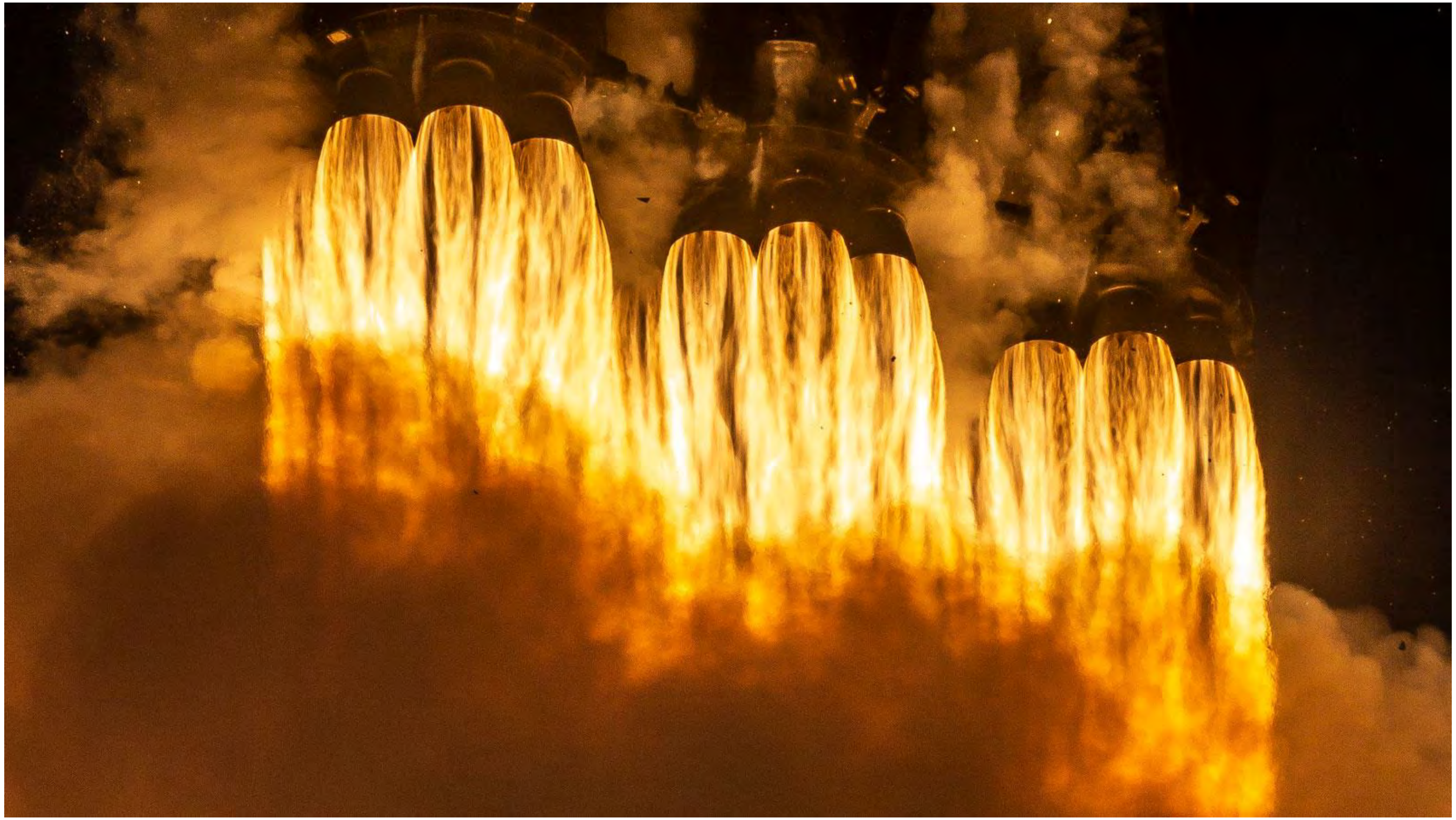
Atmospheric Impacts of Spacecraft Launches and Re-entries

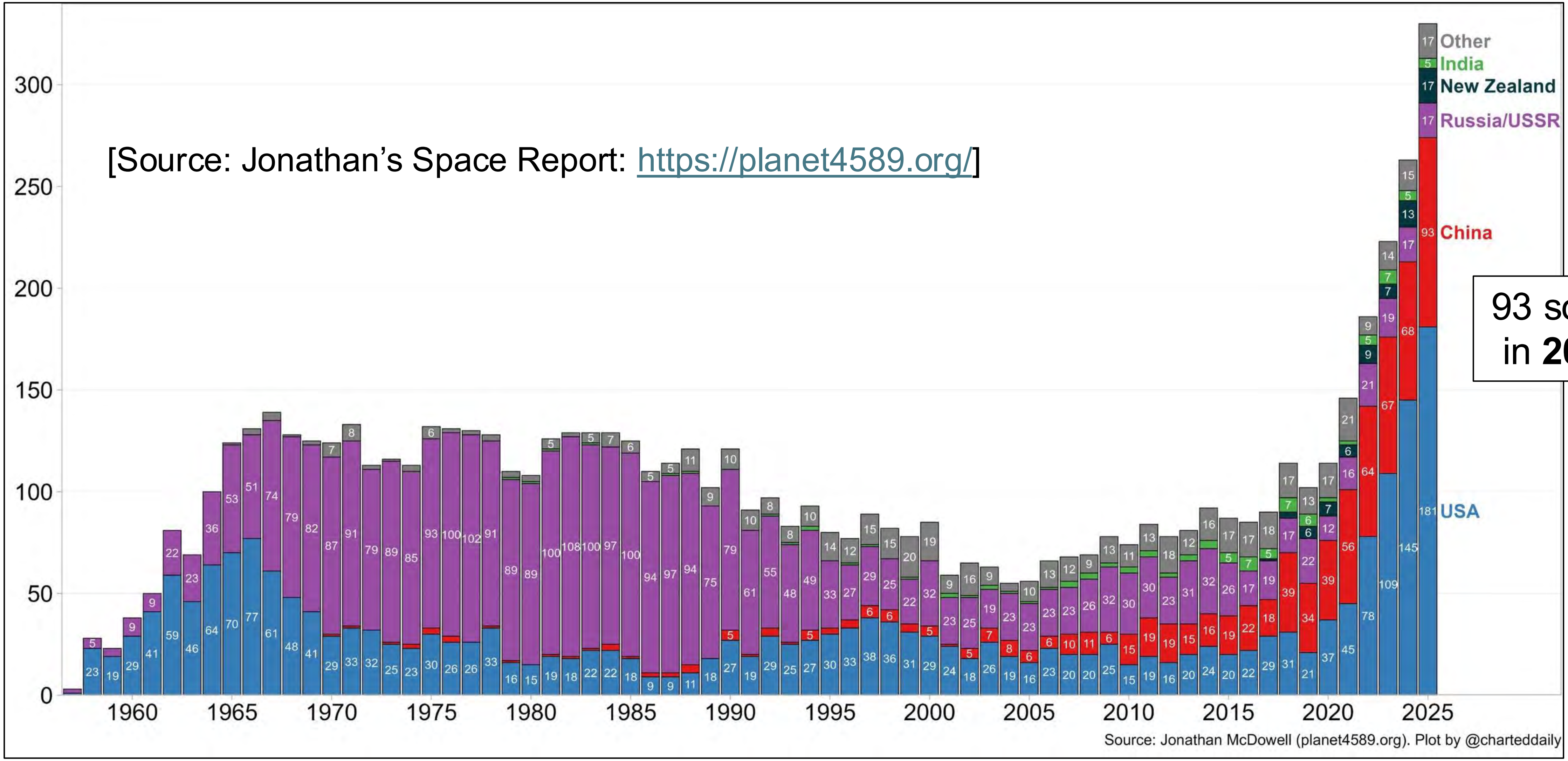


E-SWAN webinar, 23 April 2026

Eloise Marais, e.marais@ucl.ac.uk, https://maraisresearchgroup.co.uk/

Surge in Launches and Re-entries

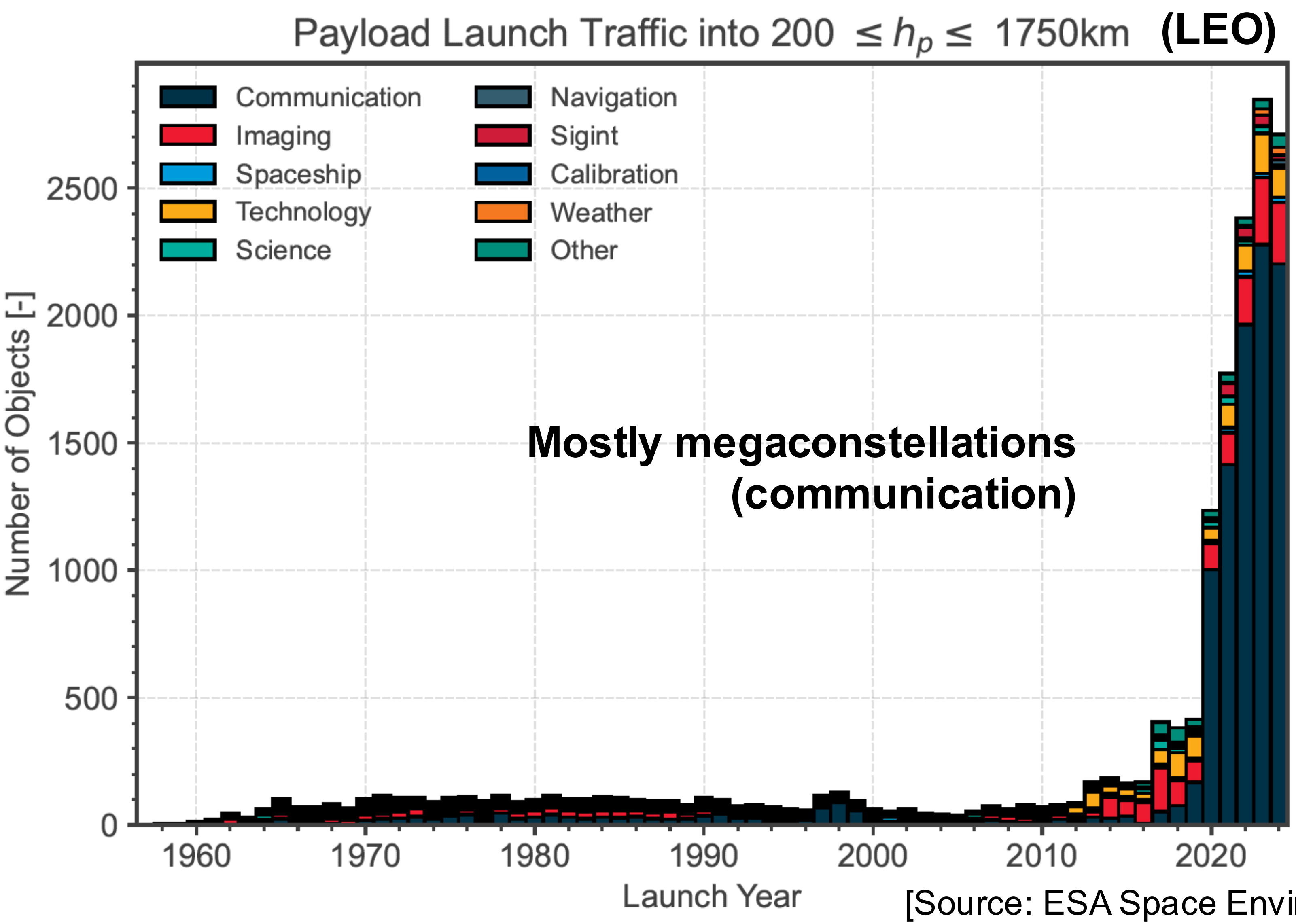
Orbital launches by year and country for 1957-2025



93 so far in **2026**

2020s increase driven by megaconstellation missions. Mostly Falcon9 rockets with reusable first stage.

Surge in payloads launched to space



[Source: ESA Space Environment Report for 2025]

What goes up, must come down (declutter orbits, ablation only viable disposal method)

Major Air Pollutants Released During Launch

Mix of pollutants depends on propellant type

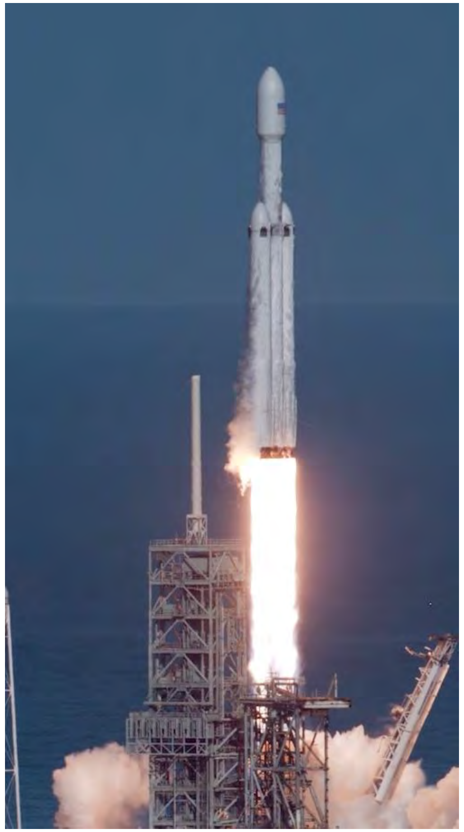
Solid

NO_x
$HCl+Cl+Cl_2$
Al_2O_3
H_2O
BC

Hypergolic

NO_x
H_2O
BC

Kerosene or Methane



NO_x
H_2O
BC

Cryogenic

NO_x
H_2O

BC: Black Carbon
Al_2O_3: Alumina

Atmospheric Impacts of Pollutants

Mix of pollutants depends on propellant type

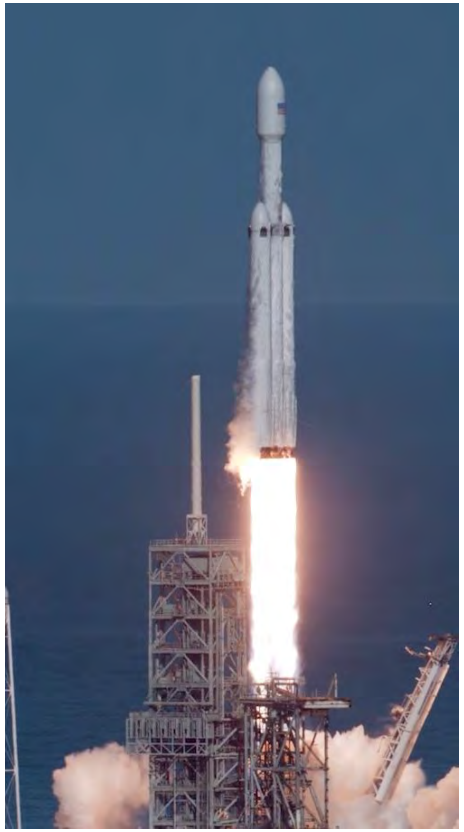
Solid

NO_x
$HCl+Cl+Cl_2$
Al_2O_3
H_2O
BC

Hypergolic

NO_x
H_2O
BC

Kerosene or Methane



NO_x
H_2O
BC

Cryogenic

NO_x
H_2O

Climate concern

Atmospheric Impacts of Pollutants

Mix of pollutants depends on propellant type

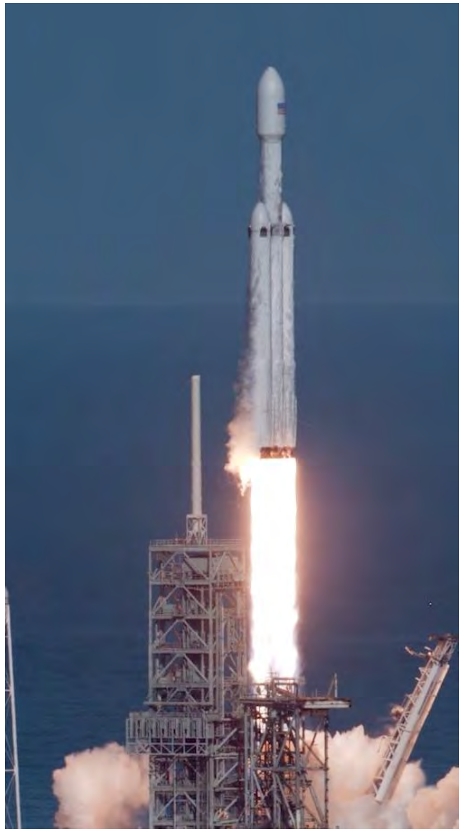
Solid

NO_x
$HCl+Cl+Cl_2$
Al_2O_3
H_2O
BC

Hypergolic

NO_x
H_2O
BC

Kerosene or Methane



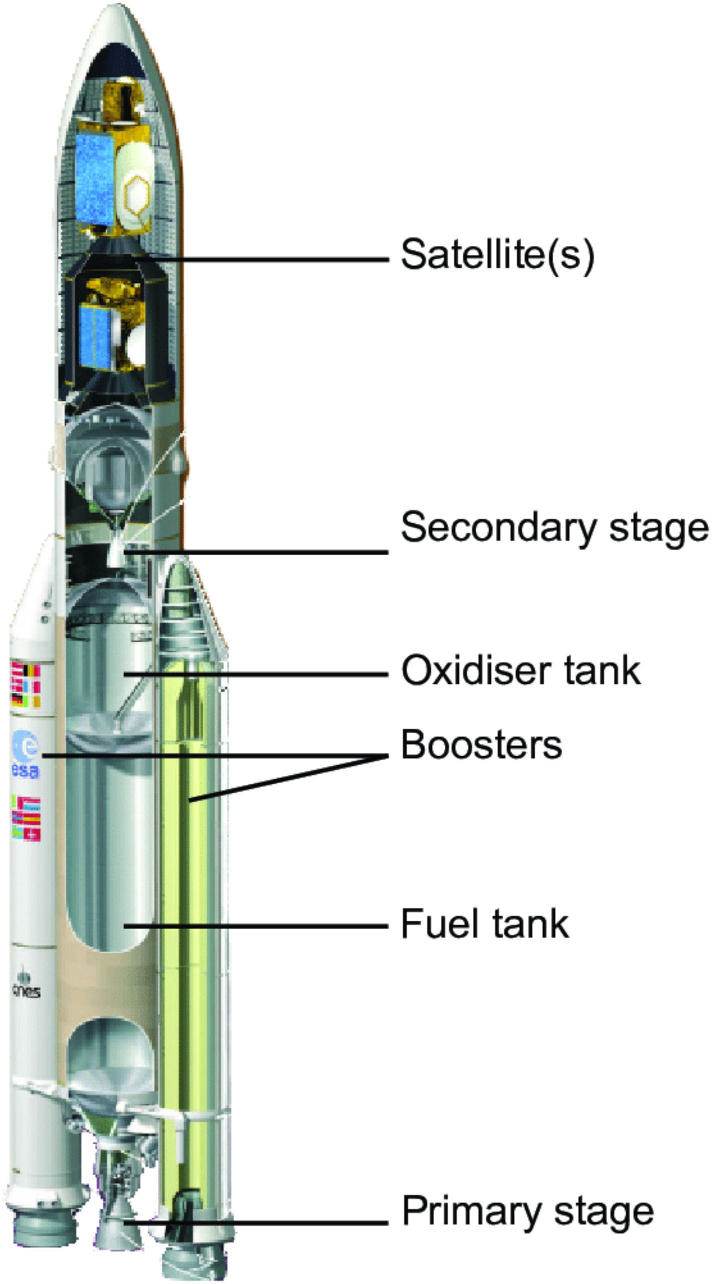
NO_x
H_2O
BC

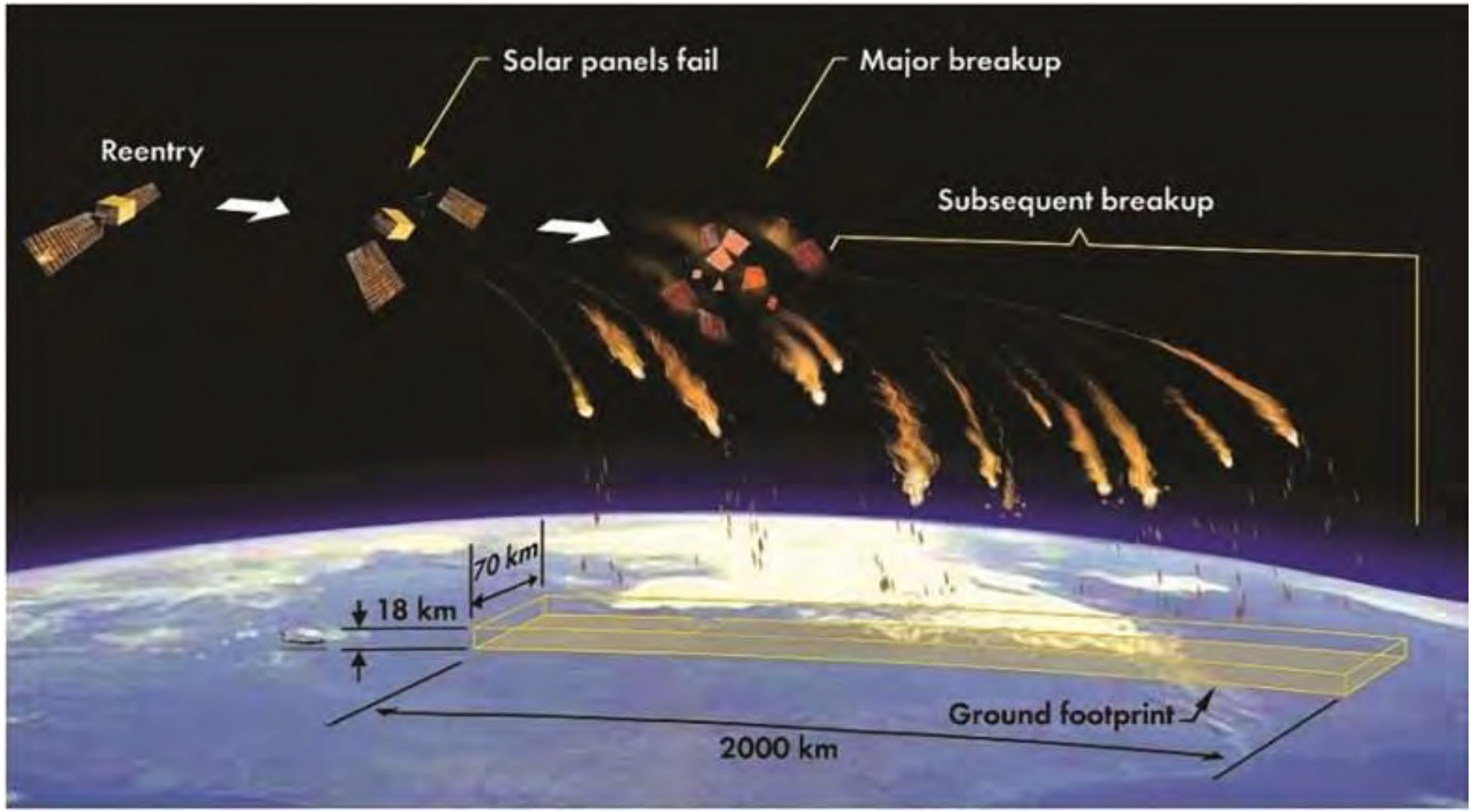
Cryogenic

NO_x
H_2O

Ozone depletion (direct reaction)

Air Pollutants Released from Object Re-entries

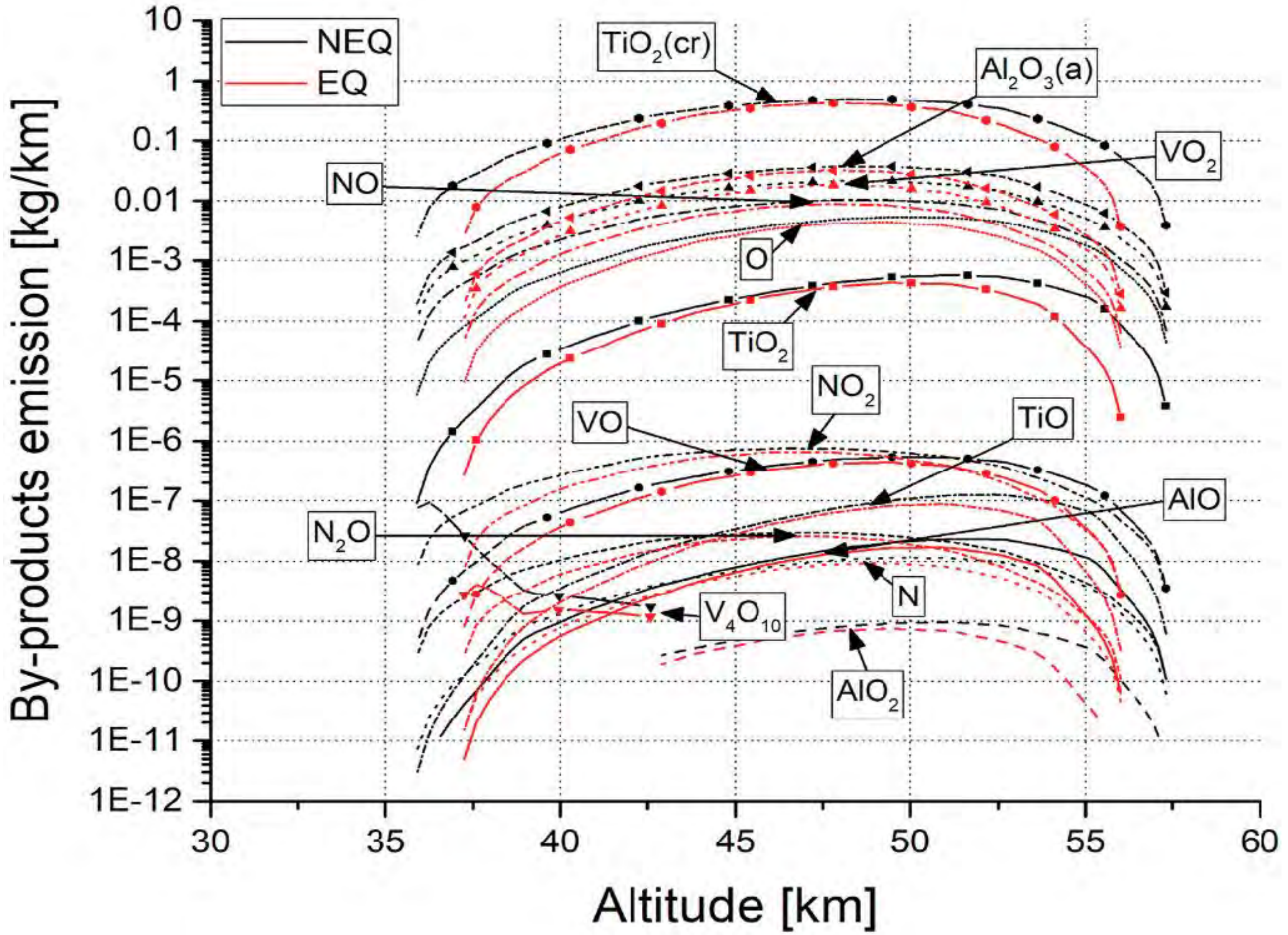




- Many spacecraft components
- Ideally demise completely to reduce risk to life on Earth
- Ablation emits nitrogen oxides (NO_x) from thermal energy
- Ablation emits metals oxides (mostly Al), BC, ammonia (NH_3) and more

Complex Mix of Pollutants: Depends on Object

Example altitude-dependent emissions profiles from a re-entry ablation 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

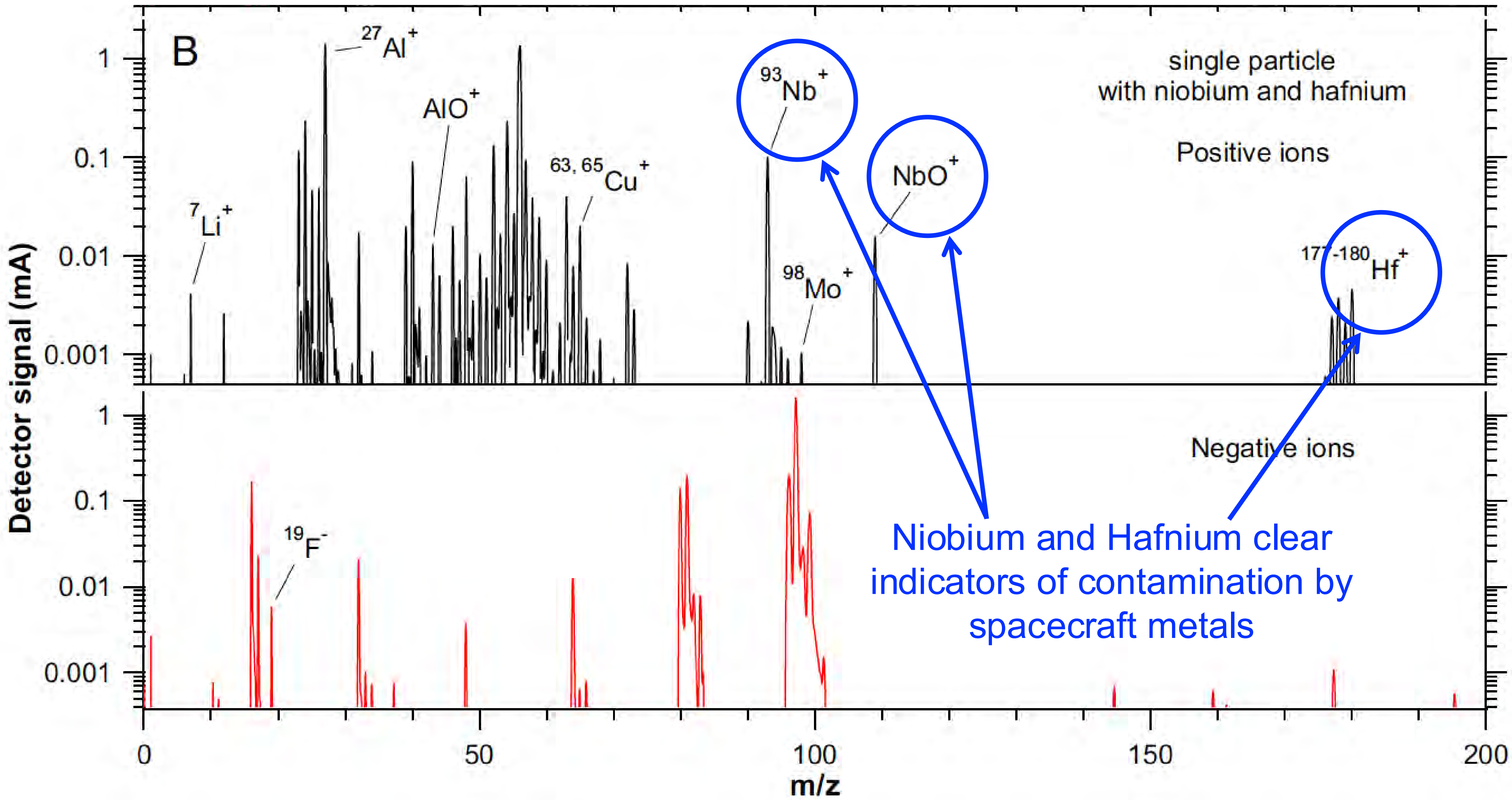
NEQ: near equilibrium

EQ: equilibrium

[Park et al., 2020]

Observational Evidence of Pollution from Re-entries

Example mass spectrum from instrument that measures composition of individual particles

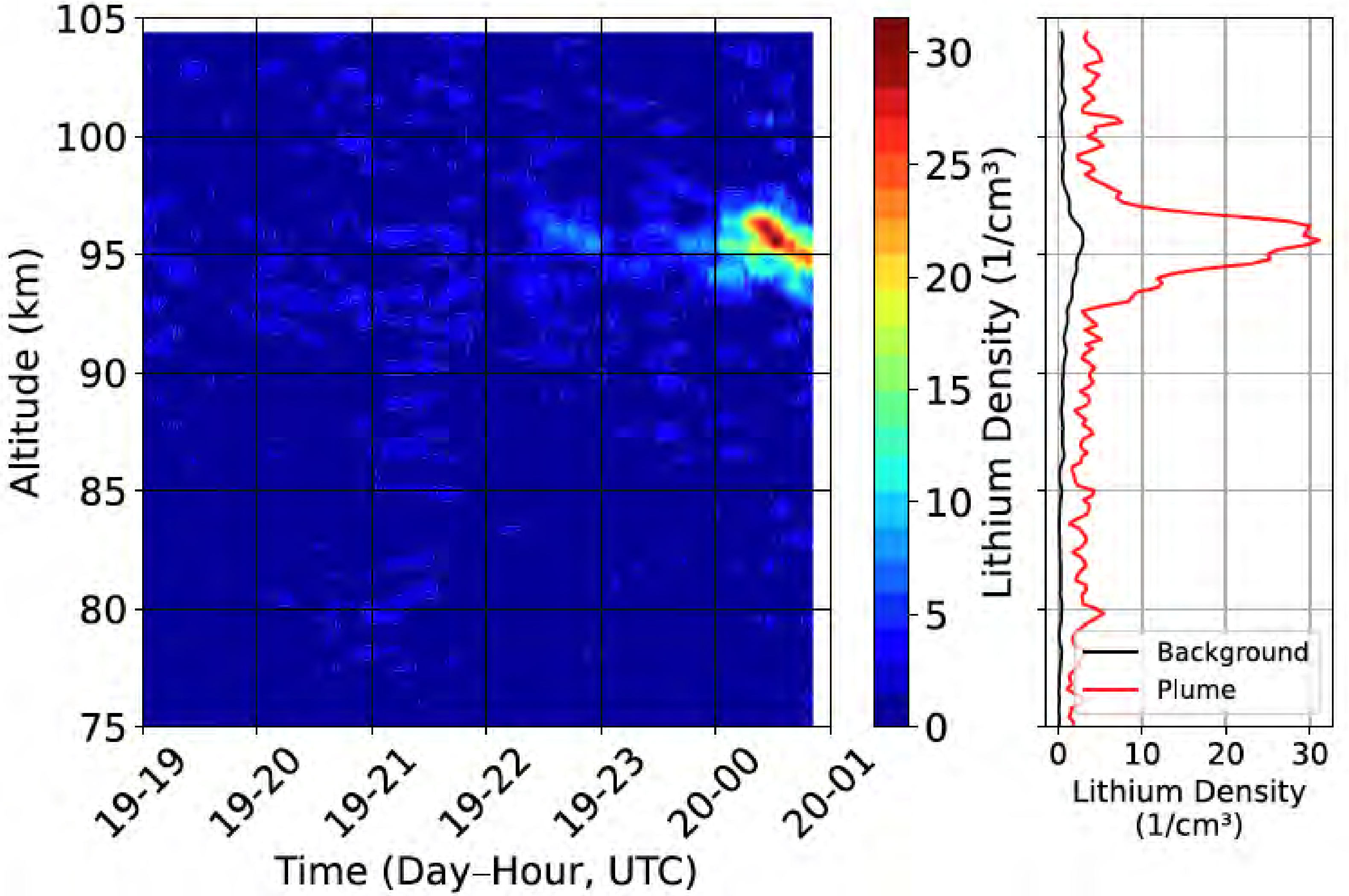


[Murphy et al., 2023]

Used these measurements to infer that 10% of stratospheric aerosol particles contaminated with metals from spacecraft re-entry in 2023

Observational Evidence of Pollution from Re-entries

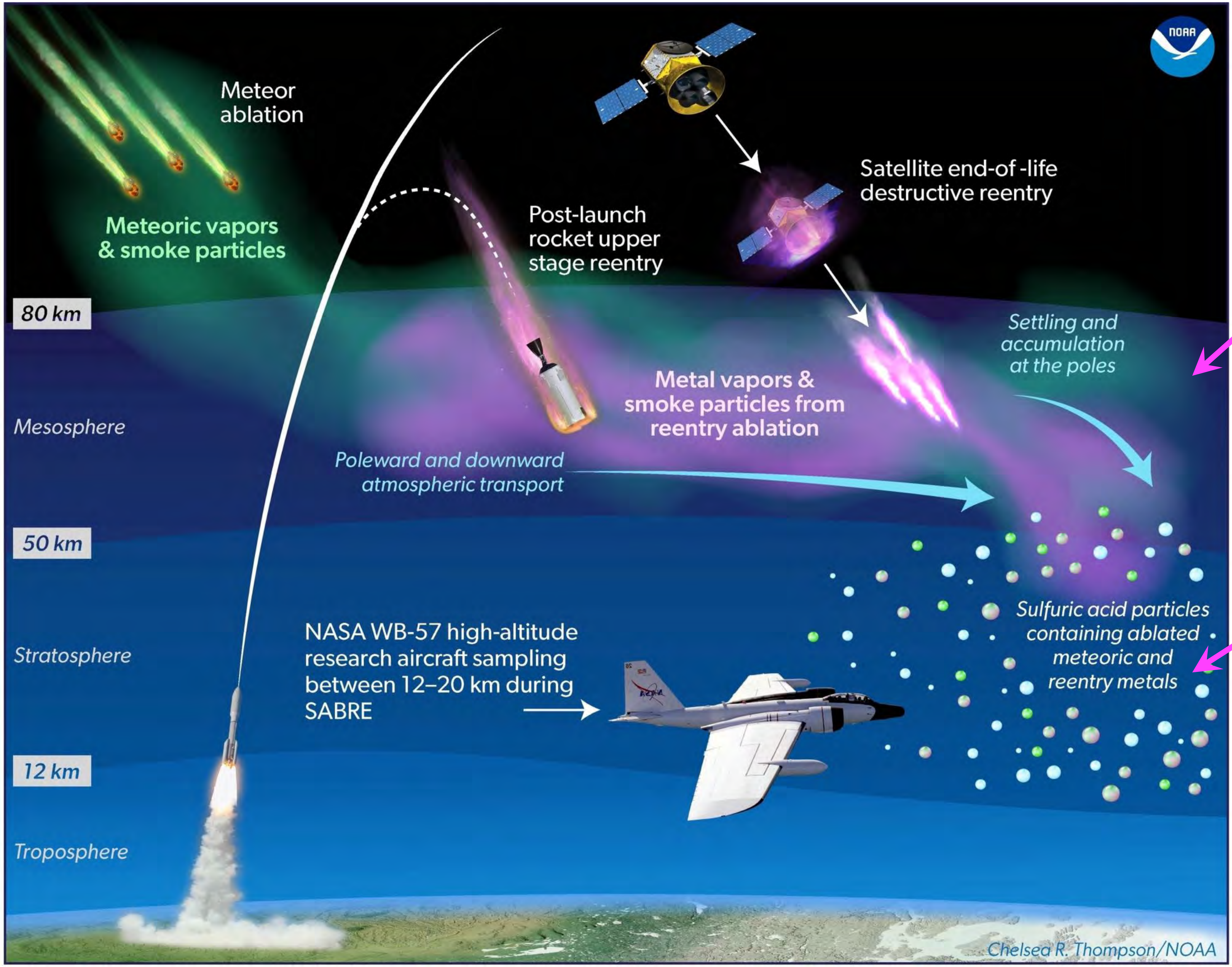
Chance detection of re-entry emissions of Li using remote sensing (LiDAR) instrument



Coupled LiDAR with other observational and modelling data to confirm origin

Adds to observational evidence of influence on atmospheric composition

[Worth et al., 2026]



Ablation layer (50-80 km)

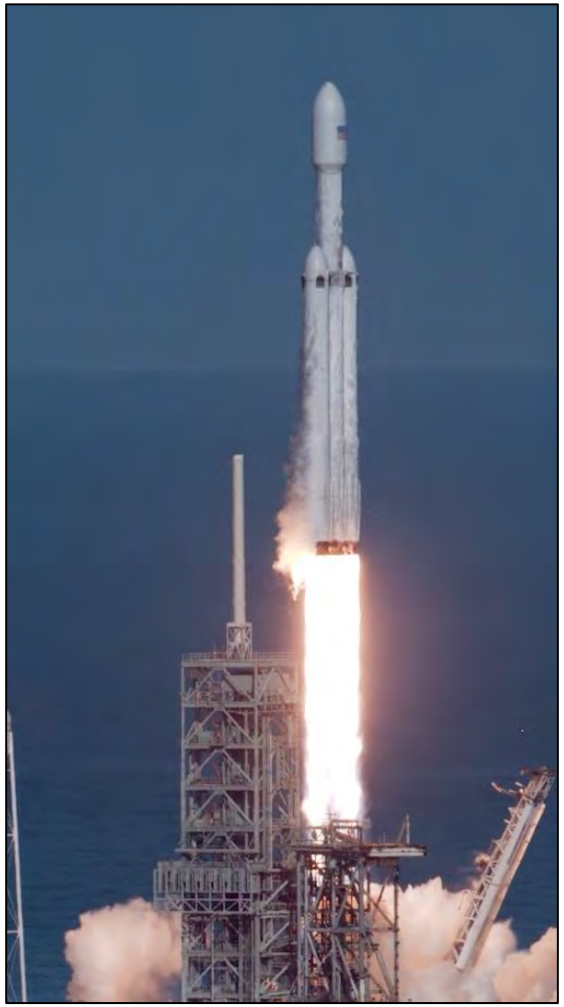
Ozone layer (12-50 km)

10% of particles in stratosphere contaminated with space junk

[Murphy et al., 2023]

Combined Impacts of Re-entry Ablation and Launch Pollution

Kerosene (SpaceX)



Pollutants injected into all atmospheric layers by rockets:

Nitrogen oxides

Water vapour

Black carbon (BC)

- Potent climate forcer
- Warms the atmosphere
- Warming speeds up ozone loss reactions
- Warming alters atmospheric circulation patterns

UCL Study: Megaconstellation Mission Atmospheric Impacts

Build an **inventory** of launch and re-entry air pollutant emissions for 2020-2022

Categorize emissions associated with megaconstellation missions (mostly Falcon 9 kerosene-fuelled rockets)

Predict emissions to 2029 for a full decade of emissions

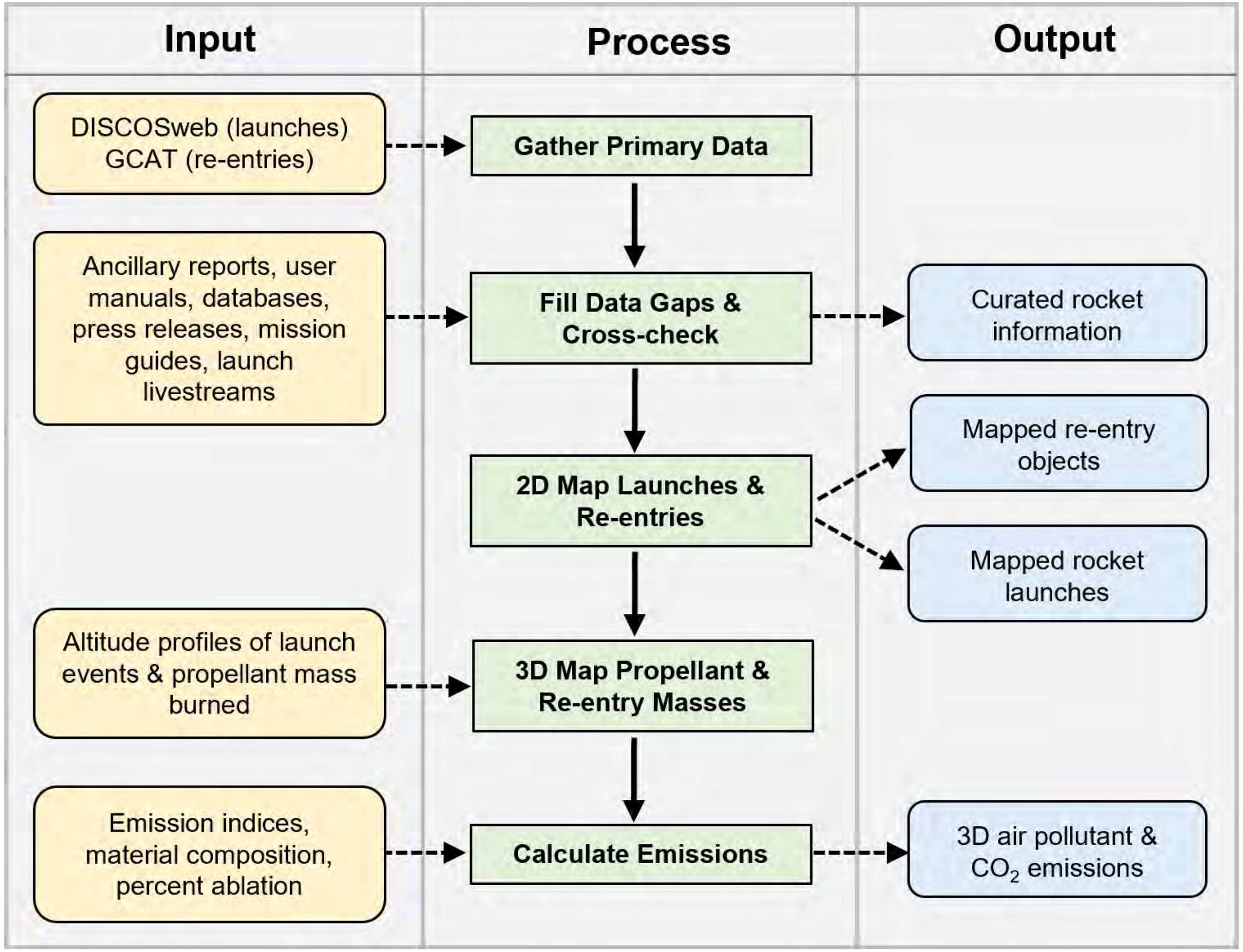
Assess emissions against high-altitude aircraft observations

Implement emissions in chemical transport **model** coupled to radiative transfer model

Quantify **atmospheric impacts** (ozone depletion, radiative forcing) due to all launches and re-entries compared to just those associated with megaconstellation missions

Emissions Inventory Processing Pipeline

Initial inventory developed for **2020-2022** legitimized by peer review



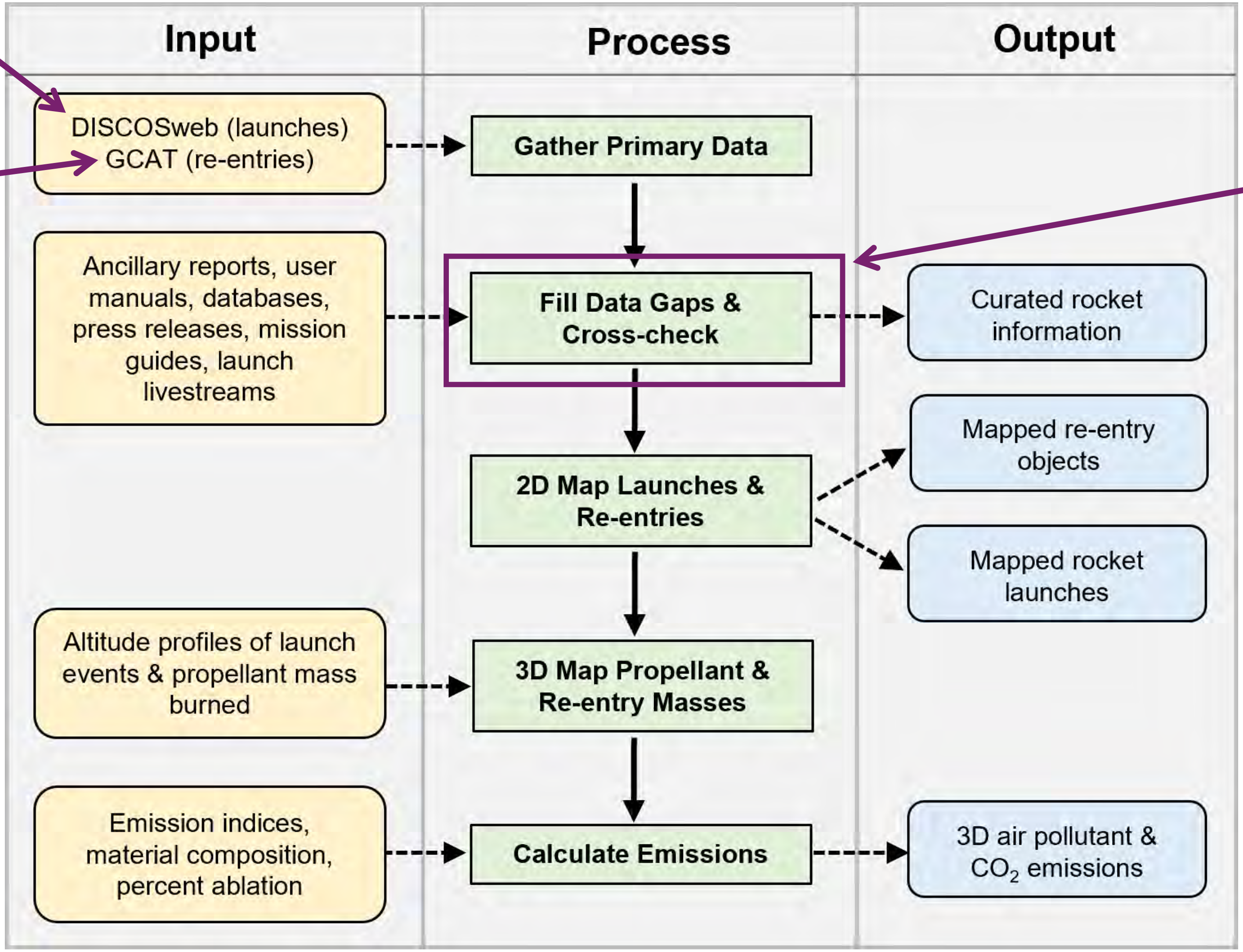
[Barker et al., https://www.nature.com/articles/s41597-024-03910-z, 2024]

Emissions Inventory Processing Pipeline

Initial inventory developed for **2020-2022** legitimized by peer review

ESA database

Catalogue maintained by Jonathan McDowell



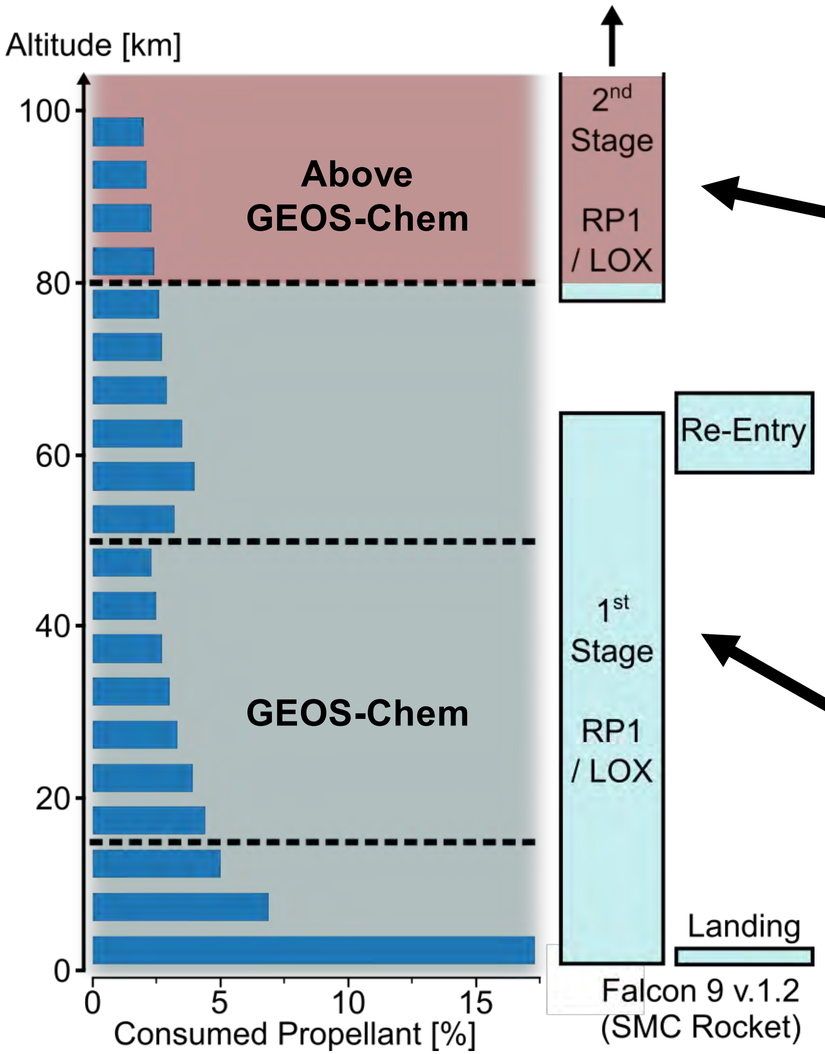
Critical step:

- Data gaps
- Incorrect data
- Inconsistent data

[Barker et al., https://www.nature.com/articles/s41597-024-03910-z, 2024]

Vertical Distribution of Launch Emissions

Example vertical mapping of Falcon 9 kerosene (RP1) rocket

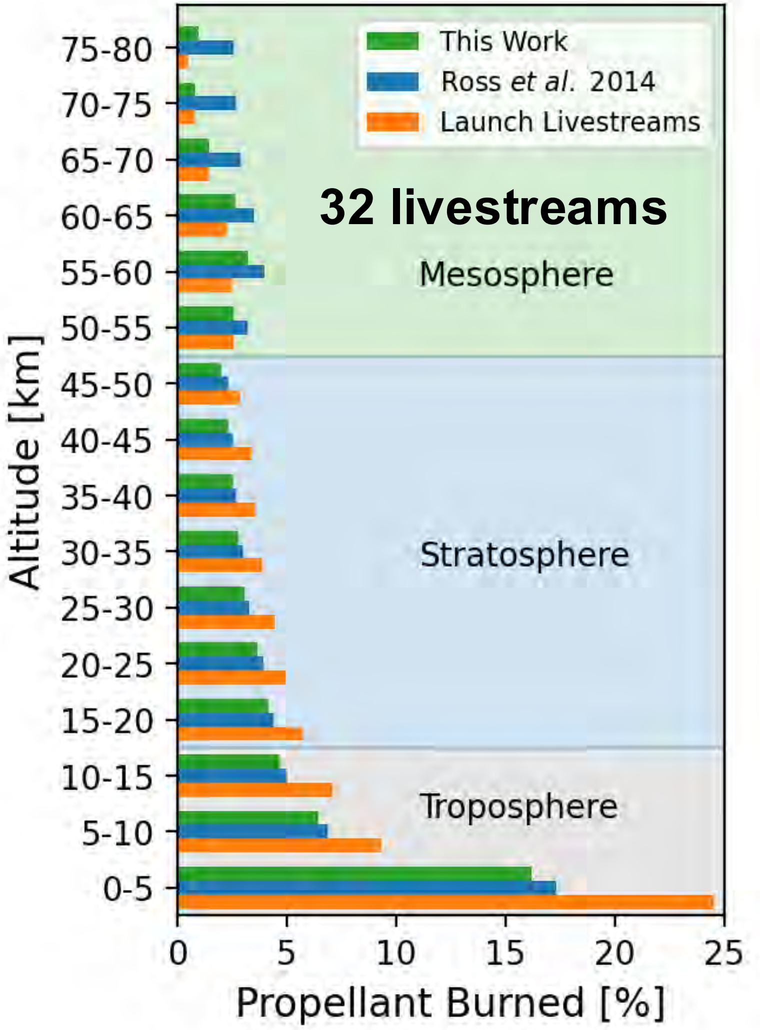


GEOS-Chem: chemical transport model

Includes altitude-dependent emission factors

Mapped using engine cut-off/ignition altitudes

Assessment against other constraints

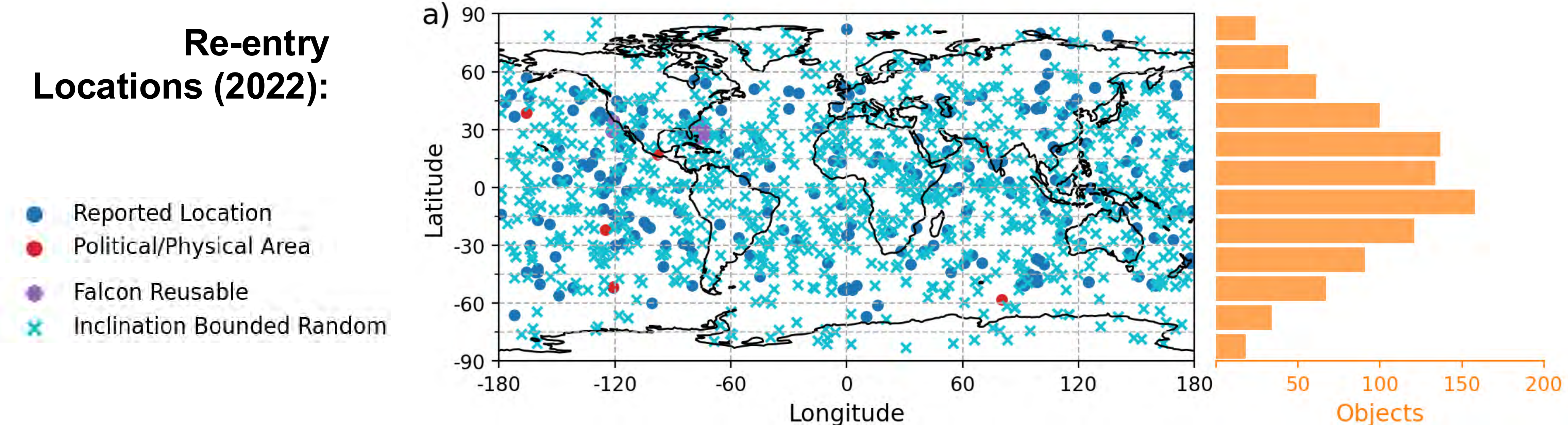


[Barker et al., 2024]

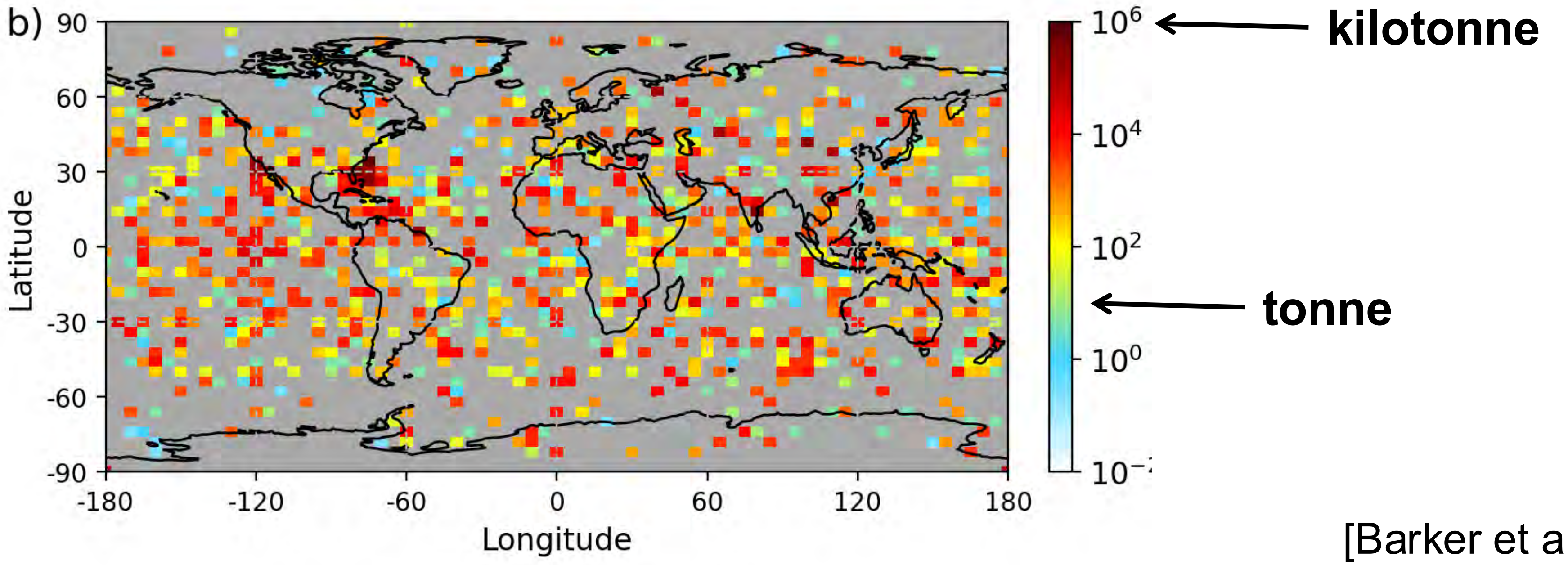
Annual propellant consumption increased from 36 kilotonnes in 2020 to 63 kilotonnes in 2022

Location and Mass of Reusable and Discarded Re-entries

Re-entry Locations (2022):

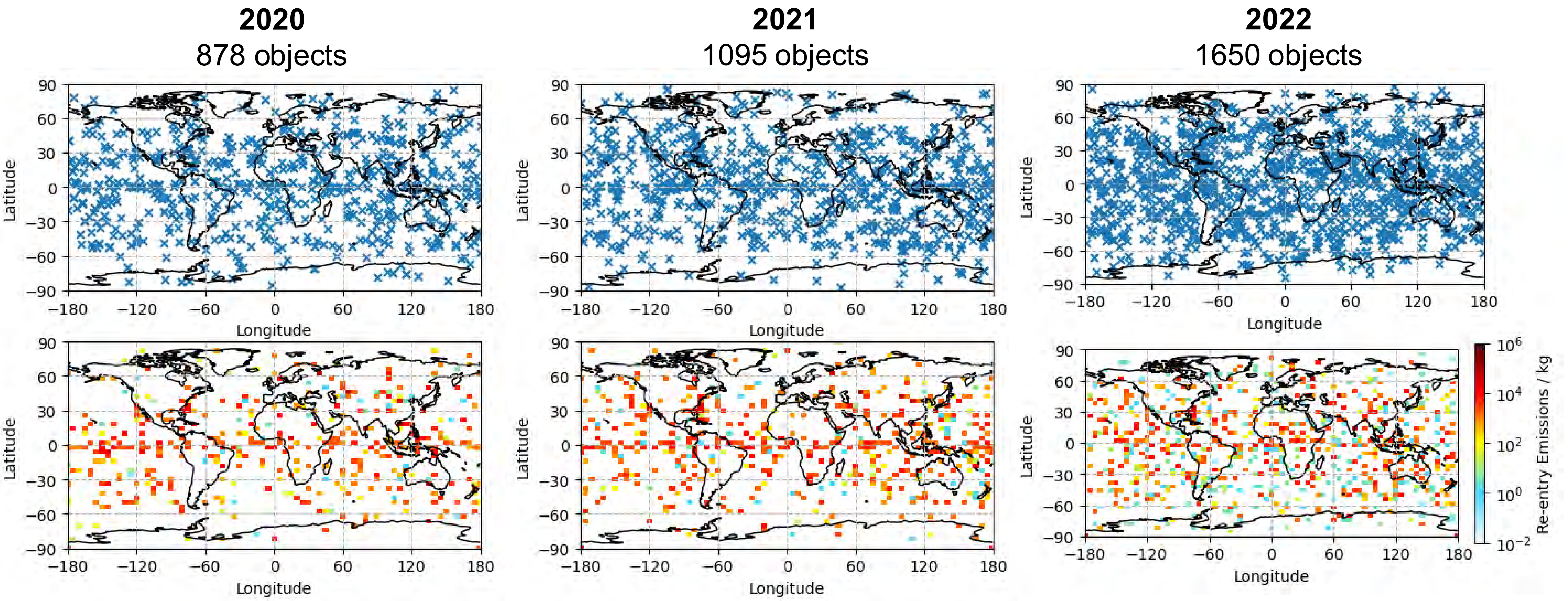


Re-entry Mass (2022):



[Barker et al., 2024]

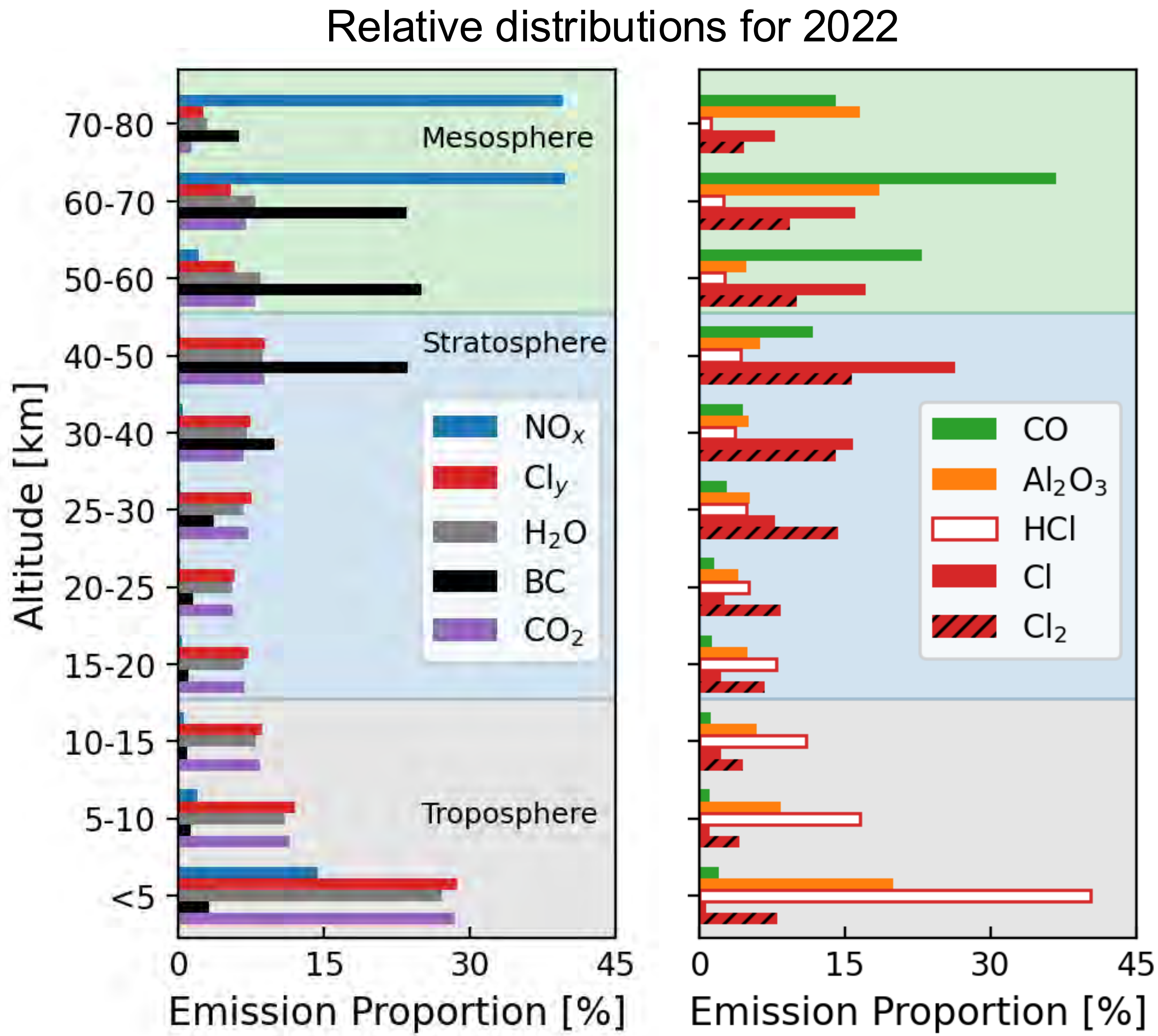
Annual Increase in the Number of Re-entering Objects



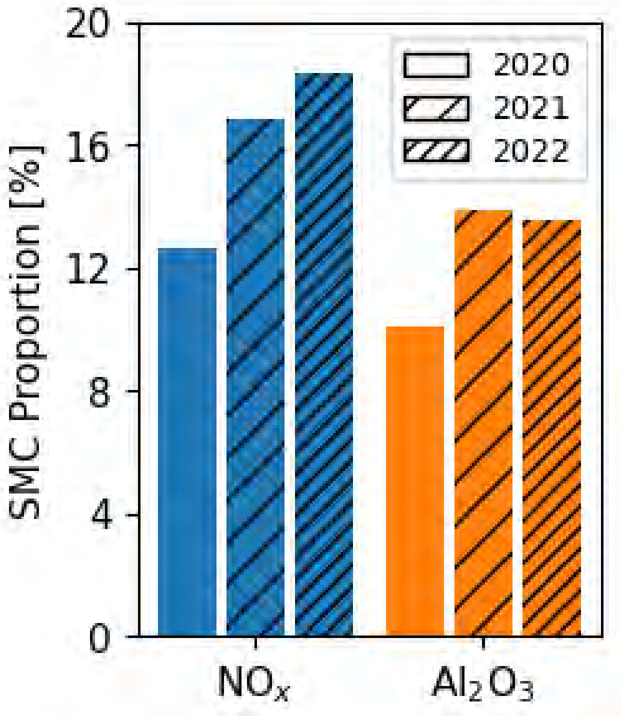
Increase in re-entry mass from 3.2 kilotonnes in 2020 to 5.0 kilotonnes in 2022 (~40% natural influx)

Megaconstellation objects increase from 18% of all re-entering mass in 2020 to 25% by 2022

Vertical Profiles of Air Pollutants and CO_2



Re-entry NO_x and Al_2O_3 dominant in mesosphere.



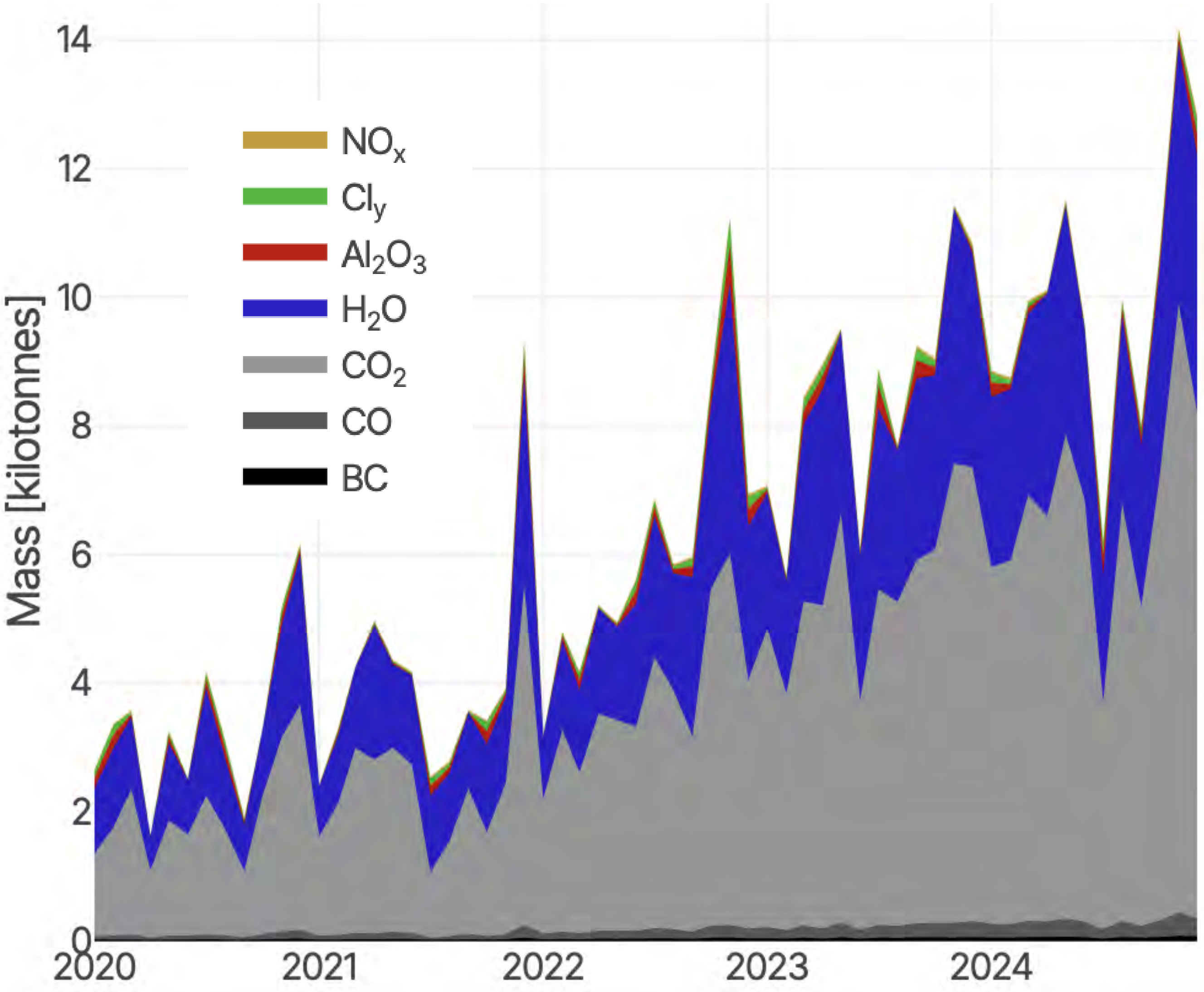
SMC contribution to re-entry NO_x increases from 13% in 2020 to 18% in 2022

[Barker et al., 2024]

Online Emissions Tracker for Launches

Extended to include 2023-2024 by UCL Astrophysics summer research student, Eric Tan

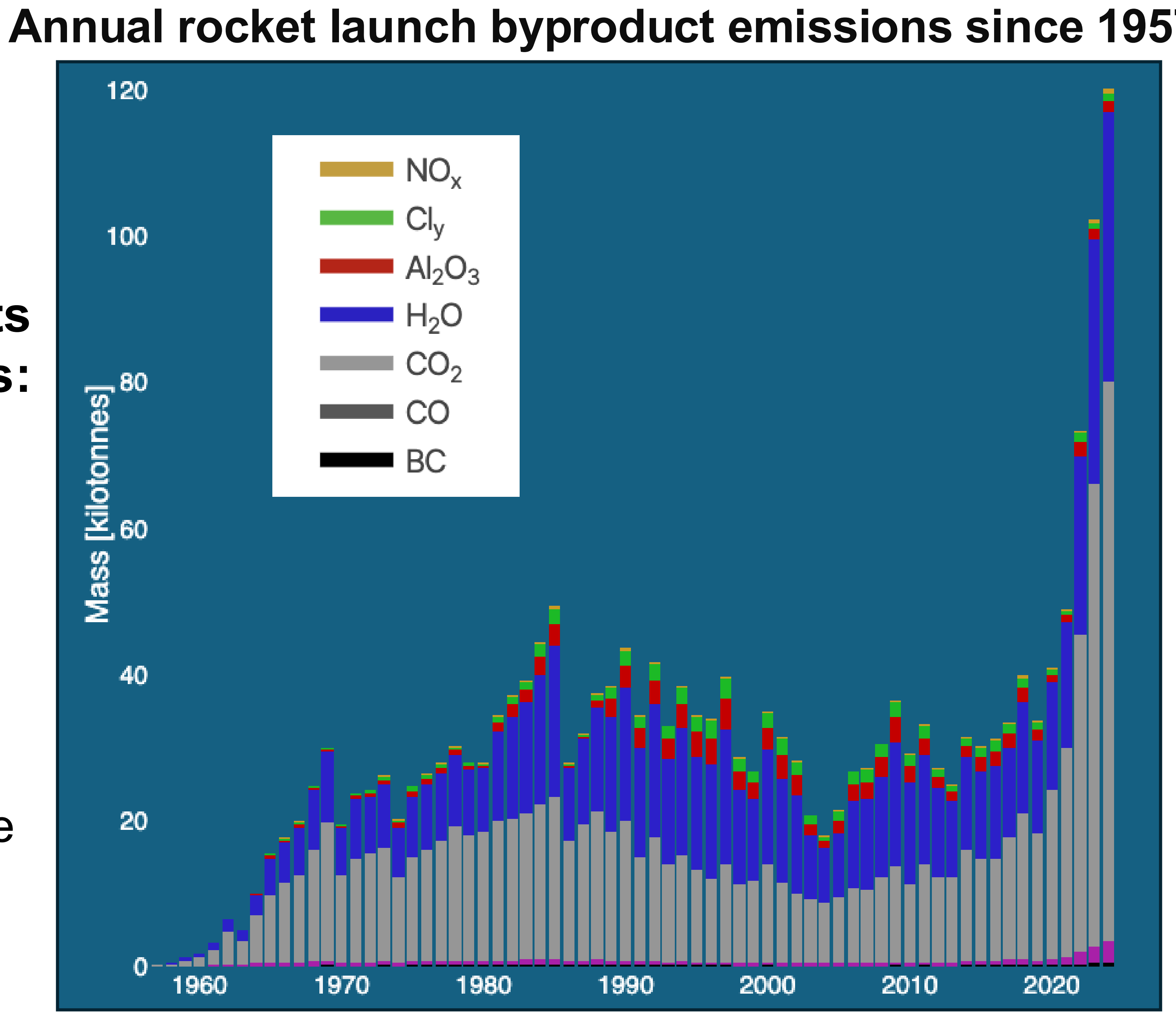
Byproducts from launches:



By 2024, propellant use for megaconstellations surpasses that for all other missions combined

Spun this out to an Online Emissions Tracker

Byproducts from launches:



By 2024, propellant use for megaconstellations surpasses all other missions combined

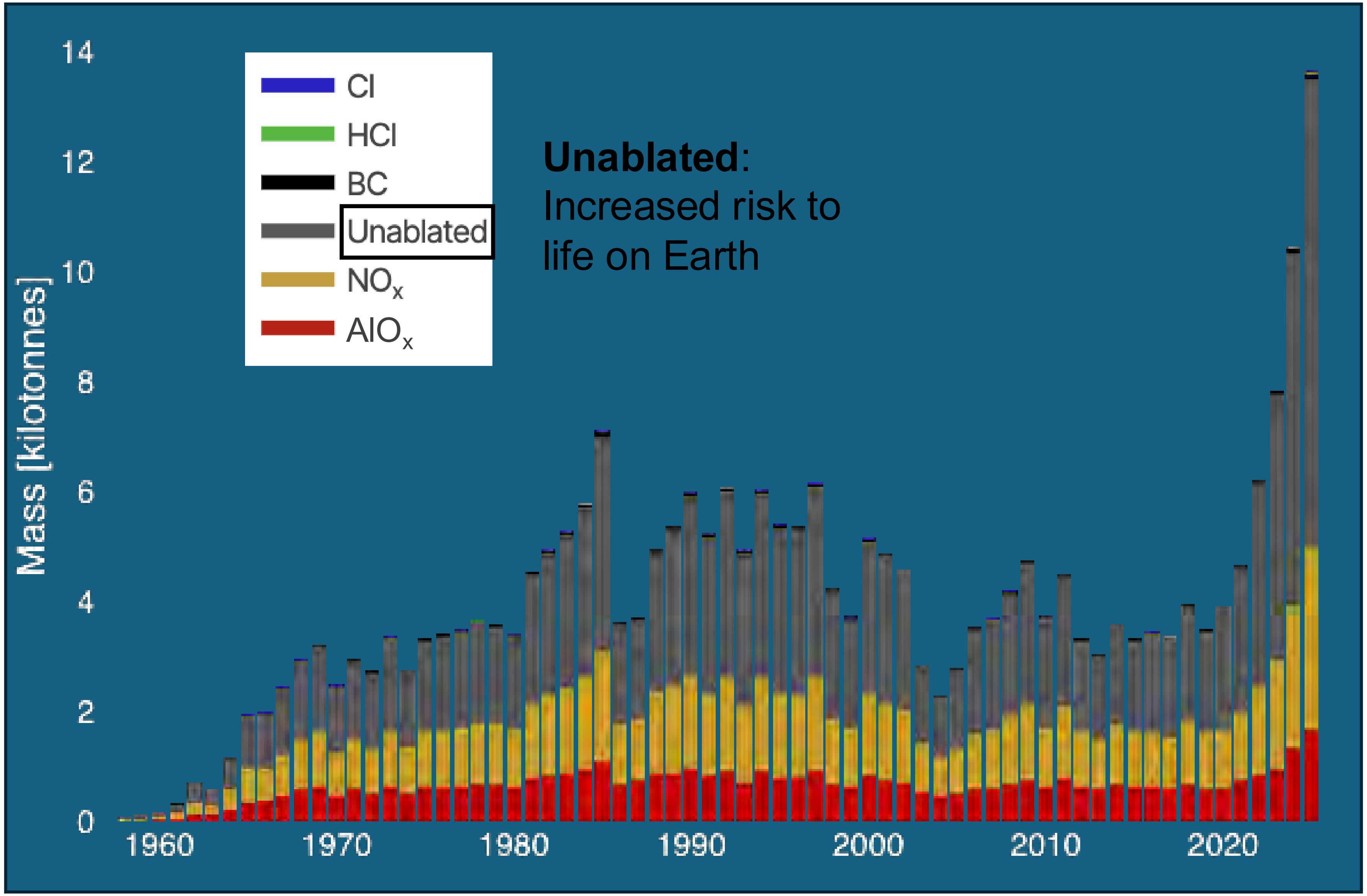
Online Emissions Tracker for Re-entries

Byproducts from re-entries:

****Preliminary****

Not exhaustive record of metals from ablation

Annual re-entry pollution and unablated mass since 1957



Give the emissions tracker a try!

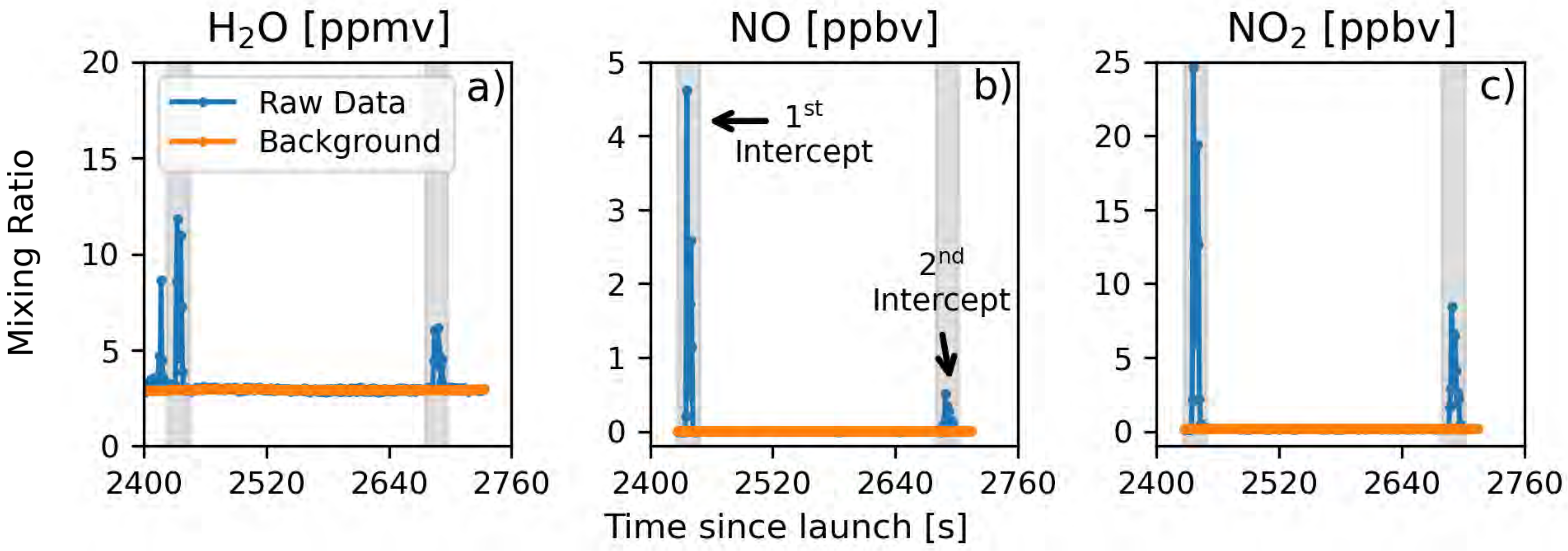
Launches byproducts

Re-entries byproducts

URL: https://cbarker211.github.io/

Rare Opportunity to Evaluate Emissions

2 SpaceX Falcon 9 plume intercepts as part of 2023 NOAA and NASA aircraft campaign



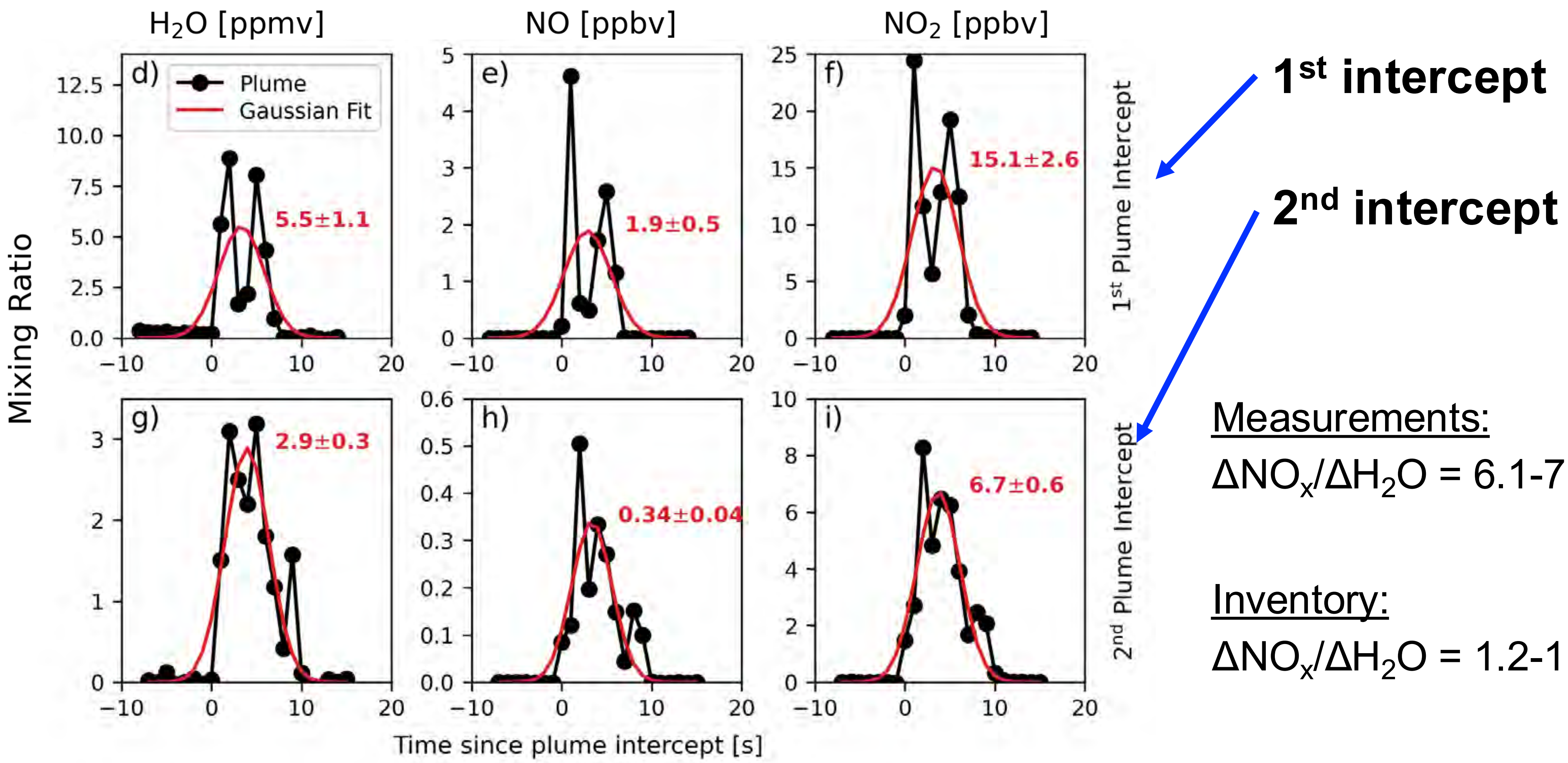
41-45 min after launched at ~16 km altitude (lower stratosphere)

Enhancement (plume) represents rocket emissions, as NO_x (NO + NO_2) and H_2O preserved (long-lived in the stratosphere)

[Barker et al., *accepted*]

Measured vs Inventory Emissions

Gaussian fit to plume to calculate mixing ratios in plume



Measurements:

$\Delta NO_x/\Delta H_2O$ = 6.1-7.6 ppb ppm^{-1}

Inventory:

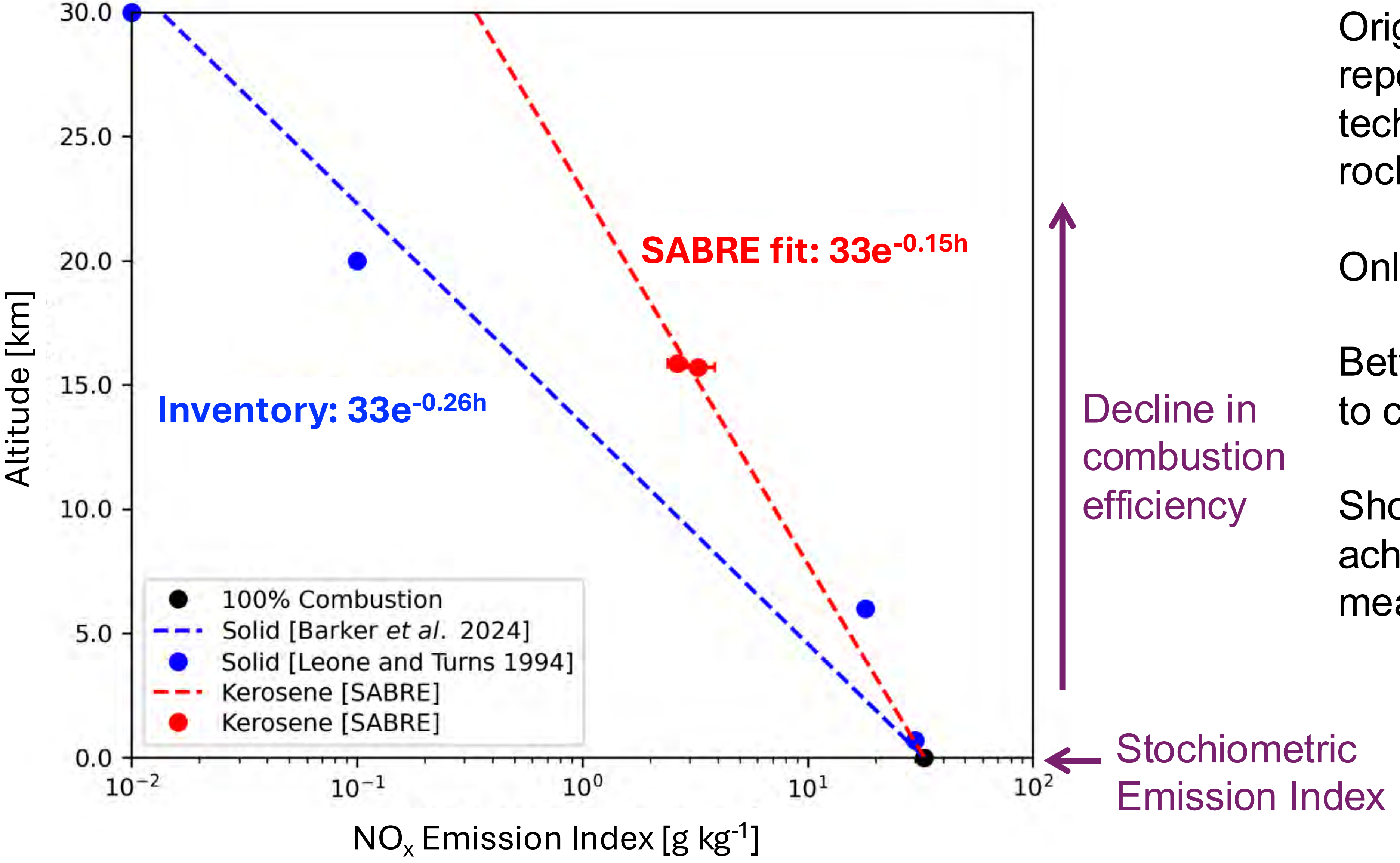
$\Delta NO_x/\Delta H_2O$ = 1.2-1.3 ppb ppm^{-1}

Divide by H_2O rather than CO_2, as H_2O is conserved with altitude

Inventory NO_x emissions at this altitude 6-fold less than is inferred from measurements

Measured vs Inventory Vertical Emissions Profiles

Altitude-dependent decline in NO_x emission indices



Original profile from 1994 report of outdated rocket technologies (mostly solid rockets)

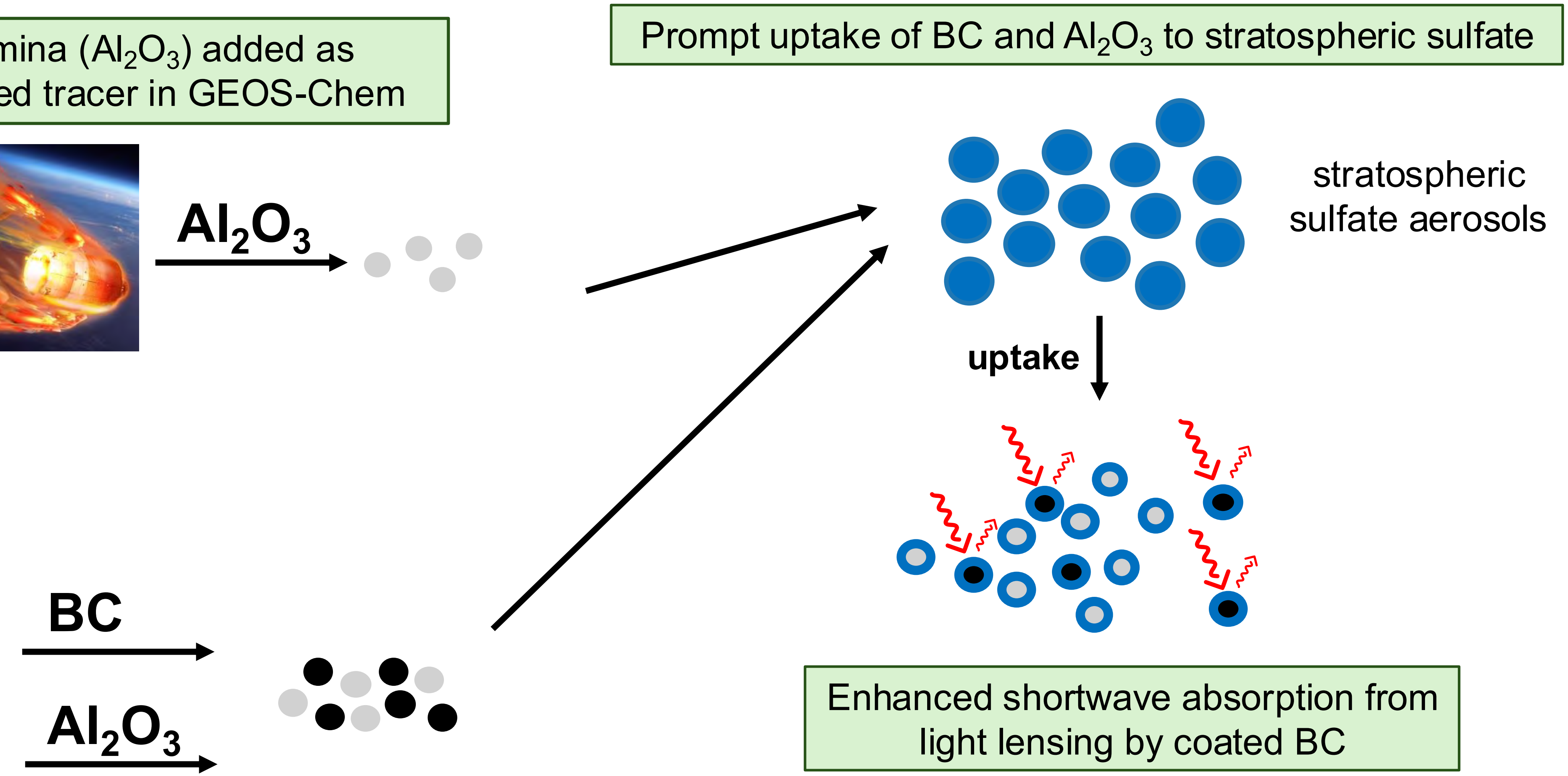
Only 2 plume intercepts

Better than currently using to constrain emissions

Shows what could be achieved with more measurements!

Comparison suggests decline in combustion efficiency much slower than assumed in the inventory

Update Model with Latest Science



Many more aerosol-phase compounds formed during re-entry that depends on composition of ablating material

****not to scale****

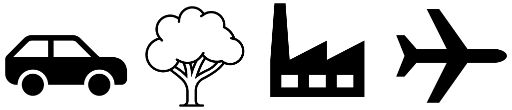
Implement Emissions in a Model

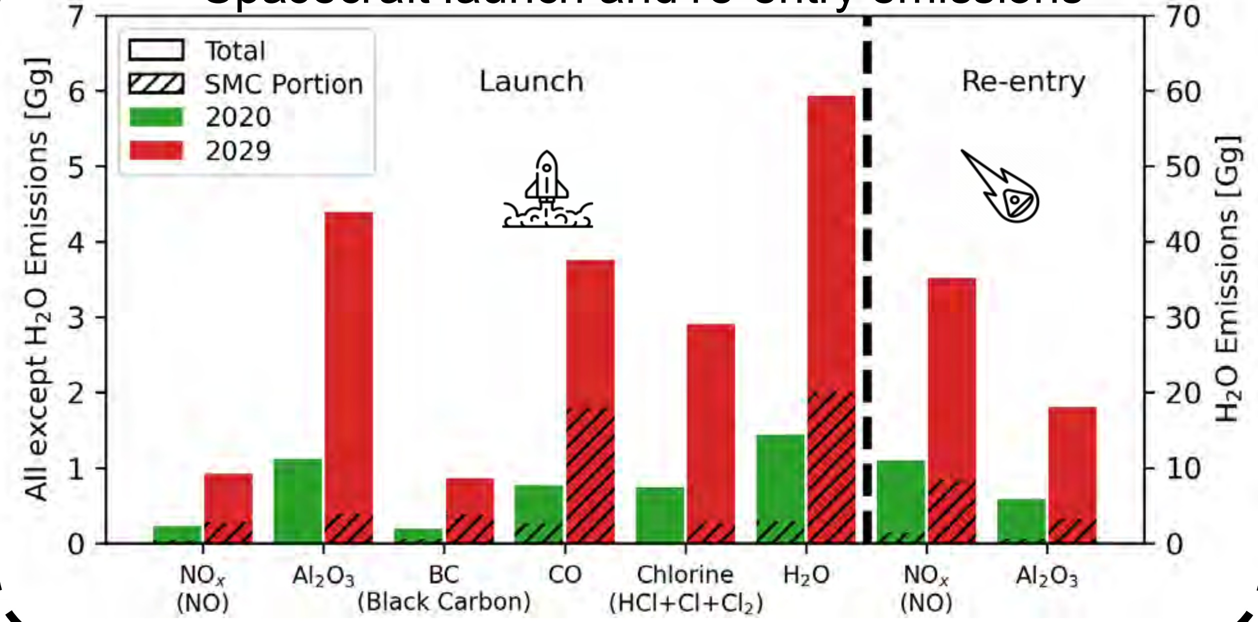
Meteorology

NASA MERRA-2 Meteorology

Emissions

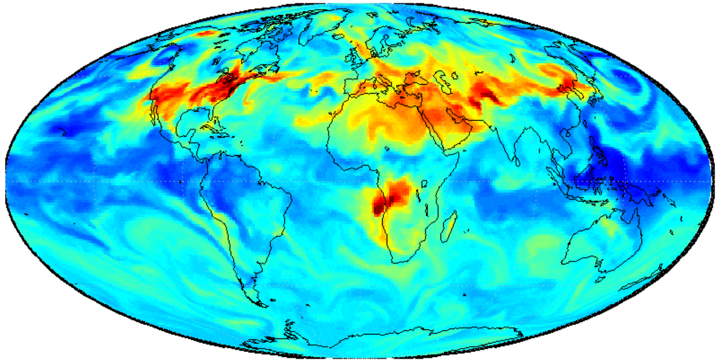
All typical precursors





GEOS-Chem

+ Radiative transfer model **(RRTMG)**



2020-2029

4° x 5°, 47 layers to 80 km

one-way coupled, RRTMG updated 3-hourly

Simulate 3 scenarios:

1. No missions
2. All missions
3. Megaconstellations only

Output

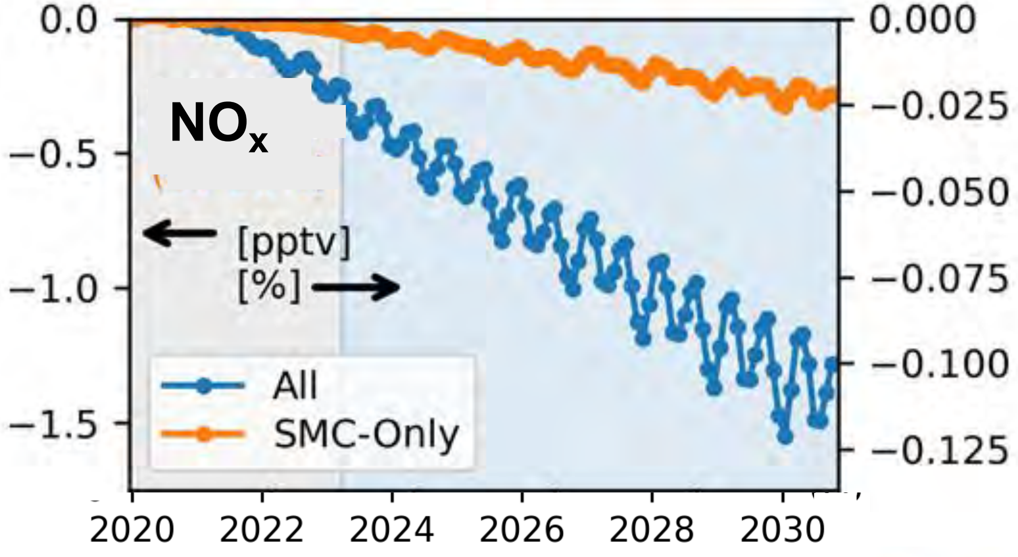
Atmospheric Composition

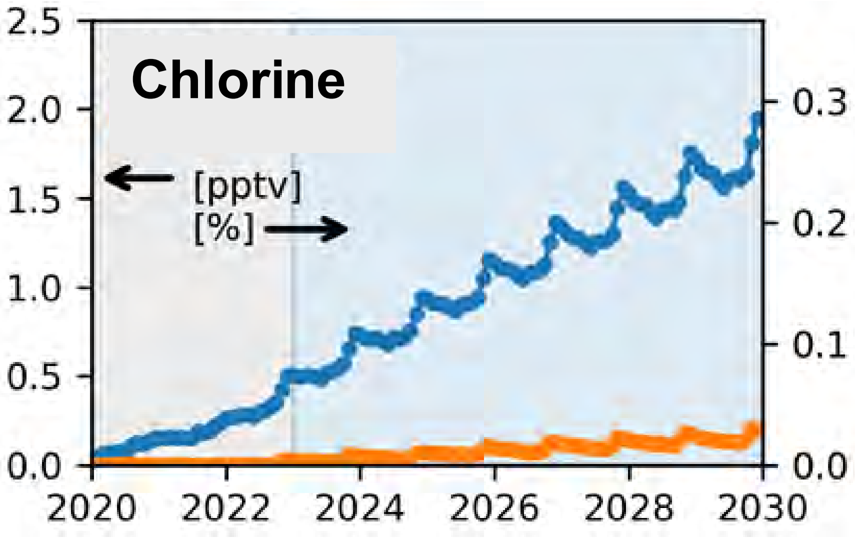
Radiative Forcing

[Barker et al., *accepted*]

Effect on Stratospheric Composition (Gas-phase)

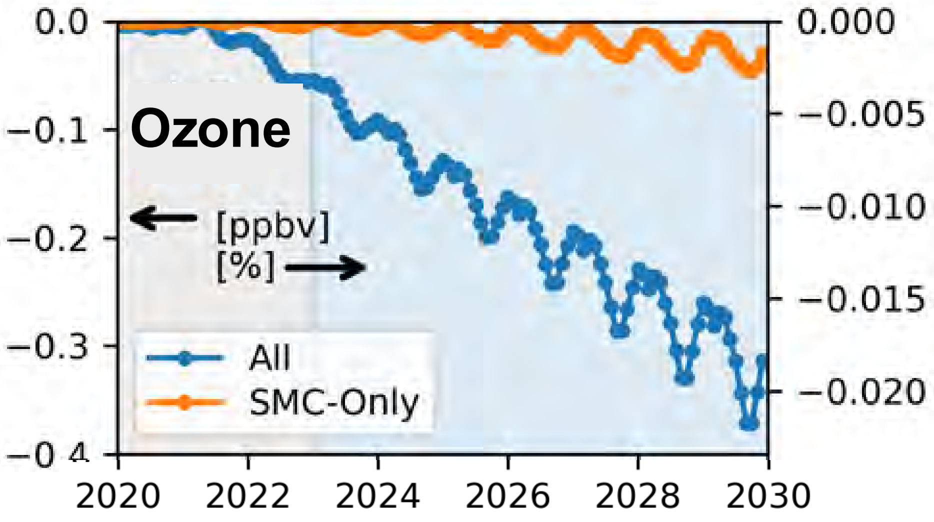
Model changes in global monthly mean stratospheric composition of gaseous compounds





SMCs Contribution:
NO_x: 15% (2020) to 20% (2029)
Chlorine: 5% to 9%
Ozone: 3% to 9%

<u>Chlorine (Cl_y)</u>:
$2Cl_2+ClNO_3+2Cl_2O_2+ClO+ClNO_2+ClOO+HCl+OClO+BrCl+HOCl+ICl+Cl$



Ozone decline only due to effect of pollutants on single and multiphase chemistry (radiative forcing also important)

Modest decline (0.03%) in ozone compared to CFCs (~2%)

Most of ozone decline due to chlorine from solid propellant not used much currently for megaconstellations

Global Radiative Forcing Changes

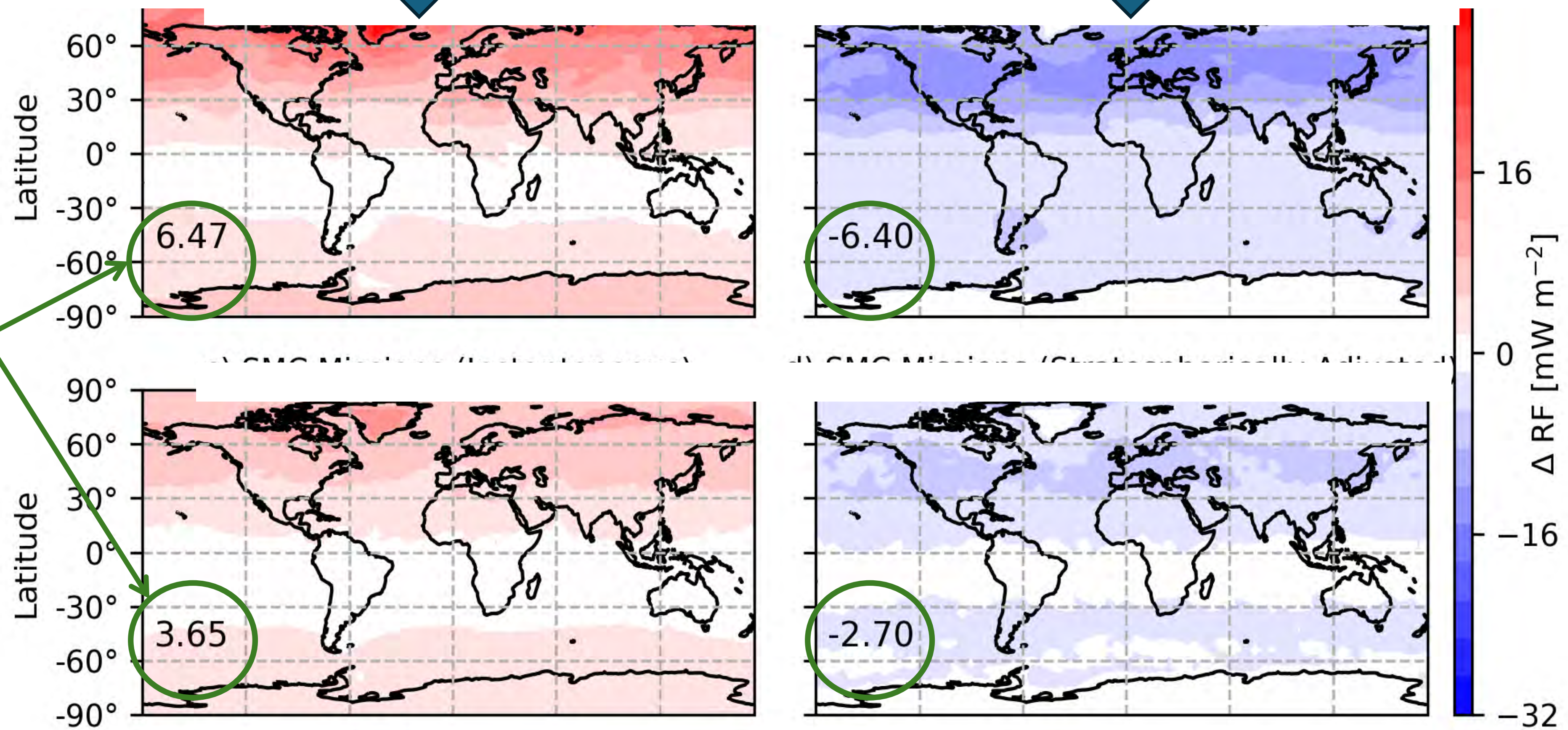
Annual mean radiative forcing by 2029 calculated with the RRTMG radiative transfer model

Instantaneous RF | **RF with stratospheric adjustment**

All missions

SMCs only

Global means



Instantaneous positive in response to absorption of incoming sunlight by aerosols in the stratosphere

Decline in incoming sunlight reaching the troposphere leads to negative stratospherically adjustment values

Biggest effect is in the northern hemisphere where almost all launches occur

Contribution of Individual Forcers

Annual global mean speciated radiative forcing in 2029 also calculated with the RRTMG

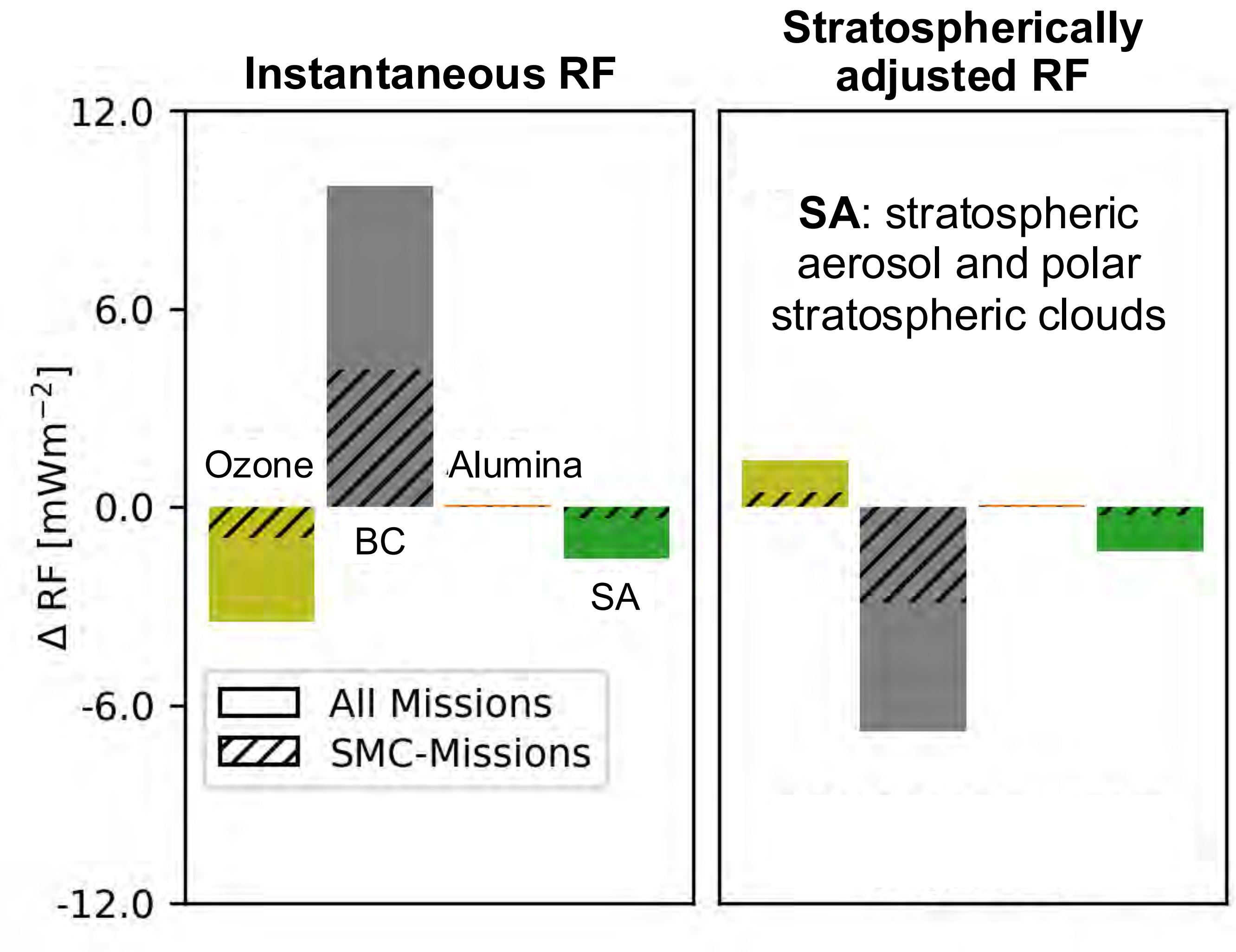
<u>Sign of instantaneous RF:</u>

Ozone: depleted in stratosphere, so absorbs less incoming sunlight

BC: greater absorption of incoming sunlight

$**Al_2O_3**$: negligible

SA: greater reflection of incoming sunlight

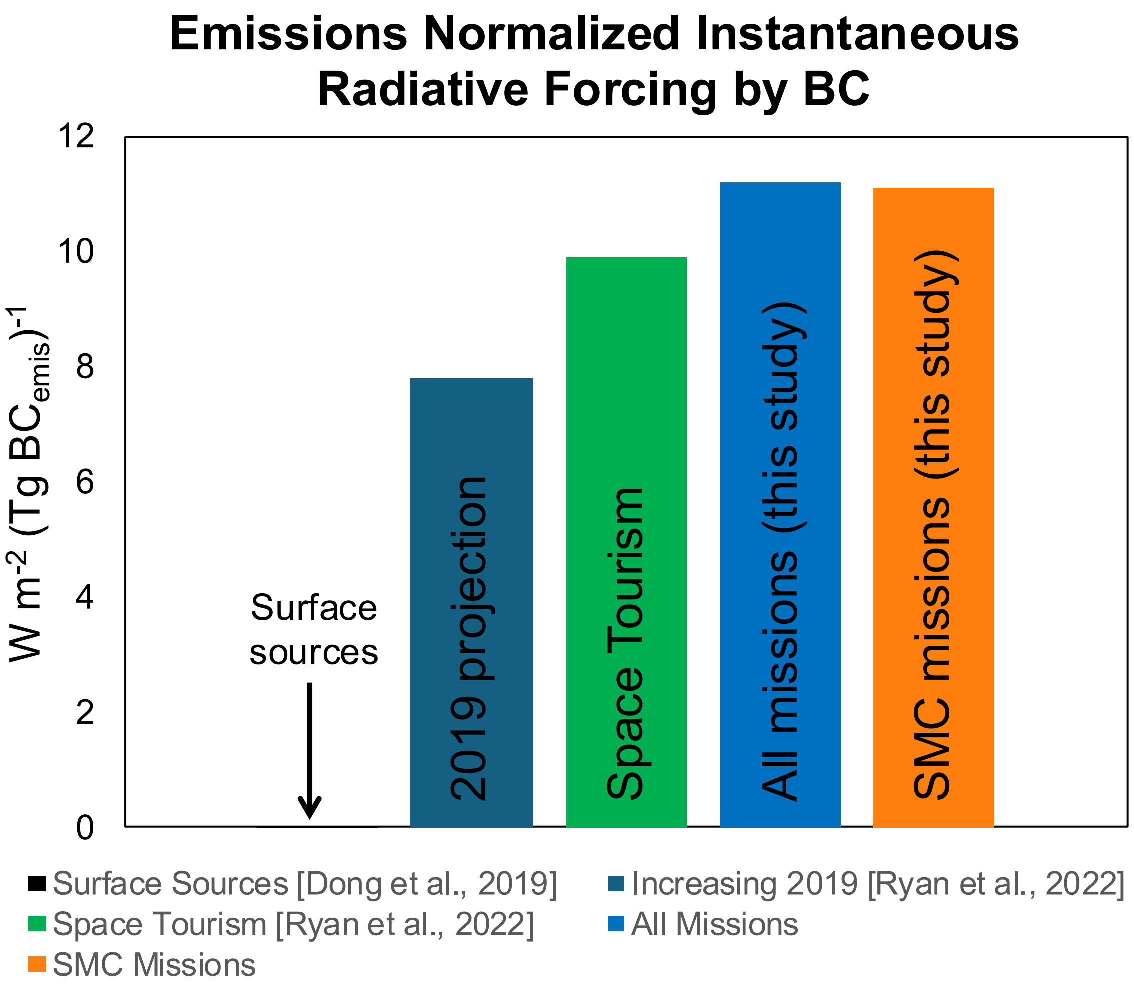


Sign flips for stratospherically adjusted RF if forcer absorbs incoming sunlight (ozone and BC), as alter amount of sunlight reaching troposphere (premise of geoengineering)

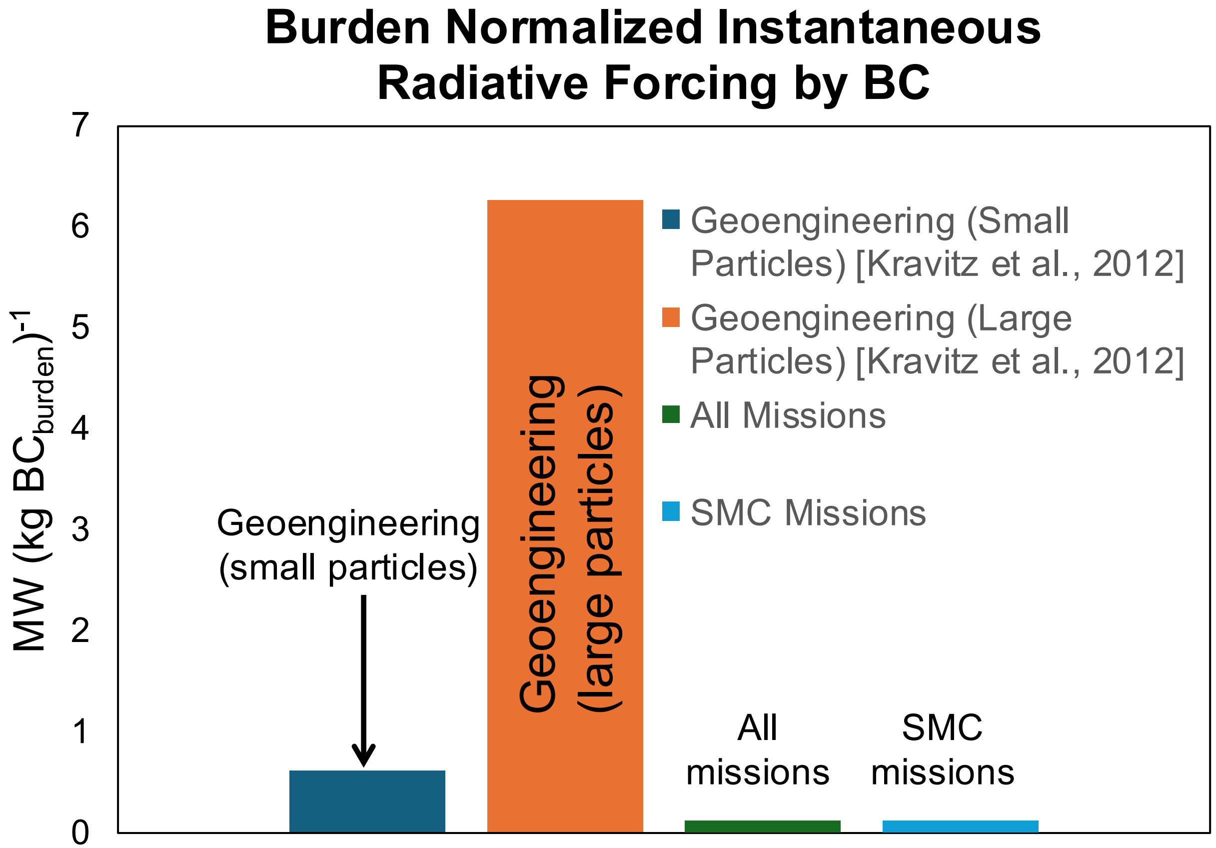
Global radiative forcing dominated by absorption of incoming sunlight by sulfate-coated BC above the tropopause

By 2029, SMCs account for 56% of the instantaneous forcing and 42% of the stratospherically adjusted forcing

Attempt at Giving Spacecraft Radiative Forcing Context



Emissions normalized forcing is ~540 times more than all Earth-bound sources, as BC persists for longer higher up



Burden normalized forcing less than theoretical geoengineering studies assessing 3 orders of magnitude more BC released to the stratosphere than is emitted by spacecraft

Summary of Main Findings

- Global ozone depletion is 0.03% from all mission types, and an order of magnitude less from SMCs, as few (<2%) SMC launches use solid rocket fuel producing ozone-depleting chlorine
- But, ozone depletion only considers direct reaction and not knock-on effects
- Sulfate-coated black carbon absorbs shortwave radiation above the tropopause, leading to positive instantaneous forcing and negative stratospherically adjusted forcing
- SMC mission only exist since 2020, but already account for about half the climate effect.
- Negative stratospherically adjusted radiative forcing is synonymous with the intent of geoengineering with stratospheric aerosols, but is untested and uncontrolled.
- Large uncertainties in composition and chemistry of re-entry metals

Relevant Links:

Emissions data **paper** link: https://www.nature.com/articles/s41597-024-03910-z

Emissions inventory **data** link: https://doi.org/10.5522/04/26325382

Atmospheric impacts **paper** preprint (pre-peer review) link (accepted version should be out soon): https://doi.org/10.22541/essoar.175978287.77438242/v1

Challenges and Issues

- Magnitude of pollutant emissions far less than Earth-bound, industrial sources, but impacts much larger per unit mass pollutant emitted (persist longer)
- May be impacts in much higher layers of the atmosphere where I'm not expert
- Very difficult to suitably observe layers of atmosphere, so rely on chance encounters and on models
- Concern over activities on horizon (difficult to predict) and implications for unregulated pollution
- Proposed so-called "cleaner" options not pollution neutral: bio-derived fuels, wooden satellites
- Industry adopting fuels that lack emissions measurements (liquid methane)
- Science can't keep up with industrial advancements, evidence from science can't then inform legislation