An Observational Study of the Relationship Between Precipitating Ions and Energetic Neutral Atoms (ENA's) Emerging From the Ion/Atmosphere Interaction

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Outline of Topics

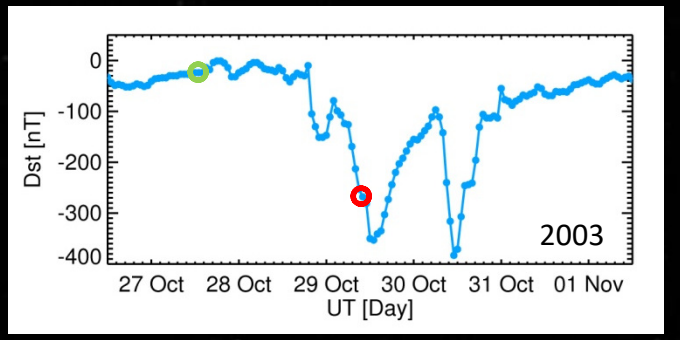
- Objective
- Introduction
- Data Analysis
- Results
  - LAE Geomagnetic Index Correlation
  - LAE/In Situ Response to Storms
  - LAE/In Situ Correlation
  - LAE/In Situ Comparison

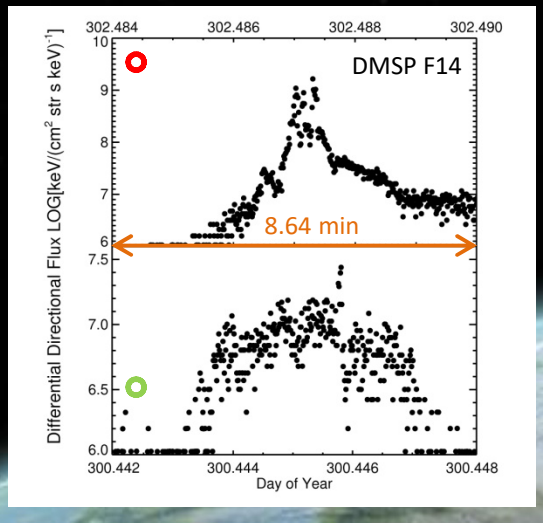
Objective

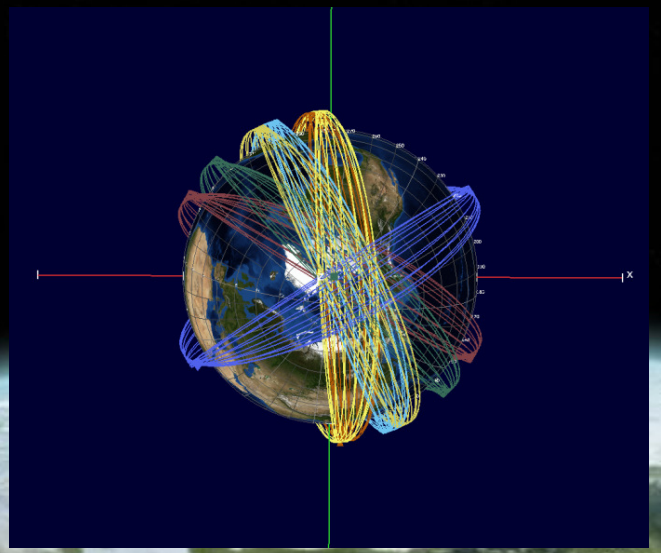
Further the understanding of the energy injected into the terrestrial atmosphere by plasma sheet ions during geomagnetic storms using Energetic Neutral Atom (ENA) imaging.

In Situ Measurement of Ion Precipitation

- Orbit ~100 minutes; Passes a precipitation region in ~5+ minutes
- Limited local time coverage:
  - Sun Synchronous







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Energetic Neutral Atoms (ENAs)

Magnetospheric ENAs

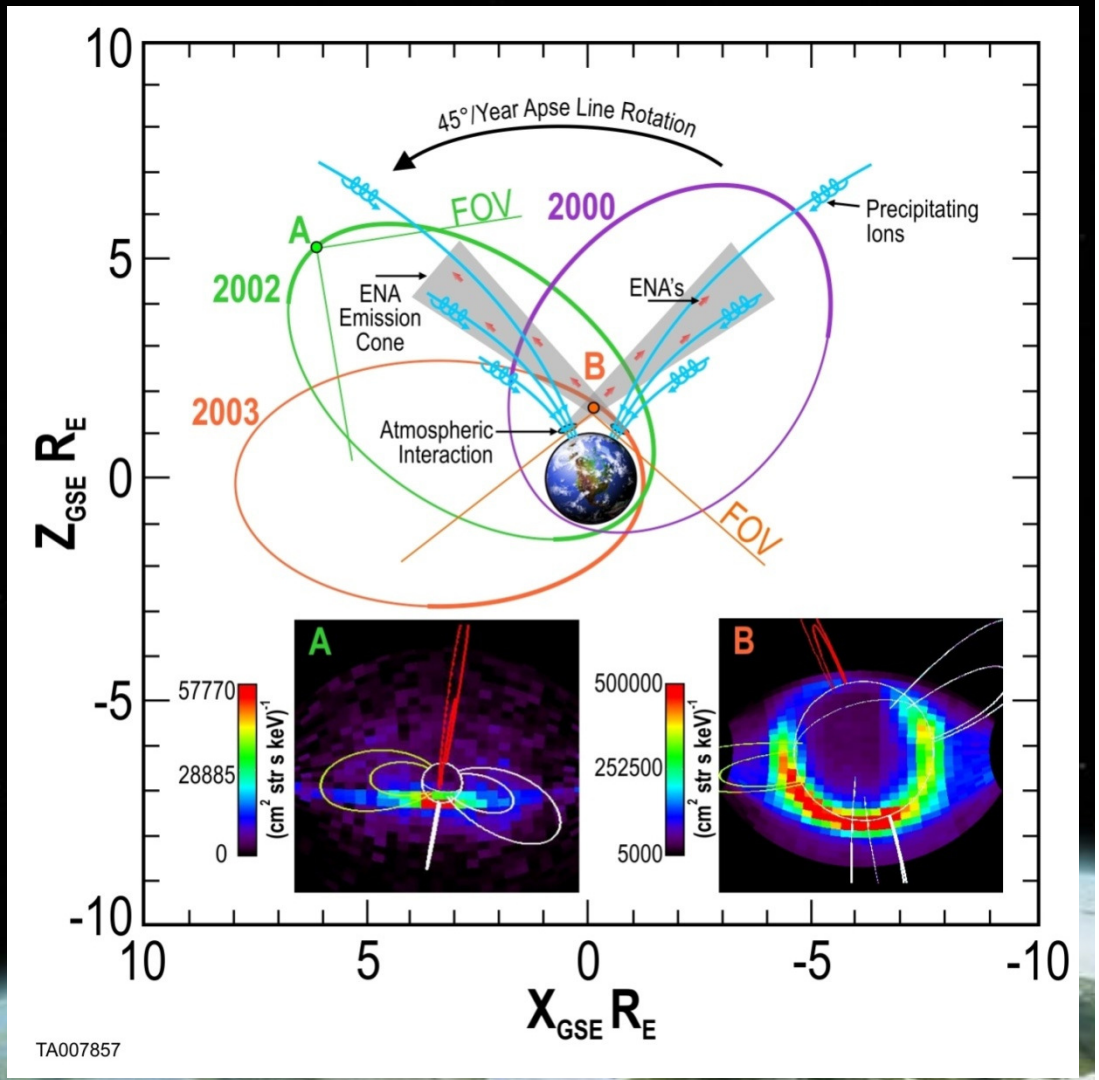
- Higher energy than ionospheric neutrals
  - 1-100s keV
- Created by charge exchange of precipitating ions with cold exospheric neutrals (oxygen exobase)
- Low Altitude Emission (LAE) – associated with high latitude footprints of Earth's magnetosphere (most intense ENAs)
- Problem: LAEs are outside the loss cone and are not precipitating ions

Do LAEs behave similarly to ion precipitation during geomagnetic activity?

Geomagnetic Emission Cone

- Observed LAEs are highly anisotropic; ENAs near mirror point
- Pitch angle slightly larger than 90° is preferential to escape
  - Escape angle
- Observation location
  - Determines local time distribution
  - Far: opposite hemisphere

Statistics!



Geomagnetic Emission Cone

Corollary – Escape Angle

Escape Angle (β) vs. Pitch Angle (α)

α: Tied to the Magnetic Field

β: Associated with the Local Atmosphere

ENA Escape Angle may be preferential to 'thinnest' path

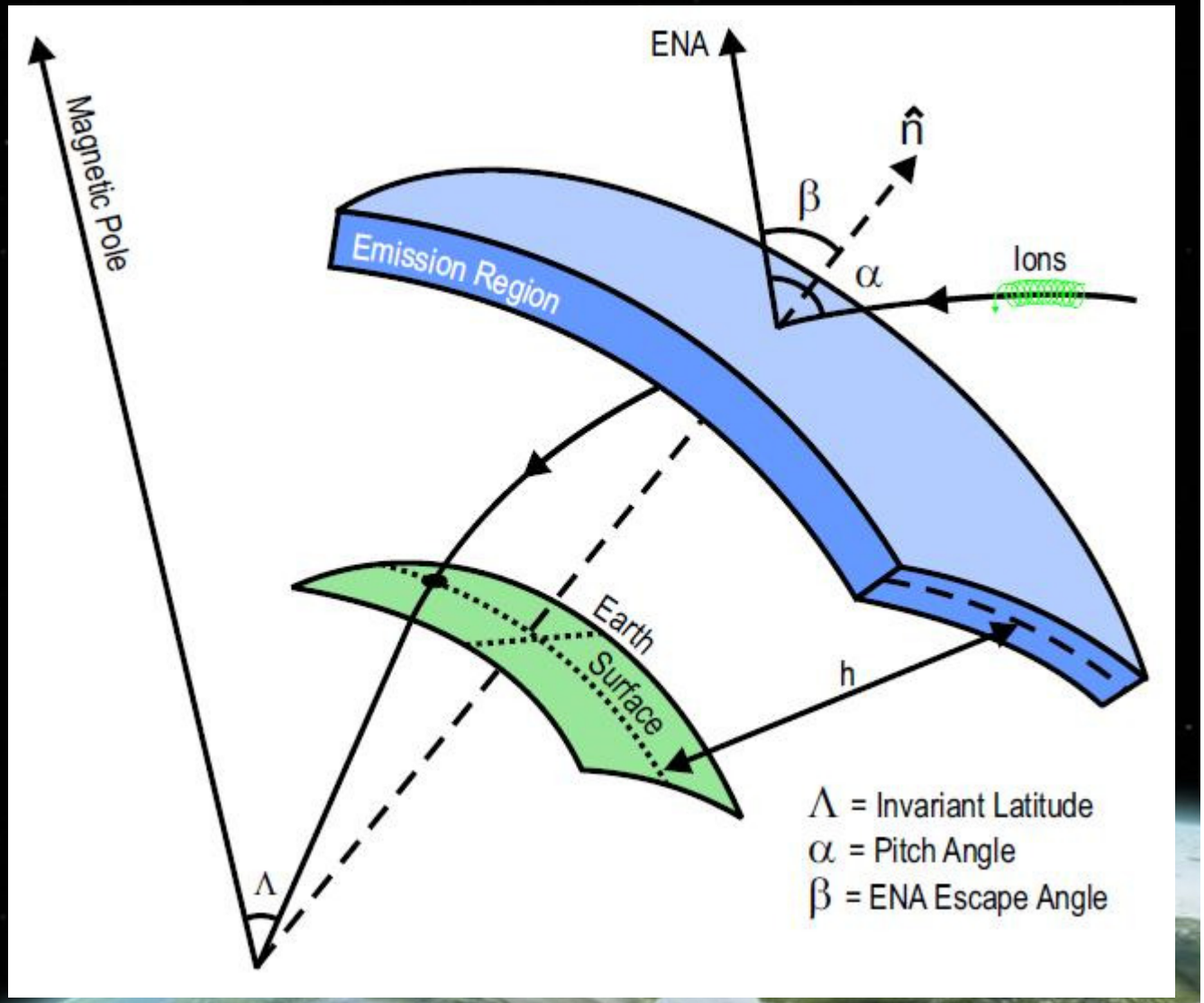


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IMAGE Mission

Imager for Magnetopause-to-Aurora Global Exploration

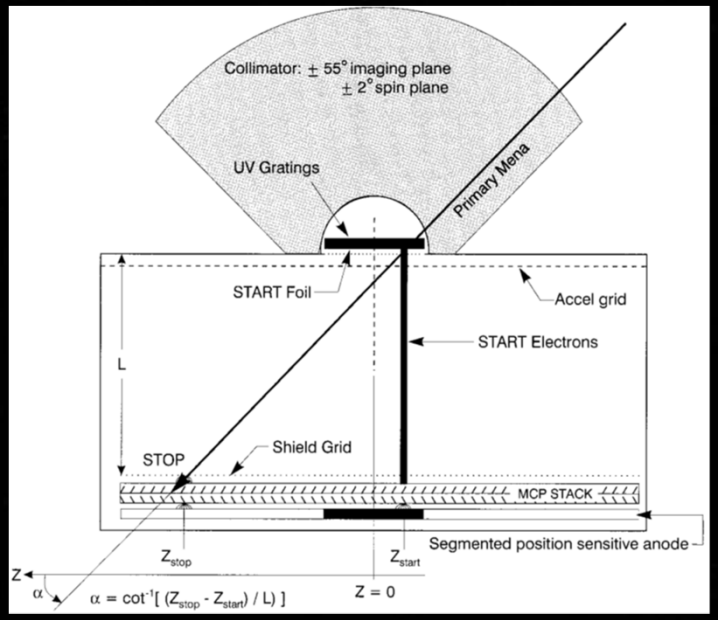
IMAGE used neutral atom, ultraviolet, and radio imaging techniques to:

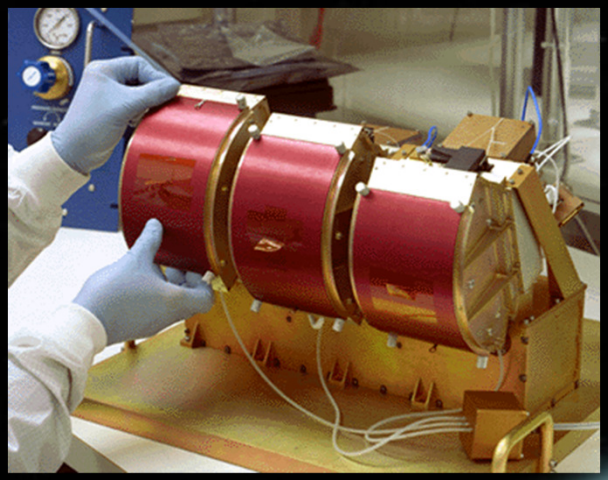
- Identify the dominant mechanisms for injecting plasma into the magnetosphere on substorm and magnetic storm time scales;
- Determine the directly driven response of the magnetosphere to solar wind changes; and,
- Discover how and where magnetospheric plasmas are energized, transported, and subsequently lost during substorms and magnetic storms.

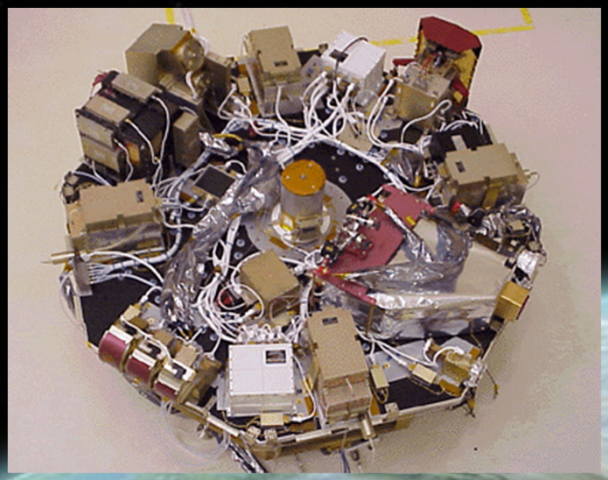
IMAGE Mission

Medium Energy Neutral Atom Imager

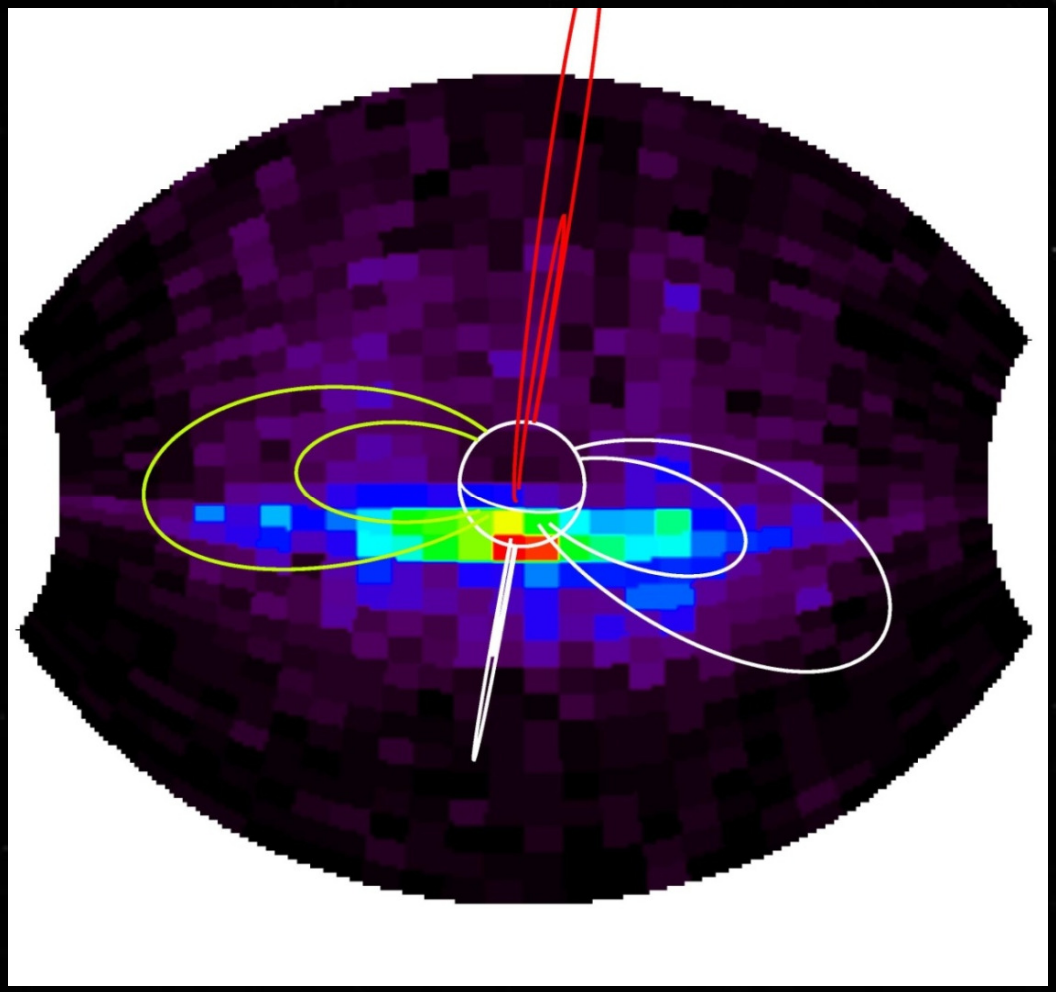
- Pinhole camera
- 3 heads combined
- 1 – 30 keV
- 2 minutes per image
- Data from 2000 - 2005





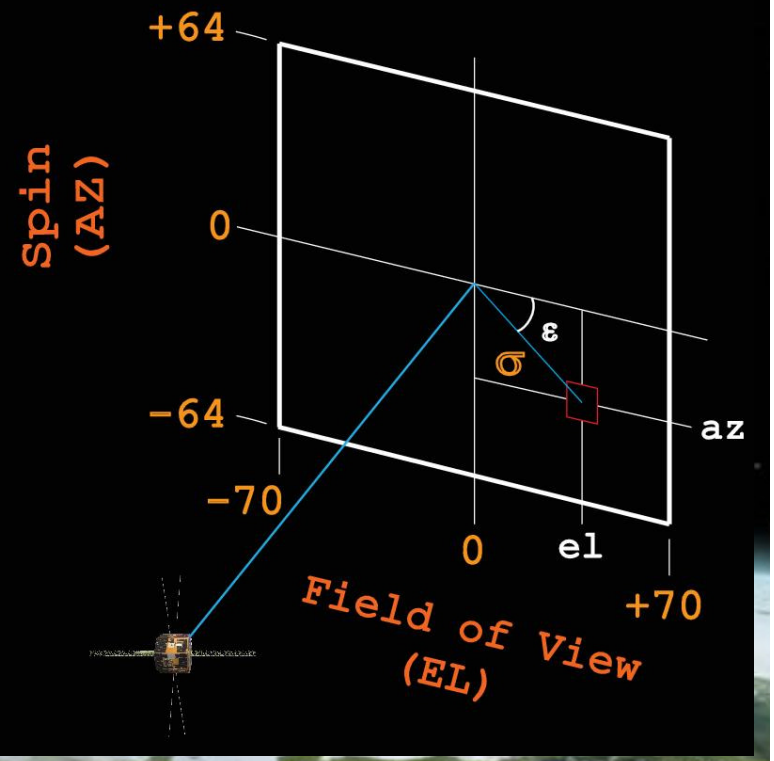


MENA Data



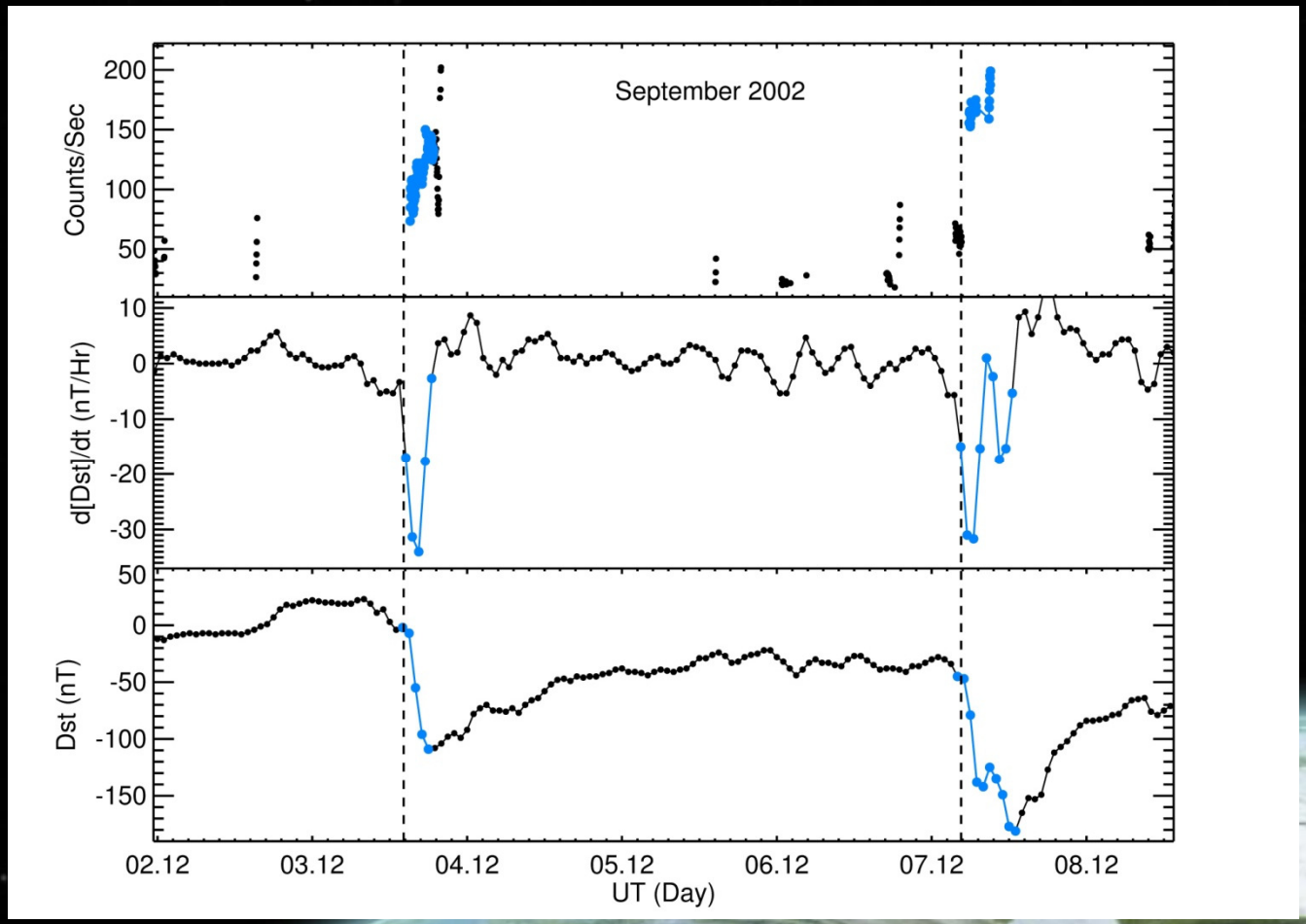
Medium Energy Neutral Atom Imager

- Energy: ~1-30 keV
  - Using ~1-12 keV
- Pixel size
  - AZ: 4° (32 pixels)
  - EL: 5° (28 pixels)
- Sigma
  - Angular ‘distance’ from center



Data Analysis – LAE Dataset

- LAE images are manually selected from MENA dataset
- Reality check: Just using LAE dataset and Dst

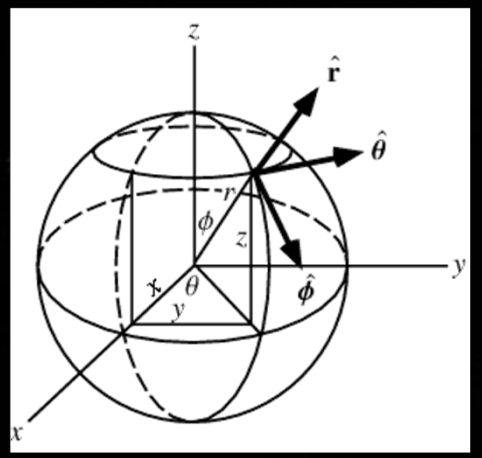


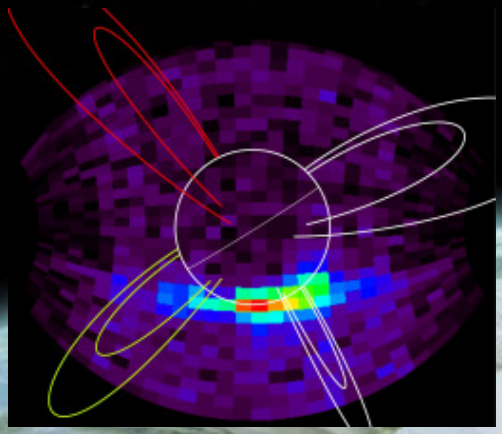
Data Analysis – Initial Points Collection

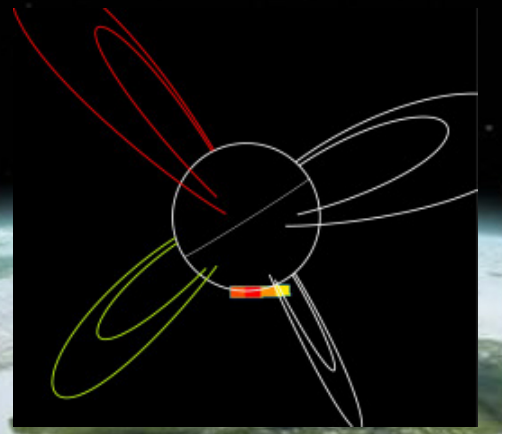
"Batch" Processor

Goal: Collect pixel coordinates and B field for four corners and center of LAE pixels

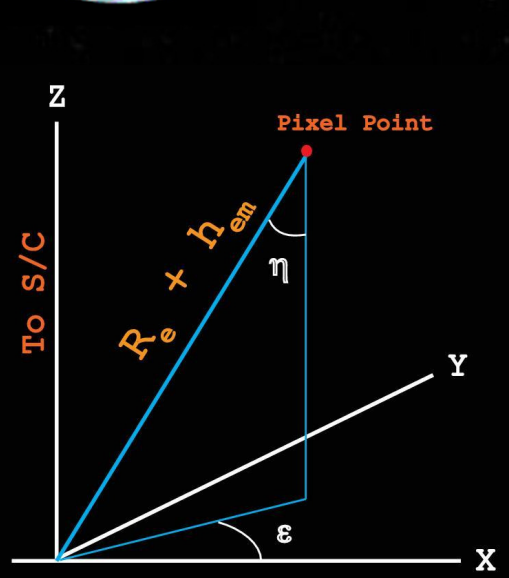
- Only consider pixels with a corner within R_e+h
- Integrate over low three energy bins (1 - 12.1 keV)
- Keep pixels most associated with LAEs
- Assume spherical emission region
  - Project pixel to a sphere of radius R_e+h
- Use the IGRF to find B

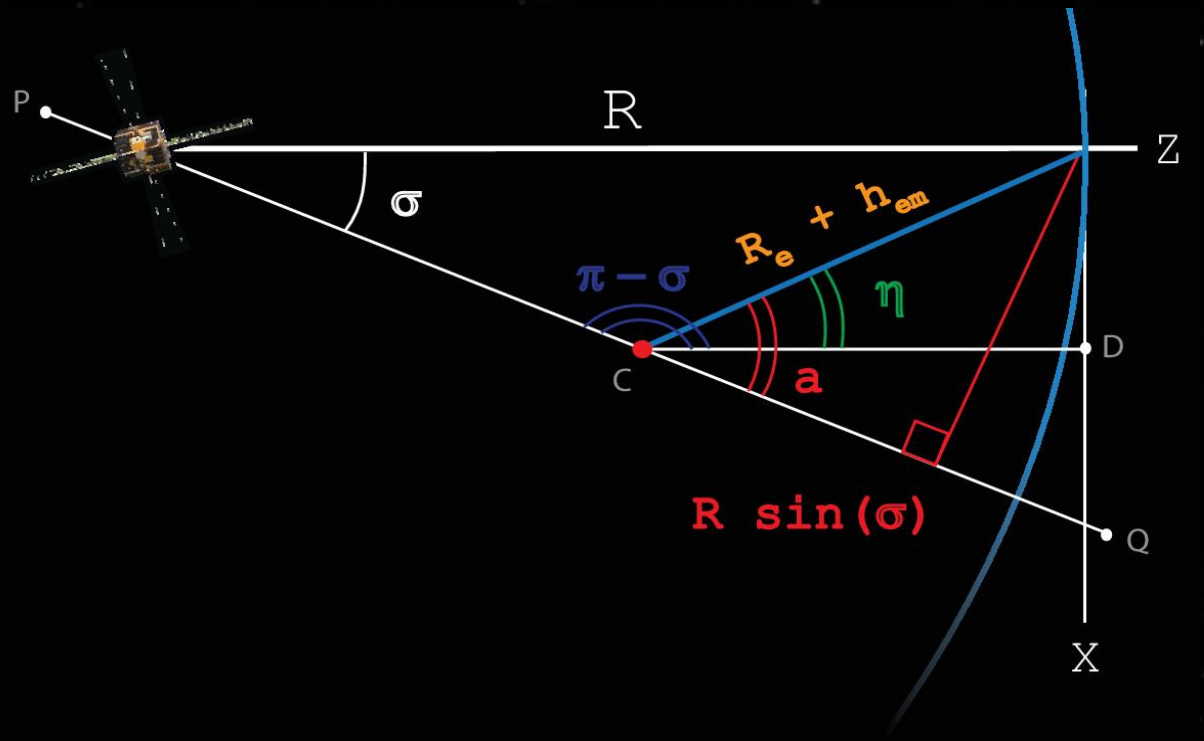






Data Analysis – Initial Points Collection





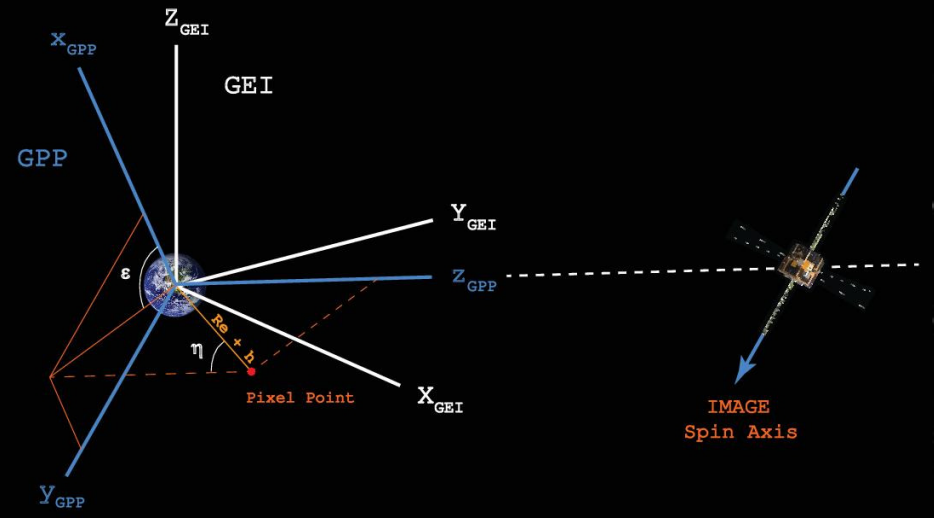
$$\eta = [\pi - sigma] - \left[\pi - \sin^{-1}\left(\frac{R \cdot \sin[sigma]}{R_e + h}\right)\right]$$

$$\varepsilon = \tan^{-1}(az\_sample / el\_sample)$$

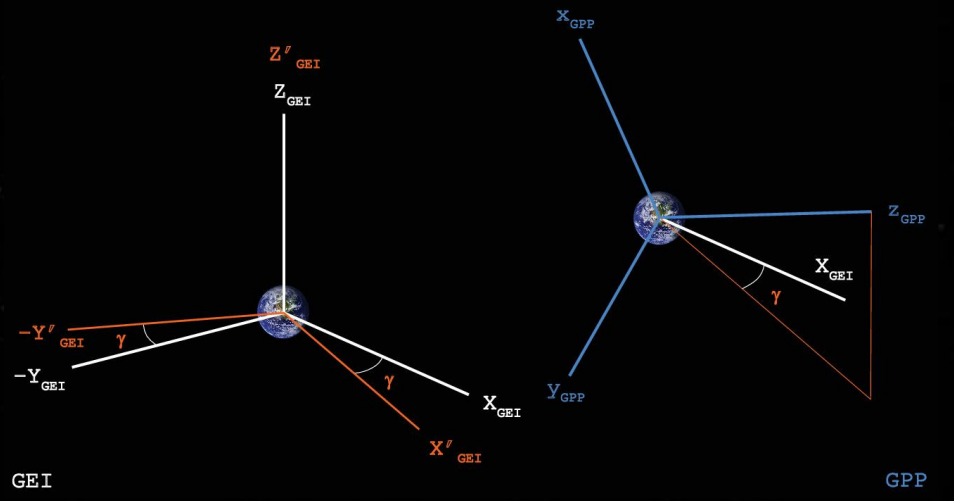
$$Pixel = [sin\eta \cdot (R_e + h)cos\varepsilon \quad sin\eta \cdot (R_e + h)sin\varepsilon \quad cos\eta(R_e + h)]$$

Data Analysis – Initial Points Collection

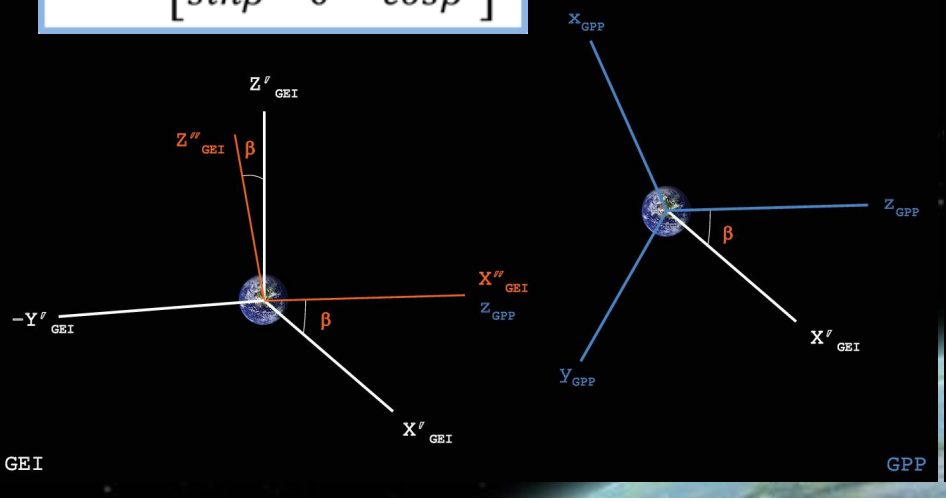
Rotation matrix



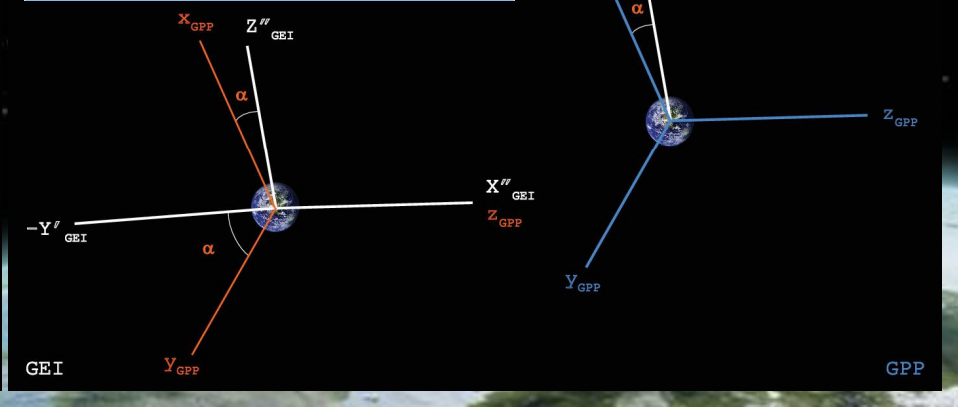
$$R^1 = \begin{bmatrix} cos\gamma & sin\gamma & 0 \\ -sin\gamma & cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



$$R^2 = \begin{bmatrix} cos\beta & 0 & -sin\beta \\ 0 & 1 & 0 \\ sin\beta & 0 & cos\beta \end{bmatrix}$$



$$R^3 = \begin{bmatrix} cos\alpha & sin\alpha & 0 \\ -sin\alpha & cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



Data Analysis – Post Processor

- Only consider points within R_e+h:

$$\lambda = \sin^{-1}\left({Z_{sm}}/{[R_e + h]}\right)$$

$$L = {(R_e + h)}\Big/{cos^2(\lambda)}$$

$$\Lambda = \cos^{-1}\left(\sqrt{{1}/{L}}\right)$$

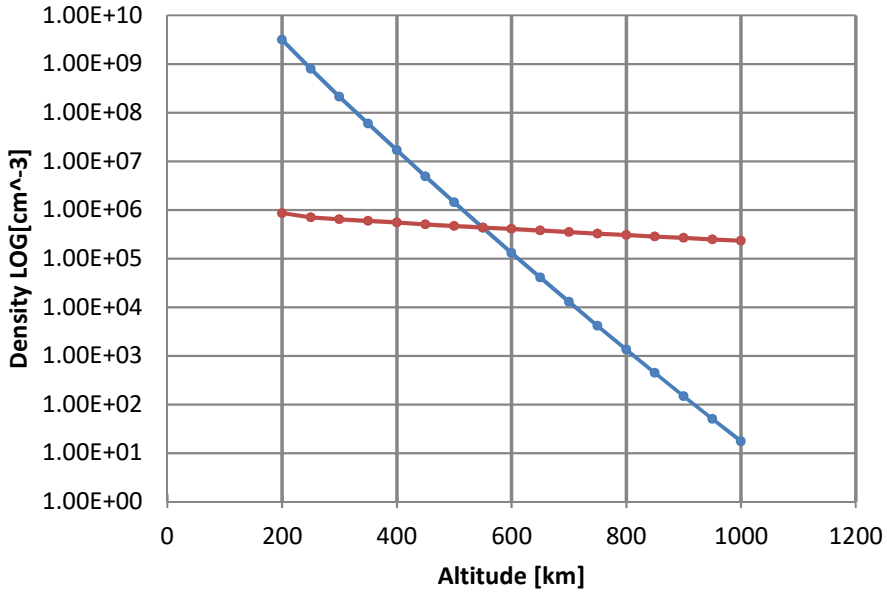
$$MLT = 12 + \left(\tan^{-1}\left({y_{sm}}/{x_{sm}}\right)/\pi\right) \times 12$$

$$\alpha = \cos^{-1}\left[\frac{\vec{v}_{ena} \cdot \vec{B}}{|\, v_{ena} \,||\, B \,|}\right]$$

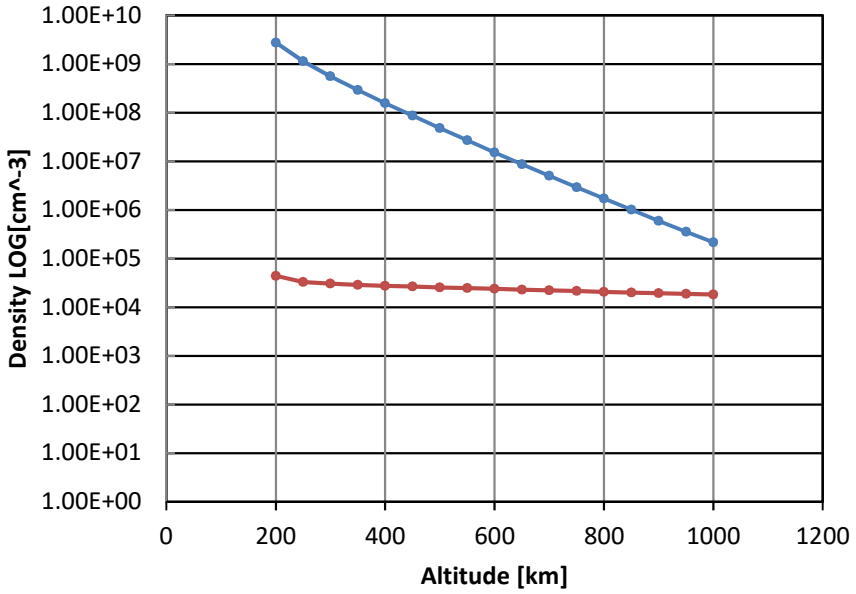
- Final data: min/max/mean/median of valid points / pixel
- Fold Southern hemisphere into Northern

Short Aside: What is h in Re+h?

Solar Min (Jan 1 2007) F10.7=50



Solar Max (June 1 2000) F10.7=350

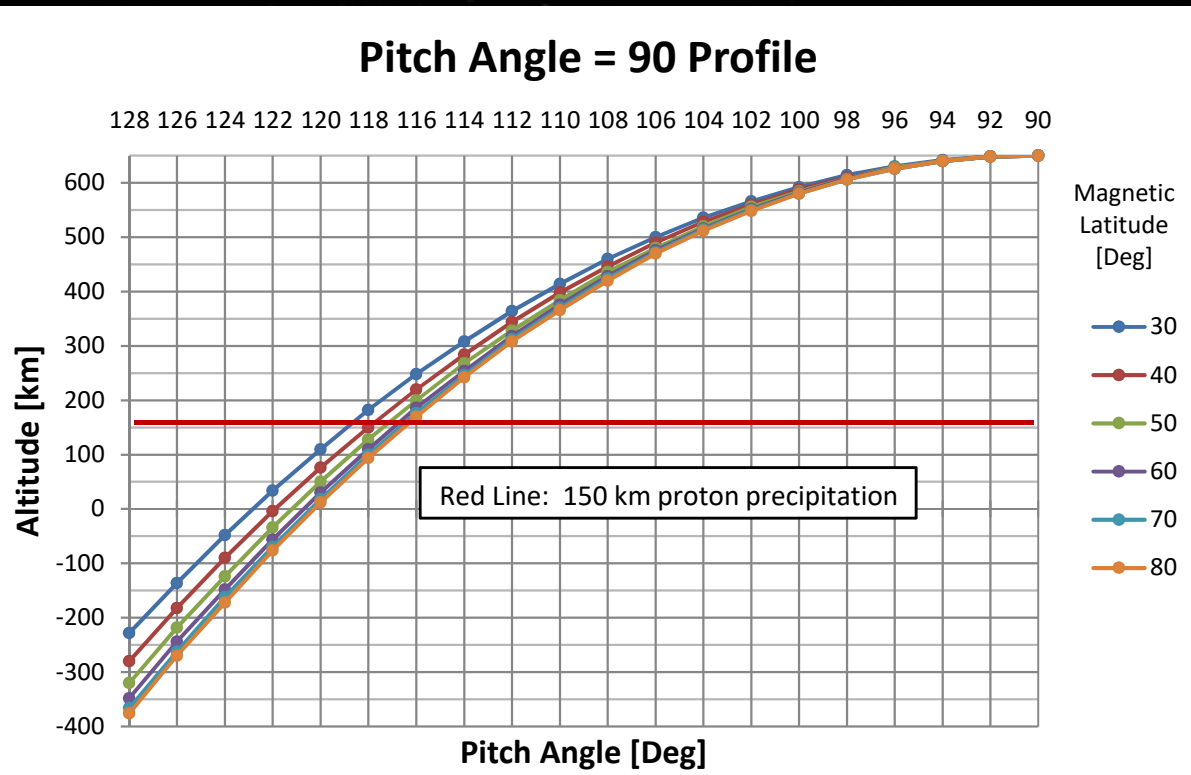


Oxygen

Hydrogen

Data Analysis – Post Processor

Only keep points that could have a mirror point above 150 km



The pitch angle at the given altitude and L shell

$\frac{sin^2\alpha_2}{sin^2\alpha_1} = \frac{B_2}{B_1}$ α_2 is the top pitch angle (given)

$\frac{sin^2\alpha_2}{B_2} B_1 = sin^2\alpha_1$

Simple dipole magnetic field:

$B = \frac{B_o}{R^3}[1 + 3sin^2\lambda]^{1/2}$ $\lambda \equiv$ magnetic latitude

$\lambda = cos^{-1}\left({}^{r}/_{L}\right)^{1/2}$ r is in Re

So given a λ, compute the L at 650 km. Follow the same L down to the mirror point

$$\sin^{-1}\left[\frac{sin^2\alpha_2}{(6370+h)^3[1+3sin^2\lambda]^{1/2}}(6370+650)^3\left[1+3sin^2\left(cos^{-1}\left[\frac{(R_e+h)}{R_eL}\right]^{1/2}\right)\right]^{1/2}\right]^{1/2} = \alpha_1$$

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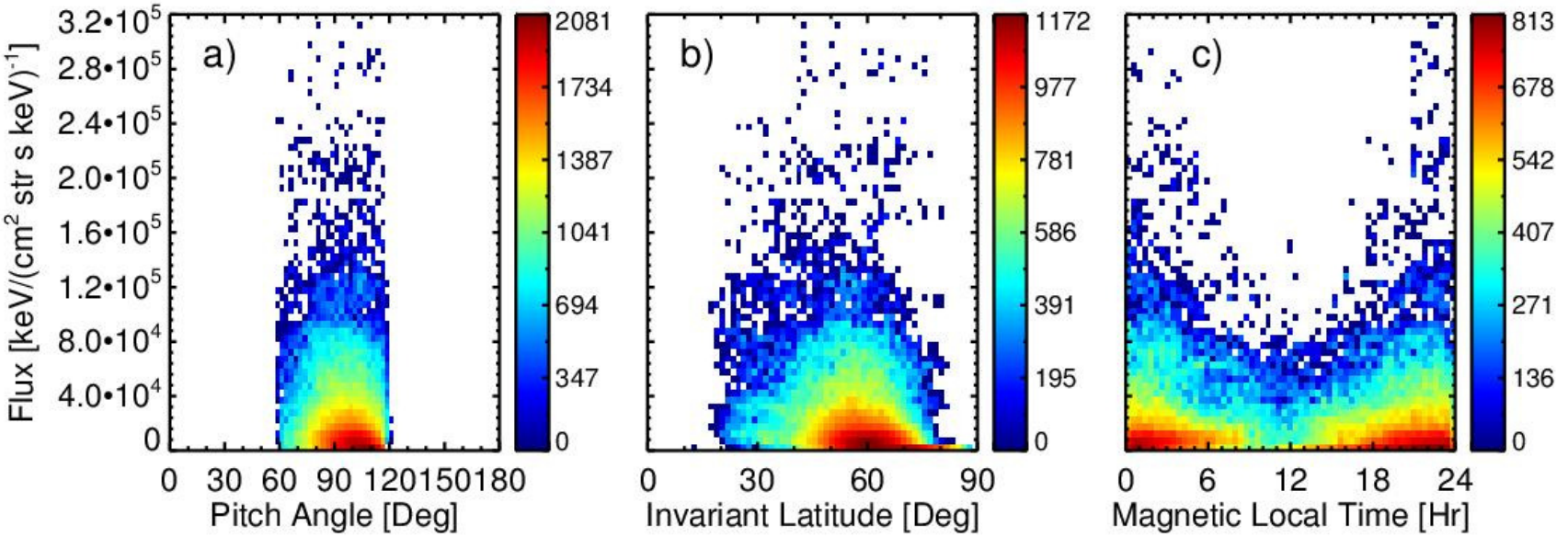
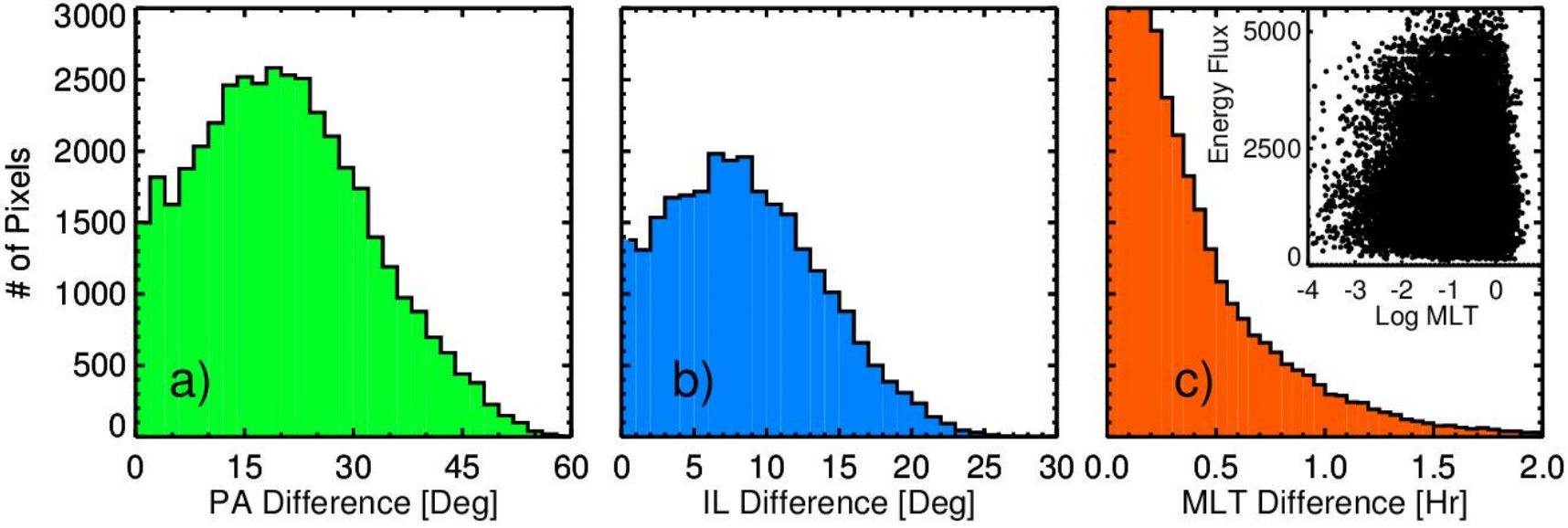
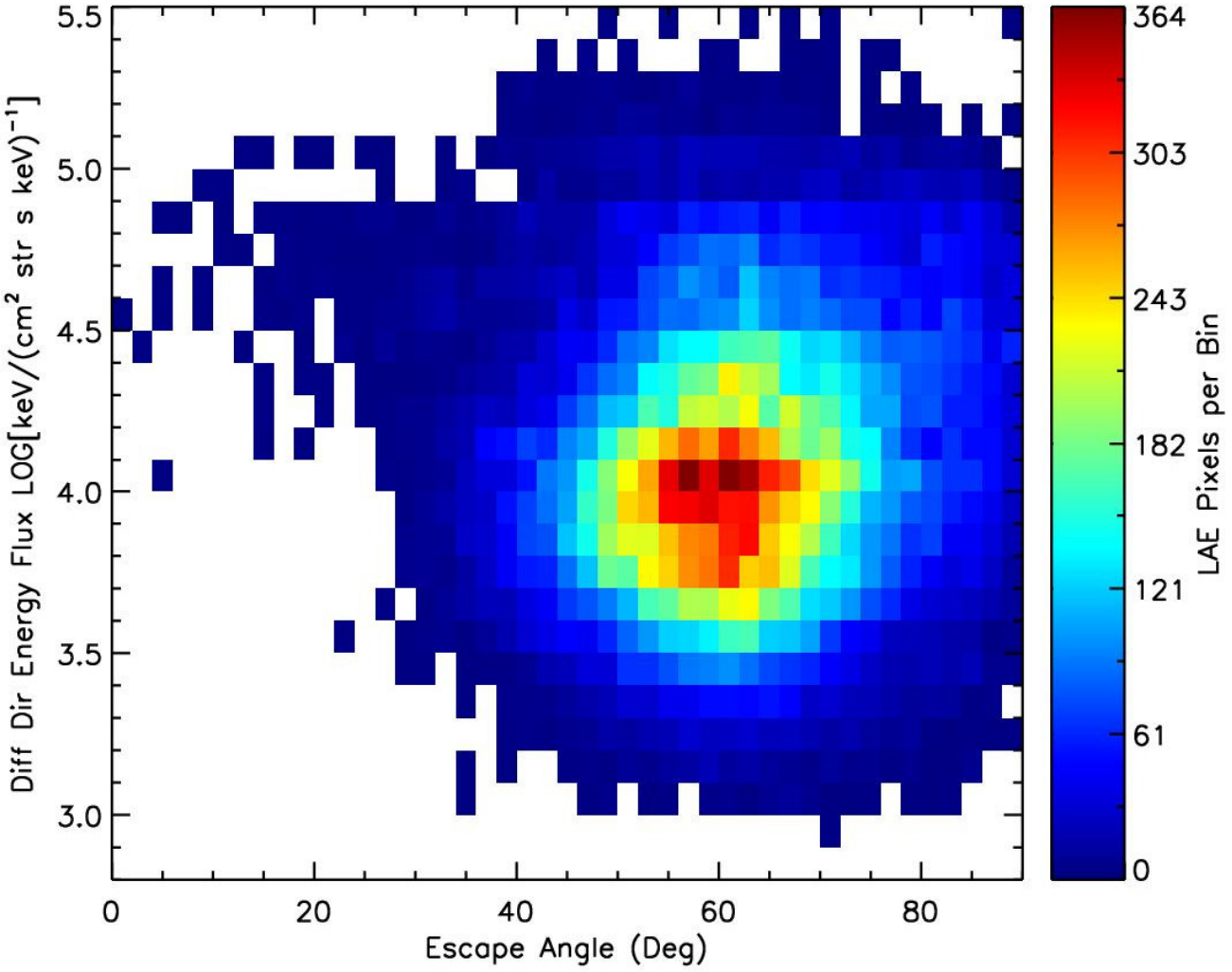
All LAE Pixels 2000 - 2005

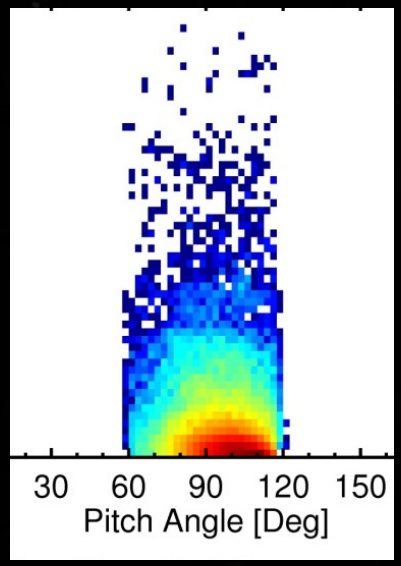




All LAE Pixels 2000 - 2005

Escape Angle





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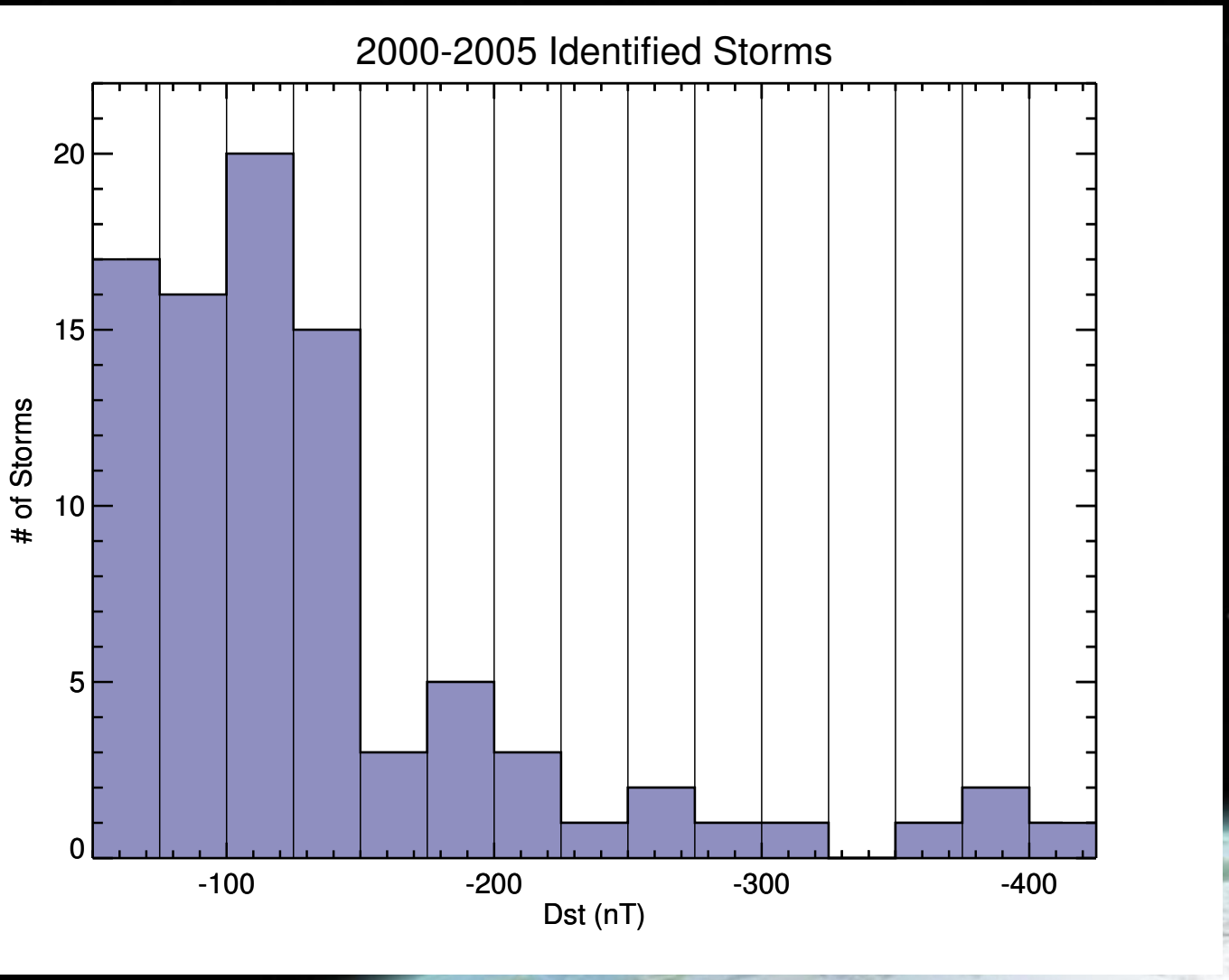
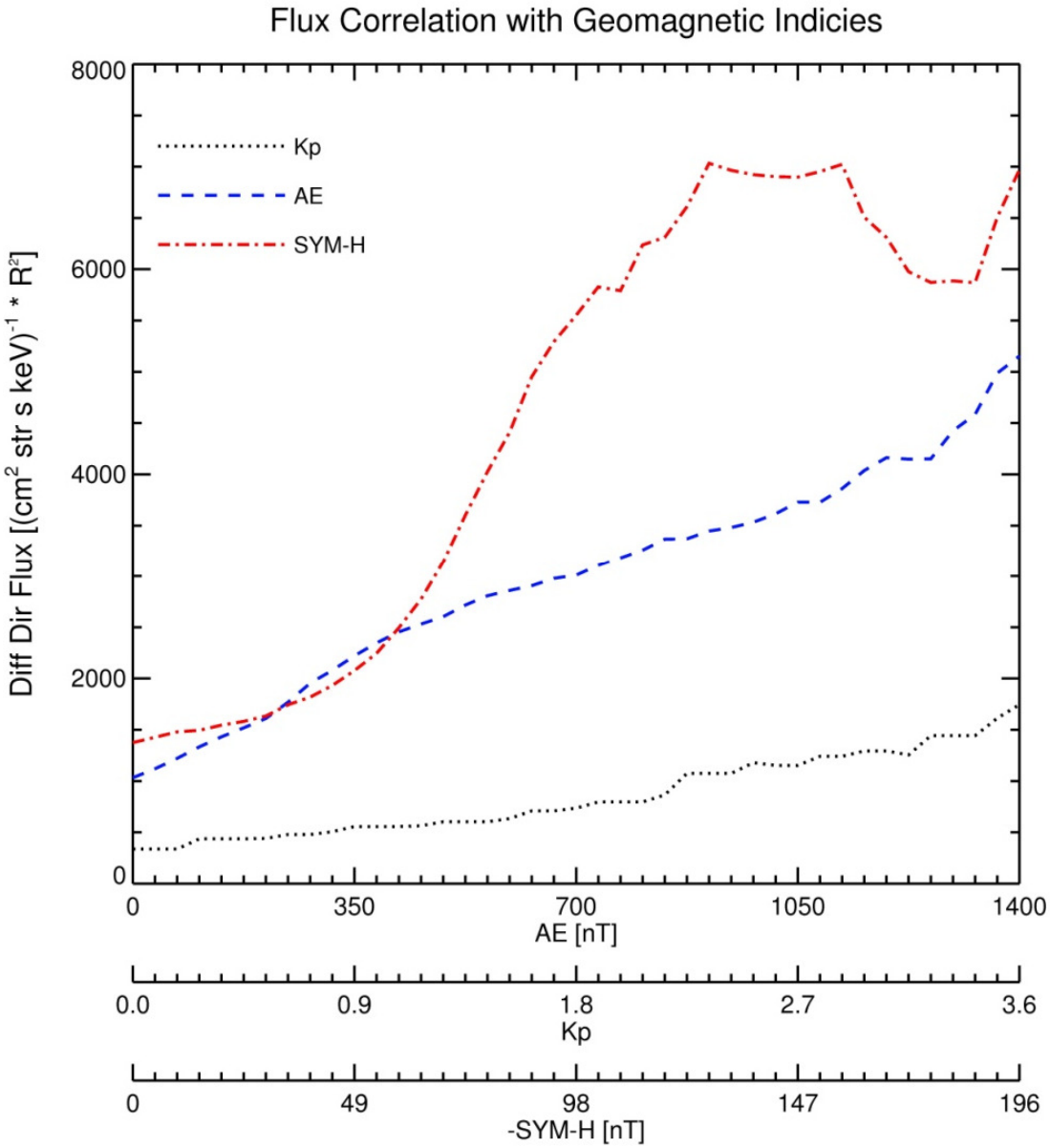
Quick Aside – Storm List

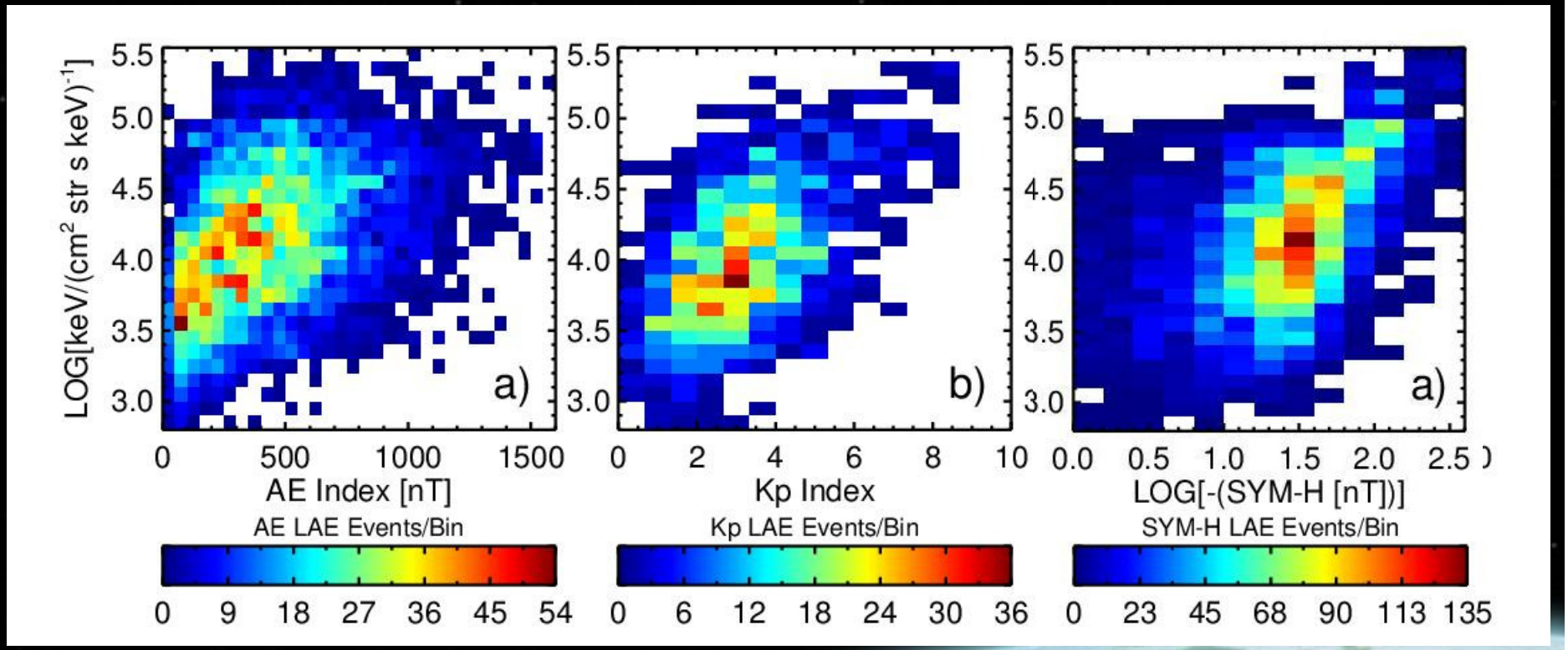


Flux Trendline

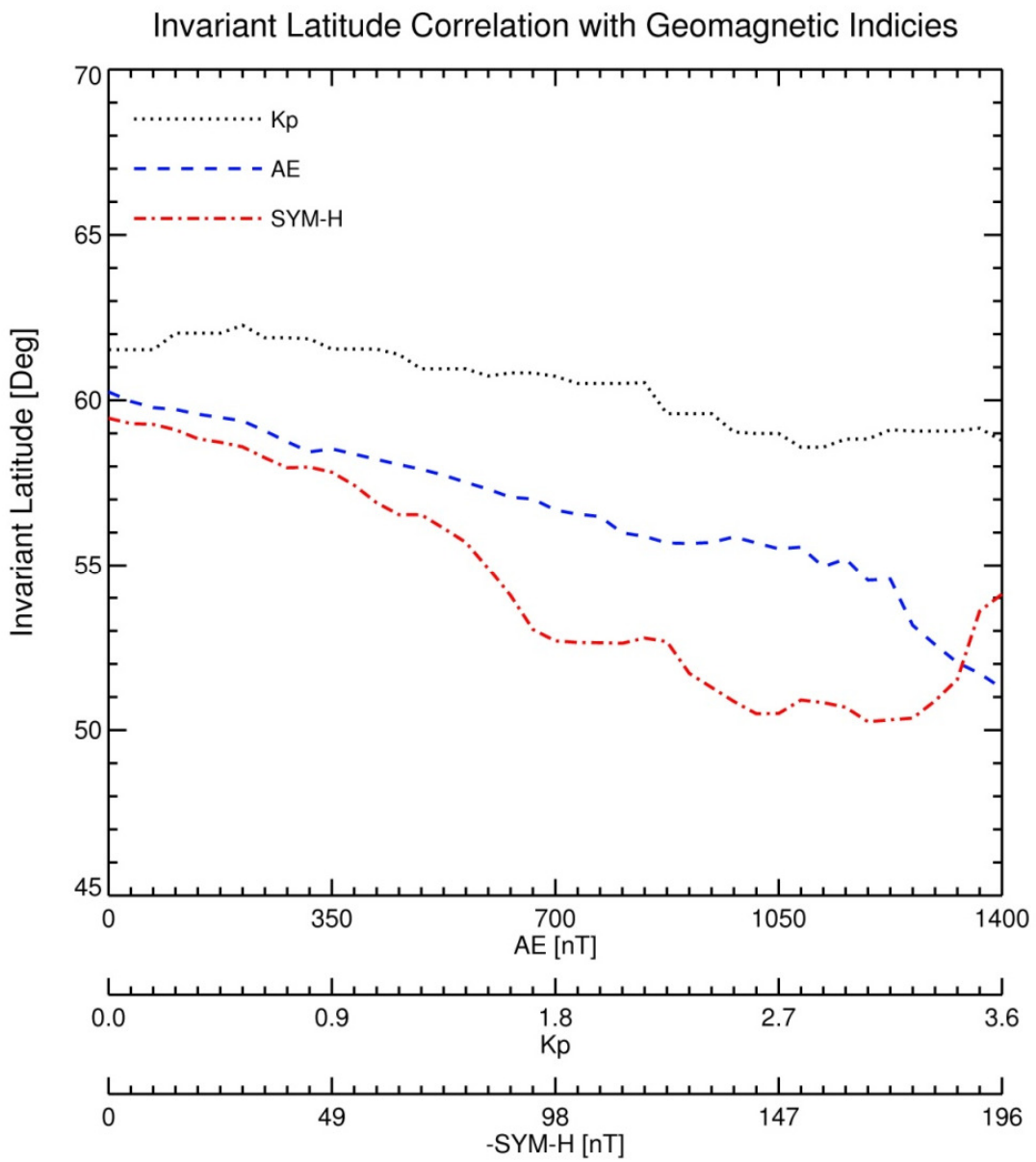


Flux Correlation

PCC: 0.388 [15%] 0.564 [32%] 0.531 [28%]

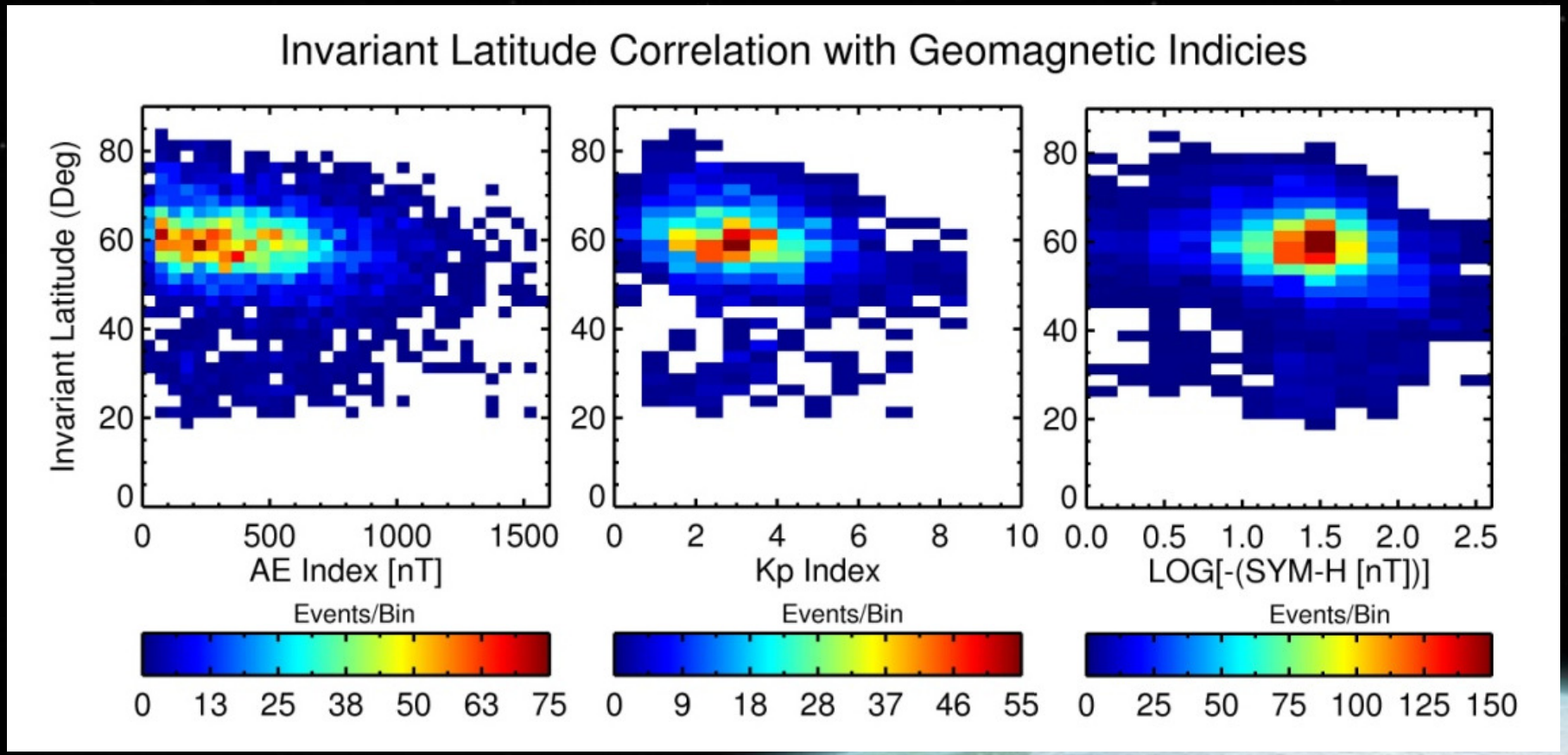


Invariant Latitude Trendline

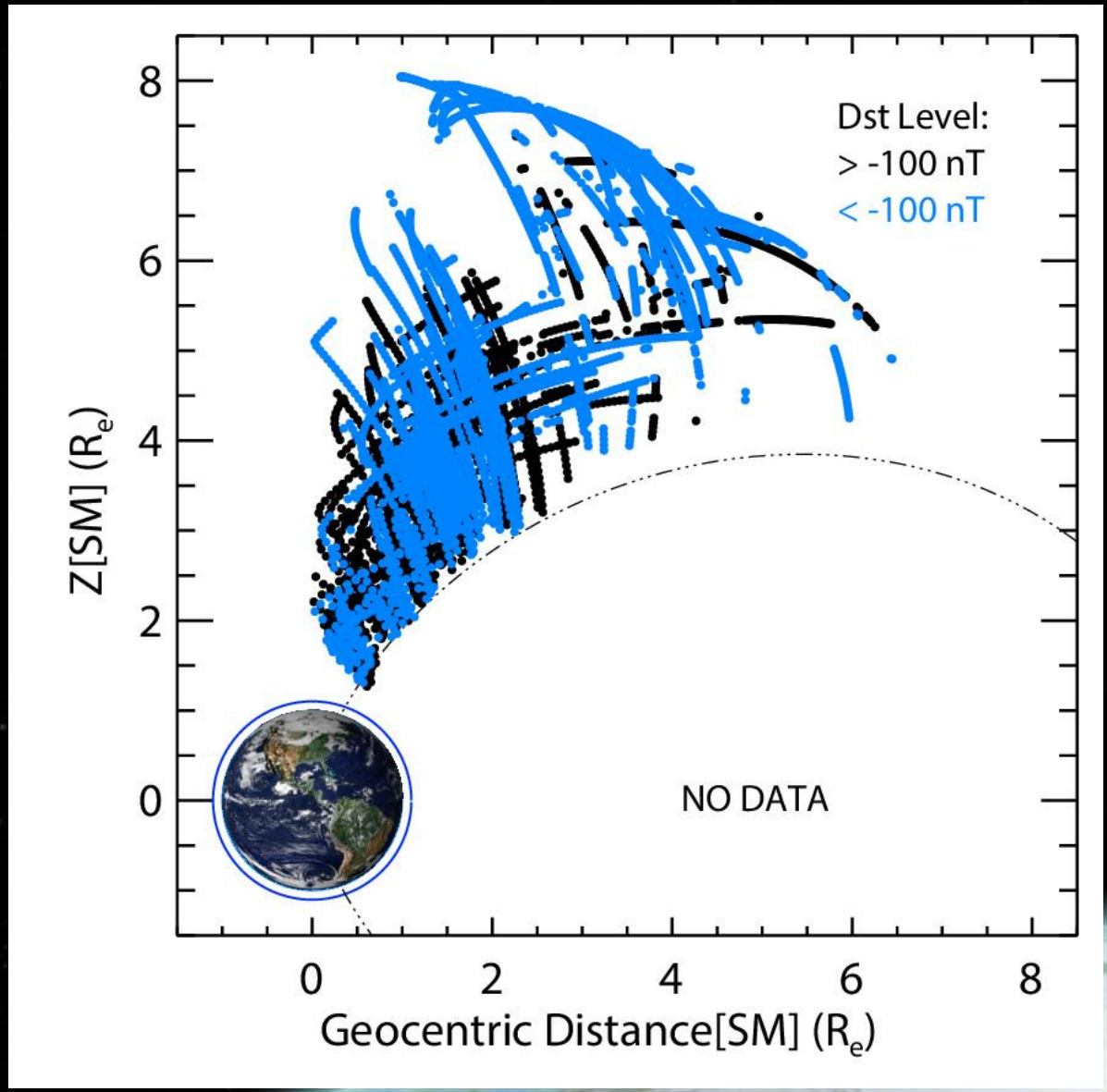


Invariant Latitude Correlation

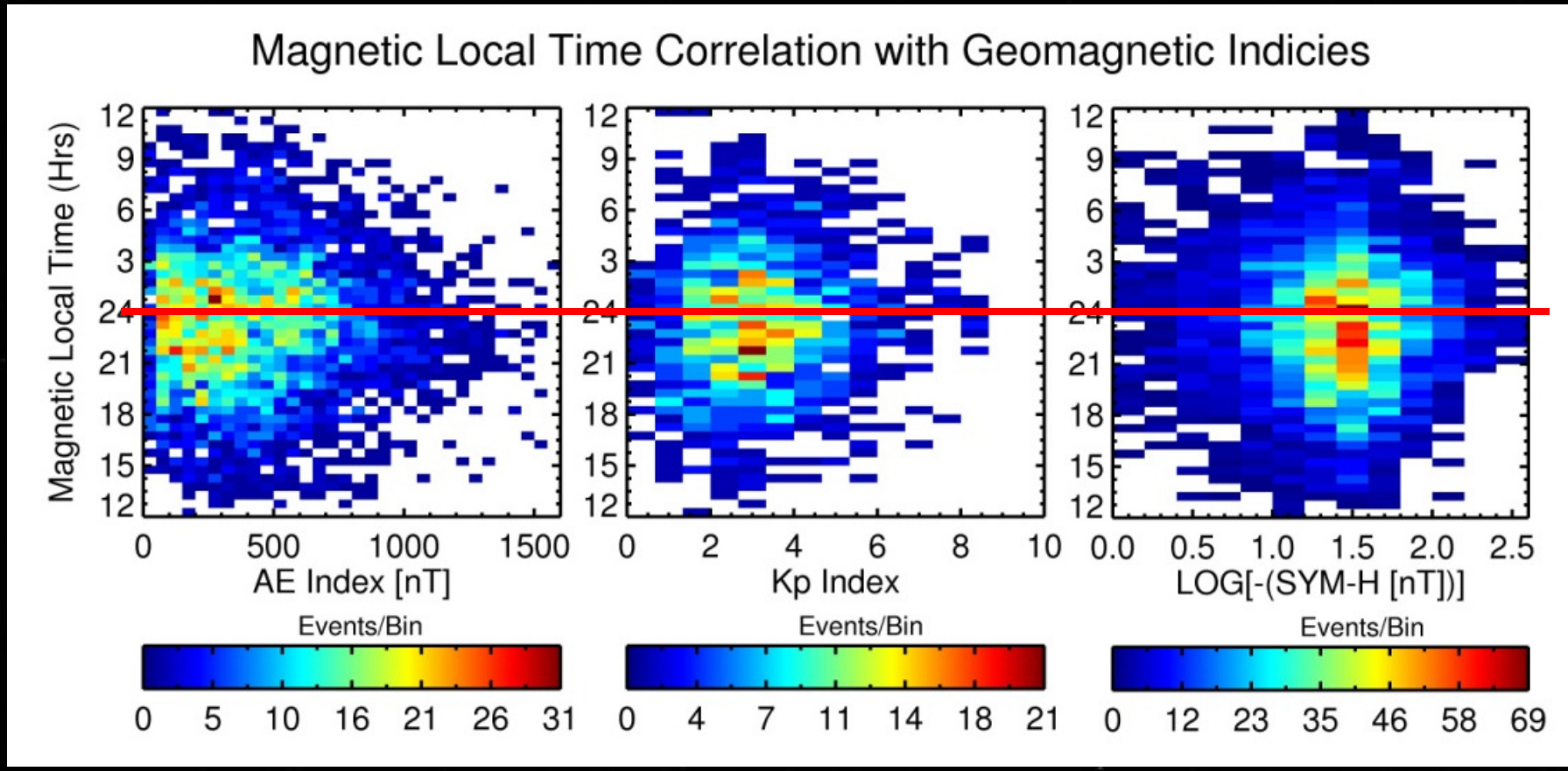
PCC: -0.186 [3.5%] -0.207 [4.3%] -0.209 [4.4%]



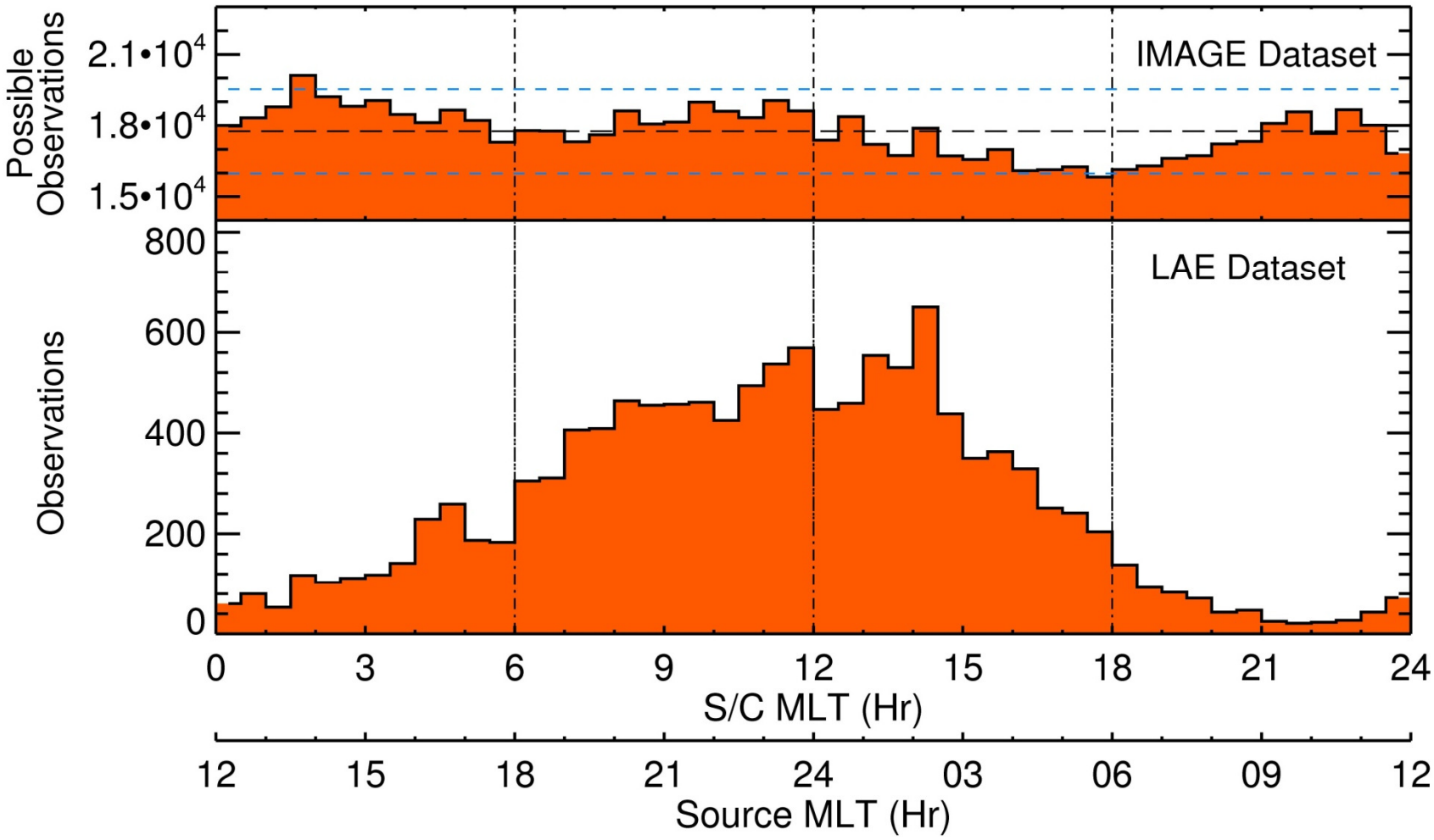
Invariant Latitude Sampling – Bias?



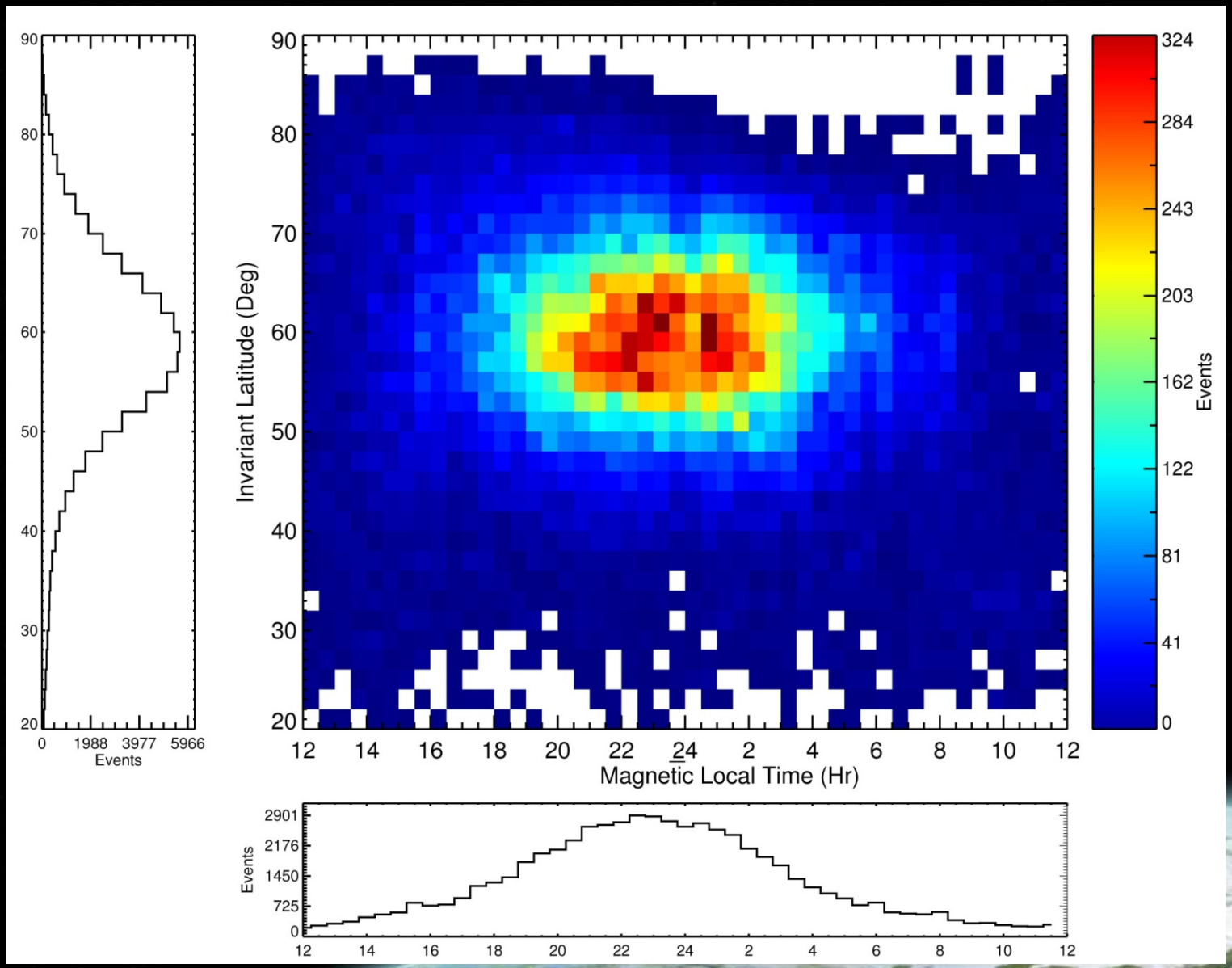
Magnetic Local Time Correlation



MLT Sampling – Bias?



MLT / IL Correlation



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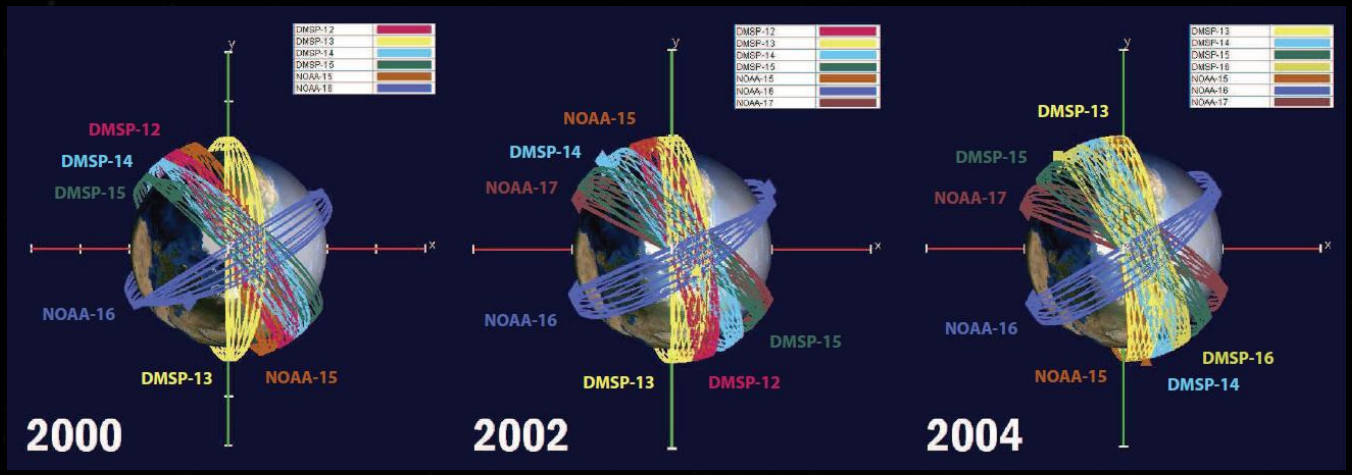
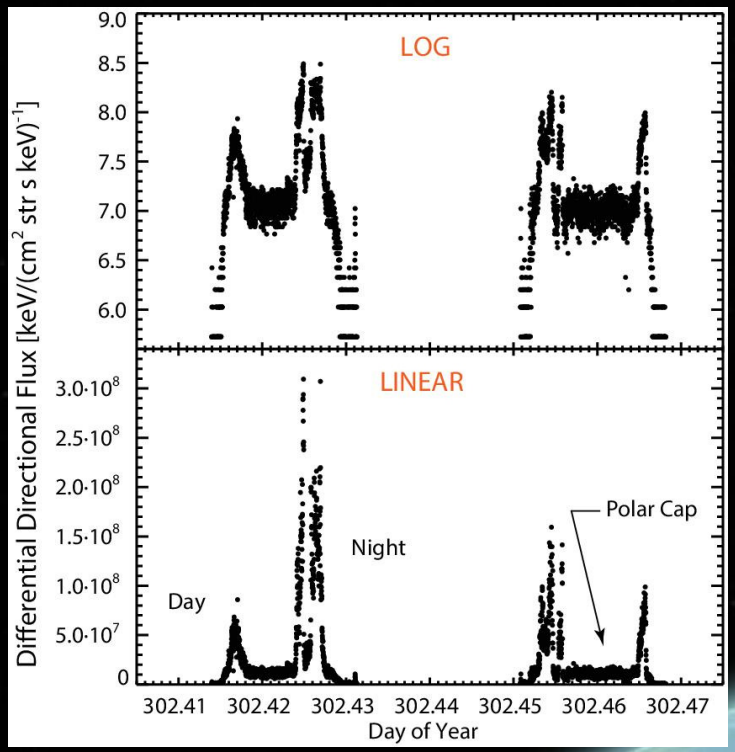
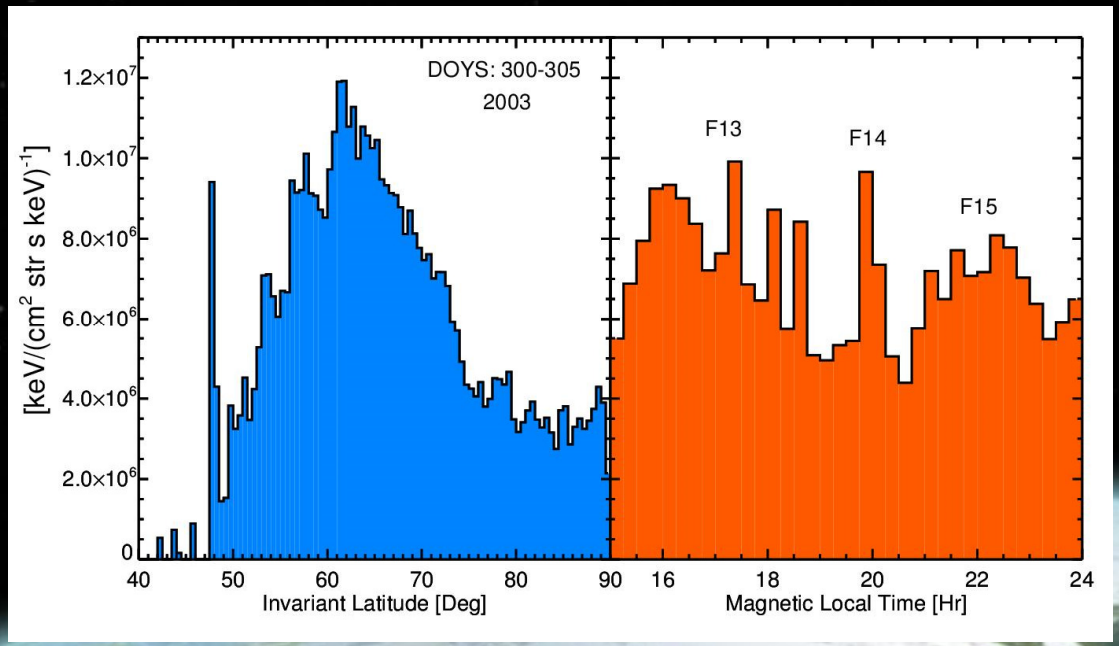
In-Situ Ion Data

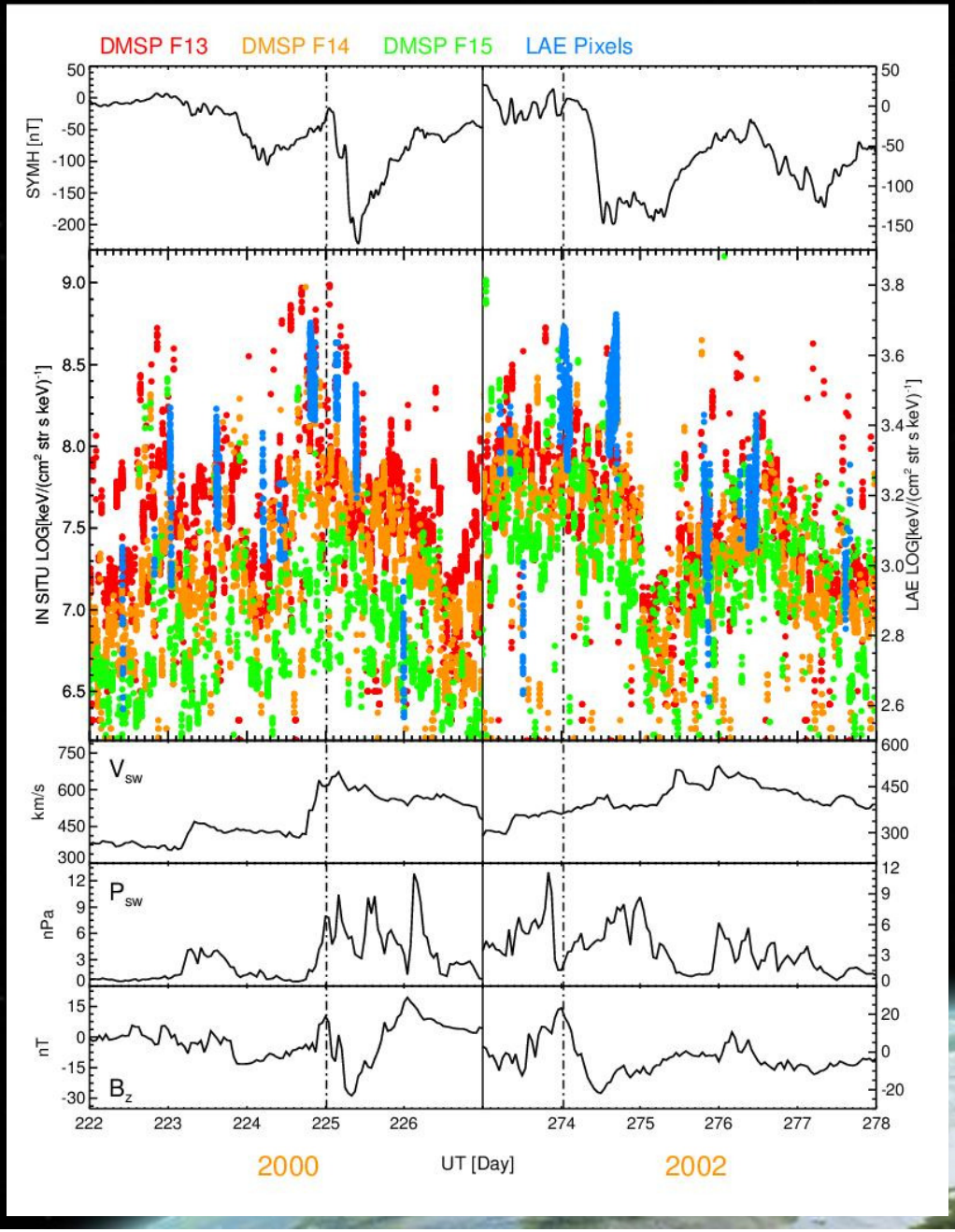
Source: DMSP SSJ/4 2000-2005



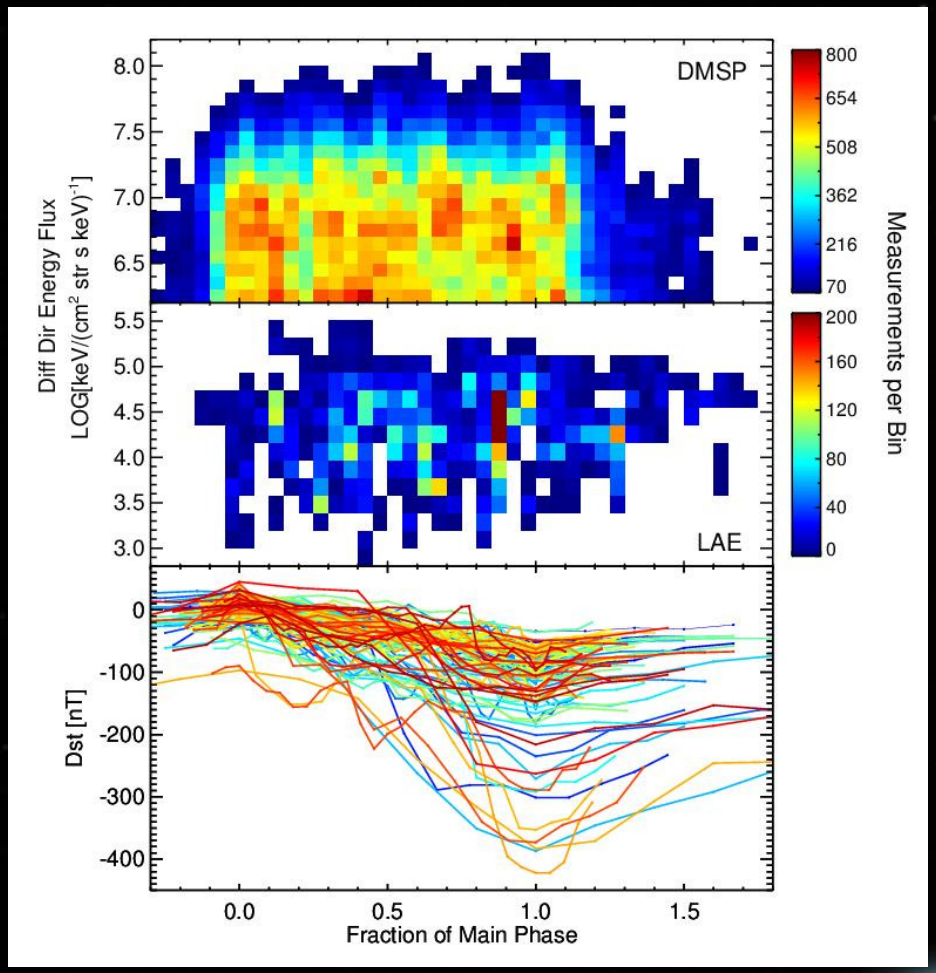


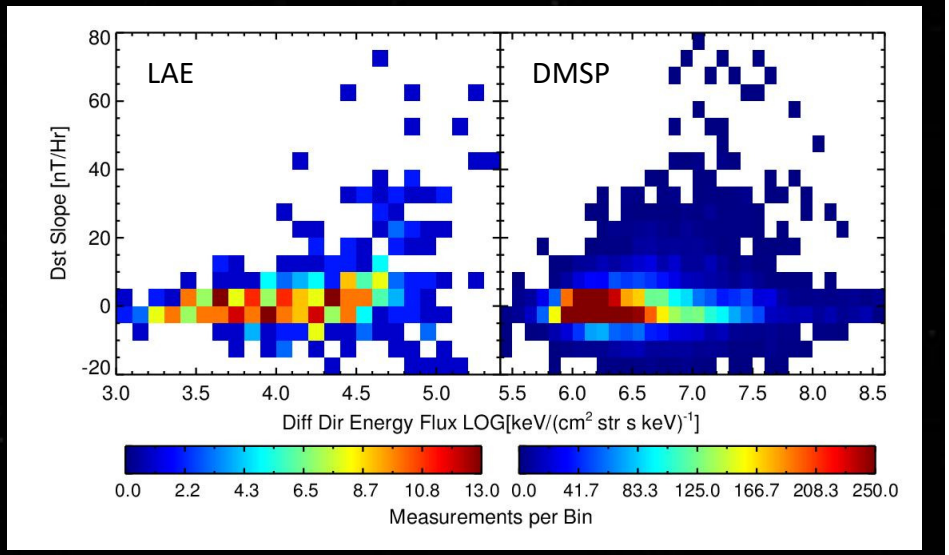


Sample Storm Response

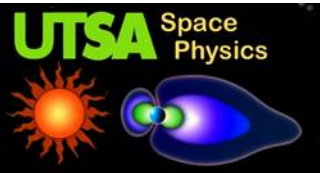


Sample Storm Response





- Geomagnetic Parameters:
  - Dst [SYM-H] Magnitude
  - Slope



- Objective / Merits of the Study
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- Results
  - LAE Geomagnetic Index Correlation
  - LAE/In Situ Response to Storms
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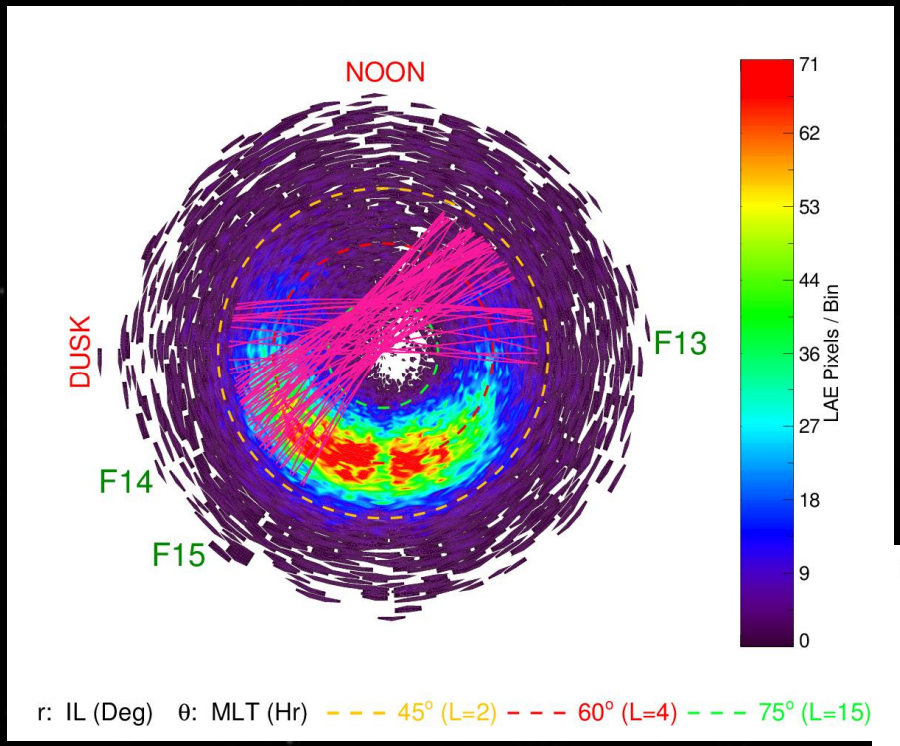
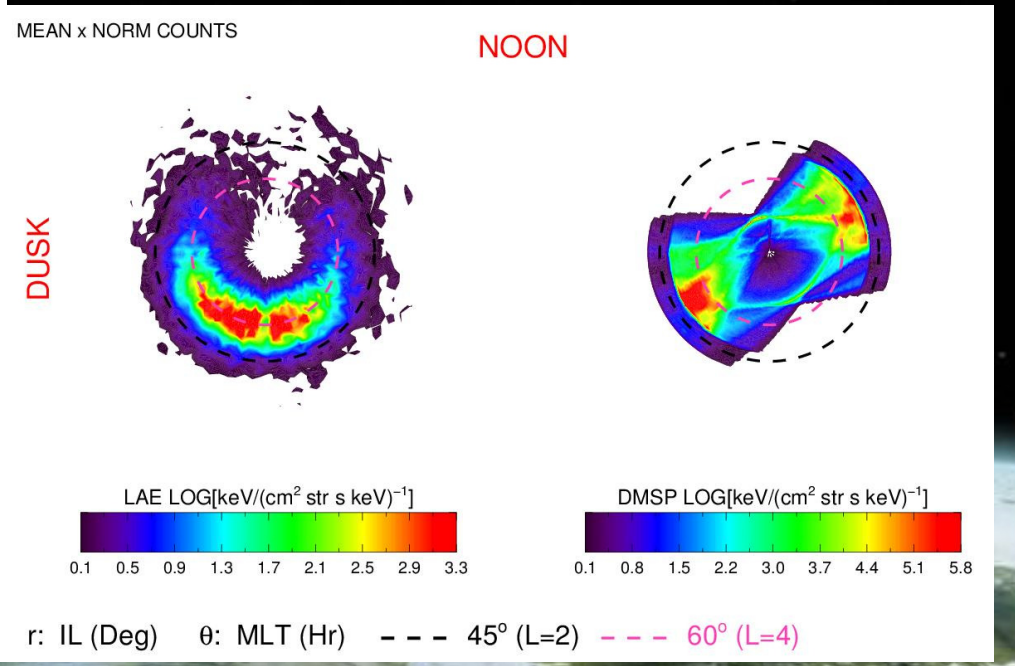
LAE / In Situ Correlation



- Southern hemisphere added to Northern hemisphere (equals)
- Bin size
  - IL: 2.5°[LAE] 0.7° [DMSP]
  - MLT: 0.25 Hr

Magenta: DMSP passes

- Bin size
  - IL: 0.7°
  - MLT: 0.25 Hr



Flux – Flux Correlation

Binned +/- 1 min to LAE pixel

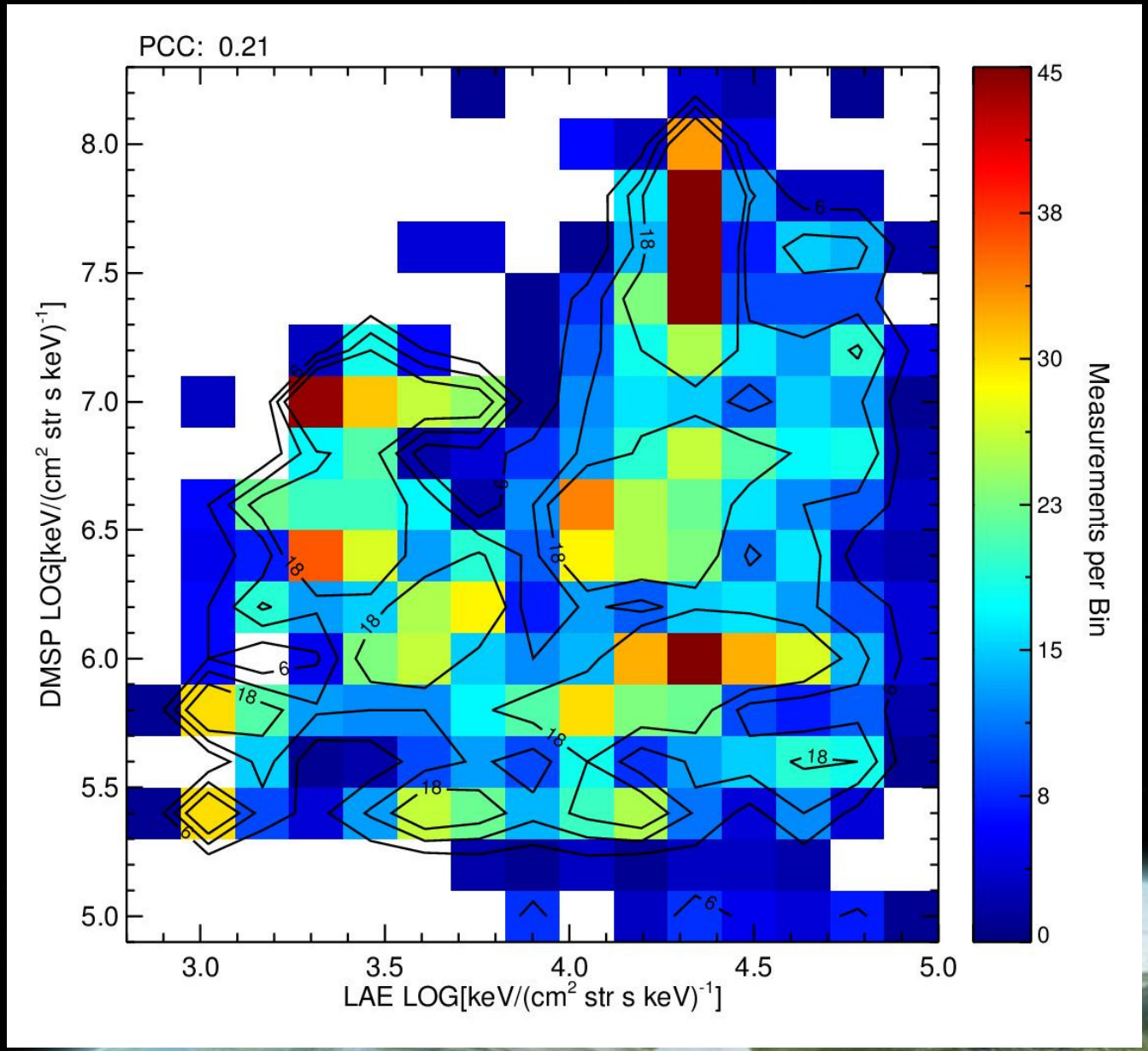
Flux Bin Size

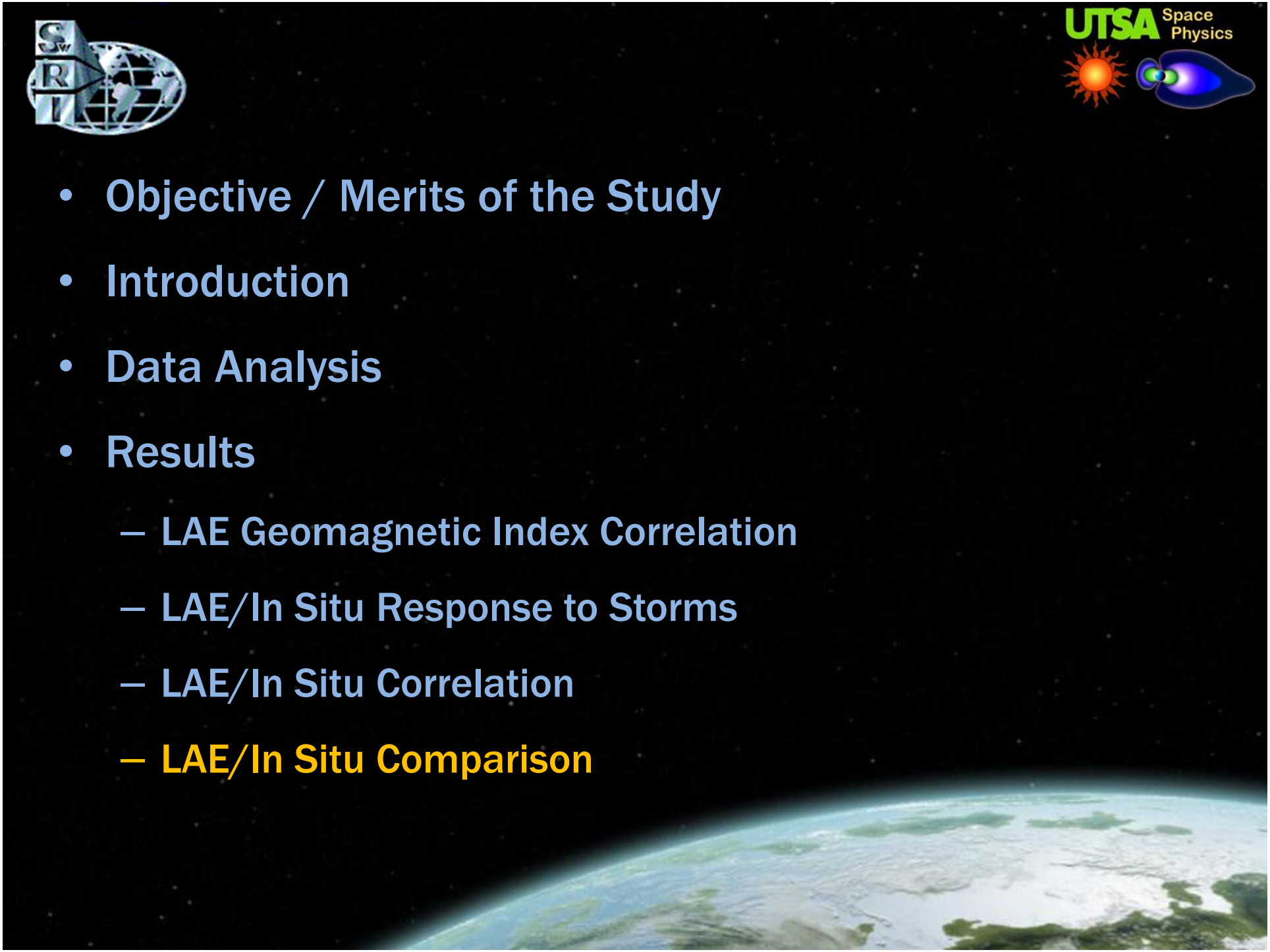
- LAE: 1.5
- DMSP: 2.0

Contours [6, 12, 18]

Not well correlated

- 4.4% of variability is related





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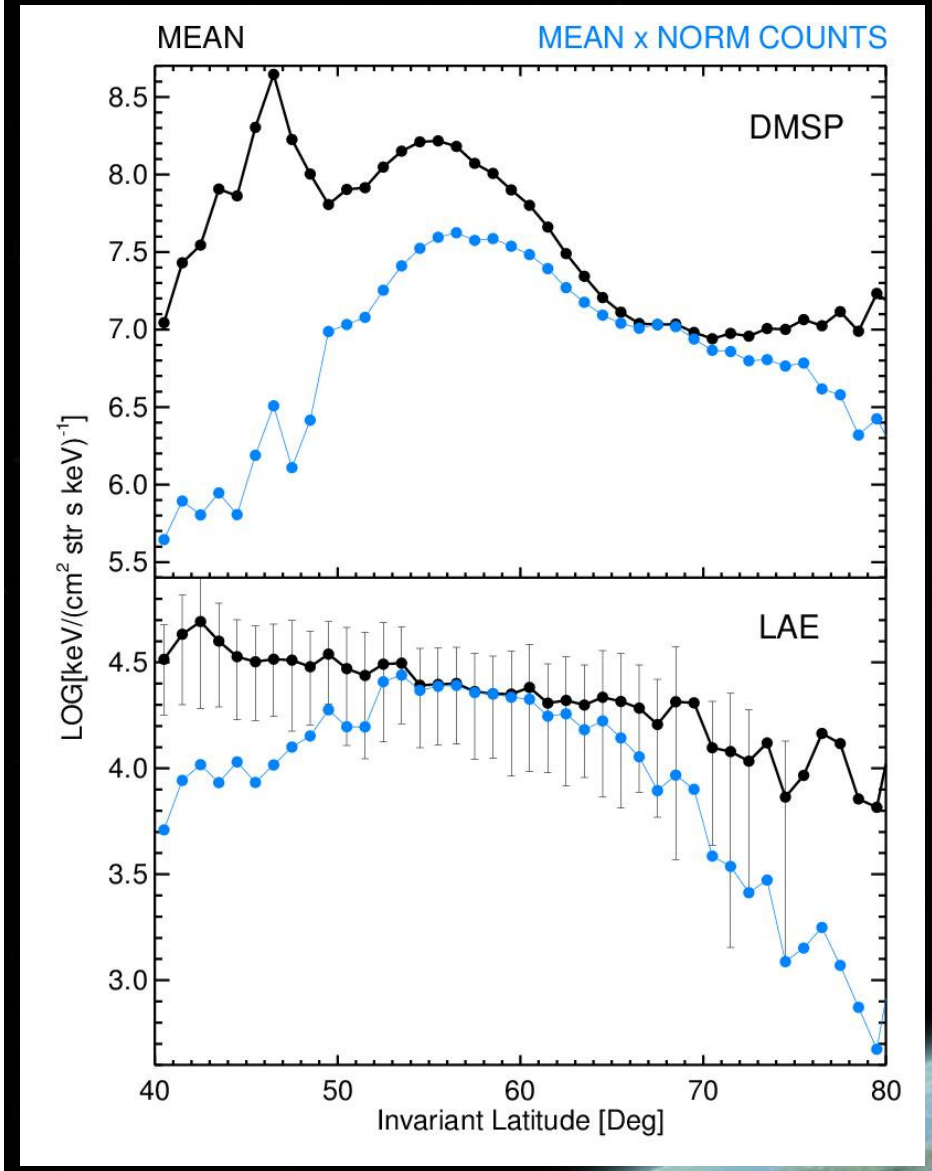
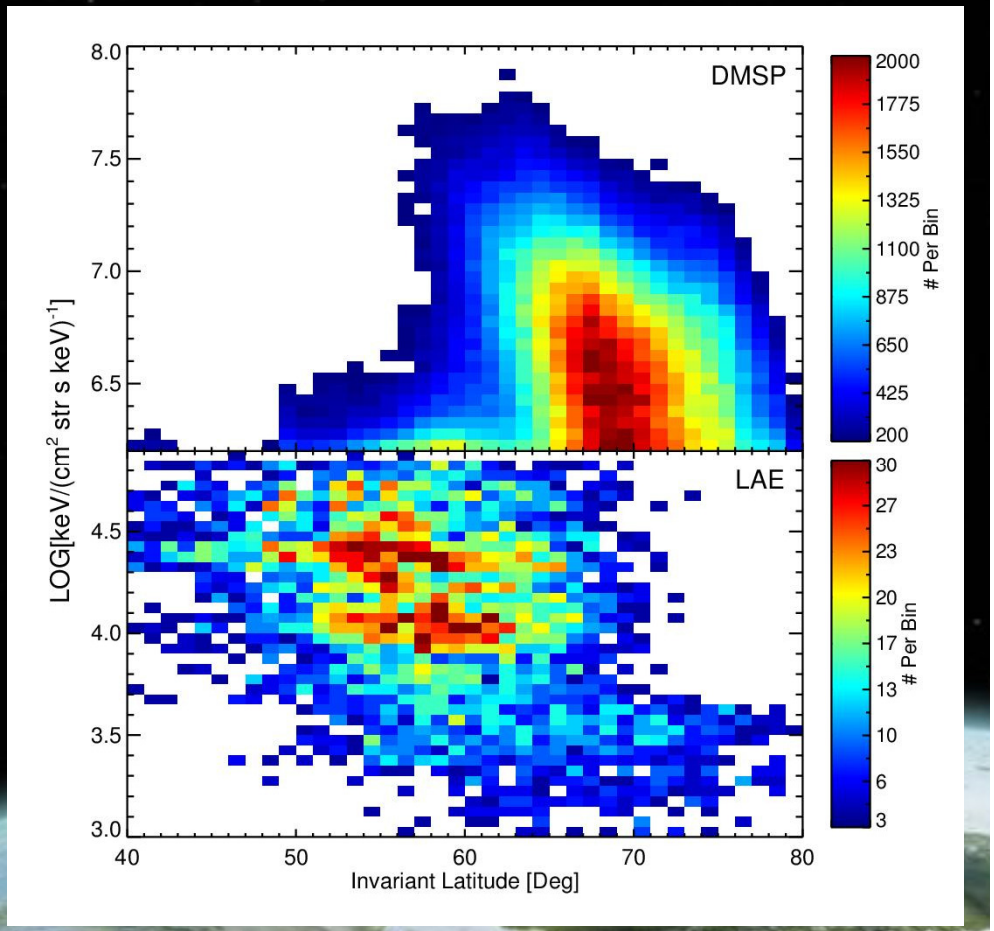
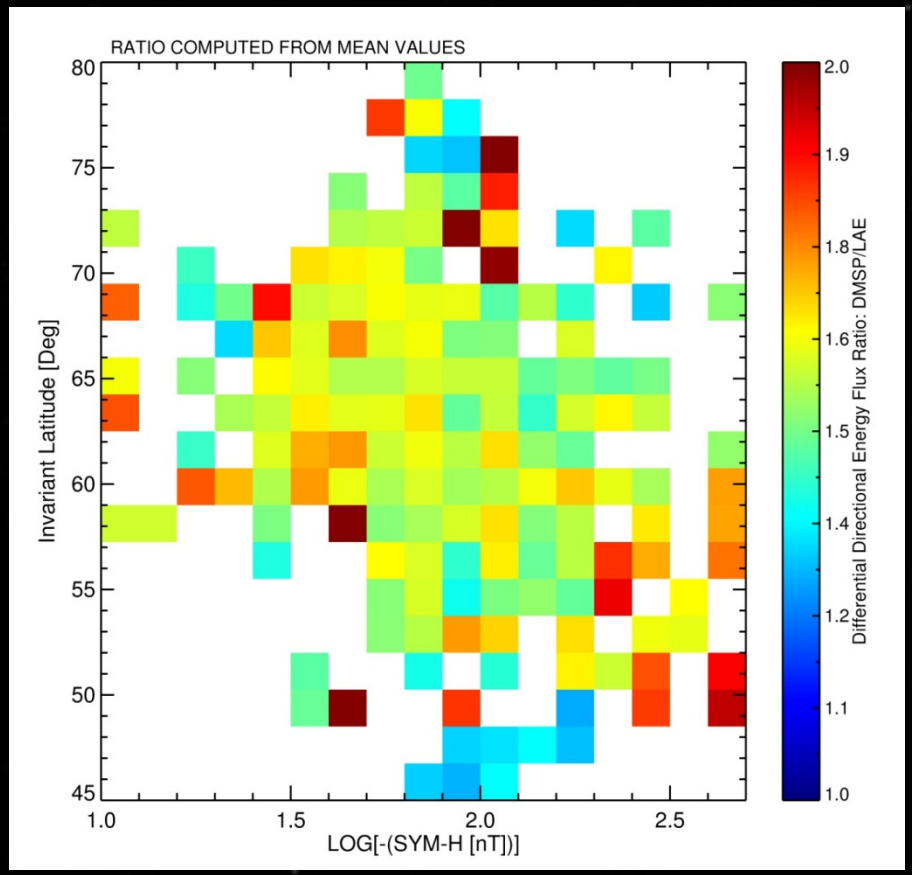
Diff Dir Energy Flux as a Function of IL

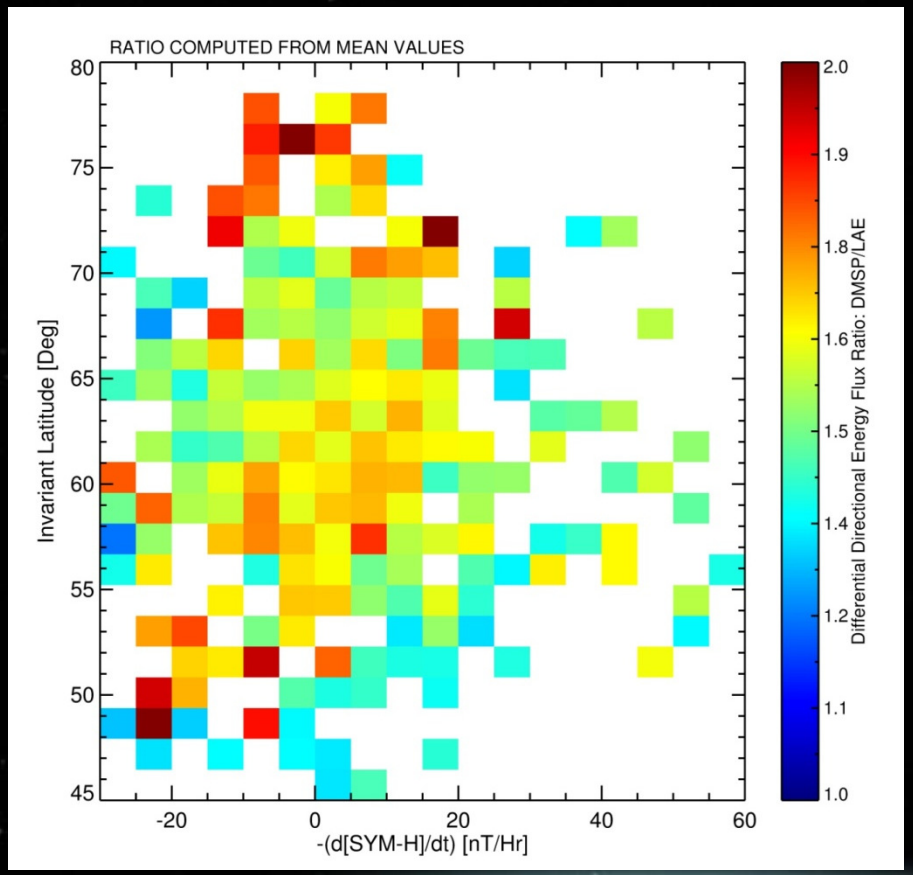




LAE / In Situ Comparisons

Ratio of the LOG Diff Dir Energy Flux





Correlation Study Conclusions

LAE Geomagnetic Correlation

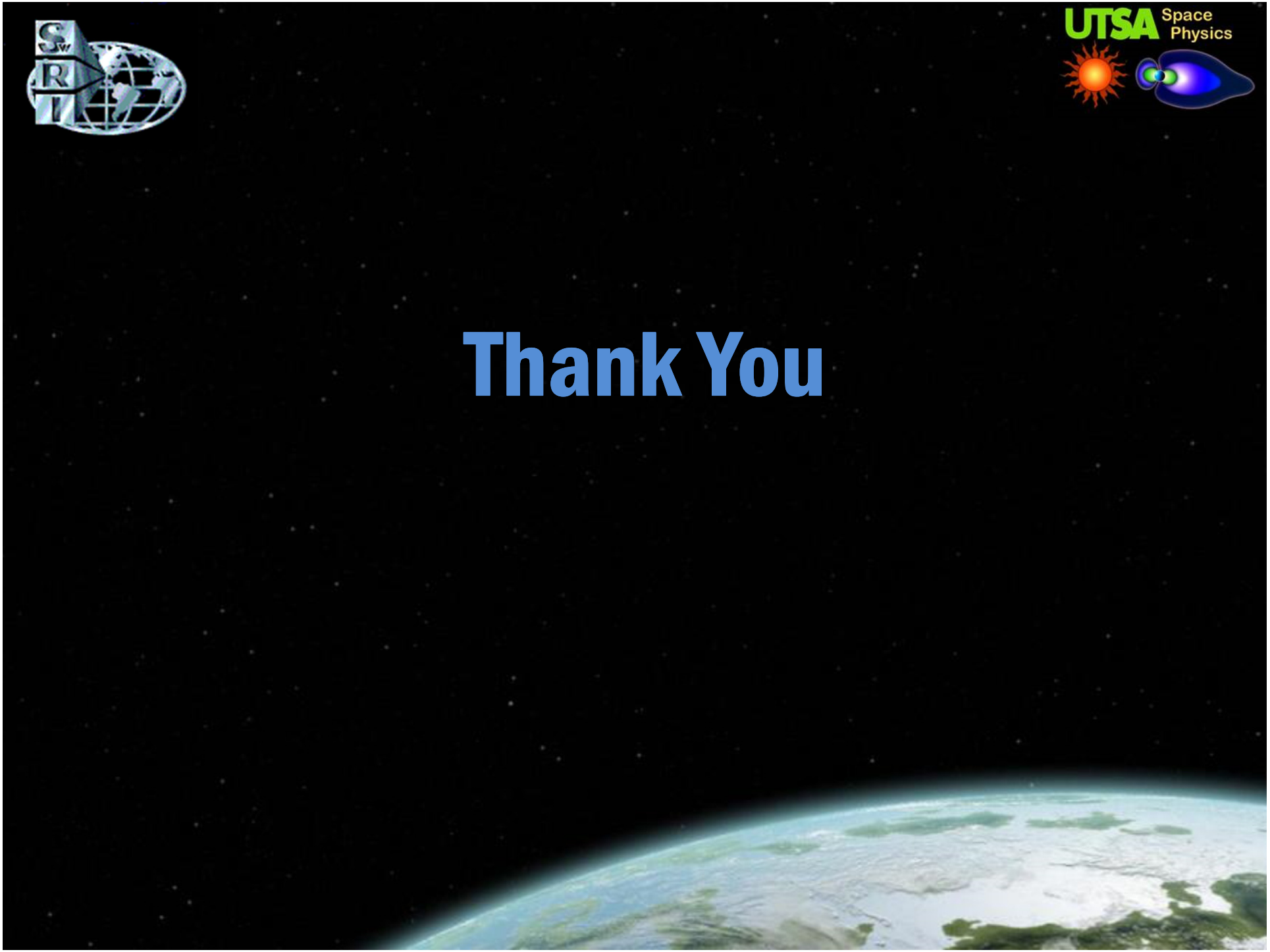
- Response of LAE flux to SYM-H is the most sensitive (rapid change)
- The Invariant Latitude of LAEs decreases (lower L-Shell) with increasing geomagnetic activity
- NOT ring current particles (too low in energy) – BUT shows an association with ring current activity
- Plasma population is most consistent to what is observed from the plasma sheet
- Invariant latitude uncertainty is not too large

Can be used for storm time studies to access ion precipitation

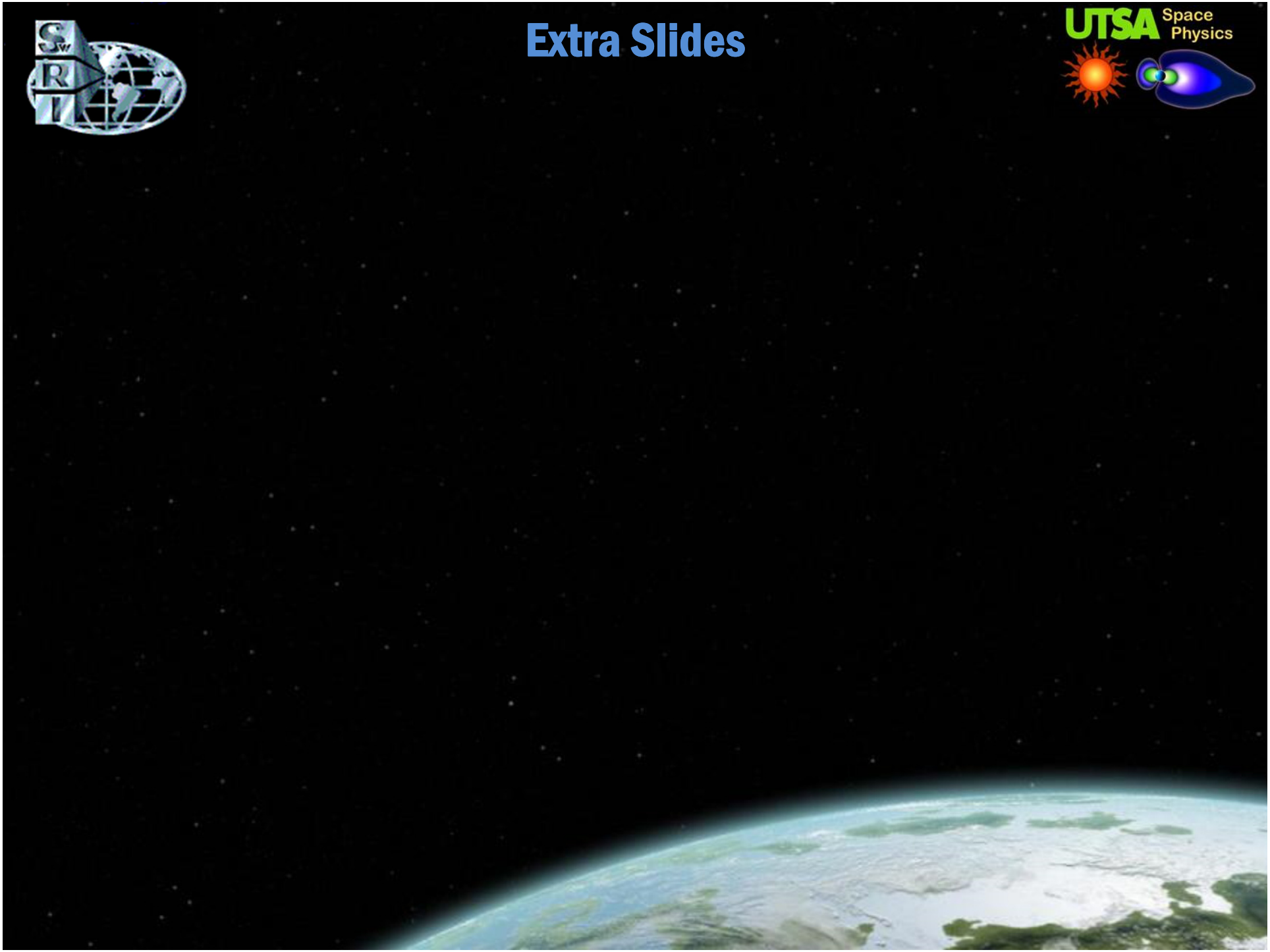
Correlation Study Conclusions

LAE DMSP Comparison

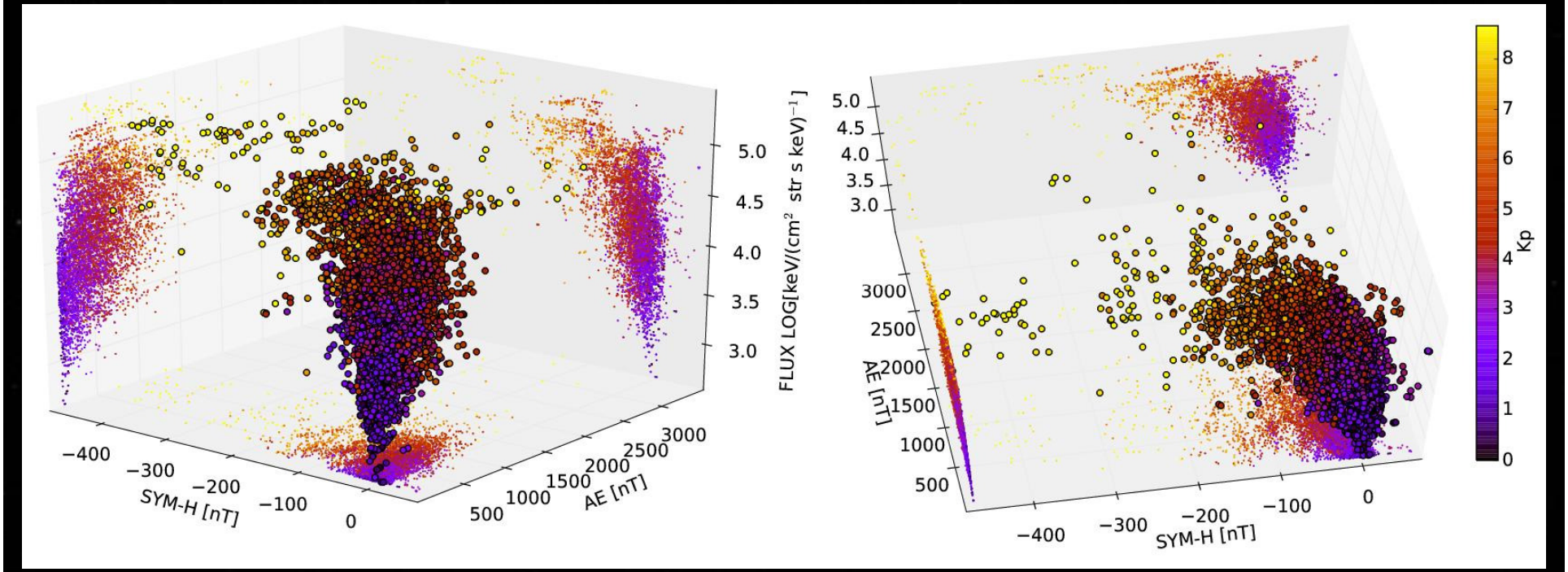
- DMSP orbit is too limited to evaluate large scale MLT dependence in flux
- Both LAE and DMSP respond similarly to geomagnetic activity, immediately increasing after beginning of main phase and ceasing shortly after end of main phase
- No Flux-Flux correlation evident
  - Spatial restrictions, Different physical processes
- IL distributions differ
  - LAE is more spread out and slightly lower
- Ratio of flux is fairly constant over geomagnetic activity
  - Possible exception of LAEs favored at higher flux, lower latitude
  - IL differences also evident in ratio


Thank You

Extra Slides



Multivariate Correlation



Multivarient Correlation Coefficient: 0.584 [34%]

Altitude Systematic Error

az_sample: 6°
el_sample: 7.5°
σ = 9.6°

$$\eta = [\pi - sigma] - \left[\pi - \sin^{-1}\left(\frac{R \cdot \sin[sigma]}{R_e + h}\right)\right]$$

$$\varepsilon = \tan^{-1}(az\_sample / el\_sample)$$

$$Pixel = [sin\eta \cdot (R_e + h)cos\varepsilon \quad sin\eta \cdot (R_e + h)sin\varepsilon \quad cos\eta(R_e + h)]$$

h_1 = 400 km % Diff in r: 4.4%
h_2 = 700 km At 5 R_e(dist. corr.): 4.2%

$$\lambda = \sin^{-1}\left({}^{Z_{sm}}/_{[R_e + h]}\right)$$

r_1 = 6771 km (1.03 R_e)
r_2 = 7071 km (1.11 R_e)

λ_1 = 45.93°
λ_2 = 50.78°

$$L = {}^{(R_e + h)}/_{cos^2(\lambda)}$$

η_1 = 44.45°
η_2 = 39.10°

L_1 = 2.13
L_2 = 2.78

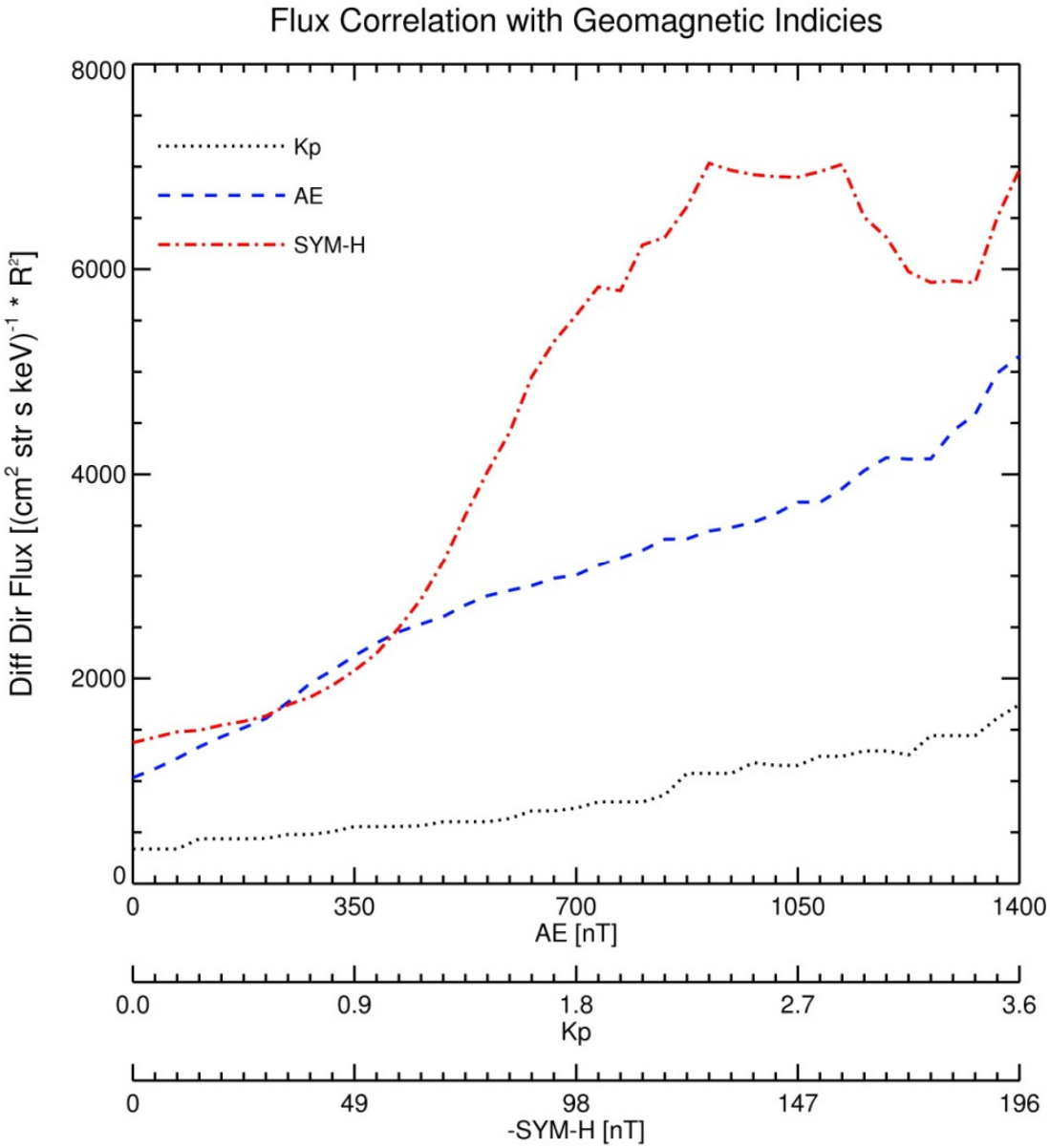
$$\Lambda = \cos^{-1}\left(\sqrt{{}^{1}/_{L}}\right)$$

$\varepsilon_{1,2}$ = 38.66

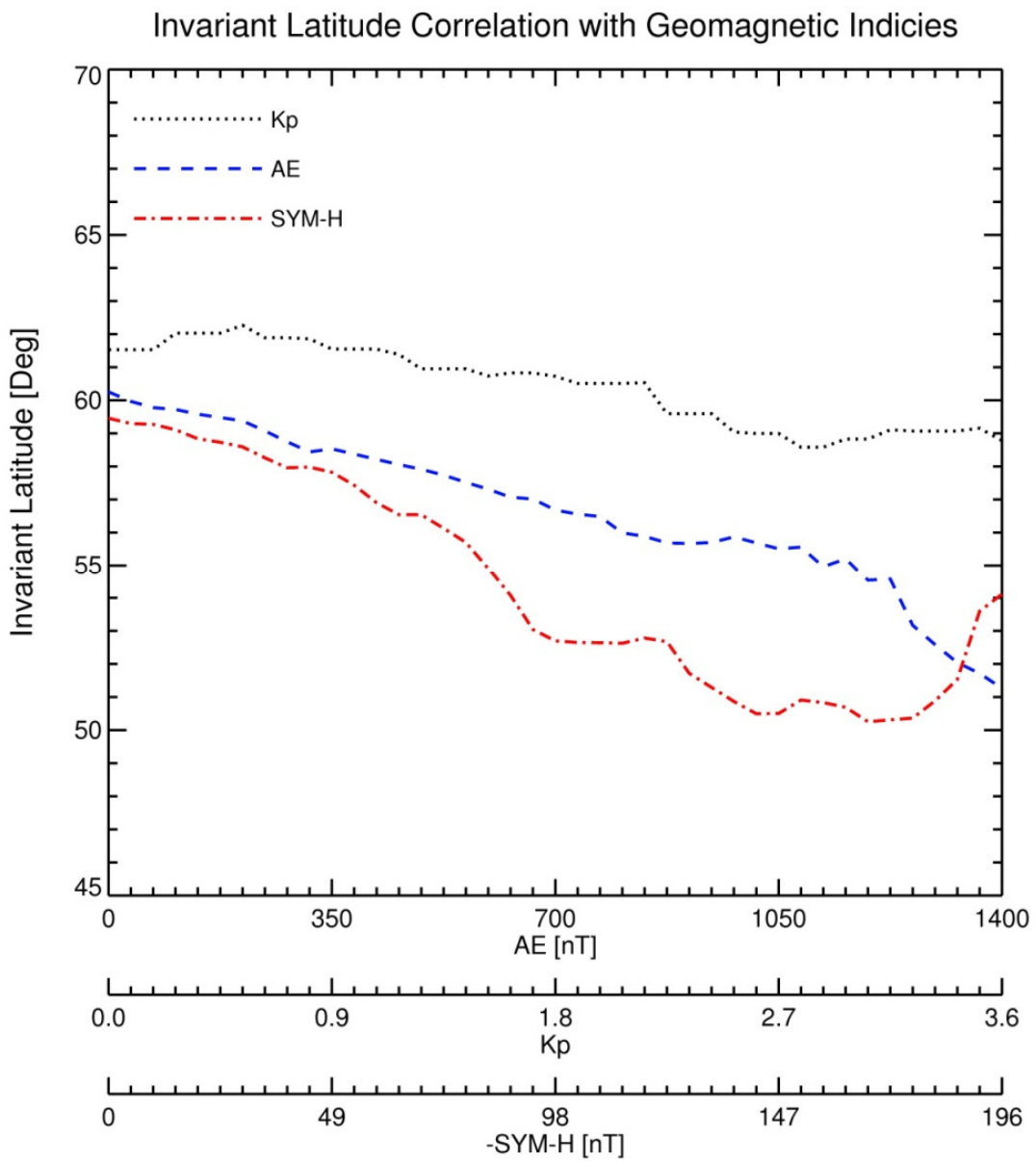
IL_1 = 46.75°
IL_2 = 53.14°
% Diff: 13.7%

$Pixel_1$ = [0.56 0.45 0.74]
$Pixel_1$ = [0.55 0.44 0.86]

Flux Trendline



Invariant Latitude Trendline



Science Questions

- How is the ENA emission, from a point where ion energy is being precipitated, distributed in both ENA velocity space and configuration space?
- How is storm-time energy deposition from precipitating ions distributed in space (latitude, MLT) and how does that spatial dependence vary with geomagnetic storm phase?
- How much energy is deposited into the upper atmosphere by precipitating ring current particles during magnetic storms, as function of storm phase?