Van Allen Probes Observation of Prompt Energization of Electrons to Ultra-relativistic Energies During the 17 March 2015 IP shock

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¥We acknowledge contributions to this work by
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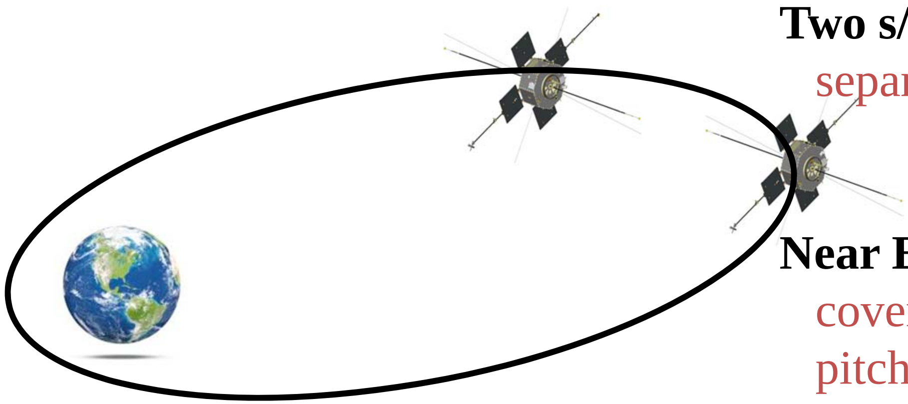
A. Jones, C. G. Kletzing, X. Li, G. D. Reeves, D. Turner, H. Spence, L. Wilson

The Van Allen Probes Mission

Mission Objective: To provide understanding ideally to the point of predictability of how populations of relativistic electrons and ions in space form or change response to variable inputs of energy from the Sun.



Two s/c with identical instruments
separation of temporal and spatial variations

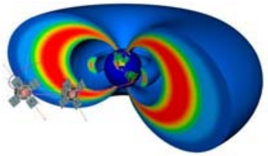
Near Equatorial orbit
covers much of the equatorial pitch angle distribution

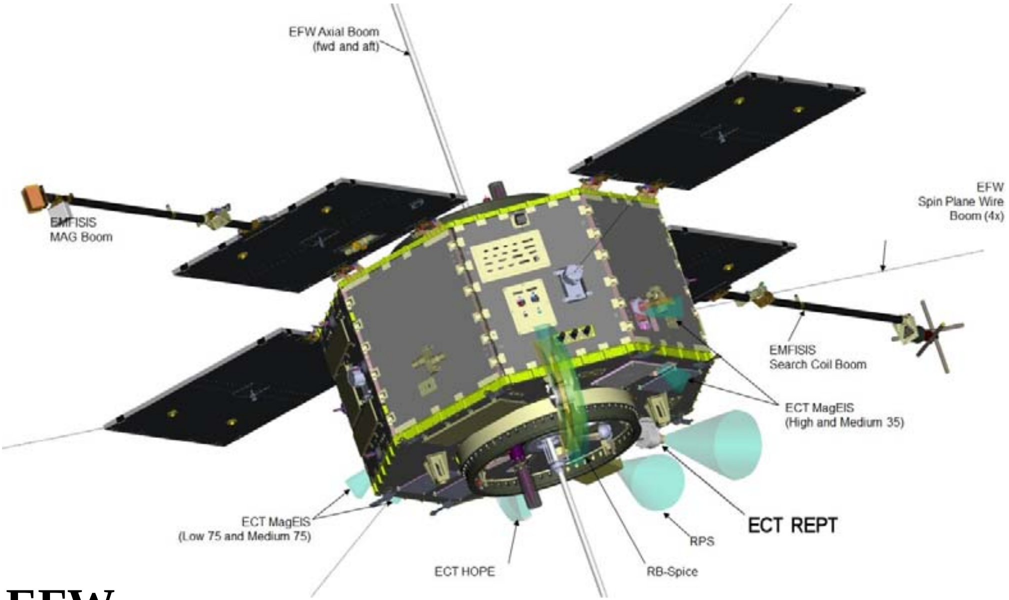
Comprehensive Instrumentation
low energy source population
energized relativistic population
fields and wave phenomena

Local time coverage
full coverage over mission lifetime

Launched Aug 30 2012
Orbit: ~630 km x ~5.8 Re
Inclination ~10°
Sun pointing, spin stabilized
Prime mission duration 2 years
Currently in Extended Phase

Van Allen Probes Spacecraft & Payload





ECT Suite - HOPE , MagEIS, REPT

(Energetic Particle, Composition, and Thermal Plasma)

- 20 eV-45 keV He+, O+, p+, e-
- 30 keV-20 MeV electrons
- 20 keV-100 MeV protons

RBSPICE - ring current studies

- 50 keV-10 MeV electrons
- 0-75 MeV Protons
- 20-1000 keV Ion

RPS - inner belt protons

- 50 MeV-2 GeV protons

EFW

Spin Plane Booms

- all four at 50 m length

Axial Booms

- 12 m tip-to-tip (extendable to 14 m)

EMFISIS

Magnetometer Booms

- Extend 3 m from edge of spacecraft

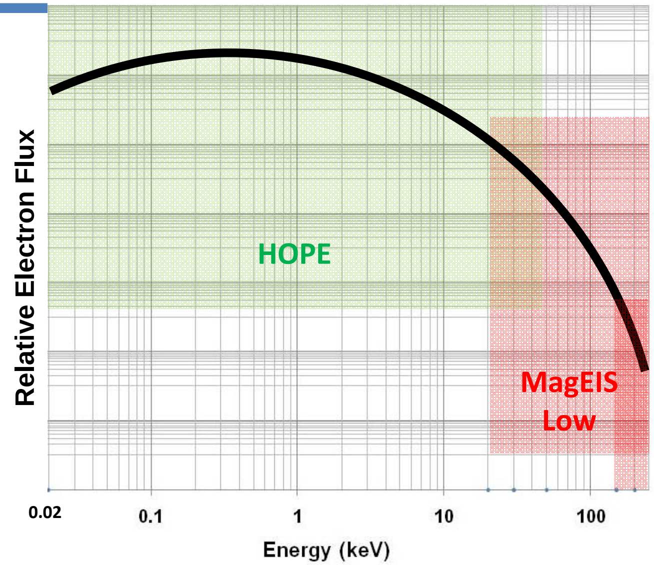
ECT Suite Instrument Overview

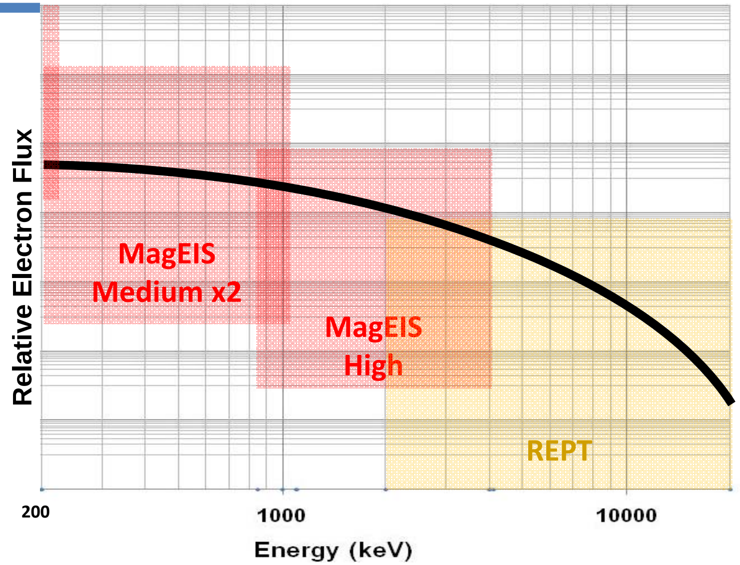
ECT consists of three coordinated sensor types:

- **HOPE**
- **MagEIS**
- **REPT**

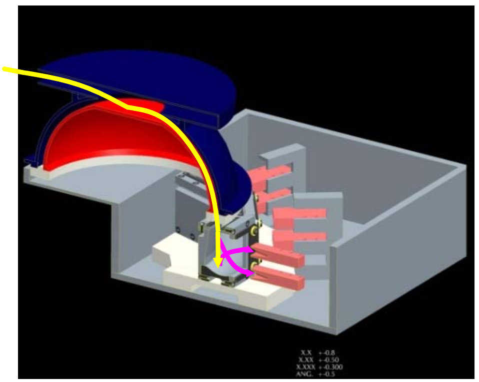
ECT measures electrons (continuously) and ions (with composition up to 50 keV) from ~20 eV to ~10's of MeV with energy resolution, and pitch angle coverage and resolution required for mission success.

PI Dr. Harlan Spence



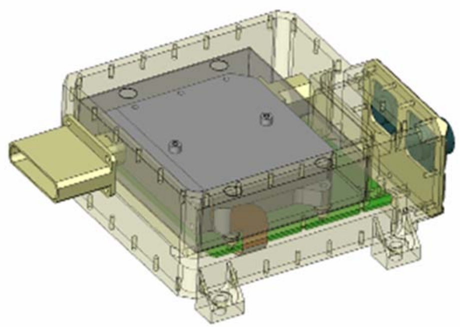


HOPE



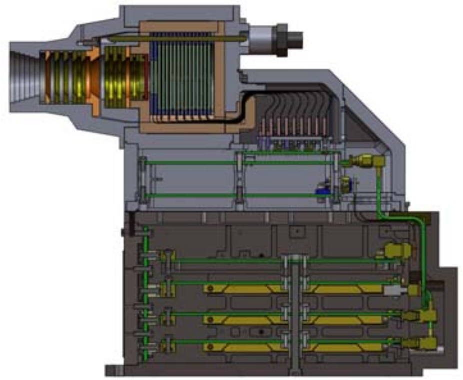
Dr. Herb Funsten
Los Alamos National Laboratory

MagEIS (4)



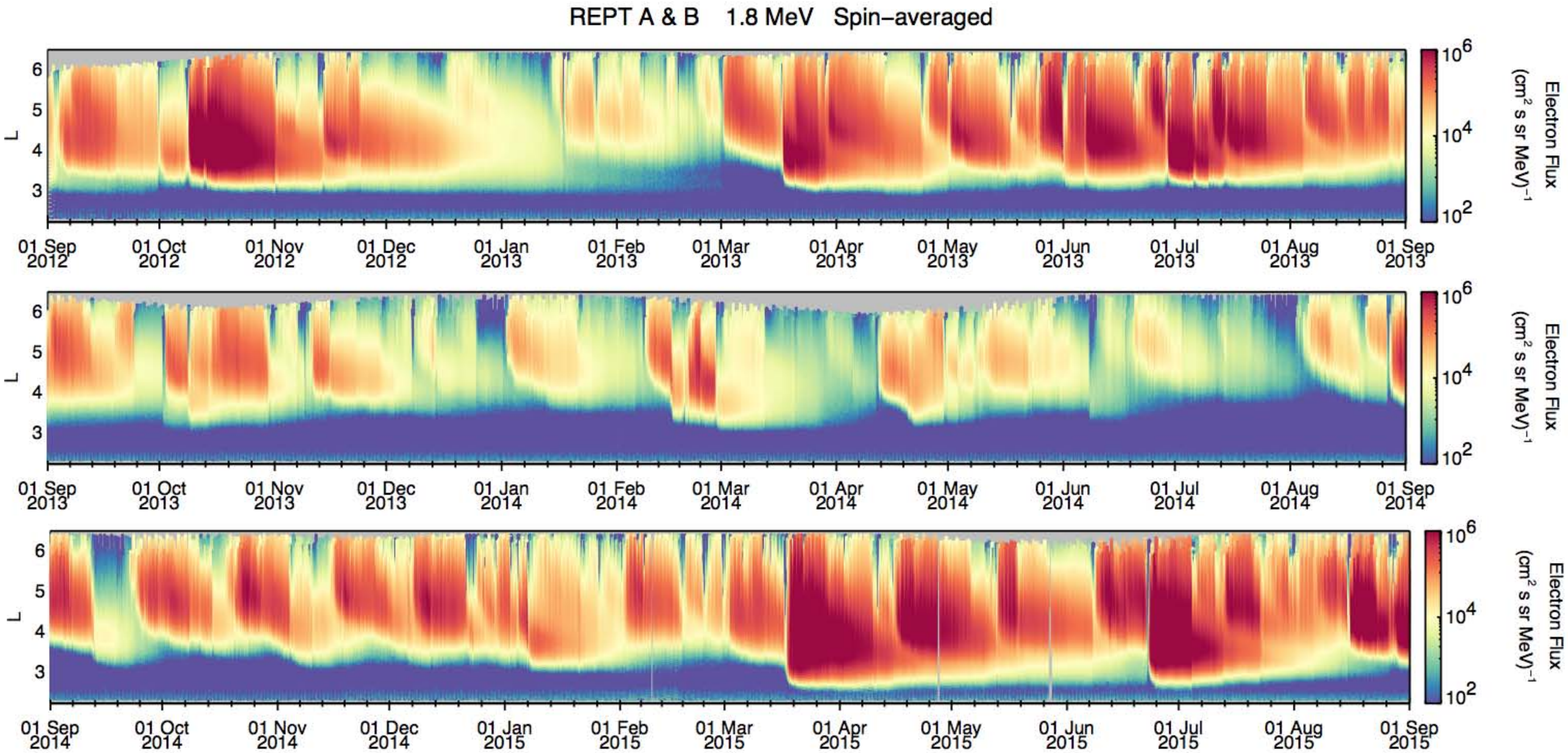
Dr. J. Bernard Blake
The Aerospace Corp.

REPT

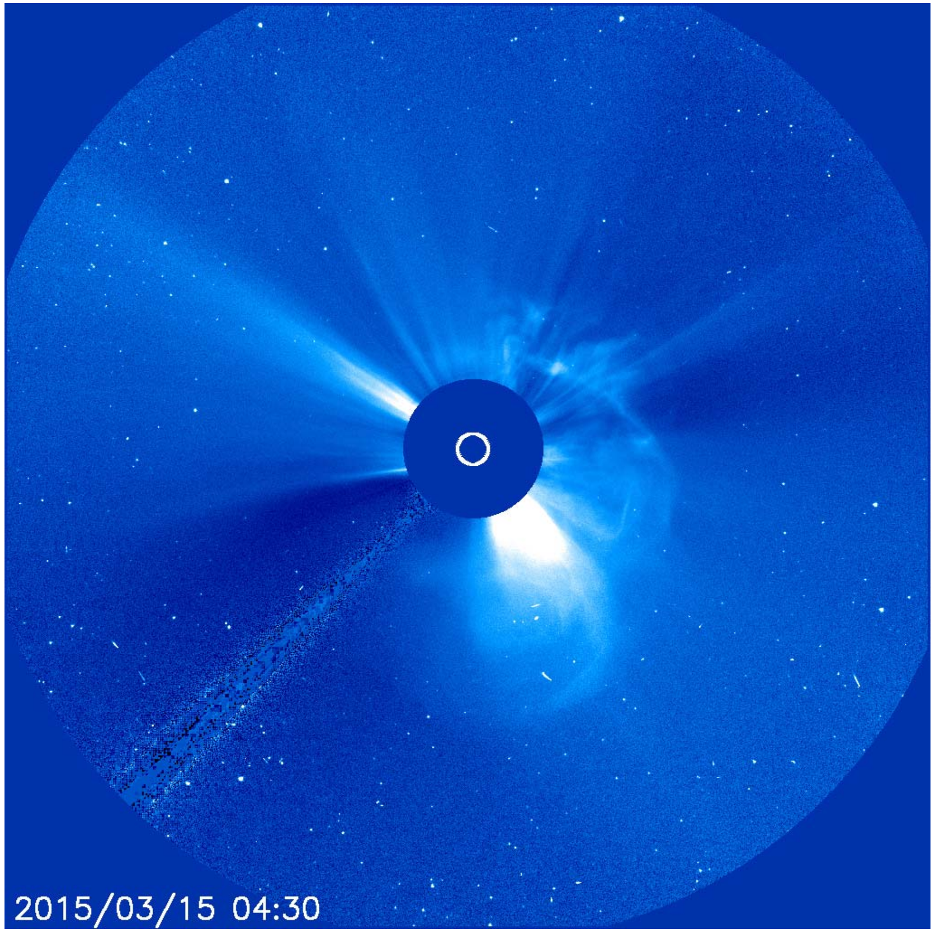


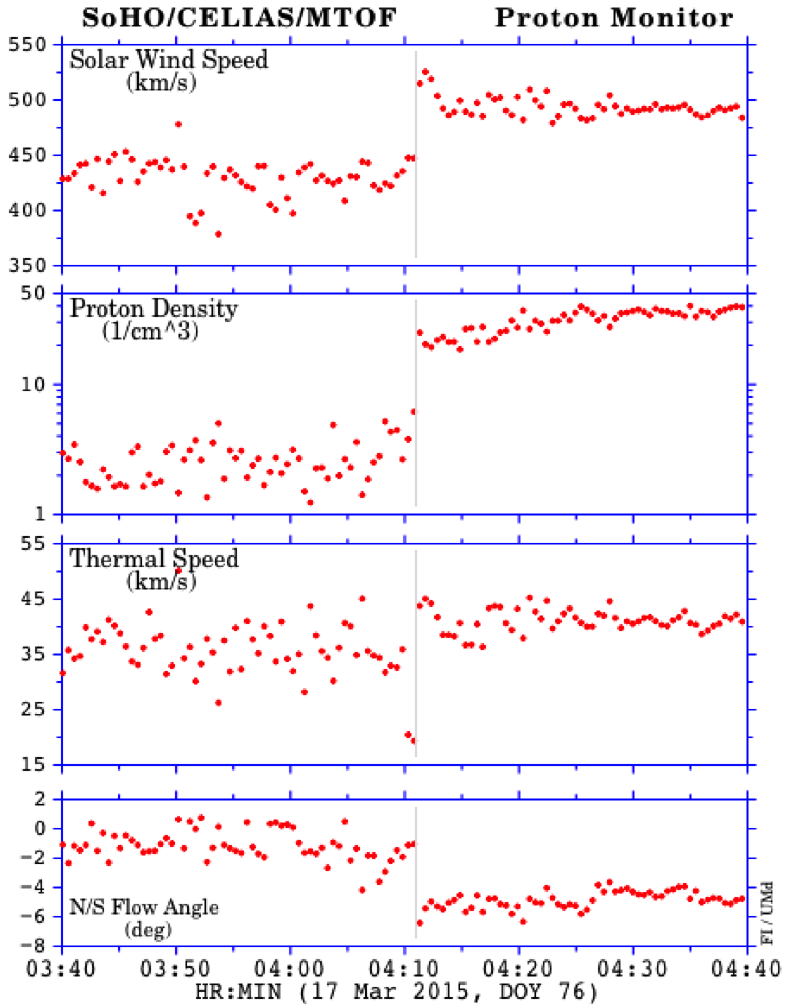
Dr. Daniel Baker
University of Colorado

REPT A & B measurements mission to date



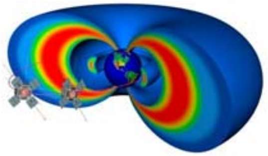
Acceleration of electrons to ultra-relativistic energies: March 2015 CME



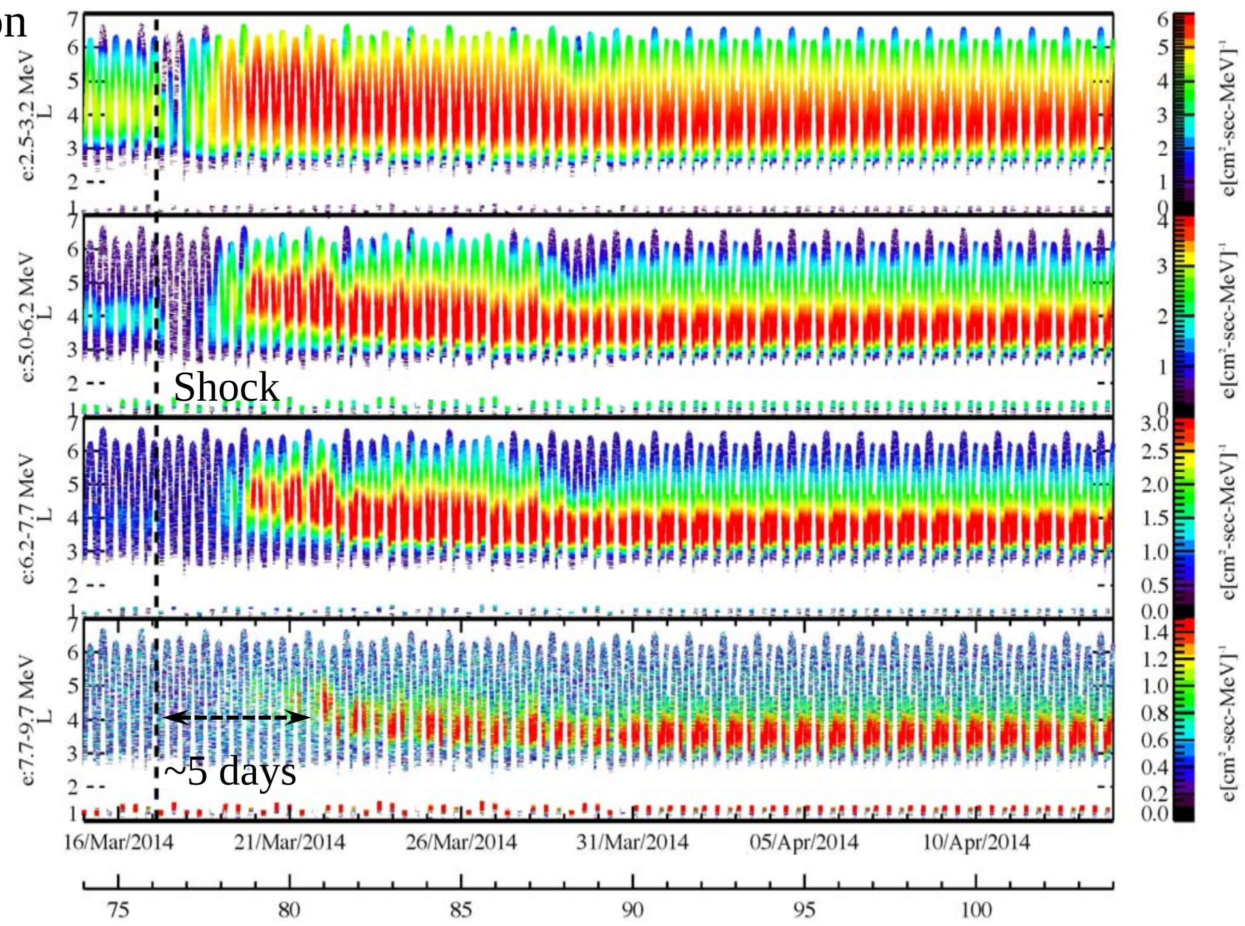


SOHO LASCO and CELIAS/PM

REPT(A) energetic electrons March 2015



- Energy dependent energization to relativistic energies
- Radial diffusion to lower Ls evident for > 5.0MeV electrons.
- Highest energy electrons (~8MeV) peak flux values appear about 5 days after shock passage.



Note: Probe B observations are nearly identical to probe A and are not shown

REPT MagEIS spectra 16-26 March 2015

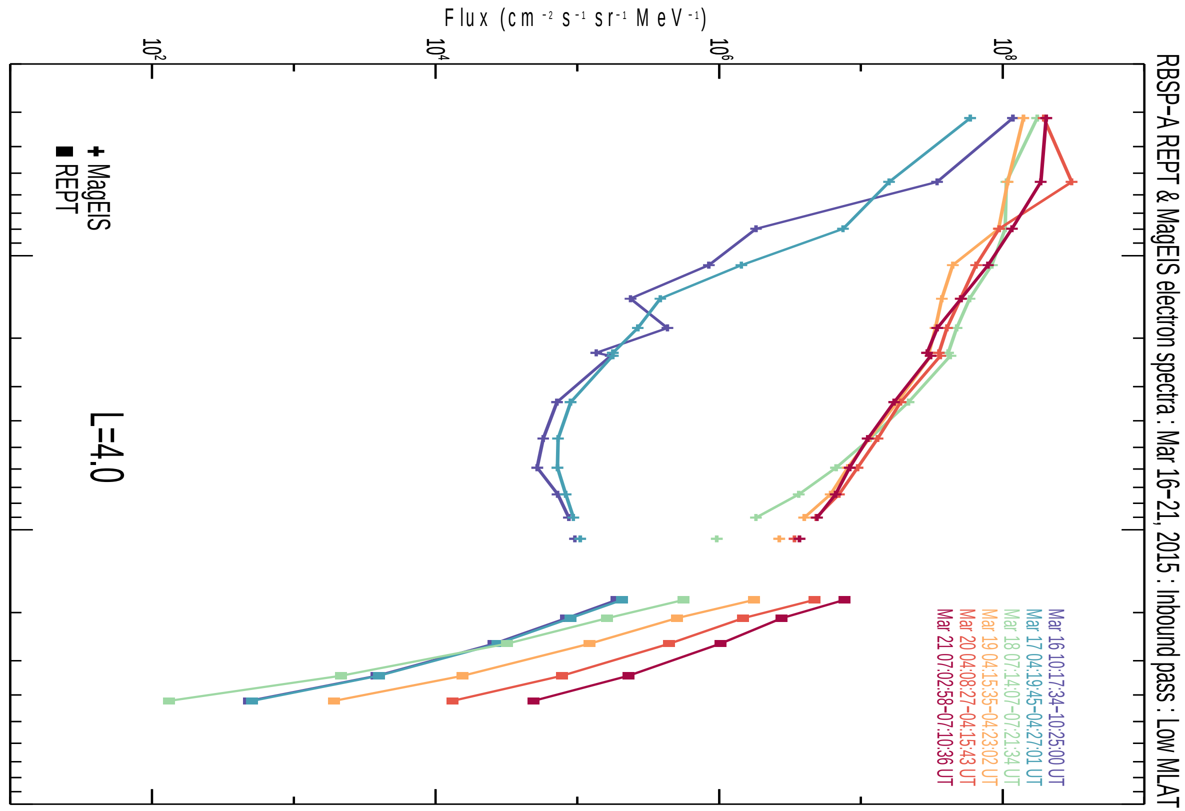
- MagEIS spectra show an abrupt hardening within a day after the shock passage

  - electrons from ~100s keV to ~1MeV

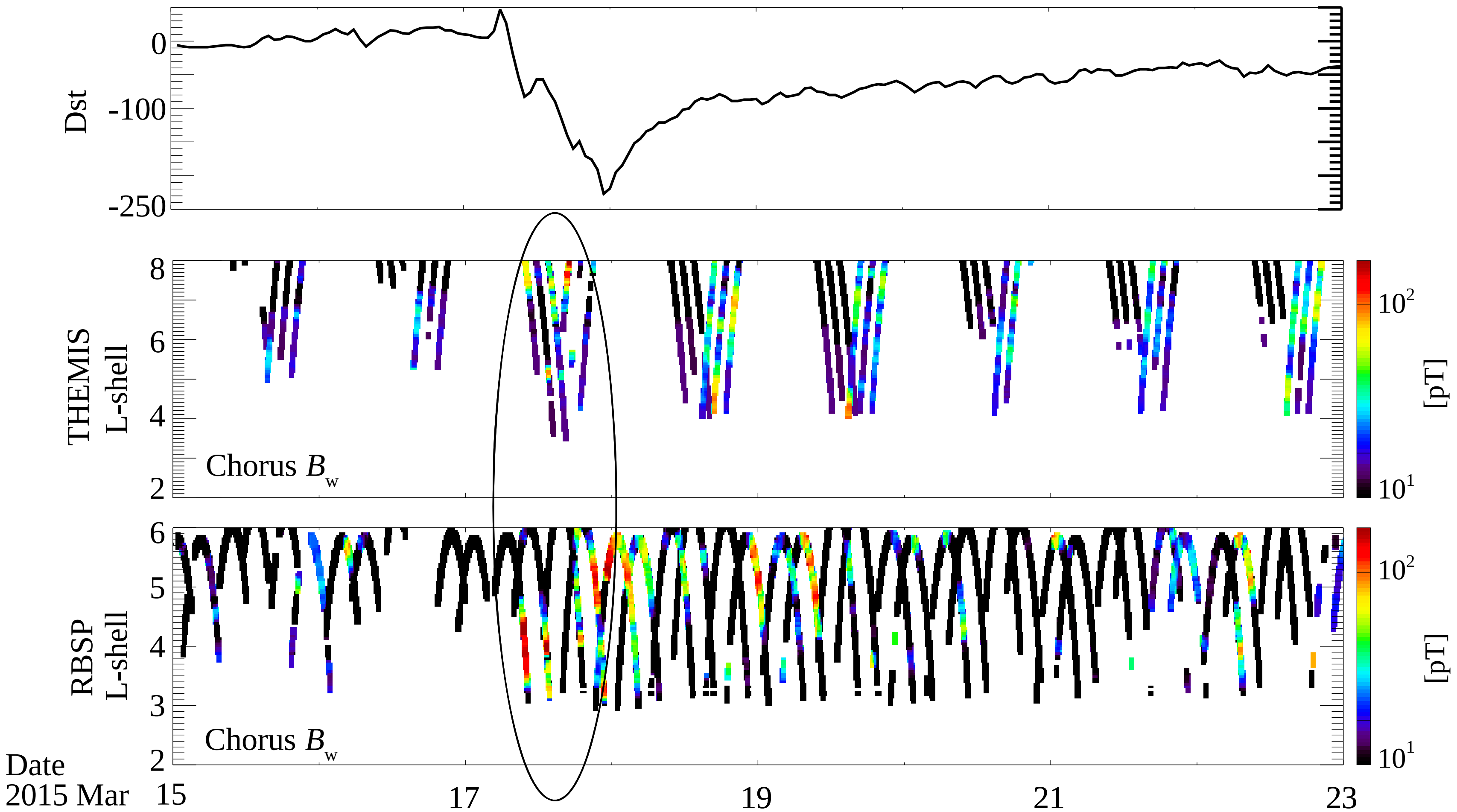
  - note fluxes at the lowest energies showed little change

- REPT spectra covering higher energies show a much more gradual hardening

- Enhanced chorus activity may be responsible for rapid energization at lower energies

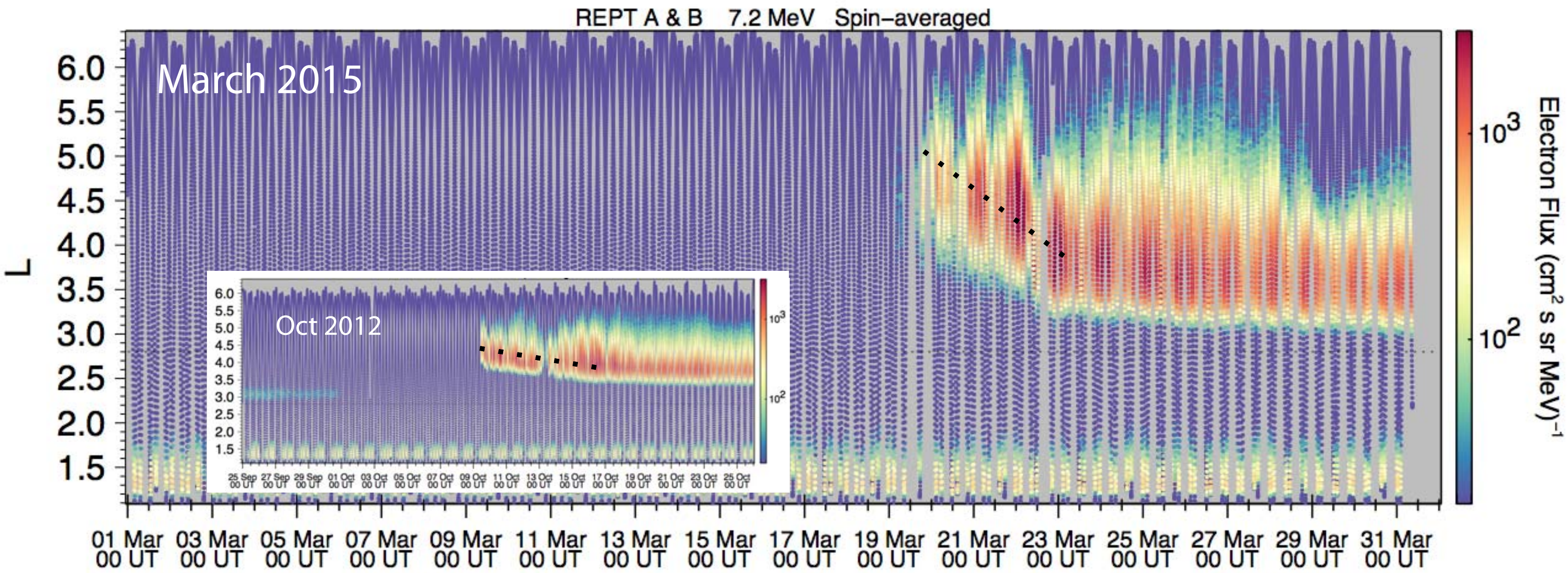


Van Allen Probes and Themis observations of chorus waves



Intense wave activity can be seen early on 17 March 2015 after shock passage

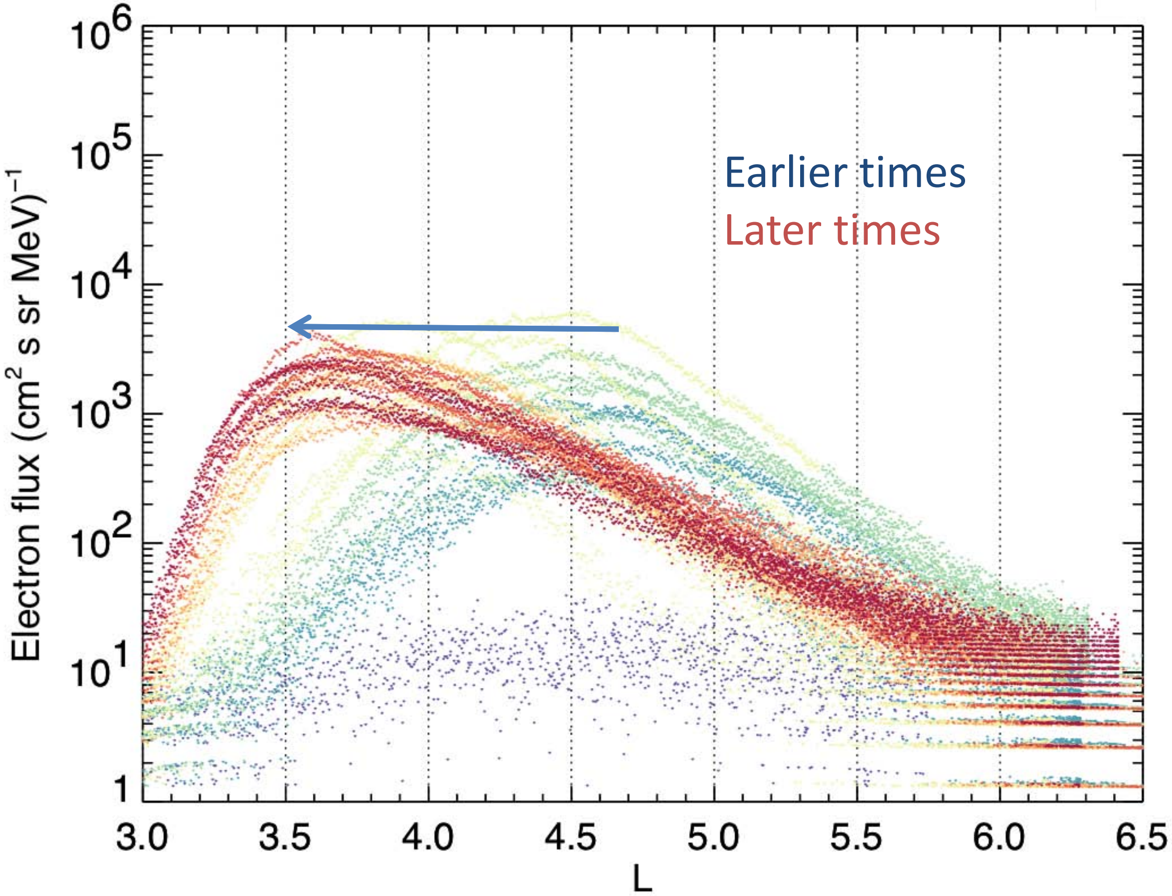
Intense chorus activity and rapid radial diffusion



Fast radial diffusion of ultra-relativistic electrons in the 7.2 MeV range, crossing 1.25 Lshell radial distance in ~2 days.

Compare to much slower diffusion seen in previous strong storm in Oct 2012 (inset).

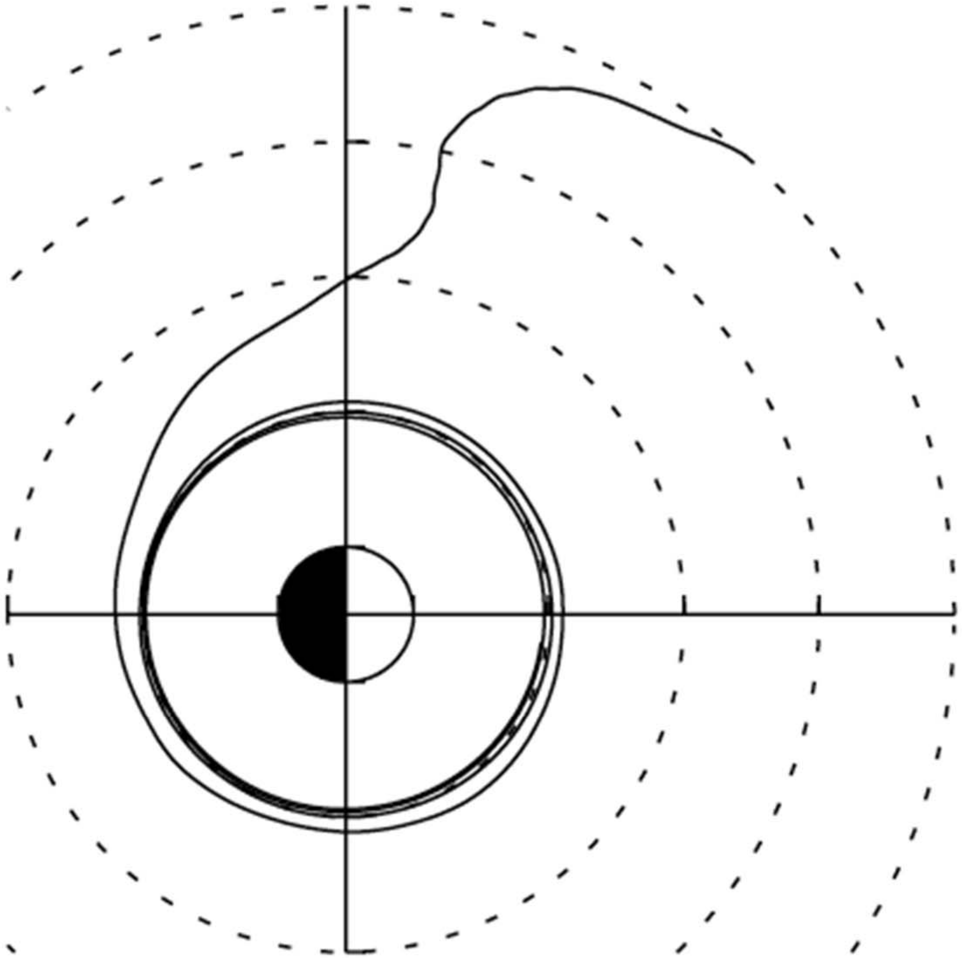
REPT-A 7.2 MeV 3/17 – 3/26



Radial profile of 7.2 MeV electron flux at equally-spaced times throughout the 17-26 March time period at orbital passes with low MLAT.

Peak is seen to move in dramatically from 20 March to 23 March.

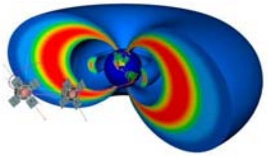
LFM simulation of March 1991 IP Shock

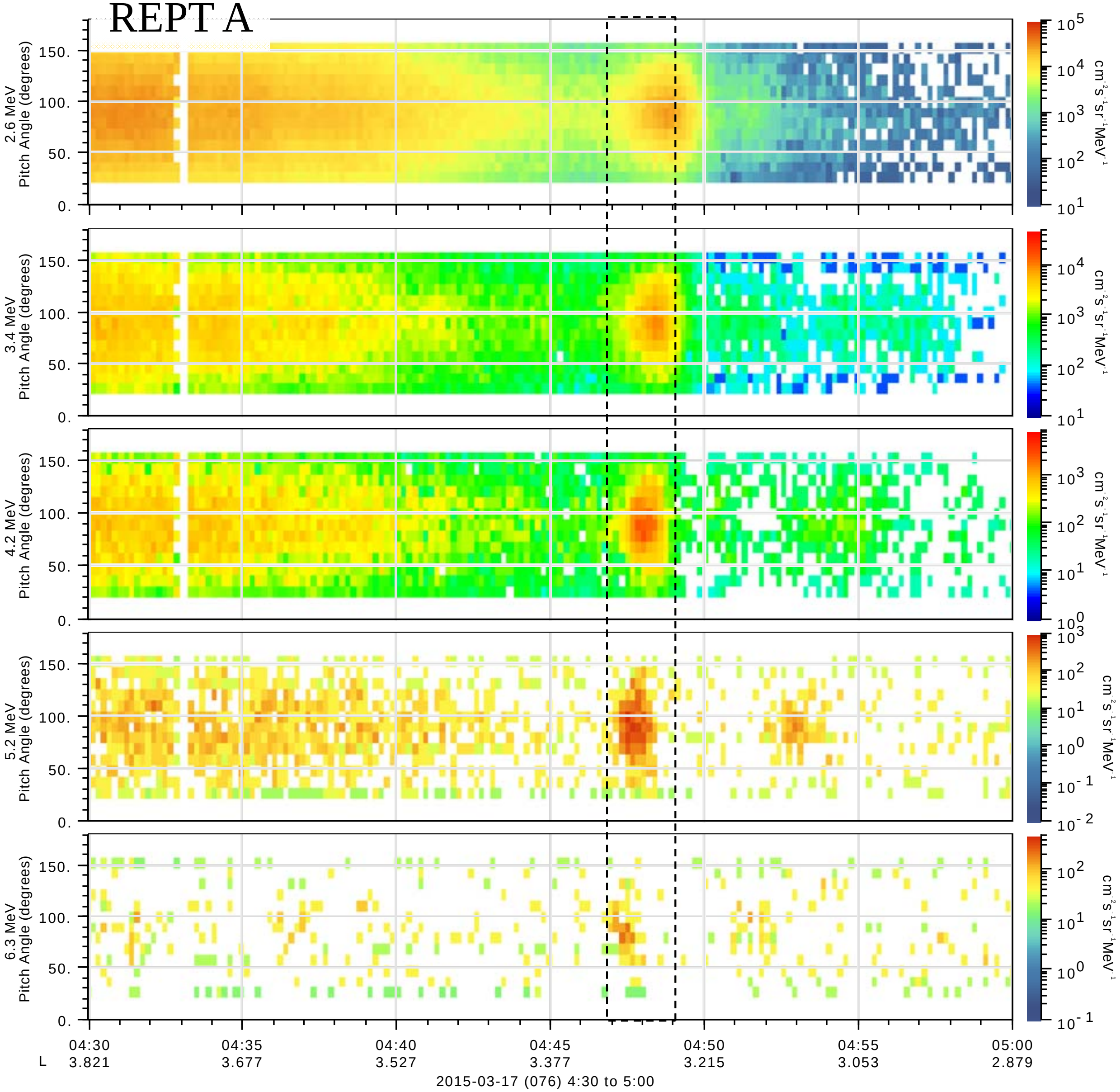


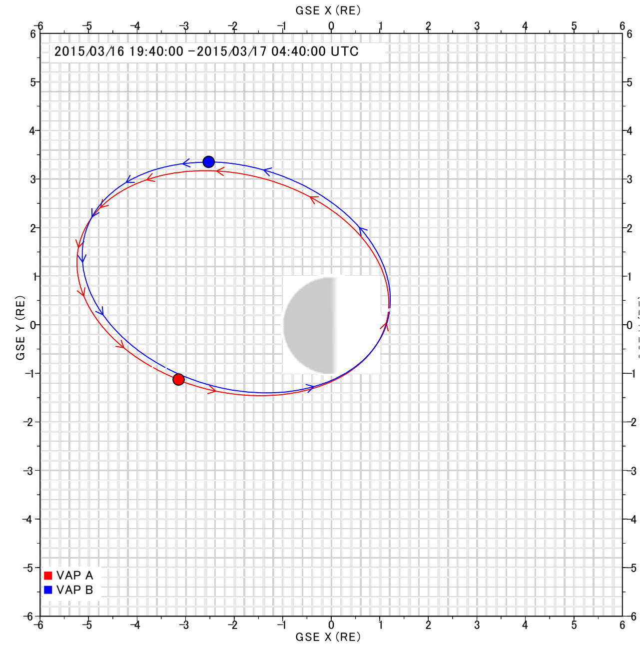
Elkington et al. 2002

Electron Trajectory: shock Injection

Prompt response: ultra relativistic electrons

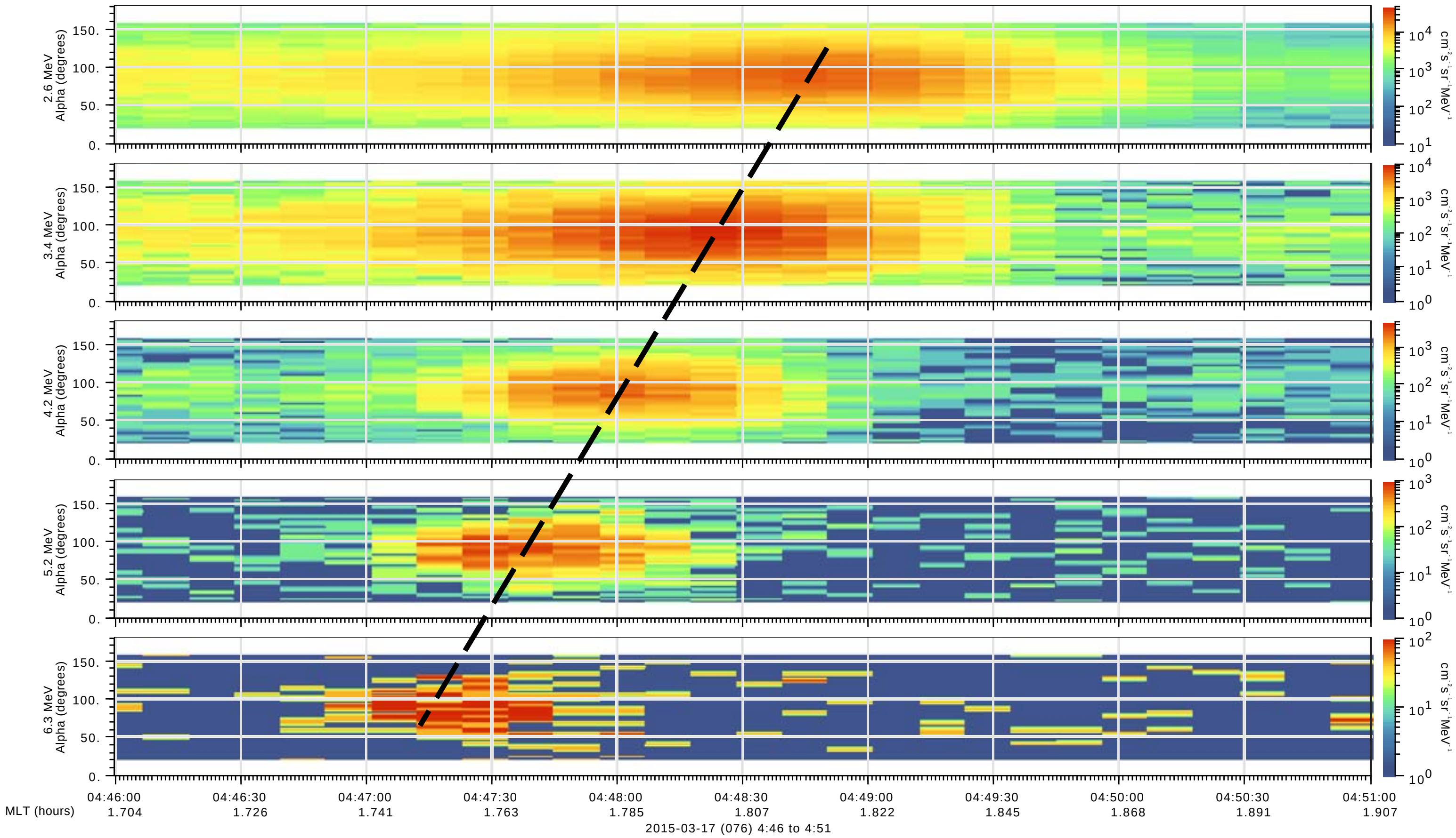






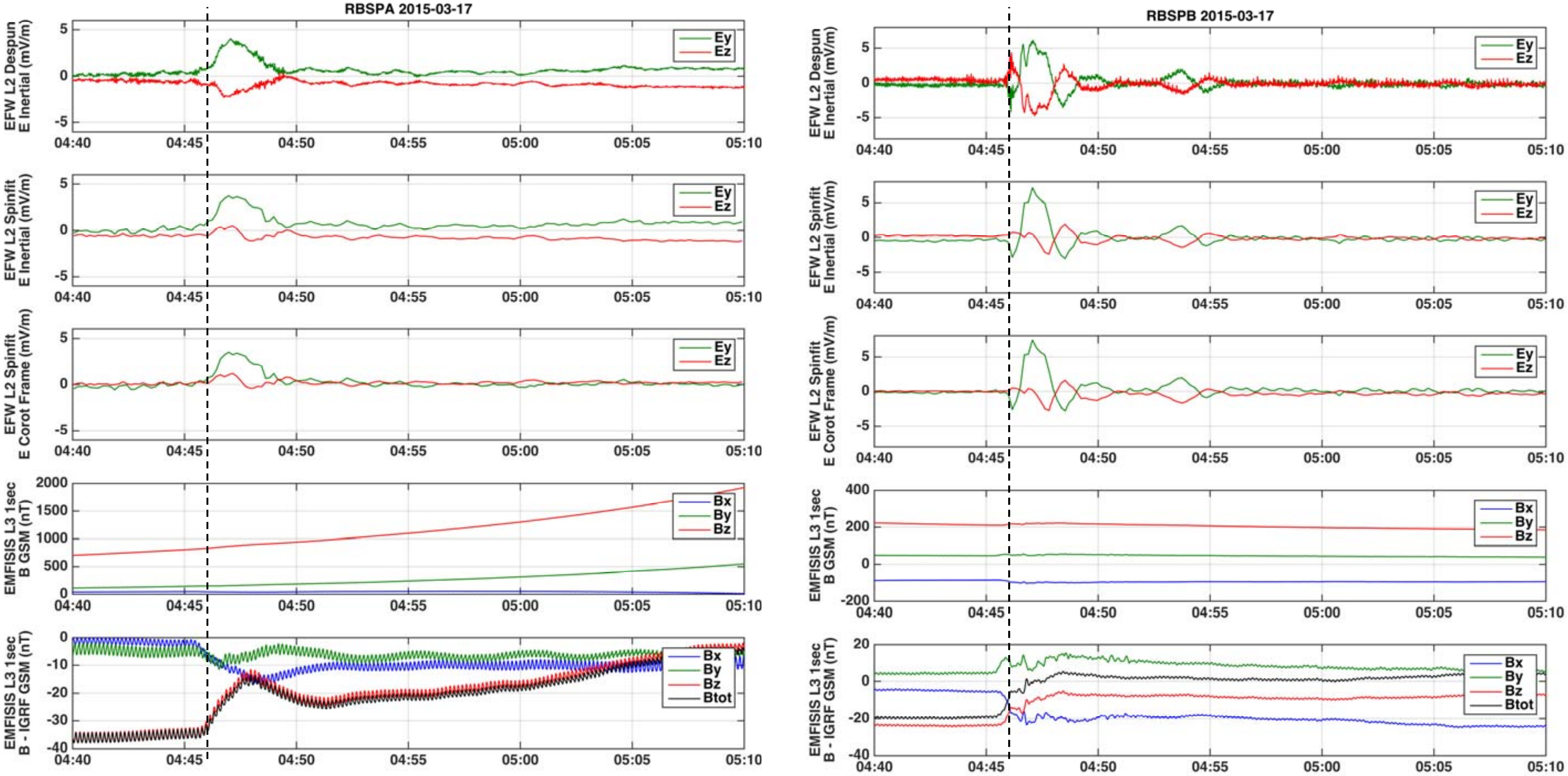
Post injection velocity dispersion

REPT A observations continued



- Electrons energized to ultra-relativistic energies (>6 MeV)
- Clear velocity dispersion suggesting local injection

E and B Fields data from EFW and EMFISIS

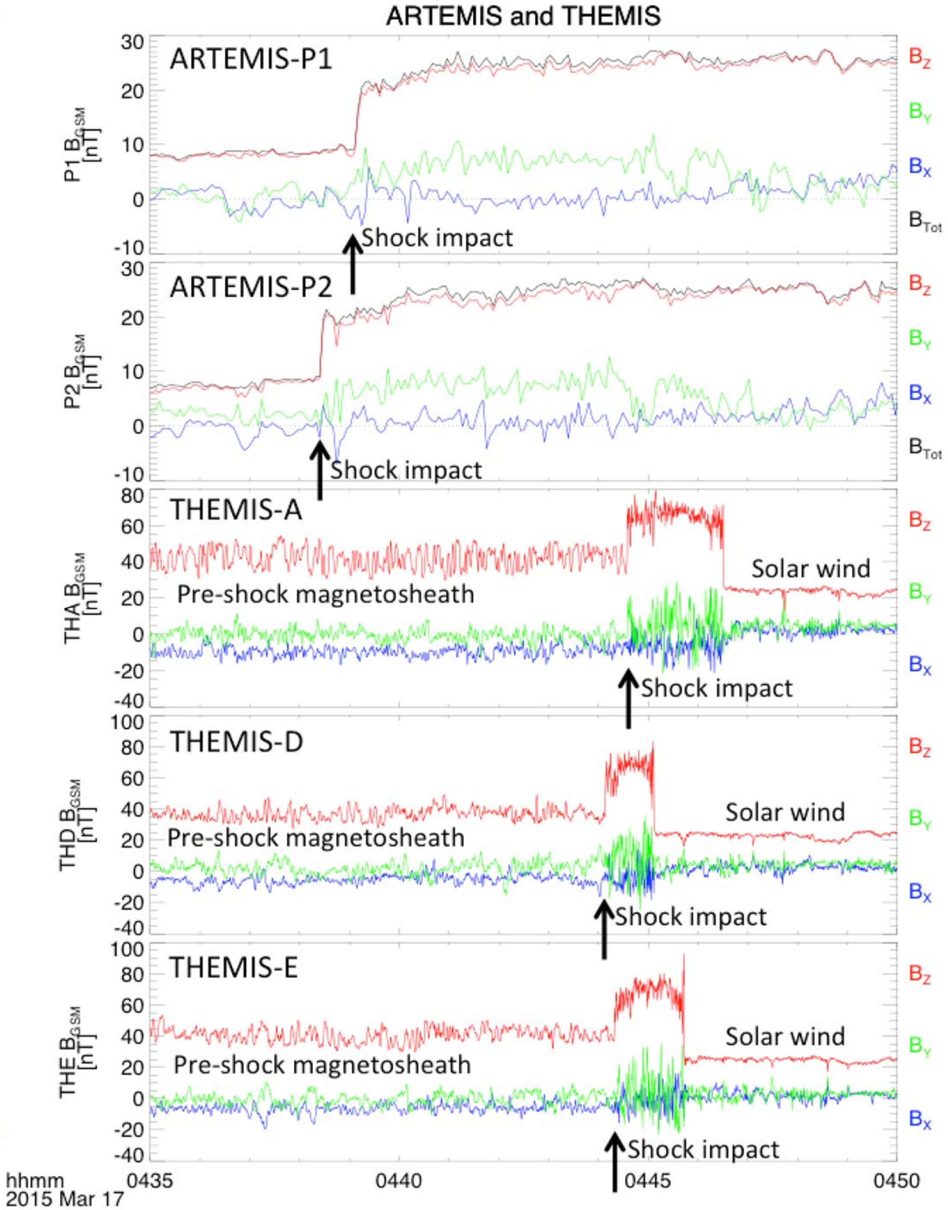


Compression of the Magnetosphere and associated E field

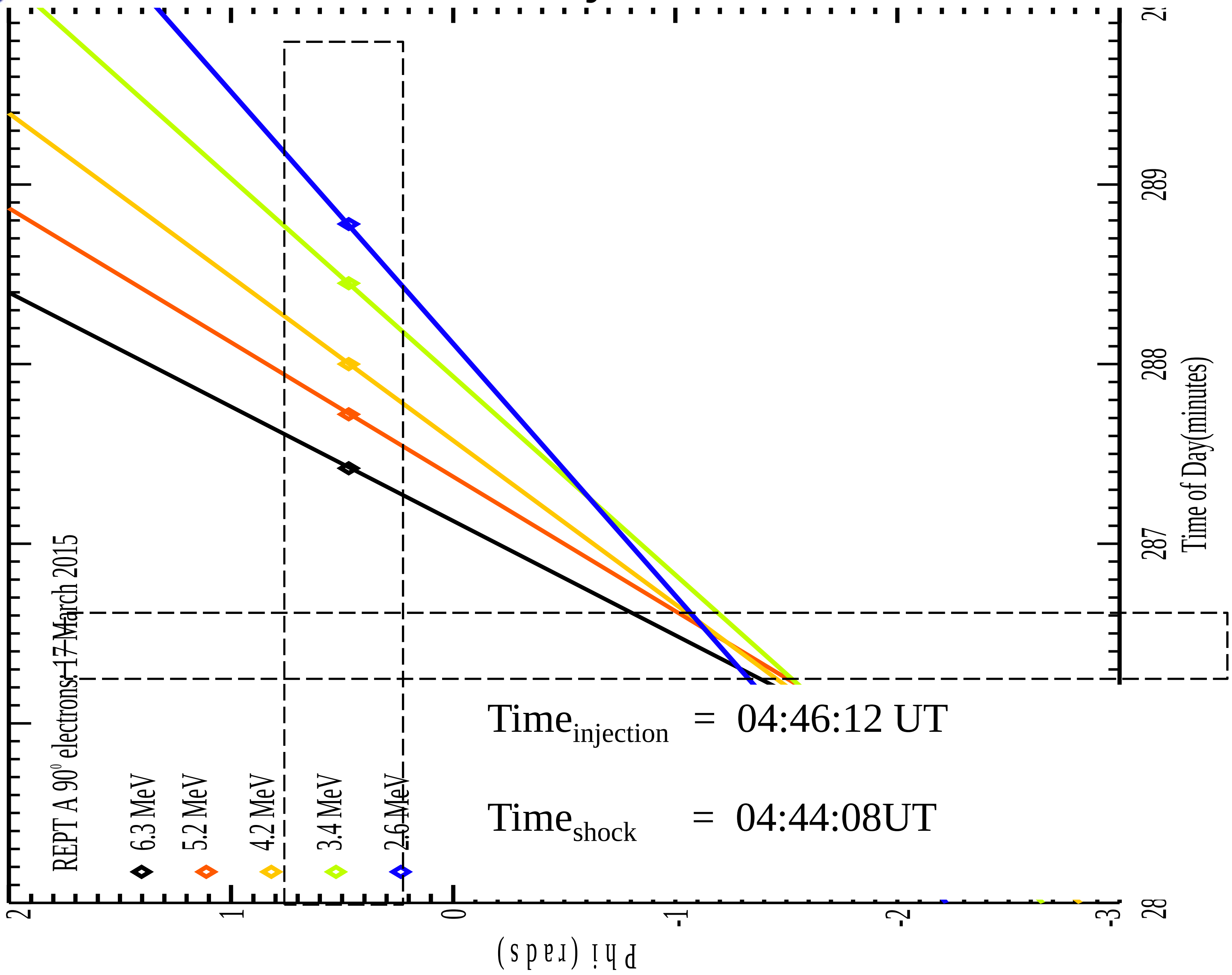
Shock timing: THEMIS and ARTEMIS

- THEMIS impact times:
  - THD: 04:44:08 UT
  - THE: 04:44:19 UT
  - THA: 04:44:34 UT

- THEMIS in the sheath at the impact
- All s/c observed more intense sheath after impact and then were thrust into the solar wind as bow shock compressed



Drift Period Analysis from REPT A

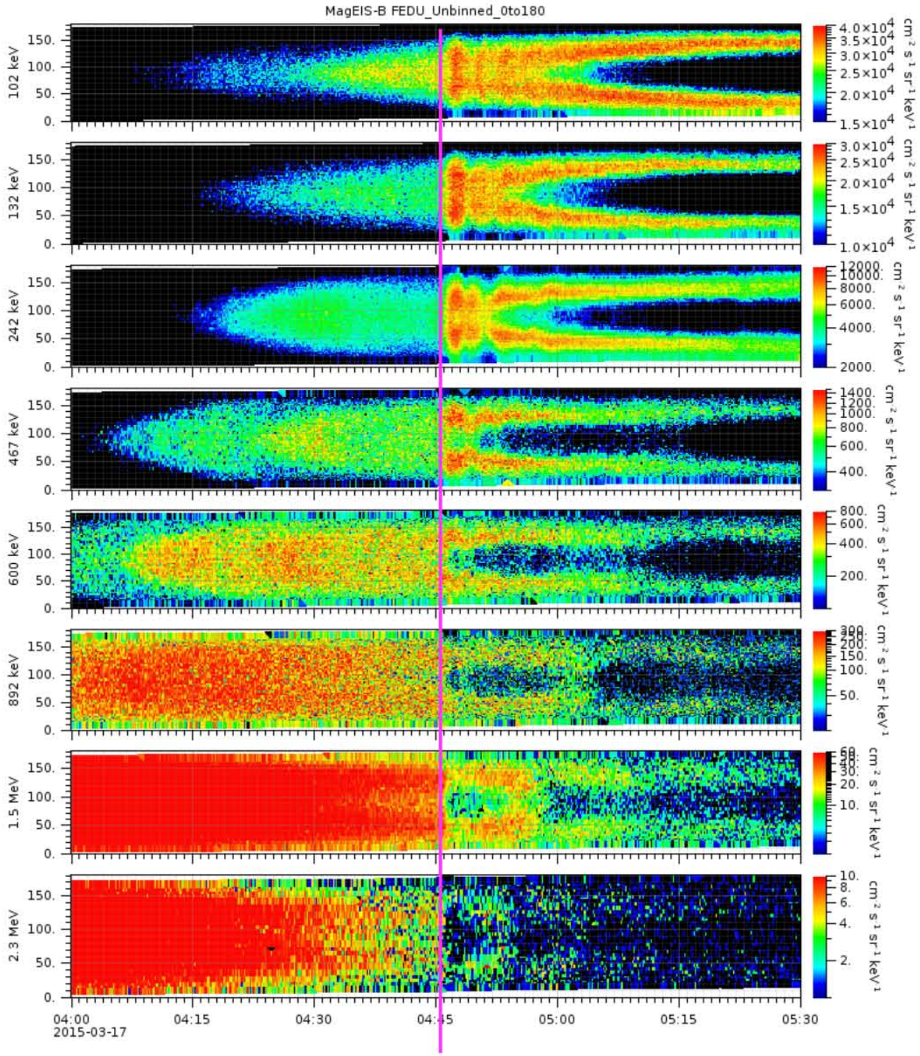


$\text{Time}_{\text{injection}}$ = 04:46:12 UT

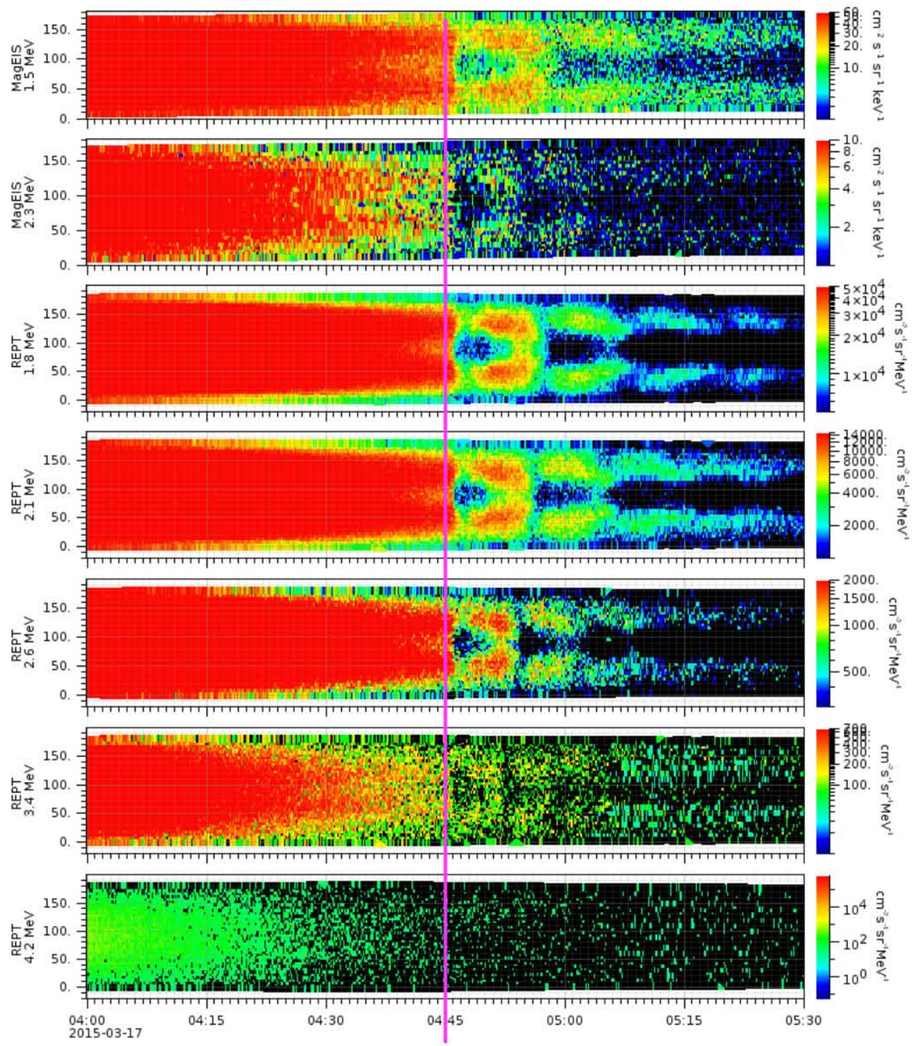
$\text{Time}_{\text{shock}}$ = 04:44:08UT

Post shock pitch angle distributions Probe B

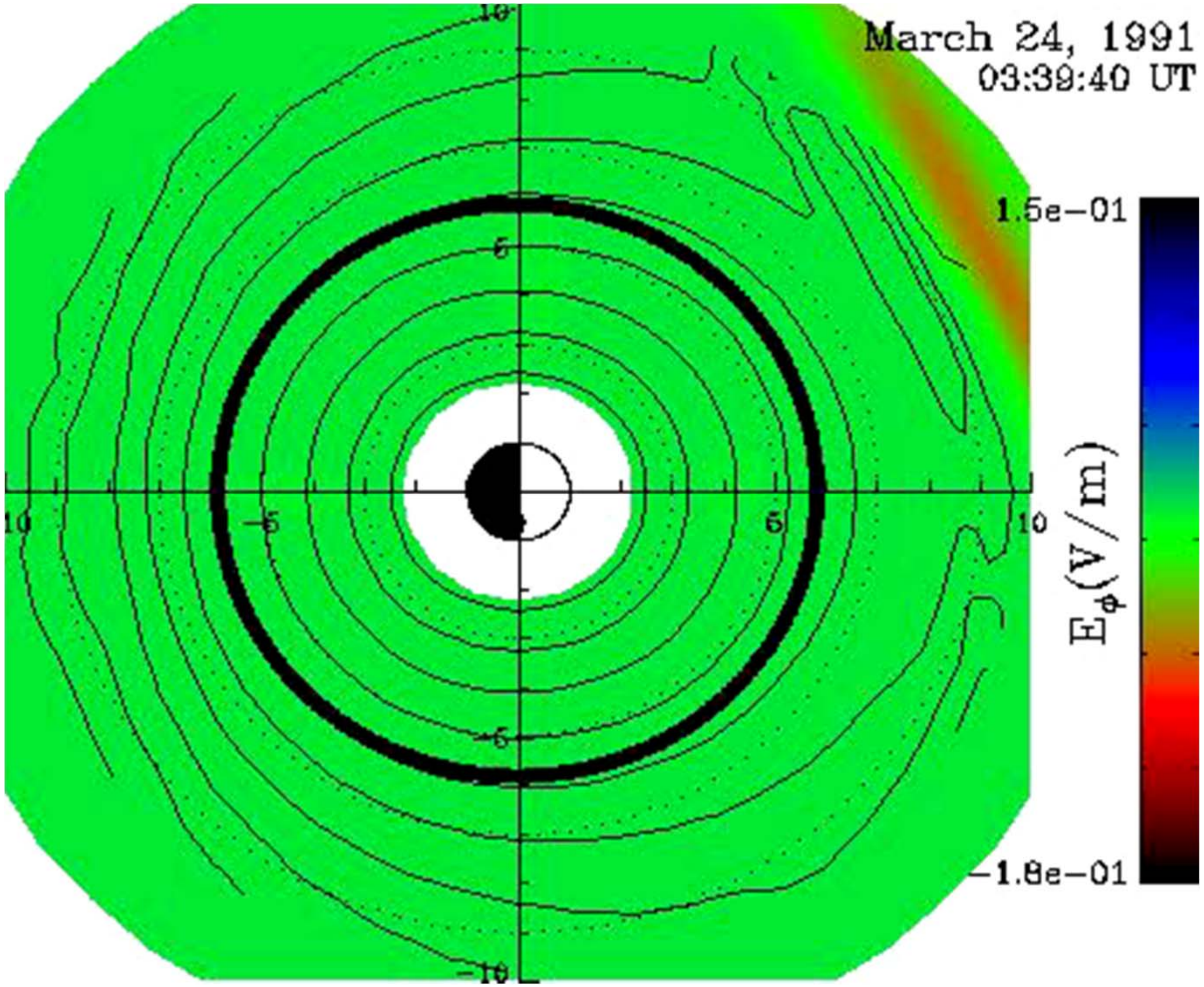
MagEIS



MagEIS & REPT



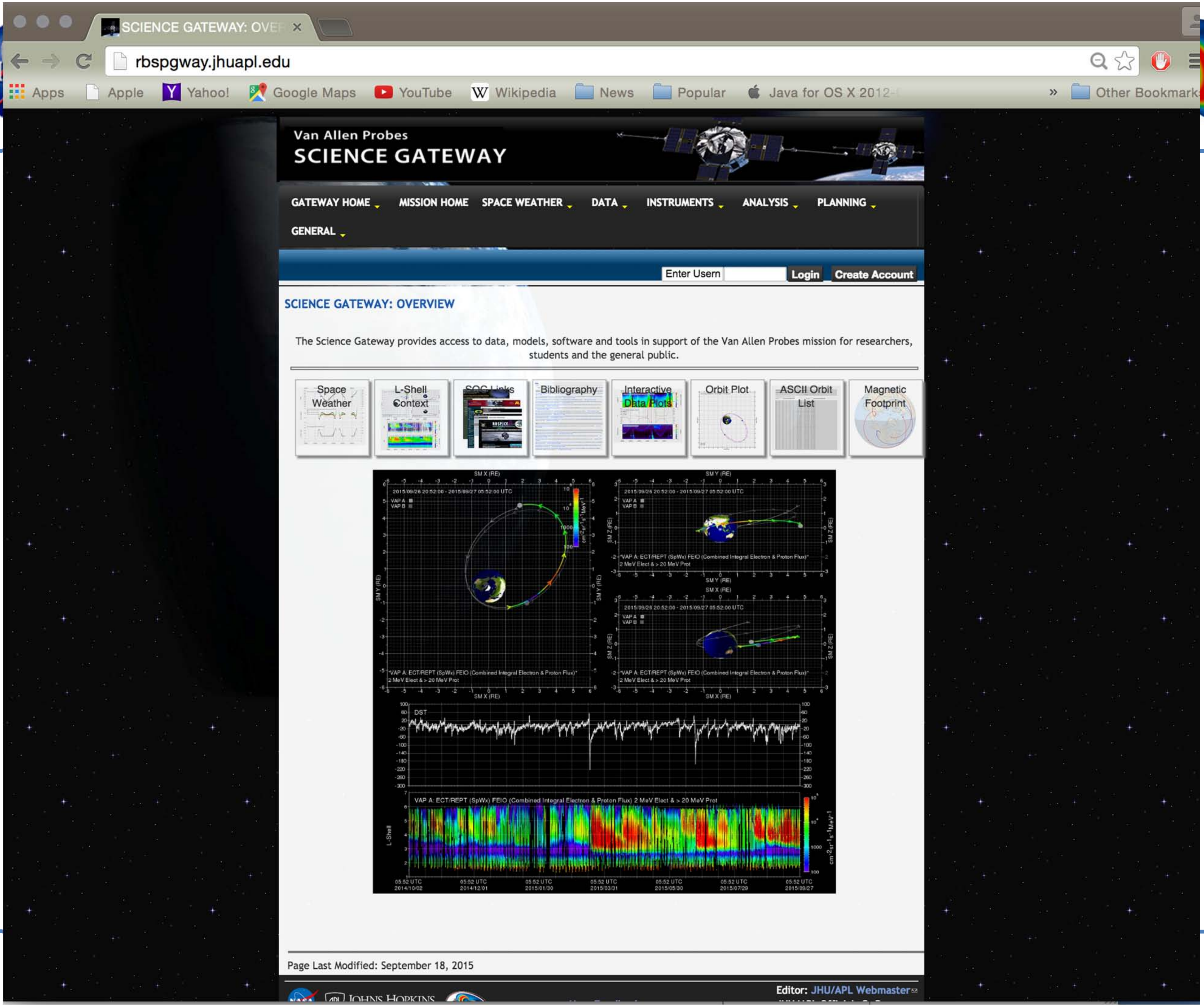
LFM simulation of March 1991 IP Shock



Elkington et al. 2002

Summary and conclusion

- Instruments onboard the twin Van Allen Probes spacecraft have provided a comprehensive view of the 17 March 2015 CME.
- Post shock passage butterfly-type pitch angle distributions were observed by REPT and MagEIS even at L shells as low as 3 deep within the magnetosphere.
- Intense chorus wave activity may have resulted in abrupt energization of ~100s keV to ~2 MeV electrons
- The ultra-relativistic fluxes also peaked somewhat abruptly albeit in an energy dependent manner and days later than the shock passage. Electron spectra however, hardened more gradually. Rapid radial diffusion of ultra rel. electrons.
- Shock response of electrons show several interesting features
  - prompt injection of ~1 to 6 MeV electrons
  - no discernible response of ~200 keV to ~1 MeV
- Ground level discontinuity 04:45 UT (shock passage)
  - Estimated time of injection 04:46:18 UT
  - Electrons energized to 6 MeV in < 2 minutes
- Drift echo times consistent with expectation [O'Brien et al.,2015]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Yahoo!
Google Maps
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News
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Java for OS X 2012-
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SCIENCE GATEWAY: OVERVIEW
The Science Gateway provides access to data, models, software and tools in support of the Van Allen Probes mission for researchers, students and the general public.
Space Weather
L-Shell Context
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Bibliography
Interactive Data Plots
Orbit Plot
ASCII Orbit List
Magnetic Footprint
Page Last Modified: September 18, 2015
Editor: JHU/APL Webmaster

REPT: Relativistic Electron Proton Telescope

- Solid state particle telescope with fast electronics and shielding.

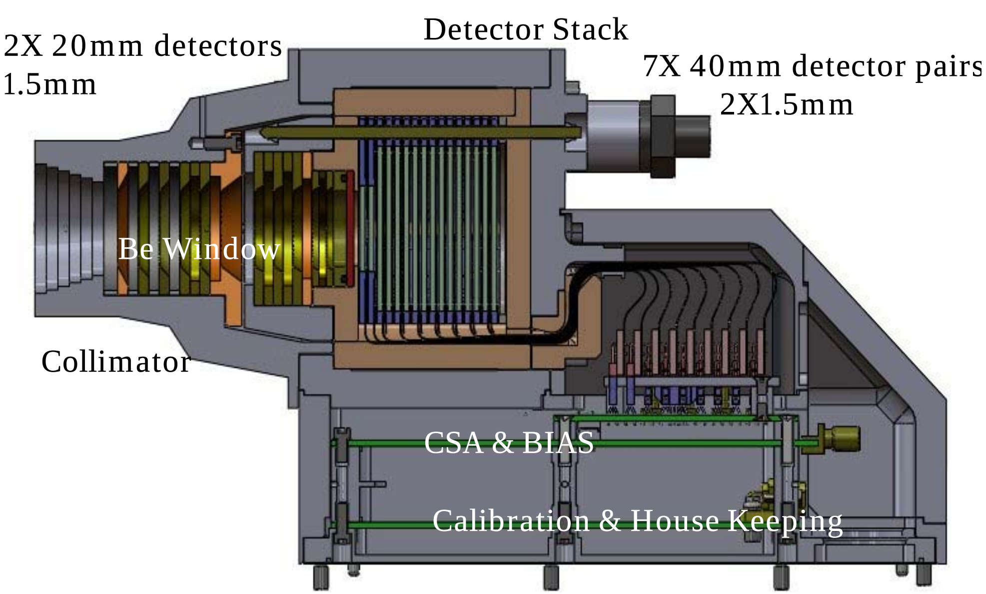
- Differential energy channels using detector coincidence, anti-coincidence and ΔE

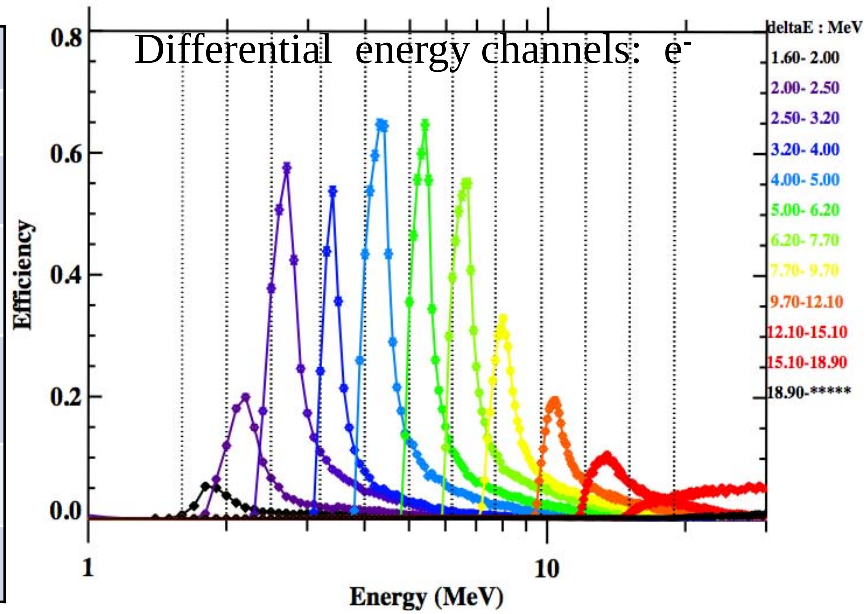
- Differential channel Logic condition

$$E_{1.6\text{-}2.0} = (R1 \geq 0.4) \bullet (R2 \geq 0.4) \bullet (\Sigma R1R2 \leq 1.35) \bullet (R3 \ldots R9 \leq 0.4)$$

- Logic software configurable in FPGA

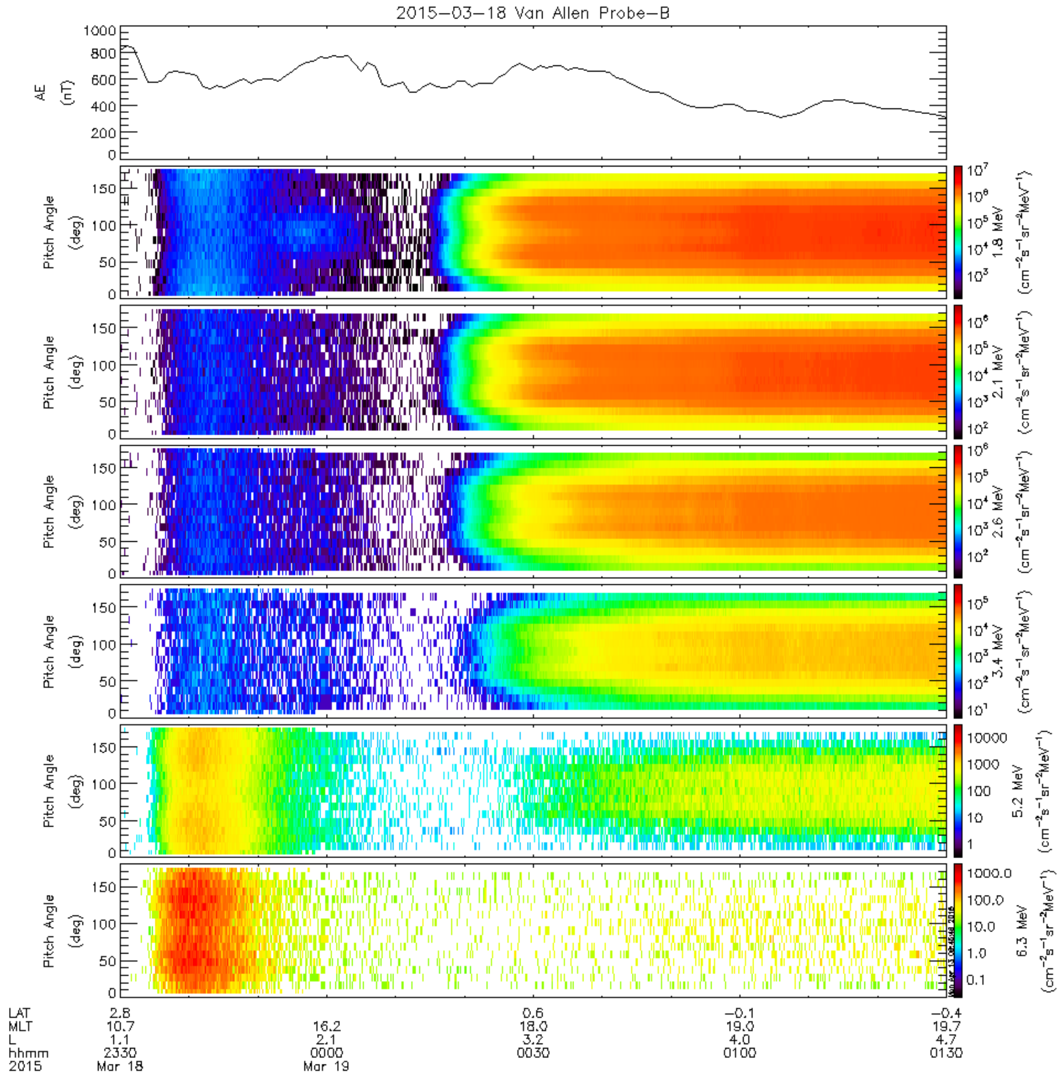
Mass	13.4 kg
Power	10.7 W
Average Telemetry Rate	1.6 kbps
Energy Range	1.6->12 MeV (electrons) 17.->100 MeV (protons)
Energy Resolution	<30% (electrons) <30% (protons)
Geometric Factor	0.2 cm^2 sr
Field-of-View	32^o





REPT observations of Butterfly PAD

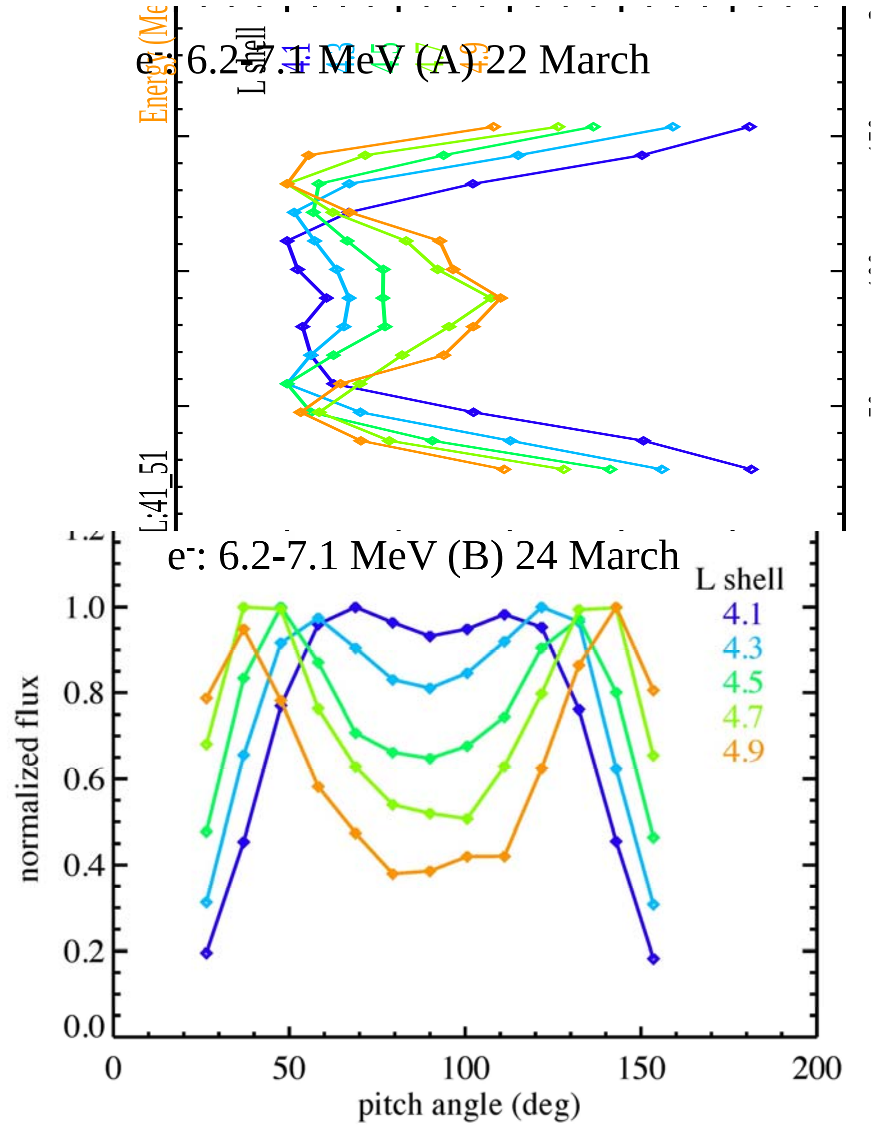
- ➢ Ultra relativistic energy electrons penetrate to low L
- ➢ Butterfly pitch angle distributions at the inner edge of the penetration can extend in energy > 5 MeV
- ➢ Note that the multi-MeV electrons do not diffuse past the "impenetrable barrier" [Baker et al., 2014]



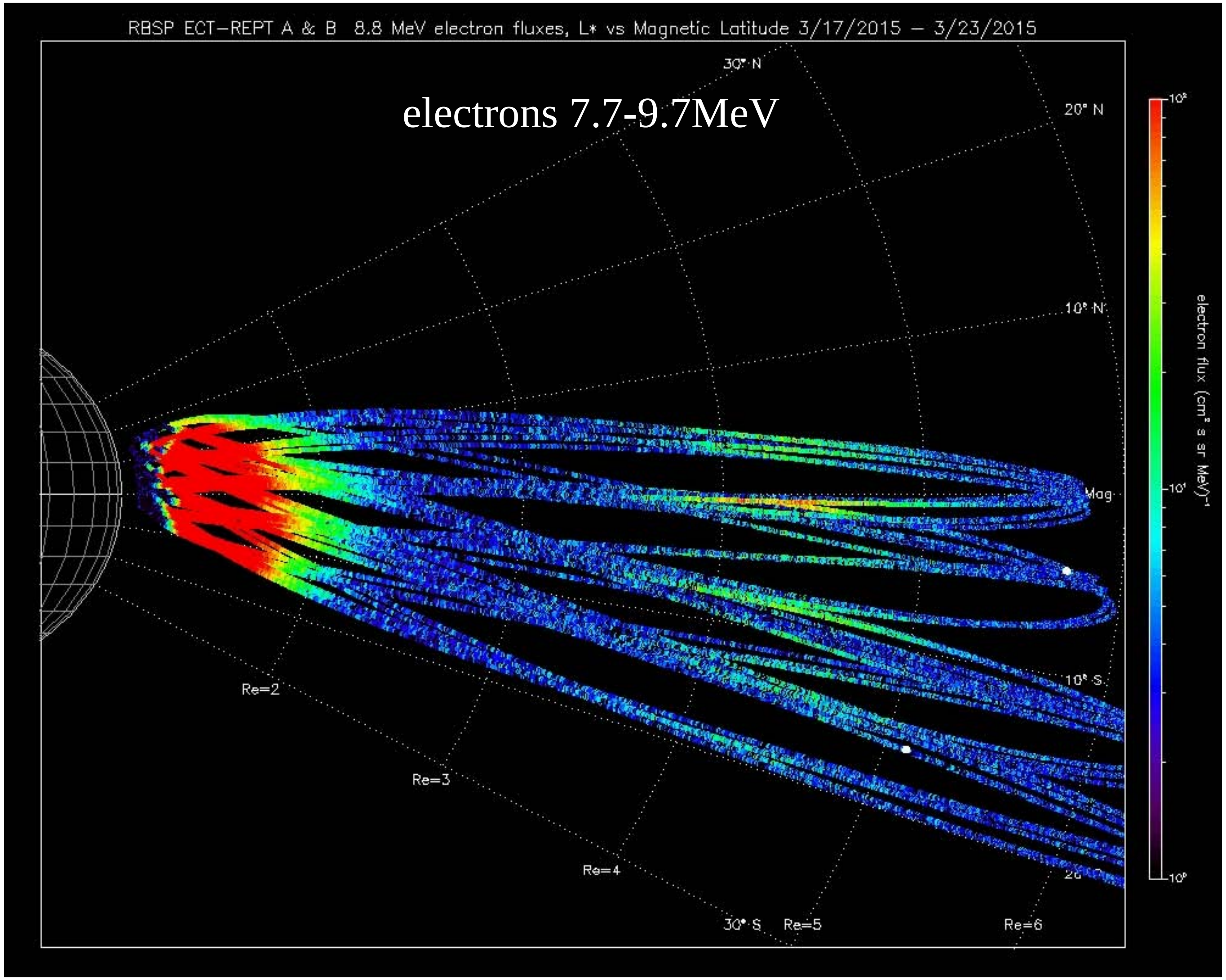
Observations of Butterfly PAD

➢ Butterfly PADs extend over a substantial L range and observed by both probes

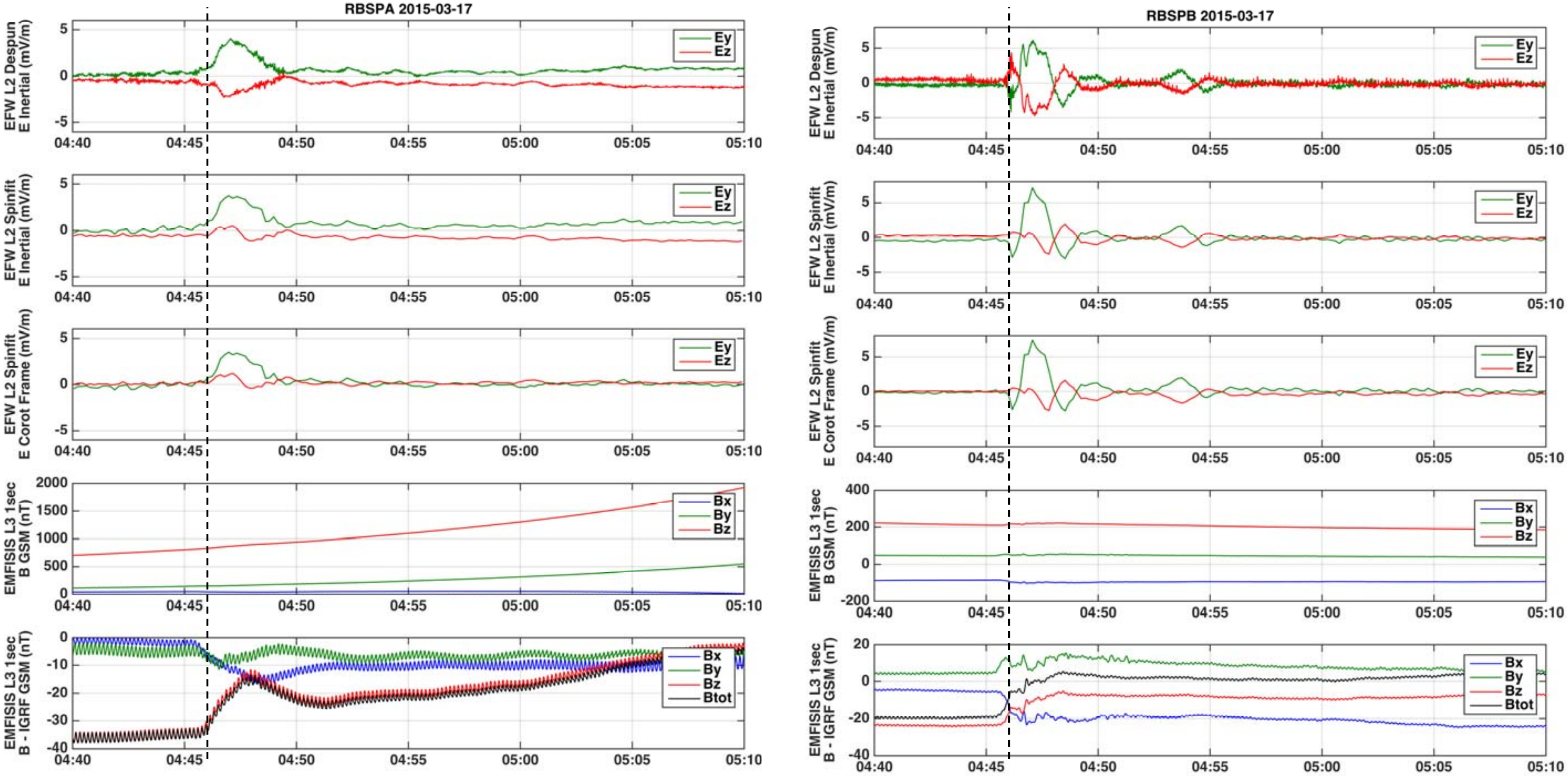
➢ Butterfly PADs persist over several days



Ultra-relativistic electrons: Latitudinal extent



E and B Fields data from EFW and EMFISIS



Drift velocity for electrons in a dipole field

$$T = \frac{2\pi}{<\dot{\phi}>} = \frac{172.4}{E}\left(\frac{1+E}{2+E}\right)\left(\frac{m}{m_e}\right)\left(\frac{r_e}{r_0}\right)\left(\frac{G(\lambda)}{F(\lambda)}\right)$$

$$<\dot{\phi}> = \frac{2\pi}{T} = 2\pi\frac{E}{172.4}\left(\frac{2+E}{1+E}\right)\left(\frac{m_e}{m}\right)\left(\frac{r_0}{r_e}\right)\left(\frac{F(\lambda)}{G(\lambda)}\right)$$

where $<\dot{\phi}>$ is bounce averaged drift velocity, m is mas of the drifting particle, m_e is electron mass, r_0 the radial distance of drifting particle and r_e radius of Earth, λ is magnetic latitude, and $F(\lambda), G(\lambda)$ are dimensionless functions of magnetic latitude [J.S. Lew, JGR,1961].

For electron observations on the 17 March 2015 event, Probe A is at 5.9^0 magnetic latitude and L≈3.3 at UTC 04:45, so that

$$\frac{r_0}{r_e} = 3.3$$

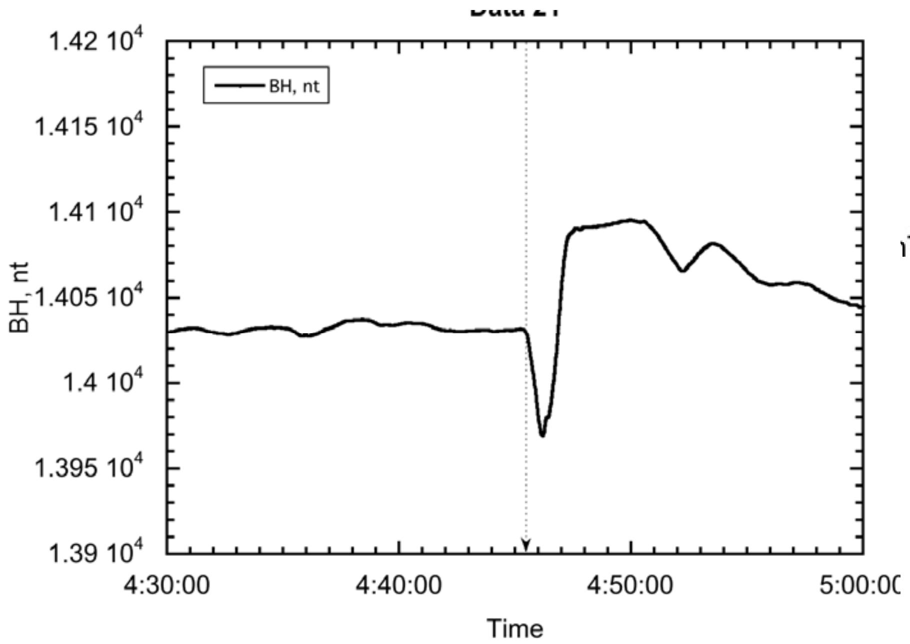
$$\frac{m_e}{m} = 1.0$$

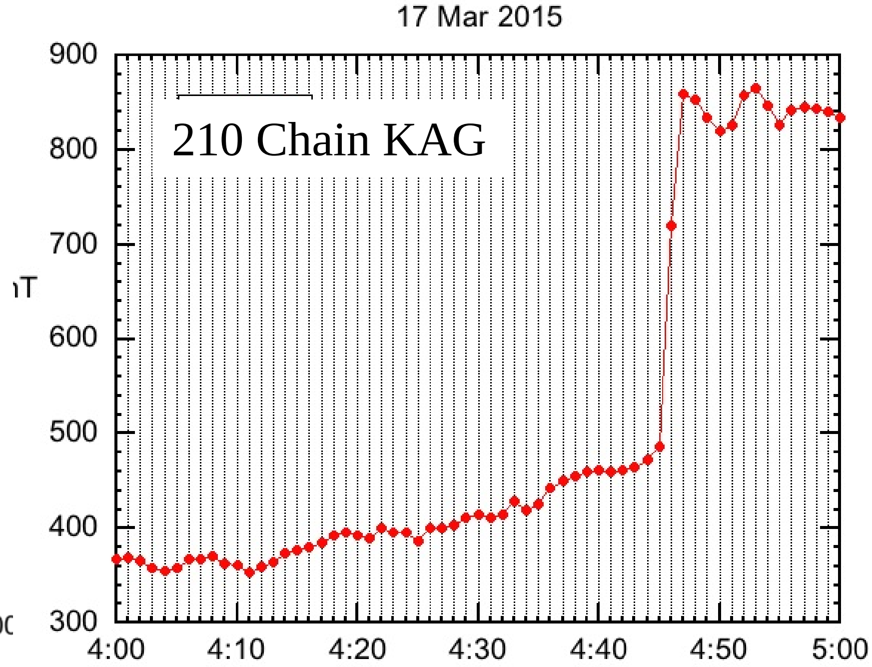
$$\frac{F(\lambda)}{G(\lambda)} = 1.0$$

so that

$$\boxed{<\dot{\phi}> = 0.12E\left(\frac{2+E}{1+E}\right)}$$

Ground magnetometer observations



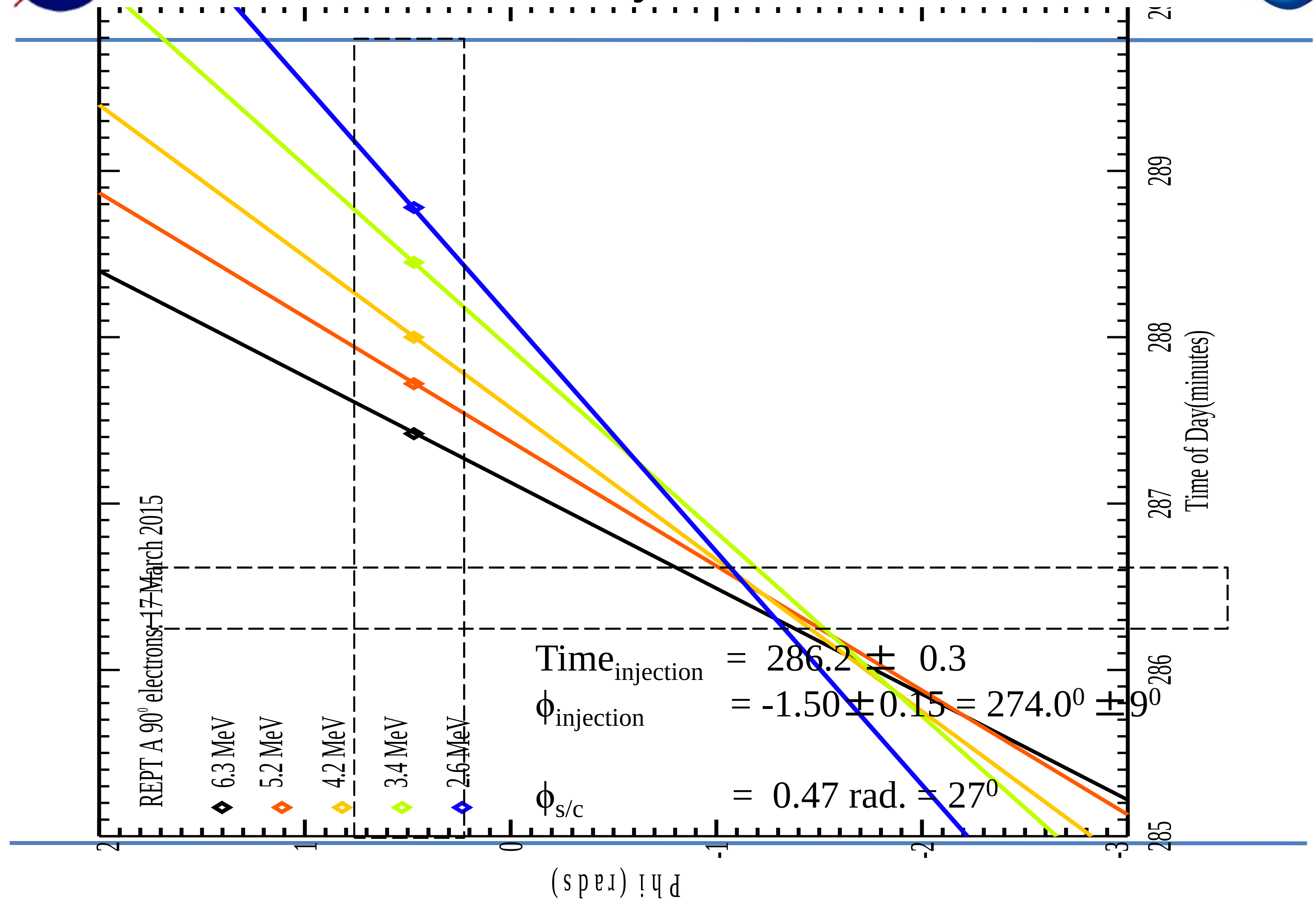


Time of shock passage 04:45 UT

Peak flux times and drift speed

E (MeV)	Vd (Rads/min)	Time (hr:min:sec)	T Mins. Of day	ϕ_0
6.3	1.572	4:47:28	287.47	0.461
5.2	1.337	4:47:43	287.65	0.464
4.2	1.097	4:48:00	287.83	0.467
3.4	0.906	4:48:27	288.38	0.471
2.6	0.713	4:48:47	288.73	0.475

Drift Period Analysis from REPT A



Shock arrival calculated from WIND compared to injection time from REPT observations

Assume Nominal Magnetopause at 11Re, i.e. 70125 km

Distance in X (GSE) travelled by shock

$$\Delta X = X_{Wind} - X_{MP}$$
$$= 1612674 - 70125 = 1542549 \text{ km}$$

Time of traversal = 1542549*0.88/510

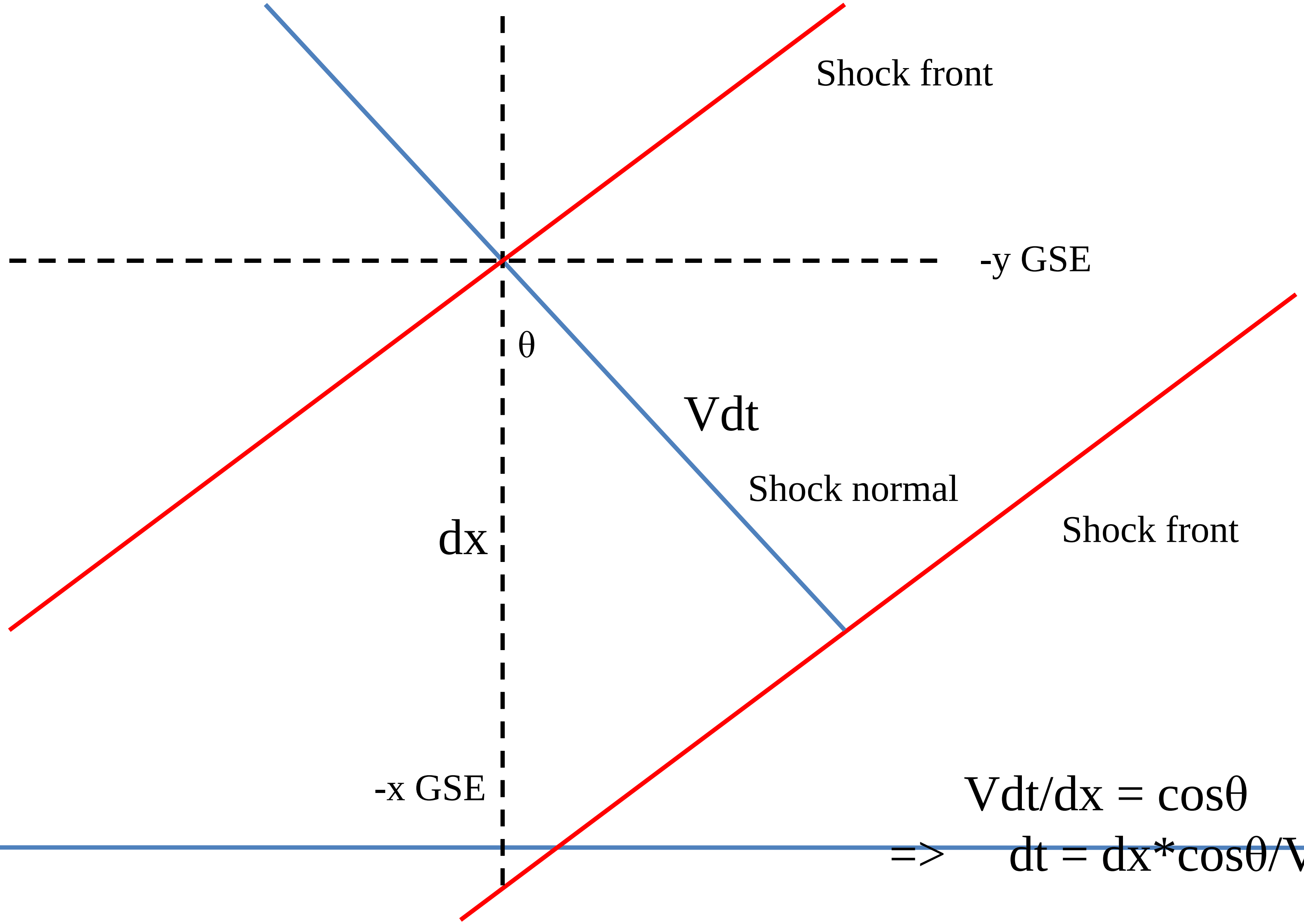
where 0.88 is cosine of shock normal angle θ

Time of traversal = 2661 sec = 44min

Time of shock at WIND = 4:00UT

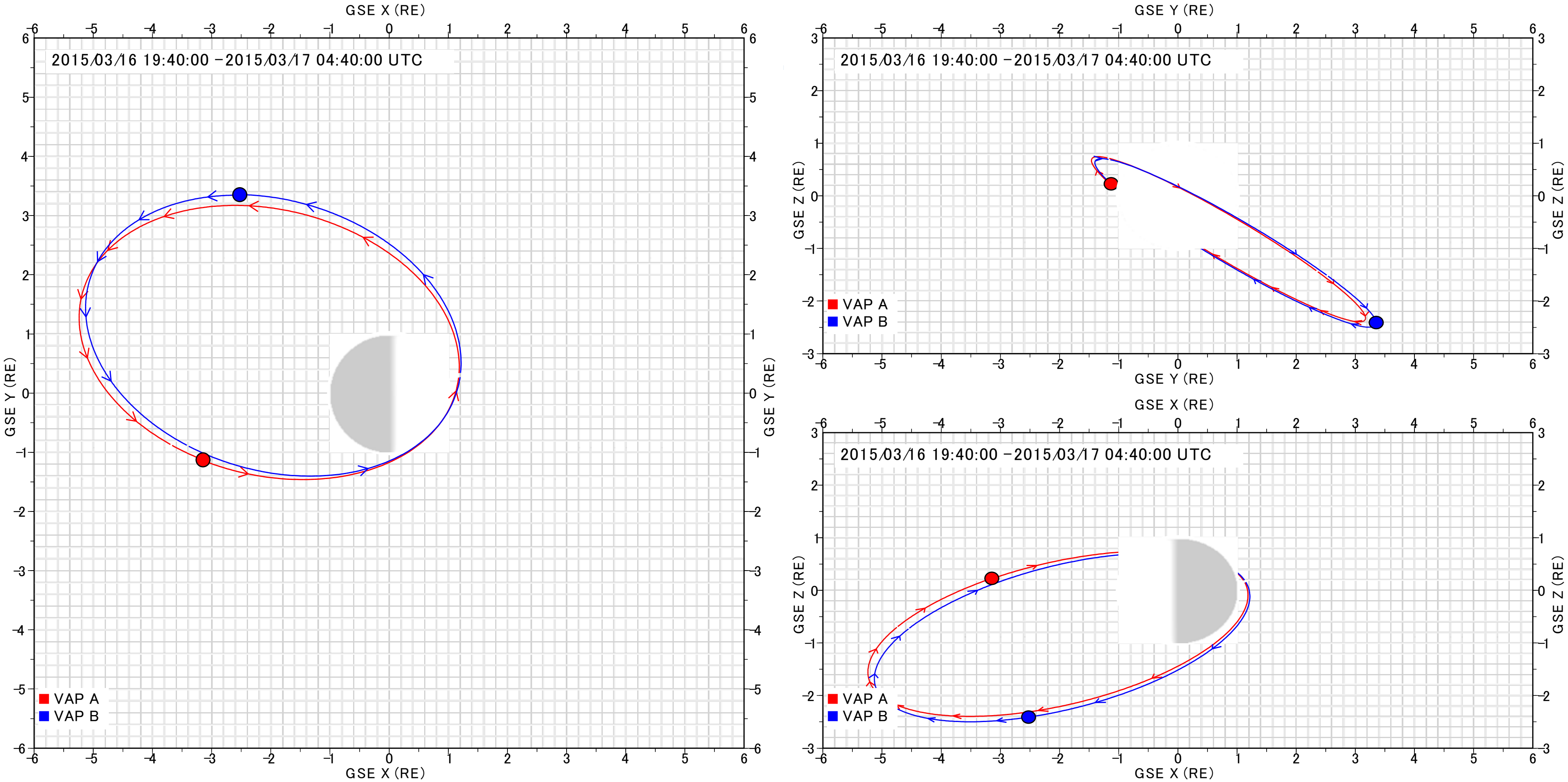
propagated time to MP nose = 4:44UT
from REPT measurements = 4.46UT

Shock Arrival calculated from WIND position and shock measurements

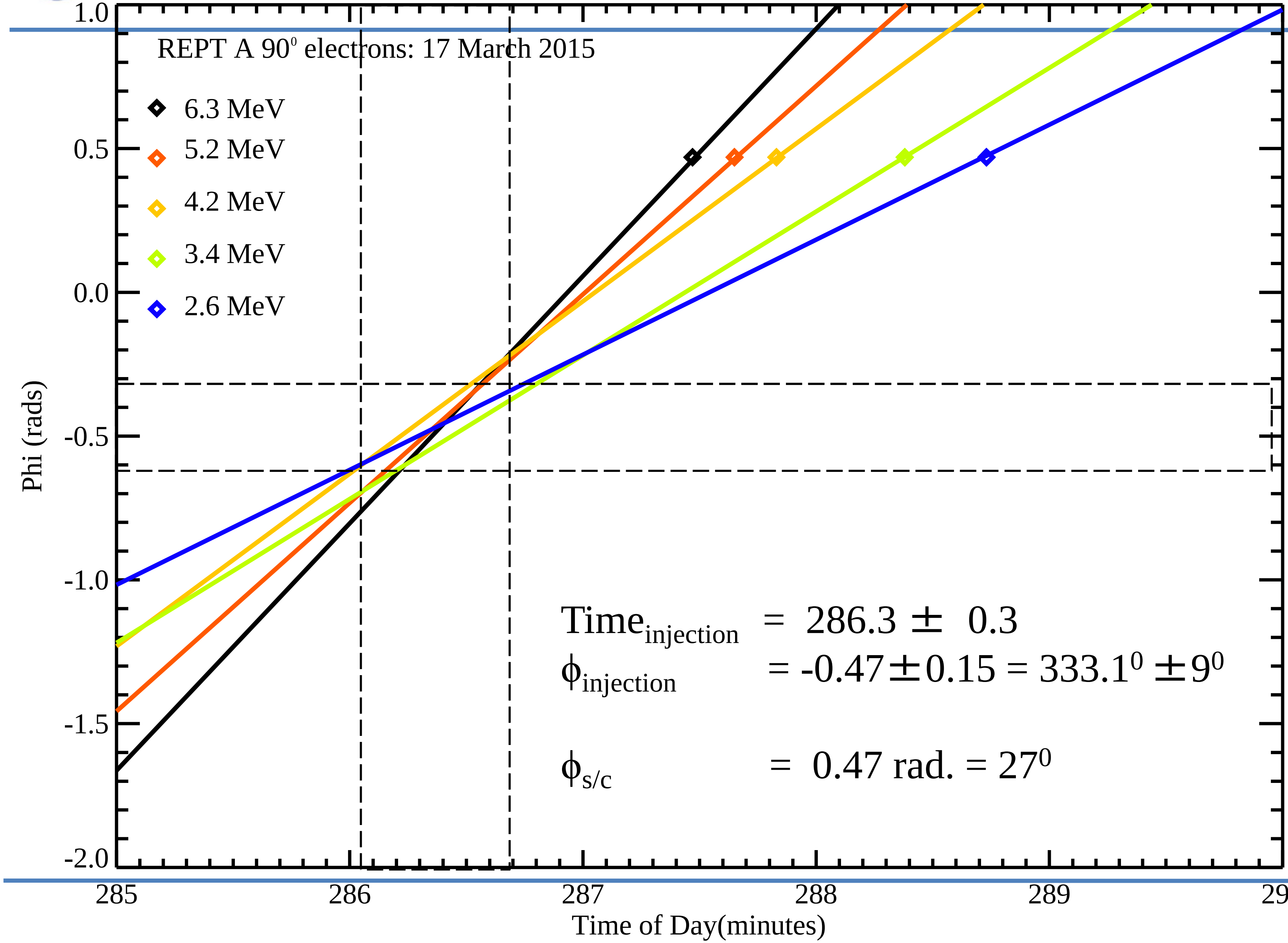


$$Vdt/dx = \cos\theta$$

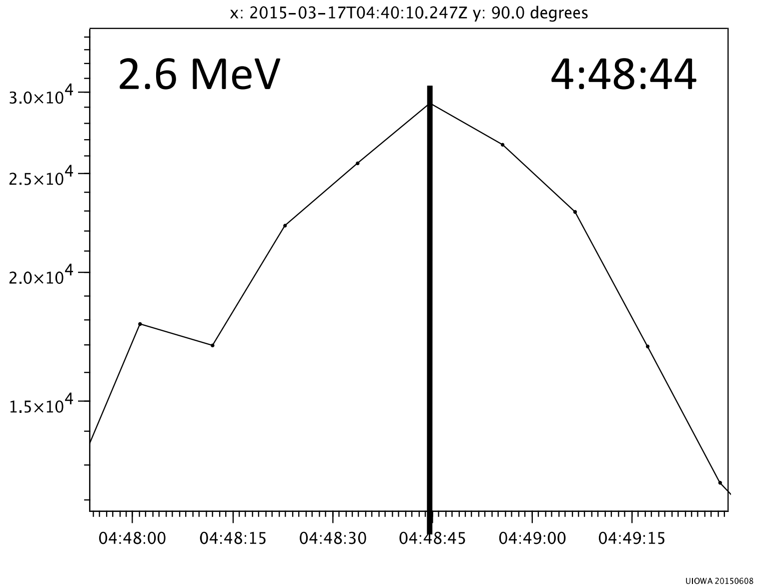
$$\Rightarrow \quad dt = dx*\cos\theta/V$$

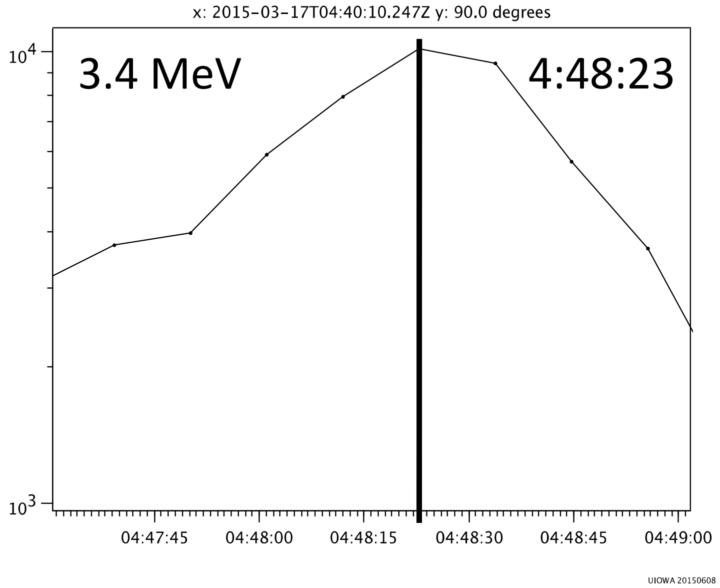

GSE X (RE)
GSE Y (RE)
2015/03/16 19:40:00 –2015/03/17 04:40:00 UTC
VAP A
VAP B
GSE Y (RE)
GSE Z (RE)
2015/03/16 19:40:00 –2015/03/17 04:40:00 UTC
VAP A
VAP B
GSE X (RE)
GSE Z (RE)
2015/03/16 19:40:00 –2015/03/17 04:40:00 UTC
VAP A
VAP B

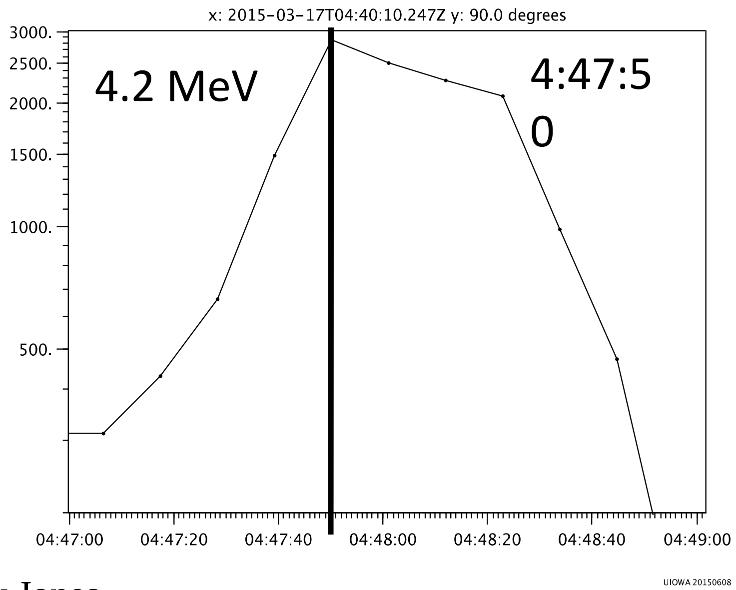
Drift Period Analysis from REPT A

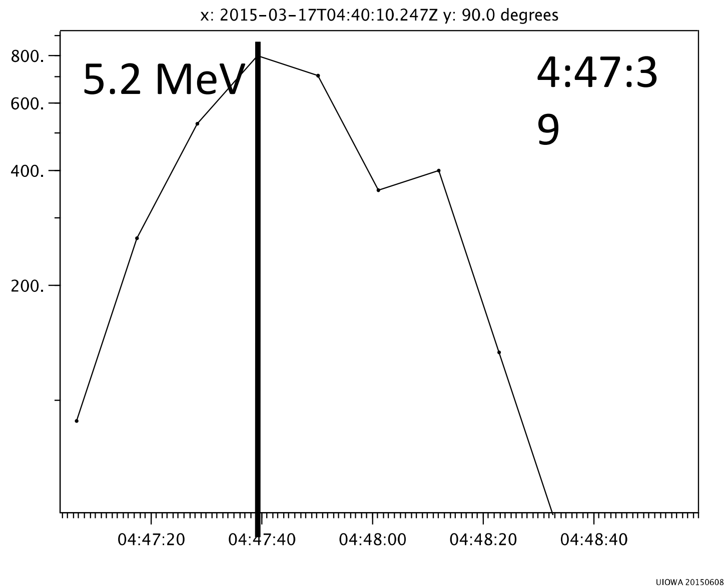


REPT A flux profiles 90^0 pitch angle









Ashley Jones

ARTEMIS and THEMIS

ARTEMIS-P1

- THEMIS impact times:
  - THD: 04:44:08 UT
  - THE: 04:44:19 UT
  - THA: 04:44:34 UT

- Notes:
  - THEMIS in the sheath at the impact
  - They all observed more intense sheath after impact and then were thrust into the solar wind as bow shock compressed
  - Shock transit time through sheath is a major unknown...

ARTEMIS-P2

Shock impact

THEMIS-A

Shock impact

Pre-shock magnetosheath

Solar wind

THEMIS-D

Shock impact

Pre-shock magnetosheath

Solar wind

THEMIS-E

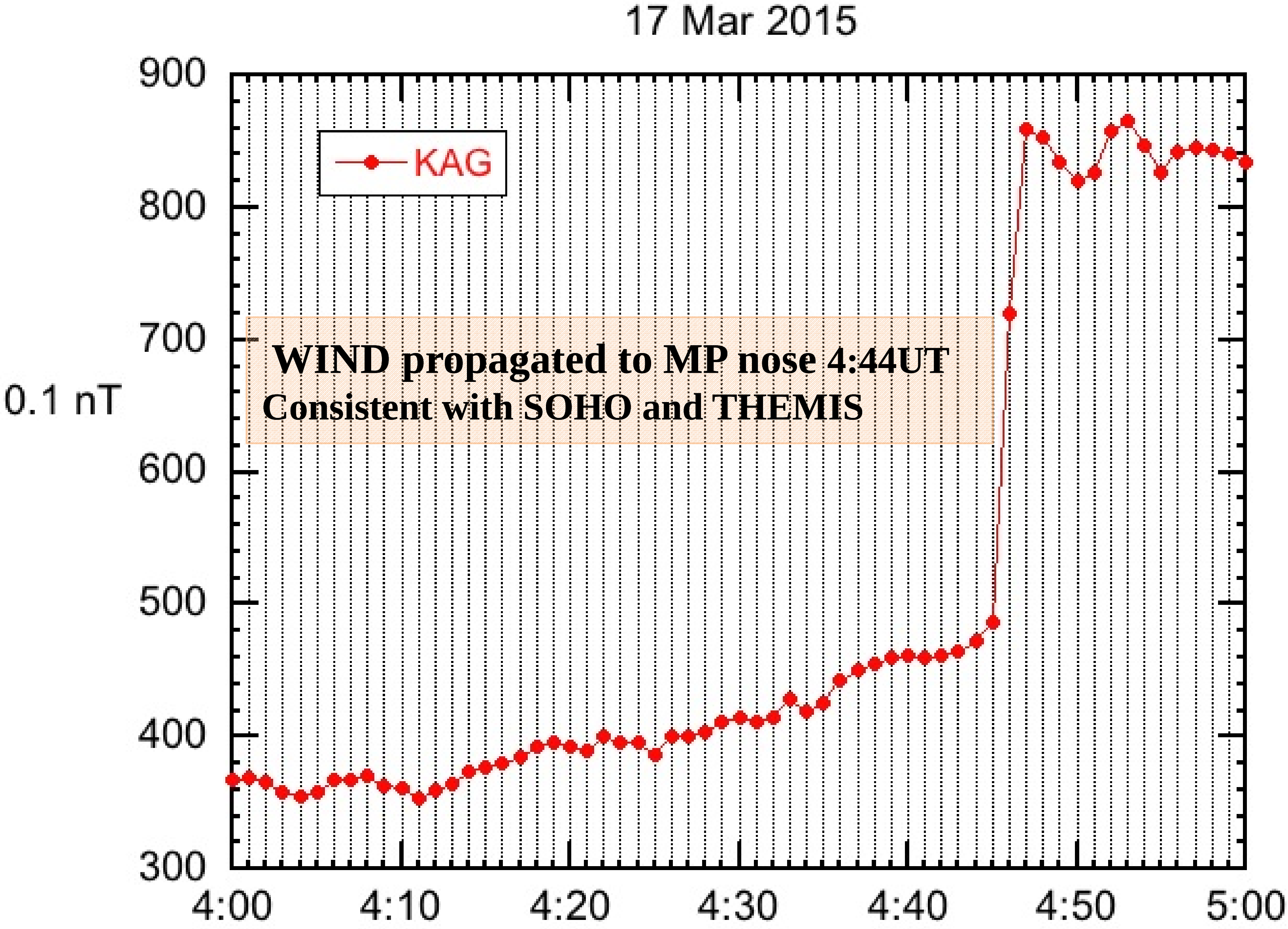
Shock impact

Pre-shock magnetosheath

Solar wind

Shock impact

Shock Analysis: WIND measurement



WIND propagated to MP nose 4:44UT

Consistent with SOHO and THEMIS

Summary and Conclusions

- Shock response of electrons show several interesting features
  - prompt injection of ~1 to 6 MeV electrons
  - no discernible response of ~200 keV to ~1 MeV

- Ground level discontinuity 04:45 UT (shock passage)
  - Estimated time of injection 04:46:18 UT
  - Electrons energized to 6 MeV in < 2 minutes

- Drift echo times consistent with expectation [O'Brien et al.,2015]