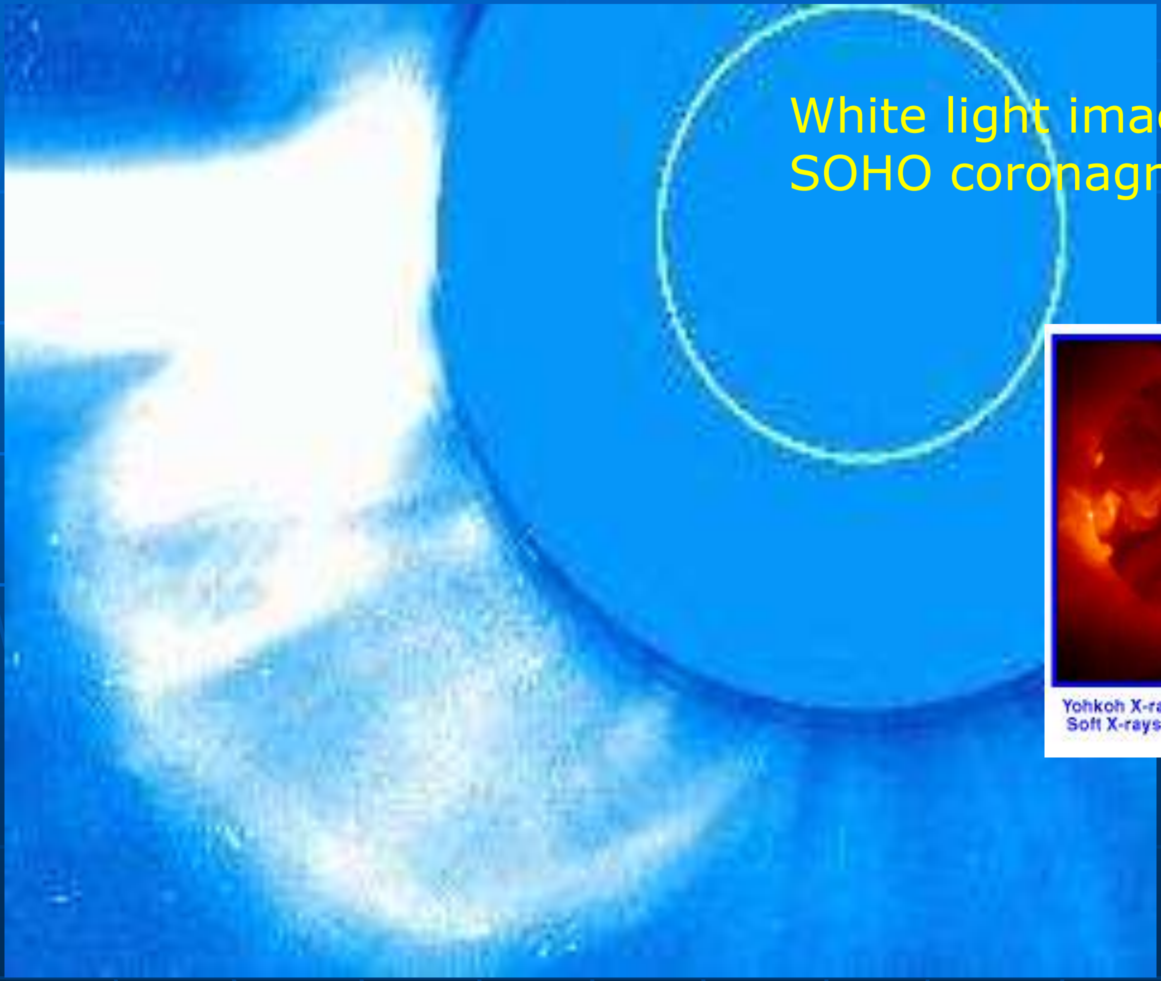
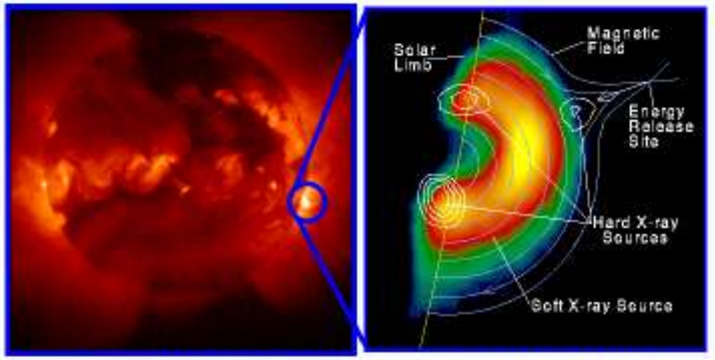
Solar Energetic Particle Trapping During Geomagnetic Storms

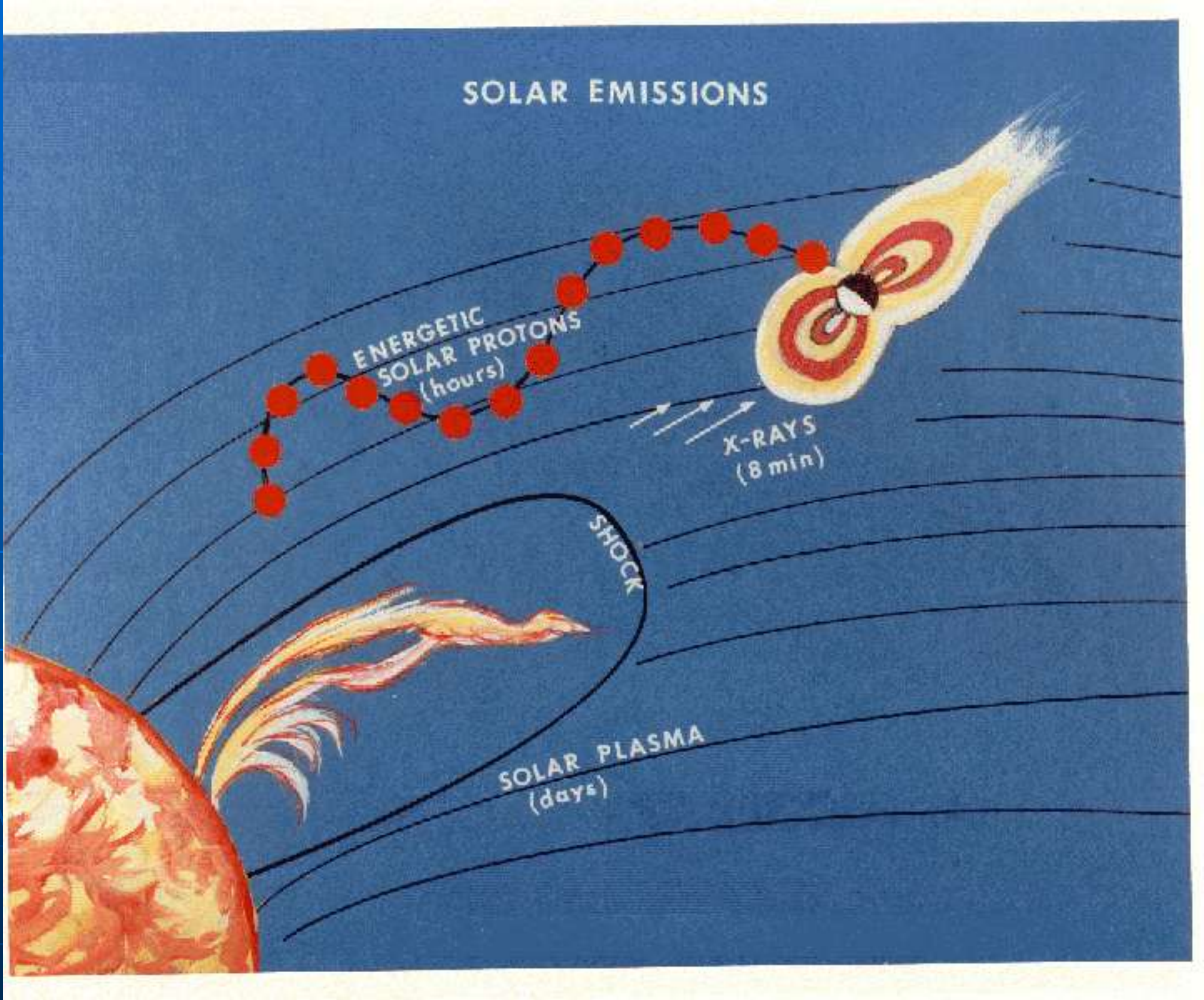
M.K. Hudson and B. T. Kress
Dartmouth College

Solar Coronal Mass Ejections produce interplanetary shocks propagating earthward; CMEs and flares produce Solar Energetic Particle events detected at 1 AU





Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.


SOLAR EMISSIONS
ENERGETIC
SOLAR PROTONS
(hours)
X-RAYS
(8 min)
SHOCK
SOLAR PLASMA
(days)

WHAT IS THE SOURCE OF SOLAR PROTONS?

MASSIVE ENERGY RELEASE ON THE SUN

(STORED MAGNETIC ENERGY)

RECONNECTION

LARGE SOLAR FLARE 10^{32} to 10^{34} ergs

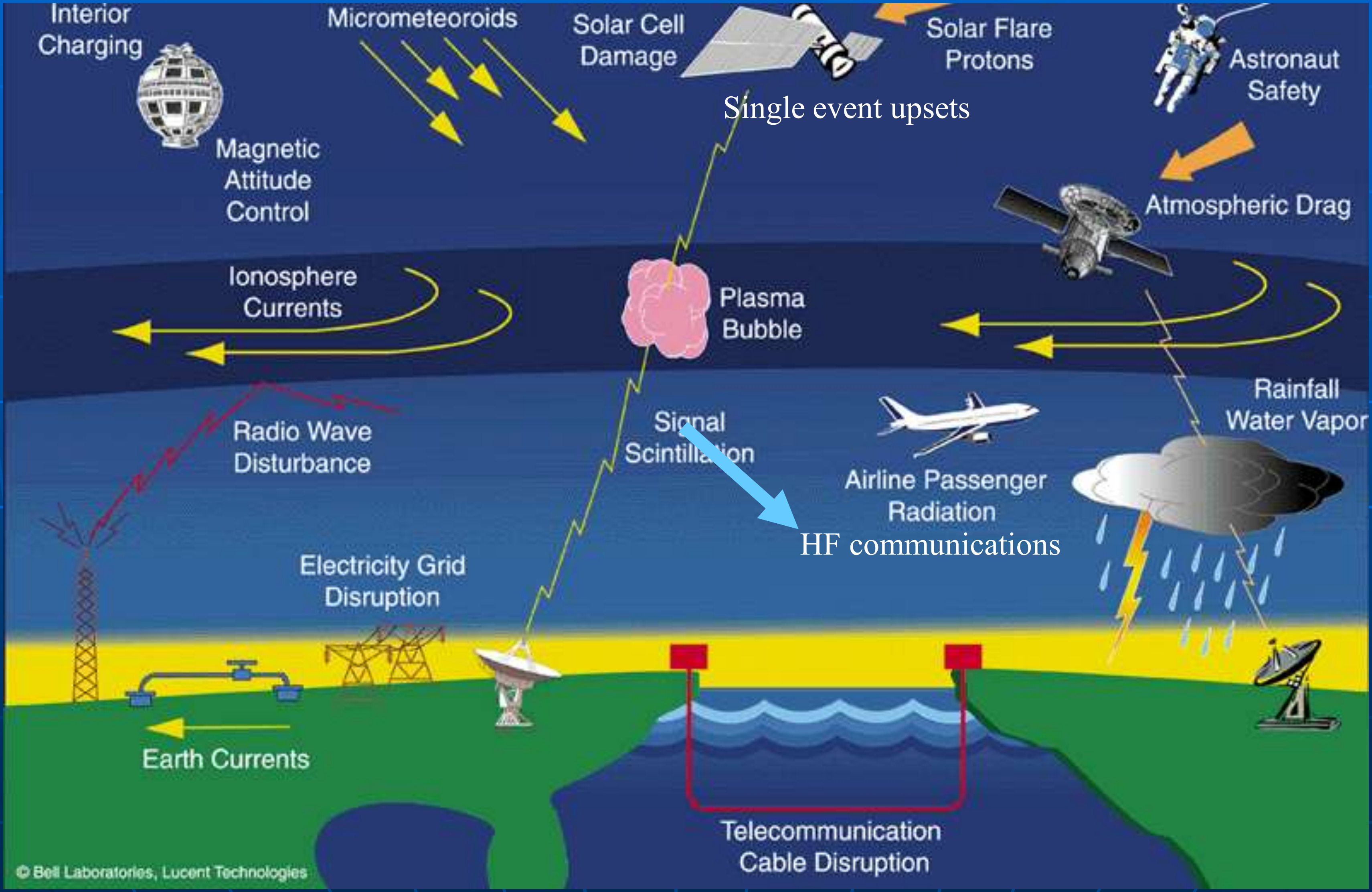
FAST LARGE CORONAL MASS EJECTION 10^{32} to 10^{34}

Some of this energy goes into charged particle acceleration

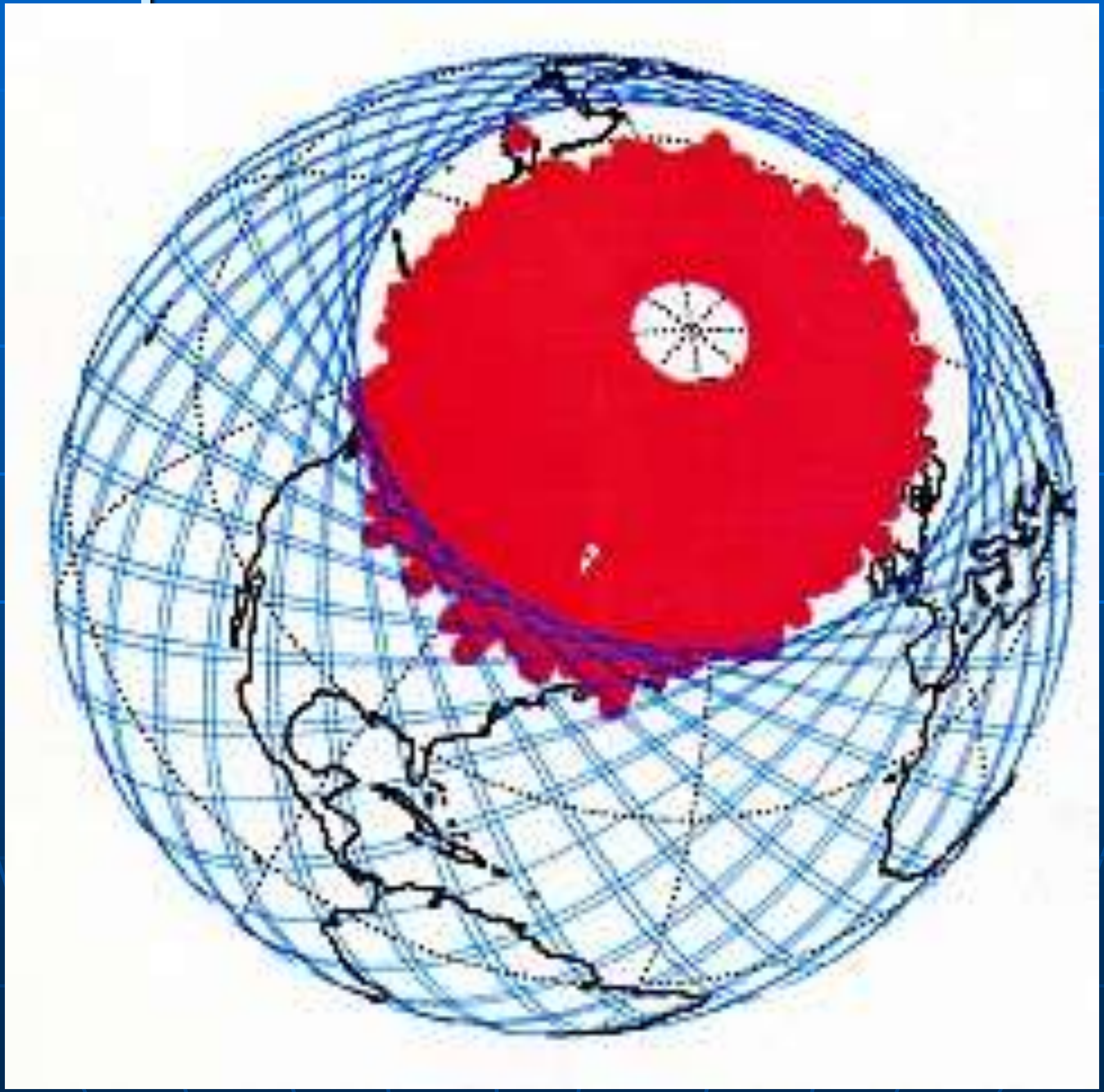
The shock acceleration scenario is currently popular

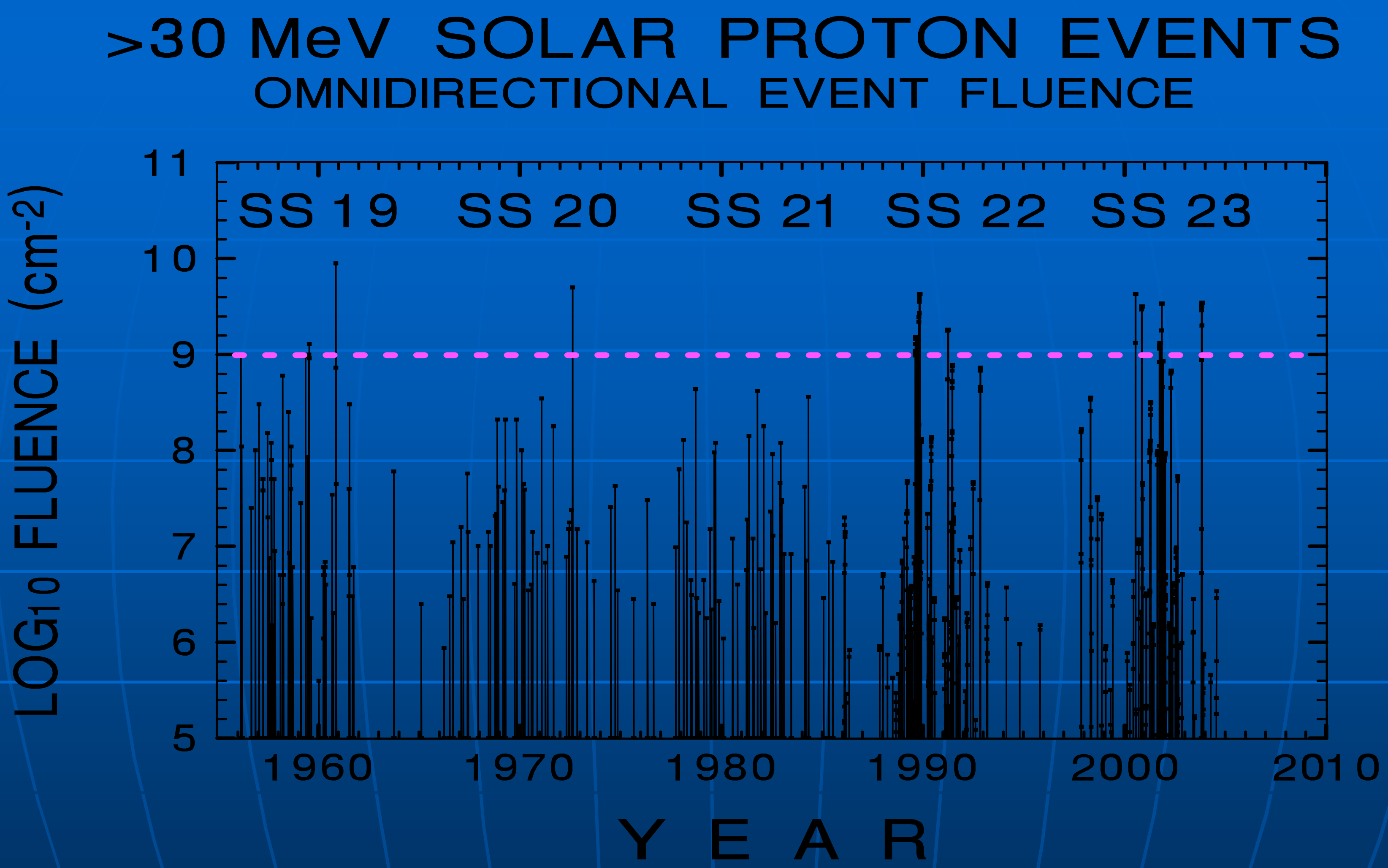
(Probably dominates at energies below 20 MeV)

Space Weather Effects



SEP access relative to International Space Station orbit

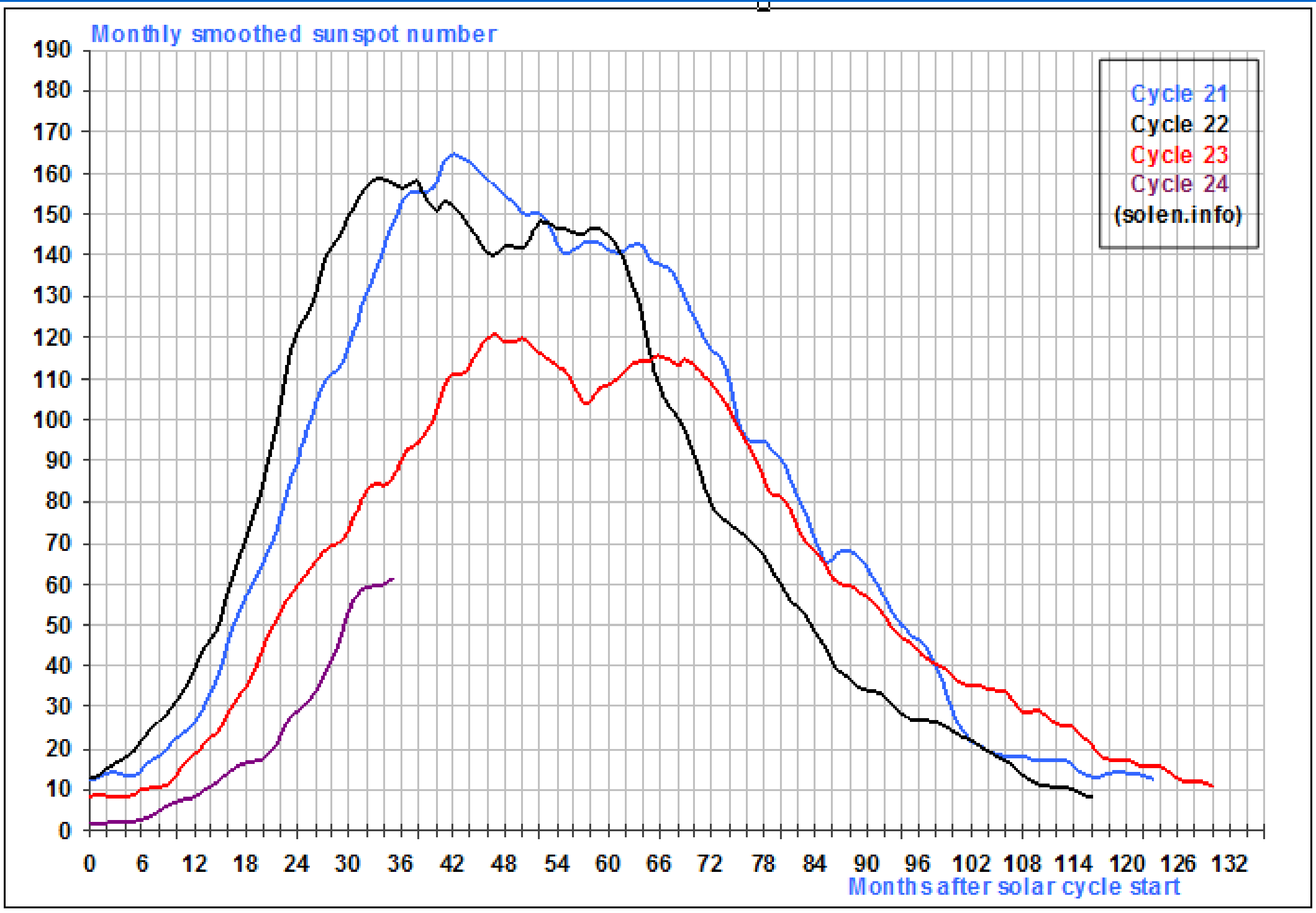




The > 30 MeV solar proton events since solar sunspot cycle 19.
The red line indicates the detection threshold.

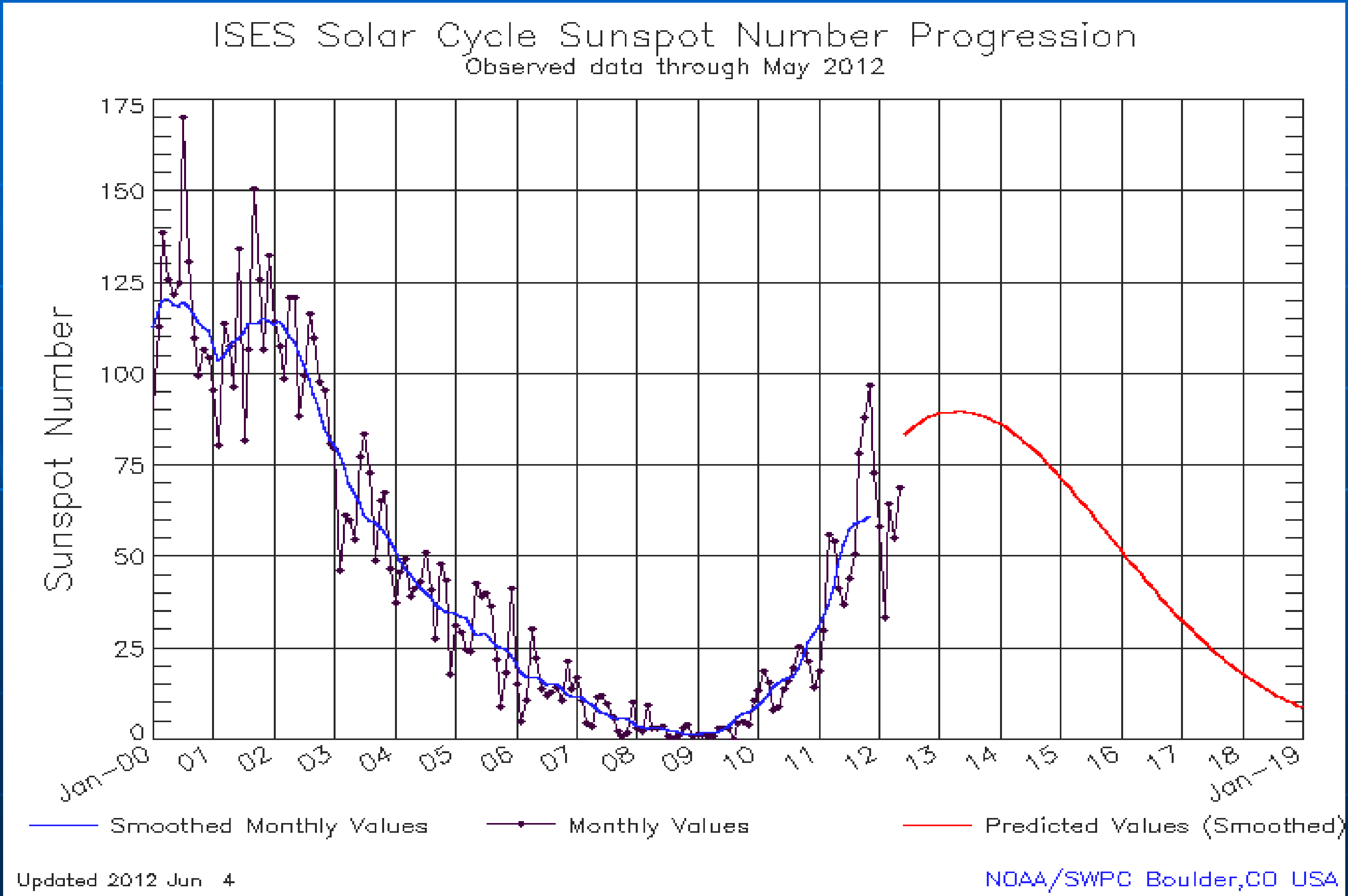
Solar Cycle Sunspot # Comparison

- **Cycle Monthly**
  - 21 Blue
  - 22 Black
  - 23 Red
  - 24 Violet

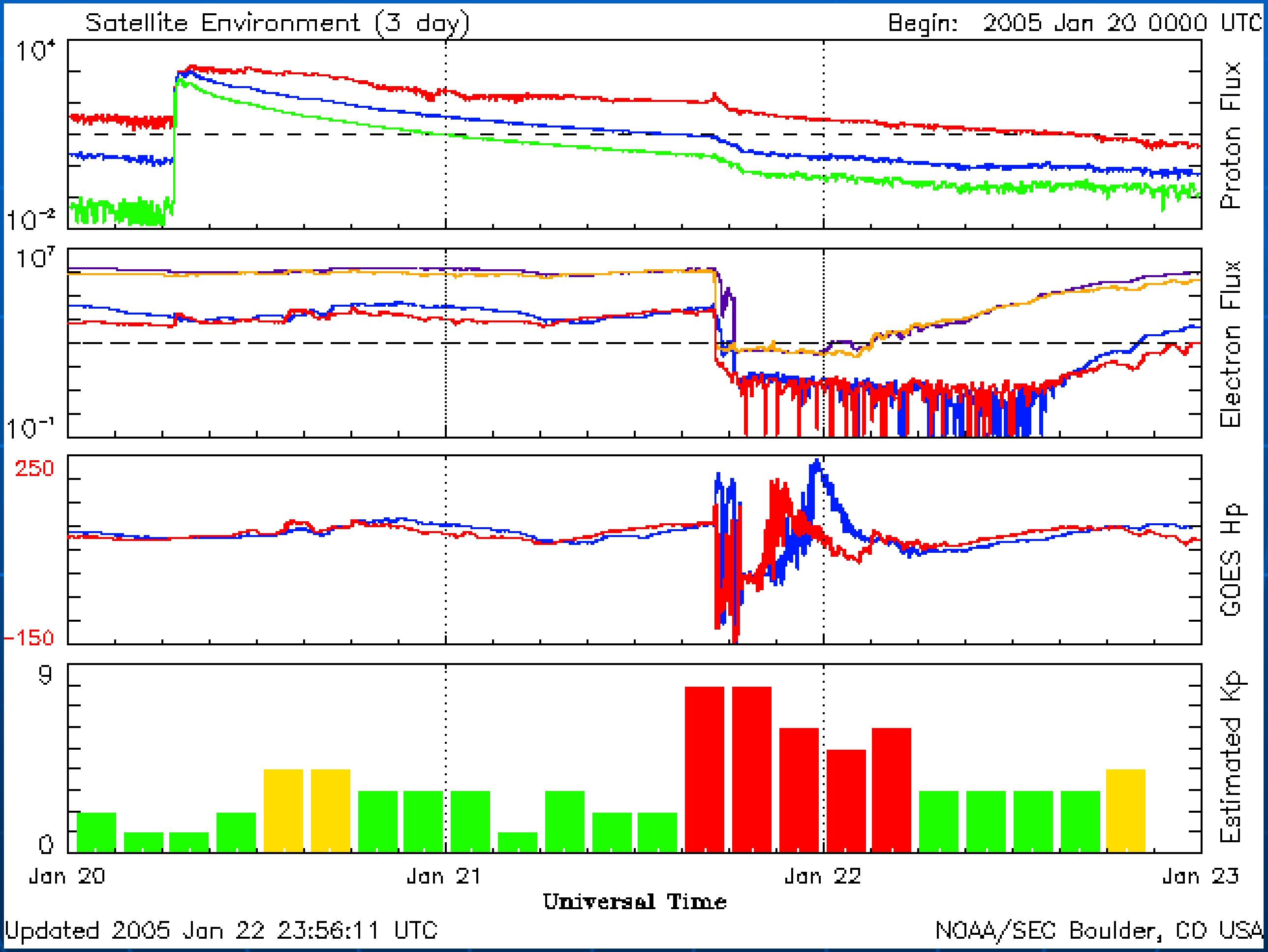


- Cycle 21 started in June 1976 and lasted 10 years and 3 months.
- Cycle 22 started in September 1986 and lasted 9 years and 8 months.
- Cycle 23 started in May 1996 and lasted 12 years and 6 months.
- Cycle 24 started in December 2008.

Solar Cycle 24 Prediction

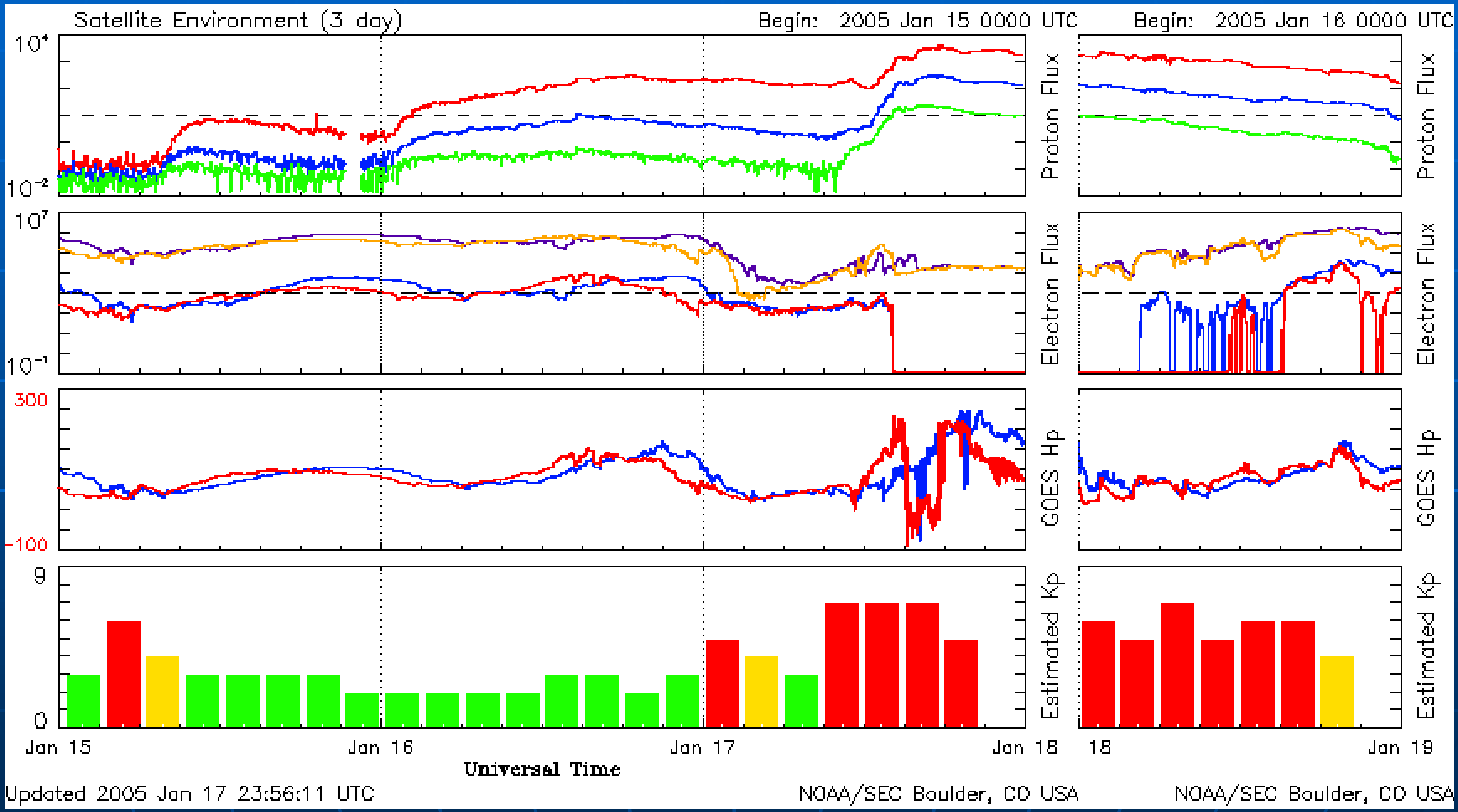


SEPs at GOES



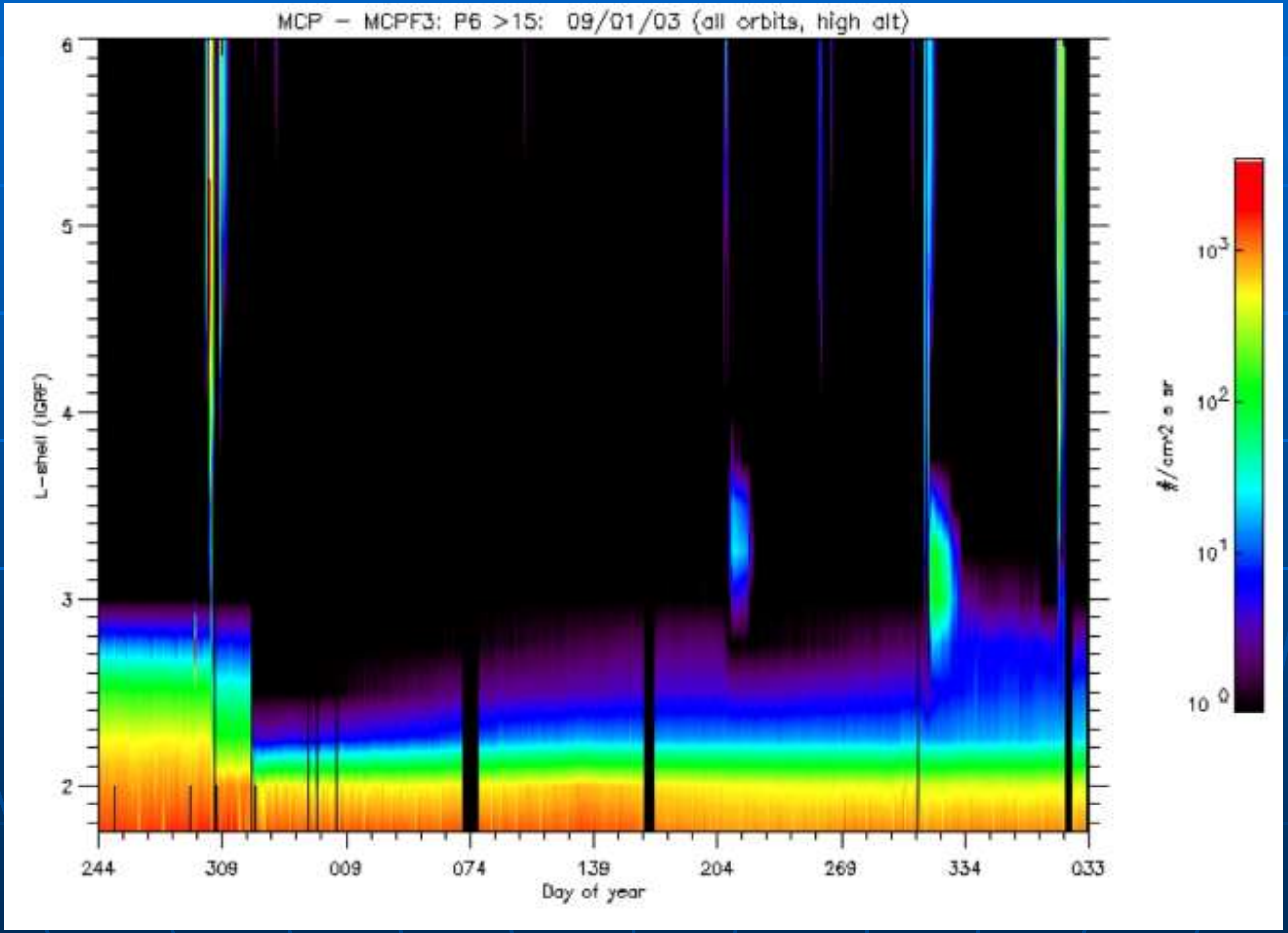
Impulsive SEP event seen at GOES

SEPs at GOES



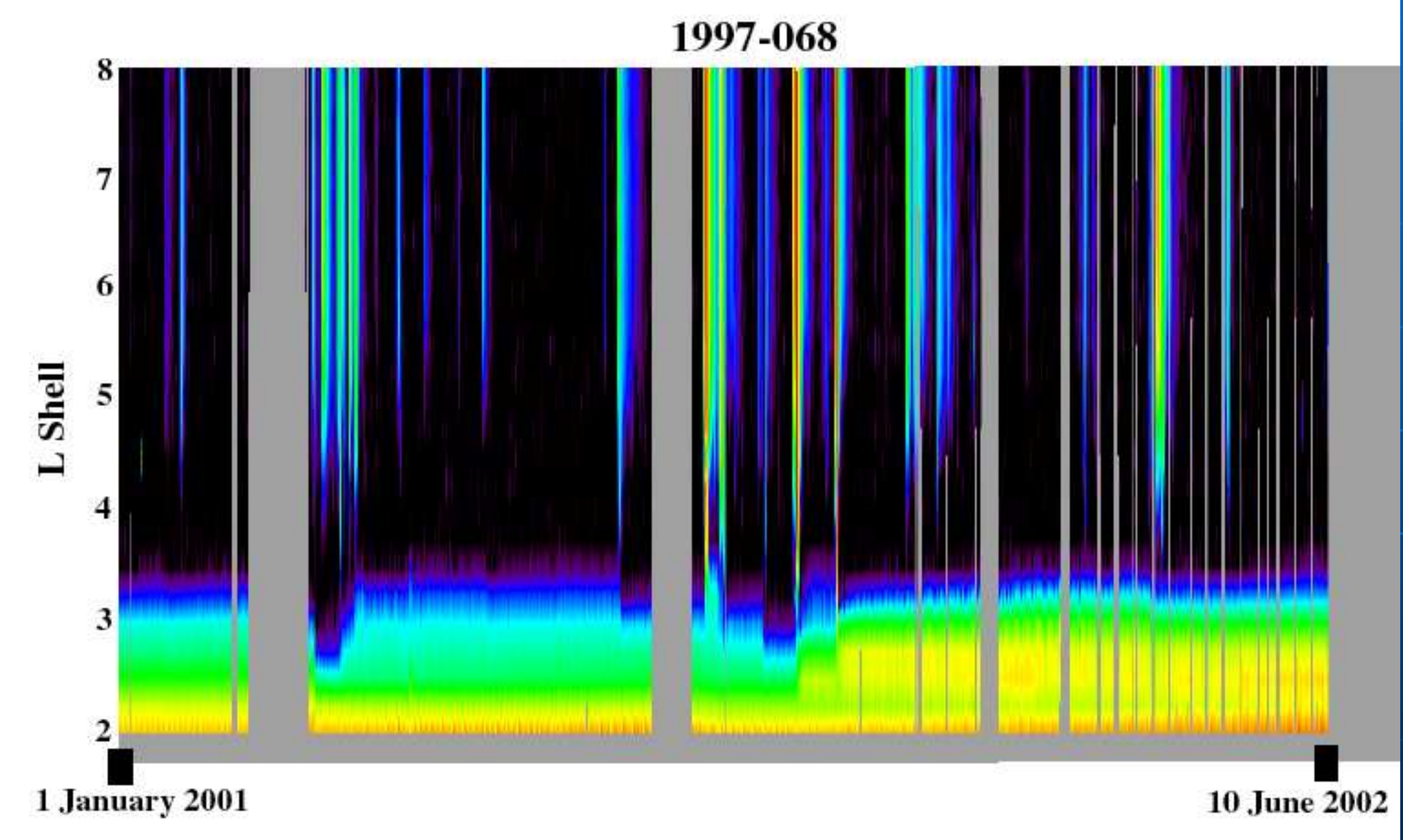
Series of gradual SEP events preceeding Jan 20 2005

2003-2005 >15 MeV HEO protons



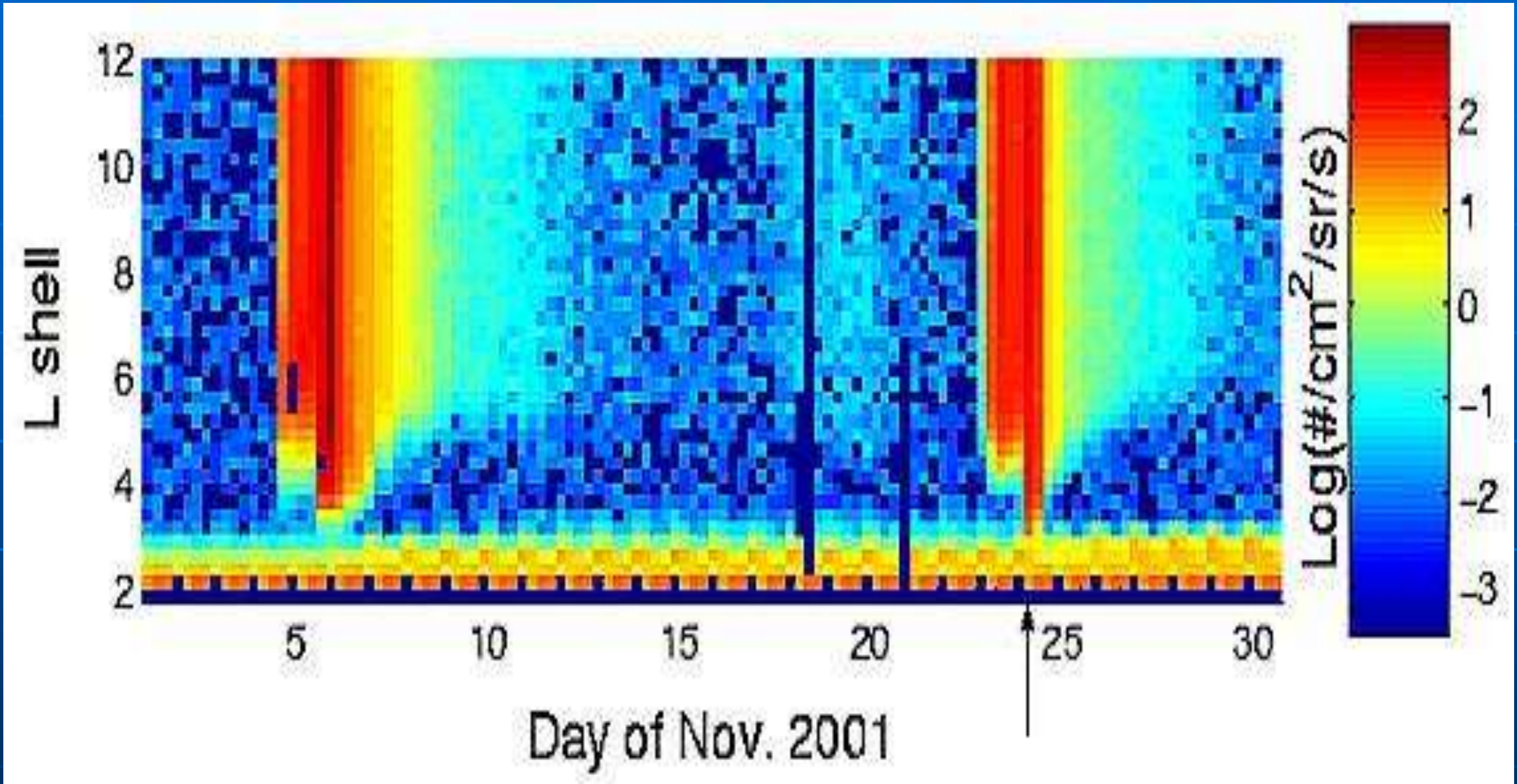
[J. B. Blake, private communication.]

SEP Events & Storms at Solar Max



E > 15 MeV protons from HEO 1997-068

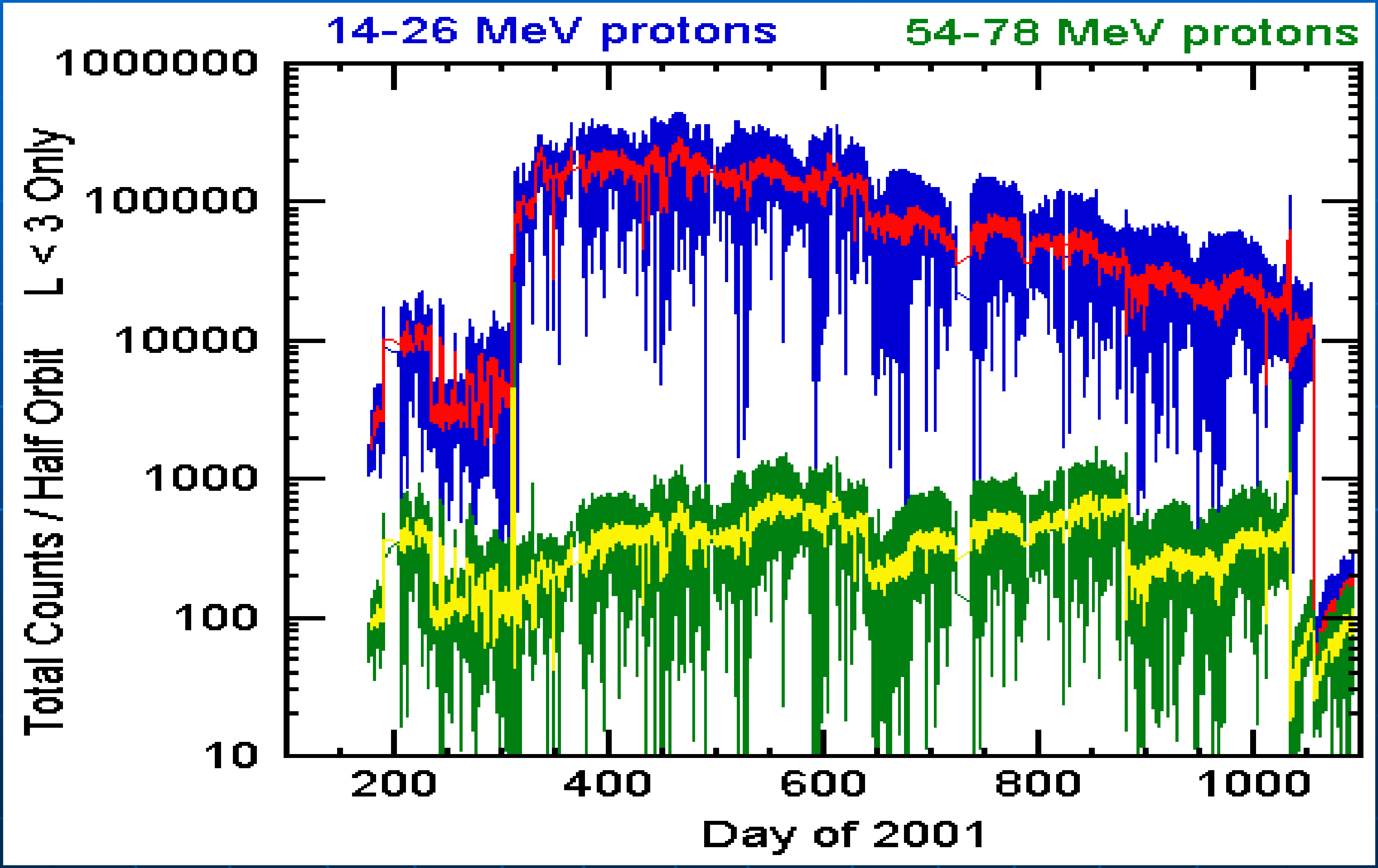
Two CME events in Nov 01 produced SEP trapping at low L

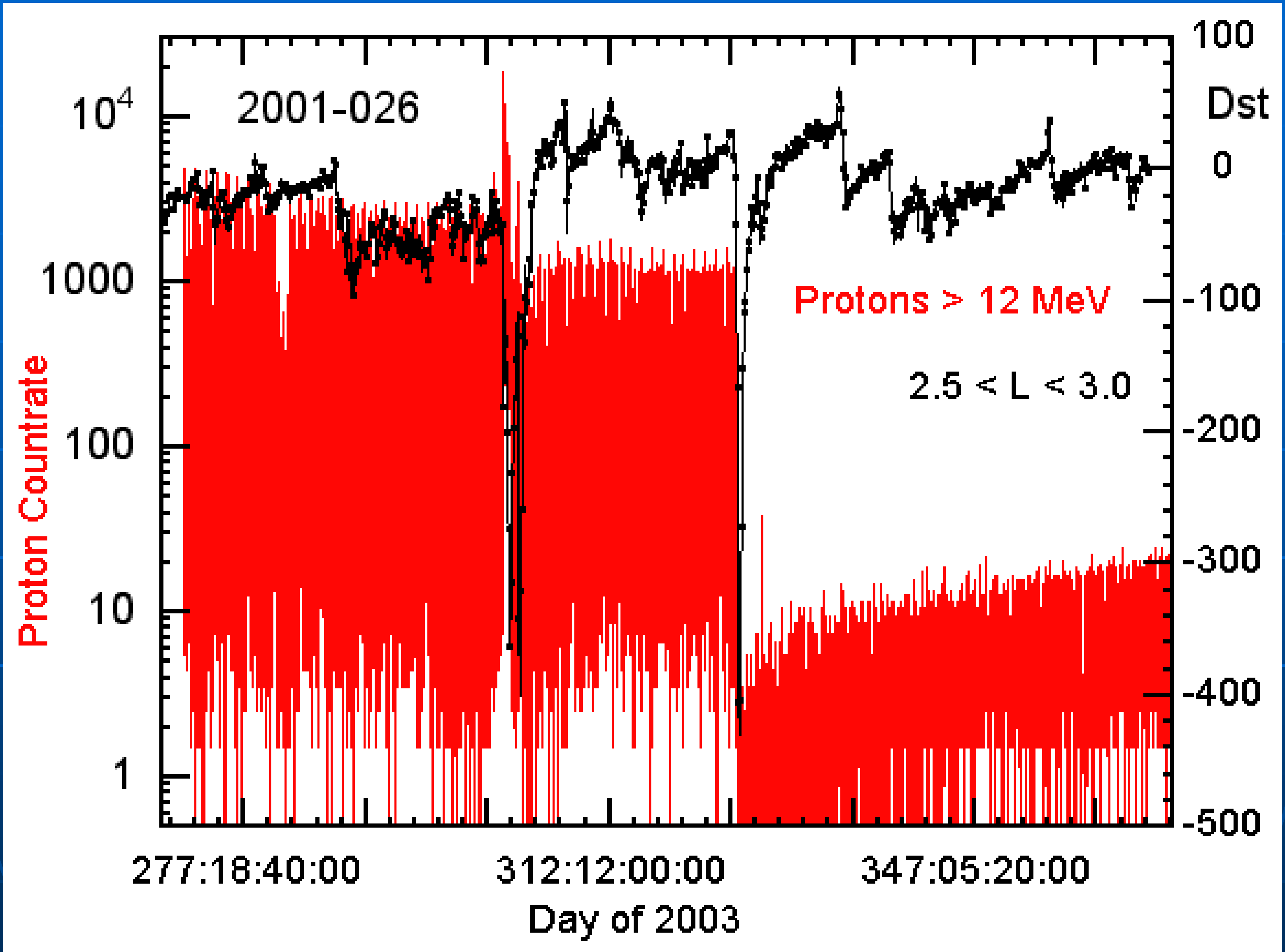


25 MeV ions measured by HEO 1997-068 are injected to low L ~ 2.5, onto trapped orbits.

Kress et al. GRL, 2004

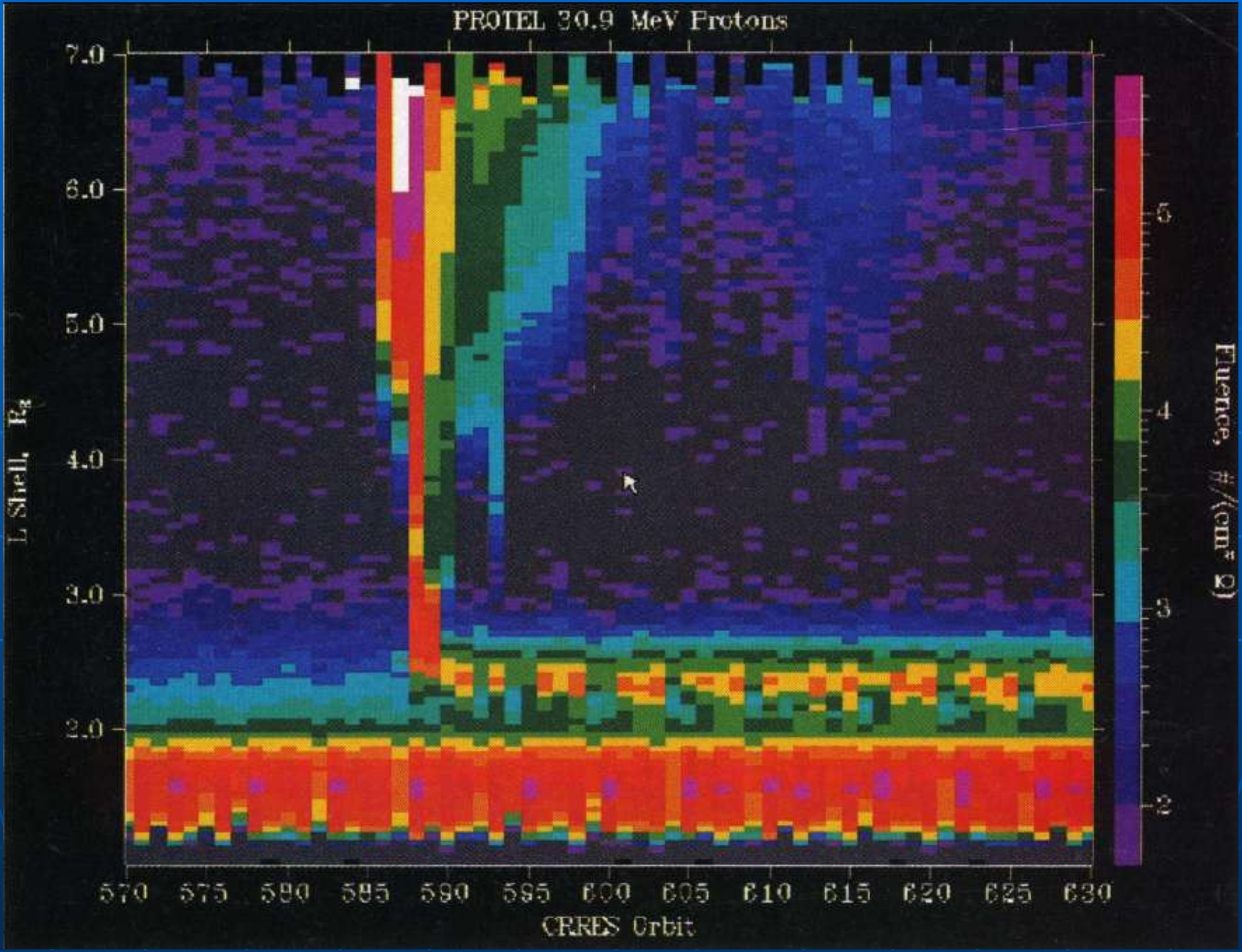
HEO SEP Trapping Nov 01





2001-026
Protons > 12 MeV
2.5 < L < 3.0
Proton Countrate
10^4
1000
100
10
1
Dst
100
0
-100
-200
-300
-400
-500
277:18:40:00
312:12:00:00
347:05:20:00
Day of 2003

CRRES March 91 Proton Injection Event

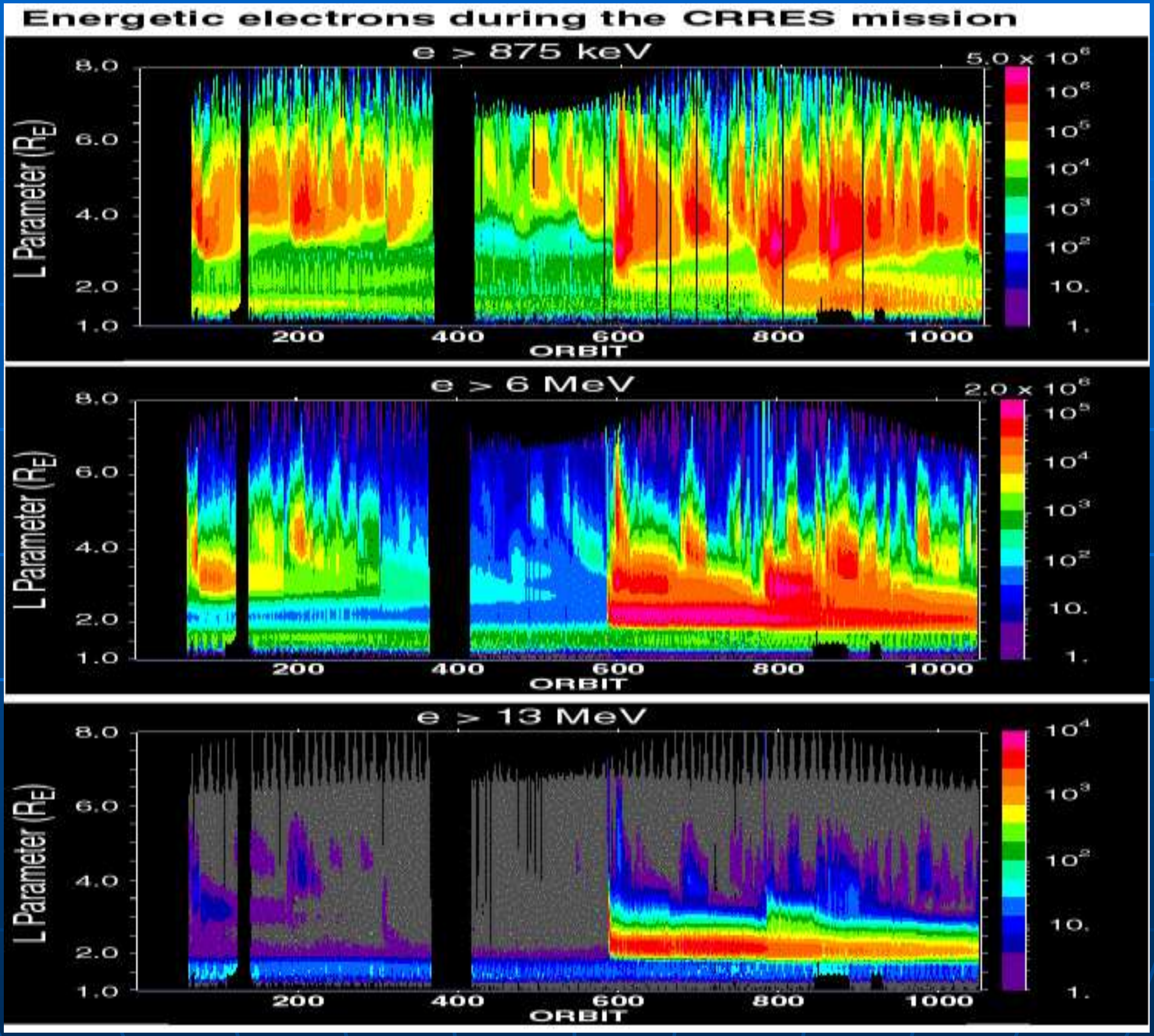


↑

March 24, 1991

Hudson et al., JGR, 1997

CRRES March 91 Electron Injection Event



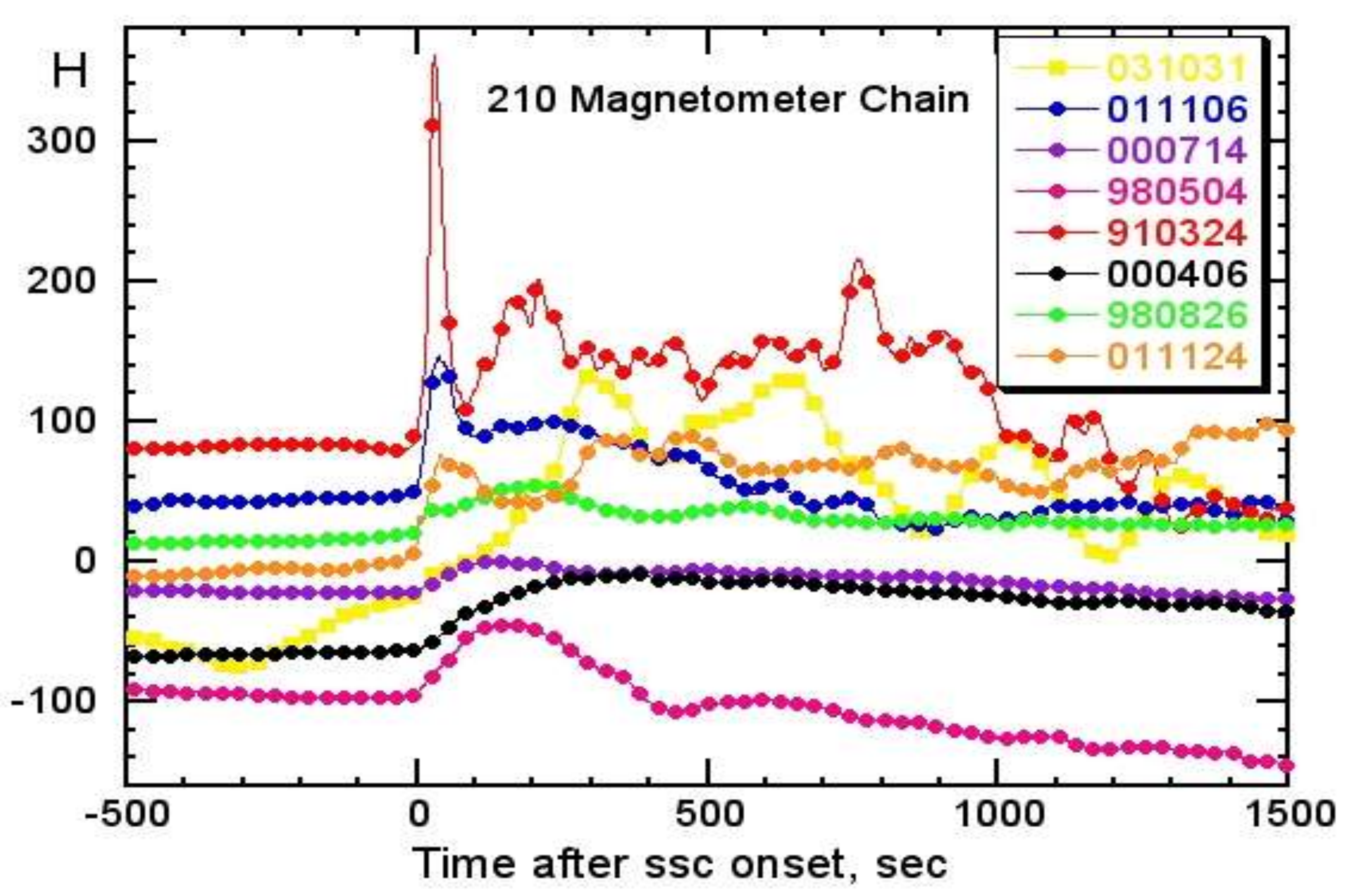
July 1990

Oct. 1991

March 24, 1991

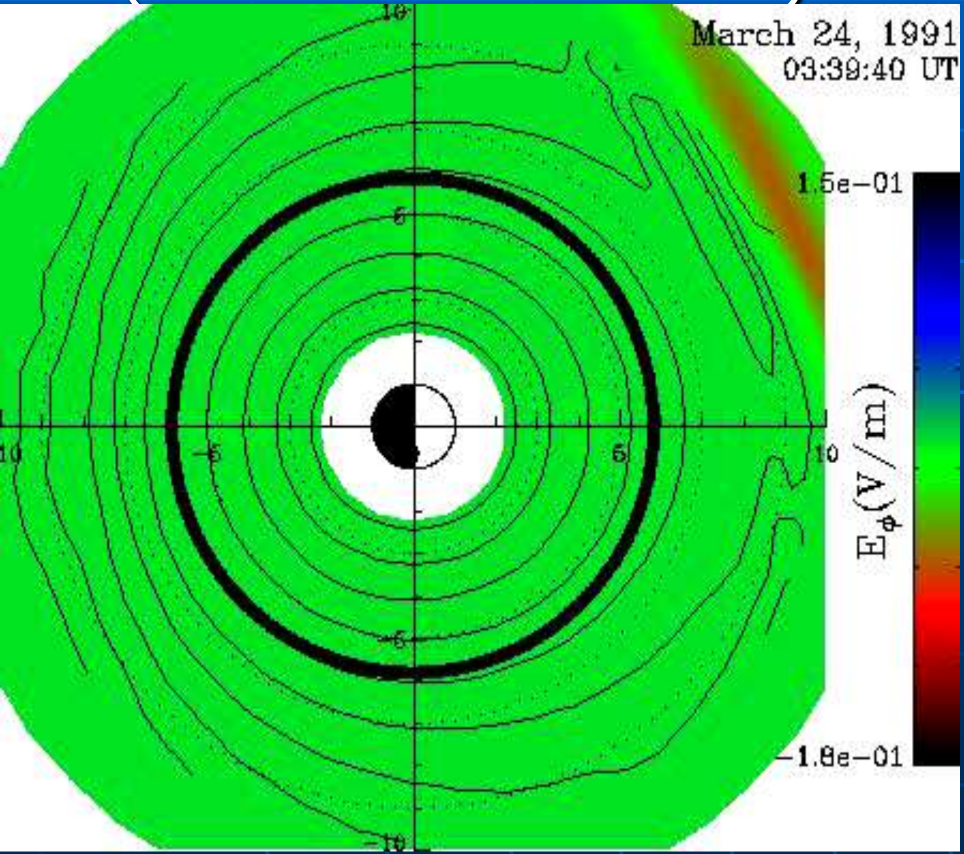
(Courtesy of J. B. Blake)

CME-SSC Ground Signatures

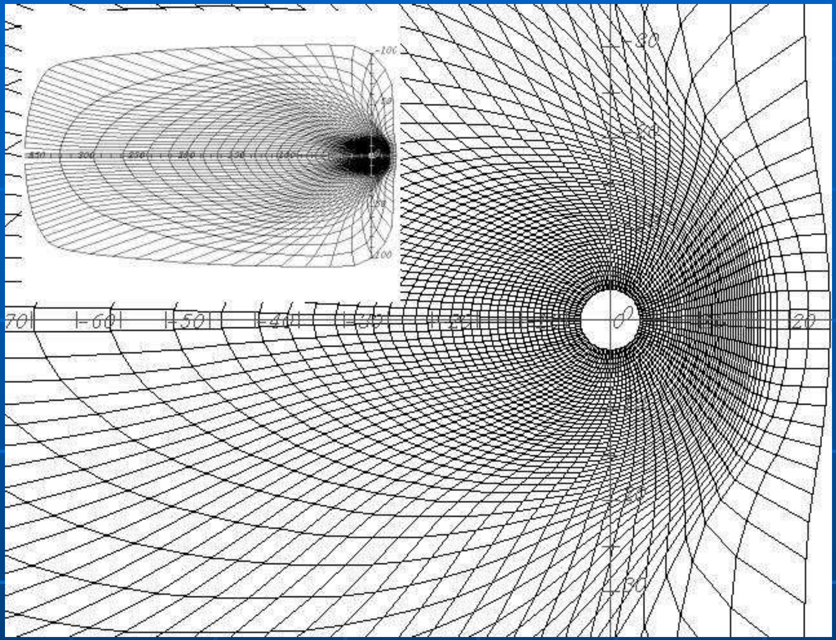


Global LFM-MHD Simulations of Magnetosphere

- Solar wind measurements made IMP8, WIND or ACE (not avail for Mar 91)

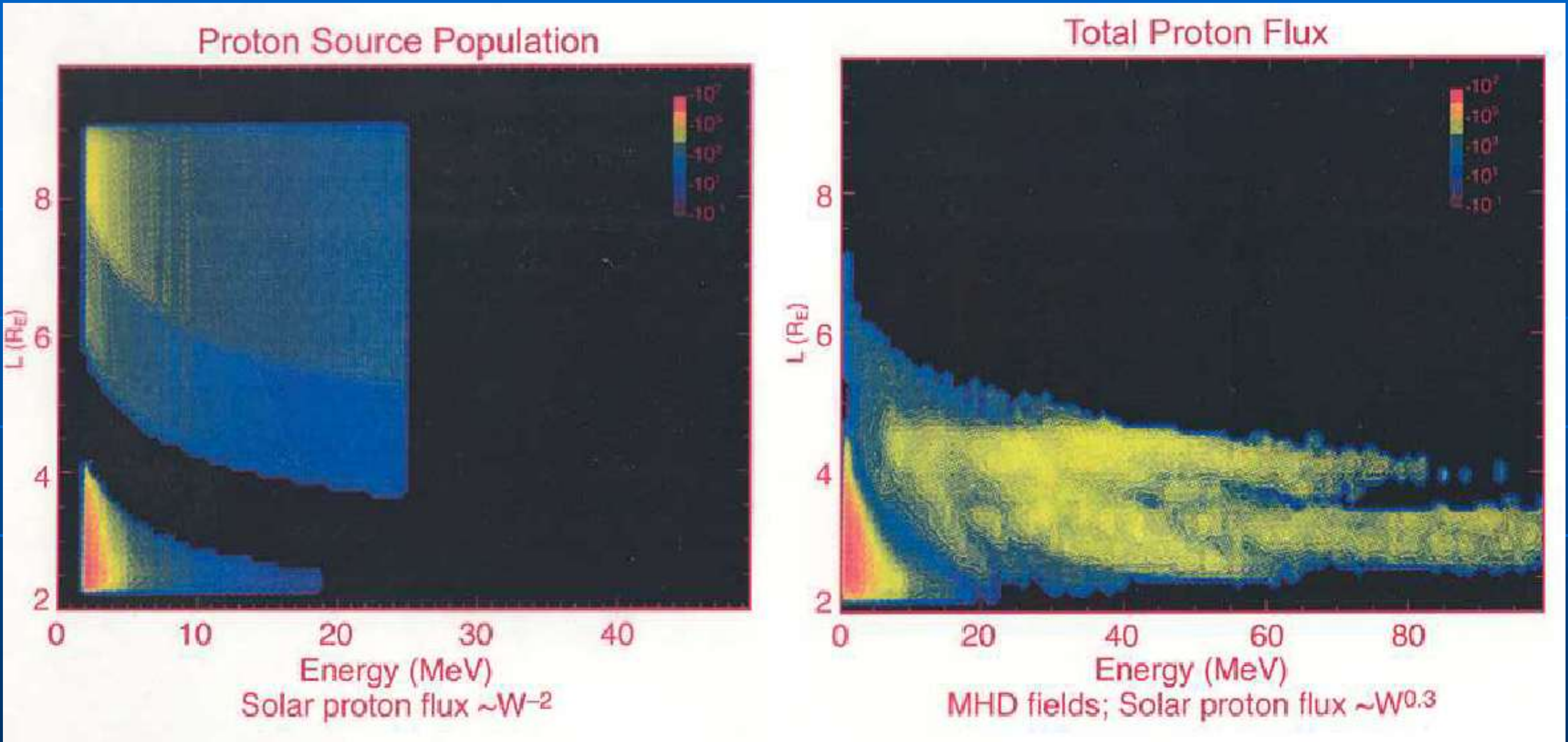


3.5 MeV at L=6.6, t=0 (M =11,150 MeV/G)



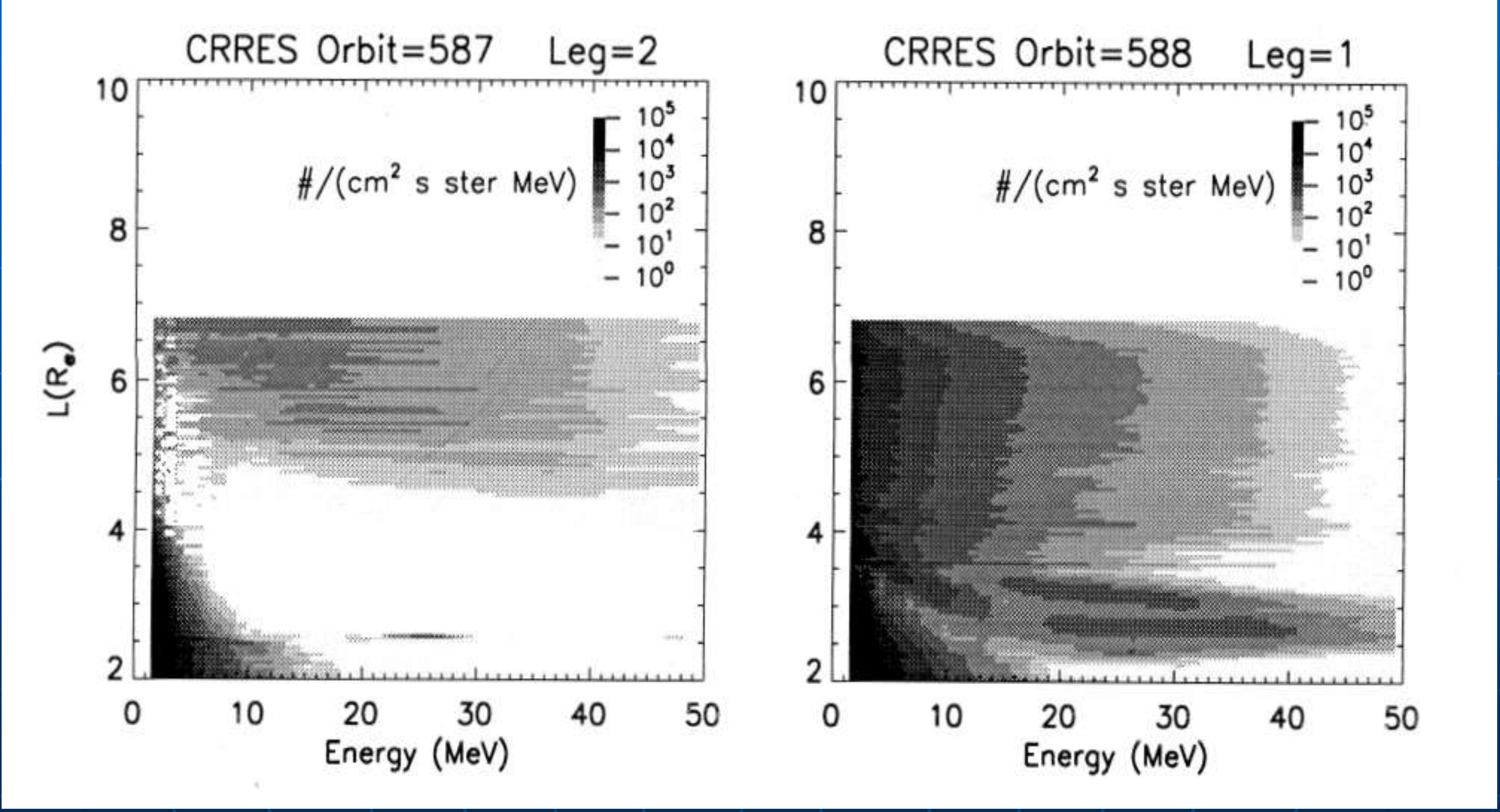
- Ideal MHD equations are solved on a computational grid to simulate the response of the magnetosphere

Equatorial plane proton simulations with MHD fields for March 24, 1991

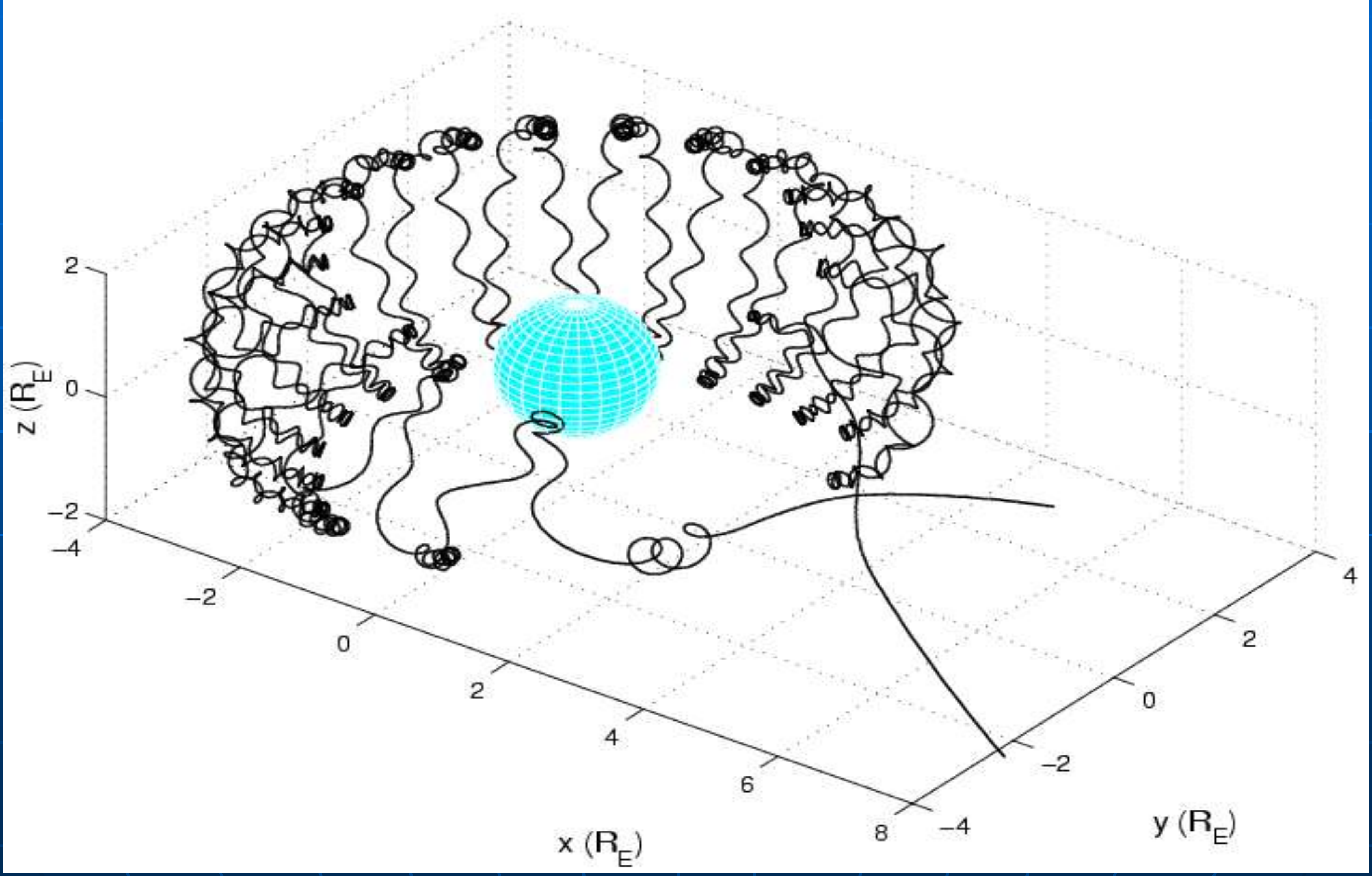


Hudson et al., JGR, 1997

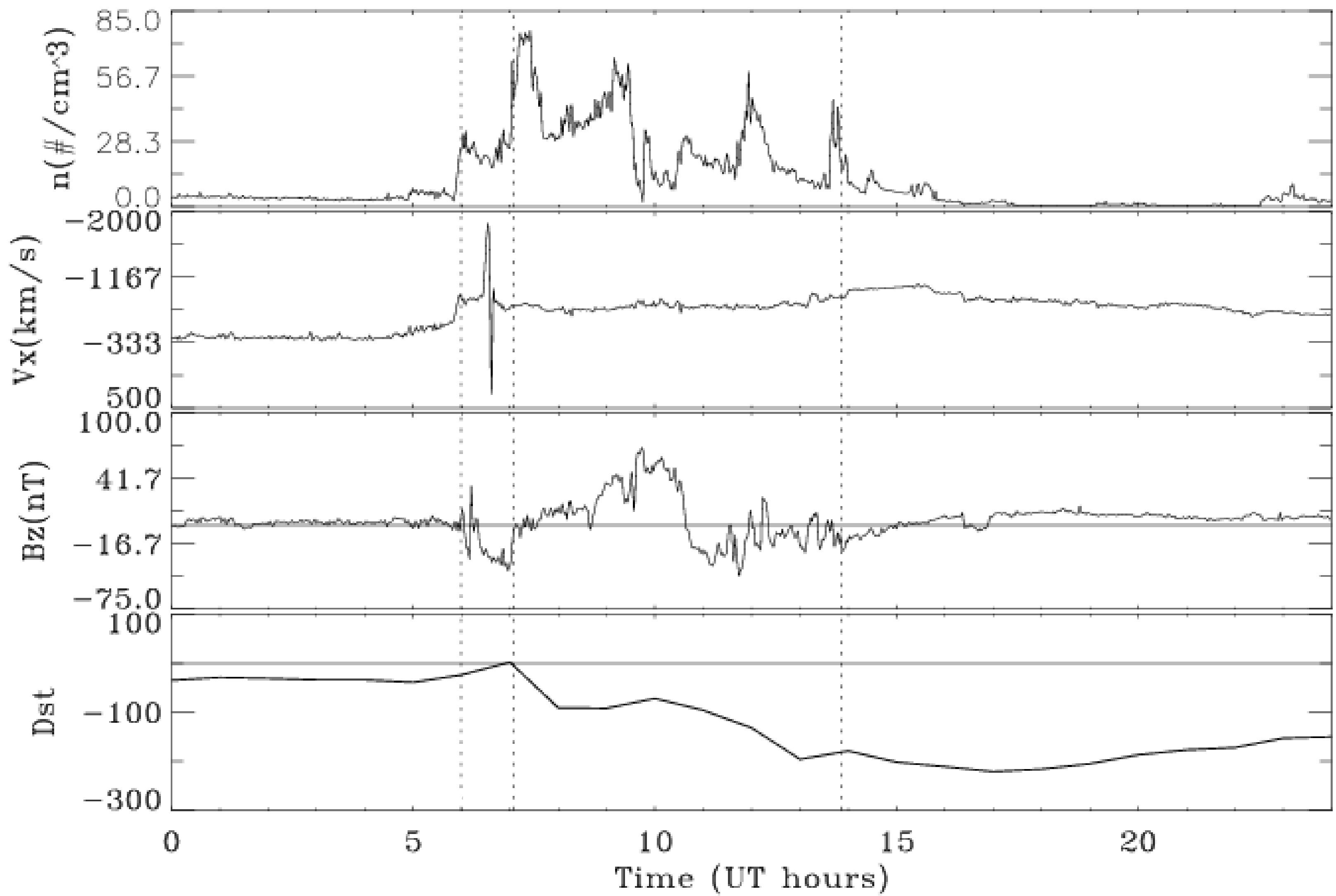
CRRES Protel Measurements



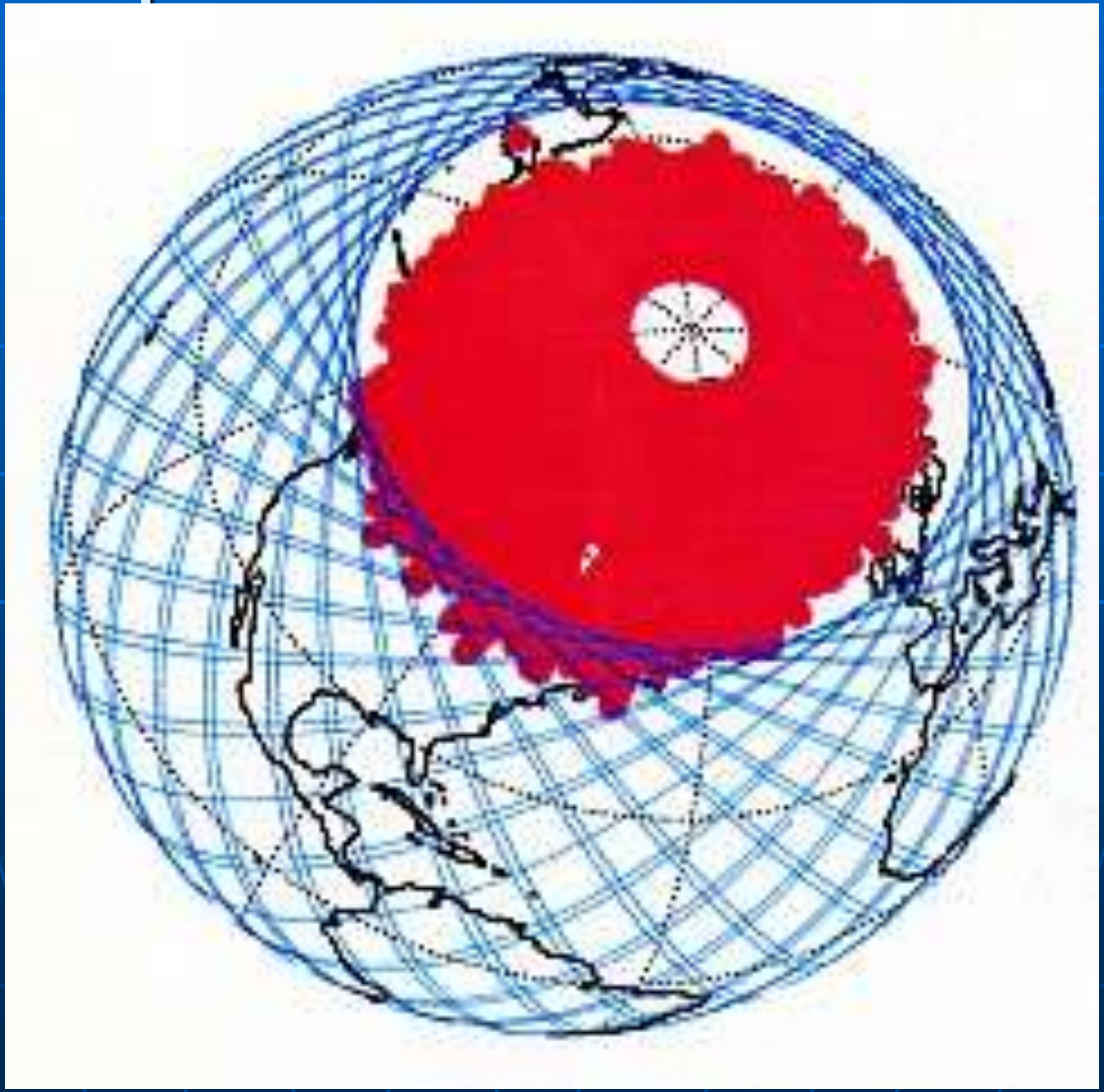
Solar Energetic Particle Access



Since 1994 Wind Spacecraft Data Available: Nov 24 2001

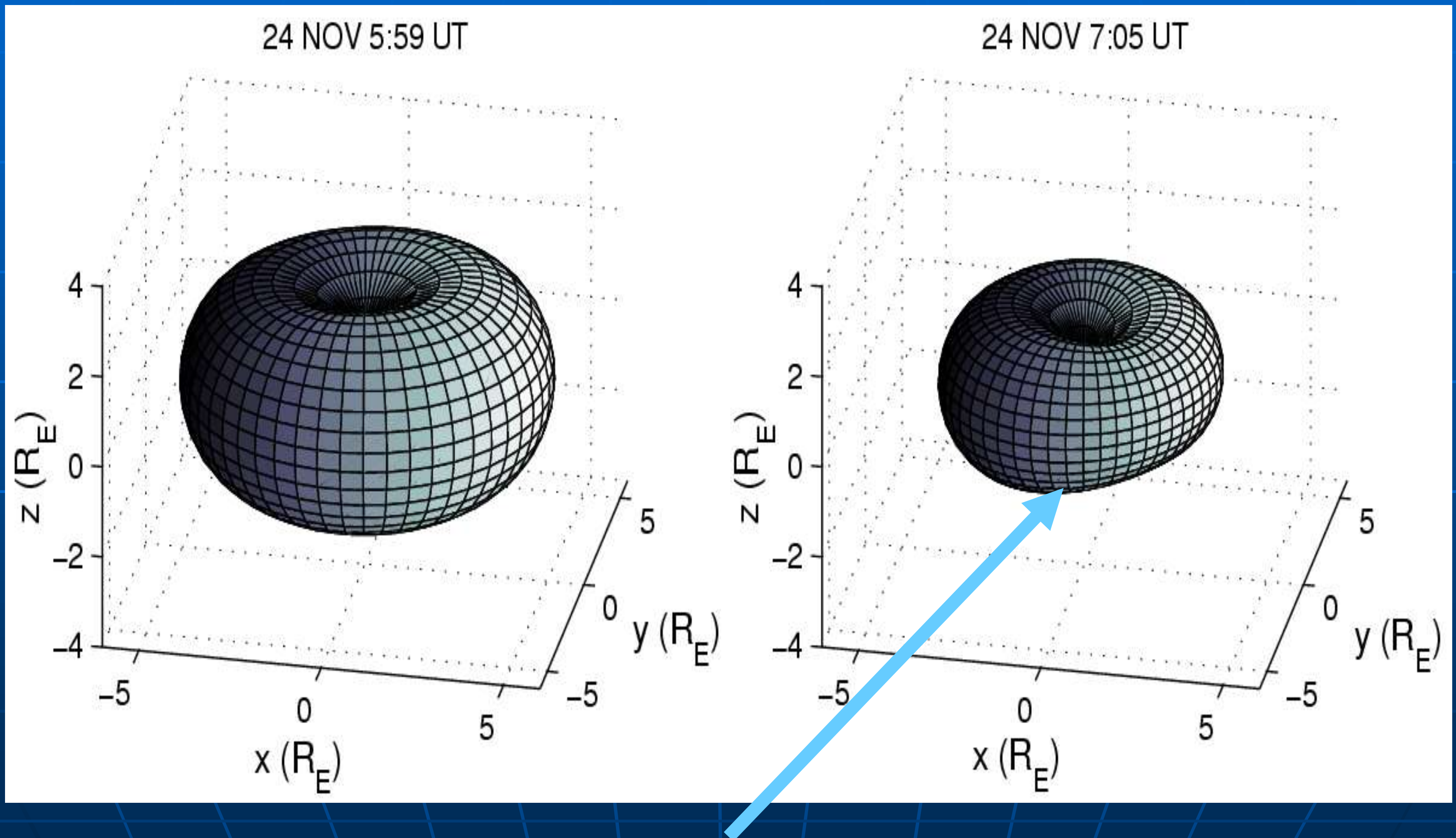


SEP access relative to International Space Station orbit



MHD-SEP simulations:

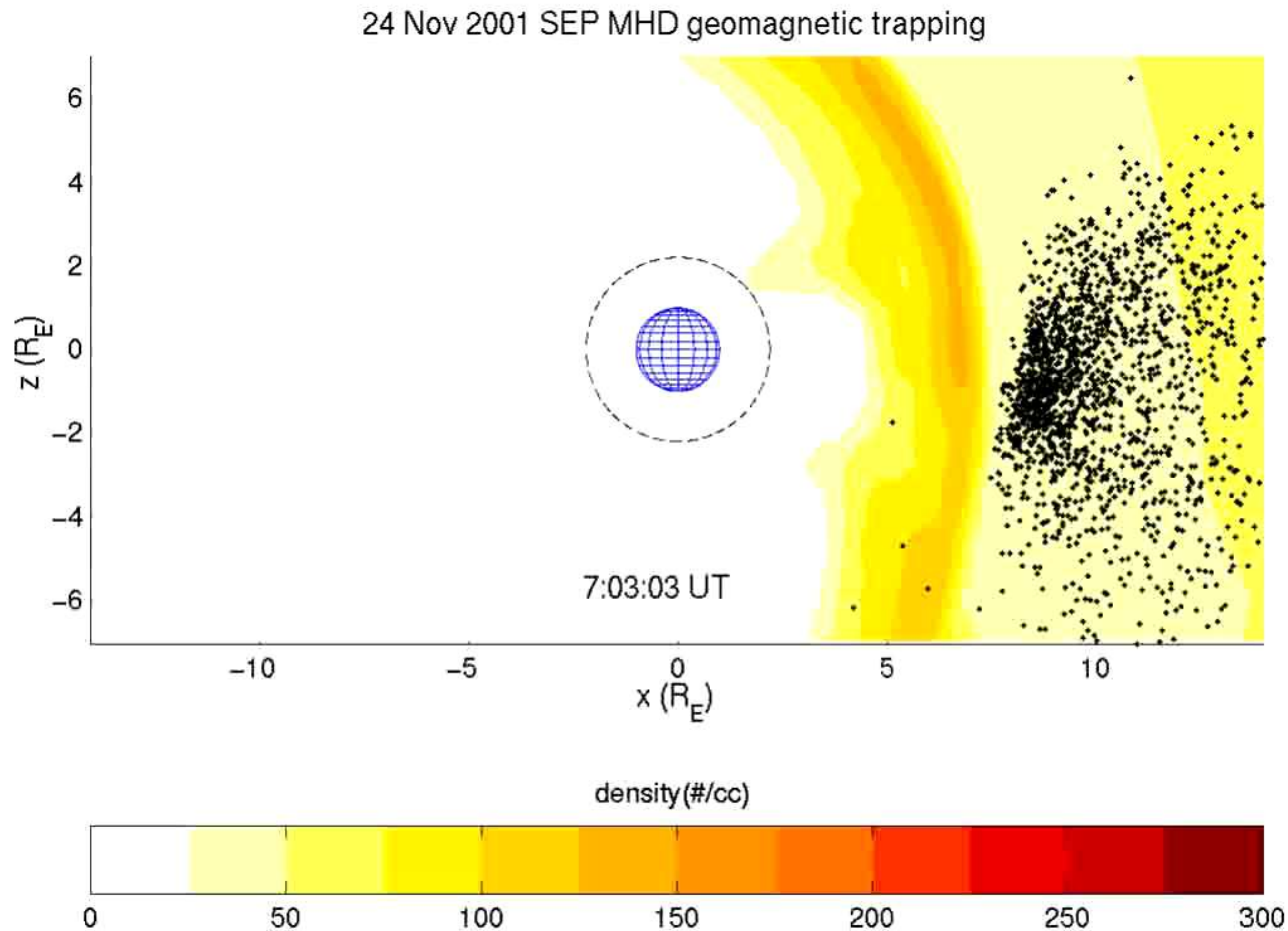
Effect of solar wind pressure pulse on SEP cutoff surface



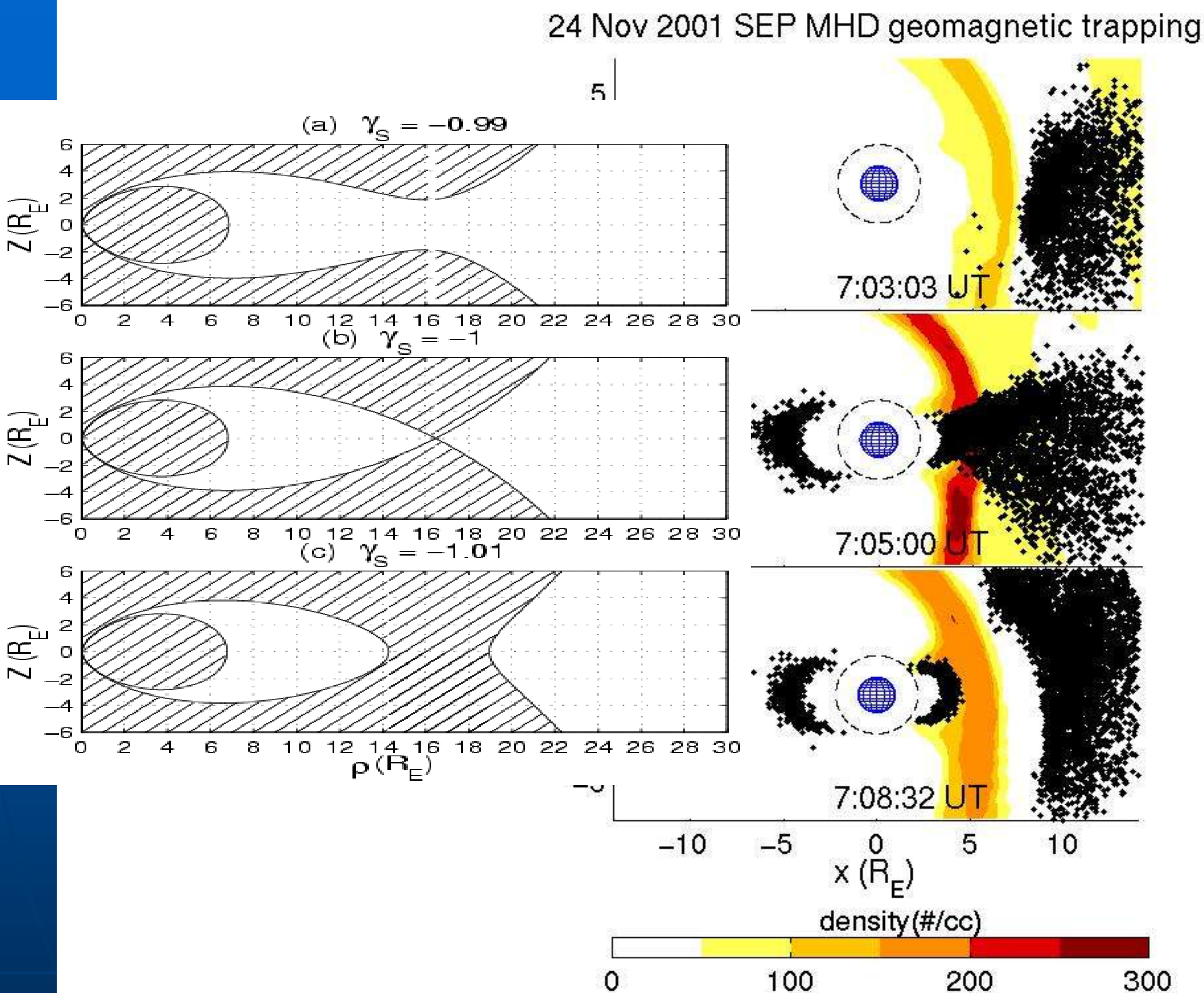
25 MeV SEP access to lower lattitude

Kress et al., GRL, 2004

25 MeV Proton Access & Trapping

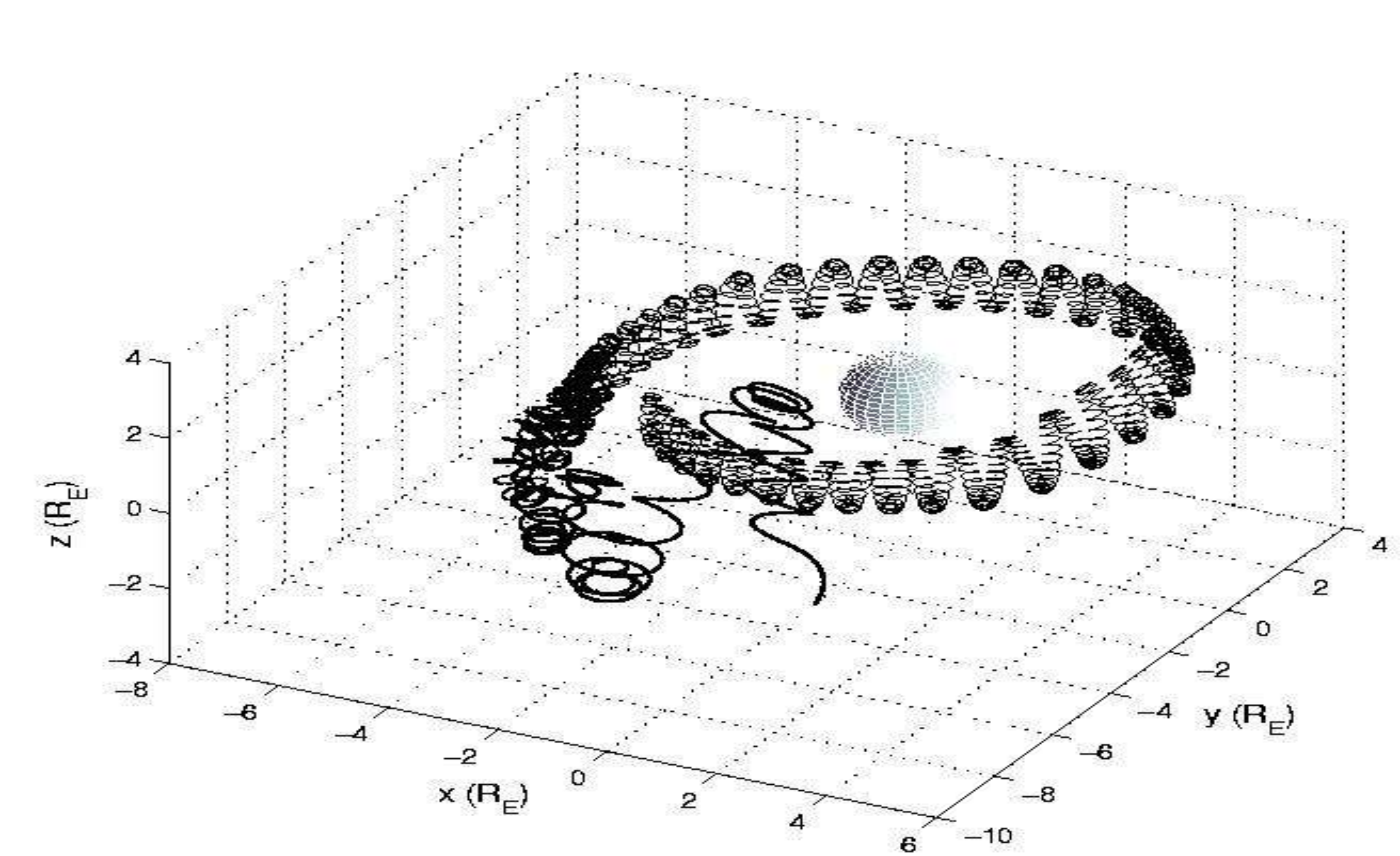


(See Kress et al. GRL 2005)



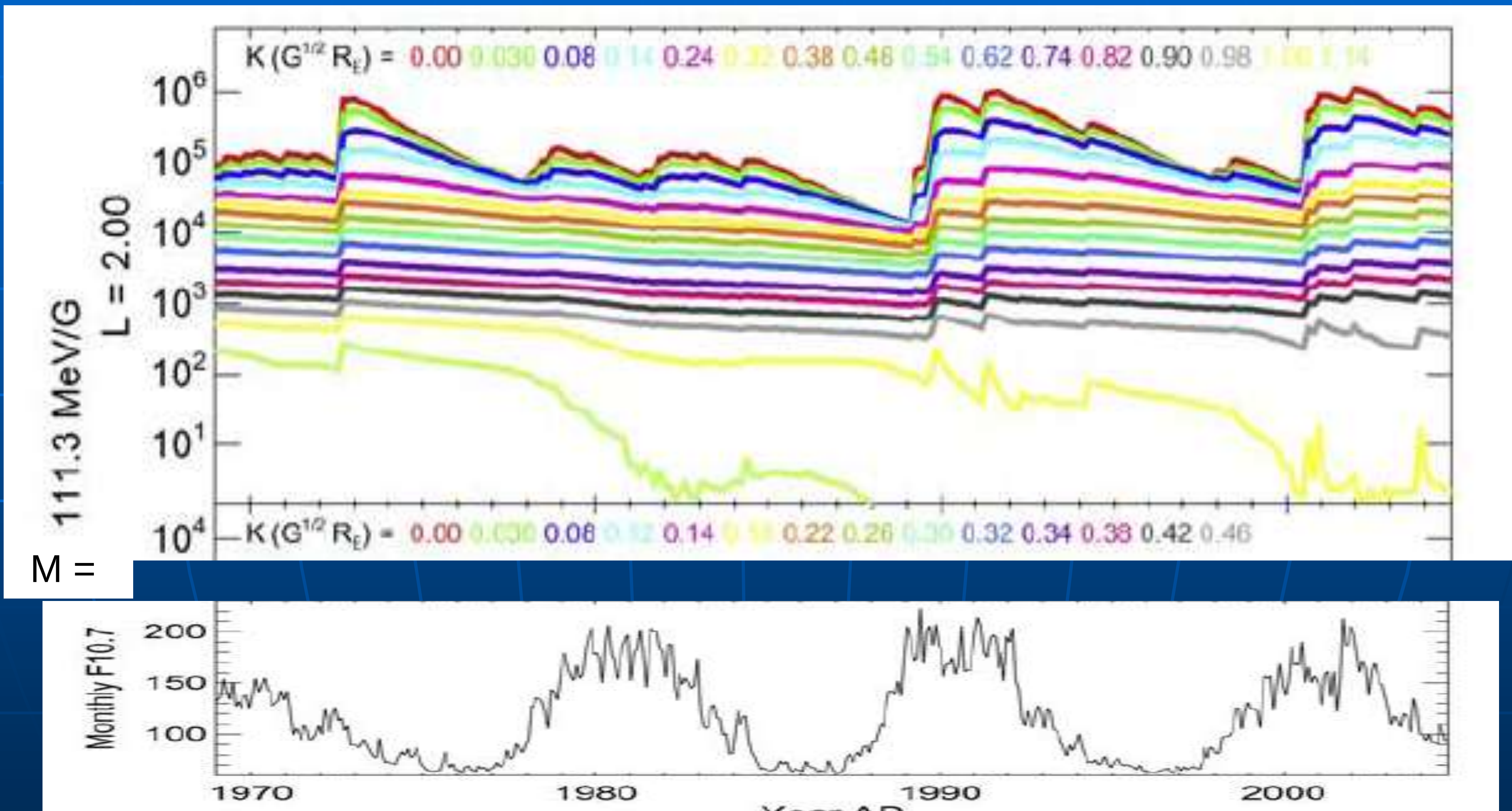
Stormer orbit cutoffs depend on generalized momentum, P_φ = p_φ + e A, therefore on B = curl A, changing with B(t)

Single proton trajectory in MHD fields for **29 Oct 2003 SSC.** The proton is launched into the solar wind at x =12 RE, transported inward to ~ 4 RE, and accelerated by the SSC electric field pulse. Initial and final energies of the proton are ~ 1 and 10 MeV respectively. Sim time 140s.



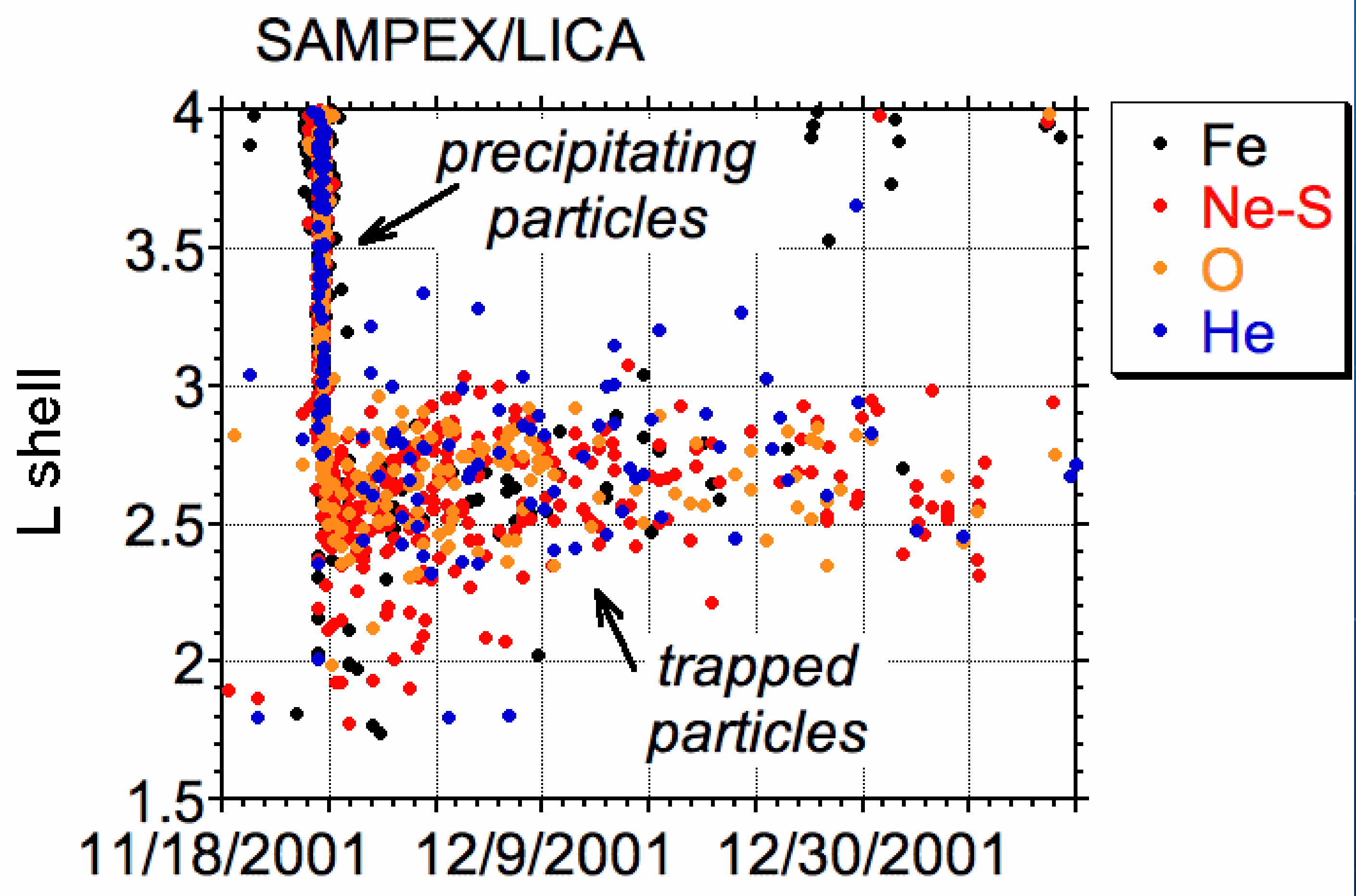
SEP Contribution to Inner Zone

Energies < 100 MeV for *L* >1.3 are dominated by solar protons, not CRAND



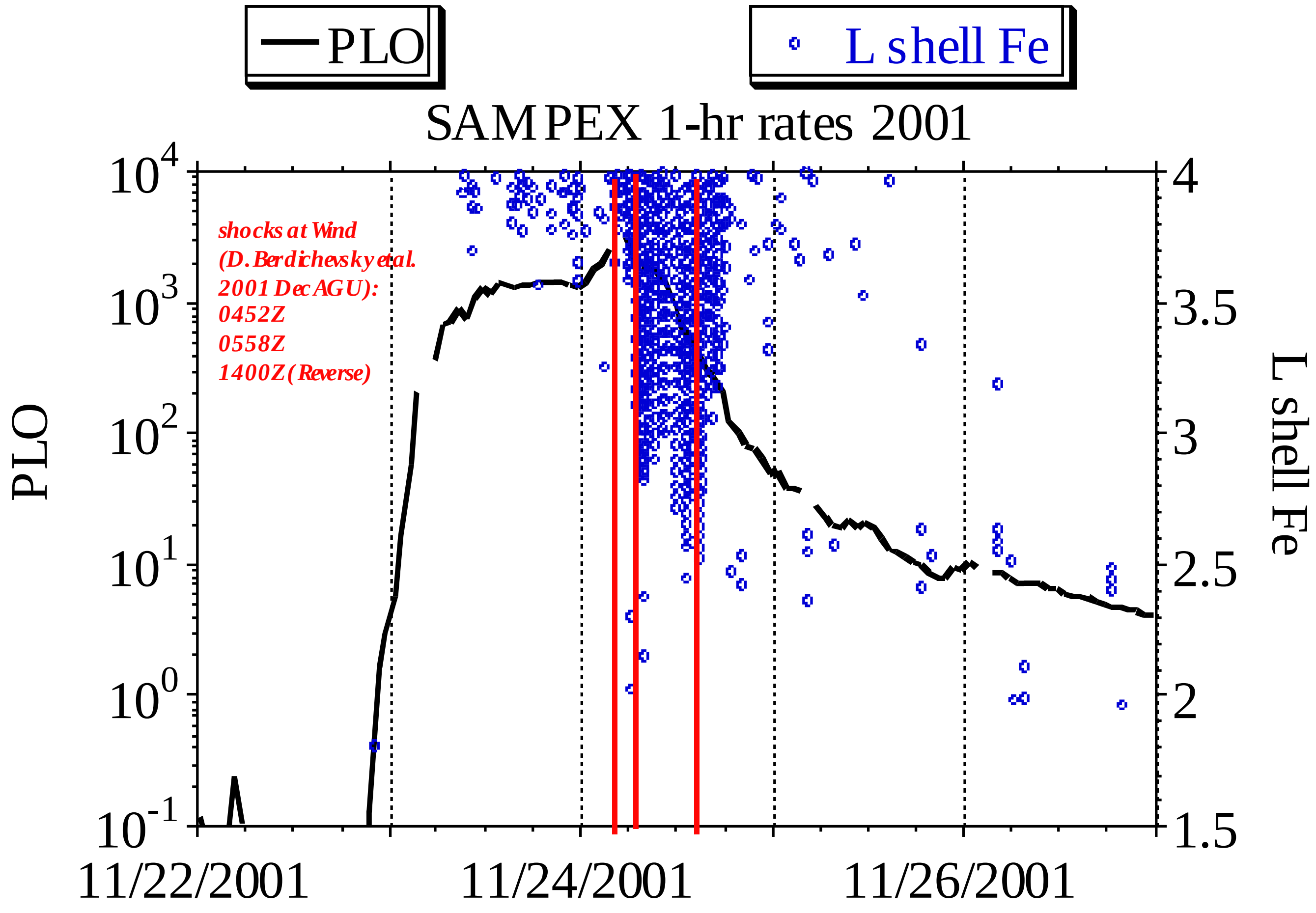
4.2 MeV equatorially mirroring proton at L=2, Selesnick et al., SW 2007

New ion belt example: 24 Nov 01



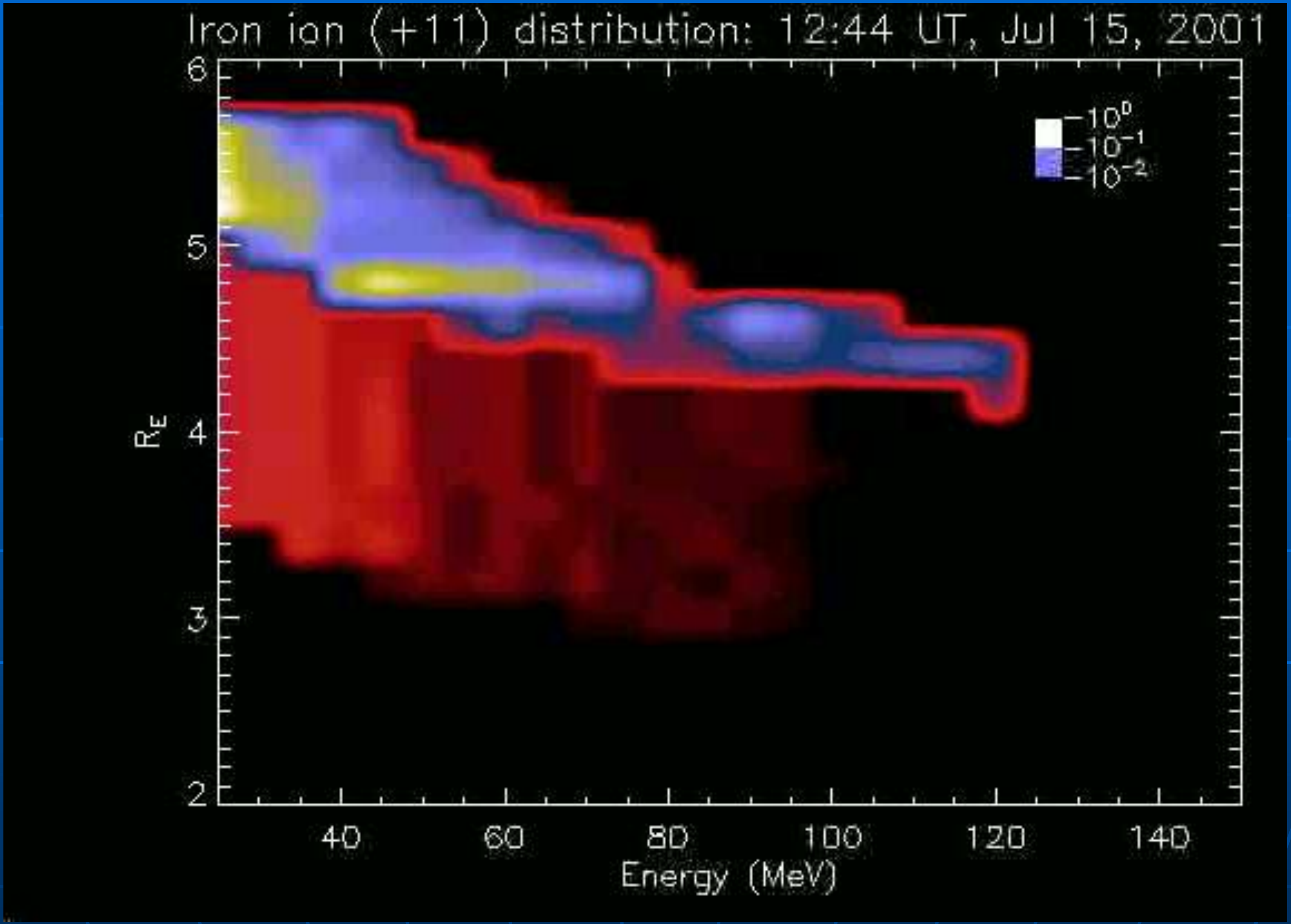
Mazur et al., AGU Monograph 165, 2006

Clear trapping of solar particles: 13 of 26 SEP penetration events inside L=4, 98-03



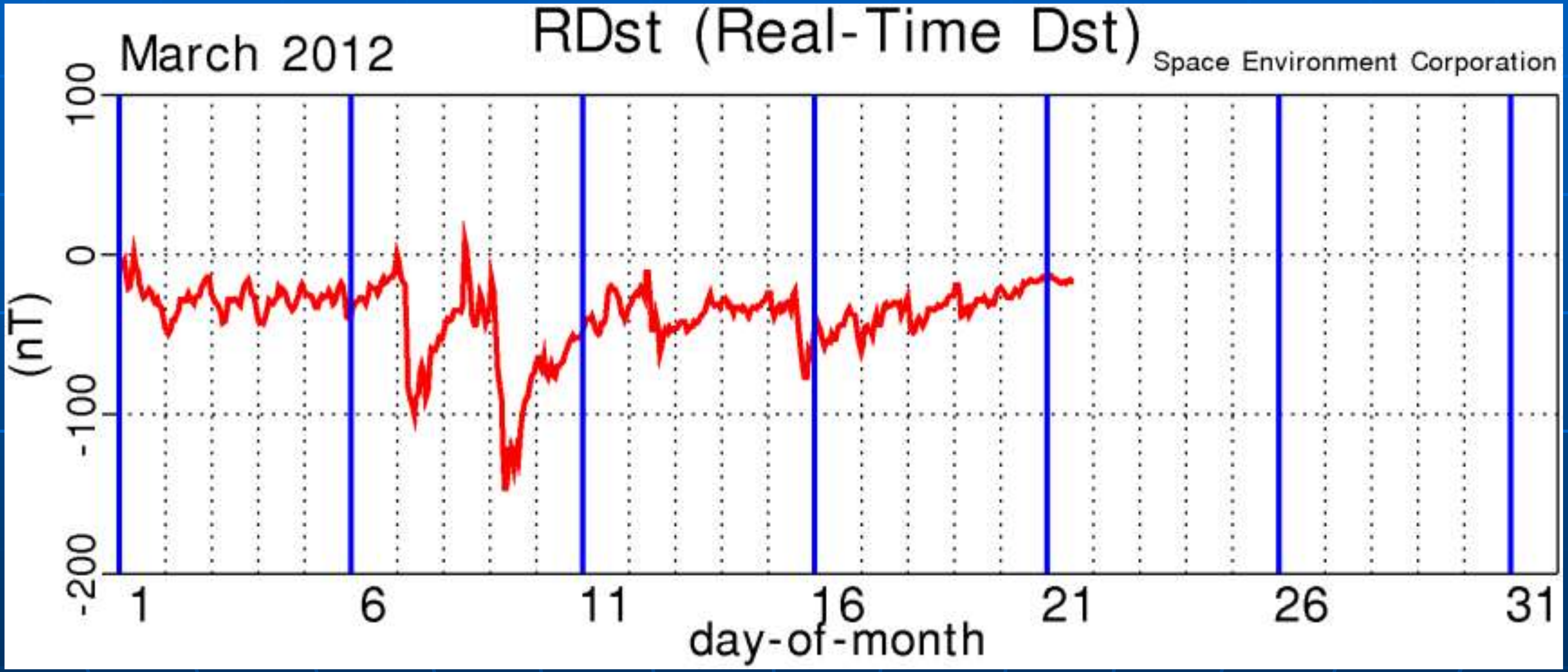
Friday, July 26, 2002

Hudson et al., Annales Geophys., 2004



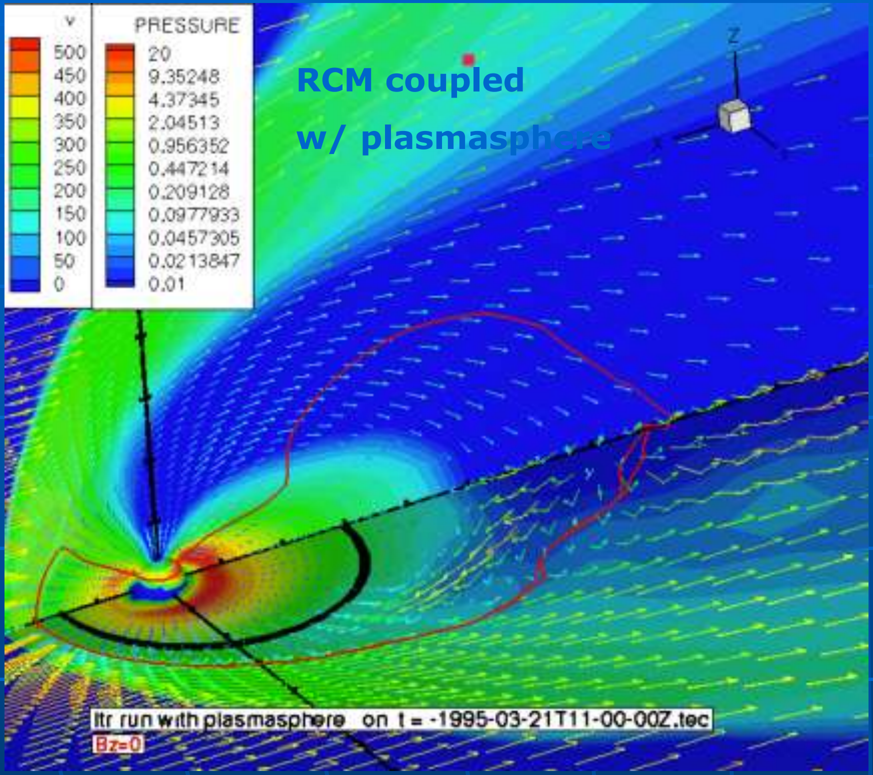
Bastille Day storm Fe+11 trapping simulation

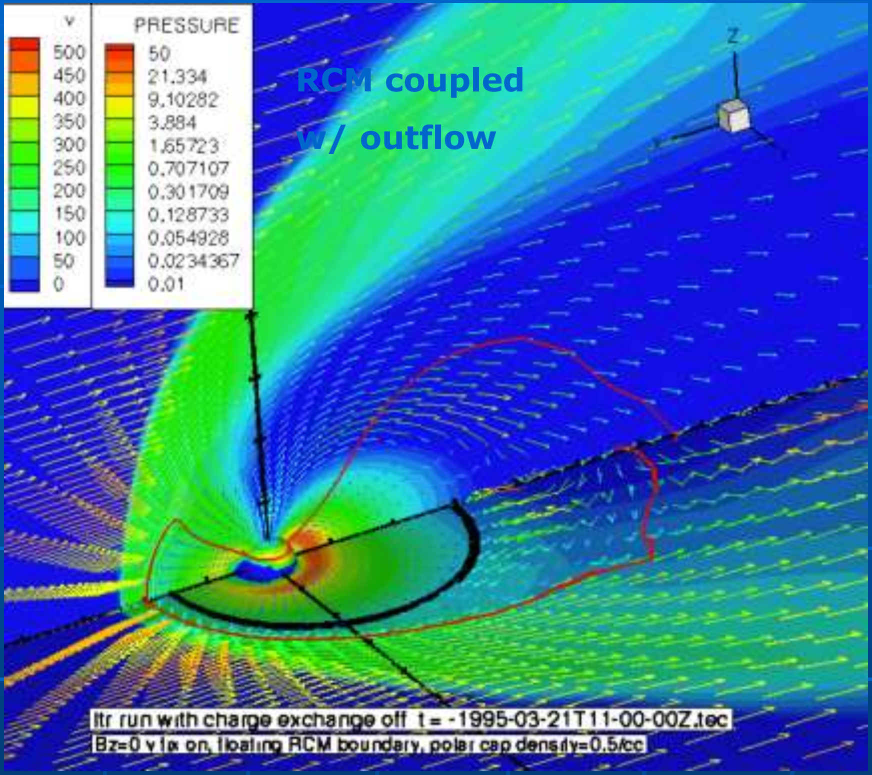
Dst Measures Stormtime Ring Current Perturbation of Earth's B-field



Ring current increases due to enhanced convection-> B_{RC} opposes B_E

LFM-RCM runs with OpenMP Code



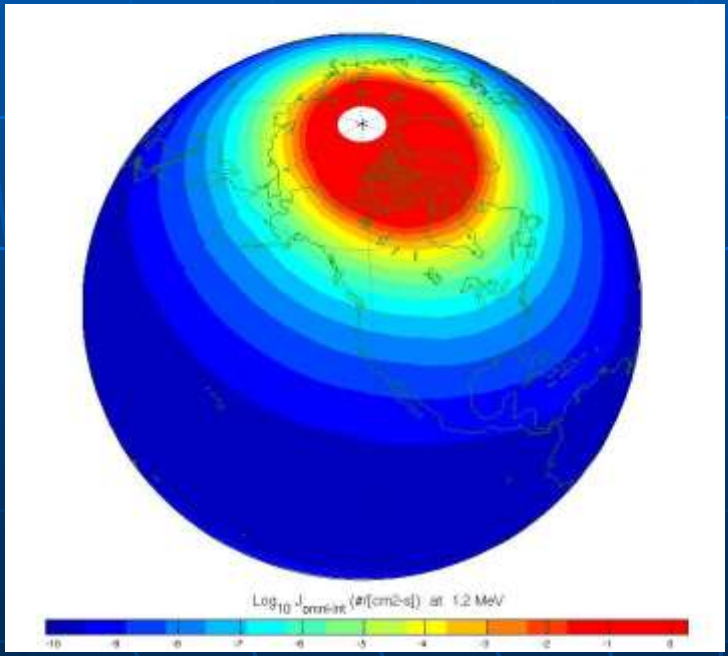


Left: Effect of simple fixed plasmasphere. **Right:** High-latitude mass outflow suppresses high speed flows on the dusk side.

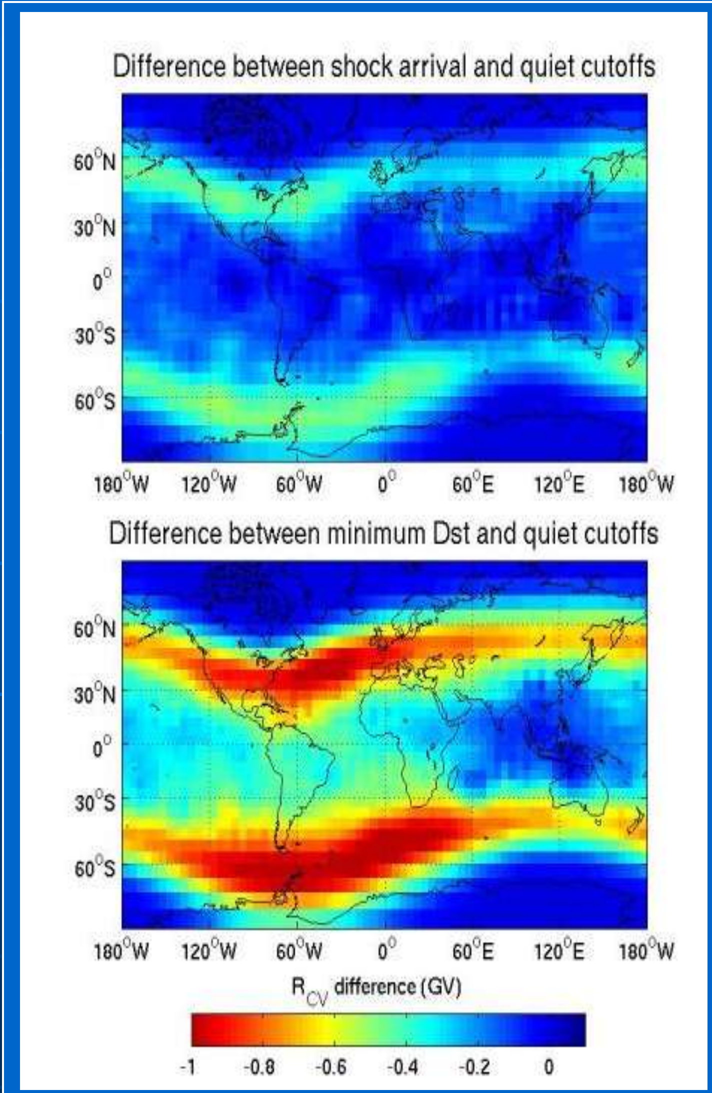
$$nkT + B^2/2\pi = \text{constant} \rightarrow p = nkT \sim 1/\sqrt{B}$$

MHD B-> SEP Cutoff Rigidities R=pc/q (MV)

- Interplanetary shock arrives 10/29/03 ~ 6 UT.
- Maps show pre- and storm cutoff rigidities at h=100 km



Integral Flux > 1.2 MeV

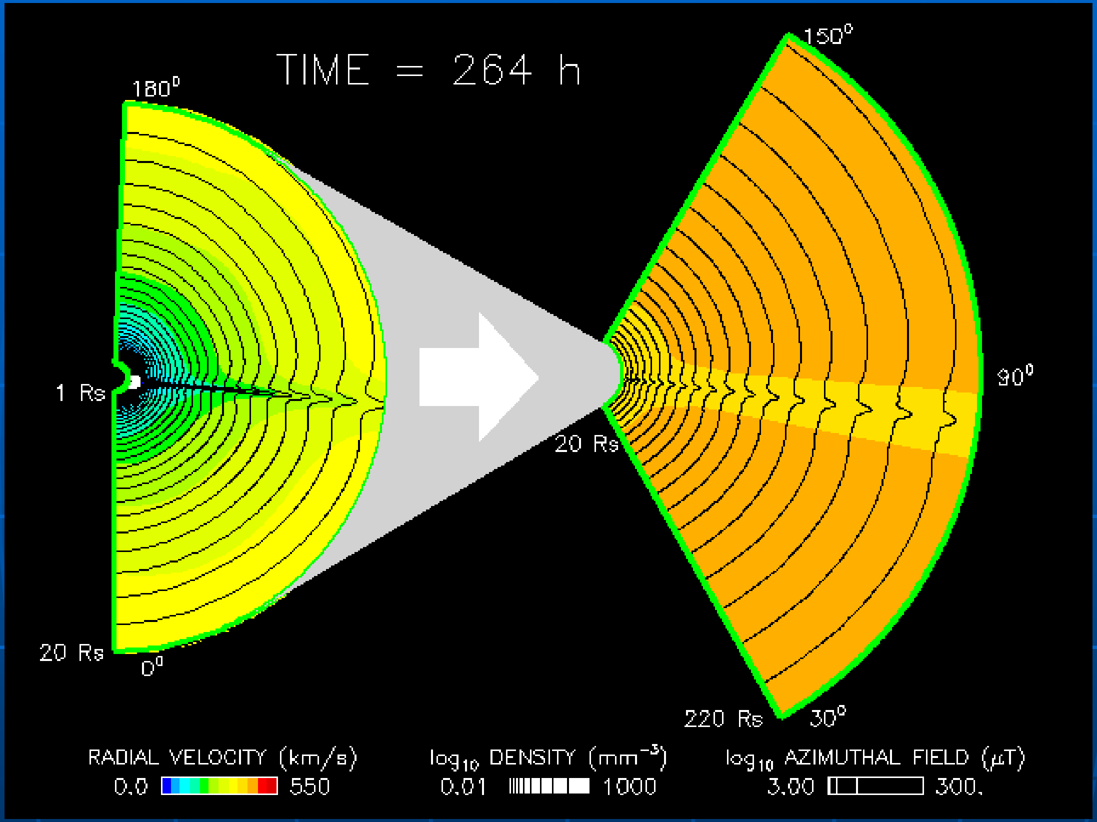


Rigidity Difference Maps

SEP Access and Trapping

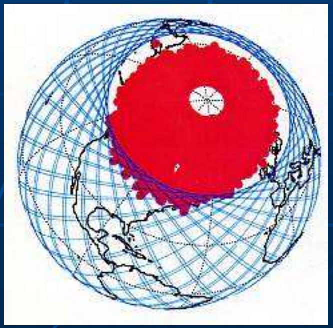
- Modeling summary
  - Take solar wind input to MHD, Solar Energetic Particle flux and calculate magnetospheric filtering of SEPs
  - Predict type of extreme events seen in March 91,Nov 01, Oct-Nov 03 & Jan 2005
  - Significant source population for inner zone
  - Goal: end-to-end model of gradual SEP events
  - Impulsive events challenging solar problem

WSA-ENLIL Coupled coronal-solar wind model for emergence, propagation of CME to Earth

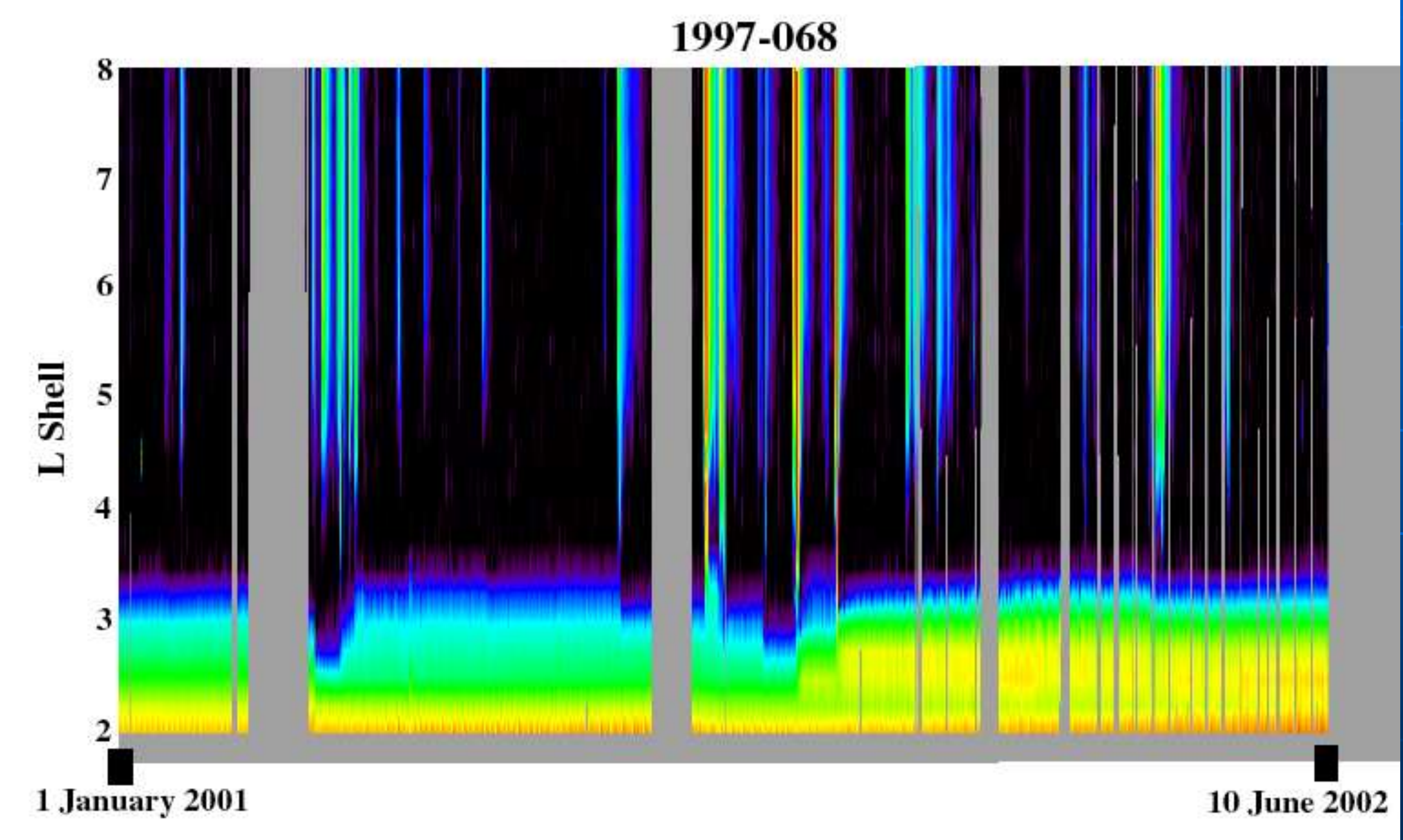


End-to-end runs:
May 12, 1997
Dec 13, 2006

Input to SEPMOD calcs:
SEP input to m'sphere →
Luhmann et al., ASR,2010

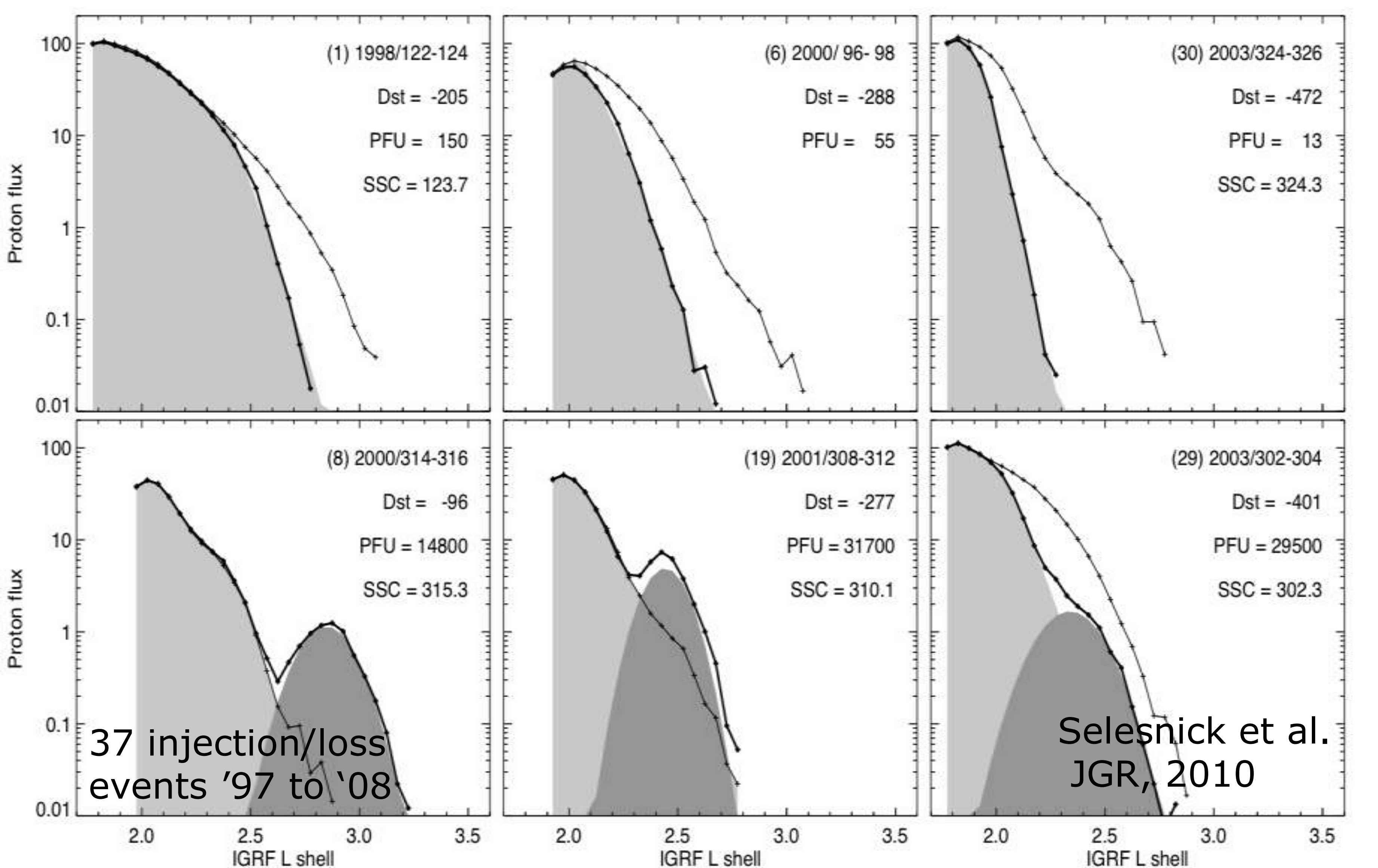


SEP Events & Storms at Solar Max



E > 15 MeV protons from HEO 1997-068

HEO Loss (top) Injection (bottom)



37 injection/loss events '97 to '08

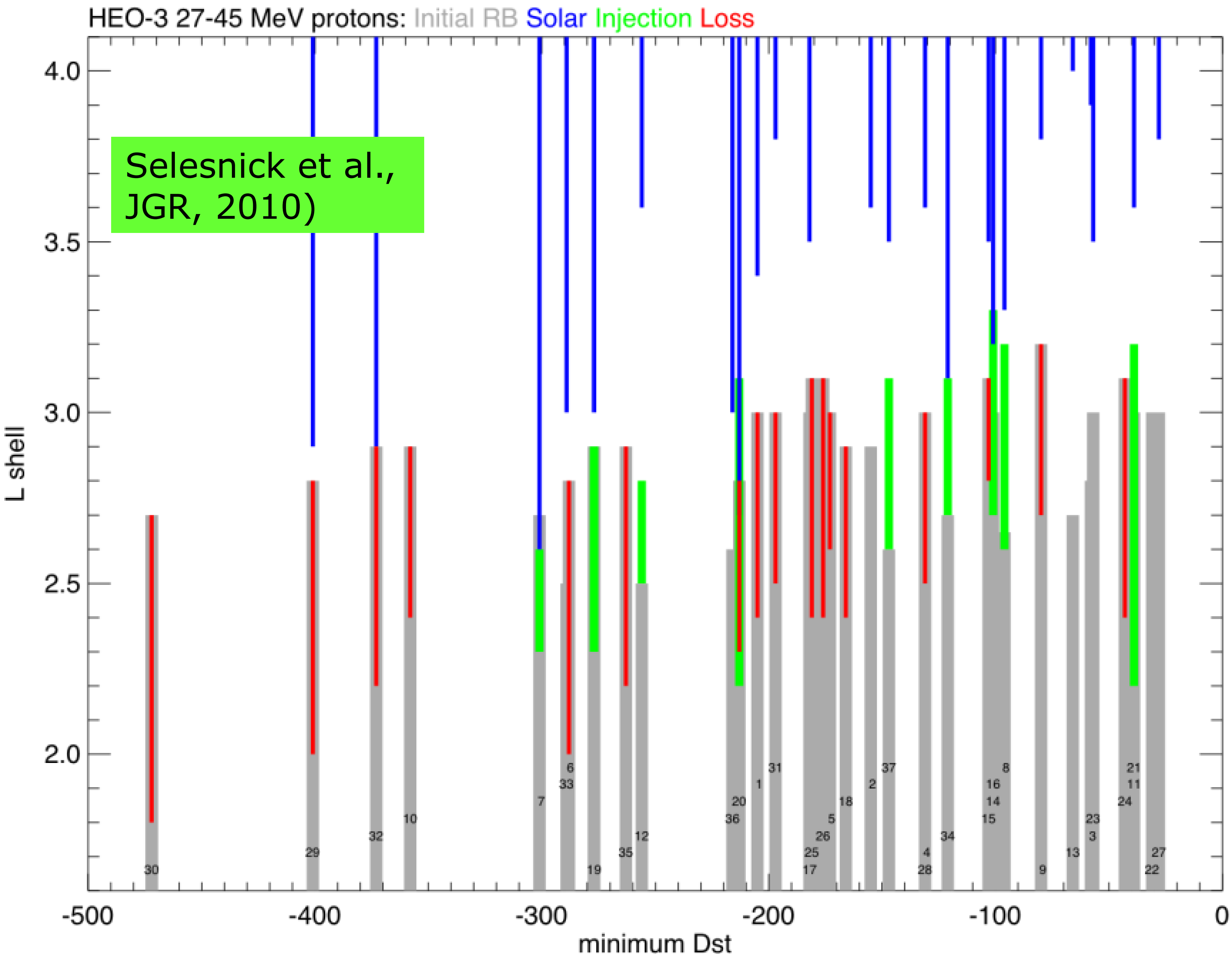
Selesnick et al. JGR, 2010

What Determines Trapping vs. Loss?

- Need strong solar proton event, high speed CME-shock vs. magnetic cloud
- Protons must have access to lower L

  (radial distance in equatorial plane in R_E)
- Not detrapped by ring current increase which decreases B and ability to conserve first invariant $\mu = p^2/2mB$ in curved field

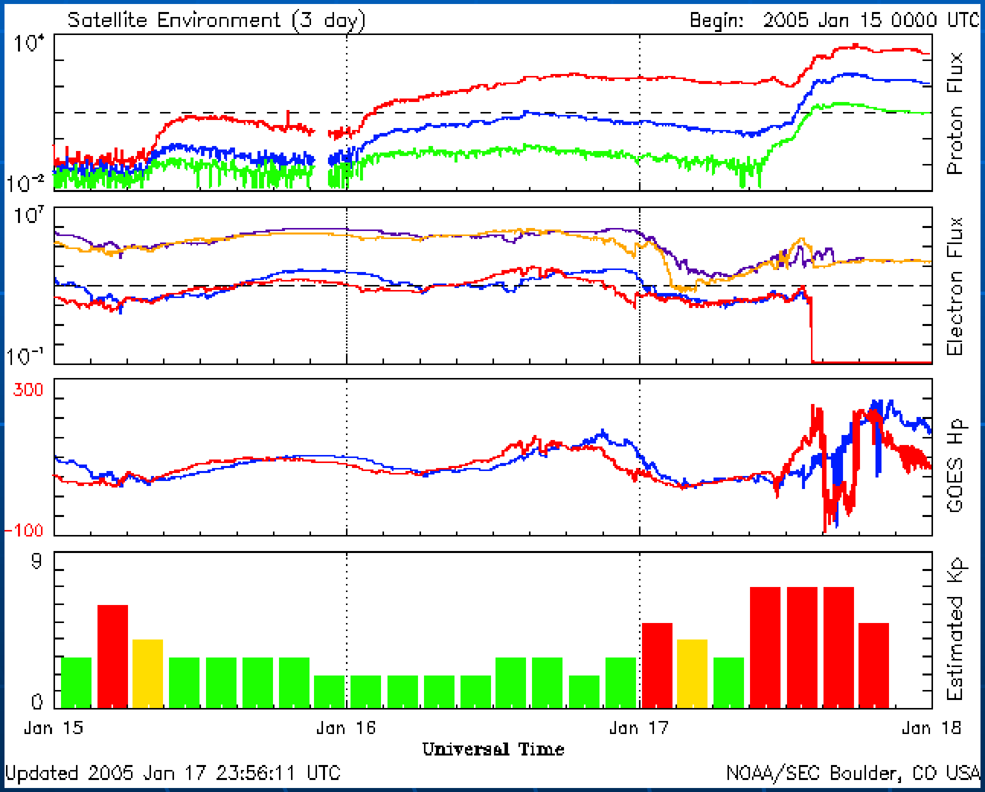
>Think of racecar driver losing control on a curve; proton is scattered into the atmosphere.

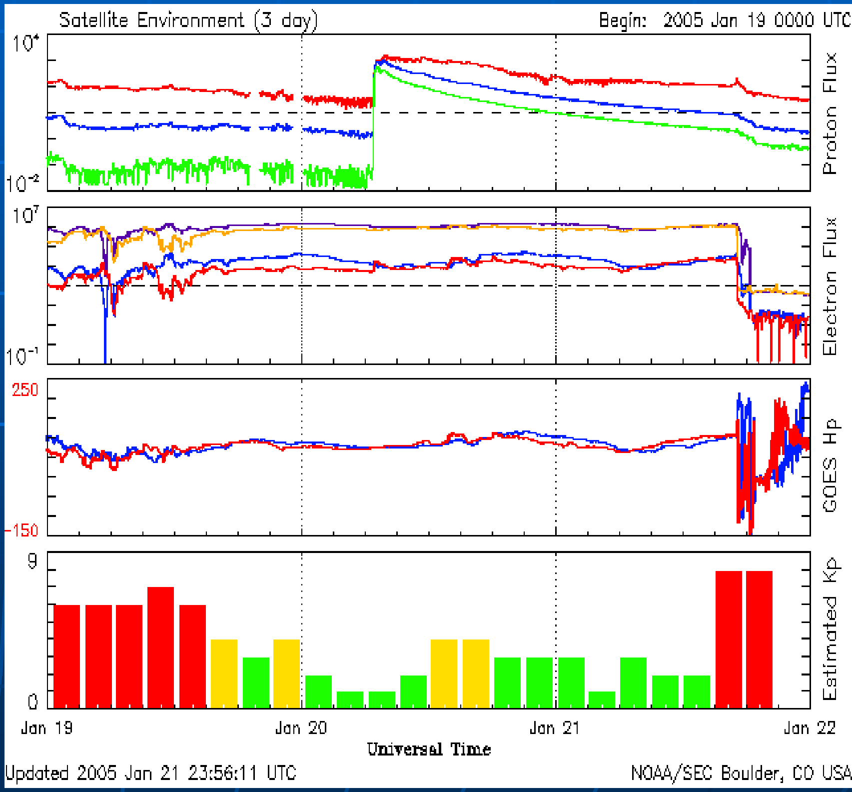


HEO-3 27-45 MeV protons: Initial RB Solar Injection Loss
Selesnick et al., JGR, 2010)
L shell
4.0
3.5
3.0
2.5
2.0
-500
-400
-300
-200
-100
0
minimum Dst

Jan 20, 2005 Impulsive SEP Event

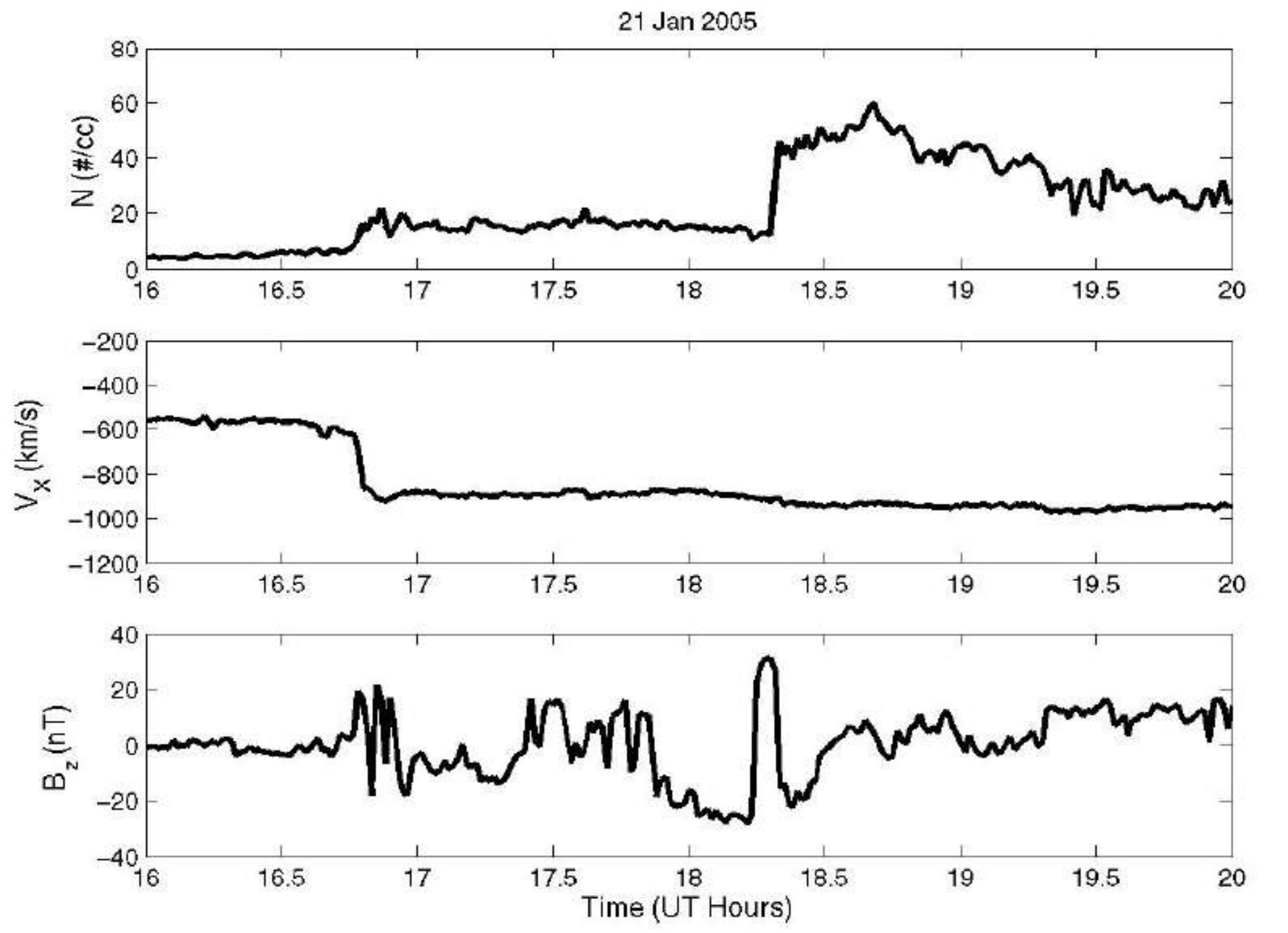
- Strong Ground Level (Neutron) Event





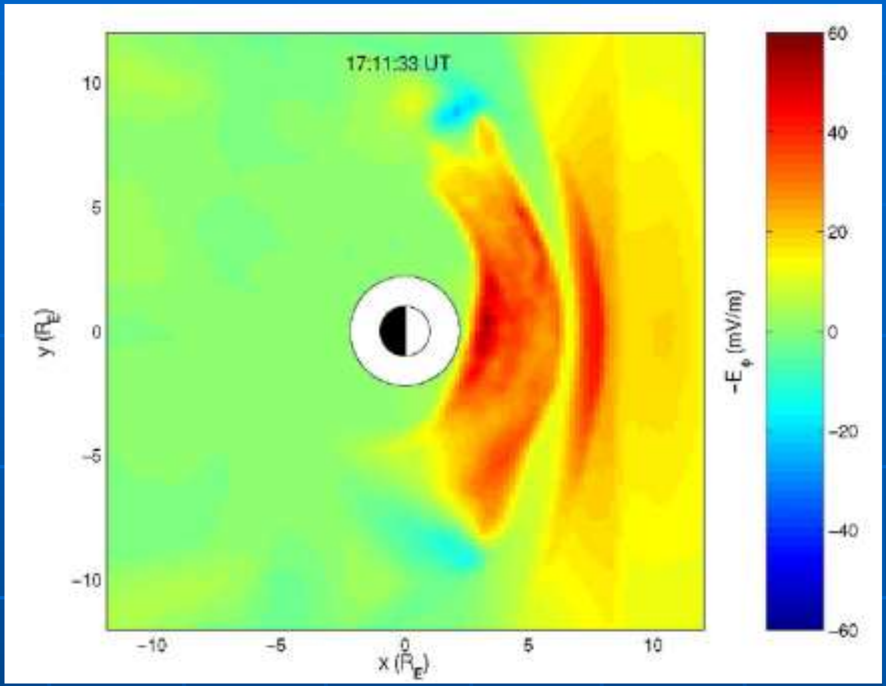
Gradual SEP events

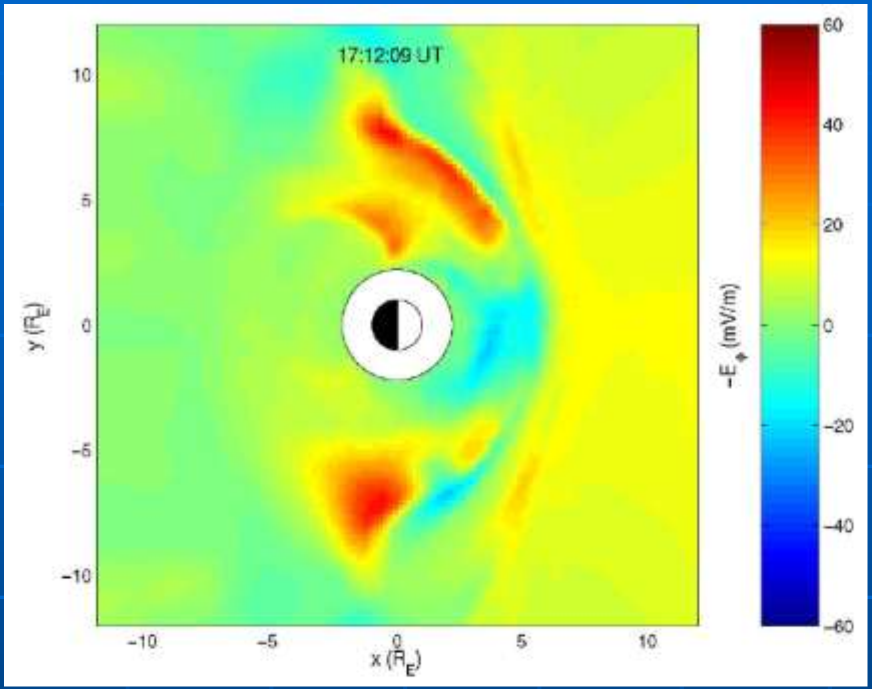
Prompt SEP event



21 Jan 2005
N (#/cc)
80
60
40
20
0
16
16.5
17
17.5
18
18.5
19
19.5
20
V_X (km/s)
−200
−400
−600
−800
−1000
−1200
B_z (nT)
40
20
0
−20
−40
Time (UT Hours)

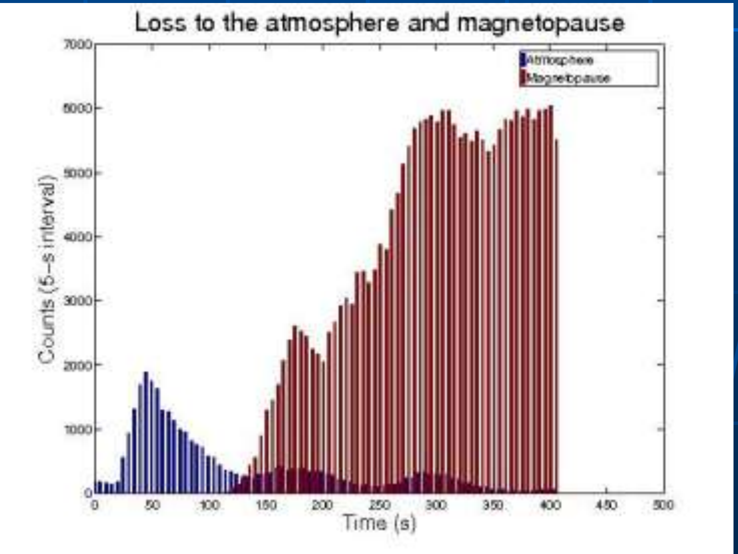
Jan 21 05 SSC MHD fields





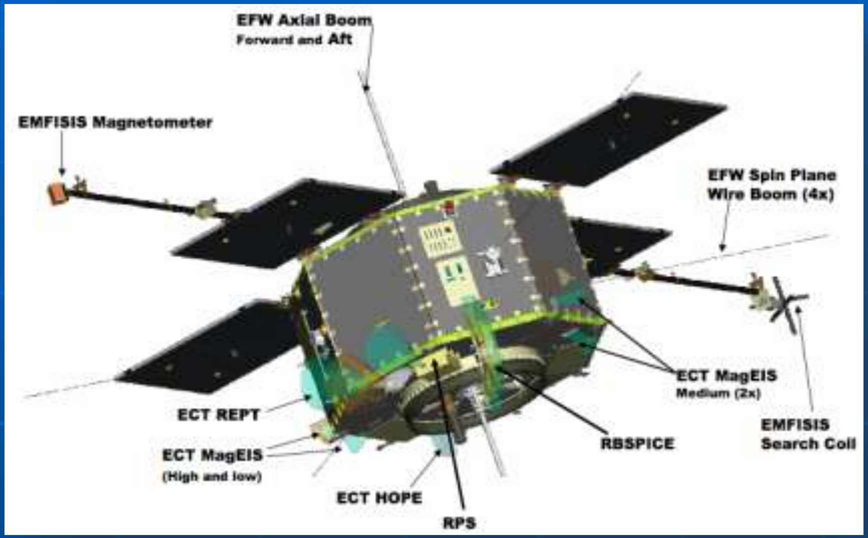
MHD E_phi (top)

Studied el loss due to 2 shocks



MINIS balloon obs loss modulated by ULF waves

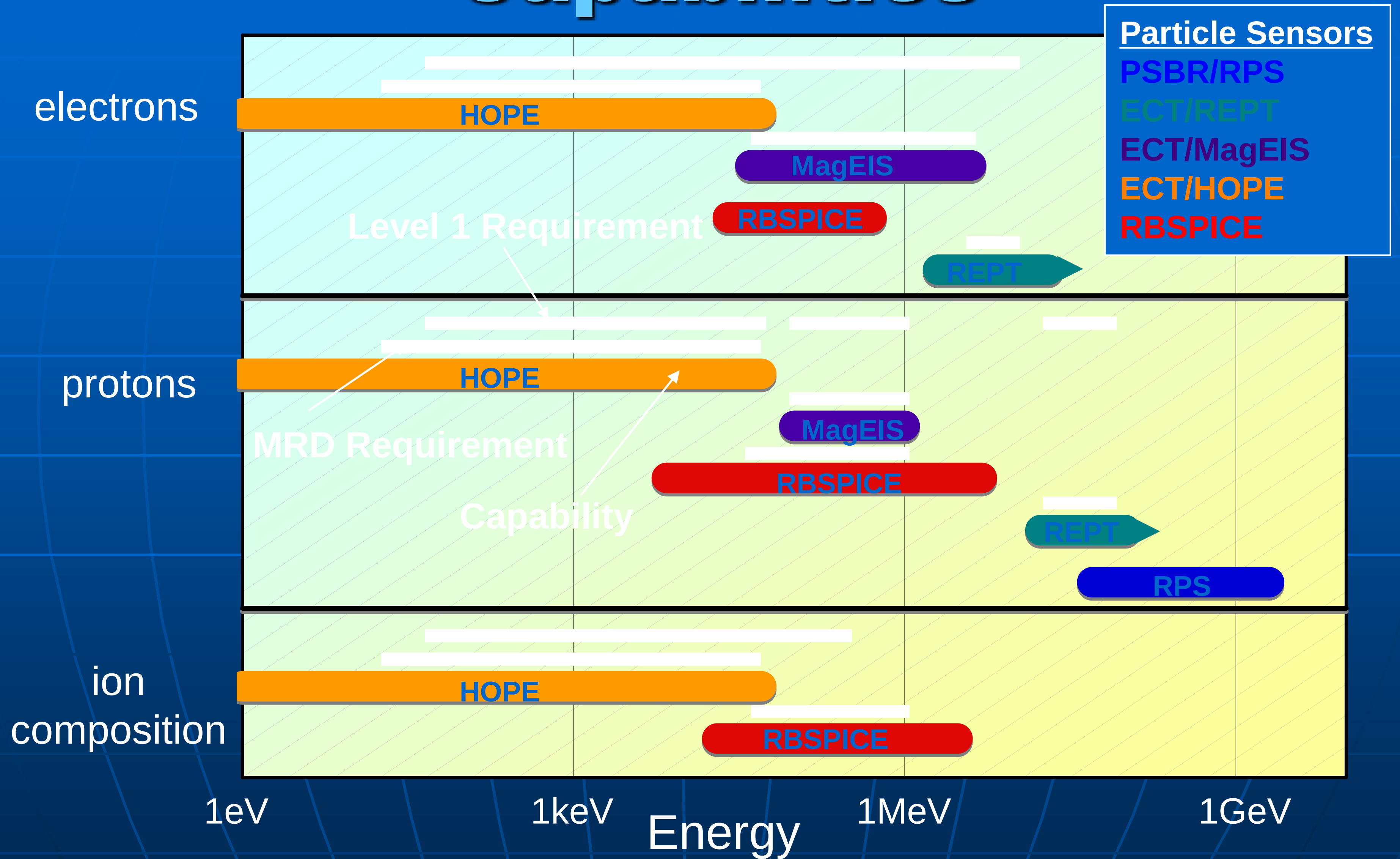
Radiation Belt Storm Probes



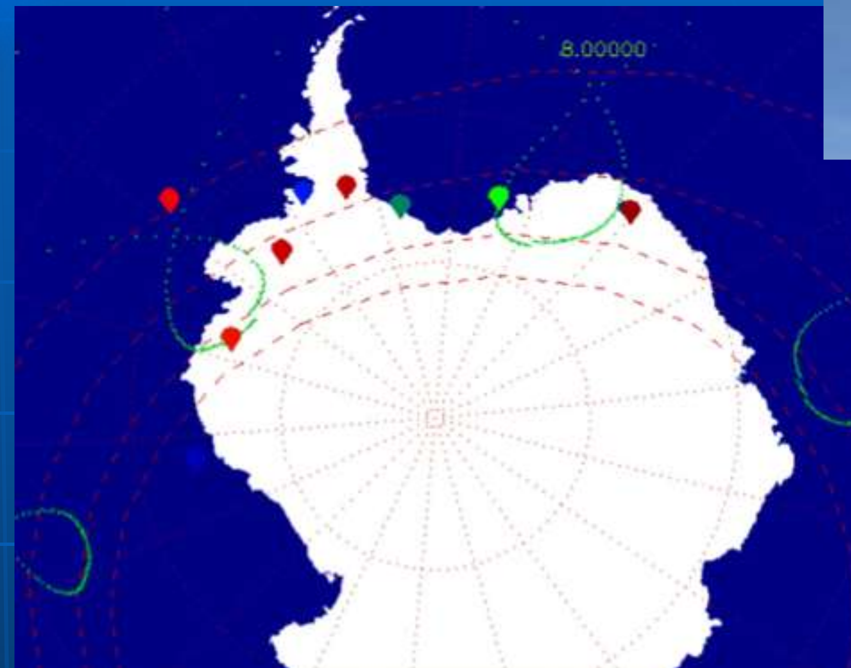
Proton Spectrometer

- *Two identical highly-instrumented spacecraft, elliptical orbits (~600 km x 5.8 R_E, 10^o inclination)*
- *Expected launch – August 23, 2012*

RBSP Particle Instrument Capabilities

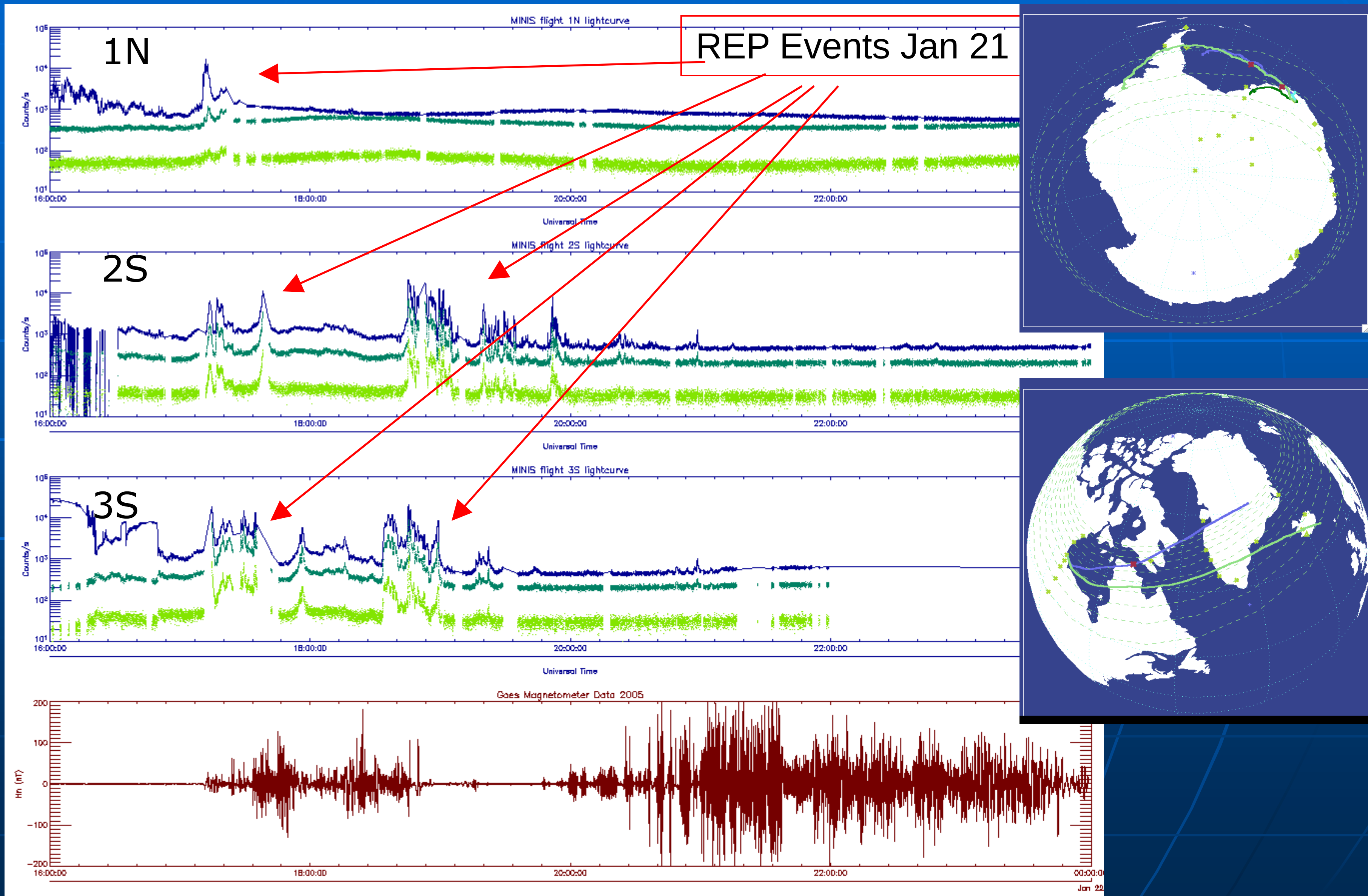


BARREL(Balloon Array for RBSP Relativistic Electron Losses)



- *Measure x-rays due to precipitating electron*
- *Two campaigns - January 2013 and 2014*
- *20 balloons launched each year*
- *Make correlated measurements with RBSP*

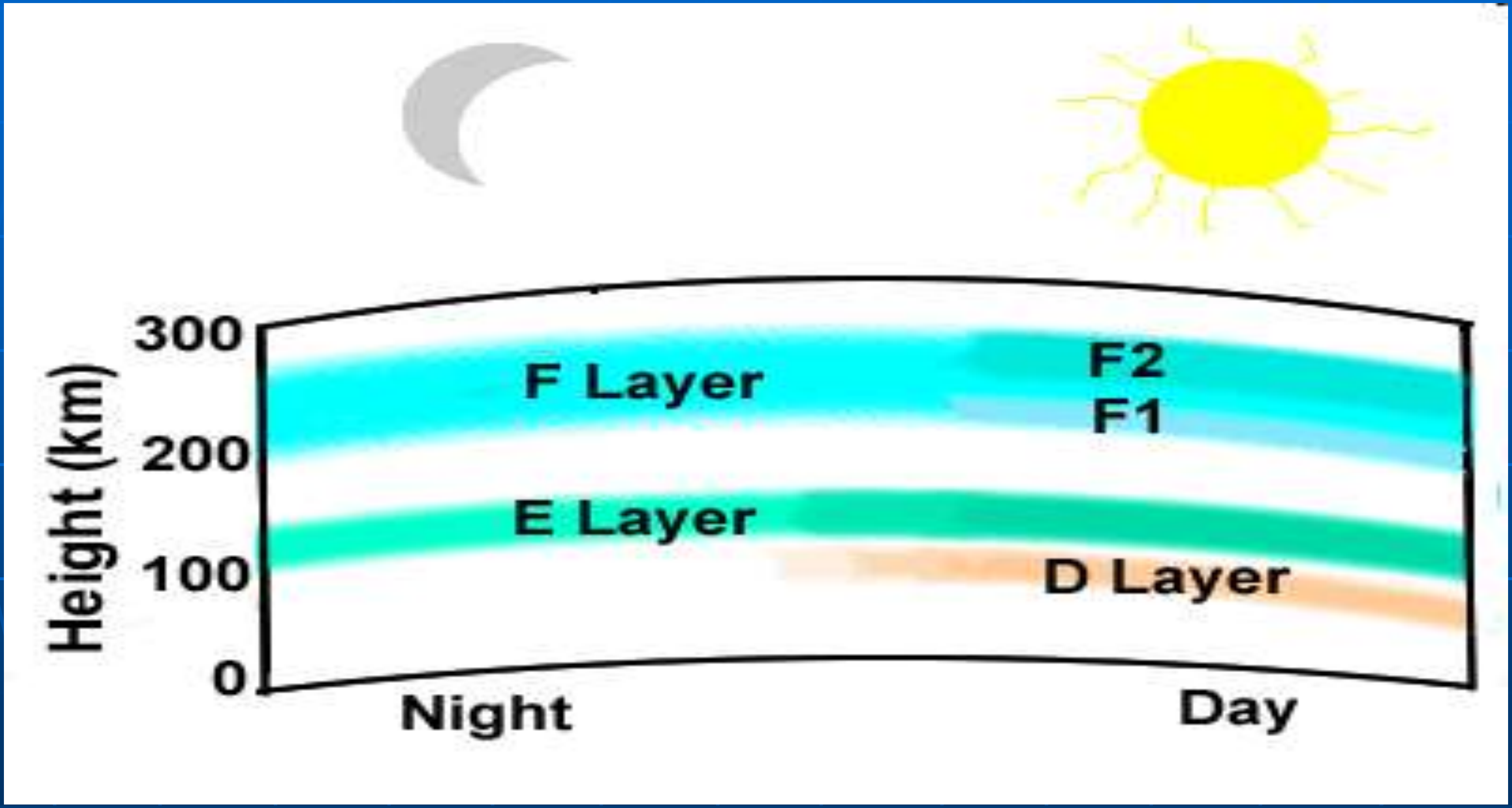
GOES – MINIS Balloons Jan 21 ‘05



Solar Proton Summary

- High energy > 100 MeV SEPS mainly due to CRAND (cosmic rays→atmos)
- W < 100 MeV, L > 1.3 SEP trapping
- Outer boundary determined by first invariant conservation at quiet times
- Curvature scattering affects Loss when B disturbed, max when Dst is min
- Injection affected by prompt cutoff surpression and relaxation on shock arrival time scale
- Trapping depends on SW SEP level, as does flux on open field lines
- Fluence to atmosphere depends on changing B

Not Covered: Ionosphere Change



Ionization at lower altitude due to solar xrays & SEPs disrupts hf comm

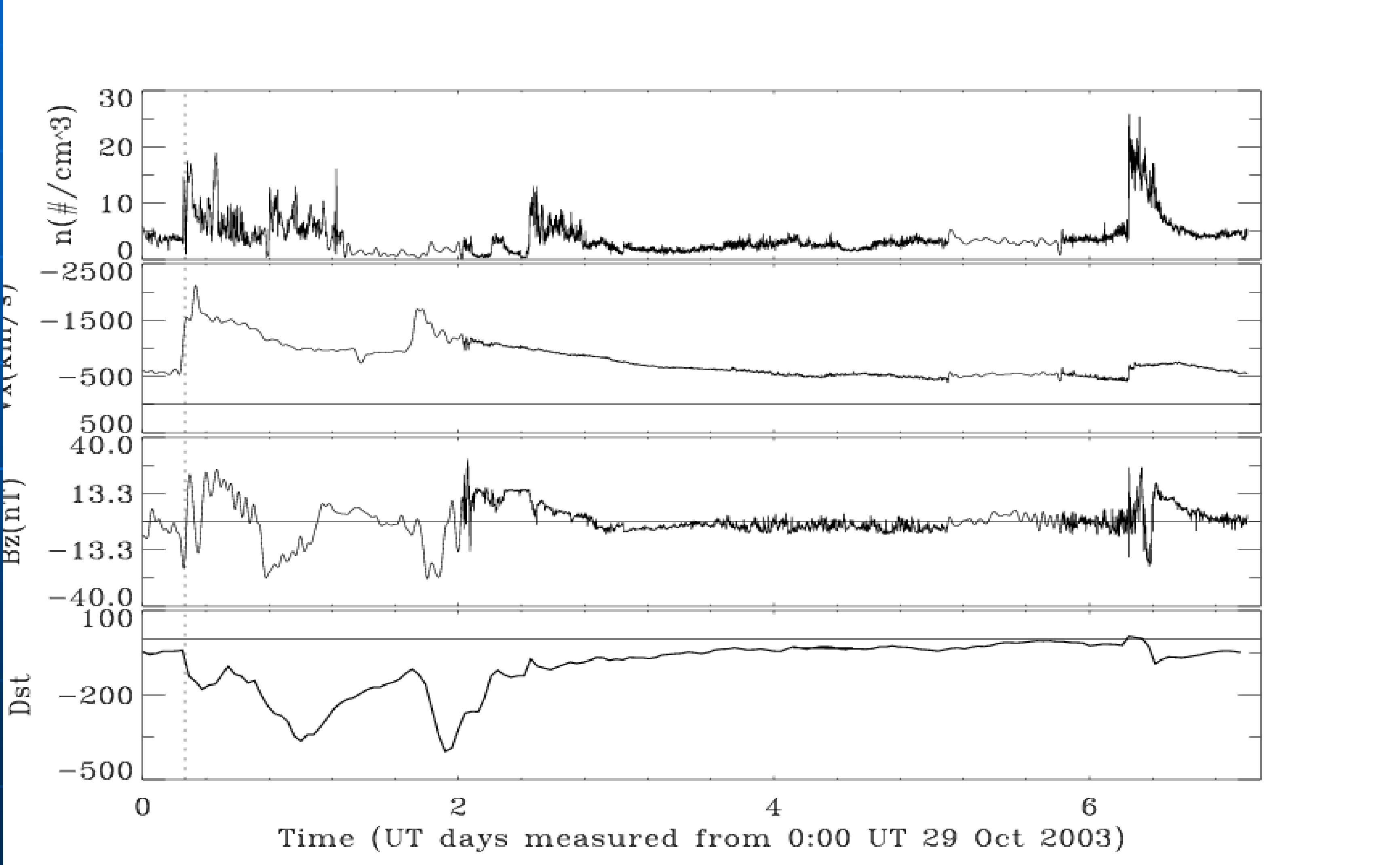
Extra Slides

24 March 1991 Event

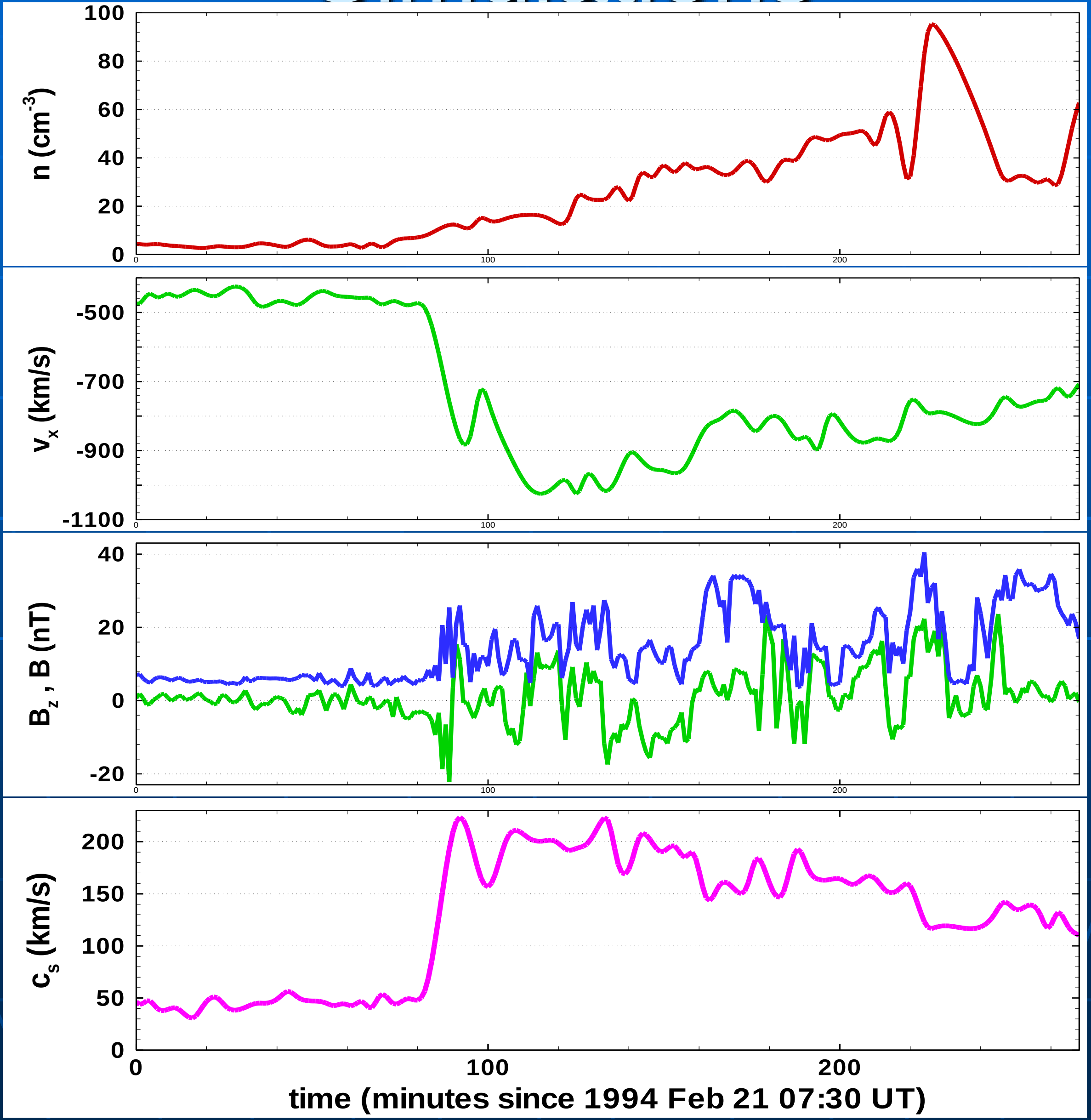
- Injection on drift time scale (minutes) to L~ 2.5 (CRRES)
- Protons and electrons in new belt
- Very high electron/proton energies > 10 MeV →Long lifetime - years
- Particles injected strongly peaked in pitch angle (perp to B)

Blake et al., GRL, 1992;
Li et al., GRL, 1993
Hudson et al., JGR, 1997

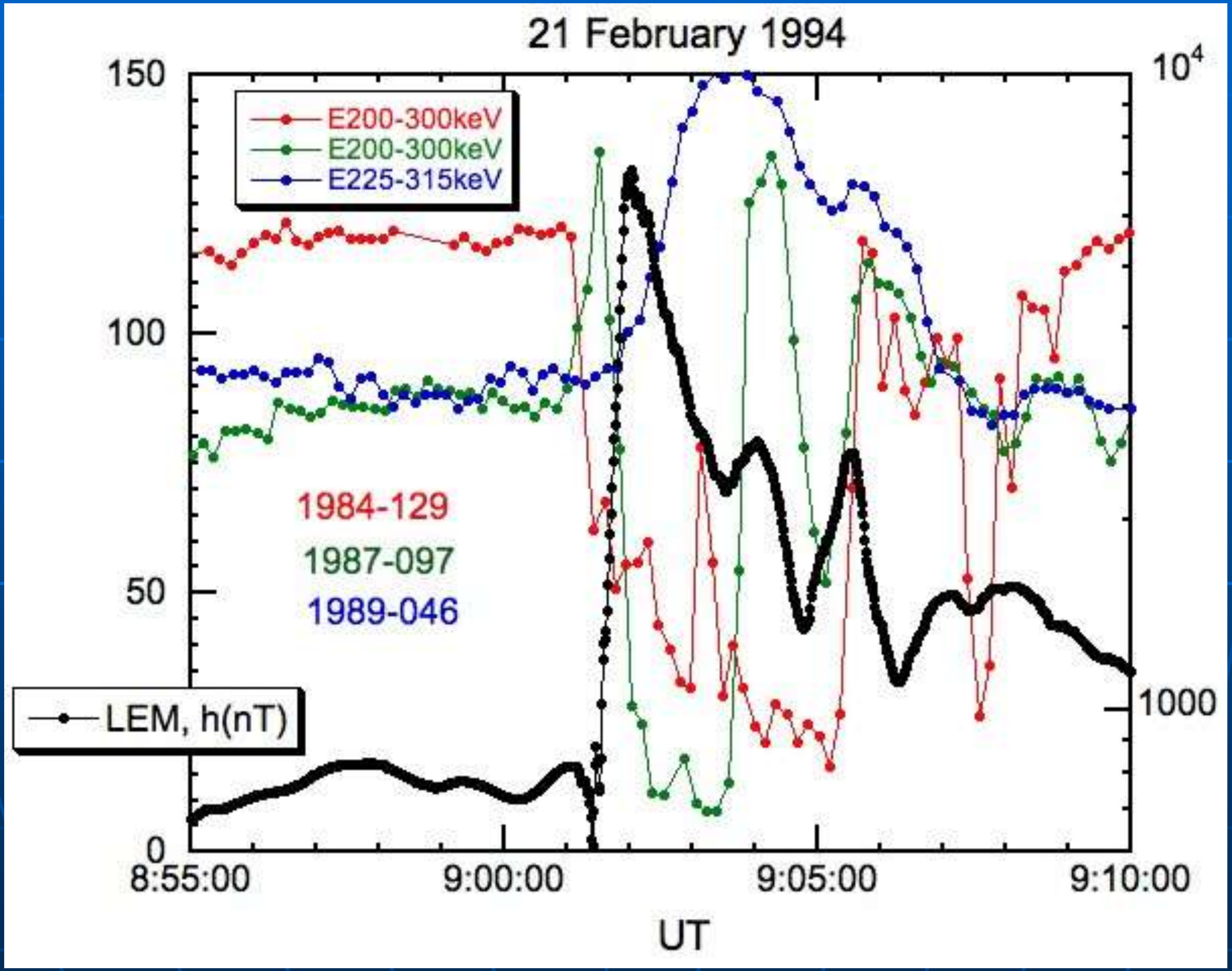
ACE Input for Halloween 03 MHD Simulations



IMP8 Data for Feb 94 MHD Simulations

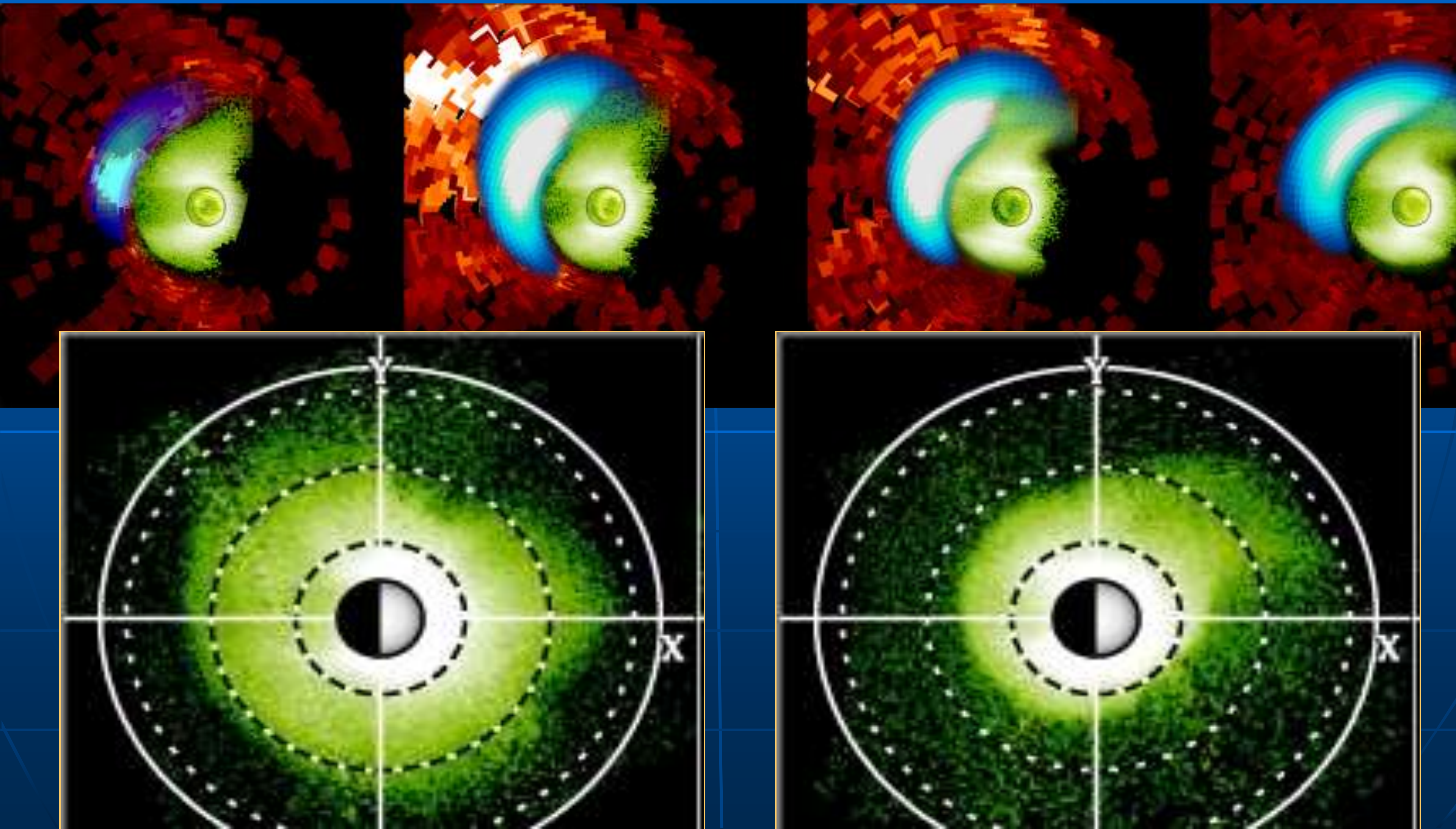


Low Energy LANL Data

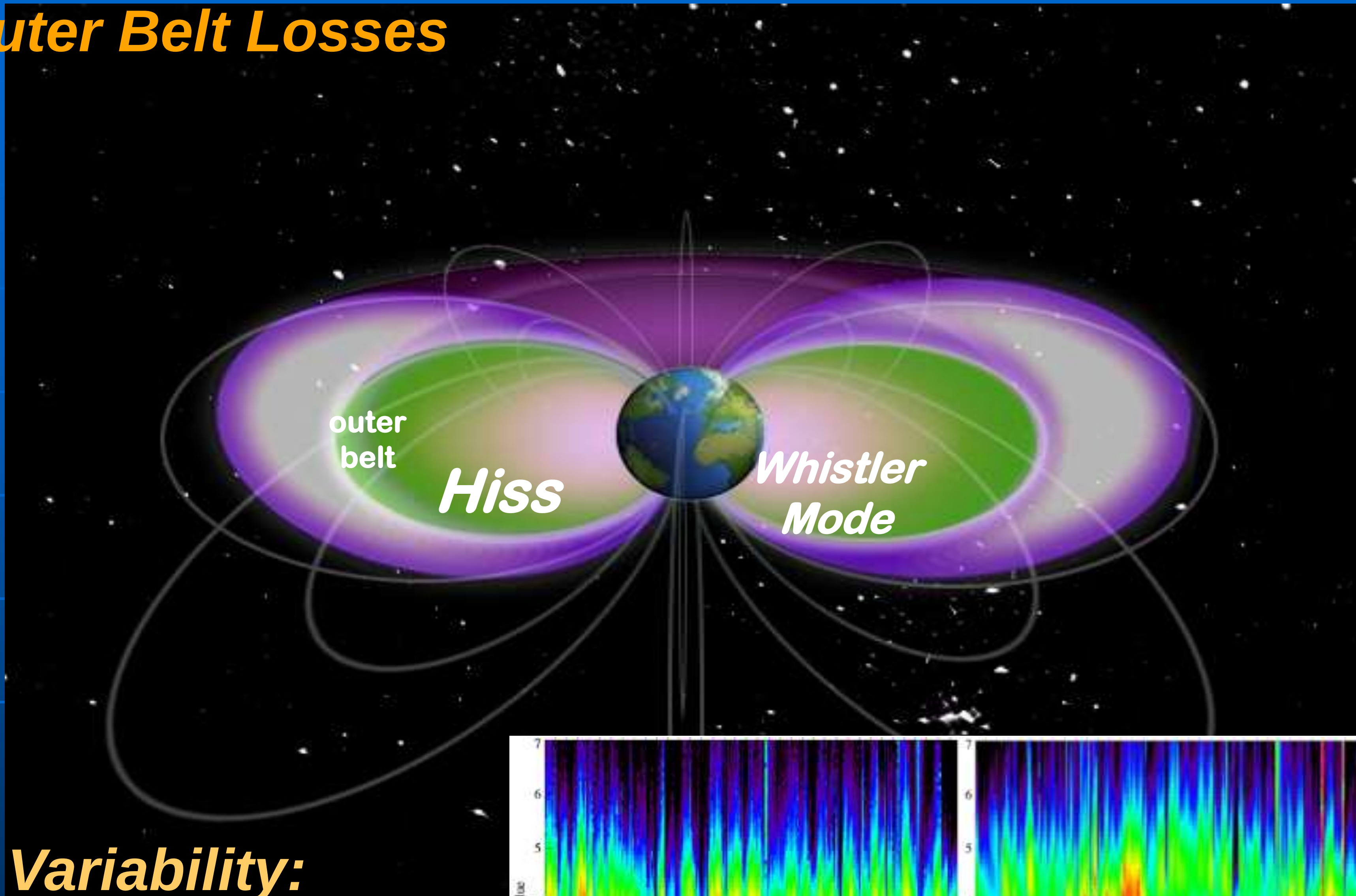


The Global Inner Magnetospere:
Coupled System of Plasmas

Ring current (blue) – Plasmasphere (green) Storm Evolution



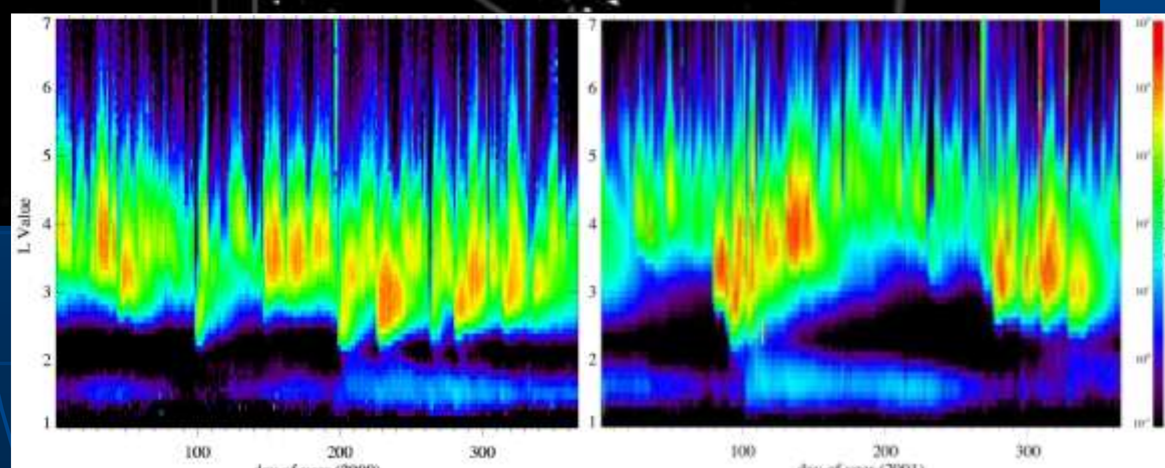
Outer Belt Losses



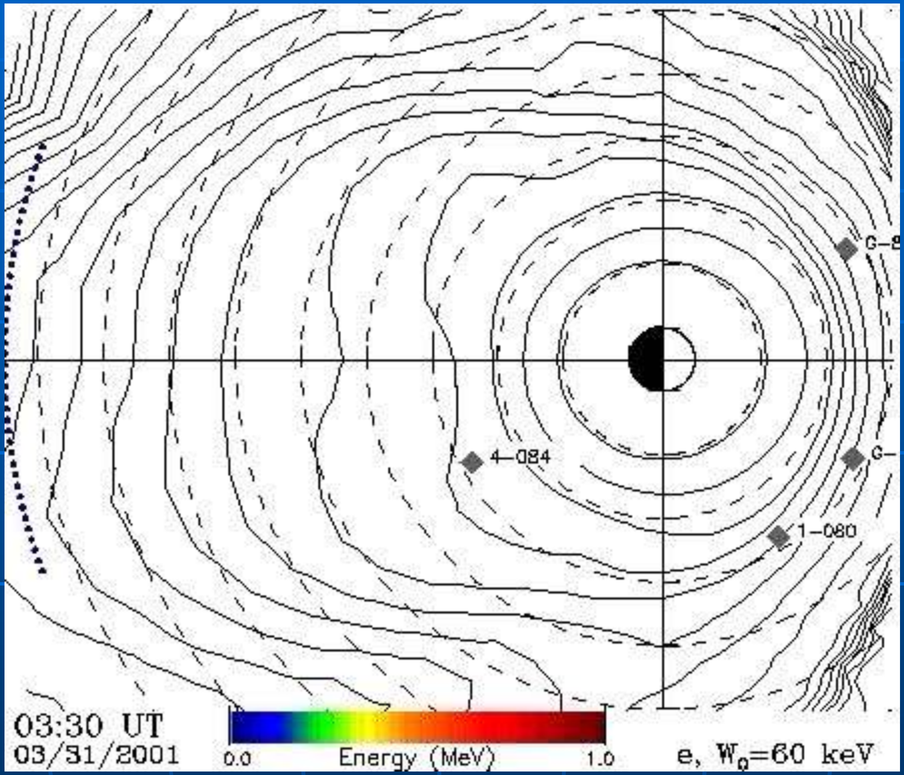
Variability:

Slot Region

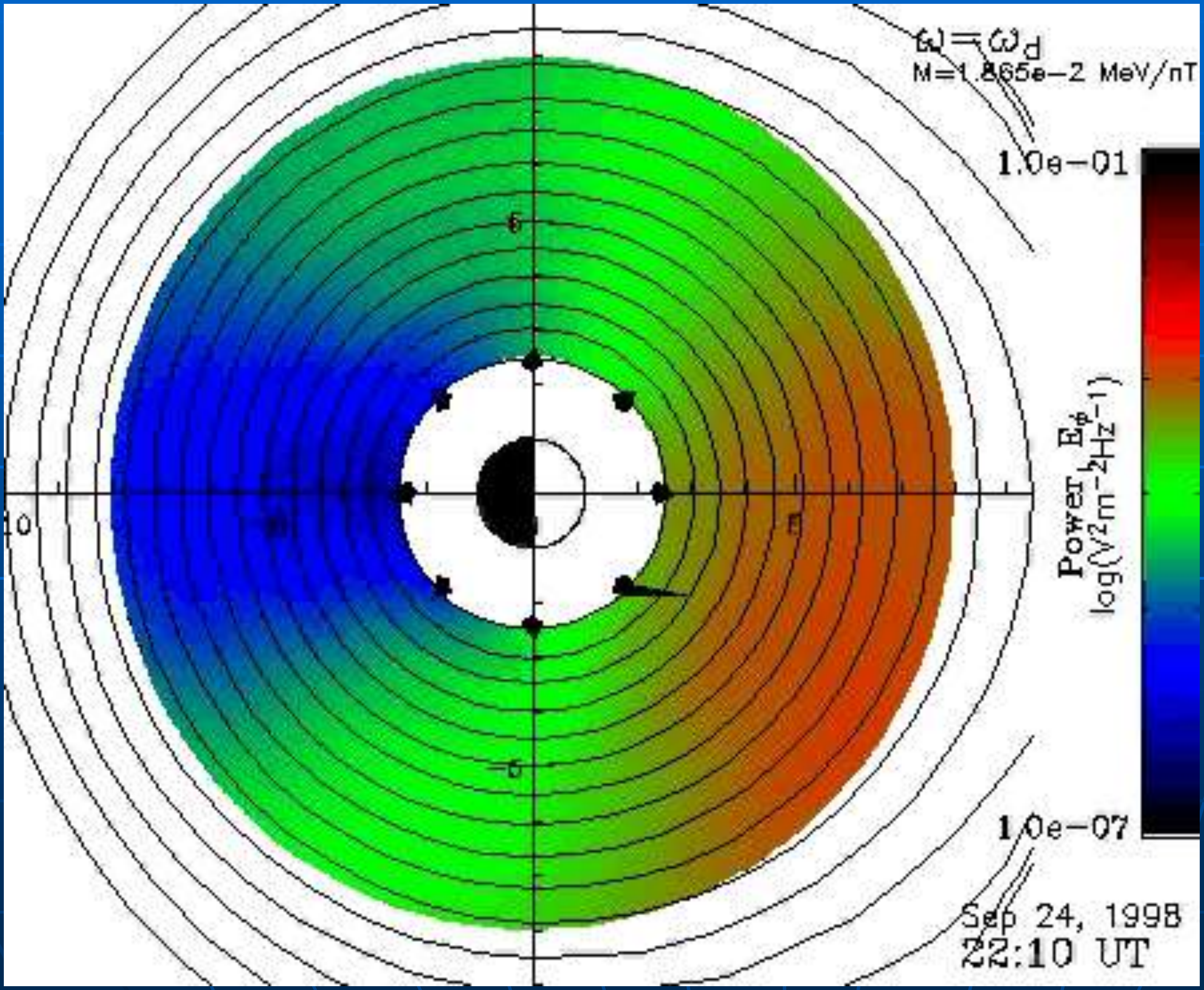
& Plasmasphere



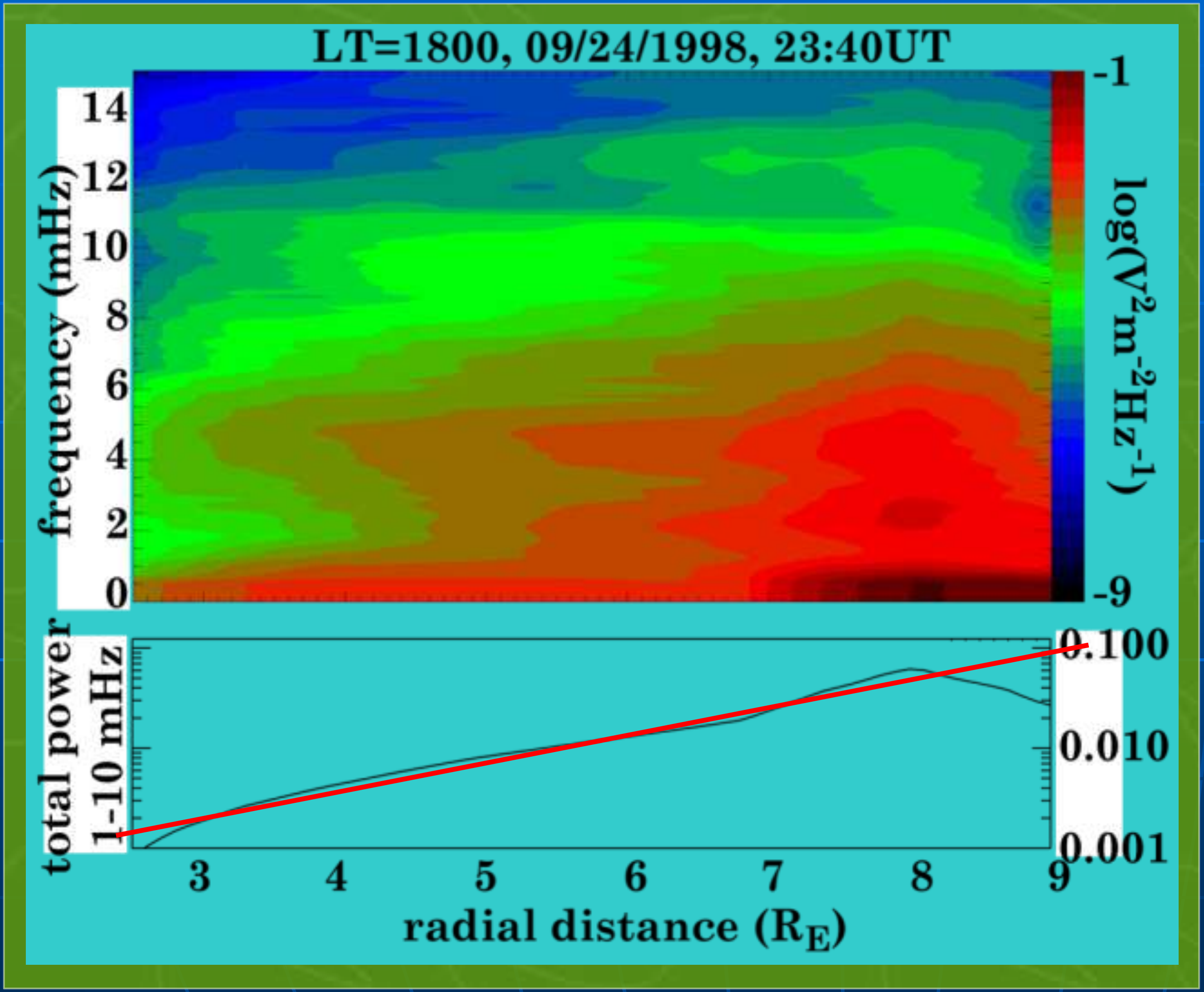
MHD Fields Injection of RadBelt Electrons



Azimuthal Distribution of P(Ephi)



L dependence of Ephi power



$$log\left(\frac{P}{P_0}\right) = m_L L$$

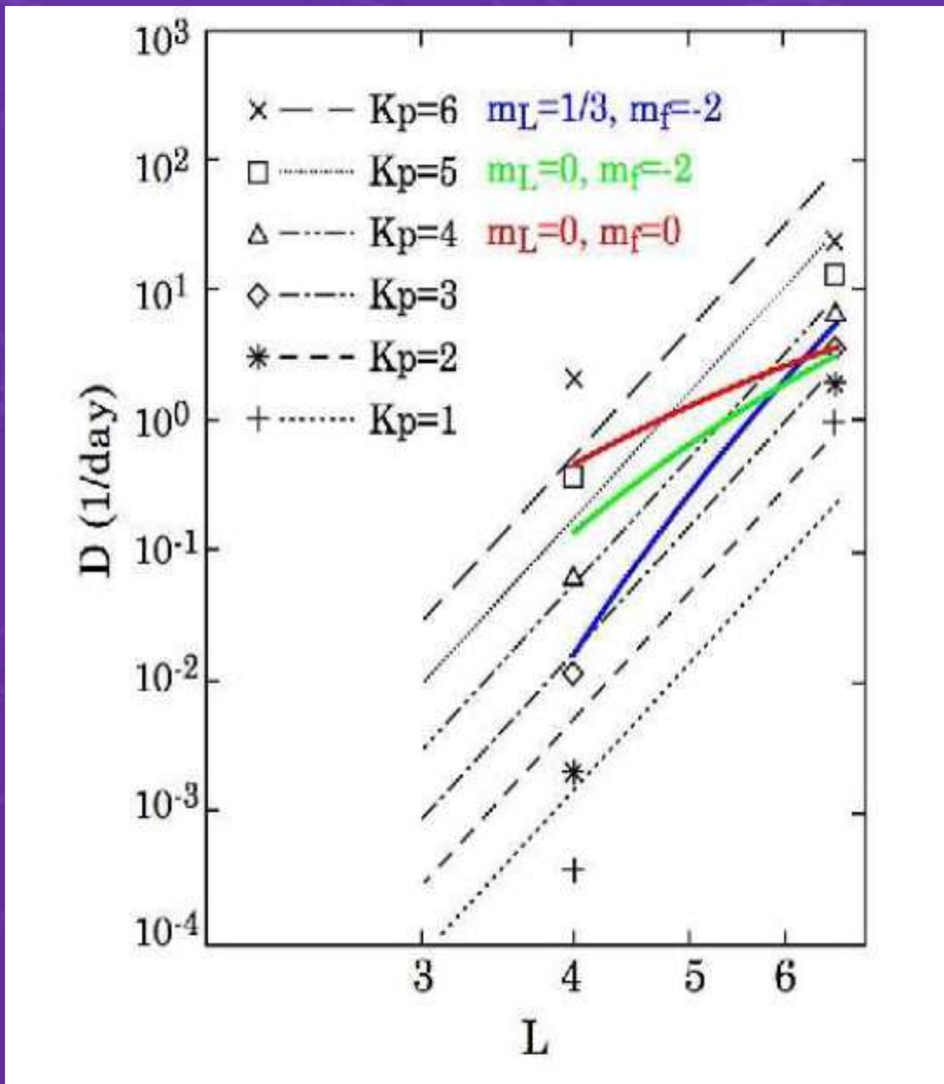
$$P(L) = P_0 10^{m_L L}$$

$$m_L = 1/3$$

0.558-15 mHz

Elkington, S. R., M. Wiltberger, A. A. Chan, and D. N. Baker, *J. Atmos. Solar Terr. Phys*., 66, 1371, 2004.

Diffusion Rates vs. L



Radial diffusion rates in model ULF wave fields
D_LL ~ L^N
Perry et al., JGR, 2005,
Include δEφ, δBr, δB//,
freq and L-dependent power, 3D trajectories
N ~ 6 for no L-dep power,
N ~ 12 with L dependence

Tau(L,E) is loss rate

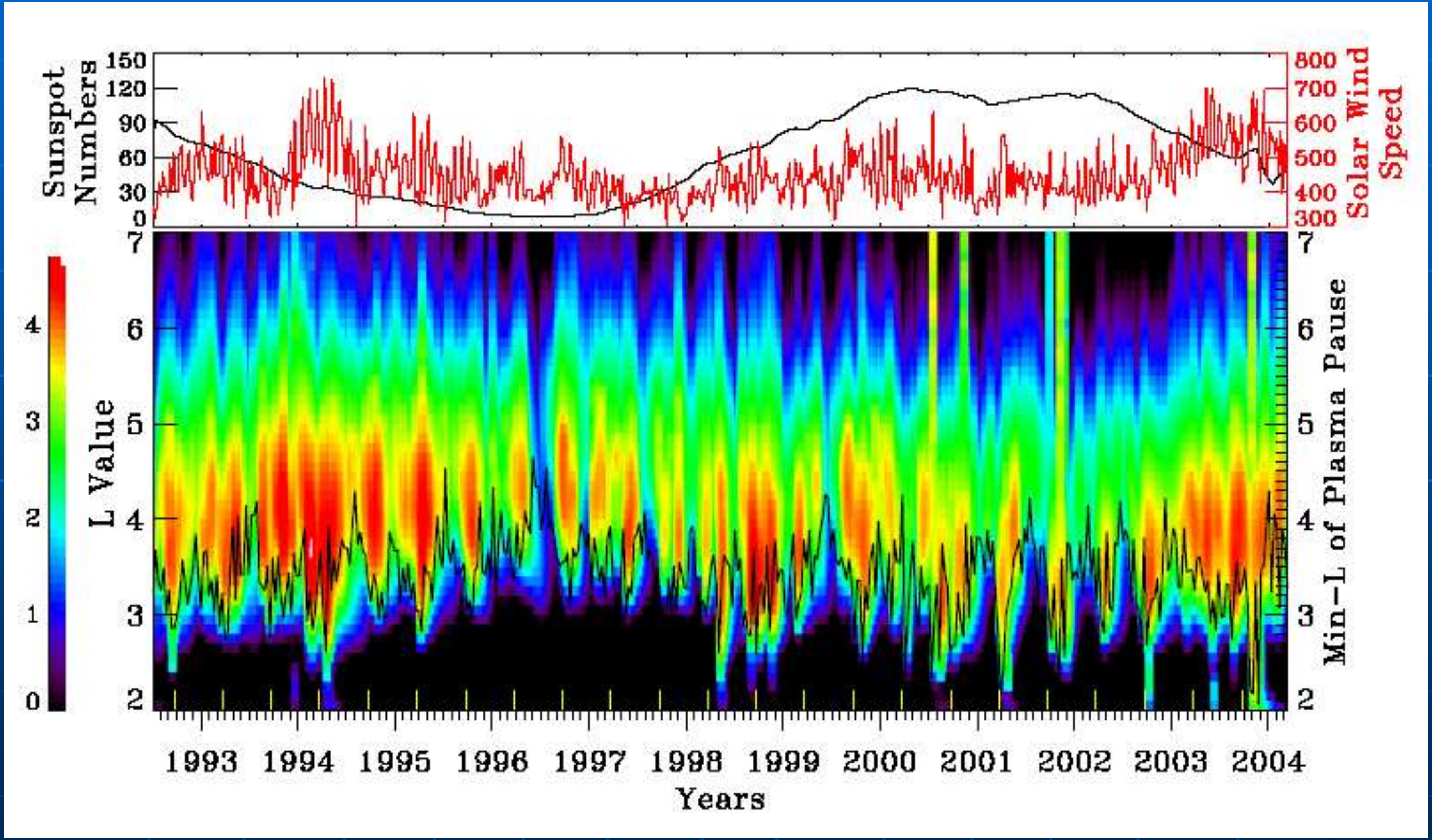
$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left[\frac{1}{L^2} D_{LL} \frac{\partial f}{\partial L}\right] - \frac{f}{\tau}$$

Braughtigam & Albert, 2000, N=6, 10; Perry et al., 2005, N=6, 12

Magnetospheric Modeling

- Goals
  - Take solar wind input to MHD, Solar Energetic Particle flux and calculate magnetospheric filtering of SEPs
  - Predict type of extreme events seen in Nov 01 & Oct-Nov 03
  - Longer term variability of electrons, max fluxes due to high speed solar wind streams during declining phase of solar cycle

Solar Cycle Dependence of 2-6 MeV Electrons



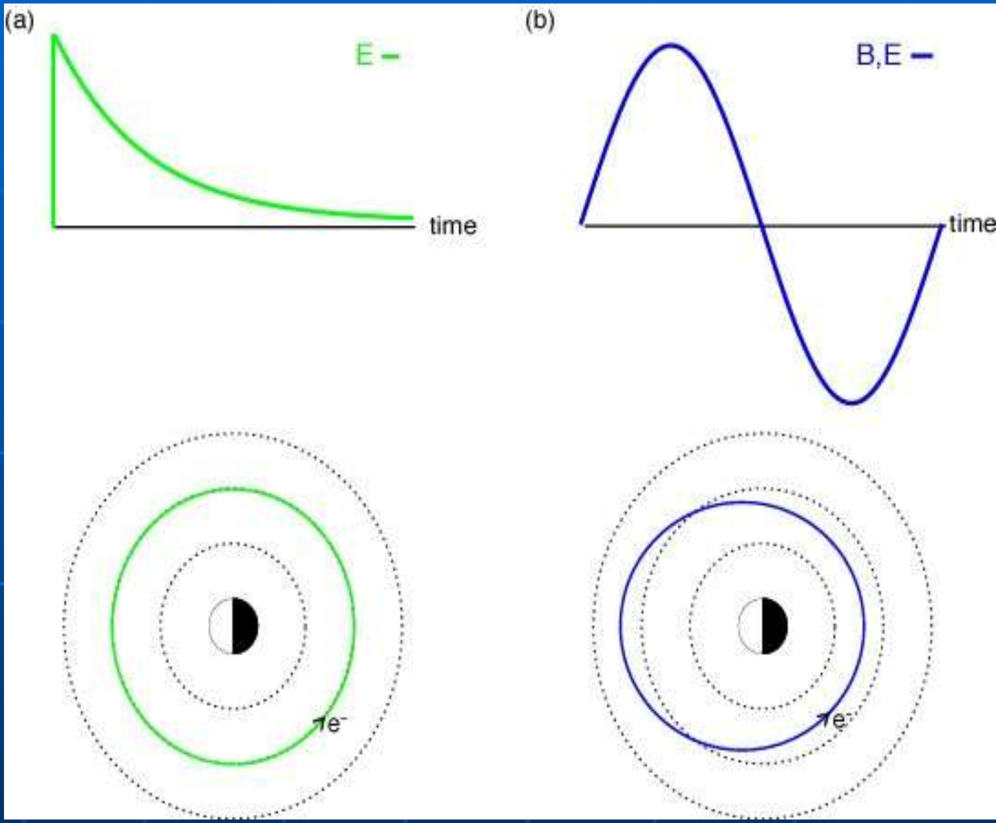
Radiation Belt Electron Energization Processes Conserving First Invariant

Particles can be energized by:

1) **Convection**: steady, or substorm and storm-enhanced

2) **Diffusion***: convection E fluctuations, ULF wave δE and δB→ δE enhance diffusion

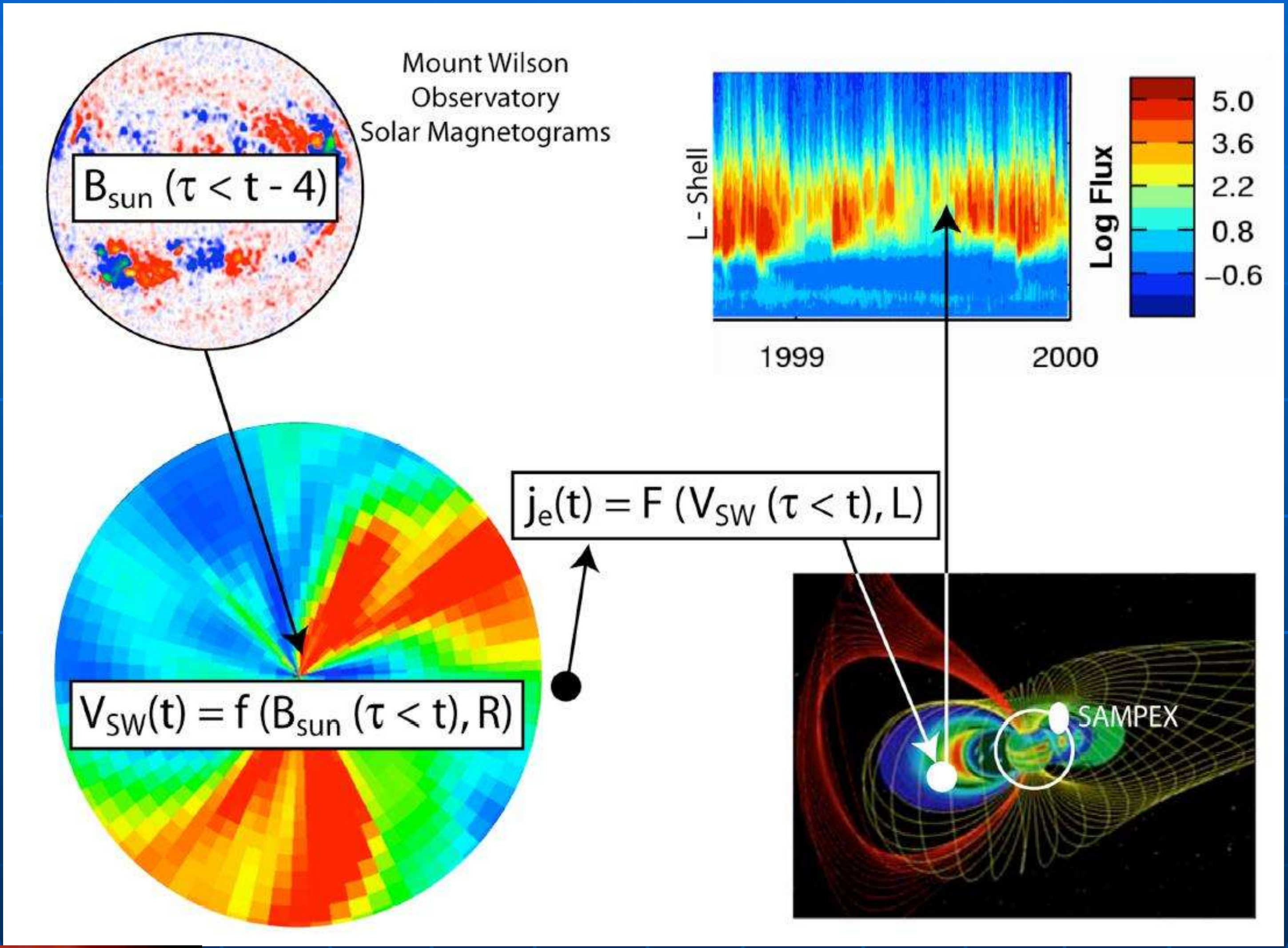
3) **Drift time scale injection** (Mar 91)



$$^*\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left[\frac{1}{L^2} D_{LL} \frac{\partial f}{\partial L}\right] - \frac{f}{\tau}$$

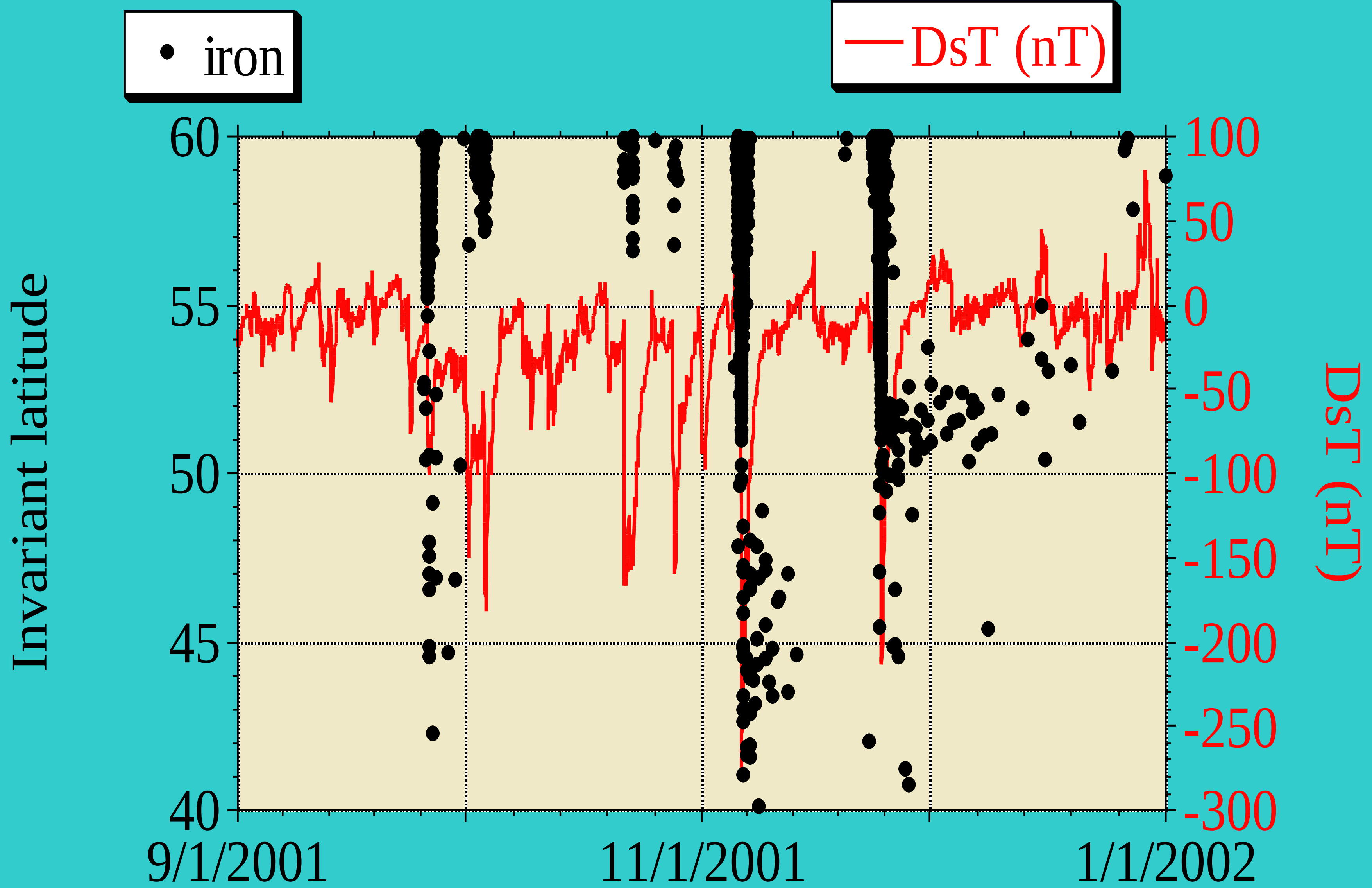
a)Falthammar, JGR, 1965;
b)Elkington et al., JGR, 2003

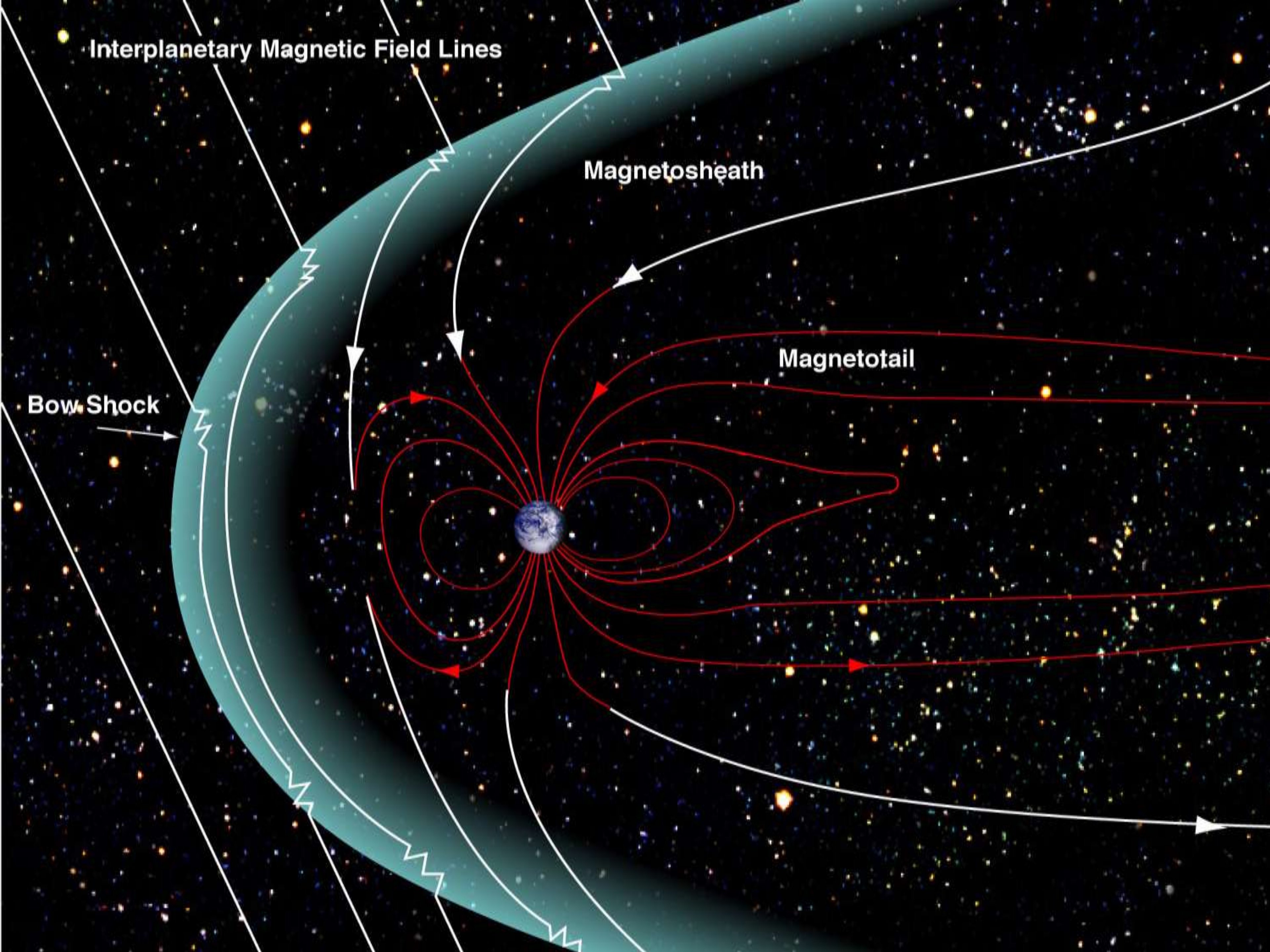
Sun-to-Earth Prediction



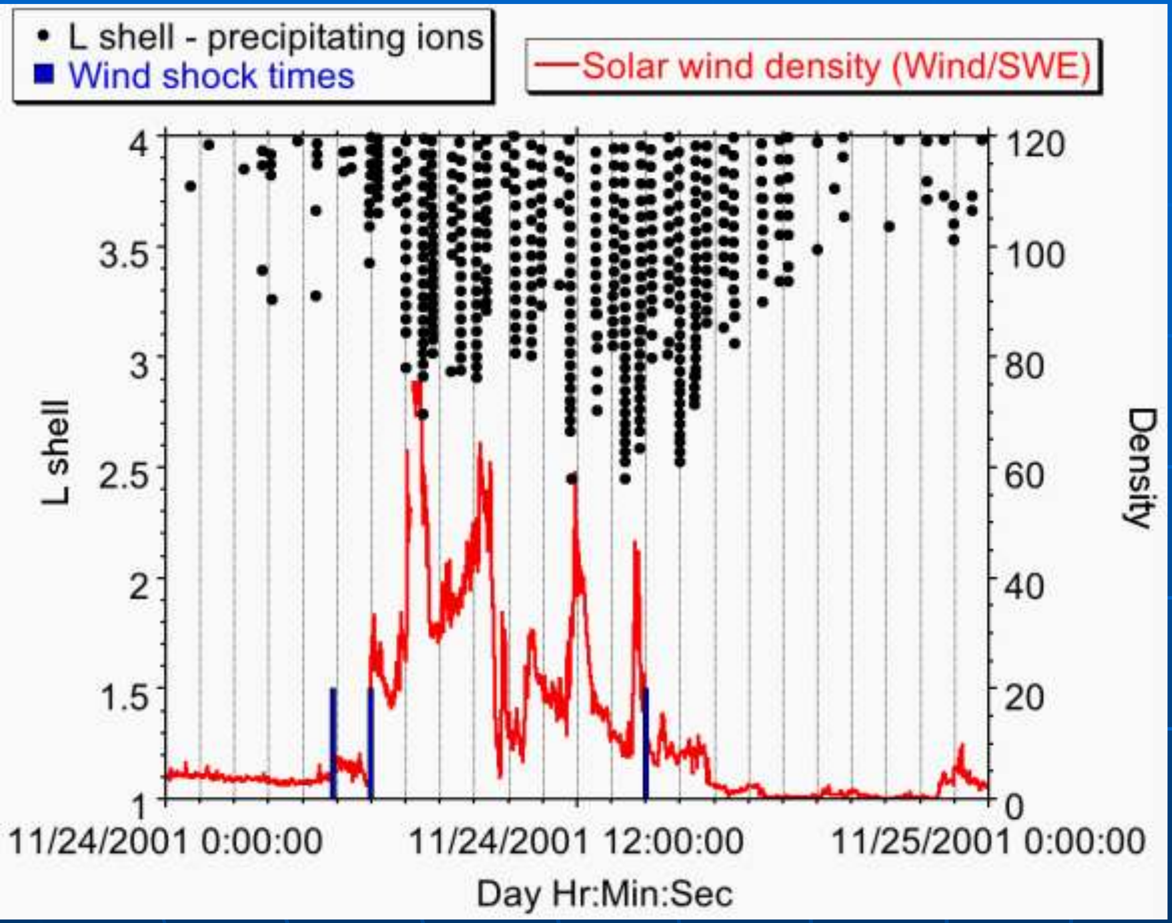
CISM
CENTER FOR INTEGRATED SPACE WEATHER MODELLING

SAMPEX/LICA low latitude iron

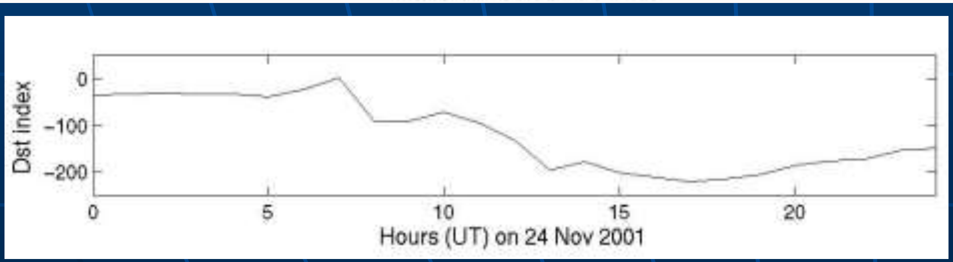



Interplanetary Magnetic Field Lines
Magnetosheath
Magnetotail
Bow Shock

SAMPEX/LICA heavy ion counts

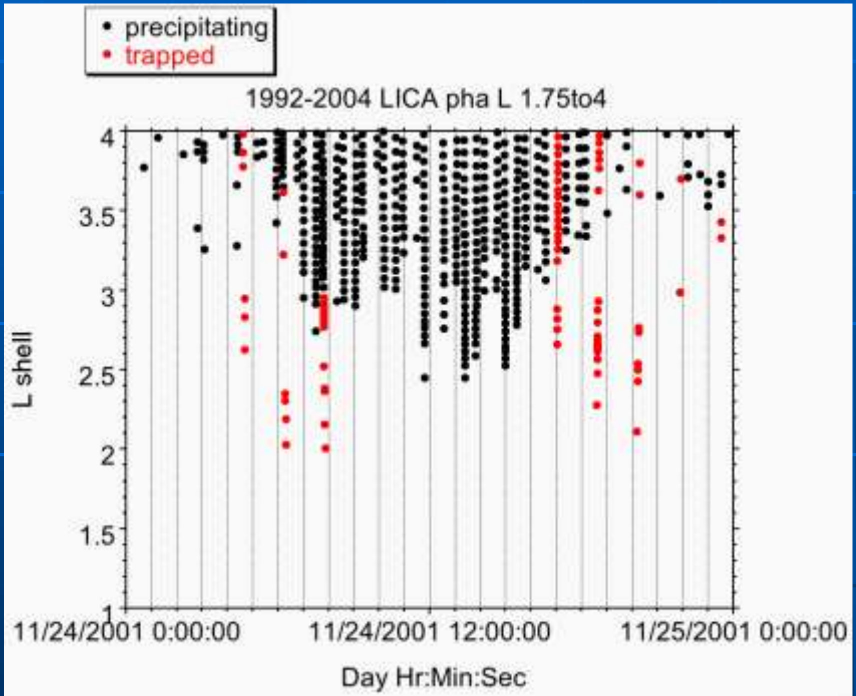


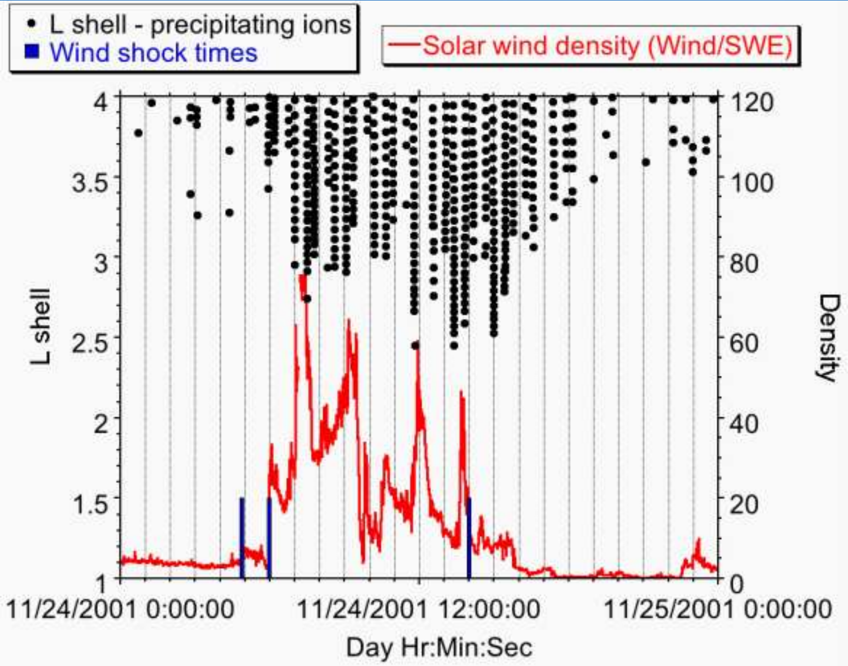
24 Nov 2001 individual heavy ion counts from LICA including He, O, Ne-S, and Fe combined, with energies ~0.25 to 5 MeV/nucleon. Tick marks are at one hour intervals starting at 0 UT. The black dots are precipitating ion counts with pitch angles in the loss cone. Shock times and solar wind density at Wind are shown in blue and red respectively (J. E. Mazur, private communication).



24 Nov 2001 Dst index from the WDC-C2 KYOTO Dst index service.

Precipitating vs. trapped solar ions





[J. E. Mazur, private communication.]

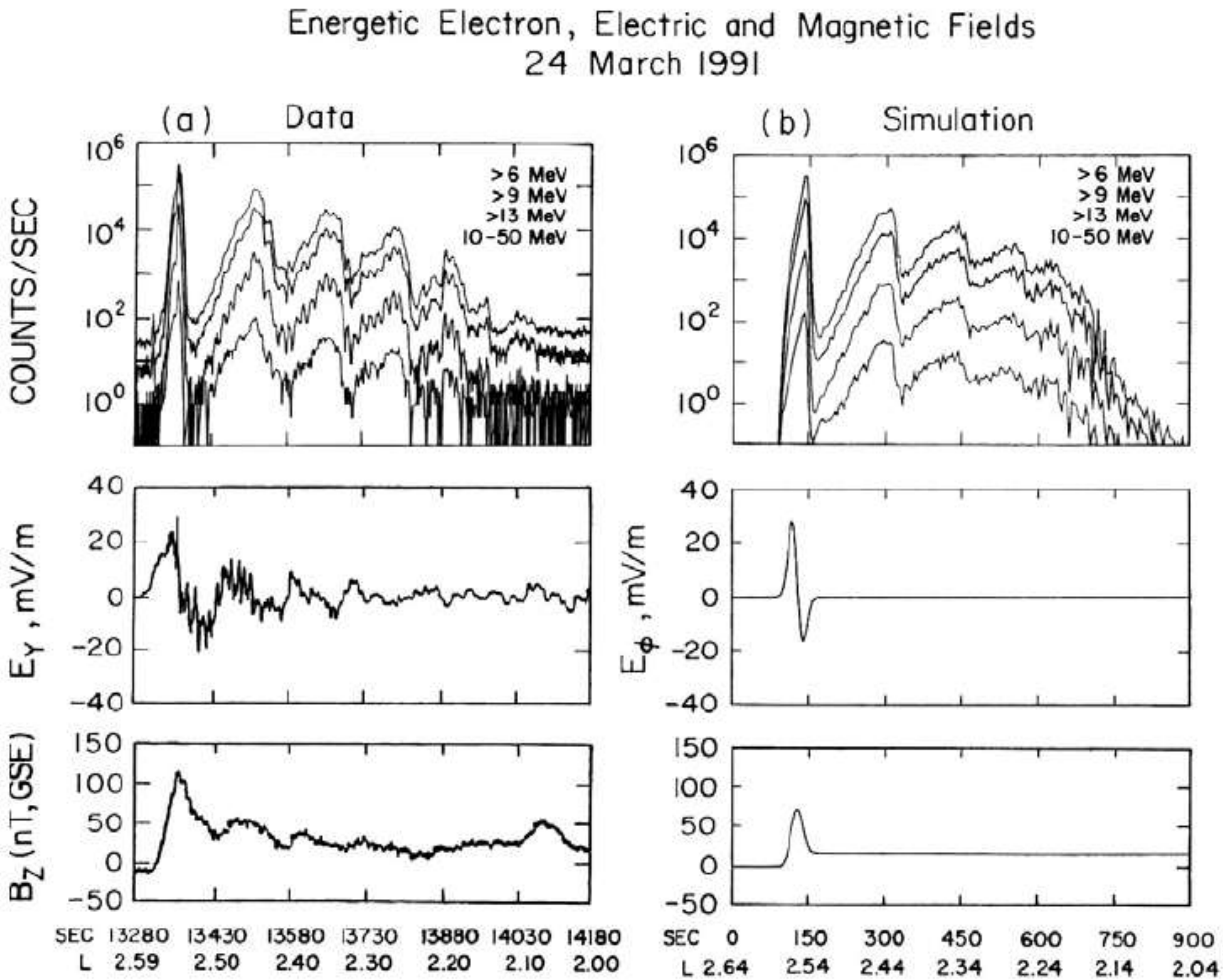
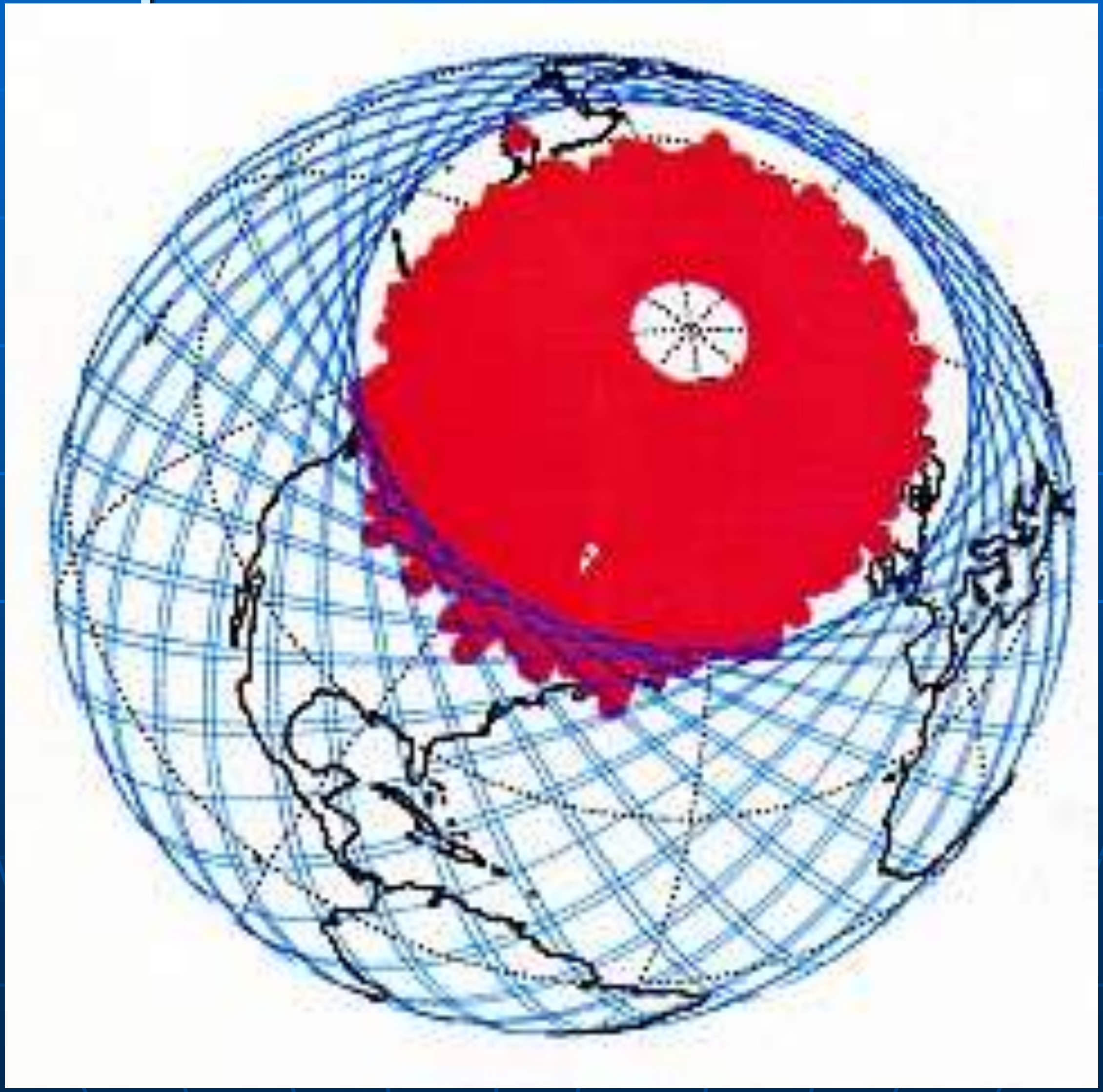


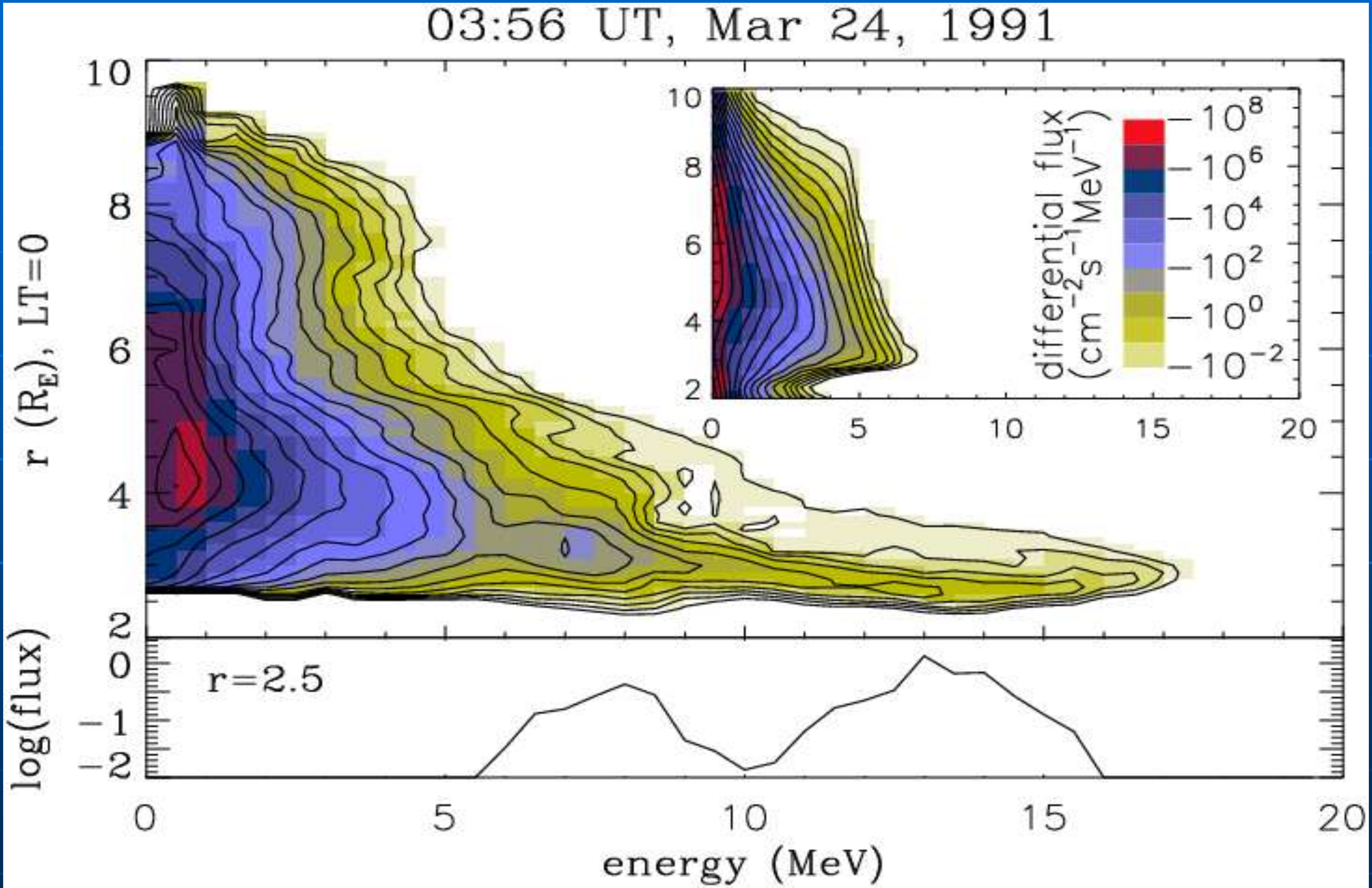
Figure 1. (a) Electron count rate and field measurements from the CRRES satellite. (b) Simulation

Li et al., GRL, 1993

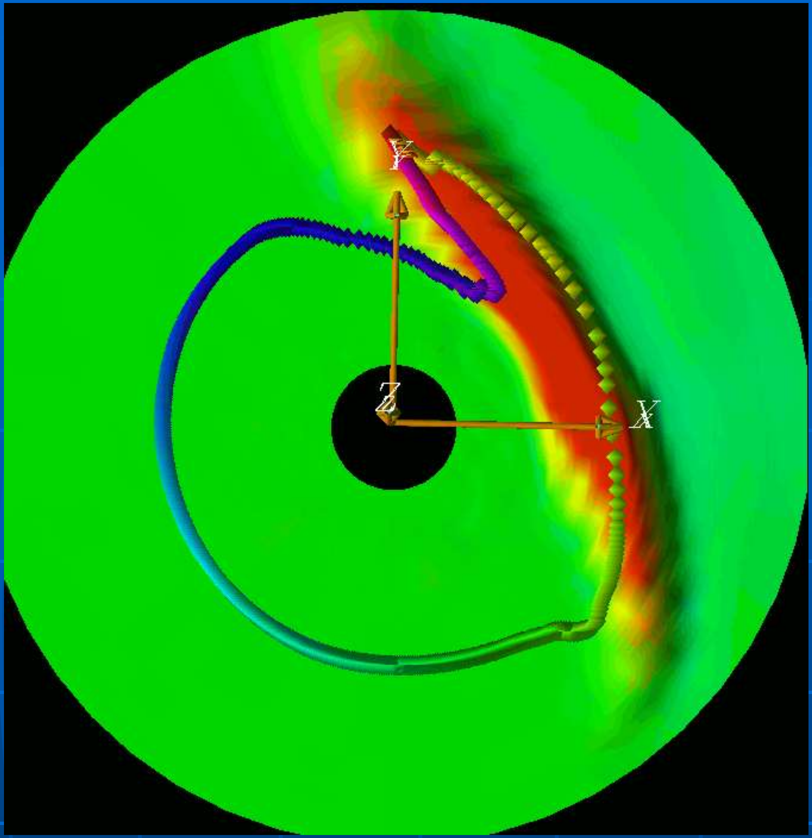
SEP access relative to International Space Station orbit



MHD-Guiding Center Simulation

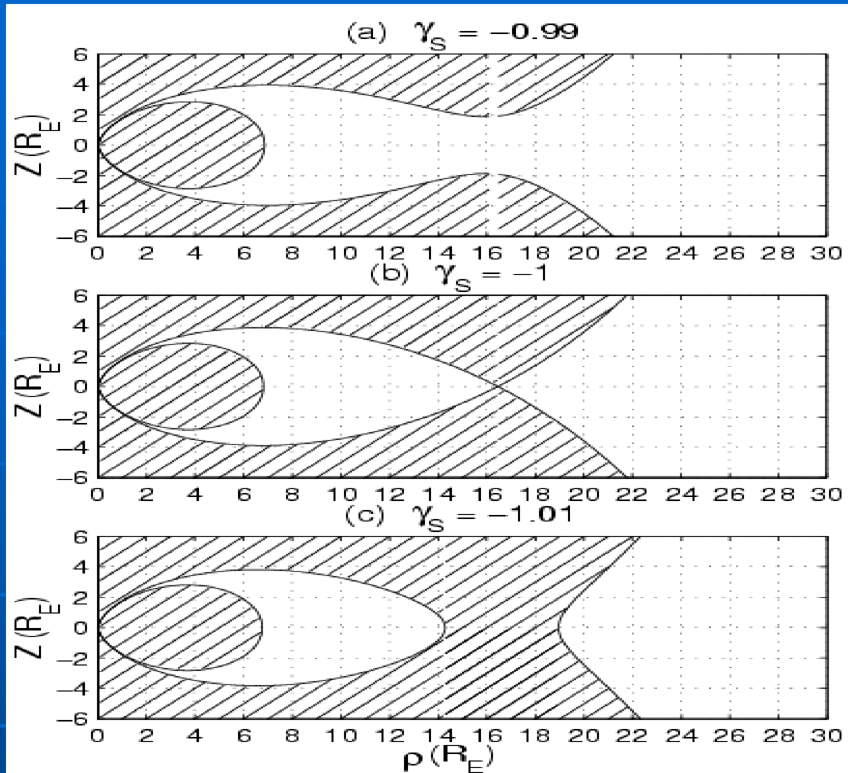


Elkington et al., JASTP, 2002; 2004



E_Φ in equatorial plane from MHD simulation of March 24, 1991 CME-interplanetary shock compression of magnetopause.

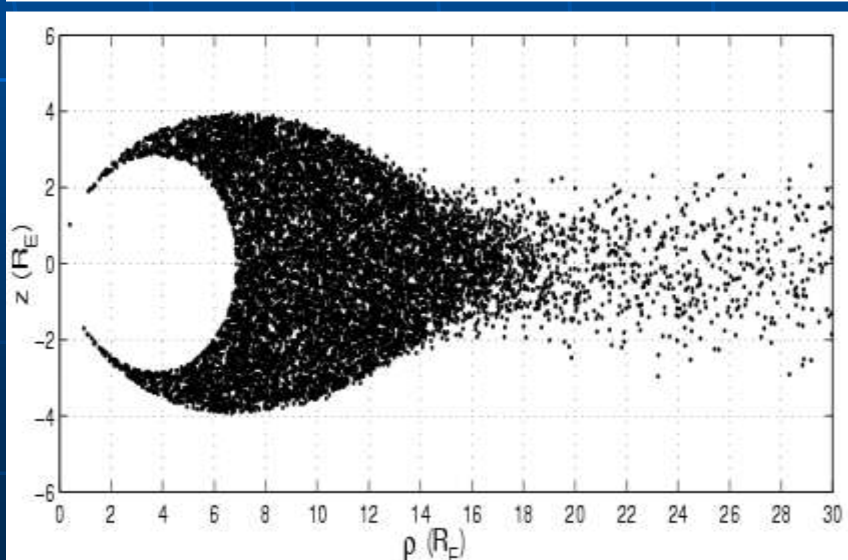
E x B transport of ring of radiation belt electrons inward by inductive **E_Φ** due to magnetopause compression dBz/dt.

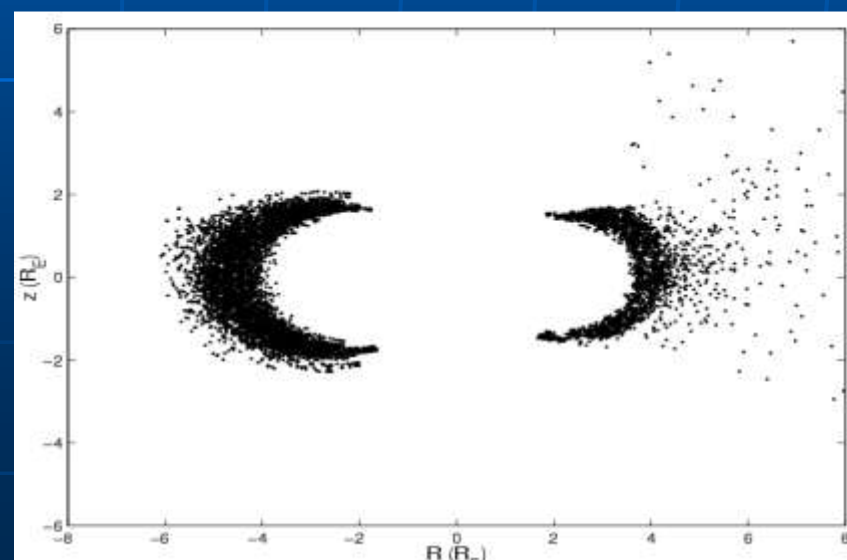


Stormer orbit cutoffs depend on generalized azimuthal momentum; protons have lower L-access in the equatorial plane when B changes, since p_φ = f(M) M = magnetic moment ~p2/2mB for v// = 0.

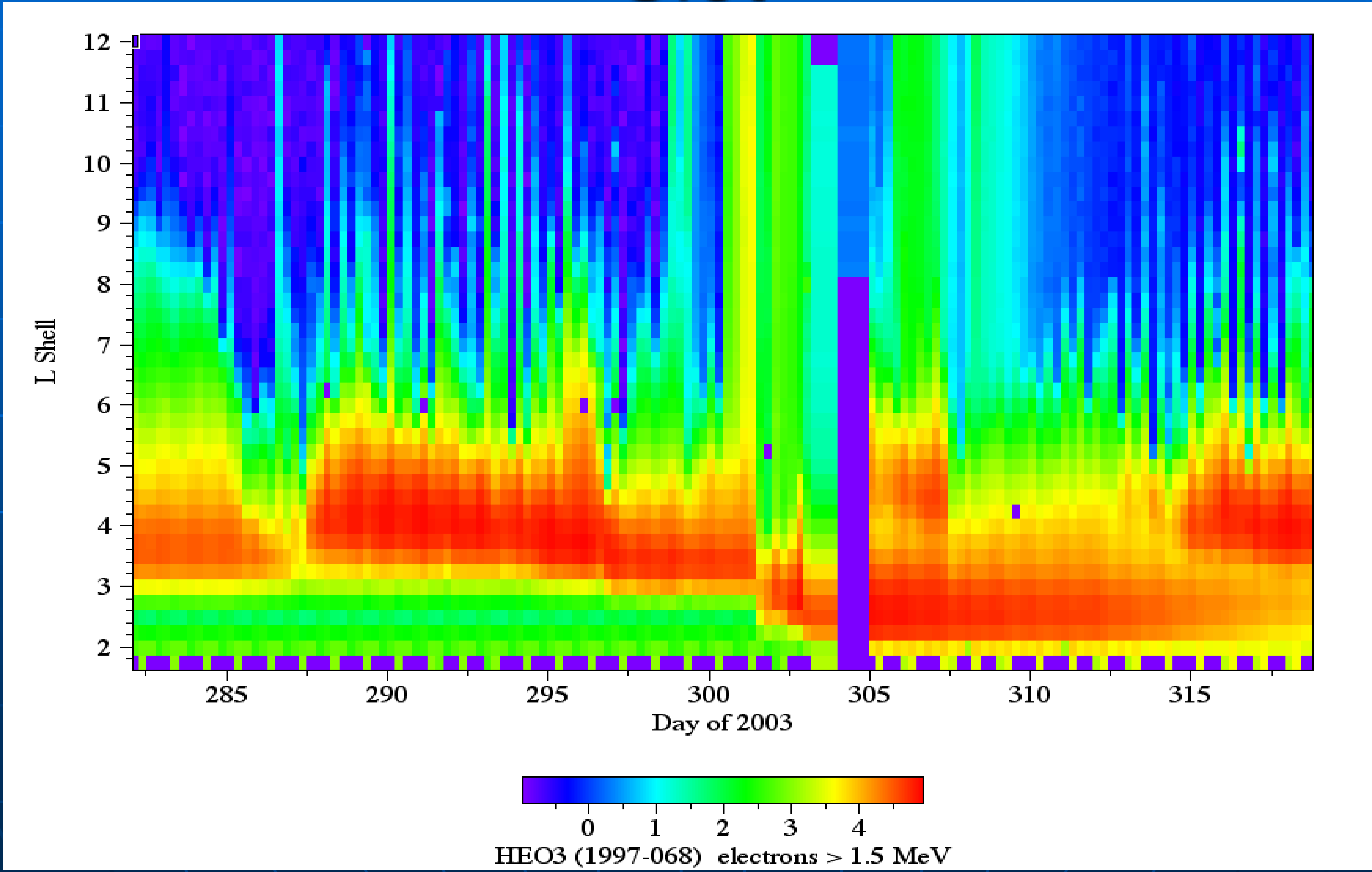
Dimensionsless γ_s ~ p_φ

Dipole lower left, MHD lower right

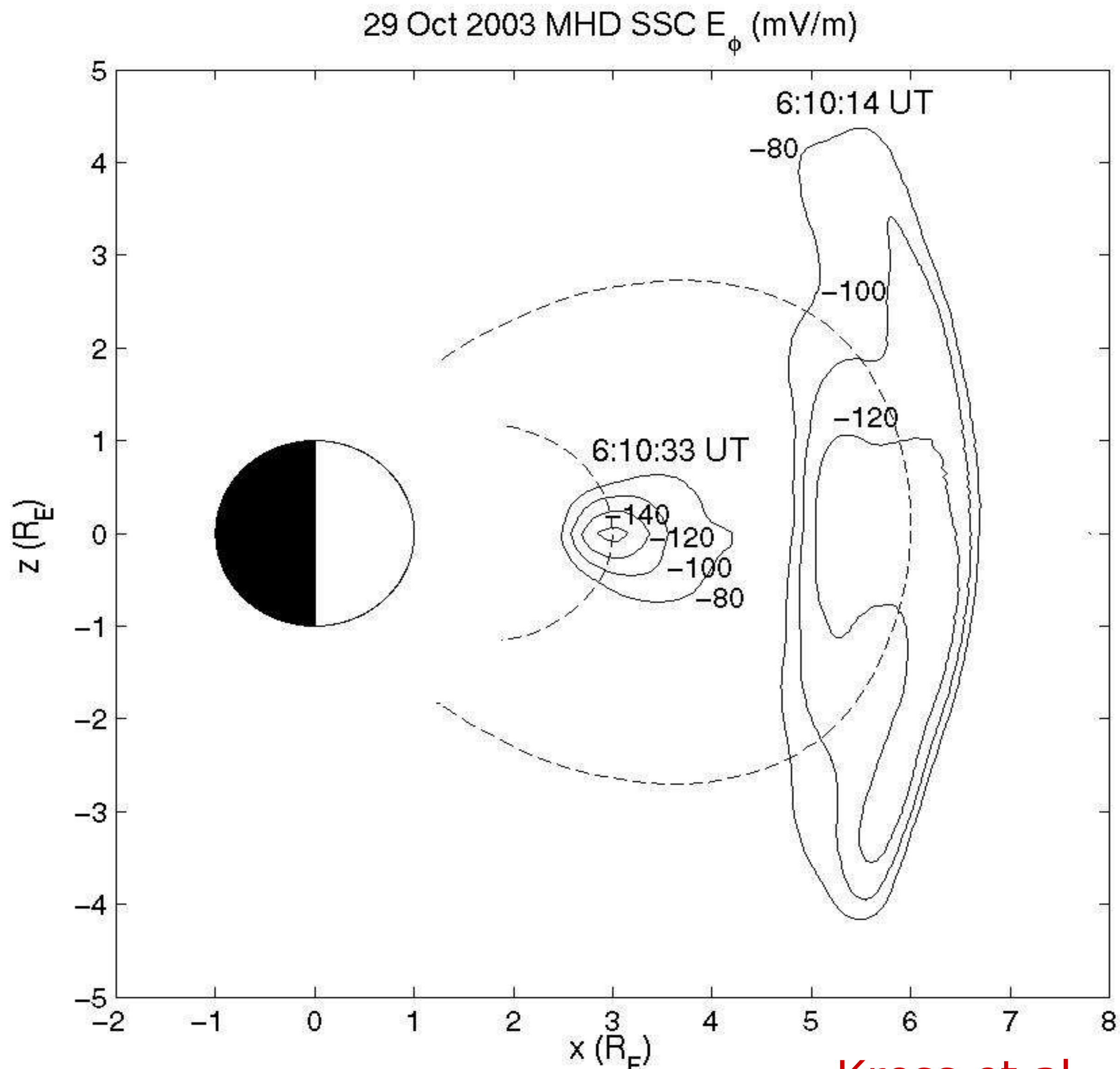




Halloween Storm Fills Electron Slot

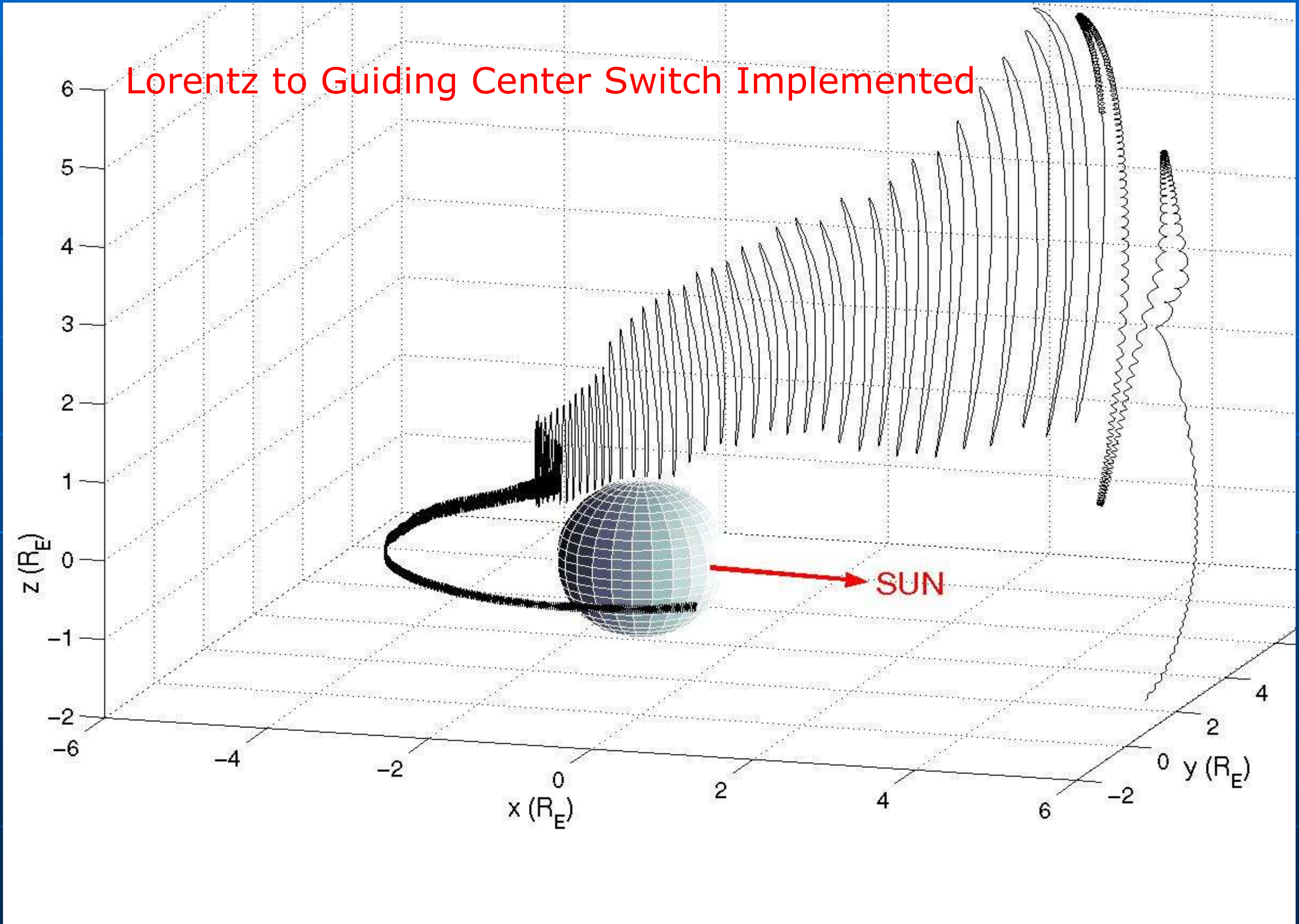


Noon-midnight Halloween '03 storm E_phi

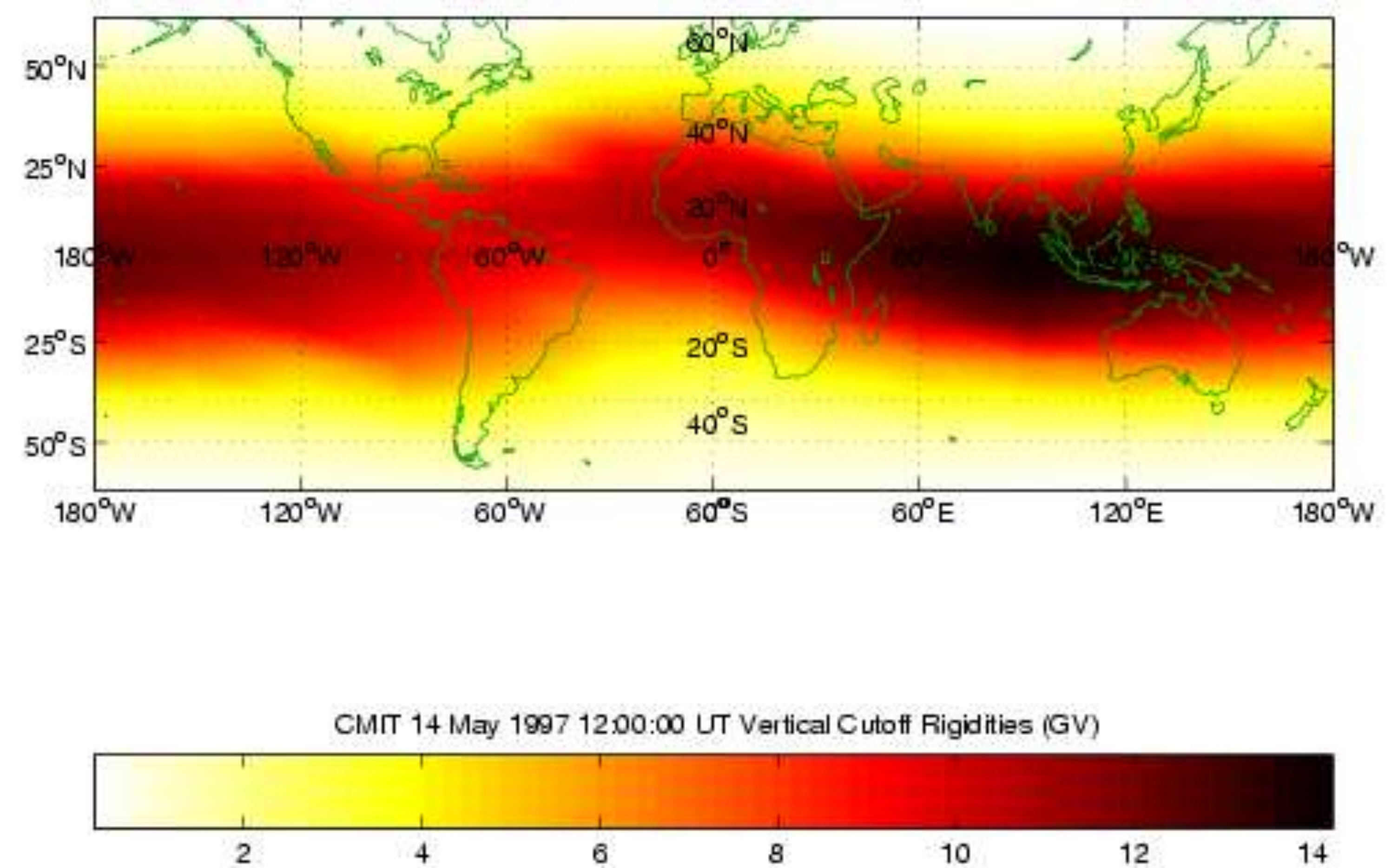


Kress et al., JGR, 2005

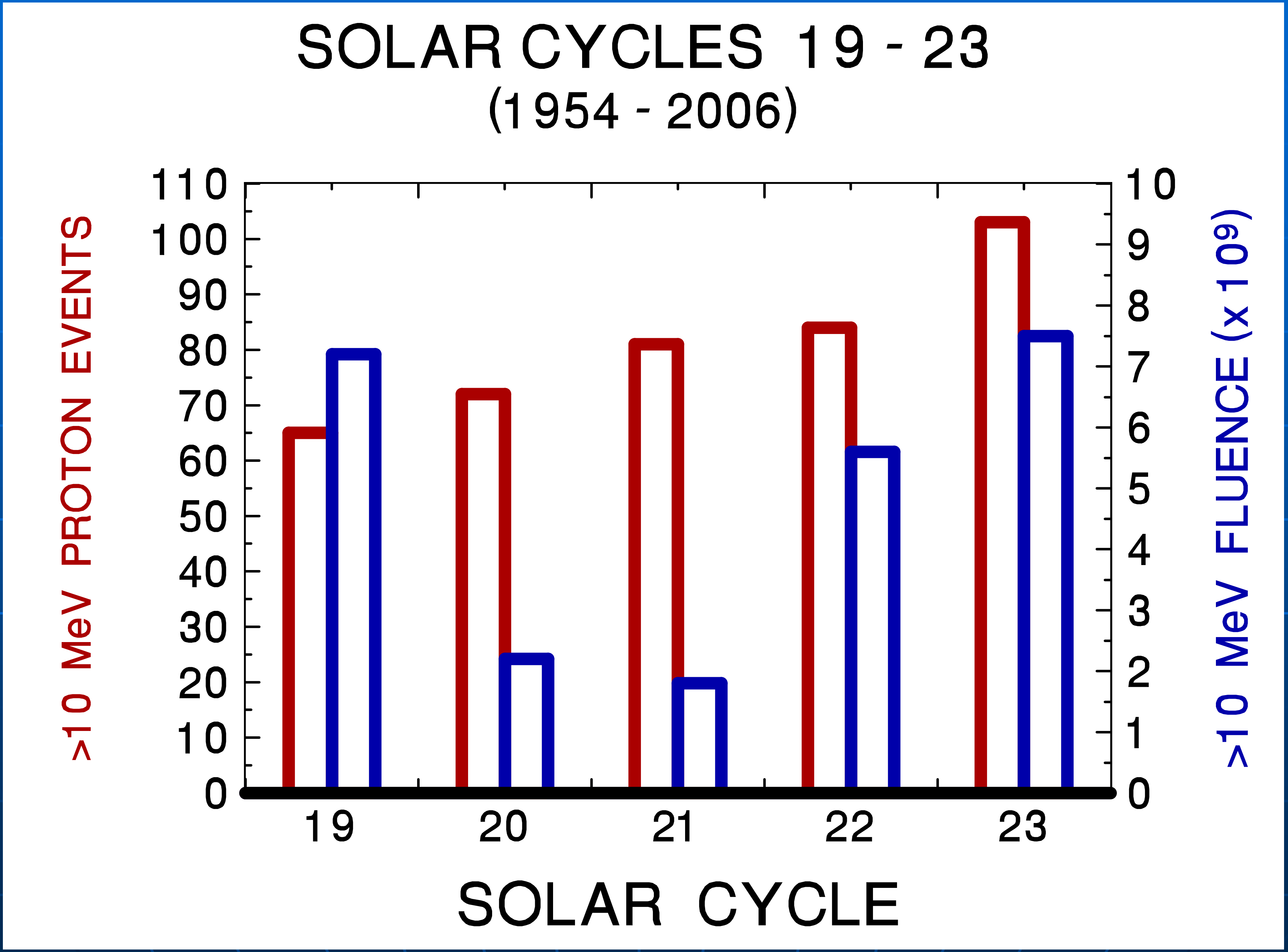
Trapped MeV electron in H-storm MHD fields



Cutoff rigidities calculated in a CISM CMIT simulation of 14 May 1997 storm



IGRF field embedded within MHD inner boundary


SOLAR CYCLES 19 - 23
(1954 - 2006)
>10 MeV PROTON EVENTS
>10 MeV FLUENCE (x 109)
110
100
90
80
70
60
50
40
30
20
10
0
10
9
8
7
6
5
4
3
2
1
0
19
20
21
22
23
SOLAR CYCLE

Event Statistics

- 37 events 1997-2008
- 22 required loss model
- 14 required injection
- 3 required both
- 4 SEP events with neither