Insights from the **NSF FIREBIRD II CubeSats** and **NASA** Van Allen Probes into Energetic Electron Precipitation

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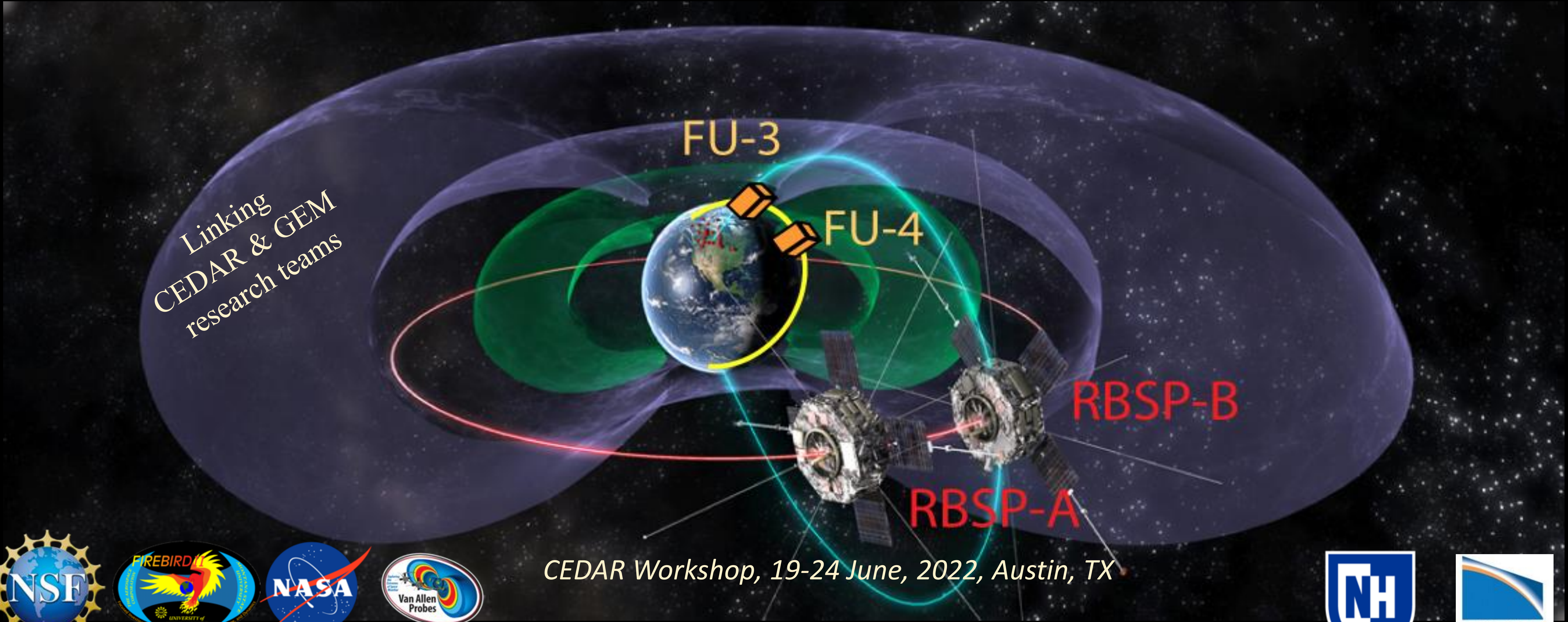
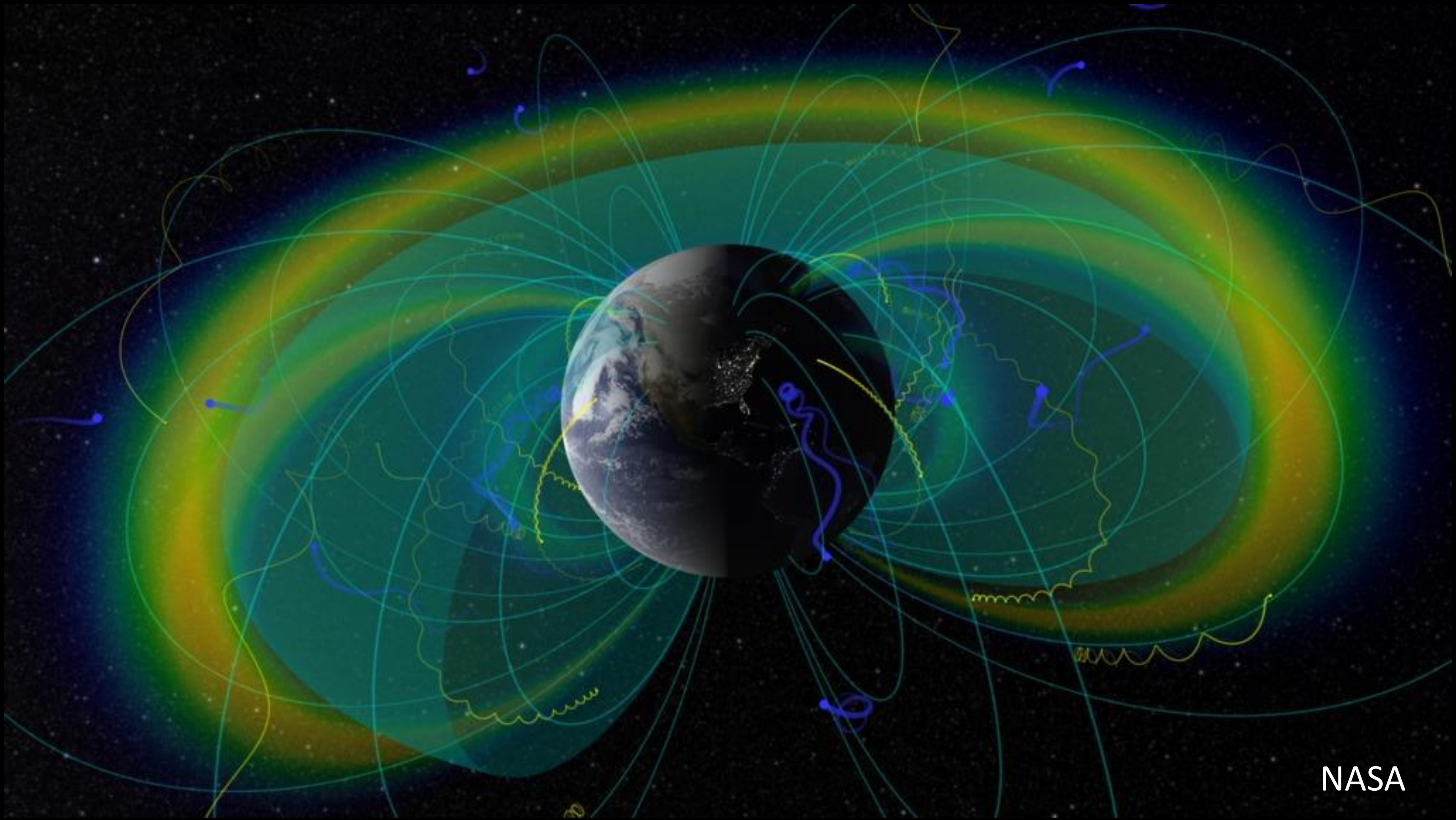
Summary of work supported by the NSF CEDAR program and led by the University of New Hampshire and NCAR
#1650738, #1650738



CEDAR Workshop, 19-24 June, 2022, Austin, TX

1. Can these observations better quantify energetic electron precipitation from the Van Allen radiation belts into the upper atmosphere?



2. How does this electron precipitation affect the ionization and chemical composition of the neutral atmosphere?

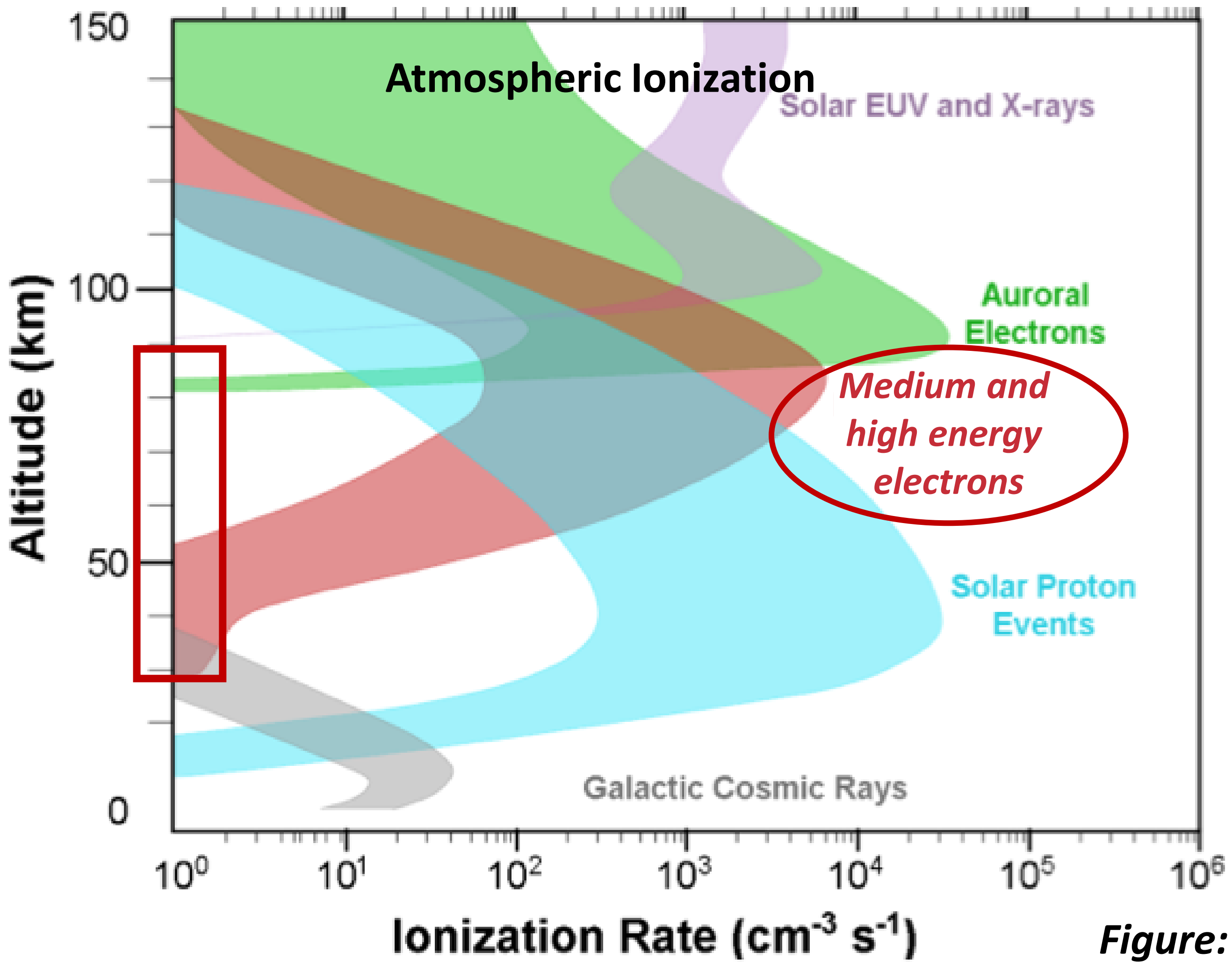


Figure: C. Jackman

Altitudes below 90 km

mesosphere / upper stratosphere

D-region ionospheric chemistry

Geomagnetic latitudes

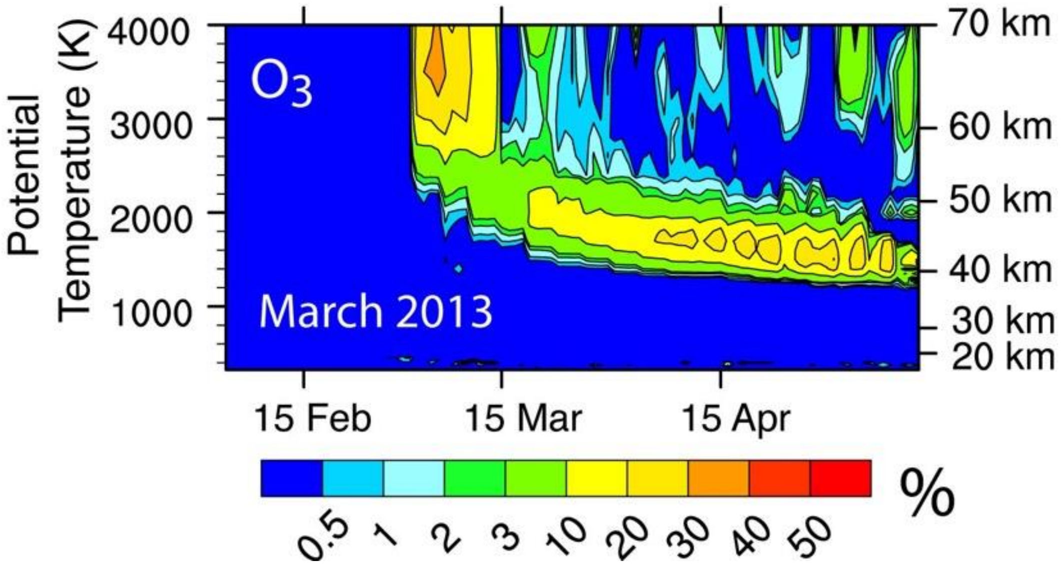
55˚-70˚

Electrons precipitating into the atmosphere ionize and dissociate N_2 and O_2, enhancing HO_x and NO_x in mesosphere and ultimately ***reducing O_3 in stratosphere***

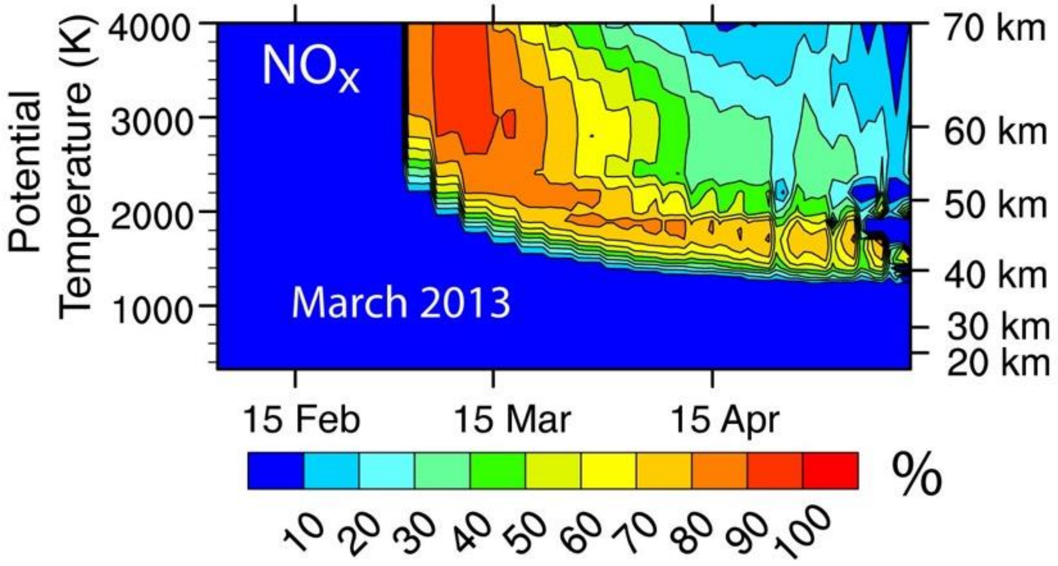
Enhance:

- odd hydrogen (**HO_x** = H+OH+HO_2)
- reactive odd nitrogen (**NO_x** = N+ NO+NO_2)

O_3 Reduction (%)



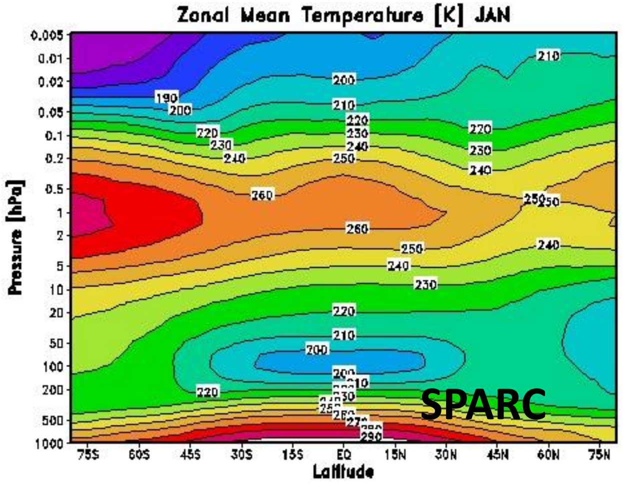
NO_x Enhancement (%)



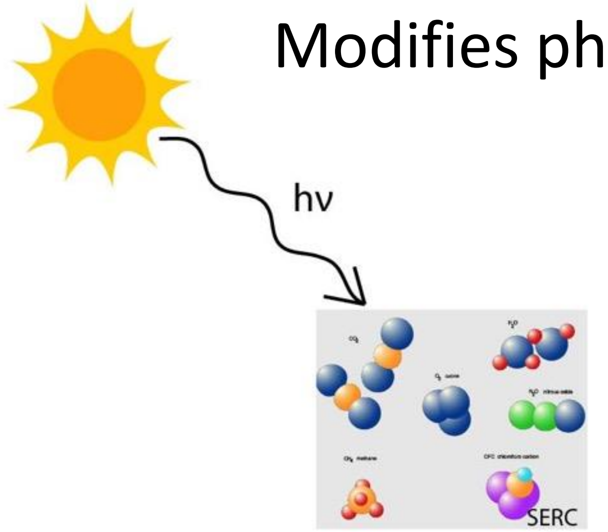
Catalytic destruction of ozone (**O_3**)… especially *during polar winter when air masses cool and descend to the stratosphere*

Ozone absorbs and re-emits energy (incoming from the Sun and outgoing from the Earth)

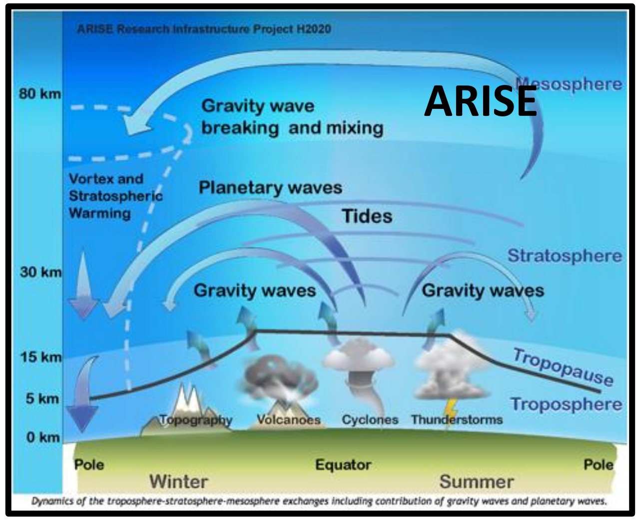
Heats (or cools) the atmosphere (affecting density)



Modifies photochemistry



Influences atmospheric dynamics (including atmospheric waves)

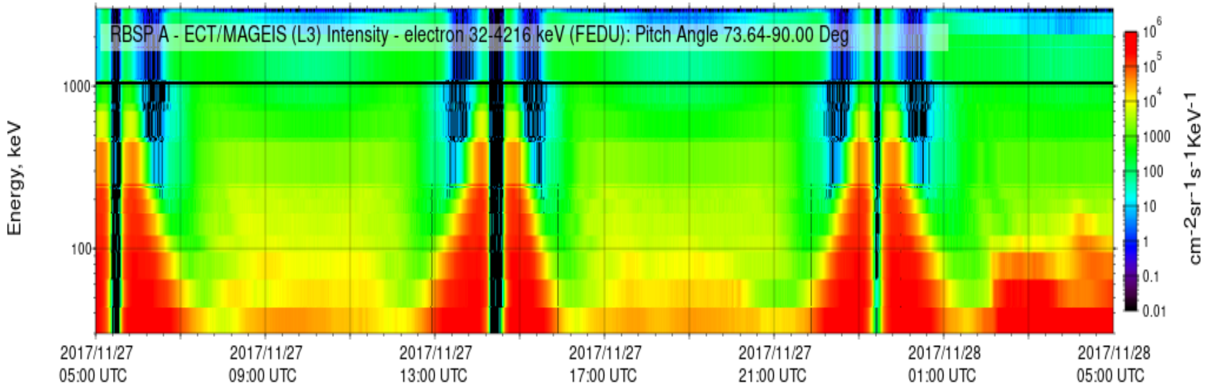


http://arise-project.eu/atmospheric-dynamics.php

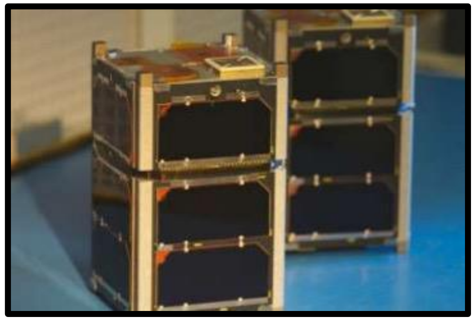
Multi-Platform Observations

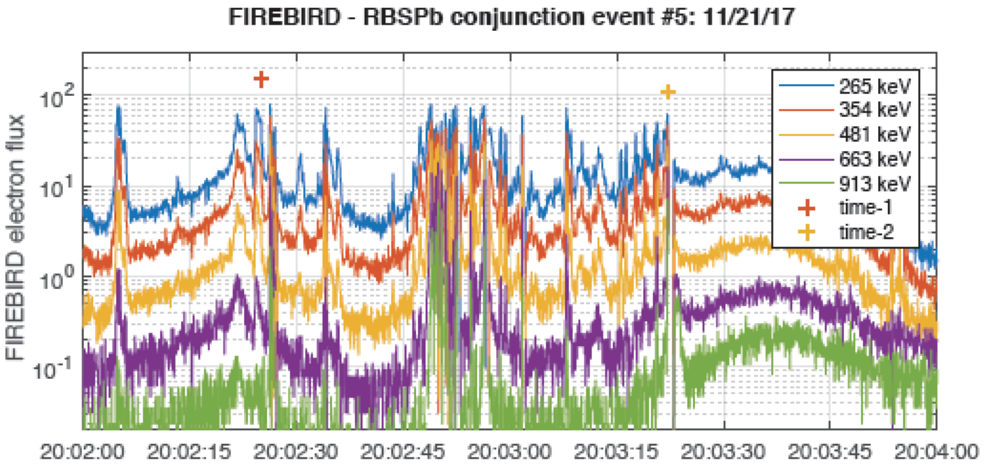
1. What can we learn from recent missions? Especially NSF CubeSats?

NASA Van Allen Probes (2012-2019)
continuous observations traveling through the radiation belts



NSF FIREBIRD-II Cubesats (2015-present)
3-4 minute snapshots of precipitating electrons in low Earth orbit





Global Atmospheric Models

2. How can global climate models be used to study atmospheric effects of electron precipitation?

WACCM

NCAR

The Whole Atmospheric Community Climate Model (WACCM) now has the capacity to directly read in electron precipitation files!

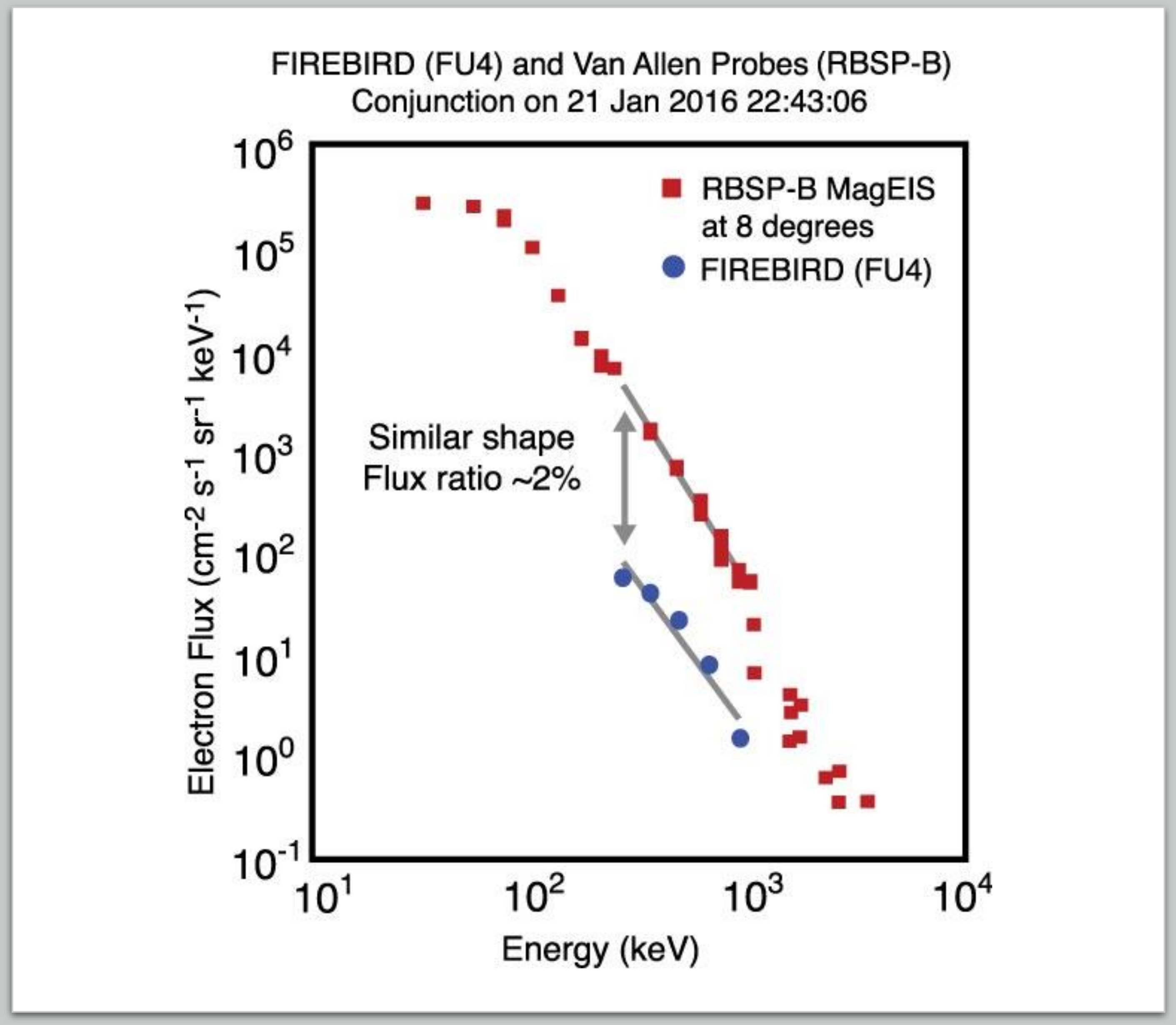
WACCM takes this precipitation at the top of the atmosphere(differential flux as a function of energy, geomagnetic latitude, and time) and calculates ionization rates throughout the model atmosphere.

As part of this CEDAR project, NCAR has written a Jupyter Notebook code (Python) for the community to create WACCM input files of precipitating electrons. Contact Dan Marsh (marsh@ucar.edu) if interested

Methods: Conjunction study (2015-2019)

Goal is to compare
the continuous observations of
Van Allen Probes (RBSP-A, RBSP-B)
near the loss cone
within the equatorial radiation belts
&
the sparse observations of
FIREBIRD-II (FU3, FU4)
within the loss cone
in low Earth polar orbit

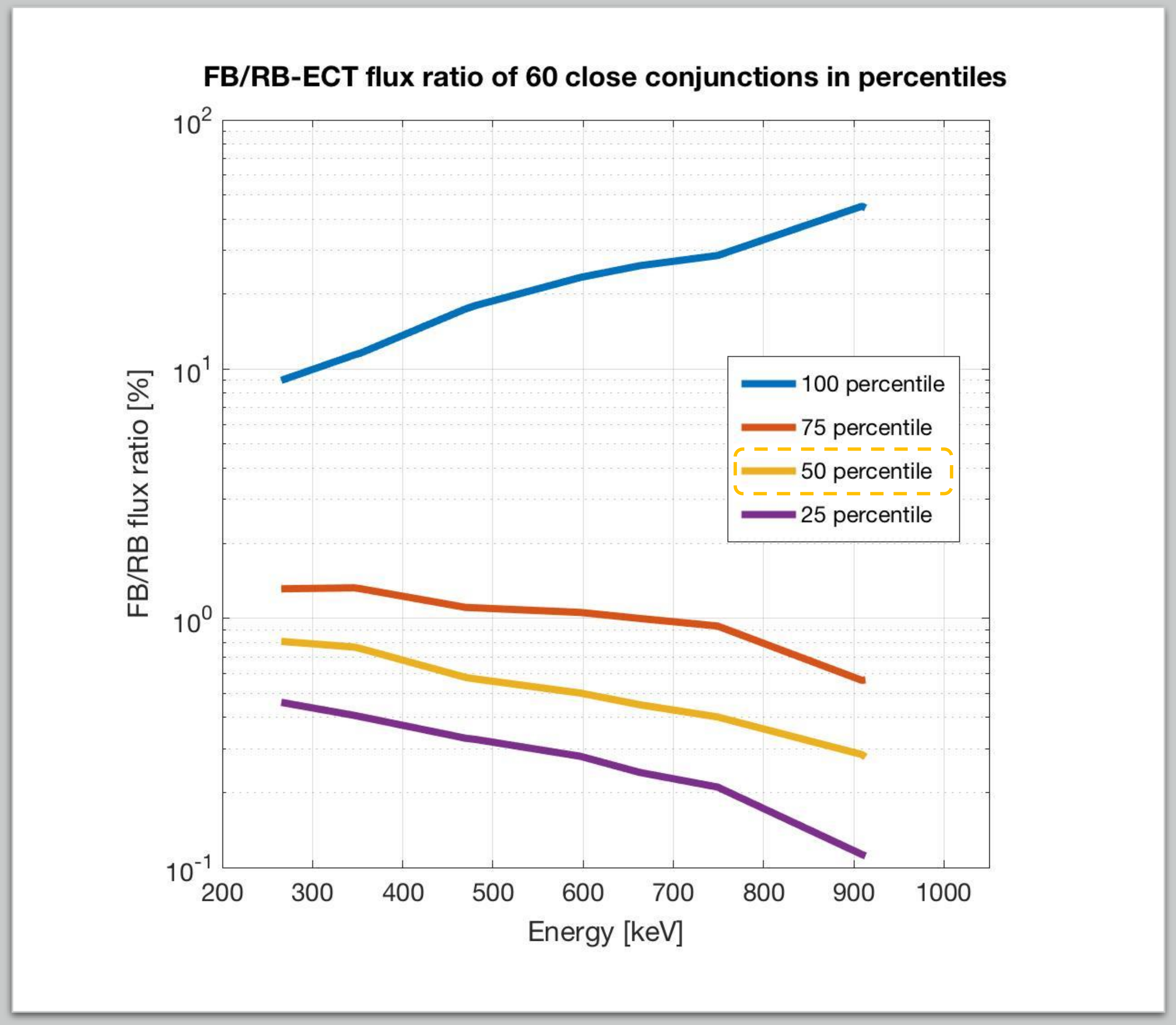
Determine the ***percentage of electrons*** observed in the outer radiation belt ***likely to precipitate into the atmosphere***…so we can estimate electron precipitation using the full Van Allen Probes dataset.



Statistical analysis of flux ratios as a function of energy during conjunctions (within 0.5 L and 0.5 MLT)

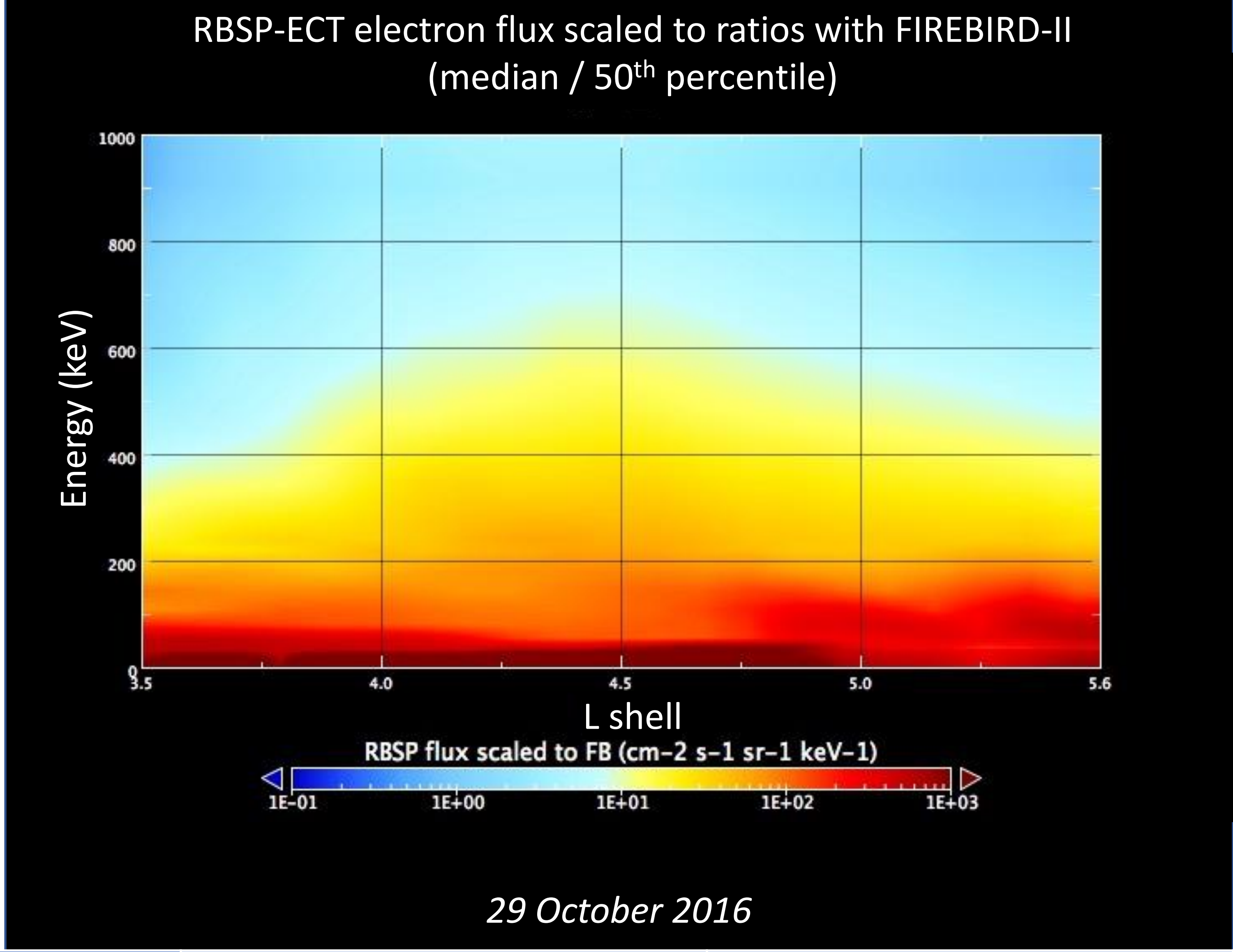
Van Allen Probes - RBSP-ECT combined dataset (HOPE-MagEIS-REPT), lowest pitch angle bin (0-4 degrees)

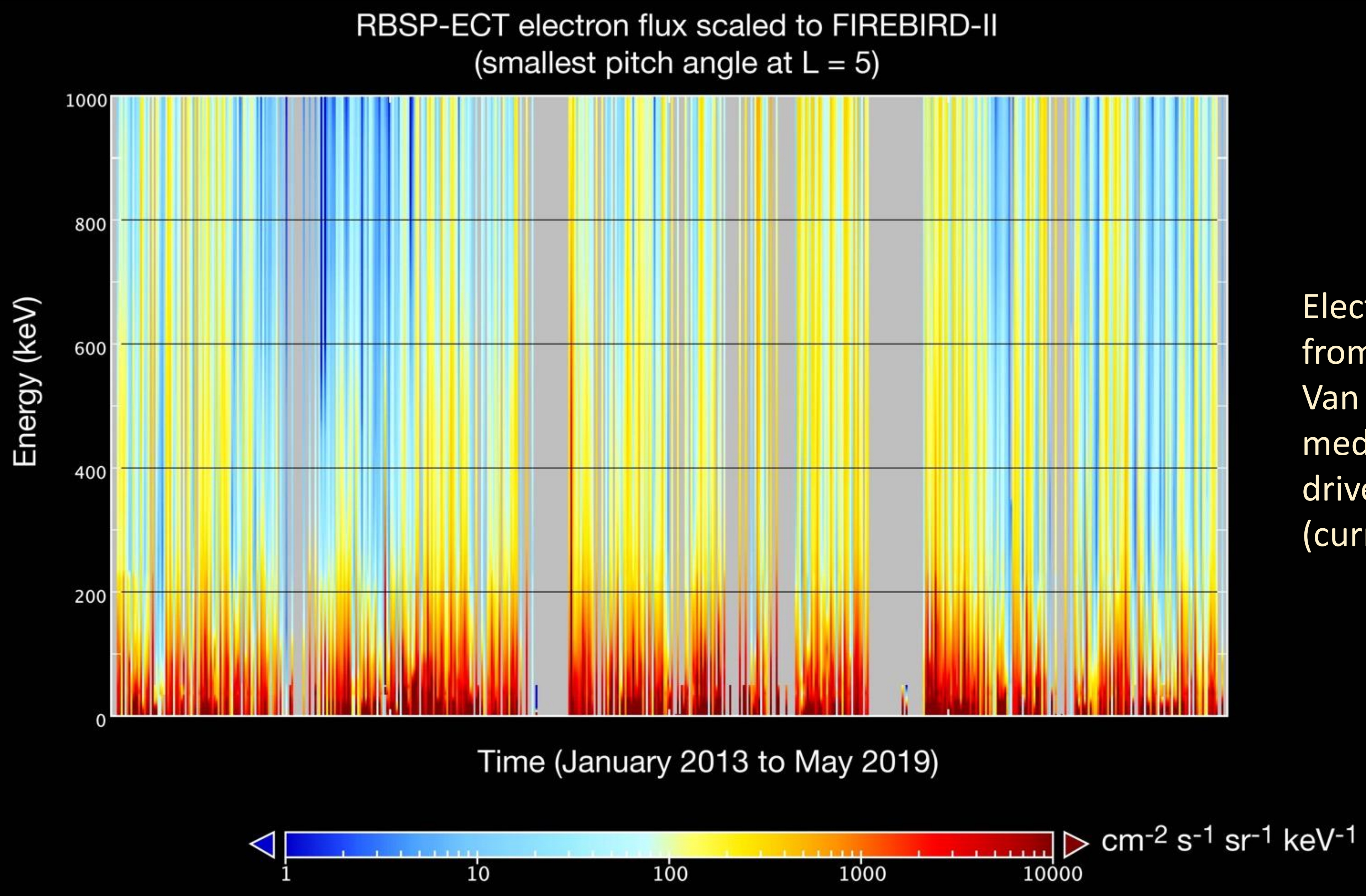
Focus on **median (50^{th} percentile**) for WACCM simulations



Use these ratios to scale the electron flux measured by the Van Allen Probes and created maps of electron flux at the top of the atmosphere.

Electron precipitation as a function of energy and L-shell.

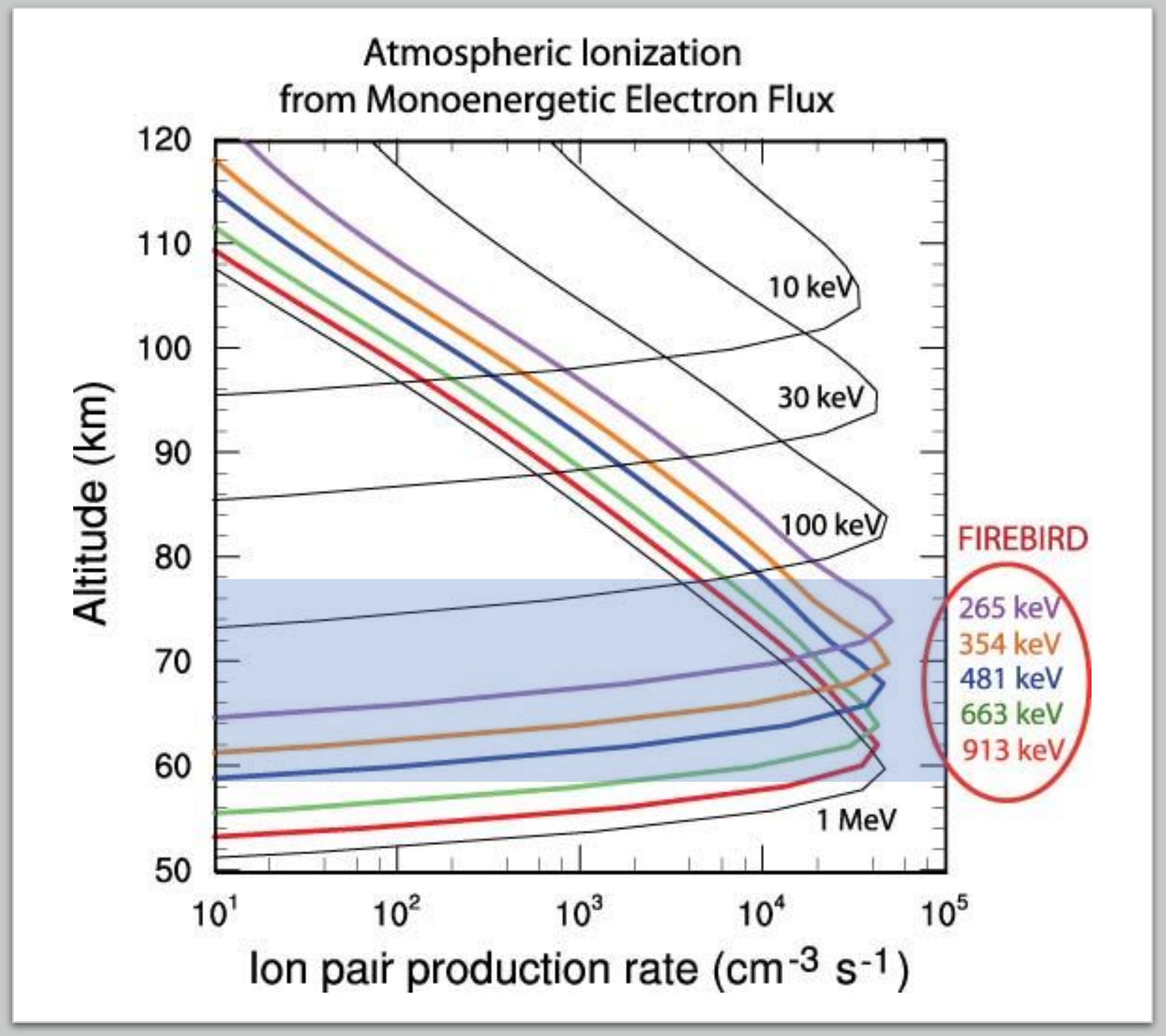




Electron precipitation map from 2013-2019 based on Van Allen Probes data and median FB/RBSP ratios to drive WACCM simulations. (currently interpolating)

What’s unique about FIREBIRD-II CubeSats and Van Allen Probes data?

***High resolution within differential energy channels important to ionization of the middle atmosphere*.**



Integrated monoenergetic ionization rates as using the methods of Fang et al. (2010).

	UARS (PEM)	SAMPEX (PET)	POES (MEPED)	FIREBIRD II[2]	Van Allen Probes (ECT/MagEIS)
Altitude	600 km	520-670 km	870 km	400-600 km	700 km to ~6 Earth radii
Inclination	57°	82°	98.7°	99.1°	10°
Energies	30 keV to 4 MeV 32 energy channels	150 keV[1] to 100s MeV E > 0.6 MeV 1.5 < E < 6MeV 2.5 < E <14 MeV	E1 >50 keV E2 >100 keV E3 > 300 keV P6 > 1 MeV	*energies and geometries* 265 keV 354 keV 481 keV 663 keV 913 keV > 1 MeV	20 keV to 4 MeV 25 energy bins
Challenges	Low L shells	High energies	Proton Contamination & **Sensitivity Limit**	Sparse & Uncertain Orientation	Equatorial "near" loss cone

References: UARS – Winningham et al. (1993); SAMPEX – Selesnick et al. (2003); MEPED – Nesse Tyssoy et al., (2016); FIREBIRD II – Crew et al., (2016); Van Allen Probes – Spence et al., (2013). [1] SAMPEX has three years of data from a >150 keV channel but most of the mission observed only higher energies. [2] FIREBIRD energy channels vary between campaigns and units. Energies are from FU3 during multiple campaigns.

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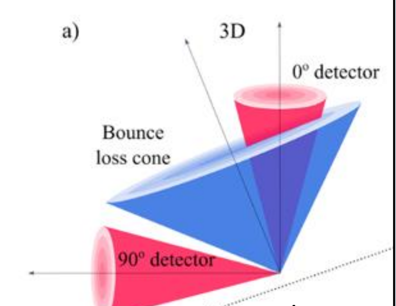
FIREBIRD-II

1. **Higher resolution** in the energy range of interest to the middle atmosphere (spectral shape).
2. **Instrument geometry** (larger geometric factors by a factor of 600 compared to POES) provides **very good sensitivity,** particularly during times of quiet and moderate activity.

Most electron precipitation estimates used in atmospheric models are based on **NOAA POES/MetOp datasets** …extensive but low energy resolution.

Coupled Model Intercomparison Project Phase 6 (CMIP6) use the ApEEP model derived from **POES MEPED 0˚ telescop**e (*van de Kamp et al., 2016; Matthes et al., 2017*)

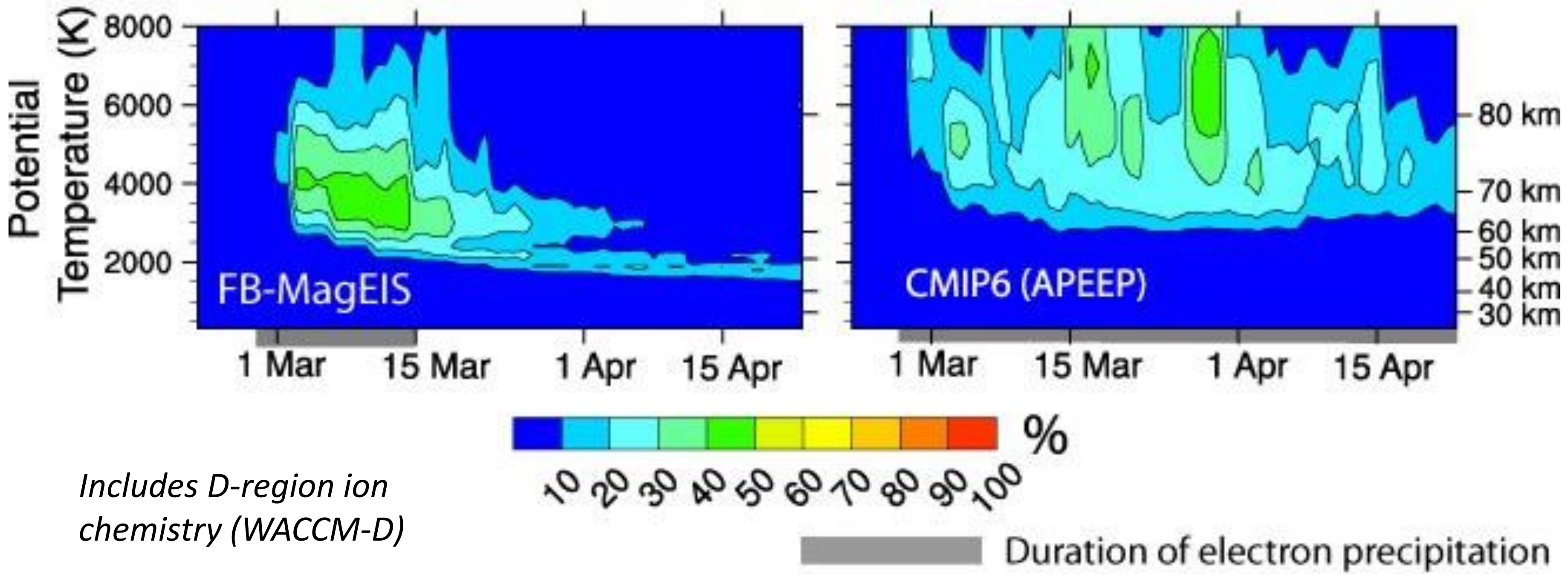


Nesse-Tyssoy et al., 2016

Results of WACCM studies

Our case studies show ***more ionization and therefore enhancements of nitrogen oxides (NO_x) at lower altitudes*** than the simulations using CMIP6 electron precipitation.

NO_x enhancements (%) averaged over NH polar vortex

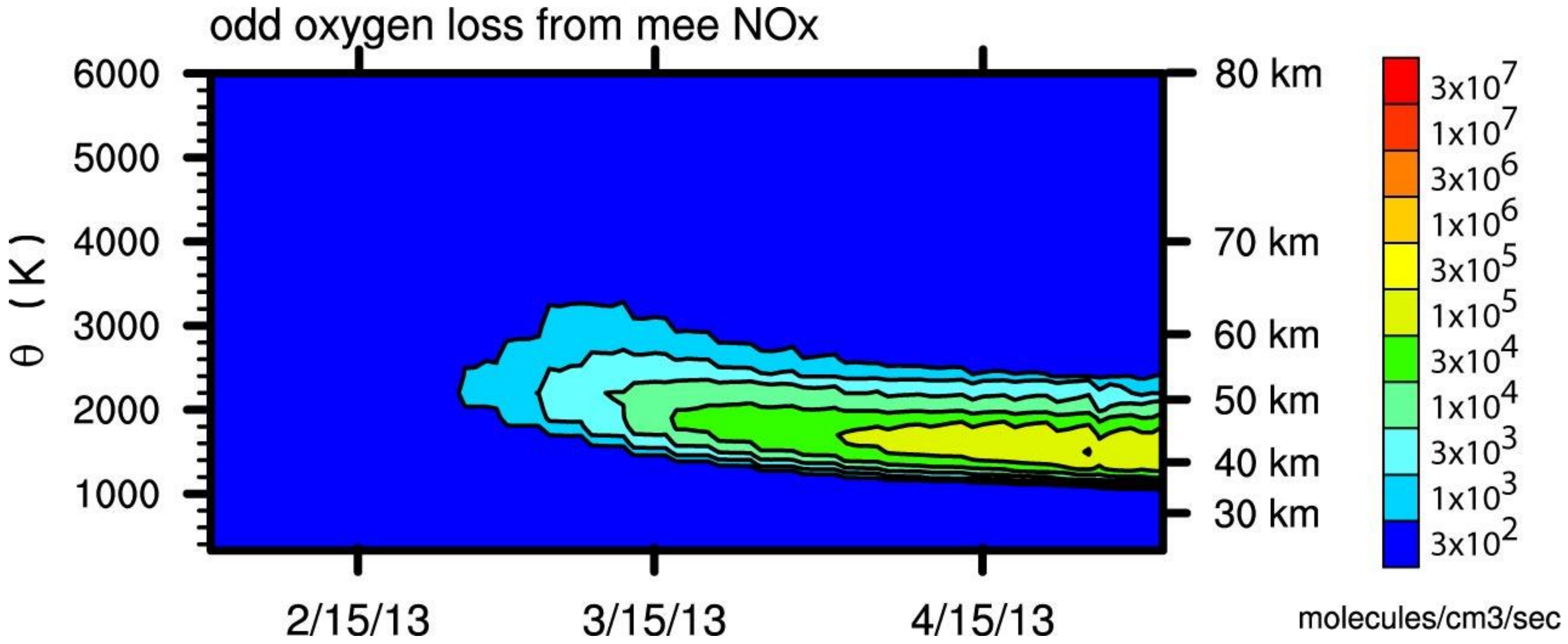


Includes D-region ion chemistry (WACCM-D)

Note: FB-RBSP electron precipitation maps for this case study did not extrapolate for lower energies / higher altitudes

Duderstadt et al., 2021

…which can lead to more O_3 reductions in the stratosphere than current CMIP6 simulations

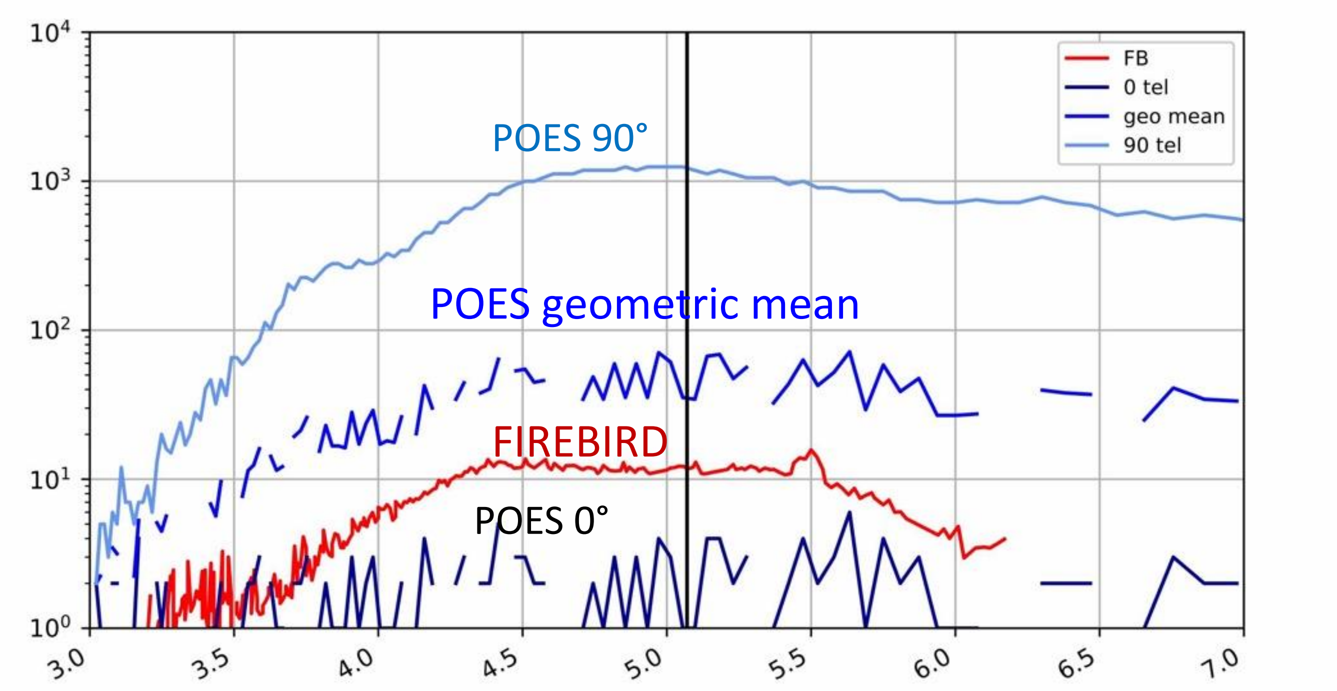


Student Research #1 – UNH undergraduate student **Isabella Householder**

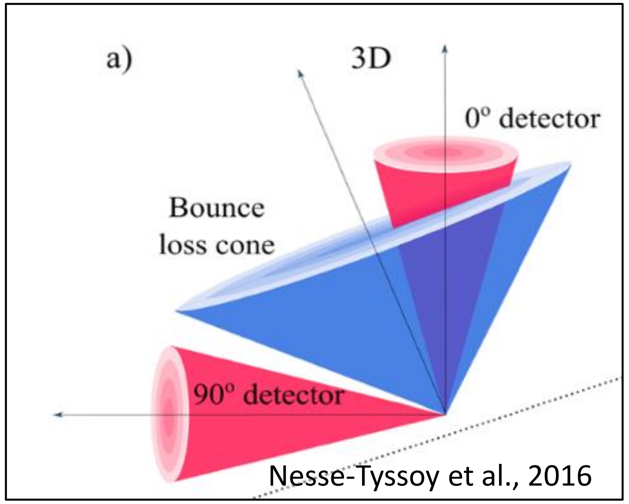
Comparison of FIREBIRD-II & POES/MetOp

Use FIREBIRD observations during spacecraft conjunctions to calculate “equivalent counts” that POES MEPED would observe, taking into account the instrument geometries (*Yando et al.,* 2011; *Johnson et al.,* 2020).

FU4 2018-09-28, SH, MLT = 21, L= 5.1, Kp = 3

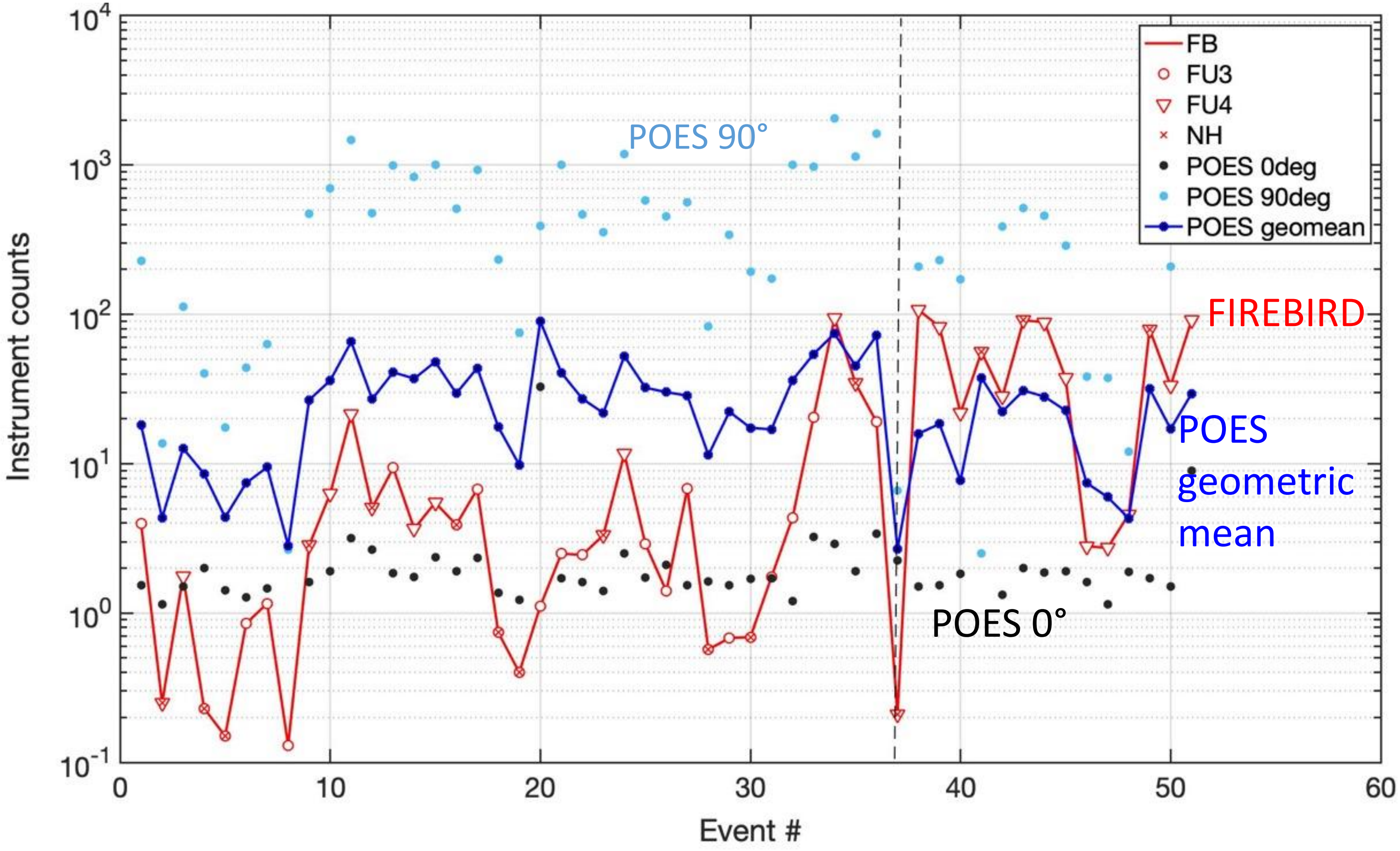


L Shell



The **geometric mean** between the POES 0° and 90° telescopes has been used as a rough estimate of precipitation (e.g., Rodger et al., 2013).

FIREBIRD-II & POES comparison > 300 keV at L = 5 (2018-2020)



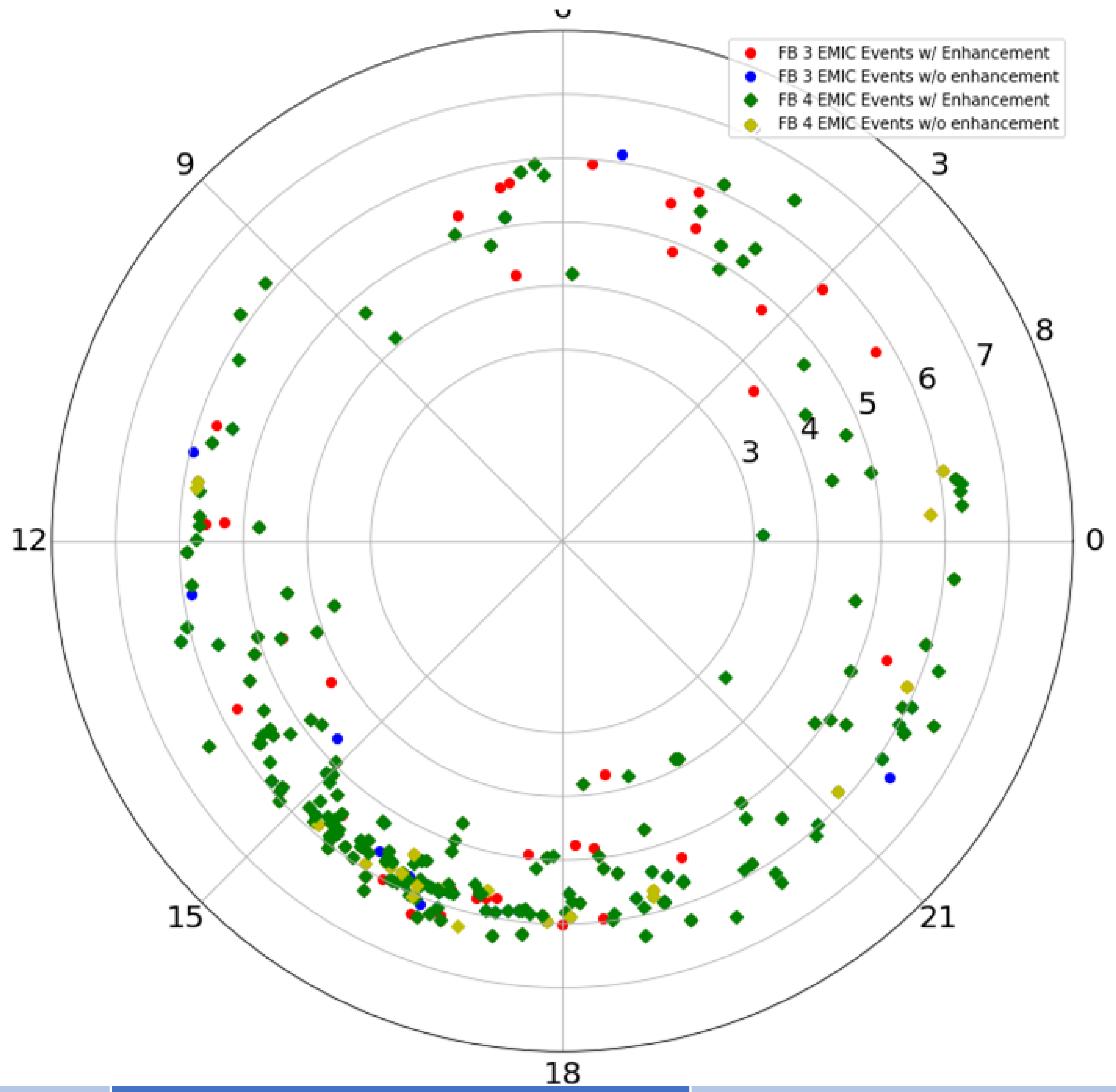
FIREBIRD-II electron counts are generally between the POES 0˚ tel and geometric mean until 2020, when levels are comparable.

Next step is to compare with datasets that do a better job combining the 0° and 90° POES telescopes. (see Josh Pettit's poster)

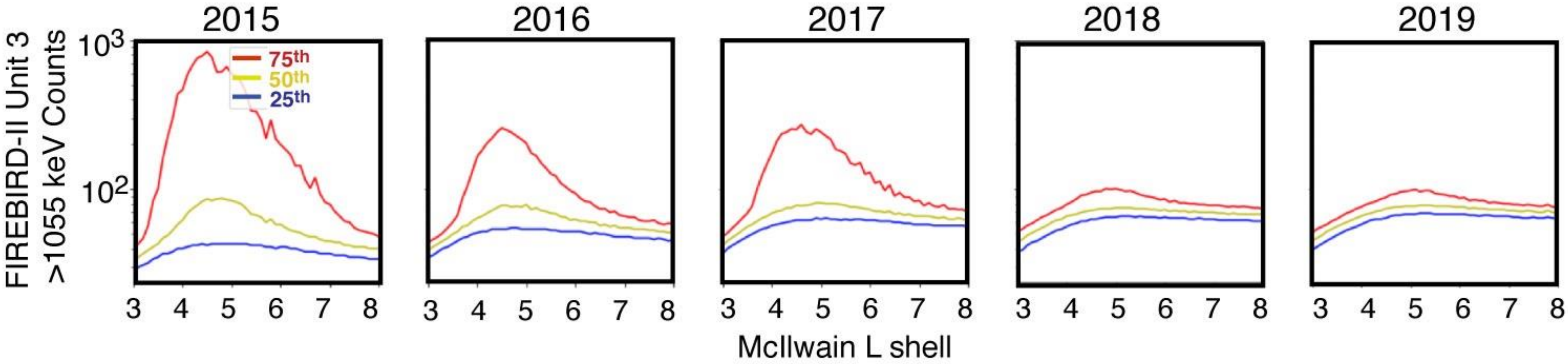
(note: < 1 equivalent counts demonstrate the ability of FIREBIRD-II to observe low flux variability below the POES sensitivity…a result of instrument geometry)

Student Research #2 - Senior Thesis of **Timothy Raeder** at UNH

Using FIREBIRD-II high energy (> 1 MeV) data to infer **evidence of electron precipitation from Electromagnetic Ion Cyclotron (EMIC) waves** observed by Van Allen Probes (EMFISIS)

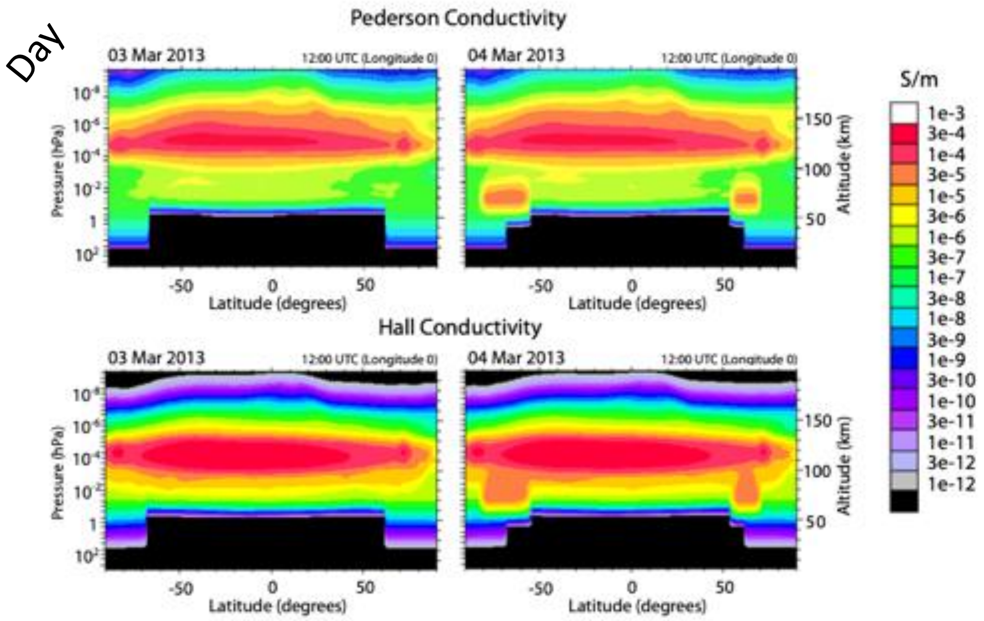


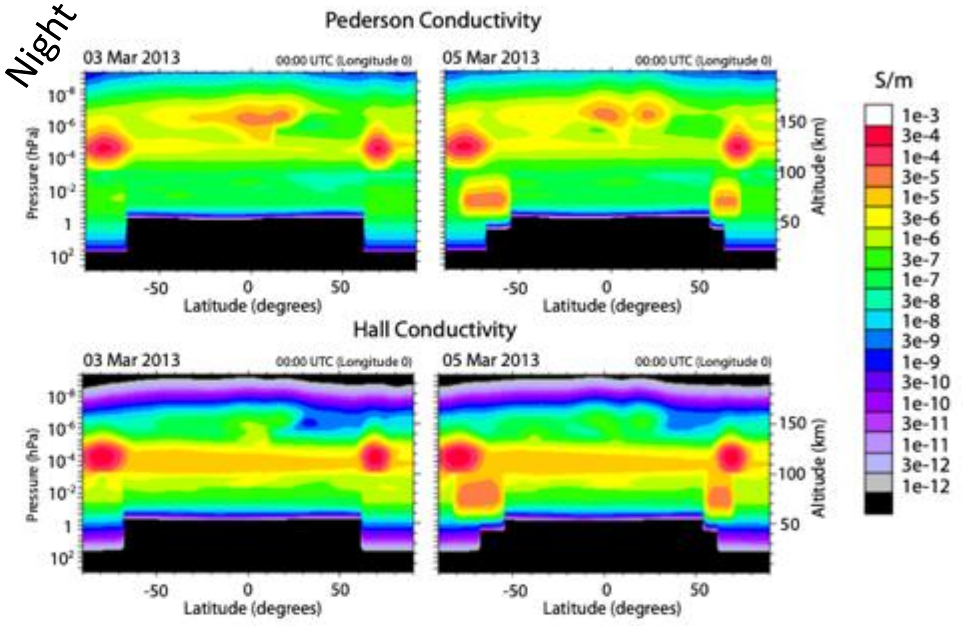
As the solar cycle decreases, strong precipitation events (75 percentile) of high energy electrons also decrease but background levels (25 percentile) increase.

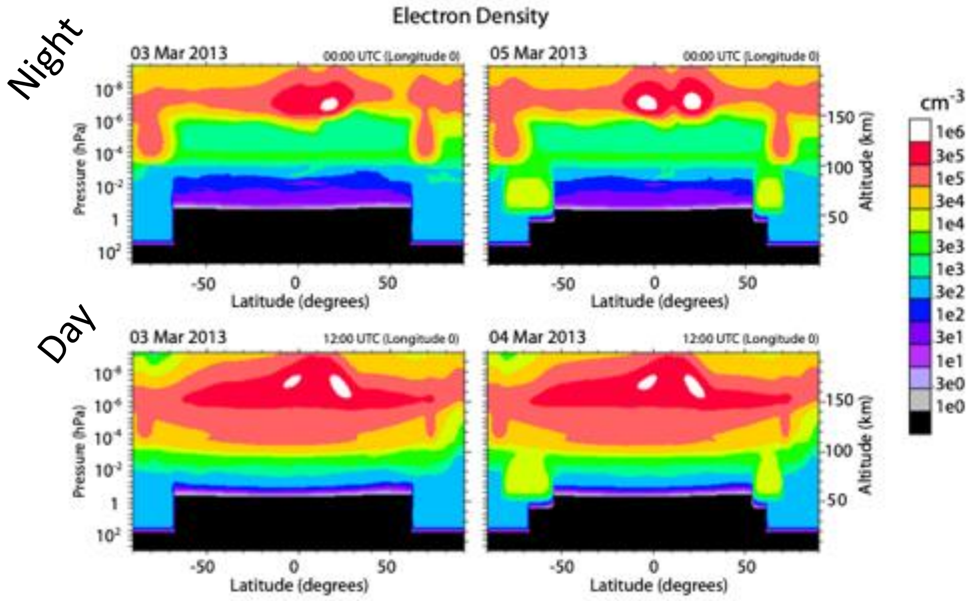


Courtesy Timothy Raeder

WACCM-X Simulations
(electron density and conductivity)







- WACCM-X: WACCM with thermosphere and ionosphere extension (0–500 km)
- We pick 50 percentile of flux ratio of all energies to simulate ionospheric impact
- Model outputs with and without RB electron precipitation at daytime and nighttime
- **With RB electron precipitation electron, there are significant enhancements in electron density, Pederson conductivity and Hall conductivity at 50-100 km**

Conclusions

1. Combining NSF FIREBIRD-II CubeSats and Van Allen Probes enables the development of a ***new electron precipitation dataset from 2013-2019*** with unique information at energies important for ionization of the middle atmosphere.

2. The effects of radiation belt electrons on the middle atmosphere may be ***larger than predicted*** by many current model simulations (e.g., CMIP6).

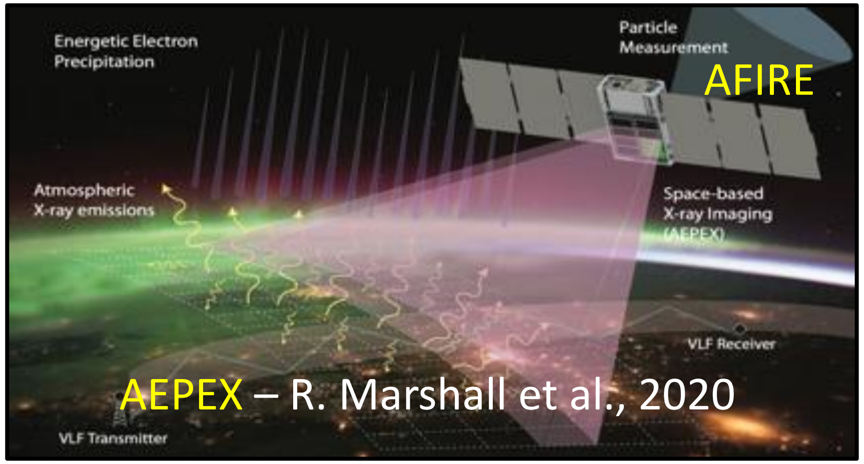
3. NCAR's WACCM ***now has the capacity to directly read in electron precipitation files*** and calculate ionization rates throughout the model atmosphere.

Looking forward, we still need…

- More **observations to assess the *pitch angle dependence of precipitating electrons*** in the loss cone near the top of the atmosphere, especially as a function of magnetospheric activity.

- More ***instruments of higher energy resolution electron flux*** like FIREBIRD – in low Earth orbit within energy range affecting the middle atmosphere (100 keV to 1 MeV).

See review articles: **HEPPA III intercomparison experiment on electron precipitation impacts**: Nesse Tyssøy et al. 2021 & Sinnhuber et al., 2021.



AEPEX – R. Marshall et al., 2020

- Modeling studies to determine ***how localized changes in ozone*** from electron precipitation affect atmospheric dynamics and radiative processes.

- Continued use of CubeSats to enhance ***undergraduate research experiences*** (beginning as freshmen!)

Acknowledgements

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Thank you CEDAR!

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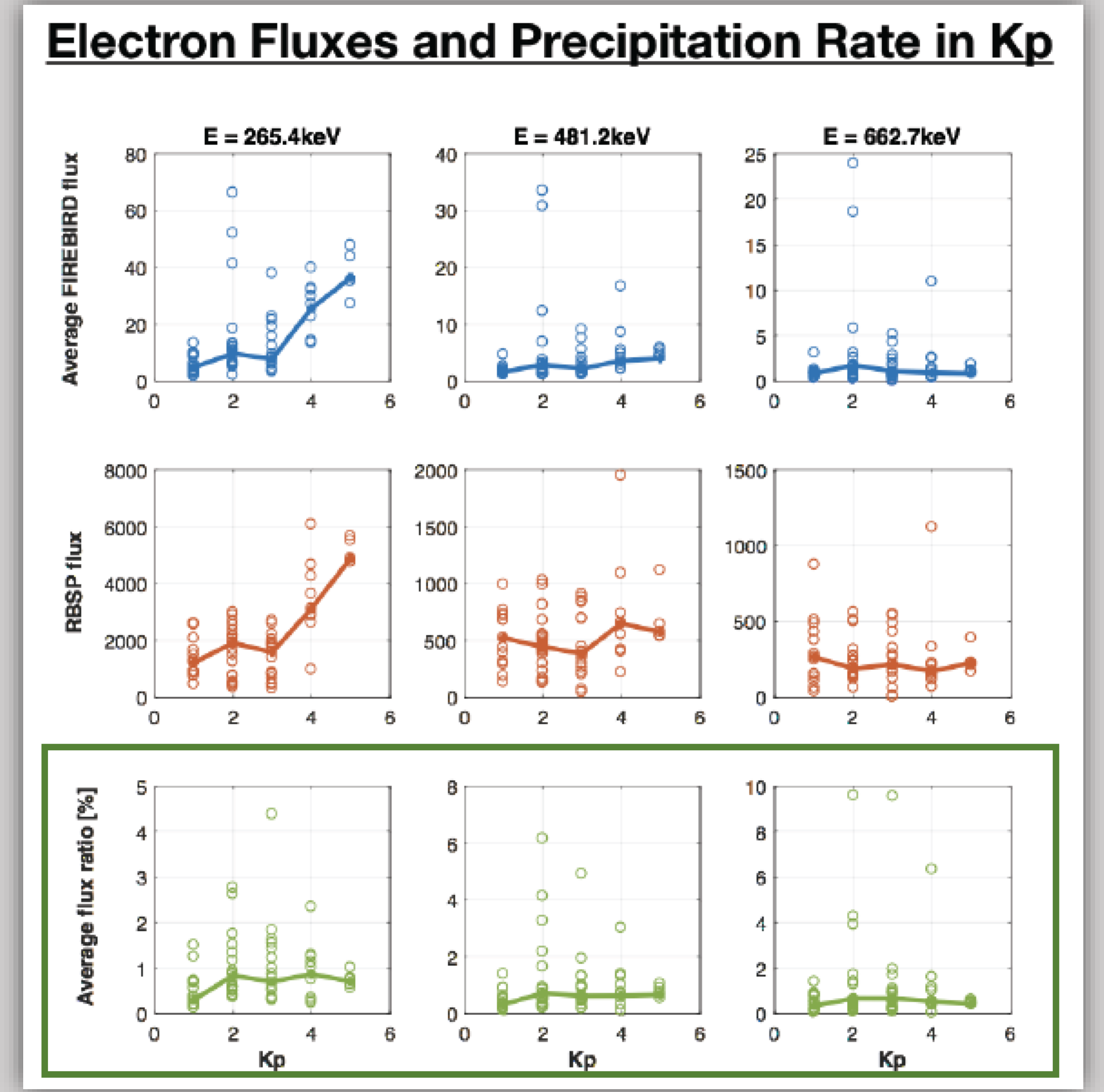
Extra Slides



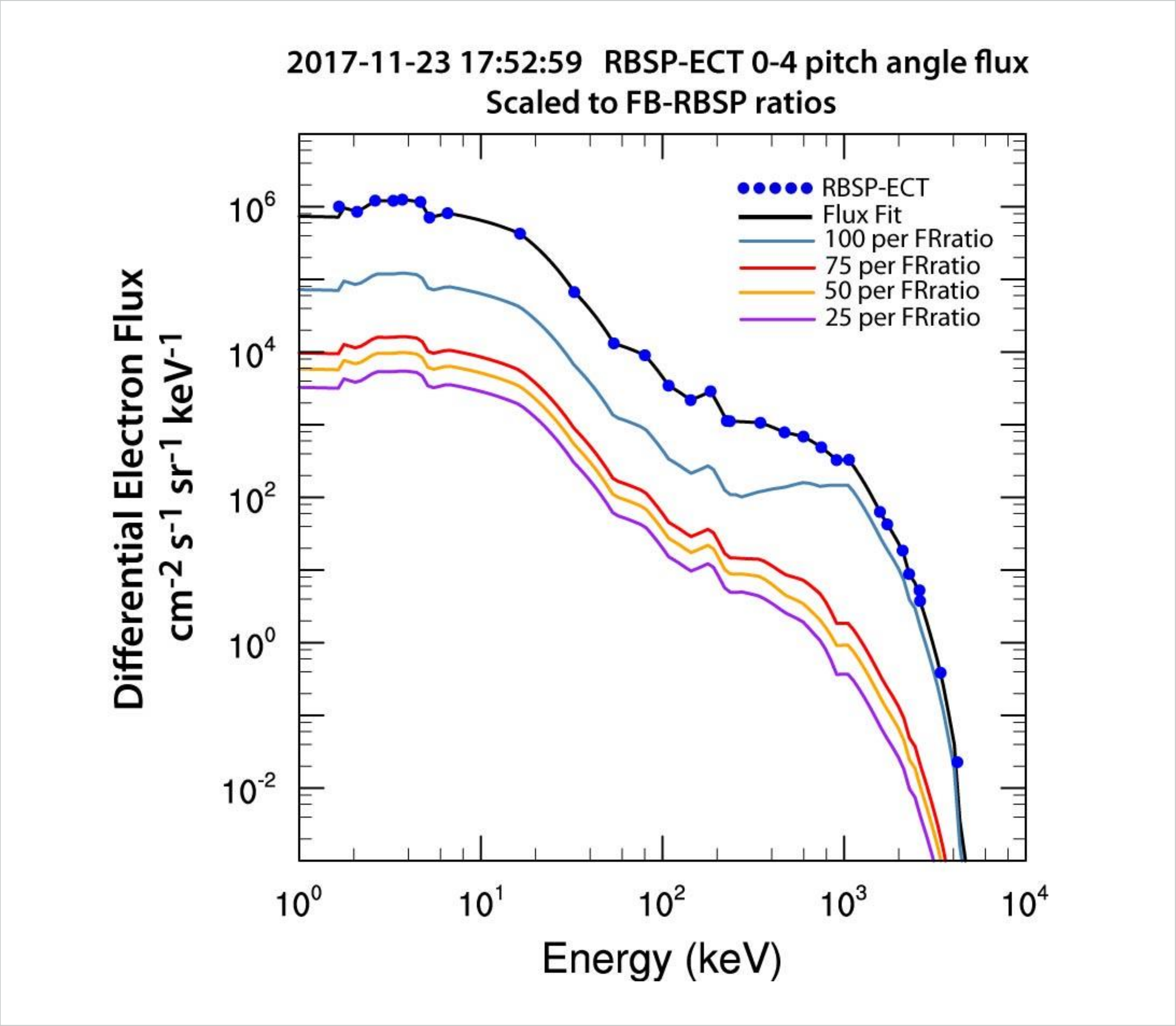
FIREBIRD-II high resolution observations are sparse.

Too few conjunctions to quantify the effect of magnetospheric activity

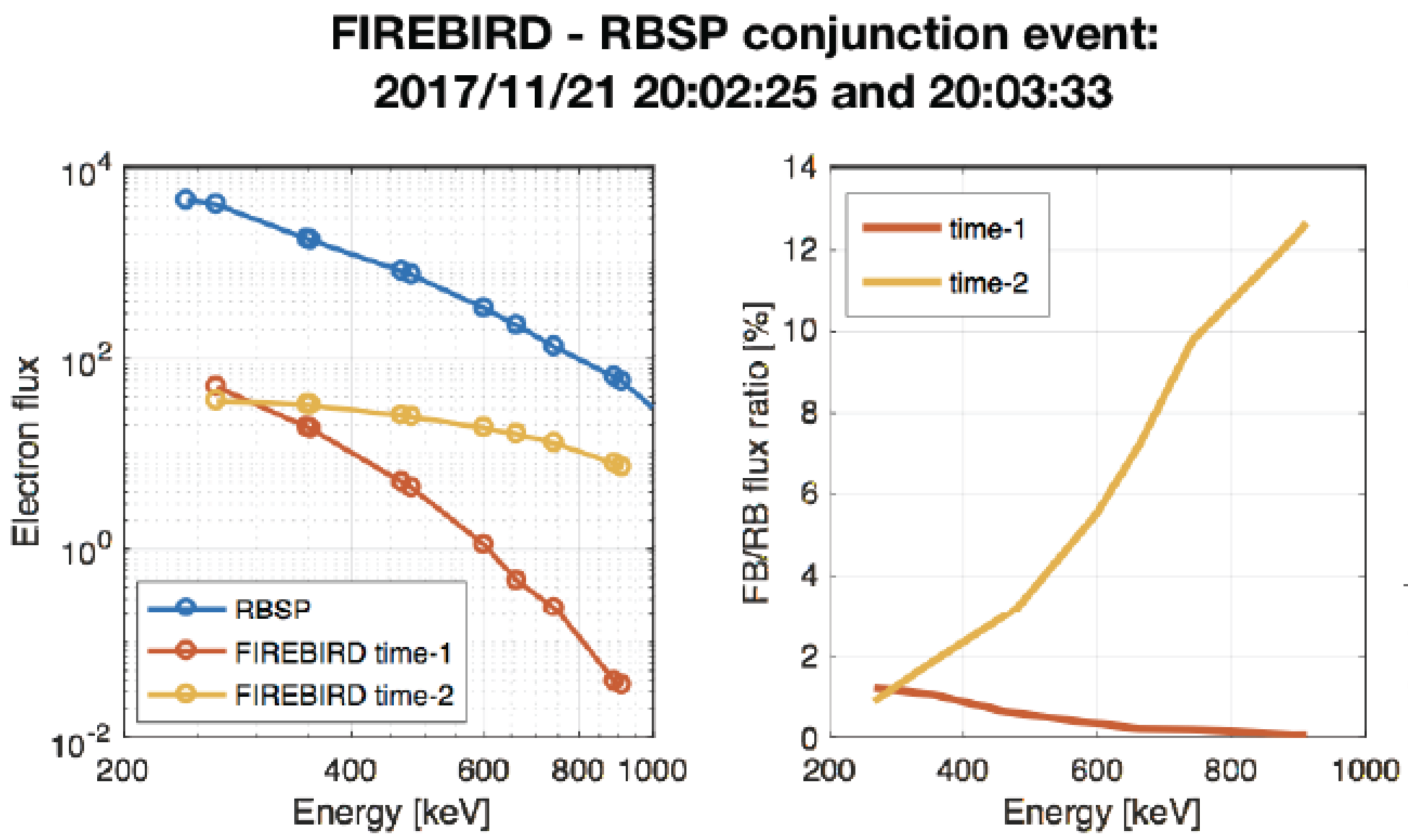
Focus primarily on times of quiet to moderate activity.

Example of scaling electron flux from the Van Allen Probes according to FB/RBSP ratios.

Use 50th percentile to represent quiet to moderate activity.



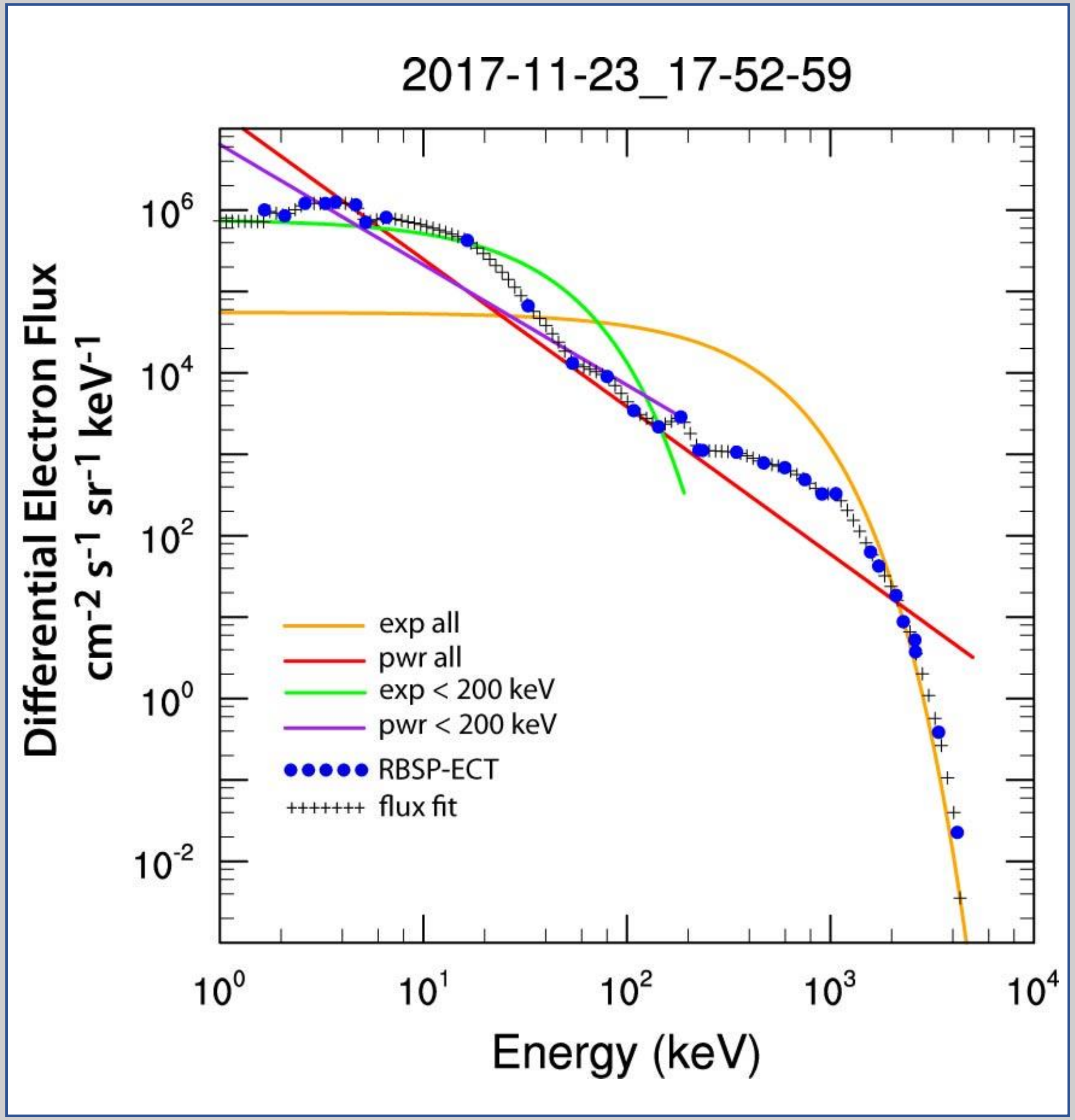
Energy dependence of the ratio of FIREBIRD-II to Van Allen Probes electrons

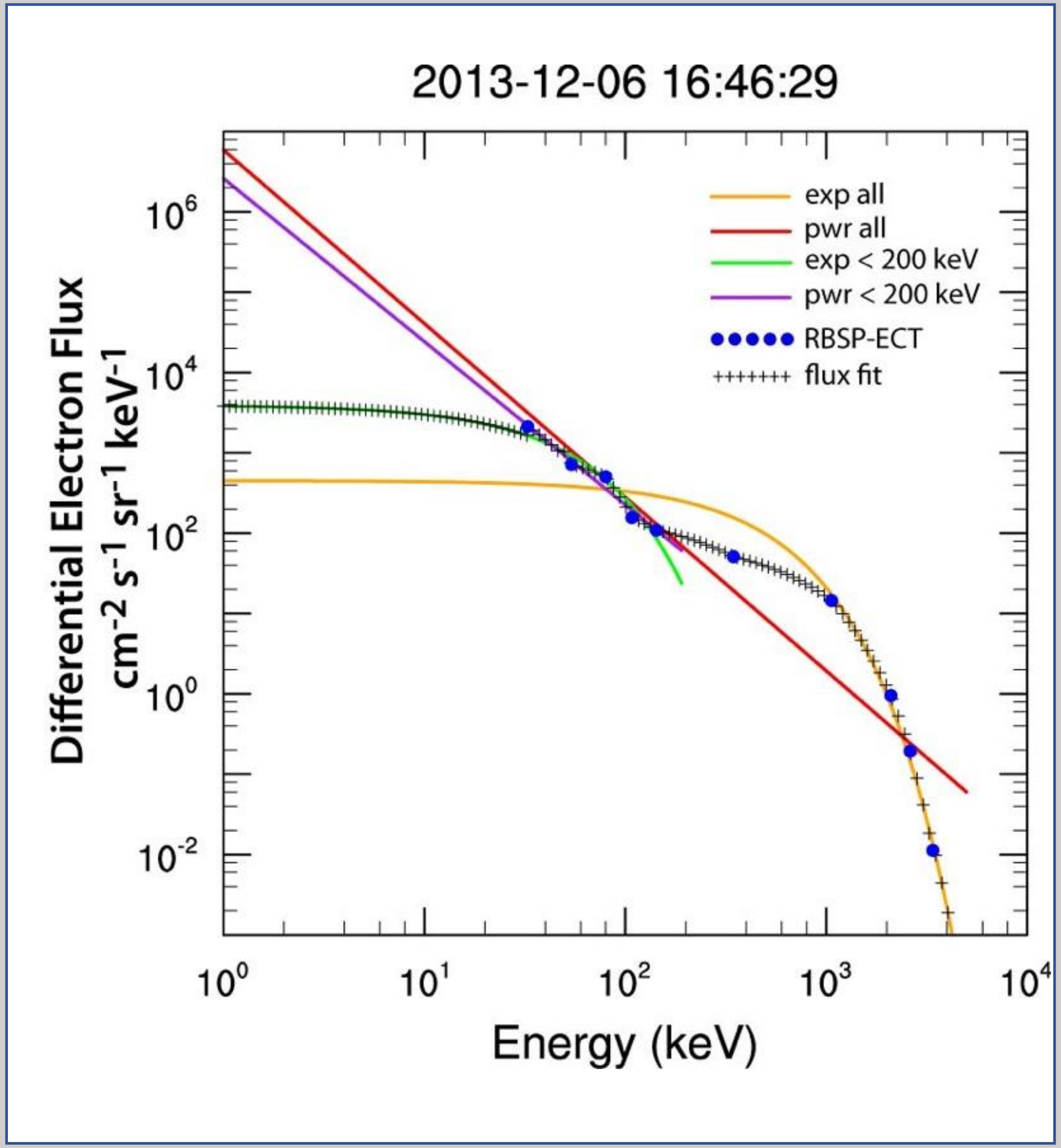


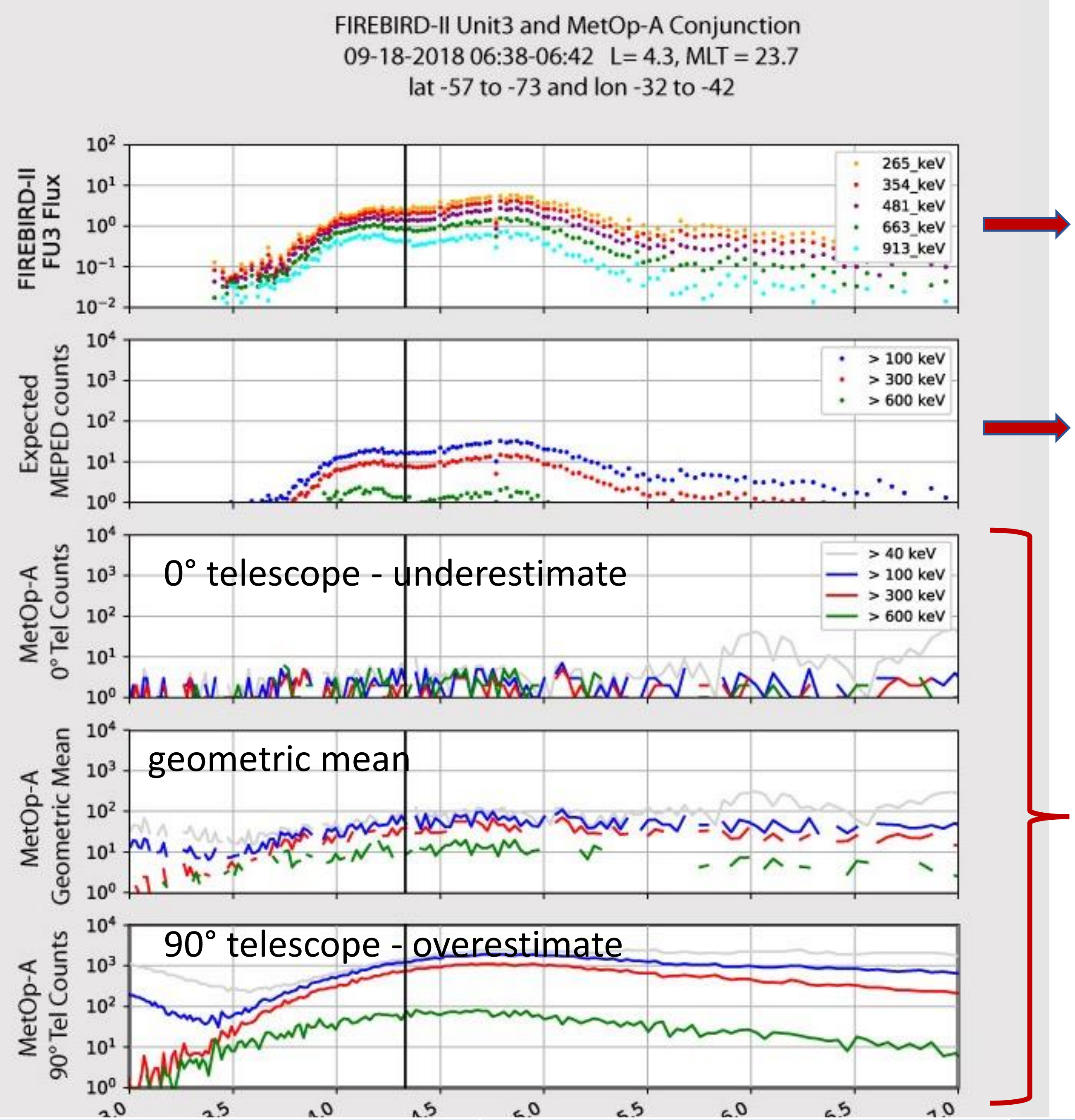
Hard spectrum
- strong precipitation

Soft spectrum
- weak precipitation

And how to address spectral shape....







FIREBIRD electron flux ($cm^{-2}\ sr^{-1}\ s^{-1}\ keV^{-1}$)

Counts expected using this flux from the POES MEPED instrument.

The geometric mean between the POES 0° and 90° telescopes provides a (very) rough estimate of precipitation, similar to Rodger et al. (2013).

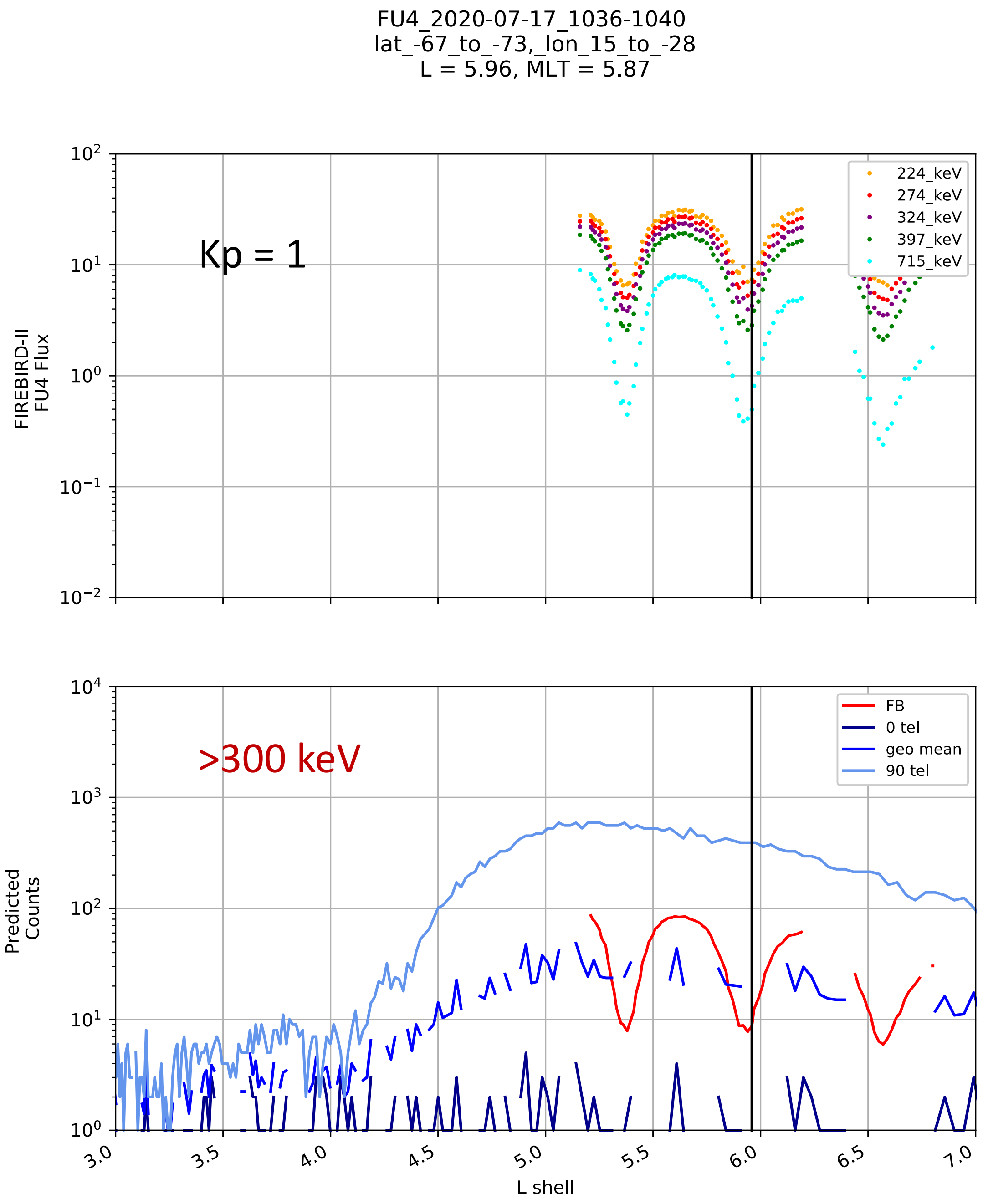
A continual challenge…

FIREBIRD-II orientation

The CubeSats were designed to passively align with the magnetic field, but their precise orientation is unknown…

…but sometimes the **spacecraft ”wobbles,”** provides insight into how electron flux varies between the precipitating (bounce loss cone) and trapped populations.

At the FIREBIRD-II orbit (400-600 km), the **majority of observed electrons likely precipitate** into the atmosphere over one drift cycle.



Conclusions

1. Combining NSF FIREBIRD-II CubeSats and Van Allen Probes datasets provide new information and insights into atmospheric electron precipitation, including understanding spectral shape at energies important for ionization of the middle atmosphere.
2. High-resolution FIREBIRD-II measurements follow the same general trends as NOAA POES and ESA MetOp while also able being able to capture variability at low flux.
3. Estimates of electron precipitation from Van Allen Probes based on ratios with FIREBIRD-II suggest CMIP6 may underestimate atmospheric ionization in the middle atmosphere.
4. High-energy (>1 MeV) electron precipitation peaks around L shell 4.5 with background precipitation increasing and strong precipitation events decreasing in the declining phase of the solar cycle.