

*Shock Geometry, Seed Populations, and the Origin of  
Energy-Dependent Fe/O in Large, Gradual Solar  
Energetic Particle Events*

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*SHINE WG3 Invited Talk*

*Big Sky, Montana*

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# Overview / Summary

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➤ *We present calculations that describe SEP spectral & compositional variability at high energies, including*

- *“Zoo” of energy-dependent Fe/O*
- *Associated morphologies in spectral shapes*
- *Energy-dependent  $\langle Q_{Fe} \rangle$*

➤ *The calculations make quantitative predictions about high-energy behavior that are consistent with the data.*

➤ *The calculations require two key ingredients:*

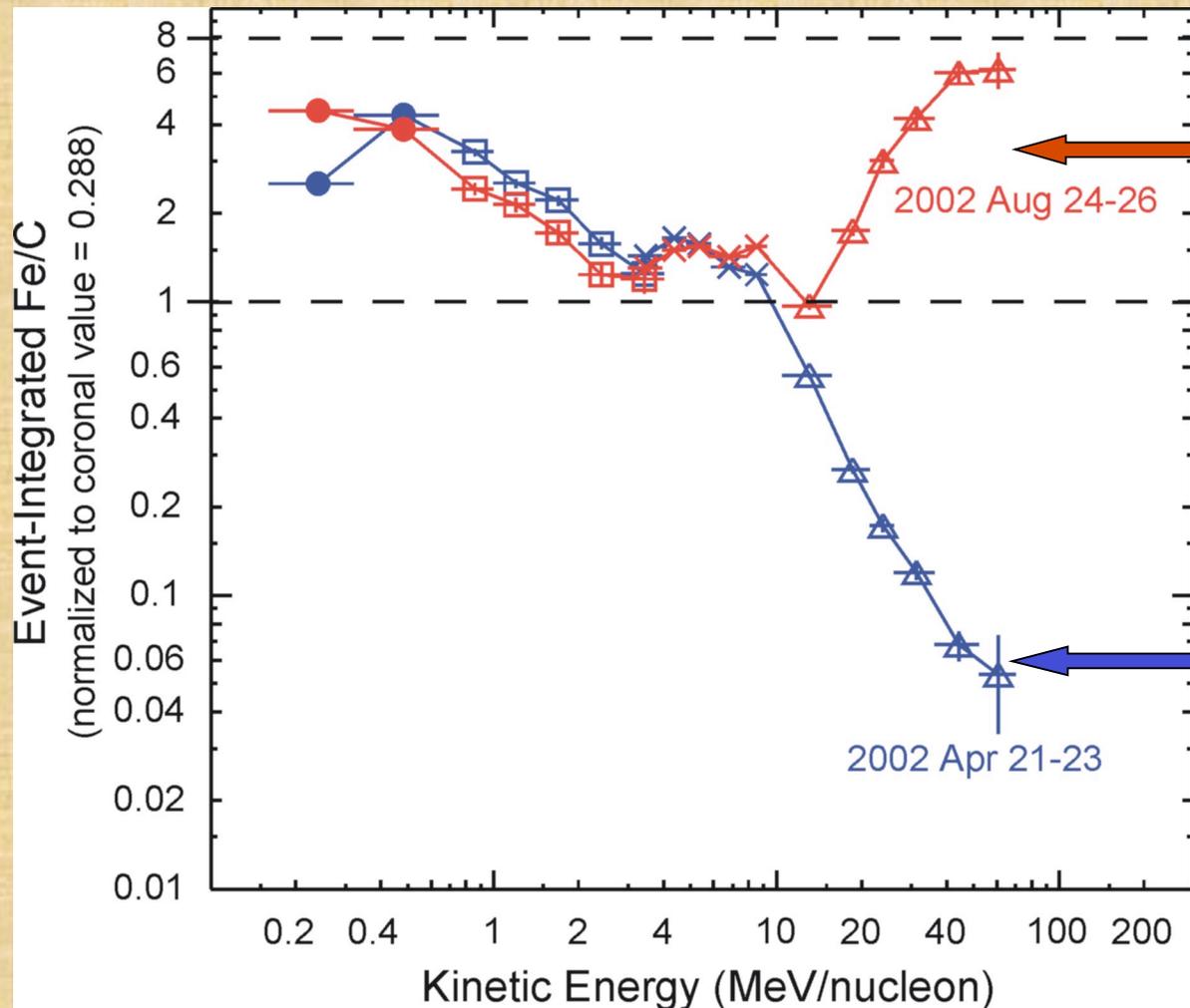
- *Variable seed population, including both SW & flare suprathermals*
- *Variable shock geometry (quasi-parallel & quasi-perp)*

➤ *The calculations are applicable to both SEPs and IP shocks at 1 AU.*

➤ *The calculations are simple, analytical, and heuristic:*

- *Certainly not the final word*
- *Useful for developing intuition about these complex problems.*
- *Encourage more rigorous investigations of these ideas.*

# *SHINE Campaign Events: 2002 April 21 & 2002 August 24*



*Tylka et al. (2004)  
suggested that:*

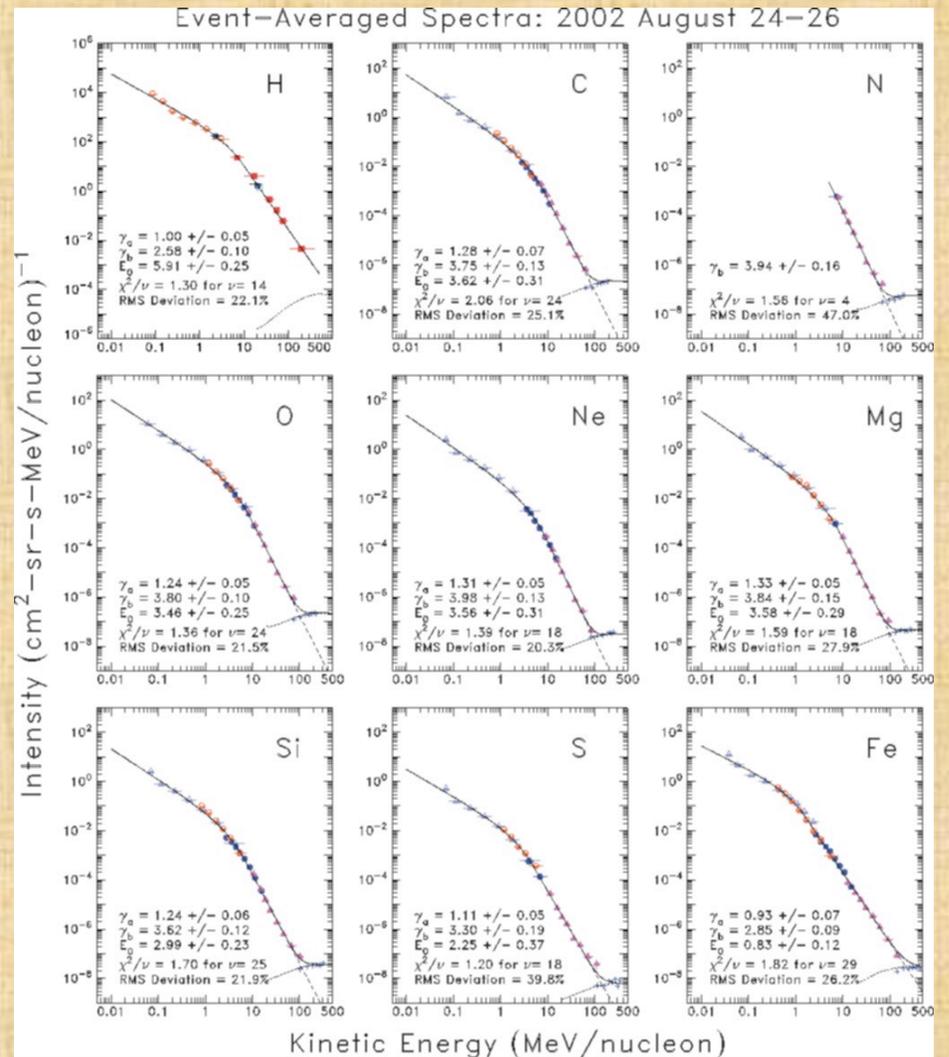
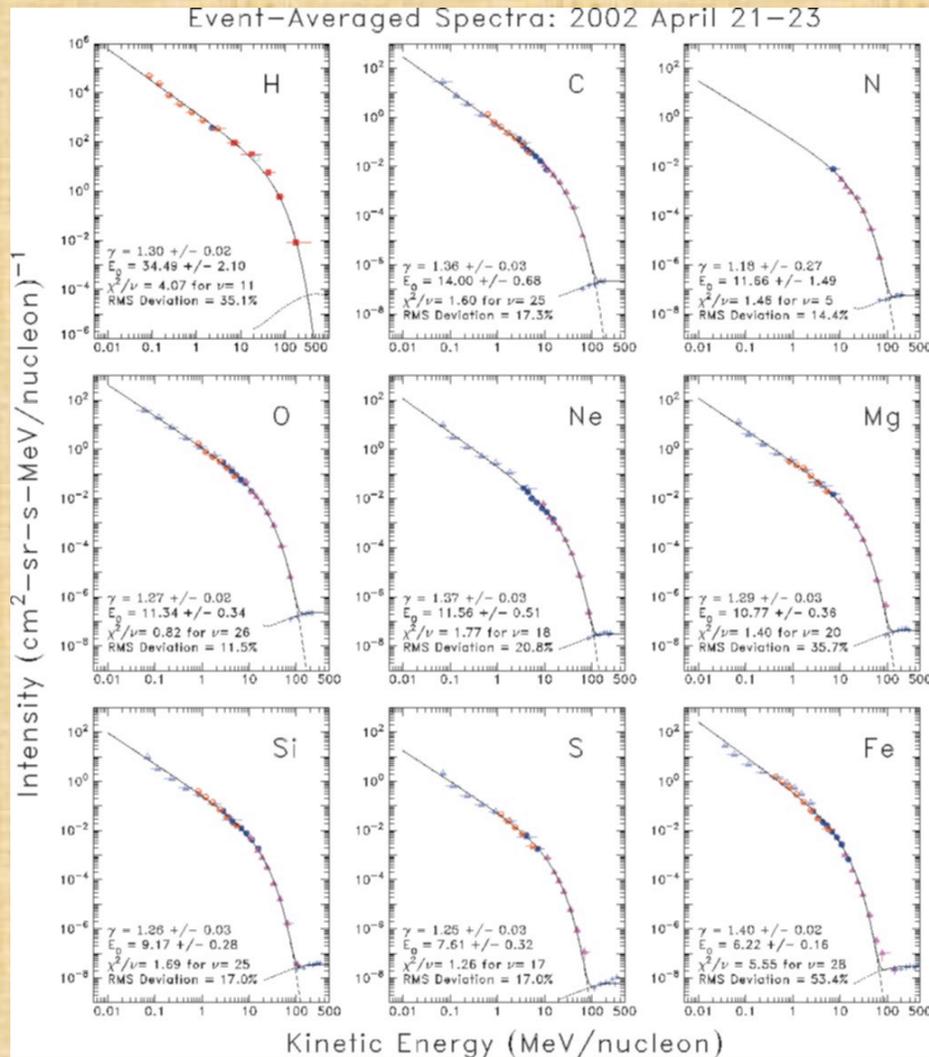
*Events like this involve  
a quasi-perpendicular  
shock operating on a  
seed population  
containing flare  
suprathermals.*

*Events like this are  
from a solar-wind seed  
population, accelerated  
by a shock, most likely  
quasi-parallel.*

*We now present analysis & modeling that support these interpretations.*

# Compare Spectra: 2002 April 21 & 2002 August 24

*We also need to account for these spectral differences!*



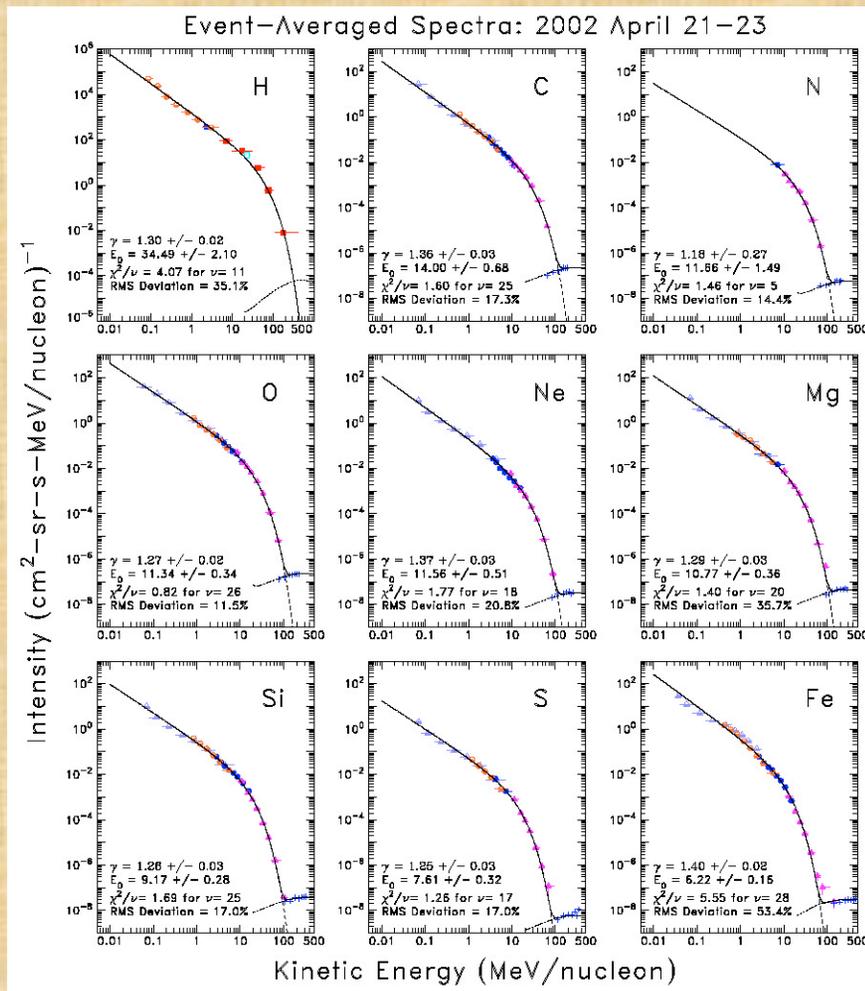
- Fits to  $F(E) \sim E^{-\gamma} \exp(-E/E_0)$
- At high energy, Fe softer than O

- Fits to “Band et al.” Functions:
- Double power-laws
- At high energy, Fe harder than O

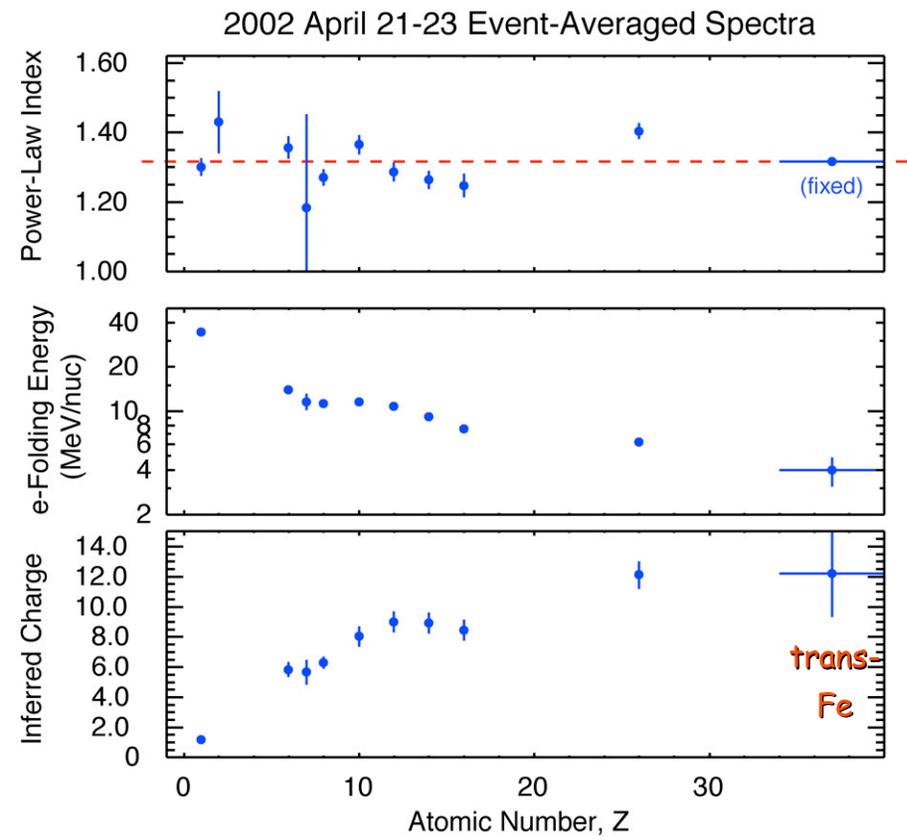
# Spectral Origin of Highly Suppressed Fe/O at High Energies

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

with  $E_{0x} \propto Q_x/A_x$   
(Ellison & Ramaty 1985)

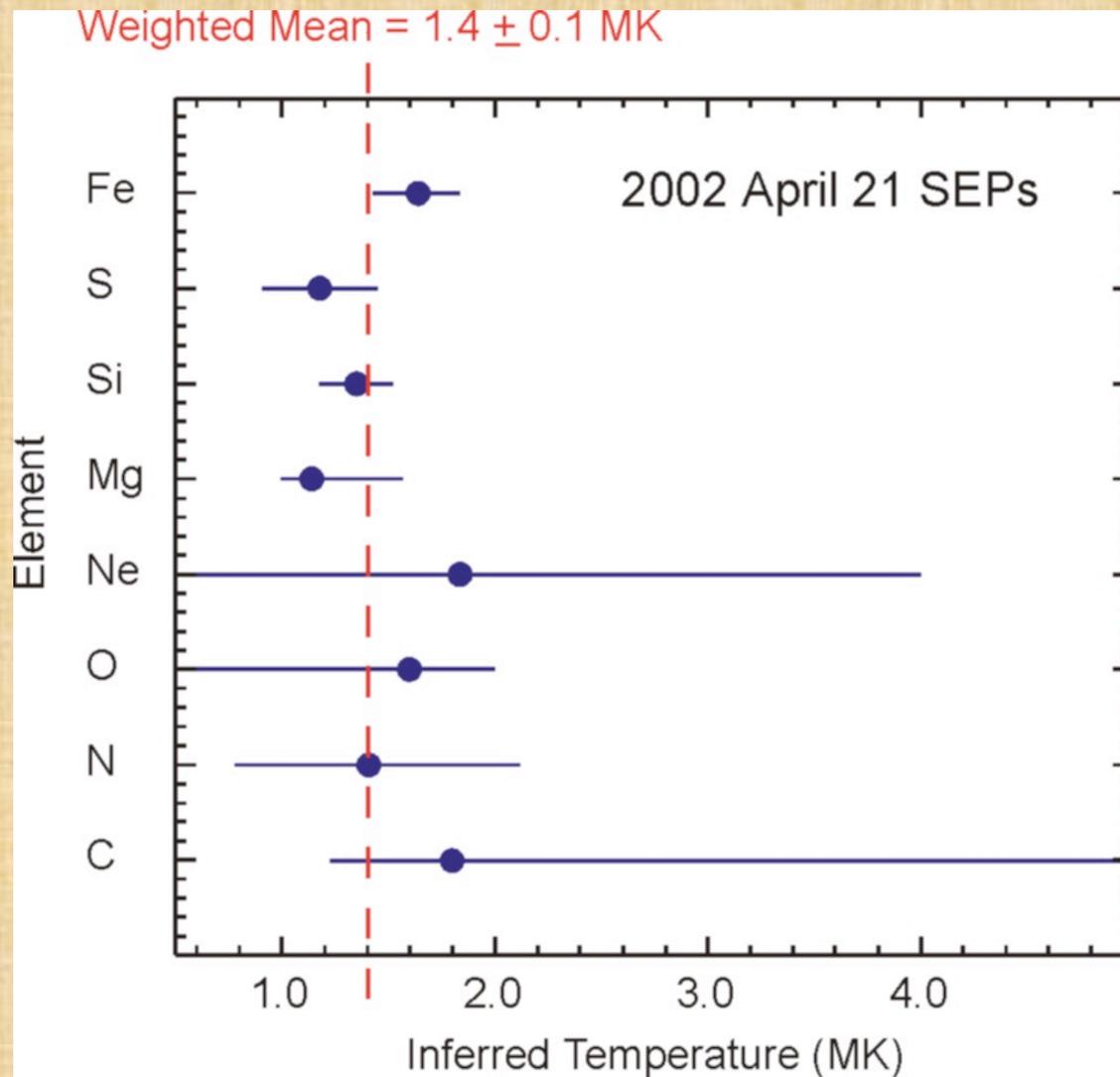


Data from 8 instruments, 5 satellites



- Oxygen charge state measured by SAMPEX
- Others inferred by scaling according to fitted  $E_0$

## *Solar-wind Seed Population in the 2002 April 21 Event*



*• Use theoretical calculations to determine source plasma temperatures from the mean ionic charge states*

*Arnaud & Rothenflug 1985  
Arnaud & Raymond 1992*

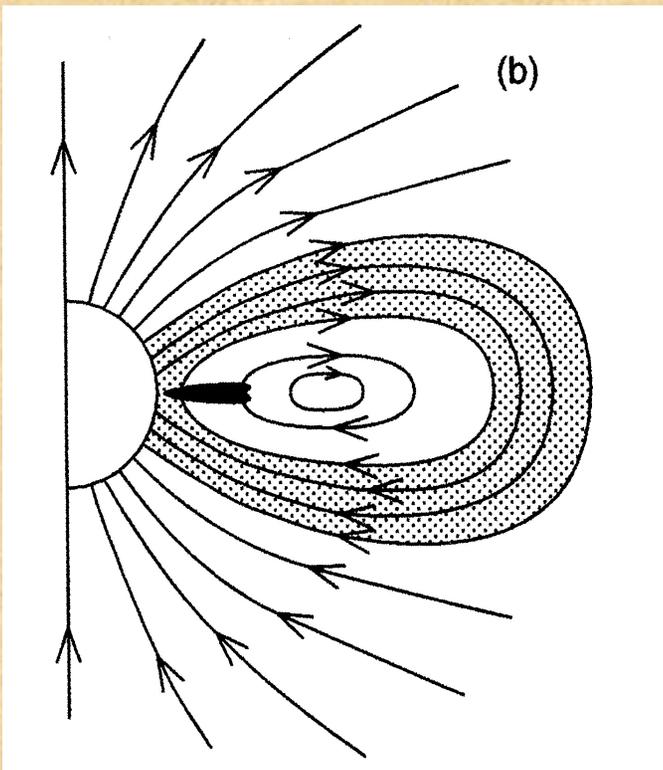
*• All species consistent with 1.4 MK, typical of the solar wind.*

*• These charge states are our justification for identifying solar wind (suprathermals) as the dominant seed population in this event.*

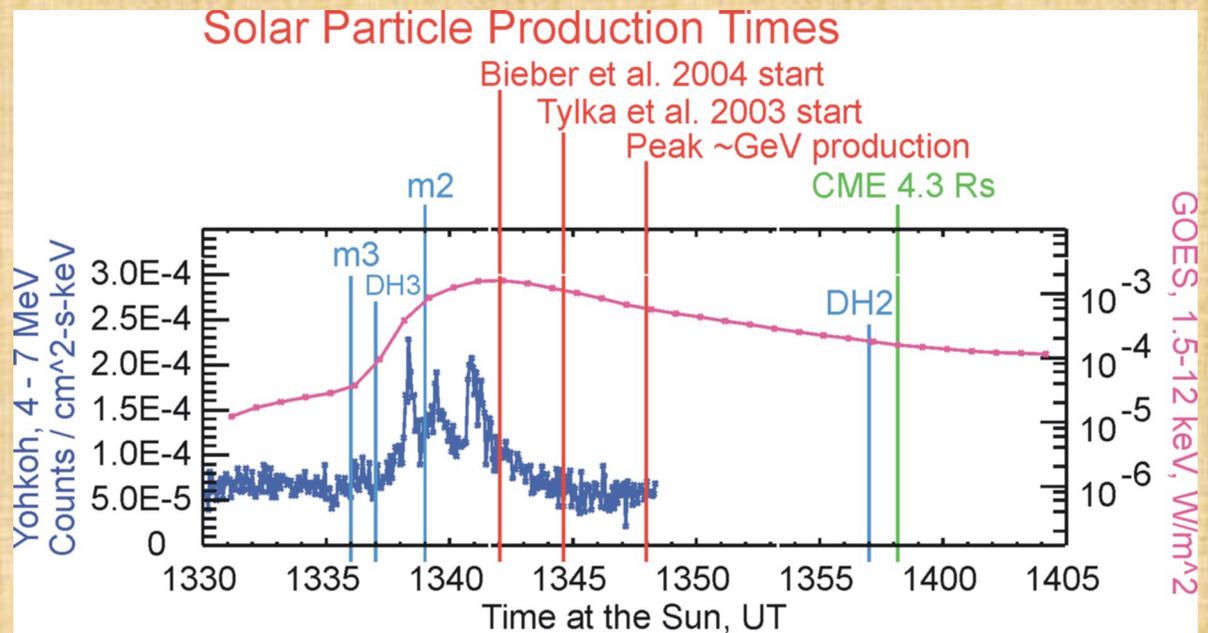
# Are there quasi-perp shocks near the Sun? Do they make SEPs?

-- almost surely!

**2001 April 15 GLE**  
(like 2002 August 24, but bigger)



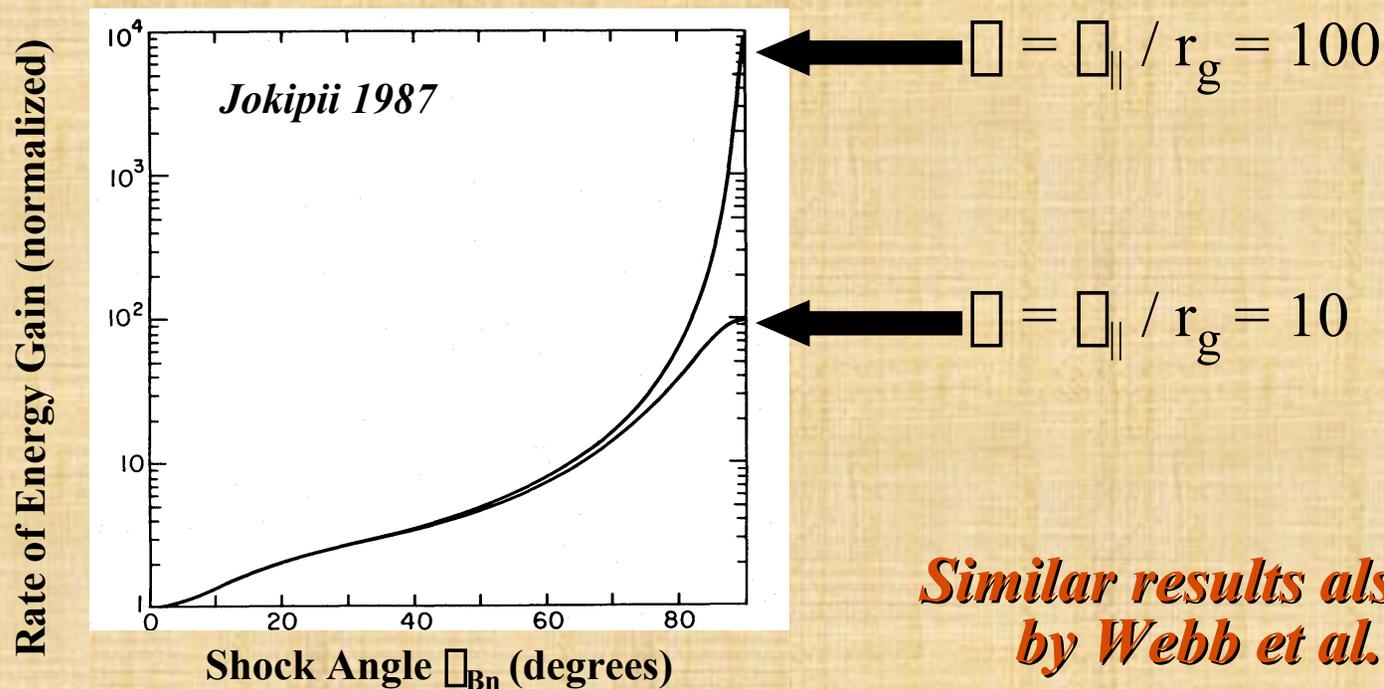
From B.C. Low, JGR 106, 25141, 2001



**SEP onsets & peak of ~GeV production  
occurred when the CME was at ~2 R<sub>S</sub>**

## *A Theoretical Insight about Quasi-Perp Shocks (A Suspicion?)*

*Rate of energy gain is higher at quasi-perpendicular shocks.*

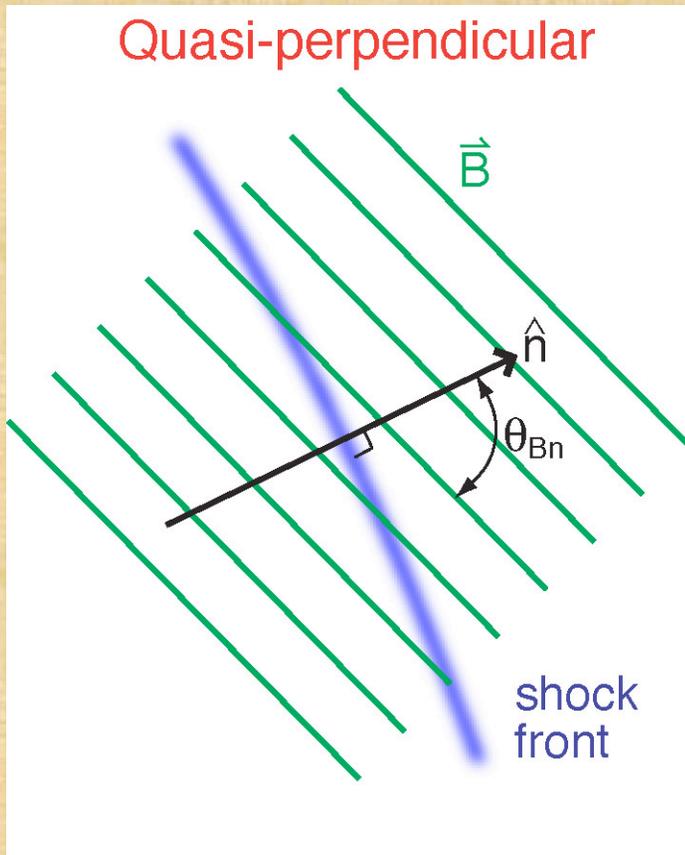


*Similar results also derived  
by Webb et al. (1995).*

**→** *If a shock takes on a range of  $\theta_{Bn}$  values, high-energies will be dominated by particles produced at  $\theta_{Bn} \sim 90^\circ$ .*

# Another Theoretical Insight about Quasi-Perp Shocks 9 (Another Suspicion??)

*Injection threshold is likely to be higher at quasi-perp shocks.*



Jokipii (1987): “[Our equations] become quite stringent constraints for low-energy particles, where  $v_{\text{particle}}$  may not be much larger than  $V_{\text{shock}}$ . These considerations lead to the expectation that low-energy injection occurs more readily when the shock is quasi-parallel. However, if the particle velocity is much higher than the shock velocity, very efficient diffusive acceleration can occur at perpendicular shocks.”

Webb et al. (1995):

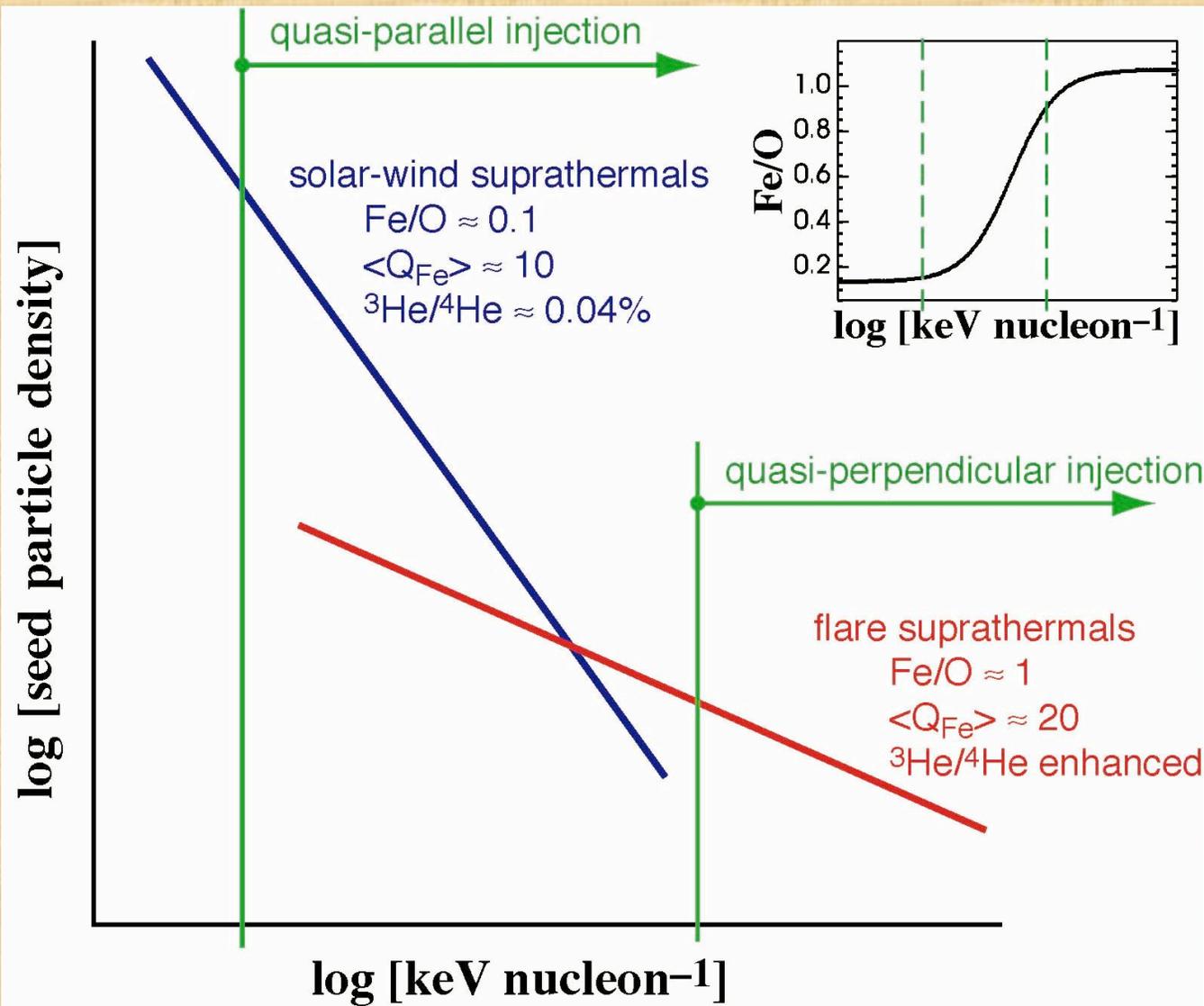
$$v_{\text{particle}} \gg 0.75 \cdot V_{\text{shock}} \quad \text{for } \theta_{\text{Bn}} = 0^\circ$$

$$v_{\text{particle}} \gg 0.75 \cdot (1 + \beta^2)^{1/2} V_{\text{shock}} \quad \text{for } \theta_{\text{Bn}} = 90^\circ$$

Webb et al. (1995) used  $\beta \approx 10$ .

**→ A quasi-perp shock preferentially ‘reveals’ the characteristics of the higher-speed seed particles.**

## How can we get $Fe/O$ increasing with energy?



• *These two components naturally lead to energy-dependent composition in the seed population.*

• *Consider varying  $\square_{Bn}$ , including both quasi-perp and quasi-parallel.*

# Effects of Averaging over a Varying Shock Angle

M.A. Lee & A.J. Tylka

$$F_X(E, \theta_{Bn}) = C_X E^{-\gamma} \exp(-E/E_{0X})$$

*Power-law index the same for all species.*

where  $E_{0X} = E_0 [Q_X/A_X] [(\sec\theta_{Bn})^{2/(2\gamma-1)}] \equiv \check{E}_{0X} [(\sec\theta_{Bn})^{2/(2\gamma-1)}]$

*Species "X" and  $\theta_{Bn}$  dependence reside in rollover,  $E_{0X}$*

Let  $\mu = \cos\theta_{Bn}$ . Average the shock-spectrum over  $0 \leq \mu \leq 1$ .

- The flare component is accessible to the shock at all  $\theta_{Bn}$  values.
- For the solar-wind component, introduce a heuristic weighting factor of  $\mu$ .
  - Solar-wind component makes no contribution at a perpendicular shock.

$$F_{x,flare}(E) = C_{x,flare} E^{-\gamma} \int_0^1 \exp(-E\mu^{2/(2\gamma-1)}/\check{E}_{0X,flare}) d\mu / \int_0^1 d\mu$$

$$F_{x,sw}(E) = C_{x,sw} E^{-\gamma} \int_0^1 \mu \exp(-E\mu^{2/(2\gamma-1)}/\check{E}_{0X,sw}) d\mu / \int_0^1 \mu d\mu$$

*SW component has steeper spectrum by  $E^{-1}$*

To get closed-form results, consider  $\gamma = 1.5$  :

$$F_{x,flare}(E) = C_{x,flare} E^{-\gamma} (\check{E}_{0X,flare}/E) [1 - \exp(-E/\check{E}_{0X,flare})]$$

$$F_{x,sw}(E) = 2C_{x,sw} E^{-\gamma} (\check{E}_{0X,sw}/E)^2 [1 - (1+E/\check{E}_{0X,sw})\exp(-E/\check{E}_{0X,sw})]$$

*Flare & SW components have different Q/A dependence*

Other parameters: Nominal flare & coronal composition:

Flare Fe/O = 1 and coronal Fe/O = 0.134

Observed flare & SW charge-state distributions:

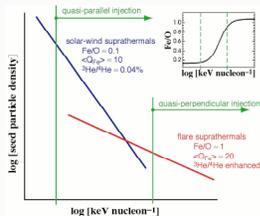
Flare:  $\langle Q_{Fe} \rangle = 17, \langle Q_O \rangle = 8$ ; SW:  $\langle Q_{Fe} \rangle = 10, \langle Q_O \rangle = 6$

Relative size of flare- and SW-seed components:

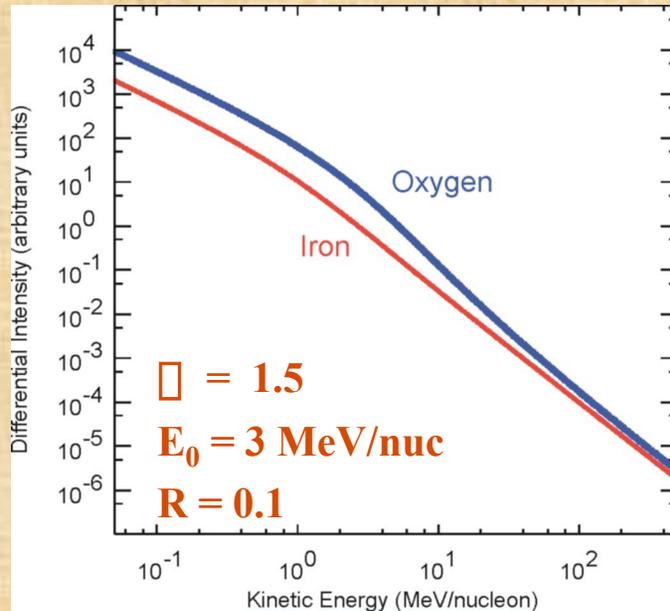
$$R = (C_{oxygen, flare}) / (C_{oxygen, SW})$$

*Parameters :*

$E_0, R$

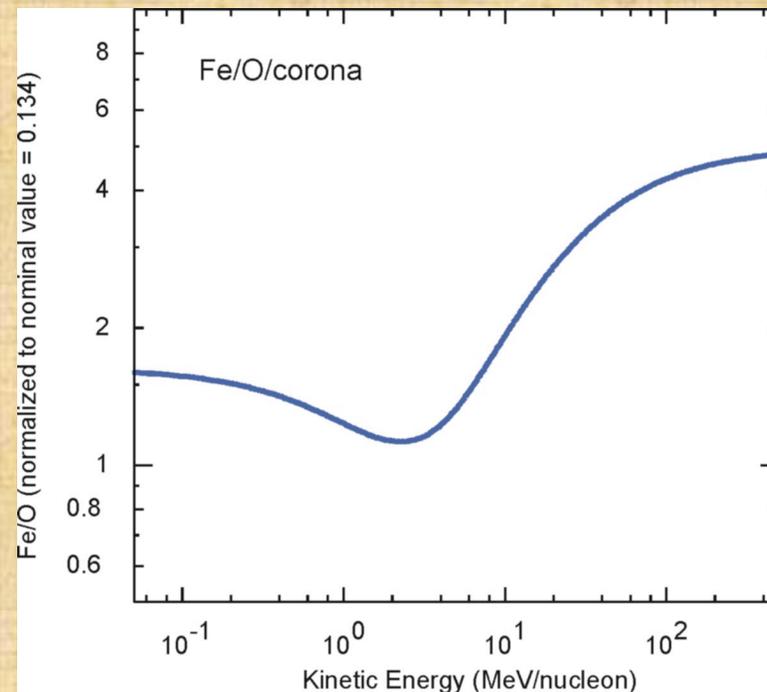
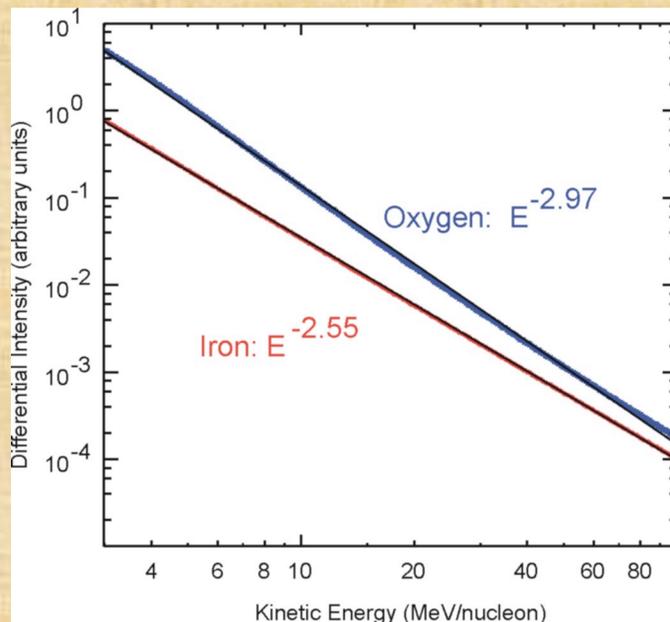


# Effects of Averaging over a Varying Shock Angle



*This simple, heuristic calculation reproduces significant features of the data:*

- *Roughly double power-law spectra*
- *(Nearly) power-laws at high energy, with Fe harder than O*
- *Fe/O increasing with energy*

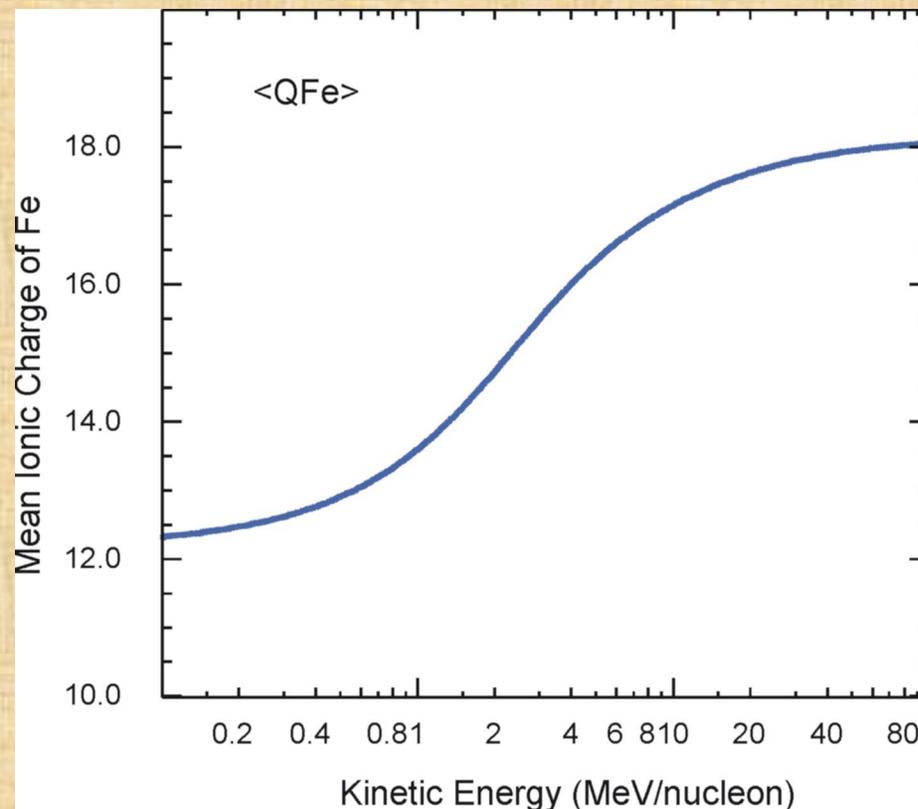
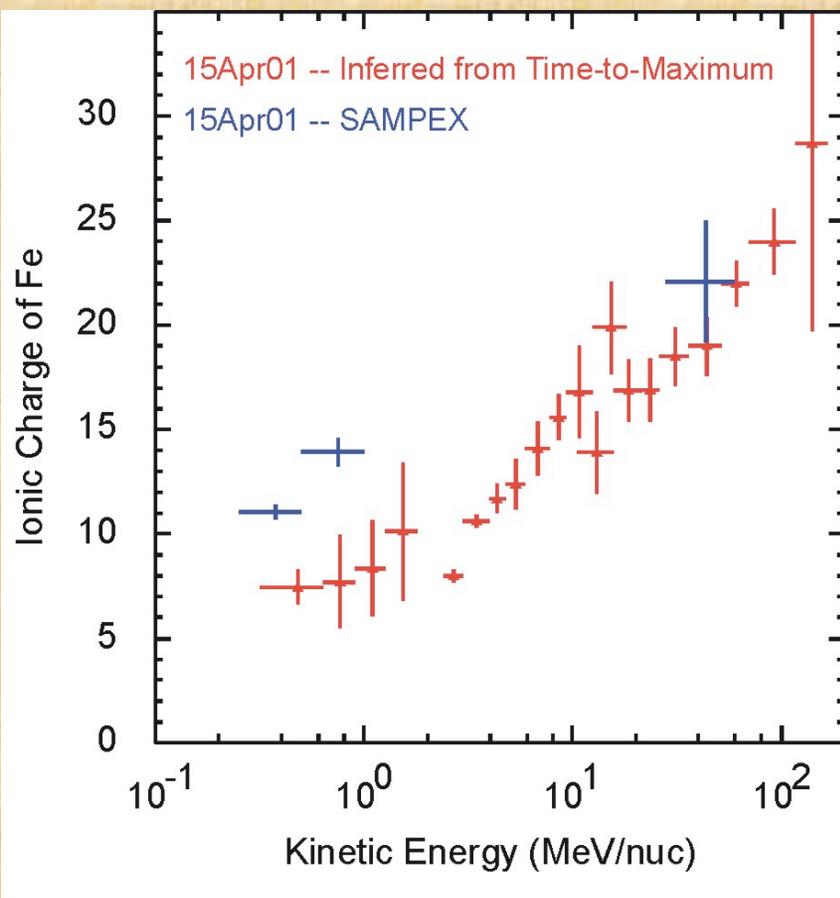


# Energy-Dependent Fe Charge States

**2001 April 15 GLE**

**(like 2002 August 24, but bigger)**

**From these calculations**



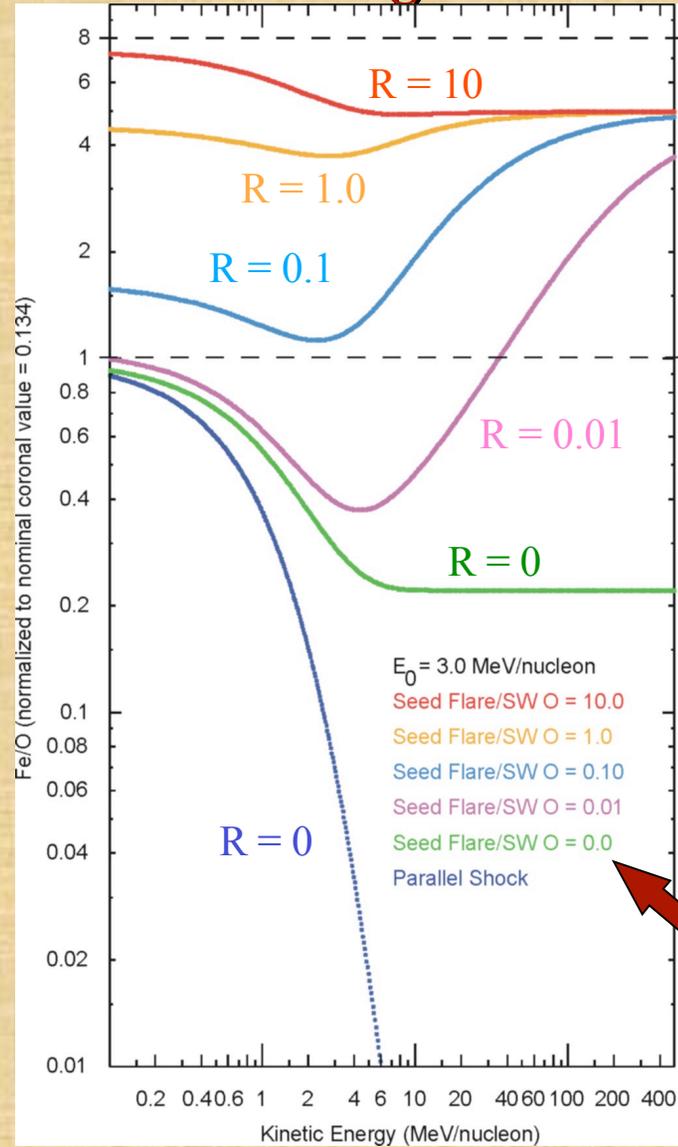
**SAMPEX: Labrador et al. 2003**

**Mazur, private communication.**

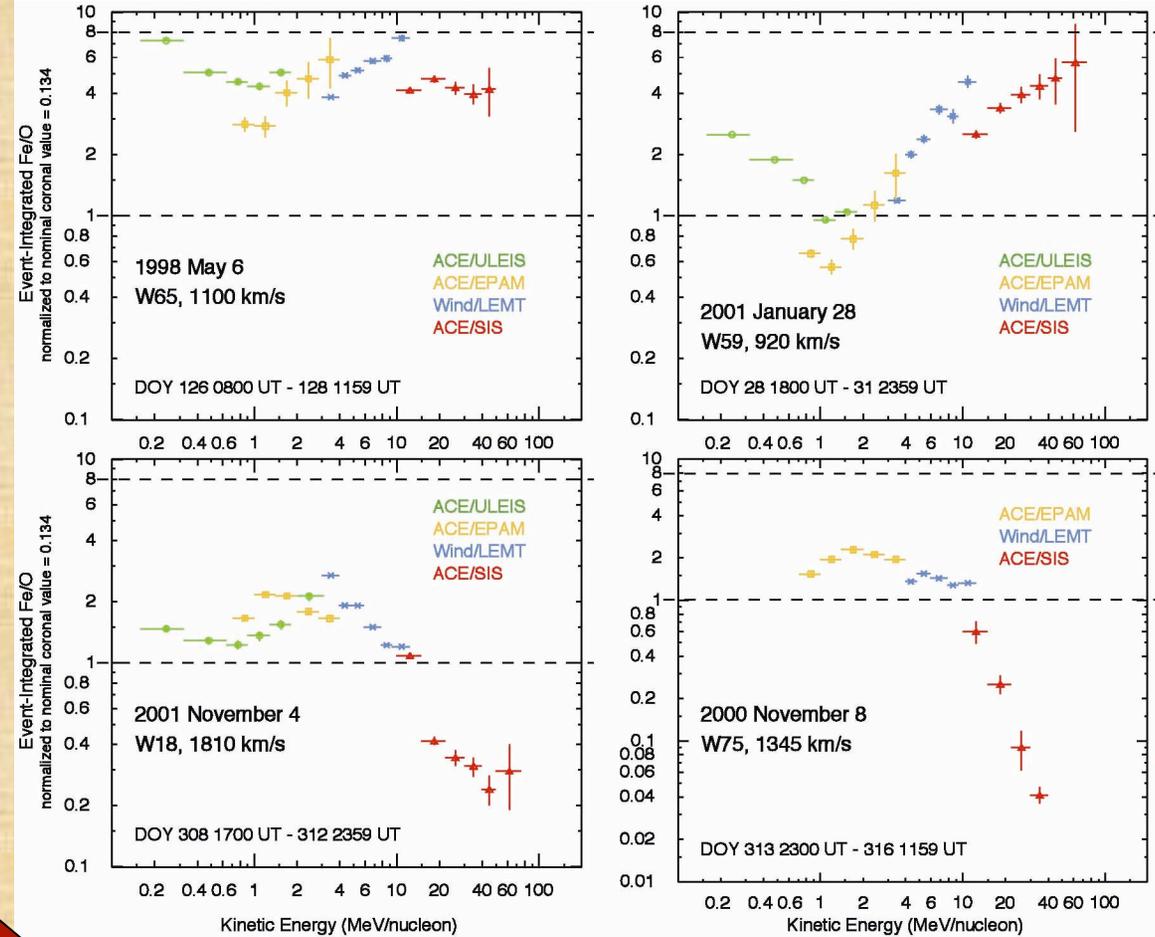
**TTM: Dietrich & Tylka 2003**

# The "Zoo" of Fe/O vs. Energy

## Modeling



## Data

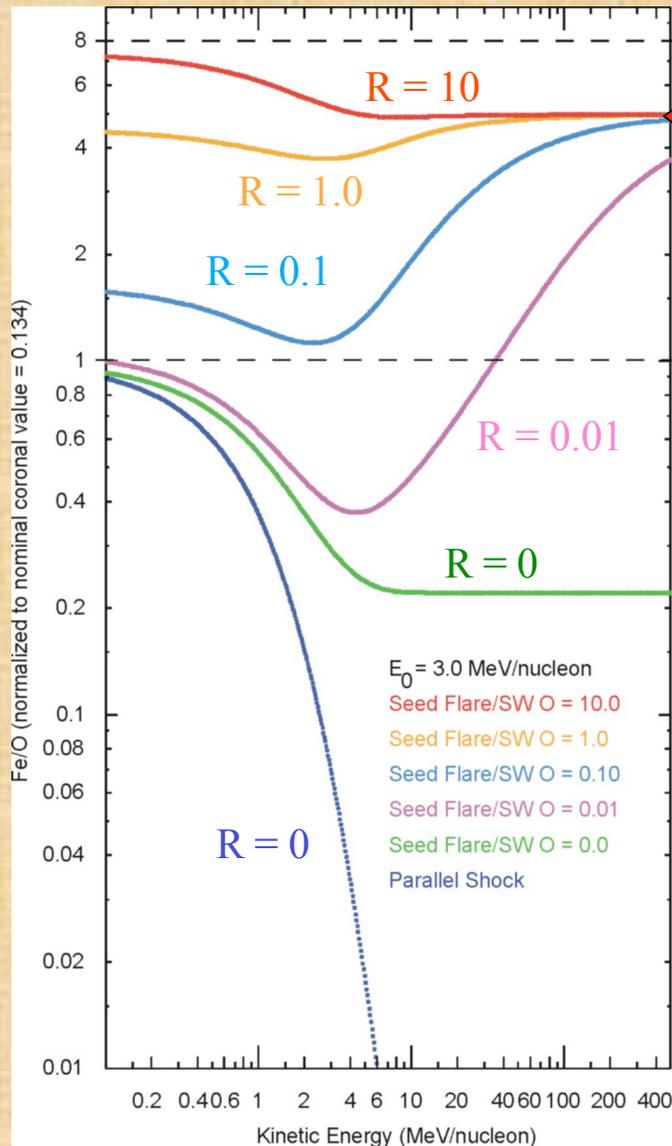


vary size of flare component in seed population:

$$R = (\text{Seed Pop Flare O}) / (\text{Seed Pop SW O})$$

# Enhanced Fe/O Asymptote at High Energies

## Modeling



Regardless of the size of the flare-component in the seed population, re-acceleration by a quasi-perp shock give an asymptotic Fe/O value at high-energies:

$$\begin{aligned}
 (Fe/O)_{shock} &= (Fe/O)_{flare} \cdot [Q/A]_{Fe, Flare} / [Q/A]_{O, Flare} \\
 &= 8 \cdot (17/56) / (8/16) \\
 &= 4.8
 \end{aligned}$$

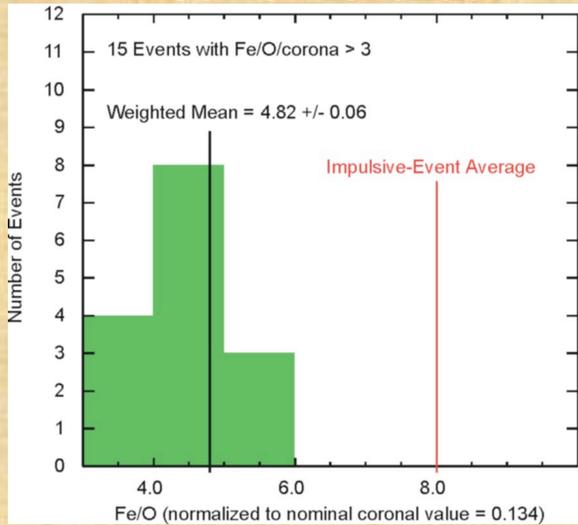
using average values for impulsive events:

$$(Fe/O)_{flare} = 8x \quad \langle Q_{Fe} \rangle = 17 \quad \langle Q_O \rangle = 8$$

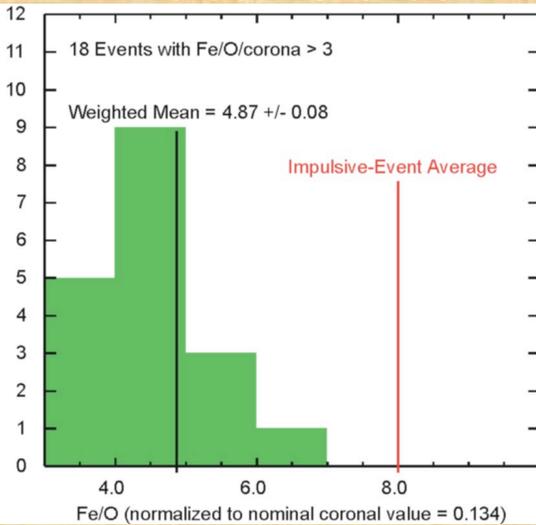
Do we see this in the data?

# Average Fe/O Enhancement at High Energies

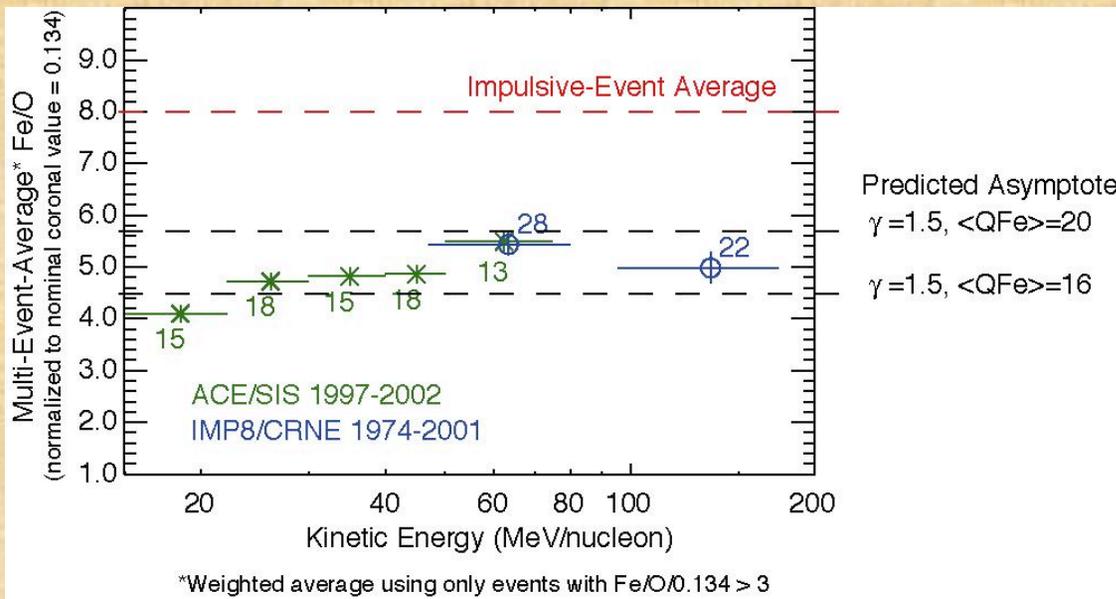
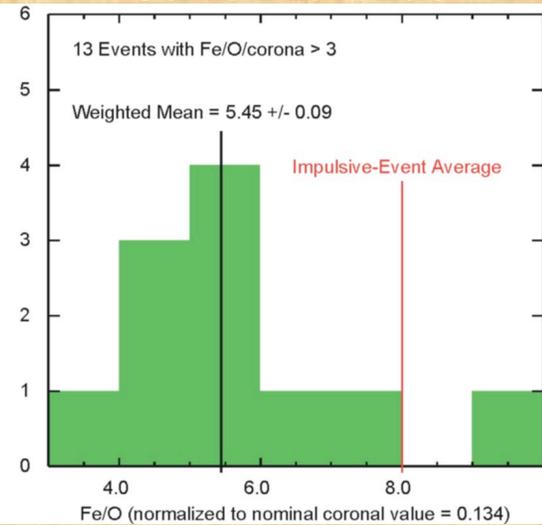
30-40 MeV/nuc



40-50 MeV/nuc



50-75 MeV/nuc

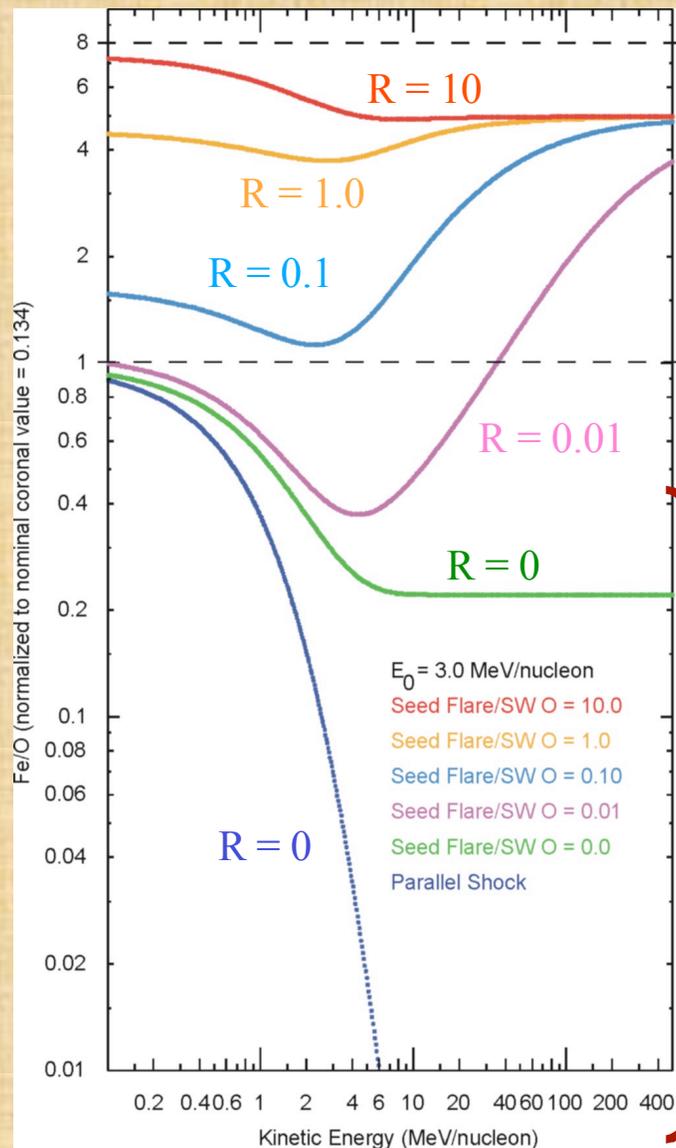


*Based on average characteristics of flare ions, we've made a prediction for the average value of enhanced Fe/O at high-energies in gradual events.*

Numbers on the datapoints tell how many events were used in the average.

# Fe/O at High Energies

## Fe/O (normalized) vs. Energy



*These two calculations have no flare particles in the seed population.*

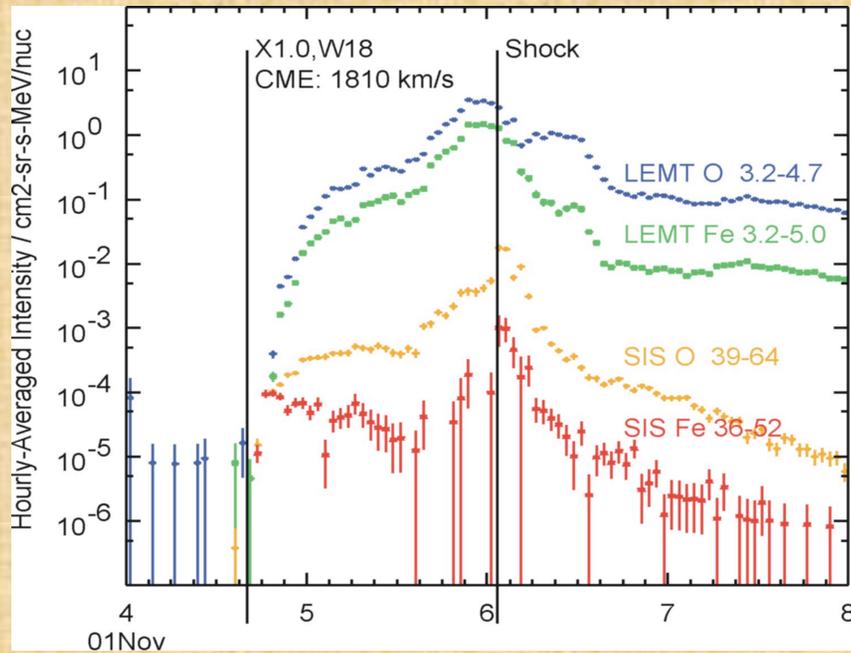
*In the quasi-perp case, Fe/O plateaus at:*

$$\begin{aligned}
 (Fe/O)_{shock} &= [Q/A]^2_{Fe, SW} / [Q/A]^2_{O, SW} \\
 &= (10/56)^2 / (6/16)^2 \\
 &= 0.22 \times \text{nominal value}
 \end{aligned}$$

*(In the parallel case, Fe/O drops precipitously.)*

*Do we see this in the data?*

# 2001 November 06\*: A Strong Quasi-Perp Shock at 1 AU<sup>18</sup>



*High-energy particle production dominated by shock's arrival at 1 AU.*

*This is a quasi-perp shock acting on a solar-wind-like seed population:*

*ACE (Q. Hu):  $\square_{Bn} = 82 \pm 3^\circ$*

*SAMPEX (A. Labrador):*

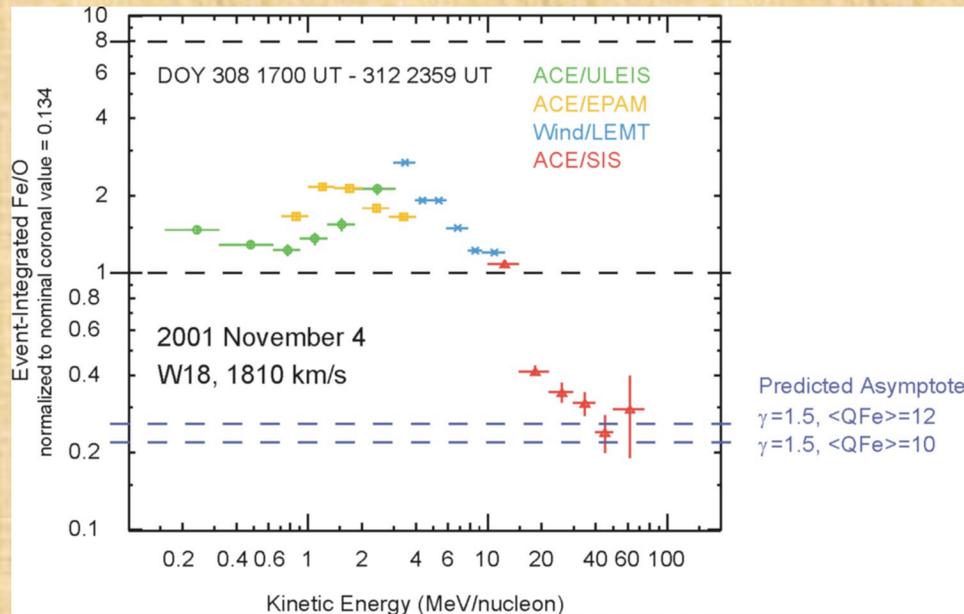
*Above ~25 MeV/nuc:*

*$\langle Q_{Fe} \rangle = 12 \pm 1$*

*$\langle Q_O \rangle = 6.6 \pm 0.3$*

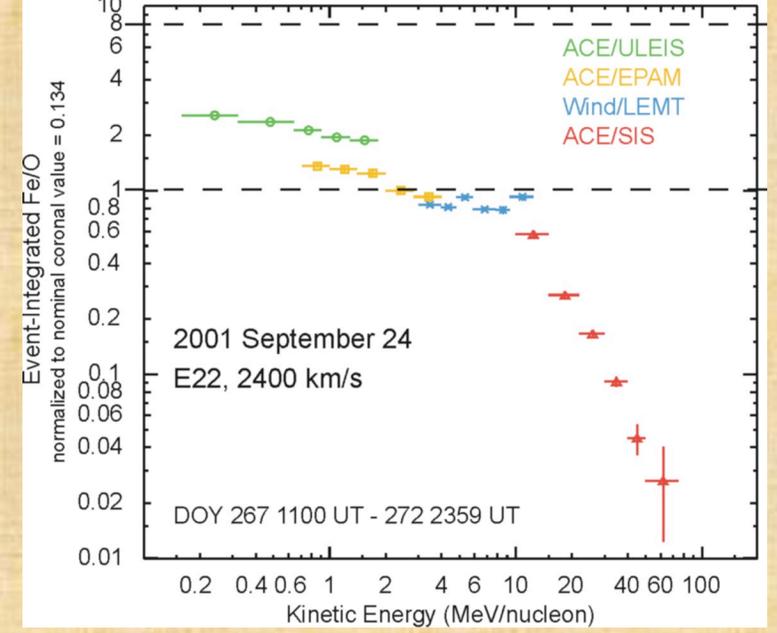
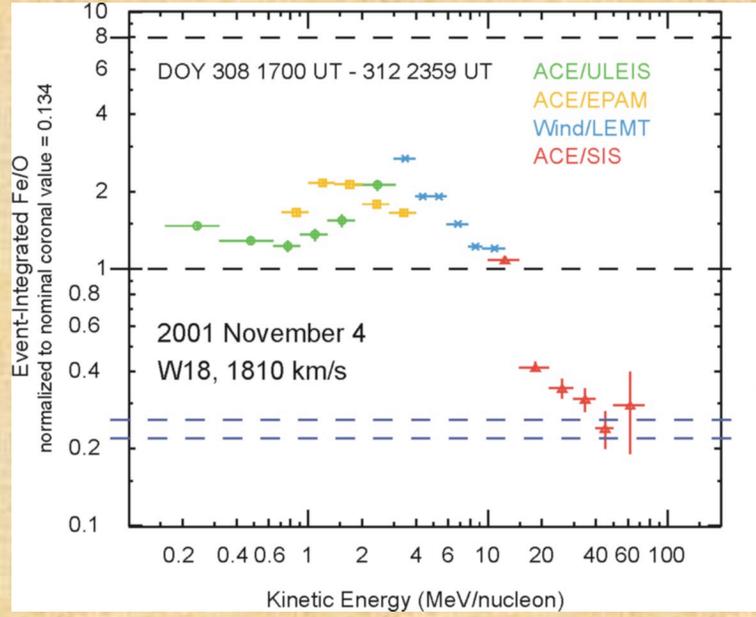
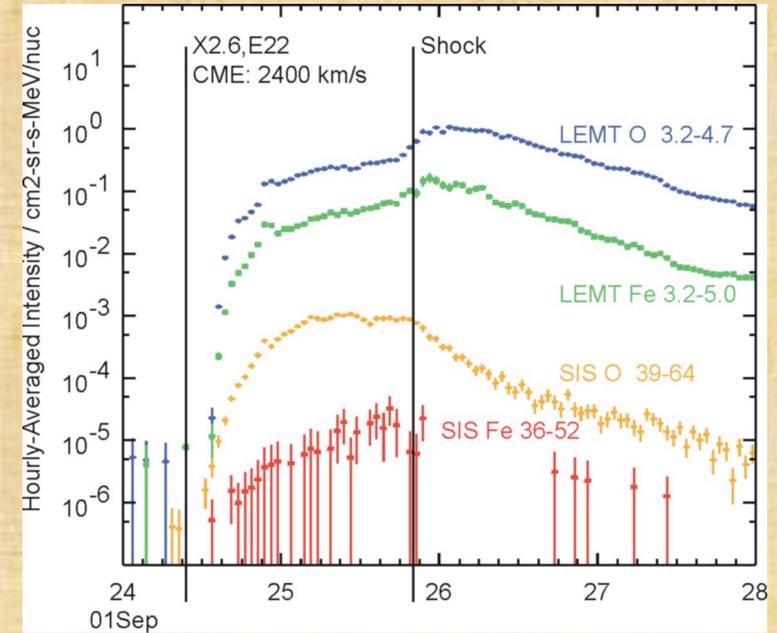
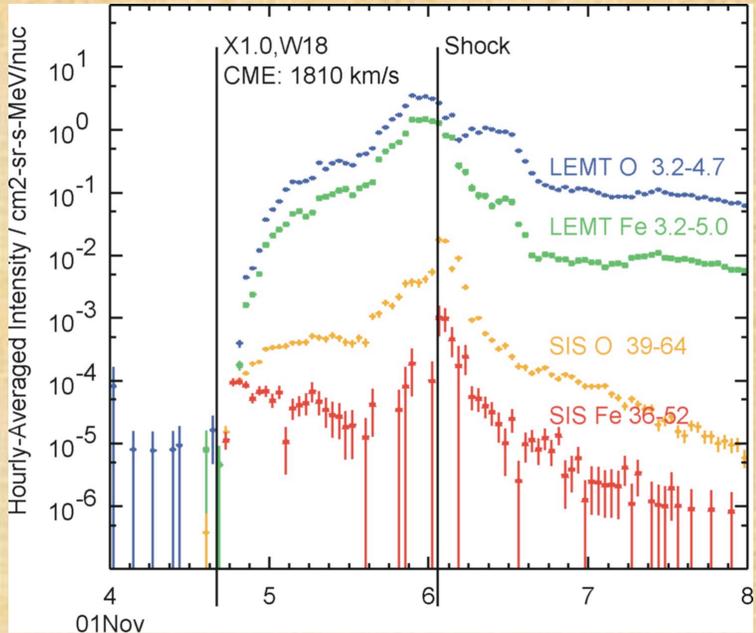
*The high-energy Fe/O "bottoms out" at 0.2 x nominal.*

*-- just as predicted for this case.*

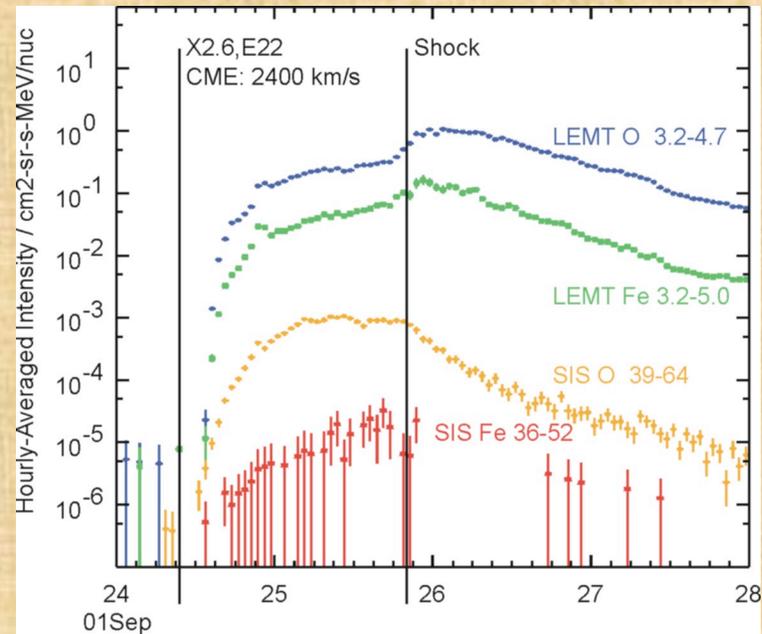
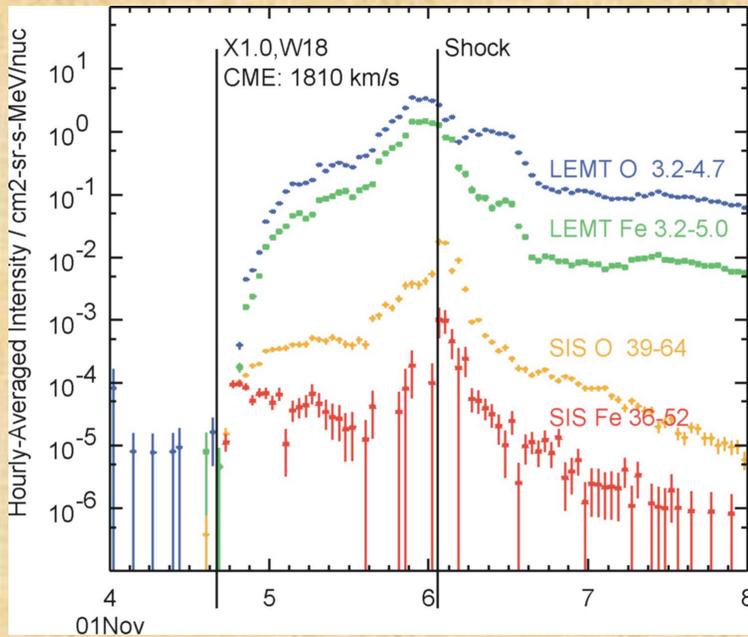


*\*Event launched on 2001 November 4.*

# Compare: 2001 November 04 & 2001 September 24



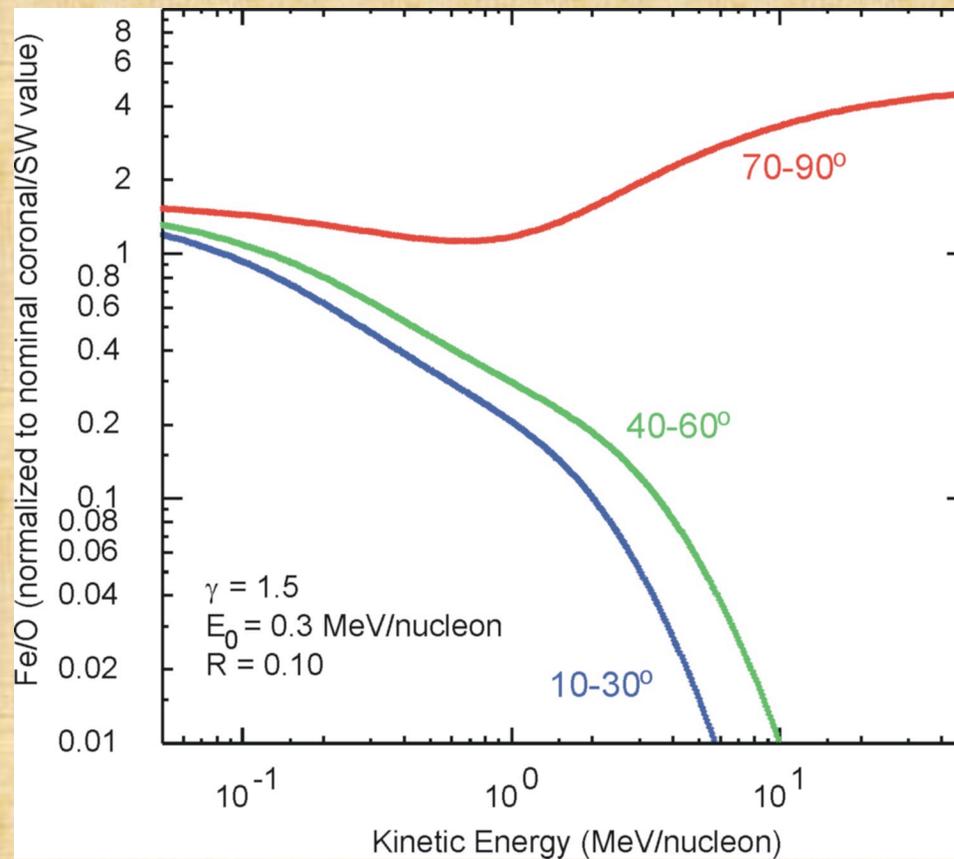
# Compare: 2001 November 04 & 2001 September 24



<i>CME Speed</i>	<i>1810 km/s</i>	<i>2402 km/s</i>
<i>Source Longitude</i>	<i>W18</i>	<i>E23</i>
<i>Sun-Earth Transit Time</i>	<i>33.0 hours</i>	<i>33.5 hours</i>
<i>Flare</i>	<i>X1.0</i>	<i>X2.6</i>
<i>SAMPEX/MAST <math>\langle Q_{Fe} \rangle</math></i>	<i><math>12 \pm 1</math></i>	<i><math>10 \pm 1</math></i>
<i><math>\langle Q_O \rangle</math></i>	<i><math>6.6 \pm 0.3</math></i>	<i><math>6.3 \pm 0.4</math></i>
<i>Fe/O/0.134 @ ~50 MeV/nuc</i>	<i><math>0.24 \pm 0.04</math></i>	<i><math>0.026 \pm 0.014</math></i>
<i>ACE <math>\square_{Bn}</math> (Q. Hu)</i>	<i><math>82 \pm 3^\circ</math></i>	<i><math>66 \pm 18^\circ</math></i>

Aw shucks!

## *Application to Traveling IP Shock Events near 1 AU*



*In carrying out these calculations, it is not necessary to average over the full range  $0 \leq \theta_{Bn} \leq 90^\circ$ .*

*The results may also be applicable to traveling IP shock events (Desai et al.).*

*$\theta_{Bn}$  naturally takes on a range of values as the magnetic connection sweeps across the non-spherical front of an approaching shock.*

# Summary

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## ➤ *Outline of the calculation:*

➤ *Simple functional form for the shock spectra:*  $F_x(E) \sim E^{-\alpha} \exp(-E/E_{0x})$

□ *Species and  $\alpha_{Bn}$  dependence in  $E_{0x} \sim [Q_x/A_x] [\sec \alpha_{Bn}]^{2/(2\alpha-1)}$*

□ *Average over  $\alpha_{Bn}$ :*

□ *Flare suprathermals are equally injectable at all  $\alpha_{Bn}$ .*

□ *SW suprathermals weighted by a factor of  $\alpha = \cos \alpha_{Bn}$ .*

□ *Use nominal composition and charge states.*

□ *Variability in the relative size of flare- and SW-components of the seeds.*

## ➤ *These calculations qualitatively account for:*

• *Spectral variability: exponential rollovers & double power-laws.*

• *Different power-laws for Fe & O at high-energies*

• *“Zoo” of energy-dependent Fe/O*

• *Energy-dependent  $\langle Q_{Fe} \rangle$*

➤ *The calculations also make quantitative predictions about high-energy behavior that are consistent with the data.*

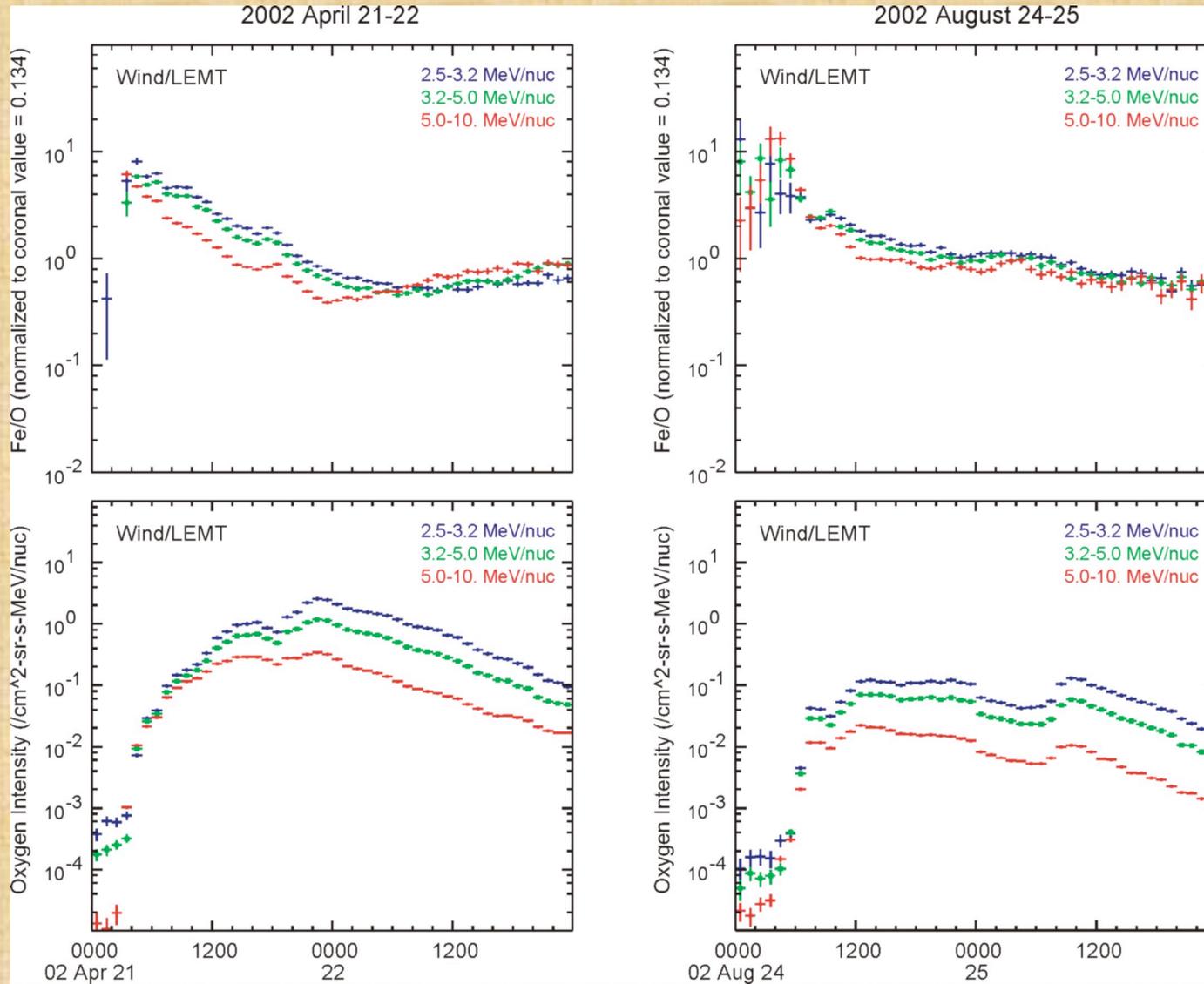
# Summary

- *The calculations are applicable to both SEPs and IP shocks at 1 AU:*
  - *In the SEP case, the averaging over  $\square_{Bn}$  may be primarily due to evolution as the shock moves out from the Sun.*
  - *In the ESP case, the averaging reflects changes in  $\square_{Bn}$  as the magnetic connection point sweeps across the approaching shock front.*
- *Given the simplicity of these calculations, they are not the final word.*
- *But they certainly justify more rigorous investigation of these ideas, including:*
  - *Time dependent simulations, with evolving  $\square_{Bn}$*
  - *Compound seed populations, with both SW & flare suprathermals.*
  - *$\square_{Bn}$ -dependence of the threshold speeds and injection efficiency.*

# Next Step: Temporal Evolution

## Wind/LEMT: 3 energy bins, 2.5-10 MeV/nuc

Fe/O/corona



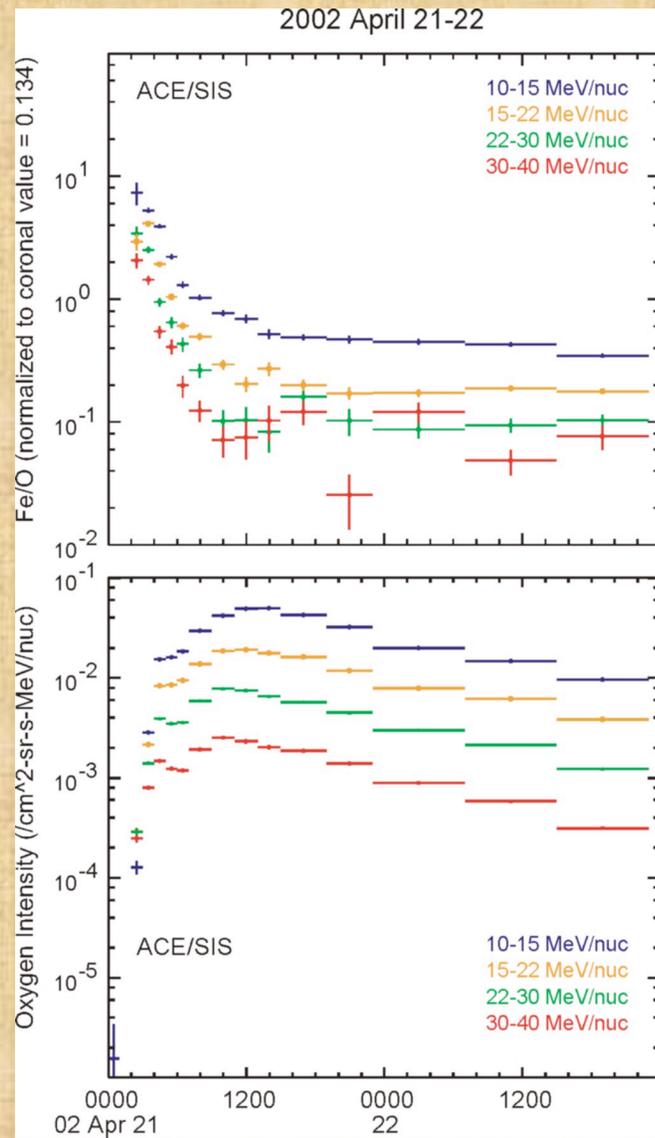
Oxygen Intensity

Time

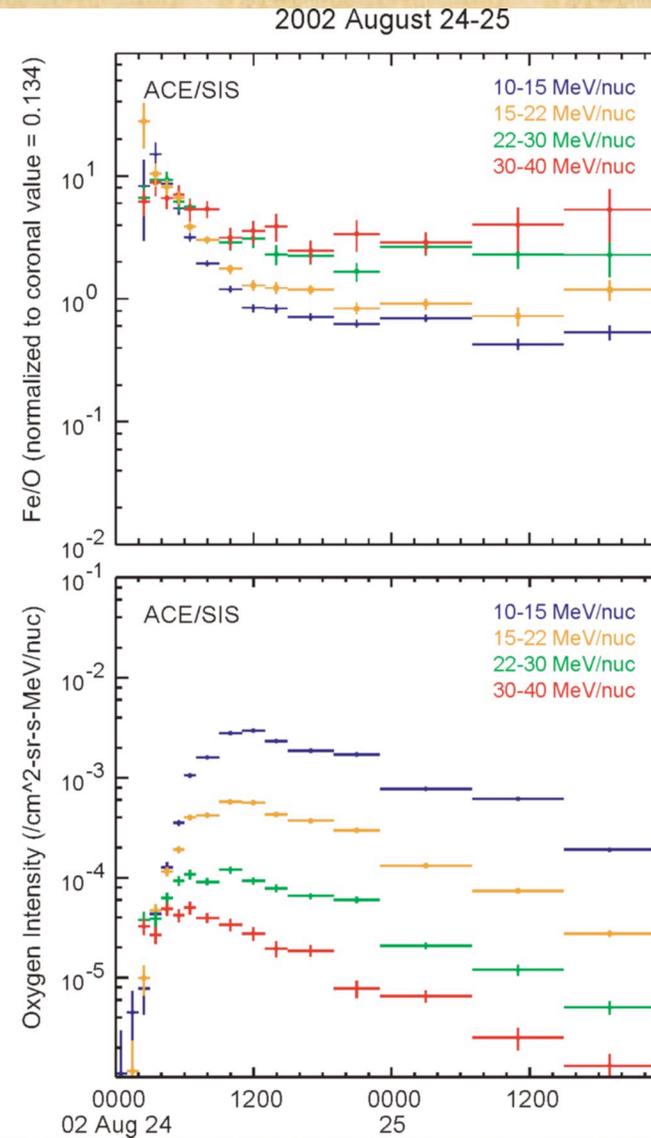
# Next Step: Temporal Evolution

## ACE/SIS: 4 energy bins, 10-40 MeV/nuc

Fe/O/corona



Oxygen Intensity



Time

# Next Step: Temporal Evolution

## ACE/SIS: Oxygen Energy Spectra: First Six Hours

