Atmospheric harm of air pollution from launches and re-entries



Eloise A. Marais, Imperial Seminar, 28 October 2026

Launch and Re-entry Emissions and Impacts

Launches (0 km to orbit)



Hydrogen
Kerosene
Methane
Hypergolic
Solid
Bio-propellants

Re-entries (60-80 km)

Payloads
Components
Capsules
Rocket Bodies
Debris

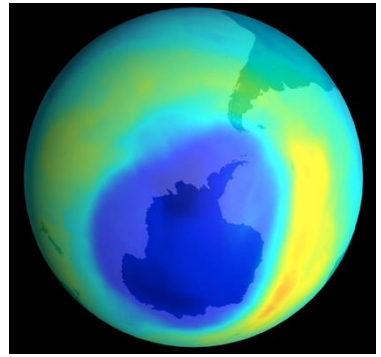


H_2O
Al_2O_3

BC
NO_x
Chlorine

Metals

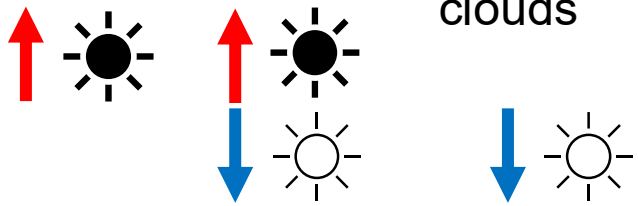
Stratospheric Ozone Loss



Affected by all emitted compounds

Instantaneous Climate Forcing

BC | Al_2O_3 | Stratospheric clouds



Al_2O_3: alumina; **BC**: black carbon (soot); **NO_x**: Nitrogen Oxides (NO + NO_2)

Mix of Chemicals Emitted Determined by Propellant

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

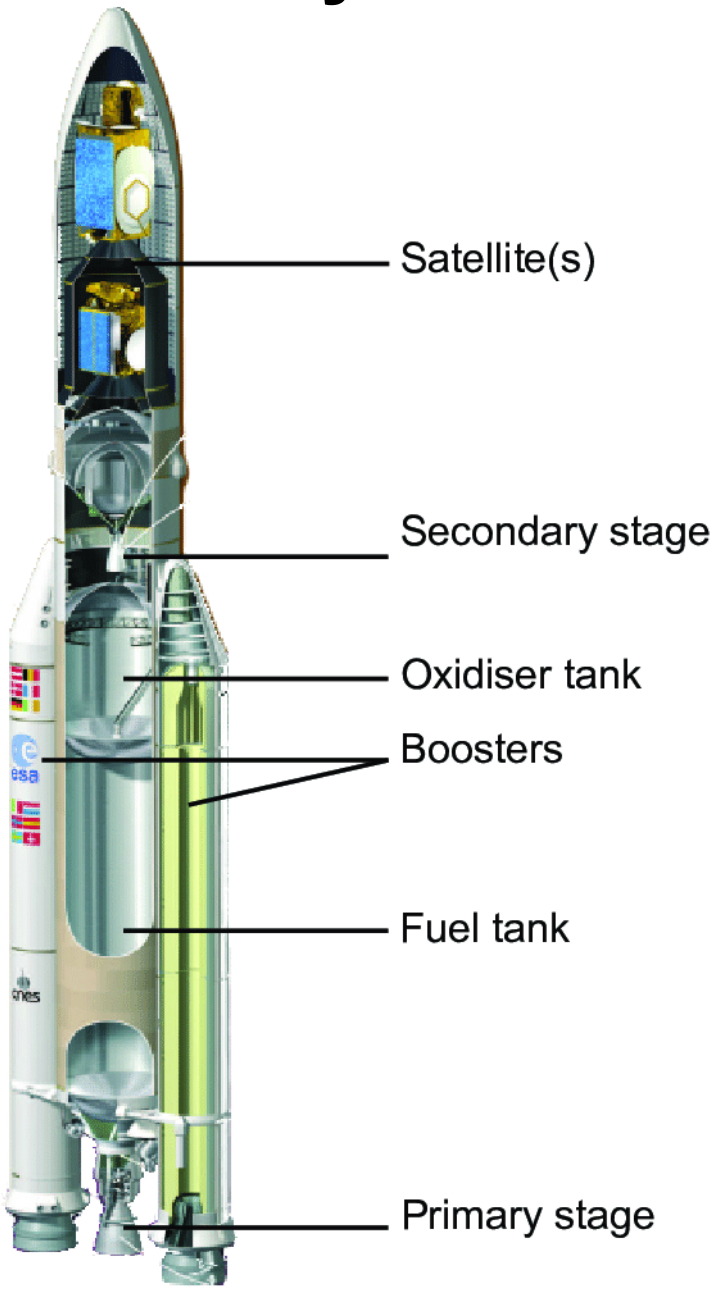
Cryogenic

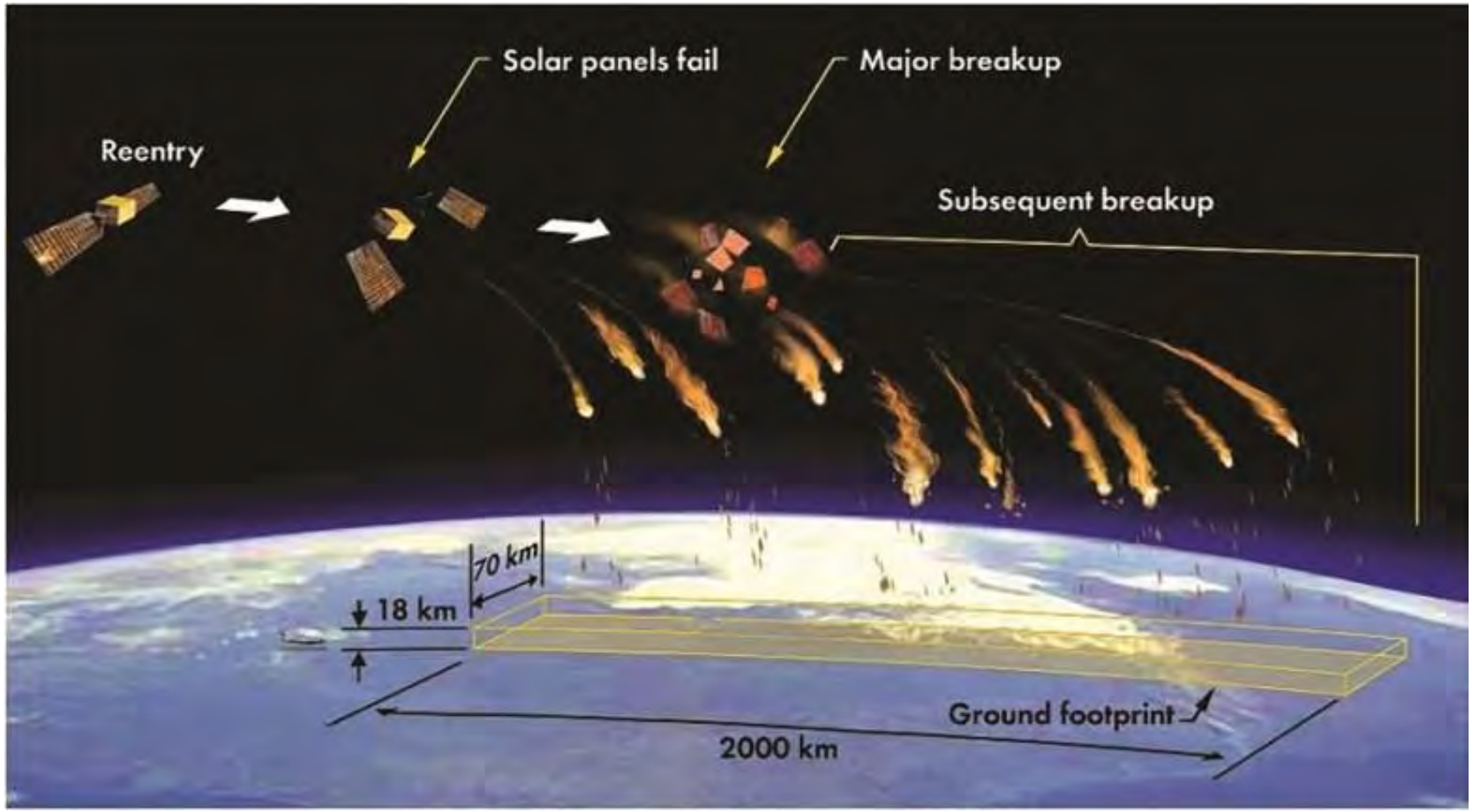


NO_x
H_2O

BC: Black Carbon
Al_2O_3: Alumina

Re-entry Emissions from Reusable and Discarded Objects





- Satellites ideally demise completely to reduce risk to life on Earth
- Ablation emits metals (mostly Al), BC, ammonia (NH_3) and much more
- Re-entry produces nitrogen oxides (NO_x) from thermal energy

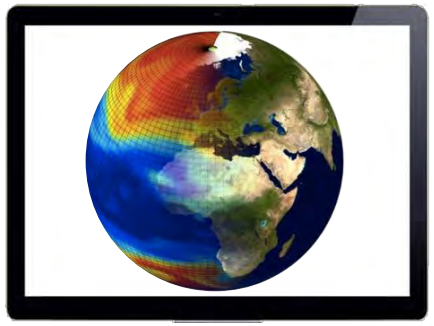
Reliance on Models to Quantify Global Impacts



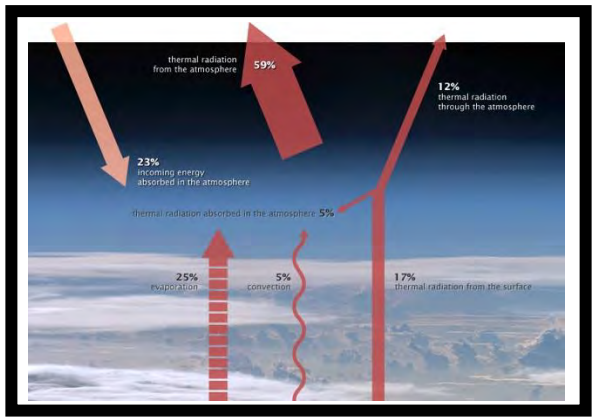


3D launch and re-entry emissions

GEOS-Chem



Chemistry Transport Model



Radiative Transfer Model

Impact on atmospheric composition (e.g., ozone loss)

Impact on climate

Calculate emissions for 2020-2022 and project to end of decade for input to GEOS-Chem

UCL Modelling Studies using GEOS-Chem: Ryan et al. (2022), Barker et al. (2026)

Update GEOS-Chem Model with Latest Science

Alumina (Al_2O_3) from launches and re-entries added to model



Al_2O_3

Prompt uptake of BC and Al_2O_3 to stratospheric sulfate

[Murphy et al., 2023]

stratospheric sulfate aerosols

uptake



BC

Al_2O_3

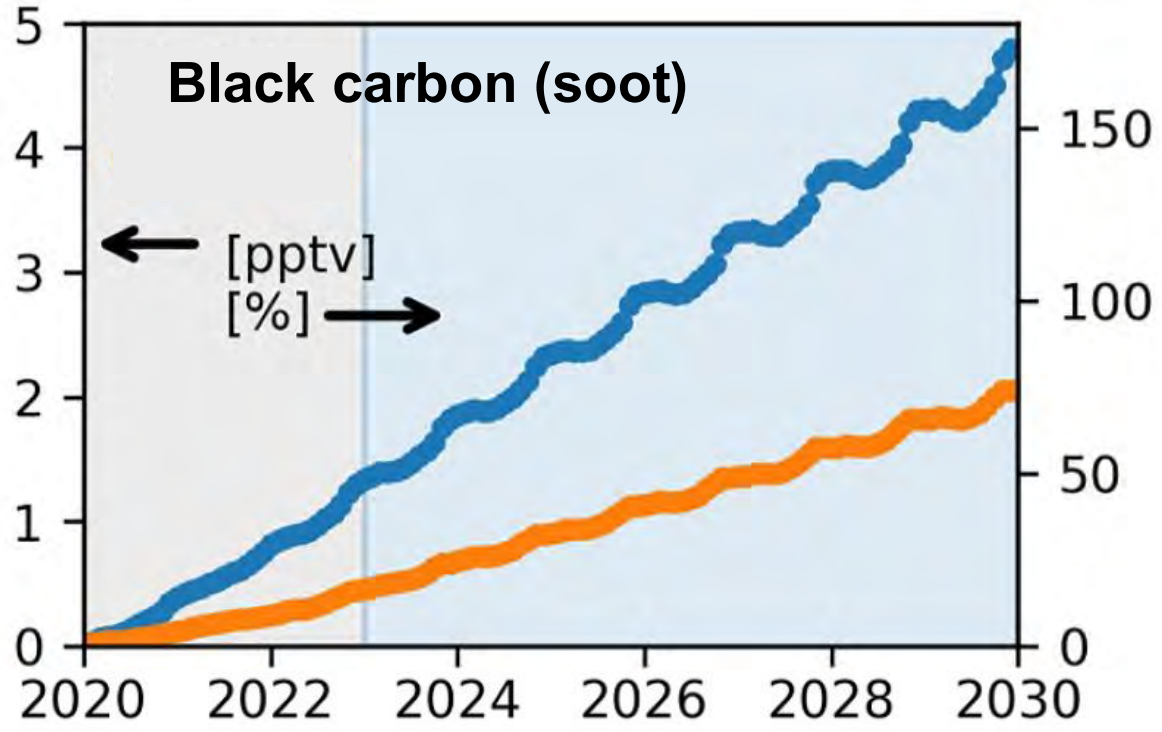
Enhanced shortwave absorption from light lensing by coated BC

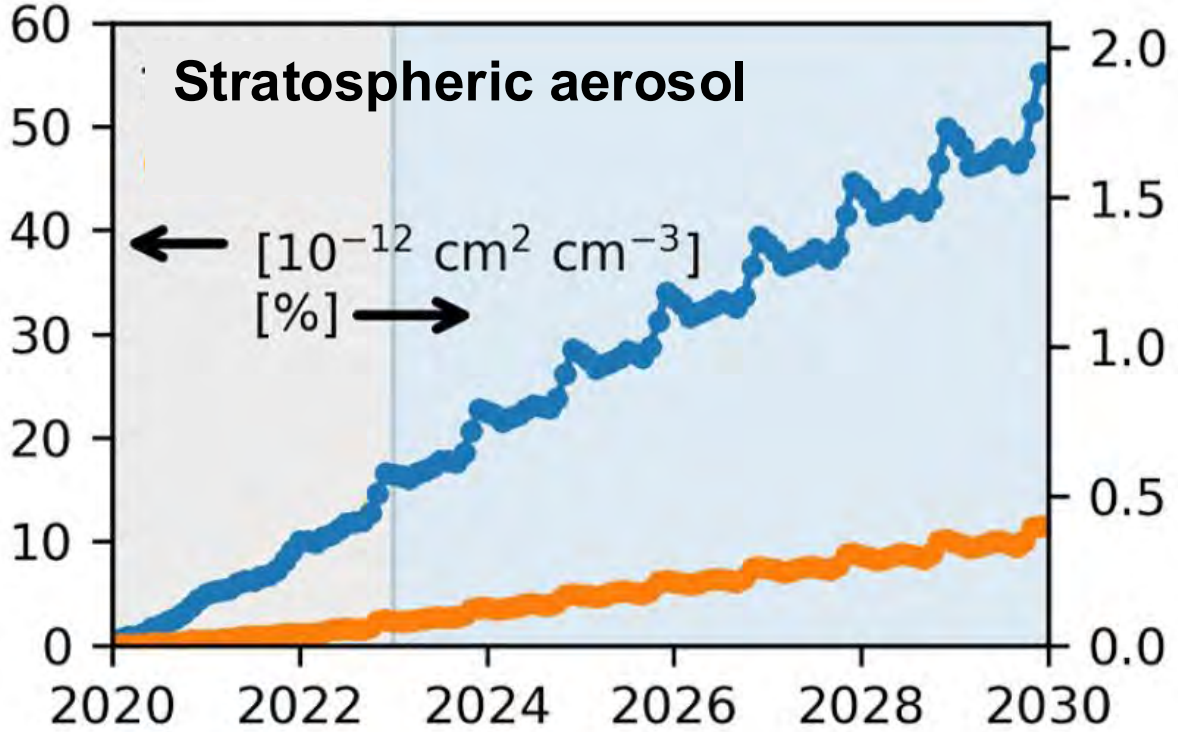
not to scale

[Barker et al., 2026]

Effects on Stratospheric Composition

Model changes in global concentrations using a chemical transport model





Orange: Megaconstellation missions
Blue: All types of missions

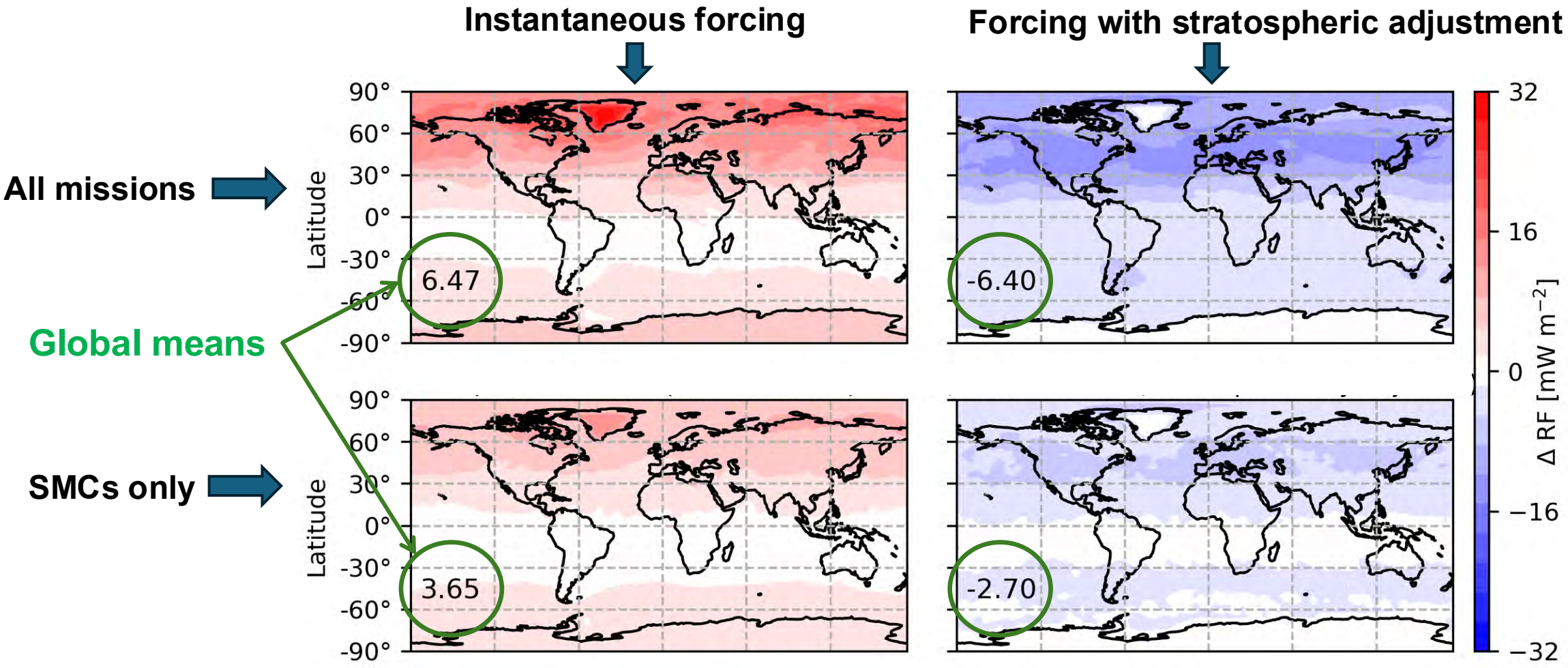
Megaconstellations ramp up from 38% of BC in 2020 to 44% by 2029

Stratospheric liquid aerosols (precursors to stratospheric clouds) increase mostly due to uptake of launch and re-entry alumina (Al_2O_3)

[Barker et al., 2026]

Global Climate (Radiative Forcing) Changes

Annual mean radiative forcing by 2029 calculated with a coupled radiative transfer model



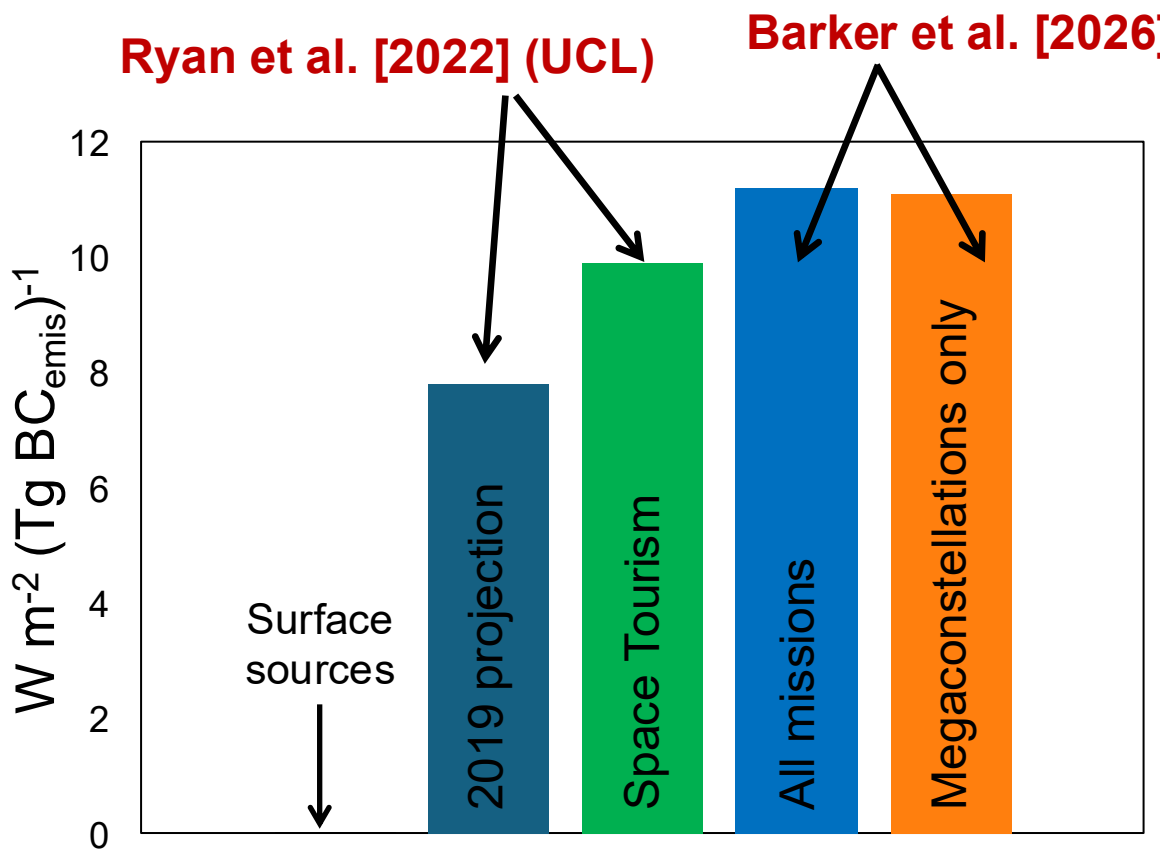
Instantaneous positive from absorption of incoming sunlight by aerosols in the stratosphere

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

Contextualizing Spacecraft Radiative Forcing

Climate impact of black carbon (soot) particles from Earth-bound sources vs rockets

Instantaneous radiative forcing per unit mass BC (**<u>risk factor</u>**):

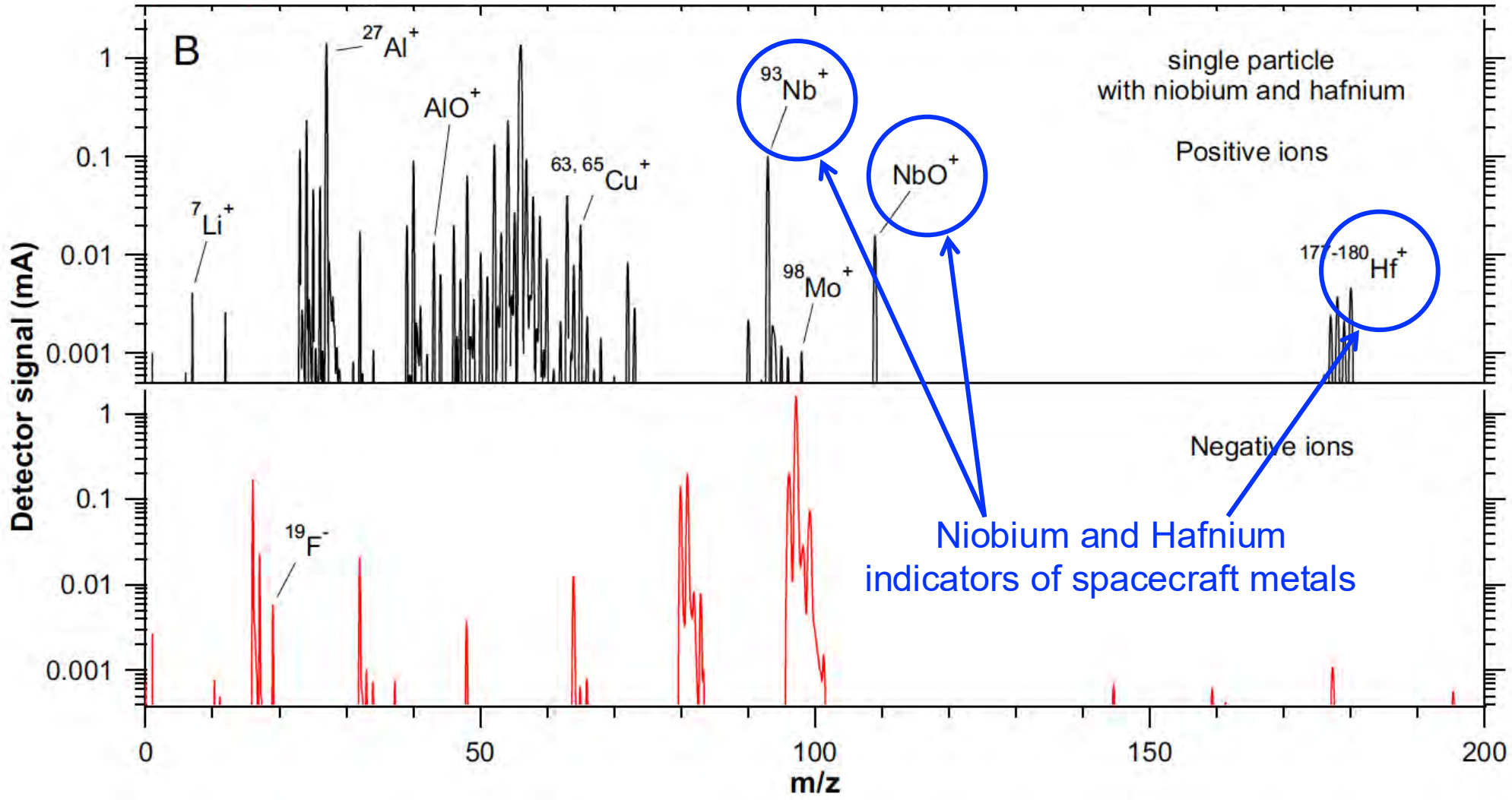


Same magnitude, opposite sign for stratospherically adjusted radiative forcing

SMC: satellite megaconstellation

Climate impact of black carbon from rockets **~540 times greater** than all Earth-bound sources

Re-entry pollution: Evidence of contamination



10% of stratospheric aerosols contaminated with metals from spacecraft re-entry pollution in 2023

(anticipate 50% contamination from megaconstellations)

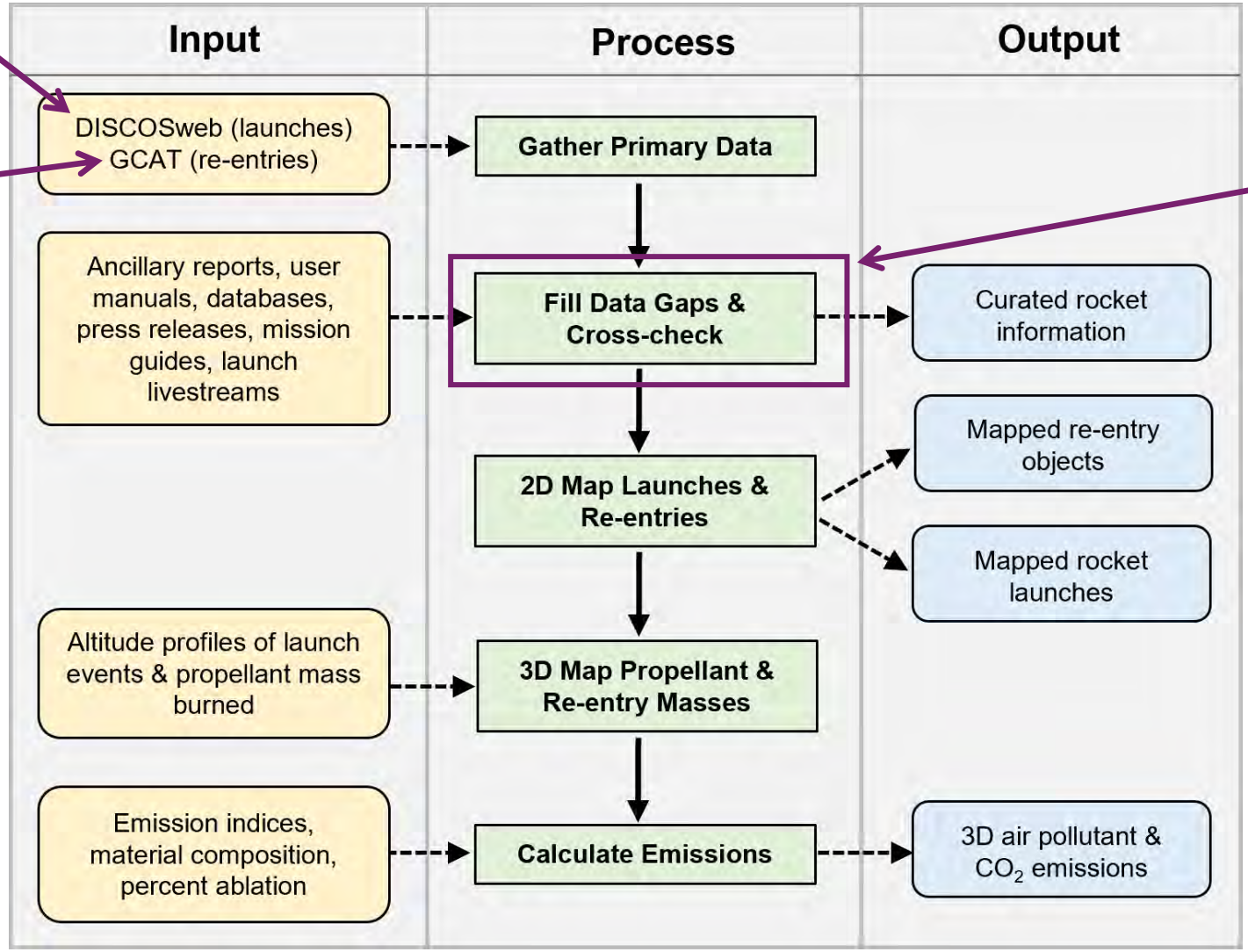
[Murphy et al., 2023]

UCL Emissions Inventory Development

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

ESA database

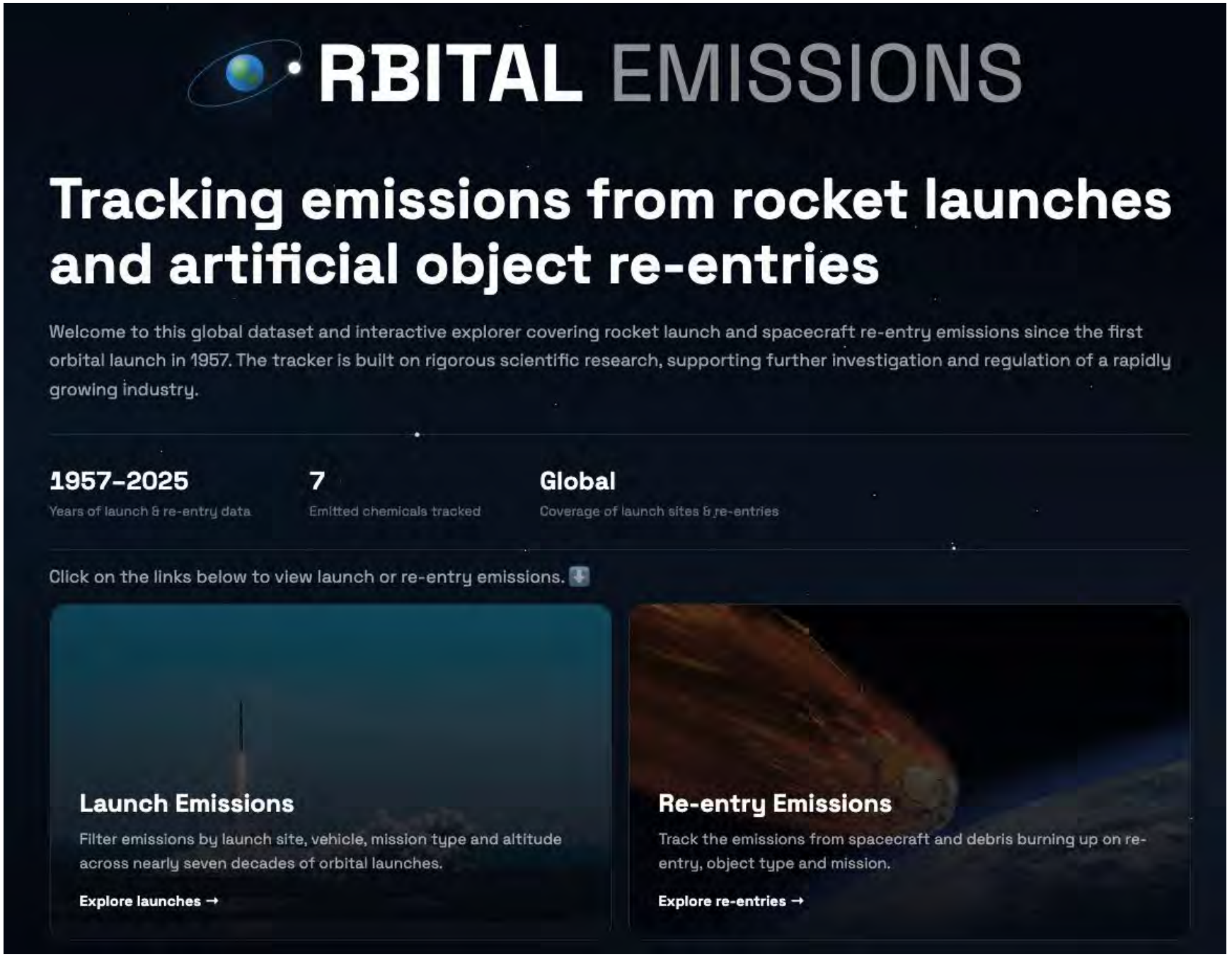
Catalogue maintained by Jonathan McDowell



Critical step:

- Data gaps
- Incorrect data
- Inconsistent data

[Barker et al., 2024]

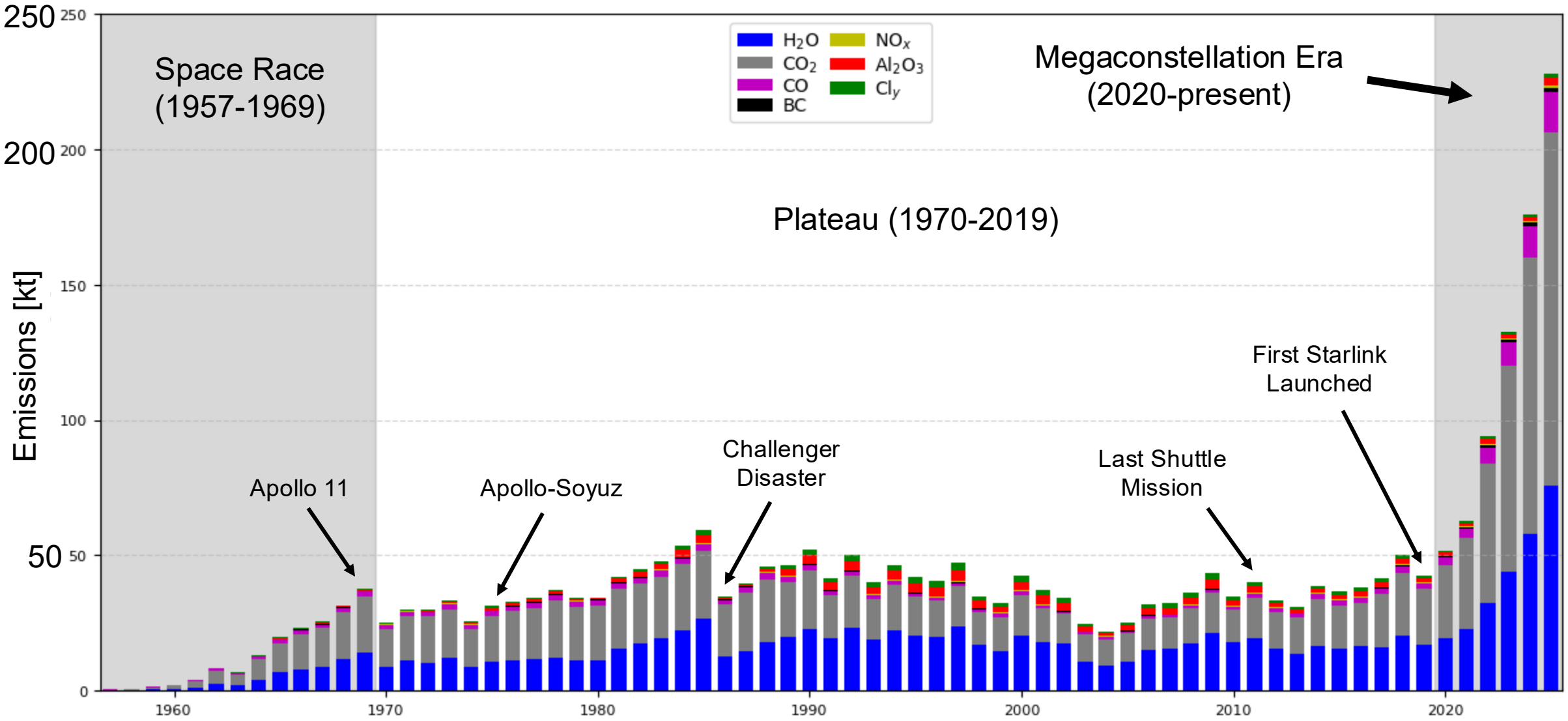


Online Emissions Tracker

Website design and development by **Connor Barker** (UCL postdoc)

In collaboration with **Jonathan McDowell**

Air Pollutant and CO_2 Emissions from Rocket Launches 1957-2025

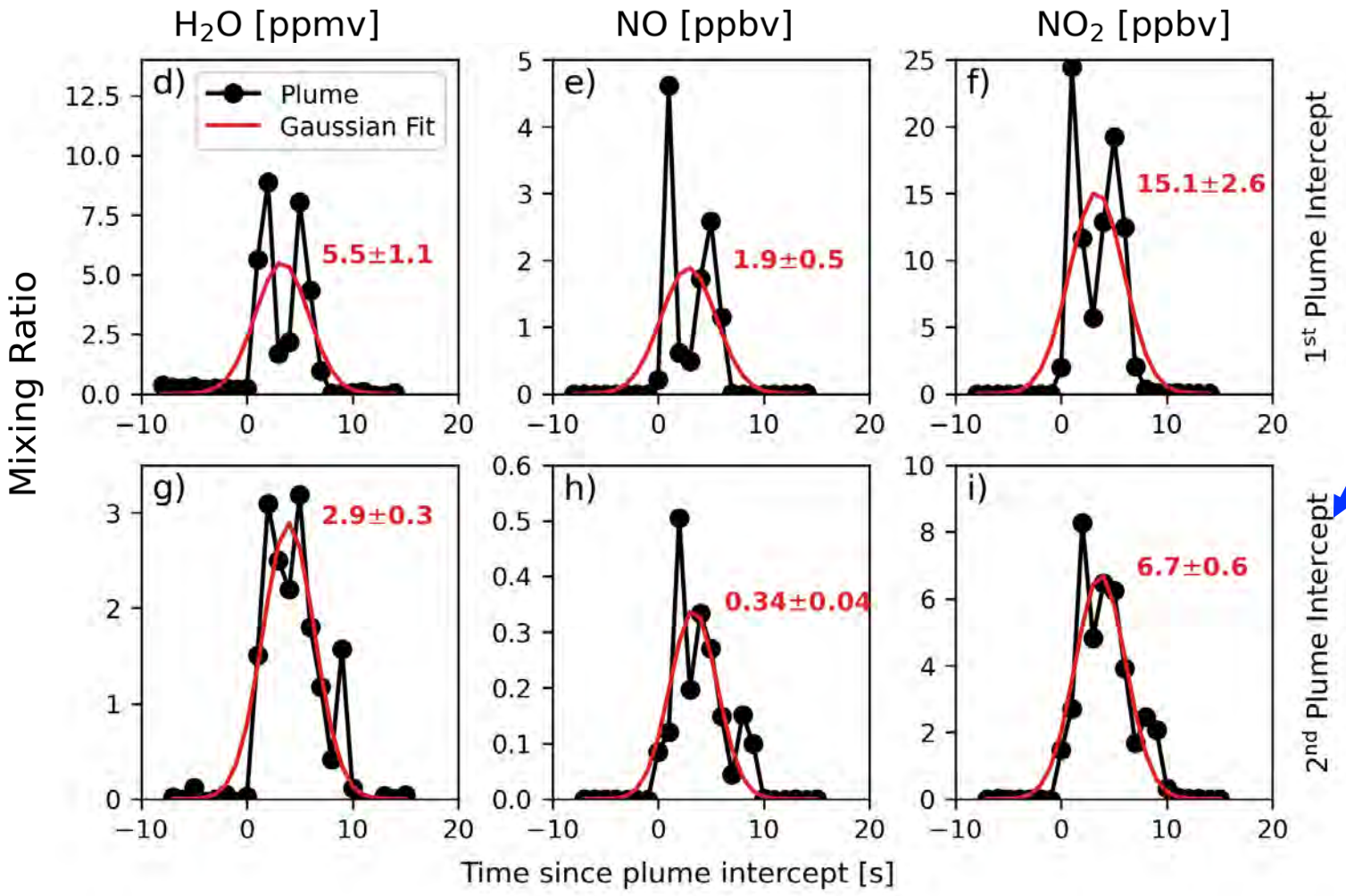


Entered a “new era” of pollution from megaconstellation launches

Similar exponential increase for re-entry pollution

Evaluation Against In Situ Aircraft Measurements

Gaussian fit to aircraft observations that intercepted a Falcon 9 plume twice



1st intercept

2nd intercept

Both intercepts at ~16 km

<u>Measurements:</u>

$\Delta NO_x/\Delta H_2O$ = 6-8 ppb ppm^{-1}

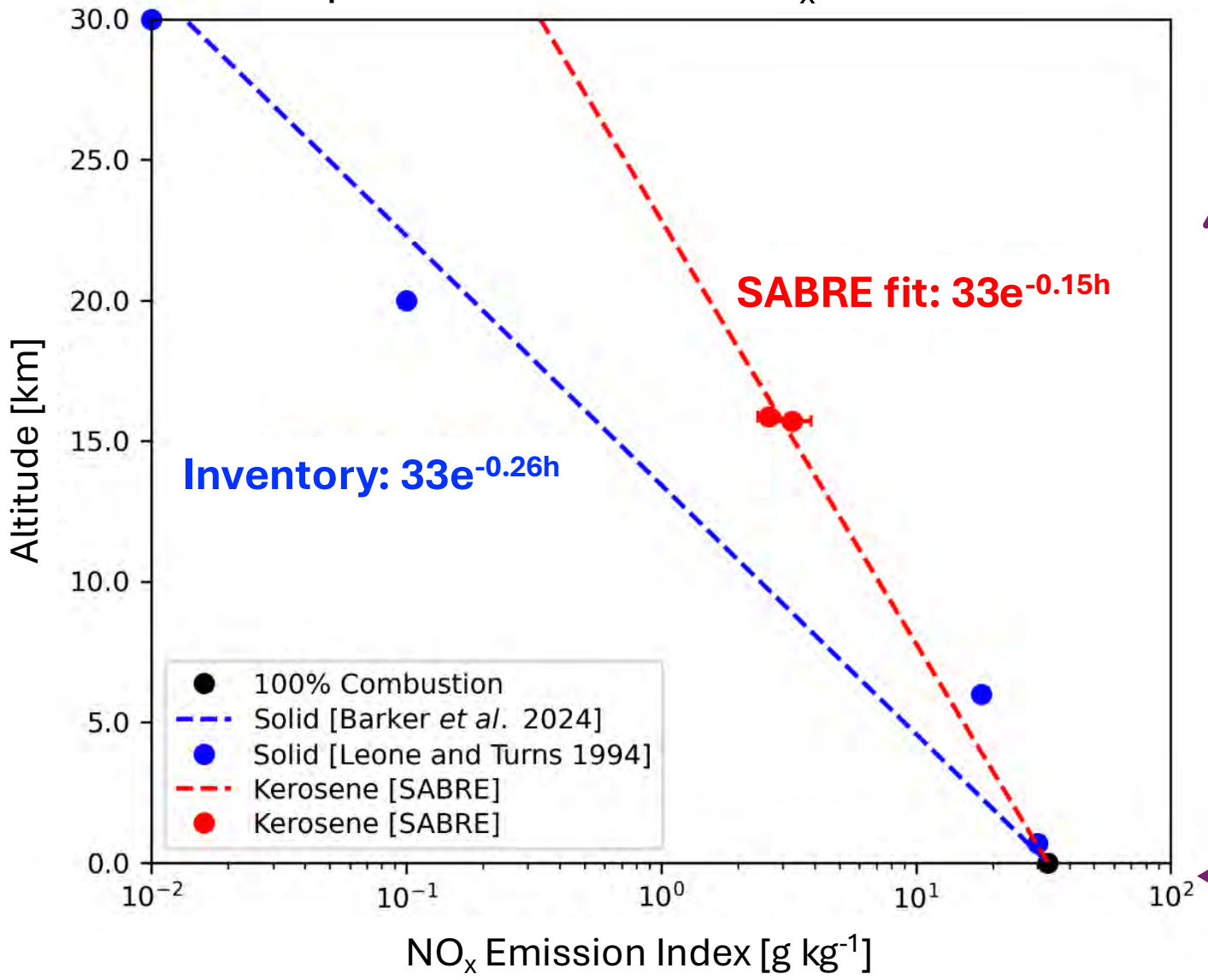
<u>Inventory:</u>

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

Use H_2O rather than CO_2, as H_2O is conserved with altitude. Similar results if integrate under plume

Measured vs Inventory Vertical Emissions Profiles

Altitude-dependent decline in NO_x emission indices



Decline in combustion efficiency

← Stochiometric Emission Index

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

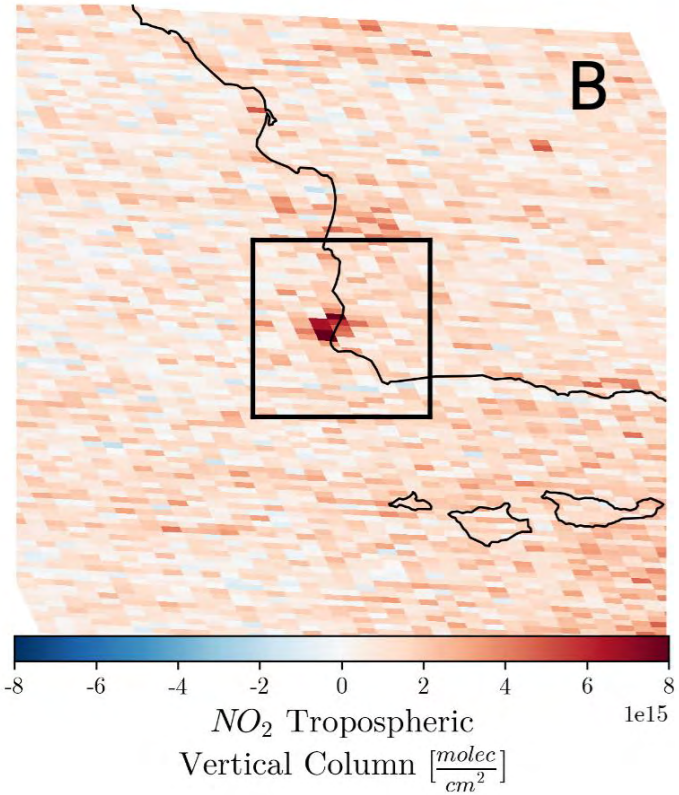
SABRE only intercepted plume twice at same altitude

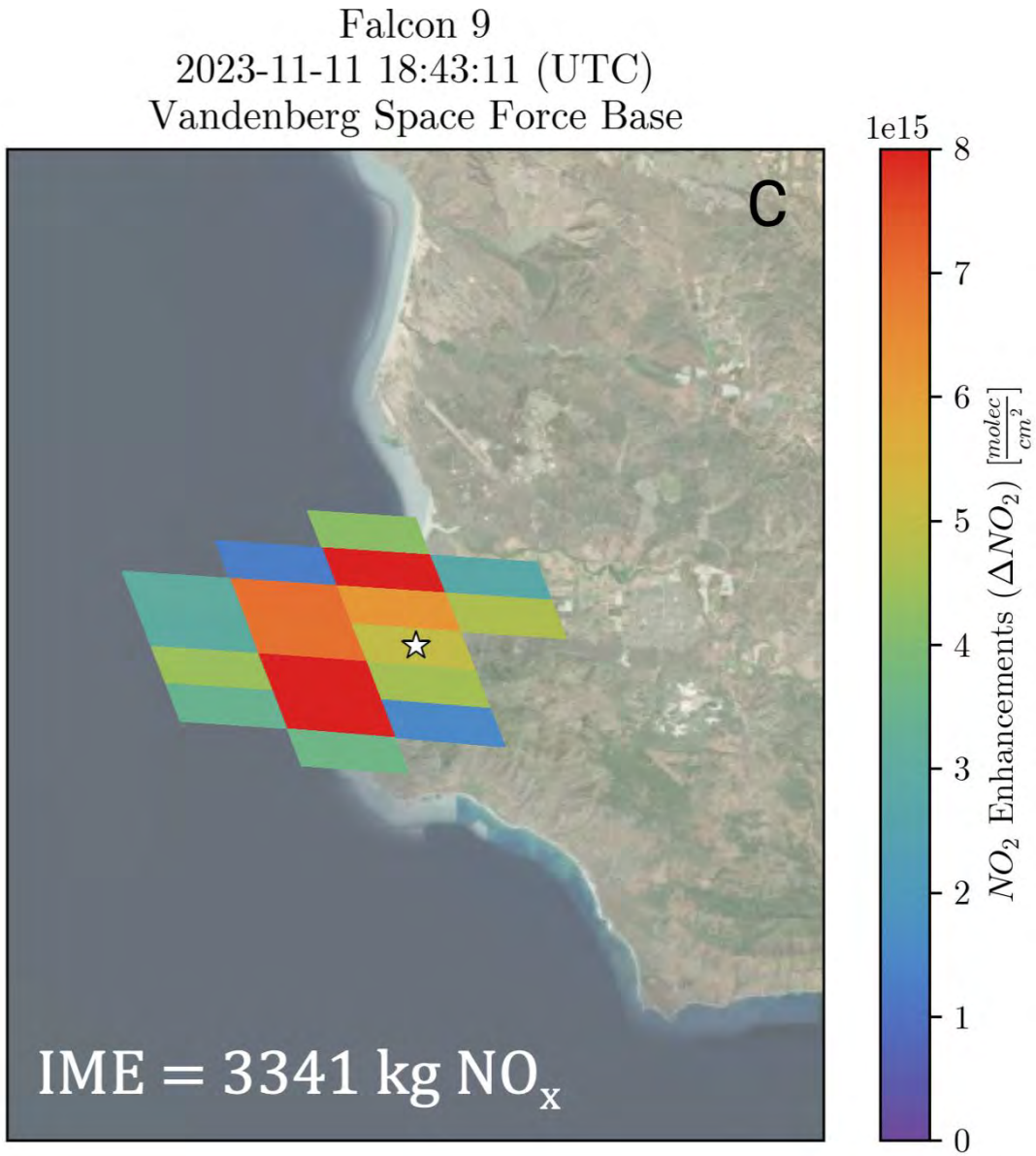
Shows what could be achieved with more measurements!

Decline in combustion efficiency with altitude more gradual than assumed in the inventory

NO_x Emissions Derived with Satellite Observations







TEMPO: space-based air quality sensor

Convert integrated tropospheric columns of NO_2 from TEMPO into NO_x emissions

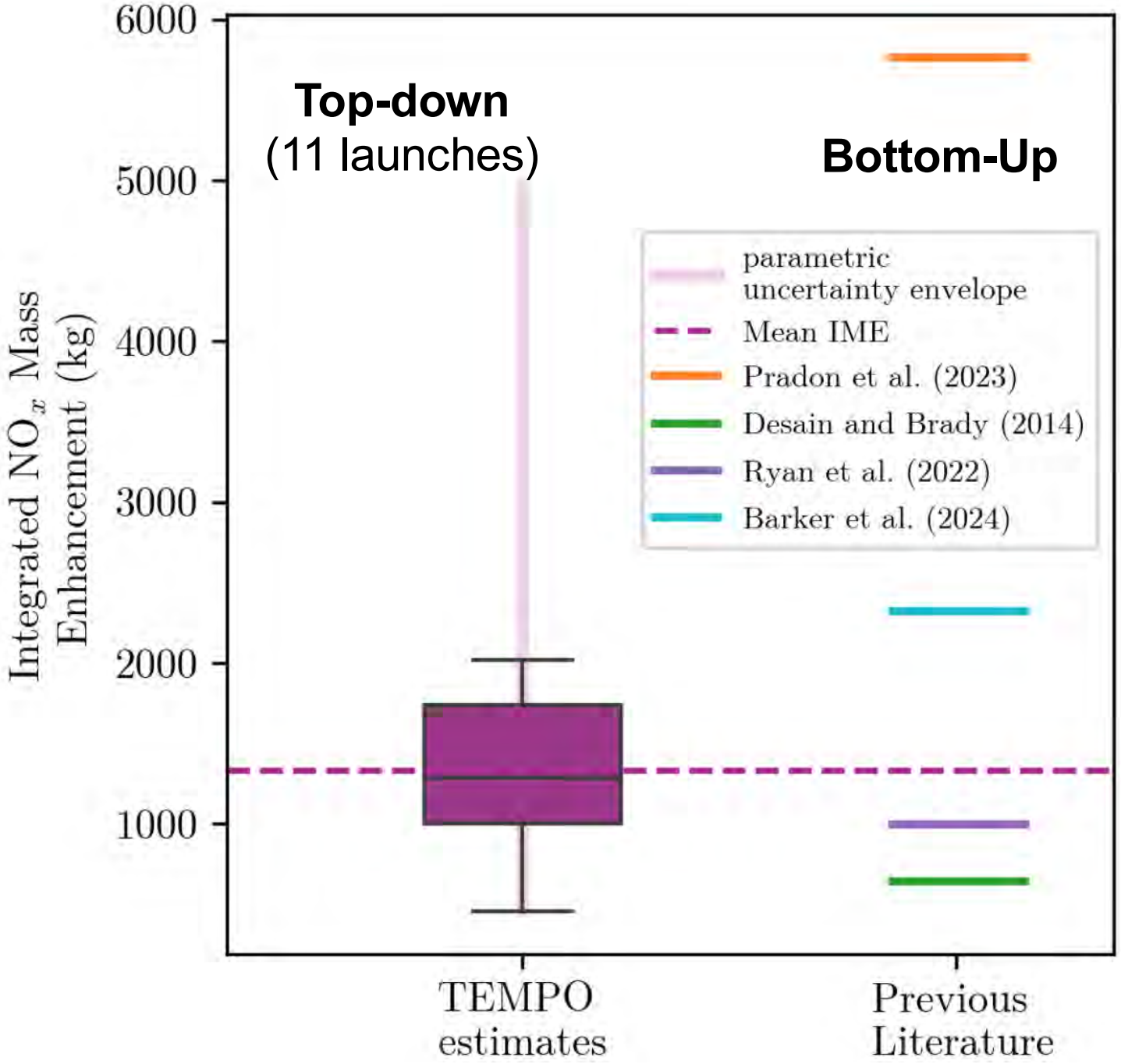
Detects plumes from rockets burning at least 500 tonnes propellant (Falcon 9 1st stage)

Plume resolved to ~2-3 km at best

18 plumes detected and quantified with this approach; mostly Falcon 9 rockets

[Palmo et al., GRL, *in review*]

Bottom-Up vs Top-Down Launch NO_x Emissions



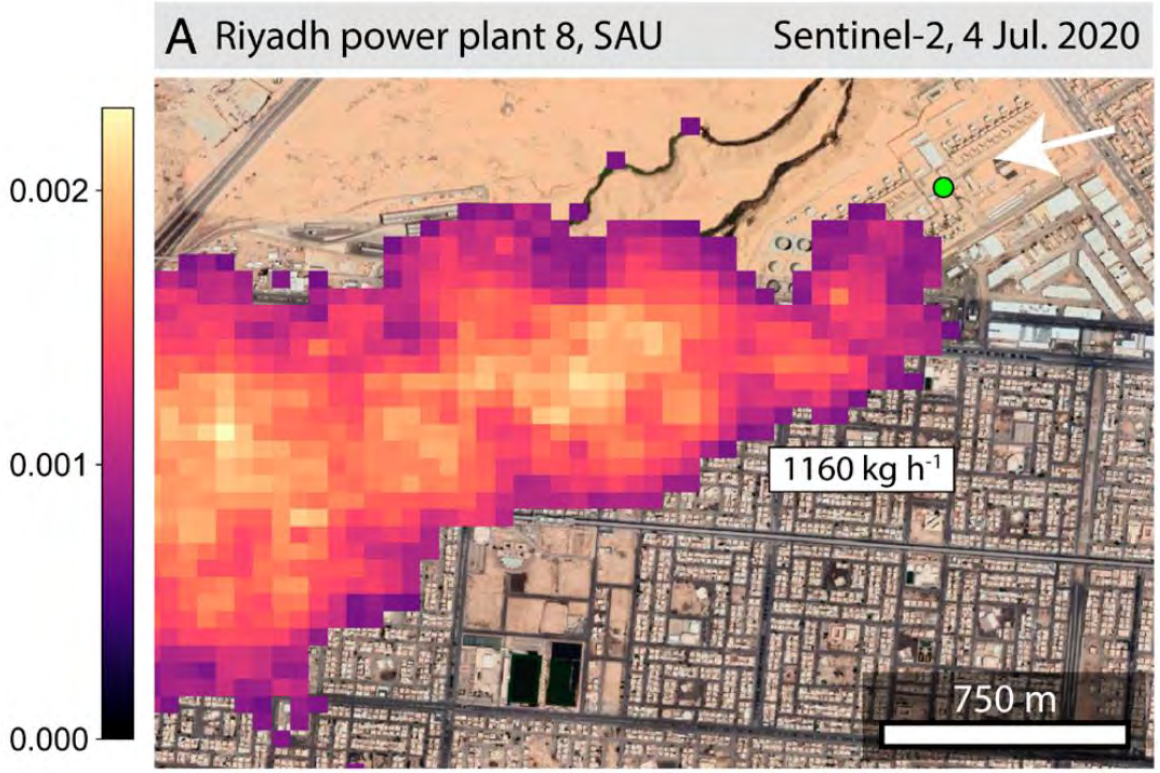
IME: integrated mass enhancement (mass-balance emission inversion)

Top-down about double estimates from our inventory (Barker et al)

[Palmo et al., GRL, *in review*]

NO_x Emissions Derived with Satellite Observations

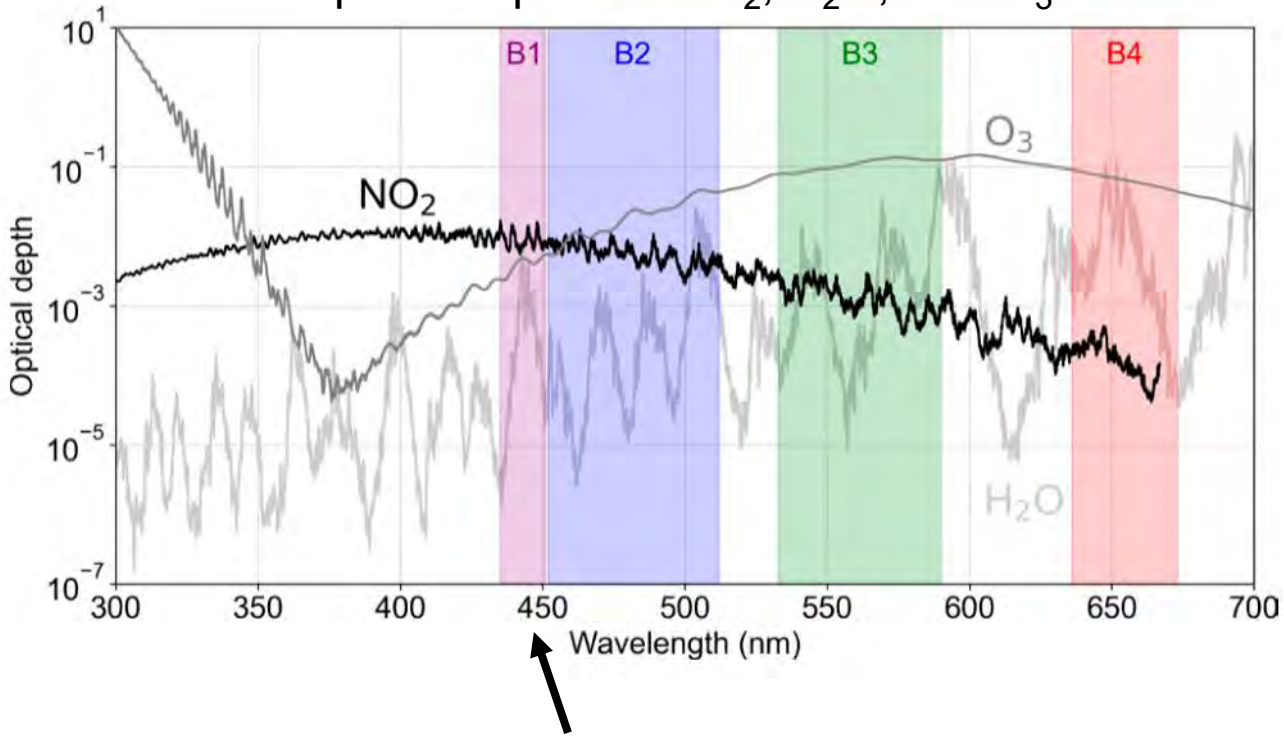
Plume NO_2 enhancement [mol m^{-2}] from Sentinel-2



Paper demonstrated use of broadband sensors to retrieve NO_2 plumes at high resolution (10-60m)

Sentinel-2: space-based optical imager

Optical depths of NO_2, H_2O, and O_3

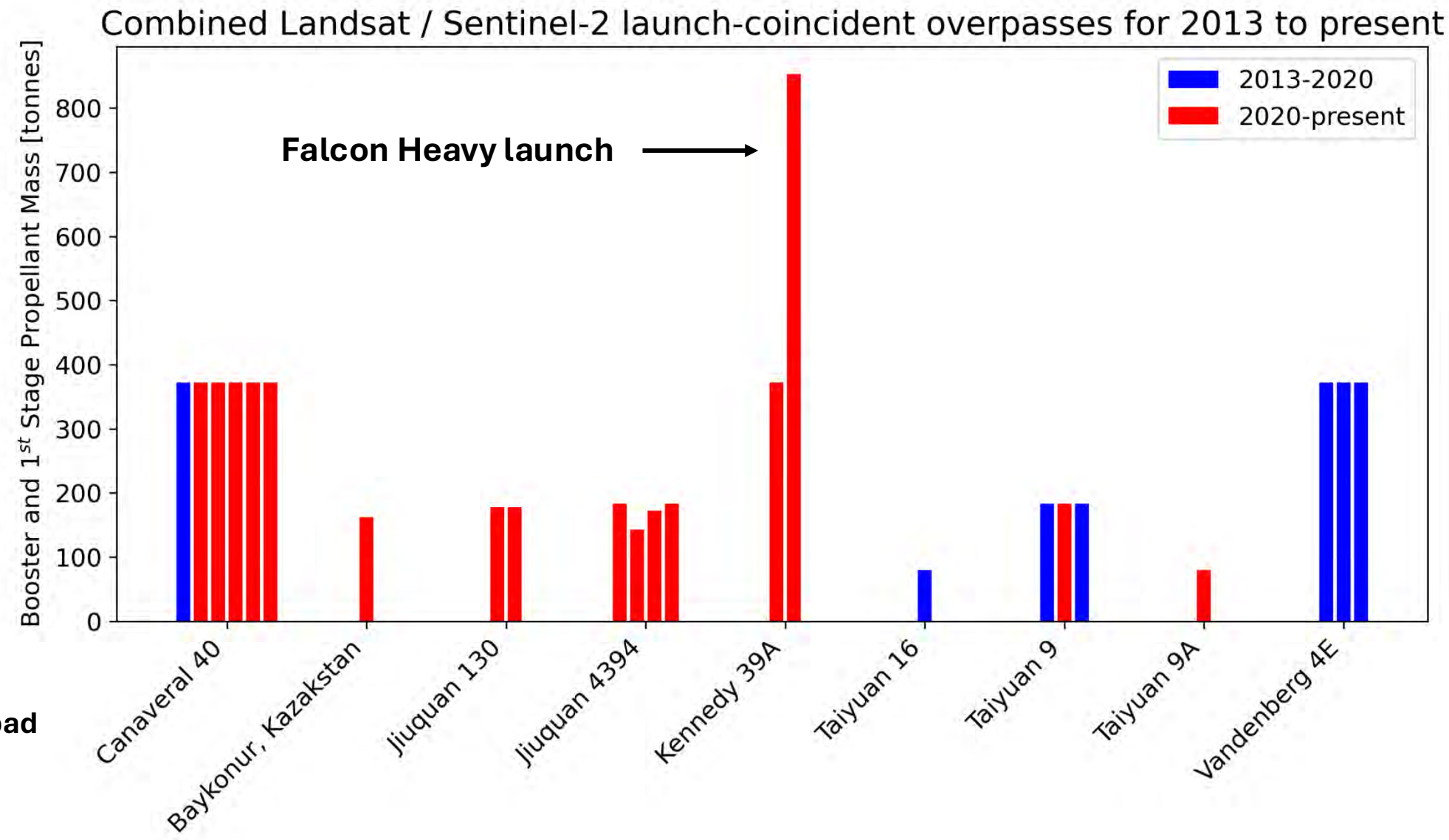


NO_2 retrieval requires ultra blue band

[Varon et al., PNAS, 2024]

Launch NO_x emission rates (>5,000 kg h^{-1}) far exceed power plant NO_x emissions, but launches are transient

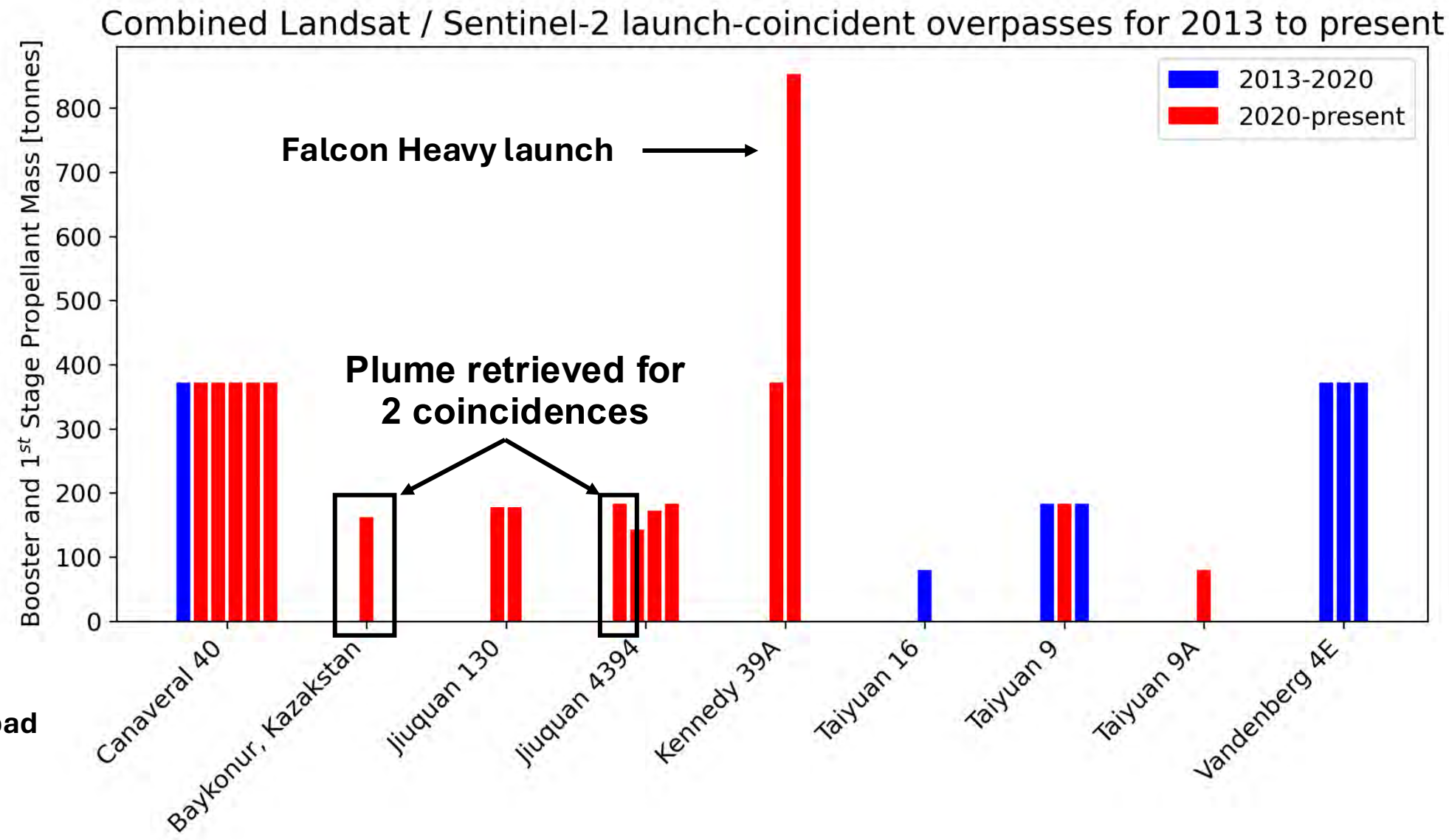
Launches and Broadband Sensor Coincidences



Launchpad names:

23 launch-coincident cloud-free overpasses detected
in the US, China, and Kazakhstan since 2013, mostly since 2020

Launches and Broadband Sensor Coincidences



Launchpad names:

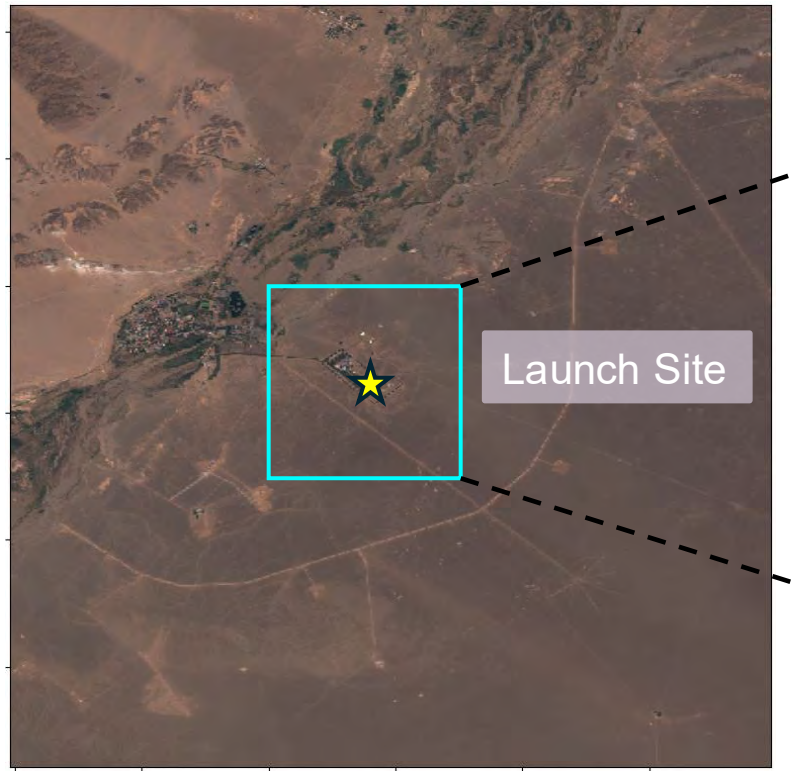
23 launch-coincident cloud-free overpasses detected
in the US, China, and Kazakhstan since 2013, mostly since 2020

Rocket Plume at Jiuquan Launch Site in China

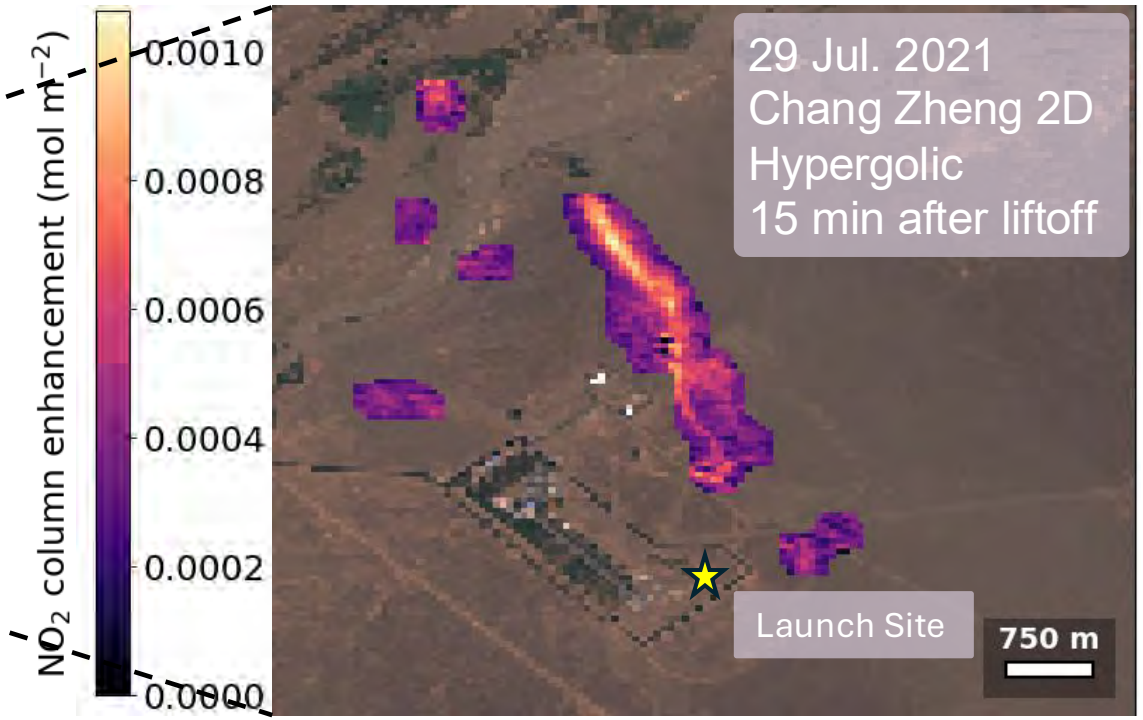
Advanced Research + Invention Agency ARIA

Detected an NO_2 plume at the Jiuquan Satellite Launch Centre in Northwest China:

Sentinel-2 RGB image of the launch site



NO_2 enhancement retrieved from Sentinel-2



Launch pad used for Chang Zheng (Long March) 2D rocket using hypergolic fuel (fuel banned in US)

****Early results**** of launch plume NO_2 from a small hypergolic propellant rocket in 2021

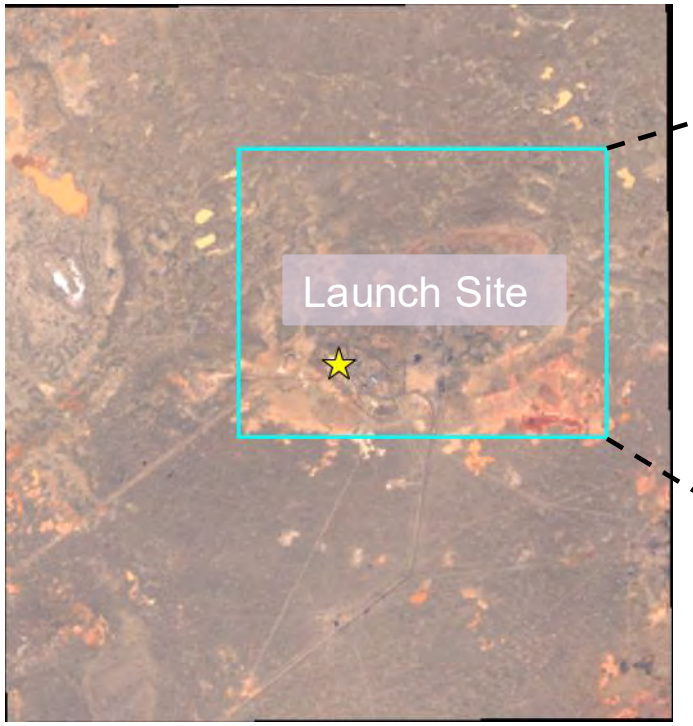
Surface water causes discontinuities in the plume

Rocket Plume at Baykonur Site in Kazakhstan

Advanced Research + Invention Agency ARIA

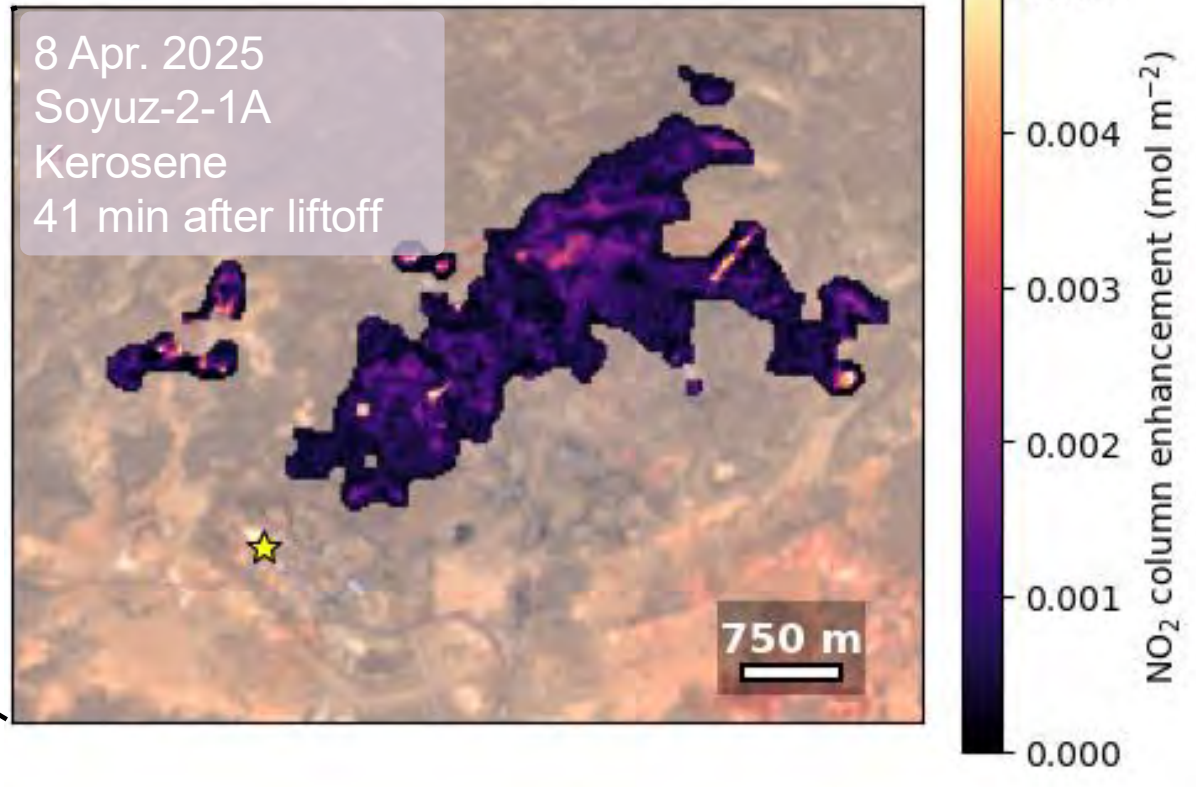
Detected an NO_2 plume at the Baykonur Launch Centre in Kazakhstan:

Landsat RGB image of the launch site



Launch pad used for Soyuz rockets using kerosene fuel (refined jet fuel)

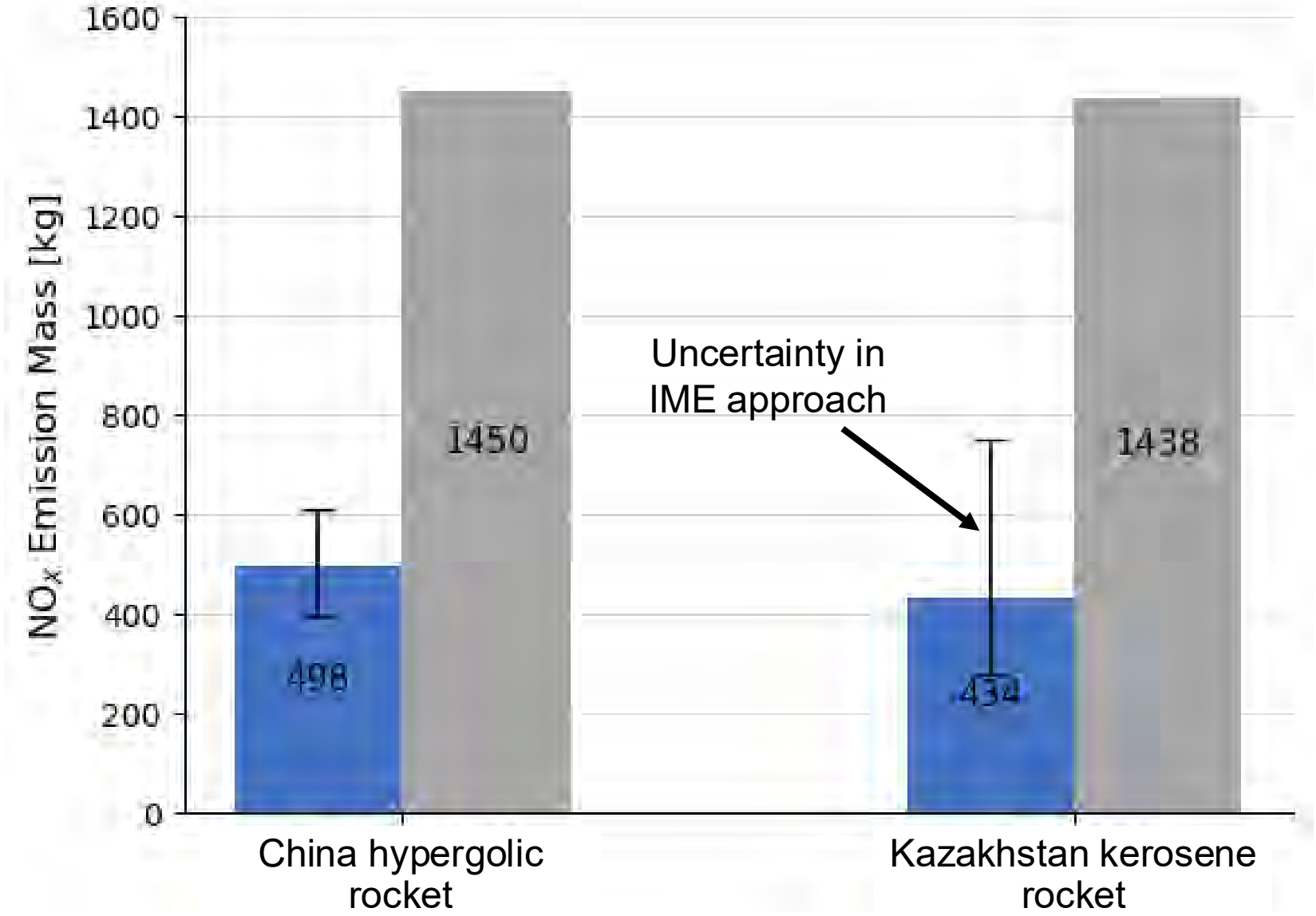
NO_2 enhancement retrieved from Landsat



****Early results**** of launch plume NO_2 from a small kerosene propellant rocket in 2025

Both rockets yield plumes ~4-5 km long.

Top-down vs Bottom-up NO_x Emissions



Top-down

Bottom-up

Top-down 3-times
more than inventory

Top-down NO_x emissions are consistent with each other, but much less than bottom-up estimate

Contemporary vs Anticipated Emissions

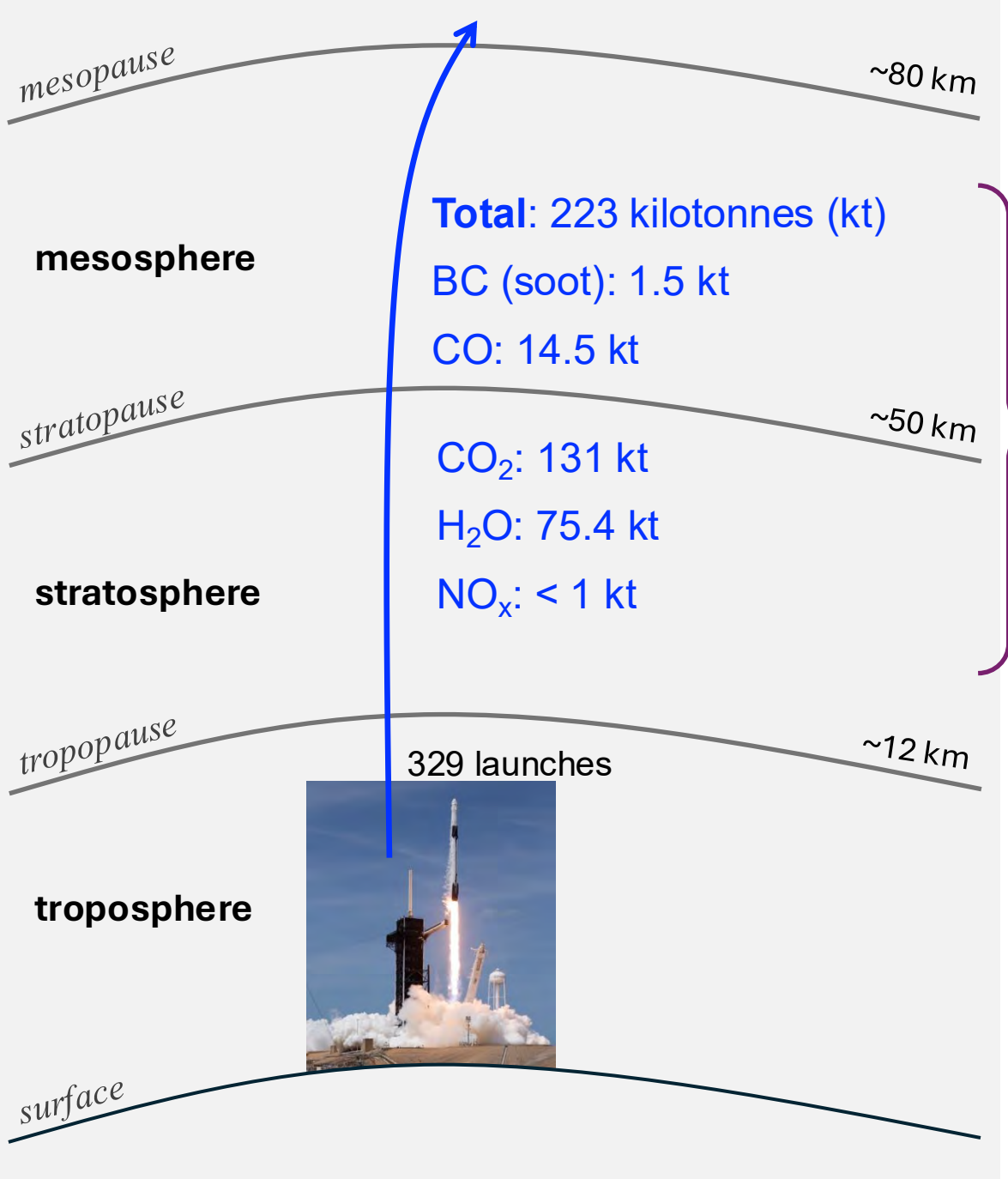
Relatively modest environmental impact from contemporary activities

How might that change with SpaceX February 2026 filing to launch 1 million satellites to establish orbital data centres?

Is an environmental assessment possible with information in filing?



Current (2025) launch influx (baseline):

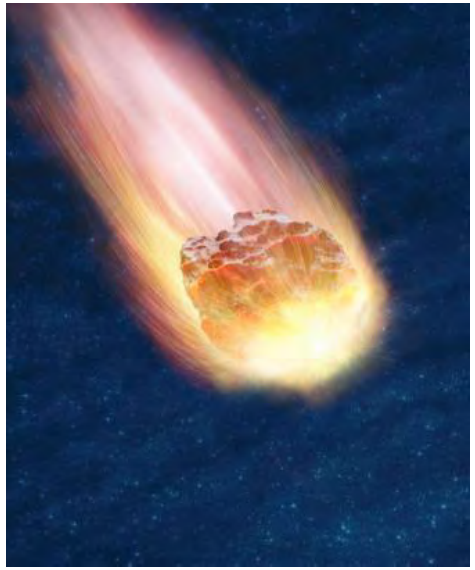


Barker et al. [2024] + Emissions Tracker

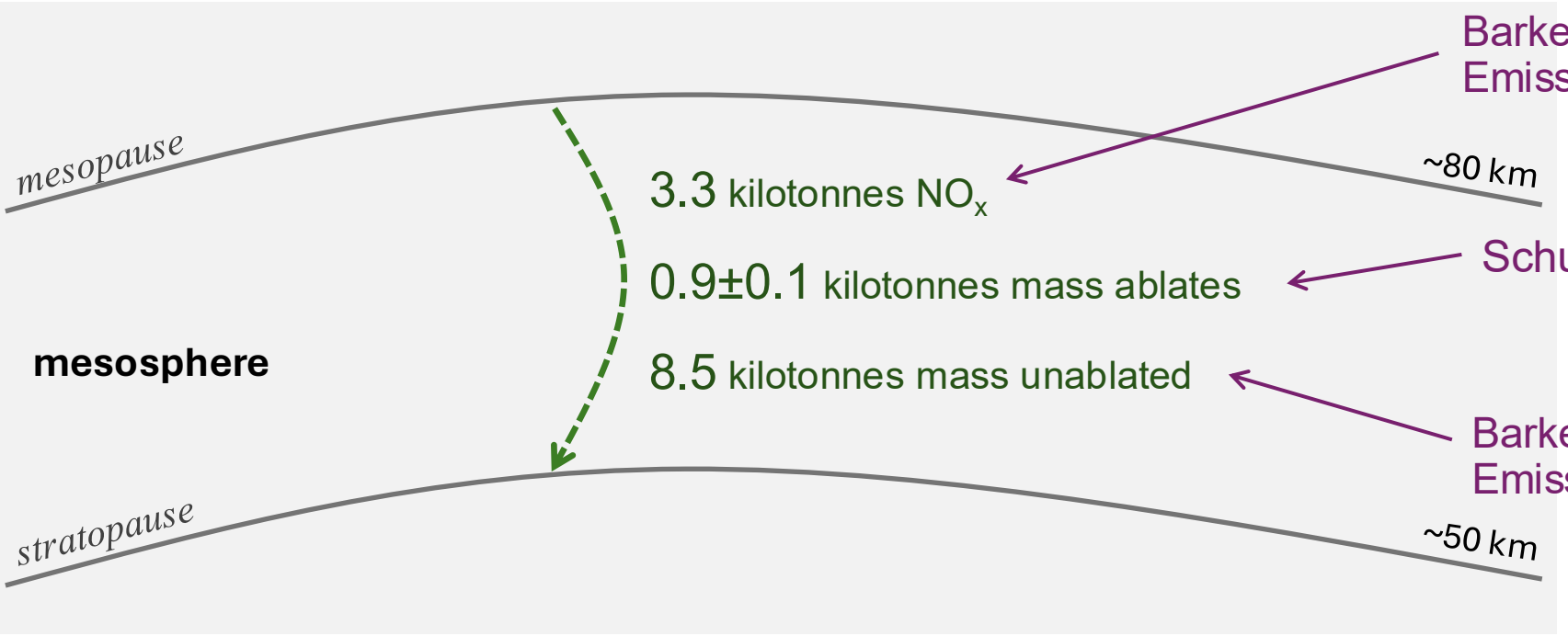
Alumina, chlorine emissions small

Current (2025) re-entry mass and chemical influx

Meteors (natural):



2-40 kt
(mass and NO_x)



Anthropogenic influx less than or on lower-end of natural mass and NO_x from meteors

Information Provided in Filing Documents

Original 4 February filing:

- 1 million tonnes to orbit each year
- Fully reusable rocket
- Satellites designed to demise completely

Orbital configuration table (uploaded almost 3 months after filing)

Group	Altitude Range (km)	Inclination Range (deg)	Number of Shells	Planes Per Shell	Satellites Per Plane	Maximum Satellites per Group
1	550-568	26-32	10	30	333	99,900
2	565-585	97.7	10	2	4,999	99,980
3	686 - 718	30	25	30	333	249,750
4	707 - 744	97.2	22	2	5,565	244,860
5	946 - 978	30	25	30	333	249,750
6	967 - 1002	99.4	22	2	5,770	253,880
TOTAL						1,000,000

Ablative re-entry

Graveyard orbits

Plan for ~200,000 (~20%) of satellites to demise

Additional information sought to constrain launch emissions

Variable	Value or Specificity	Source
Rocket	Starship Block 4	Assumed
Payload mass	200+ tonnes	GCAT
1st stage propellant mass	4050 tonnes	GCAT, Wikipedia
2nd stage propellant mass	2300 tonnes	GCAT

Able to rely on reputable source

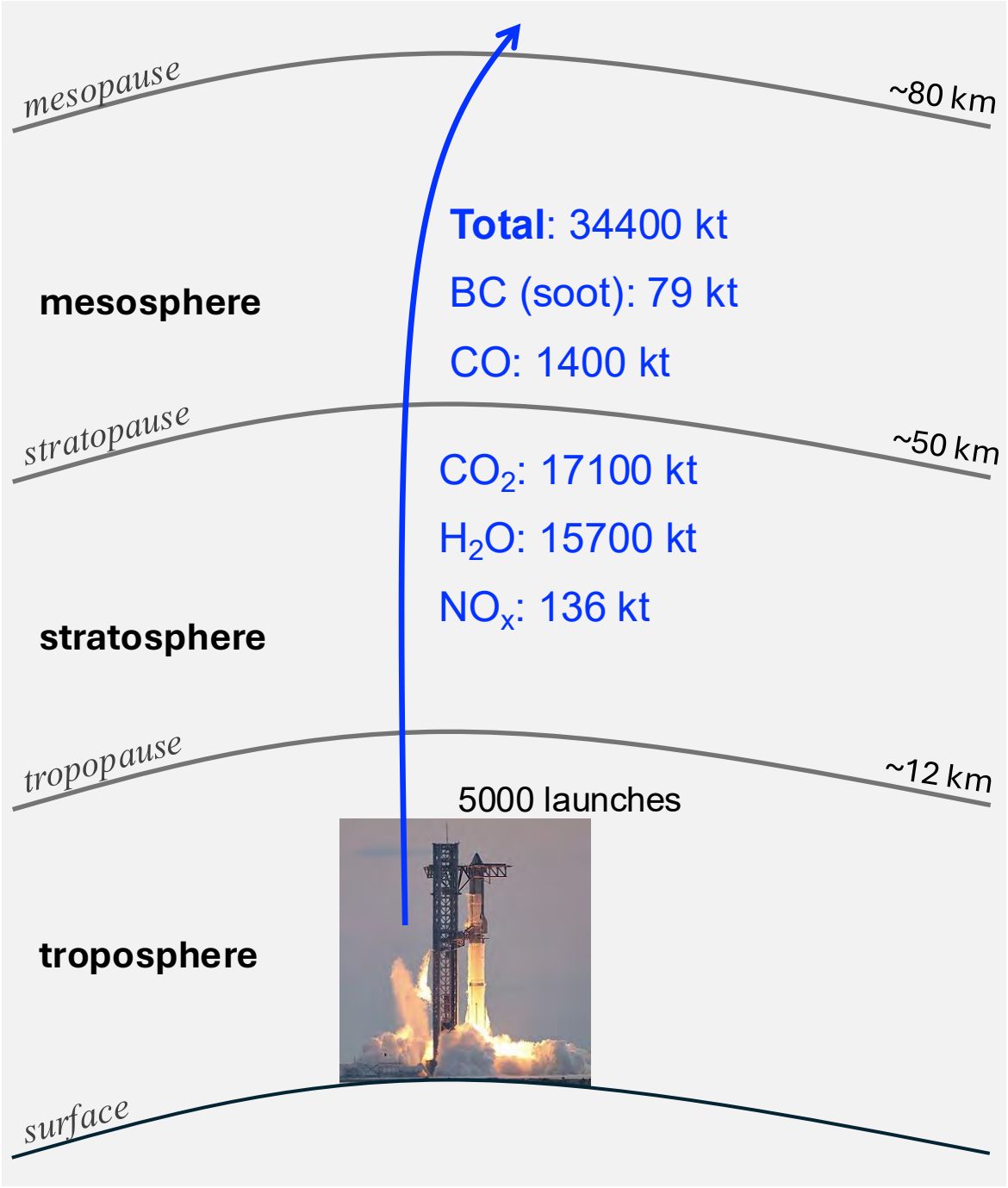
GCAT:

GCAT: General Catalog of Artificial Space Objects

Jonathan C. McDowell

Object Catalogs

Influx for a year of data centre launches:



Other concerns:

- Surface air quality
- Fugitive emissions of methane (CH_4)

Additional information sought to constrain re-entry emissions

Variable	Value or Specificity	Source
Methalox propellant	22:78 LCH_4:LOX mass ratio	FAA Environmental Assessment
Rocket body heat shields	On both stages	Wikipedia
Re-entry approach	60° angle “bellyflop” approach	Wikipedia
Re-entry propellant use	No entry burn	Space Expl. Stack Exchange
Unused LCH_4 fuel	5 tonnes	FAA Environmental Assessment
Reserve propellant for return	~1% of total	Inferred from Falcon 9
1^{st} stage re-entry velocity	1.1 km s^{-1}	Fandom wiki site
2^{nd} stage re-entry velocity	7.5 km s^{-1}	Fandom wiki site

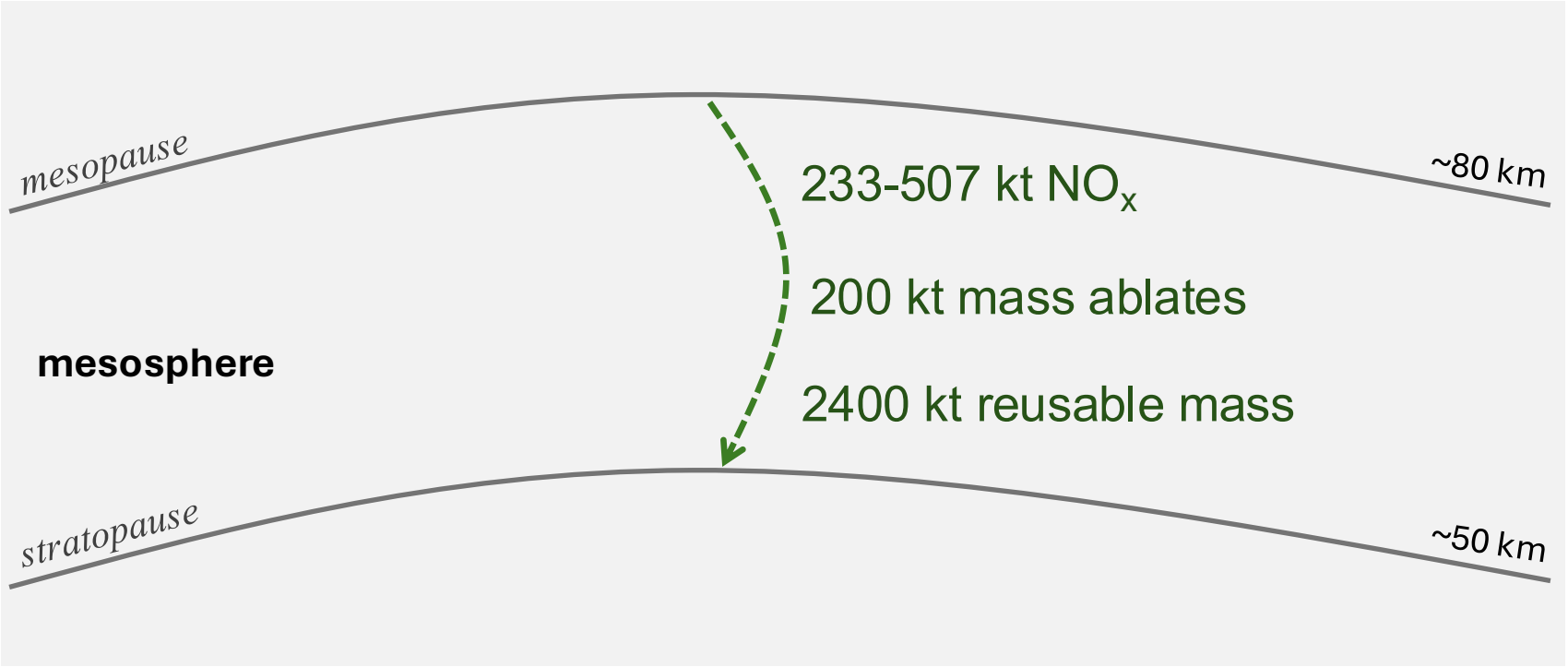
Reliant mostly on **unvetted/unconfirmed sources** and need to invoke many assumptions

Re-entry influx from a year of data centre launches

Meteors (natural):



2-40 kt
(mass and NO_x)

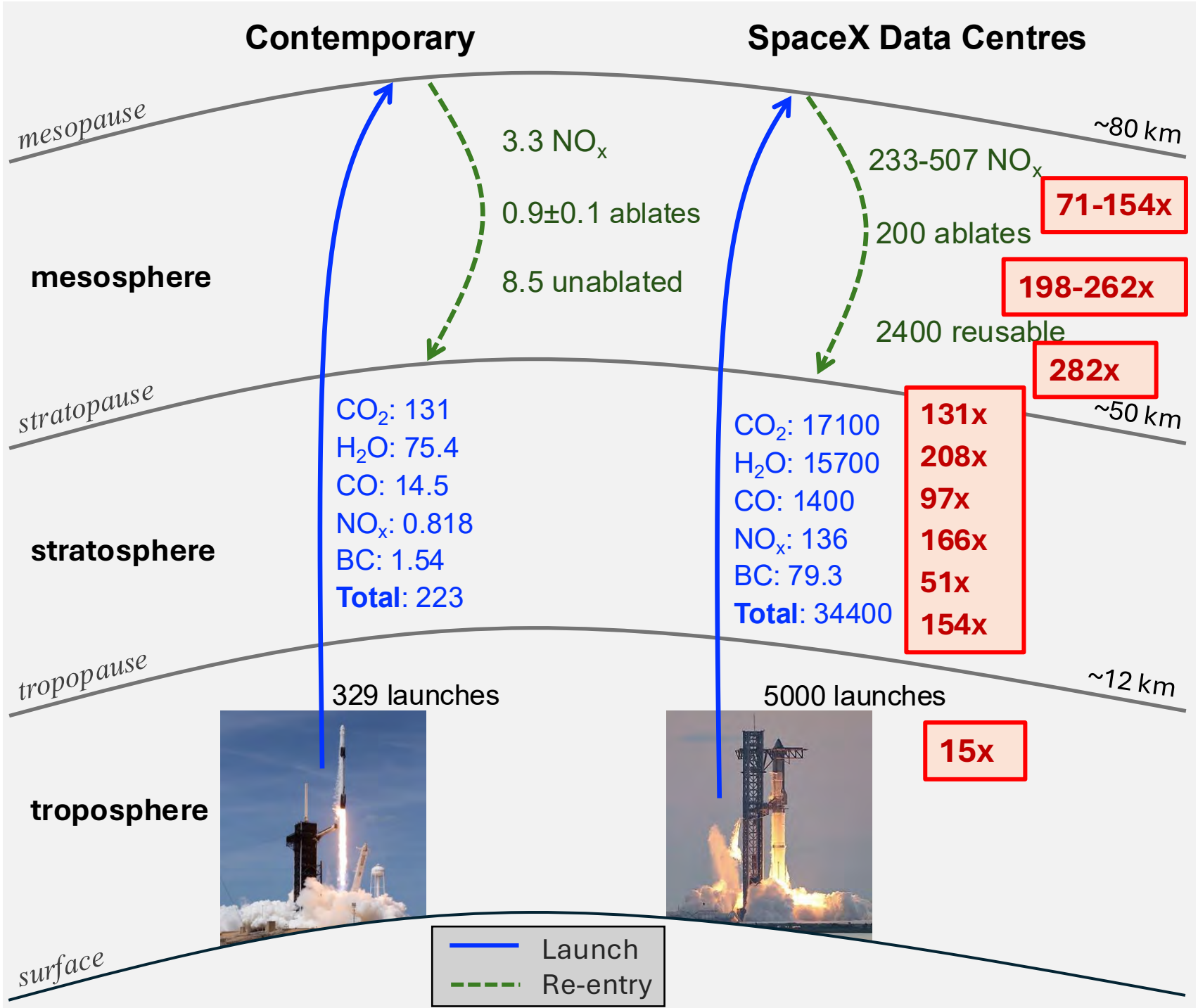


Anthropogenic >> natural

Can’t determine metal and non-metal influx, as no material composition data

Scale of growth:

Units for green and blue values: kilotonnes



70-150 times more re-entry NO_x

200-300 times more re-entry mass

50-200 times more launch emissions

Closing Remarks

- Far more observations (and funding!) needed to address science gaps, to arbitrate between top-down and bottom-up, to validate model results, and to track atmospheric changes due to launches and re-entries
- Current atmospheric harm is modest, but has potential to change fast
- No regulatory measures to prevent harm in the future
- 2 orders of magnitude increases in mass and chemicals with orbital data centre ambitions (even if not fully realised, environmental review is needed)
- Orbital data centres would shift upper atmosphere to anthropogenic state (offset chemical balance, alter nitrogen cycle in mesosphere, change stratospheric aerosol composition and characteristics etc.)
- Our calculations (albeit back-of-envelope) provide steer to regulators on bare minimum information needed to enable environmental review
- A million data centre satellites emission estimates [Marais, Barker, 2026] is in review