A Laboratory View of Exoplanet Cloud Particles & their Properties

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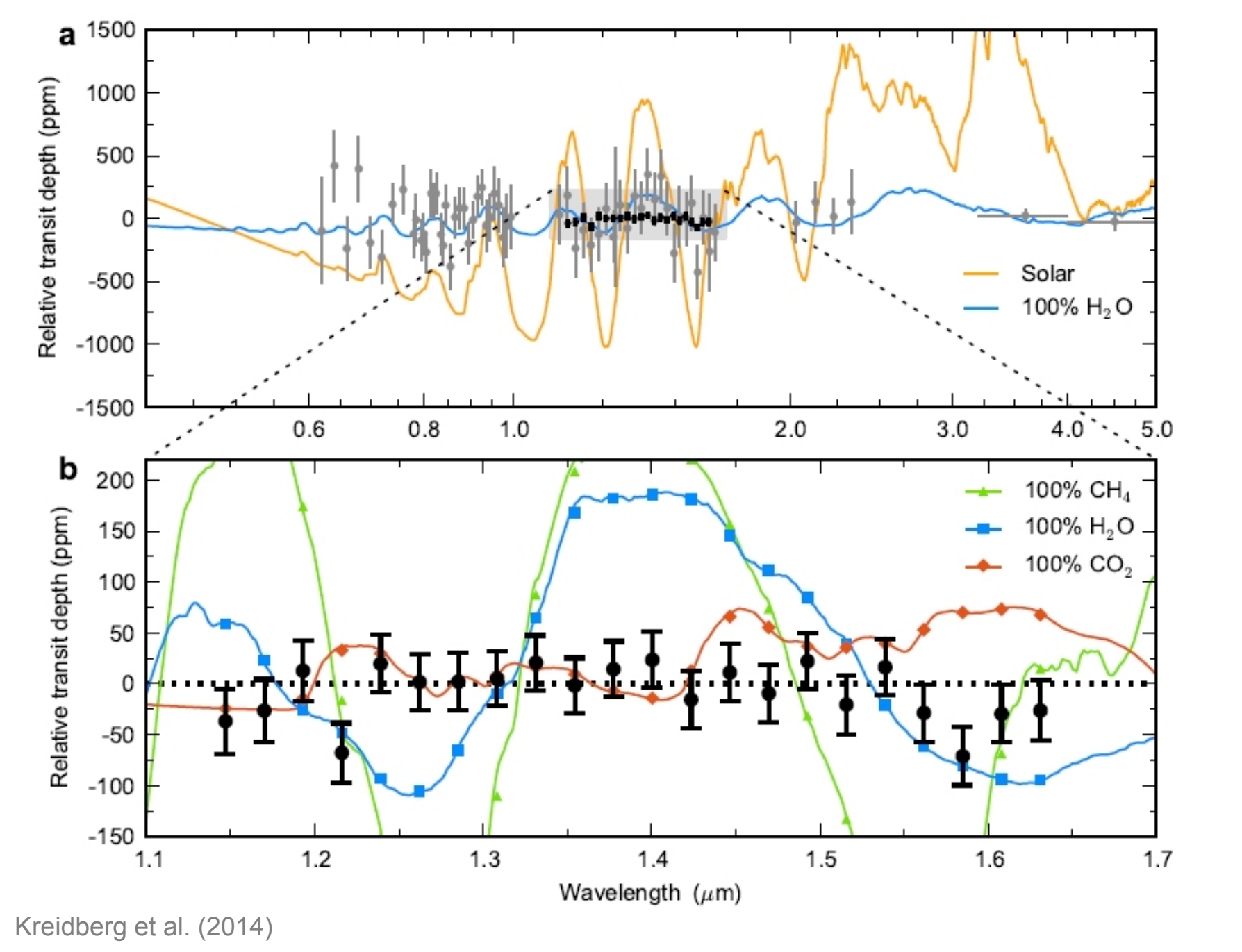
MOTIVATION

The lack of strong spectral features of some exoplanet atmospheres may suggest the presence of a high cloud layer blocking our view of the atmosphere below and poses great challenges for overall atmospheric characterization

- GJ1214b, a sub-Neptune suspected of hosting an atmosphere, has been observed to have a flat transmission spectrum



Kreidberg et al. (2014)

- It is reasonable to assume the presence of clouds in exoplanet atmospheres is a wide spread phenomena, therefore **understanding and characterization of exoplanet atmospheres is linked to our understanding of the clouds and particulates contained within them**

OBJECTIVE

Investigate how exoplanet cloud particles interact with radiation from their host stars, the optical properties of these particles, and how they effect our sampling of the atmosphere

- ***Why?*** Limited understanding of exoplanet atmospheric particulates, their characteristics, and what properties (if any) may be exploited for remote characterization
- ***What?*** The scattering and polarization of light by particulates across the visible spectrum
- ***How?*** By leveraging terrestrial based cloud knowledge and instrumentation in the laboratory setting

This work is the first of its kind. We hope it will support the interpretation of transmission spectroscopy and planetary phase curve observations as well as aid in exoplanet atmospheric modeling

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METHODS

Electrodynamic Balance (EDB)

- **Single, charged particle levitation in an electric field allowing for highly realistic cloud particle studies**
  - Simulated residence lifetimes (minutes, hours, days)
  - Simulated parcel trajectories through an atmosphere
  - No substrate effects

Experimental Details

- **Monitored particle and environmental properties:** Particle location, aerodynamic diameter, temperature, partial pressure of water (relative humidity), light scattered to PMT at fixed location
- **Current system specifics**
  - Temperature range: 183 K to 473 K
  - Particles sizes: 15-30 μm in diameter
  - Input gases: N_2 (dry carrier) and H_2O
  - Inner shroud pressure: Sea level (~1000 mb)
  - Laser wavelengths: 405 nm, 532 nm, 660 nm
  - Variable laser power between 0 & 100 mW
  - Scattered light viewing angles: 45°, 90°, 135°

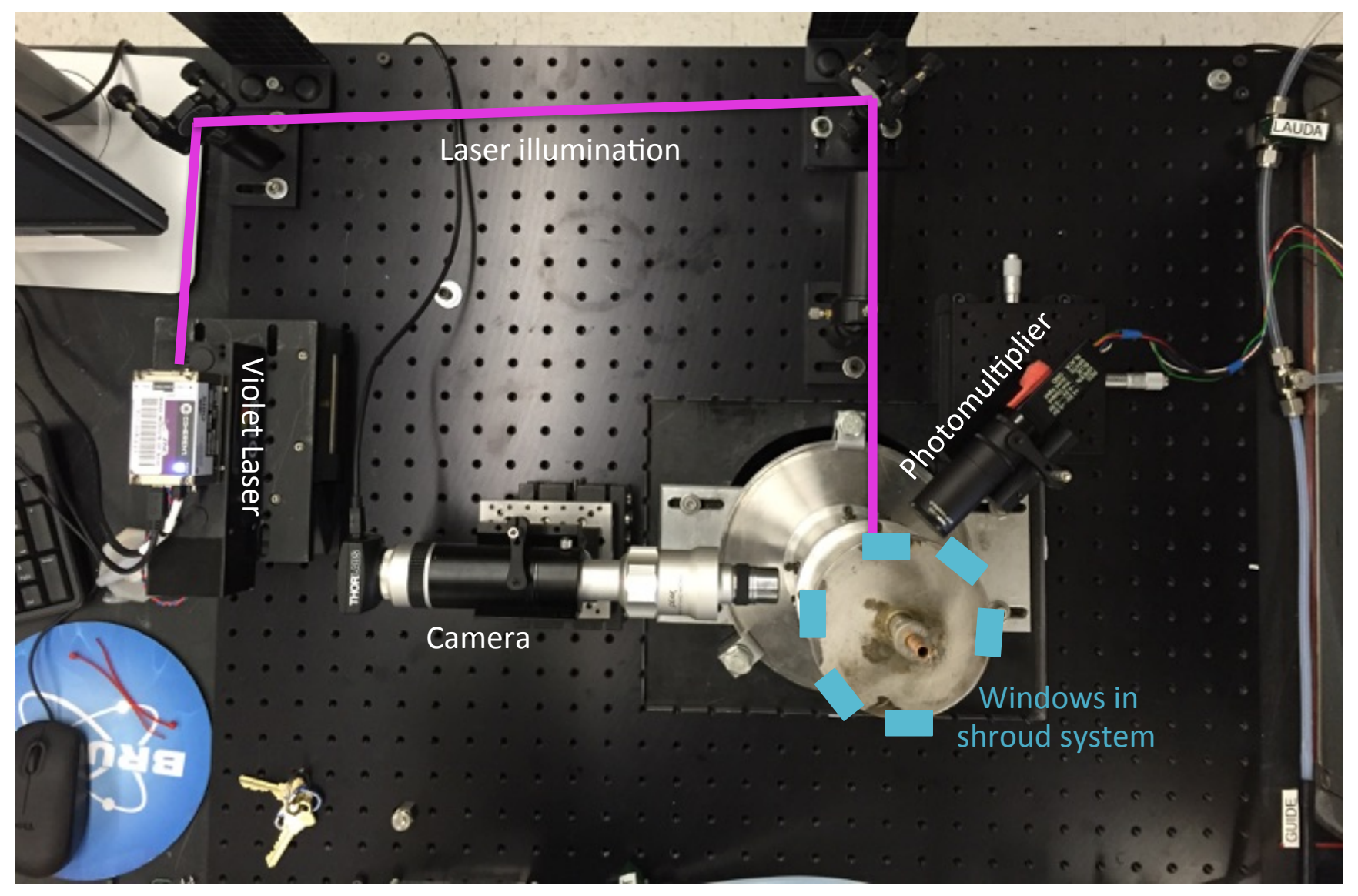
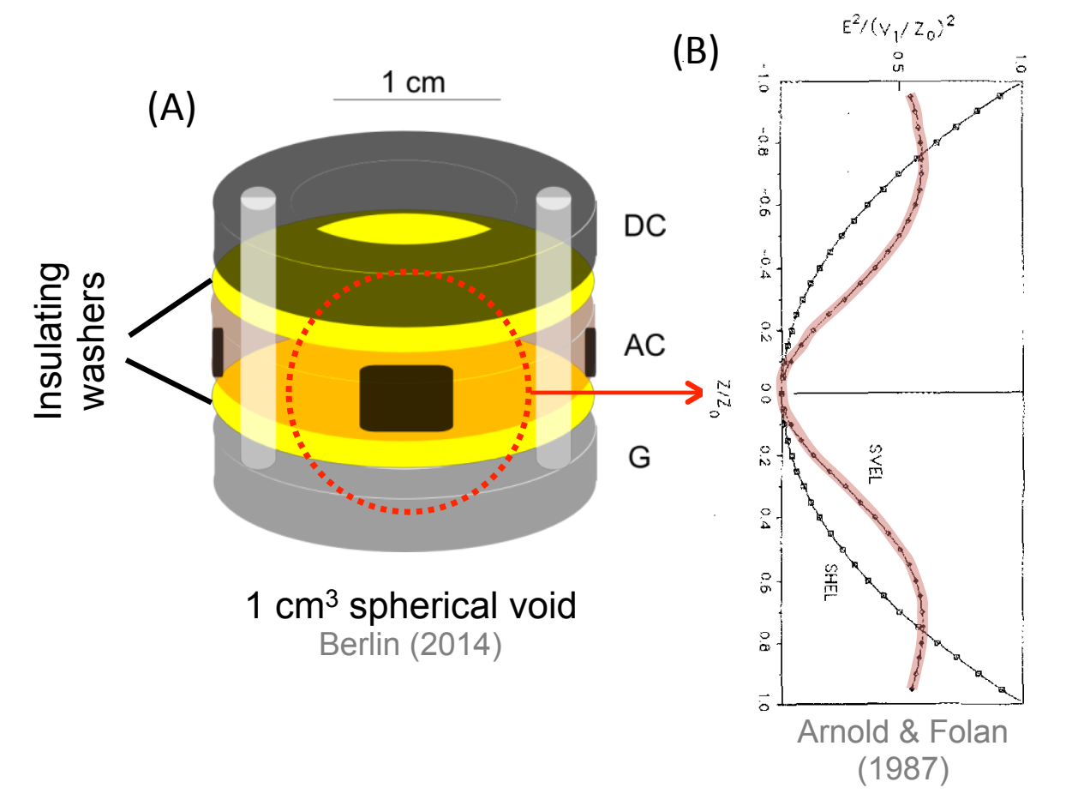


Fig. 3: Top view of EDB system in the laboratory. Keys for scale.

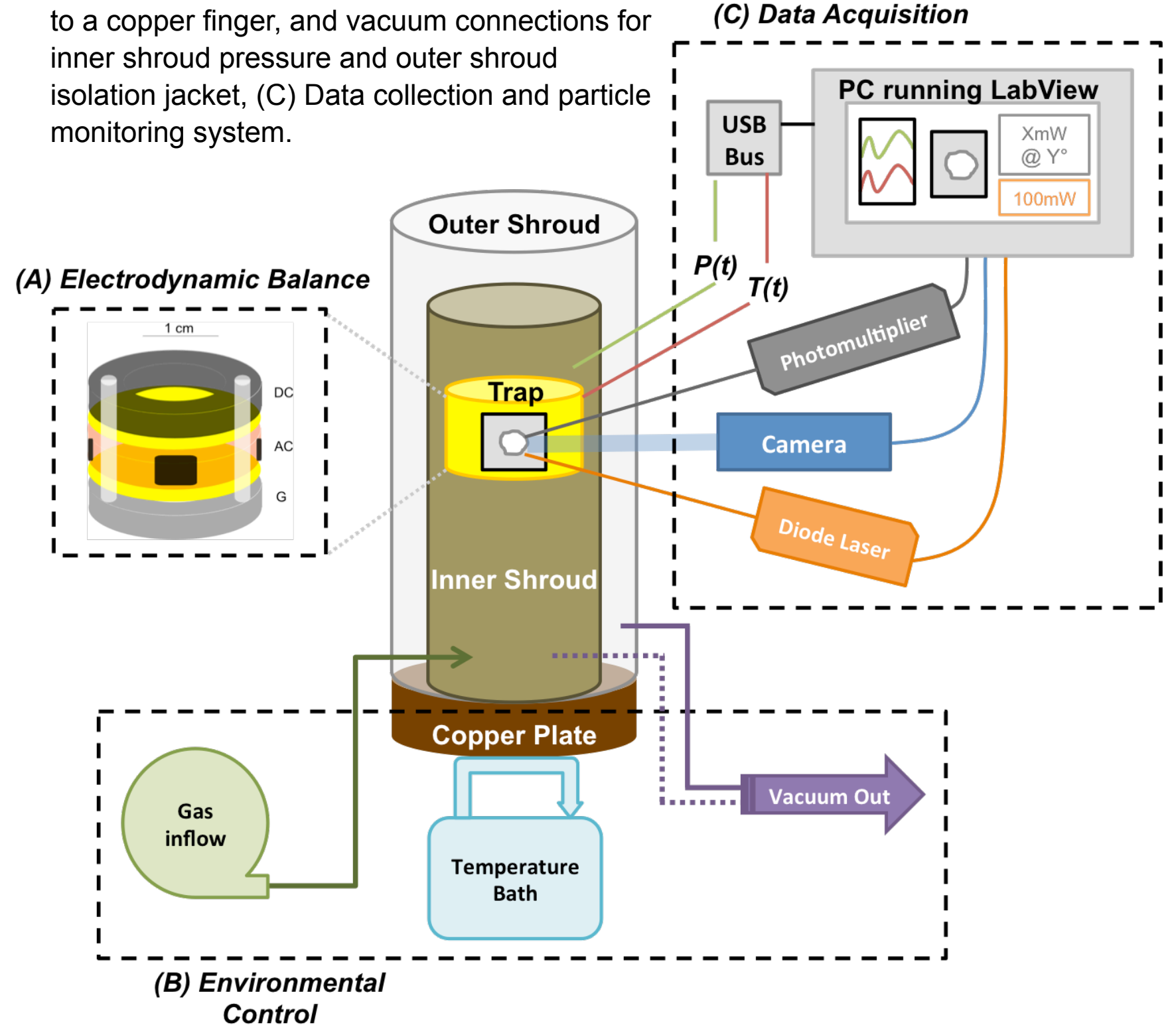


1 cm³ spherical void
Berlin (2014)

Arnold & Folan (1987)

Fig. 1: (A) Diagram of three electrode EDB. DC and G electrodes counteract gravitational pull on the particle while the AC electrode creates a minimum potential well in which the particle is stably trapped. (B) Normalized effective potential for a spherical void EDB (SVEL) highlighted in red.

Fig. 2: EDB shroud system consisting of (A) the EDB (see Fig. 1), (B) Environmental controls consisting of flow controlled particle carrier gas and changing atmospheric input gases, circulating temperature bath connected to a copper finger, and vacuum connections for inner shroud pressure and outer shroud isolation jacket, (C) Data collection and particle monitoring system.



Ammonium Nitrate

- We have chosen Ammonium Nitrate (NH_4NO_3) as our test substance due to its **unique crystal properties that can be used for system characterization.** Ammonium Nitrate is also a common, **well studied aerosol in Earth's atmosphere and may be present in cooler, super-Earth atmospheres**
- **Properties of interest**
  - Reversible reaction at Earth atmospheric conditions
  - Hygroscopicity with hysteresis effects
  - **Crystal to crystal phase changes with temperature (Table 1 & Fig. 4)**

System	Temperature (°C)	State	Volume Change (%)
-	> 169.6	liquid	-
I	169.6 to 125.2	cubic	+2.1
II	125.2 to 84.2	tetragonal	–1.3
III	84.2 to 32.3	α-rhombic	+3.6
IV	32.3 to –16.8	β-rhombic	–2.9
V	–16.8	tetragonal	-

Table 1: Temperature and structure associated with Ammonium Nitrate crystal to crystal and crystal to liquid phase change at Earth atmospheric pressure (Wikipedia).

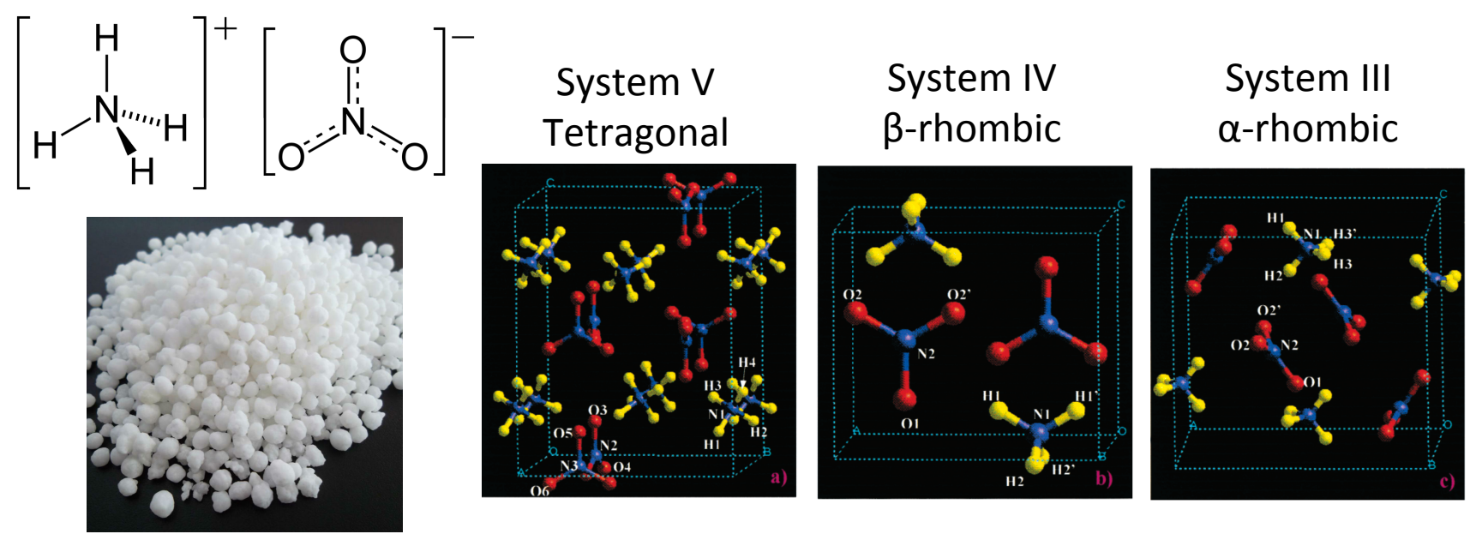


Fig. 4: Counter-clockwise from left top - Ammonium Nitrate chemical structure, bulk crystal, and crystal structure of phases V, IV, and III, the three structures studied in this work, with state properties as denoted in Table 1 (Sorescu and Thompson 2001).

RESULTS

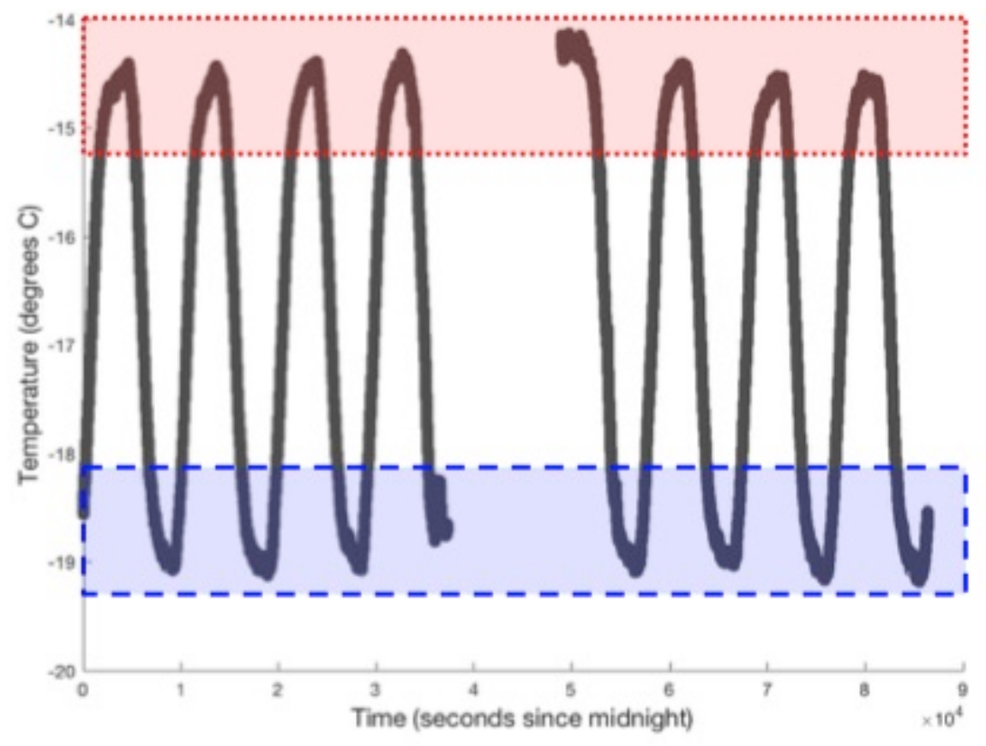


Fig. 5: Temperature vs. time for one Ammonium Nitrate experiment on a single crystal at the -16.8°C crystalline transition. An experimental run consists of oscillating between and sitting at temperatures just above and below the crystalline phase transition. Boxes represent the areas of interest for signal out comparison where ΔT/Δt is small.

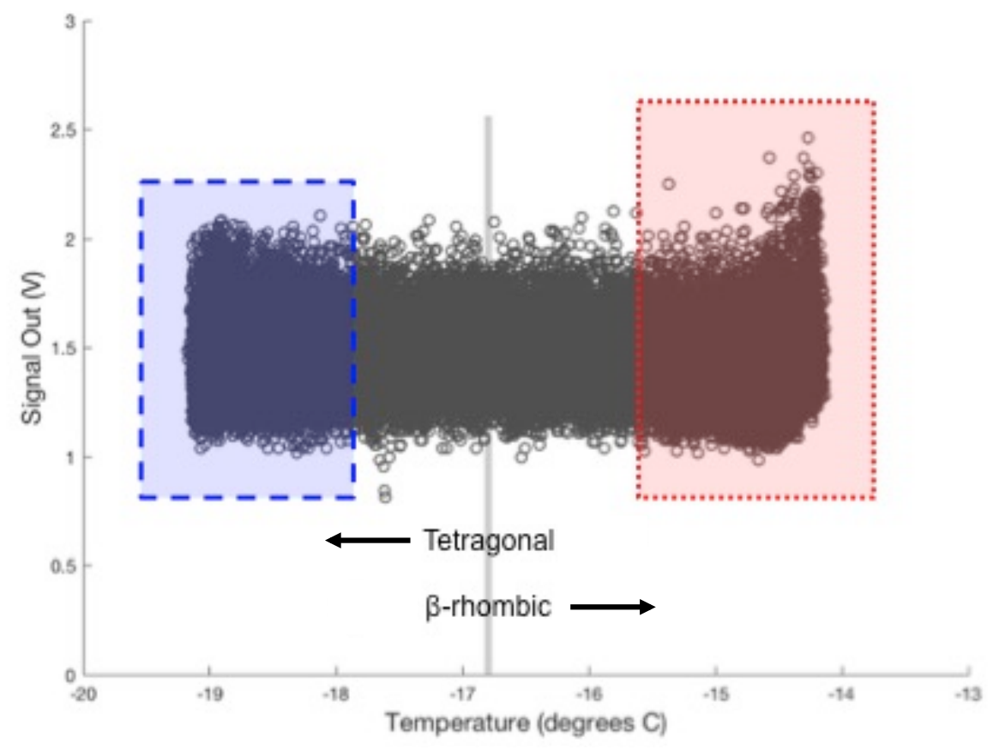


Fig. 6: PMT signal out vs. temperature corresponding to the run plotted in Fig. 5. Higher voltages indicate more light was scattered to, and collected by, the stationary PMT (135°). Boxes correspond to those in Fig. 5. Similar data was collected for background light noise.

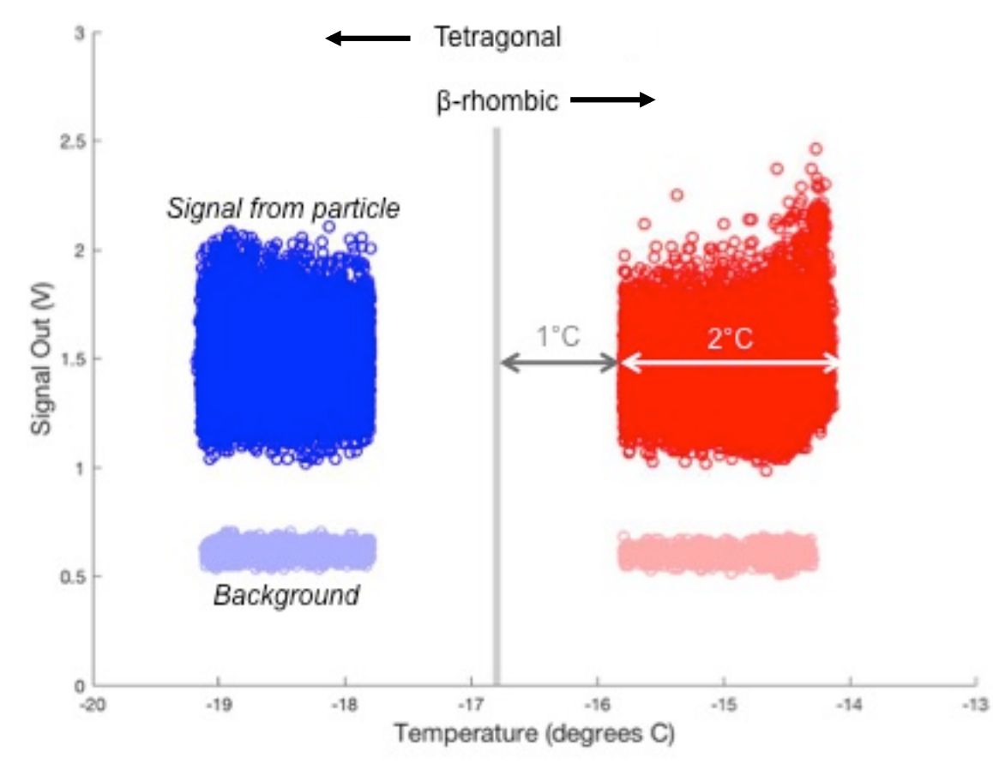


Fig. 7: Particle and background scattering data are isolated and from these an average, corrected PMT signal is calculated and population statistics are analyzed. Typically data within 1°C of the transition is omitted due to high ΔT/Δt, and isolated data spans 2°C above that.

Investigations into whether or not we could observe an average difference in the scattered light detected by the PMT (in Volts and at a fixed location) between crystalline states. The a basic procedure for this is outlined in Figs. 5, 6, and 7.

More light is scattered toward 135° as we move across the crystalline transitions from lower to higher temperatures

- **Transition from Tetragonal to β-rhombic at -16.8°C**
  - Average corrected Tetragonal signal = 0.82 to 0.86 V
  - Average corrected β-rhombic signal = 0.79 to 0.81 V
  - **Signal difference of ~ +3.6 to +5.0%**

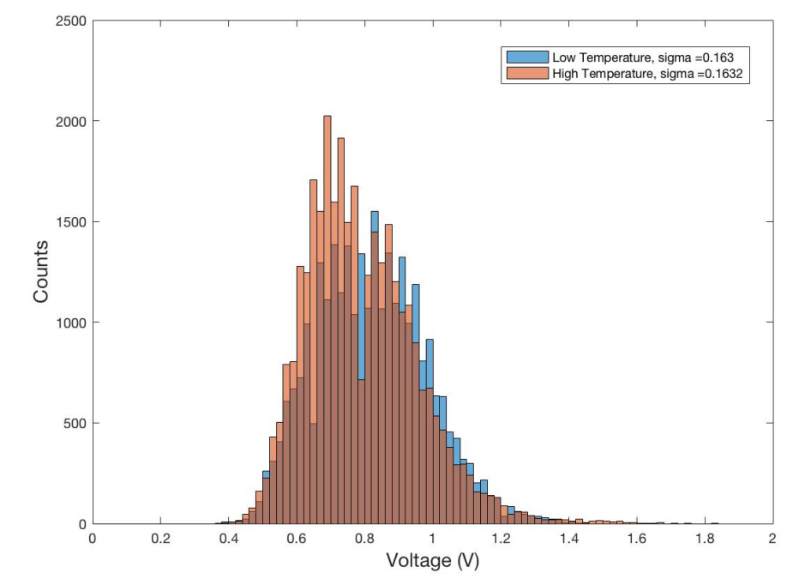


Fig. 8: Histogram of corrected voltage data for one -16.8°C crystalline transition study. A two sample t-test indicates that the mean of the voltage distributions above and below the transition are different at the 5% significance level.

- **Transition from β-rhombic to α-rhombic at 32.3°C**
  - Average corrected β-rhombic signal = 0.56 V
  - Average corrected α-rhombic signal = 0.59 V
  - **Signal difference of ~ +5.9%**

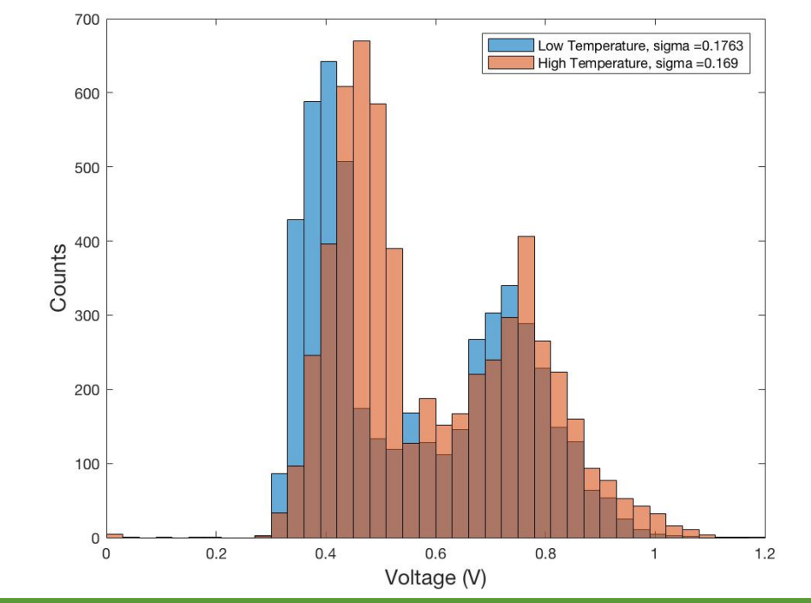


Fig. 9: Histogram of corrected voltage data for one -32.3°C crystalline transition study. A two sample t-test indicates that the mean of the voltage distributions above and below the transition are different at the 5% significance level.

CONCLUSIONS

Our novel experiment has proven useful for detailed investigations into the scattering of light by atmospheric aerosols across minute changes in particle properties.

With further exploration the sensitivity of our instrument to different particle physical properties can be determined and we can begin to collect data on proposed exoplanet cloud particles

The results thus far are motivation to dig deeper

- Small signal from a small physical change in particles d = 15-30 μm
- Methodology in place for continued parameter space exploration

- **Next steps: Building statistics, further exploration, better detection capabilities**
  - Scattering at 45° and 90°
  - Illumination at 532 nm and 405 nm
  - Examine light scattered across remaining crystalline phase changes, melting point, under volatile conditions and during hygroscopic interactions
  - *New, advanced EDB for the collection of full scattering phase functions and polarimetry!*
- **Moving into Exoplanet substances**
  - Examining proposed Super-Earth, Sub-Neptune cloud particle scattering properties
  - Expanding the list of potential atmospheric substances in Super-Earth, Sub-Neptune clouds

NEW CHAMBER

The design and build of an advanced EDB specifically for exoplanet studies is currently underway.

The relatively closed three ring, spherical void design (shown in Figs. 1 and 2) will be replaced with a quadrupole EDB, following the design of a Button Electrode Levitator system for terrestrial clouds in operation at Penn State (Harrison et al. 2016)

Key benefits of this design:

- Maximizes angles of scattered light collection, with almost full 0°-180° viewing, sufficient for polarimetry studies and retrieval of full scattering phase functions
- More precise temperature and environmental control
- Proven design for nucleation and growth experiments
- Custom build ensures the system is designed for high temperature operation

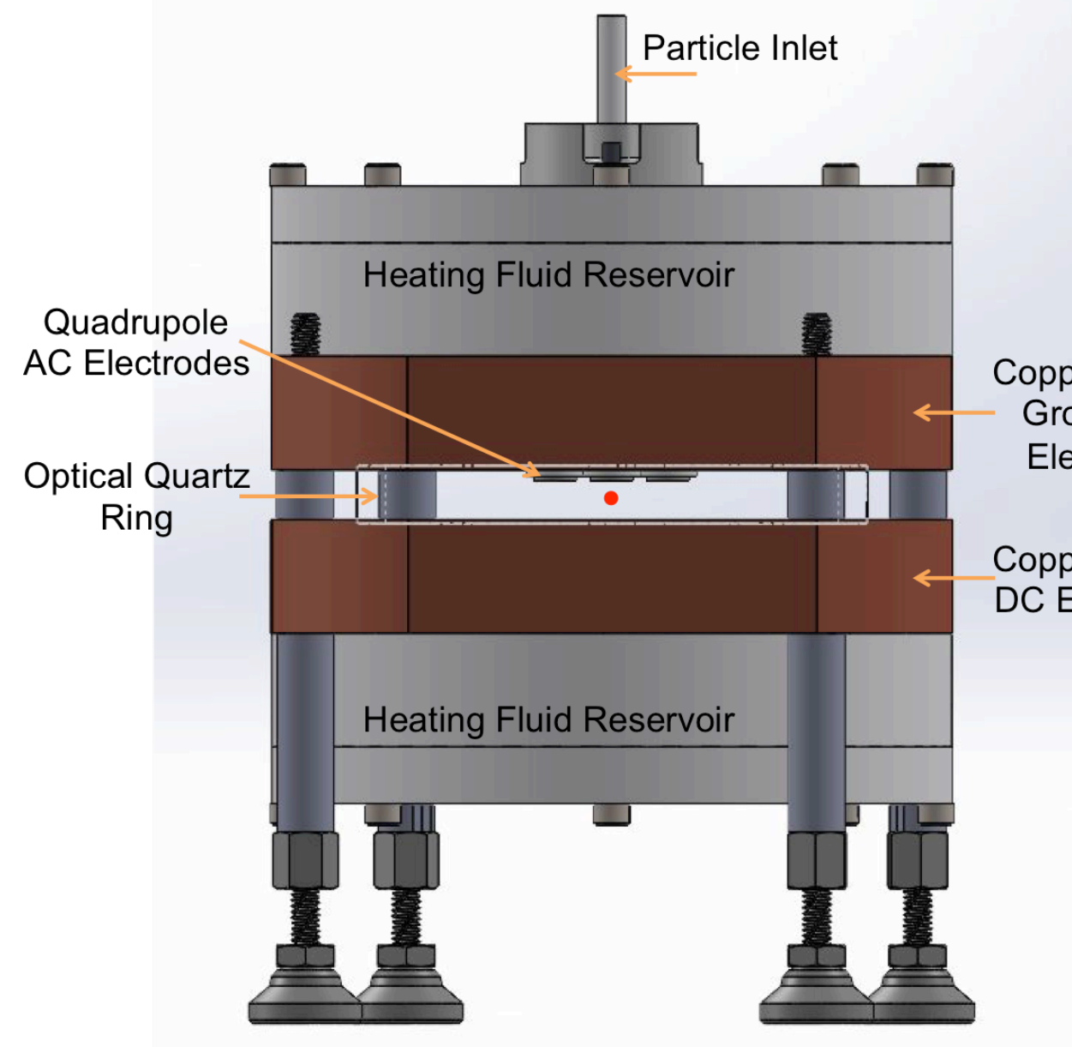


Fig. 10: Side view of Advanced EDB. Two copper plates acting as DC and G electrodes are in contact with a thermal bath, each at a slightly different temperature, as a means to establish precise temperature and vapor diffusion gradients. The chamber is isolated by an optical quartz ring. Charged particles are introduced through a particle inlet and will sit at the location indicated by the red dot.

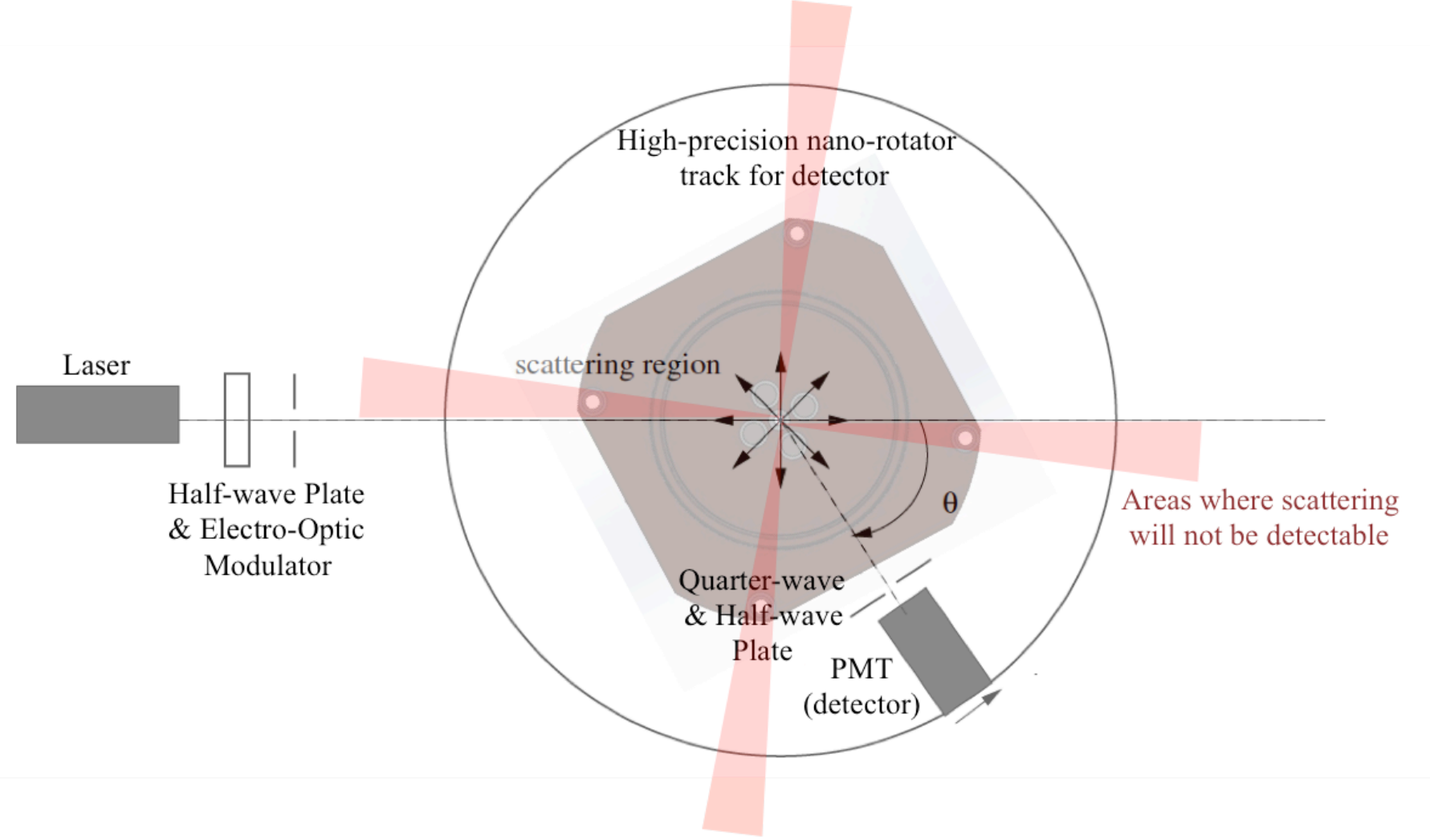


Fig. 11: Bottom up view of top electrodes with polarimeter block diagram overlay. Red areas indicate the regions where supports in the EDB limit our ability to detect scattered light. However, adjustment of the incoming laser position and use of a nano-rotator should allow us to work around these regions to obtain nearly full scattering phase functions.

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