Very minor ions in the magnetosphere: **a hub** of the mesospheric, ionospheric, magnetospheric, solar wind, lunar, and meteoroid **sciences**

ISSI team #518 (https://www.issibern.ch/teams/mmiconmagnet/)

M Yamauchi[1], S Christon[2], I Dandouras[3], S Haaland[4], D Kastinen[1], LM Kistler[5], I Mann[6], S Nozawa[7], JMC Plane[8], Y Saito[9], L Schulz[10], S Watababe[11], P Wurz[12], and AW Yau[13]

recently submitted to Space Sci. Rev.

1 Swedish Institute of Space Physics (IRF), Kiruna, Sweden; <M.Yamauchi@irf.se>
2 Focused Analysis and Research (FAR), USA; 3 IRAP, Toulouse, France; 4 U Centre Svalbard, Norway; 5 U New Hampshire, USA; 6 UiT, Tromsø, Norway; 7 Nagoya U, Japan; 8 U Leeds, UK; 9 ISAS, Japan; 10 TU-Braunschweig, Germany; 11 Hokkaido Information U.; 12 U Bern, Switzerland; 13 U Calgary, Canada

Sharing is encouraged

EGU24-5648 (X3.73)

Magnetosphere is zoo of many ions

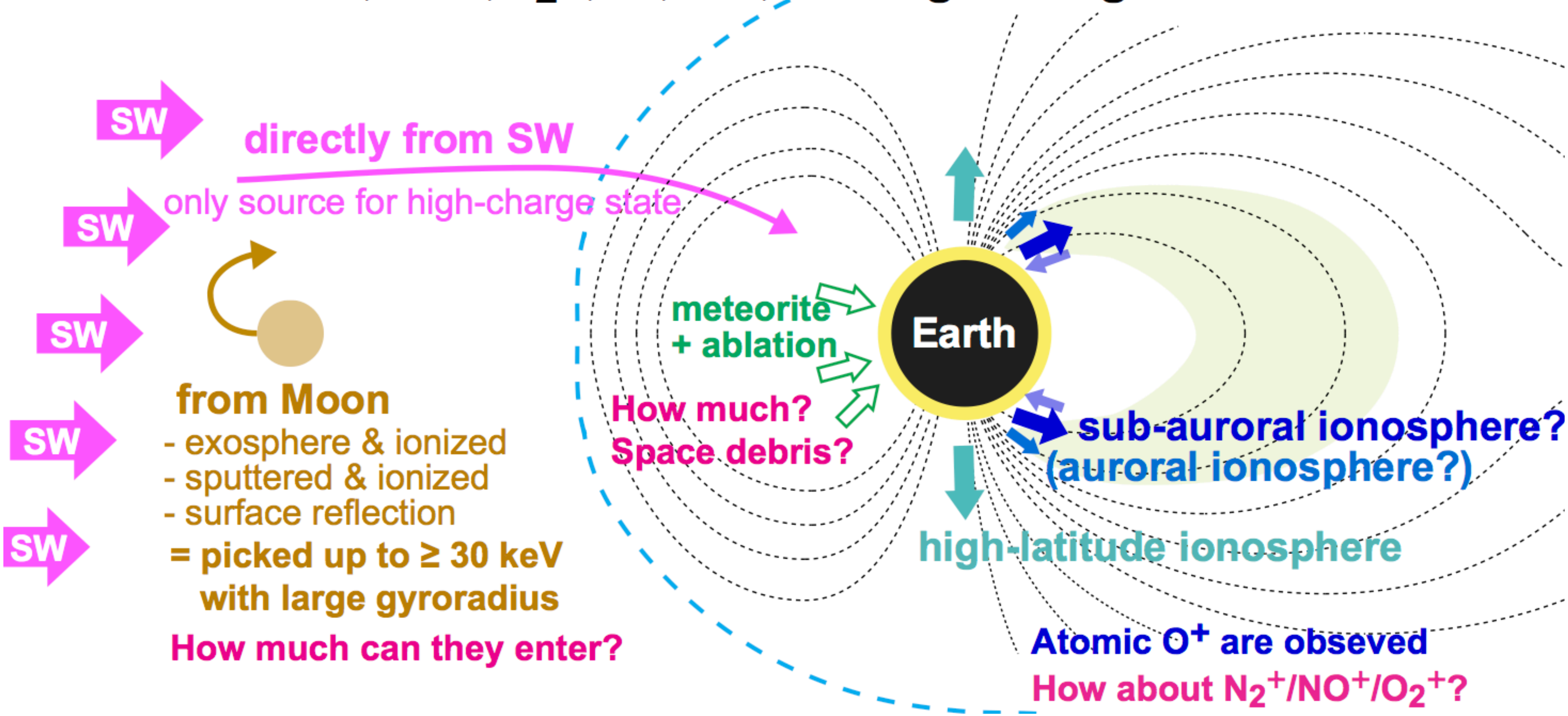
Very minor ions ⇒ Ions from **minor sources can be detected**

(1) Molecular ions : **Ionosphere**

(2) Low charge-state metallic ions **:** **Moon** (+ Solar Wind) **+ Thermosphere/Mesosphere**

(originally from **Meteoroid** (+ Space debris?))

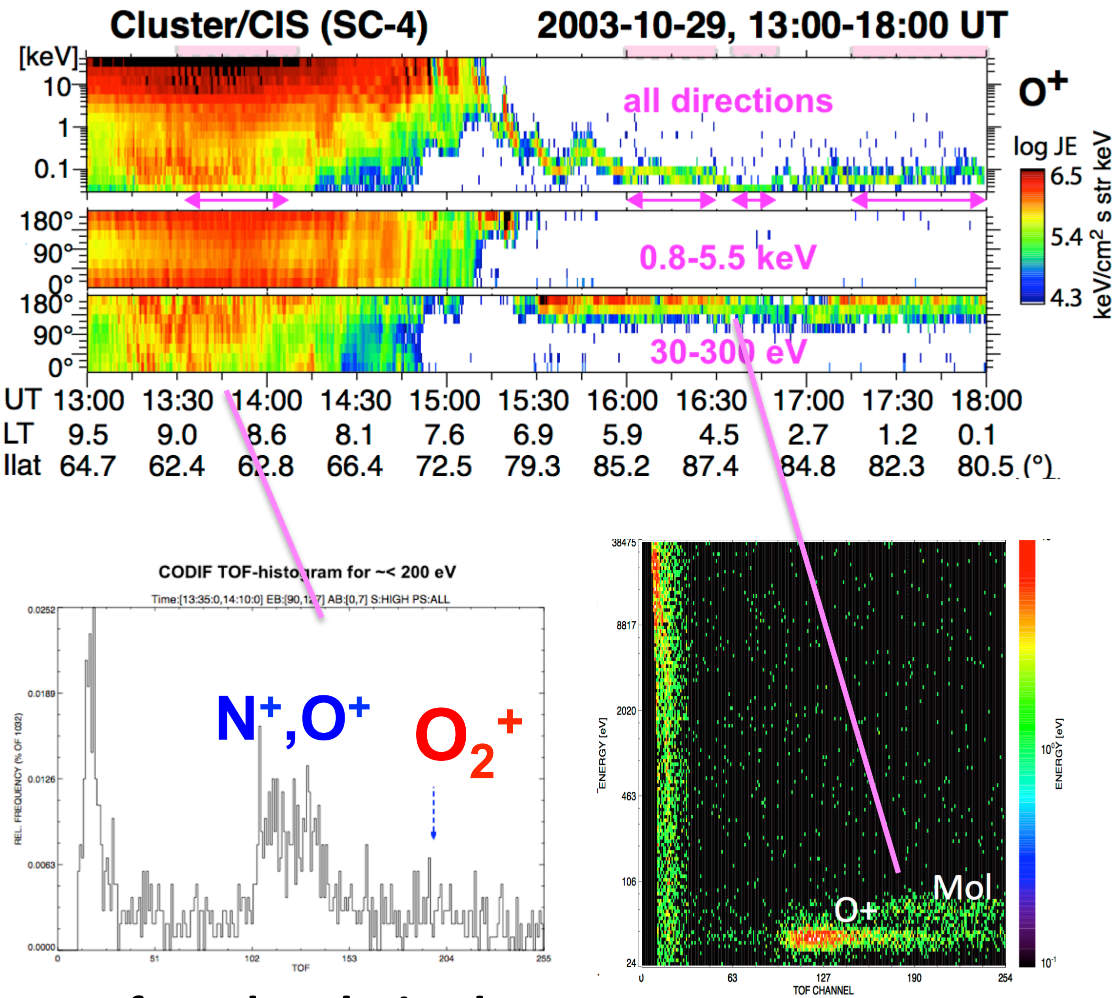
sources of Si^+, Fe^+ ,O_2^+, …, Al^+, and high-charge state ions



Cluster

Molecular ions of m/q > 20

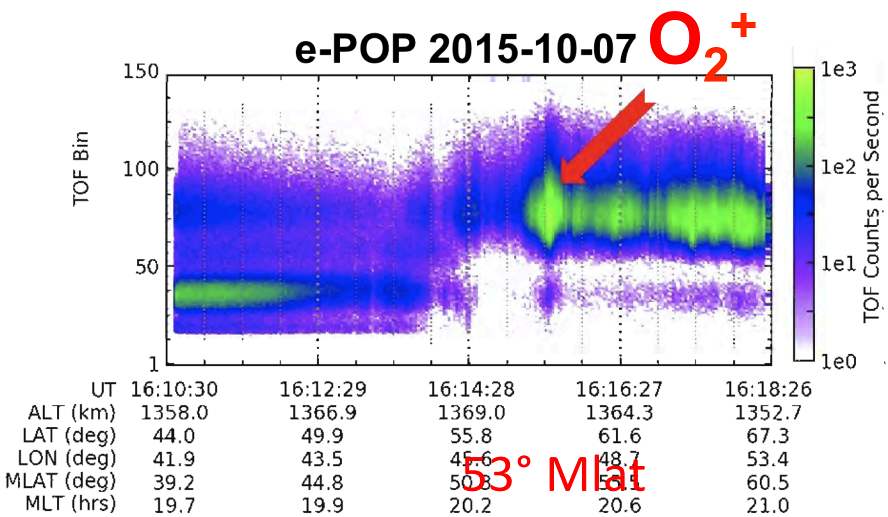
Examining only field-aligned heavy ions



from low latitude

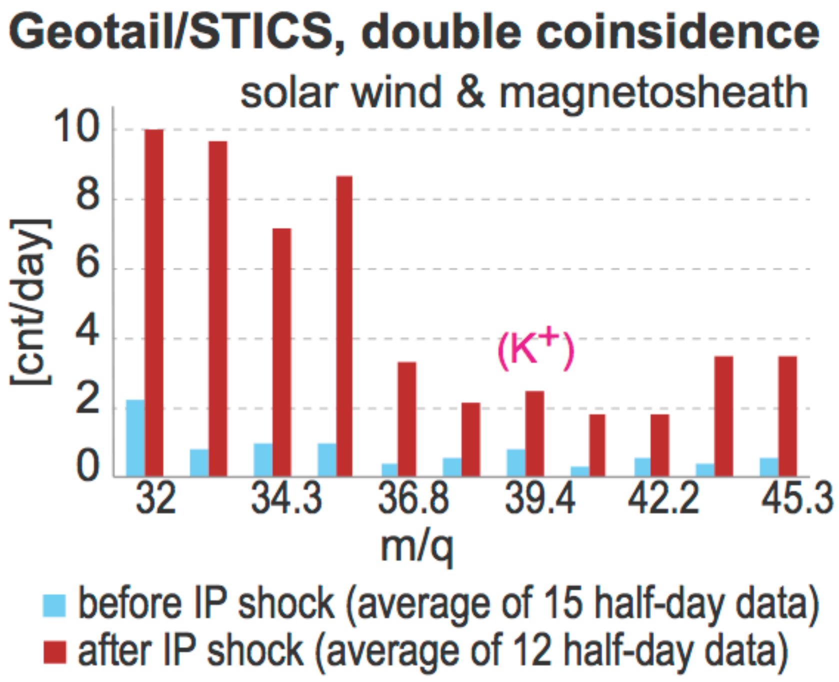
from high latitude

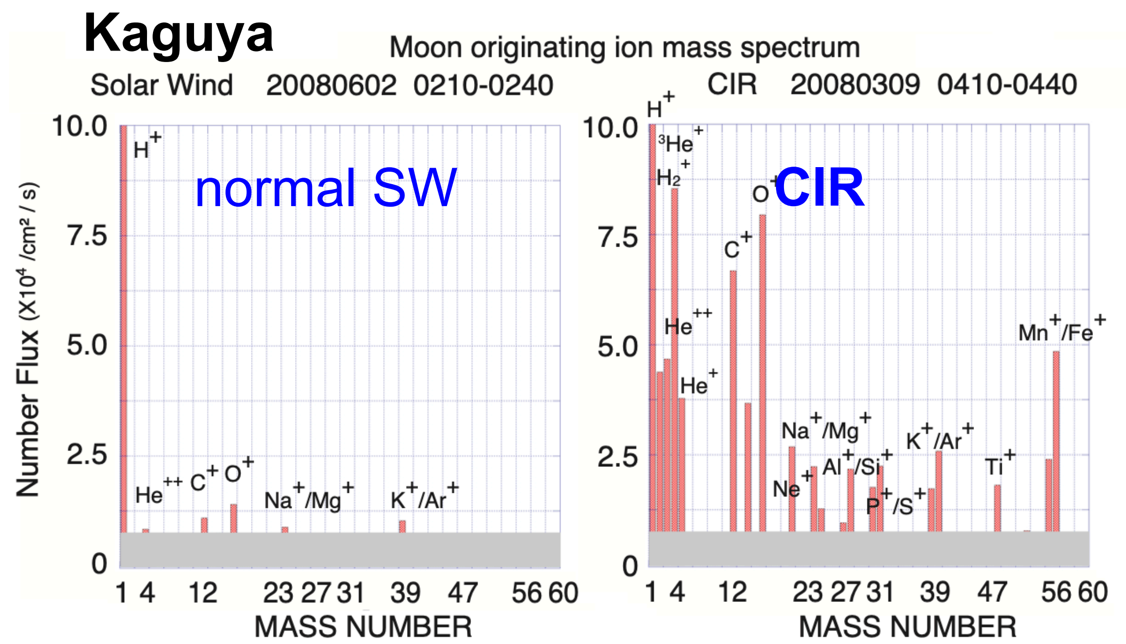
We recently found **direct low-latitude source** in addition to **high-latitude source** both in magnetosphere (Cluster) and above the ionosphere (e-POP)



⇒ science of **ionospheric process + acceleration**

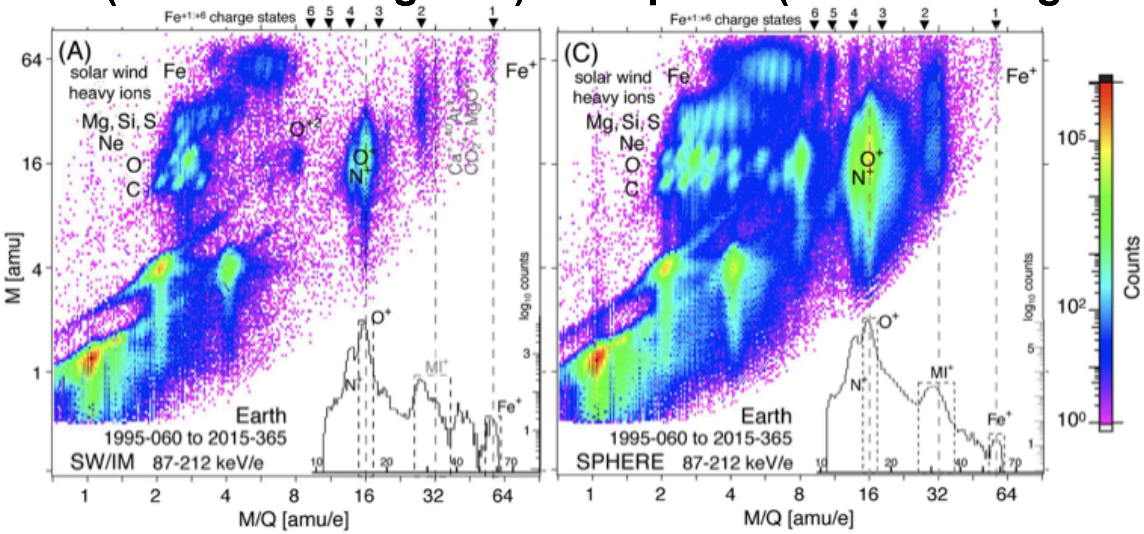
Low charge-state metallic ions





Geotail **(Christon et al, 2017)**

SW (outside average BS) **M' sphere (inside average MP)**



- Increase during CIR @ moon
- Increase after CME in SW

⇒ **clear** **Moon** **source**

- Finite flux m/q ≈ Si^+, S^+, K^+ exists even in upstream

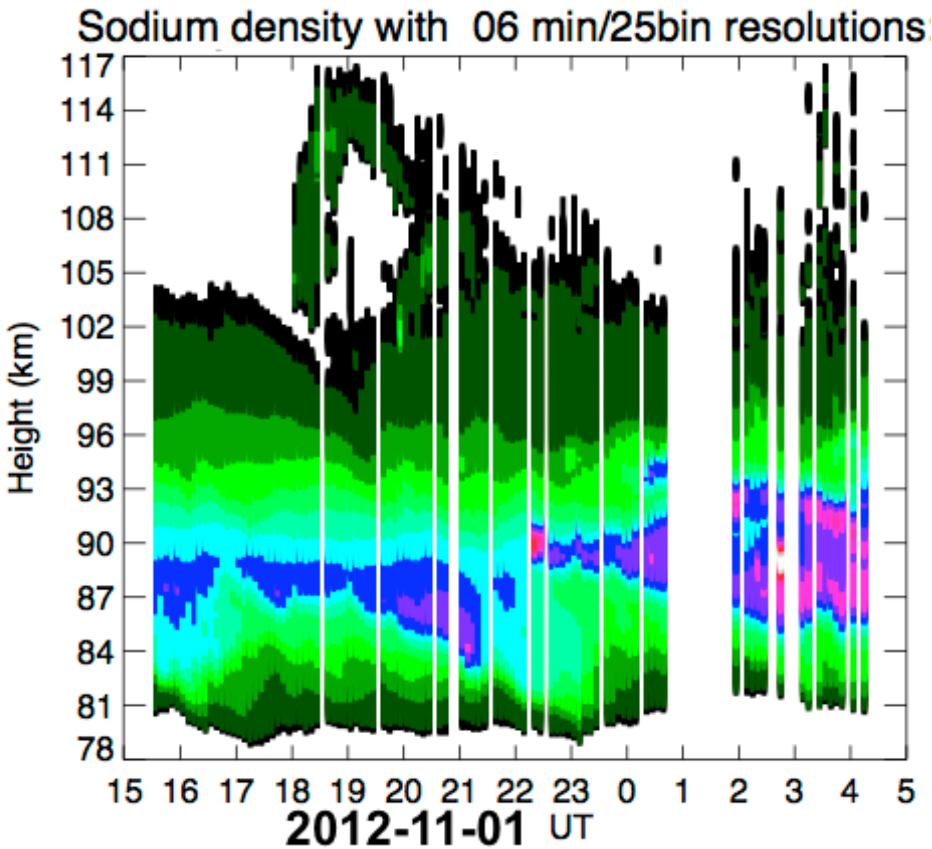
⇒ **some could from** **SW?**

Low charge-state metallic ions

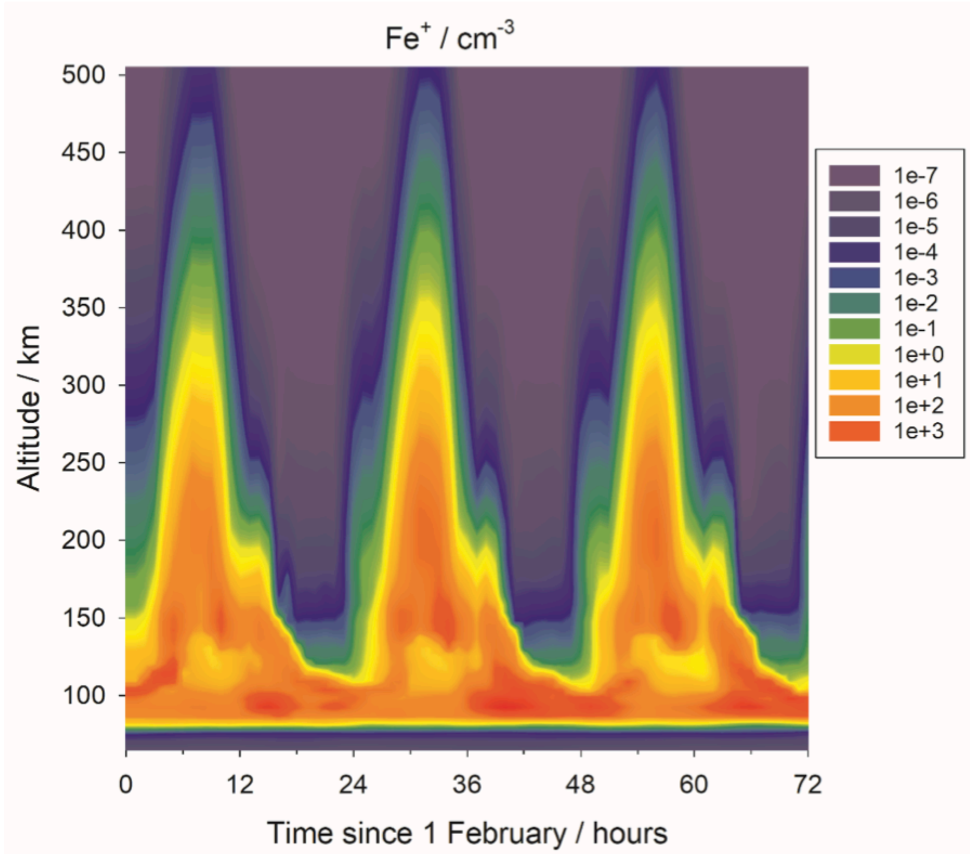
Upward lift during Geomagnetic Storm

Might reach exobase during summer

Na lidar



WACCM-X Model



- Na lidar detected lifting to ionosphere
- model expects reaching to the exobase.

⇒ **Mesospheric source**

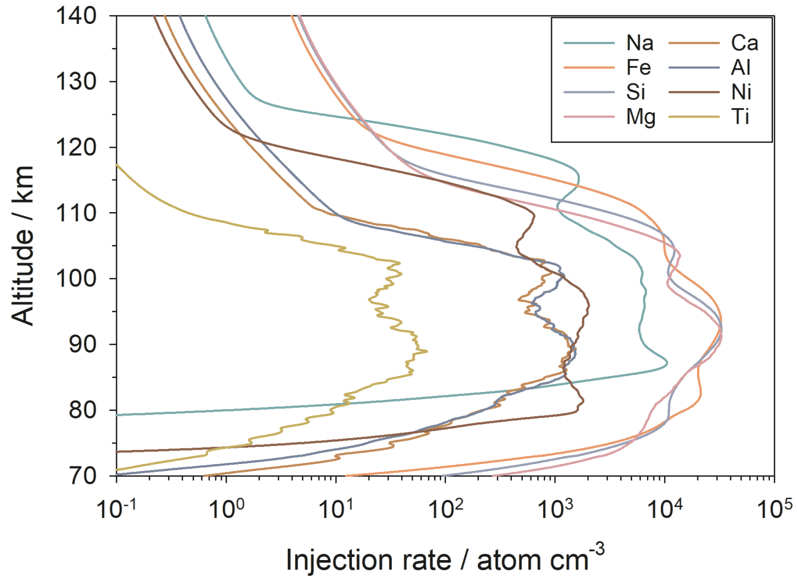
Low charge-state metallic ions

(3) Ultimate supply to the mesosphere

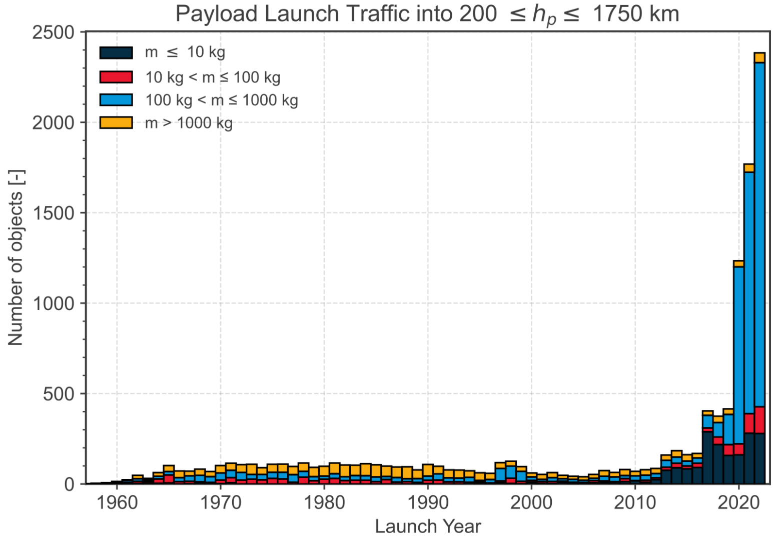
⇒ meteoroid **ablation** physics

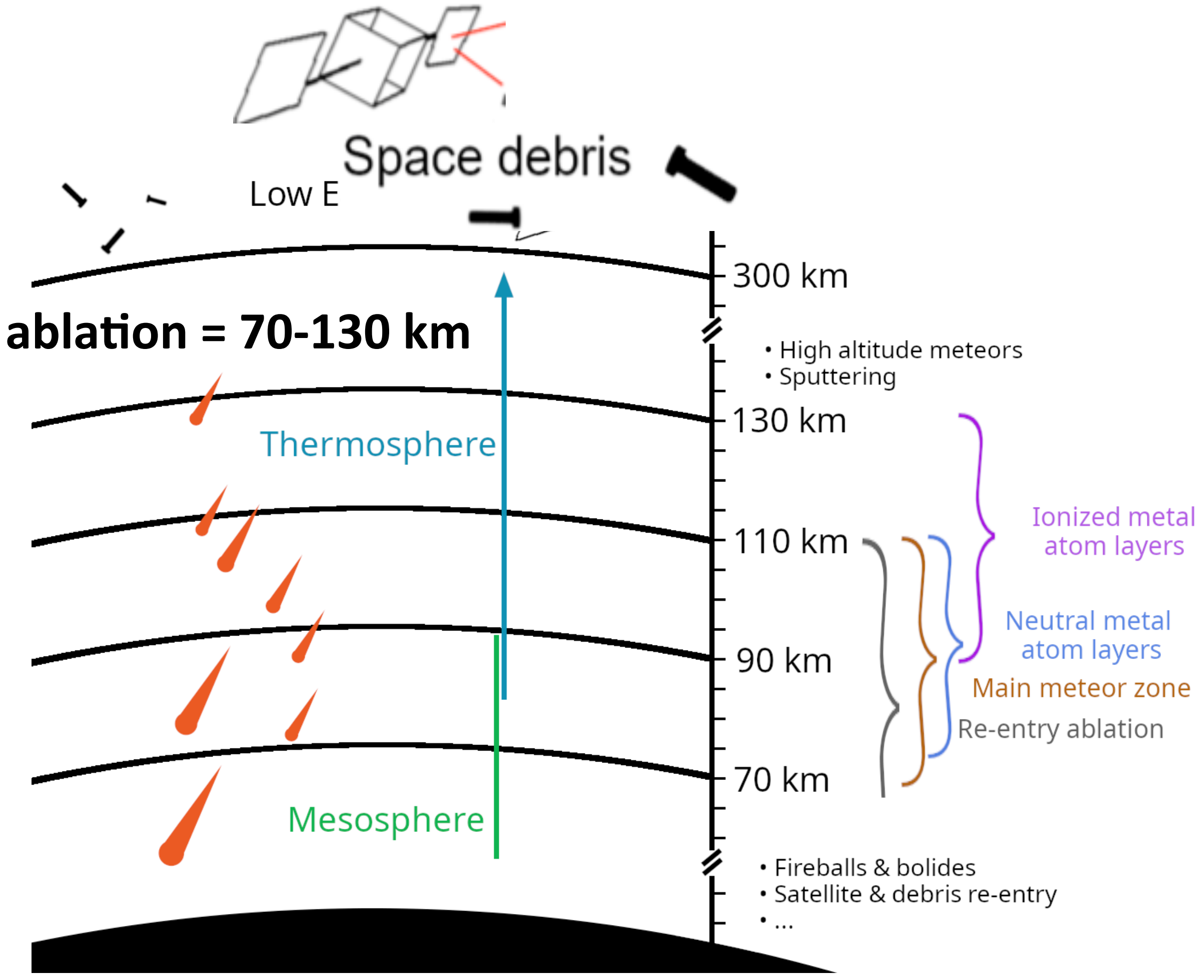
⇒ why not **space debris?** (=no data)

Model (ablated meteoroid)



sharp increase of satellites





Thus, science of heavy ions (m/q>20) is interdisciplinary

(1) **Molecular ions**: recently found **low-latitude source** in addition to **high-latitude source** ⇒ need **ionospheric** observation and models

(2) **Low charge-state metallic ions**: coming from both **upstream** and **ionosphere**

- **Moon** observations are qualitatively consistent
- Direct contribution from the **solar wind** cannot be removed
- **Mesospheric/thermospheric** observations/models are qualitatively consistent
- **Meteoroid** observations and model also support mesospheric source
- Even detectable contamination from **space debris** is expected from the model

Scientific roles of very heavy ions

(1) molecular ions

source	science
Ionosphere	**acceleration**

(2) low charge-state metallic ions

source	science
Solar wind	**as marker** to enter the magnetosphere
Moon	above + **moon wake effect**
Metal layer	thermospheric/mesospheric **dynamics**
Meteoroid	**ablation process**
Space debris	above + **monitoring pollution**

However, too few observations @ inner magnetosphere

(1) Dedicated obs. (molecular ions)

mission	specification
Arase	altogether (0.05–100 keV)
e-Pop,	altogether (<50 eV)
Akebono, DE-1	each (<50 eV)
Geotail, Wind, Ampte	altogether (>100 keV)

(2) Dedicated obs. (metallic ions)

mission	specification
Geotail, Wind	each (> 100 keV)

⇒ **Need missions** + monitoring of source (Moon, mesosphere….)

(A) Best is **dedicated mission**, even as a secondary objective of any mission.

(B) Realistic option is placing a set of instruments **on non-science missions**

- **Earth Observation** Satellites
- **Space Safety** missions (including geostationary one)
- Transfer spacecraft to/from the coming Lunar Gateway.
- The **Lunar Gateway** itself
  (already plan have Ion Mass Spectrometer (SPAN-Ai) with 2 eV - 40 keV, m/Δm ≈10).

Why was detecting difficult, and how should we design?

1. Limited energy range in the past design (< 90 eV/q for e-POP or > 10 keV for Geotail).
2. Finite entrance cross-section of the instrument reduces the mass resolution.
3. Small geometric factor with very low ion flux.
4. Fragmentation of molecular ions at the start foil of time-of-flight (TOF).

1 - 3 ⇒ new design available for 0.01 – 30 keV with m/Δm ≈ 50 (BepiColombo/MIO)
& for < 0.02 keV with m/Δm ≈ 1000 (JUICE)

Recommended payload for future missions

Key instruments

(1) First ion mass spectrometer with **m/Δm > 60** for wide mass range up to Fe^+ (**m/q > 60**),

(2) Second ion spectrometer with lower mass resolution (yet m/Δm > 15) but sufficient **angular resolution < 22.5°** (6° is ideal to detect the position where the ions are generated around the Moon), while keeping mass range up to **m/q > 60**.

Other instrument

(3) Total ion flux without mass resolution but with **very good ΔE/E** for absolute accuracy in velocity and density

(4) **optical limb observation** from satellites has also advanced, e.g. sounding of Mg+.

For all (1)-(3), The energy range are divided into (a) < 20 eV, (b) 0.01-30 keV, (c) > 20 keV.