Drivers of SEP Variability at High Energies:
SHINE Campaign Events: 2002 April 21 & 2002 August 24

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with thanks to generous and insightful colleagues:

Ed Cliver, Christina Cohen, Bill Dietrich, Mihir Desai, Marty Lee,

Carol Maclennan, Glenn Mason, Chee Ng, Don Reames

Overview/Summary

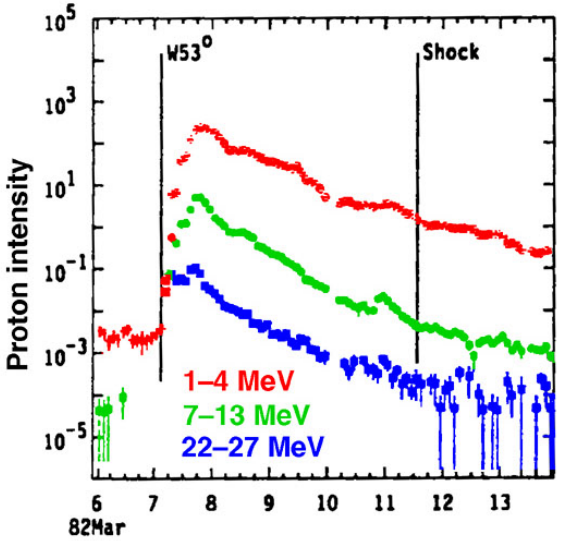
- *Minor Ions (especially Fe/C or Fe/O) serve as probes of SEP physics*
- *Compare 2 SEP events: 2002 April 21 & 2002 August 24*
  - *ostensibly similar solar/interplanetary conditions*
  - *but extremely different Fe/C behavior above ~10 MeV/nuc*
- *Compare to 2 ESP events ("shocks at 1 AU", from M. Desai):*
  - *same qualitative behavior, but at lower energies.*
- *Hypothesis: Shock geometry drives the behavior:*

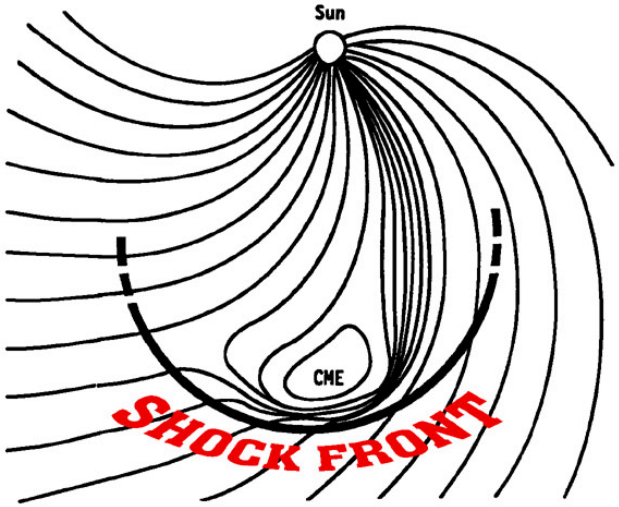
Quasi-parallel v. Quasi-perpendicular

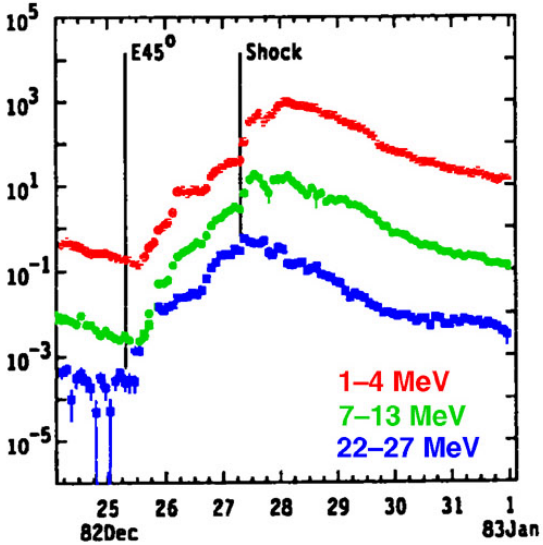
- *Statistical studies of SEP & ESP events appear to support the hypothesis.*
- *Challenges for SHINE*

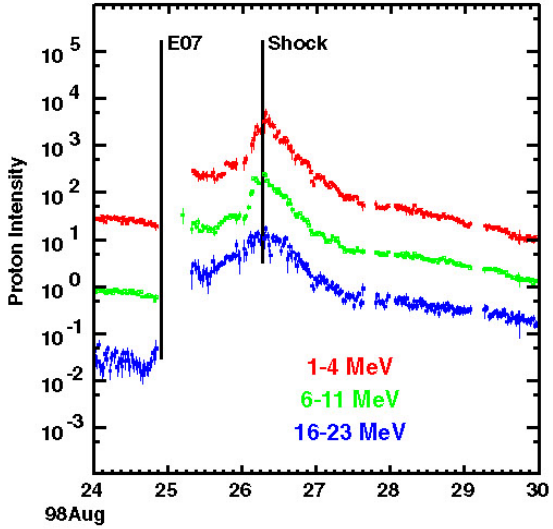
Solar Energetic Particles & CMEs

after Cane et al. (1988); Reames et al. (1996).





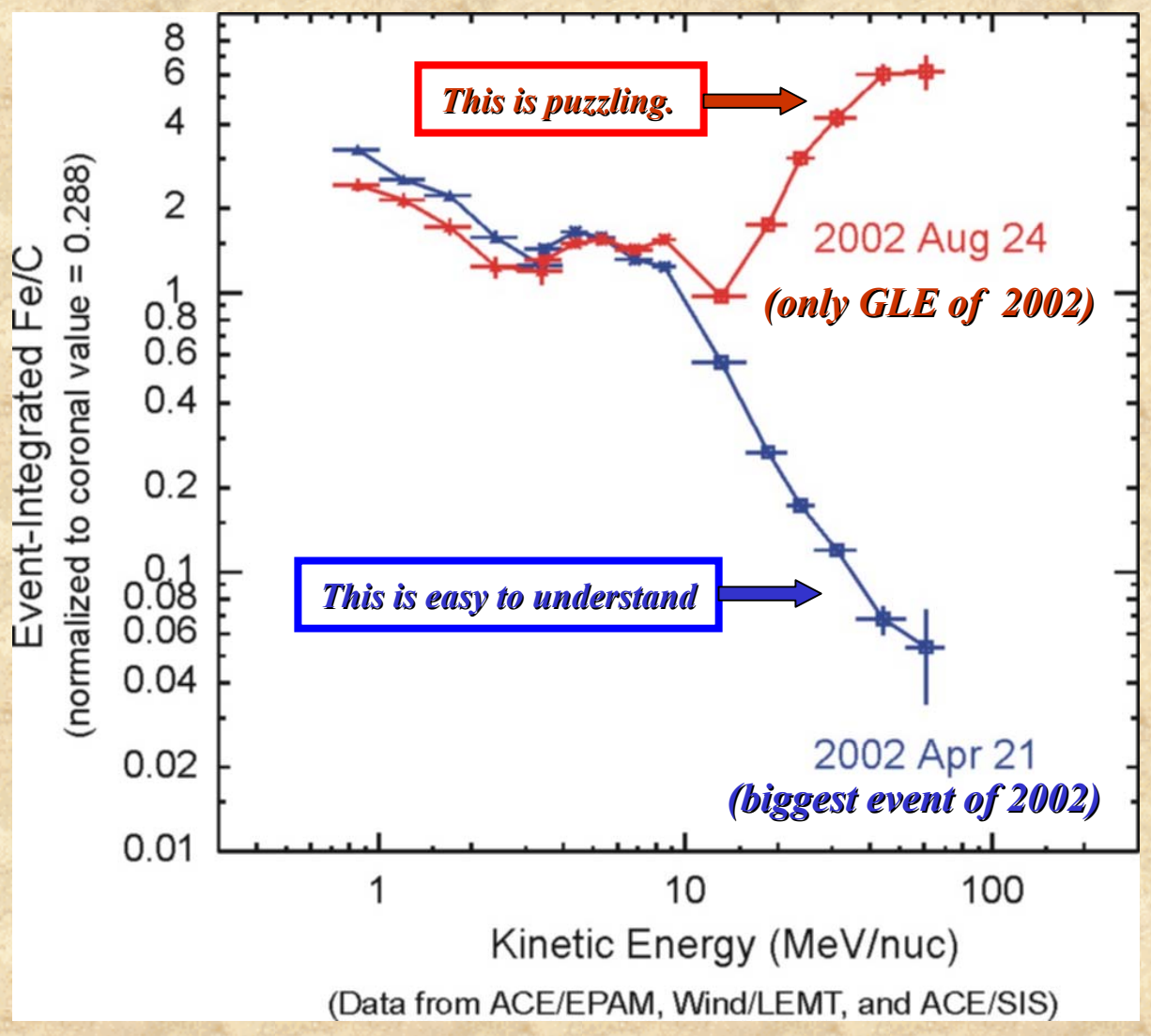




Only the fastest CMEs (top 1-2 %) drive shocks which make high-energy particles.

CMEs and the geometry of the Parker spiral explain the longitudinal dependence of SEP time profiles.

Compare SEP Fe/C vs. Energy



Fe/C nearly identical at ~0.5 - 10 MeV/nuc

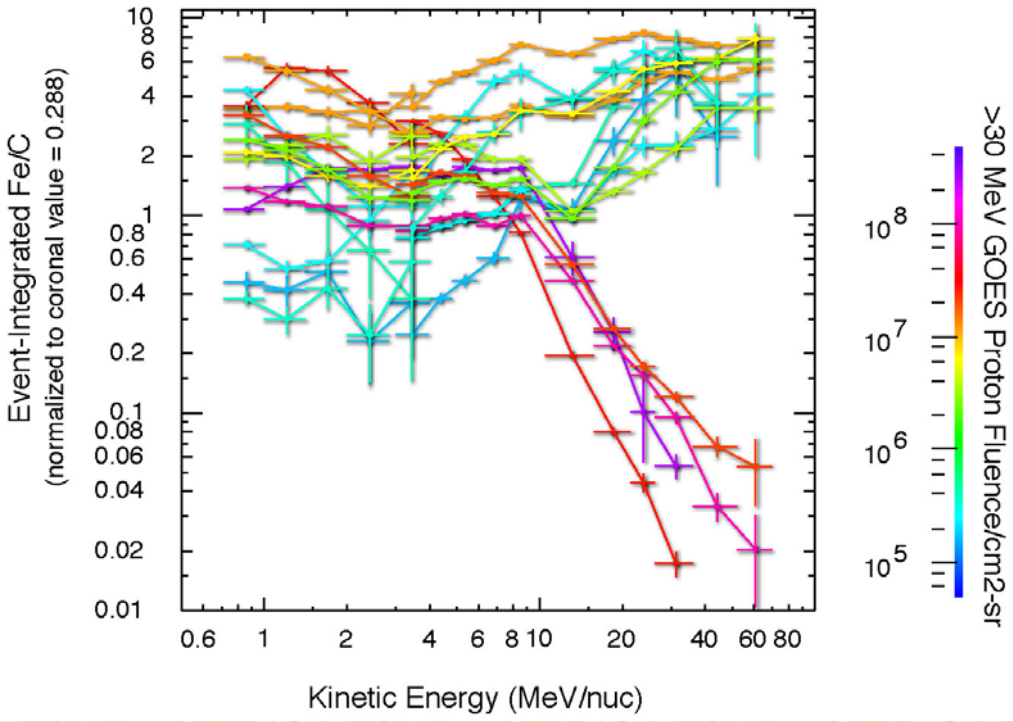
But the two events diverge dramatically at higher energies

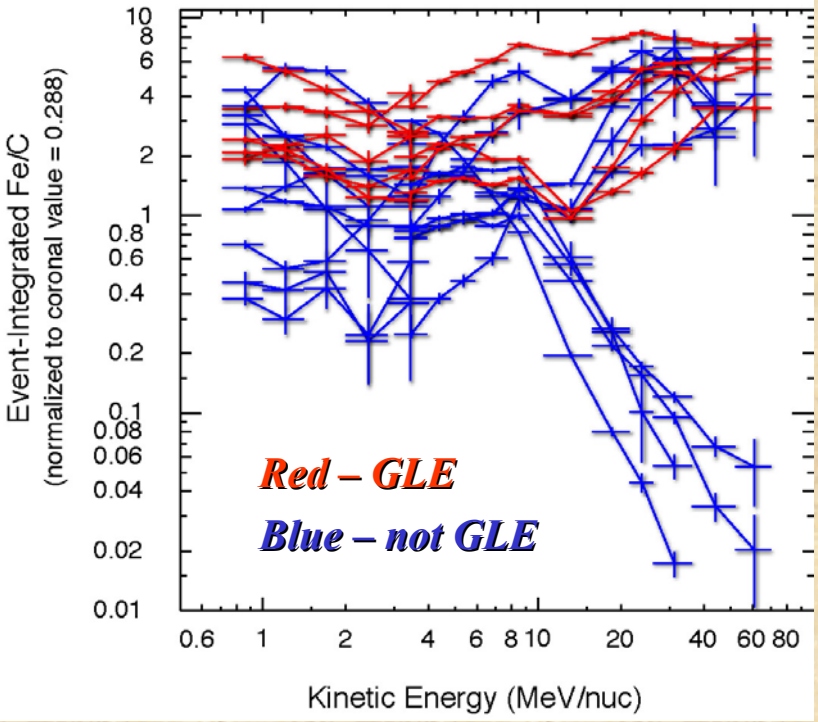
-- Fe/C differ by a factor of ~100 at 50 MeV/nuc.

The origin of this behavior is perhaps the biggest puzzle to have emerged from Cycle 23 SEP observations.

More SEP Events

- *The "campaign" events are <u>not</u> the only ones showing this morphology.*
- *14 out of the ~50 largest SEP events of Cycle 23 show strong energy-dependence in Fe/C, either increasing or decreasing.*





Why these two events?

Nearly identical solar/interplanetary conditions:

-- a 'controlled' experiment!

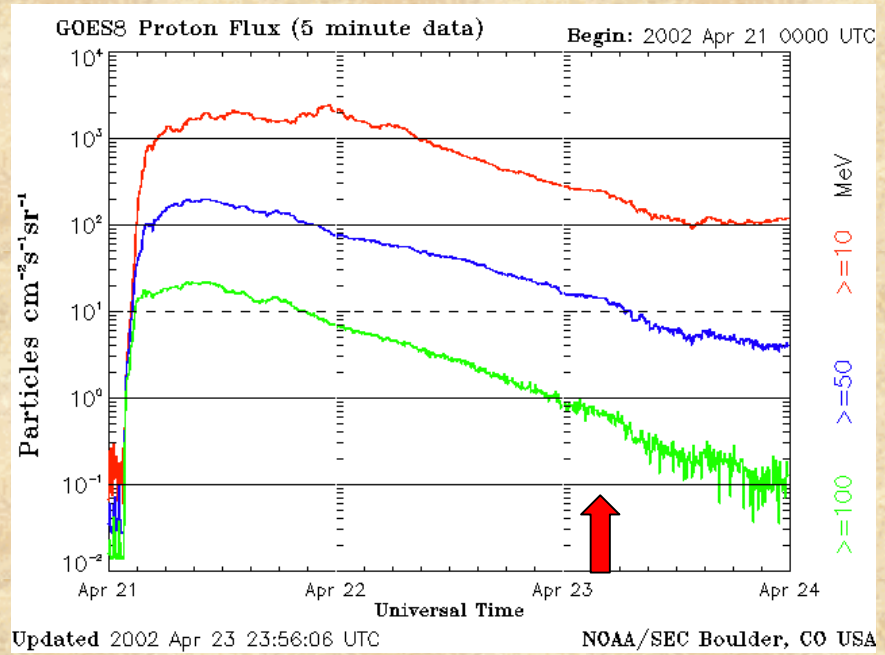
	21 Apr 2002	24 Aug 2002
CME Characteristics (S. Yashiro):		
Speed (km/s)	2400	1900
Width (deg)	240	360
Flare Characteristics (NOAA/SGD):		
Size	X1.5 / 1F	X3.1 / 1F
Location	S14W84	S02W81
Duration: Start to Maximum/e (min)	115	42
SW Speed* at 1 AU (km/s), (CDAWeb)	~475	~385
Associated Shock (C.W. Smith):		
Transit Time to 1 AU (hours)	51	58
Velocity Jump (km/s)	~200	~100
ESP increase?	< 1 MeV only	< 0.5 MeV only

* Averaged over the first 6 hours.

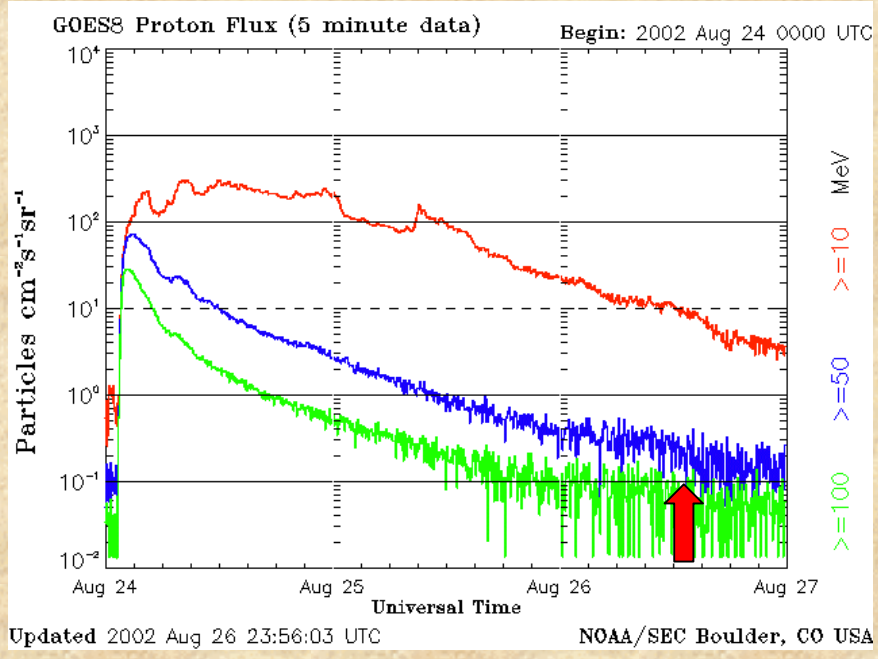
GOES Protons

>10 MeV >50 MeV >100 MeV

21 April 2002
(Fe-poor at high energies)



24 August 2002
(Fe-rich at high energies)

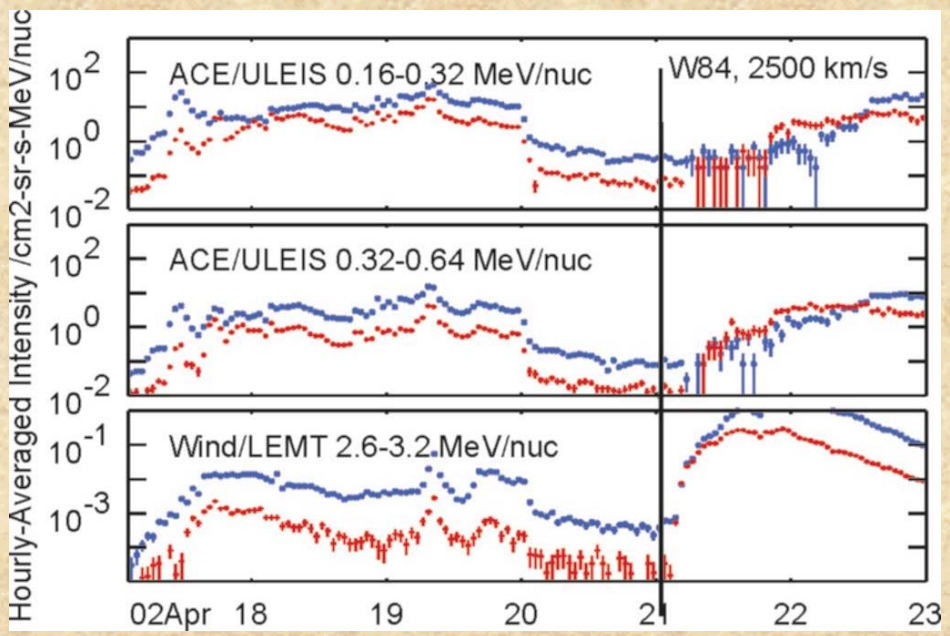


- *>10 MeV profiles very similar, except for normalization.*
- *But >50, >100 MeV profiles have different shapes in the two events.*
- *No increase in high-energy particles at shock arrival at Earth (arrows).*

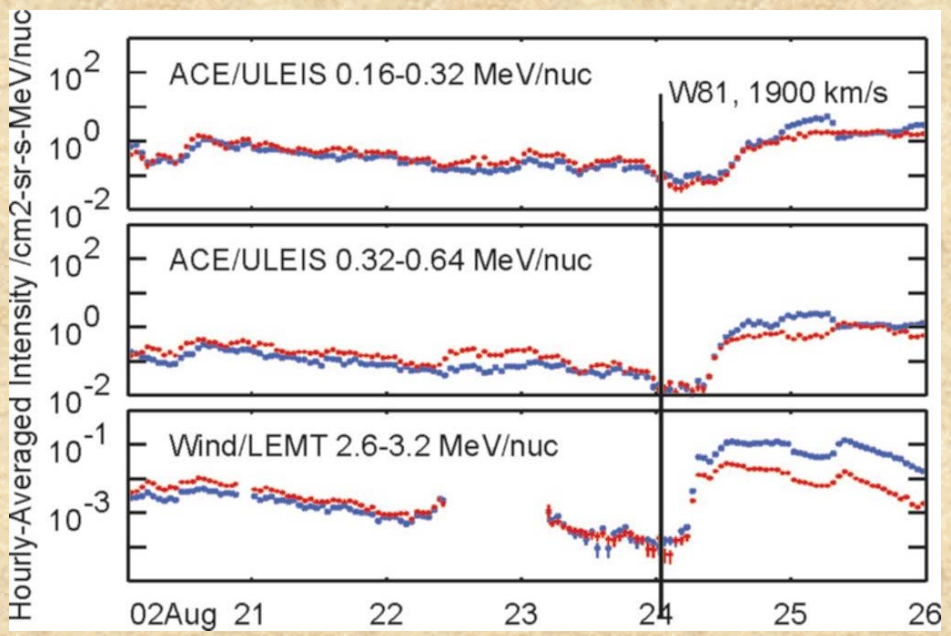
Pre-Event Particle Background

Blue: Oxygen **Red: Iron**

17-23 April 2002



20-26 August 2002

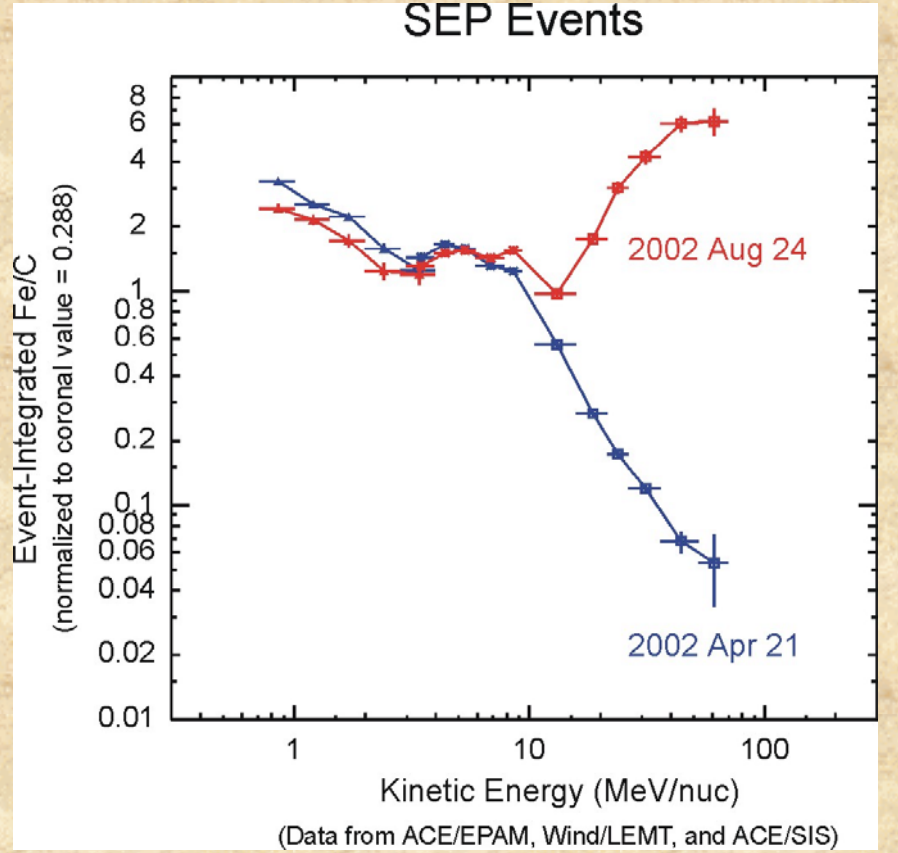


Nominal Fe/O ~ 0.1 in the 4 days preceding the event

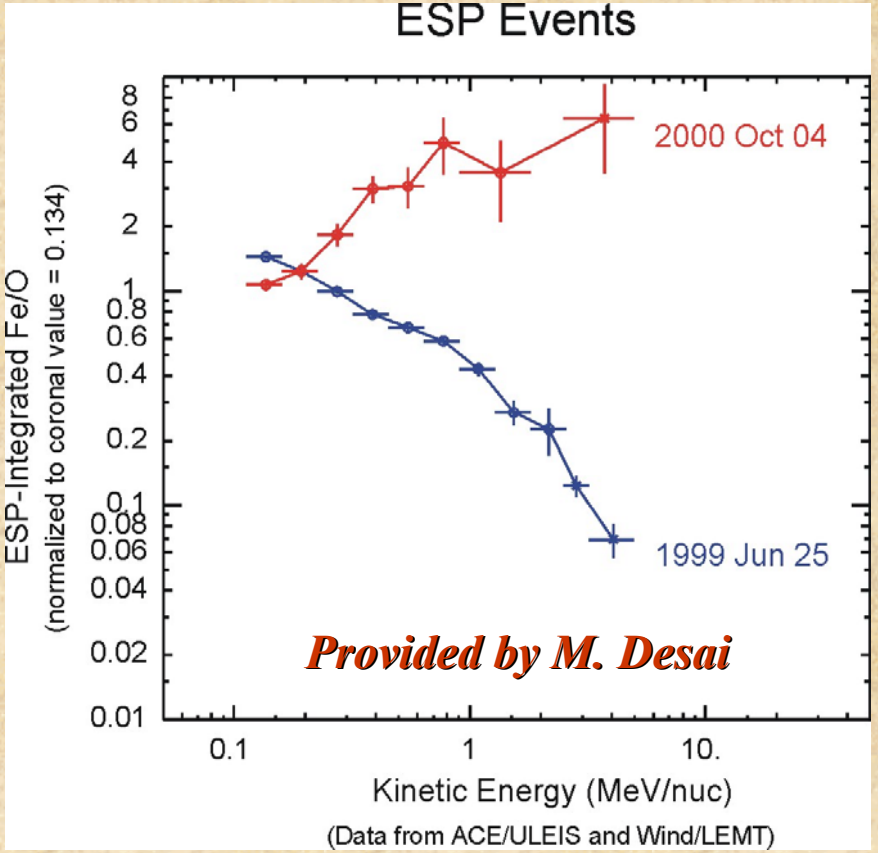
Enhanced Fe/O ~ 1 in the 4 days preceding the event

SEPs and ESPs

Solar Energetic Particles
(accelerated near the Sun)



Energetic Storm Particles
(accelerated locally, near 1 AU)

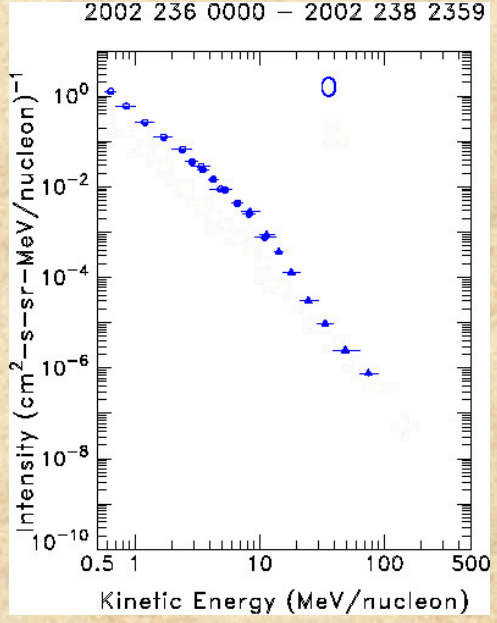


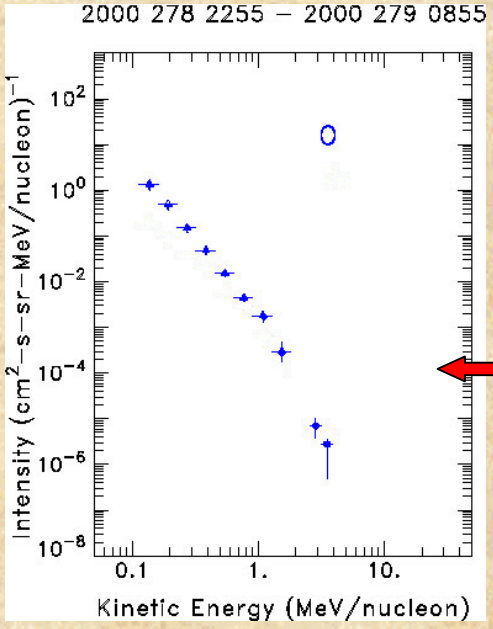
Same range of behavior observed in both SEP and ESP events.
Suggests a common mechanism, associated with shocks.
What other differences can we find between Fe-rich & Fe-poor events?

SEP Events

ESP Events

Fe- Rich
at the highest energies

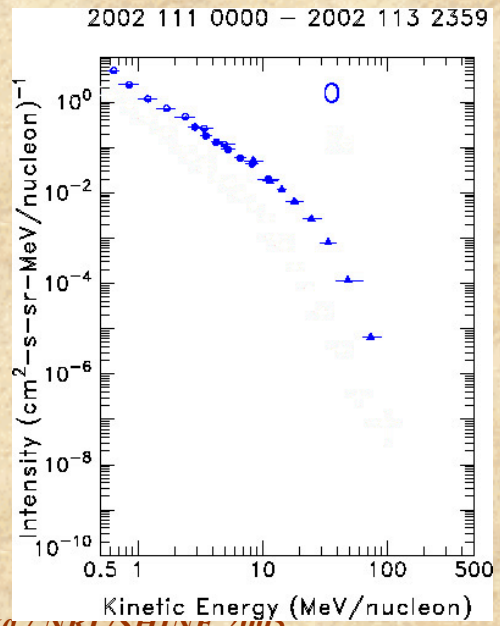


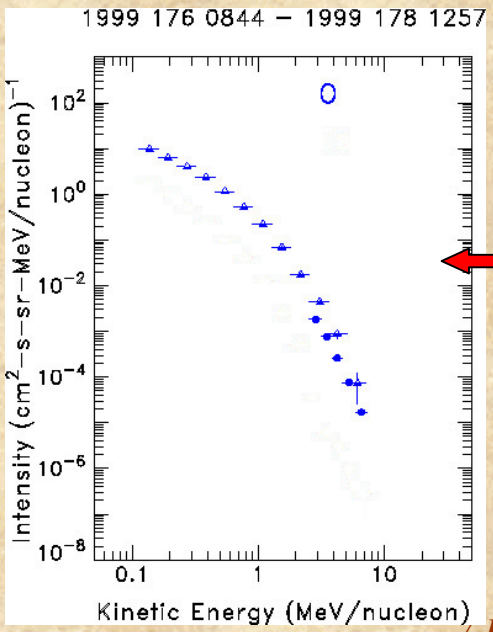


Compare oxygen spectra:

Nearly power-laws in Fe-rich events.

Fe- Poor
at the highest energies





But clear rollovers in Fe-poor events

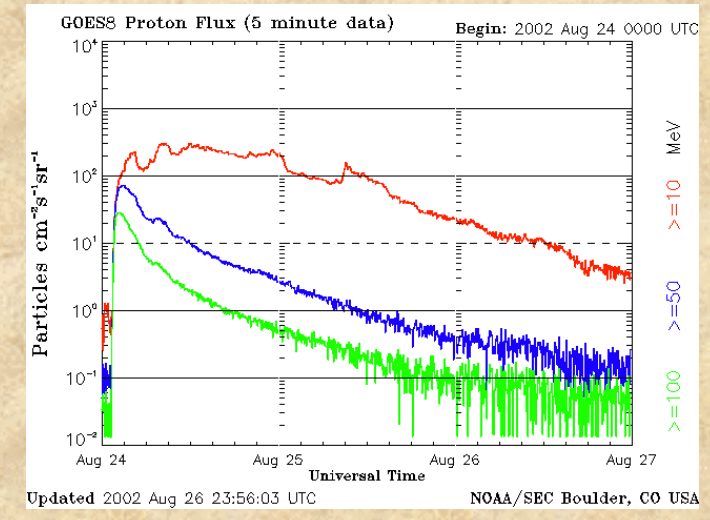
SEP Events

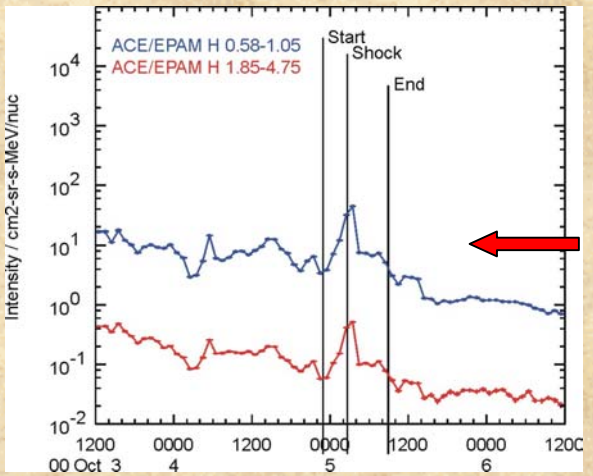
GOES Protons (>10, >50, >100 MeV)

ESP Events

ACE/EPAM Protons (0.6, 2.0 MeV)

Fe- Rich
at the highest energies



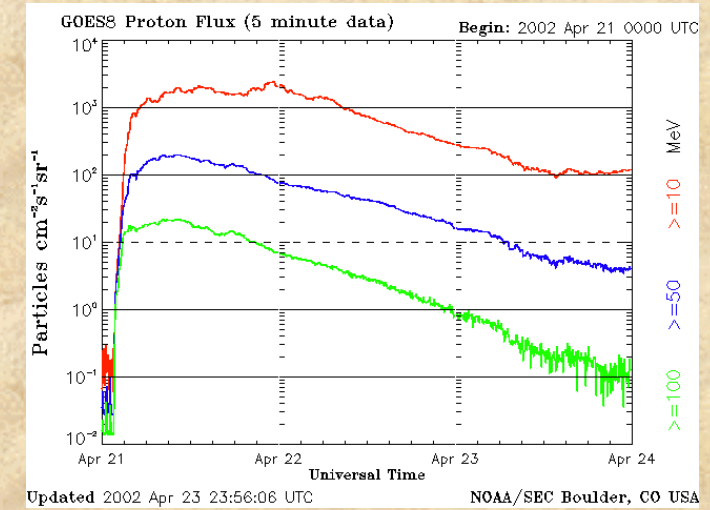


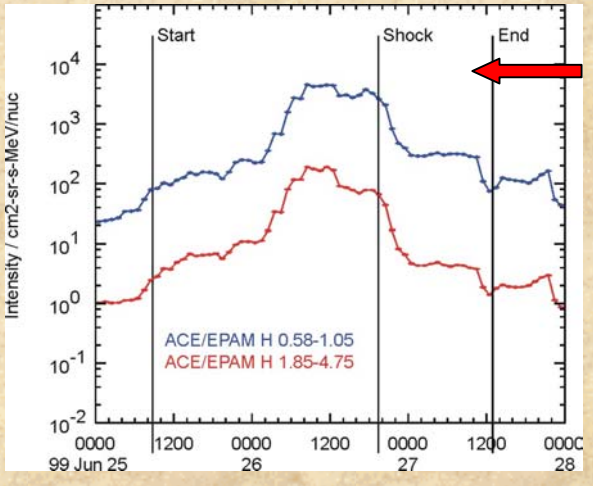
Compare proton time profiles:

"Spikes":

Quasi-perp shock

Fe- Poor
at the highest energies





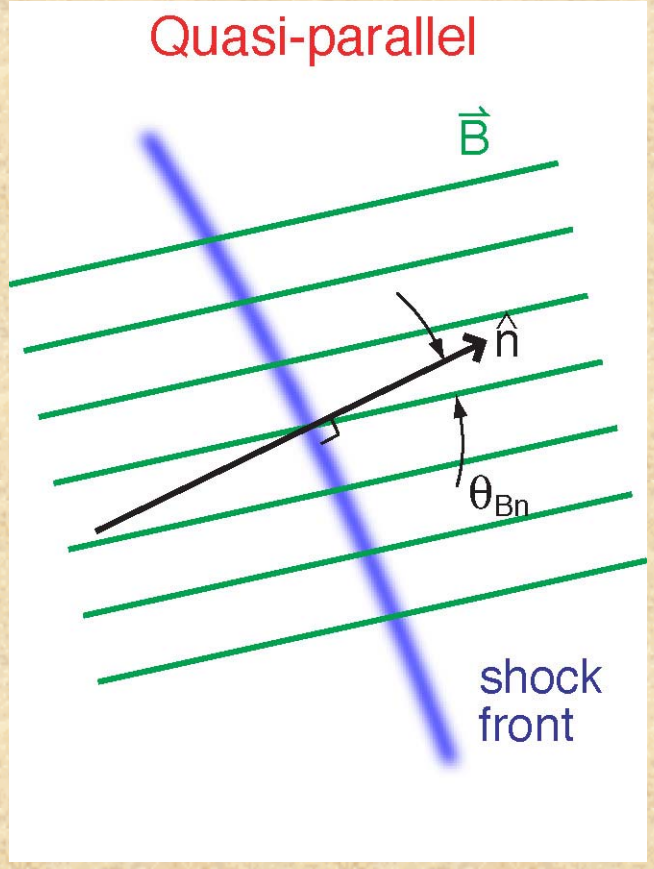
Extended enhancements

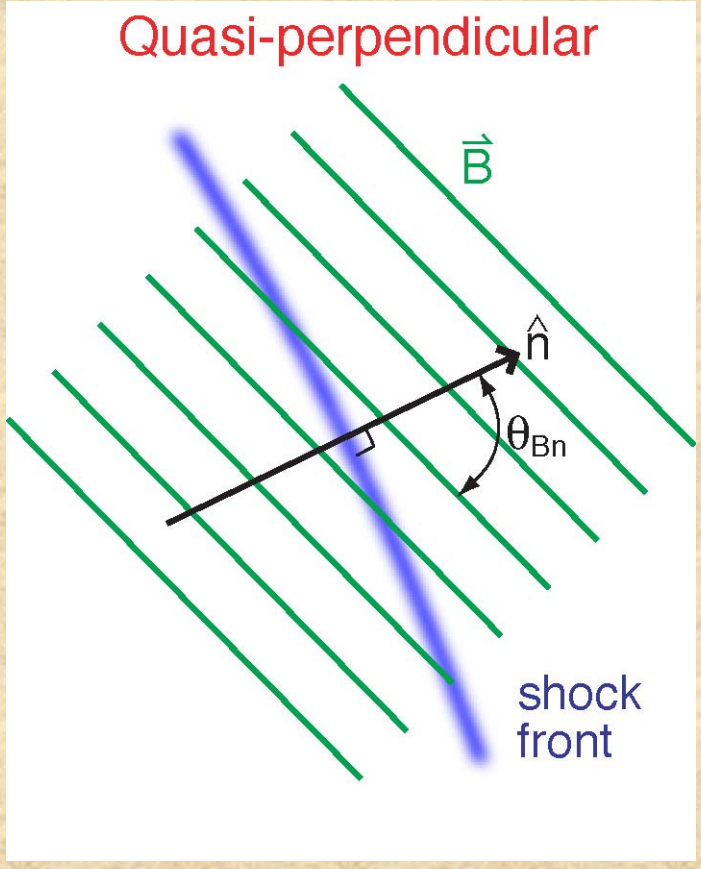
Quasi-parallel shock

(Tsurutani & Lin 1985)

Shock Geometry: The 1-Minute Explanation

- *Shock rides over a given field line for a long time.*
- *Extended particle time profiles*





- *Shock quickly crosses a given field line.*
- *Particle 'spikes'*

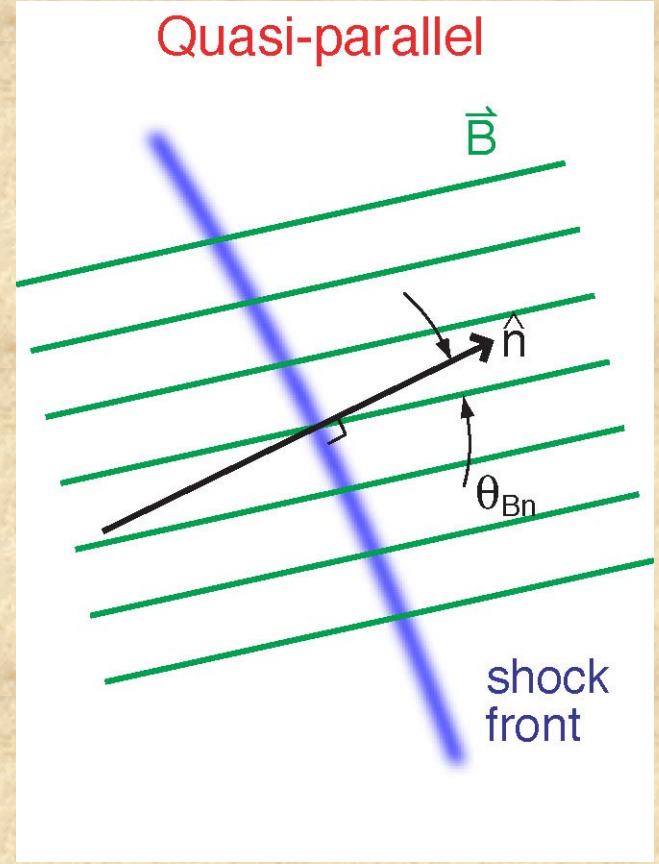
Notes:

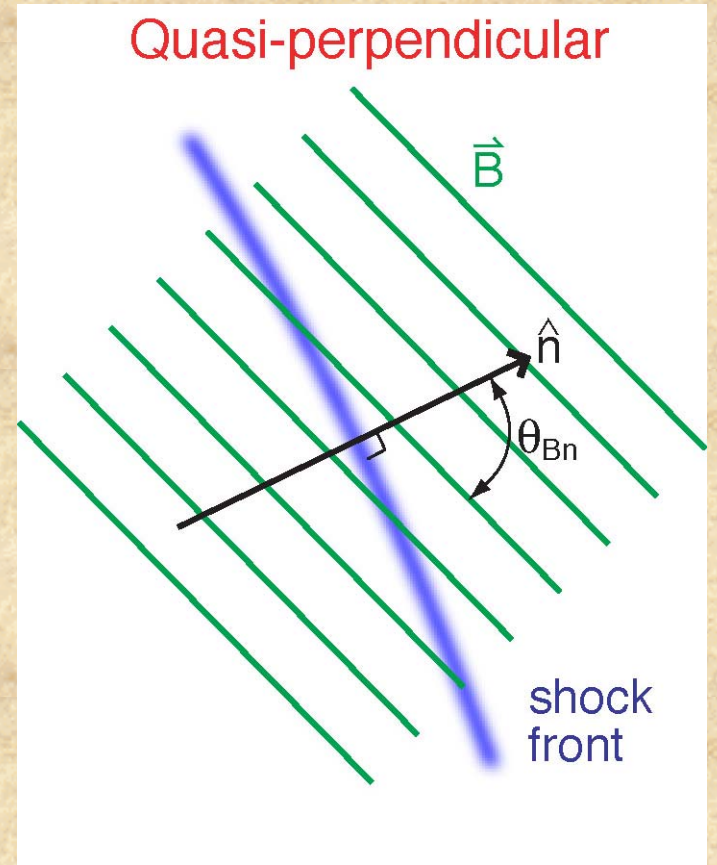
1. *Terminology refers to B-field and shock-<u>normal</u>.*
2. *θ_{Bn} changes as the CME moves out.*
3. *For high-energy SEPs, near-Sun geometry is important.*

Shock Geometry: The 1-Minute Explanation

Escape from Shock: $\kappa_{escape} \sim \cos^2\theta_{Bn}$

- *Easy escape from shock region:*
- *Soft spectra at high energy*





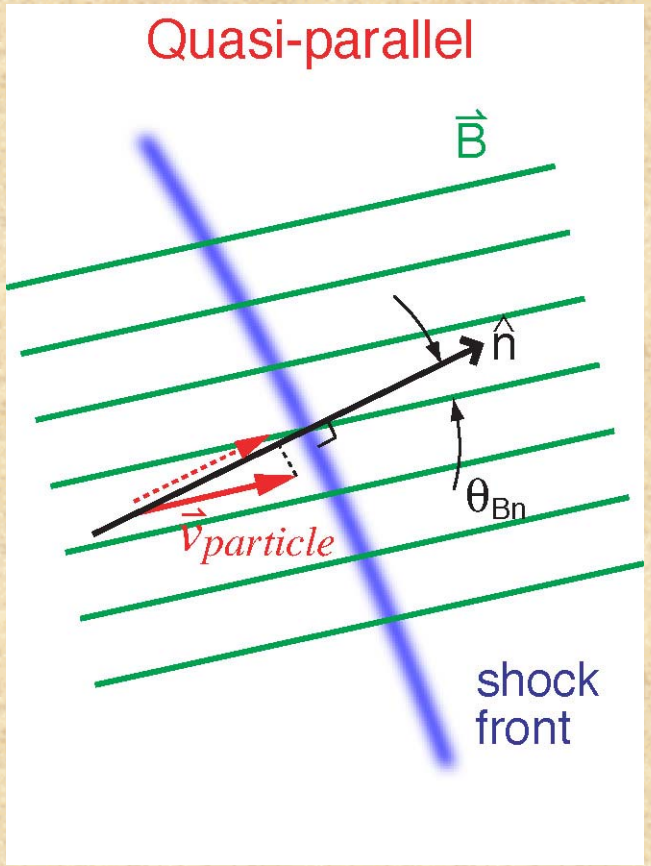
- *Harder to escape shock region, due to B field:*
- *Quick acceleration*
- *Hard spectra at high energy*

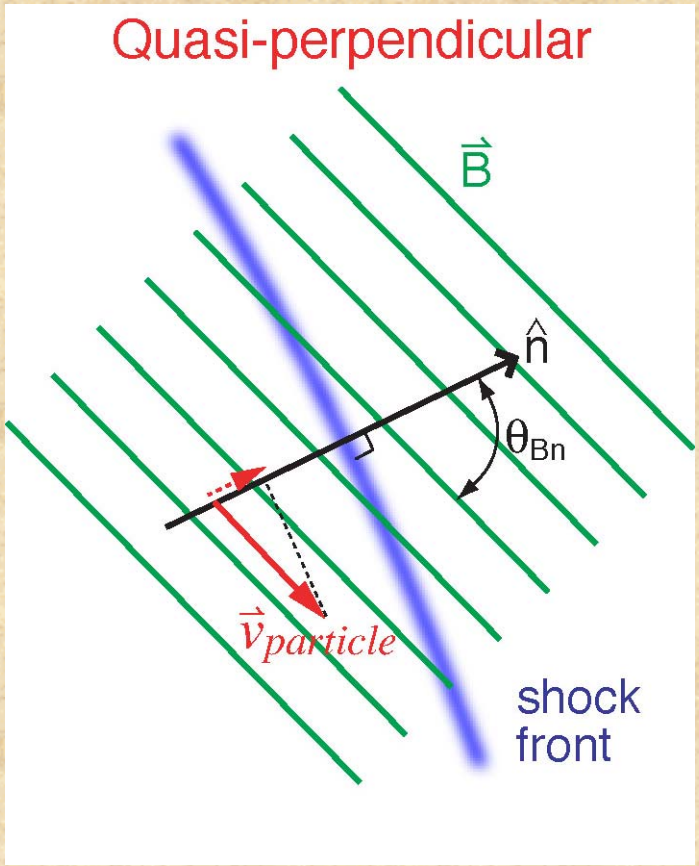
For quasi-perp shocks, field inhibits escape from the shock region, allowing particles to be accelerated to higher energies.

Shock Geometry: The 1-Minute Explanation

Injection Threshold: $v_{particle} \cos\theta_{Bn} > V_{shock}$

- *Low injection threshold*



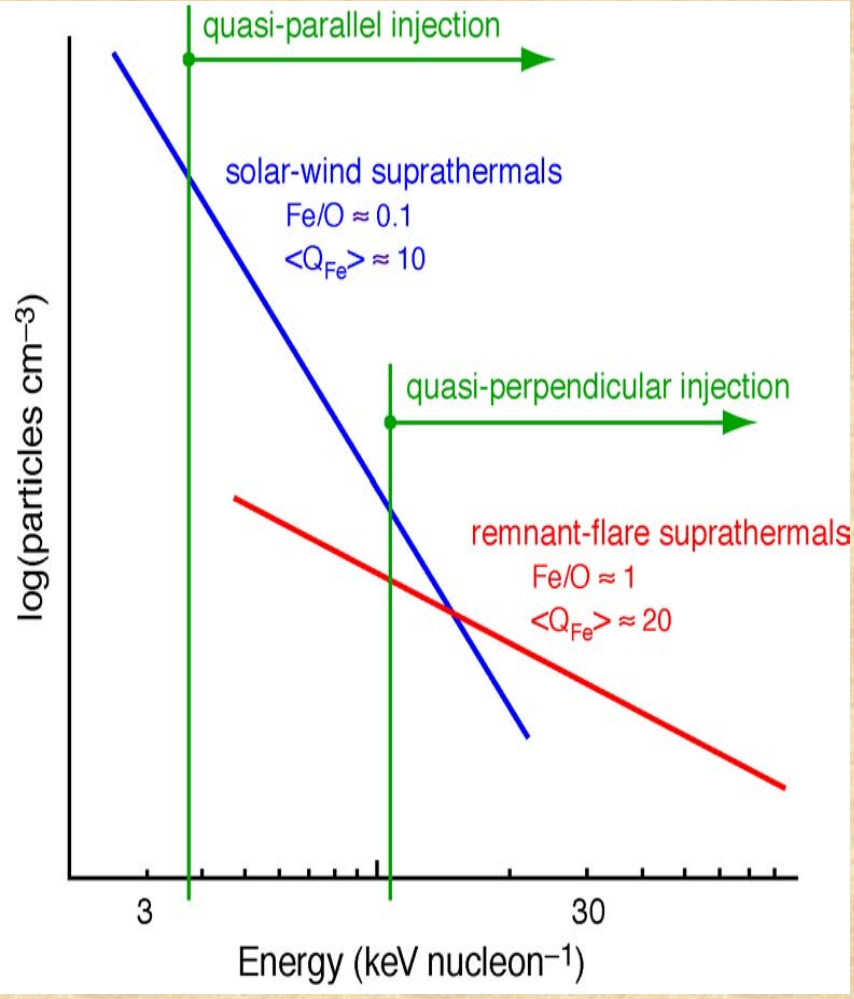


- *High injection threshold*

Initial speeds must be sufficiently fast so that particles can 'catch-up' from behind the shock.

How does shock geometry relate to Fe/O? Scenario…

Seed Population for Shock Acceleration



Quasi-parallel shocks: low injection threshold.

- ***Flare suprathermals are more likely to be outnumbered by coronal/SW suprathermals in quasi-parallel shocks***

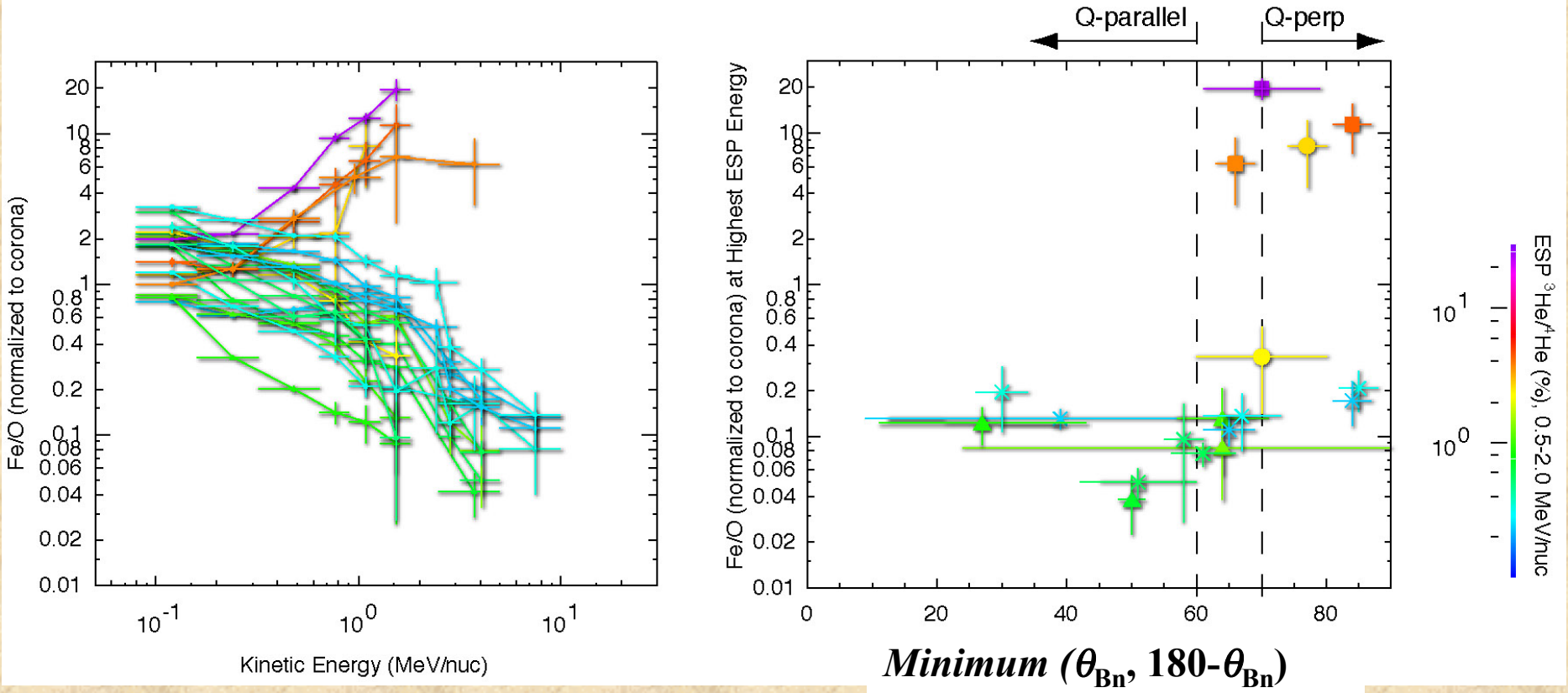
Quasi-perp shocks: high injection threshold.

- ***Quasi-perp shocks are more likely to reflect the presence of flare-accelerated suprathermals in the source population.***

Hypothesis: Enhanced Fe/O (and high QFe) at high energies are signatures of quasi-perp shocks near the Sun.

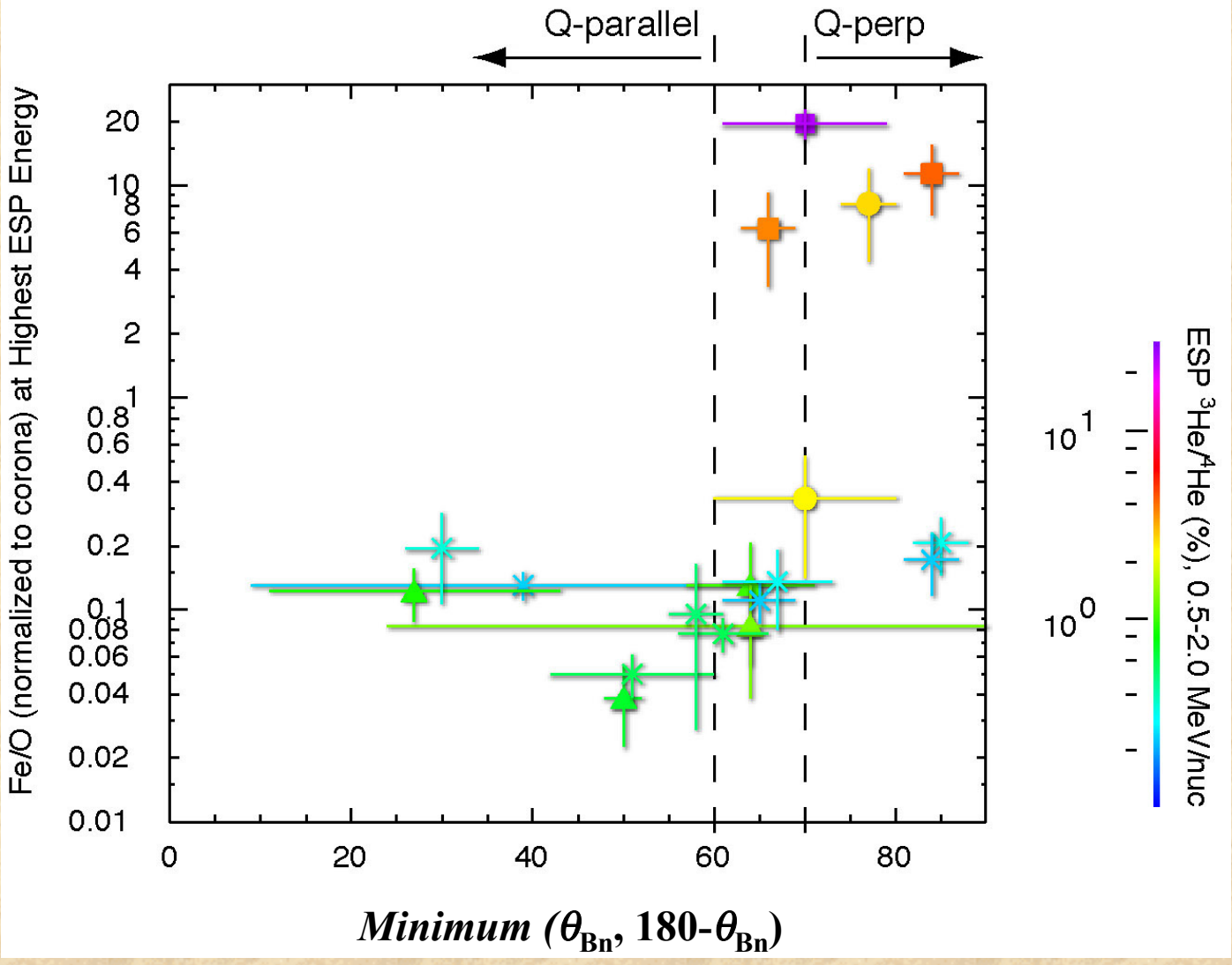
Shock Geometry and ESP ("Shocks at 1 AU") Events

- *72 ESP Events, 1997-2002 (Desai et al. 2003)*
- *55 with measured θ_{Bn} (C. Smith/ACE website)*
- *18 with strongly energy-dependent Fe/O (this study – preliminary!)*



Data from ACE/ULEIS & Wind/LEMT

Shock Geometry and ESP ("Shocks at 1 AU") Events



Measured ESP ^{3}He / ^{4}He provides direct indicator of remnant flare suprathermals in the seed population

Consequences of the "Quasi-perp v. Quasi-parallel" Hypothesis for SEPs

1. *Quasi-parallel shocks have a lower injection energy.*

   Larger seed population → biggest events in this category.

   Check: High-Energy Fe/O anticorrelates with proton fluence

2. *Quasi-perp shocks have rapid acceleration time scales.*

   Emax decreases as shock moves out; GLEs should be mostly quasi-perp.

   Check: Most GLEs show enhanced Fe/O at high energies

3. *Spectral softening:* $F(E) \sim E^{-\gamma} \exp(-E/E_0)$, *where* $E_0 \sim \sec \theta_{Bn}$

   Spectra from quasi-perp shocks look more like power laws.

   Check: High-Energy Fe/O anticorrelates with spectral softening.

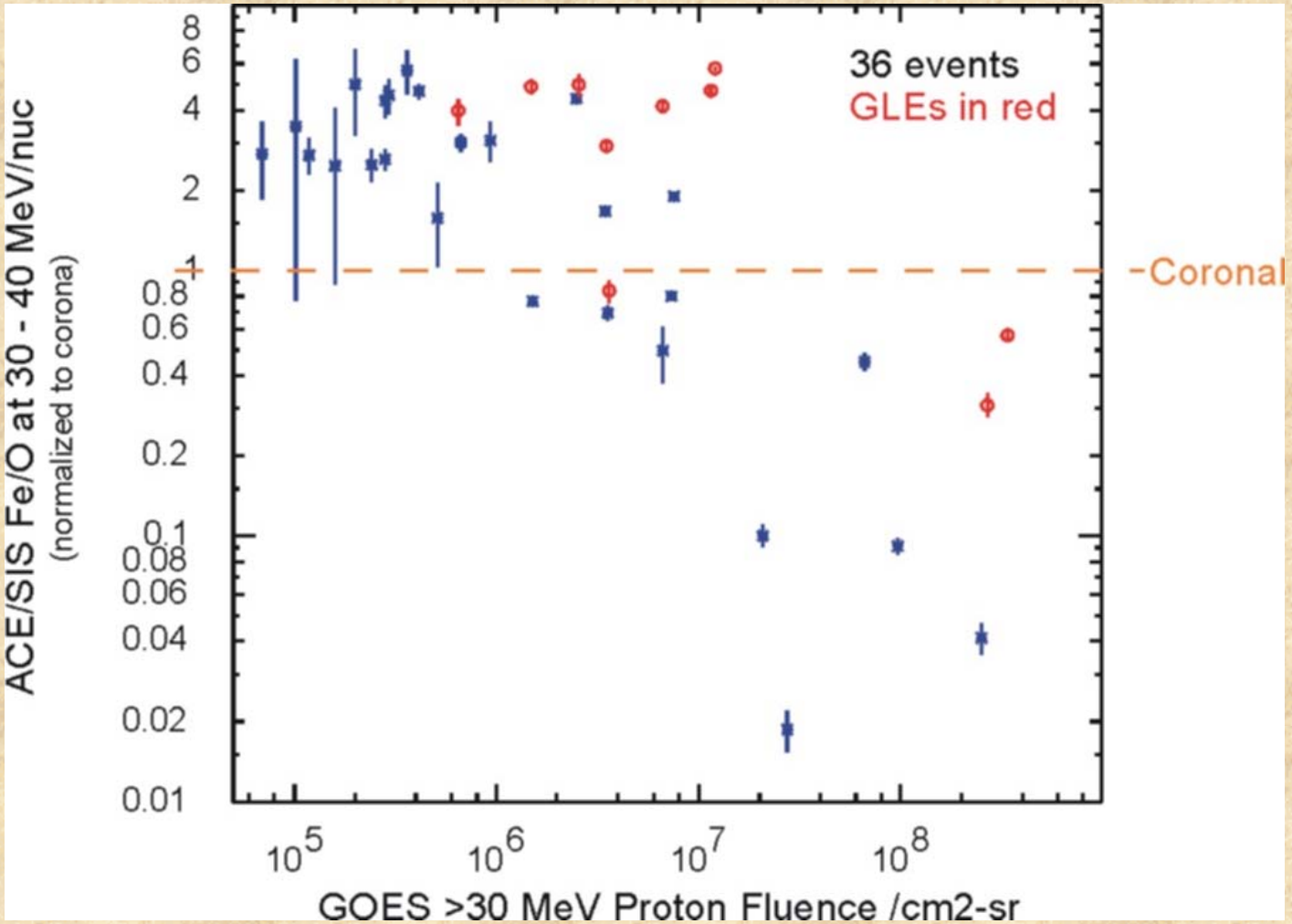
4. *Duration: Quasi-perp shocks produce shorter-duration enhancements.*

   Check: High-Energy Fe/O anticorrelates with duration of >100 MeV protons

- *All of these checks are true for the 21Apr02 and 24Aug02 events.*
- *What about other events?*

Statistical Study: 36 SEP events, 1997-2002, with ACE/SIS Fe/O at 30-40 MeV/nuc

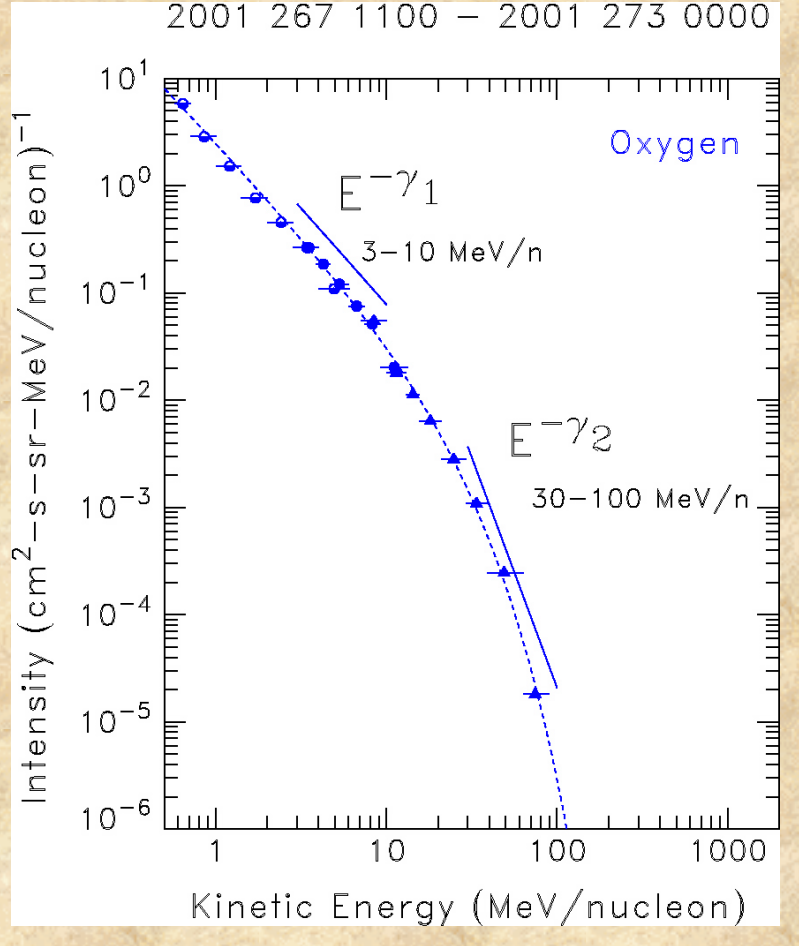
Fe/O v. Event Size



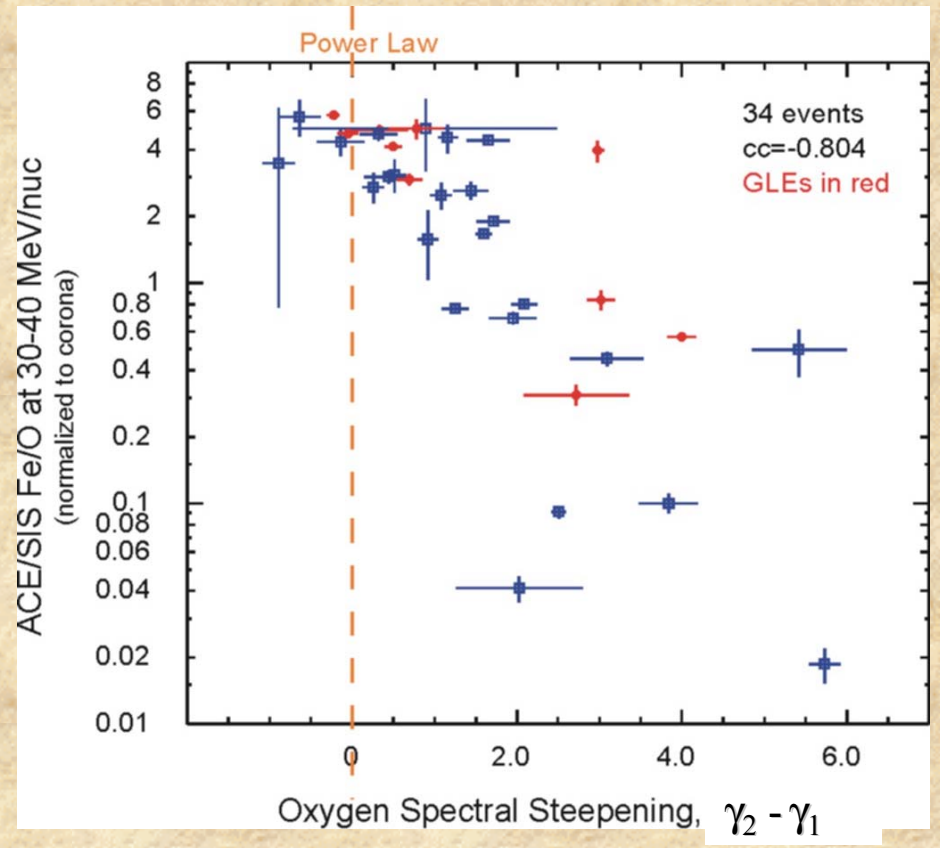
On high-energy Fe/O and GLEs: see also Dietrich & Lopate, Proc. 26th ICRC (SLC) 6, 71-74, 1999.

Spectral Steepening

Event-Integrated Oxygen Spectrum



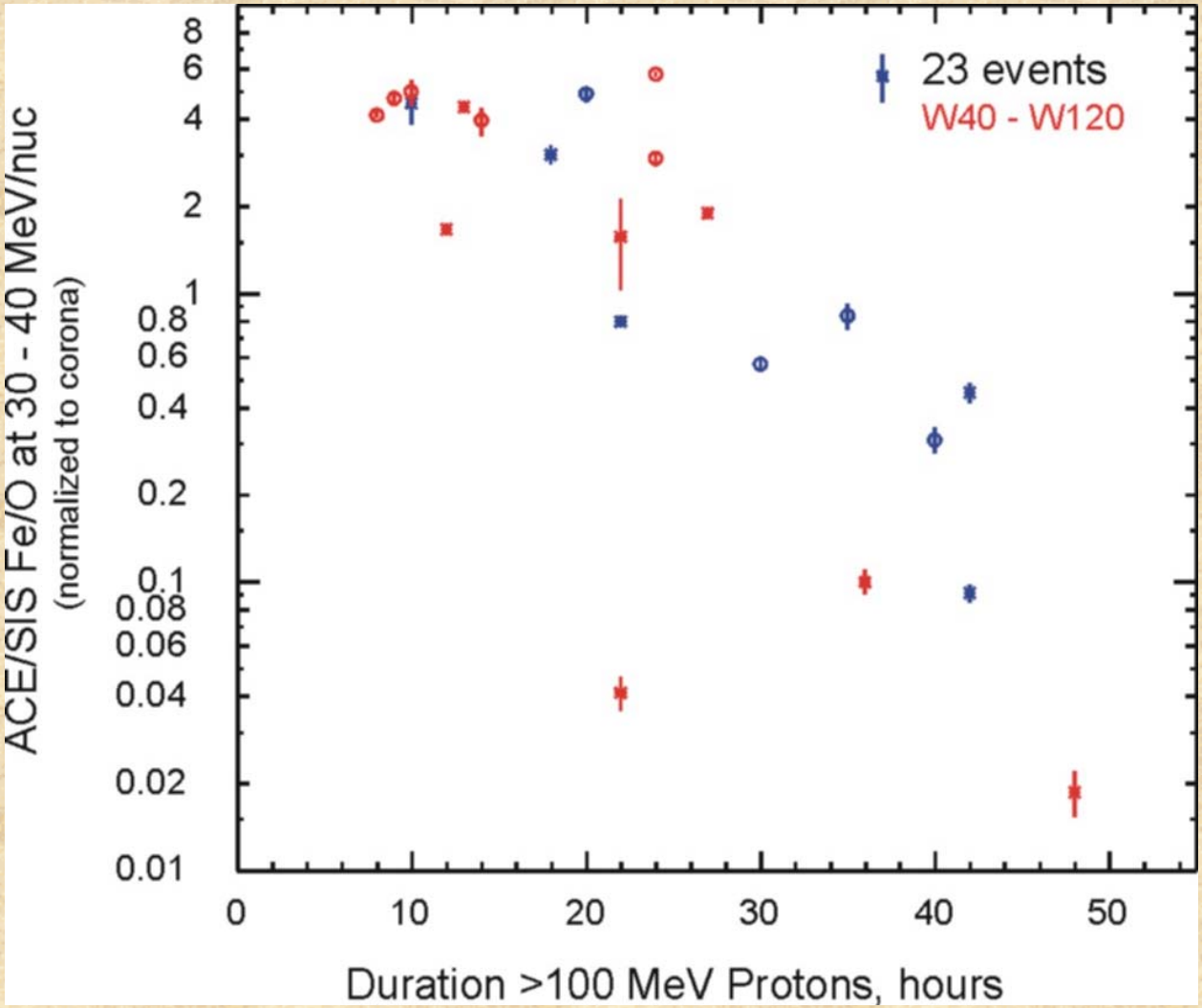
Fe/O at 30-40 MeV/nuc v. $\gamma_2 - \gamma_1$



For weak rollover (quasi - ⊥) $\gamma_2 - \gamma_1 \approx 0$

For strong rollover (quasi - ||) $\gamma_2 - \gamma_1 > 0$

Fe/O v. Duration



** Duration measured from onset to 10% of maximum in the decay phase.*

Summary

***Hypothesis*: Shock Geometry (quasi-parallel vs. quasi-perp) is a key factor in SEP variability at high energies:**

- ***Especially important near the Sun, where the shock is generally more prolific at making high-energy particles.***
- ***Enhanced Fe/O at high energies (because of flare suprathermals in the seed population) indicates a quasi-perpendicular shock.***
- ***Statistical study of SEP events supports this hypothesis:***

  Enhanced SEP Fe/O at high energies:

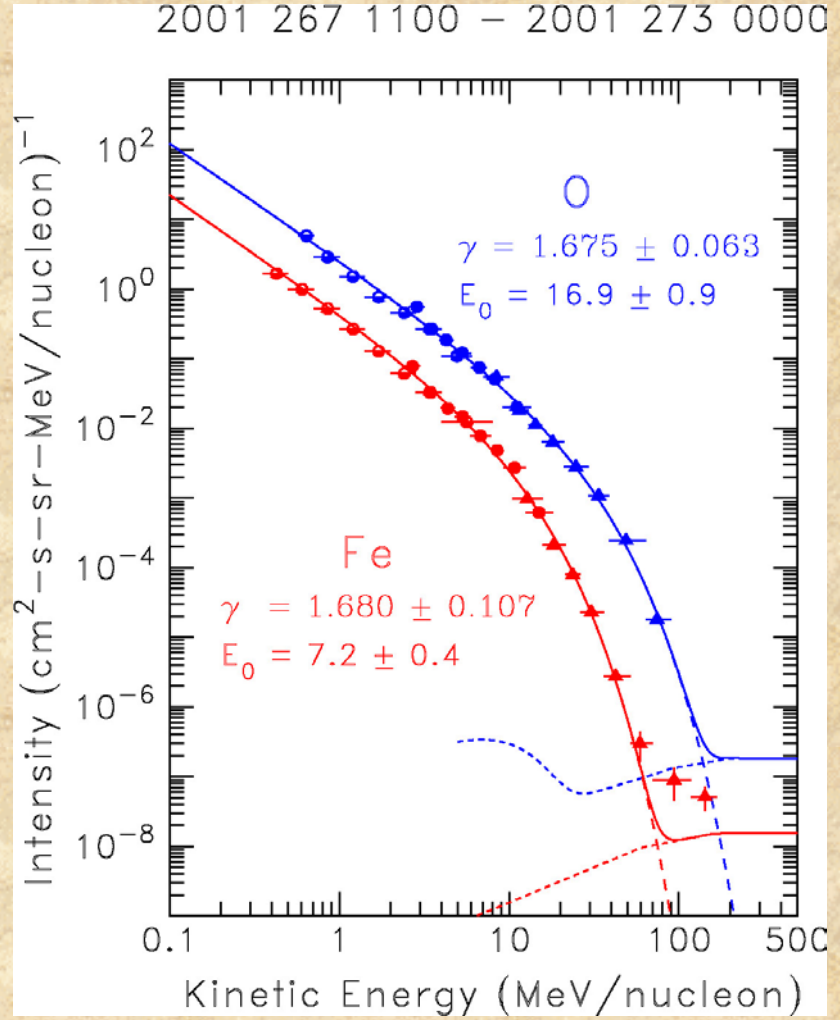
  - ✓ ***Anticorrelates with event-size***
  - ✓ ***Is observed in most GLEs***
  - ✓ ***Anticorrelates with spectral steepening***
  - ✓ ***Anticorrelates with >100 MeV proton duration***
- ***Preliminary ESP analysis also appears to support the hypothesis.***

Challenges for SHINE

- *Is the "quasi-parallel v. quasi-perp" hypothesis correct?*
  - *What are its weaknesses?*
  - *What further tests can we do?*
  - *Are there better hypotheses?*
- *How do the solar/IP characteristics of these two events differ?*
  - *Magnetic Field Observations & Modeling: Nariaki Nitta*
  - *RHESSI: David Alexander*
  - *EIT: Matt West*
  - *LASCO: Mike Andrews*
  - *Radio Emissions: Mike Reiner*
- *Can these observations confirm or refute the hypothesis?*
- *Do they suggest alternative hypotheses?*

Backups

Spectral Origin of Highly Suppressed Fe/O at High Energies: 24 Sept. 2001: 4th Largest Event of Cycle 23 (>30 MeV Fluence)



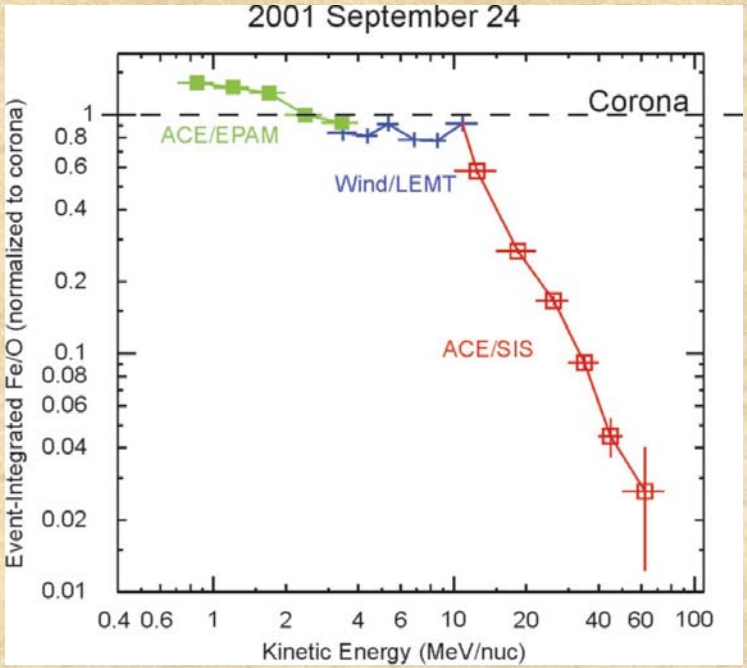
Shock-Accelerated Spectra:

(Ellison & Ramaty 1985)

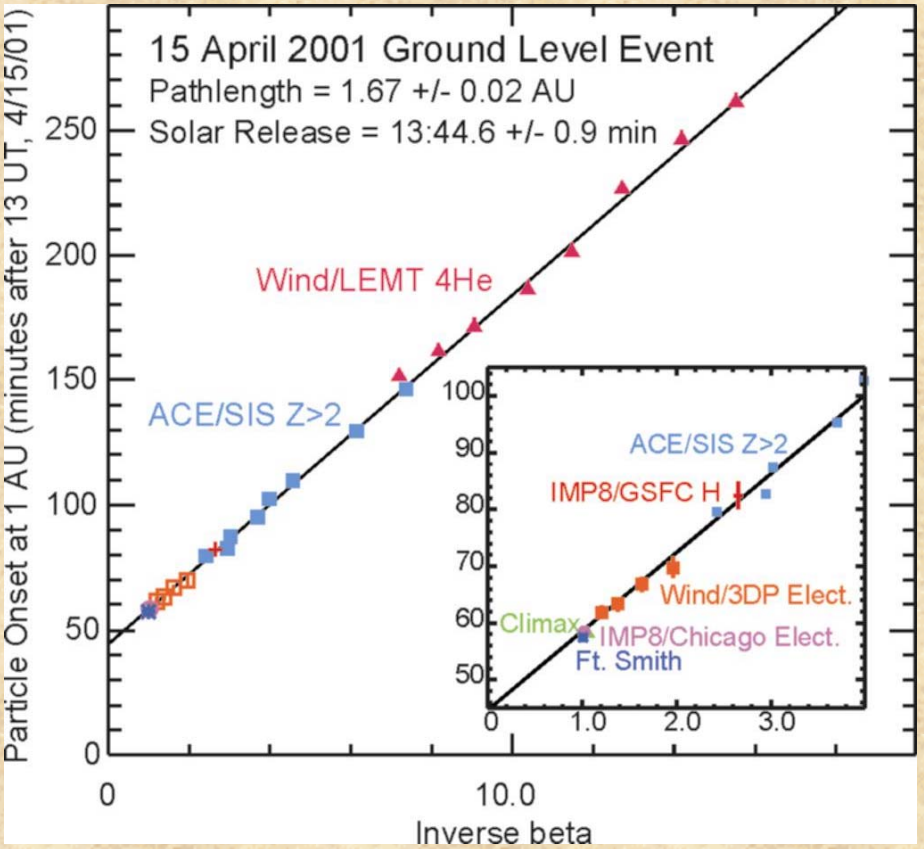
$$F_x(E) \sim E^{-\gamma} \exp(-E/E_{0x})$$

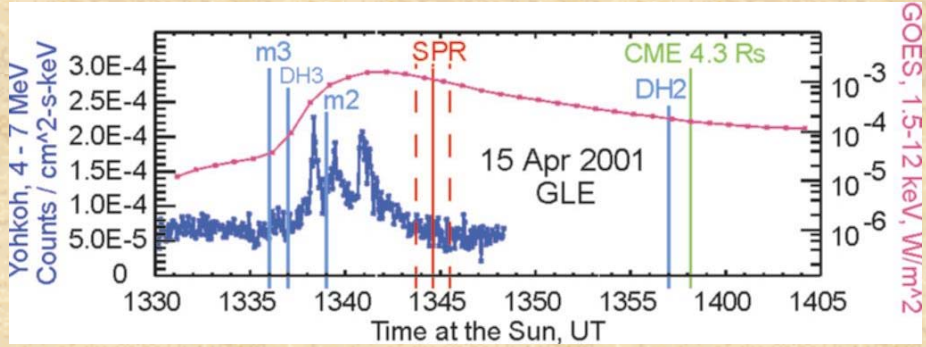
-- If $\lambda_{shock} \propto$ *Rigidity, then* $E_{0x} \propto Q_x/A_x$

-- In this event, $\langle Q_O \rangle \sim 7$ *and* $\langle Q_{Fe} \rangle \sim 11$



Timing: 15 April 2001 GLE



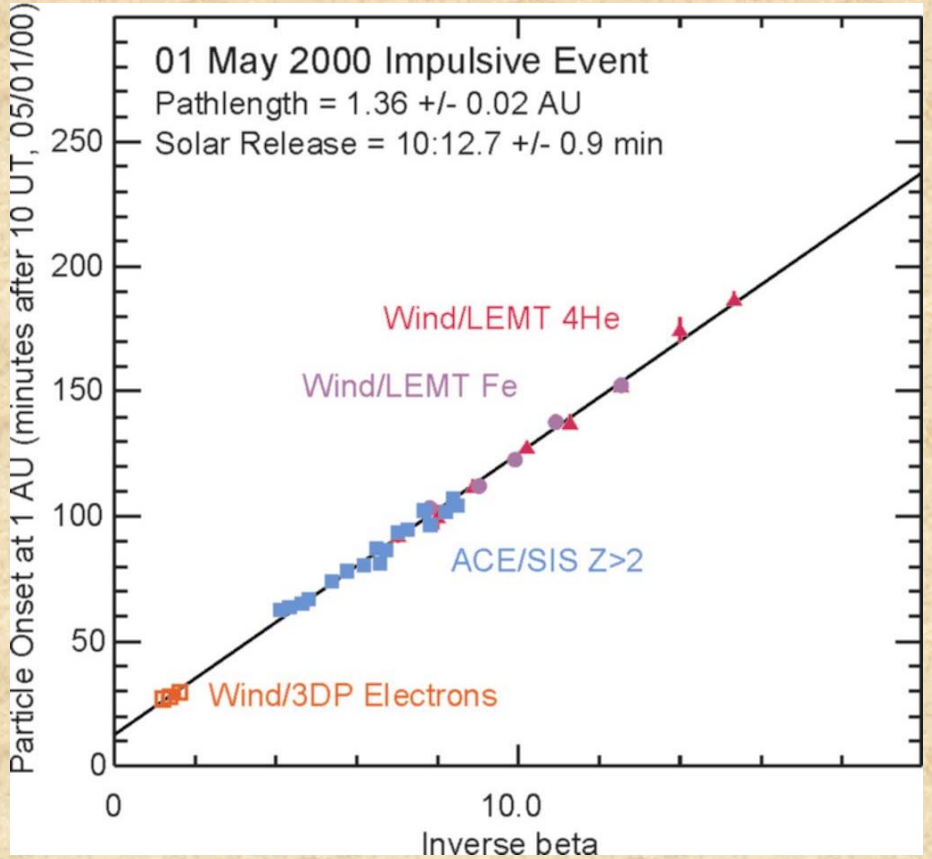


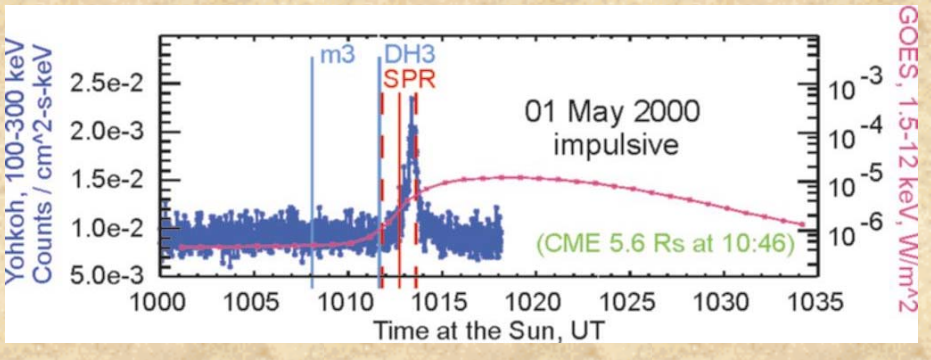
Particle release comes >5 minutes after the γ- ray emission:

- ***Inconsistent with flare origin***
- ***Consistent with shock origin***

Tylka et al., 2003, Proc. 28th ICRC, in press.

Timing: 1 May 2000 Impulsive Event





Particle release coincident with hard x-ray flare, lasting ~1 minute.

Tylka et al., 2003, Proc. 28th ICRC, in press.