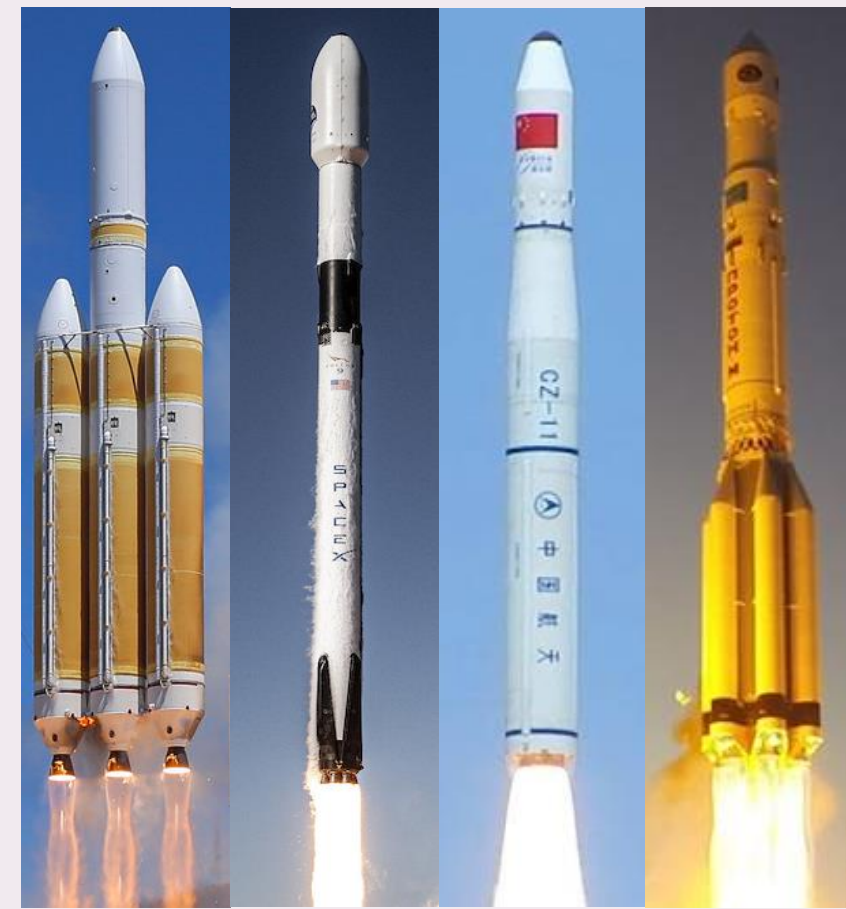
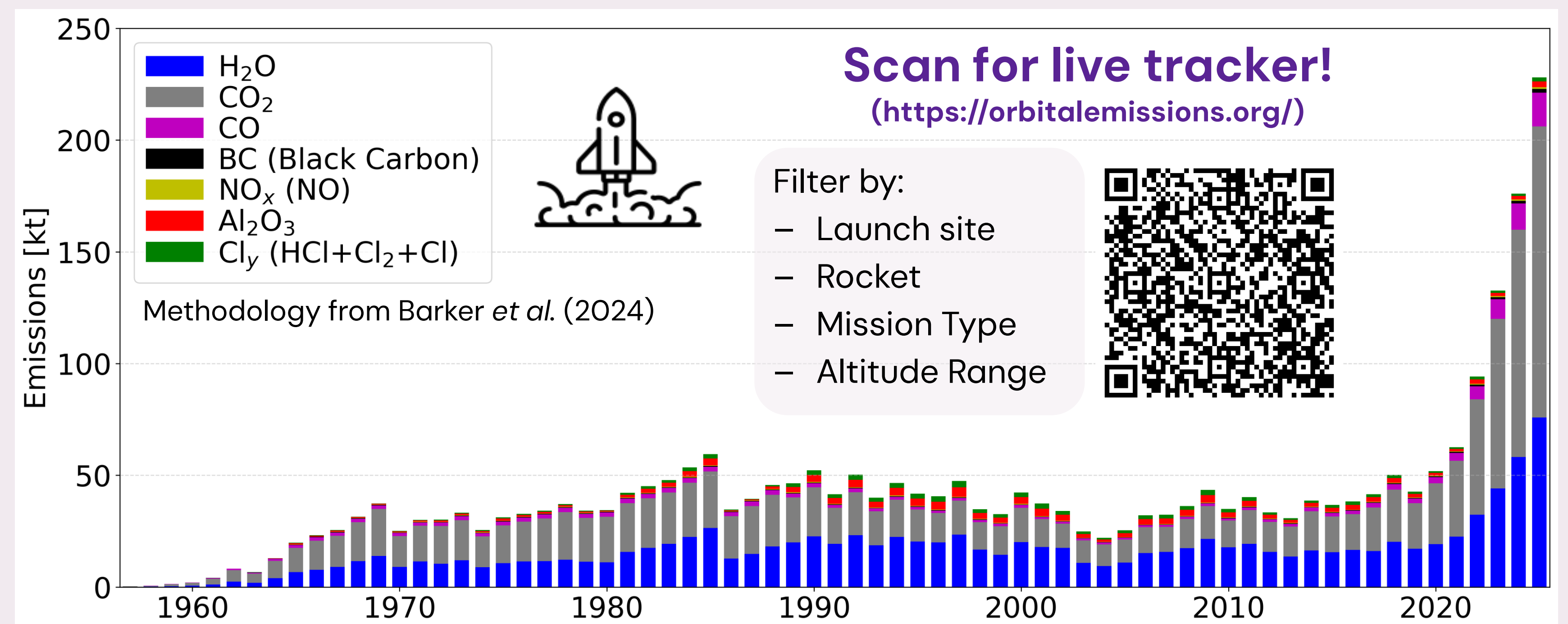


1. Rapid growth of the space industry

- There were a record **329** rocket launches in 2025, up from an average of 78 from 2000–2019.
- This surge is driven by satellite megaconstellations (SMCs) such as Starlink, OneWeb, Amazon Leo, Qianfan, and Guowang.



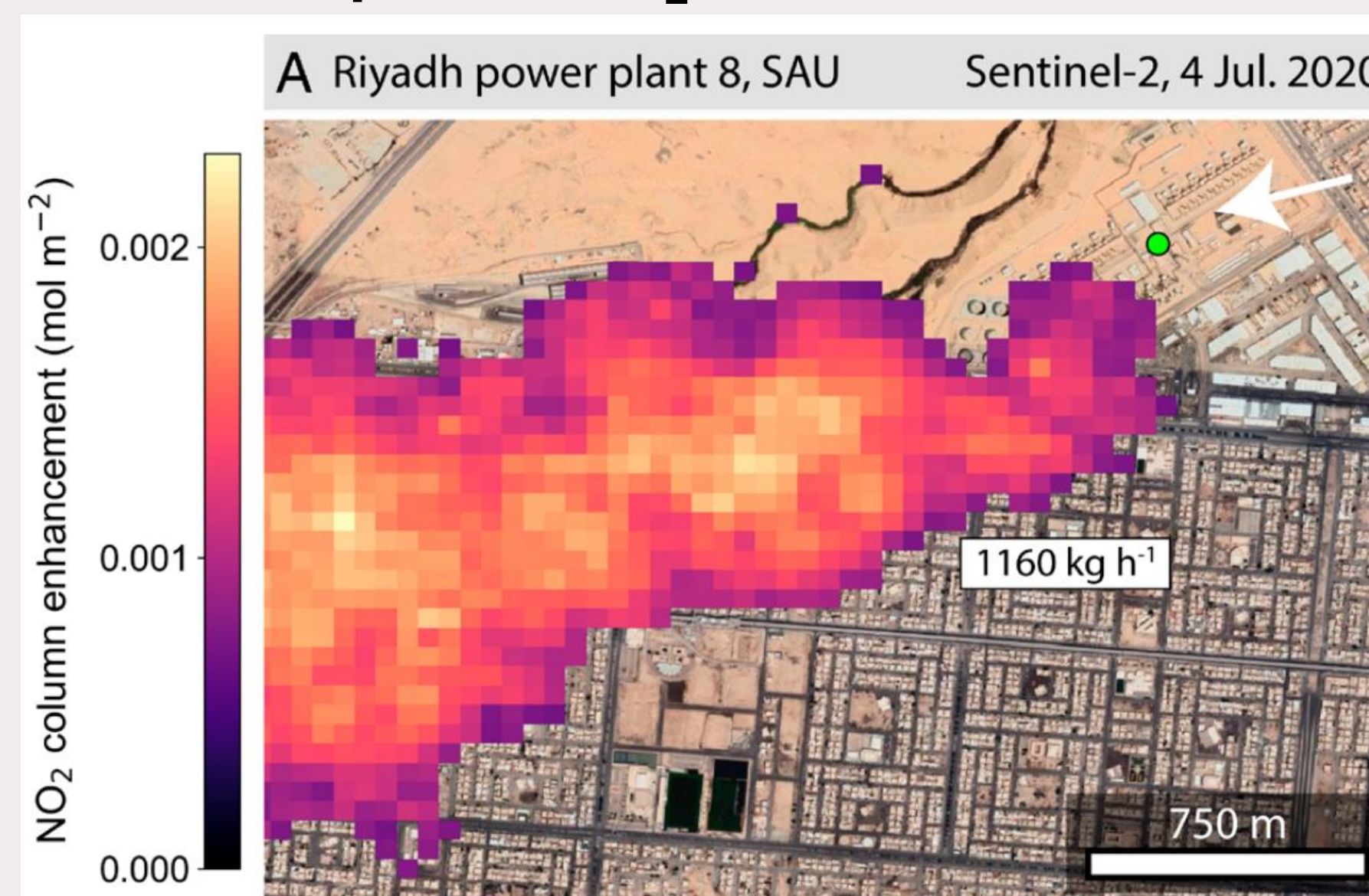
2. Online tracker of rocket launch emissions



Exponential increase in rocket launch air pollutant and CO₂ emissions released throughout the atmosphere.

4. Quantifying NO₂ plumes using remote sensing

Retrieved plume NO₂ enhancement [mol m⁻²]



Broadband sensors (Sentinel-2, Landsat) can be used to detect power plant plume NO₂ at high resolutions (10–60m).

Challenges applying to rocket launches:

- Low probability of a launch-coincident satellite overpass.
- Retrieval may also detect co-emitted condensed water vapour and aerosol.
- Retrieval is not suitable over water, eliminating coastal sites.

5. Retrieval process

- Building the Reference**

 Identify similar reference scenes using red band, then combine into one 'idealized' reference
- Normalized Reflectance Ratio**

$$r = \frac{c R_i}{R_j}$$

 Account for scene-wide reflectance offsets and isolate plume signal
- NO₂ Vertical Column**

$$\Delta\Omega_V = -\frac{\ln(r)}{\sigma \times AMF}$$

 Convert the ratio to the NO₂ vertical column ($\Delta\Omega_V$) in units of mol m⁻²
- Plume Detection**

 Smooth and use a percentile filter to detect the plume
- Second Retrieval**

 Repeat steps 2–4, with plume pixels now excluded from the scale factor calculation. This is to isolate the scene-wide scaling from background pixels only.

27 suitable scenes have been identified out of 2015 launches since 2013 (1.3%)

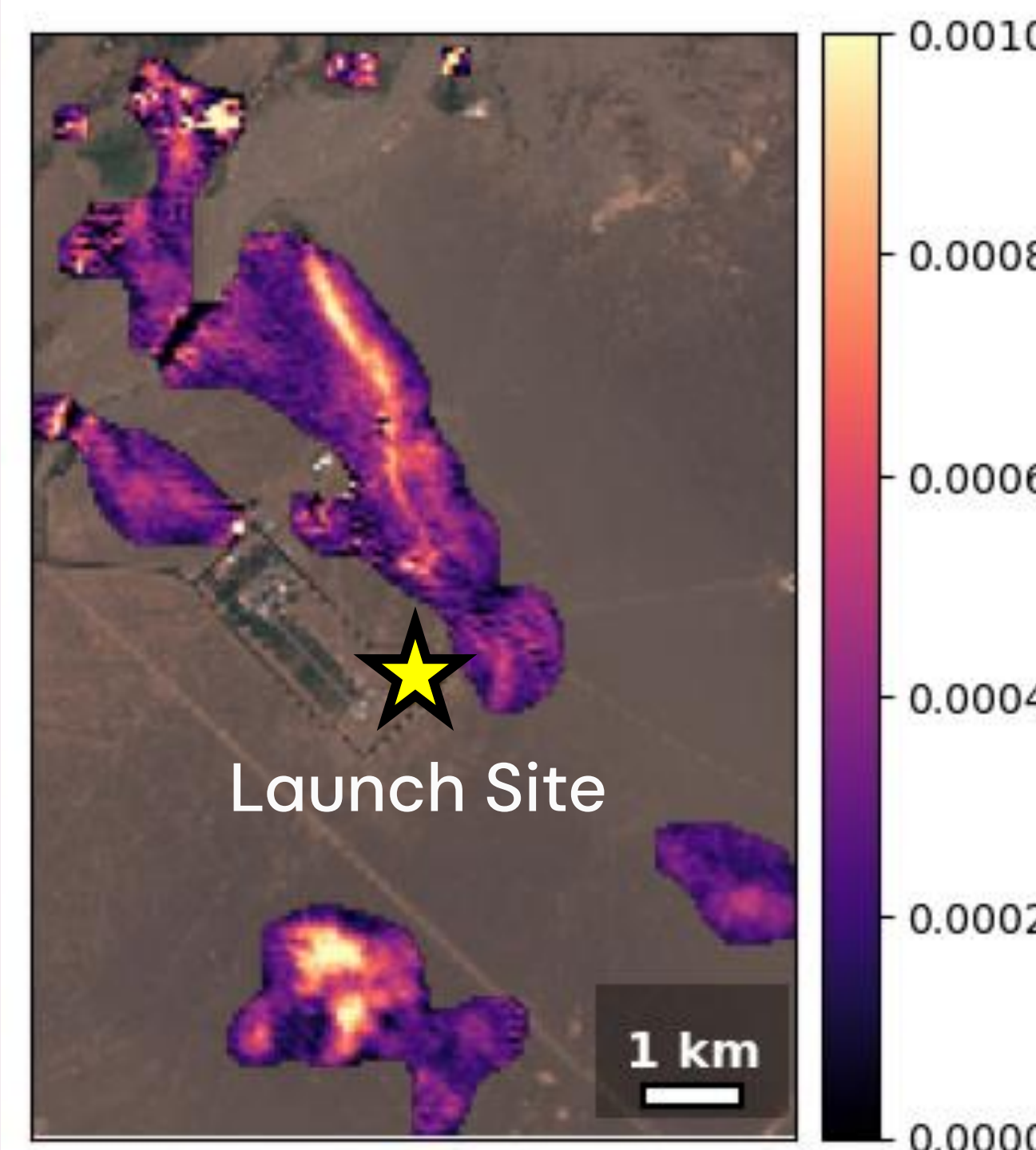
8. Future work and references

- Analyse the additional 69 suitable scenes identified from the Planet SuperDove satellite constellation.
- Assess the impact of absorption by launch-emitted black carbon and condensed water vapour on our retrievals using forward radiative transfer modelling.

McDowell, J.C. (2025). General Catalog of Artificial Space Objects, Release 1.8.7, <https://planet4589.org/space/gcat>
 Barker, C.R. et al. (2026). *Earth's Future*, 14, e2025EF007229.
 Barker, C.R. et al. (2024). *Nature Sci Data*, 11, 1079.
 Varon, D.J. et al. (2024). *PNAS*, 121, 27.

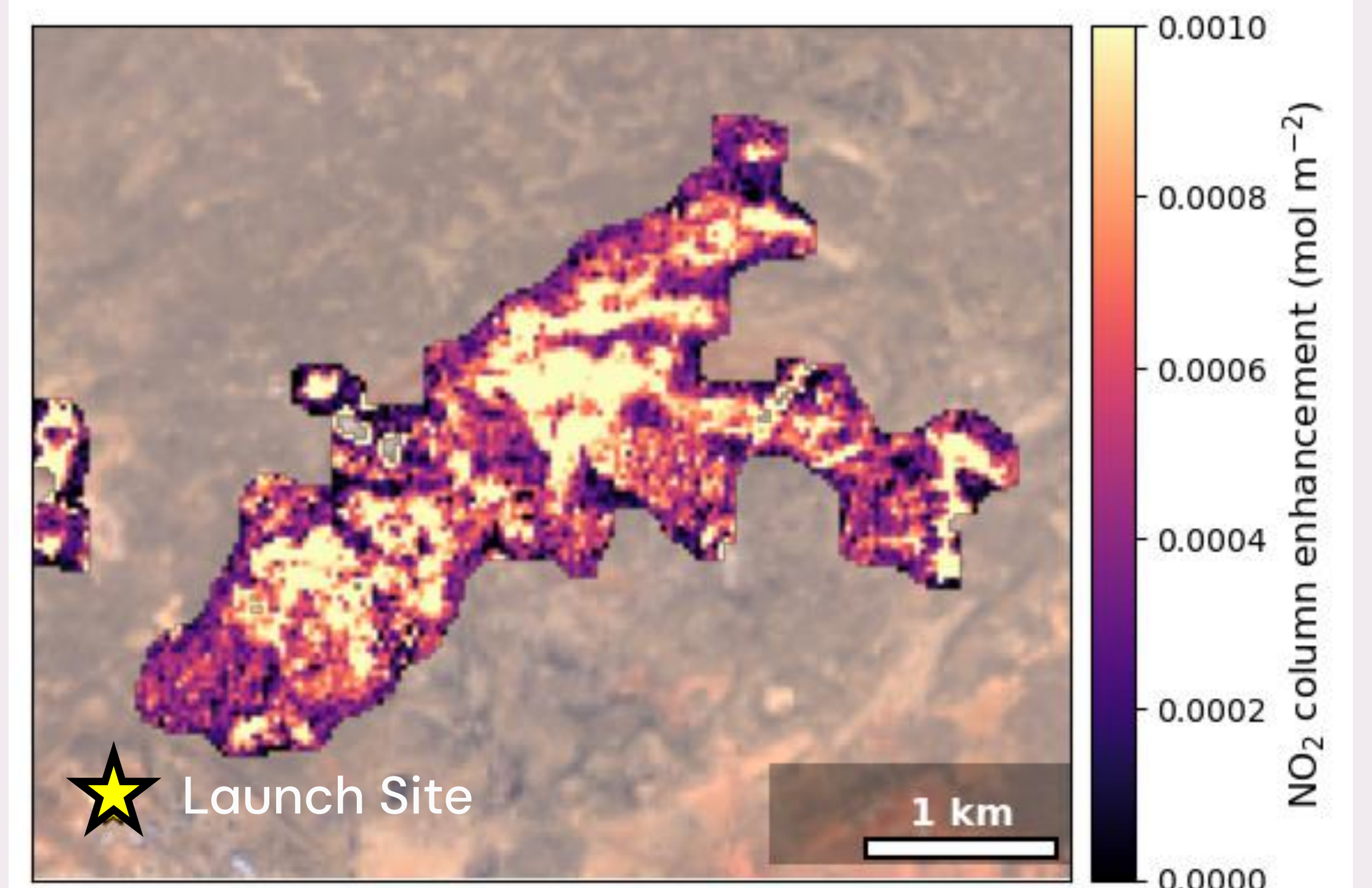
6. Rocket launch plumes detected so far

Jiuquan Satellite Launch Center, Northwest China



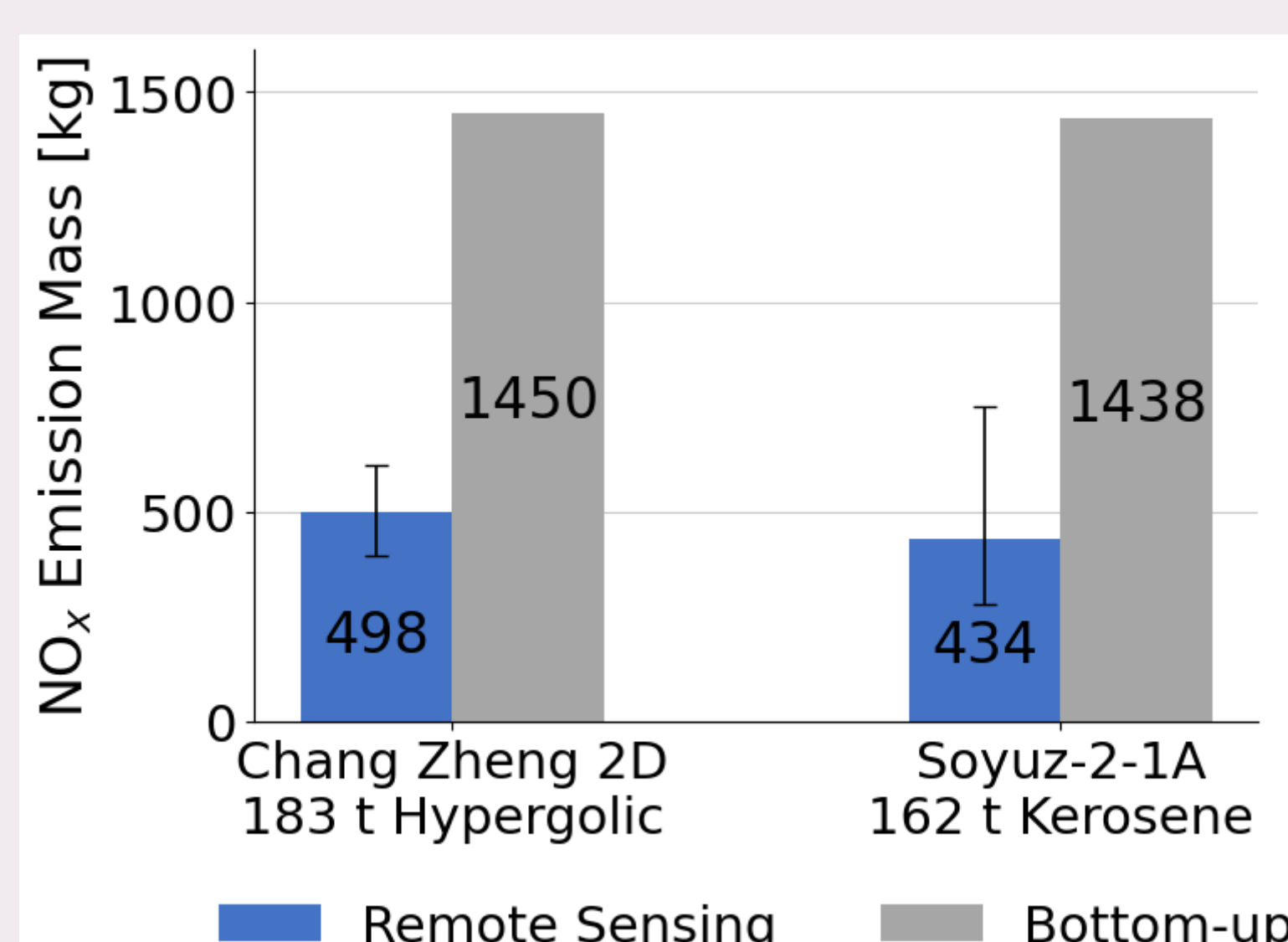
Sentinel-2
 29 July 2021
 Chang Zheng 2D
 Hypergolic propellant
 15 mins after liftoff

Baikonur Launch Centre, Kazakhstan



Landsat 8/9
 8 April 2025
 Soyuz-2-1A
 Kerosene propellant
 41 mins after liftoff

7. Rocket NO₂ emissions estimates



- The Integrated Mass Enhancement approach is used to quantify total NO_x emissions from the detected plume.
- This calculation step accounts for plume processing since the launch and the conversion of NO₂ to total NO_x.

The satellite-derived NO_x emissions are consistent across overpasses, but much lower than bottom-up estimates.