Finite-Time Shock Acceleration and Fits to ESP Ion Spectra

Chanruangrith Channok,[1] David Ruffolo,[1] Mihir Desai,[2] and Glenn Mason[2]
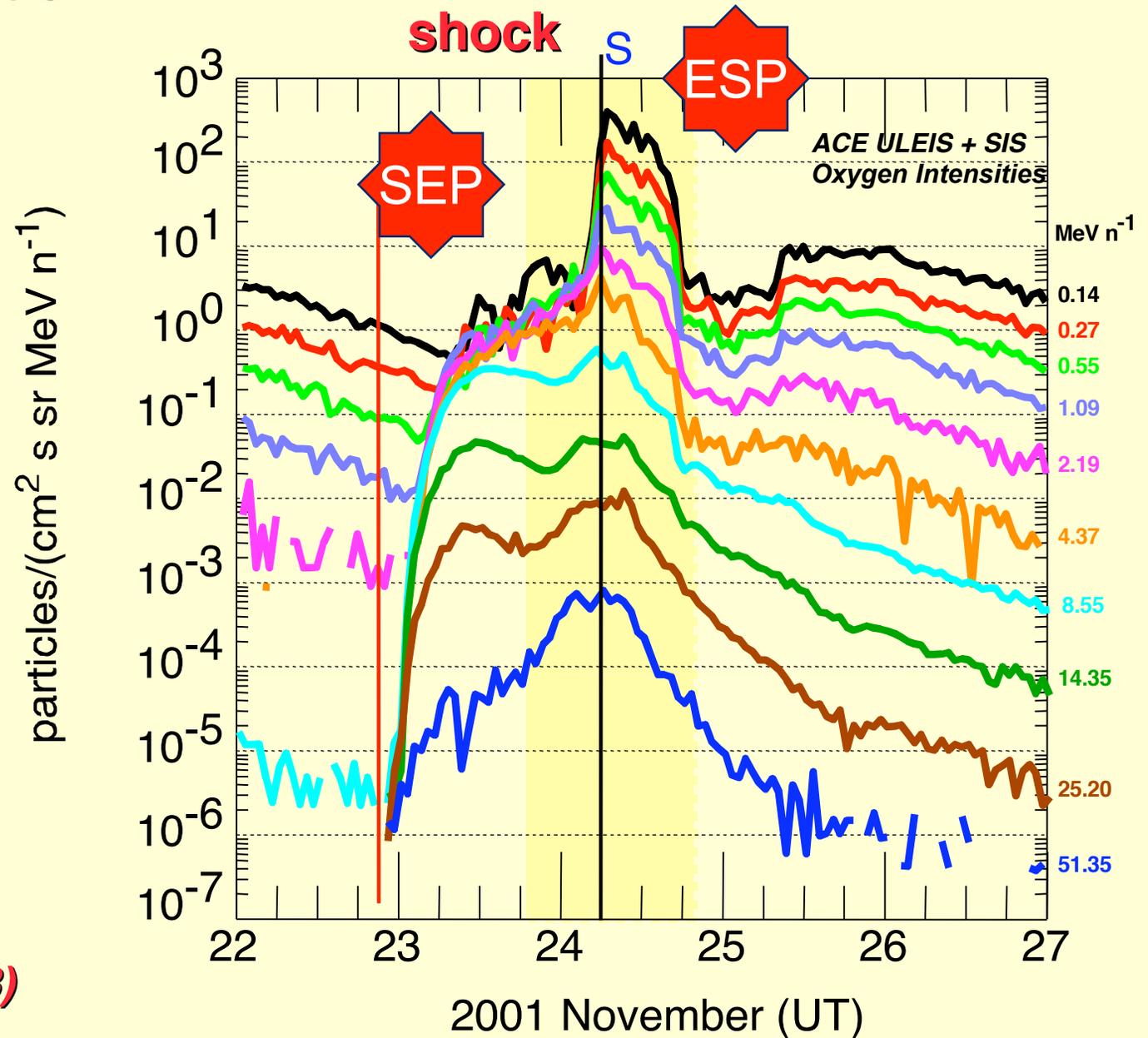
[1]THAILAND   [2]USA

... *and in the spirit*
End-to-End Modeling of CMEs and SEPs,
a few words on

- Modeling SEP transport to infer injection and transport parameters

- Interplanetary turbulence and perpendicular transport

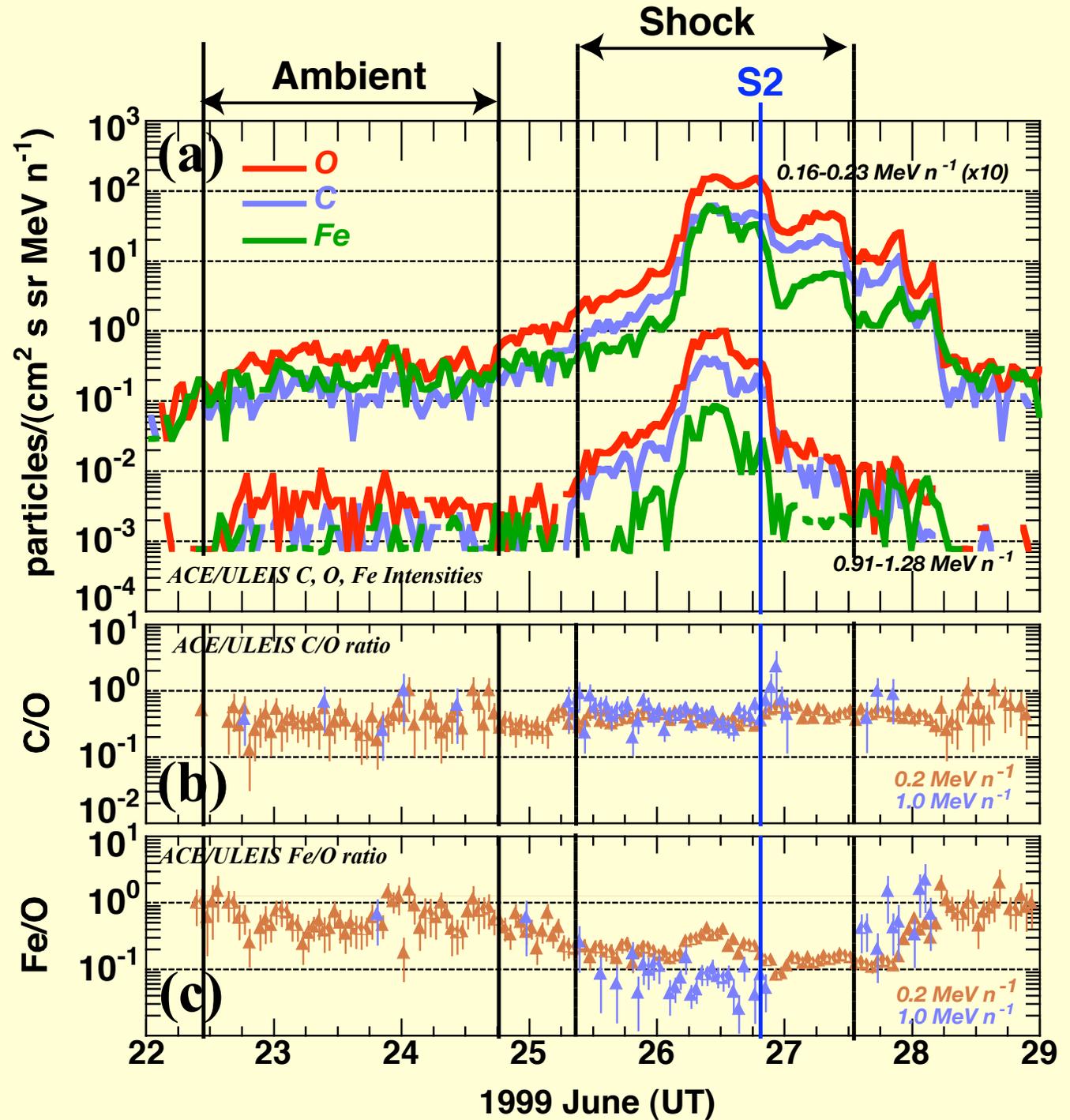**Oxygen Intensities for November 24 2001 IP shock**

(Desai et al. 2003)

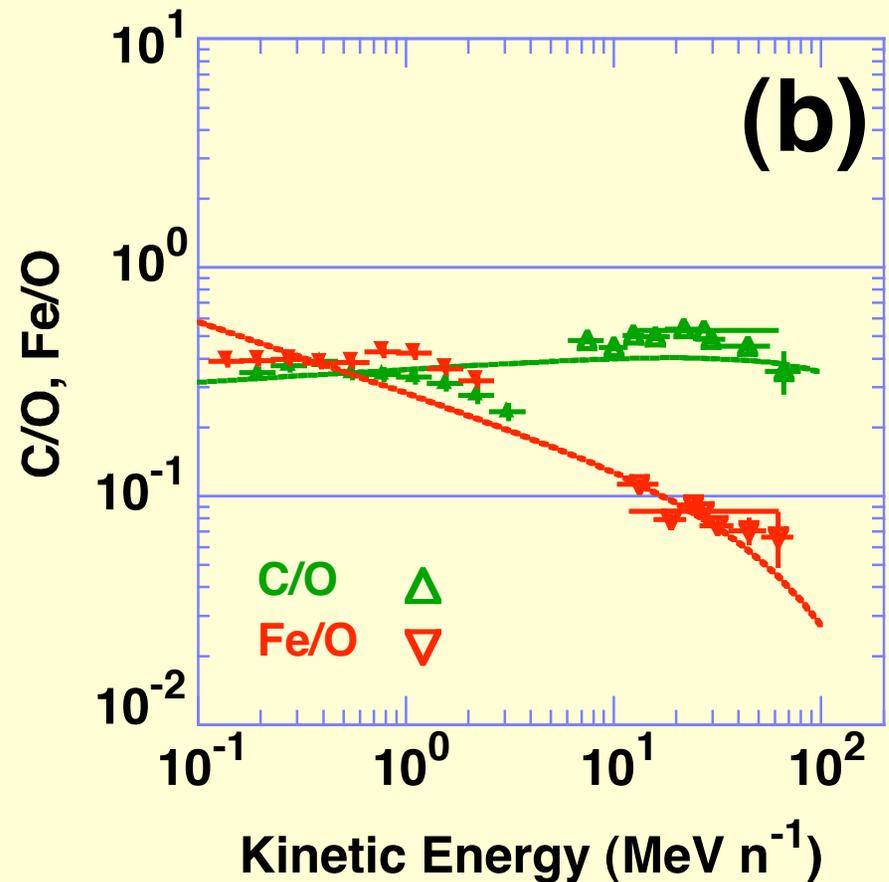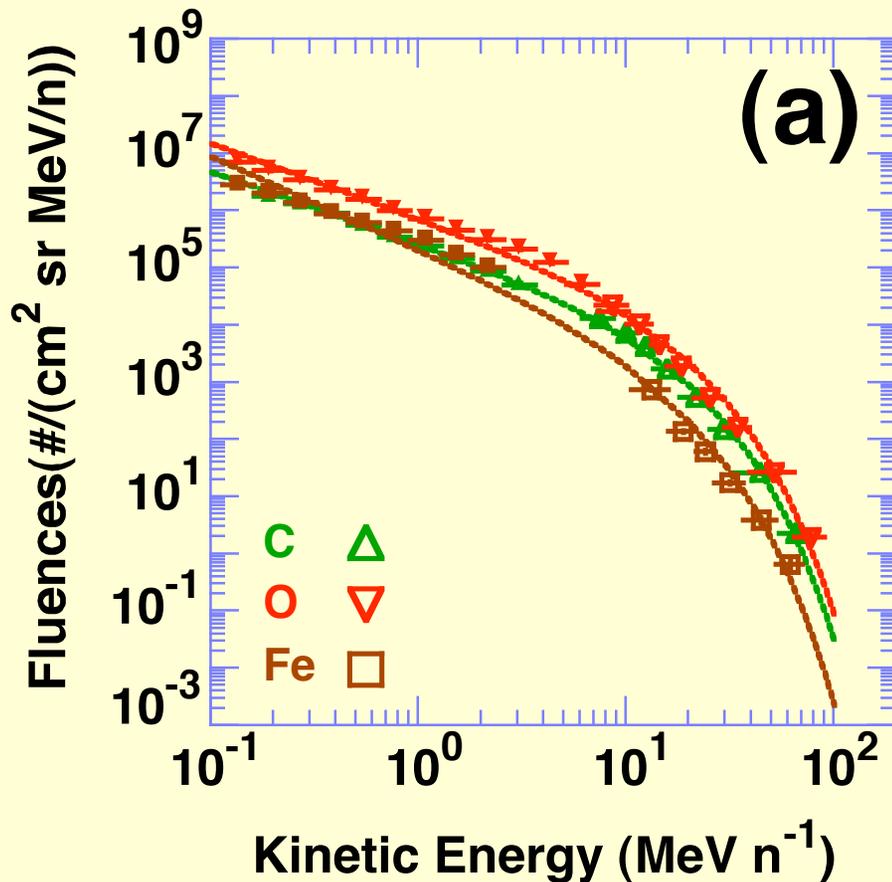Fe/O at IP shocks is depleted relative to ambient values

Larger decrease at higher energy

(Desai et al. 2004)

Spectra and abundances for Nov. 24 2001 IP shock

(Desai et al. 2004, ApJ).

Why do ESP spectra roll over at ~ 0.1 - 10 MeV/n?

(data - see also: Gosling et al. 1981; van Nes et al. 1985)

Possible mechanisms suggested by Ellison & Ramaty (1985)

- shock thickness ~ $\_/u$ → energy is too low

- drift over shock width → rollover at ~ 100 MeV/Q

- finite time for shock acceleration → *considered here*

  (see also: Klecker et al. 1981; Lee 1983)

Finite-Time Shock Acceleration

- Probability approach (like Bell 1978, Drury 1983)
- Acceleration rate, $r = 1/\_t$ Escape rate, ε

  Time at present (age of shock), t

  Simulation parameters:

- $\_ = \_0 (P/ MV)\_$ so vary $\_0$ and $\_$ (shorter $\_0$ is equivalent to longer time duration)
- Time t fixed by observations, $v_0 = 200\ km/s$ in wind frame, shock angles & speeds as observed.

We solve the PDE …

$$\frac{\partial N(p,t)}{\partial t} = I(p,t) - \frac{\partial}{\partial p}\left[R(p,t)\,N(p,t)\right] - \epsilon(p,t)N(p,t),$$

… discretized as a system of ODEs

$$\frac{dN_n(t)}{dt} = I_n - (r_n + \epsilon_n)N_n(t) + r_{n-1}N_{n-1}(t).$$

Initial & inflow conditions correspond to the observed ambient seed spectrum

Rollover energy (E_c/A)

(well above injection energy)

$\underline{\quad = \text{const.}\quad}$

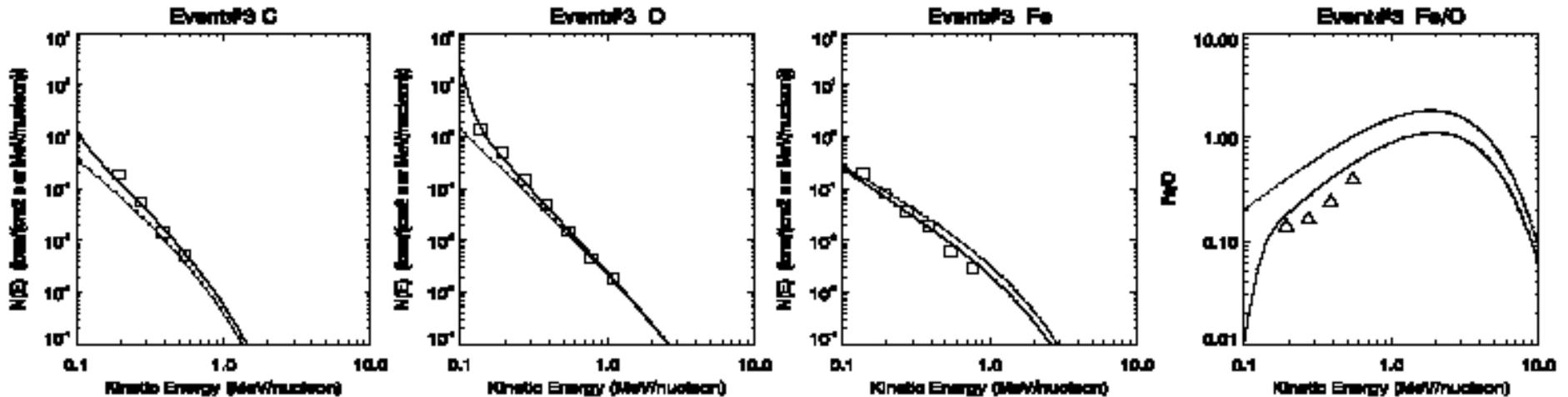$$E_c/A \propto t^2, \text{ independent of } Q/A$$

$\underline{\quad \propto P_-\quad}$

$$E_c/A \propto t^{2/(\_+1)} (Q/A)^{2\_/(\_+1)}$$

We use the FTSA model to fit 3 ESP events from the sample of Desai et al. (2004):
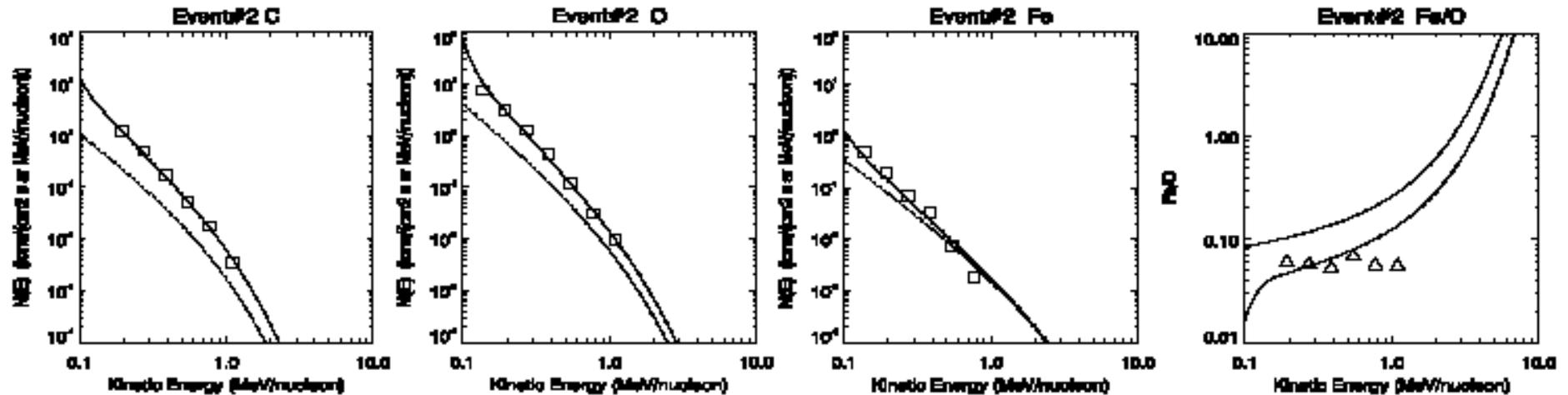
Number	Date of shock passage	θ_1 (deg)	θ_2 (deg)	u_1 (km s^{-1})	u_2 (km s^{-1})	B_2/B_1	t (hours)	λ_0 (AU)	α
1......	1999 Jun 26	50	73	131	56.4	2.2	84.3	0.0040	0.07
2......	1999 Sep 22	64	79	131	54.6	2.3	60.5	0.042	0.10
3......	2000 Oct 05	66	80	188	78.3	2.3	99.3	0.24	0.18

Event #3: $\lambda_0 = 0.24$ AU, $\tau = 0.18$

- τ is consistent with typical IP values
- FTSA rollover is at lower E,
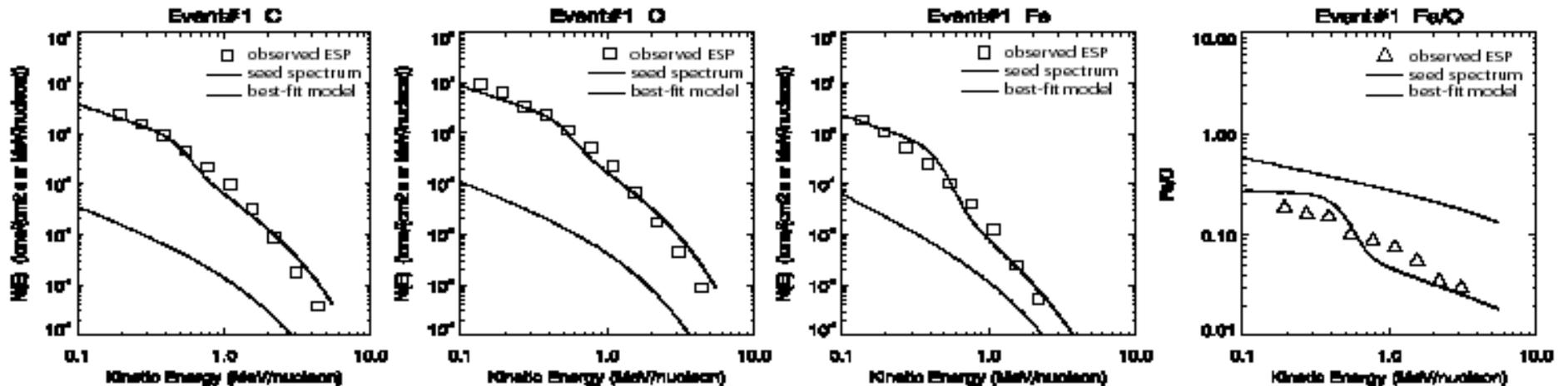 minor accel. of seed population

Event #2: $\lambda_0 = 0.042$ AU, $\tau = 0.10$

- τ is smaller but not inconsistent with IP values
- FTSA rollover is at lower E,
    moderate accel. of seed population

Event #1: $\kappa_0 = 4.0 \times 10^{-3}$ AU, $\delta = 0.07$
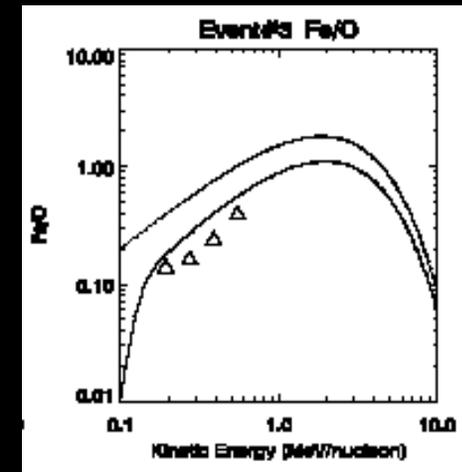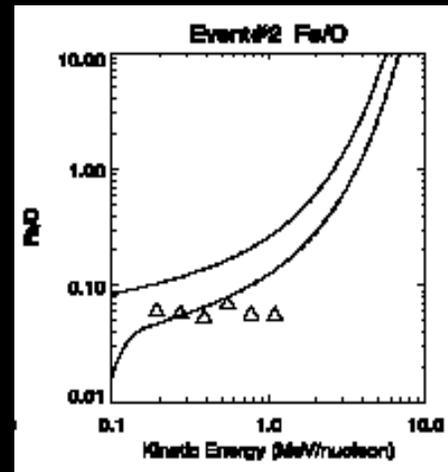

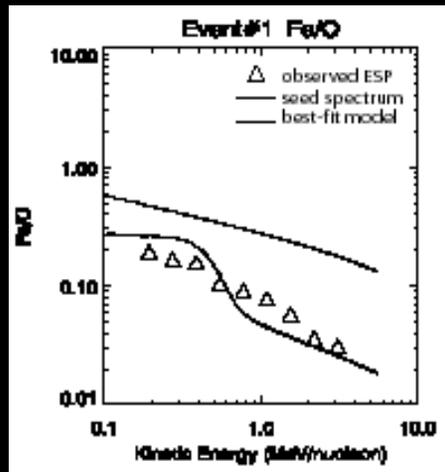- δ at shock is much lower than typical IP values …
- … as expected for proton-amplified waves [Ng et al. 1999]
- model rollover is sharper than observed, probably
  due to use of spatially const. κ

Fe/O ratios

- Fe/O lower at shock, due to higher _ for Fe
- model does not match observed trend for Event 2
- expect trend vs. E like seed population above the rollover

Conclusions on ESP spectra …

1. Finite-time shock acceleration model
   - power law spectrum at low energy
   - faster dropoff at high energy
2. Expect E_c/A _ $.^{2/(\_+1)}$ $(Q/A)^{2\_/(\_+1)}$
3. For 3 events, able to simultaneously fit measurements
   of C, O, and Fe ions
4. Fits to weak events: Infer _ as typical IP values
5. Fit to strong event: Infer much lower _, consistent with
   expectations for proton-amplified waves

… but wait – there's more!

Key processes of interplanetary transport

- Scattering   [Jokipii 1966]
- Focusing (a.k.a. mirroring)   [Roelof 1969]
- Solar wind effects   [DR 1995]
  - Convection
  - Adiabatic deceleration

Note: mean free path is ~ 0.1 to 3 AU

Aim to <u>quantitatively</u> explain profiles of <u>intensity</u> & <u>anisotropy</u> vs. time

Pitch-angle transport equation [DR, ApJ '95]

$$\frac{\partial F(t,\mu,z,p)}{\partial t} = -\frac{\partial}{\partial z}\mu v F(t,\mu,z,p) \qquad \text{(streaming)}$$

$$-\frac{\partial}{\partial z}\left(1-\mu^2\frac{v^2}{c^2}\right)v_{sw}\sec\psi F(t,\mu,z,p) \qquad \text{(convection)}$$

$$-\frac{\partial}{\partial\mu}\frac{v}{2L(z)}\left[1+\mu\frac{v_{sw}}{v}\sec\psi - \mu\frac{v_{sw}v}{c^2}\sec\psi\right]$$

$$\cdot(1-\mu^2)F(t,\mu,z,p) \qquad \text{(focusing)}$$

$$+\frac{\partial}{\partial\mu}v_{sw}\left(\cos\psi\frac{d}{dr}\sec\psi\right)\mu(1-\mu^2)$$

$$\cdot F(t,\mu,z,p) \qquad \text{(differential convection)}$$

$$+\frac{\partial}{\partial\mu}\frac{\varphi(\mu)}{2}\frac{\partial}{\partial\mu}F(t,\mu,z,p) \qquad \text{(scattering)}$$

$$+\frac{\partial}{\partial p}pv_{sw}\left[\frac{\sec\psi}{2L(z)}(1-\mu^2)+\cos\psi\frac{d}{dr}\sec\psi\mu^2\right]$$

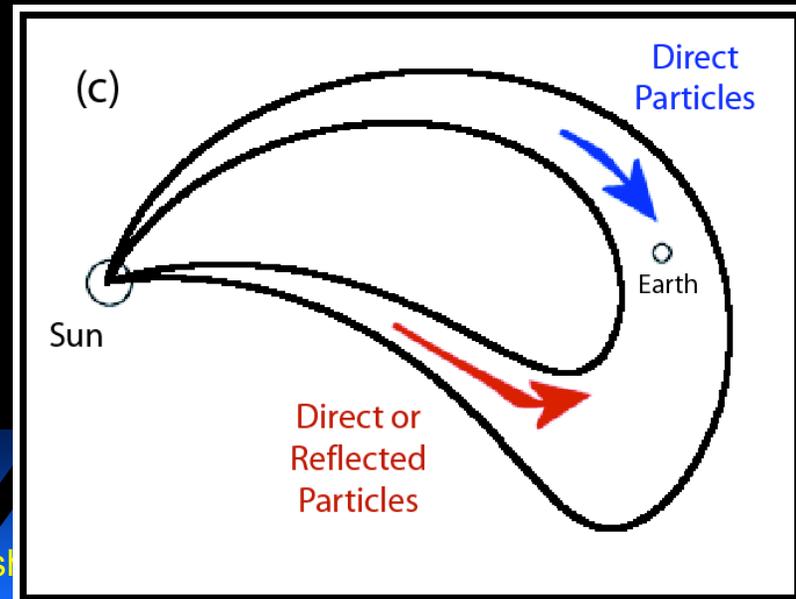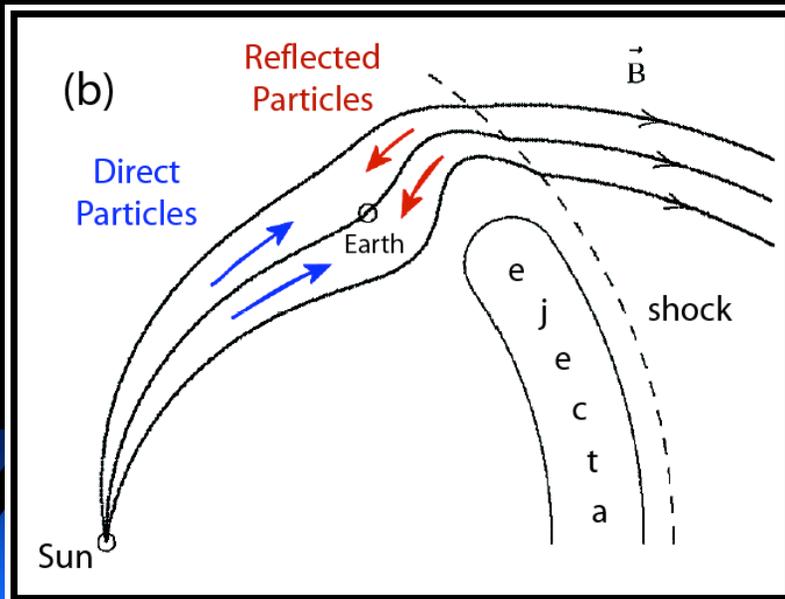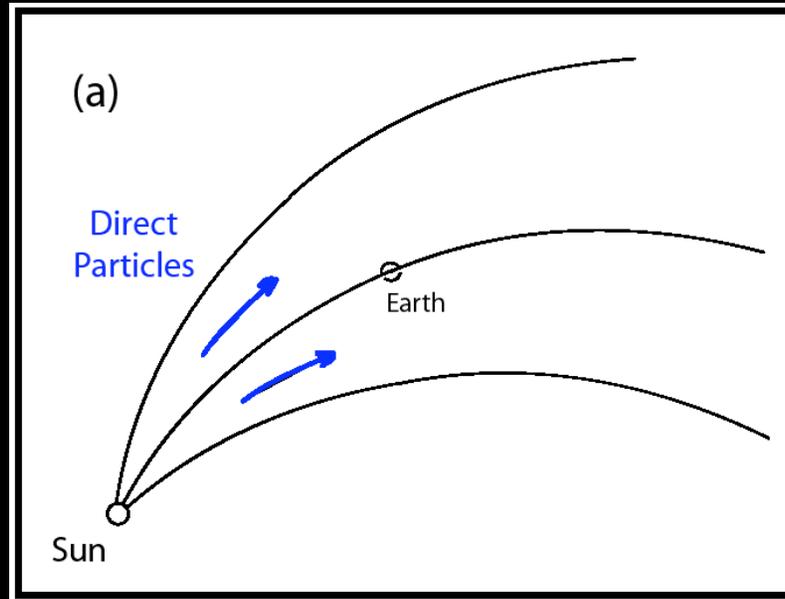$$\cdot F(t,\mu,z,p). \qquad \text{(deceleration)}$$

Simulation of interplanetary transport

- Specify magnetic field configuration

- Solve PDE

- Runs in a few minutes [Nutaro et al. 2001]

Fitting SEP data

- Simultaneous fit to intensity vs. time

  anisotropy vs. time

- Optimal piecewise linear injection (least squares)

- Optimal scattering mean free path, _ [Ruffolo et al. 1998]

- Optimal magnetic configuration [Bieber et al. 2002]

Magnetic Configurations

Results of fitting GLE data (relativistic solar protons)

- Bastille Day: July 14, 2000 - magnetic bottleneck [Bieber et al. 2002]

- Easter: April 15, 2001 - full Spaceship Earth network, 1-minute timing of injection [Bieber et al. 2004]

- October 22, 1989 - injection along both legs of a closed interplanetary loop [poster, this meeting]

- October 28, 2003 … well, we don't claim to understand *everything* … [Bieber et al. 2005]

- January 20, 2005 - possible effect of self-generated waves: nonlinear transport! [poster, this meeting]

Comparison with EM timing

EMISSION	APR. 15, 2001 [Bieber et al. 2004]			OCT. 28, 2003 [Bieber et al. 2005]		
	START	PEAK	END	START	PEAK	END
Relativistic Protons	**13:42**	13:48		**11:03**	11:41	
Soft X-rays	13:11	**13:42**	13:47	10:52**	**11:02**	11:16
H-alpha	13:28	13:41	15:27	09:53	11:57	14:12
Type III radio burst	13:36		13:38	-		-
CME liftoff*	*13:24-31*			*10:53-58*		
Type II radio burst	13:40		13:47	10:54		11:03
Type IV radio burst	13:44		14:57	10:25		15:23

* Linear - quadratic fits   ** Sudden onset of intense emission

All times are "Solar Time" or UT minus 8 min. for EM emissions

Sun
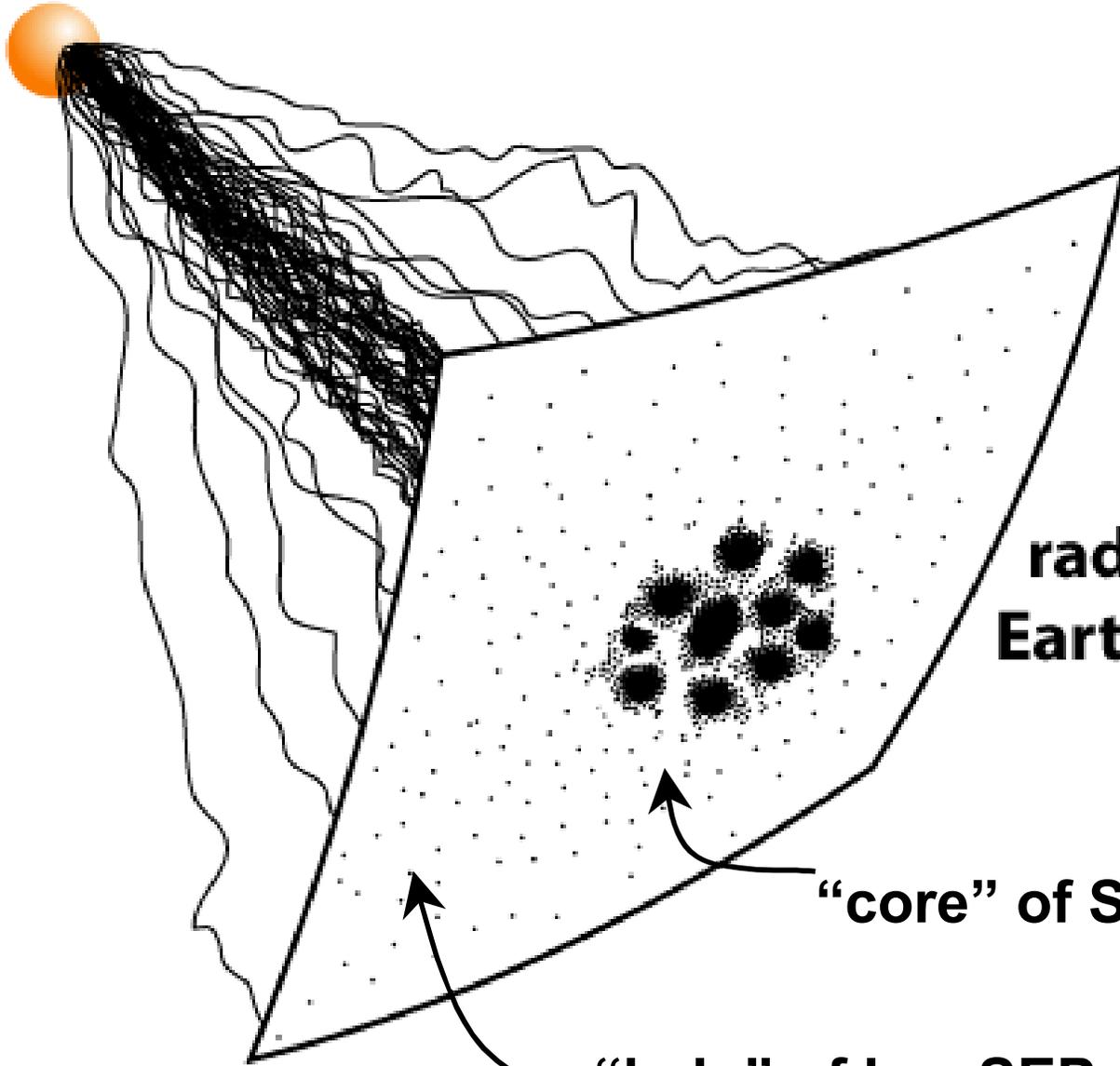
radius of Earth orb

"core" of SEP with dropouts

"halo" of low SEP density over wide lateral region

[DR, Matthaeus, & Chuychai 2003]

Thank you for your attention
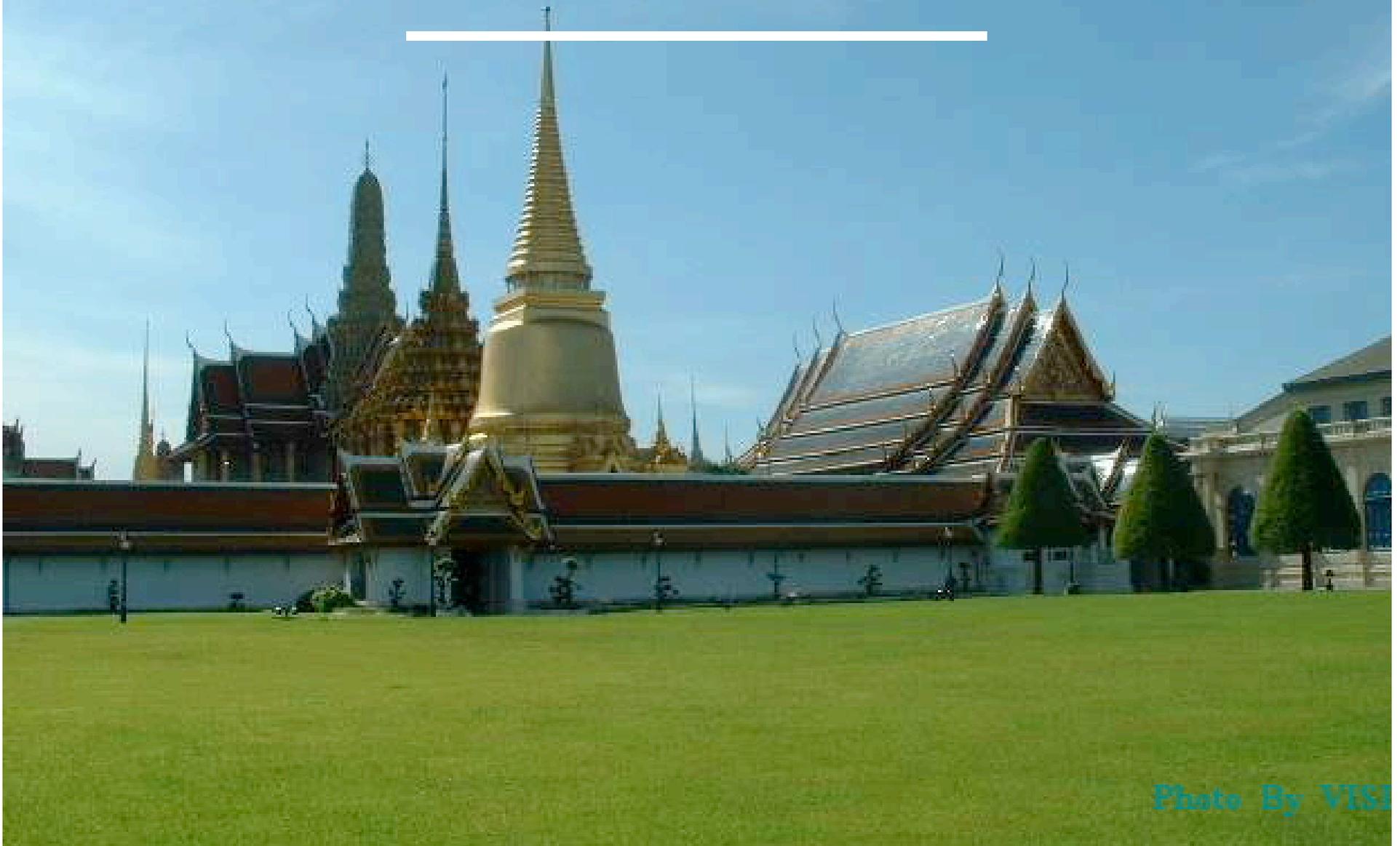
Photo By VISI

… and also in the spirit
End-to-End Modeling of CMEs and SEPs:

See some posters!

87   DR et al. – Turbulence, dropouts, and suppression
        of the field line random walk

96   Bieber et al. – Record-setting Ground Level
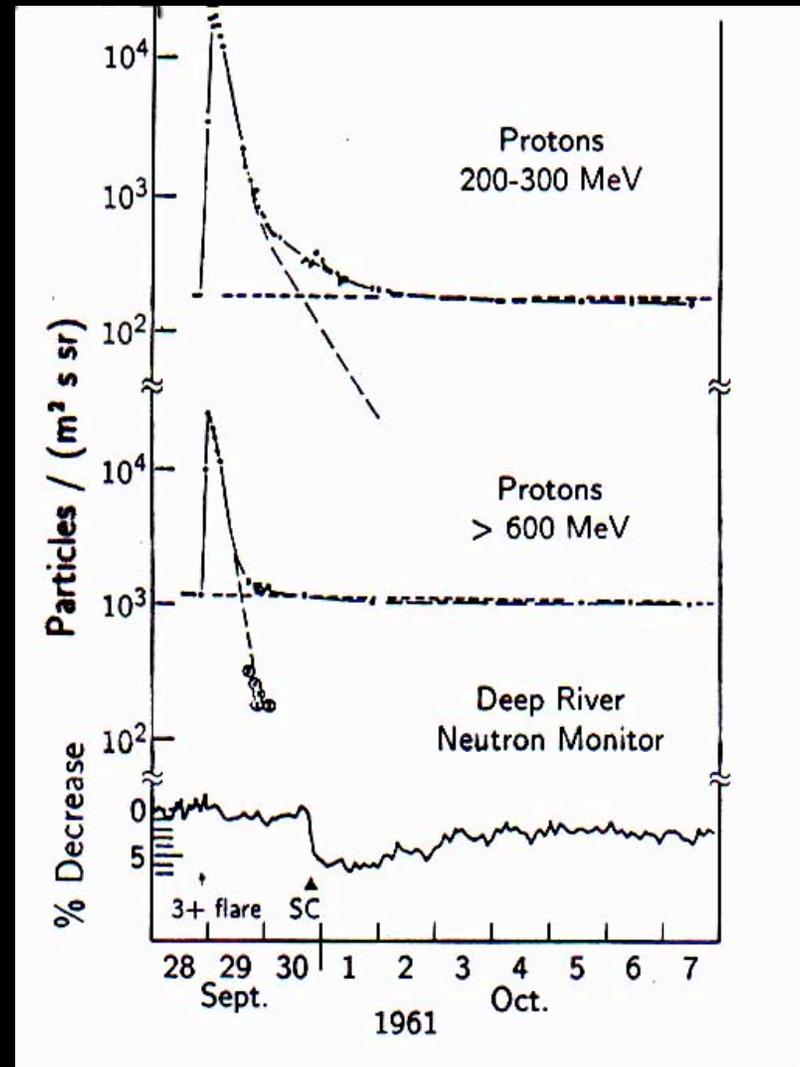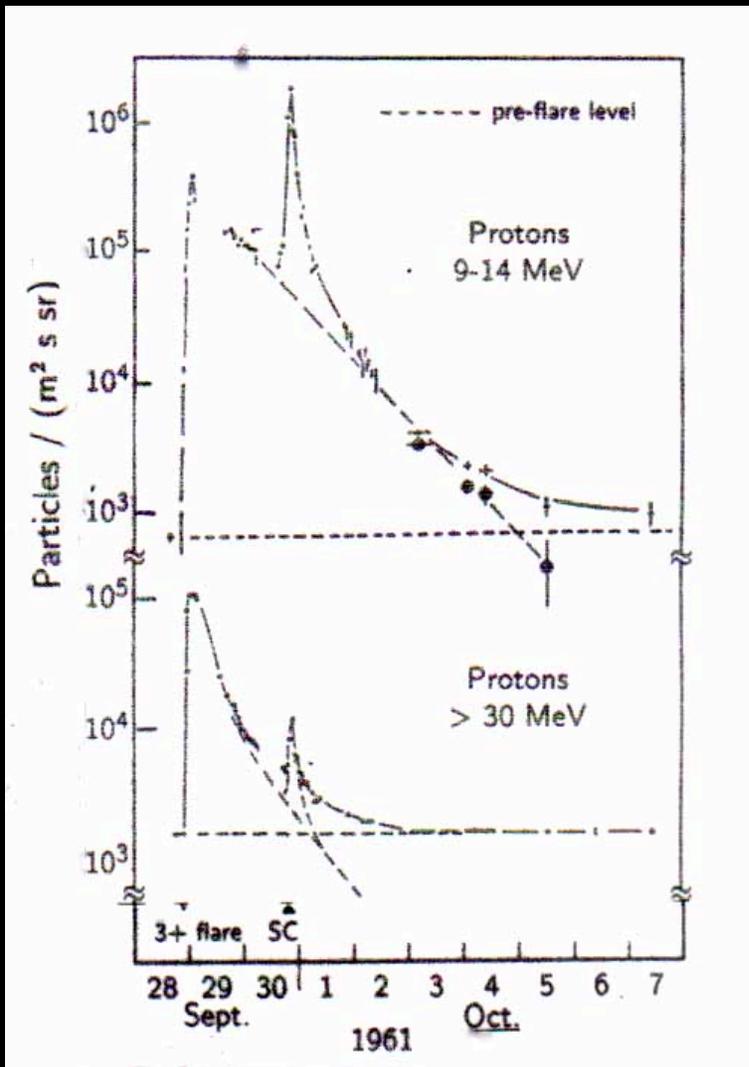   Enhancement: January 20, 2005

107   DR et al. – Relativistic Solar Protons on 1989
        October 22: Injection along Both Legs of a Loop

… and also someone else's poster …

105   Mulligan et al. – validates our results for July 14, 2000!

Early observations [Bryant et al. 1962]

Spectral Properties of Heavy Ions Accelerated by Interplanetary Shocks Near 1 AU

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Co-Authors:
G. M. Mason, C. M. S. Cohen, R. A. Mewaldt, M. E. Wiedenbeck, J. E. Mazur, J. R. Dwyer, A. C. Cummings, E. C. Stone, R. A. Leske, R.E. Gold, E. R. Christian, S. M. Krimigis, C.W. Smith, Q. Hu, R. M. Skoug, and T. T. von Rosenvinge
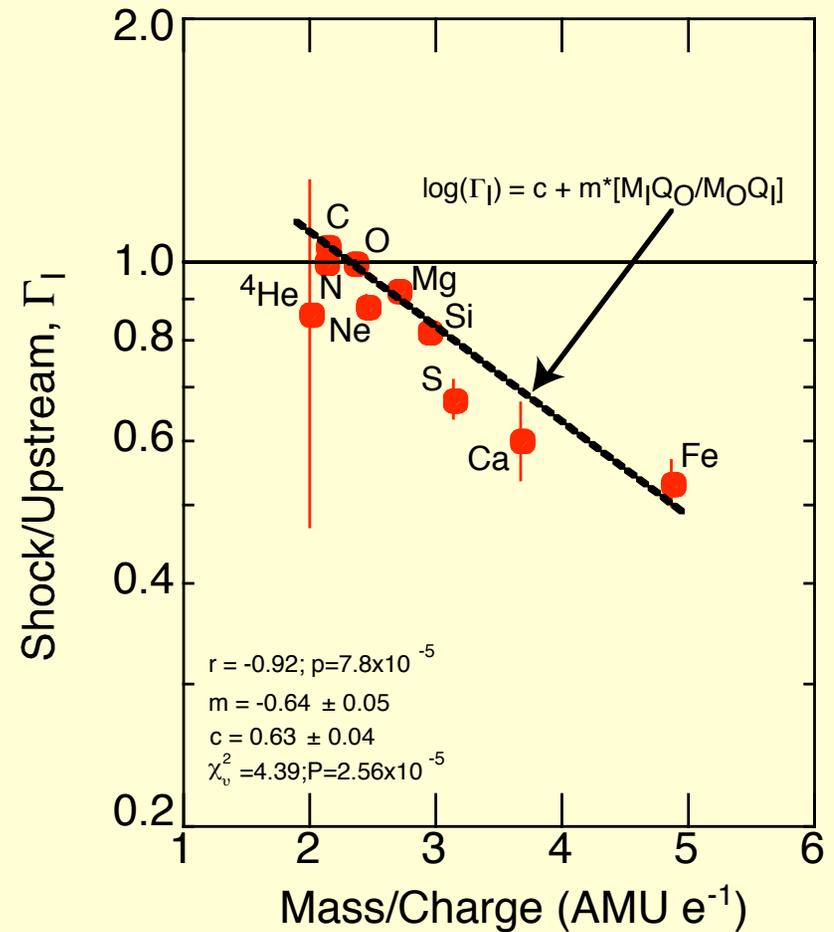
(Desai et al. 2003 ApJ 558, 1149).

Solar wind & IP shock abundances
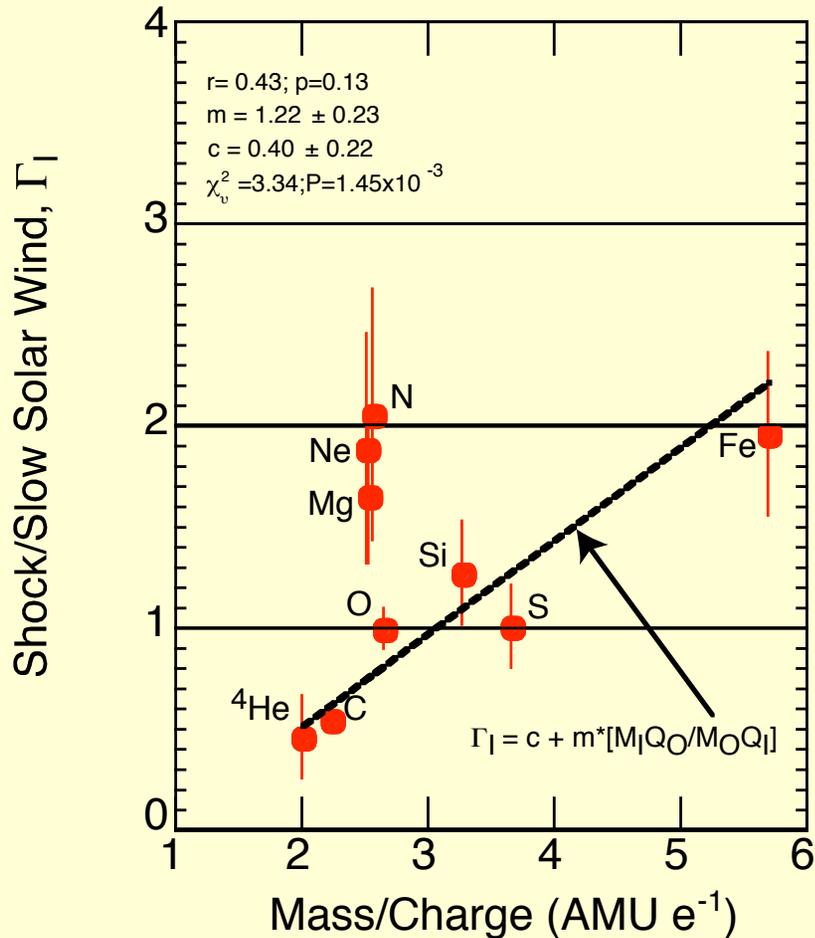
Upstream & IP shock abundances
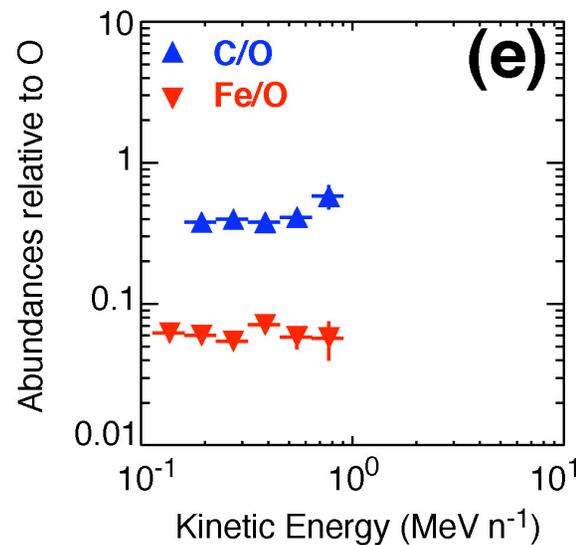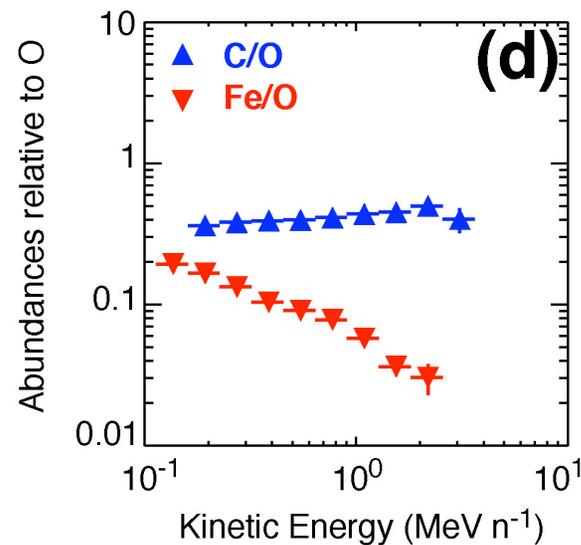
Upstream and SEP Abundances
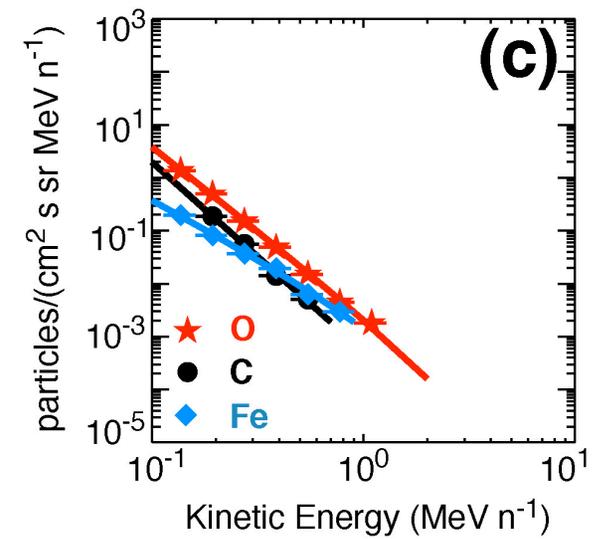## (Desai et al. 2003 ApJ 558, 1149).

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

Impulsive SEPs
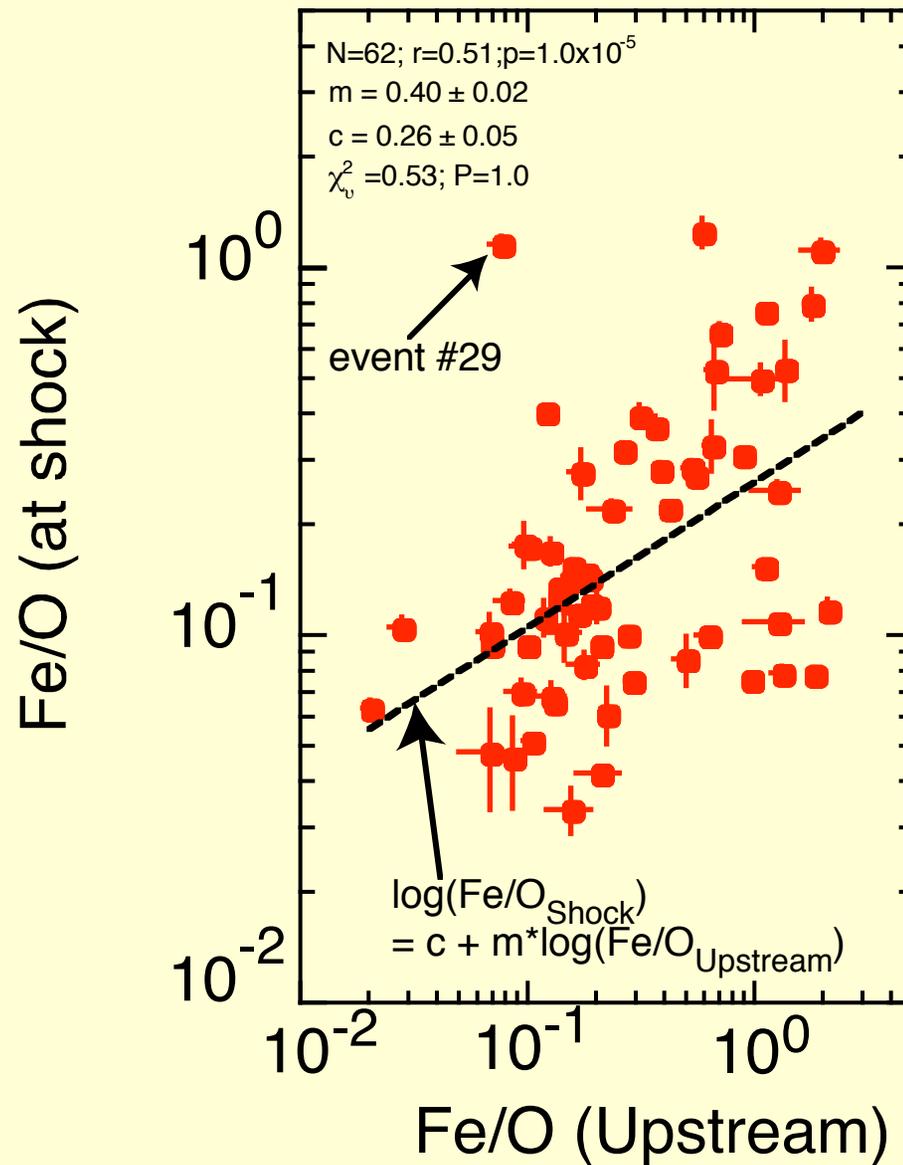
Upstream Material

Gradual SEPs
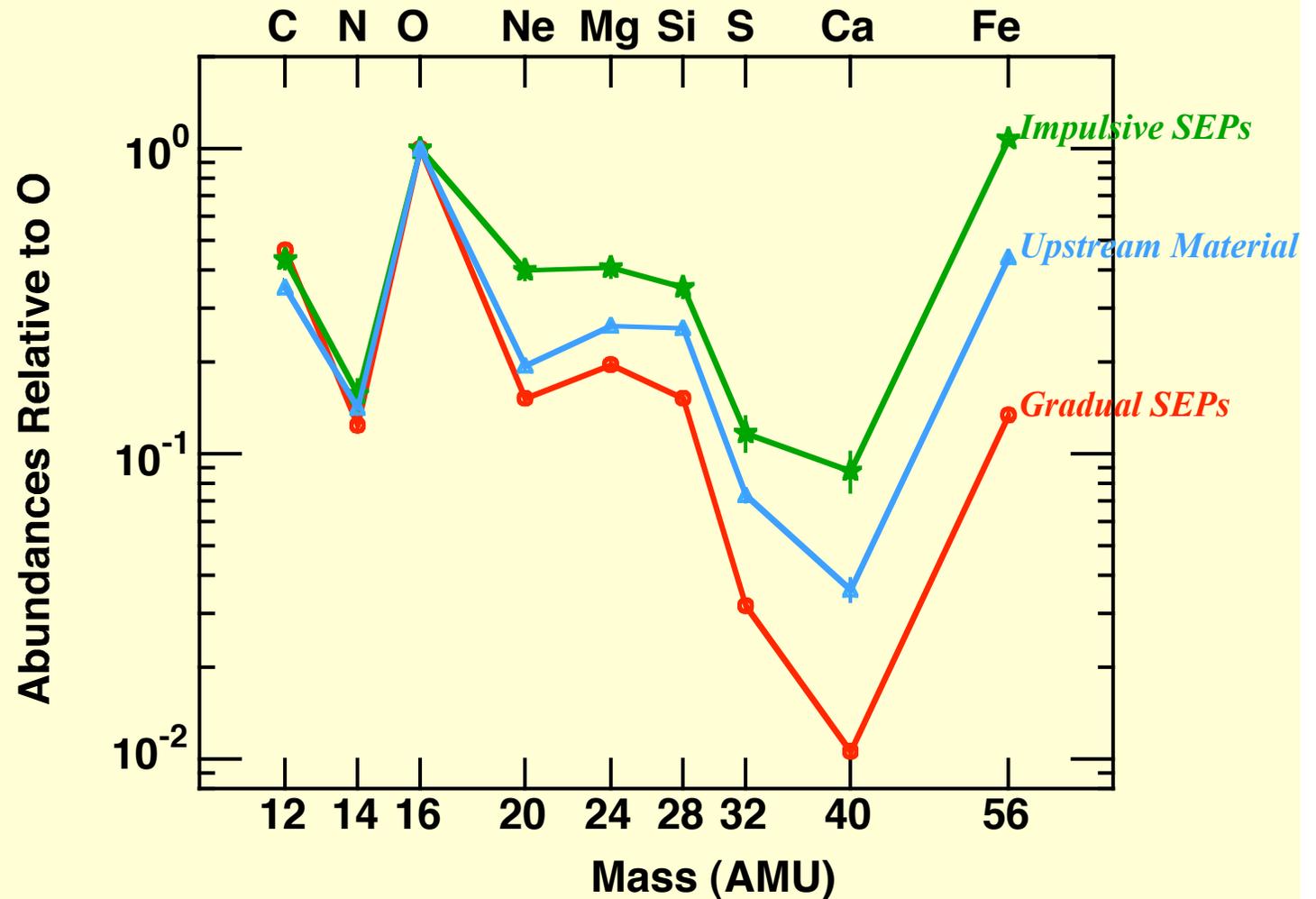
Spectral Variability in IP shocks
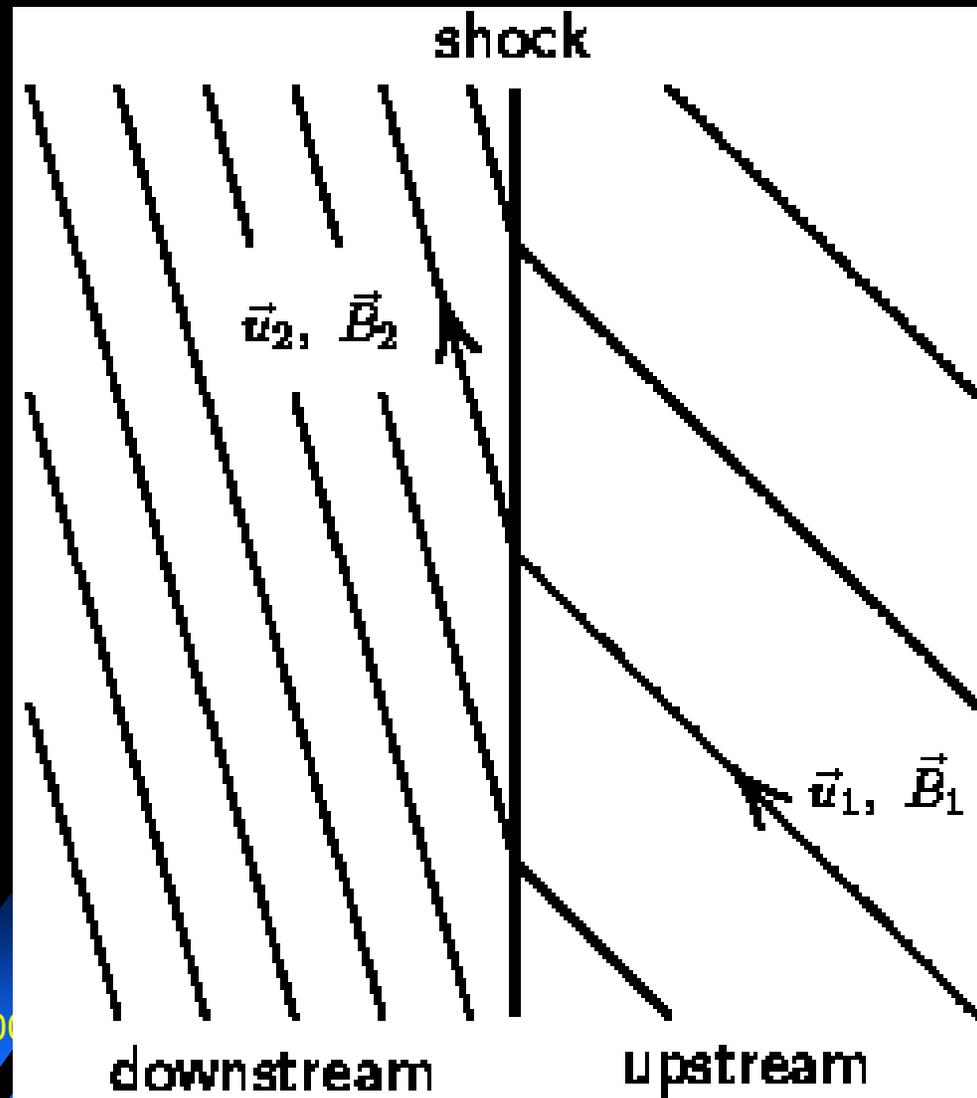
(Desai et al. 2003 to be submitted to ApJ).
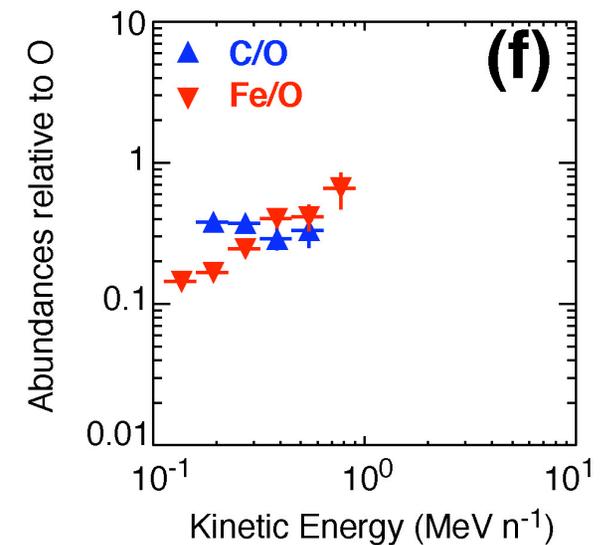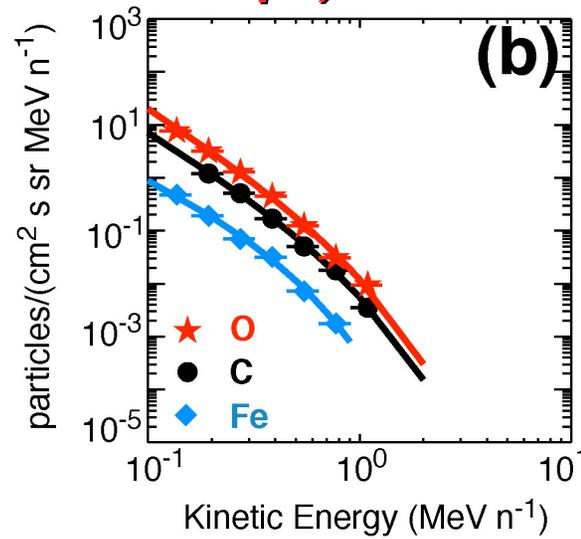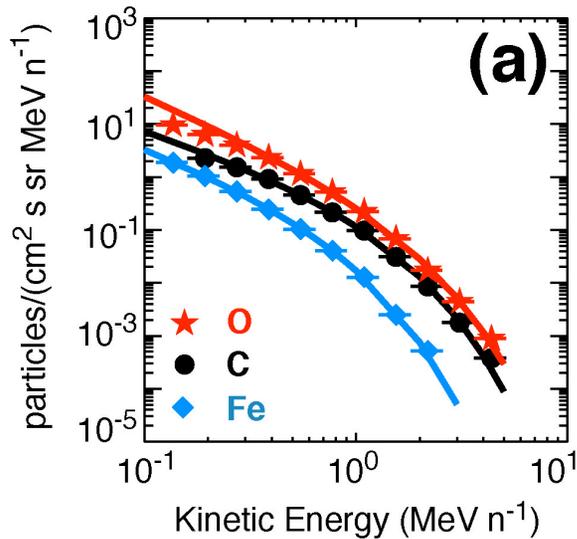
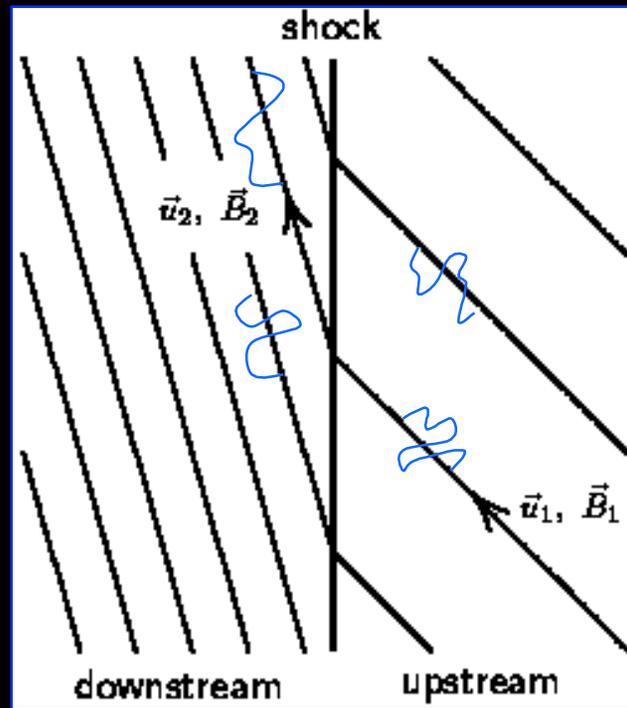**Fe/O Ratio at shock versus Fe/O ratio upstream** *(Desai et al. 2003 ApJ vol. 558, 1149)*

3. Particle acceleration in space: Shock acceleration

shock

$\vec{u}_2,\ \vec{B}_2$

$\vec{u}_1,\ \vec{B}_1$

downstream   upstream

Fundamental mechanism of shock acceleration

Following collision with a scattering center: lose energy

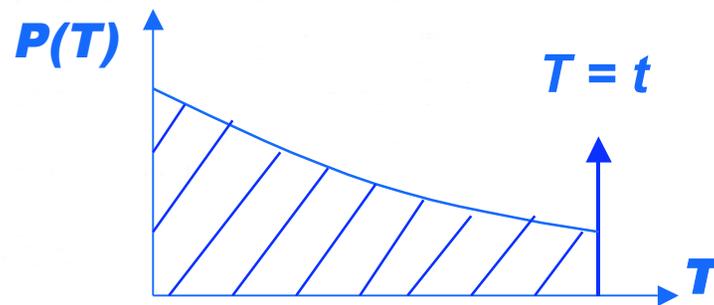Head-on collision with a scattering center: gain energy

Since $u_1 > u_2$ there is a net gain in energy

Distribution of <u>residence time</u> *T* for particles with <u>escape rate</u> ε

$$P(T) = \varepsilon\, e^{-\varepsilon T} + e^{-\varepsilon t}\, \delta(T - t)$$

P(T)

T = t $T \le t$

t is <u>time at present</u>

Poisson distribution for *n* acceleration events with <u>accel. rate</u> r

$$P(n, T) = (rT)^{n}\, e^{-rT} / n!$$

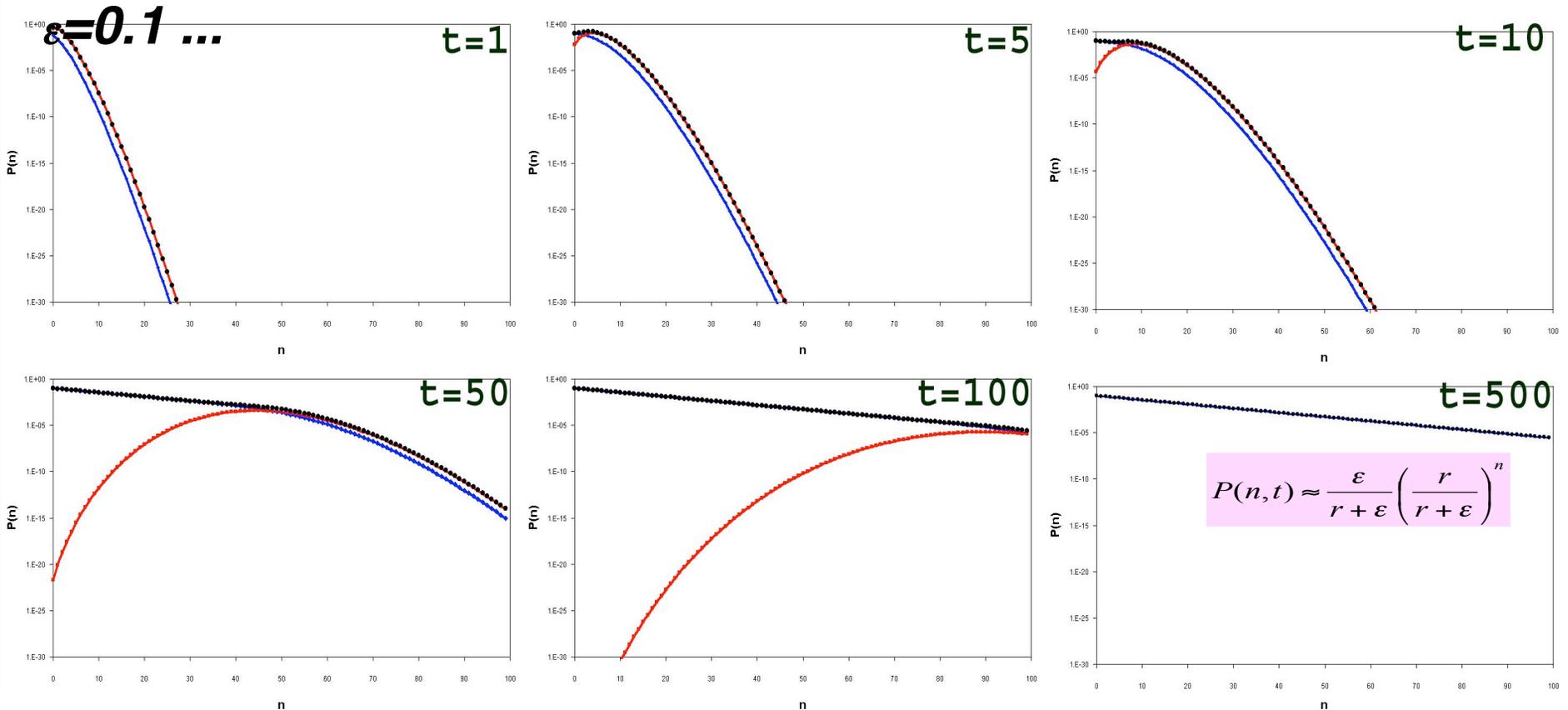# Overall probability of *n* acceleration events after time *t*
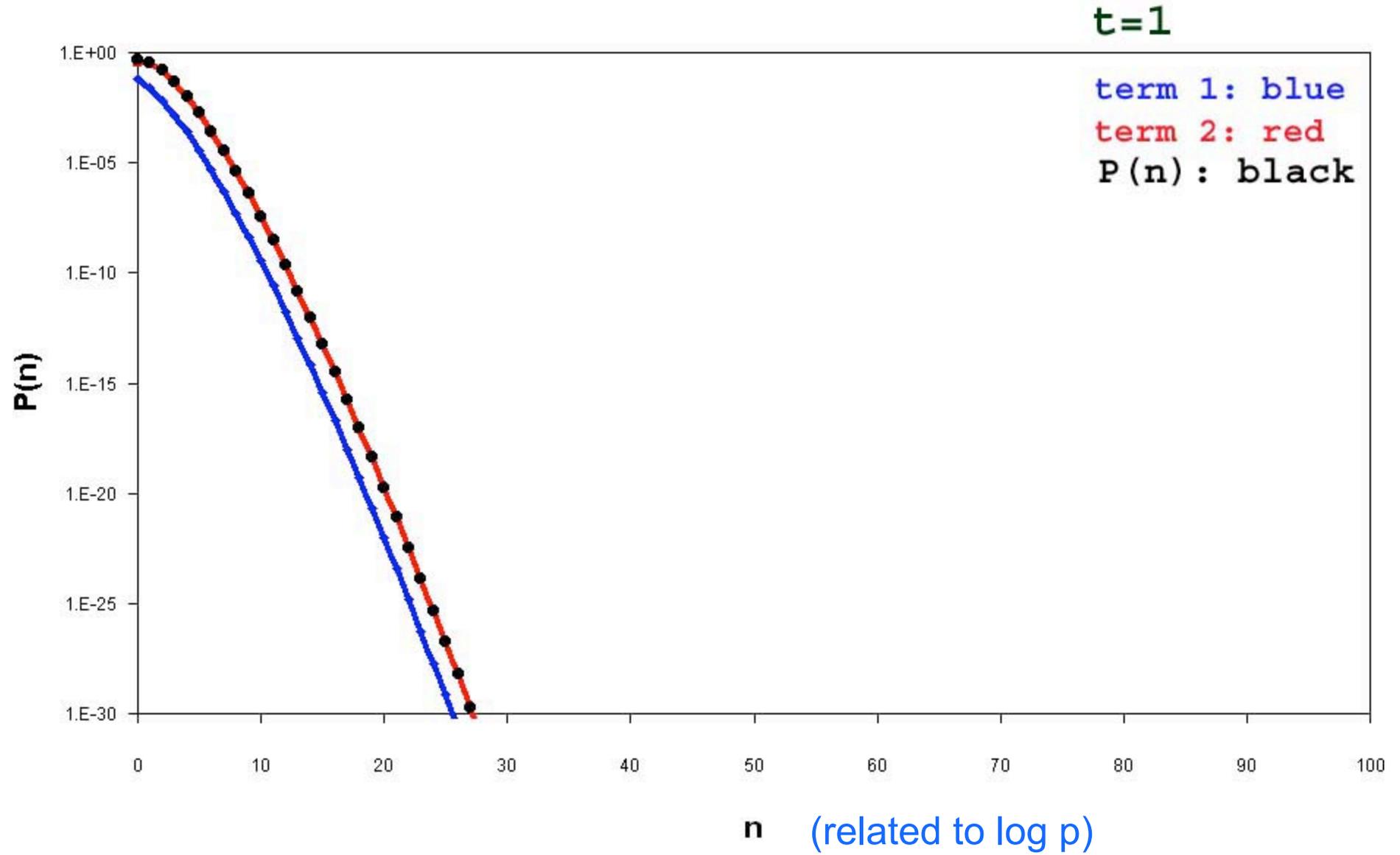
$$P(n, t) = \int_{0}^{t} P(n, T)\, P(T)\, dT$$

$$P(n,t) = \frac{\varepsilon}{r+\varepsilon}\left(\frac{r}{r+\varepsilon}\right)^n e^{-(r+\varepsilon)t} \sum_{k=n+1}^{\infty} \frac{[(r+\varepsilon)t]^k}{k!} \quad + \frac{(rt)^n}{n!} e^{-(r+\varepsilon)t}$$
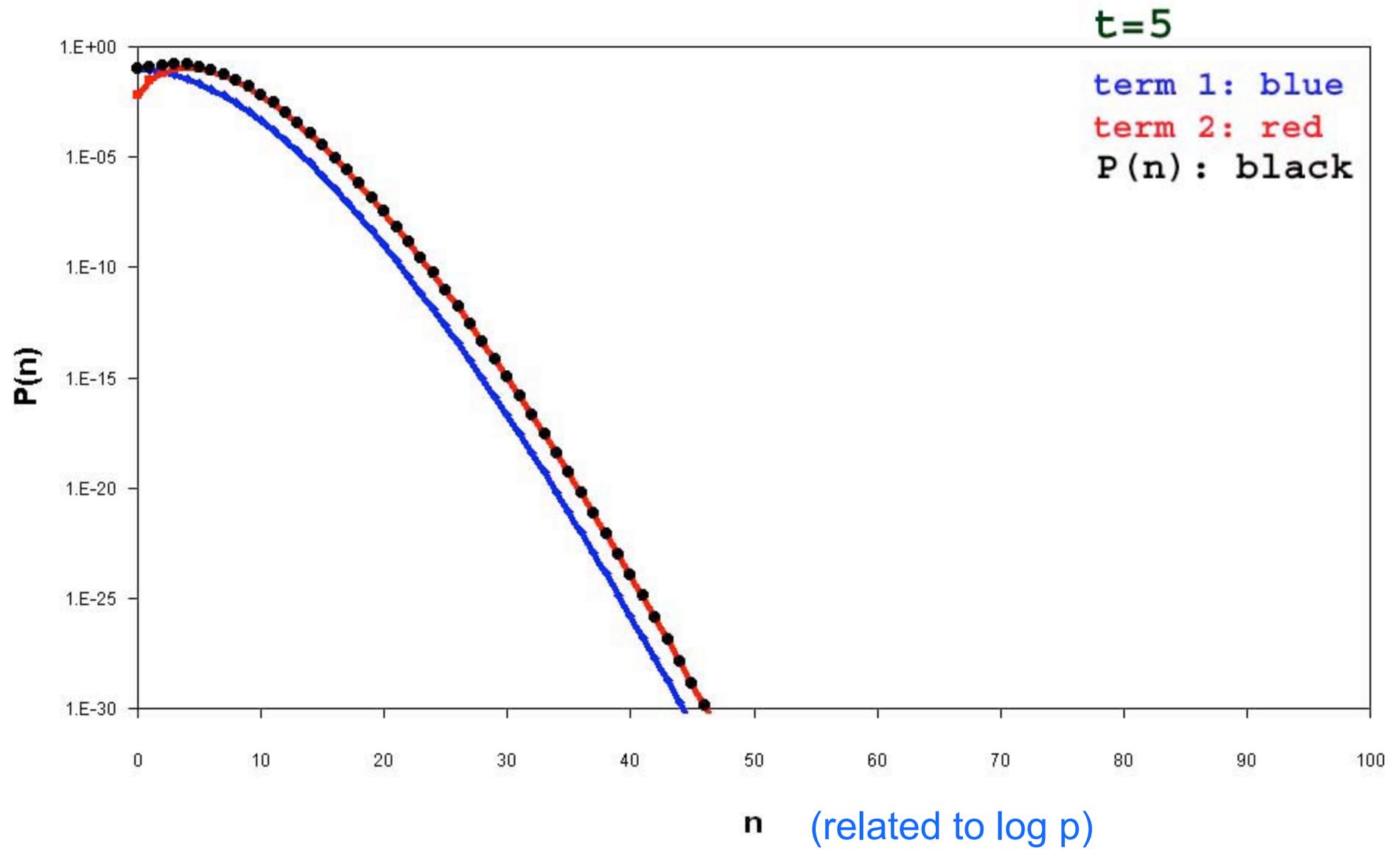
T < t (temporary residents)

T = t
(*permanent residents*)

Using r=0.9 & ε=0.1 ...

term1:blue   term2:red   P(n):black

$$P(n,t) \approx \frac{\varepsilon}{r+\varepsilon}\left(\frac{r}{r+\varepsilon}\right)^n$$

t=1

term 1: blue
term 2: red
P(n): black

n   (related to log p)

(related to log p)

t=10

term 1: blue
term 2: red
P(n): black

n   (related to log p)

t=50
term 1: blue
term 2: red
P(n): black

(related to log p)

t=100

term 1: blue
term 2: red
P(n): black

P(n)

n   (related to log p)

t=500

term 1: blue
term 2: red
P(n): black

P(n)

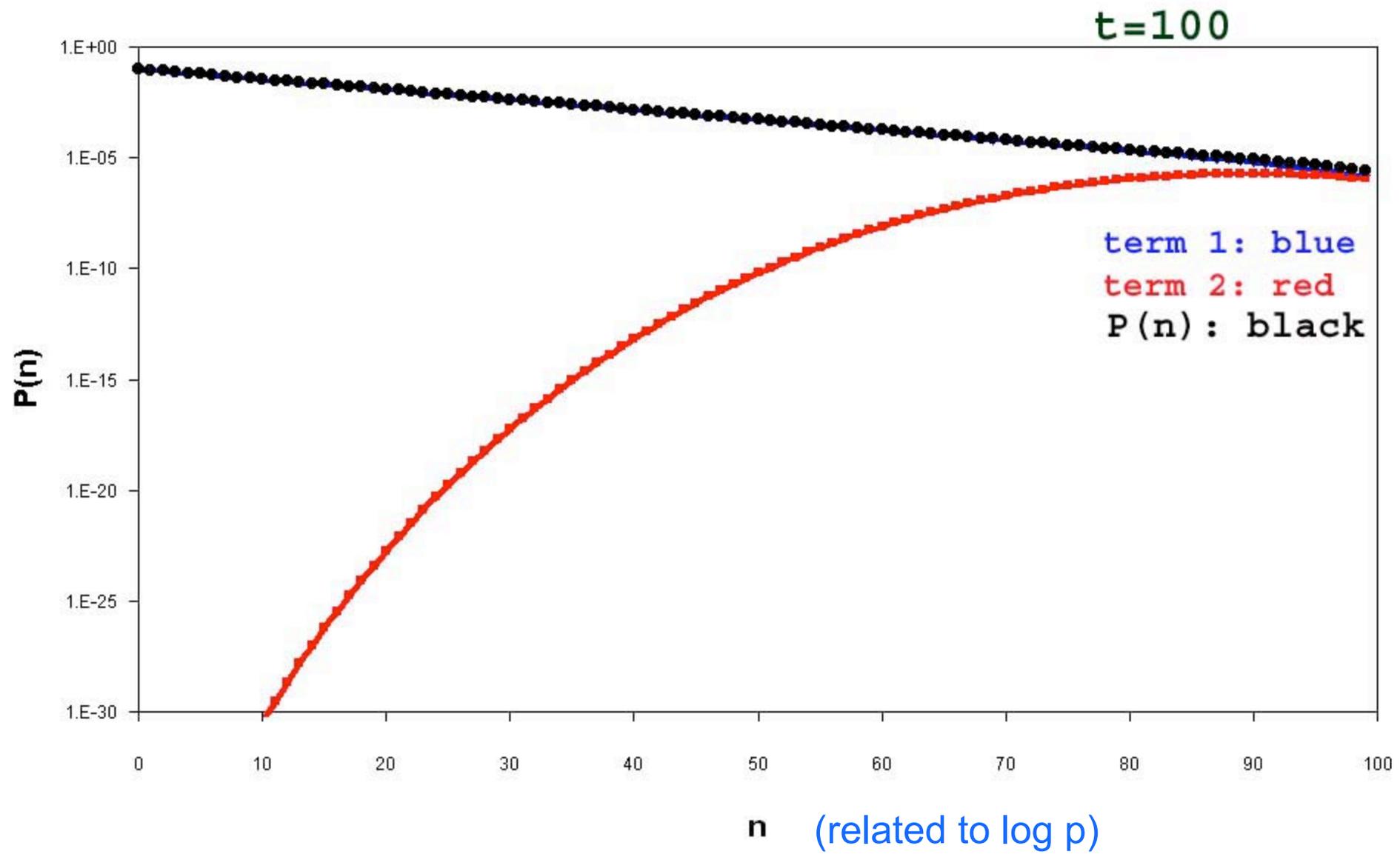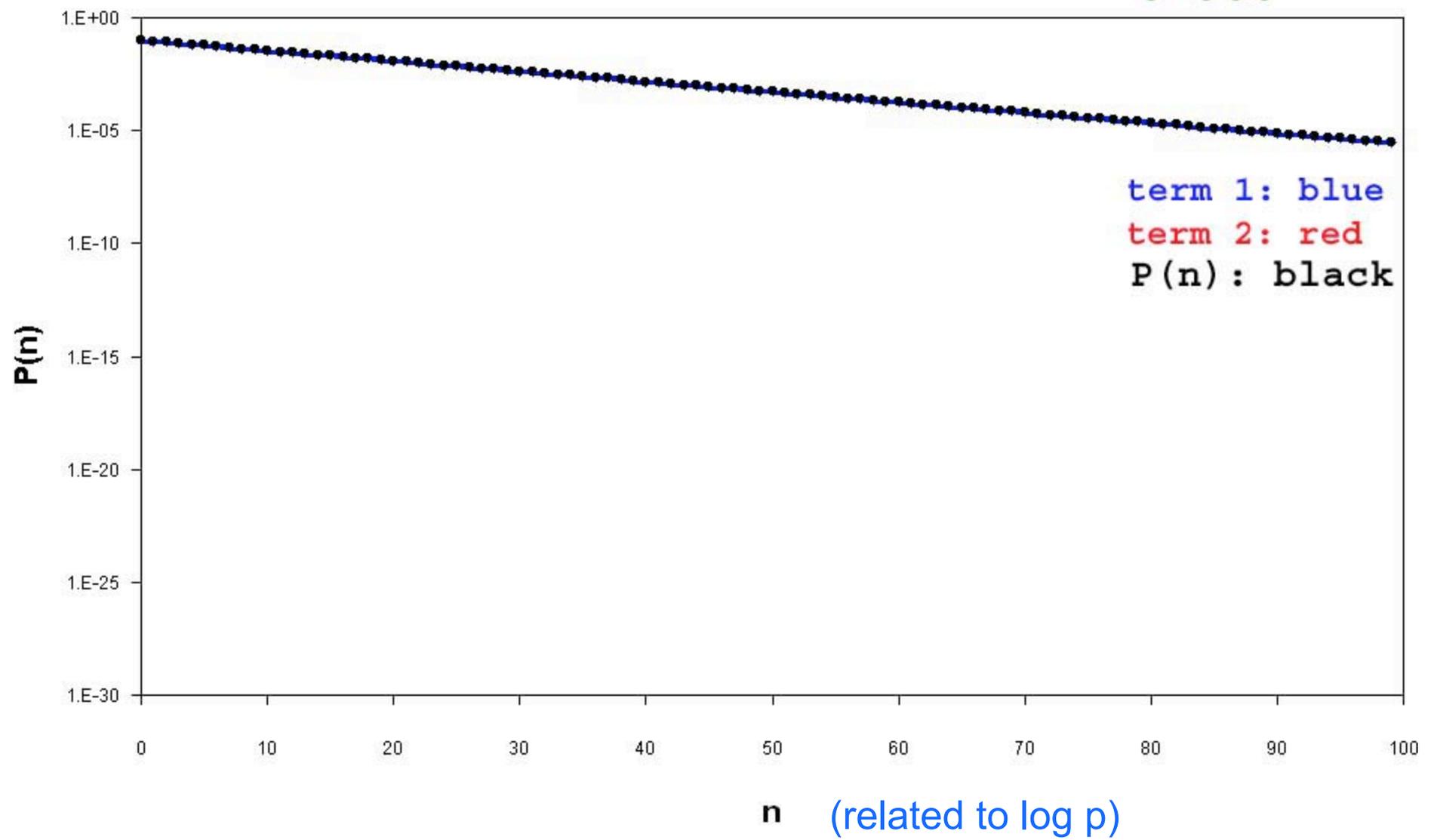n   (related to log p)
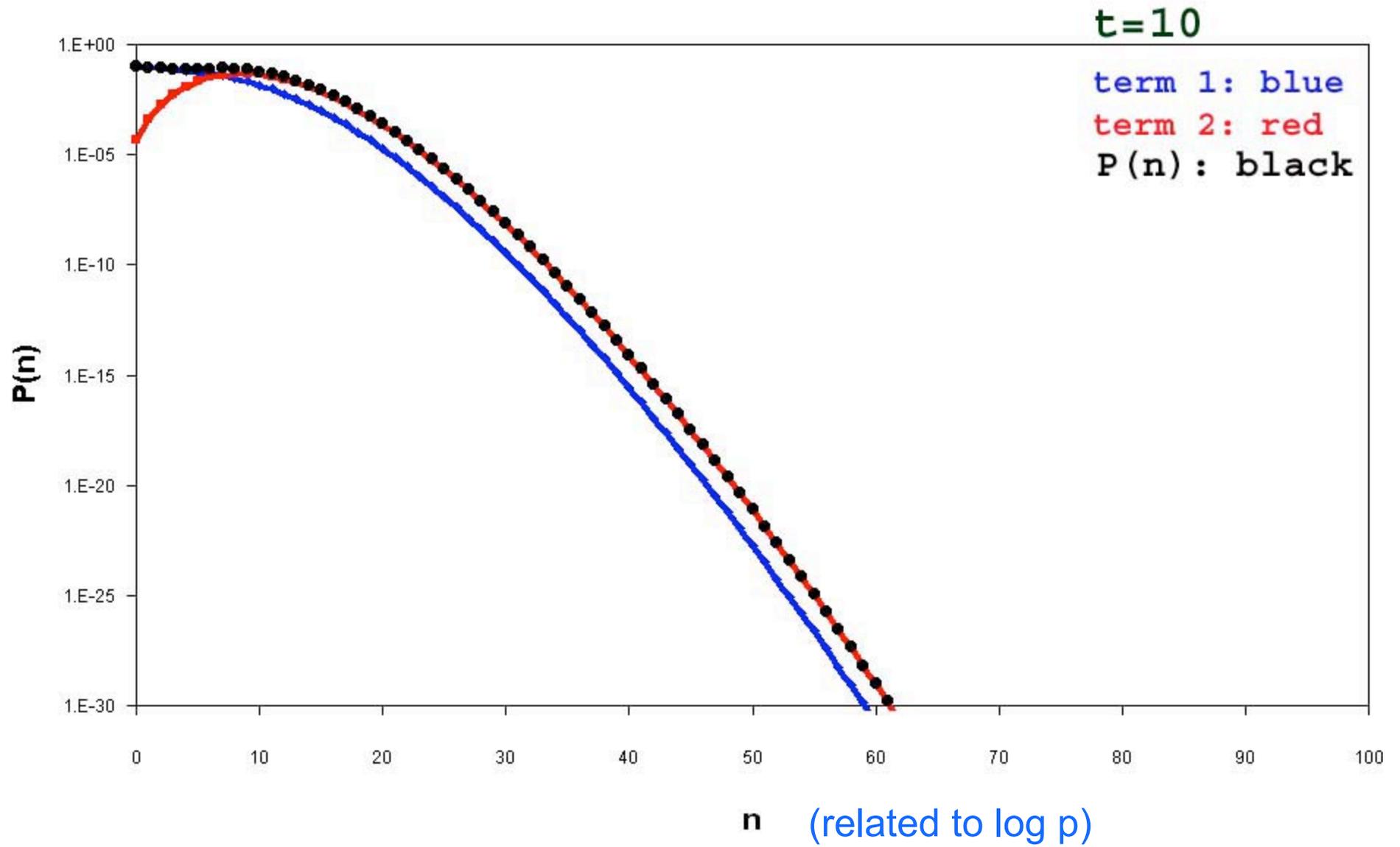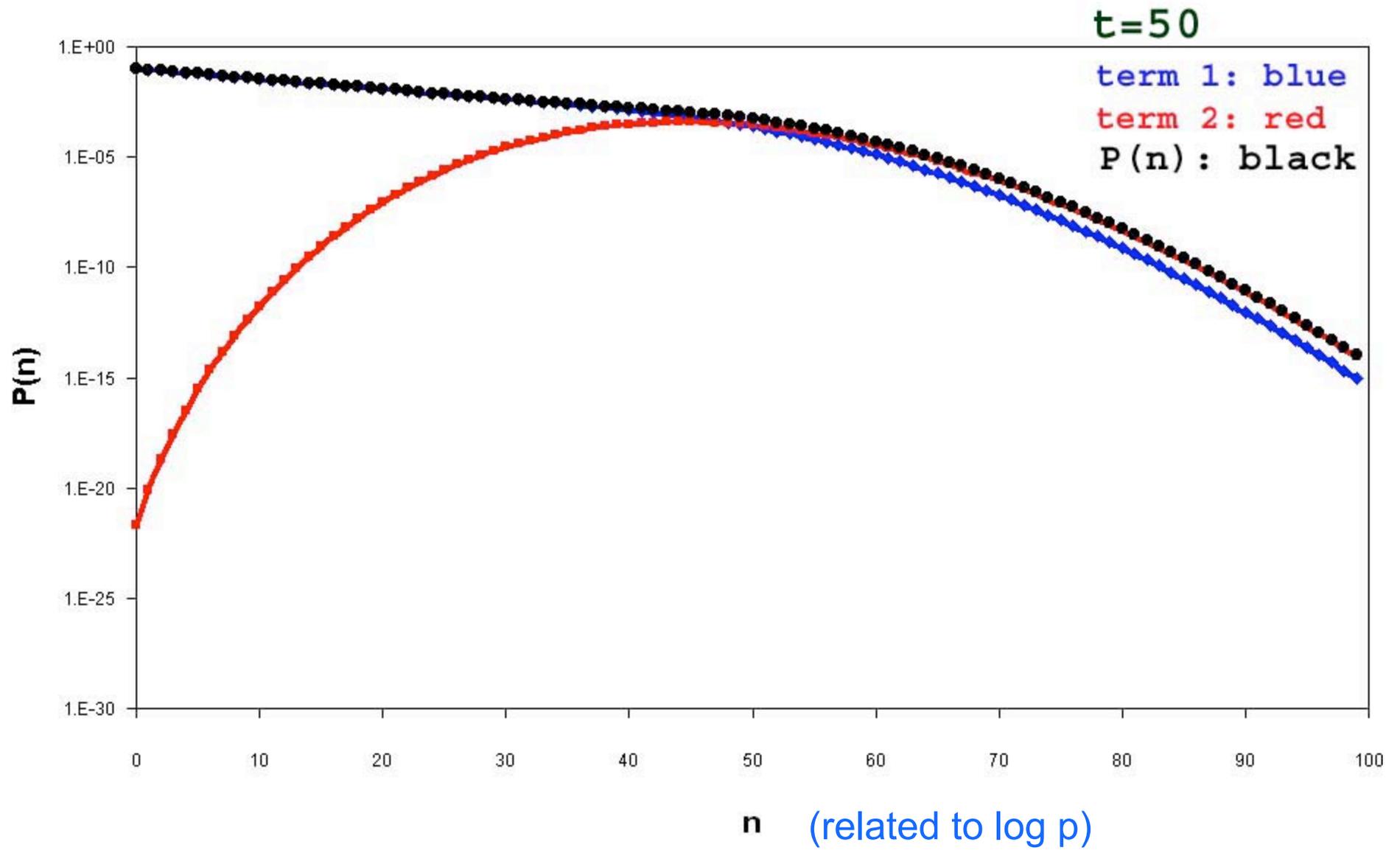
Application to an interplanetary shock: What if ε, r vary with time?

- Physical characteristics of a shock change greatly as it moves out from the Sun

- Observations: high energy particles are accelerated only when shock is near the Sun

- Near Sun: t_{acc} (=1/r) was low, t /t_{acc} was high, spectrum does not roll over until high energy (rollover mechanism not clear)

- Interplanetary space: t_{acc} greatly increased

- Effectively decouple SEP, ESP acceleration

r, ε varying - ODE model

$$P(n,t) = E(n,t) + A(n,t)$$

$$dA(n,t)/dt = r_{n-1}A(n-1,t) - (r_n + \varepsilon_n)A(n,t)$$

$$dE(n,t)/dt = \varepsilon_n A(n,t)$$

$$A(0,0) = 1, \ A(n \geq 1,0) = 0, \ E(n,0) = 0$$

Analytic solution:

$$P(n,t) = \epsilon_n \prod_{i=0}^{n-1} r_i \sum_{j=0}^{n} \frac{1 - e^{-(r_j + \epsilon_j)t}}{(r_j + \epsilon_j) \prod_{\substack{k=0 \\ k \neq j}}^{n} (r_k - r_j + \epsilon_k - \epsilon_j)} + \prod_{i=0}^{n-1} r_i \sum_{j=0}^{n} \frac{e^{-(r_j + \epsilon_j)t}}{\prod_{\substack{k=0 \\ k \neq j}}^{n} (r_k - r_j + \epsilon_k - \epsilon_j)}$$

More model parameters ...
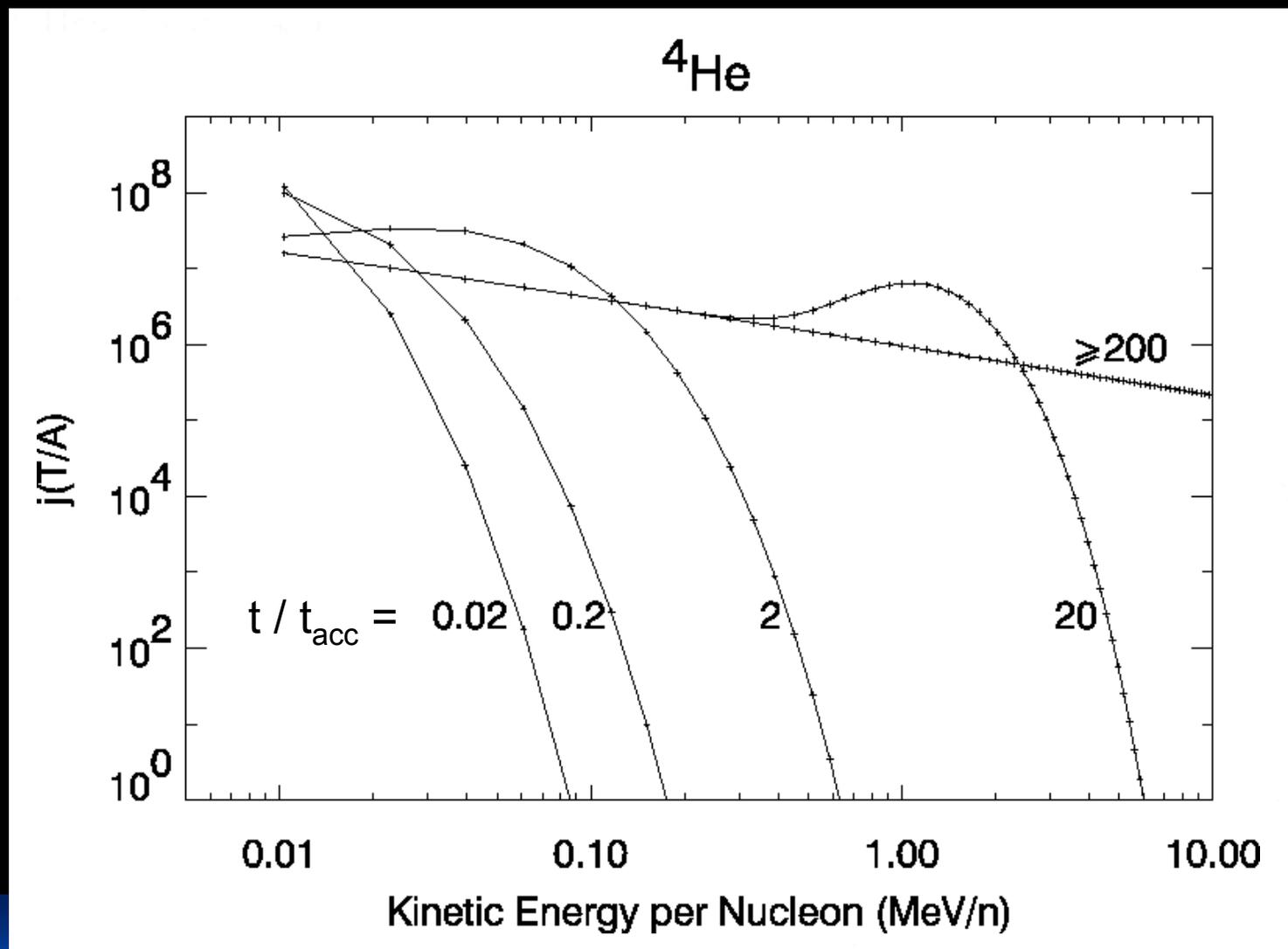
$$r_n = \frac{v_n/4}{\kappa_1/u_1 + \kappa_2/u_2}$$

$$\epsilon_n = \frac{u_2(\cos\theta_2/\cos\theta_1)}{(\kappa_1/u_1 + \kappa_2/u_2)(1 - 4u_2\cos\theta_2/(v_n\cos\theta_1))}$$

$$\frac{p_n}{p_{n-1}} = 1 + \frac{4}{3}\frac{u_1\cos\theta_1 - u_2\cos\theta_2}{v_{n-1}\cos\theta_1}$$

... after Drury (1983)

Numerical Results

Four Lines of Work:

2. Magnetic Turbulence & Effects on Particle Transport

3. Detection/ Data Analysis

1. Particle Acceleration

4. Earth Effects

CME