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Using Data-Intelligent Models to Understand the Physics of the Inner Magnetosphere

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Three provocative motivations for DI

- Physics-based numerical models are mathematical expressions of what we think we know
- Statistics and artificial intelligence are numerical models that predict the behavior of systems we don't understand
- Data assimilation is a little of both

What Do I Mean by Data-Intelligence?

- Firstly: I just made it up, but…
- What I mean is utilizing data and numerical techniques to provide intelligence about a system, where 'intelligence' means discovering secrets and understanding the inner workings
- Working in the opposite direction: using data and numerical techniques to provide intelligence about observations; i.e. getting more information and understanding from existing observations

Is Reproducing the Data or Prediction the Goal?

- Many of our current techniques (Data Assimilation, Statistical Methods, Neural Networks/AI…) are primarily used to reproduce observations - especially using one set of data to reproduce another

- By extension we often treat prediction as the holy grail

- If the agreement between the numerical model and the independent data set is 'reasonably good' then we assume the model is capturing the important dynamics in one way or another: physics-based, statistical, or even 'black box' methods

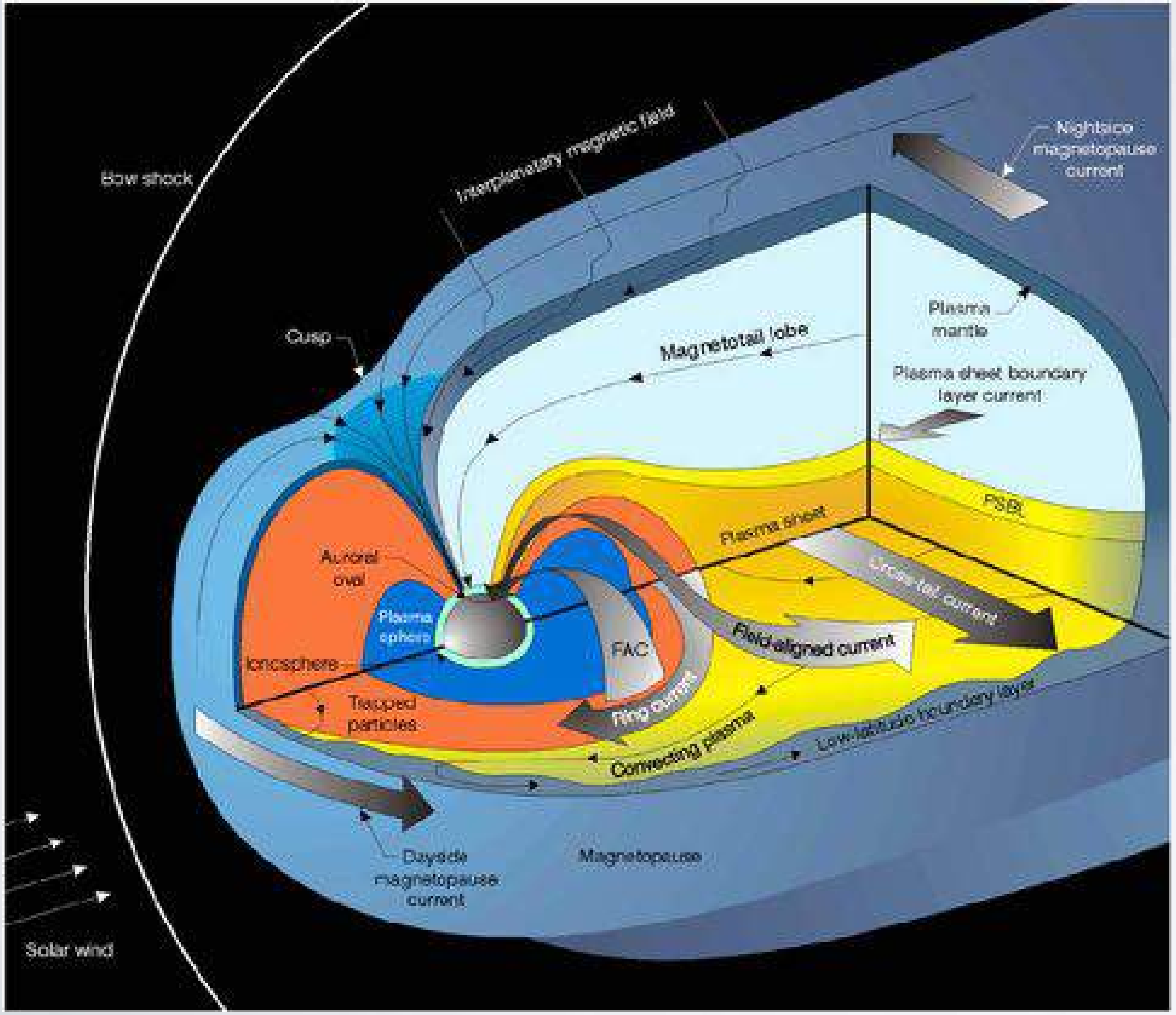
Beyond Good Agreement

- I believe that data-intelligence could take us beyond 'good agreement' to provide more new discoveries and more physical insights
- What do errors and residuals tell us about missing physical processes in the model and/or missing inputs?
- Can we identify an 'ideal' set of inputs/data for specifying a system?
- Could we use models to improve the quality of the observational data or quantify uncertainties in the data?

Caveats

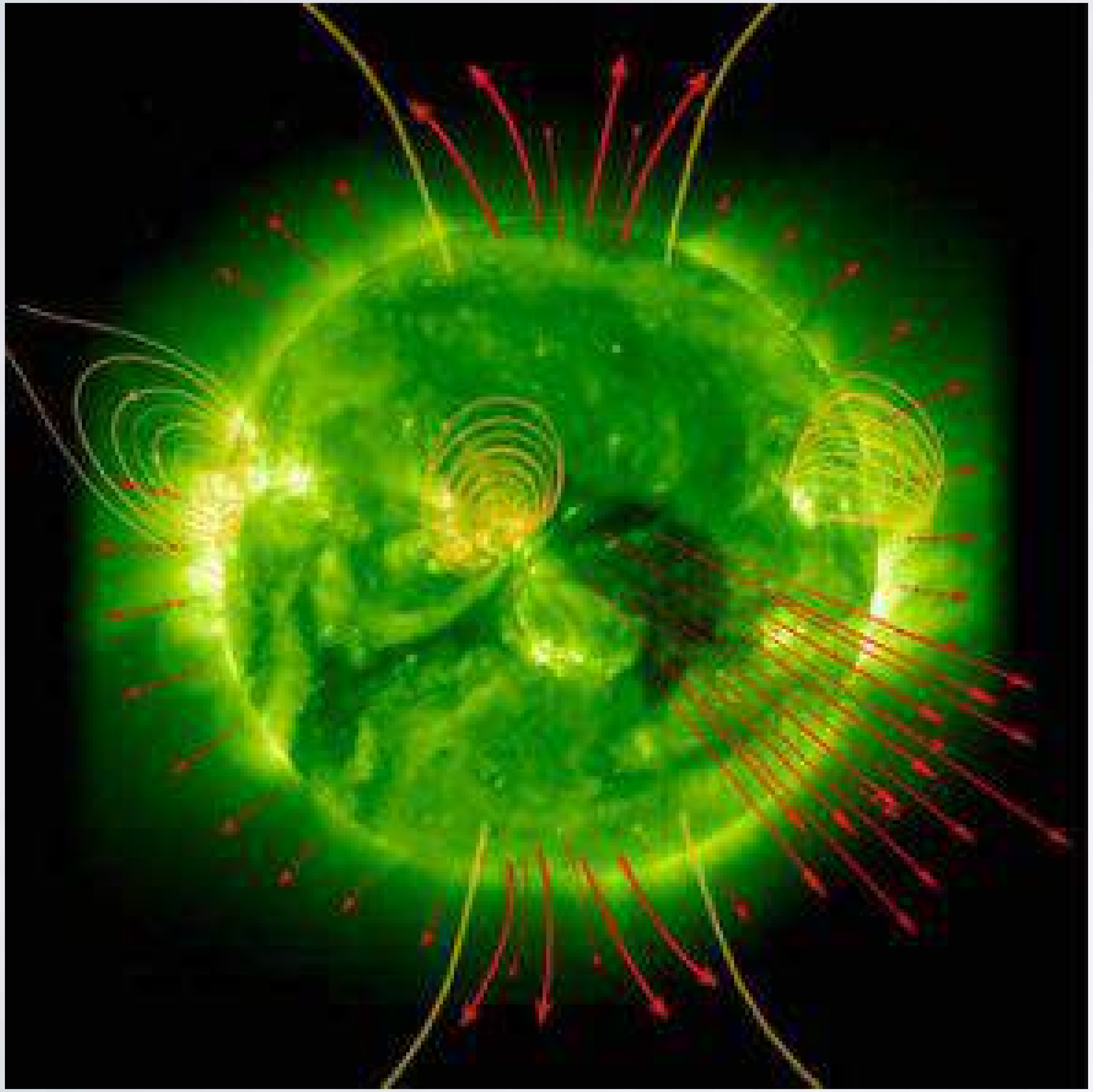
- Don't ever start your talks with apologies. But…
- Although I've been lucky to participate in a number of studies, I am not an expert on data assimilation, AI, or statistics
- This talk is not a review of data assimilation, space physics, or the radiation belts
- I'll provide some examples from my own studies and experience that I hope will stimulate some thought and discussion

Anatomy of the Earth’s Magnetosphere



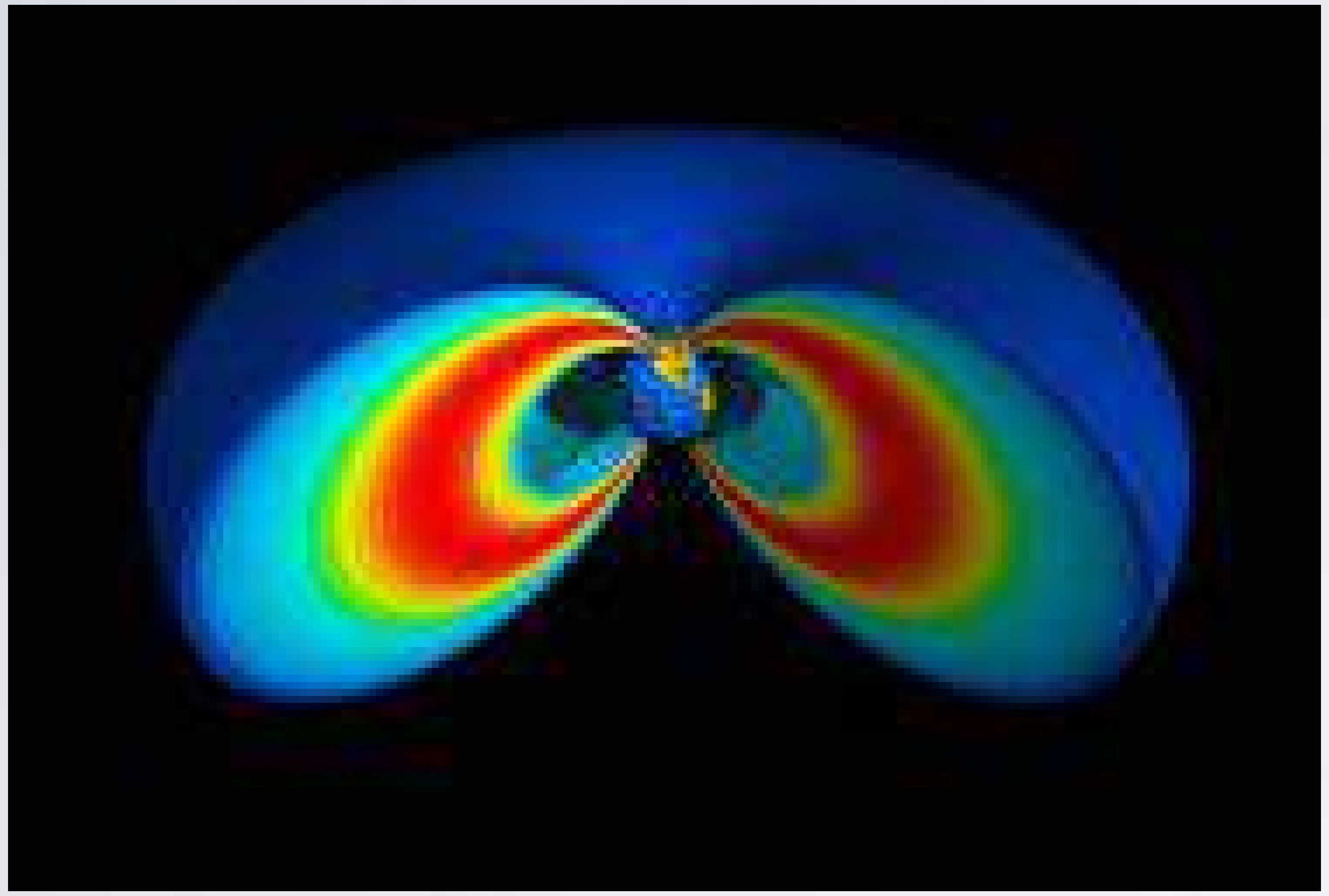
- ❖ The magnetosphere is compressed on the sunward side forming both a ‘bow shock’ and ‘magnetopause’
- ❖ Magnetic reconnection on the day side transports flux to the night side forming an elongated ‘magnetotail’
- ❖ The ‘inner magnetosphere’ is roughly the region between the dayside magnetopause and night side plasmasheet
- ❖ Important particle populations in the inner magnetosphere are the radiation belts, ring current, and plasmasphere

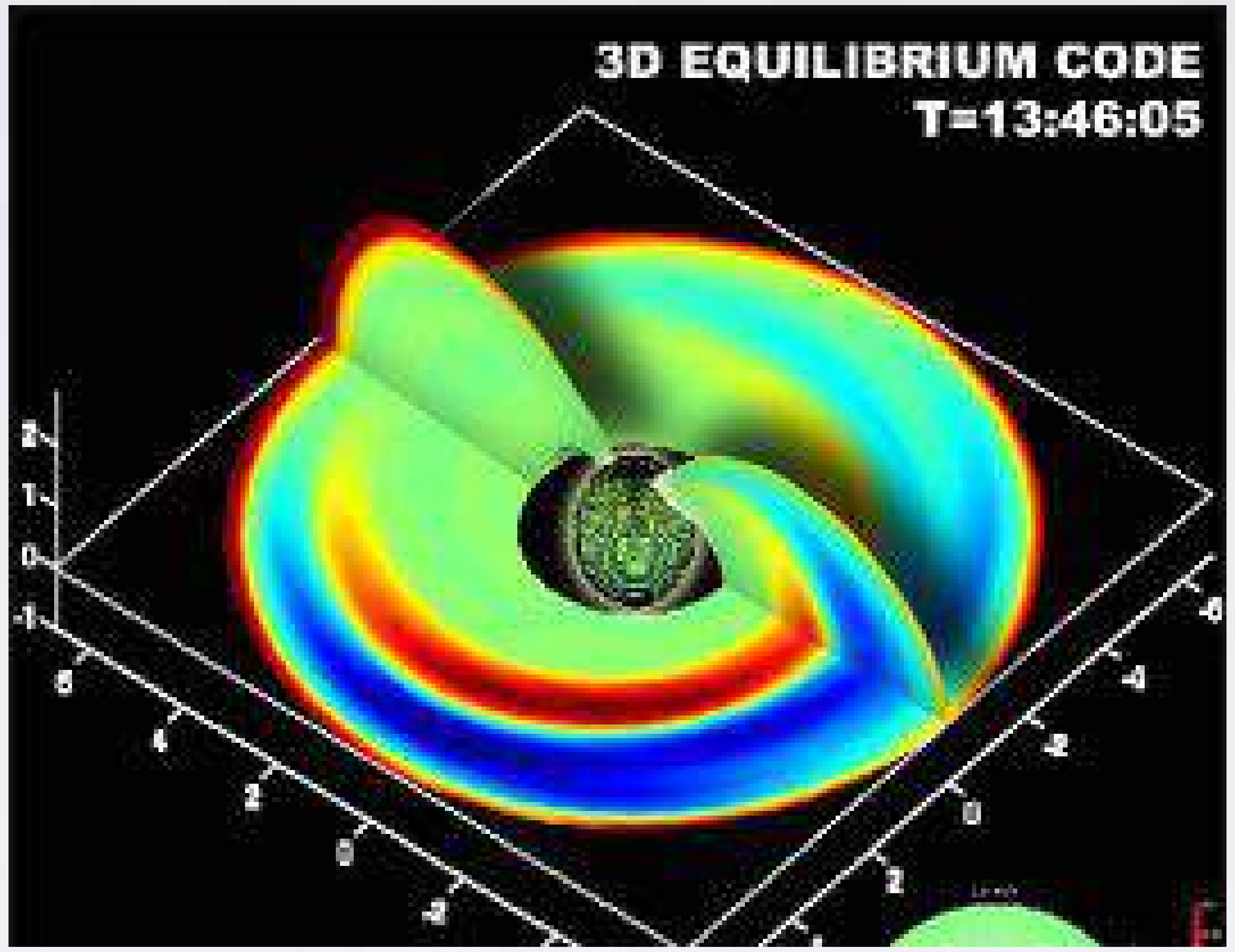
Anatomy of a Typical Star - Our Sun

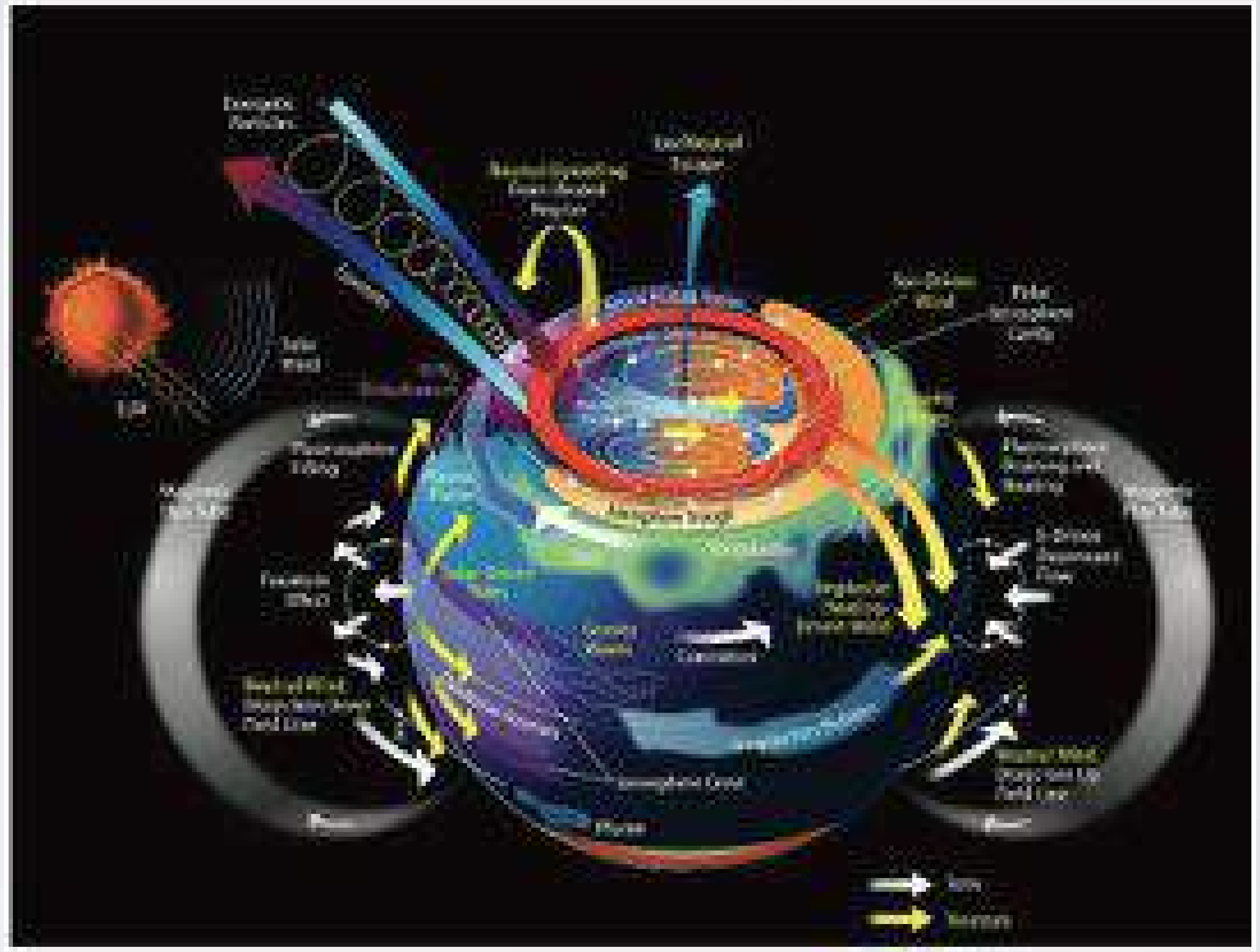


- If the sun was static and boring the magnetosphere would be too
- 'Active regions' and sunspots are regions of looped magnetic fields and high gradients that often explode (through reconnection) to produce 'flares' and/or 'CME's
- Regions of open magnetic flux are called 'coronal holes' where rapid escape of solar plasma produces high speed solar wind
- 'High speed streams' from <u>equatorial</u> coronal holes can overtake slower solar wind producing sometimes complex 'coronating interaction regions'

Anatomy of the Inner Magnetosphere







Radiation Belts:
≳ 1 MeV electrons
≳ 10 MeV protons

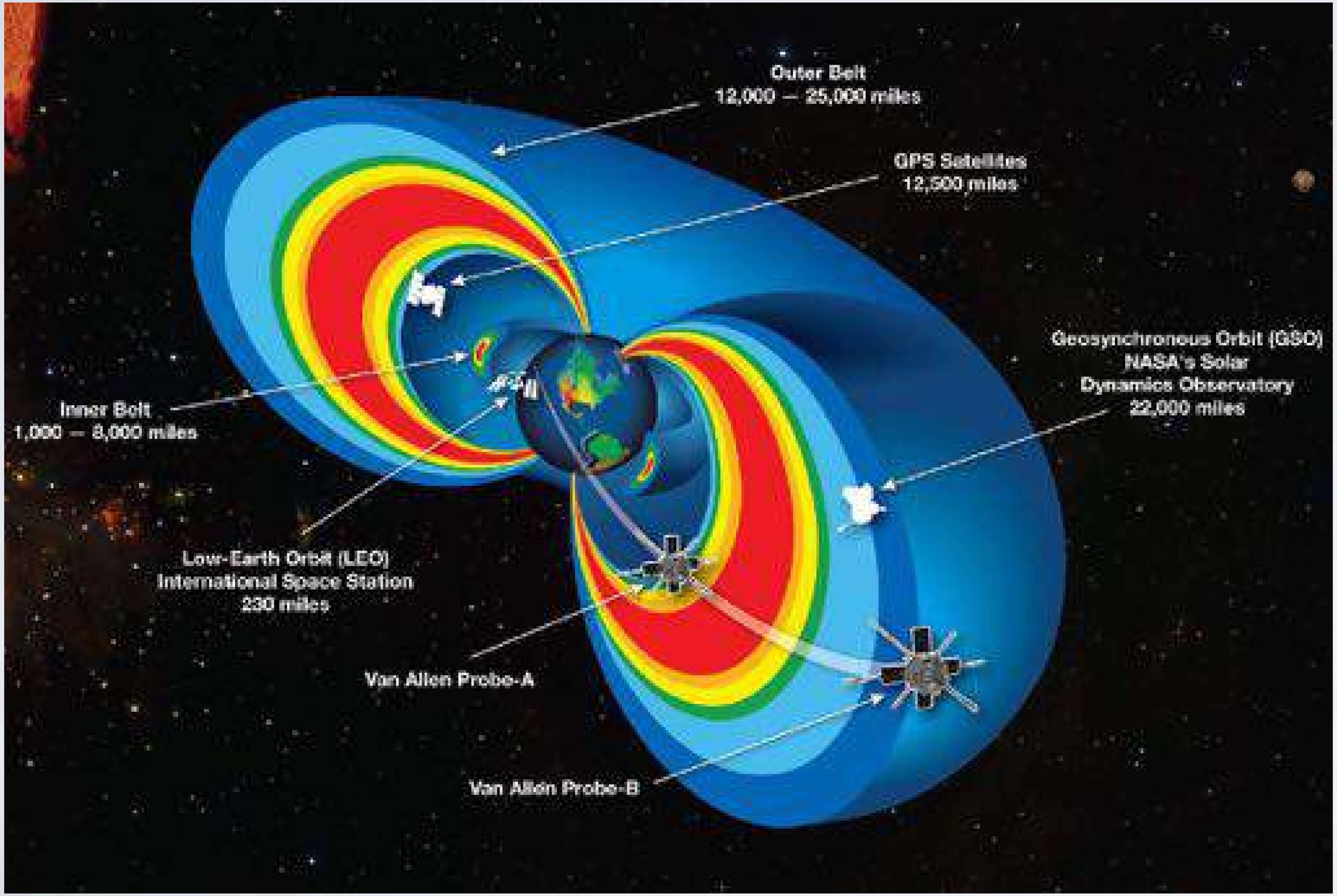
Ring Current:
10s-100s keV protons
electrons usually neglected

Plasmasphere:
cold: $T \approx 1$ eV
dense: $N \approx$ 100s-1,000s cm^{-3}

- The three populations overlap & interact
- Lower energy systems have increasing dimensionality and inputs

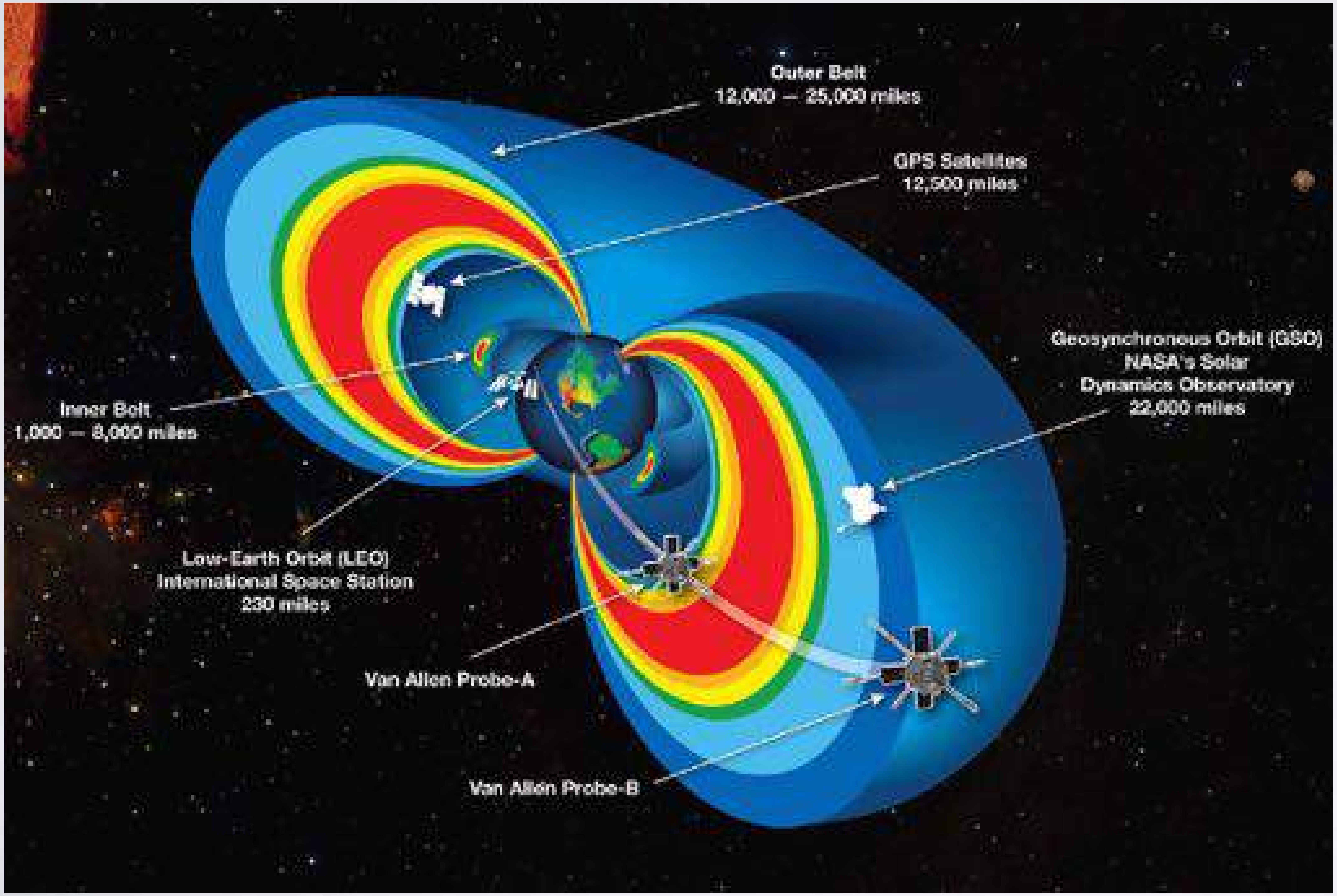
Image Credits
Henderson & Reeves
Jordanova +
Huba +

Anatomy of the Radiation Belts



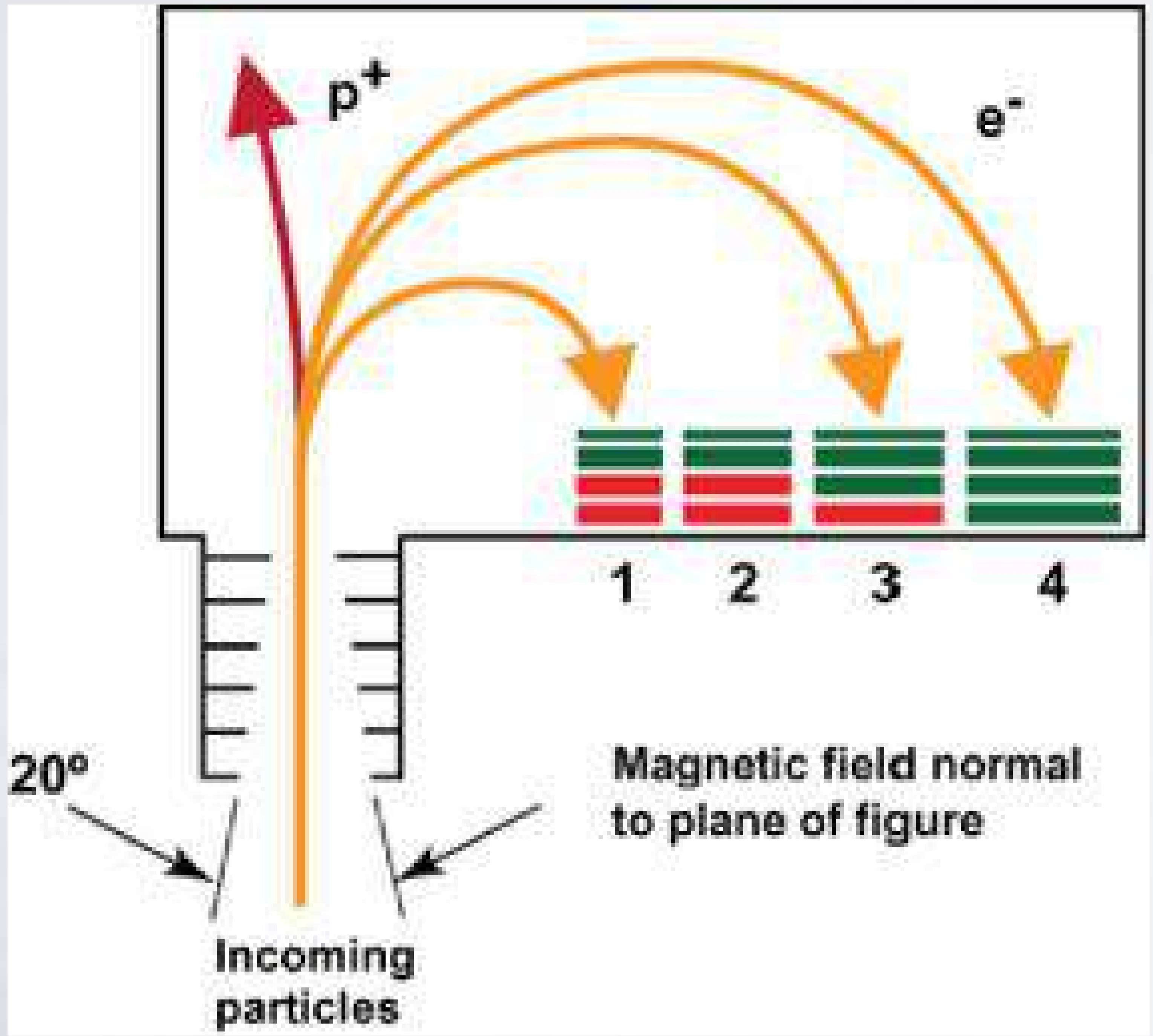
- The radiation belts (or Van Allen belts) are regions of extremely high energy electrons ($\gtrsim 1$ MeV) and protons ($\gtrsim 10$ MeV)
- Their physical structure is prescribed by gyration, bounce, and drift motions
- and by various physical processes that transport, accelerate, scatter, or remove particles

Anatomy of the Radiation Belts



- There is a dynamic 'outer belt' and stable 'inner belt' separated by a 'slot region'
- This was first measured by Explorer 1in 1958
- This two-belt structure is well-understood (e.g. Lyons & Thorne, 1972)
- But… if that were true we would never have flown an expensive mission to study them

New Data = New Discoveries



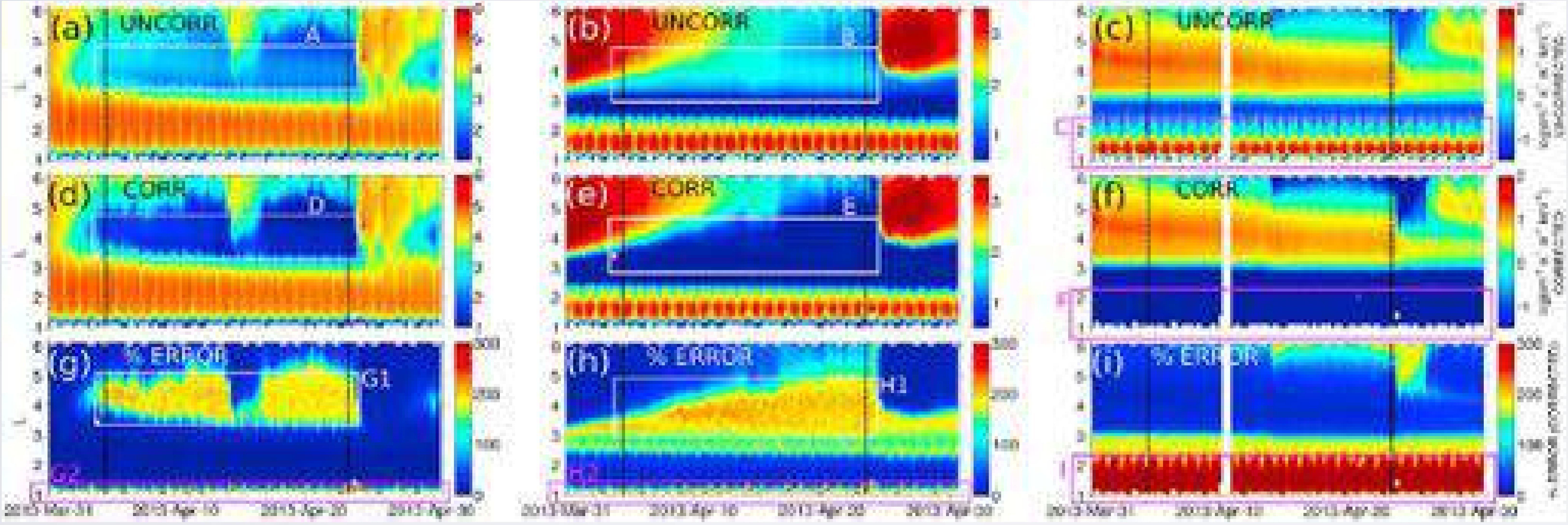
Blake et al., SSR, 2013

- The Van Allen Probes carried some of the most sophisticated instruments ever to take measurements inside the radiation belts
- MagEIS (~30 keV - 4 MeV) was the first instrument that could unambiguously identify 'real' electrons from 'background' particles that penetrate the instrument
- Only electrons that come in the aperture have the right match of position (magnetic spectrometer) and deposited energy (solid state detectors)

Fennell+, JGR, 2015
Claudepierre+, JGR, 2015
Li, X+, JGR, 2015

First: Know Your Data

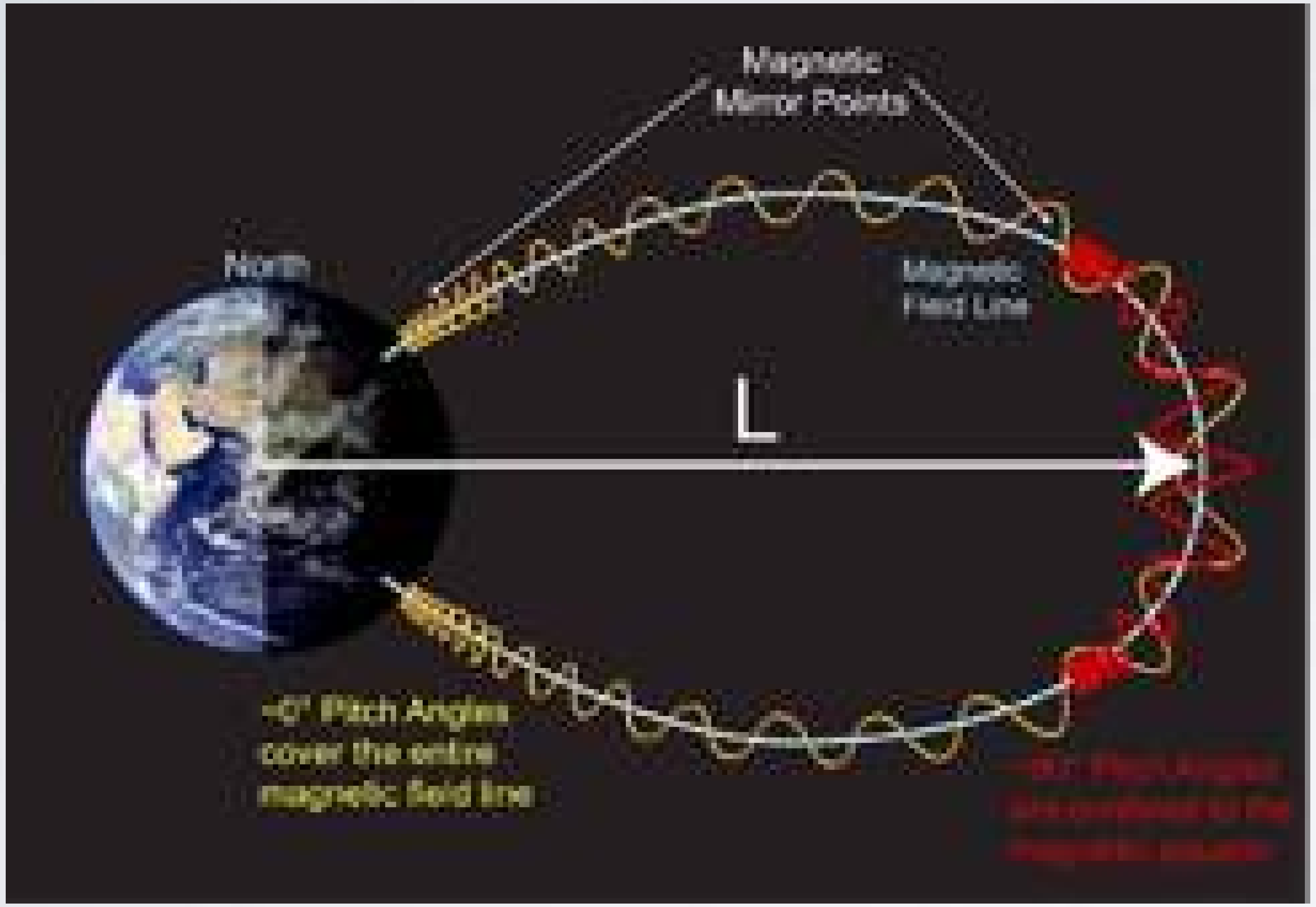
100 keV   470 keV   2.5 MeV

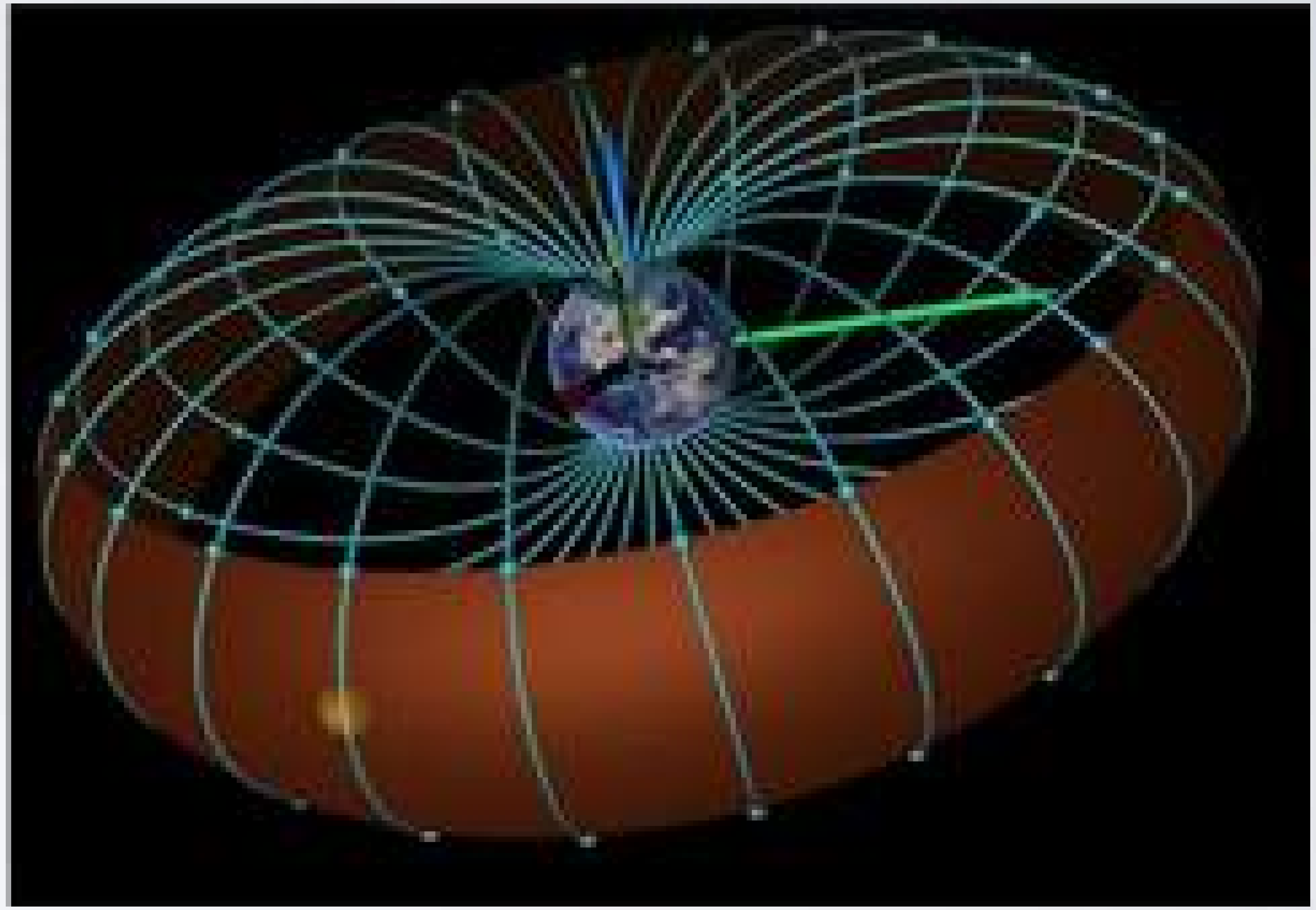


- ❖ There is no MeV inner belt.
- ❖ Maximum inner belt energies ~800 keV
- ❖ Slot region electron fluxes are over-estimated

- ❖ What are the implications for data assimilation if the data are wrong?
- ❖ How do we interpret results that do produce an inner electron belt at MeV energies?
- ❖ How do we re-evaluate results on electron lifetimes in the slot region?
- ❖ Can re-analysis tell us something new about the physics of transport and loss?

Radiation Belts and the Geomagnetic Field

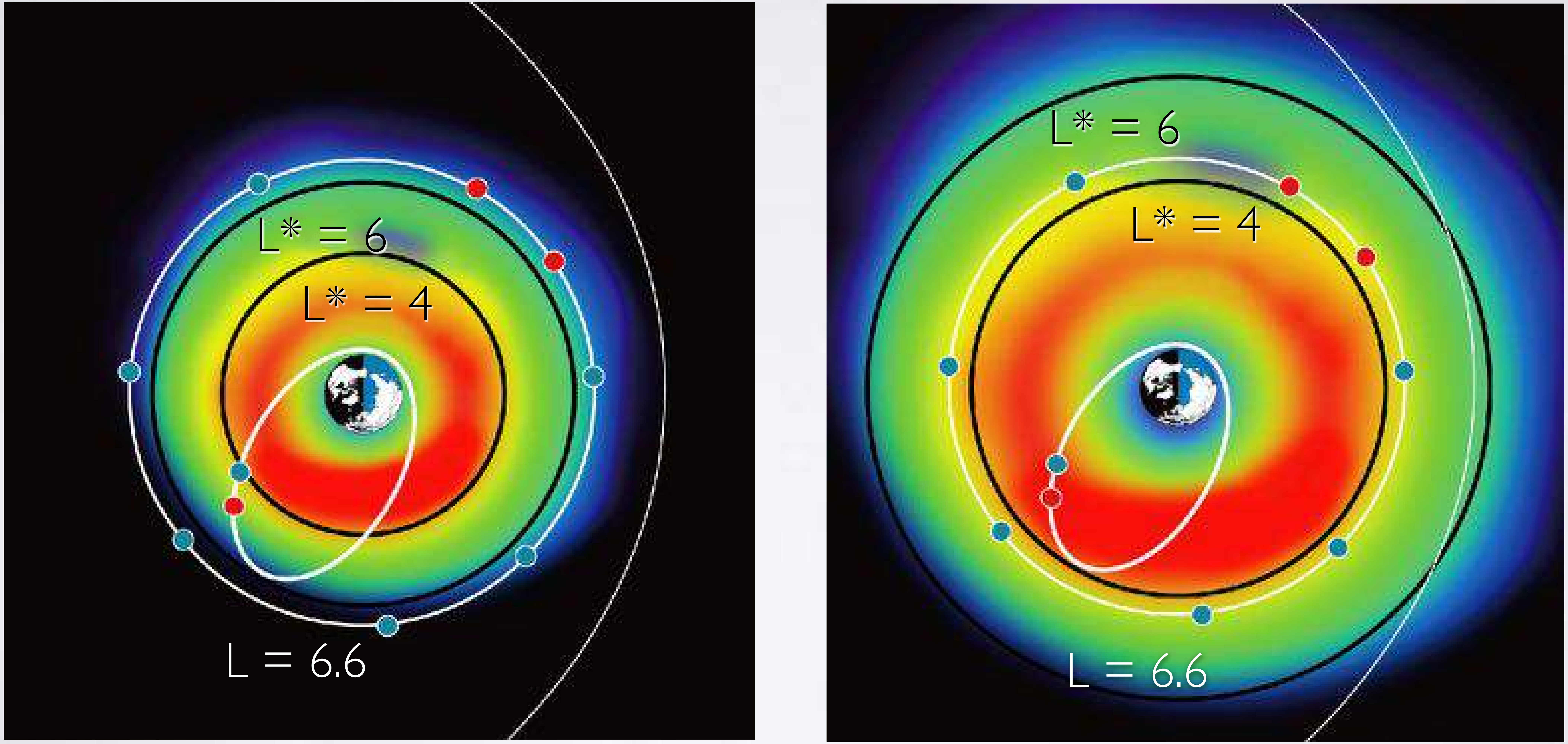




- Defining phase space density at fixed magnetic invariants reduces the dimensionality and removes first-order adiabatic changes in **B**

Reeves et al., Space Weather, 2012

L* and the ‘Dst Effect’

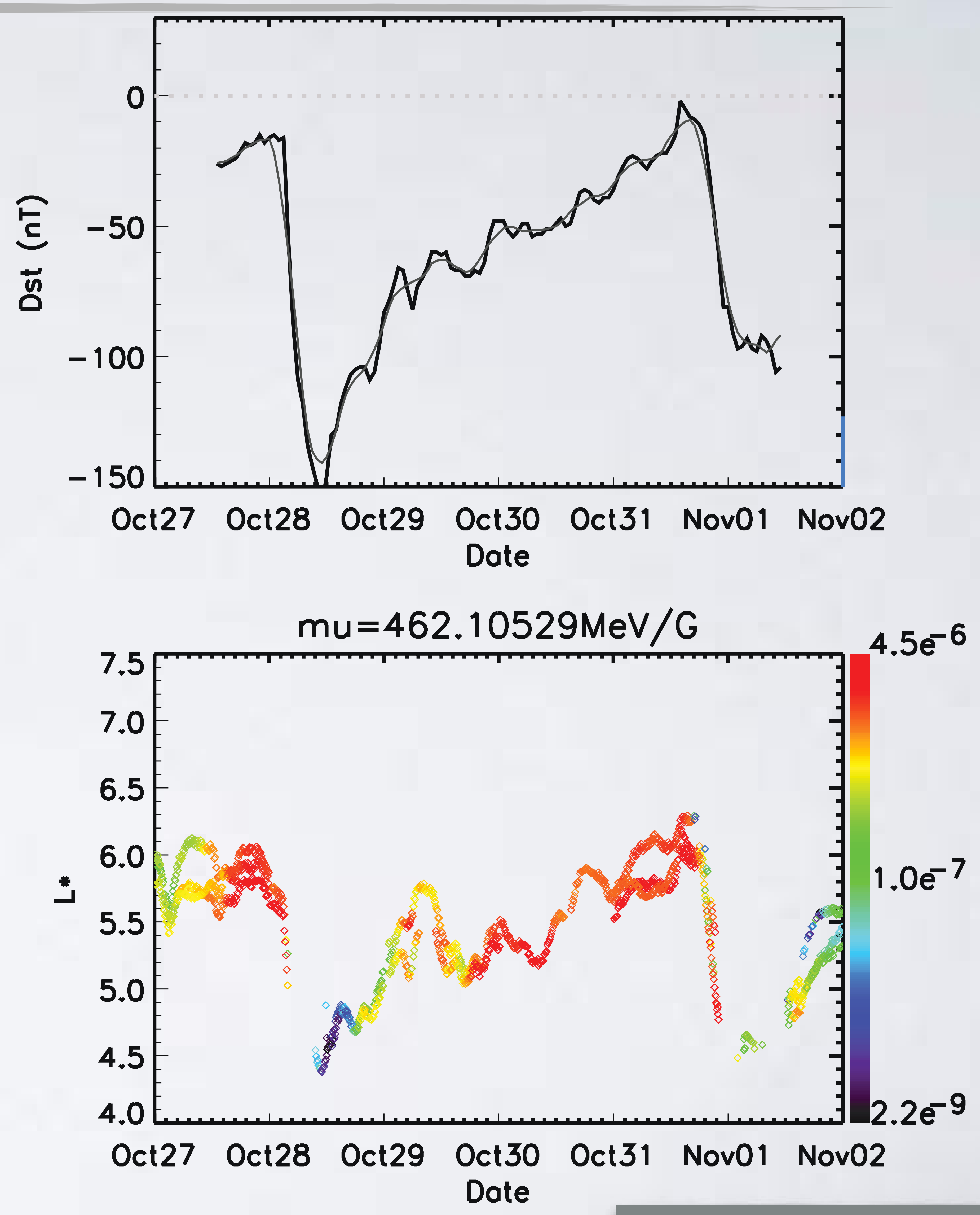


Reeves et al., Space Weather, 2012

Magnetic Field Changes Appear as Satellite ‘Motion’

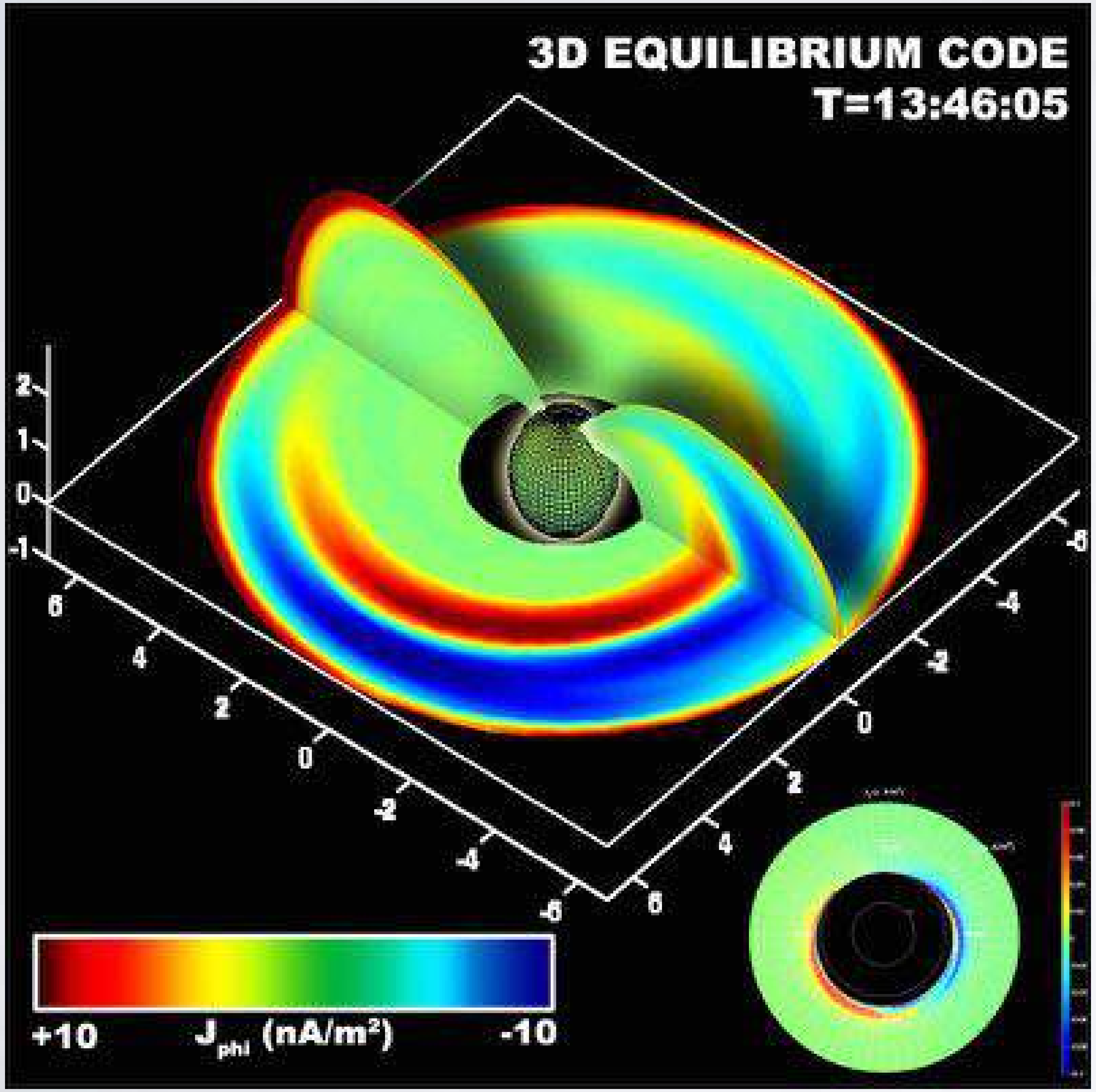
- Drift shells expanding across a satellite at a fixed point in space are equivalent to the satellite ‘moving’ relative to the drift shells. Large flux changes can actually be due only to radial gradients

- The same thing can happen with night-side tail stretching. Most butterfly pitch angle distributions are due to tail stretching, gradients, and drift shell splitting - not magnetopause shadowing or WPI



Reeves et al., Space Weather, 2012

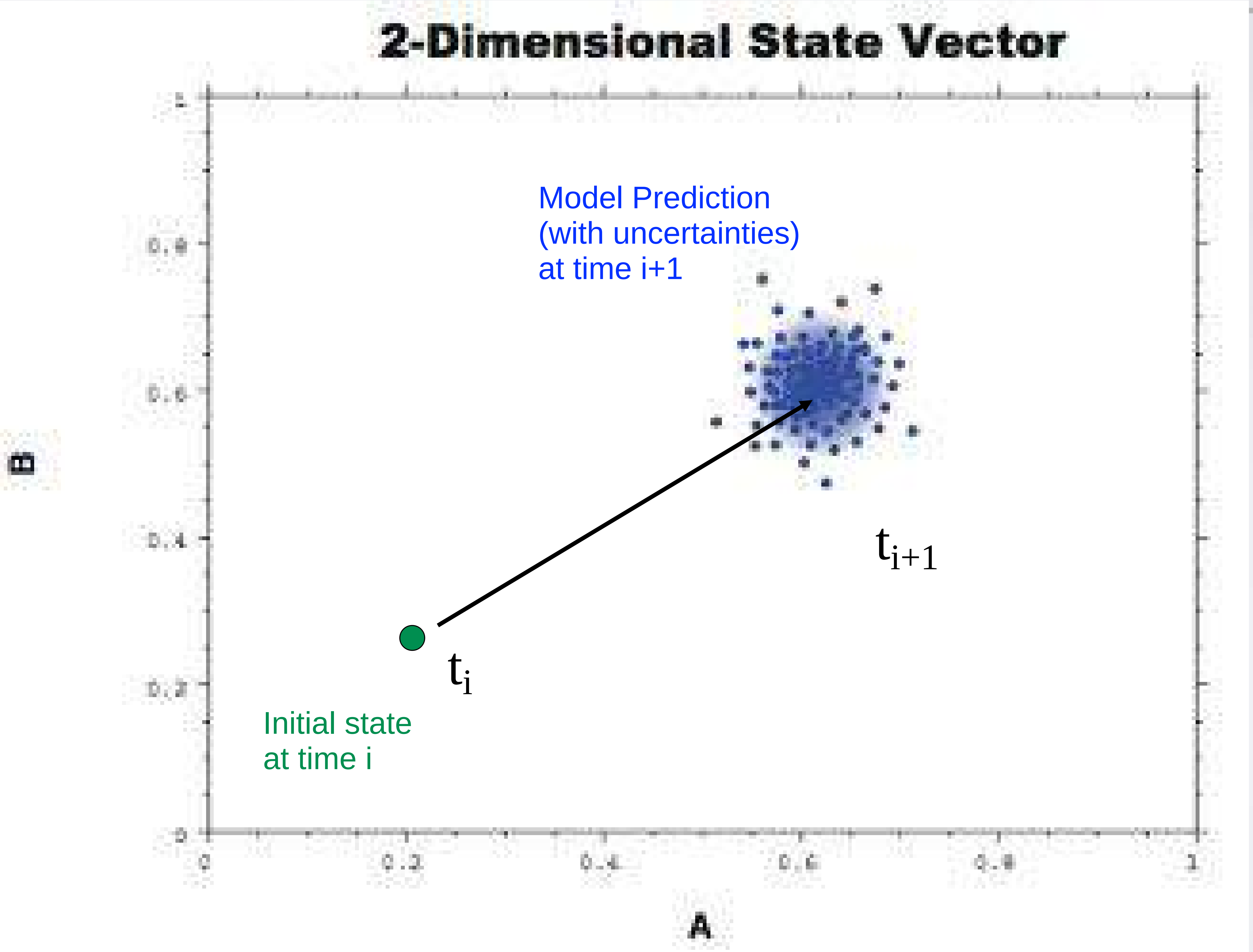
The Ring Current and Global Magnetic Fields



Zaharia+, JGR, 2006; 2008; Jordanova+, JGR, 2016

- Most ring current models are solved in a dipole field
- Exceptions are RAM-SCB and ring current models embedded in global MHD models
- DI studies that couple radiation belt - ring current - global B could be used to test and improve all three

A Simplistic Schematic of Data Assimilation



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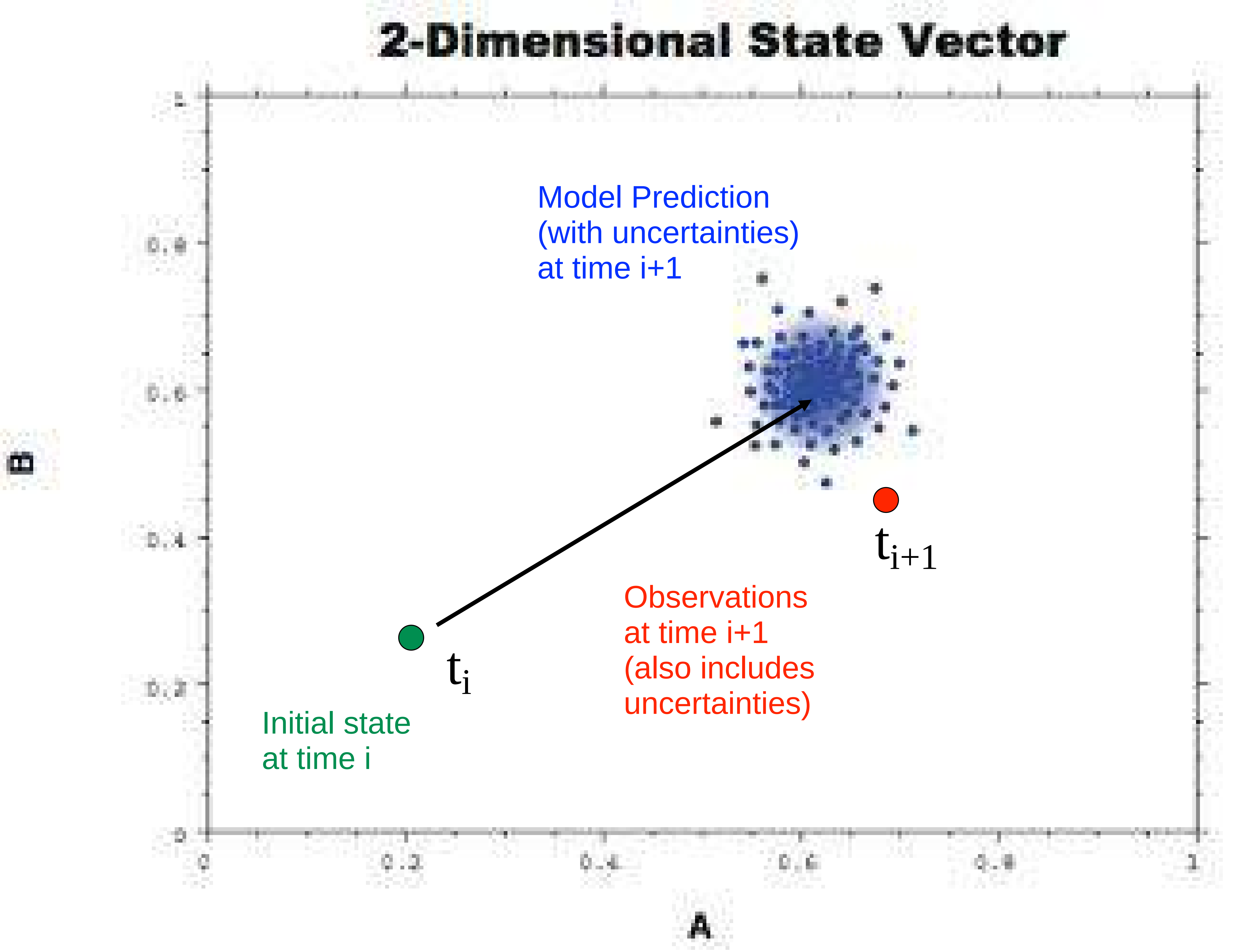

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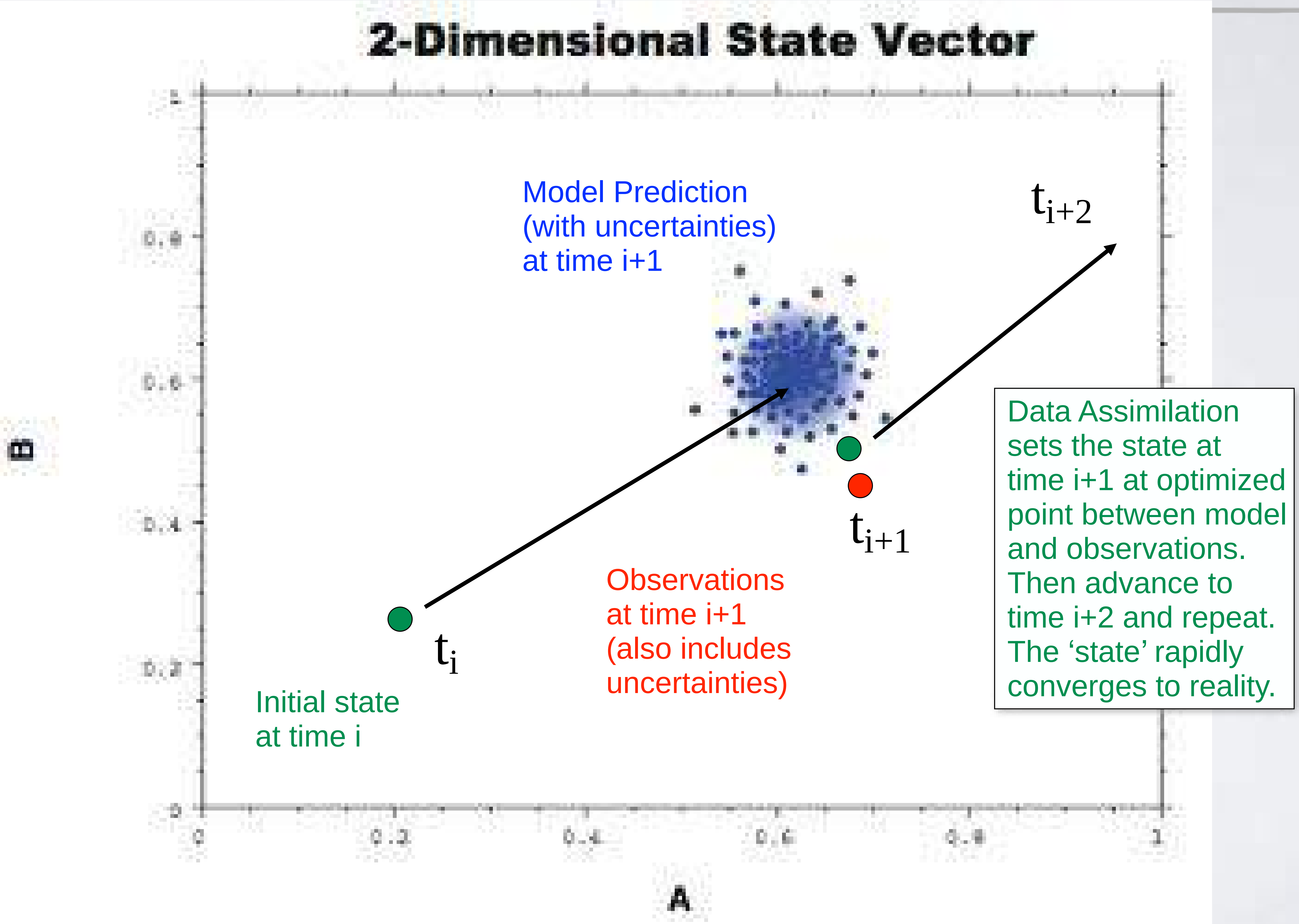
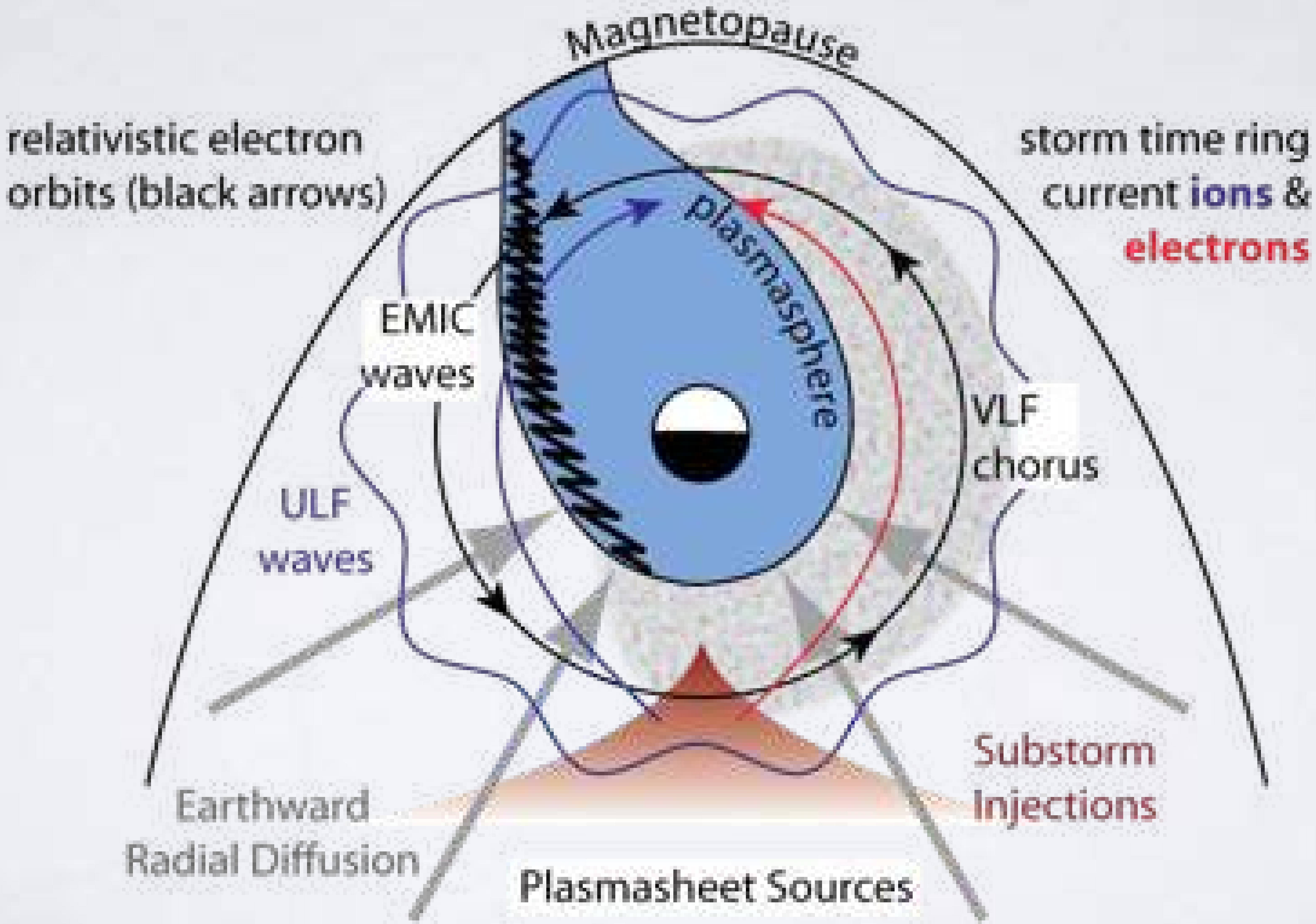
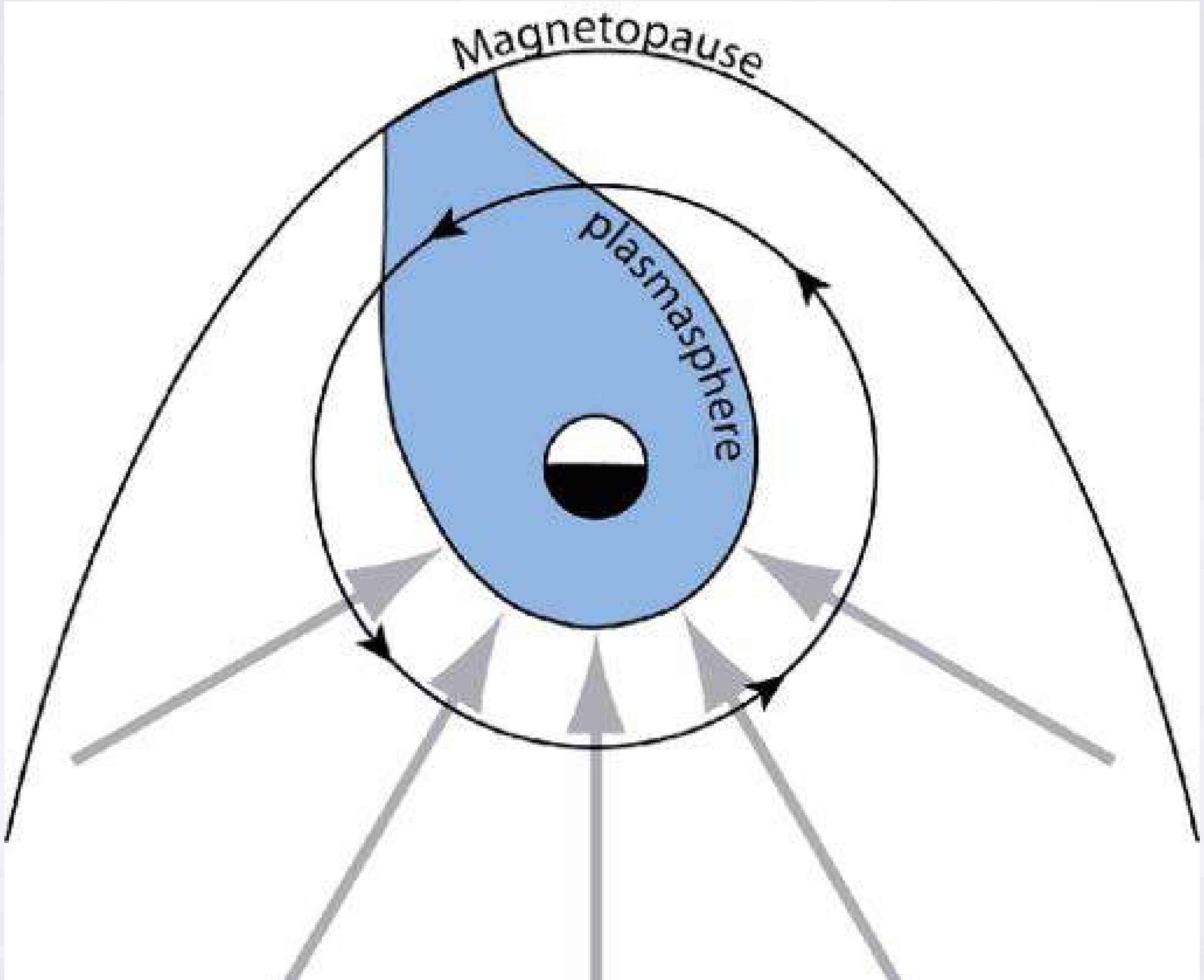


Application of DA and DI to the Radiation Belts

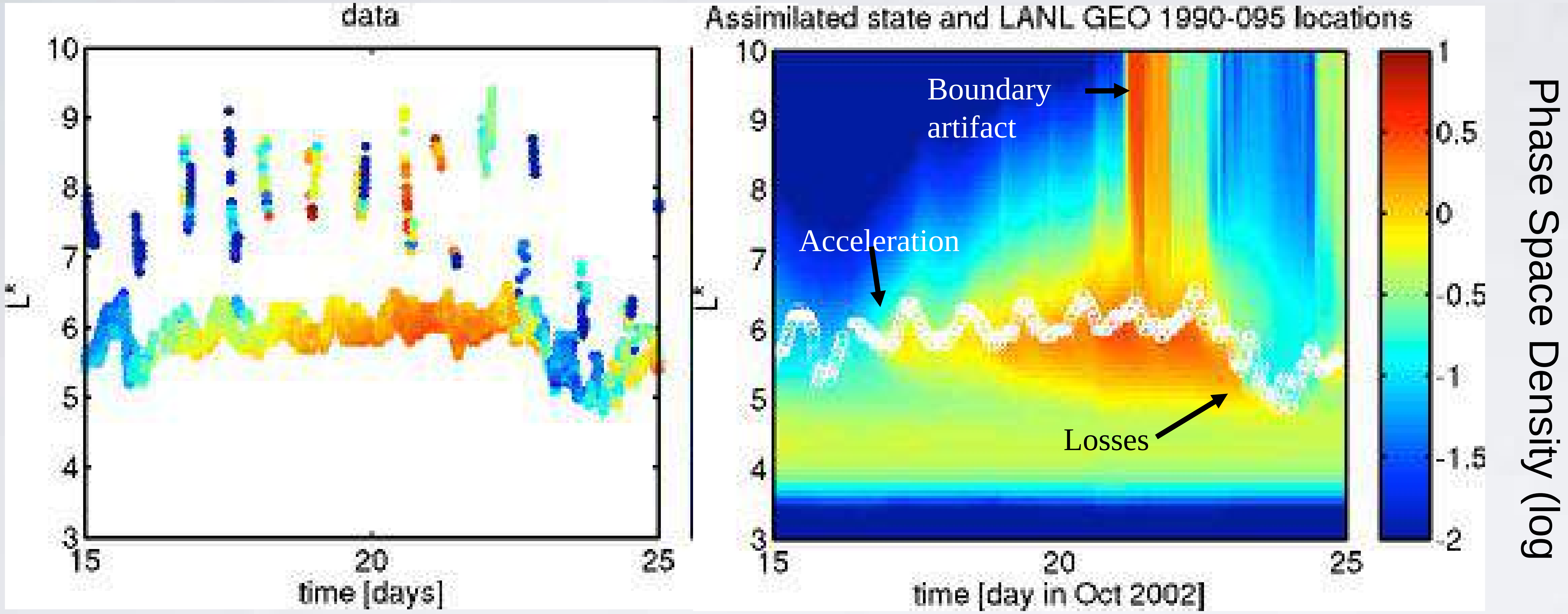


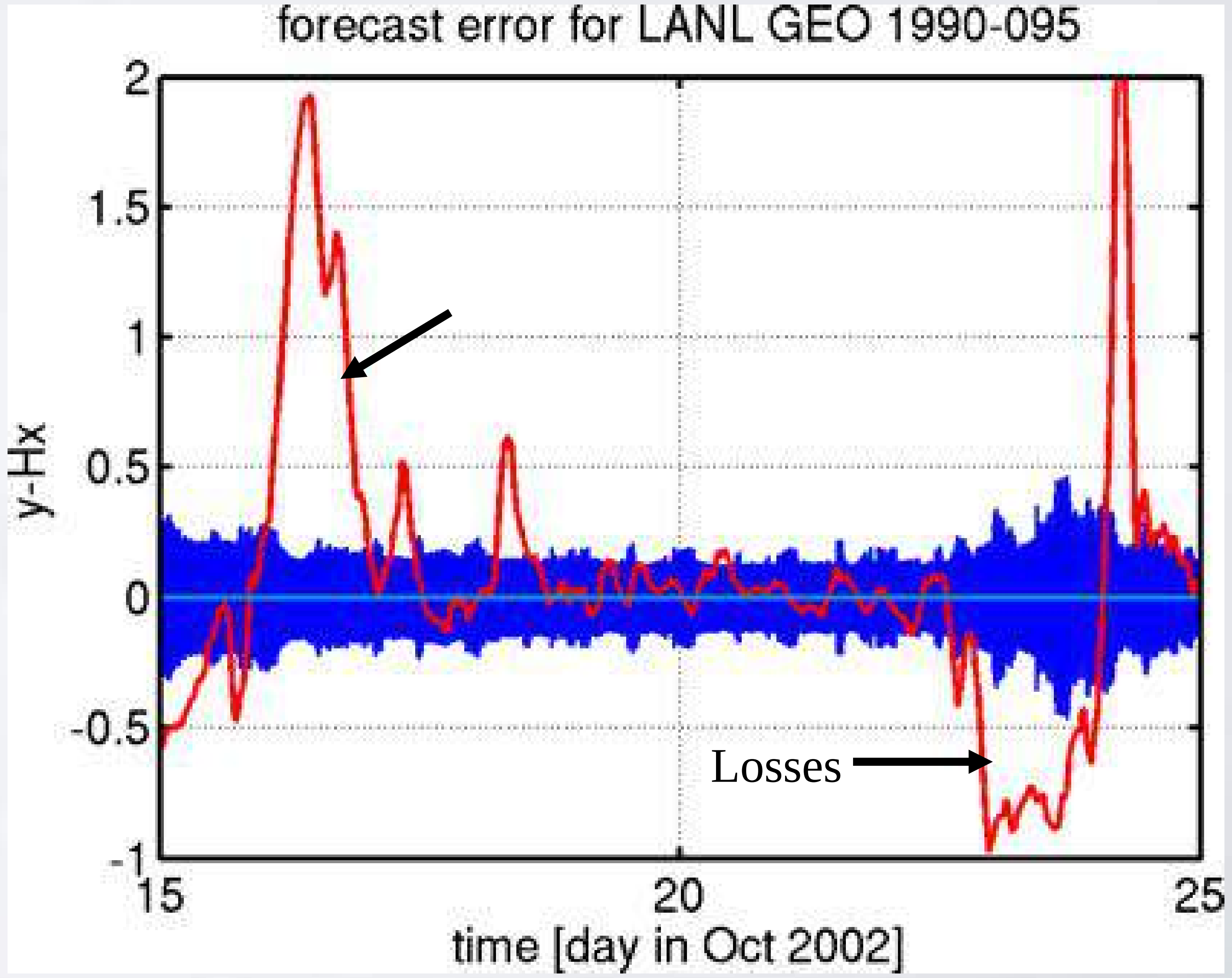
Reeves+, Space Weather, 2007

Application of DA and DI to the Radiation Belts



Beyond Good Agreement - a simple example





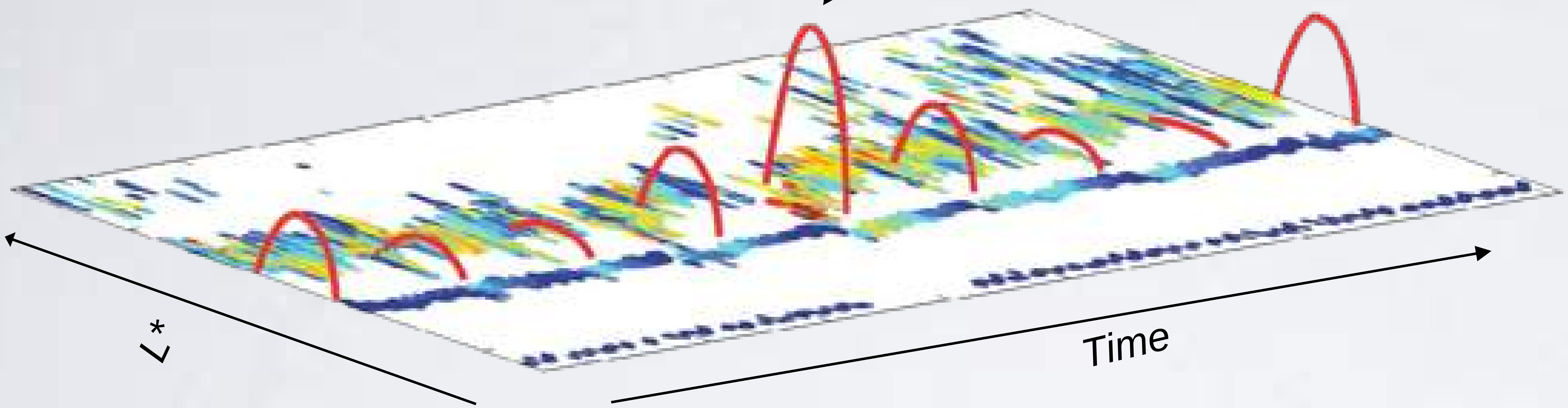
- Acceleration and loss processes can still be identified and quantified using a 1D radial diffusion model that does not include

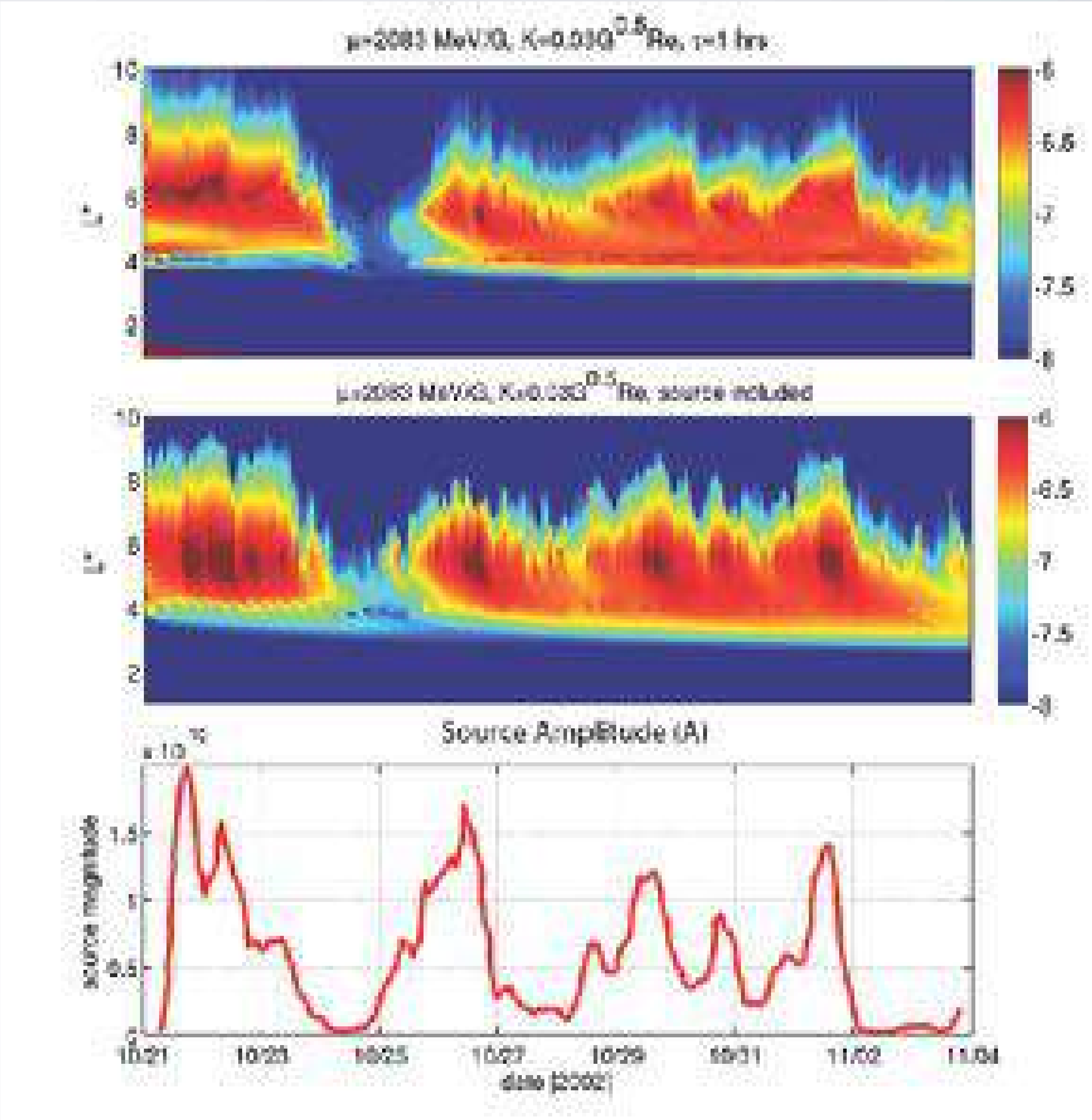
Reeves et al., Space Weather, 2012

The State Vector can include More than Data

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(\frac{D_{LL}}{L^2}\frac{\partial f}{\partial L}\right) + S(A)$$

PSD Source Term





- Heterogeneous sources of 'data' can be included in the state vector
- Because DA is an optimization algorithm it can be used for 'parameter estimation'

Reeves et al., Space Weather, 2012

Modern Radiation Belt Models

- Newer, 3D and 4D radiation belt models are much more sophisticated
- They include wave-particle interaction physics
- They *can* include precipitation and magnetopause losses
- They *can* include MLT-dependent physics and convection

$$\boxed{f = \frac{j}{p^2}}$$

$$\frac{\partial f}{\partial t} = L^2 \frac{\partial}{\partial L}\left(D_{LL} L^{-2} \frac{\partial f}{\partial L} \right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 \left\langle D_{pp}(y,p) \right\rangle \frac{\partial f}{\partial p} \right) + \frac{1}{T(y)y}\frac{\partial}{\partial y}\left(T(y)y \left\langle D_{yy}(y,p) \right\rangle \frac{\partial f}{\partial y} \right) - \frac{f}{\tau}$$

Radial (L)

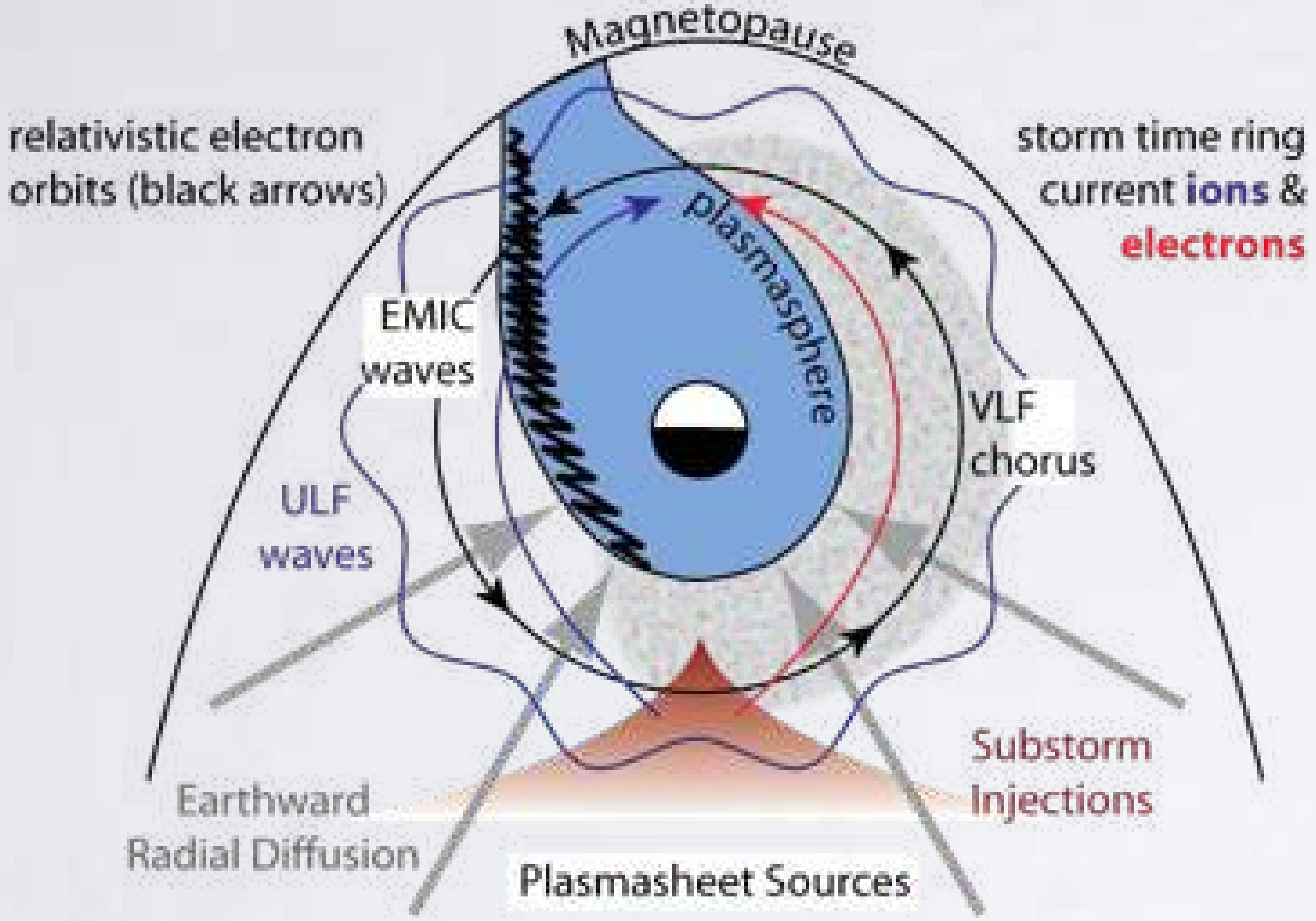
Momentum or Energy

Pitch Angle $y = \sin(\alpha)$

these two are linked

- But they still have limitations and therefore opportunities for discovery

But Even Our Best Models Have Limitations



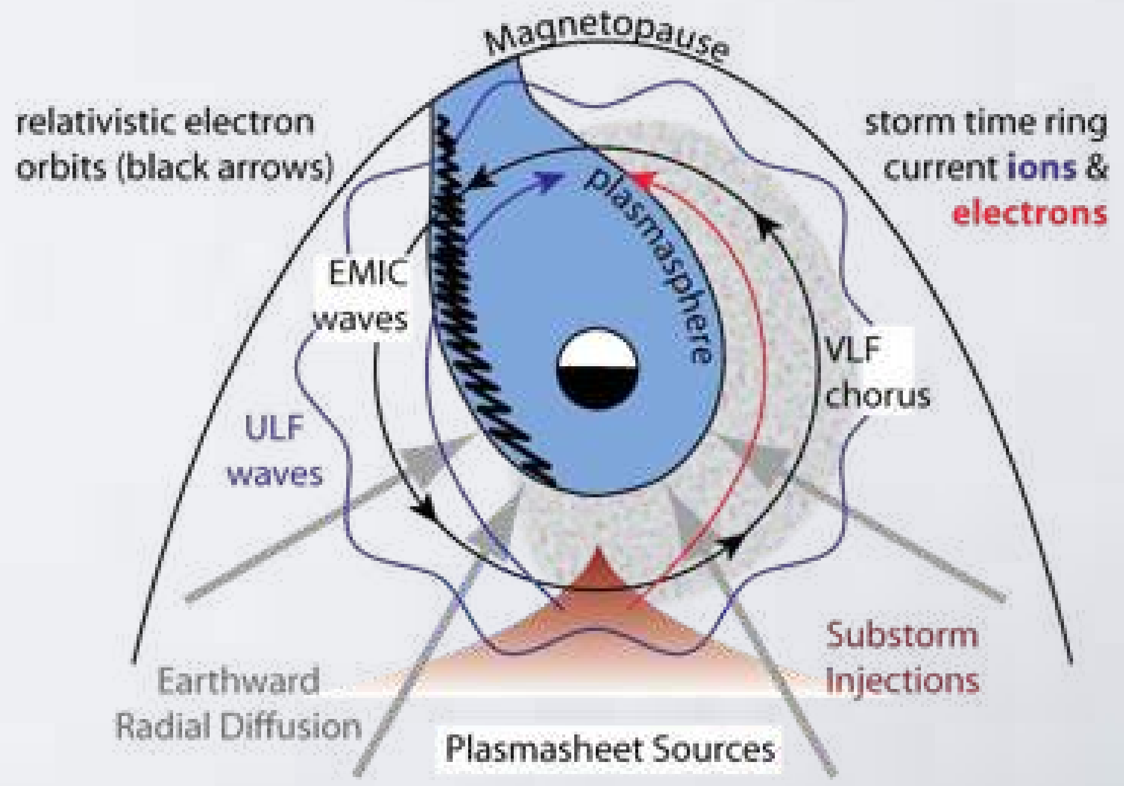
- Many important physical parameters and processes are specified by indices (Kp, AE, Dst, etc) or statistical distributions. E.g. radial diffusion, wave properties
- MHD-based GGCMs don’t specify parameters of interest to radiation belt models and haven’t been ‘tested’ using radiation belt dynamics
- Even models that calculate WPI using dynamic plasma density models don’t include spatial structure of the plasmasphere

There are almost limitless opportunities for DI

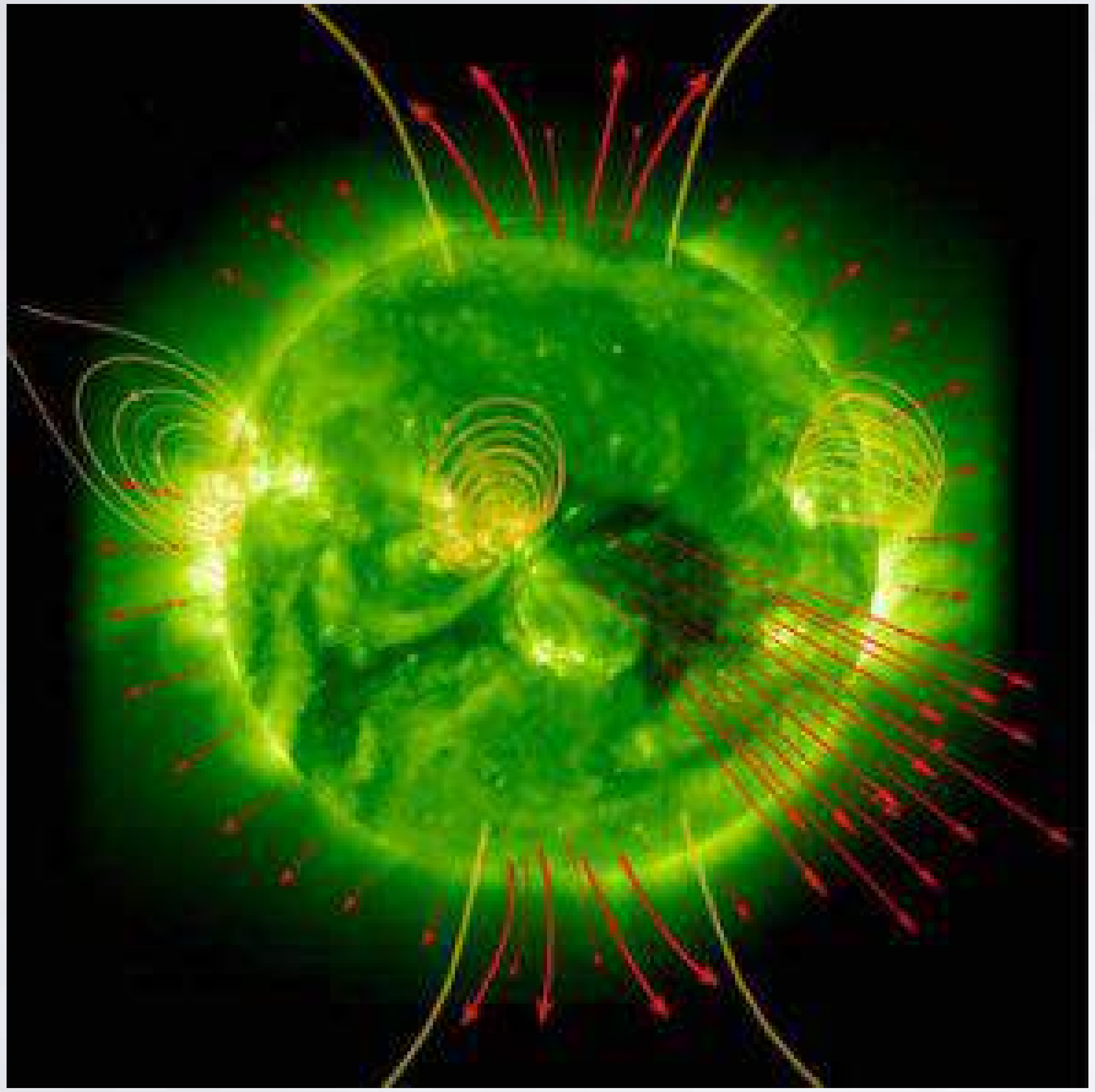
- If we have to use indices to drive other models (e.g. radial diffusion, empirical B-fields, etc) then what are the parameters that minimize residual errors? Are there numerical or observational limits of parameter estimation? Can we make indices obsolete?

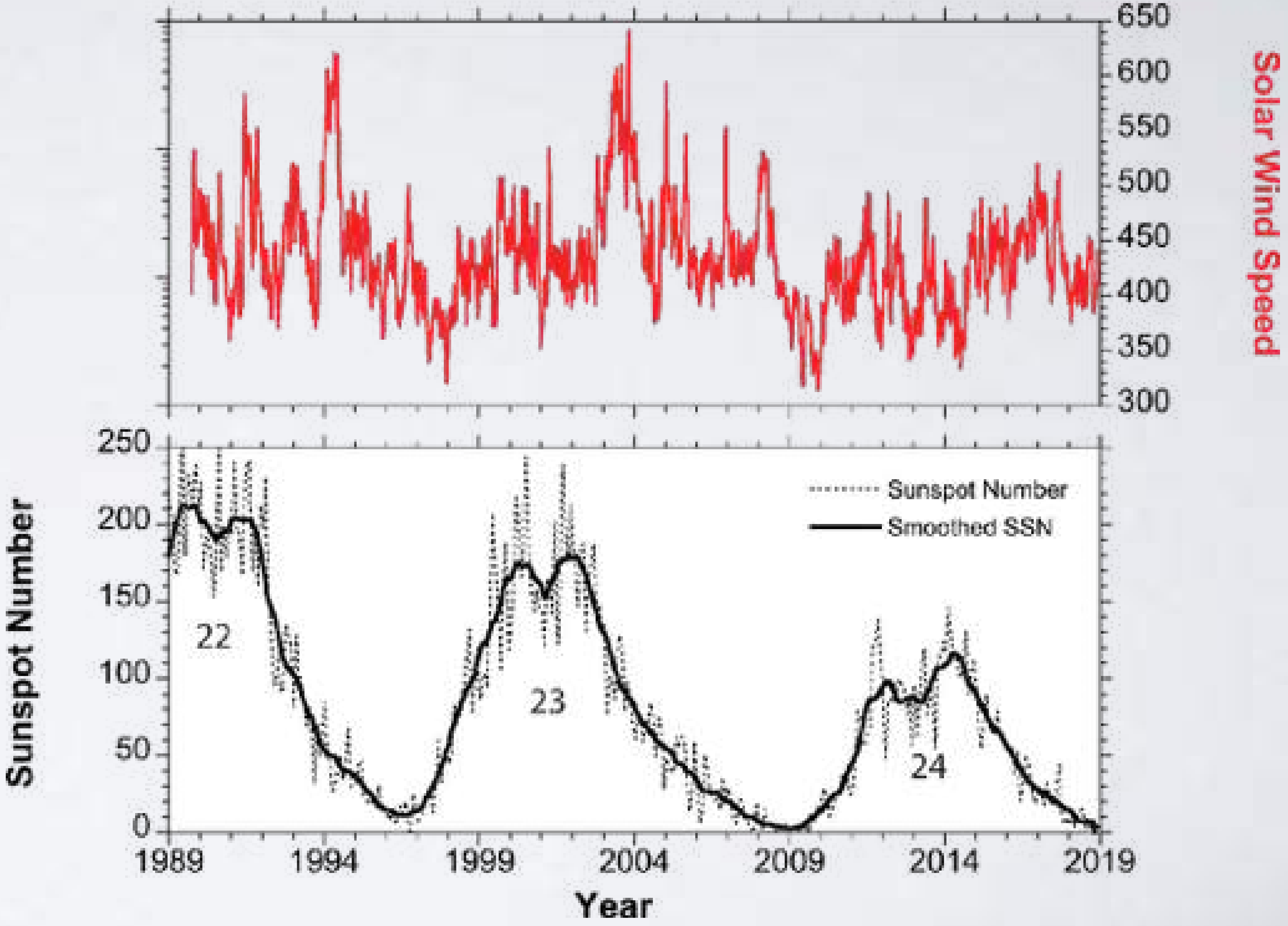
- How do we probe deeper into known physical processes using clever combinations of models and observations?

- Can we combine statistical, AI, and DA techniques to reveal more than any one alone?

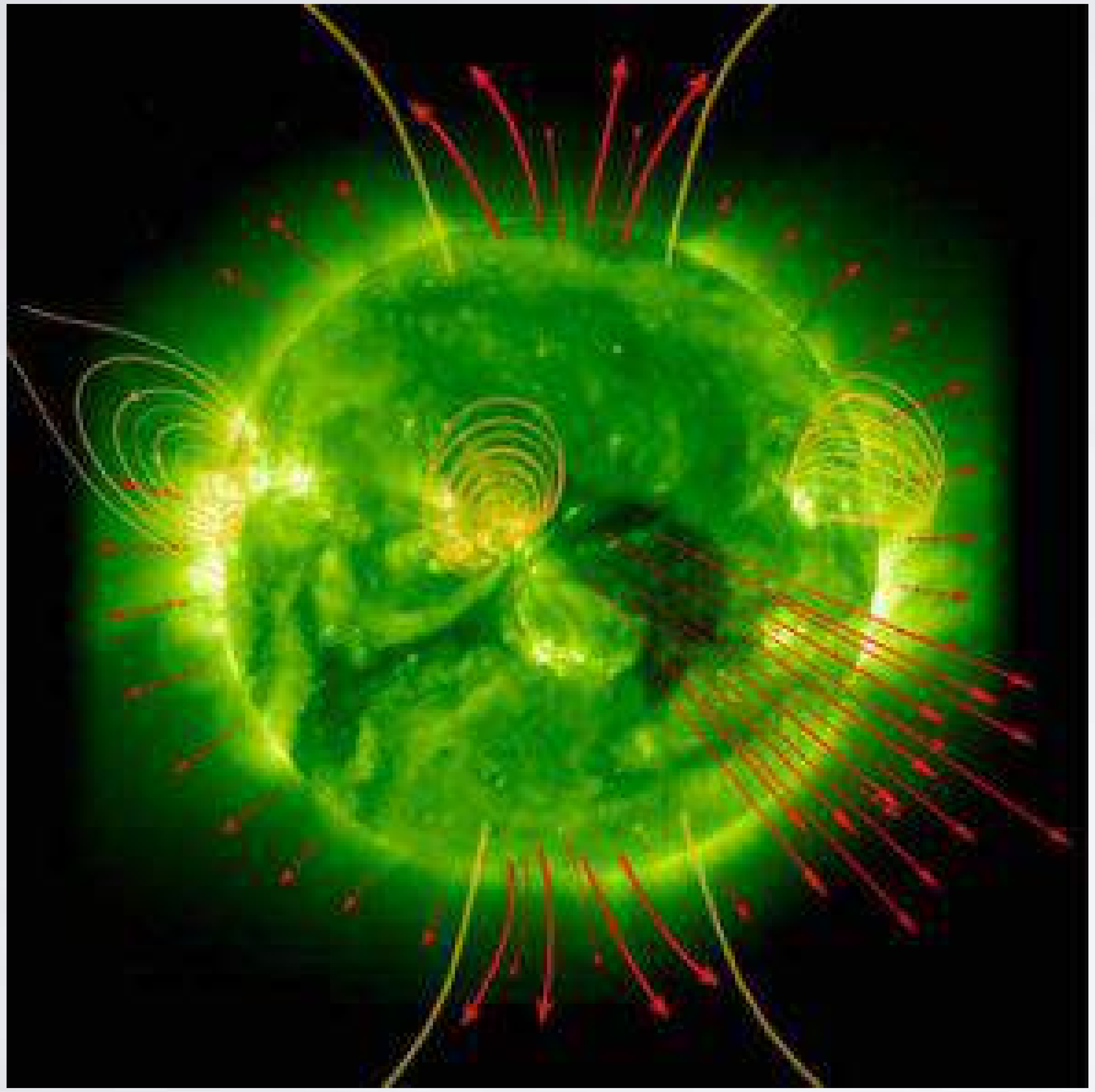


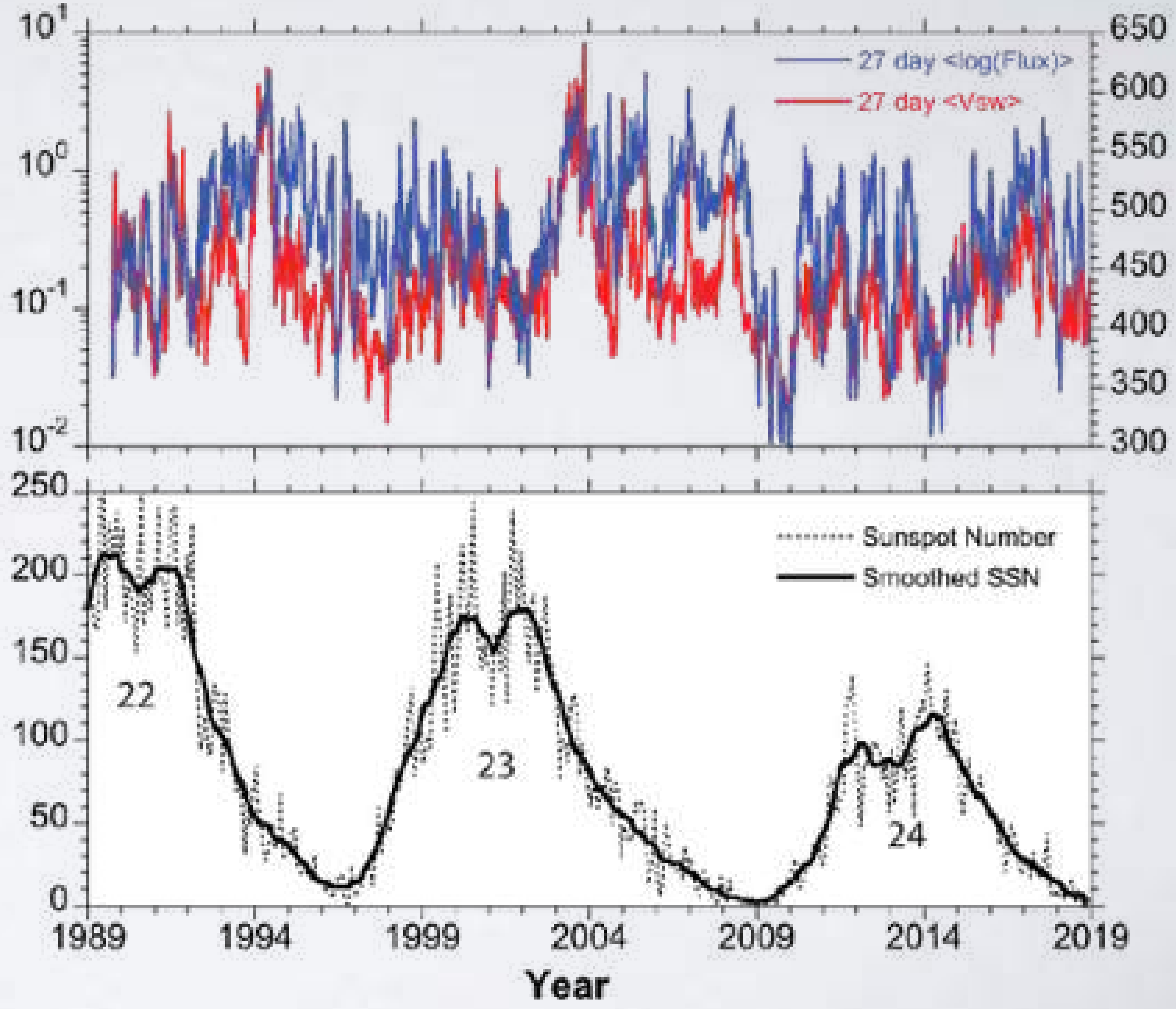
One Example: The Solar Cycle & The Radiation Belts



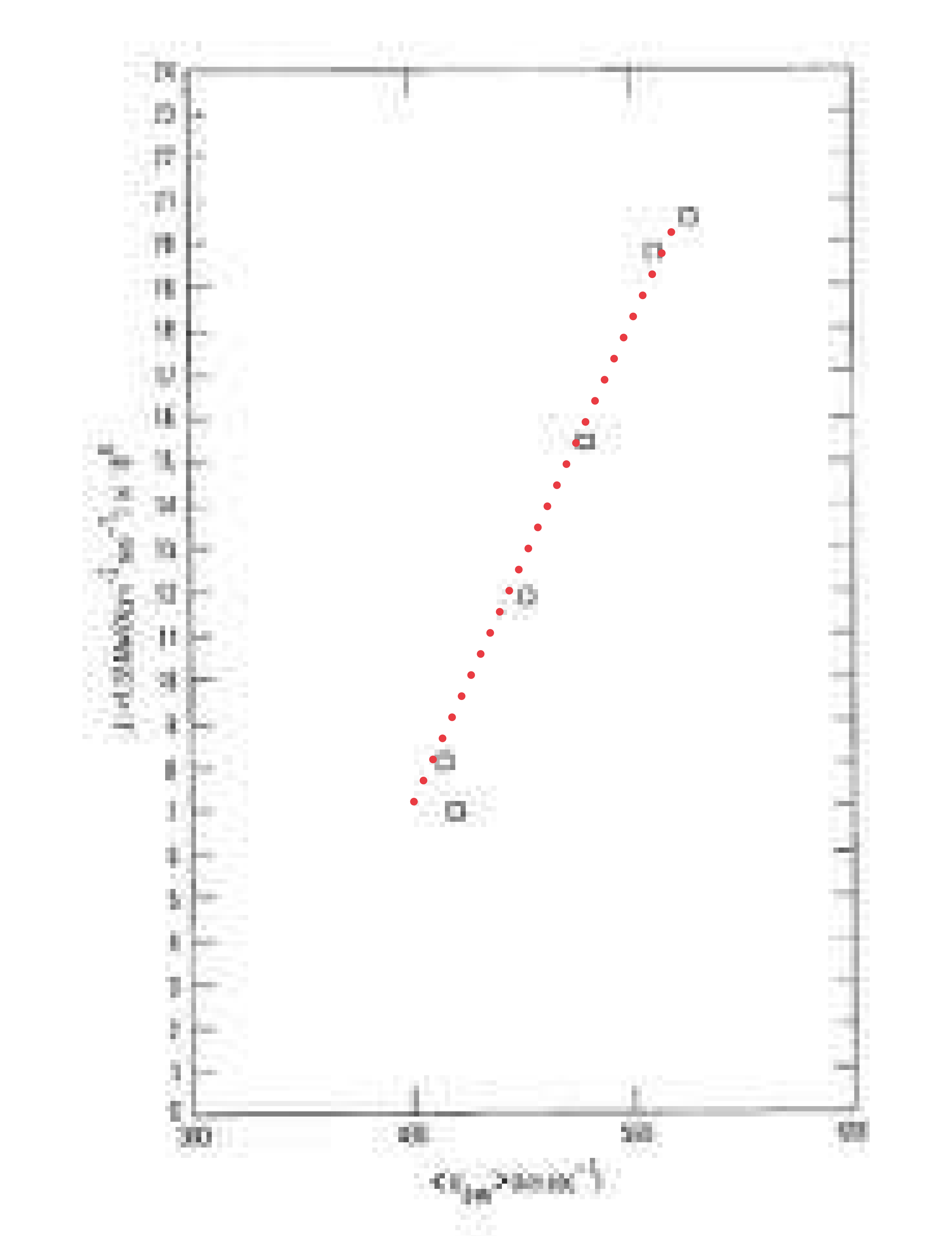


Solar Cycle & The Radiation Belts

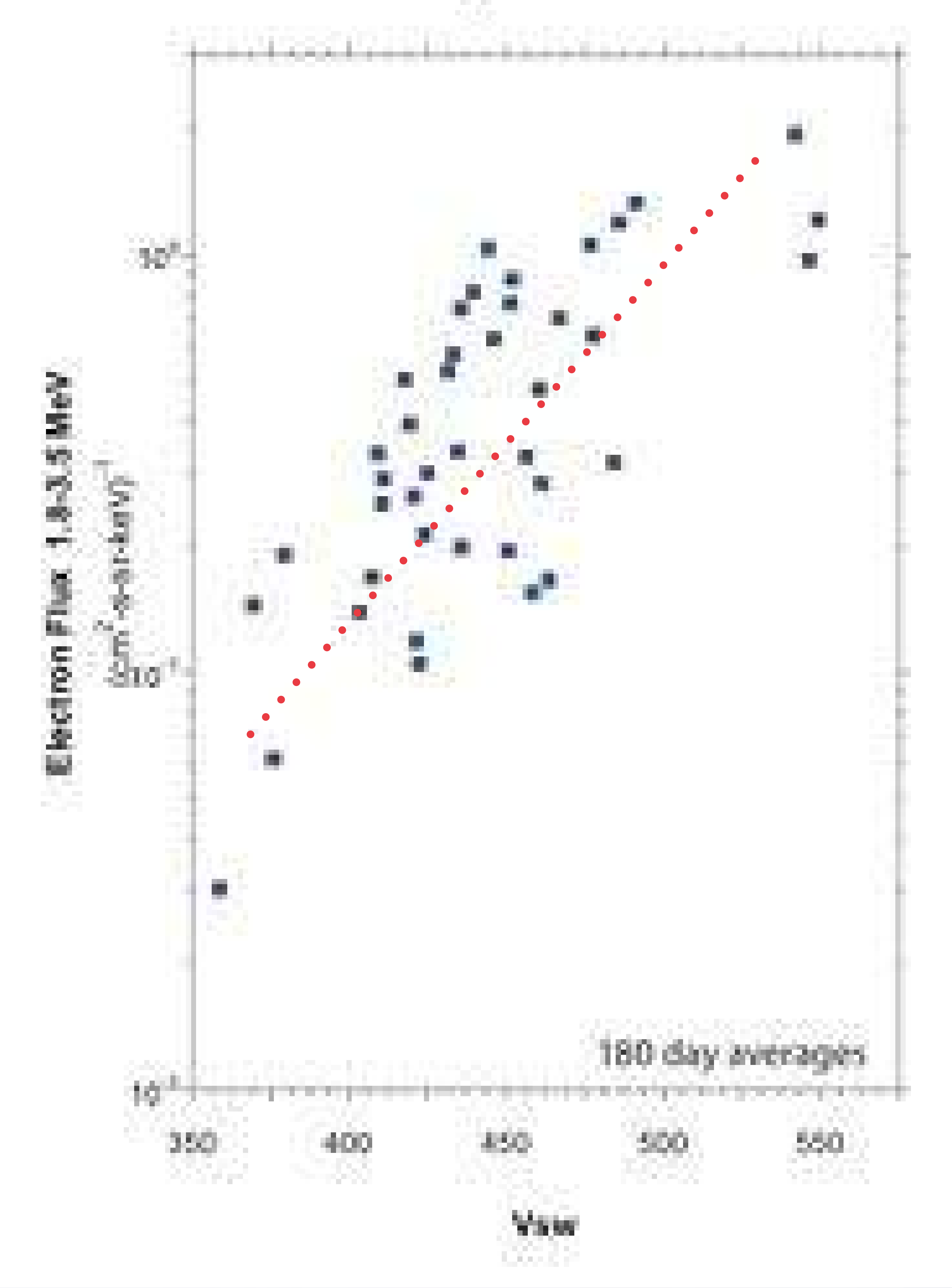




Solar Wind Speed and Radiation Belt Flux



Paulina's & Blake, JGR, 1979

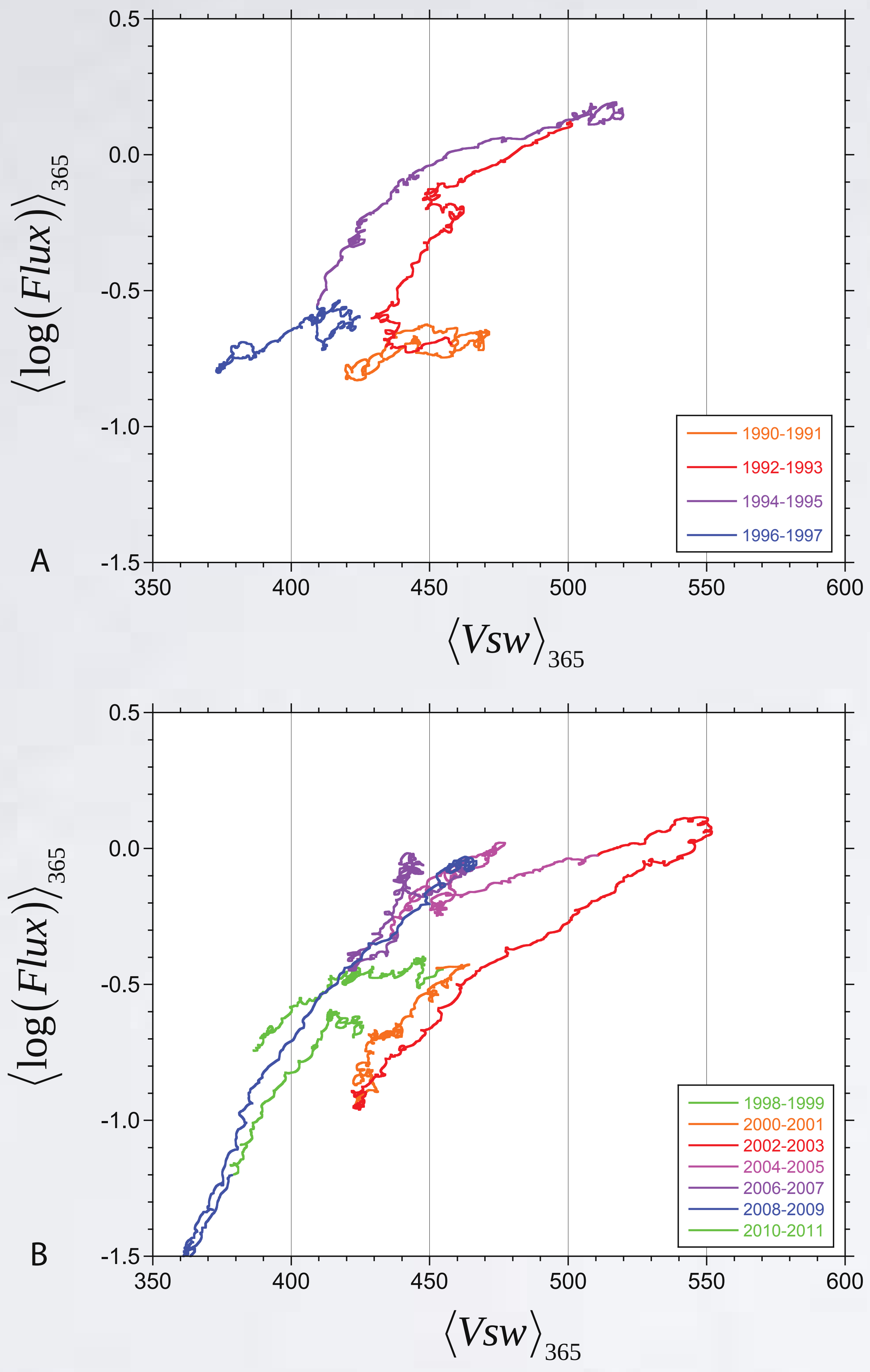


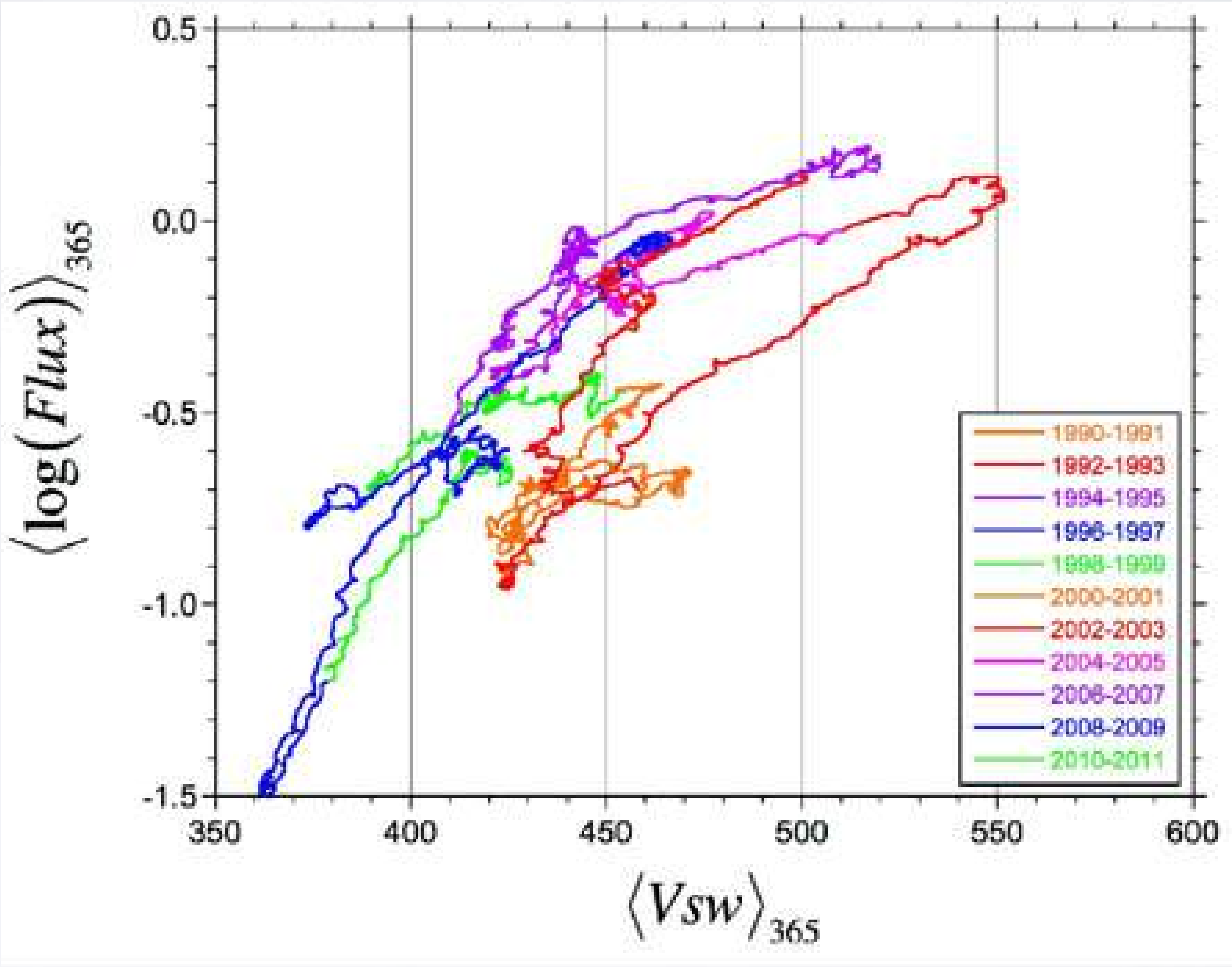
Reeves+, JGR, 2011

Can some differences in statistics be explained by data selection?

Cycle 22

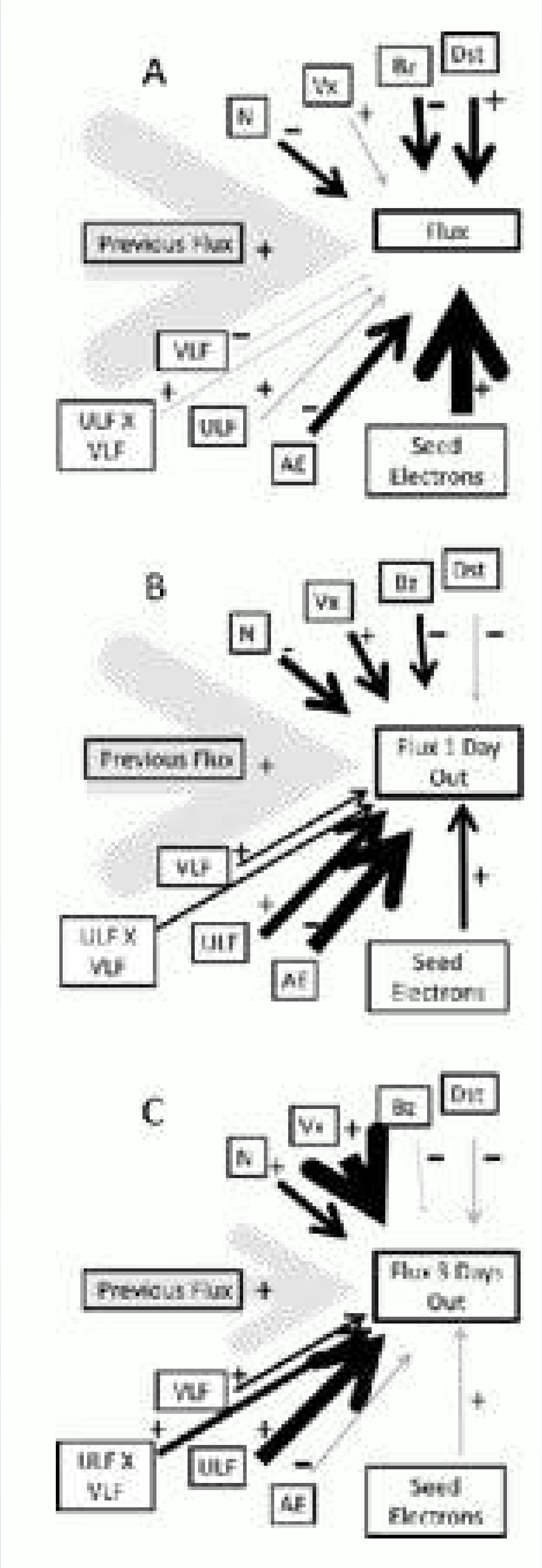
Cycle 23





When we have enough data can we use DI to understand the cause of variation within the statistics and their effects on model predictions. What about long-term climatology?

What Other Parameters are Important?

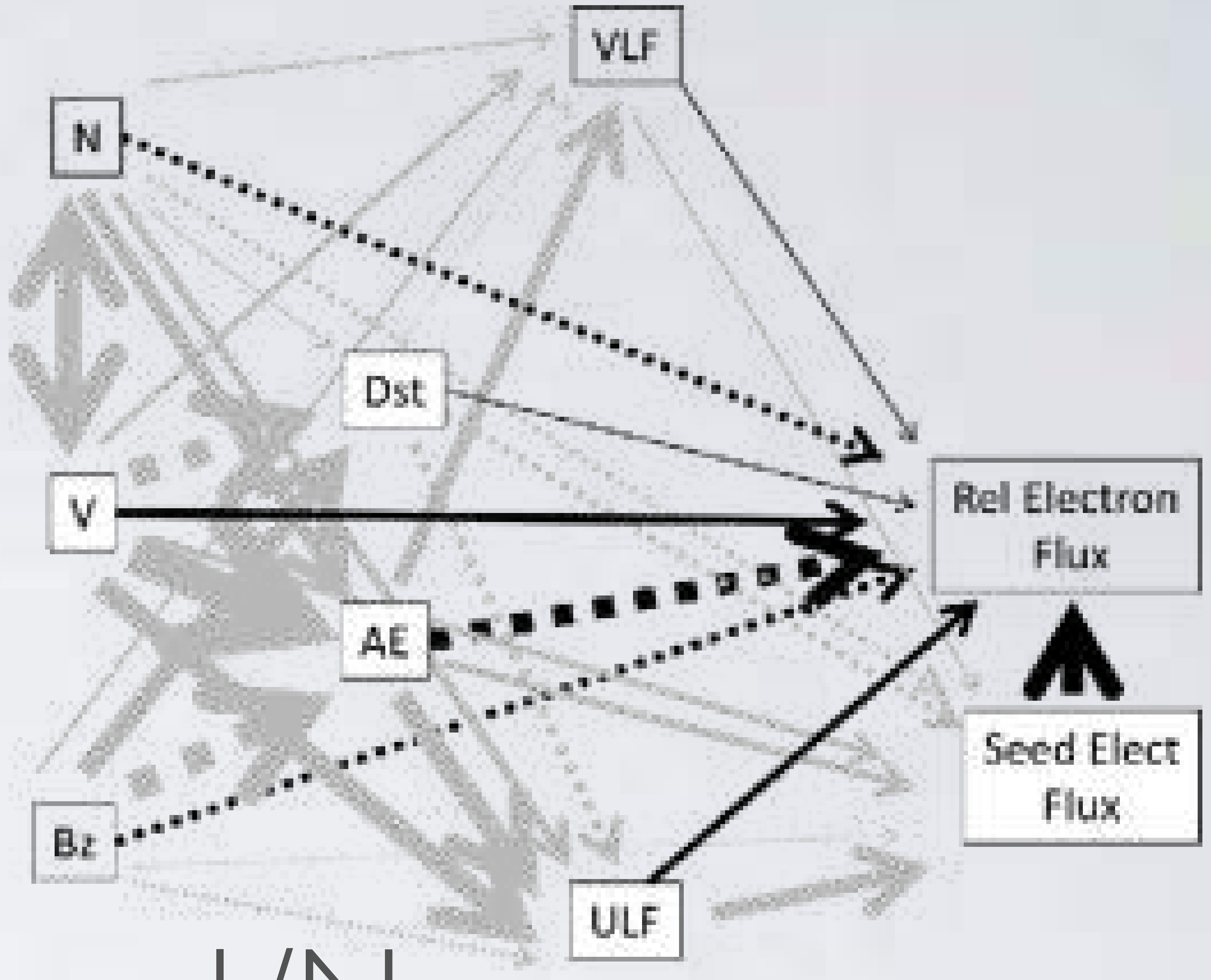


Nowcast

1-day
Forecast

3-day
Forecast

- Different techniques seem to produce different results

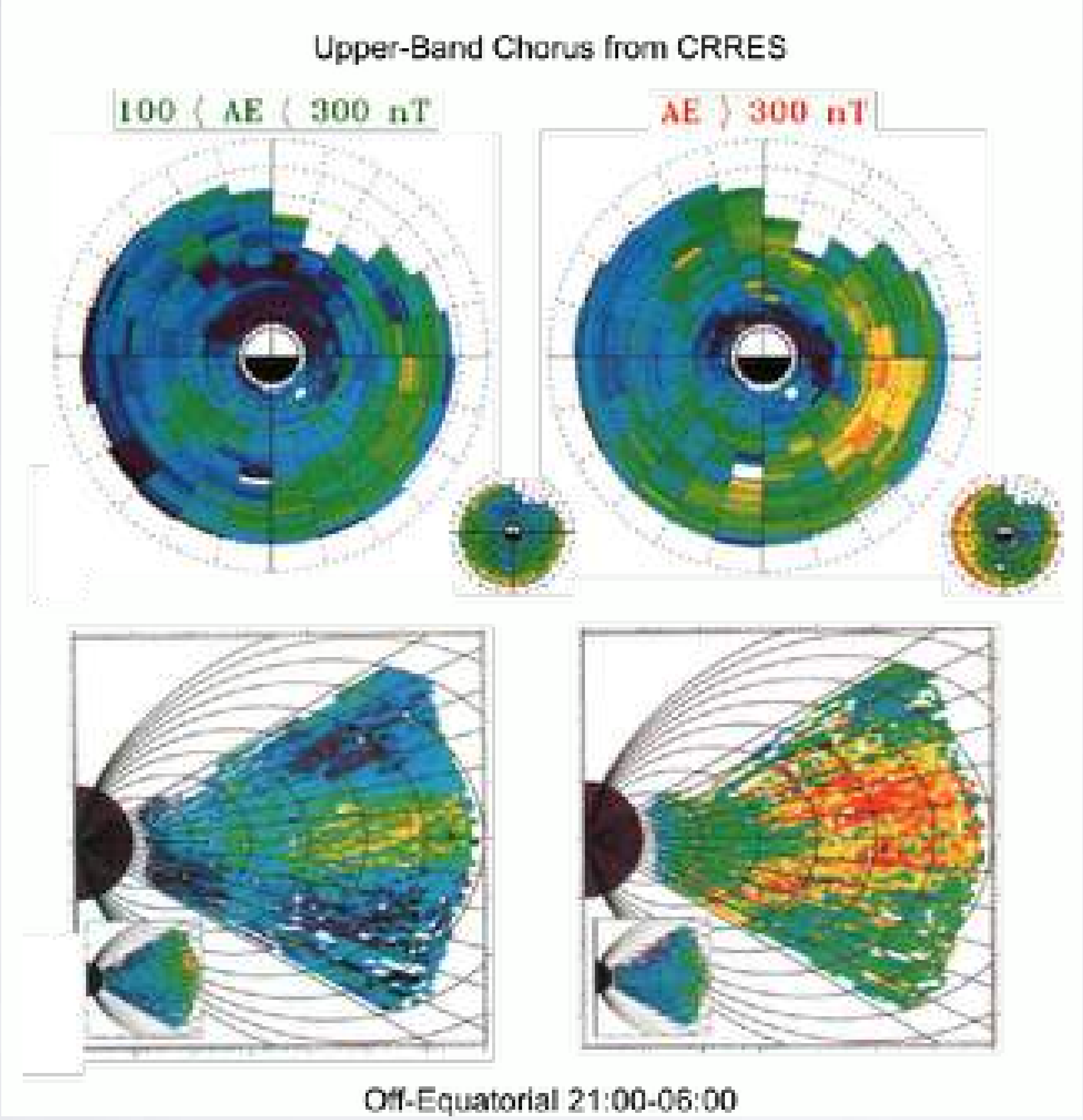


- Most emphasize density, but could identify N or N^2 or 1/N

- How can we design data+statistics+physics-based models to better understand which parameters are most important, when, and why

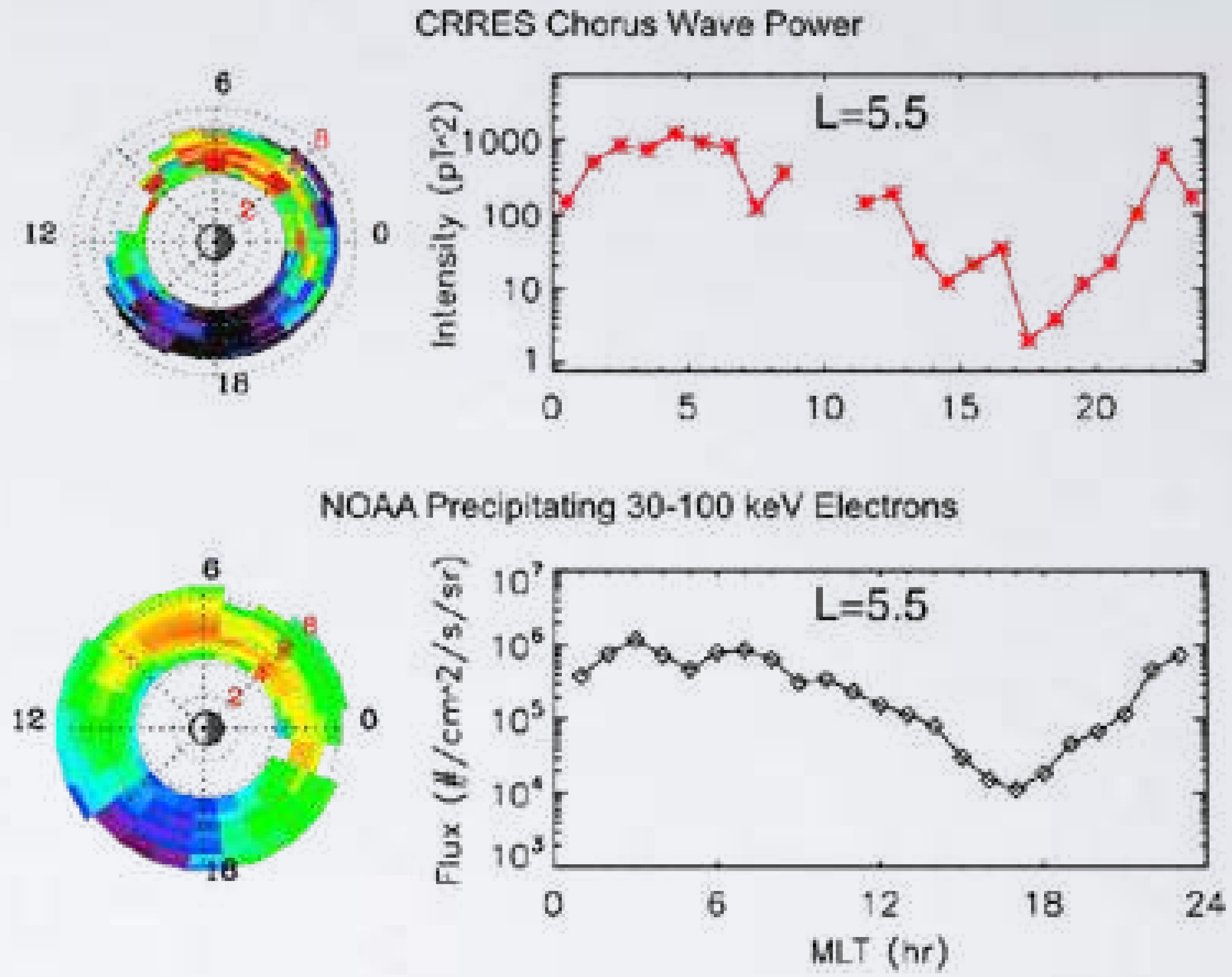
Simms+, JGR, 2016

Data, Statistics, and Physics-Based Models



- Physics-based models often use statistical inputs or statistics scaled by single point measurements

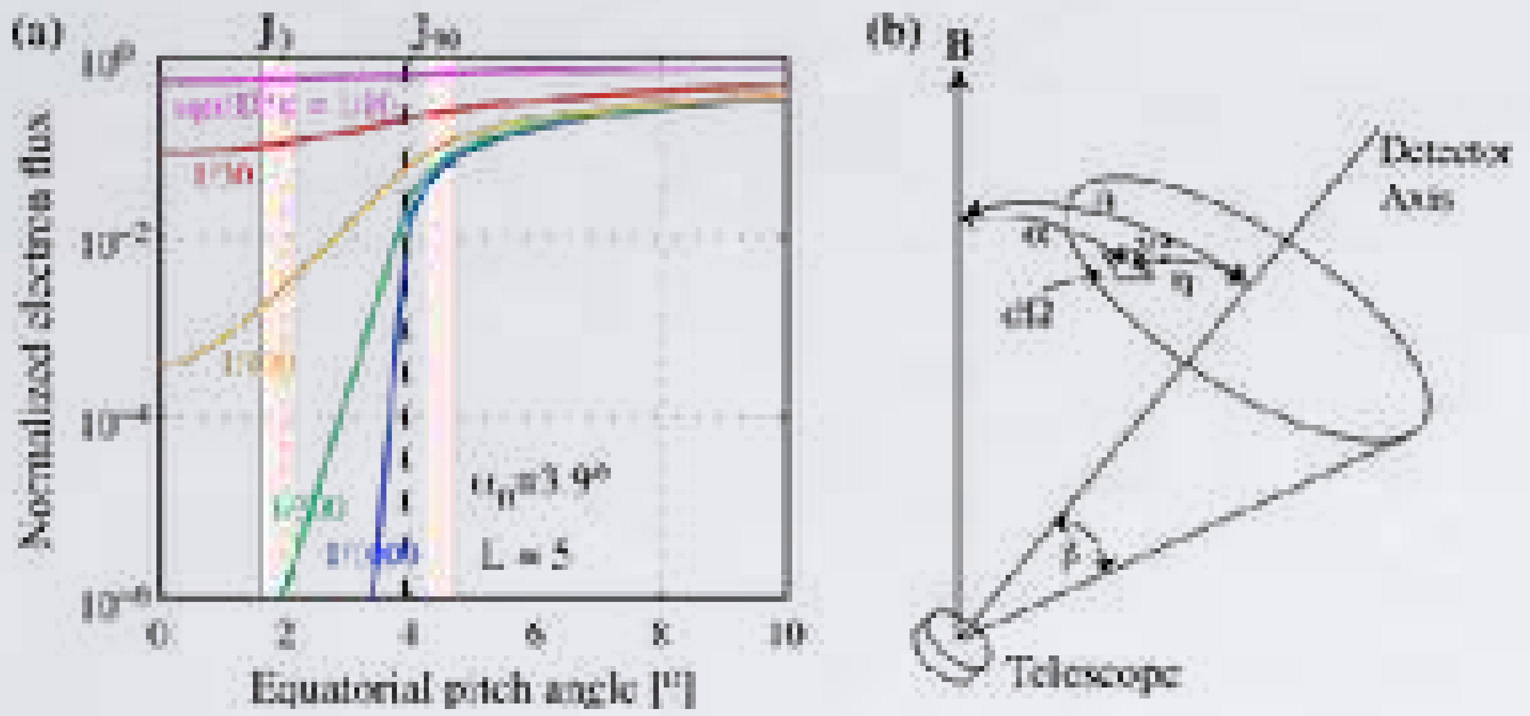
Meredith+, JGR, 2001

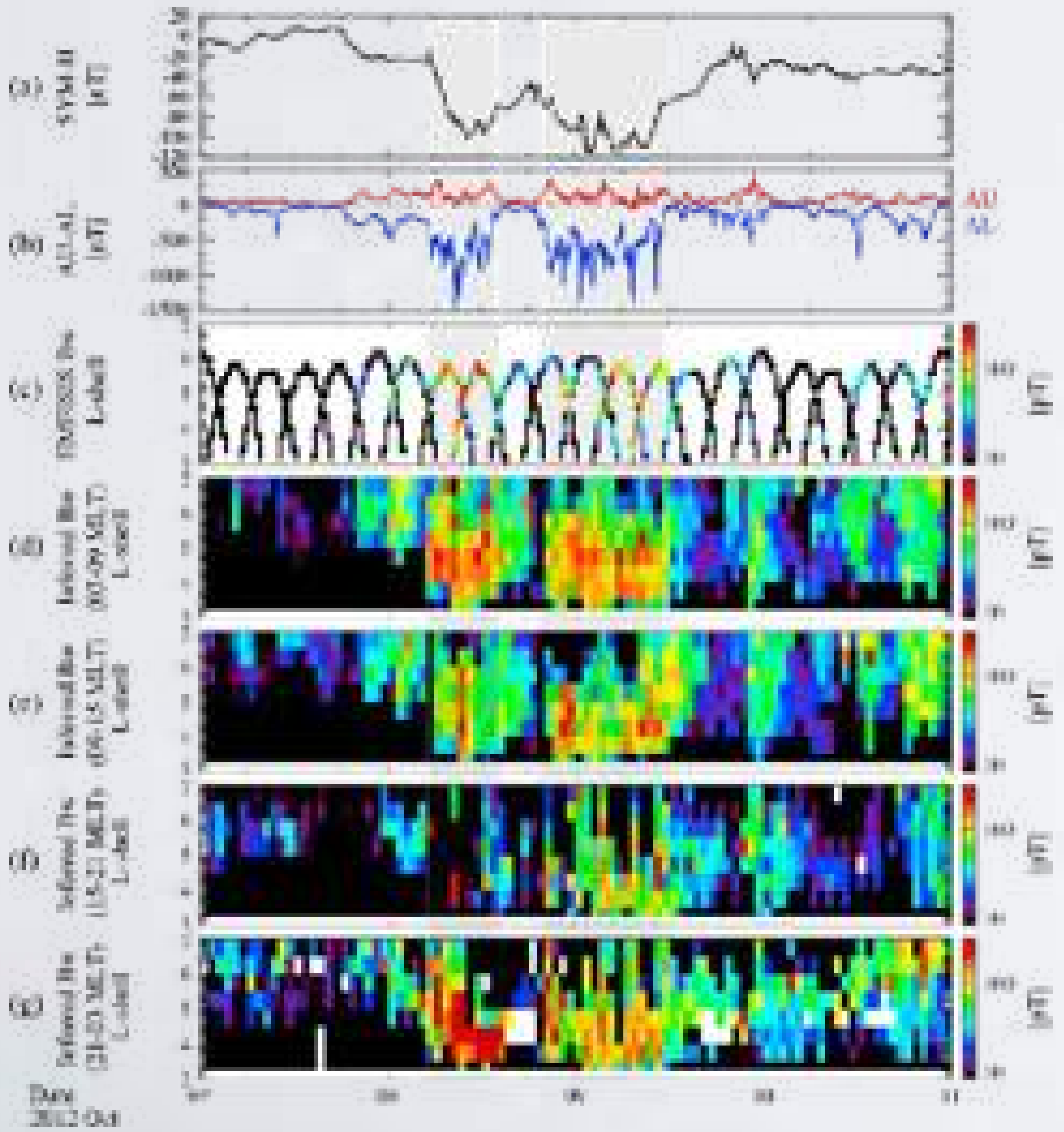


- Wave power and spatial distribution can also be inferred from observed precipitating particle fluxes which allows hour-by-hour wave inputs

Chen+, GRL, 2014

A DI approach to studying chorus generation & effects





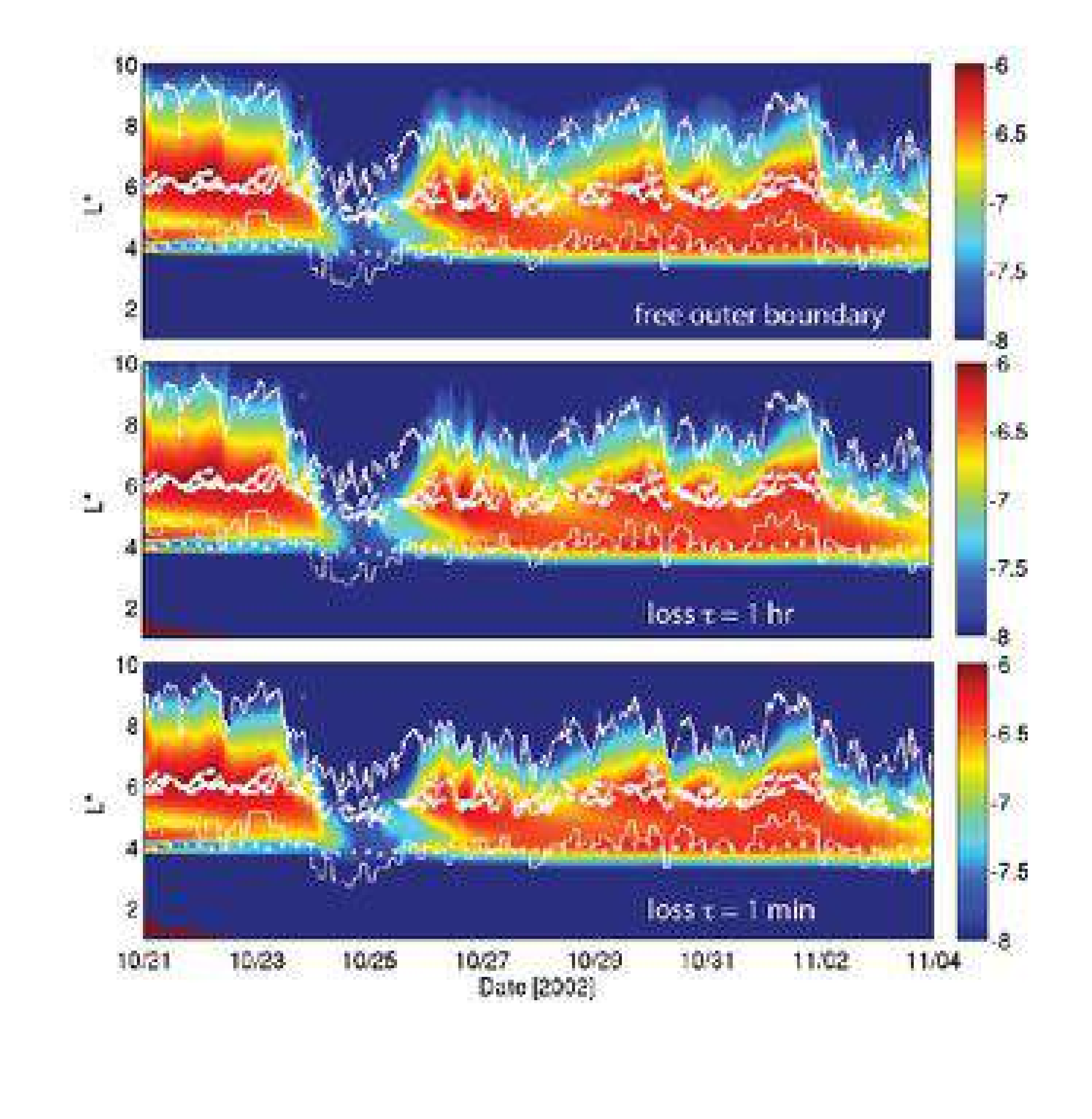
- An even more detailed analysis can be done by combining POES measurements from the 0° and 90° detectors and physics models. The optimal pitch angle diffusion rates then specify chorus wave power

- Using multiple POES satellites in different sun-synchronous orbits, we can determine the chorus wave power as a function of L and MLT at ~9 hr temporal resolution which can, in turn, be used to calculate radiation belt acceleration rates

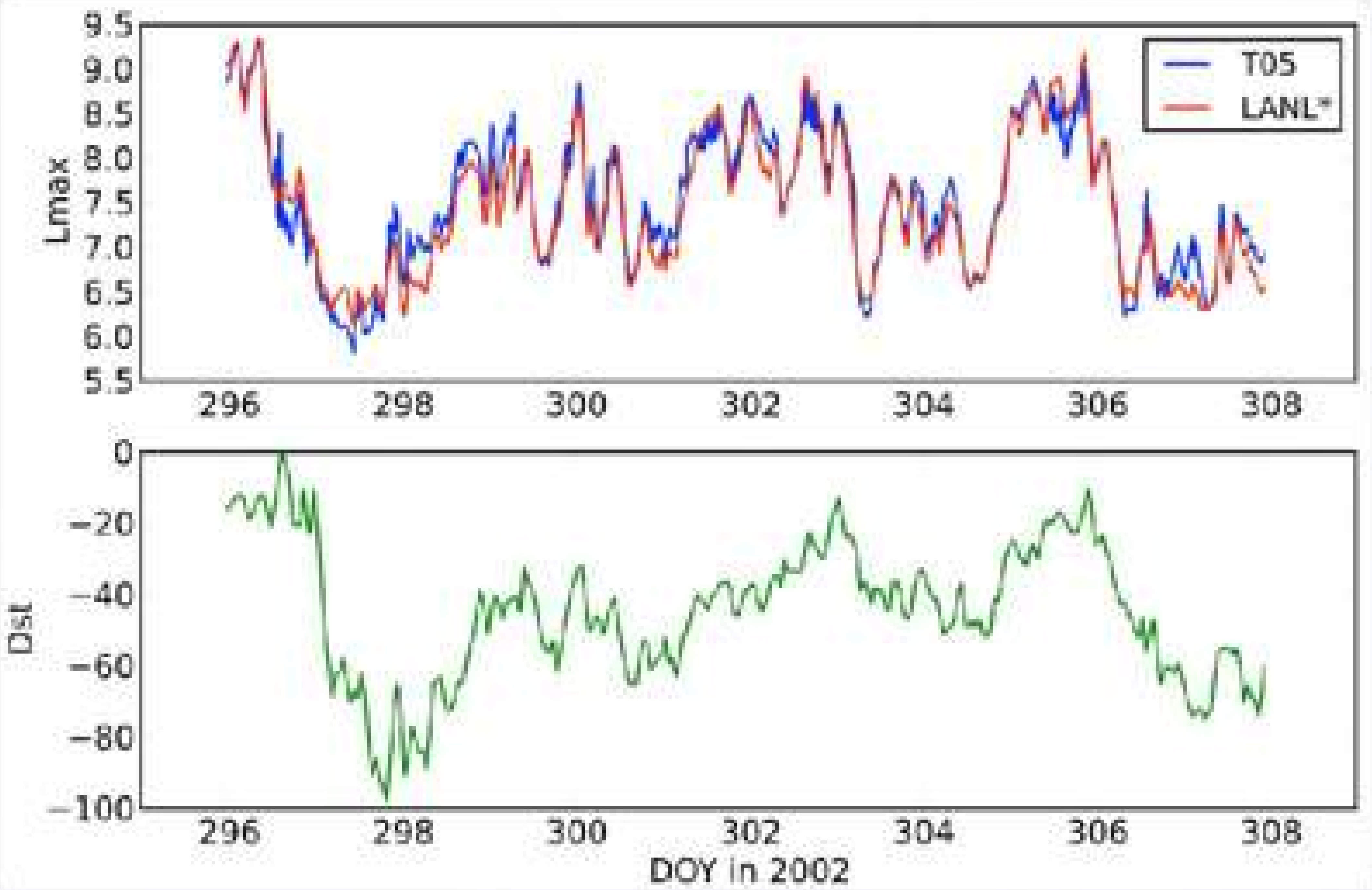
- Is it possible to go further and study the L-MLT distribution of the 'seed' electrons injected by substorm activity?

Wen Li+, GRL, 2013

Data, Neural Nets and Physics-Based Models

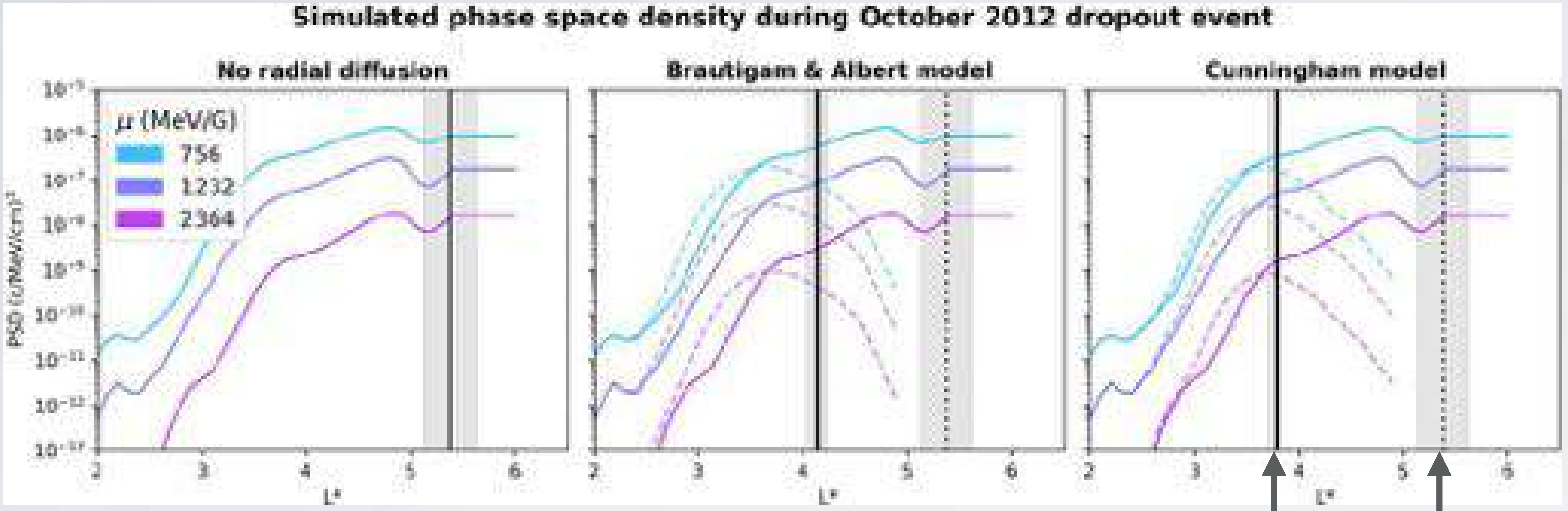


Koller & Zaharia, Geosci. Model Dev., 2011



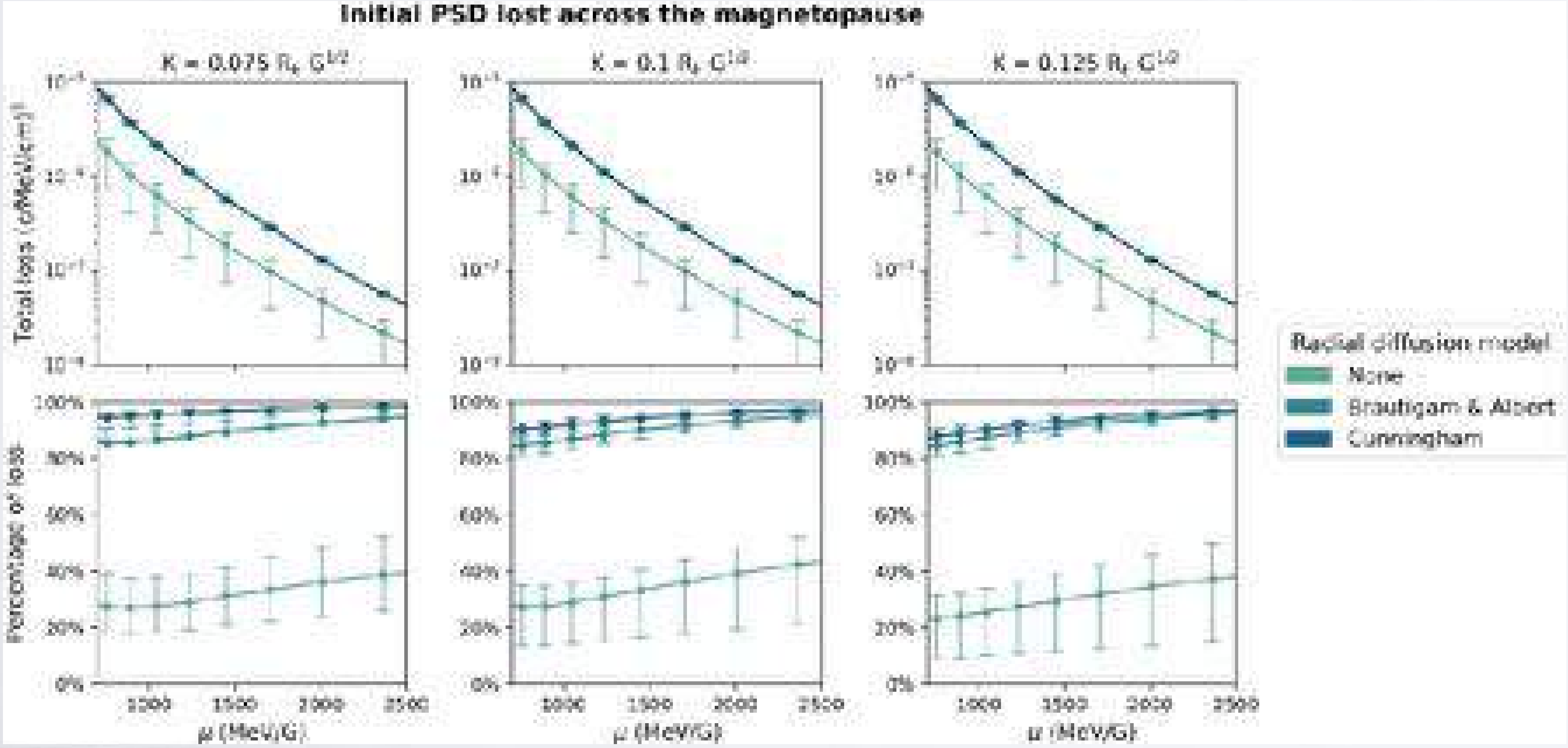
- DREAM uses an 'open' outer boundary at the last closed drift shell (~ the magnetopause) but calculation is slow
- Koller developed a neural net model of the last closed drift shell based on real time inputs

A DI approach to understanding magnetopause losses



Electrons past here are lost to the magnetopause

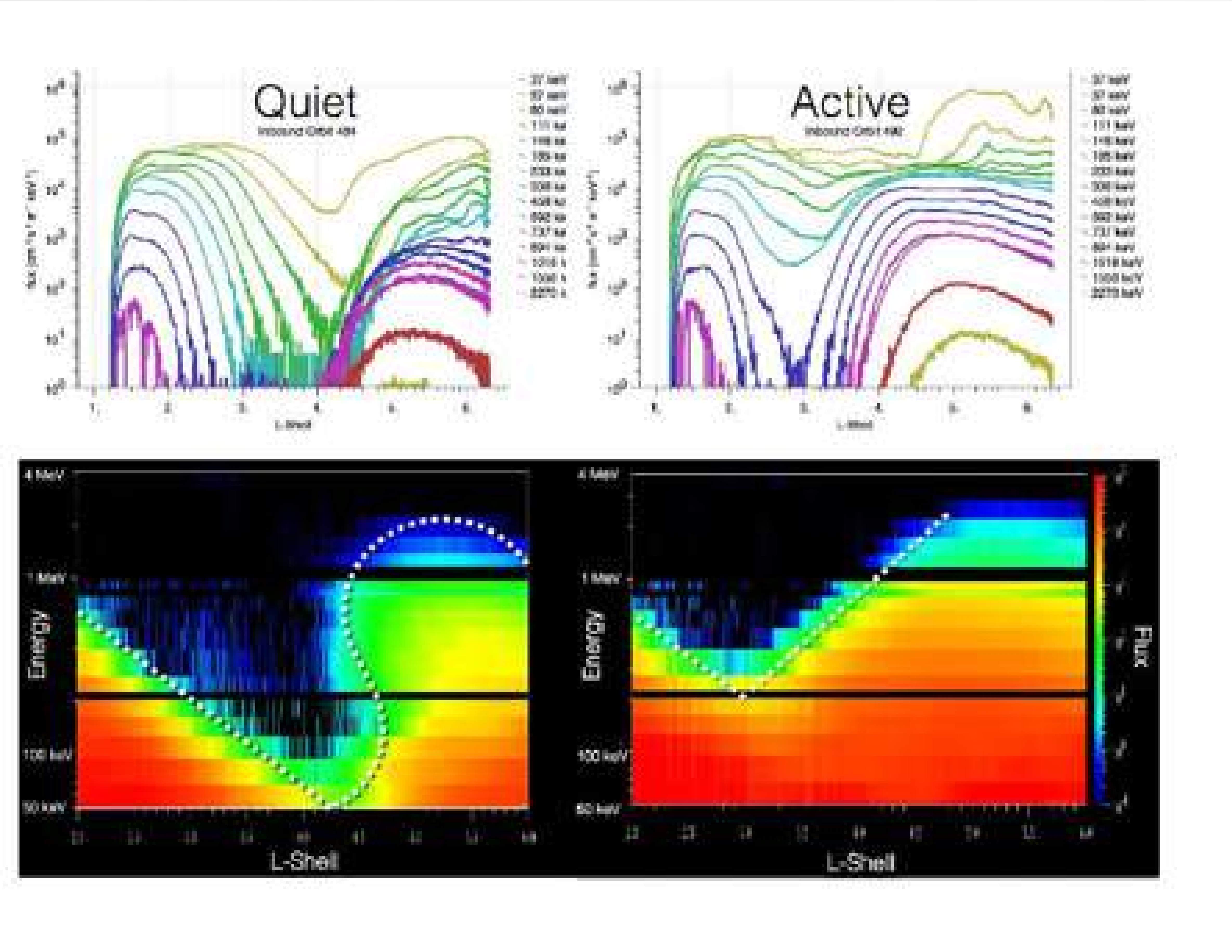
LCDS-min



Harriet George+, JGR, 2022

- George et al. calculated the amount of PSD lost to the magnetopause due to magnetopause shadowing alone and shadowing + outward radial diffusion
- The Cunningham diffusion model incorporates non-dipole magnetic field effects
- Outward radial diffusion plays a major role in losses even down to very low L*

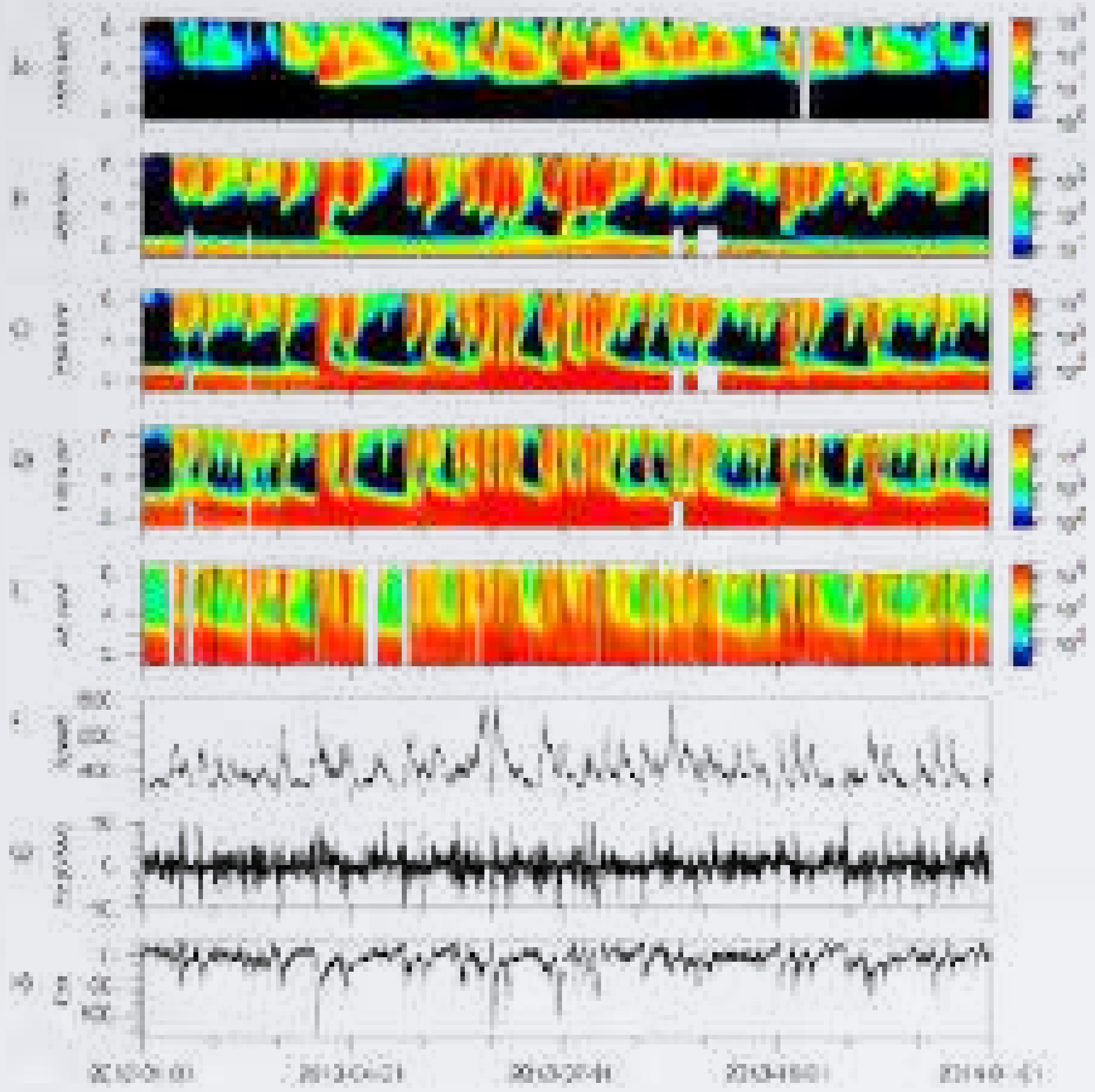
Radiation Belts - Plasmasphere - Ionosphere

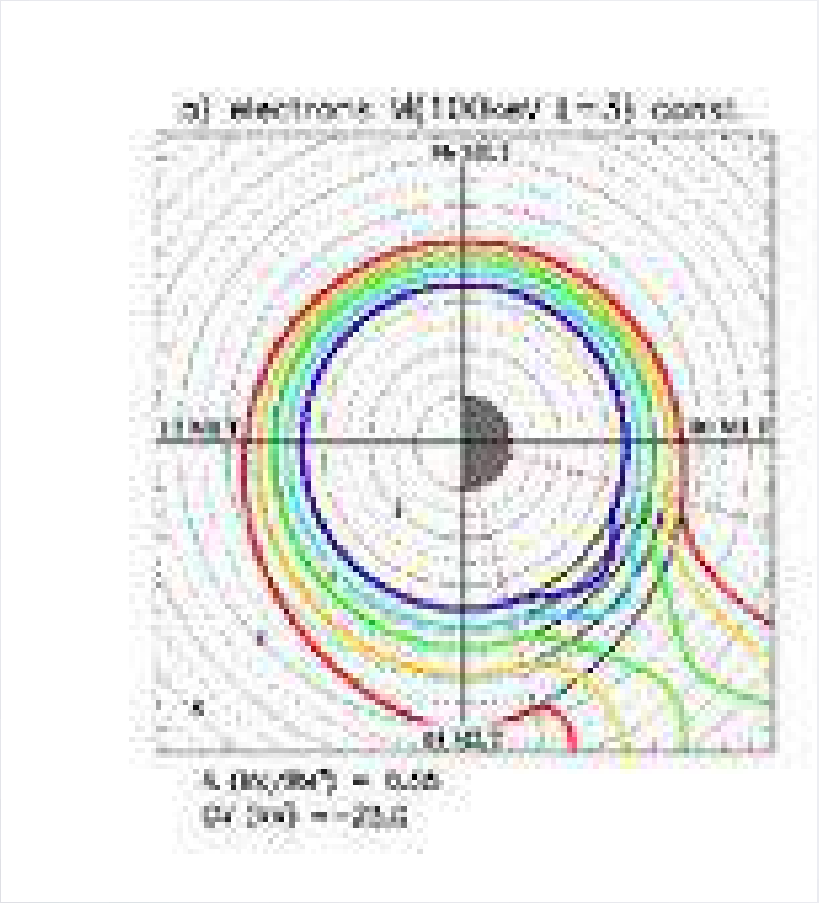


- In active times radiation belt electrons are accelerated in the outer belt
- 'Medium energy' electrons can be injected to very low L-shells and into the inner zone
- Between energization events, plasmaspheric hiss precipitates electrons and the slot region is formed
- All these processes depend on energy and L-shell

Reeves+, JGR, 2016

Radiation Belts - Plasmasphere - Ionosphere





Reeves+, JGR, 2016; Turner+, JGR, 2016, Lejosne+, GRL, 2018, Ryan Sault

- Lower-energy electrons fill the slot more frequently but energies up to 100s keV can reach the inner zone
- These are not standard substorm injections
- Lejosne et al. propose the mechanism is SAPS electric fields that also produce STEVE and SAR arcs
- How can radiation belt and auroral observations be combined with models to understand global, dynamic electric fields and magnetosphere-ionosphere coupling?

The COSPAR task group on establishing an International Geospace Systems Program (IGSP or ISTP-NEXT)

A coordinated strategy and roadmap for scientific advancement and discovery in upcoming decades

Larry Kepko
NASA Goddard Space Flight Center
On behalf of the COSPAR IGSP Task Group

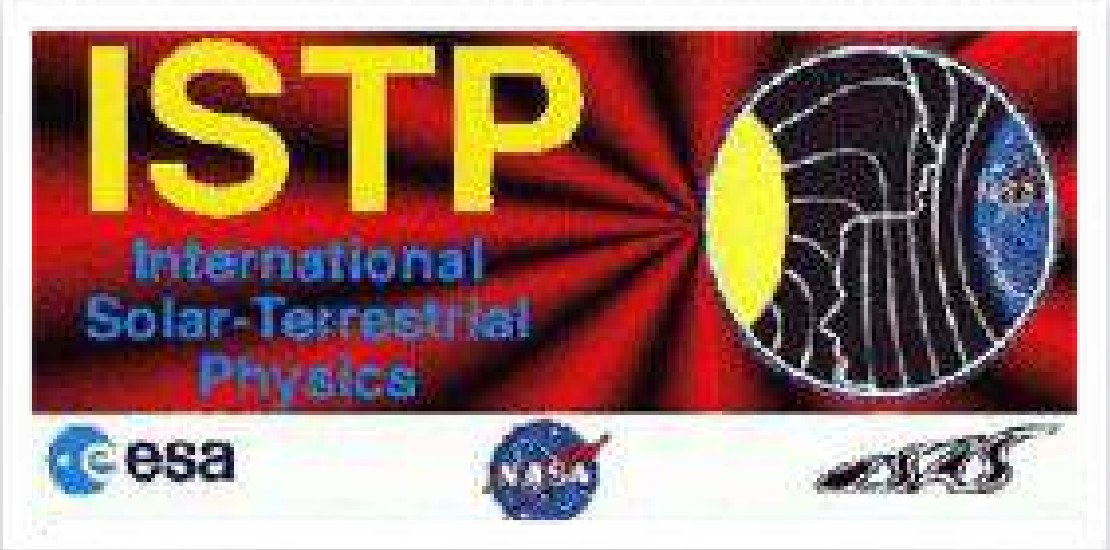
Space Physics has had 4 primary eras

The 5th era is up to us to define

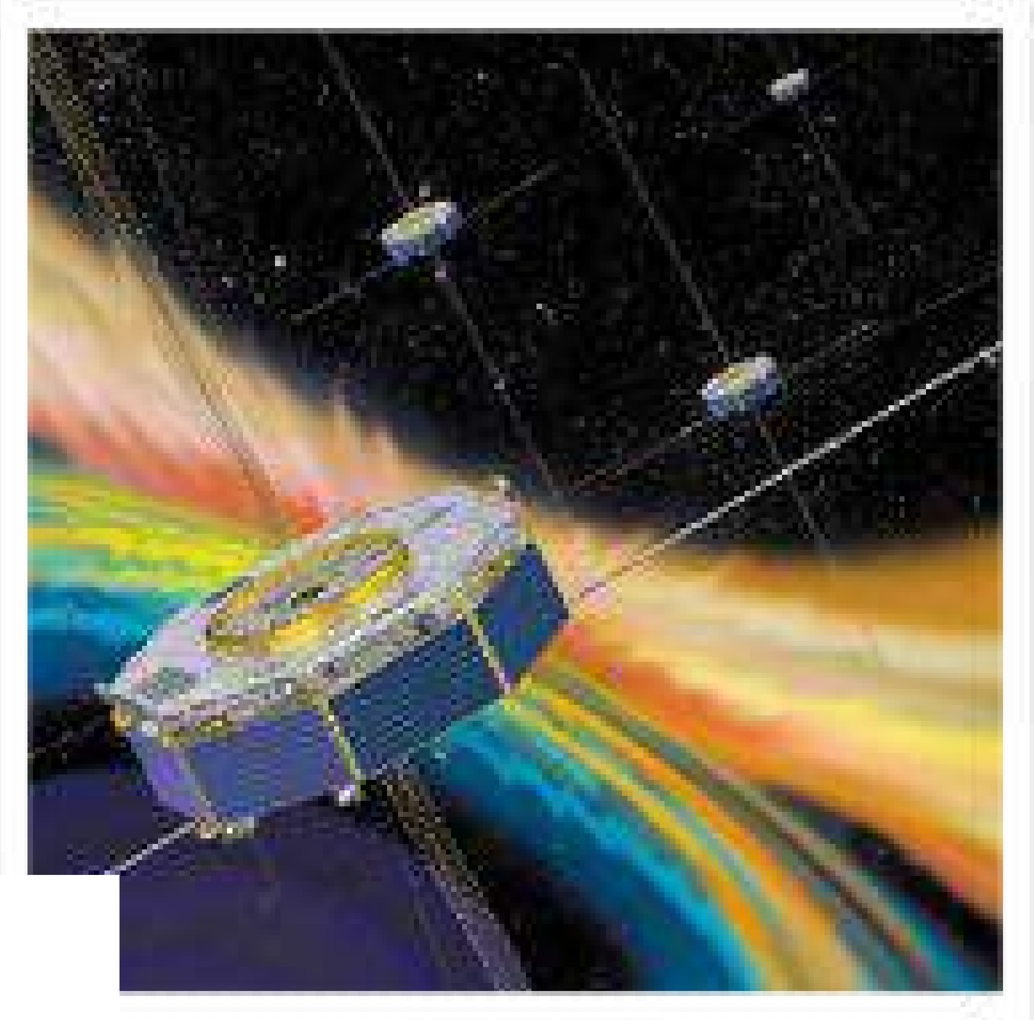
Discovery era - Regions

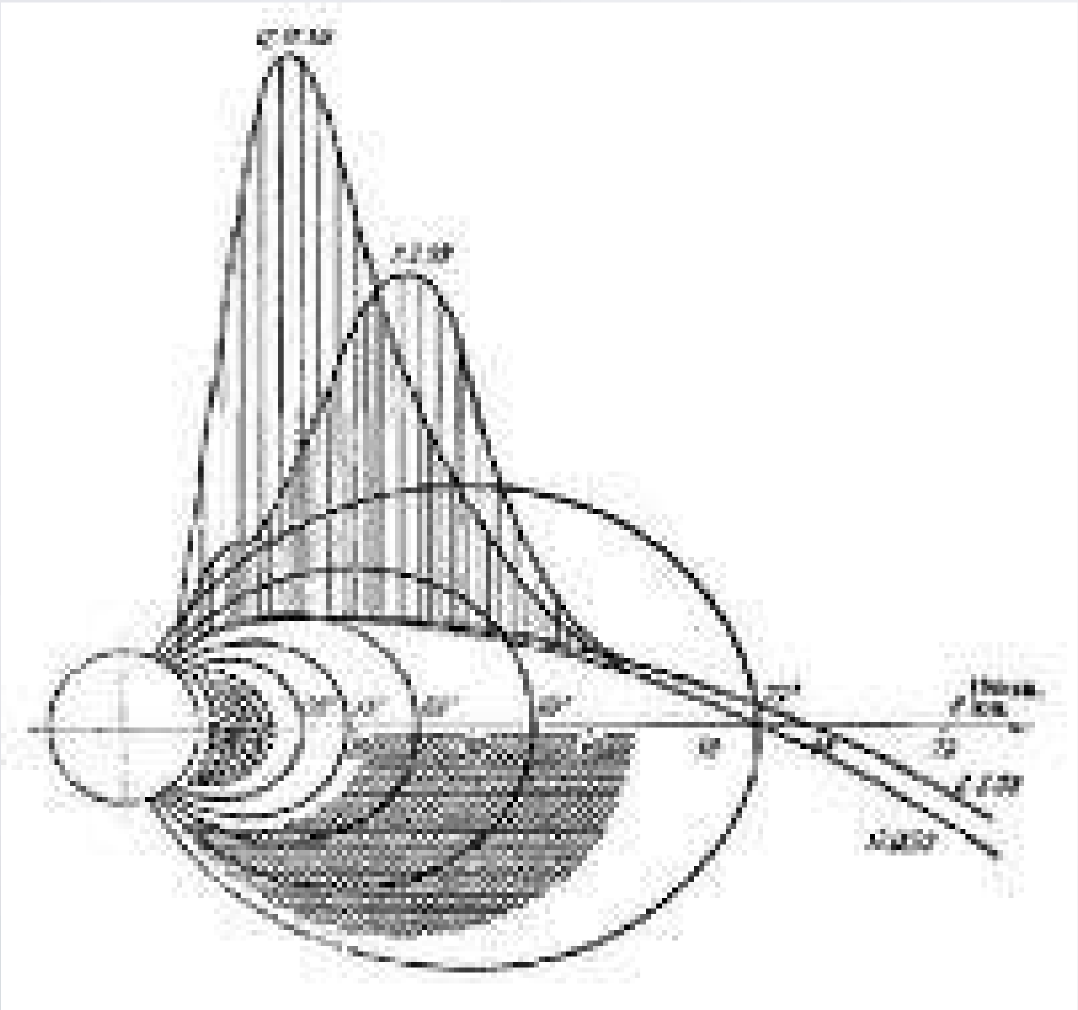
Discovery era - Dynamics

Era of coarse system science (ISTP)

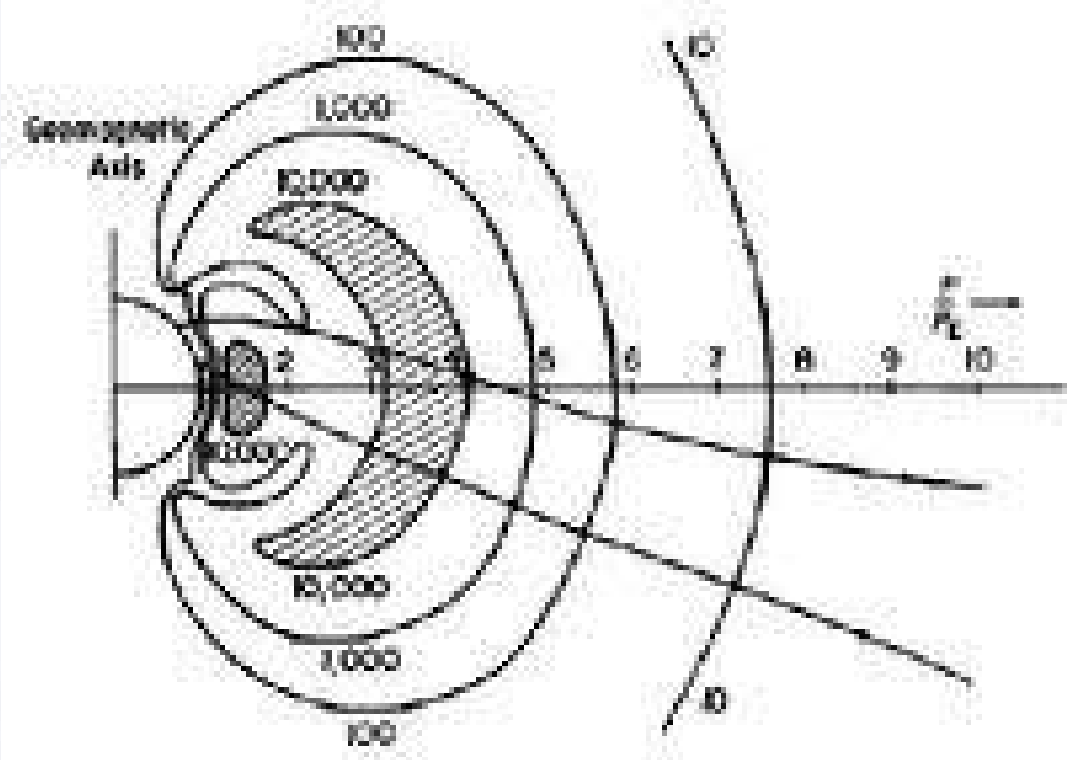


Era of details

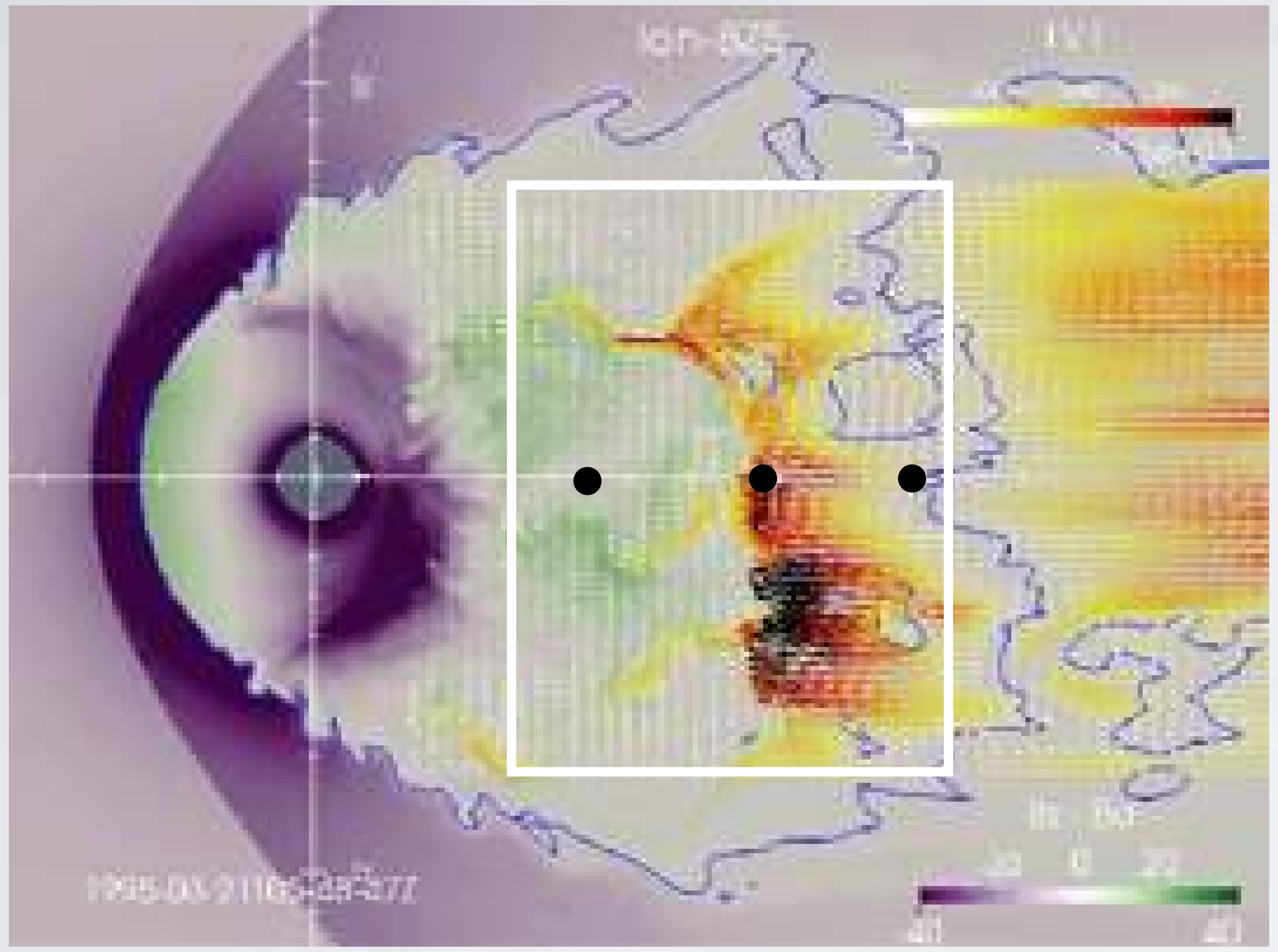


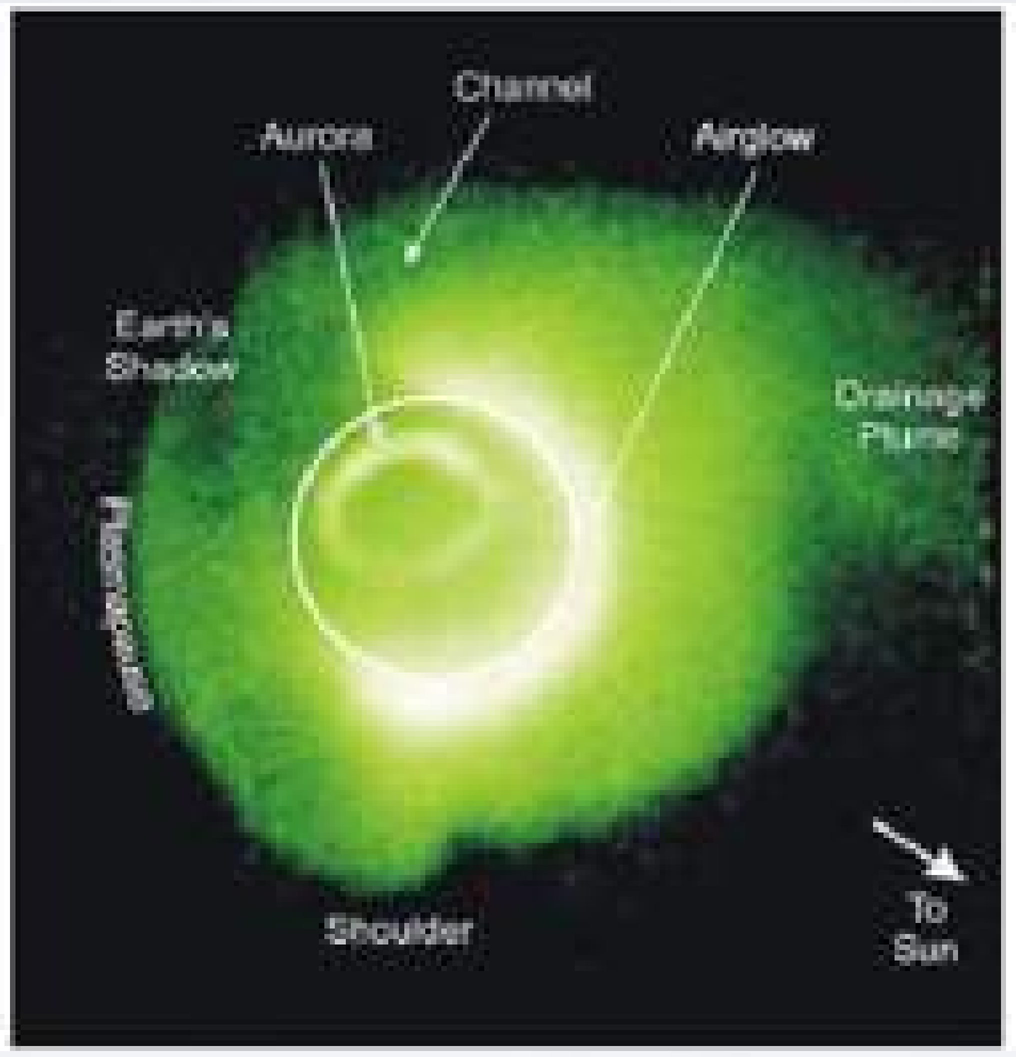


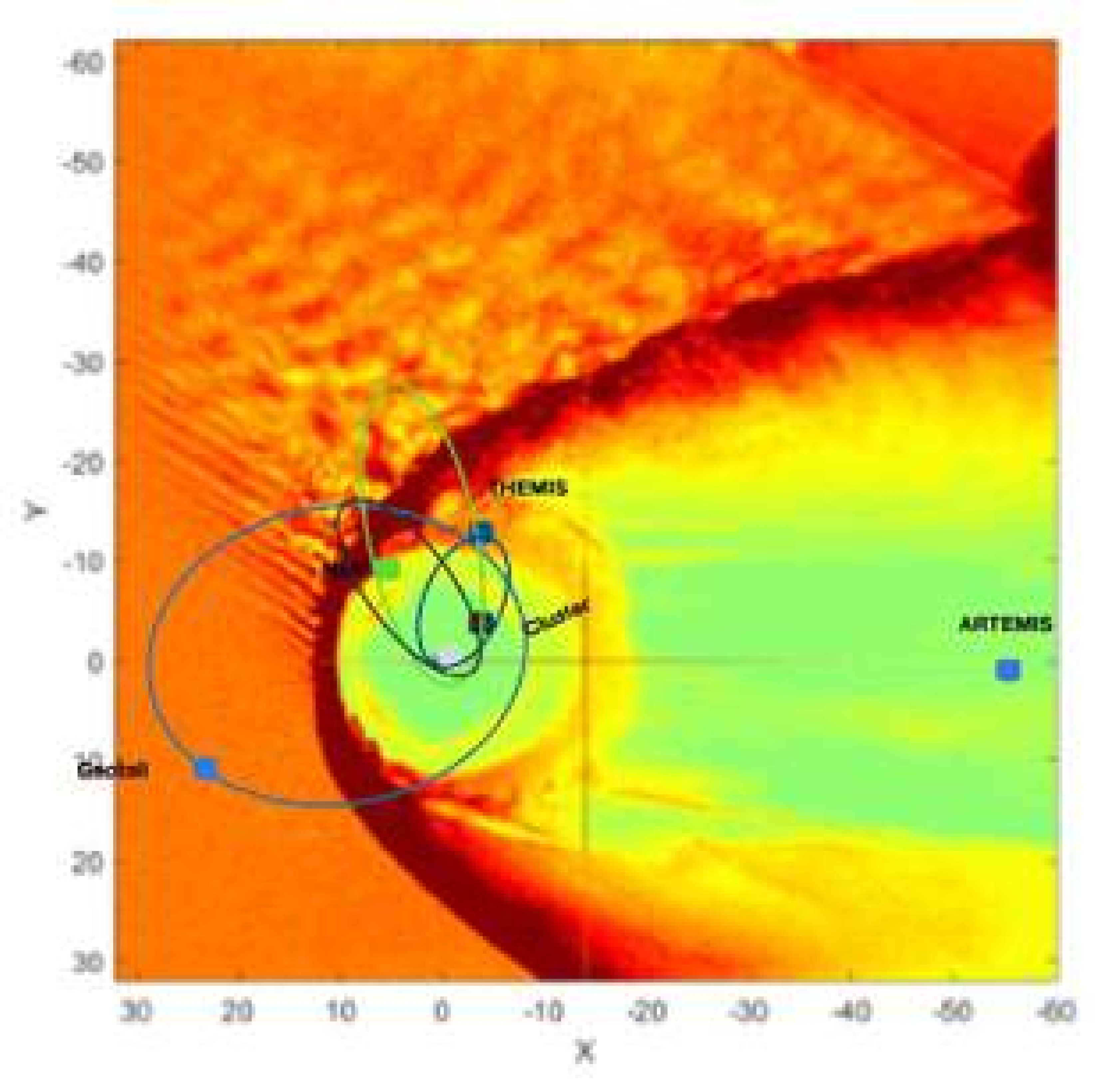
The 5th era should focus on the **mesoscales**, aka the "missing middle" and the magnetosphere as a System of Systems

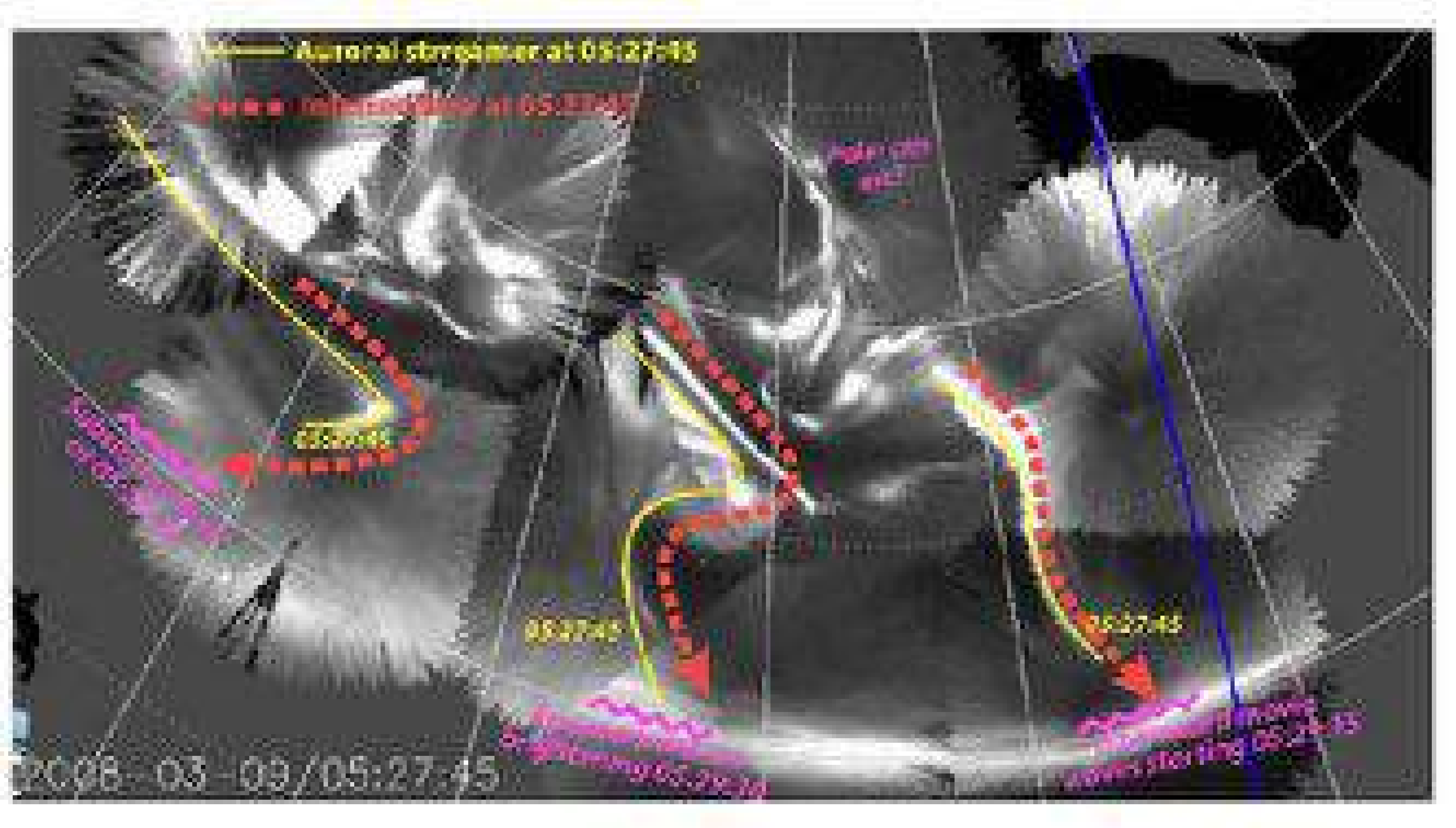


We need all the tools at our disposal to understand the physics of a system-of-systems









Using Data-Intelligent Models to Understand the Physics of the Inner Magnetosphere

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