Evaluating the contribution of young pulsar wind nebulae to the Galactic high-energy neutrinos

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Outline

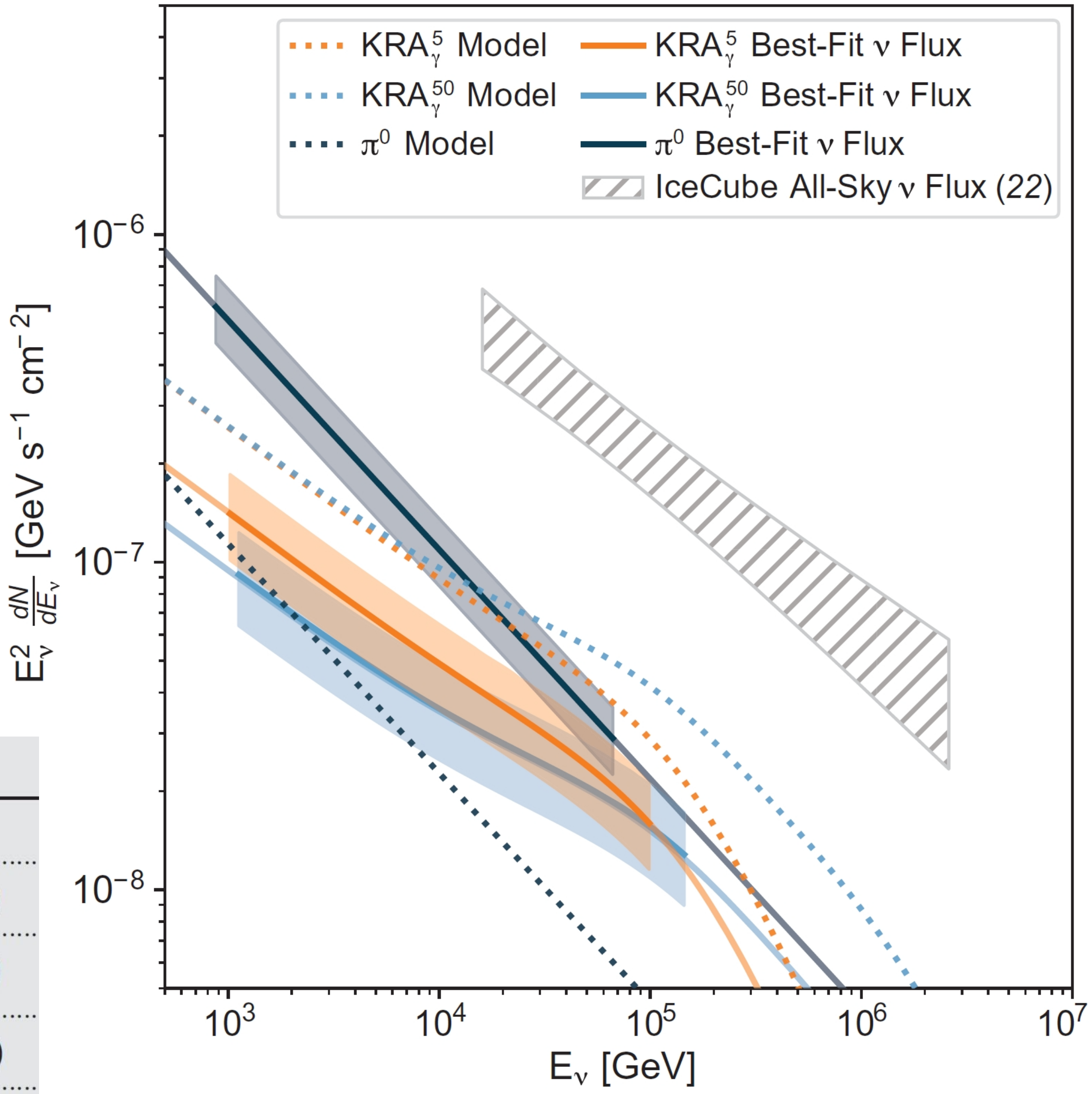
- Introduction: neutrino & PWN
- PWN model & Crab fitting
- Sampling & result
- Summary

Neutrino emission from Galactic plane

Diffuse emission or point sources?

- Statistical difference: not prominent
- PWN as neutrino source in the Galaxy (e.g. Bednarek 2003, Di Palma+2017)

	Flux sensitivity Φ	*P* value
		Diffuse Galactic plane analysis
π^0	5.98	1.26×10^{-6} (4.71σ)
KRA_γ^5	0.16 × MF	6.13×10^{-6} (4.37σ)
KRA_γ^{50}	0.11 × MF	3.72×10^{-5} (3.96σ)
		Catalog stacking analysis
SNR		5.90×10^{-4} (3.24σ)*
PWN		5.93×10^{-4} (3.24σ)*
UNID		3.39×10^{-4} (3.40σ)*



Energy spectra for different Galactic plane models from IceCube 2023

Pulsar wind nebula

- Possible spectral hardening at ~ PeV of the Crab -- Possible proton contribution (LHAASO 2021)

- Injection from the pulsar

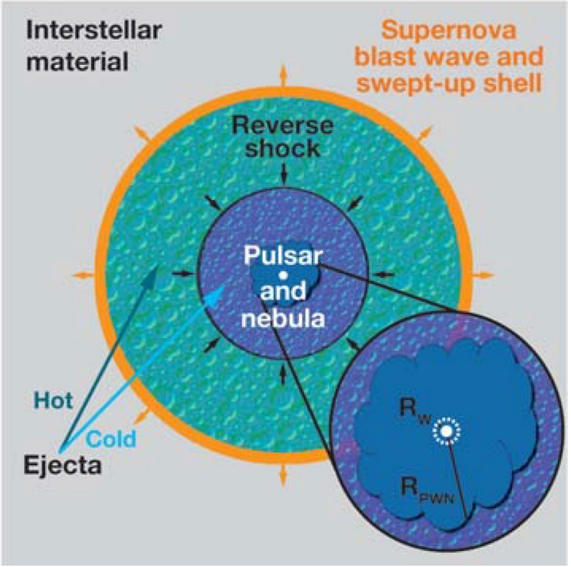
➢ Typically $\eta_B + \eta_e = 1$; now $\eta_B + \eta_e + \eta_p = 1$

➢ (10–50)% of the spin-down energy converted into proton (Liu+2021)

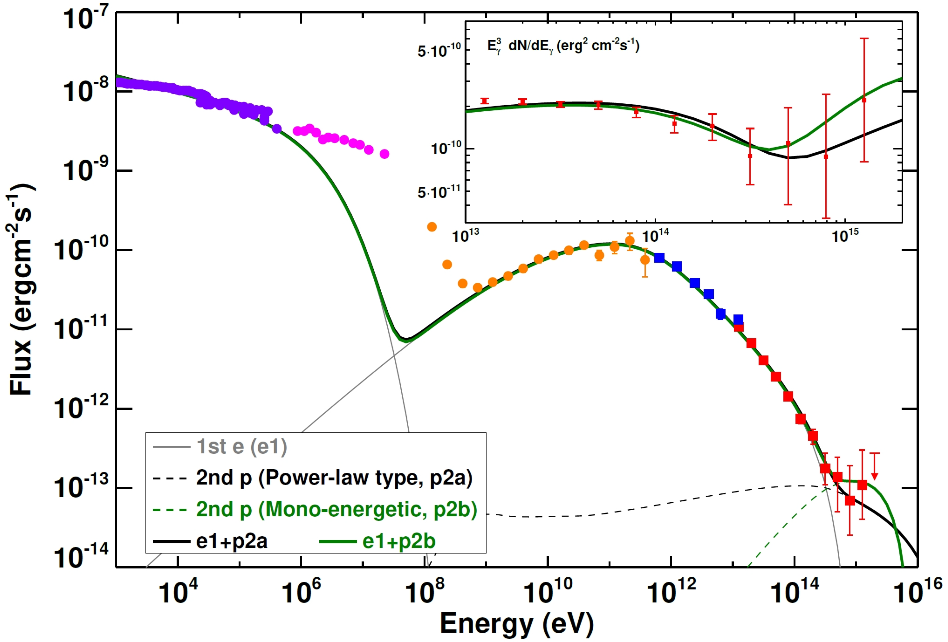
- Young pulsar wind nebula

➢ Free expansion phase

➢ More particles being injected; higher cutoff energy



A schematic diagram of a PWN-SNR system (Gaensler+2006)



A two-zone scenario with a proton population (LHAASO 2021)

Phenomenological modelling of Crab

- Two different populations of electrons

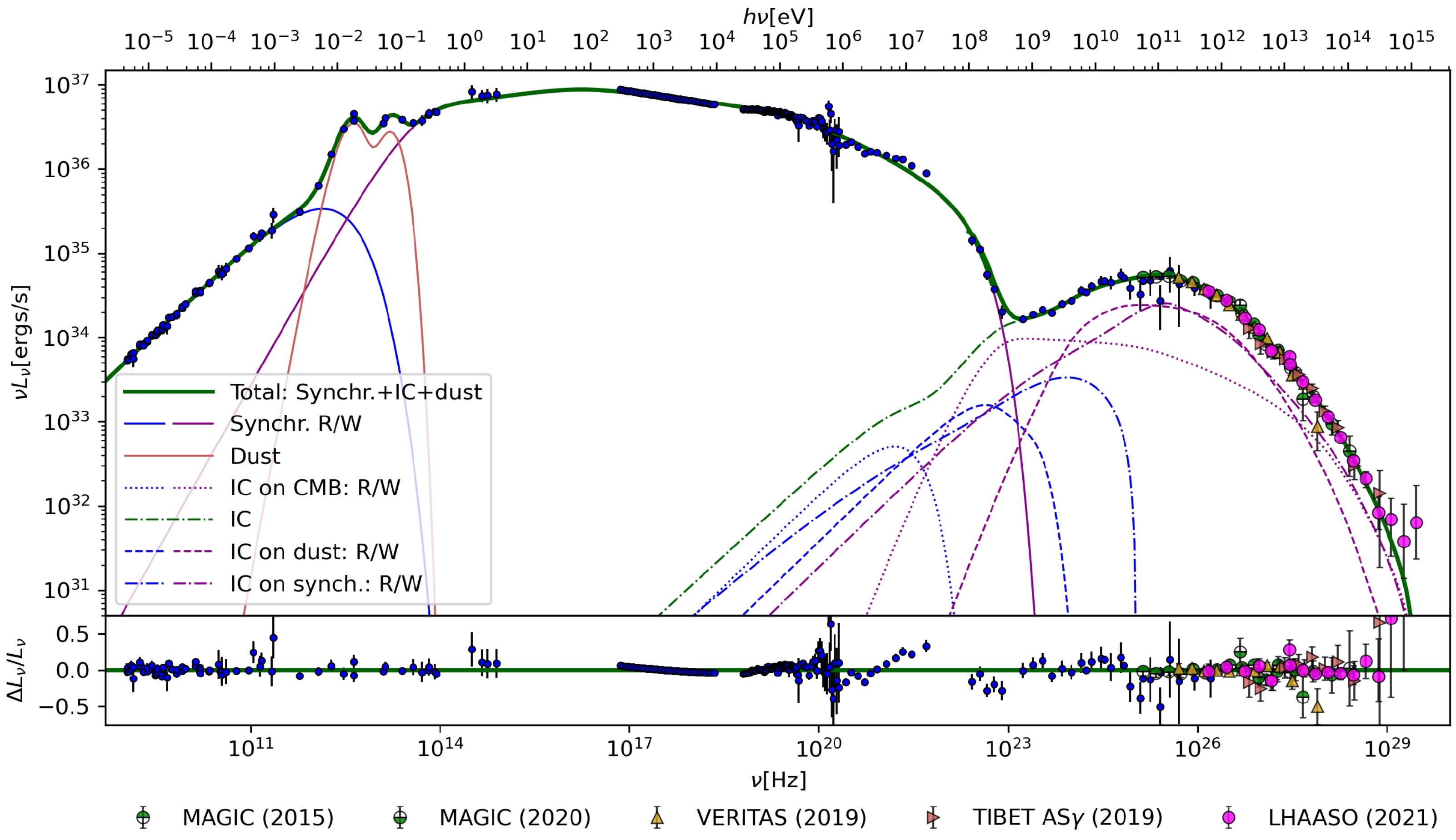
➢ Radio e: not well understood; stochastic acceleration? (e.g. Tanaka & Asano 2017)

➢ Wind e: accelerated at the wind termination shock

- B-field

$$B(r) = B_0 \left(\frac{r}{r_{\rm ts}}\right)^{-\alpha}, \ \ \alpha \sim 0.5$$

(Dirson+2023, Aharonian+2024)



Dirson+2023

Evolution of the nebula

Vorster+2013

Lu+2017

Peng+2022

$$V(r,t) = V_f \frac{R_{\rm pwn}(t)}{t} \left(r/R_{\rm pwn}(t)\right)^{-\beta}, 0 < V_f < 1$$

spherically symmetric

$$B(r,t) = B_0(t)(r/R_{\rm ts}(t))^{\beta-1} \begin{cases} \frac{dW_{\rm B}(t)}{dt} = \eta_{\rm B} L(t) - \frac{W_{\rm B}(t)}{R_{\rm pwn}(t)} \frac{dR_{\rm pwn}(t)}{dt} \\ W_{\rm B}(t) = \int B^2(r,\, t) r^2 dr/2 \end{cases}$$

$$D(r,E,t) = D_0(r/R_{\rm ts}(t))^{1-\beta}(E/E_{\rm cut})^{1/3}, D_0 = \frac{cE_{\rm cut}}{3eB}$$

- Inner boundary: $R_{\rm ts} = \sqrt{L/4\pi c P_{\rm pwn}}$; stops increasing after reaching 0.13 pc
- Outer boundary: $R_{\rm pwn}$: an approximation given by Bandiera+2021; $R_{\rm pwn} = 2$ pc at $T_{\rm age} = 970$ yr

$E_{\rm sn}$	$M_{\rm ej}$	$n_{\rm ISM}$	n	L_{s0}	τ_0
1×10^{51} erg	$9\ M_{\rm sun}$	$0.1\ {\rm cm}^{-3}$	2.519	3×10^{39} erg/s	680 yr

Particles in the nebula

$$Q_{\rm inj}^{\rm e}(\gamma_{\rm e}, t) = Q_0^{\rm e}(t)\begin{cases}\left(\frac{\gamma_{\rm e}}{\gamma_{\rm b}}\right)^{-\alpha_1} & \gamma_{\rm e,min} \leqslant \gamma_{\rm e} < \gamma_{\rm b} \\ \left(\frac{\gamma_{\rm e}}{\gamma_{\rm b}}\right)^{-\alpha_2} & \gamma_{\rm b} \leqslant \gamma_{\rm e} \leqslant \gamma_{\rm e,max}\end{cases}$$

$$\gamma_{\rm e,max} = \frac{3\varepsilon e}{m_{\rm e}c^2}\sqrt{\frac{\eta_{\rm B}L(t)}{c}}$$

synchotron and adiabatic loss

$$Q_{\rm inj}^{\rm p}(\gamma_{\rm p}, t) = Q_0^{\rm p}(t)\left(\frac{\gamma_{\rm p}}{\gamma(1\ {\rm TeV})}\right)^{-\alpha_{\rm p}} e^{-\frac{\gamma_{\rm p}}{\gamma_{\rm p,cut}}}$$

$$\gamma_{\rm p,min} = \frac{1\ {\rm TeV}}{m_{\rm p}c^2}, \gamma_{\rm p,cut} = \frac{3\varepsilon e}{m_{\rm p}c^2}\sqrt{\frac{\eta_{\rm B}L(t)}{c}}$$

adiabatic loss

$$\frac{\partial n_i}{\partial t} = D_i\frac{\partial^2 n_i}{\partial r^2} + \left[\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 D_i) - V\right]\frac{\partial n_i}{\partial r} - \frac{1}{r^2}\frac{\partial}{\partial r}[r^2 V]n_i + \frac{\partial}{\partial \gamma_i}[\dot{\gamma}_i n_i] + Q_i,$$

Boundary conditions

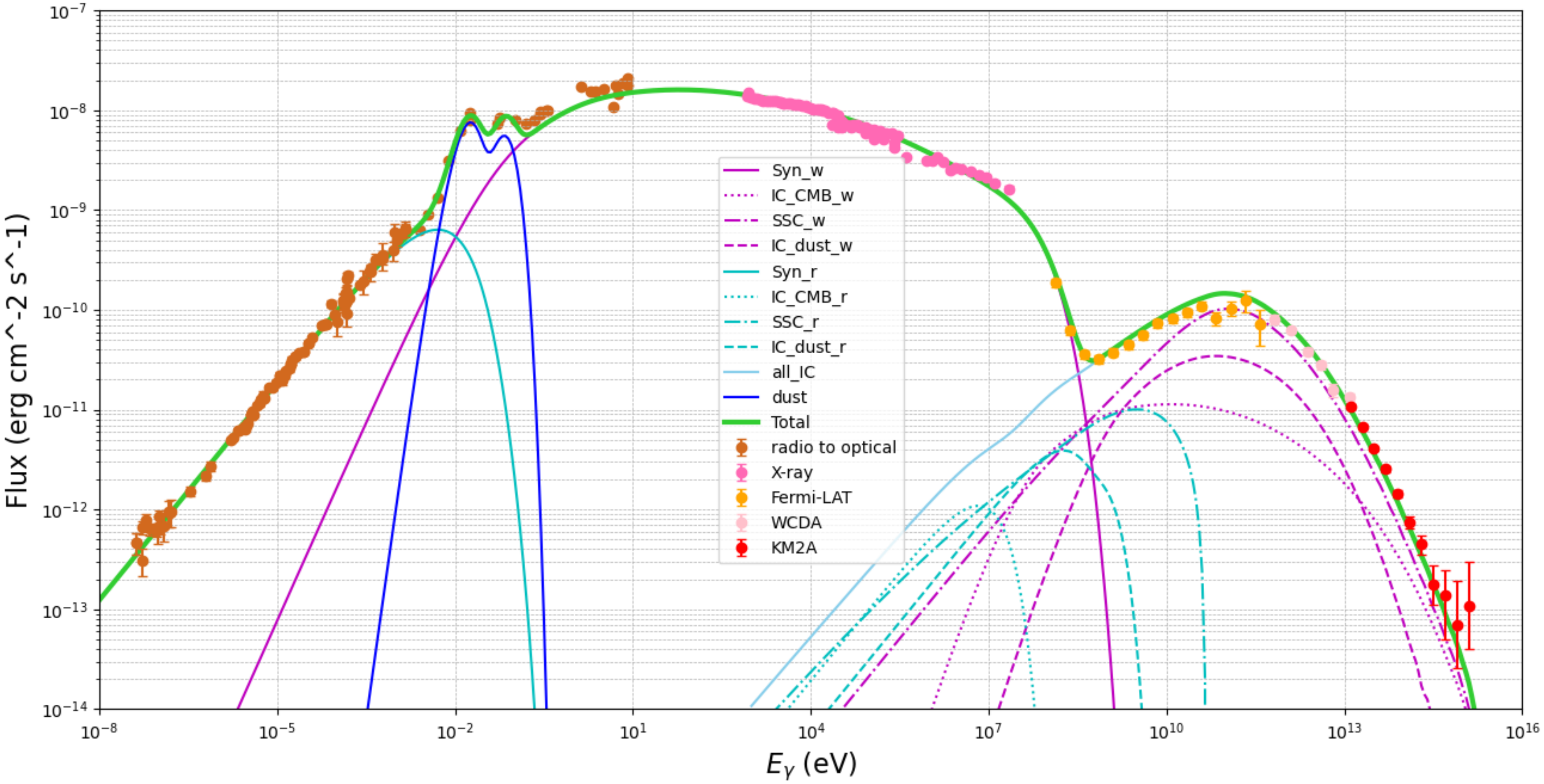
$$V_0 n_i - D_i(R_{\rm ts}, \gamma_i, t)\frac{\partial n_i}{\partial r} = \frac{Q_{i,\rm inj}}{4\pi R_{\rm ts}^2(t)}$$

$$n_i(R_{\rm pwn}, \gamma_{\rm i}, t) = 0$$

Crab fitting

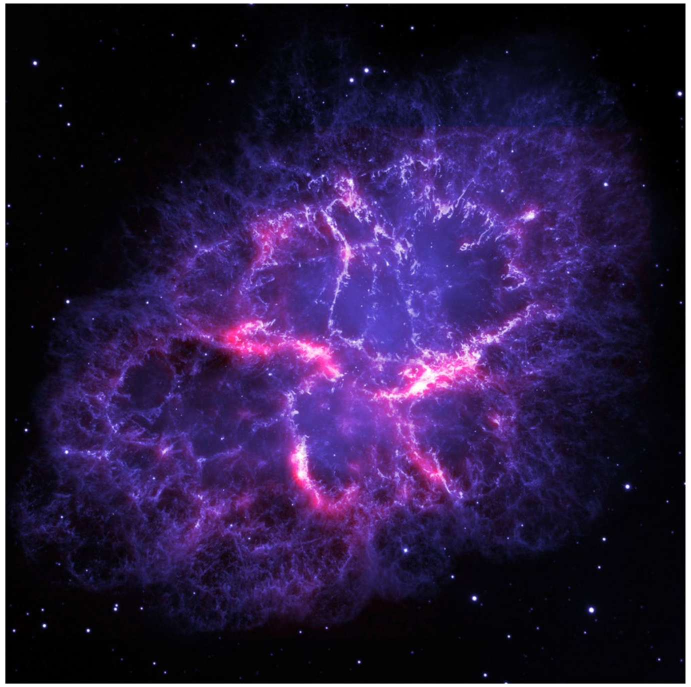
- Dust and radio e following Dirson+2023
- Not strictly fitted, especially the optical to UV data
- $B_0 \approx 190\mu G$, slightly weaker compared to Dirson+2023 & Aharonian+2024

α_1	α_2	$\gamma_{e,min}$	$\gamma_{e,b}$	η_B	η_e	η_p	β	V_f
1.7	2.3	2e5	1e6	0.013	0.927	0.06	0.5	0.15

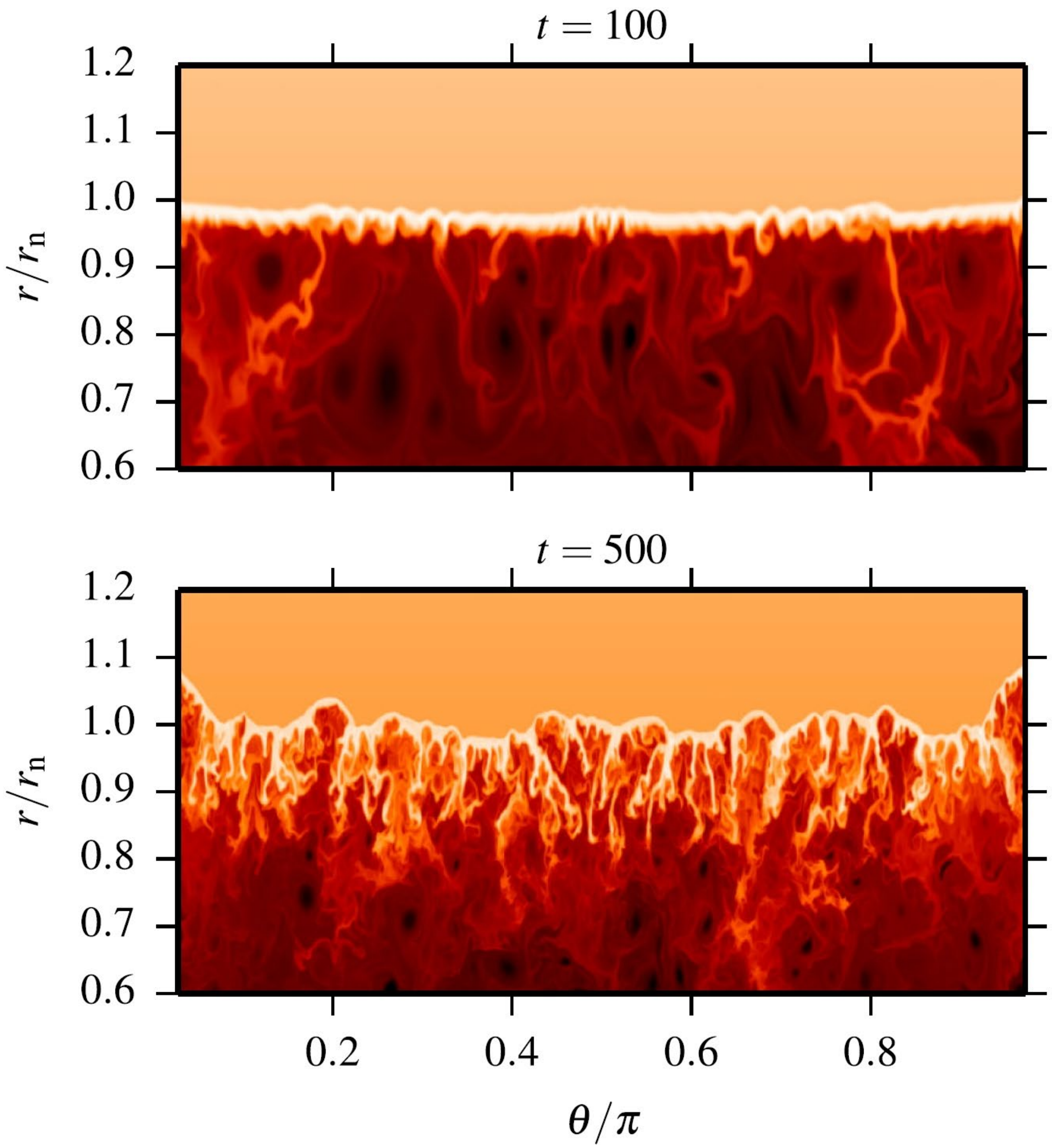


Filaments in the Crab

- Formed by R-T instability
- Mass in Crab 7.2 M_{sun}(Owen+2015), ~ 80% of $M_{\mathrm{ej}}(= 9M_{\mathrm{sun}})$



Composite image of the Crab (Owen+2015)

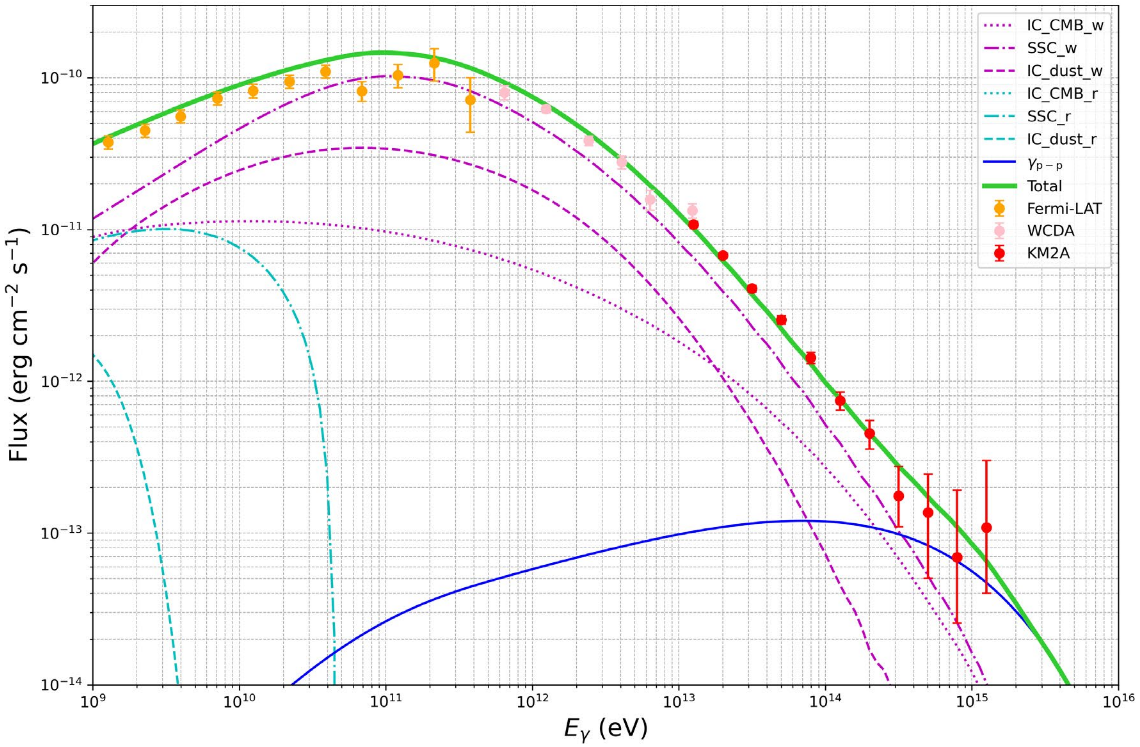


MHD simulation (Porth+2014)

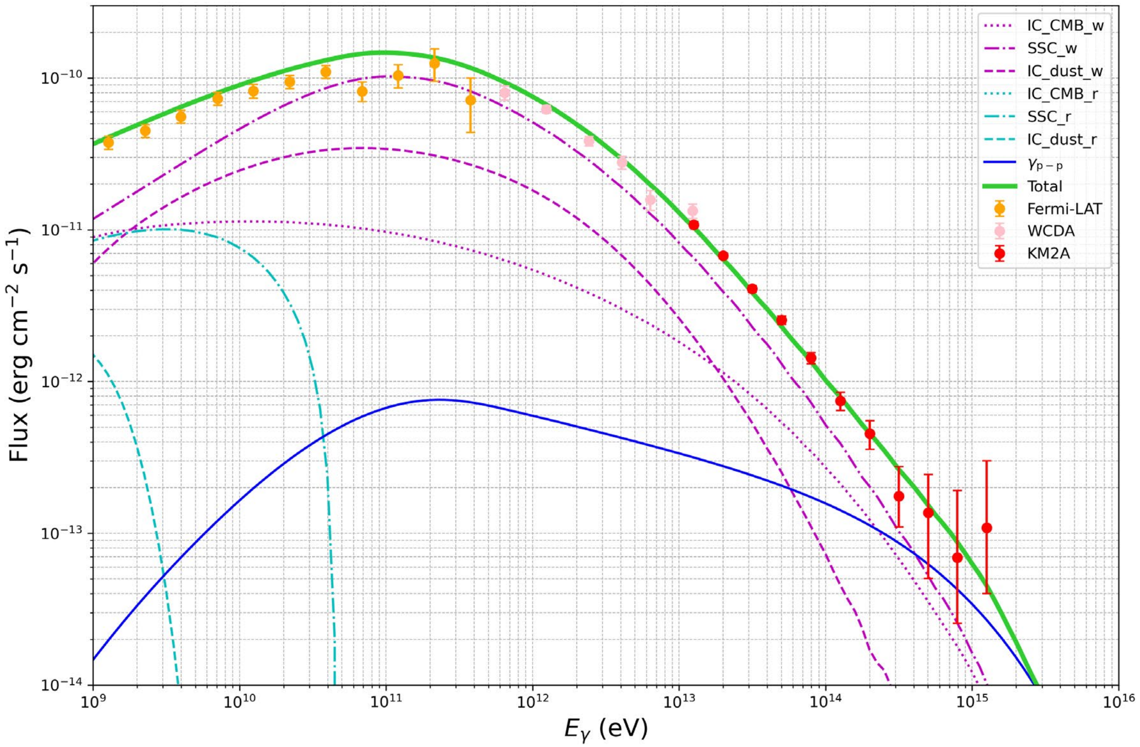
Amplification factor

- Effective density > mean density -- inhomogeneous distribution of the gas (Atoyan+1996)
- (0.5-1) $R_{\rm pwn}$: filled with filaments, $0.8M_{\rm ej}/V_{\rm fila}=\rho_{\rm fila}\rightarrow n_{\rm fila}$
- Amplification factor $f_{\rm a}=n_{\rm eff}/n_{\rm fila}$

$\alpha=1.5, f_{\rm a}\approx 10$

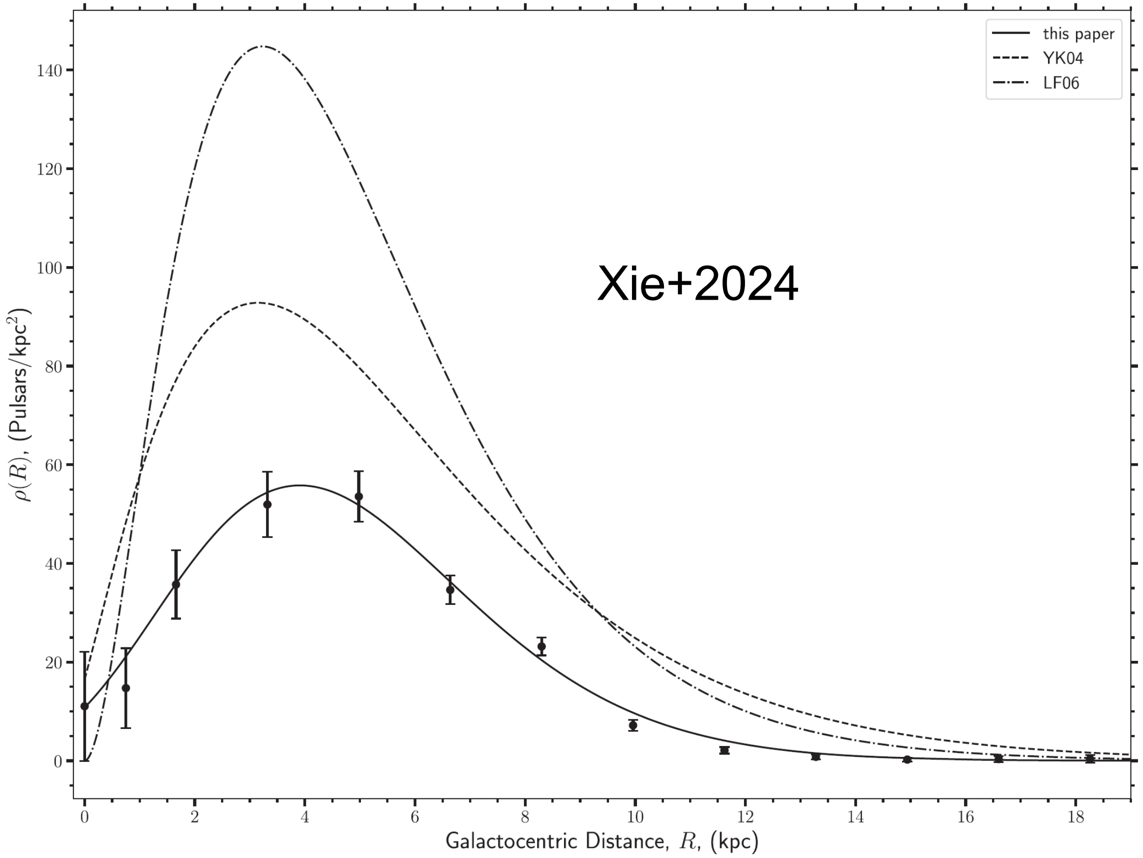


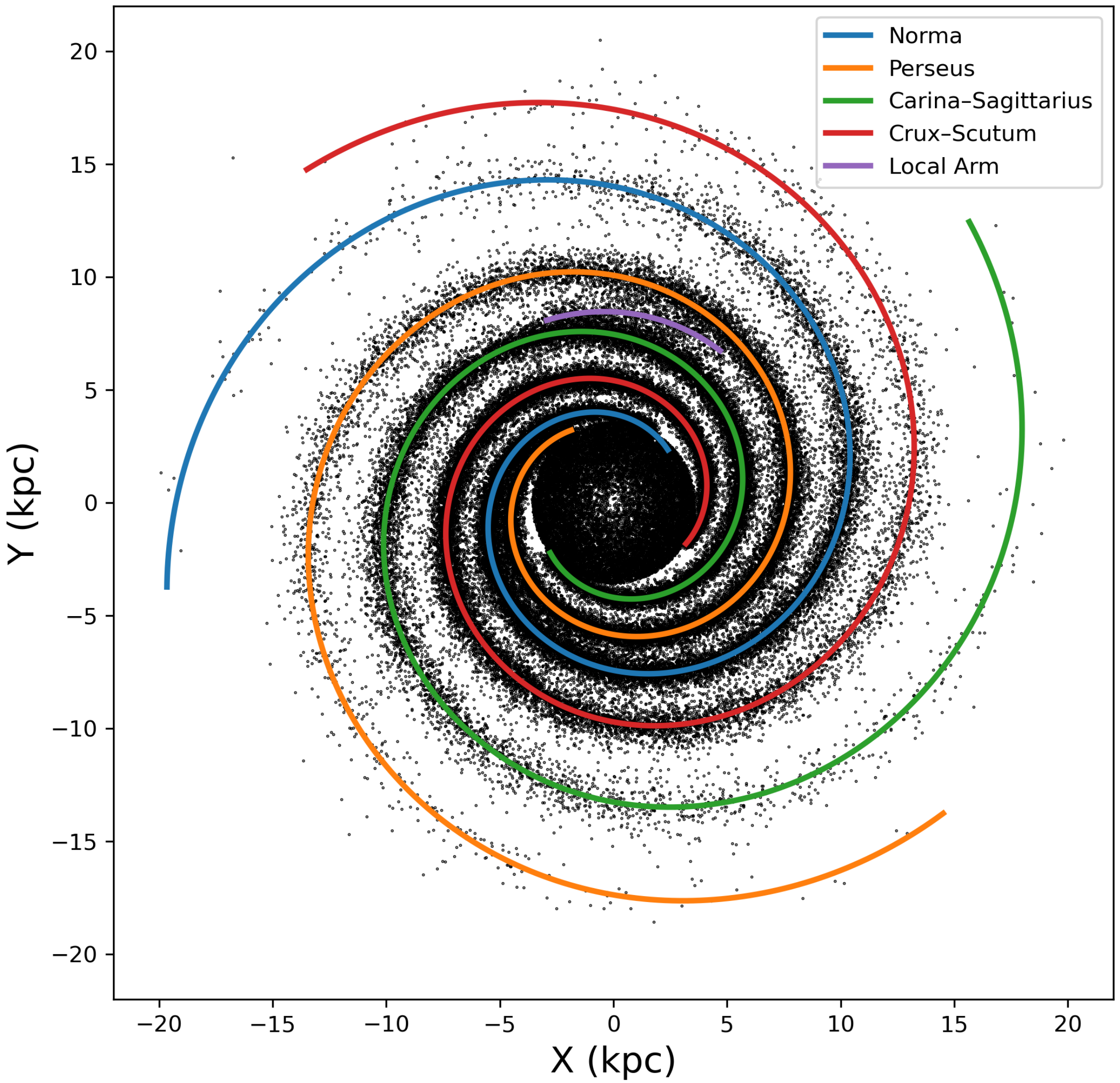
$\alpha=2.0, f_{\rm a}\approx 20$



Pulsar distribution

- Radial distribution of pulsar surface density from Xie+2024
- ~1.1×10^5 pulsars after beaming correction (Tauris+1998)



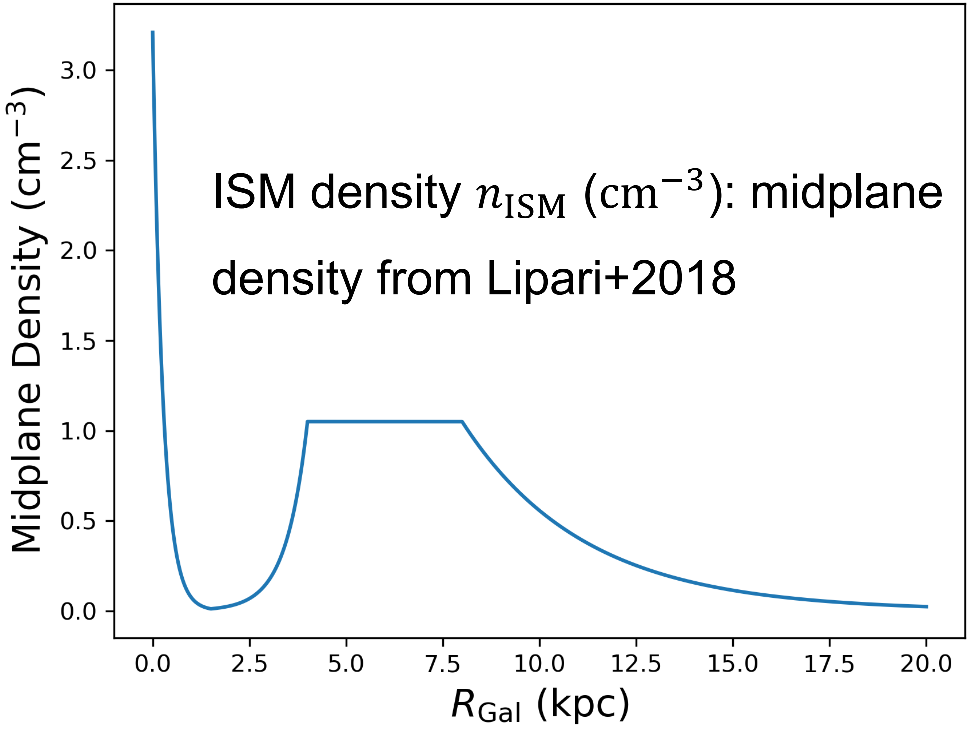


An example of the simulated distribution of pulsars in the Galaxy (arm structure based on Hou+2014)

Parameters

- Variable parameters

	E_{sn} (erg)	M_{ej} (M_{sun})	P_0 (ms)	B_s (G)
distribution	$\log_{10}$normal	normal	normal	$\log_{10}$normal
μ	51	10	50	12.65
σ	0.2	2	35	0.55
note	$0.5-4\times10^{51}$(Kasen +2009)	range: 5-15	truncated at 10	



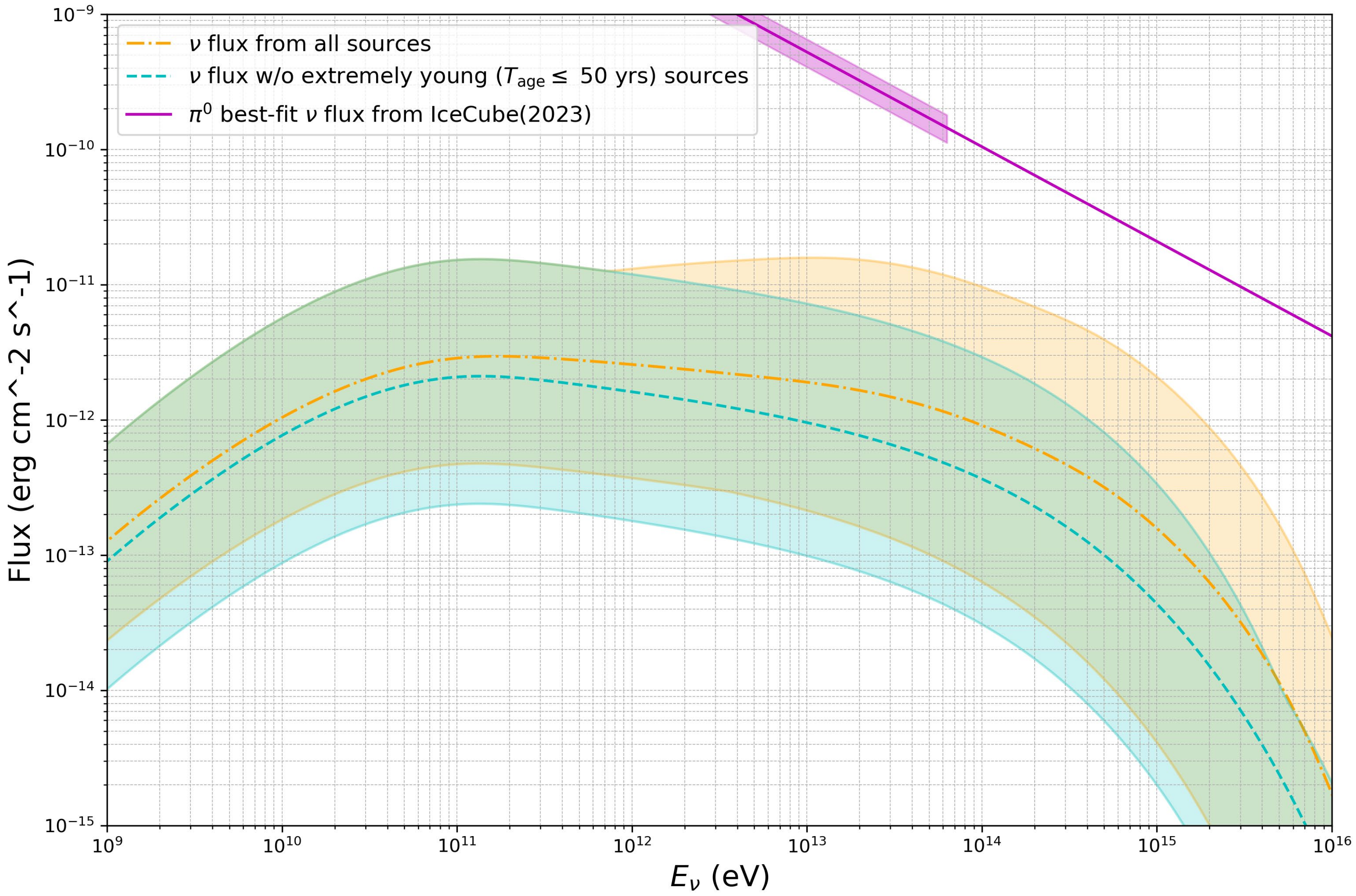
- Fixed parameters

➢ $T_{\rm age} \geq 500$ yr, $M_{\rm fila} = 0.8 M_{\rm ej}$, $\rm n = n_{\rm eff}$ for (0.5-1) $R_{\rm pwn}$

n	η_B	η_p	β	pulsar birth rate (per century)	V_f
3	0.02	0.1	0.5	1.5	0.5

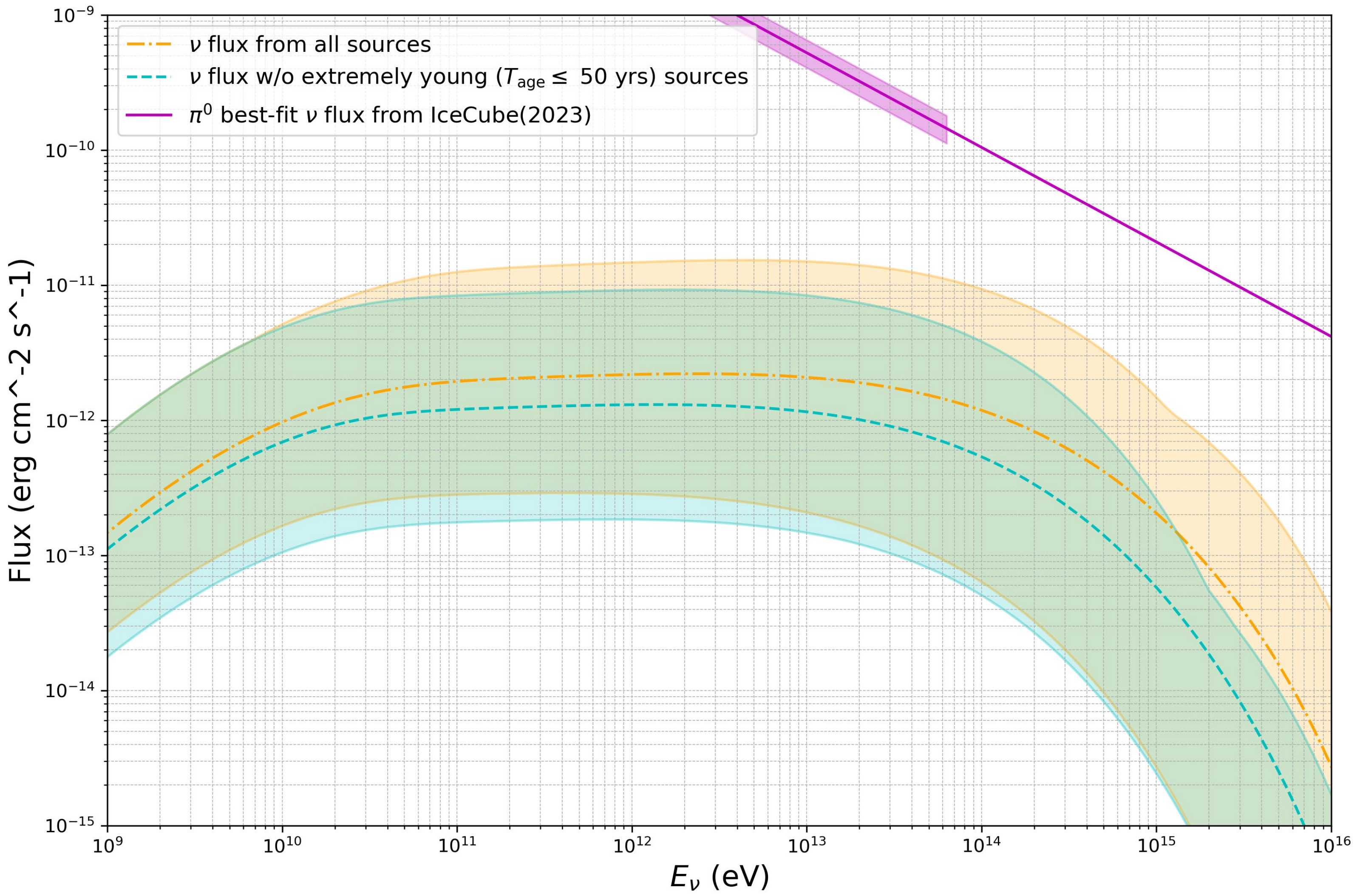
Result

- Sampling 20 times
- Green region: the overlap between the orange and cyan region
- $\alpha = 2.0, f_a = 20$; optimistically, ~ 10% of the IceCube π^0 best-fit result at 100 TeV



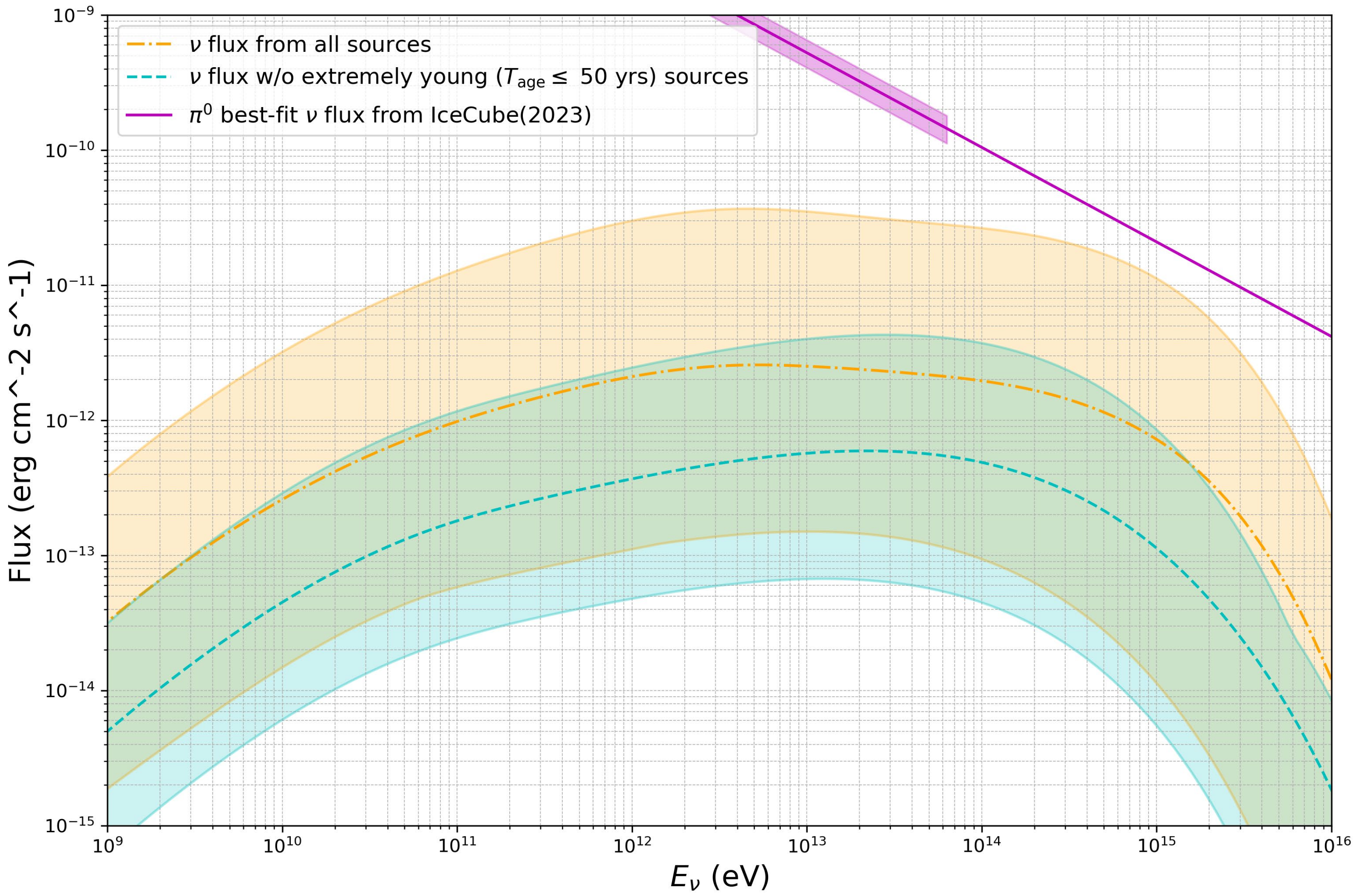
Result

- NO diffusion
- Similar optimistic result, ~ 10% of the IceCube π^0 best-fit result at 100 TeV



Result

- $\alpha = 1.5, f_a = 10$
- Up to ~ 25% of the IceCube result at 100 TeV
- ~ 50% of the simple power law extrapolation to 1 PeV



Summary

- The Crab nebula is treated as a standard of the PWN model.
- A slightly weaker magnetic field $B \approx 190\mu\mathrm{G}$ is obtained and about 6% of the spin-down energy is converted into protons.
- Amplification factor $f_{\mathrm{a}} = n_{\mathrm{eff}}/n_{\mathrm{fila}}$ describes the relation between the effective number density and the average number density of the filaments.
- For $\alpha = 2.0$, the synthetic young PWNe may contribute ~ 10% of the IceCube π^0 best-fit flux at 100 TeV in the optimistic case. For a harder spectrum $\alpha = 1.5$, the number rises to ~ 25%.
- Further discussion is needed for different values of the parameters.