Isolating Solar Eclipse Features using Supervised Machine Learning

Mateo Cardona Serrano[1] (they/them)

Advisors: *Sevag Derghazarian[2], Larisa Goncharenko[2], Shunrong Zhang[2], Dupinder Singh[2]*

[1]University of California, Berkeley, CA
[2]MIT Haystack, Westford, MA

Millstone Hill Ionospheric Steerable Antenna (MISA)

MIT HAYSTACK OBSERVATORY

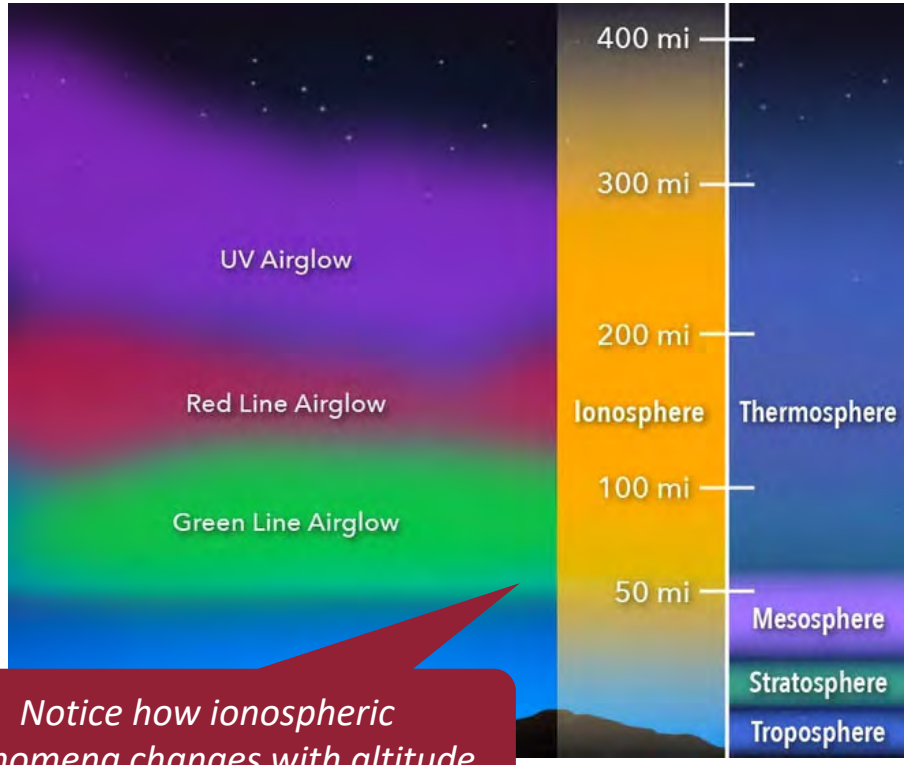
MISA pointed south-west-ish in Westford, MA

- The radar emits high-power radio waves (2.5 MW)
  - The waves are scattered incoherently off the electrons in the ionosphere
  - The returned power yields the electron density and other observations
- 90 to 1000km altitude range
  - Wide latitude and longitude range
  - From the arctic circle to the state of Florida
- Records electron density and temperature.

The Ionosphere in a Nutshell

MIT HAYSTACK OBSERVATORY

- Spans 50 – 400 mi (~80 – 600km) above the surface of the Earth.
- Energy from the sun hits neutral molecules in the atmosphere, causing them to release an electron.
  - sun's energy -> more ionization -> more electrons & ions -> more plasma
  - Quantified as electron density (Ne) [m-3]

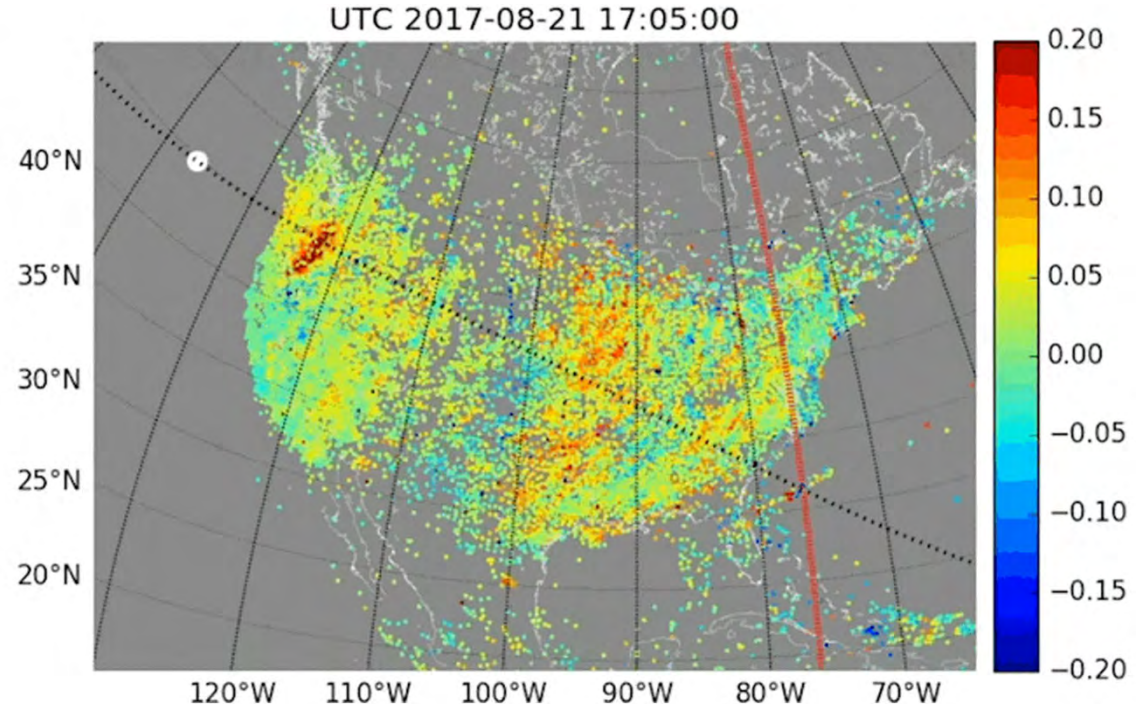


Notice how ionospheric phenomena changes with altitude.

2017 Eclipse Ionospheric Effects

MIT HAYSTACK OBSERVATORY

Solar eclipse illustrates how ionosphere is affected by activity:

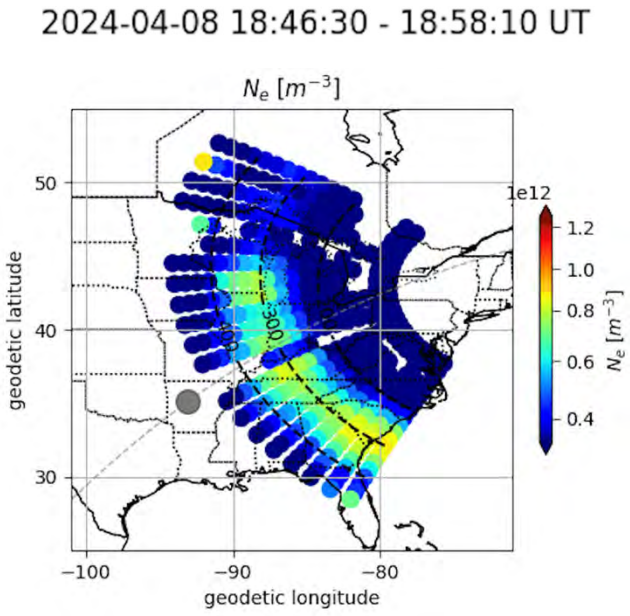


Zhang, S.-R., Erickson, P. J., Goncharenko, L. P., Coster, A. J., Rideout, W., & Vierinen, J. (2017). Ionospheric bow waves and perturbations induced by the 21 August 2017 solar eclipse. Geophysical Research Letters, 44. https://doi.org/10.1002/2017GL076054

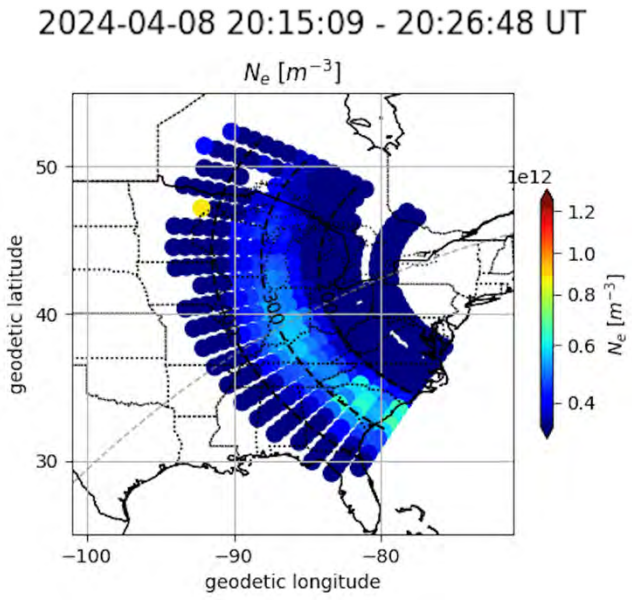
2024 Eclipse Data (Low Confidence)

MIT HAYSTACK OBSERVATORY

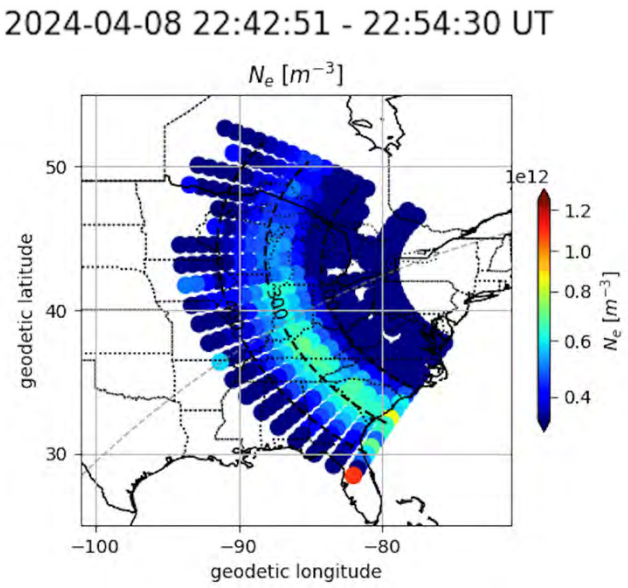
Recorded Electron Density at three different times, on the day of the eclipse:



Umbra approaching.
13:00 LT

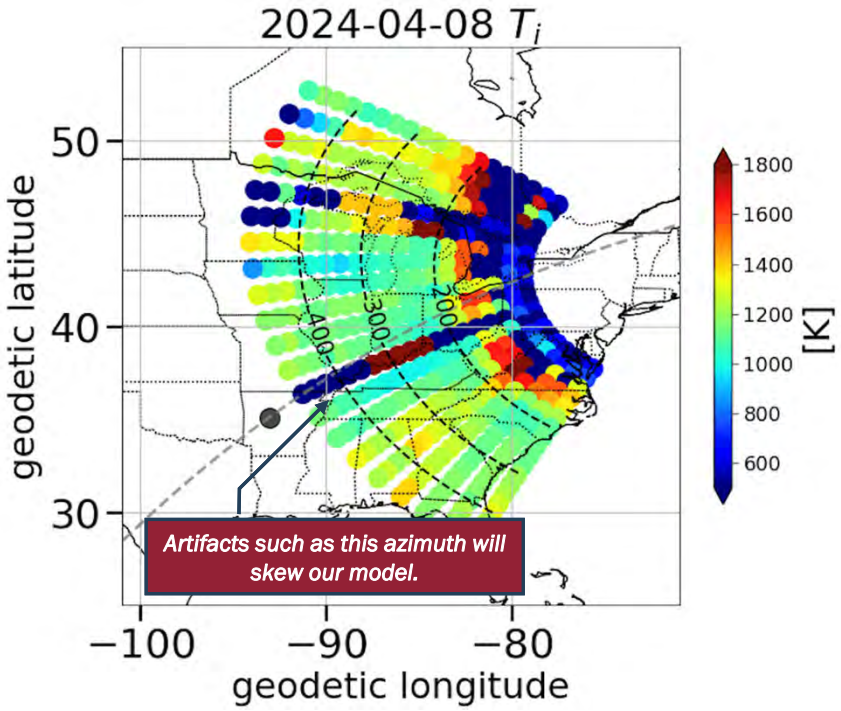


1.5 hours after umbra.
14:30 LT



4.0 hours after umbra.
17:00 LT

Cleaning Up Artifacts



Recorded electron density (Ne), electron temperature (Te), ion temperature (Ti), and line-of-sight velocity (Vo) on April 8th.

The eclipse event was preceded by a period of elevated geomagnetic activity earlier in the day, making isolating the eclipse's effects on the ionosphere challenging.

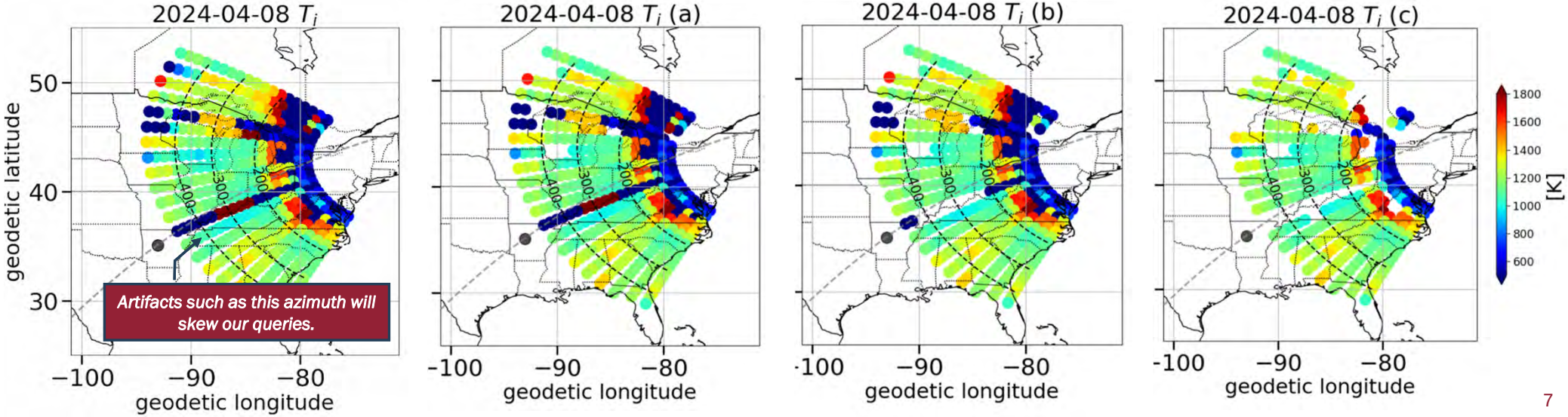
If we could clean up and filter out everything except the effects of the eclipse, we could record the magnitude of its effects!

Filtering Chain

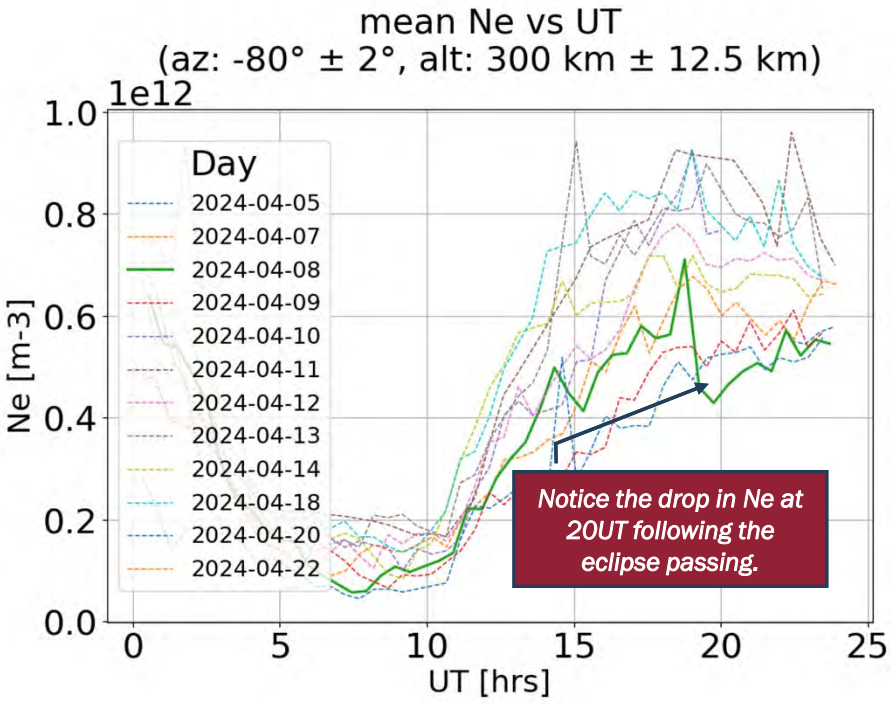
MIT HAYSTACK OBSERVATORY

First, we must filter out artifacts from the data products:

Unfiltered data → **Elements exceeding a 25% instrument rel. error are removed.** → **Elements in a given azimuth exceeding 2.5 standard deviations are removed.** → **Data is binned by alt. The bottom ~5th percentile of data within each bin is removed.**



Isolating the Eclipse Effects



- We are interested in isolating the eclipse features from the geomagnetic storm.
- Theory:
  - *eclipse day – background = eclipse features!*

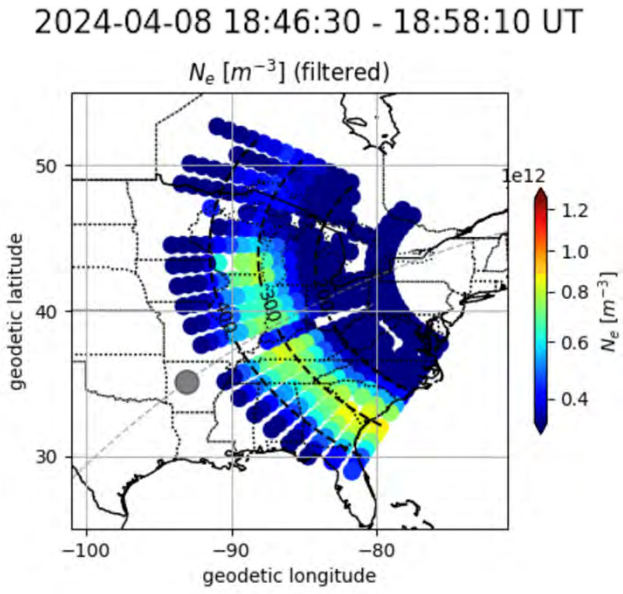
Problem Statement:

How do we identify which features are a result of the solar eclipse, and which are of the preceding geomagnetic storm?

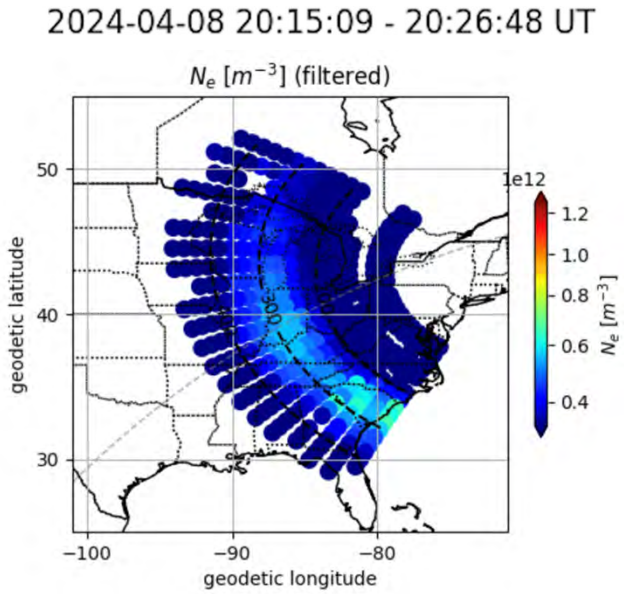
2024 Filtered Eclipse Data

MIT HAYSTACK OBSERVATORY

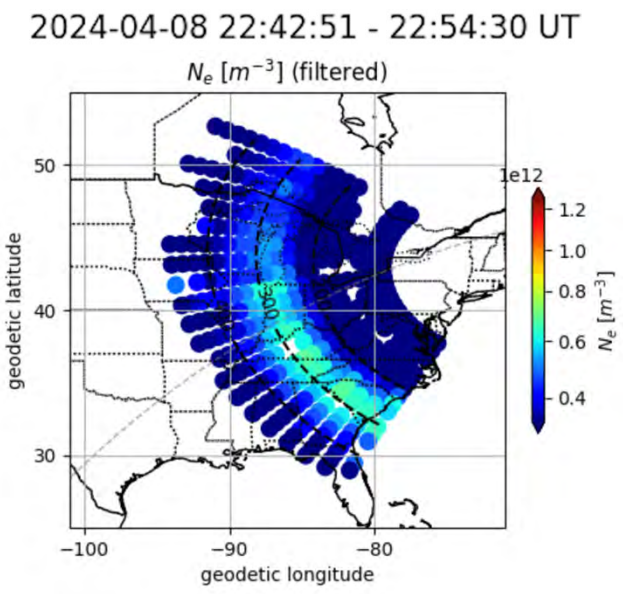
Another view of the effects we want to isolate:



Umbra approaching.

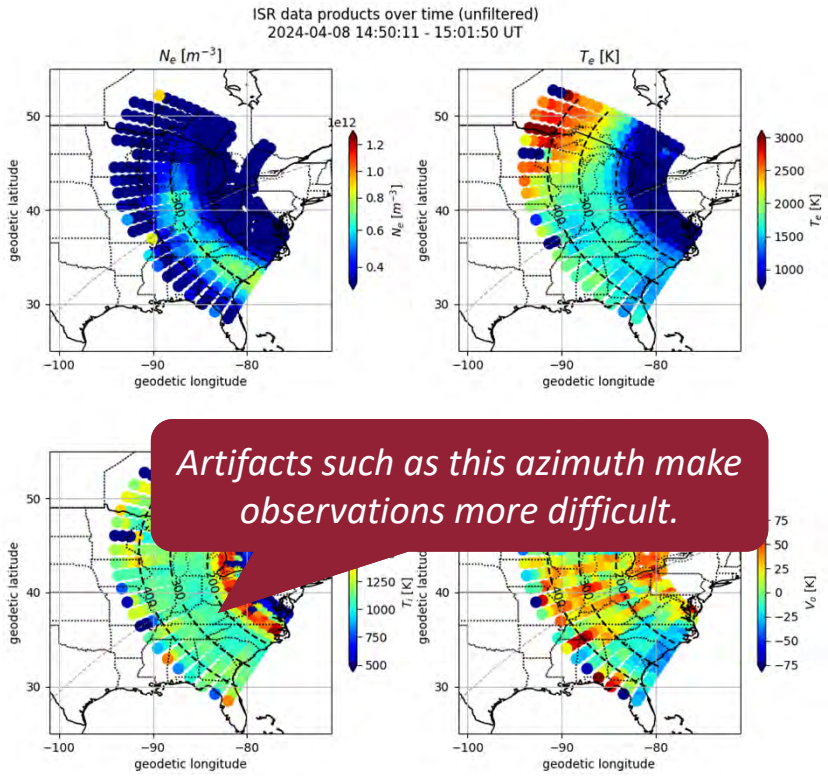


1.5 hours after umbra.



4.0 hours after umbra.

More 2024 Eclipse Data



Recorded electron density (Ne), electron temperature (Te), ion temperature (Ti), and line-of-sight velocity (Vo) on April 8th.

MIT HAYSTACK OBSERVATORY

- Eclipse event preceded by a period of elevated geomagnetic activity.
- Makes isolating the eclipse's effects on the ionosphere challenging.

Principal Challenge:

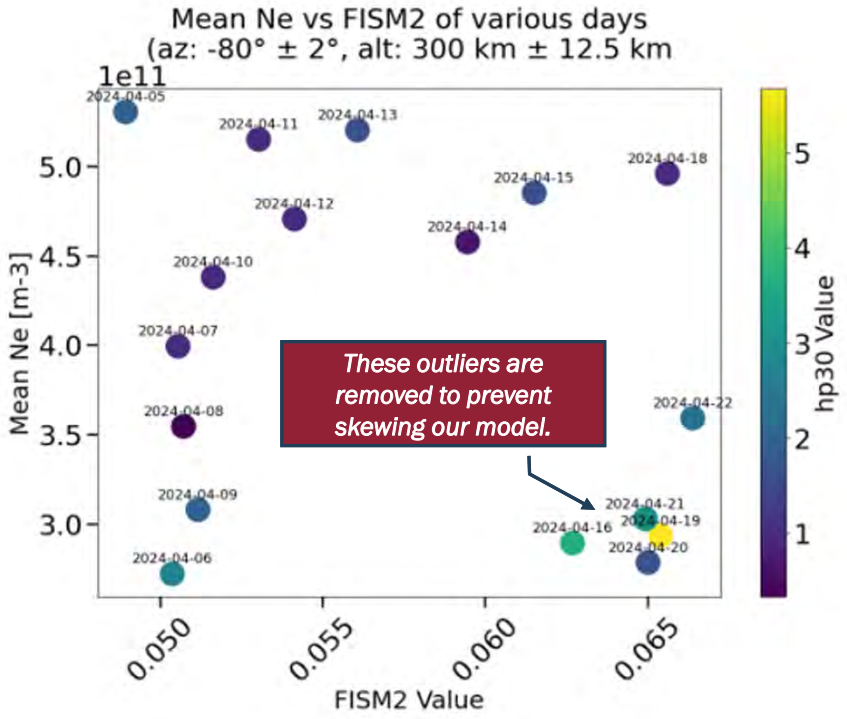
How do we identify which features are a result of the solar eclipse, and which are of the preceding geomagnetic storm?

If we could clean up and filter out everything except the effects of the eclipse, we could record the magnitude of its effects!

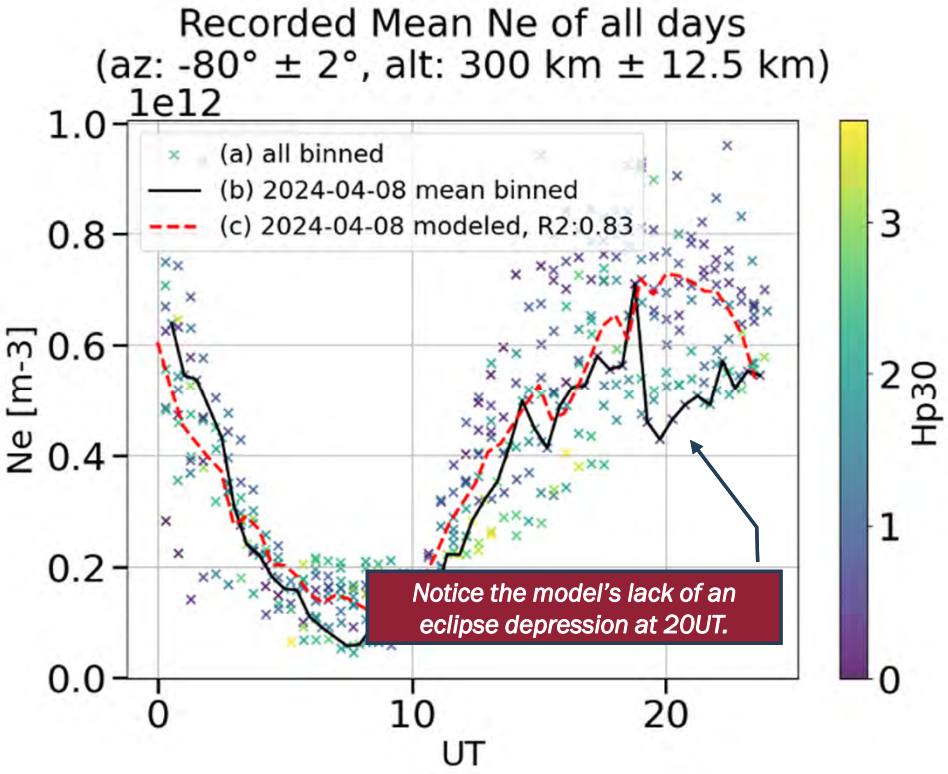
Quality and Correlation

MIT HAYSTACK OBSERVATORY

- Input Variable -> Model -> Output Variable
  - Output quality improves if the training data is correlated.
- Geomagnetic indices describe the magnetic activity at a planetary scale.
  - We use Flare Irradiance Spectral Model (FISM2) and HP30 index.
  - More nuanced variants of f10.7 and KP index.
- Results motivated us that geophysical indices could be used to create a good model after removal outliers.



Training The Model



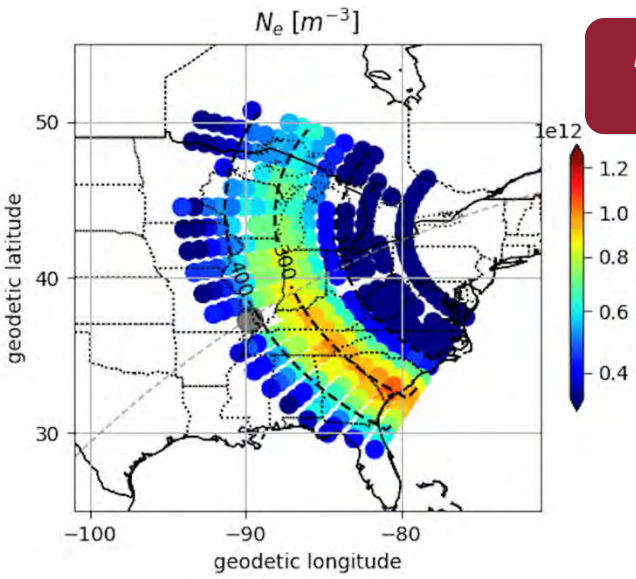
- Data binned by altitude and azimuth
  - Decreases model compute
  - Captures regional behavior
  - Maintains data architecture
- Geophysical indices Flare Irradiance Spectral Model 2 (FISM2) and Hpo are appended
- 4th-degree linear regression trained as fn of UT, FISM2, and HP30.

Results – April 8th Modeled

MIT HAYSTACK OBSERVATORY

Modeled background data during eclipse:

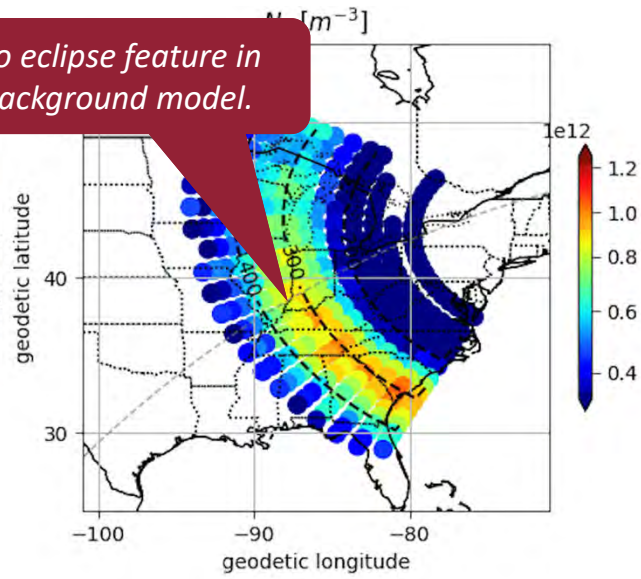
2024-04-08 1900 UT



Umbra approaching.

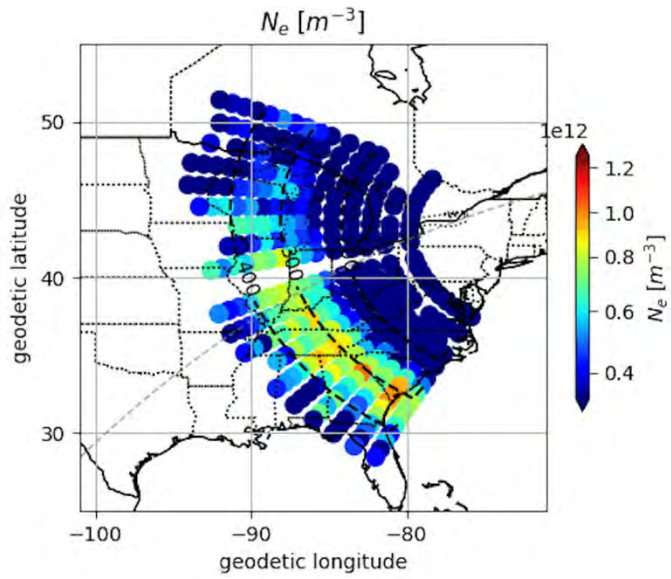
2024-04-08 2050 UT

No eclipse feature in background model.



1.5 hours after umbra.

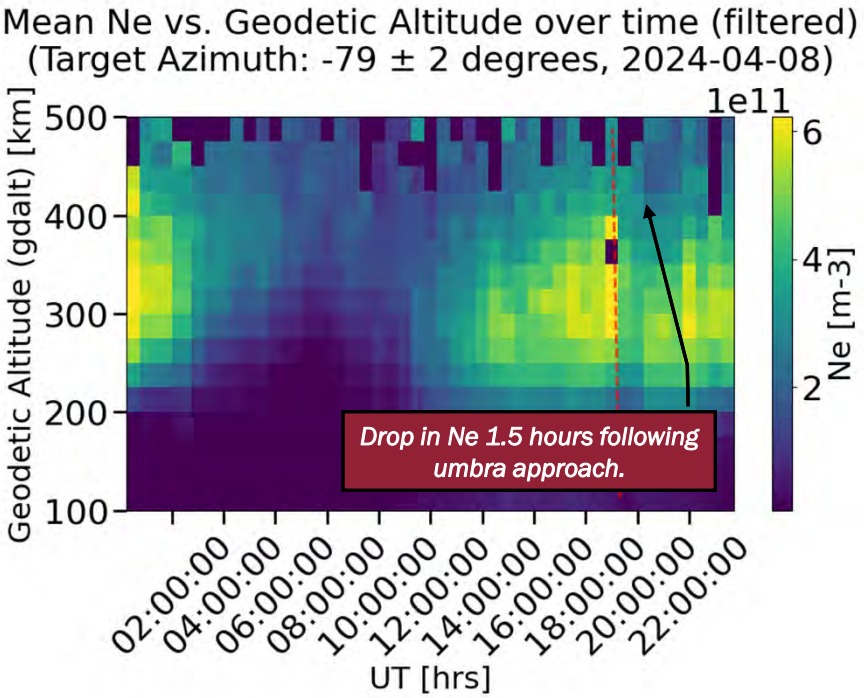
2024-04-08 2300 UT

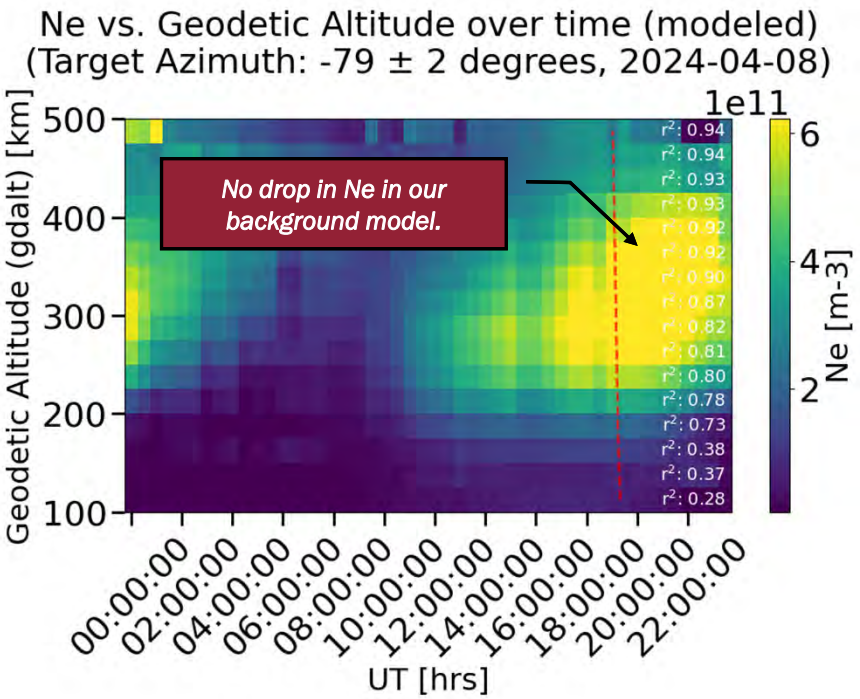


4.0 hours after umbra.

Results – Using the Model

MIT HAYSTACK OBSERVATORY

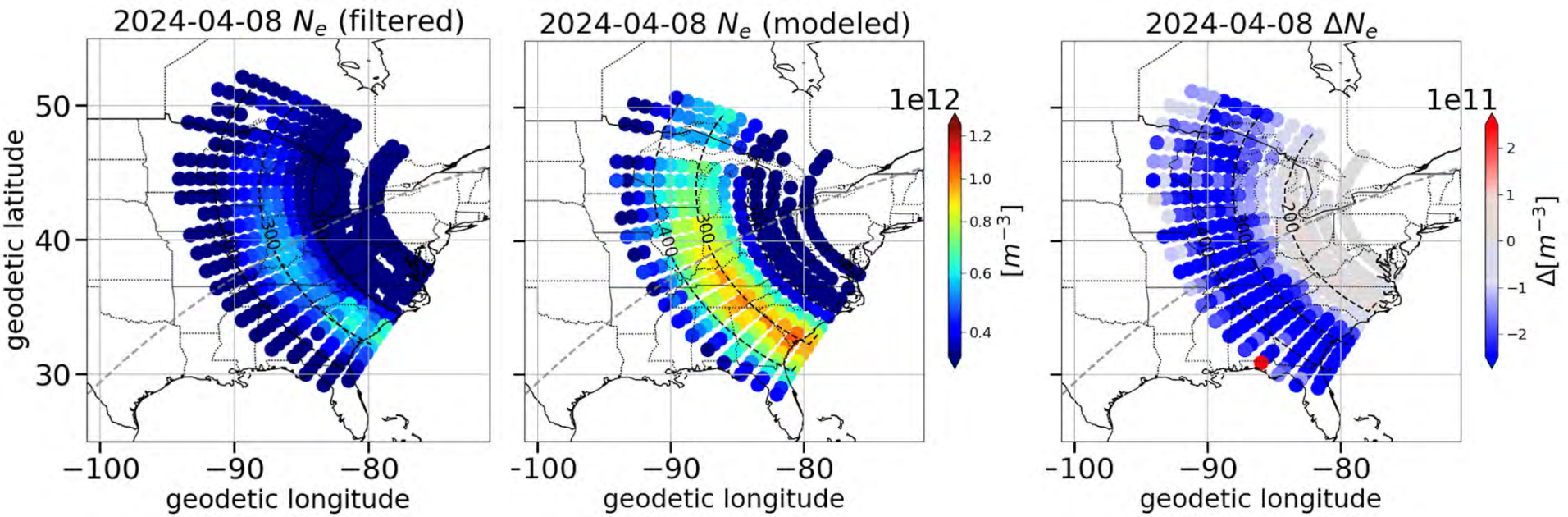




The difference of these two figures will give us the magnitude of the eclipse effects.

Results – Removing the Background

MIT HAYSTACK OBSERVATORY



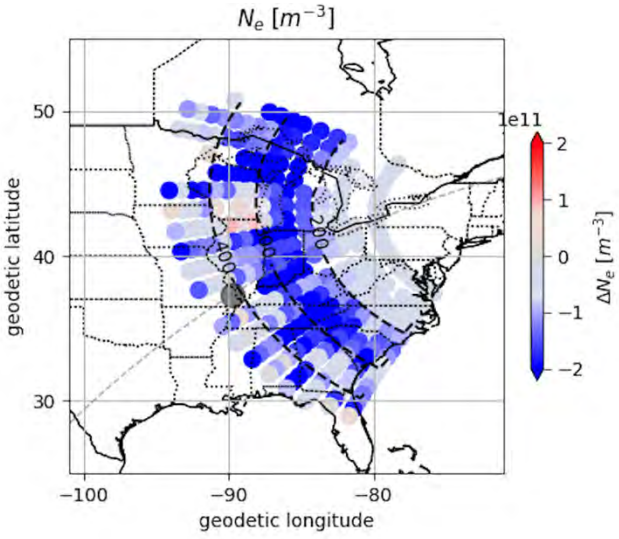
Recorded, modeled background, and difference map of electron density (respectively) at 20.5 UT.

Results – Difference Over Time

MIT HAYSTACK OBSERVATORY

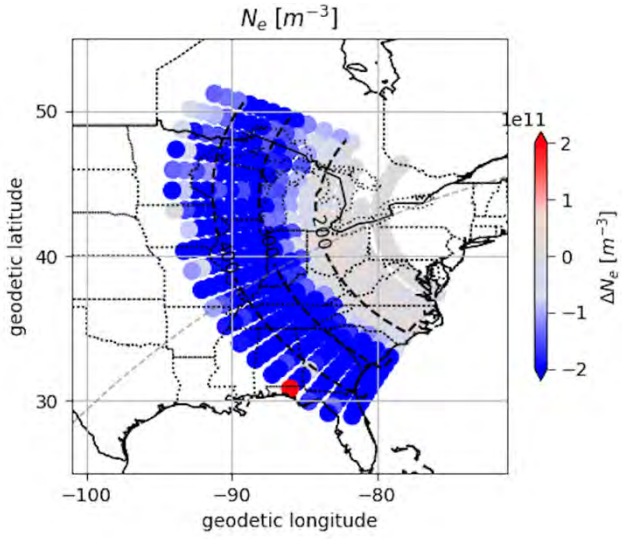
Difference in Electron Density at three different times:

2024-04-08 1900 UT



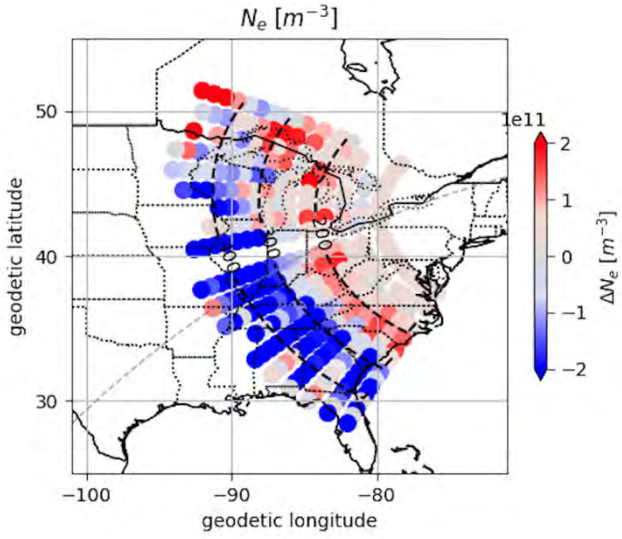
Umbra approaching.

2024-04-08 2050 UT



1.5 hours after umbra.

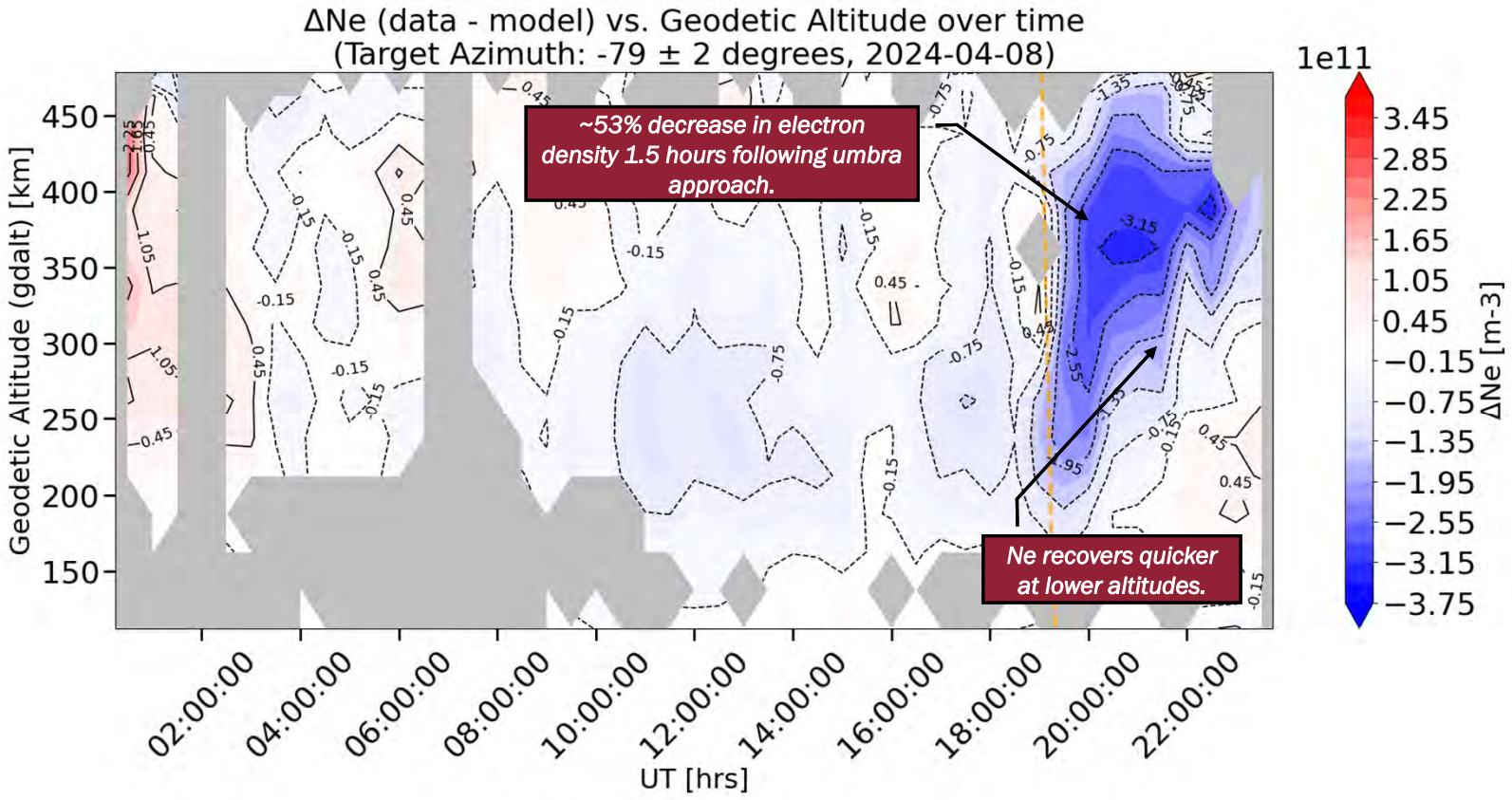
2024-04-08 2300 UT



4.0 hours after umbra.

Results – Ne Altitudinal View

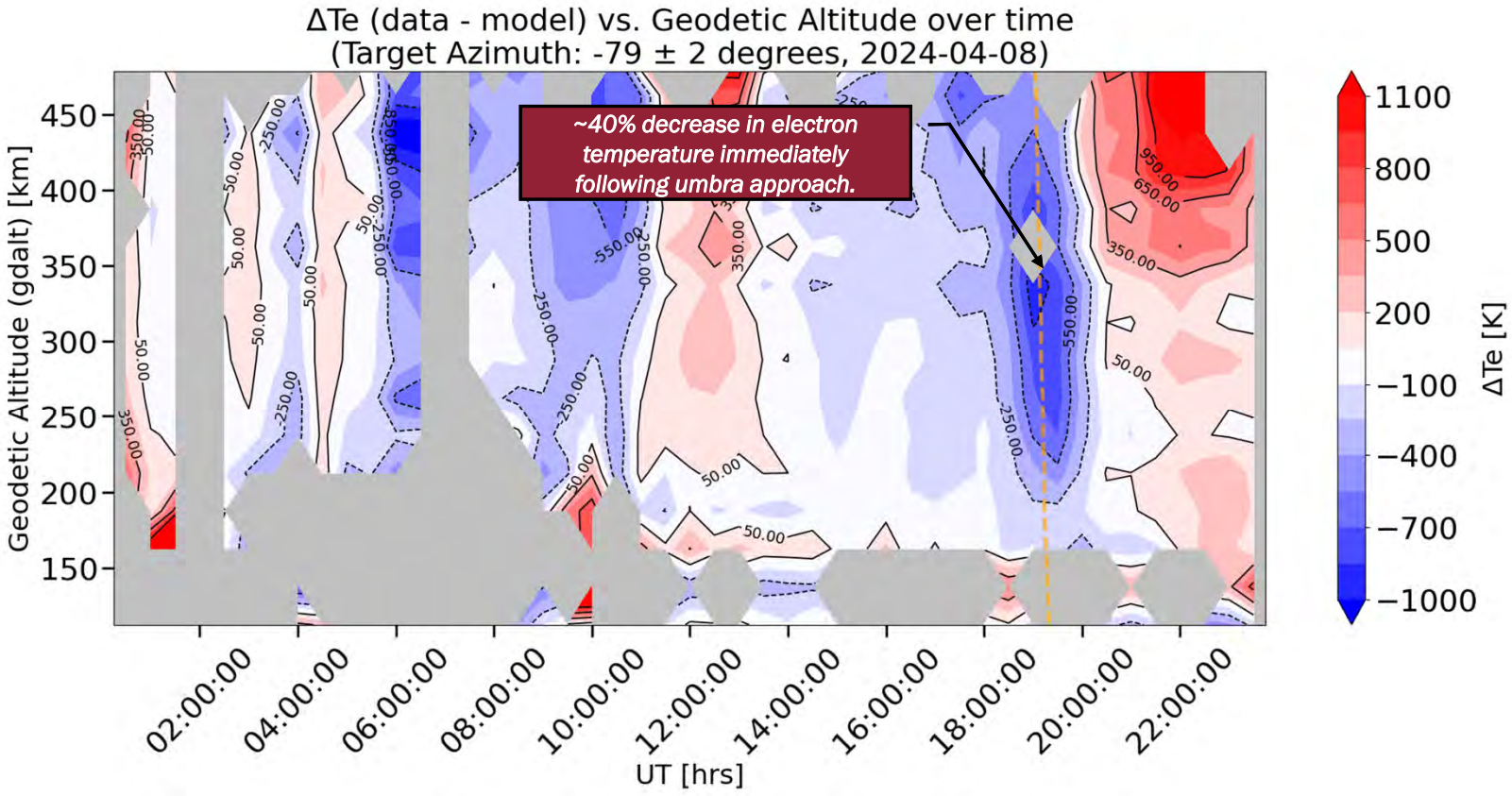
MIT HAYSTACK OBSERVATORY



Difference between recorded Ne of a particular bin on day of eclipse and modeled Ne of same conditions.

Results – Te Altitudinal View

MIT HAYSTACK OBSERVATORY



Difference between recorded Te of a particular bin on day of eclipse and modeled Te of same conditions.

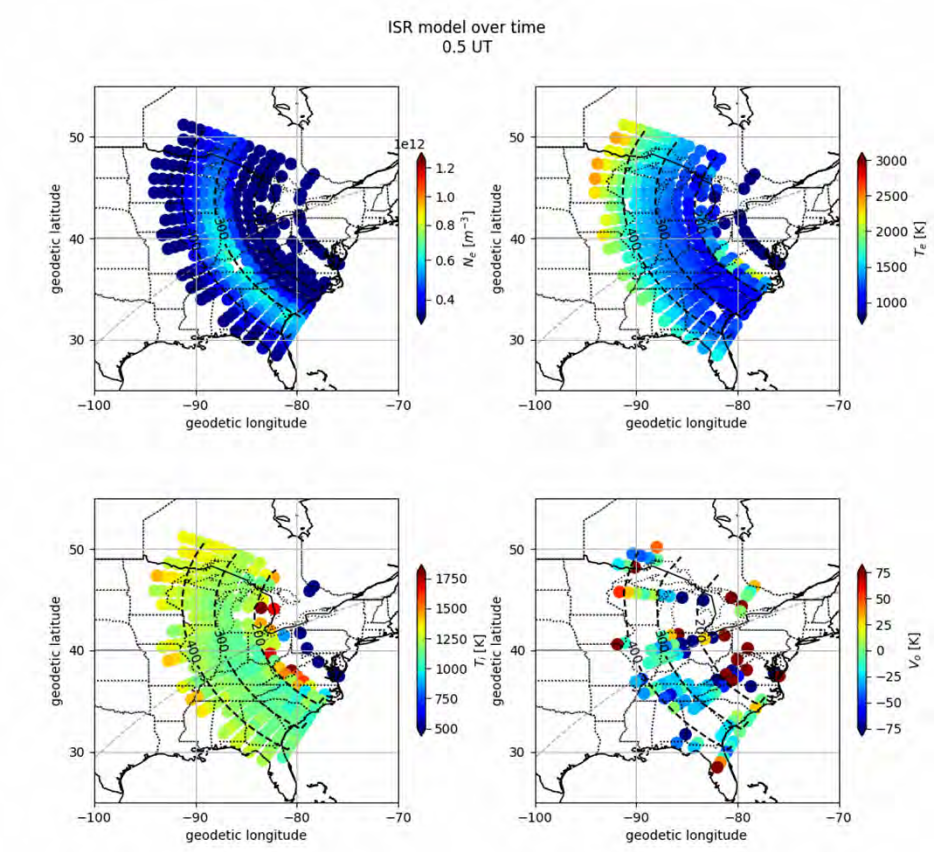
MIT
HAYSTACK
OBSERVATORY

Questions?

😊

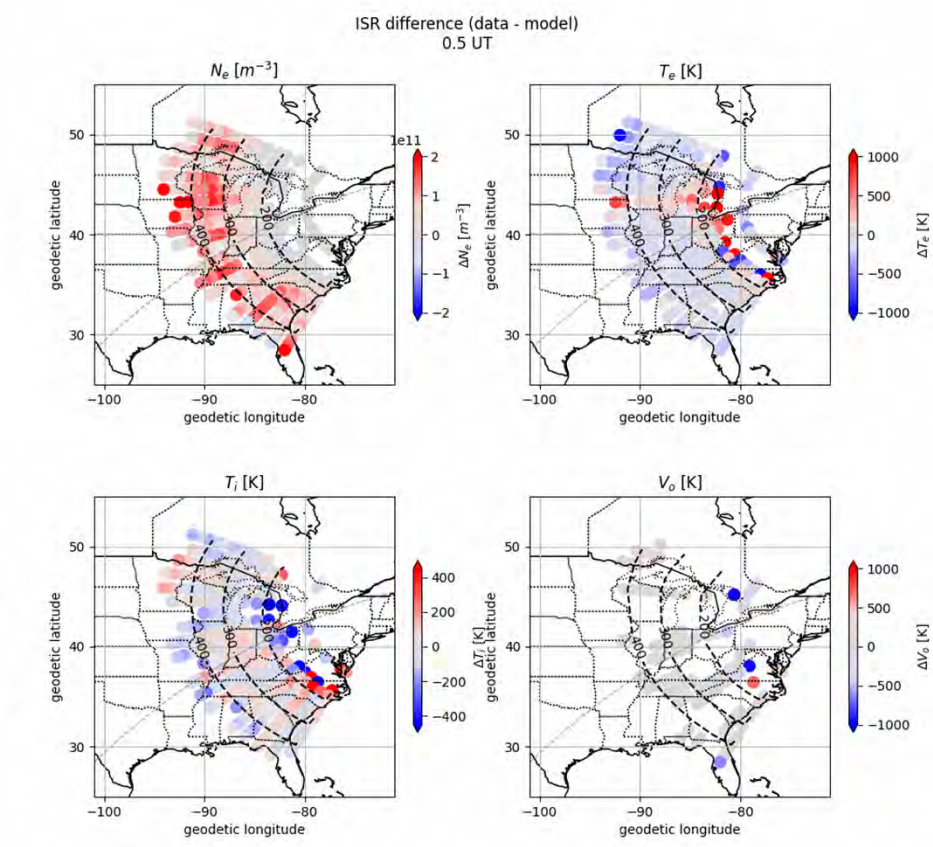
Results – Modeled ISR Projection

MIT HAYSTACK OBSERVATORY



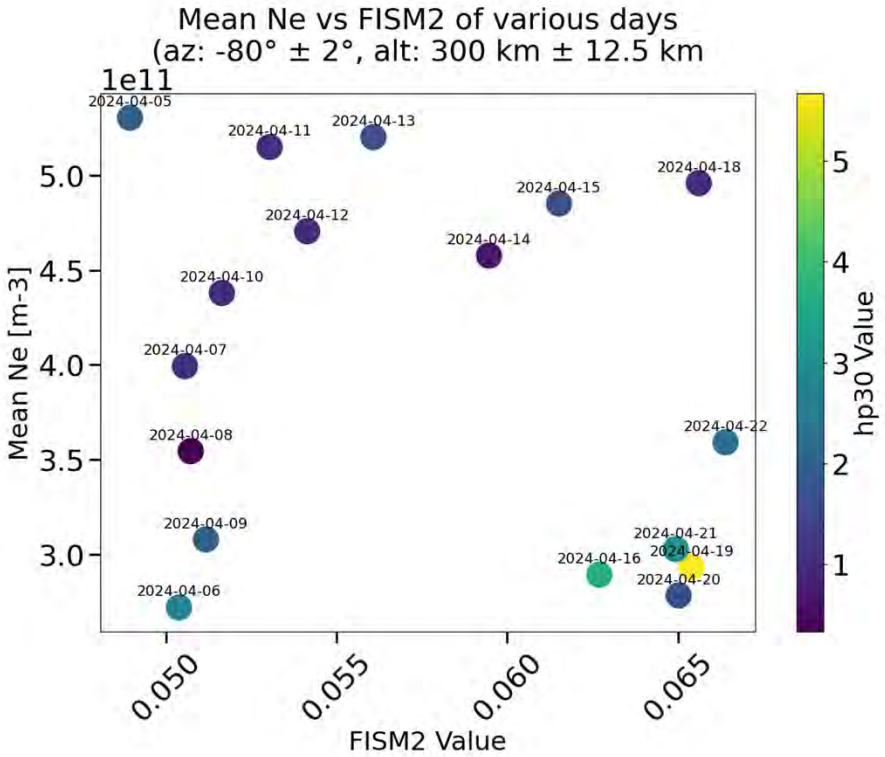
Results – Difference ISR Projection

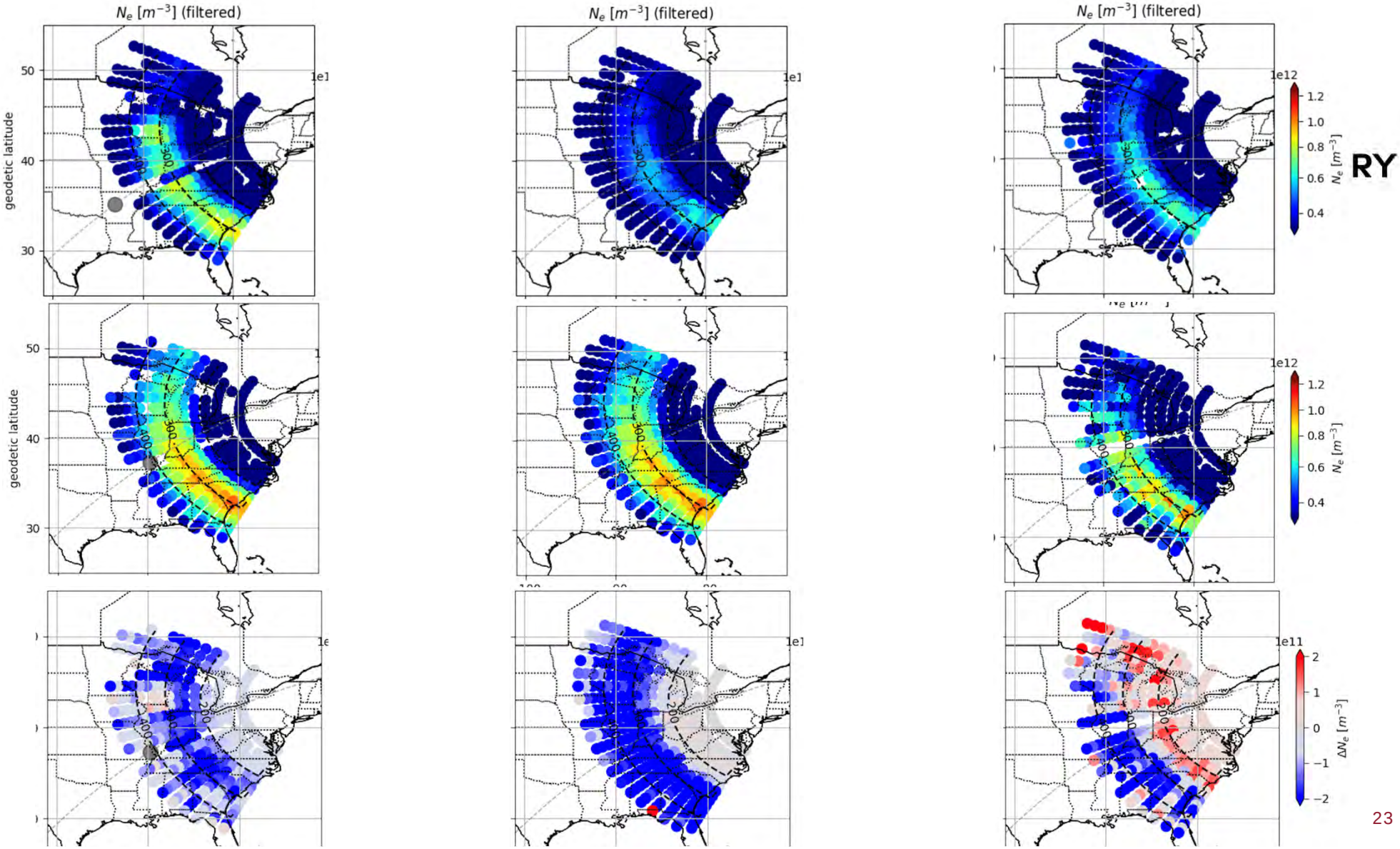
MIT HAYSTACK OBSERVATORY



Results – Geophysical Indices Correlation

MIT HAYSTACK OBSERVATORY




N_e [m^{-3}] (filtered)
N_e [m^{-3}] (filtered)
N_e [m^{-3}] (filtered)
geodetic latitude
geodetic latitude
1e12
1e12
1e11
N_e [m^{-3}]
ΔN_e [m^{-3}]
RY