Detection of Contrails - Challenges and Future Perspectives

Dr. Tina Jurkat-Witschas and **Prof. Dr. Christiane Voigt**

Institute of Atmospheric Physics

09.06.2022: Online Lecture, RAeS Hamburg, DGLR, VDI, ZAL & HAW Hamburg

https://doi.org/10.5281/zenodo.6720795

Tina.jurkat@dlr.de

DLR

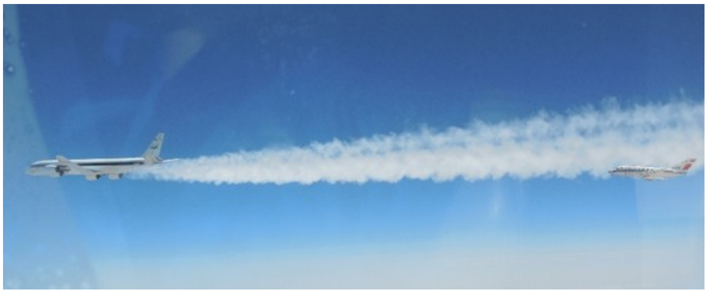
Deutsche Gesellschaft für Luft- und Raumfahrt Lilienthal-Oberth e.V. Bezirksgruppe Hamburg | ROYAL AERONAUTICAL SOCIETY HAMBURG BRANCH e.V. | ZAL | VDI Verein Deutscher Ingenieure Hamburger Bezirksverein e.V. Arbeitskreis Luft- und Raumfahrt

HAW HAMBURG

Hamburg Aerospace Lecture Series

Hamburger Luft- und Raumfahrtvorträge

RAeS Hamburg in cooperation with the DGLR, VDI, ZAL & HAW invites you to a lecture



Detection of Contrails – Challenges and Future Perspectives

Dr. **Tina Jurkat-Witschas** and Prof. Dr. **Christiane Voigt**

Institut of Atmospheric Physics, German Aerospace Center (DLR)

Date: **Thursday, 09 June 2022, 18:00 CET**

Online: https://purl.org/profscholz/zoom/2022-06-09

Contrail and cirrus that evolve from contrails represent the **largest share of the climate impact from aviation**, even larger than the contribution from CO2. In order to reduce this climate impact and the uncertainties related to it, the fundamental science of contrails and their impact on the atmosphere from a present and future aircraft fleet needs to be based on accurate and reliable airborne measurements.

Research at DLR has focused on the detection of contrails in a suite of **measurement campaigns** in the past decade. Different evolution stages of contrails from the first second behind the aircraft until they evolve into contrail cirrus have been measured with national and international partners like NASA and NRC. We present recent results on contrail properties measured with DLR's unique research aircraft fleet. The observations are further used to guide model evaluation from the plume to the global scale.

While new carbon-free technologies like **hydrogen powered engines** now come into perspective, their impact on contrail formation is largely unknown. We will comment on the importance of airborne measurements of these new type of contrails, the challenges and potentials that come with it to frame a sustainable future air traffic.

Dr. Tina Jurkat-Witschas is Project Leader of the DLR Research Group H2CONTRAIL and Prof. Dr. Christiane Voigt is Head of Department Cloud Physics at the DLR and Professor at the University of Mainz.

DGLR / HAW Prof. Dr.-Ing. Dieter Scholz Tel.: 040 42875 8825 info@ProfScholz.de

RAeS Richard Sanderson Tel.: 04167 92012 events@raes-hamburg.de

Hamburg Aerospace Lecture Series DGLR HAW Hamburg RAeS VDI ZAL

DGLR Bezirksgruppe Hamburg https://hamburg.dglr.de

RAeS Hamburg Branch https://www.raes-hamburg.de

VDI, Arbeitskreis L&R Hamburg https://www.vdi.de

ZAL TechCenter https://www.zal.aero

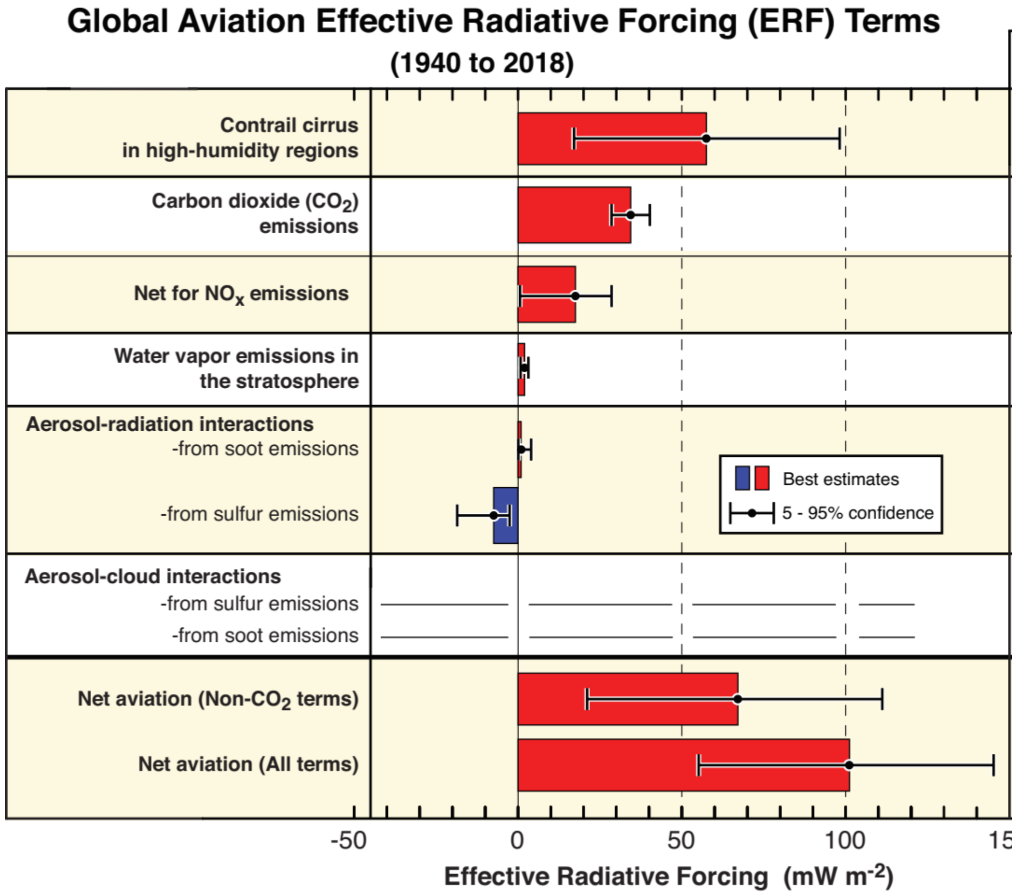
Hamburg Aerospace Lecture Series (AeroLectures): Jointly organized by DGLR, RAeS, ZAL, VDI and HAW Hamburg (aviation seminar). Information about current events is provided by means of an e-mail distribution list. Current lecture program, archived lecture documents from past events, entry in e-mail distribution list. All services via http://AeroLectures.de.

Outline

- Motivation: Why do we care about contrails?
- How do contrails form?
- How do we detect contrails and their microphysical properties at different evolution stages?
- How can we reduce the climate impact from contrails?
- Outlook:

  How much do we know about contrails from H_2 combustion and H_2 fuel cell electric power? What are the needs from the research perspective?

The climate impact of aviation - today

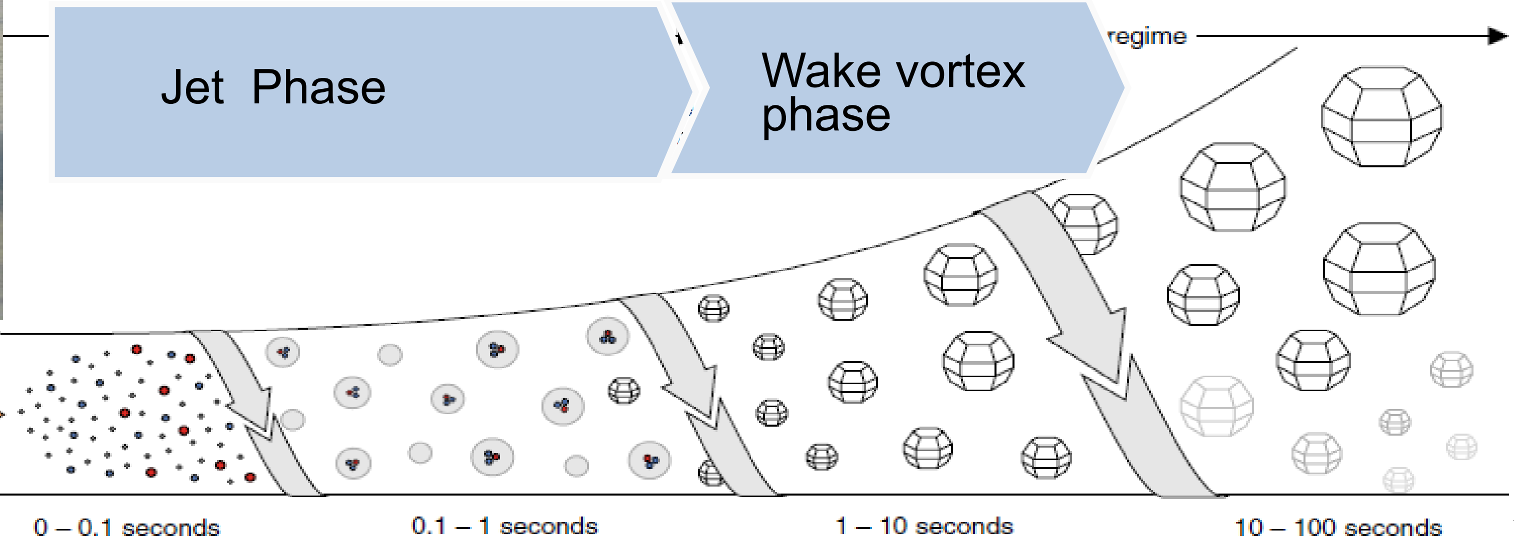


Adapted from Lee et al., 2021

- The global effective radiative forcing (ERF) from aviation in 2018 was about 100 mWm^{-2} ; which is 3,5% of the total ERF
- The larges share comes from non-CO2- effects which comprise about 2/3 of the total ERF
- Contrails and Contrail Cirrus (57%) have the largest contribution
- Uncertainties of the non-CO_2 effects are 8 times larger than the CO_2 effect

- Contrails have the potential to immediately reduce the climate impact from aviation!

Formation of contrails : the micro scale



~550K TEMPERATURE -220K

Depending on atmos. Conditons: a fraction of ice particles will sublimate

Direct emissions: soot, CO_2, H_2O, NO_x, SO_2, Hydro Carbons, volatile aerosol particles…

Water droplets form on soot particles

Droplets freeze and form ice particles

Ice particles grow due to uptake of ambient water vapor

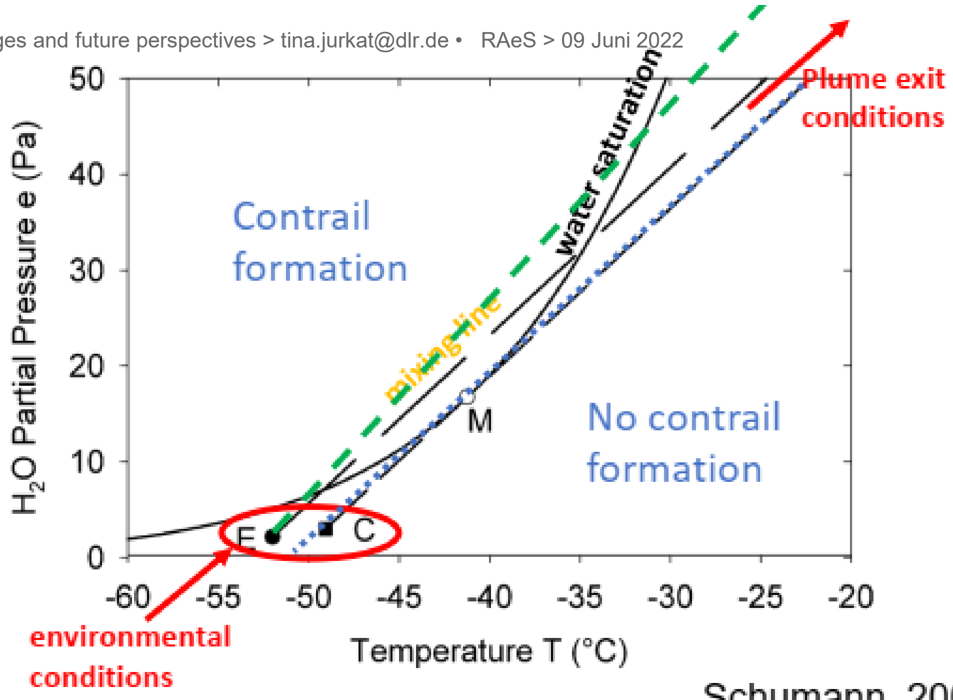
Adapted from Kärcher, Nature Communications, 2018

DLR

Recap:

Principles of contrail formation

Schmidt- Appleman Criterion



Schumann, 2005

Contrail formation when plume conditions exceed water saturation.
Contrail persists when ambient air ice supersaturated.
Many ice crystals form when ambient temperature are well below the formation threshold temperature

Slope of mixing line

$$G = EI_{H2O}\, p c_p / [\varepsilon Q (1 - \eta)]$$

Propulsion efficiency

$$\eta = FV/(m_f Q)$$

EI_{H2O}: H_2O emission index Q: specific heat of combustion
η: overall propulsion efficiency p: ambient pressure
ε = 0.622: ratio of molar masses water vapour and dry air
c_p: specific heat capacity m_f: fuel flow F: thrust
V: air speed of aircraft

See also presentation from Ulrike Burkhardt, RAeS, 02.12.2021

DLR

Contrail and Contrail Cirrus properties during aging

Jet Phase	Vortex Phase	Dispersions Phase: formation of contrail cirrus
0 – 10 seconds	1 – 4 Minutes	Minutes to Hours

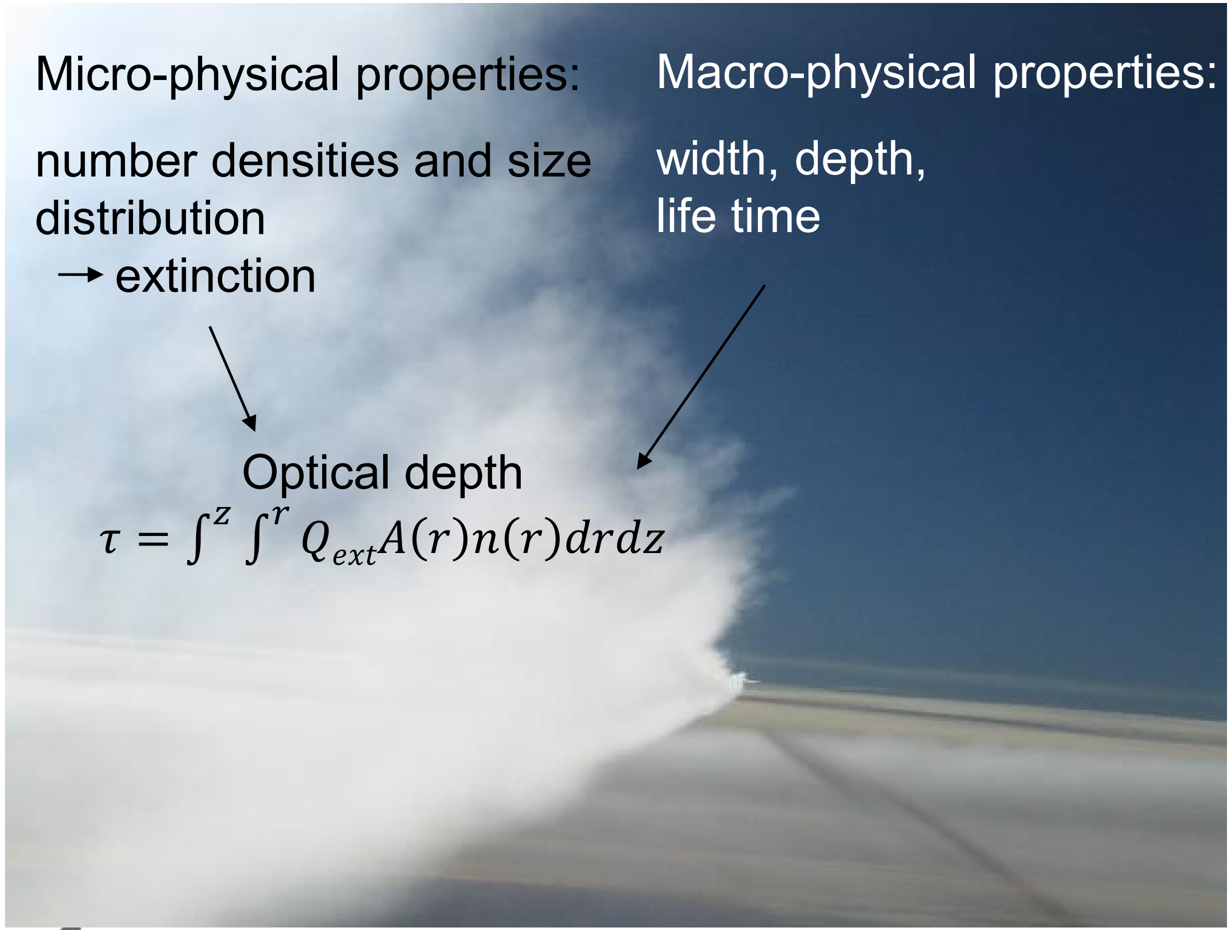
Ice particle size

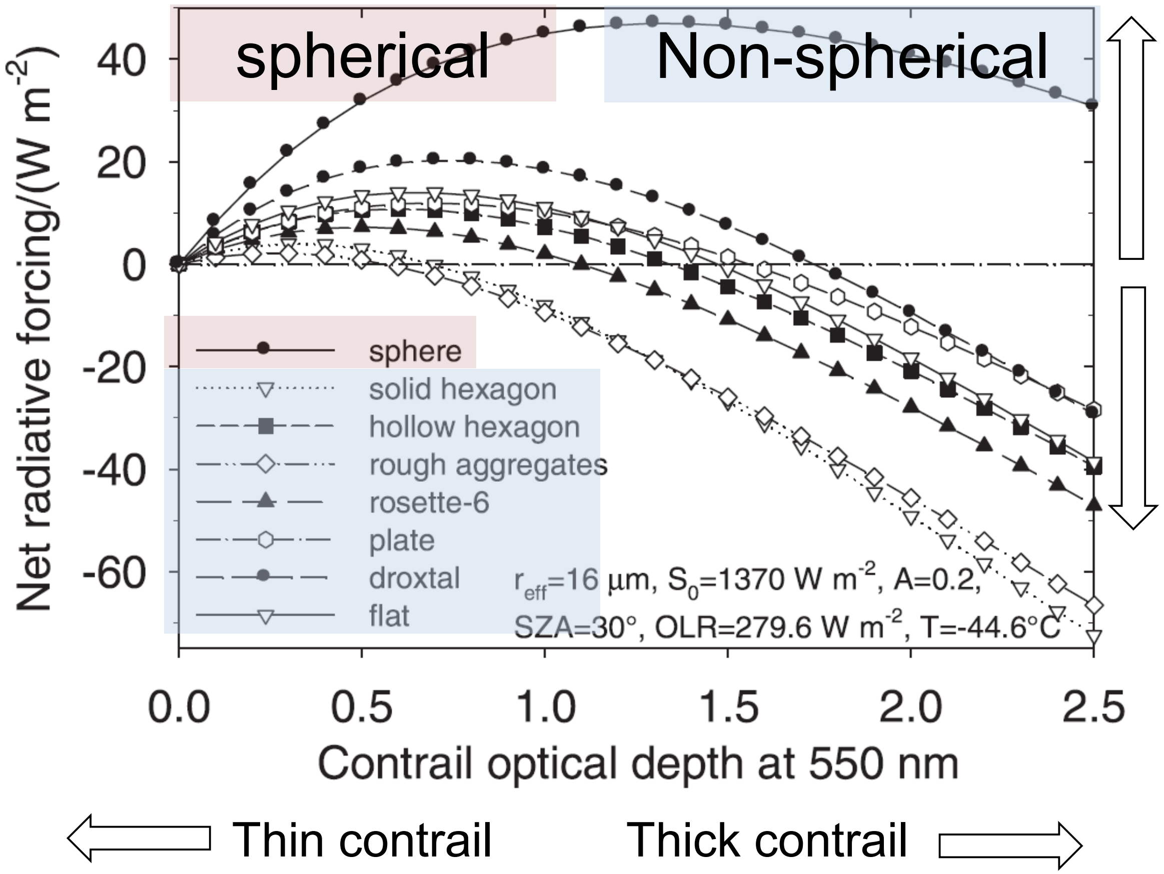
Climate relevance

Micro- and macrophysical properties of contrails matter!

→ Number, size and shape of the contrail ice particles are climate important parameters!

→ Size and Life cycle of contrails has an impact on the radiation budget





Schumann et al. 2012

Outline

- Short introduction: Why do we care about contrails?
- How do contrails form?
- **How do we detect contrails and their microphysical properties at different evolution stages?**
- How can we reduce the climate impact from contrails?
- Outlook:

  How much do we know about contrails from H_2 combustion and H_2 fuel cell electric power? What are the needs from the research perspective?

Contrail and Contrail Cirrus properties during aging

Jet Phase	Vortex Phase	Dispersions Phase: formation of contrail cirrus
0 – 10 seconds	1 – 4 Minutes	Minutes to Hours

DLR Dassault Falcon 20

DLR Gulfstream HALO

Contrail and Contrail Cirrus properties during aging: Measurement platforms

Jet Phase	Vortex Phase	Dispersions Phase: formation of contrail cirrus
0 – 10 seconds	1 – 4 Minutes	Minutes to Hours

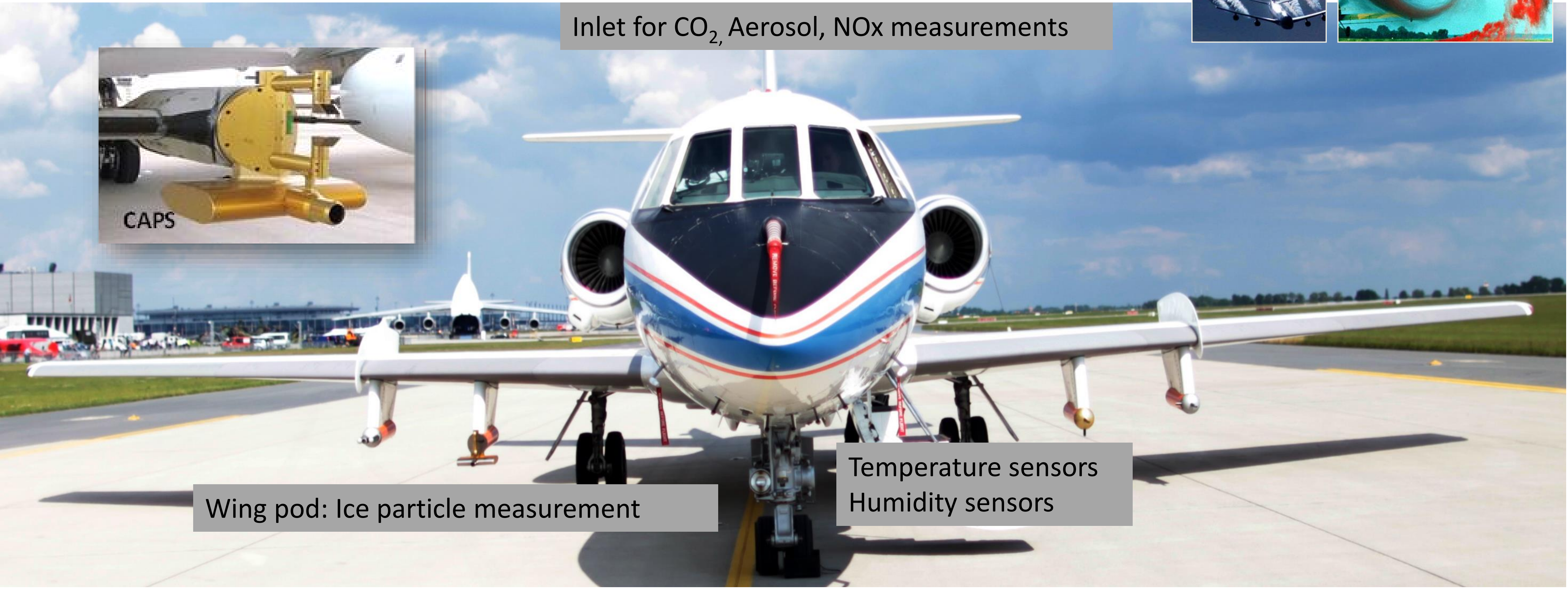
DLR Dassault Falcon 20

DLR Gulfstream HALO

- Range: 3500 km, 5 flight hours
- Altitude: certified for 12.8 km
- Maximum payload about 2 tons

- Range: 10000 km; more than 10 flight hours
- Altitude: certified for more than 15 km
- Maximum payload of 3 tons → 25 to 30 instruments

Measurement of contrails with the DLR-Falcon

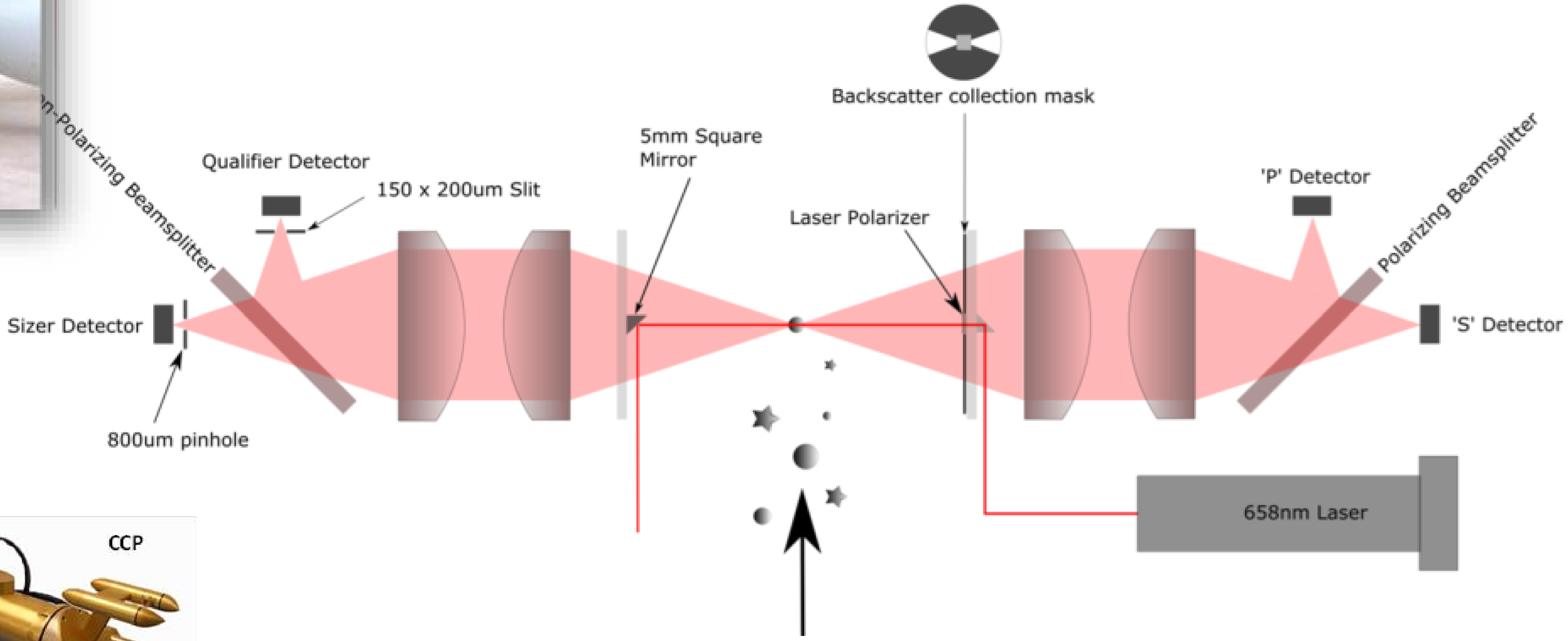


DLR

Instruments for measurements of contrail ice particles: light scattering

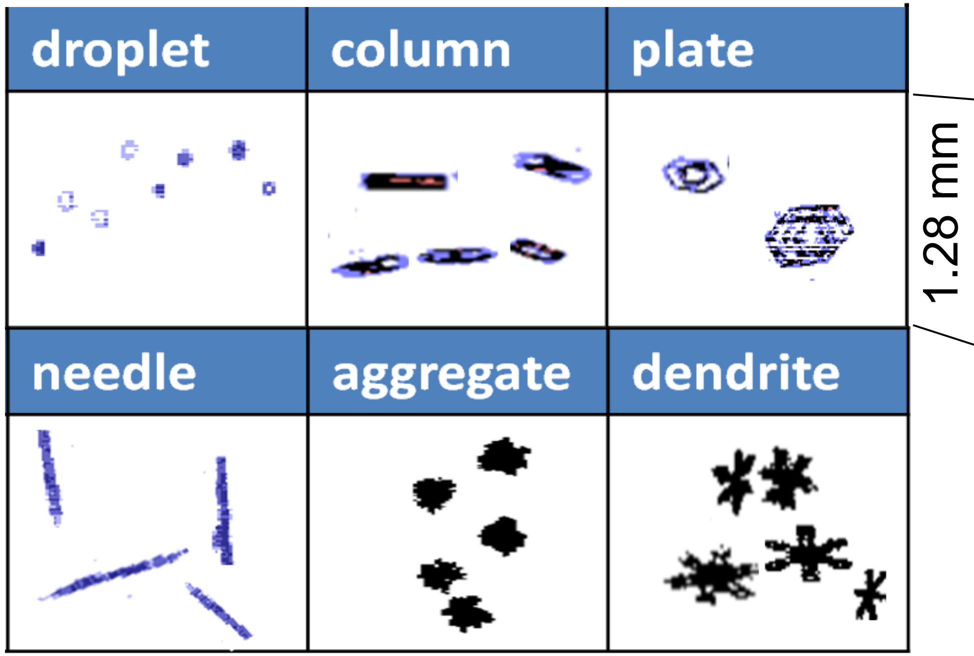
Forward scattered light:
sizing and counting of ice particles

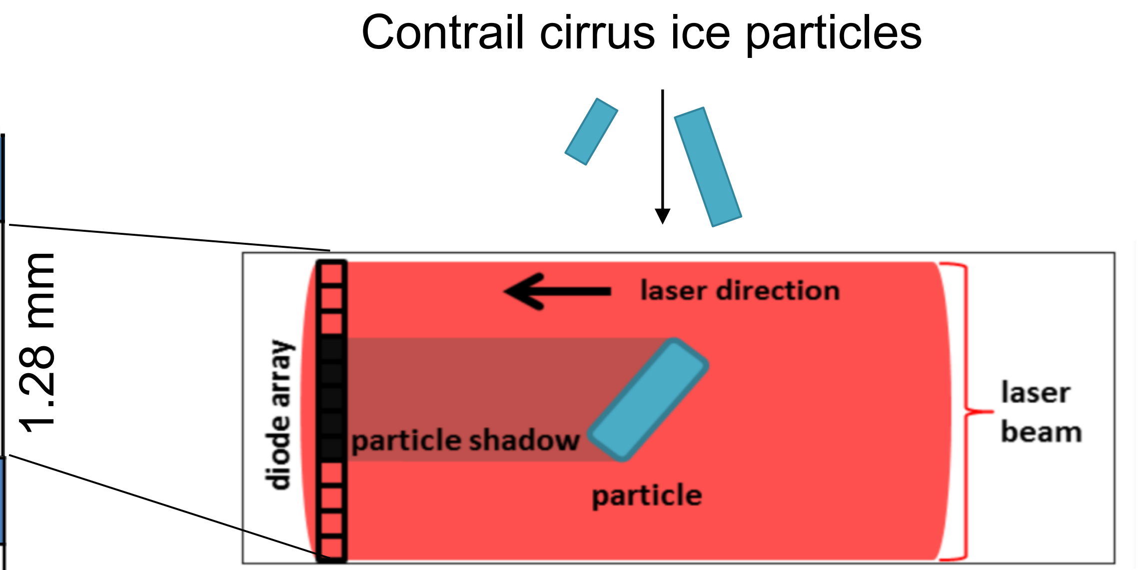
Backward scattered light:
shape of ice particles



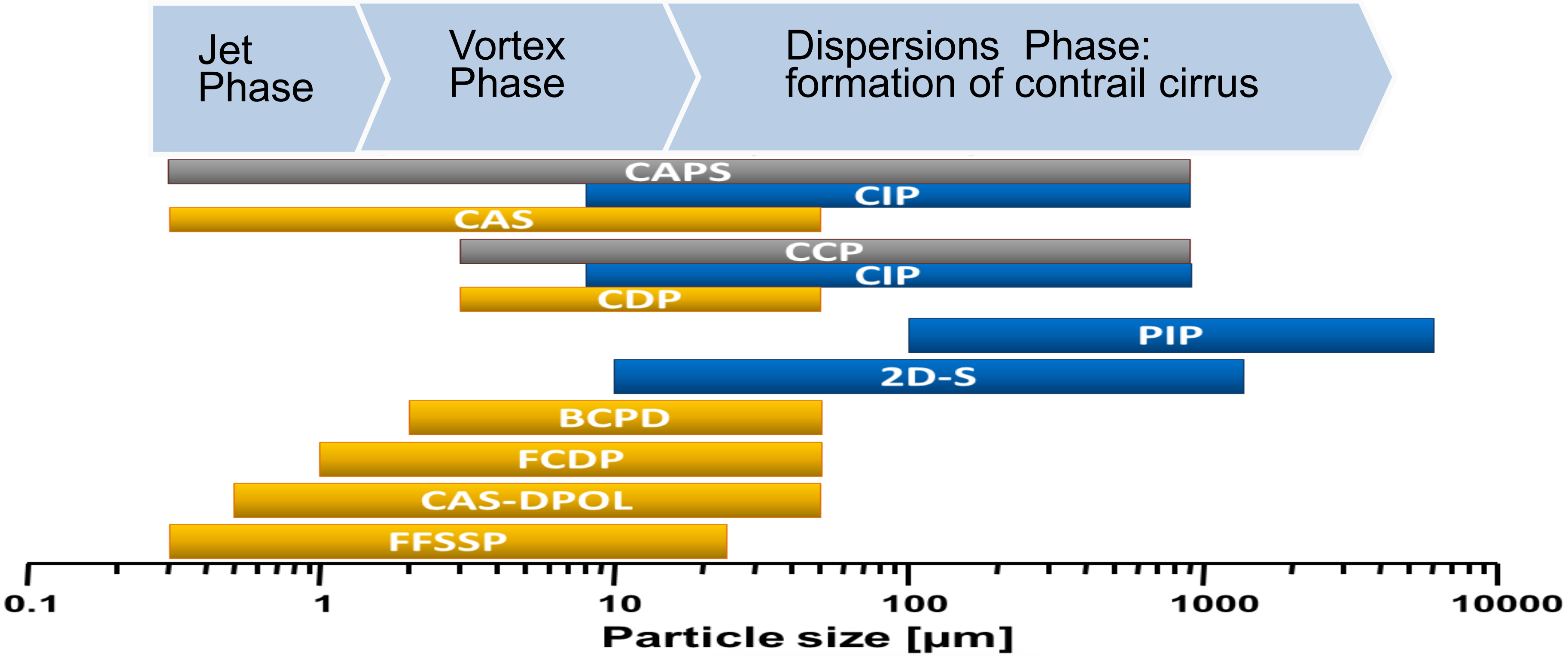
Contrail ice particles

Instruments for measurements of contrail cirrus ice particles: imaging

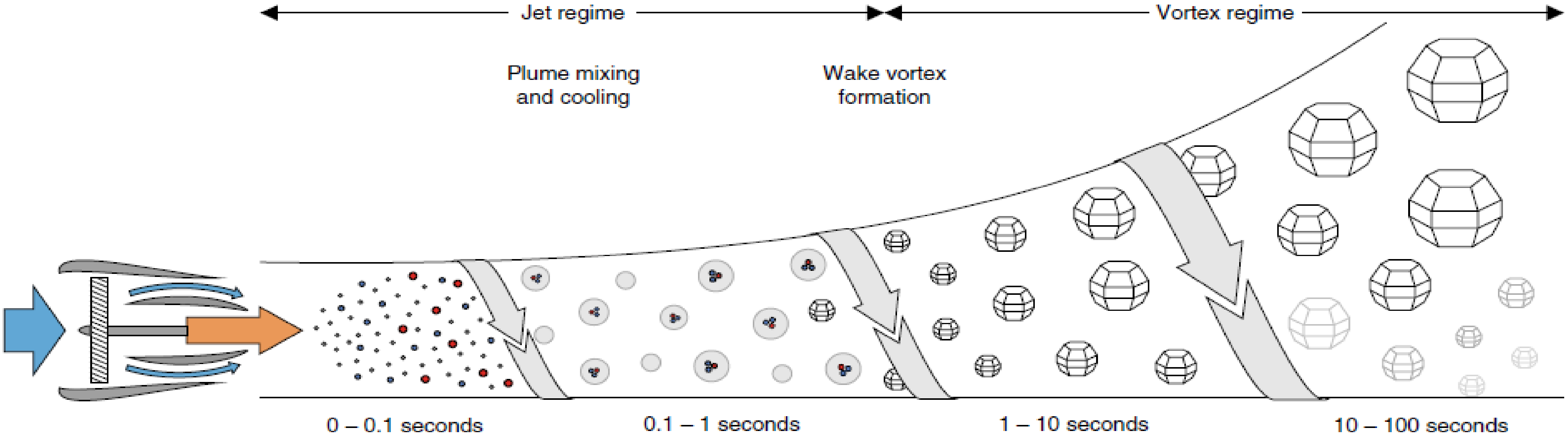




DLR Instruments for measurements of contrail ice particles: full size spectrum

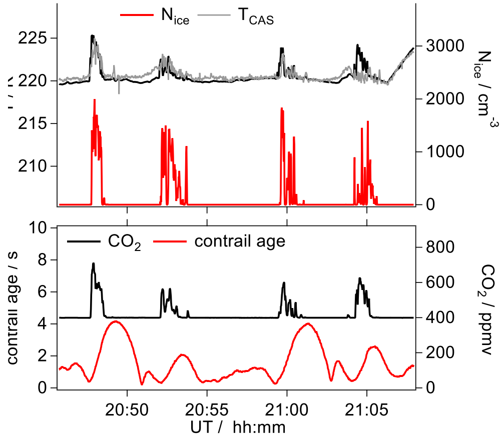


Detection of contrail ice particles: the jet regime



ACCESS-2: Alternative Fuel Effects on Contrails and Cruise Emissions Study

Detection of contrail ice particles: the jet regime



The Jet regime:
Inhomogeneous, turbulent region behind aircraft where the contrail forms

→ High resolution measurements are needed to resolve the contrail structure and evolution

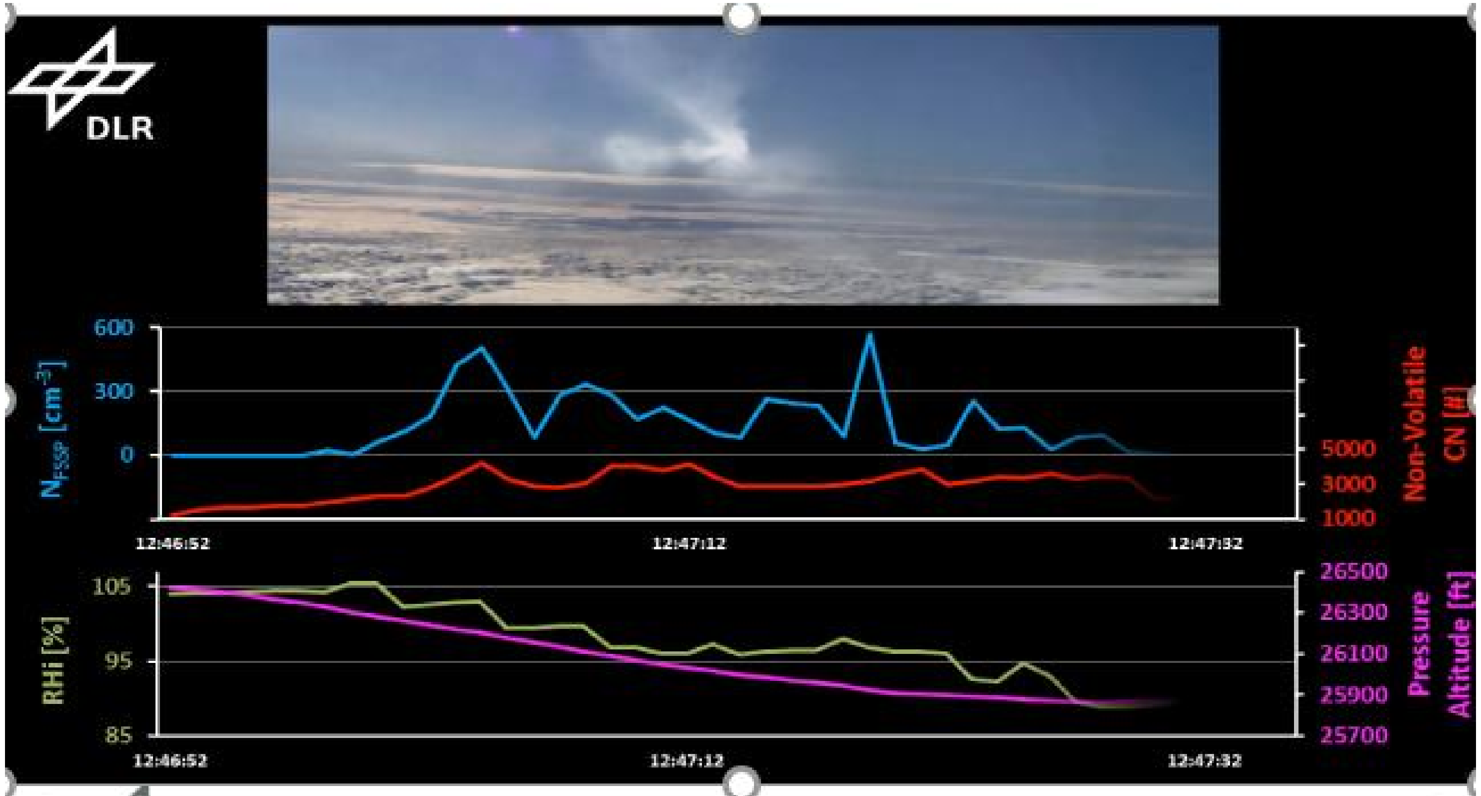
AEI= Apparent Ice Emission Index
→ number of ice particles formed per kg burned fuel

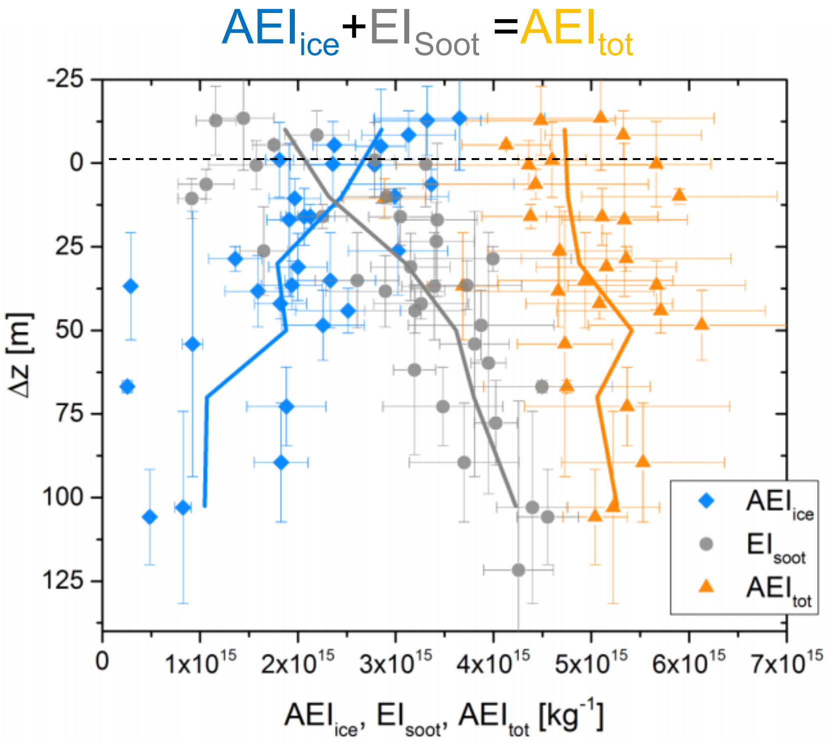
$$\mathrm{AEI} = \frac{\Delta \mathrm{N_{ice}}}{\Delta \mathrm{CO_2}} * \left(\frac{\mathrm{M_{air}}}{\mathrm{M_{CO2}} * \rho_{\mathrm{air}}}\right) * \mathrm{EI_{CO2}}$$

Jurkat-Witschas et al., in prep

Detection of contrails : the vortex phase

ECLIF/NDMAX: Contrail of the ATRA (A320) measured by the DLR-Falcon and the NASA-DC8





Kleine, et al., 2018

Detection of contrail cirrus and natural cirrus – the dispersion phase: HALO campaigns ML-CIRRUS and CIRRUS-HL

Bundesministerium für Bildung und Forschung

Bundesministerium für Wirtschaft und Technologie

DFG

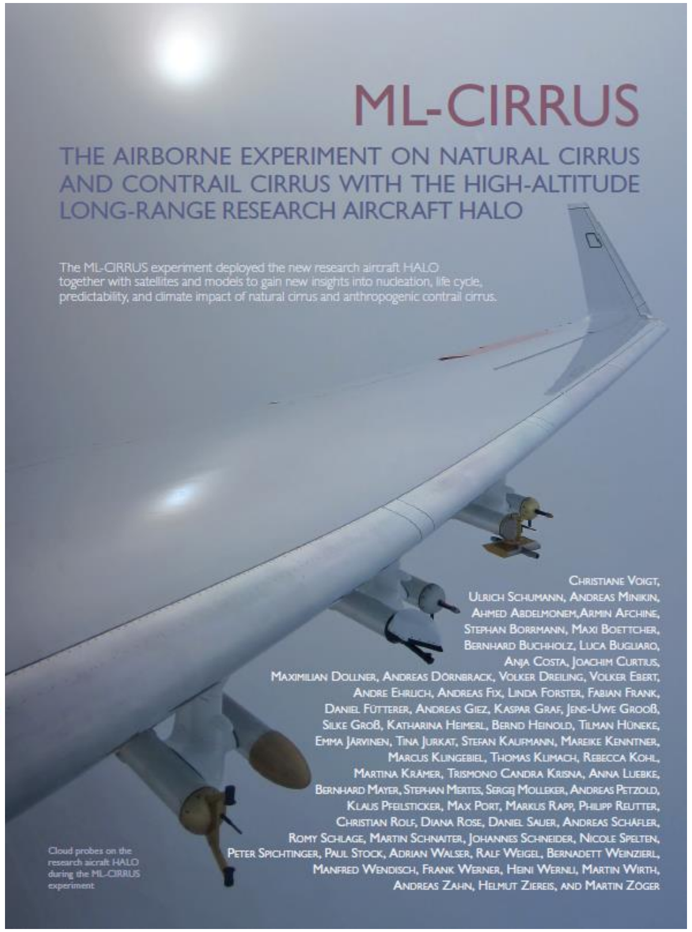
GFZ Helmholtz Centre Potsdam

HELMHOLTZ GEMEINSCHAFT

LEIBNIZ-INSTITUTE FOR TROPOSPHERIC RESEARCH

JÜLICH FORSCHUNGSZENTRUM

KIT Karlsruher Institut für Technologie

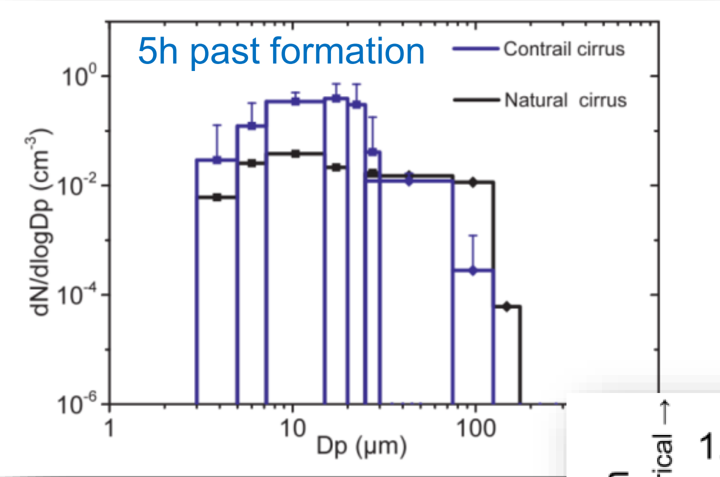

ML-CIRRUS

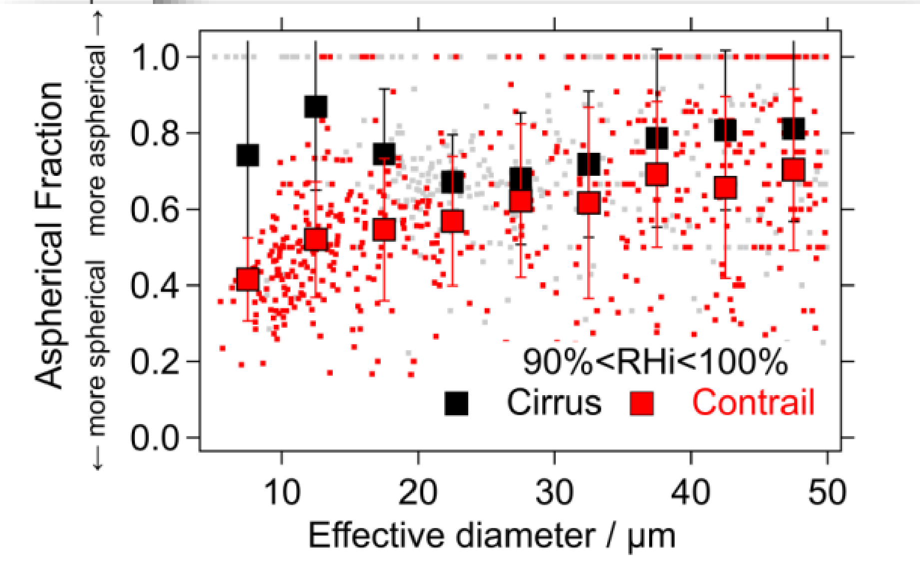
THE AIRBORNE EXPERIMENT ON NATURAL CIRRUS AND CONTRAIL CIRRUS WITH THE HIGH-ALTITUDE LONG-RANGE RESEARCH AIRCRAFT HALO

The ML-CIRRUS experiment deployed the new research aircraft HALO together with satellites and models to gain new insights into nucleation, life cycle, predictability, and climate impact of natural cirrus and anthropogenic contrail cirrus.

Christiane Voigt, Ulrich Schumann, Andreas Minikin, Ahmed Abdelmonem, Armin Afchine, Stephan Borrmann, Maxi Boettcher, Bernhard Buchholz, Luca Bugliaro, Anja Costa, Joachim Curtius, Maximilian Dollner, Andreas Dörnbrack, Volker Dreiling, Volker Ebert, Andre Ehrlich, Andreas Fix, Linda Forster, Fabian Frank, Daniel Fütterer, Andreas Giez, Kaspar Graf, Jens-Uwe Grooß, Silke Groß, Katharina Heimerl, Bernd Heinold, Tilman Hüneke, Emma Järvinen, Tina Jurkat, Stefan Kaufmann, Mareike Kenntner, Marcus Klingebiel, Thomas Klimach, Rebecca Kohl, Martina Krämer, Trismono Candra Krisna, Anna Luebke, Bernhard Mayer, Stephan Mertes, Sergej Molleker, Andreas Petzold, Klaus Pfeilsticker, Max Port, Markus Rapp, Philipp Reutter, Christian Rolf, Diana Rose, Daniel Sauer, Andreas Schäfler, Romy Schlage, Martin Schnaiter, Johannes Schneider, Nicole Spelten, Peter Spichtinger, Paul Stock, Adrian Walser, Ralf Weigel, Bernadett Weinzierl, Manfred Wendisch, Frank Werner, Heini Wernli, Martin Wirth, Andreas Zahn, Helmut Ziereis, and Martin Zöger

Voigt et al., BAMS, 2017





DLR

CIRRUS-HL - Advancing our understanding of cirrus in high and mid-latitudes and aviation impact

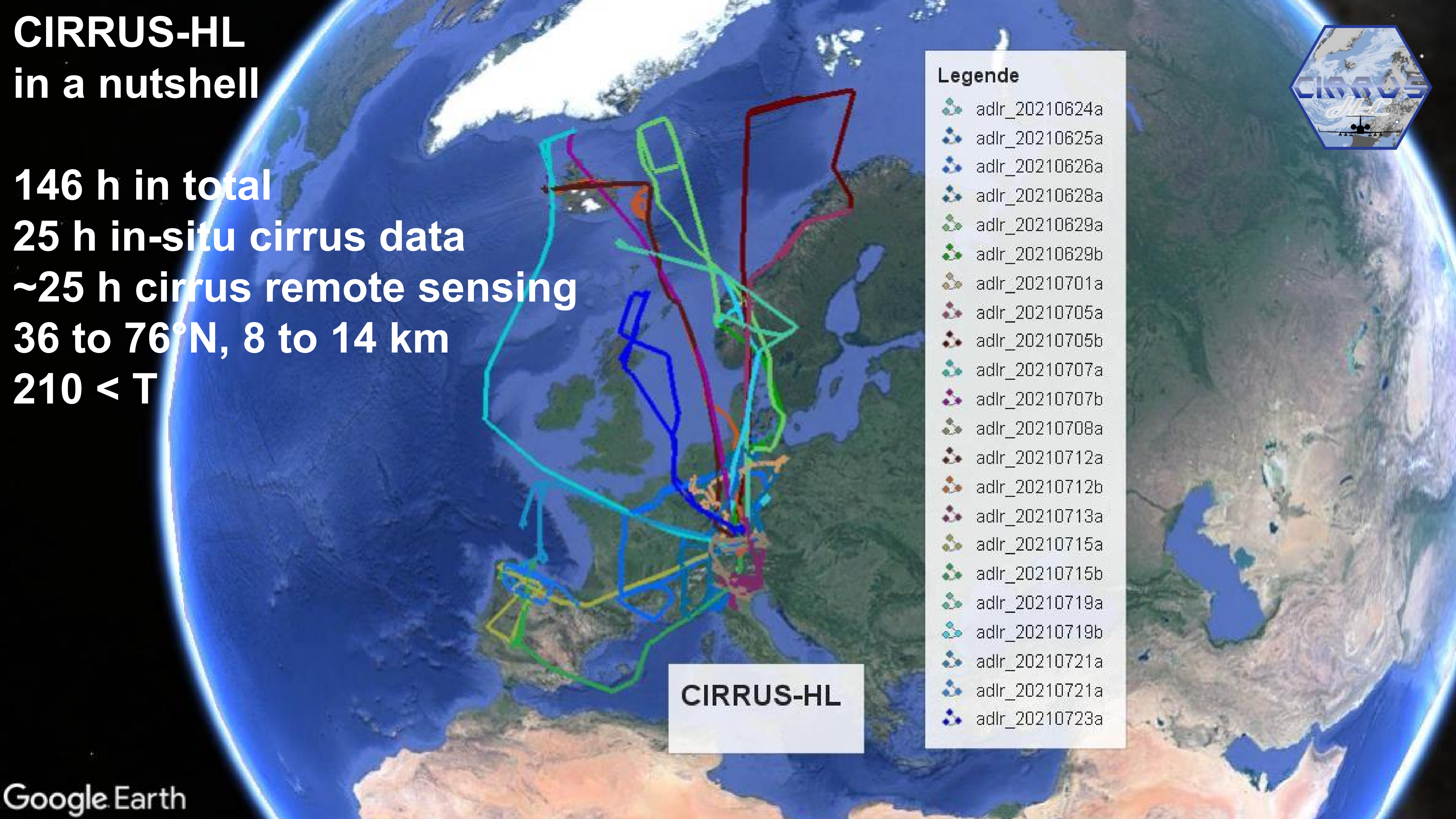
Coordination: Voigt and Jurkat-Witschas
Participants: DLR, 4 universities, 4 research centres, > 100 participants

www.cirrus-hl.de

DLR
DFG
JG|U
LMU
KIT
TROPOS
ETH
HELMHOLTZ GEMEINSCHAFT
HALO

CIRRUS-HL
in a nutshell

146 h in total
25 h in-situ cirrus data
~25 h cirrus remote sensing
36 to 76°N, 8 to 14 km
210 < T

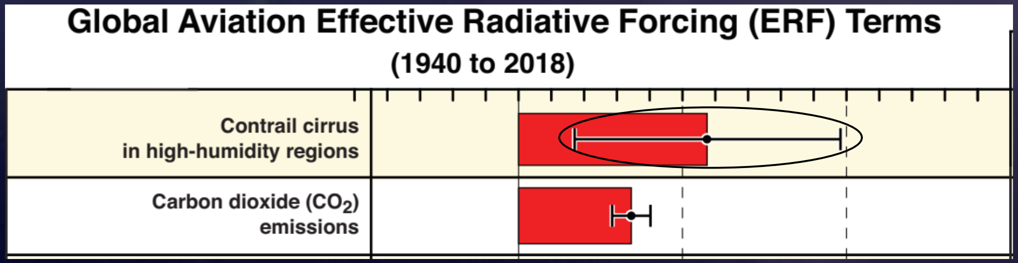


Objectives of the campaign

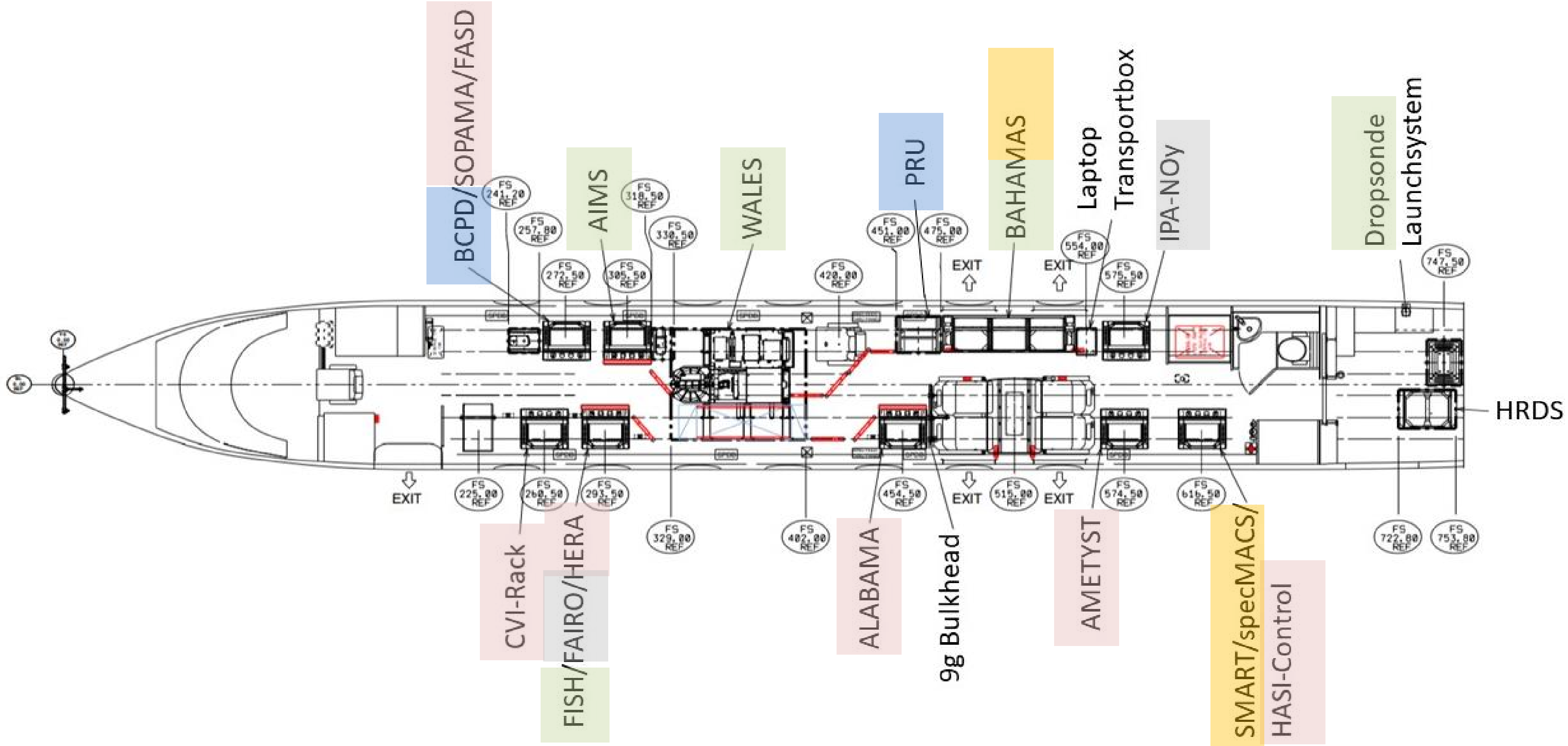
(1) Understand the formation, microphysical properties and radiative impact of high and mid-latitude cirrus
→ Do we see an aviation impact on the cloud properties?

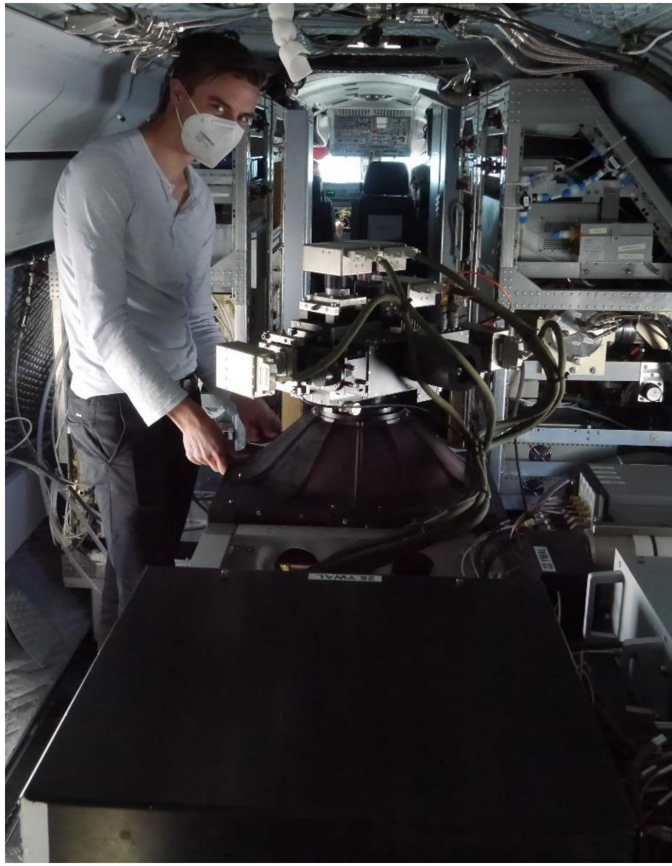
(2) Investigate cooling daytime contrails (in contrast to warming night time contrails)

(3) Advance weather, cloud and global models



Cabin instrumentation CIRRUS-HL





Comprehensive aerosol – water vapor –trace gas - ice particle – radiation payload!

HALO- Instrumentation for studies of contrail and contrail cirrus : state of the art cloud probes and water vapor instruments

Bundesministerium für Bildung und Forschung

Bundesministerium für Wirtschaft und Technologie

DFG

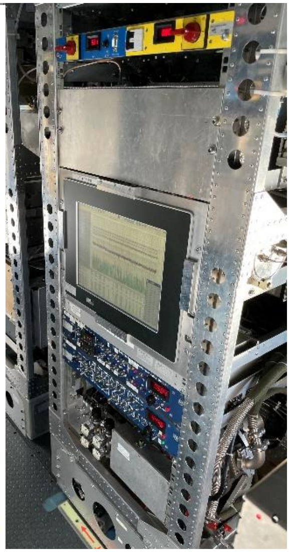
GFZ Helmholtz Centre Potsdam

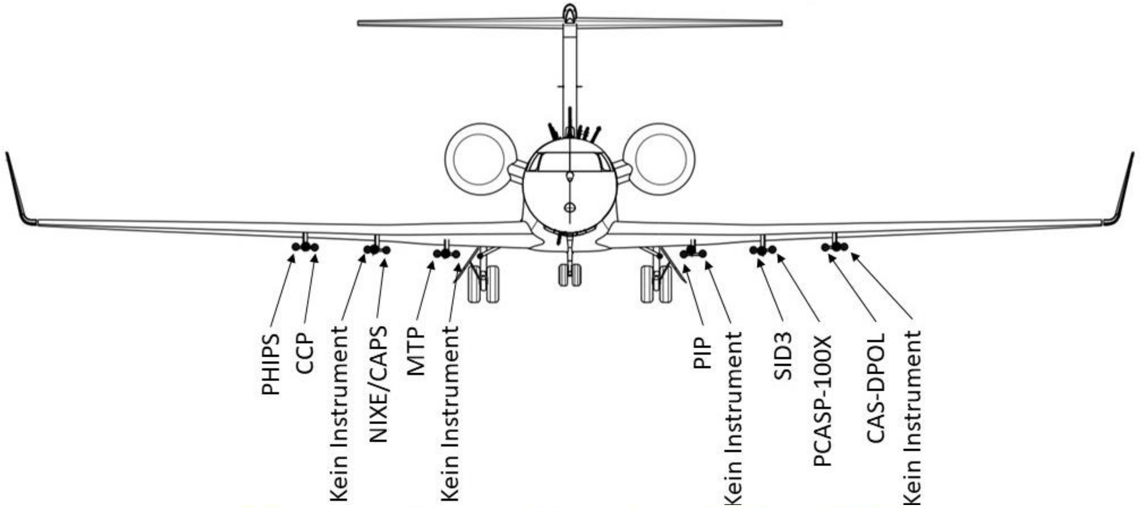
HELMHOLTZ GEMEINSCHAFT

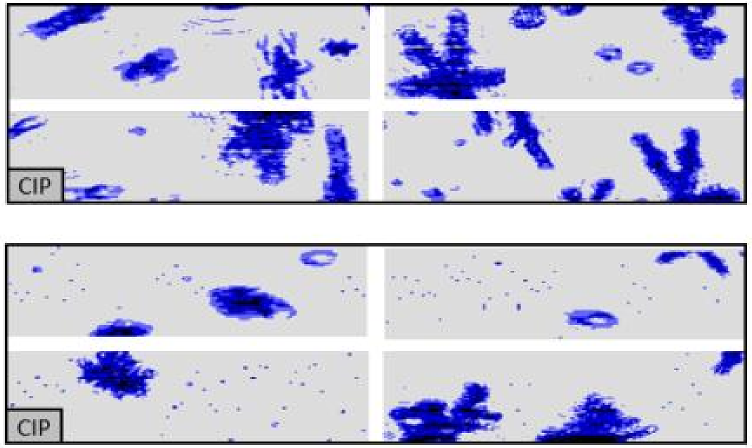
LEIBNIZ-INSTITUTE FOR TROPOSPHERIC RESEARCH

JÜLICH FORSCHUNGSZENTRUM

KIT Karlsruher Institut für Technologie



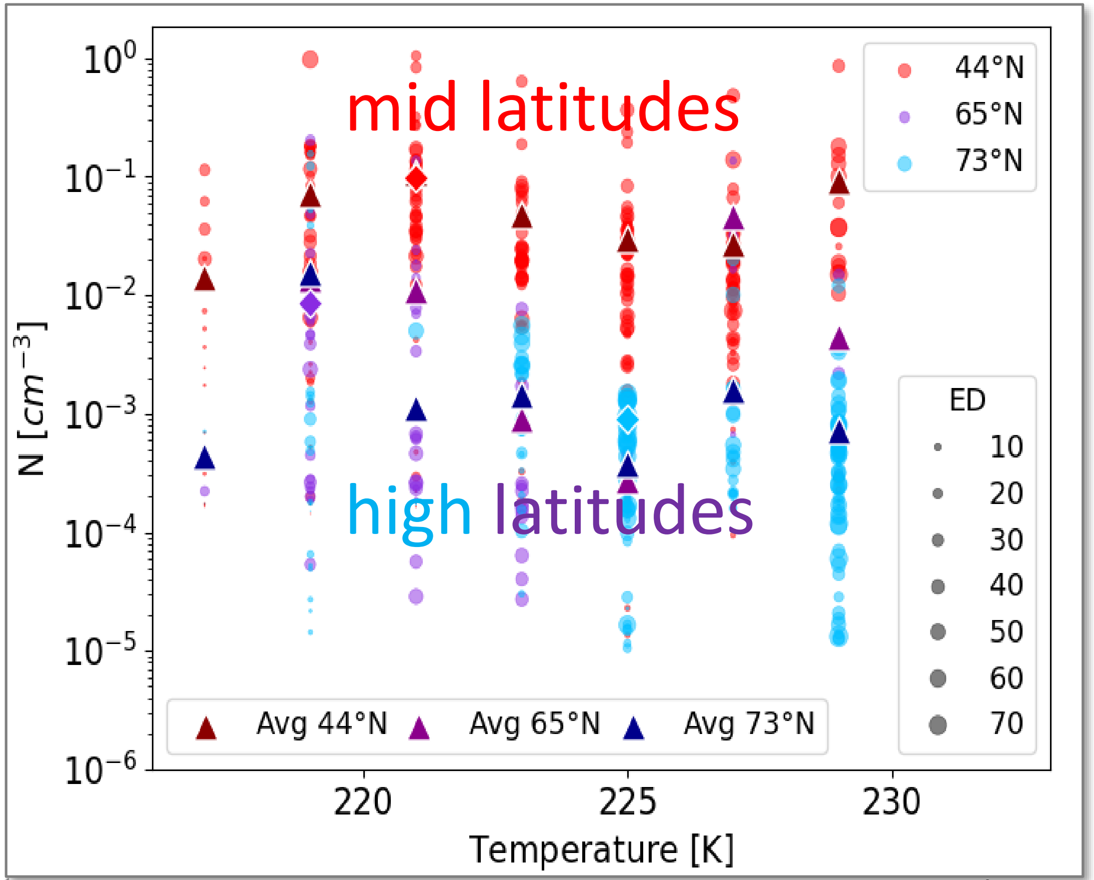




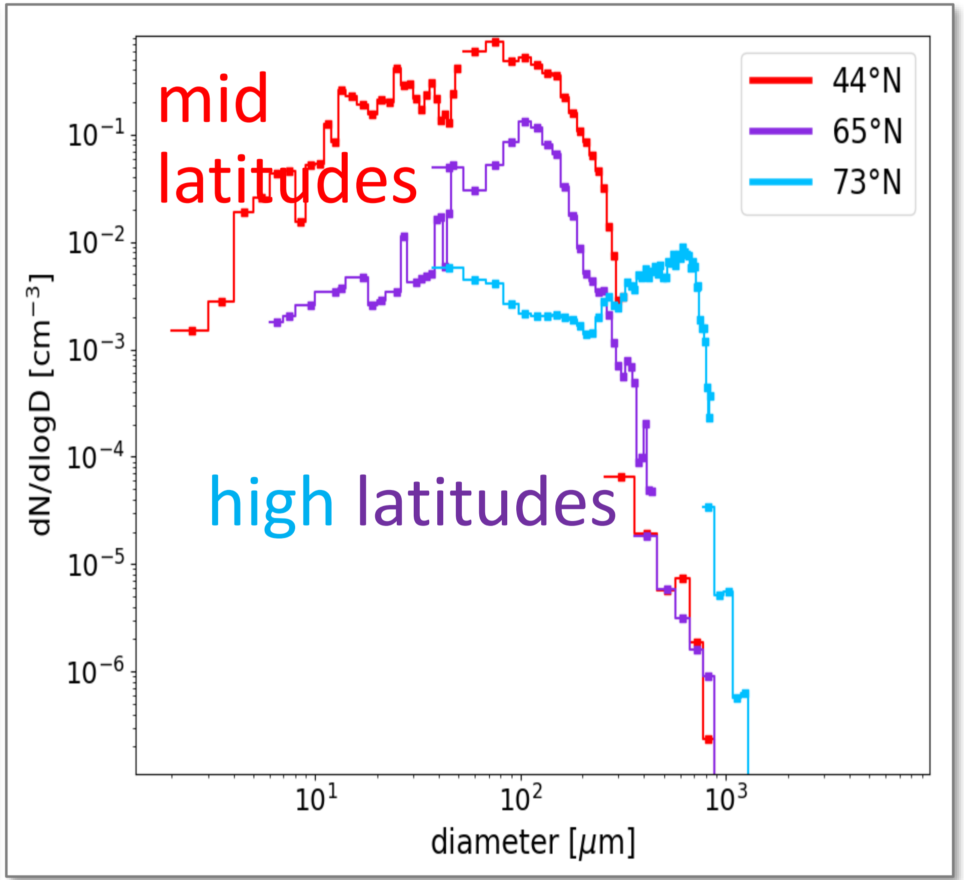
Arctic cirrus ice particles

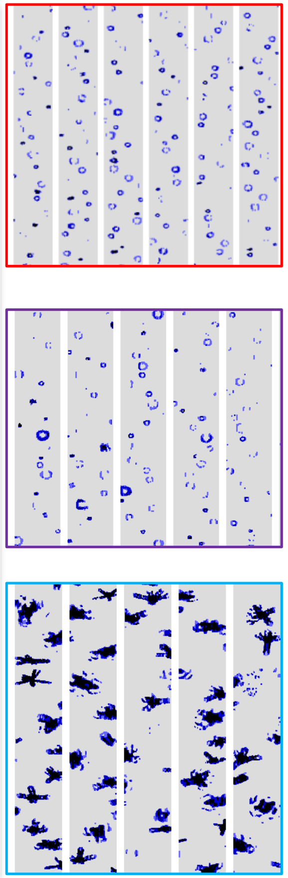
Higher ice crystal numbers in mid-latitude cirrus
Aviation impact?

Ice number concentrations in cirrus



Particle size distributions

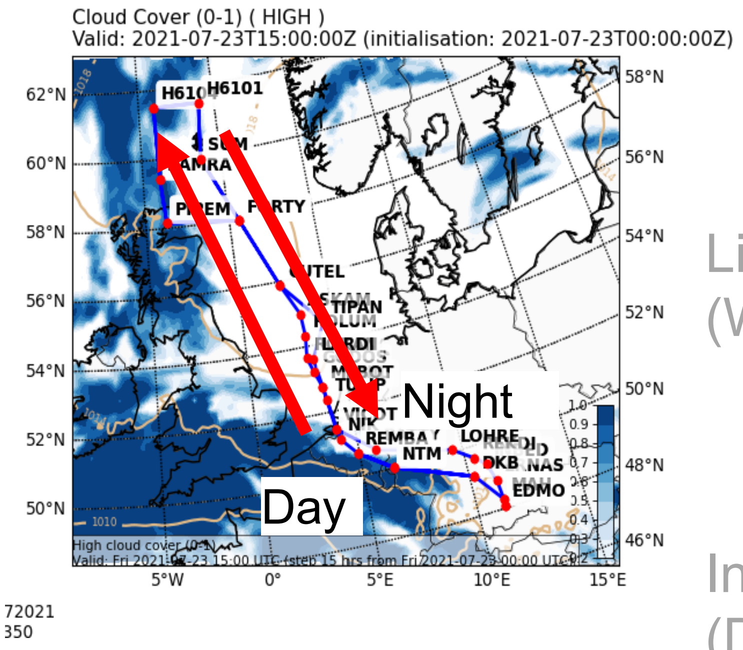


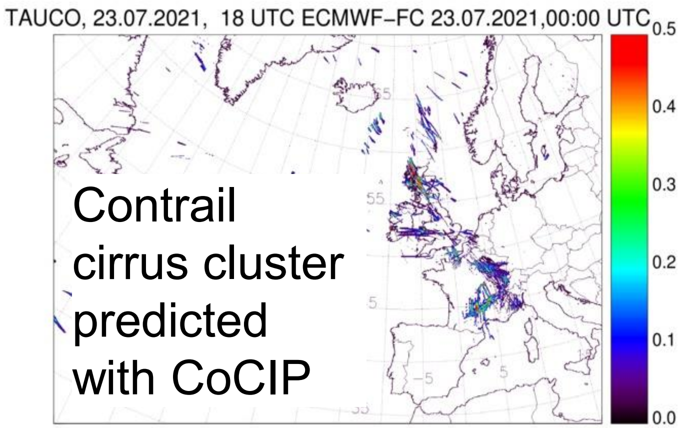


CCP/PIP: De la Torre Castro, Hahn, Moser, Jurkat-Witschas, Voigt, DLR, Uni Mainz

Measurement of the day vs night time radiative properties of contrail cirrus

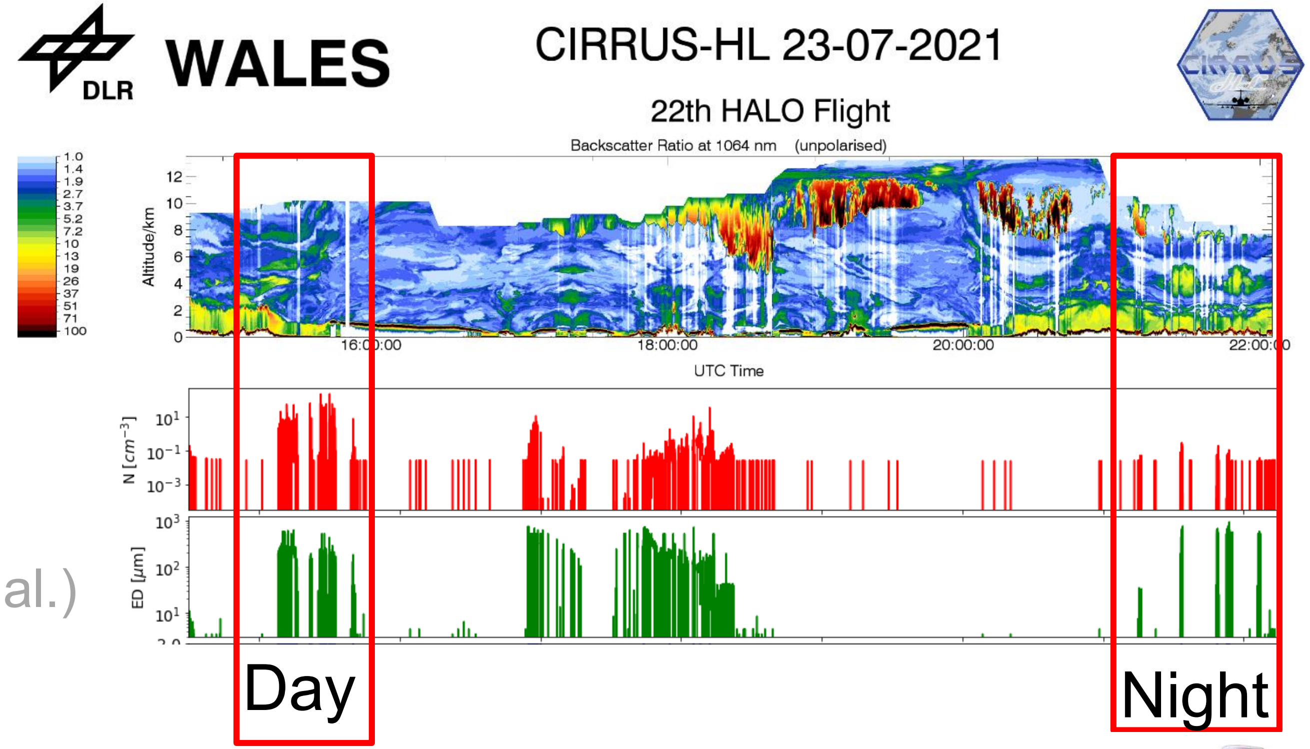
Aim: probe a contrail cluster during day and night





Lidar
(Wirth et al.)

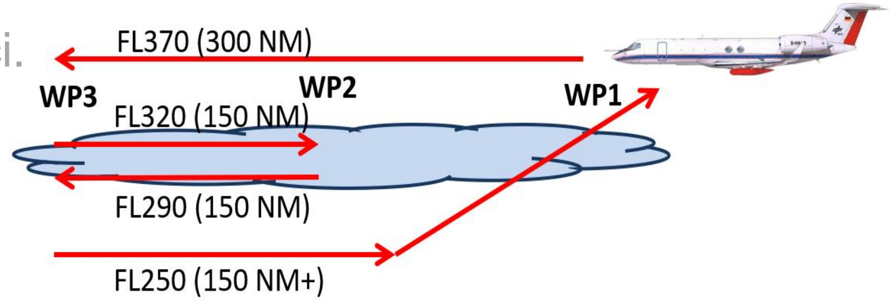
In-situ
(De la Torre et al.)



Lidar and radiation above contrail ci.

In-situ in contrail cirrus

Radiation below contrail cirrus



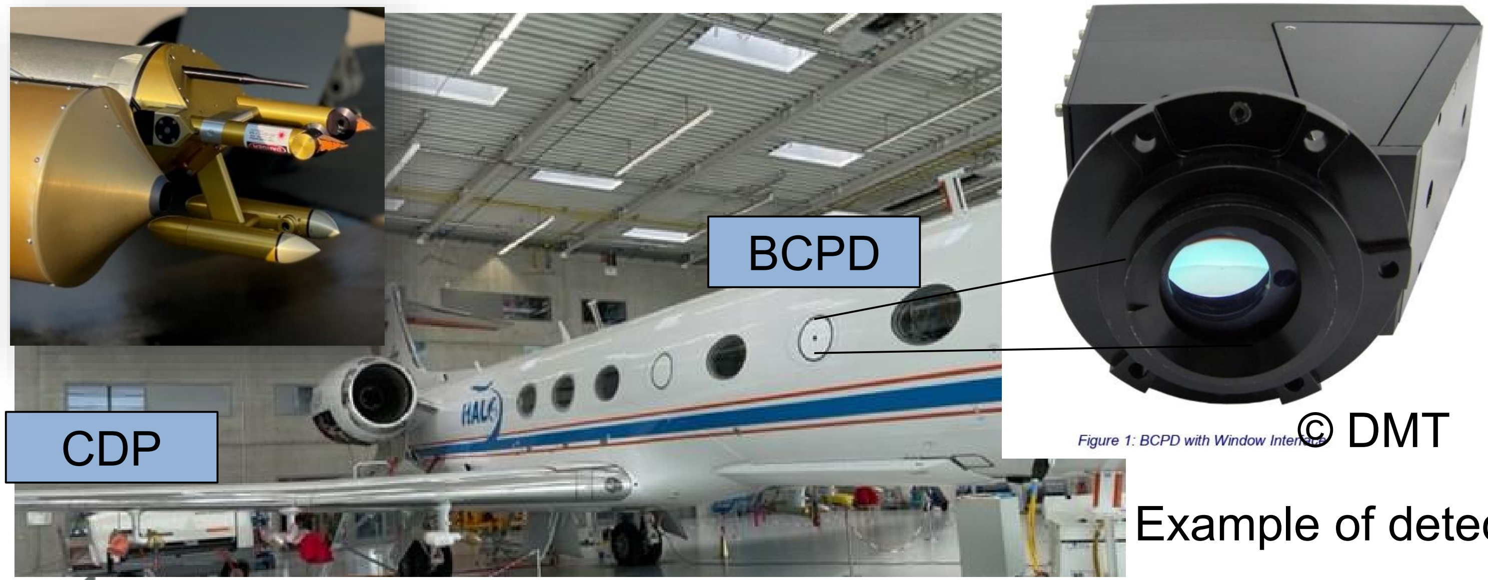
Contrail particle measurements with the BCPD

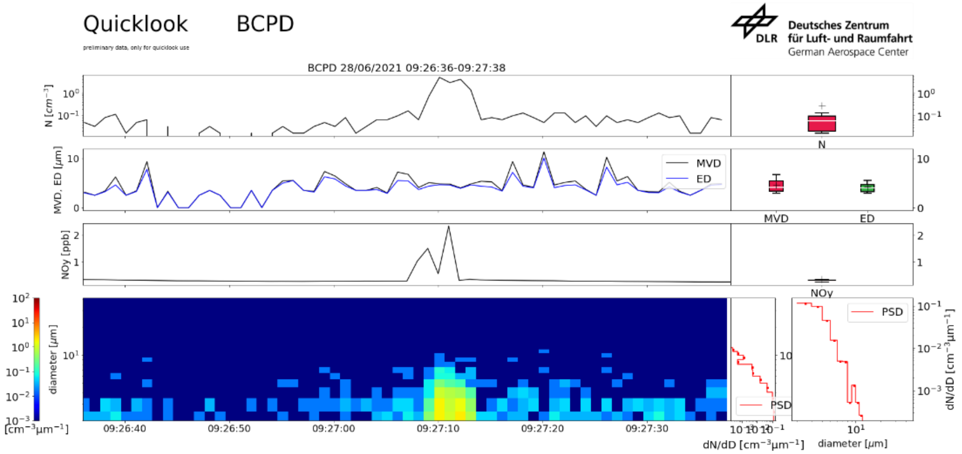
- **B**ackscatter **C**loud **P**robe with **P**olarization **D**etection
  - particles in the size range 2-50 µm measured by scattered light in the 145° angle
  - Polarisation measurements to detect the phase of particles

- **Advantage: no drag, low weight, window mounted, easy to operate**

Light-weight instrument for contrail cirrus outbreak detection

Measurement of small cloud particles: (supercooled droplet) icing conditions, contrails and contrail cirrus at flight altitude





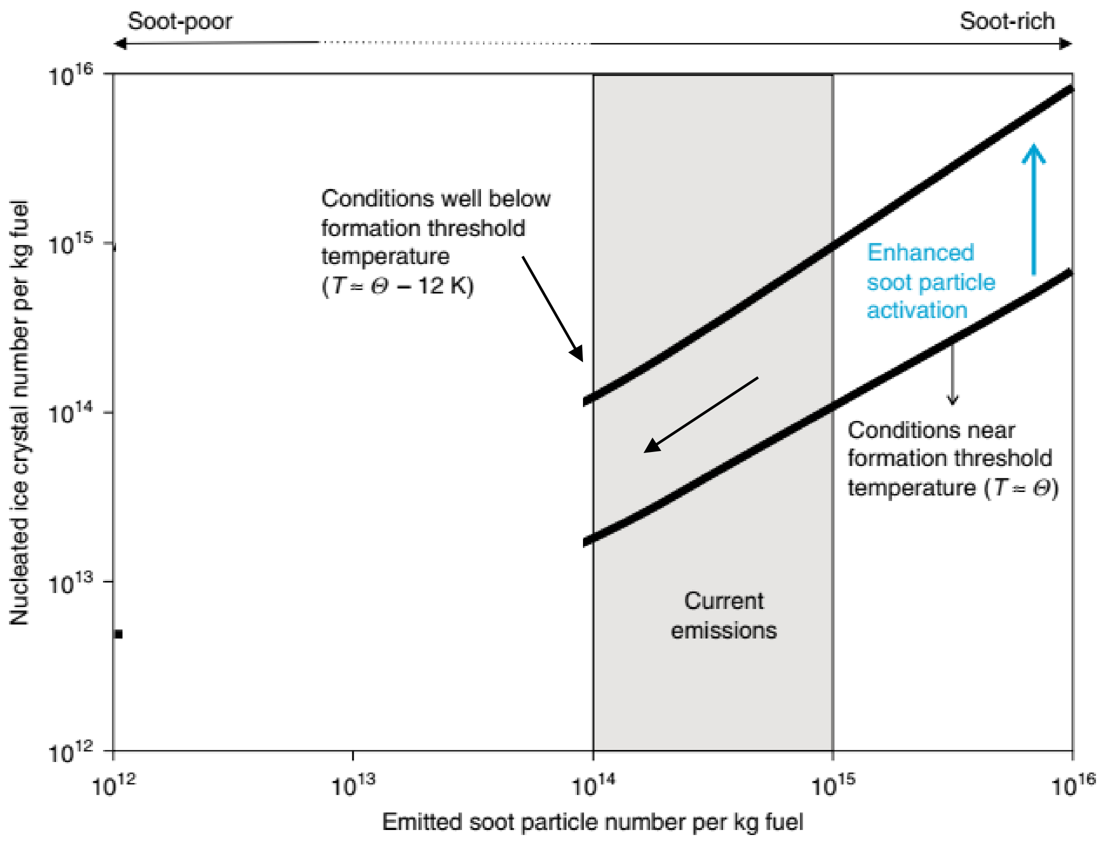
Example of detection of contrails and contrail cirrus with BCPD

Outline

- Short introduction: Why do we care about contrails?
- How do contrails form?
- How do we detect contrails and their microphysical properties at different evolution stages?
- **How can we reduce the climate impact from contrails?**
- Outlook:

  How much do we know about contrails from H_2 combustion and H_2 fuel cell electric power? What are the needs from the research perspective?

Relationship of emitted soot particles and nucleated ice crystals



- **Soot-rich regime**:

  - nucleated ice crystals per kg of burned fuel is linearly dependent on the number of emitted soot particels per kg of burned fuel

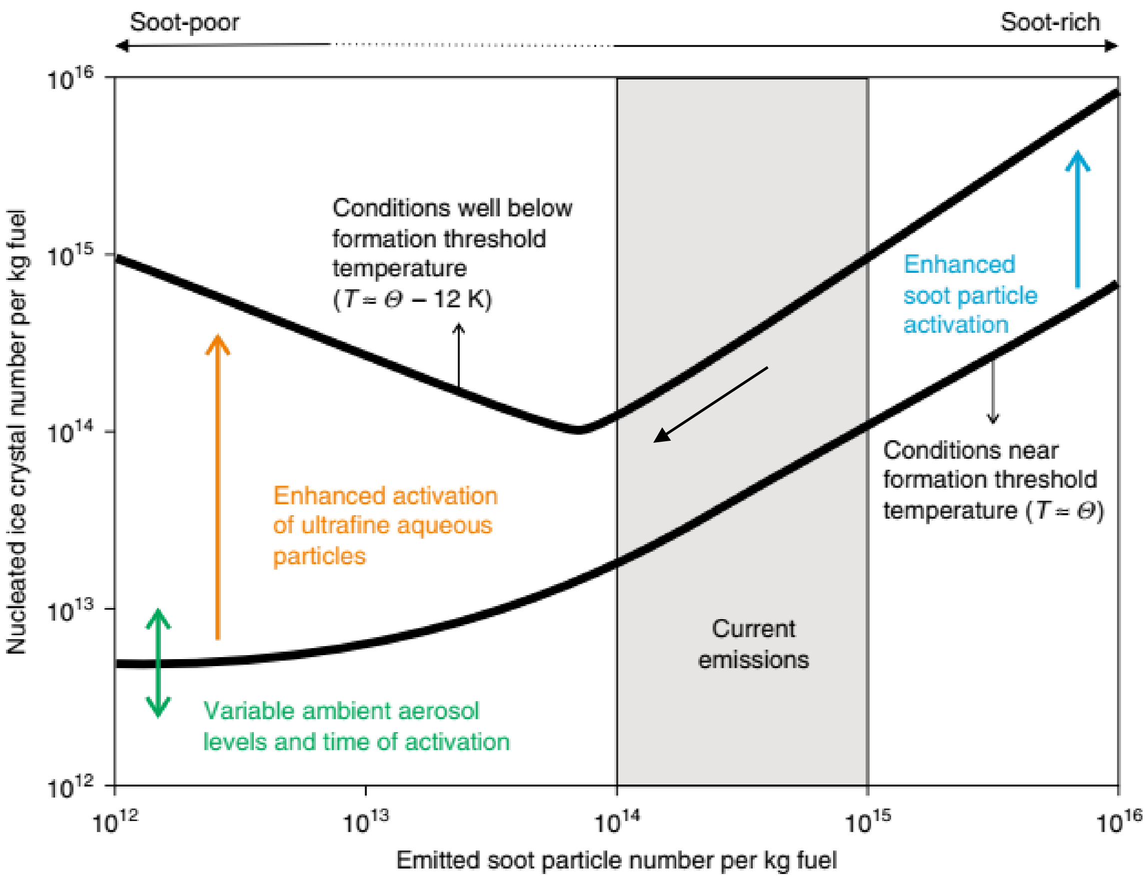
  - number of nucleated ice crystals depends on ambient temperature below the contrail formation temperature

- at low ambient temperatures:
  every soot particle forms one ice crystal

$$AEI = \frac{\Delta N_{ice}}{\Delta CO_2} * \left(\frac{M_{air}}{M_{CO2} * \rho_{air}}\right) * EI_{CO2}$$

Adapted from Kärcher, Nature Communications, 2018

Relationship of emitted soot particles and nucleated ice crystals



- **Soot-poor regime**:

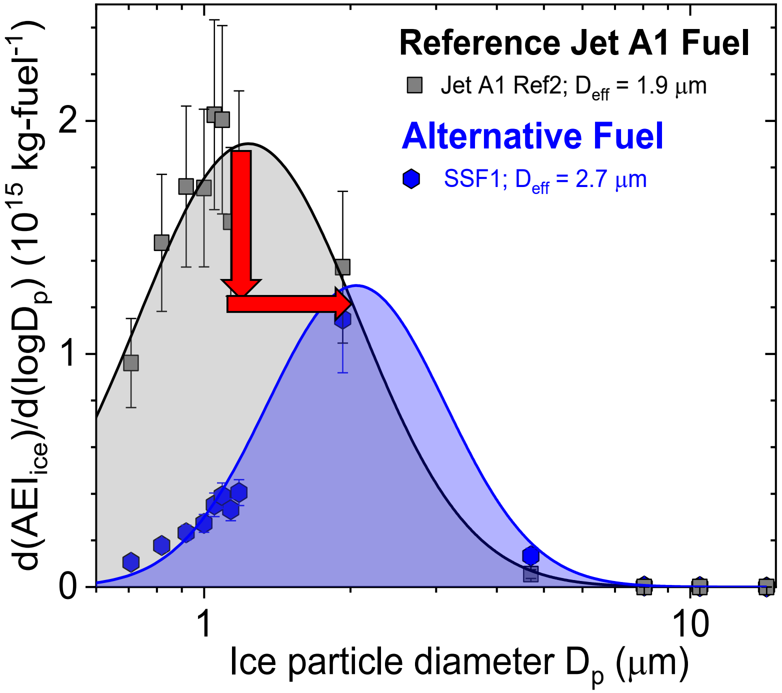
  - at temperatures near the theshold formation temperature Θ:

  - number of nucleated ice crystals depends on ambient temperature below the contrail formation temperature

Adapted from Kärcher, Nature Communications, 2018

Cleaner burning jet fuels reduce contrail cloudiness

Contrail ice crystal size distribution

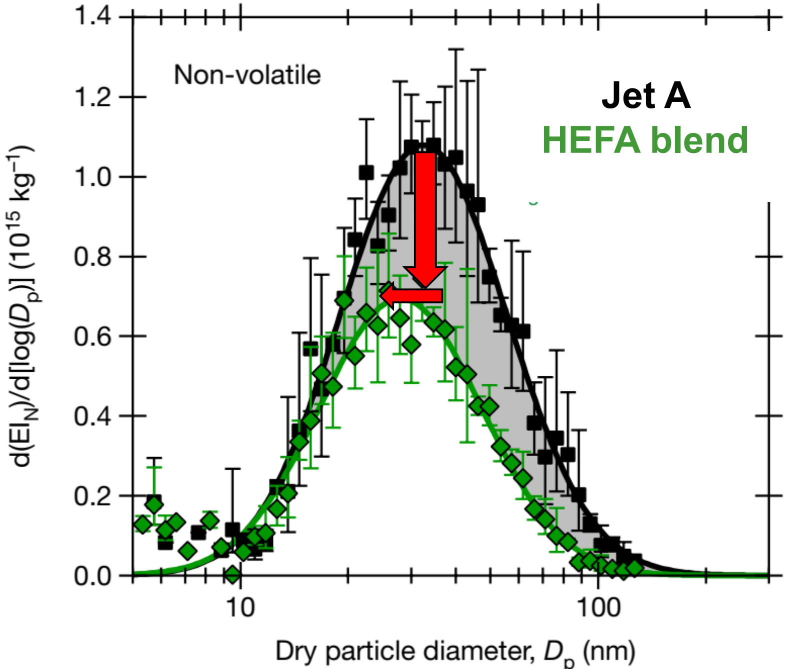


Voigt et al., Nature Comm EE, 2021

The use of sustainable aviation fuels with low aromatic content leads to

- Reduction in soot particles number
- Reduction in initial ice particle number
- Increase in ice particle diameter
- Reduction of contrail cirrus life time and optical depth

Soot size distribution



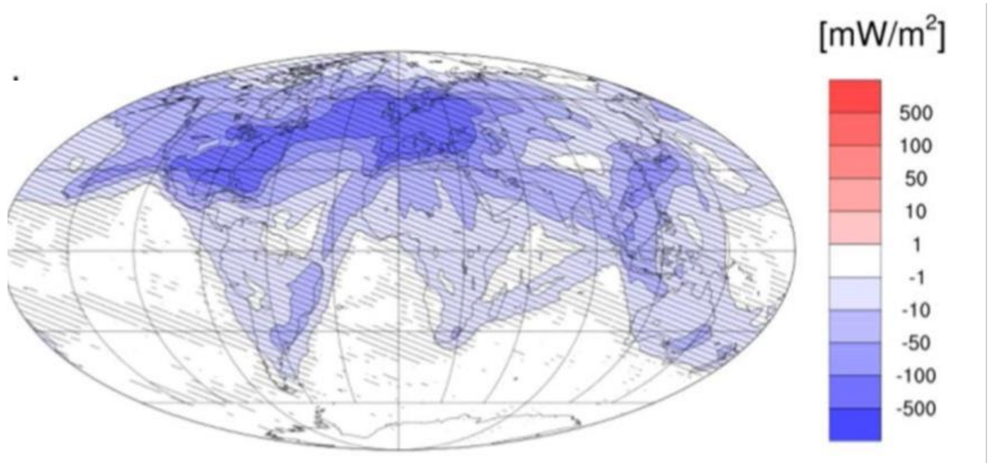
Moore et al., Nature, 2017

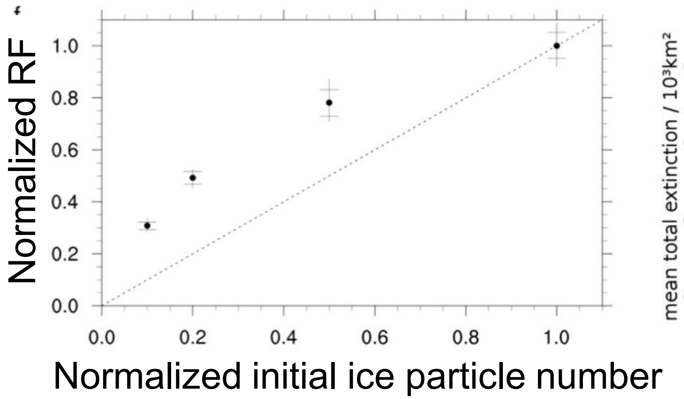
See also presentation from Christiane Voigt, RAeS, 28.04.2022

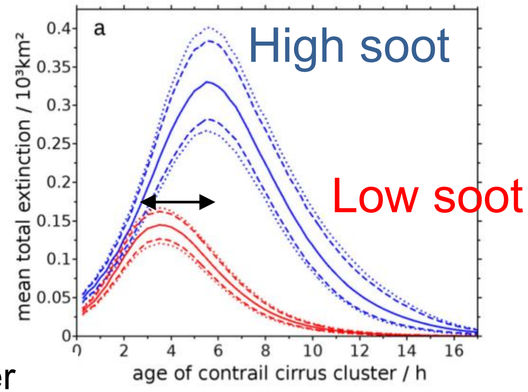
Impact of the initial contrail ice particle number on the global radiative forcing of contrail cirrus

- Reduction in initial ice particle number reduces the radiative forcing from contrails on global and on the local scale
- Contrail coverage and optical depth is reduced
- Largest effects are seen in ice supersaturated regions and in the North Atlantic Flight corridor
- Contrail cirrus life time is reduced by 4 to 5 hours compared to present fleet
- A reduction of 80% of the initial contrail ice number reduces the global radiative forcing by 50%

Main questions: How and in how far can the initial contrail ice number be reduced ?







Burkhardt et al., NPJ Climate and Atmospheric Science, 2018

Outline

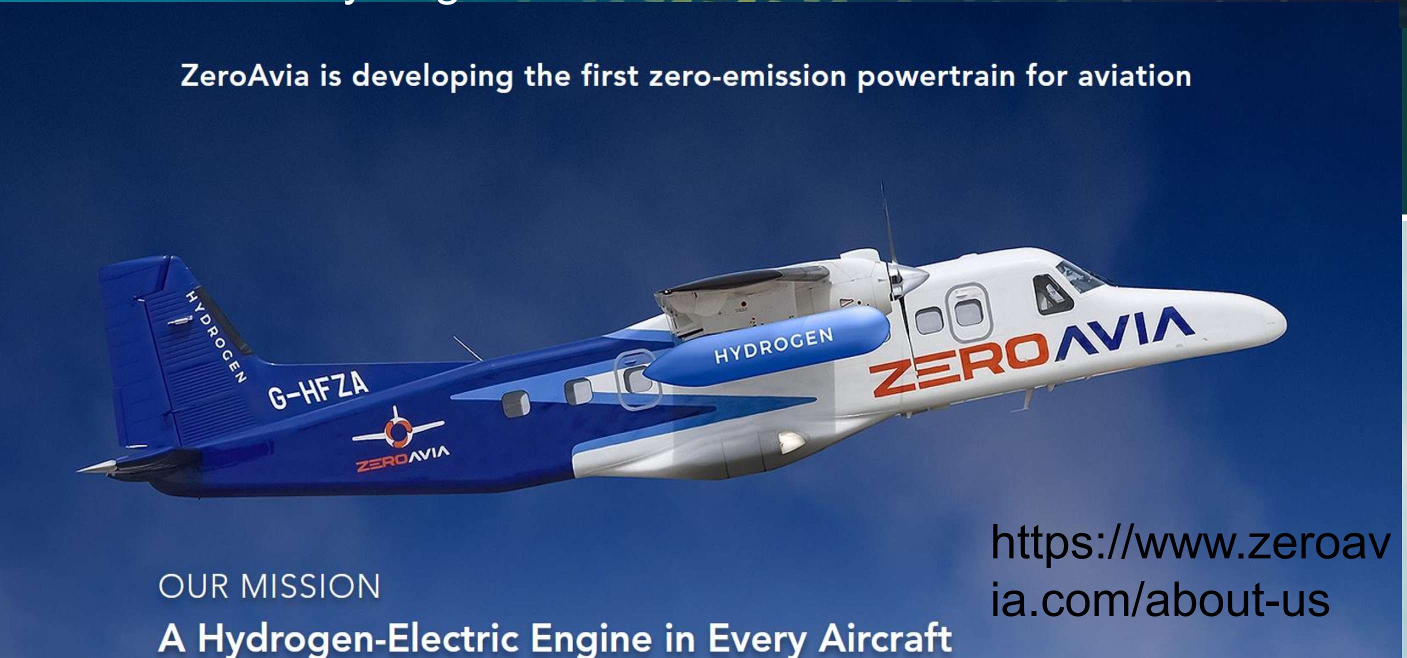
- Short introduction: Why do we care about contrails?
- How do contrails form?
- How do we detect contrails and their microphysical properties at different evolution stages?
- How can we reduce the climate impact from contrails?
- **Outlook:**

  How much do we know about contrails from H_2 combustion and H_2 fuel cell electric power? What are the needs from the research perspective?

H_2 contrails : The next generation contrails

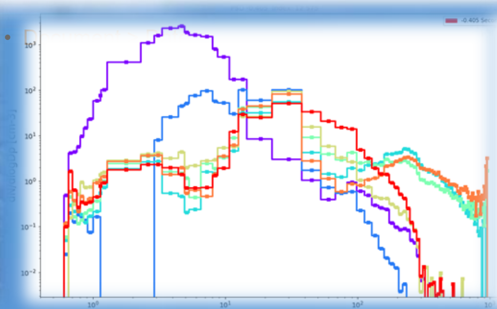
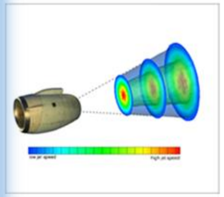
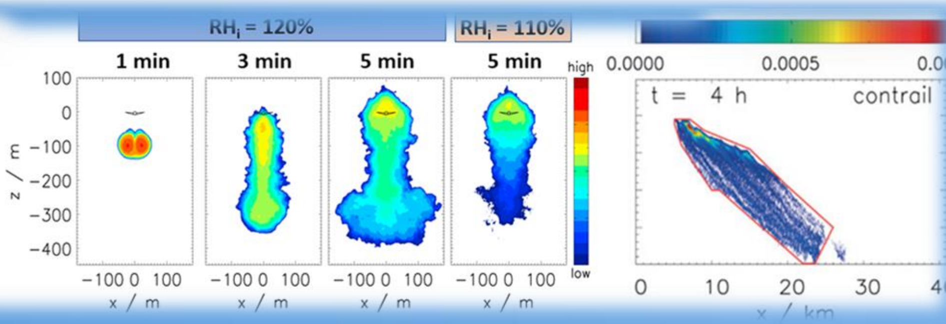
https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe

https://www.dlr.de/content/en/articles/news



https://www.zeroavia.com/about-us

https://de.deutscheaircraft.com/news

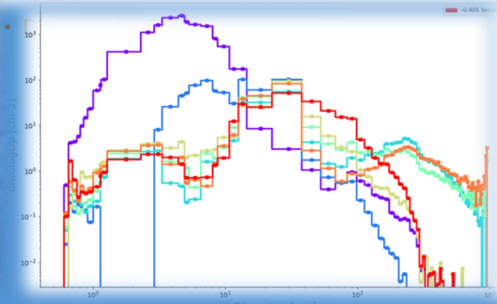





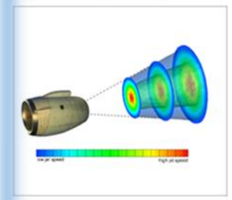
DLR-research group H2CONTRAIL:
Impact of H_2-based engines on contail properties

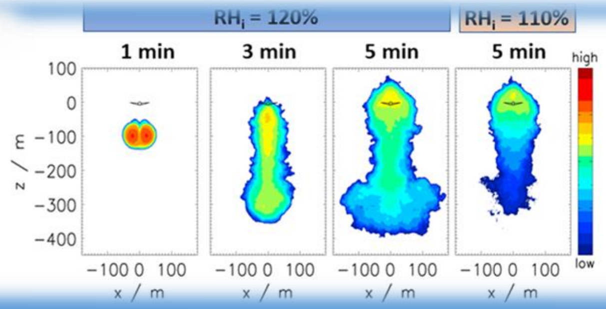
Contact tina.jurkat@dlr.de and simon.unterstrasser@dlr.de

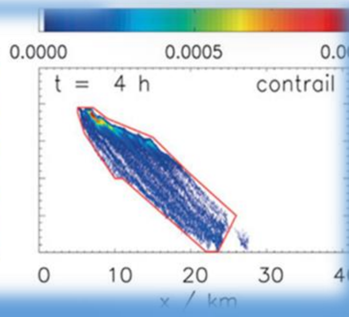
Linking high resolution models and measurements to answer:

How and where do H_2 contrails form?
What are their properties ?
How are climate relevant parameters modified?









Linking high resolution models and measurements :

H_2 combustion chamber simulations

Modelling of contrails from H_2-engines

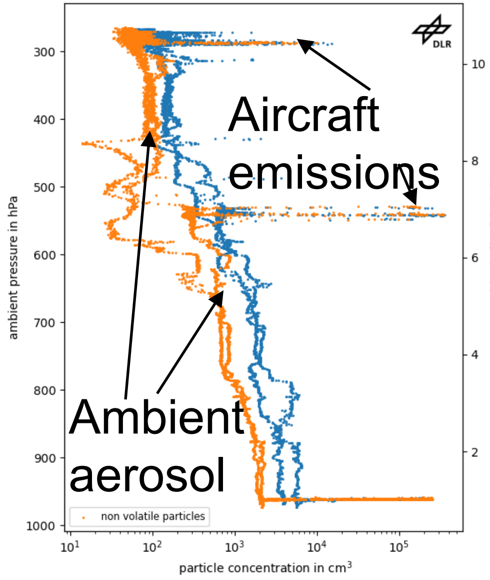
Designing instruments and H_2 contrail measurements in demo mission

Scale to large jet aircraft

Derive climate relevant parameters

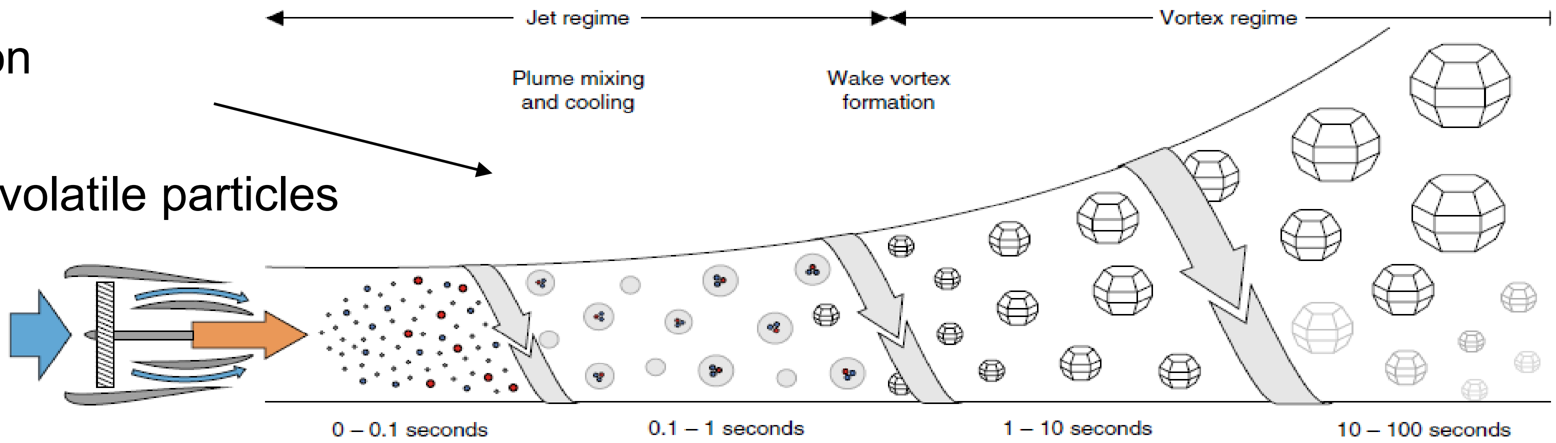
Contrail properties from H_2 combustion

Example of aerosol variability in the atmosphere vs aircraft plumes



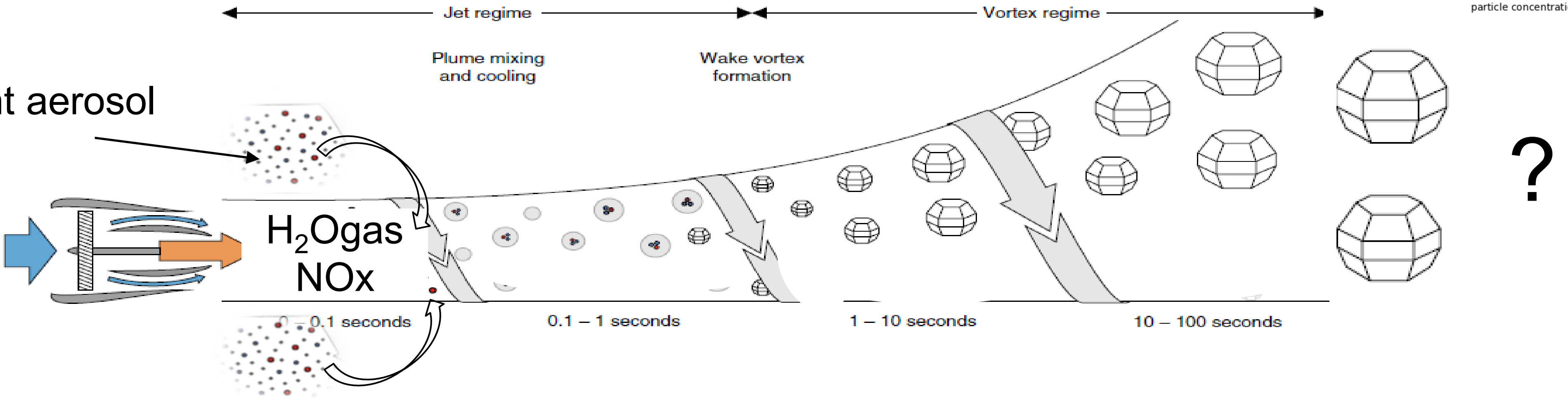
Kerosene combustion

Soot and volatile particles



Hypothetical picture:
H_2 combustion

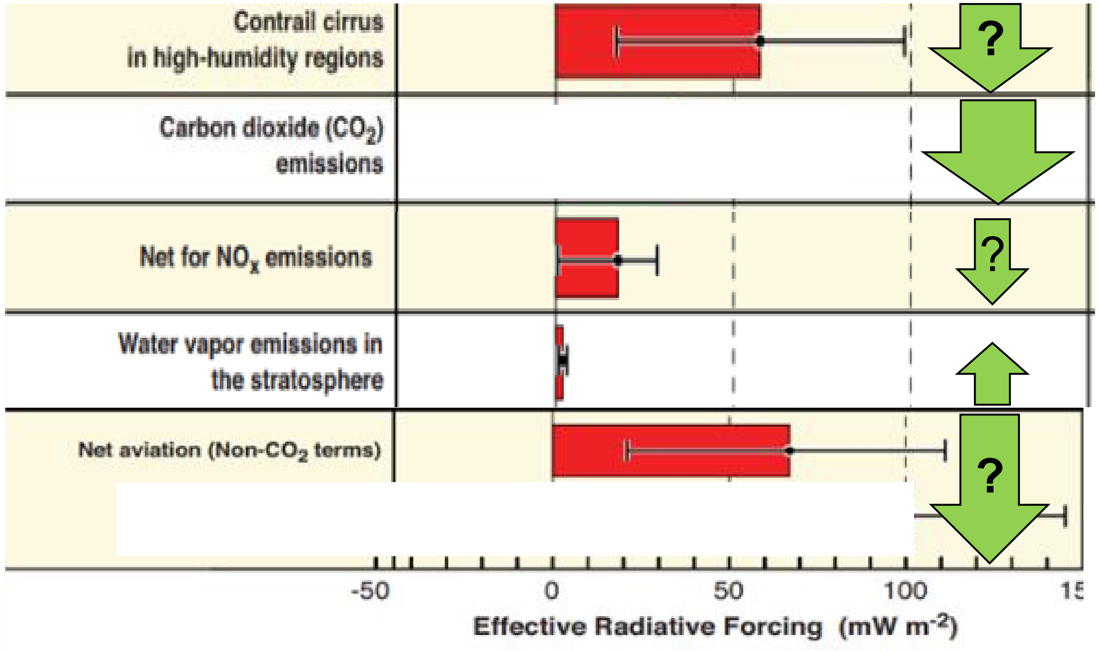
Ambient aerosol



But: Measurements and model studies are needed to prove theory and to perform a valid climate impact assessment !!

Research needs on contrails from H_2 combustion for a future climate impact assessment

According to theory, H_2 combustion has the potential to reduce the contrails optical properties & life time and thus reduce the climate impact from aviation



Modified Lee et al (2021)

But: Measurements and model studies are needed to prove theory and to perform a valid climate impact assessment !!

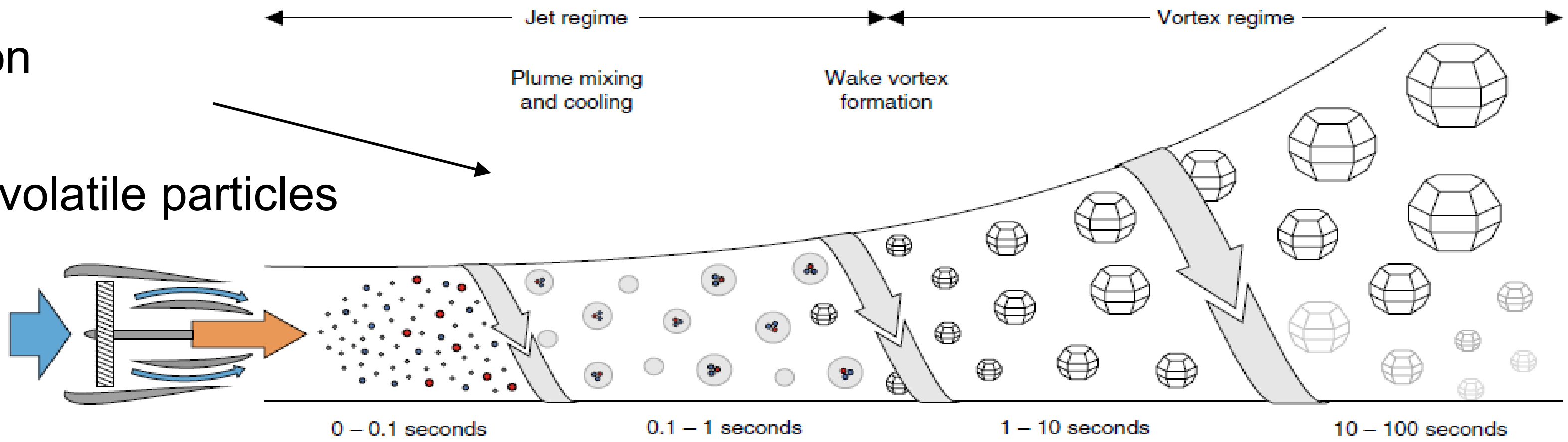
Required:
use of green hydrogen!

DLR

Contrail properties from H_2 fuel cells

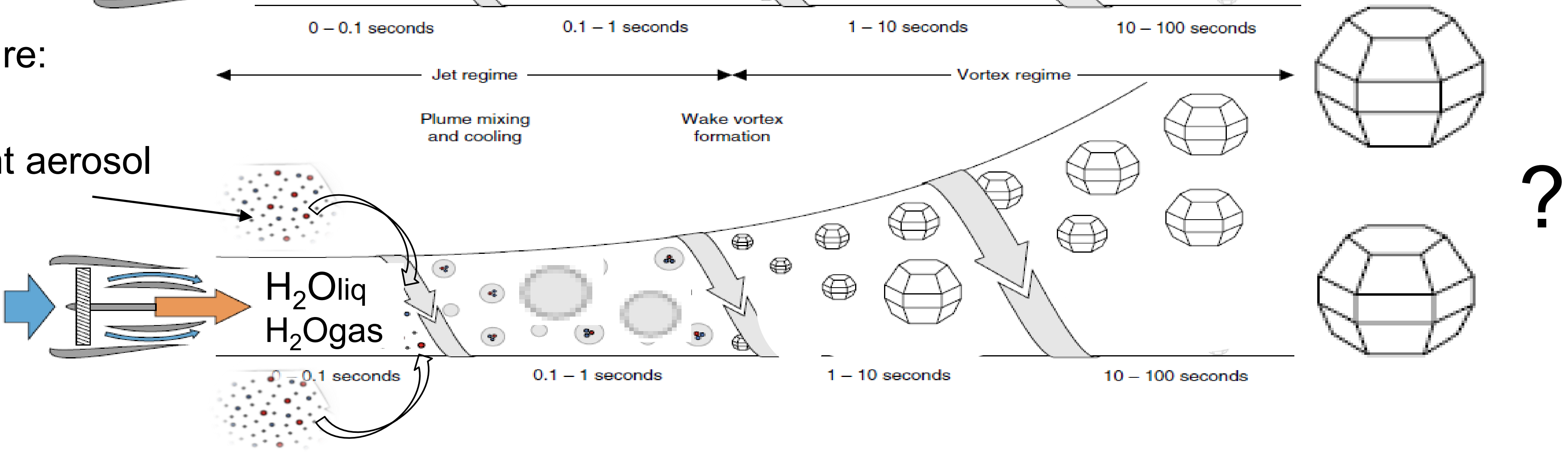
Kerosene combustion

Soot and volatile particles



Hypothetical picture:
H_2 Fuel Cell

Ambient aerosol



But: Measurements and model studies are needed to prove theory and to perform a valid climate impact assessment !!

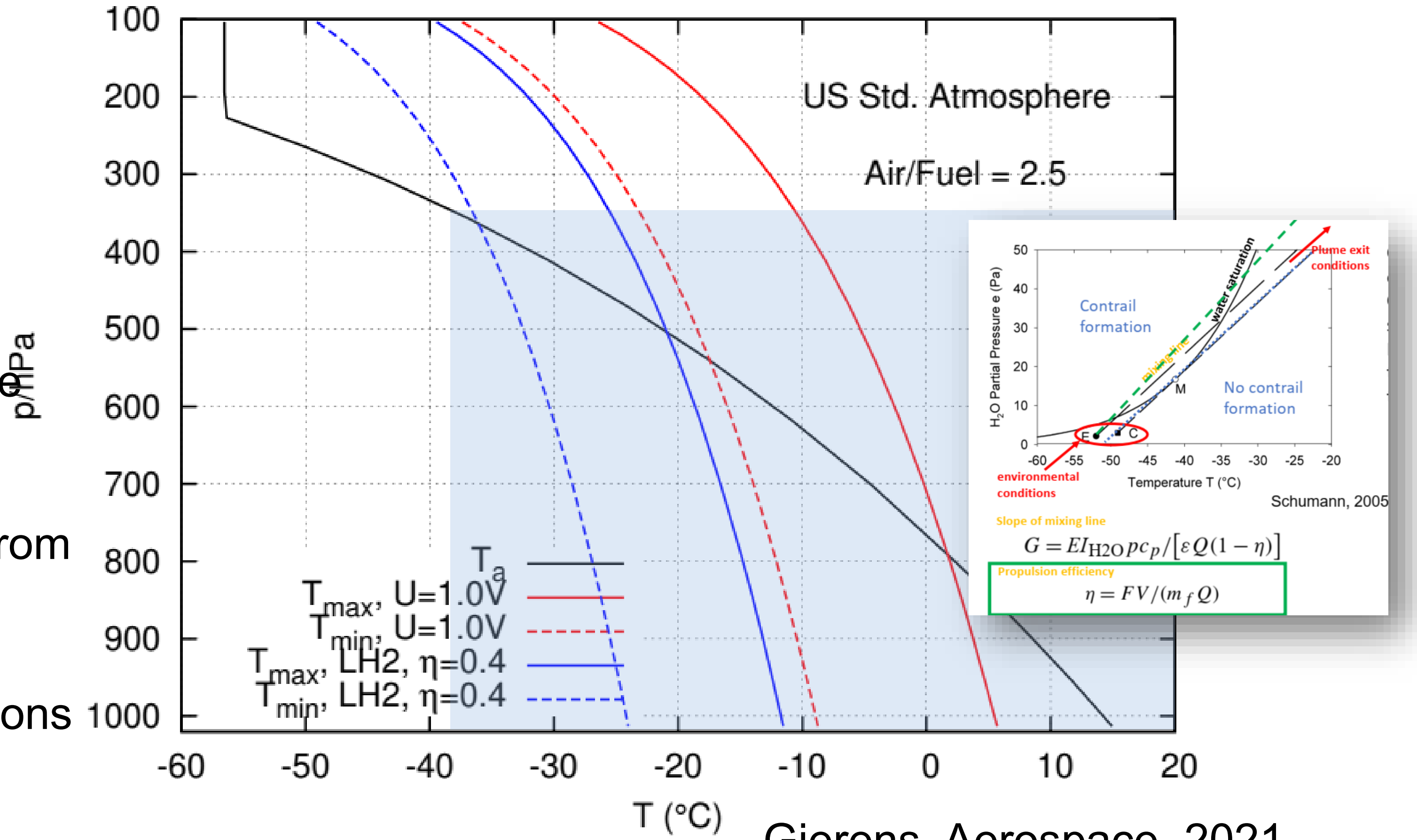
Theory of contrail formation altitude from H_2 combustion and H_2 Fuel Cells

- Contrail formation altitude for

- LH_2 combustion
- H_2 Fuel cell powered engine

- But contrails from fuel cells will most likely be
  - optically thinner
  - have shorter life times
  - and are recommended for use in aviation from the climate perspective

- Fuel cells have no NOx and no CO_2 emissions



Gierens, Aerospace, 2021

New set of DLR- instruments for H_2 contrail detection in demo missions

H_2 contrail ice particles
© Jurkat-Witschas, Voigt

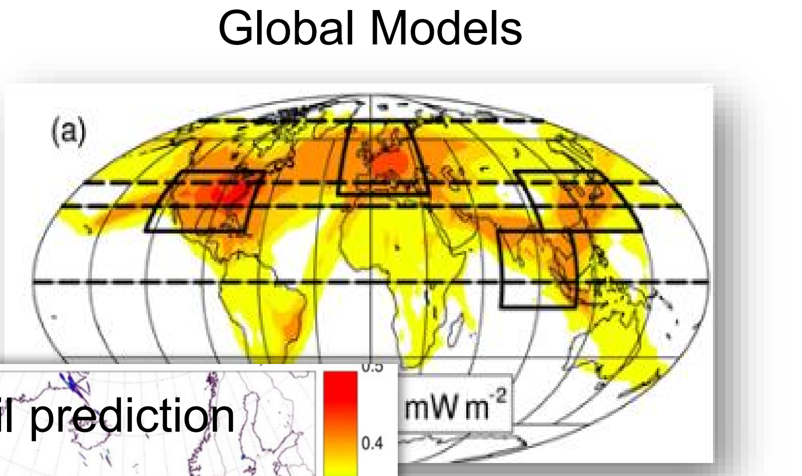
H_2O measurements
© Marsing, Kaufmann, Voigt

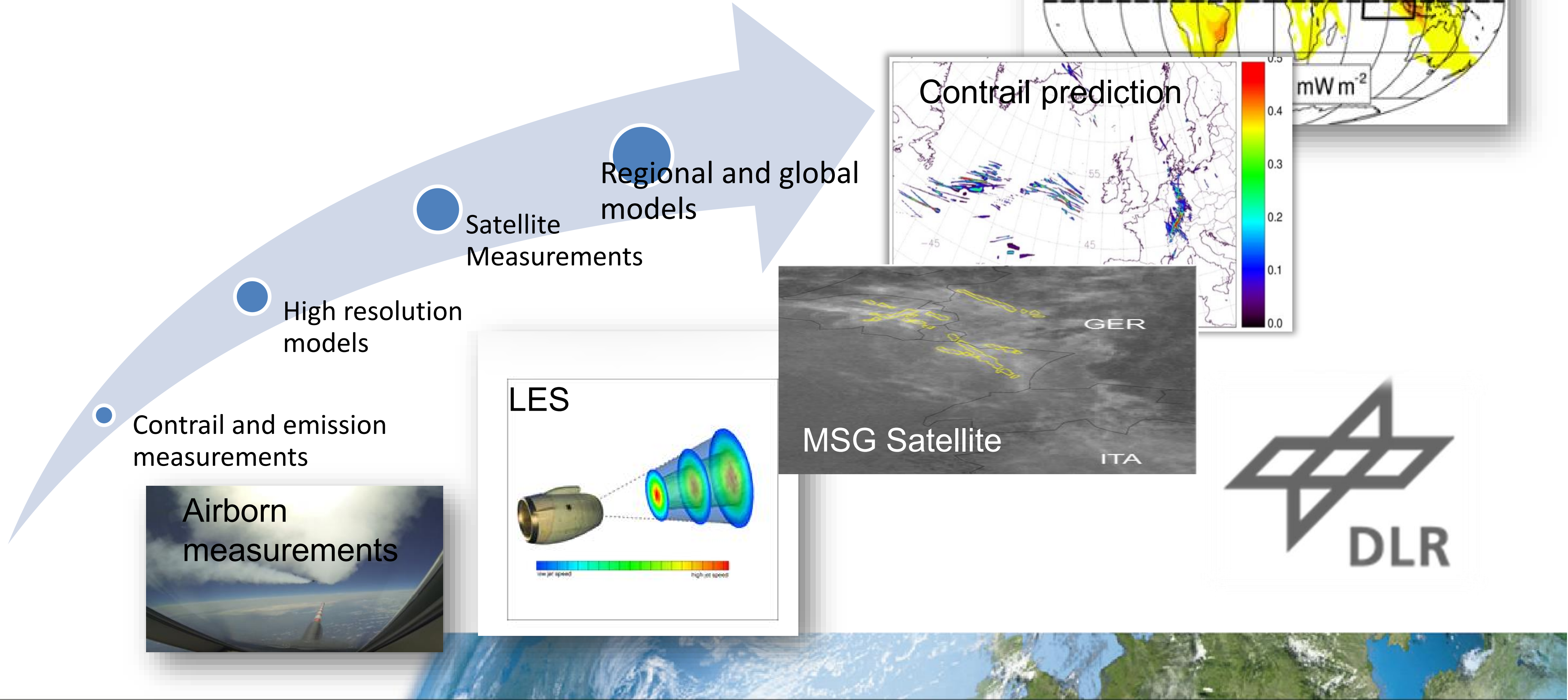
Airborne instrumentation adaptable to different aircraft, speed and altitude ranges

aerosol and trace gas measurements
© Sauer, Heckl, Stock, Neumann

NOx measurements
© Roiger, Stock, Harlass

DLR provides expertise on contrail measurements and modelling on multiple scales





Thank you for your attention!

tina.jurkat@dlr.de
christiane.voigt@dlr.de

With contributions from
Ulrike Burkhardt, Simon Unterstrasser, Elena de la Torre Castro, Johannes Lucke, Martin Wirth, Klaus Gierens and the CIRRUS HL team