10^{15}eV- 10^{18}eV Cosmic Rays from Trans Relativistic SuperNovae

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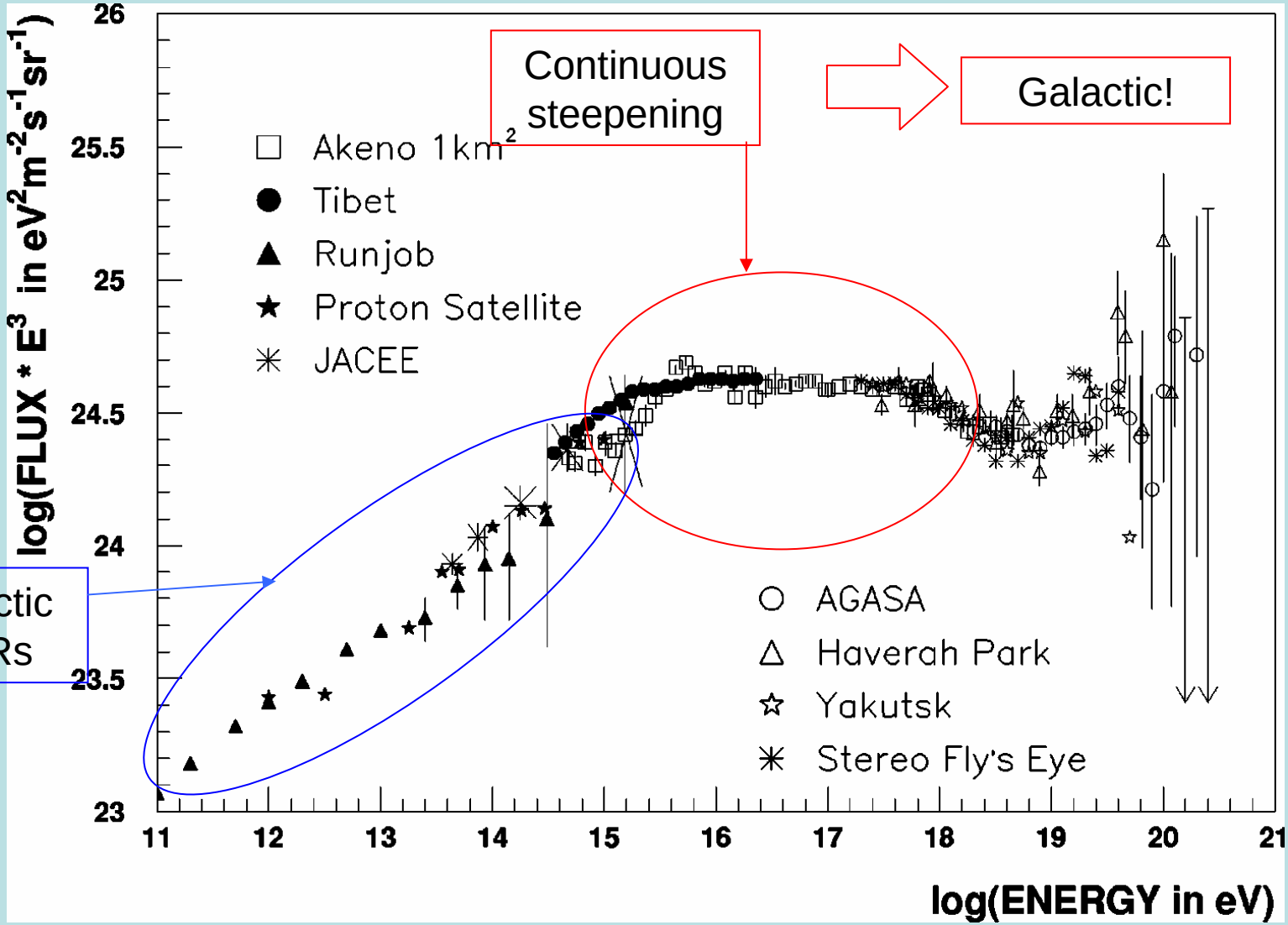
CR spectrum:



Nagano & Watson 2000

Wang et. al 2007:
Extra Galactic

Acceleration in SNR collisionless shocks

- Maximum energy: $\varepsilon_{\max} \sim eBVR$

- SNR:
  - $E_{SN} \sim 10^{51}$erg, $M_{ej} \sim \#M_{\odot}$, $n_{ISM} \approx 1 cm^{-3}$

$$\Rightarrow \quad R \sim \left(\frac{M_{ej}}{\rho_{ISM}}\right)^{1/3} \sim 1pc \qquad V \sim \left(\frac{E}{M_{ej}}\right)^{1/2} \sim 3 \cdot 10^{3} Km/s \quad (\beta \sim 0.01)$$

$$\varepsilon_B \approx 0.1, \qquad \Rightarrow \quad \varepsilon_{\max} \sim 10^{15} eV$$

Requires upstream amplification!

Constraint I:
Max E

- In a wind profile:

$$\varepsilon < 10^{16} Z_1 \epsilon_{B,-1}^{1/2} \left(\frac{\dot{M}_{-5}}{v_{w,8}} \right)^{1/2} \beta_{\rm ej,-2}^2 \gamma_{\rm ej} \, {\rm eV}$$

- In a homogeneous ISM:

$$\varepsilon < 3 \times 10^{17} Z_1 \epsilon_{B,-1}^{1/2} \left(\frac{M_{\rm ej}}{10 M_\odot} \right)^{1/3} n_0^{1/6} \beta_{\rm ej,-2}^2 \gamma_{\rm ej}^{2/3} \, {\rm eV}$$

Constraint II: Rates & Energetics

Demand : $\dot{N}_s \tau_{conf} \geq 1, \quad \frac{\dot{N}_s E_s \tau_{conf}}{V_G} = u_{CR}$

$$\zeta \left(\frac{E_s}{10^{51} erg} \right) < 0.03 \left(\frac{\dot{N}_{SN}}{10^{-2} yr^{-1}} \right)$$

$$\frac{\dot{N}_s}{\dot{N}_{SN}} > 3 \times 10^{-3} \left(\frac{\tau_{conf}}{10^{4.5} yr} \right)^{-1} \left(\frac{\dot{N}_{SN}}{10^{-2} yr^{-1}} \right)$$

$\zeta \approx 1$ is relative efficiency of acceleration at 10^{18}eV Vs. 10^{9}eV

Constraint III: Internal structure

- Producing 10^{18}eV flux while avoiding overproduction at 10^{15}eV:

$$\frac{E_k(>\beta(\varepsilon))}{E_k(>\beta(10^{18}eV))} < \left(\frac{\varepsilon}{10^{18}eV}\right)^{-1}$$

$$10^{15}eV < \varepsilon < 10^{18}eV$$

SNRs

1. Uniform velocity ejecta ("bulk velocity"):

$$\zeta\left(\frac{E_s}{10^{51}\,erg}\right) < 0.03\left(\frac{\dot{N}_{SN}}{10^{-2}\,yr^{-1}}\right) \Rightarrow E_s << 10^{51}\,erg$$

$$\beta \approx 0.1, 1 M_{Sol} \Rightarrow E_s > 10^{52}\,erg > E_{SN}$$

A uniform SN ejecta is excluded !

2. Velocity structure:

$$E_k(>\beta) \propto \beta^{-5} \propto \varepsilon^{-\frac{5}{2}}$$

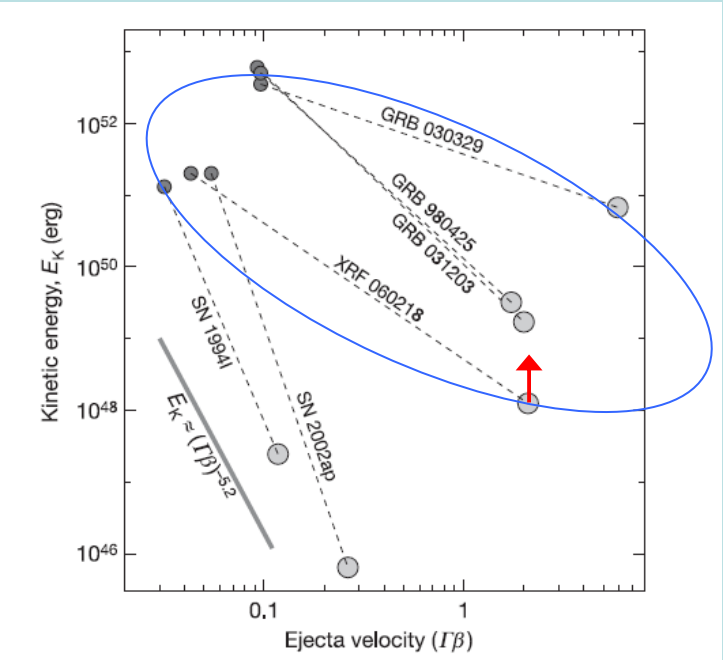
e.g. Matzner & McKee 1999

$$\frac{E_k(>\beta(\varepsilon))}{E_k(>\beta(\varepsilon_h))} \not< \left(\frac{\varepsilon}{\varepsilon_h}\right)^{-1}$$

The velocity gradient is too steep!

Trans Relativistic SuperNovae

- 4 known events:
  - 1998bw, 2003dh, 2003lw, 2006aj
- All associated with GRBs/XRF (Early detection)
- $\frac{E(>\gamma\beta\sim 1)}{E_{tot}} \geq 1\%$



Soderberg et.al. 2006

Kulkarni et. Al. 2000

Waxman 2004

Campana et. Al. 2006

Waxman, Meszaros, Campana 2007

TRSNe CRs

$$\frac{\dot{N}_{TRSNe}}{\dot{N}_{SNe}} \approx 10^{-2.5\pm0.5}$$

$$\frac{E_{TRSNe}}{E_{SNe}} \approx 10^{-1.5}$$

$$\zeta\left(\frac{E_s}{10^{51}\,erg}\right) < 0.03\left(\frac{\dot{N}_{SN}}{10^{-2}\,yr^{-1}}\right)$$ ✓

$$\frac{\dot{N}_s}{\dot{N}_{SN}} > 3\times10^{-3}\left(\frac{\tau_{conf}}{10^{4.5}\,yr}\right)^{-1}\left(\frac{\dot{N}_{SN}}{10^{-2}\,yr^{-1}}\right)$$ ✓

$$\left(\text{Since } R_L \approx 40\left(\frac{B}{3\mu G}\right)^{-1}\left(\frac{\varepsilon}{10^{18}\,eV}\right)\left(\frac{Z}{10}\right)^{-1} pc, \text{ no large anisotropy expected}\right)$$

Summary

- We derived 3 independent constraints on Galactic candidate sources of CRs in the range 10^{15}eV- 10^{18}eV.
- Classical SNR ejecta can not be the source of these CRs.
- The properties of TRSNe allow them to satisfy all the constraints.

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THE END

Definition of ζ

$$\varepsilon^2 \frac{dN}{d\varepsilon} = \zeta_{\rm s}(\varepsilon) E_{\rm s}.$$

$$\zeta \equiv \zeta_{\rm s}(10^{18}\ {\rm eV}) / \zeta_{\rm SN}(10^{9}\ {\rm eV}).$$

Under our assumptions ζ~1 !