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The ubiquitous nature of lubrication oil in aero gas turbine exhaust

Z. C. J. Decker[1], P. A. Alpert[1], J. G. Slowik[1], M. Ammann[1], L. Durdina[2], J. Edebeli[2], C. Spirig[2], J.G. Anet[2], F. Ungeheuer[3], A.L Vogel[3], A. S. H. Prévôt[1], M. Gysel-Beer[1] and B. T. Brem[1]

[1]Laboratory of Atmospheric Chemistry, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland
[2]Centre for Aviation, ZHAW Zurich University of Applied Sciences, 8401 Winterthur, Switzerland
[3]Institute for Atmospheric Sciences, Goethe-University Frankfurt, Frankfurt am Main, 60438, Germany

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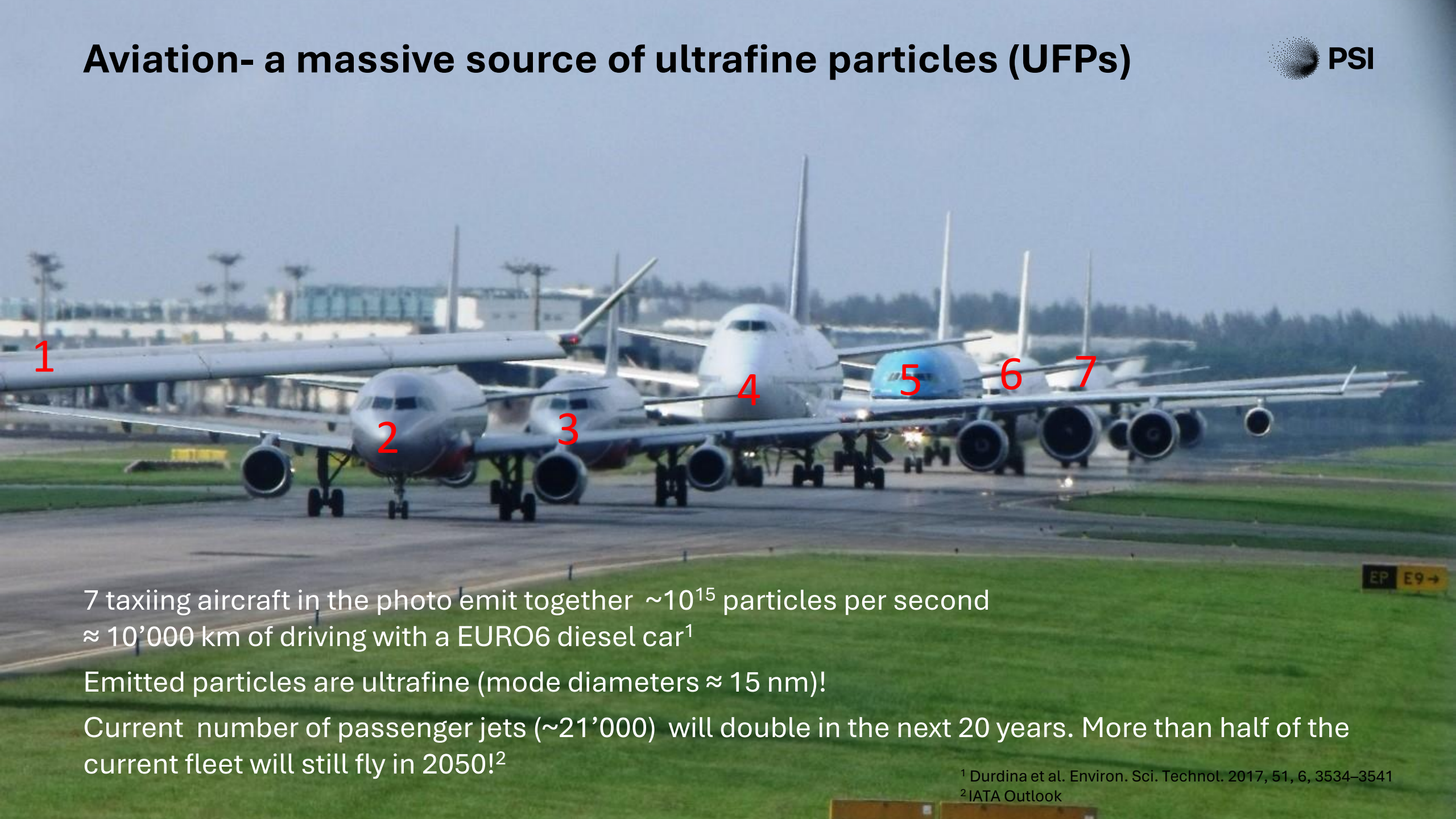
Aviation- a massive source of ultrafine particles (UFPs)



7 taxiing aircraft in the photo emit together ~10^{15} particles per second
≈ 10’000 km of driving with a EURO6 diesel car[1]

Emitted particles are ultrafine (mode diameters ≈ 15 nm)!

Current number of passenger jets (~21’000) will double in the next 20 years. More than half of the current fleet will still fly in 2050![2]

[1] Durdina et al. Environ. Sci. Technol. 2017, 51, 6, 3534–3541
[2] IATA Outlook

Aviation turbine oil properties and emissions

Oil properties:

- Composed of synthetic pentaerythritol esters (95%) with small amounts of specialized performance additives such as e.g. tricresyl phosphate (TCP)
- Designed for operational stability over a large temperature range between -40 and 204 °C
- Boiling point ~230 -250 °C
- Density ~ 1 g/cm^3

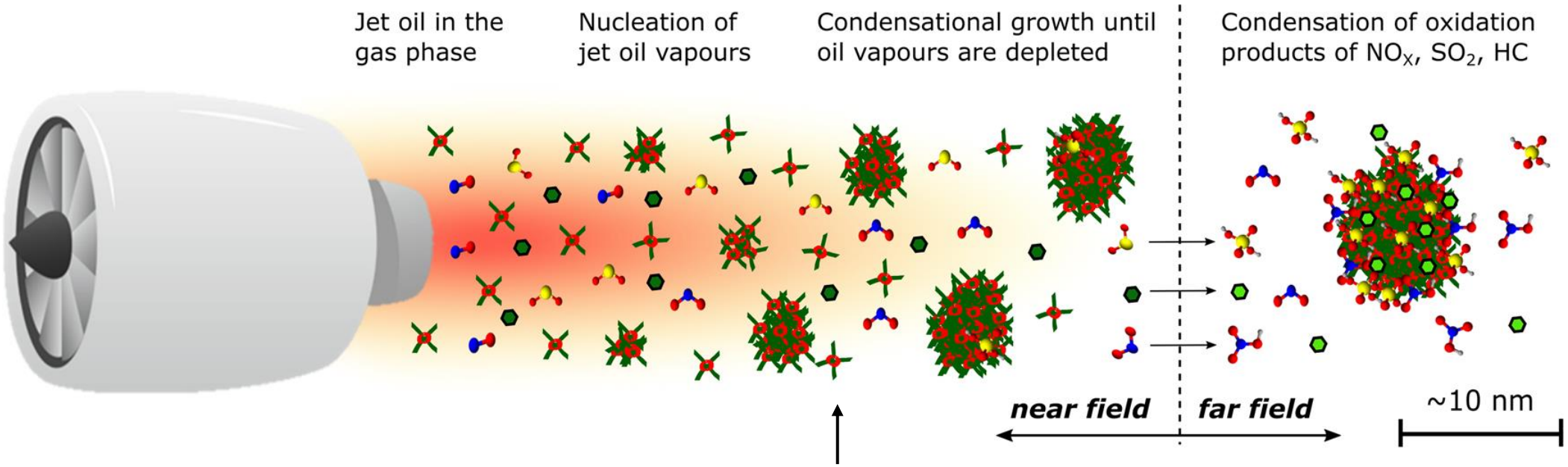
Oil emissions:

- Engine oil systems ingest air in the bearing cavities, and thus a breather/ air-oil separator is installed to remove air
- The breather is vented to the outside air → source of emissions
- Location and type of breather vent depends on engine manufacturer/ model and has implications for emissions:

- Manufacturer allowed oil consumption limit 0.3 -0.5 L/hr
- Emission indices reported in the range of 2-12 mg/kg[1]
- Oil constituents found 4km downwind of Frankfurt airport[2]

[1]Yu et al.,2010, Environmental Science and Technology 44(24):9530-4
[2]Ungeheuer et al., 2022, Commun Earth Environ 3, 319

Objectives of this study

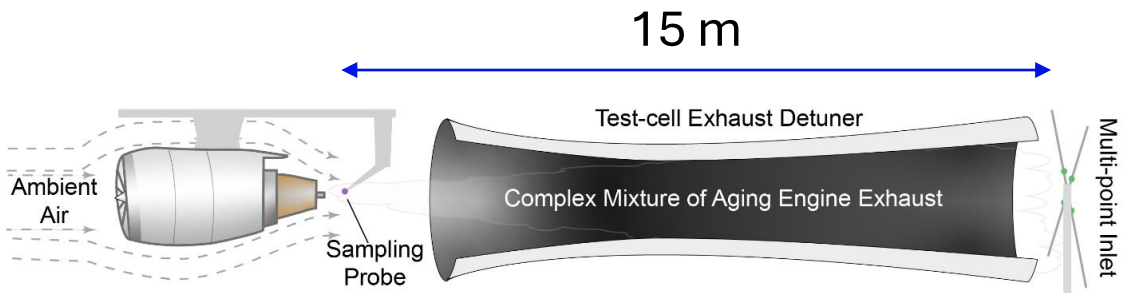


Ungeheuer, et al. (2022) *Comm. Earth. Env.*

We are investigating this step in the evolving plume (0.2 to1 s after emission) with the following research questions:

1. Can oil emissions be measured in all engines?
2. Is there a thrust dependence in oil emissions and composition?
3. Is the composition particle size dependent?

Measurement setup



Dilution with ambient air by a factor ~ 8 to 20, depending on engine thrust

ZHAW Container

Aerodynamic Aerosol Classifier (AAC)

CPC

Bypass for polydisperse

Extractive Electrospray Ionization Mass Spectrometer (EESI-MS)

Detailed aerosol molecular composition (150 – 1200 g/mol)

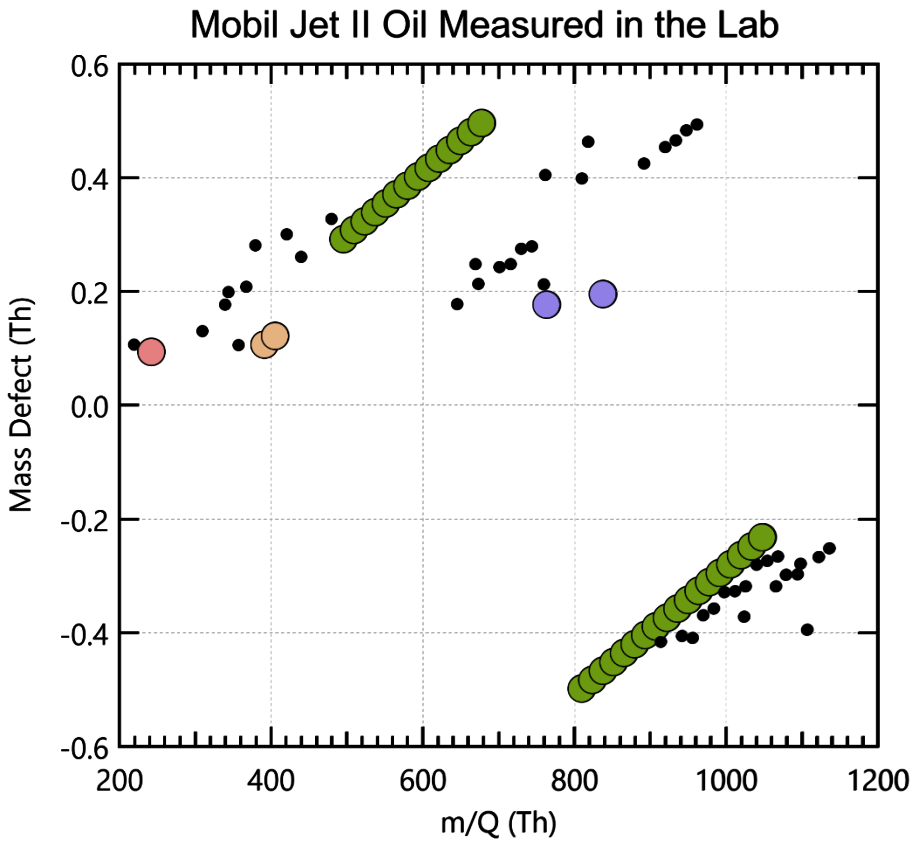
Nano-MOUDI

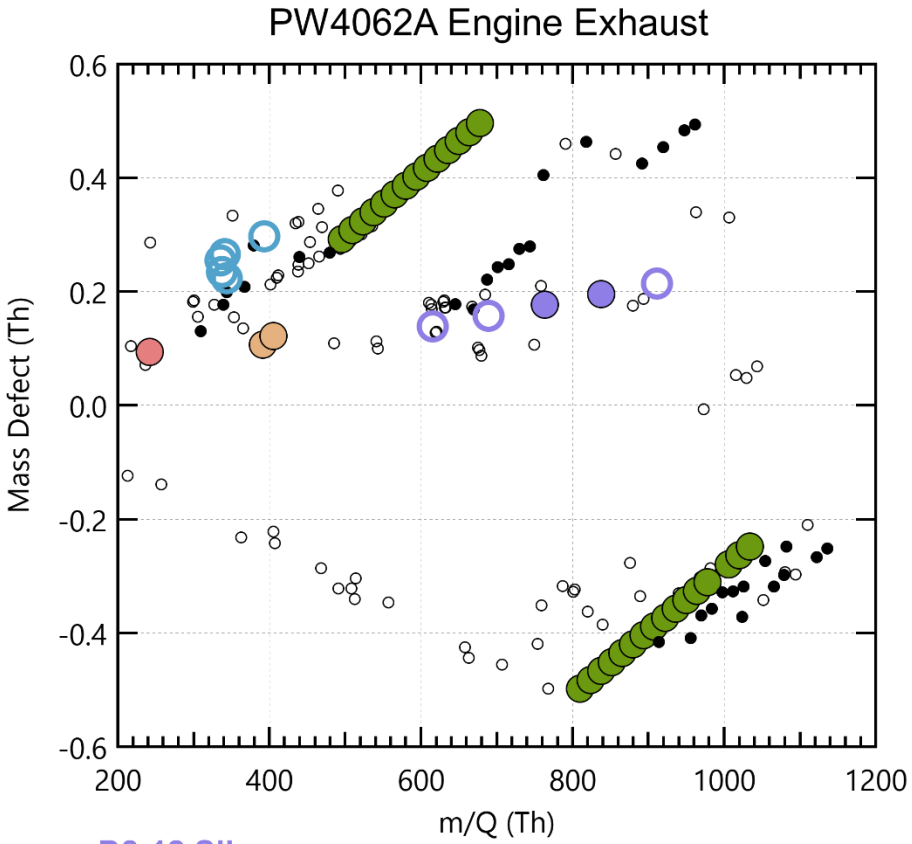
Size selected filter sampling for offline analysis

Tests performed

Engine	Airframe	No. of Tests	Engine Oil	SR Technics reported oil consumption (L/h)
CFM56-7B variants	Boeing 737	4	3x Mobil Jet II, 1x Turbonycoil 600	0.1 – 0.35
PW4000-94” variants	Boeing 767	2	2x Mobil Jet II	Non- measurable - 0.12
PW4000-100” variants	Airbus A-330	1	Mobil Jet II	0.15

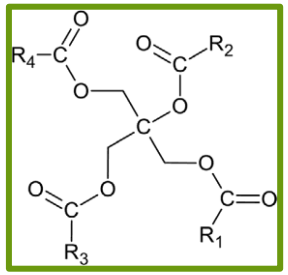
Oil markers can clearly be identified in aircraft exhaust

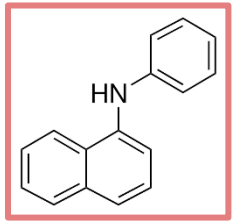


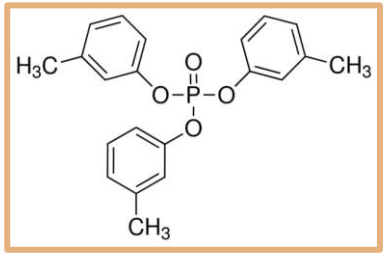


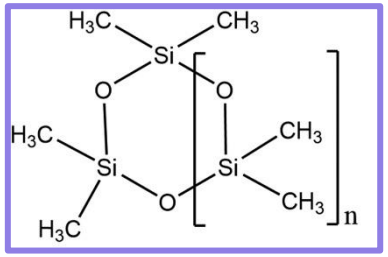
- Mobil Jet II Oil Marker with assigned formula
- Mobil Jet II Oil marker with unkown formula
- Additional Masses observed at SRT with assigned formula
- Additional Masses observed at SRT with unknown formula

D8-12 Siloxanes
N-phenyl-1-naphthylamine
Ambient Aerosol Markers
C_{25} - C_{38} & C_{42} - C_{60} Pentaerythritol Esters
Tricresyl Phosphate



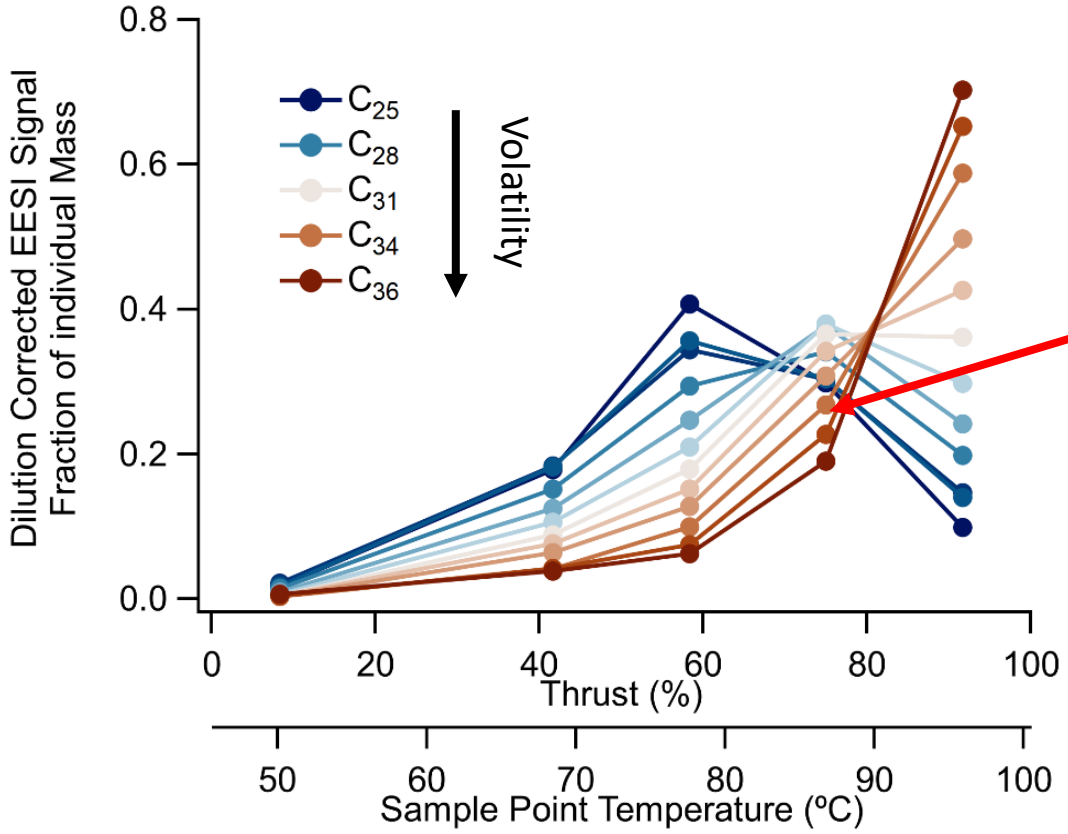






Decker et al. *in preparation*

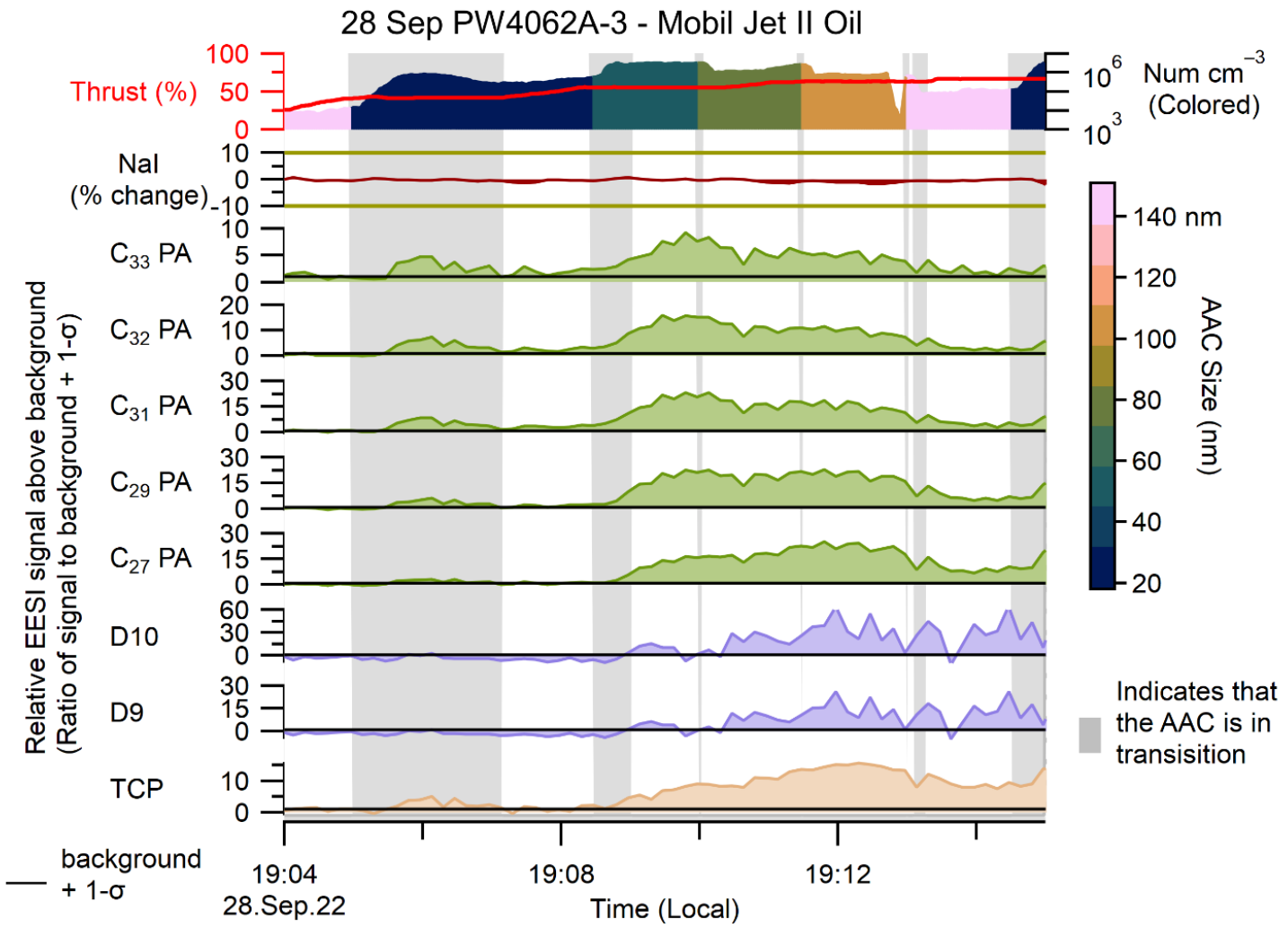
Oil emissions experience gas to particle partitioning



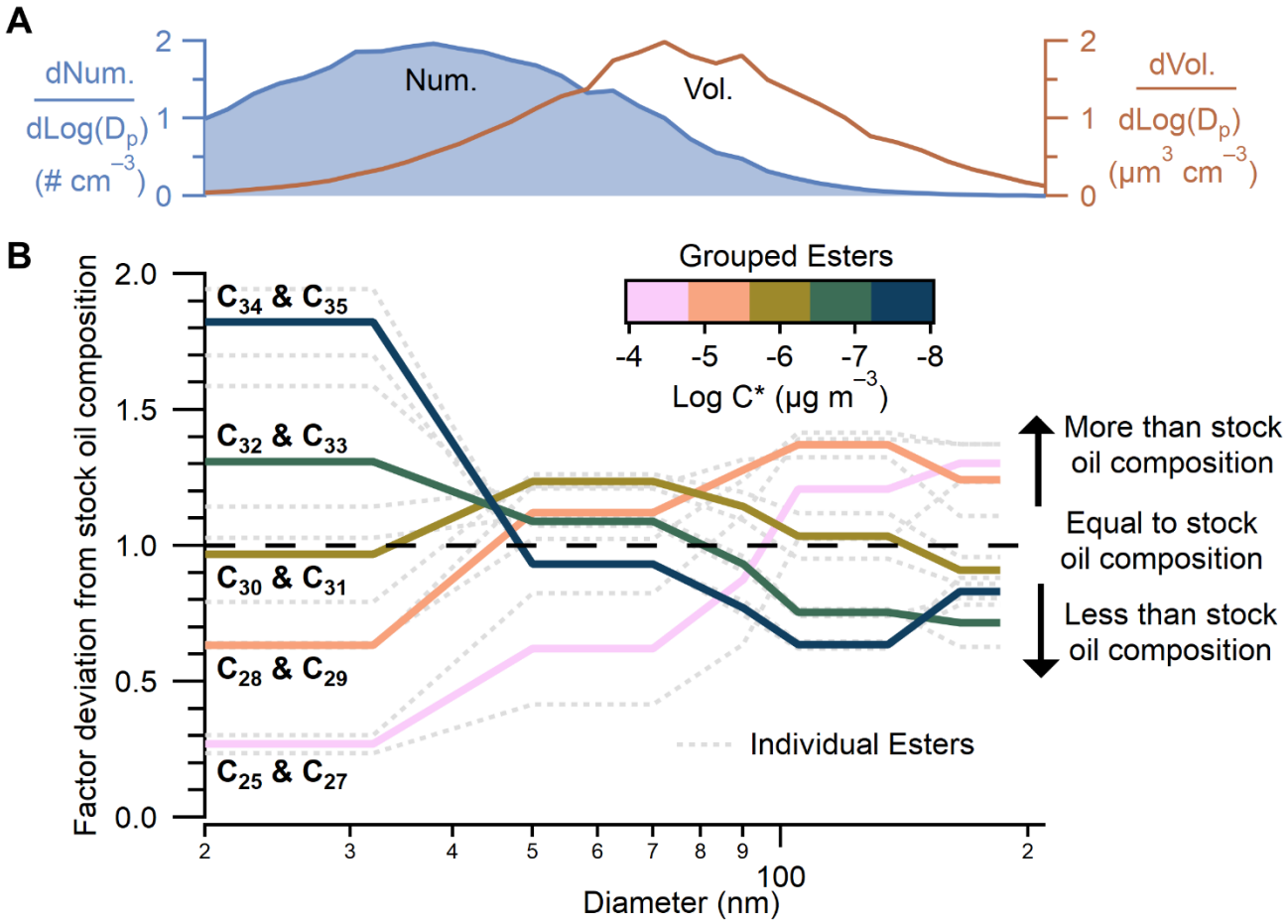
Lighter oil esters have not fully condensed into PM phase → heavier long chained esters start to dominate the signal

Decker et al. *in preparation*

Data example of a size resolved PW4000-94” measurement



Smaller particles contain more low-volatility oil esters



- The fraction of heavy esters is greatest for the smallest particles while the fraction of lighter esters increases with particle size
- Suggest that heavier esters can potentially independently nucleate early in the plume and serve as condensation sink

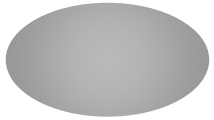
Decker et al. *in preparation*

Offline analysis of impactor samples also indicates a widespread presence of oil

Nano-MOUDI

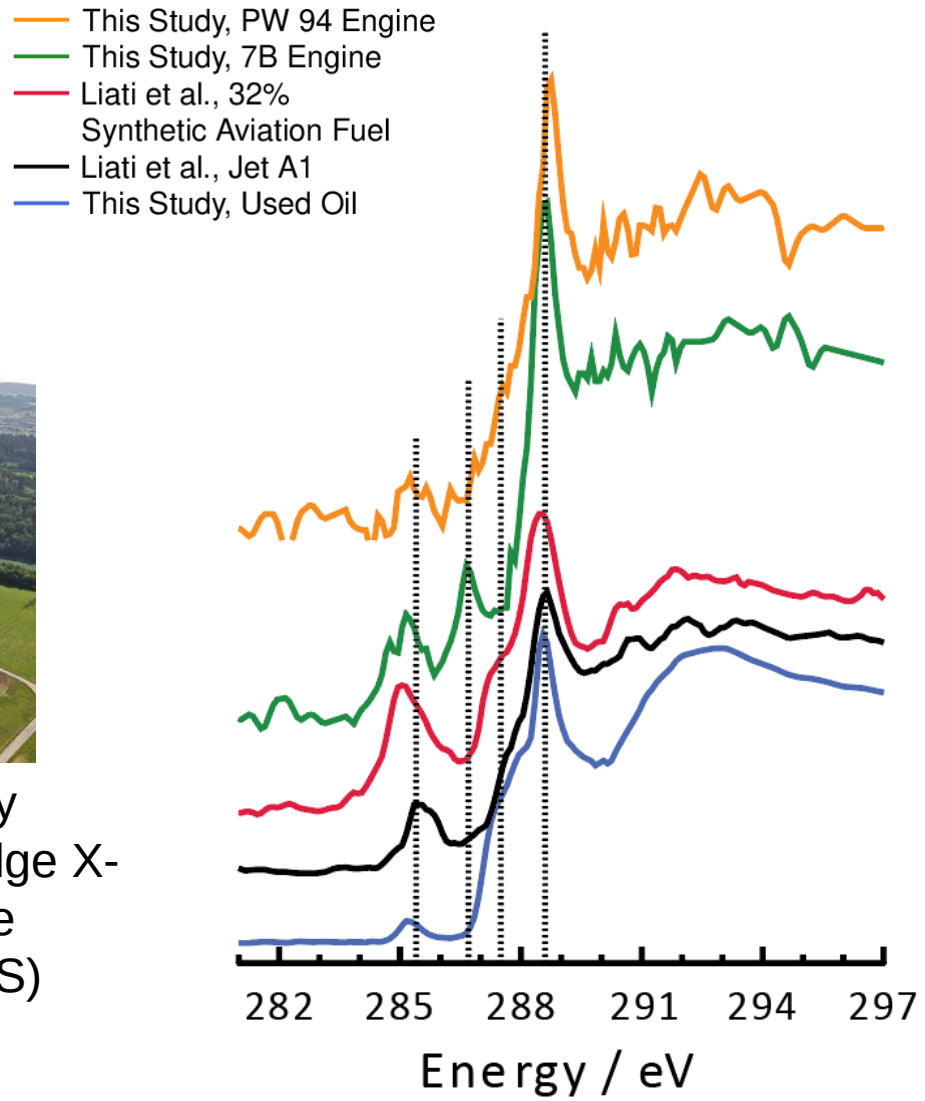
“Stage 9”

320 – 560 nm particles

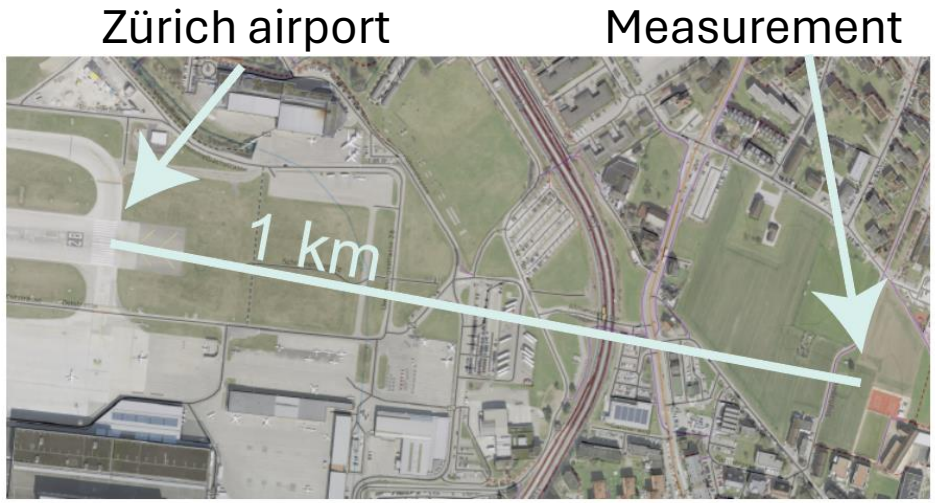


Swiss Light Source

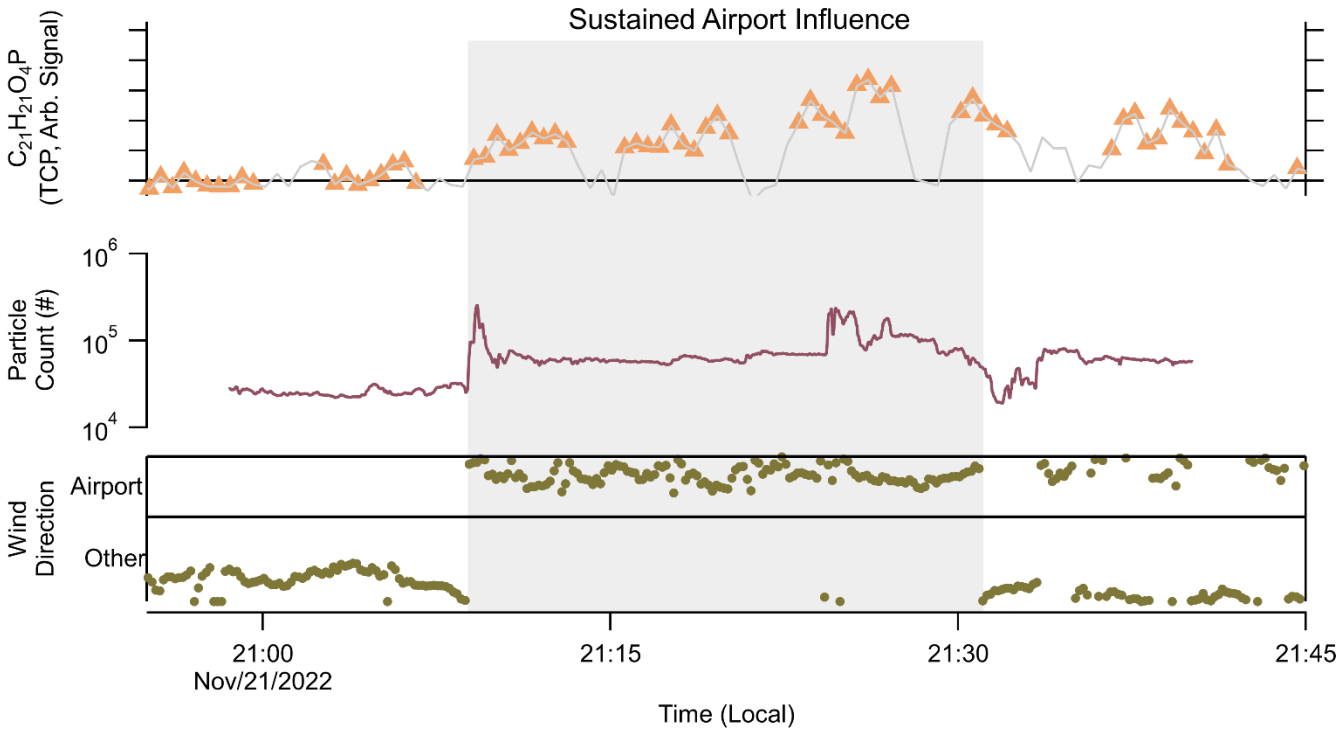
Scanning Transmission X-ray Microscopy coupled with Near-Edge X-ray Absorption Fine Structure Spectroscopy (STXM/NEXAFS)



Oil markers are detected online and *in situ* near Zürich airport



Preliminary Data



Summary and Conclusions

- Lubrication oil is commonly observed in aircraft exhaust while direct quantification in exhaust remains an analytical challenge → Estimated emission indices range from 0.05 to 0.3 g/kg fuel (based on consumption data) which is at par or even higher than soot emissions
- Oil emissions exhibit a thrust dependence with higher concentrations at higher thrusts
- Gas to particle partitioning plays a role in the early stage of the plume
- Size resolved measurements indicate lower volatile esters at smaller particle sizes
- Oil spectral signatures are observed in all offline samples
- Oil markers such as TCP can be detected online and *in situ* 1km away from the runway at Zürich airport

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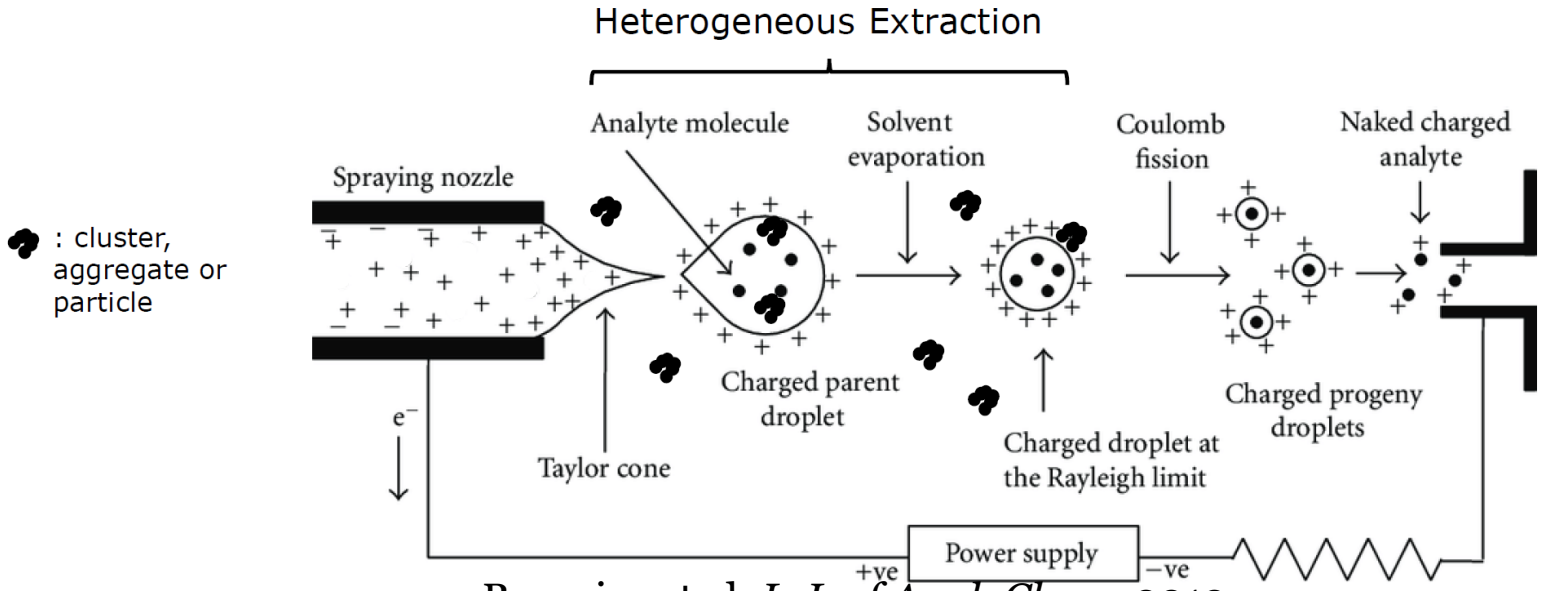
Appendix: Particle-phase molecular composition by EESI mass spectrometry

- **E**xtractive **E**lectro**S**pray **I**onization (EESI)
- Measurement of aerosol chemical composition
- Captures whole molecules, in contrast to Aerosol Mass Spectrometry
- High mass resolution (m/Δm > 8000)
- High time resolution (1 Hz)
- Sodium ion added to analyte molecule



Banerjee et al. *I. J. of Anal. Chem.* 2012