Molecular Ion Outflow: Implications to Habitability

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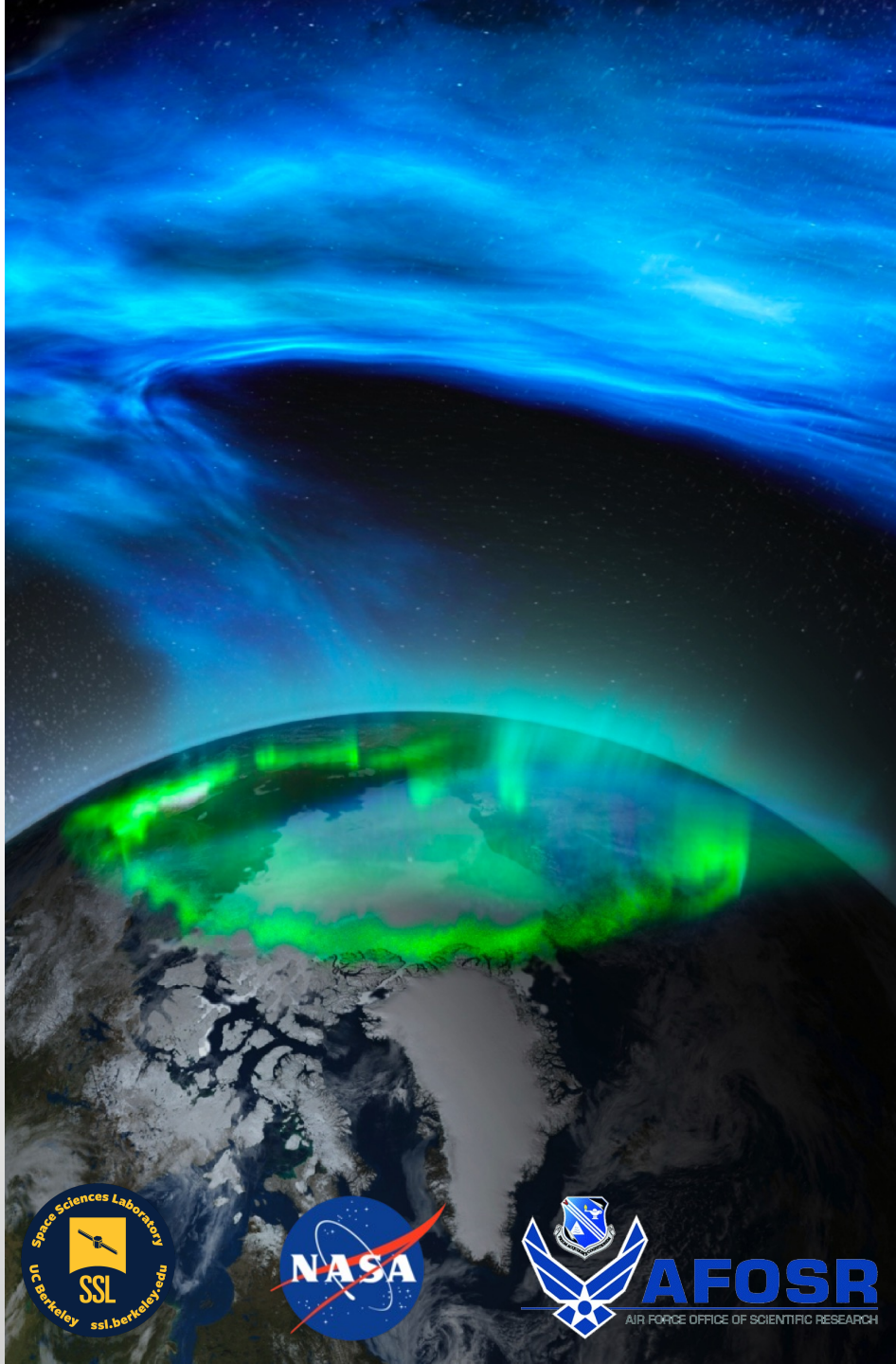
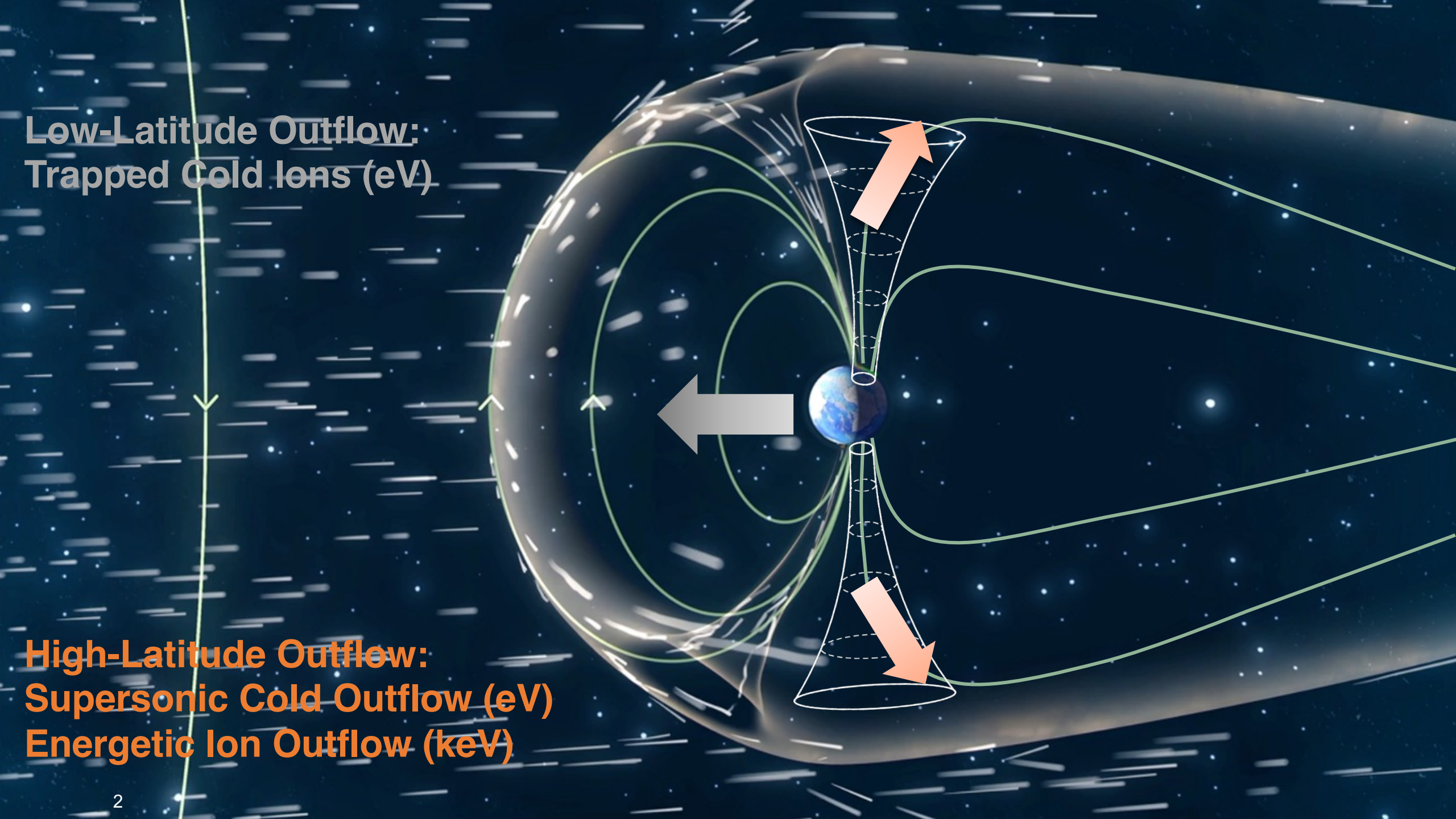
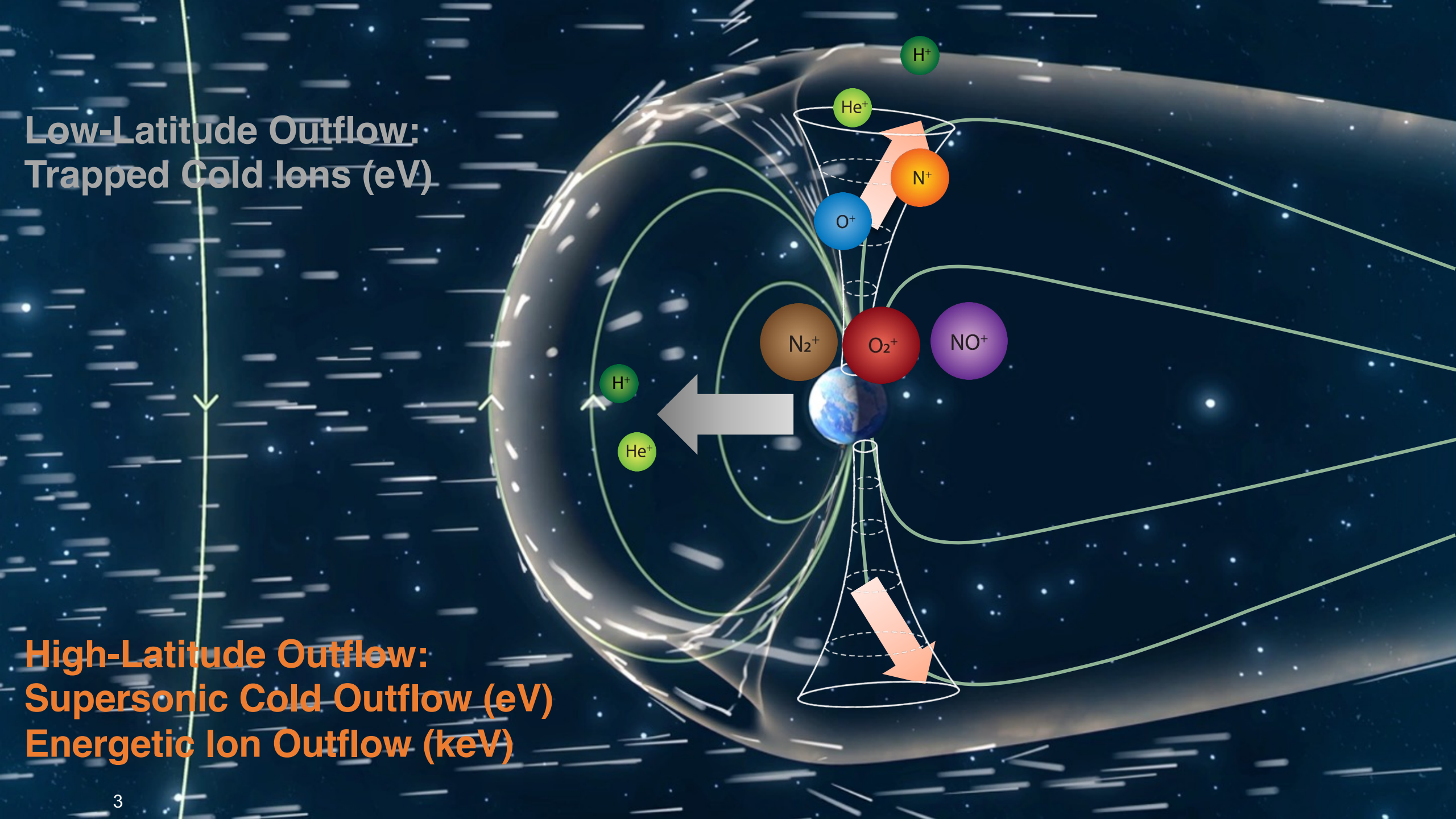
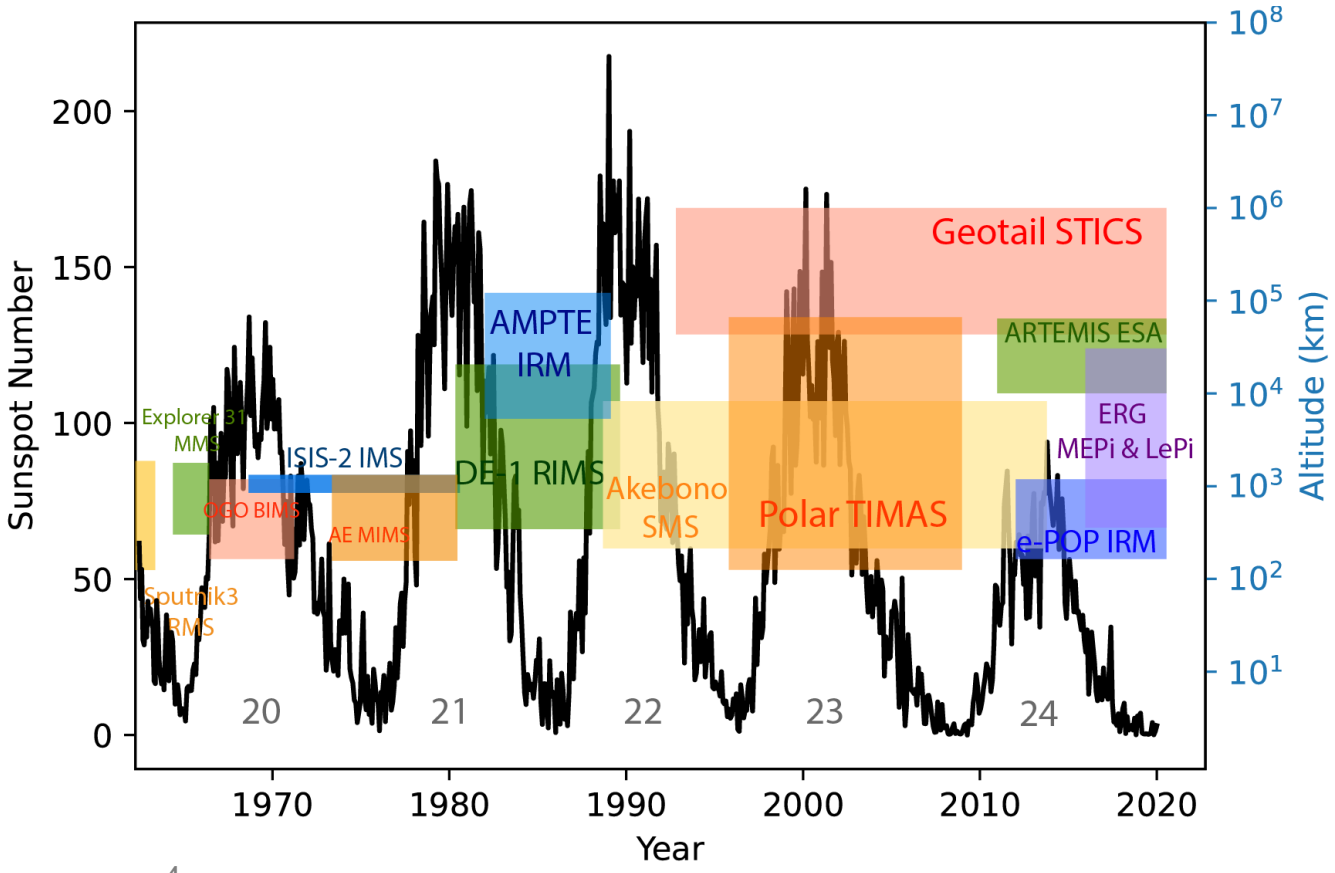
HERA HELIOPHYSICS RESEARCH & APPLICATIONS

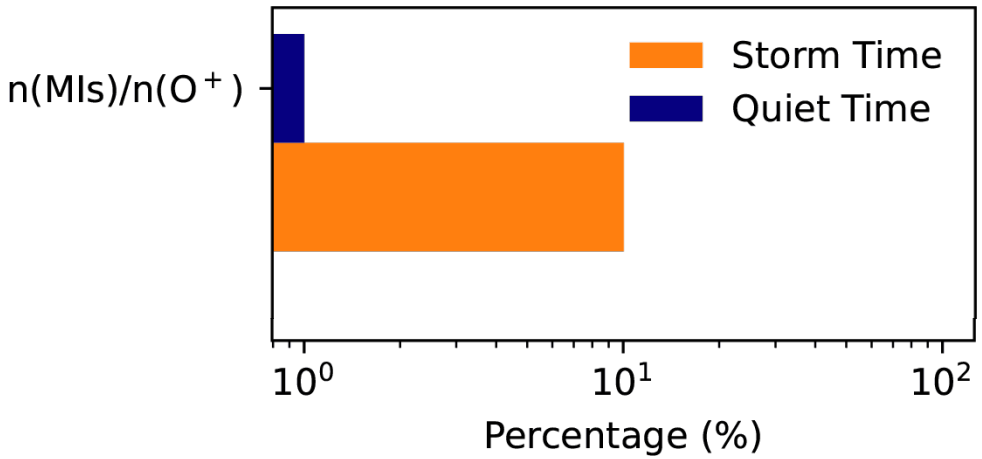



Low-Latitude Outflow:
Trapped Cold Ions (eV)
High-Latitude Outflow:
Supersonic Cold Outflow (eV)
Energetic Ion Outflow (keV)


Low-Latitude Outflow:
Trapped Cold Ions (eV)
High-Latitude Outflow:
Supersonic Cold Outflow (eV)
Energetic Ion Outflow (keV)
H+
He+
N+
O+
N2+
O2+
NO+
H+
He+

Do Molecular Ions Stay in the Ionosphere?



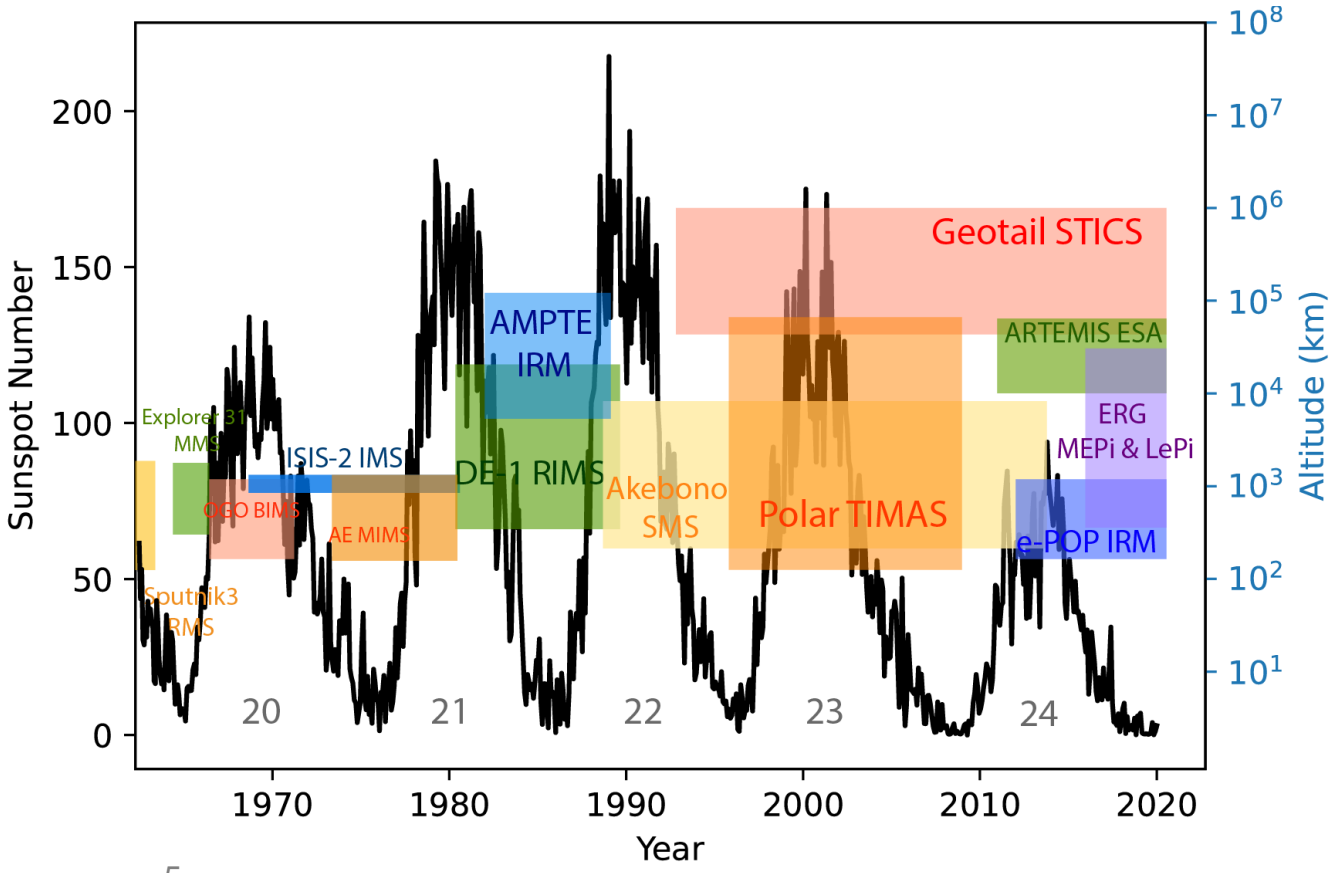


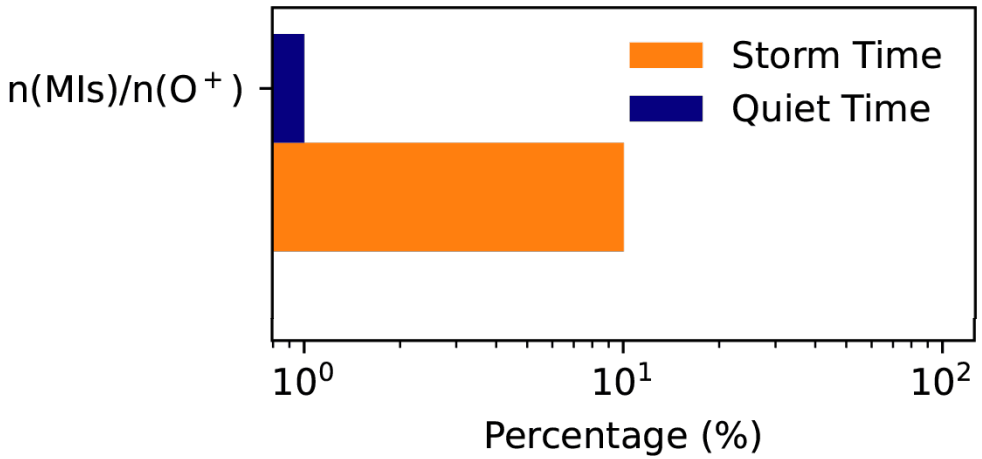
Abundances of molecular ions are sensitive to the geomagnetic activities.

[Lin & Ilie, 2022]

Do Molecular Ions Stay in the Ionosphere?

- An increasing number of molecular ion observations in Earth's magnetosphere and ionosphere from the past ten years, mostly due to improved instruments technology.





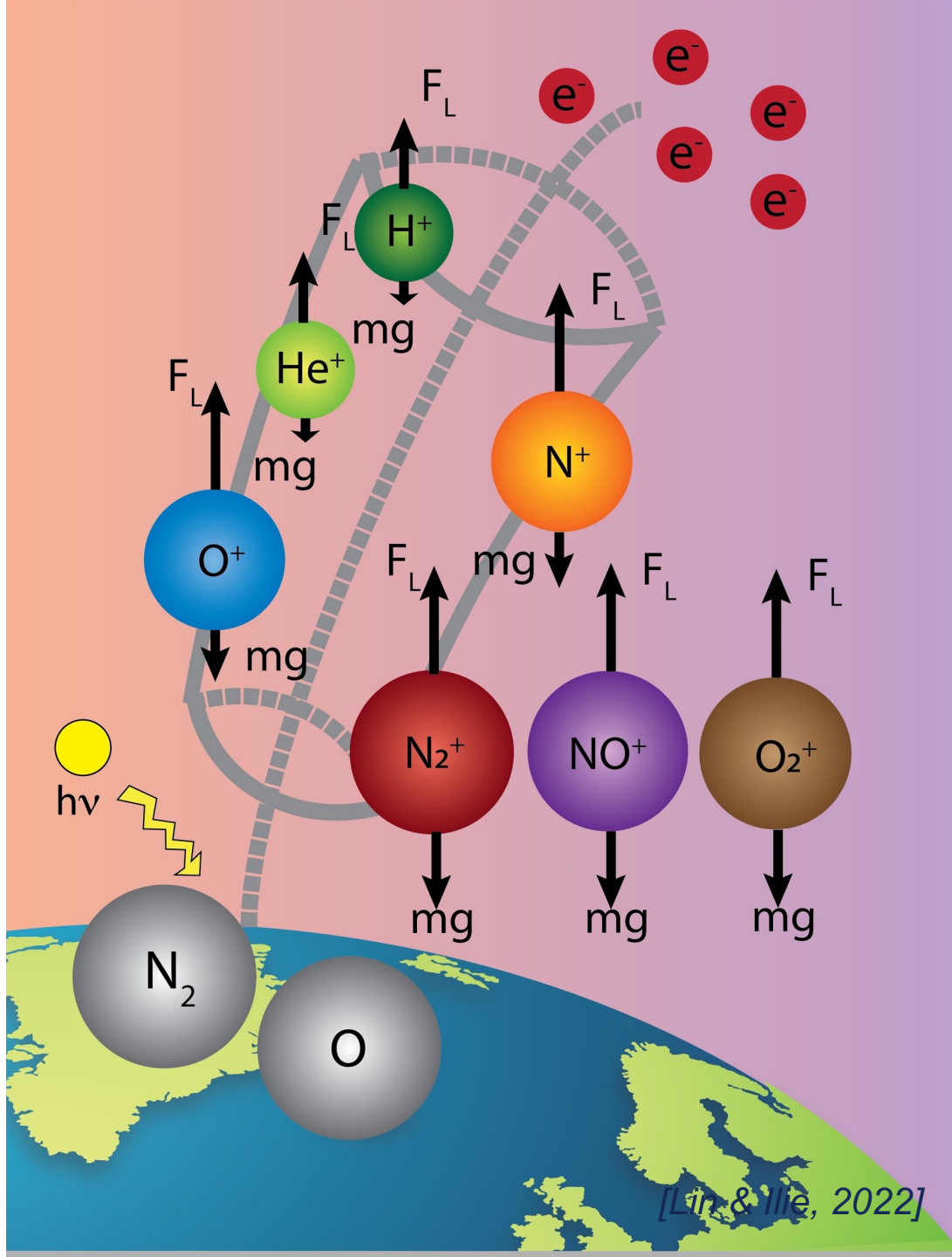
Abundances of molecular ions are sensitive to the geomagnetic activities.

[Lin & Ilie, 2022]

Why Study Molecular Ions?

- Their abundances are relevant with the composition of lower thermosphere and ionosphere, as well as neutral atmosphere.

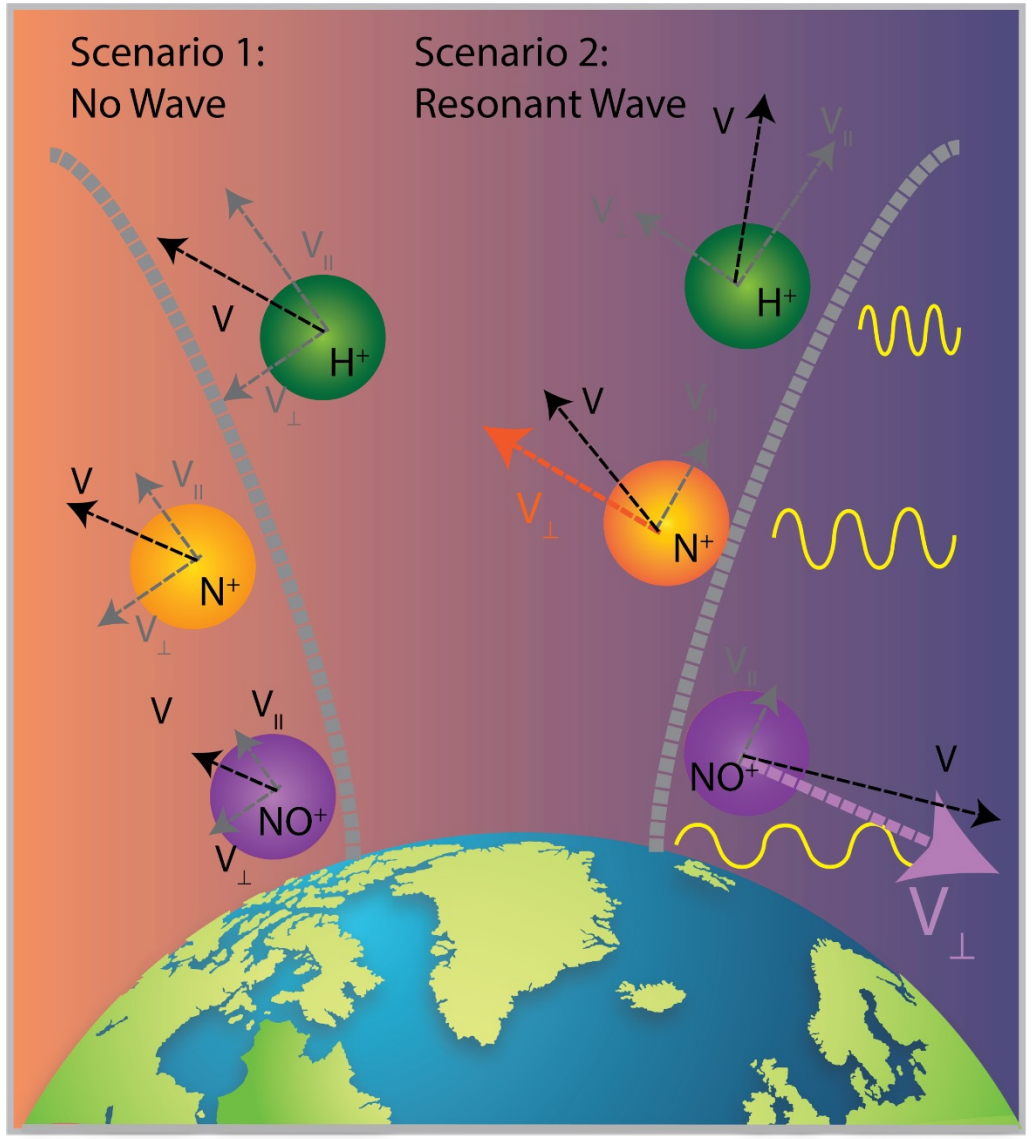
- Indicator of critical transport and energization mechanisms, particularly during the extreme conditions.
  - Key to understand the atmospheric escape in the habitability world.



How are Molecular Ions Energized?

$$m_i \frac{dv_{i\parallel}}{dt} - q_i E_{\parallel} + \frac{G m_i M_{Earth}}{r^2} + \mu_i \nabla_{\parallel} B = 0$$

- *Electric field perturbation (E_A) caused by waves increases $V_\perp$*
- $V_\perp \uparrow$; $\mu_i \uparrow$
- $V_{/\!/} \uparrow$



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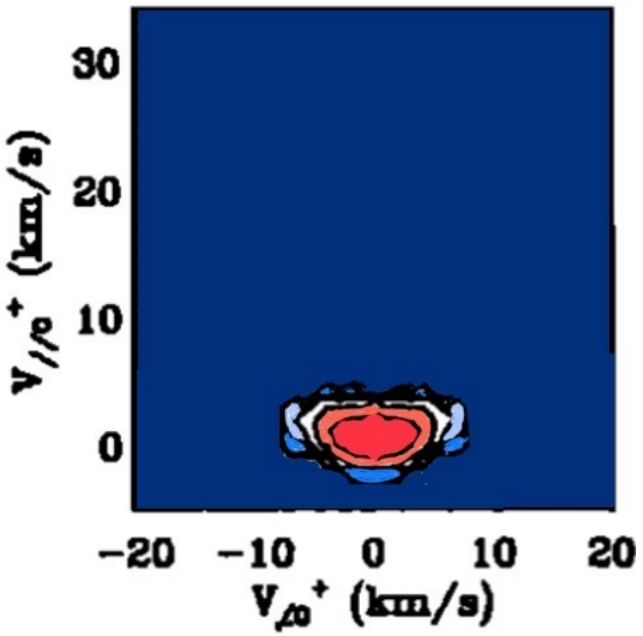
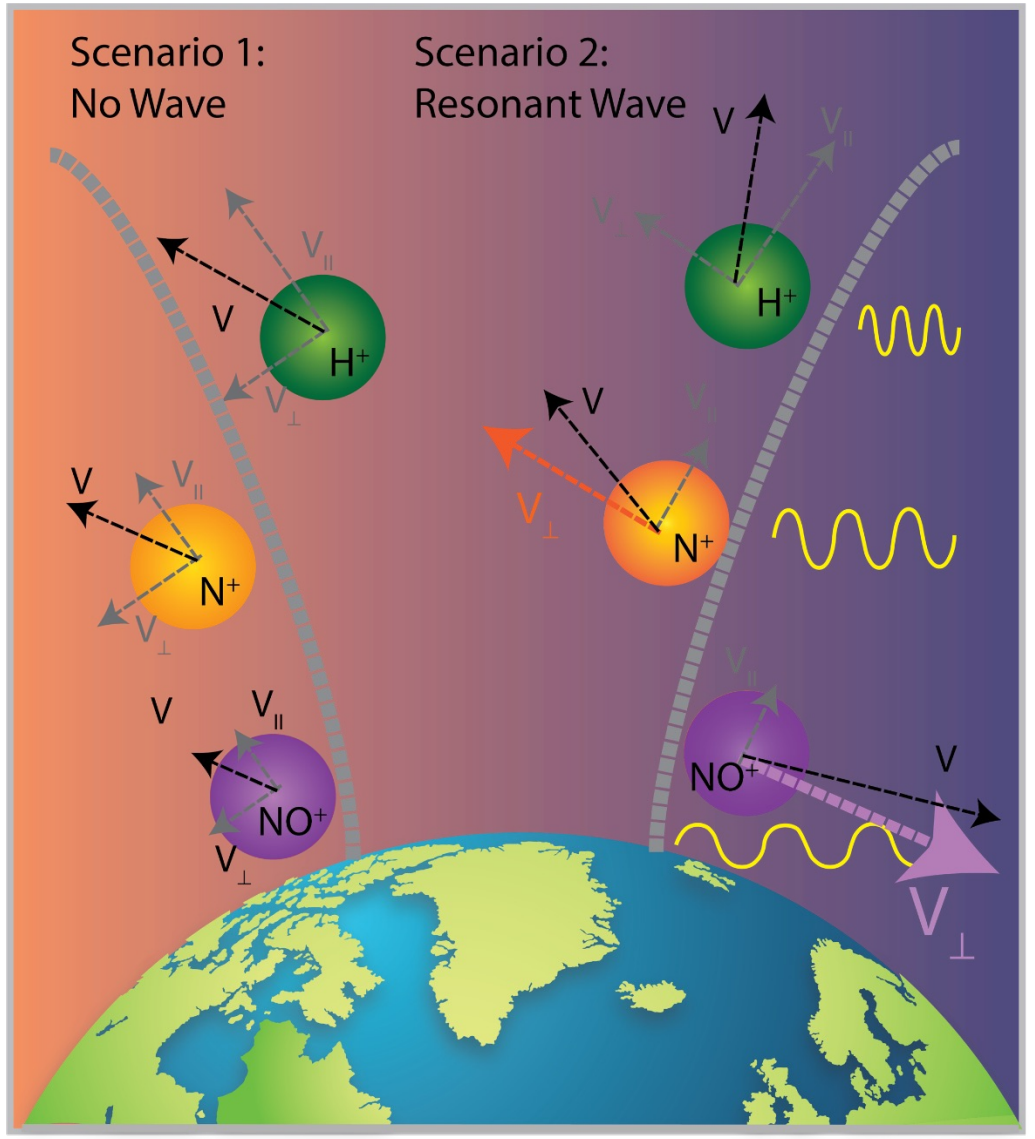
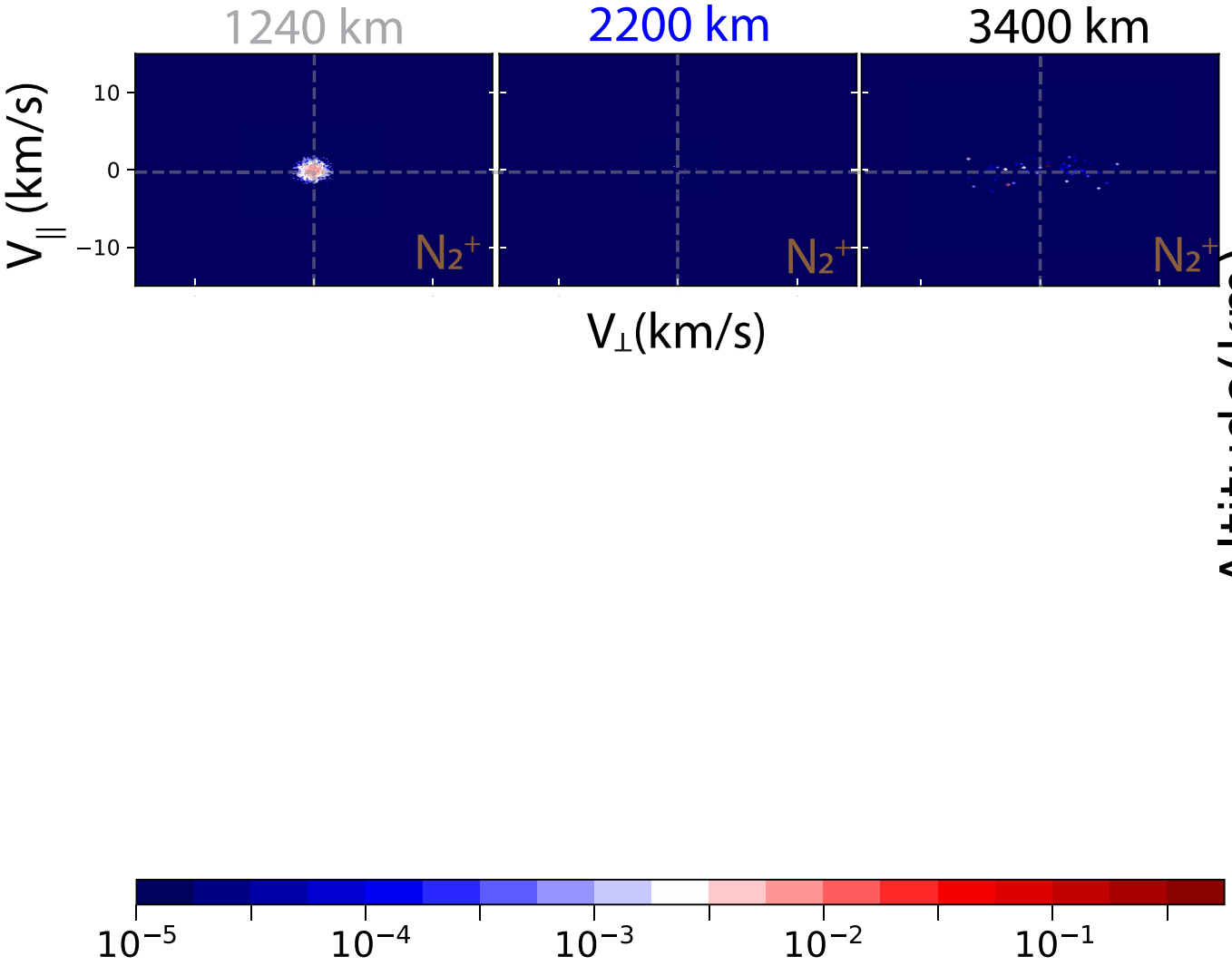
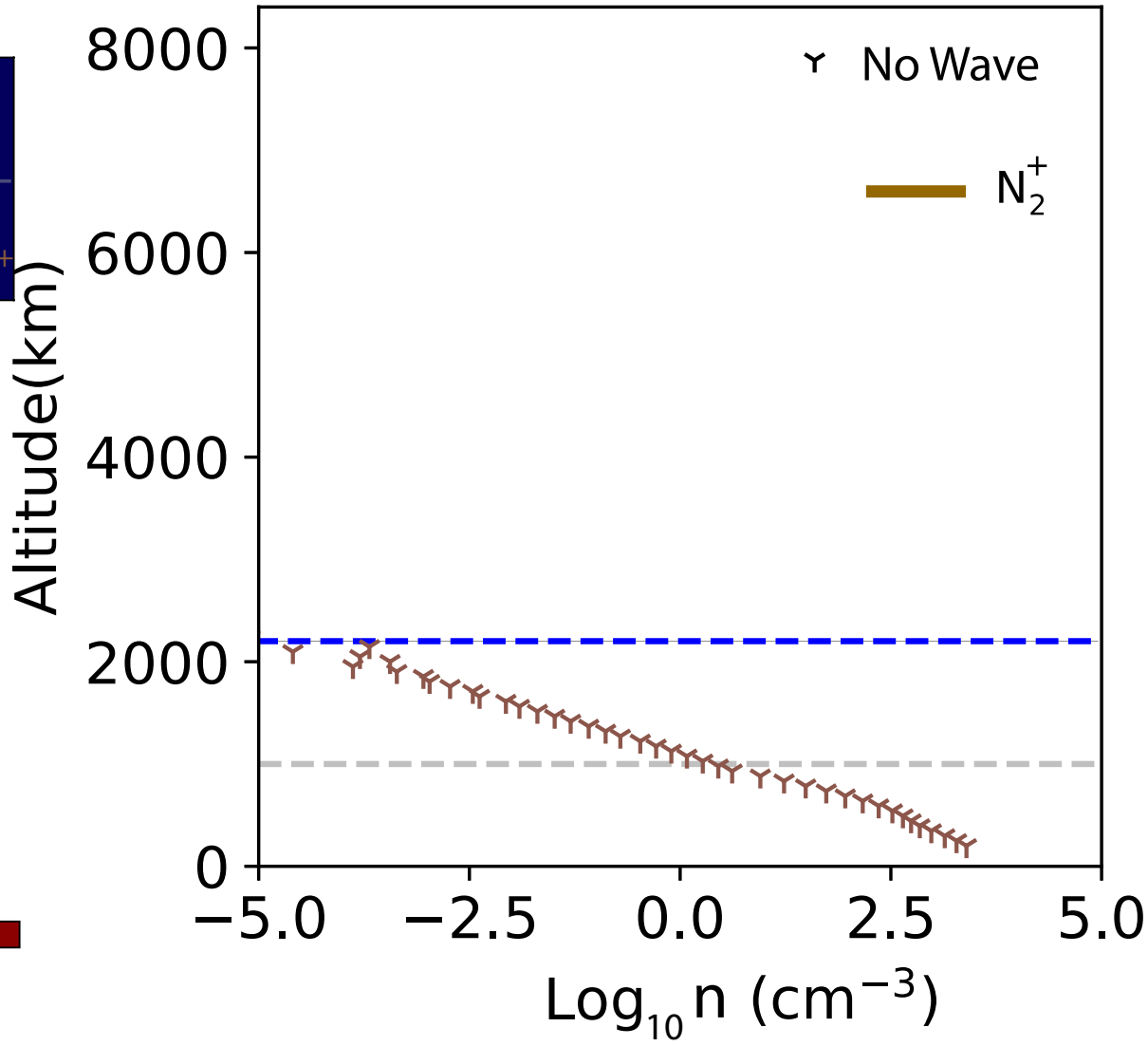


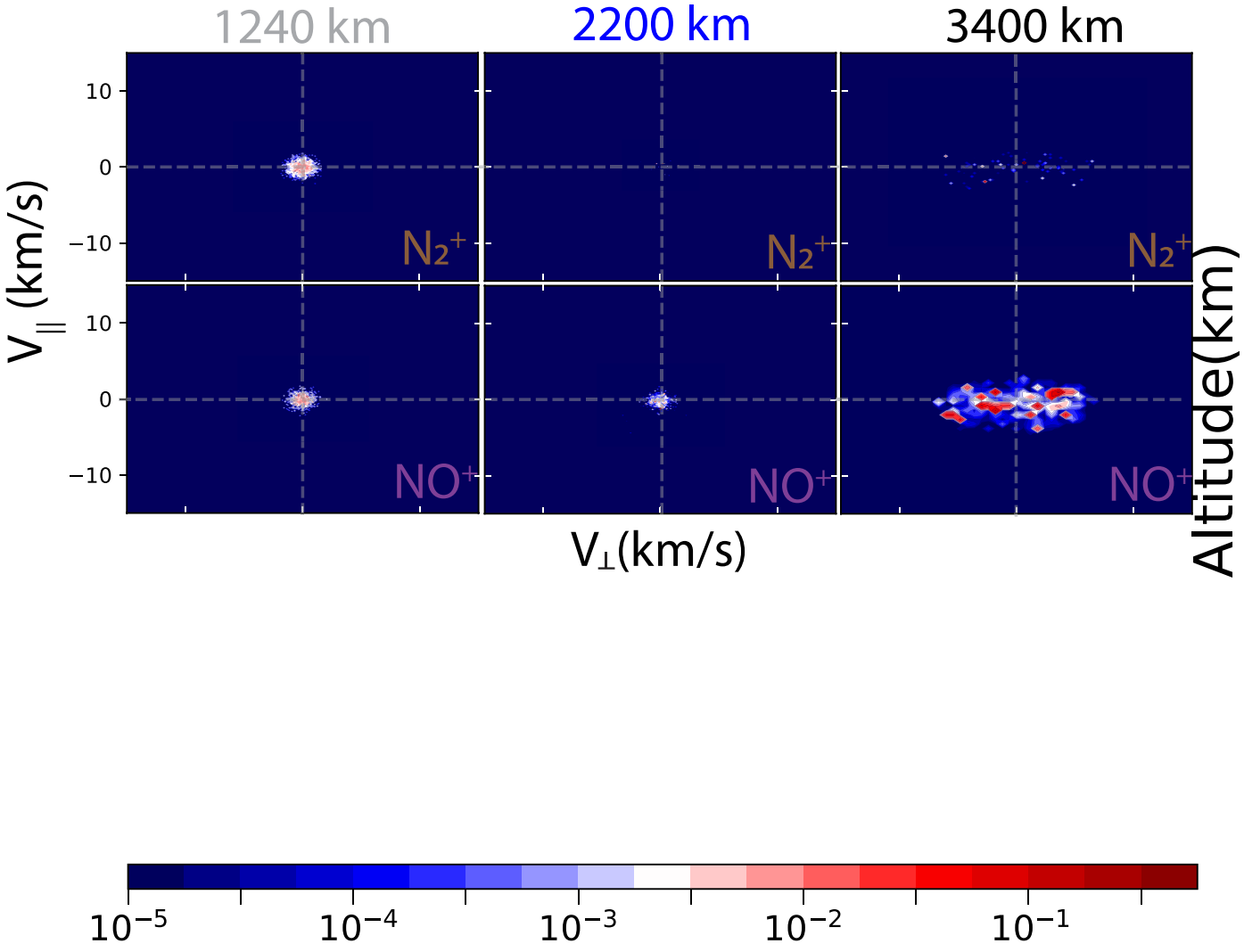


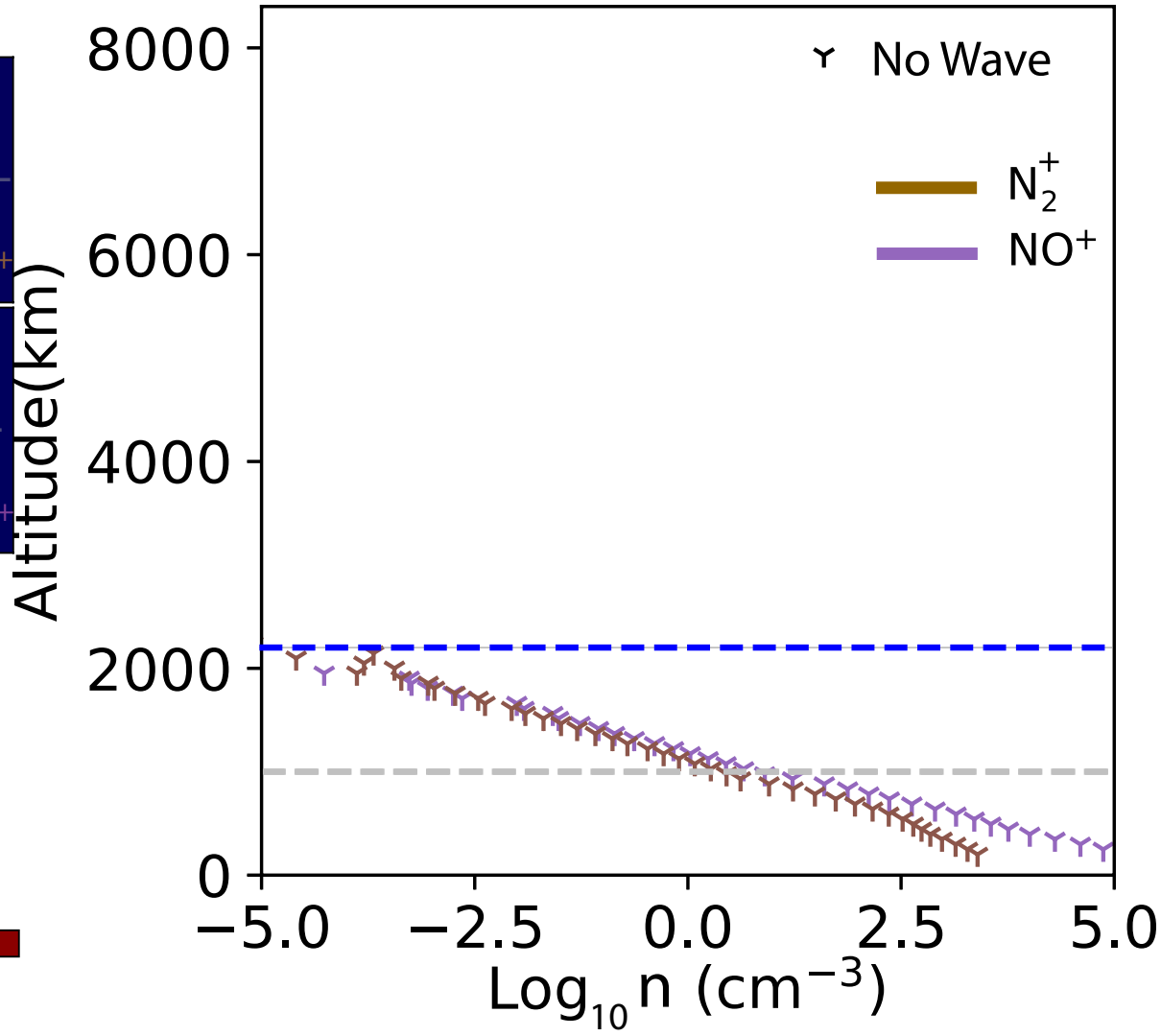
No Wave


1240 km
2200 km
3400 km
10
0
−10
$V_{||}$ (km/s)
N_2^+
N_2^+
N_2^+
$V_\perp$(km/s)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

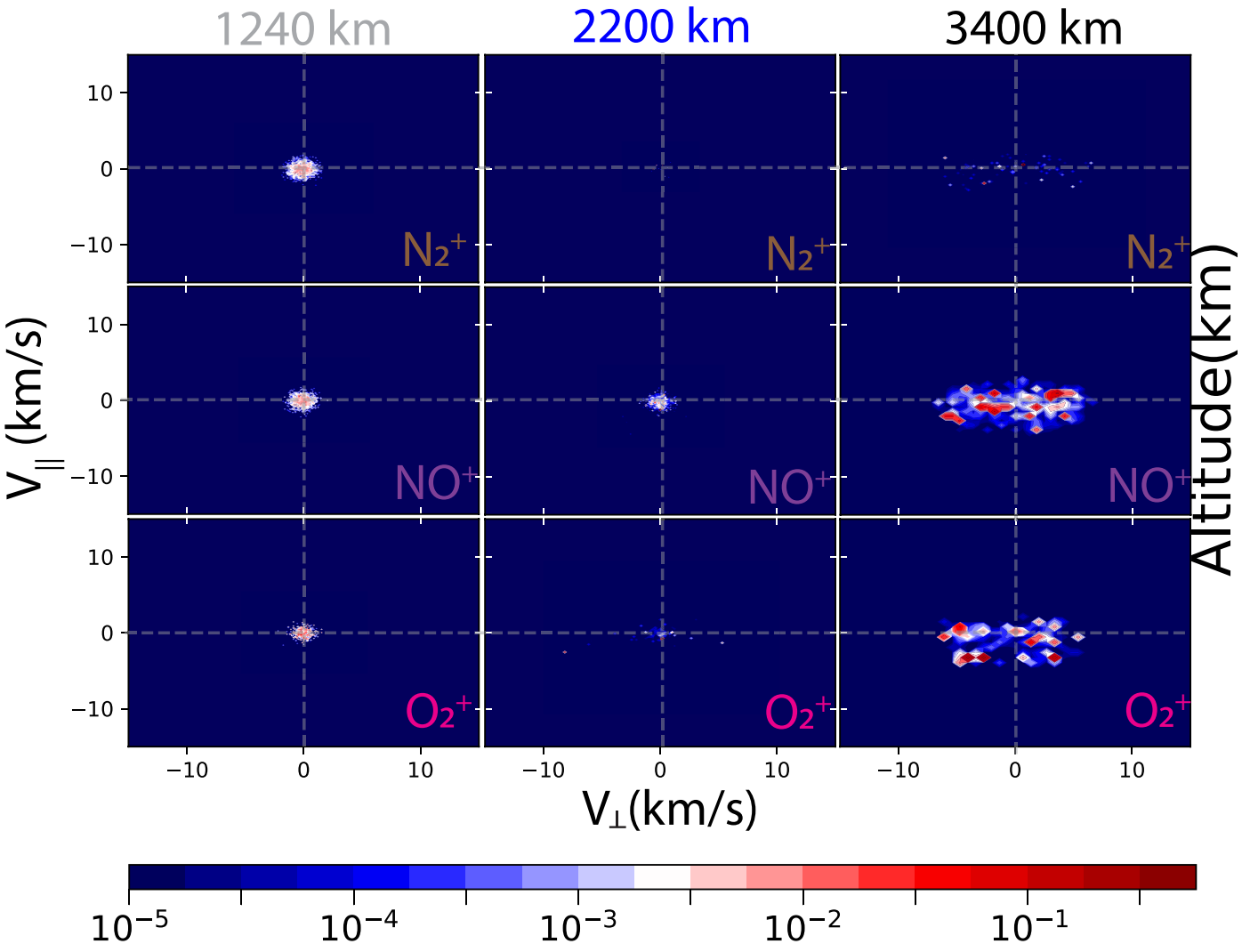

No Wave
N_2^+
8000
6000
4000
2000
0
Altitude(km)
−5.0
−2.5
0.0
2.5
5.0
Log_{10} n (cm^{-3})

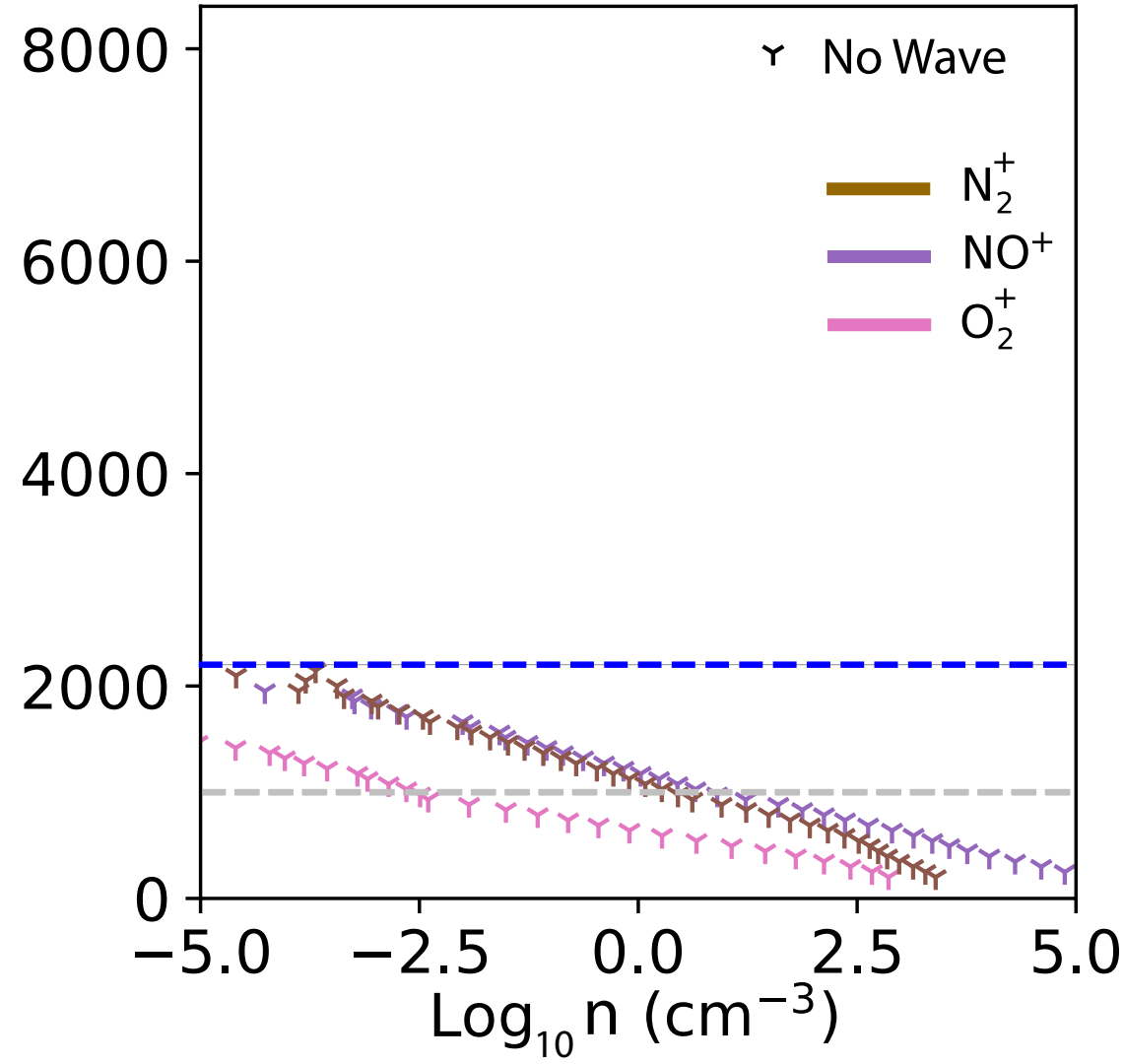
No Wave


1240 km
2200 km
3400 km
10
0
−10
N_2^+
NO^+
$V_{||}$ (km/s)
$V_\perp$(km/s)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

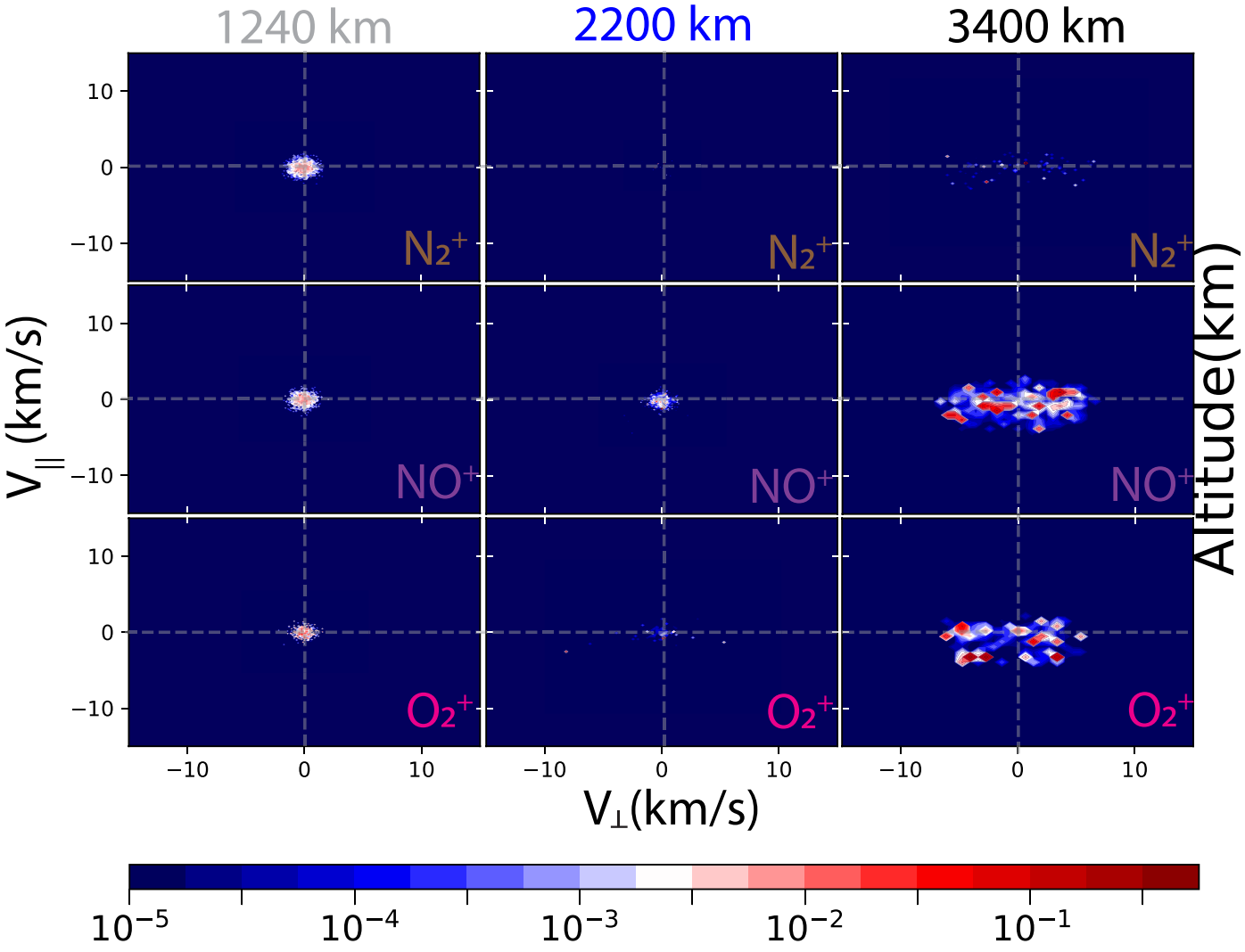

No Wave
N_2^+
NO^+
Altitude(km)
8000
6000
4000
2000
0
−5.0
−2.5
0.0
2.5
5.0
Log_{10} n (cm^{-3})

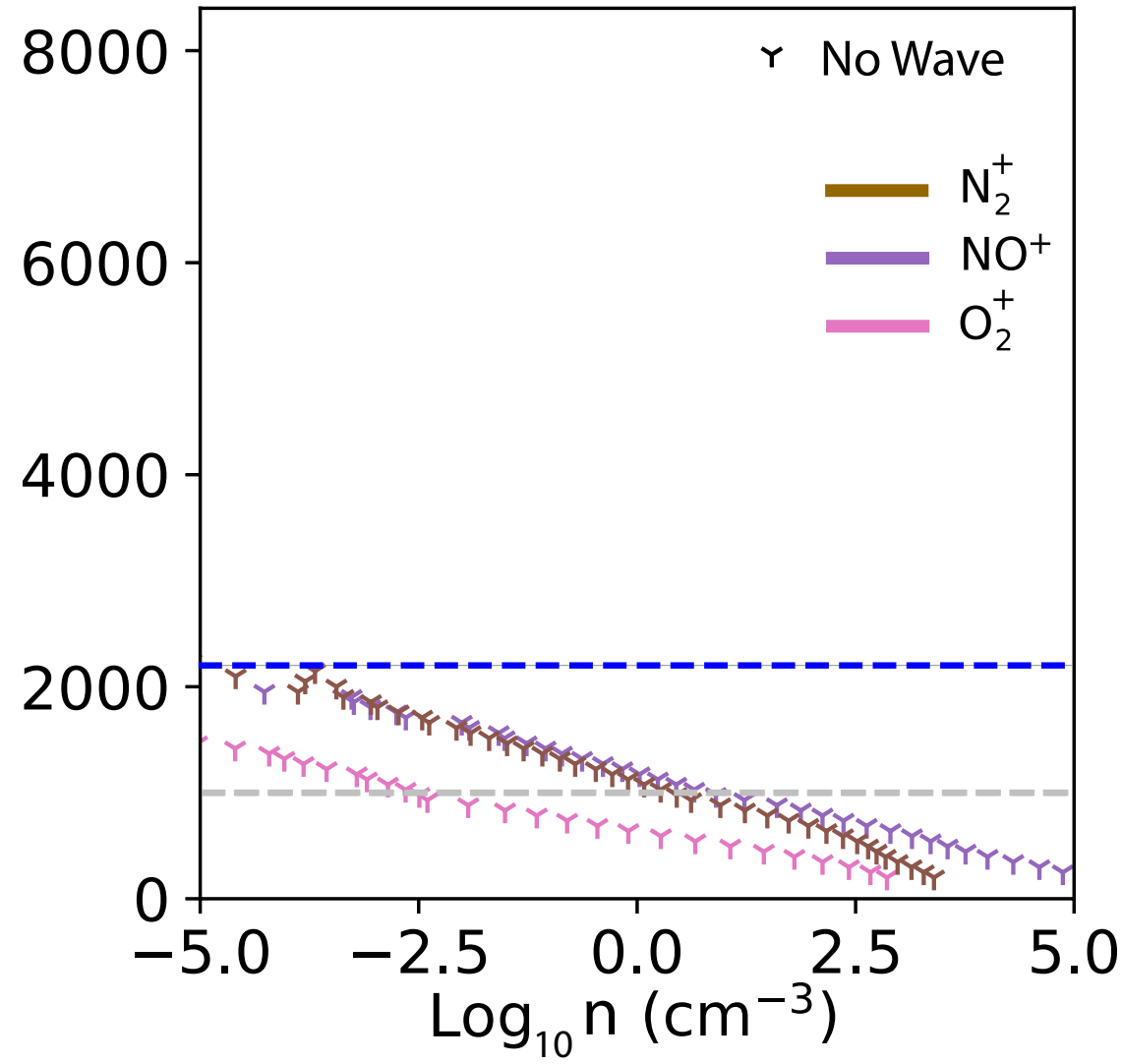
No Wave


1240 km
2200 km
3400 km
N_2^+
NO^+
O_2^+
$V_{||}$ (km/s)
$V_\perp$(km/s)
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}

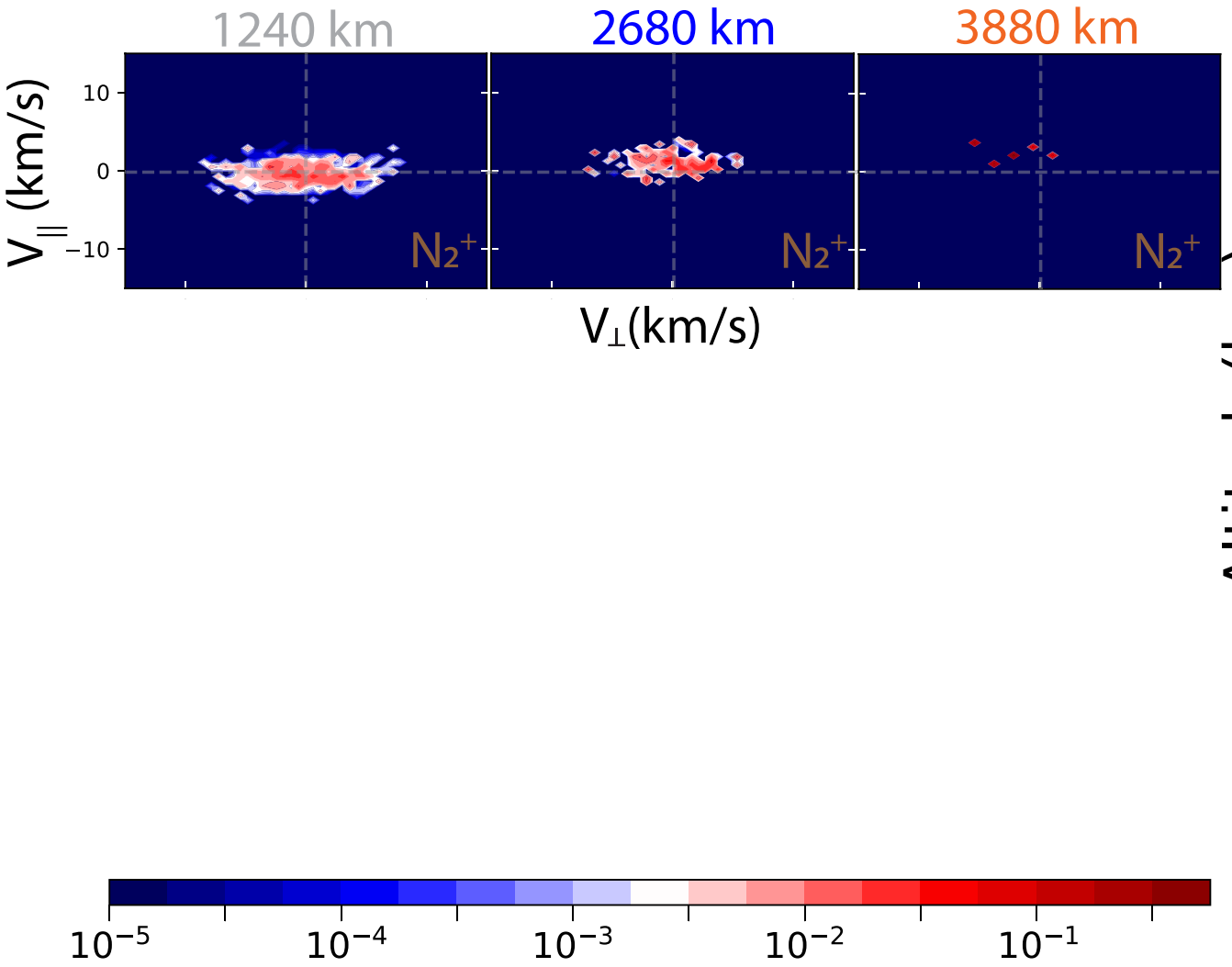

No Wave
N_2^+
NO^+
O_2^+
Altitude(km)
$\mathrm{Log}_{10}\, n\ (\mathrm{cm}^{-3})$

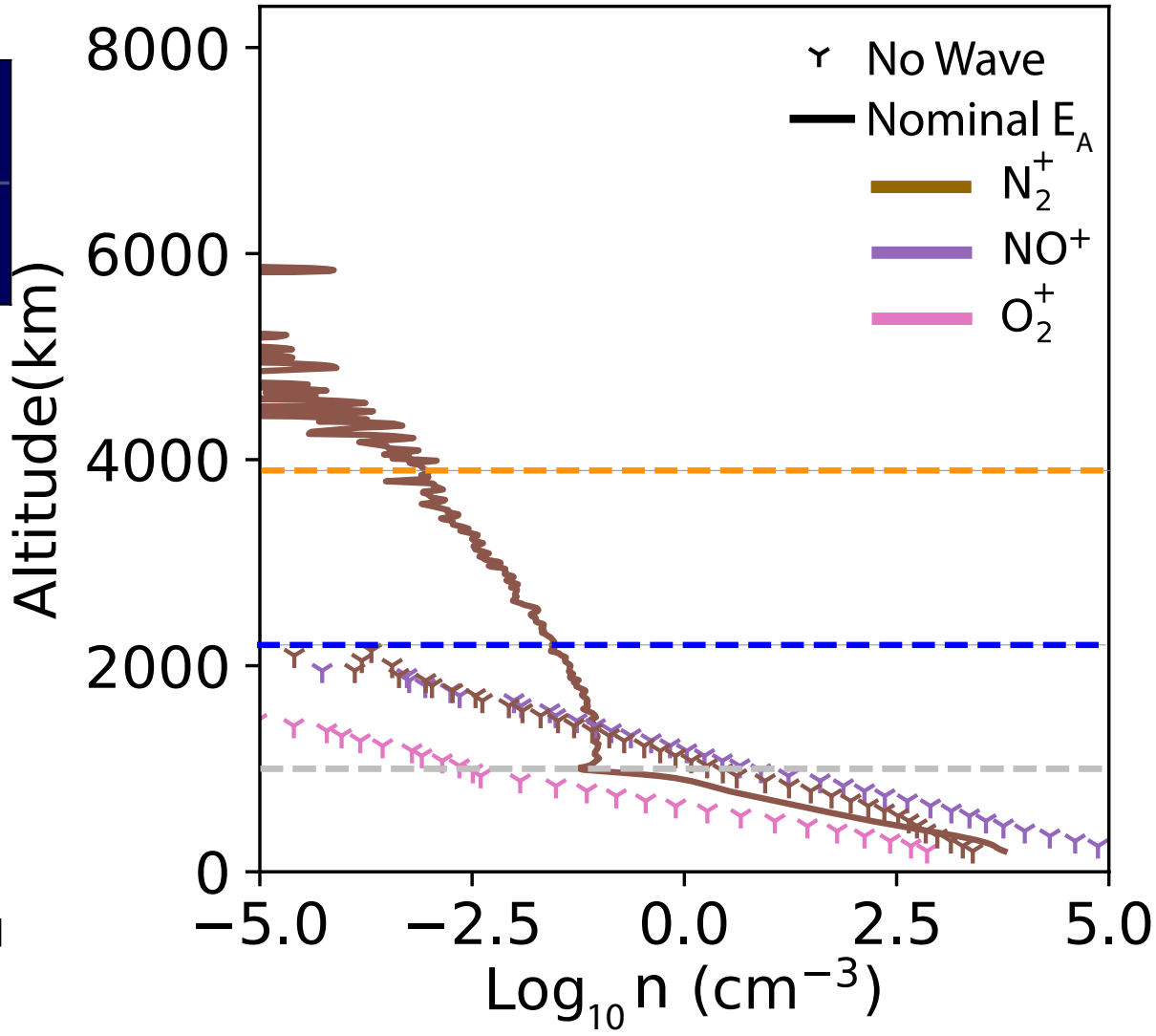
No Wave → No Molecular Ion Upflow or Outflow



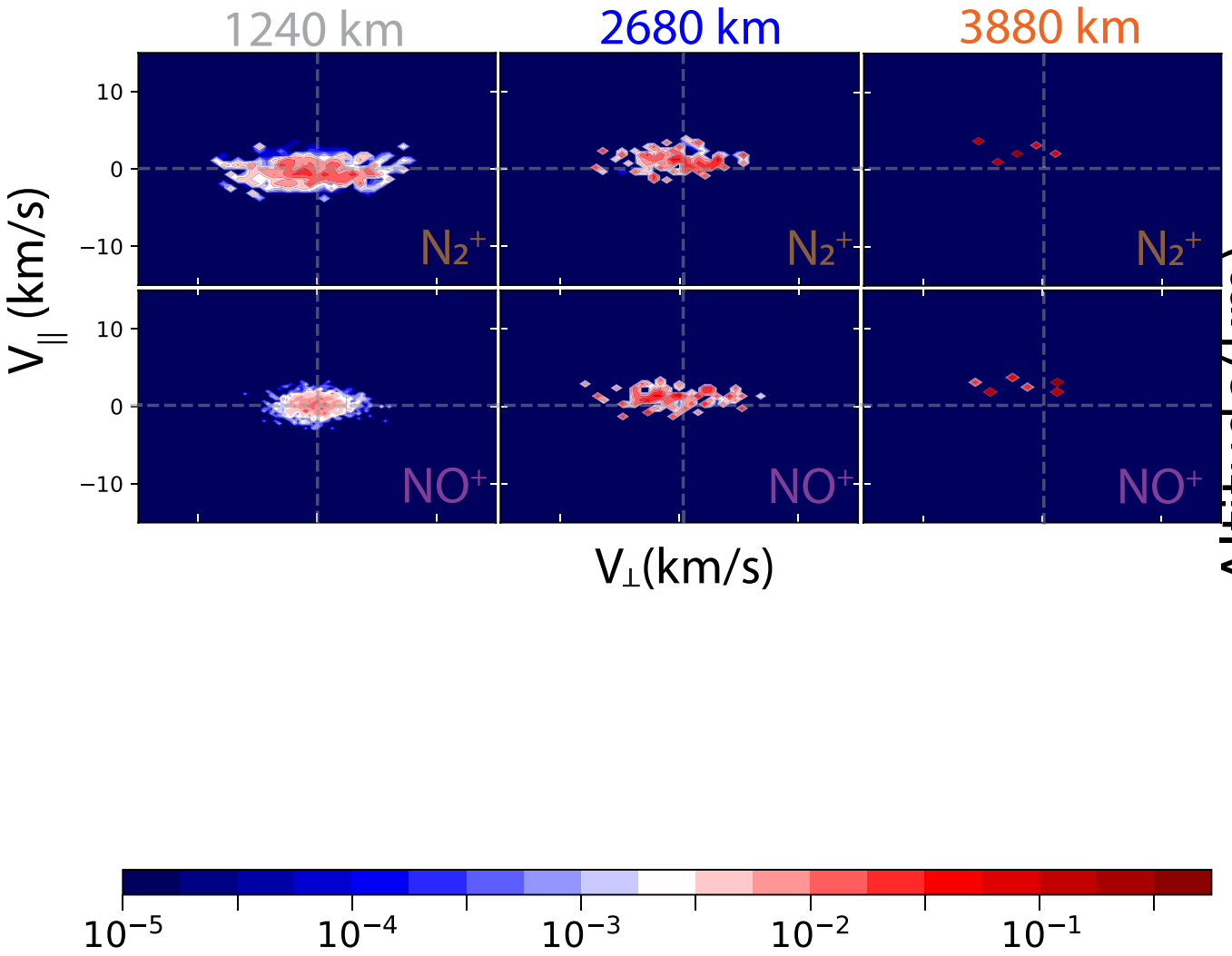


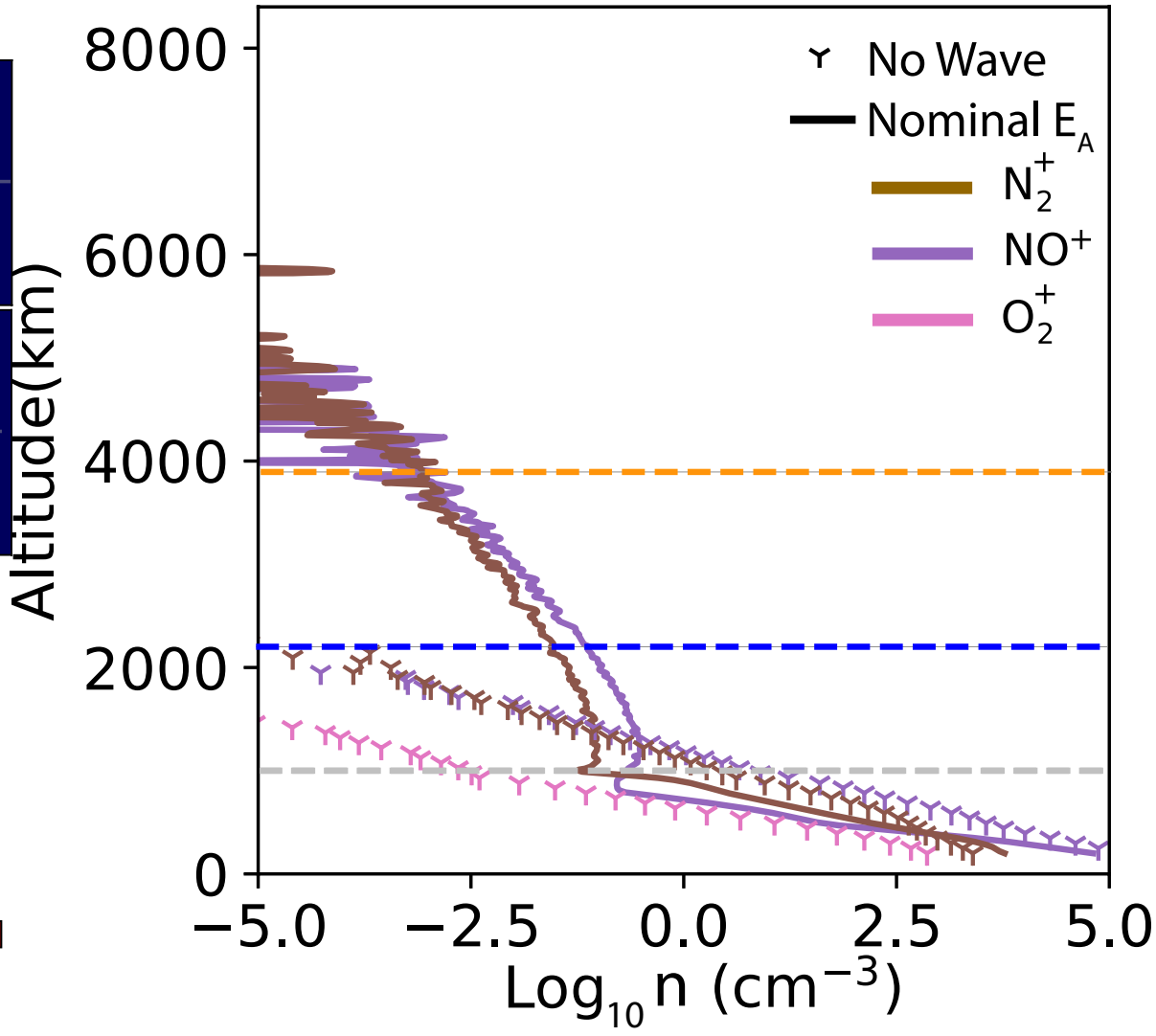
Nominal Wave Energy (E_A)



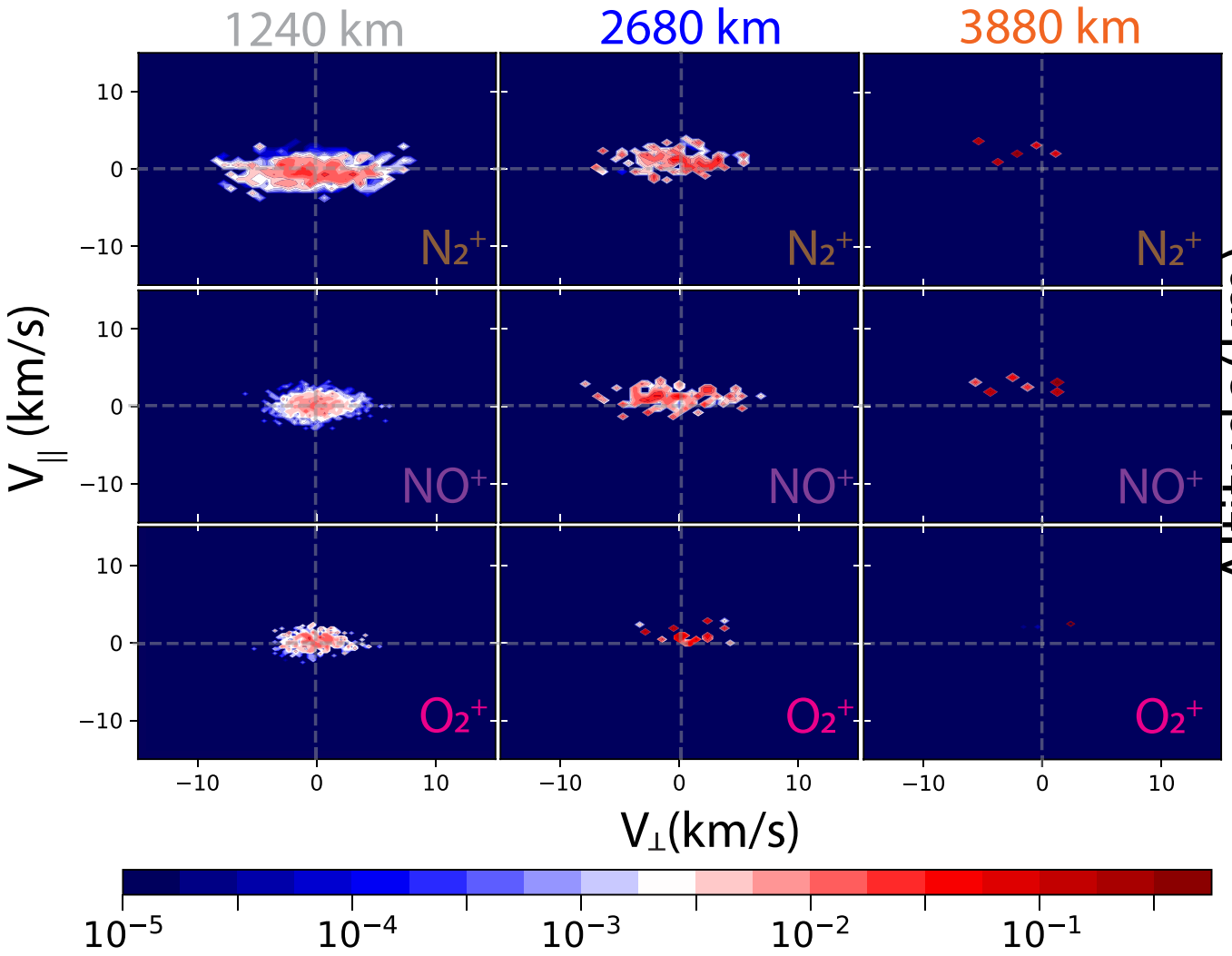


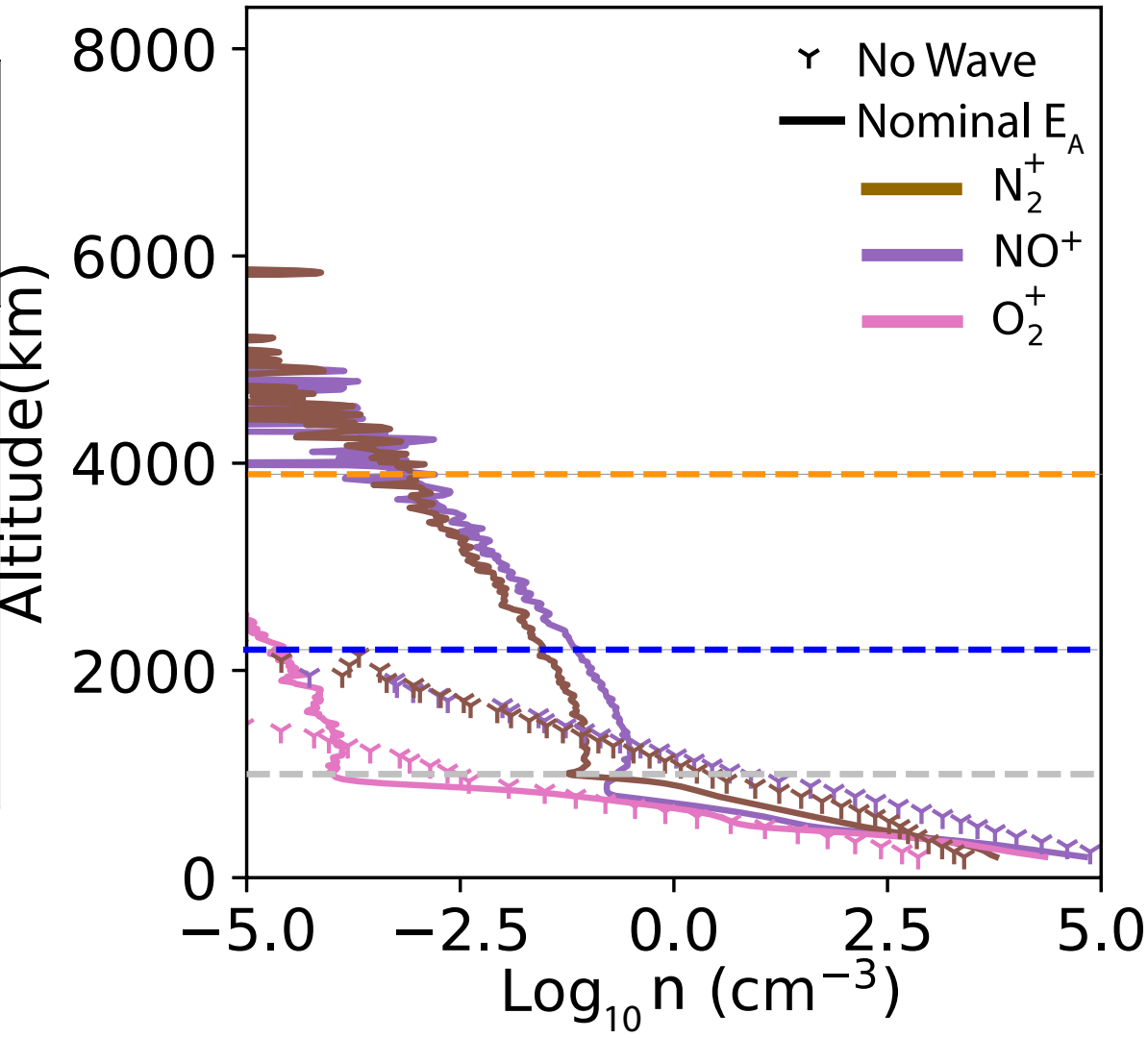
Nominal Wave Energy (E_A)



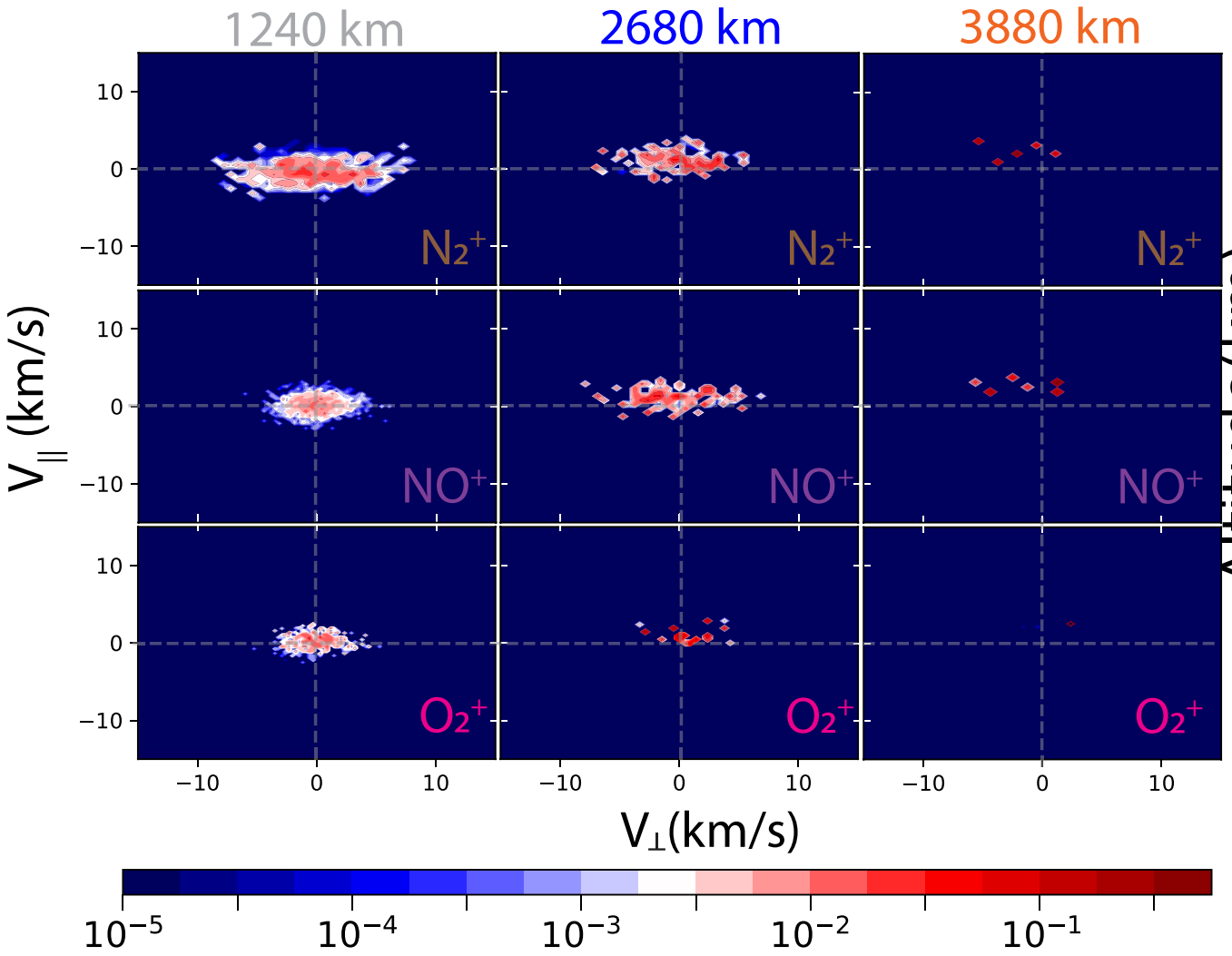


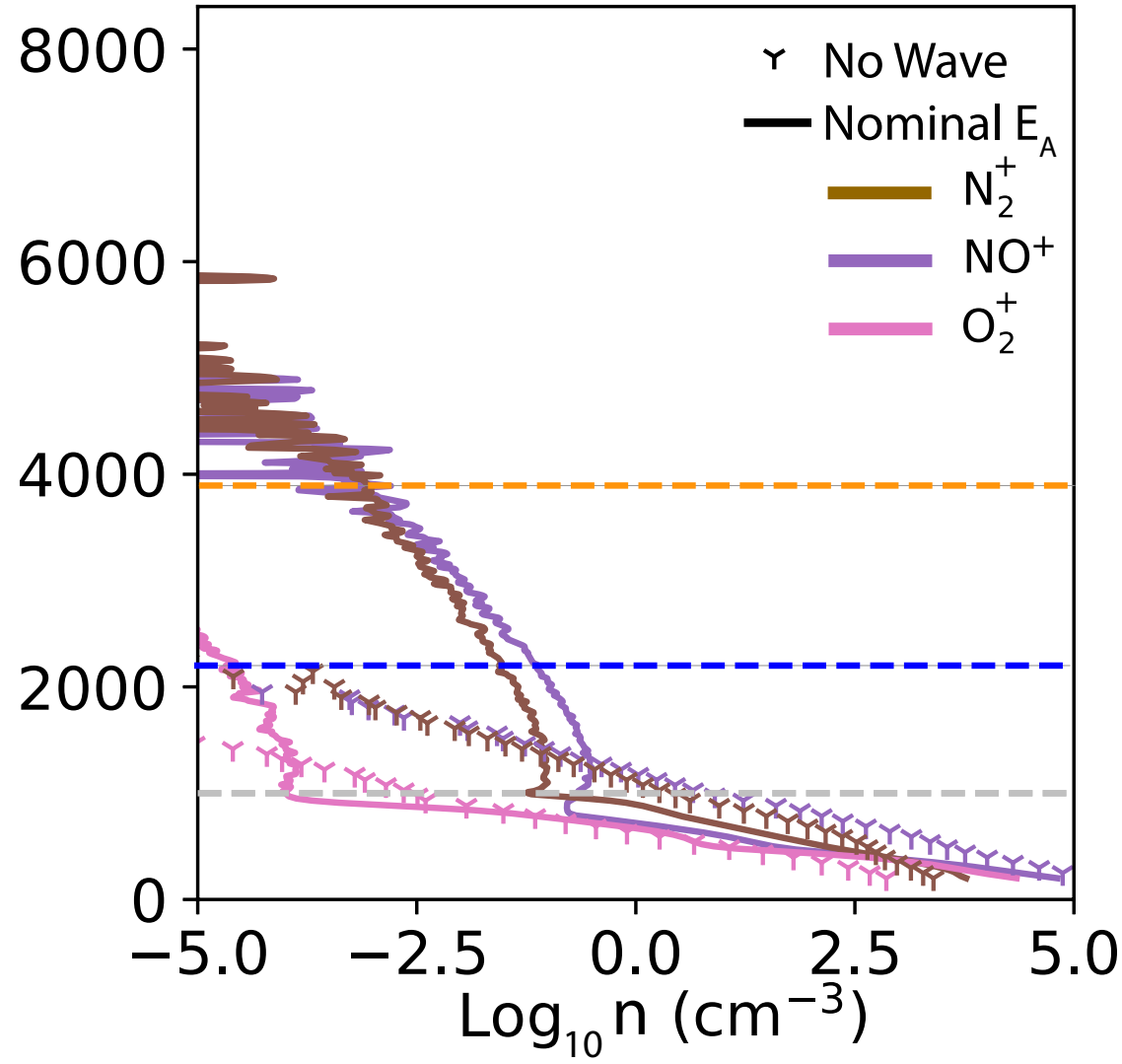
Nominal Wave Energy (E_A)



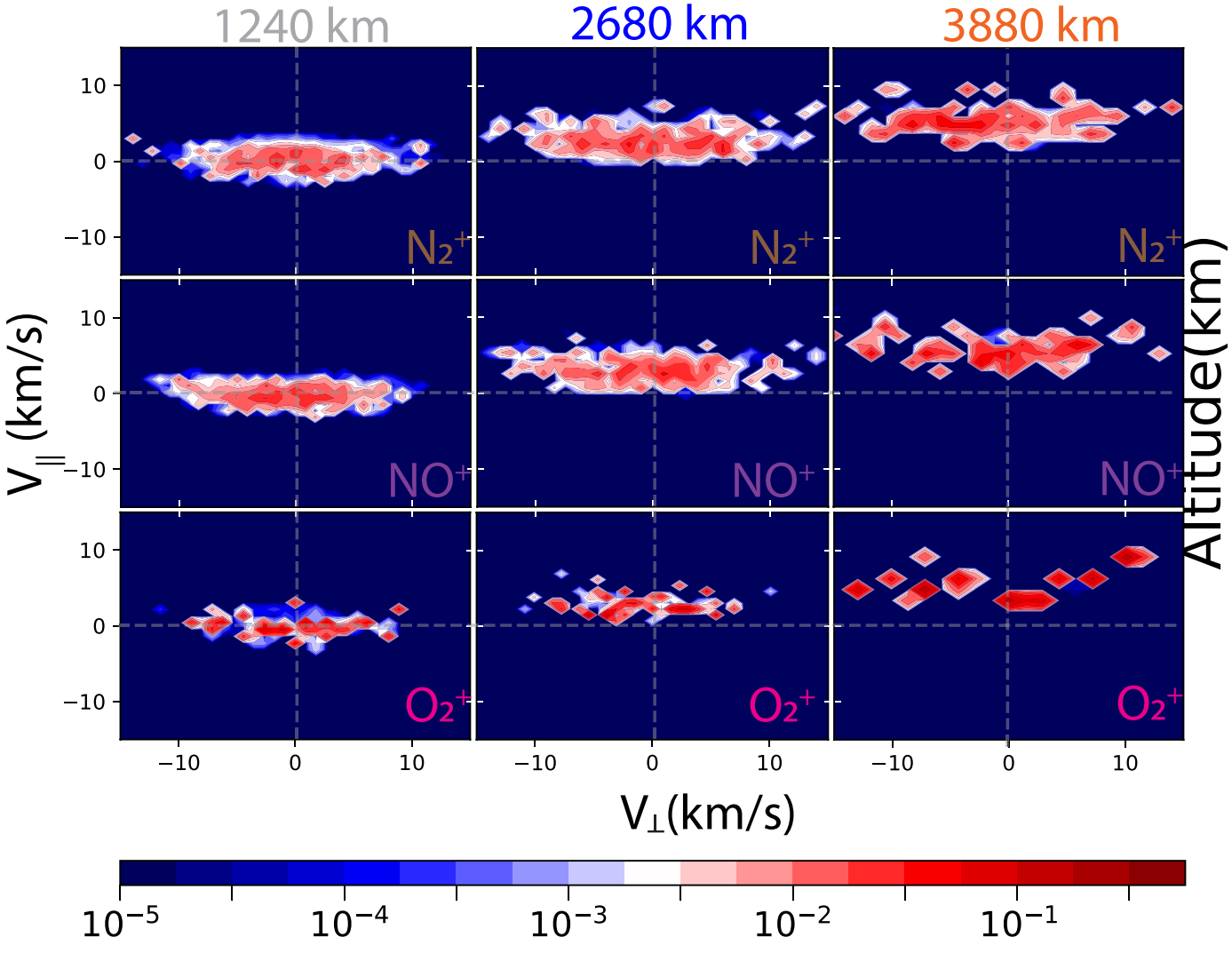


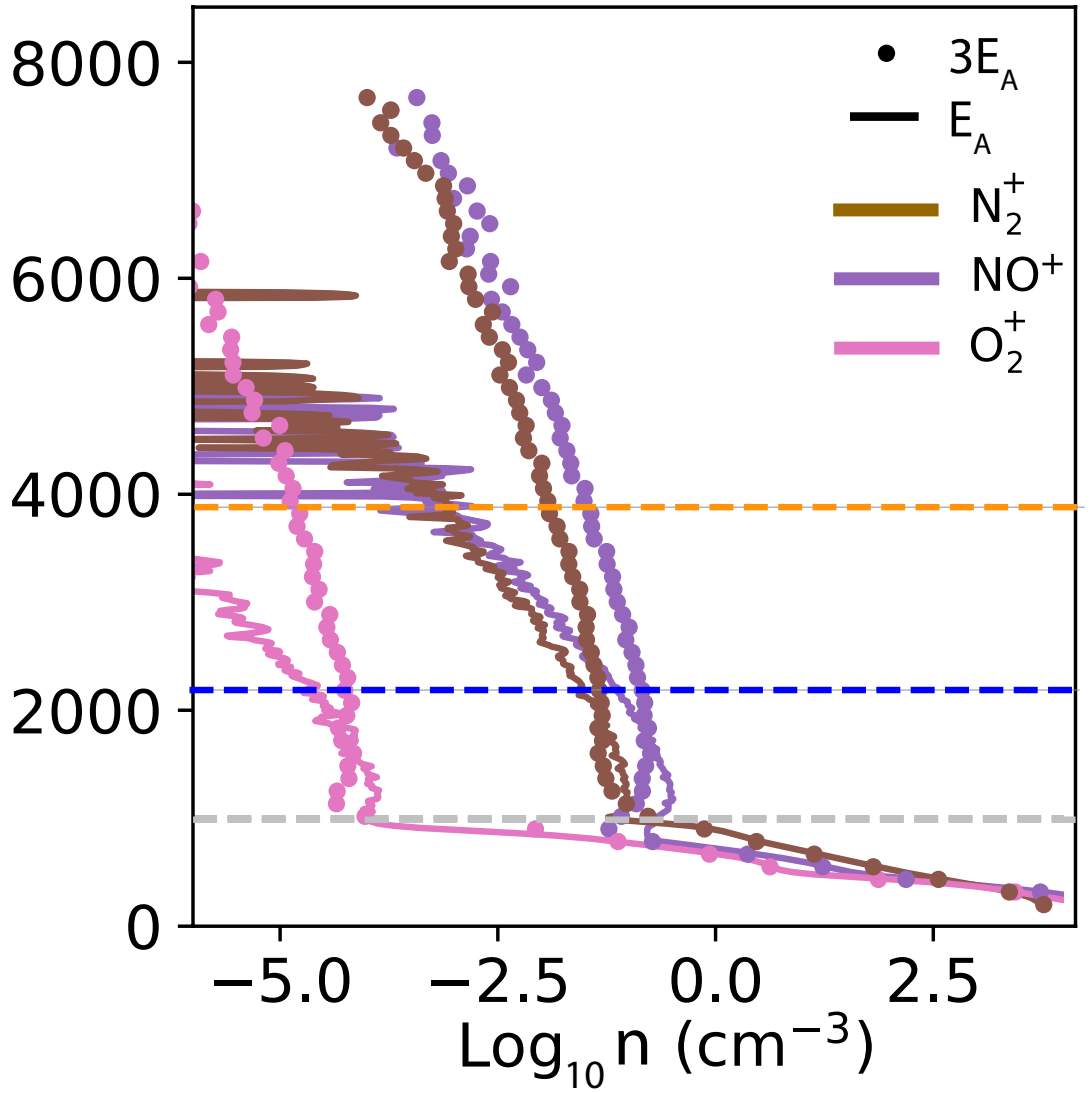
Nominal Wave Energy (E_A) → Molecular Ion Upflow



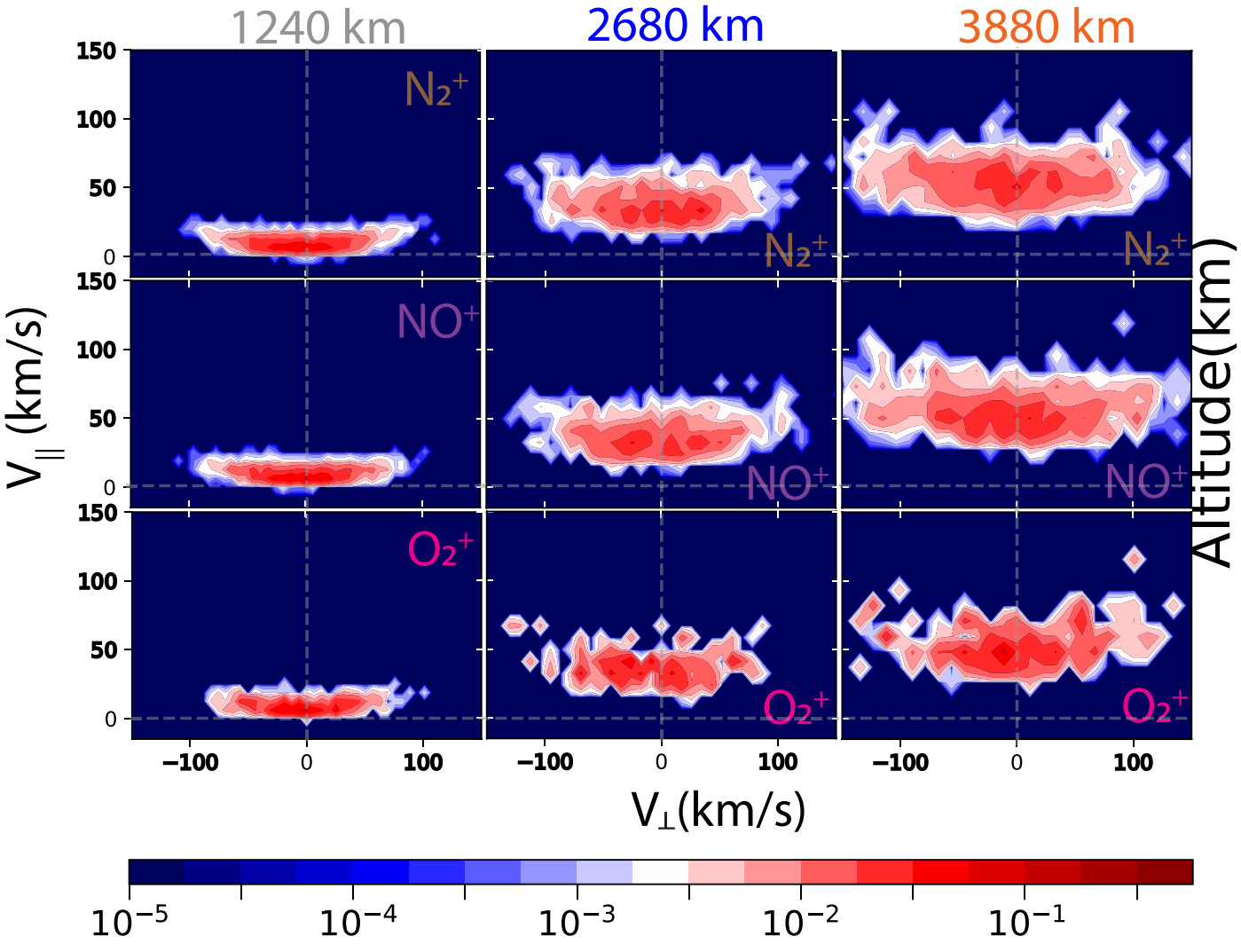


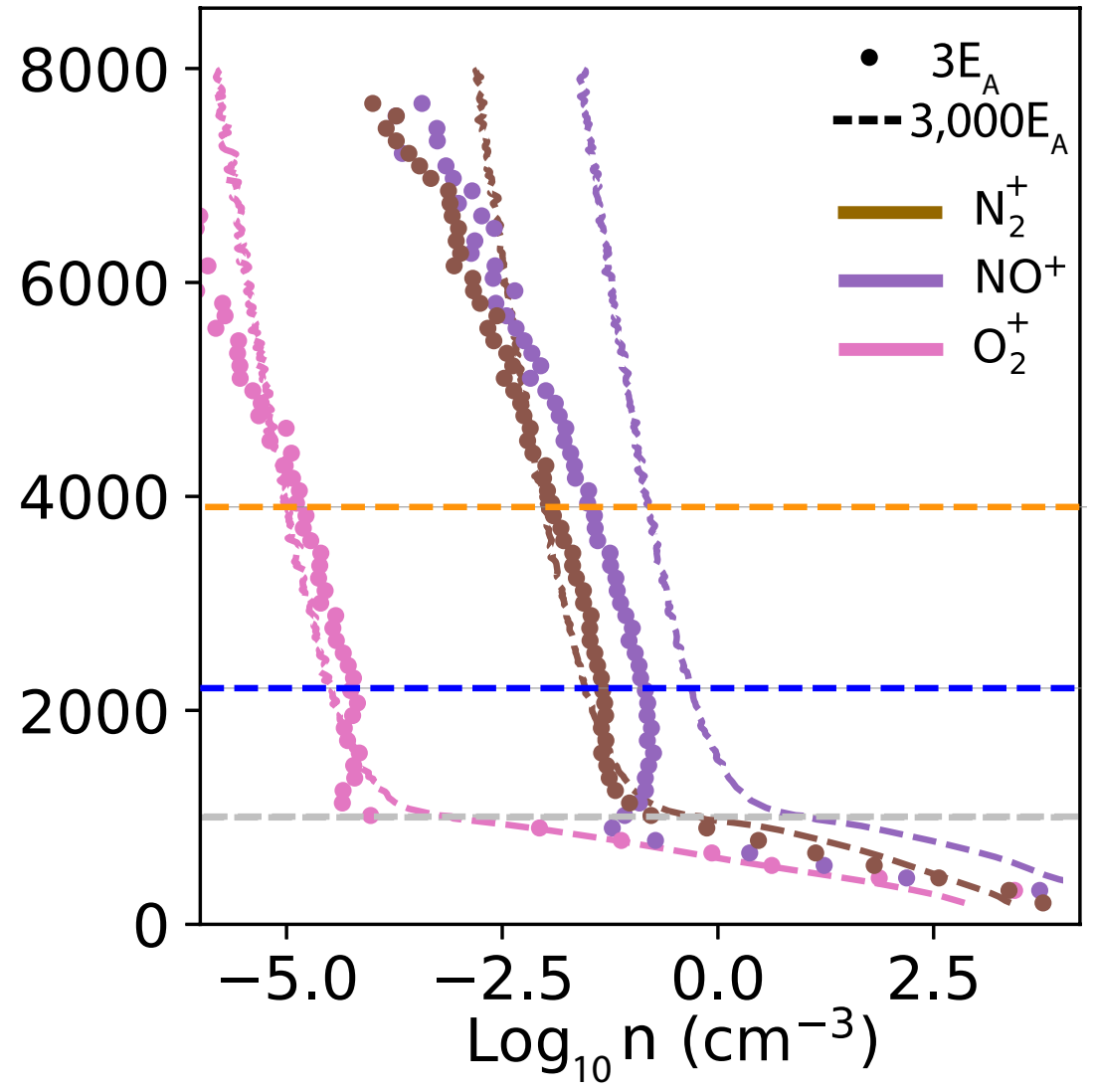
3 E_A → Molecular Ion Outflow





3,000 $E_A \rightarrow$ Max Molecular Ion Outflow





Summary

- Molecular ions are efficiently energized by wave-particle interaction. An increase in the wave energy input ($E_A \propto 1/B$) by a factor of 3 leads to immediate enhancement in the molecular ion fluxes by two orders of magnitude.
- Ionospheric chemistry plays a critical role in regulating the abundance of molecular ion outflow, while the wave energy controls how far up molecular ions are transported.
- Tracking heavier ion species, such as metallic Mg^+ and Fe^+ ions (awarded 2023 Jack Eddy Fellowship), provides a clue on how atmospheric escape behaves in Earth's different geological timescales.