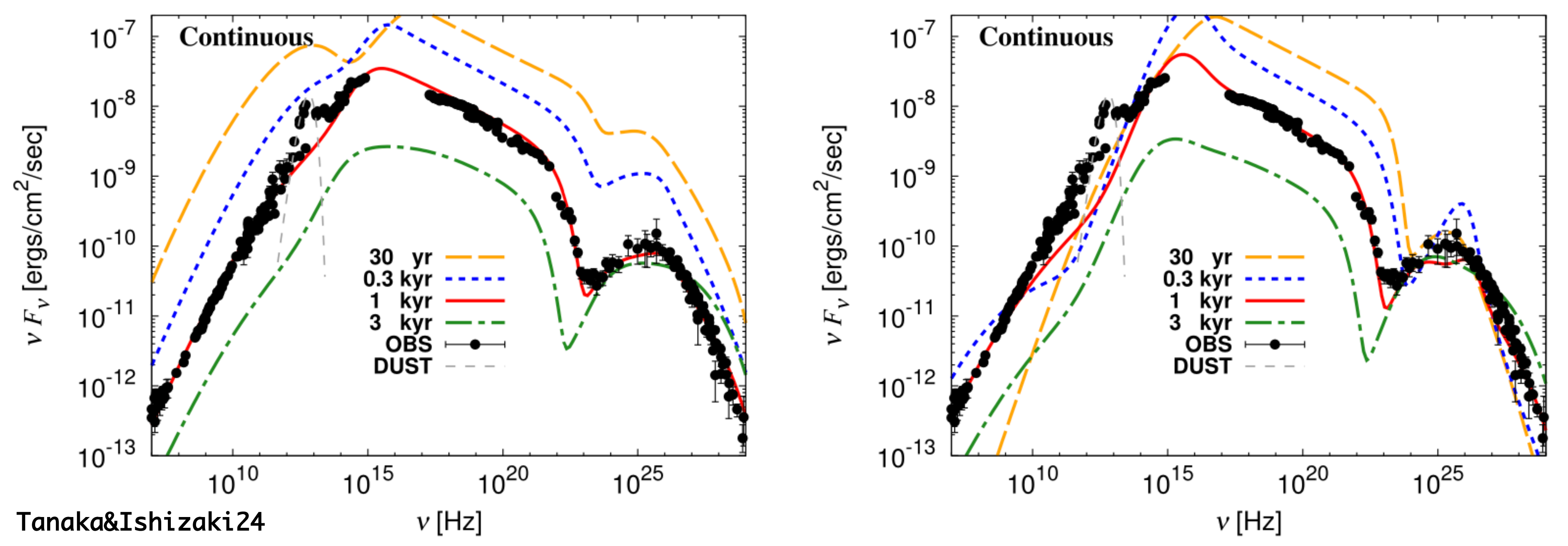
Electron Energy Spectrum↓



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

Results

$\tau_{\mathrm{acc},0} = 3\ \mathrm{yr}$ $\tau_{\mathrm{acc},0} = 30\ \mathrm{yr}$



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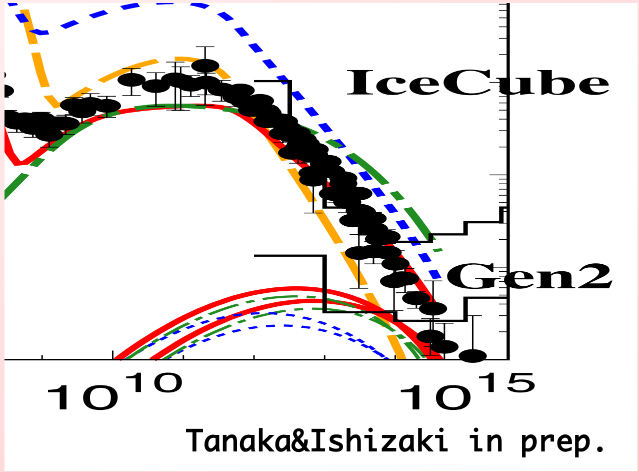
Acceleration time-scale should be < 10 yr

Conclusions

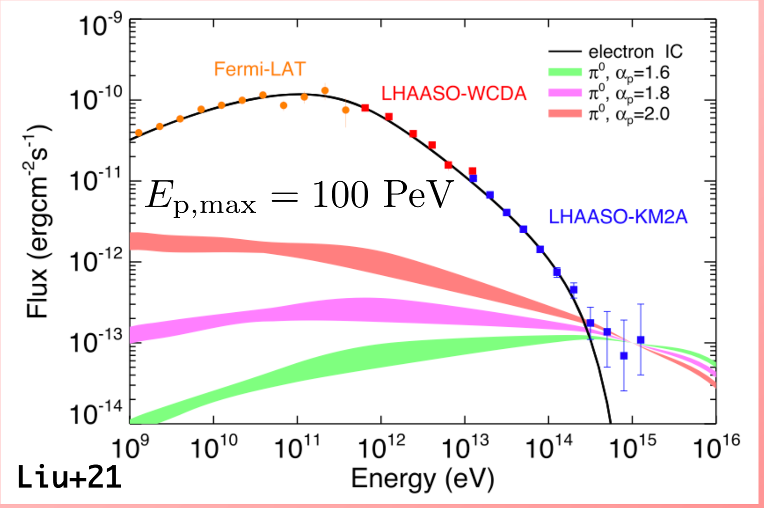
Stochastic accel. model including backreaction to turbulent energy

- **A physical model of the origin of radio-emitting particles (could be a solution to κ-problem).**

- **Neutrino signal which is different from previous studies is expected from our model!**



Tanaka&Ishizaki in prep.



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