# 中等年龄超新星遗迹中的宇宙线加速与逃逸

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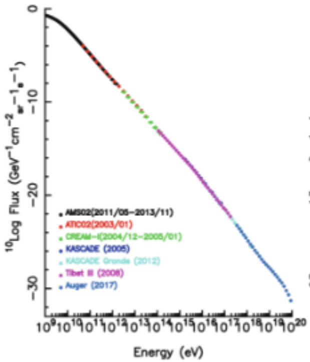
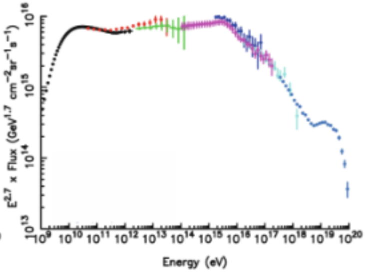
# Background




超新星遗迹作为宇宙线源的优势：

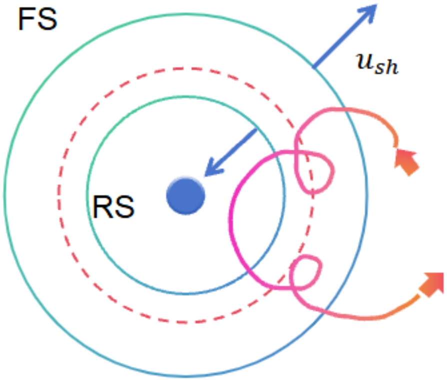
爆发能~$10^{51}erg$，转化率~0.1

超新星遗迹作为宇宙线源的挑战：

能否加速至PeV

逃逸宇宙线与远处分子云相互作用

# Model




$$f_0(t, p) = \frac{3\,\zeta_{CR}\,u_{sh}^2(t)\,\rho_0}{4\pi c\,(m_p c)^4\,\Lambda(p_{max,0}(t))}\left(\frac{p}{m_p c}\right)^{-\alpha}\Theta\,[p_{max,0}(t) - p]$$

能量转化率

归一化系数 $P_{CR} = \zeta_{CR} u_{sh}^2(t)\,\rho_0$

谱指数
( $\alpha$~4-4.4 from DSA)

假设：

(1)幂律谱

(2)能量转化率恒定

(3)遗迹内外扩散系数一致

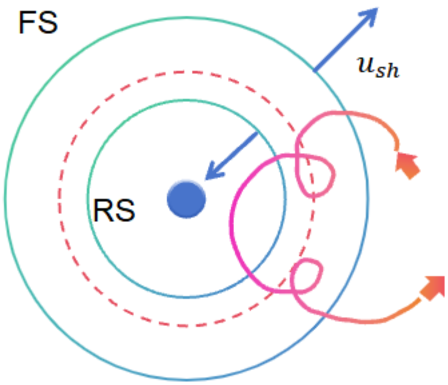
$$D_{in} = D_{out} = \chi 10^{28}\left(\frac{pc}{10GeV}\right)^{1/3} cm^2\, s^{-1}$$

(4)球对称ST阶段演化

$R_{sh} \propto t^{2/5}$　　$u_{sh} \propto t^{-3/5}$

S. Celli et al. 2019

# Model




contact discontinuity

S. Celli et al. 2019

$$p_{max,0}(t) = \begin{cases} p_M(t/t_{sed}), & t \le t_{sed} \\ p_M(t/t_{sed})^{-\delta}, & t > t_{sed} \end{cases}$$

SNR加速质子峰值能量

激波加速粒子能量逐渐衰减

逃逸时间 $$t_{esc}(p) = t_{sed}(p/p_M)^{-1/\delta}$$

逃逸半径 $$R_{esc}(p) = R_{sh}(t_{esc}(p))^{-1/\delta}$$

$$R_{\rm sh}(t) = \left(\xi_0 \frac{E_{\rm SN}}{\rho_0}\right)^{1/5} t^{2/5},$$

$$u_{\rm sh}(t) = \frac{2}{5}\left(\xi_0 \frac{E_{\rm SN}}{\rho_0}\right)^{1/5} t^{-3/5}$$

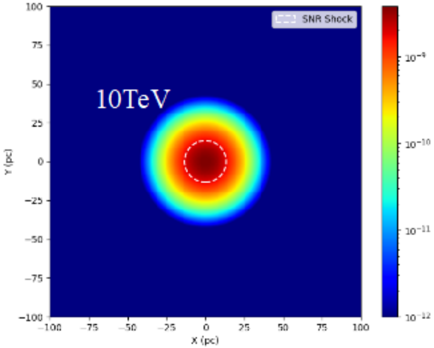
$$\frac{\partial f}{\partial t} + v \cdot \nabla f = \frac{p}{3} \frac{\partial f}{\partial p} \nabla \cdot v + \nabla \cdot [D \nabla f]$$

SNR内束缚宇宙线分布（$t < t_{esc}$）

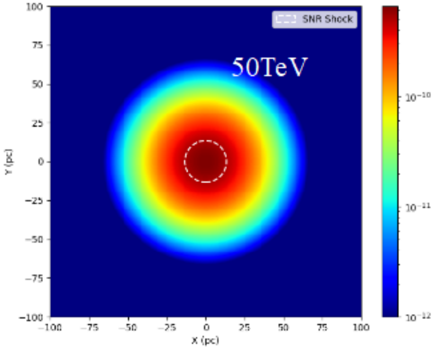
$$\frac{\partial f_{con}}{\partial t} + v \cdot \nabla f_{con} = \frac{p}{3} \frac{\partial f_{con}}{\partial p} \nabla \cdot v$$

逃逸宇宙线分布（$t > t_{esc}$）

$$\frac{\partial f_{esc}}{\partial t} = \nabla \cdot [D \nabla f_{esc}]$$




$\alpha$=4




不同能量的逃逸CR同一时间的空间分布

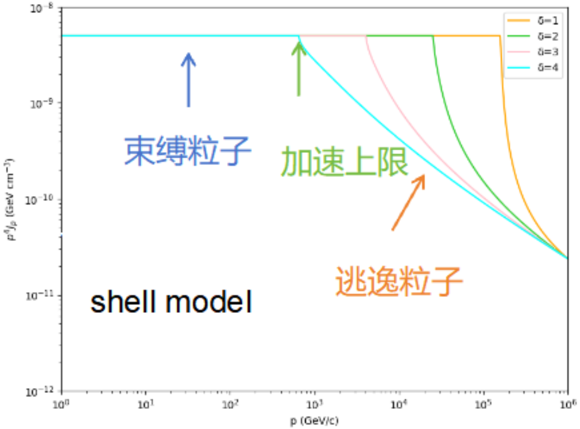
# Model

shell model:

$$J_p^{\rm in}(t,p) = \frac{4\pi}{V_{\rm SNR}} \int_0^{R_{\rm sh}(t)} [f_{\rm esc}(t,r,p) + f_{\rm conf}(t,r,p)]\, r^2 dr,$$

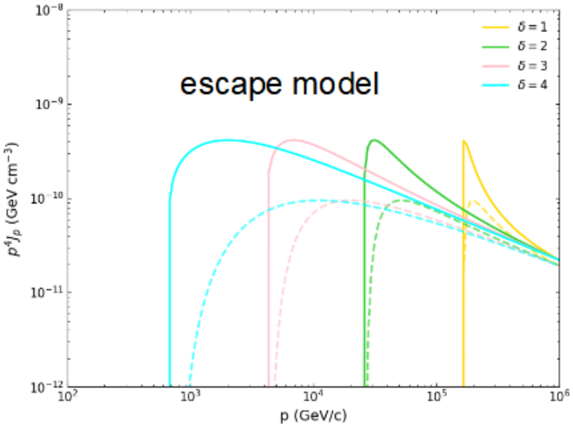
escape model:

$$J_p^{\rm out}(t,p) = \frac{3}{R_2^3 - R_1^3} \int_{R_1}^{R_2} [f_{\rm esc}(t,r,p)]\, r^2\, {\rm d}r.$$




SNR内部宇宙线能谱

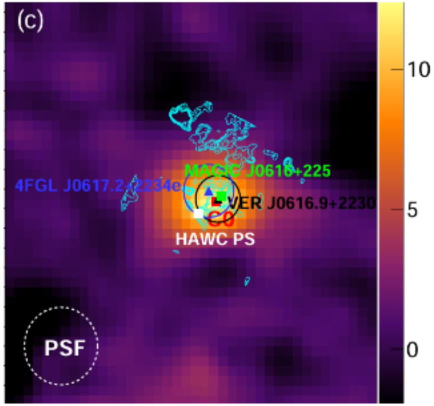
$\alpha$=4

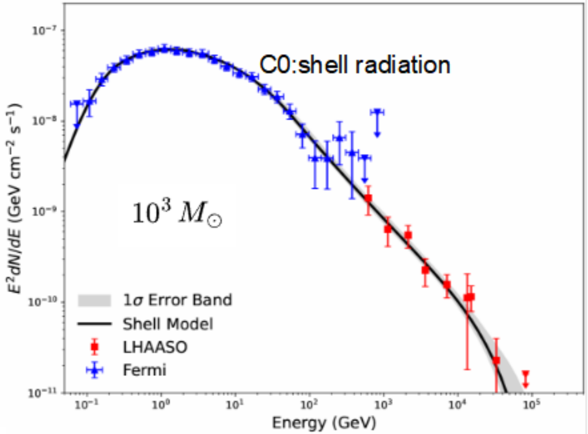


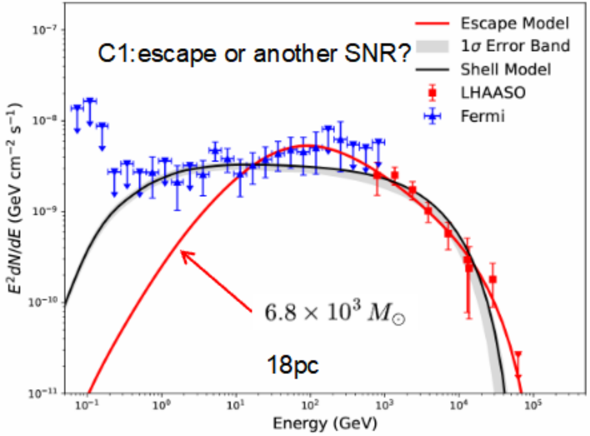

虚线：2Rsh-3Rsh
实线：1Rsh-2Rsh

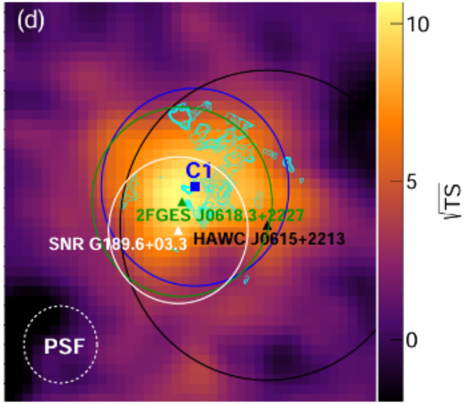
SNR外逃逸宇宙线能谱

# Radiation from IC 443




IC 443: ~10kyr, 10pc, 1.5kpc

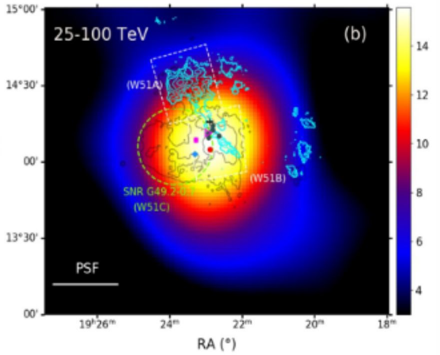
α~4.34 $p_M$~220TeV η~4% $D \sim 4 * 10^{26}(\frac{pc}{10GeV})^{1/3} cm^2 s^{-1}$

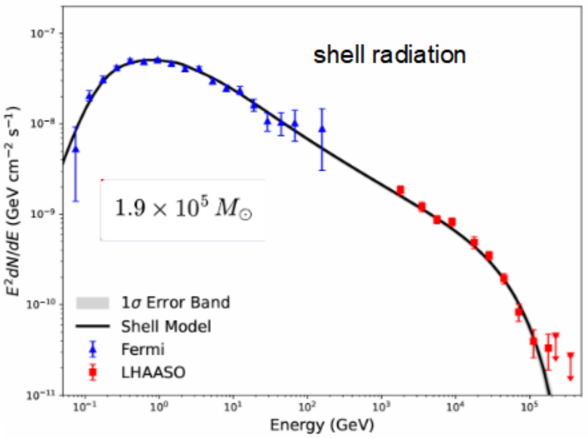
G189.6+03.3: ~100kyr, 20pc, 1.5kpc

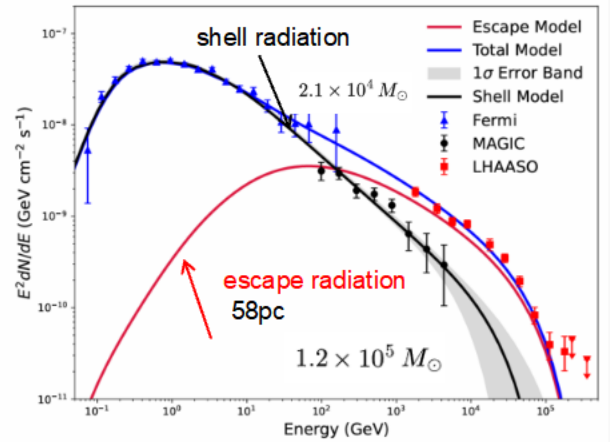
α~4 $p_M$~56TeV η~2% $D \sim 2 * 10^{24}(\frac{pc}{10GeV})^{1/3} cm^2 s^{-1}$

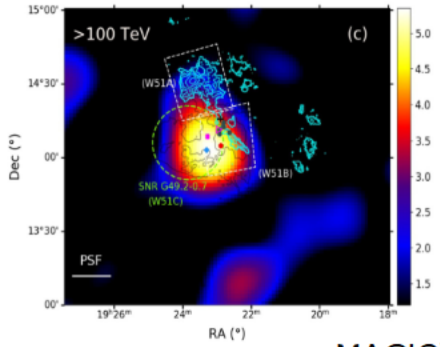
Zhen Cao, et al 2026

# Radiation from W51C




W51C: ~30kyr，24pc，5.5kpc

α~4 $p_M$~540TeV

η~4% $D \sim 3 * 10^{27} (\frac{pc}{10GeV})^{1/3} cm^2 s^{-1}$

LHAASO和Fermi来自同一成分

α~4.25 $p_M$~550TeV

η~11% $D \sim 1 * 10^{27} (\frac{pc}{10GeV})^{1/3} cm^2 s^{-1}$

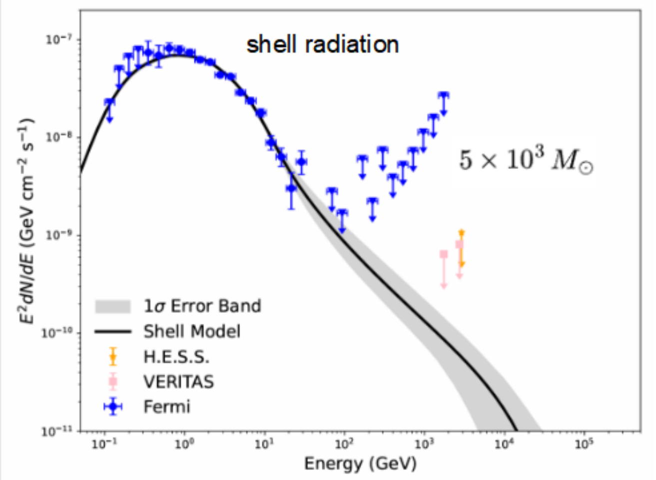
MAGIC和Fermi来自同一成分

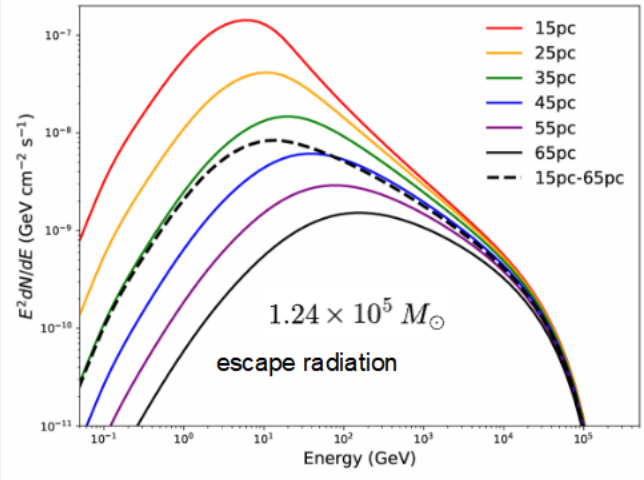
LHAASO coll. 2024

Fermi-LAT coll. 2009

MAGIC coll. 2012

# Radiation from W44



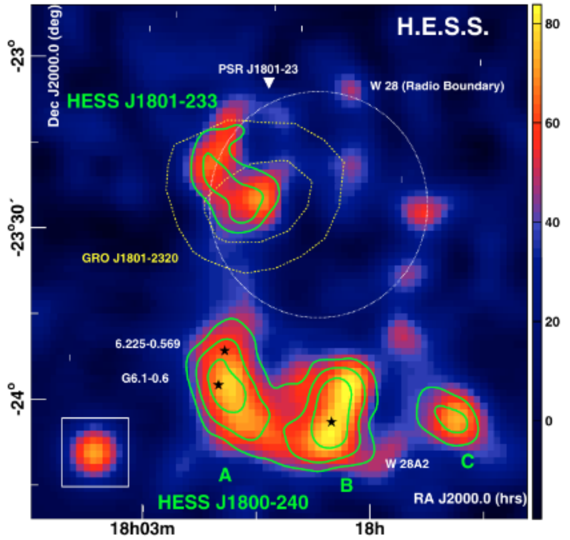

MAGIC coll. 2025

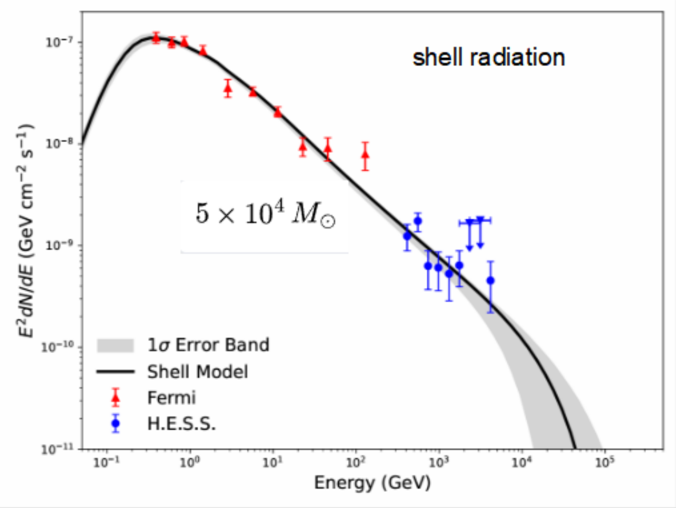
W44: ~20kyr, 13pc, 2.2kpc

α~4.25 $p_M$~105TeV

η~1% D~$1.8 * 10^{27}(\frac{pc}{10GeV})^{1/3} cm^2 s^{-1}$

# radiation from W28




H.E.S.S. coll. 2008

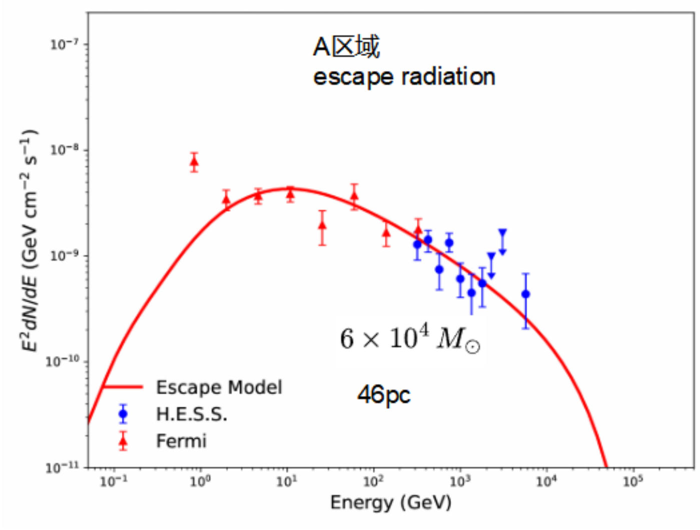
Yudong Cui,et al， 2018

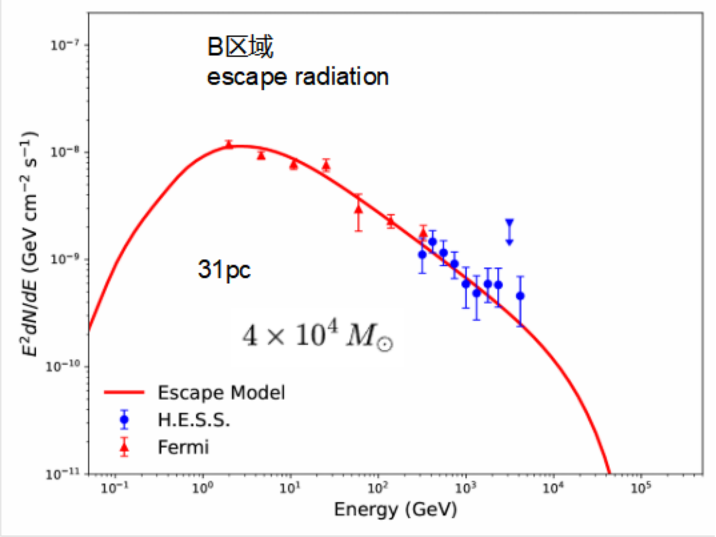
W28: ~35kyr，13pc，1.9kpc

α~4.21 $p_M$~170TeV

η~3% $D \sim 1.3 * 10^{27} (\frac{pc}{10GeV})^{1/3} cm^2 s^{-1}$

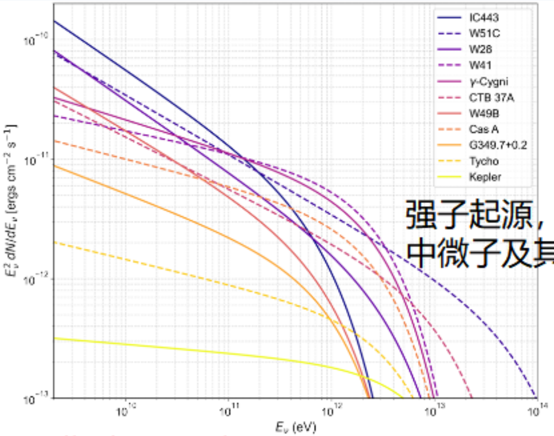
# radiation from W28



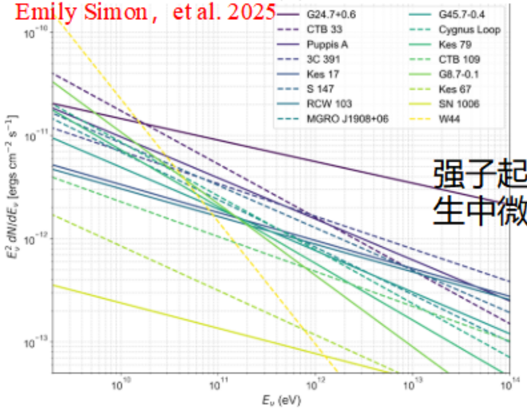

H.E.S.S. coll. 2008

# Neutrino

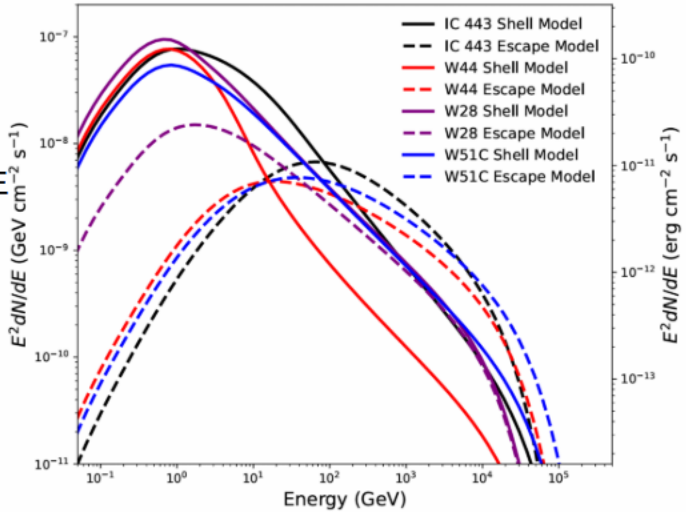



强子起源，有TeV辐射，产生中微子及其可能被探测

Emily Simon，et al. 2025




强子起源，没有TeV辐射，产生中微子不一定被探测




加入逃逸的贡献使得TeV以上中微子流量显著增加

# Discussion and summary

| SNR | $\mathcal{E}_{SN}$ [$10^{51}$ erg] | $\tau_{SN}$ [kyr] | $d$ [kpc] | $\alpha$ | $\delta$ | $\chi$ | $P_M$ (TeV $c^{-1}$) | $\eta_{cr}$ [a] |
|---|---|---|---|---|---|---|---|---|
| W51C [b] | 3.6 | 30 | 5.5 | $4.26^{+0.09}_{-0.08}$ | $3.50^{+0.31}_{-0.38}$ | $0.11^{+0.05}_{-0.04}$ | $164^{+345}_{-110}$ | 0.11 |
| W51C [c] | 3.6 | 30 | 5.5 | $4.00^{+0.005}_{-0.002}$ | $3.89^{+0.08}_{-0.10}$ | $0.29^{+0.03}_{-0.03}$ | $543^{+70}_{-59}$ | 0.04 |
| IC 443 | 1.0 | 10 | 1.5 | $4.34^{+0.03}_{-0.04}$ | $3.01^{+0.26}_{-0.29}$ | $0.04^{+0.01}_{-0.01}$ | $375^{+327}_{-183}$ | 0.04 |
| G189.6+3.3 | 1.0 | 100 | 1.5 | $4.03^{+0.04}_{-0.02}$ | $2.49^{+1.01}_{-1}$ | $0.0002^{+0.0008}_{-0.0001}$ | $56^{+27}_{-13}$ | 0.02 |
| W44 | 5.0 | 20 | 2.2 | $4.25^{+0.06}_{-0.08}$ | $1.82^{+0.34}_{-0.36}$ | $0.18^{+0.05}_{-0.04}$ | $105^{+385}_{-83}$ | 0.01 |
| W28 | 1.0 | 35 | 1.9 | $4.21^{+0.05}_{-0.05}$ | $2.97^{+0.48}_{-0.46}$ | $0.13^{+0.07}_{-0.04}$ | $172^{+393}_{-128}$ | 0.03 |

[a] $M_{cl} = 2.1 \times 10^4 M_\odot$ (W51C), $10^3 M_\odot$ (IC 443), $10^3 M_\odot$ (G189.6+3.3), $5 \times 0^3 M_\odot$ (W44), $5 \times 10^4 M_\odot$ (W28)
[b] For scenario 2.
[c] For scenario 1.

- 质子的最大能量被约束在约100–300 TeV。
- 加速宇宙线的谱指数被约束在一个较窄的范围内，约α ~ 4.2–4.3，这比标准扩散激波加速（DSA）模型的预言更陡，但与非线性（NL）DSA模型的预期一致。
- 超新星遗迹逃逸的扩散系数低于银河系平均值。对于10 GeV的质子，其典型值约为$10^{27}$ cm$^2$ s$^{-1}$，比标准值$10^{28}$ cm$^2$ s$^{-1}$低约一个量级，表明在超新星遗迹附近的扩散受到抑制。
- W51C的伽马射线数据存在两种解释。纯壳层模型虽能拟合Fermi和LHAASO谱形，但需要较硬的注入谱（α~4.0）。更倾向于双组分图像：壳层CR解释Fermi和MAGIC辐射，早期逃逸CR解释LHAASO的UHE辐射。
- IC 443的C0可由壳层模型解释。C1有两种可能：邻近SNR G189.6+3.3的壳层辐射（但α~4.03偏极端，扩散系数极其小）；逃逸CR与分子云相互作用（但低能区拟合较差）。强子模型均非完美，C1的轻子贡献不能被排除。