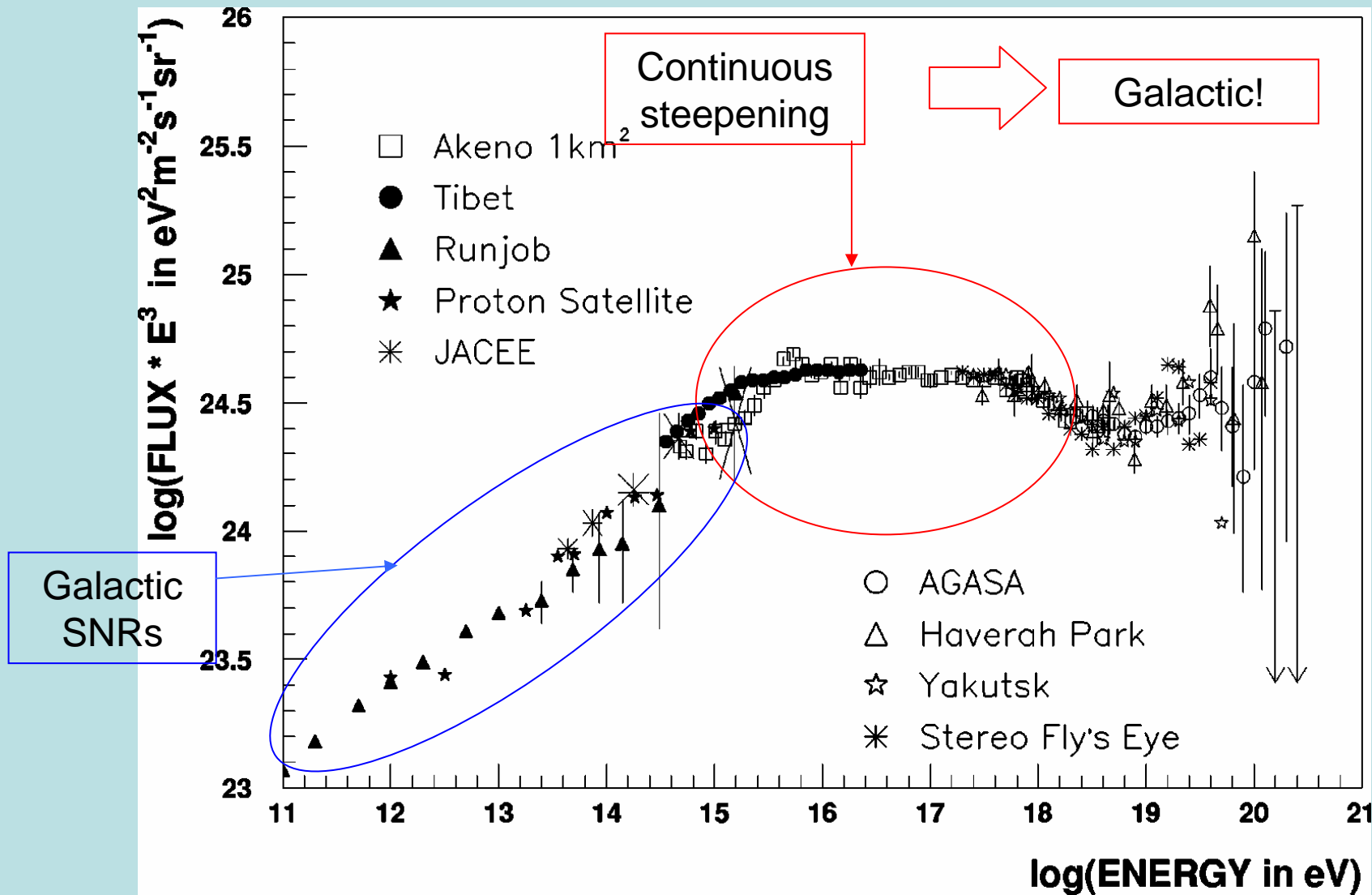


# $10^{15}\text{eV}$ - $10^{18}\text{eV}$ Cosmic Rays from Trans Relativistic SuperNovae

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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:

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

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

$$\varepsilon_B \approx 0.1,$$

$$\Rightarrow \varepsilon_{\max} \sim 10^{15} \text{ eV}$$

Requires upstream amplification!

# Constraint I: Max E

- In a wind profile:

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

- In a homogeneous ISM:

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

# Constraint II: Rates & Energetics

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

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

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

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

# 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”):

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

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

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

$$\frac{E_k(> \beta(\varepsilon))}{E_k(> \beta(\varepsilon_h))} \propto \left( \frac{\varepsilon}{\varepsilon_h} \right)^{-1}$$

The velocity gradient is too steep!

# Trans Relativistic SuperNovae

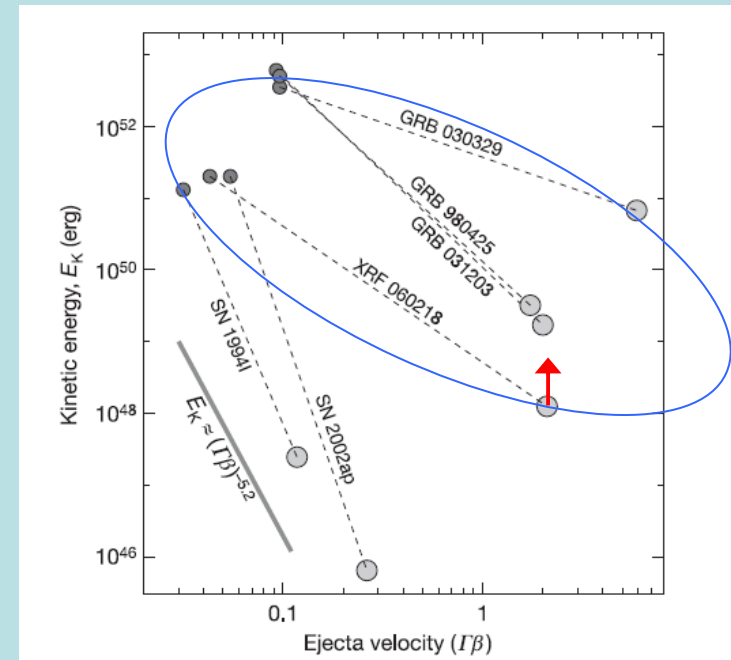
- 4 known events:
  - 1998bw, 2003dh, 2003lw, 2006aj
- All associated with GRBs/XRF (Early detection)
- $\frac{E(> \gamma\beta \sim 1)}{E_{tot}} \geq 1\%$

Kulkarni et. Al. 2000

Waxman 2004

Campana et. Al. 2006

Waxman, Meszaros, Campana 2007



Soderberg et.al. 2006

# TRSNe CRs

$$\frac{\dot{N}_{TRSNe}}{\dot{N}_{SNe}} \approx 10^{-2.5 \pm 0.5}$$

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

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

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

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

# Summary

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

**THE END**

# Definition of $\zeta$

$$\varepsilon^2 \frac{dN}{d\varepsilon} = \zeta_s(\varepsilon) E_s.$$

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

Under our assumptions  $\zeta \sim 1$  !