Why are there so few solar proton events in Solar Cycle 24?

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With thanks to Dick Mewaldt, Randy Jokipii, Jozsef Kota, and Federico Fraschetti

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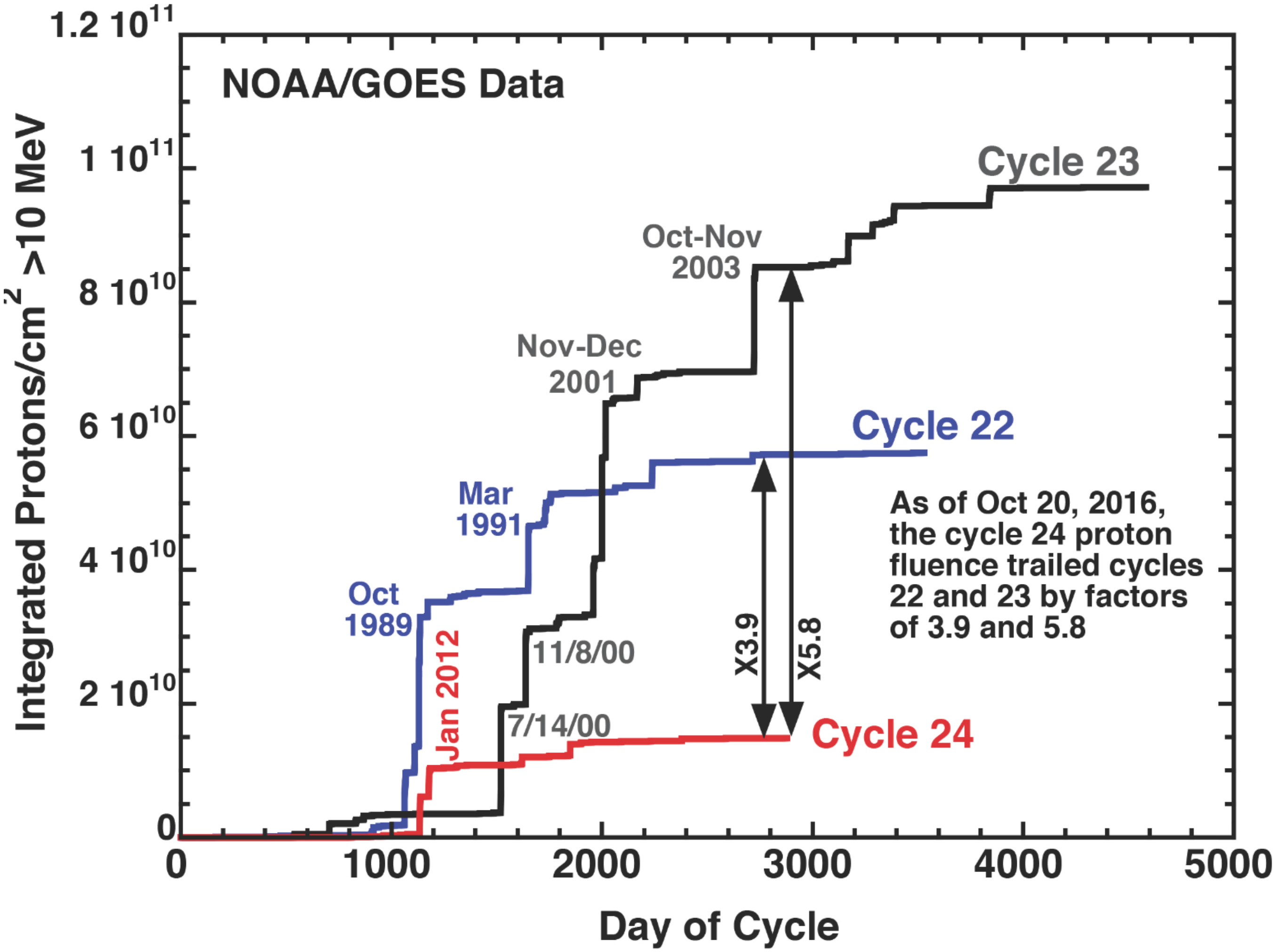
Washington DC, April 26, 2017.

(figure courtesy D. Mewaldt)

Progression of Solar Cycles 22, 23, and 24

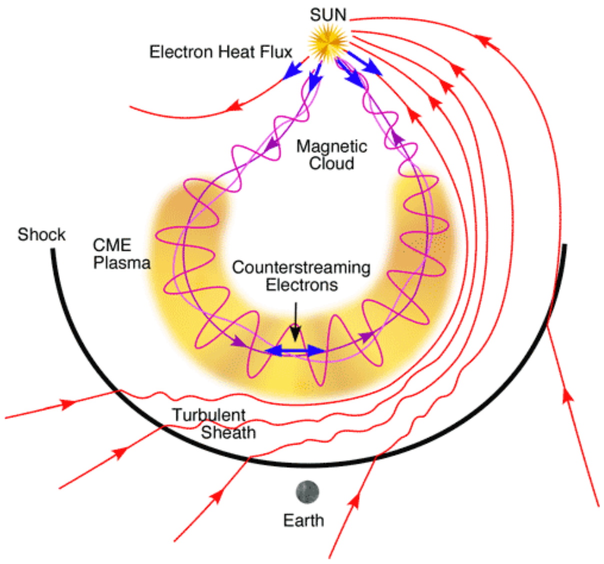


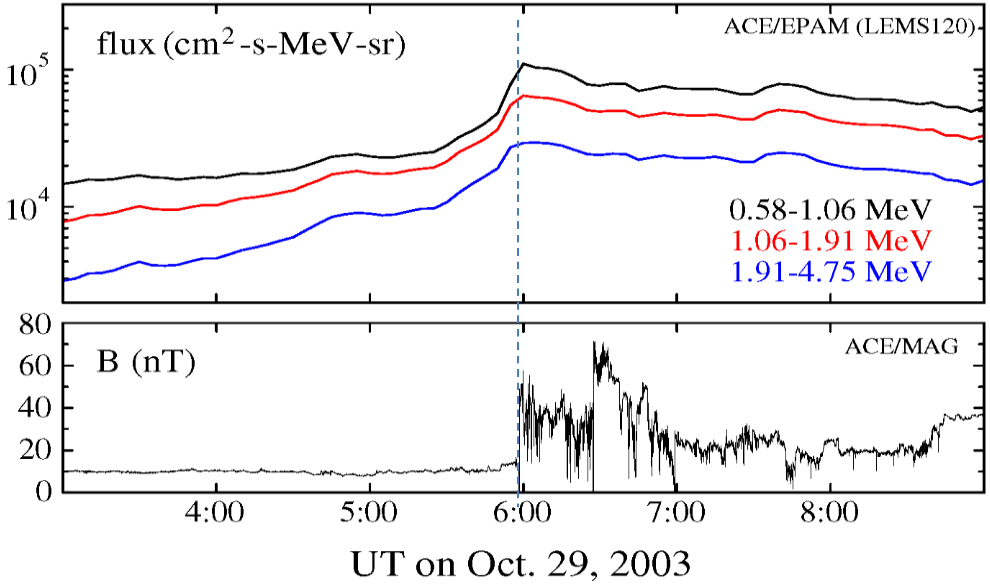
As of Oct 20, 2016, the cycle 24 proton fluence trailed cycles 22 and 23 by factors of 3.9 and 5.8

There have been few large SPEs this cycle; including only 1 (2?) GLEs this cycle compared to 13 at a similar stage of the previous cycle.

The acceleration mechanism involved in producing Solar Protons Events (SPE)

- The largest SPEs are almost always associated with fast CMEs (usually halo CMEs)
- At 1AU, at energies below several MeV, the peak proton intensity is almost always coincident with the passage of the CME shock.





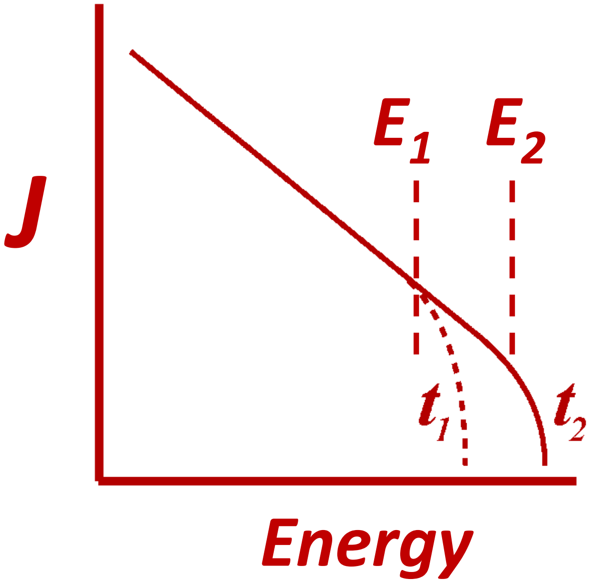
The most widely accepted mechanism is diffusive shock acceleration (DSA) at CME-driven shocks

Acceleration time scale in DSA

For a planar shock, the time to accelerate particles from E_0 to E is

$$\tau_{acc} = \frac{(3/2)}{U_1 - U_2} \int_{E_0}^{E} \left(\frac{\kappa_1(E')}{U_1} + \frac{\kappa_2(E')}{U_2} \right) \frac{dE'}{E'}$$

Where *κ* is the diffusion coefficient normal to the shock front. The subscripts refer to upstream (1) and downstream (2) of the shock



For a CME-driven, propagating shock, *E* is the "spectral break energy". Below this, the spectrum is power law, and above this it is steeper (sometimes to another power law).

The intensity at the highest energies depends critically on the spectral break energy, and, therefore, on the acceleration time scale (or rate).

Dependence of acceleration time on …

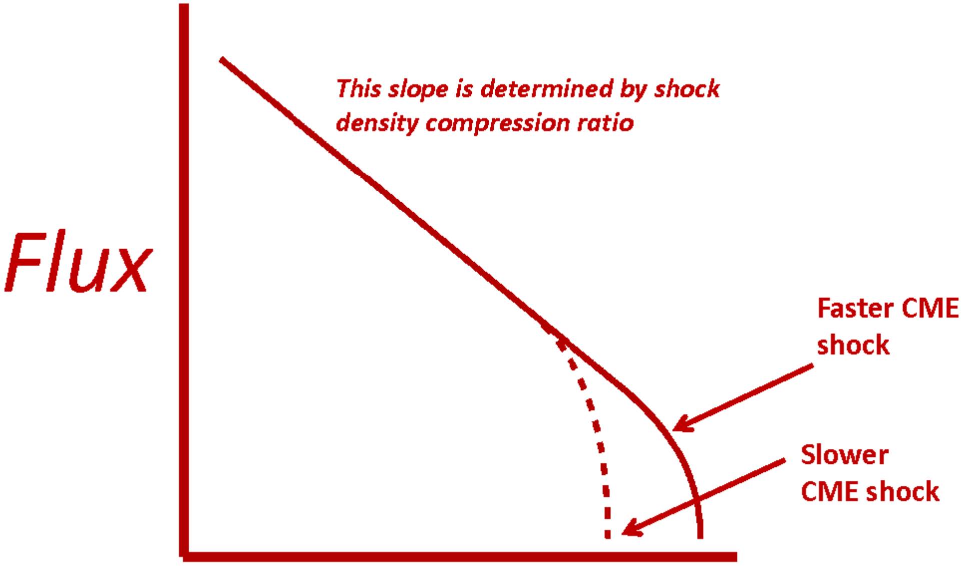
CME speed:

- The acceleration time varies with $1/U_1^2$. Faster CMEs accelerate particles more rapidly, and the spectral break occurs at a higher energy, leading to more particles at high energies.
- For a slower CME, the spectrum will roll over from a power law at a lower energy, and … **the intensity at the highest energies seen at 1 AU will be significantly reduced** compared to a faster CME shock.

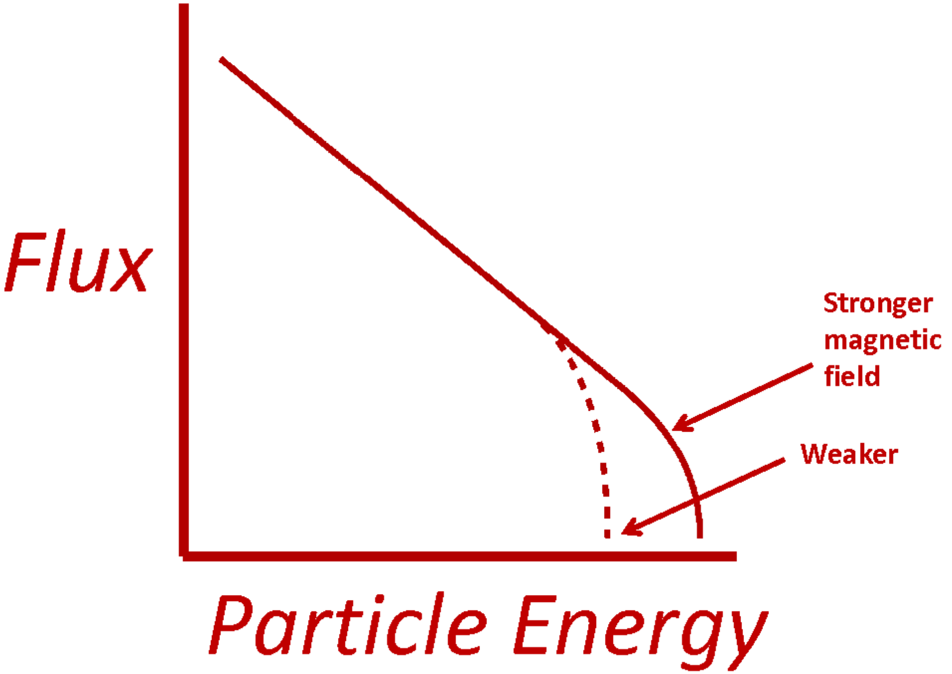
Magnetic field strength:

- Generally, a weaker magnetic field will lead to a larger diffusion coefficient along the magnetic field, and a *slower* acceleration rate (longer acceleration time).
- Thus, the spectrum will roll over from a power law at a lower energy for a weak magnetic field, and … **the intensity at the highest energies seen at 1 AU will be significantly reduced** compared to that of a stronger magnetic field.

- A slower CME shock does not create as many high-energy particles as a faster one

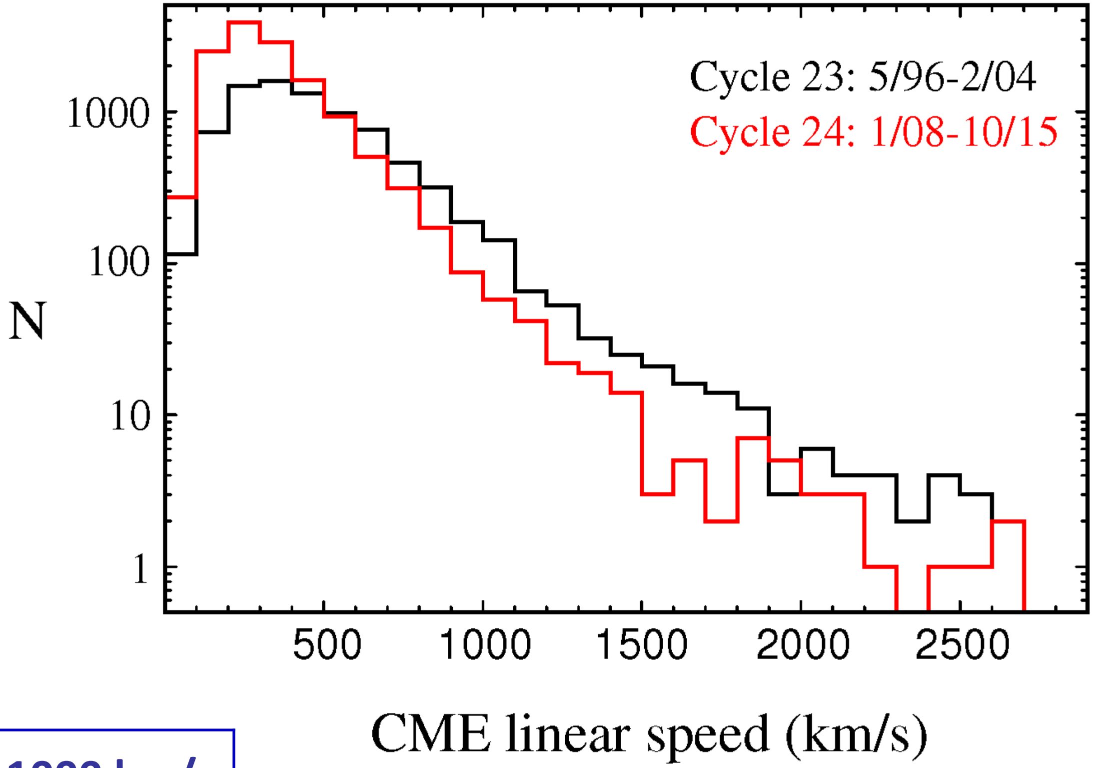


- When the solar magnetic field is weaker, shocks do not create as many high-energy particles compared to when it is stronger



Distribution of CME speeds from SoHO/LASCO catalog

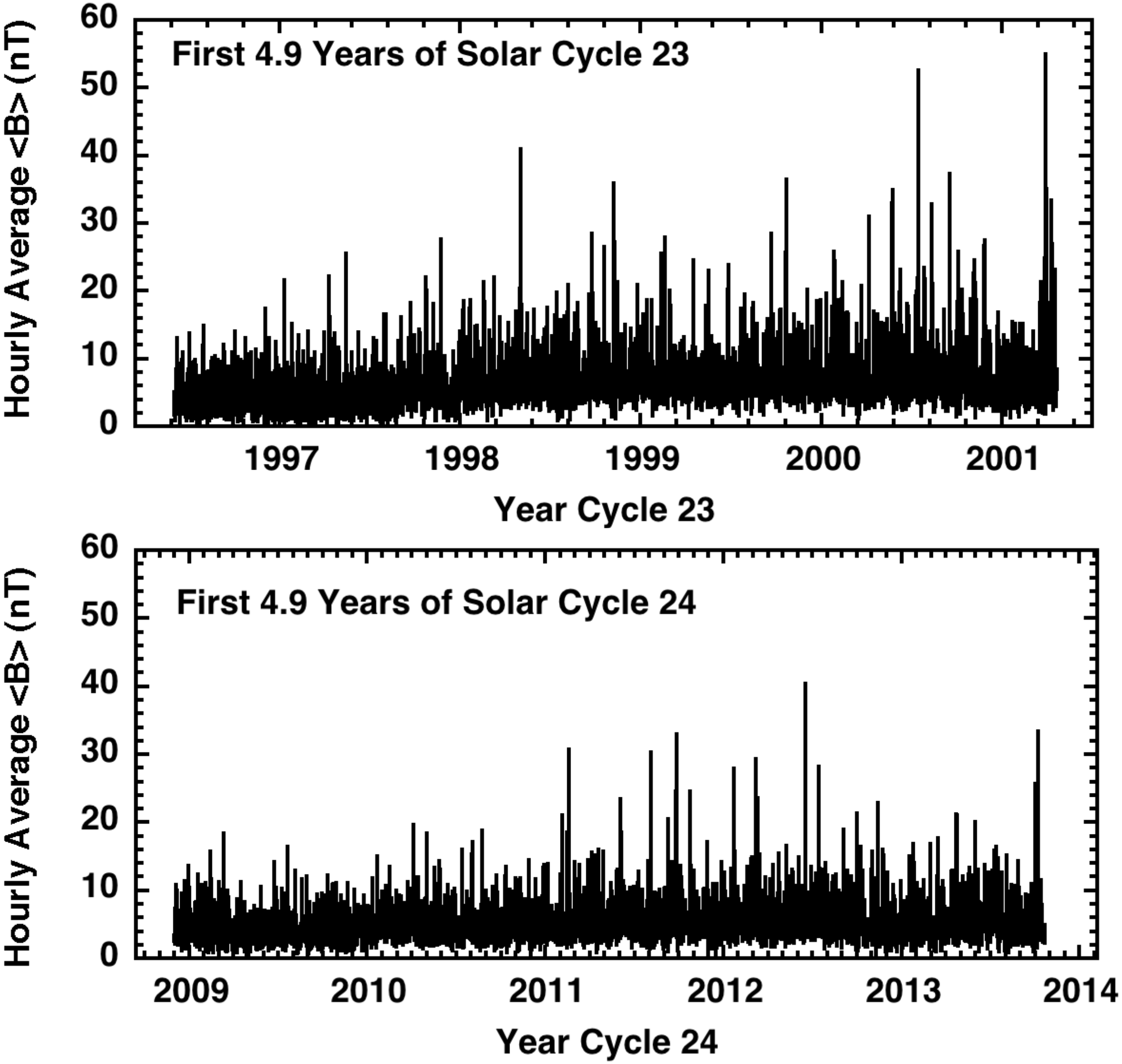
There have been noticeably more CMEs this cycle compared to a similar stage of the previous cycle; but fewer fast ones (by over 50%)



Cycle	ALL	>500 km/s	>1000 km/s
23	8,382	3,137	408
24	13,328	2,193	188

data source: http://cdaw.gsfc.nasa.gov/CME_list

The interplanetary magnetic field is significantly weaker during the rise to maximum of cycle 24 - a pattern that was also very evident during the extended solar minimum.



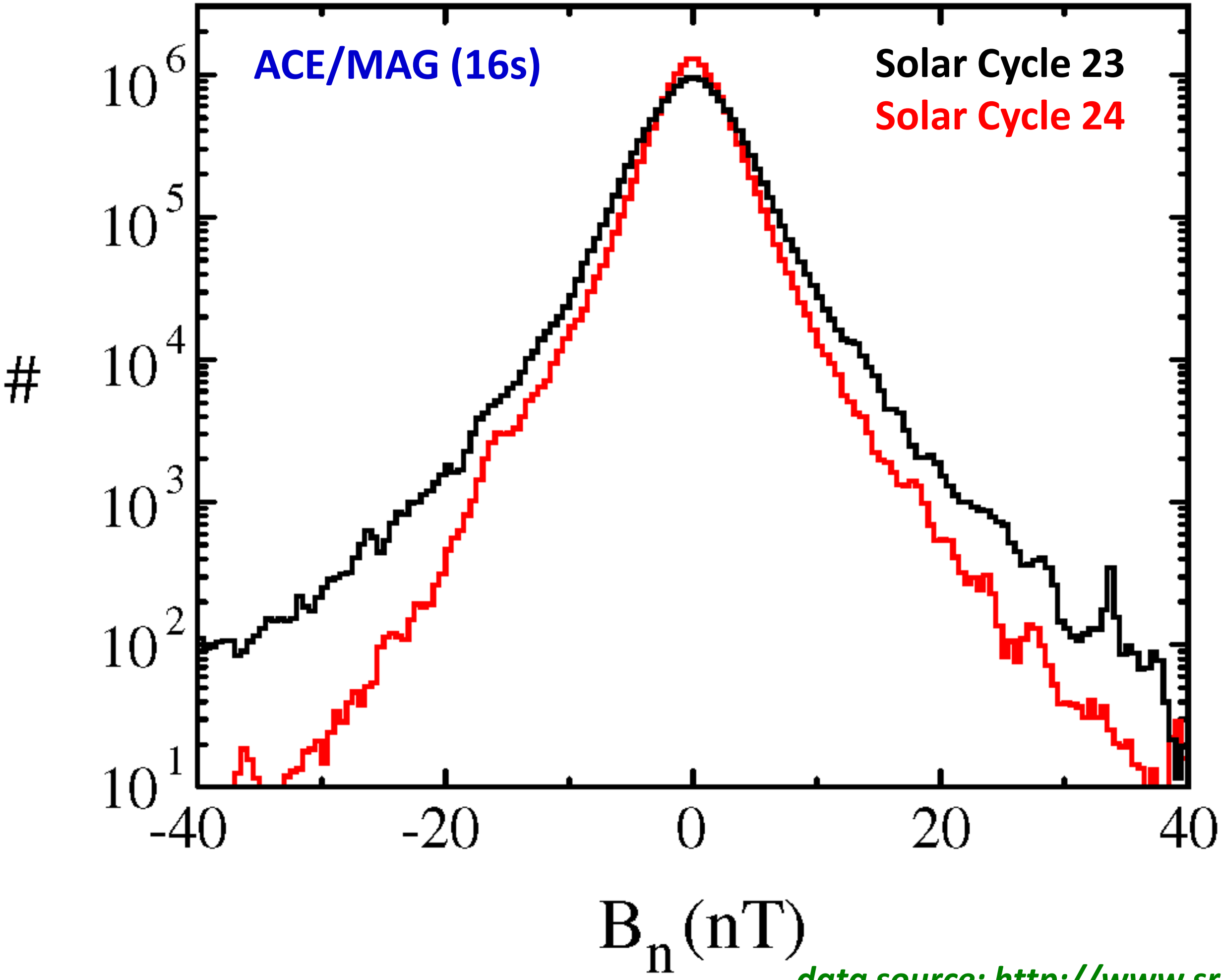
<B> = 7.04 nT

<B> = 5.24 nT

Adapted from slide provided by D. Mewaldt: averages include more-recent data

The r.m.s. value of the turbulent component of the IMF is also smaller in solar cycle 24 than it was in cycle 23.

But, the ratio is nearly unchanged → dB/B is not noticeably different (Mewaldt, 2015 fall AGU meeting).



Solar Cycle 23

$\mathrm{sqrt}(\langle B_n^2\rangle)$ = 4.12 nT

$\langle B\rangle$ = 7.04 nT

ratio = 0.584

Solar Cycle 24

$\mathrm{sqrt}(\langle B_n^2\rangle)$ = 3.11 nT

$\langle B\rangle$ = 5.24 nT

ratio = 0.593

data source: http://www.srl.caltech.edu/ACE/ASC/level2/index.html

The acceleration rate in DSA depends on the spatial diffusion coefficient, which depends on ***<u>both</u>*** |**B**| and dB/B.

The (parallel) diffusion coefficient is given by:

$$\kappa(w) = \frac{w^2}{4}\int_0^1 \frac{(1-\mu^2)^2 d\mu}{D_{\mu\mu}}$$

Where

$$D_{\mu\mu}(\mu) = \frac{\pi}{4}(1-\mu^2)\Omega_0 \frac{f_r P(f_r)}{B_0^2}$$

Pitch-angle diffusion coefficient

$$f_r = \frac{\Omega_0 V_0}{w\mu}$$

Resonant frequency

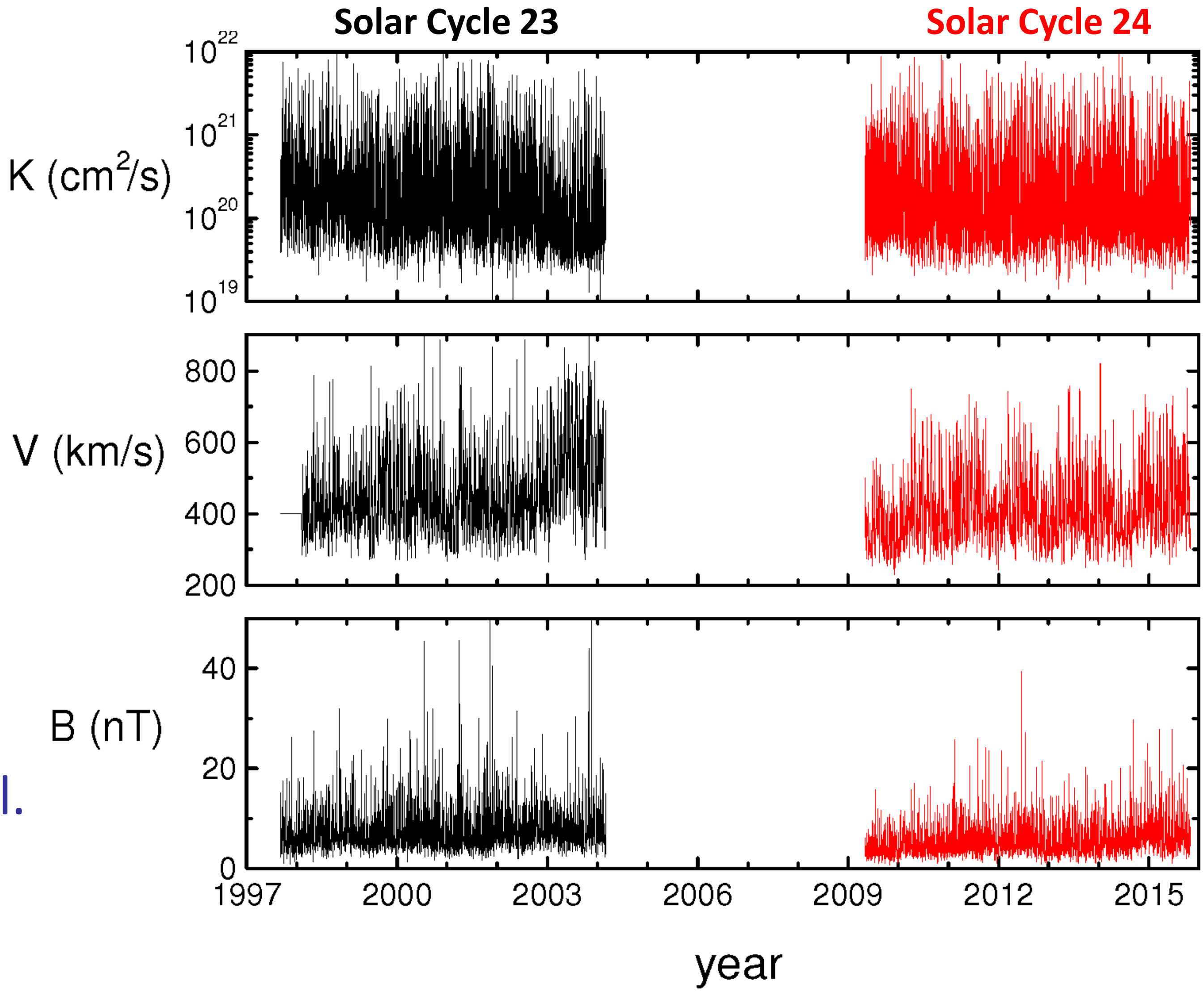
P(x) is the *frequency* power spectrum of the random component of the IMF, B_0 is the field strength, V_0 is the solar-wind speed, Ω_0 is the cyclotron frequency, and *w* is the particle speed.

Diffusion coefficients for 100-MeV protons as a function of time using ACE MAG & SWEPAM data.

K is from the expression on the previous slide

Power spectra of B_n were computed using 6-hour time intervals of 16-s MAG data.

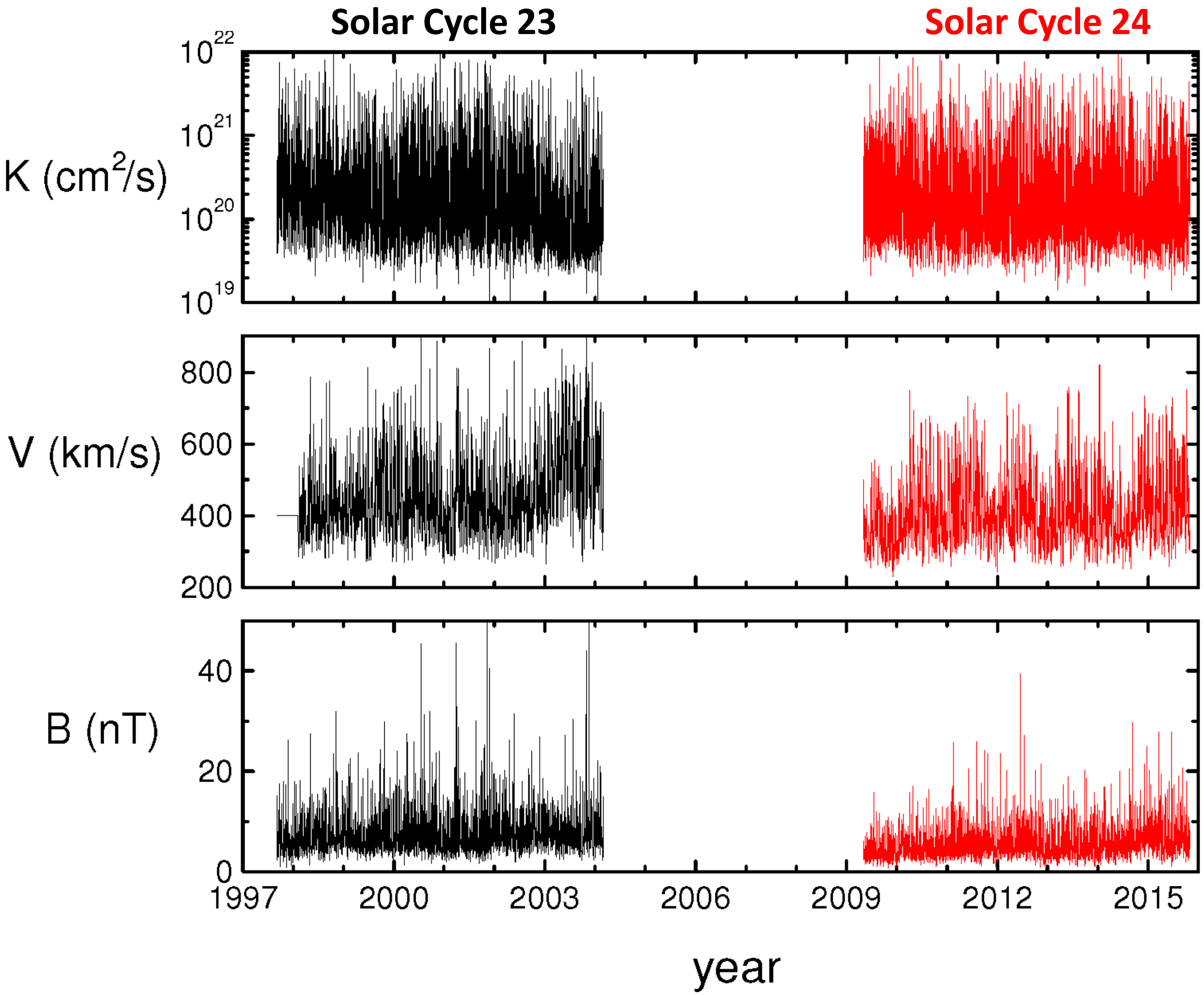
B (to get Ω_0) and V were averaged over each 6-hour interval.



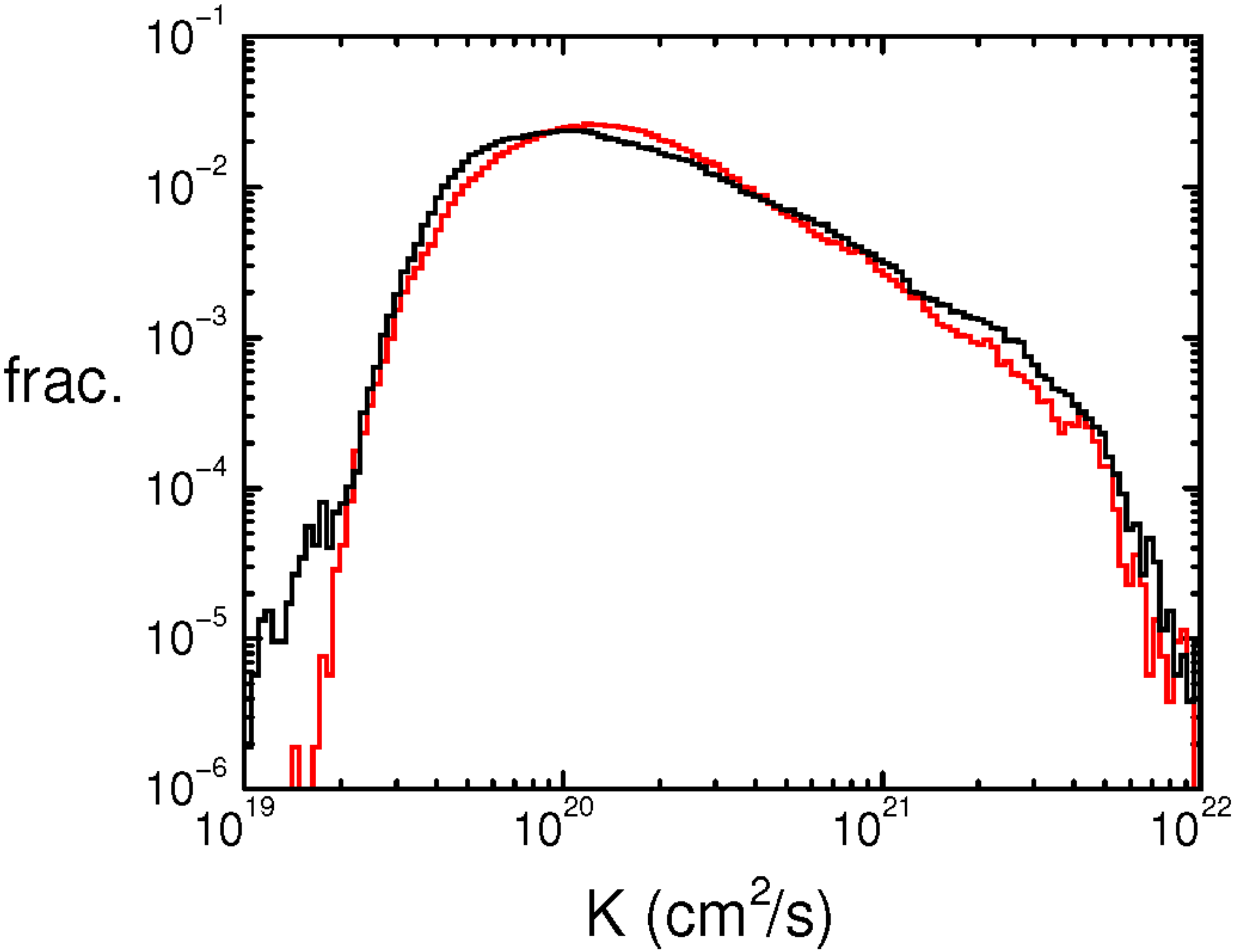
Diffusion coefficients for 100-MeV protons as a function of time using ACE MAG & SWEPAM data.

Total time interval in both sets are the same, and the start is at the same phase of the cycle

(Start of Cycle 23 occurred before ACE launch, and Cycle 24 had not ended at the time of the most-recent data available.)



Distribution of diffusion coefficients of 100-MeV protons computed from ACE data and quasi-linear theory (QLT)



Solar Cycle 23

<K> = 2.6×10^{20} cm^2/s

Solar Cycle 24

<K> = 2.5×10^{20} cm^2/s

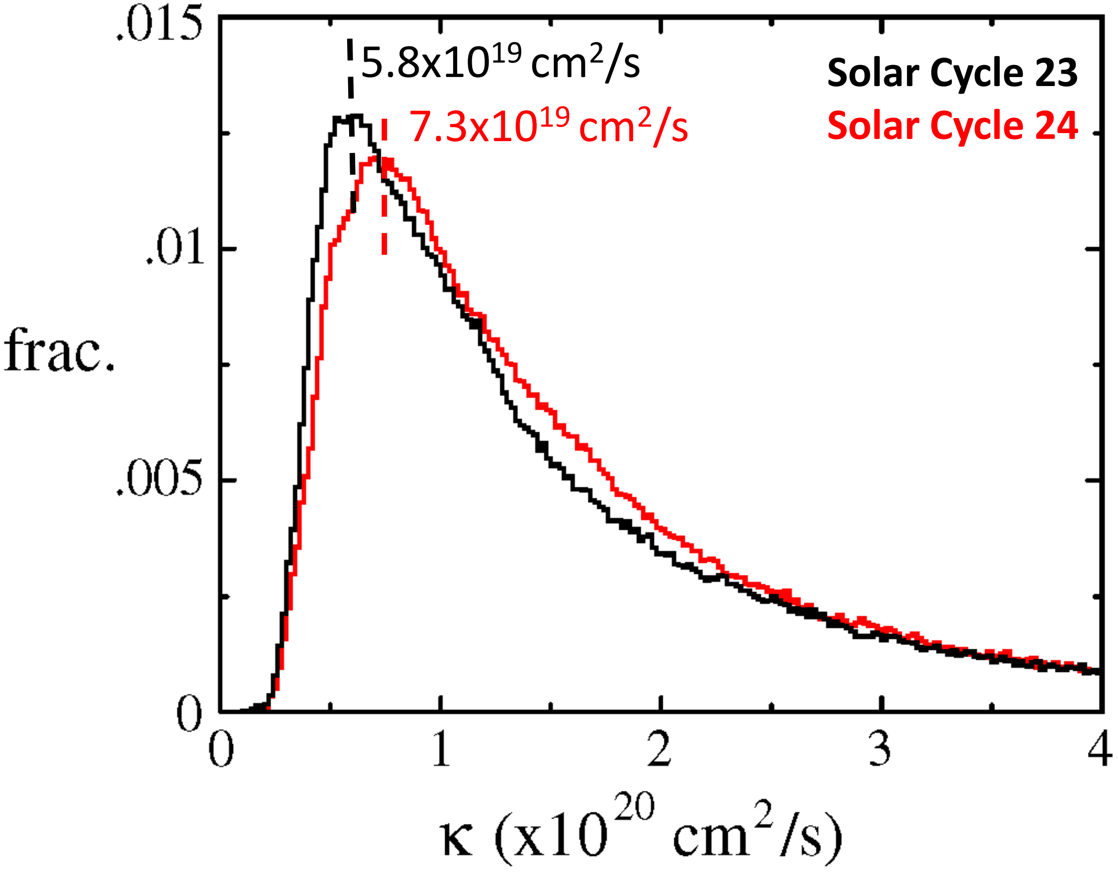
The mean is very nearly the same in the two cycles

For $\kappa < 4 \times 10^{20}$ cm^2/s, the distributions differ significantly

Distribution of diffusion coefficients of 100-MeV protons computed from ACE data / QLT

The peak in the distribution for cycle 23 is shifted towards a lower κ compared to that of cycle 24.

The location of the maximum in cycle 24 occurs at a ~30% larger κ than that of cycle 23



$\kappa_{\text{at peak}}$ (cycle 23) = 5.8×10^{19} cm^2/s

$\kappa_{\text{at peak}}$(cycle 24) = 7.3×10^{19} cm^2/s **≈ 1.3 $\kappa_{\text{at peak}}$ (cycle 23)**

Would a 30% increase in the diffusion coefficient, and a reduction in the number of fast CMEs, lead to the observed decrease in the number of SPE events?

To quantify this, we consider a model that solves the acceleration of particles at a shock and uses the observed CME speeds to estimate the cumulative number of protons > 10MeV at 1 AU.

A quantitative model:

- We solve the Parker transport equation using a spherically-symmetric geometry, for a shock moving radially outward from the Sun.

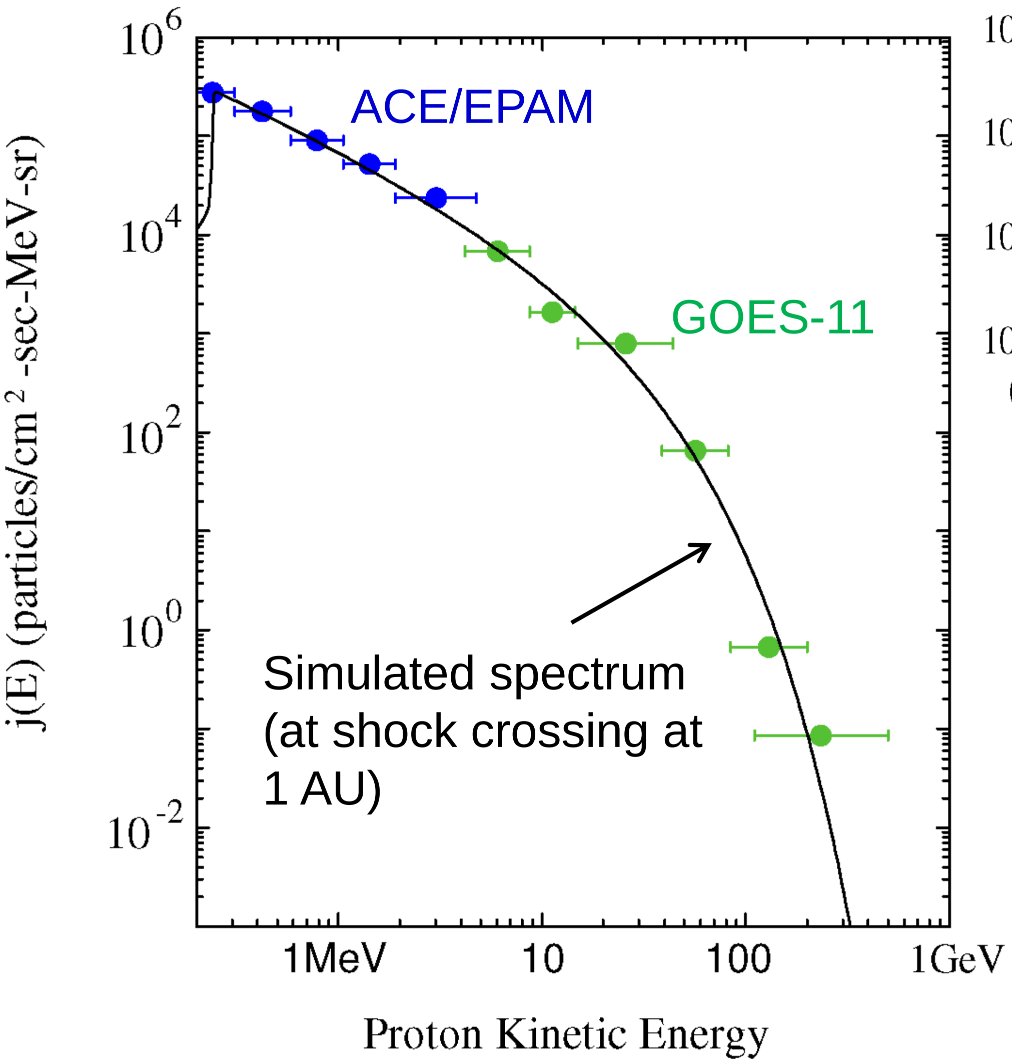
$$\frac{\partial f}{\partial t} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 \kappa_{rr}\frac{\partial f}{\partial r}\right) - U\frac{\partial f}{\partial r} + \frac{1}{3r^2}\frac{\partial (r^2 U)}{\partial r}\frac{\partial f}{\partial \ln p} + Q = 0$$

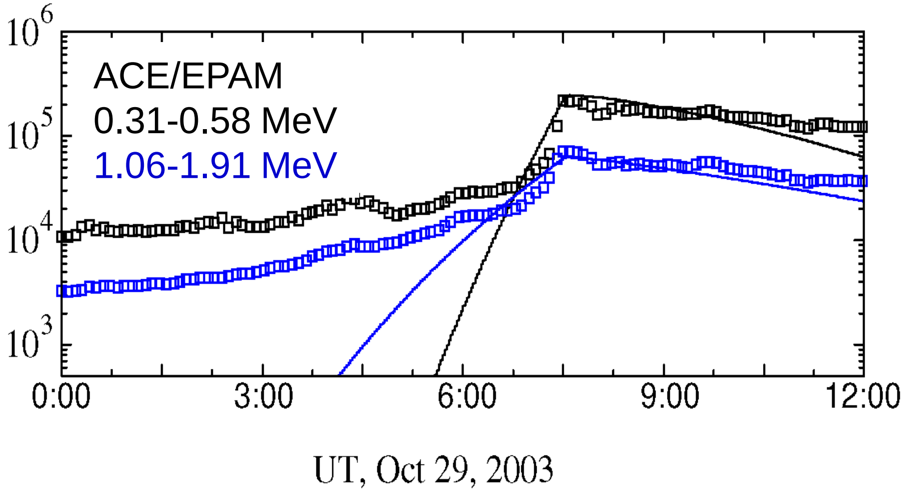
- Solved using a standard finite-difference approach.
- The plasma speed is determined kinematically (consistent with that expected for a radially propagating interplanetary shock).
- The diffusion coefficient is assumed as follows:

$$\kappa_{rr} = \kappa_0 (E/1\ \mathrm{MeV})^{\gamma} (r/1\ \mathrm{AU})^2$$

- Where K_0 and γ are input parameters. The dependence on r given above is simply an assumption. It is not well constrained, but reasonably, one would expect K_{rr} to scale roughly inversely with the mag. field strength B.

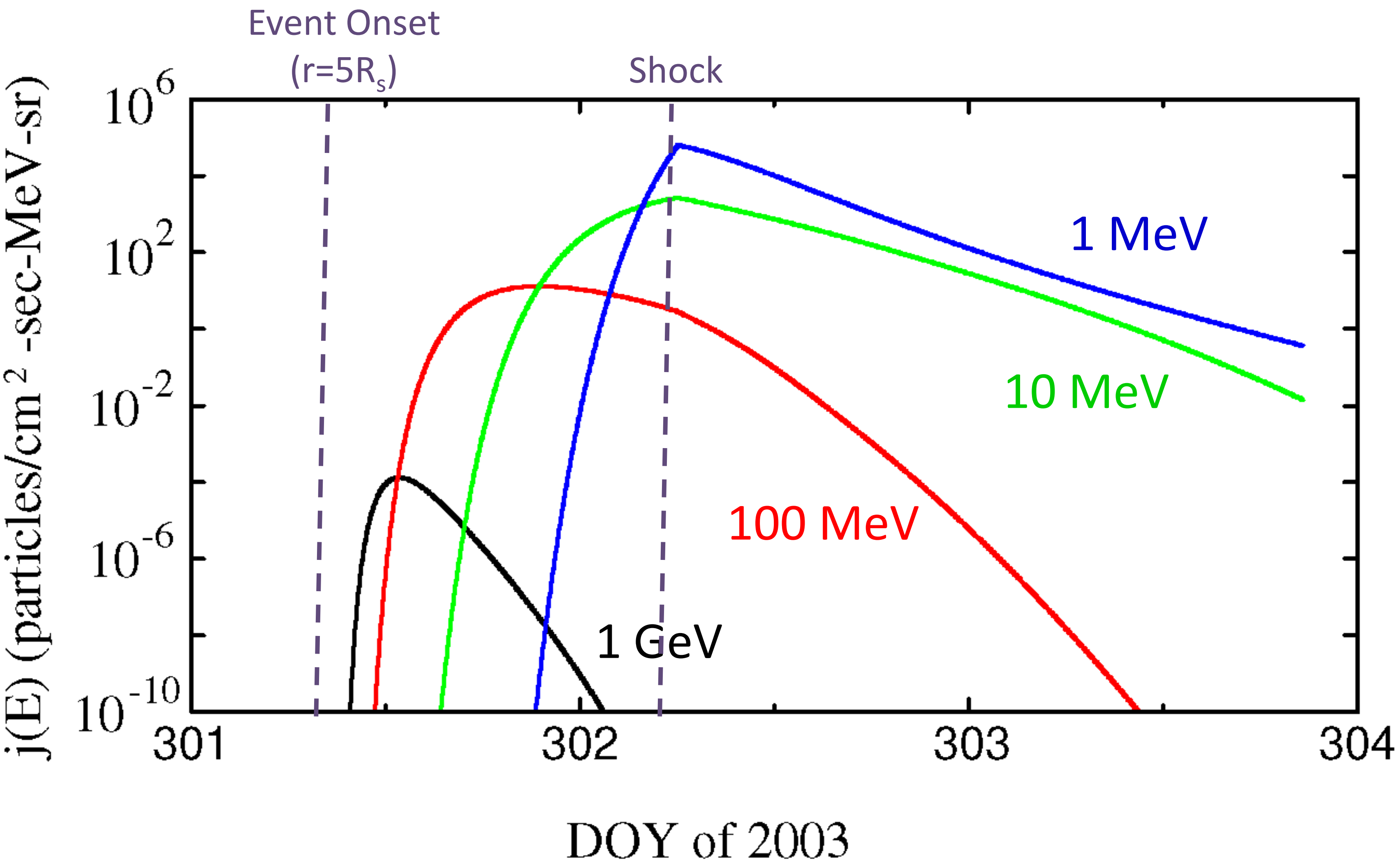
Normalization provided by comparison of simulation with observations of the large SEP event seen on DOY 302, 2003 (Halloween event)





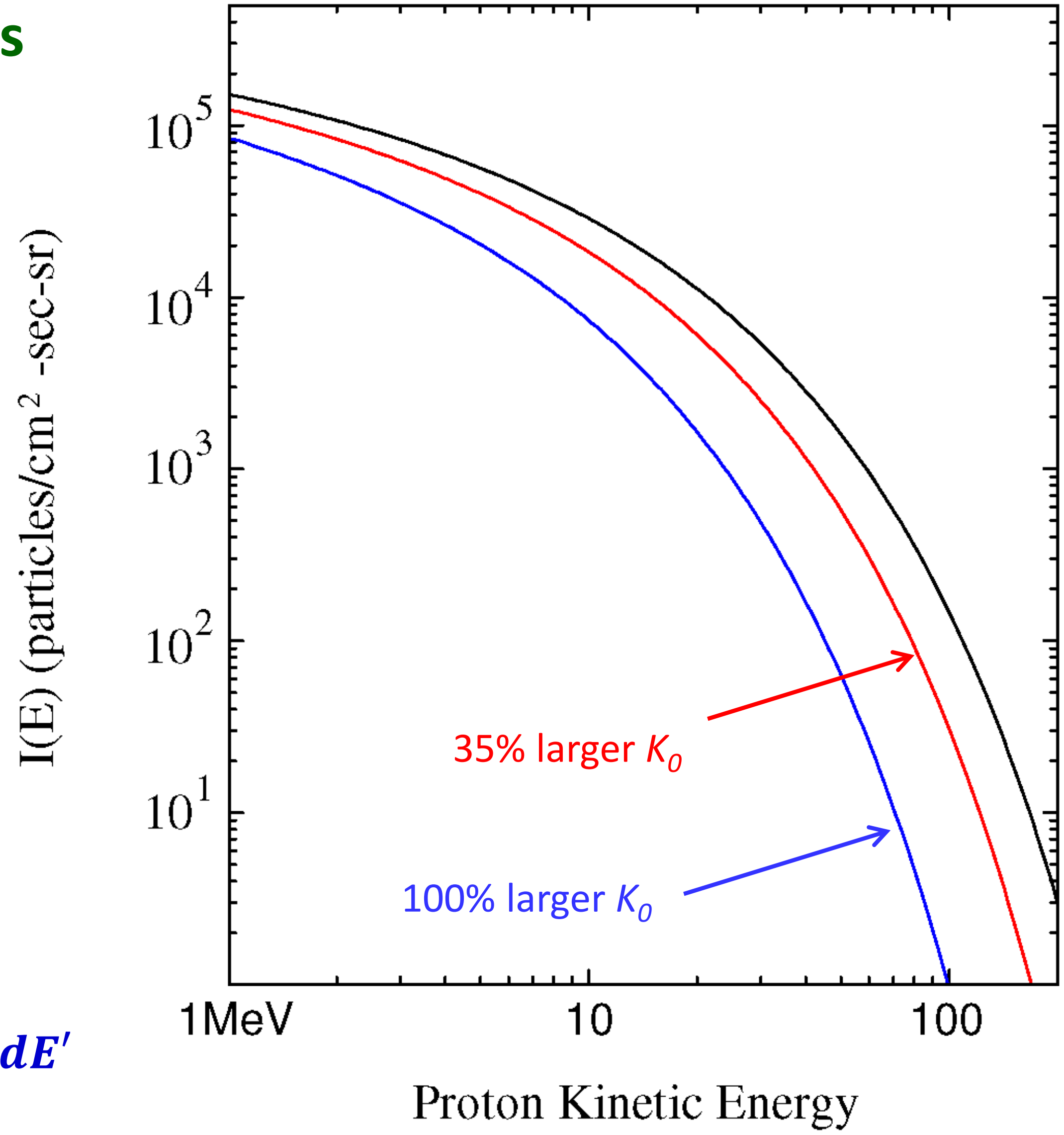
- Shock speed is that at 1AU
- $n_{ep} = 10^{-4}$ used to determine the source function (injection at the shock with E_{inj}=250 keV).
- K_0 and γ determined from 1 AU observations by fitting energetic particle intensities ahead of shock to exponential

SEP intensities vs. time at 1 AU



Integrated spectra, at the time of passage of the shock at 1AU

V_{sh} = 1900 km/s
V_{sw} = 780 km/s

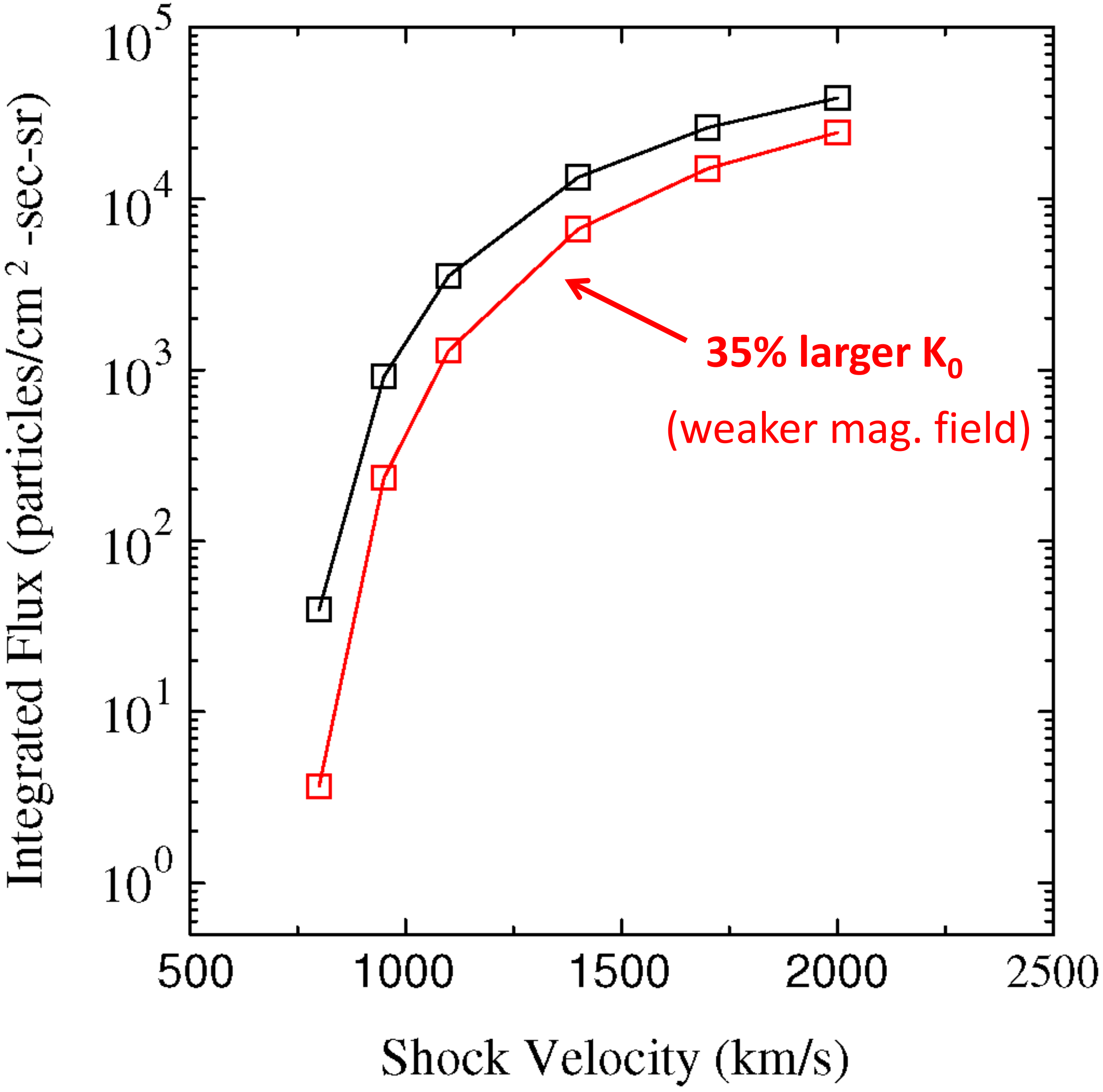


$$I(E) = \int_E^\infty \frac{dJ(E')}{dE} dE'$$

- Total integrated intensity above 10 MeV, as a function of the shock velocity for two different values of K_0

- The difference is very significant at lower shock speeds (nearly an order of magnitude)

V_{sw} = 500 km/s

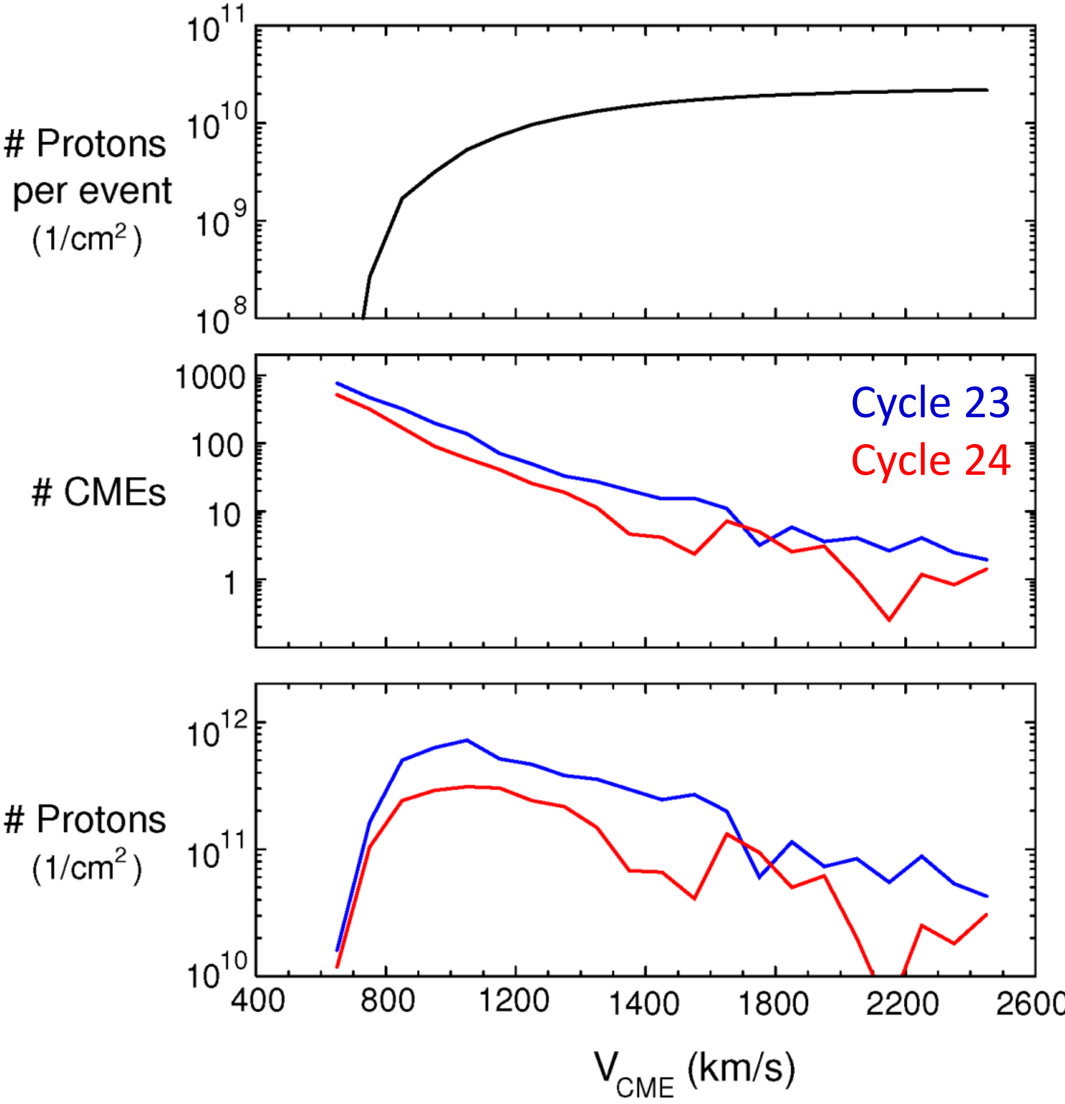


35% larger K_0

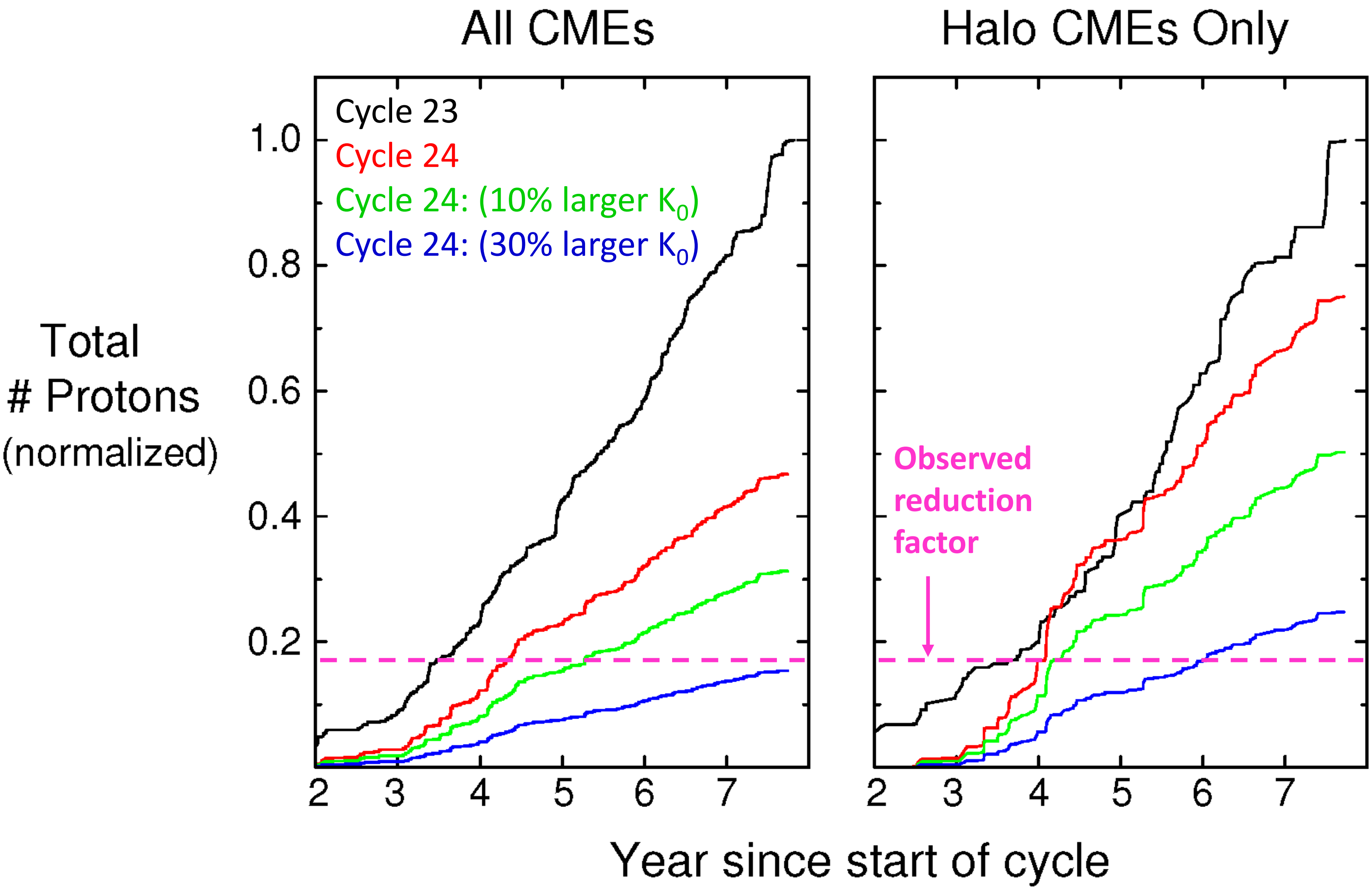
(weaker mag. field)

Combined Modeling with CDAW/CME list to estimate TOTAL protons

- We run this model for a wide range of CME (shock) speeds, based on the SoHO/LASCO CME catalog from CDAW for cycles 23 and 24
- Each CME is treated separately in our calculation and we sum all the events vs. time since start of cycle
- The greatest contribution comes from CMEs with speeds ~1000 km/s



Results: Progression of SPEs during solar cycle



Conclusions

There have been fewer SPE events in the current solar cycle (cycle 24) compared to previous ones

(A) There have been ~ 50% fewer fast (>100 km/s) CMEs during cycle 24 compared to cycle 23

(B) The diffusion coefficients, computed from ACE data using quasi-linear theory, have a peak occurrence at a value that is ~30% larger in cycle 24 compared to cycle 23.

According the DSA theory, the combination of (A) and (B) will lead to fewer SPE events because the acceleration rate is slower, resulting in fewer particles at very high energies

A quantitative model for particle acceleration at individual CME shocks, and using the observed CME speeds during the previous 2 solar cycles, gives a cumulative amount of > 10 MeV protons at 1 AU in solar cycle 24 that is smaller than that of cycle 23 by an amount that is roughly consistent with observations