

Cas A: broadband spectrum & (present) CR production

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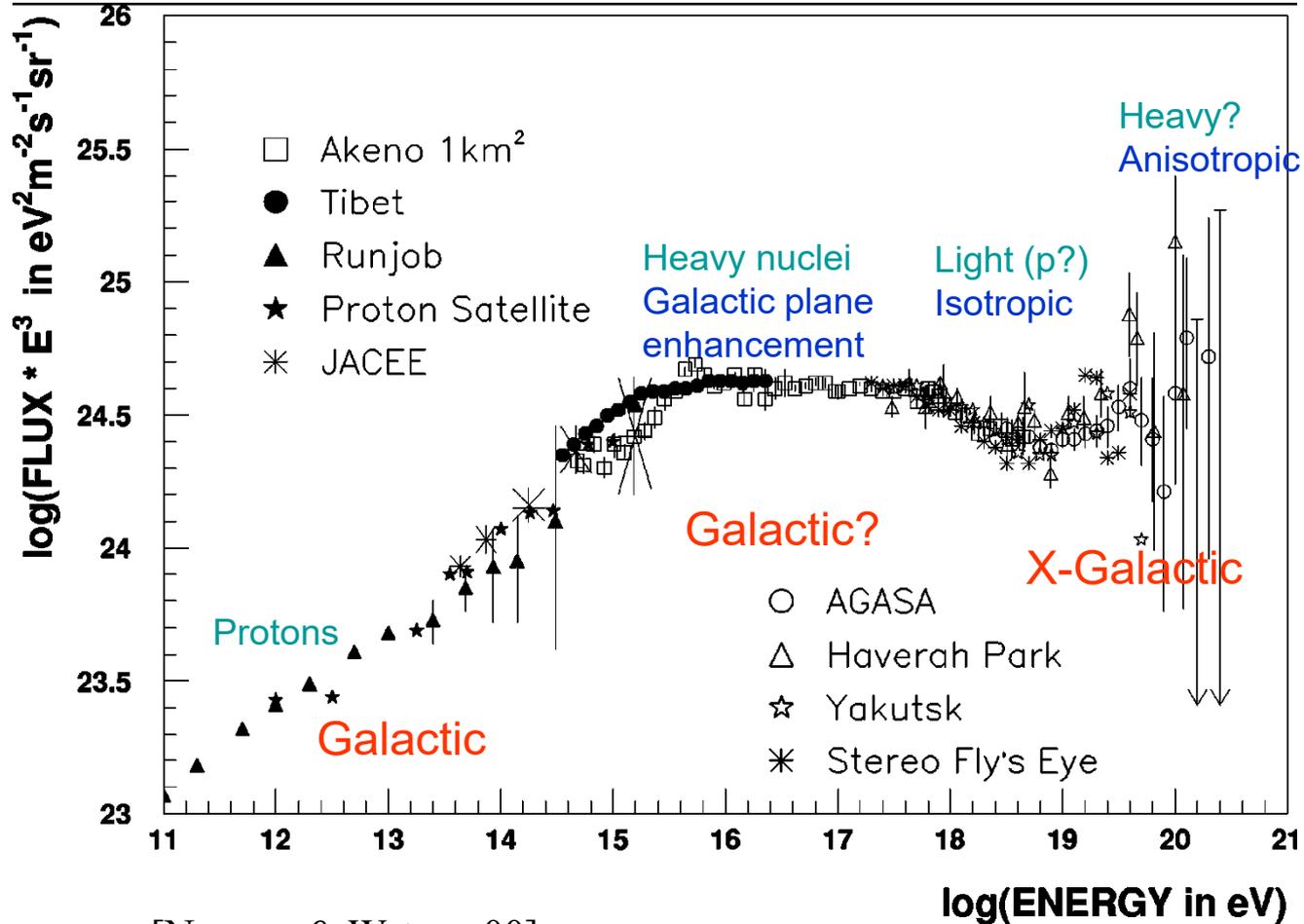
w/ SH Zhan, BT Li, W Wang (WHU)

Symposium of Ultra-High-Energy Gamma Rays from Supernova
Remnants and the Origin of Galactic Cosmic Rays

2026.02.28 - Chengjiang, Yuxi, Yunnan

CR origin?

Smoothly bended knee: likely Galactic (SNe?)

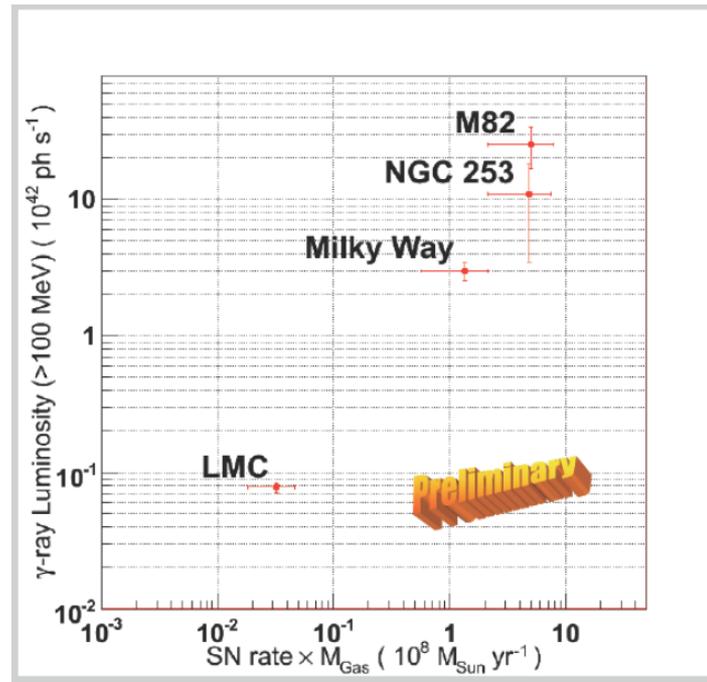


[Nagano & Watson 00]

Galactic CR sources: SNe?

- Motivation for SNe as sources:
 - * $L_{G,CR} \sim 10^{-1.5} L_{G,SN}$
 - * e^- acceleration to $\sim 10^{15} eV$ from non-therm X-ray
e.g. $20keV \rightarrow >200TeV(B/10\mu G)$
 - * e/p accelerated to $>10TeV$ from $>10TeV$ photons from SNR

- GeV_γ -SN relation



[Fermi-LAT team]

Which SNe?

- **Young** SNR with age \sim deceleration time, most promise as PeVatrons

$$E_p \lesssim 5 \frac{\mathcal{E} \epsilon_{B,-2}^{1/2} n_{-1}^{1/6}}{\mathcal{M}^{2/3}} \text{PeV}$$

E: in 10^{51} erg;
M: in $10 M_{\text{sun}}$

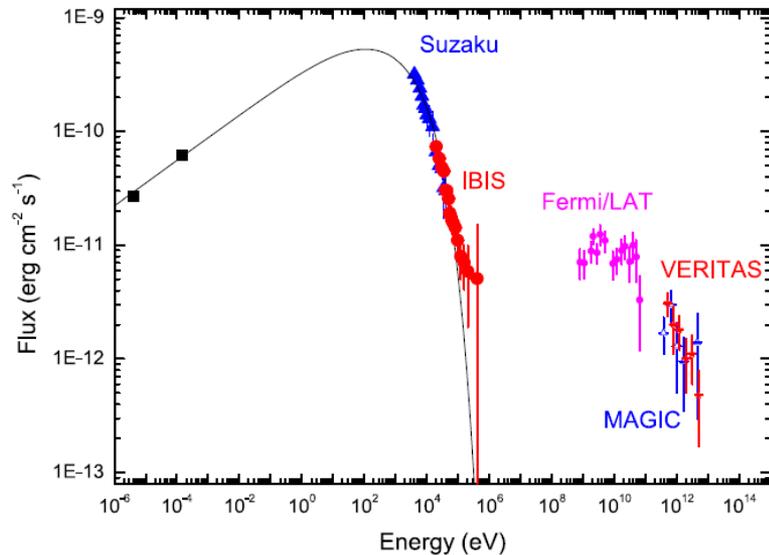
*But ISM B-field may not work

- Acceleration time (μG) \sim deceleration time $\rightarrow E < 100 \text{TeV}$

- **Type II SNe** more popular and energetic
- TeV photons from SNRs
 - * pp pion production?
 - * 100TeV photons from SNR?

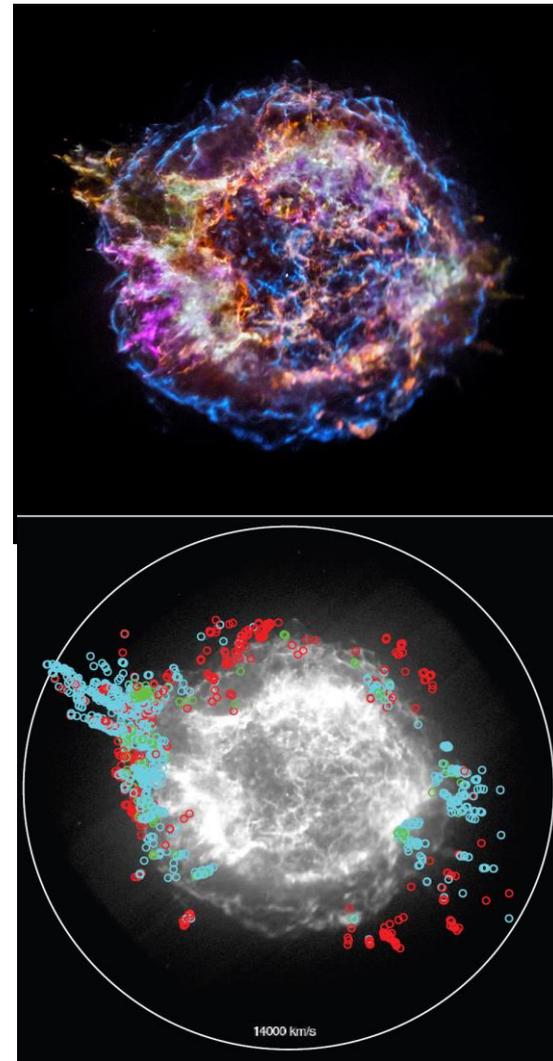
Cas A

- Type IIb; $t=350\text{yr}$, $d=3.4\text{kpc}$
- X-ray image: asymmetry
 - Shell: 5500km/s
 - Bipolar jets: $\sim 10\text{deg}$; ejecta knot prop motion $5500\text{-}14500\text{ km/s}$
- Broadband spectrum



[Wang&Li16]

Chandra



[Fesen+06]

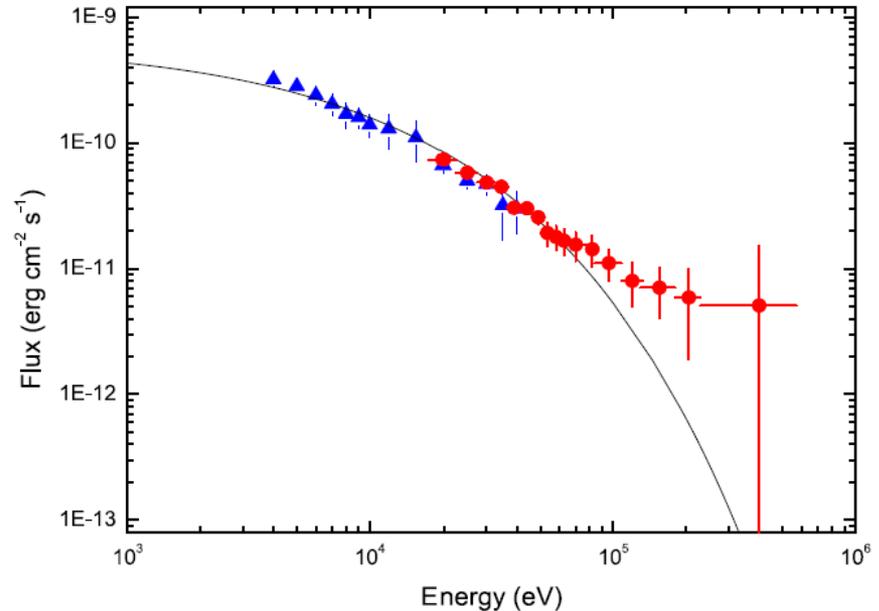
Integral hard X-ray data

- PL index ~ 3.1 , extending up to $>220\text{keV}$
- inconsistent with **exp decay by DSA theory**
- Max synch $\sim \text{keV}$: acc vs cooling

$$\epsilon_{\text{max}} \sim 3.8\xi^{-1}(\nu/5000 \text{ km s}^{-1})^2 \text{ keV}$$

- $>100\text{keV}$ origin \rightarrow require high **$v \sim 0.1c \gg \text{SN shell}$**
- **High-speed jet** model:
PL velocity profile \rightarrow PL hard X-ray:

$$v \simeq v_0 \left(\frac{\theta}{\theta_0} \right)^{-0.27}$$

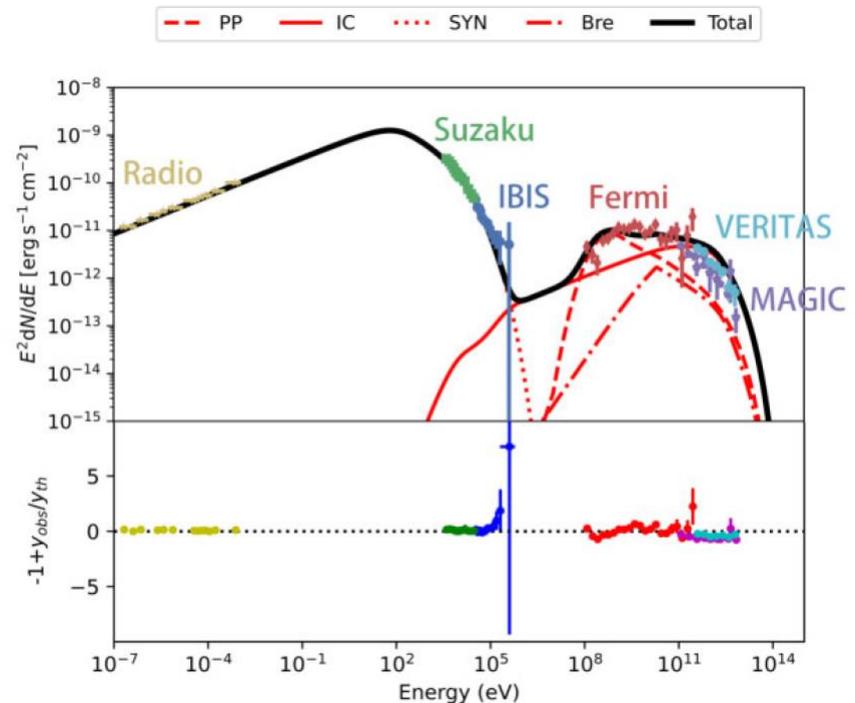
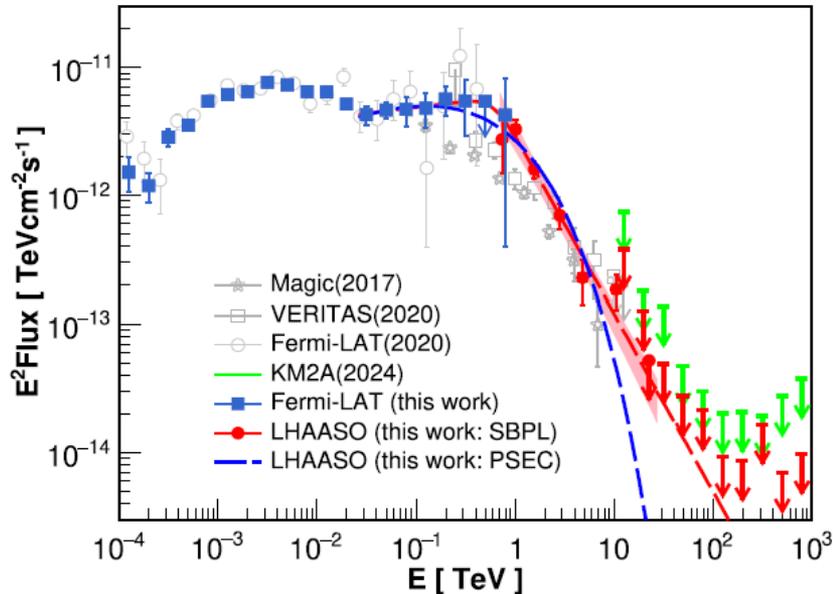


Data inconsistent with
Zirakashvili & Aharonian 07 model

[Wang & Li 16]

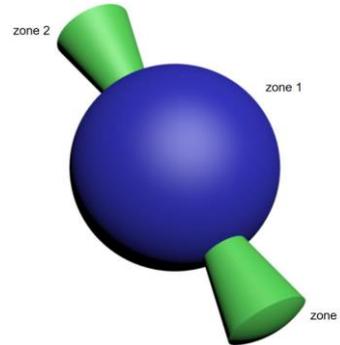
Fermi+LHAASO data

- Two components in UHE range [Cao+25]
- GeV-10TeV origin: **shell IC+pp** [Zhan+22]
- jet contribution?



Two-zone: shell+jet

- Components:
 - shell+jet
 - e+p (leptonic+hadronic)
- DSA framework



$V_{sh}=5000\text{km/s}$,
 $V_{jet}=30000\text{km/s}$
 $B_{sh}/B_{jet}=6$

$n_H=0.9/\text{cc}$ [Lee+14]

$$N_e(E) = A_e \left(\frac{E}{1 \text{ TeV}} \right)^{-\alpha} \exp \left(-\frac{E}{E_{cut,e}} \right) \times \begin{cases} 1 & E_{min,e} < E \leq E_b \\ (E/E_b)^{-1} & E > E_b \end{cases}$$

$$E_{min,e} = \max\{(\alpha - 2)(\alpha - 1)^{-1} m_p \epsilon_e v^2, 2m_e c^2\}$$

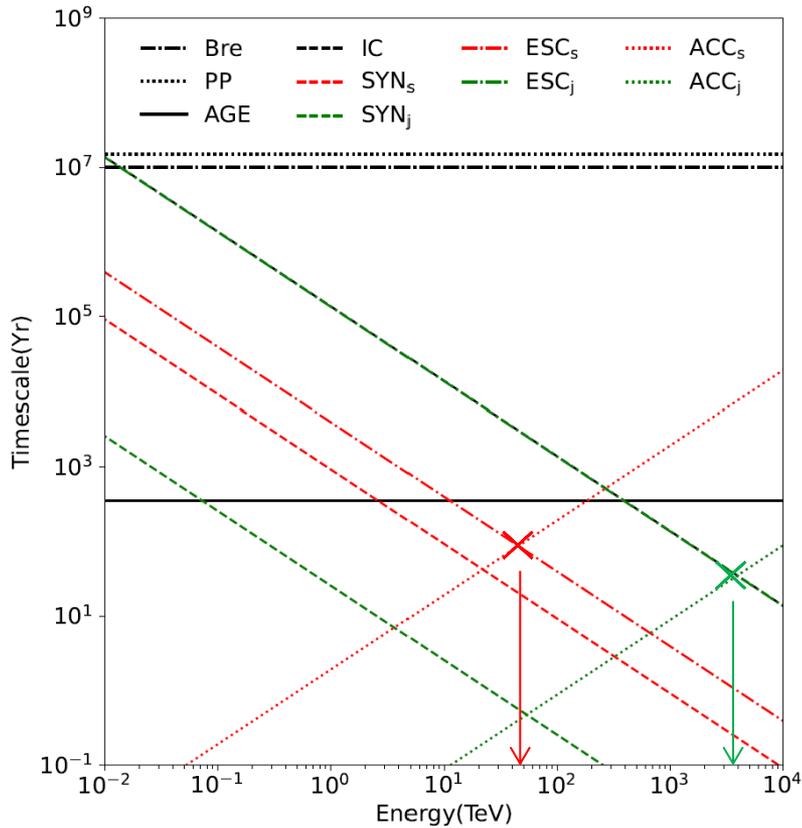
$$E_b \simeq 4 \left(\frac{B_d}{100 \mu\text{G}} \right)^{-2} \left(\frac{t_{age}}{350 \text{ yr}} \right)^{-1} \text{ TeV}$$

$$N_p(E) = A_p \left(\frac{E}{1 \text{ TeV}} \right)^{-\alpha} \exp \left(-\frac{E}{E_{cut,p}} \right)$$

$$E > E_{min,p}$$

$$E_{min,p} \simeq 2m_p c^2$$

Timescales, Max E



$$t_{\text{acc}} \approx \frac{20D}{v_s^2} = \eta_g \frac{20D_B}{v_s^2} = \eta_g \frac{20Ec}{3eB_u v_s^2}$$

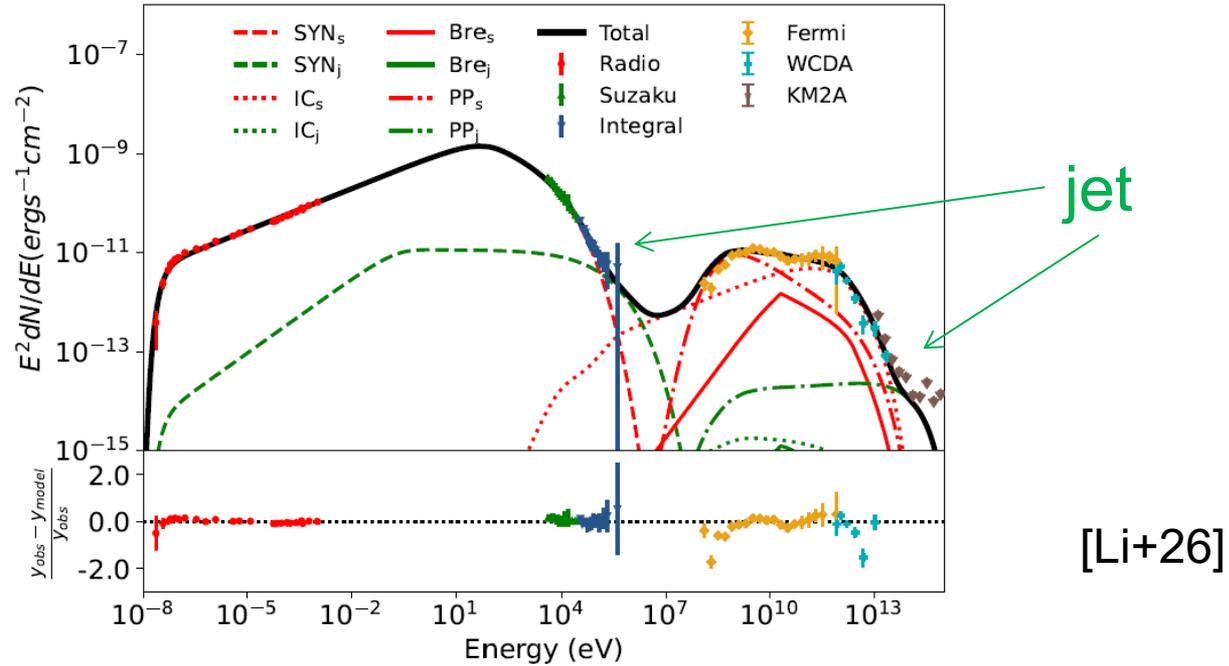
$$\tau_{\text{esc}} = \frac{(\kappa R)^2}{D} = \frac{(\kappa R)^2}{\eta_g D_B} = \kappa^2 \frac{3eB_u R^2}{\eta_g Ec}$$

$$E_{\text{cut,e}} \simeq \frac{40}{(\eta_g m)^{1/2}} \left(\frac{B_d}{100\mu\text{G}} \right)^{-1/2} \left(\frac{v_s}{5 \times 10^8 \text{cm s}^{-1}} \right) \text{TeV}$$

$$E_{\text{cut,p}} \simeq \frac{11.3}{\eta_g m} \left(\frac{B_d}{600\mu\text{G}} \right) \left(\frac{v_s}{0.1c} \right) \left(\frac{\kappa R}{0.3\text{pc}} \right) \text{PeV}$$

$$B_d/B_u \simeq m$$

Spectral modelling



Model	Zone	B_d (μG)	A_e (TeV^{-1})	A_p (TeV^{-1})	α	$E_{\text{cut},e}$ (TeV)	$E_{\text{cut},p}$ (TeV)	E_b (TeV)	W_e (erg)	W_p (erg)
M3	shell	119	5.37×10^{46}	3.16×10^{48}	2.44	21.75	45.12	2.60	8.53×10^{49}	1.75×10^{50}
	jet	714	2.00×10^{44}	2.51×10^{46}	2.00	53.46	3898	0.07	3.91×10^{45}	5.40×10^{47}

Model parameters

Cas A-like SNR as PeVatron?

- Jet CR insufficient? (leaky box)
 - $W_p = 5E47 \text{ erg}$
 - CR injection rate: $Q = W_p / 100 \text{ yr}$
 - $Q(E=1 \text{ PeV}) = 7E27 / \text{s GeV}$ for flat spectrum
 - CR intensity $J(E) = (c/4\pi)Q(E) t_{\text{conf}}(E) / \pi r_G^2 h_G = 9E-17 / \text{cm}^2 \text{ s sr GeV}$ @1PeV
 - $t_{\text{conf}}(1 \text{ PeV}) = 1.5 \text{ Myr}$, comparable to GeV CR

What CR production rate required for PeVatron?

How low is the 100TeV gamma-ray emission from SNR to rule it out?

Cas A-like SNR as PeVatron?

- PeV CR: **explosive SN + fast propagation**
 - **clumpy PeV CR distribution** in the Galaxy?
 - $J(E) = (c/4\pi)EN(E)/\pi r_c^3$
 - $r_c = 0.2 \text{ kpc}$, comparable to the Galactic thickness
 - To be clumpy needs: $t_{\text{conf}}/100\text{yr} < (r_G/r_c)^2$
 - $t_{\text{conf}}(1\text{PeV}) < 0.3\text{Myr}$

Observed PeV CR originated from past, local/nearby Cas A-like SN

summary

- 100keV emission/X-ray image
→ high-speed, $\sim 0.1c$, ejecta/jet
- → likely particle acceleration to 1PeV(B/muG)
- Shell: Max $E < \sim 100\text{TeV}$, **presently**
- Jet: possible PeVatron, but constrained by KM2A,
 $W < \sim 5E47\text{erg}$

- Cas A-like SNR still likely PeVatron, if with high-speed **jet**
& **clumpy** PeV CR. [Li+26]
- Deeper 100TeV observation for Cas A.