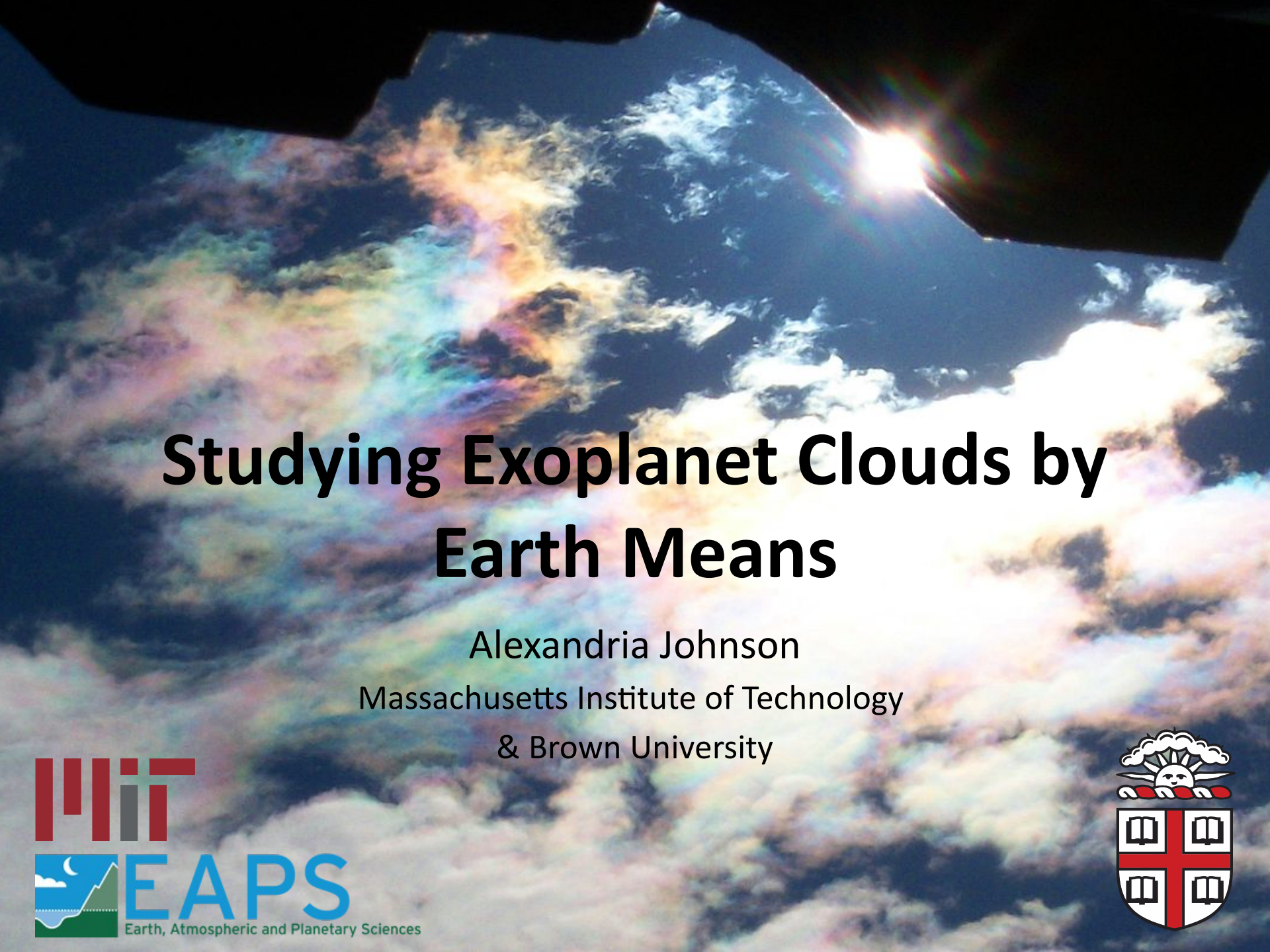

Studying Exoplanet Clouds by Earth Means

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& Brown University

EAPS

Earth, Atmospheric and Planetary Sciences

Goal for this work:

Use proven, Terrestrial based, methods to study the properties of (proposed) exoplanet cloud particles in the laboratory

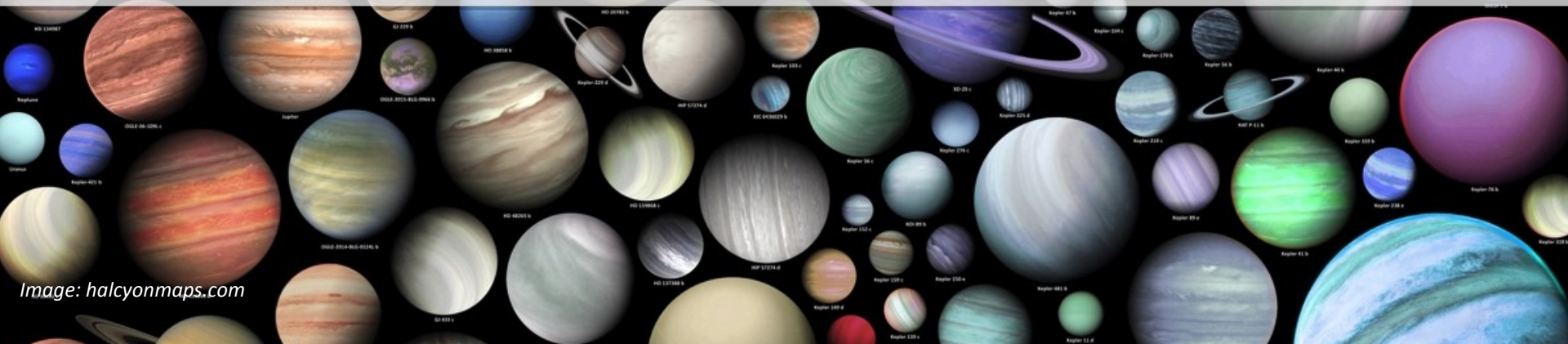
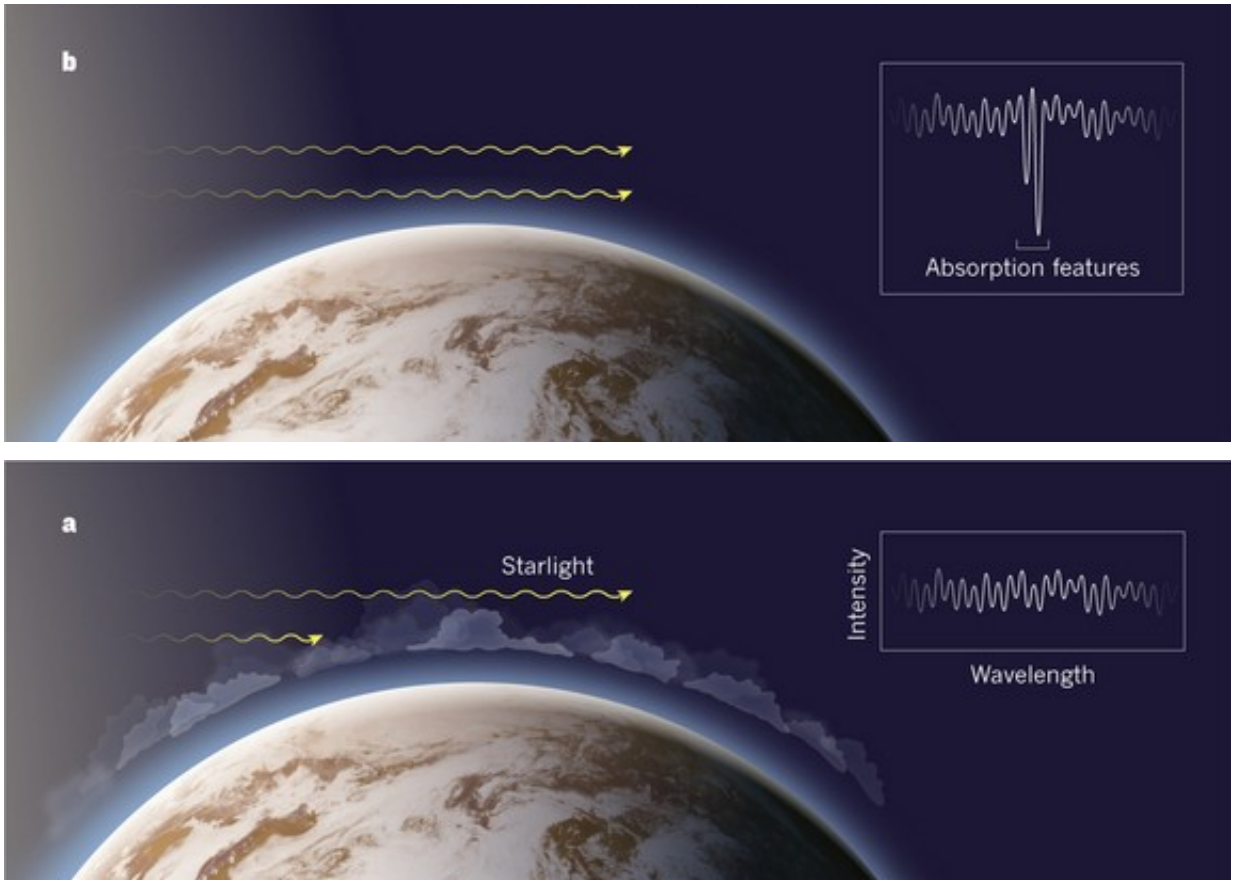


Image: halcyonmaps.com

Why?

Kempton (2014)



Clouds prose an enormous challenge in characterizing exoplanet atmospheres through spectroscopic characterization

How can Earth based methods help?

- Atmospheric scientists have built a suite of techniques to study particles (aerosols, hazes, clouds) in Earth's atmosphere
- …Further application to solar system bodies

- Our question: How do exo-cloud particles interact with radiation from their host stars?
  - Implications for atmospheric detection and characterization… exo-climates, exo-life

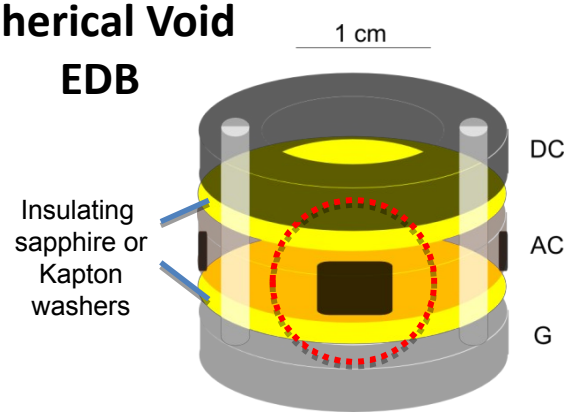
- Our approach: Measure the light scattered by *single particles* as a function of morphology and wavelength

Electrodynamic Balance (EDB)

- *Allows for the levitation of a charged particle in a superposition of AC and DC electric fields, and the study of physical or chemical transformations without interactions from surfaces or other particles*

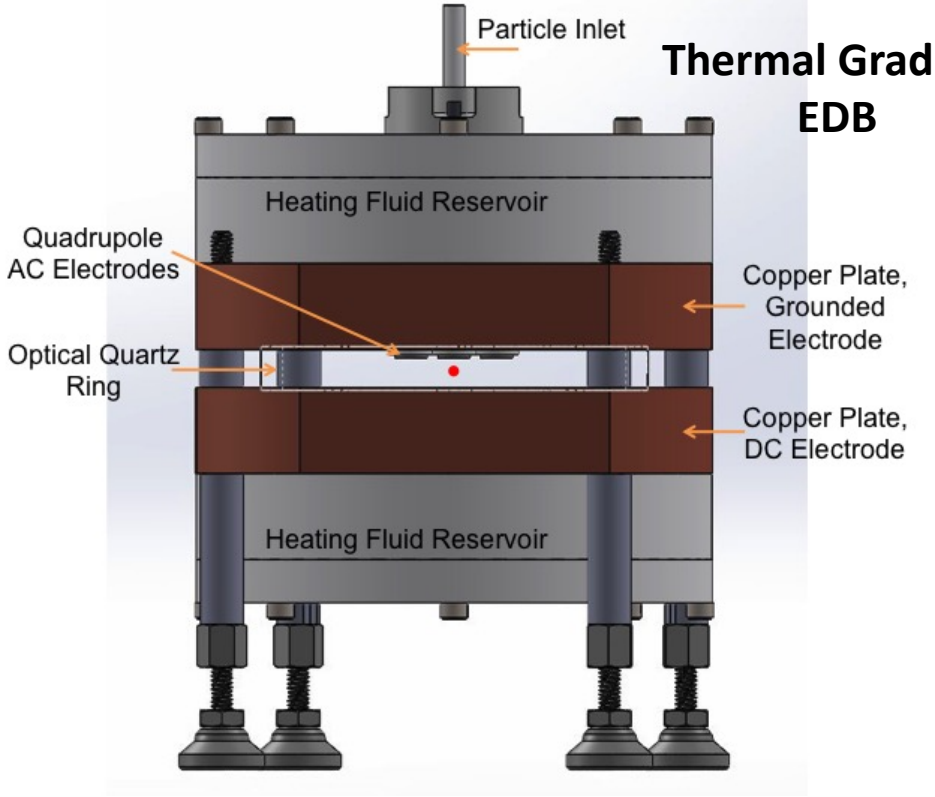
- Two geometries…

Spherical Void EDB

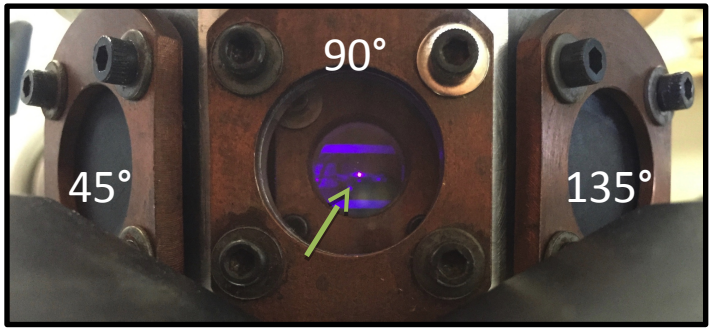


S. Berlin (2014)

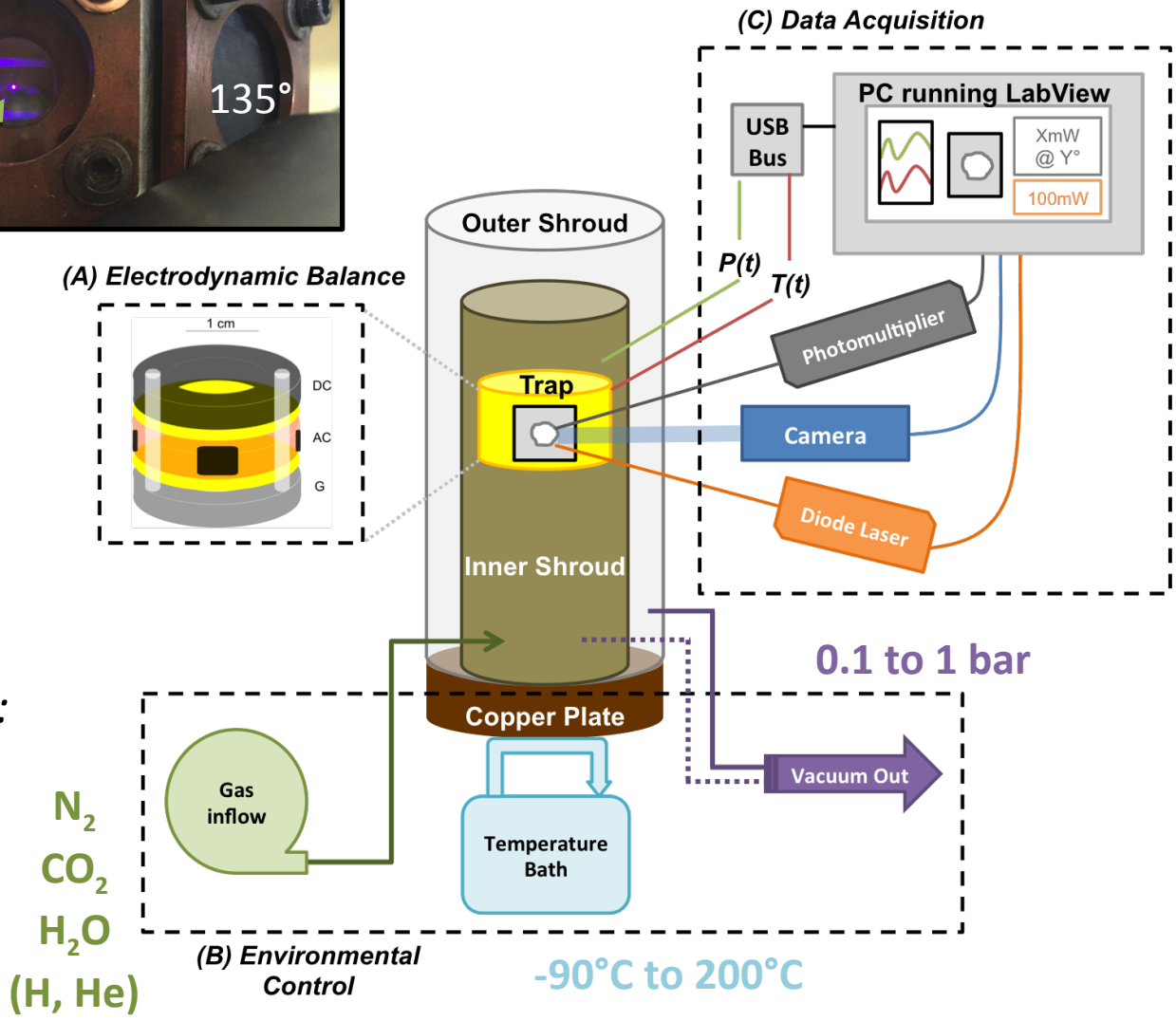
Thermal Gradient EDB



Spherical Void EDB



- *Wavelengths:* 405, 532, and 660 nm
- *Typical diameter:* 15 and 30 µm
- *Residence lifetime:* hours to days

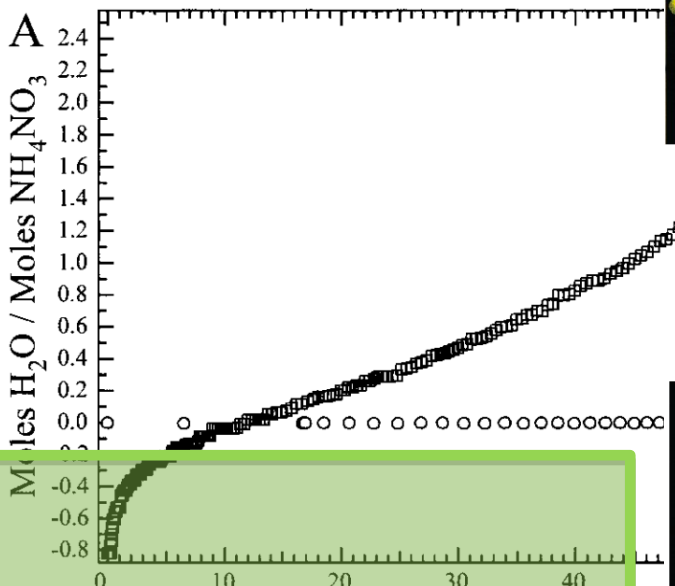


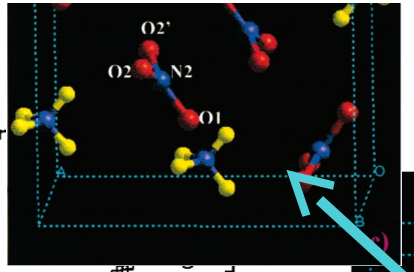
Ammonium Nitrate

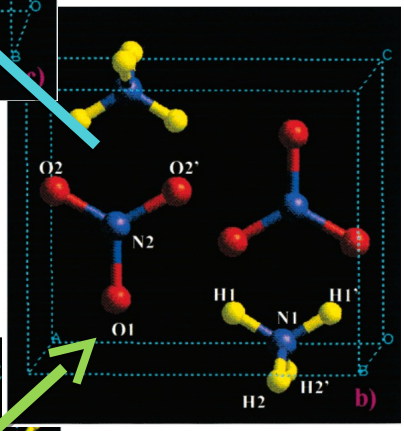
- Reversible reaction
- Hygroscopic
- Crystalli

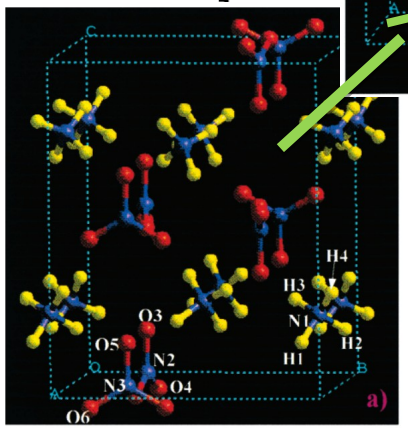
$$\underset{\text{AN}}{NH_4NO_{3(m)}} \rightleftarrows NH_{3(g)} + HNO_{3(g)}$$

System	Temperature (°
-	> 169.6
I	169.6 to 125.2
II	125.2 to 84.2
III	84.2 to 32.3
IV	32.3 to –16.8
V	–16.8

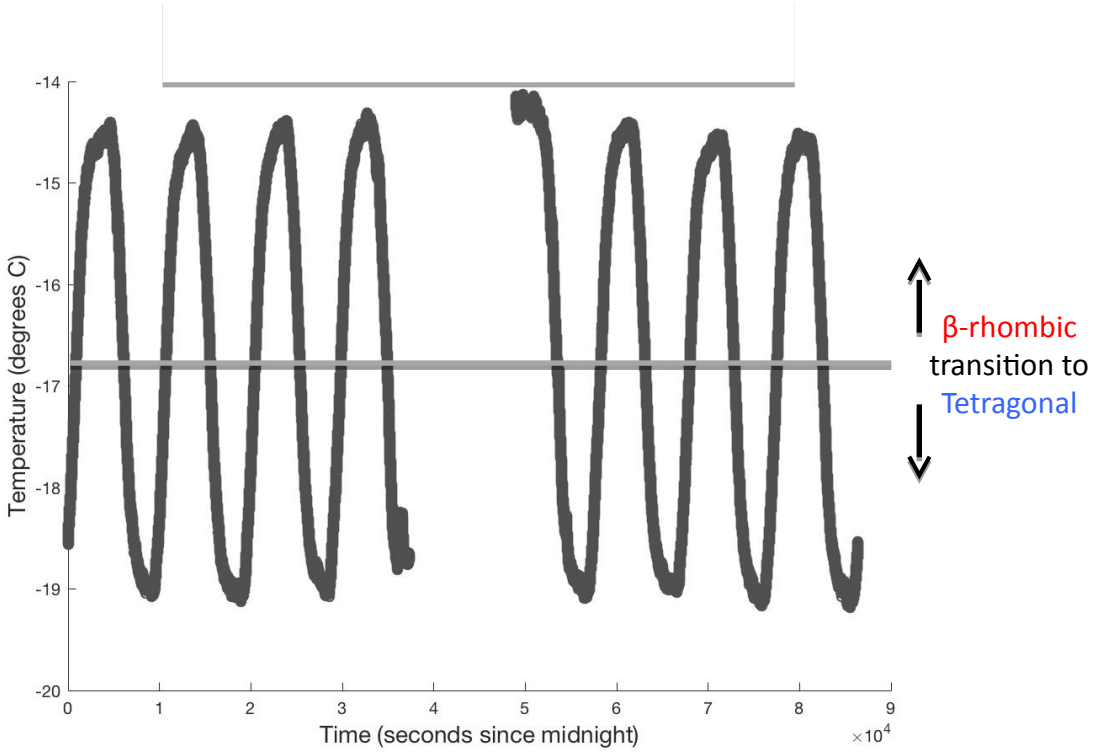






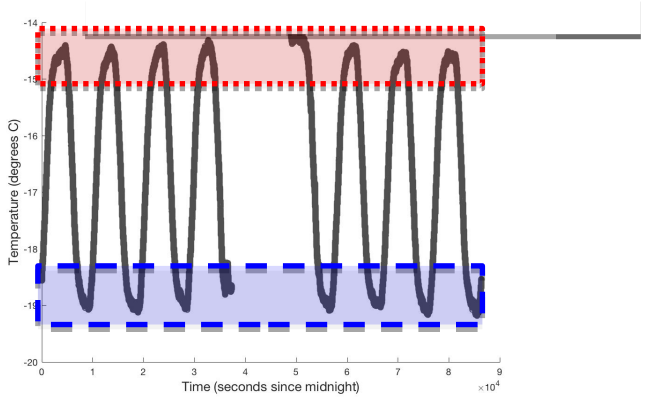


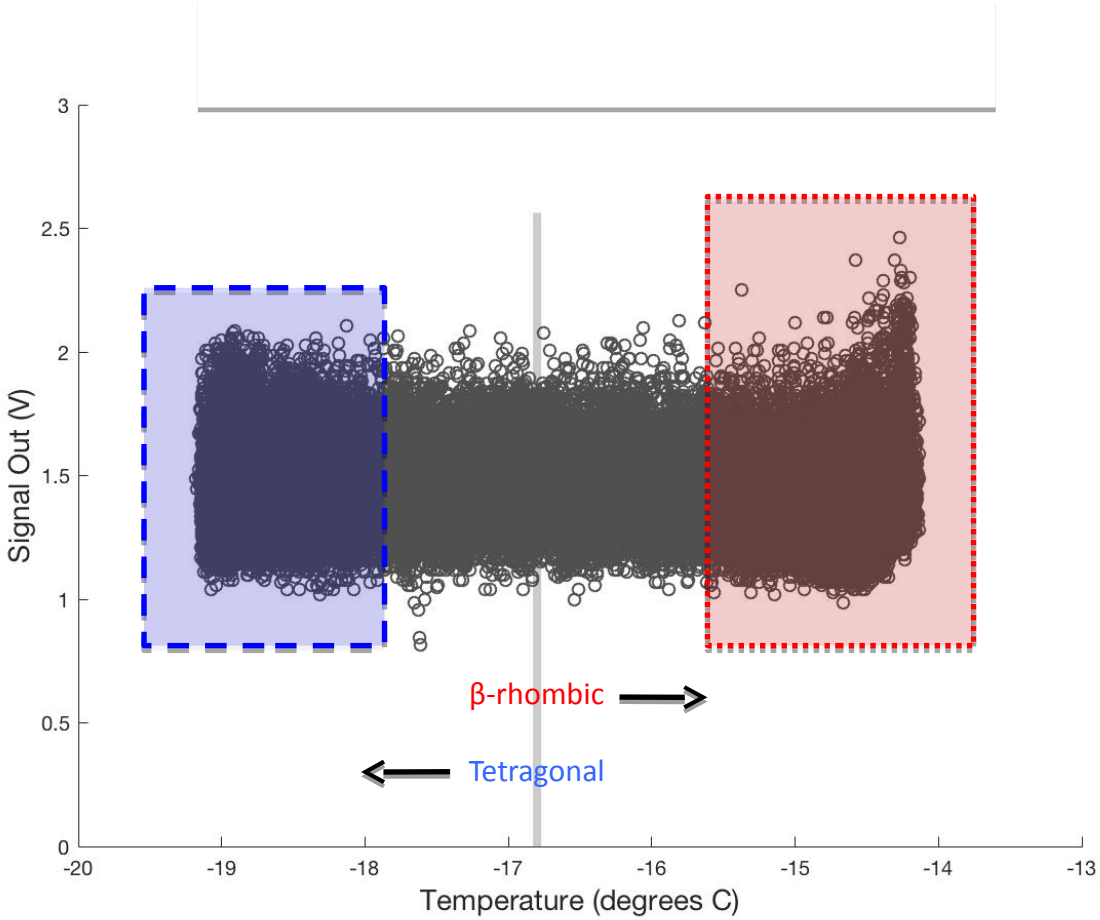
Example experiment:
Tetragonal to β-rhombic transition



Transition temperature: -16.8°C
Scattering at 45°, 660 nm

Example experiment:
Tetragonal to β-rhombic transition





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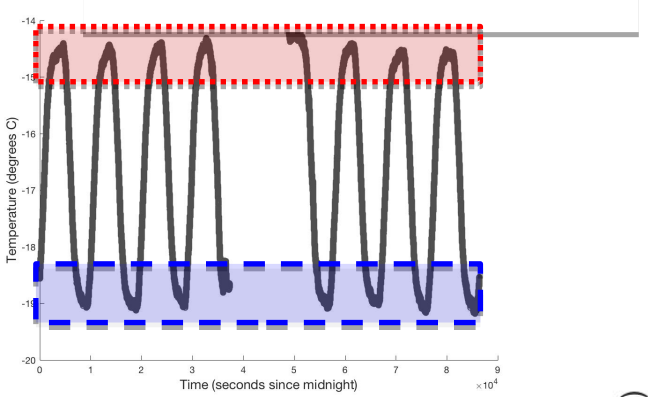
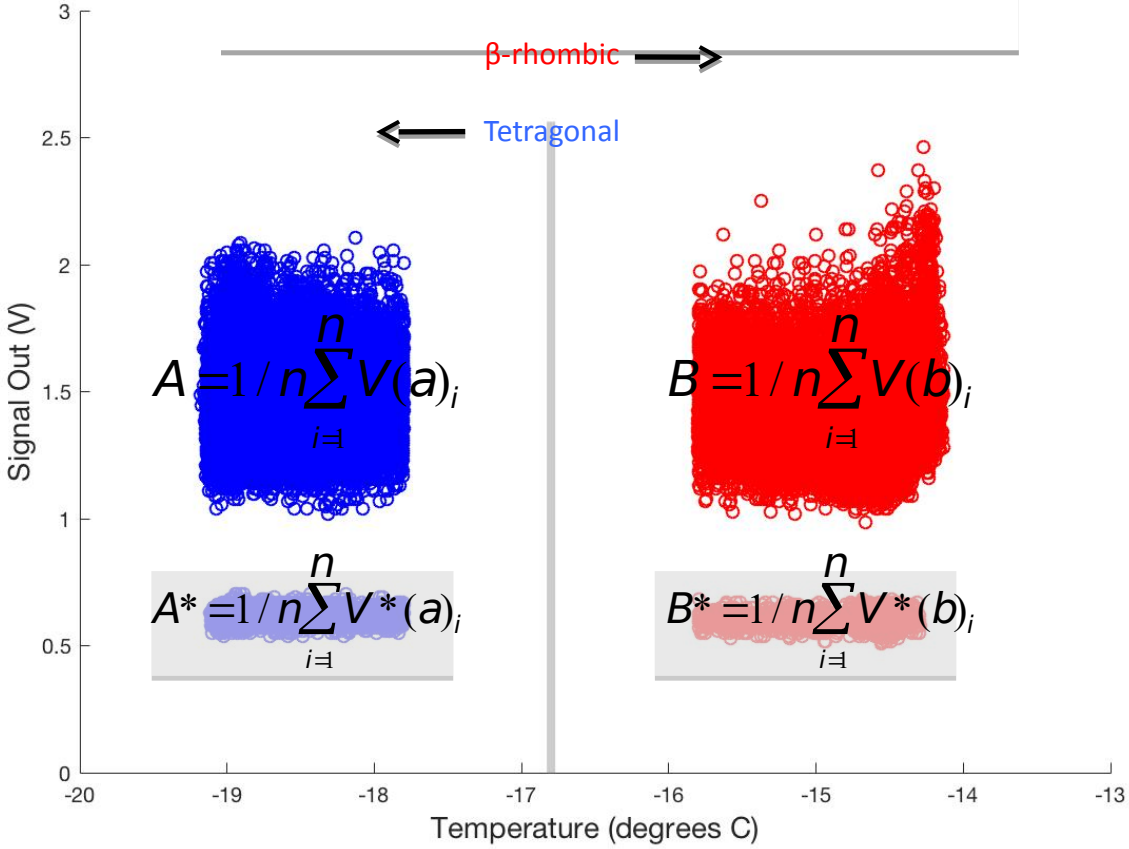
Example experiment:
Tetragonal to β-rhombic transition

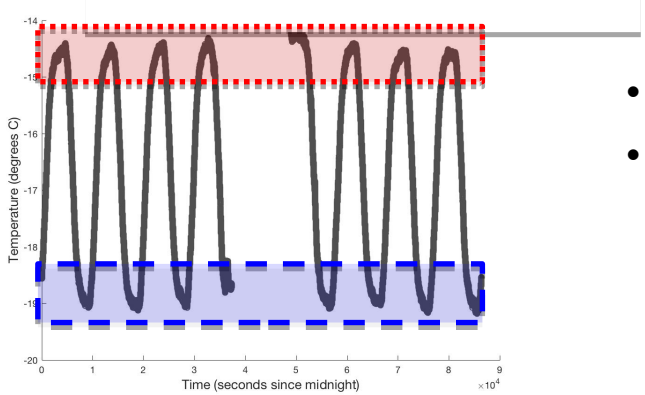


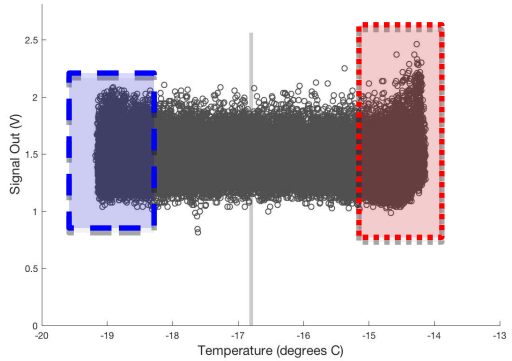


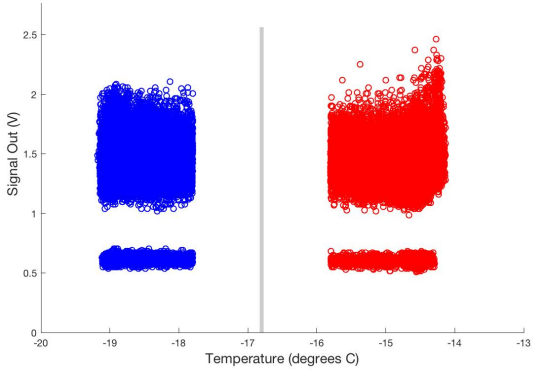
$$A_{corr} = A - A^* \qquad B_{corr} = B - B^*$$

Transition temperature: -16.8°C
Scattering at 45°, 600 nm

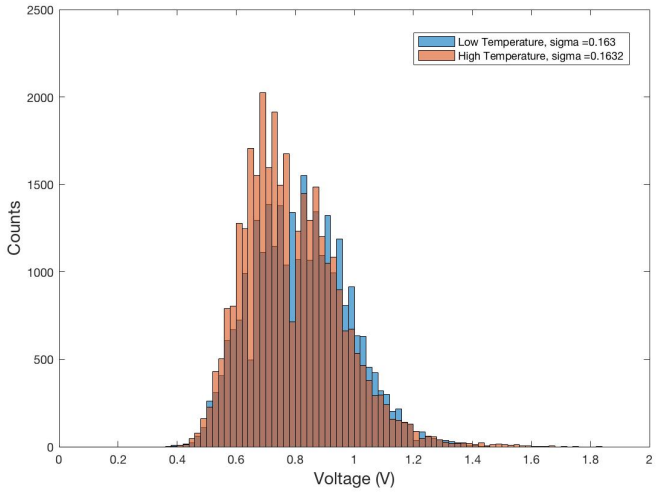
Example experiment:
Tetragonal to β-rhombic transition







- Difference between A_{corr} & B_{corr}: -5%
- Statistical analysis: Two populations have different means at the 5% significance level



Conclusion: We are looking at independent sets of data, one for each crystal structure, and the β-rhombic crystal scatters less light to 45° than Tetragonal

Transition temperature: -16.8°C
Scattering at 45°, 660 nm

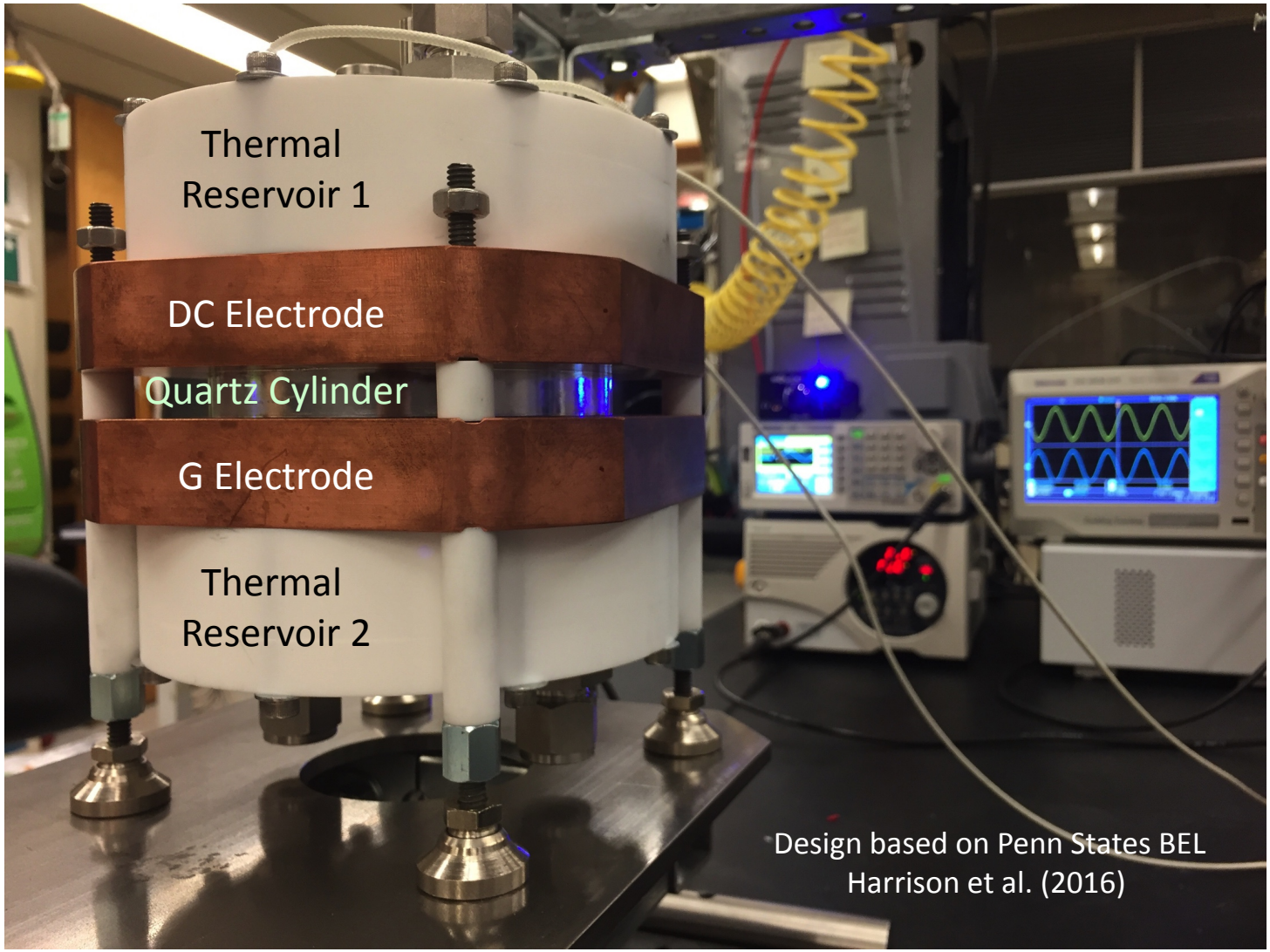
Spherical Void EDB Findings

- *Scattered light at 45°*
  - Tetragonal to β-rhombic *Δ -3.5 to -5%*
  - β-Rhombic to α-Rhombic *Δ +6%*
- *Scattered light at 90°*
  - Tetragonal to β-rhombic *Δ +1%*
  - β-Rhombic to α-Rhombic *Δ -1.5%*

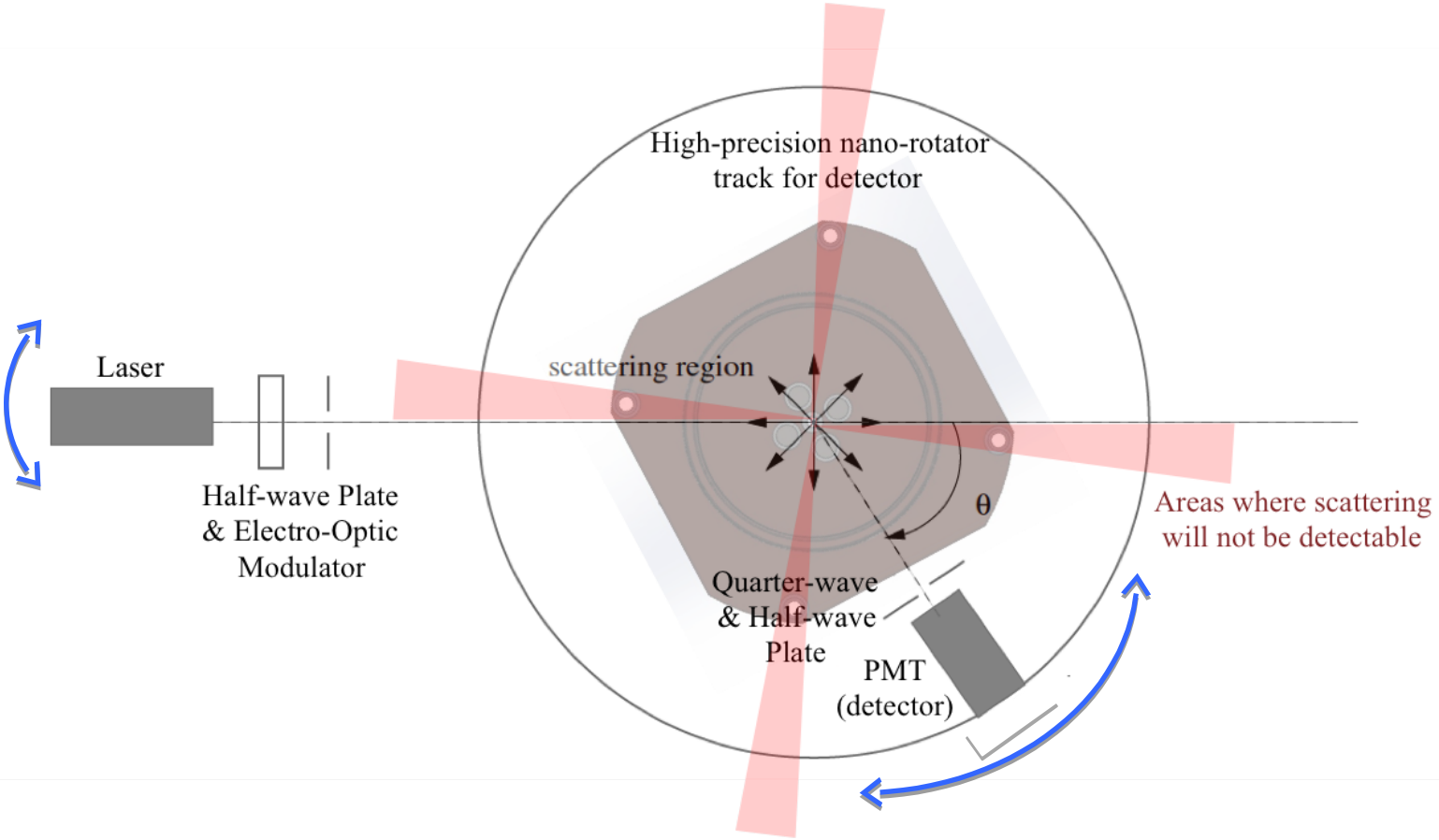
- We see small change in signal, from a small physical change on the single particle basis even at angles where less light is collected overall

- *What we need now…*
  Collection of scattered light at more angles

Thermal Gradient EDB

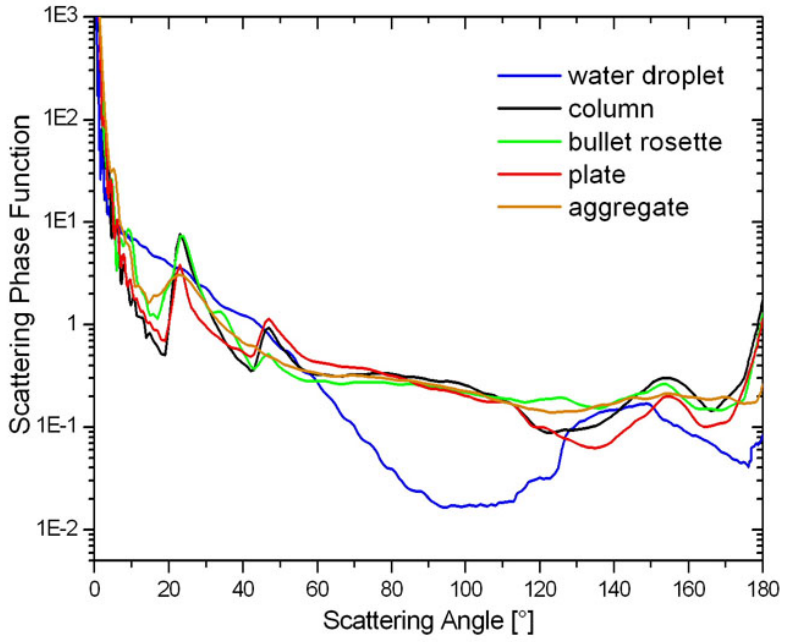


Scattering *and Polarization*



Bench Tests

Modeled Scattering phase functions



ene Latex Spheres - 500 nm

With polarization measurements…

$$\mathbf{S}' = \begin{bmatrix} s_0' \\ s_1' \\ s_2' \\ s_3' \end{bmatrix} = \mathbf{MS} = \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{20} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} s_0 \\ s_1 \\ s_2 \\ s_3 \end{bmatrix}$$

Thank you!

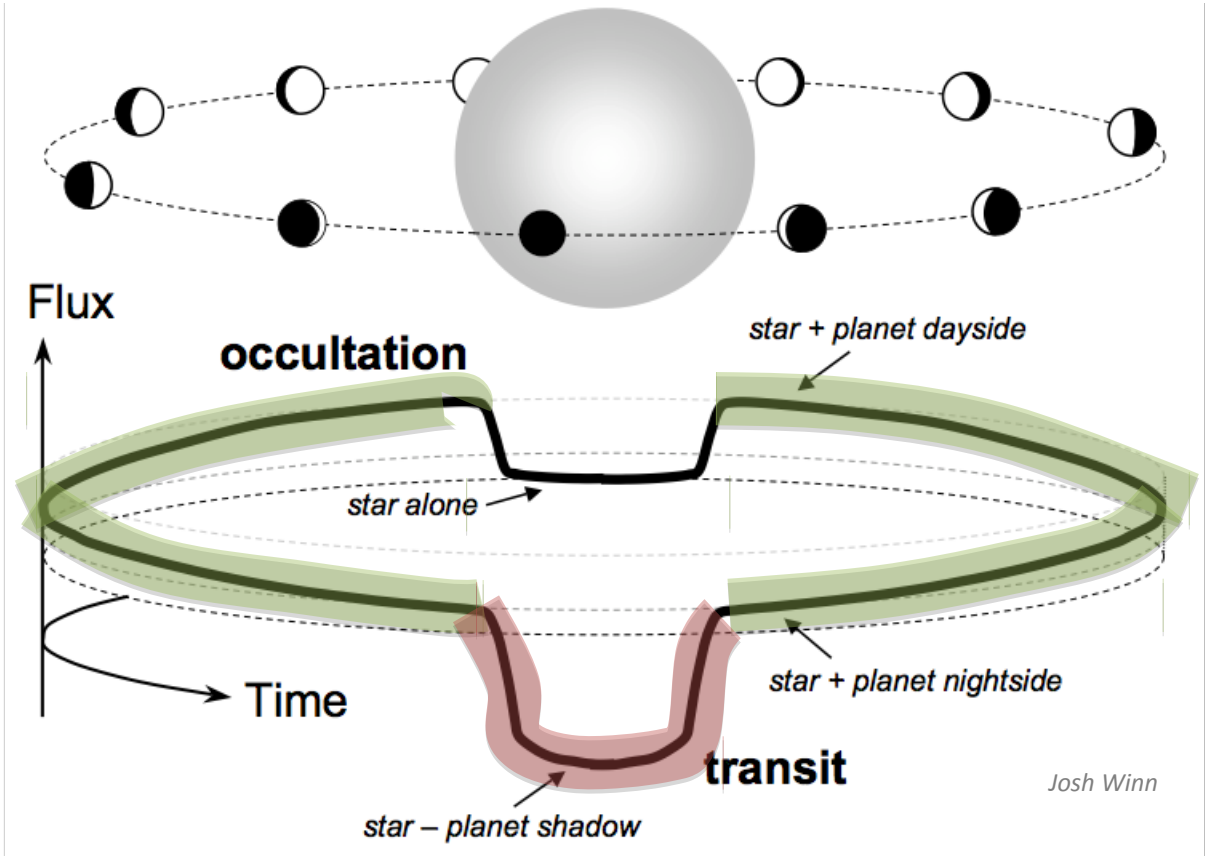
I would like to acknowledge the Cziczo and Seager groups members at MIT, as well as David Charbonneau, David Latham, and those supported by Templeton at Harvard CfA for their guidance and support.

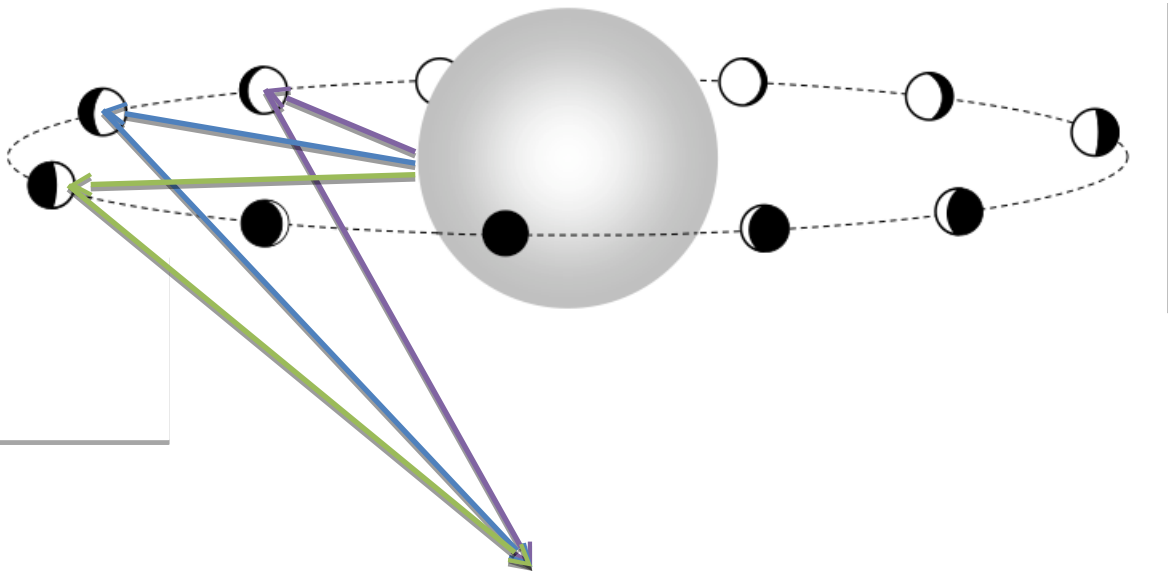
This work is generously funded by:

SIMONS FOUNDATION

JOHN TEMPLETON FOUNDATION

SUPPLEMENTAL MATERIAL


Flux
occultation
star + planet dayside
star alone
Time
star + planet nightside
transit
star – planet shadow
Josh Winn

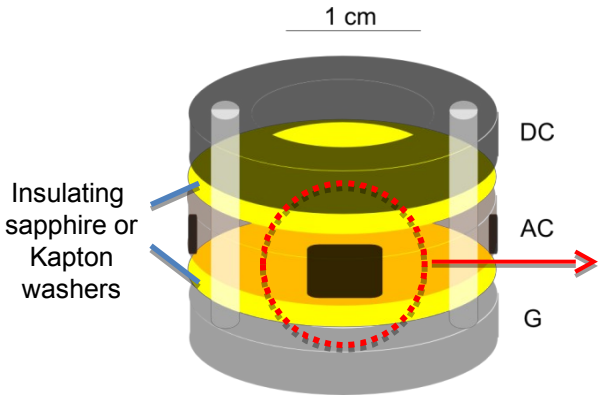


Experiments

- *Procedure*
  - Suspend a **single particle** -- D = 10 to 30 µm
  - **Illuminate particle** -- 660 nm
  - **Scan temperature**
  - **Monitor particle**
  - **Measure scattered light** with PMT -- 45°
  - **Drop particle & scan temperature** -- Background scatter

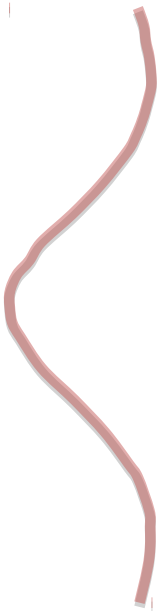
- *Repeat* – New particles, new conditions

Electrodynamic Balance

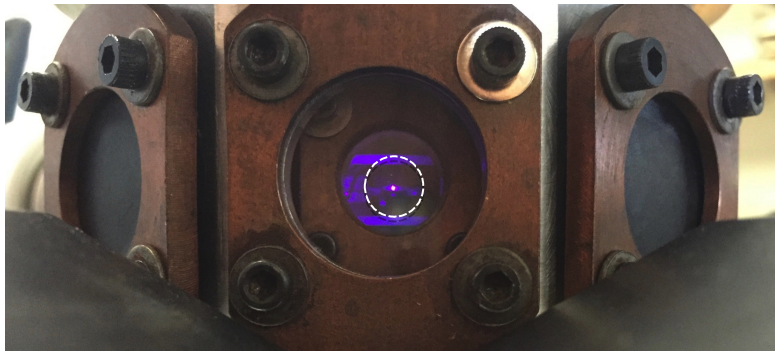


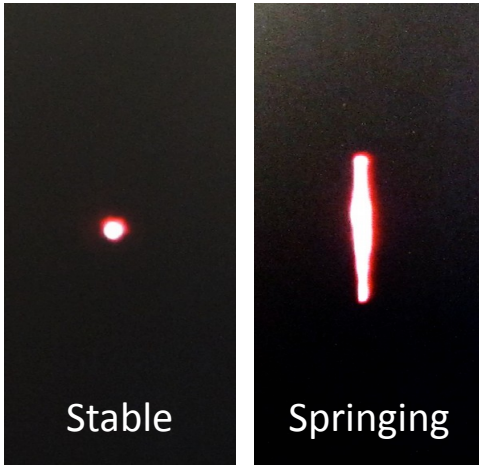
1 cm^3 spherical void

S. Berlin (2014)

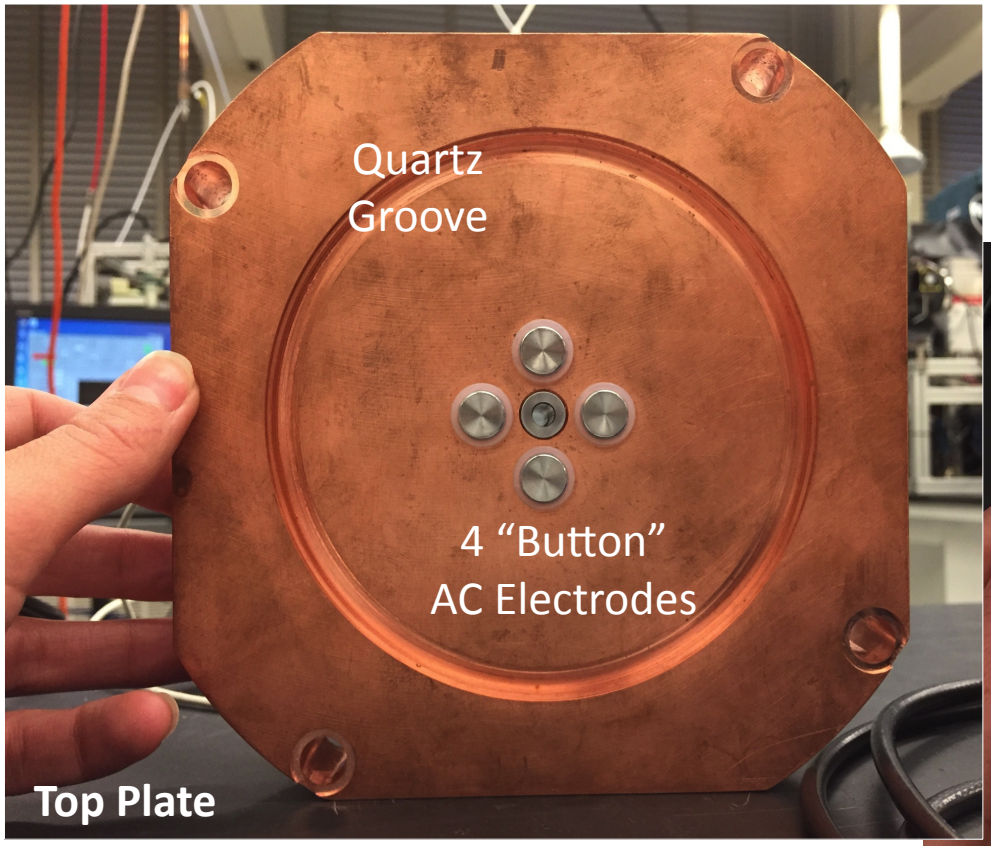


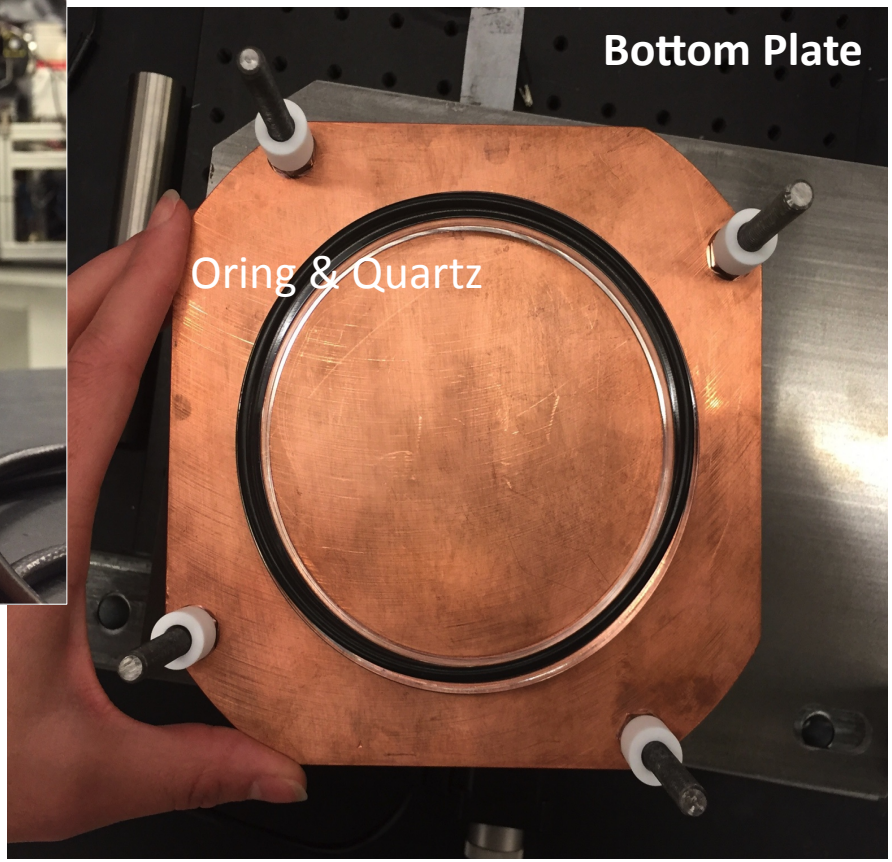
Arnold & Folan (1987)





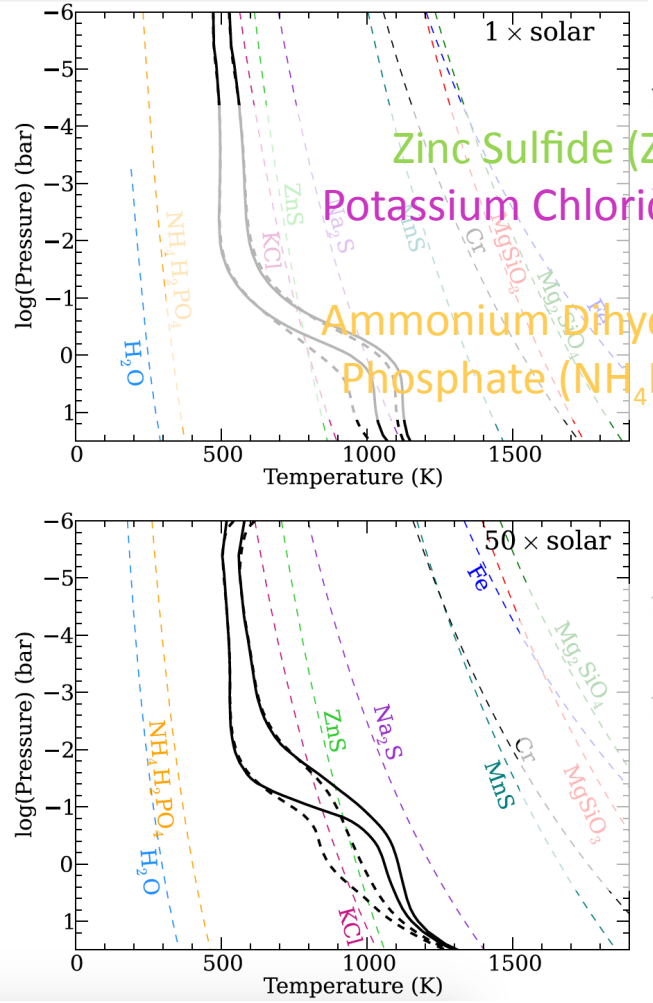
The Future is Now





Exoplanet Aerosols

Morley et al. (2014)

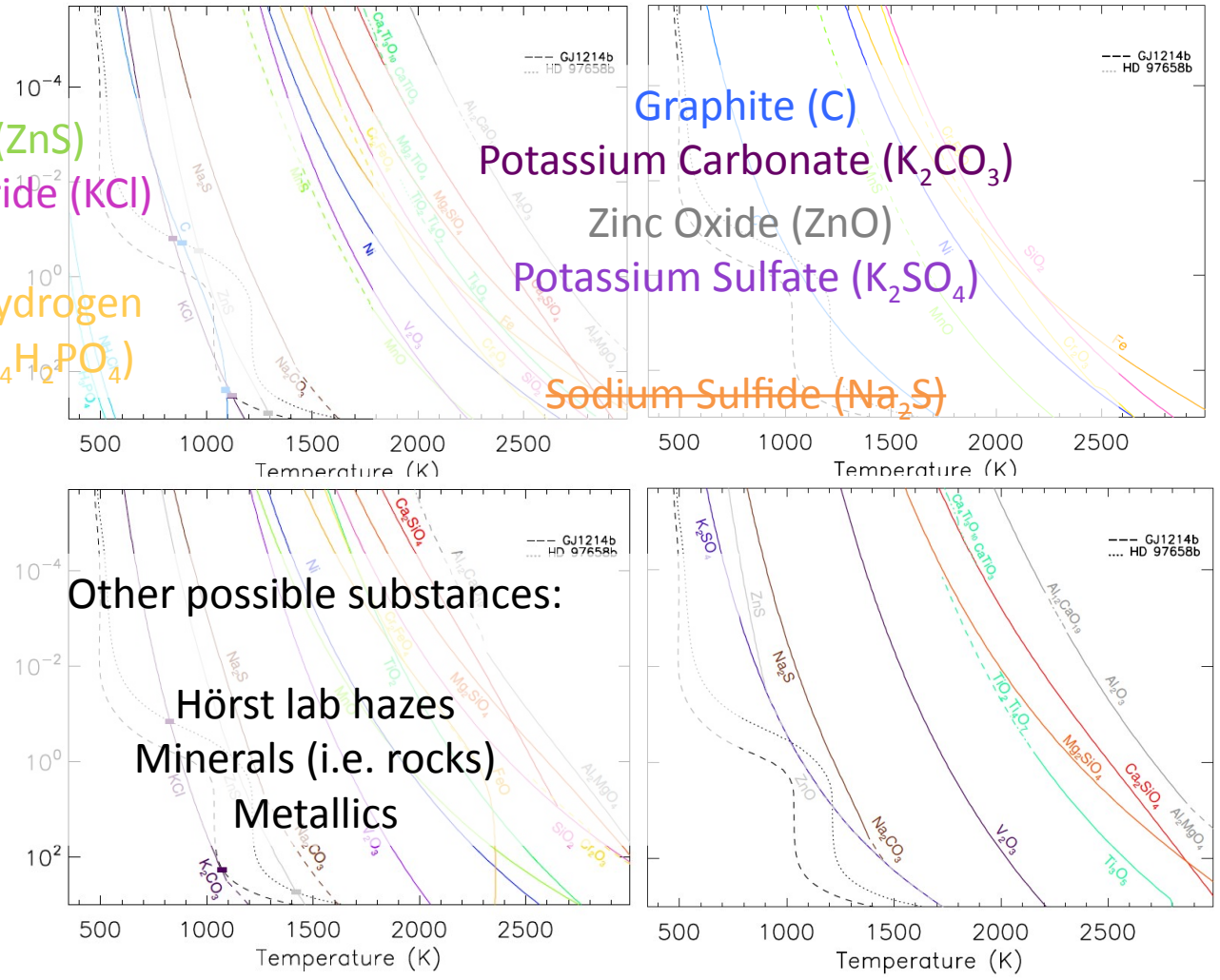


Zinc Sulfide (ZnS)

Potassium Chloride (KCl)

Ammonium Dihydrogen Phosphate ($NH_4H_2PO_4$)

Mbarek & Kempton (2016)



Graphite (C)

Potassium Carbonate (K_2CO_3)

Zinc Oxide (ZnO)

Potassium Sulfate (K_2SO_4)

~~Sodium Sulfide (Na_2S)~~

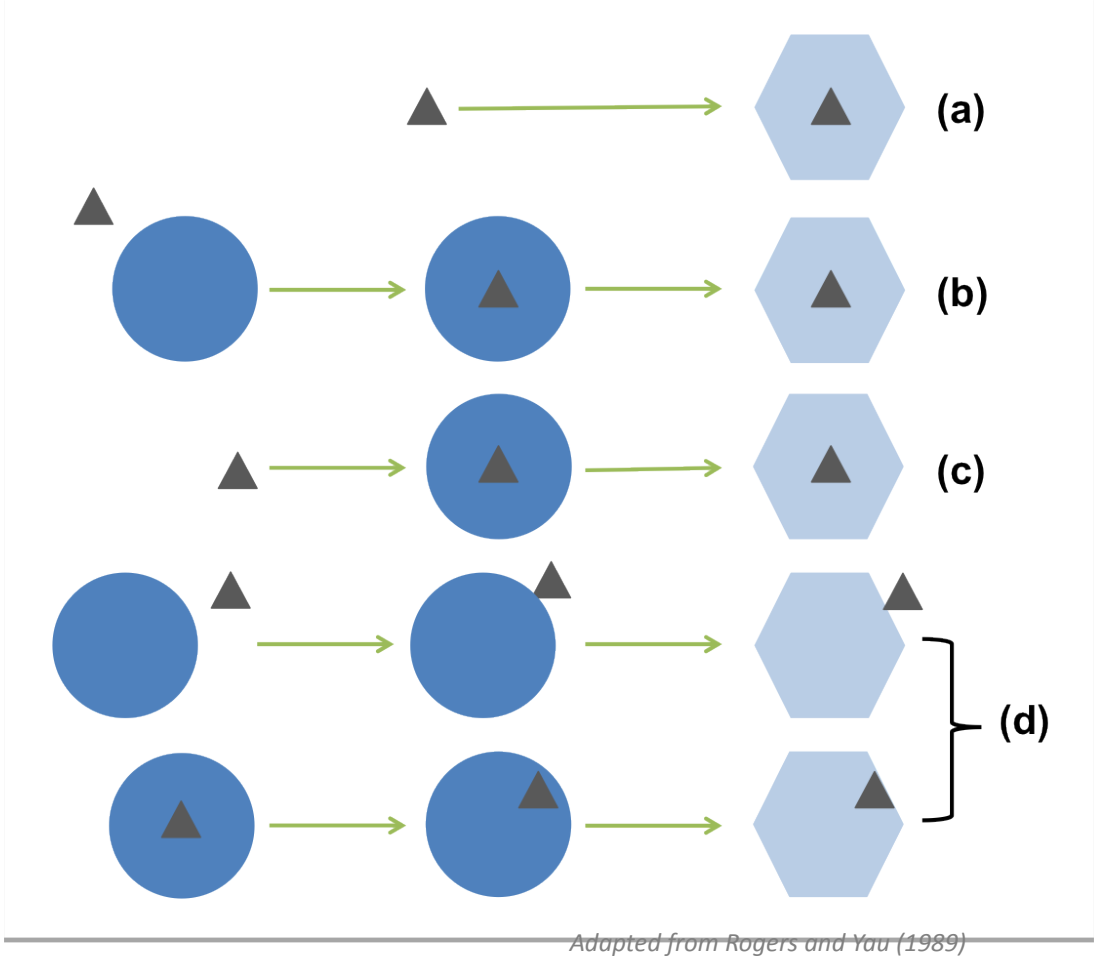
Other possible substances:

Hörst lab hazes

Minerals (i.e. rocks)

Metallics

Heterogeneous Nucleation



Adapted from Rogers and Yau (1989)