# DREAM

## Radiation Belt Forecasting for Space Situational Awareness

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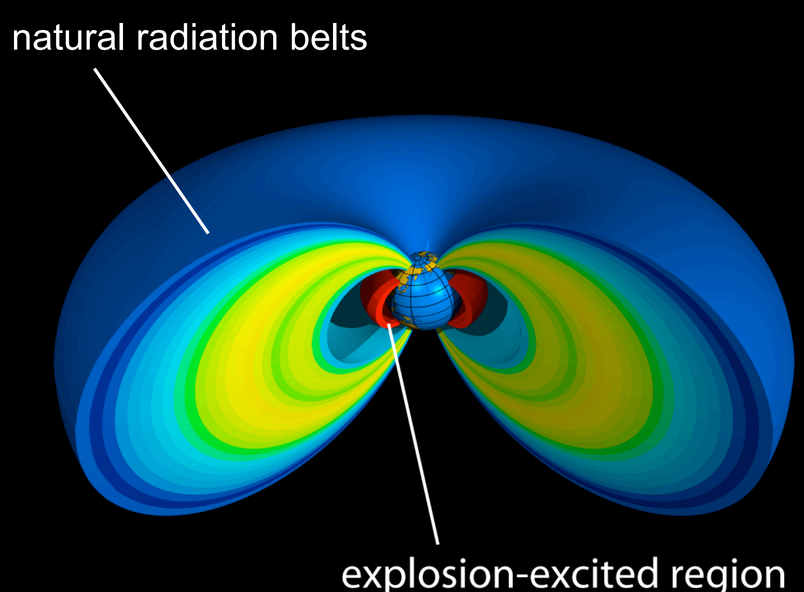
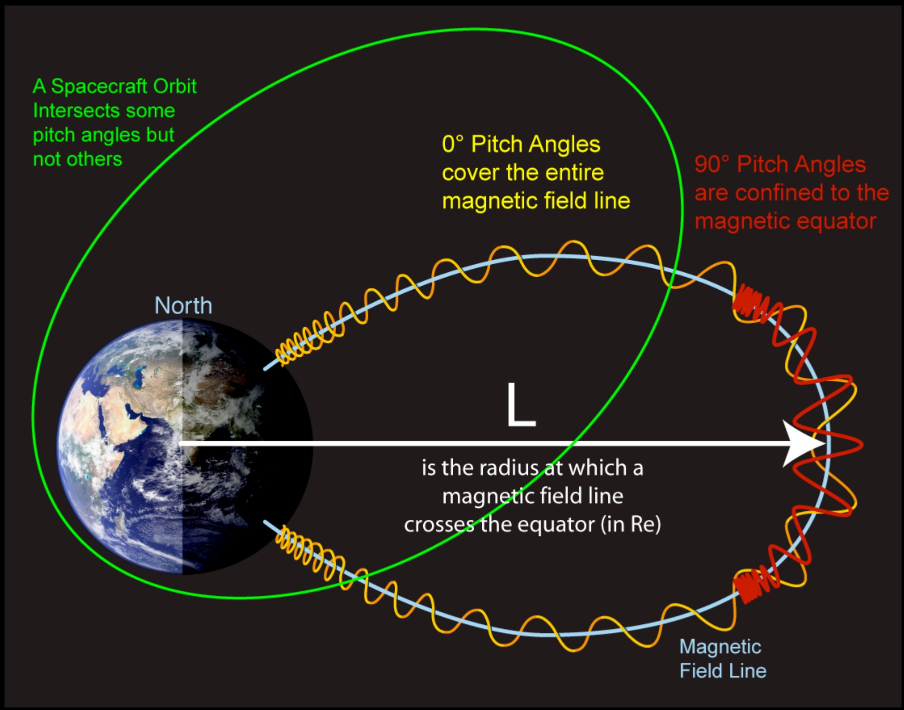
# DREAM: The Dynamic Radiation Environment Assimilation Model

- Developed by LANL to quantify risks from natural and nuclear belts
- Uses Data Assimilation with GEO, GPS and other observations
- Couples ring current, magnetic field, and radiation belt models
- Goals: Specification, Prediction, and Understanding



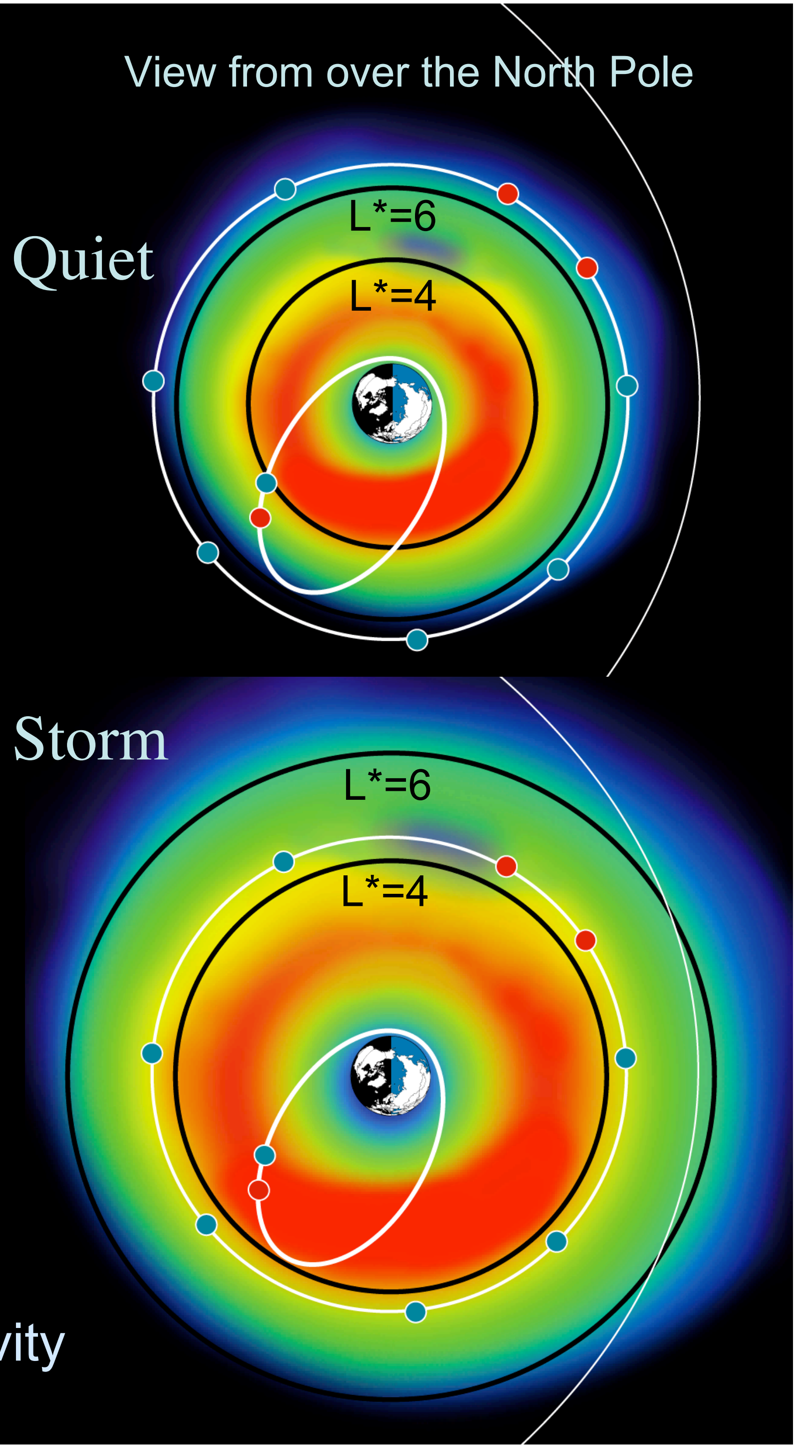

- Radiation belts produced by high altitude nuclear explosions are not included in this talk

# Coordinates are important: L vs L*



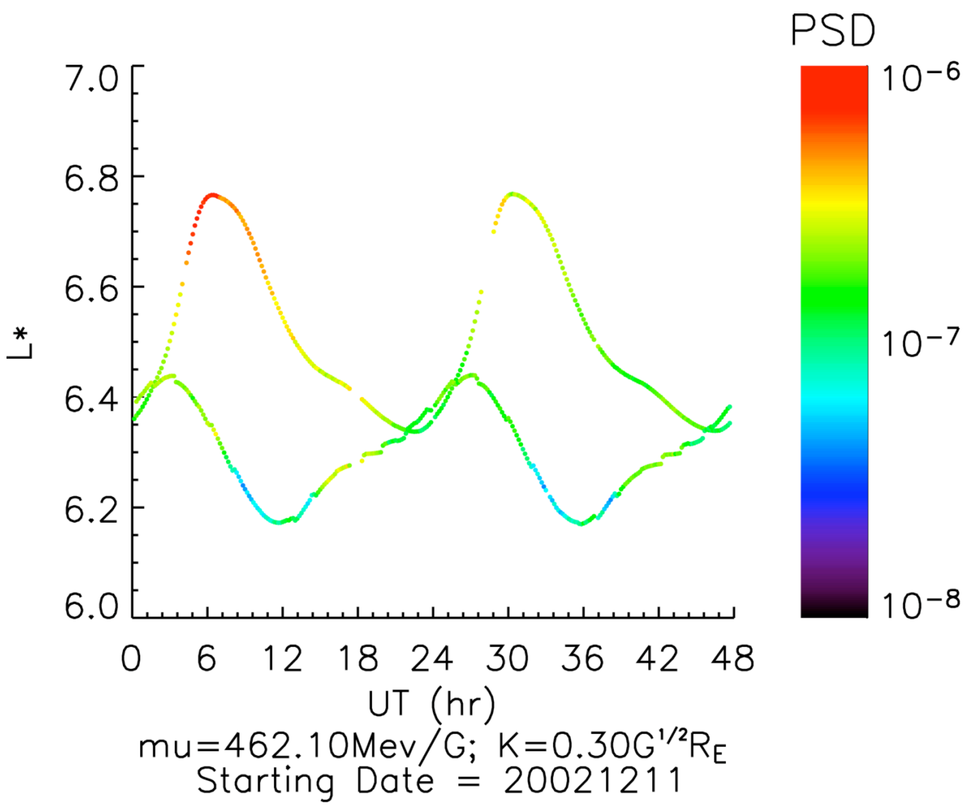

L is a local quantity
It is nearly constant for equatorial satellites

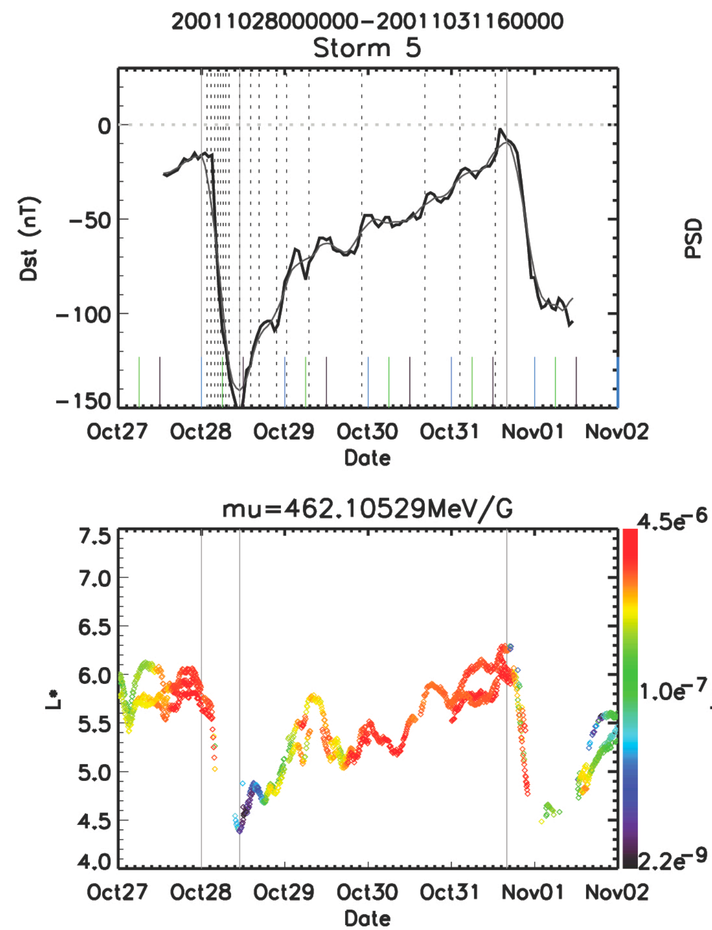
L* is a global quantity
It varies considerably with geomagnetic activity



# Phase Space Density in dynamic magnetic coordinates (μ, K, L*)

- Places observations in coordinates needed for physical equations
- Eliminates one spatial dimension
- Enables self-consistency check
- Captures adiabatic changes

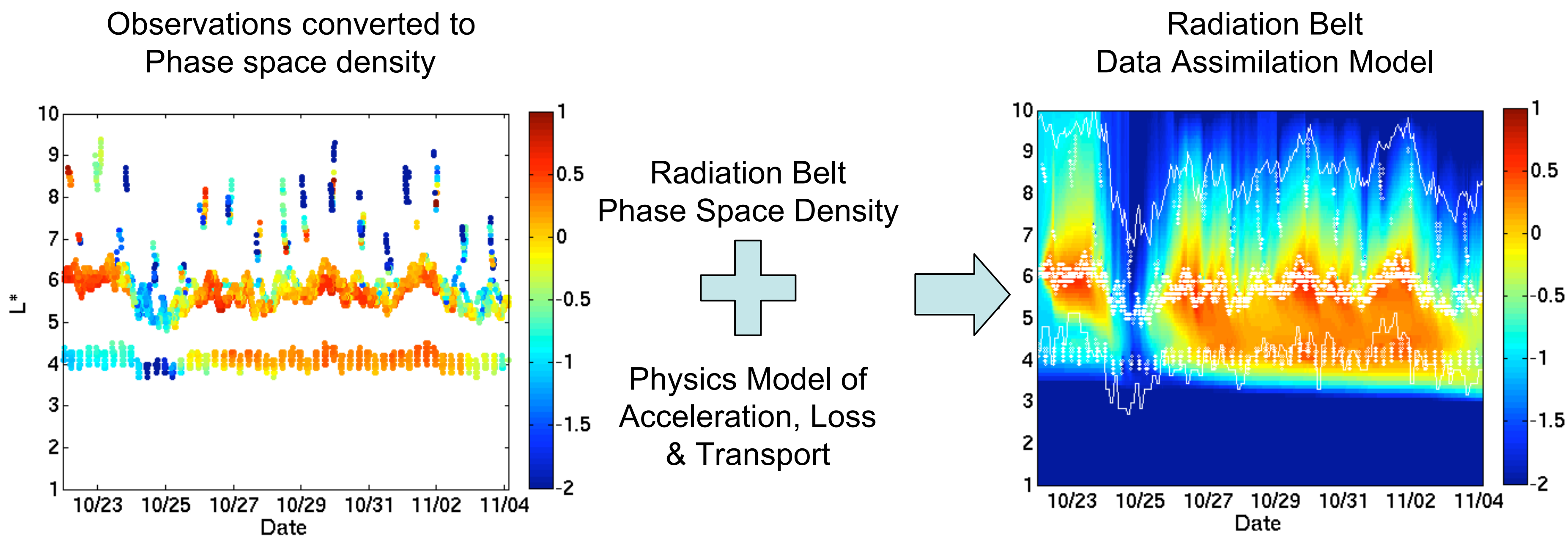


# Physical Models can have an arbitrarily large number of “knobs” to adjust

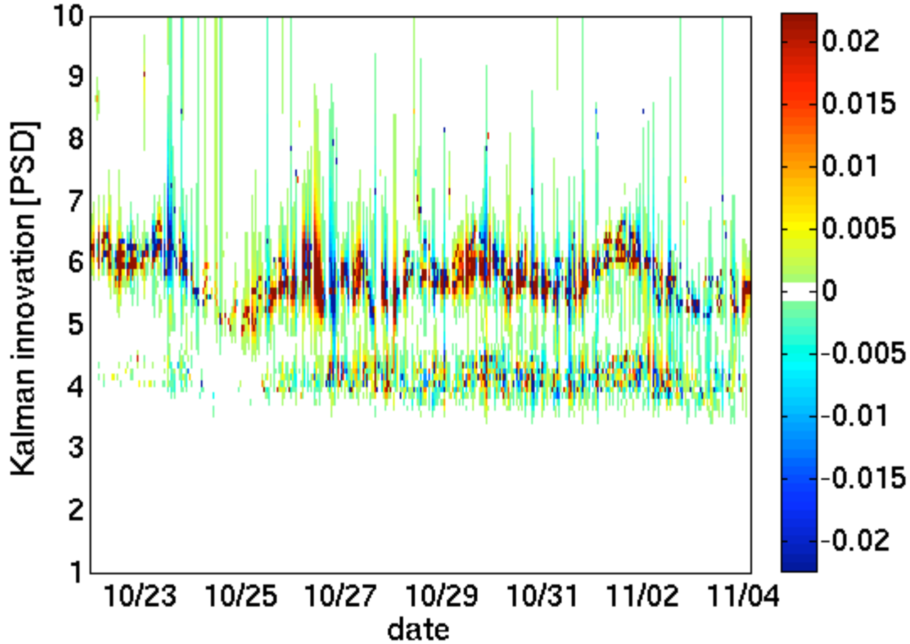
- Radial Diffusion: $D_{LL}(L,t)$
- Inner and outer boundary conditions
  - Fixed, Lossey (magnetopause), or variable (free parameter)
- Losses through precipitation - $f/\tau$
  - Inside the plasmasphere, Outside the plasmasphere
  - Kp dependent? Enhanced losses in main phase?
- Local Acceleration
  - Adding a source of phase space density - S(L, t)
  - Adding energization / energy diffusion - $D_{EE}$ and $D_{\alpha\alpha}$ - also function of L & t
  - Adding cross terms - $D_{E\alpha}$
- Even with our best guesses, the problem is under-constrained

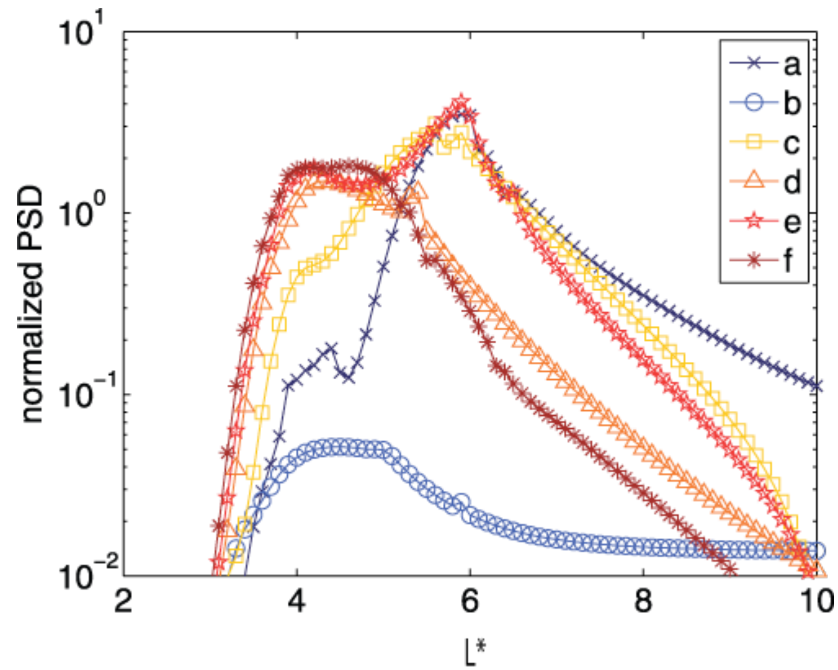
# Data assimilation:
# Available data + minimal physical models




- DREAM uses
  - + data from GPS, GEO and POLAR
  - + A physics model with radial diffusion + losses in three spatial regions
- Other data sources or numerical models are easily substituted
- Unknown parameters can be fixed or determined by Kalman Filter

# Assimilated data changes more than just the local values



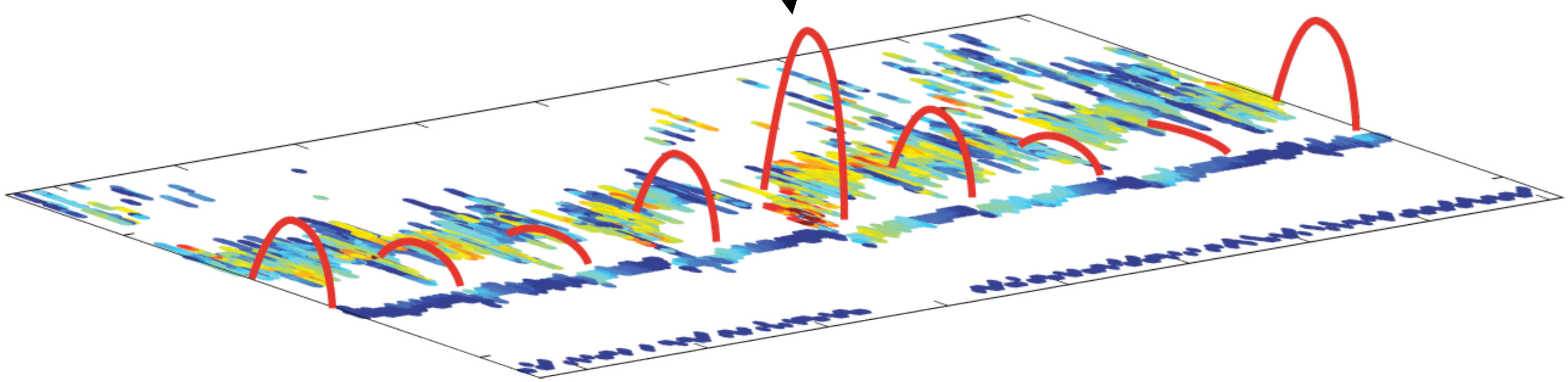

- Fluxes outside of GEO orbit can be well reproduced by assuming a lossey outer boundary at the magnetopause (specified in L*)
- The innovation as a function of time and L* shows the need for time-dependent acceleration in the model

# Can an explicit source improve predictions? A less complicated first step

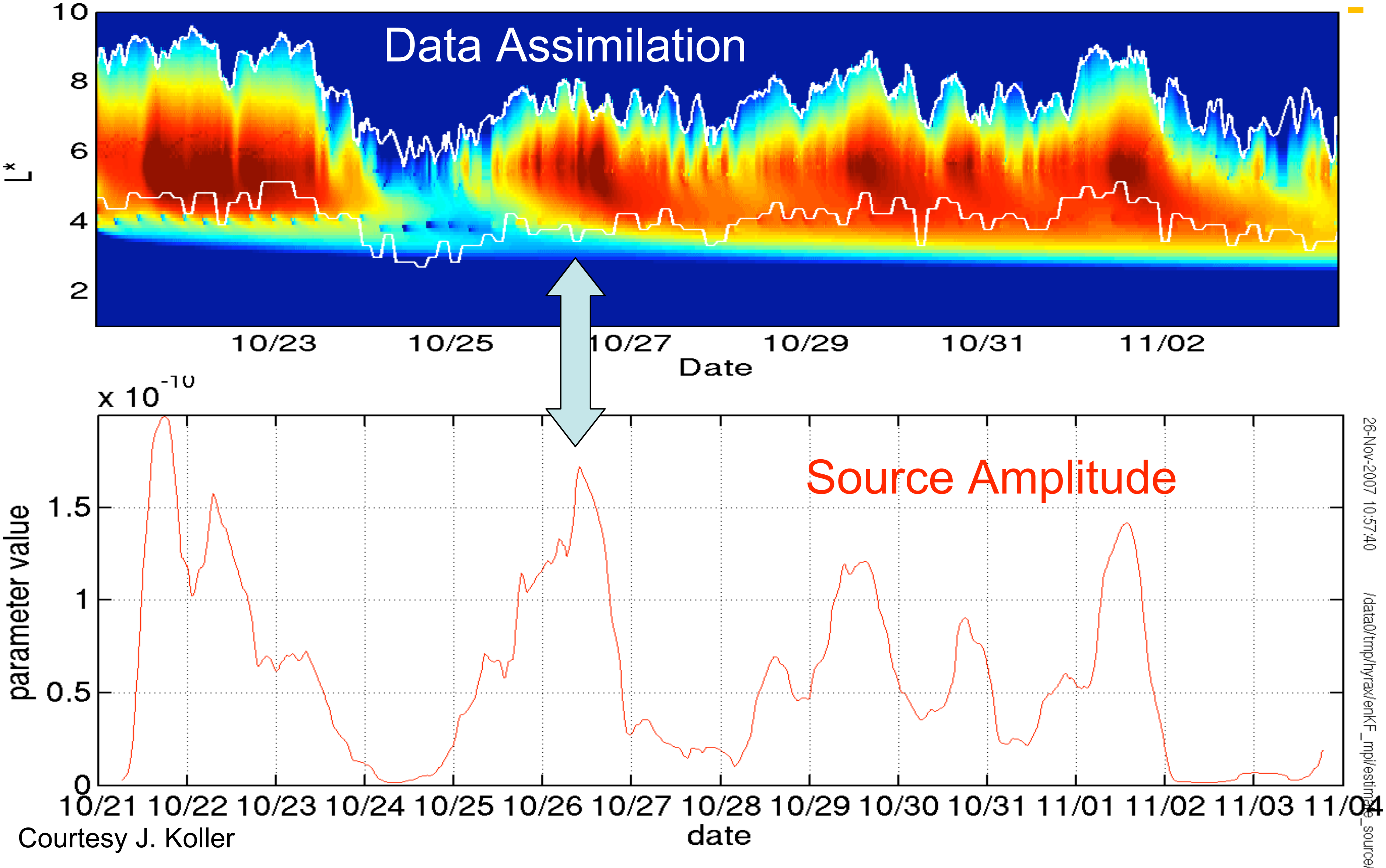
- We include a hypothetical source term in the radial diffusion equation at fixed μ and K
- We let the amplitude of the source be a free parameter chosen by the Kalman Filter
- The source has fixed location and width (but this is not required)

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

PSD Source Term

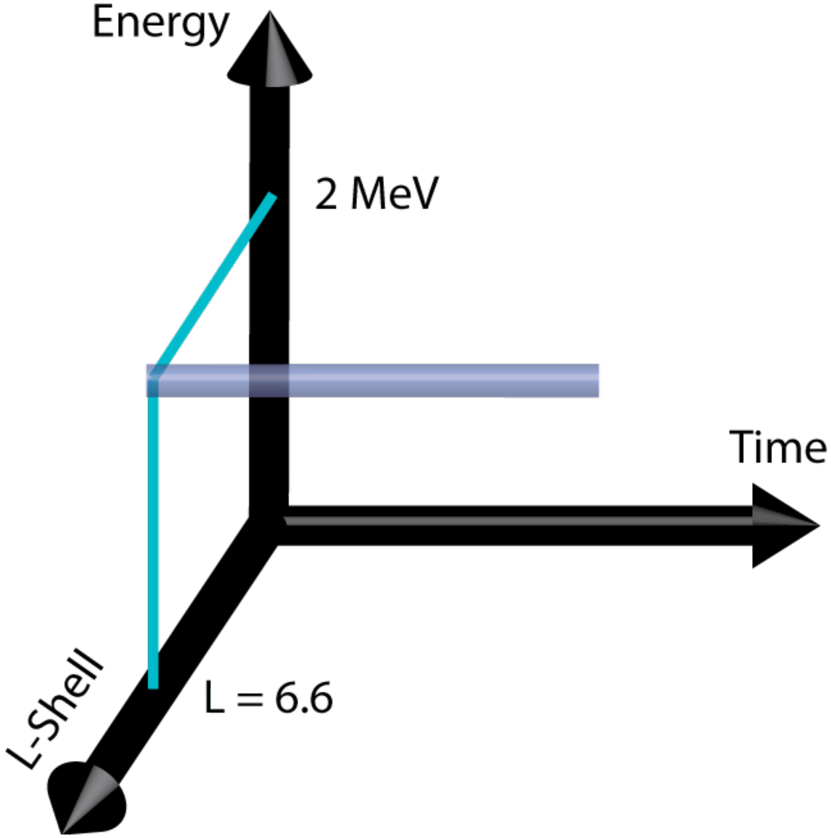


# The Data Assimilation picks source amplitudes that are quite reasonable

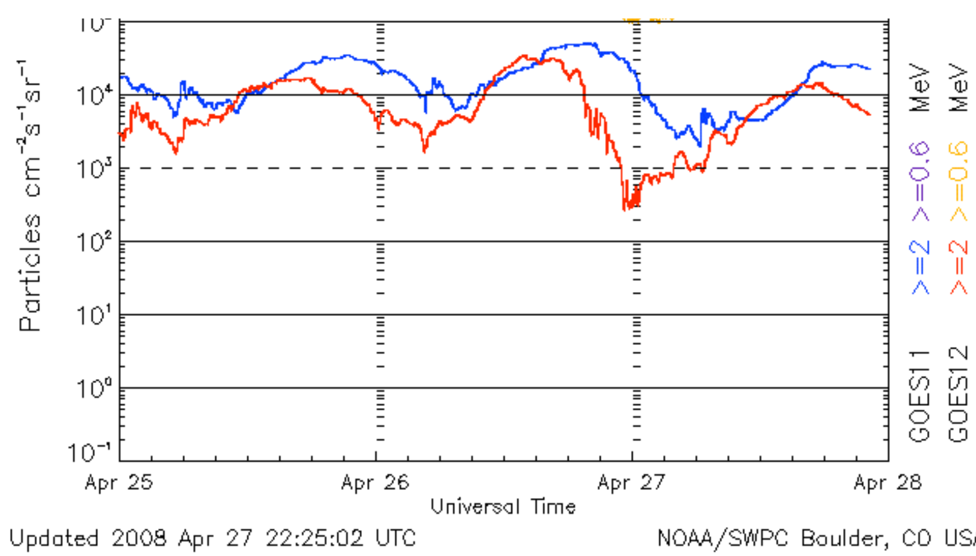



Courtesy J. Koller

# DREAM:
# Applications to specification and forecasting




- 1D: fixed energy and L-shell
- Specification is simply the current satellite conditions
- Forecast projects one value in time



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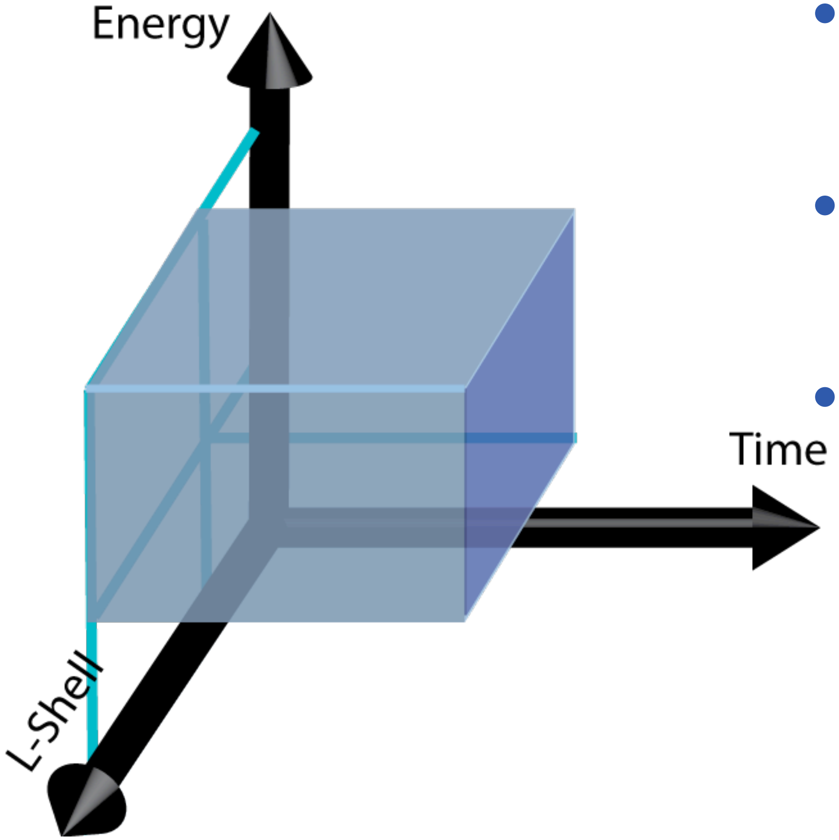
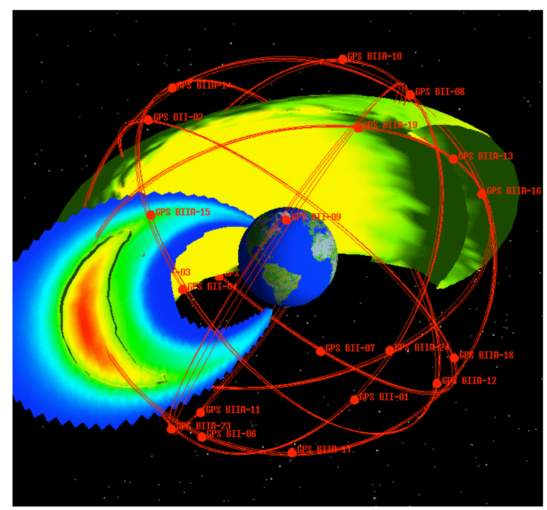
# Applications to specification and forecasting

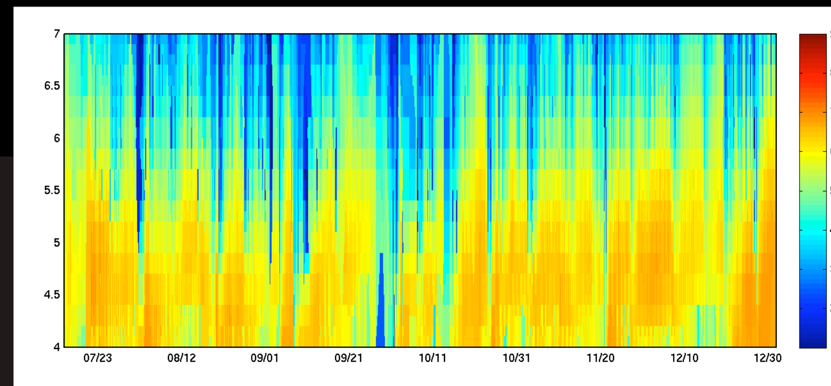


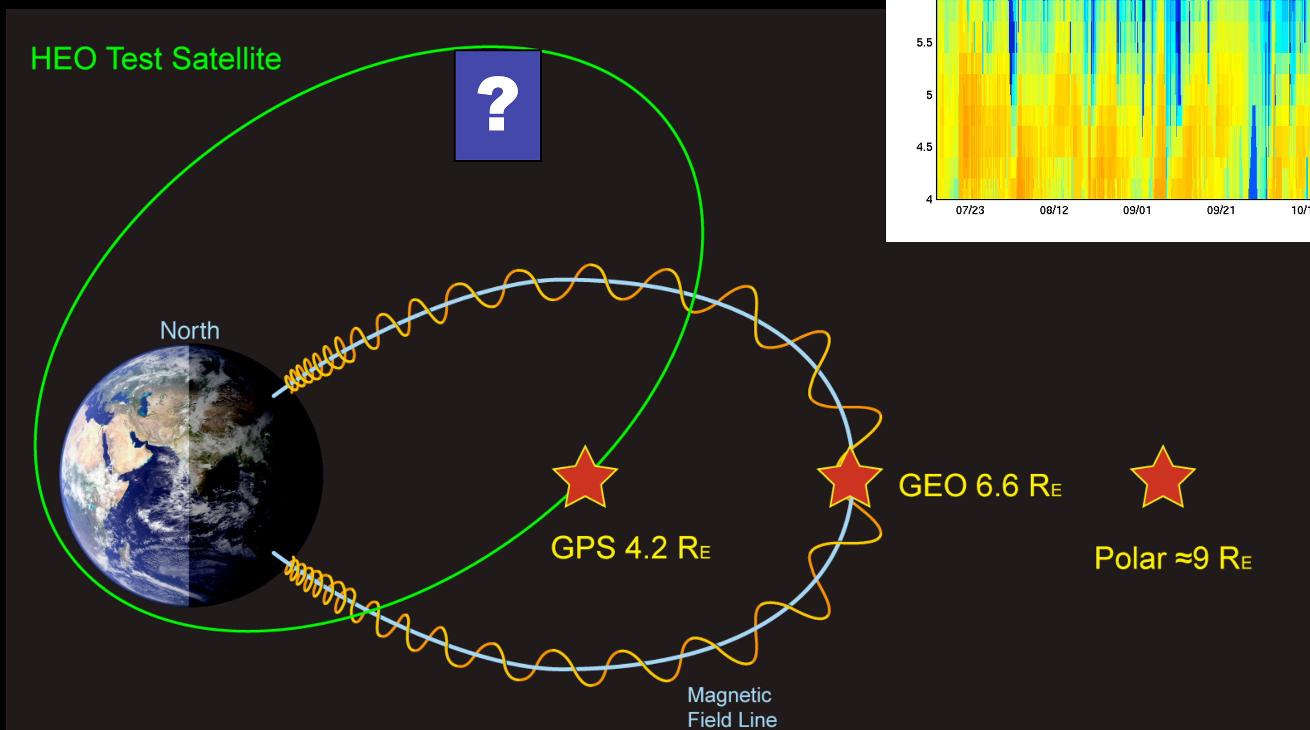

- 3D: Covers a range of energy, L-shell, and latitude
- Specification must determine conditions at any location
- Forecast projects a volume



# Using DREAM to specify the environment at a HEO satellite based on Geo, GPS, & Polar

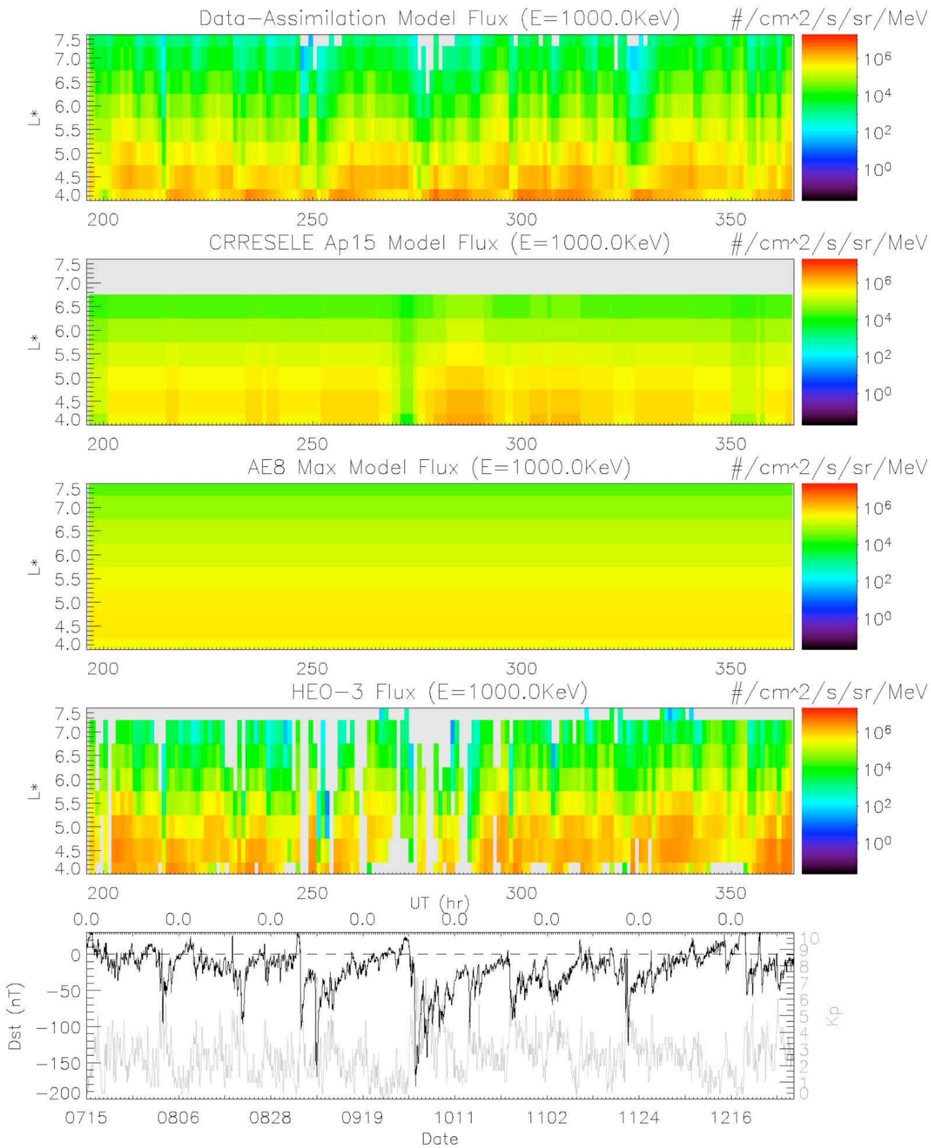
~ 1 MeV electron flux at HEO-3




HEO is a different orbit and is not used as input to DREAM

# Even very limited data and simple physics produce highly-accurate specifications




DREAM Data Assimilation

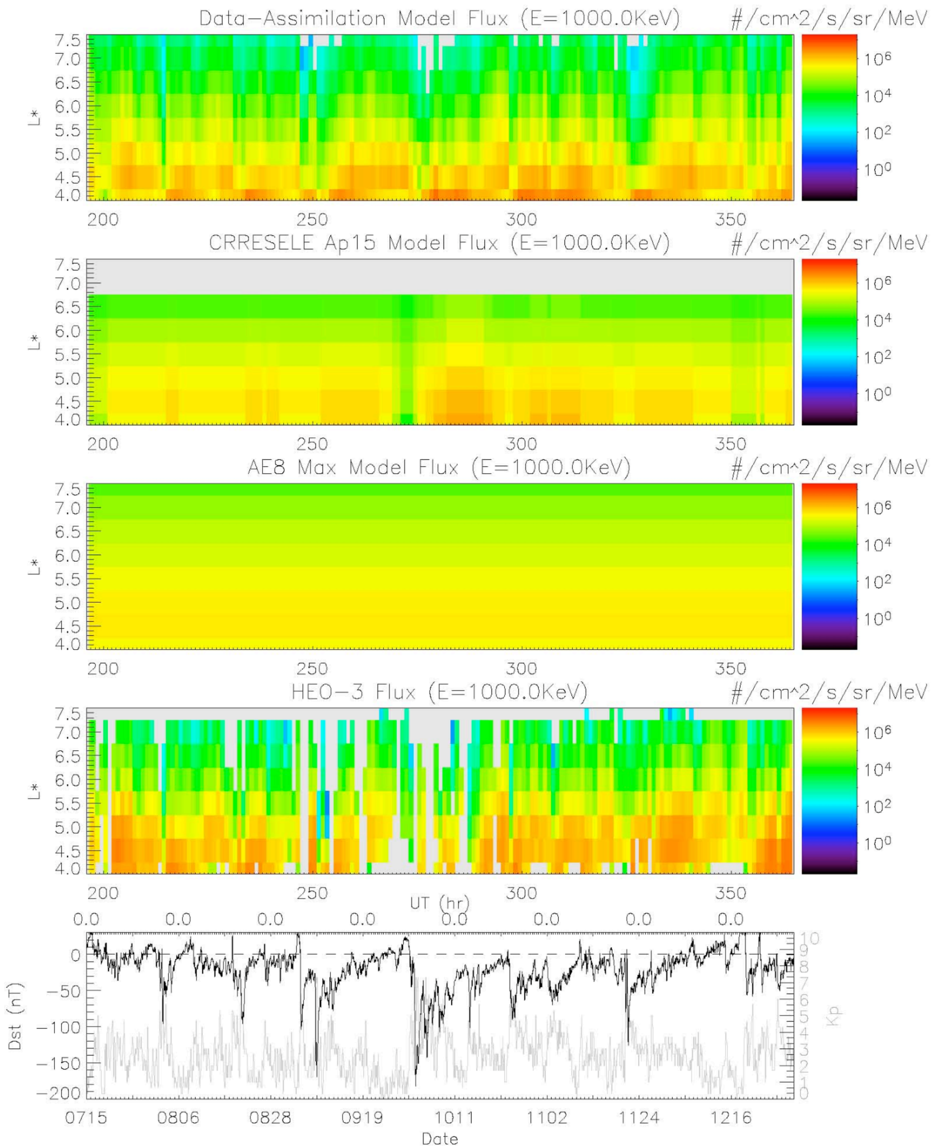
CRRES Model

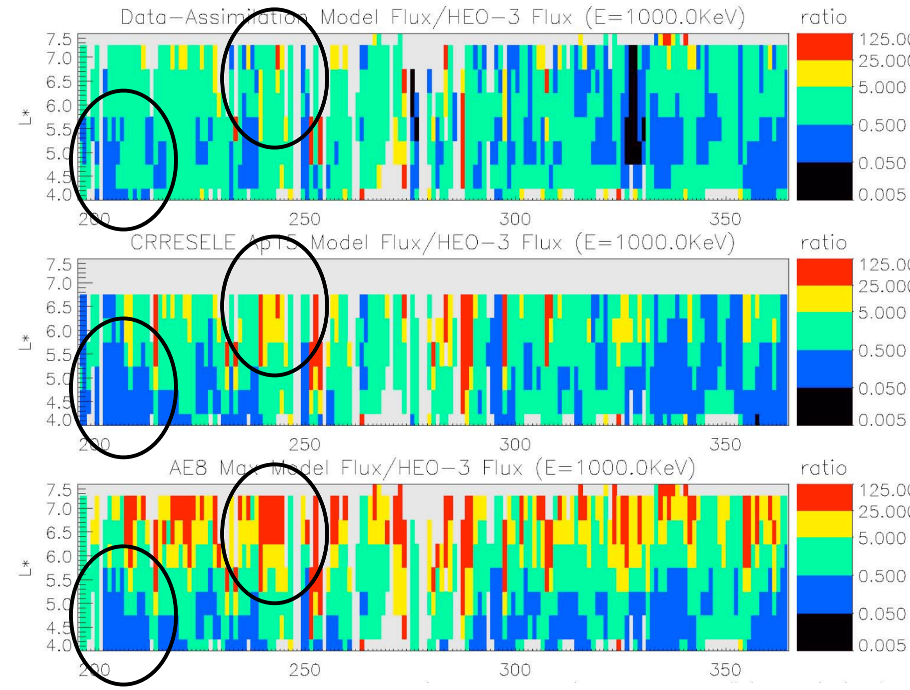
AE8 Model

HEO Observations

Geomagnetic Activity

# The ratio of Model Flux/Observed Flux gives quantitative assessment of accuracy



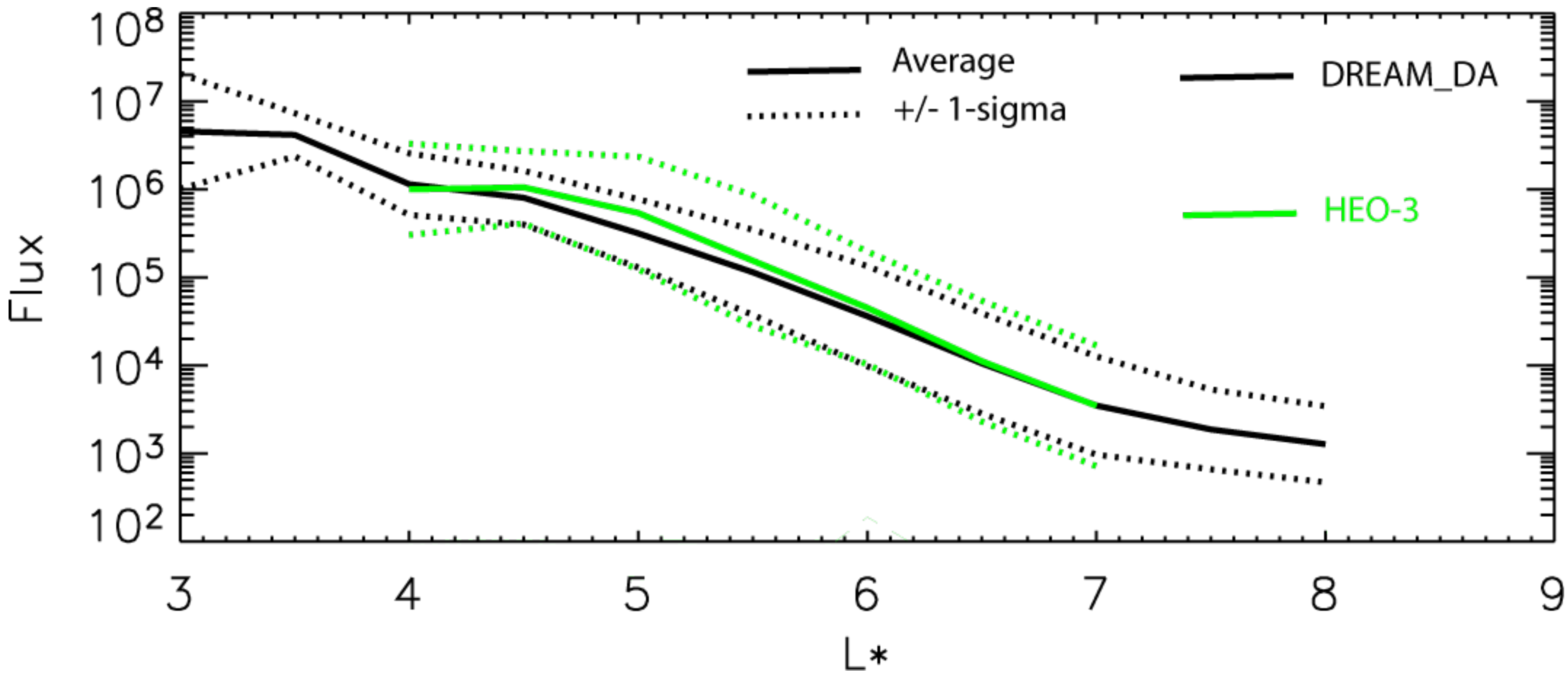




Model predicts observations in HEO orbit

Model ~20x too low

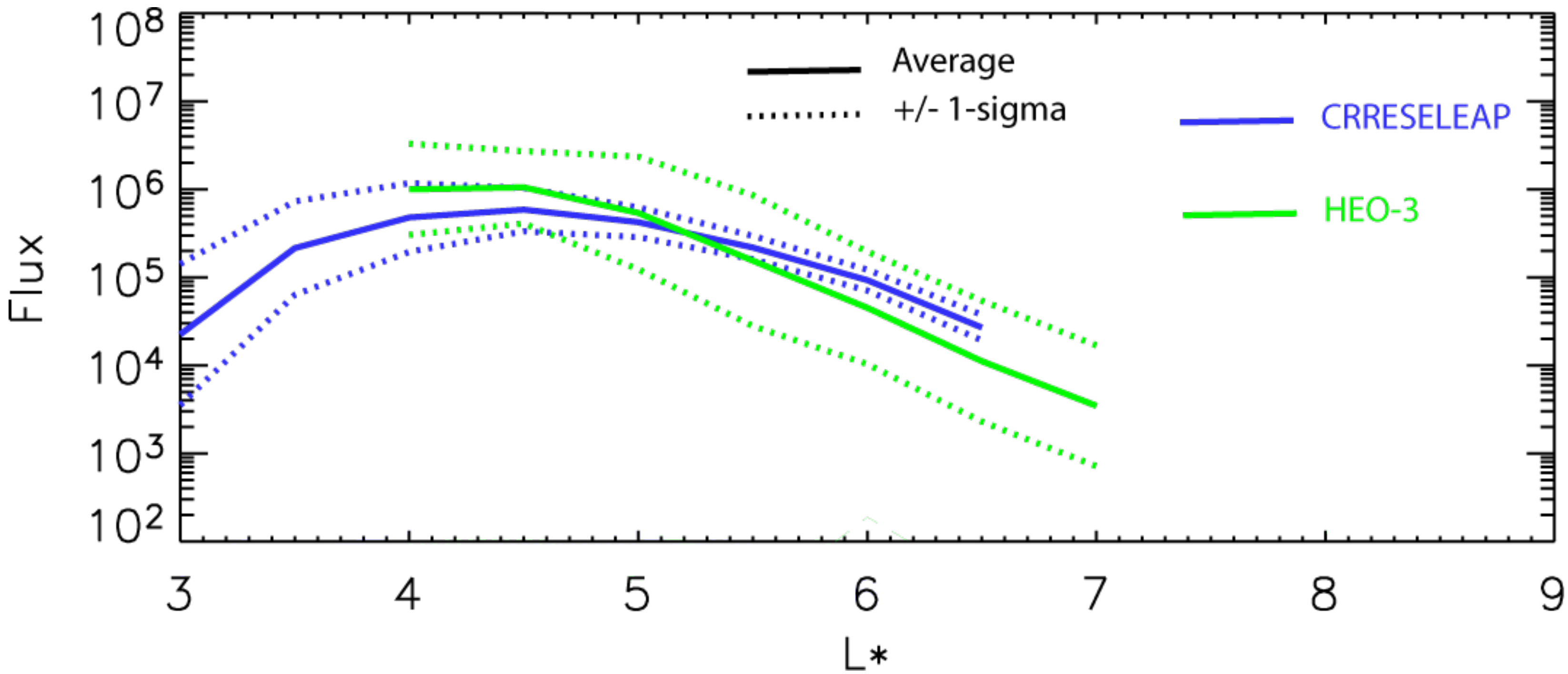
Model ~100x too high

# Average HEO flux(L*) compared to DREAM, CRRES-EL, and AE8



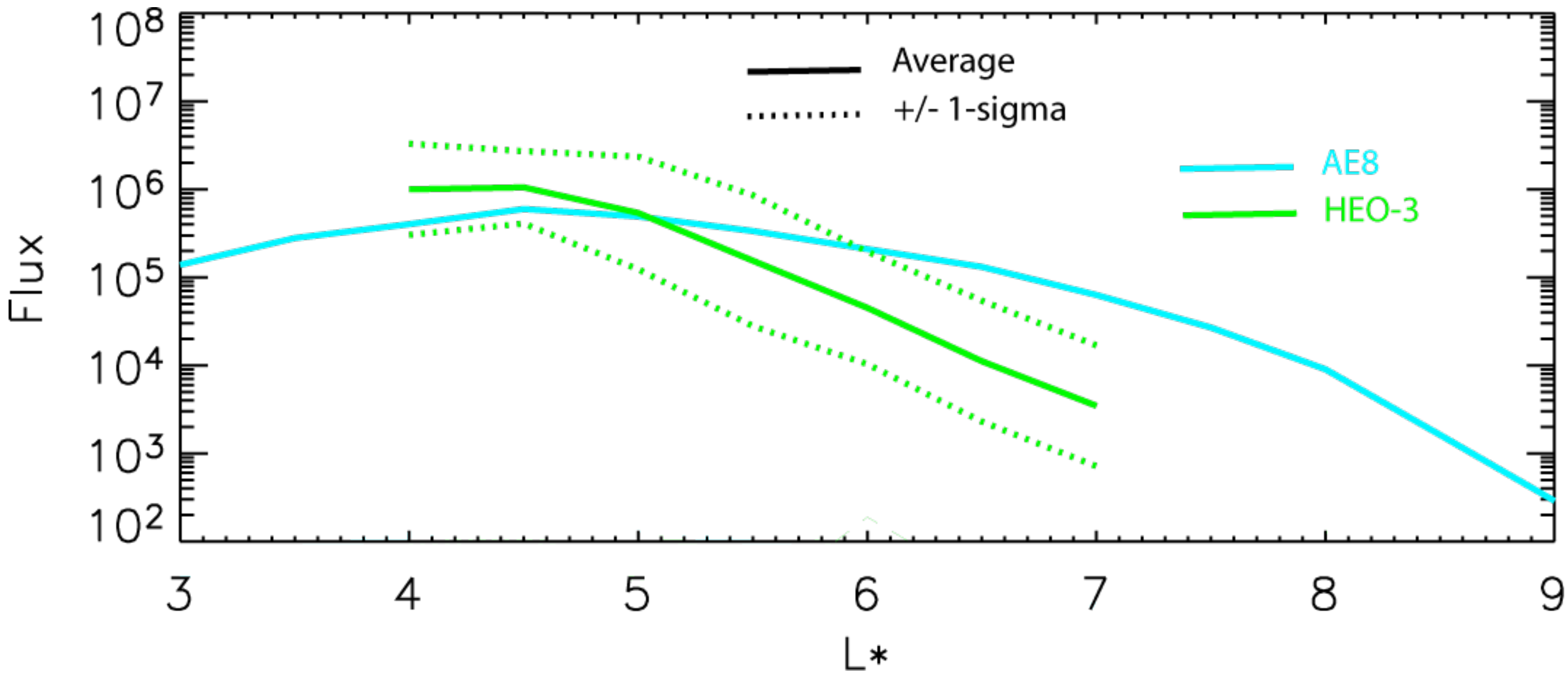

- DREAM with GEO and GPS data
- Model has losses but no acceleration or pitch angle scattering
- HEO data <u>not used</u> in the assimilation

# Average HEO flux(L*) compared to DREAM, CRRES-EL, and AE8



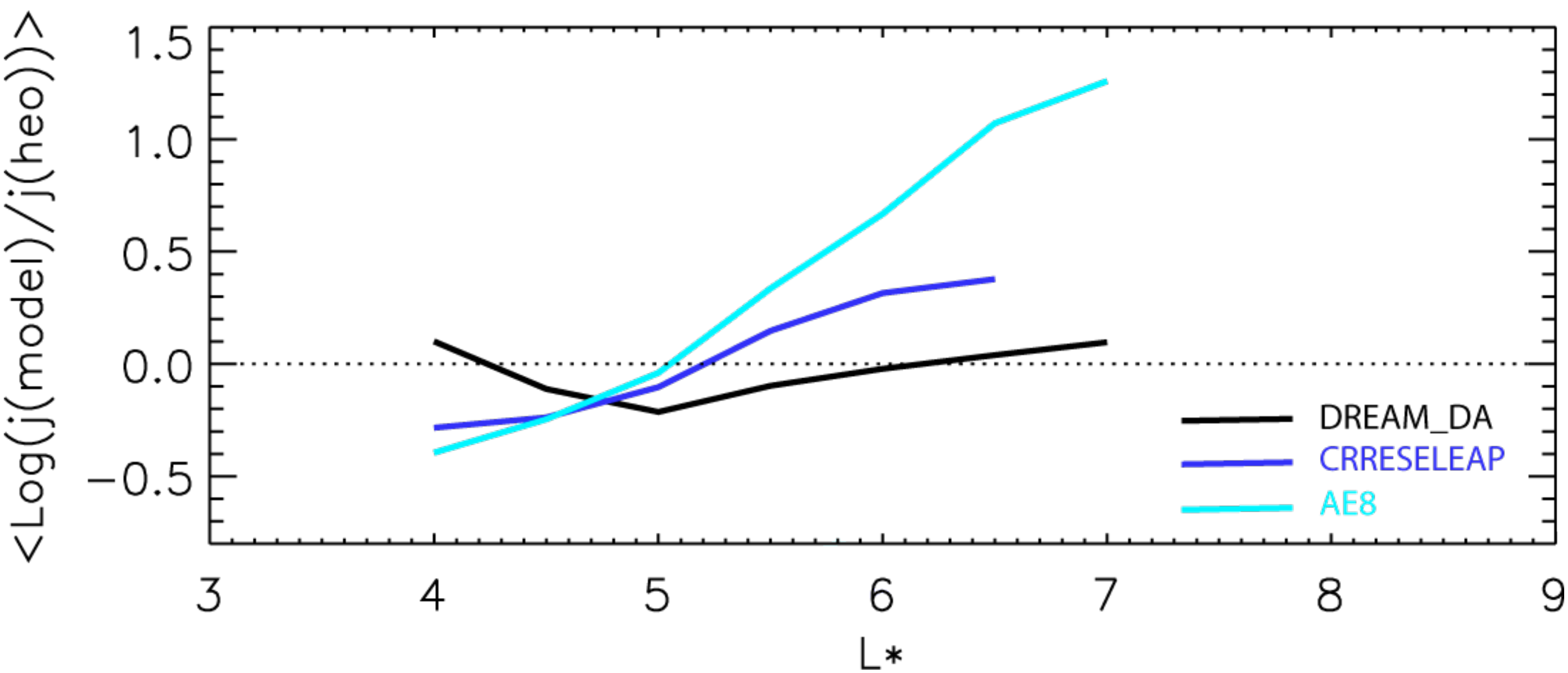

- CRRES Electron model based on 1990-1991 data
- Wrong average profile for 1 MeV
- Small standard deviation due to limited model variation with activity

# Average HEO flux(L*) compared to DREAM, CRRES-EL, and AE8



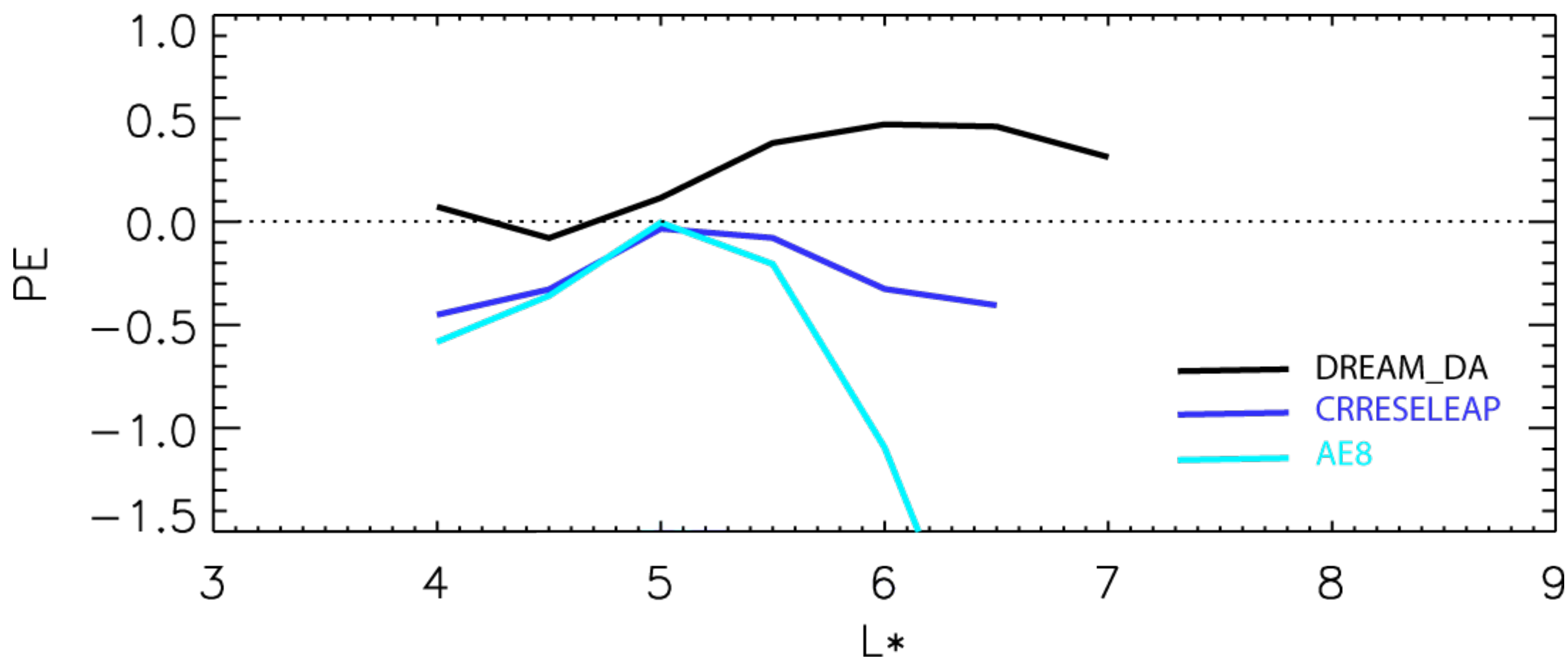

- AE-8 model
- Wrong average profile
- Standard deviation = 0

# Average Ratio of Fluxes
# Model Flux / Observed Flux



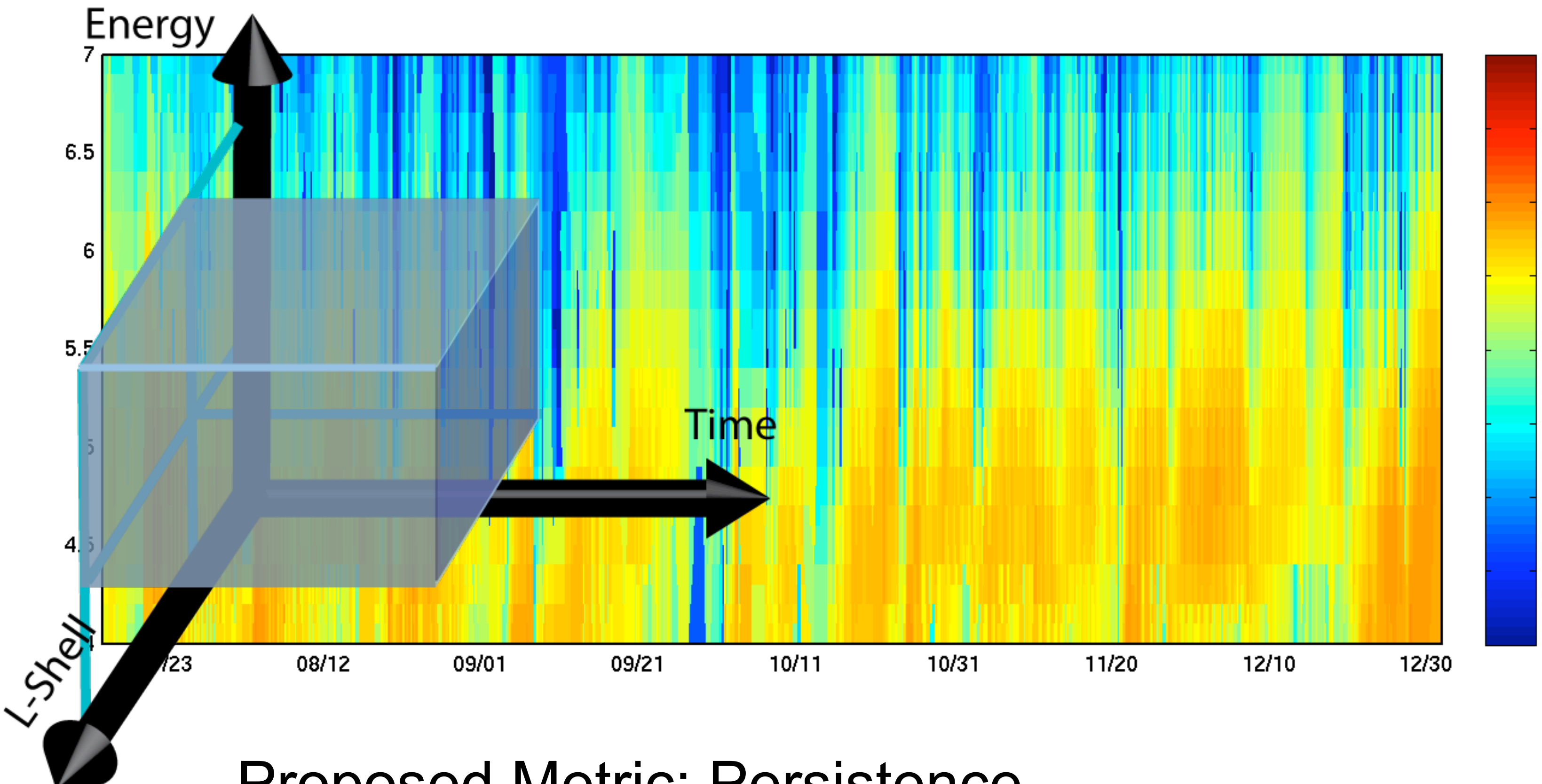

- Flux ratio is one metric for comparison
- Log scale:  0 = perfect match
- Inclined profiles can only be made to match at one L

# Prediction Efficiency for global specification tests spatial nowcast



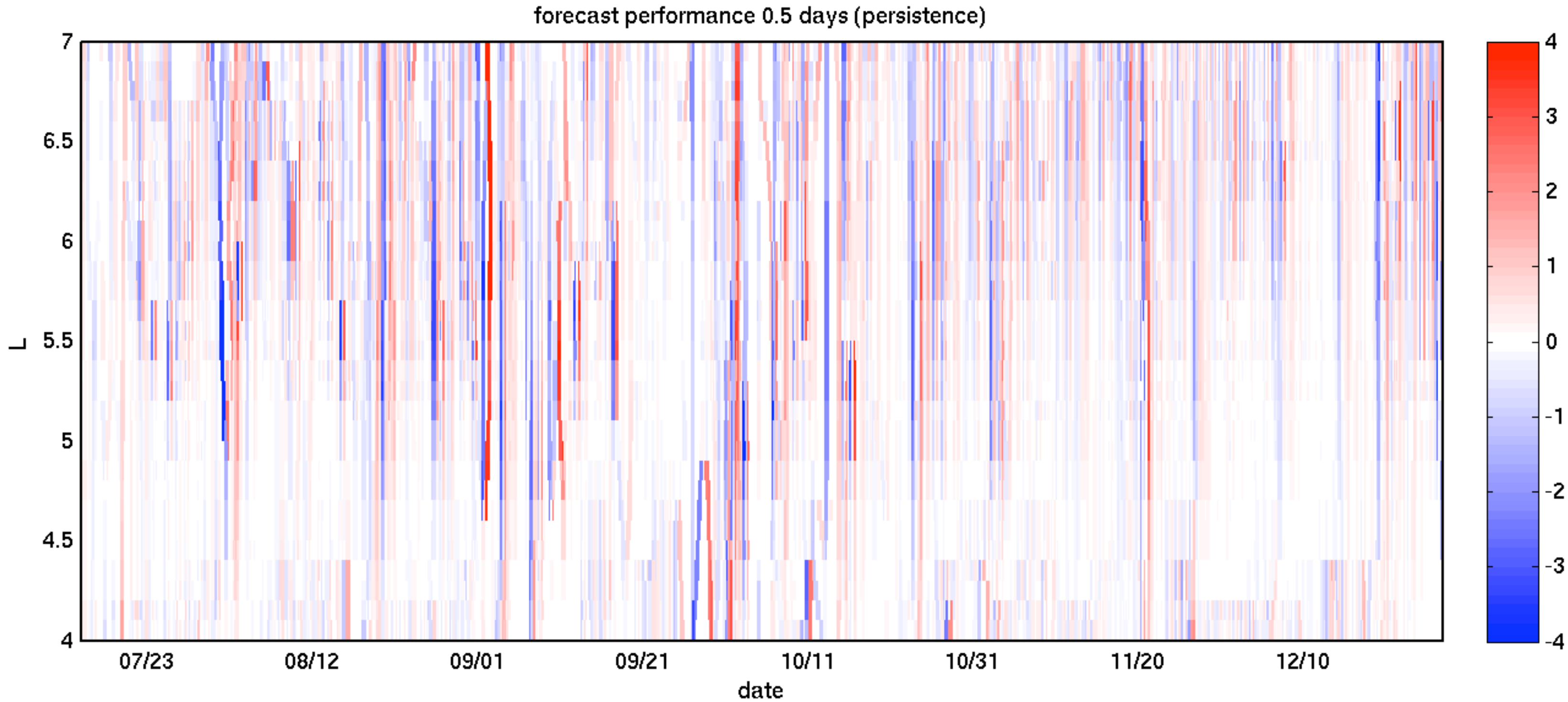

- Prediction Efficiency: 1 = perfect match
- PE = 1 - $\dfrac{\Sigma\,(\text{model - measurement})}{\Sigma\,(\text{ measure - <measure>})}$

# Global Forecasting
# The first step is to establish a baseline metric



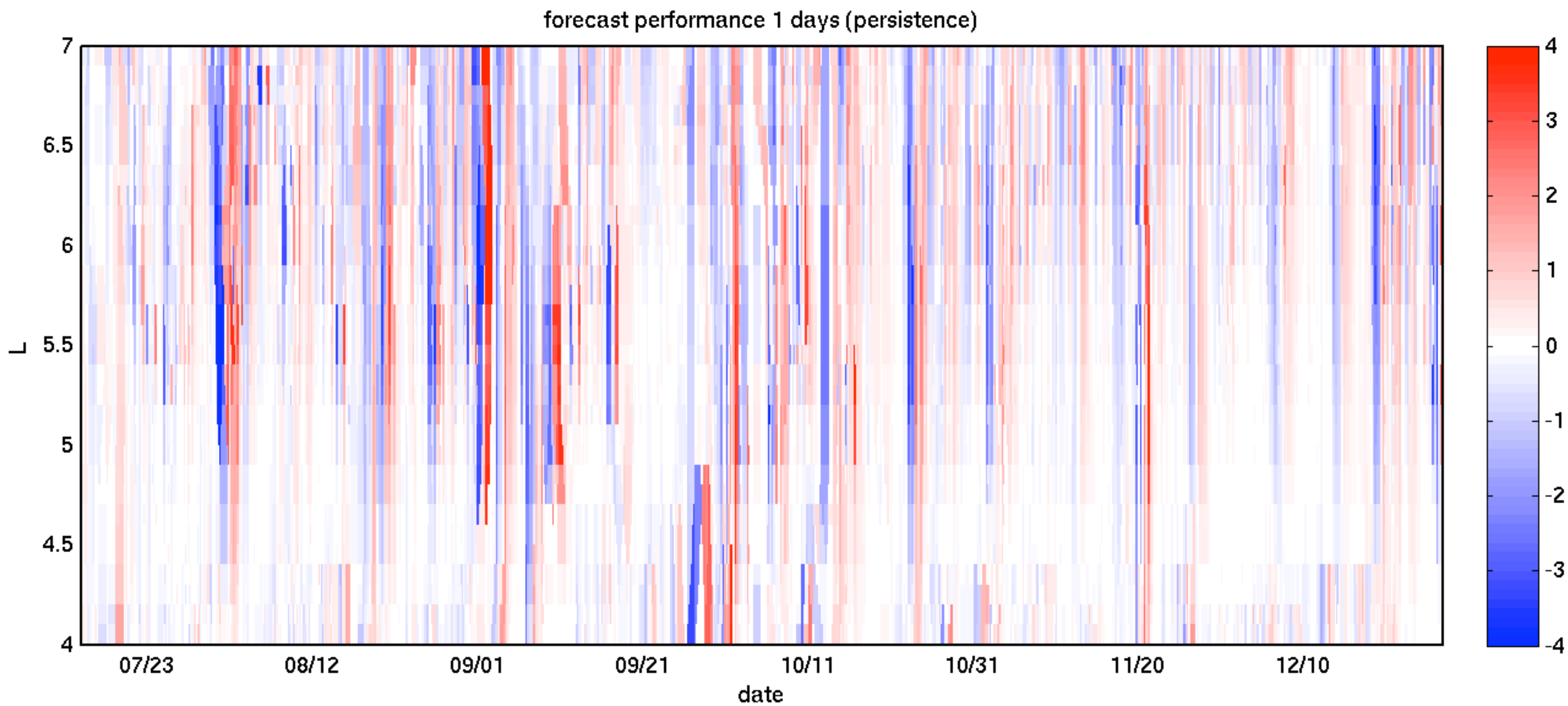

Proposed Metric: Persistence
Single Energy (1MeV) as a function of L and Time
Interpolated to a regular grid

# Error vs. L and Time
# 1/2 day persistence forecast



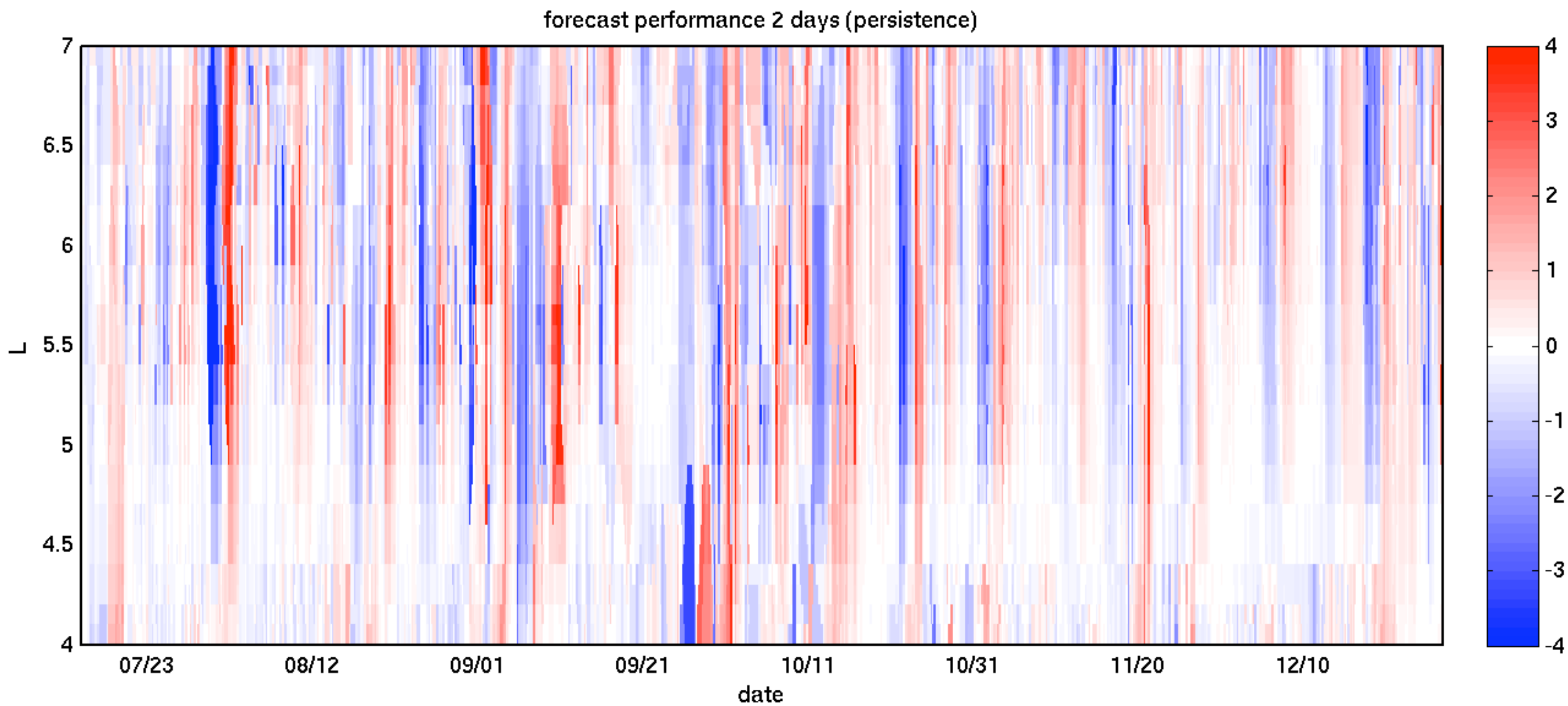

- Log (current measurement / persistence value)
- Persistence value = measurement at earlier time
- Notice the dynamic range is $10^8$

# Error vs. L and Time
# 1-day persistence forecast



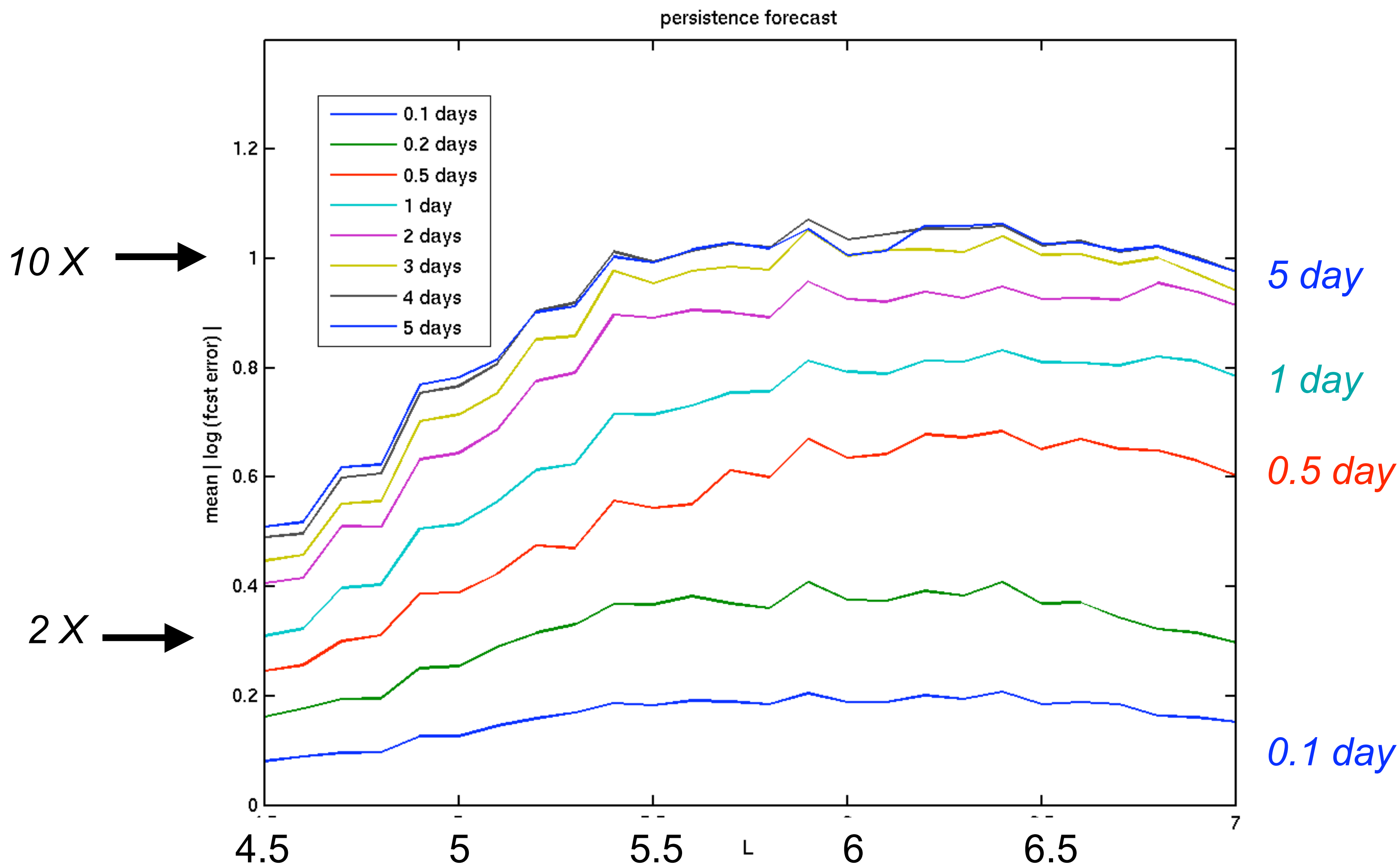

- Log (current measurement / persistence value)
- Persistence value = measurement at earlier time

# Error vs. L and Time
# 2-day persistence forecast

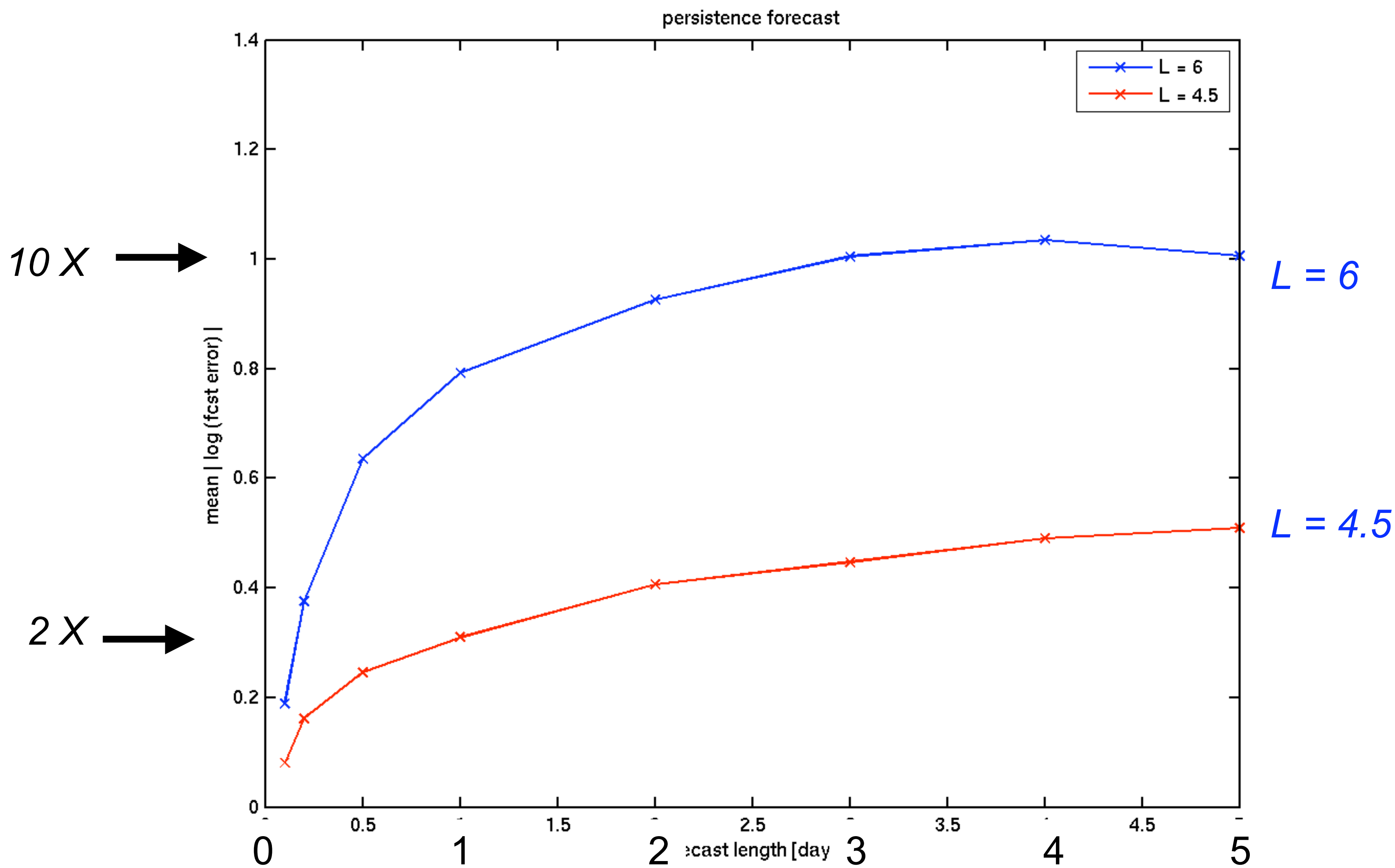



- Log (current measurement / persistence value)
- Persistence value = measurement at earlier time

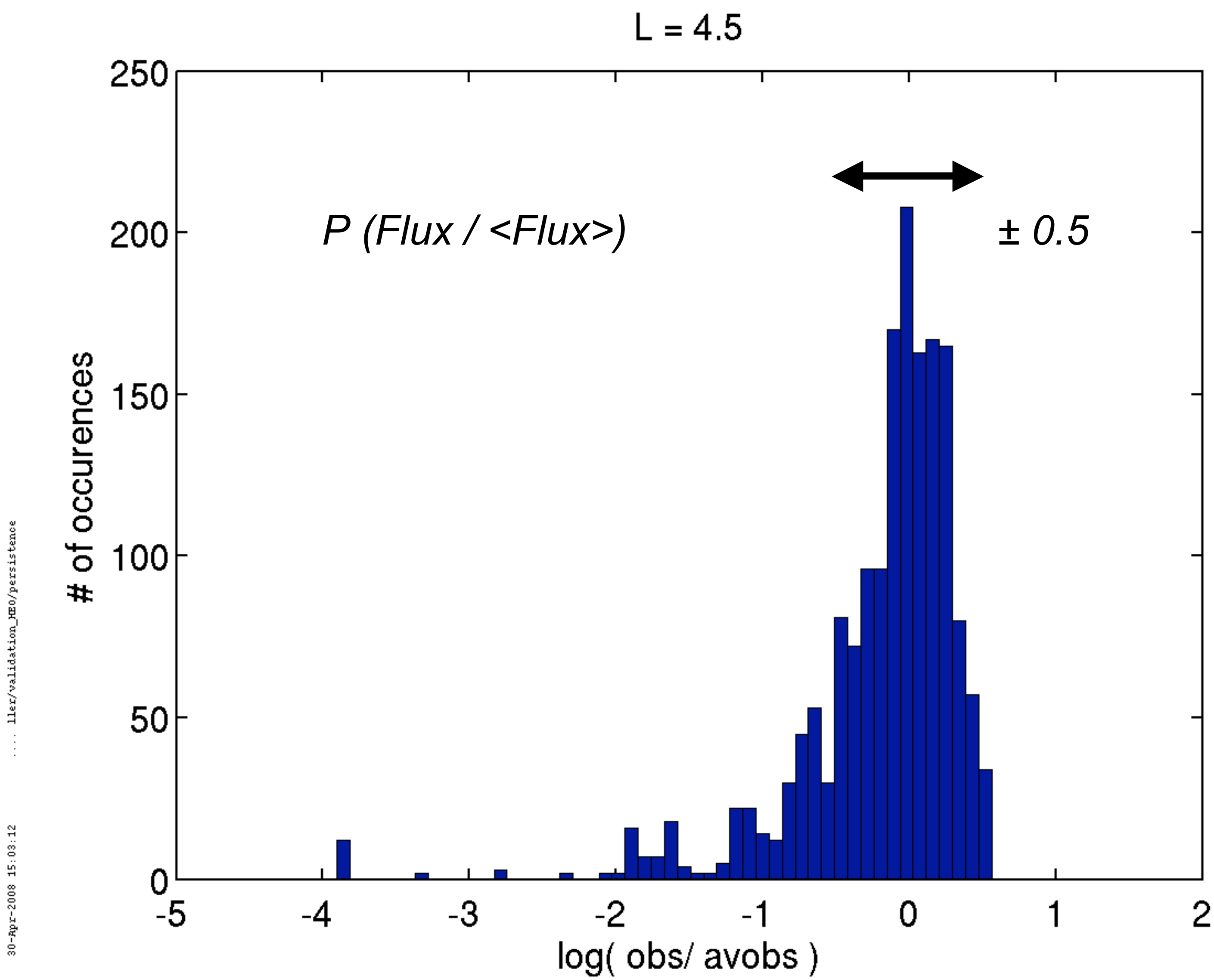
# Persistence Forecast Error vs L
# 0.1 to 5 days



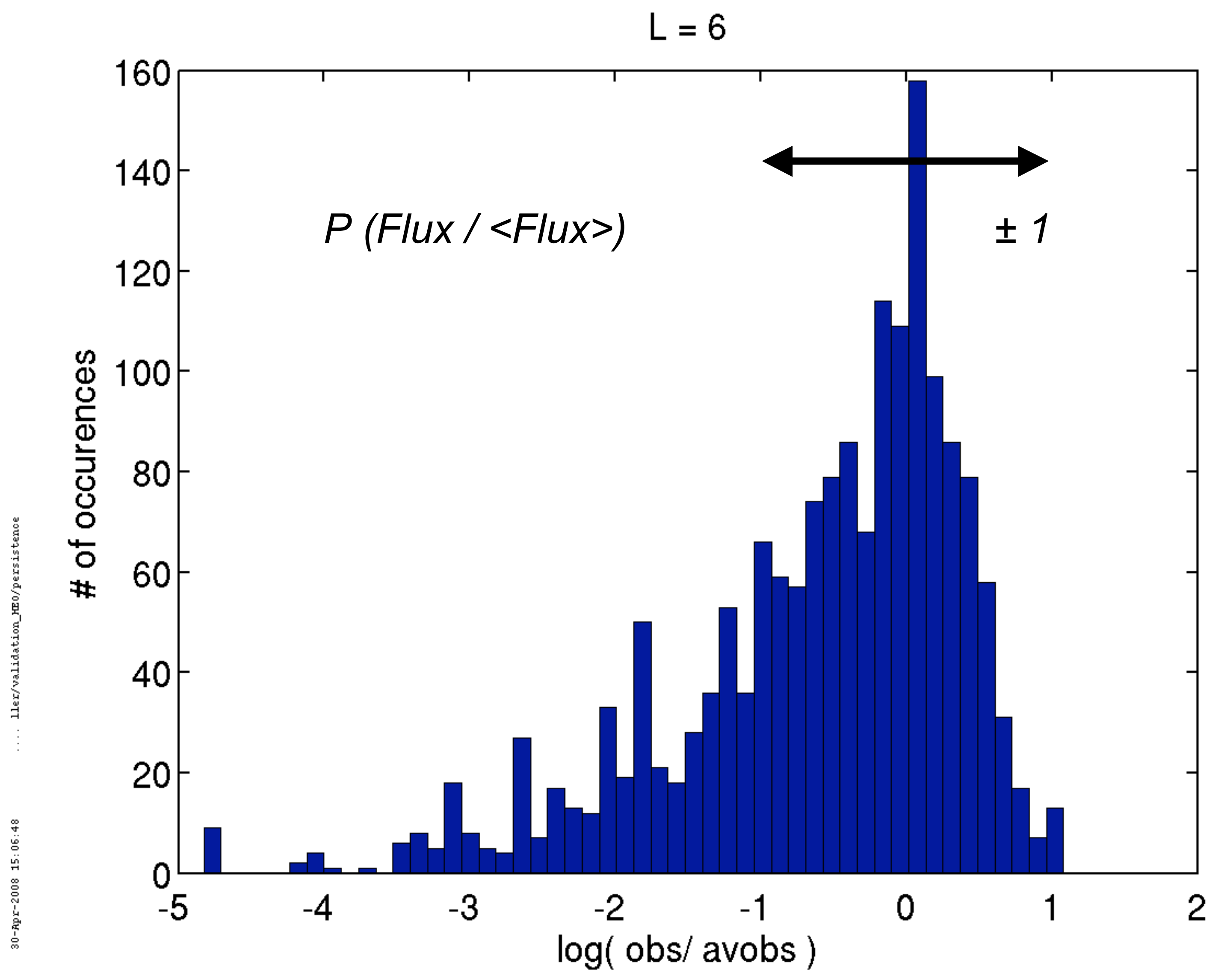
# Persistence Forecast Error vs Time
# The Error 'saturates' but at different values



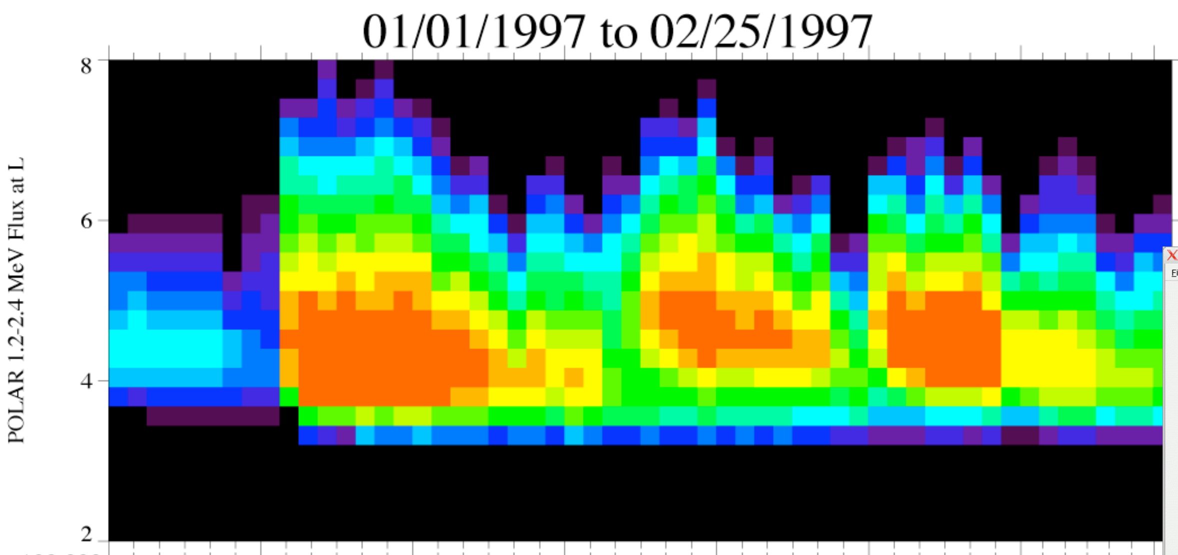
# Distribution of HEO Fluxes at L = 4.5 Relative to average flux

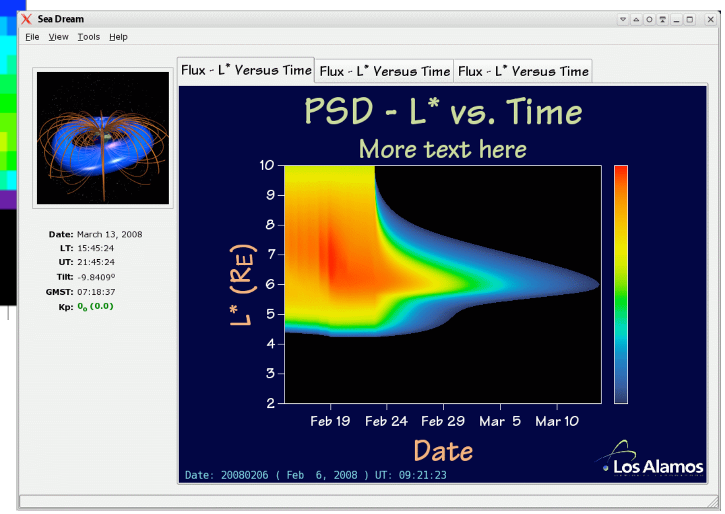


# Distribution of HEO Fluxes at L = 6 Relative to average flux



# Next Steps
# How much better is it to assume ‘relaxation’



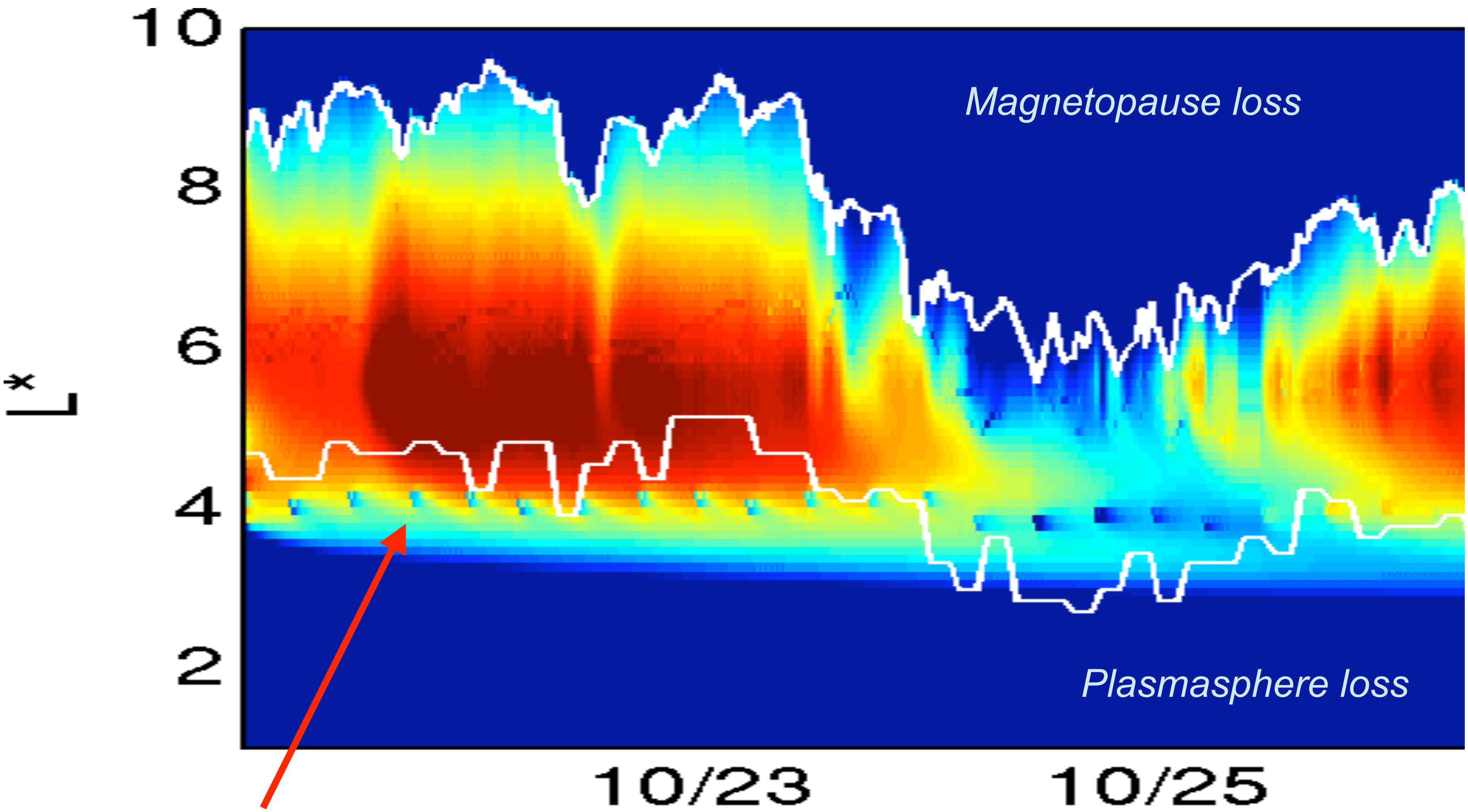




- Assume that without activity the system will relax toward equilibrium

- No worse than persistence in predicting sudden changes

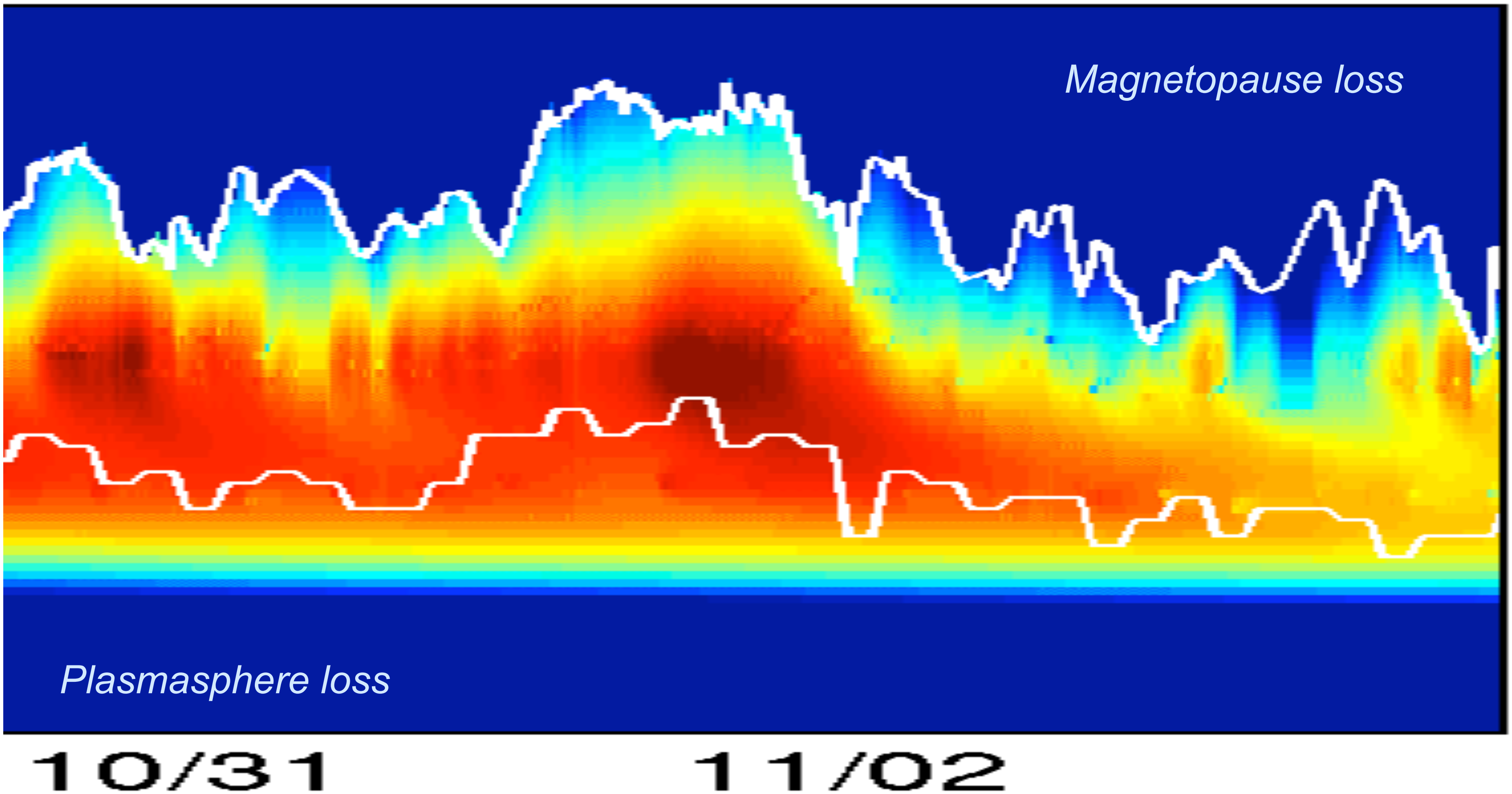
- Forecast uncertainty could, later, incorporate the probability of a sudden event

# The DREAM assimilation assumes relaxation in the 6-hour gaps in GPS data at L=4




Implications: Diffusion is too strong (fast) or losses are too weak (slow)

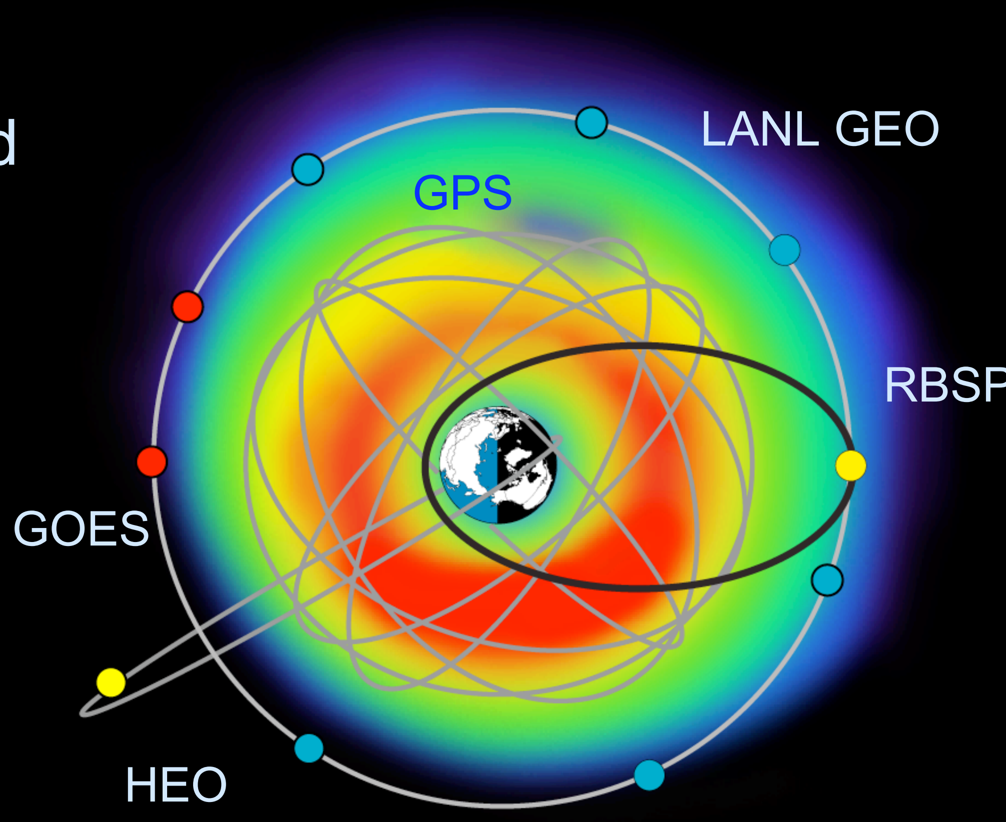
## The DREAM assimilation assumes relaxation in the 6-hour gaps in GPS data at L=4




But: It is time-dependent and not scaled by Kp

# Prospects for current and advance-warning Space Environmental Awareness

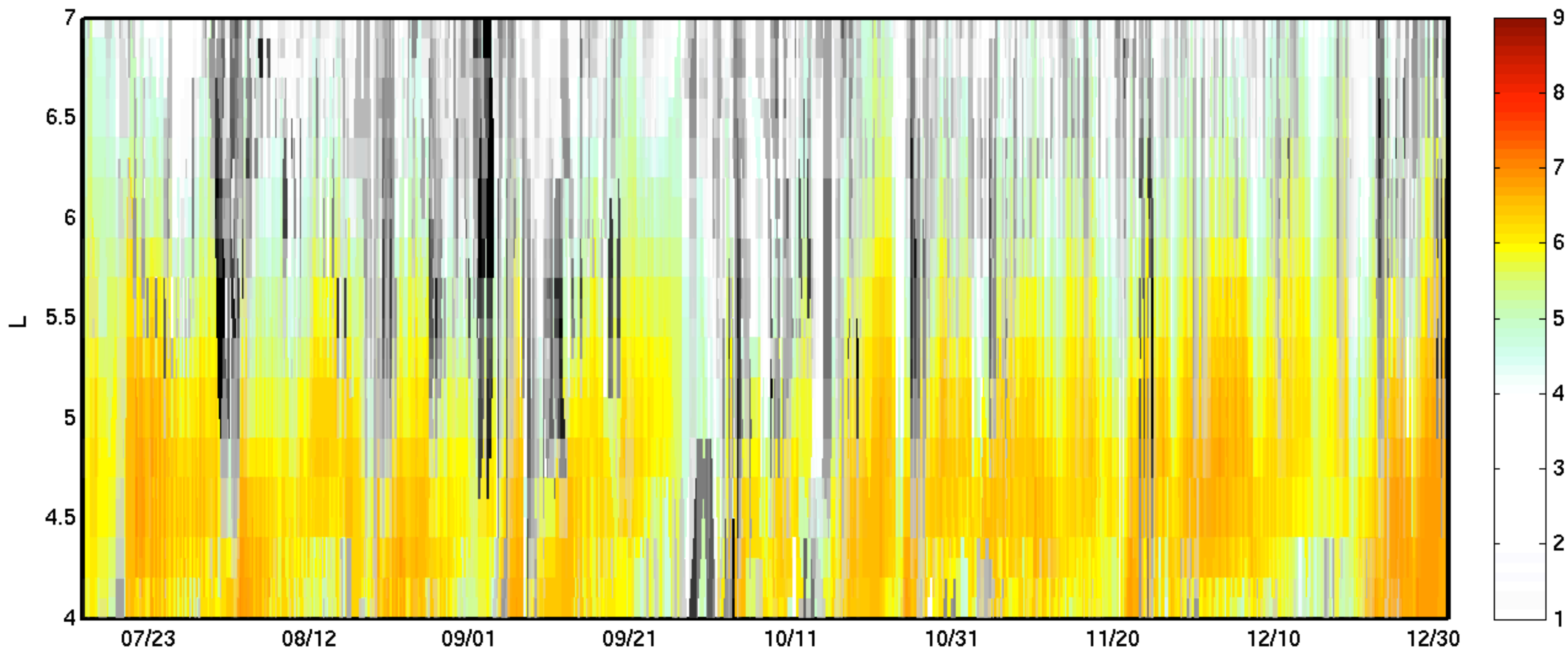
- Data-assimilation based global specification (L, Mlat, E, T) is very good
- Could be even better if all available data were used
- 2+ day orbit-averaged forecasts should be possible
- New Physical Models + data should enable SEA at any satellite any time
- Go RBSP !



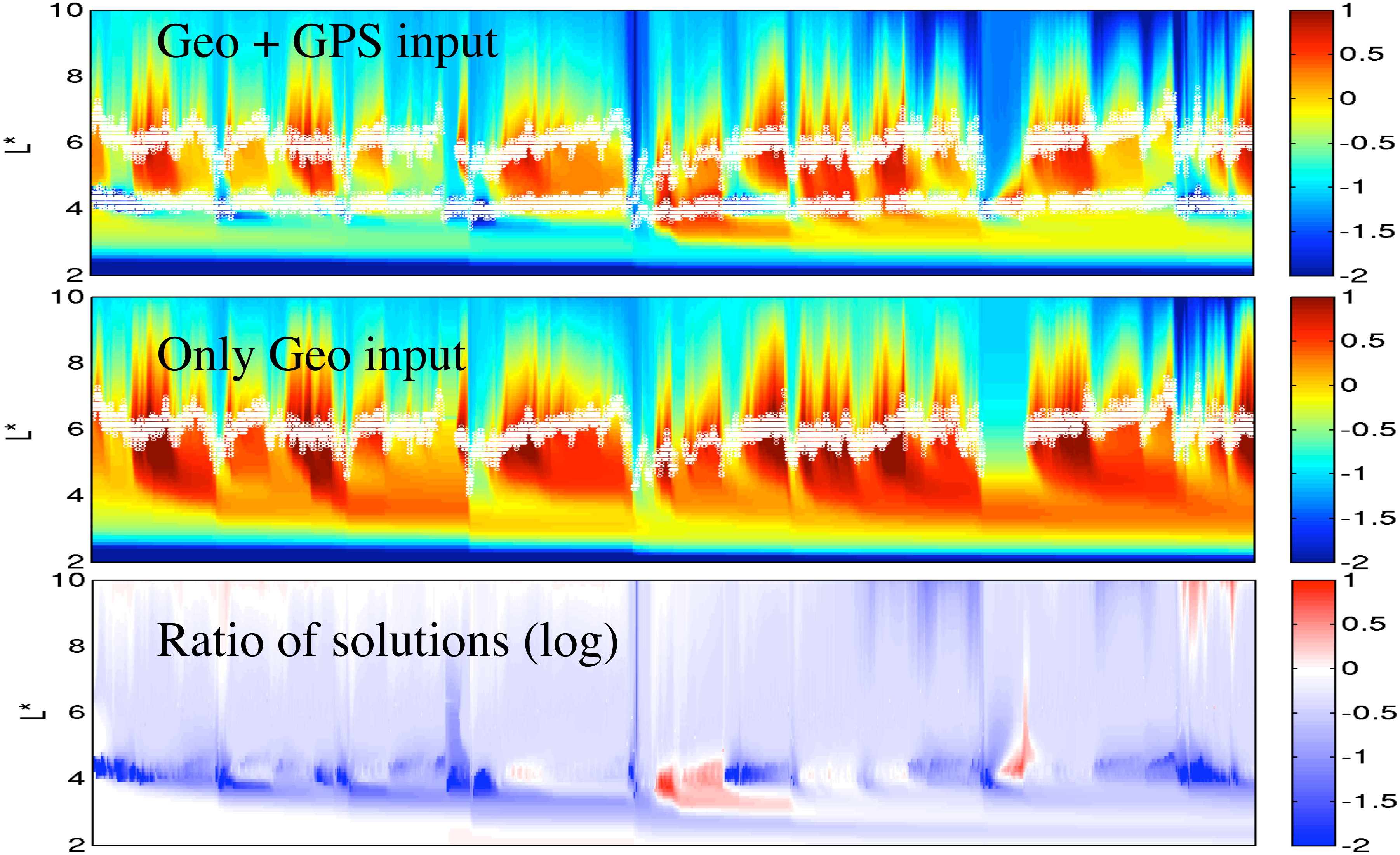
# ¿ Questions ?

And Backup Slides

# Where is persistence good?



# Data Assimilation is ideally suited for spiral development - models or data

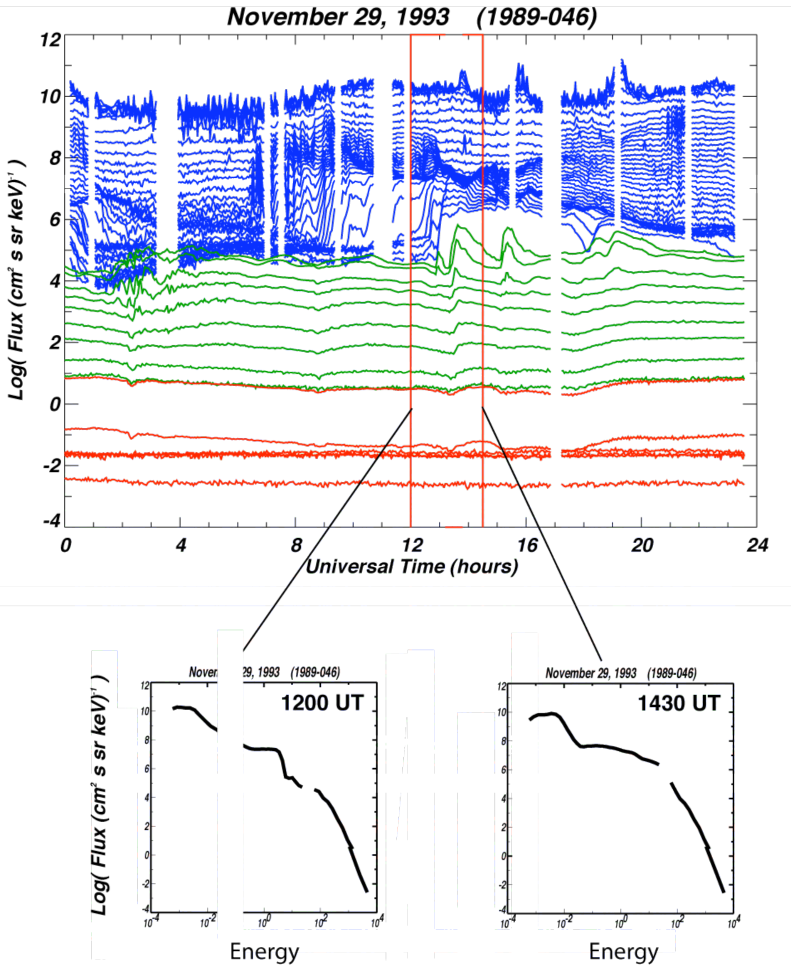


# Observations are in Flux
# Physical equations use phase space density

**Geosynchronous Flux**

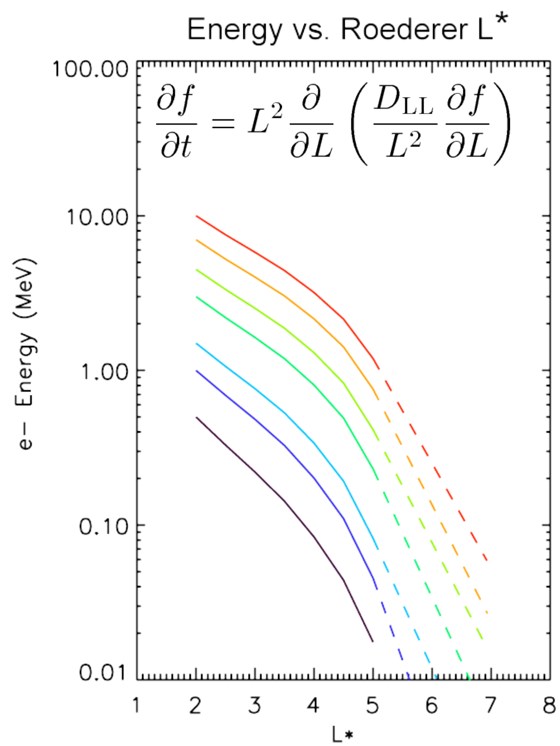
>80 channels 1 eV - $10^7$ eV

$10^{16}$ dynamic range

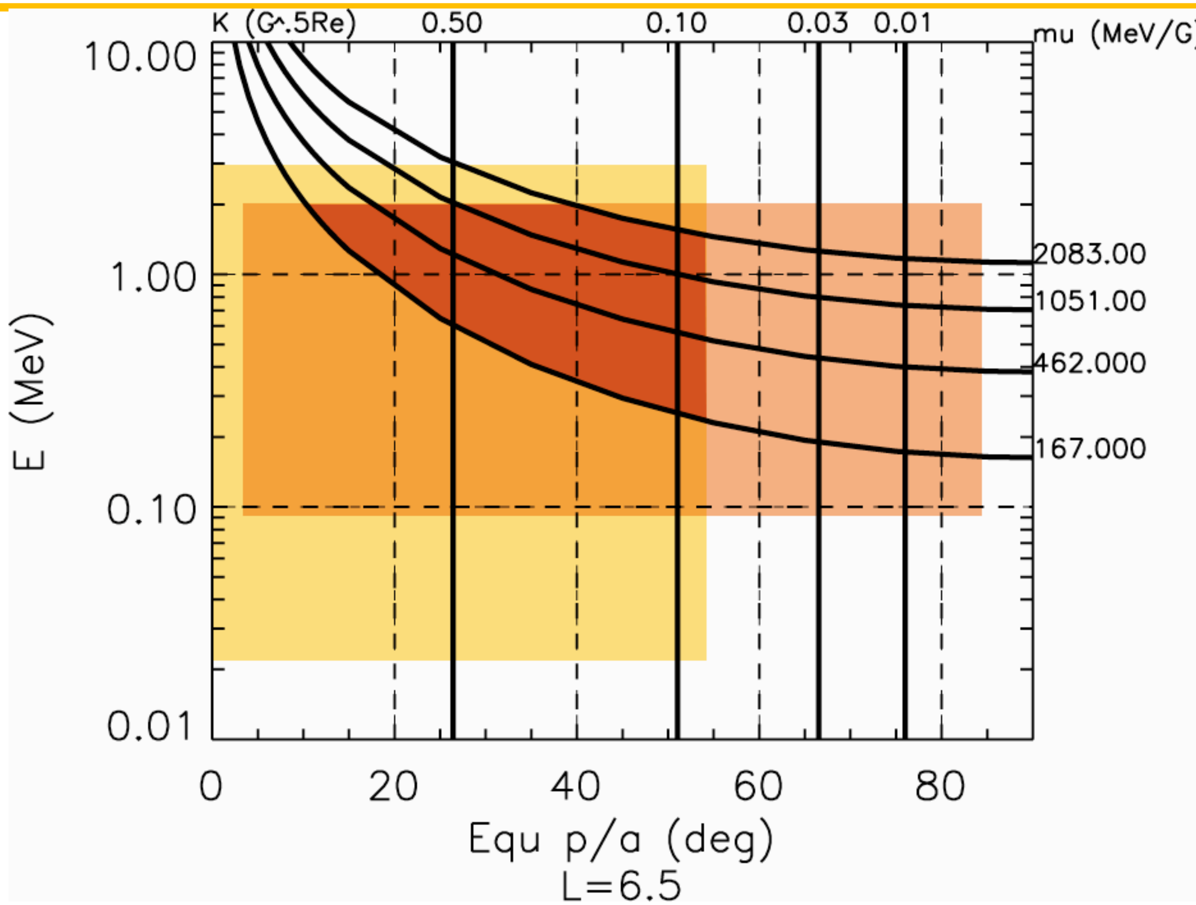



**Phase Space Density (PSD)**

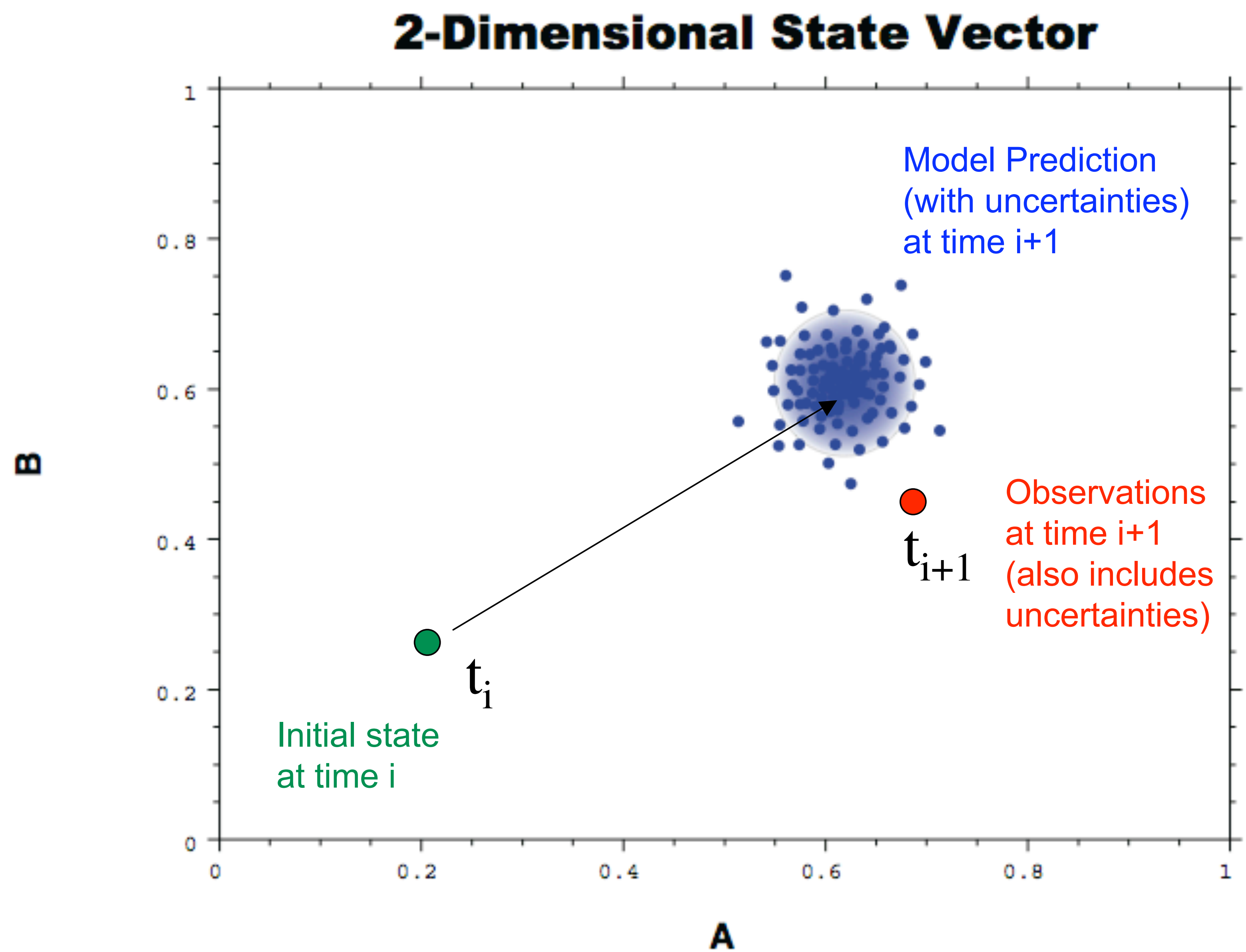
$$\text{PSD} = \frac{\text{Flux}}{(\text{Momentum})^2}$$



# Testing forecasts required data with good L, pitch angle, and energy information



# How Data Assimilation (Kalman Filter) Works



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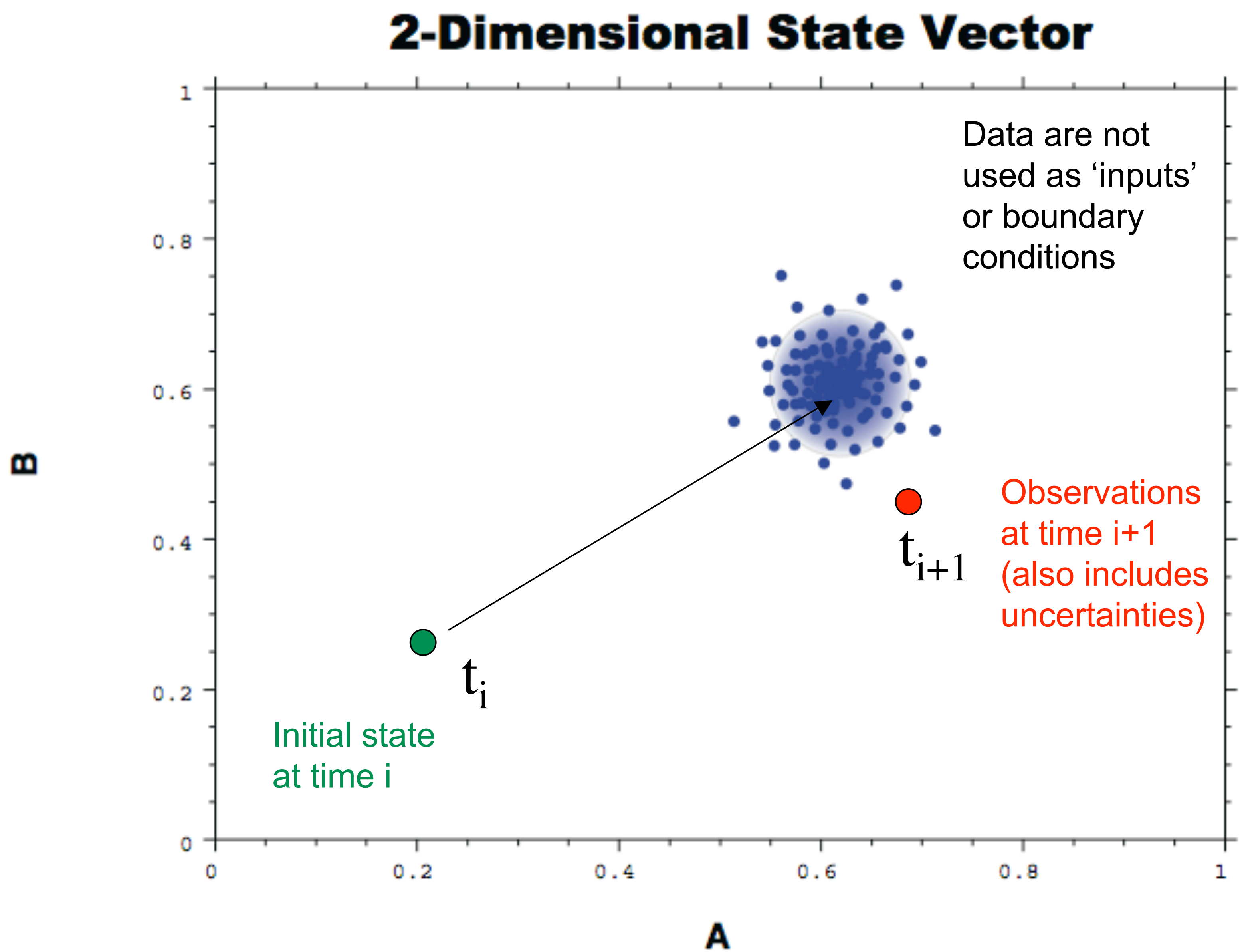

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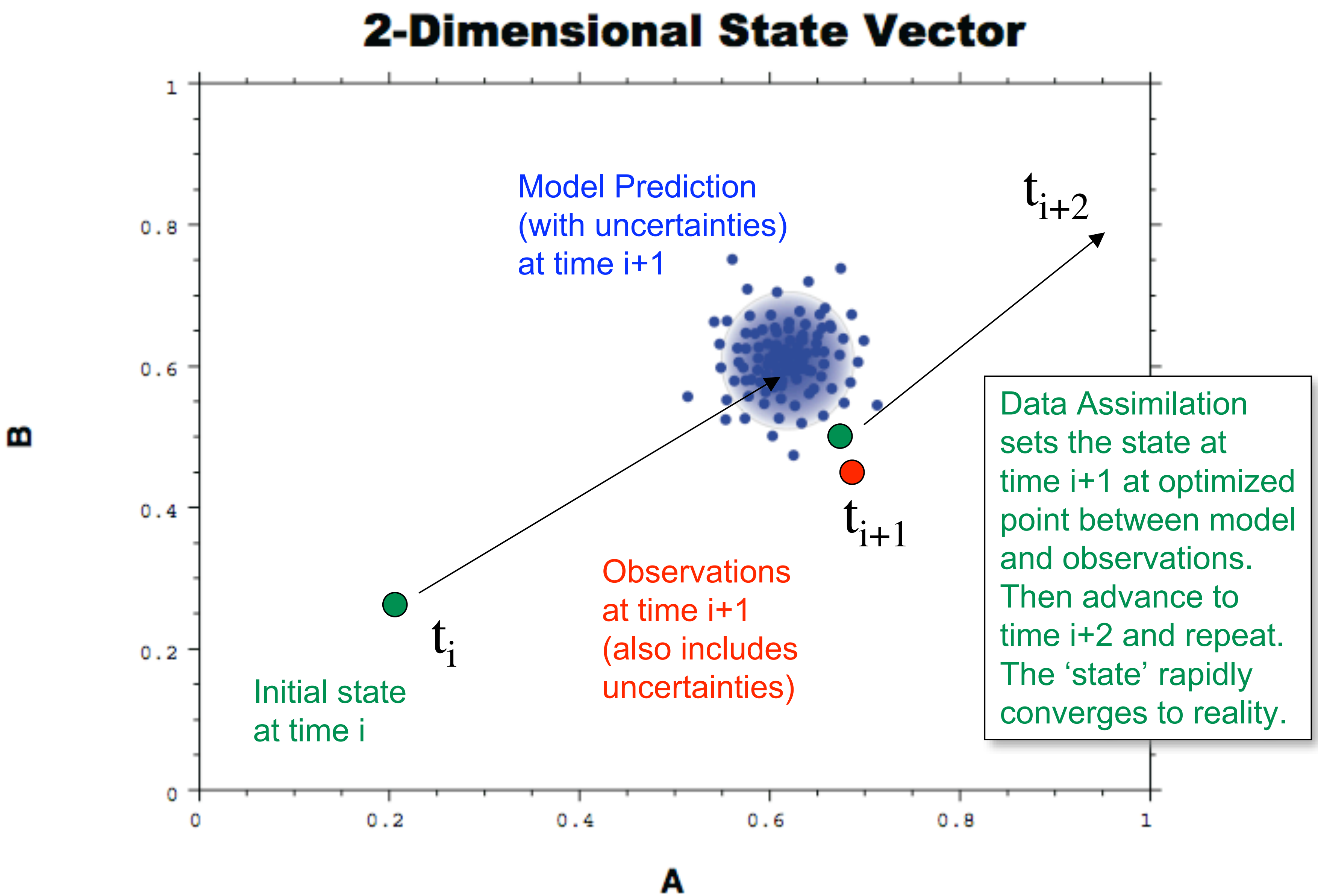
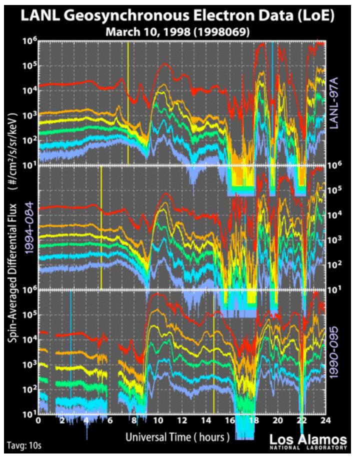
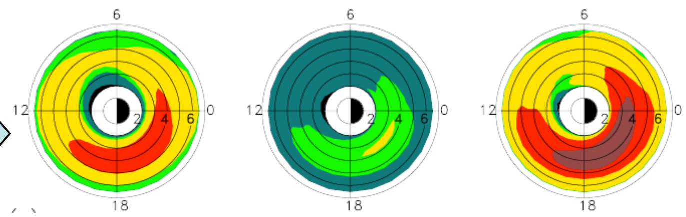


# DREAM - The Dynamic Radiation Environment Assimilation Model

Geosynchronous Boundary Conditions



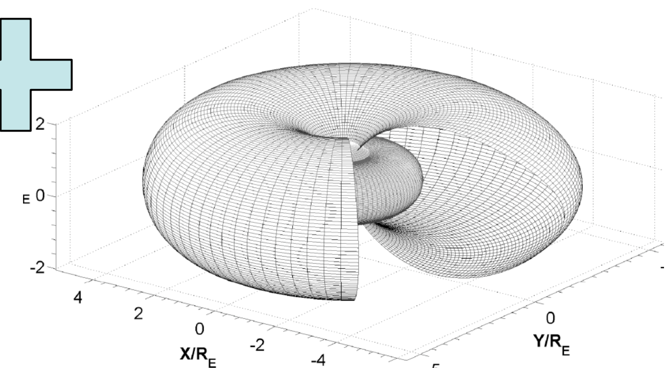

Global Ring Current Model = RAM

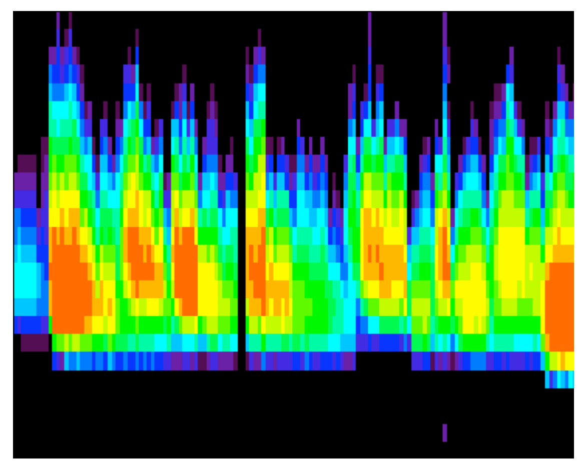



H+ He+ O+

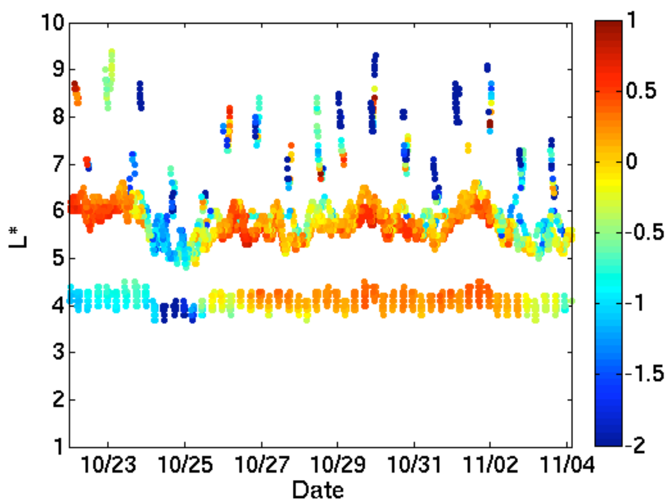
Energy Density

Self-consistent, Non-Dipole Magnetic Field Model



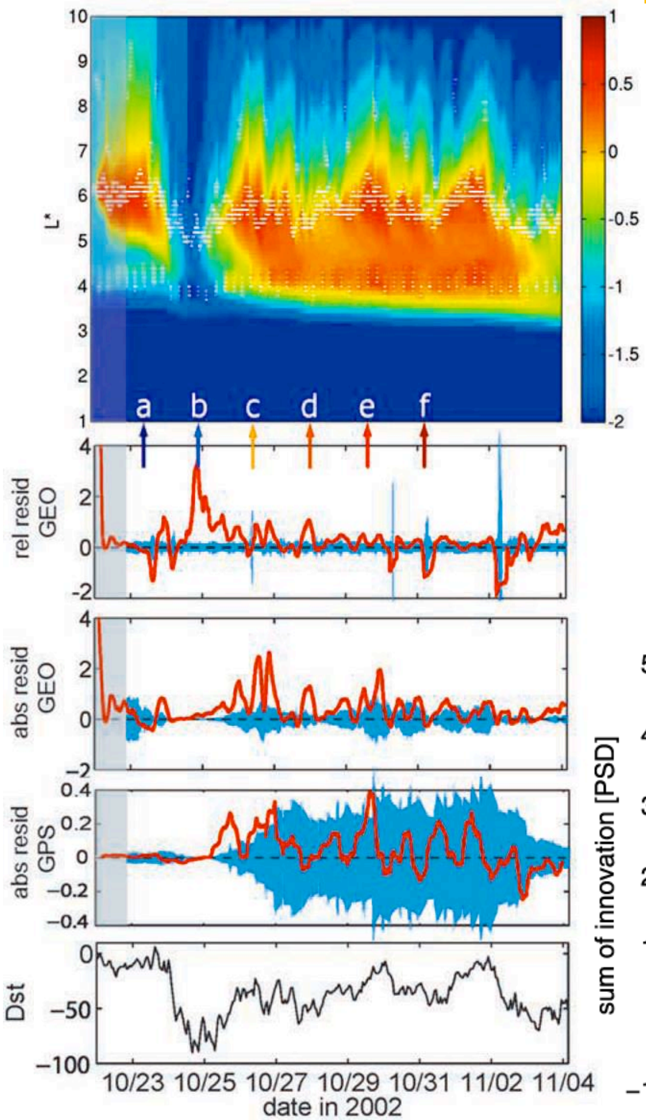



Radiation Belt Data




Relativistic Electron Phase Space Density

# Kalman innovation vector shows where and when PSD must be added or removed

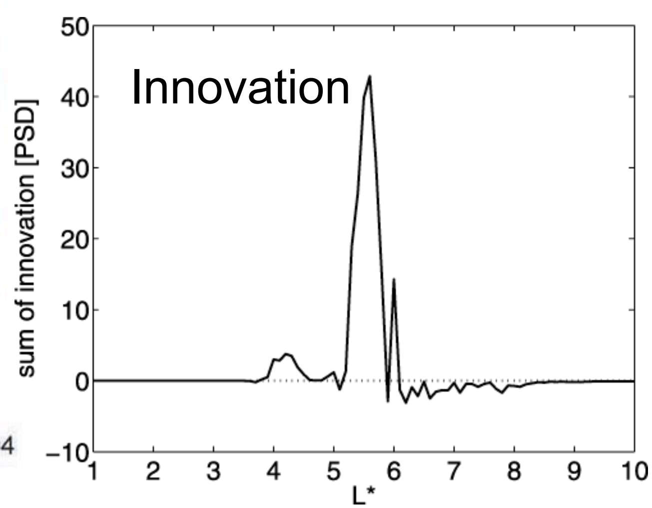


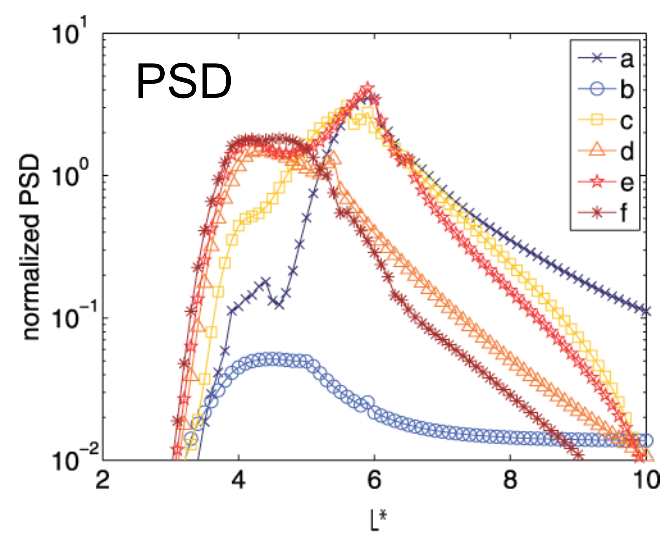

Koller et al., 2007

• In a physics model where the only acceleration process is diffusion the data must constantly 'pull' the state vector back toward reality.

• Knowing where and when that 'pull' (or 'innovation') occurs pinpoints where there are missing processes such as acceleration or loss

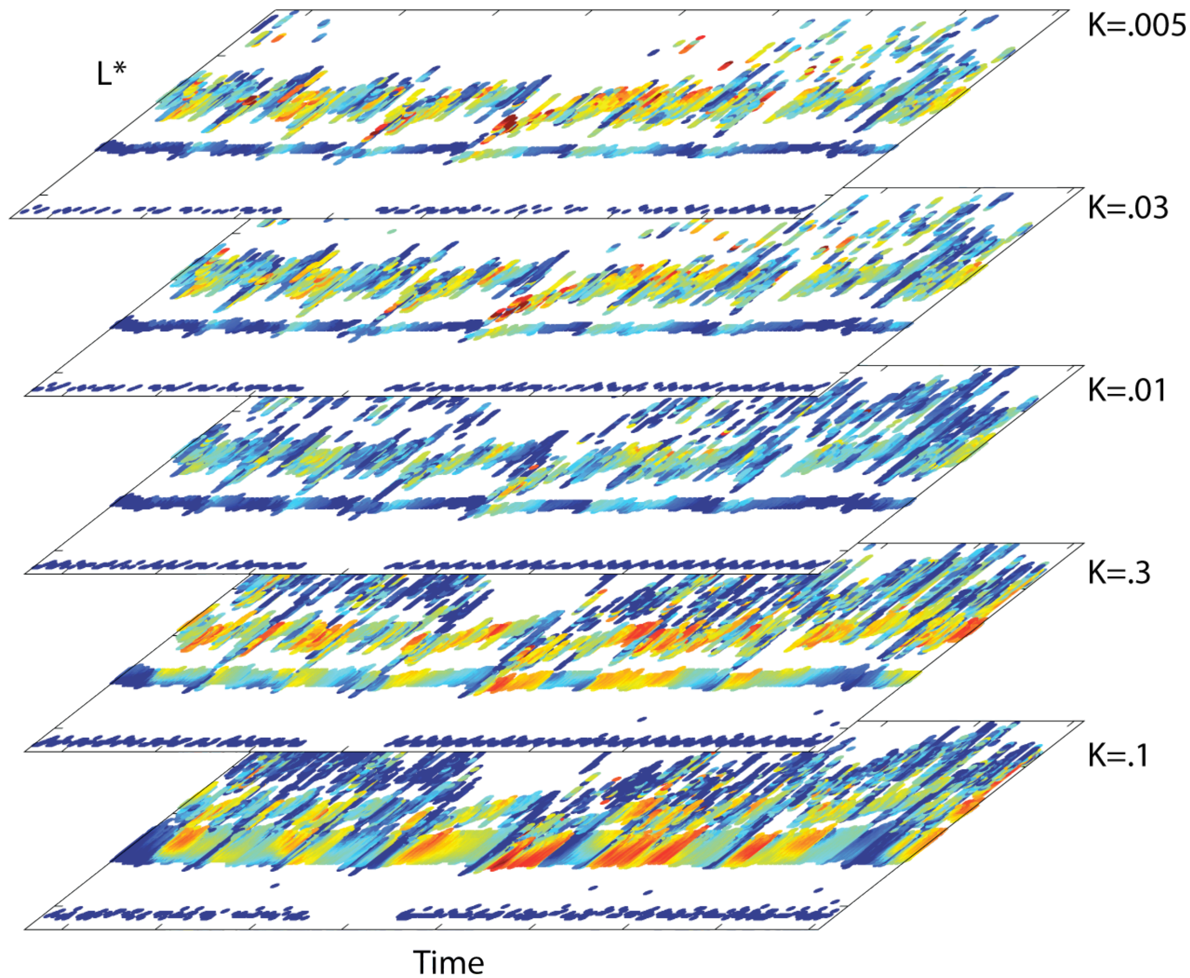
• As a result the predicted state still shows the peaks in PSD characteristic of local acceleration



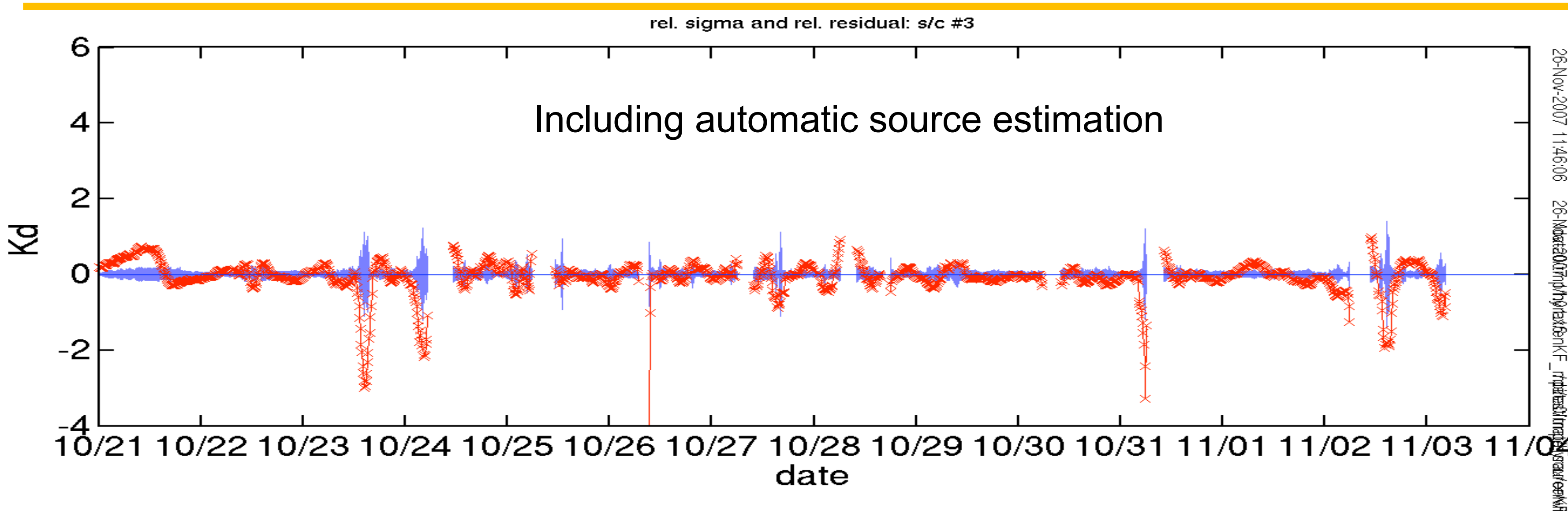
# Multi-dimensional data assimilation

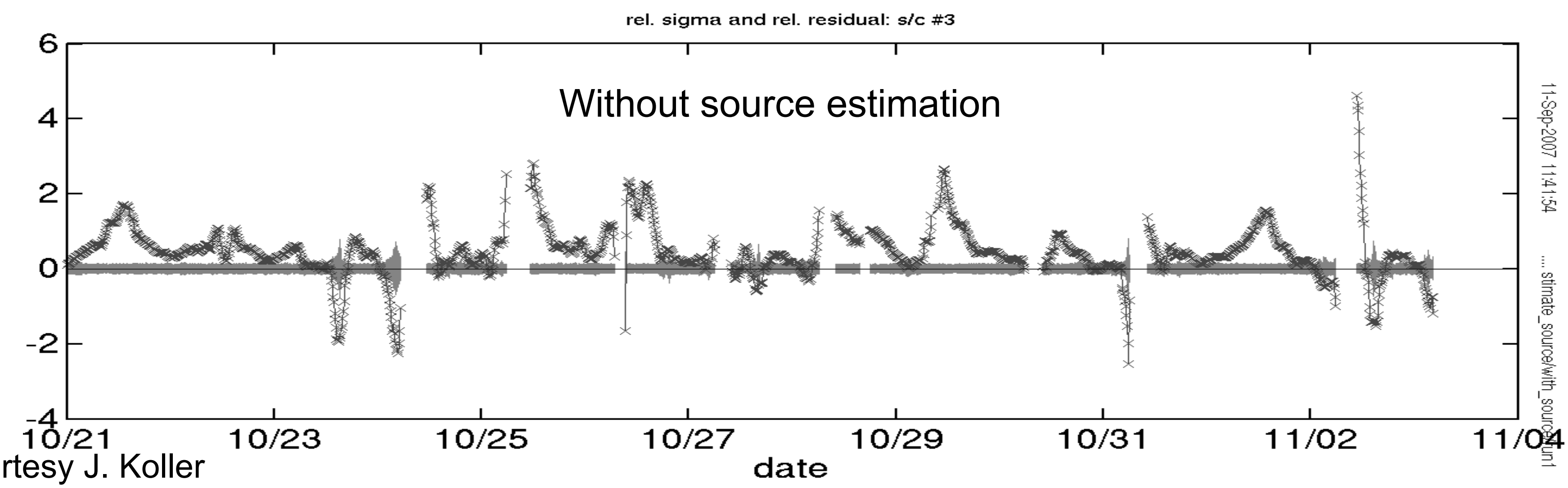
- Each radial diffusion simulation can be represented as a plane in μ, K, L*
- Radial diffusion moves PSD within a plane
- Energy or pitch angle diffusion move across planes in both dimensions: μ and K
- Data Assimilation provides multiple, & multi-dimensional constraints on the models but is complex



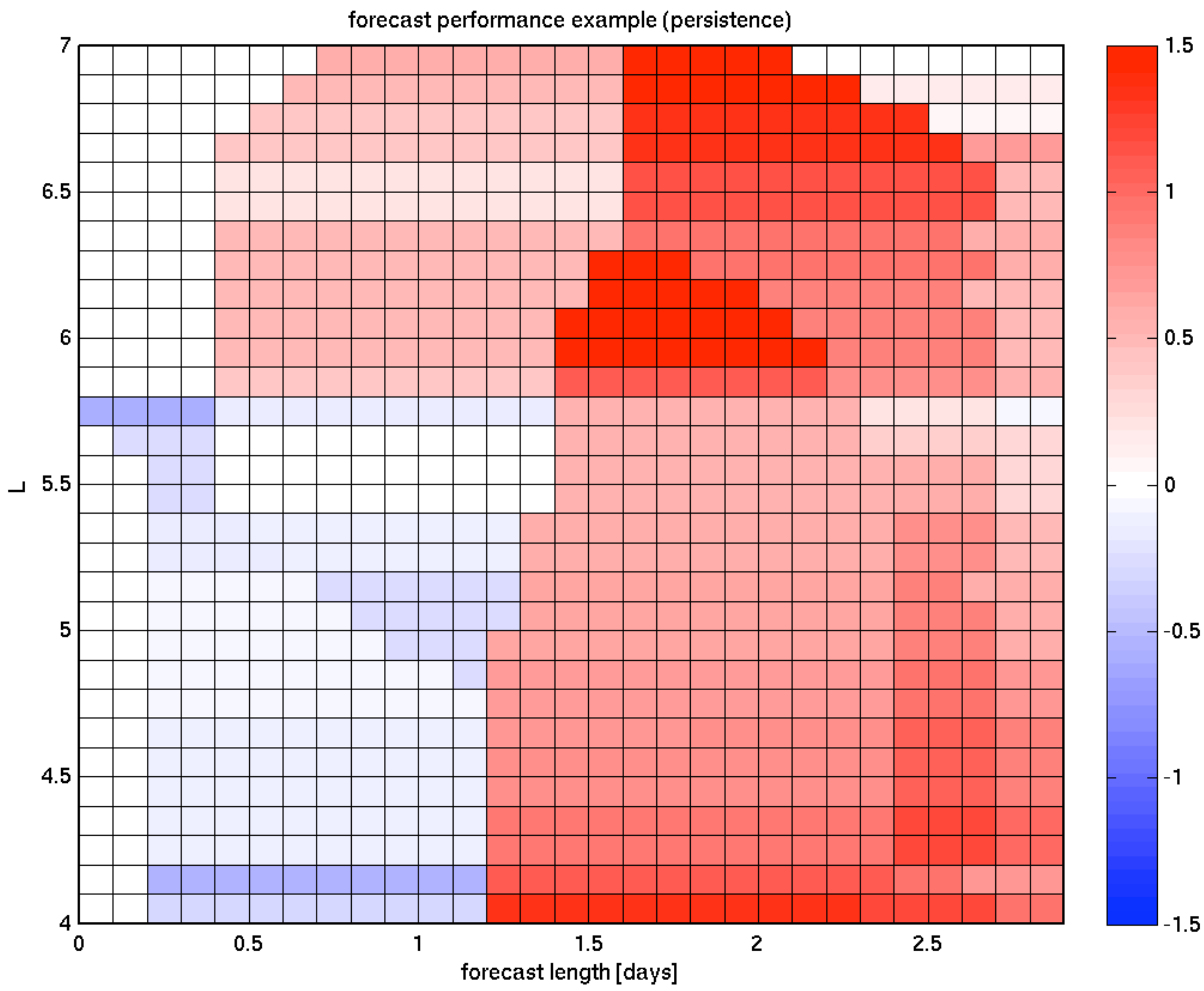

See Koller et al Thurs. PM: SM43E-06

# The quantitative comparison gives us confidence in applying this to $D_{EE}$ and $D_{\alpha\alpha}$




Courtesy J. Koller


forecast performance example (persistence)
L
forecast length [days]
7
6.5
6
5.5
5
4.5
4
0
0.5
1
1.5
2
2.5
1.5
1
0.5
0
-0.5
-1
-1.5