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# Geospace at the System Level: Reductionism v. Complexity

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# Acknowledgments

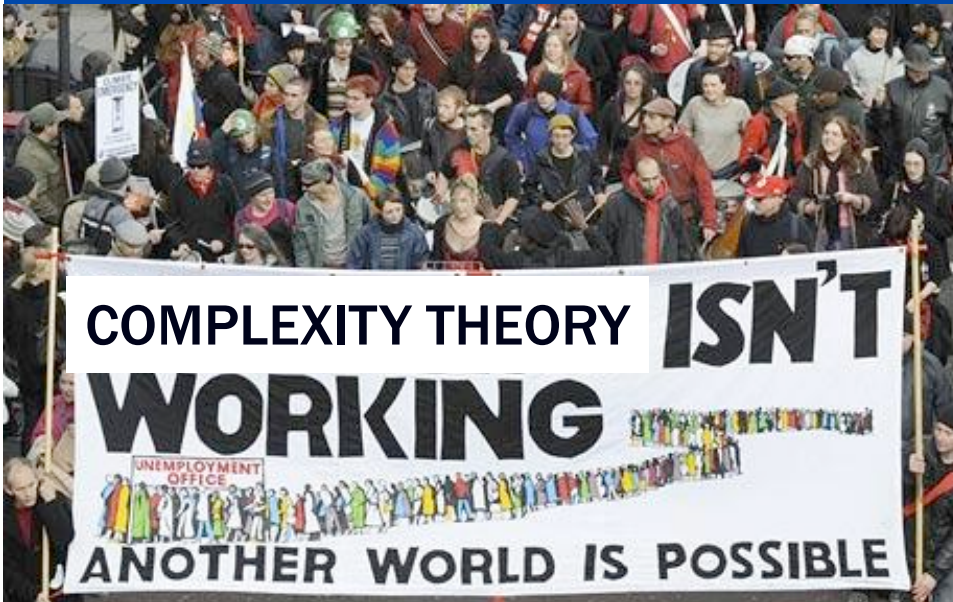
- Michelle Thomsen had no input on the content of these slides
  - Also: I've had more than 45 minutes prep time
- However, an ISSI team of which I was a part did have significant influence
  - Led by Mark Lester and Eric Donovan
  - Half a dozen CEDAR and GEM regulars on the team

# System-Level Science

- Two approaches: reductionism and complexity
- Reductionism:
  - Reduce a big problem into component problems
  - System-level reductionism
    - Don't worry about subsystem details, parameterize
- Complexity:
  - Toss out components completely
    - Look for relationships that are "scale-free": power law function
    - Intervals with the same power law = same physics
    - Slope of power law = something about the physics

# "System" or "Systems" Level?

- One split:
  - Reductionism is *systems*-level
  - Complexity is *system*-level
- The battle rages in the streets

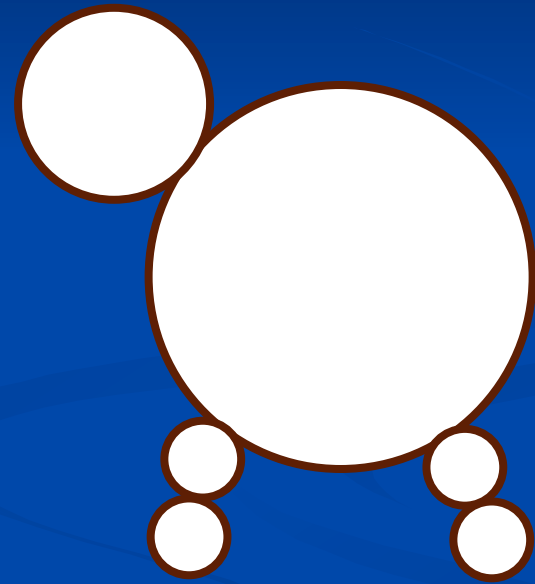
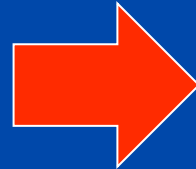
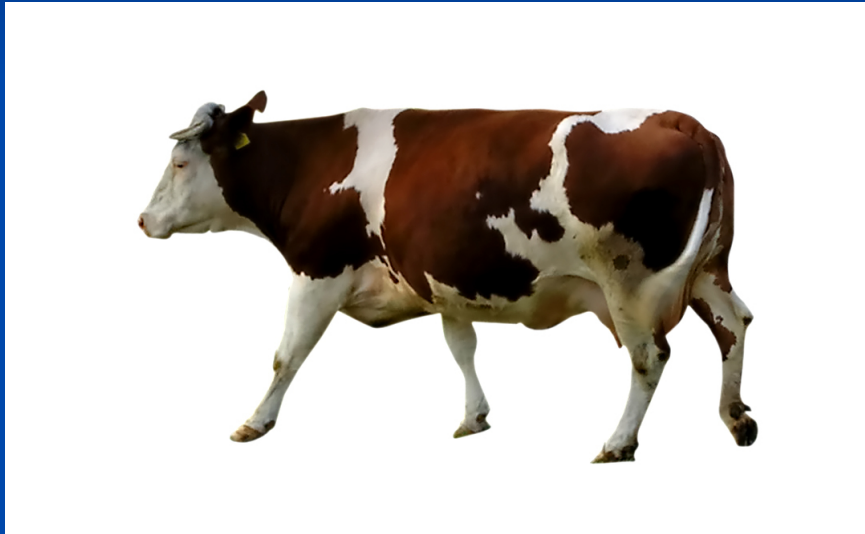


# Reductionism

- Basic meaning:
  - Understand a complicated system by understanding its component subsystems
- Some built-in assumptions
  - Assumes the system can be compartmentalized
  - Assumes regions can be described with physical equations
  - Assumes inter-regional couplings are known
  - Assumes components interact at the boundaries
- If these are met, then...
  - Works great!

# The Spherical Cow

- Reductionism in its purest form

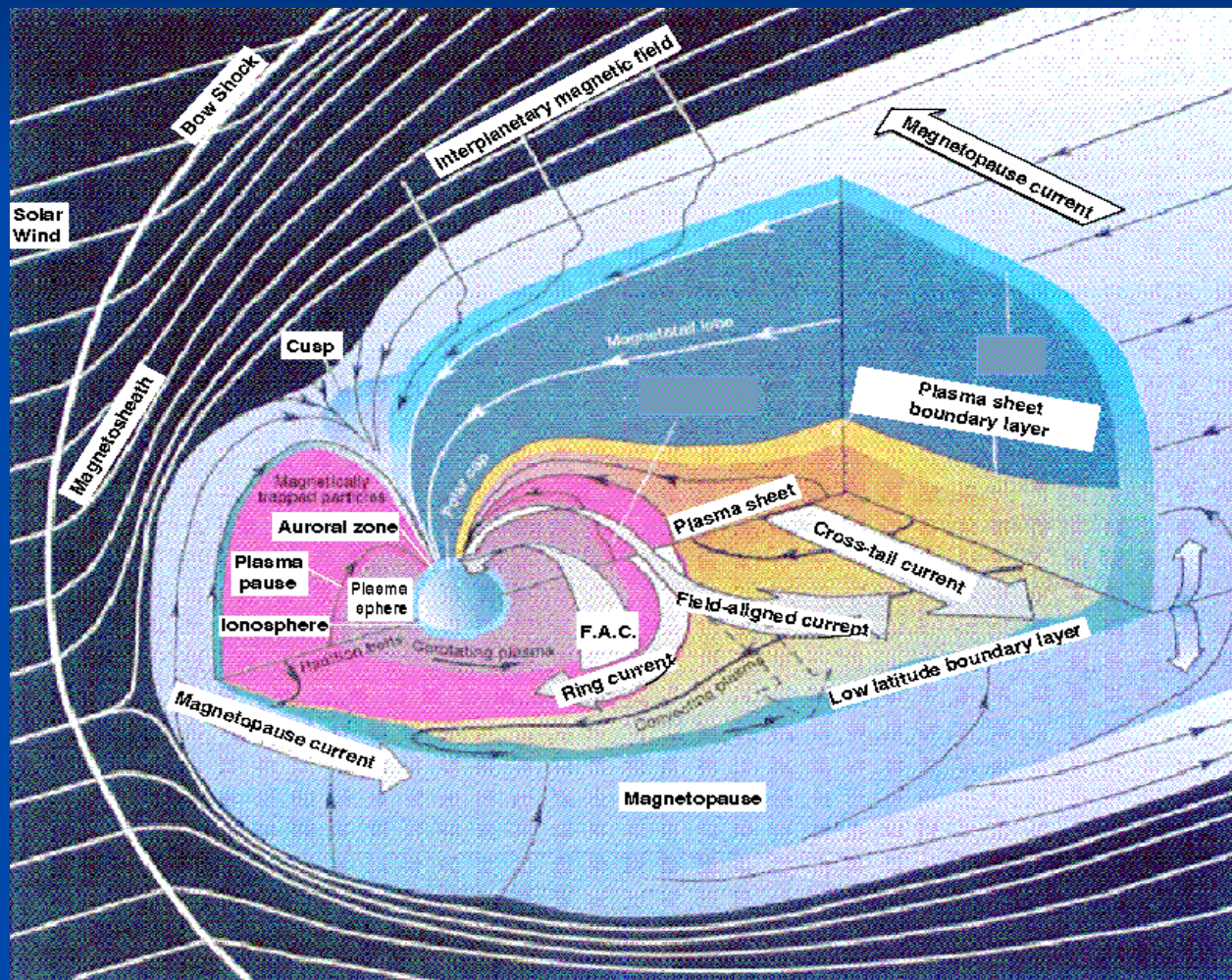


# System Level Reductionism

- Reductionism assumes boundary conditions between the components
  - Can we really understand the whole system by simply understanding each component separately?
  - As long as the flow is one-way through the system
- What if it isn't?
  - What if there is a feedback cycle within the system?
  - Example pic: cow's stomach is empty, tells brain to eat, cow eats, stomach gets full, tells brain to stop eating

# What About Geospace?

- The classic schematic of geospace
  - Well compartmentalized regions (shaded different colors)



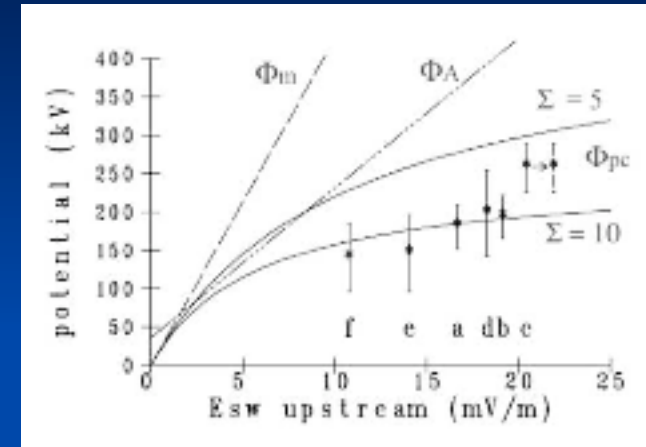
# Geospace at the System Level

- Mass and energy flow in a particular direction
  - Solar wind into the magnetosphere
  - Ionosphere into the magnetosphere
  - Outer magnetosphere into the inner magnetosphere
  - Magnetosphere into the ionosphere/thermosphere
- What makes this a system-level issue
  - Feedback
    - When the input to one region can be modified by the response within that region
  - Time history
    - When the pre-existing state of a region changes how it responds to a certain input

# Examples of Feedback and Time History

## ■ Feedback

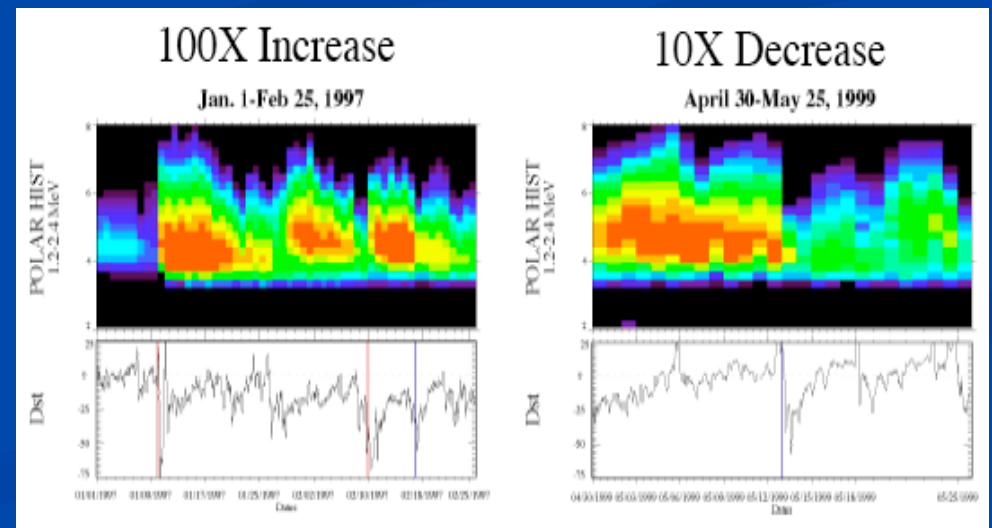
- Polar cap electric potential saturation
- At strong SW driving, internal processes reduce the efficiency of each new increase in SW driving



Hairston et al, 2003

## ■ Time History

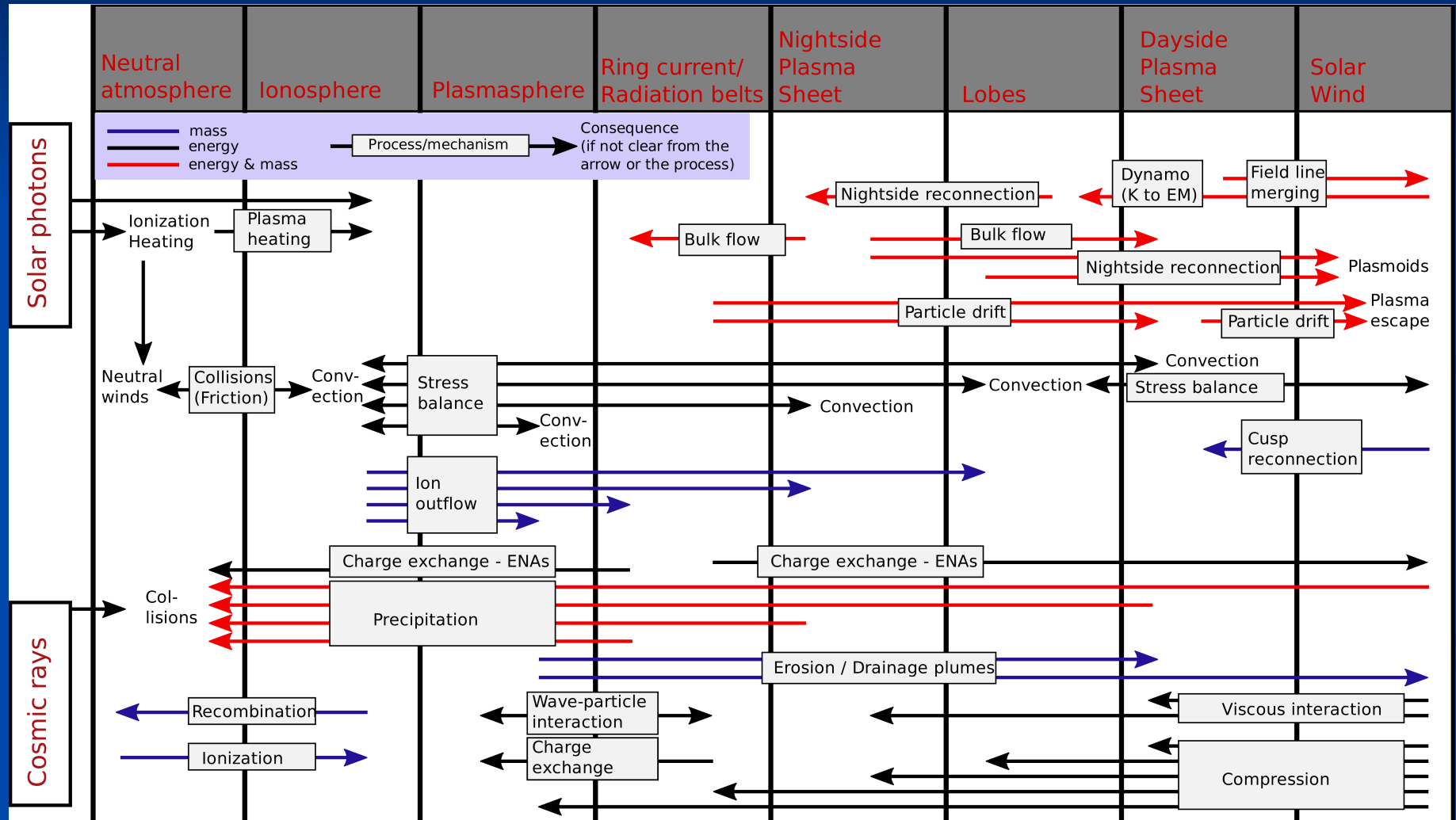
- Radiation belt dynamics
- Depends on plasmasphere and ring current, which develop over hours to days



Reeves et al, 2003

# Mass and Energy Flow Through Geospace

- A detailed listing of the couplings



# Regional System-Level Science

- Not all reductionist system-level science has to involve the entirety of geospace
  - Inter-regional couplings and feedback loops
  - Time-history influences within a single region
- Example: the inner magnetosphere
  - Some approaches are clearly not system level
  - At some level of sophistication, the analysis becomes a system-level scientific study

# Levels of Analyzing the Ring Current 1

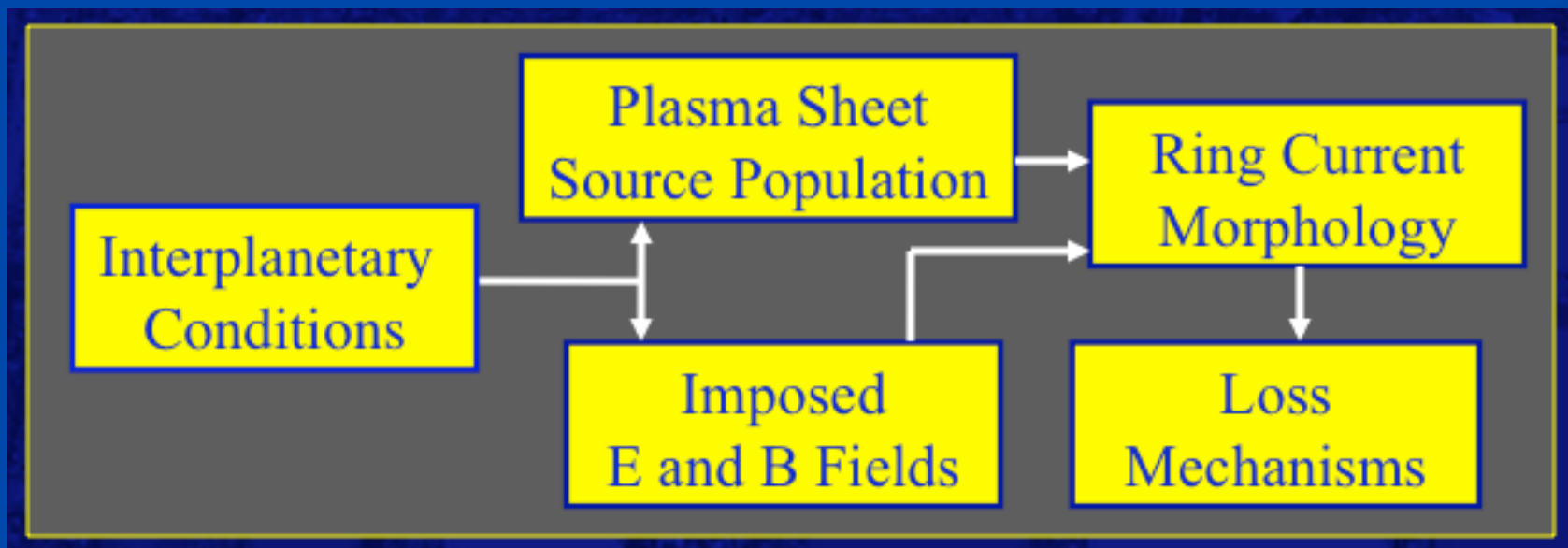
- Very simple level:
  - Estimate  $Dst^*$  and then guess
  - Use a linear or non-linear filter for the first arrow
  - Use empirical models of ion flux for the second arrow



- This is a "Bretherton Diagram" for the ring current
  - Bretherton Diagram = famous block diagram for atmospheric science that served them very well

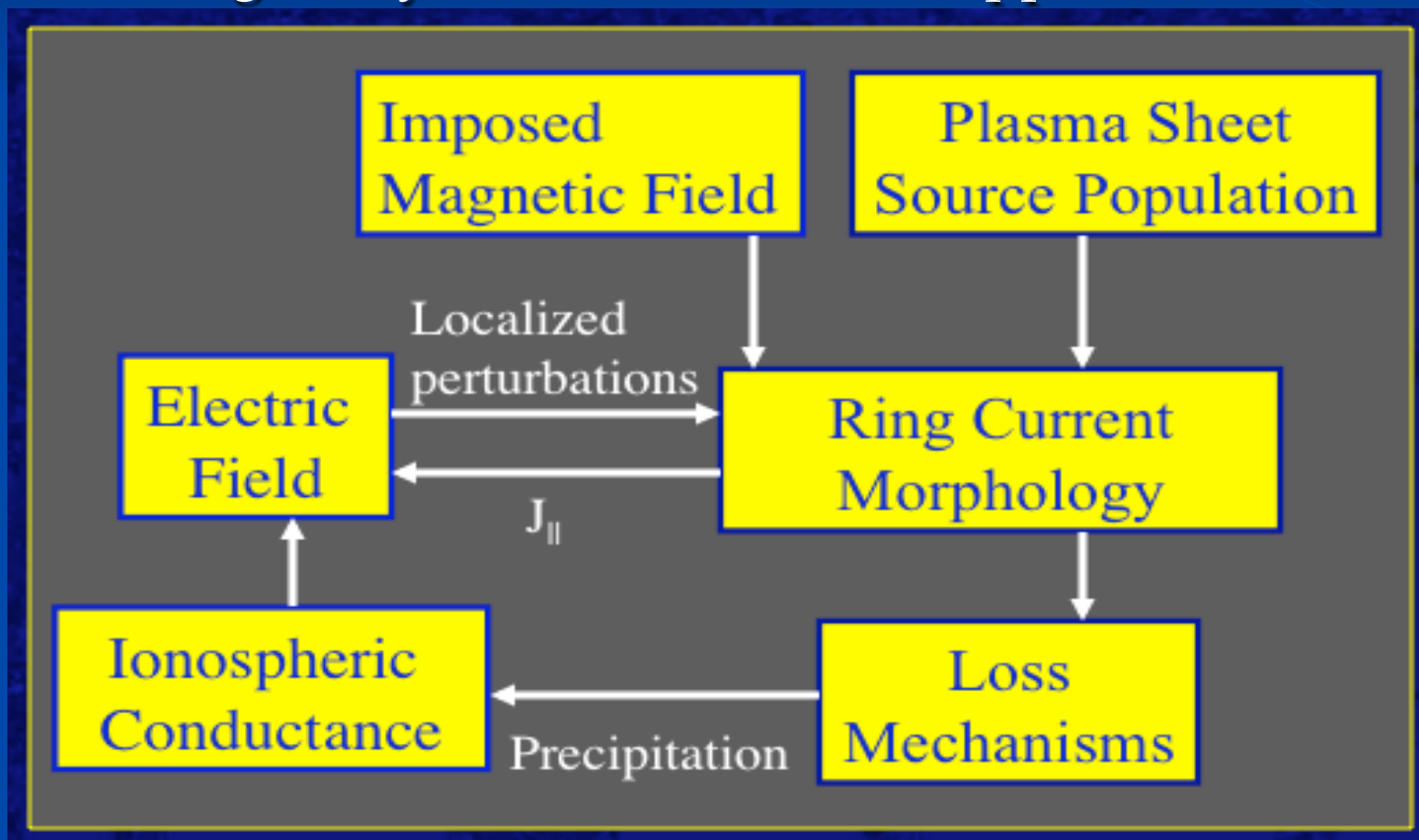
# Levels of Analyzing the Ring Current 2

- Solve the kinetic equation
  - Still simplistic: given initial and boundary conditions
  - Empirical relations or event-specific data for inputs



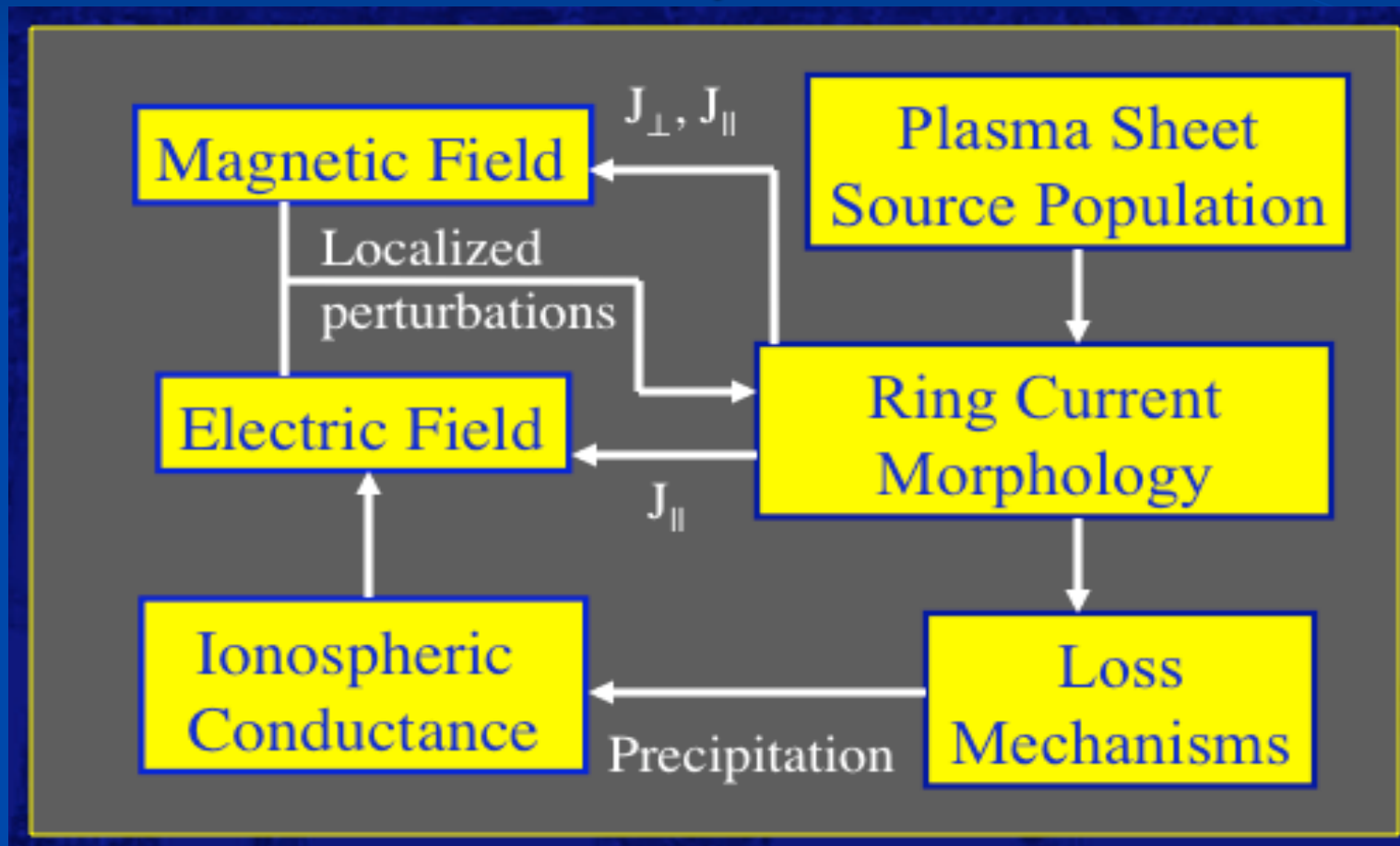
# Levels of Analyzing the Ring Current 3

- Electric field “self consistency”
  - Electric field “driver” modified by ring current solution
  - First stage of system level scientific approach



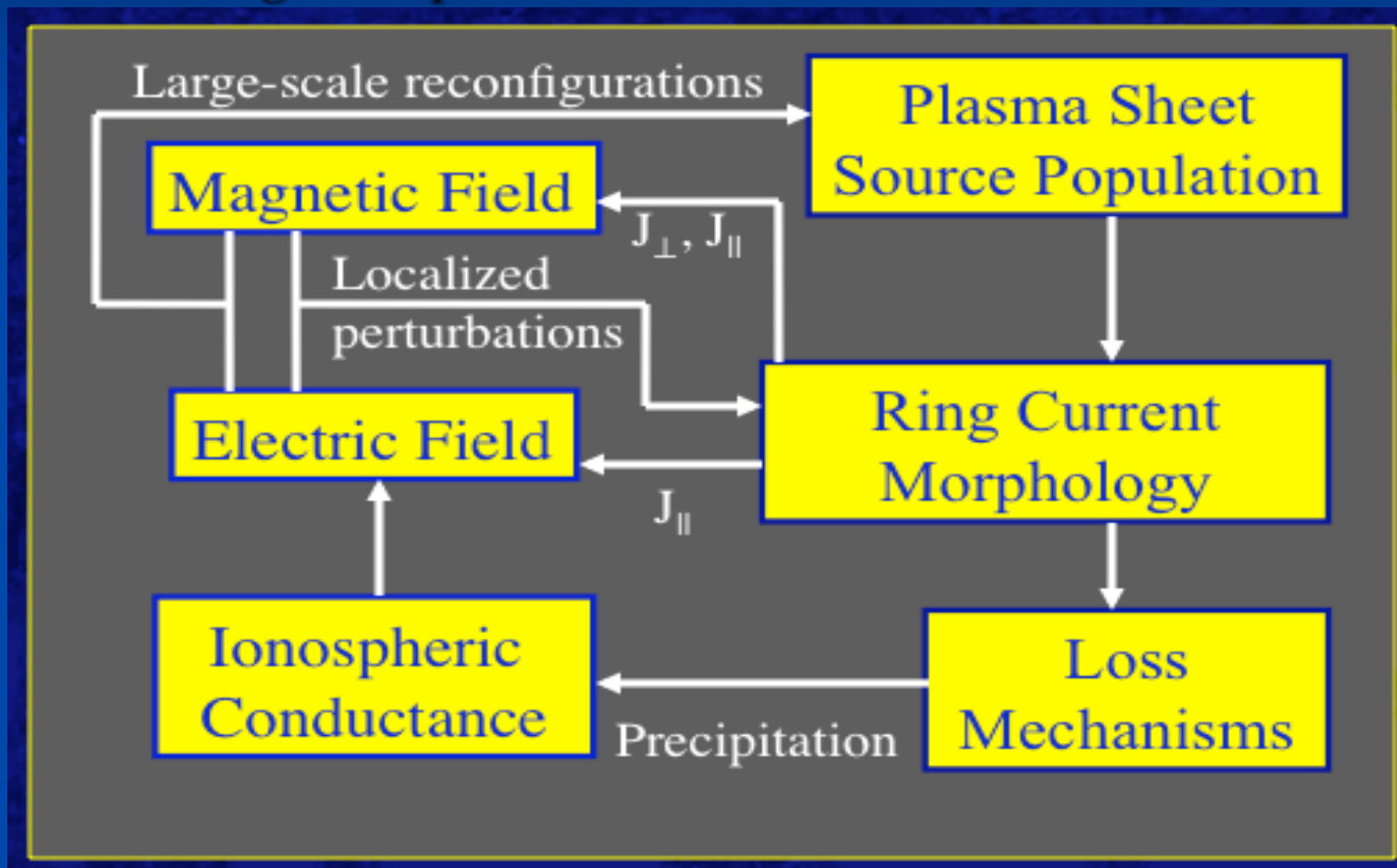
# Levels of Analyzing the Ring Current 4

- Add in magnetic field feedback
  - Field distortions due to solution-derived currents
  - Even more self-consistency



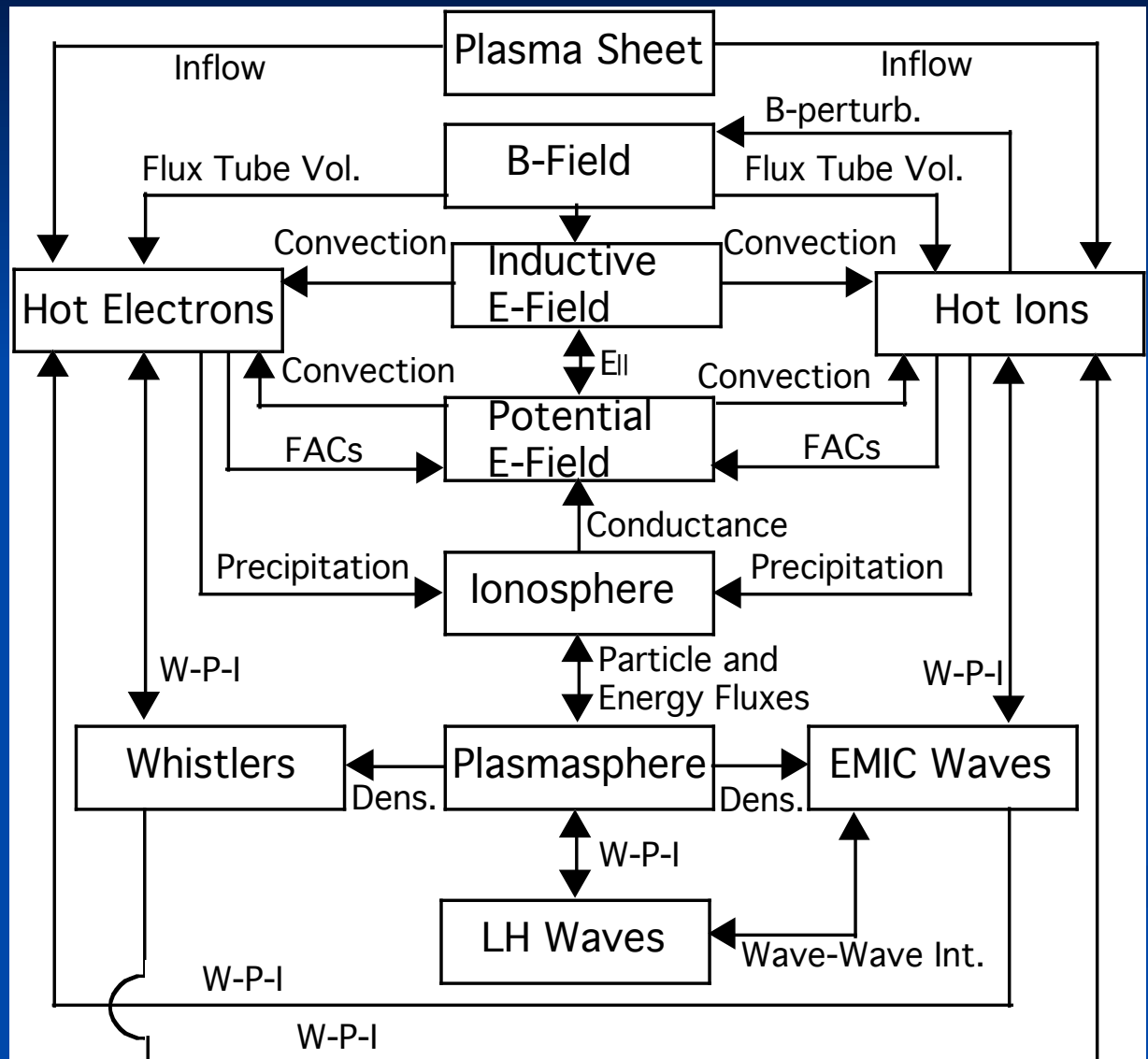
# Levels of Analyzing the Ring Current 5

- Solving the entirety of geospace
  - Allowing the inner magnetospheric solution to modify the outer magnetospheric solution



# Levels of Analyzing the Ring Current 6

- One can add as many subsystems as one wishes
- Solving each box and arrow
  - Range of approaches
    - Parameterizations
    - First principles



# Reductionist to the Core

- WINDMI model: circuit model of geospace
  - Actually works for understanding feedback and time history in the geospace system

$$L \frac{dI}{dt} = V_{sw} - V + M \frac{dI_1}{dt} \quad (1)$$

$$C \frac{dV}{dt} = I - I_1 - I_{ps} - \Sigma V \quad (2)$$

$$\frac{3}{2} \frac{dP}{dt} = \Sigma \frac{V^2}{\Omega} - u_0 K_{\parallel}^{1/2} \Theta(I - I_c) P - \frac{P}{\tau_E} \quad (3)$$

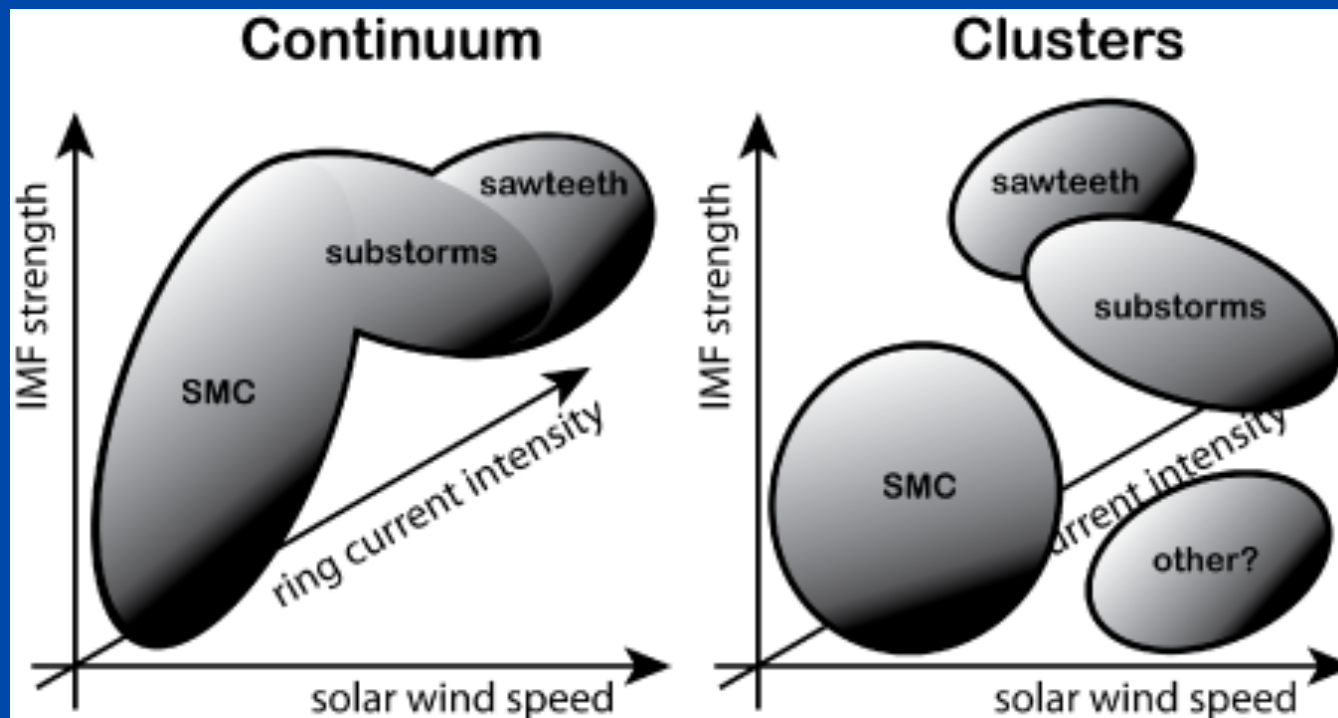
$$\frac{dK_{\parallel}}{dt} = \alpha P^{1/2} V - \frac{K_{\parallel}}{\tau_{\parallel}} \quad (4)$$

$$L_1 \frac{dI_1}{dt} = V - V_1 + M \frac{dI}{dt} \quad (5)$$

$$C_1 \frac{dV_1}{dt} = I_1 - \Sigma_I V_1. \quad (6)$$

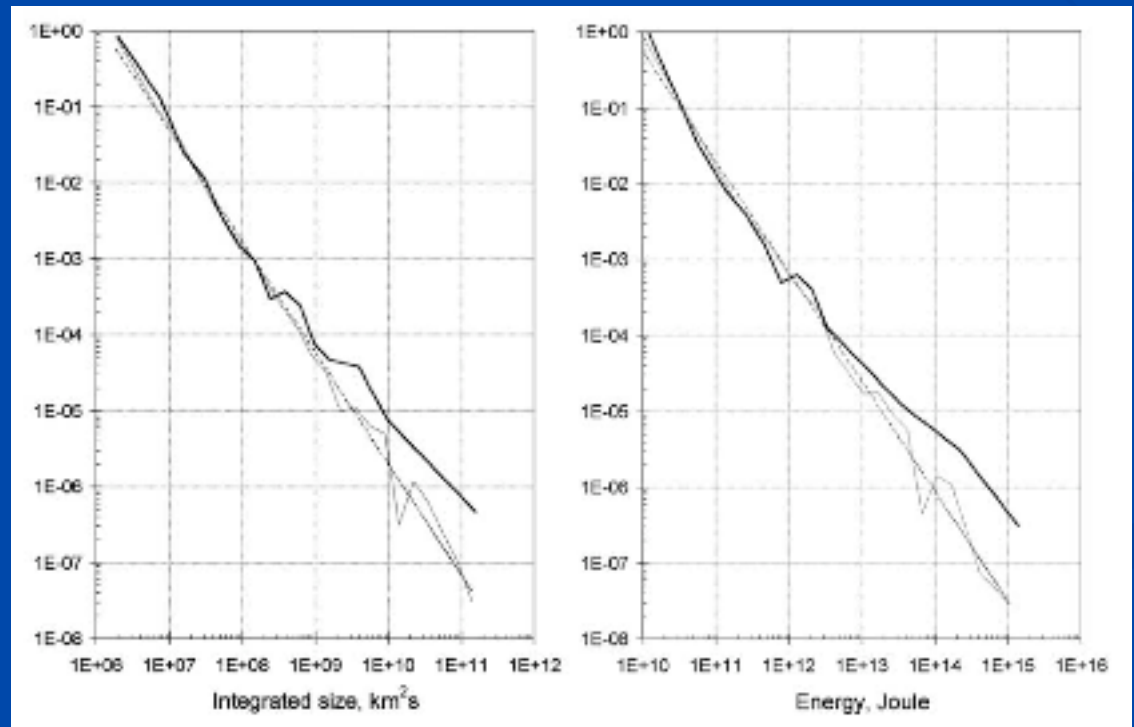
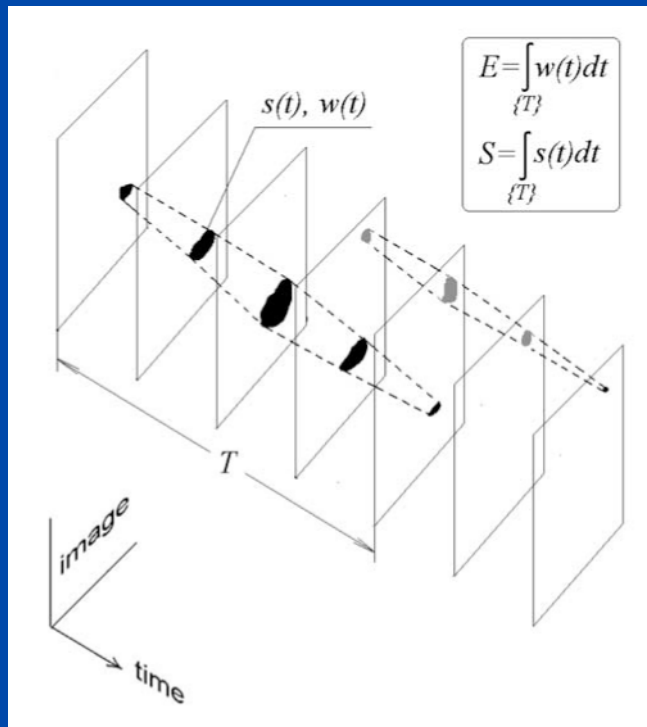
# Modes of Geospace Response

- We like to classify geospace activity
- Example: substorms, SMCs, and sawtooth oscillations
  - Are they distinct modes or do they form a continuum?



# Are They Different Modes?

- Complexity theory can help us answer this question
- Auroral brightening analysis
  - Power law => all events in this range have similar physics



# Quick Review

- Reductionism: understanding a system by understanding its component subsystems
- System-Level Reductionism:
  - Non-negligible coupling between the subsystems
  - Two important terms: *Feedback* and *Time History*
- Is a system-level approach necessary?
  - No. Highly dependent on the question posed
  - Only you can be answer this for your particular topic
  - Some problems can be answered very well with a “local” analysis
  - Question to ask yourself: are feedback and time history negligible or important?

# Looking Forward

- Reductionism works
  - Approach of many space physicists
  - Still more to do
    - Just entering the age of reductionist system-level scientific analysis of geospace
- Complexity-reductionism compatibility
  - Each approach needs the other
  - Complexity analysis constrains the reductionist analysis
  - Reductionist interpretation grounds complexity analysis in reality

# The Ultimate System-Level Question

- This protester said it best...

