General Constraints on Shocks from Cosmic-Ray Observations

R. Cowsik

McDonnell Center for the Space Sciences and Physics Department
Washington University in St. Louis

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The Nuclear Component

- $F \sim E^{-2.67}$ which requires $M \approx 2.5$

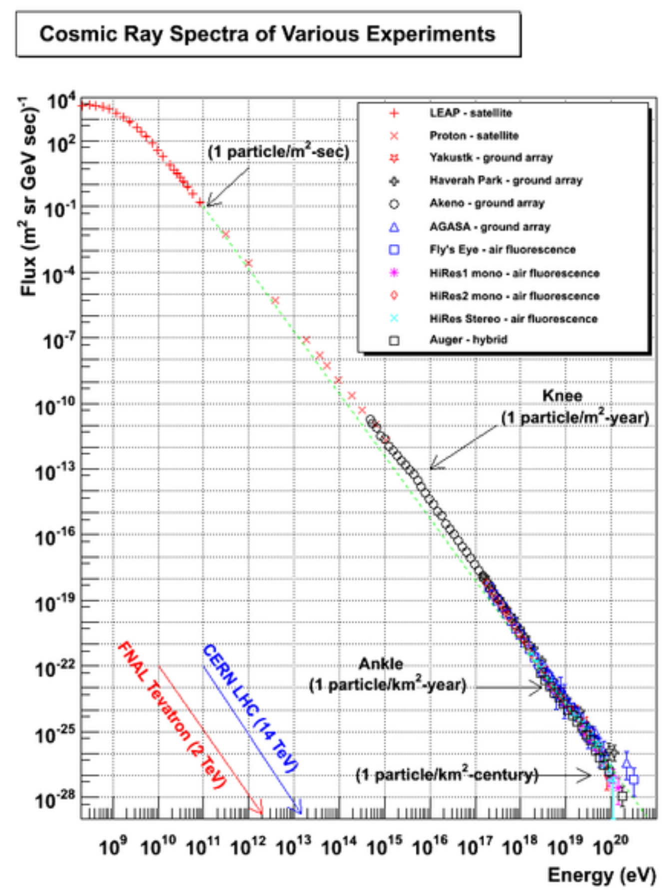
$$\rho_{CR} \sim 10^{-12}\ erg\ cm^{-3}$$

$$L_{CR} \sim \frac{\rho_{CR} V_G}{\tau_{CR}} \sim 10^{41}\ erg\ sec^{-1}$$

$$L_{kinetic}(SN) \lesssim \frac{10^{51}\ erg}{30yr} \approx 10^{42}\ erg\ s^{-1}$$

- For SNs to be responsible, shocks must slow from $M \sim 1000$ to $M \sim 2.5$

$$E_{kin} \sim \frac{1}{400} \times 10^{42} \approx 10^{40}$$

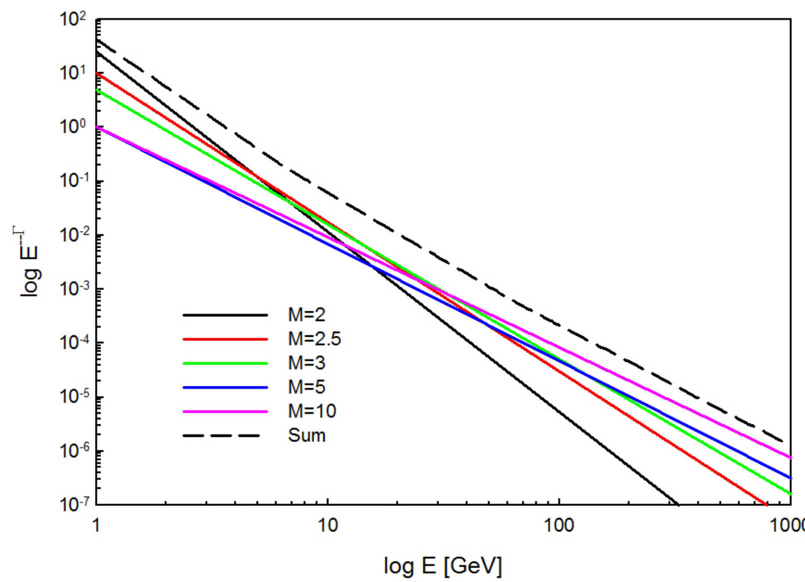


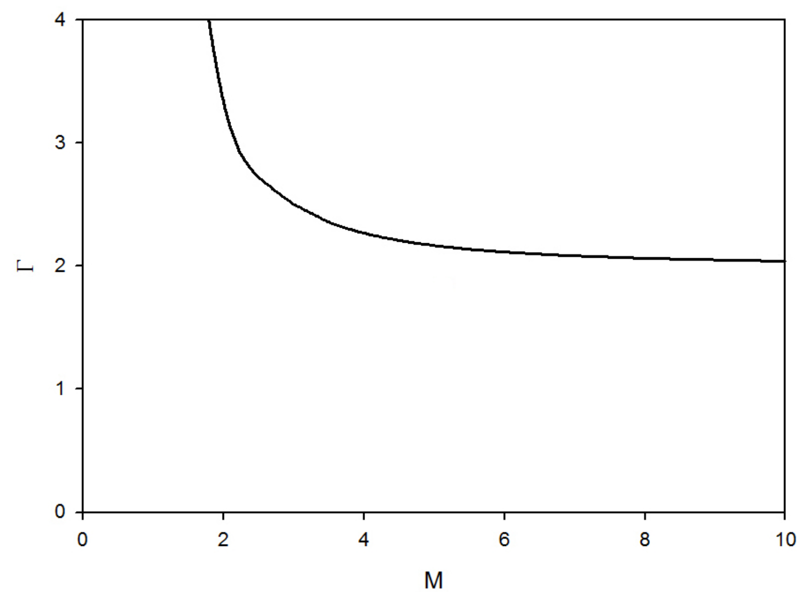
Spectra From Shocks

- How do we reproduce the spectrum up to the GZK cutoff ~10^{20} eV?
- If multiple shocks contribute, can they match up to the observed spectrum?

$$\Gamma = \left(\frac{x+2}{x-1}\right)$$

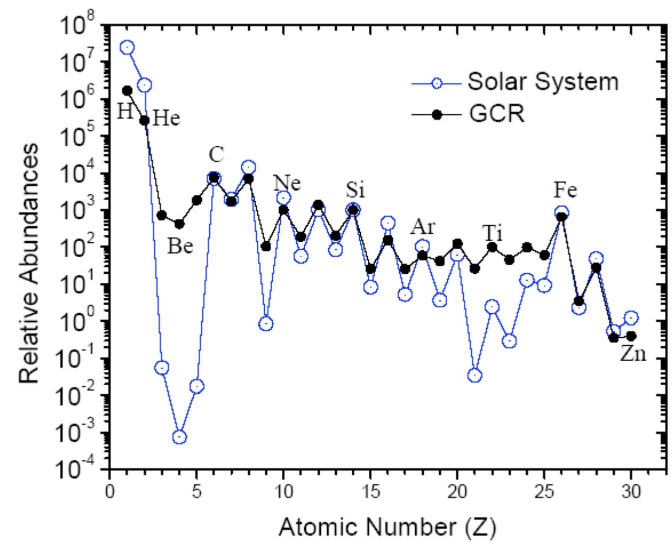
$$\frac{1}{x} = \left(\frac{\gamma-1}{\gamma+1}\right) + \frac{2}{M^2(\gamma+1)}$$

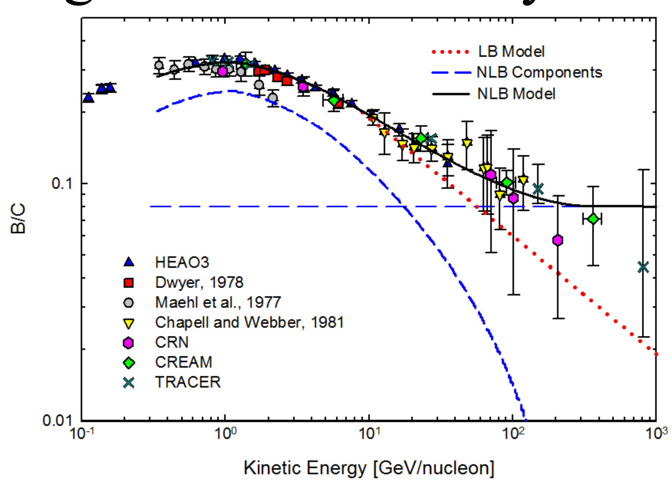


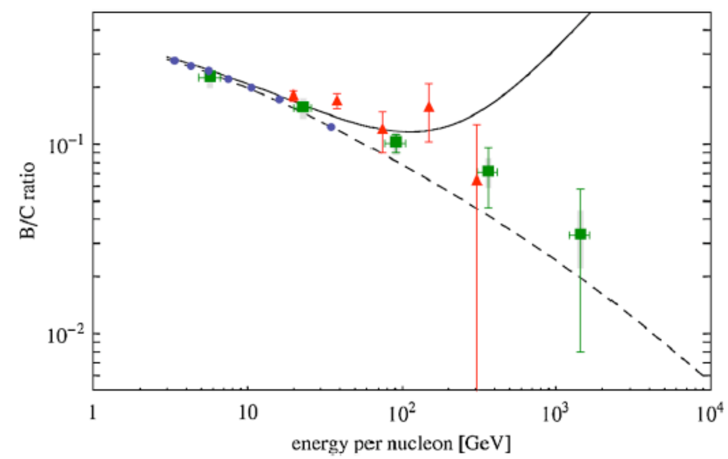


Cosmic Ray Composition

- Elemental abundances at sources (solar + massive stars): ^{22}Ne, Ga, …
- Spallation also in the sources, but no reacceleration
- What is the effect of SN shocks on galactic cosmic rays?







Cowsik, ApJ, **241**, 1195 (1980); Mertsch & Sarkar, PRL, **103**, 081104 (2009); Cowsik and Burch, arXiv:0908.3494

Time Delay After Nucleosynthesis

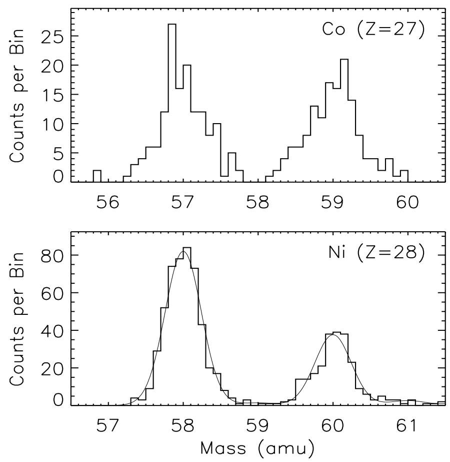
No ^{59}Ni but there is ^{59}Co

$$^{55}Co \xrightarrow[182h]{ec,\beta^+} {}^{55}Fe \xrightarrow[2.6yr]{ec} {}^{55}Mn$$

$$^{56}Ni \xrightarrow[6.1d]{ec} {}^{56}Co \xrightarrow[77d]{ec,\beta^+} {}^{56}Fe$$

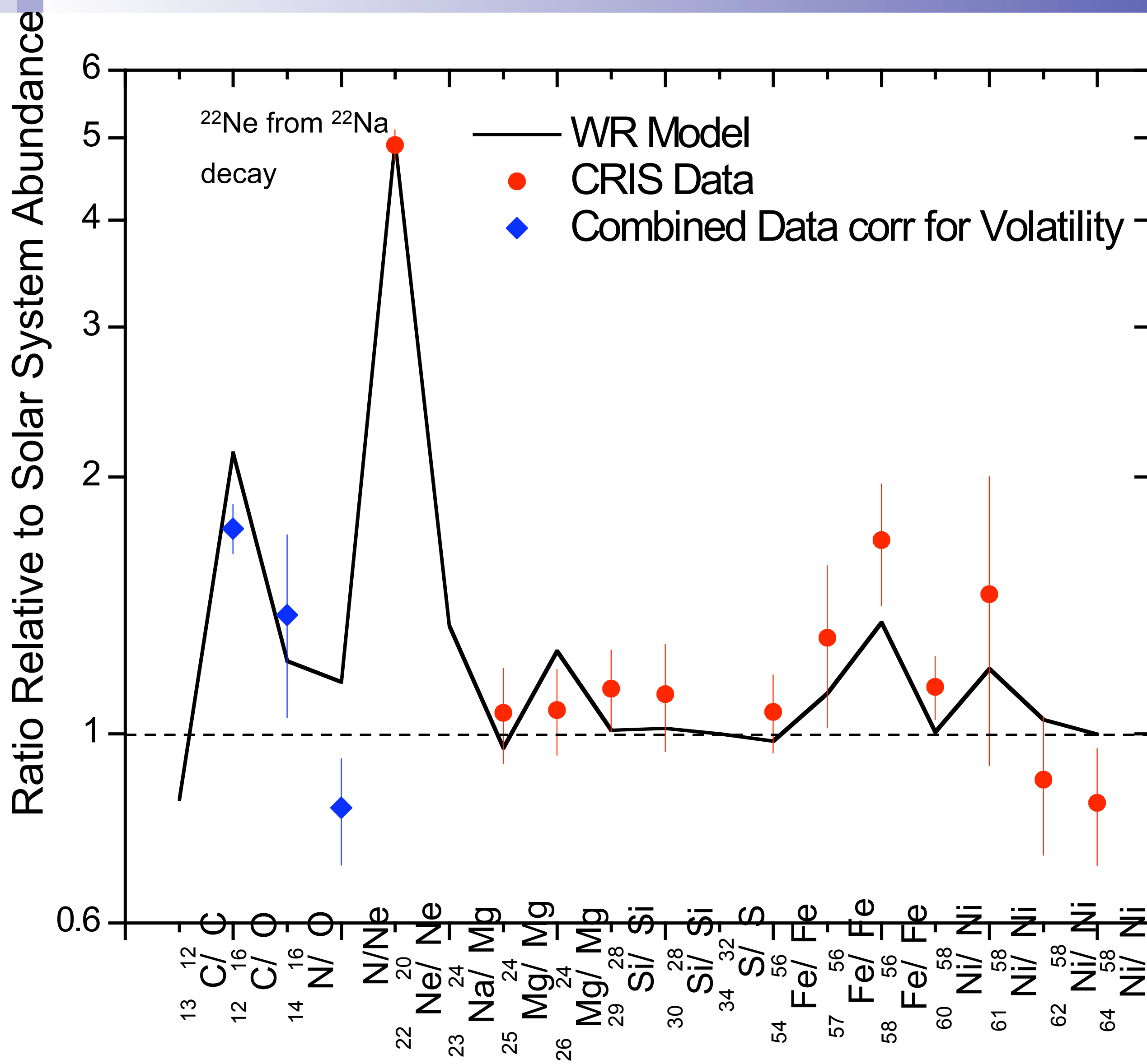
$$^{57}Ni \xrightarrow[36h]{ec,\beta^+} {}^{57}Co \xrightarrow[270d]{ec} {}^{57}Fe$$

$$^{59}Cu \xrightarrow[81s]{ec,\beta^+} {}^{59}Ni \xrightarrow[8\times10^4yr]{ec} {}^{59}Co$$



Delay > 10^5 years

From Wiedenback et al., 1999.

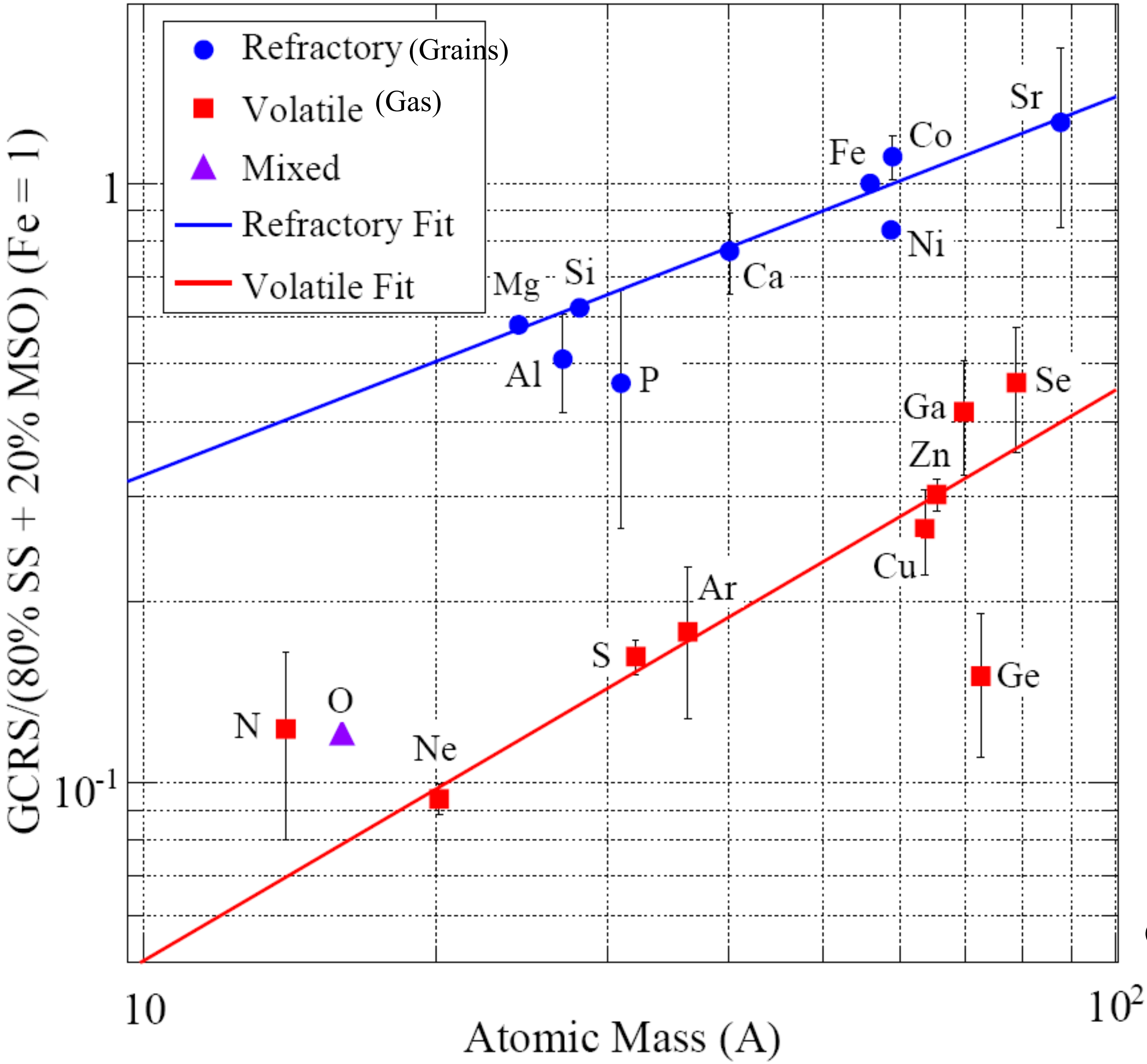


Data points give cosmic-ray source abundance ratios relative to SS.

Line shows expected composition from a mixture of 80% SS abundances plus 20% outflow from Wolf-Rayet stars.

The composition suggests OB associations as the location of cosmic-ray acceleration

Binns et al. *Ap.J.* **634** 351 (2005)



Now compare GCR source abundances with a mixture of 80% SS (Lodders) and 20% Massive Star Outflow (Woosley & Heger).

About 12% of oxygen is expected to be in grains, so the position of O between the two lines is about right.

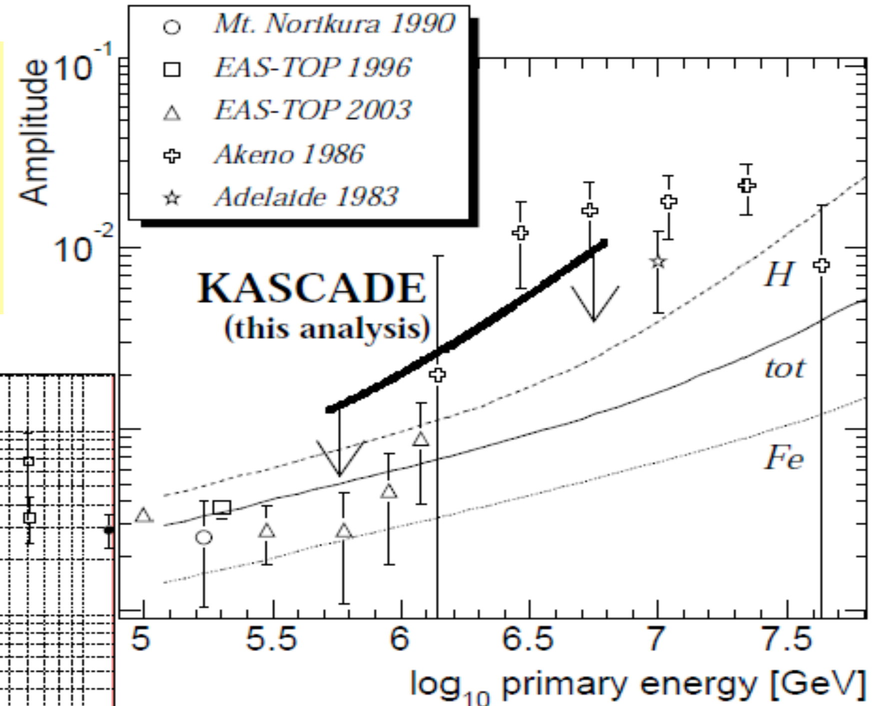
Sputtered refractory grains contribute to cosmic rays.

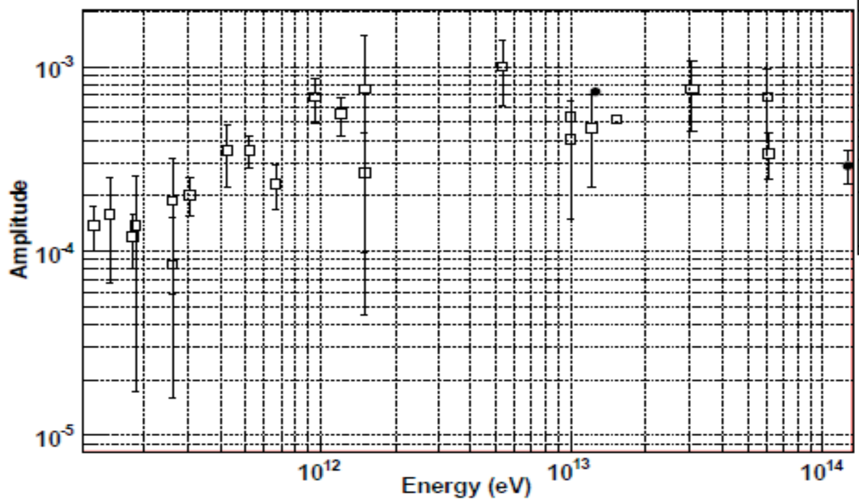
OB Associatons match abundances.

(M.H. Israel, private communication)

Isotropy and Constancy

Isotropy at high energies requires large number of contributing sources, and residence time independent or weakly dependent on energy.

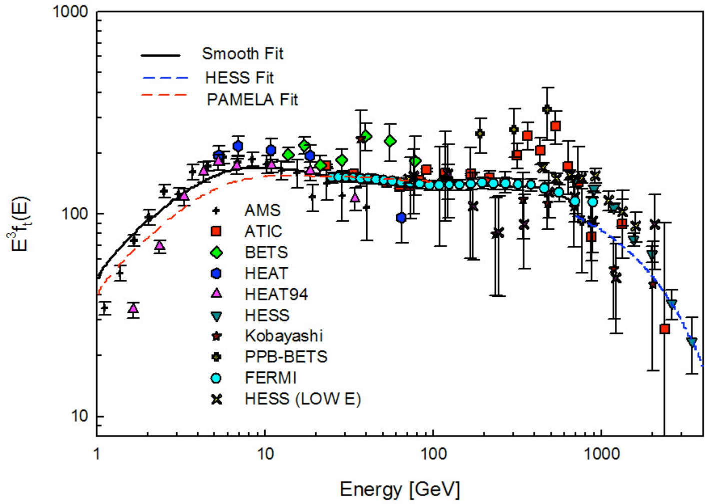


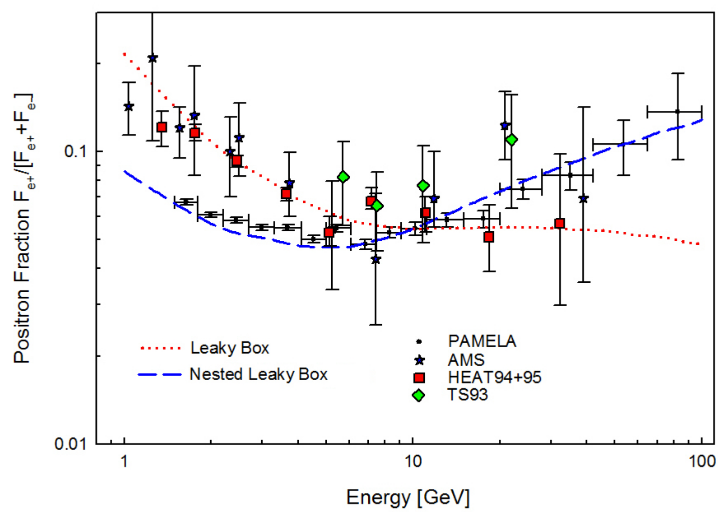


^{10}Be in ocean sediments indicate that cosmic-ray intensities were nearly constant over the last 10 million years. Again, a smooth distribution of sources in time and space is indicated.

The Electronic Component

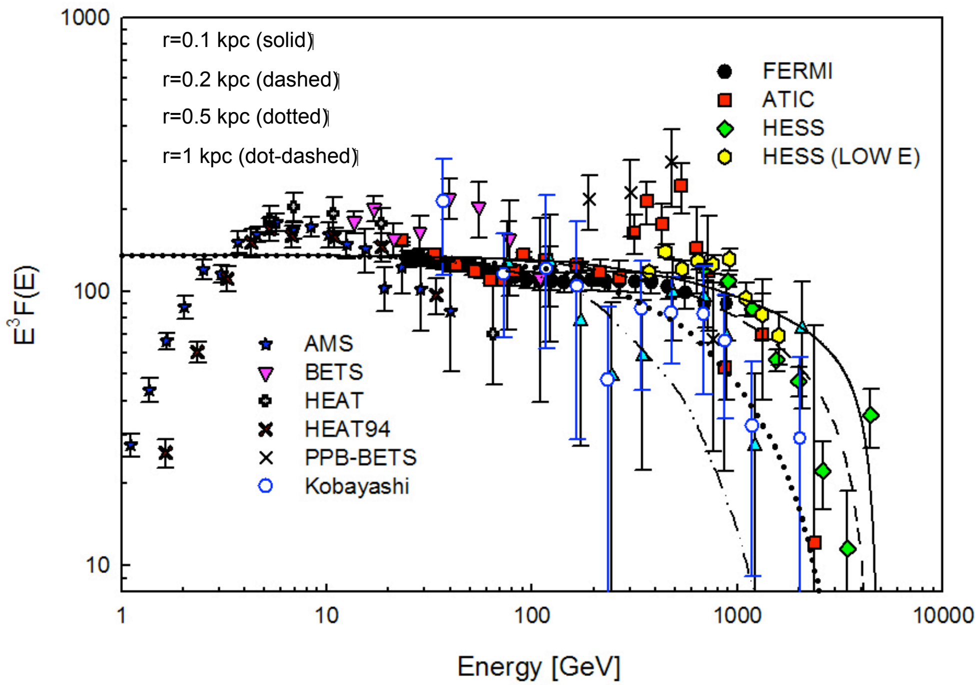
- 1/100 of the nuclear component at 1 GeV
- Extends up to 4 TeV
- Does this different spectrum of electrons come from the same source?



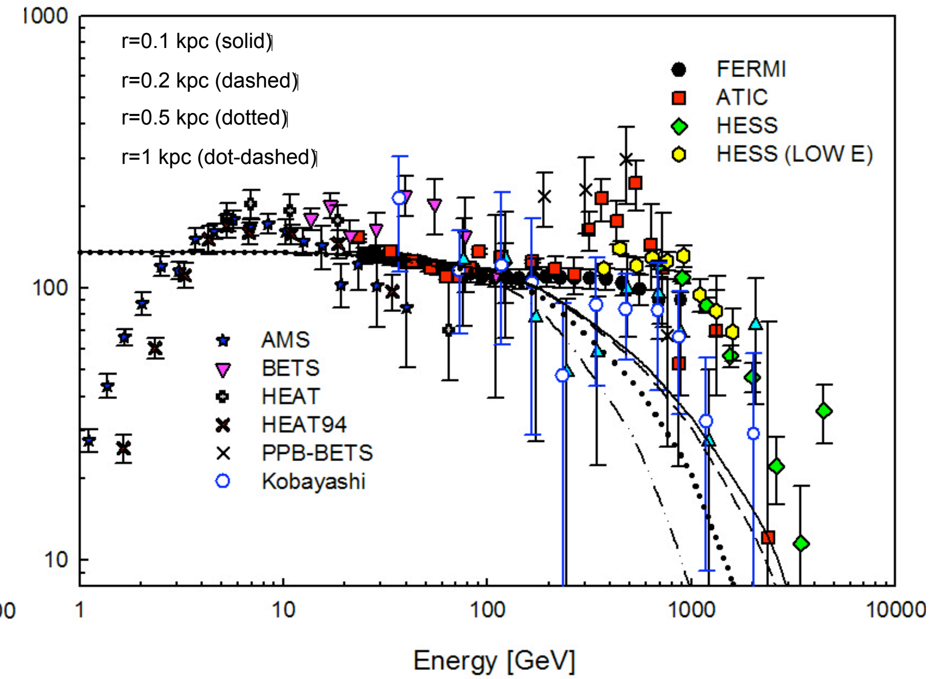


Discrete Sources

Single source



Sum over sources out to 10 kpc



Nearby sources at ~ 100-200 pc are needed.

Cowsik and Burch, arXiv:0908.3494; Coswik and Lee, ApJ, **228**, 297 (1979).

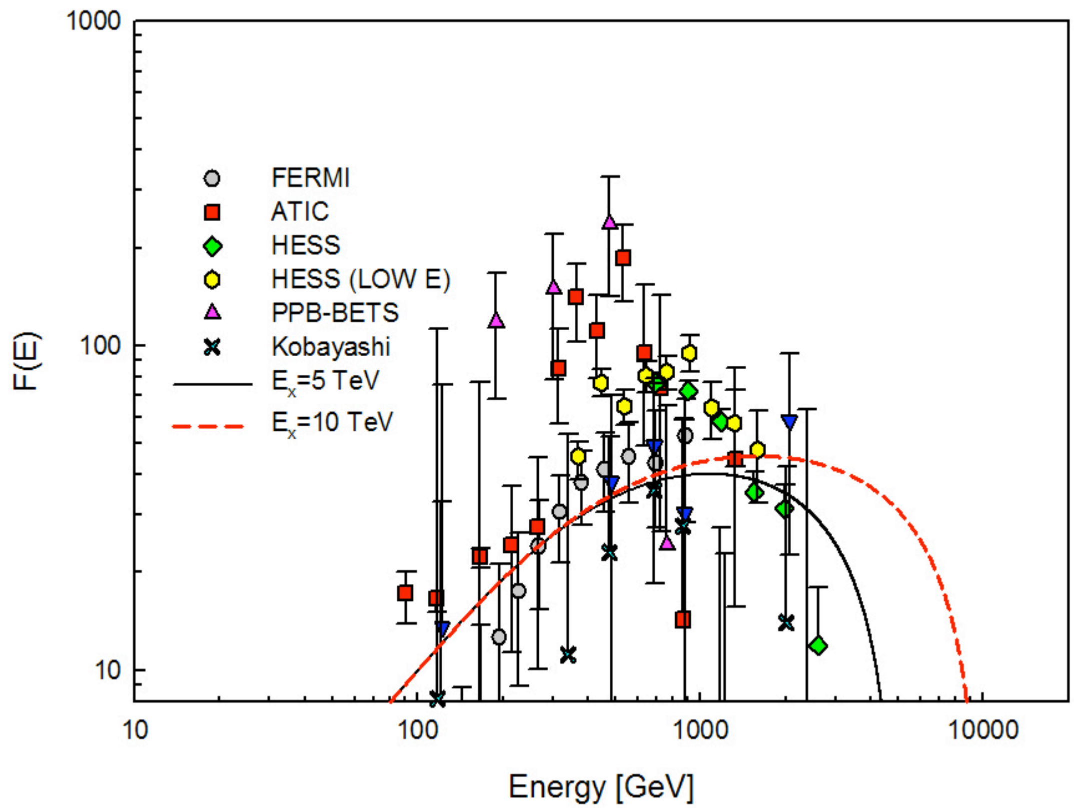
Leftover Shock-like Spectrum at 600 GeV?

- Particle acceleration at planar shocks of high Mach number lead to a power law input up to a cutoff energy

$$Q_{shock}(E) \sim Q_0 E^{-2}$$

- Results in a spectrum which reasonably fits the excess in the primary spectrum

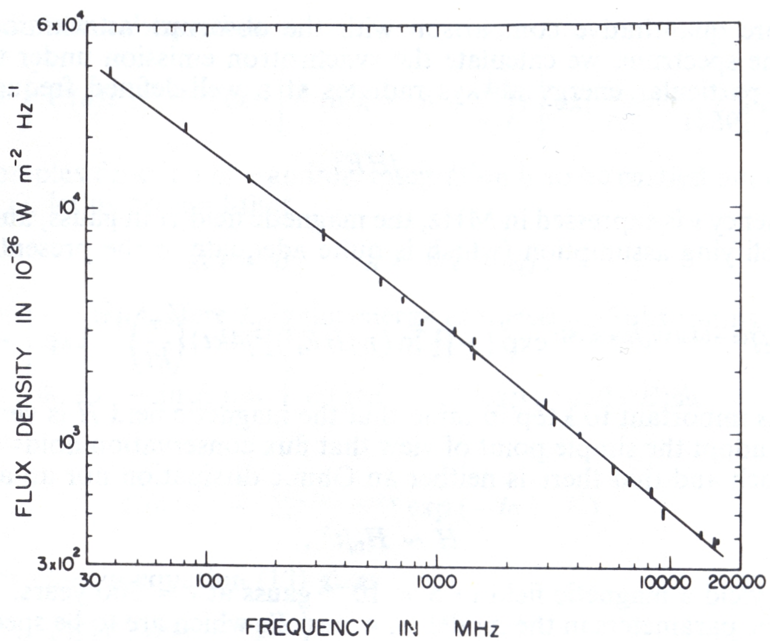
$$f_2(E) = \frac{\tau Q_0}{E^2}\left(1 - e^{-\frac{E_x - E}{bEE_x\tau_G}}\right)$$



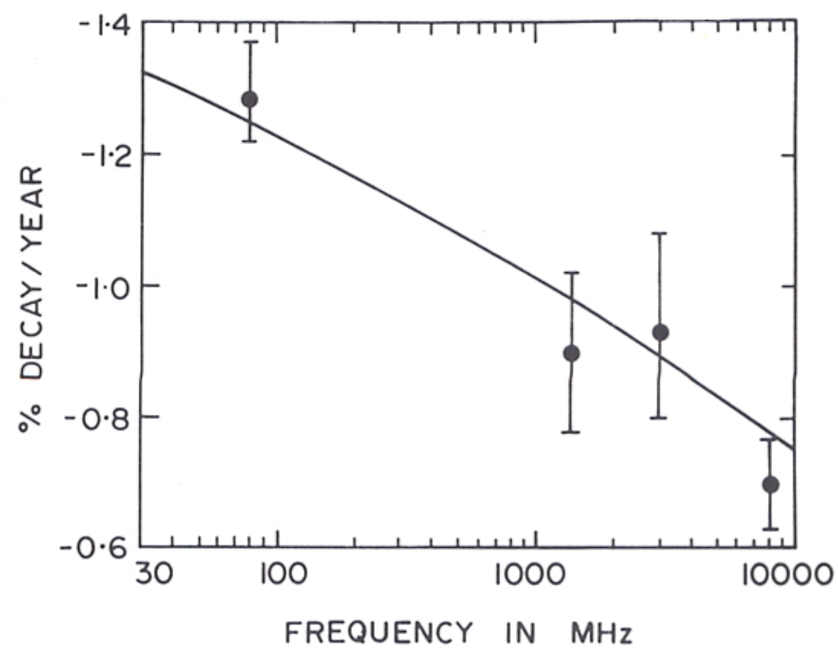
Cowsik and Burch, arXiv:0908.3494

Cassiopeia A

$$\frac{\partial n}{\partial t} = -\frac{n}{\tau_e} - aE\frac{\partial n}{\partial E} + kE^2\frac{\partial^2 n}{\partial E^2} + I$$



Spectrum of Cas A at epoch 1964.4 (From Wills 1973). The continuous line is the theoretical spectrum, for parameter values: E_i=1 MeV; a=-2.6k; k=1.44 x 10^{-2}.



Decay of the Cas A flux density as a function of frequency (from Dent et al. 1974) is compared with the theoretical values.

Cowsik, ApJ, **227**, 856 (1979).

Summary

- Constraints from the spectra of the nuclear component of cosmic rays.
- Constraints from the composition.
- Constraints from isotropy and constancy.
- Constraints from the spectrum of the electronic component and the positron fraction.