# Cloud Seeding, Cloud Chamber Experiments, and Cloud Observations


## Dr. David Delene

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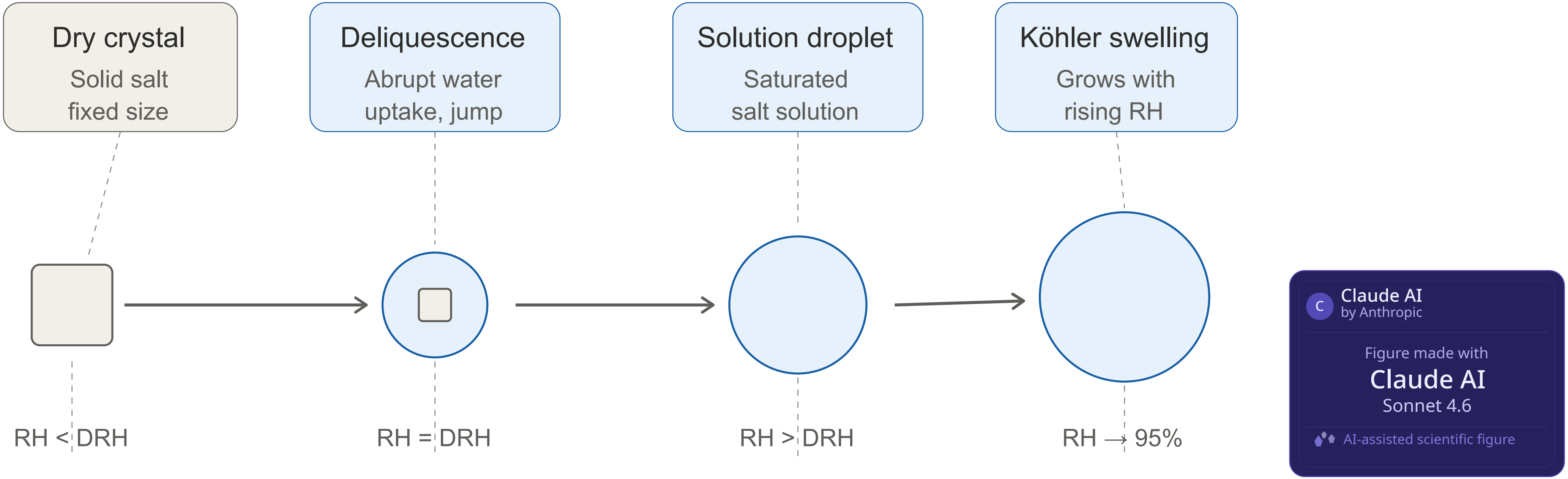
# Hygroscopic Particles and Condensational Growth: Implications for Cloud Seeding

# Objective: Particle Growth from Crystal to Droplet

Understanding particles size changes with time.

- Relative Humidity (RH) < 95 %
  - Deliquescence (DRH – Deliquescence Relative Humidity)
- Relative Humidity (RH) > 95 %
  - κ-Köhler Theory (Petters & Kreidenweis 2007)



# Methodology: Use Claude AI

3 Independent Parcels (κ-Köhler with Deliquescence

– 100 nm NaCl (κ=1.28),

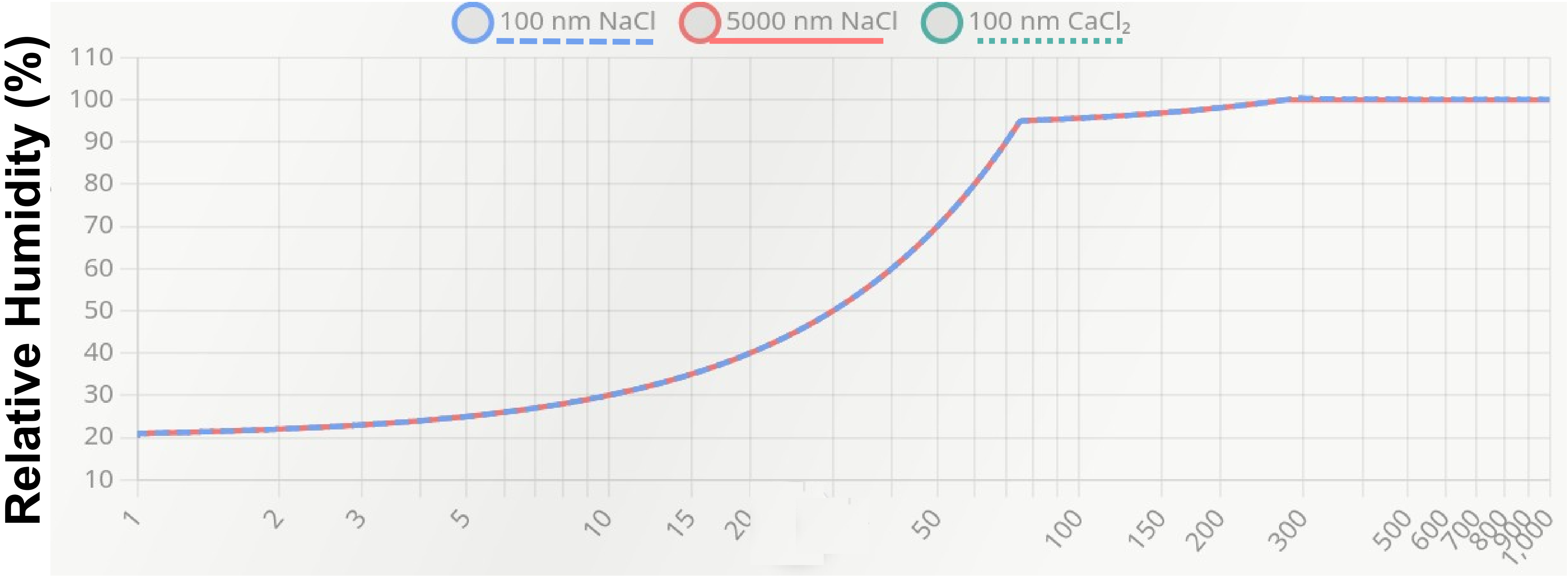
– 5000 nm NaCl

– 100 nm $CaCl_2$ (κ=1.12).

Forced Ramp 20 → 95% at 1%/s, then Prognostic.

- Updraft After 95% (m/s) – 0.5
- Relative Humidity Ramp Rate (%/s) - 1.0
- 100 nm NaCl Particles (per cc) 100
- 5000 nm NaCl Particles (per L) – 10
- 100 nm $CaCl_2$ Particles (per cc) - 100

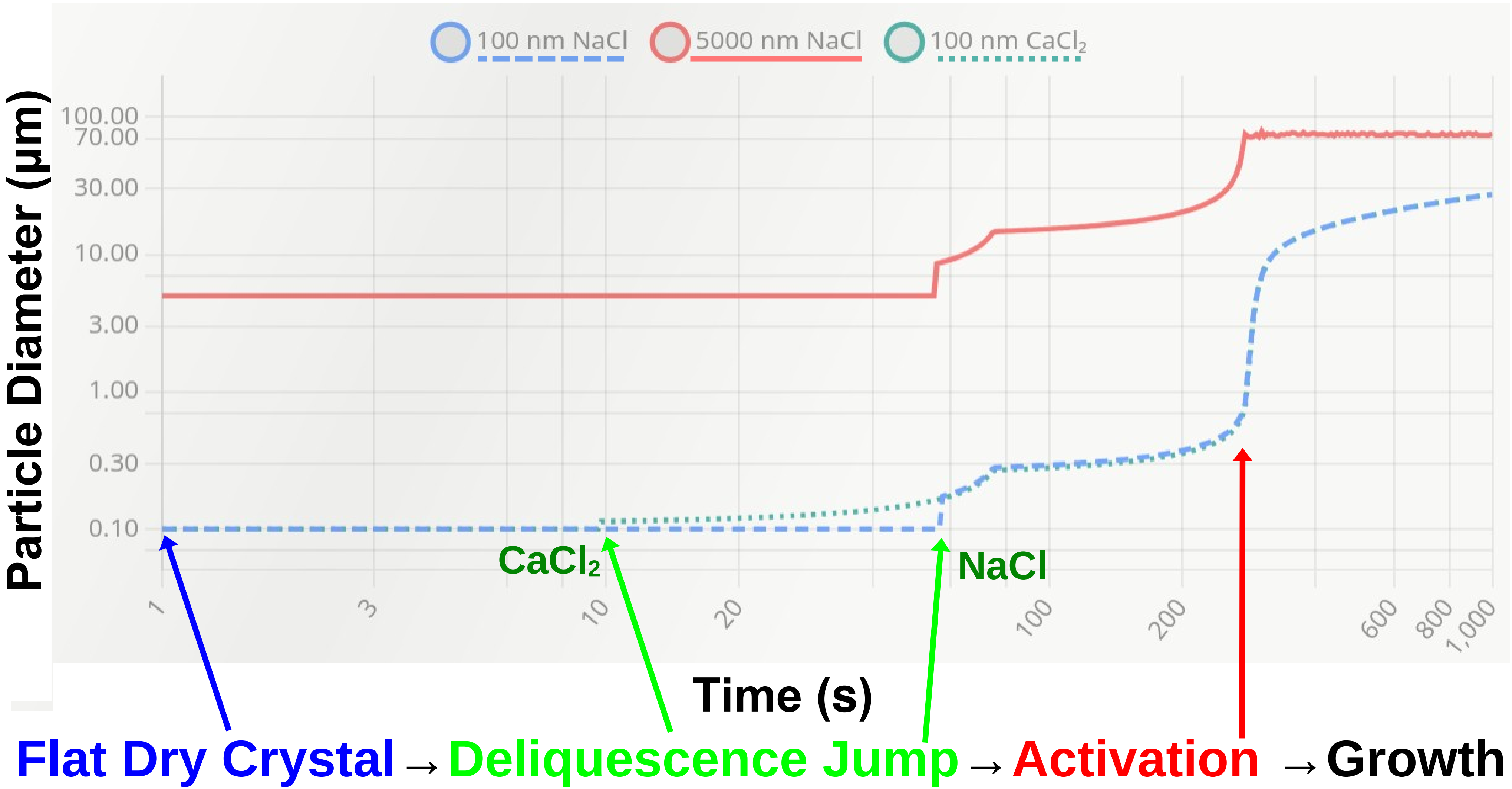
# Particle Environment




$CaCl_2$ Deliquescence RH - ~30 %

NaCl Deliquescence RH - ~75 %

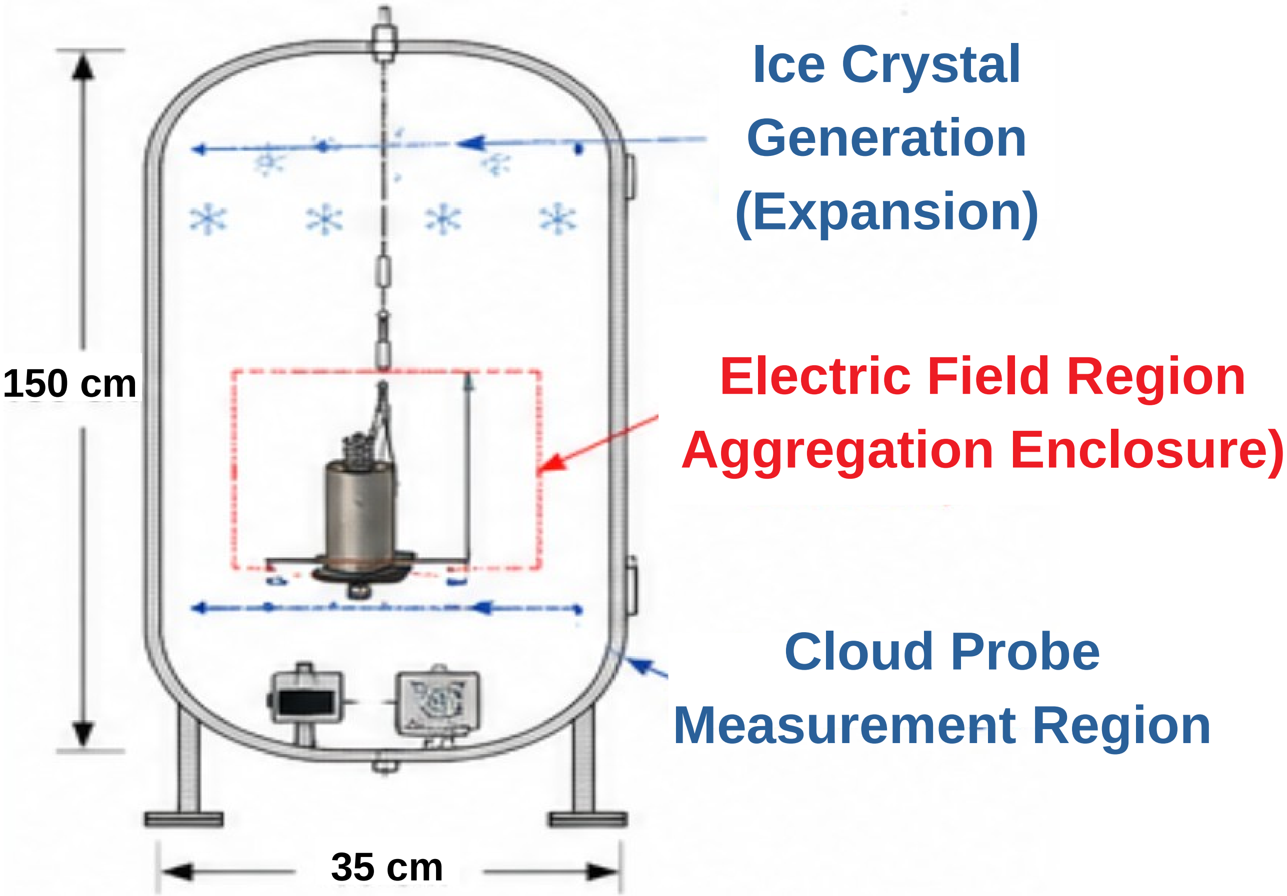
# Particle Diameter Comparison



# Conclusions:
# Hygroscopic Particles & Condensational Growth

- Particle deliquescence (dry→wet transition) and activation (κ-Köhler theory) are separate phase-transition property.
  - In deliquescence, humidity causes the crystal lattice to dissolve.
  - Droplet activation and growth of droplets are governed by the κ equilibrium.
  - $CaCl_2$ has a lower deliquescence; however, NaCl has higher hygroscopicity parameter κ, which give <u>better droplet actiavtion</u>.
- For the same size particle, $CaCl_2$ deliuescence at lower RH; however, the growth of droplets is nearly the same.
- **<u>The particle size is what really makes a difference!</u>**

# Quantifying Electrical Influences on Ice Crystal Aggregation

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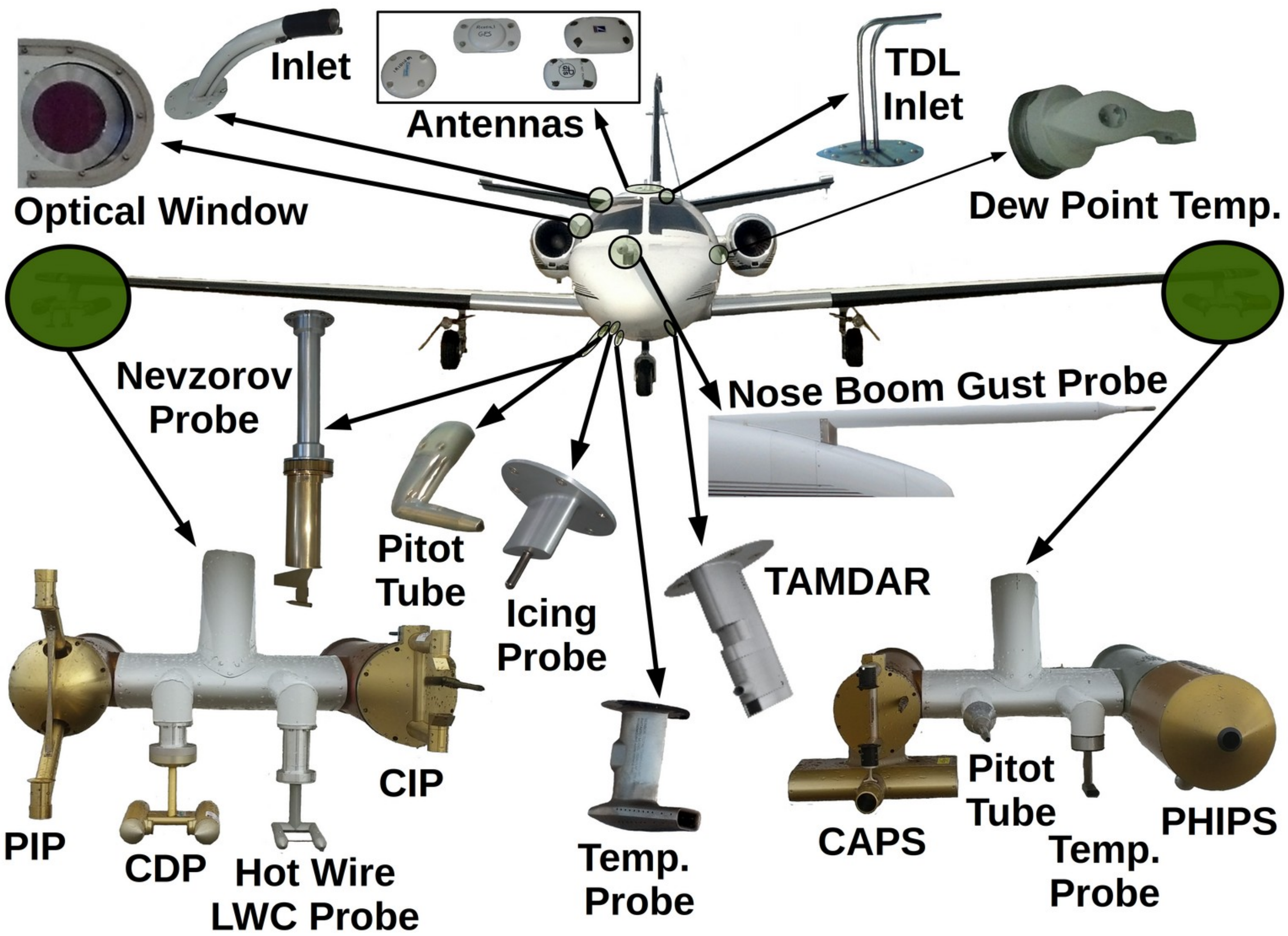
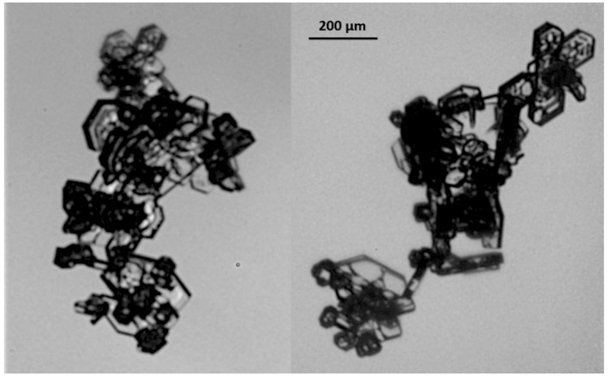
# Aircraft Field Project Observations




<u>High Resolution Probes:</u>

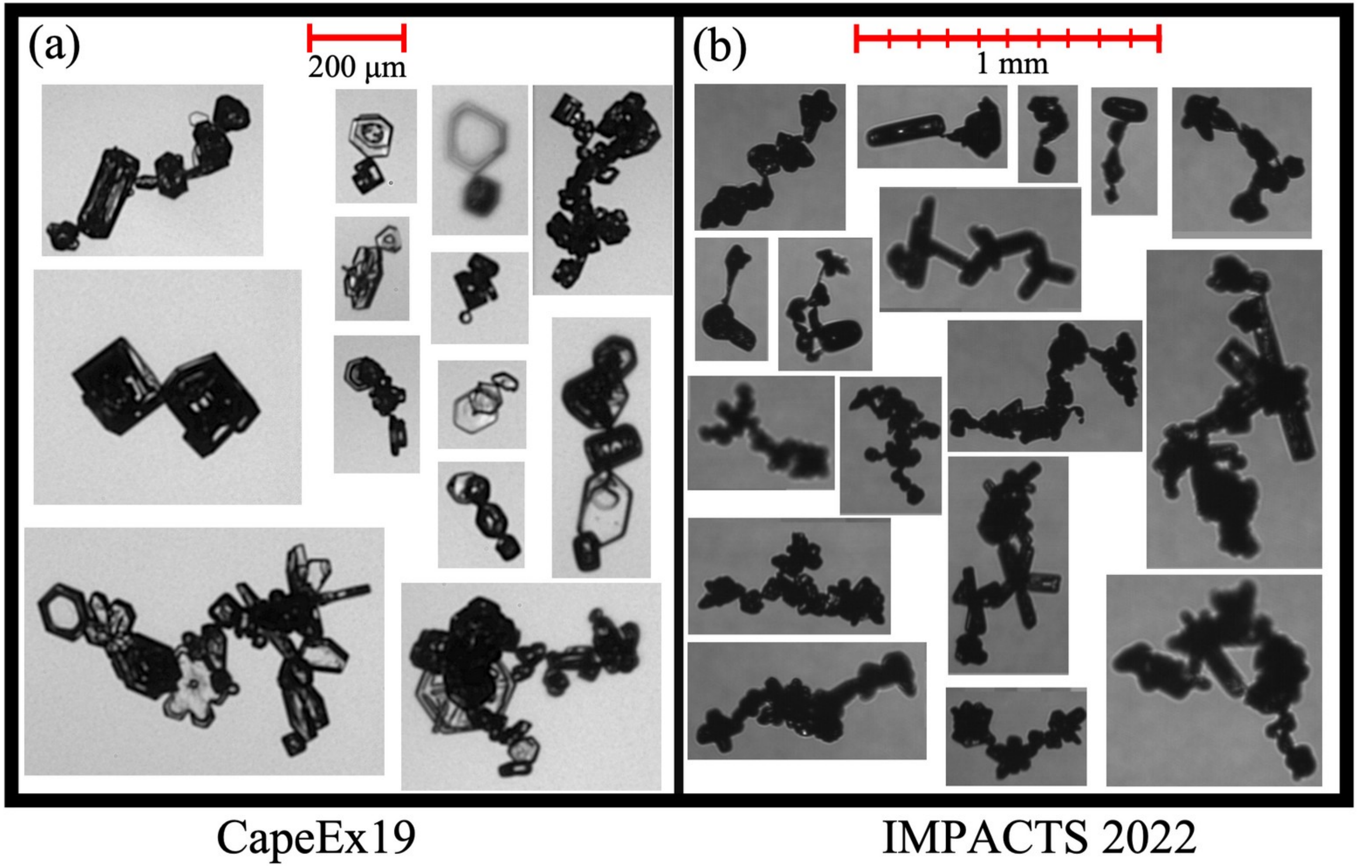
- Cloud Particle Imager (CPI)
- Particle Habit Imaging and Polar Scattering (PHIPS)

**2019/07/26 #5,134**




Stereo image pairs of chain aggregates obtained within Cirrus cloud anvils over Florida.

# Observations: Chain Aggregates




Collage of chain aggregates (a) imaged by the Particle Habit Imaging and Polar Scattering (PHIPS) probe during the Cape Canaveral Experiment in 2019 (CapeEx19) and (b) imaged by the Hawkeye-Cloud Particle Imaging (CPI) probe during the Investigation of Microphysics and Precipitation for Atlantic Coast-Threatening Snowstorms (IMPACTS) field campaign in 2022. Emma Järvinen and Martin Schnaiter provide PHIPS images.

# Project Objective

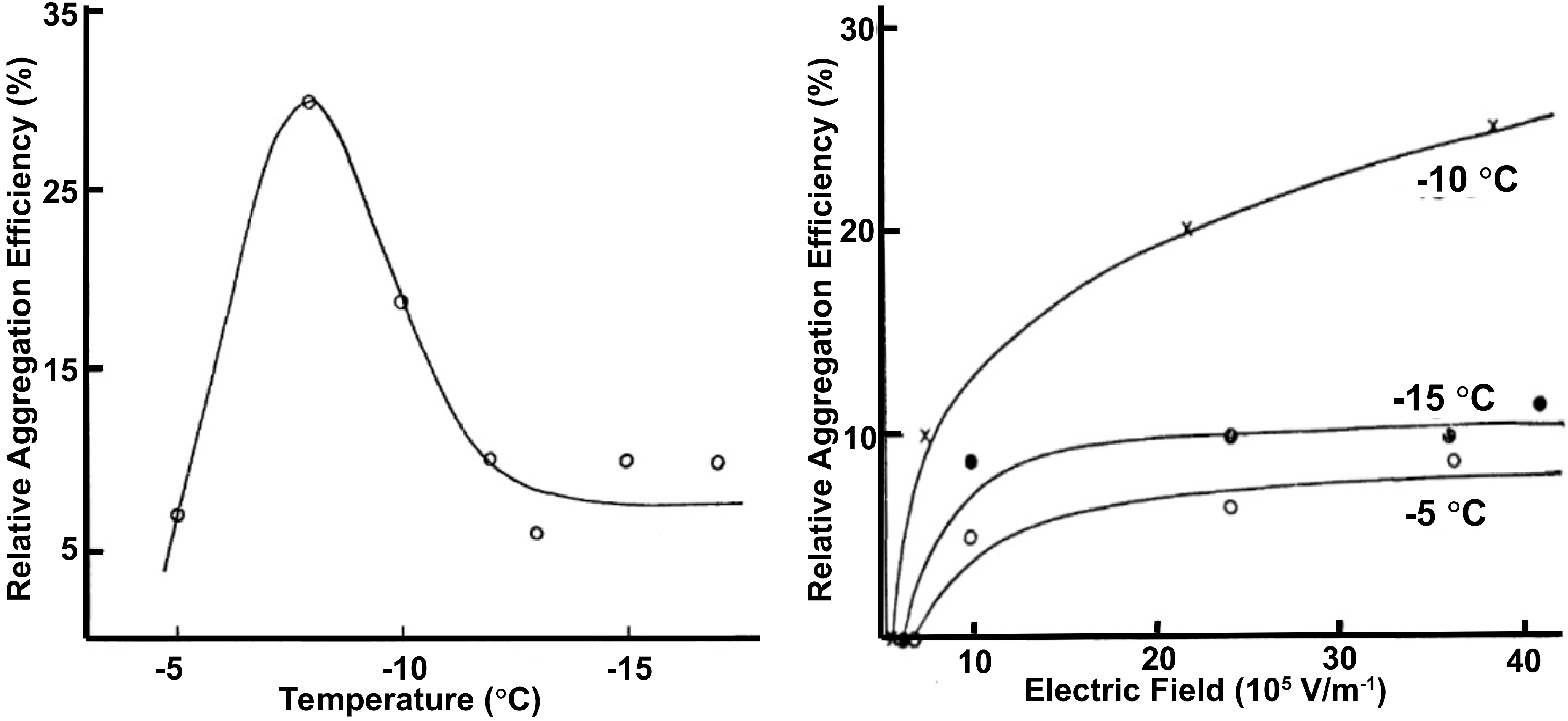
Quantify the role of electric fields in ice crystal chain aggregation under realistic cloud conditions using the controlled environment of a cloud chamber.

NIMS Cloud Chamber, Expansion Types, Volume 29.3 $m^3$

# Primary Task: Relative Aggregation Efficiencies

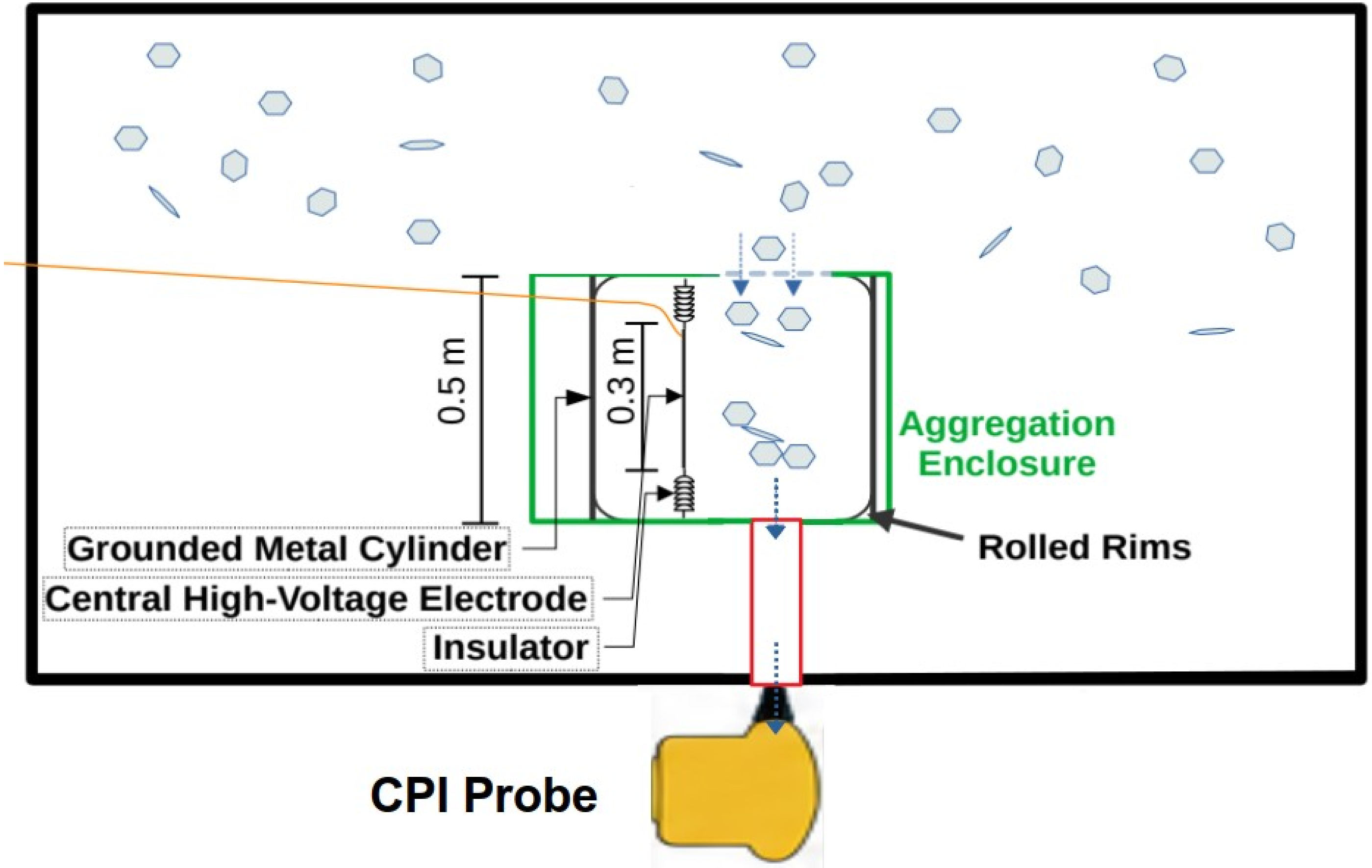
Measure ice crystal chain aggregation amount under varying electric field strengths using advanced, state-of-the-art instrumentation.

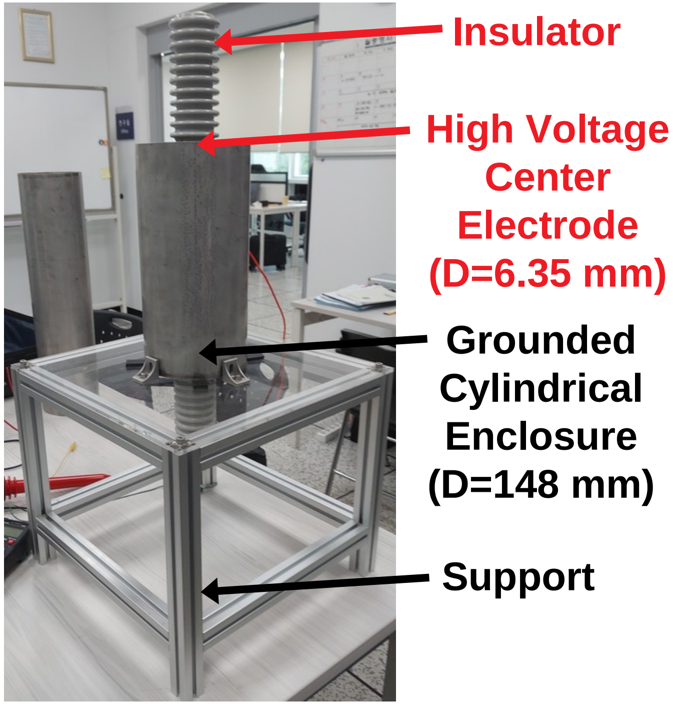
- The Cloud Particle Imager (CPI) is used to assess the change in relative aggregation efficiency with electric field strength over a range of temperatures.
    - Compare the statistical distribution of chain aggregate parameters derived from images produced in the cloud chamber experiments with in-situ observations from recent field campaigns to determine how realistic are the produced chains.




Adapted from Saunders and Wahab (1975). Left panel shows the relative aggregation efficiency as a function of temperature for an electric field of 200 kV $m^{-1}$, ice crystal concentration of 3-4 x $10^6$ $m^{-3}$ and size ~50 μm in diameter. Right panel shows the relative aggregation efficiency as a function of electric field for three values of temperature using the same ice crystal concentrations and ice sizes as panel (a).

# Methodology: Chamber Setup




Aggregation Enclosure
52 mm Sampling Radius

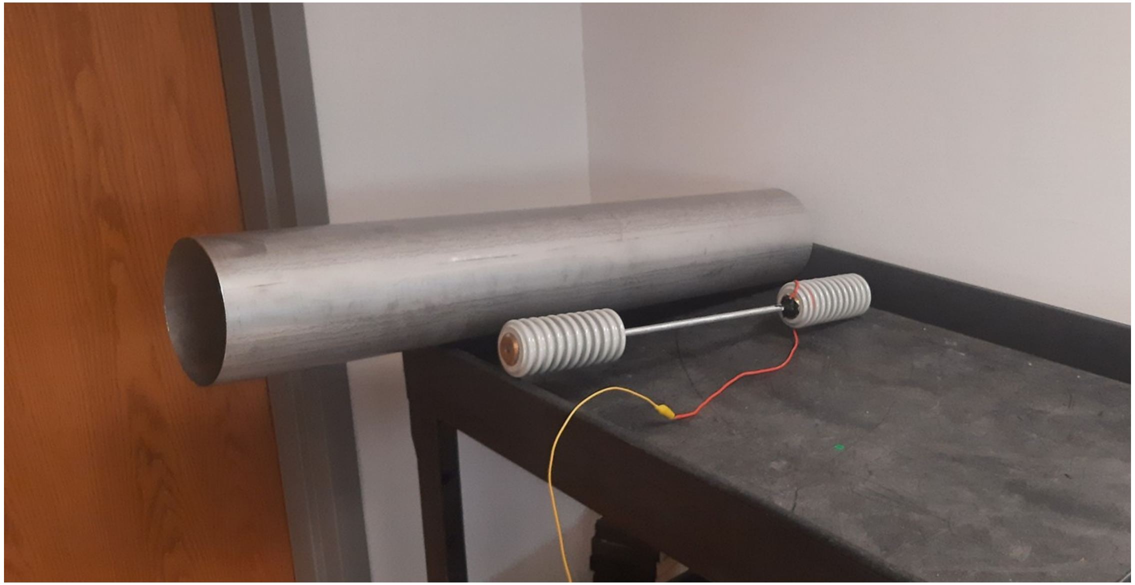
Schematic showing the Aggregation Enclosure within the cloud chamber. Ice crystals are generated using pressure drops at a constant rate to create a supersaturated environment. A “Aggregation Enclosure” is placed inside the cloud chamber. The Sample Area is where the cloud probe measures the ice crystals.

# Aggregation Enclosure

- A high-voltage power supply is used to generate a horizontal electric field that can affect ice crystals falling under gravity.
- An electric field potential difference is created between the central high-voltage electrode and surrounding Grounded Metal Cylinder to produce electric fields up to $1.2×10^5$ V $m^{-1}$.
- The stainless steel rod is coated with a Fluoro Silane compound (1H,1H,2H,2H-Perfluorooctyltriethoxysilane) to create a hydrophobic (water-resistant) surface.
  - Nanometer-thin insulating layer that does not materially alter the electrode geometry.

# Aggregation Enclosure

- The rod ($r_1$=3.175 mm) is connected to a high-voltage (up to 30,000 volts) power supply located outside the chamber.
- An outer conductive cylinder is grounded and serves as the outer electrode ($r_2$=74 mm), smooth, thin-wall (0.065 in) metal cylinder).

# Electric Field Environment

- The coaxial configuration ensures a symmetric and well-defined field within the Aggregation Enclosure
- The electric field within this geometry is governed by the classical solution for coaxial cylindrical conductors.

$$E(r) = \frac{V}{r \cdot \ln \frac{r_2}{r_1}}$$

$E(r)$ is the electric field at a distance $r$ from the axis
$V$ is the applied voltage
$r_1$ is the radius of the inner rod
$r_2$ is the inner radius of the outer conductive cylinder.

- The maximum field strength occurs at the surface of the inner electrode.
- The equation remains valid with the fluorosilane coating as it’s effects on electric field geometry is negligible

# Cloud Chamber Cycle Run

- **Control Experiment:** The aggregation efficiency is measured with no electric field applied at a fixed temperature to provide a baseline reference.
- **Electric Field Variation:** At each fixed temperature of the Control Experiment, electric field strength is varied to determine its influence on aggregation efficiency.
- **Temperature Variation:** Conduct runs at specific temperatures of -8, -15, -22 and -29 °C

**Questions on Cloud Chamber Experiment**

# Ice Nuclei Seeding Material Testing

http://aerosol.atmos.und.edu/CloudChamberVideos_2018.html

## June 21, 2018 – **3:14**

0:23 - Injection starts.

1:14 - Start to see some ice.

2:16 - More turbulent eddies.

2:33 - Ice is becoming more prevalent.

3:52 - In the upper right corner, a large dark area.

5:22 - Ice continue to increase.

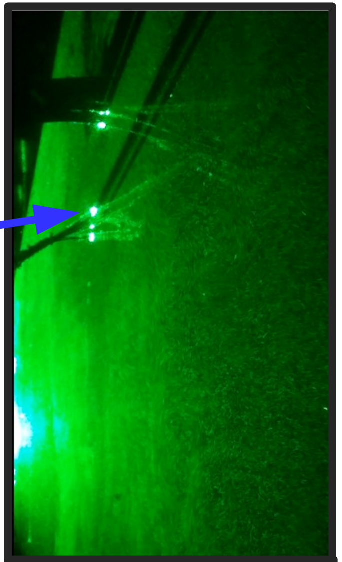
7:00 - Water drops depleting as more dark spots apparent

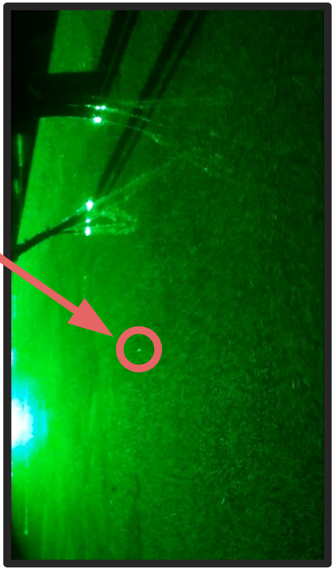
8:37 - Very little super cooled drops left.

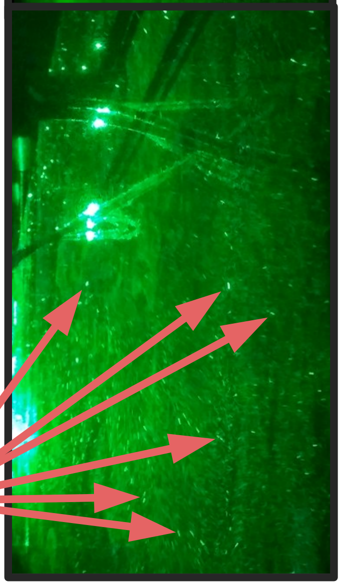
9:06 – Lot of the ice particles apparent.

9:33 - Water drops increasing.

10:15 - Chamber mainly ice particles.

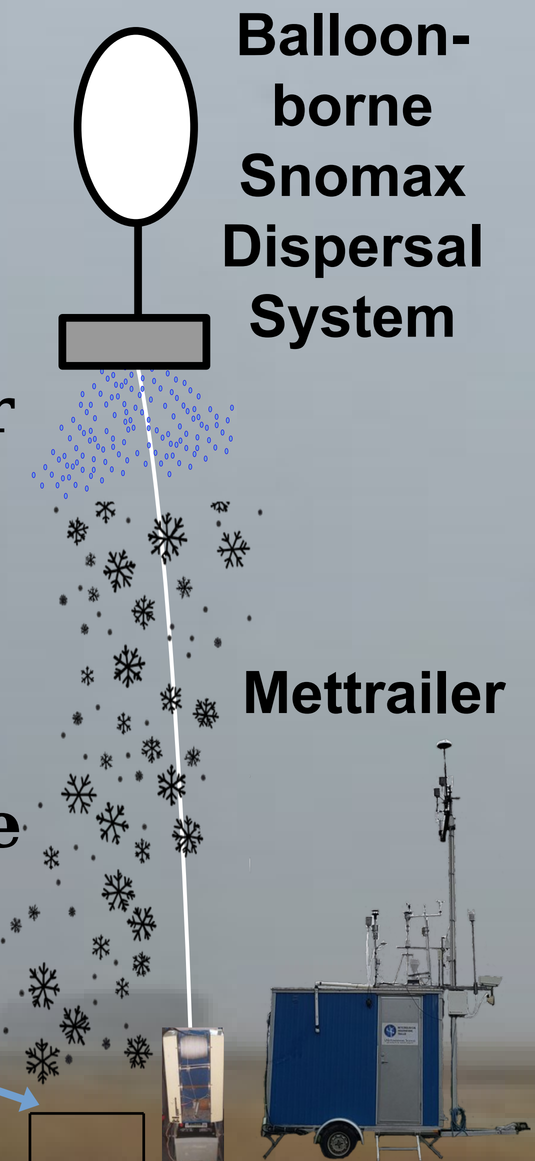


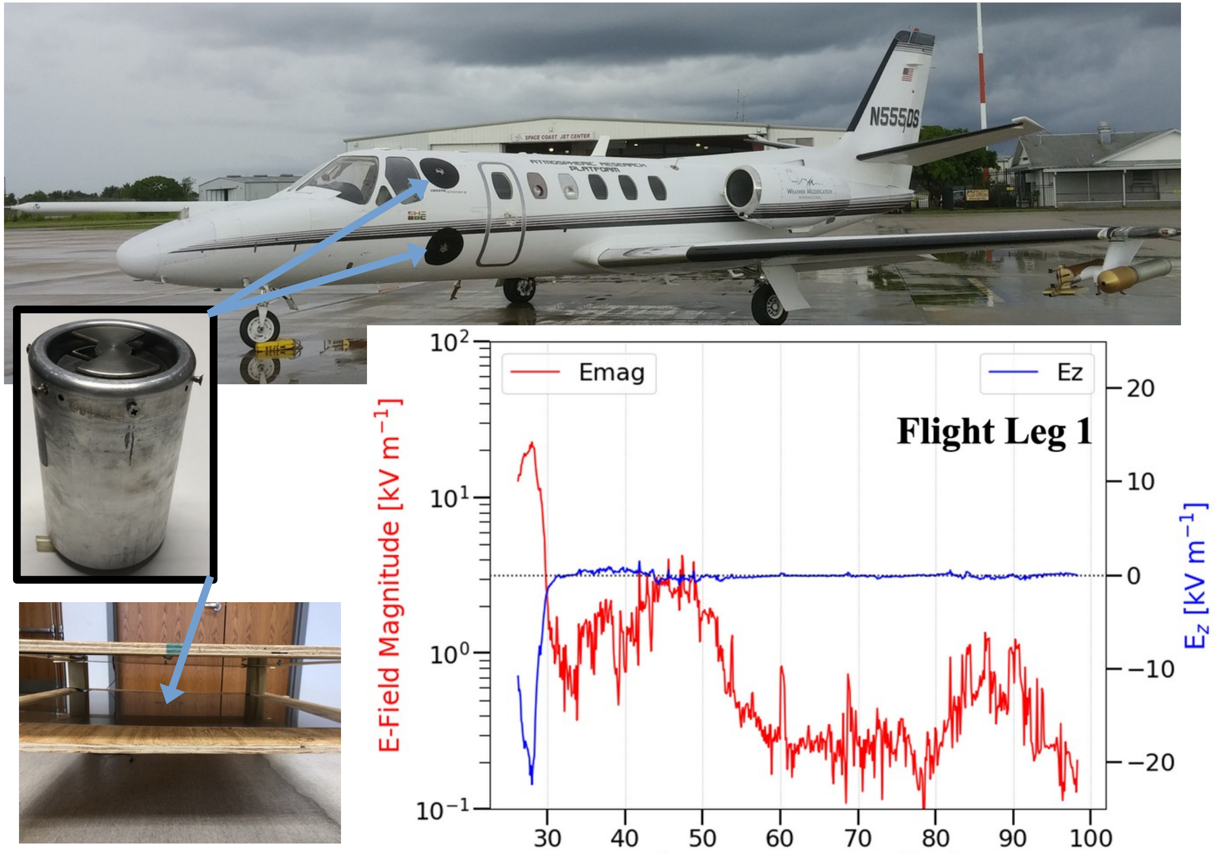



# Secondary Ice Production (SIP): Super-cooled Fog Experiment

- **Cloud chambers have a limited volume, and SIP mechanisms are statistically rare.**
- **Natural supercooled fog is a laboratory for larger-scale SIP experiments.**
- **Electron microscopy is used to analyze Formvar Slides to count crystals with and without visible ice nucleing particles.**
- **The proportion of primary to secondary ice is compared for height to determine significance of fall distance to SIP.**



# Aircraft Electric Field Measurements



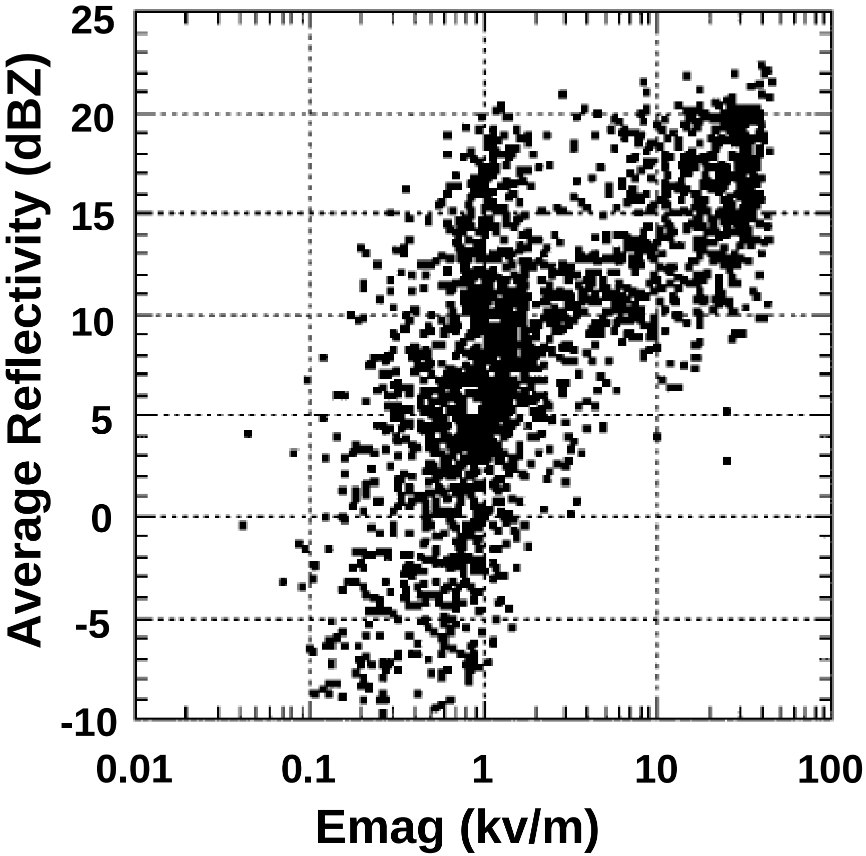
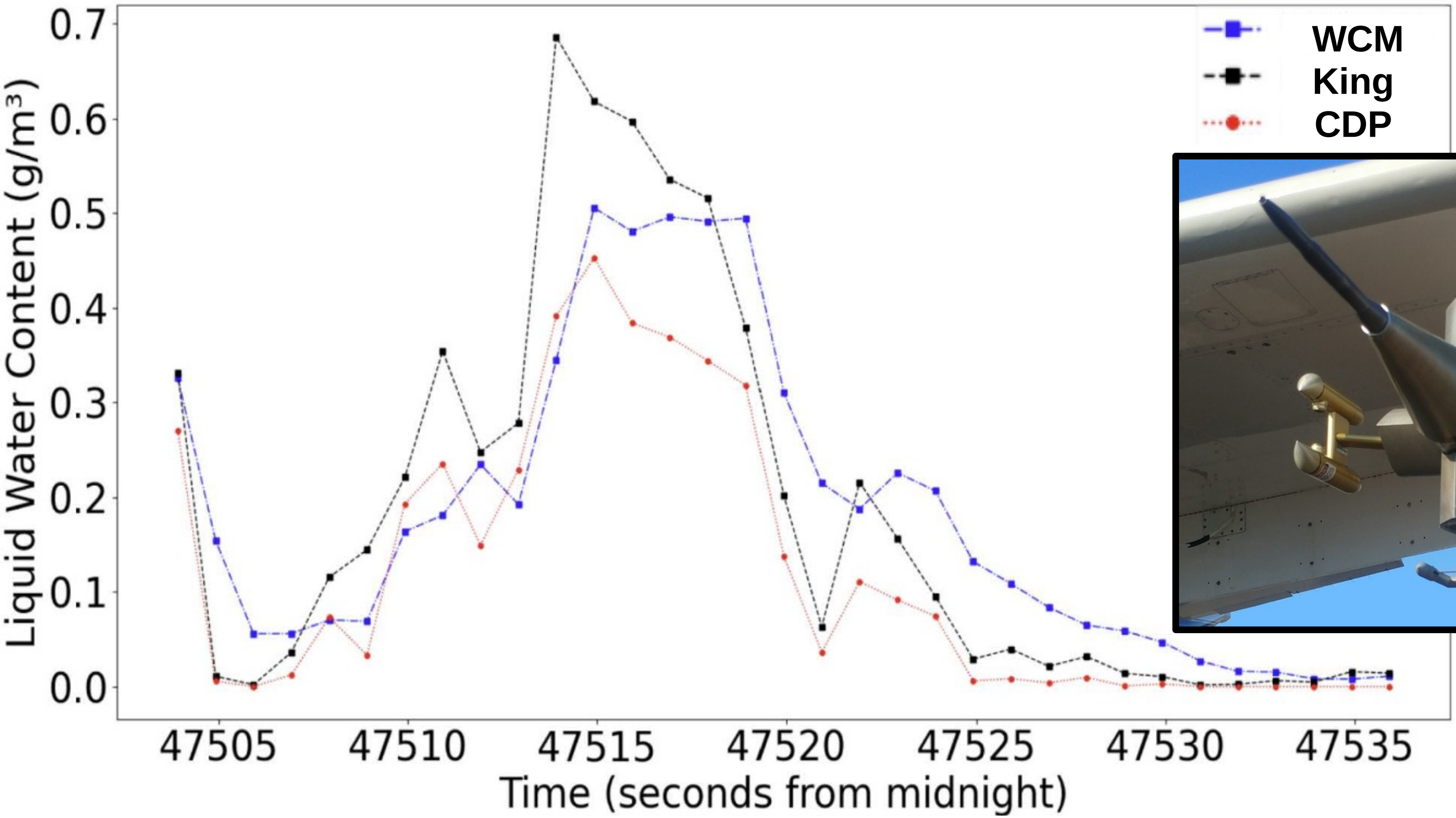



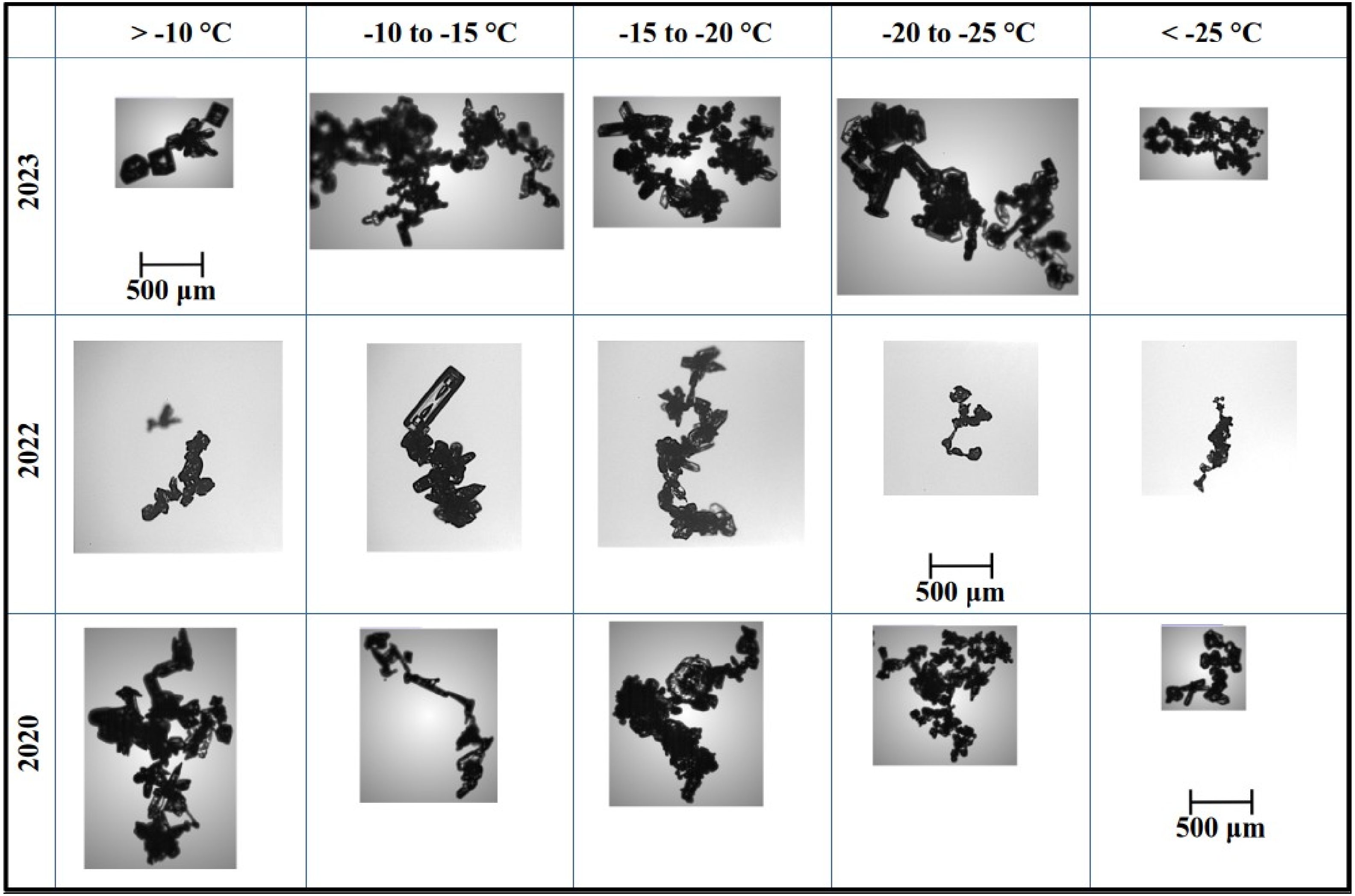

Image of the Citation Research Aircraft on deployment to Florida for CapeEx19 field project. Flight leg include cloud electric field measurement on 3 August 2019. Plot showing in-cloud electric field Emag as compared to average average reflectivity that is adapted from Dye et al., 2007, doi: 10.1029/2006JD007550.

# Aircraft Water Content Meter (WCM) Probe

## 16 December 2022




# Chain Aggregation Observation during NASA IMPACTS



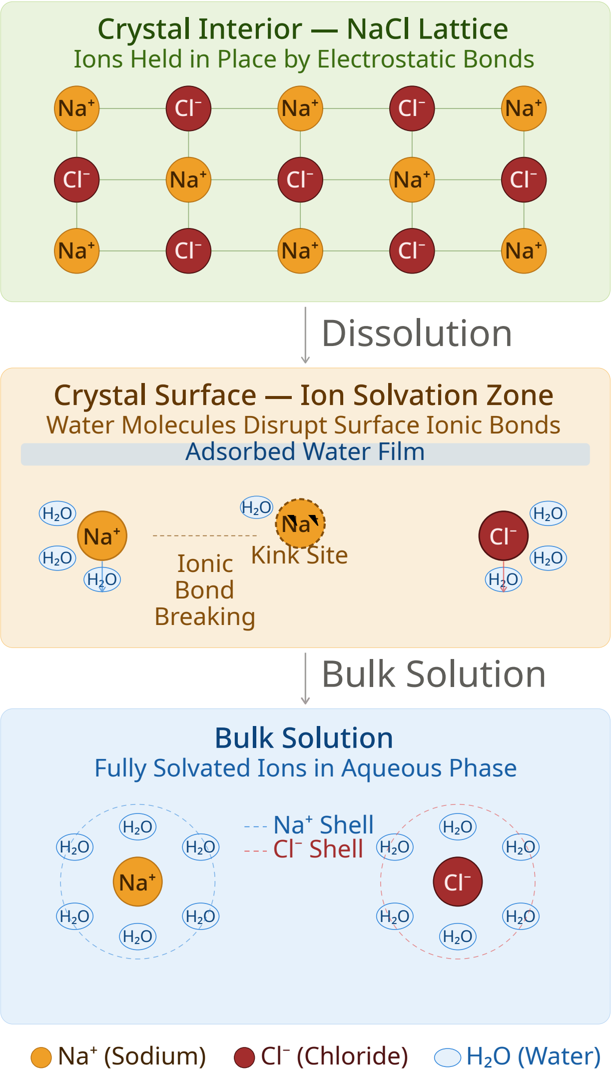
# Thank You - Team Effort

People in top imaged from left to right: David Delene, Shawn Wagner (Research Scientist), Christian Nairy (Ph.D.), Jenna Post (Undergrad), Jacob Halmos (Undergrad), Bryce Rickbeil (Undergrad), and Conrad Slad (Undergrad). People in left image from bottom/left to top/right: David Delene, Liz Cardoza (undergrad), Summer Coleman (Grad), Ashley Vos (Undergrad), Paramvir Singh (Undergrad), Benjamin Guida (Undergrad), and Tree (Kevin) Norby (Graduate).

# Additional Discussion Slides

# Theory: Particle Deliquescence (Phase Transition)

- Process by which a solid aerosol particle absorbs water vapor from the surrounding air and spontaneously dissolves into a liquid droplet.
- There is an abrupt, first-order phase transition where the surface water layers become sufficient to solvate ions at the crystal surface, breaking ionic bonds.
- Once dissolution begins, it is self-reinforcing as the now-dilute solution has a lower water vapor pressure than the saturated solution, drawing in more water vapor and driving further dissolution.



# Theory: Droplet Activation (Critical Point Dynamics)

- Order Parameter Jump
  - Before activation, the system is pure vapor; after, it contains coexisting liquid droplets. The liquid volume fraction undergoes a discontinuous transition, defining a macroscopic order parameter.
- Critical Radius
  - The Kelvin equation defines a threshold nucleus size: droplets below this radius evaporate (unfavorable surface tension), above it grow spontaneously (favorable bulk condensation). This sharp stability boundary is phase-transition-like.
- Spinodal-like Behavior
  - As supersaturation increases, the critical radius shrinks. When it matches the size of available CCN particles, the system crosses an effective spinodal — the limit of metastability — and nucleation becomes explosive.

# κ-Köhler (Petters & Kreidenweis 2007)

$$S(D) = [(D^3 - D_d^3)/(D^3 - D_d^3(1-\kappa))]\cdot \exp(4\sigma M_w/(RT\rho_w D))$$

- A single hygroscopicity parameter κ replaces the van't Hoff / molar-mass bookkeeping.
  - κ(NaCl)=1.28
  - κ($CaCl_2$)=1.12
- Both highly hygroscopic, NaCl slightly more so per unit dry volume.
  - NaCl has higher hygroscopicity parameter κ → Beter Activation
  - $CaCl_2$ lower deliuescence RH → Easier dissolve of crystal lattice structure

# Simulation Details

- Updraft after 95 % RH of 0.5 m/s (~100 ft/min)
- Below 95 % RH, 1.0 % increase per second.
- 100 nm NaCl and 100 nm $CaCl_2$ has 100 #/$cm^3$
- 5000 nm NaCL has 10 #/$cm^3$

- For 1500 s simulation (Parcel starts at 20 °C and 1000 mb):

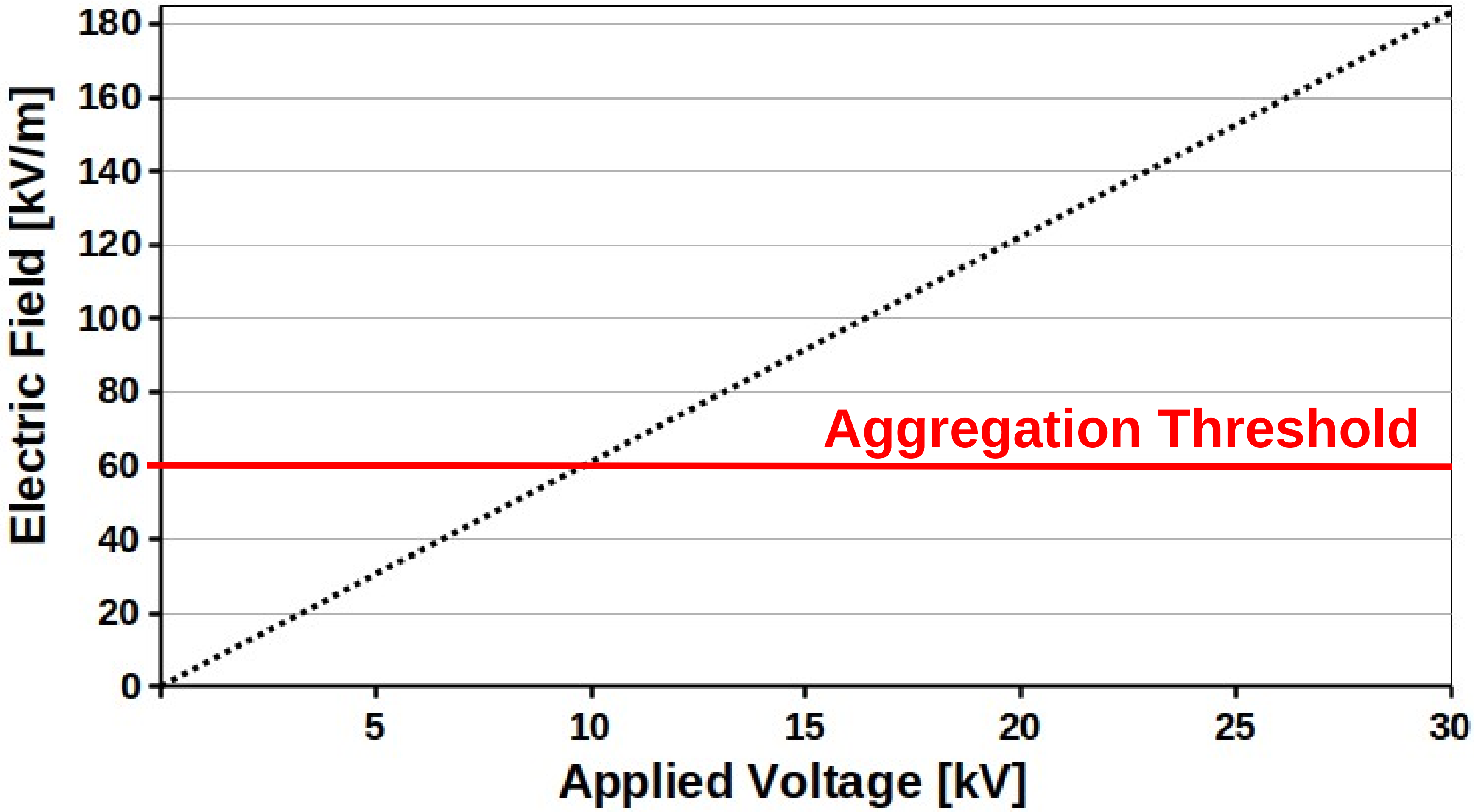
| **Particle** | **100 nm NaCl** | **5000 nm NaCl** | **100 nm $CaCl_2$** |
|---|---|---|---|
| Final Size | 32.6 µm | 37.9 µm | 36.6 µm |
| Max SS | 0.106 % | 0.000% | 0.113 % |
| DRH (298 K) | 75.65 % | 75.3 % | ~30 % |

# Quantifying Electrical Influences on Ice Crystal Aggregation

David Delene,
Christian Nairy and
Young-Suk Oh

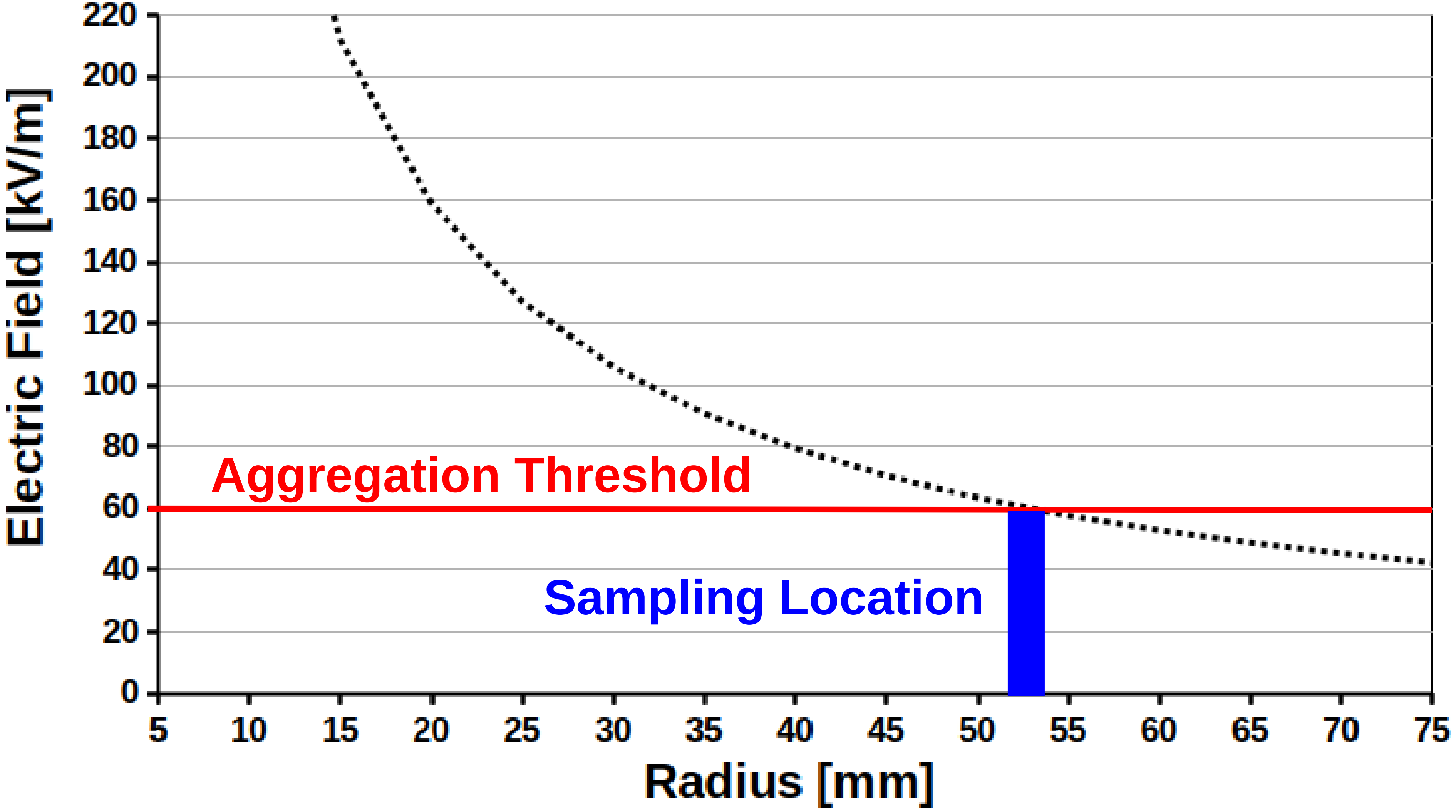
Atmospheric Sciences Department
University of North Dakota

# Generated Electric Field in Aggregation Enclosure




Electric breakdown (STP) at 3 million volts per meter (3 MV/m).

# Generated Electric Field in Aggregation Enclosure



# Related Publications

Schmidt, Jerome M., Piotr J. Flatau, Paul R. Harasti, Robert D. Yates, David J. Delene, Nicholas J. Gapp, William J. Kohri, Jerome R. Vetter, Jason E. Nachamkin, Mark G. Parent, Joshua D. Hoover, Mark J. Anderson, Seth Green, and James E. Bennett, Radar Detection of Individual Raindrops, Bulletin of the American Meteorological Society, 100, 2433-2450, 2019, https://doi.org/10.1175/BAMS-D-18-0130.1.

Wagner, S. W. and Delene, D. J., Technique for comparison of backscatter coefficients derived from in-situ cloud probe measurements with concurrent airborne Lidar, Atmos. Meas. Tech., 15, 6447-6466, https://doi.org/10.5194/amt-15-6447-2022, 2022.

Gapp, Nicholas, David J. Delene, Jerome Schmidt, and Paul Harasti, Comparison of Concurrent Radar and Aircraft Measurements of Cirrus Clouds, Journal of Atmospheric Sciences, in review (JAS-D-24-0014), 2024.

Nairy, Christian M., David J. Delene, Jerome M. Schmidt, Paul R. Harasti, Emma Järvinen, Case Study of Chain Aggregates in Florida Cirrus Cloud Anvils from Electrified Thunderstorms. Journal of Geophysical Research: Atmospheres. In Review 2026.

Nairy, Christian M., David J. Delene, Joseph A. Finlon, John E. Yorks, Emma Järvinen, Martin Schnaiter, Andrew J. Heymsfield, Andrew G. Detwiler, Lynn A. McMurdie, 2026: In situ Observations of Ice Crystal Chain Aggregates in Winter Storms. Geophysical Research Letter, 53, e2025GL118365, https://doi.org/10.1029/2025GL118365.