Session 2: Opportunities and Challenges Measuring, Monitoring, & Modeling Emissions, Environmental Change & Impacts

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Re-entry lab experiments: Wind tunnel facilities

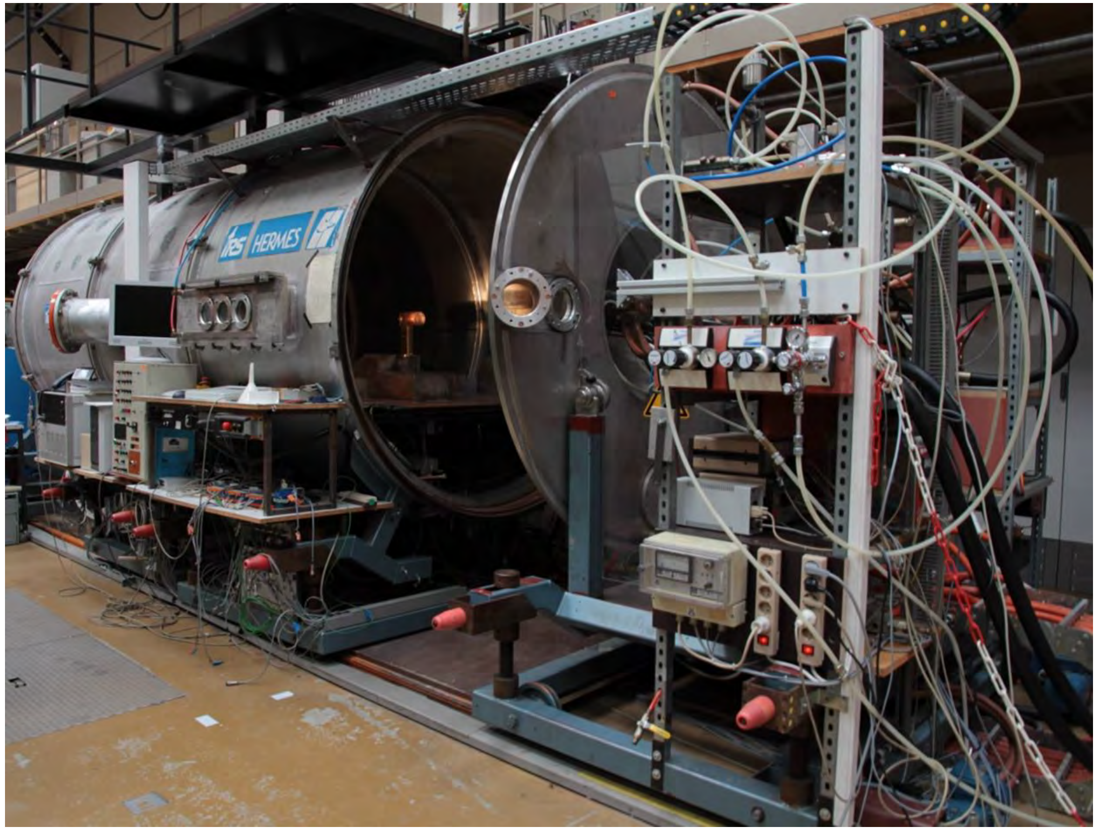
Byproduct measurements in wind tunnels simulating atmospheric re-entry

German Space Agency (DLR) wind tunnel

Satellite electronics box

[https://www.esa.int/ESA_Multimedia/Images/2021/04/Testing_reentry]

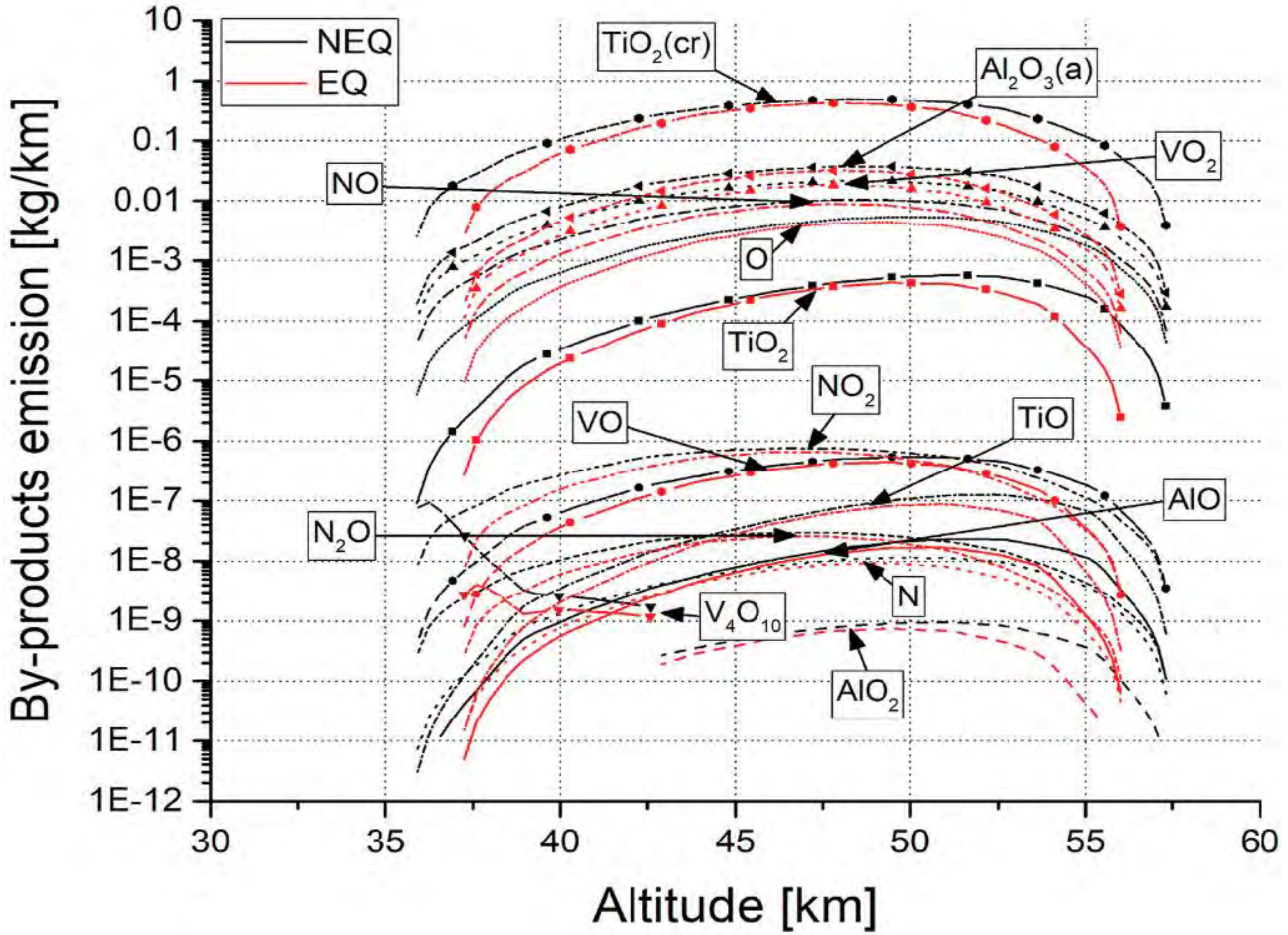
U. Stuttgart Institute of Space Systems wind tunnel



[https://www.esa.int/ESA_Multimedia/Images/2023/08/PWK1_Plasma_Wind_Tunnel_Facility_at_IRS]

Re-entry ablation modeling: Byproducts and re-entry characteristics

Example altitude-dependent emissions profiles from 3DOF model



Original object:

87.7-91% Ti

5.5-6.75% Al

2.5-4.5% V

0-0.3% Fe

0.2% O

0-0.08% C

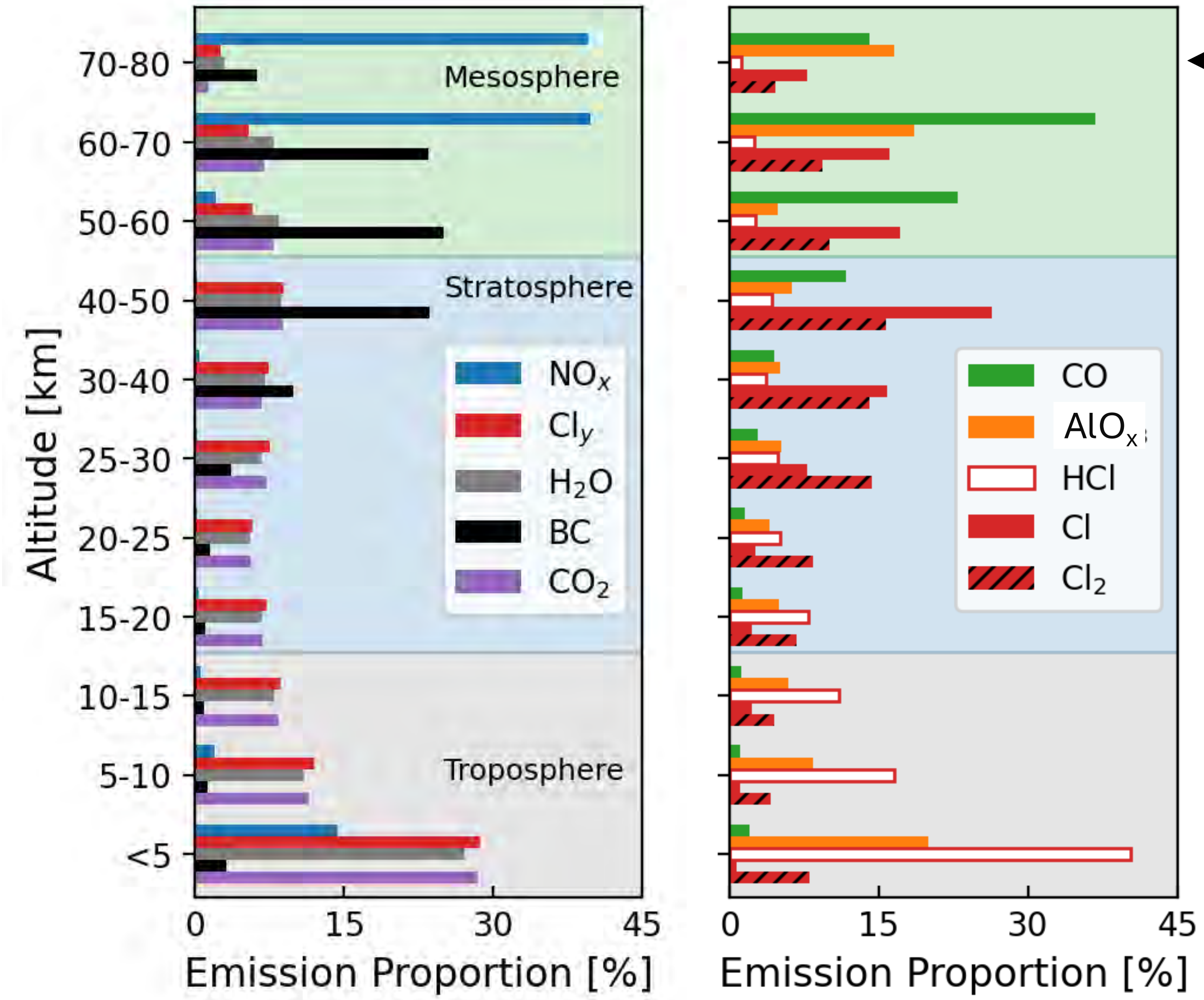
Common models:

SCARAB, ORSAT, DRAMA/SESAM, DEBRISK,

[Park et al., 2020]

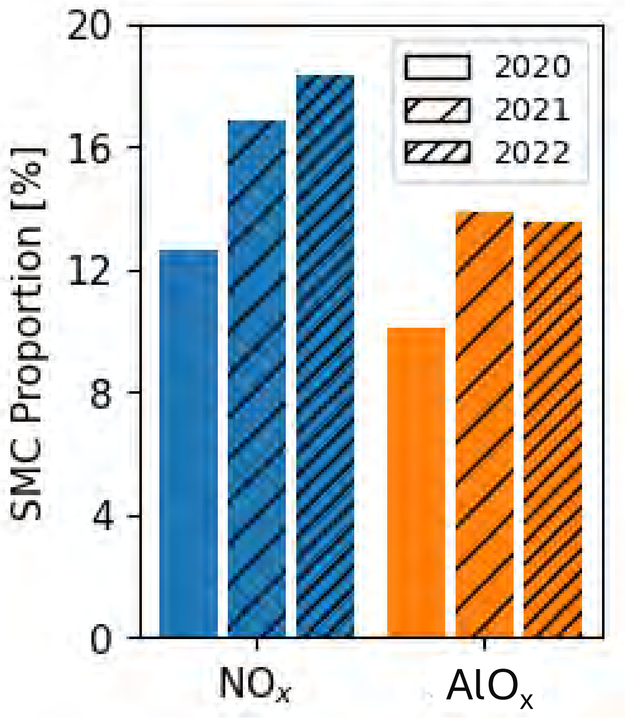
Precursor emissions inventory: 4D resolved for input to models

Relative distributions for 2022



Re-entry NO_x and AlO_x dominant in mesosphere.

Proportion from satellite megaconstellations



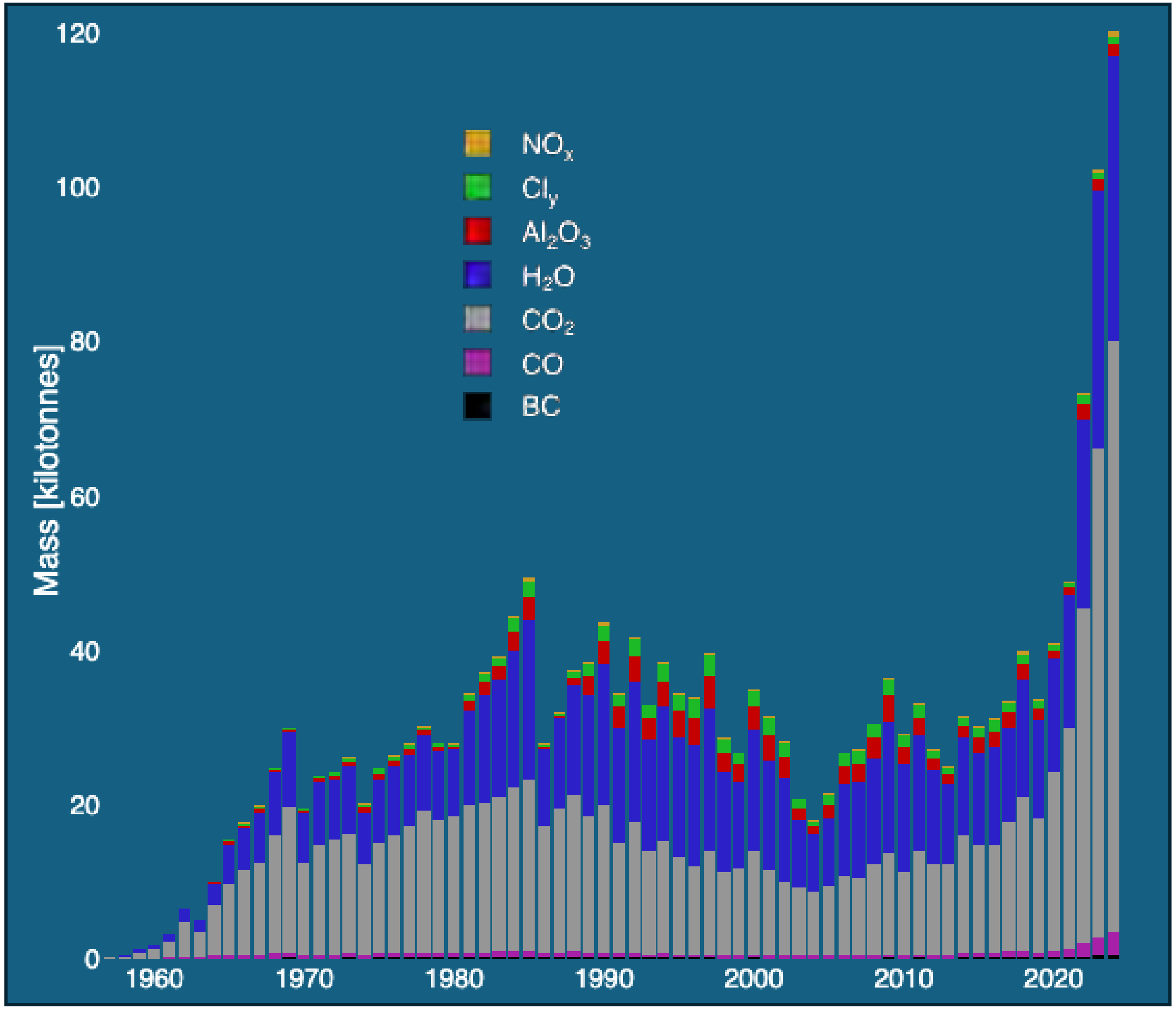
[Barker et al., 2024]

Online emissions tracker: Context for the scale of growth

Rocket launches:

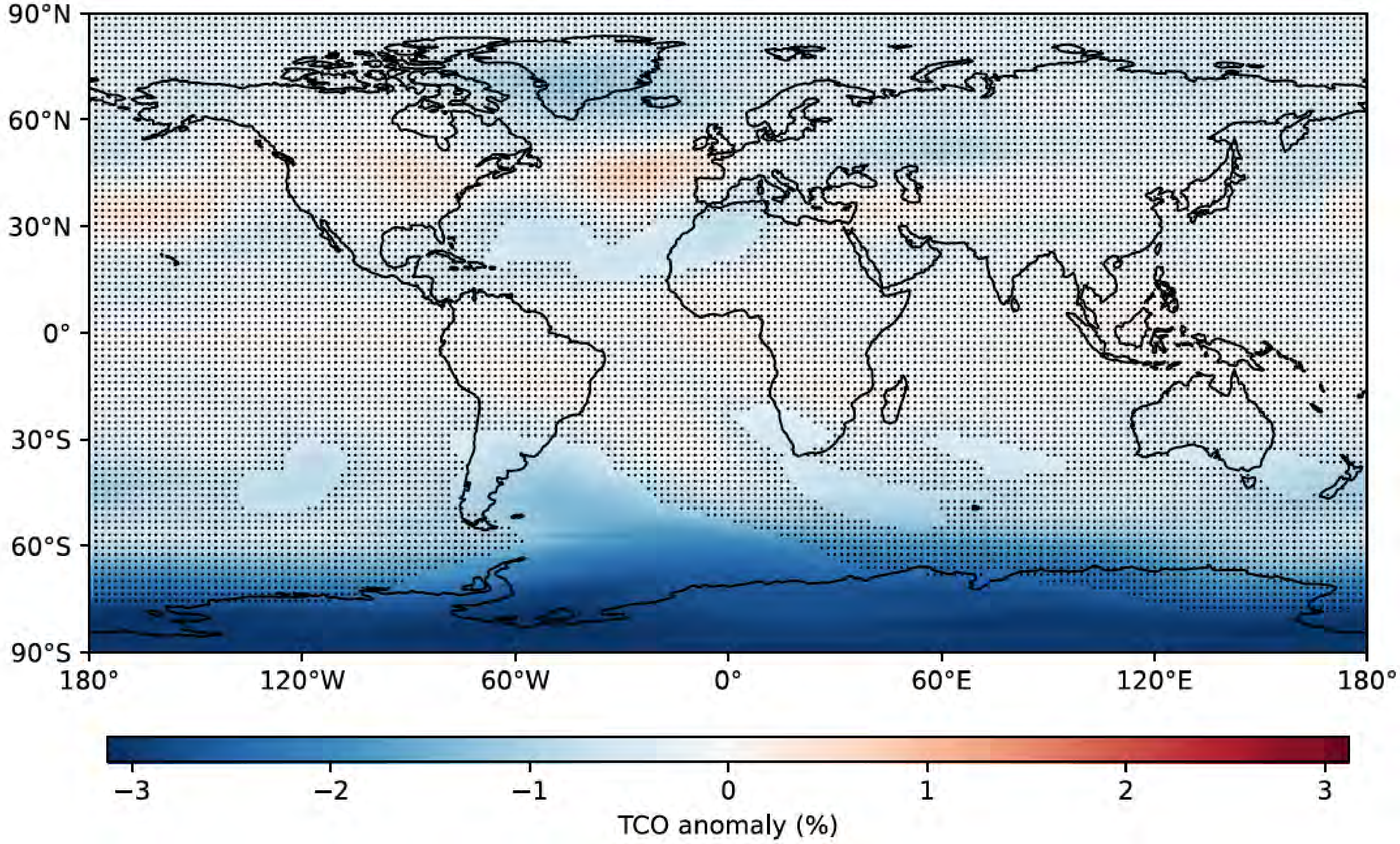
Object re-entries:

Rocket launch byproduct emissions since 1957



Global Modeling: Future launch scenario ozone layer depletion

Change in total column ozone (TCO) for very ambitious growth scenario (2040 launches per year)



Future rocket launch composition mimics 2019

Rocket launch emissions only

Used SOCOLv4 model (MPI ESM heritage)

Stippling: not significant at 95% confidence

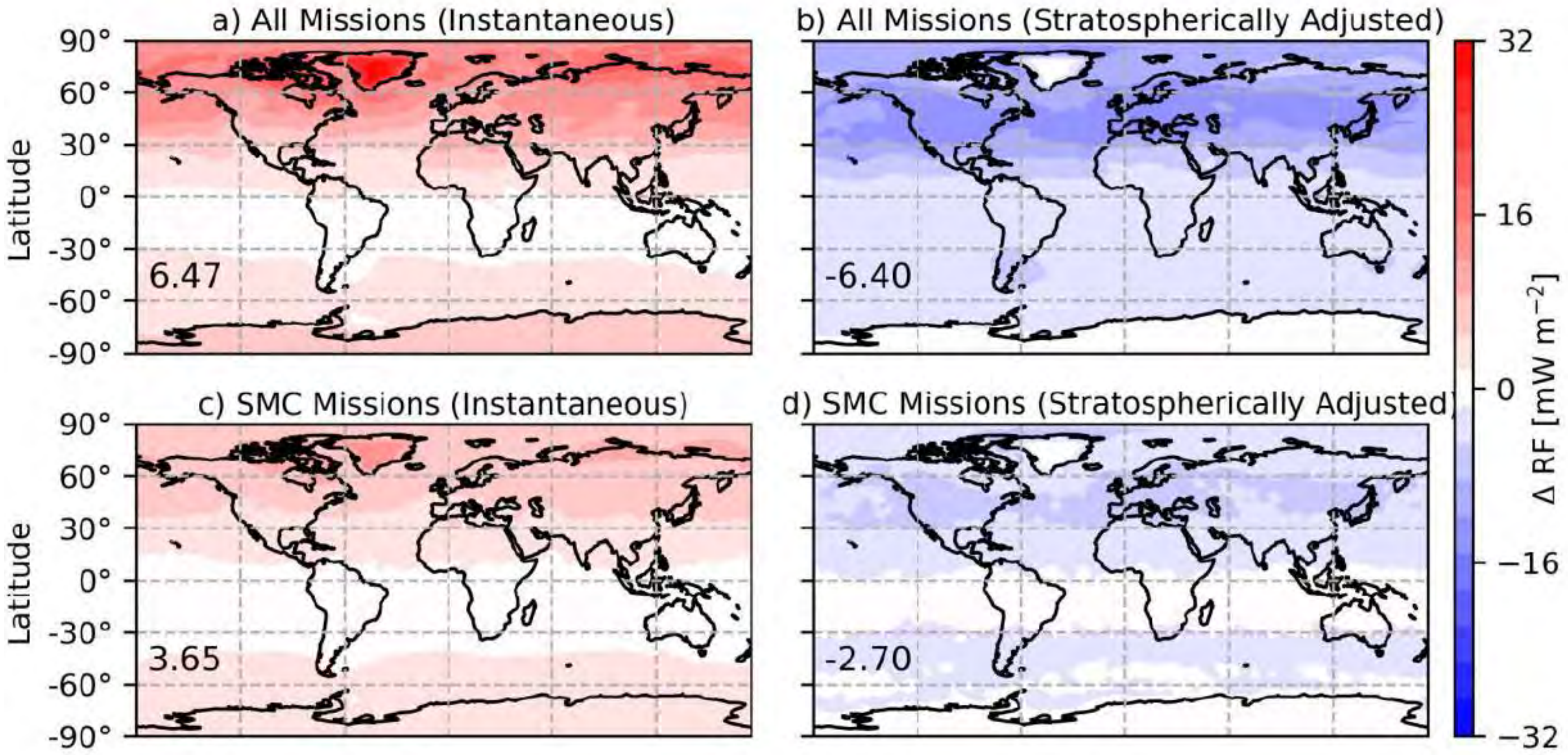
Large (3%) Antarctic ozone loss dominated by launch chlorine emissions from solid rocket motors

Exceeds ozone loss attributed to Montreal Protocol regulated CFCs (1%)

[Revell et al., 2025]

Global Modeling: Activity (megaconstellations) impact on climate

Radiative forcing attributed to all and megaconstellation launch and re-entry pollution



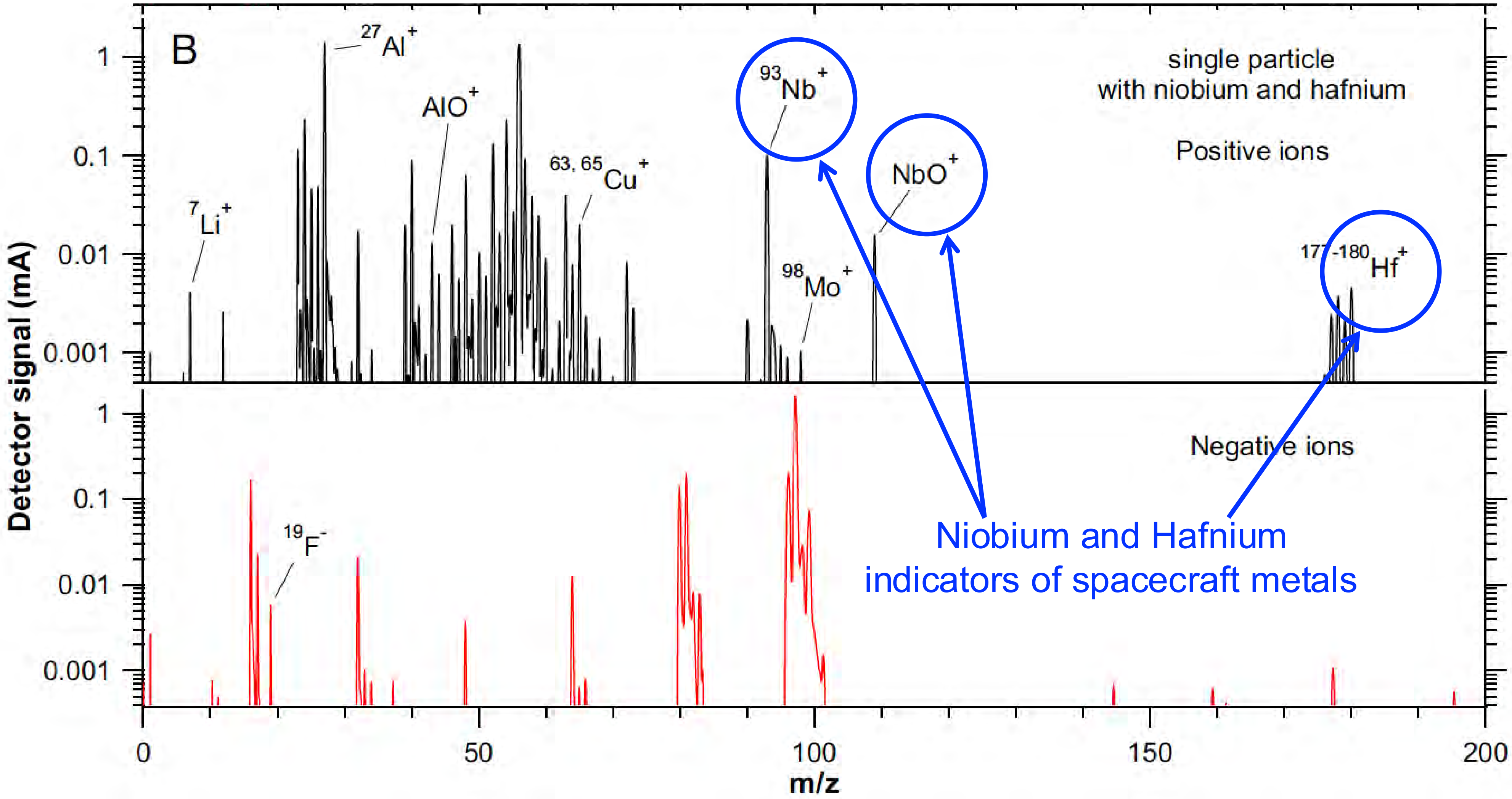
- Launch and re-entry pollution
- Climate effect mostly launch BC
- No feedback on temperature or meteorology

Megaconstellations are about half the climate effect by 2029 (a decade of business-as-usual growth in megaconstellation and non-megaconstellation missions)

[Barker et al., in review, 2026]

Intentional campaign measurements: Lower stratosphere aerosols

SABRE campaign aircraft measurements of aerosol composition as evidence of influence



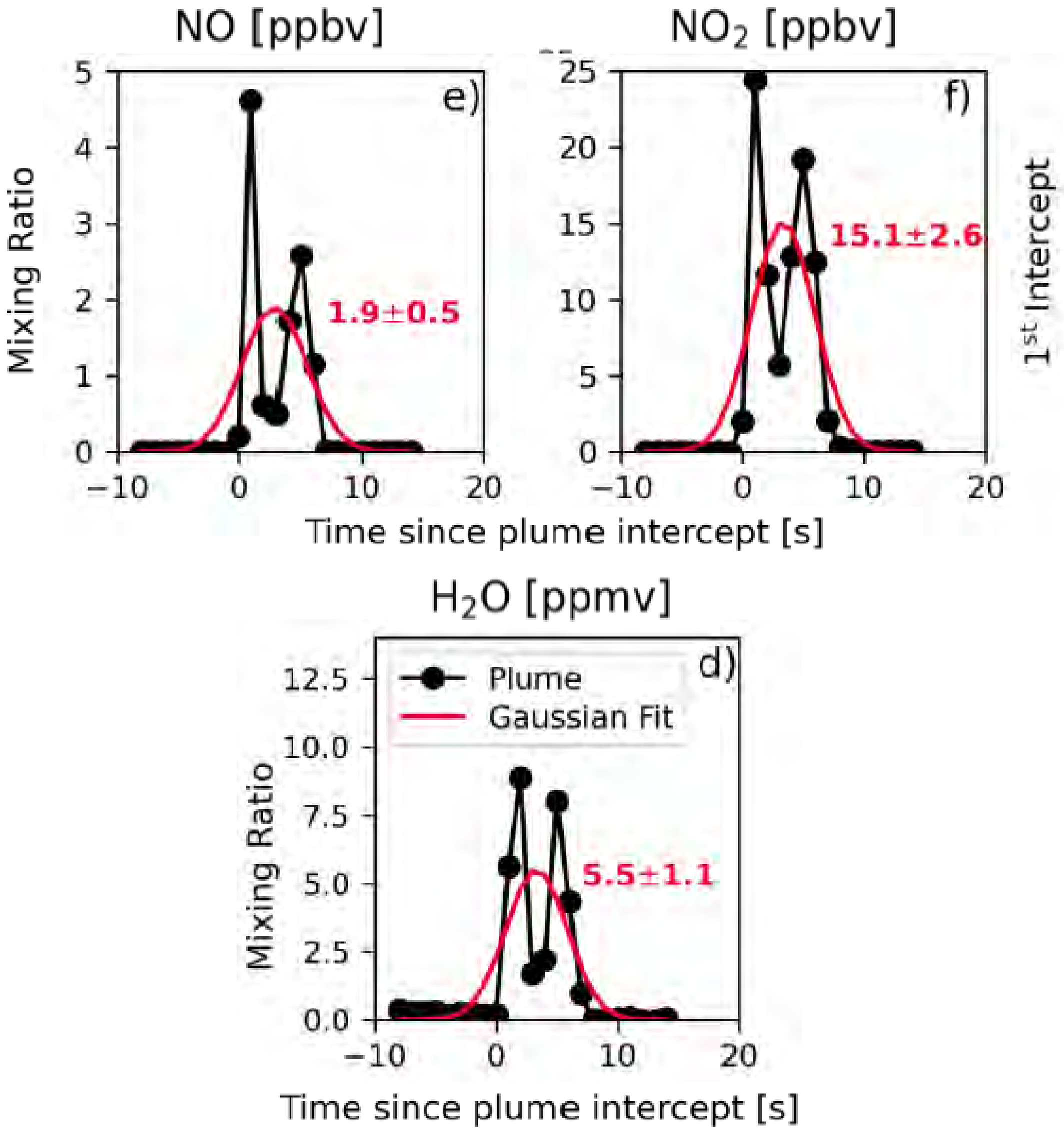
10% of stratospheric aerosols sampled contaminated with metals from spacecraft re-entry pollution

[Murphy et al., 2023]

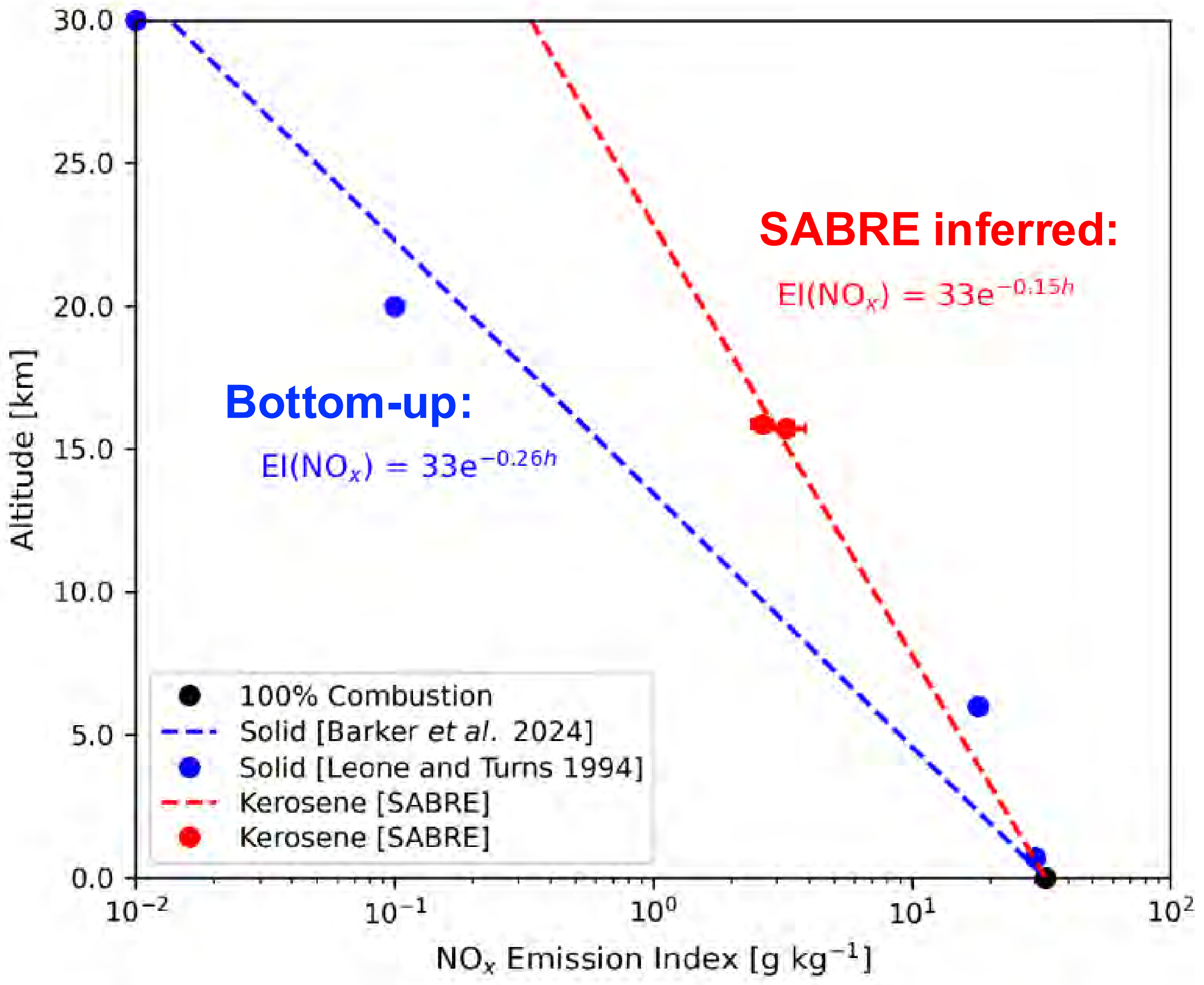
Intentional campaign measurements: Rocket plume at ~16 km

SABRE aircraft measurements as constraints on rocket launch nitrogen oxides (NO_x) emissions

Plume enhancements in NO_x and H_2O



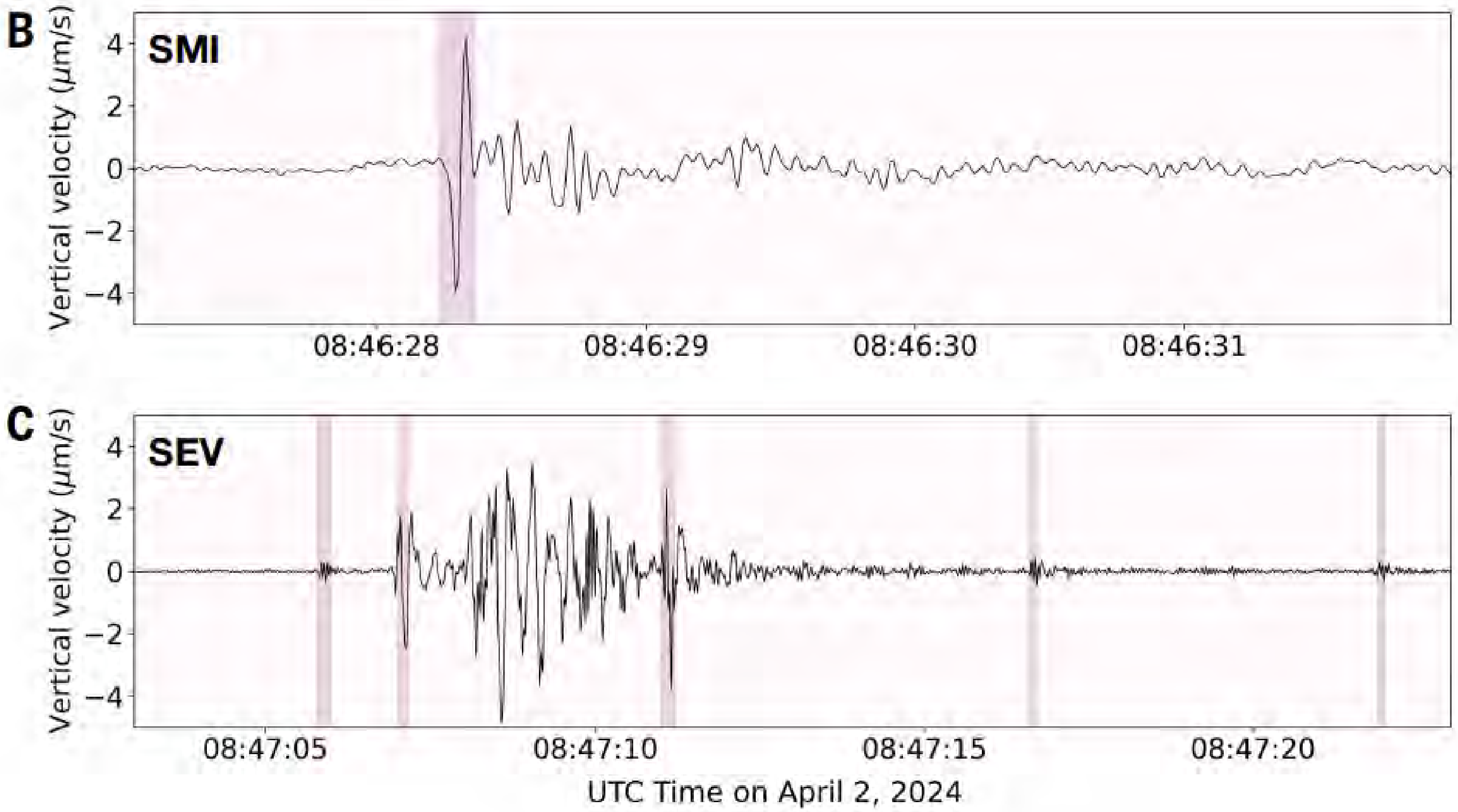
Altitude-dependence of NO_x emissions



[Barker et al., in review, 2026]

Opportunistic measurements: Seismometers detect re-entry boom

Example application of seismometer network to detect sonic boom of re-entries



SMI: off coast of California

SEV: inland (east of Bakersfield)

Applied to re-entry of Long March orbital module

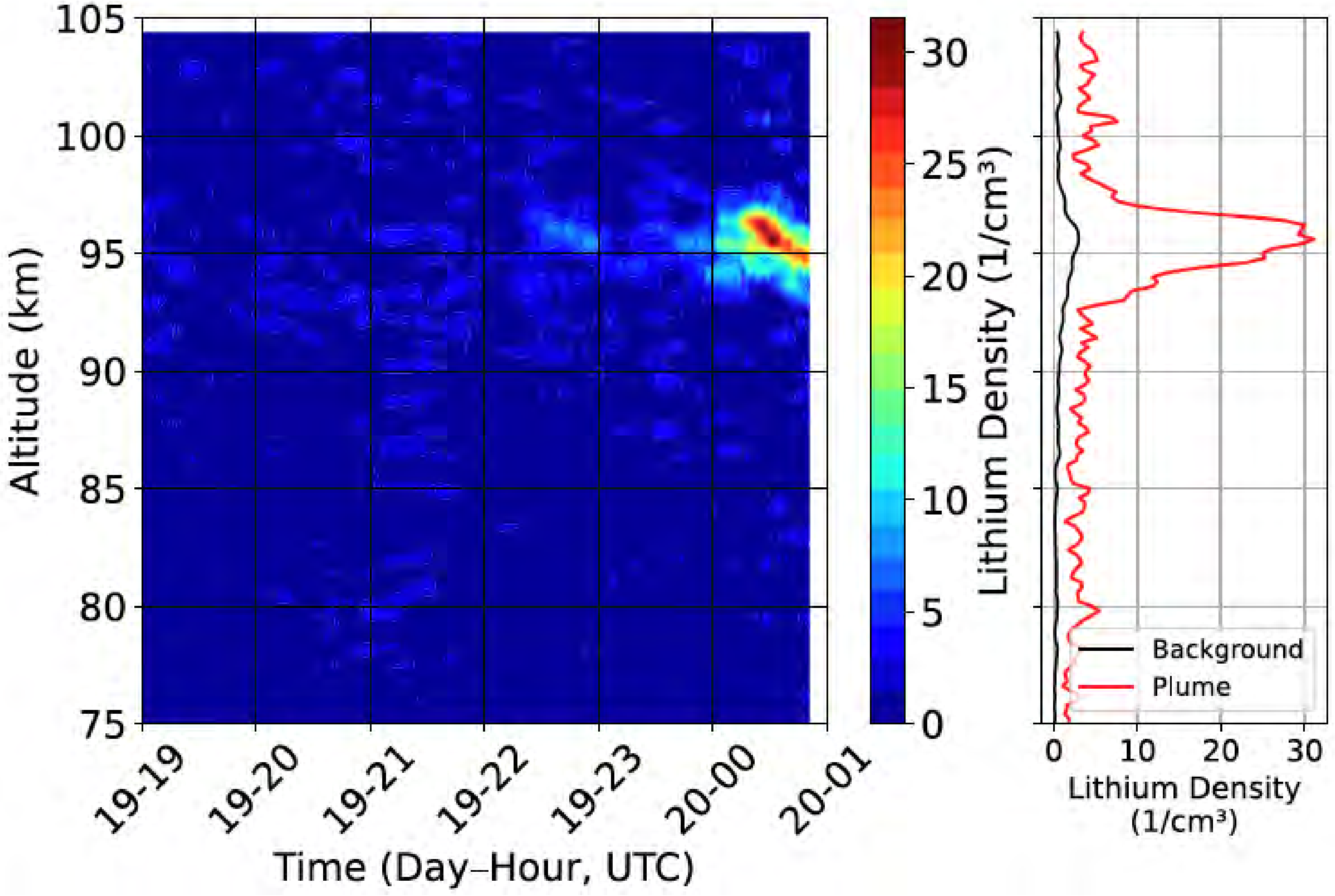
Scalable: cheap sensors, global network

Demonstrate use to determine debris trajectory, speed, altitude, descent angle, size, and fragmentation patterns (key for emissions inventory development)

[Fernando & Charalambous, 2026]

Opportunistic measurements: LiDAR observations of re-entry Lithium

Chance detection of re-entry emissions of Li using remote sensing (LiDAR) instrument



Coupled LiDAR with other observational and modelling data to confirm origin

Adds to observational evidence of influence on atmospheric composition

[Worth et al., 2026]

Measurement Activities on the Horizon or in Progress

- Stratospheric aerosol composition NASA's 1980-2020 Cosmic Dust Programme. Link to Quentin Taupin's work: https://meetingorganizer.copernicus.org/EPSC-DPS2025/EPSC-DPS2025-1899.html

- Space-based sensors:
  → Nadir-viewing TEMPO and GEMS UV-visible air quality sensors (in orbit)
  → Nadir-viewing plume-resolving broadband sensors (in orbit and scheduled)
  → Limb-viewing STRIVE mission (awarded)

- SABRE summer aircraft campaign

- DRACO: re-entry ambient experiment kitted with measurement sensors (2027)

- Sounding rockets

Destructive **R**eentry
Assessment **C**ontainer **O**bject

Challenges and Issues

- Heavy reliance on models to quantify scale of impact of space sector pollution
- Ambient measurements not at scales or frequency needed for model validation
- Heavy reliance on inventive use of existing instruments deployed for other purposes
- Remote sensing only viable way to observe middle and upper atmosphere
- Emission inventory development relies on “good faith” maintenance of datasets and databases tracking activities like re-entries
- Regulation not in place to drive monitoring programmes and resource development
- Are future scenarios tested so far plausible? Is there risk of undermining integrity of findings?
- Challenges forecasting the future when landscape changing fast (industry ambitions, changes in relative proportion of propellant burned over time).
- Is science sufficiently mature to determine tipping points?