Investigating the Atmospheric Response to Radiation Belt Electron Precipitation: Preliminary Work

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Disclaimer: I am from the radiation belt/magnetosphere community, and just starting to learn more about the atmosphere and WACCM.
Feedback and collaboration requests are very much welcome!

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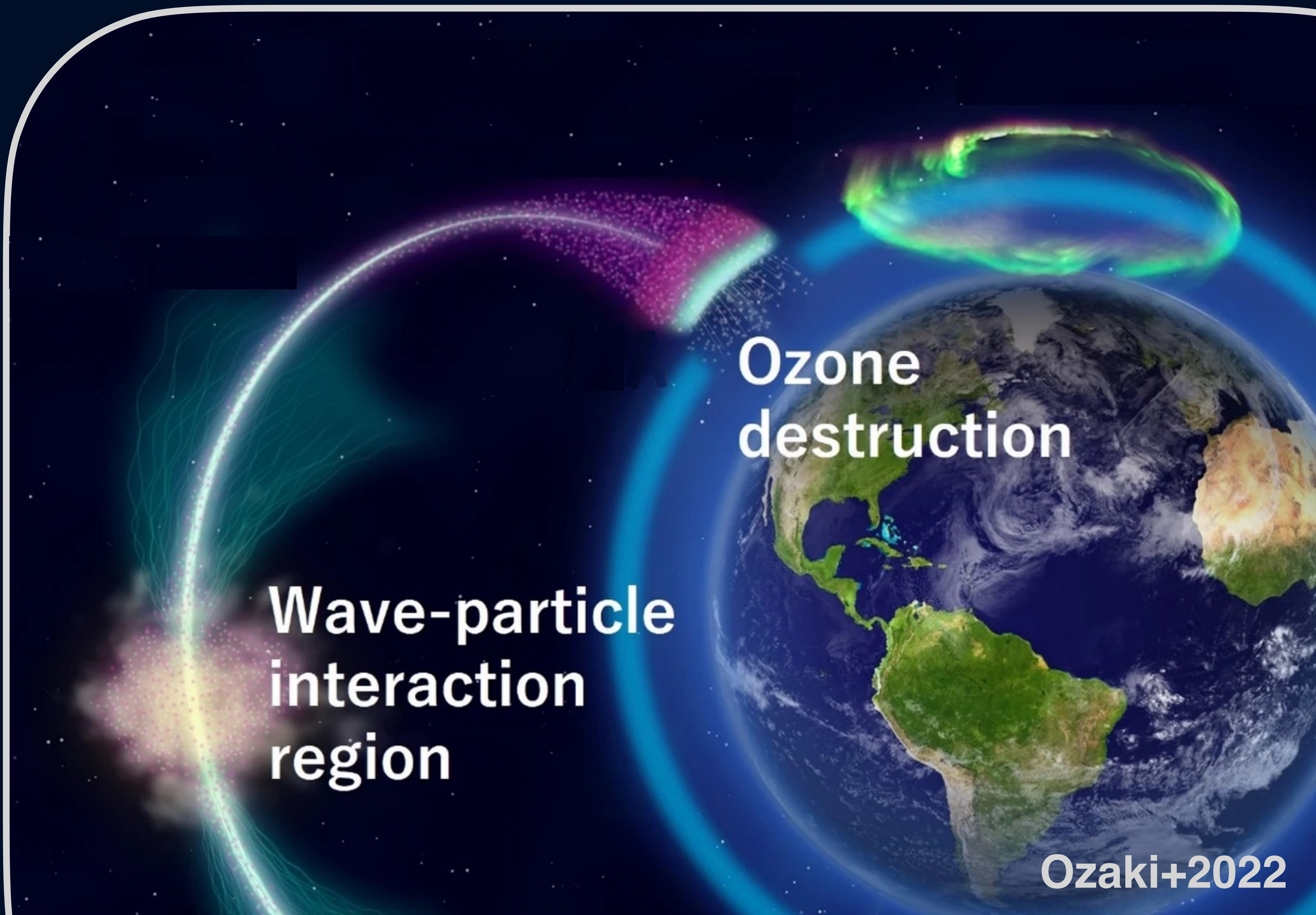
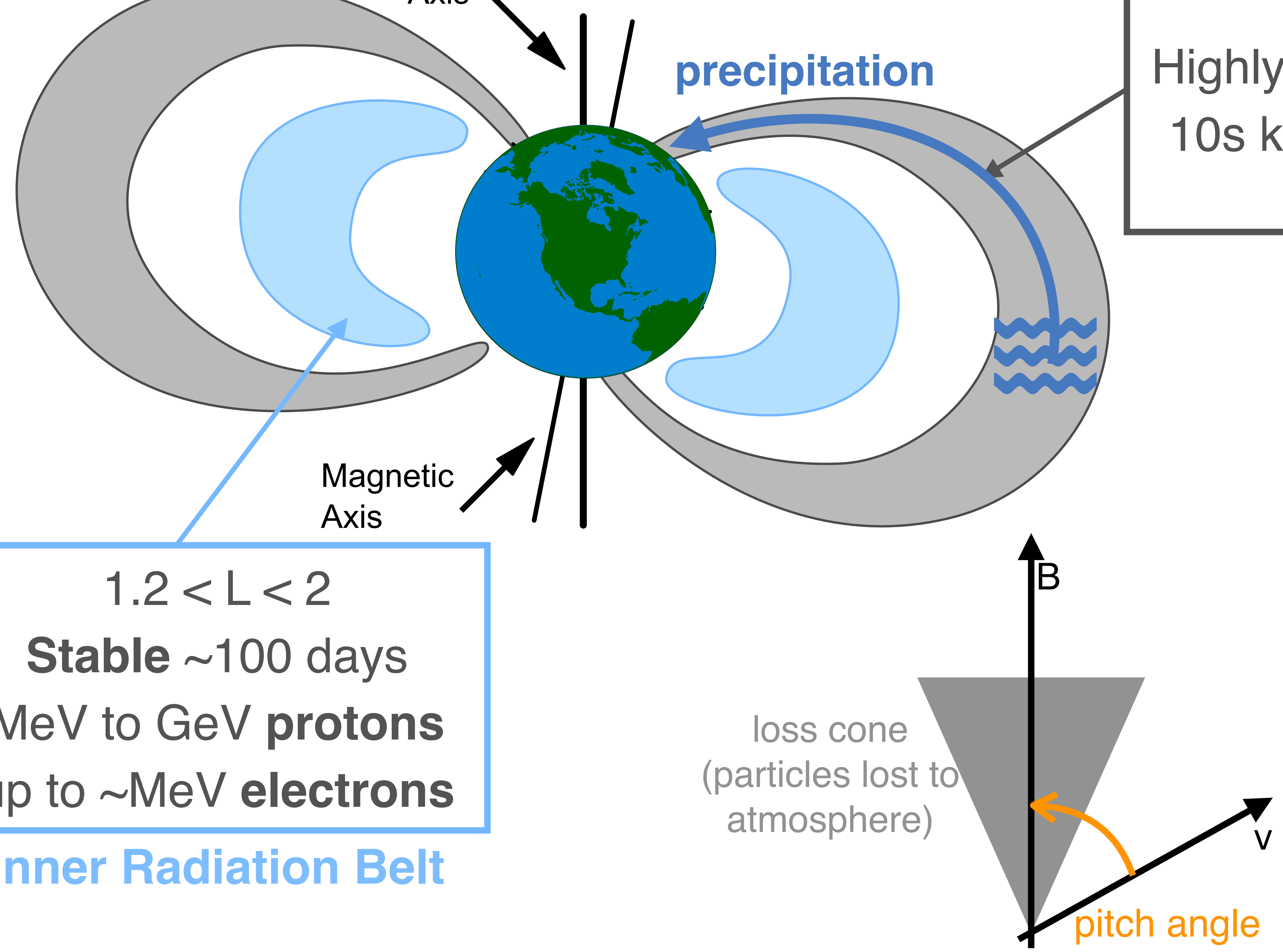


Introduction: The Radiation Belts



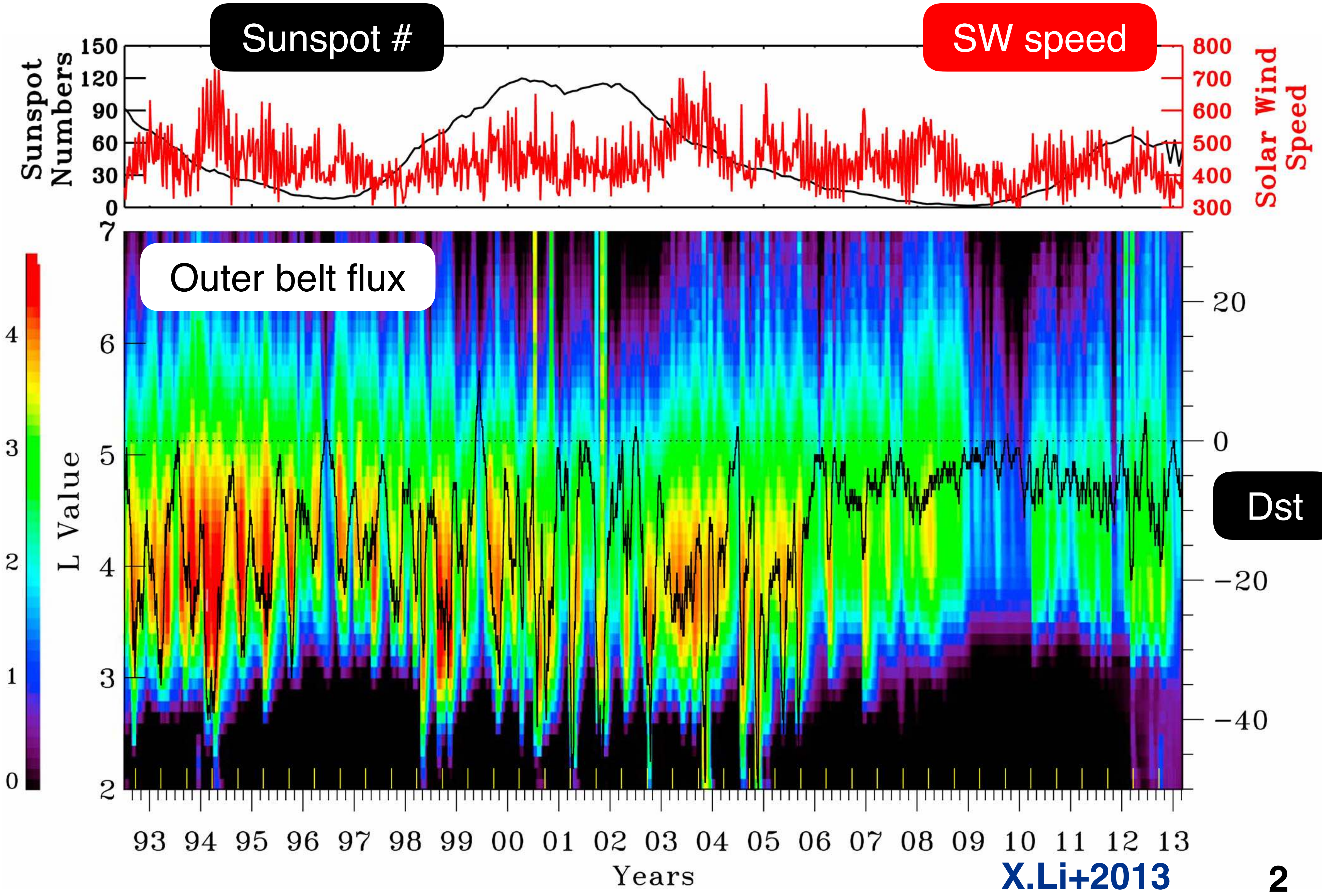
Outer Radiation Belt

3 < L < 7
Highly **variable** ~hours
10s keV to multi-MeV **electrons**

1.2 < L < 2
Stable ~100 days
MeV to GeV **protons**
up to ~MeV **electrons**

Inner Radiation Belt

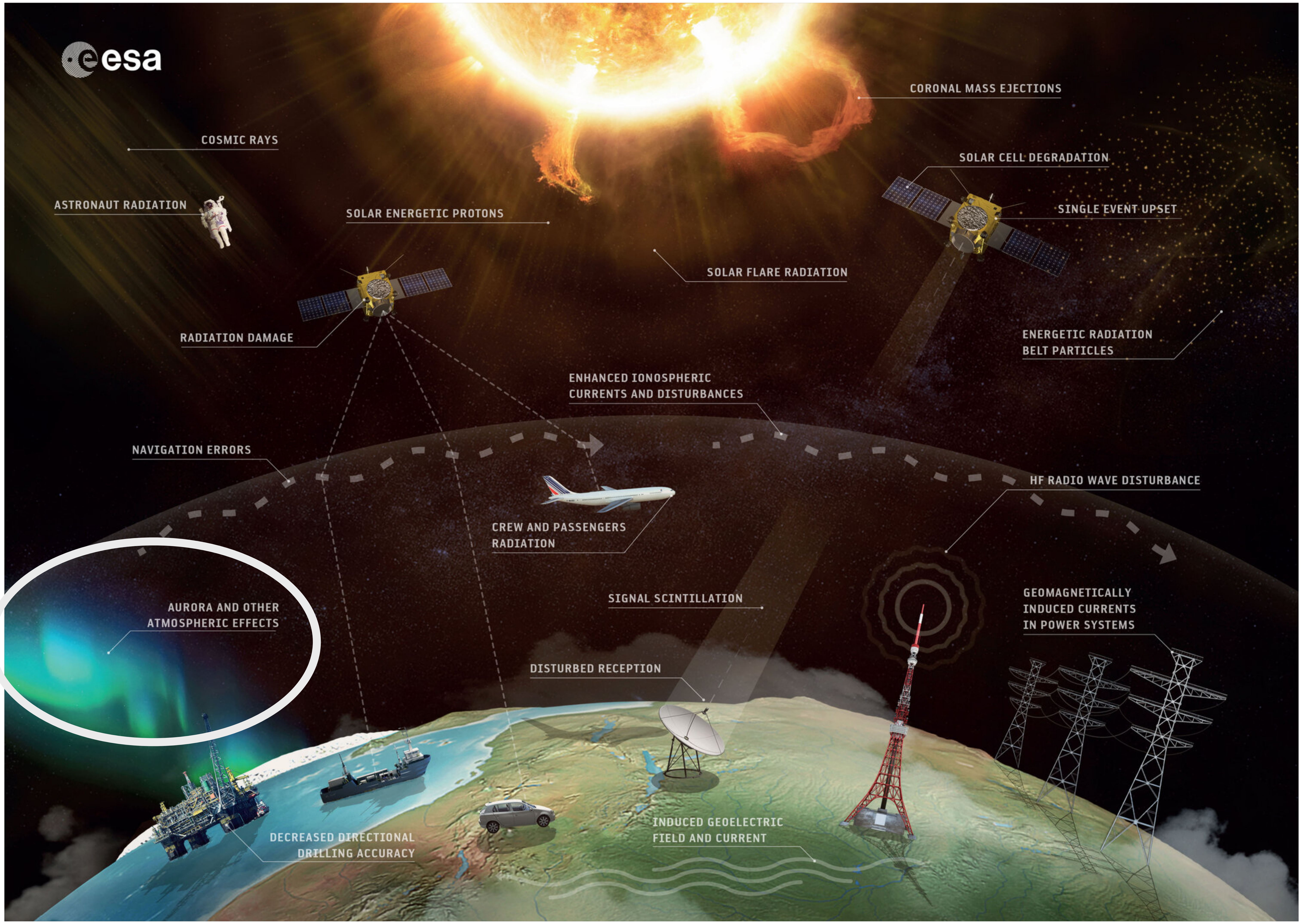
The **outer belt** is highly dynamic, responding to solar wind fluctuations and the resulting geomagnetic activity (storms & substorms)



X.Li+2013

The RB structure results from acceleration, transport and loss of electrons in the magnetosphere, heavily dependent on wave-particle interactions

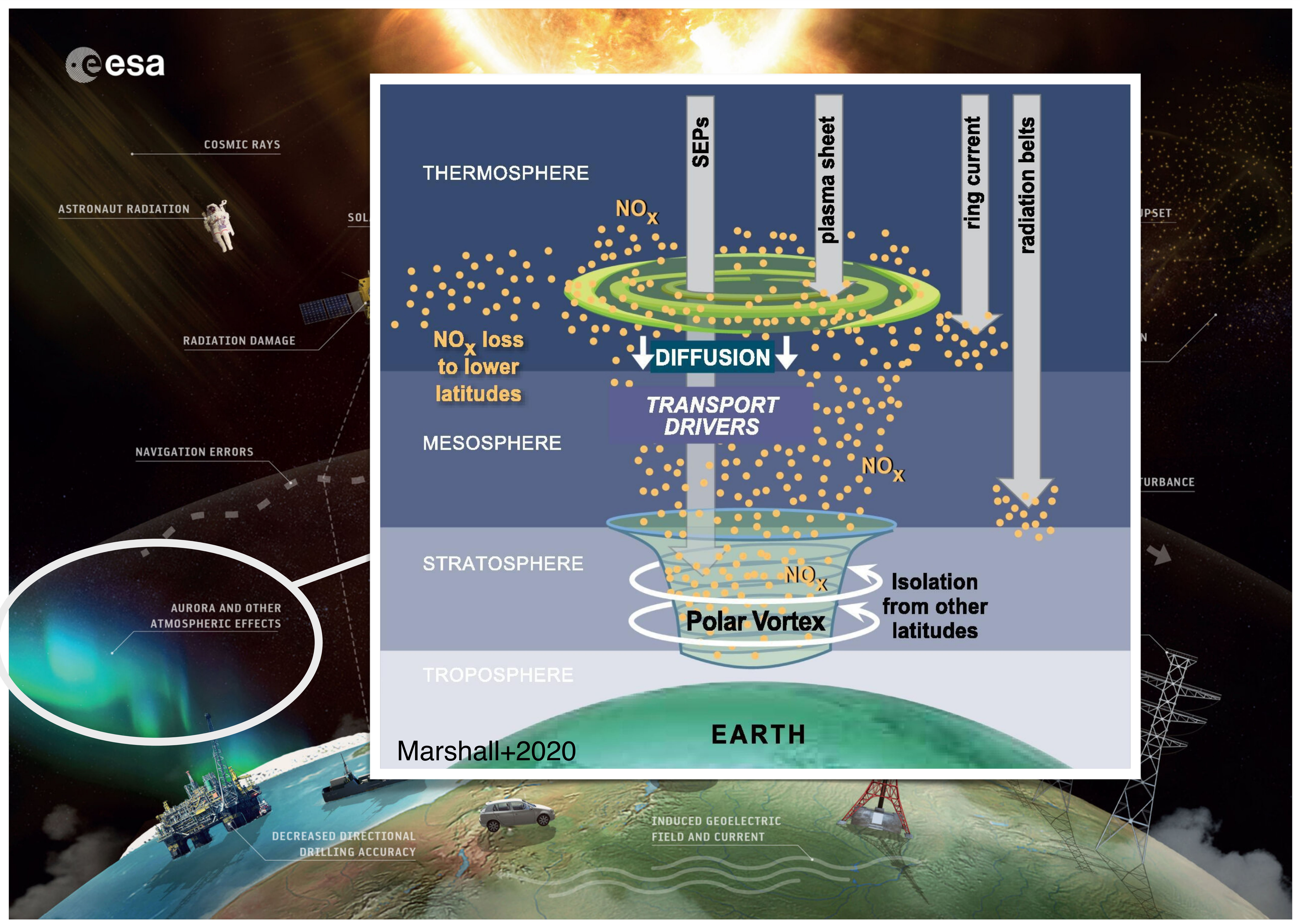
Motivation



The RBs are part of the near-Earth environment, contributing to Space Weather

- Precipitation of RB particles affects **ionospheric conductivity**
- **Energy input** into upper atmosphere alters **atmospheric chemistry** enhancing ozone loss
- There is **no consensus** on the RB energy input, especially the high-energy tail

Motivation



Marshall+2020

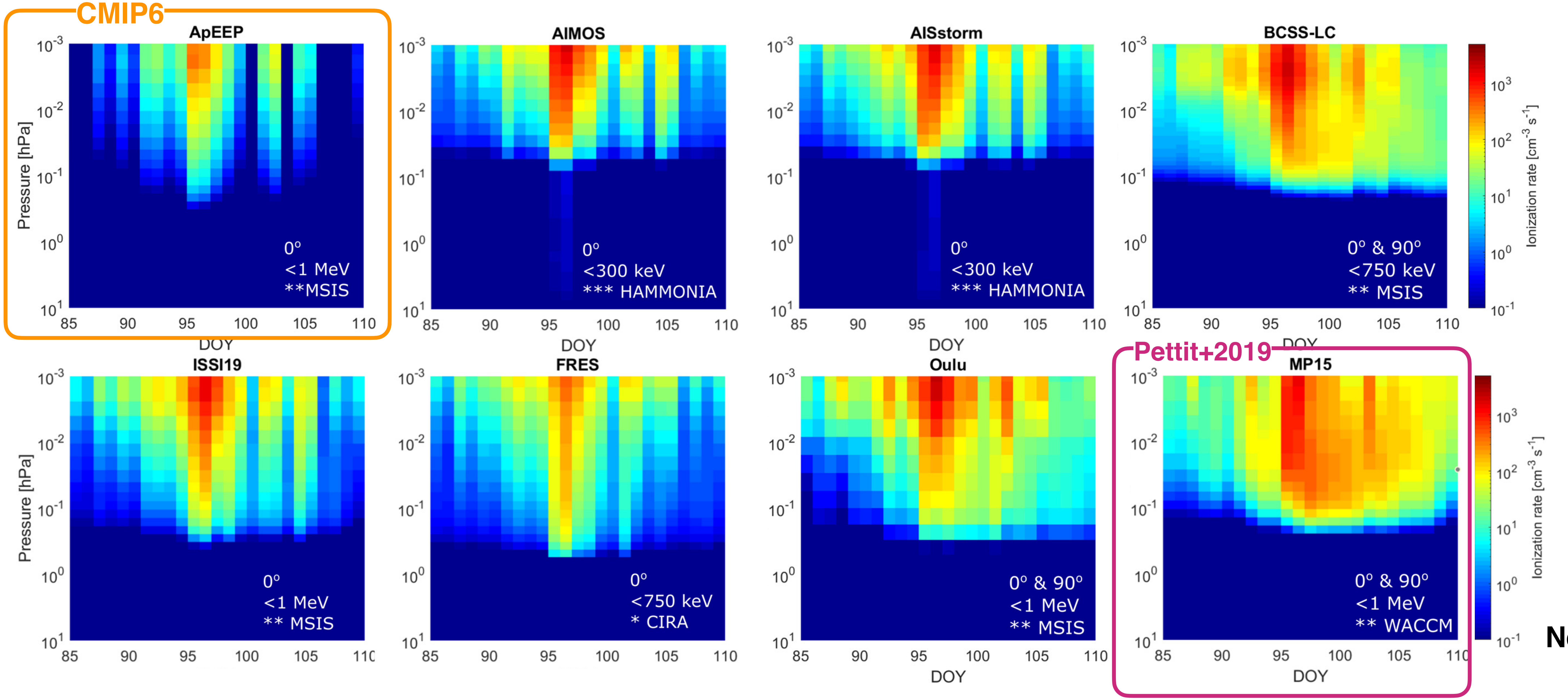
- Precipitation of RB particles affects **ionospheric conductivity**
- **Energy input** into upper atmosphere alters **atmospheric chemistry** enhancing ozone loss
- There is **no consensus** on the RB energy input, especially the high-energy tail
- **NOx enhancement** due to SEP, GCRs, and auroral electrons is underestimated

The RBs are part of the near-Earth environment, contributing to Space Weather

AGU CHAPMAN CONFERENCE
Melbourne, Australia | 14-21 February 2025
Particle Precipitation: Drivers, Properties, and Impacts on Atmosphere, Ionosphere, Magnetosphere Coupling

Background Work: Inputs & Response

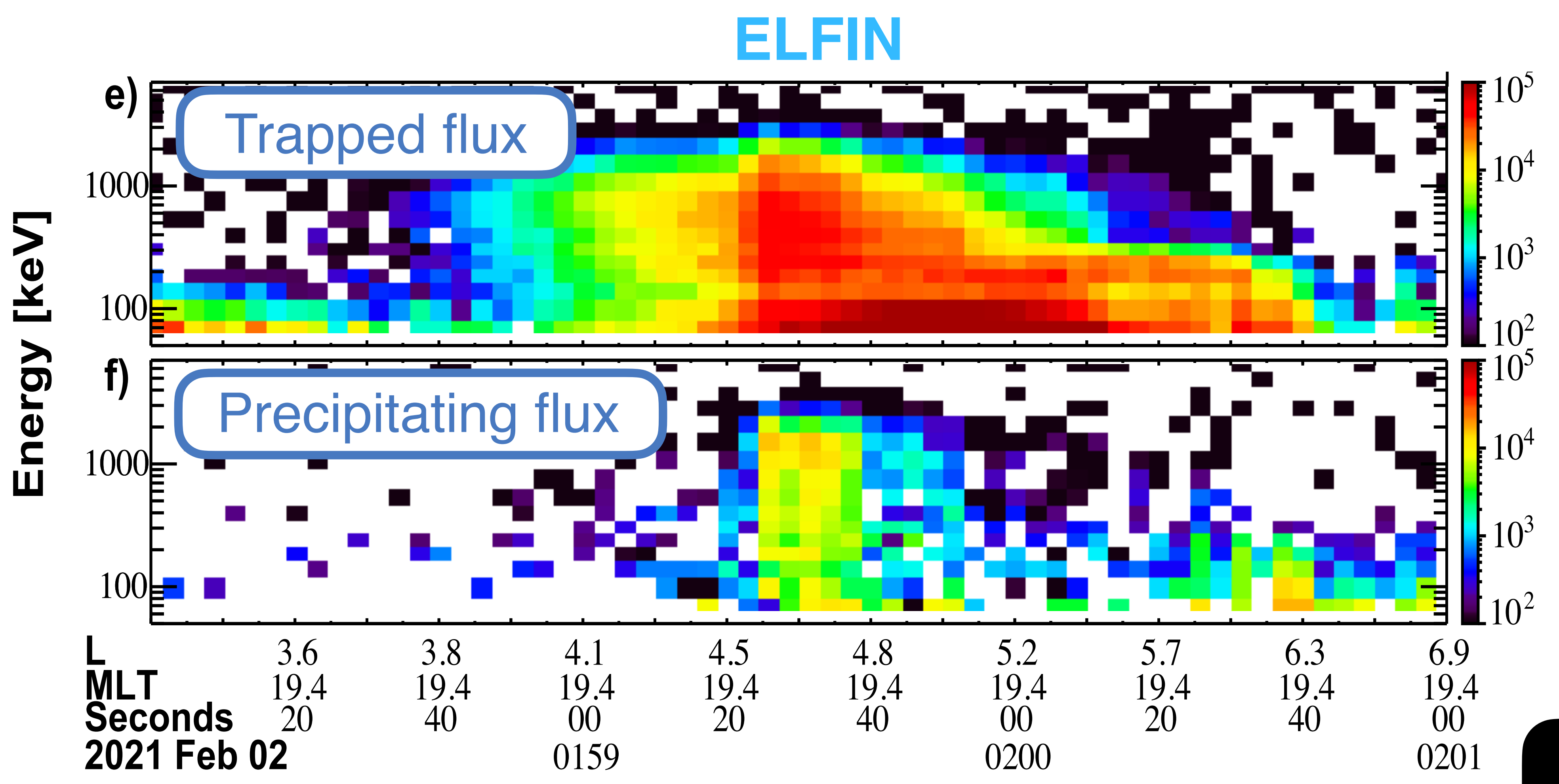
- Ionization rates due to RB precipitation vastly differ across research groups, even if the same exact data source (POES) and event (Mar-Apr 2010) are considered
- POES data is assumed to detect "precipitation" no matter the true precipitation intensity

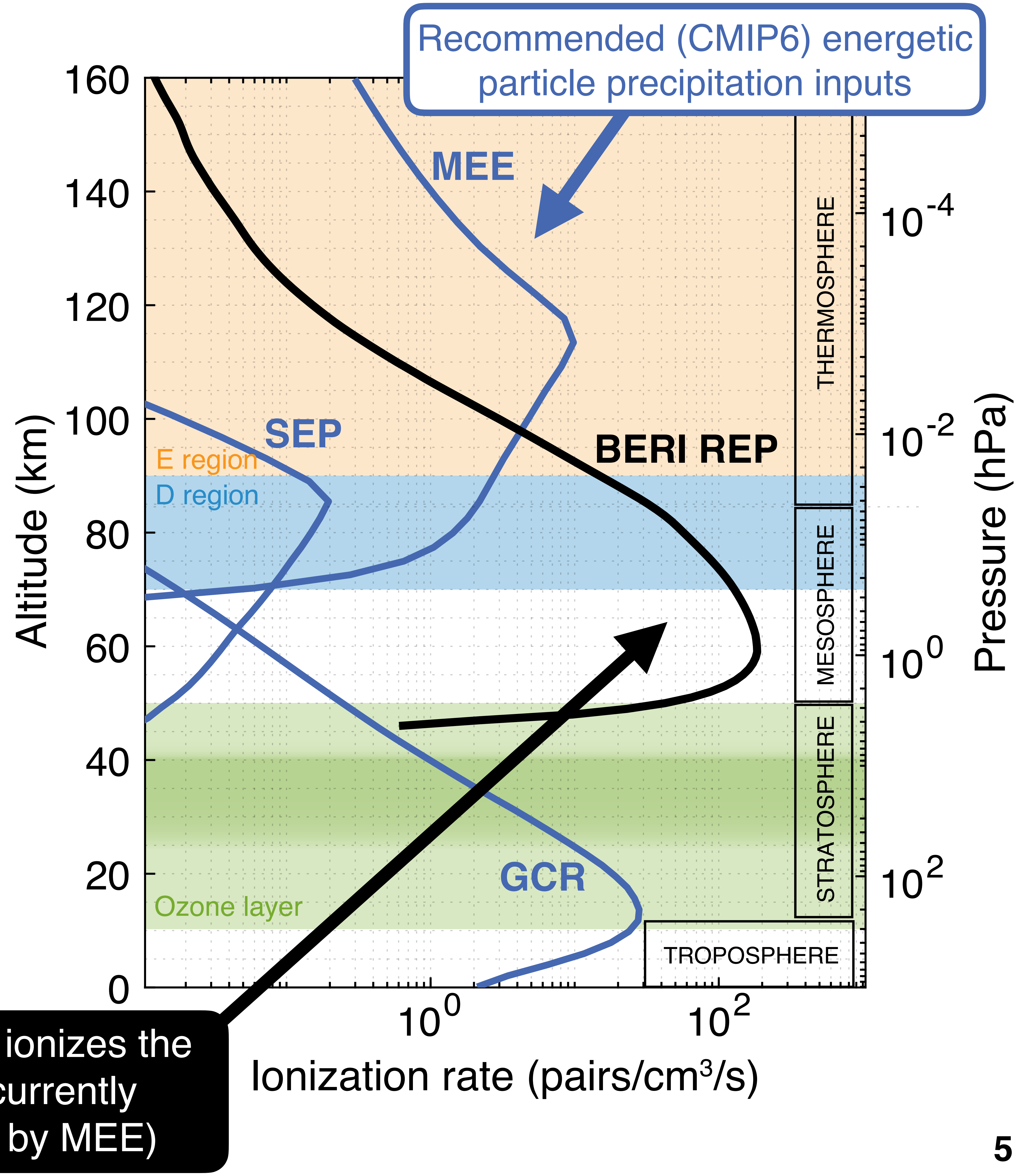


Nesse+2022

Background Work: Inputs & Response

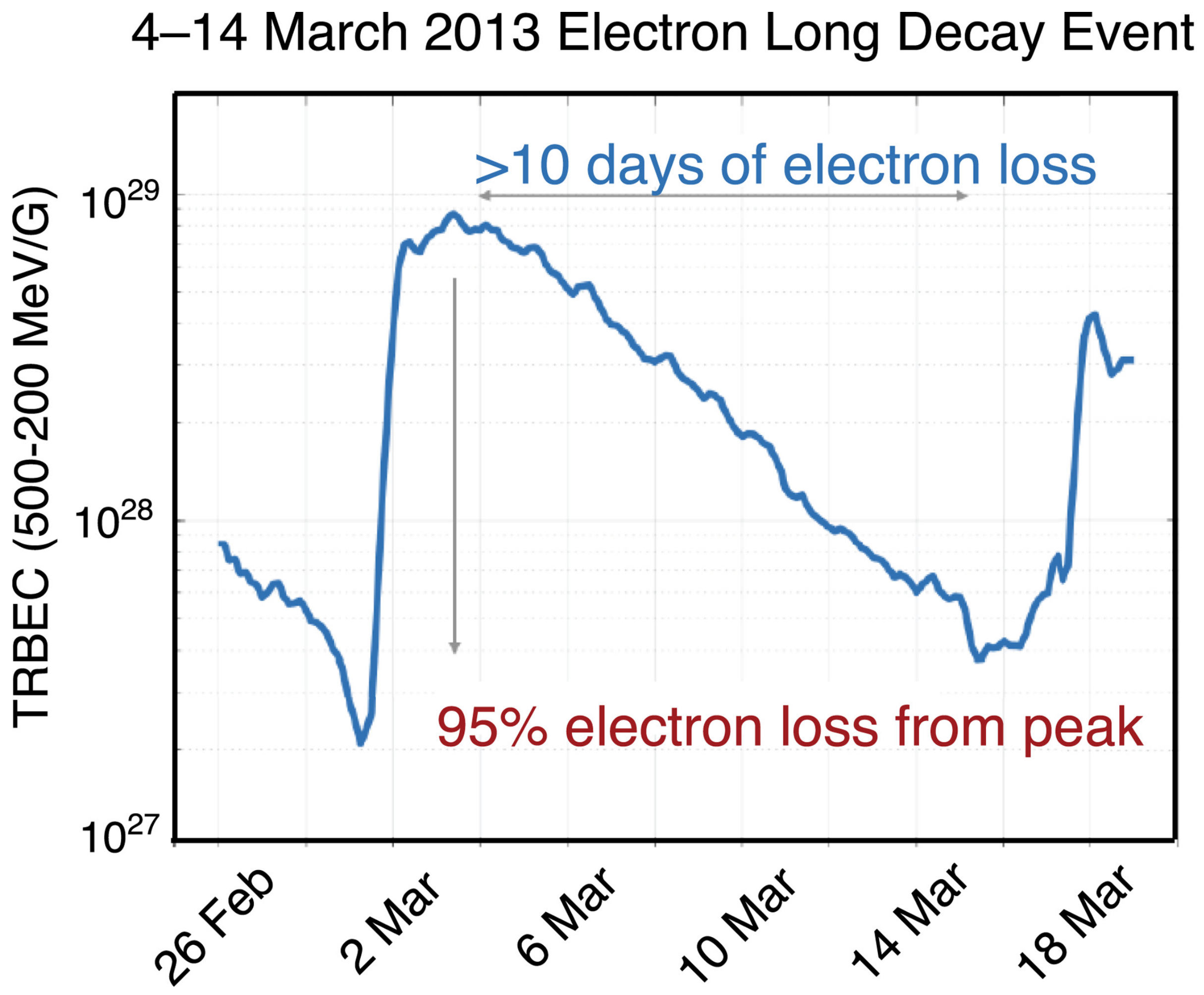
- Collection of ~144 precipitation events (from single-pass ELFIN CubeSats), specifically at **relativistic energies**
- New ionization rate method: **BERI** (Boulder Electron Radiation to Ionization) model [Xu+2020]:
  - Monte Carlo model adapted from Lehtinen+1999
  - 33 keV – 33 MeV, past [Fang+2010] method
- Calculate ionization rates for relativistic electron precipitation



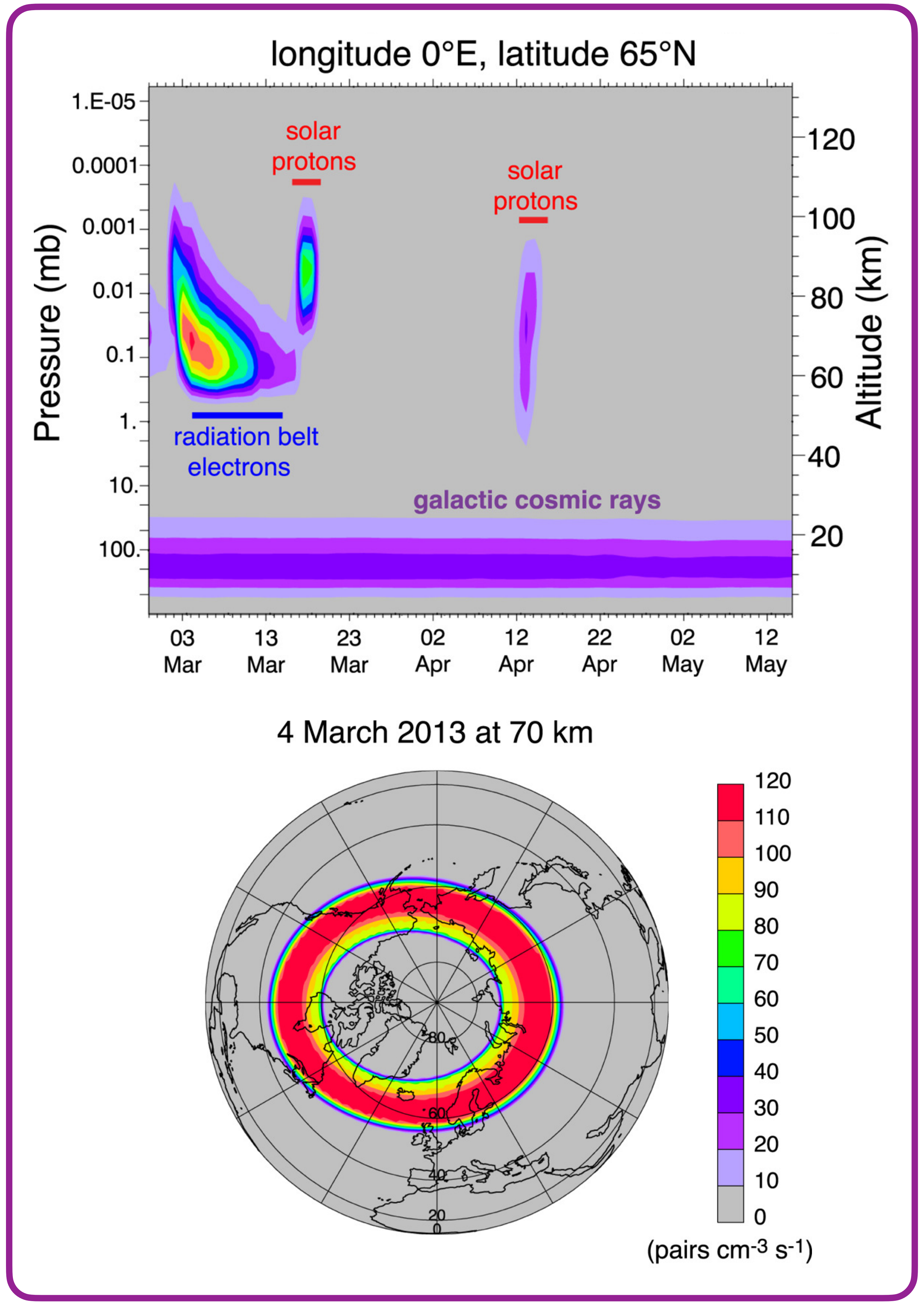


Background Work: Inputs & Response

- **NOx production** is enhanced during RB electron precipitation, leading to some **ozone depletion**

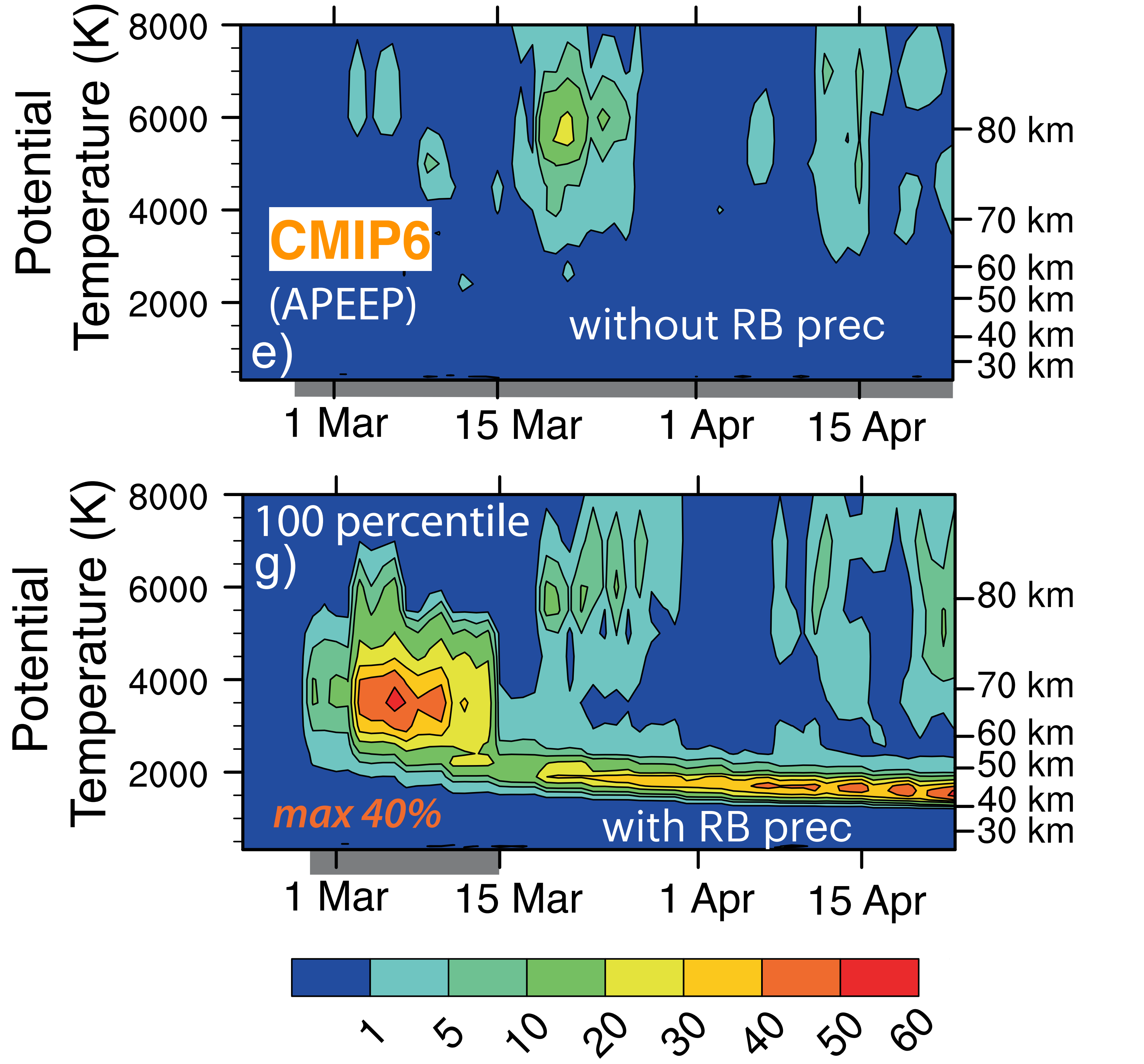


Ionization rates
~265 keV – 1 MeV
[Fang+2010]



WACCM simulations

Northern Hemisphere vortex-averaged O_3 reduction (%) compared to simulations without radiation belt electrons

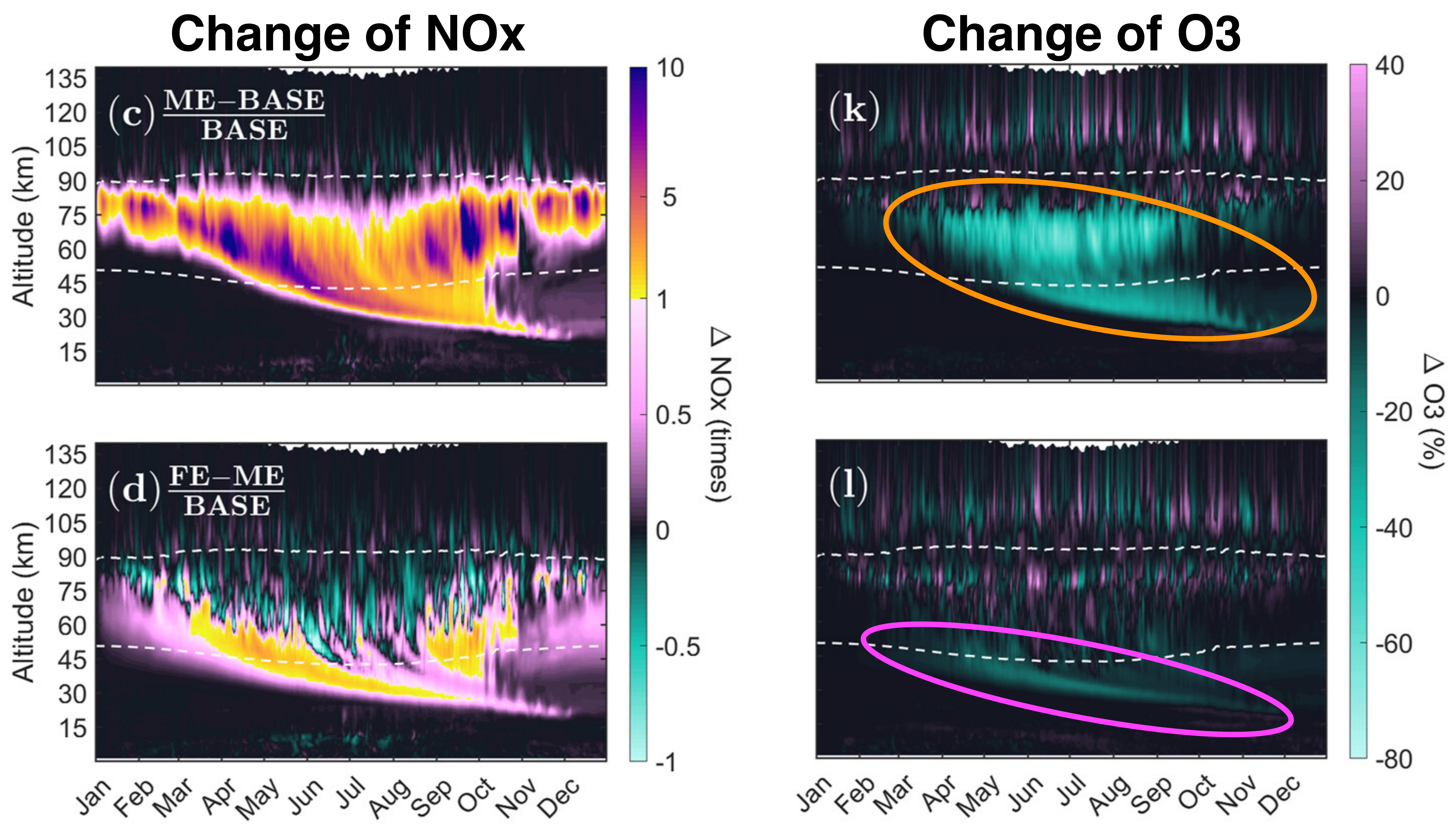


Background Work: Inputs & Response

- **NOx production** is enhanced during RB electron precipitation, leading to some **ozone depletion**

27 keV – **1** MeV

27 keV – **9** MeV



~37% O3 loss at 40 km

Additional ~17% O3 loss at 40 km

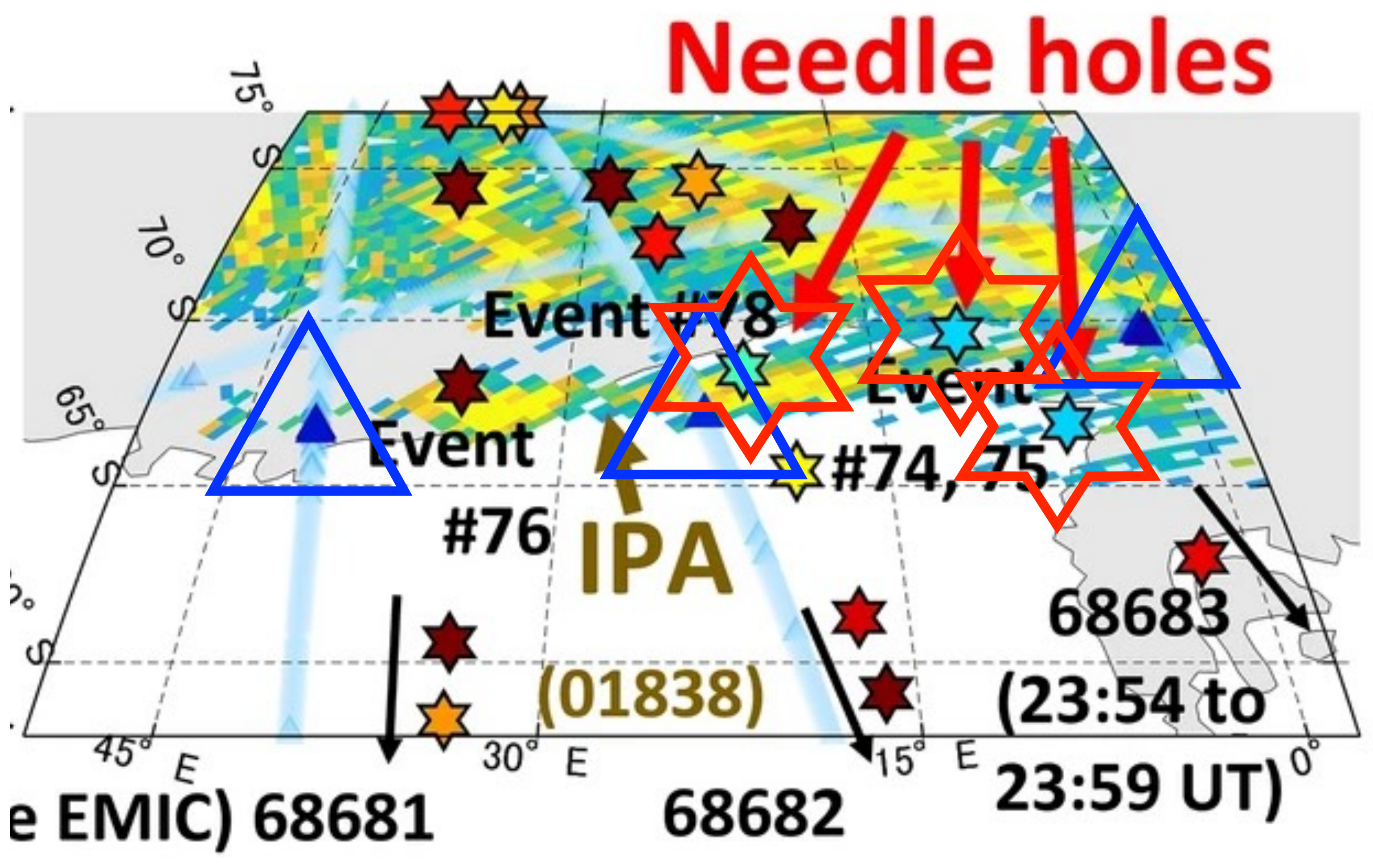
Ionization rates from BERI [Xu+2020] as input to WACCM for year 2003

Pan+2025
*serve as a max RB precipitation effect

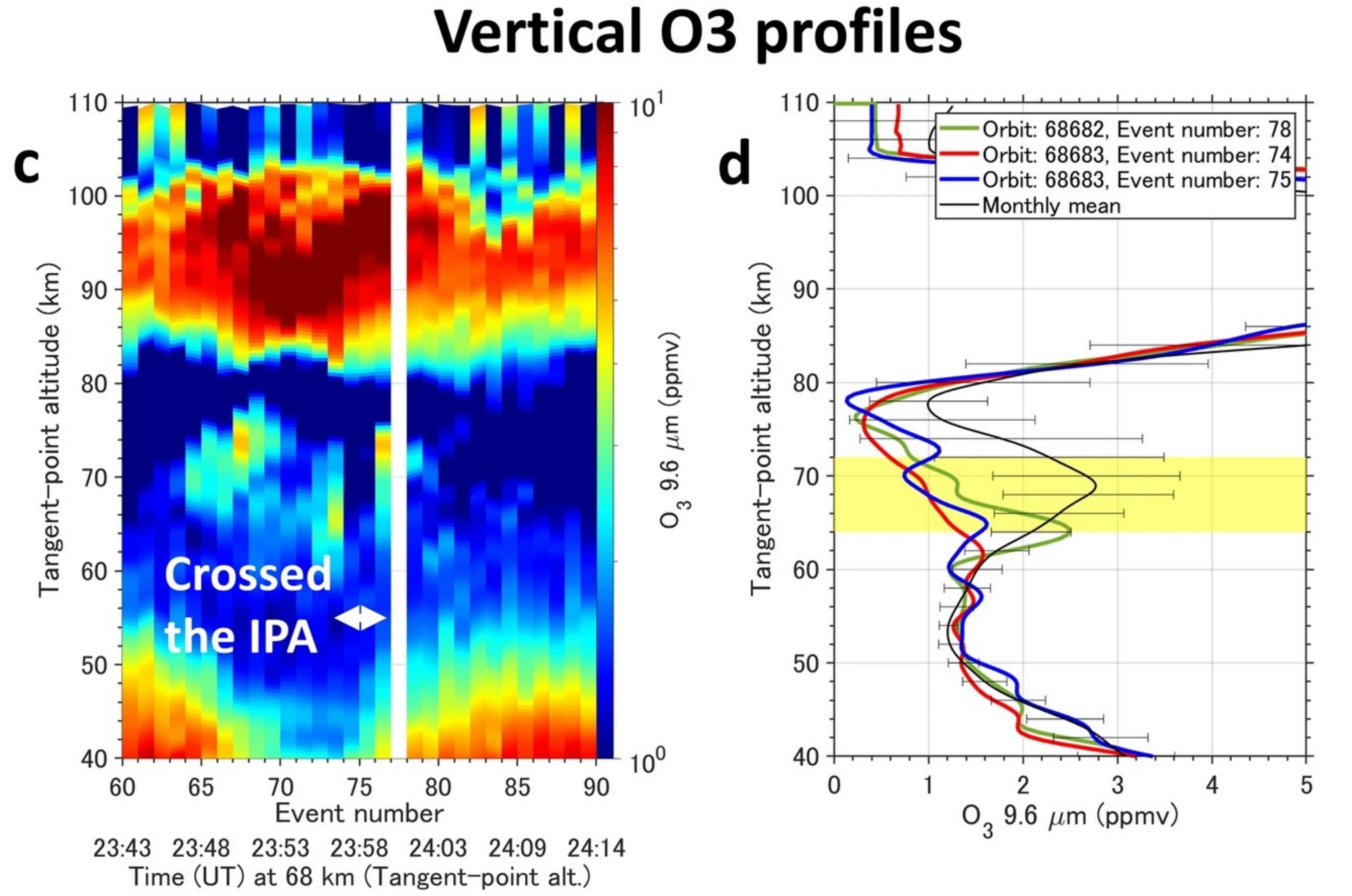
Background Work: O3 Depletion Evidence

- **NOx production** is enhanced during RB electron precipitation, leading to some **ozone depletion**

REP from POES observations



O3 depletion from TIMED/SABER observations



Ozaki+2022

What are the effects of these % changes of O3?

Objectives

Key Science Questions*

❖ What is the realistic energy input from REP?

❖ What are the resulting effects?

**focus on relativistic electron precipitation (REP)*

- Consider **realistic precipitation regions** rather than a “constant” drizzle of relativistic electrons (which overestimates the energy input and may be realistic for sub-relativistic electrons only)
- Specifically target the **atmospheric response to relativistic (~>700 keV) electrons** rather than sub-relativistic ones, to understand if these alone affect the response
- Consider the **realistic local-time dependence** of precipitation patches rather than assuming they span all longitudes
- **Quantify realistic O3 loss** – affect radiative heating, atmospheric thermal structure, and in turn zonal winds, wave propagation, circulation and strength of descent in polar winter

Data & Methodology

Electron Precipitation: LEO satellites

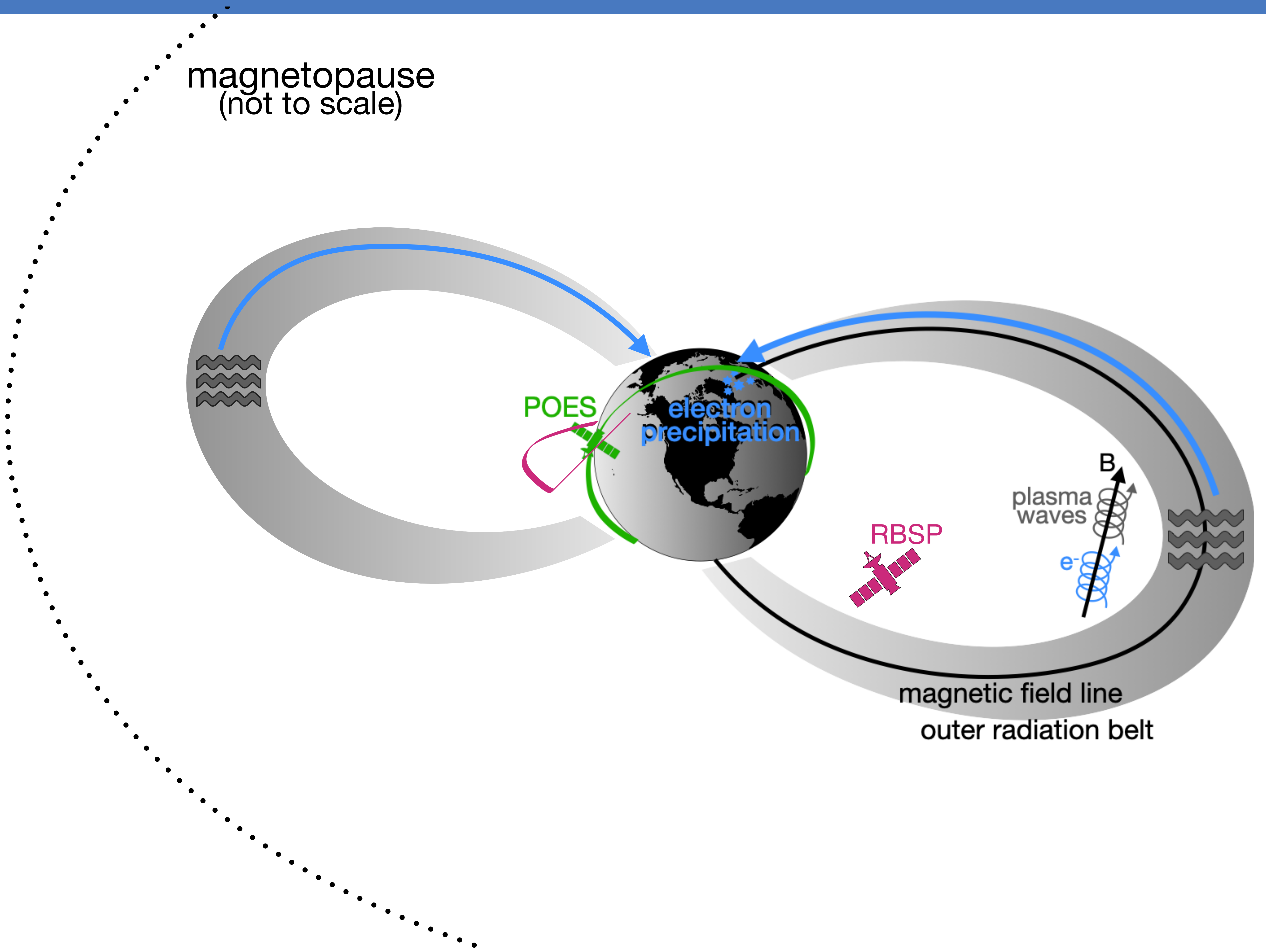
- **POES/MetOp** [2012–now]
  - 2-sec
  - 2 look directions
  - >30, >100, >300, **>700 keV electrons**
  - 10s–100s keV **protons**
- Collect relativistic electron precipitation events (**REP**, >700 keV) into **patches** (regions of precipitation)

Ionization Rates: BERI

- Boulder Electron Radiation to Ionization model [Xu+2020]
- 33 keV – 33 MeV

Atmospheric Modeling: WACCM

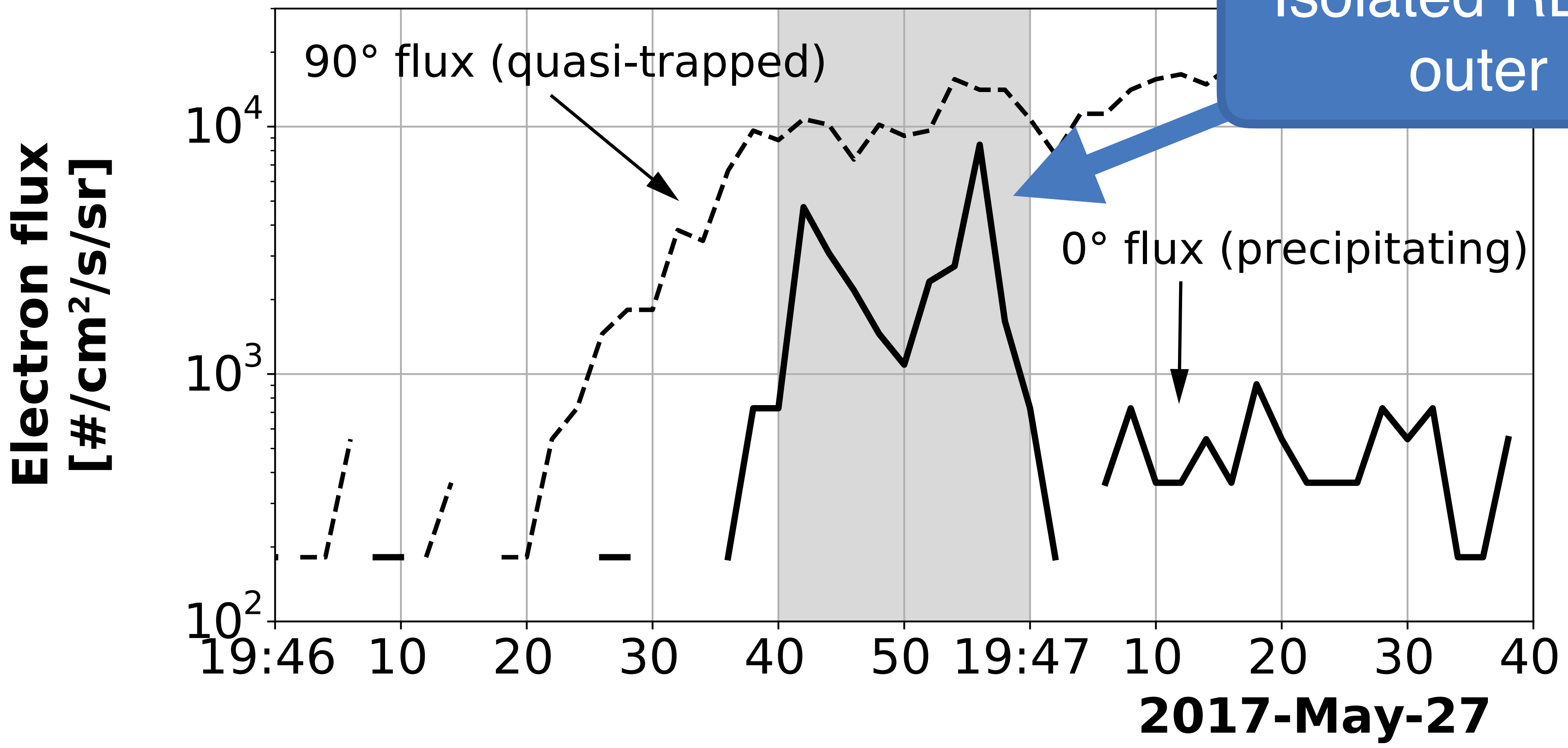
- CESM 2.1
- Forced by ocean sea surface temperature
- Specified Dynamics + D ionization scheme
- 1°x1° resolution



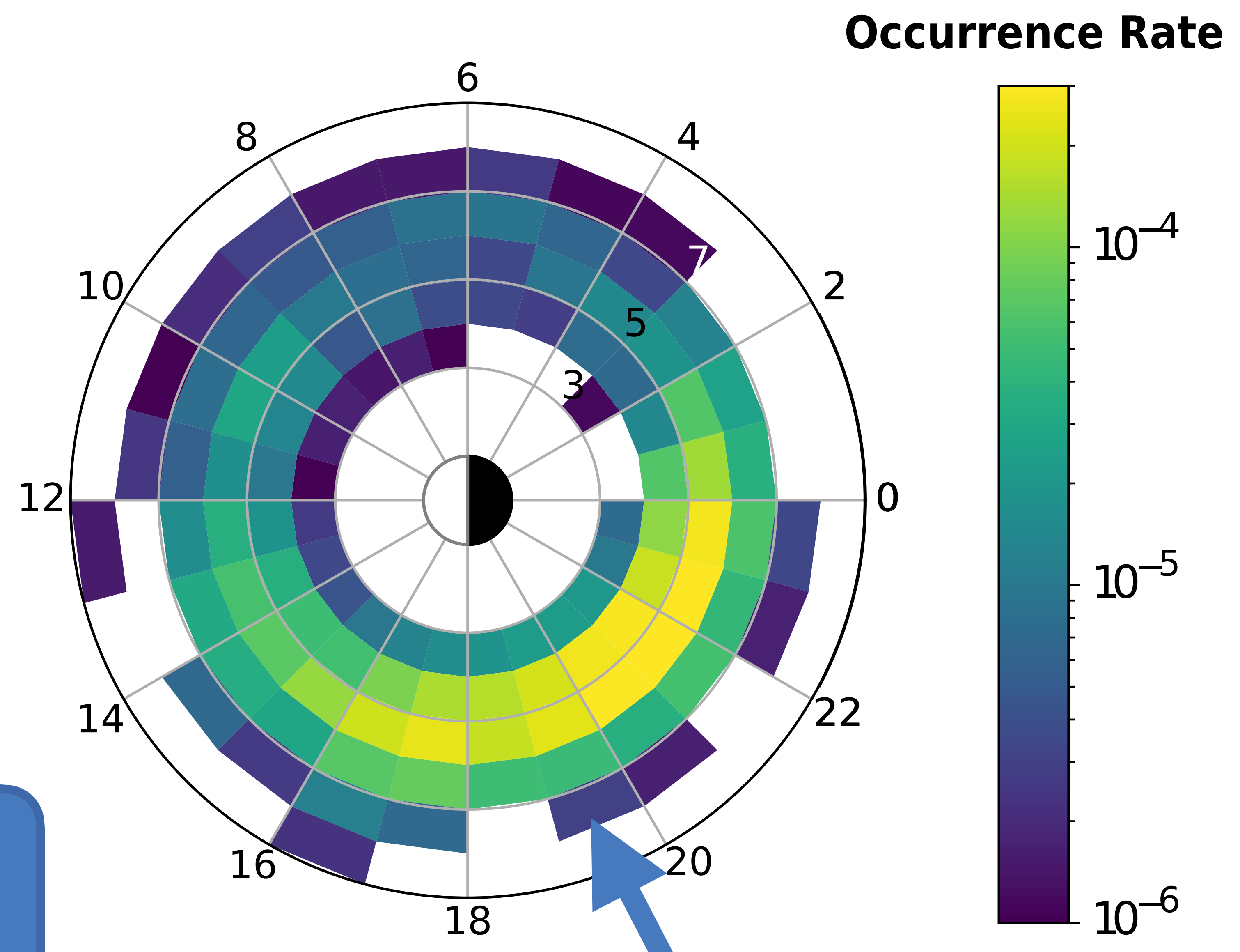
- Build a customized input file of **realistic** REP patches
- Evaluate local&global response vs no-REP conditions
- Quantify key players in response (flux, area, time, etc.)

Capannolo+2024b,2025

REP properties

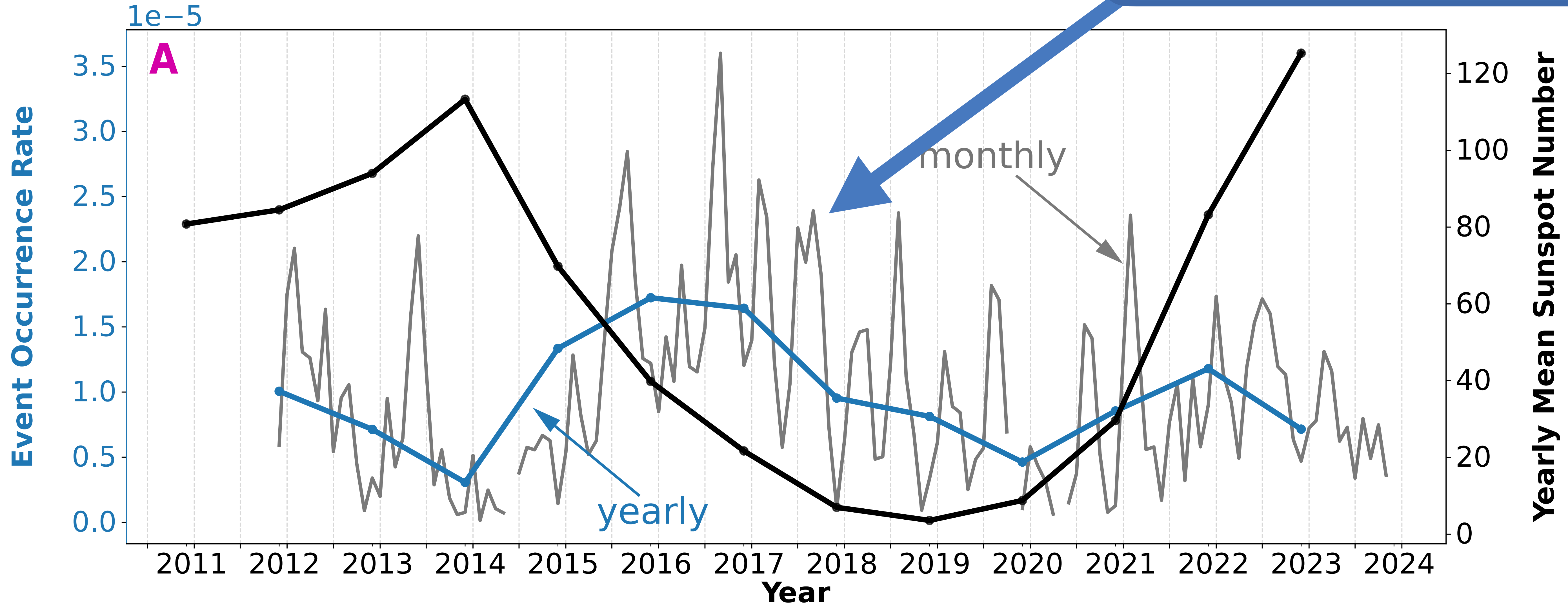


Isolated REP within outer belt



Wave-driven

REP occurrence is enhanced during the declining phase and solar max, and exhibits a semi-annual periodicity



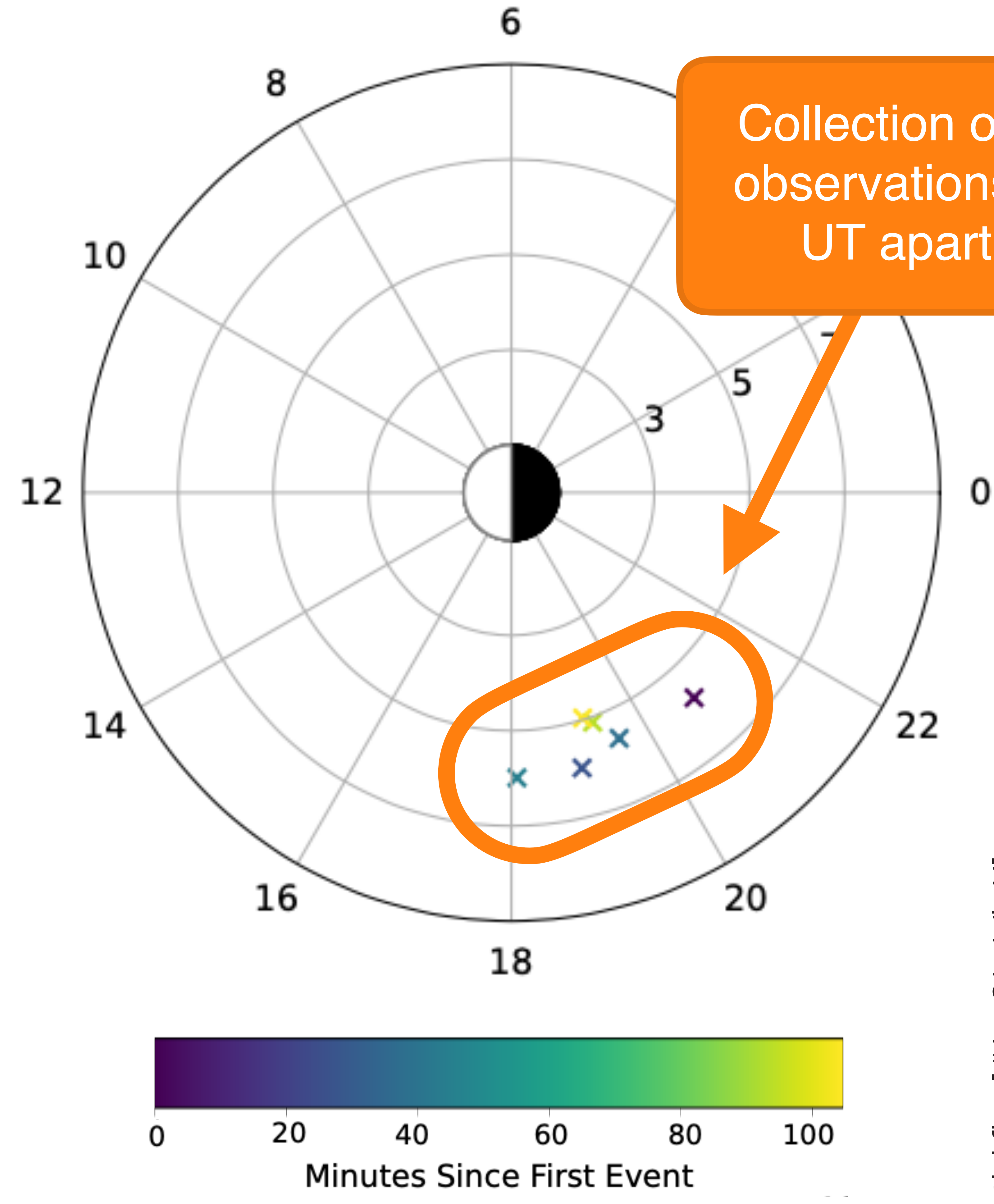
Wave-driven REP occurs everywhere, but primarily 14–02 MLT

*This region overlaps with where **EMIC waves** are most efficient at pitch-angle scattering electrons*

- REP region is generally more extended than a single LEO satellite pass, forming a “patch of precipitation”

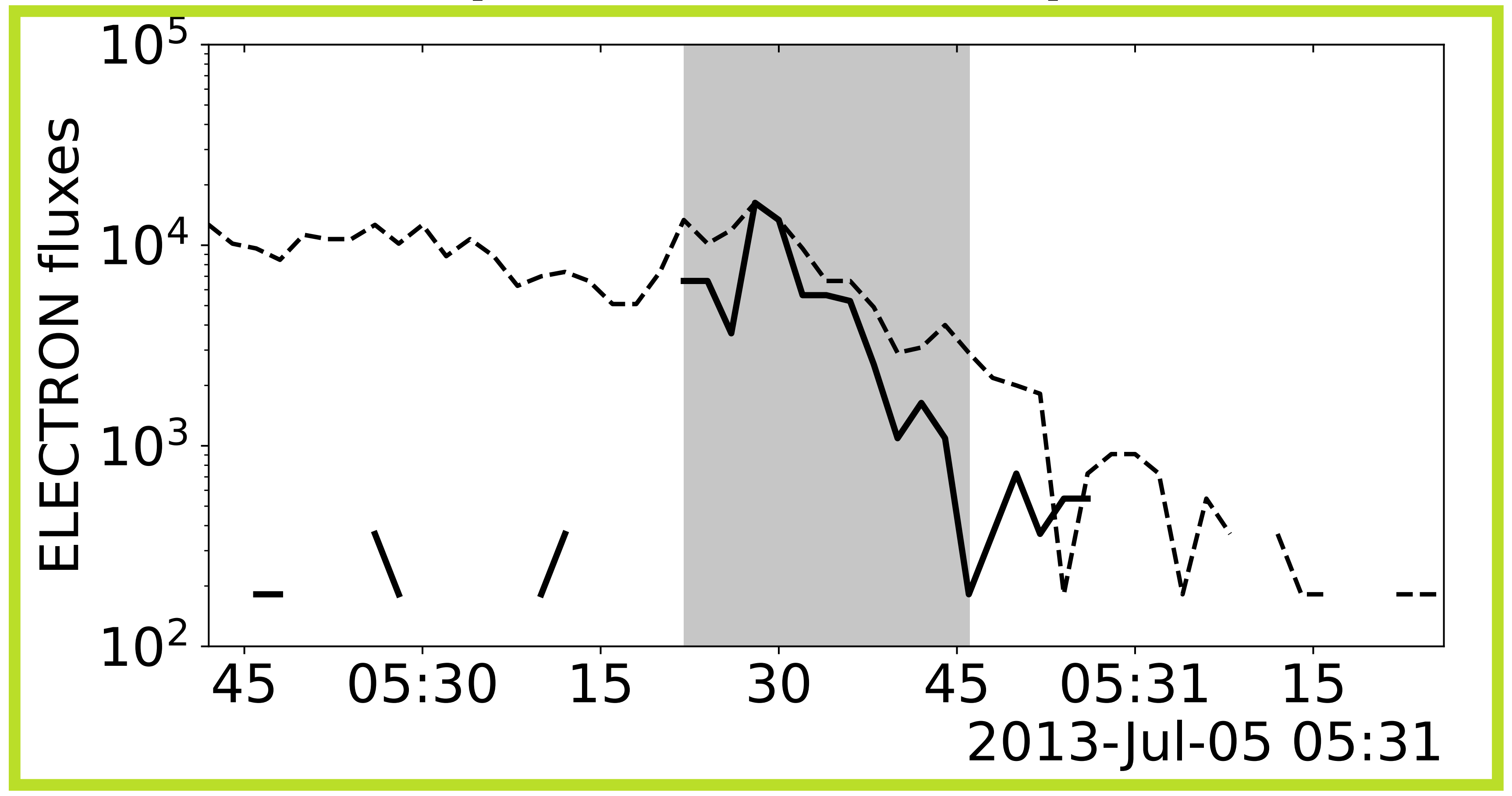
A REP patch example: 2013-07-05 03:56 to 05:41 UT

Collection of 6 REP single-pass observations (max 1 L, 2 MLT, 1 UT apart from each other)



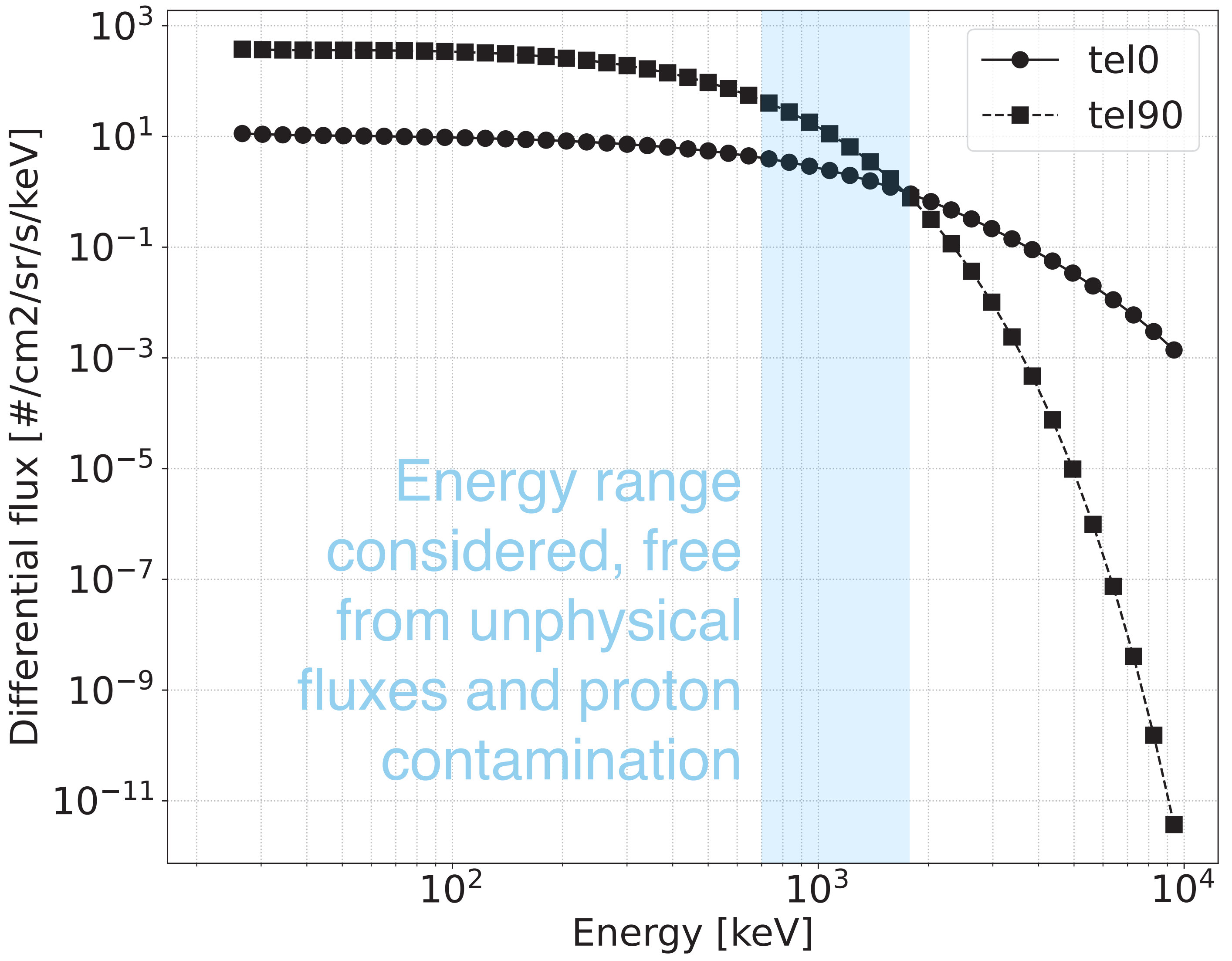
The REP patch extends over 60.5°–65.7° (North&South) geomagnetic lats

Example of REP in the patch

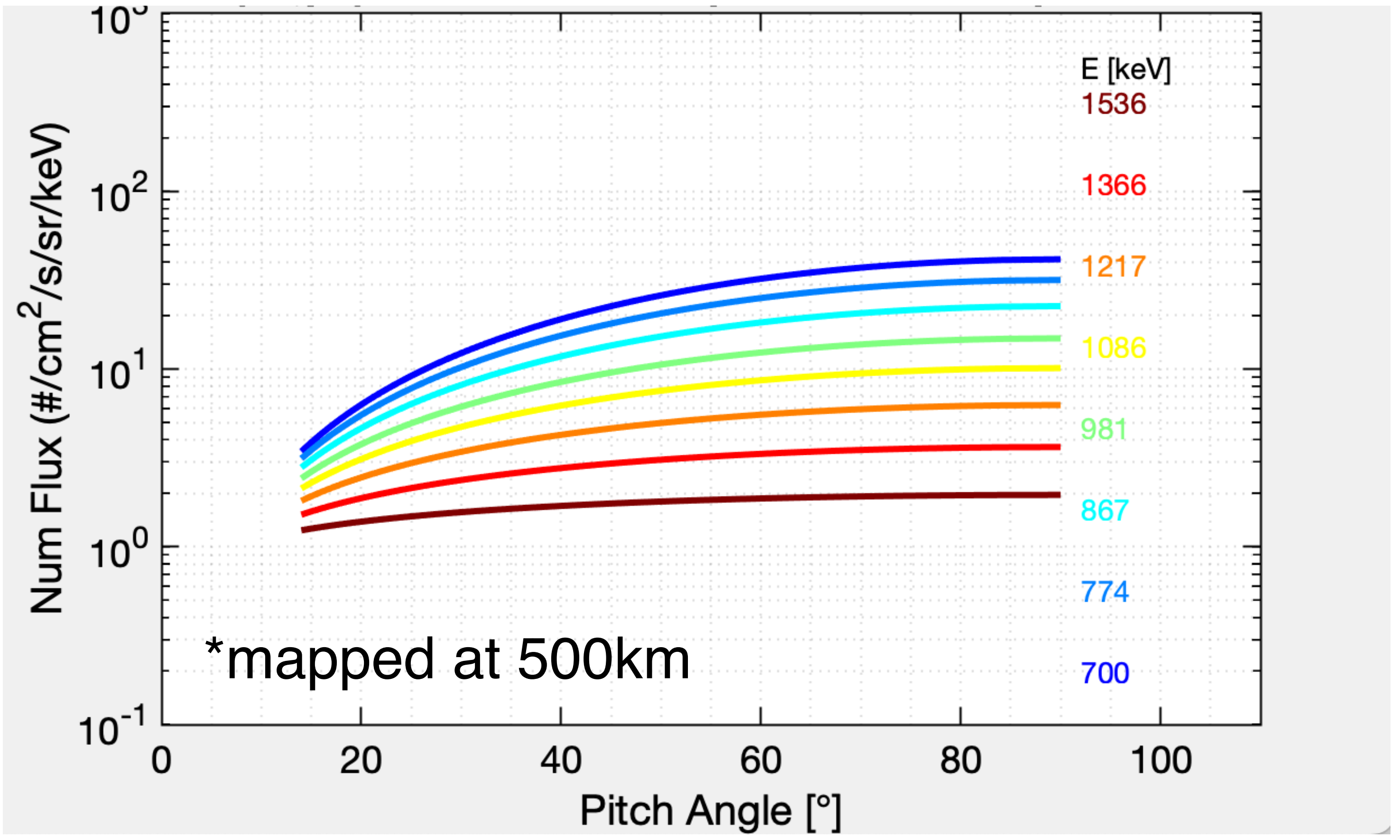


we assume this as a representative REP for the whole patch, calculate the differential flux (following Peck+2015) and then the BERI ionization rate

Avg. Differential Flux [Peck+2015]

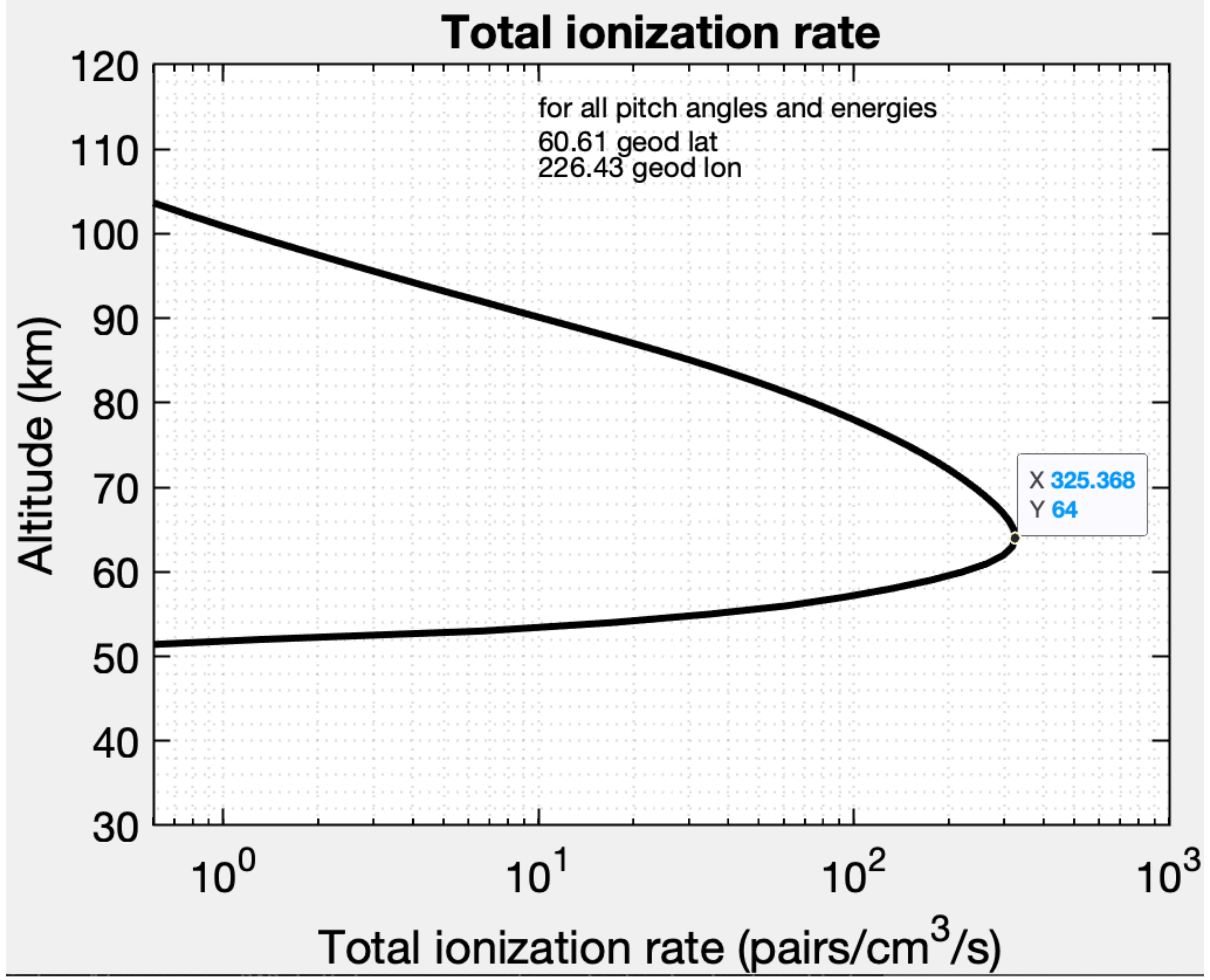


Pitch-angle distribution for BERI input

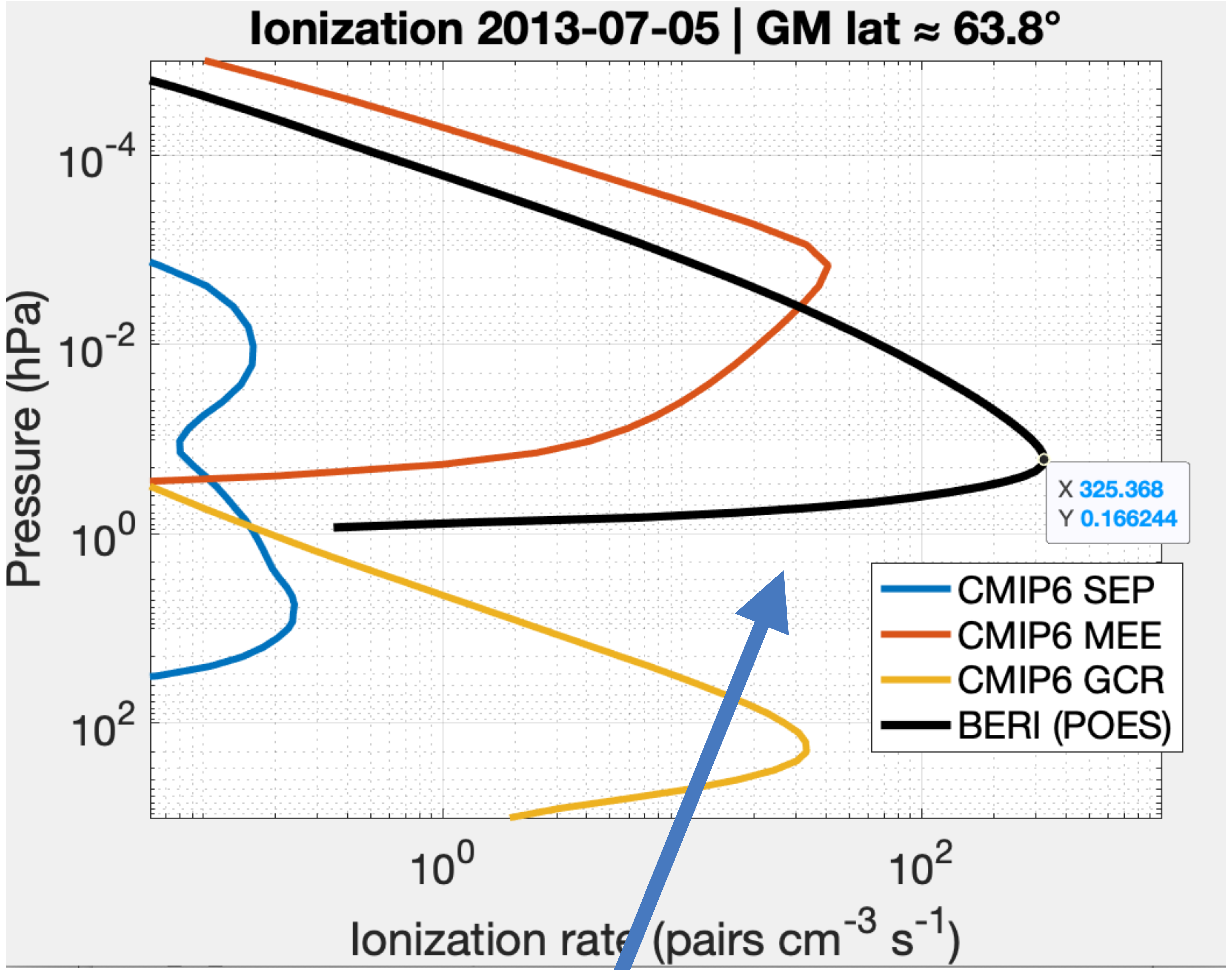


A REP patch example: Ionization Rates

Ionization rate from BERI



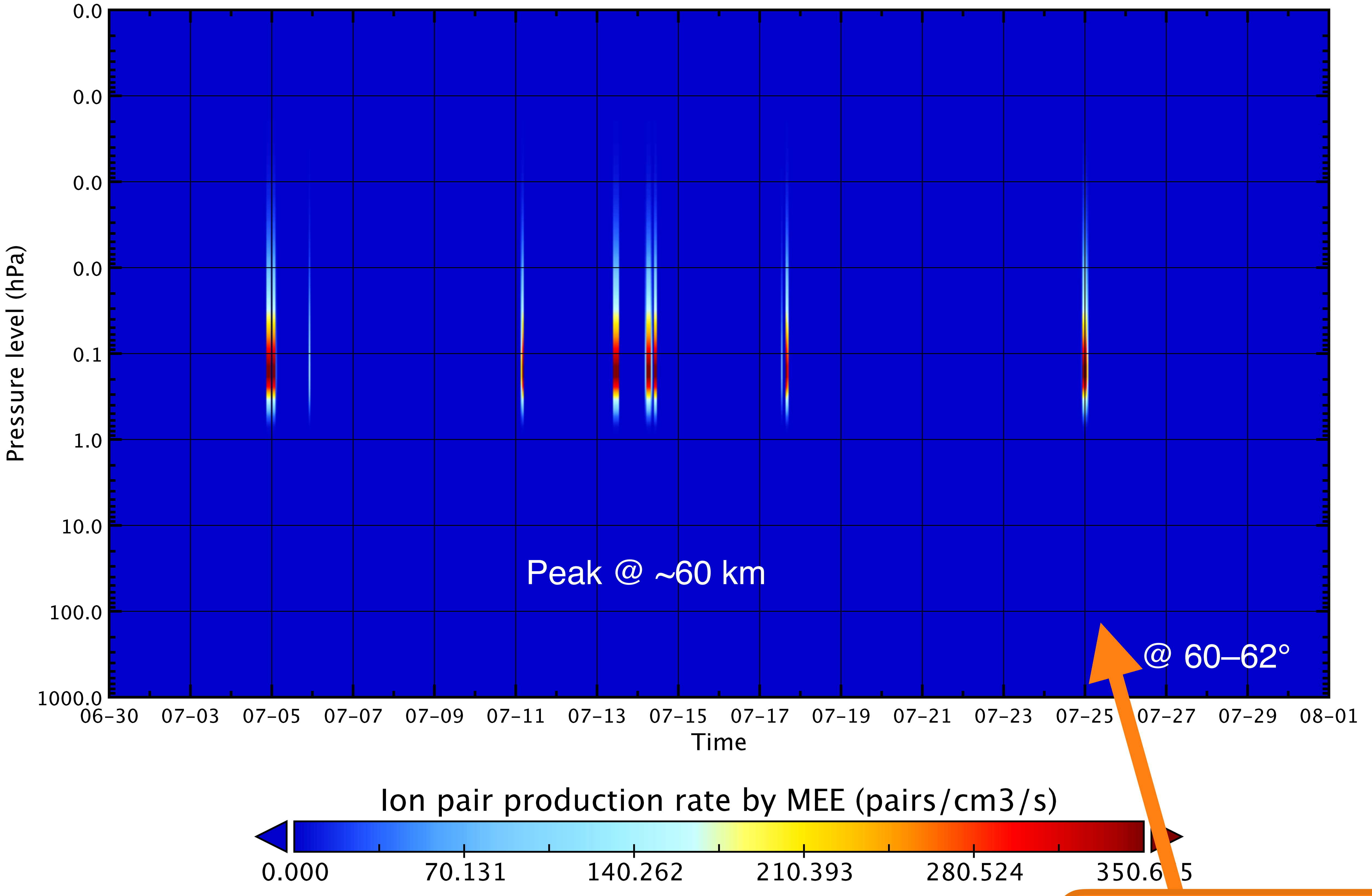
Ionization rate from BERI vs CMIP6 recommendations



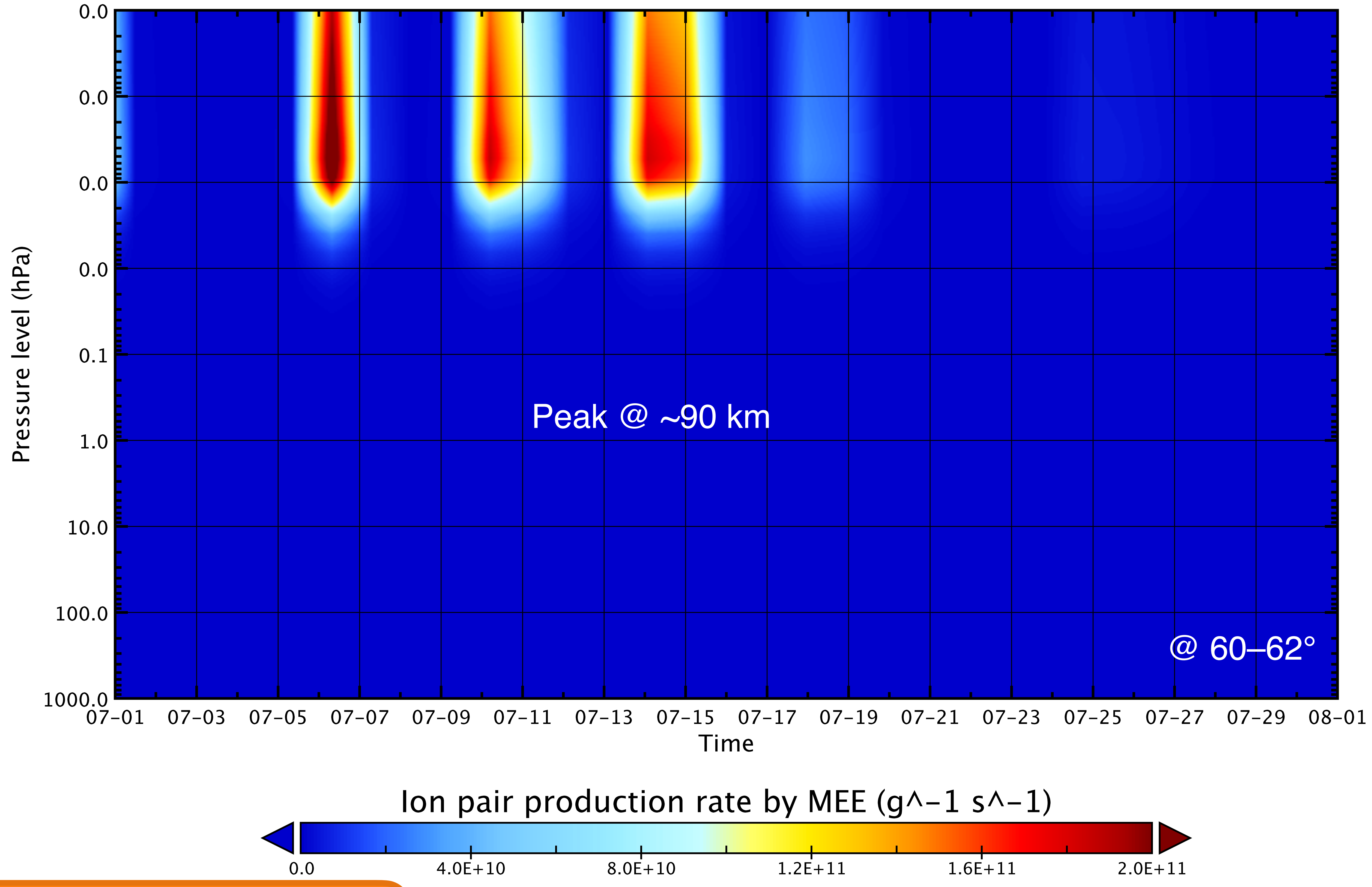
REP precipitation ionizes the mesosphere, not covered by MEE

Ionization rates for July 2013 (custom input) vs CMIP6

Custom REP inputs: Ionization rate from BERI



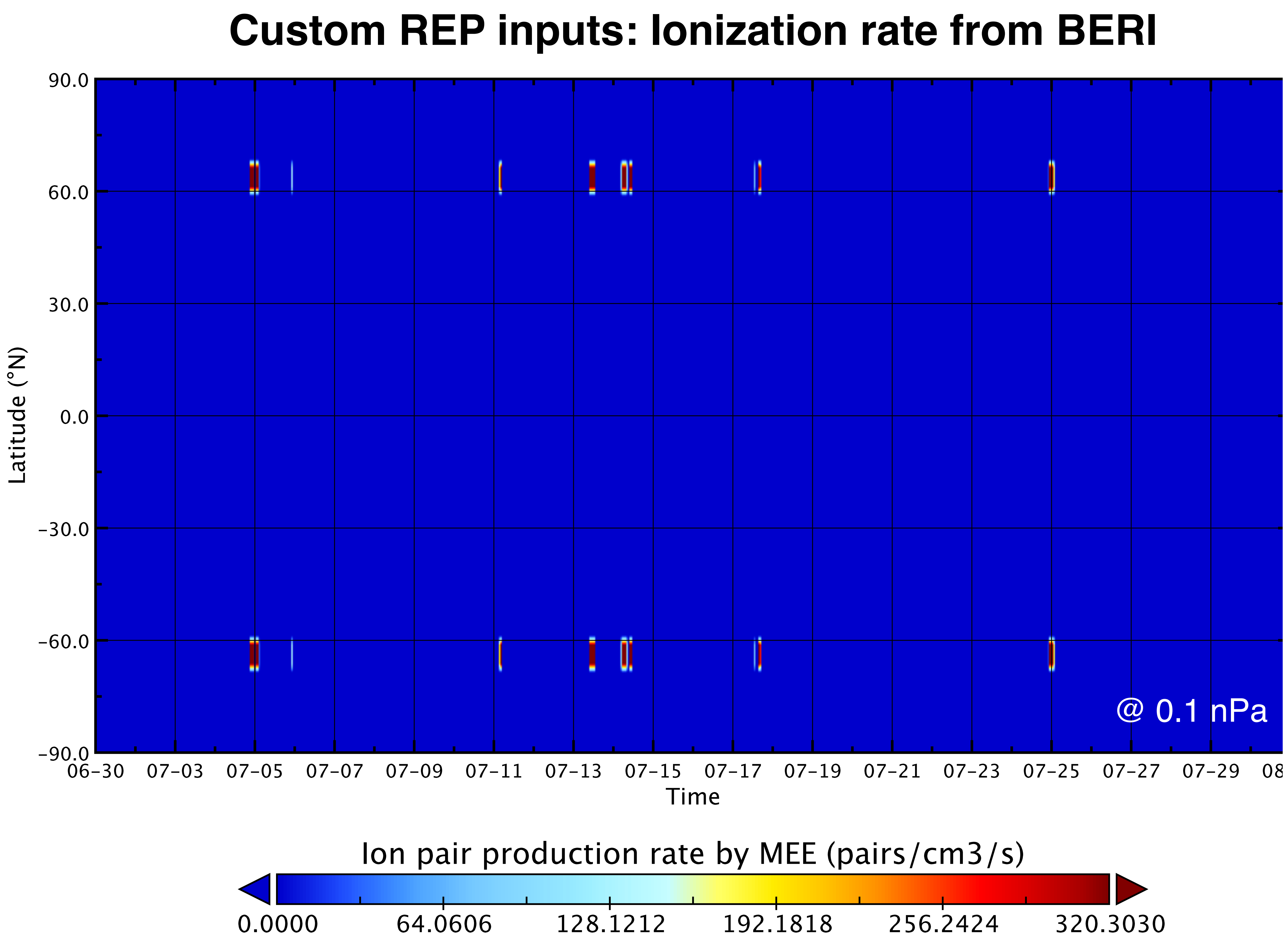
CMIP6 Medium Electron Energy input from Fang+2010

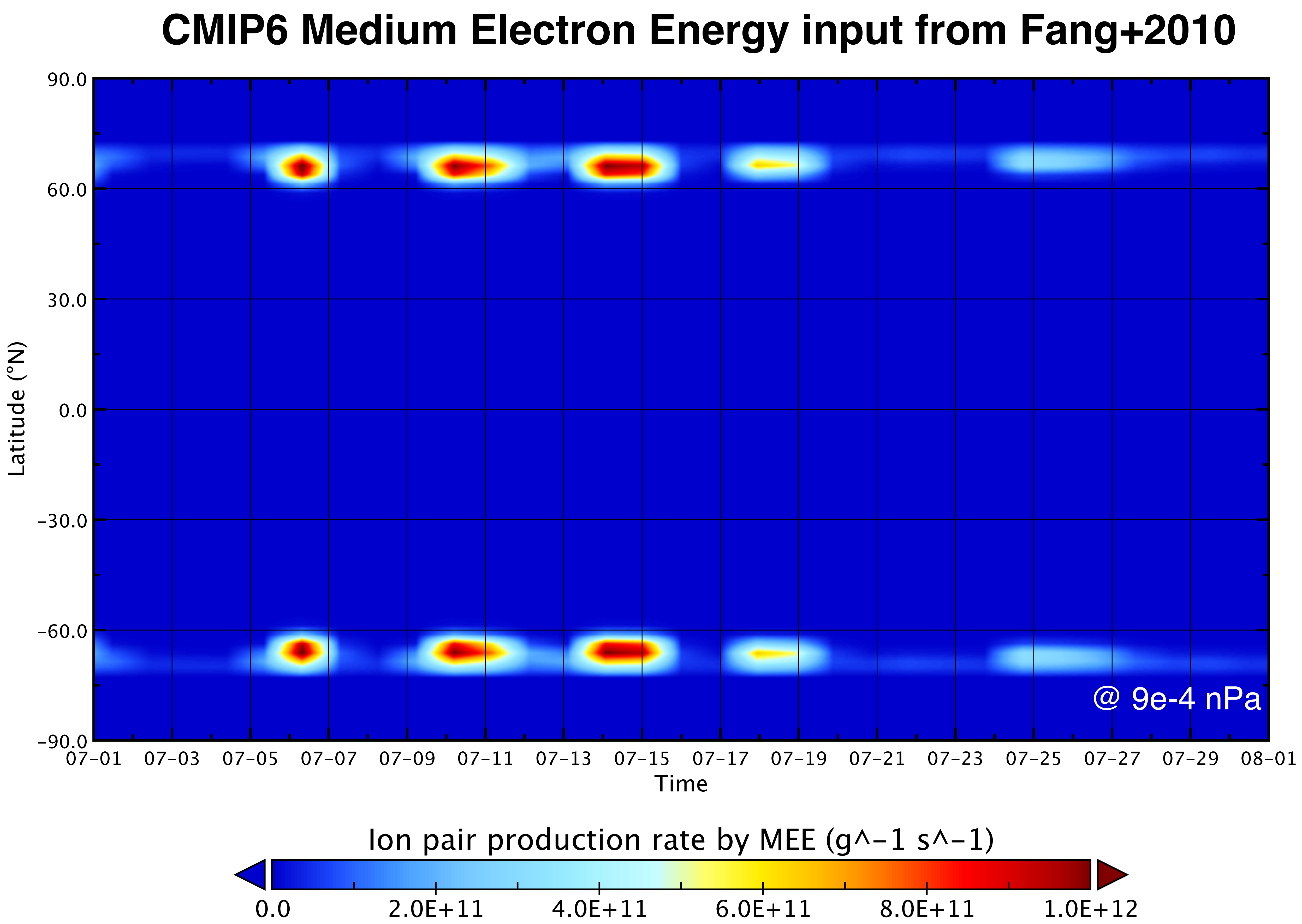


Precipitation is not as sustained (limited by realistic REP patches), but deposits energy at lower altitudes

*different units
**assume patches extend at all longitudes

Ionization rates for July 2013 (custom input) vs CMIP6





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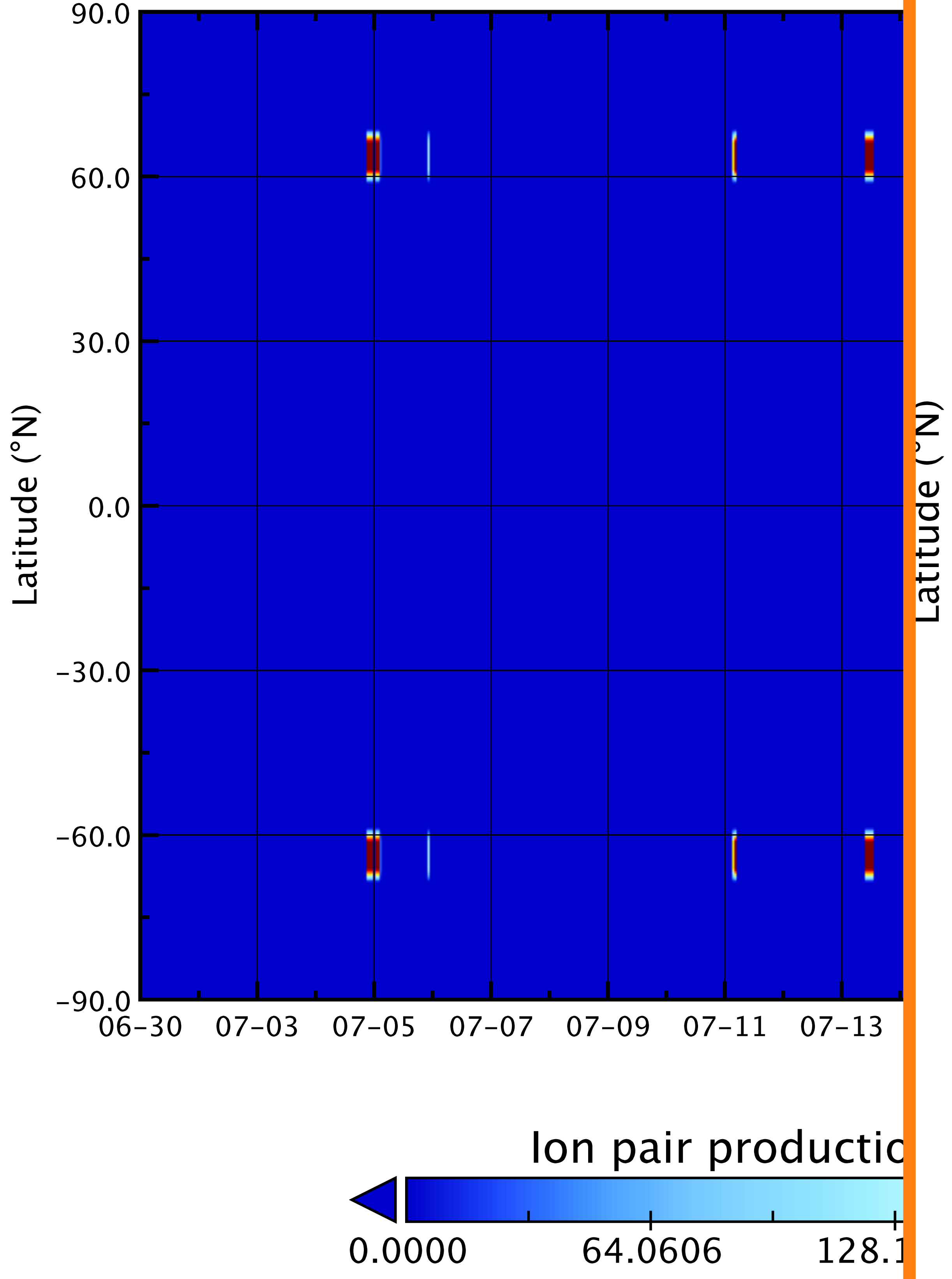
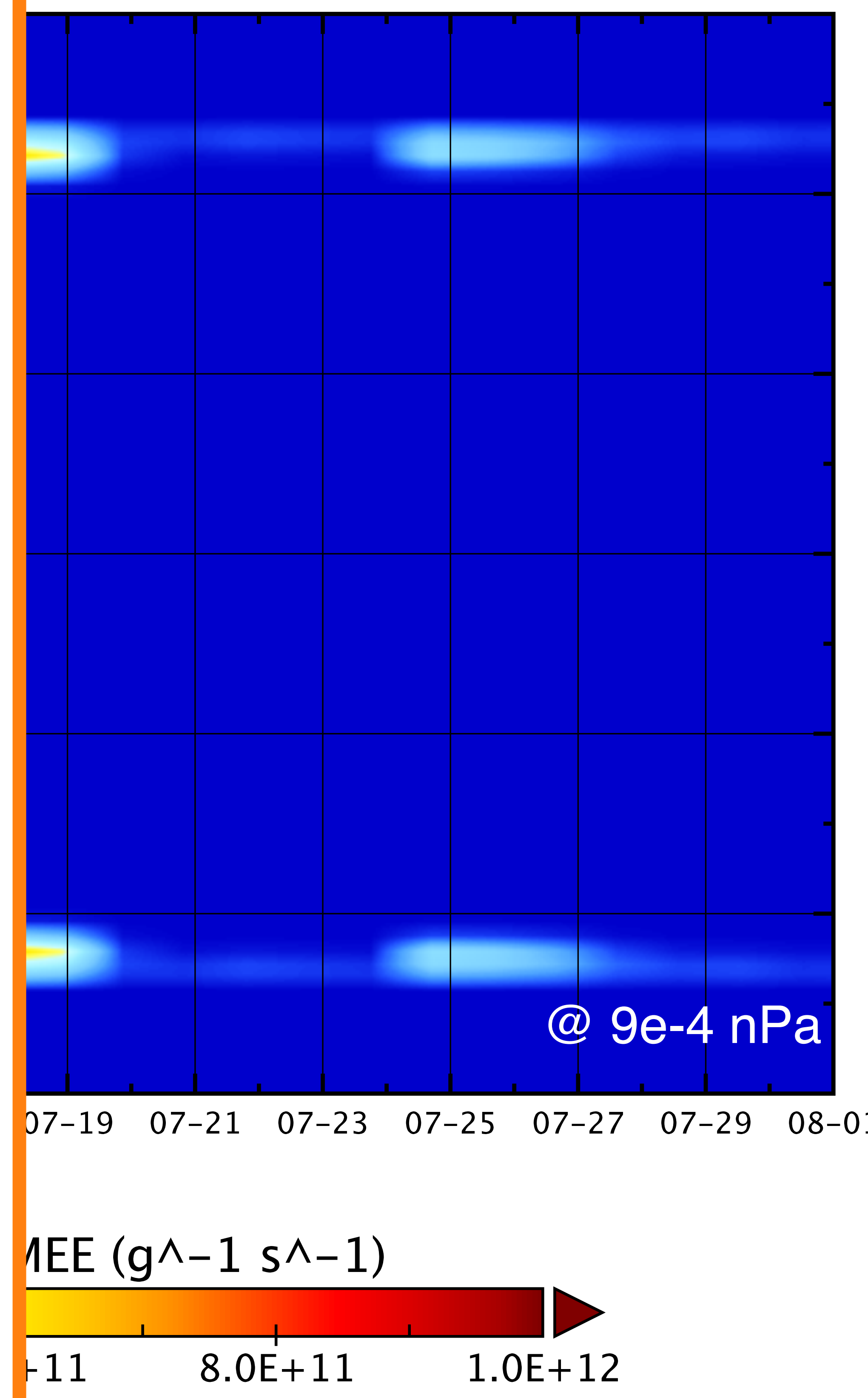
Ionization rates for July 2013 (custom input) vs CMIP6

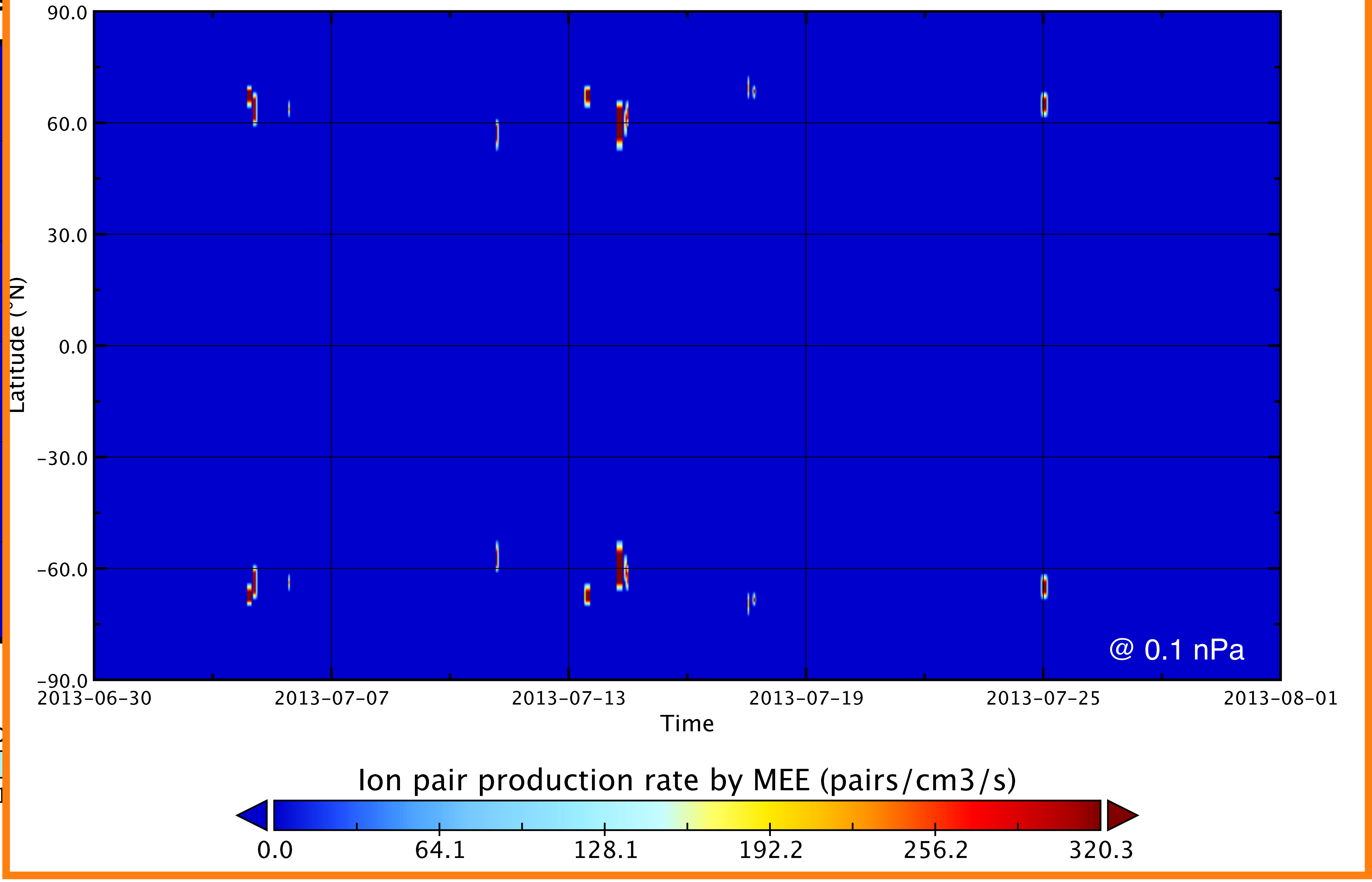
Custom REP inputs



y input from Fang+2010



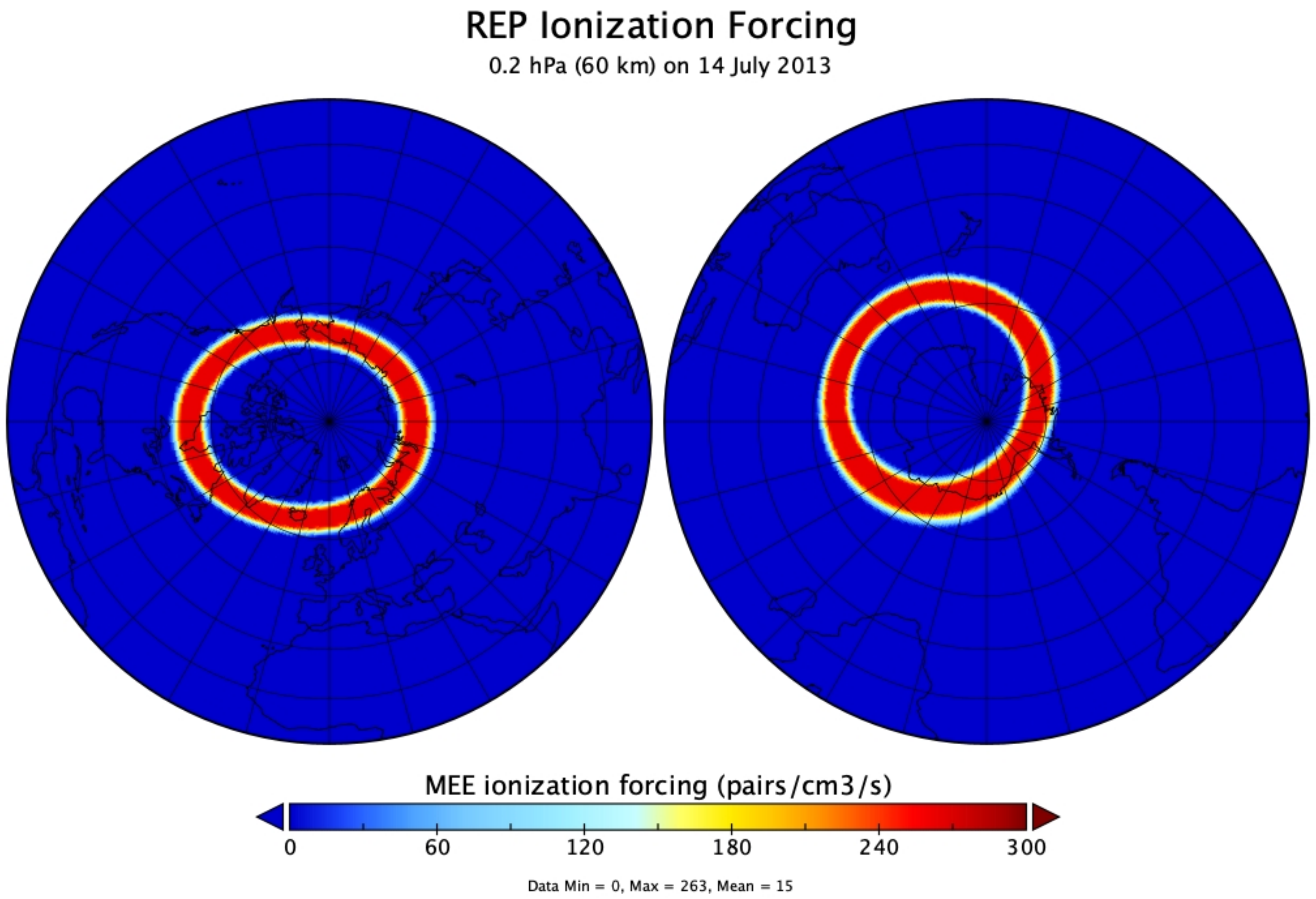
Realistic latitudinal extent of observed REP patches

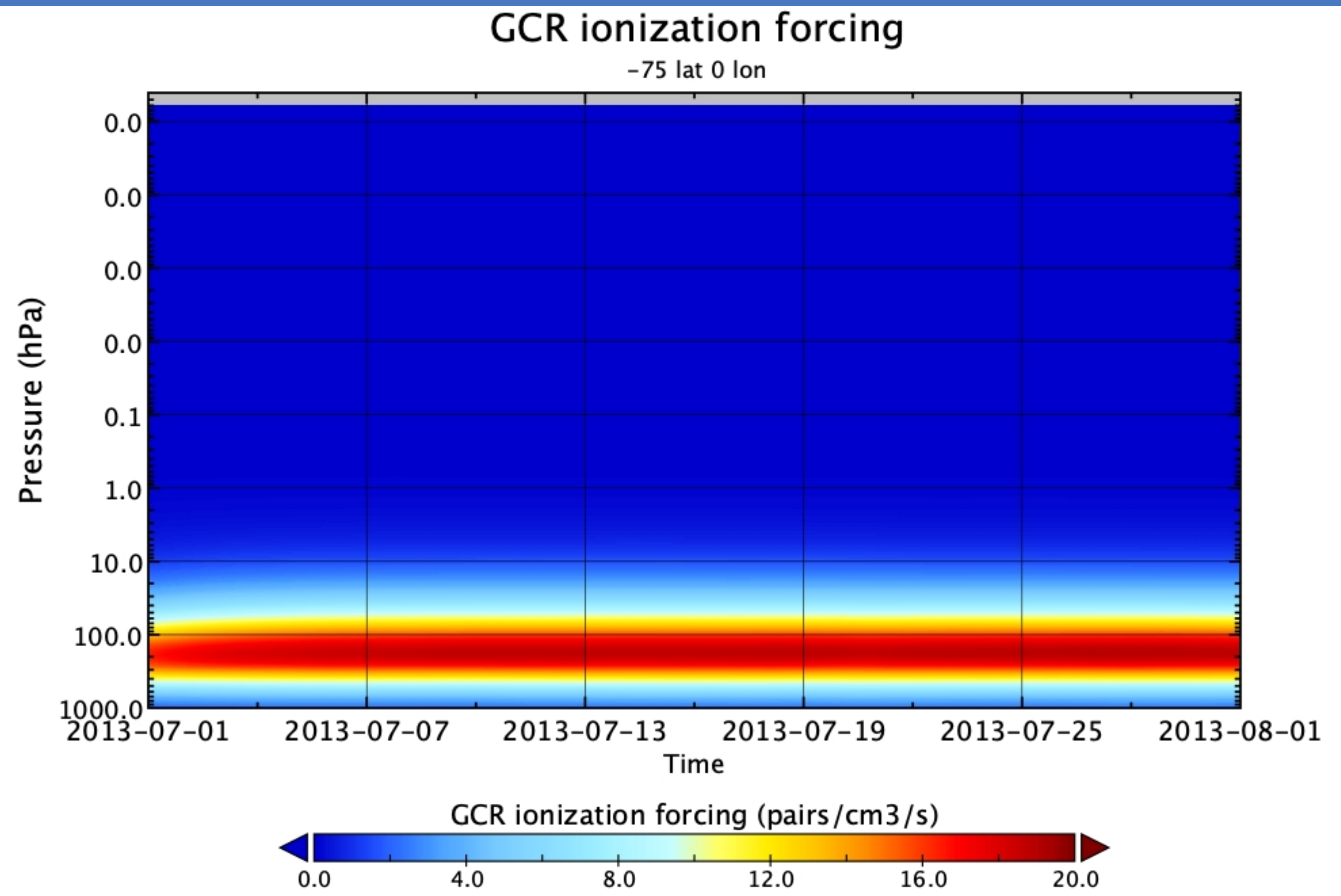


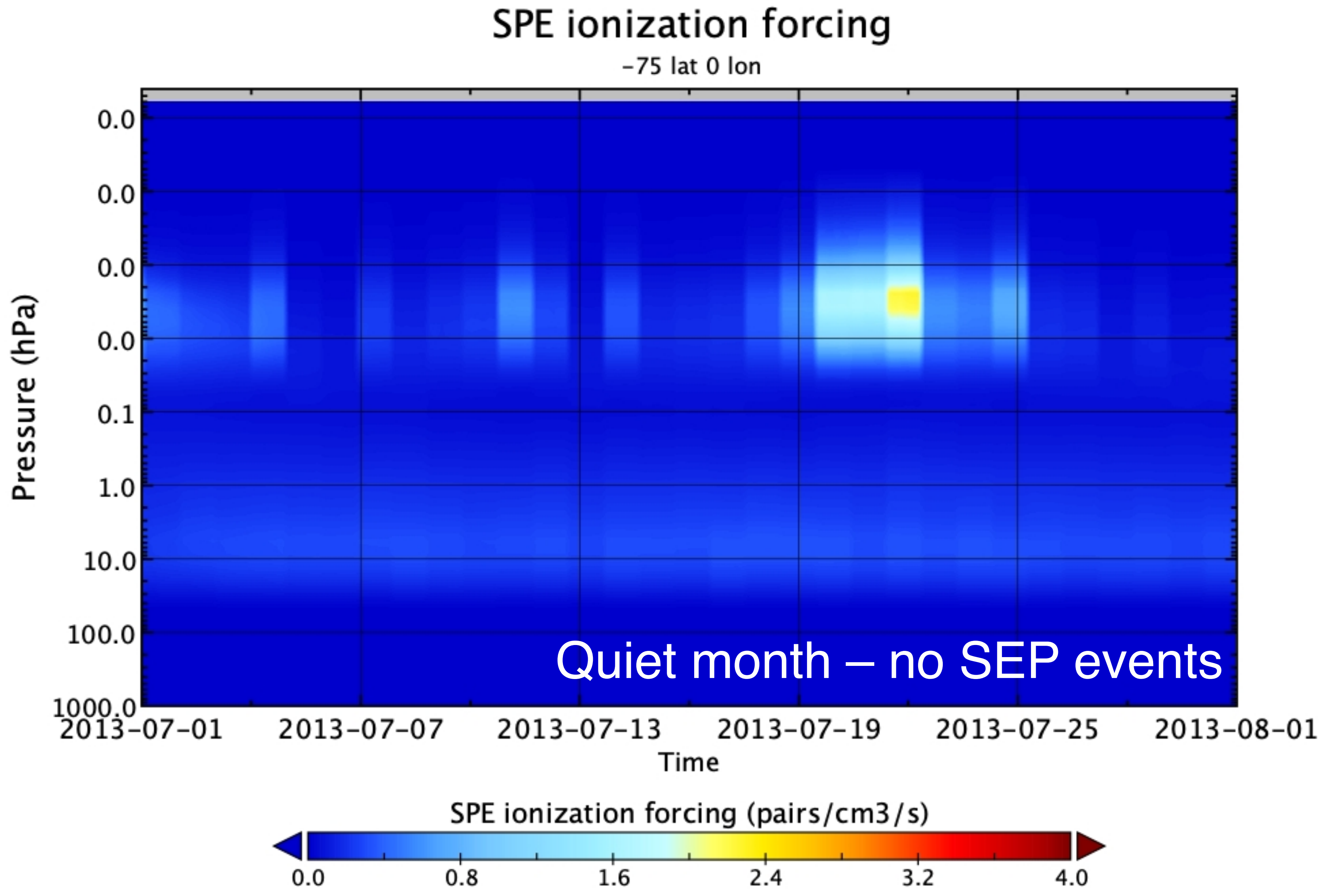
*different units

**assume patches extend at all longitudes

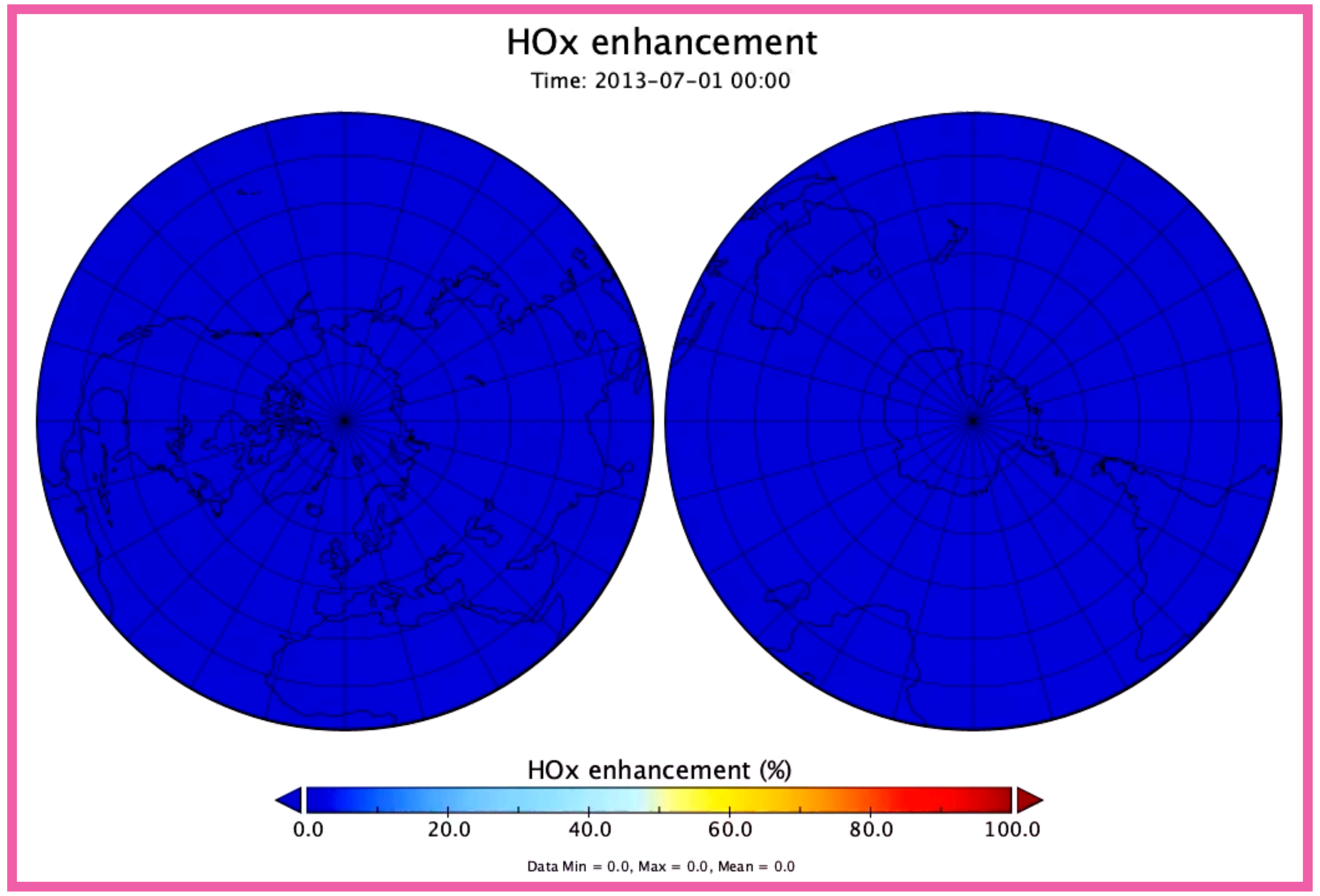
Ionization rates for July 2013 (custom input)



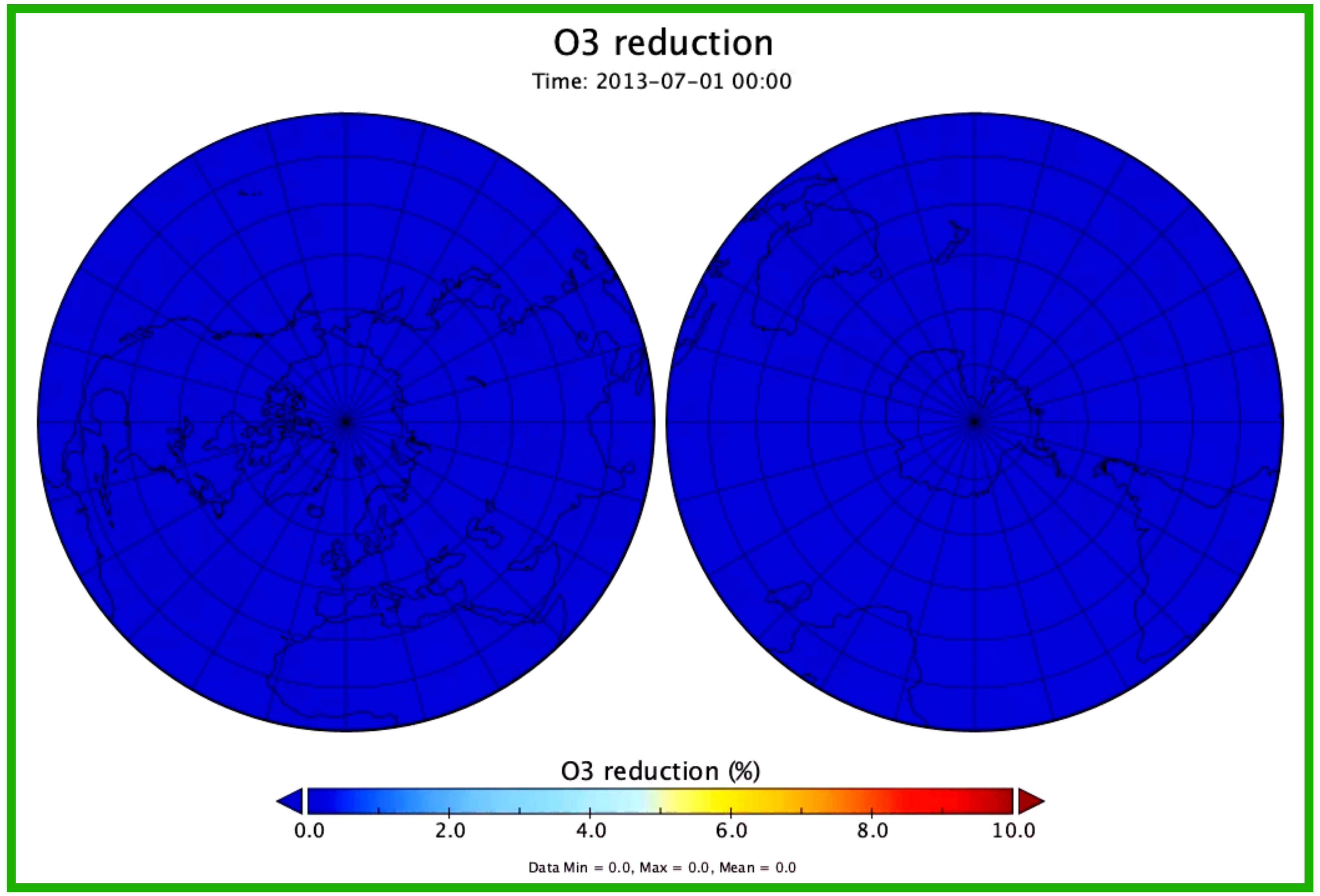




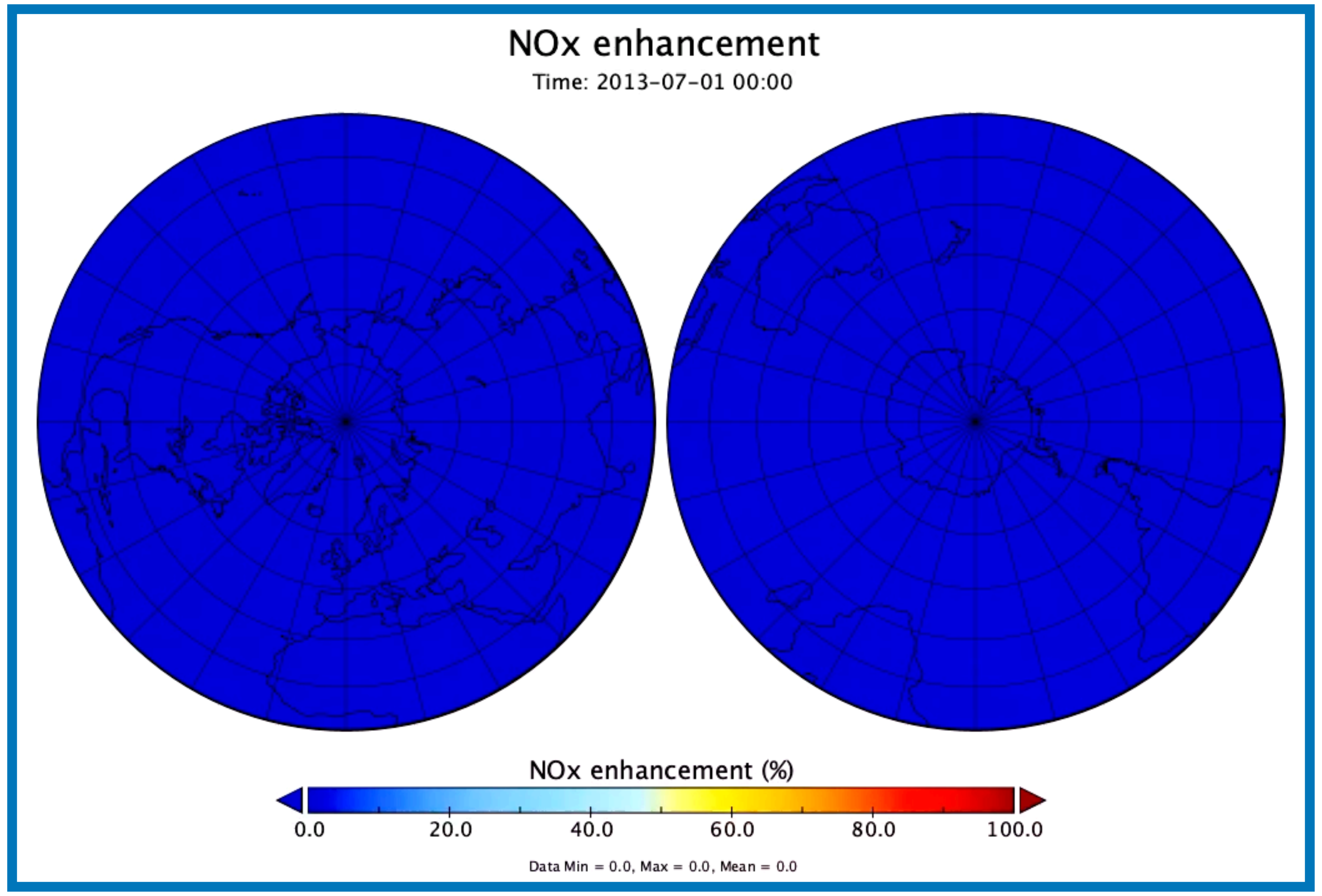
Preliminary results: HOx & NOx Enhancement, O3 Loss



HOx remains elevated during polar night



O3 can reach ~10%, locally, most in polar night



NO_x enhancement

…only quick preliminary results!

*0.2 nPa (~ 60km)

Summary & Future Work

- Radiation Belt precipitation input is possibly underestimated, especially at relativistic energies
- Relativistic Electron Precipitation (REP) deposits energy in the mesosphere, with the primary ionization peak at ~60km
- From a database of POES/MetOp observations of REP (2012–2023), we can identify REP regions or “patches”
- We develop a custom input to WACCM to specifically study REP effects on the atmosphere (NOx, HOx, O3)
- Simulations of WACCM to evaluate the REP effects on the atmosphere are ongoing:
  - Are there any visible/impactful changes?
  - Are the effects local or global, and sustained over time?
  - What is the main REP characteristic (flux, regional extent, temporal duration, etc.) that impacts the local/global effects the most?

Email me for feedback and collaborations!

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