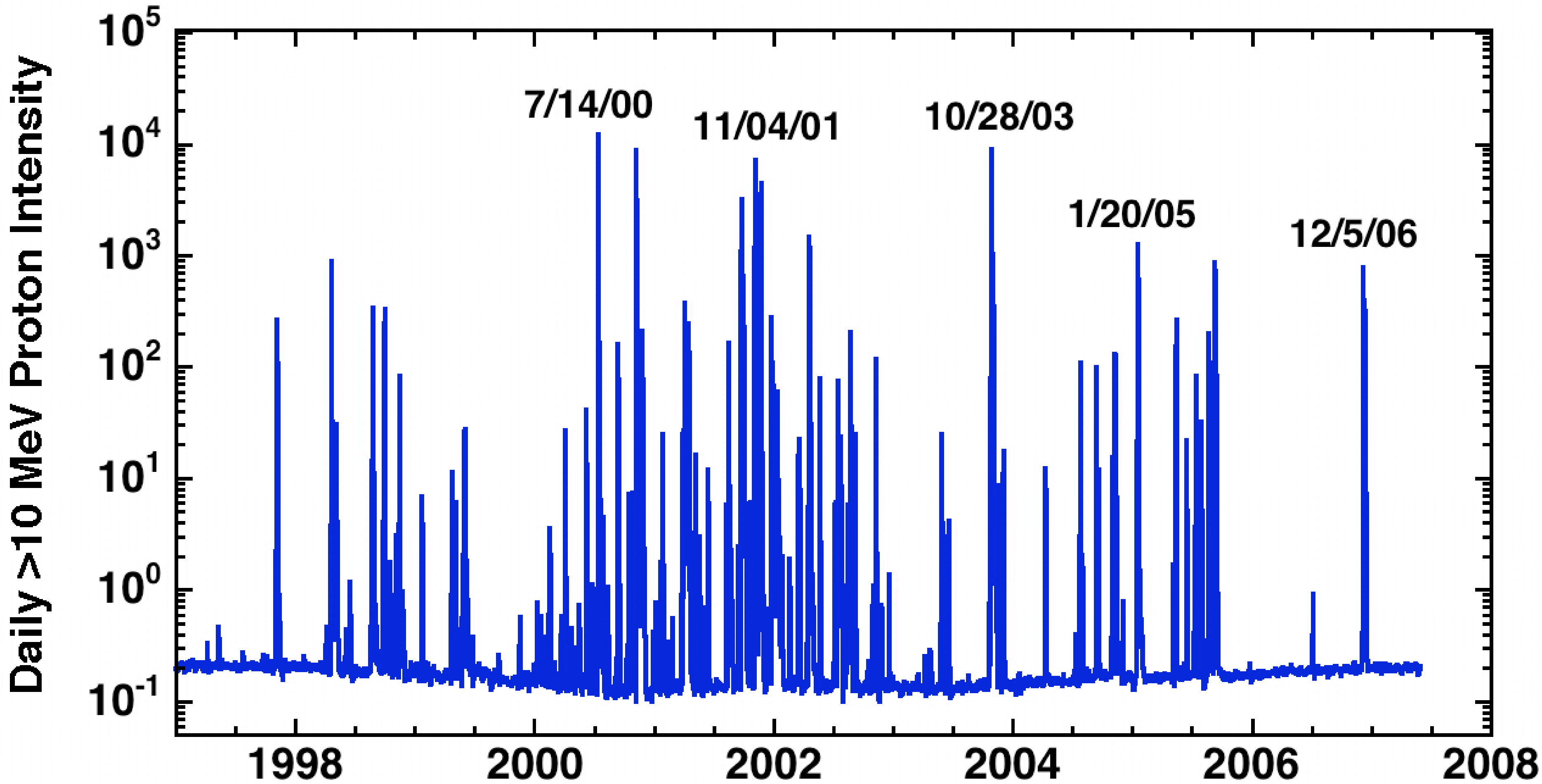
Estimating the Energy Content of Solar Energetic Particle Events

R. A. Mewaldt[1], C. M. S. Cohen[1], J. Giacalone[2], G. M. Mason[3], A. Vourlidas[4], E. E. Chollet[1], D. L. Haggerty[3], and M. L. Looper[5]

[1]Caltech, [2]Univ. Arizona, [3]JHU/APL, [4]Naval Research Laboratory, [5]Aerospace Corp

Solar Activity during the Onset of Solar Cycle 24
Global Energetics Working Group
Napa, CA
December 7, 2008

SEP Events of Solar Cycle 23



GOES-8 & 11 data

Sources of SEP Data

ACE:

SIS:	$2 \leq Z \leq 28$;	~10 to 200 MeV/nuc
ULEIS:	$1 \leq Z \leq 26$;	~0.1 to 8 MeV/nuc
EPAM:	Protons	~0.03 to ~5 MeV
	Electrons	~0.03 to 0.3 MeV

STEREO

LET:	H, He:	2 to 12 MeV
	$3 \leq Z \leq 28$:	4 to 30 MeV/nuc
HET:	H, He:	14 to 100 MeV
	Electrons:	0.7 - 4 MeV

SAMPEX:

PET:	H, He	~20 to ~400 MeV/nuc
	Electrons	2 to 8 MeV

GOES-8, 11	H, He	~5 to ~100 MeV/nuc

Approaches to Fitting Spectra:

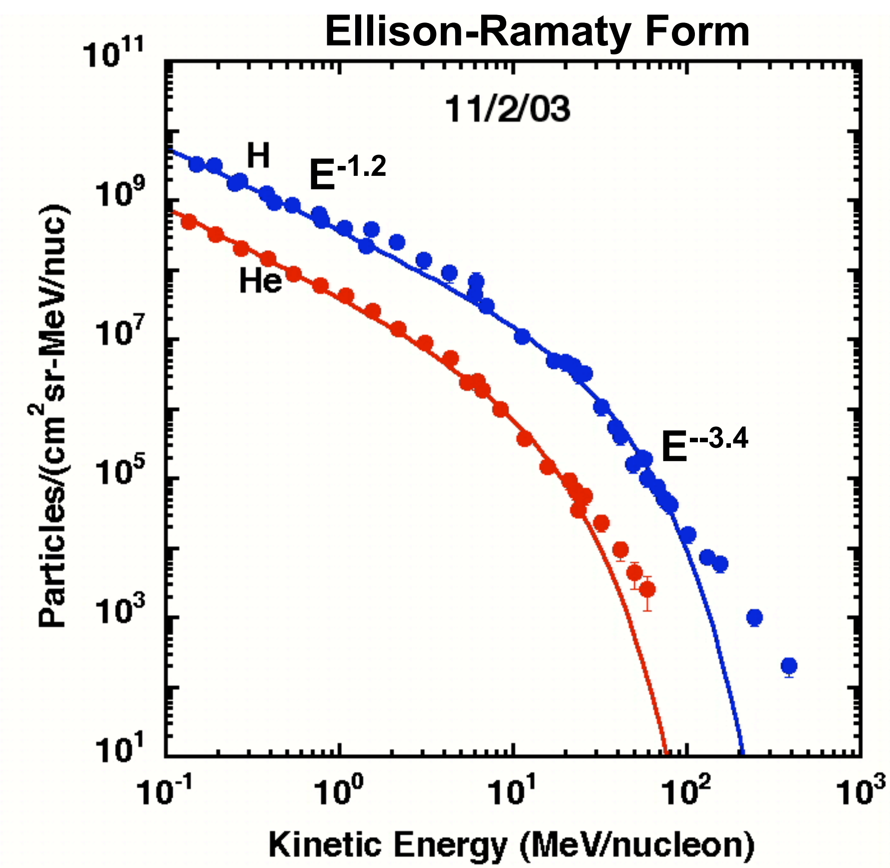
Ellison and Ramaty (1985) proposed a shock-acceleration spectral form:

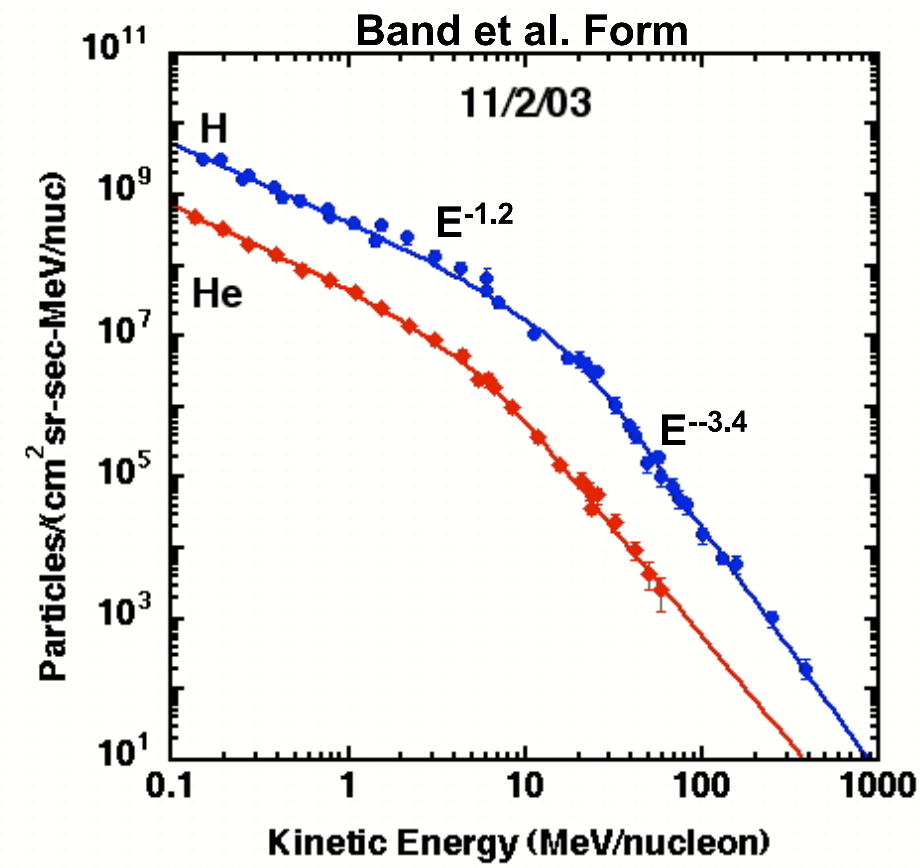
$$dJ/dE = J_o(E^2+2mE)^{-\gamma}\ \mathrm{Exp}(-E/E_o)$$

Tylka et al. (2005) use a double-power-law form due to Band et al. (1993):

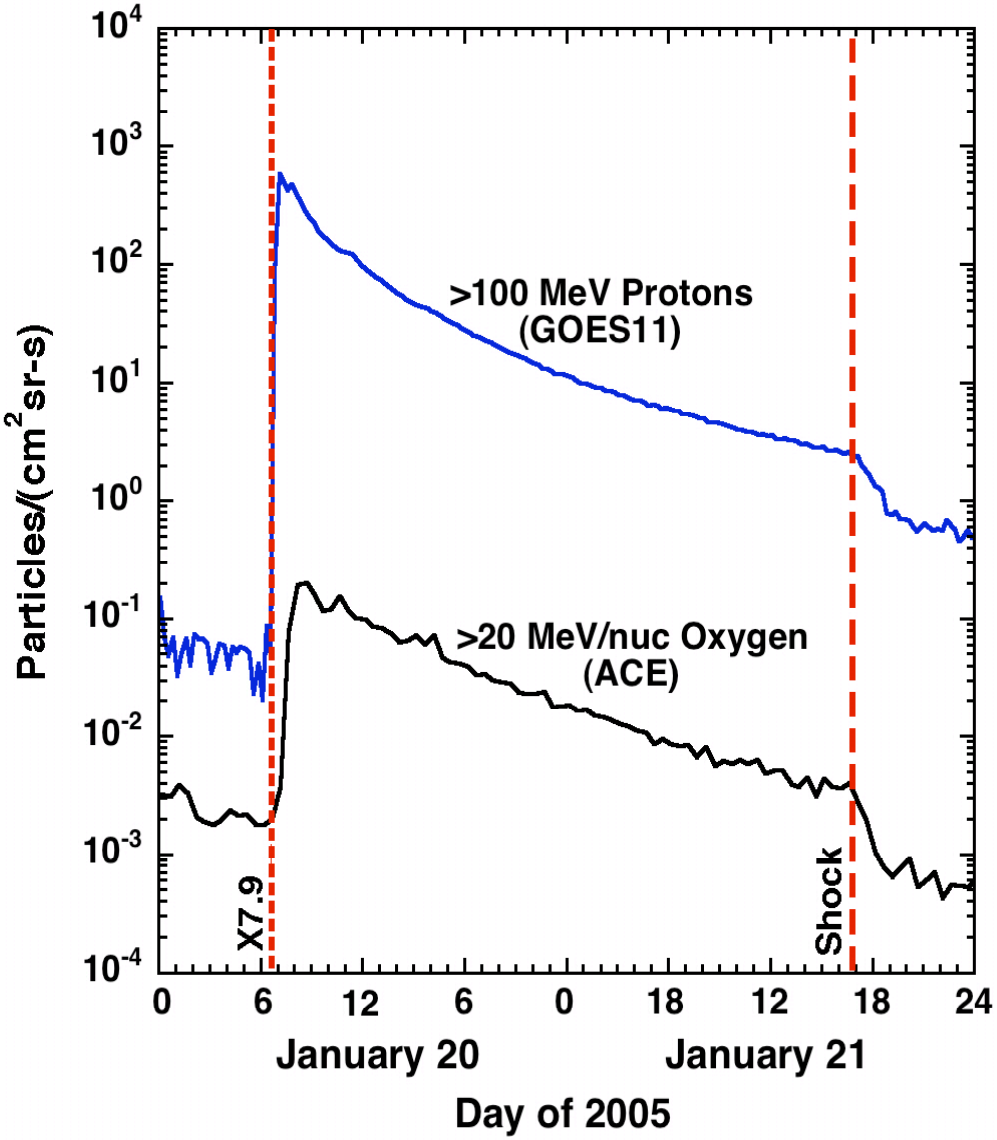
$$dJ/dE = CE^{-\gamma_a} \exp(-E/E_o) \qquad \text{for } E \le (\gamma_b - \gamma_a)E_o;$$

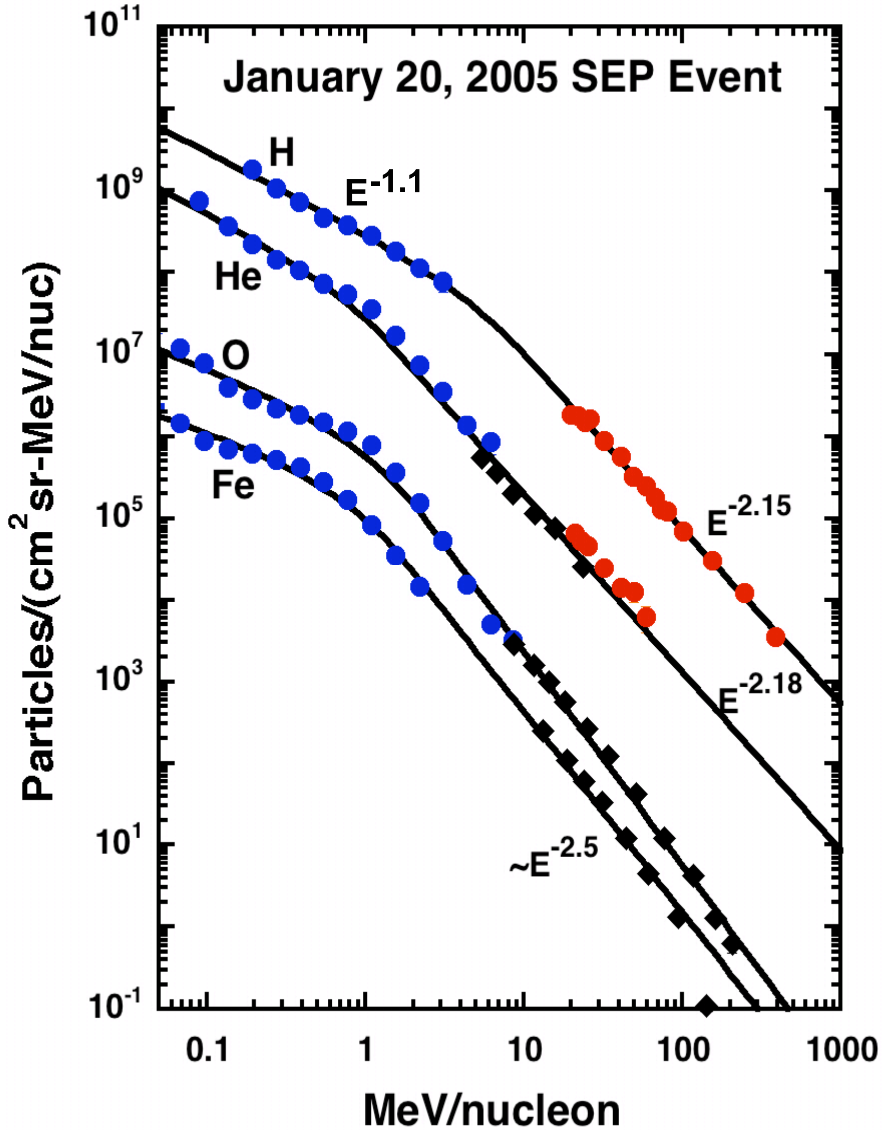
$$dJ/dE = CE^{-\gamma_b} \{[(\gamma_b - \gamma_a)E_o]^{(\gamma b-\gamma a)} \exp(\gamma_b - \gamma_a)\} \qquad \text{for } E \ge (\gamma_b - \gamma_a)E_o$$



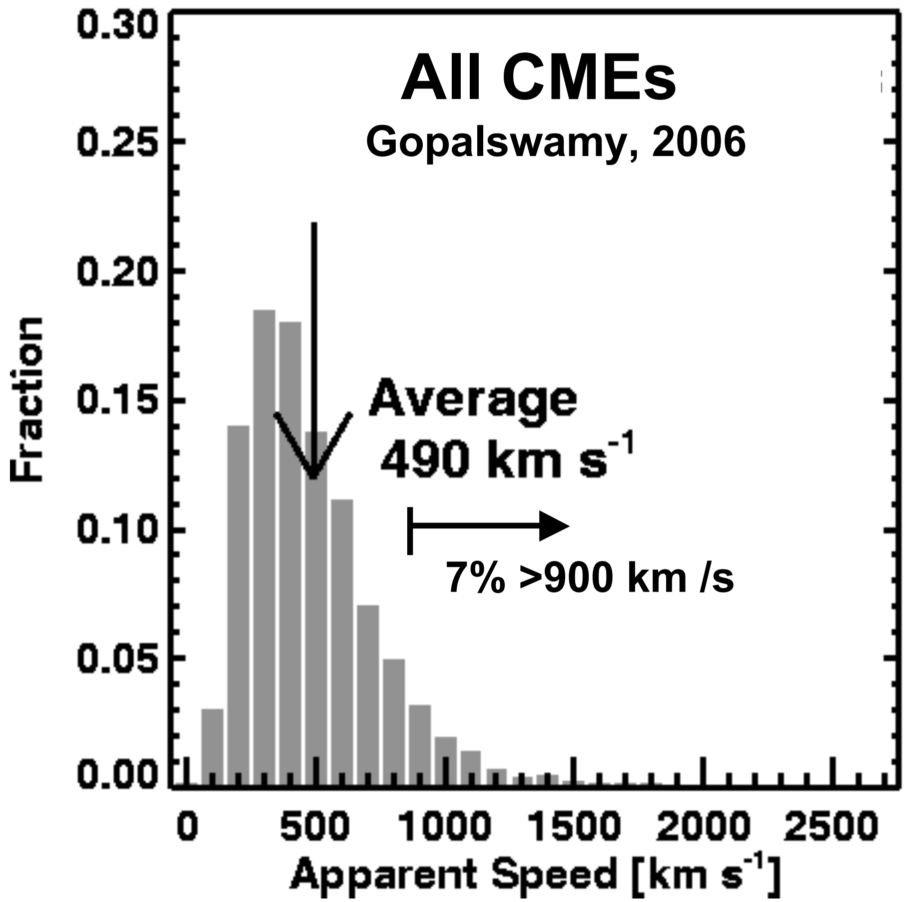


The January 20, 2005 event: a challenge to space weather forecasters

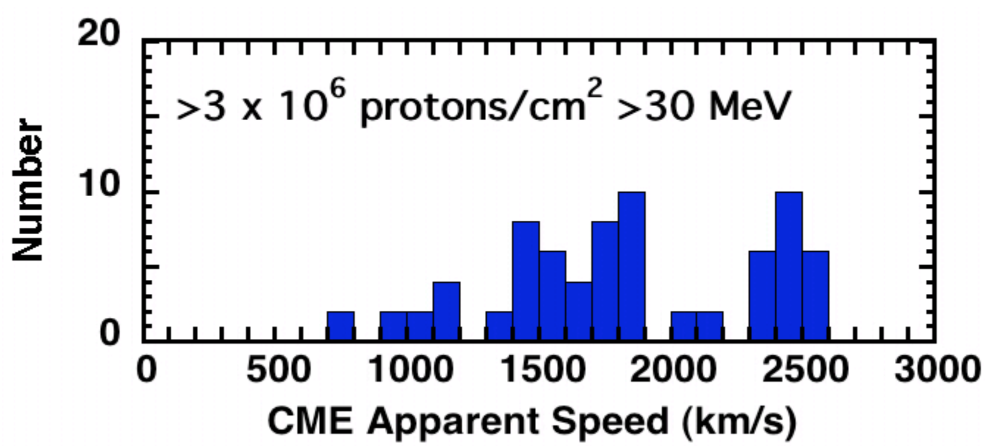




Mewaldt et al. 2005

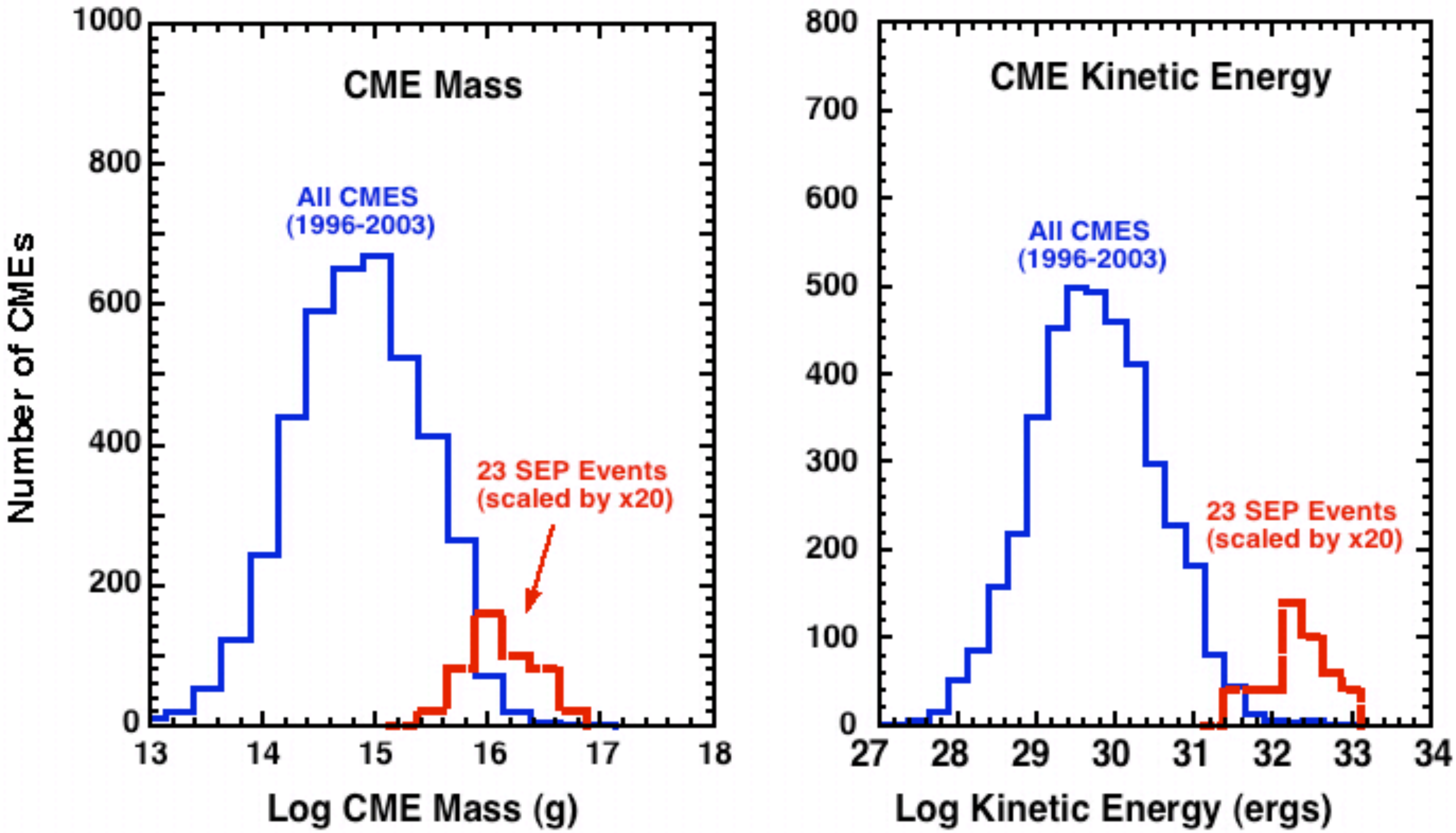


The largest SEP events are due to CMEs with speeds of 1500-2500 km/s

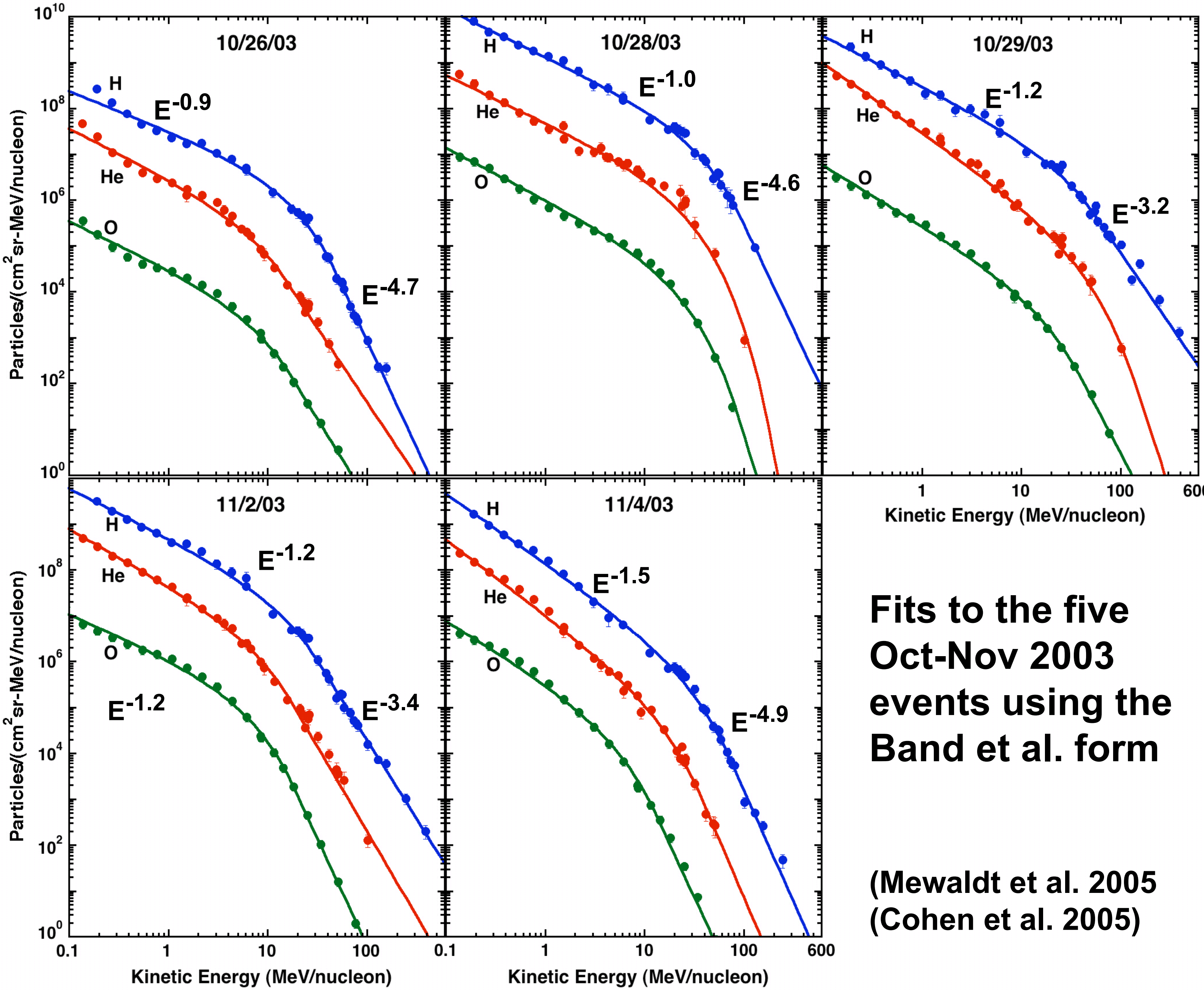


CME apparent speeds for the top 50 SEP events of solar cycle 23

Large SEP events are associated with very massive, energetic CMEs

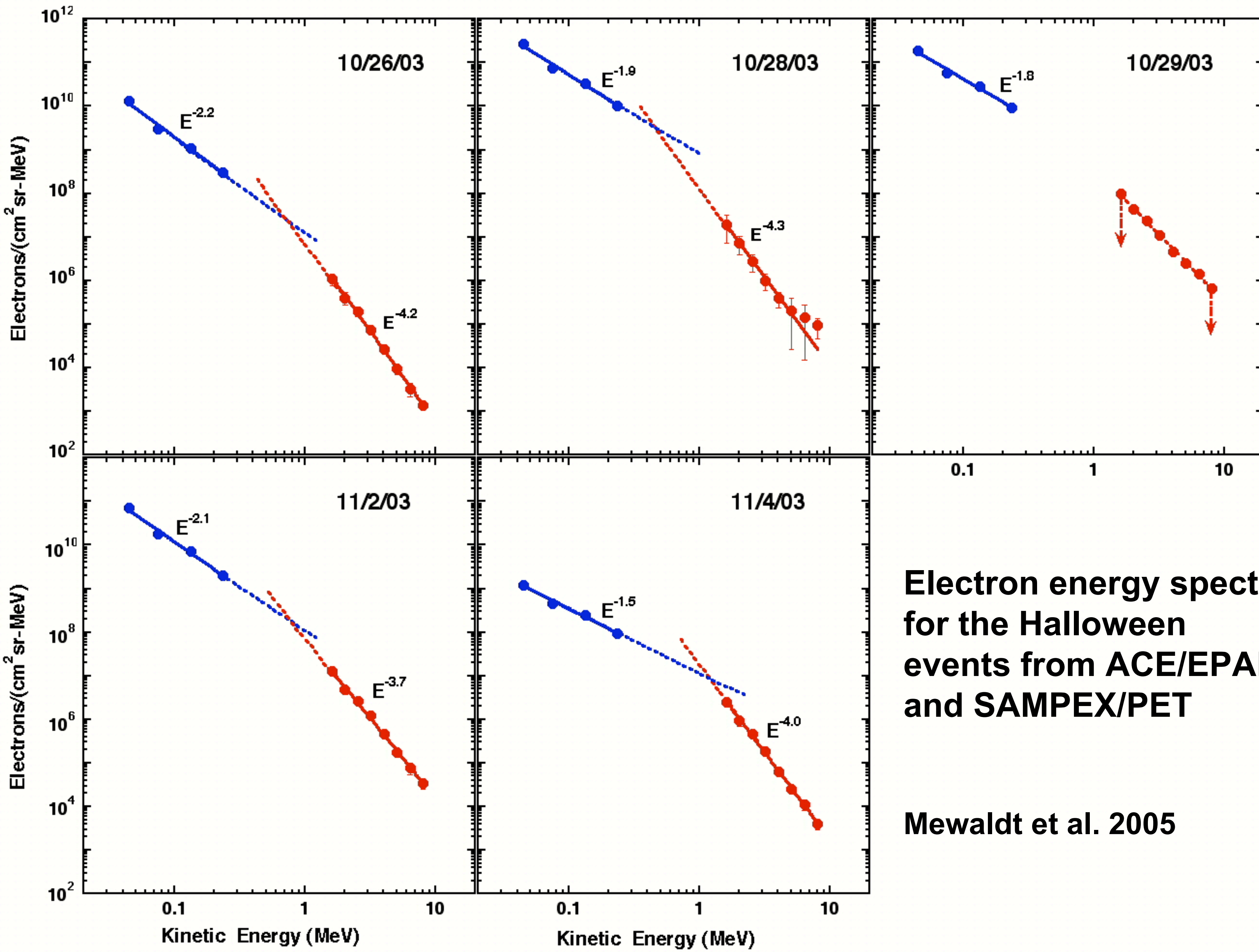


CME data from Gopalswamy 2006



Fits to the five Oct-Nov 2003 events using the Band et al. form

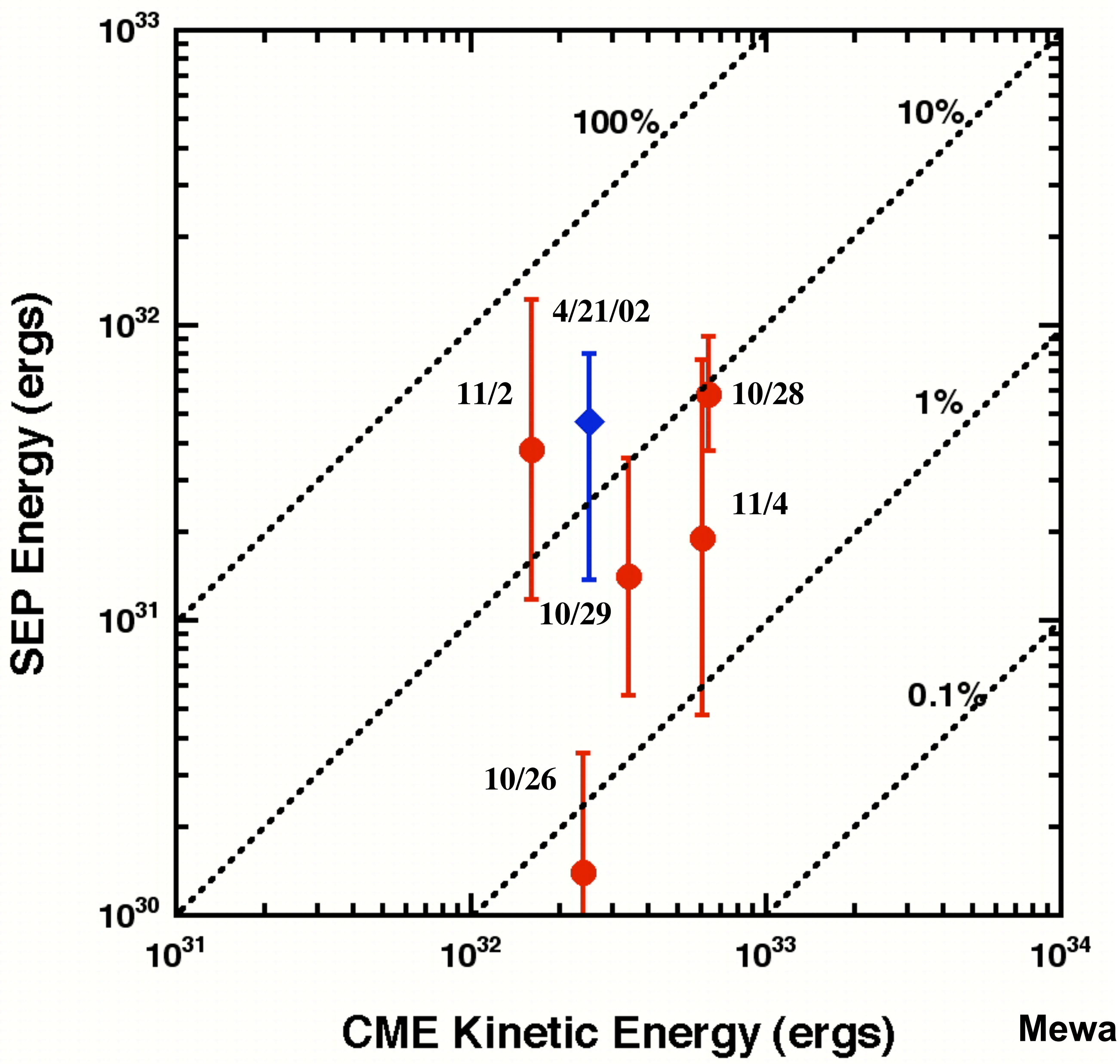
(Mewaldt et al. 2005)
(Cohen et al. 2005)



Electron energy spectra for the Halloween events from ACE/EPAM and SAMPEX/PET

Mewaldt et al. 2005

Comparison of SEP and CME kinetic energies for the 4/21/02 and Halloween Events



Mewaldt et al. 2005

Contributions to the SEP Kinetic Energy

(based on 6 SEP events studies in great detail)

Protons	69% - 82%
He	10% - 19%
Z > 2	3% - 10%
Electrons	1% - 11%

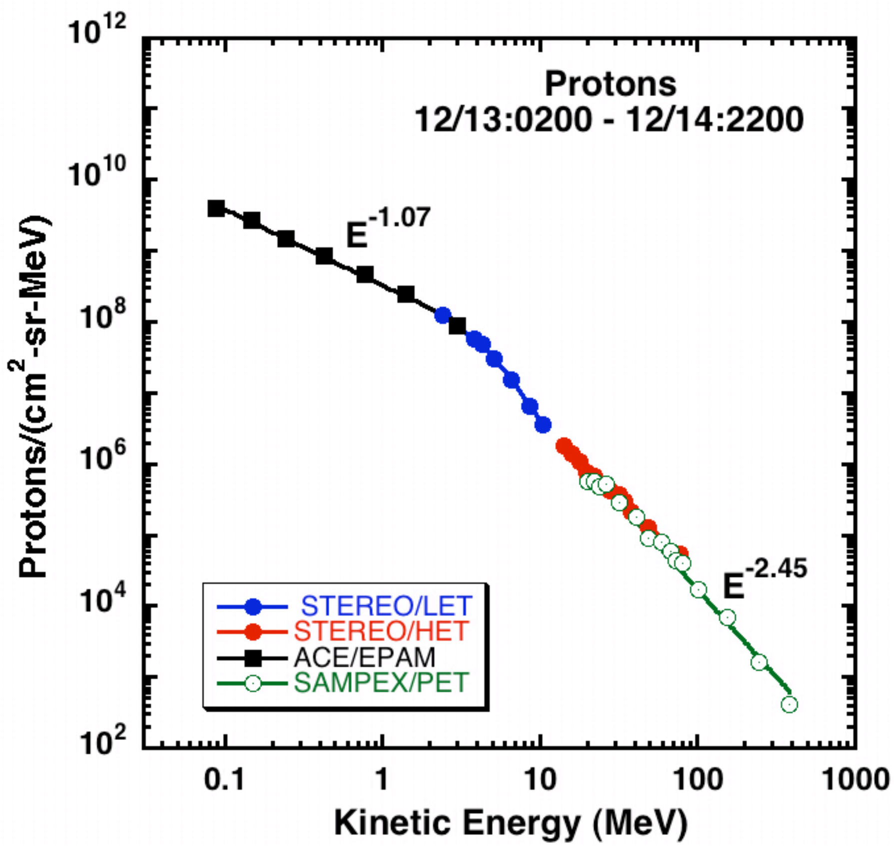
For the remaining 17 events we use only fits to the proton spectra and assume protons represent 75% of the kinetic energy

Mewaldt et al. (2005)

Using near-Earth SEP fluence spectra we can integrate the energy per cm^2 of SEPs escaping to the outer heliosphere

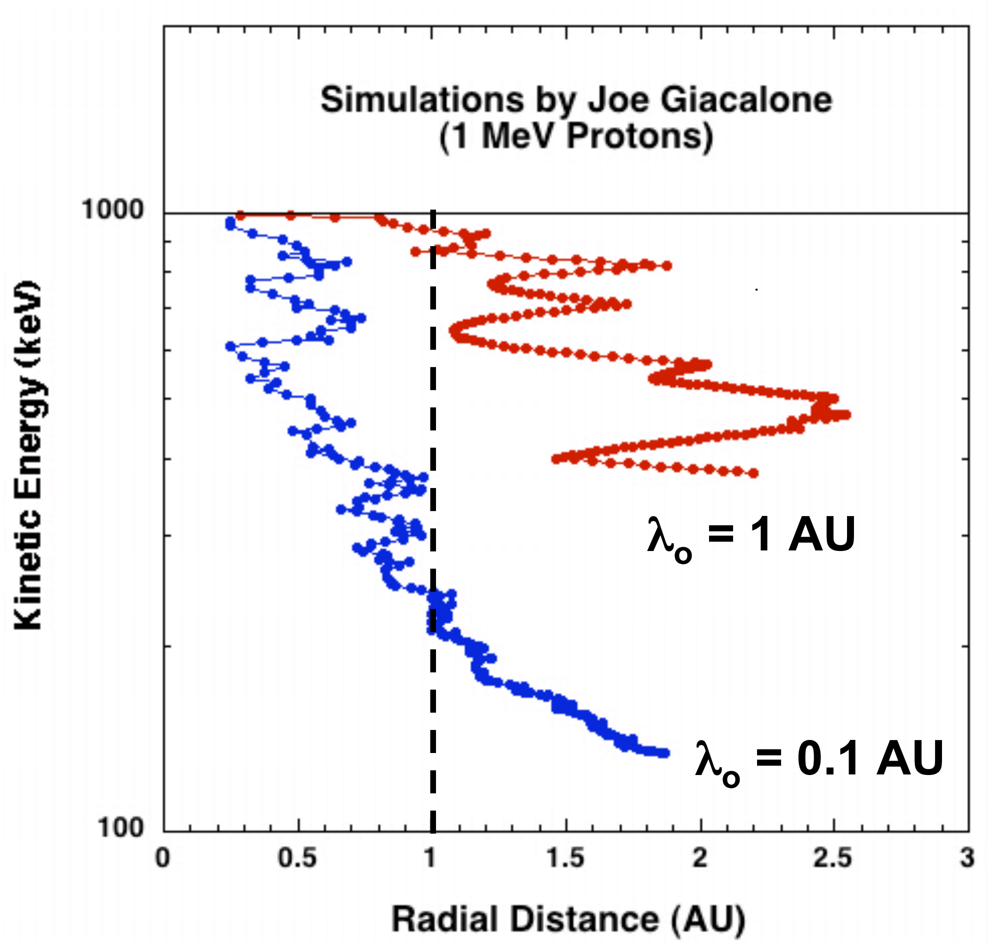
However, we need to worry about corrections for the following:

- Relative location of Earth and the CME eruption
- Transport effects on the measured energy spectra



As solar particles move outward from the Sun they undergo pitch-angle scattering which has two effects:

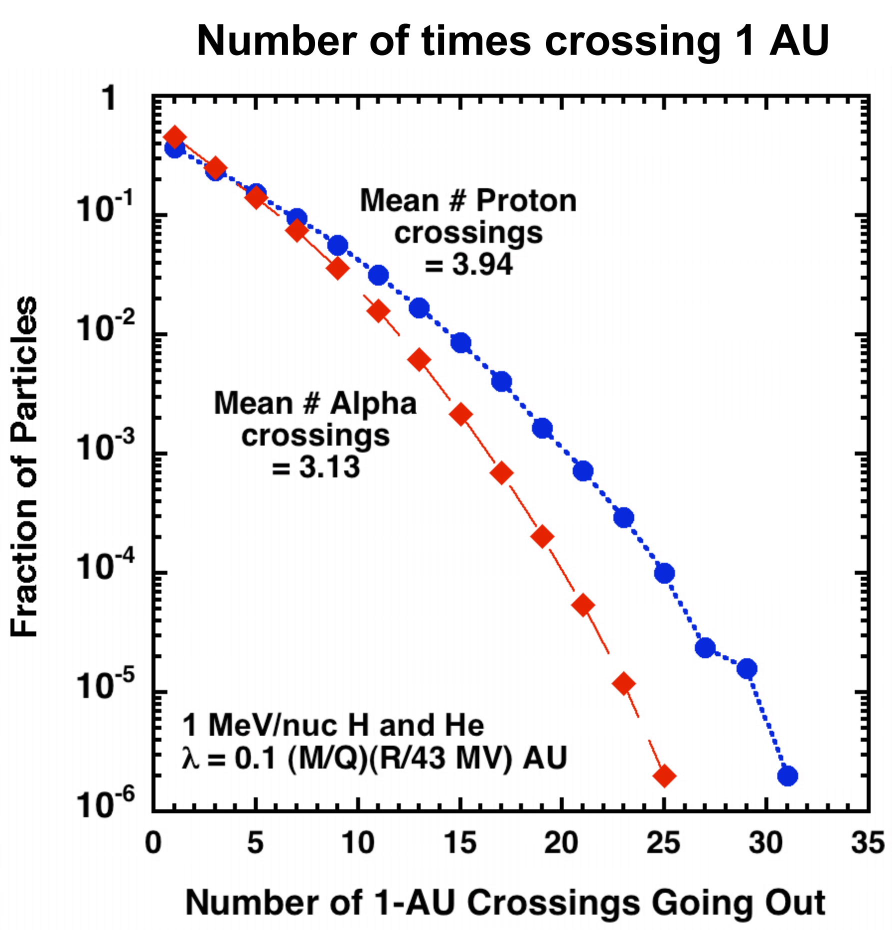
- They typically cross 1 AU more than once
- They undergo adiabatic energy loss

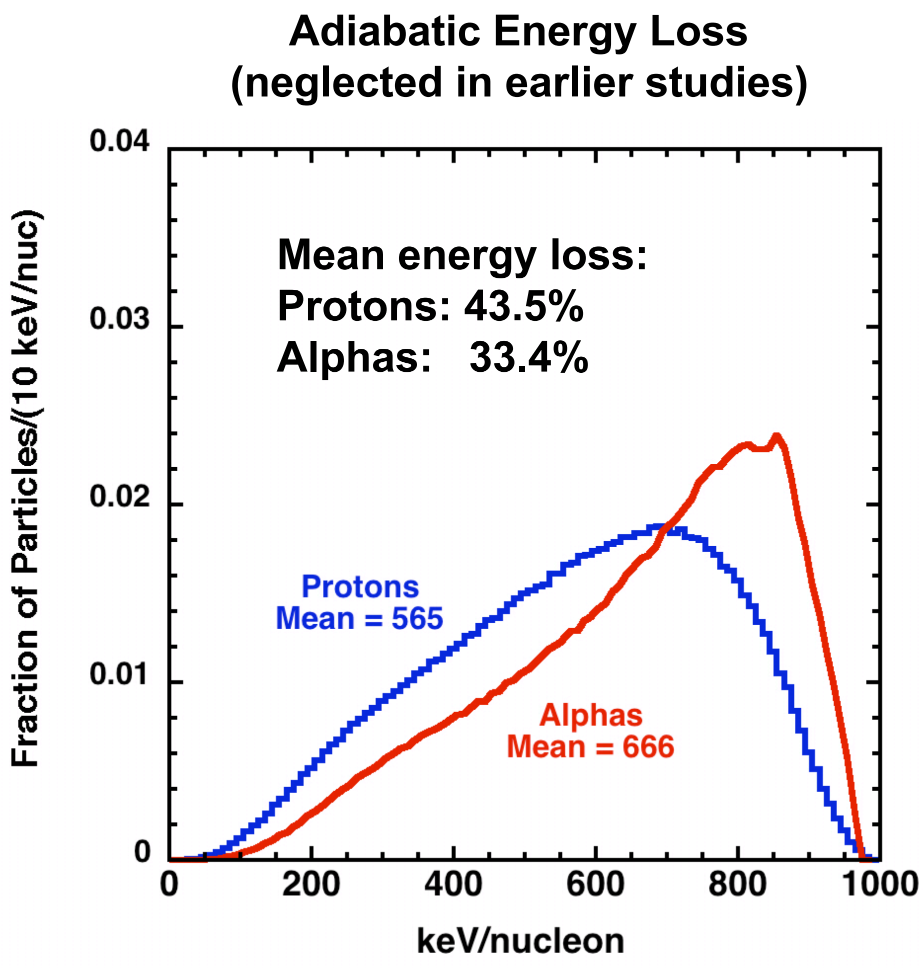


The amount of scattering and degree of energy loss depend on the scattering mean free path (λ_o)

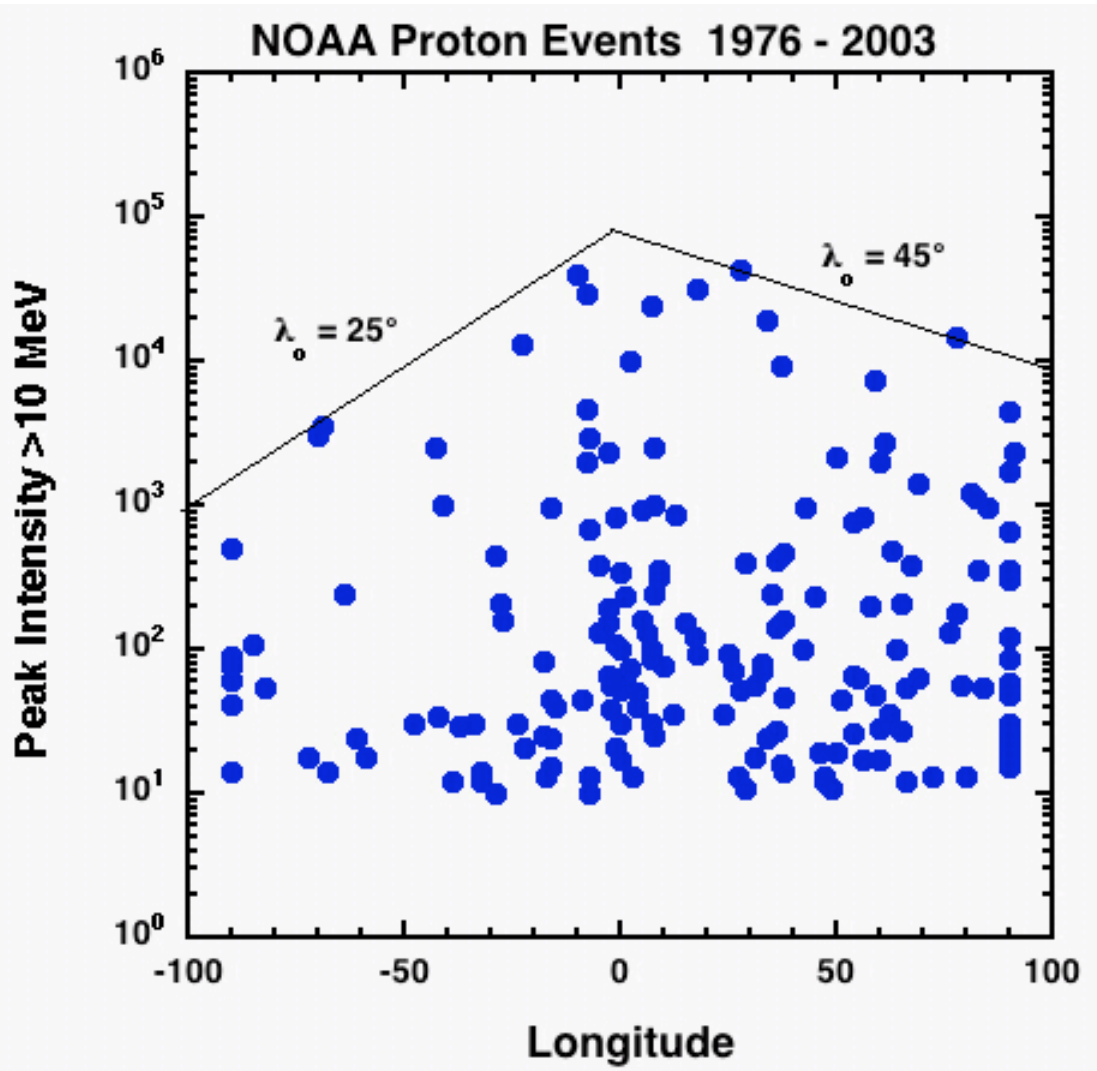
Simulations of 1 million protons and alphas transported from 0.1 to 1 AU:

Simulations by E. Chollet and J. Giacalone



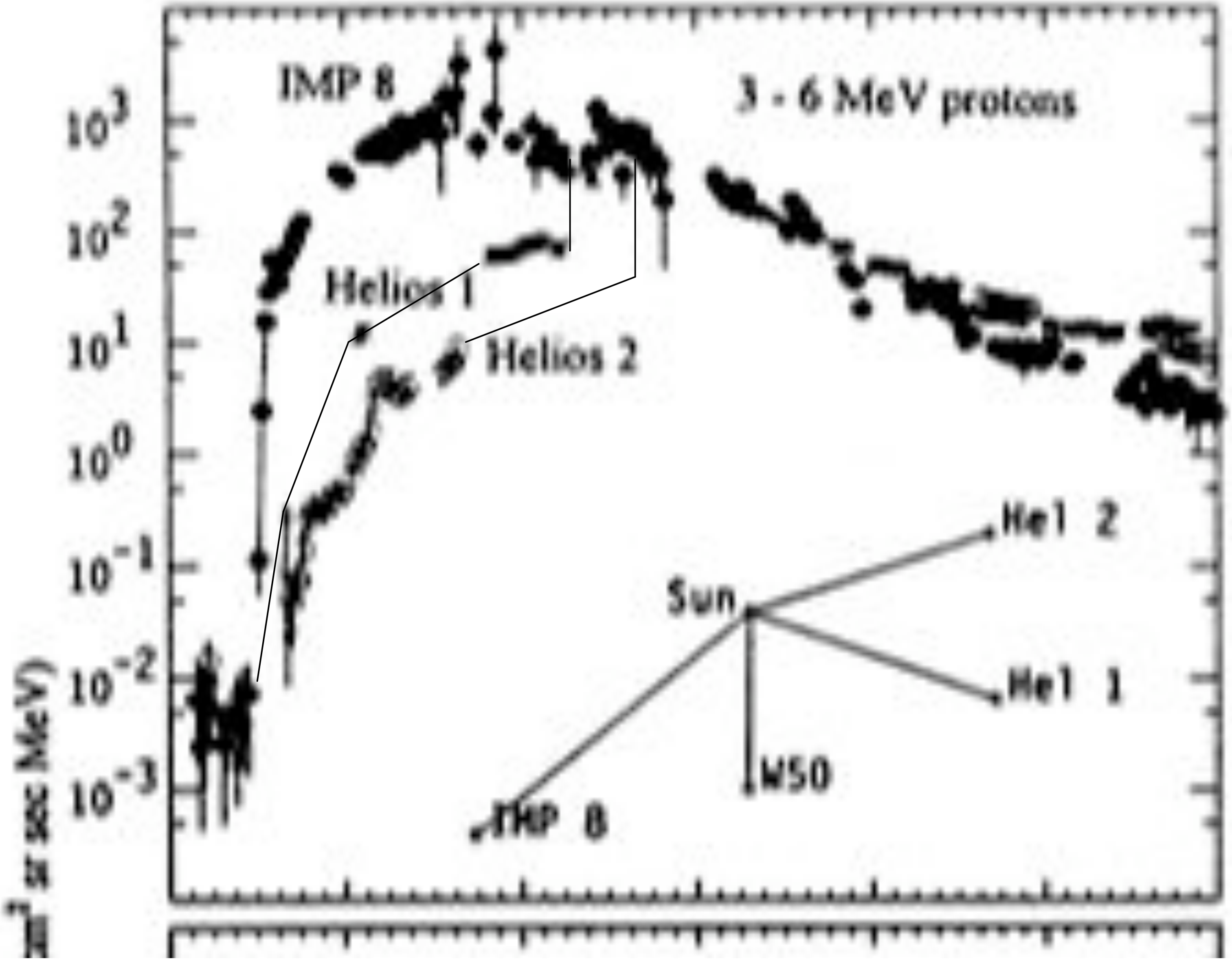


To obtain the total SEP kinetic energy we integrate over the longitudinal and latitudinal distribution of SEPs



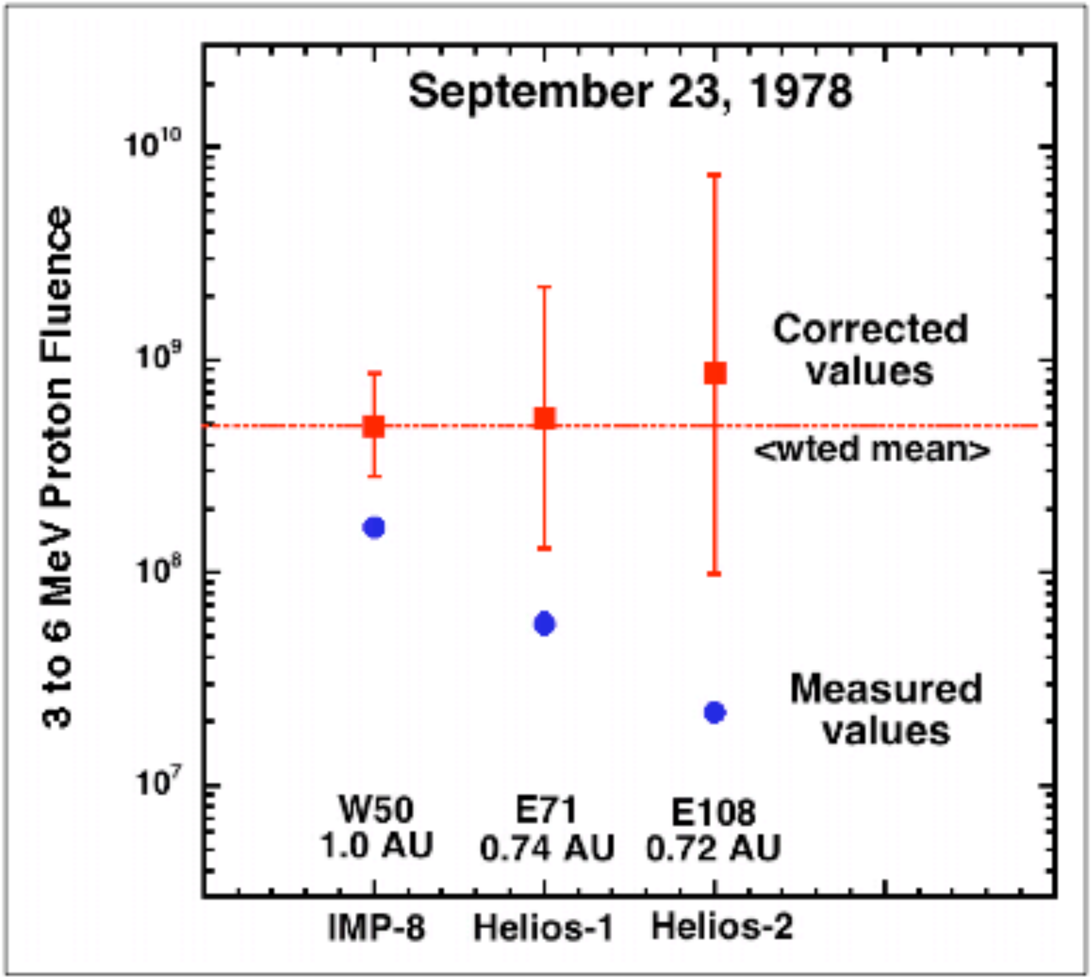
Assume SEP fluences decline exponentially for source locations away from the central meridian (Emslie et al. 2004):

Western events: $\lambda_o = 45°$
Eastern events: $\lambda_o = 25°$
Hi/Lo Latitudes: $\lambda_o = 35°$



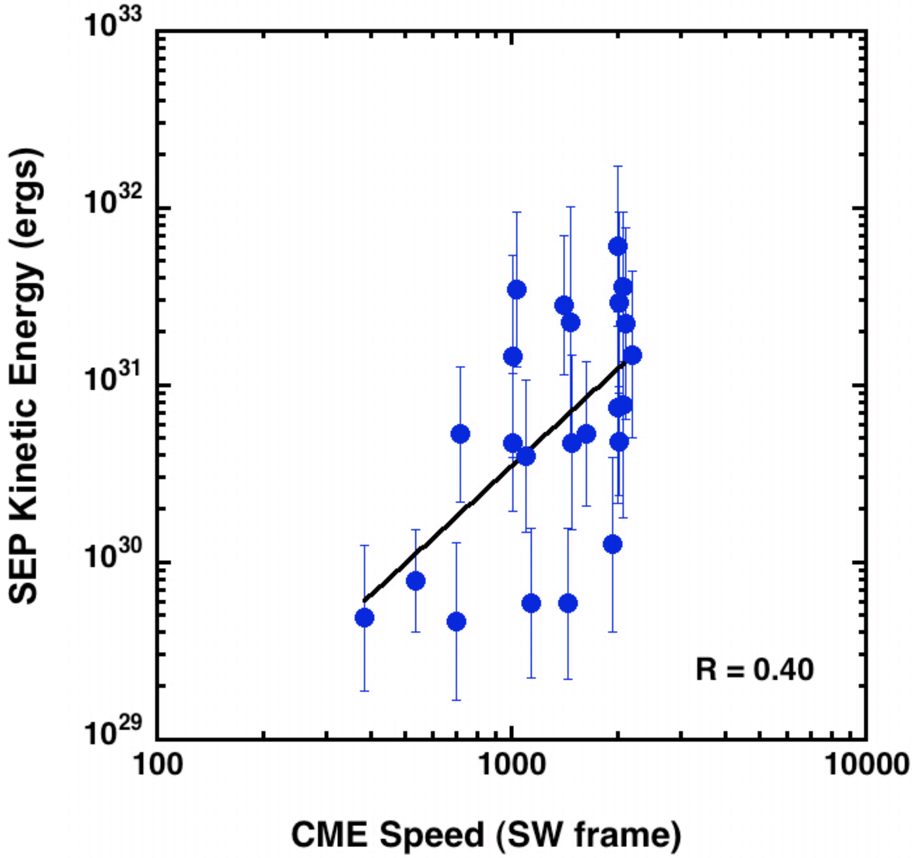
9/23/78 SEP event observed by IMP-8 and Helios

Measurements of 3-6 MeV protons from 3 widely separated points of view give consistent founces when corrected for longitude and radial locations

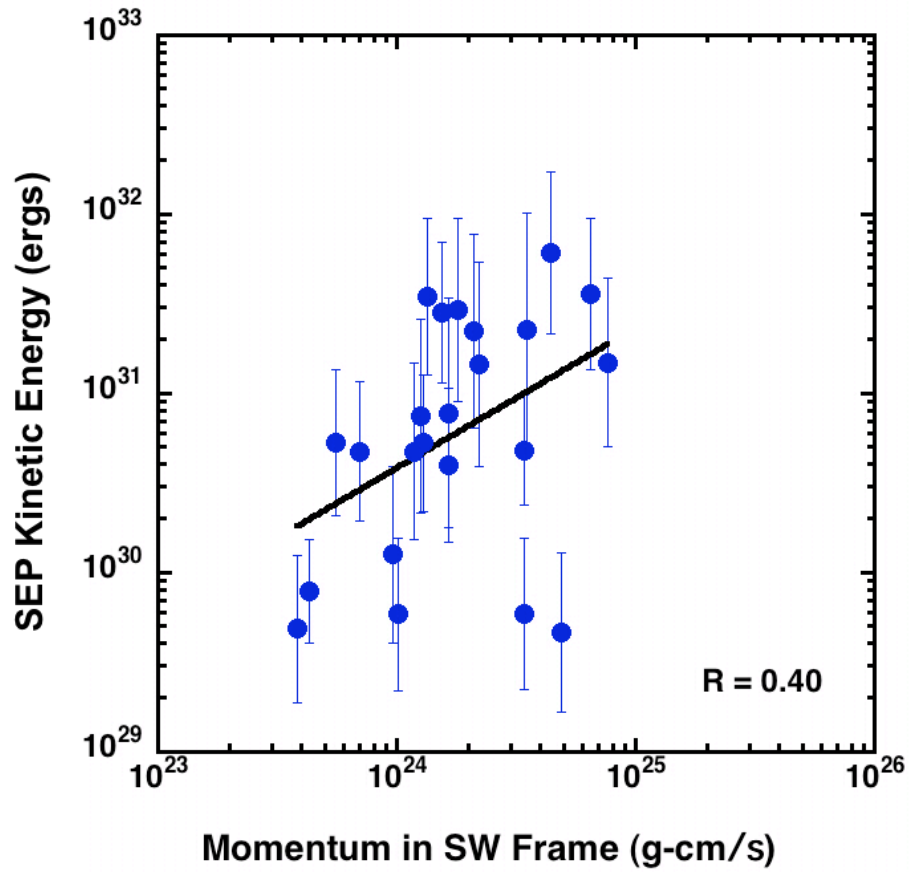


Correlate SEP Kinetic Energy with Related Parameters

SEP KE vs CME Speed

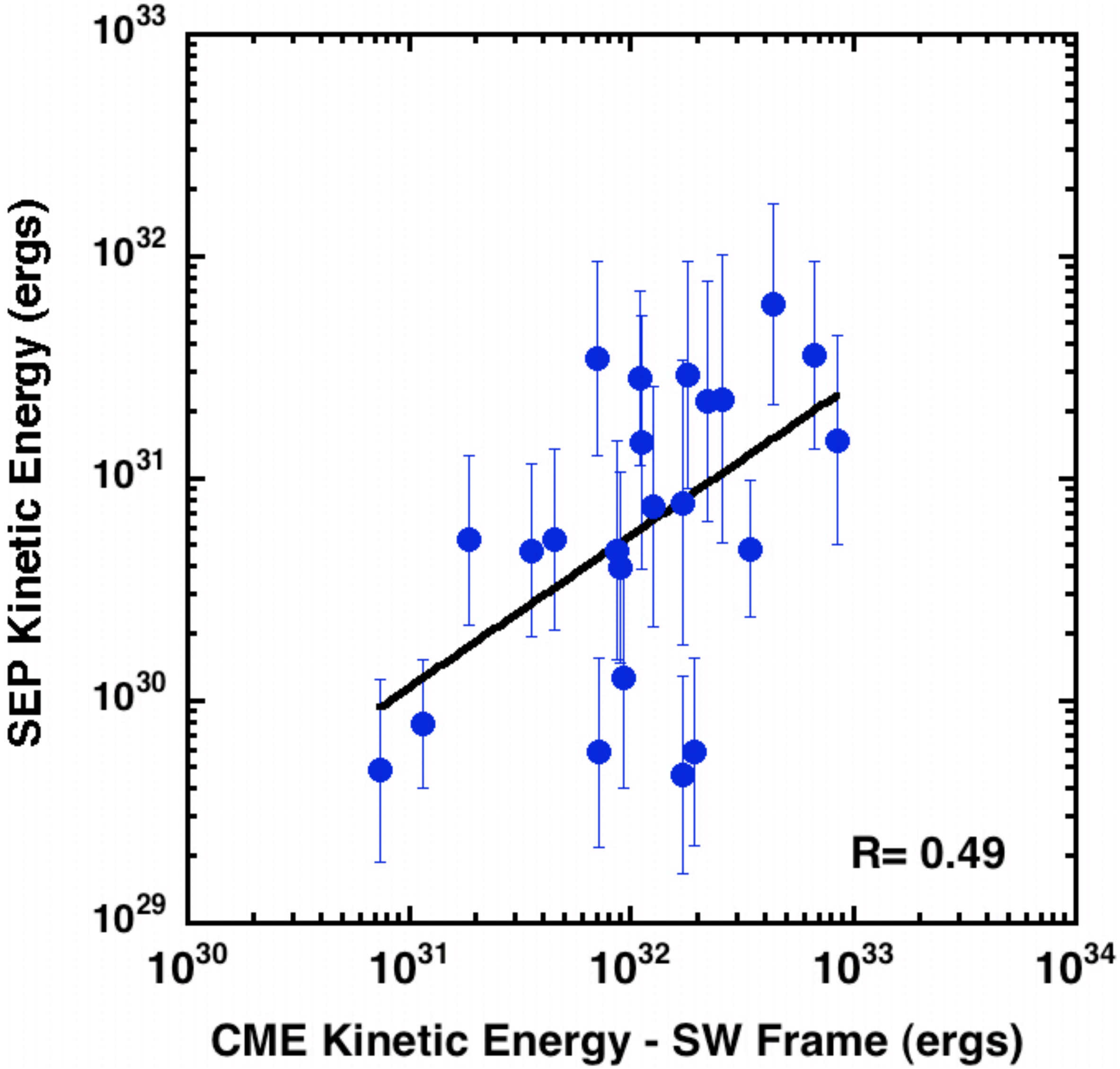


SEP KE vs CME Momentum

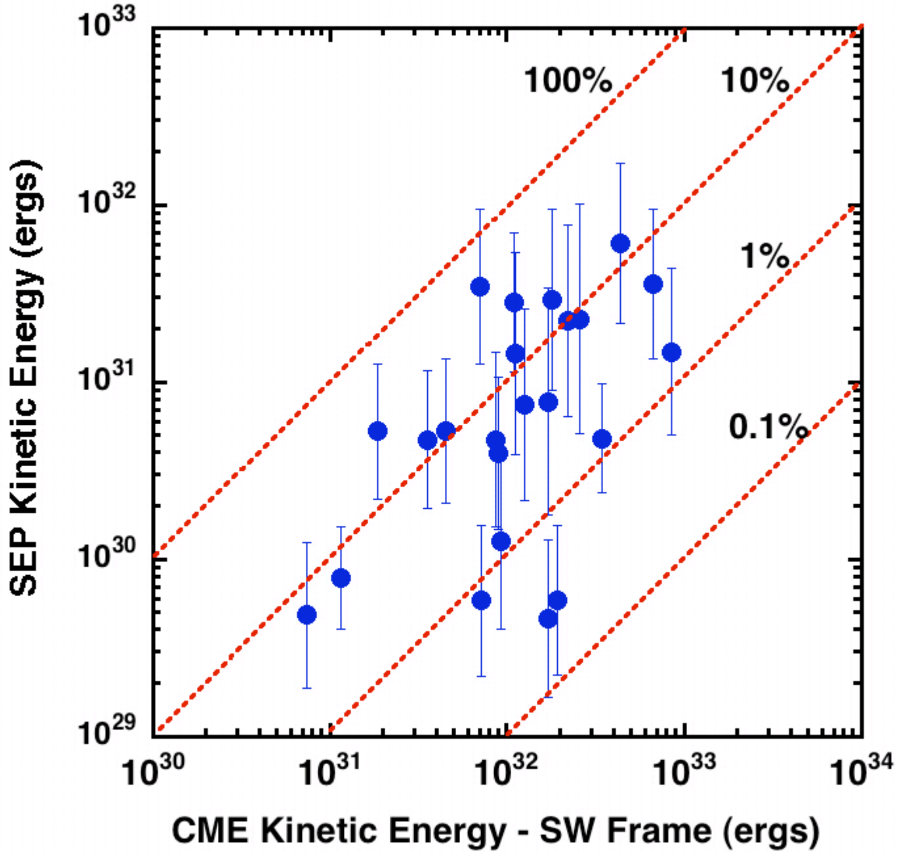


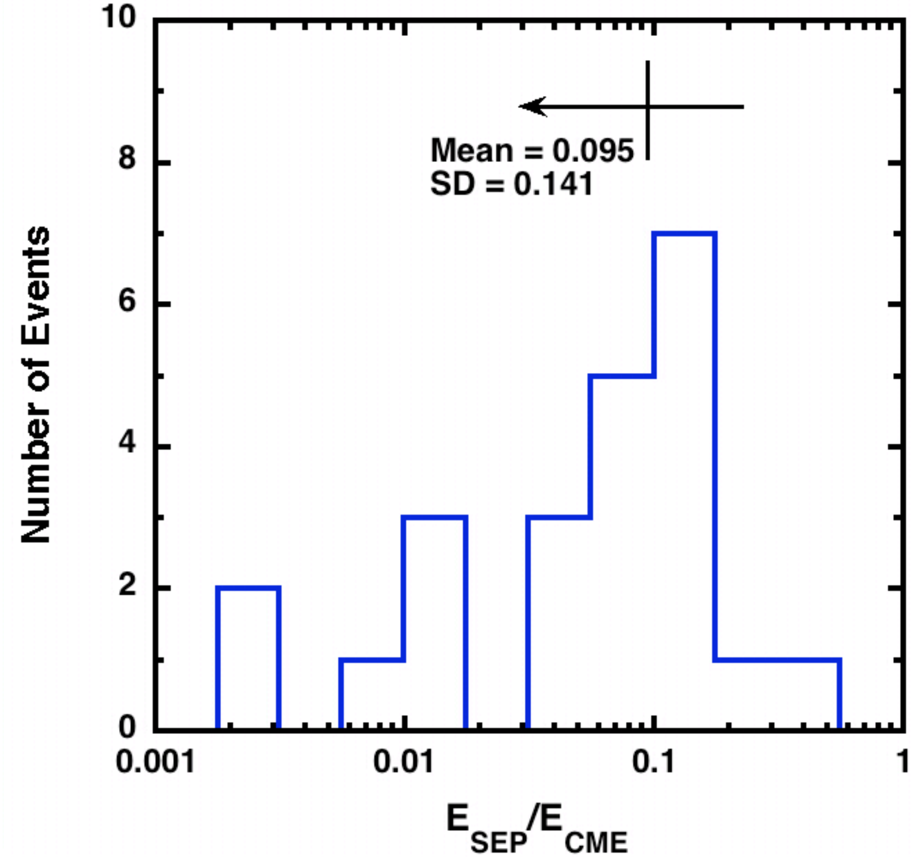
Transform to solar wind frame by subtracting 400 km/s from all CME speeds

SEP KE vs CME Kinetic Energy (SW frame)



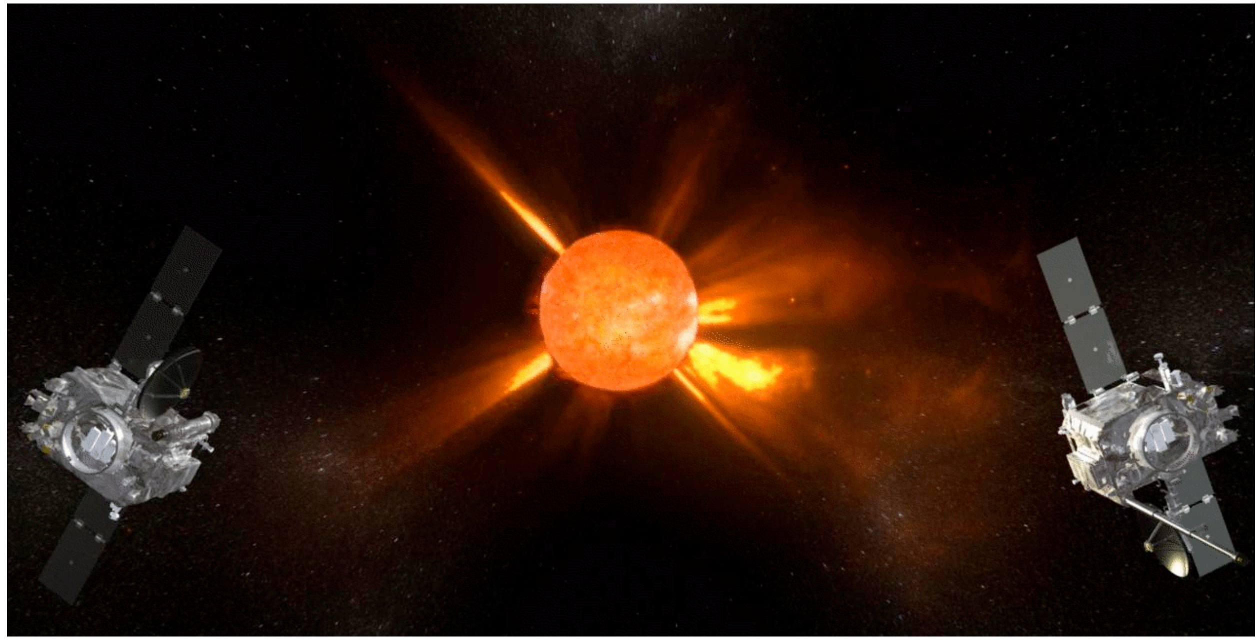
How efficient are CME-driven shocks at accelerating energetic particles?





Apparently, it is not uncommon for ~10% of the CME kinetic energy to go into accelerated particles

A similar efficiency is required for cosmic ray acceleration by supernova shocks



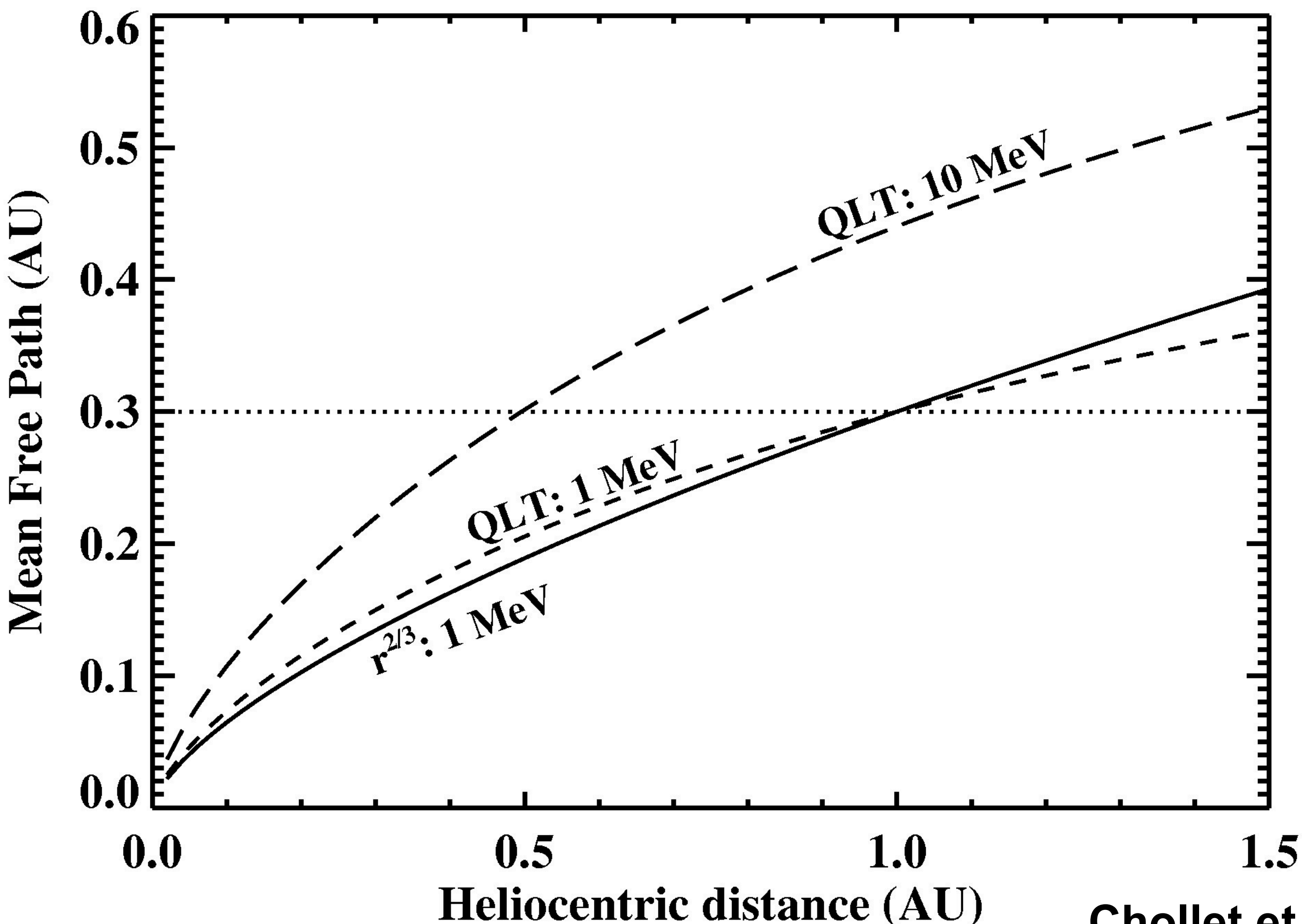
What's Next?

- New simulations by Chollet and Giacalone have tested the dependence of corrections on transport assumptions
- Angelos Vourlidas and Veronica Ontiveros are working on improved CME mass and kinetic energy estimates
- Additional events to analyze from solar cycle 23

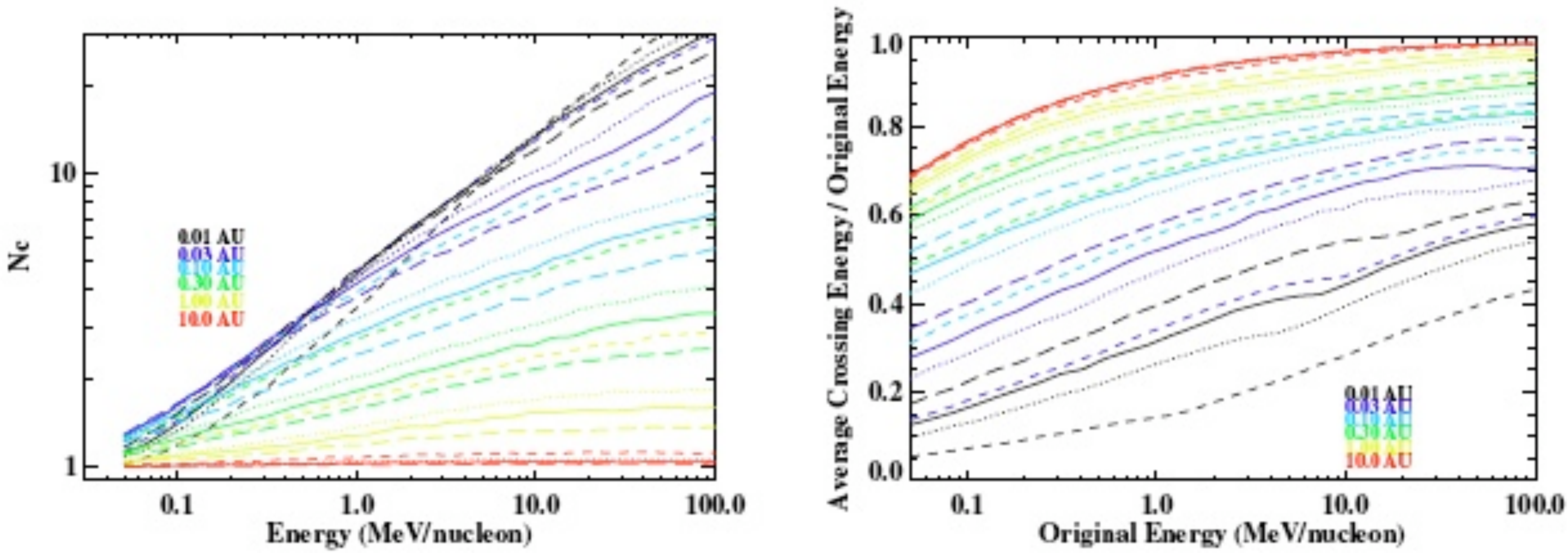
Solar Cycle 24 - Multi-point imaging and in situ data

- With 2 and 3 point images will always have a limb view, giving improved accuracy with cross checks on CME energies
- With 2 and 3 point SEP measurements will improve longitudinal corrections and at least one will be well-connected.

New simulations by Chollet, Giacalone, & Mewaldt are testing the dependence of our energy estimates on assumptions about SEP transport



Chollet et al.



<u>Constant Mean Free path</u>

Protons - dashed

Helium - dotted

Oxygen - slid

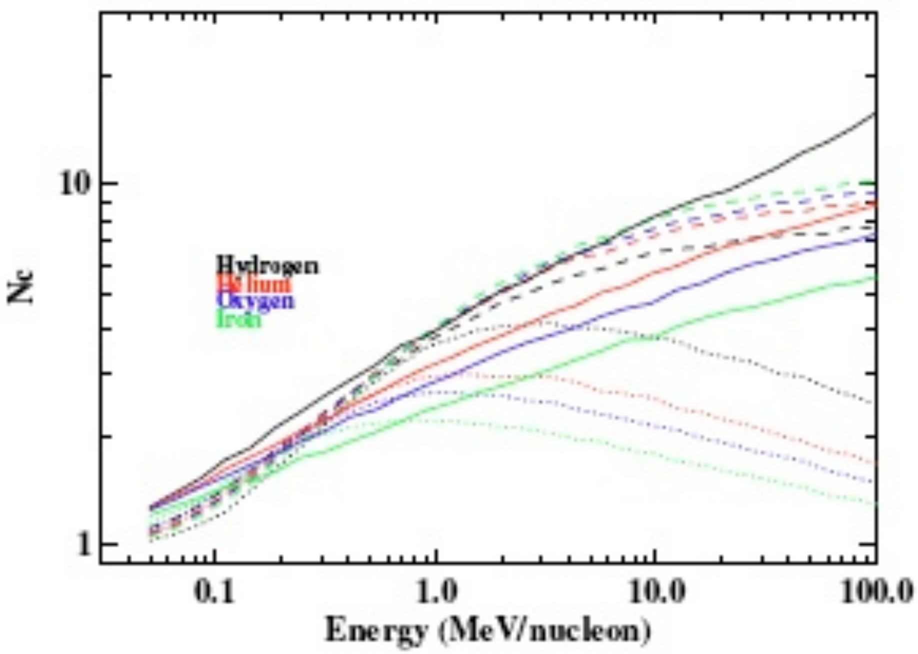
Fe - long dashed

Short mean free paths cause more energy-loss and also lead to more 1-AU crossings.

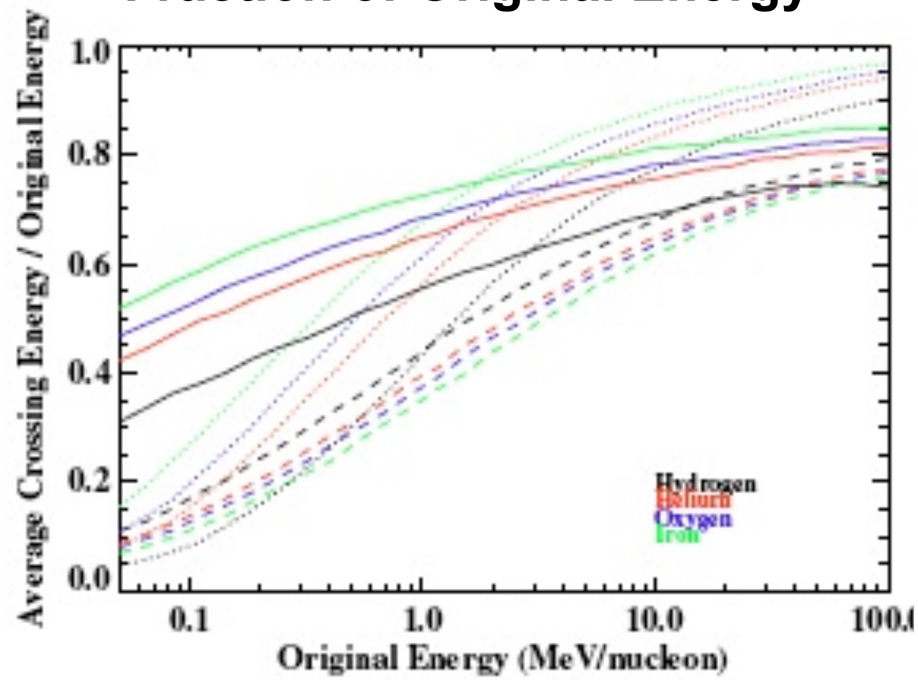
As a result these two corrections tend to cancel.

Chollet et al.

Number of Crossings



Fraction of Original Energy

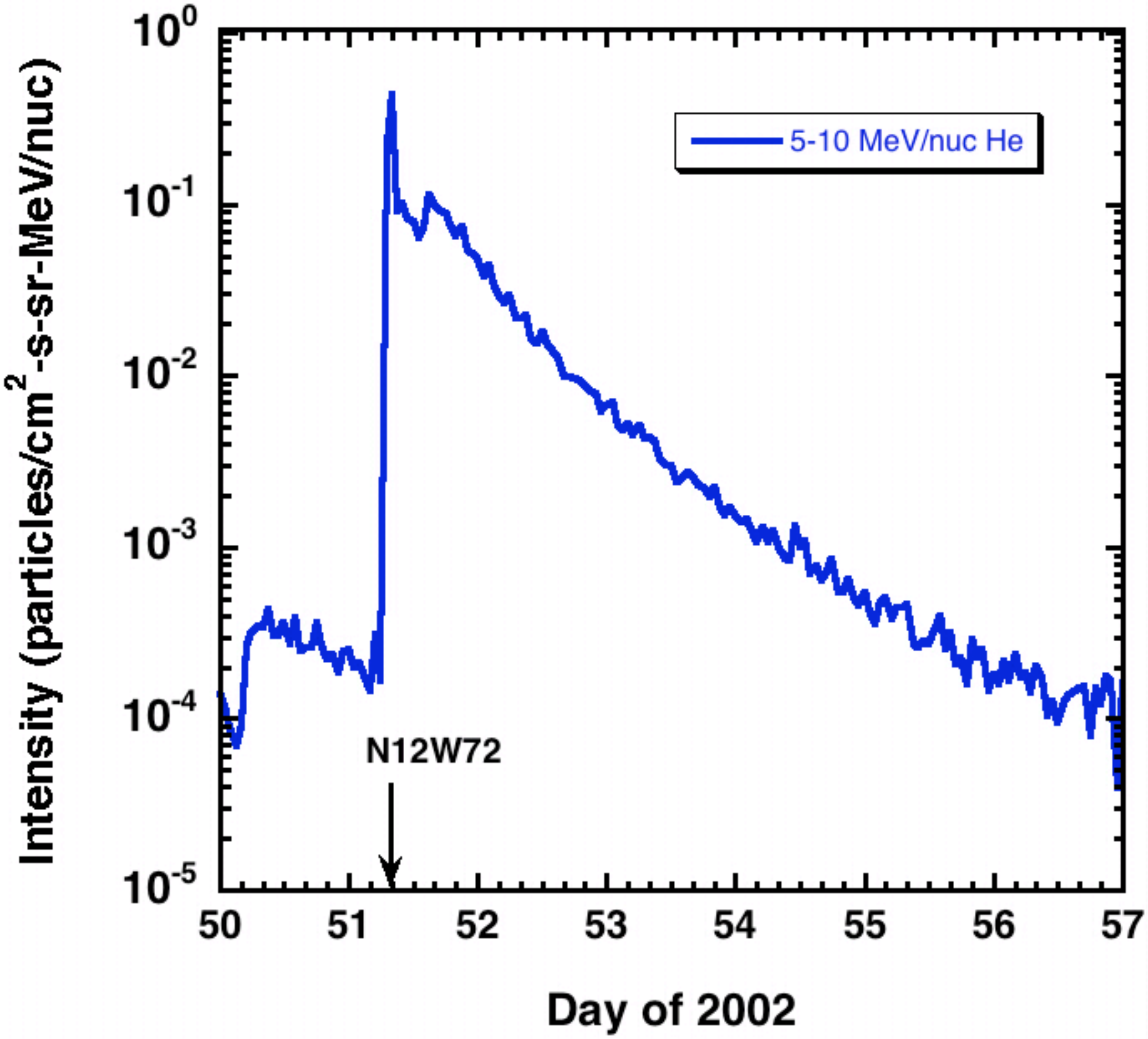


Solid: Constant mfp
Dashed: $r^{2/3}$ mfp
Dotted: QLT mfp

For all above curves λ_o = 0.1 AU at 1 AU

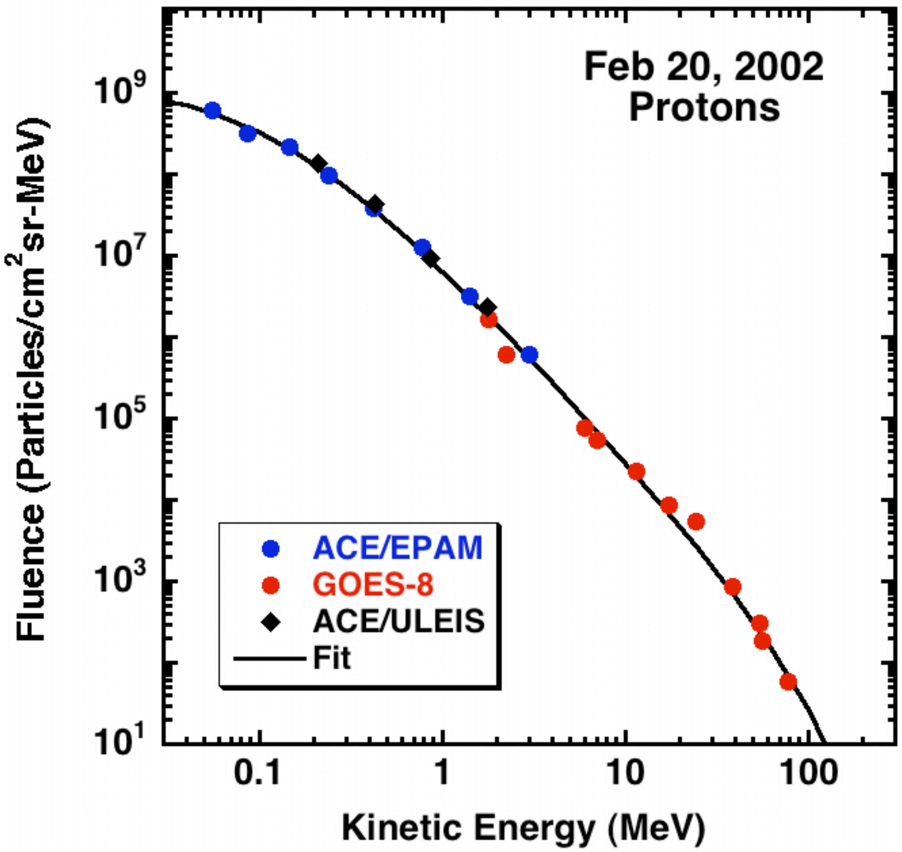
Chollet et al.

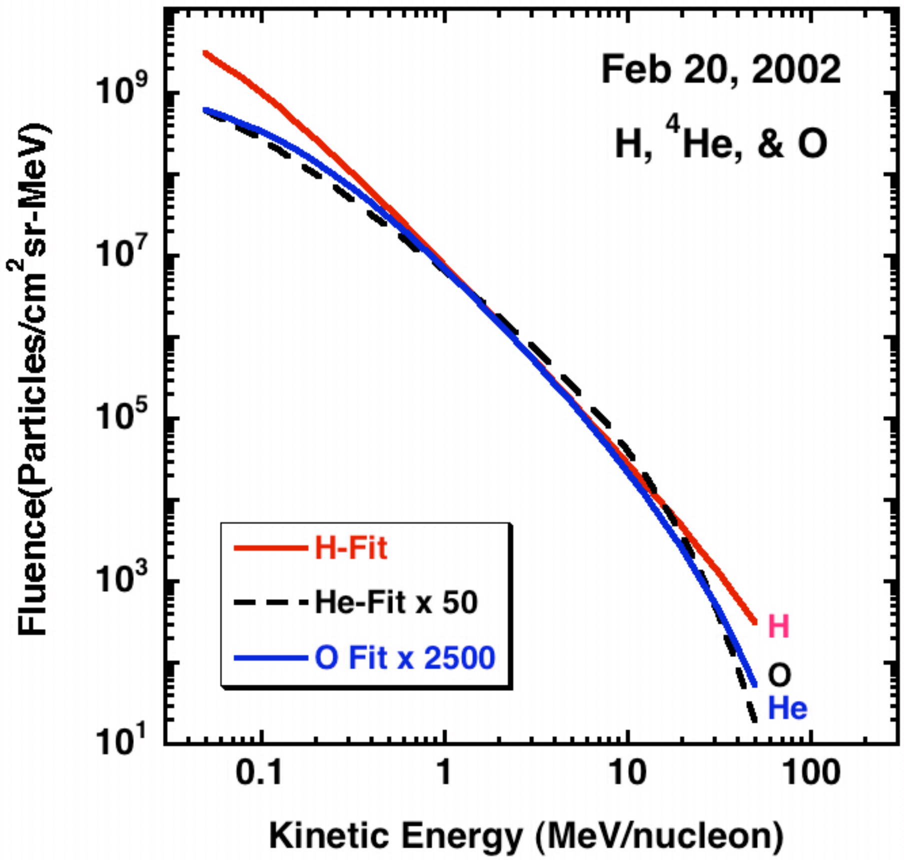
The February 20, 2002
Solar Energetic Particle Event



This is alarge,
impulsive,
^{3}He-rich event

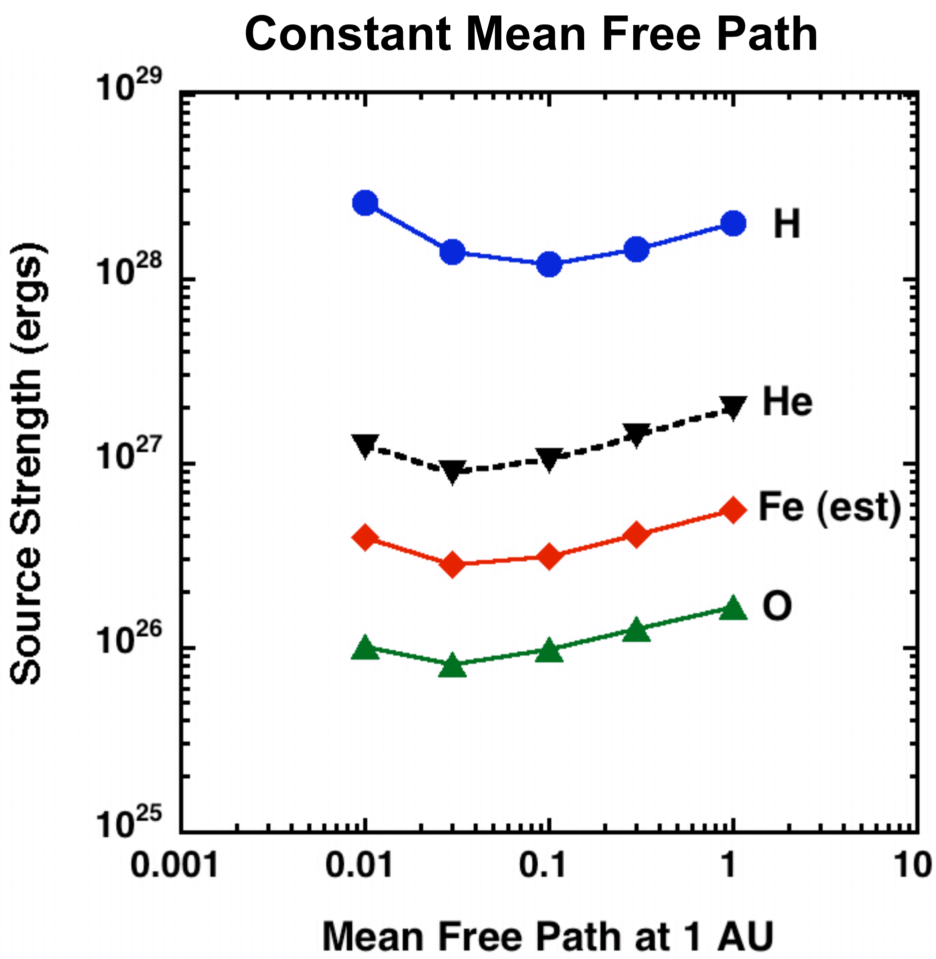
Spectral Fits for the February 20, 2002 Impulsive SEP Event

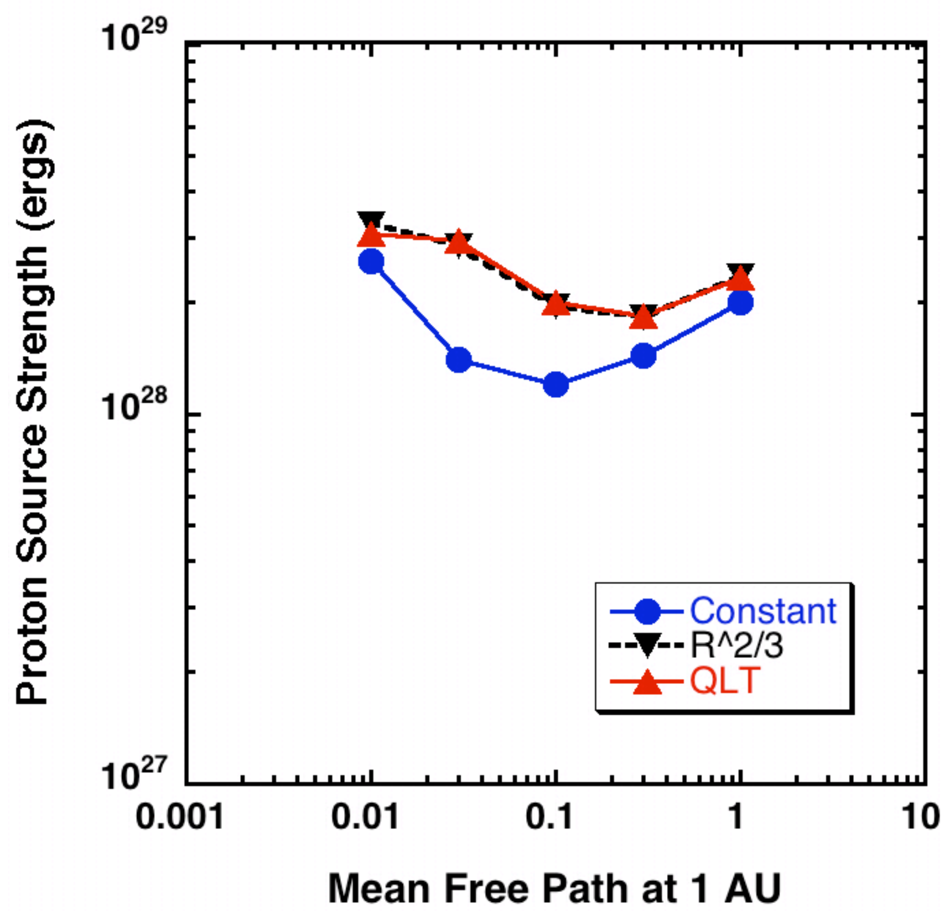




The derived source strength is independent of the transport assumptions to within ± x2

(source strength assumes constant intensity inside ± 20° cone)

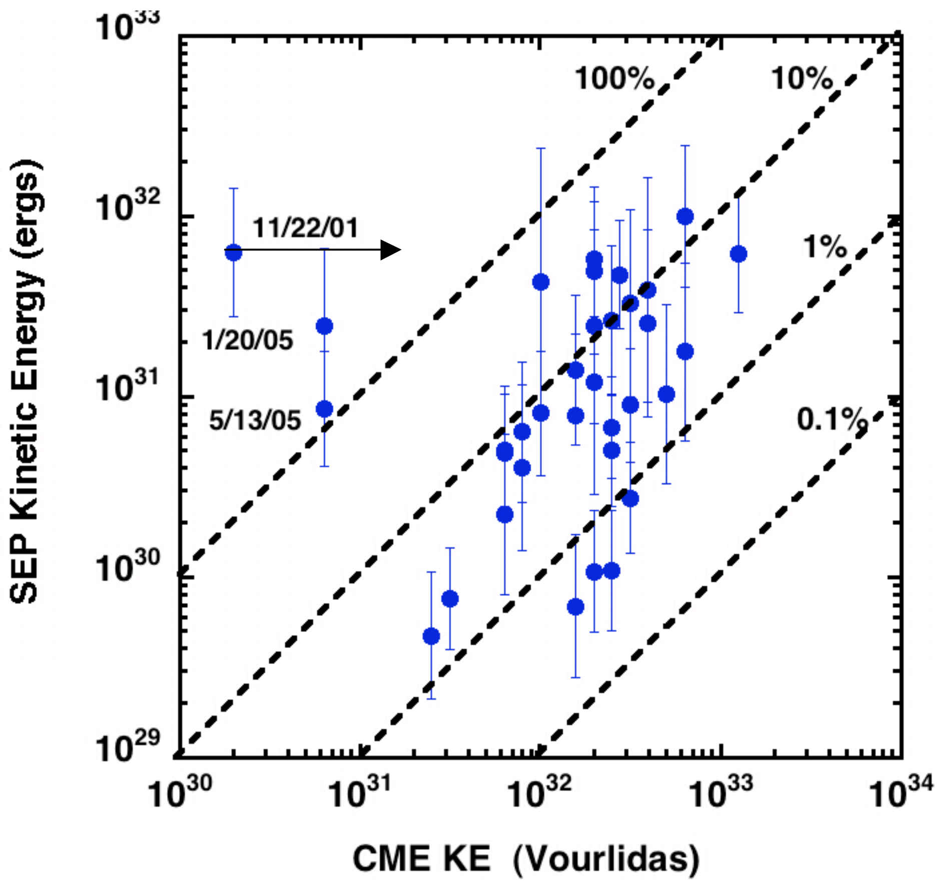


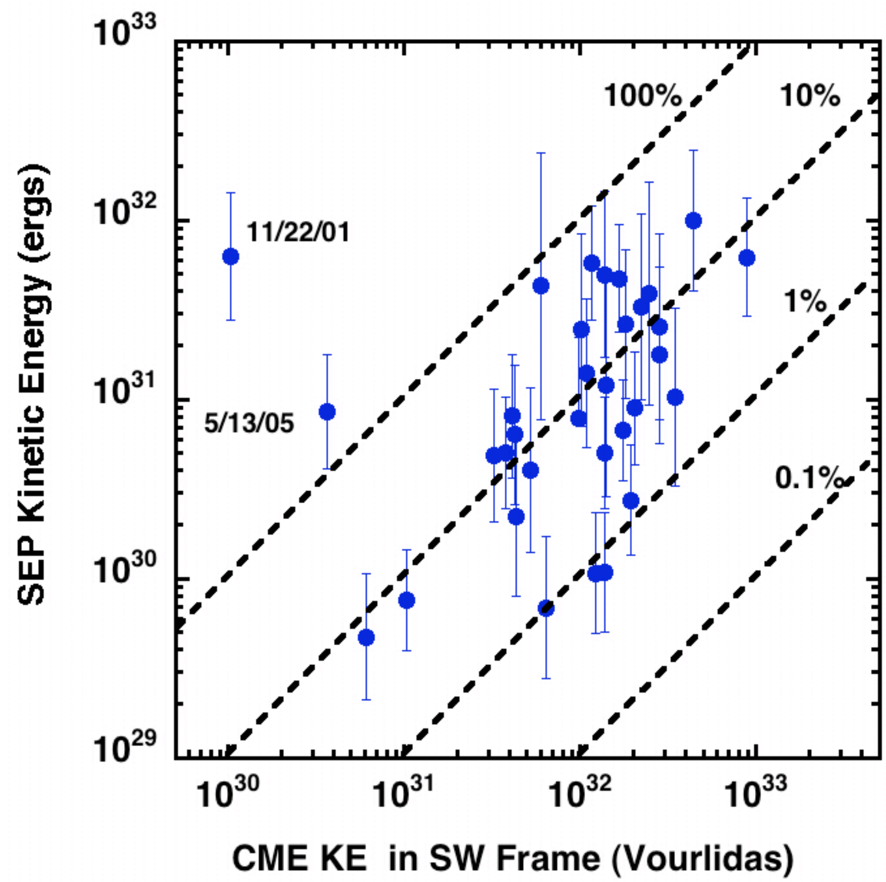


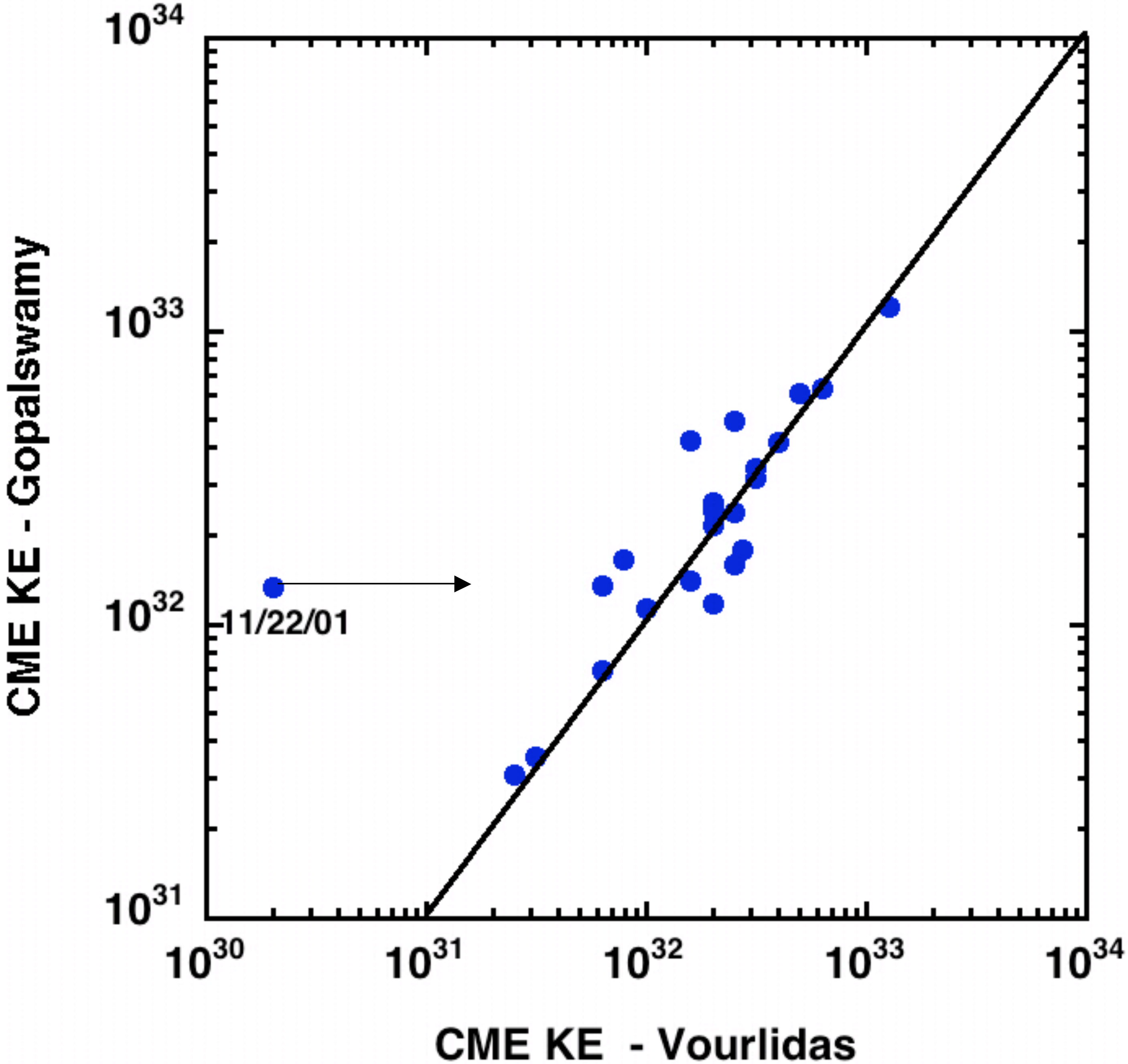
Summary

- With additional events and improved corrections for transport effects we continue to find that shock acceleration is <u>sometimes</u> a very efficient process
- Question: What conditions affect this efficiency?
    - Seed particle density
    - Shock geometry
    - Pre-conditioning by earlier CMEs
- On-going work will improve the SEP and CME estimates
- During cycle 24, STEREO + 1 AU assets will provide improved energy estimates and cross checks

Including additional Events from Vorlidas







CME KE - Gopalswamy
CME KE - Vourlidas
11/22/01
10^30
10^31
10^32
10^33
10^34