Spectral Properties of Heavy Ions Associated with Interplanetary Shocks at 1 AU

SHINE 2004
Big Sky, Montana

M. I. Desai

University of Maryland, College Park, MD 20742, USA

Co-Authors:
G. M. Mason: University of Maryland
C.M.S.Cohen & M. E. Wiedenbeck: SRL, Caltech, CA
J. E. Mazur: Aerospace Corp
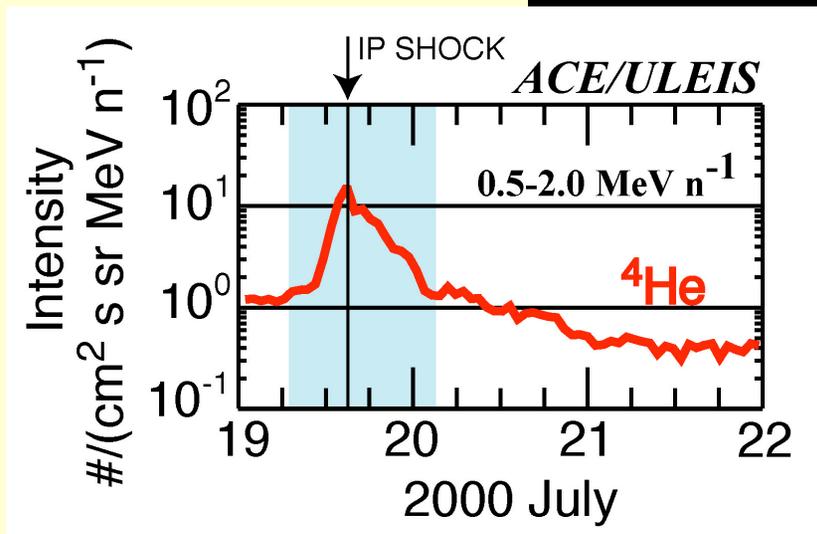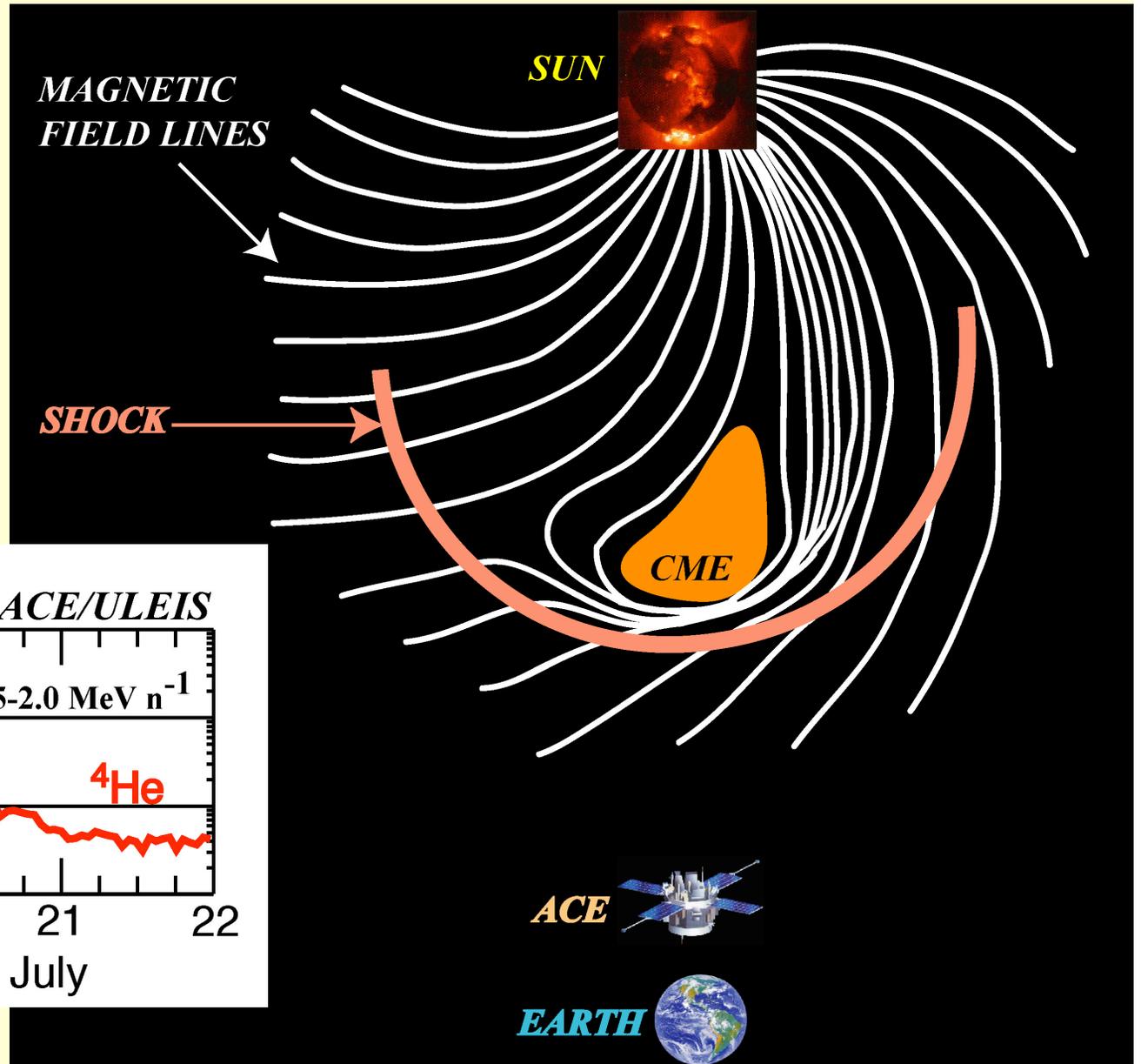J. R. Dwyer: Florida Institute of Technology
R.E. Gold & S. M. Krimigis: JHU/APL
C.W.Smith: University of New Hampshire
Q. Hu: IGPP, UC Riverside, CA
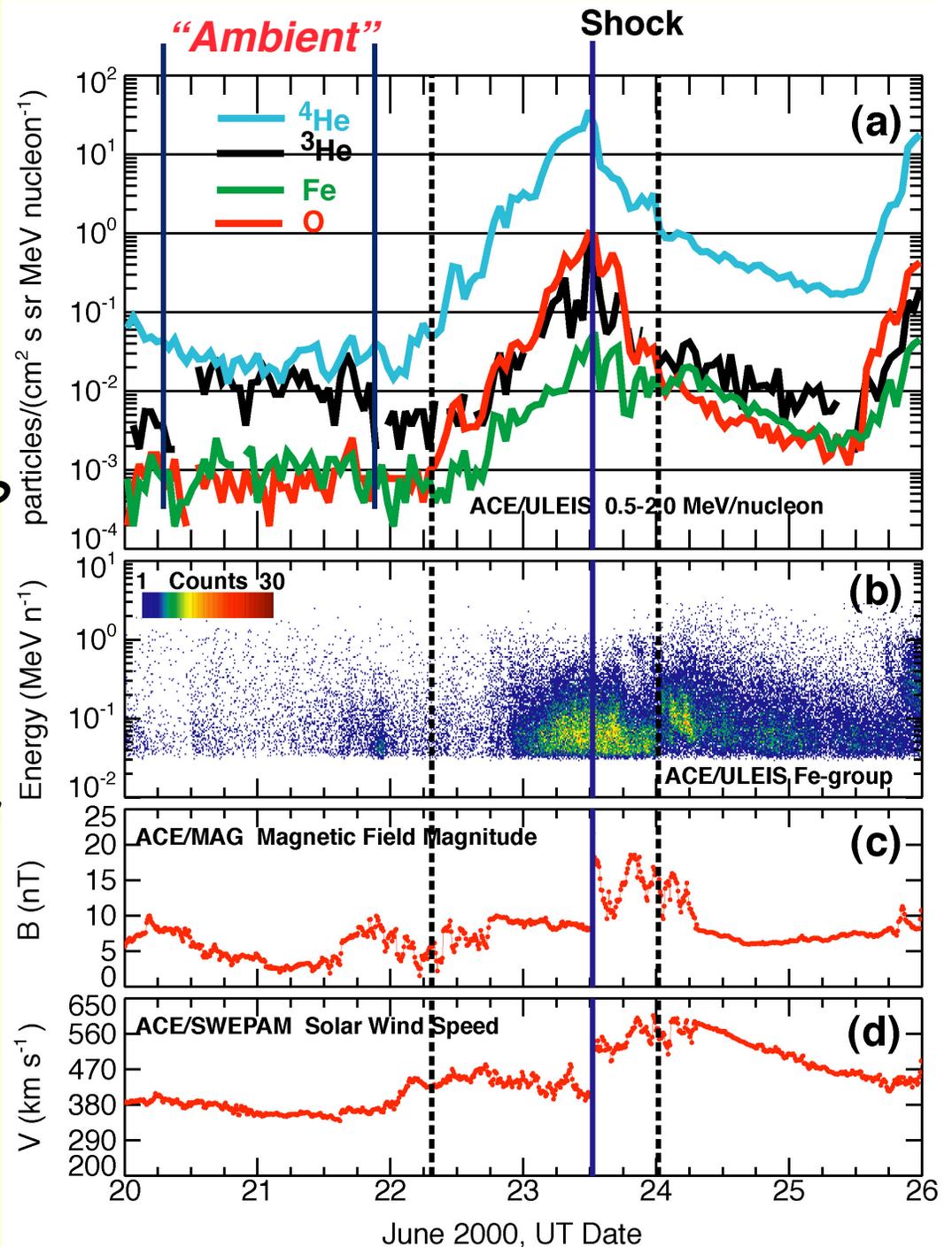R. M. Skoug: Los Alamos National Laboratory

CME-driven Interplanetary Shocks
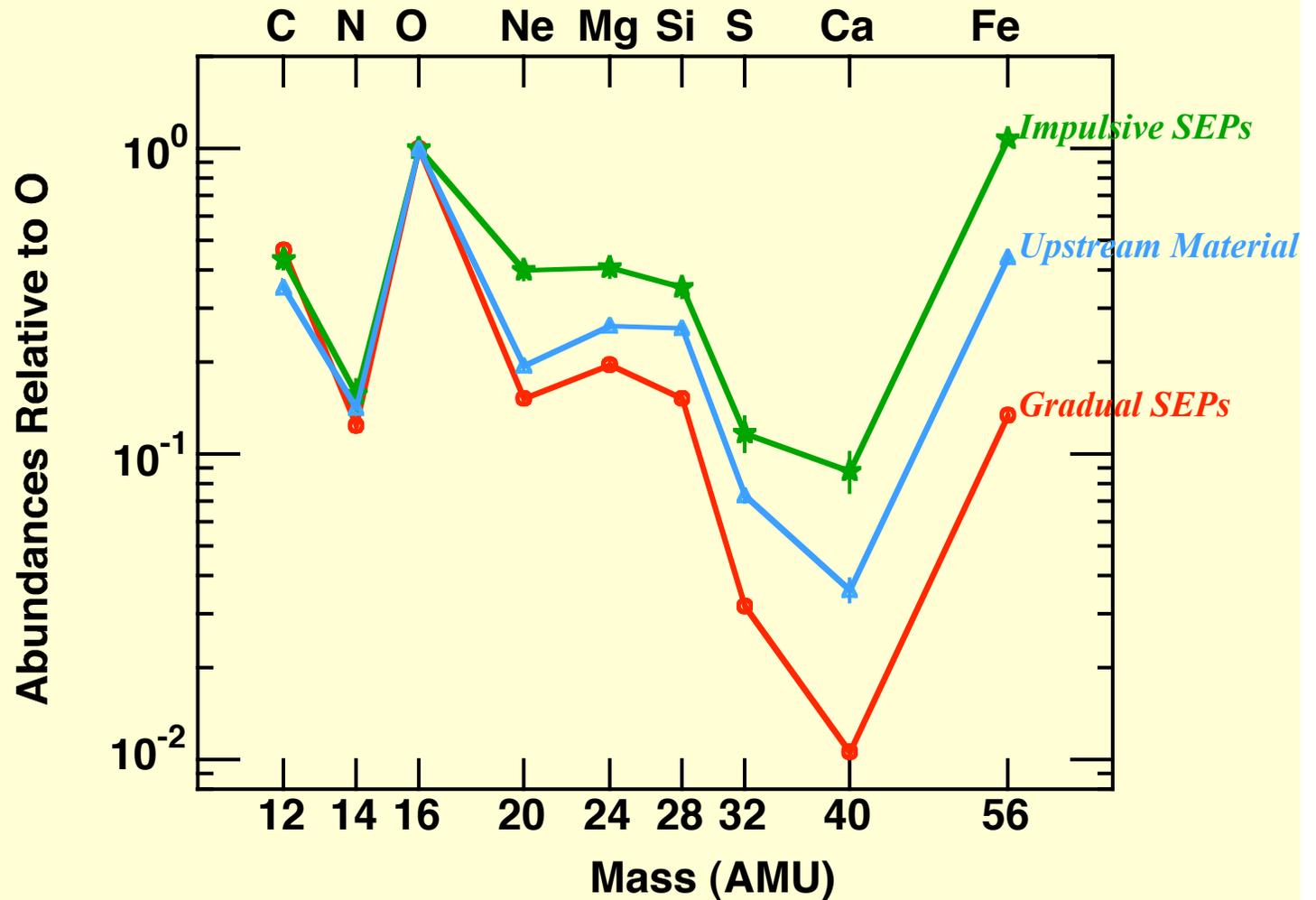
Intensity-time profiles for an IP shock

- Surveyed 72 shocks between Oct. 1997-Oct. 2002

- ^{3}He ions accelerated in 45 IP shocks

- Pre-shock intervals provide a "proxy" for ambient particles in the IP medium

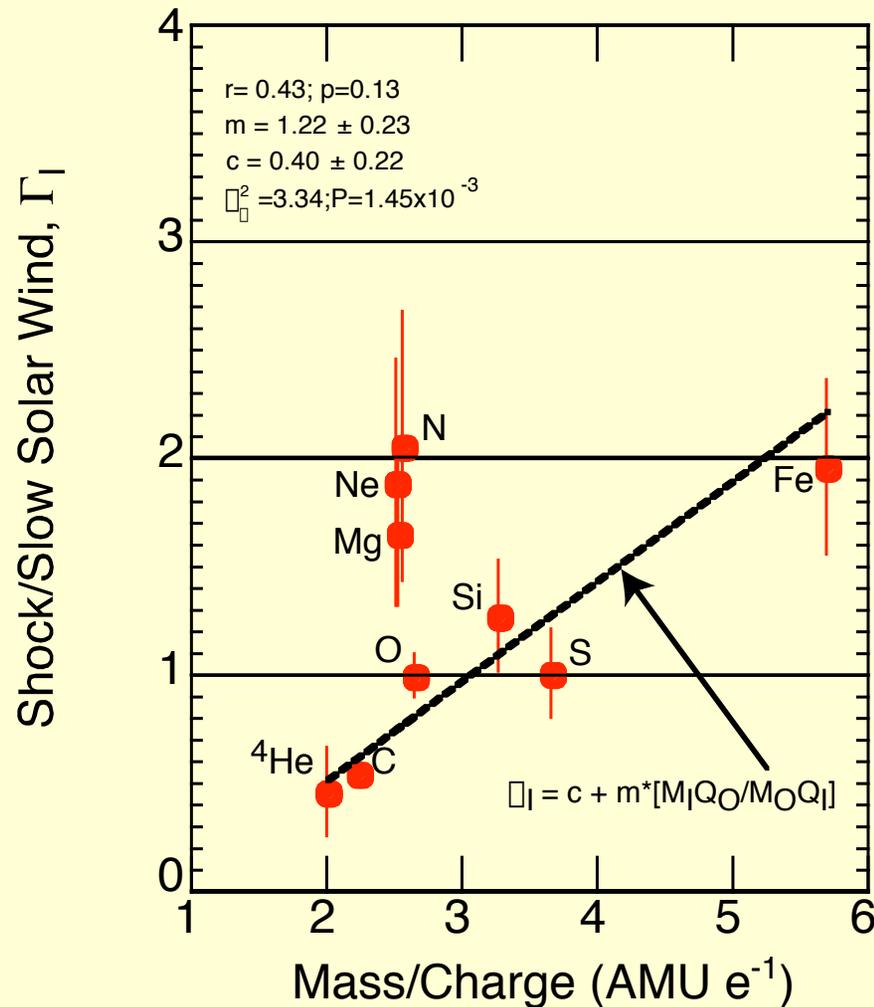(Desai et al. 2001, *ApJ* 553, L89 & 2003, *ApJ, 588, 1149*).

Ambient and SEP Abundances

Ambient material comprises ~30% from impulsive flares, and ~70% from large gradual SEPs

(Desai et al. 2003 ApJ, 588, 1149).

IP Shock compared with solar wind abundances

r= 0.43; p=0.13
m = 1.22 ± 0.23
c = 0.40 ± 0.22
$\chi_\upsilon^2 =3.34; P=1.45 \times 10^{-3}$

Shock/Slow Solar Wind, Γ_I

Mass/Charge (AMU e^{-1})

N

Ne

Mg

Fe

Si

O

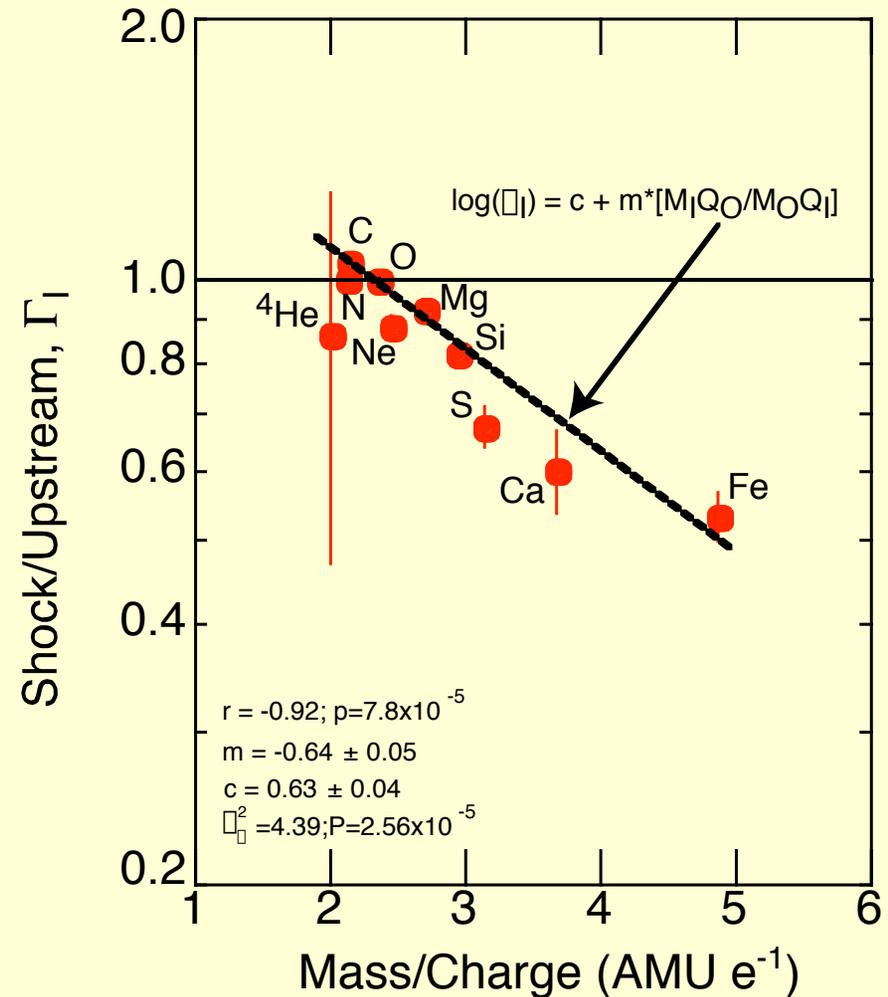S

^{4}He   C

$\Gamma_I = c + m*[M_I Q_O / M_O Q_I]$

- *Shock abundances are poorly correlated with solar wind abundances*

- *No clear dependence on M/Q*

- *Difficult to understand in terms of rigidity-dependent acceleration of solar wind ions*

(Desai et al. 2003 ApJ, 588, 1149).

# IP Shock compared with ambient suprathermal abundances

- *Shock abundances are well correlated with ambient suprathermal abundances*

- *Exhibit a M/Q-dependent depletion*

- *Consistent with rigidity-dependent shock acceleration of ambient suprathermals*

$$\log(\Gamma_I) = c + m*[M_I Q_O / M_O Q_I]$$

r = -0.92; p=7.8x10^{-5}
m = -0.64 ± 0.05
c = 0.63 ± 0.04
χ_ν^2 =4.39;P=2.56x10^{-5}

Shock/Upstream, Γ_I

Mass/Charge (AMU e^{-1})

(Desai et al. 2003 ApJ, 588, 1149).

Fe/O at IP shocks is depleted relative to ambient values
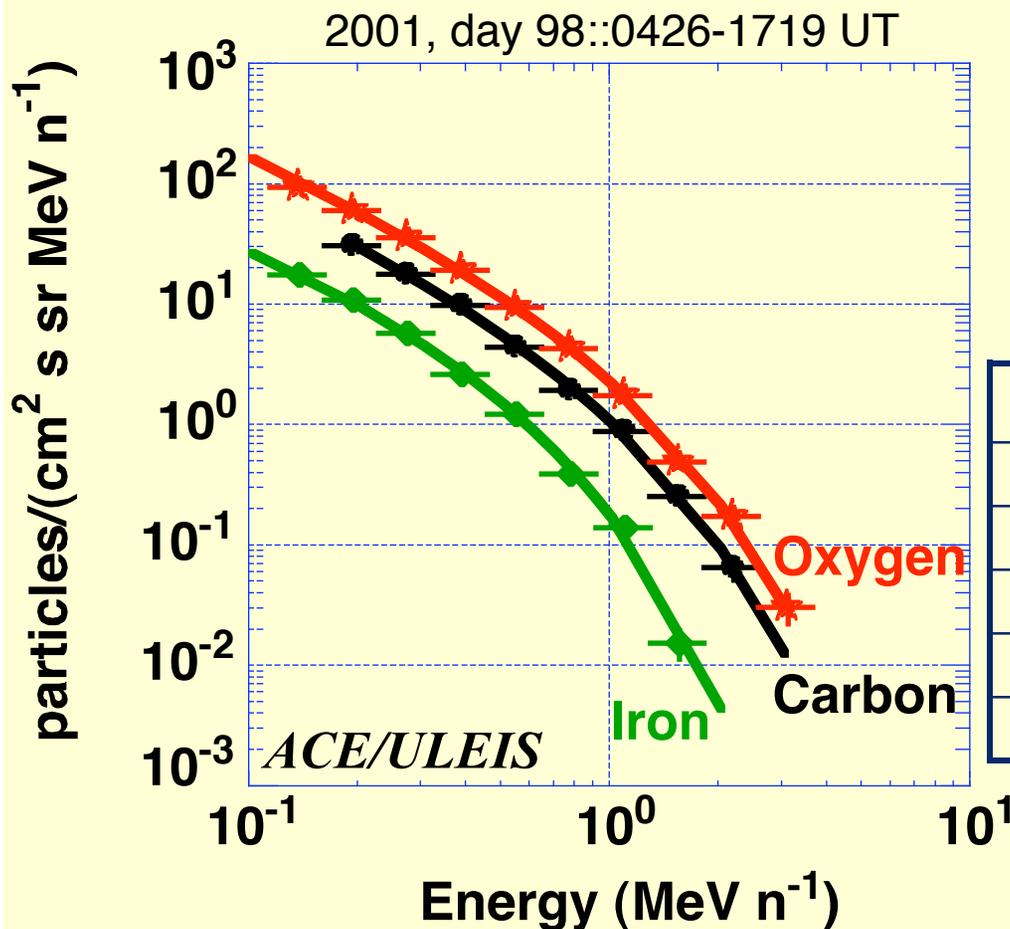
Larger decrease at higher energy
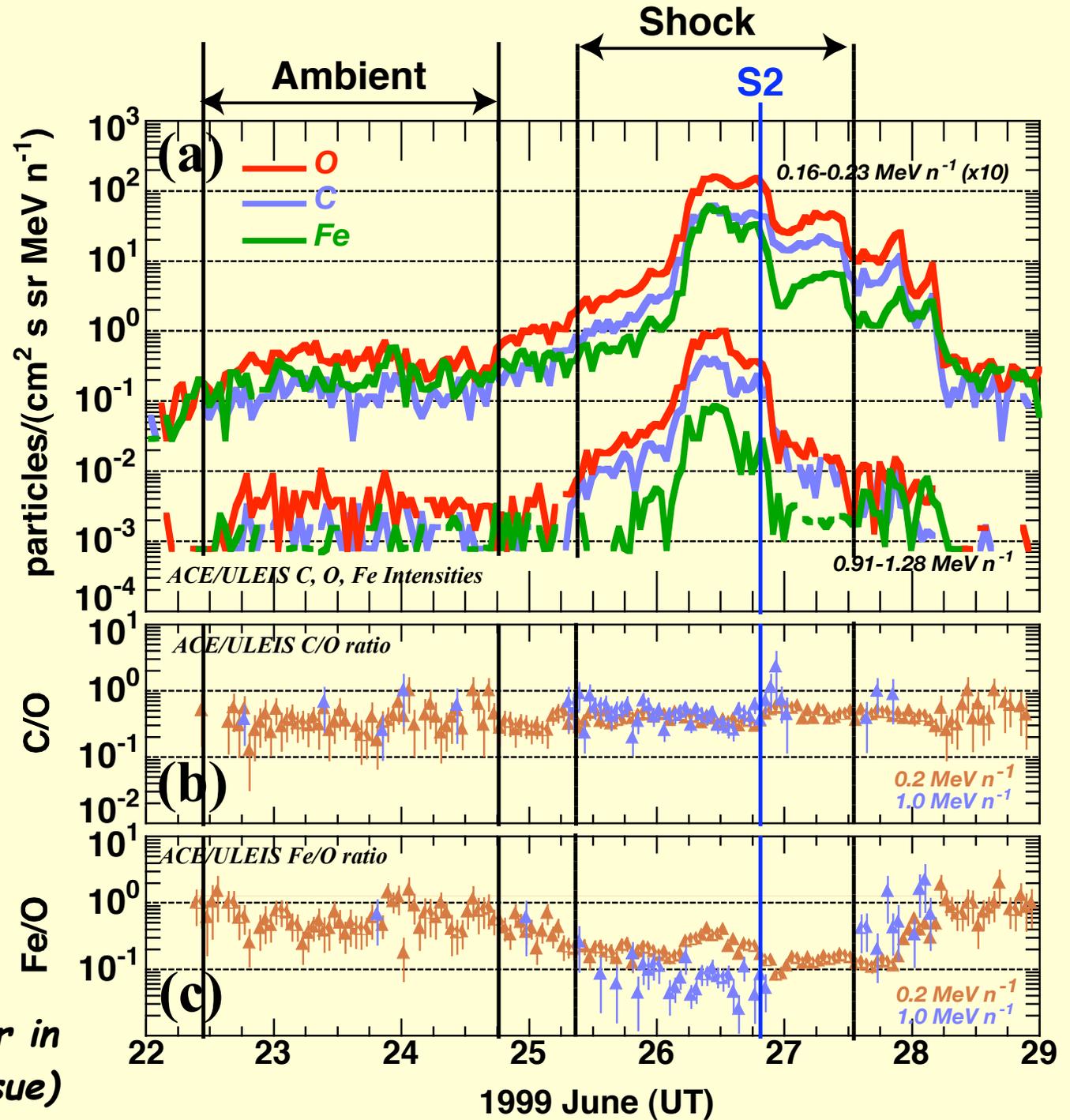
(Desai et al. *To appear in ApJ. Aug. 20, 2004 issue)*

Energy Spectra during an IP shock:
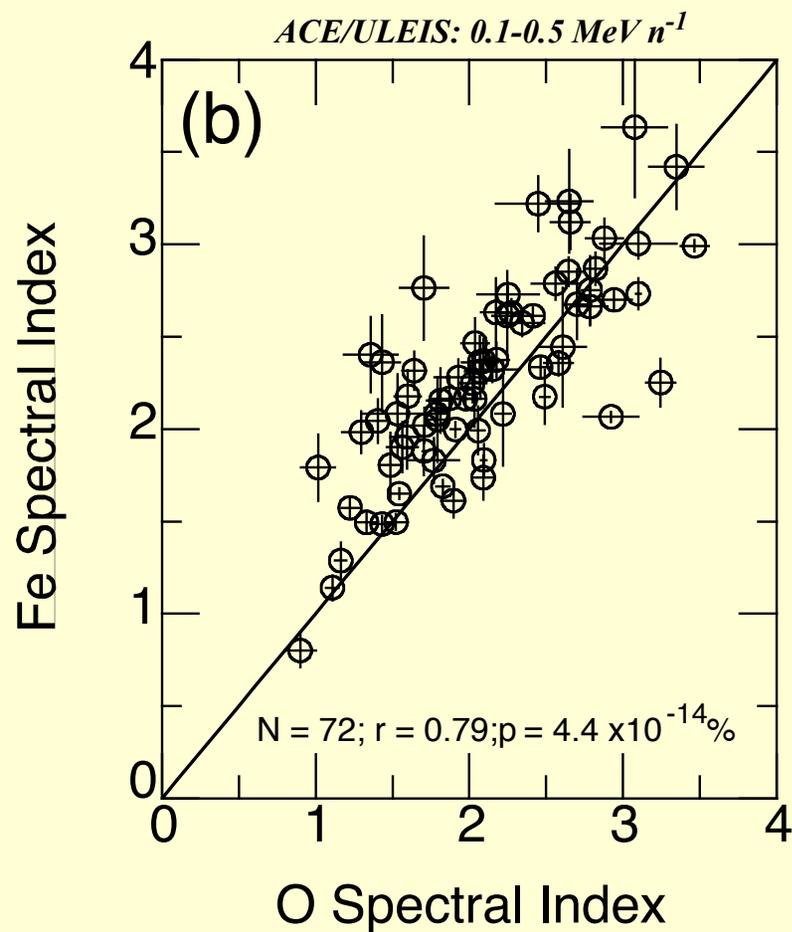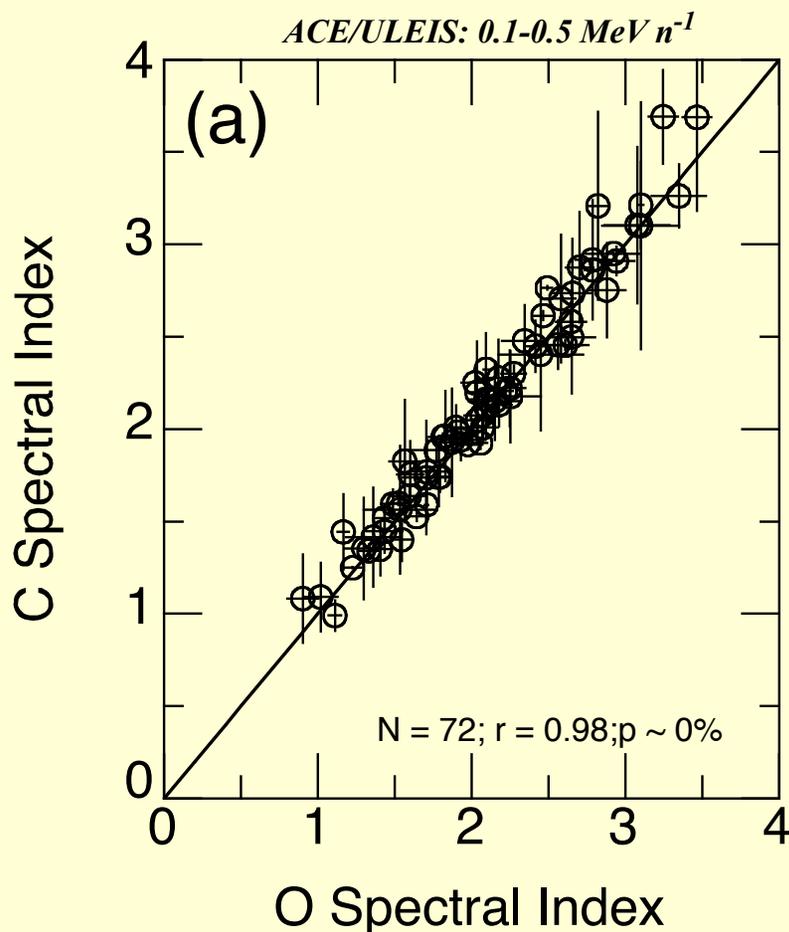# All Spectra fitted by $j = j_0 E^{-\gamma} exp(-E/E_0)$

however, γ and E_0 are coupled;
Use only 0.1-0.5 MeV n^{-1} to
obtain the power-law indices

2001, day 98::0426-1719 UT

particles/(cm^2 s sr MeV n^{-1})

Energy (MeV n^{-1})

ACE/ULEIS

Oxygen

Carbon

Iron

Parameter	Carbon	Oxygen	Iron
No. of Points	8	10	8
j_0	4.64 ± 0.87	9.32 ± 1.21	3.17 ± 1.49
γ	1.36 ± 0.11	1.33 ± 0.09	1.08 ± 0.27
E_0	0.69 ± 0.09	0.72 ± 0.06	0.35 ± 0.06
χ^2/ν	0.87	0.91	0.88

Spectral indices of C, O, & Fe

Differences in Fe and O indices are at odds with injection of a mono-energetic seed population

ACE/ULEIS: 0.1-0.5 MeV n^{-1}

(a) C Spectral Index vs O Spectral Index

N = 72; r = 0.98; p ~ 0%

ACE/ULEIS: 0.1-0.5 MeV n^{-1}

(b) Fe Spectral Index vs O Spectral Index

N = 72; r = 0.79; p = 4.4 x10^{-14}%

(Desai et al. *To appear in ApJ. Aug. 20, 2004 issue*)

O e-folding energy vs. shock parameters

## E-folding energy is independent of local shock parameters
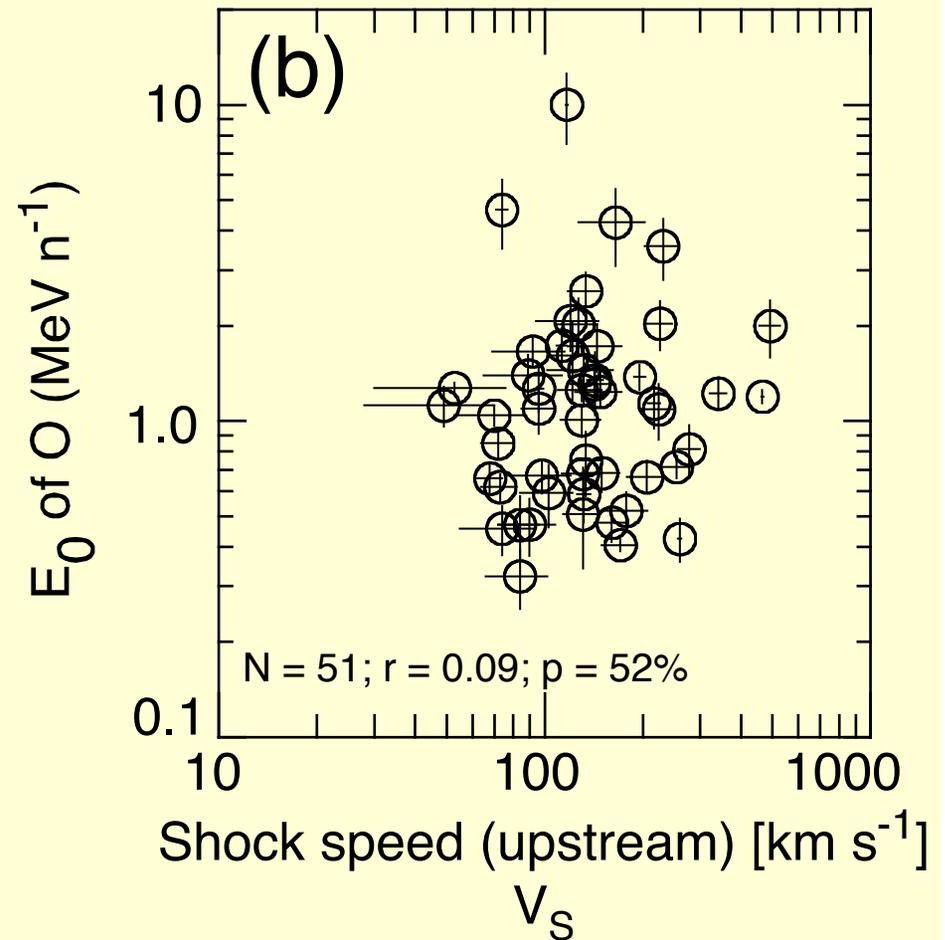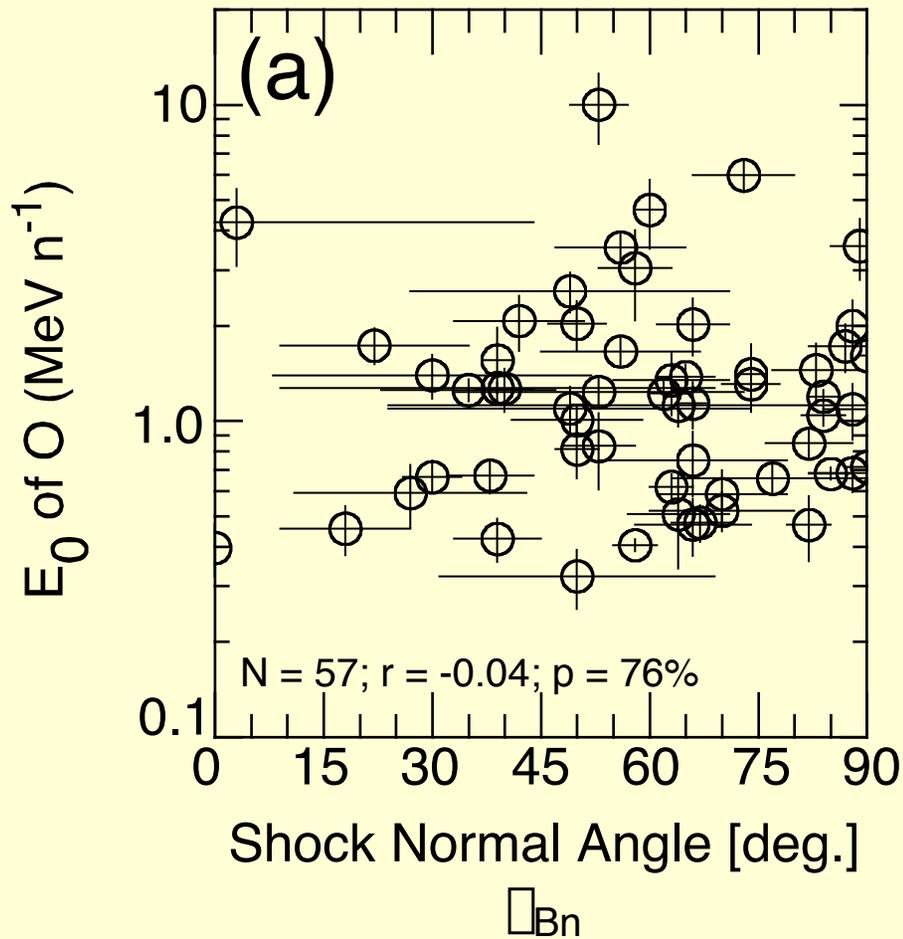
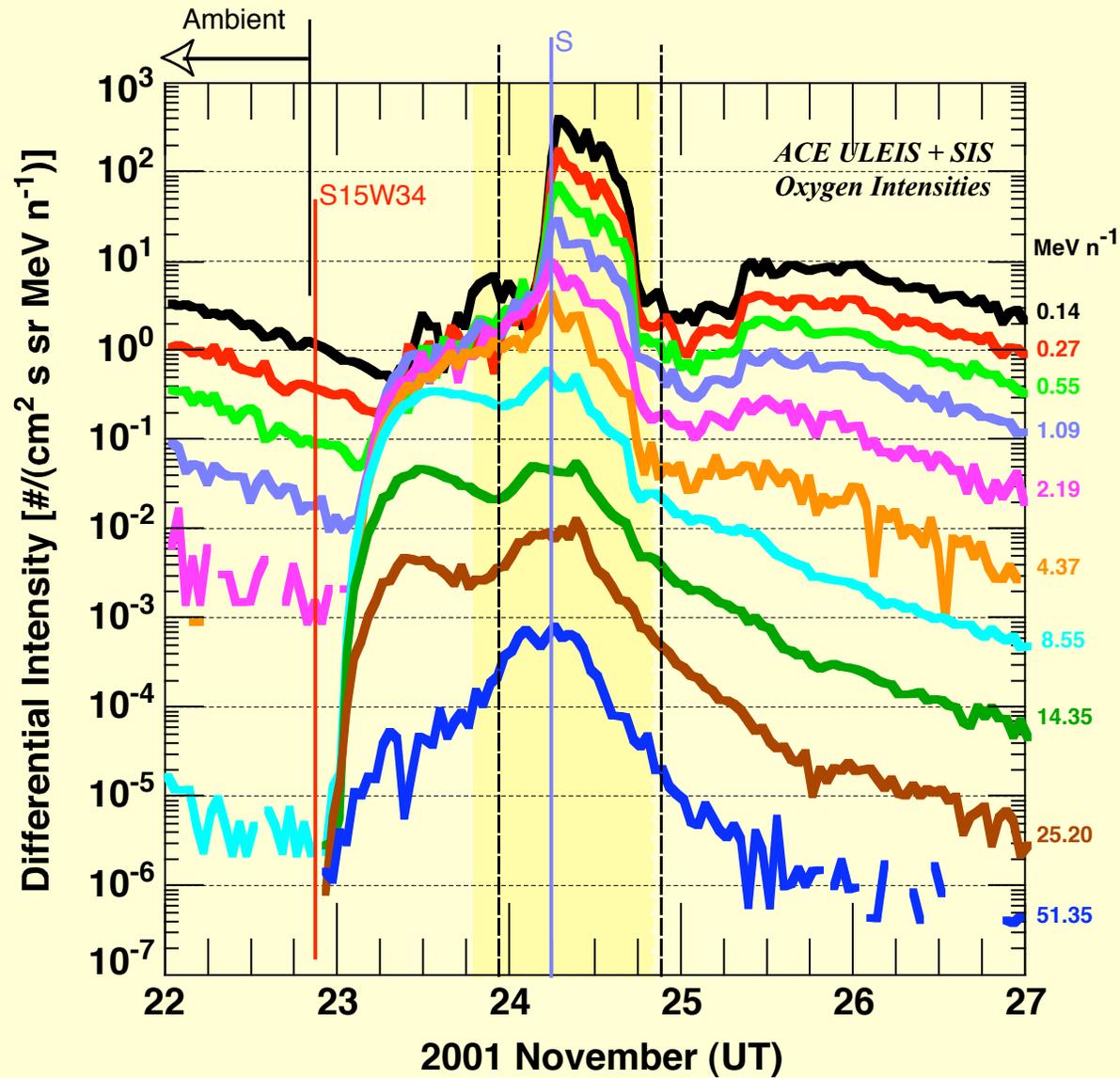(Desai et al. *To appear in ApJ. Aug. 20, 2004 issue*)

2-hr. av. O spectral index vs. (M+2)/(2M-2)

ACE/ULEIS 0.1-0.5 MeV n^{-1}

➜ *Spectral index is poorly correlated with compression ratio, M*

➜ *Results are at odds with predictions of simple steady-state models*

N = 60; r ~ 0.09; p ~ 51%

O Spectral Index (2-hour avergaes)

(M+2)/(2M-2)

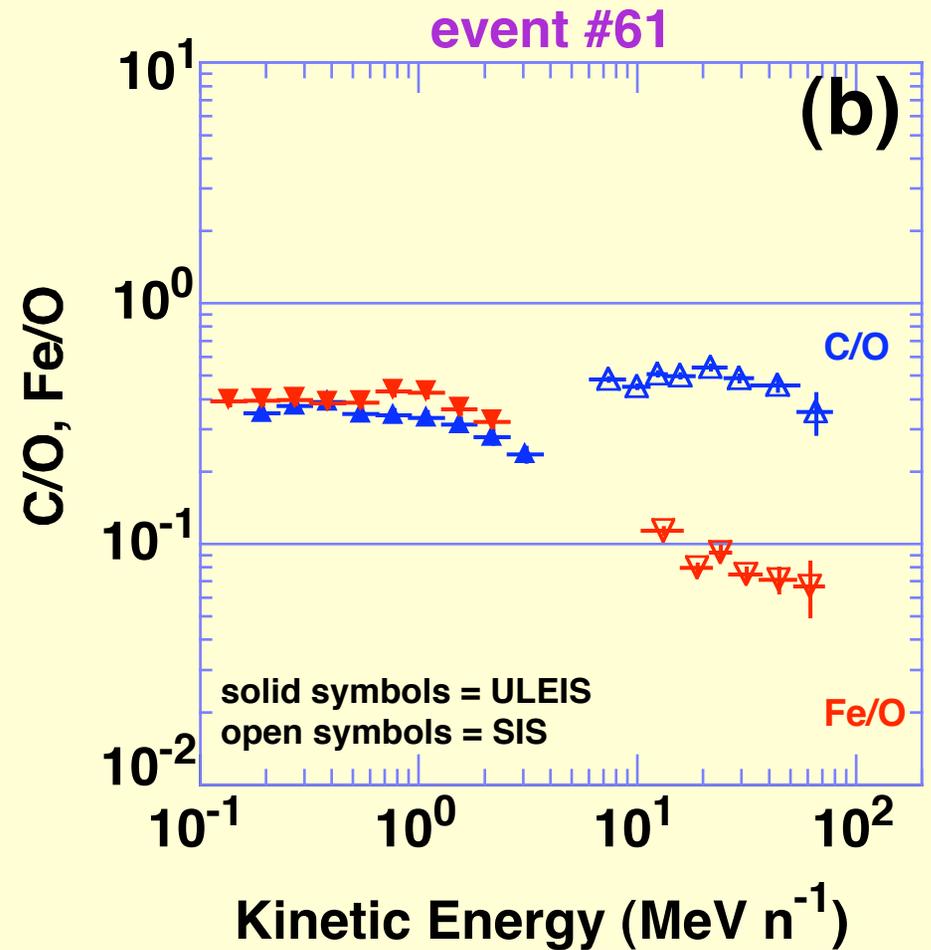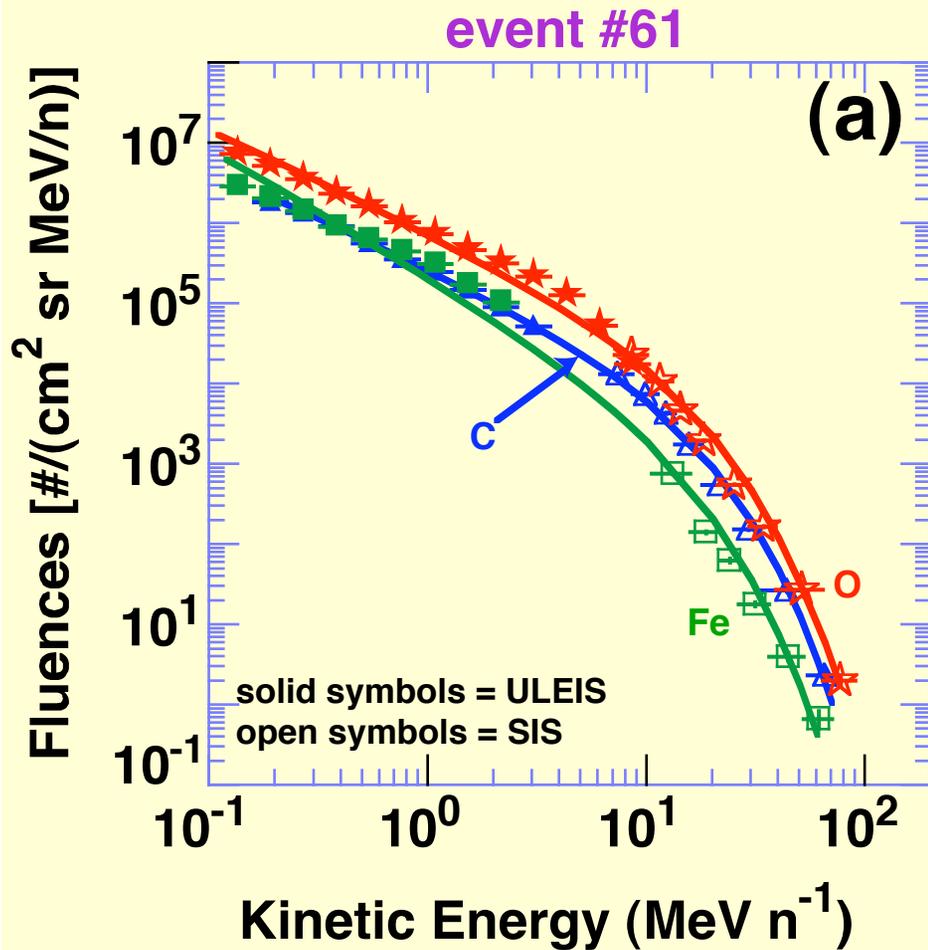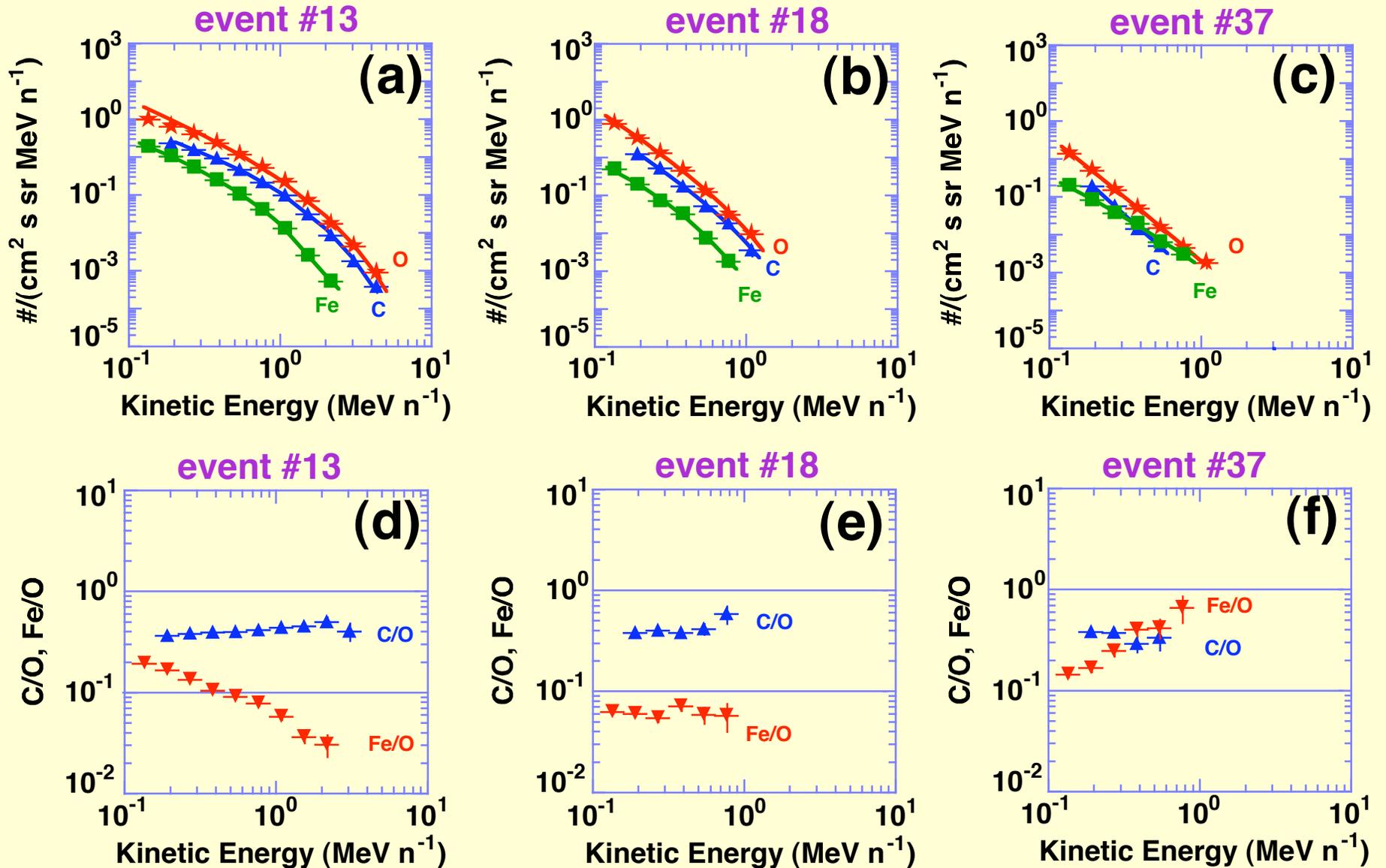(Desai et al. *To appear in ApJ. Aug. 20, 2004 issue)*
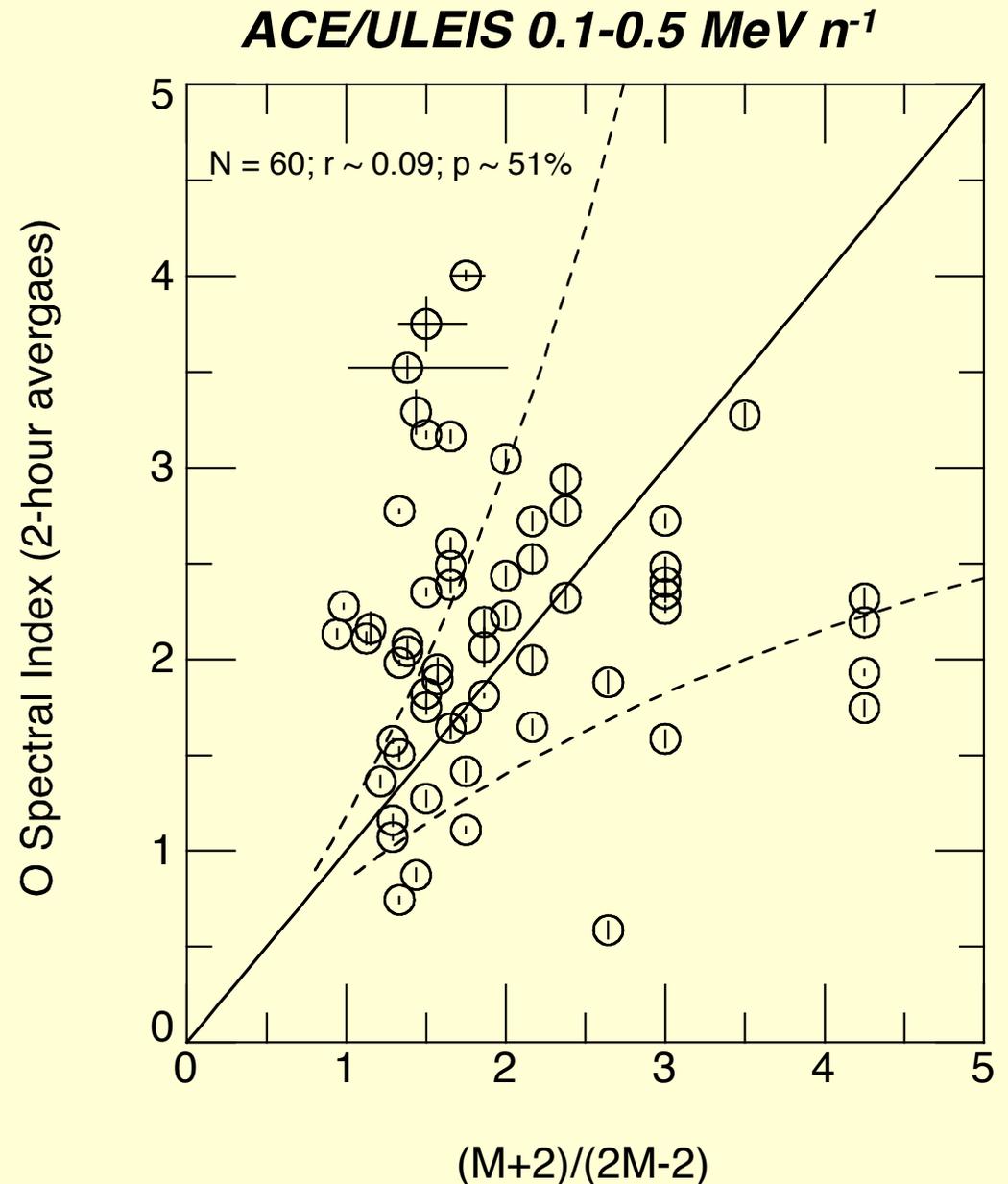
IP shock event measured by ULEIS & SIS

(Desai et al. *To appear in ApJ. Aug. 20, 2004 issue*)

Energy spectra measured by ULEIS & SIS

event #61

(a)

Fluences [#/(cm^2 sr MeV/n)]

10^7

10^5

10^3

10^1

10^{-1}

C

O

Fe

solid symbols = ULEIS
open symbols = SIS

10^{-1} 10^0 10^1 10^2

Kinetic Energy (MeV n^{-1})

event #61

(b)

C/O, Fe/O

10^1

10^0

10^{-1}

10^{-2}

C/O

Fe/O

solid symbols = ULEIS
open symbols = SIS

10^{-1} 10^0 10^1 10^2
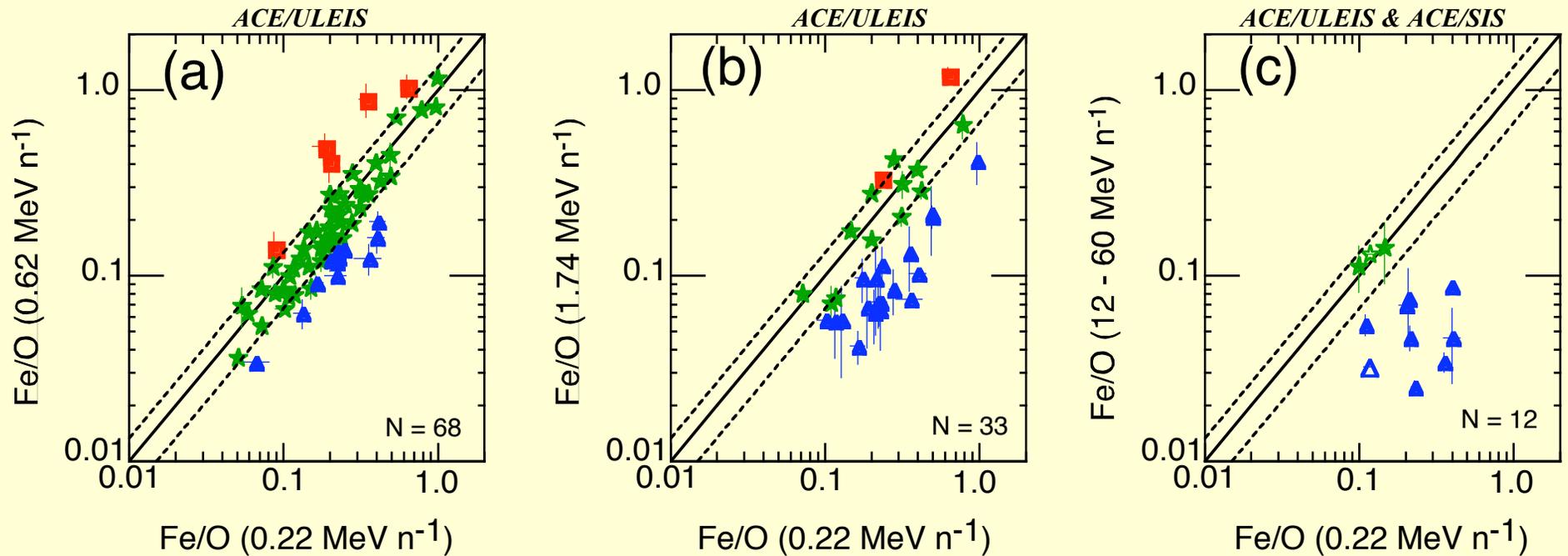
Kinetic Energy (MeV n^{-1})

(Desai et al. *To appear in ApJ.Aug. 20, 2004 issue*)

3 Classes of Fe/O energy-dependence
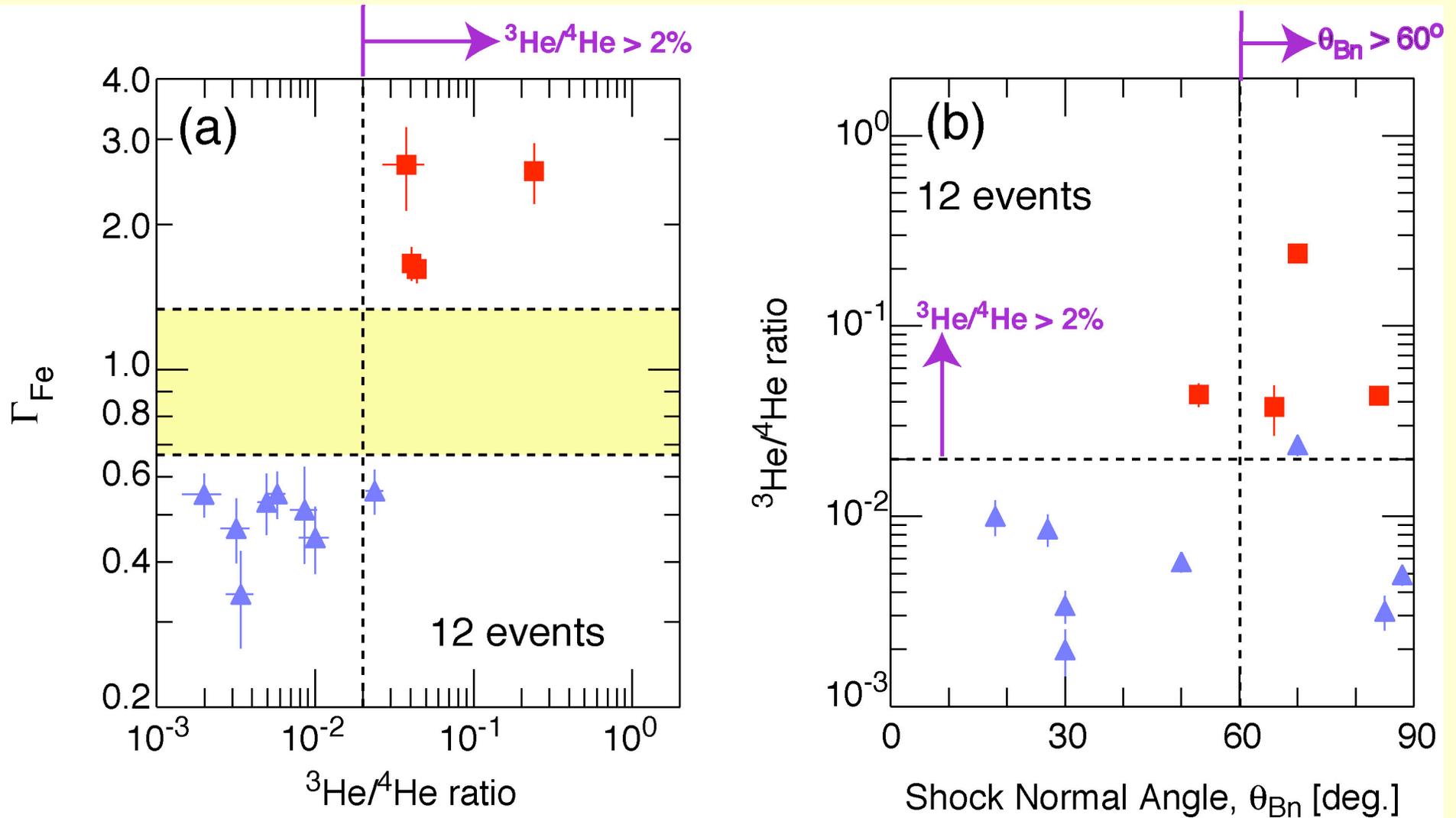

(Desai et al. *To appear in ApJ. Aug. 20, 2004 issue*)

Energy-dependence of Fe/O

$$\Gamma_{Fe} \quad = \quad \frac{Fe/O \ (0.62 \ MeV/n.)}{Fe/O \ (0.22 \ MeV/n.)}$$

(Desai et al. *To appear in ApJ. Aug. 20, 2004 issue)*

Γ_{Fe} vs. ^{3}He/^{4}He ratio; ^{3}He/^{4}He ratio vs. θ_{Bn}
Extreme Events Only

(Adapted from Desai et al. 2004, *To appear in ApJ. Aug. 20, 2004*)

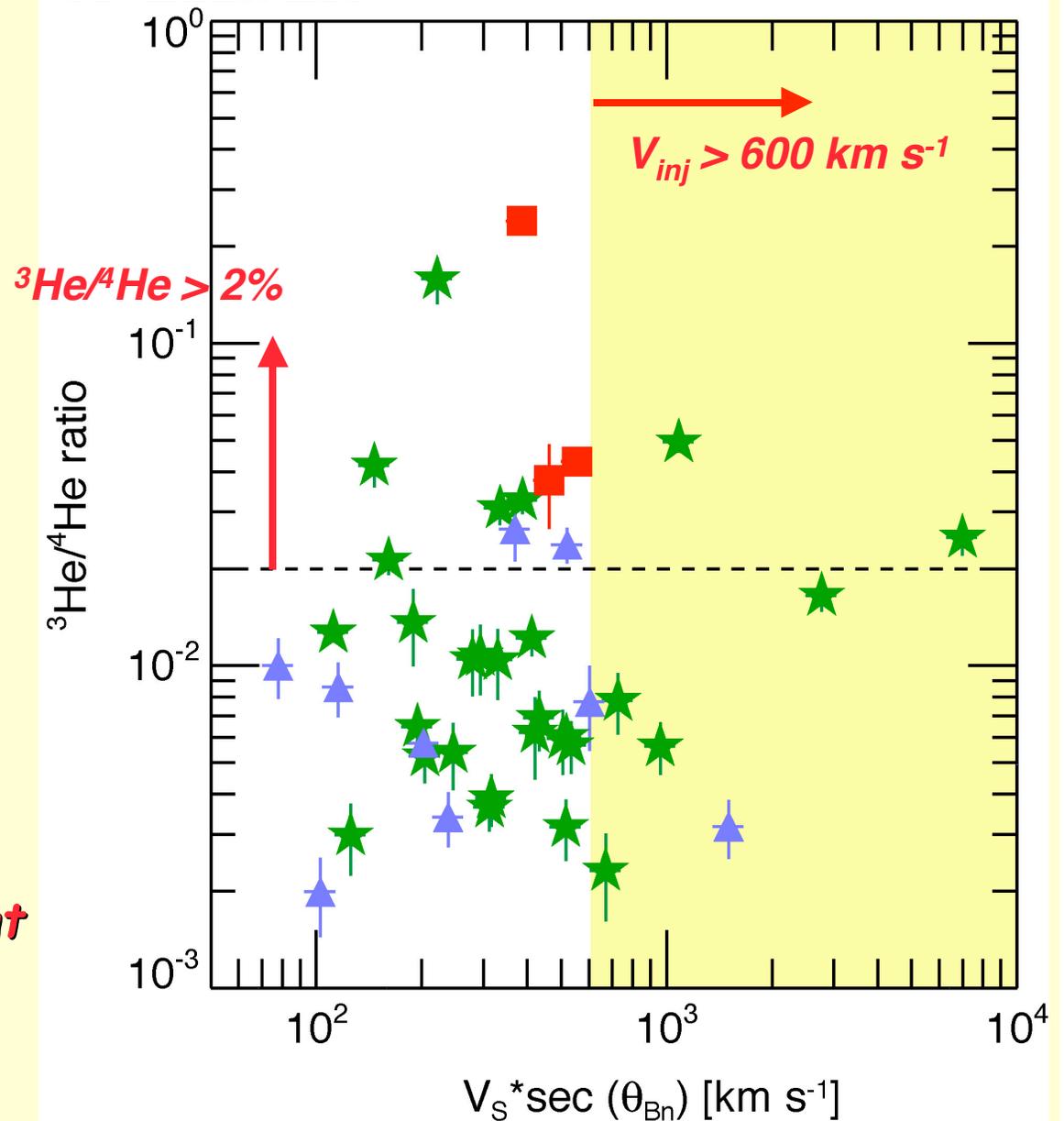Γ_{Fe} vs. ^{3}He/^{4}He ratio; ^{3}He/^{4}He ratio vs. θ_{Bn}
All events
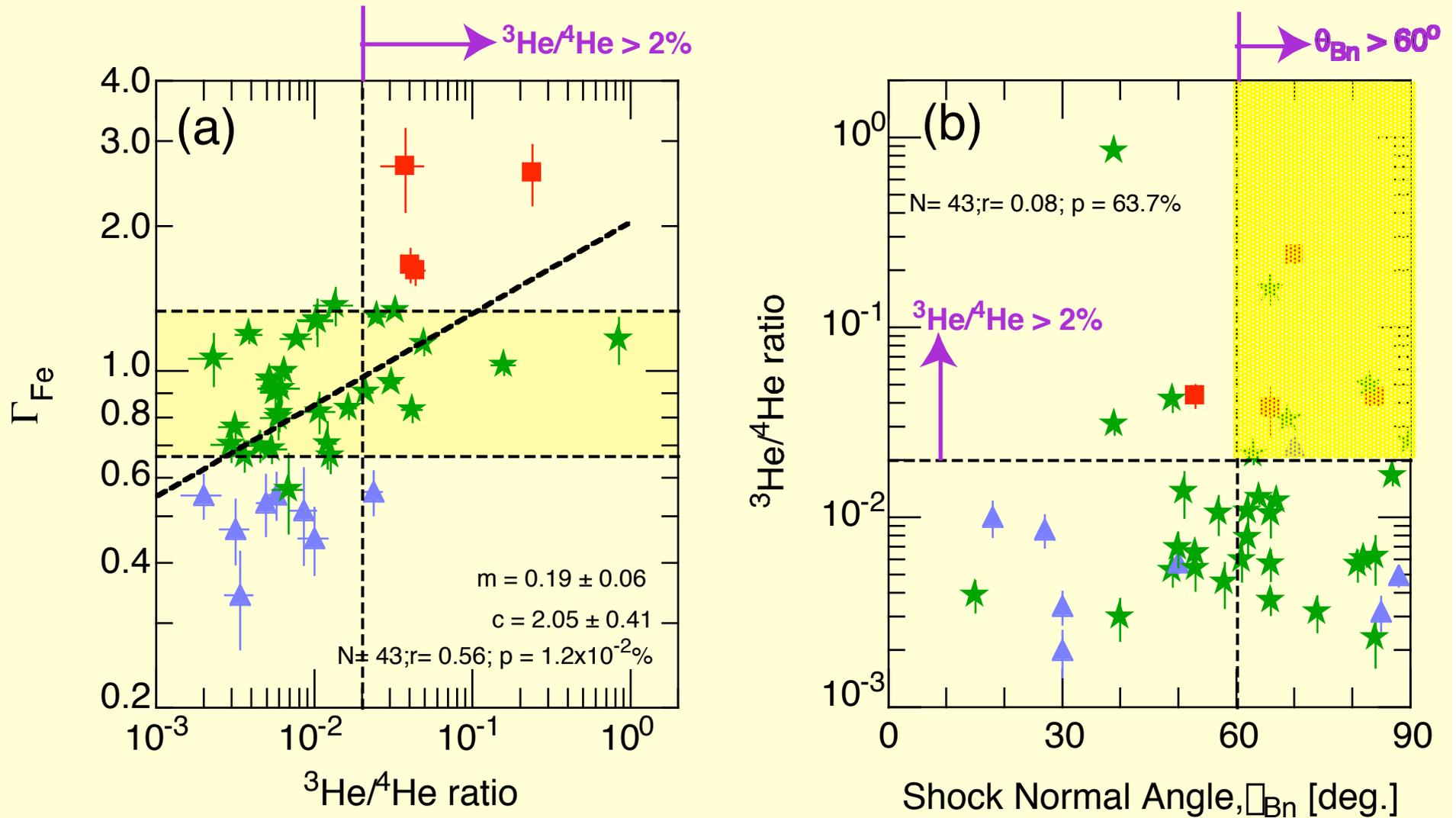
(Desai et al. *To appear in ApJ.Aug. 20, 2004 issue*)

^{3}He/^{4}He ratio vs. Injection Threshold Speed, V_{inj} = $V_s*sec(\theta_{Bn})$

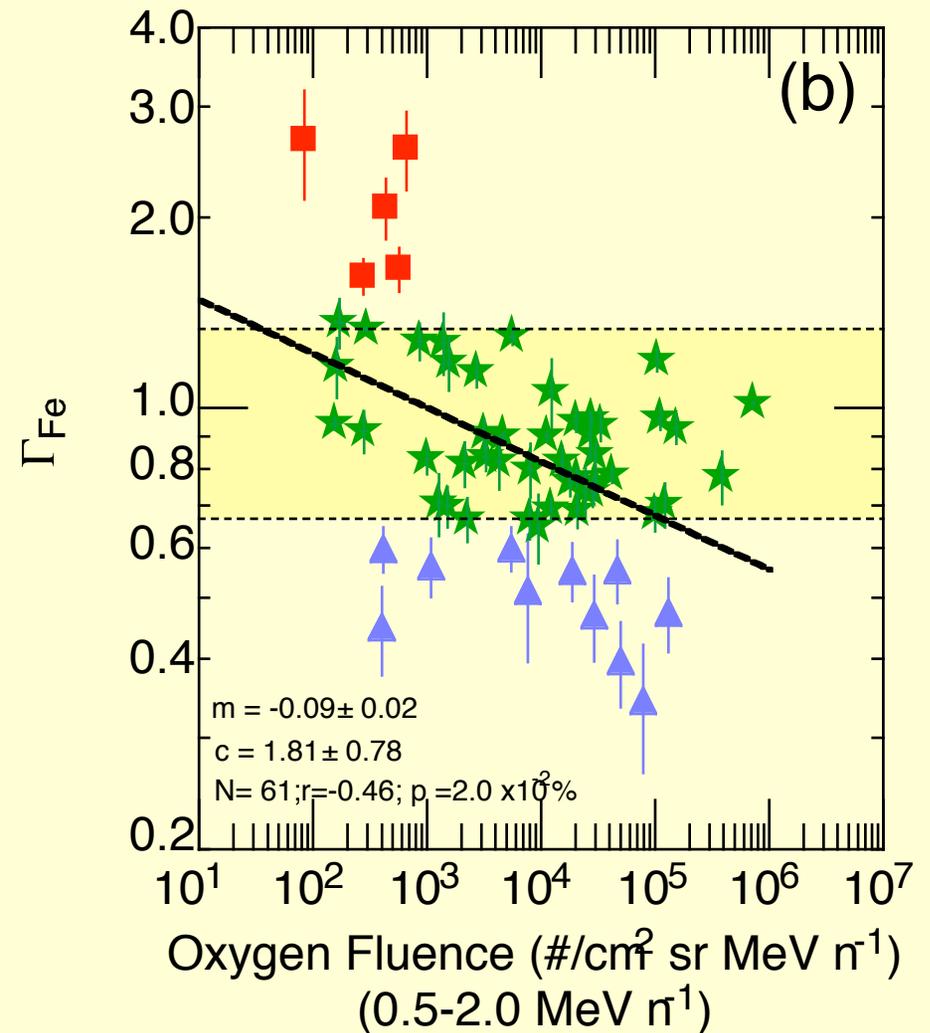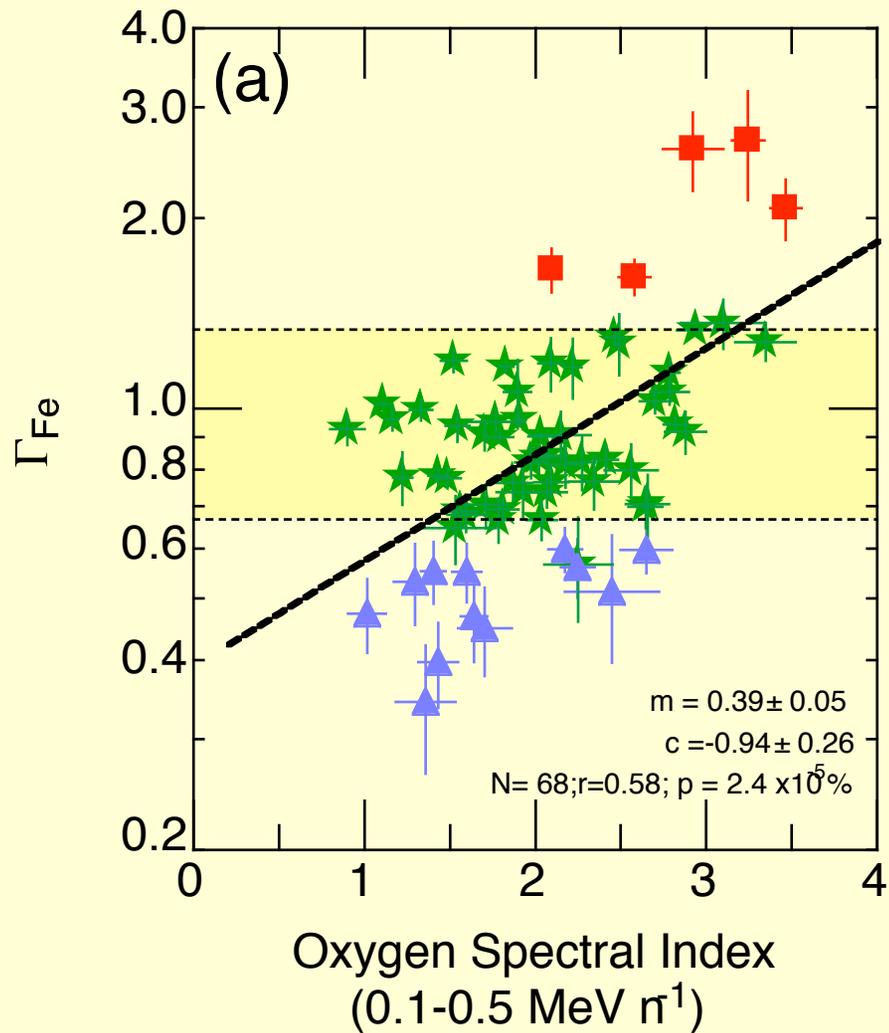Most IP shocks including the 3 with rising Fe/O ratios have $V_{inj}<2*V_{sw}$

^{3}He/^{4}He ratio and Γ_{Fe} are poorly correlated with V_{inj}

Conclusion: Injection threshold speeds do not appear to play a significant role in the energy-dependent behavior of Fe/O

Γ_{Fe} vs. O spectral index & O fluence

(a)

m = 0.39± 0.05
c = -0.94± 0.26
N= 68;r=0.58; p = 2.4 x10⁻⁵%

Γ_{Fe}

Oxygen Spectral Index
(0.1-0.5 MeV n⁻¹)

(b)

m = -0.09± 0.02
c = 1.81± 0.78
N= 61;r=-0.46; p =2.0 x10⁻²%

Γ_{Fe}

Oxygen Fluence (#/cm² sr MeV n⁻¹)
(0.5-2.0 MeV n⁻¹)

(Desai et al. *To appear in ApJ.Aug. 20, 2004 issue*)

Fe/O at IP shocks vs. ambient

Fe/O ratios at IP shocks and ambient are well correlated

$N=62; r=0.51; p=1.0 \times 10^5$

$m = 0.40 \pm 0.02$

$c = 0.26 \pm 0.05$

$\chi_v^2 = 0.53; P = 1.0$

event #29

$\log(Fe/O_{Shock}) = c + m*\log(Fe/O_{Upstream})$

Fe/O (at shock)

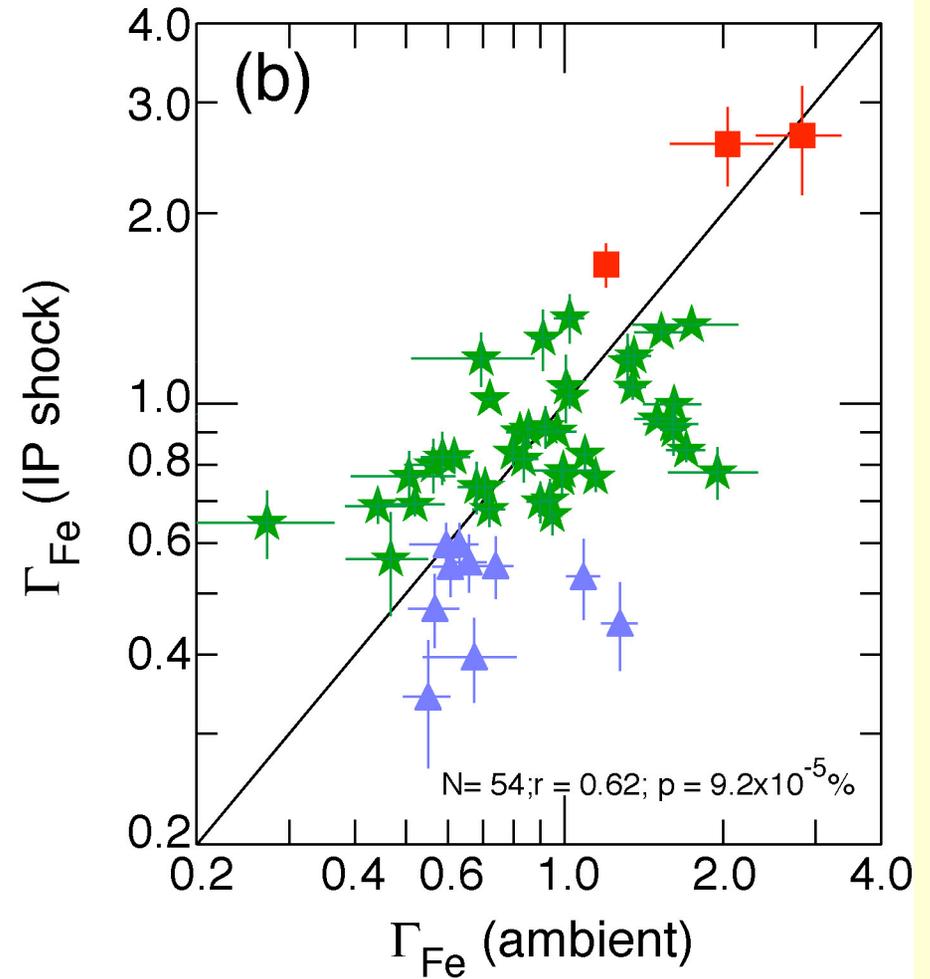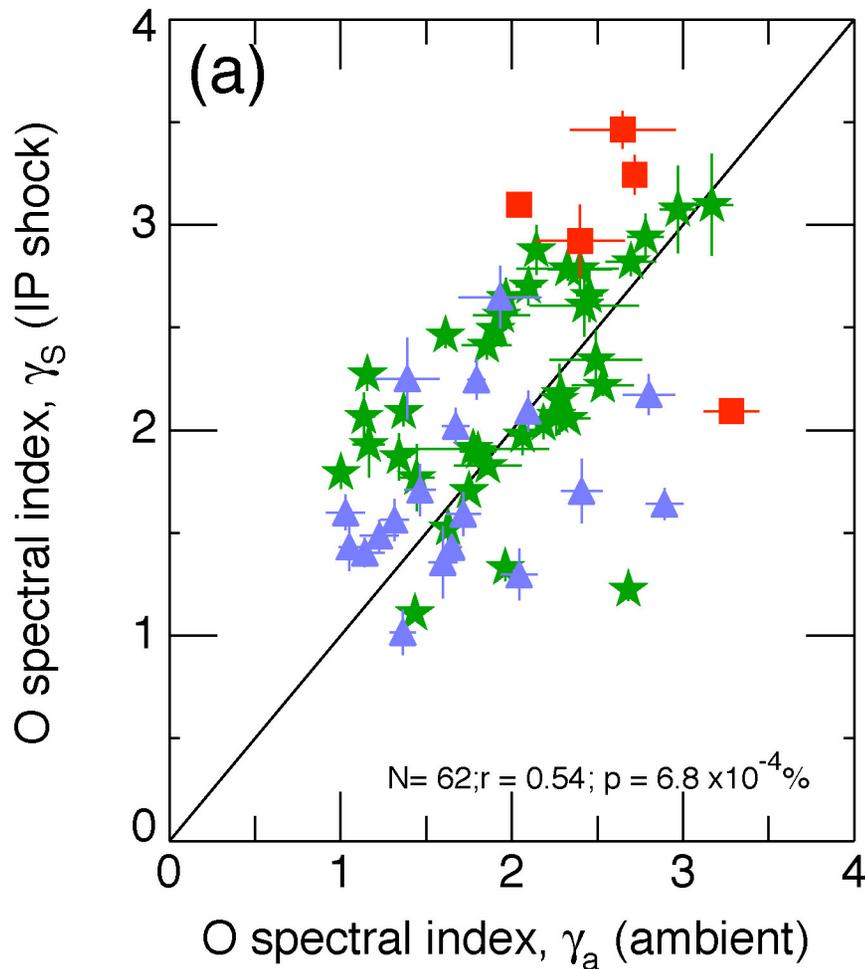Fe/O (Upstream)
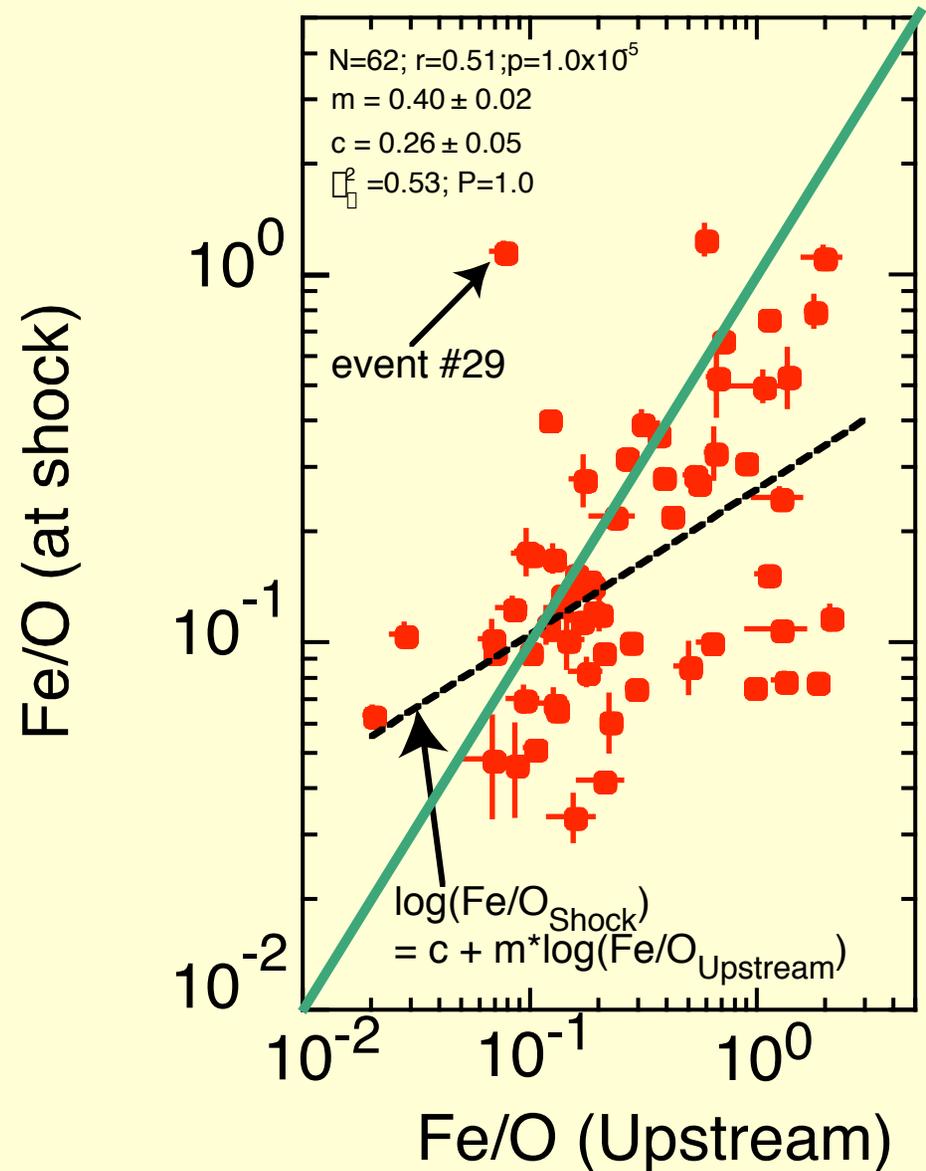
(Desai et al. 2003 ApJ, 588, 1149).

Shock C/O & Fe/O normalized to ambient values

- Fe/O ratios are depleted by ~30% relative to ambient values

- Energy-dependence of Fe/O is diminished when compared with ambient Fe/O - not expected from mono-energetic injection
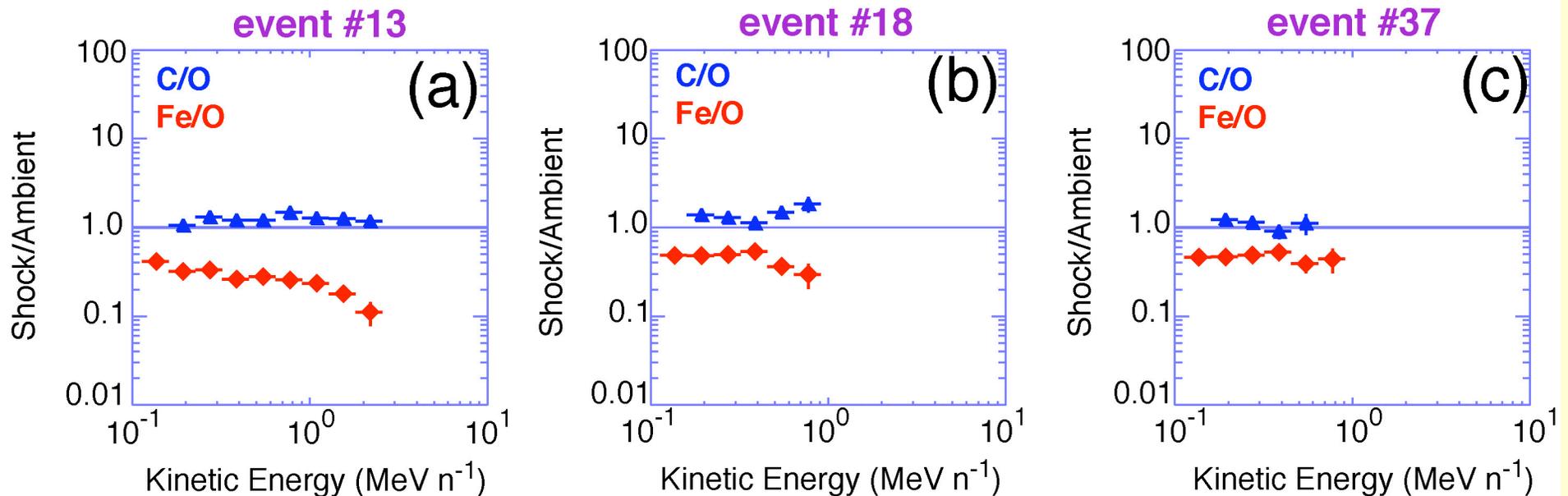
(Desai et al. *To appear in ApJ.Aug. 20, 2004 issue*)

# O Spectral index & Fe/O dependence at IP shocks vs. Ambient

(Desai et al. *To appear in ApJ. Aug. 20, 2004 issue*)

Summary

- *Spectral parameters and energy-dependence of Fe/O are independent of local shock parameters*

- *5 out of 72 events (~7%) have rising Fe/O with energy; Fe/O in other events are constant or decrease with energy*

- *Fe/O at IP shocks are typically ~30% lower than in the ambient population*

- *The O spectra and energy-dependence of Fe/O are similar at IP shocks and in the ambient population*

Sketch of Re-acceleration of Seed spectra at IP shocks
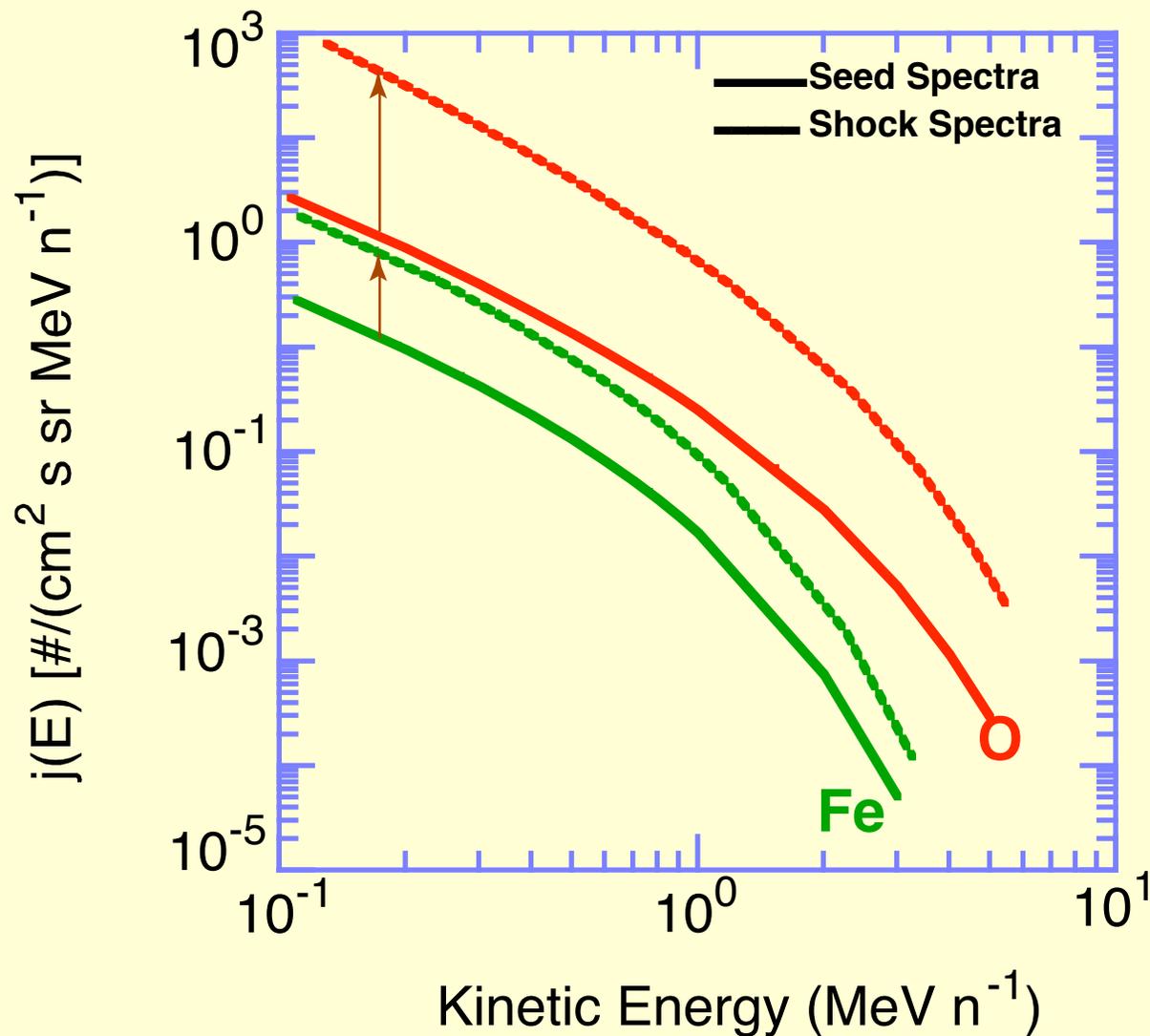
(Desai et al. *To appear in ApJ.Aug. 20, 2004 issue*)

Conclusion

IP shocks accelerate seed spectra composed of suprathermal ions from gradual and impulsive SEP events by a systematic rigidity-dependent mechanism where ions with higher M/Q are accelerated less efficiently than those with lower M/Q

Relevant Issues

- **How common are IP shock events with rising Fe/O ratios?**

  ➡ *~7% of events have rising Fe/O with energy*

- **What are the key differences between IP shocks with rising and decreasing Fe/O ratios?**

  ➡ *No appreciable differences in shock properties*

- **Does any particular local shock parameter play a role in determining the energy-dependent behavior of Fe/O?**

  ➡ *Cannot rule this out completely, but no evidence that local shock properties are important*

- **The primary cause of rising Fe/O in IP shocks**

  ➡ *Re-acceleration of energetic ion seed spectra that themselves have rising Fe/O with energy*

THE END

He mass histograms during quiet periods 1997-1999

- *Energetic ^{3}He ions from impulsive flares are present in the interplanetary medium*

- *Remnant impulsive ^{3}He-rich material could be re-accelerated at CME-driven IP shocks*

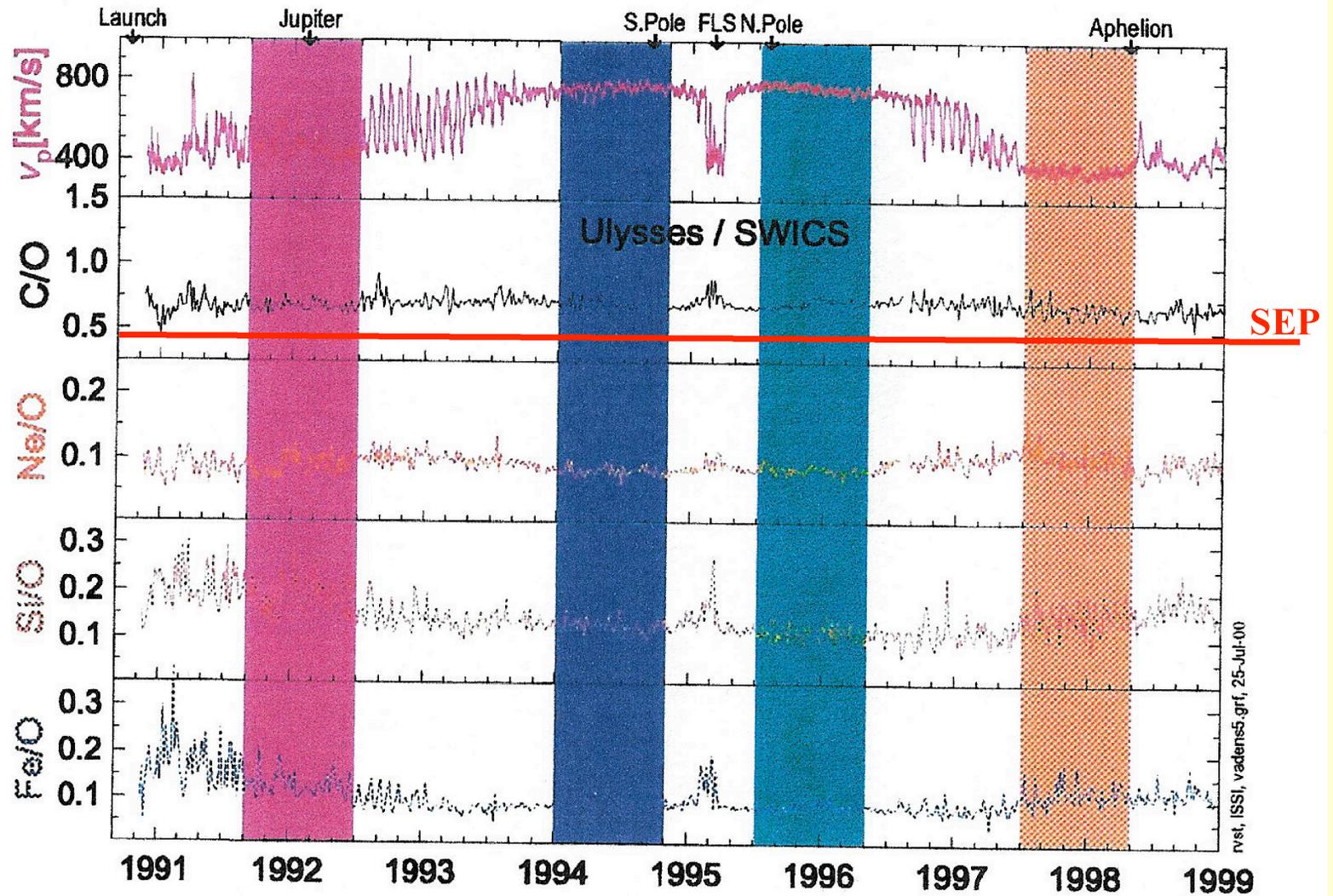- *IP shock abundances should exhibit solar cycle dependence*

ACE / ULEIS quiet time Helium - "Level B"
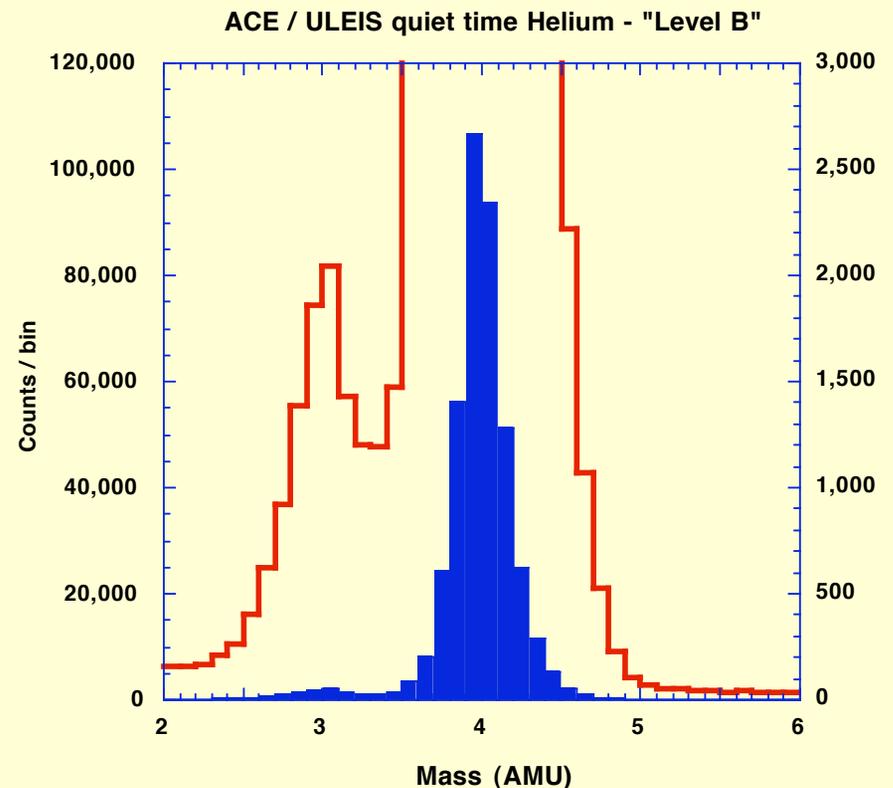
(Mason et al. 1999 ApJ, 525, L133).
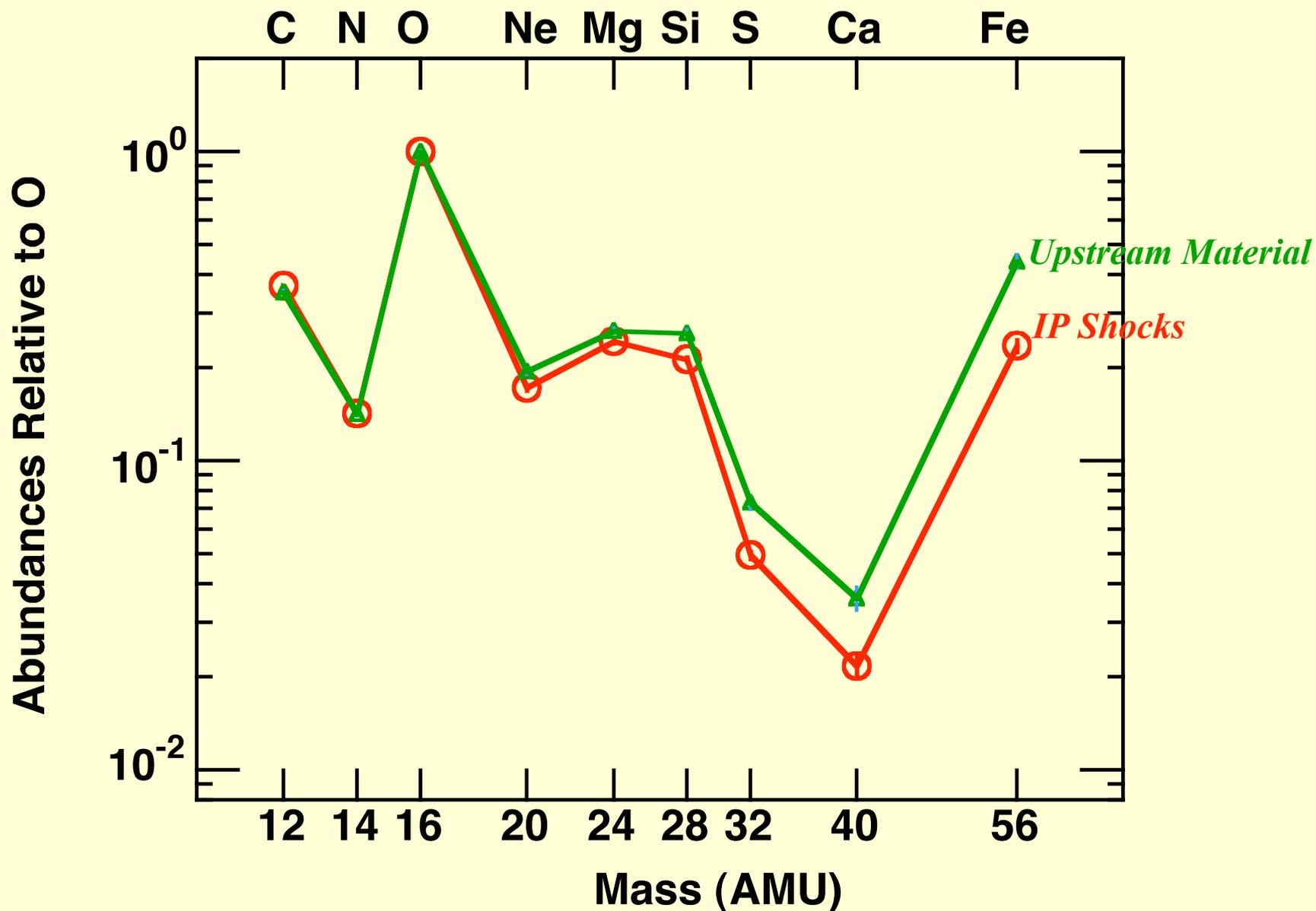
Wind/STEP ~100 keV n⁻¹ Fe Intensity
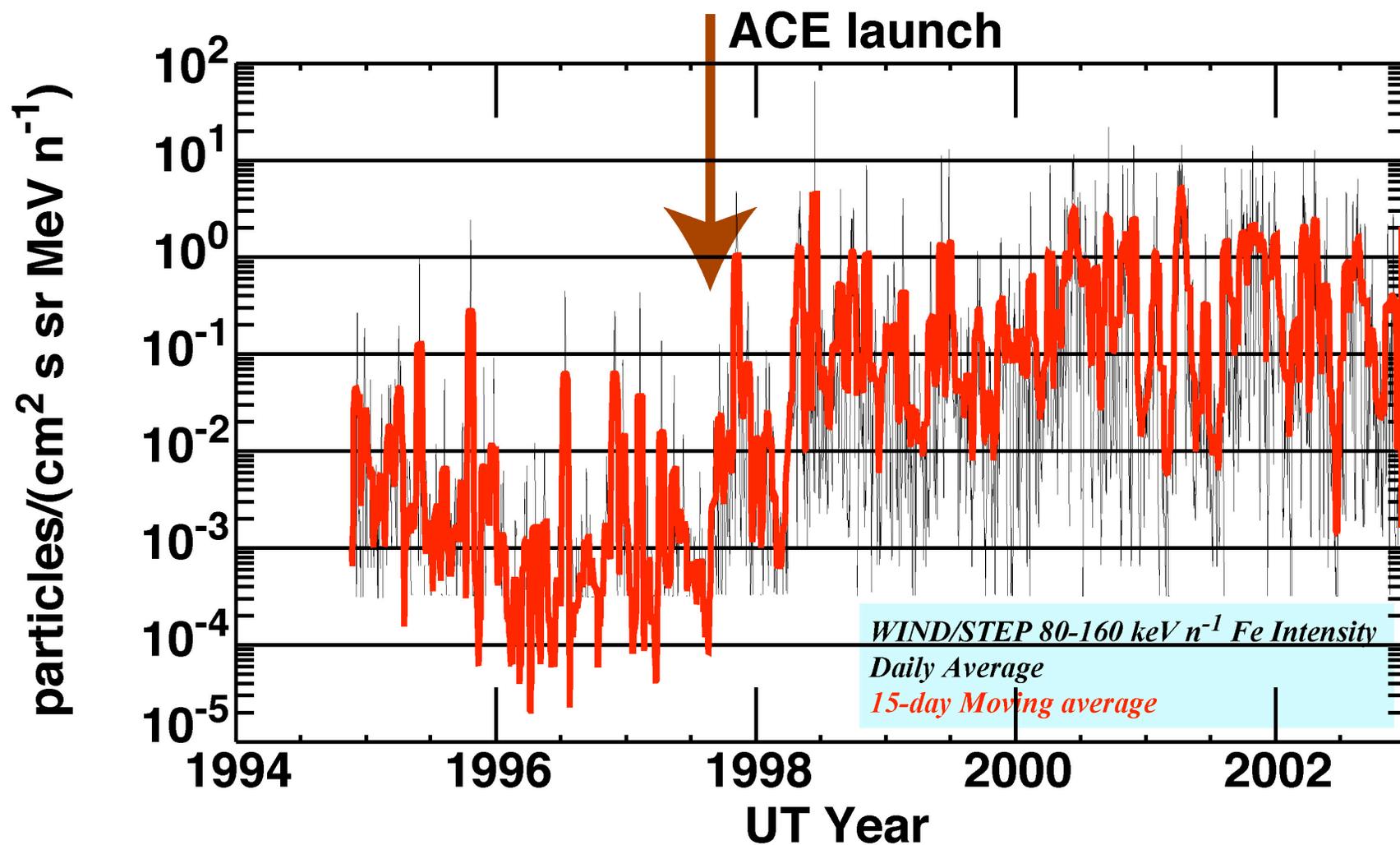
Solar Wind Abundance Ratios

von Steig

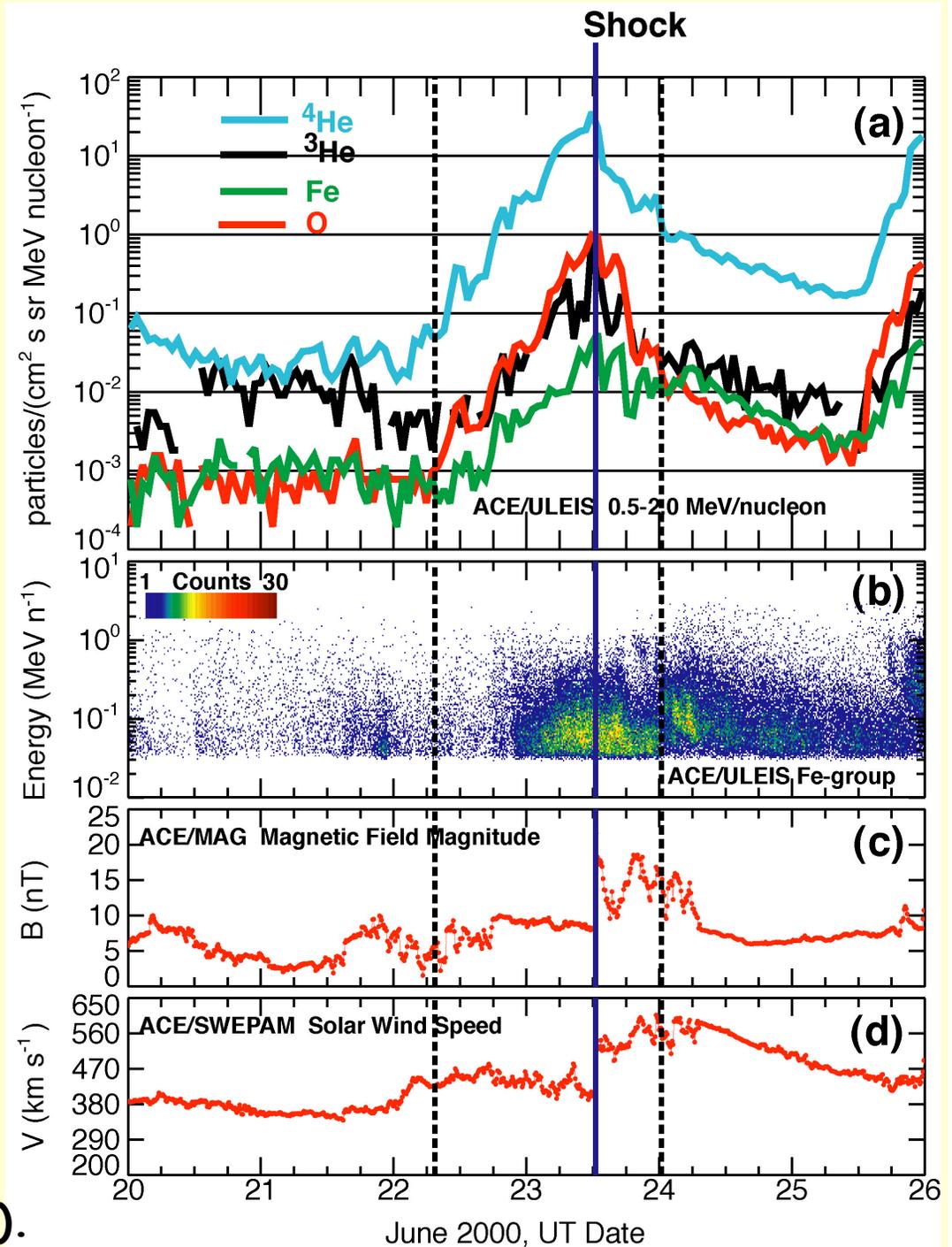Von Steiger et al., (2000, JGR , vol. 105, 27217)

Shock Abundances and Ambient Abundances
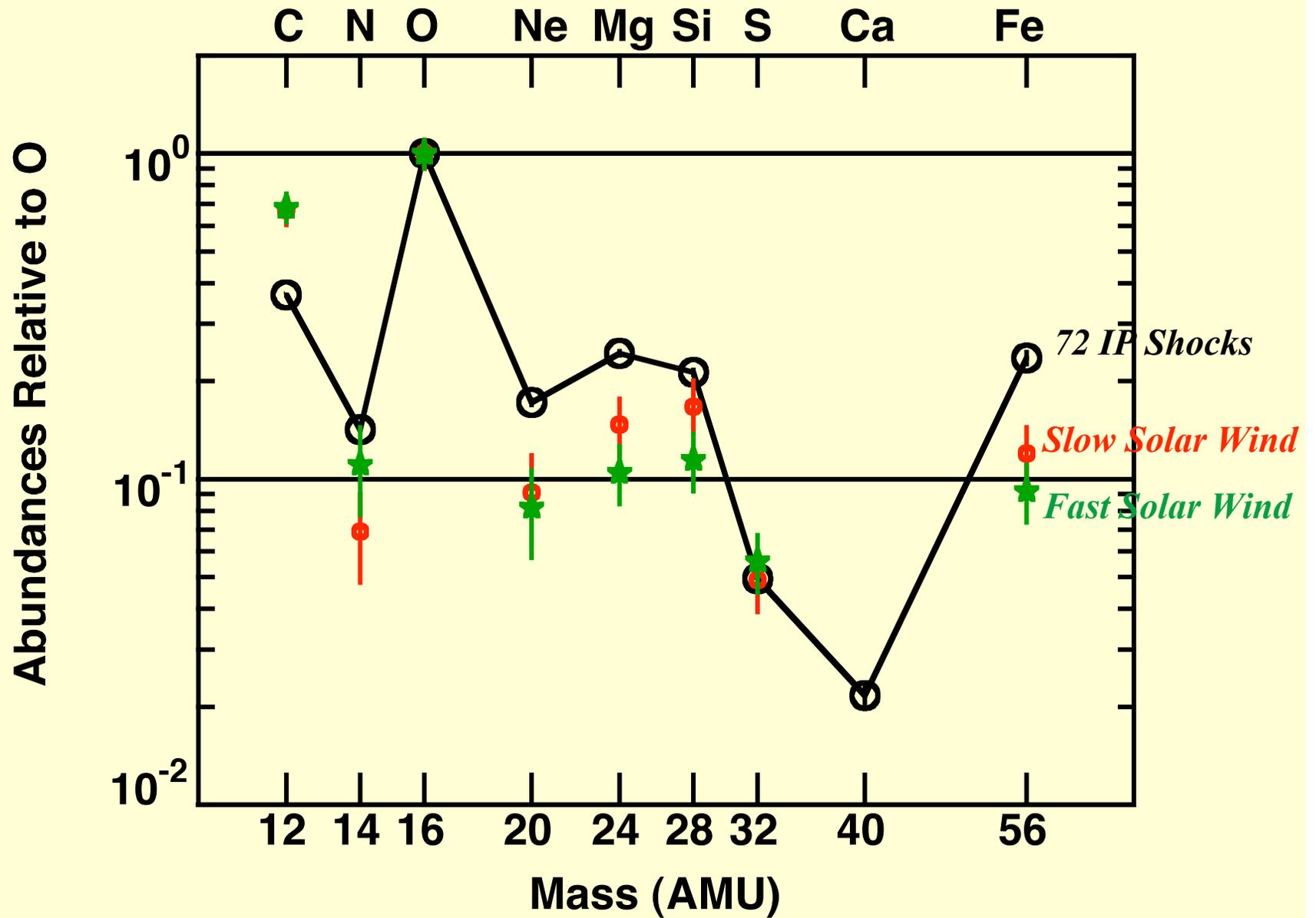

(Desai et al. 2003 ApJ, 588, 1149).

Intensity-time profiles for an IP shock

Surveyed 72 IP shocks between Oct. 1997– Oct. 2002

(Desai et al. 2003 ApJ, 588, 1149).

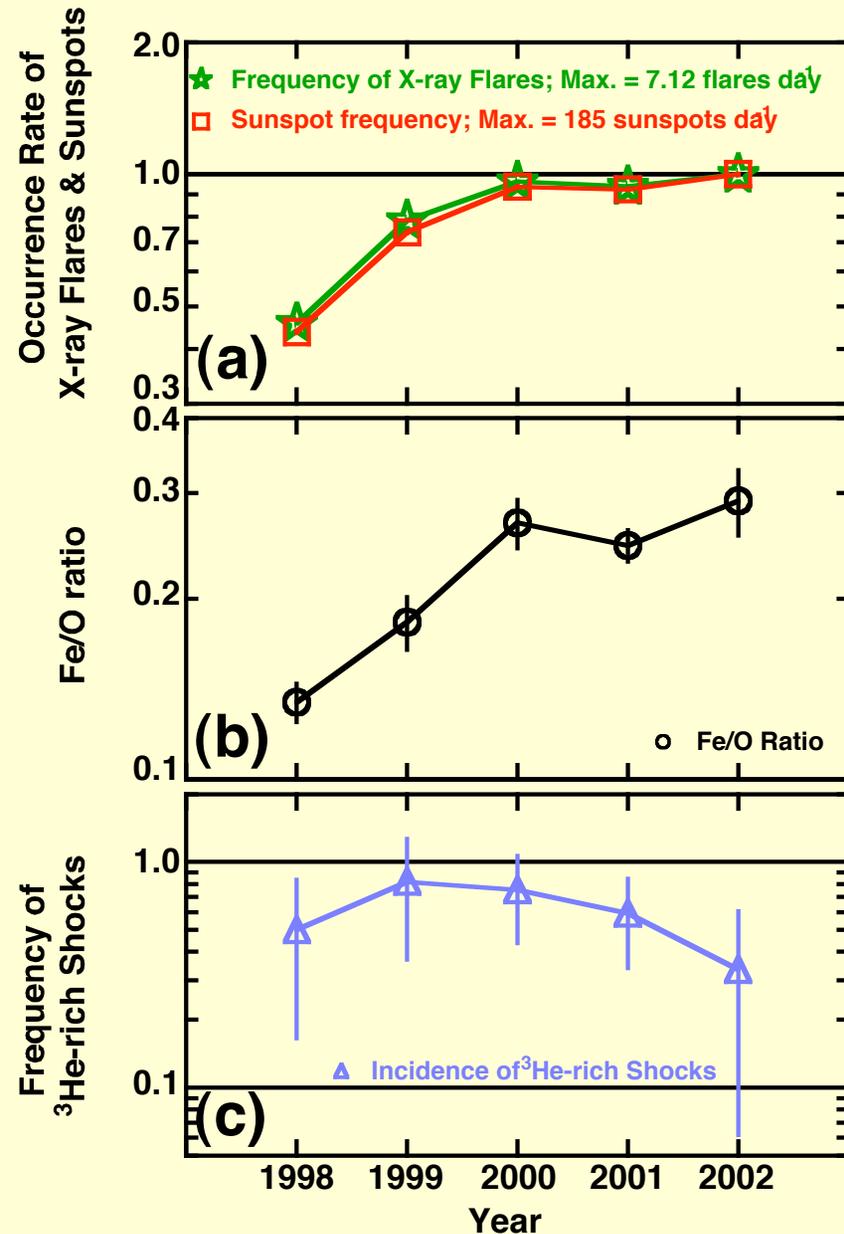**Shock abundances versus solar wind**

C N O Ne Mg Si S Ca Fe

Abundances Relative to O

10^0

10^{-1}

10^{-2}

72 IP Shocks

Slow Solar Wind

Fast Solar Wind

12 14 16 20 24 28 32 40 56

Mass (AMU)
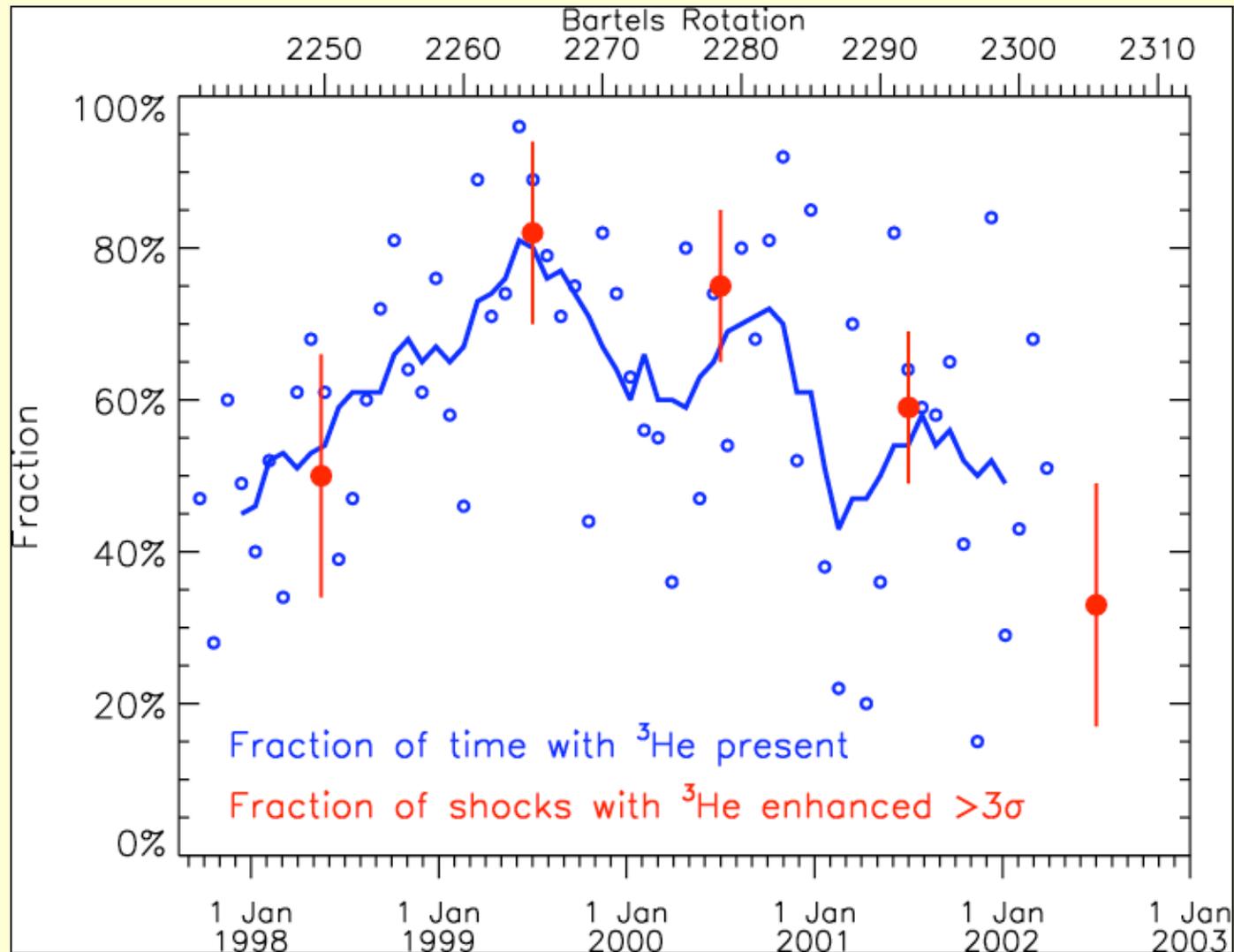
(Desai et al. 2003 ApJ, 588, 1149).

Solar cycle dependence of shock abundances

- *Fe/O ratio in interplanetary medium and in IP shocks show clear solar cycle dependence*

- *Solar wind abundances show no such solar cycle effects*

- *Dominant source of material is not solar wind but interplanetary suprathermals*

(Desai et al. 2003 ApJ, 588, 1149).

(a) Occurrence Rate of X-ray Flares & Sunspots
- Frequency of X-ray Flares; Max. = 7.12 flares day^{-1}
- Sunspot frequency; Max. = 185 sunspots day^{-1}

(b) Fe/O ratio
- o Fe/O Ratio

(c) Frequency of ^{3}He-rich Shocks
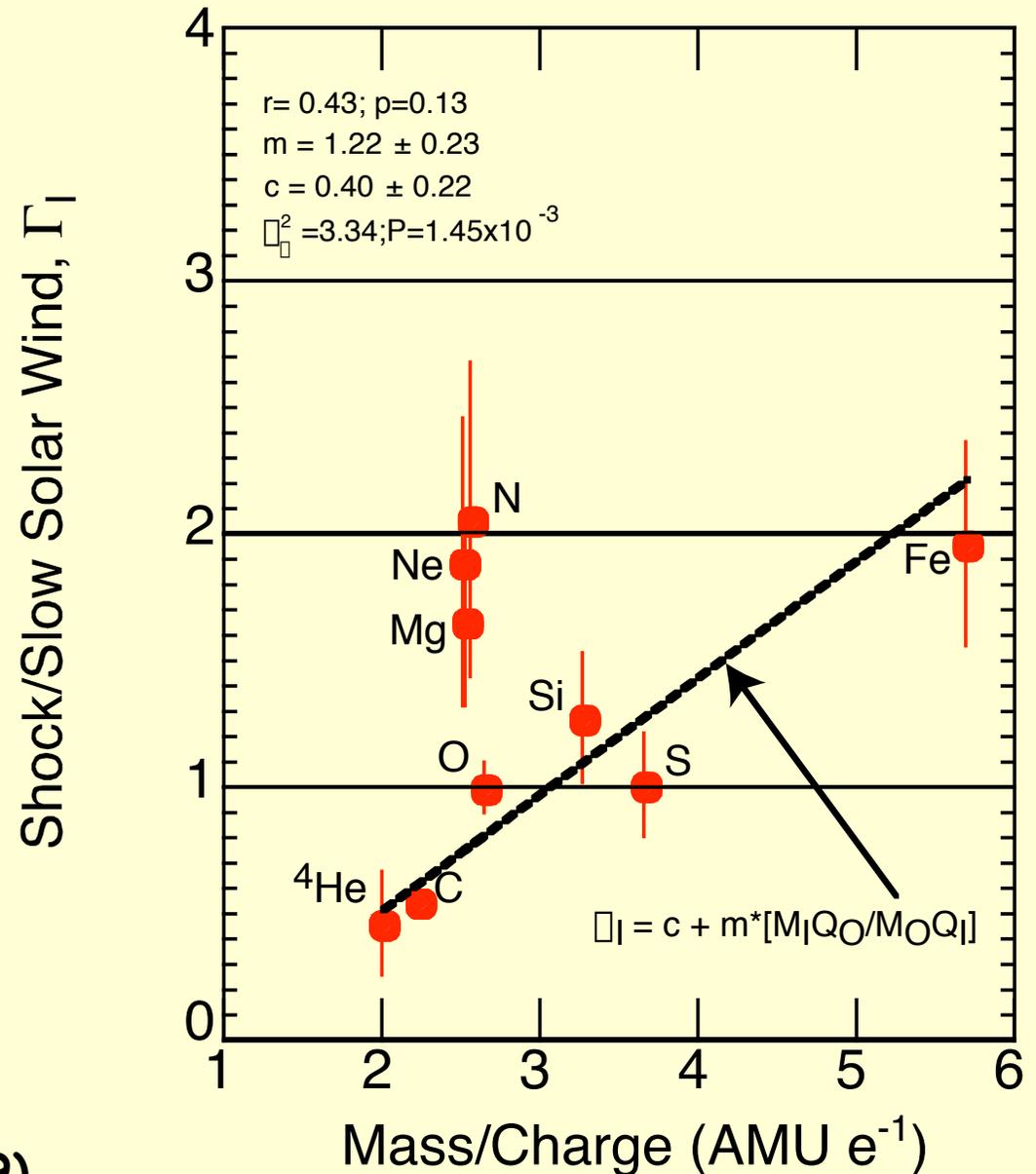- △ Incidence of ^{3}He-rich Shocks

Year

Frequency of 3He-rich shocks, fraction of time 3He ions are present in the IP medium

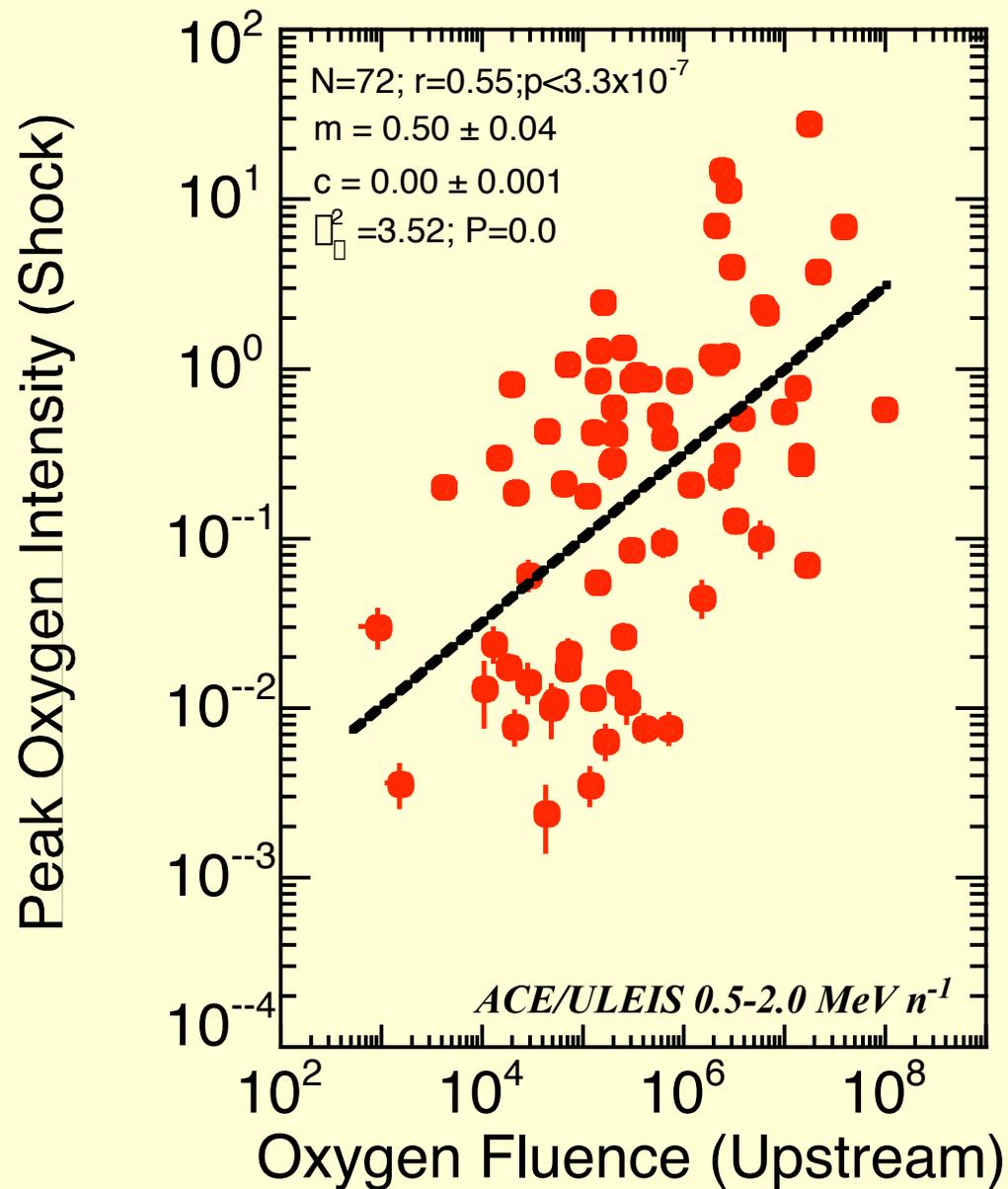(from Desai et al. 2003, ApJ vol. 558, 1149; Wiedenbeck et al SW10).

Shock/Solar Wind Abundances versus M/Q

- *IP shock and solar wind abundances are poorly correlated*

- *Fe is enhanced, while C is depleted by ~40%*

- Difficult to understand in terms of rigidity-dependent acceleration

r= 0.43; p=0.13
m = 1.22 ± 0.23
c = 0.40 ± 0.22
$\chi_v^2 =3.34; P=1.45 \times 10^{-3}$

$\Gamma_I = c + m*[M_I Q_O / M_O Q_I]$

Shock/Slow Solar Wind, Γ_I

Mass/Charge (AMU e^{-1})

(Desai et al. 2003 ApJ, 588, 1149).

Peak Oxygen Intensity at shock vs. Oxygen Fluence during a 5-day interval upstream

N=72; r=0.55; p<3.3x10^{-7}

m = 0.50 ± 0.04

c = 0.00 ± 0.001

χ_v^2 =3.52; P=0.0

ACE/ULEIS 0.5-2.0 MeV n^{-1}

Peak Oxygen Intensity (Shock)
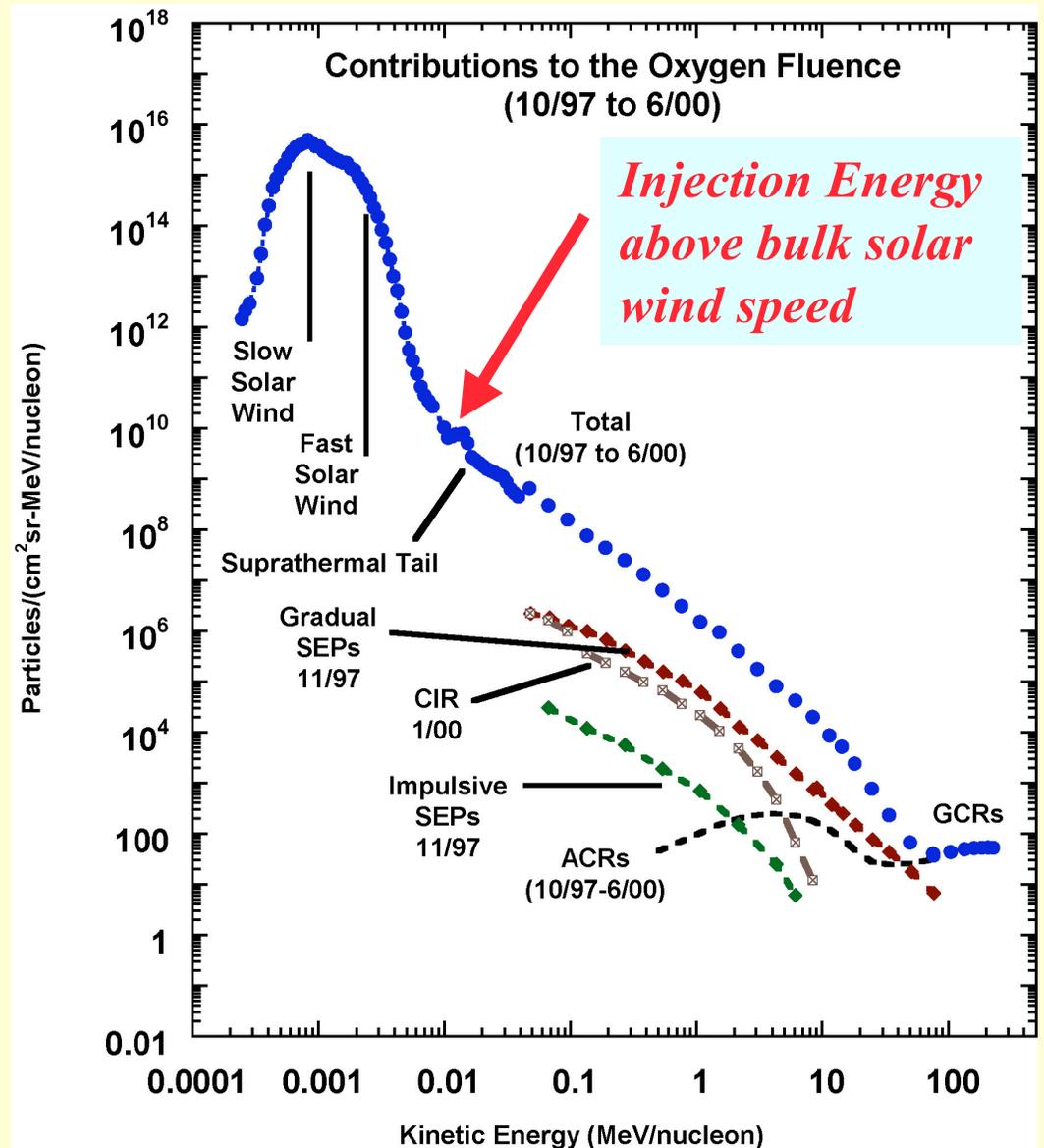
Oxygen Fluence (Upstream)

Contributions to Long-Term O Fluences

Suprathermal tail comprises:

- **Solar wind suprathermals**

- **Interstellar and inner source pickup ions**

- **Residual suprathermals from solar and interplanetary activity**

(Mewaldt et al., 2001 AIP conference Proceedings 598, 165)

Contributions to the Oxygen Fluence (10/97 to 6/00)

Injection Energy above bulk solar wind speed

Slow Solar Wind

Fast Solar Wind

Suprathermal Tail

Total (10/97 to 6/00)

Gradual SEPs 11/97

CIR 1/00

Impulsive SEPs 11/97

ACRs (10/97-6/00)

GCRs

Particles/(cm²sr-MeV/nucleon)
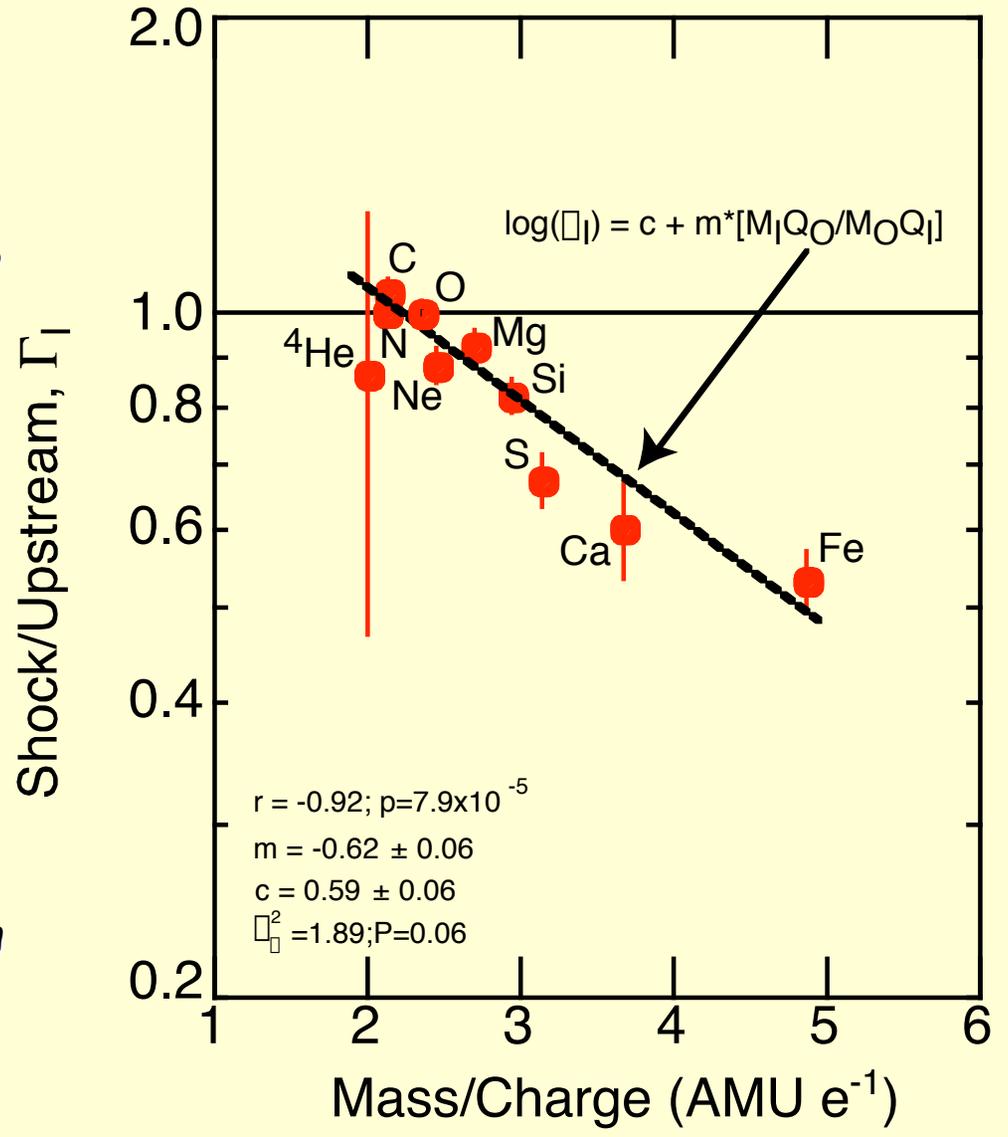
Kinetic Energy (MeV/nucleon)

Wind/STEP ~100 keV n⁻¹ C/O and Fe/O ratios

C/O and Fe/O ratios exhibit a clear solar cycle behavior

CIR-like at solar minimum SEP-like at solar maximum

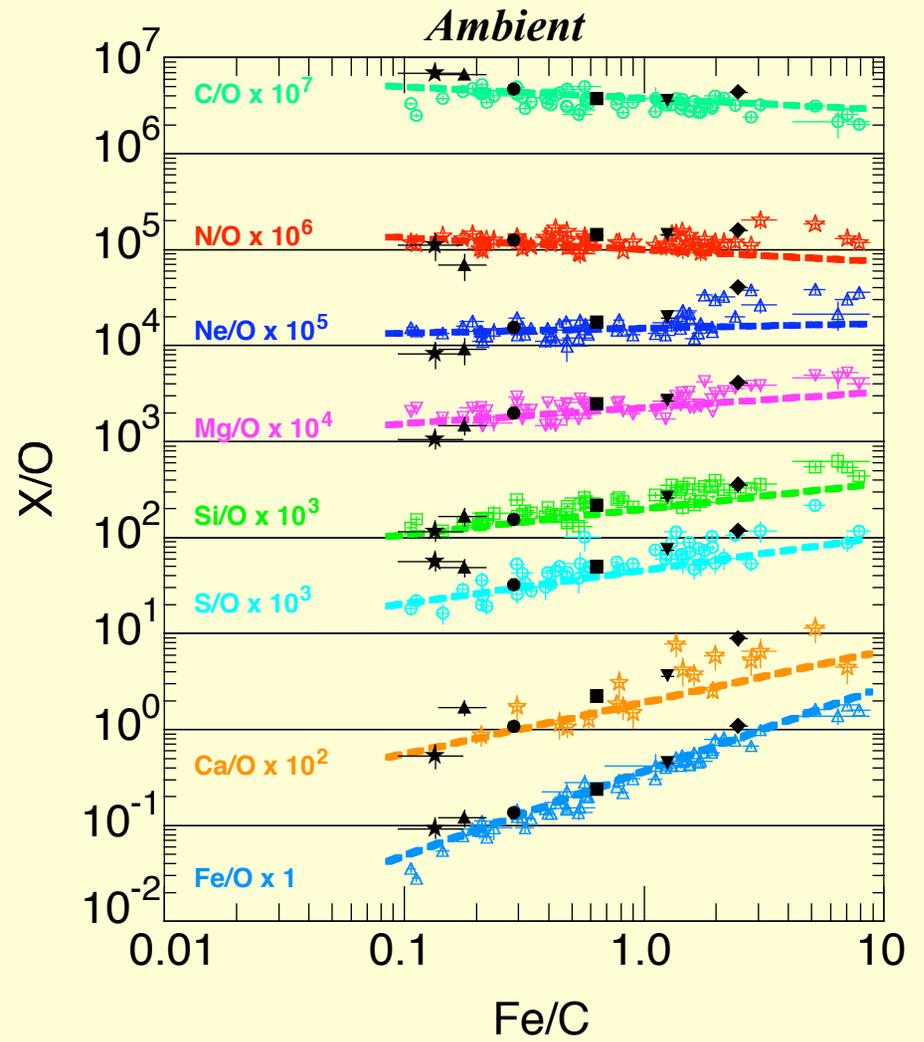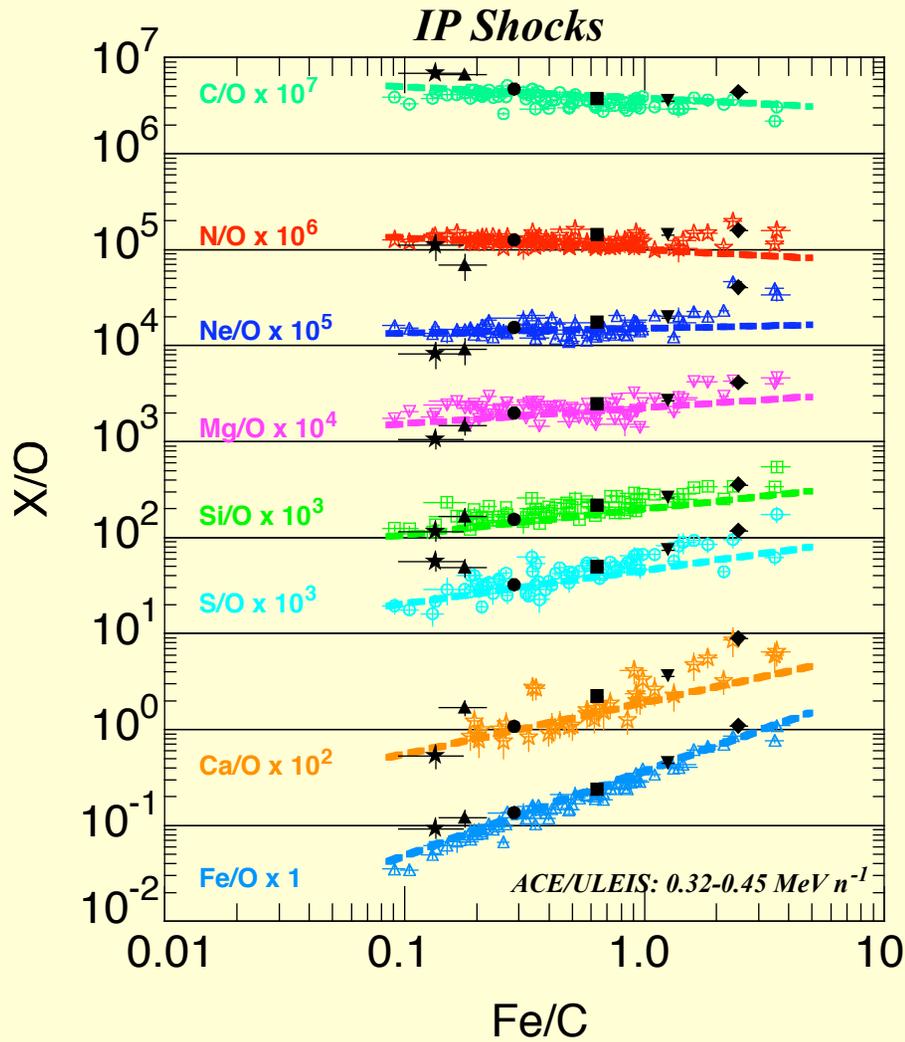Wind/STEP::80-160 keV/n Daily Ratios
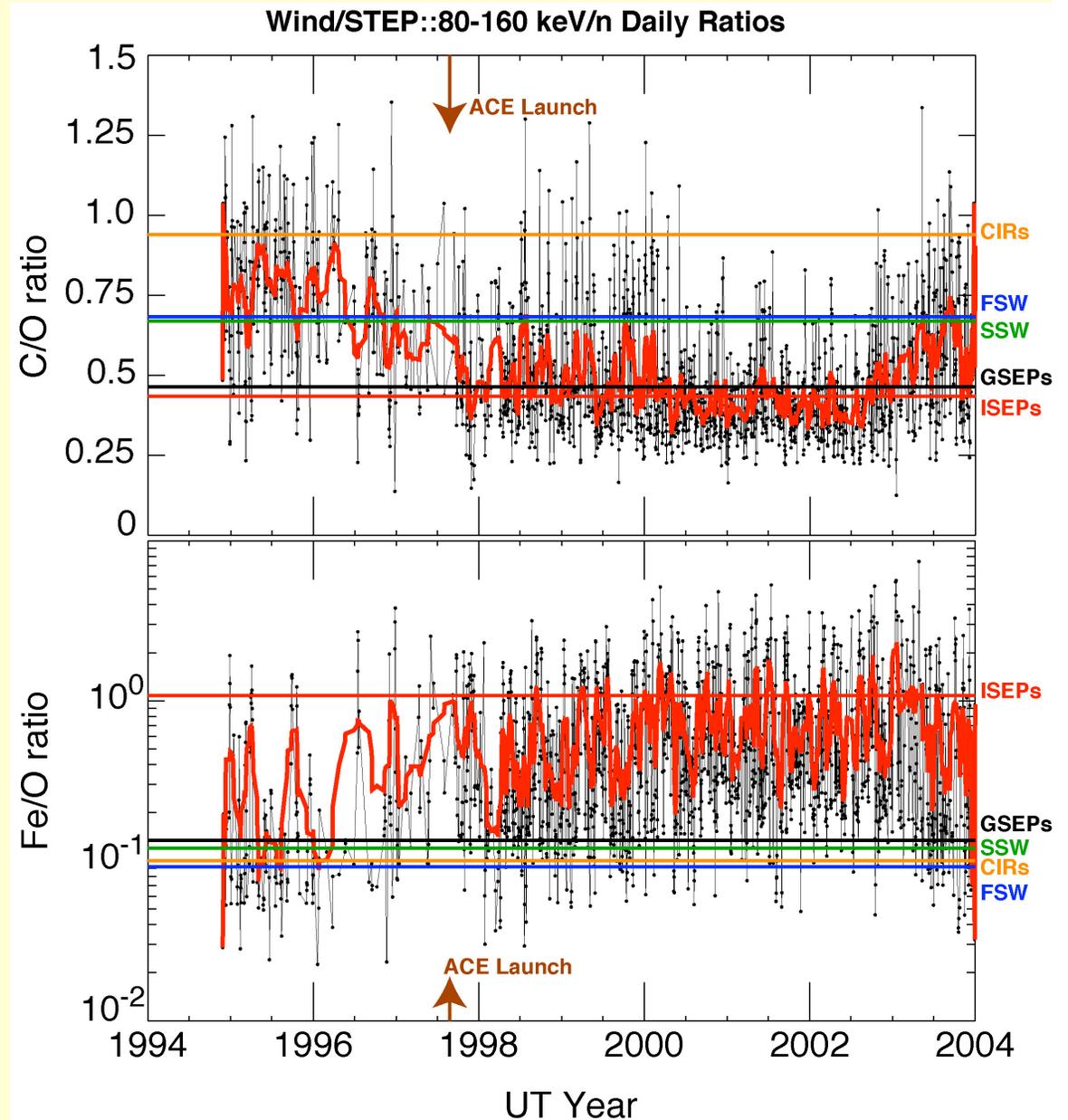
Shock /Ambient versus M/Q

- *C/O & N/O ratios similar in IP shocks and ambient*

- *Ne-Fe abundances show an M/Q-dependent depletion; Fe is depleted by 30-40%*

- *Systematic differences due to rigidity-dependent acceleration*

$$\log(\Gamma_I) = c + m^*[M_I Q_O / M_O Q_I]$$

$r = -0.92; p = 7.9 \times 10^{-5}$
$m = -0.62 \pm 0.06$
$c = 0.59 \pm 0.06$
$\chi^2_\upsilon = 1.89; P = 0.06$

(Desai et al. 2003 ApJ, 588, 1149).

3 Classes of Fe/O energy-dependence

ACE/ULEIS: 0.32-0.45 MeV n^{-1}

IP Shocks

Ambient

C/O x 10^7
N/O x 10^6
Ne/O x 10^5
Mg/O x 10^4
Si/O x 10^3
S/O x 10^3
Ca/O x 10^2
Fe/O x 1

X/O
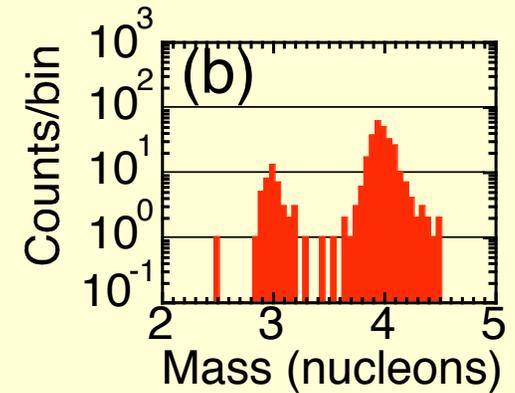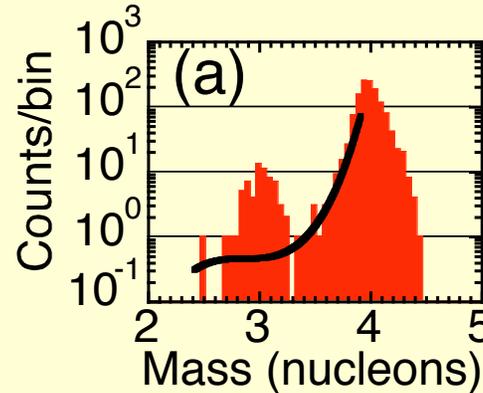
Fe/C

(Desai et al. *To appear in ApJ.Aug. 20, 2004 issue*)

Helium Mass histograms for 6 IP shocks
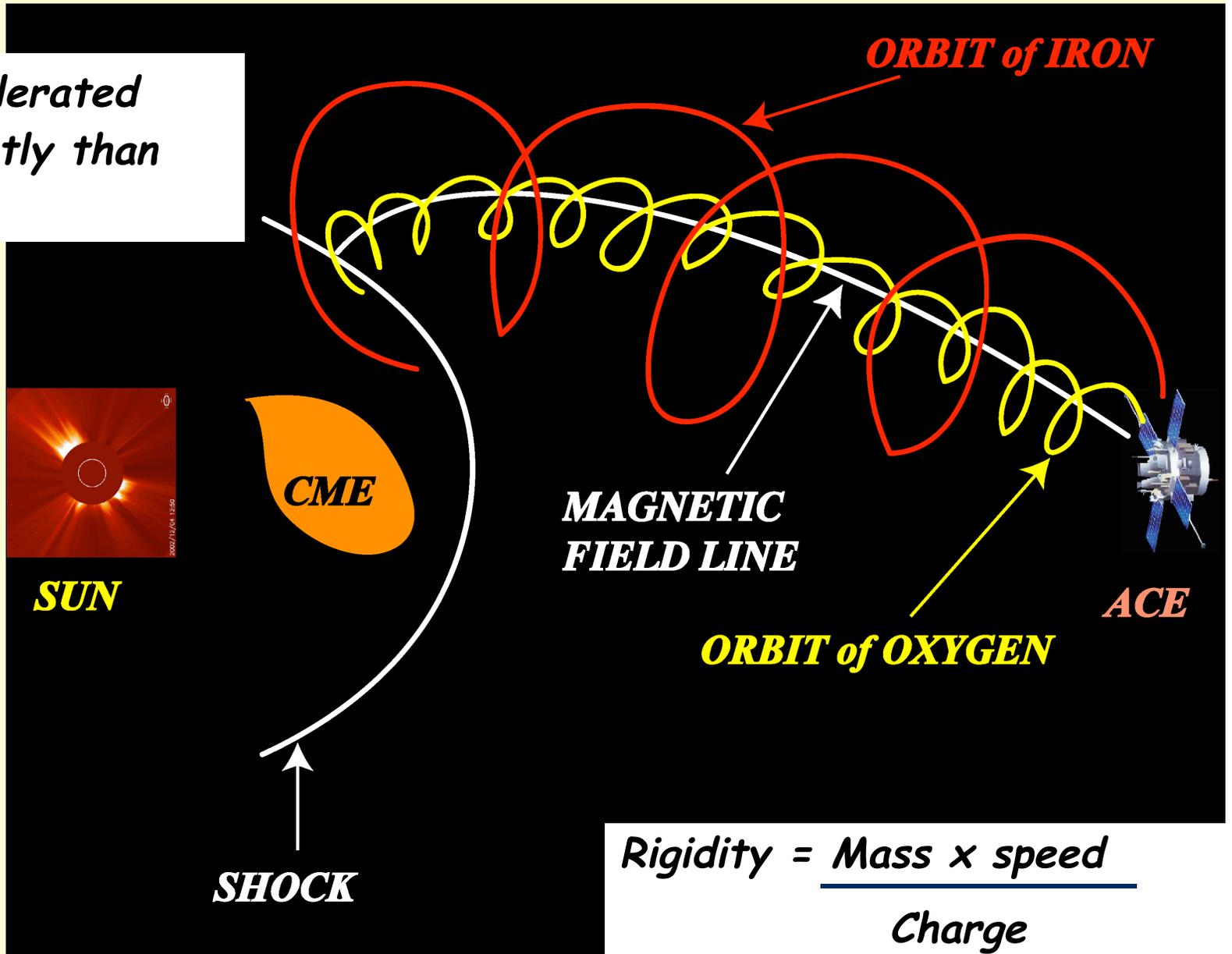
- *³He ions accelerated in 45 IP shocks*

- *Enhancements between factors of ~4-2000 over solar wind value*

- *³He/⁴He ratio ~100 times greater the solar wind value in 7 events*
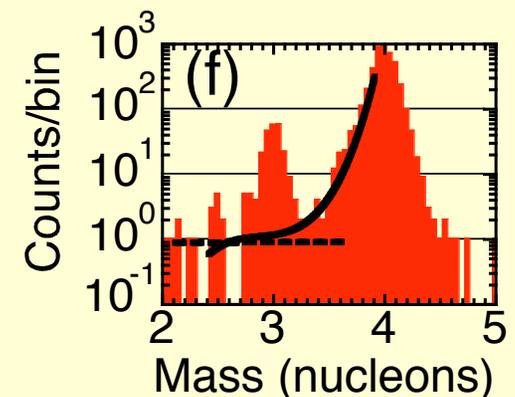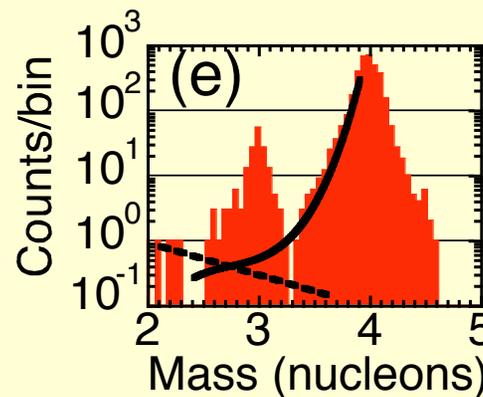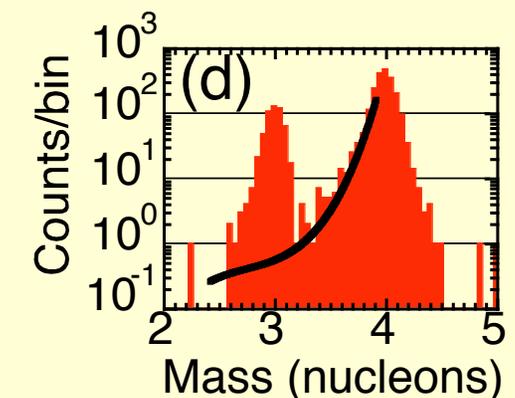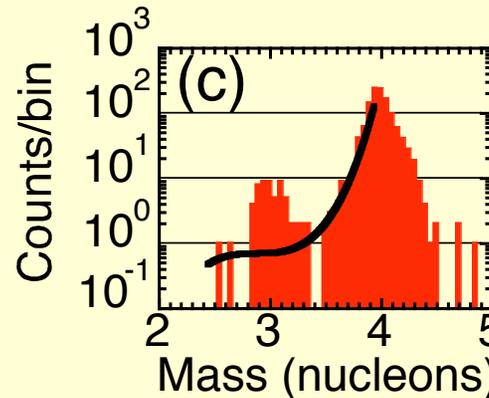
(Desai et al. ApJ 2001 553, L89)

Rigidity-dependent acceleration at shocks

Iron is accelerated less efficiently than oxygen

ORBIT of IRON

SUN

CME

MAGNETIC FIELD LINE

ORBIT of OXYGEN

ACE

SHOCK

$$Rigidity = \frac{Mass \times speed}{Charge}$$

Motivation

- How common are IP shock events with rising Fe/O ratios?

- What are the key differences between IP shocks with rising and decreasing Fe/O ratios?

- Does any particular local shock parameter play a role in determining the energy-dependent behavior of Fe/O?

- What causes the energy-dependent behavior of Fe/O in IP shocks?