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Coordinates and Templates

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Outline

- Introduce coordinate systems for AE9/AP9/SPM
  - What coordinates are used
  - How they're computed
- Introduce concept of templates
  - What are they
  - How are they used
- Give examples of constructing templates

AE9/AP9 Coordinate Systems

- **AE9/AP9 use coordinates based on adiabatic invariants**
  - **Particle energy E**
  - **Modified 2nd adiabatic invariant** $K = \int_{s_{m'}}^{s_m} \left[B_m - B(s) \right] ds,$
  - **3rd adiabatic invariant** $\Phi = \oint A \cdot dx = \iint_{\pi} B_e \cdot dS$
    - **or h_{min}, the minimum altitude on a drift shell**
- **Two grids**
  - **Global: $K^{1/2}$ – $\log_{10} \Phi$**
  - **Low-altitude: $K^{1/2}$ – h_{min}**
- **SPM uses a single grid in L_m – α_{eq}**

Computation (1)

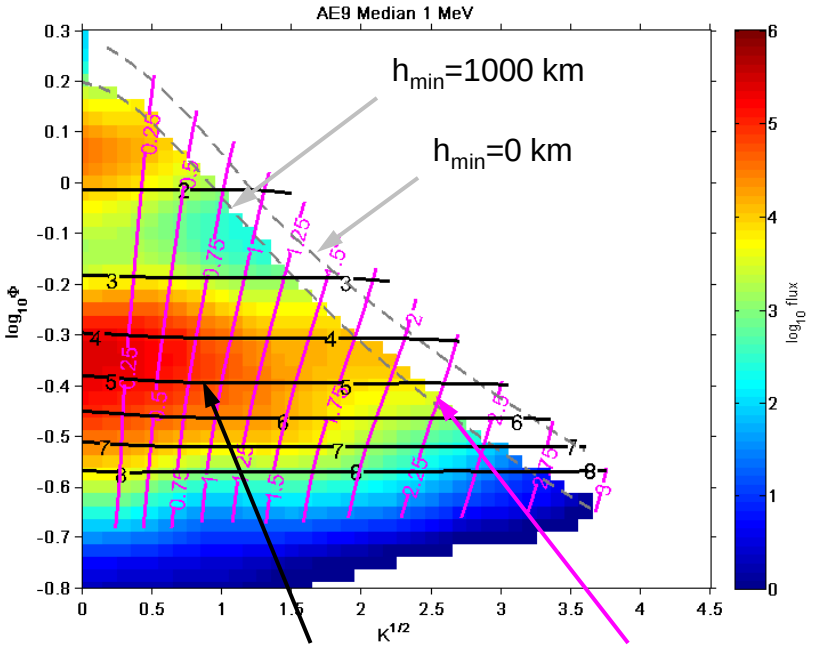
- Calculations performed with modified IRBEM-LIB
  - calculates h_{min}, defined as minimum altitude on a drift shell
  - h_{min} provides better resolution of large flux gradients at low altitudes, where flux is controlled by atmospheric neutral density
- Olson-Pfitzer Quiet 1977 + IGRF magnetic field
- For each time-tagged ephemeris point we calculate K, Φ, h_{min} (for appropriate pitch angle)

Computation (2)

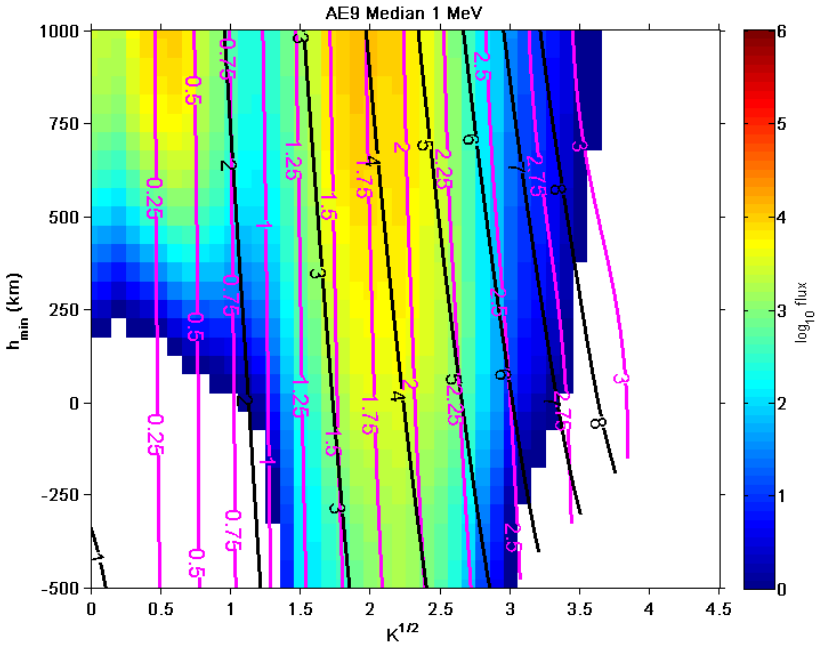
- Other parameters needed for completeness:
  - L_m, L*, MLT, B_{local}, B_{min}
- Φ and h_{min} can also be computed using neural network
  - allows calculation of Φ and h_{min} nearly as quickly as L_m
- Approximate methods developed to convert K/Φ to/from B/L

Flux Maps in the Two Grids

K-Φ Grid



K-h_{min} Grid



What Is a Template?

- Templates are a-priori estimates of the shape of the θ distribution derived from
  - examination of data sets
  - physics-based modeling
  - or other prior knowledge
- Templates are not models
  - BUT, a model can form a template
  - e.g., AE8, Milillo plasma model
- There may be several templates for each species, representing different dynamic states of radiation belts or different underlying assumptions

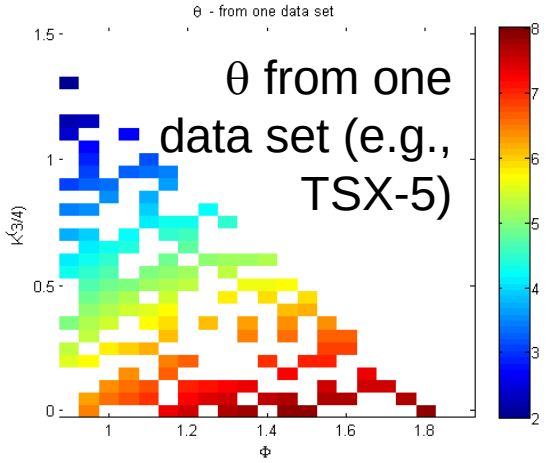
Why Do We Need Templates?

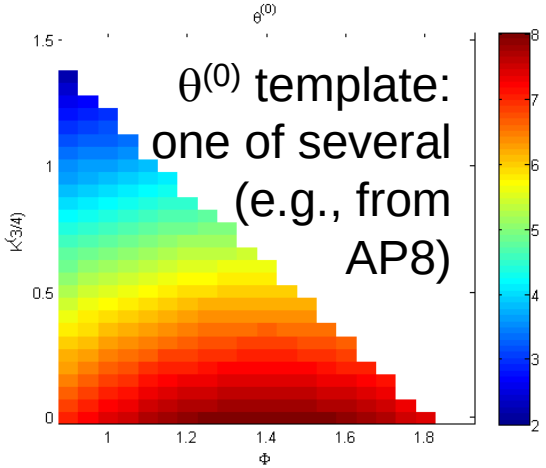
- No sensor covers entire space of (E, K, Φ) or (E, K, h_{min})
- Templates are used to fill in spatial and spectral gaps
- The use of templates allows us to address correlated errors (e.g., some particular sensor is a little higher than the others in some regions of space).

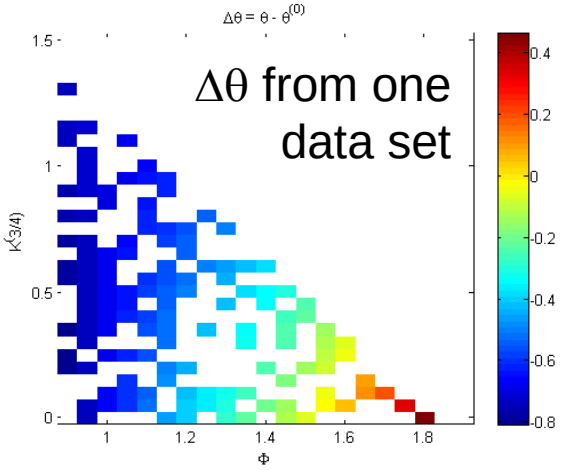
How Are Templates Used?

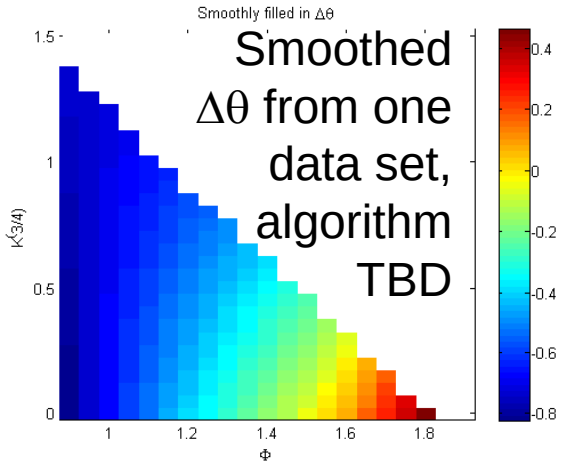
- **For a given data set we:**
  - **Randomly perturb original $\underline{\overline{\theta}}$ based on a normal distribution characterized by $\mathrm{cov}(\delta\underline{\theta})$ in each bin**
  - **Compute $\Delta\underline{\theta} = \underline{\overline{\theta}} - \underline{\theta}^{(0)}$**
  - **Fill in $\Delta\underline{\theta}$ grid using nearest-neighbor averaging & smoothing**
  - **Compute the full $\underline{\overline{\theta}}$ grid**
  - **Repeat N times**
  - **Repeat for all energies**
- **This process is repeated for each data set …**
- **And for multiple templates**

Illustration of Building a Whole Flux Map from One Data Set

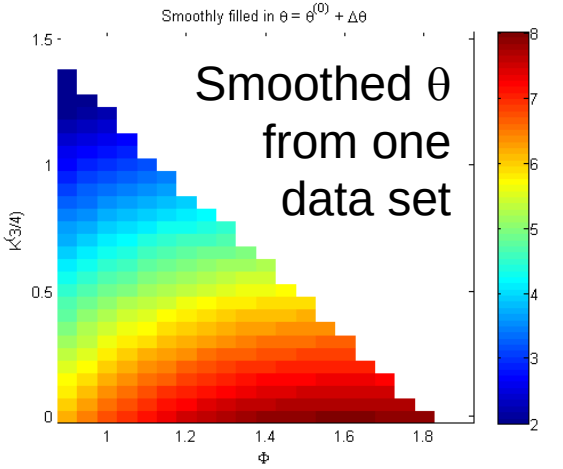








We bootstrap over templates, errors in θ (δθ) and combinations of data sets to estimate the error in the filled-in flux map



Requirements for Templates

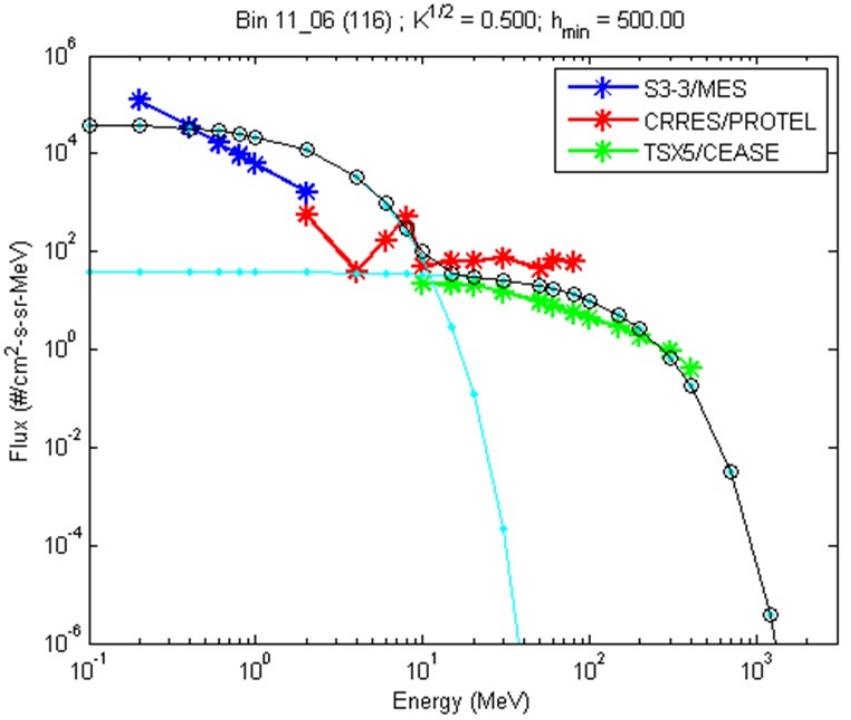
- Cover full range of (E, K, Φ) or (E, K, h_{min})
- Relatively smooth spatially and spectrally
- Reflect prior knowledge of flux distributions
- Reflect variation and uncertainty

Templates Used in V1.0

Model	Templates	
AE9	K-hmin: AE8MAX, AE8MIN	K-Phi: CRRES (post-storm, percentiles), AE8MAX, AE8MIN
AP9	K-hmin: S33+CRRES+TSX5 (percentiles)	K-Phi: Polar/IPS+CRRES+TSX5 (percentiles)
SPME	Hydra (all, dawn, dusk, midnight, noon) x(mean, percentiles)	
SPMH	Mililllo (all, dawn, dusk, midnight, noon), (Niehof-CAMMICE, Roeder-CAMMICE) x (all, dawn, dusk, midnight, noon) x (mean, percentiles)	
SPMHE	(Niehof-CAMMICE, Roeder-CAMMICE) x (all, dawn, dusk, midnight, noon) x (mean)	
SPMO	(Niehof-CAMMICE, Roeder-CAMMICE) x (all, dawn, dusk, midnight, noon) x (mean)	

Protons

- **Proton spectra are generally well described by sum of exponentials**
- **Combine spectra from multiple sensors**
  - **K-Φ: Polar/IPS, CRRES/Protel, TSX5/CEASE**
  - **K-h_{min}: S3-3, CRRES/Protel, TSX5/CEASE**
- **Determine fitting parameters**
  - **set to nominal values if insufficient data**
- **Smooth and extrapolate parameters**
- **Derive template from fits**



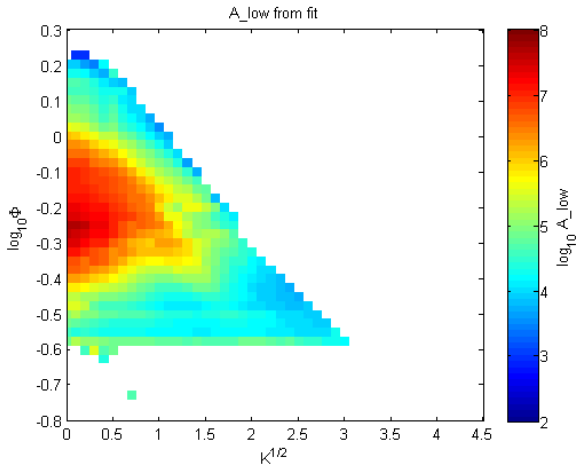
$$j = A_{low} \exp\left(-\frac{E}{E0_{low}}\right) + A_{high} \exp\left(-\frac{E}{E0_{high}}\right)$$

Smoothing of Parameters

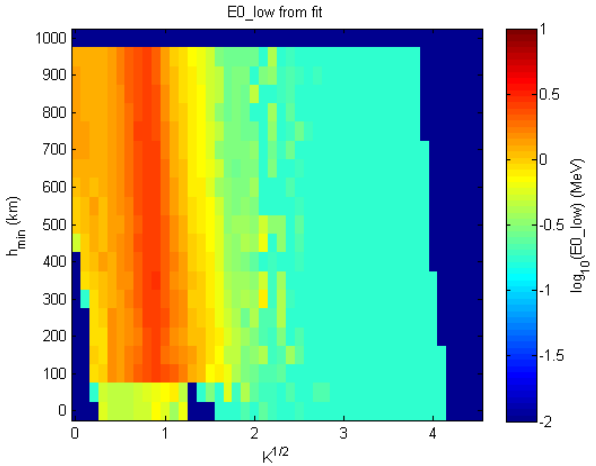
K-Φ Grid

K-h_{min} Grid

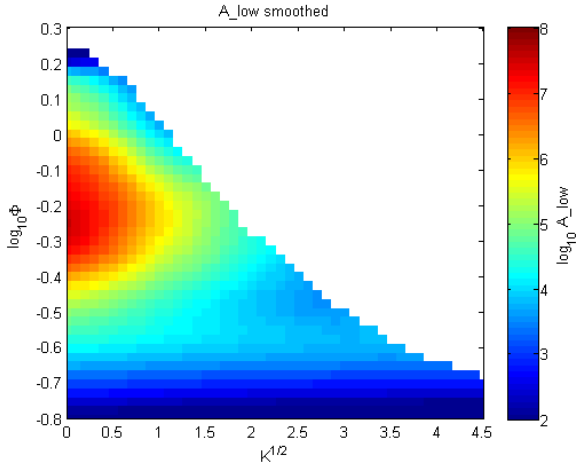
A_{low} from fit



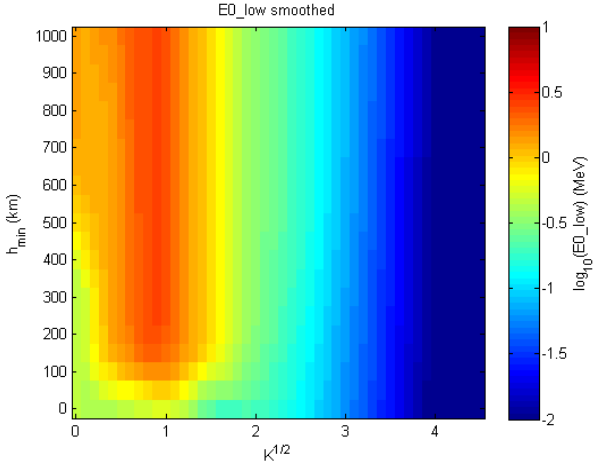
$E0_{low}$ from fit



A_{low} smoothed



$E0_{low}$ smoothed

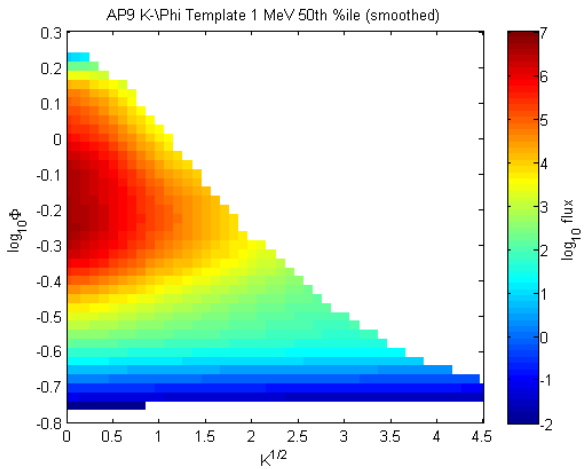


Proton Template Flux Maps

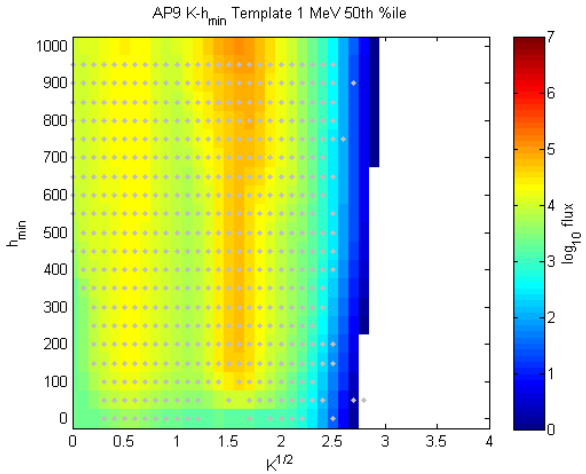
K-Φ Grid

K-h_{min} Grid

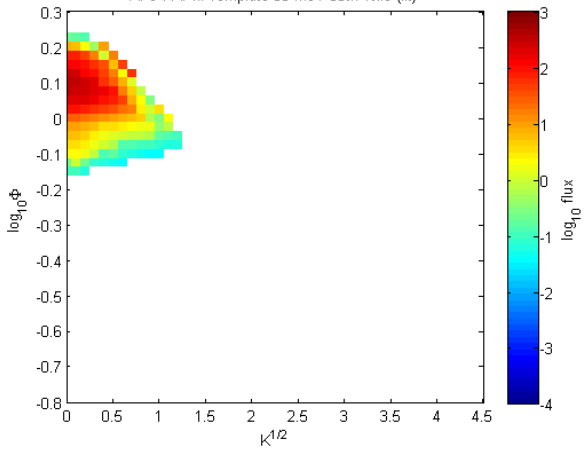
1 MeV



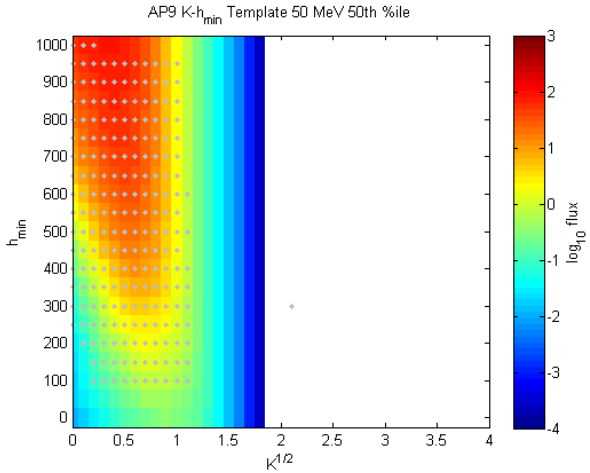
1 MeV



50 MeV



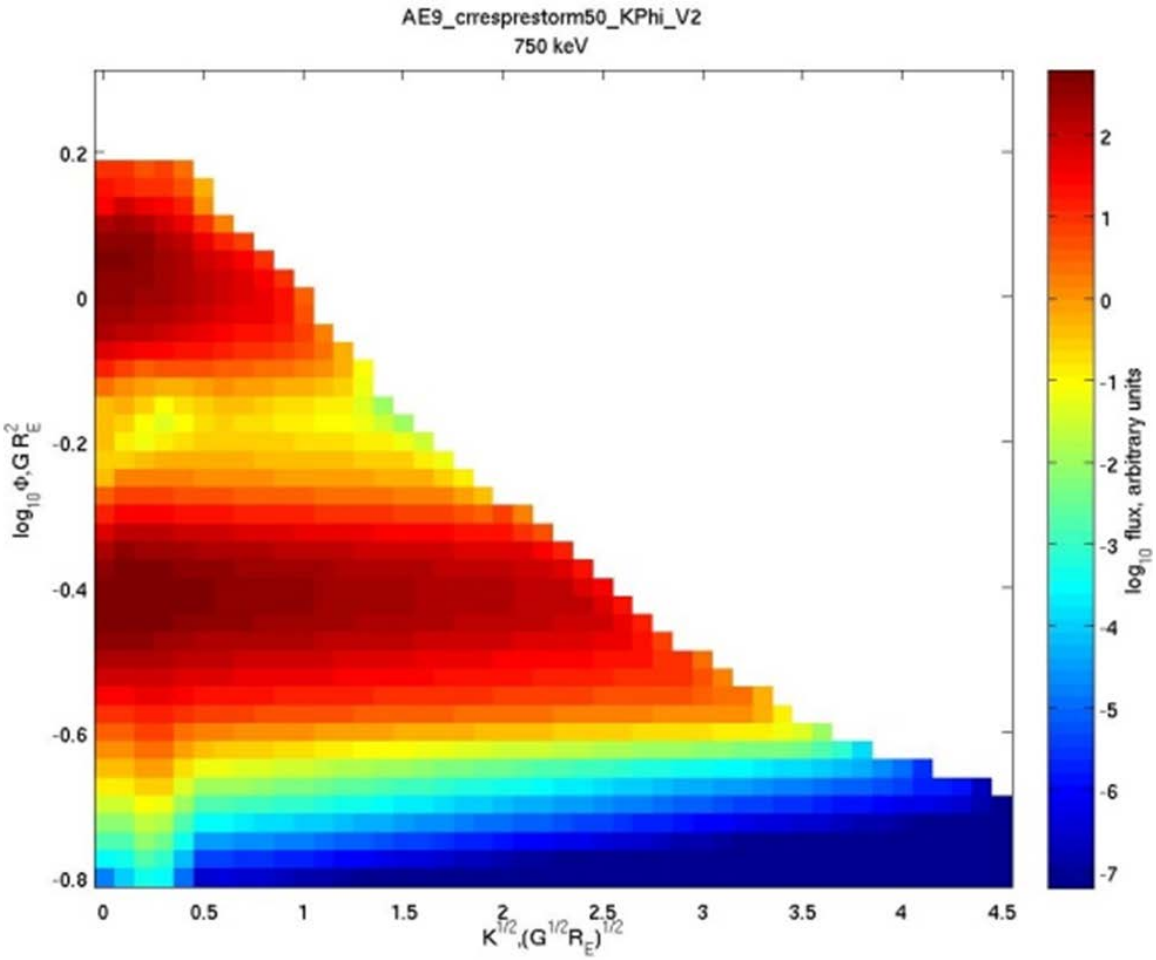
50 MeV



Electrons

- **Highly variable energy spectra**
  - **exponential (outer belt)**
  - **power-law (inner belt)**
  - **“bump on tail” (slot)**
- **Template sources:**
  - **AE8**
  - **CRRES/MEA + CRRES/HEEF (pre- and post-storm)**
- **Process:**
  - **Interpolate/extrapolate fluxes in E, K, or Φ**
  - **Fill in missing bins or energies from nearest neighbors**
  - **Smooth in K-Φ space**

Electron Template Flux Map



Summary

- **Building templates is as much art as science – considerable ad hoc processing**
- **We aim to capture as much "prior knowledge" as possible**
- **We particularly welcome templates:**
  - **Based on physical or semi-empirical models**
  - **Based on different data sets**
  - **Reflecting natural variability**
  - **Including the inner zone and/or atmosphere gradients**

Questions?