A Stochastic Acceleration Model of Pulsar Wind Nebulae

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with
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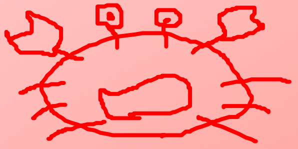
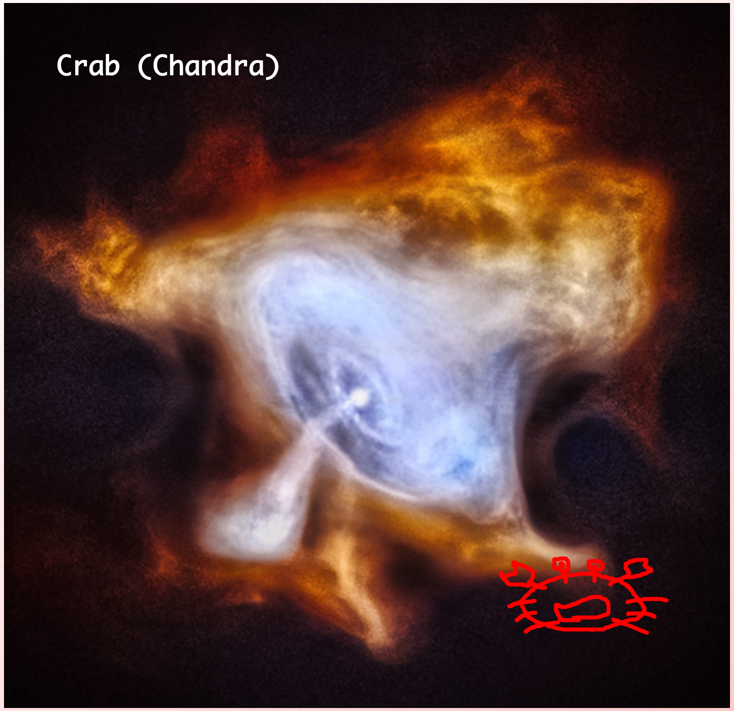
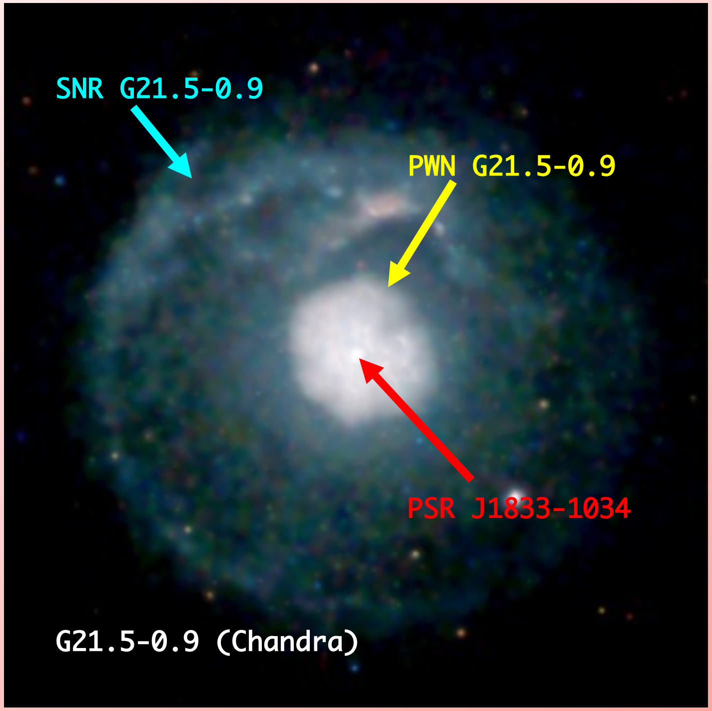


Introduction

PSRs, PWNe & SNRs



powered by pulsars

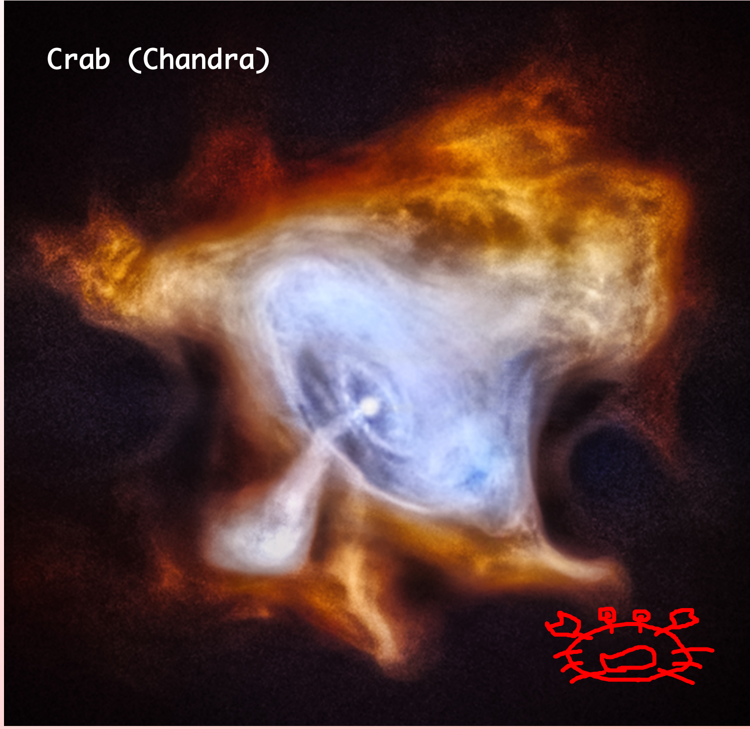


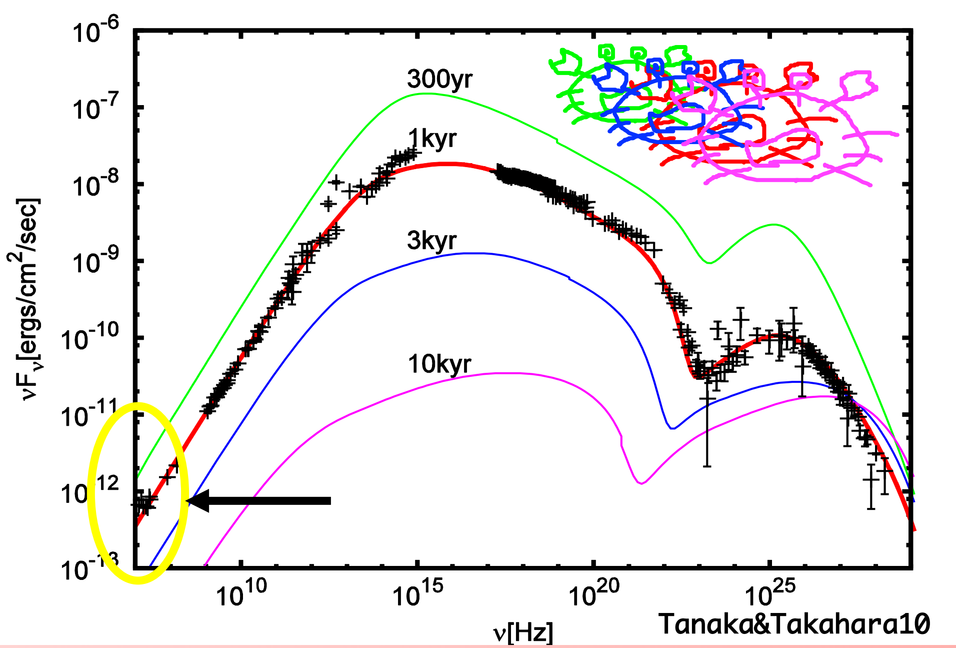
confined by SNR

κ-problem of PWNe

Problem about particle abundance inside PWNe

- Syn. & IC emission of Non-thermal $e^{\pm}$
- L_X/L_γ => mean B-field of PWNe
- $F_{syn,\nu} \propto B$, $\nu_{syn} \propto B\gamma^2$ (↓)
- Lowest γ particles dominate in #.



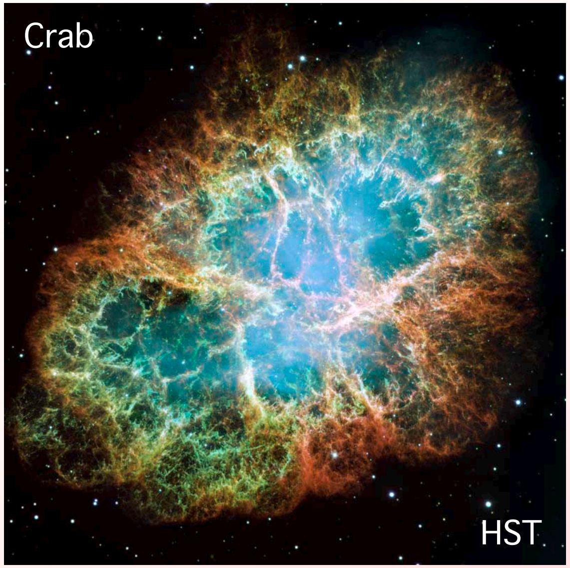


- Injection from pulsar

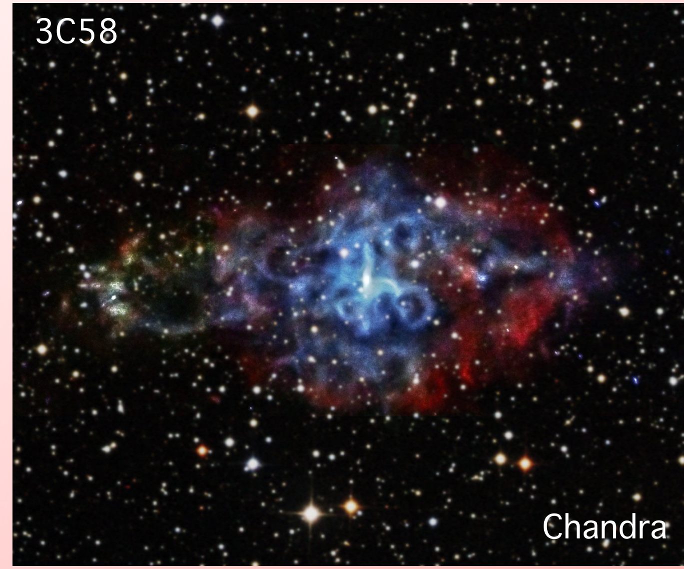
$$L_{\rm spin} = I\Omega\dot{\Omega} = \kappa \dot{N}_{\rm GJ}\Gamma_{\rm wind} m_{\rm e} c^2 (1+\sigma)$$

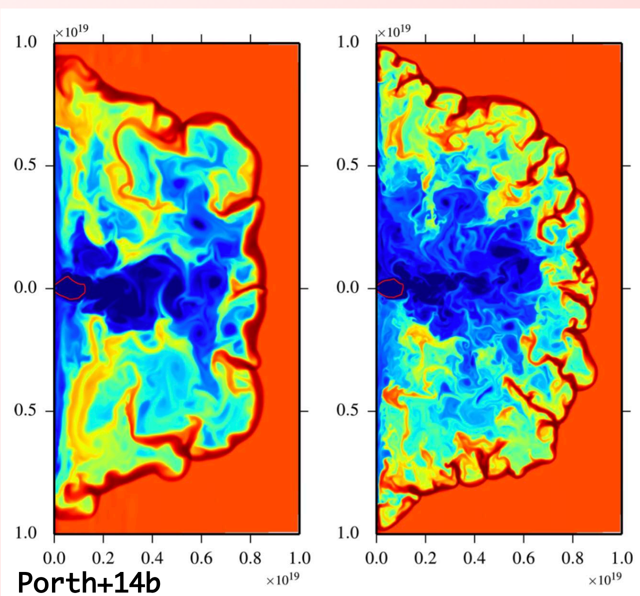
- # of $e^{\pm}$ inside PWNe $\sim \kappa \dot{N}_{\rm GJ} t_{\rm age}$ for κ ~ 10^6.
- κ >> 10^5 is difficult! Timokhin&Harding15

Turbulence in PWNe

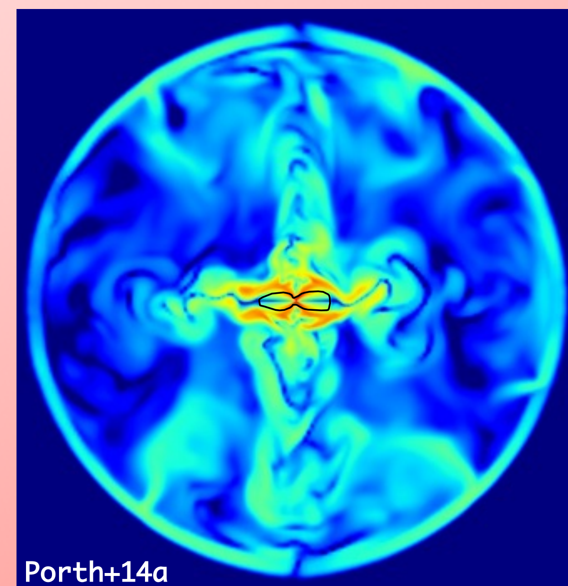


<= PWN-SNR interaction



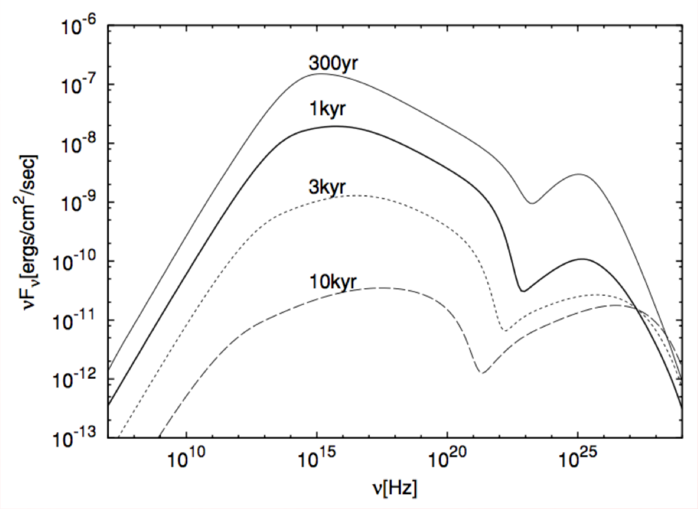


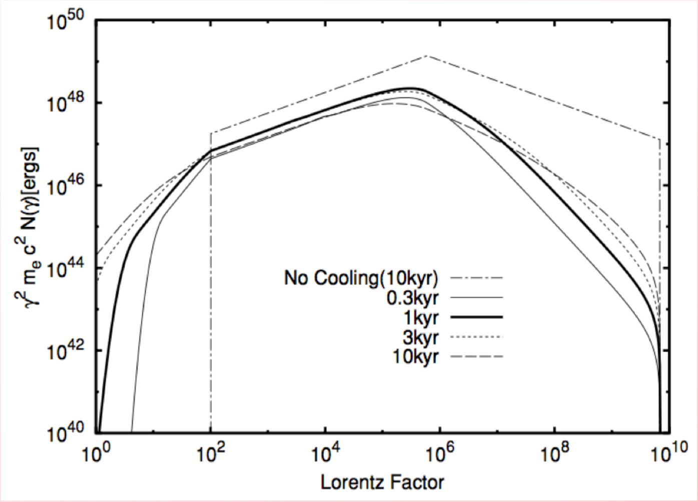
=> PWN-PW interaction



Motivation

most past studies
Broken power-law injection from central pulsar





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

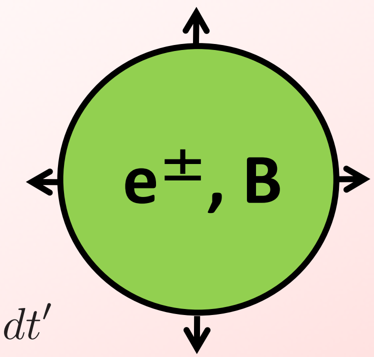
Single power-law injection from central pulsar @ high energy & **external particle injection** + stochastic accel.

Tanaka&Asano16 in prep.

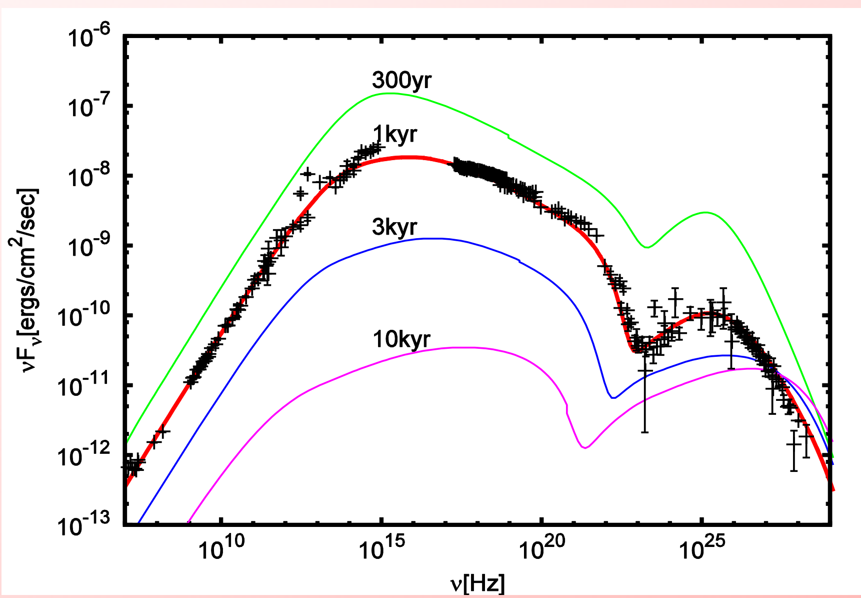
Model

One-zone Model

One-zone approx.
from our past studies

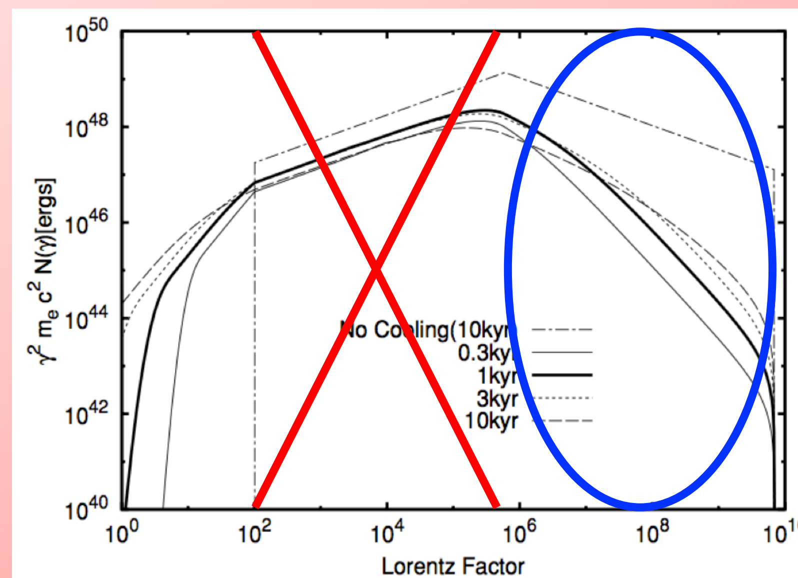


$$\frac{4\pi}{3}R^3(t)\frac{B^2(t)}{8\pi} = \eta_{\rm B}\int_0^t L_{\rm spin}(t')dt'$$



Only the high energy part is supplied from the PSR

Single power-law injection
$\gamma_{min} \sim 10^5$, $\gamma_{max} \sim 10^9$



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

$$D_{\gamma\gamma}=\frac{\gamma_{\rm min}^2}{2\tau_{\rm accel}}\left(\frac{\gamma}{\gamma_{\rm min}}\right)^q \exp\left(-\frac{t}{\tau_{\rm decay}}\right)\exp\left(-\frac{\gamma}{\gamma_{\rm decay}}\right)$$

- q: spectrum of turbulence (5/3 vs. 2 in this study)
- $t_{\rm accel}$: acceleration time normalized at $\gamma_{\rm min}$
- $\gamma_{\rm decay}$: characteristic length of turbulence
- $\tau_{\rm decay}$: decay time-scale of turbulence

Extra Injection

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

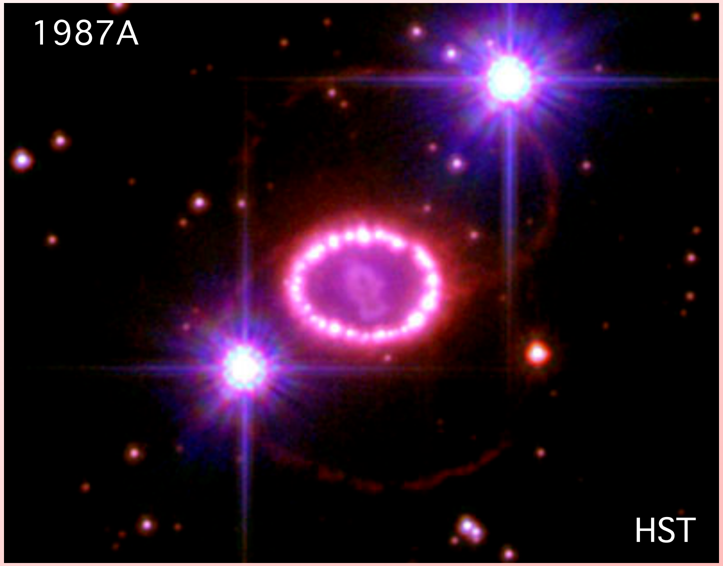
cooling effects

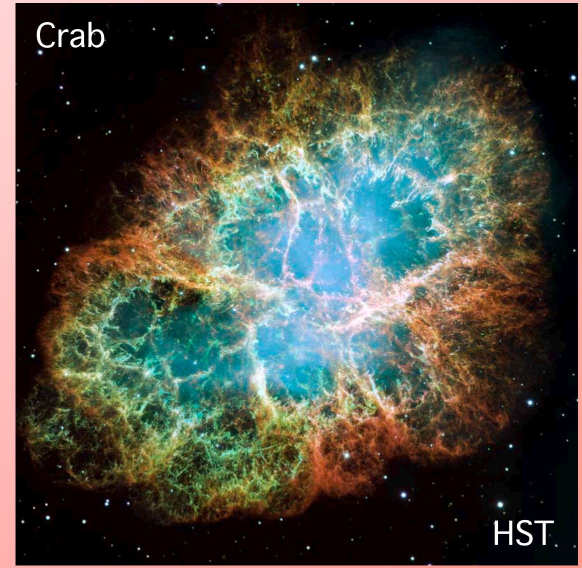
stochastic accel.

from pulsar

Extra injection

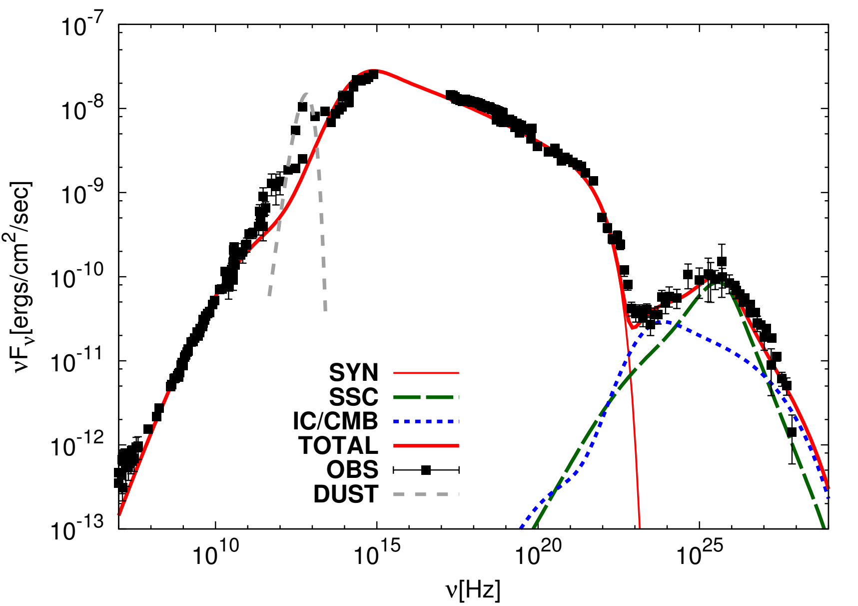
$$Q_{\rm ext}(t)=N_{\rm ini}\delta(t-t_{\rm ini})+Q_{\rm ej}\left(\frac{t}{t_{\rm age}}\right)^s$$

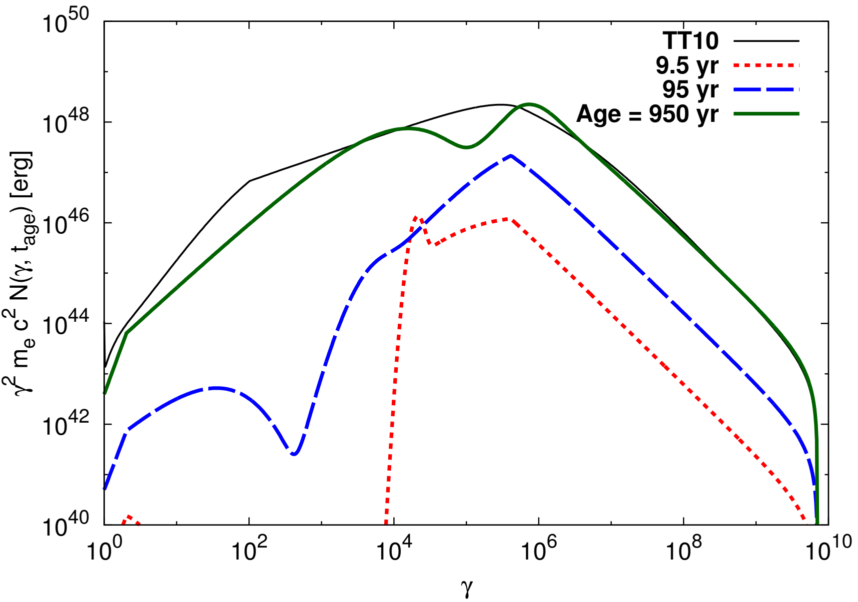




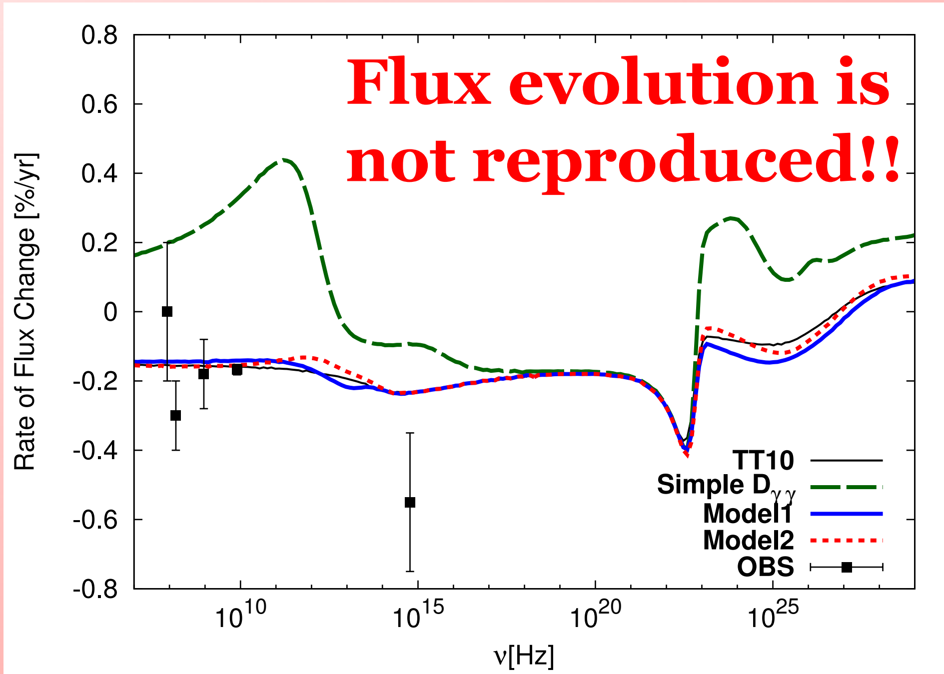
Results & Conclusion

Simple $D_{\gamma\gamma}$ model

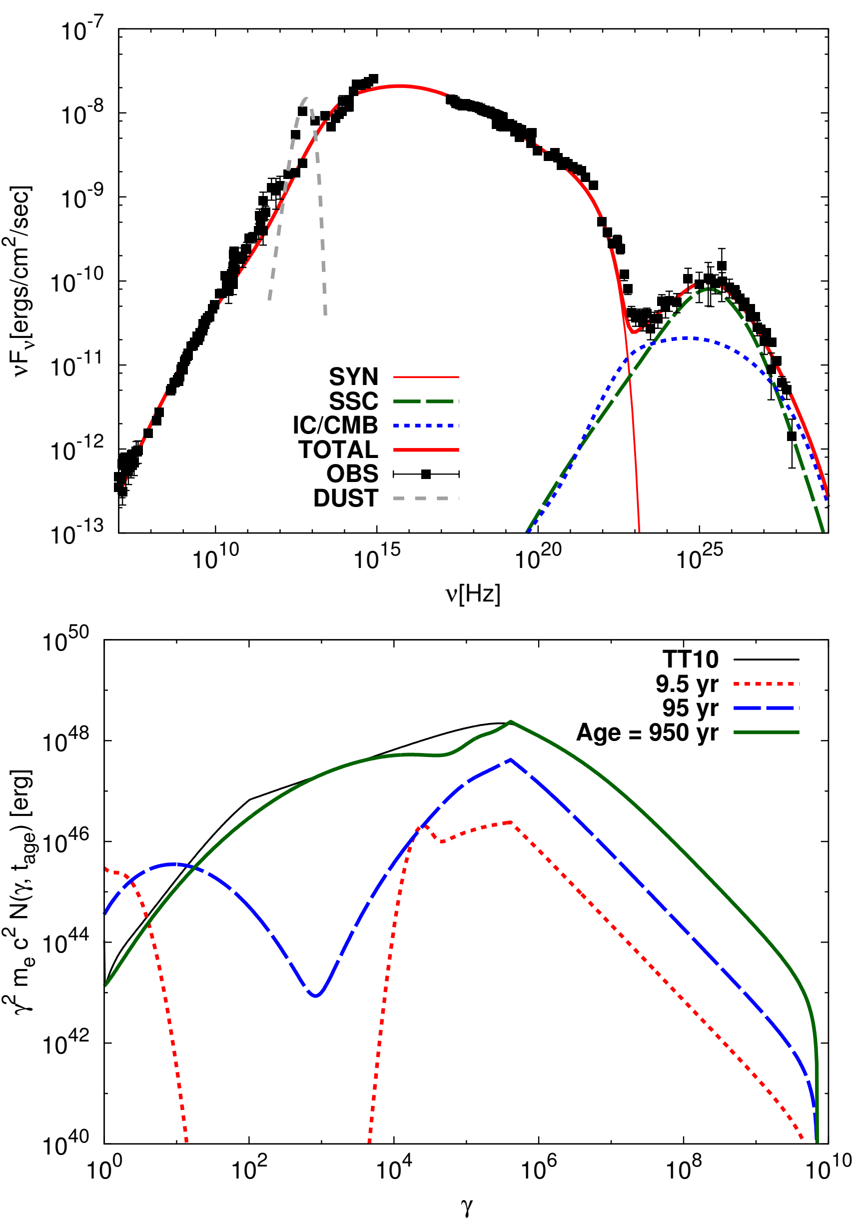




- $\tau_{accel} = t_{age}$
- $q = 5/3$ (Kolmogorov)
- $\tau_{decay} = \gamma_{decay} = \infty$
- $Q_{ej} = 10^{41}\ s^{-1}$



Alternative Models



- τ_{decay} = 300yr < t_{age}
- τ_{accel} = 50yr ≪ t_{age}
- q = 2 (hard-sphere)
- $\gamma_{decay} = 10^5 \sim \gamma_{min}$
- N_{ini} = 2 x 10^{51}

$D_{\gamma\gamma}$ is not simple.

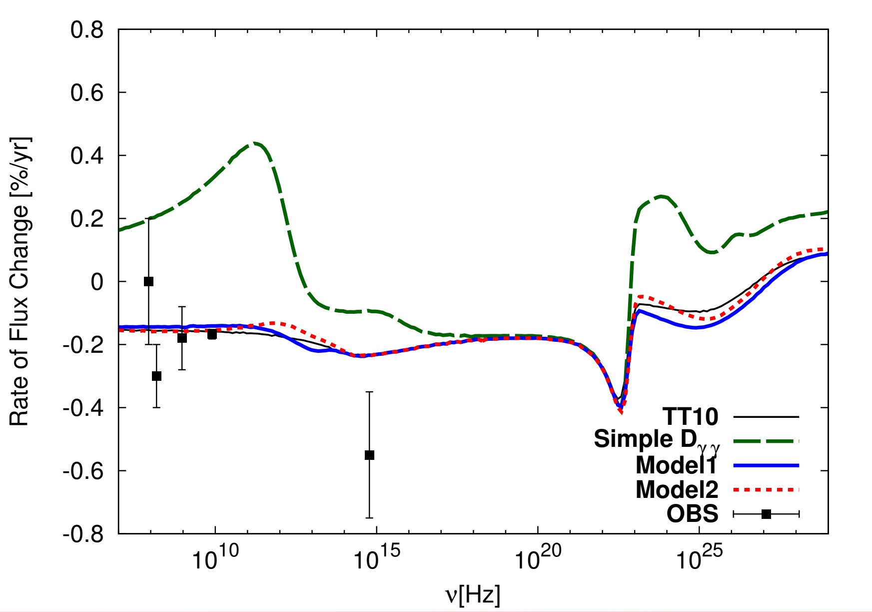
Both N_{ini} & Q_{ej} models are allowed.

Both q = 5/3 & 2 models are allowed.

Conclusions

- N_{ini} & Q_{ej} should be tuned to fit the radio flux level.

$$n_{\rm inj} = \frac{Q_{\rm ej}}{S v_{\rm inj}} \sim 10^{-4} {\rm cc}^{-1} Q_{\rm ej,41} S_{\rm pc^2}^{-1} v_{\rm inj,8}^{-1}$$



- Simple $D_{\gamma\gamma}$ model does not fit to observed flux evolution. (The turbulence should have decayed already.)

- Finite values of γ_{decay} & τ_{decay} reproduce flux evolution.

- Flux evolution observations divide the models.

Model	0.1TeV	TeV	10TeV	100TeV
Simple $D_{\gamma\gamma}$ (%/yr)	+0.092	+0.15	+0.18	+0.21
Alternative (%/yr)	-0.12	-0.056	+0.042	+0.097

We've already observed the Crab Nebula far more than 10yrs in TeVs.

Simple $D_{\gamma\gamma}$ model