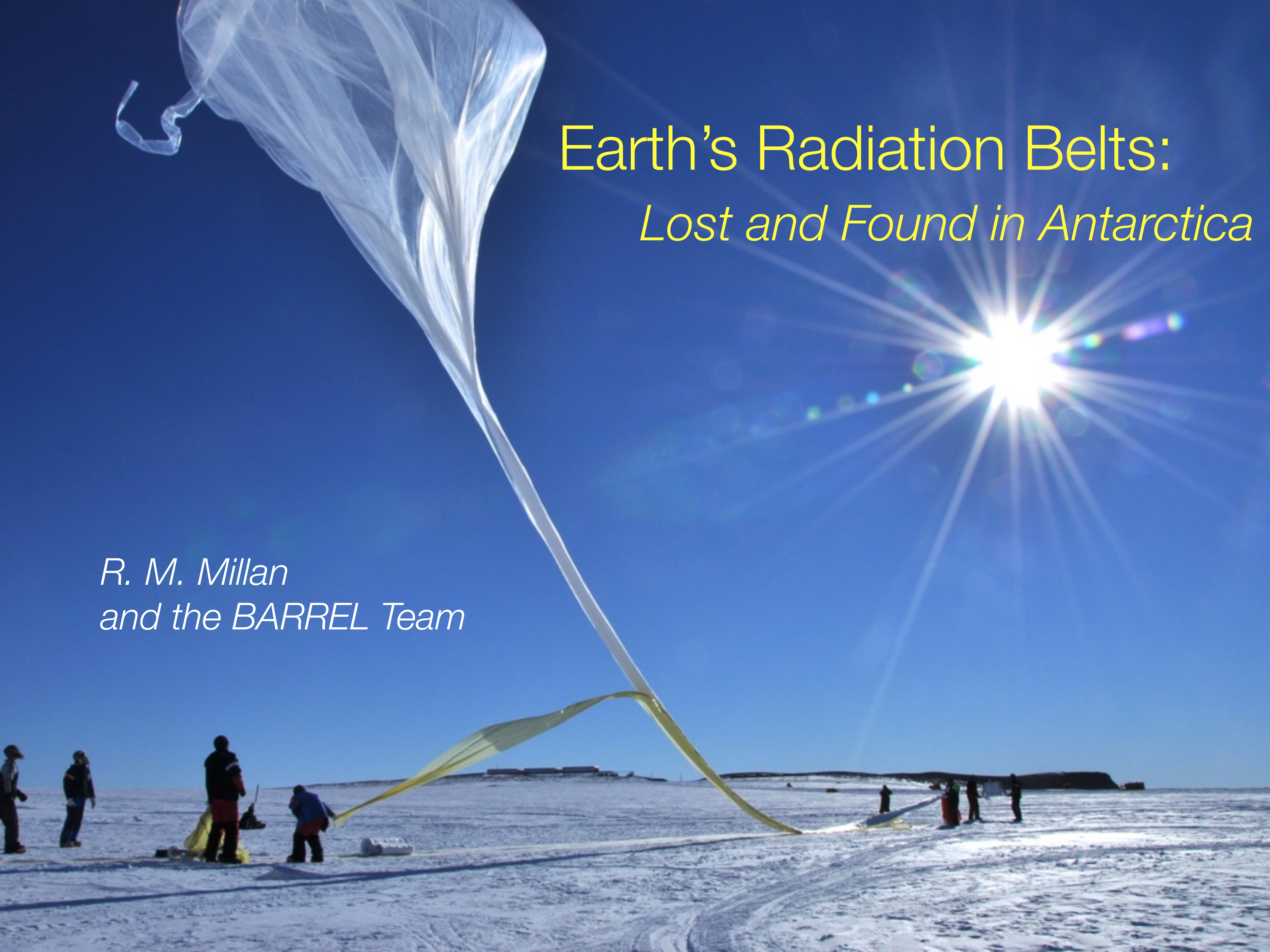
Earth's Radiation Belts:
Lost and Found in Antarctica

R. M. Millan
and the BARREL Team



Outline

1. Overview of Earth's Radiation Belts
2. Review of radiation belt particle dynamics
   a. Particle trapping in the Earth's magnetic field
   b. Source and acceleration of relativistic electrons
3. Loss of electrons from the radiation belts
   a. Magnetopause loss versus atmospheric loss
   b. Open science questions
   c. BARREL (Balloon Array for Radiation-belt Relativistic Electron Losses)

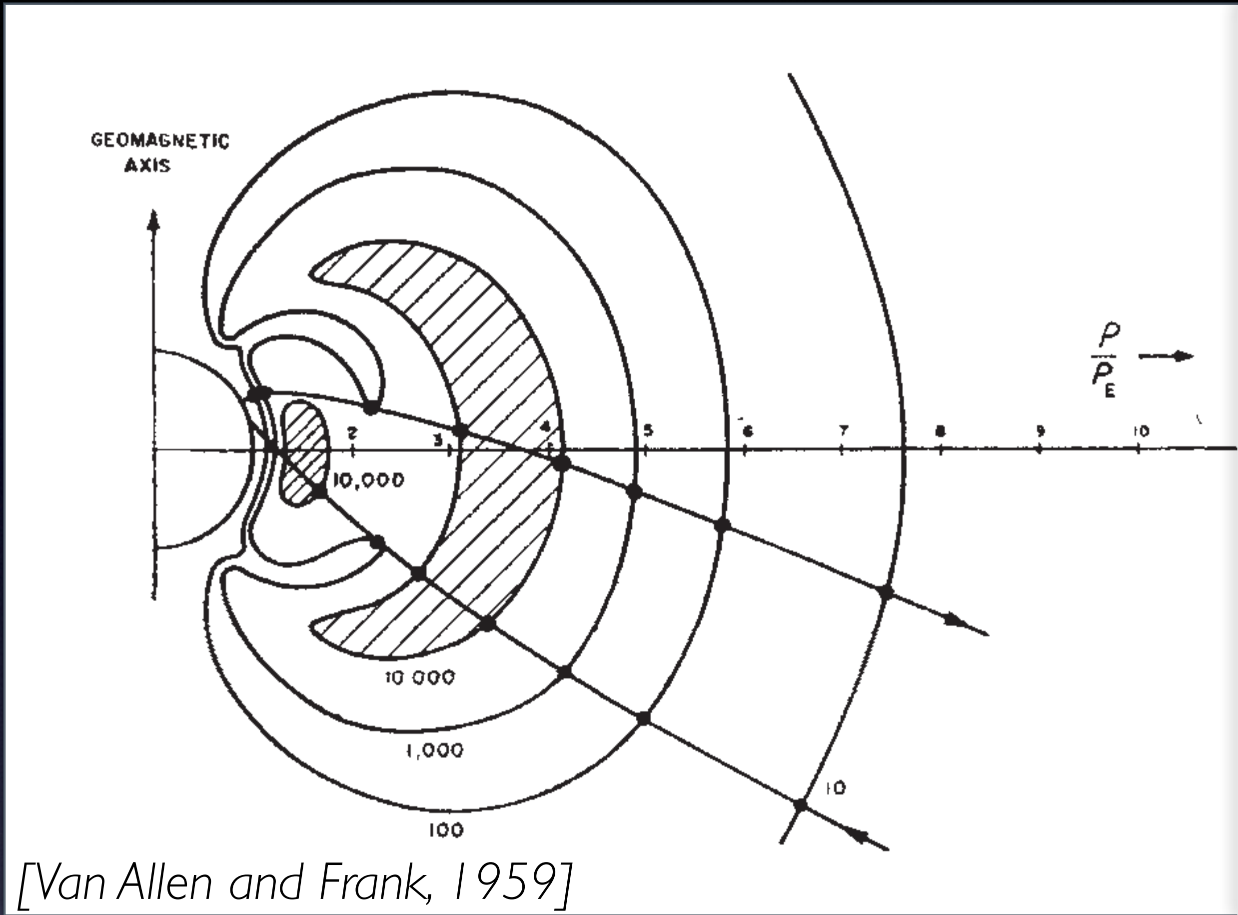
Discovery of the Radiation Belts

- First discovery of the Space Age!
- Explorer I (first US satellite)
  - launched January 31, 1958
  - carried Geiger counter for cosmic ray studies
  - James Van Allen credited with discovery.
- Sputnik 2 was first to detect the particles but the data weren't immediately available for analysis.

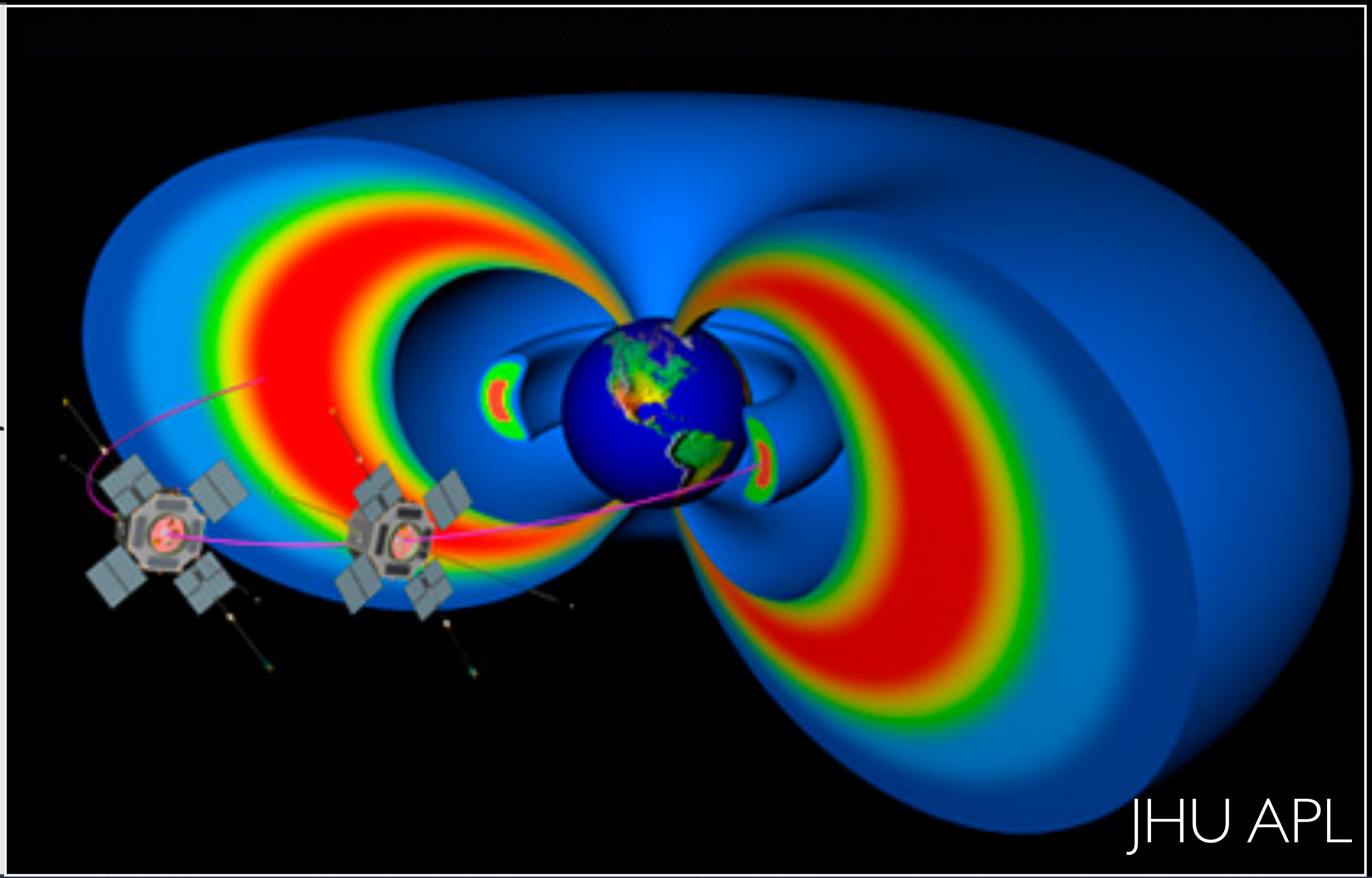

Launch of Explorer 1

Left to right: William Pickering, James Van Allen, Wernher von Braun

Earth's Radiation Belts



[Van Allen and Frank, 1959]



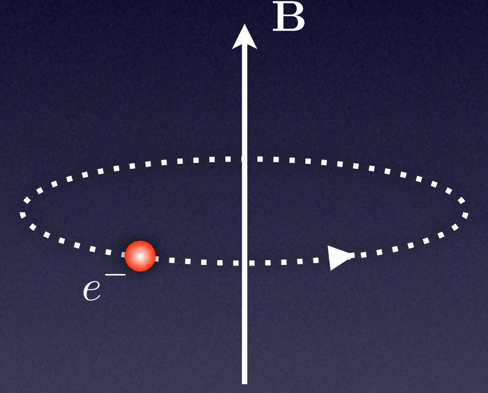
JHU APL

- Toroidal region extending from near Earth's surface to just beyond geosynchronous orbit (~7R_E)
- Energetic (~100 MeV) protons are concentrated near Earth.
- Electrons (up to ~10MeV) are found in two "zones" - inner and outer
- Magnetic field is nearly dipolar in this region
  => energetic particles (>200 keV) are trapped

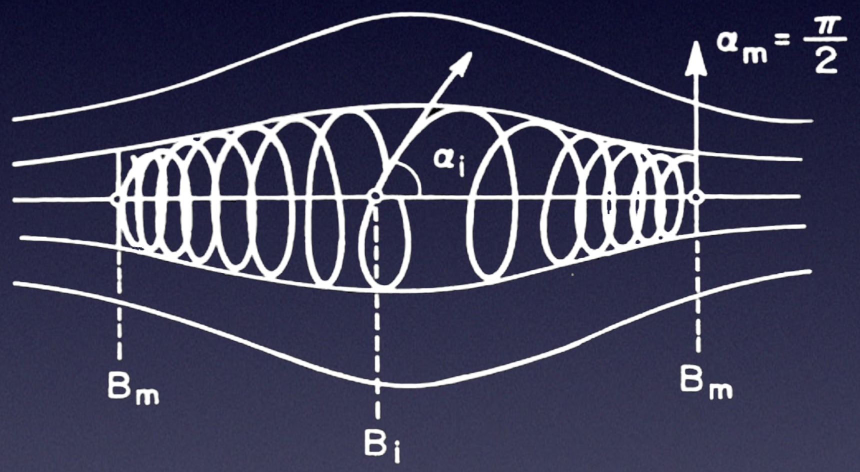
Particle Motion in a Magnetic Field

- charged particle motion in a non-uniform magnetic field exhibits three types of motion

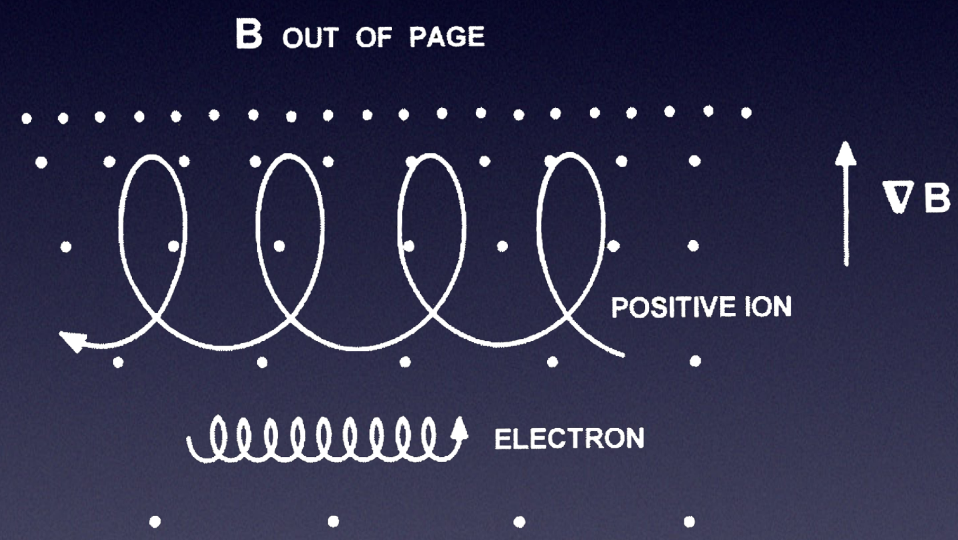
Gyration



Bounce



Drift



Particle Motion in a Magnetic Field

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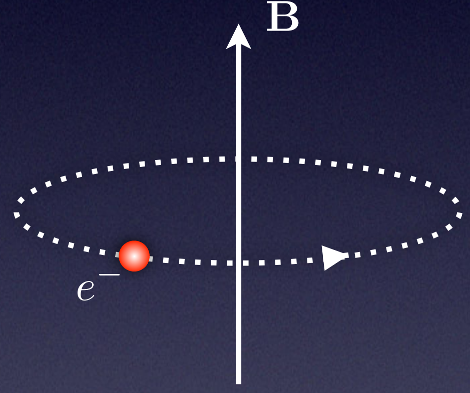
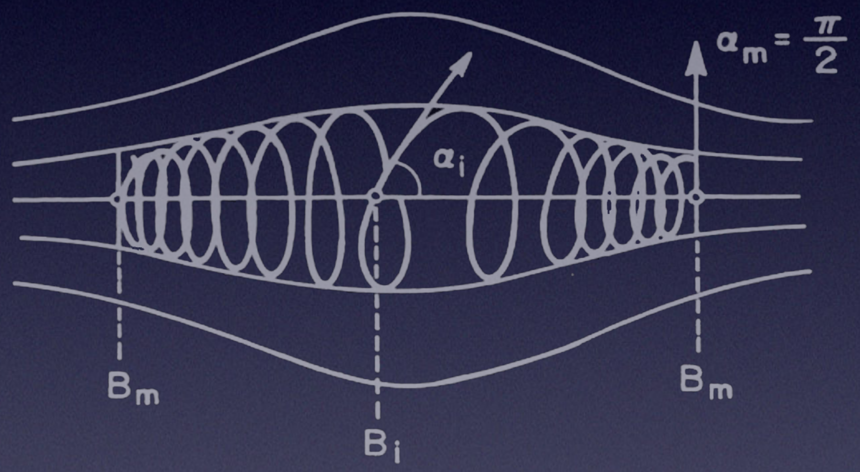
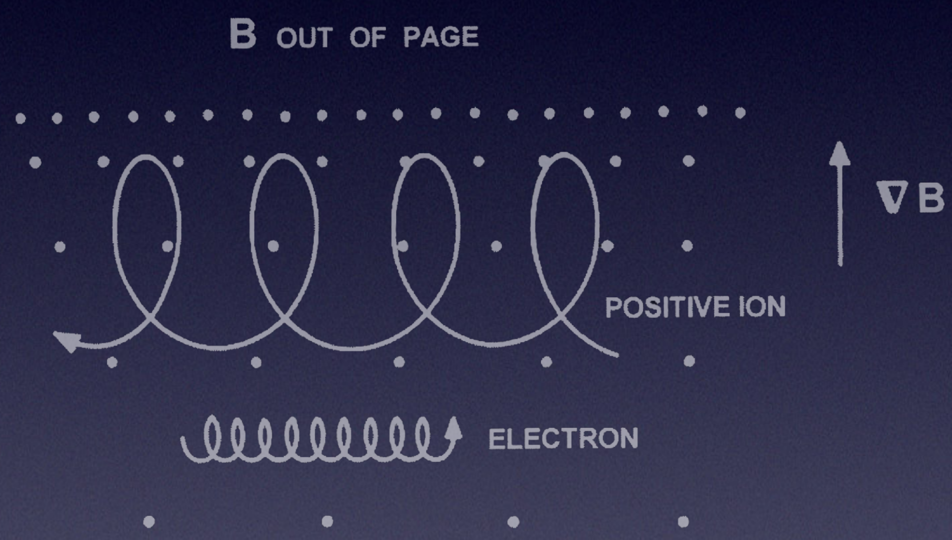


Bounce



Drift



$$\vec{F} = q\vec{v} \times \vec{B}$$

$$\Omega_g = \frac{qB}{m}$$

$$R_g = \frac{p}{qB}$$

Particle Motion in a Magnetic Field

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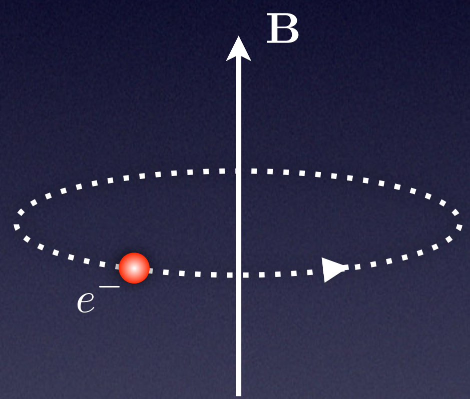
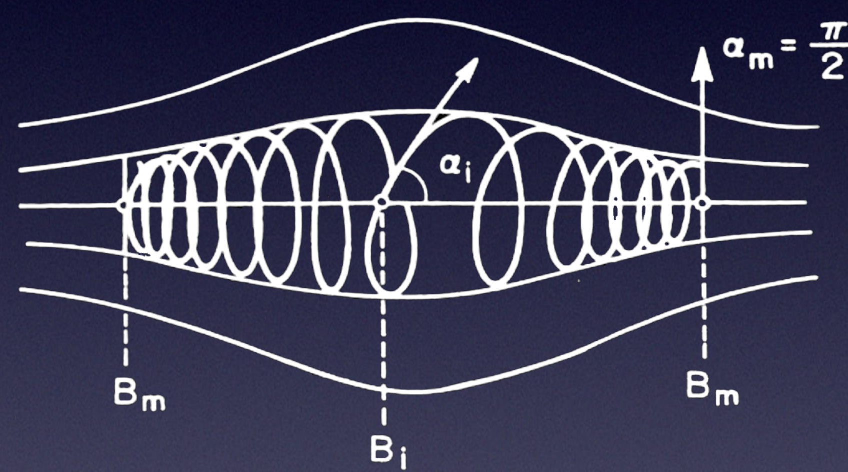
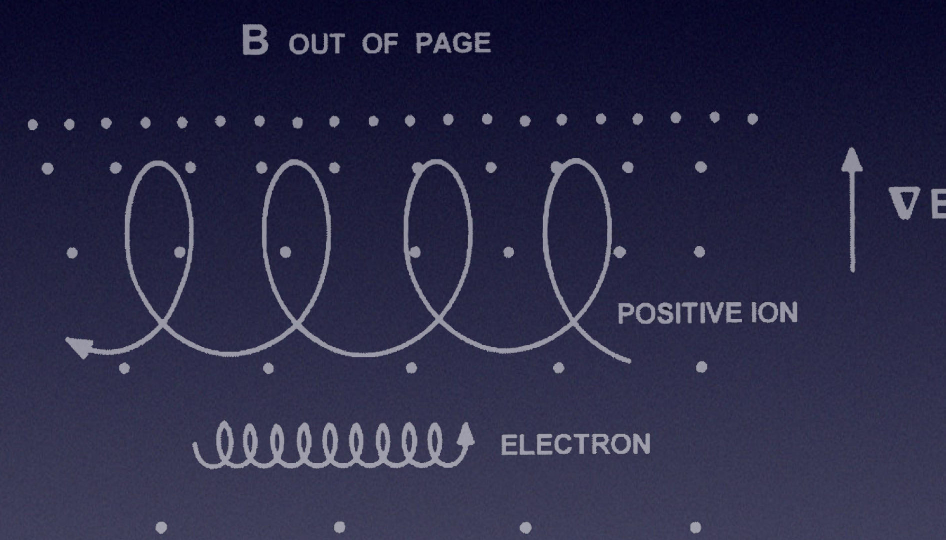
Gyration

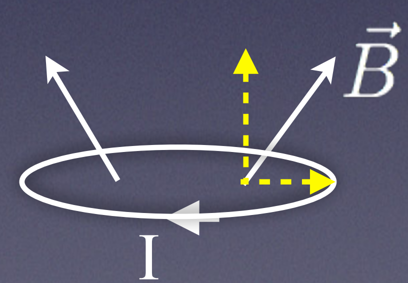


Bounce



Drift





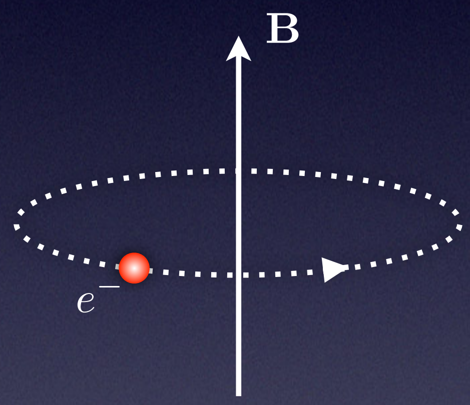
$$\vec{F} = I d\vec{\ell} \times \vec{B}$$

net upward force pushes
current loop towards
region of weaker field

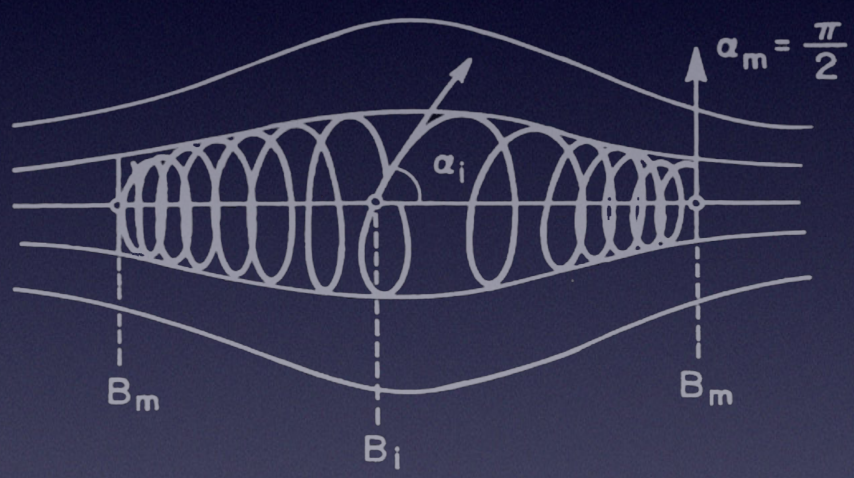
Particle Motion in a Magnetic Field

- charged particle motion in a non-uniform magnetic field exhibits three types of motion

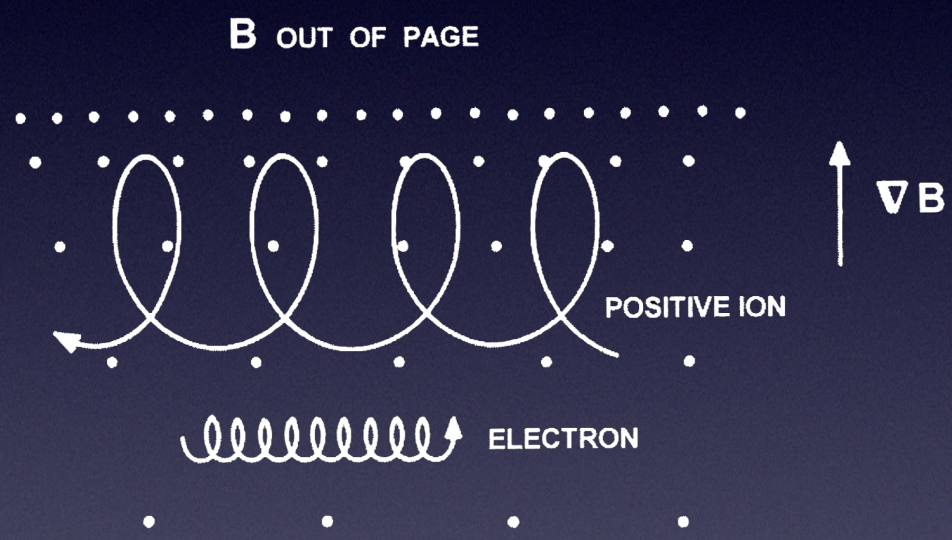
Gyration



Bounce



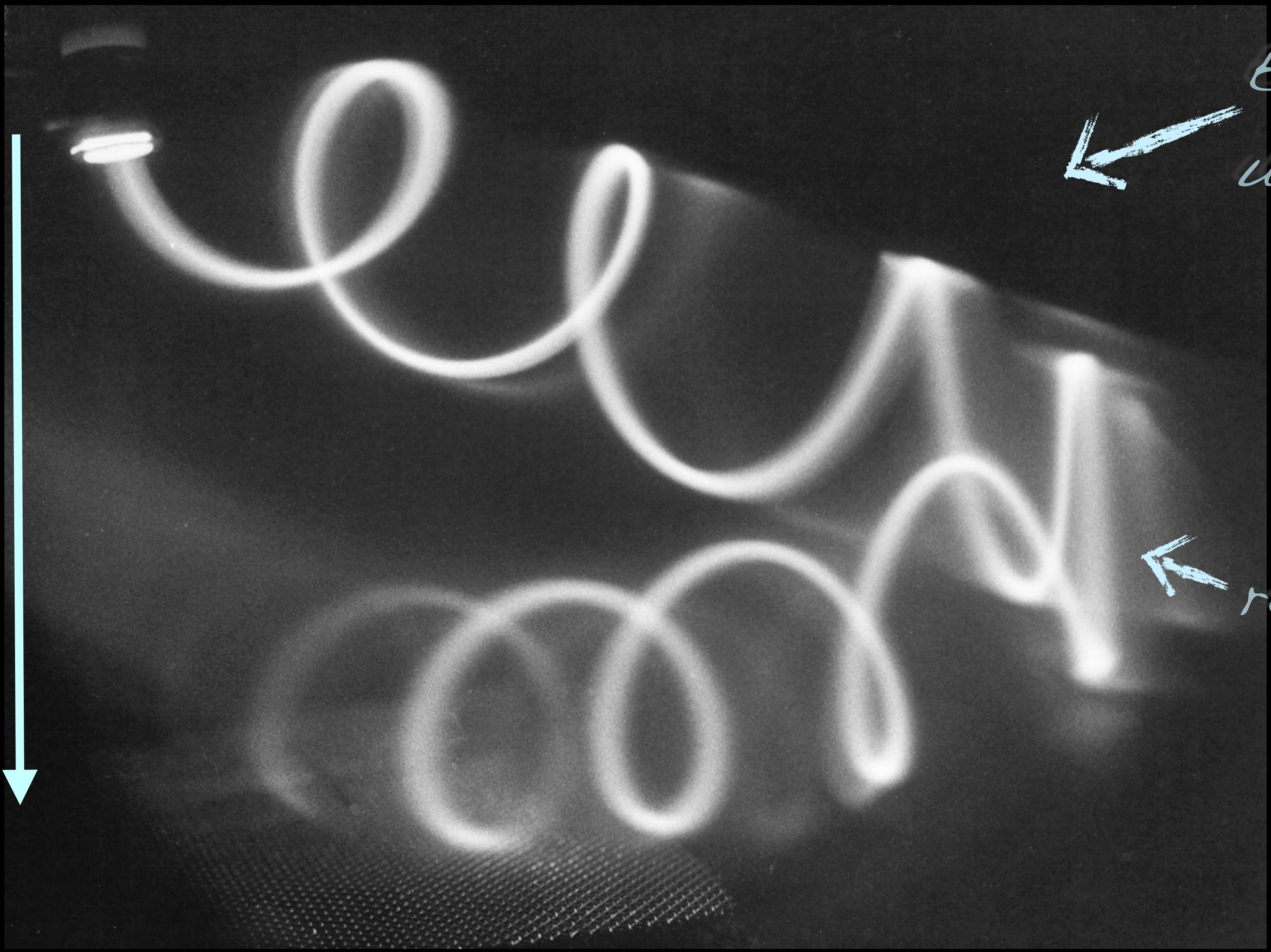
Drift



$$R_g = \frac{p}{qB}$$

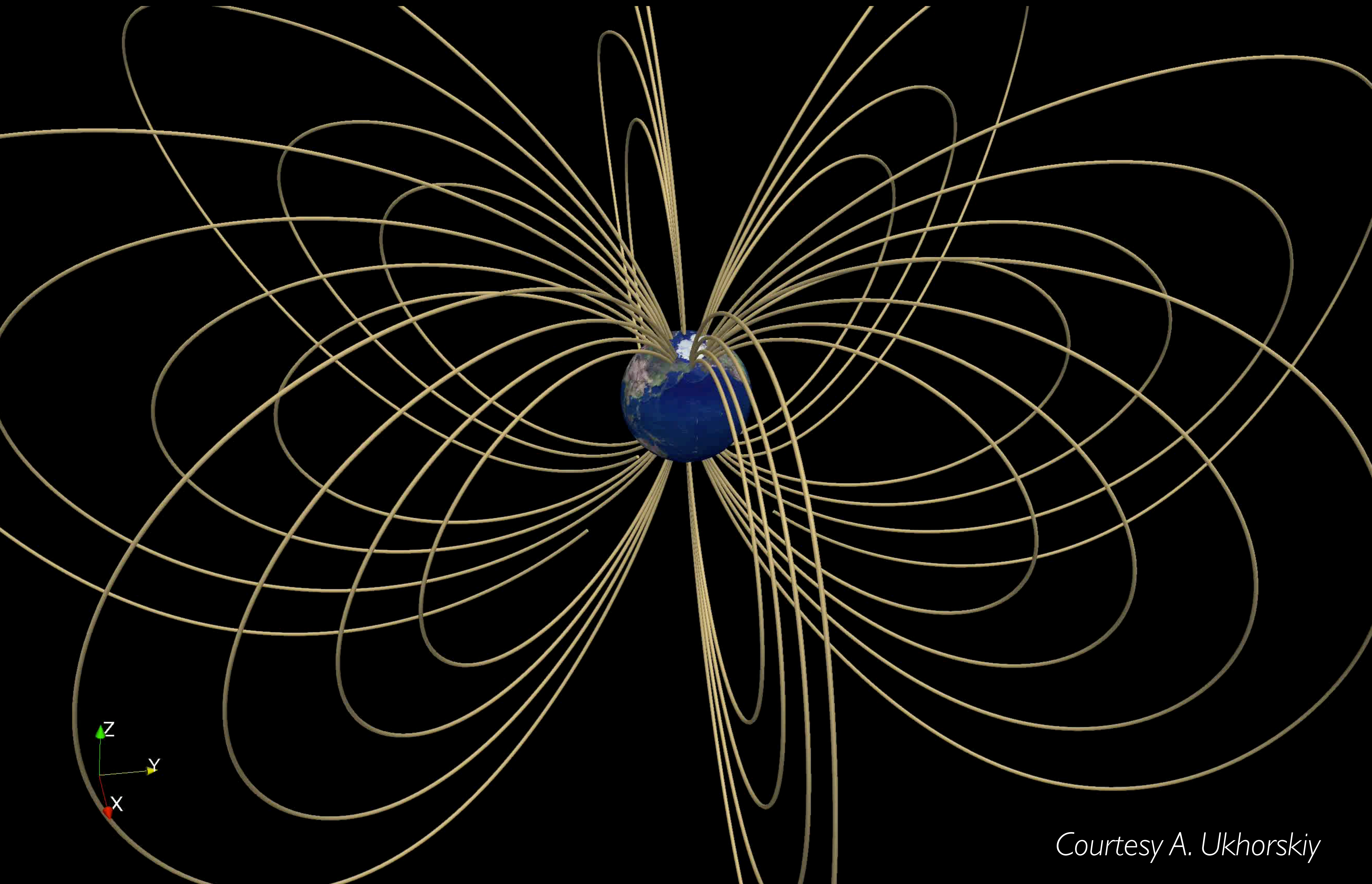
Radius of gyration
smaller where B is larger

Particle Motion in a Non-uniform Field



From plasma group webpage at UCLA
http://www.physics.ucla.edu/plasma-exp/beam

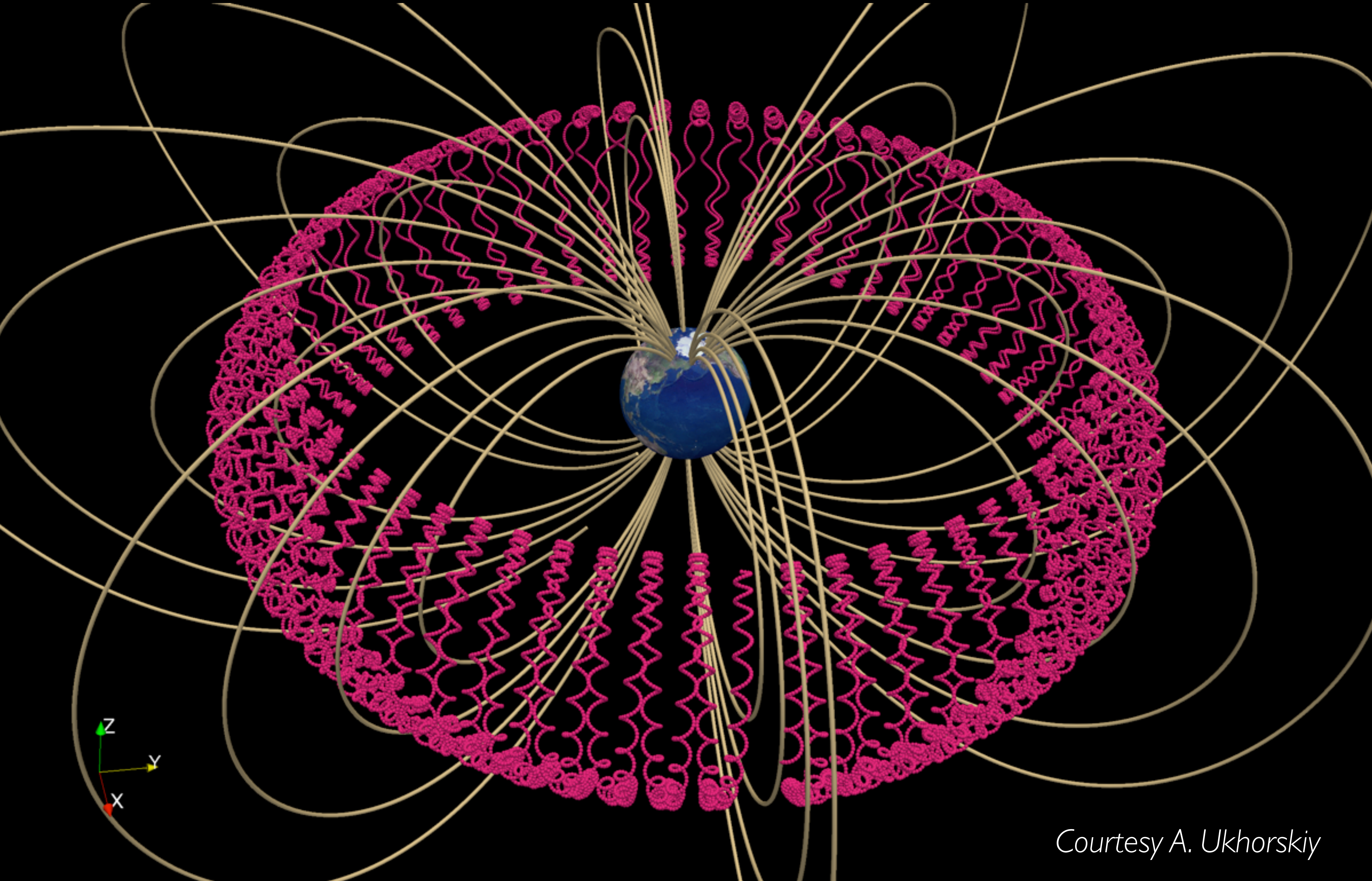
Particle Motion in the Geomagnetic Field



Courtesy A. Ukhorskiy

Particle Motion in the Geomagnetic Field

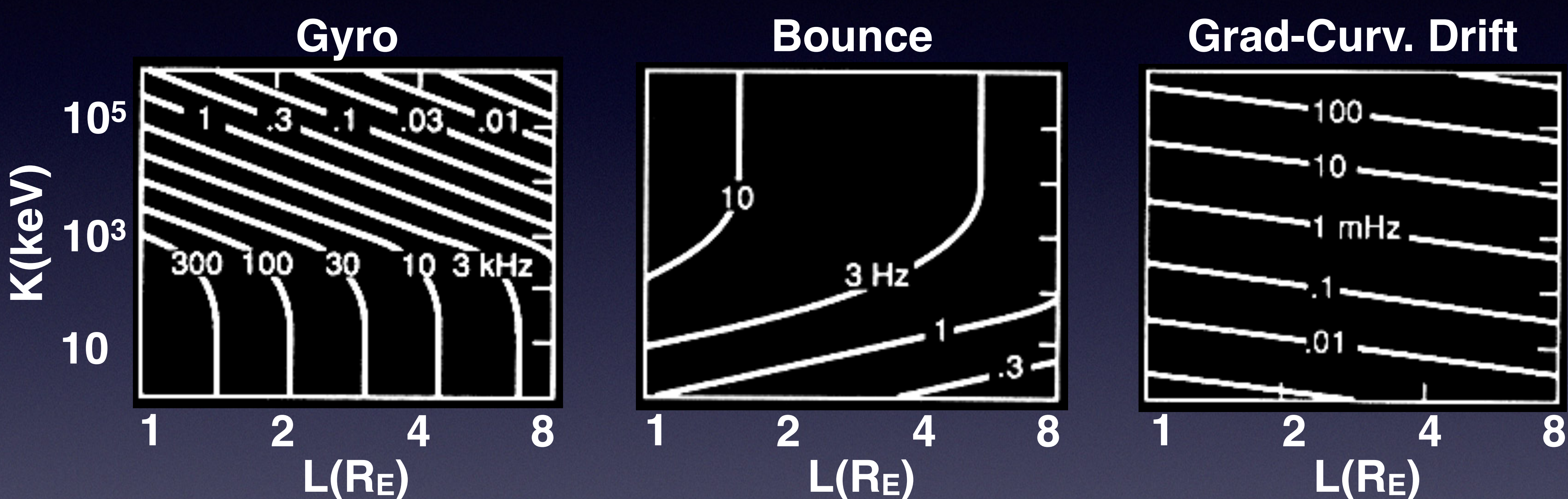
$\underline{K\text{=1 MeV}, m\text{=20 } m_e}$



Courtesy A. Ukhorskiy

Timescales of Motion in a Dipole Field

- Characteristic timescales of three quasi-periodic motions in a dipole magnetic field are separated by ~3 orders of magnitude:



Gyrofrequency: $f_c \sim 1$ kHz

Bounce frequency: $f_B \sim 1$ Hz

Drift frequency: $f_D \sim 1$ mHz

Adiabatic Invariants

- For periodic motion, adiabatic invariants are the action integrals taken over period of motion or area in phase space: $J = \oint p\,dq$

Example: Simple Pendulum

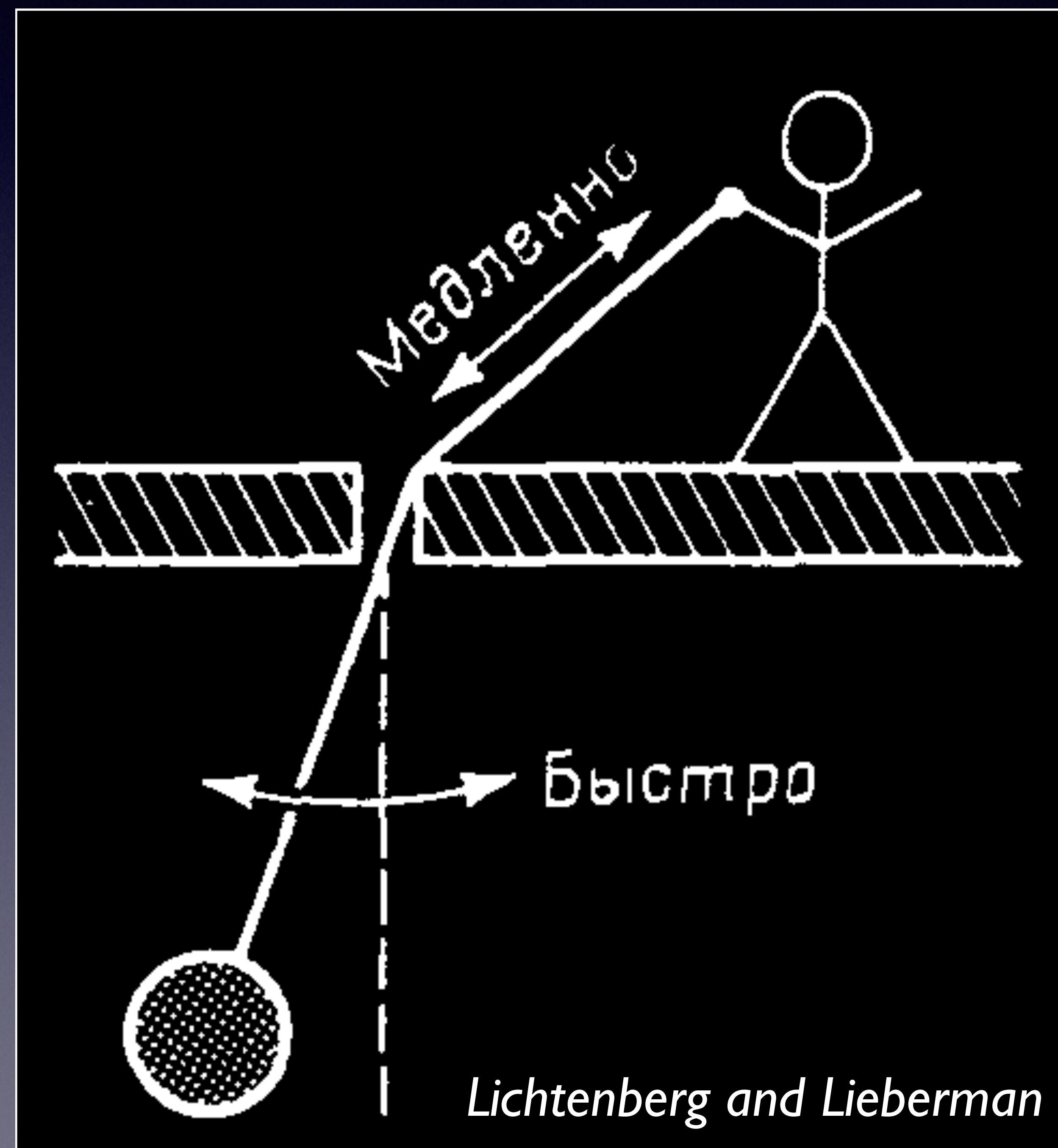
$$J = \frac{E}{\omega}$$

What happens when we slowly shorten the string?

$$\frac{d\omega}{dt} \ll \frac{\omega}{\tau} \Rightarrow \frac{1}{\omega^2}\frac{d\omega}{dt} \ll 1$$

where $\omega = \sqrt{\dfrac{g}{\ell}}$

J conserved!

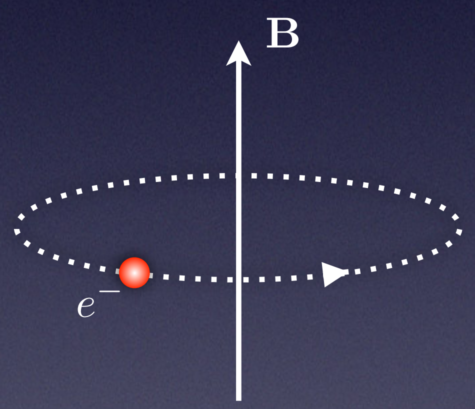


Lichtenberg and Lieberman

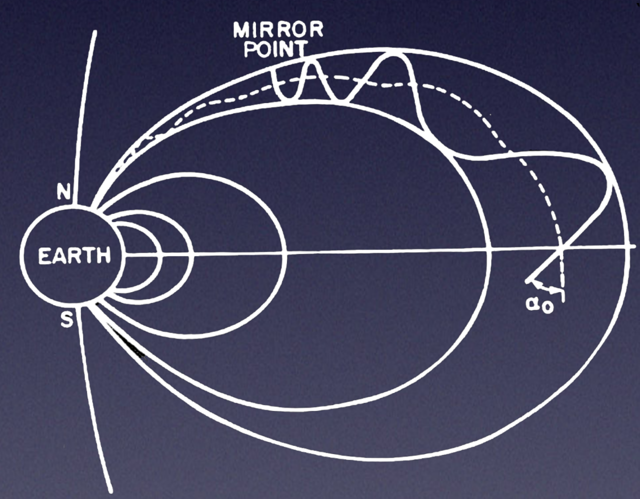
Adiabatic Invariants in the Radiation Belts

- At Earth: three periodic motions with very different timescales => three adiabatic invariants
- As long as field varies slowly relative to the period of motion (e.g. gyroperiod), the adiabatic invariant is approximately constant.

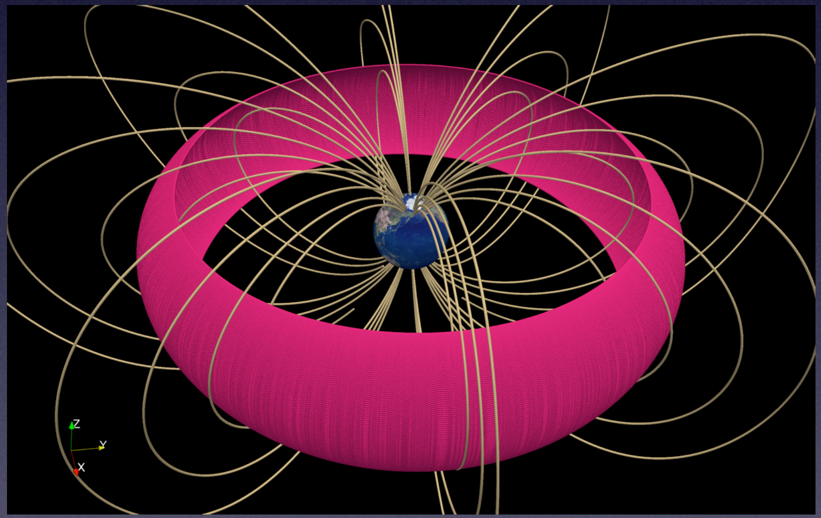
Gyration
1st invariant



Bounce
2nd invariant



Drift
3rd invariant



$$\mu = \frac{p_\perp^2}{2mB} \qquad J = \oint p_\parallel ds = pI;\ I = \oint \sqrt{1 - \frac{B(s)}{B_m}} ds \qquad \Phi = \oint \mathbf{A} \cdot d\mathbf{l}$$

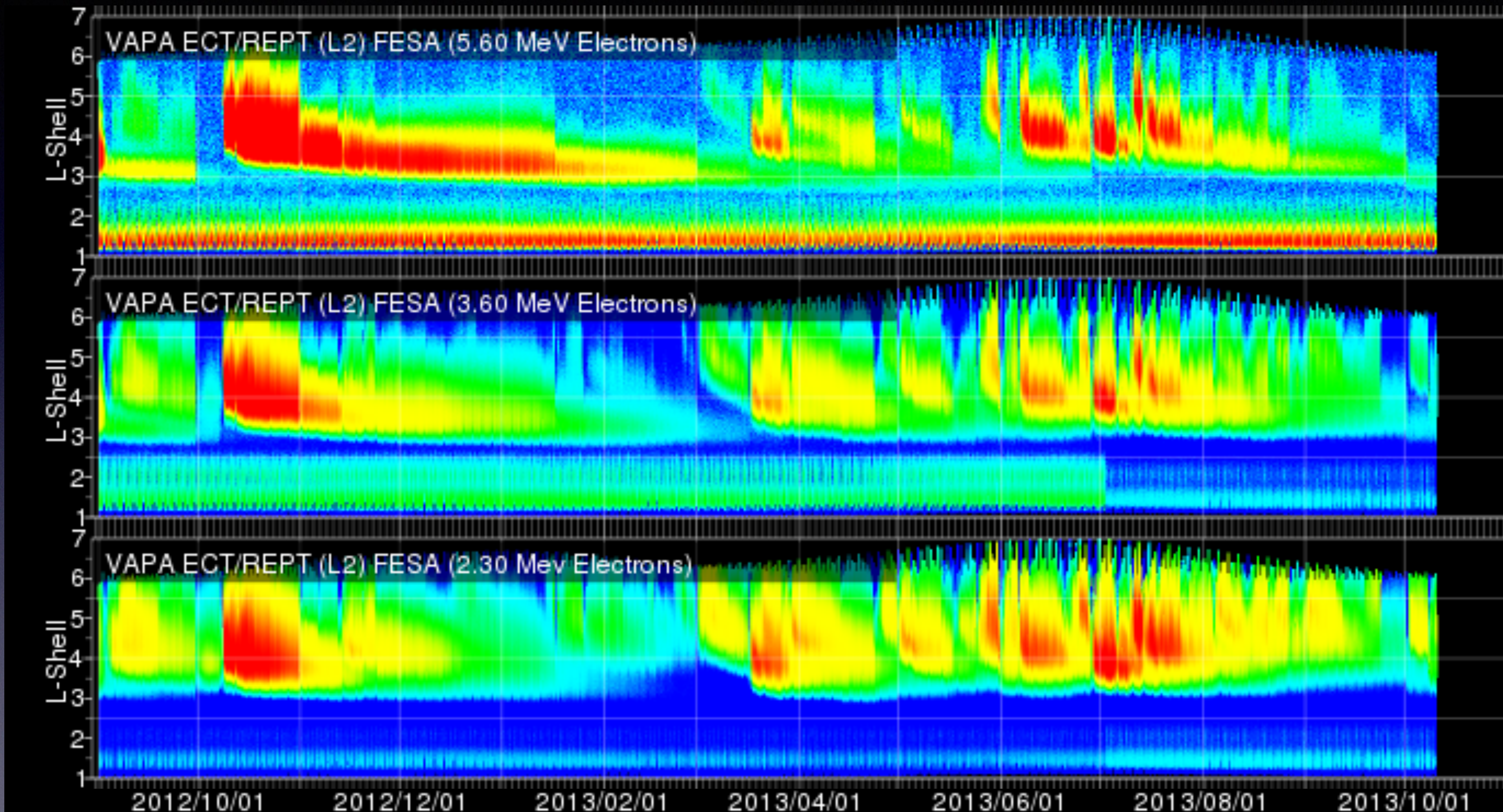
Recent review: Ukhorskiy and Sitnov, 2012 (Space Science Reviews)

Source of Relativistic Electrons

- Potential external Sources
  - Jupiter
    - when IMF lines connect Earth and Jupiter, particles can enter Earth's magnetosphere
    - not an important source!
  - Solar Wind
    - not enough MeV electrons there!
- Internal acceleration of "seed" particles

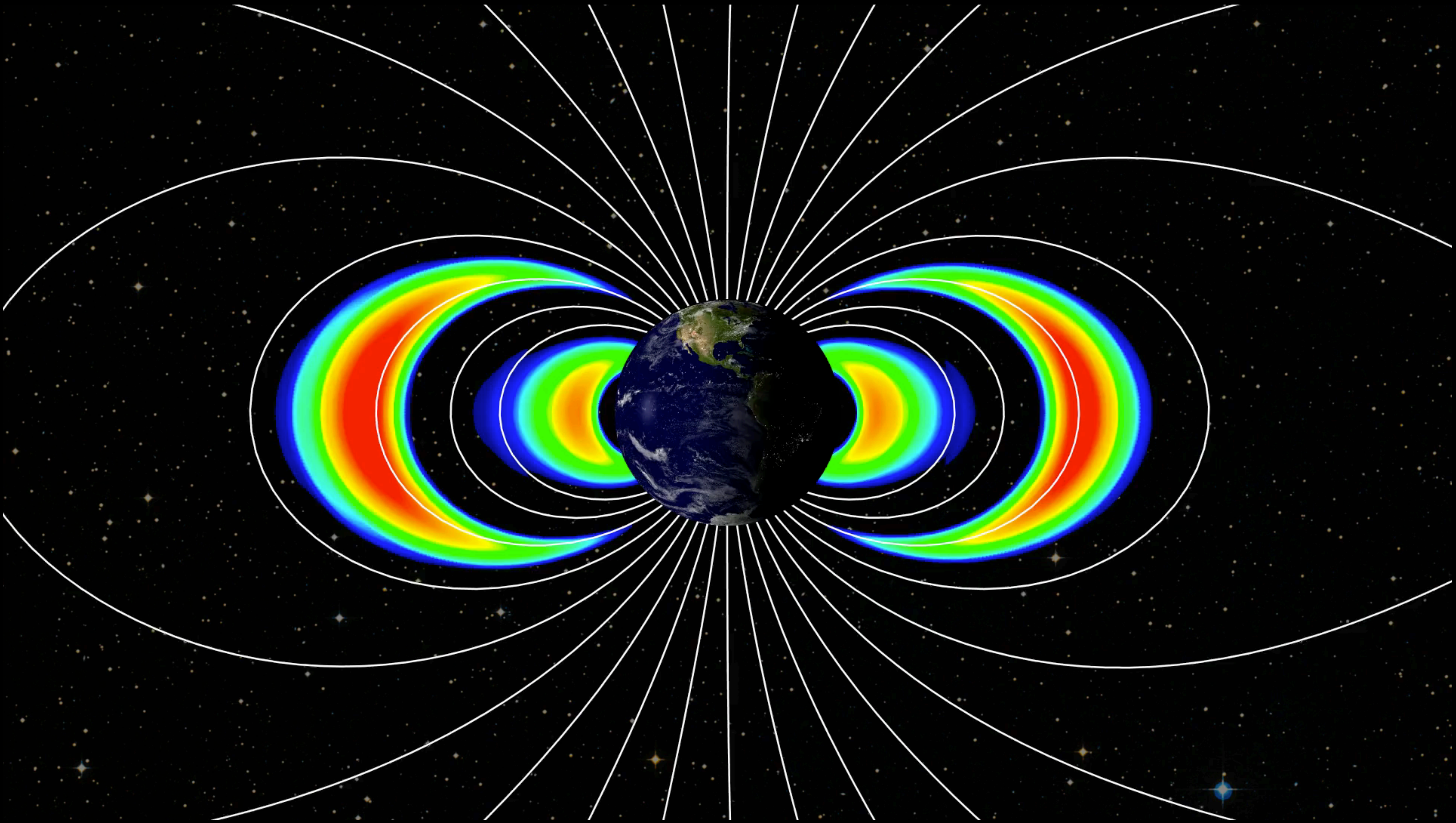
➡ Earth is a particle accelerator!

Variability of the Radiation Belts



Summary plot from Van Allen Probes Science Gateway

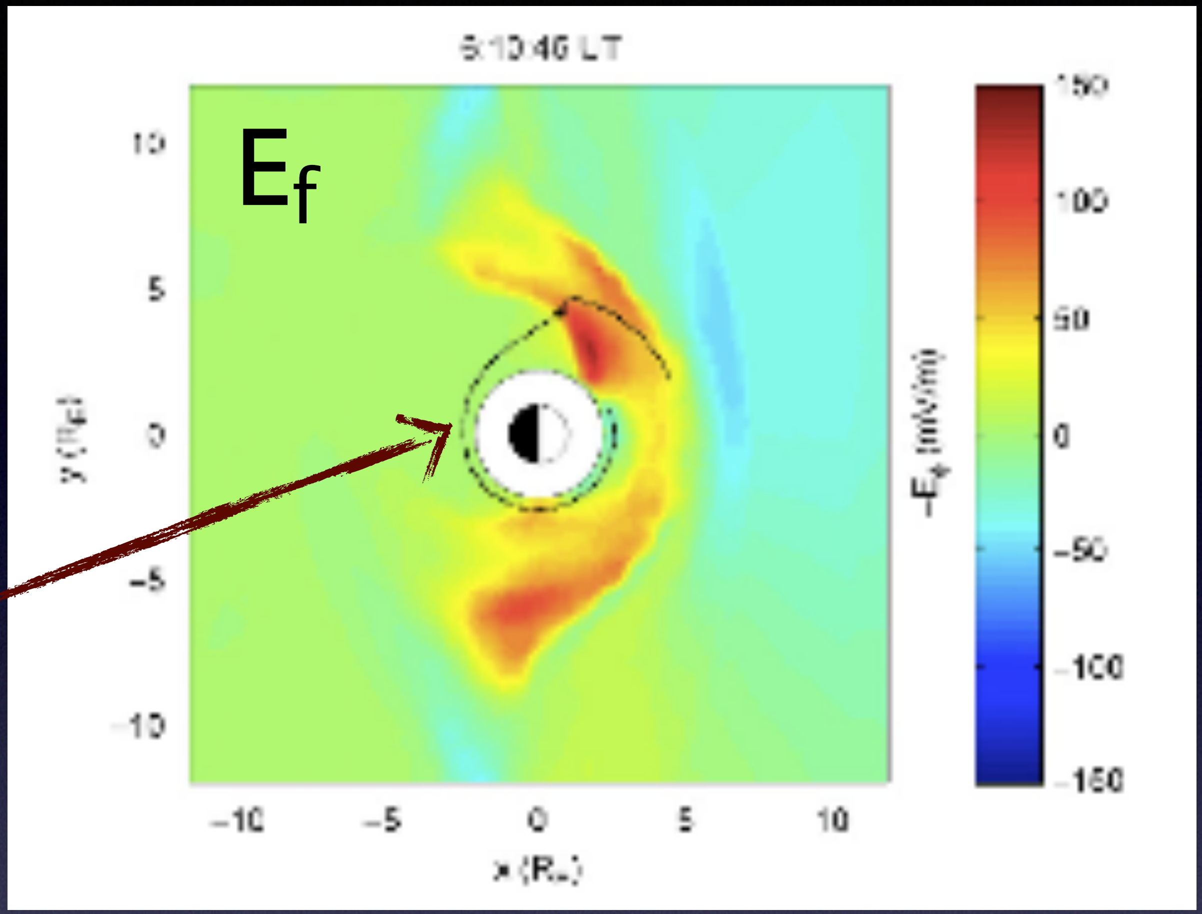
Three Radiation Belts?



Credit: D. Baker (LASP), Grant Stephens and Robin Barnes (JHU/APL)

Fast Radial Transport ($\tau \lesssim T_D$)

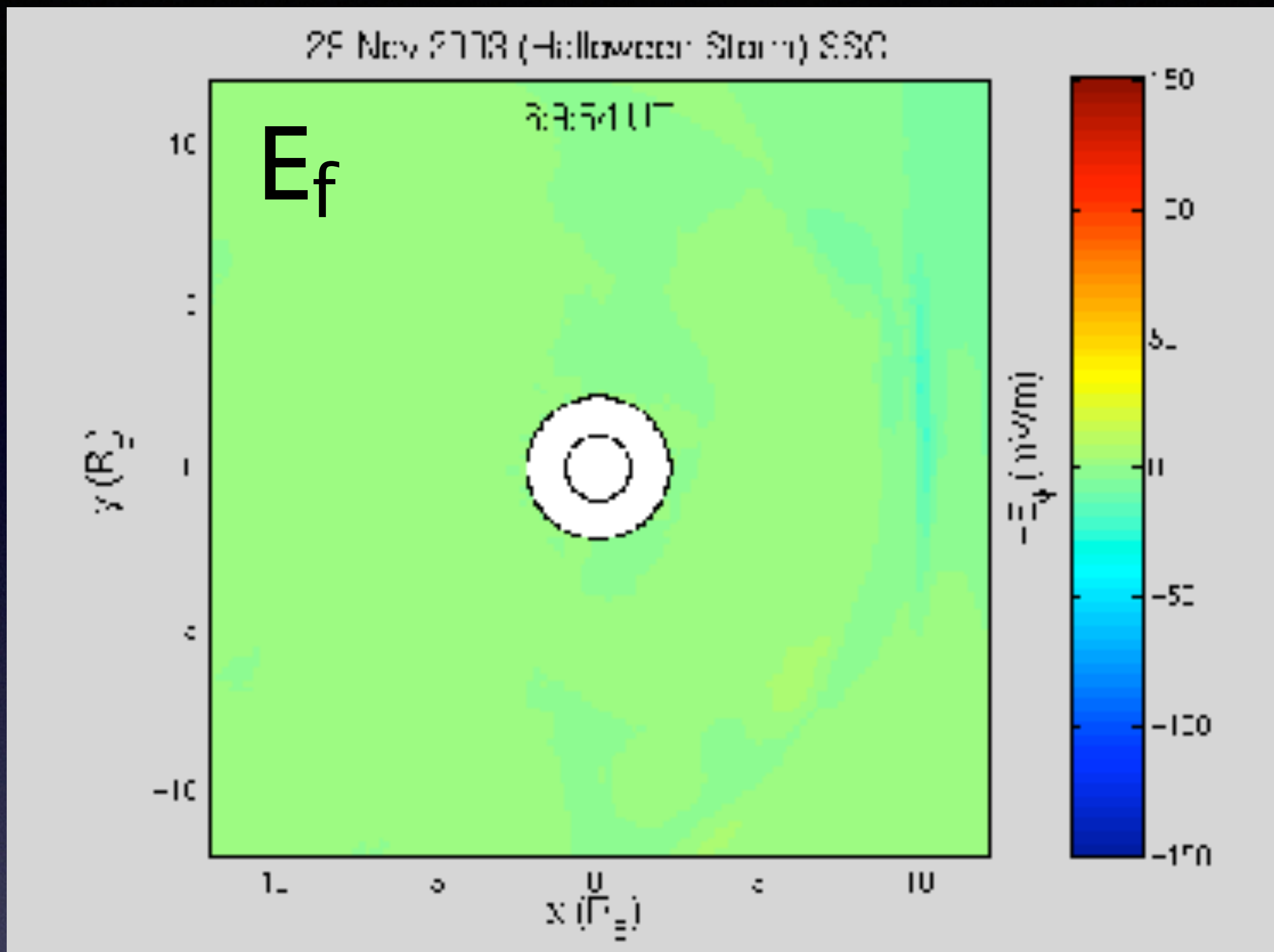
Drift-resonant
electron



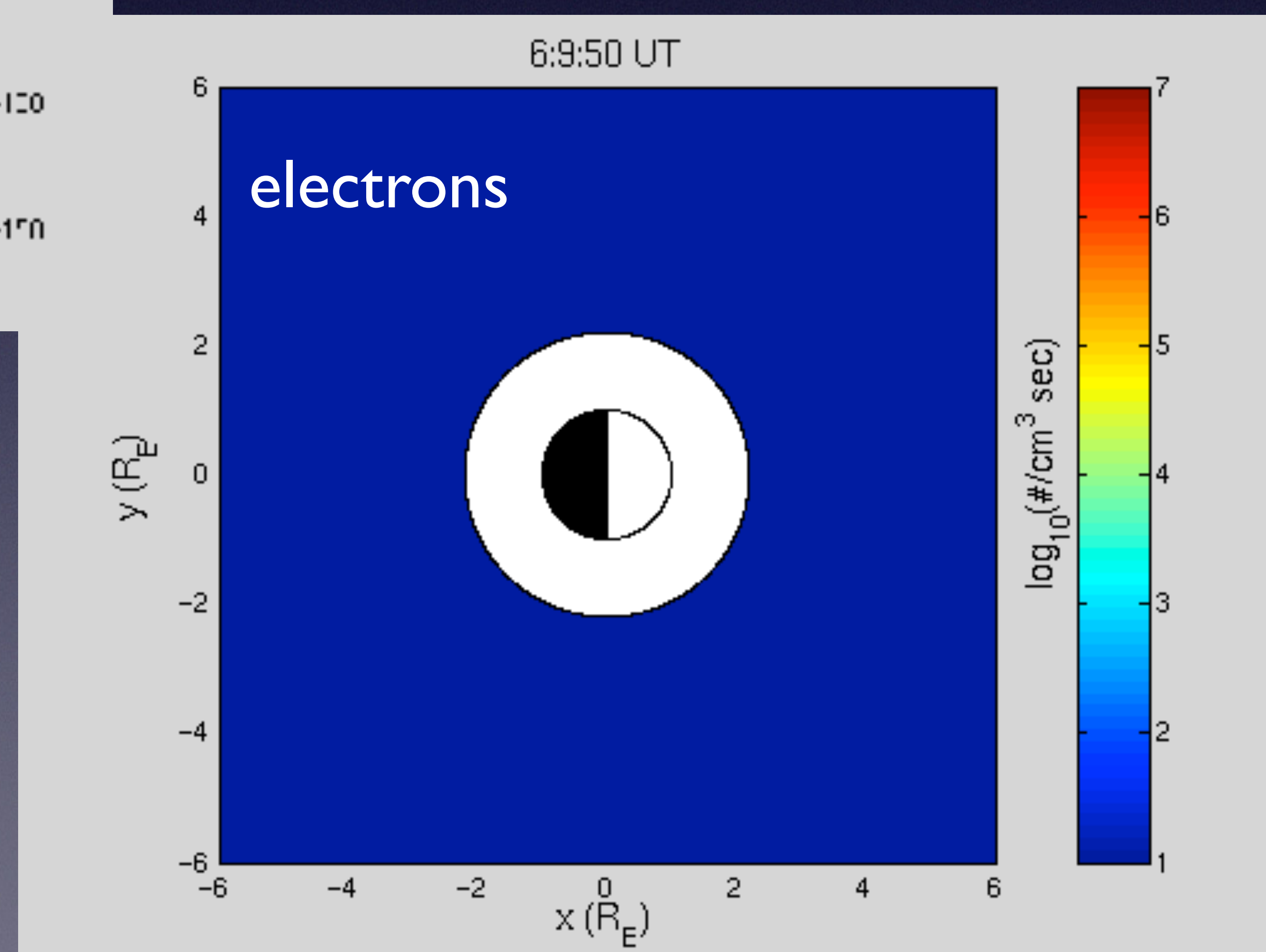
[Kress et al., 2007]

- Rapid compression of magnetic field due to solar wind (dB/dt)
  => induction electric field (azimuthal)
- Drift-resonant electrons see nearly constant E-field
  => transported radially inward and energized to 10-15 MeV

Fast Transport: Simulation



Electric field due to compression of magnetic field by solar wind

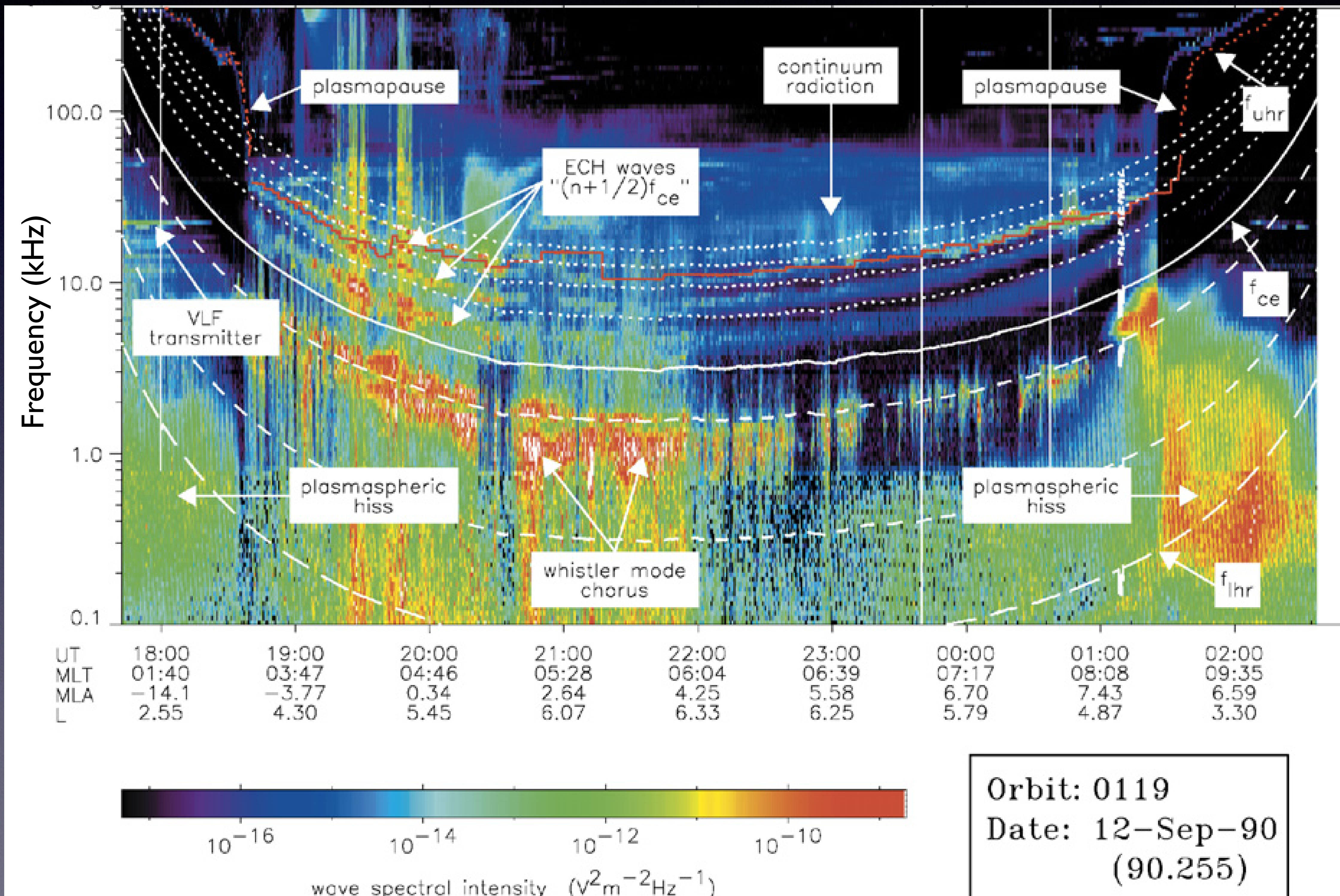


Test particle simulation shows how electrons move inward and gain energy

Courtesy B. Kress

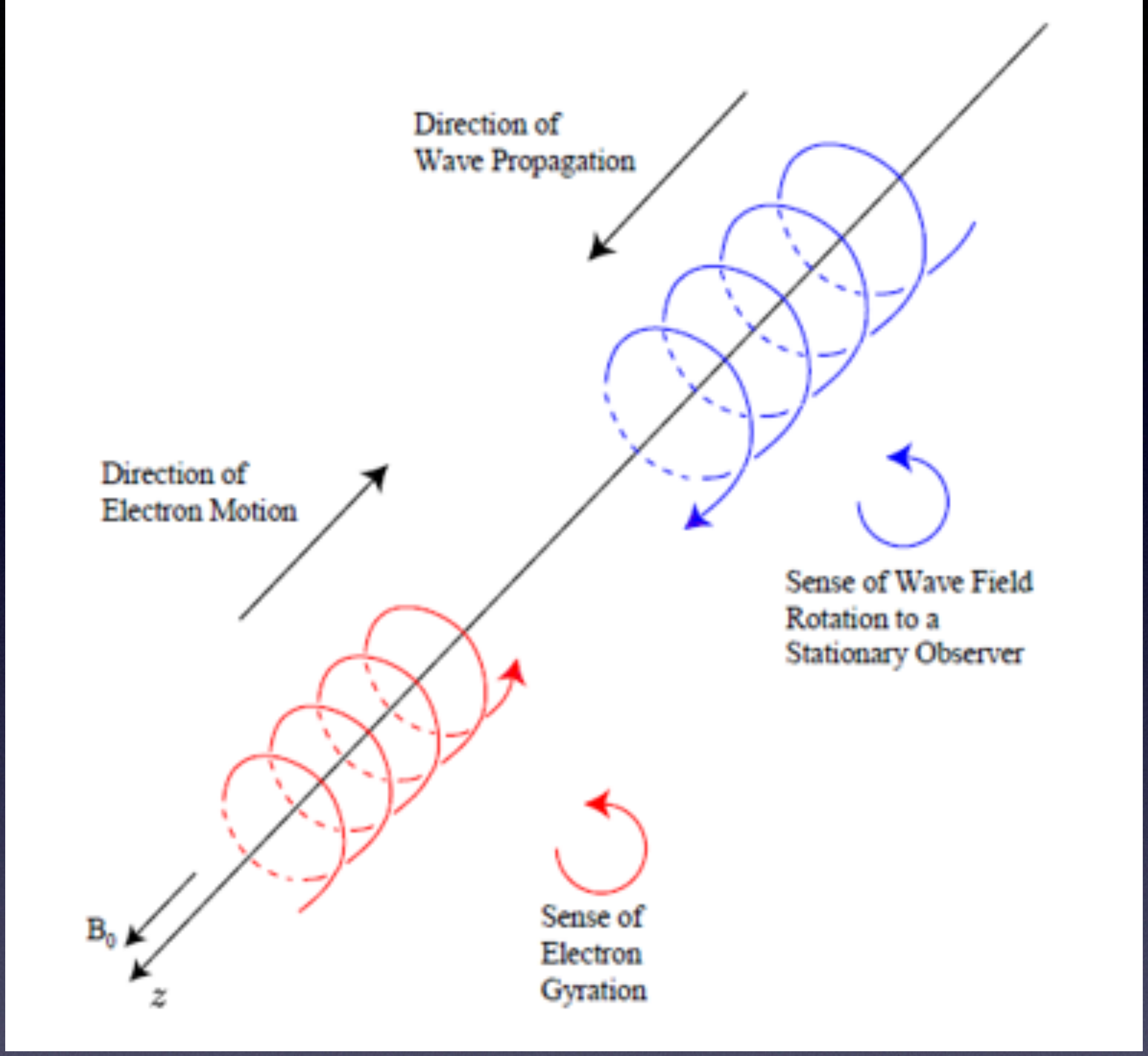
High Frequency Plasma Waves

- Electrons encouter a variety of plasma waves as they drift around Earth - seen here in this wave spectrogram from the CRRES satellite.



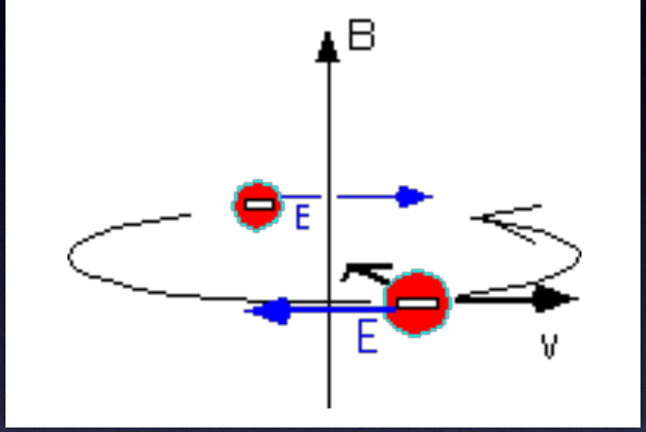
[Meredith et al., 2004]

Gyro-resonant interaction



Stanford VLF Group

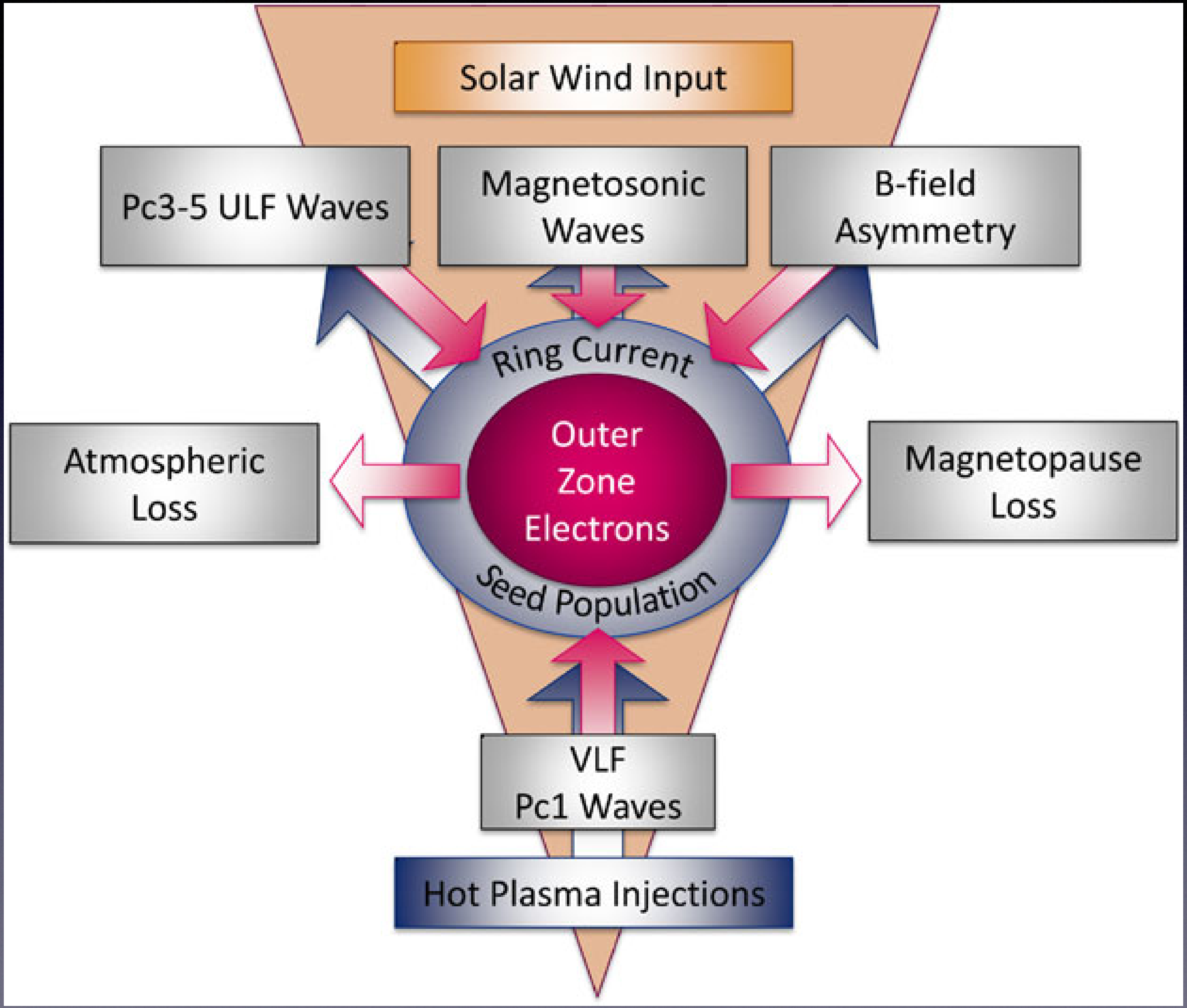
$$\omega - \vec{k} \cdot \vec{v} = \frac{\Omega_g}{\gamma}$$



- Can lead to energization of particles
- Can also cause electrons to be scattered into the atmosphere

See e.g. Reeves et al, 2013 (Science), Thorne et al., 2014 (Nature)

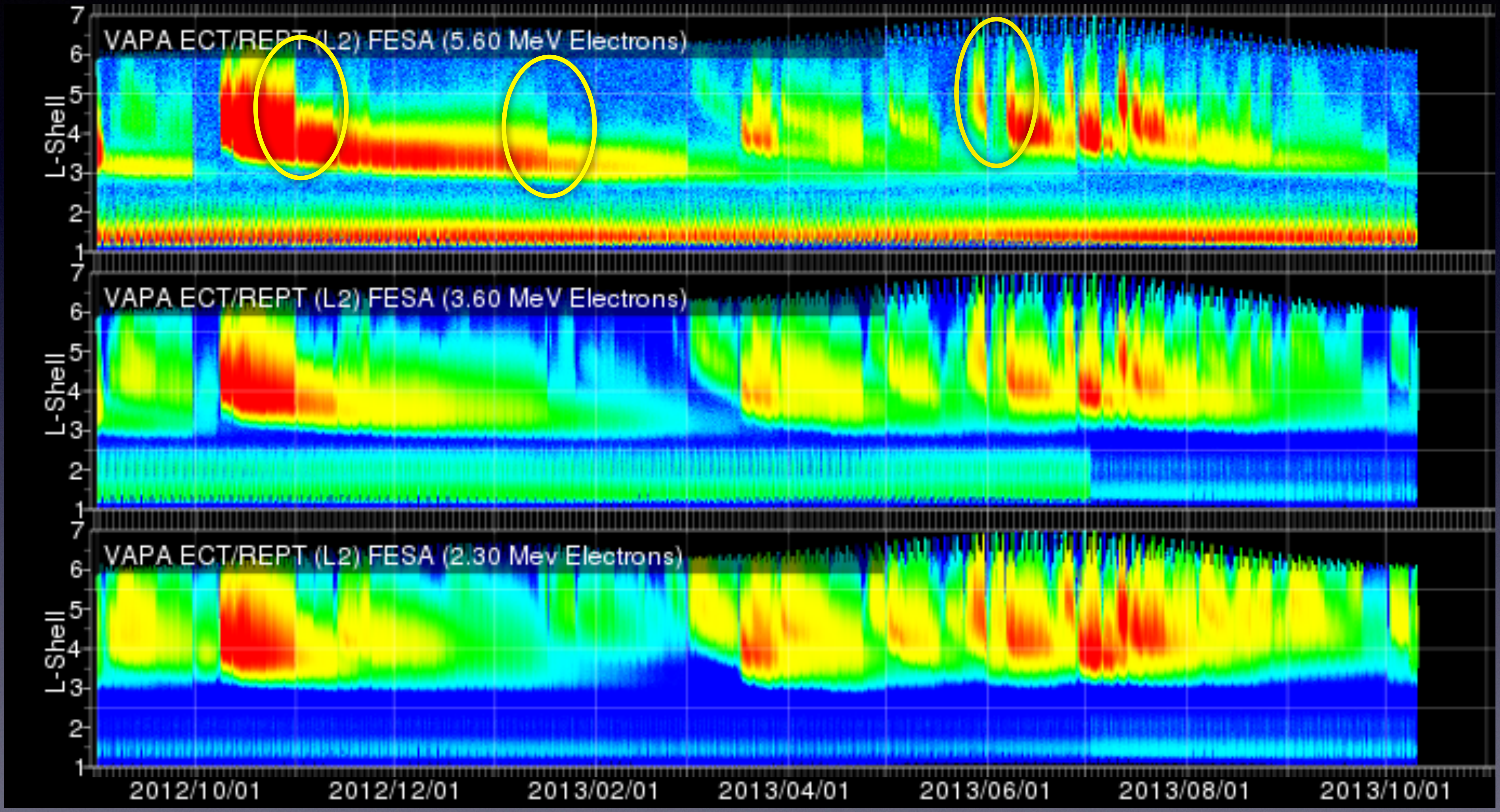
Radiation Belt Processes



Millan and Baker, 2012

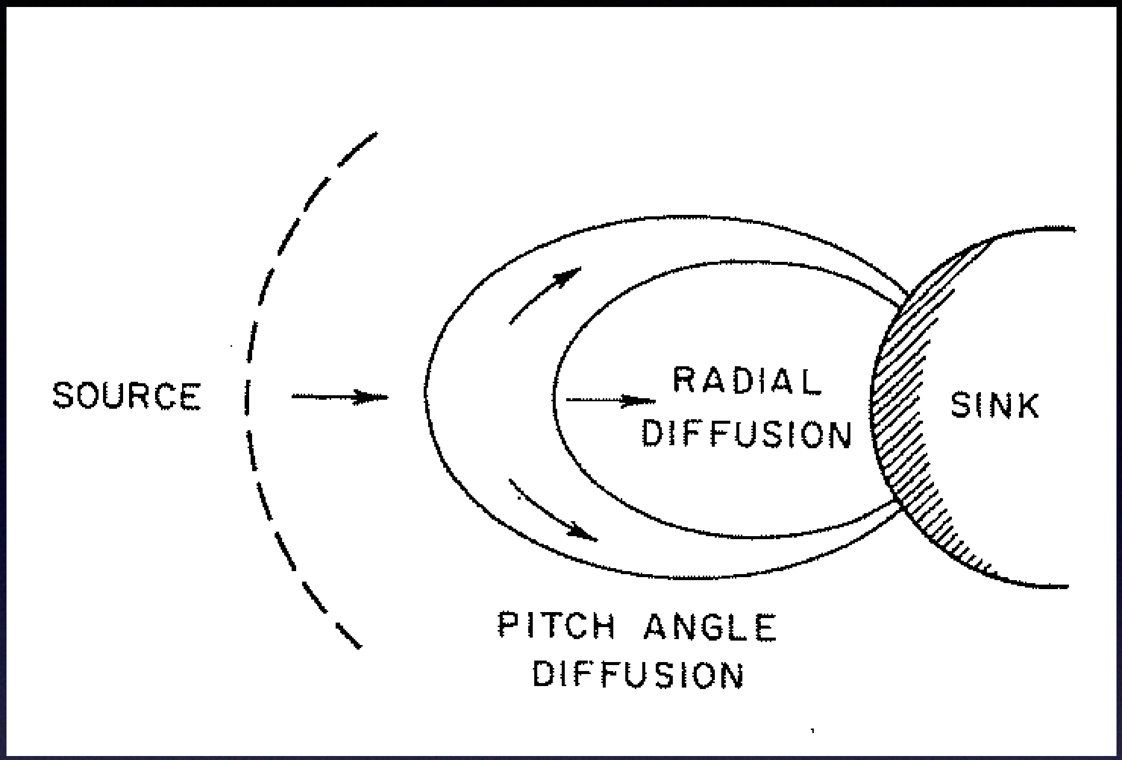
Radiation Belt Dropouts

Where do the electrons go?

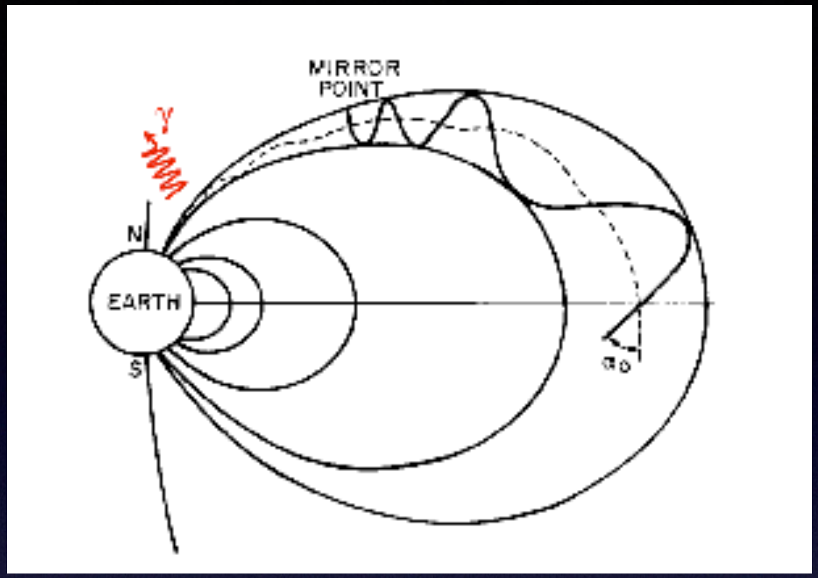


Summary plot from Van Allen Probes Science Gateway

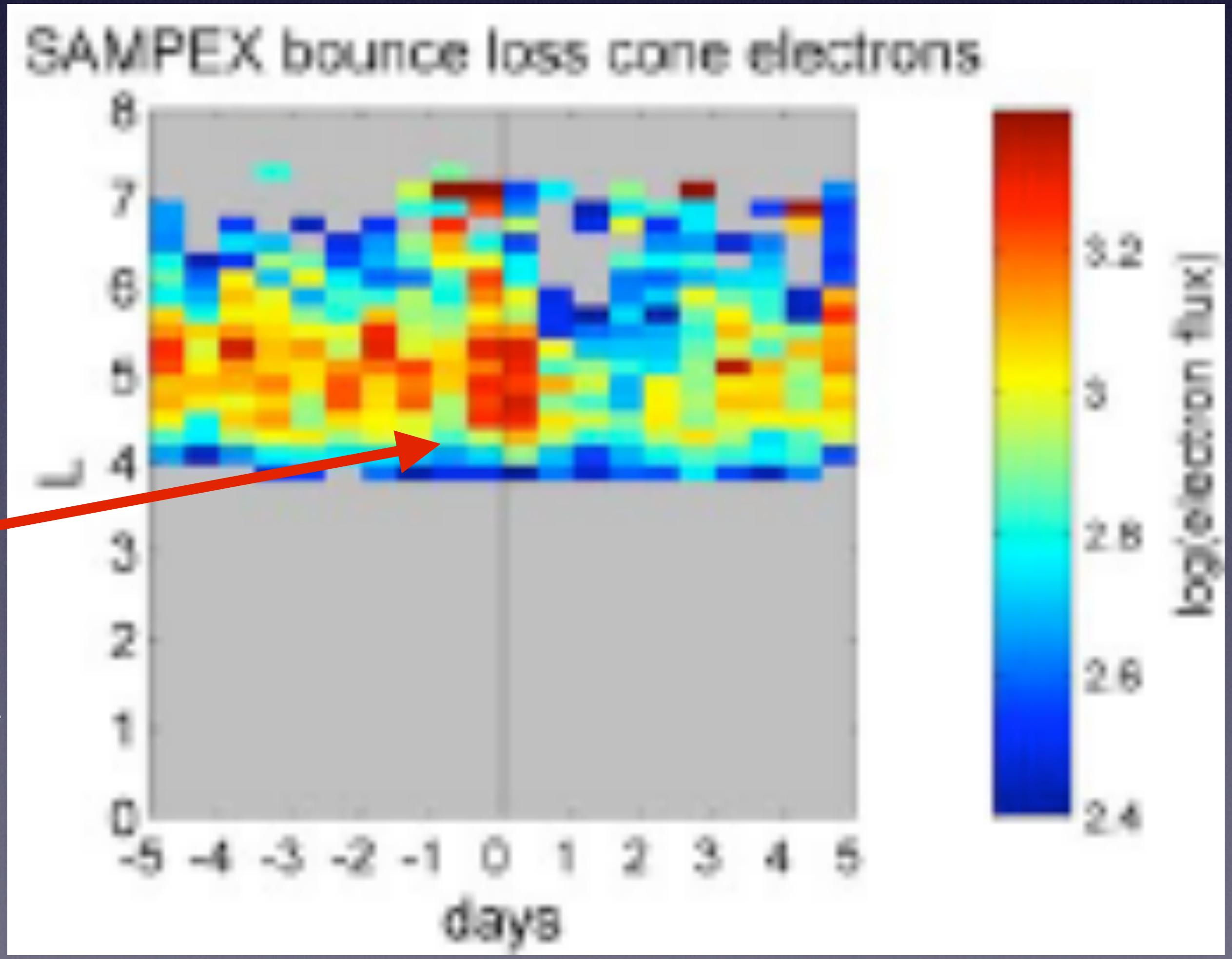
Loss to the Atmosphere



Sketch of radiation belt dynamics from Roederer, 1967

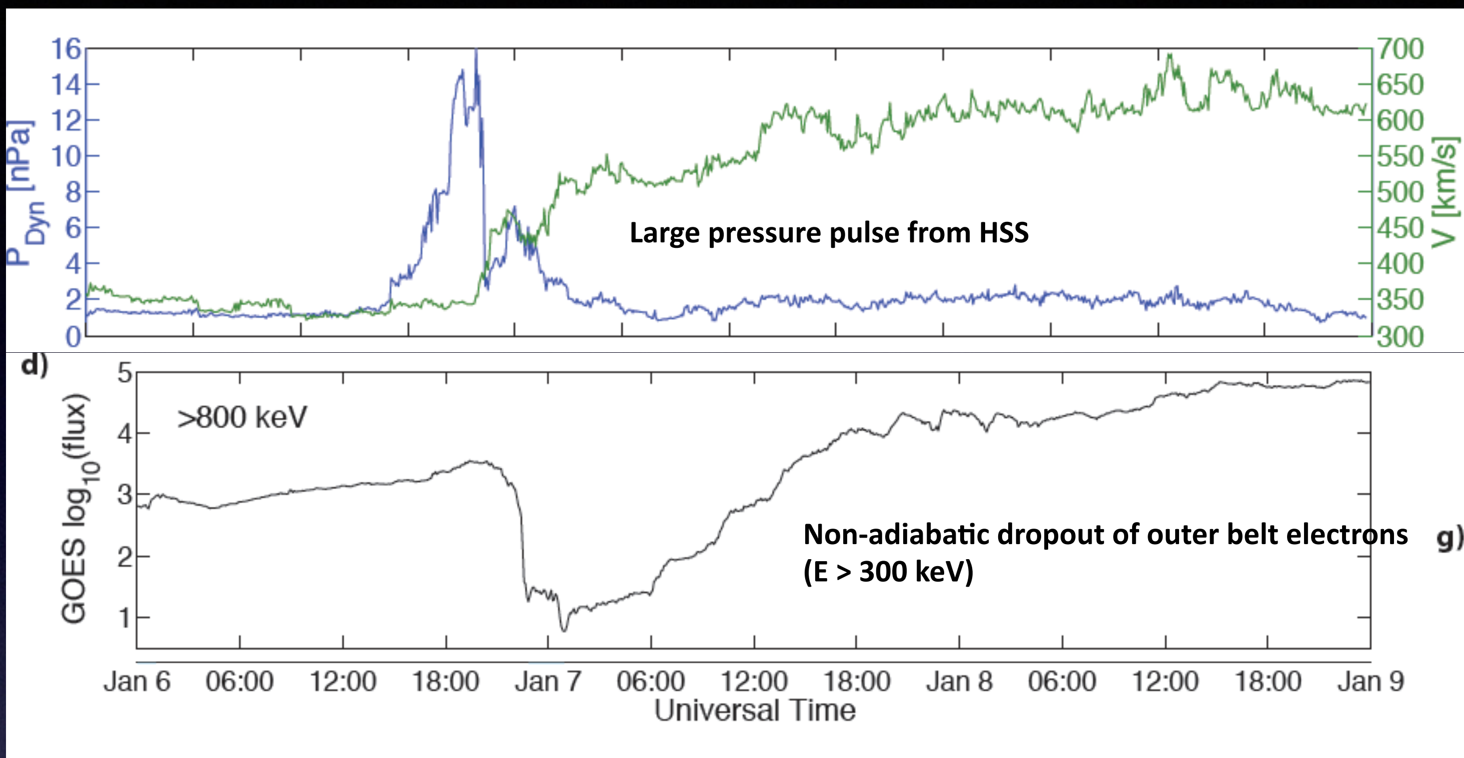


- Superposed epoch analysis during dropout events
- Increase in SAMPEX precipitation
- Selesnick 2006: strong precipitation during main phase

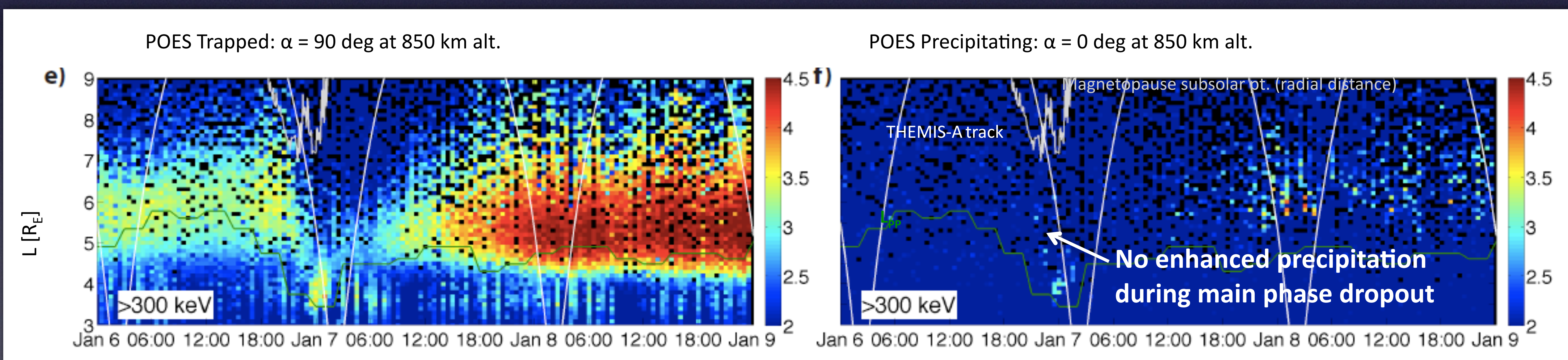


(Green et al., 2004)

Observational Evidence of Magnetopause Loss



- Ohtani et al., 2009 found dropouts occur during compression events
- Millan et al., 2007 POES precipitation confined to low L
- Turner et al., 2012: no precipitation observed during depletion event.
- See also Turner et al., 2014



[Turner et al., 2012]

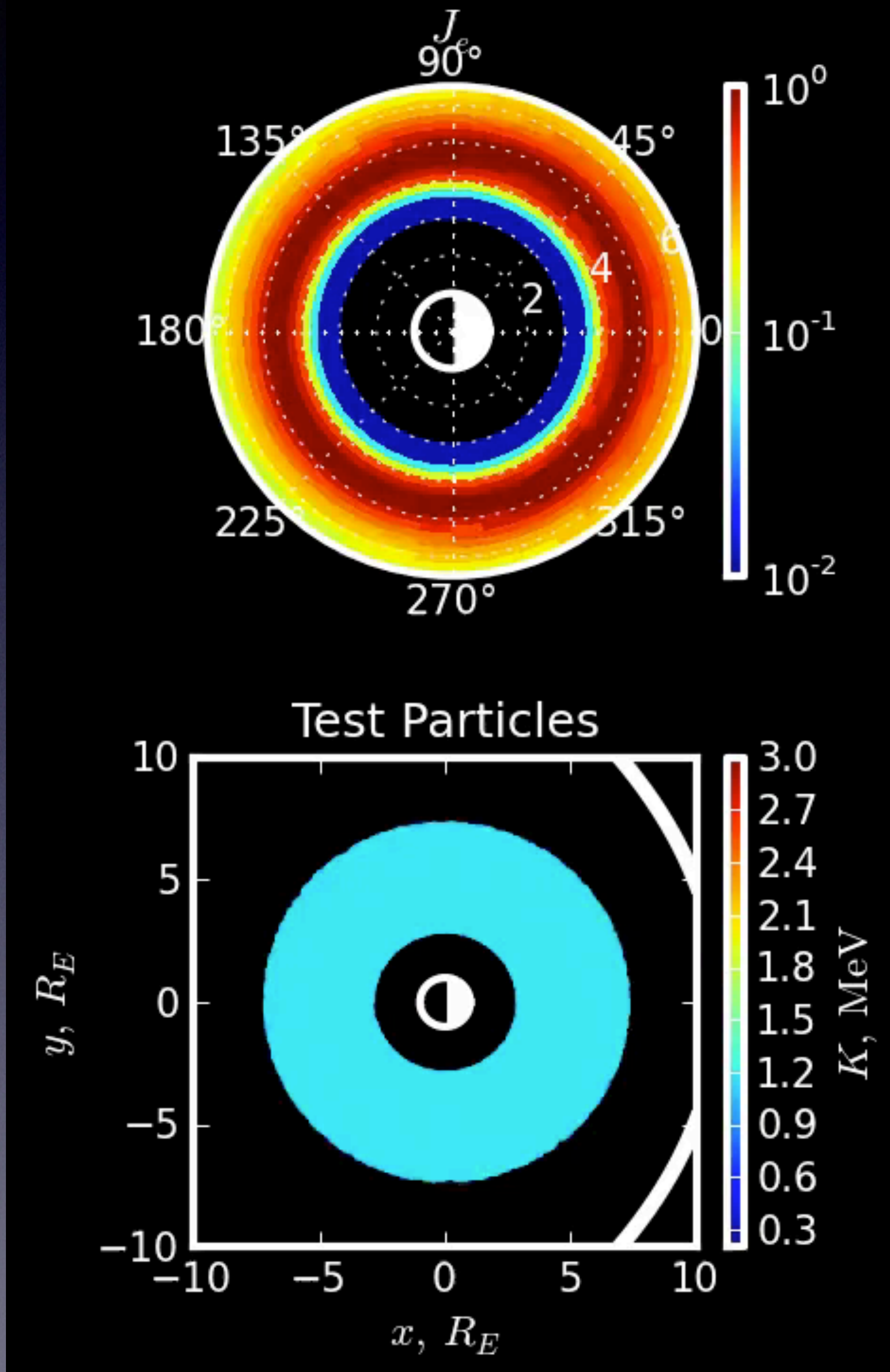
- Can magnetopause lossesaccount for loss deep in inner magnetosphere (L~4)?

Simulation of Magnetopause Losses

Four Effects

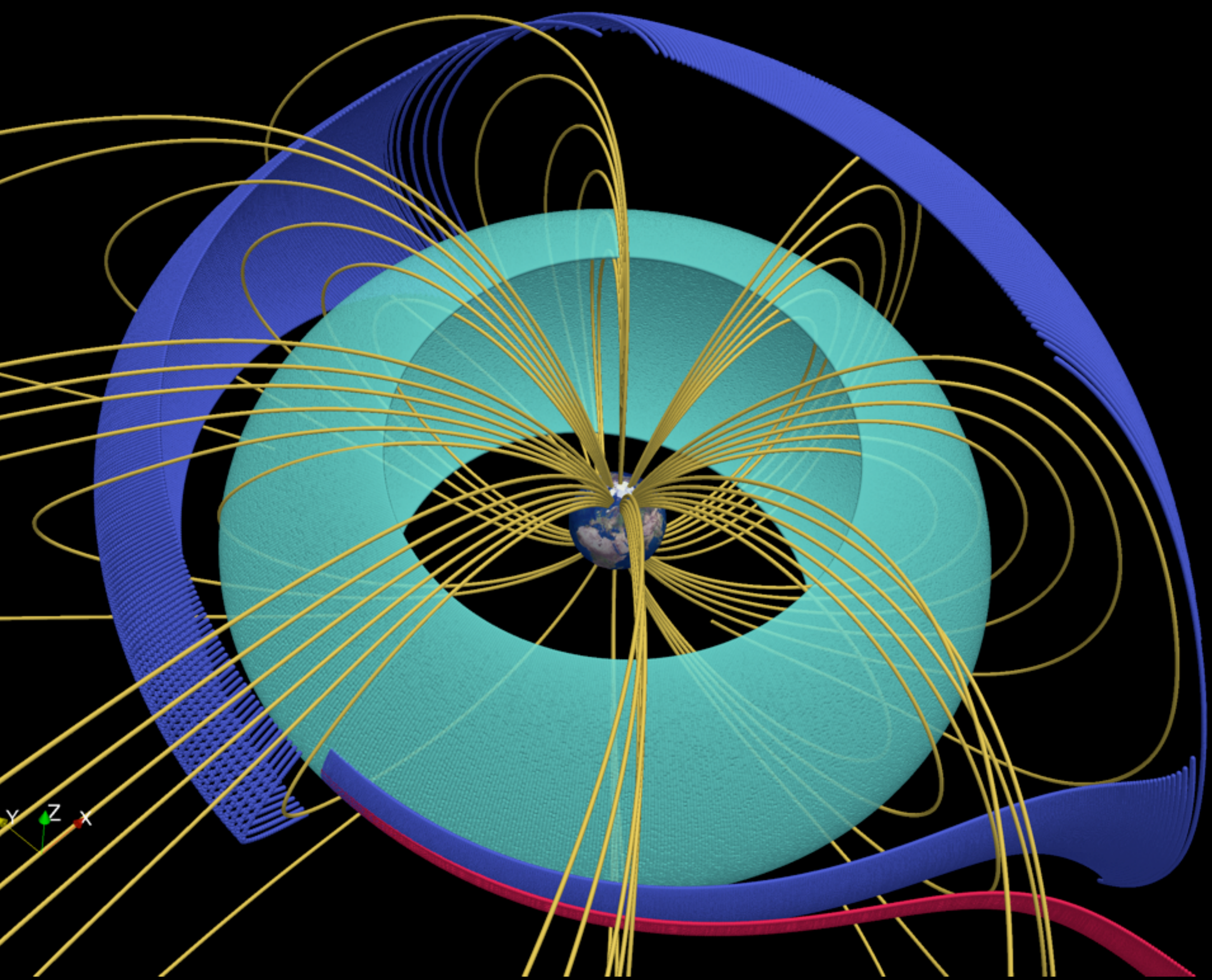
- Magnetopause shadowing
- Diamagnetic Effect
- Drift orbit bifurcation
- Radial transport

(Ukhorskiy et al., 2006, 2011, 2014; Hudson et al., 2013)



Courtesy Sasha Ukhorskiy

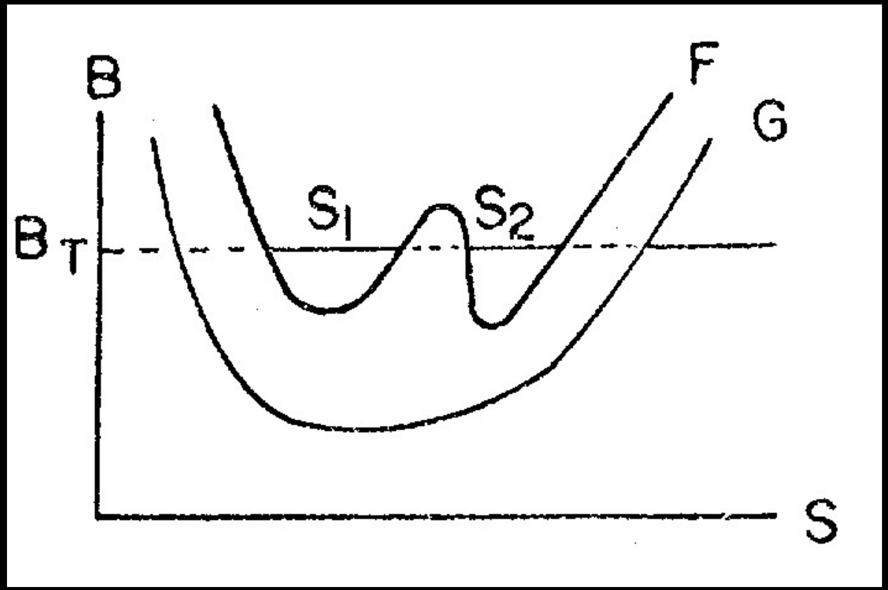
Electron Trajectories in the Compressed Field



<u>P_{dyn}=3 nPa; r_0=(-8,0,0)</u>

- stable: $\alpha_{eq}=20°$
- magnetopause loss: $\alpha_{eq}=80°$
- unstable (DOB): $\alpha_{eq}=59°$

Dayside & Nightside Profiles of B-field



[Northrop and Teller, 1960]

Ukhorskiy and Sitnov, 2012

Science Questions

1. What fraction of radiation belt loss is due to atmospheric precipitation vs. magnetopause loss?

2. What fraction of precipitation losses are due to microbursts versus duskside precipitation vs. something else?

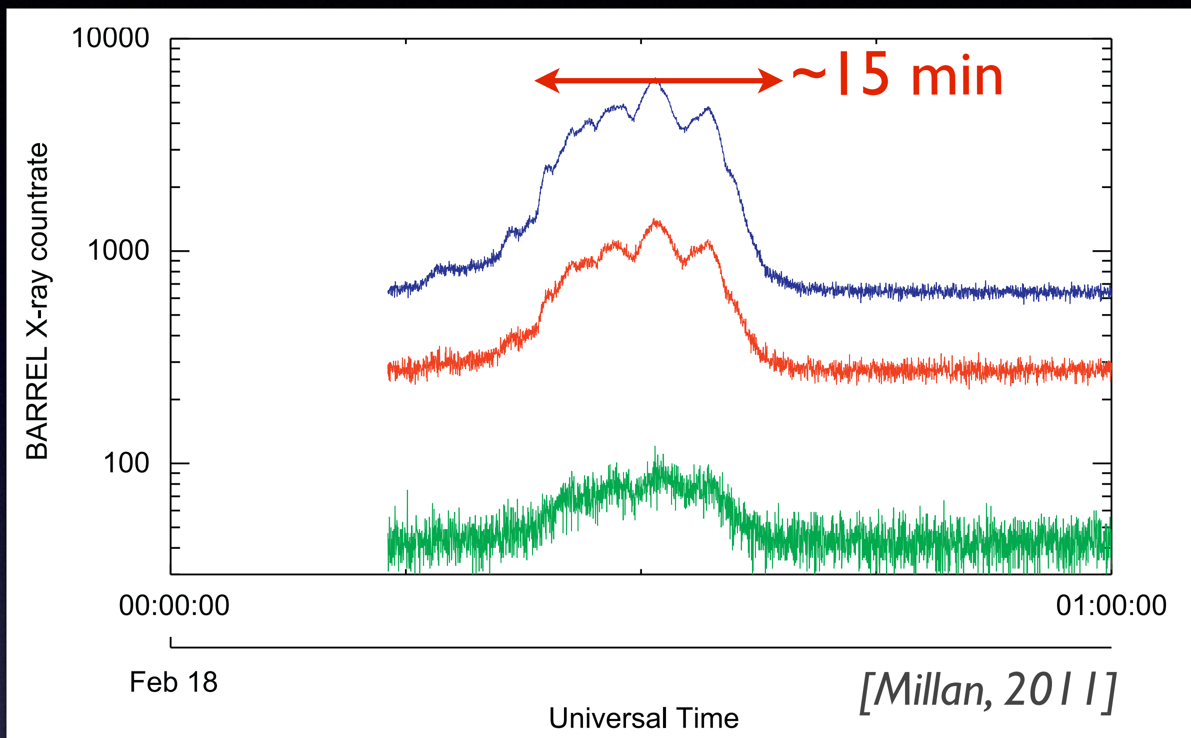
3. What causes relativistic electron microbursts, duskside bursts?

4. What causes observed ULF timescale modulation of precipitation?

5. How does precipitation evolve in space and time? What role is played by magnetospheric boundaries (e.g. plasmapause)?

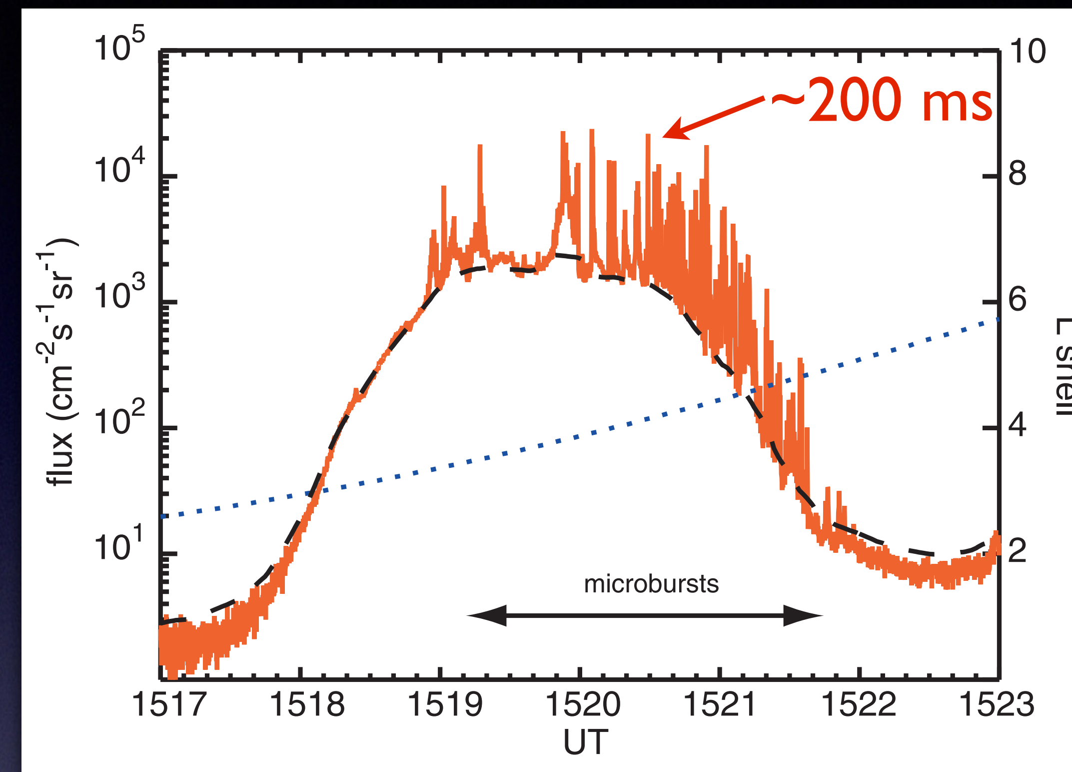
Types of Energetic Precipitation

Duskside (DREP)



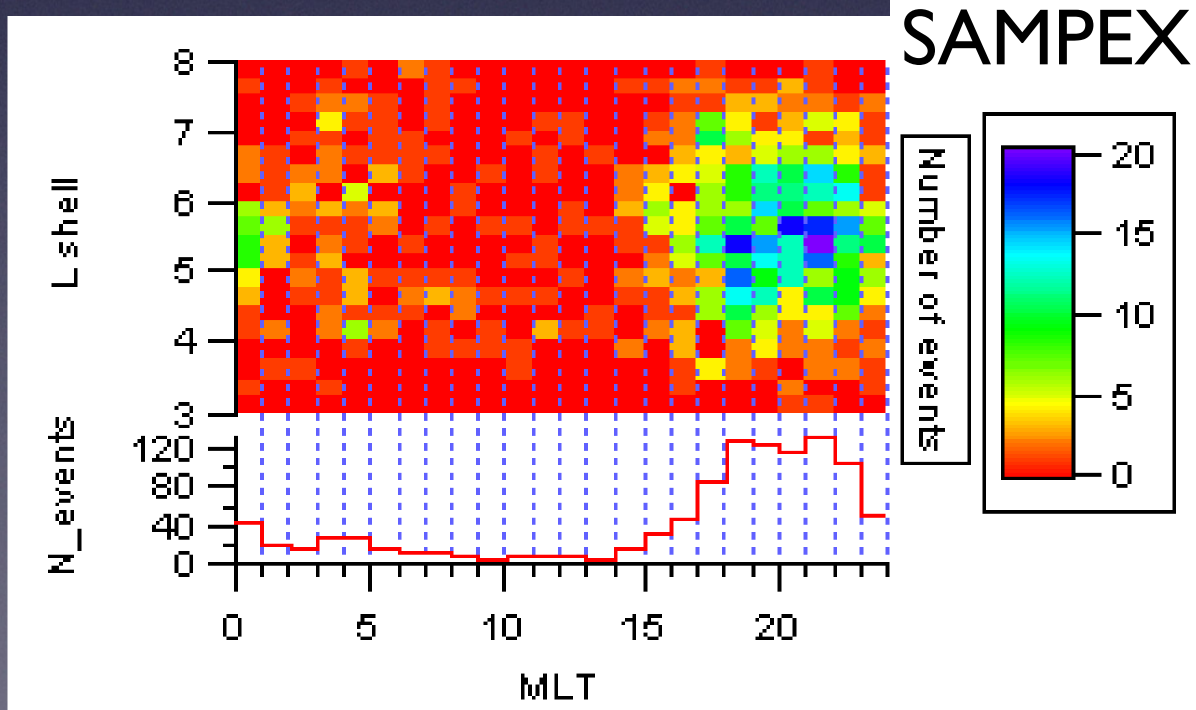
[Millan, 2011]

Microbursts

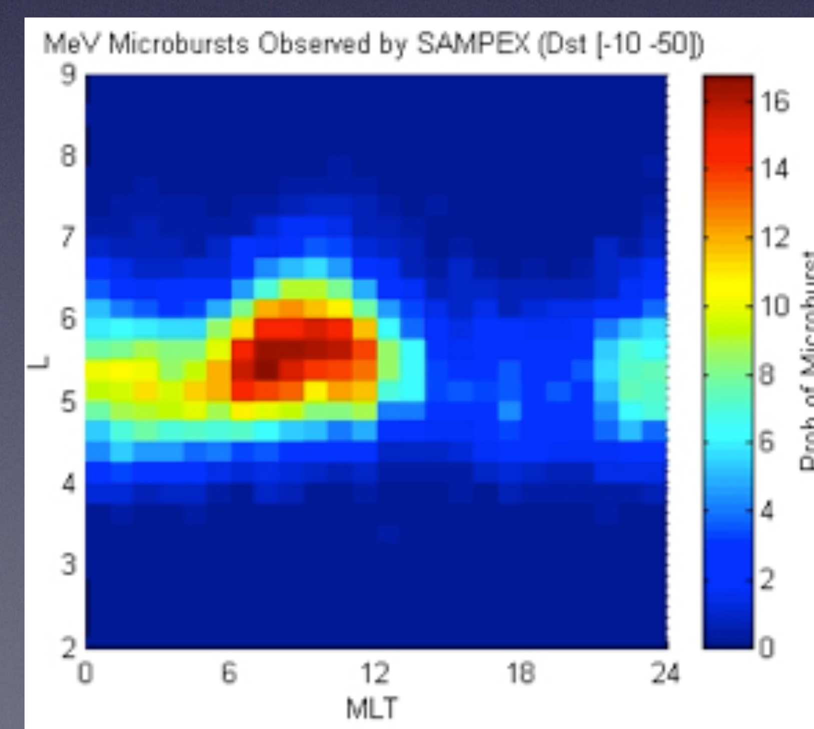


[Lorentzen et al., 2001]

SAMPEX

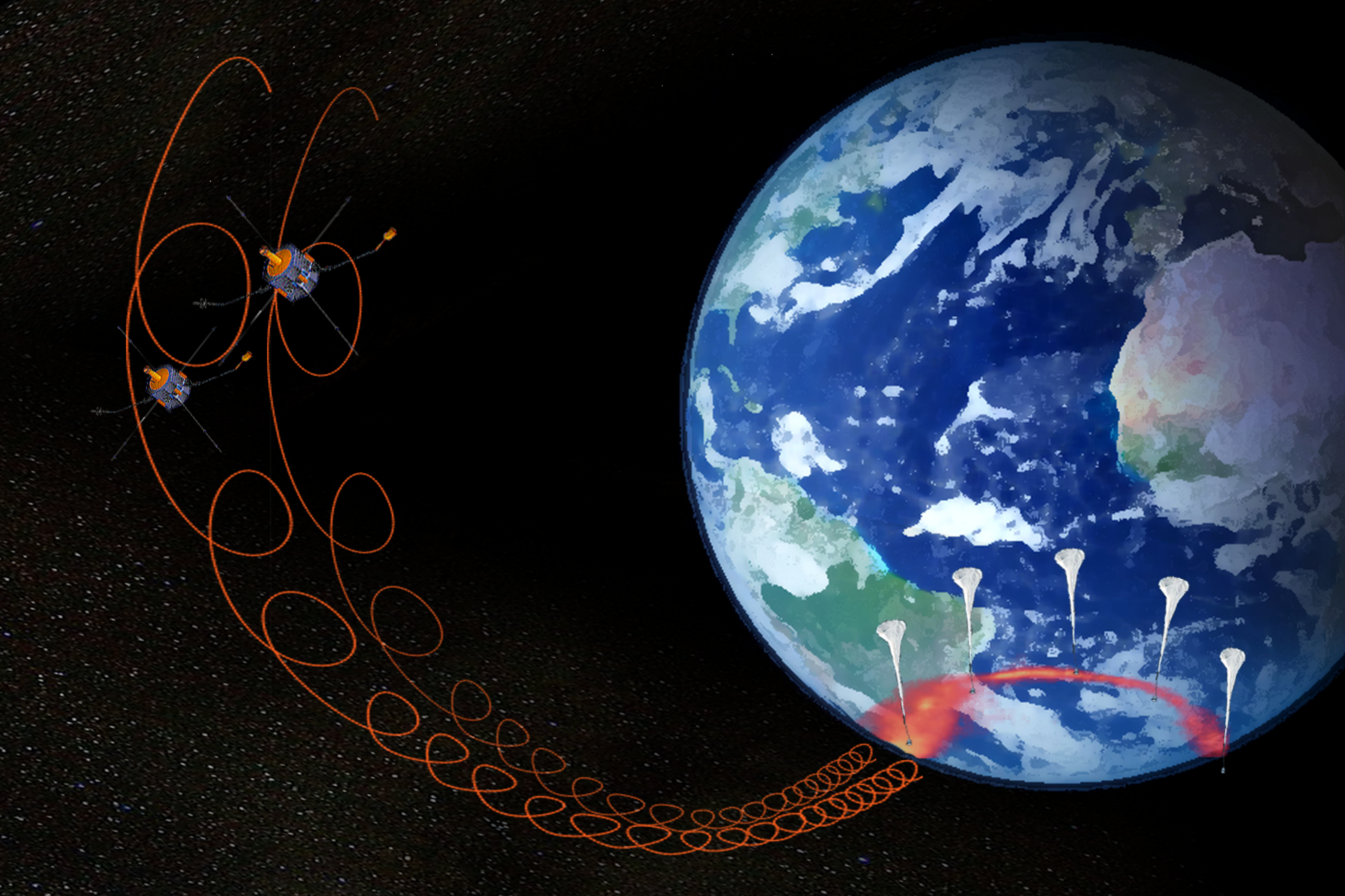


Comess et al., 2013

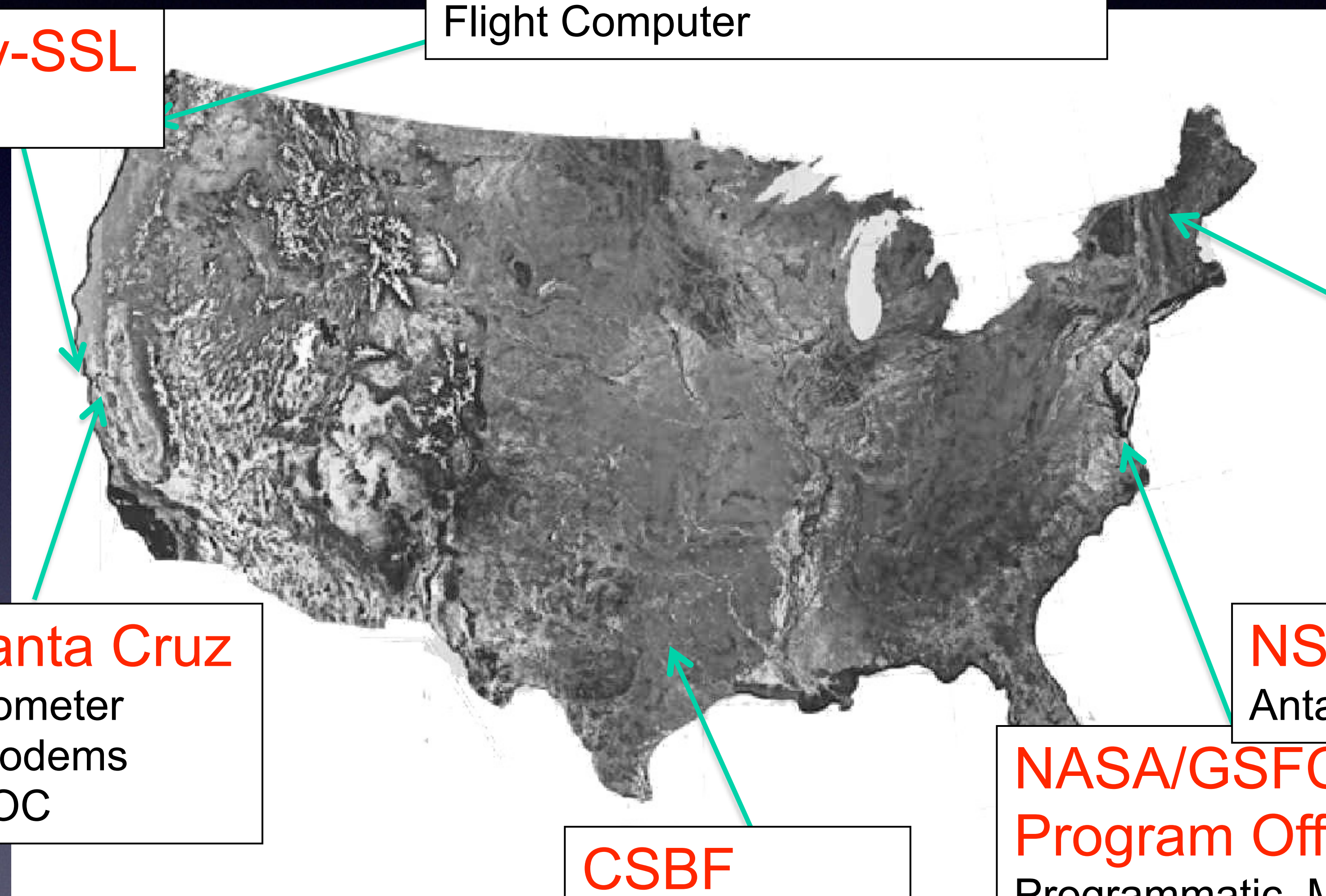


Courtesy T. P. O'Brien

Balloon Array for Radiation belt Relativistic Electron Losses



BARREL Collaboration



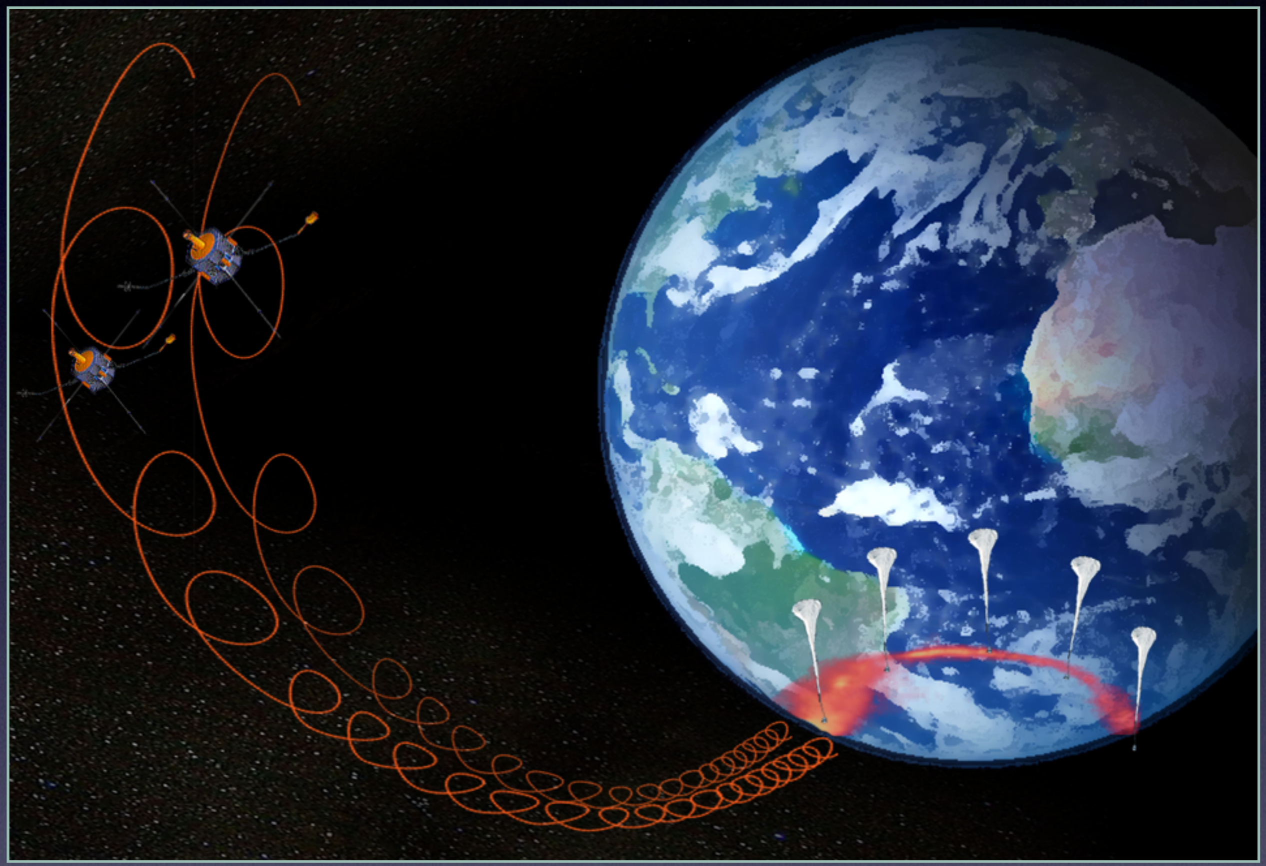
Campaign and science support

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

South African National Antarctic Programme
SANAP
understand, develop, conserve

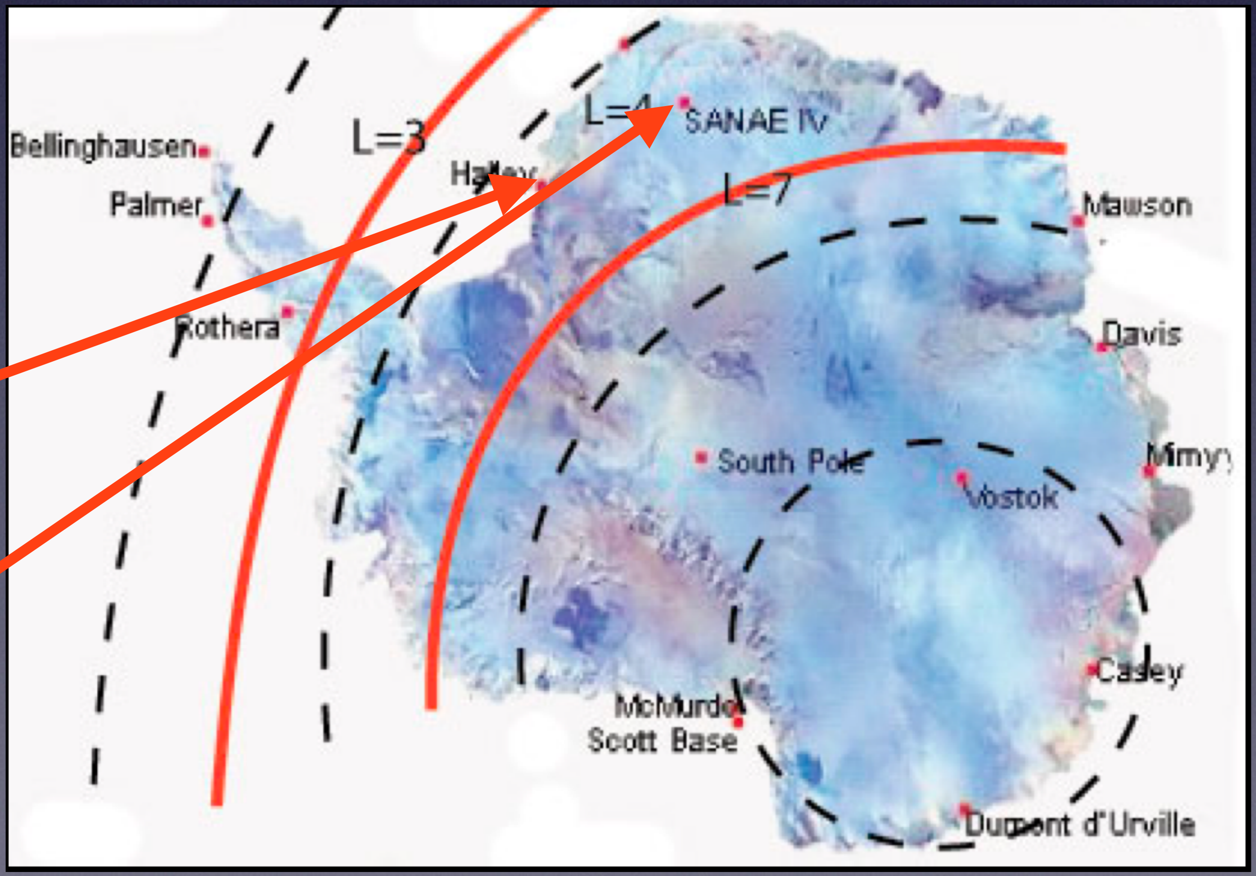
Platform - Balloon Array

- BARREL is a multiple-balloon experiment designed to study radiation belt electron loss to the atmosphere



- 5-8 balloons aloft at a time
- Avg. flight duration: 12 days
- 20 balloons each in 2013 & 2014

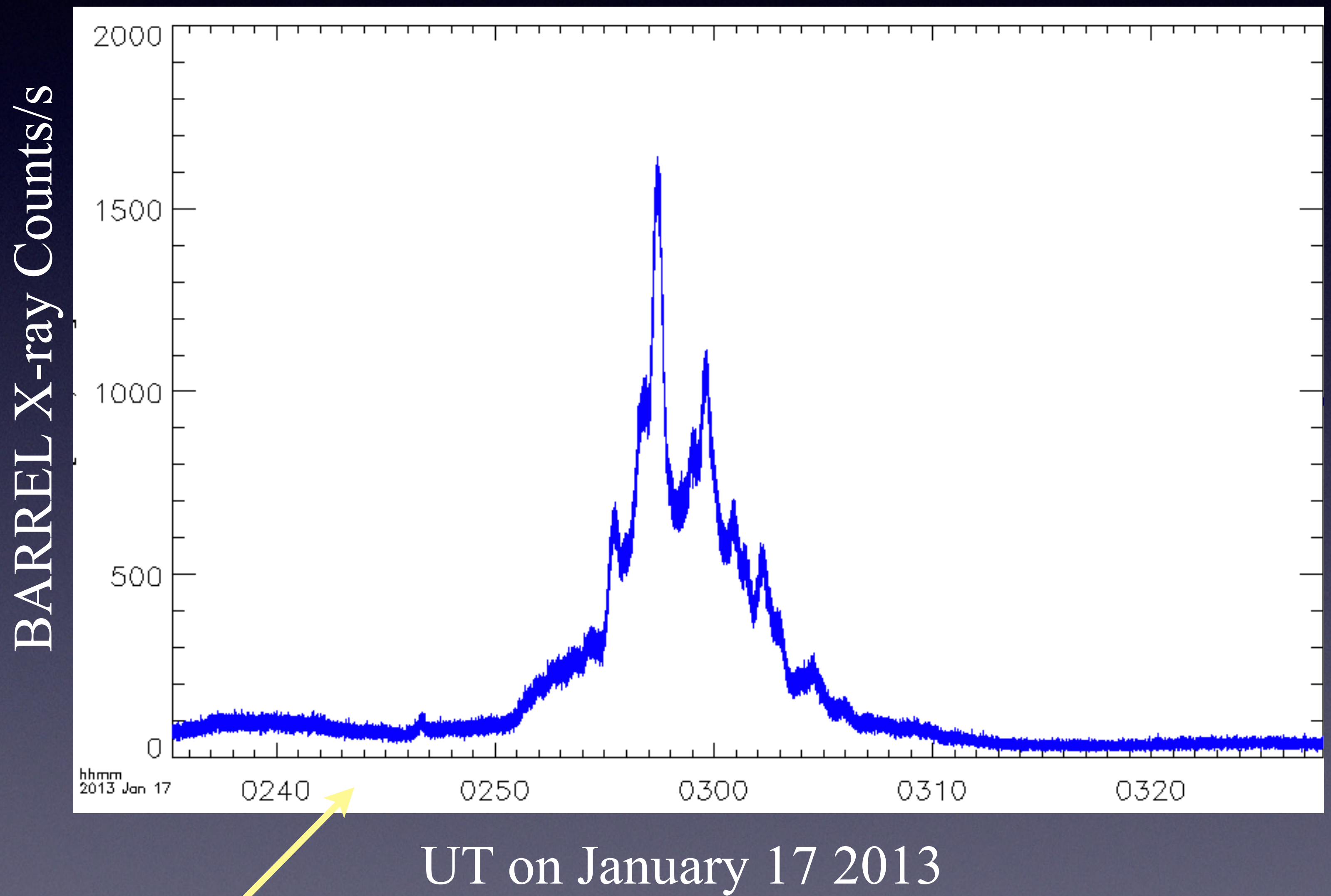
Two Antarctic launch sites:
- Halley (UK)
- SANAE IV (South Africa)

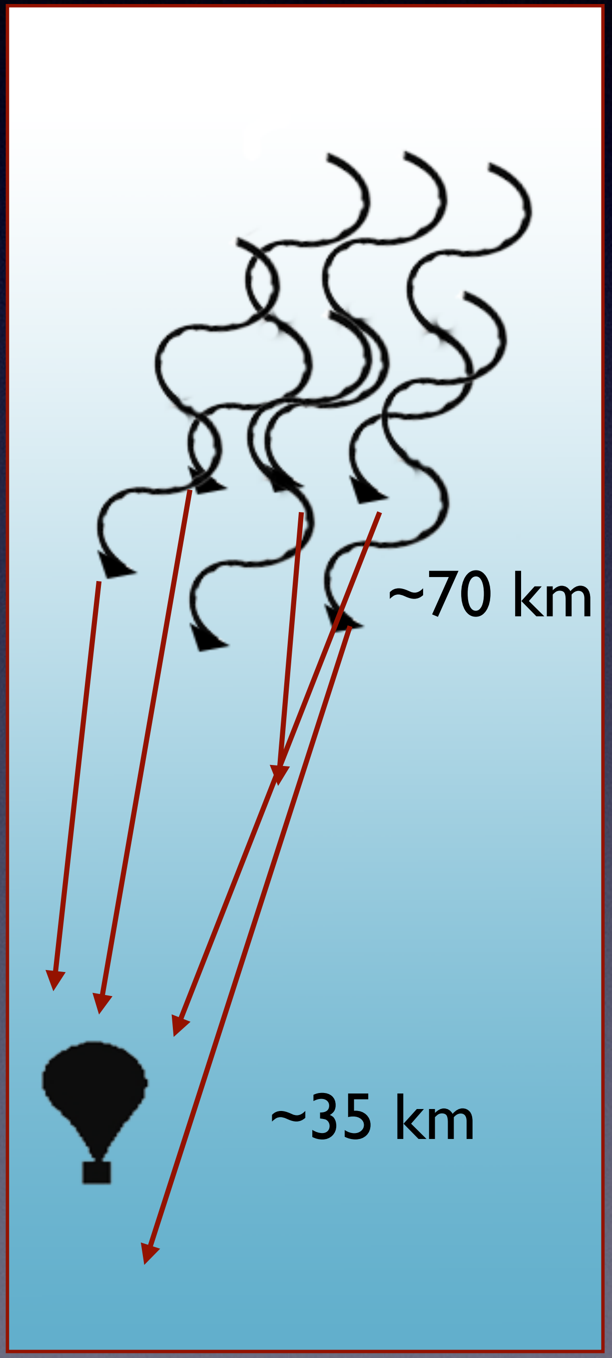


[Millan et al., 2013]

Balloon Observations of Electron Loss

- Bremsstrahlung X-rays are produced as electrons collide with atmospheric neutrals.

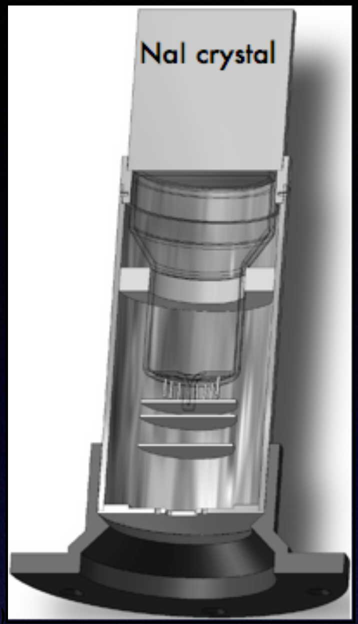


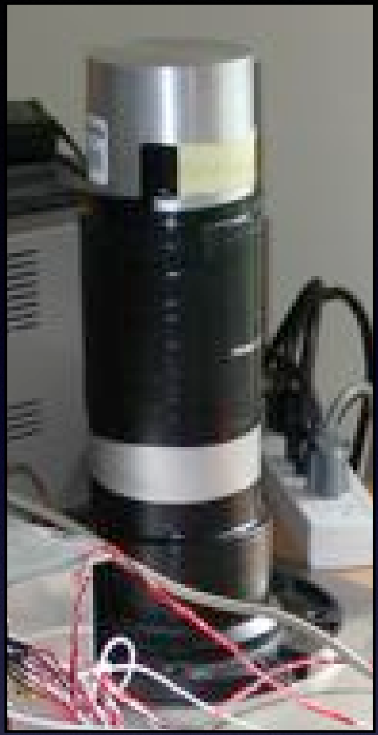


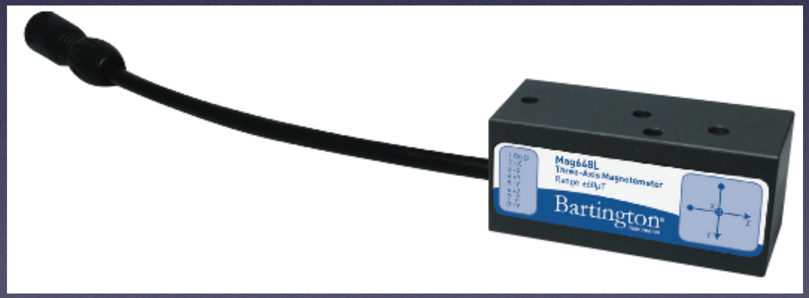
Relativistic electron precipitation event detected during 2013 BARREL campaign

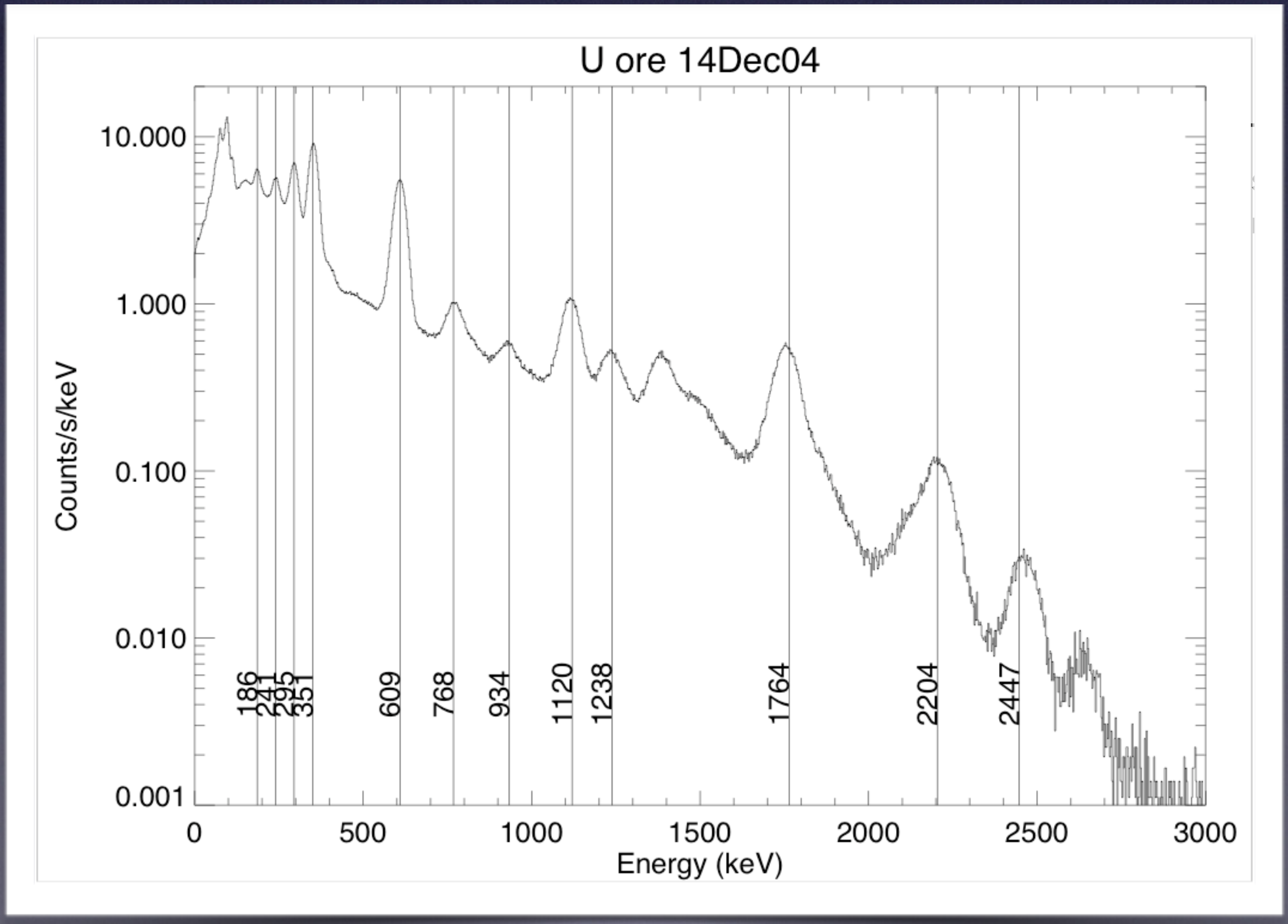
BARREL Science Instruments

- X-ray spectrometer
  - 3" x 3" sodium iodide scintillator
  - Energy range: 20 keV - 6 MeV
  - Effective area: 16cm^2 (photopeak)
  - Energy resolution: 10% at 1 MeV
  - Time resolution: 50 ms in 4 energy bands





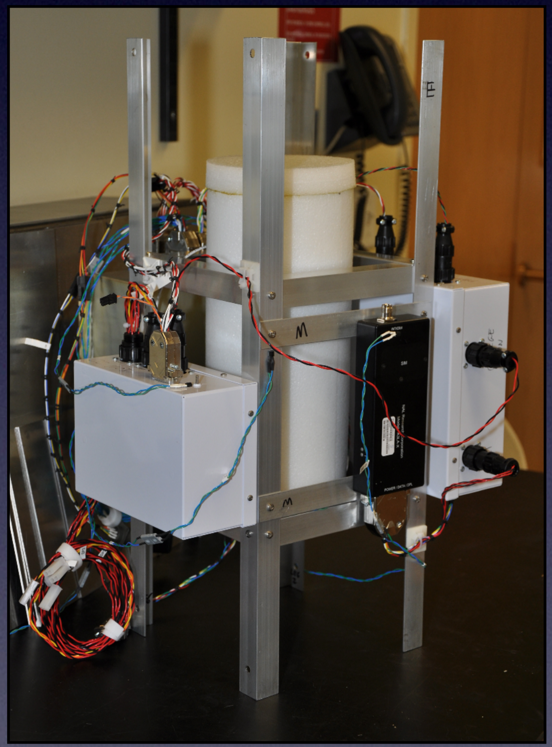


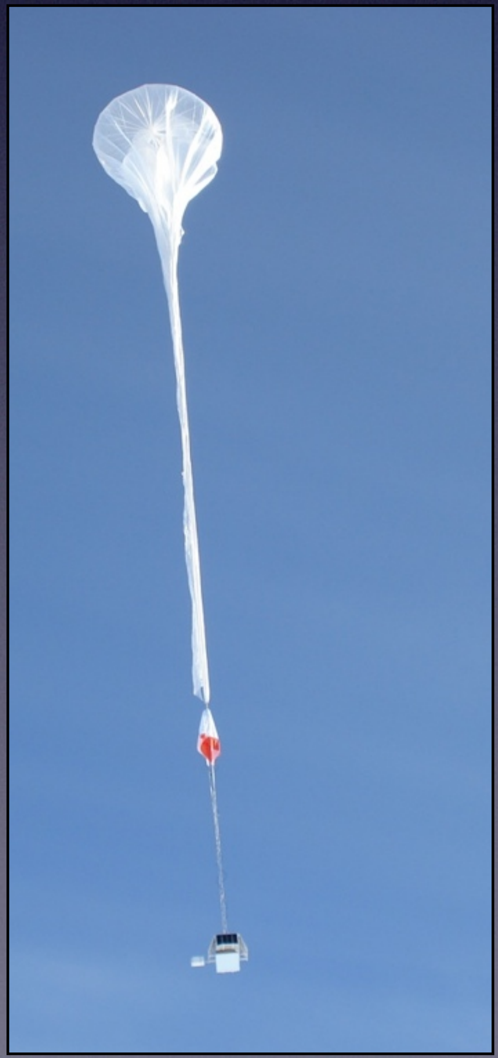


- DC Magnetometer
  - Bartington fluxgate
  - Sensitivity: 0.1 nT
  - Sampling at 4 Hz

BARREL Payload Design

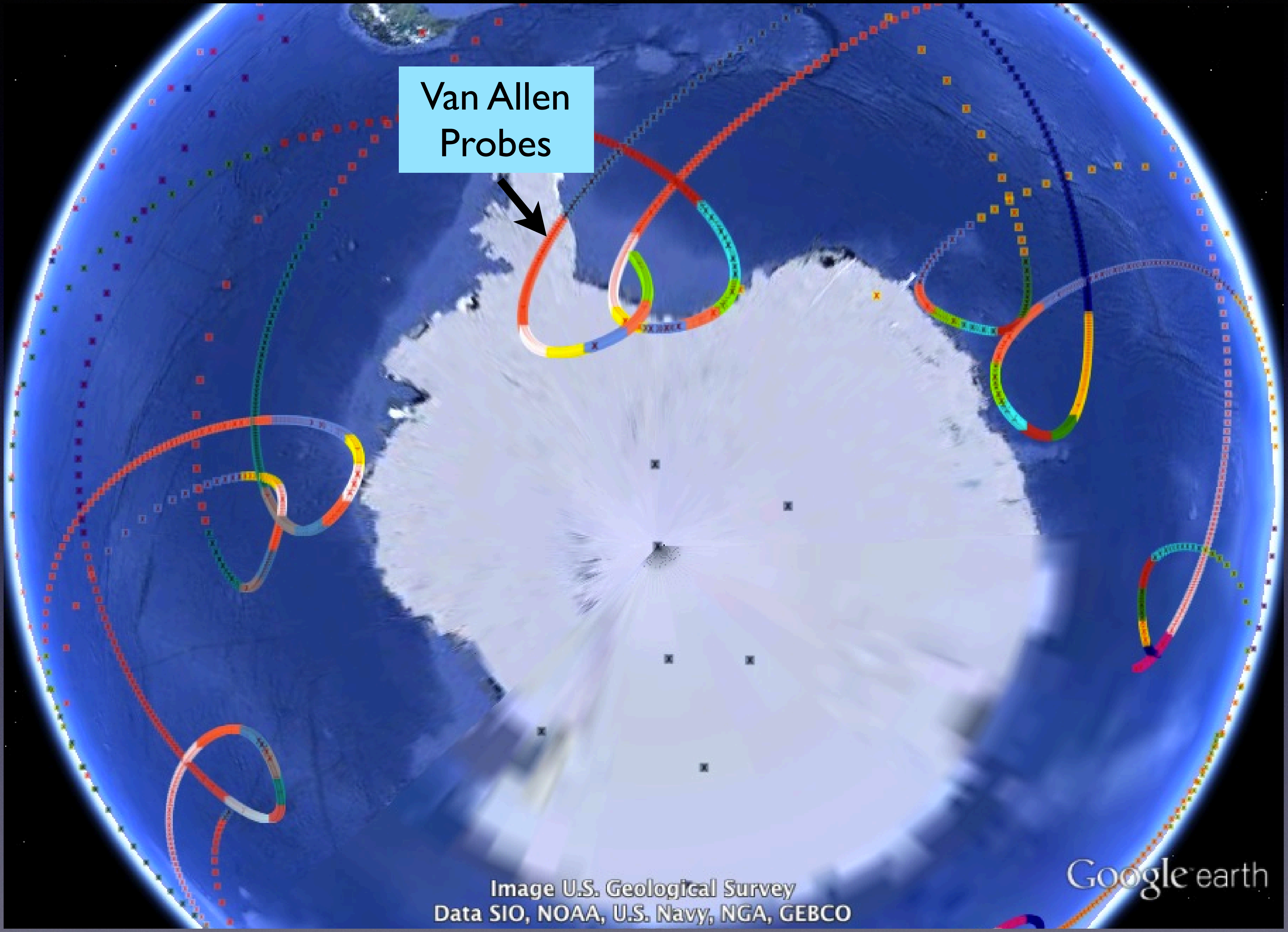
- Supporting Instrumentation
  - GPS time and position: Trimble Lassen SQ
  - Custom data acquisition system
  - Telemetry: Iridium satellite network ~2 kbits/s



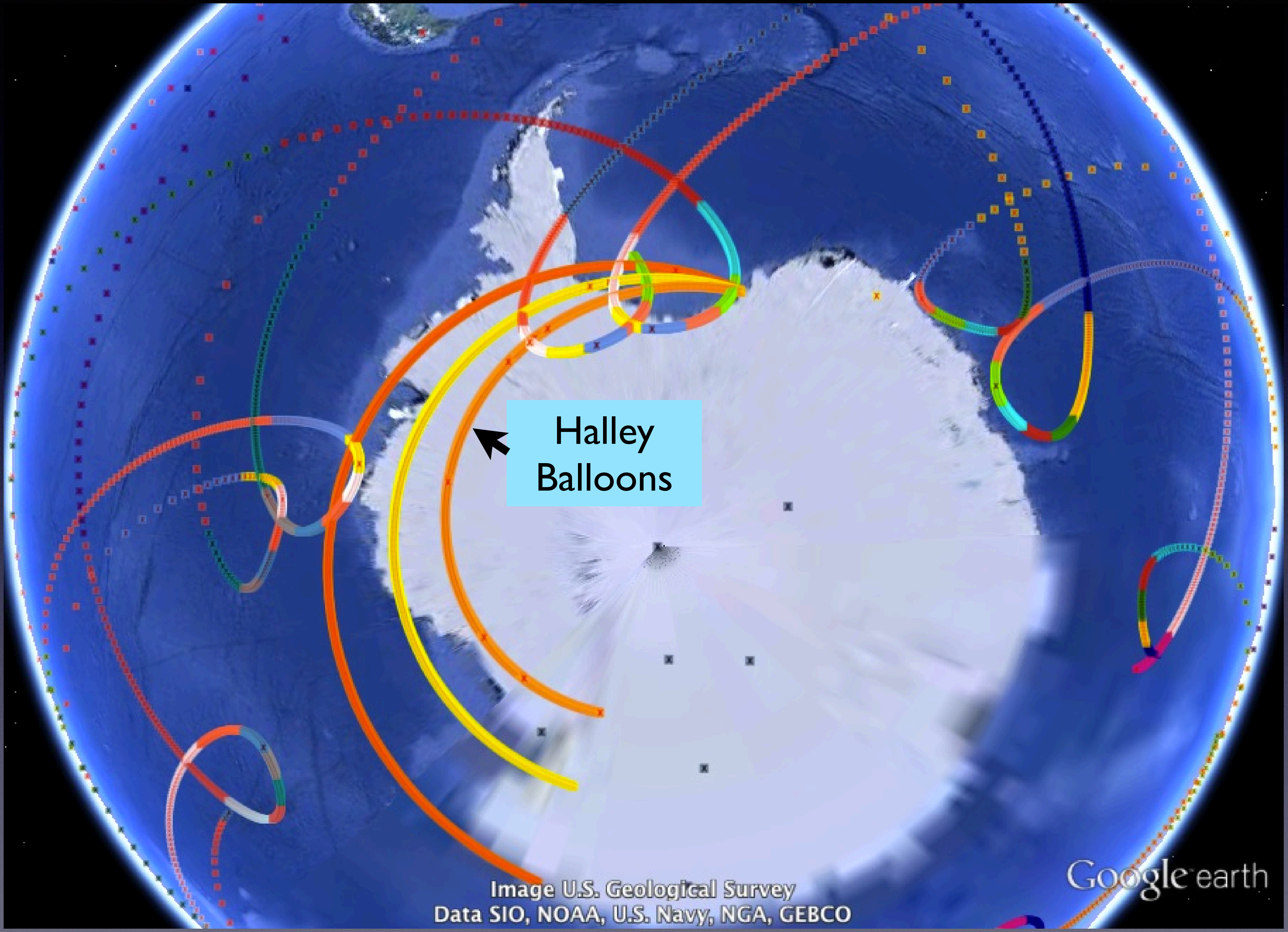


- Payload
  - Suspended mass: ~20 kg
  - Power: ~5W supplied by PV panels
  - Hand-launched on 300,000 ft balloon

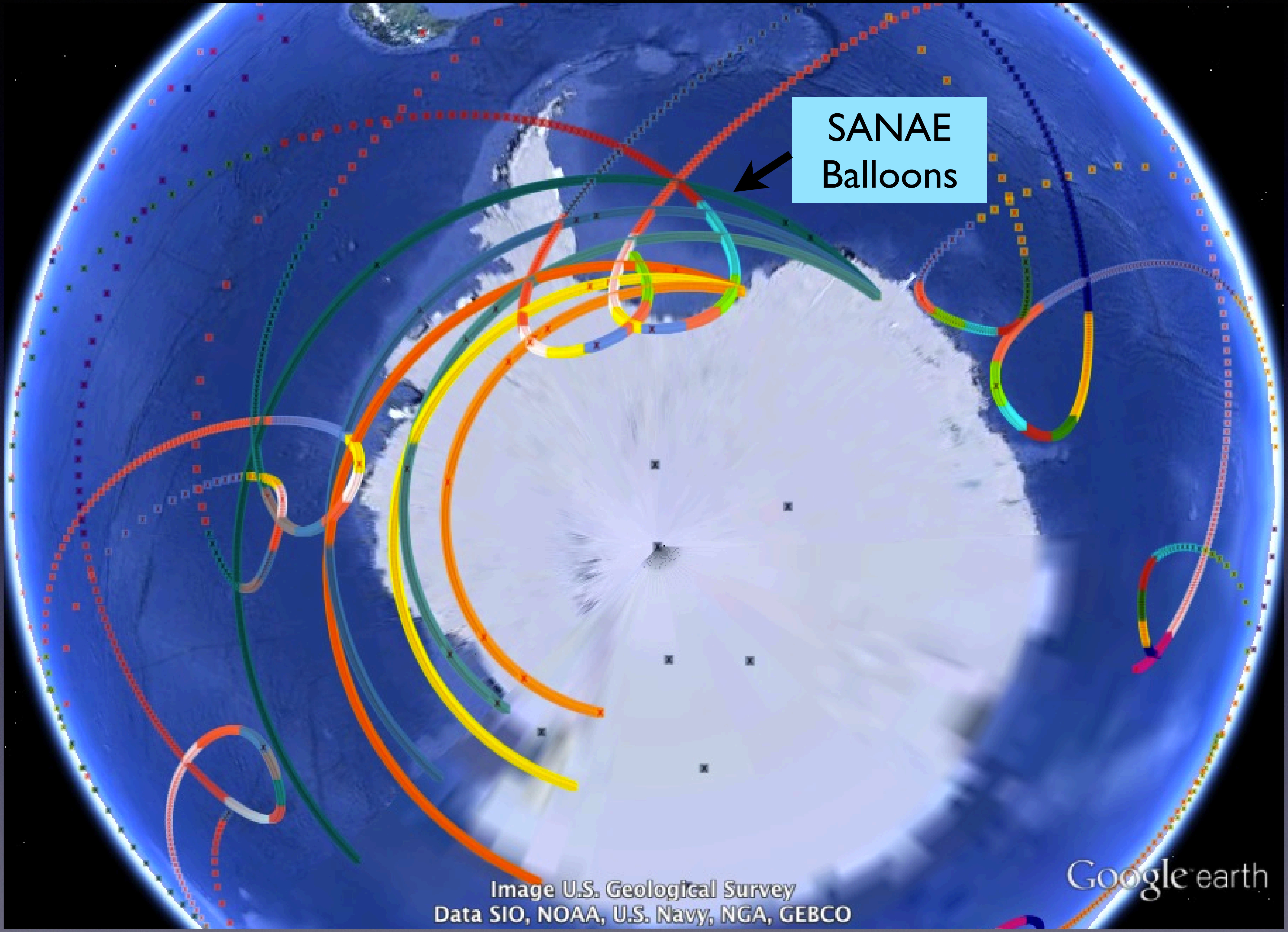
The Plan: Conjunctions with Van Allen

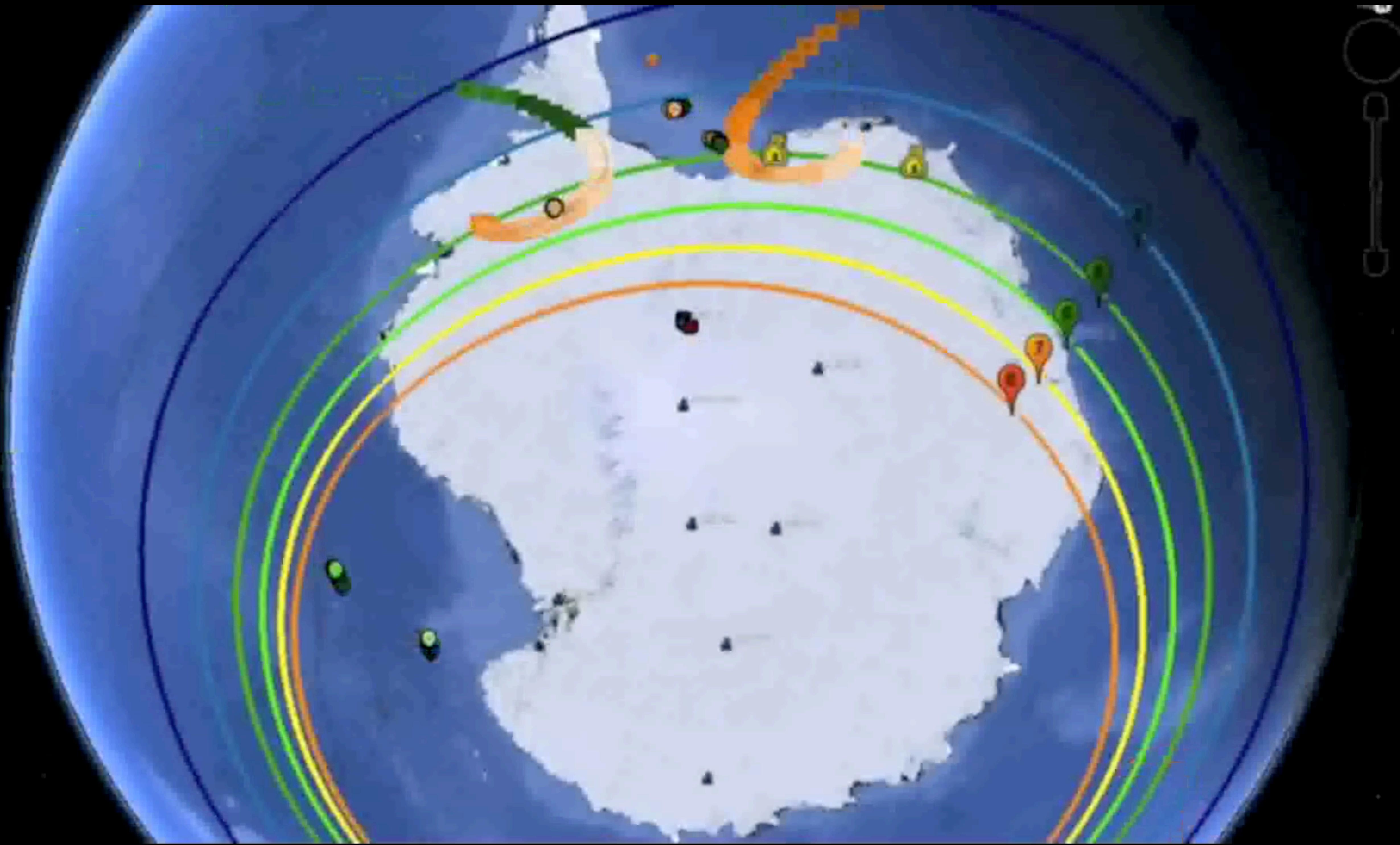


The Plan: Conjunctions with Van Allen

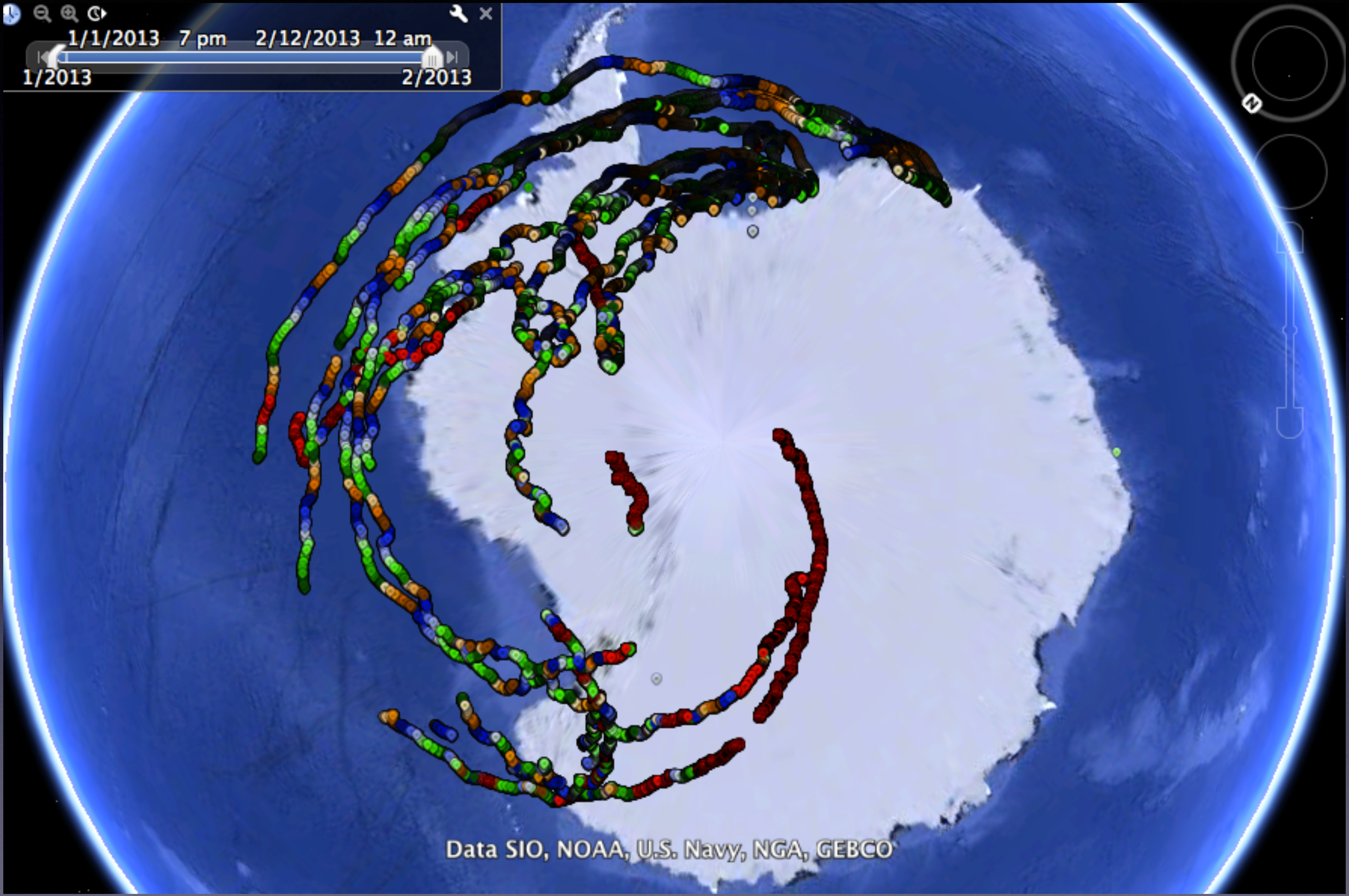


The Plan: Conjunctions with Van Allen

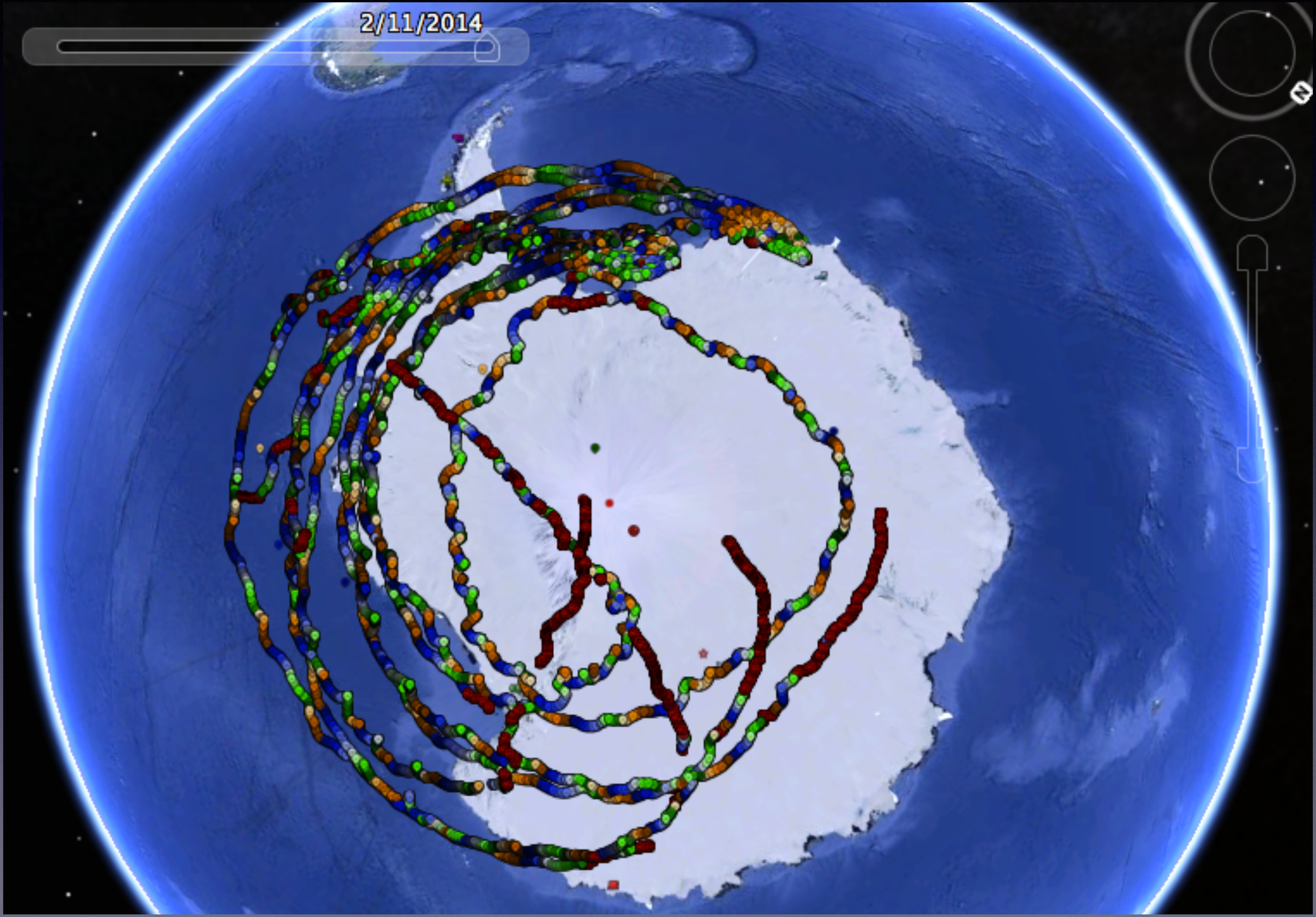




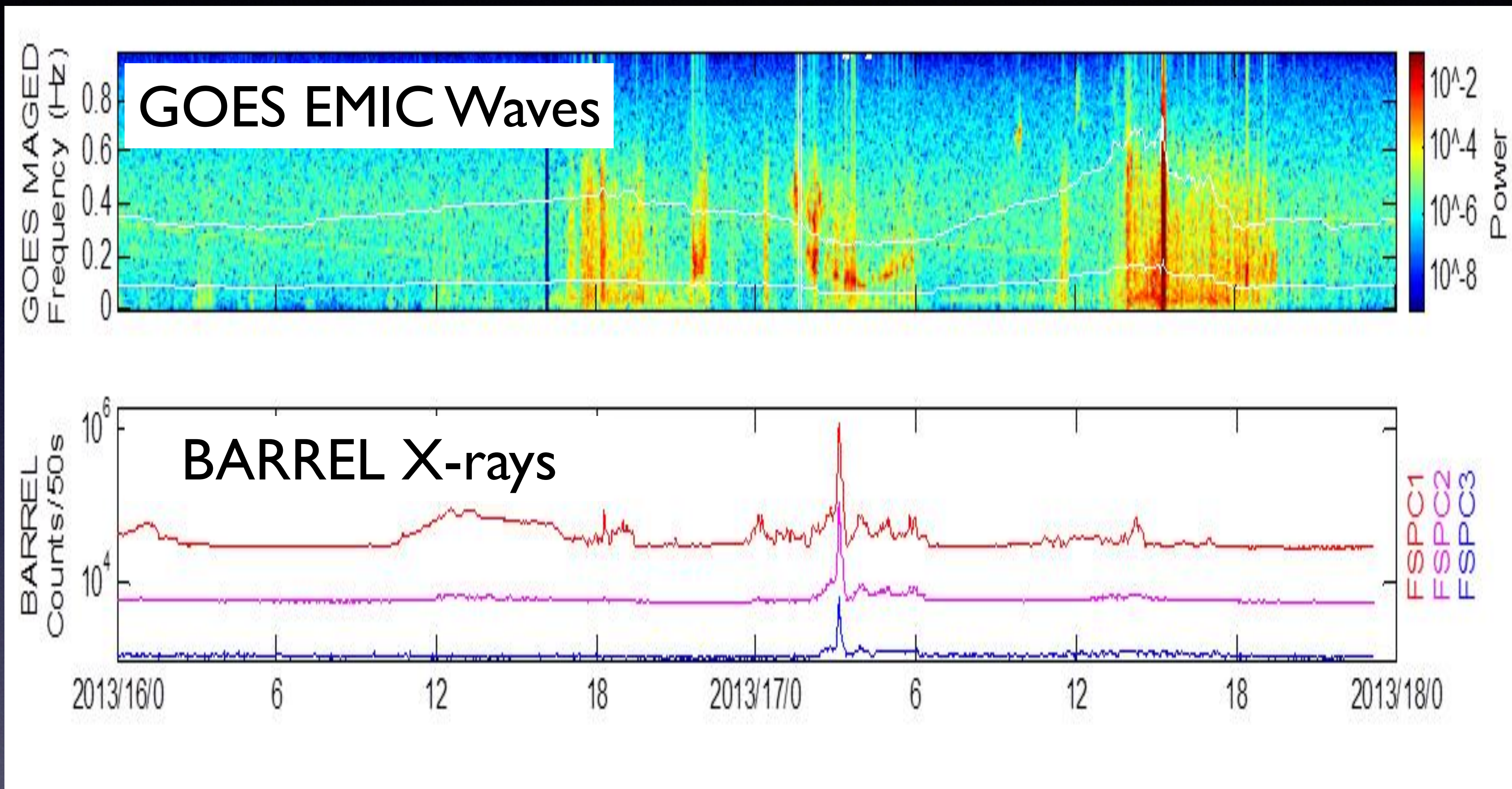
BARREL 2013 Balloon Trajectories

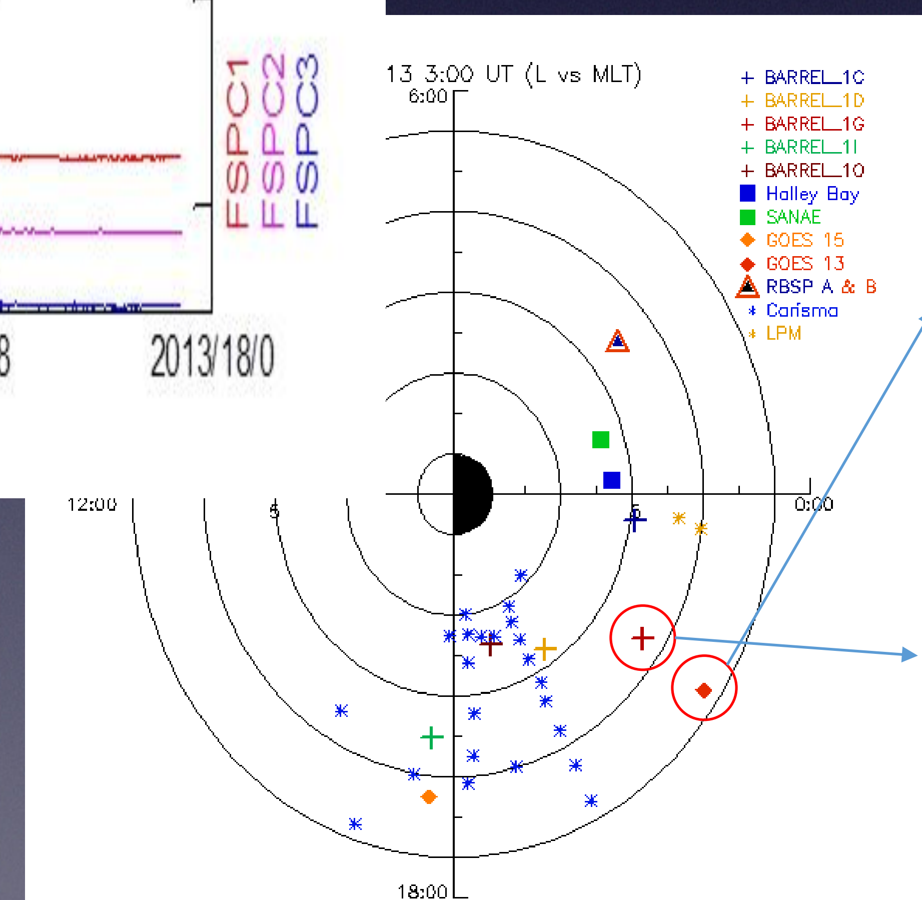


BARREL 2014 Balloon Trajectories



BARREL Observations of Relativistic Electron Precipitation



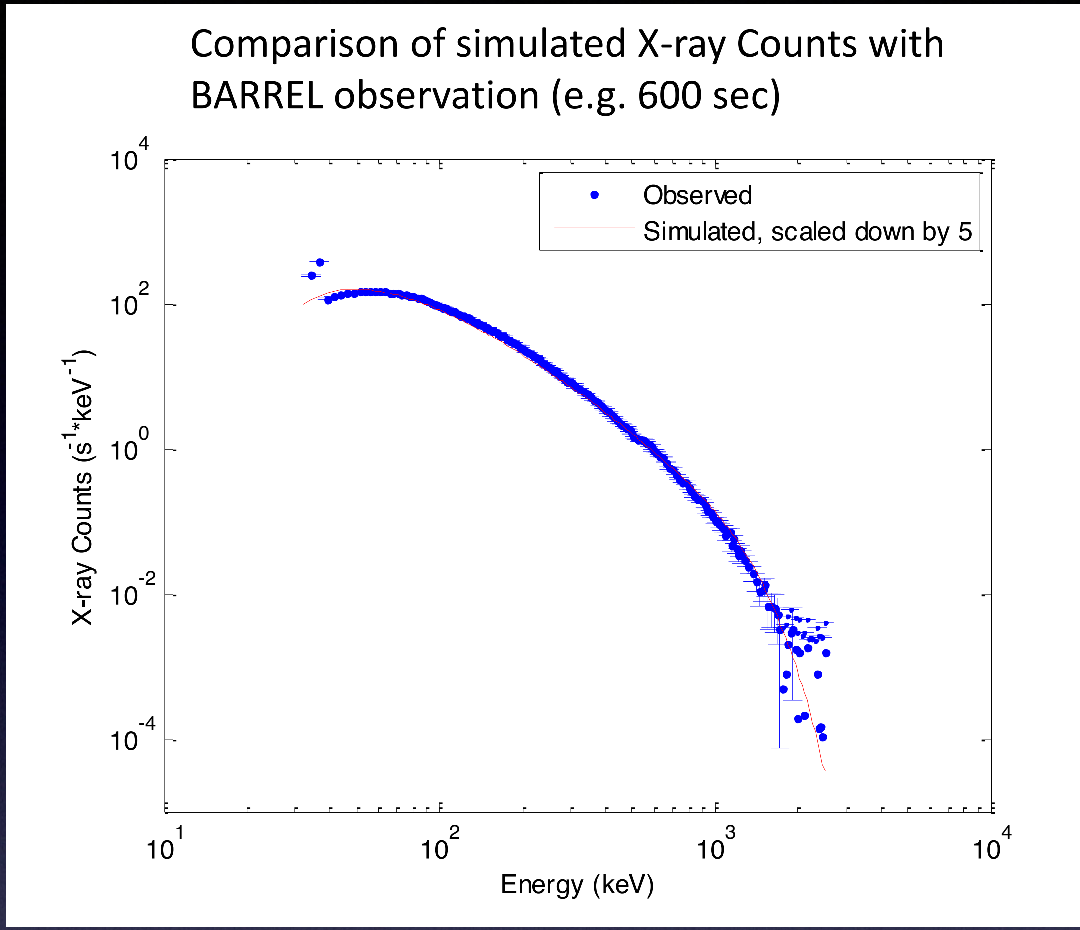


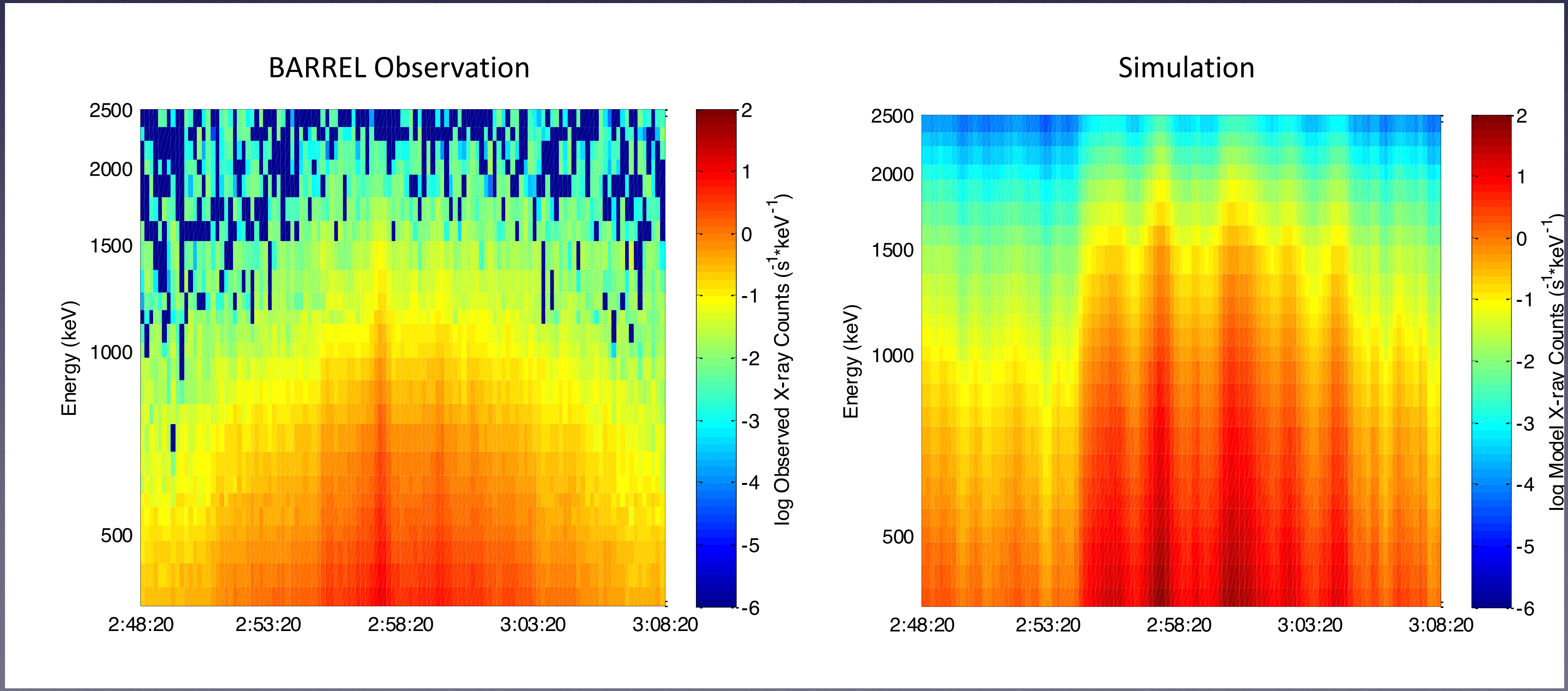
- Associated with a magnetospheric compression
- EMIC waves observed during precipitation event

Li et al., in prep.

Quantitative Test of EMIC Scattering

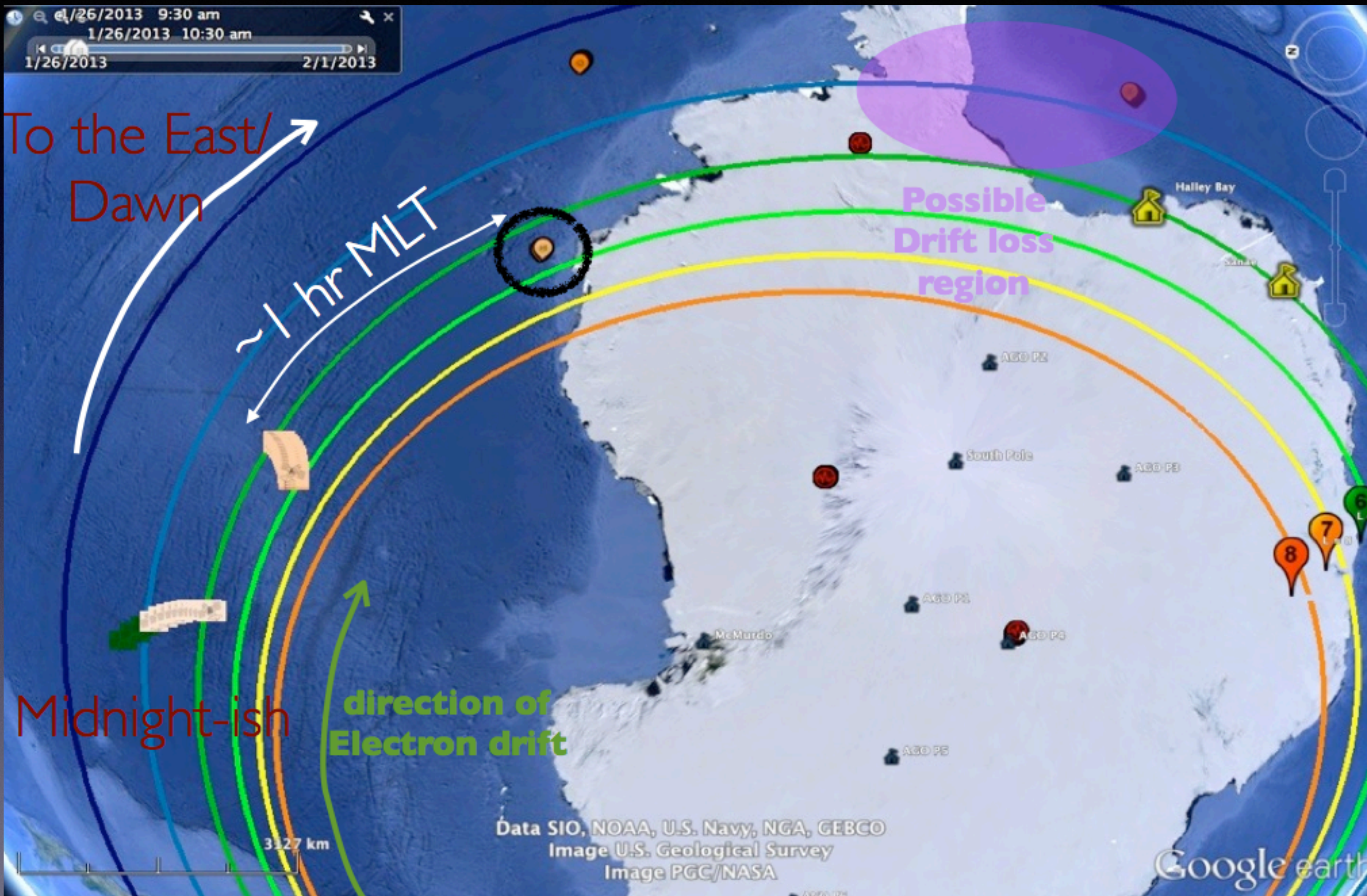
- Quasi-linear diffusion model to simulate wave-particle interaction
- Calculate diffusion coefficients
  - GOES wave parameters
  - plasma and energetic particle parameters from RBSP





Li et al., in prep.

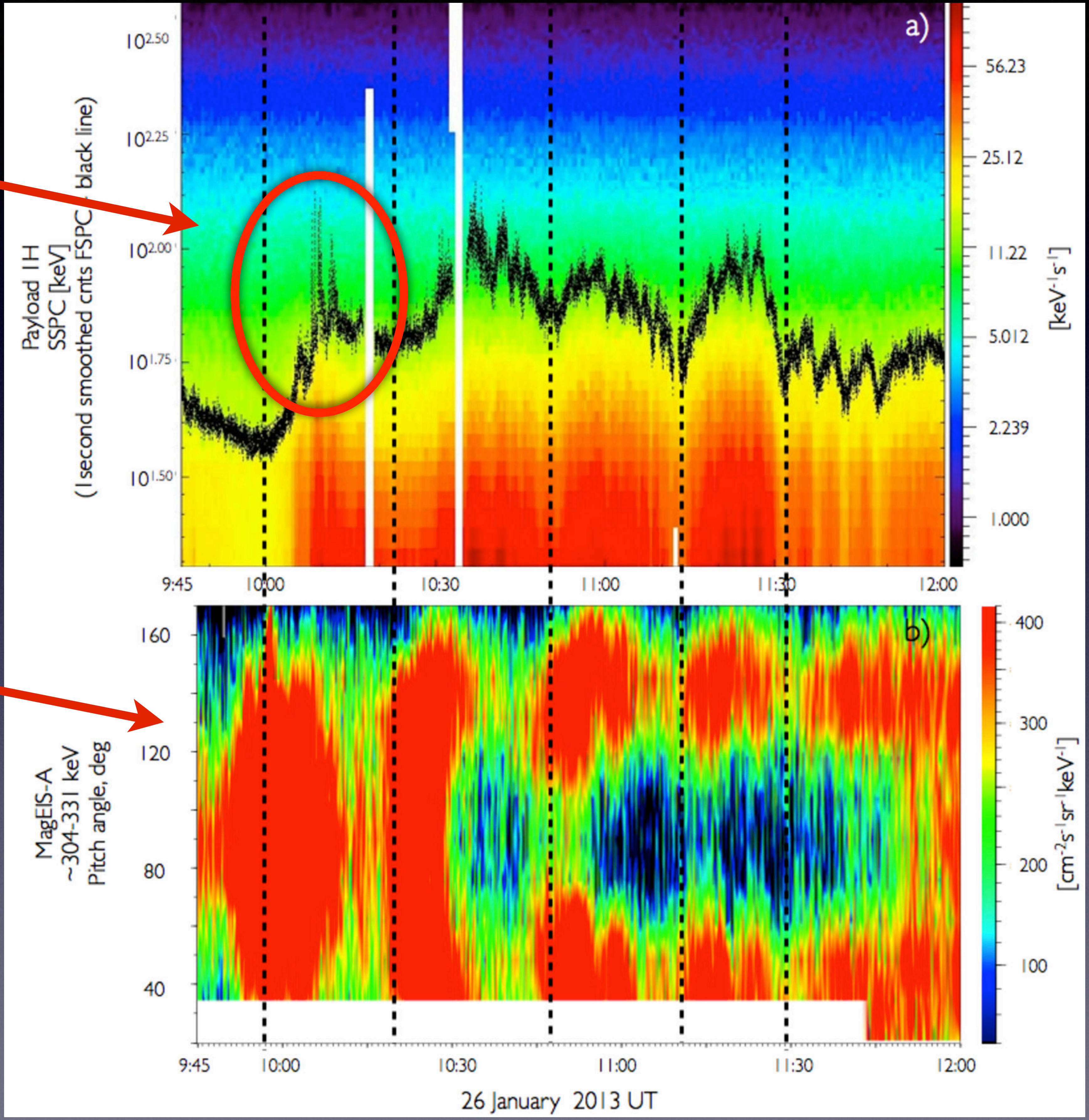
Conjunction with Van Allen on Jan. 26, 2013



Drift Echo Modulation

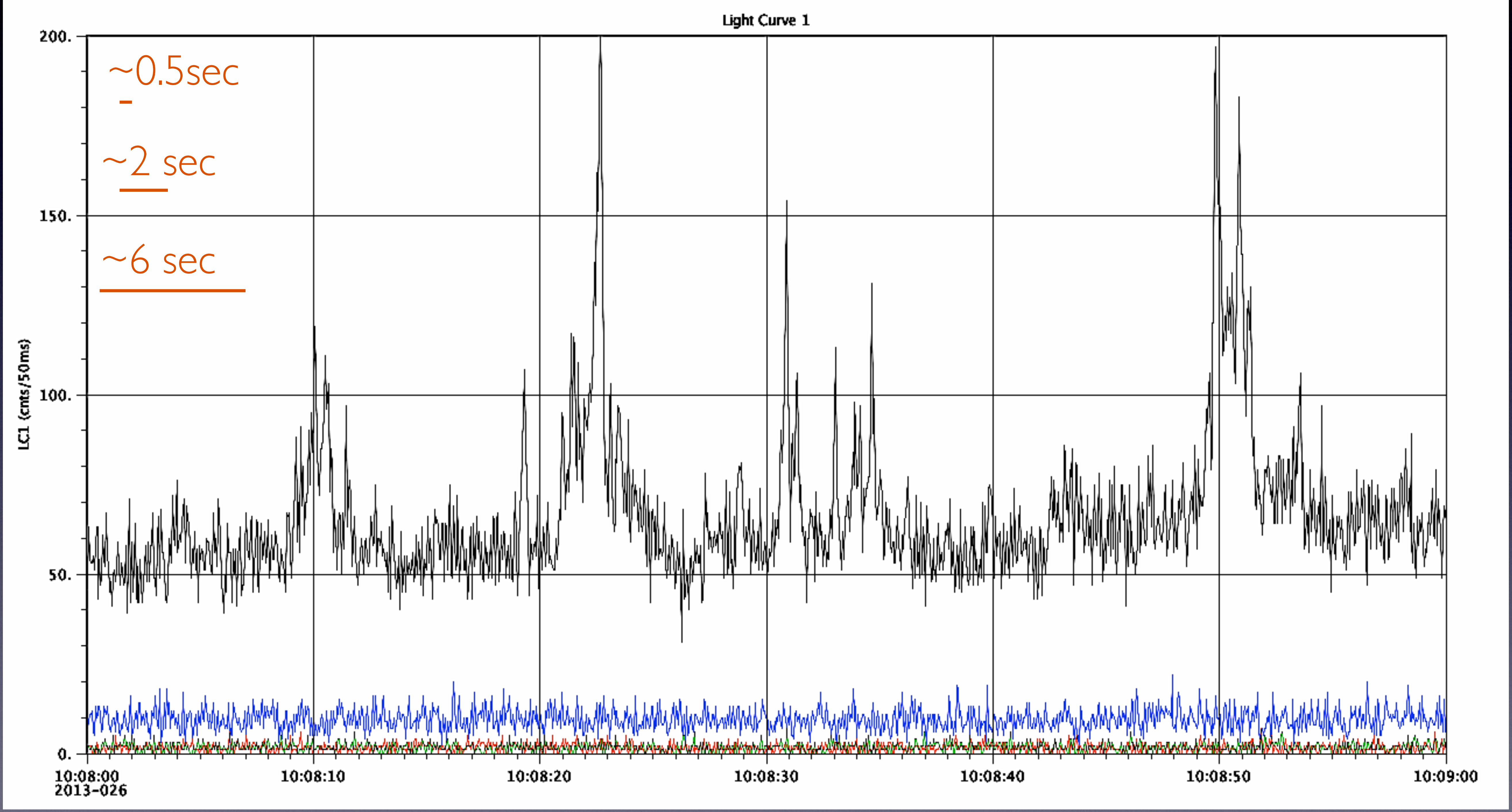
BARREL X-ray Observations

Van Allen (MagEIS) 300 keV electrons

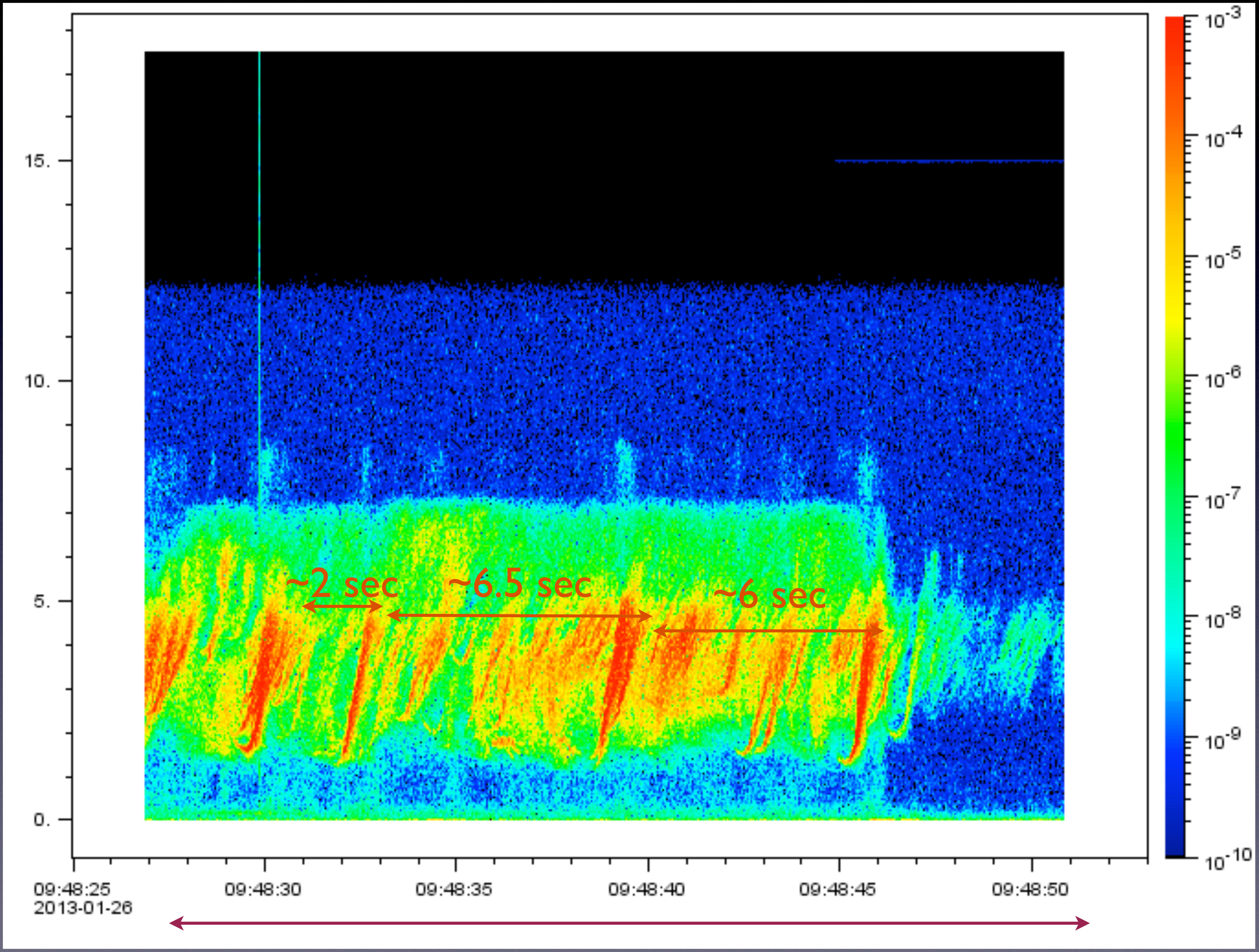


Halford, et al., in prep.

Payload 1H sees microbursts.



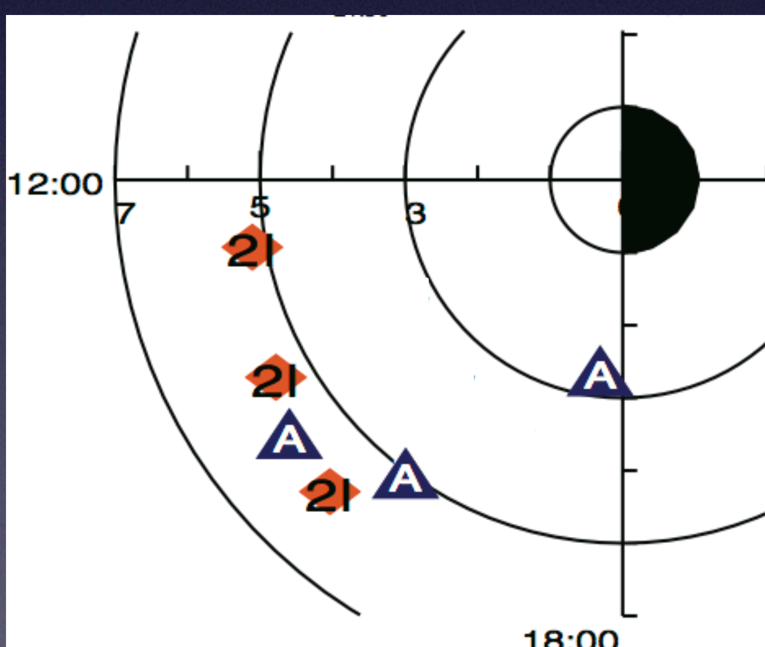
EMFISIS Whistler Waves

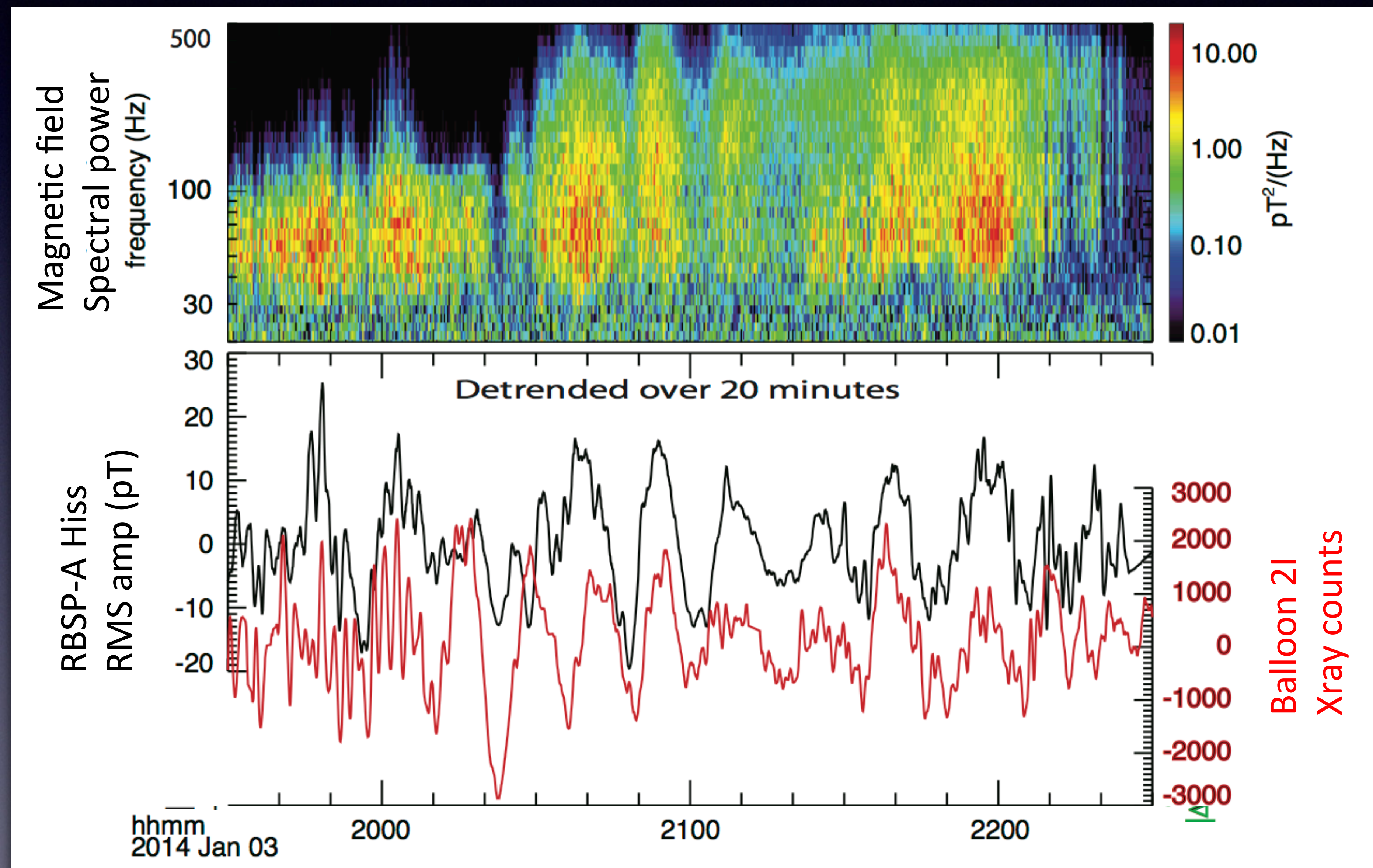


24 seconds

Jan. 3, 2014: Precipitation and Hiss

- Correlation between plasmaspheric hiss amplitude and precipitation

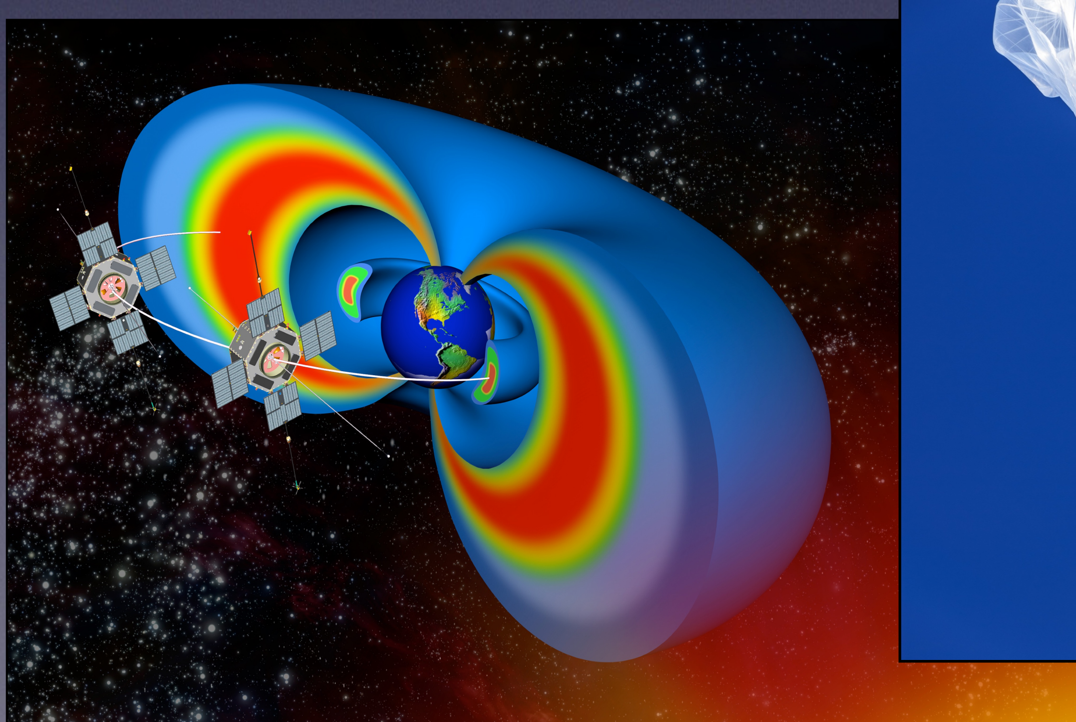


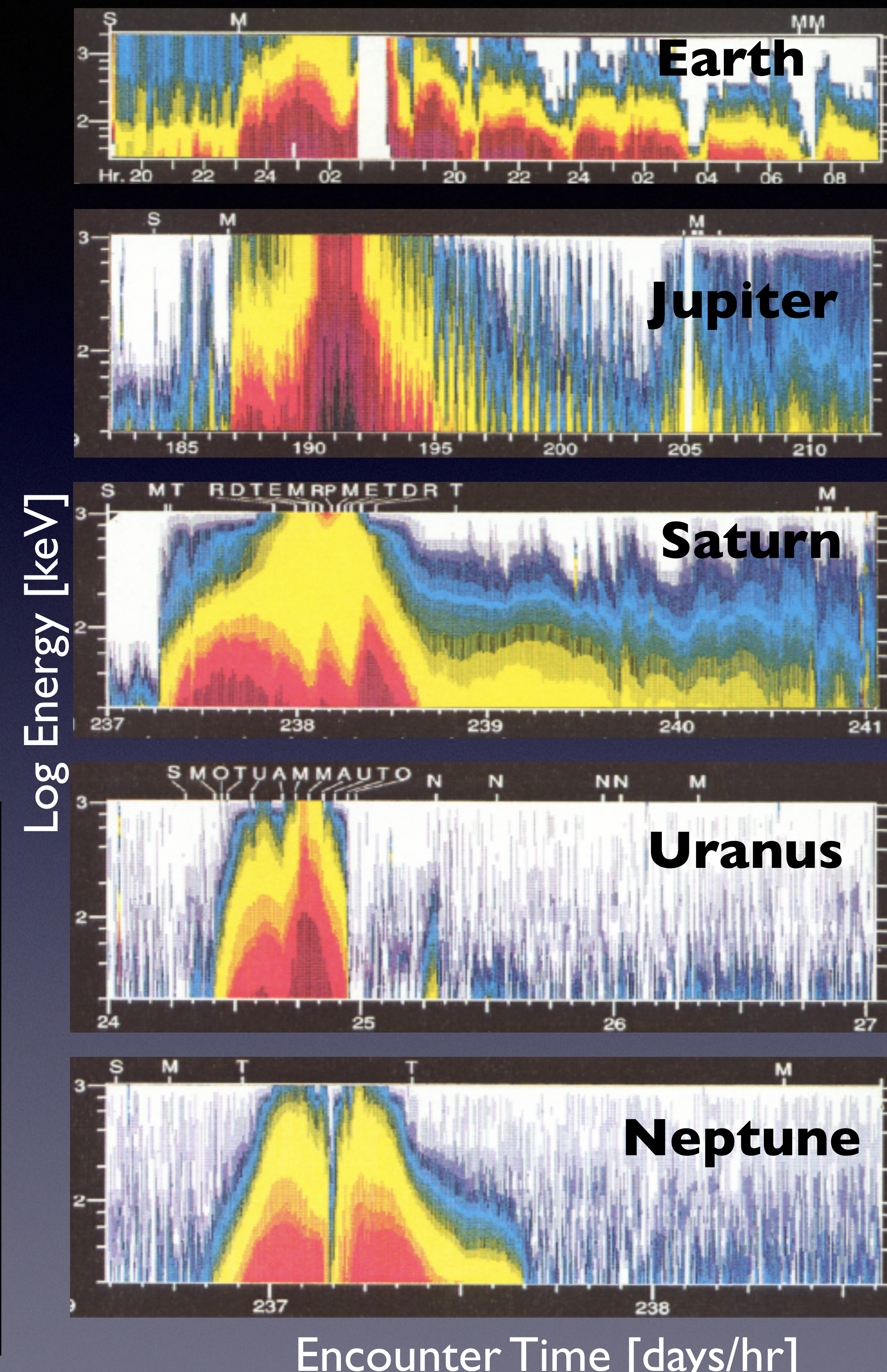


Breneman et al., in prep.

Conclusions

- Earth's Radiation belts are an accessible region for studying particle acceleration
- Provide a laboratory for understanding physics of trapped particles
- Lack of comprehensive measurements thus far
  - => variability is still a mystery
  - => processes are not well understood
- Van Allen and BARREL provide a unique opportunity to study the physics





Websites

BARREL Project Website: http://www.dartmouth.edu/~barrel

BARREL Blog: http://relativisticballoons.blogspot.com

Summary Plots and Data Access:

- http://earthweb.ess.washington.edu/mccarthy/BARREL/
- http://soc2.ucsc.edu