Characterization and first applications of the Portable Ice Nucleation Experiment PINE

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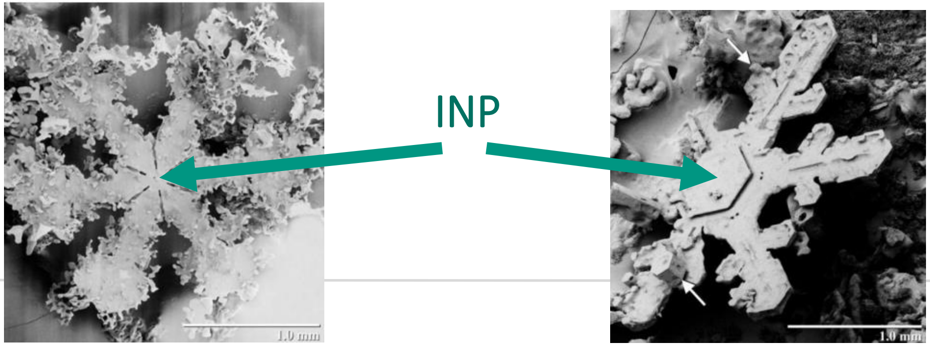
Why do we care about ice-nucleating particles?

- Impact on cloud radiative properties (e.g. Lohmann et al., 2002; McCoy et al., 2015; Tan et al., 2016; Solomon et al., 2018; Lohmann and Neubauer, 2018; Desai et al., 2019)
- Impact on precipitation formation (e.g. Mülmenstädt et al., 2017; Field and Heymsfield et al., 2015)
- INP parameterizations in models have to be based on precise and accurate measurements (Storelvmo et al., 2011; Fan et al., 2014; Tan and Storelvmo, 2015; Vergara-Temprado et al., 2018; Garmiella et al., 2018)



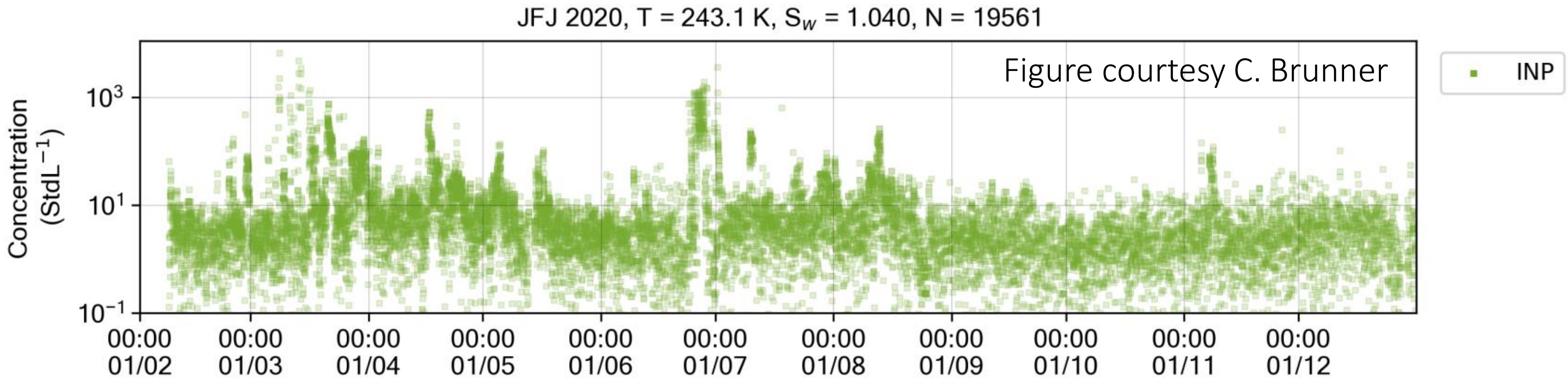
Wergin et al., 1998

Monitoring of INP

- To improve our understanding of the spatio-temporal distribution of INPs throughout the atmosphere
- Development of monitoring networks, such as ACTRIS Topical Centre for Cloud In-Situ Measurements (CIS), for long-term observations of
  - INP concentration
  - Cloud particle number and size distribution
  - Bulk cloud water chemistry
  - liquid water content, droplet effective diameter
- Need for consistent and uniform INP measurements, calibration standards, and consistent data interpretation

Newly developed automated online INP instruments

- CFDC-IAS (Bi et al., 2019),
  - automated version of the CSU-CFDC (Rogers et al., 2001)
  - 2 months of continuous operations between -20°C and -30°C in Beijing, China
- HINC-Auto (Brunner and Kanji, 2021)
  - based on the UT-CFDC (Kanji and Abbatt, 2009) and HINC (Lacher et al., 2017)
  - continuous measurements at -30°C at Jungfraujoch, Switzerland
  - https://www.psi.ch/en/lac/projects/last-72h-of-aerosol-data-from-jungfraujoch

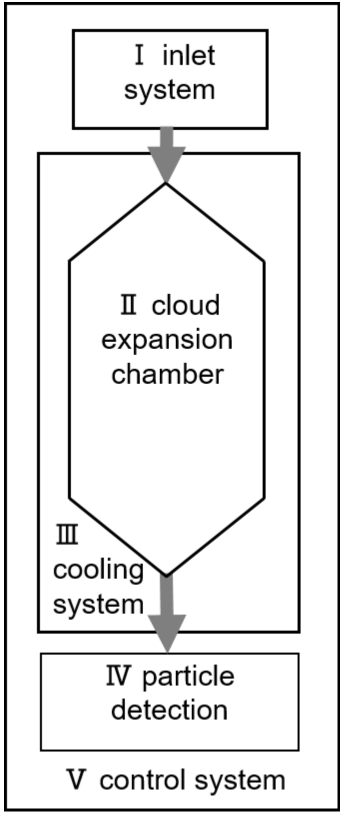


PINE

- Expansion-type cloud chamber
- Developed with University of Leeds (group Prof. Ben Murray) and Bilfinger Noell GmbH
- INP measurements at -10°C to -35°C (mixed-phase cloud regime, immersion freezing)
- INP measurements down to -60°C will be examined (cirrus cloud regime)
- Detection limit ~ 0.5 INP L^{-1} per experiment (~6 minutes)
- Frost-free walls (zero background)
- Continuous and automated operation
- Minimal user input, can be controlled remotely

Working principle

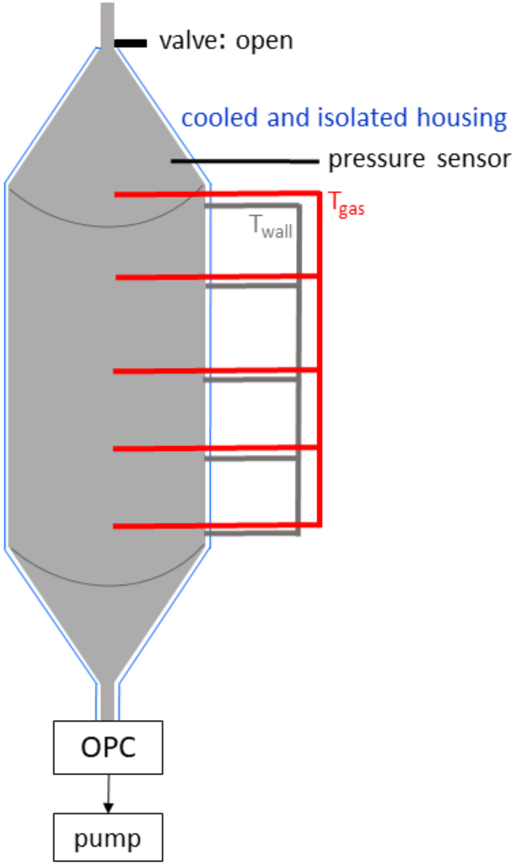
- Five parts
  - Inlet system: Inlet tube, nafion diffusion dryer, humidity sensor, bypass- and filter-flow section
  - Cloud expansion chamber (~7/10 liter)
  - Cooling system: Vacuum tight vessel for thermal isolation, combined with a Stirling cooler (liquid-free cooling)
  - Particle detection:
    - Optical particle counter “fidas” and welas-2500 (Palas GmbH)
    - LED white light source with dynamically changeable photomultiplier settings
    - Measurement range from 0.7 – 220 µm
    - Side-ward scattering angle (90°) to best detect a-spherical ice crystals
  - Control system: LabVIEW program



Möhler et al., 2020, AMTD preprint

Working principle

- Cycled mode
  - Flush (~4 minutes)
  - Expansion (~1 minute)
  - Refill (~ 1 minute)



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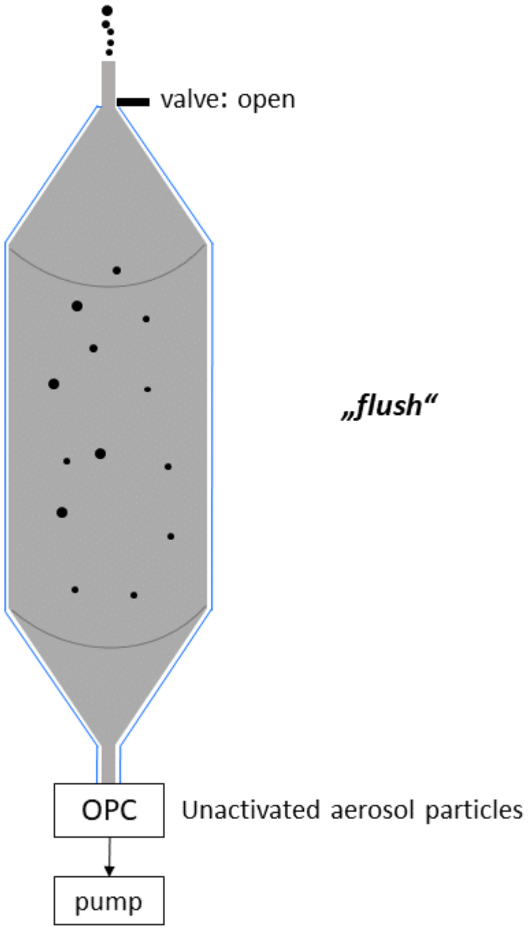

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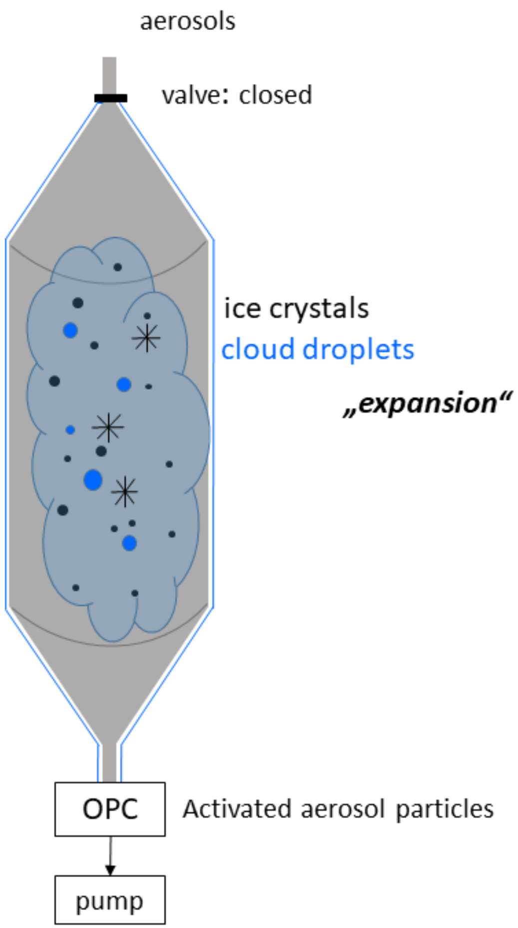
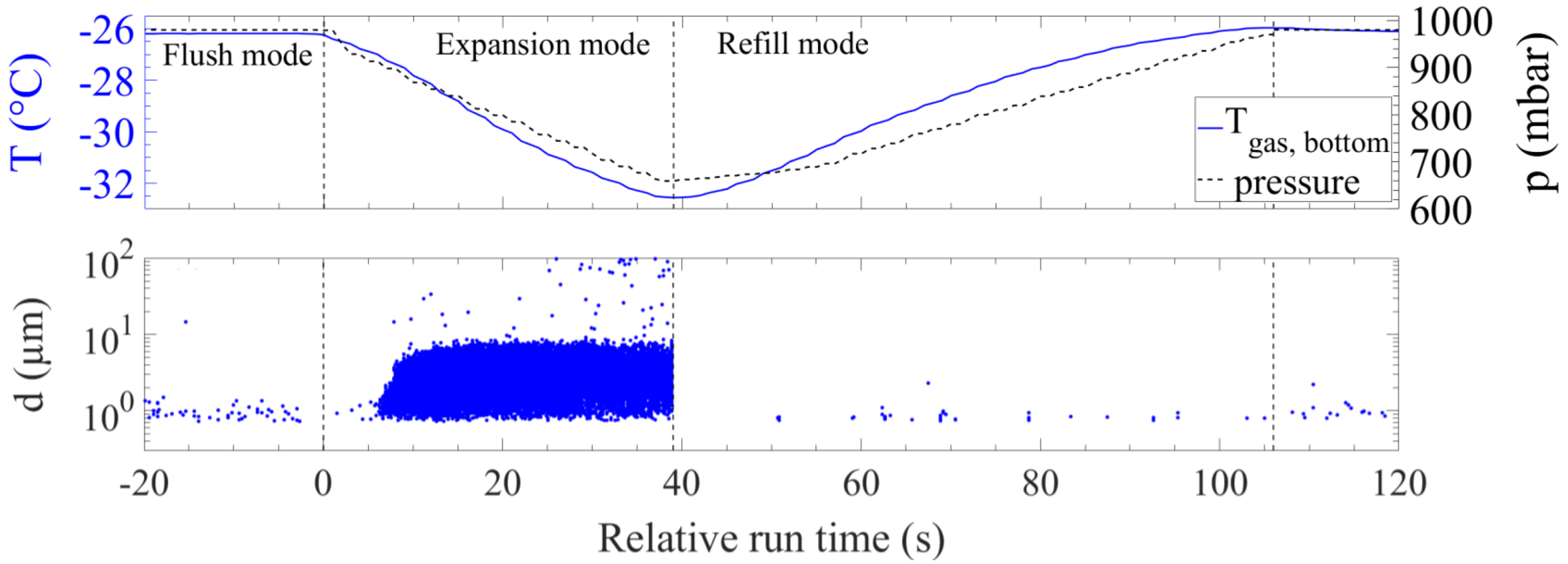


Operation modes: Flush, expansion and refill

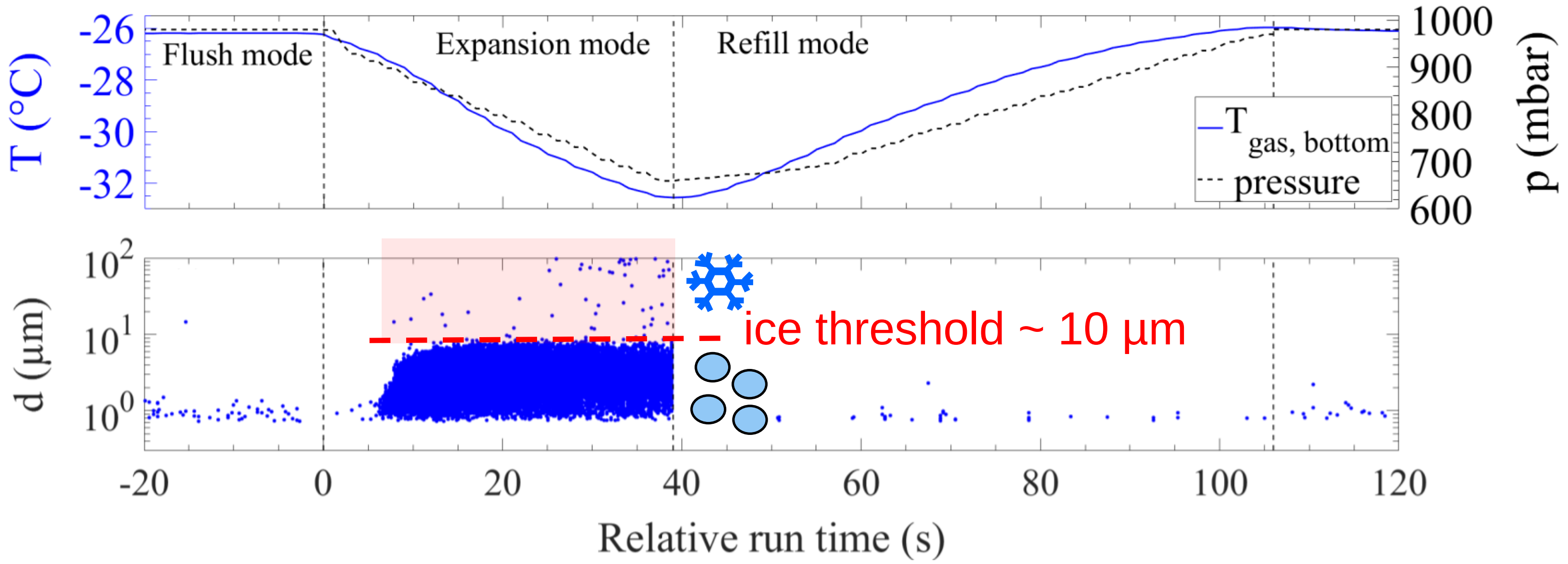
- Measurements below the frost point temperature to form cloud droplets
  → Immersion freezing



Möhler et al., 2020, AMTD preprint

Operation modes: Flush, expansion and refill

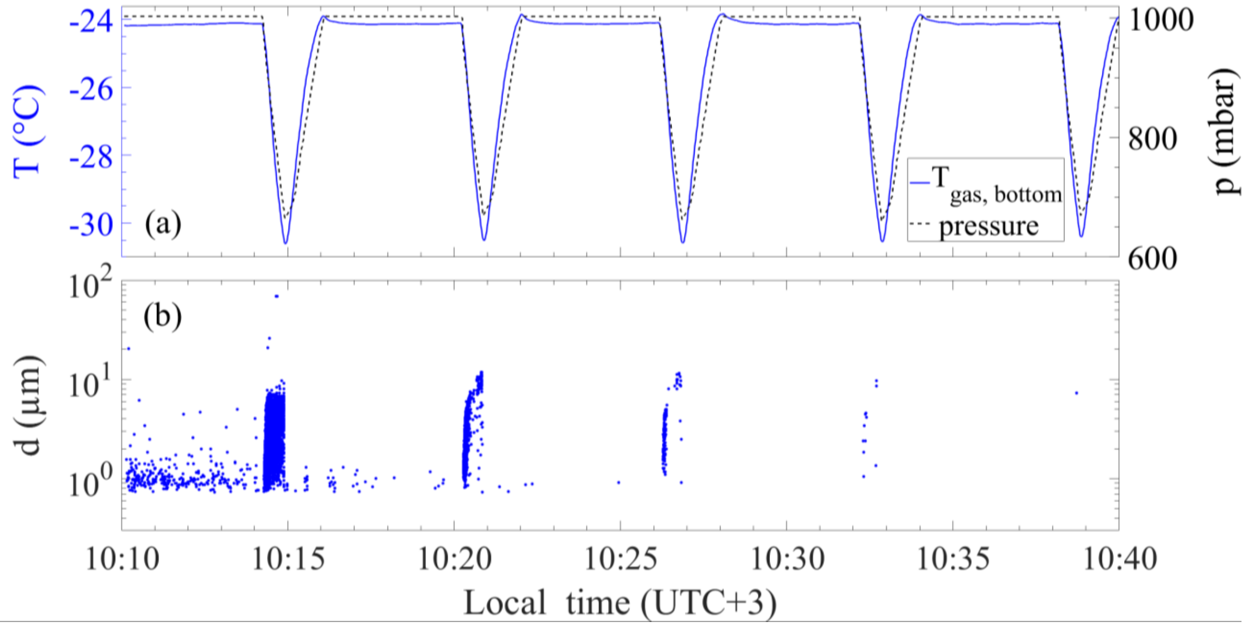
- INP concentration: Detected ice crystals / volume during expansion
- Nucleation temperature: Coldest measured temperature during expansion



Möhler et al., 2020, AMTD preprint

Operation conditions and background measurements

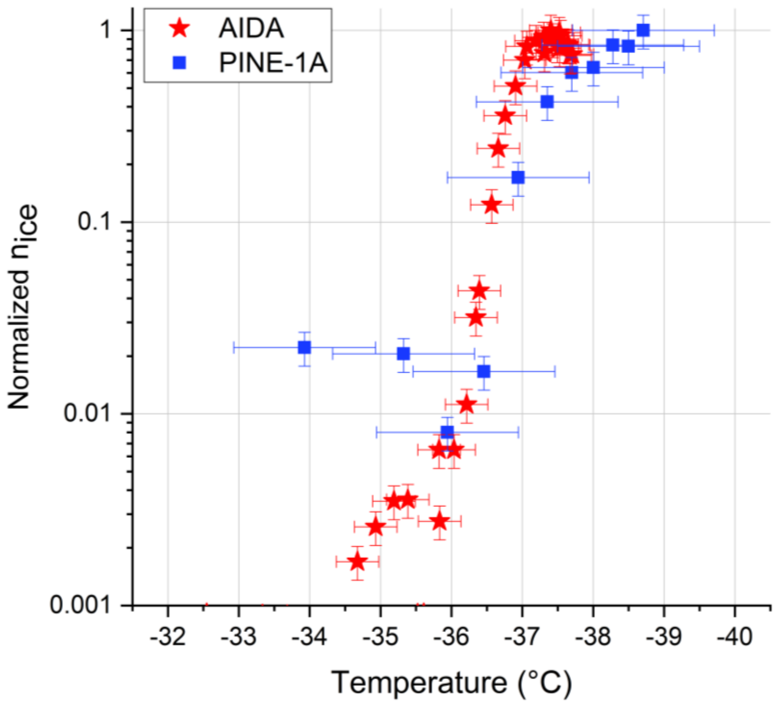
- Measurements over a filter to remove all aerosol particles
- No particles visible after consecutive 5 experiments



Möhler et al., 2020, AMTD preprint

Validation and verification experiments

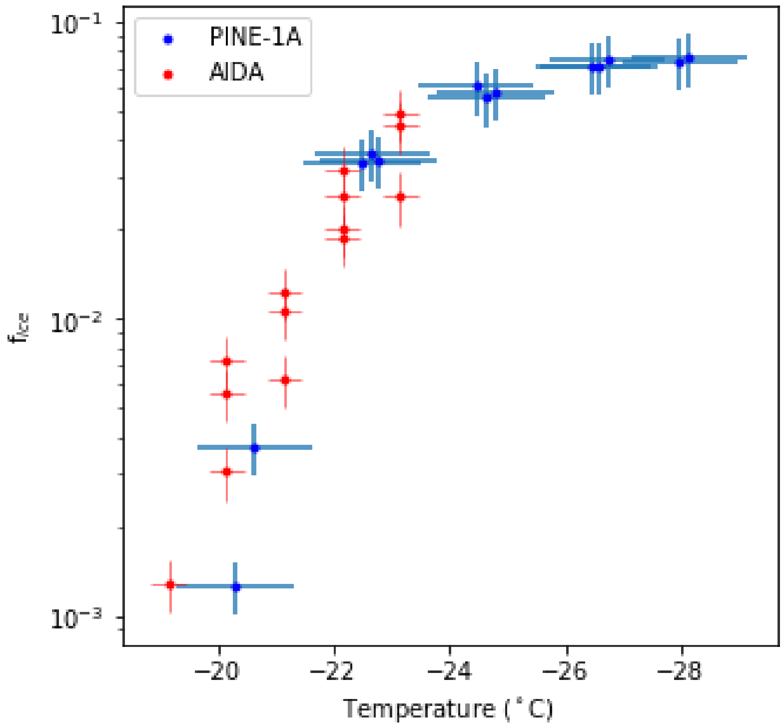
- Homogeneous freezing of sulfuric acid
- Ice onset regarding normalized number concentration of formed ice crystals
- Onset temperature compares well to AIDA (Aerosol Interaction and Dynamics in the Atmosphere) and classical nucleation theorie (Koop et al., 2000; Benz et al. 2005; Koop and Murray, 2016)
- PINE temperature uncertainty ±1°C arising from inhomogeneous temperature distribution



Möhler et al., 2020, AMTD preprint

Validation and verification experiments

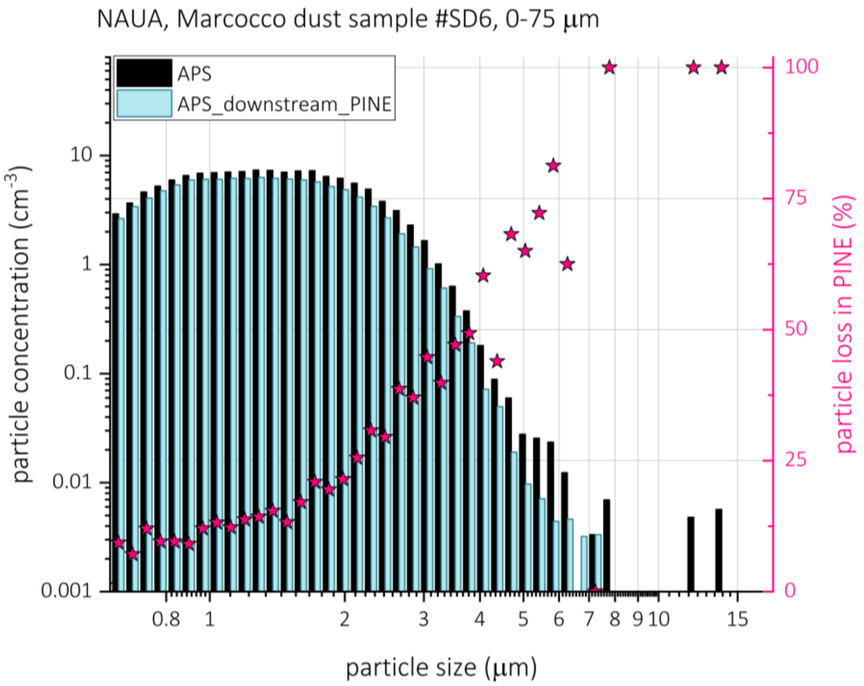
- Quantification of INP concentration using ATD
- Ice-active fraction as function of temperature from PINE and AIDA compares well
- Estimated uncertainty of INP concentration 20% mainly from uncertainty in the optical detection volume of the OPC



Möhler et al., 2020, AMTD preprint

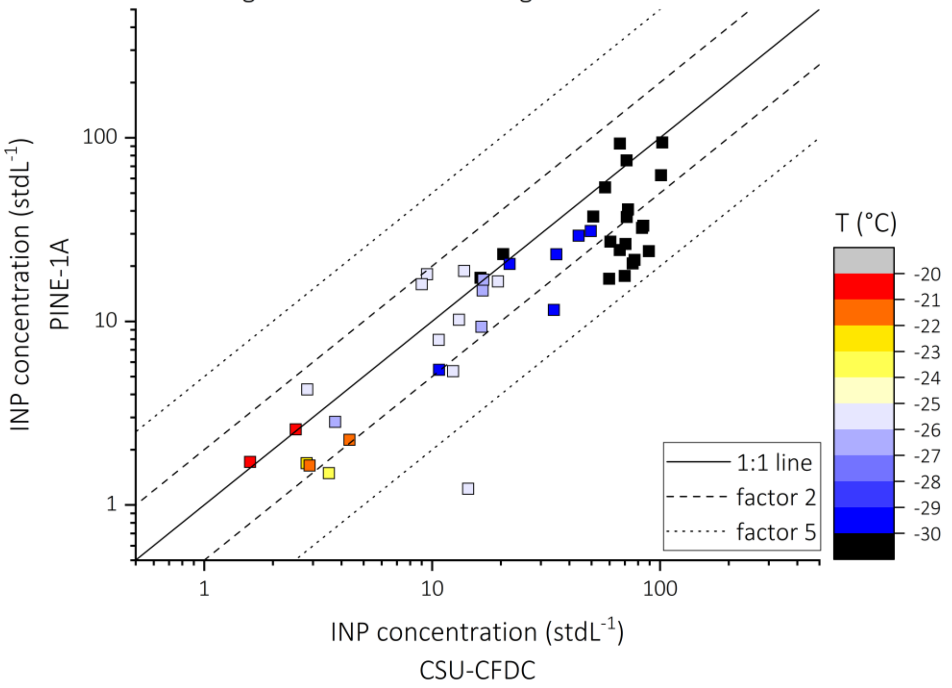
Inlet efficincy

- Transmission of > 80% of particles larger than 2 µm



„PICNIC“ field campaign

- Puy de Dôme, October 2018
- Intercomparison study on several online and offline INP instruments
- Good agreement within factor 2 between PINE and CSU-CFDC



CSU-CFDC data courtesy P. DeMott; Lacher et al., in preparation

„PICNIC“ field campaign

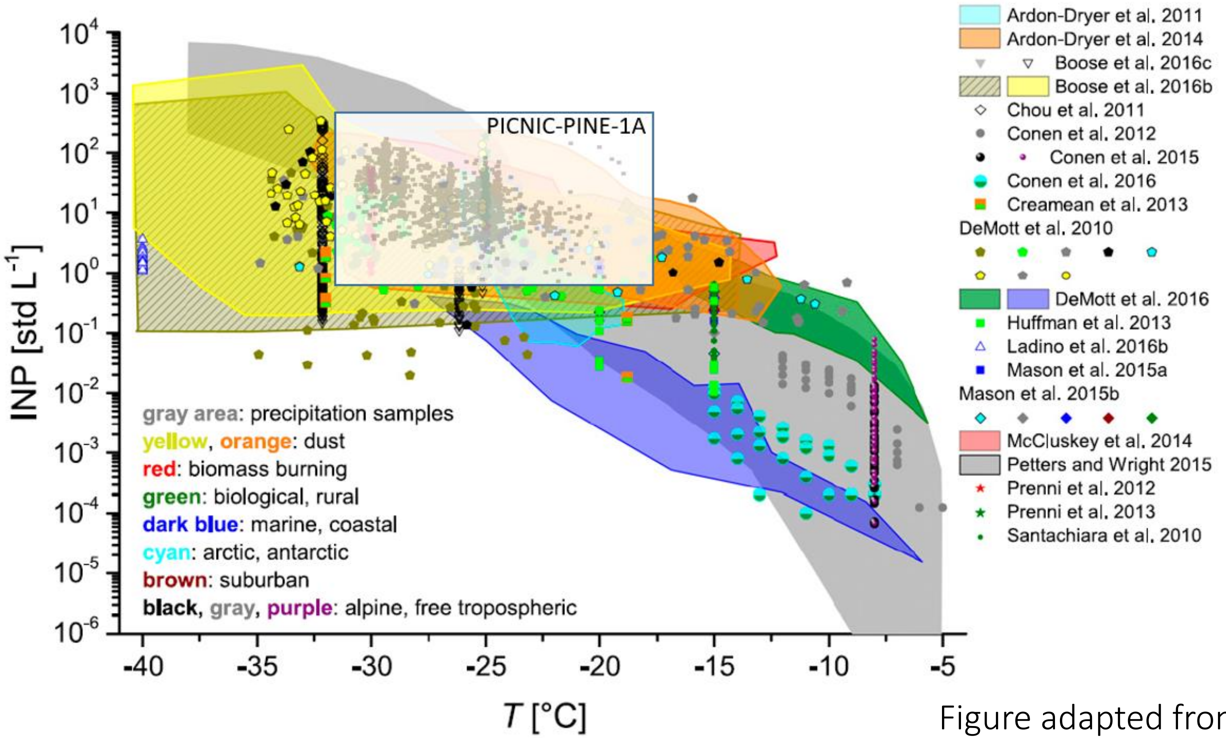
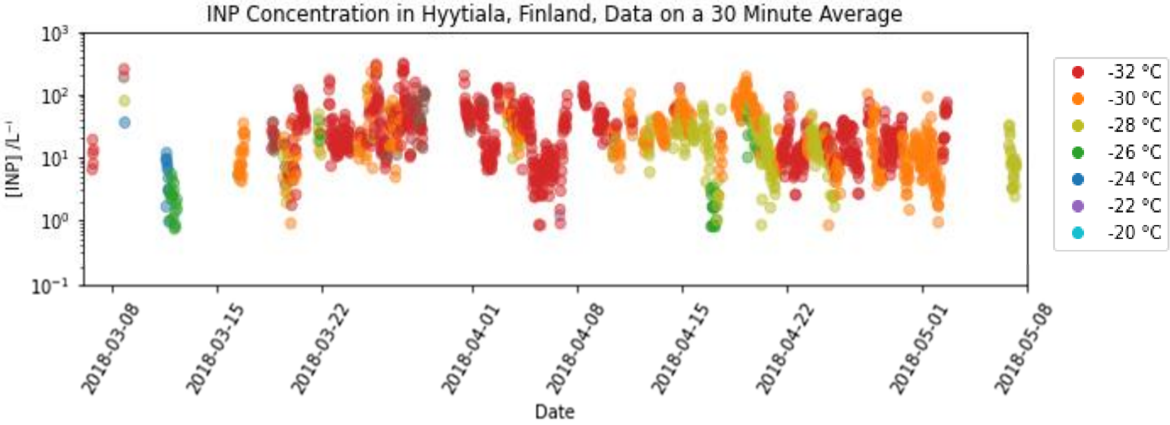


Figure adapted from Kanji et al., 2017

„HyICE“ campaign

- Measurements in Hyytiälä in the boreal forest (F. Vogel, M. Adams)
- Transition time from winter (snow-covered ground) to spring
- 2 months of continuous measurements

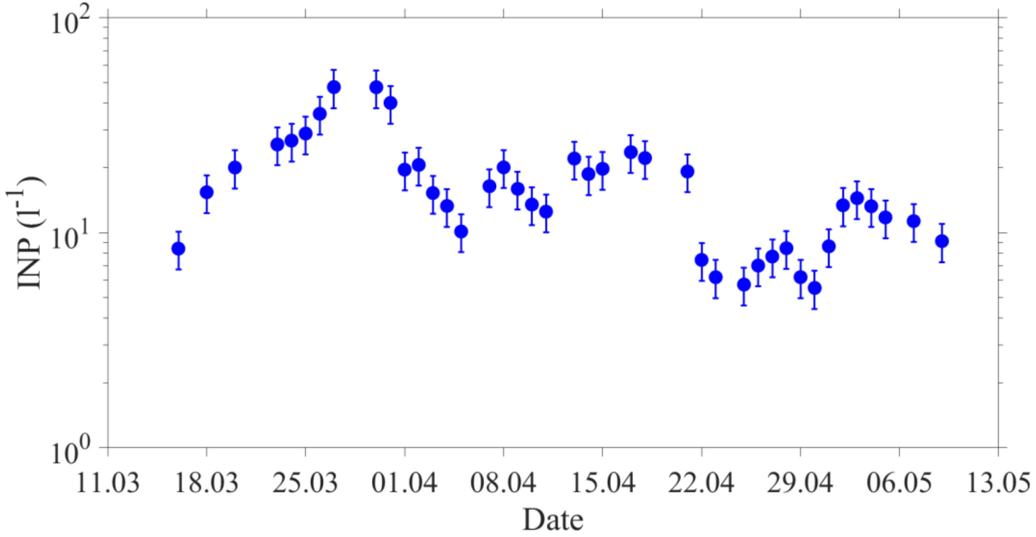
Picture courtesy O. Möhler



Adams et al., in preparation

„HyICE“ campaign

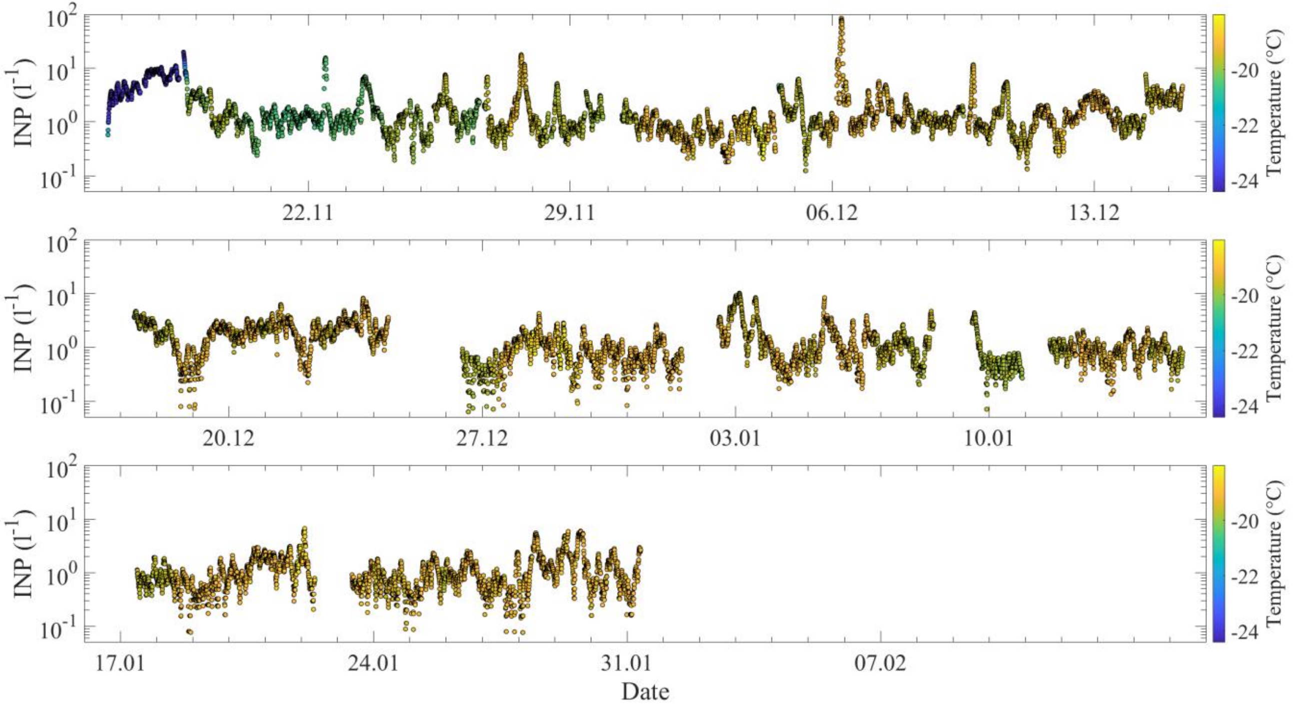
- Measurements in Hyytiälä in the boreal forest (F. Vogel, M. Adams)
- Transition time from winter (snow-covered ground) to spring
- 2 months of continuous measurements
- INP concentration at -29°C



Adams et al., in preparation

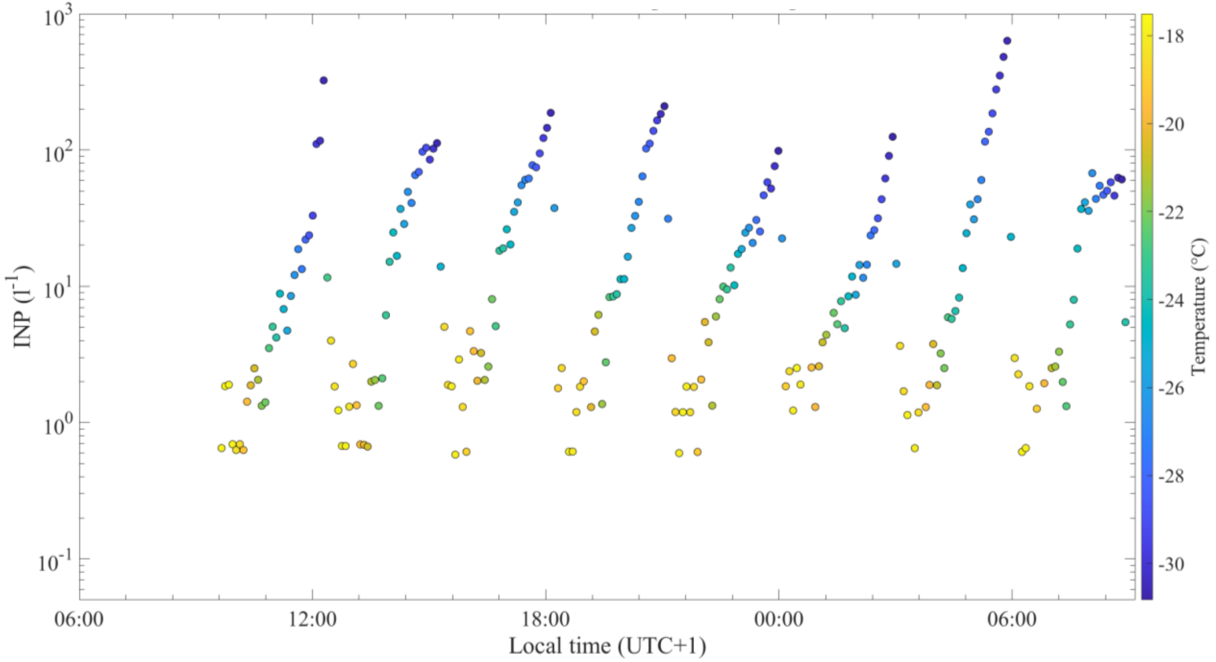
„CORONA“ campaign

- Measurements at KIT since November 2020 at KIT (PI F. Vogel)
- Mostly remote control of PINE during CORONA lockdown



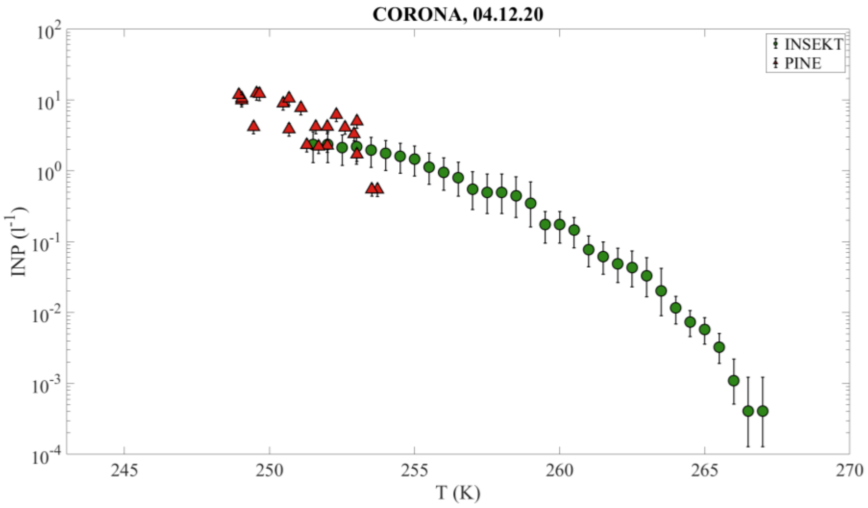
„CORONA“ campaign

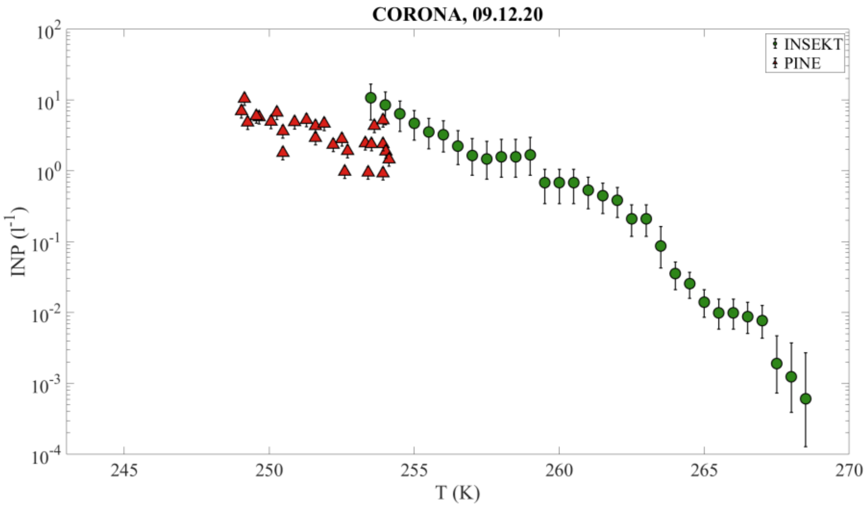
- Regular temperature scans between -18°C and -30°C
- Scan-time ~ 2 hours
- Scans one day a week



„CORONA“ campaign

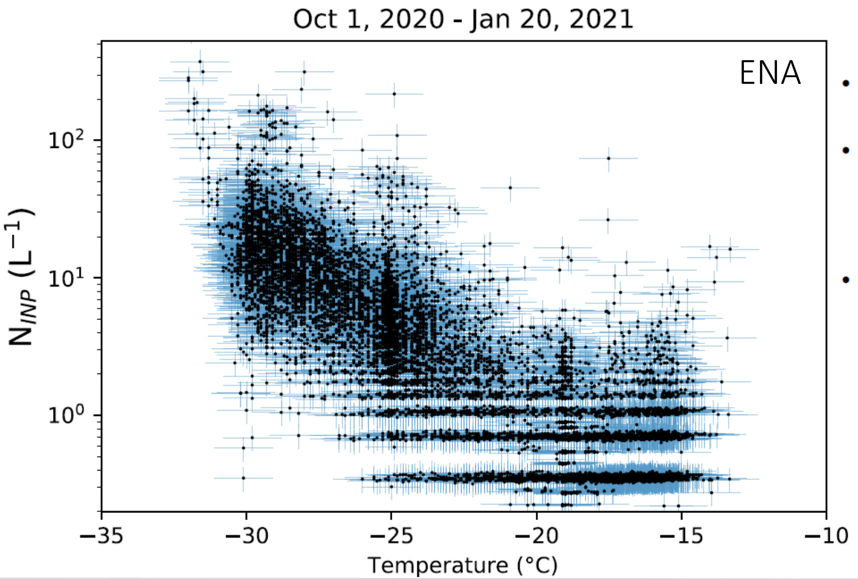
- Good agreement to simultaneous filter measurements for offline analysis with INSEKT (Ice Nucleation Spectrometer of the Karlsruhe Institute of Technology same principle as the Ice Spectrometer (IS), Hill et al., 2016)





„EX-INP SGP & ENA“ campaigns

- Measurements at DOE ARM sites SGP and ENA (PI N. Hiranuma)
- Autumn 2019 (SGP) and autumn/winter 2020/2021, remote control of PINE
- Temperature spectra from -10°C to -33°C



Wilbourn et al., in preparation

Ongoing PINE activities

- Investigating heterogeneous nucleation at cirrus cloud conditions (PhD project Leon King)
- PINEair: Development of airborne PINE instrument for HALO (DFG project, Pia Bogert), INP measurements at cirrus cloud conditions
- Coupling PINE to a single-particle mass spectrometer (DAAD PRIME project, Larissa Lacher)
- AIDAm (PINE-like instrument) inside the cooling housing of AIDA to perform continuous INP measurements during AIDA experiments (Franziska Vogel)
- Field campaigns:
  - National Atmospheric Observatory in Košetice (spring 2021, Franziska Vogel)
  - Sonnblick Observatory (spring/summer 2021, Pia Bogert)
  - DOE ARM Northern Slope of Alaska @ Utqiagvik (summer 2021, Naruki Hiranuma)
  - Swabian Alb, MOSES campaign (summer 2021, Ottmar Möhler)
  - Storm Peak Laboratory, winter 2022 (Larissa Lacher, Dan Cziczo)
  - Yorkshire, “CountIce” (Mike Adams, Ben Murray)
  - Labrador Sea and Baffin Bay, “M-Phase cruise” (Ben Murray)
  - Langmuir lab in New Mexico “DCMEX” (Ben Murray)

Summary

- PINE as a novel mobile cloud expansion chamber
- Autonomous and continuous INP measurements at mixed-phase cloud conditions between ~ -10°C to -35°C
- Measurement range for cirrus-relevant INP concentrations down to -60°C will be explored
- Time resolution of ~ 6 minutes with a detection limit of 0.5 INP L^{-1}
- Validation of temperature uncertainty (± 1°C)
- Suitable for laboratory and field applications
- Successful deployment during several field campaigns to monitor INP concentrations autonomously over several months

Thank you!

- KIT team
- HyICE team
- PICNIC team
- ARM technicians and administration
- WT Office of Information Technology
- KIT technology transfer project N059
- U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research (Award Number DE-SC-0018979 and DE-SC0020006)