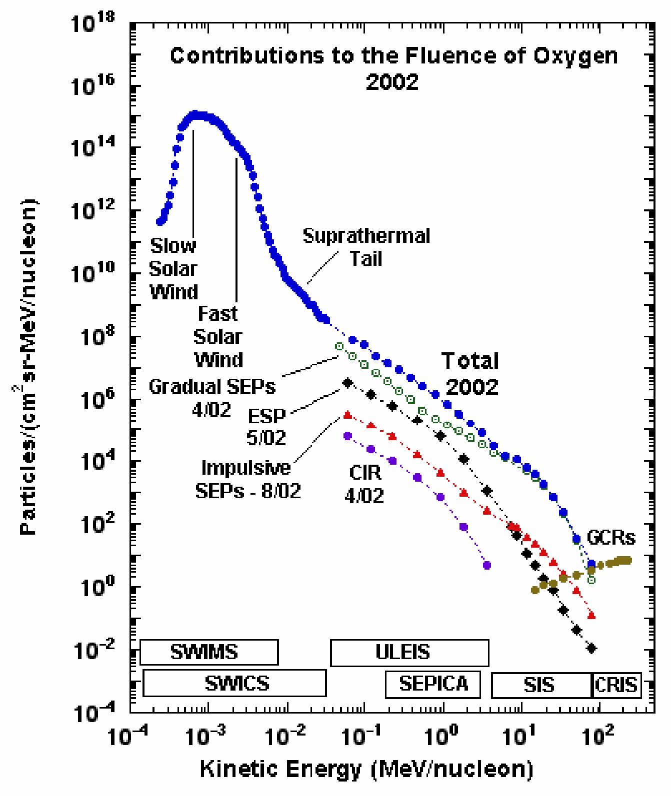
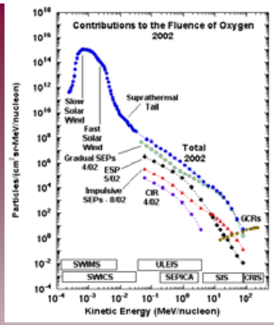
SEP Acceleration



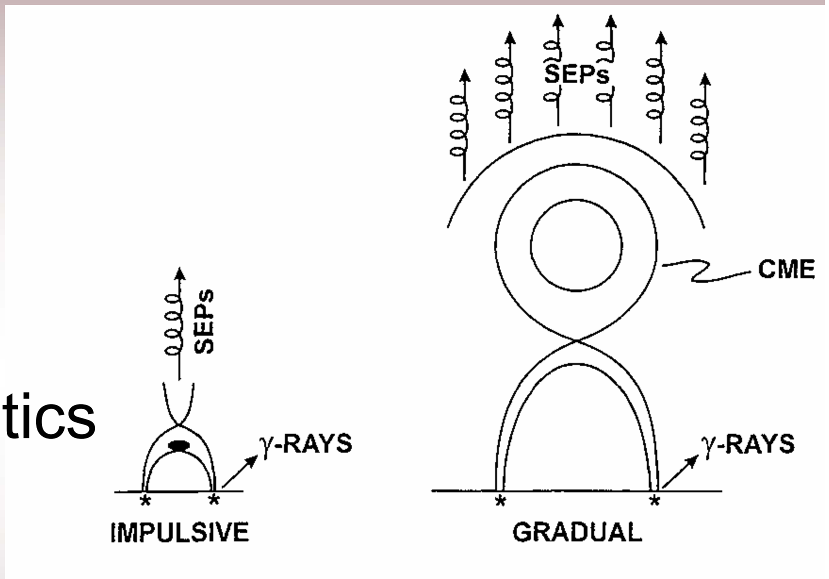
C.M.S. Cohen

Caltech

Outline

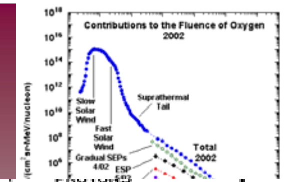


- Shock acceleration in the IPM
  - ESP events
  - Observations vs theory
  - Observations driving theory
- Flare acceleration
  - Impulsive SEP event characteristics
  - Shocks in flares?
- Time of Flight studies
  - Technique
  - Usefulness and questions
- Remaining Questions



Shocks and ESPs

- Bryant 1962, Explorer 12, 9/30/61
  - Associated with Forbush decrease and geomagnetic storm → ‘Energetic Storm Particles’
- Determined that they are ‘locally’ shock accelerated particles (1970s)
  - 2 categories: classic and spike
  - 2 acceleration mechanisms
- Nice because can also measure shock parameters



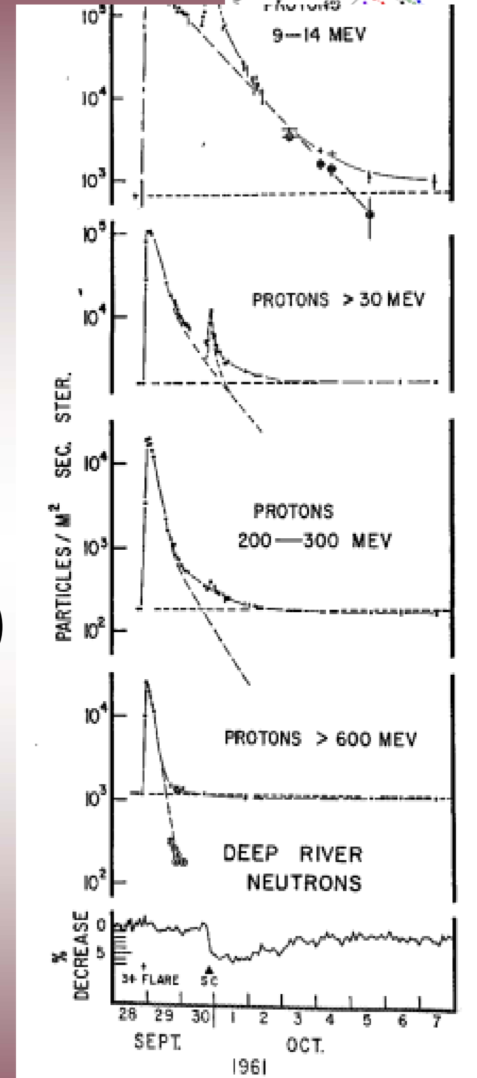
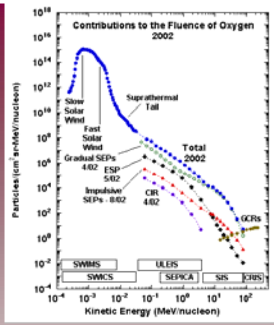


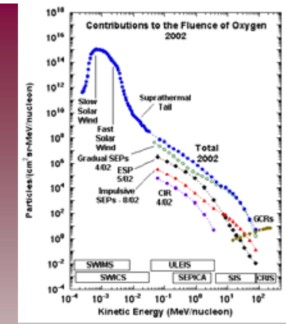
Fig. 18. Representative proton intensities between September 28 and October 7, 1961; the decay of the solar proton event and the arrival of the energetic storm particles late on September 30 are shown. The Deep River neutron monitor

ESP and Spike Events

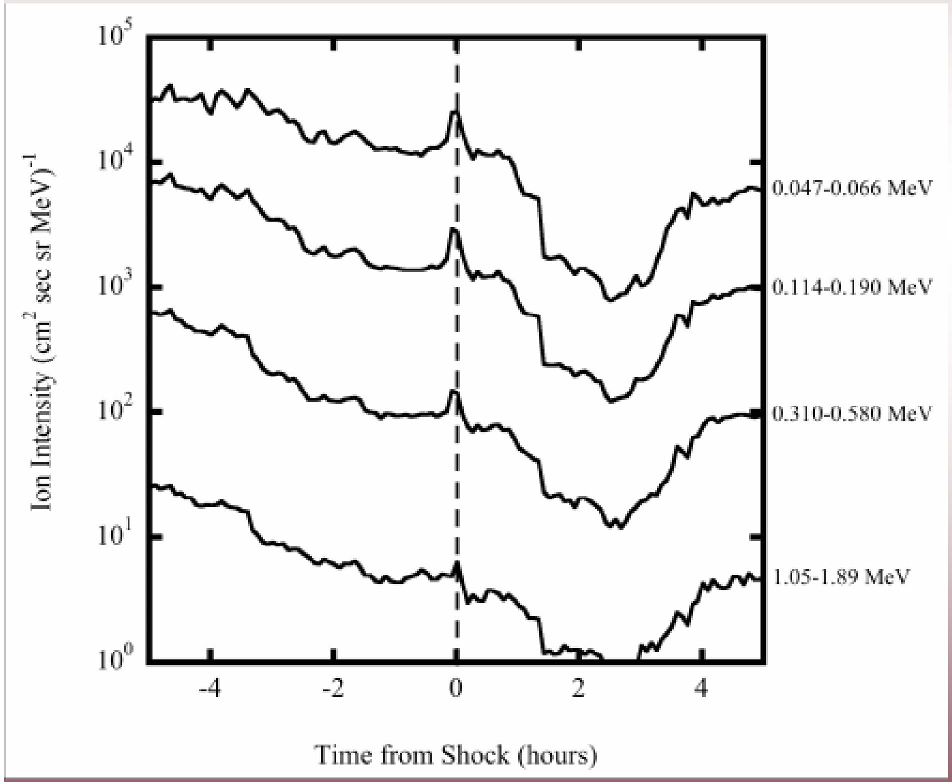


- Spike (LESP)
  - Duration of 5-20 minutes
  - Arrival within 5-10 minutes of shock
  - Rarely exceeds 5 MeV
  - Shock drift acceleration at quasi-perpendicular shocks
- ESP
  - Duration of several hours
  - Arrival maybe ahead or behind shock
  - May extend to ~20 MeV
  - Diffusive shock acceleration at oblique or quasi-parallel shocks

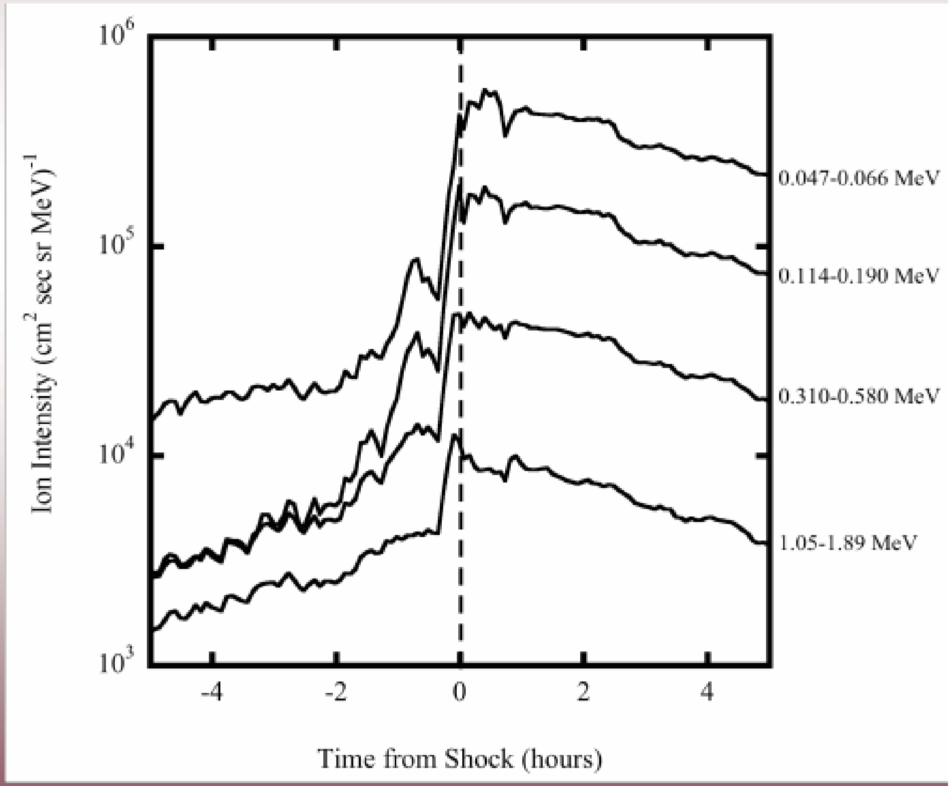
ESP and Spike Events



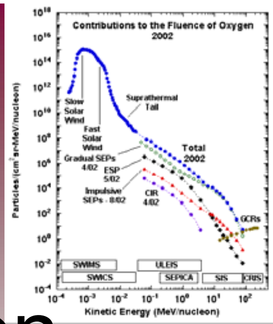
- Spike (LESP)



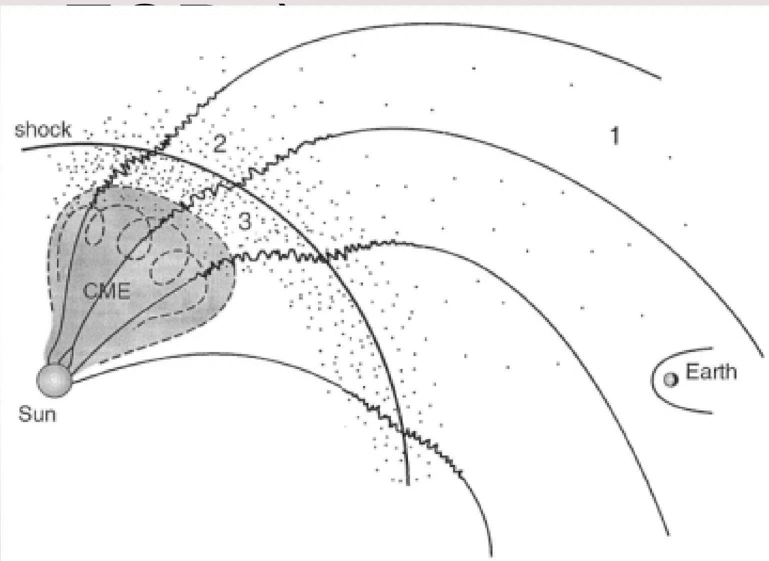
- ESP

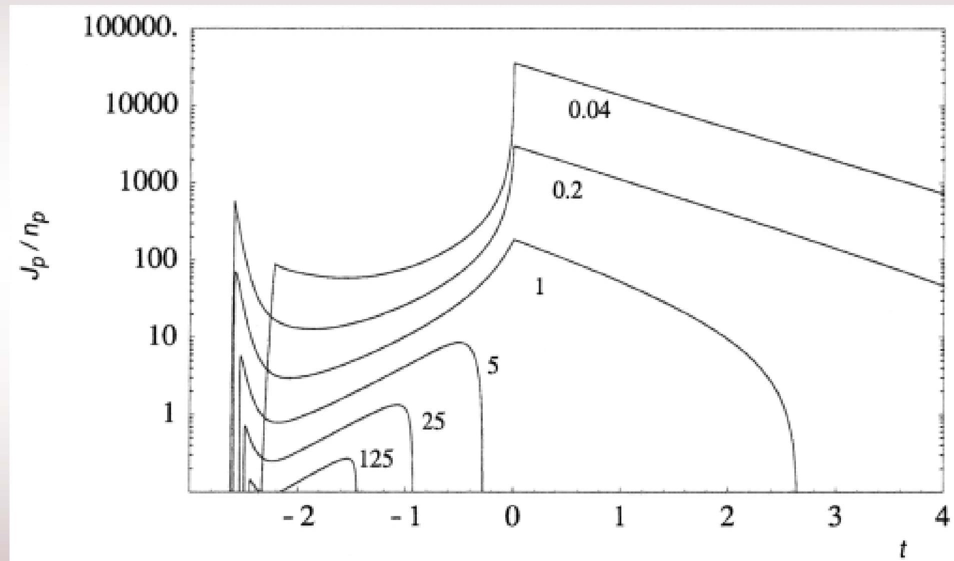


Shock Theory and Observations



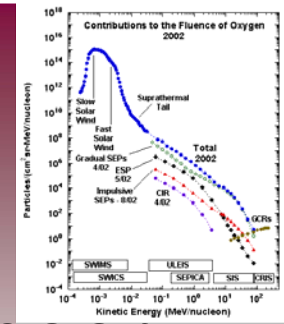
- Lee 2005 is currently the definitive work on shock acceleration for gradual SEP events (and



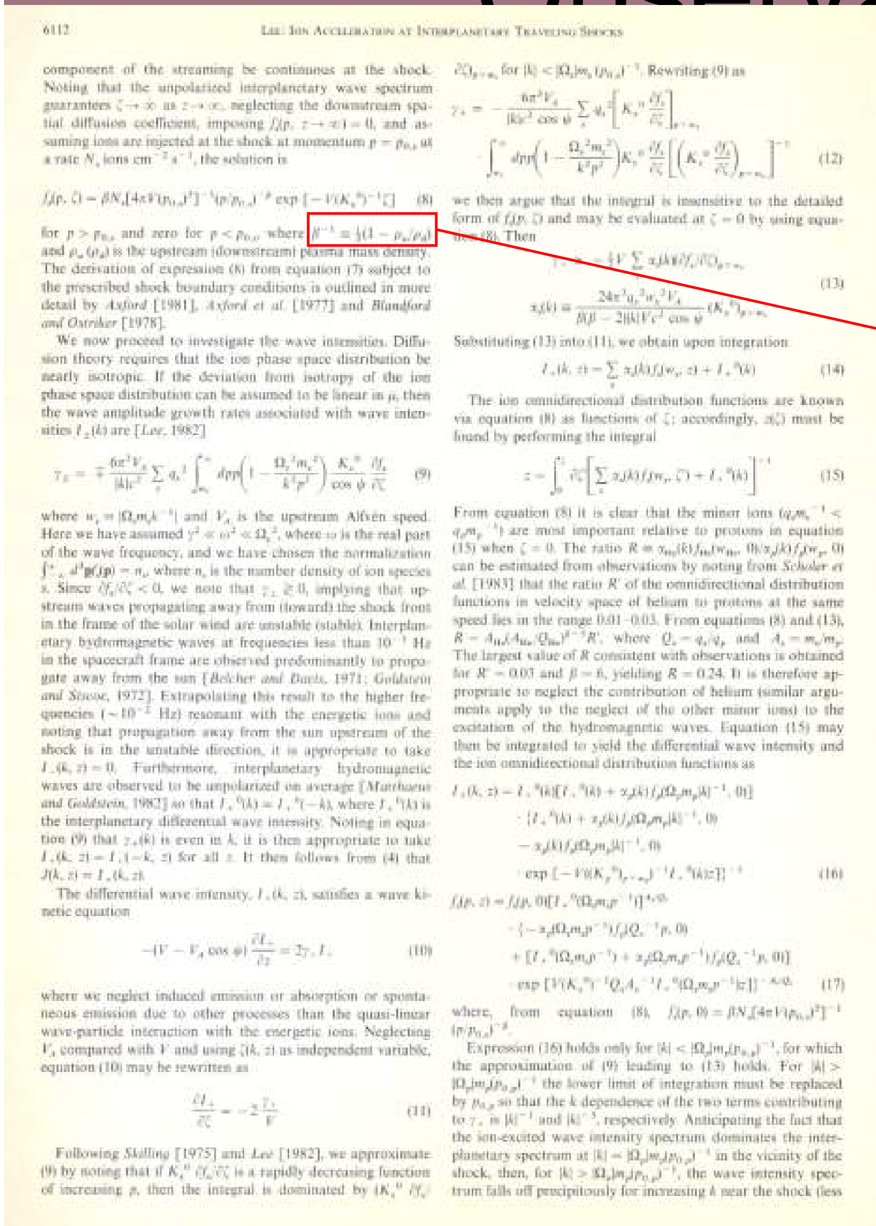


- But a paper with 105 equations tends to scare experimenters into using something more simple.

Shock Theory and Observations



d simple 1-D shock theory



6112 Lee: Ion Acceleration at Interplanetary Traveling Shocks

component of the streaming be continuous at the shock. Noting that the unpolarized interplanetary wave spectrum guarantees $\zeta \to \infty$ as $z \to \infty$, neglecting the downstream spatial diffusion coefficient, imposing $f_s(p, z \to \infty) = 0$, and assuming ions are injected at the shock at momentum $p = p_{0,s}$ at a rate N_s ions cm^{-2} s^{-1}, the solution is

$$f_s(p, \zeta) = \beta N_s [4\pi V (p_{0,s})^3]^{-1} (p/p_{0,s})^{-\beta} \exp[-V(K_s{}^0)^{-1}\zeta] \quad (8)$$

for $p > p_{0,s}$ and zero for $p < p_{0,s}$, where $\beta^{-1} \equiv \frac{1}{3}(1 - \rho_u/\rho_d)$ and ρ_u (ρ_d) is the upstream (downstream) plasma mass density. The derivation of expression (8) from equation (7) subject to the prescribed shock boundary conditions is outlined in more detail by *Axford* [1981], *Axford et al.* [1977] and *Blandford and Ostriker* [1978].

We now proceed to investigate the wave intensities. Diffusion theory requires that the ion phase space distribution be nearly isotropic. If the deviation from isotropy of the ion phase space distribution can be assumed to be linear in μ, then the wave amplitude growth rates associated with wave intensities $I_\pm(k)$ are [*Lee*, 1982]

$$\gamma_\pm = \mp \frac{6\pi^2 V_A}{|k|c^2} \sum_s q_s^2 \int_{p_s}^{\infty} dp\, p \left(1 - \frac{\Omega_s^2 m_s^2}{k^2 p^2}\right) \frac{K_s{}^0}{\cos\psi} \frac{\partial f_s}{\partial \zeta} \quad (9)$$

where $w_s = |\Omega_s m_s k^{-1}|$ and V_A is the upstream Alfvén speed. Here we have assumed $\gamma^2 \ll \omega^2 \ll \Omega_s^2$, where ω is the real part of the wave frequency, and we have chosen the normalization $\int d^3 p f_s(p) = n_s$, where n_s is the number density of ion species s. Since $\partial f_s/\partial \zeta < 0$, we note that $\gamma_\pm \gtrless 0$, implying that upstream waves propagating away from (toward) the shock front in the frame of the solar wind are unstable (stable). Interplanetary hydromagnetic waves at frequencies less than 10^{-1} Hz in the spacecraft frame are observed predominantly to propagate away from the sun [*Belcher and Davis*, 1971; *Goldstein and Siscoe*, 1972]. Extrapolating this result to the higher frequencies ($\sim 10^{-1}$ Hz) resonant with the energetic ions and noting that propagation away from the sun upstream of the shock is in the unstable direction, it is appropriate to take $I_-(k, z) = 0$. Furthermore, interplanetary hydromagnetic waves are observed to be unpolarized on average [*Matthaeus and Goldstein*, 1982] so that $I_+{}^0(k) = I_+{}^0(-k)$, where $I_+{}^0(k)$ is the interplanetary differential wave intensity. Noting in equation (9) that $\gamma_+(k)$ is even in k, it is then appropriate to take $I_+(k, z) = I_+(-k, z)$ for all z. It then follows from (4) that $J(k, z) = I_+(k, z)$.

The differential wave intensity, $I_+(k, z)$, satisfies a wave kinetic equation

$$-(V - V_A \cos\psi) \frac{\partial I_+}{\partial z} = 2\gamma_+ I_+ \quad (10)$$

where we neglect induced emission or absorption or spontaneous emission due to other processes than the quasi-linear wave-particle interaction with the energetic ions. Neglecting V_A compared with V and using $\zeta(k, z)$ as independent variable, equation (10) may be rewritten as

$$\frac{\partial I_+}{\partial \zeta} = -2\frac{\gamma_+}{V} \quad (11)$$

Following *Skilling* [1975] and *Lee* [1982], we approximate (9) by noting that if $K_s{}^0\, \partial f_s/\partial \zeta$ is a rapidly decreasing function of increasing p, then the integral is dominated by $(K_s{}^0\, \partial f_s/\partial \zeta)_{p = w_s}$ for $|k| < |\Omega_s| m_s (p_{0,s})^{-1}$. Rewriting (9) as

$$\gamma_+ = -\frac{6\pi^2 V_A}{|k|c^2 \cos\psi} \sum_s q_s^2 \left[K_s{}^0 \frac{\partial f_s}{\partial \zeta}\right]_{p = w_s} \cdot \int_{w_s}^{\infty} dp\, p \left(1 - \frac{\Omega_s^2 m_s^2}{k^2 p^2}\right) K_s{}^0 \frac{\partial f_s}{\partial \zeta} \left[\left(K_s{}^0 \frac{\partial f_s}{\partial \zeta}\right)_{p = w_s}\right]^{-1} \quad (12)$$

we then argue that the integral is insensitive to the detailed form of $f_s(p, \zeta)$ and may be evaluated at $\zeta = 0$ by using equation (8). Then

$$\gamma_+ = -\tfrac{1}{2} V \sum_s \alpha_s(k)(\partial f_s/\partial \zeta)_{p = w_s}$$
$$\alpha_s(k) = \frac{24\pi^3 q_s^2 w_s^2 V_A}{\beta(\beta - 2)|k| V c^2 \cos\psi} (K_s{}^0)_{p = w_s} \quad (13)$$

Substituting (13) into (11), we obtain upon integration

$$I_+(k, z) = \sum_s \alpha_s(k) f_s(w_s, z) + I_+{}^0(k) \quad (14)$$

The ion omnidirectional distribution functions are known via equation (8) as functions of ζ; accordingly, $z(\zeta)$ must be found by performing the integral

$$z = \int_0^{\zeta} d\zeta \left[\sum_s \alpha_s(k) f_s(w_s, \zeta) + I_+{}^0(k)\right]^{-1} \quad (15)$$

From equation (8) it is clear that the minor ions ($q_s m_s^{-1} < q_p m_p^{-1}$) are most important relative to protons in equation (15) when $\zeta = 0$. The ratio $R = \alpha_{He}(k) f_{He}(w_{He}, 0)/\alpha_p(k) f_p(w_p, 0)$ can be estimated from observations by noting from *Scholer et al.* [1983] that the ratio R' of the omnidirectional distribution functions in velocity space of helium to protons at the same speed lies in the range 0.01–0.03. From equations (8) and (13), $R = A_{He}(A_{He}/Q_{He})^{\beta-3} R'$, where $Q_s = q_s/q_p$ and $A_s = m_s/m_p$. The largest value of R consistent with observations is obtained for $R' = 0.03$ and $\beta = 6$, yielding $R = 0.24$. It is therefore appropriate to neglect the contribution of helium (similar arguments apply to the neglect of the other minor ions) to the excitation of the hydromagnetic waves. Equation (15) may then be integrated to yield the differential wave intensity and the ion omnidirectional distribution functions as

$$I_+(k, z) = I_+{}^0(k)[I_+{}^0(k) + \alpha_p(k) f_p(\Omega_p m_p |k|^{-1}, 0)] \cdot \{I_+{}^0(k) + \alpha_p(k) f_p(\Omega_p m_p |k|^{-1}, 0) - \alpha_p(k) f_p(\Omega_p m_p |k|^{-1}, 0) \cdot \exp[-V(K_p{}^0)_{p=w_p}^{-1} I_+{}^0(k) z]\}^{-1} \quad (16)$$

$$f_s(p, z) = f_s(p, 0)[I_+{}^0(\Omega_p m_p p^{-1})]^{A_s/Q_s} \cdot \{-\alpha_p(\Omega_p m_p p^{-1}) f_p(Q_s^{-1} p, 0) + [I_+{}^0(\Omega_p m_p p^{-1}) + \alpha_p(\Omega_p m_p p^{-1}) f_p(Q_s^{-1} p, 0)] \cdot \exp[V(K_s{}^0)^{-1} Q_s A_s^{-1} I_+{}^0(\Omega_p m_p p^{-1}) z]\}^{-A_s/Q_s} \quad (17)$$

where, from equation (8), $f_p(p, 0) = \beta N_p [4\pi V (p_{0,p})^3]^{-1} (p/p_{0,p})^{-\beta}$.

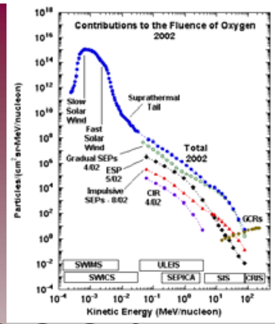
Expression (16) holds only for $|k| < |\Omega_p| m_p (p_{0,p})^{-1}$, for which the approximation of (9) leading to (13) holds. For $|k| > |\Omega_p| m_p (p_{0,p})^{-1}$ the lower limit of integration must be replaced by $p_{0,p}$ so that the k dependence of the two terms contributing to γ_+ is $|k|^{-1}$ and $|k|^{-3}$, respectively. Anticipating the fact that the ion-excited wave intensity spectrum dominates the interplanetary spectrum at $|k| = |\Omega_p| m_p (p_{0,p})^{-1}$ in the vicinity of the shock, then, for $|k| > |\Omega_p| m_p (p_{0,p})^{-1}$, the wave intensity spectrum falls off precipitously for increasing k near the shock (less

$$\beta^{-1} \equiv \tfrac{1}{3}(1 - \rho_u/\rho_d)$$

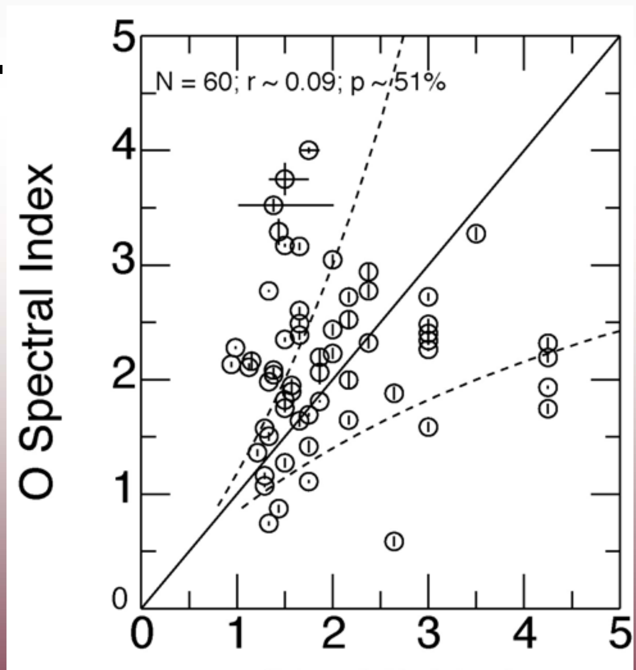
One prediction is a simple relationship between SEP spectral index and shock compression ratio (regardless of species)

pulsive flare th. Questions

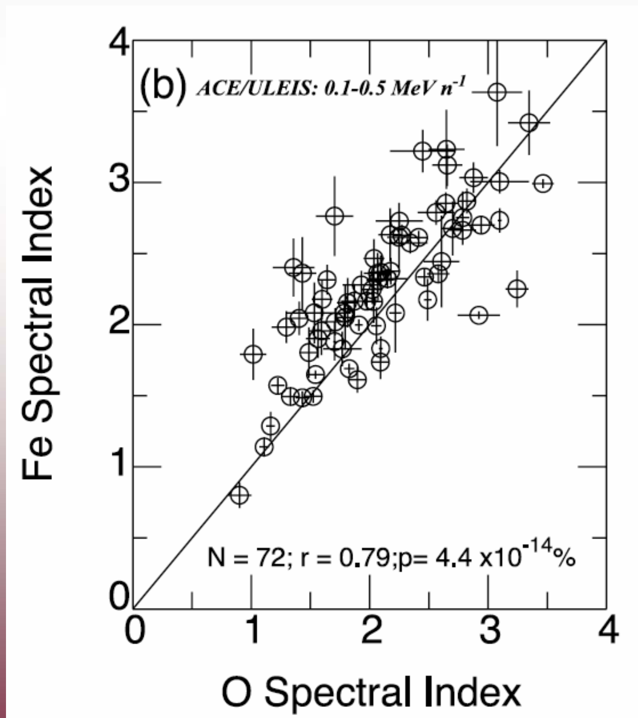
Shock Theory and Observations



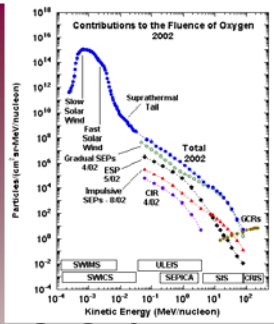
- Late 1970s produced simple 1-D shock theory
- Although Lee (1983) cautioned against blindly applying this to all energies, experimenters did anyway...



Desai et al. 2004

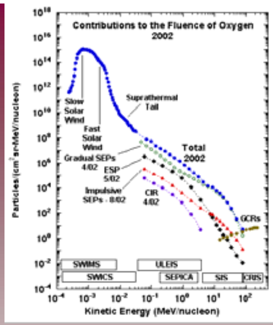


Shock Theory and Observations

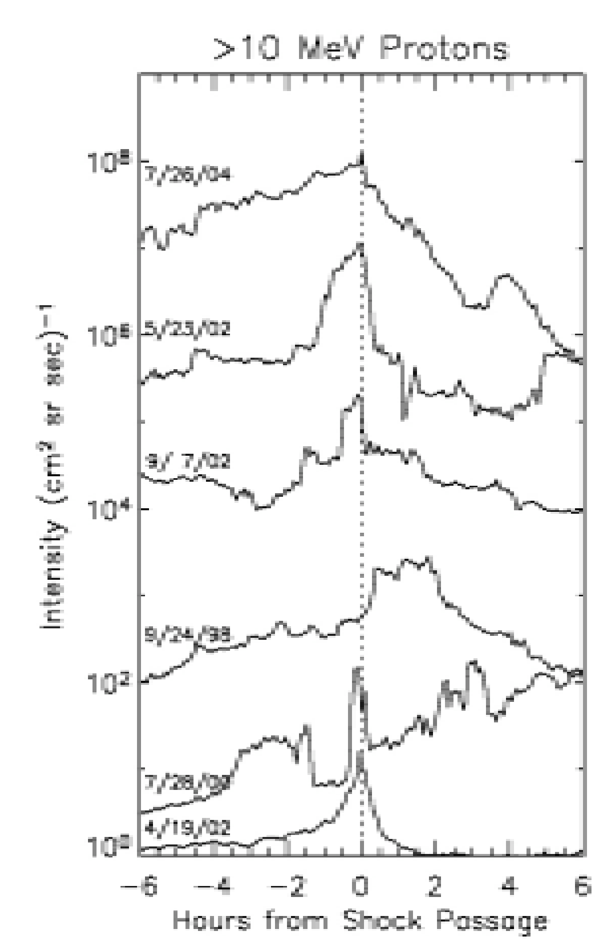


- Late 1970s produced simple 1-D shock theory
- Although Lee (1983) cautioned against blindly applying this to all energies and all events, experimenters did anyway...
  - And found agreement was not so good
  - Lee has suggestions as to why (as any good theorist would)

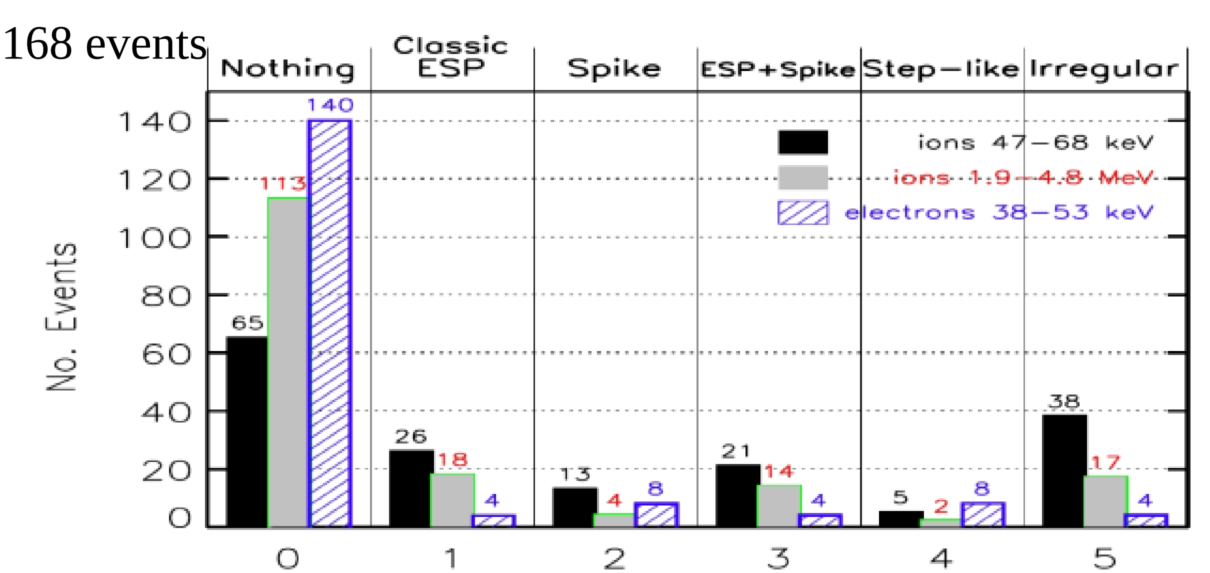
Shock Theory and Observations



- ESP events are extremely variable



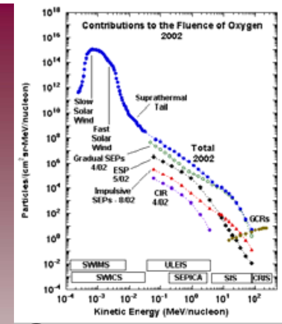
Cohen et al. 2005



Lario et al., 2003

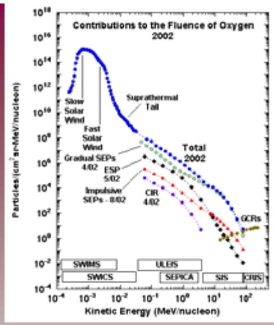
ESPs Shock Th. Impulsive flare th. Questions

Shock Theory and Observations



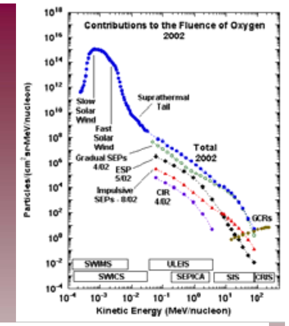
- ESP events are extremely variable and we aren’t careful about which ones the theory applies to
  - Not initially hard spectra
  - Not quasi-perpendicular shocks
  - Not being transported (rather than accelerated)
- Correct frame of mind
  - Need to evaluate the compression ratio in the wave frame not the plasma frame

Shock Theory and SEP events

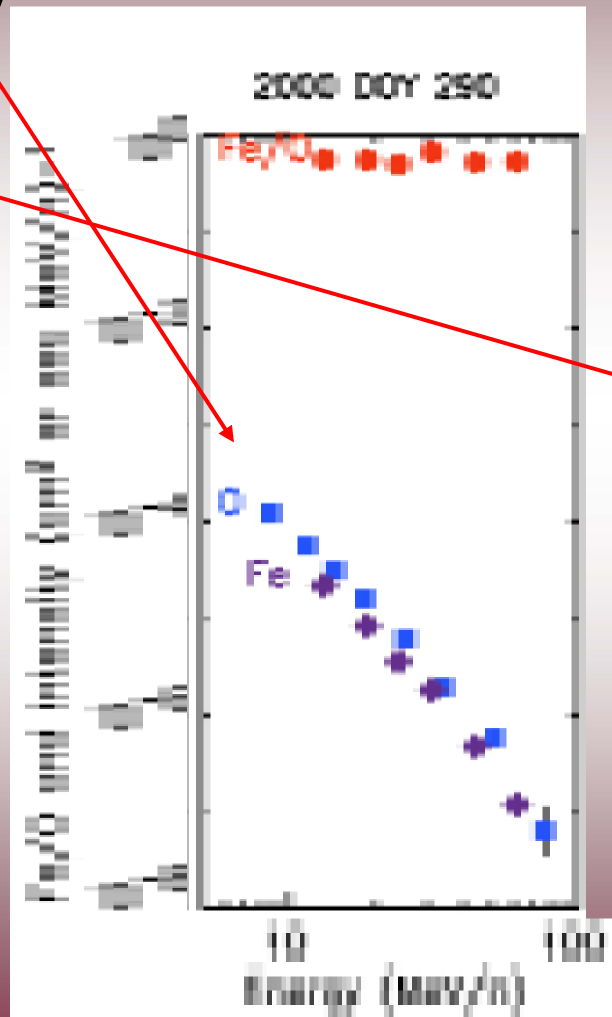


- Complications with SEP events
  - Effects of escaping the shock region
  - Effects of transport (diffusion)
  - Evolution of the shock (orientation, strength, etc)

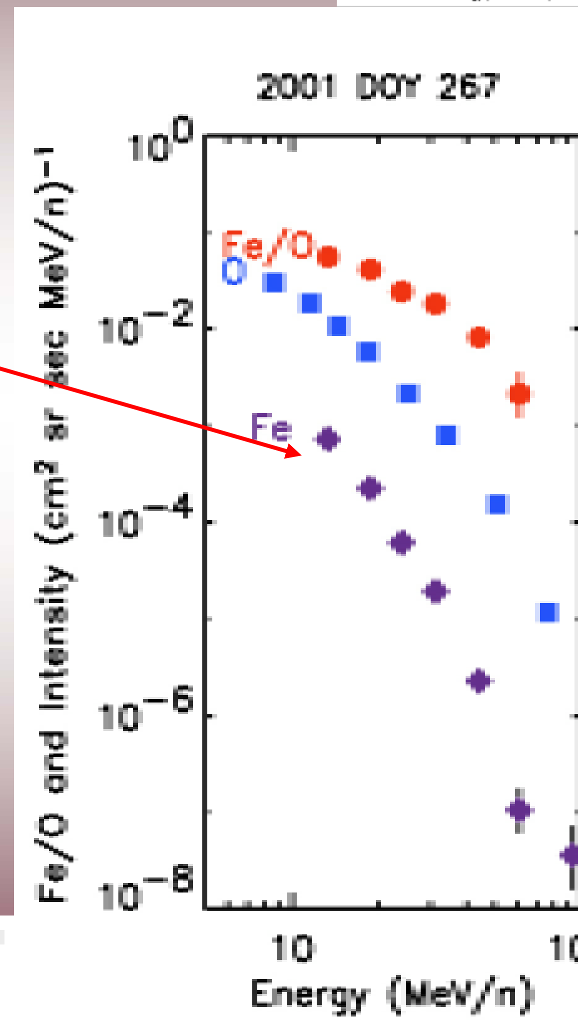
Diffusion/Trapping Signatures



- Although shock theory predicts this
- We often see this



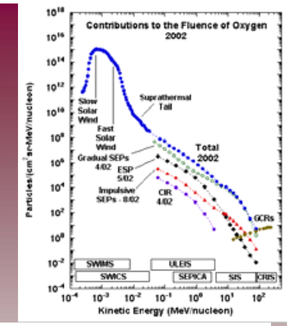
Cohen et al. 2002



Cohen et al. 2002

ESPs   Shock Th.   Impulsive   flare th.   Questions

Diffusion/Trapping Signatures



- Although shock theory predicts this
- We often see this
- Signature of diffusion

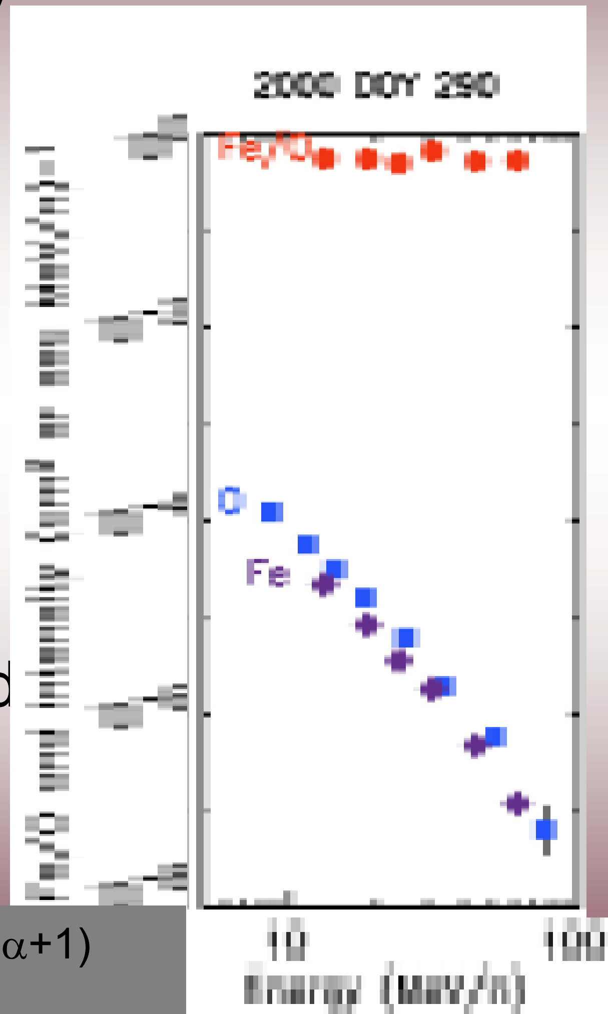
$$\kappa = 1/3\ v\ \lambda$$

- Assume λ is a power-law in rigidity

$$\kappa \sim (M/Q)^{\alpha}\ E^{(\alpha+1)/2}$$

- Break energies should occur at same value of κ

$$E_1/E_2=[(Q/M)_1/(Q/M)_2]^{2\alpha/(\alpha+1)}$$



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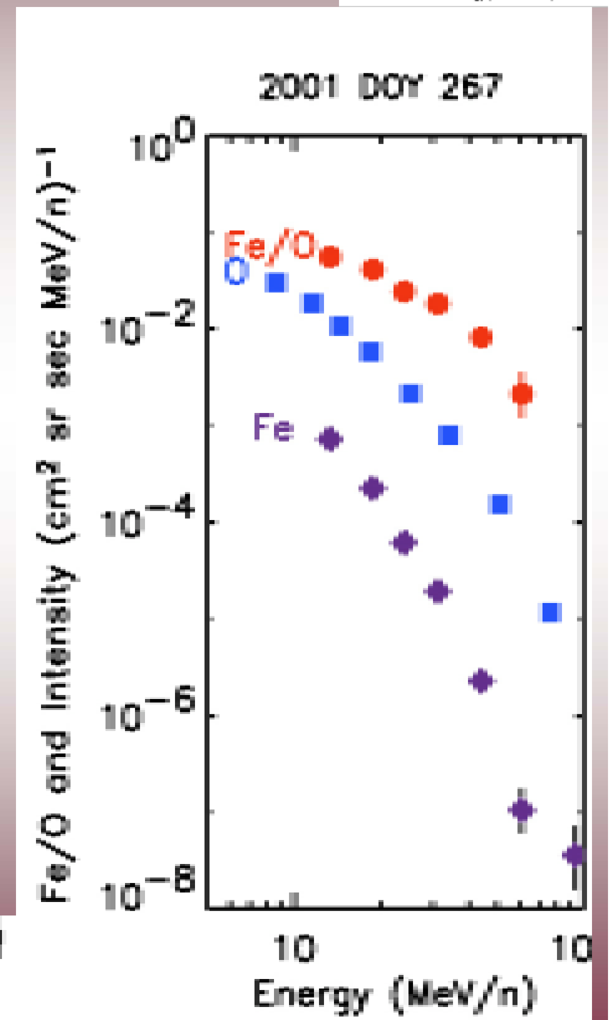
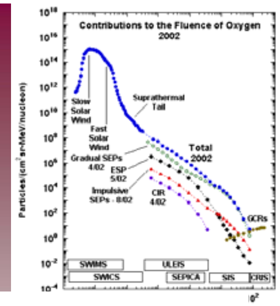
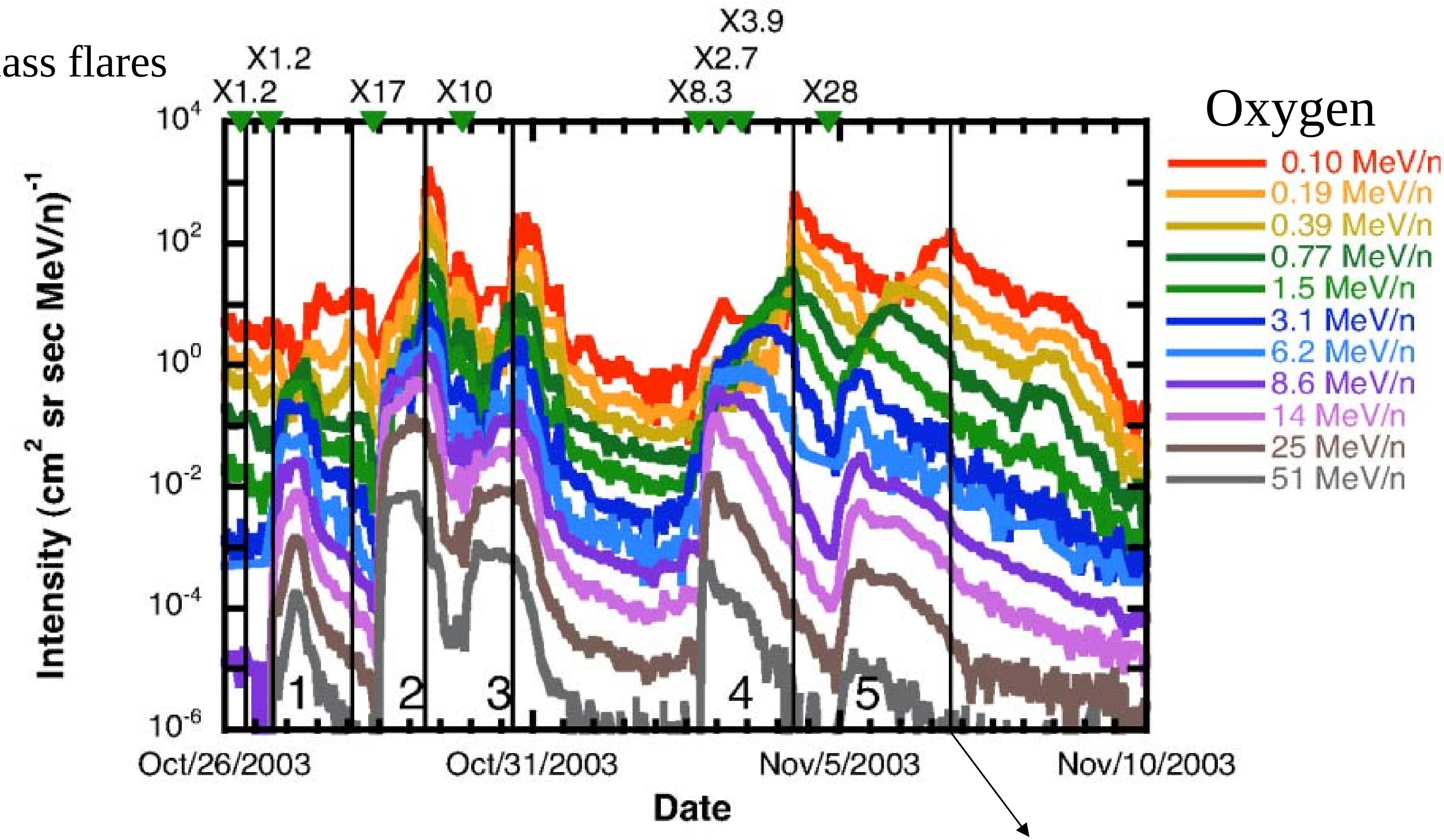


Cohen et al. 2002

Application to Big SEP Events

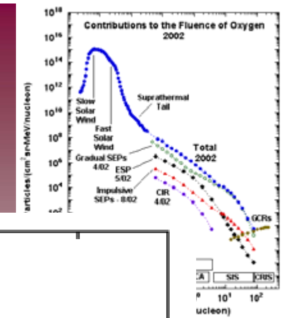


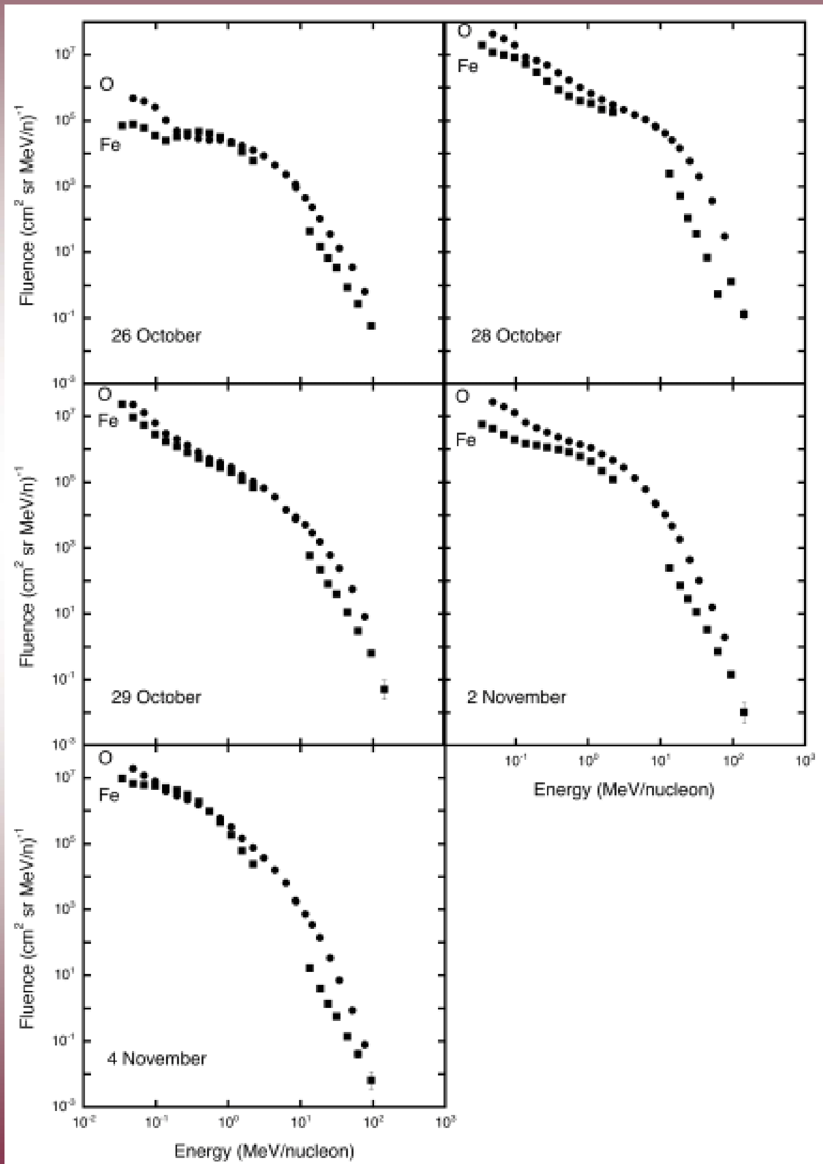
X class flares

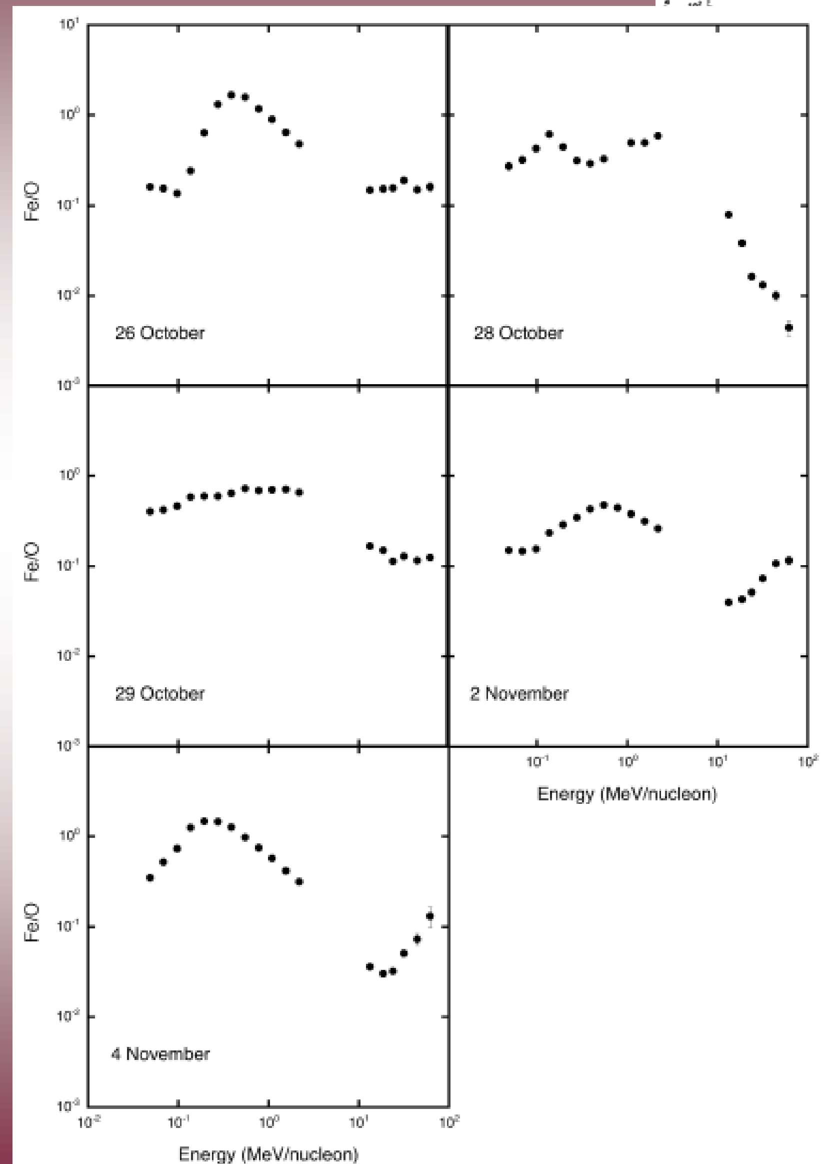


ESPs Shock Th. Impulsive flare th. Questions

Application to Big SEP Events







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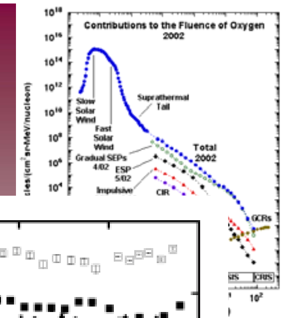
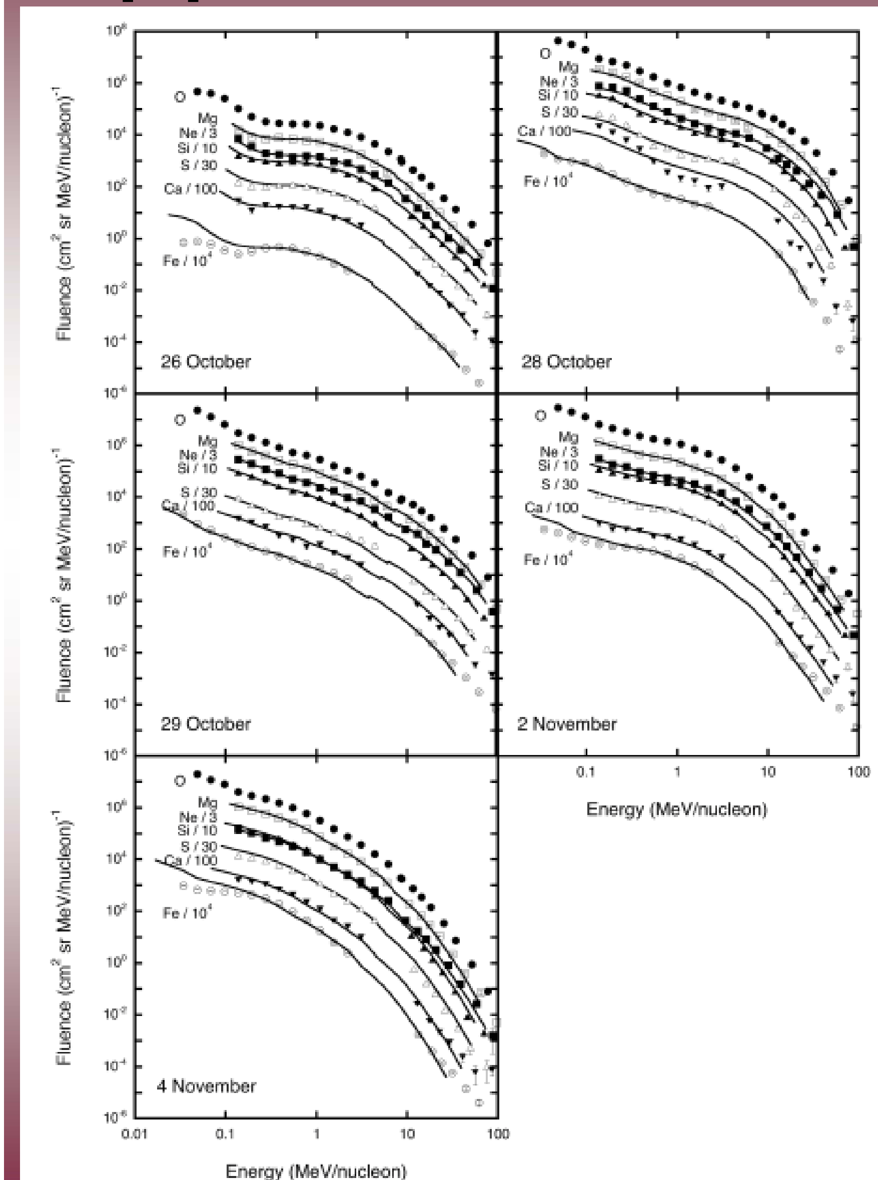
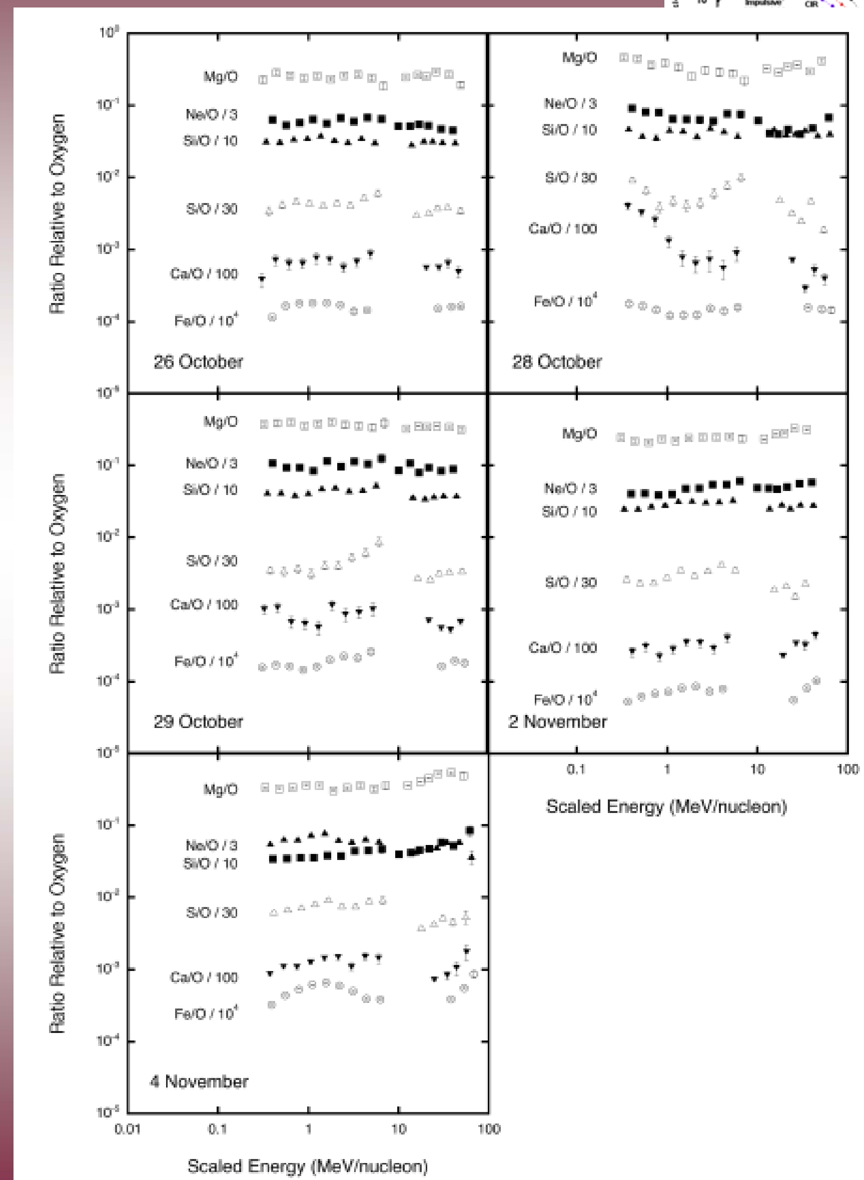
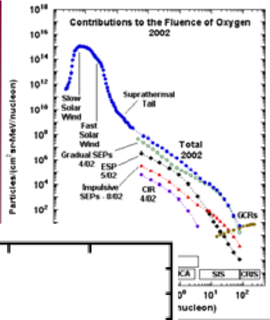






Application to Big SEP Events

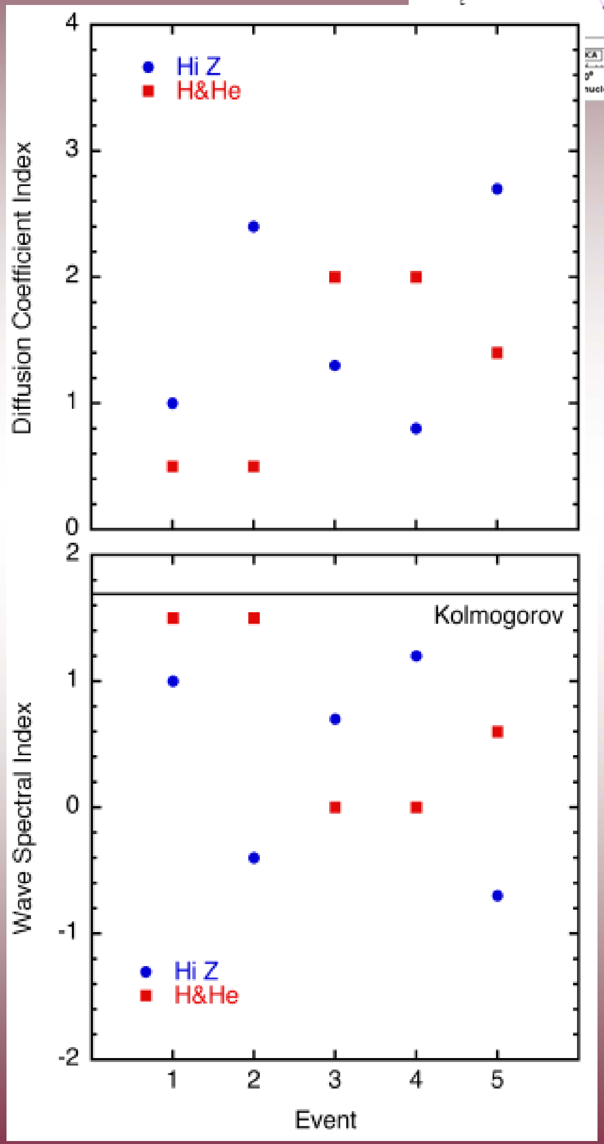


- α values differ for heavies and H, He and vary from event to event
- Values of α can be related to turbulence spectrum $\sim k^{-q}$

$$\alpha = 2-q$$

(Droege, 1994)

- Wave indices < 5/3 suggest there is an additional source of turbulence present



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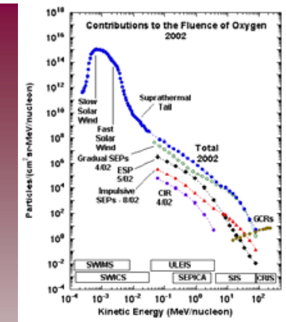

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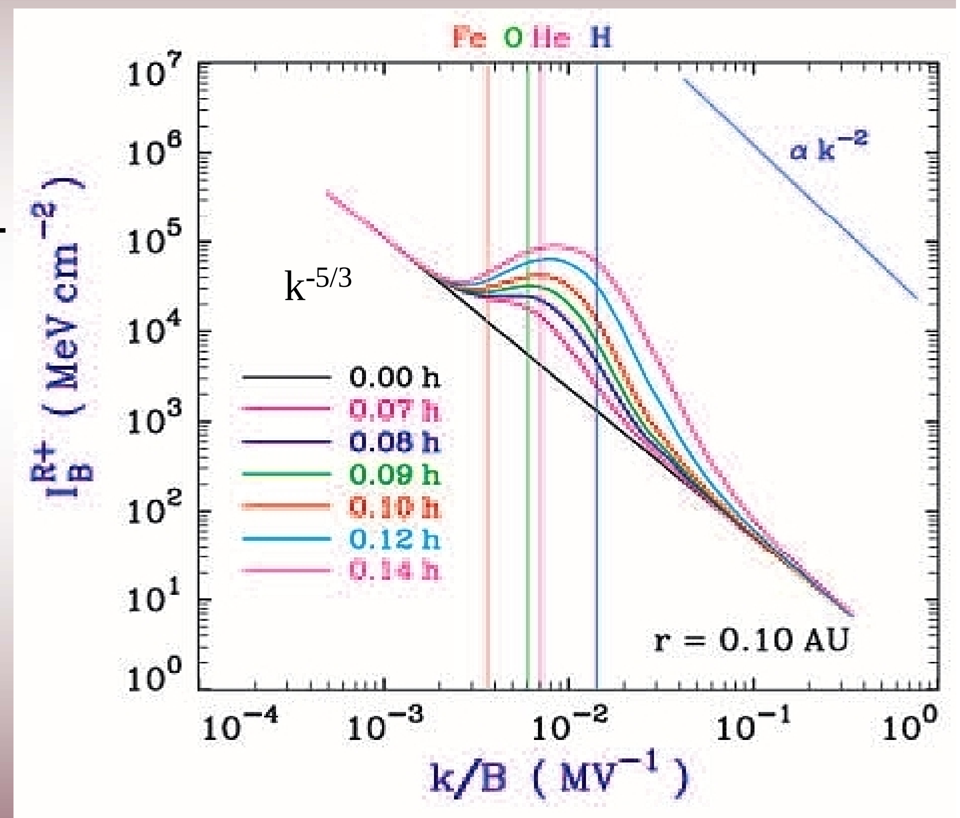
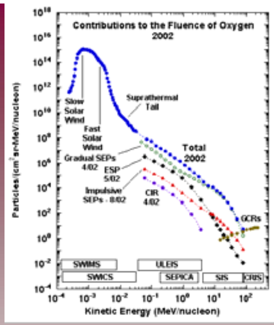
(Droege, 1994)

- Wave indices < 5/3 suggest there is an additional source of turbulence present
- Perhaps proton amplified Alfvén waves

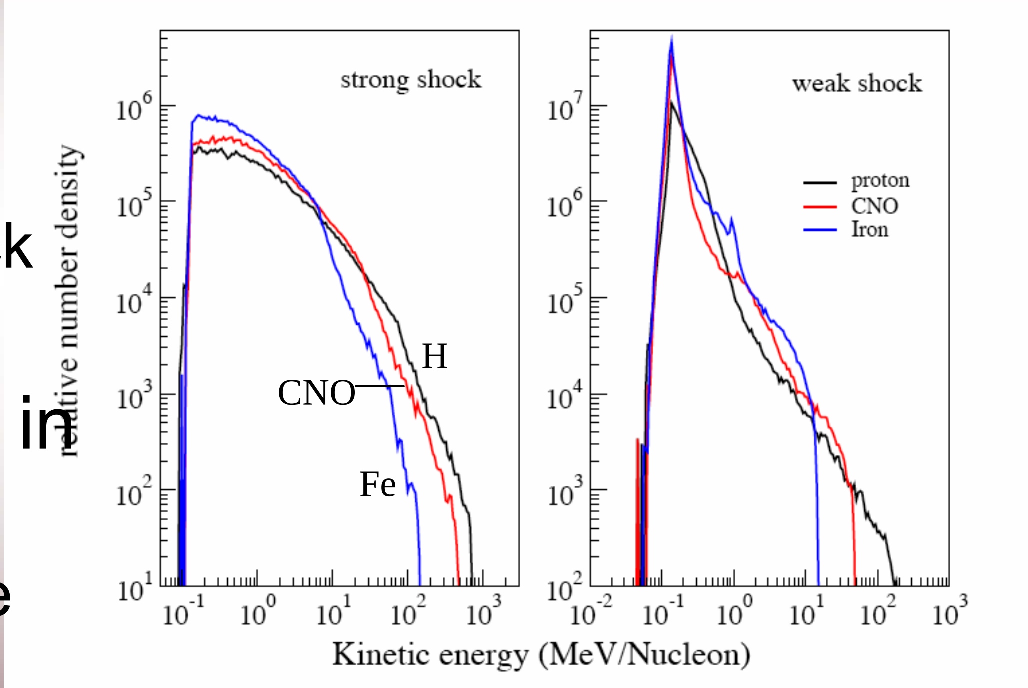


Ng, Reames & Tylka 2003

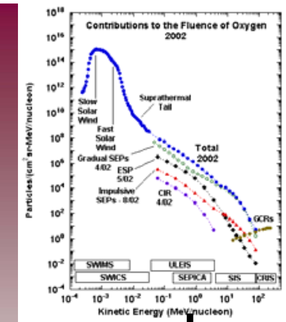


Other Shock Models

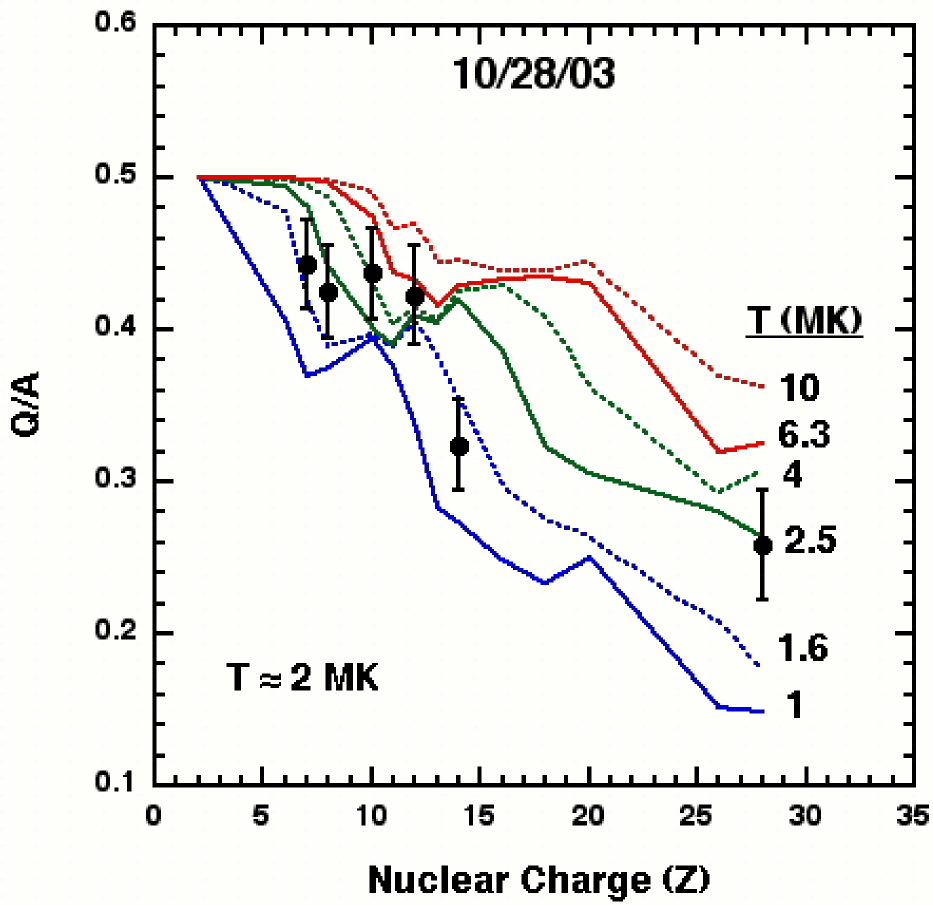
- Li et al. have created a numerical model which incorporates
  - waves and turbulence
  - evolution of shock
  - transport away from shock
  - heavy ion response
- Ion spectra have breaks in them due to escape
  - Break points should scale as $(Q/M)^2$

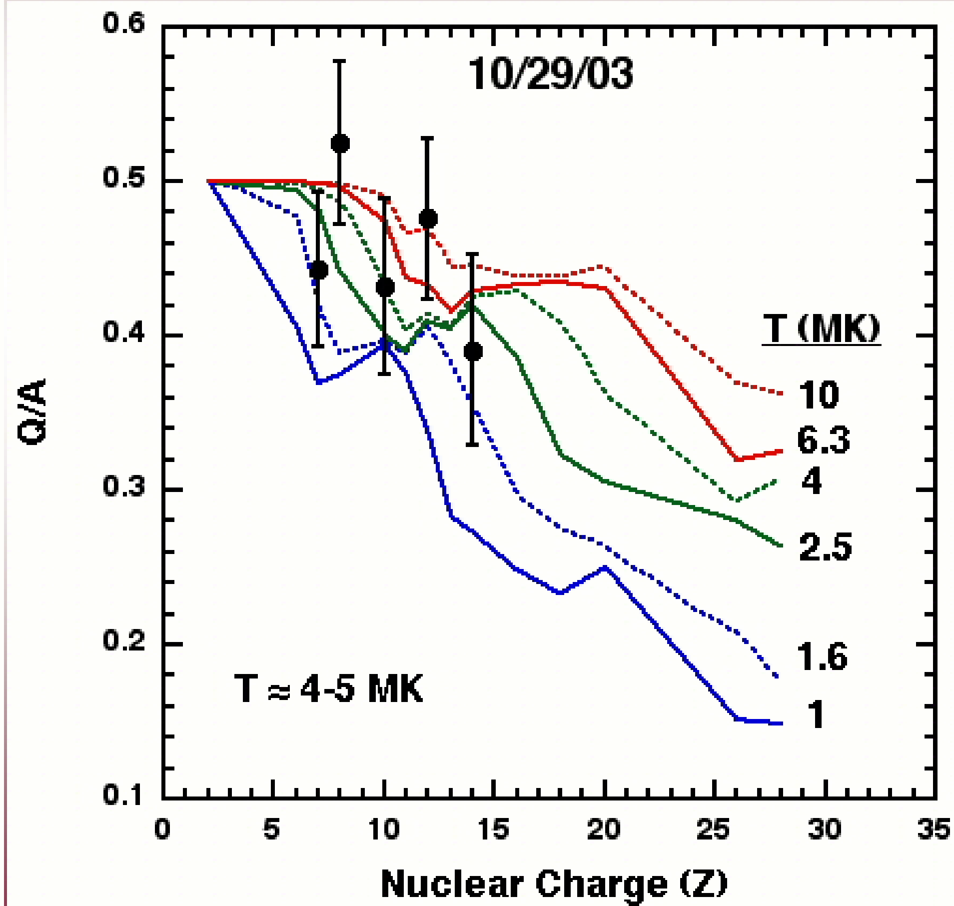


Other Shock Models vs Data



- During big October 2003 events SAMPEX measured Q for several elements





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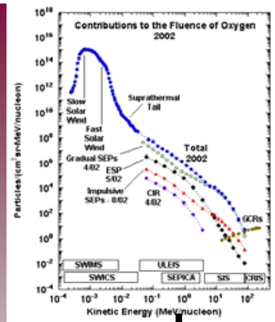

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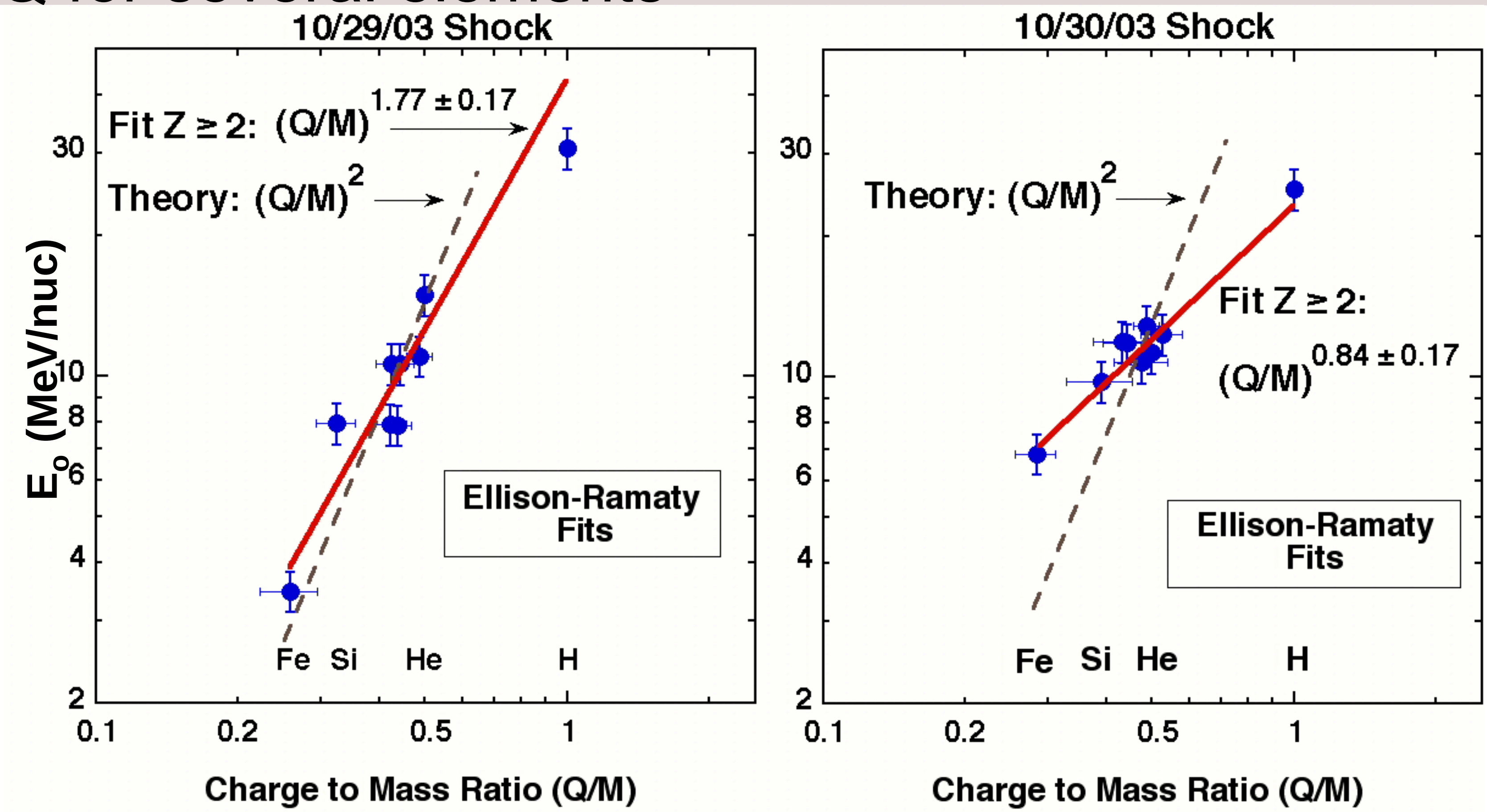
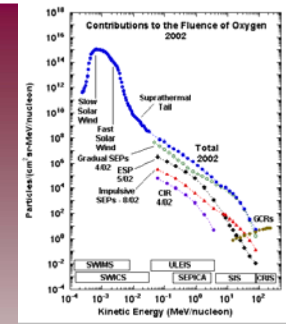
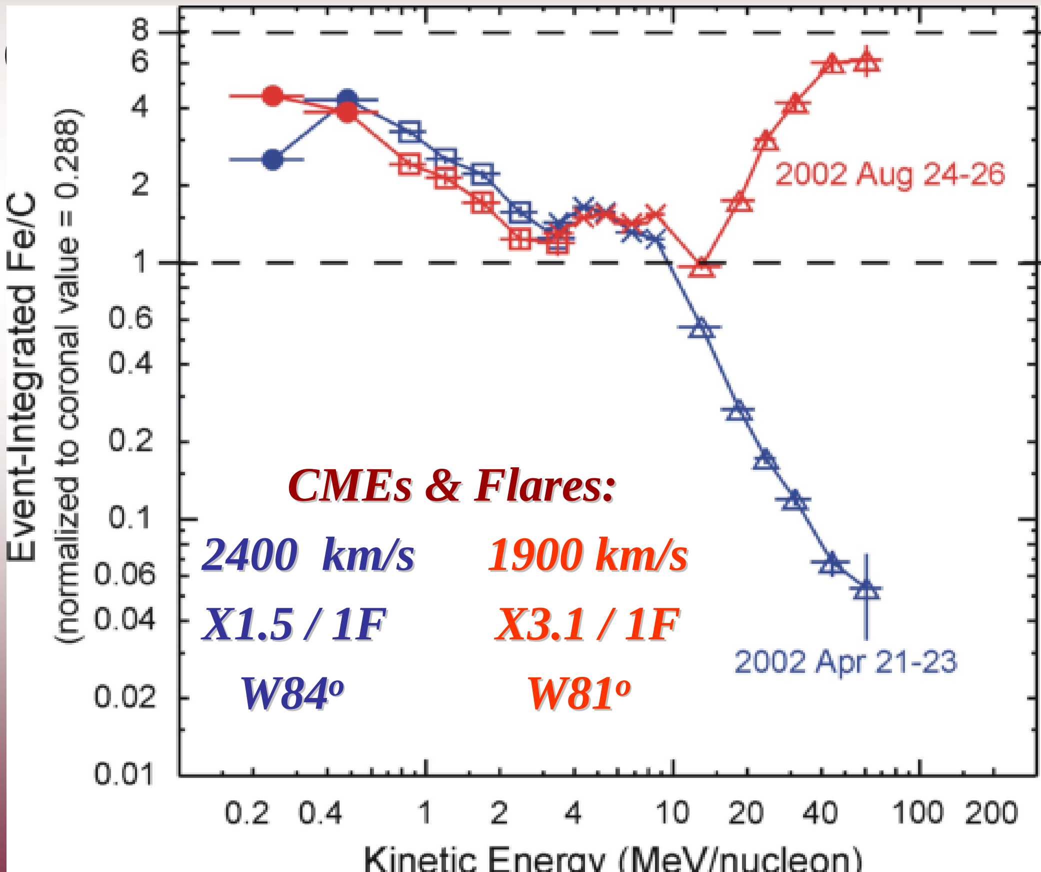


Observation Driving Models



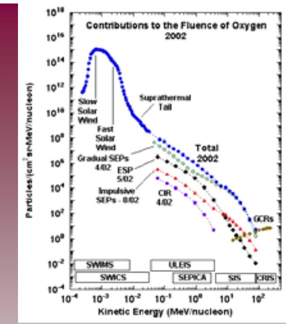
- Can shock acceleration explain the observations of Fe-enriched (energy dependent



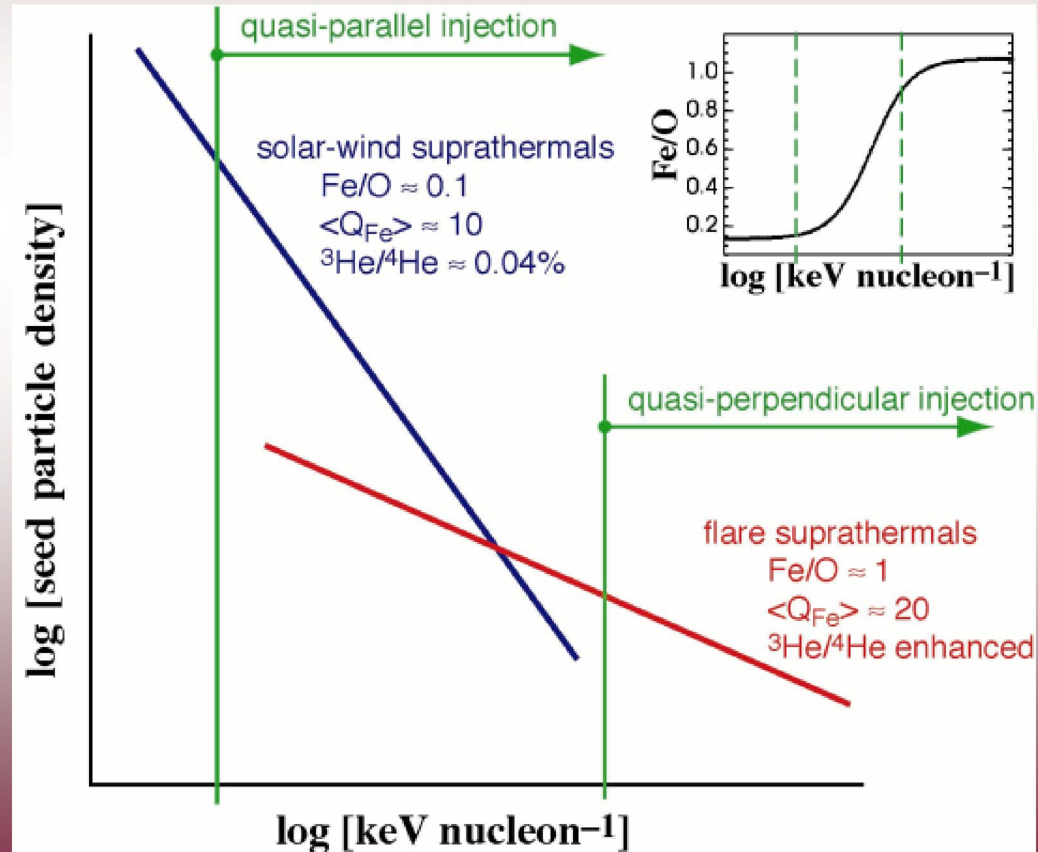
-

These two events had similar solar signatures...why are they so different at >10 MeV/nuc??

Observation Driving Models



- Can shock acceleration explain the observations of Fe-enriched (energy dependent composition)?
- Idea of Tylka et al.
  - seed population is energy dependent
  - injection energy is higher for Q-perp



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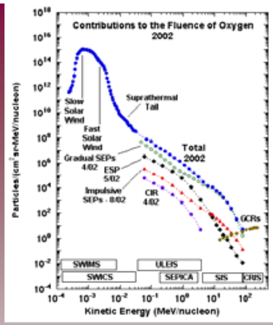

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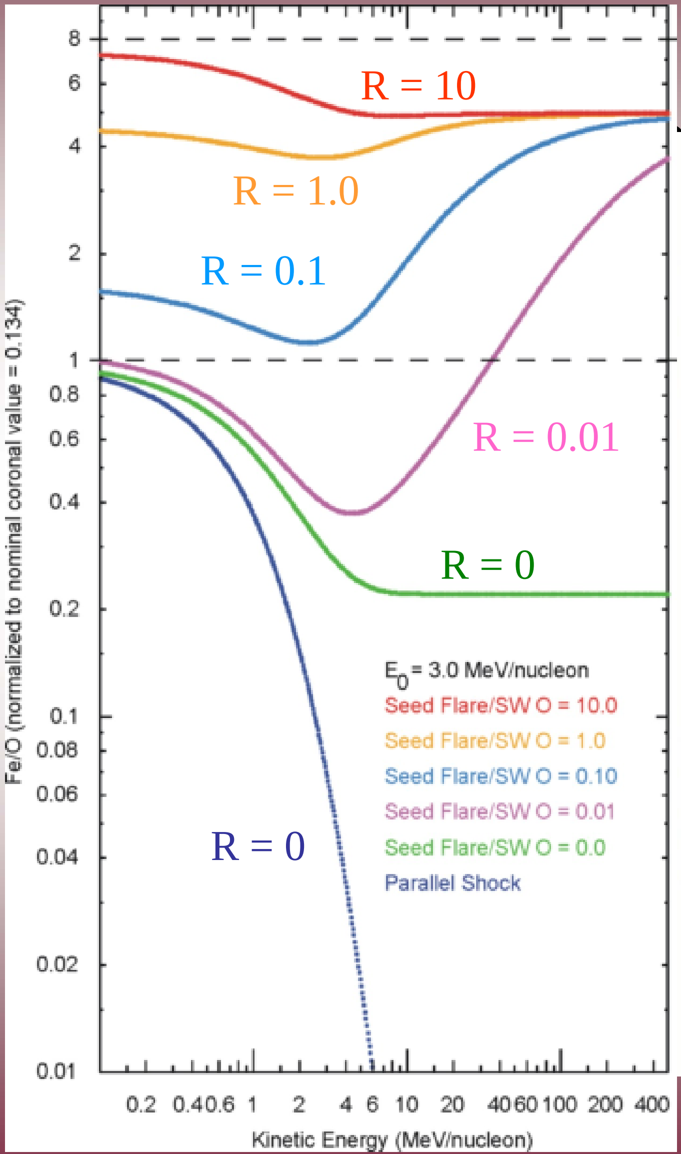
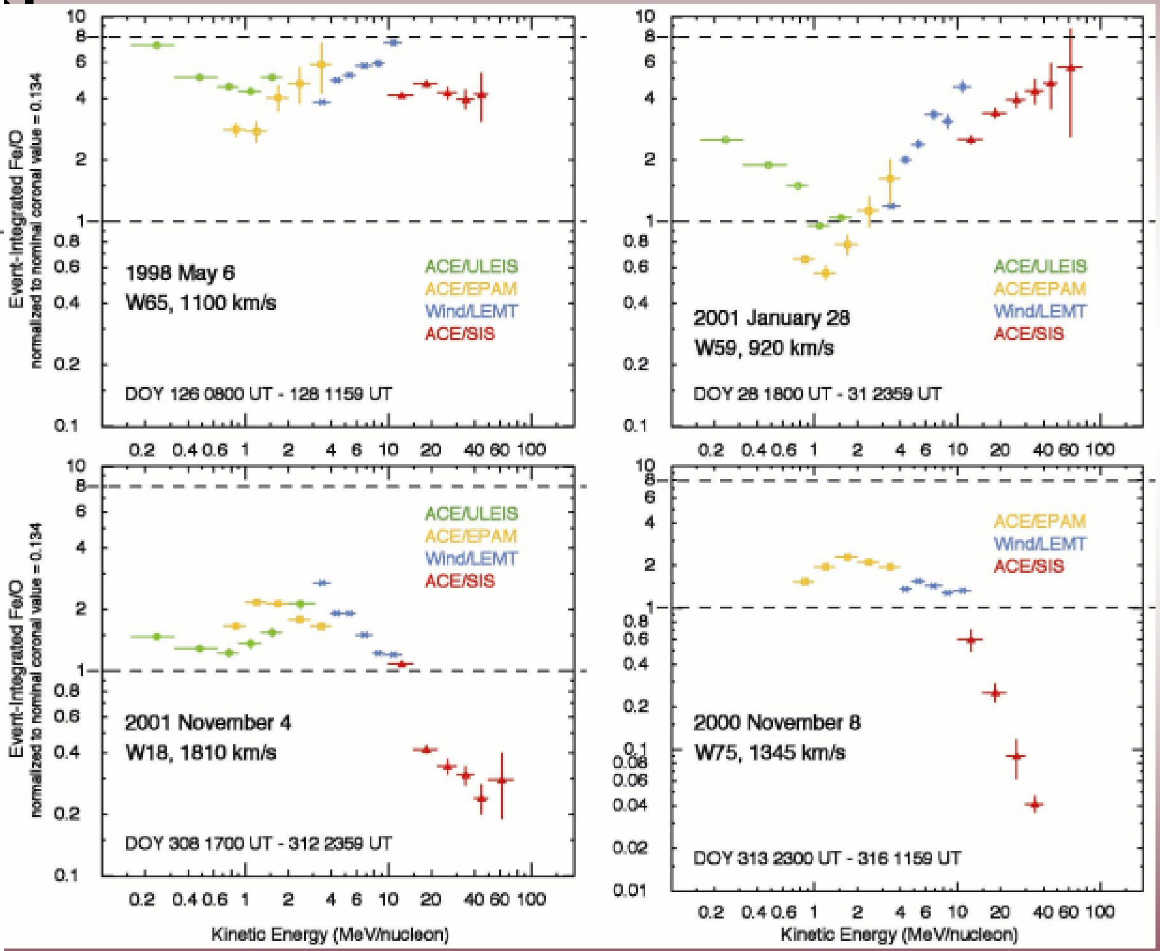
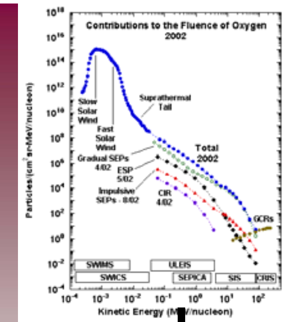


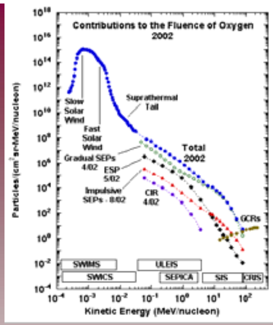


Impulsive SEP Events

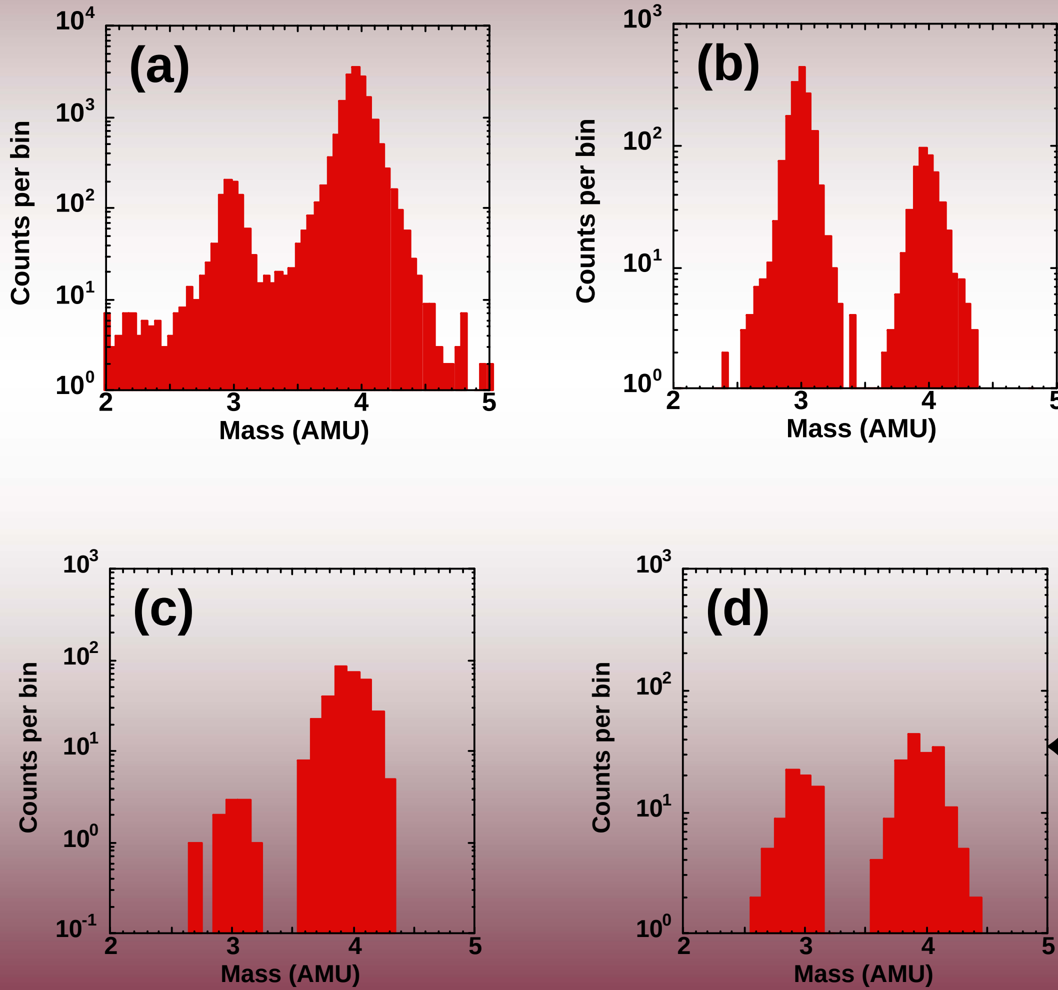


- Thought to be a result of flare acceleration only
- Characteristics
  - $^3He/^4He$ enhanced by large factors (x10^4)
  - Enhanced Ne-Si and Fe over CNO as compared to gradual SEP events
  - Enhancement of 'ultra heavy' ions ($Z \geq 30$)
  - electron rich
  - small intensities and short duration (flares and SEPs)

Impulsive SEP Events



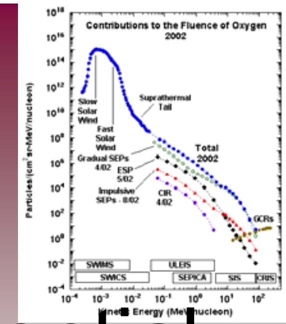
- ACE can resolve events with much lower $^3He/^4He$ ratios than previous missions



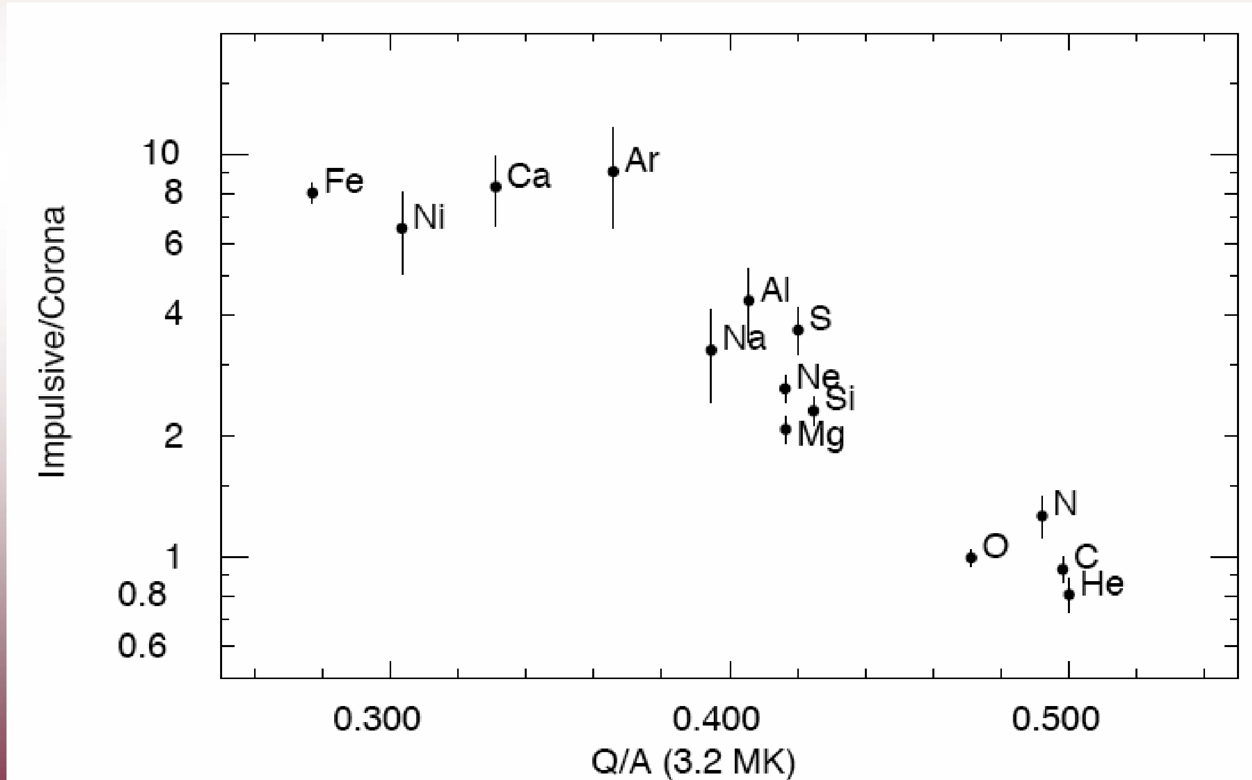
← 750 keV/n

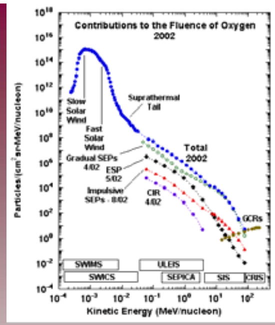
← 7.5 MeV/n

Impulsive SEP Events



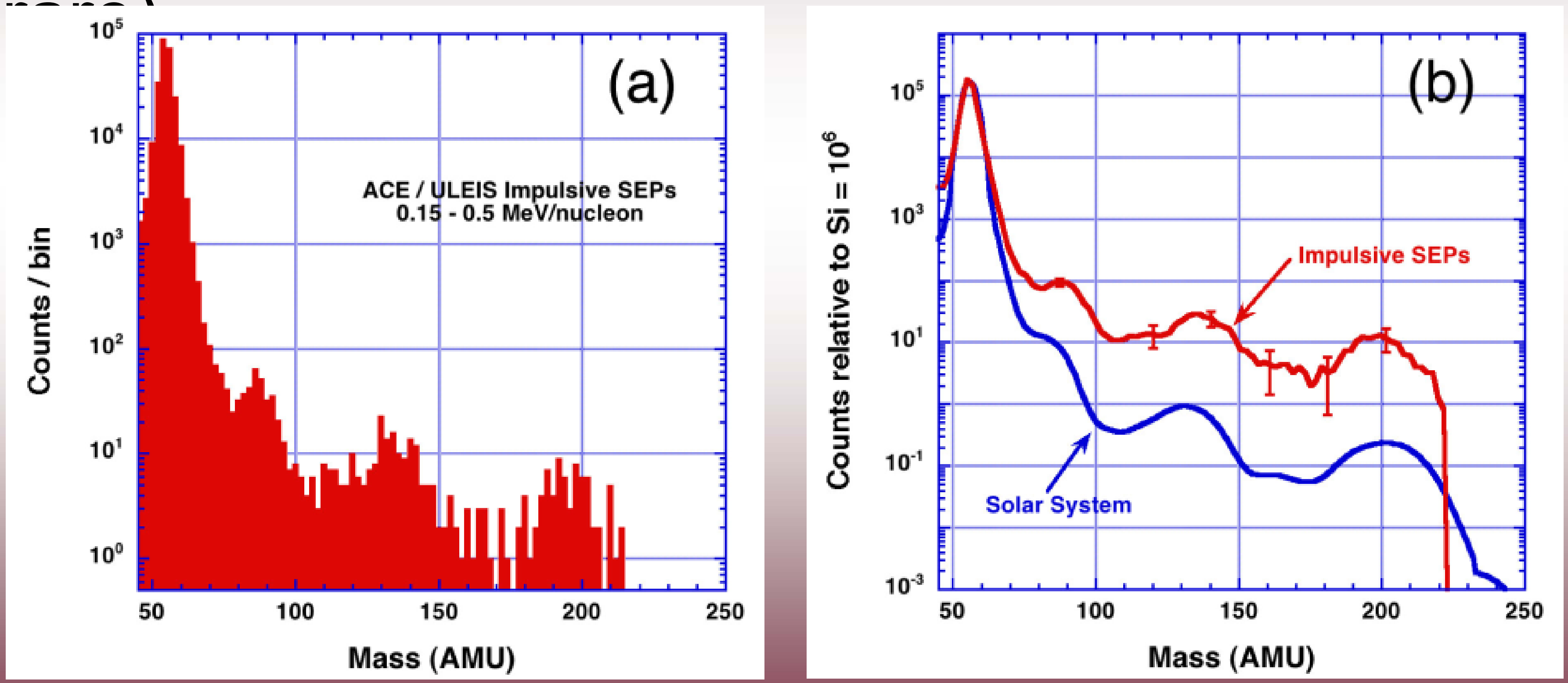
- Composition is understood to be a preferential acceleration dependent on Q/A (rigidity)





Impulsive SEP Events

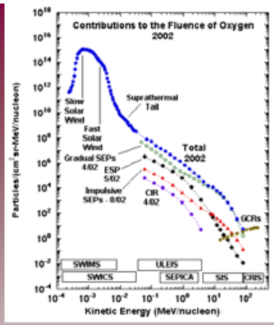
- Ultraheavy ions are enhanced greatly (although hard to observe because still very rare)



Mason et al., 2004

ESPs Shock Th. Impulsive flare th. Questions

Impulsive SEP Events



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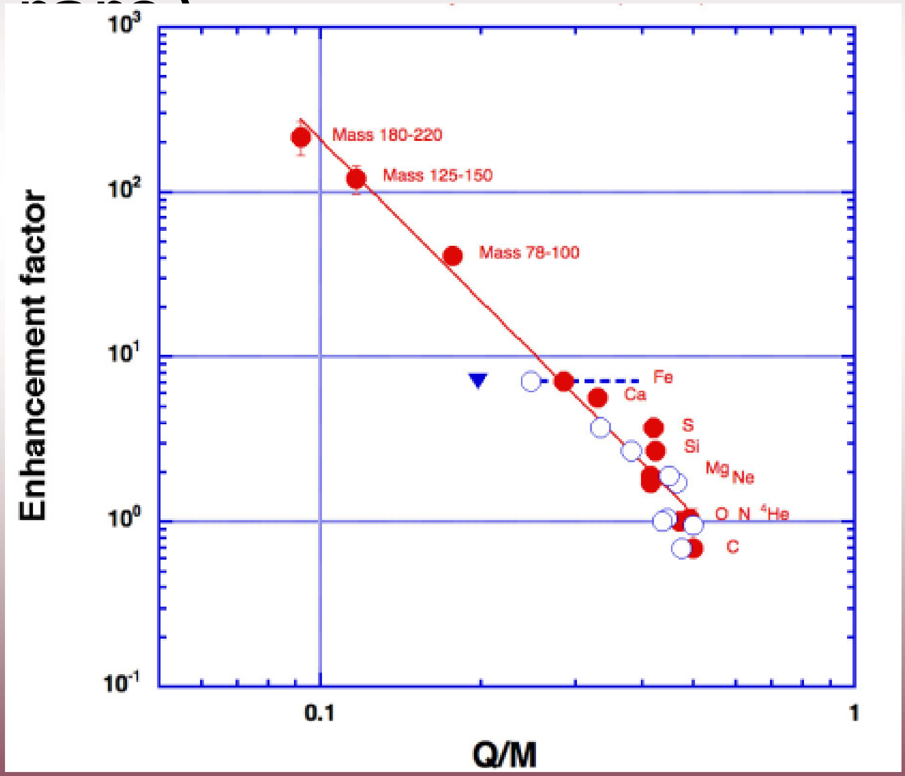
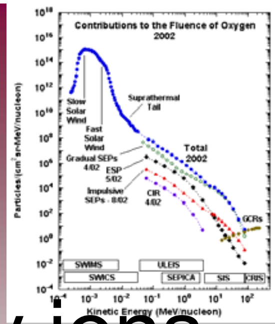


Mason et al., 2004

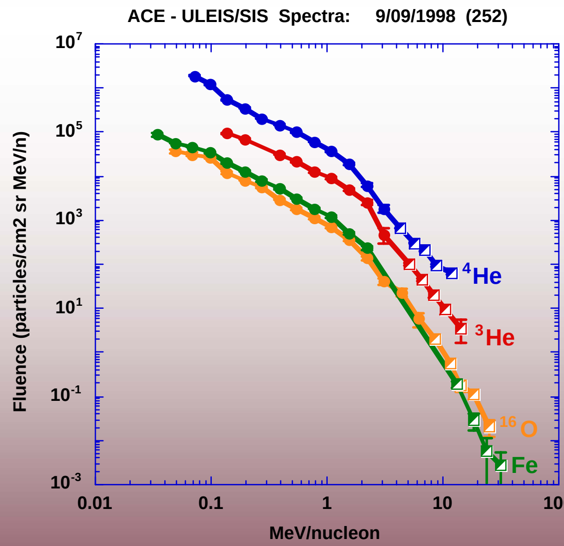
- Roughly scales as Q/M, but...
- Unclear what Q/M to use (particularly if there is stripping)

Impulsive SEP Events

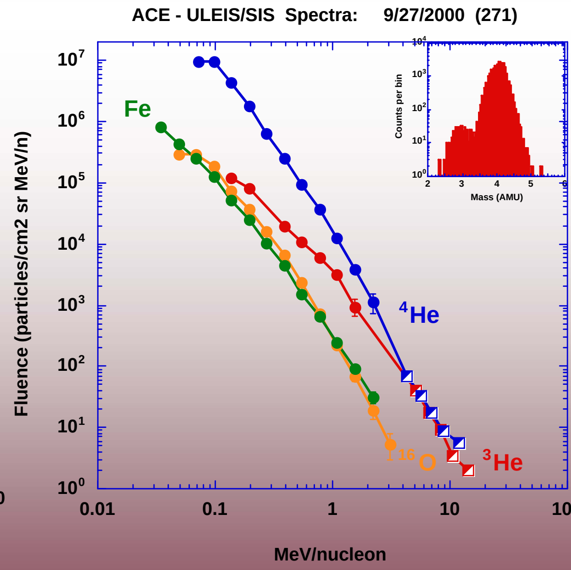


- Can make spectra of ^{3}He, ^{4}He, and heavy ions
- ^{3}He is often quite different

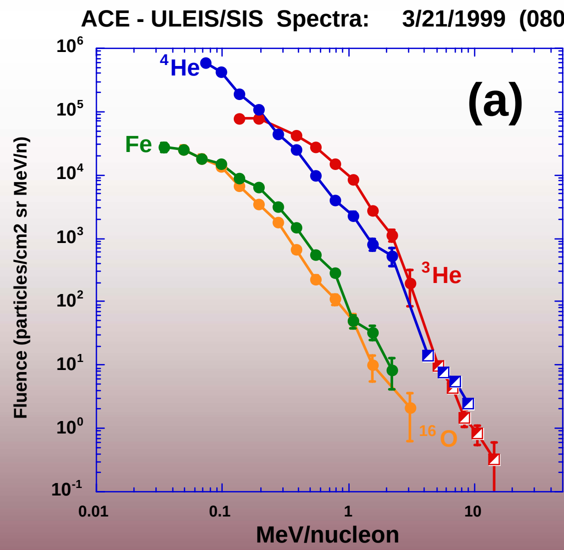
All similar



Only ^{3}He broken

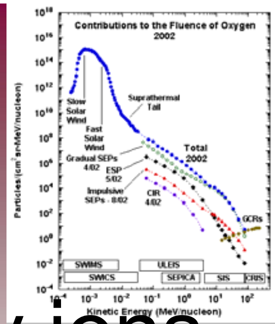


^{3}He & Fe rounded

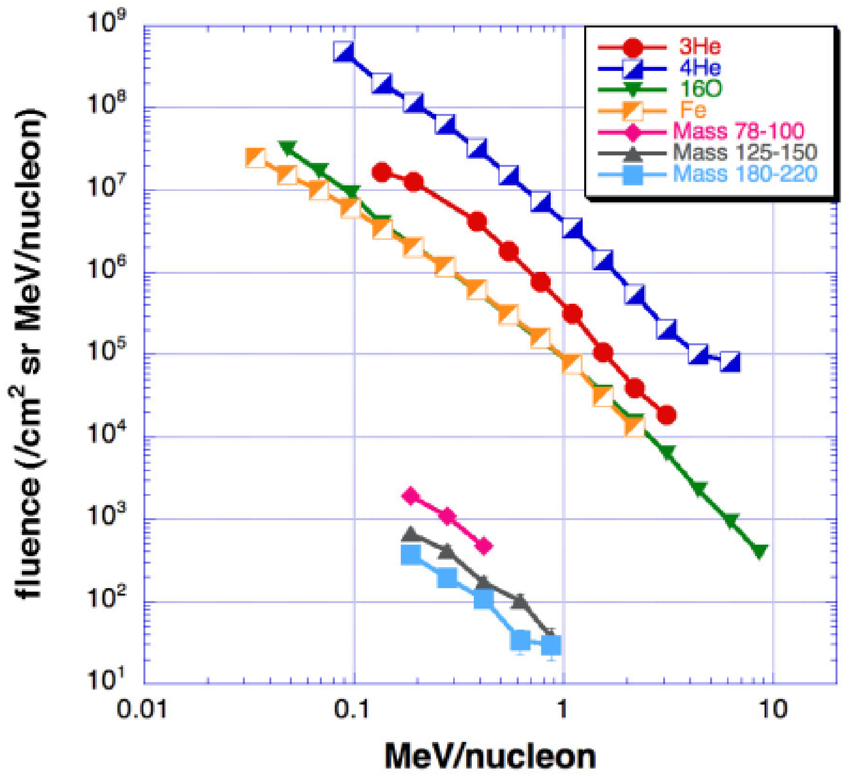


Mason et al., 2002

Impulsive SEP Events

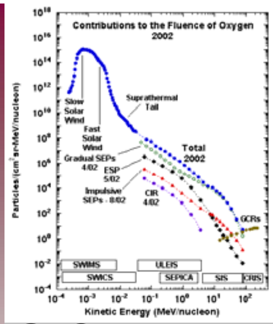


- Can make spectra of ^{3}He, ^{4}He, and heavy ions
- ^{3}He is often quite different
- But on average ultraheavies are similar in shape



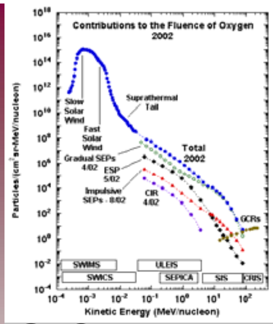
Mason et al., 2002

Flare Acceleration Theory



- General model involves resonance between waves and ions which cascades to higher Q/M values
  - Fe with lowest Q/M gets enhanced first
  - Ne-Si gets enhanced next
- Wave energy may be used up before reaches highest Q/M values
- ^{3}He is done separately through special heating first

Flare Acceleration Theory



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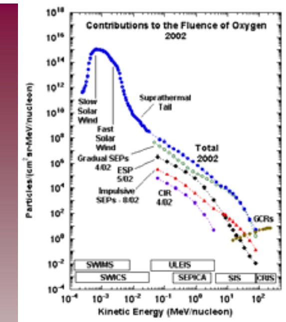

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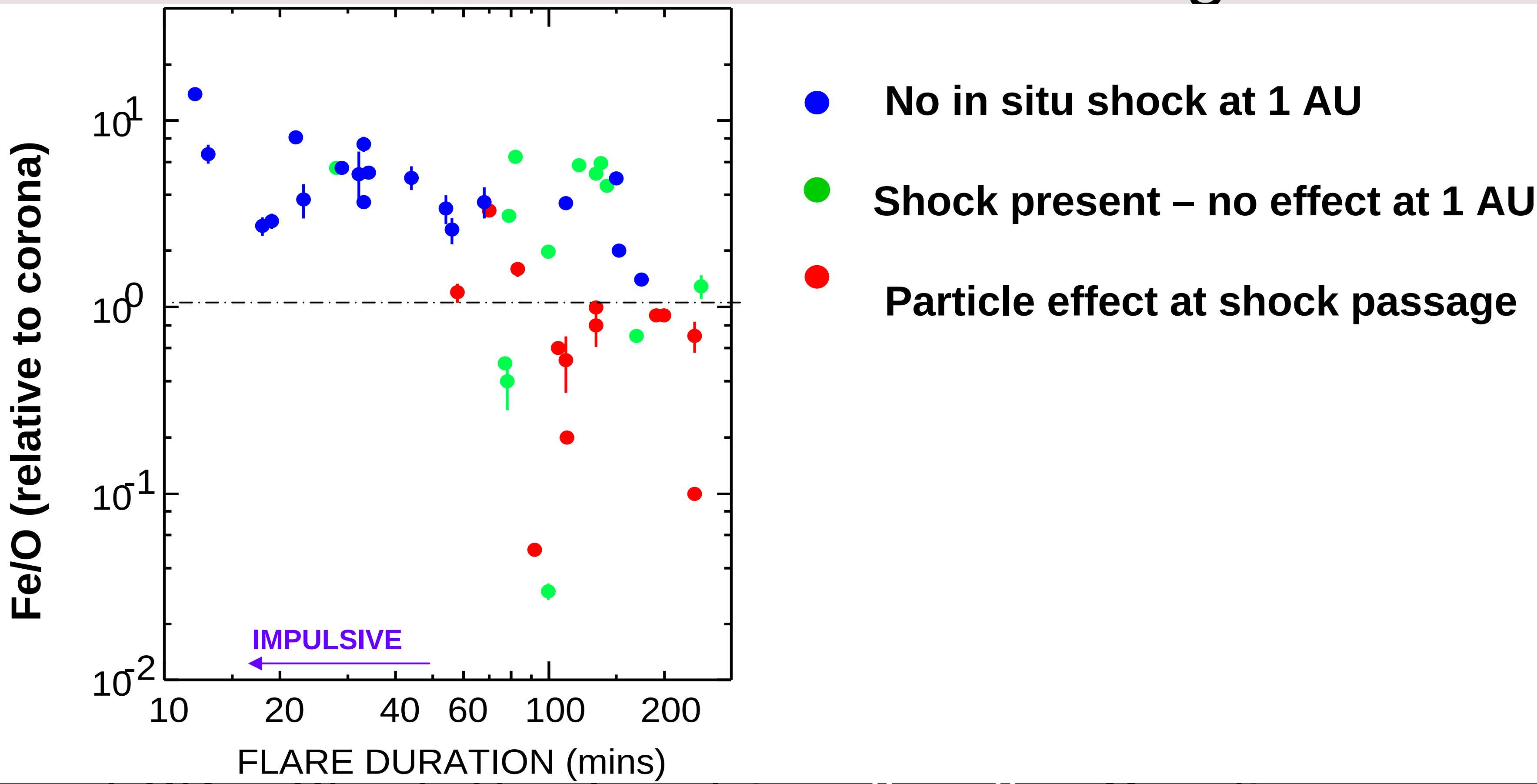

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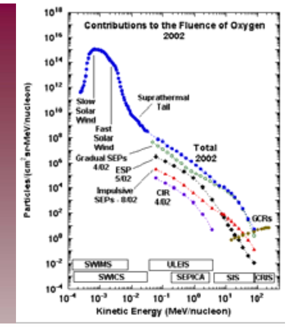
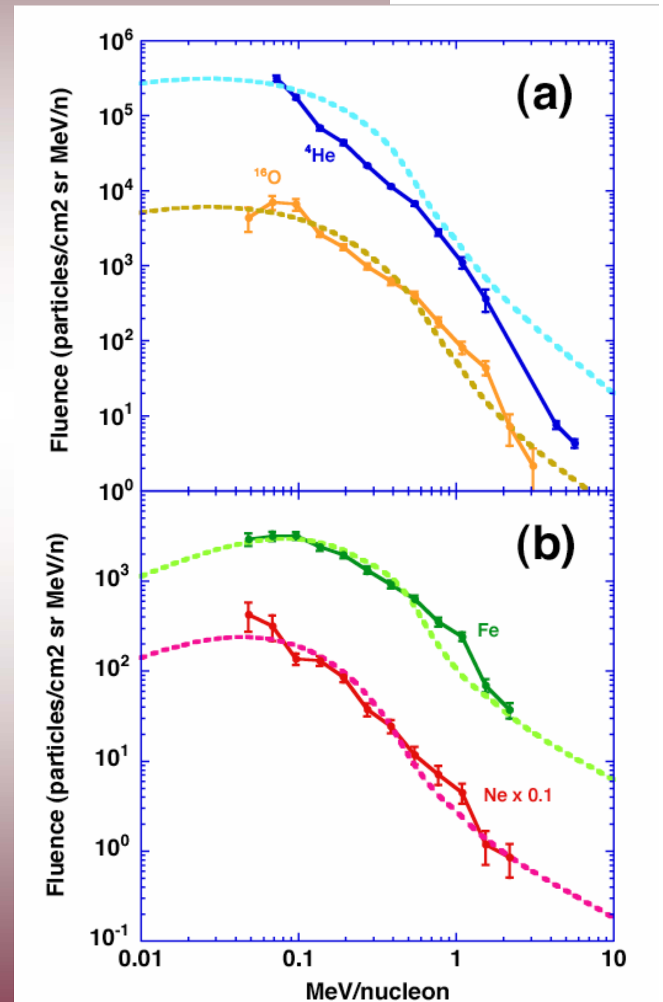


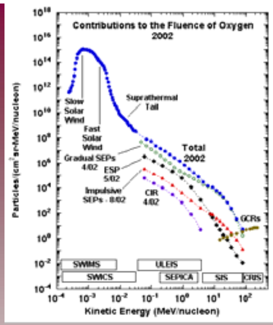
- Can match the data fairly well
- Stochastic model of Petrosian can even reproduce complex ^{3}He and ^{4}He spectra



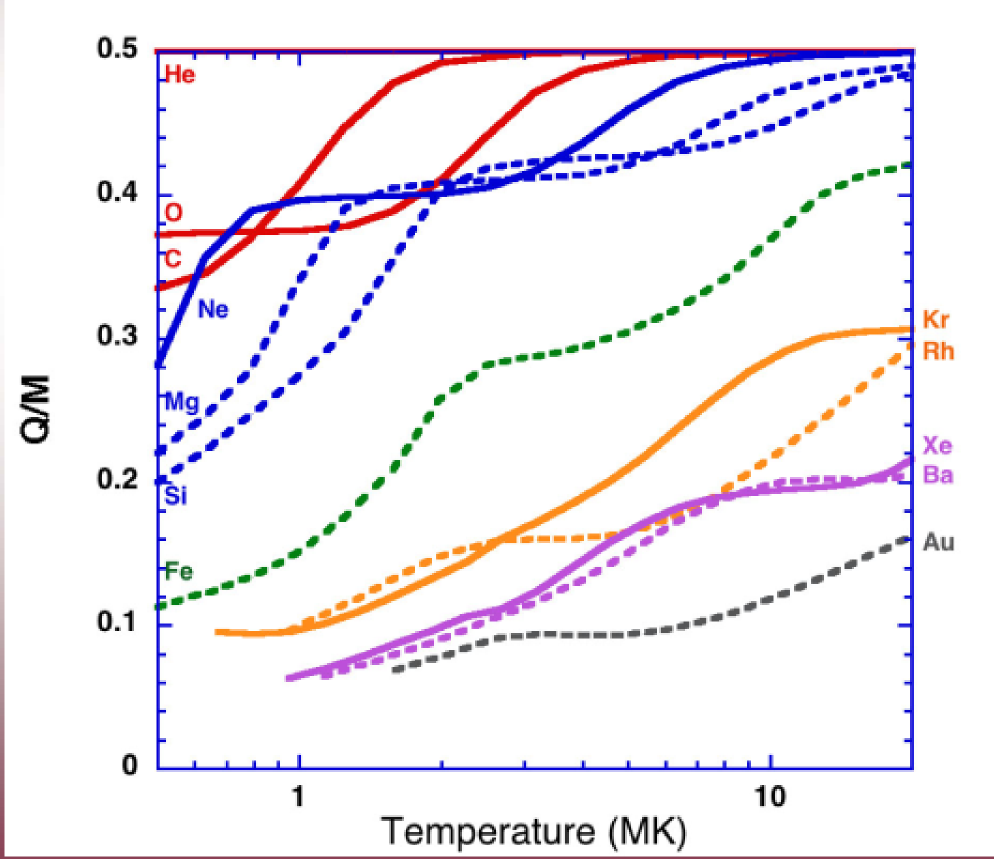
- But doesn't do heavy ions

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

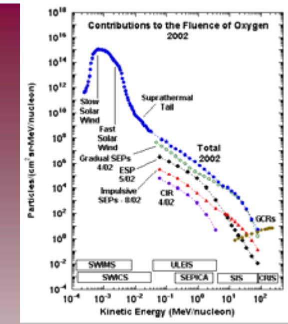
Flare Acceleration Theory



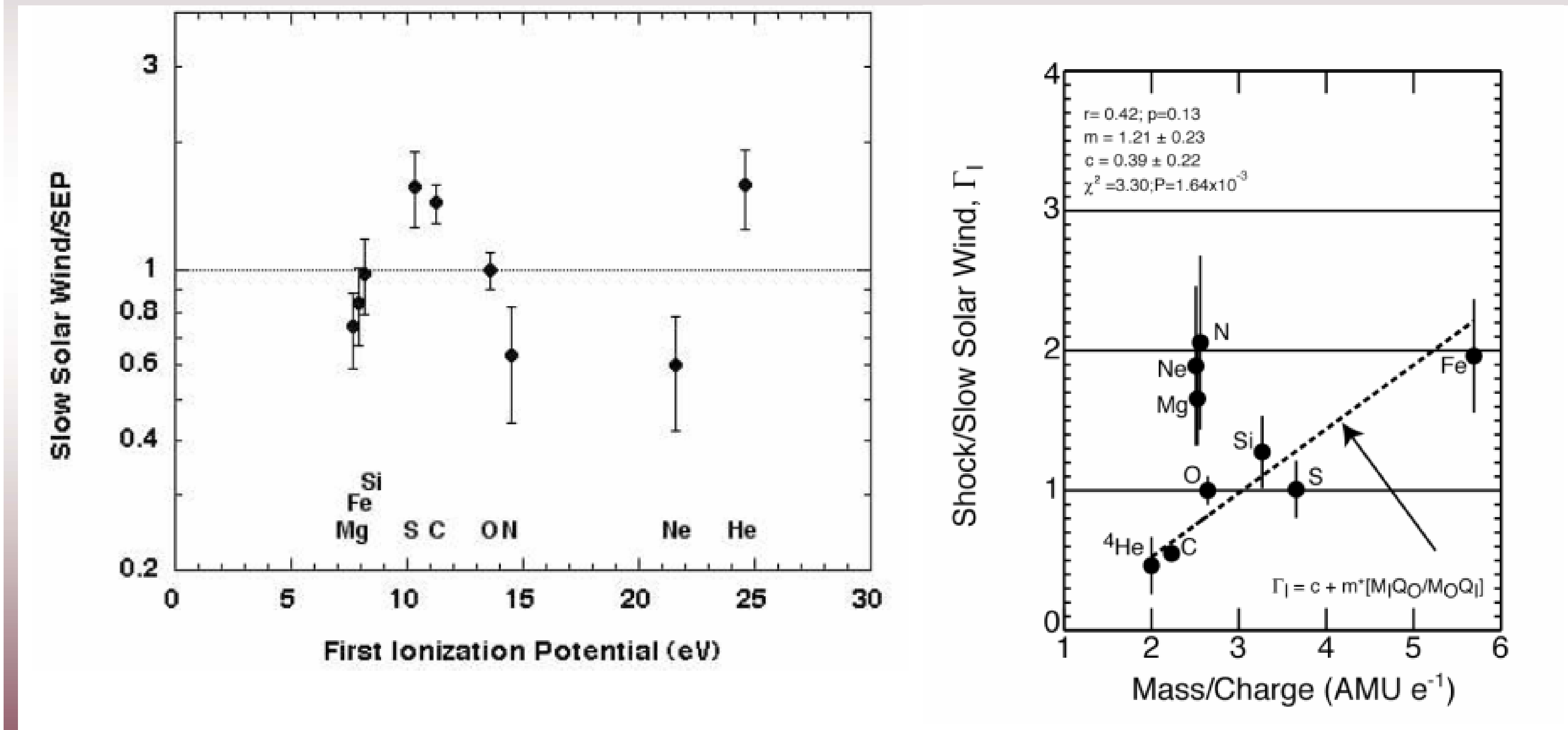
- But can cascading waves enhance ultraheavies with their much smaller Q/M?
- May run out of energy before getting to Fe...
- So far unable to match observations



Remaining Questions



- What?
  - Solar wind is supposed to be seed for gradual SEPs



s?

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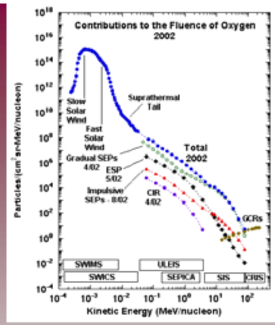
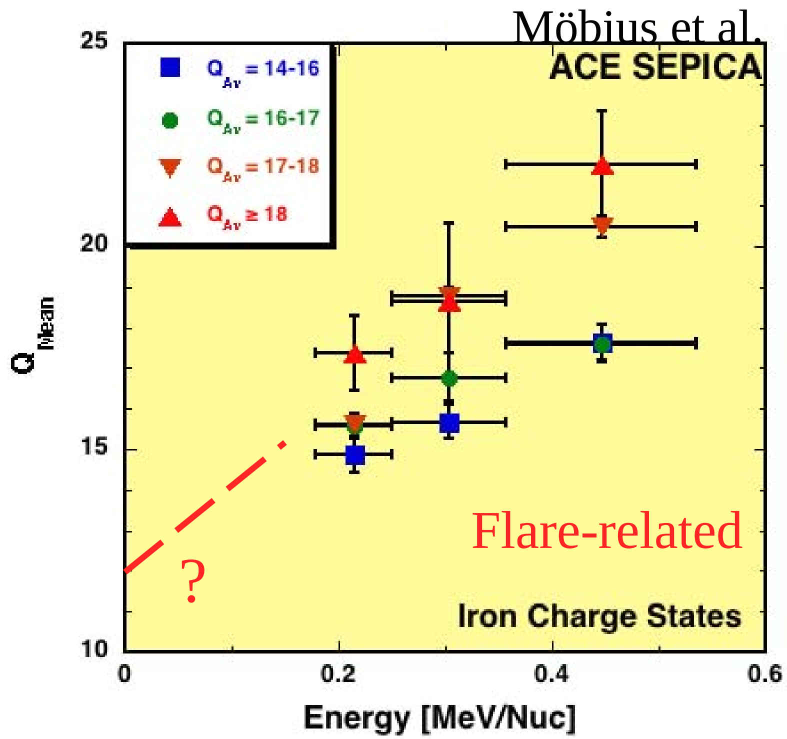


- What?
  - Solar wind is supposed to be seed for gradual SEPs
  - Coronal (?) material seed for impulsive SEPs

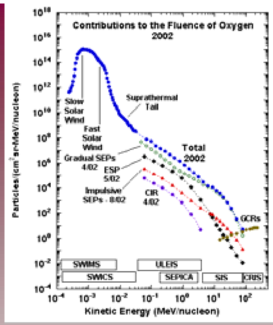
How low is Q at suprathermal energies?

s?



ESPs Shock Th. Impulsive flare th. Questions

Remaining Questions



- What?
  - Solar wind is supposed to be seed for gradual SEPs
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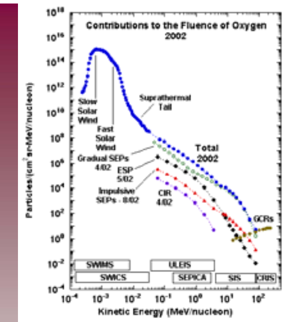
- Where?
  - How low can a shock form in corona and accelerate ions?
- How?
  - Flare mechanism is still unclear for all circumstances
  - Do quasi-perp shocks have high injection energy?
- Can we tell?
  - Maybe by looking at extremes
  - Separation at 1 AU may be difficult

Remaining Questions



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