SAE/2024_Gulfstream/2025_Jun_ETH_Conference/
R.Miake-Lye_vPM_and_nvPM_Emissions.pptx

25th ETH Nanoparticle Conference
Zürich, Switzerland
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Volatile and non-Volatile PM emissions: SAF & Fuel composition effects

Prepared and Presented by:

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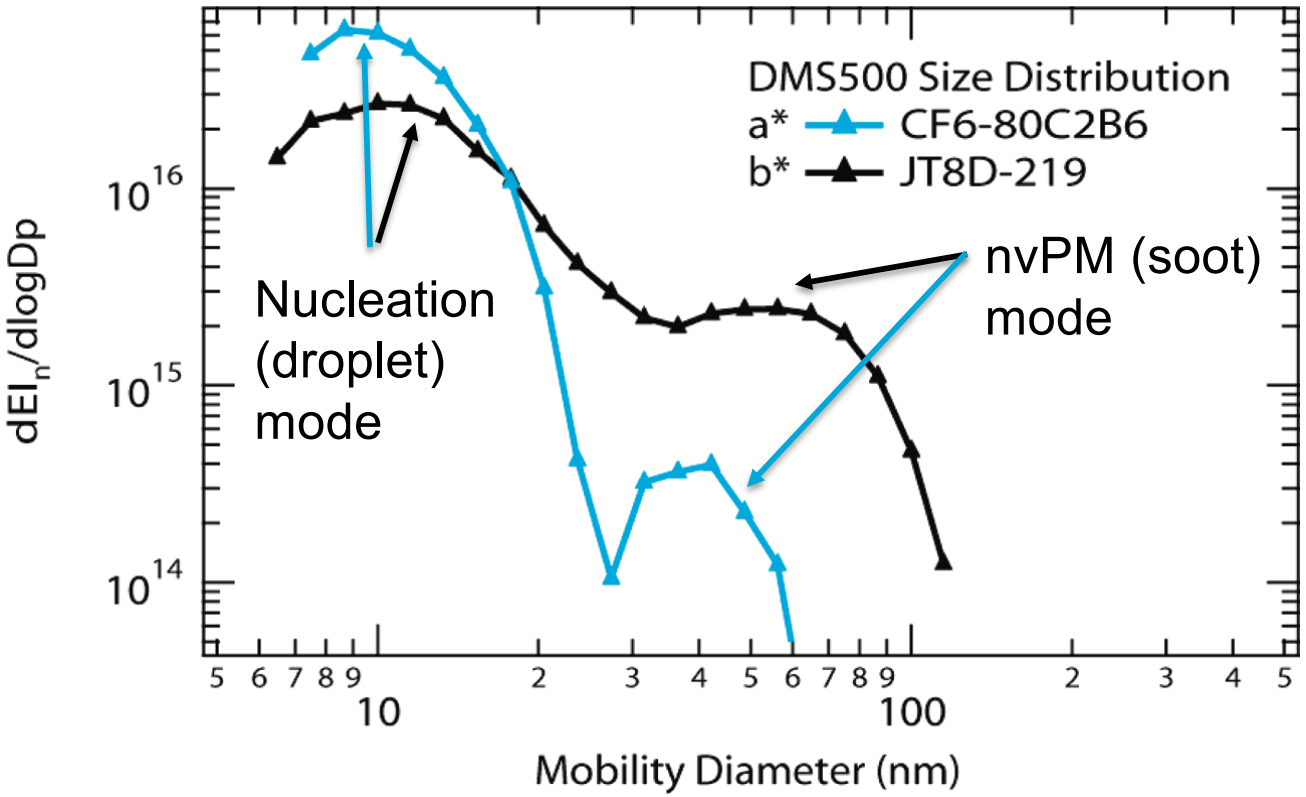
Sustainable Aviation Fuels

- Bio-sourced fuels (SAFs) a major interest for commercial aviation: help mitigate CO_2 footprint
- Have found SAFs can decrease soot (nvPM) significantly (cleaner burning)
  - Local Air Quality benefits
  - Less soot for contrail formation: does this affect contrails' radiative forcing?
  - Due to decrease in aromatic species in fuel
    - *similar gains could be obtained with fossil fuel of same composition*
- May also affect vPM (and gaseous pollutant) emissions . . . Impacts of vanishing FSC?

Volatile particles add to soot downstream



from: Herndon et al., *Env. Sci. Technol.* **2008,** *42,* 1877–1883, 26 - 29 September 2004, MS&T (UMR) measurements at Hartsfield-Jackson International Airport, *with annotation added*.

- Advected plumes at airport (100s of m)
- Bimodal distributions indicate both soot mode and a smaller mode
- Smaller mode can be 1 to 2 orders of magnitude more numerous than soot mode
- Many additional engine and airport studies

Importance of volatiles in total PM

- Volatile PM contributions to the various PM modes:
  - newly formed volatile particles (smallest mode: nucleation mode)
  - condensed species on soot surfaces
  - oil mode (sometimes a separate, larger mode)
- Species involved:
  - H_2SO_4 (with water)
  - Organic species due to incomplete combustion
    - some raw fuel (at idle)
    - partially oxidized HCs
    - pyrolytic species, other HCs, etc.
  - oil vapors and droplets emitted from oil system vent
- Aerosol Mass Spectrometer (AMS) sees Aerosol Composition:
  - oil mode (when present: some engines vaporize the oil when venting)
  - soot coating composition (organics, sulfate)
  - nucleation mode usually too small for AMS to see

Ground-based emissions measurements

Boeing ecoDemonstrator 2022 Ground Test

nvPM Mass:

- Laser-Induced Incandescence (LII)
- Photo Acoustic (MSS)
- Cavity Attenuated Phase shift (CAPS)

PM Number:

- Various particle counting (CNC)

PM Size:

- Scanning Diffusion column (SMPS)
- Rapid parallel column (DMS, EEPS)
- Parallel CNCs

Boeing ecoDemonstrator 2021 Ground Test

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Gulfstream G700 SAF 2024 ground test

Gulfstream Photo Credit

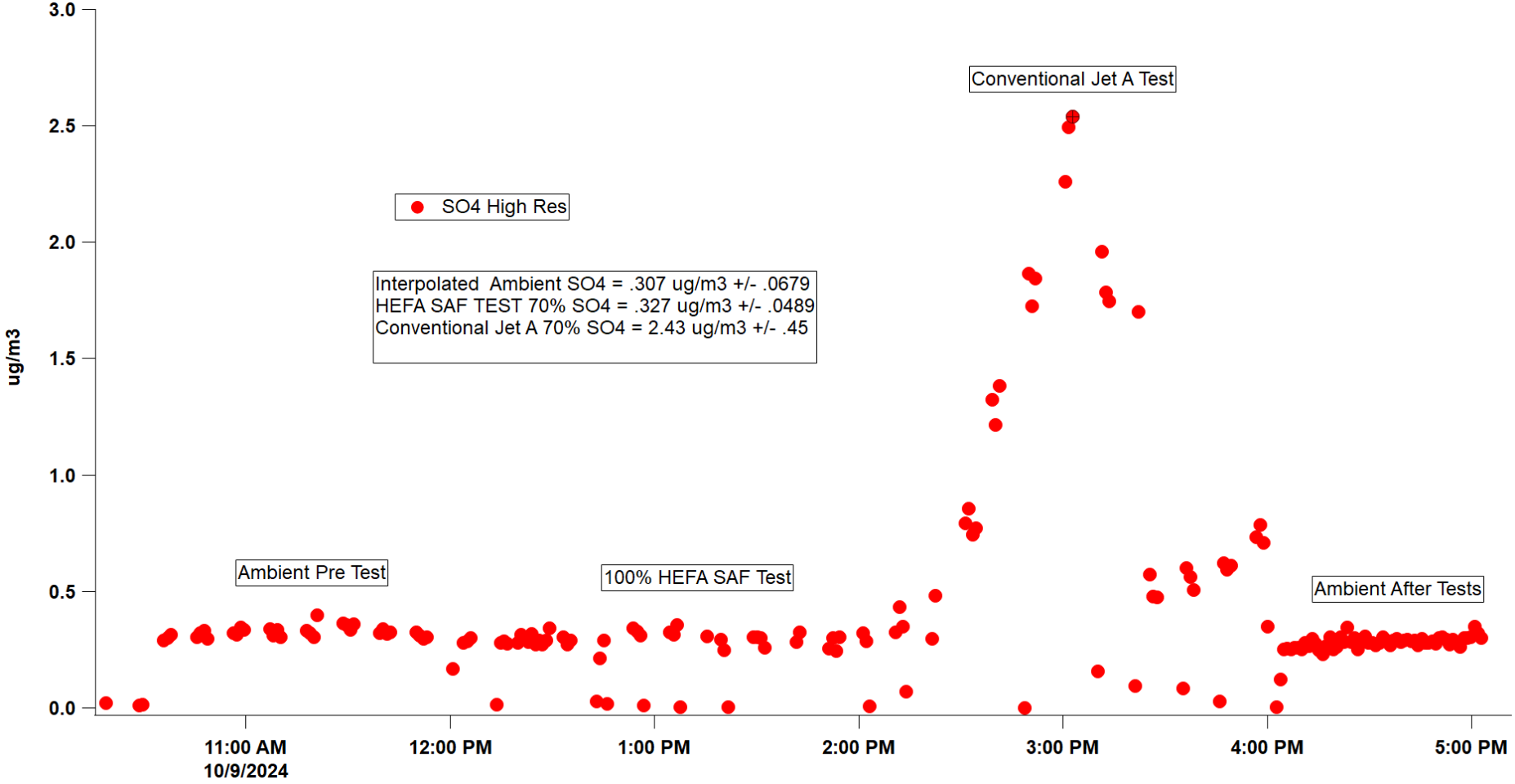
Gulfstream G700 SAF 2024 ground test

- Aerodyne, MS&T, FAA, NASA, Colorado State, Rolls Royce (Germany), Gulfstream Team
  - Press release, 31 October 2024:

  https://www.gulfstreamnews.com/en/news
- World Energy, World Fuel Services for HEFA SAF
- 3 Fuels: 100% SAF; 30%SAF/70%JetA; JetA
  - Rolls Royce Pearl 700 engine, sampled at ~ 21 m
  - minimal to ***no sulfur contamination*** of 100% SAF
  - potential of 100% neat SAF for improving local air quality near airports
  - possible benefits of reducing the formation of condensation trails.
- Also deflected/redirected oil vent flow to minimize oil contributions to exhaust emissions (not discussed here)

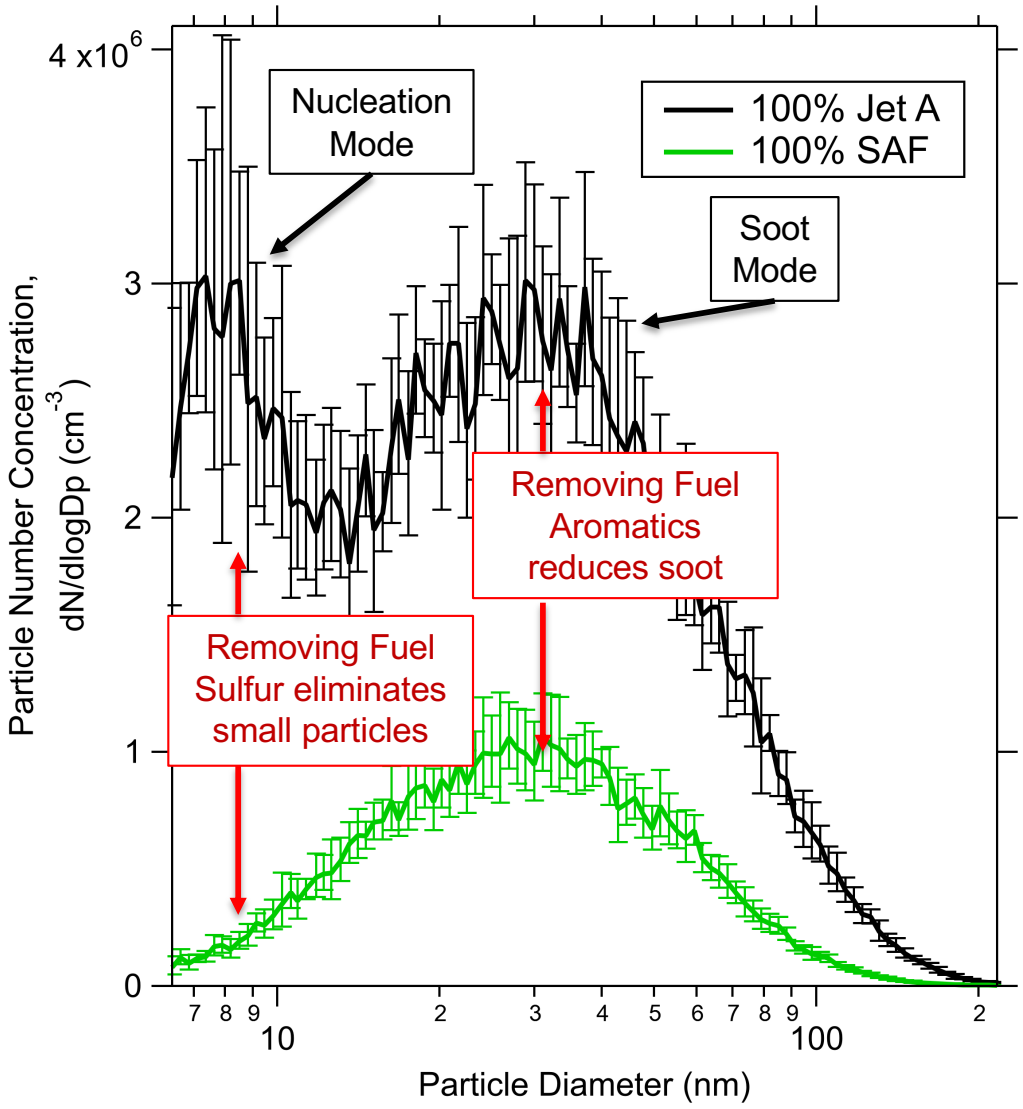
Sulfur on soot is gone with S → 0

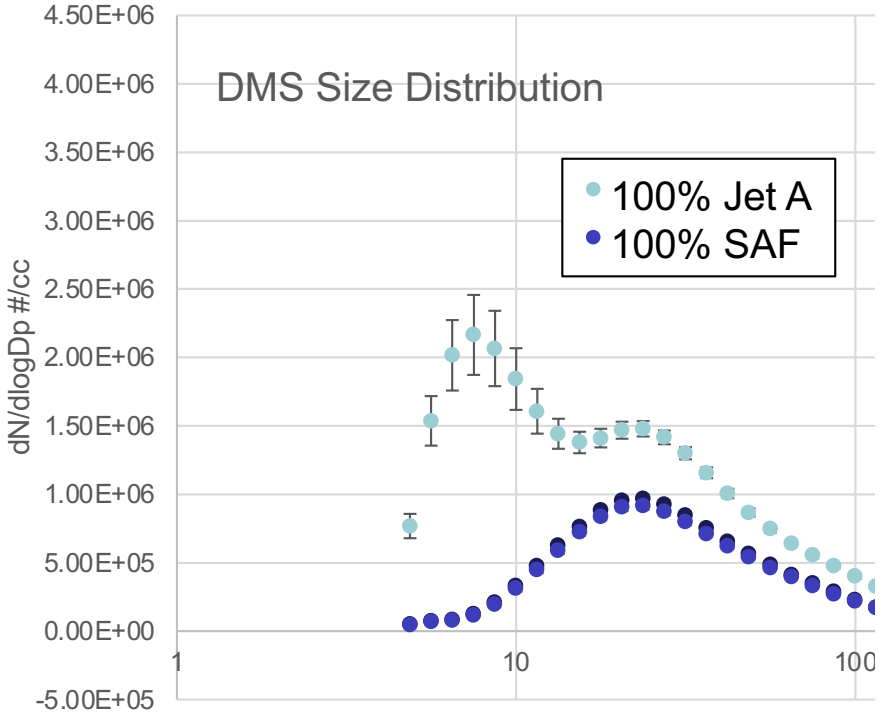
AMS high-resolution SO_4 time series from Day 1 Test: 100% SAF and Jet A



Gulfstream G700 SAF 2024 ground test

Nucleation Mode is gone with S → 0





- Nucleation mode accounts for most particles at >100 m downstream
- Major change in microphysics: new particles are not formed
- If no nucleation, what are implications for soot activation for contrails?

Gulfstream G700 SAF 2024 ground test

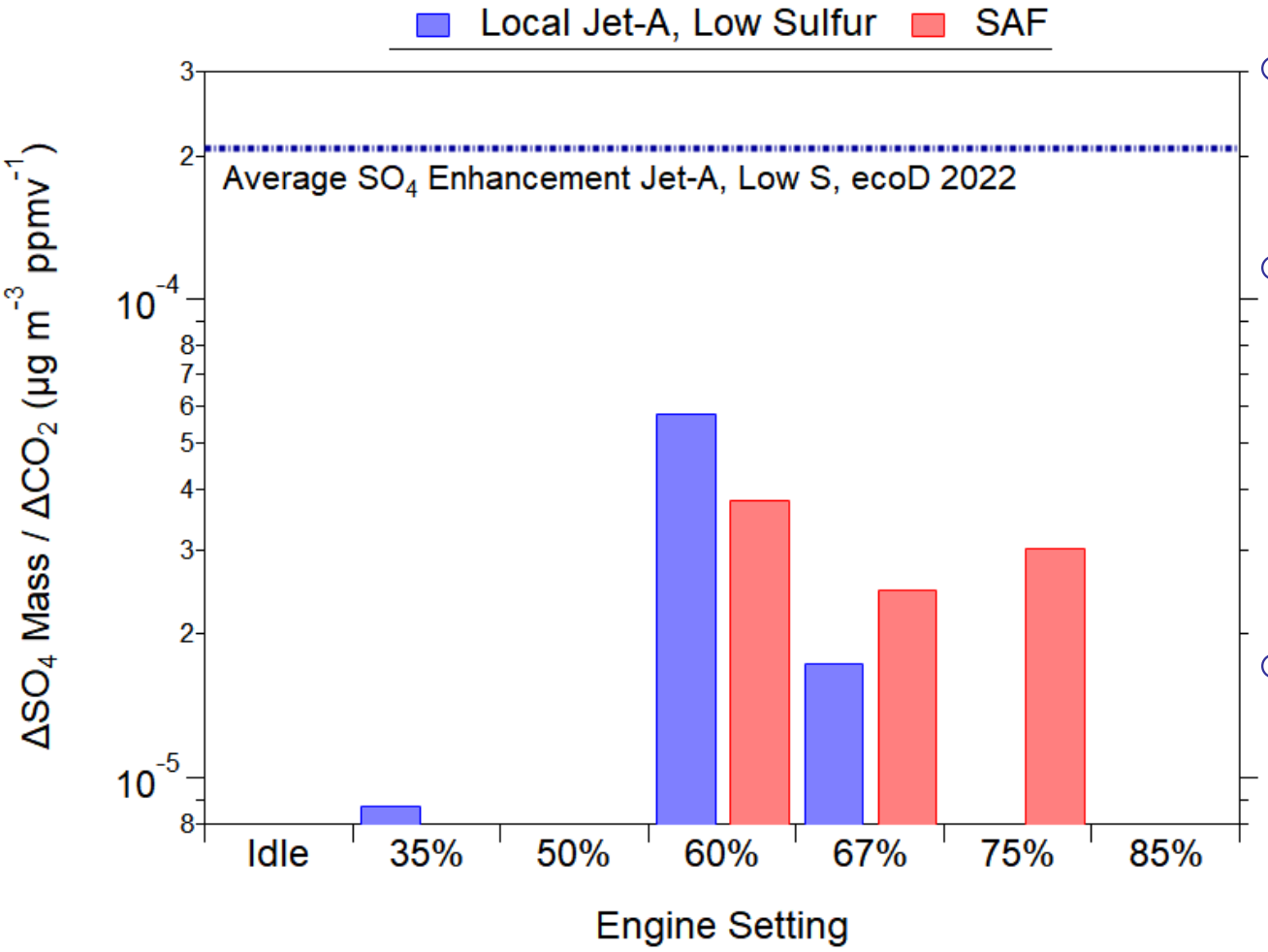
Boeing ecoDemonstrator 2023 Ground Test

- Boeing Everett Field
- LEAP 1B engine
- sampled at ~40 m
- Fuels :
  - 100% sustainable aviation fuel (SAF)
  - petroleum-based low-sulfur Jet A
- Aerodyne, MS&T, FAA, NASA, Scripps, NRC GE/CFM, Boeing Team

Boeing Photo Credit

Sulfate from AMS Boeing ecoDemonstrator 2023

- Sensitivity of Aerosol Mass Spectrometer (AMS) to Fuel Sulfur Content (FSC) depends on soot surface available and on ambient background levels. (Can't see nucleation mode sulfate.) Soot levels low for LEAP 1-B.



- Condensed sulfate appears lower in 2023 than 2022
- Near detection limit for both Low S and SAF fuels with few ppmm FSC, but non-zero
- Need better quantification of Fuel Sulfur Content at these low S levels

vPM role in contrail formation?

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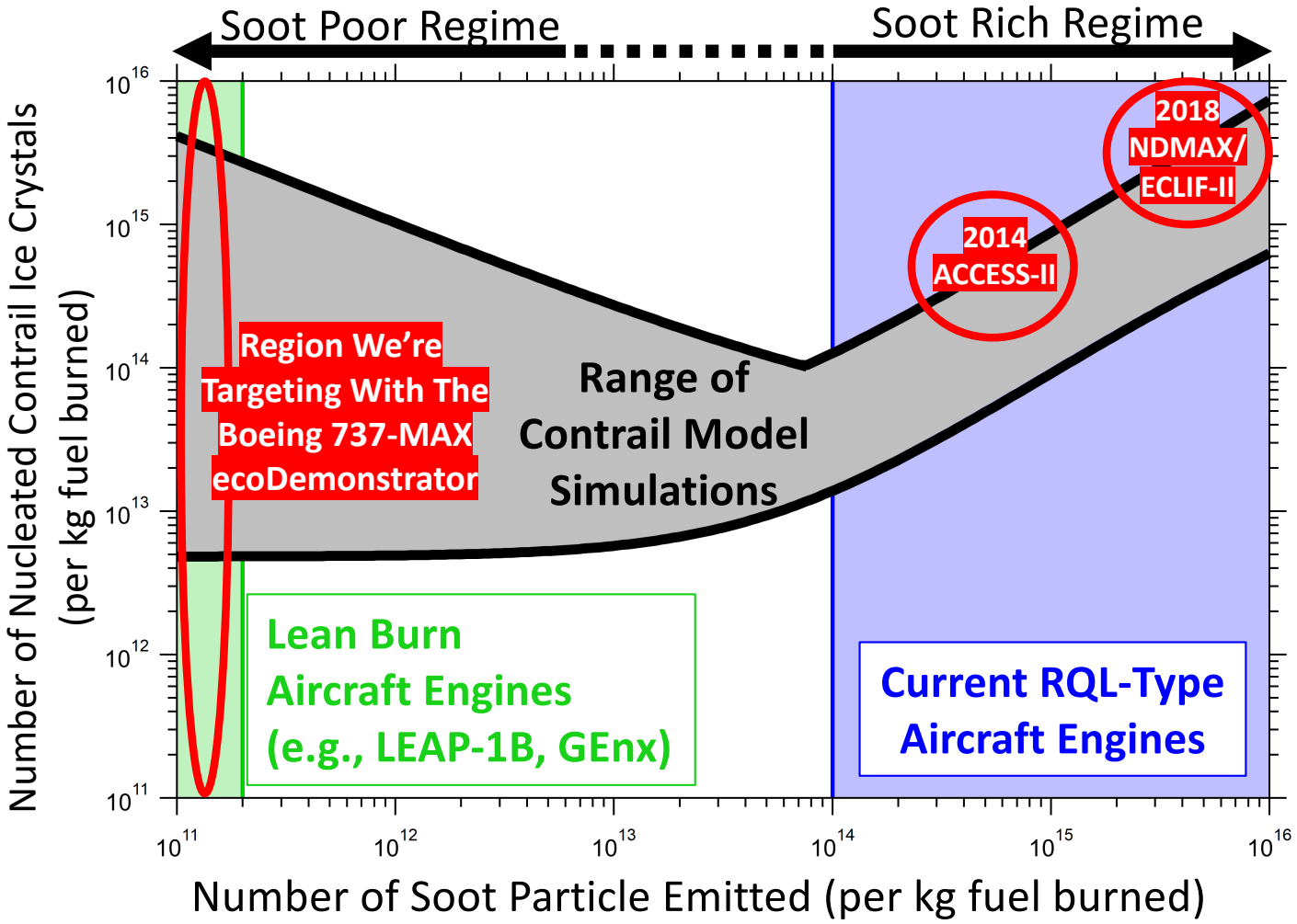
Great Potential of SAF and Advanced Combustor Technology



Need to understand engine particle emissions in the "soot-poor" regime in order to connect to contrail formation and climate impacts

Emissions reductions also beneficial for air quality

Figure adapted from Kärcher, *Nature Communications*, 2018.

Red circles show the approximate Number EIs observed during the 2014 ACCESS-II and 2018 ND-MAX/ECLIF-II flight test series.

Moore et al., Nature, 2017; Voigt et al., Nature Comms. Earth & Environ., 2021

Rich Moore (NASA) TAC-5 talk 2022

When nvPM is very low, contrails form on vPM?

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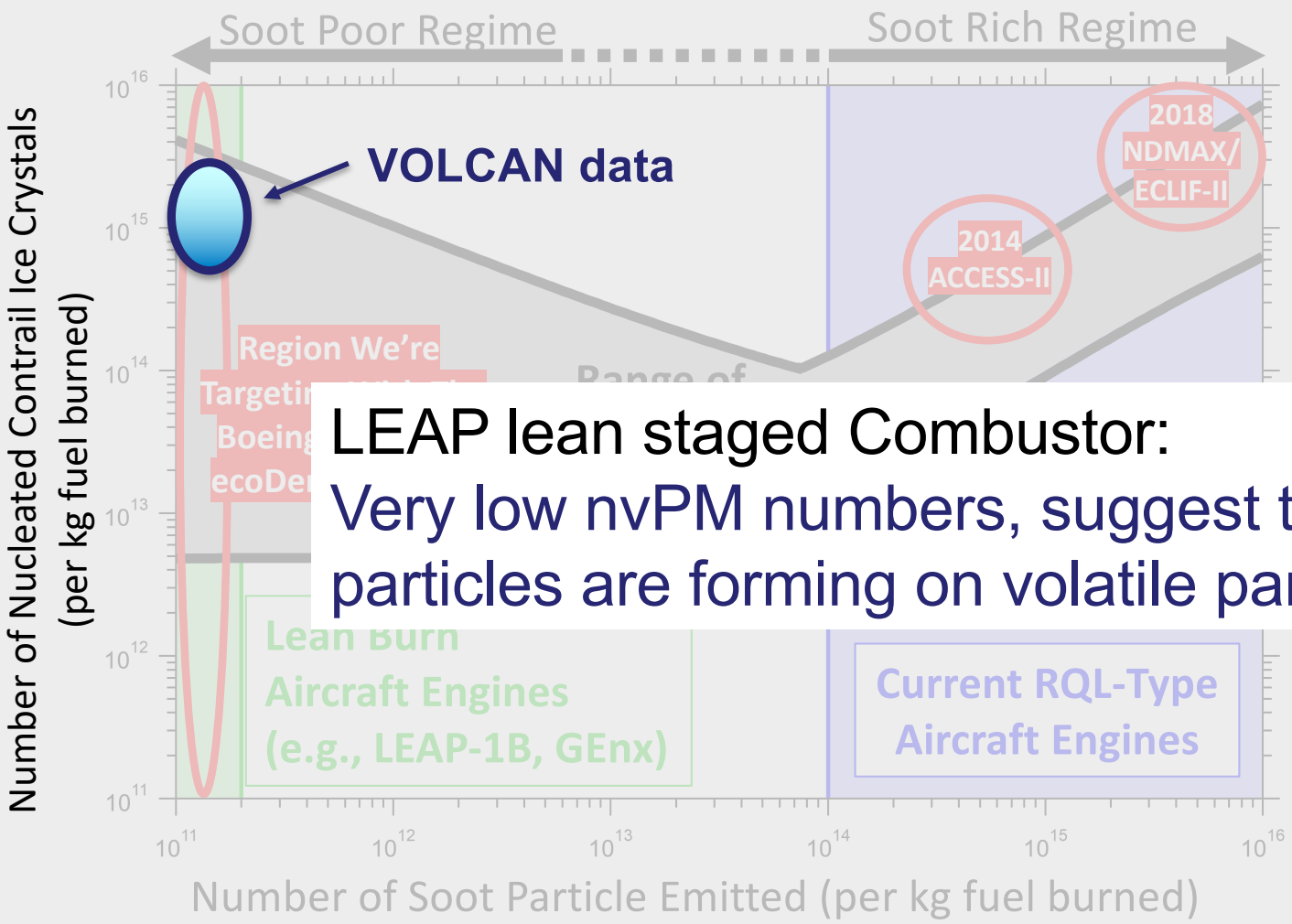

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LEAP lean staged Combustor:
Very low nvPM numbers, suggest that contrail particles are forming on volatile particles, not soot

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Christiane Voigt (DLR) TAC-5 data, 2022

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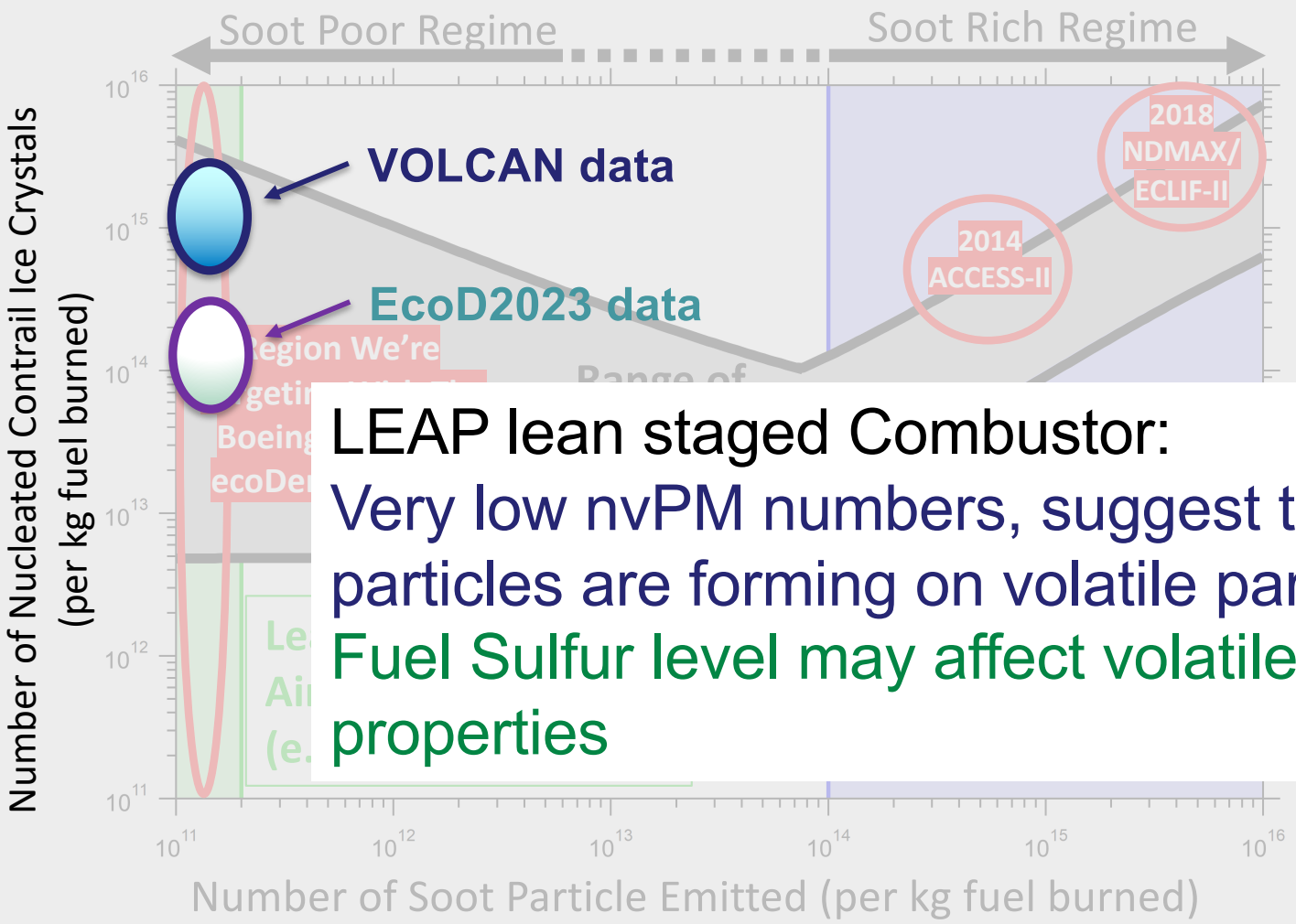

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Fuel Sulfur level may affect volatile particle properties

Number EIs observed during the 2014 ACCESS-II and 2018 ND-MAX/ECLIF-II flight test series.

Moore et al., Nature, 2017; Voigt et al., Nature Comms. Earth & Environ., 2021

Volcan data: Christiane Voigt (DLR) TAC-5 data, 2022

Summary

- Oil is a major contribution to vPM in aircraft exhaust
  - Currently not controlled or regulated as an emission
  - Useful to look at combustion emissions with oil diverted/ redirected
- Sulfur in fuel causes emissions of H_2SO_4
  - H_2SO_4 can be observed on soot particles* with few ppmm FSC
  - In Gulfstream tests, removed effect of H_2SO_4 nucleation, demonstrating that H_2SO_4 is needed for new particle formation in engine plume → show for other engines, other oil systems, other T, r.h., etc.
  - Possible implications for soot activation: Can low enough H_2SO_4 preclude soot contrail activation? → test contrail properties for this low fuel sulfur level . . . and find way to quantify low S levels
- Decreasing fuel sulfur (well below [?] 1 ppmm) and oil emissions could dramatically reduce vPM emissions around airports

* depending on soot concentration and background sulfate levels

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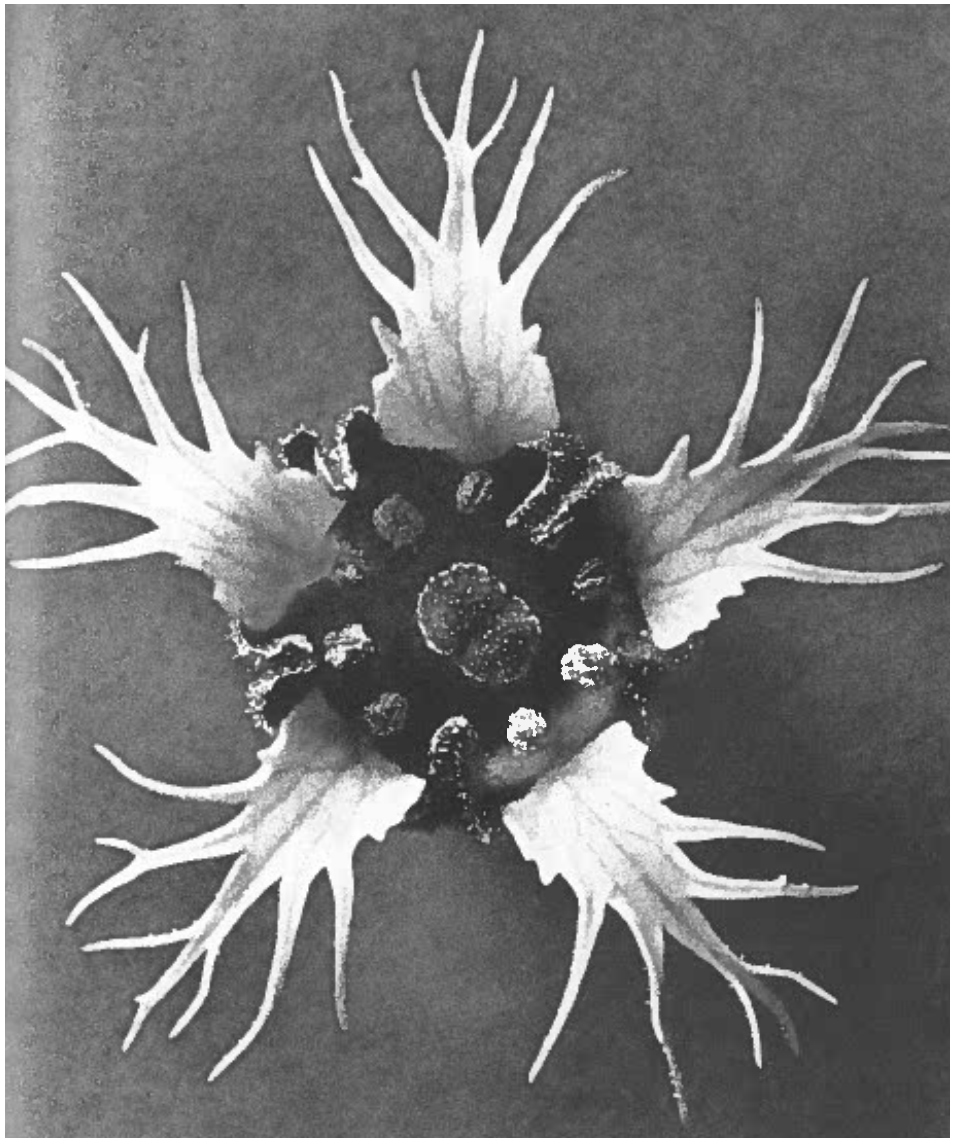
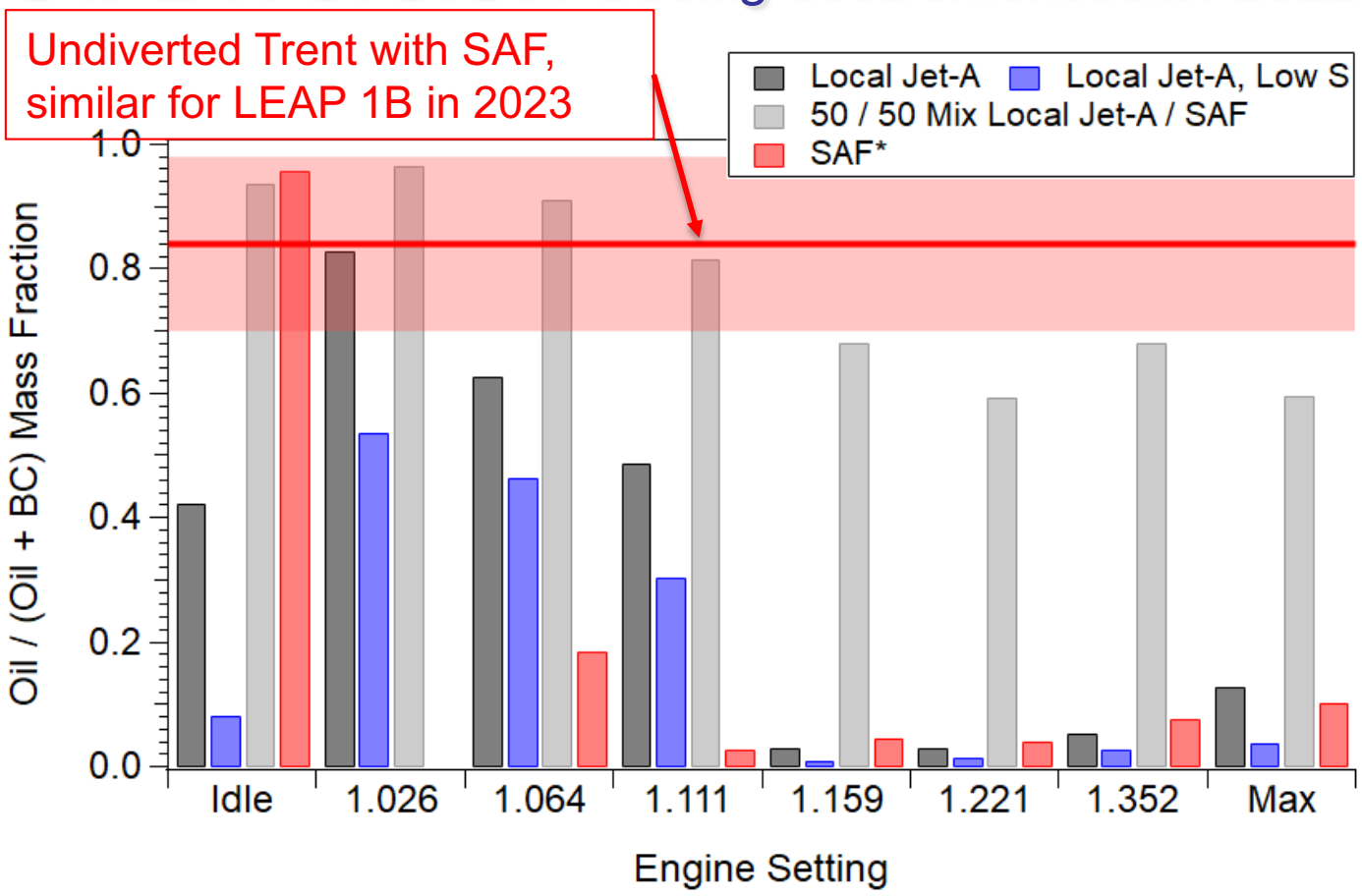
Not only, then, in the world of art, but equally in the realm of science, is Nature our best teacher.

Karl Blossfeldt, 1932



Oil Diversion Boeing ecoDemonstrator 2022

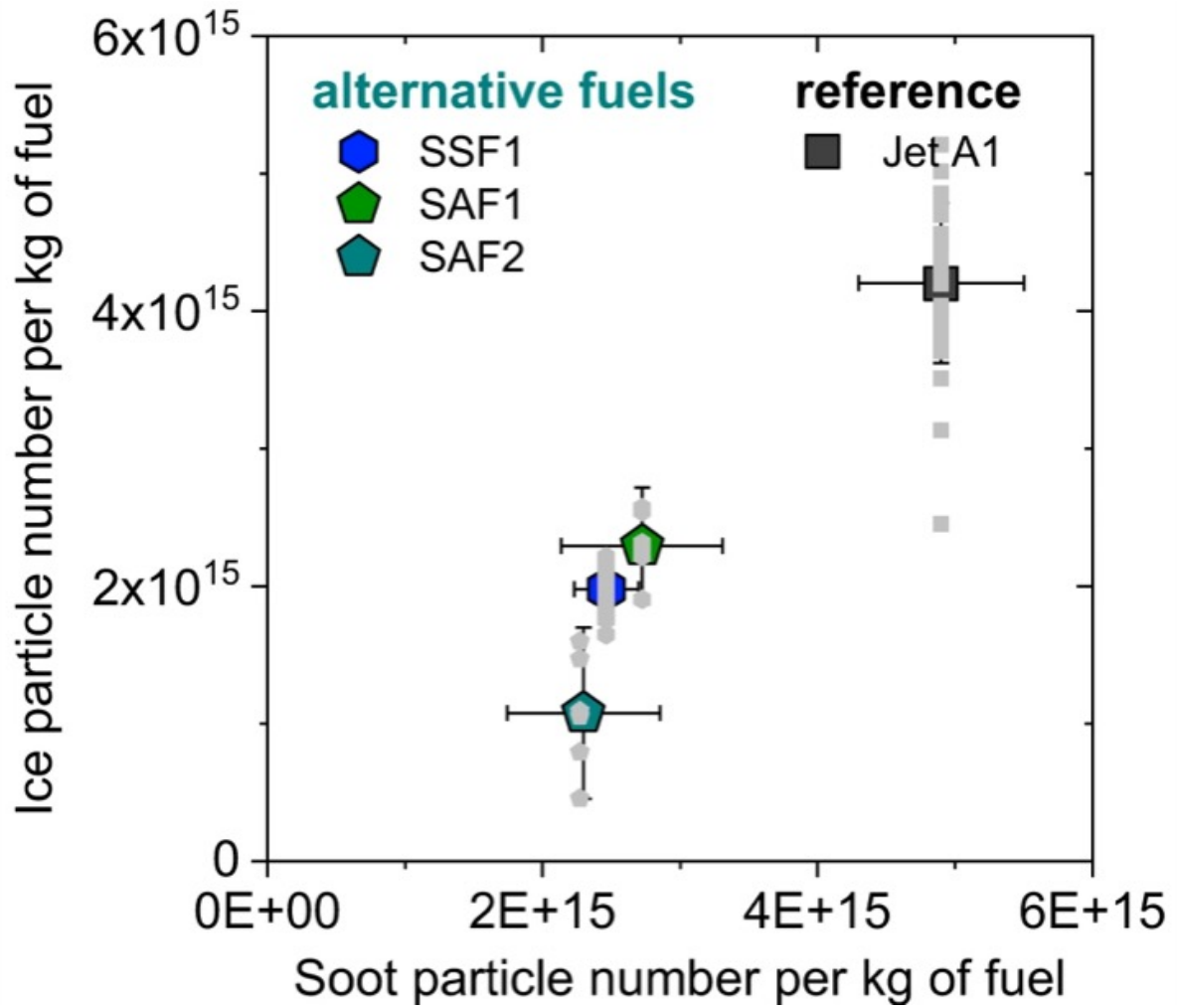


- Oil mass comparable to BC mass emissions with no oil diversion
- Oil is a major emission that is not currently regulated

- Oil diversion using long hose attached to vent tube of Trent engine
  - 50/50 Mix: no diversion
  - Other fuels: Varying success, with best diversion at higher powers with engine powers balanced
  - Room for improvement in future tests

ND-MAX/ECLIF2 results: V2527 (RQL)

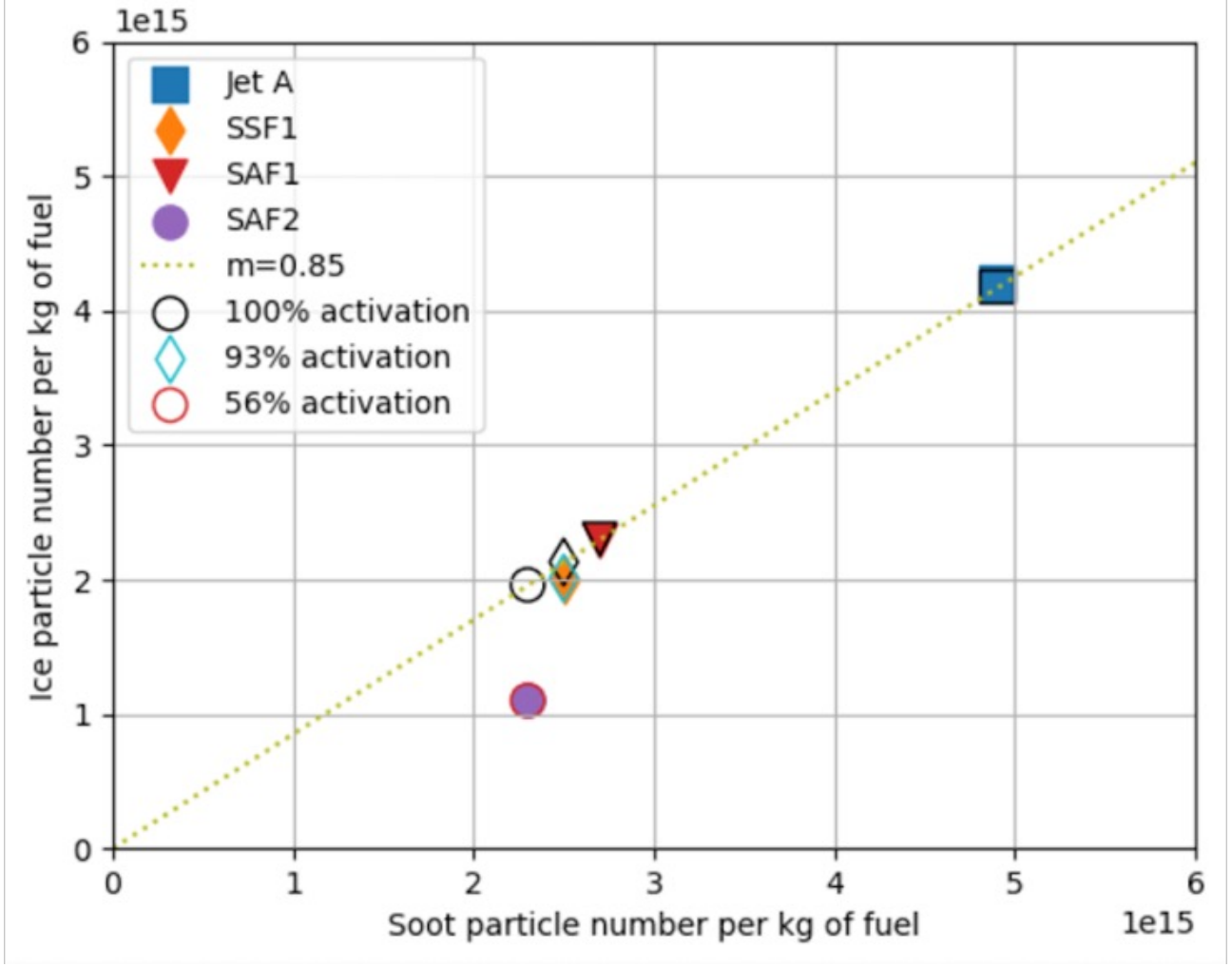
- Voigt et al., Communications Earth & Environment, 2021 *Figure 4* https://doi.org/10.1038/s43247-021-00174-y.



Effects of soot numbers for engine in “soot rich” regime

Decreased SO_4 activation simulations

Jones & Miake-Lye, (2023) Meteorol. Z. DOI 10.1127/metz/2023/1180



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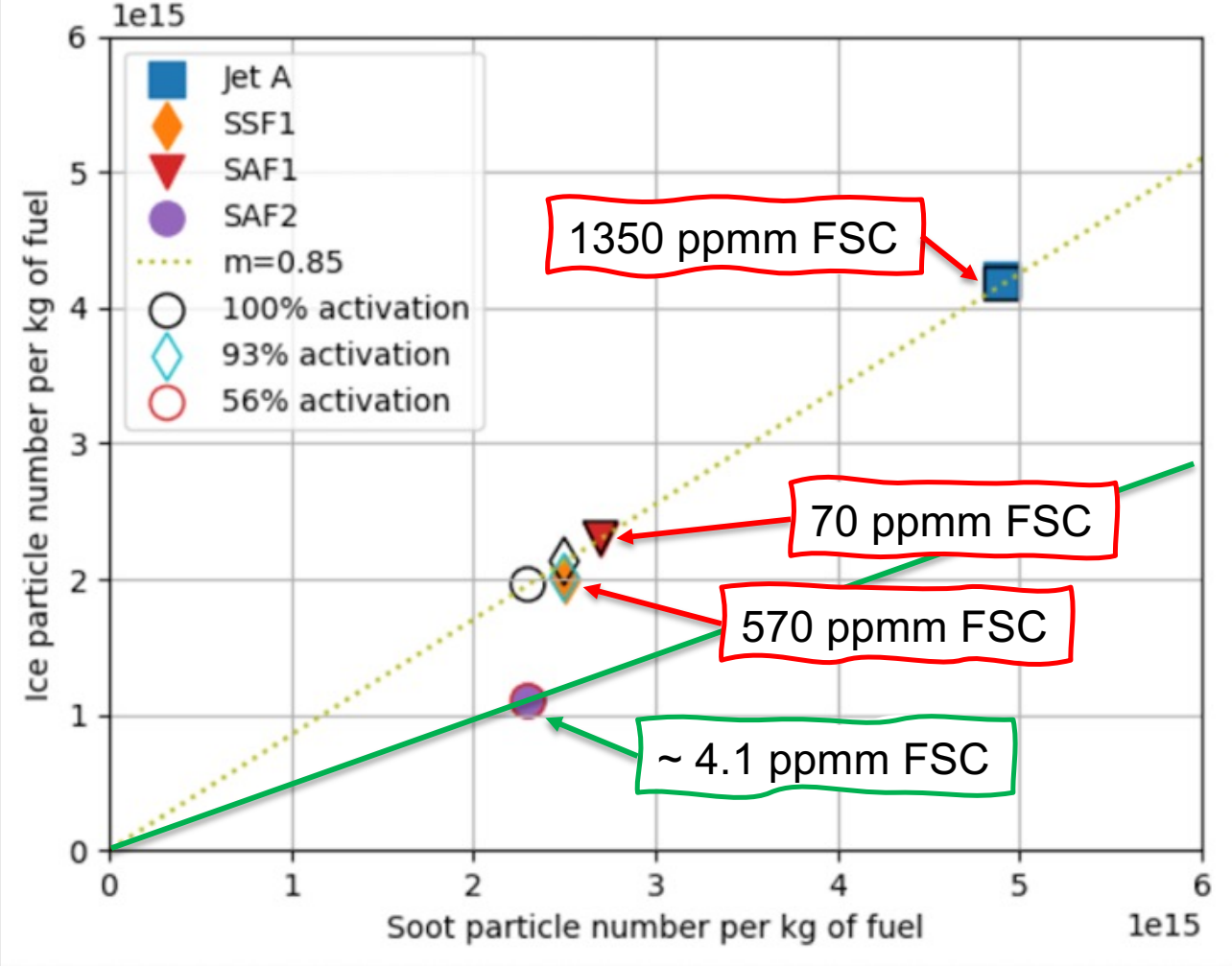

". . . and that careful experiments with FSC of below 0.1 ppmm, and preferably below 0.05 ppmm, would be needed . . . "