University of Colorado Boulder
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Atmospheric Signatures of Radiation Belt Precipitation and their Relationship to Precipitating Flux and Spectra

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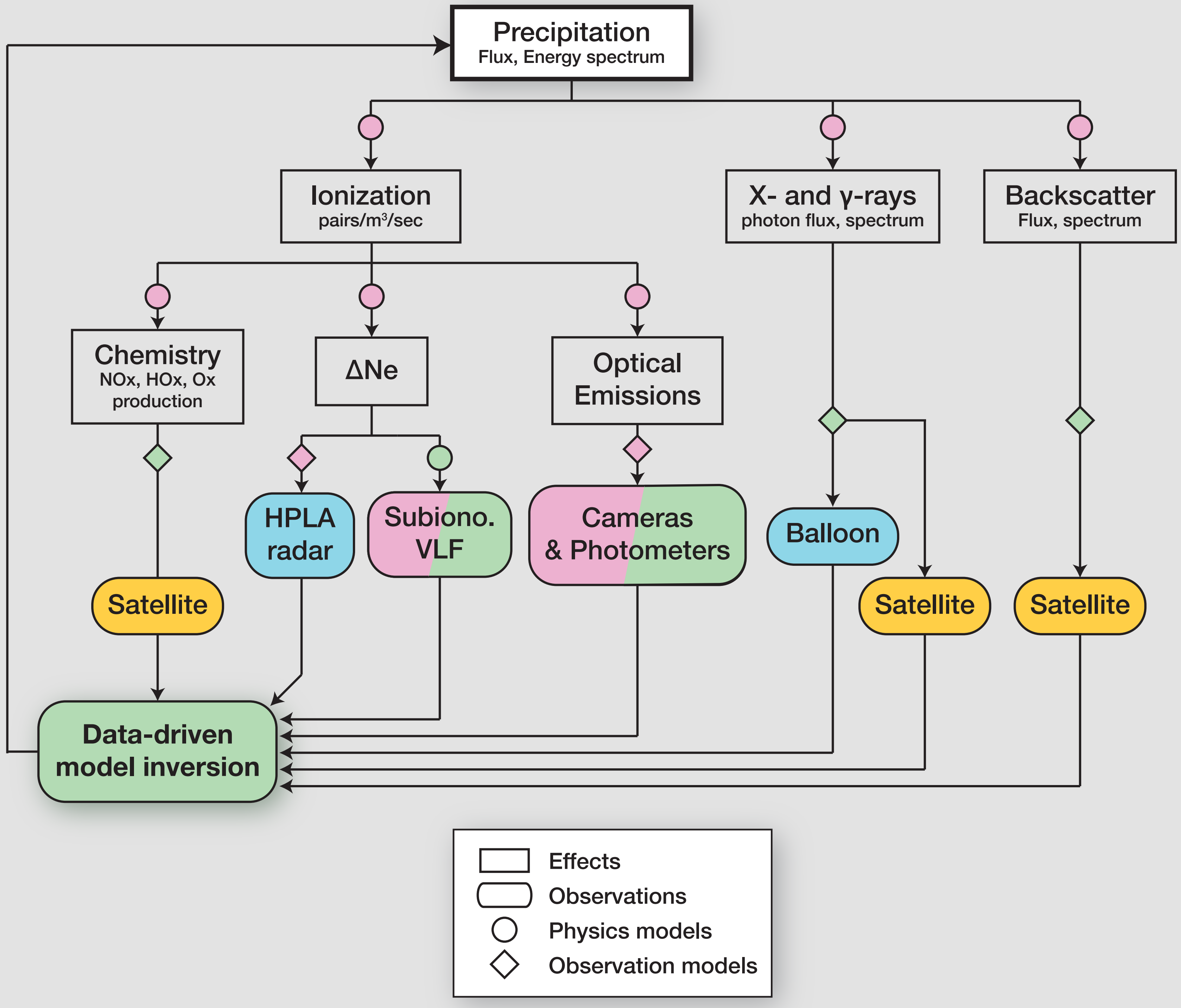
Better title:

Towards Continuous Radiation Belt Precipitation Monitoring from Ground and Space-based Observations

Assessing EPP through its signatures

- **A full assessment of EPP requires:**
  - Flux
  - Spectra
  - Time scales
  - Spatial scales
- **Not to mention:**
  - Connection between observables and these physical parameters



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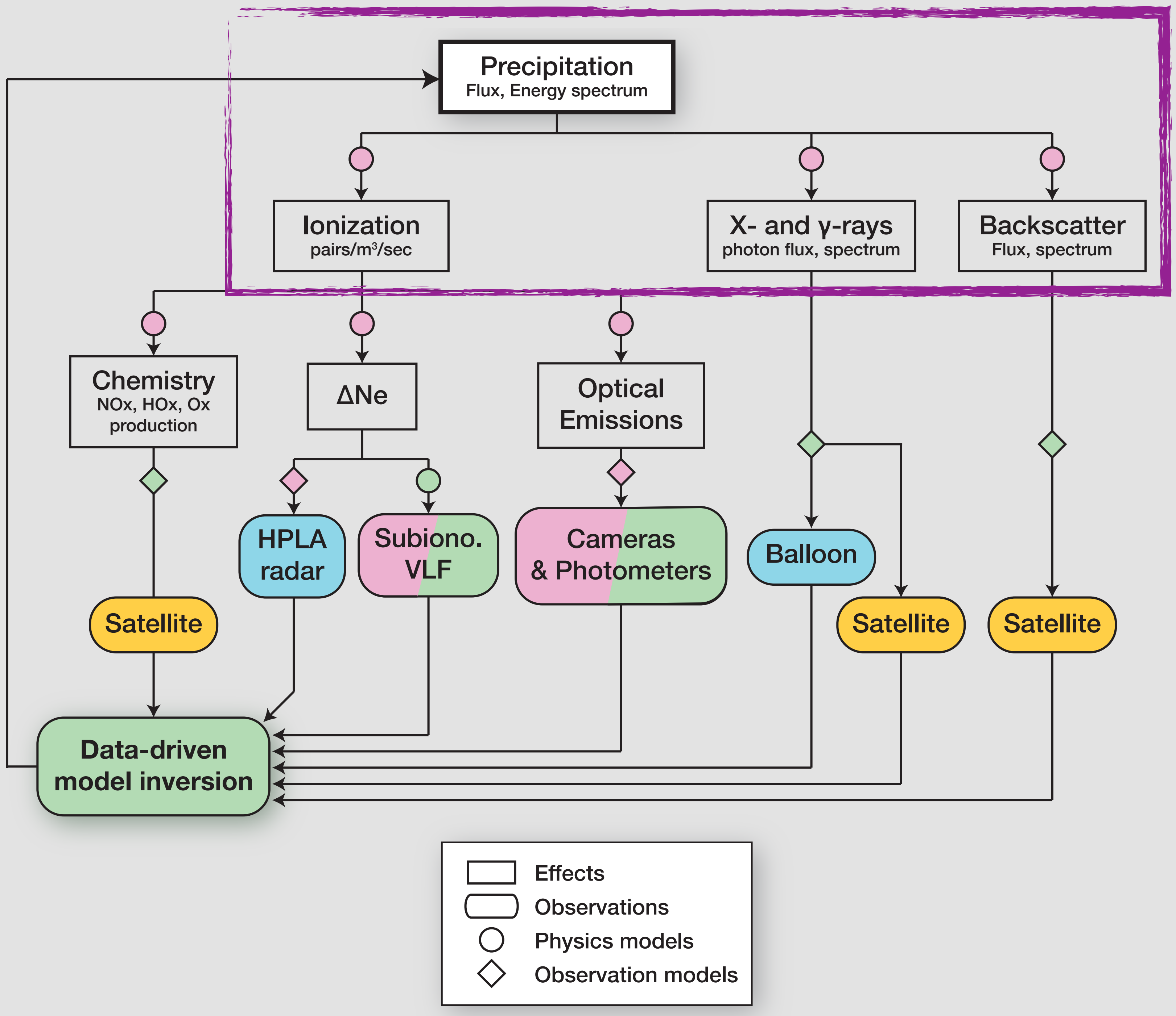

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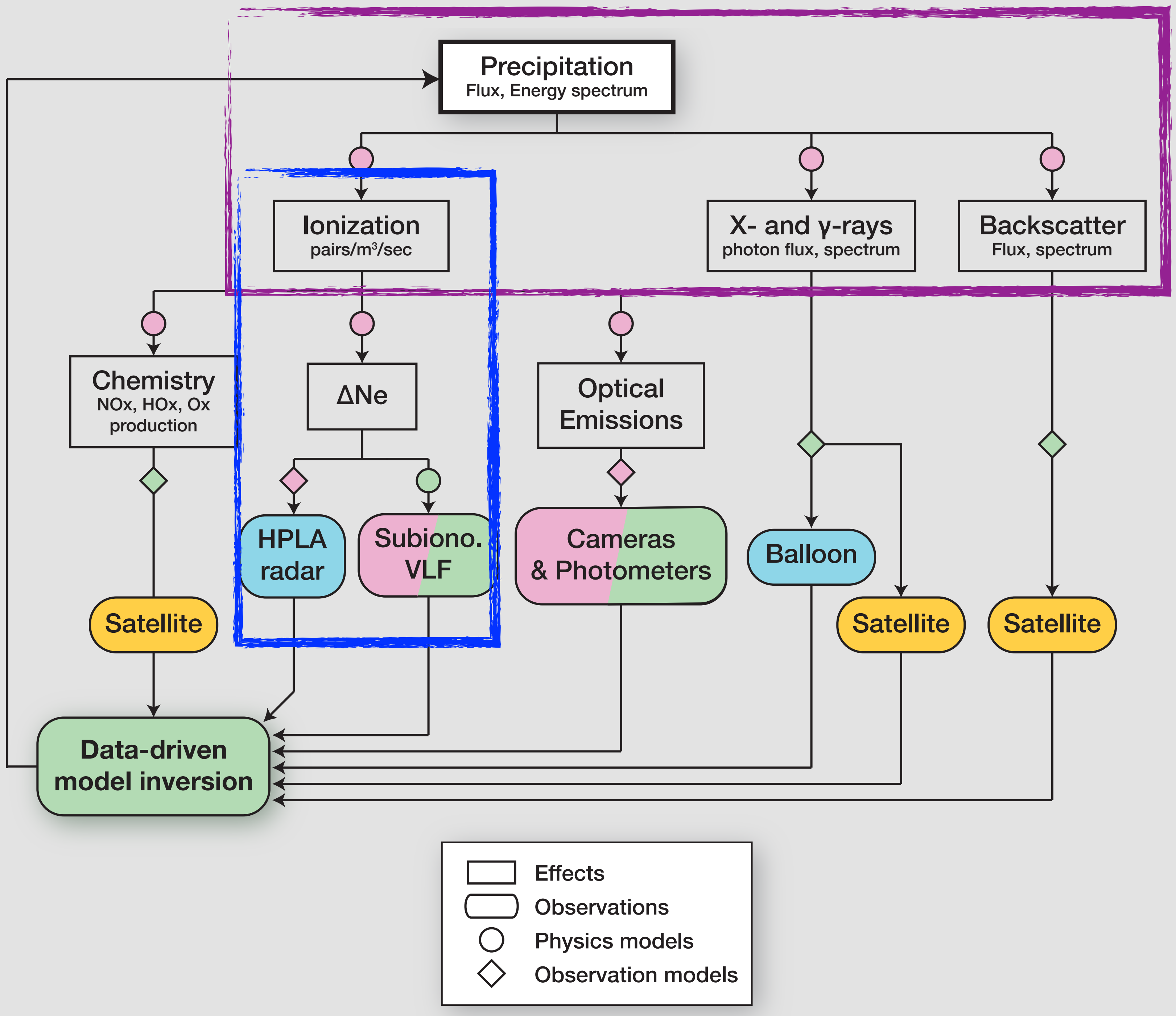

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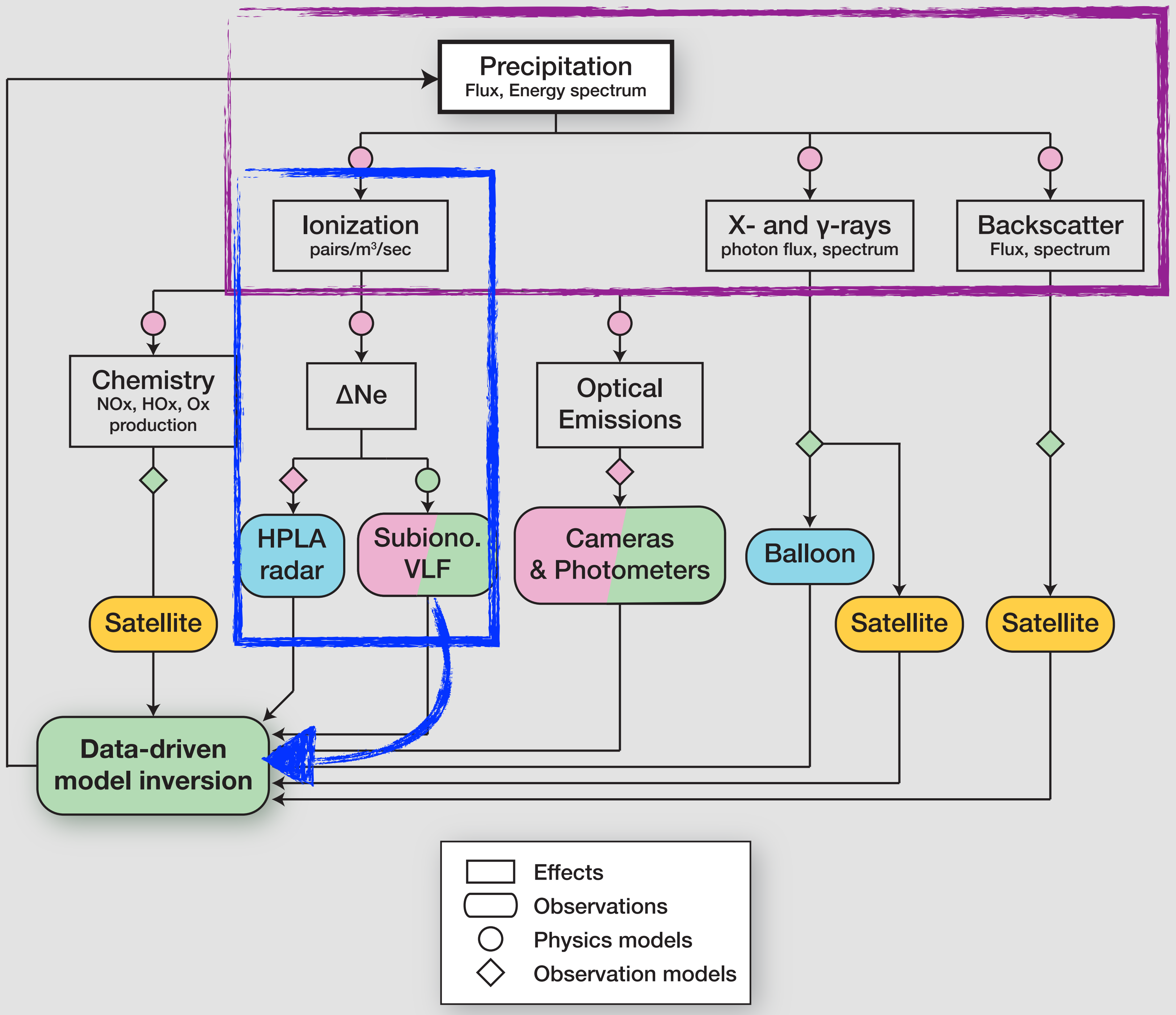

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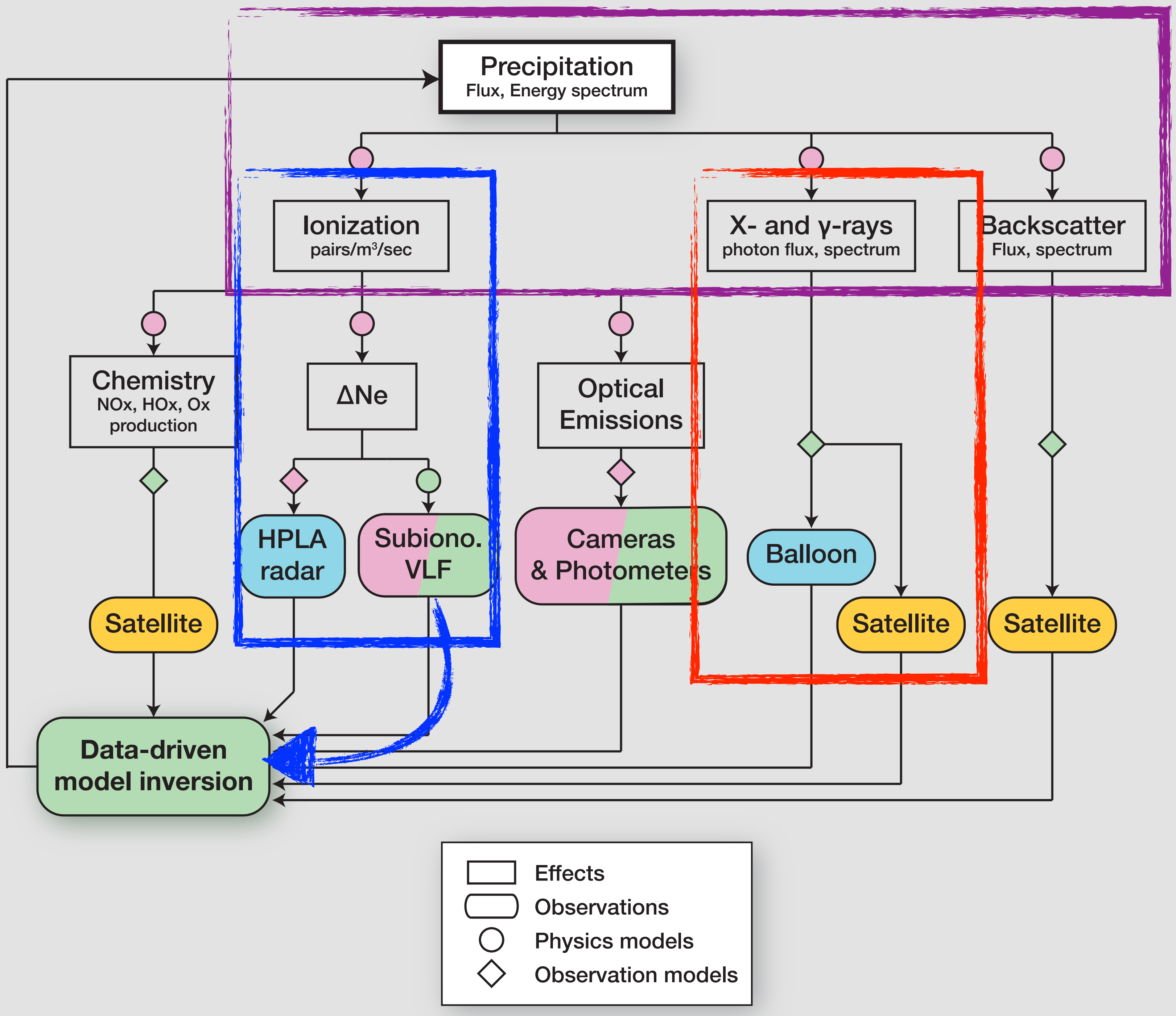

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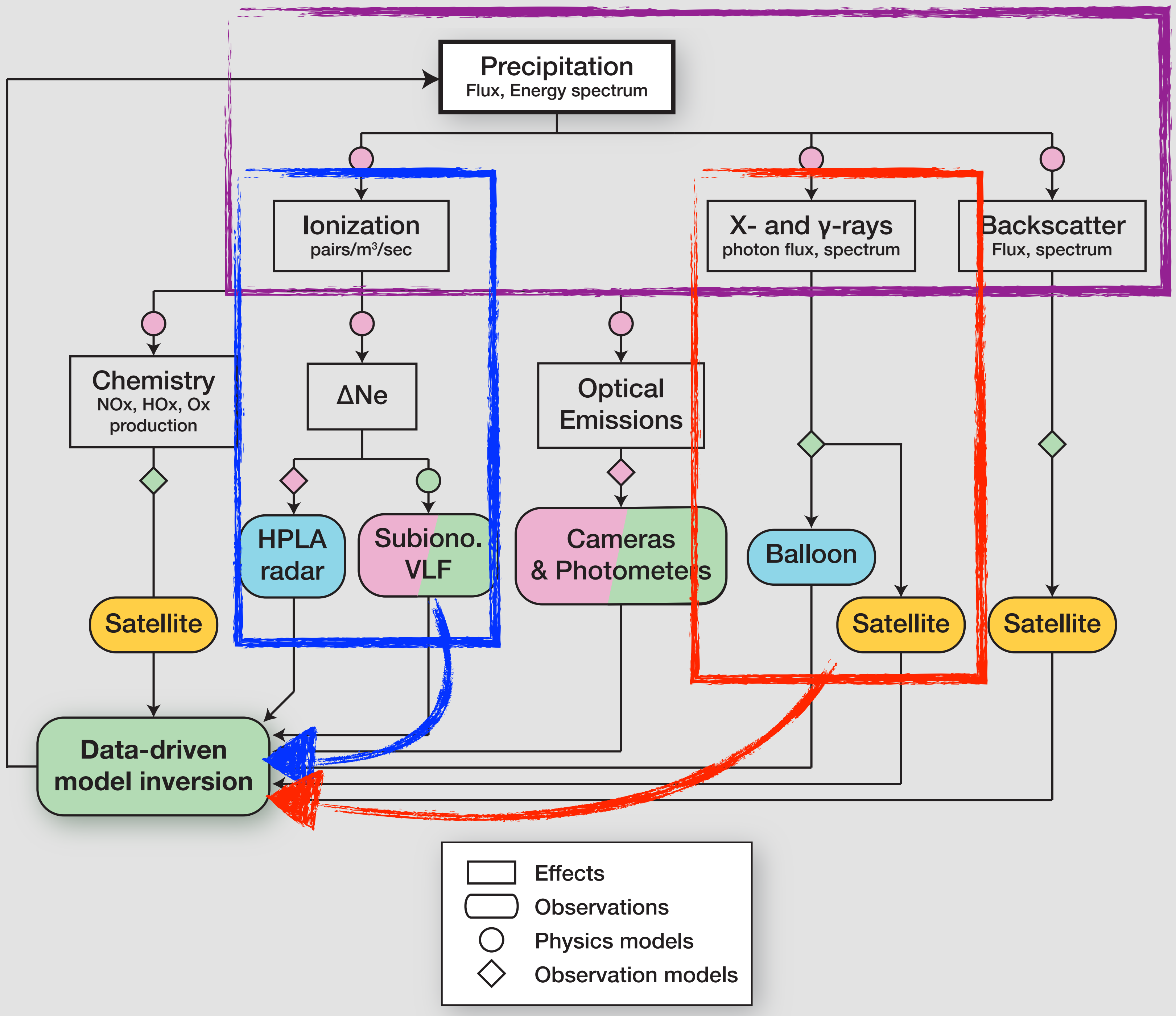


Spatial Scales

- FIREBIRD: Crew et al [2016]: microburst scale sizes down to 11 km (120 km eq.)
- AC6: Blake and O’Brien [2016]
- BARREL: Clilverd et al [2017]: 1.5–3.5 h MLT
- BARREL + AC6: Anderson et al [2017]: microburst region spanning 4h MLT and L = 5–10
- POES: Shekhar et al [2017]: 31,000 events: dL = 0.5L (morning/dusk) or 1–2.5L (nightside), dMLT ~ 3h for both
- Also don’t forget SAMPEX, e.g. Blake et al [1998]: 2-3 degrees in latitude near outer boundary

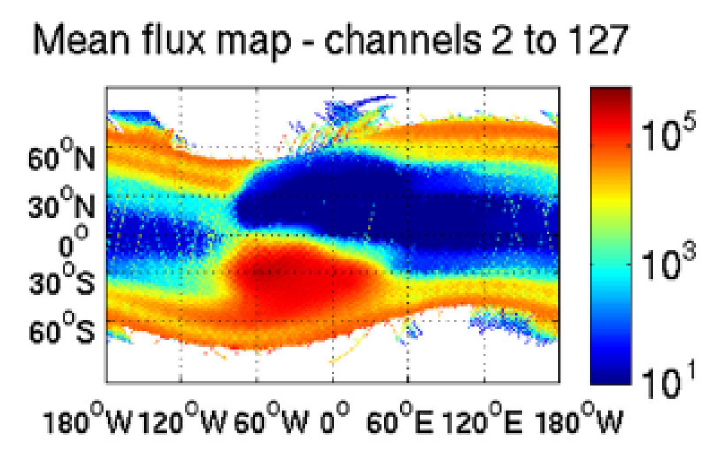
- **What about regular, continuous observations and monitoring of precipitation?**

Outline

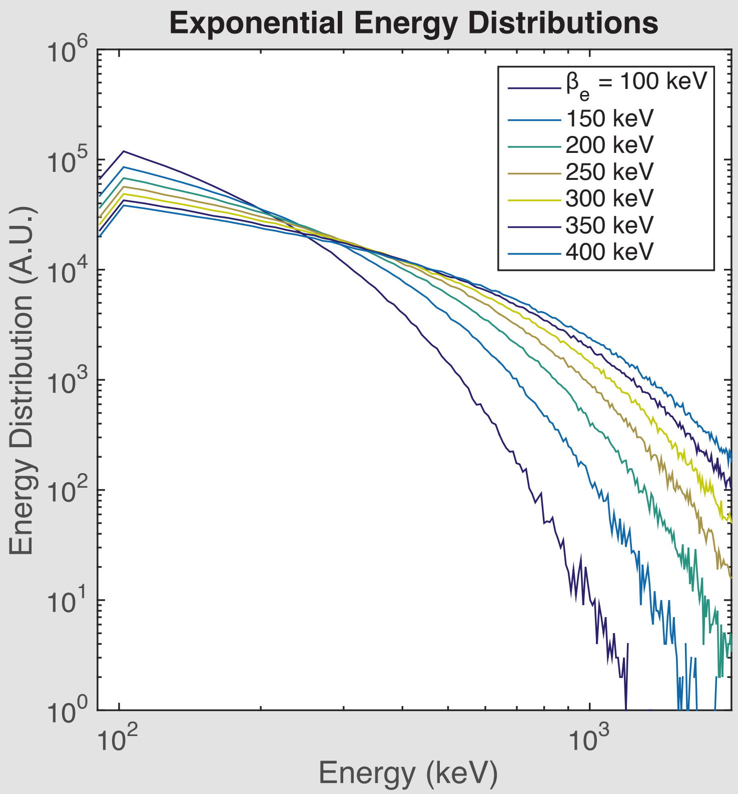
1. Forward modeling overview
2. Subionospheric VLF remote sensing of precipitation
    1. single-path assessment
    2. 2D inversion
3. X-ray observation of precipitation

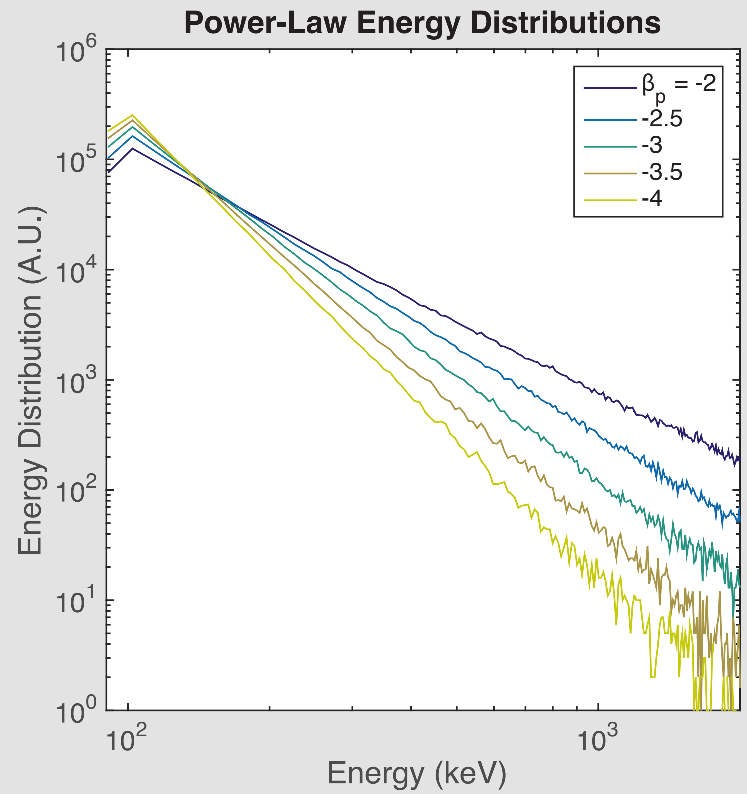
EPP Simulations: Input Electron Distributions

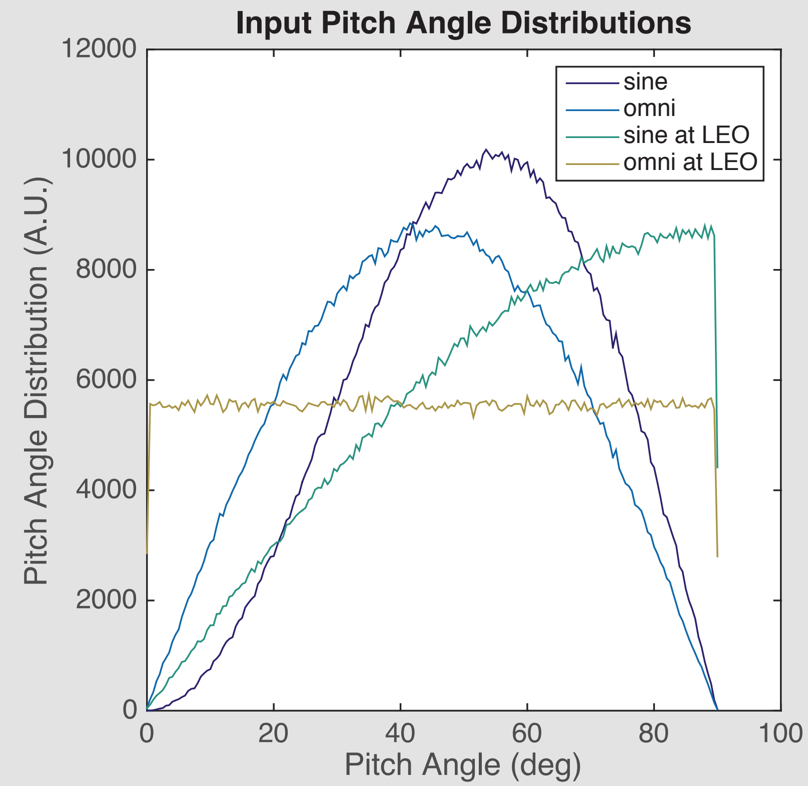
- We assume a mean input integrated flux of 10^5 electrons/cm^2/sec
  - estimated from years of DEMETER observations published by *Whittaker et al* [2013] –>



- Energy distributions given by exponential or power-law:
  - $f(E) = f_0\, e^{-E/E_0}$ (exponential, $E_0 \in [100\ 400]$ keV)
  - $f(E) = f_0\, E^{-\alpha}$ (power law, $\alpha \in [2\ 4]$)
- Pitch-angle distributions (PADs) can be arbitrary: sine (at LEO), sine (at equator), omnidirectional, isotropic, etc.
  - Work shown in this talk uses isotropic PAD ("omni at LEO" below)







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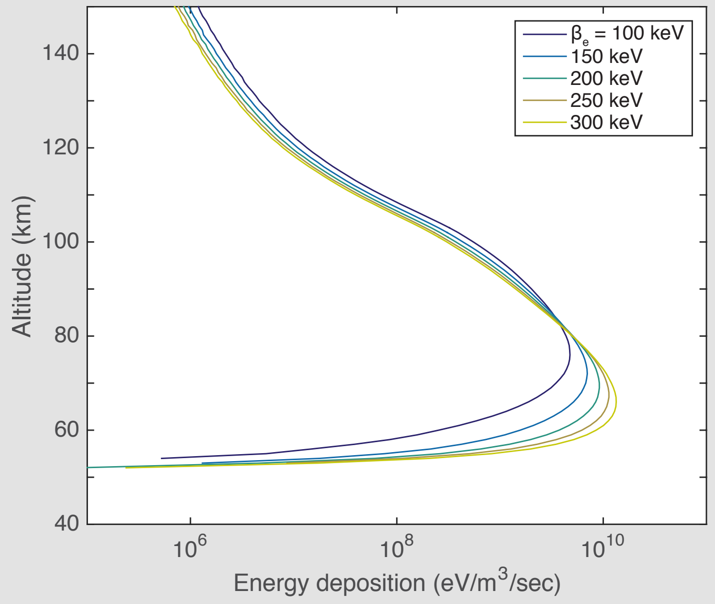
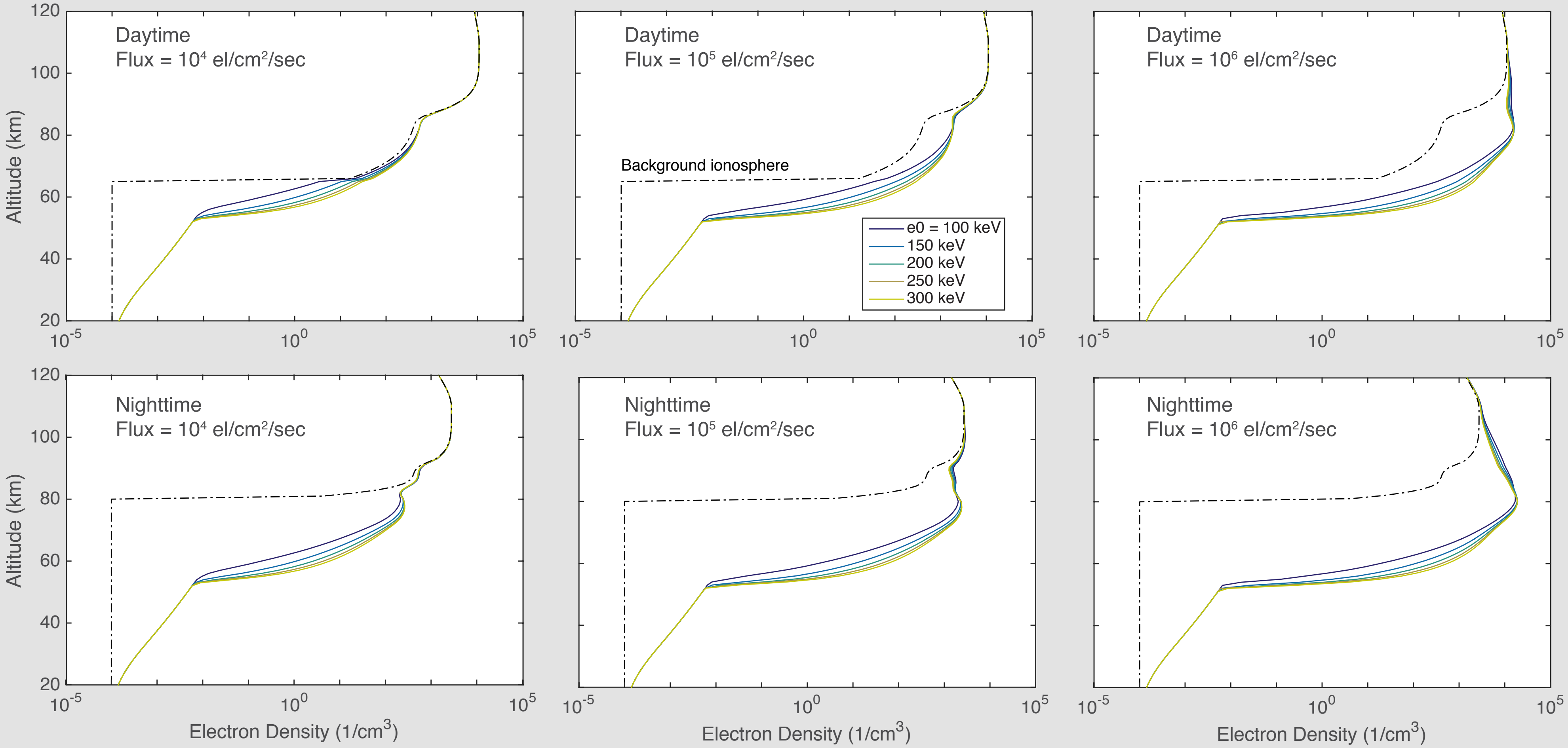
Energy Deposition and Electron density

- Given an input energy / pitch angle distribution, Monte Carlo modeling is used to determine the energy deposition profiles
- Then, we use chemistry modeling to determine electron density disturbance
  - Below uses 5-species GPI chemistry model [*Glukhov et al*, 1992; *Lehtinen and Inan*, 2009]





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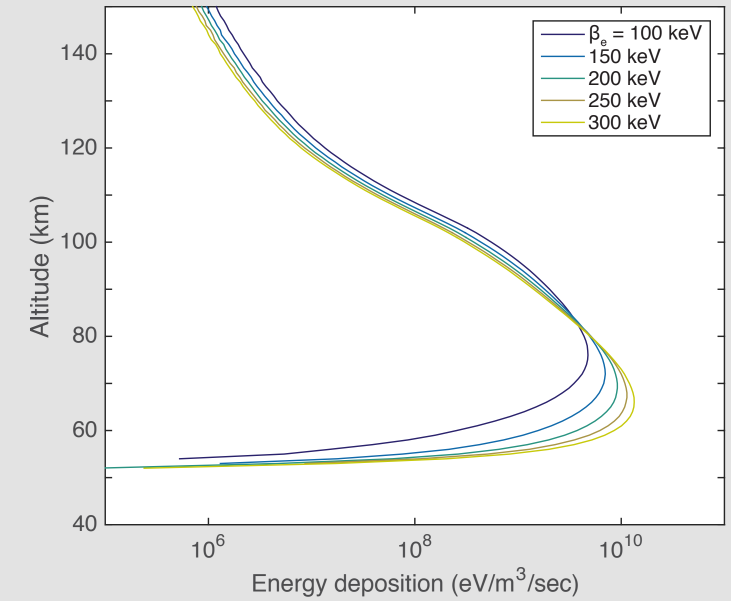
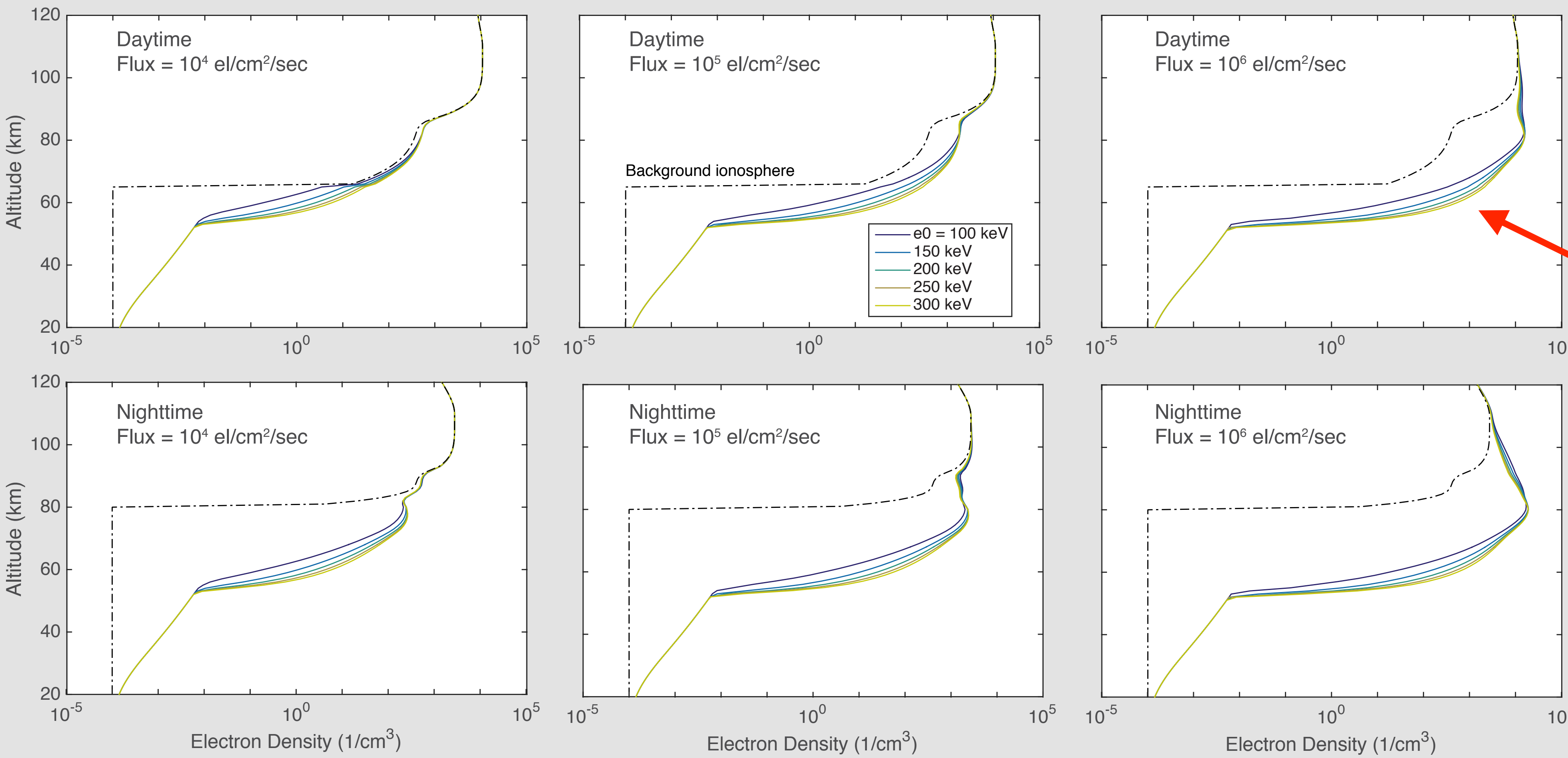
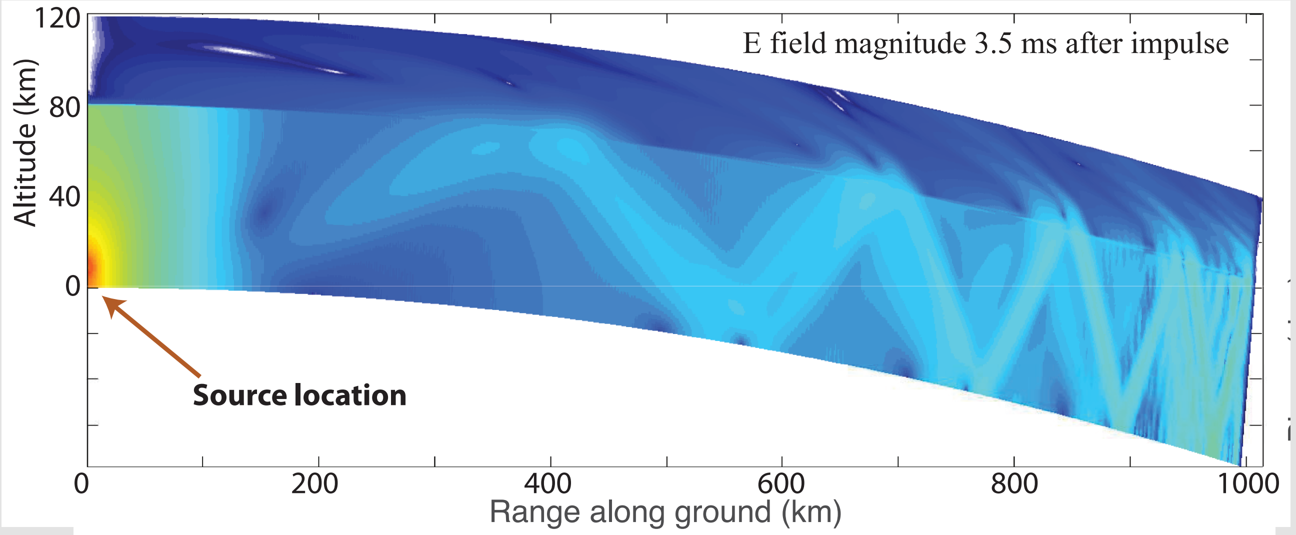


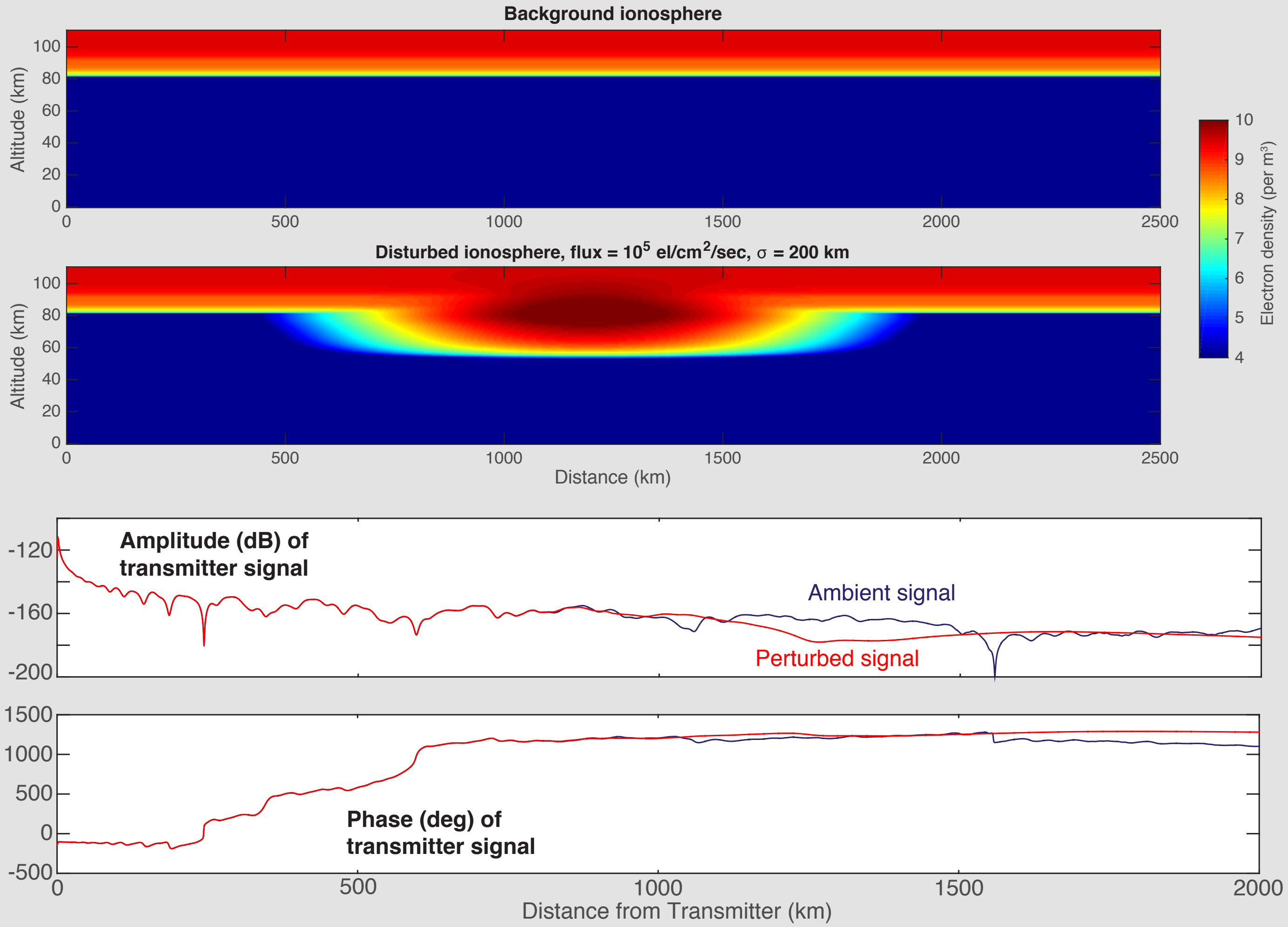


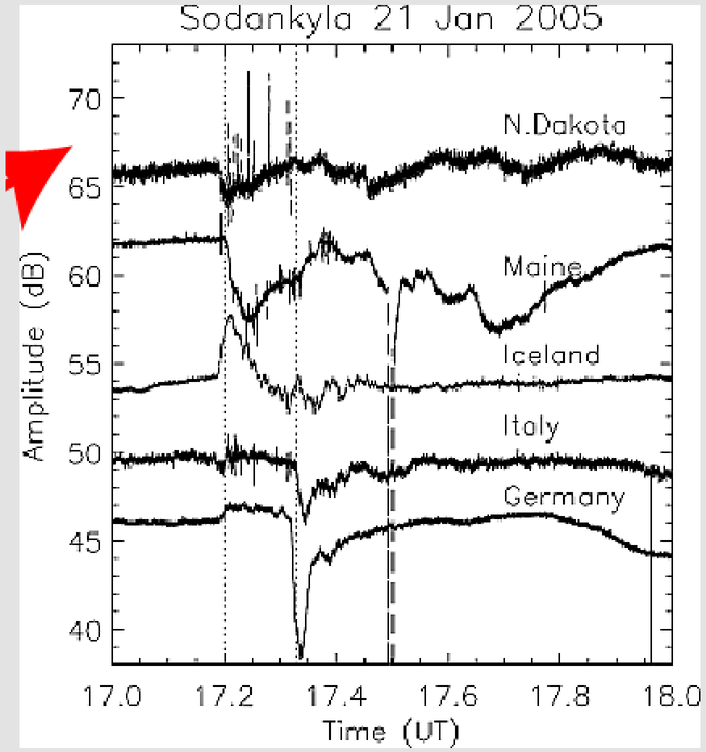
We need to measure the D-region density profile in order to infer the preciptating energy flux / spectrum

Modeling VLF signatures of Precipitation

- Electron density perturbations are used as input to 2D VLF Propagation models which simulate expected amplitude and phase along the ground
  - Finite-Difference Time-Domain (FDTD) model [*Marshall*, 2012, JGR]
  - LWPC: US Navy mode solver
  - Model with and without precipitation; subtract to determine perturbation

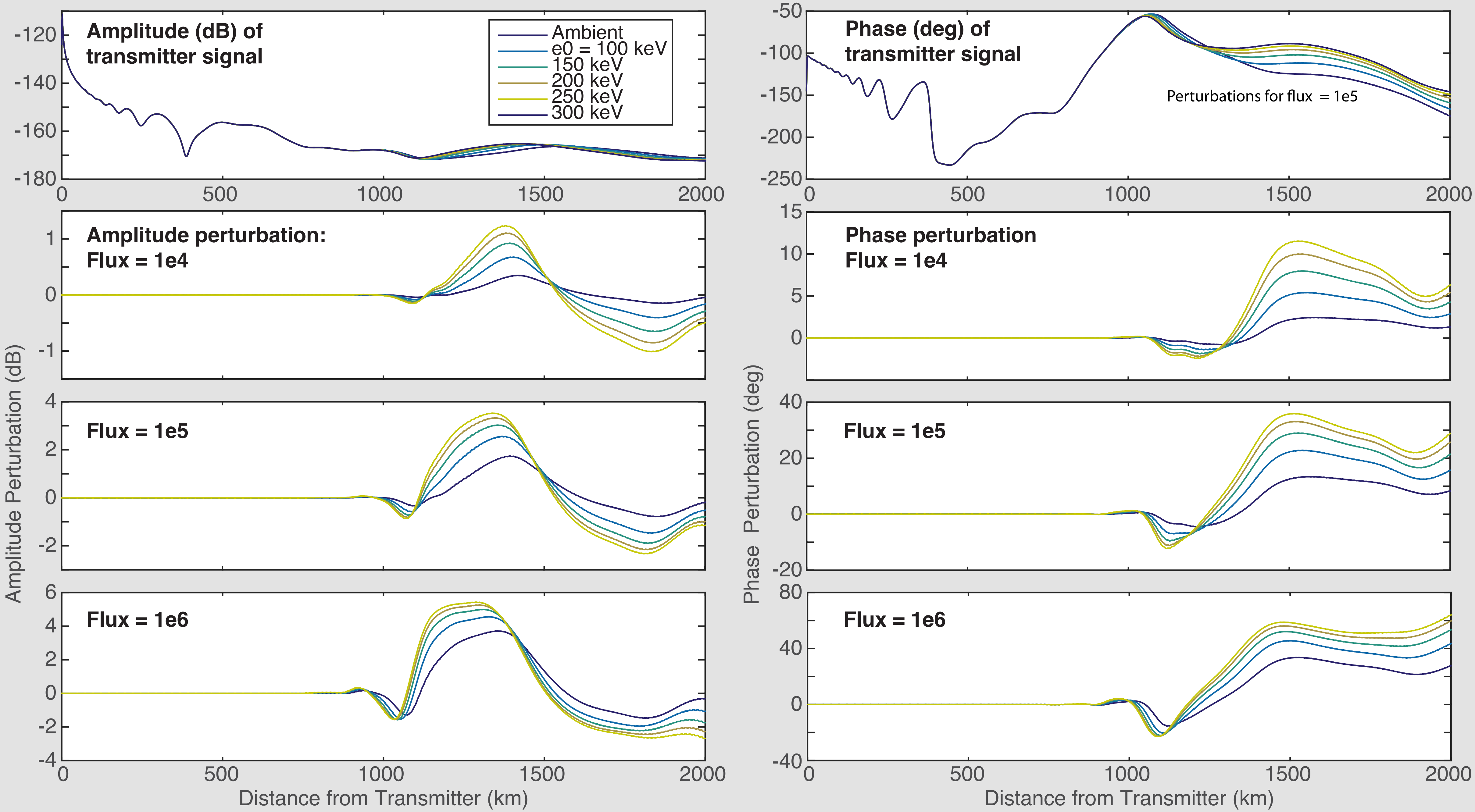






VLF perturbations vs. Flux parameters

- precipitation patch is 200 km (gaussian radius), centered at 1200 km
- VLF perturbations at 24 kHz, from NAA (Maine) towards somewhere in Canada



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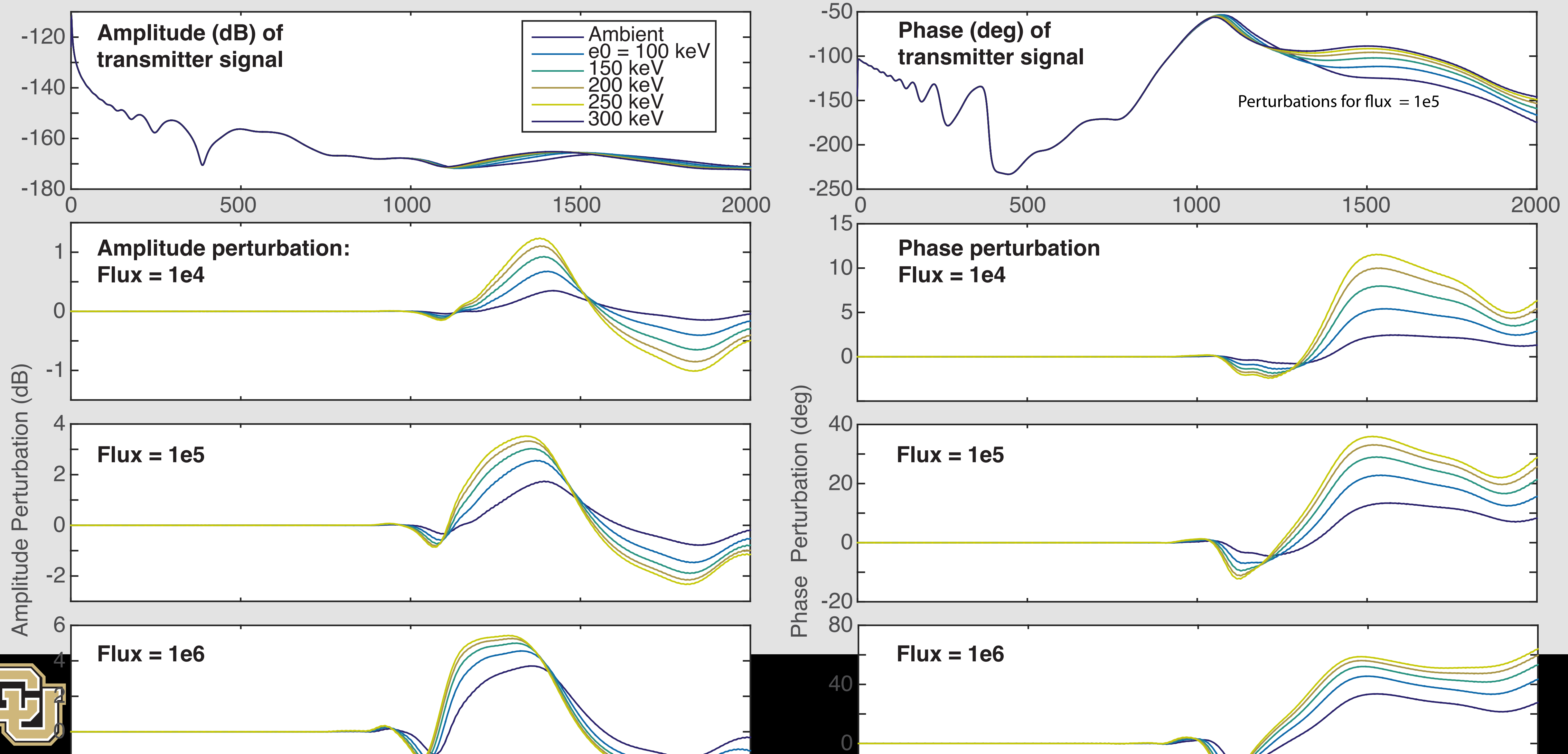

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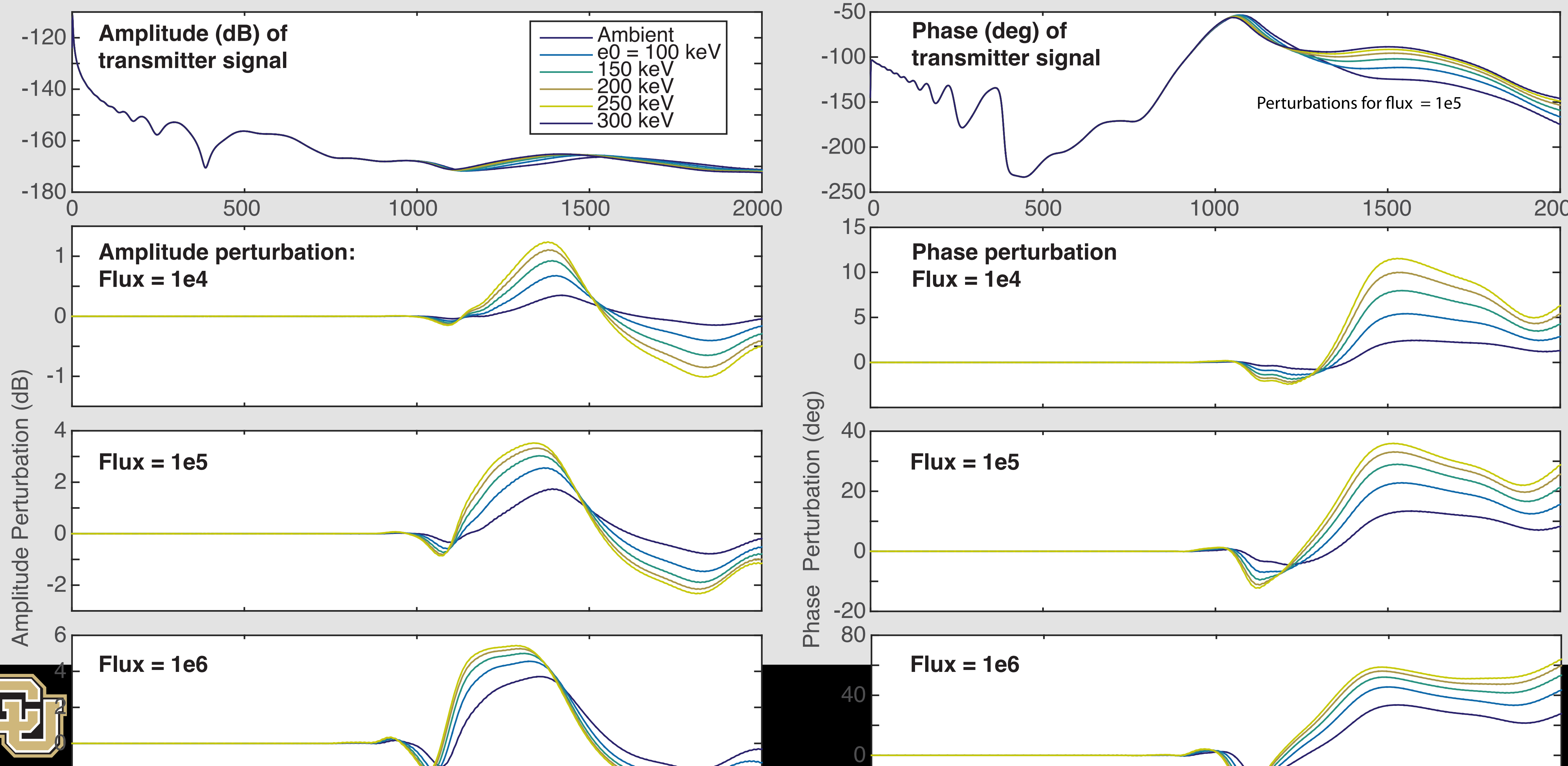
- **No clear, definitive correlation between precipitation signatures and observed VLF response**



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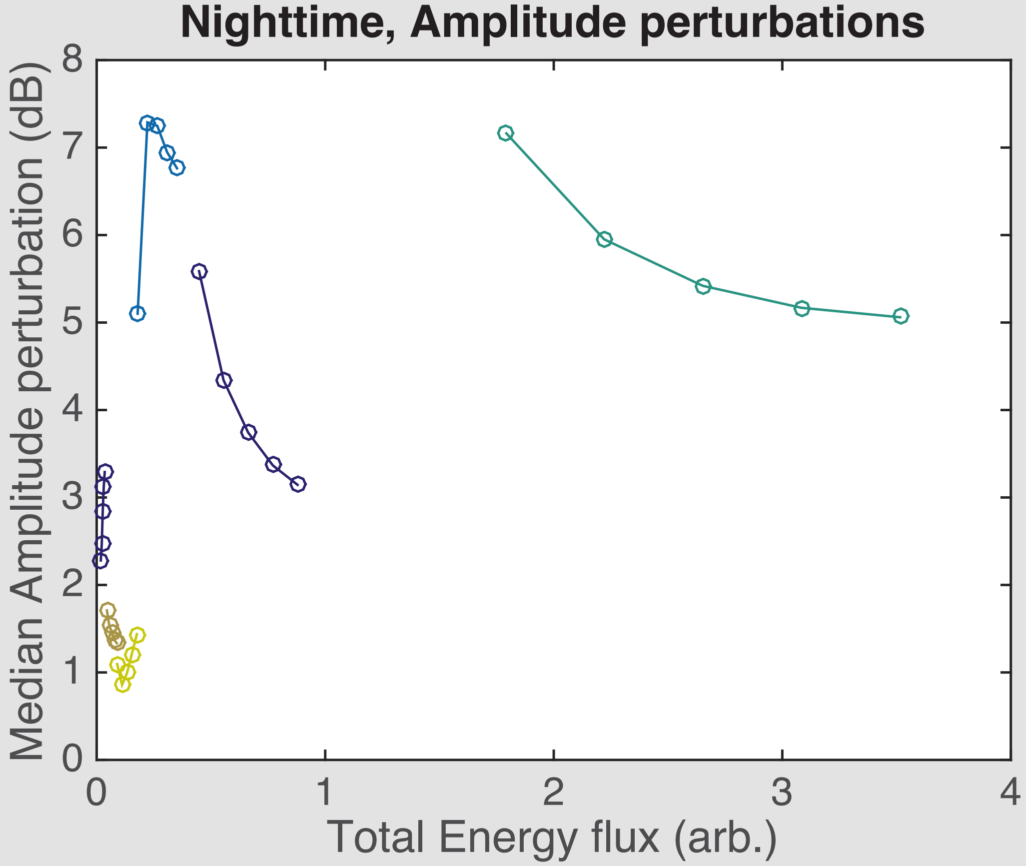
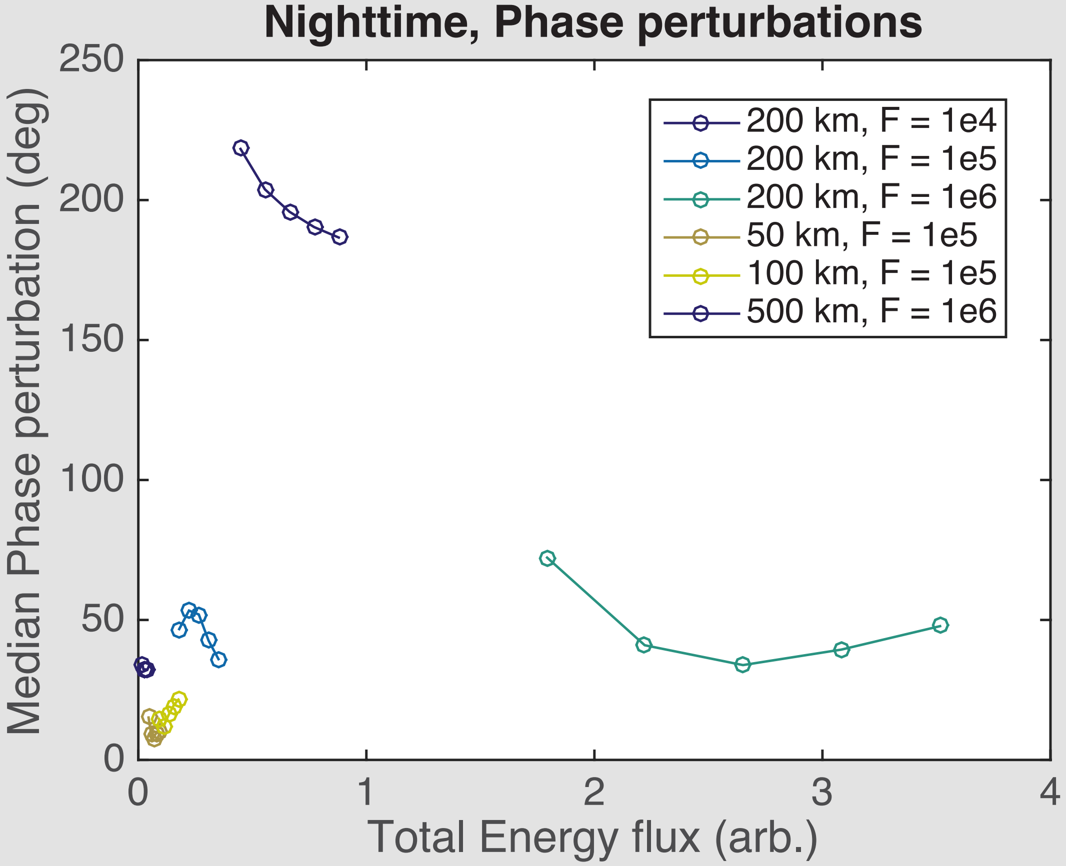
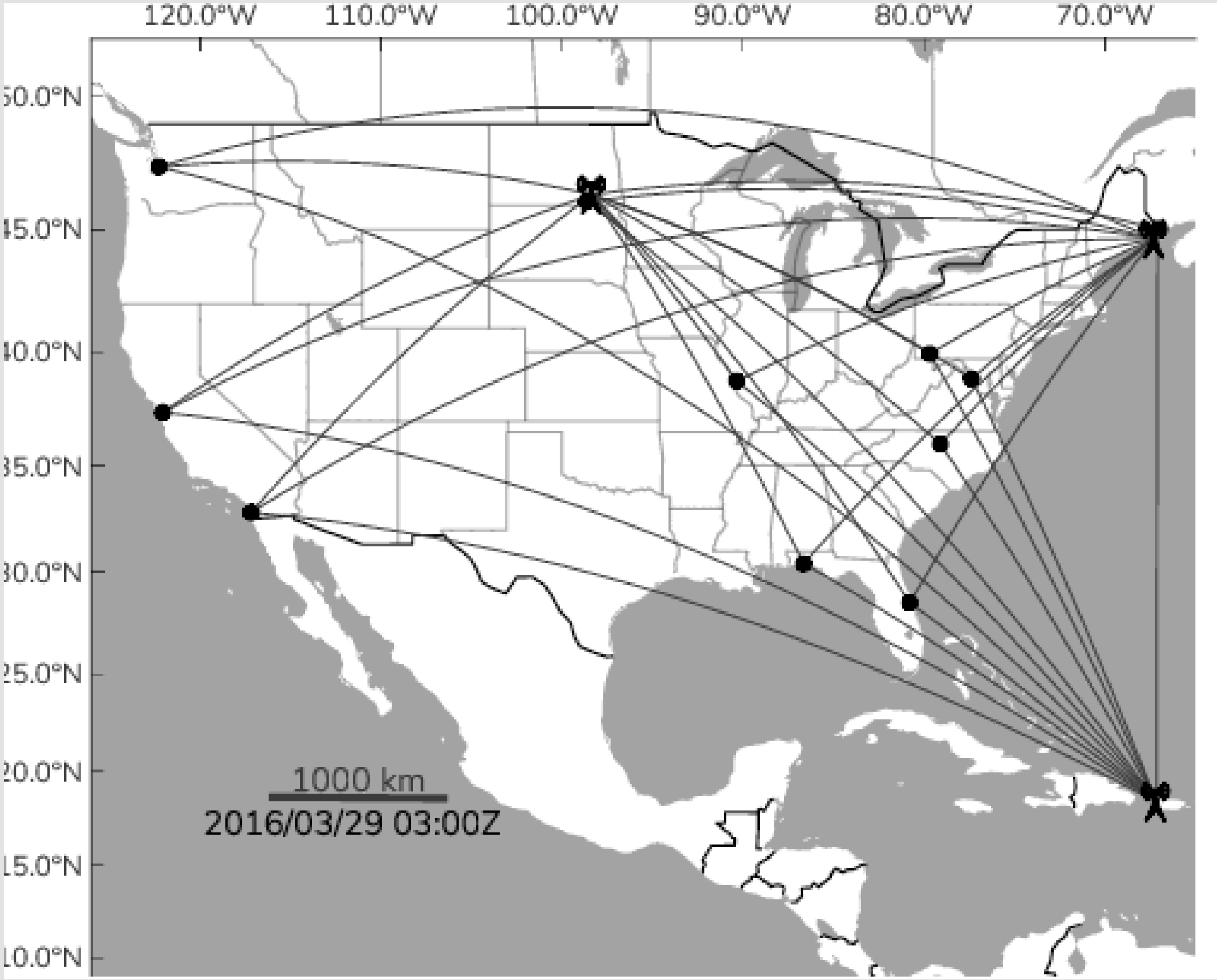




Better: Direct 2D inversion

- **Segue: the next few slides are not about precipitation.**
- We are trying to estimate the state of the ionosphere, over a large spatial region, using VLF amplitude and phase.
- **Using a set of overlapping transmitter-receiver paths, can we estimate the state of the ionosphere in 2D?**
- Idea goes back to *Inan et al* [1990] and others since then, but never applied full 2D inversion problem



Inan, U.S., Knifsend, F.A. and Oh, J., 1990. Subionospheric VLF "imaging" of lightning-induced electron precipitation from the magnetosphere. *Journal of Geophysical Research: Space Physics*, *95*(A10), pp.17217-17231.

ensemble Kalman Filter (EnKF)

What is an EnKF?

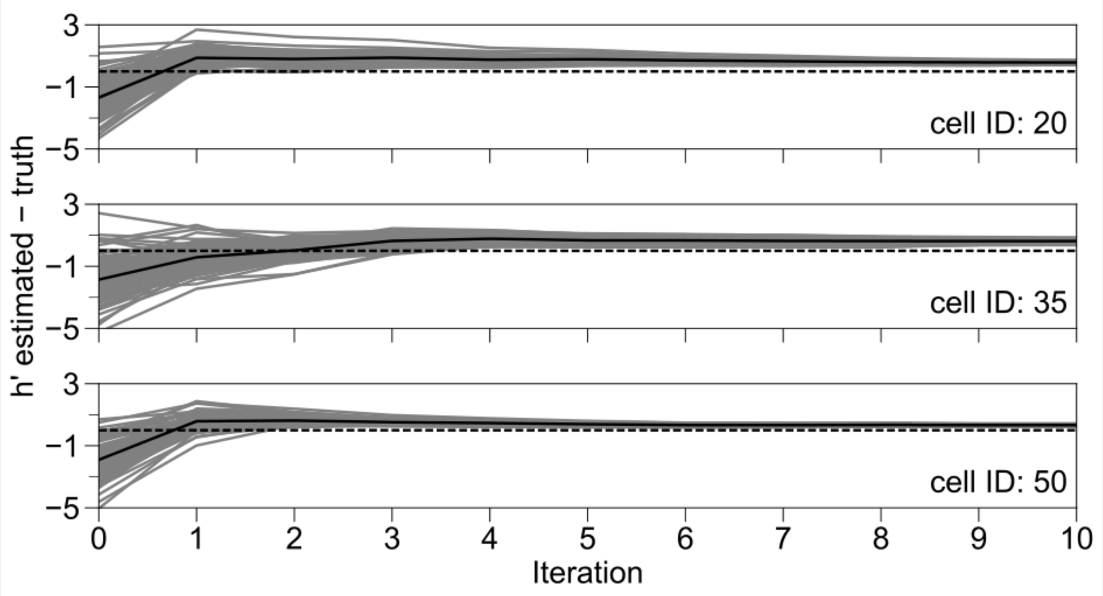
- A statistical method to improve the ionosphere estimate with VLF receiver measurements

How does it work?

- Compares LWPC-simulated (model) and real receiver measurements
- Updates ionosphere estimate by optimally weighting model and measurements based on uncertainty in each
- Model uncertainty is characterized by the sample covariance of an ensemble of estimated ionospheres

EnKF Implementation

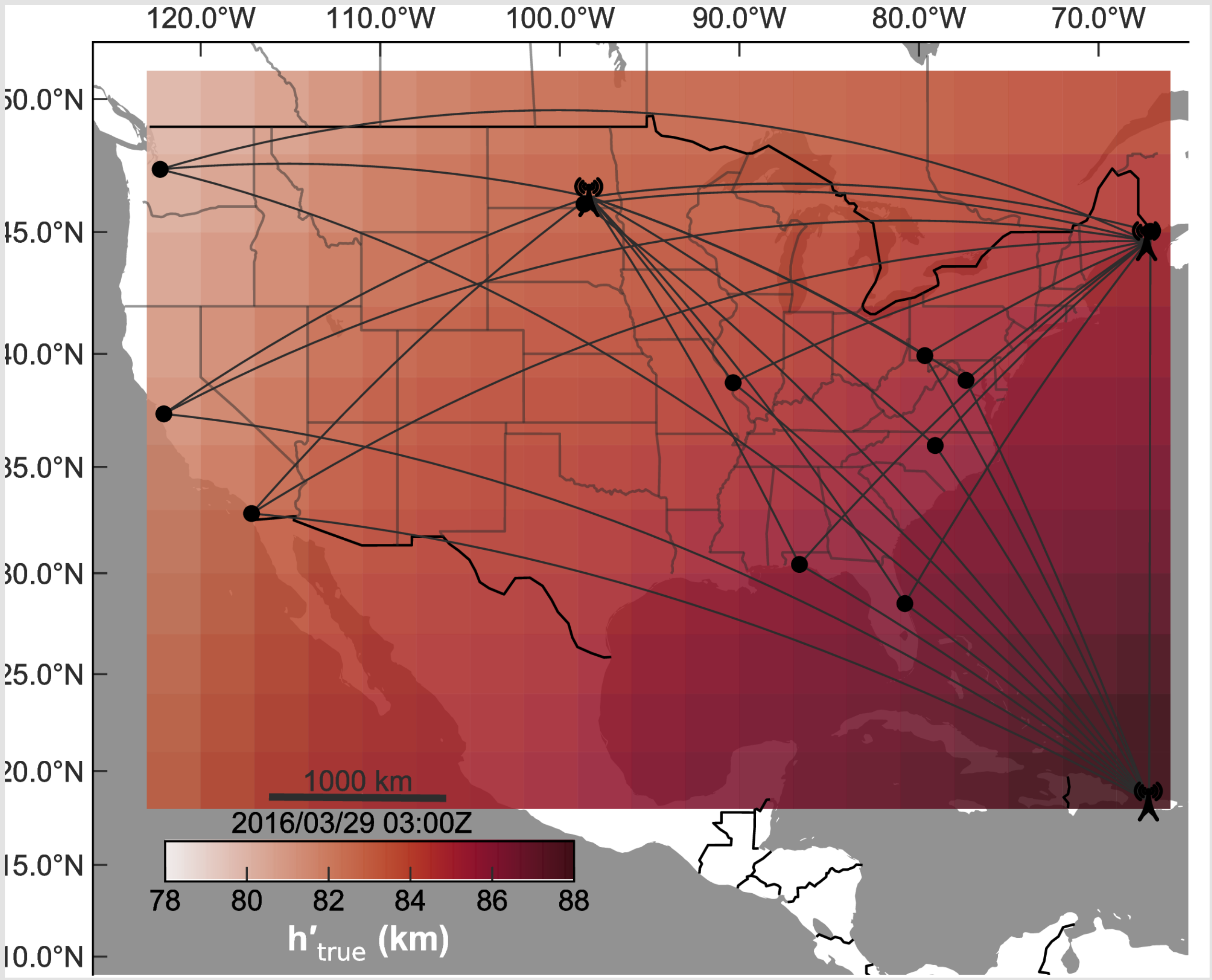
- Ensemble consists of ~100 ionospheres sampled around the "best guess" ionosphere
- LWPC is run for every transmitter/receiver path through each ensemble ionosphere (~3000 runs/iteration)
- EnKF can iterate continuously as measurements are received. Only ~10 *serial* iterations required for convergence

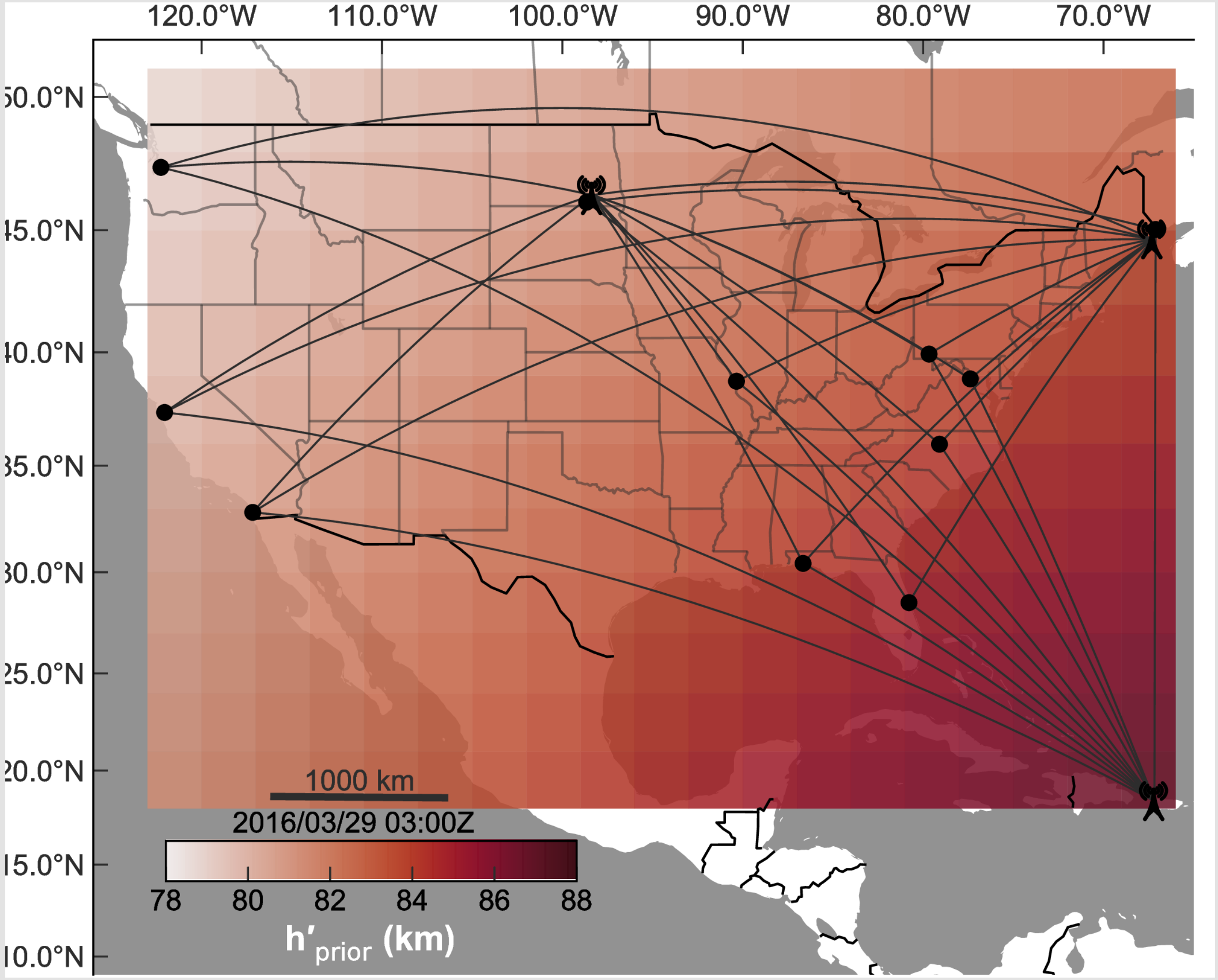


h' estimation error for three different ionosphere grid cells. The initial ensemble considered a large range of possible true ionospheres, but quickly converged to within half a kilometer of the truth.

EnKF applied to D-region estimation

- Ionosphere is approximated by $n_e = 1.43 \times 10^7 \, e^{-0.15h} \, e^{-(\beta-0.15)(h-h')}$





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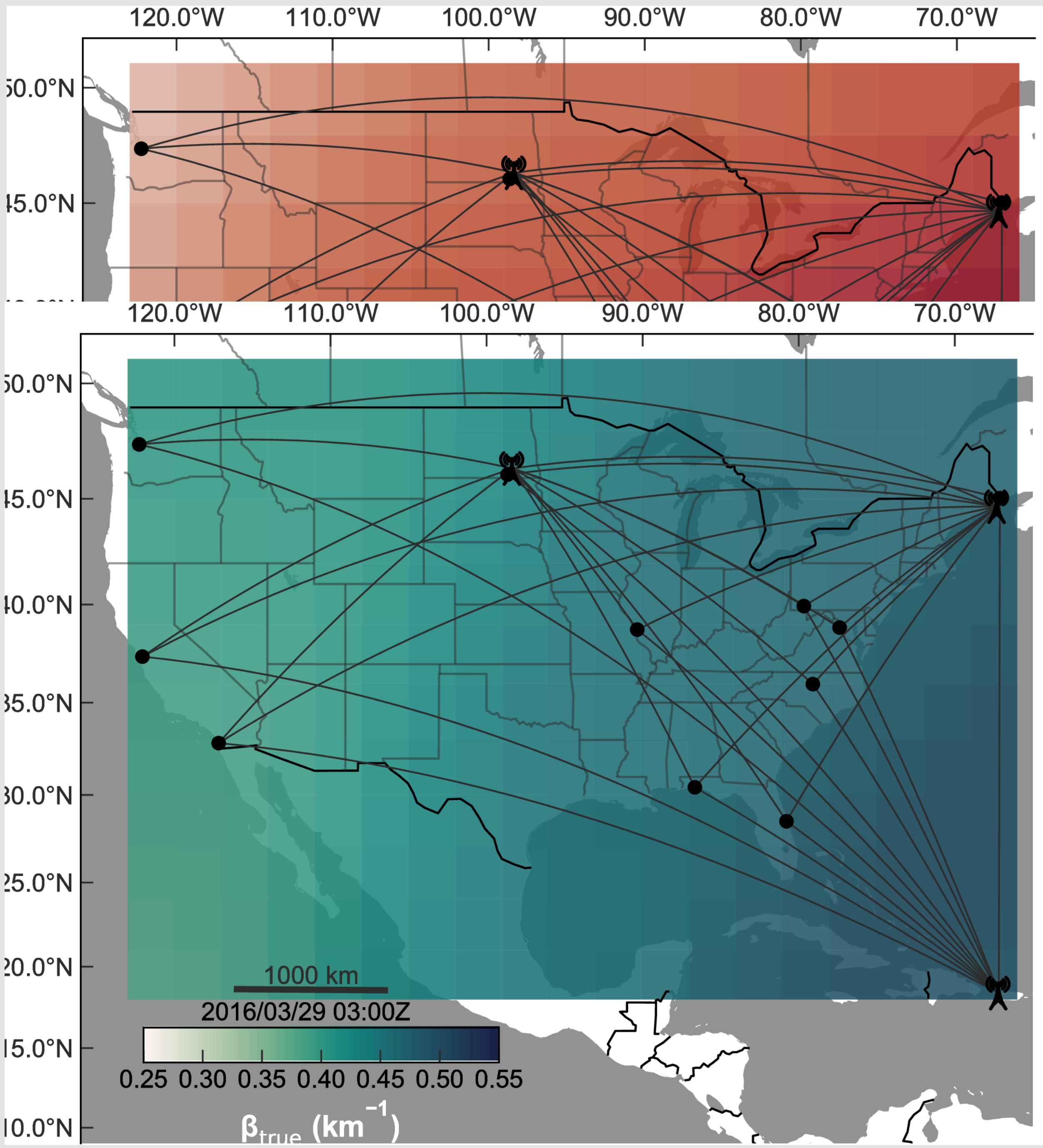
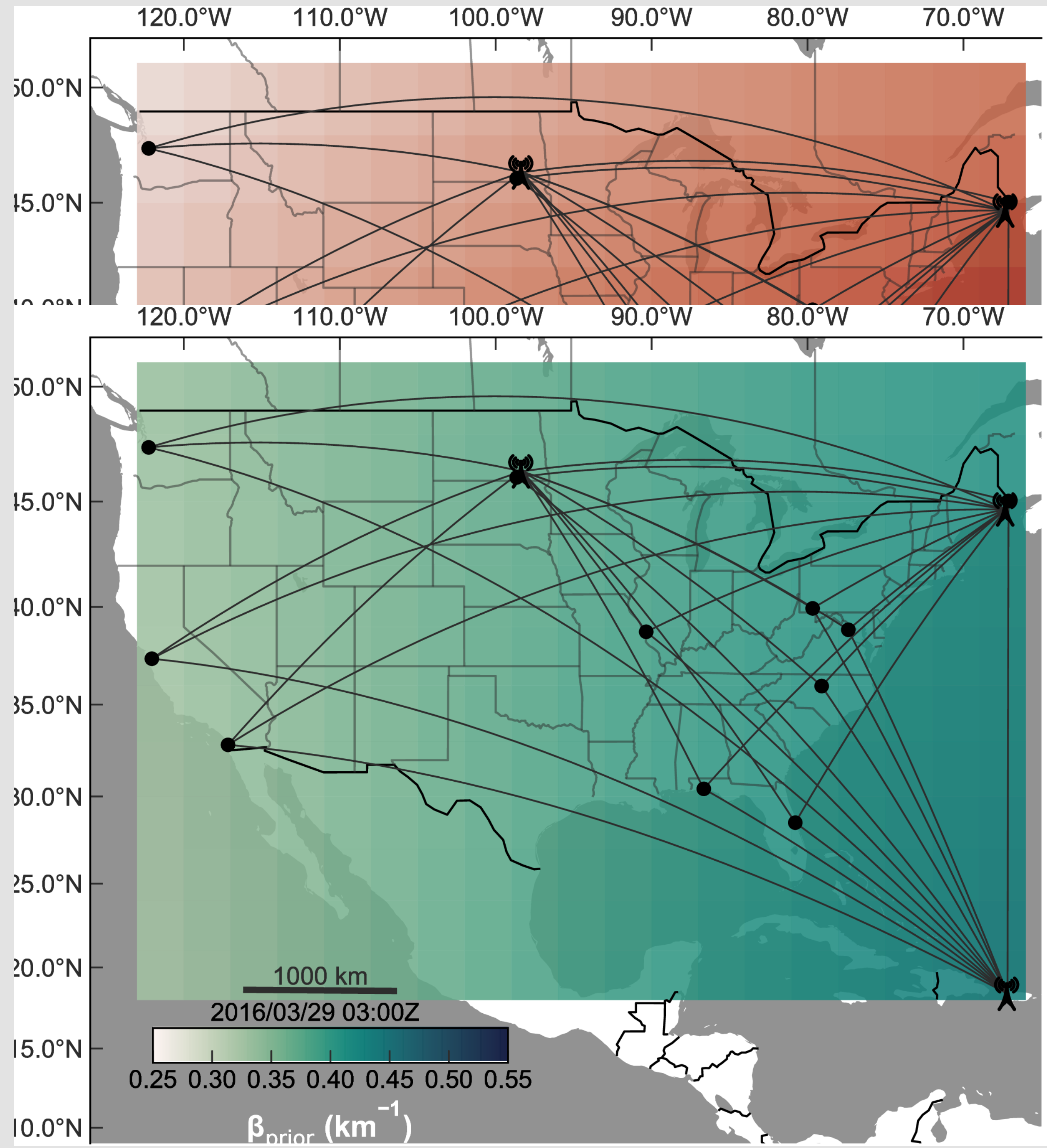
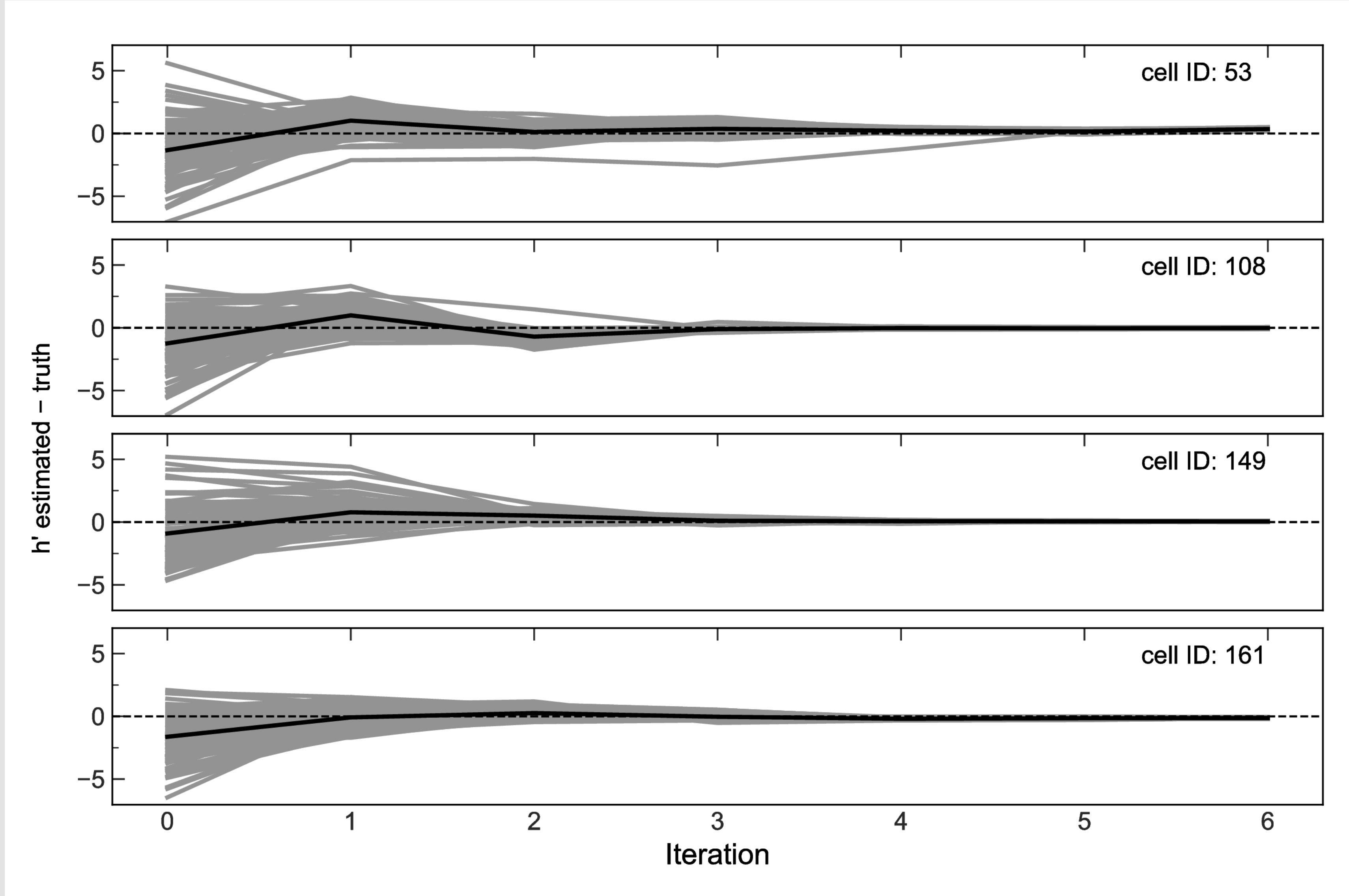


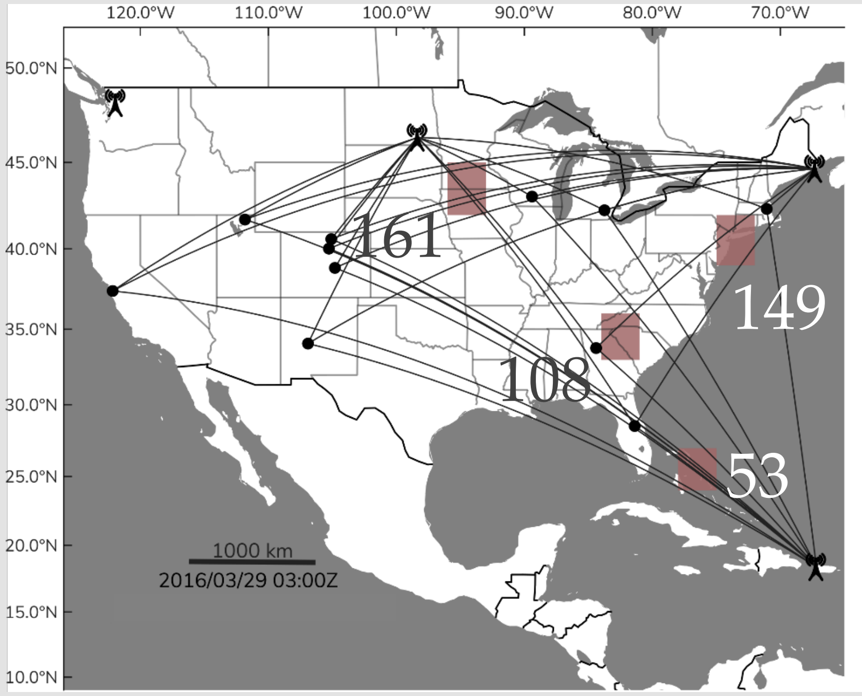


Sample h’ Ensemble Errors

- Each gray line is from 1 ensemble member ionosphere
- Black line is ensemble mean

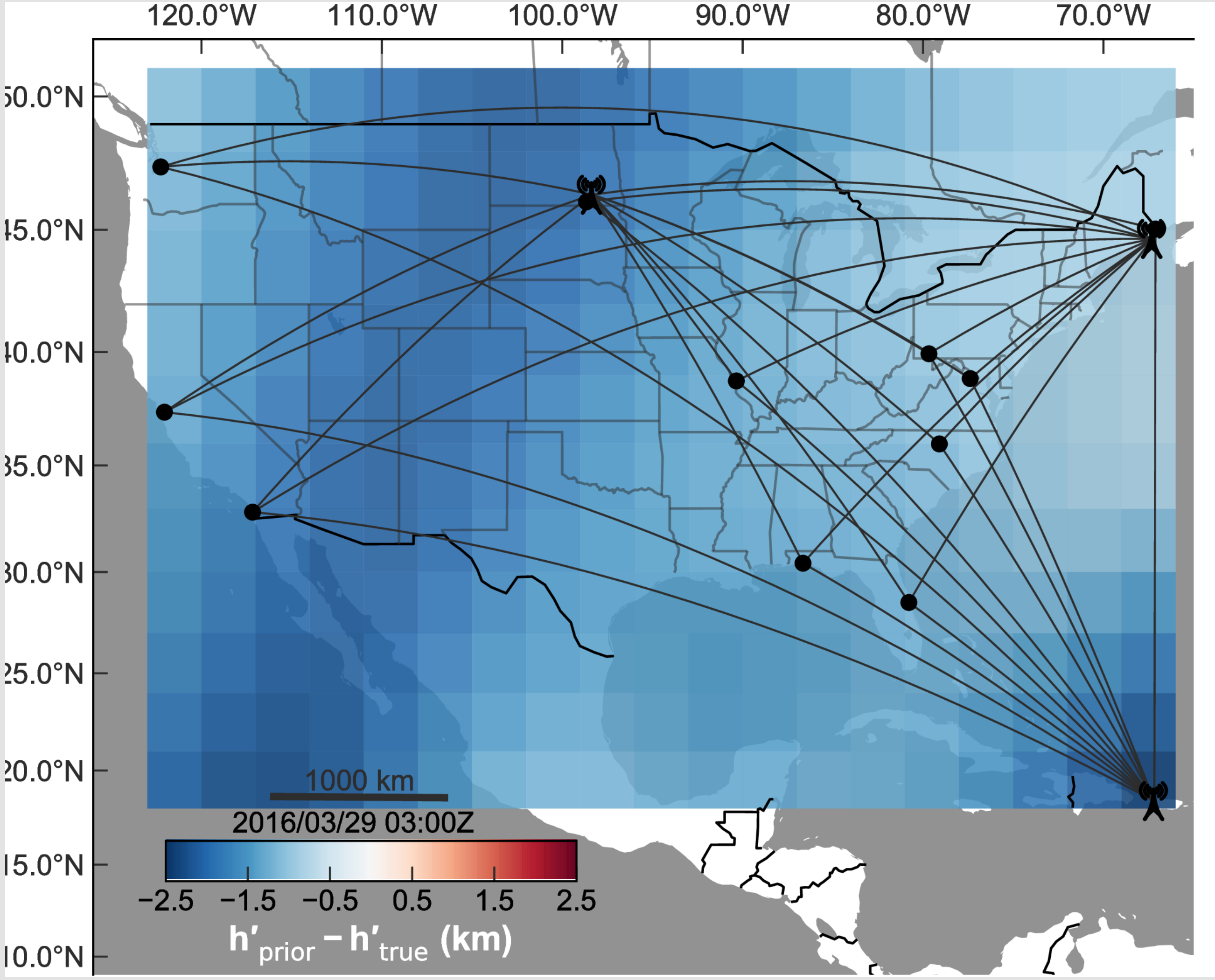
- Initial ensemble distribution is +/- 5 km
- Estimate converges in 3-4 iterations (measurements)

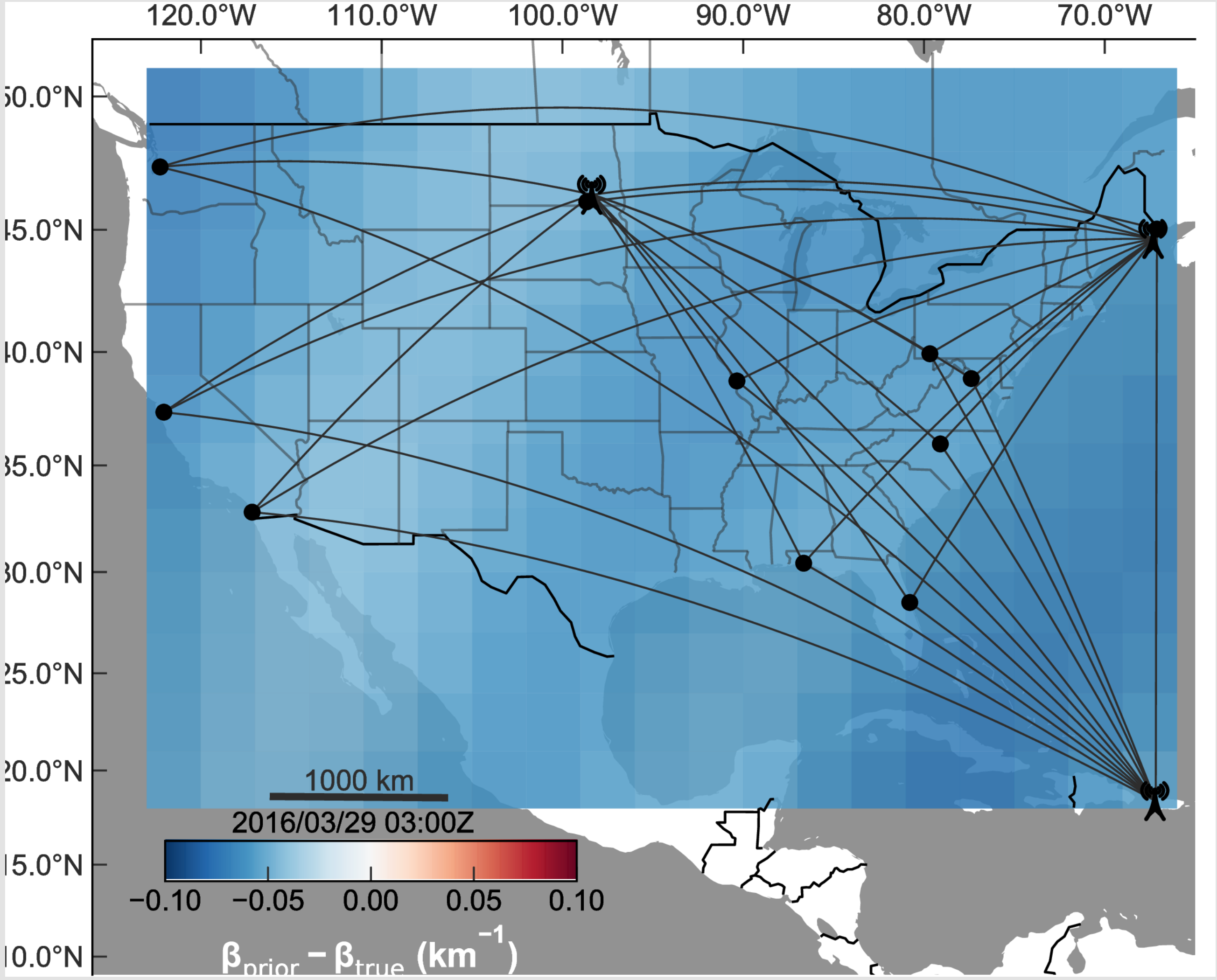




D-region estimation error

- h' and β estimated over entire US with about 0.5 km (h') / 0.05 km^{-1} (β) accuracy
- Model includes realistic receiver noise
- Clear regions where model does poorly, due to poor path coverage





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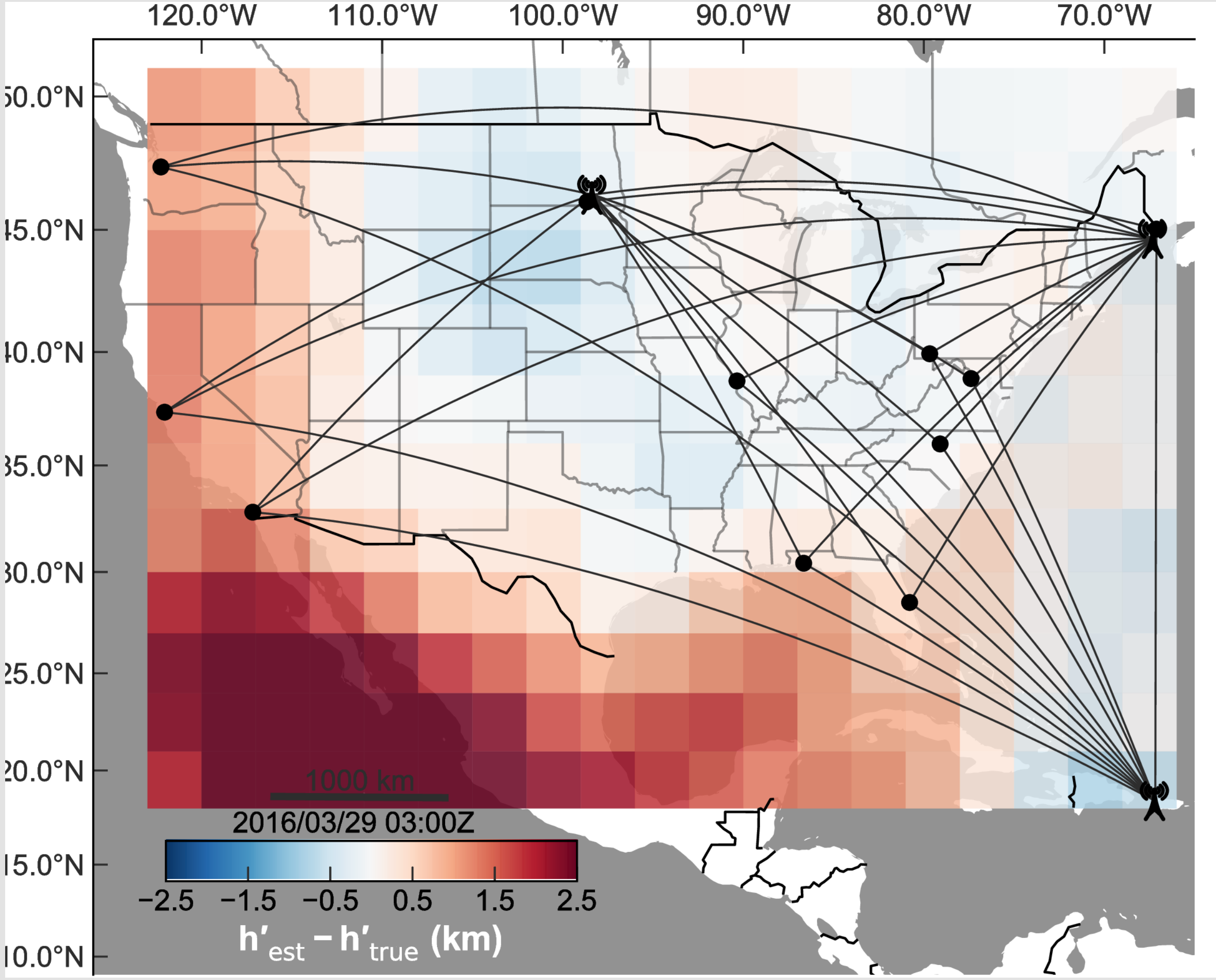
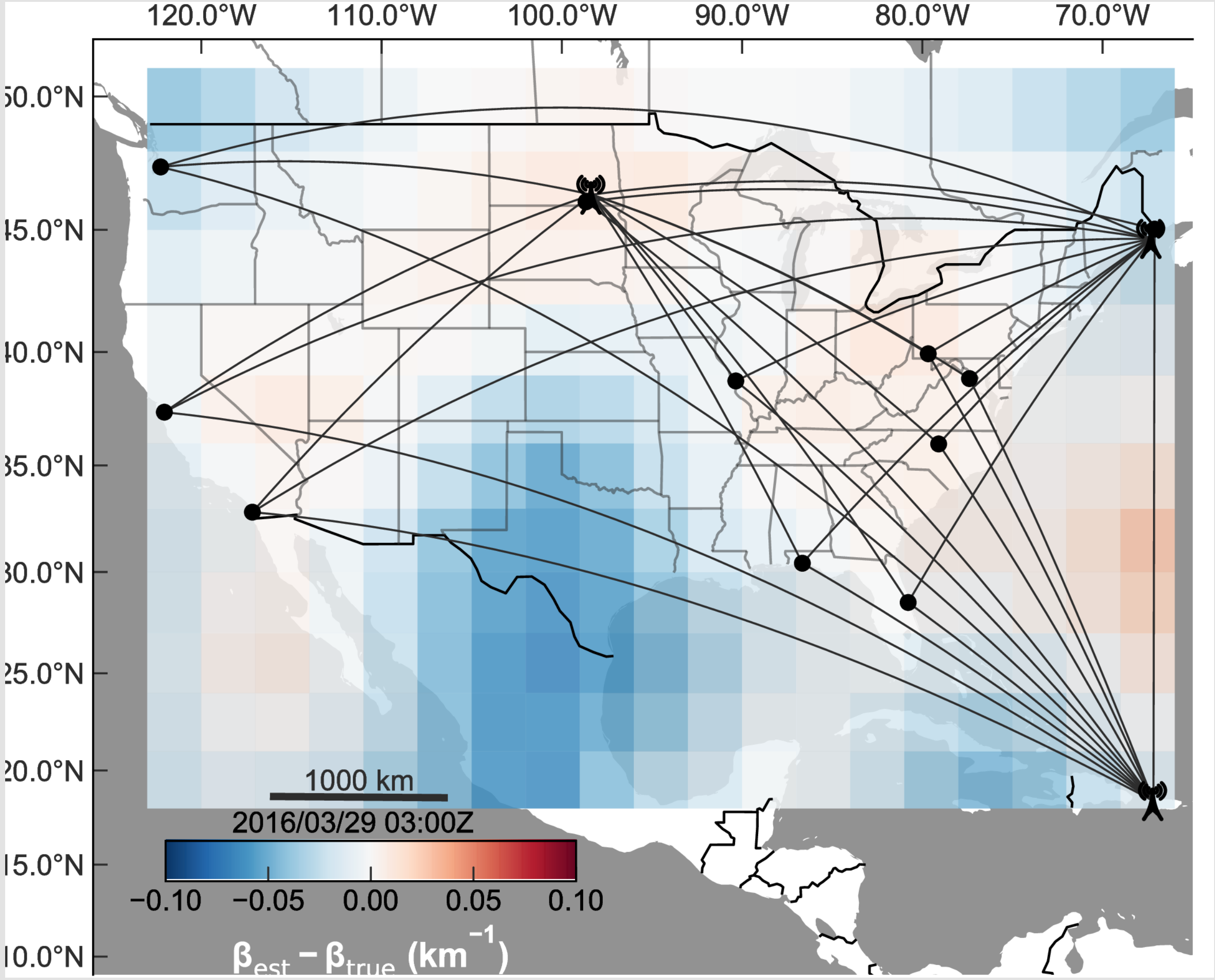
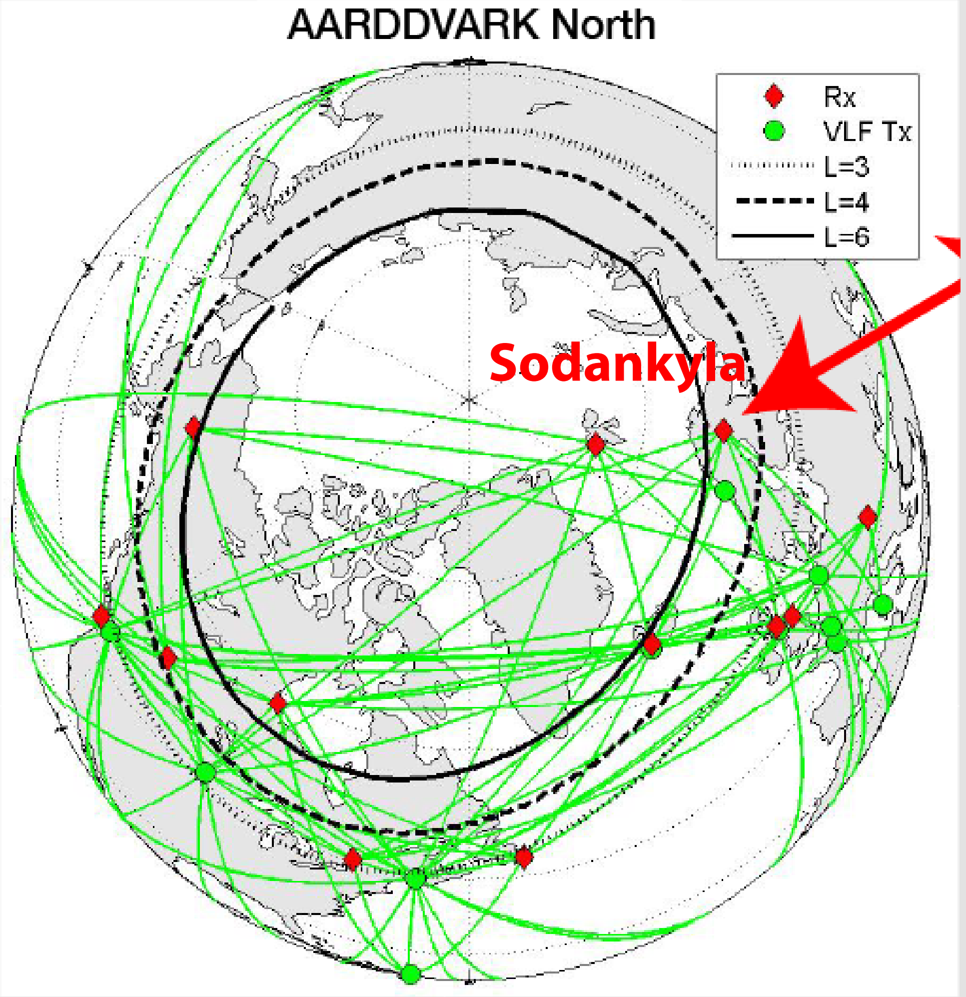




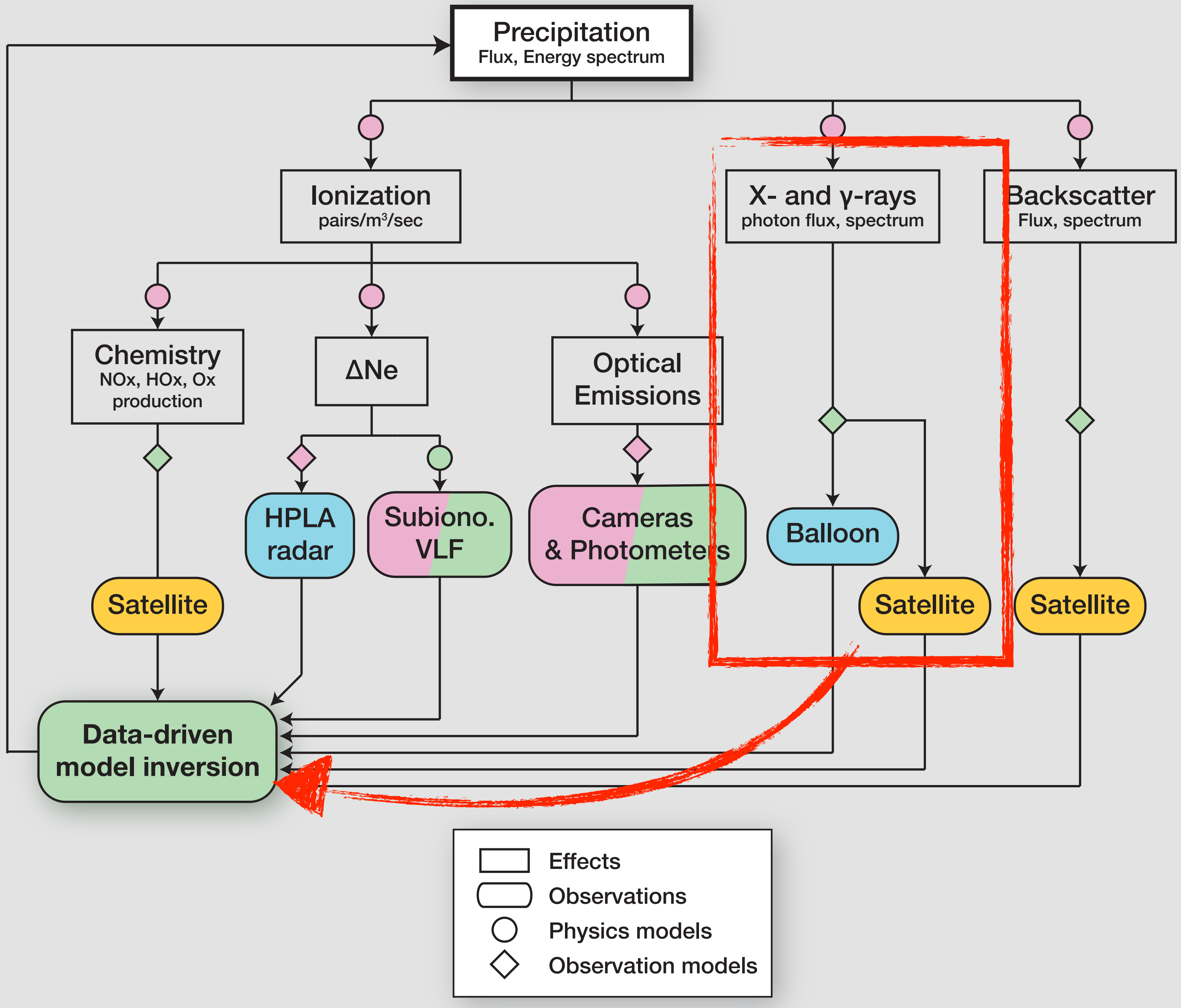
VLF Next Steps…

- **We've determined the 2D D-region ionosphere in terms of h' and beta. Next we need to:**
  - Convert that to precipitation fluxes in each grid cell
  - Assess precipitation regions
  - Move the whole problem to higher latitudes



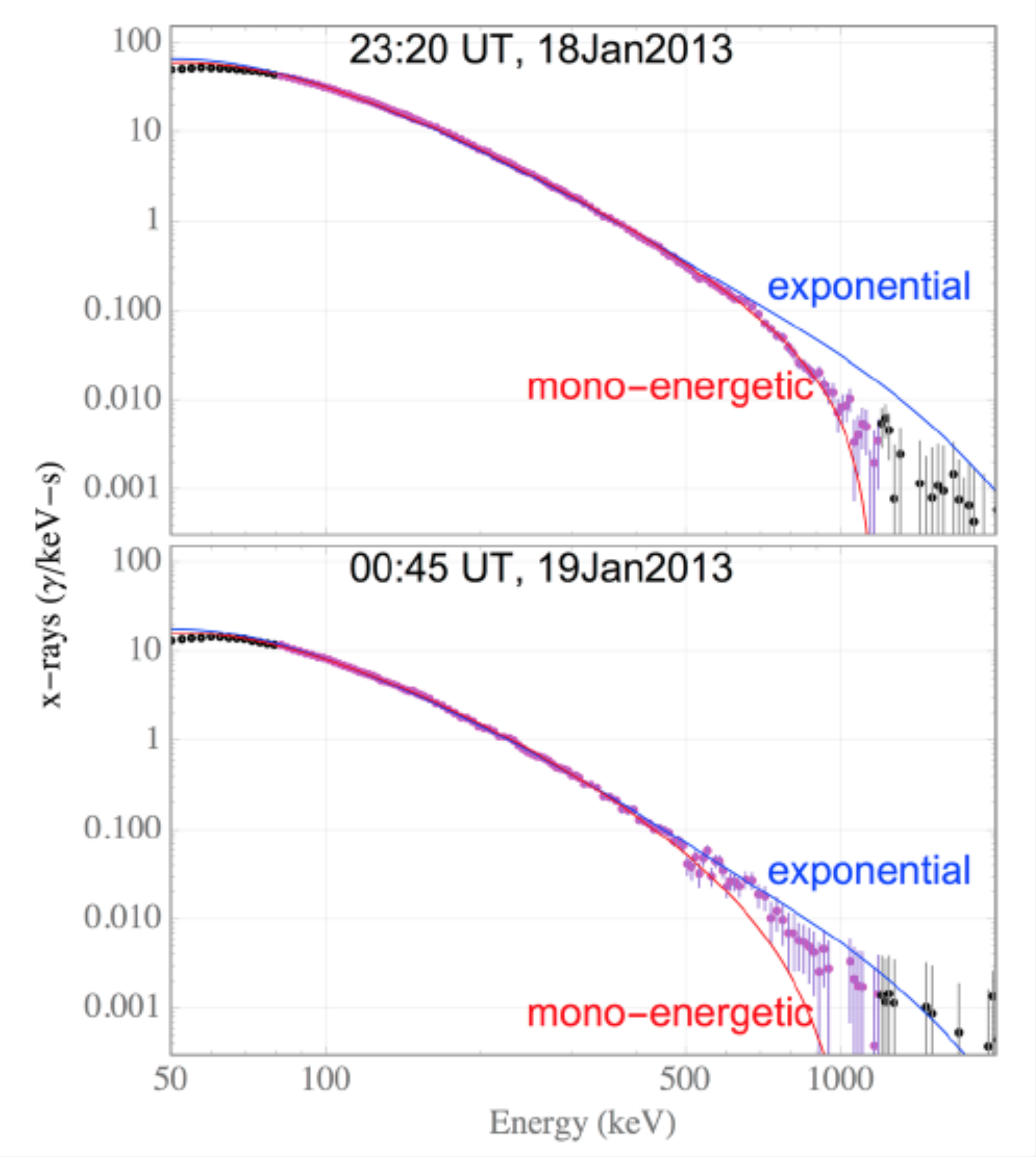
Outline

1. Forward-modeling EPP in the atmosphere: Monte Carlo model
2. forward modeling VLF signatures
3. VLF inversion: enKF
4. **forward modeling X-ray signatures**
5. **X-ray inversion: curve fitting**
6. Ongoing / Future work



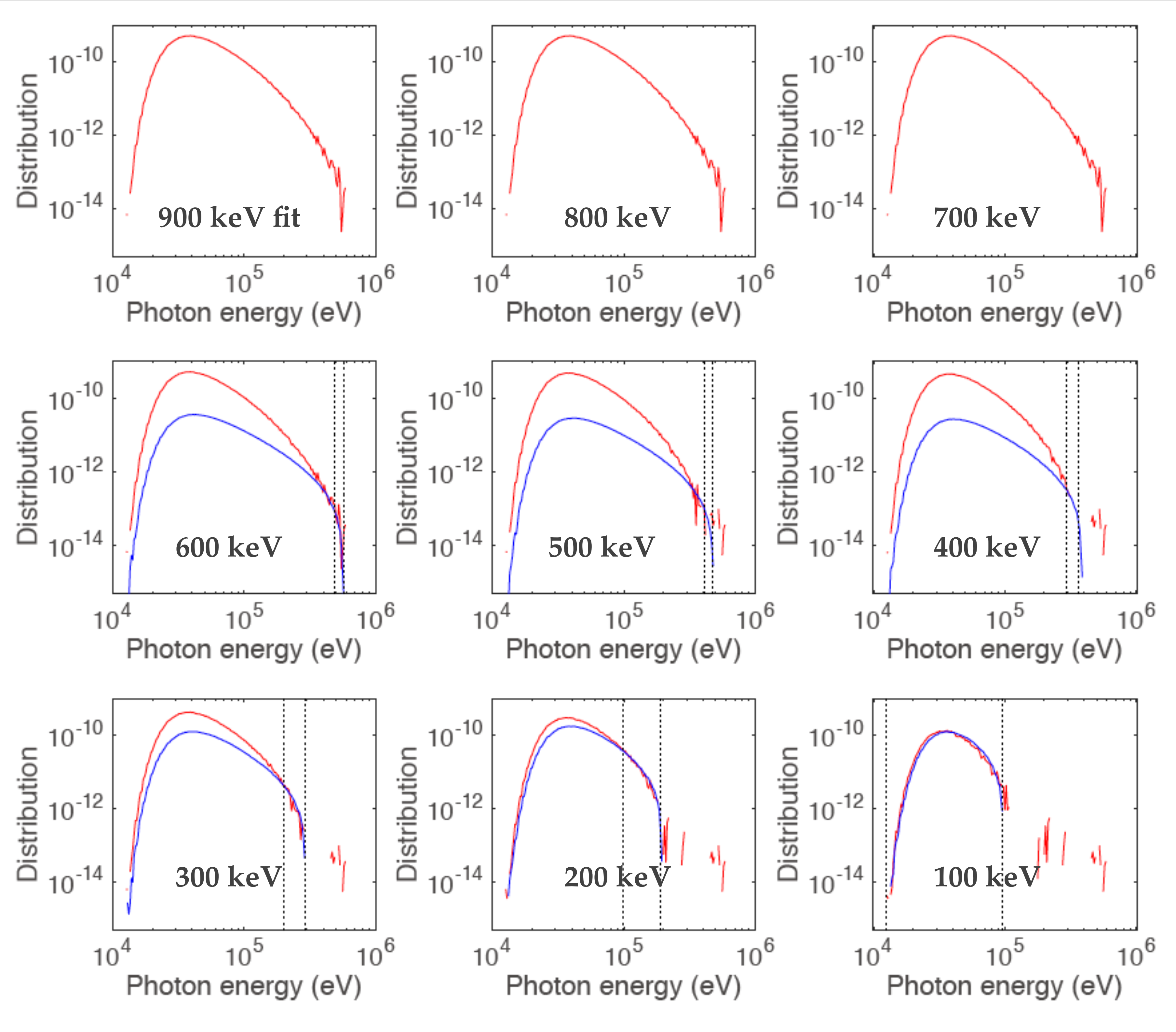
X-ray inversion

- How do we determine the precipitating electron flux and energy distribution from X-ray observations?
- First attempts by Clilverd et al [2017]: basic "best fit" approach
- **Our approach (so far):**
  - Build a set of impulse responses to monoenergetic beams at range of energies
  - Fit data with linear combination of the inpulse responses



Curve fitting to simulated X-ray distribution

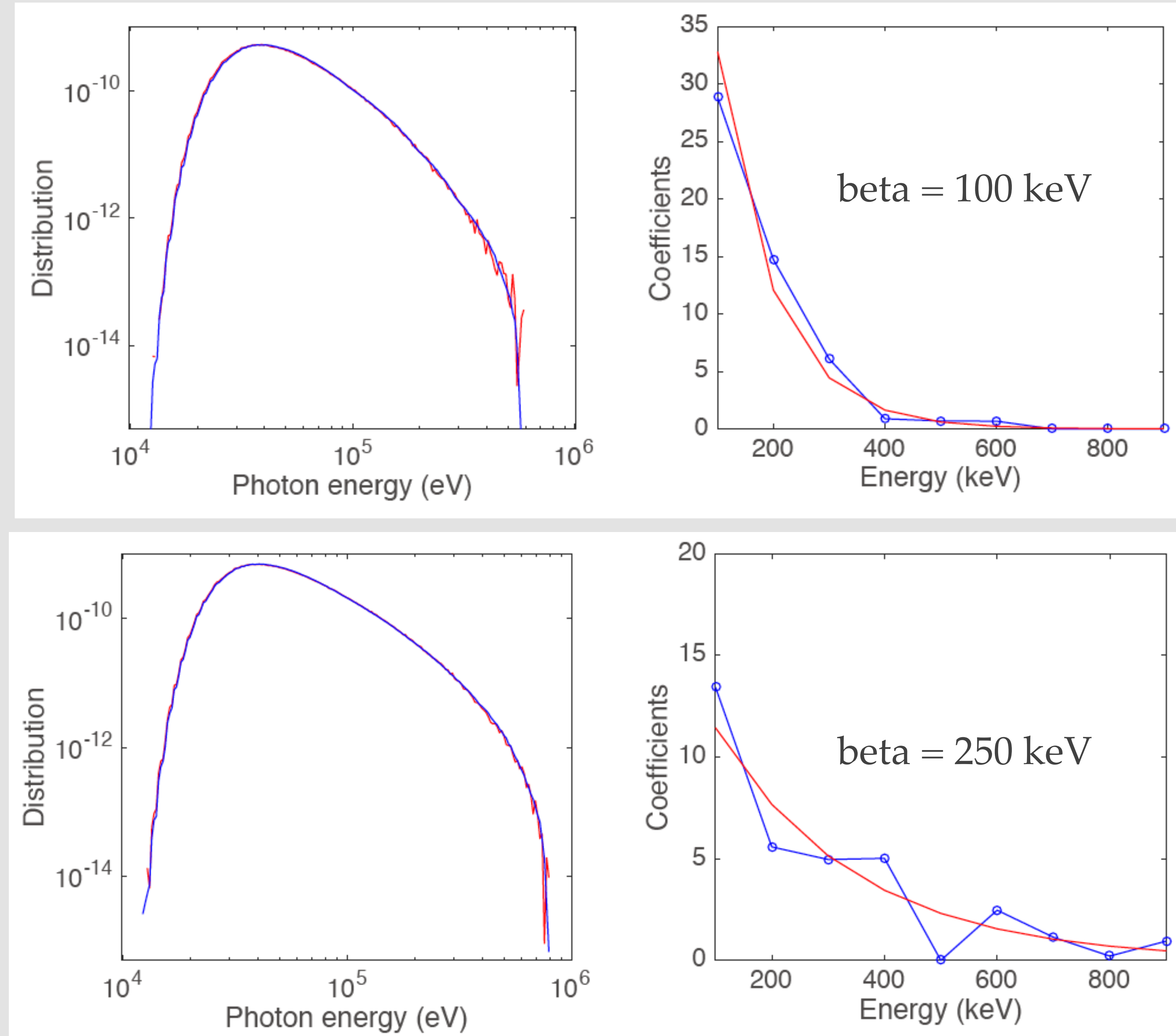
- Successively fit to highest-energy beam; subtract; repeat
- Requires assumed balloon altitude
- Assumes an atmospheric density profile
- Instrument response not yet accounted for



Curve fitting results

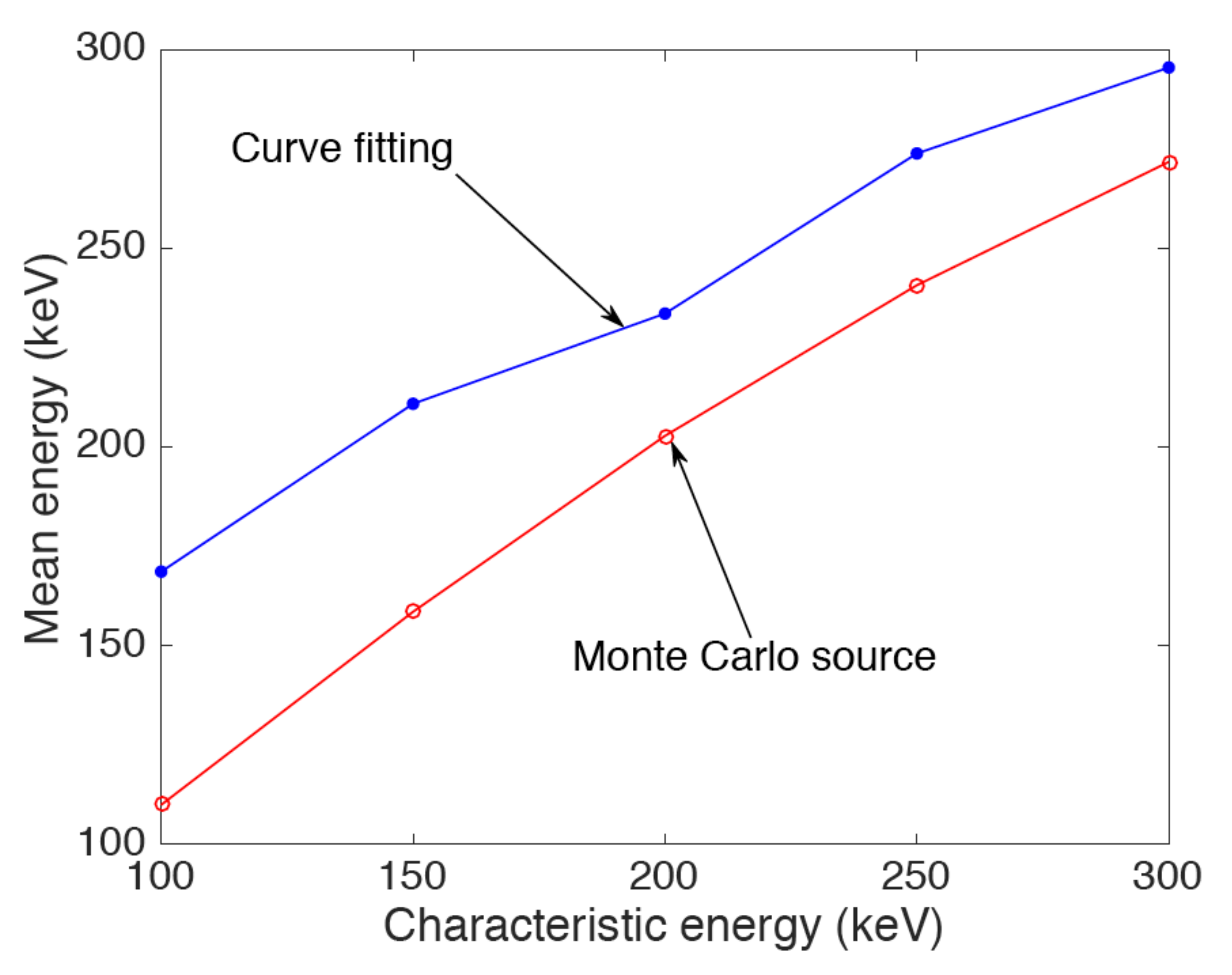
- Fit to X-ray distribution (left) is consistent with input
- Extracted electron energy distribution is quite good!
    - Simulated through identical atmosphere; need to test with uncertain atmosphere
- But, due to low particle fluxes at high energies, the fitting isn't always so smooth…

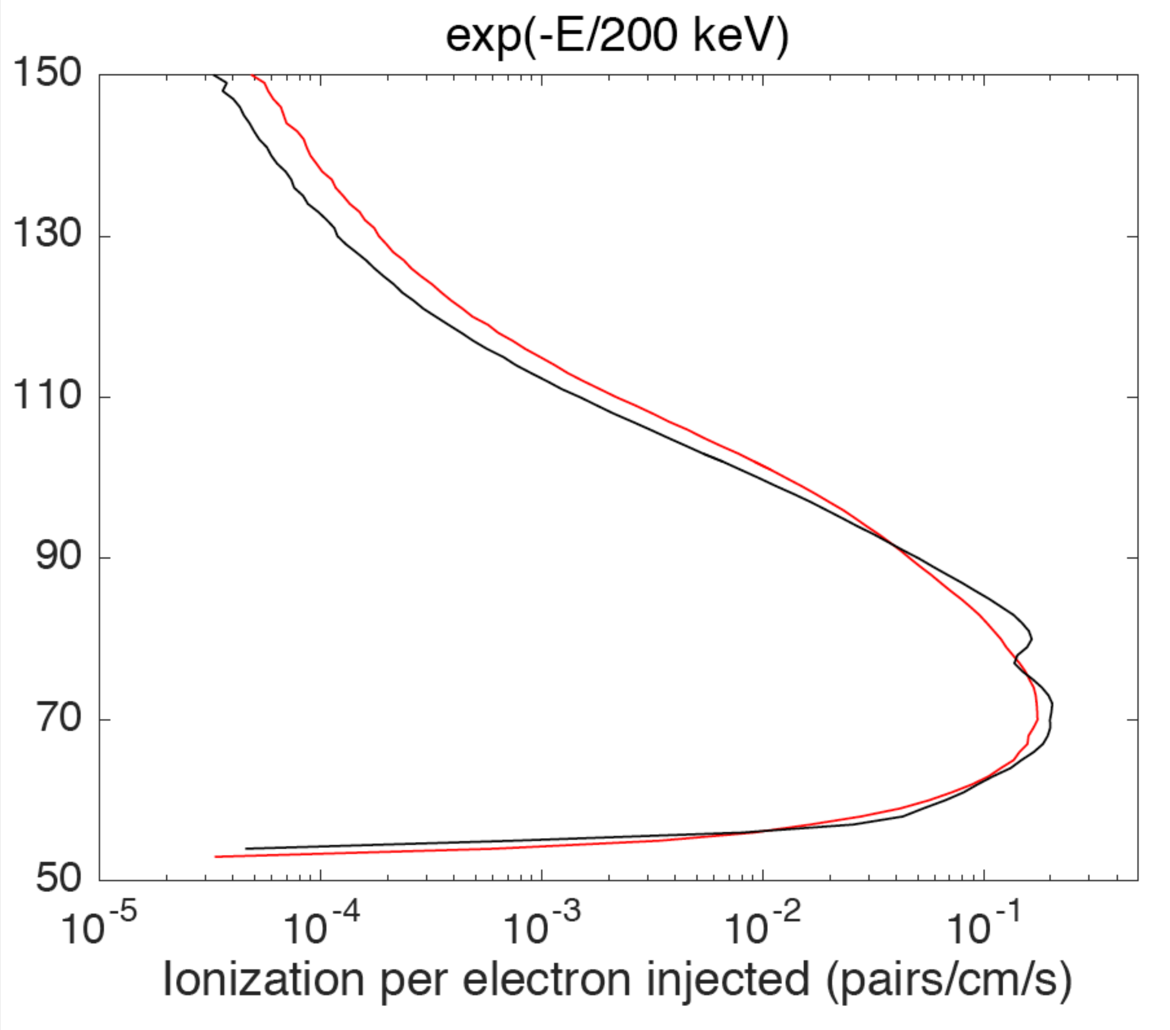
Initial vs. inferred Photon distribution | **Initial vs. inferred Electron distribution**



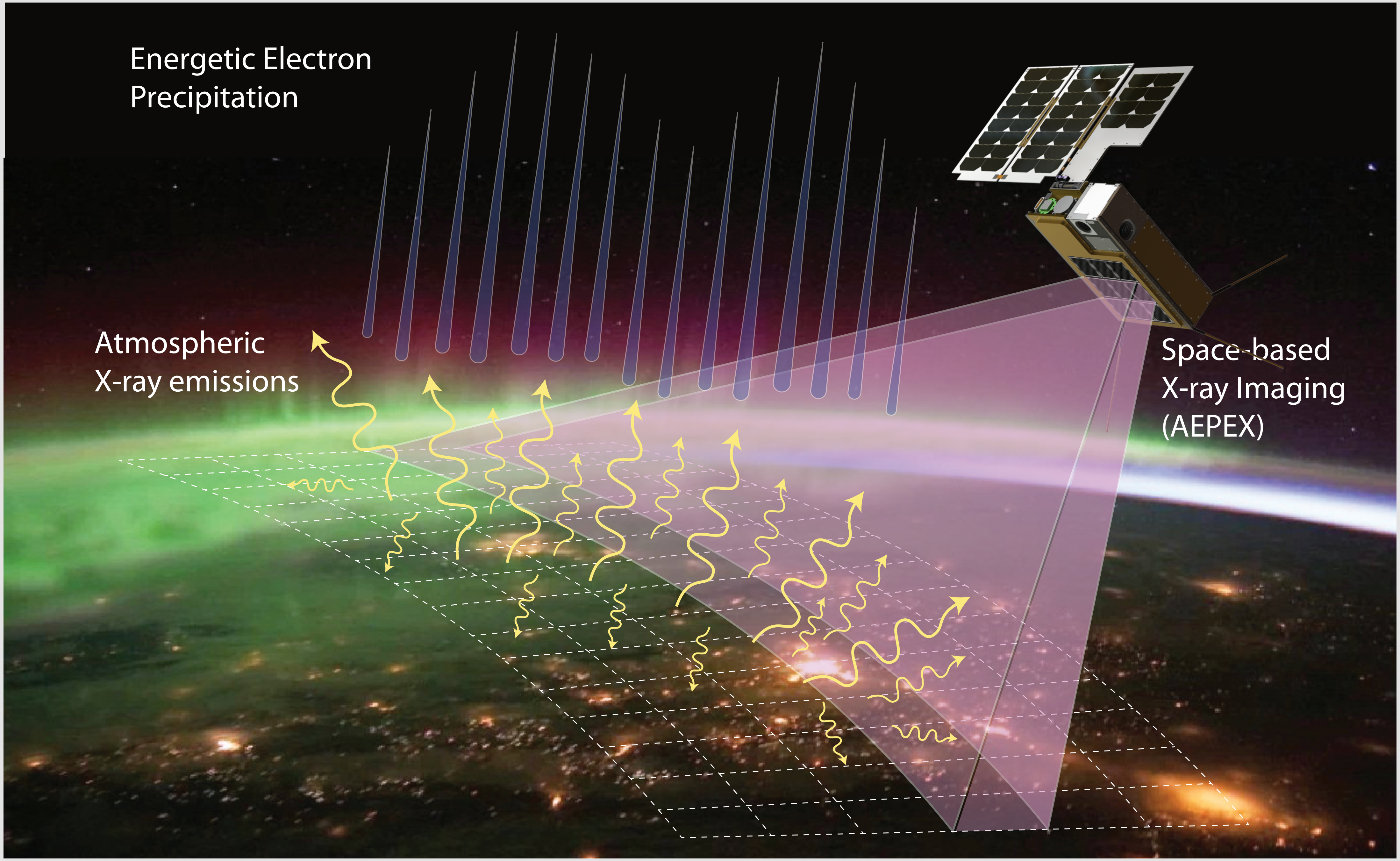
Curve fitting: Energy flux

- … but, in all cases the energy flux estimate is quite good, and the resulting atmospheric deposition profile is very good.
- **Ongoing work: refining the method; extending to 2 MeV; applying to BARREL data**





Space-based X-ray measurements



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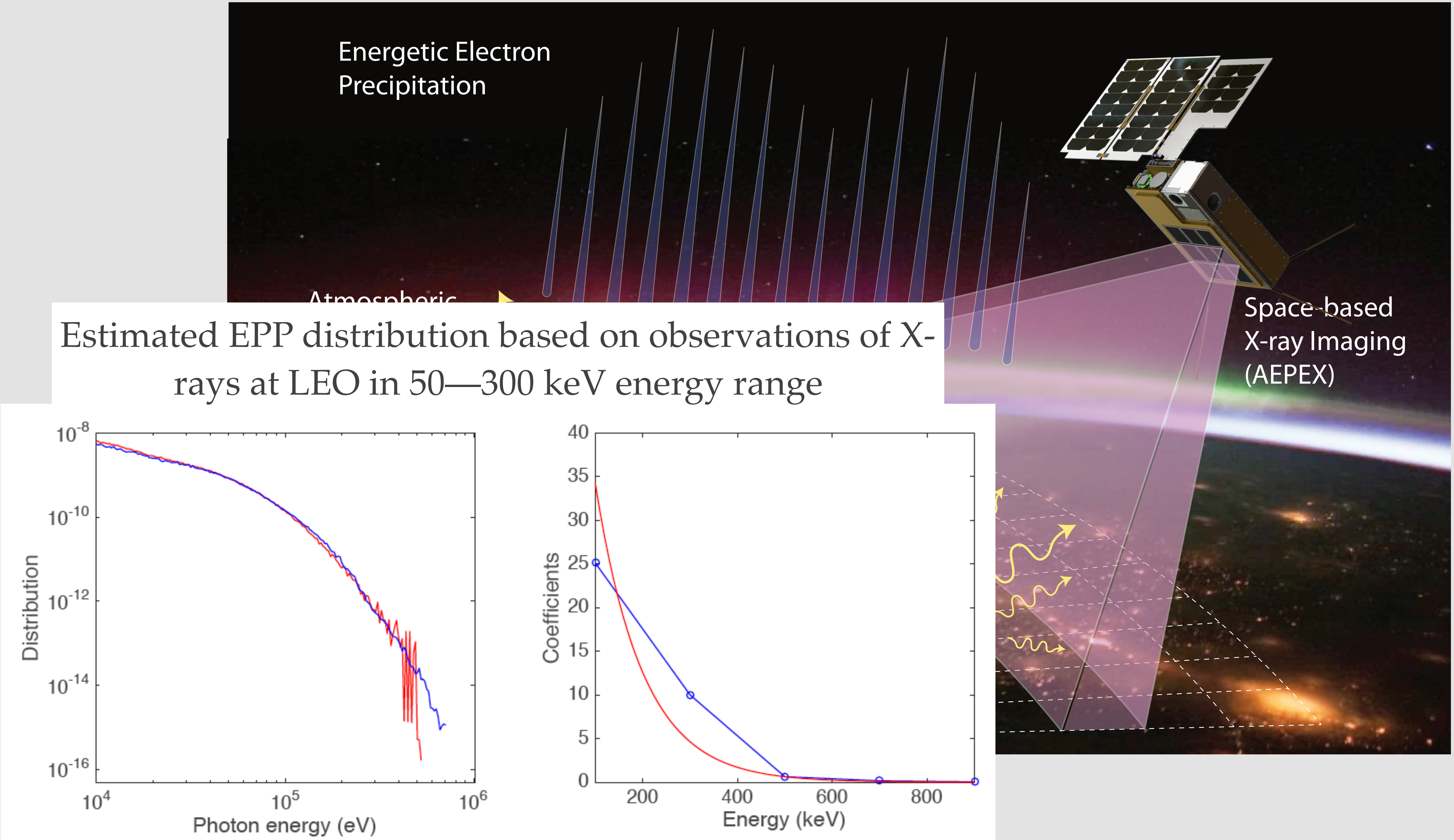

Summary

- VLF amplitude and phase on single transmitter-receiver path is poorly correlated with precipitation flux, spectrum, spatial size…
- VLF “tomography” has promise for measuring the D-region ionosphere over large regions, and in turn inferring the precipitation signatures
- Developed a model of X-ray signature inversion to EPP spectrum
- Future X-ray observations from above will also address spatial scales