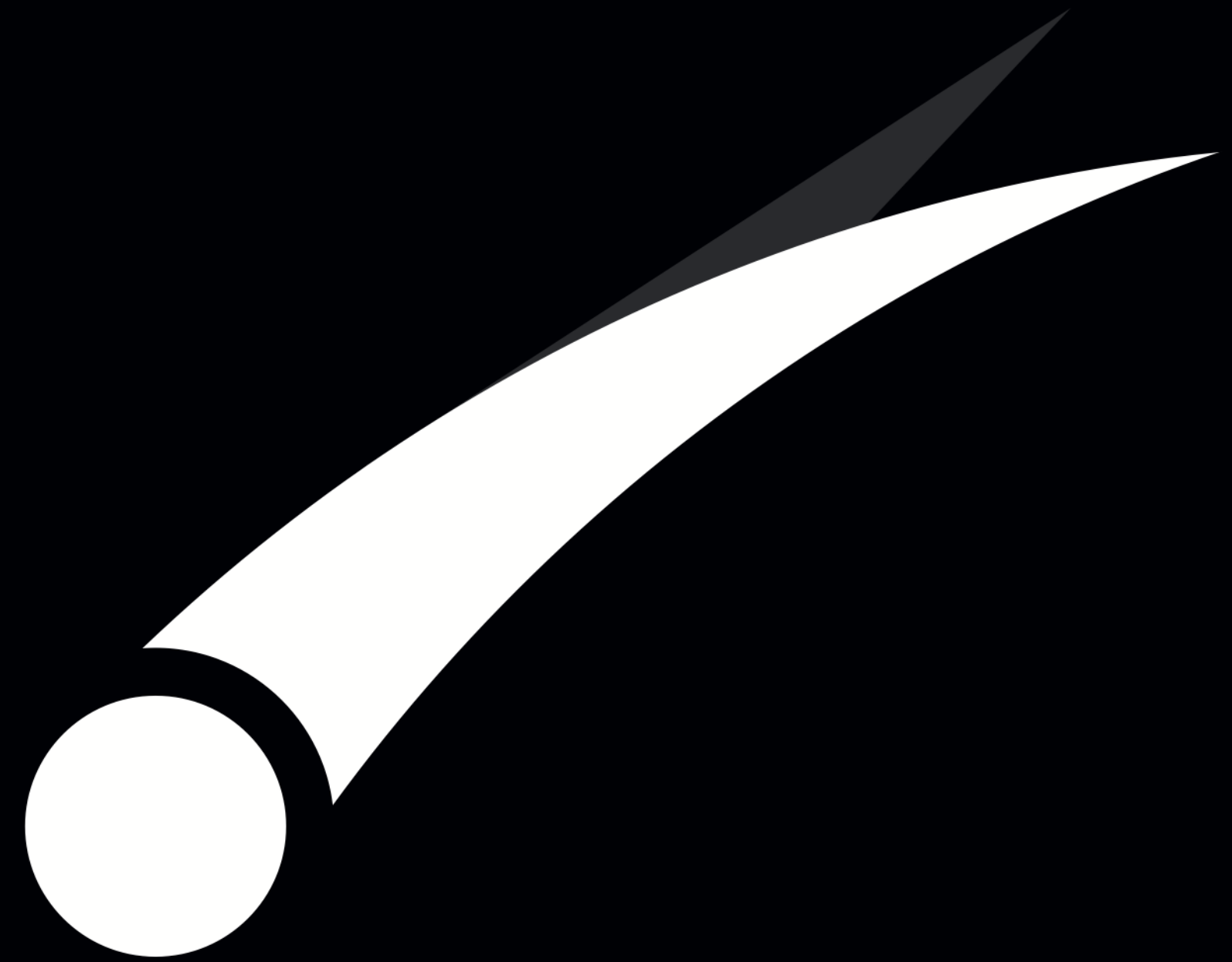


An Approach to Challenging Pebble Accretion

using THz Spectroscopy

Linus Leo Stöckli



General Assembly swissvacuum
25.6.2026

Physikalisches Institut der Universität Bern

u^b

b
**UNIVERSITY
OF BERN**

How did you get here?

4.6 billion years ago...

- Collapse of Molecular Cloud
- Protoplanetary Disk
- Gas, Ice and Dust
- Planetary Formation



Artist's Concept

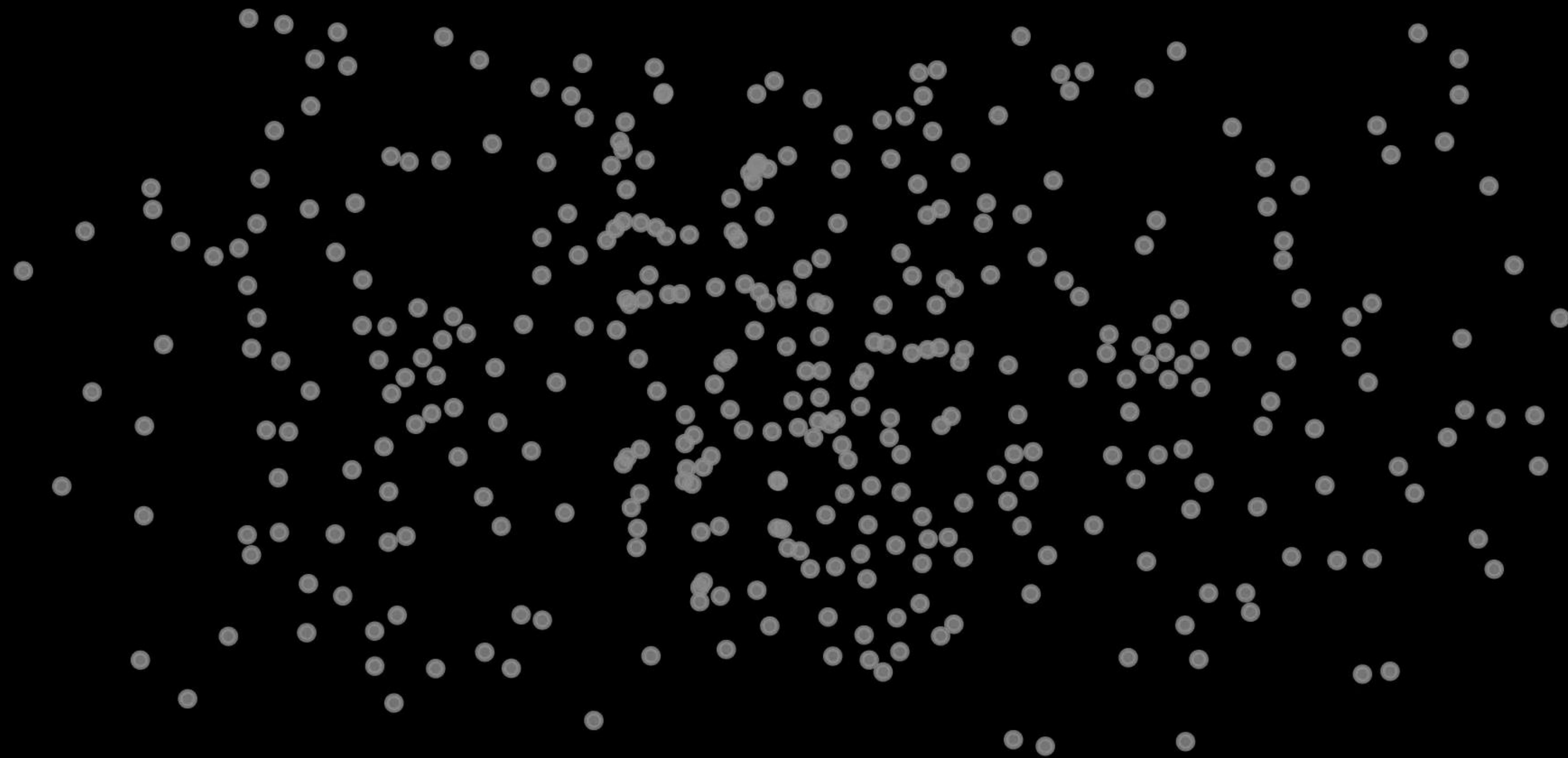
Illustration: NASA-JPL

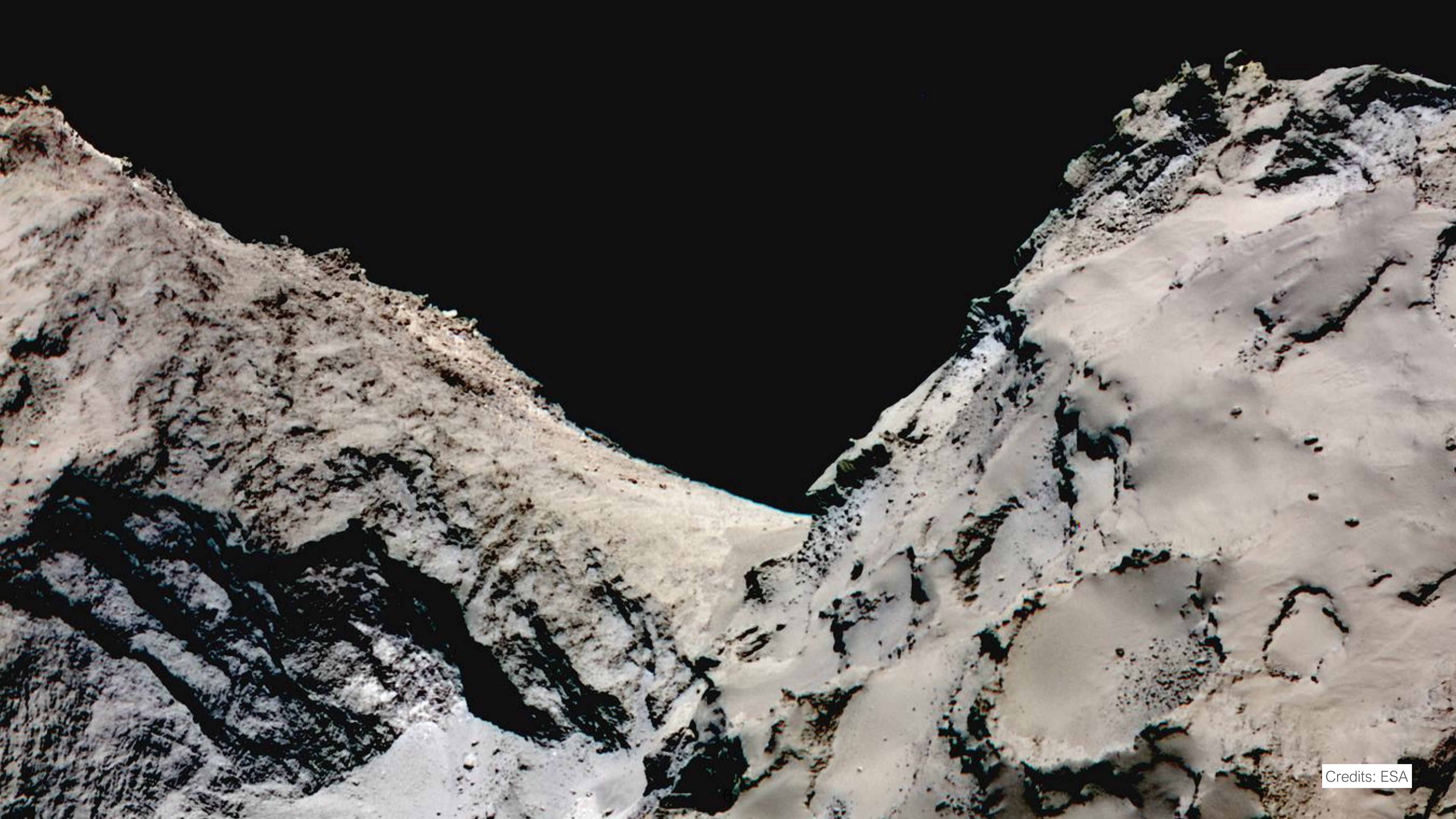
Classical Hierarchical Growth

- Hierarchical accumulation of small micrometer sized particles
- Slow

Pebble Accretion

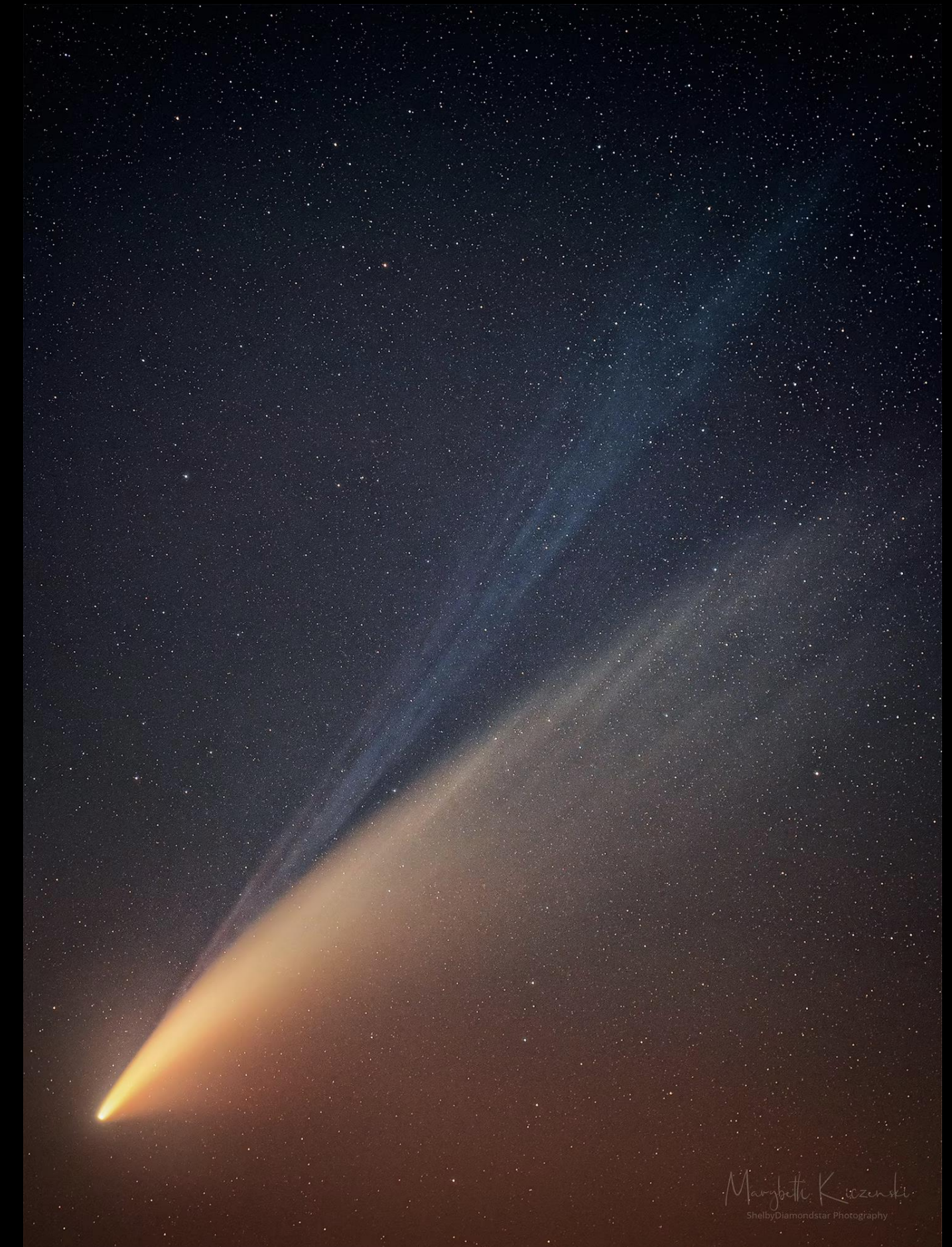
- Hierarchical accumulation of small micrometer sized particles
- After centimeter sized pebbles form, they collapse to form planetesimals
- Fast





Comets

- Remnants of the early days of planetary formation
- Highly elliptical orbits
- Dust (Organics, silicates)
- Ice (H_2O , CO_2 , CO)

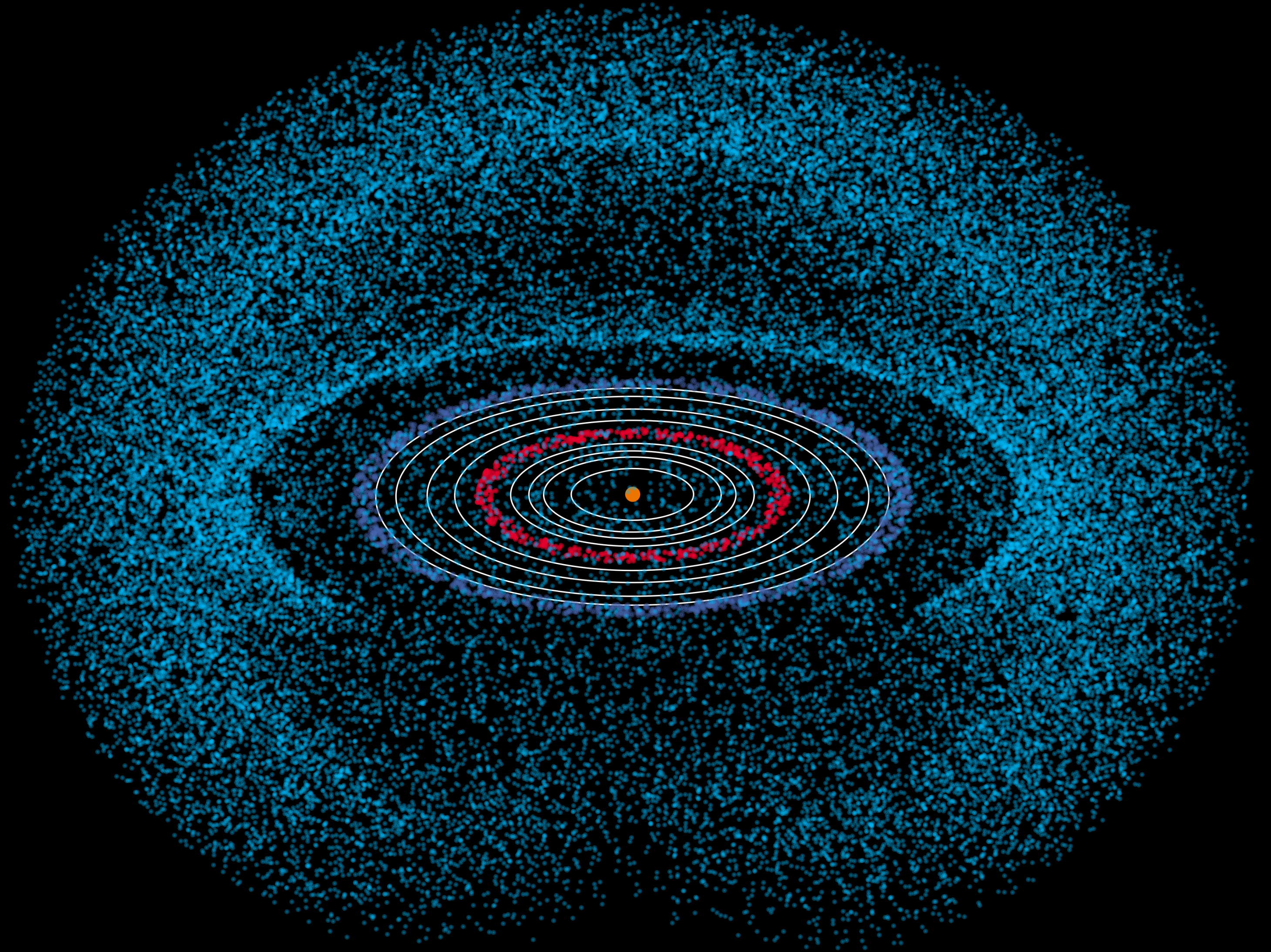


Photograph: Shelbydiamondstar Photography

Comets

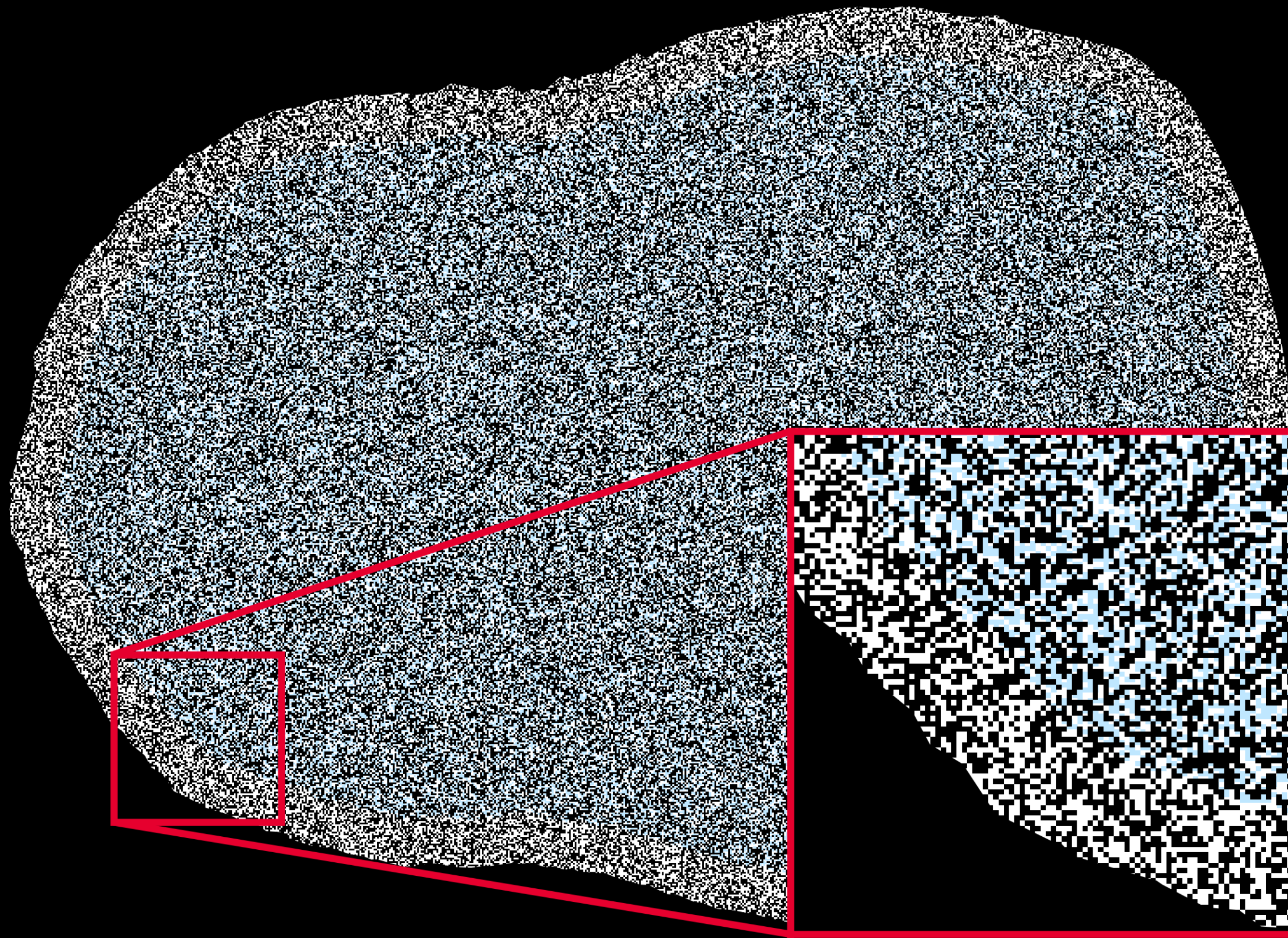
Origin

- Oort Cloud
- Kuiper Belt
- Asteroid Belt

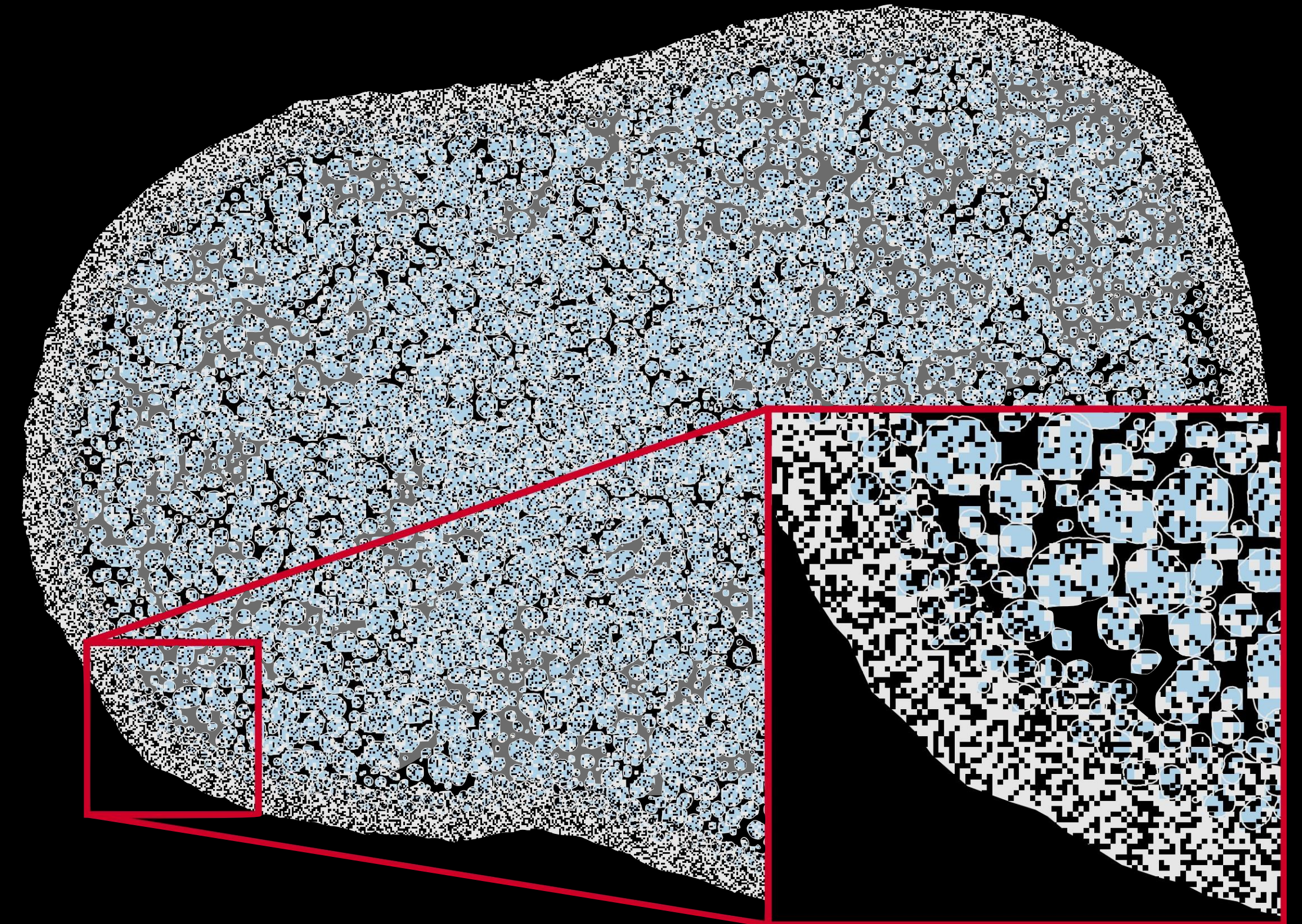


Comets

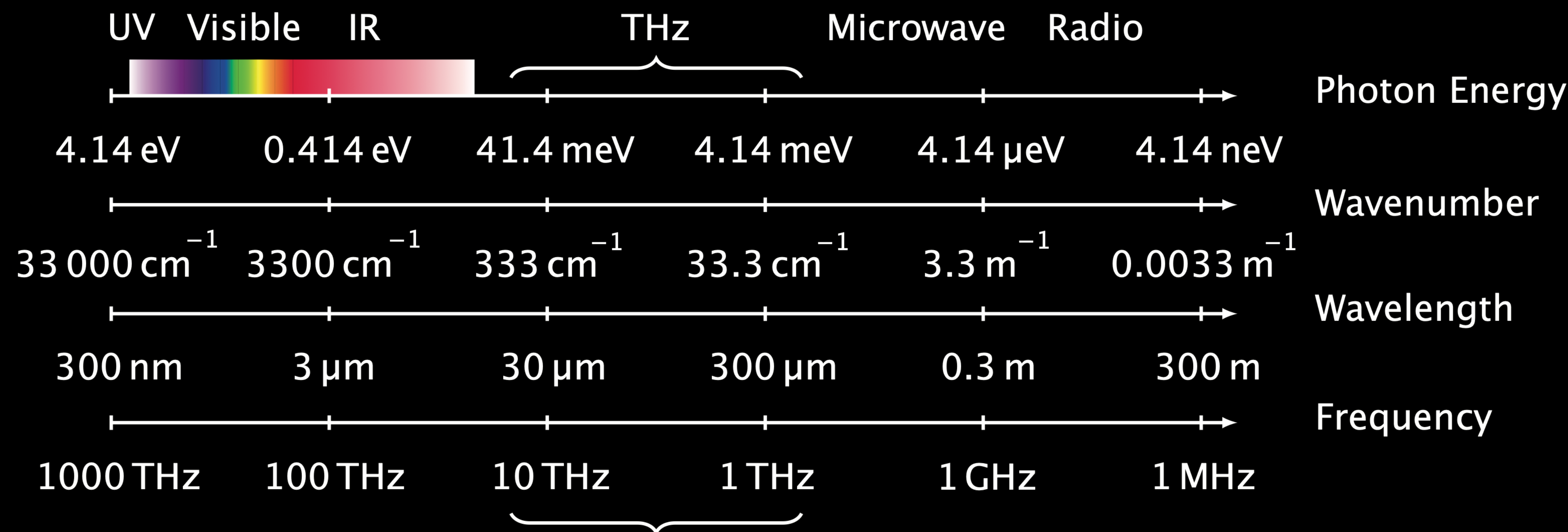
Classical Hierarchical Growth



Pebble Collapse

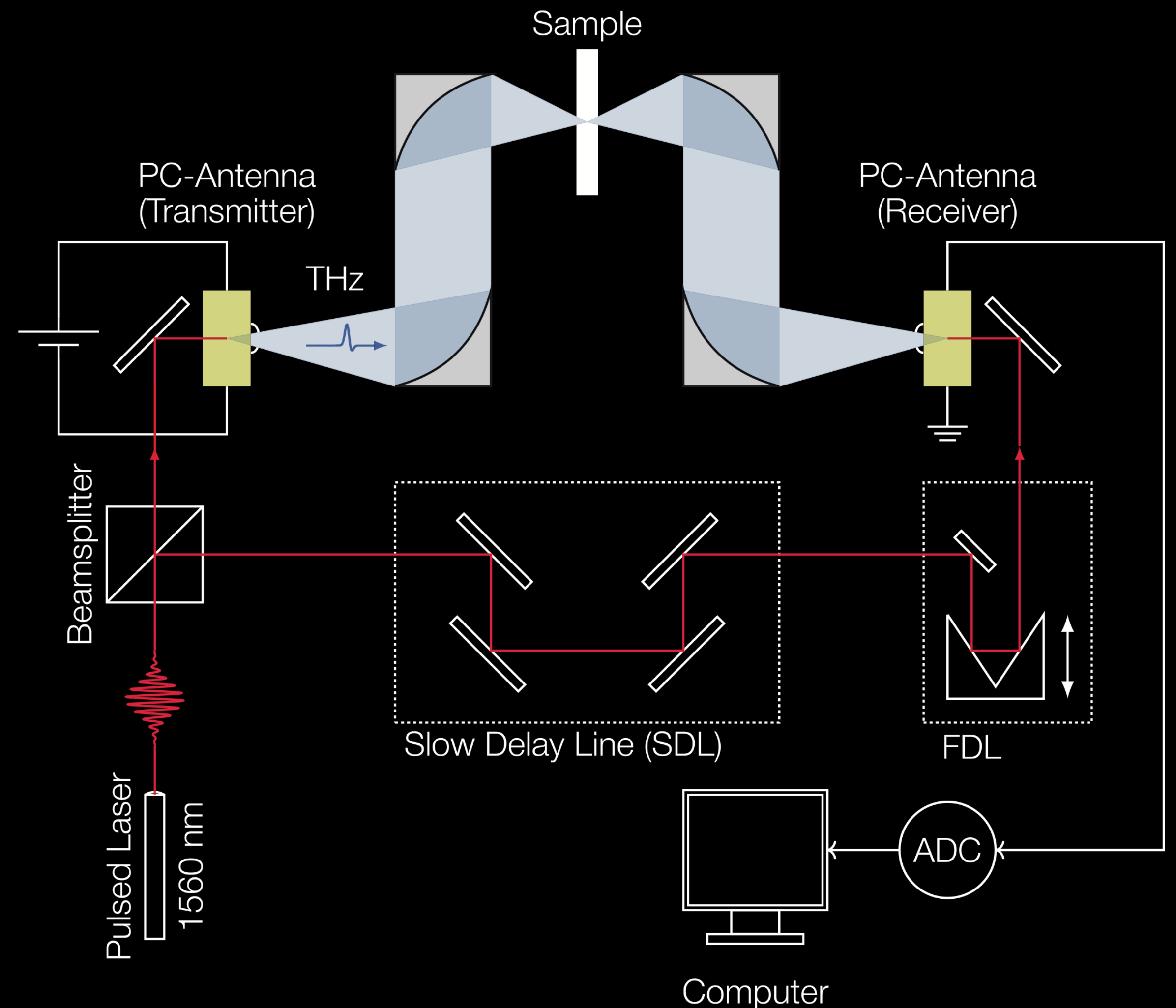


Exploration



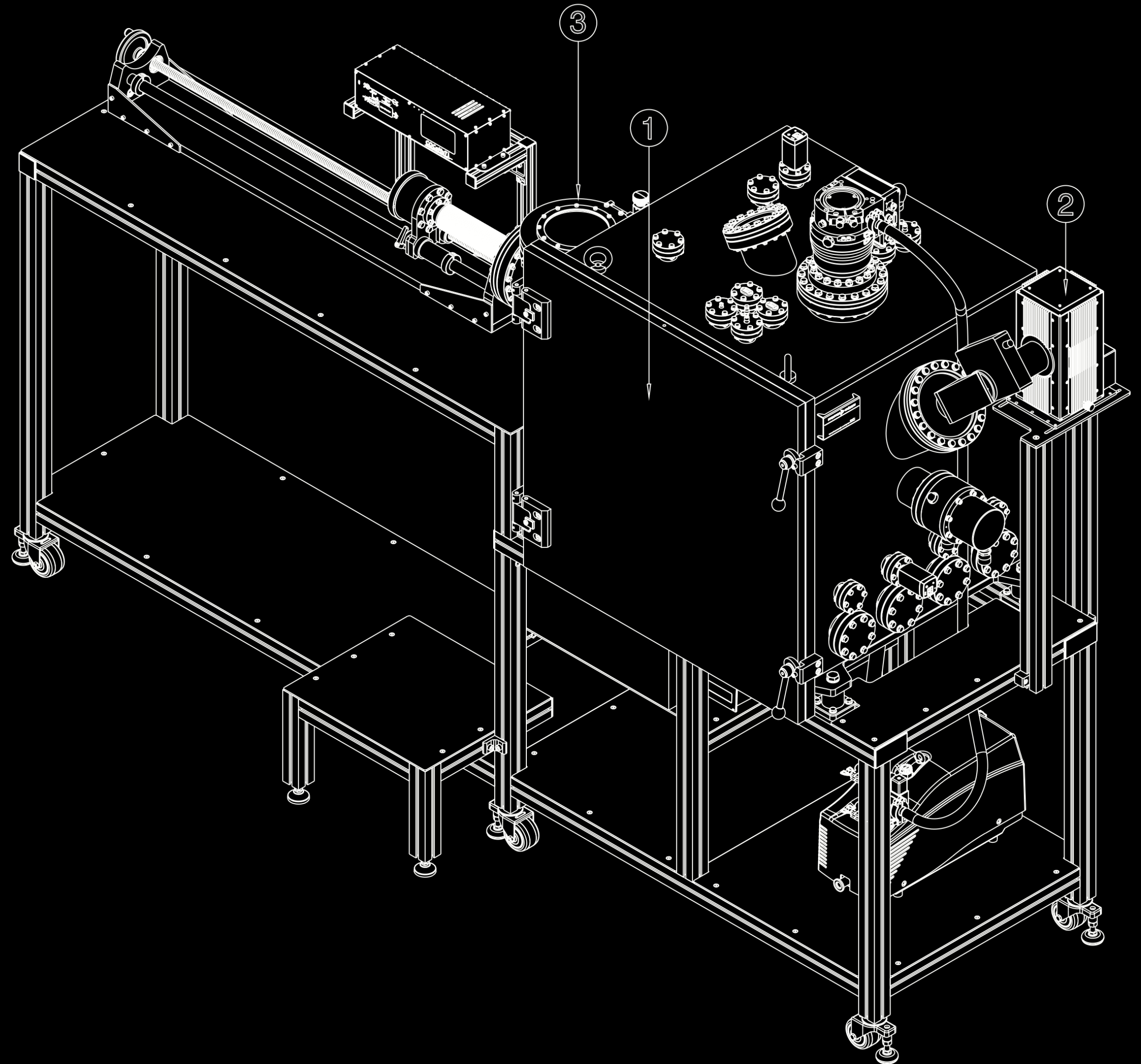
THz Spectrometer

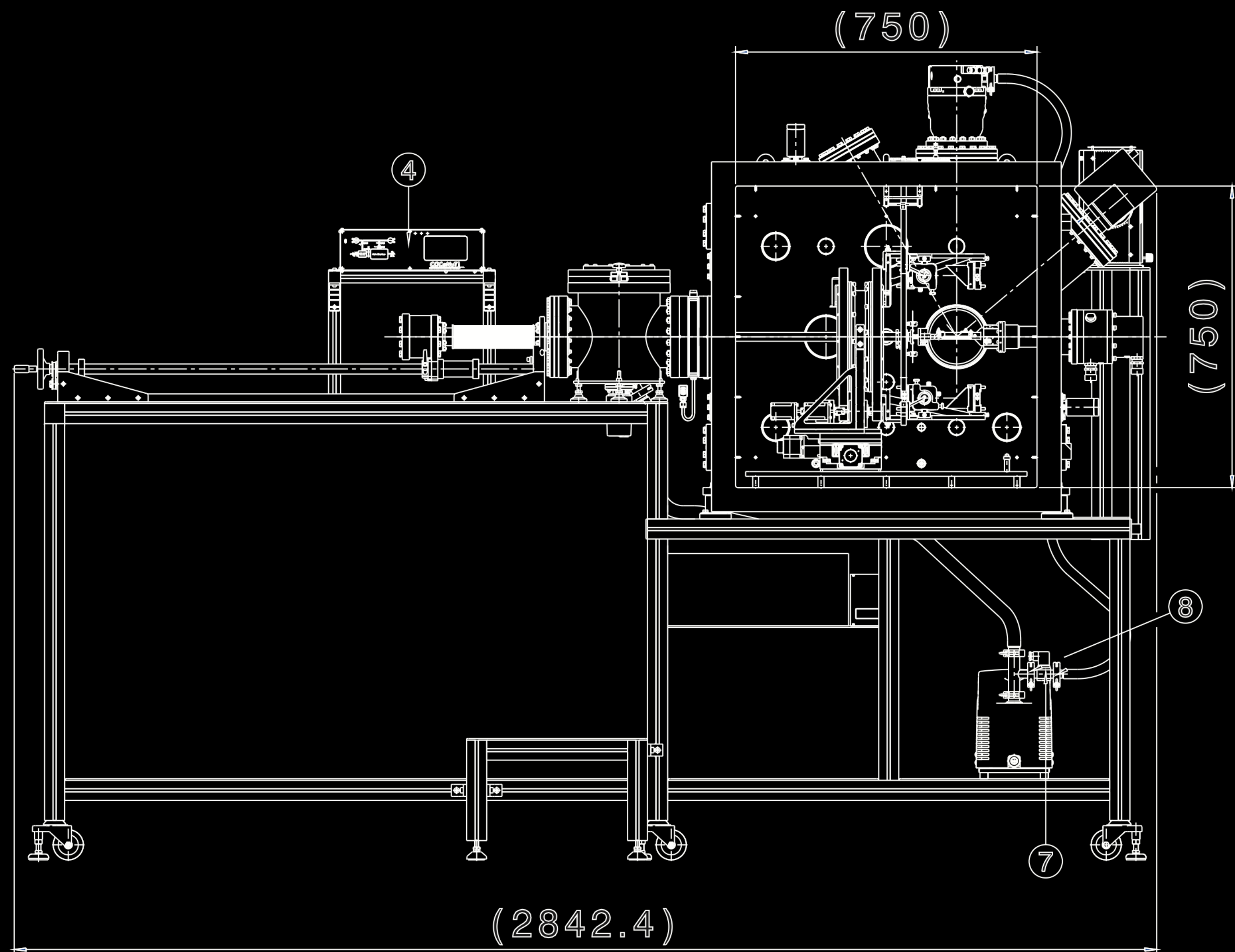
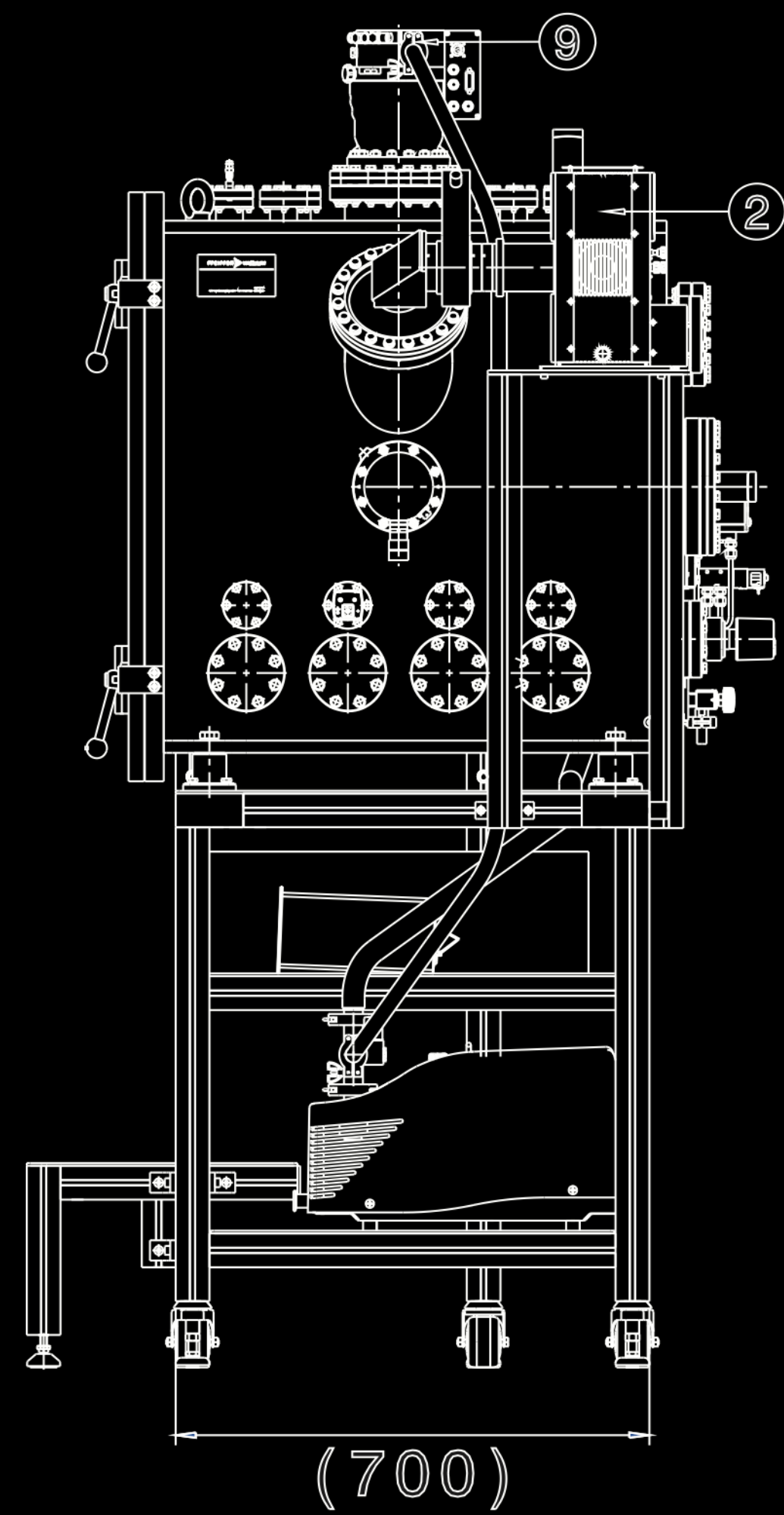
- Pulsed Laser (fs)
- Photoconductive Antennas
- Slow Delay Line
- Fast Delay Line



COCO NuT

*Characteristic Observation of
Cometary Nuclei using THz
spectroscopy*



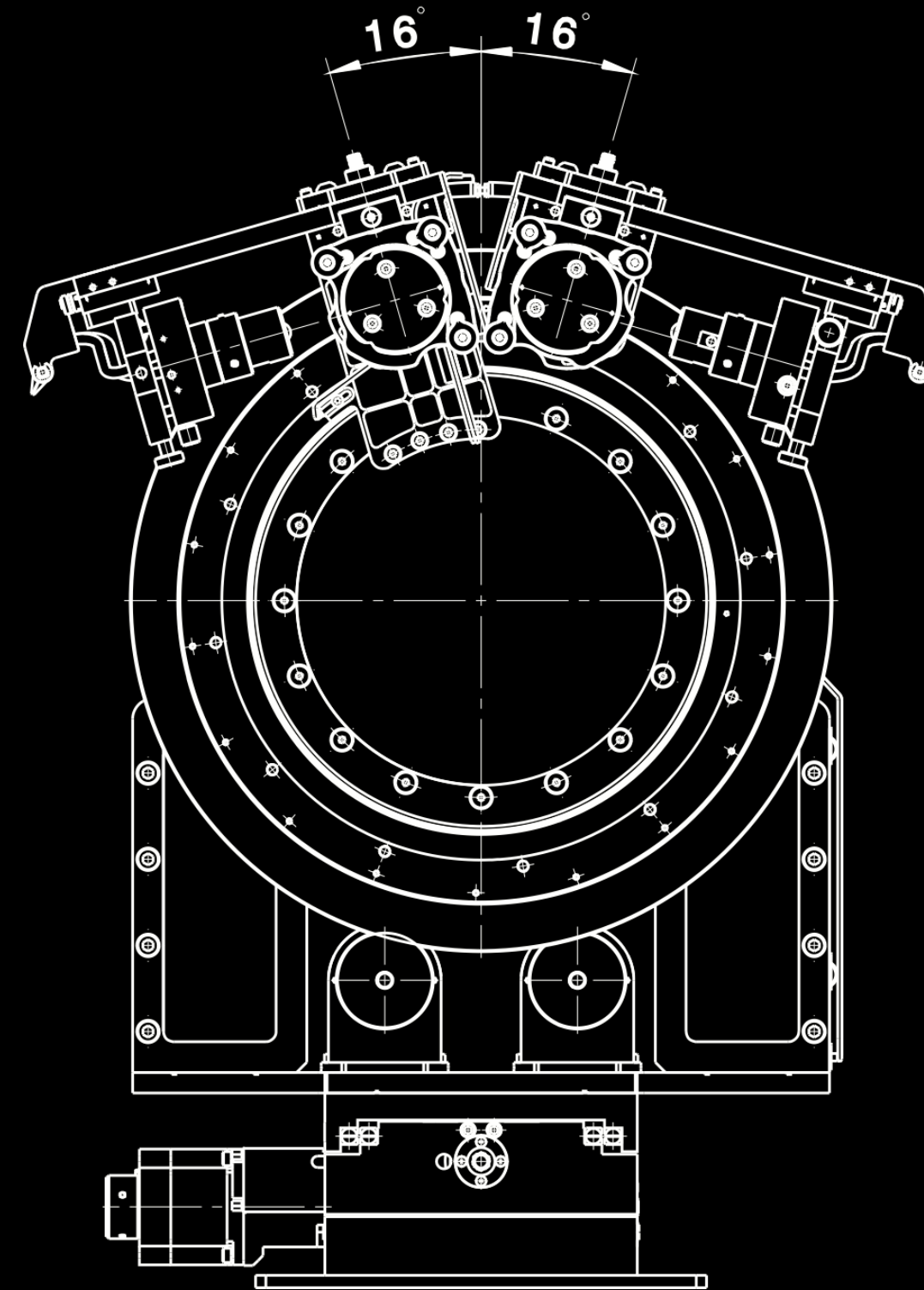


Design

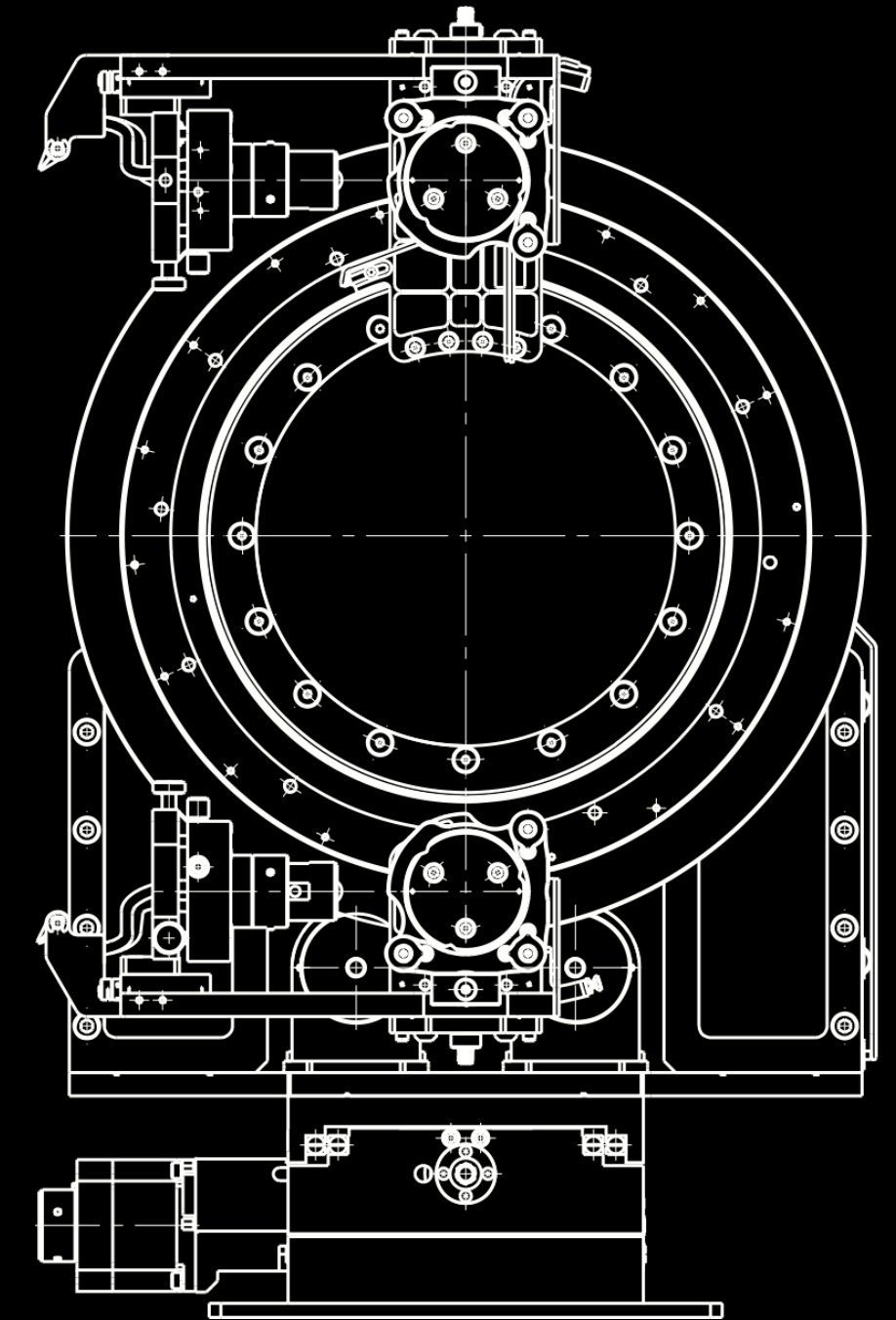
Spectro - Goniometer

- $32^\circ - 180^\circ$, 0.5° steps
- 104 mm x 104 mm, 0.01 mm steps

Reflection Mode



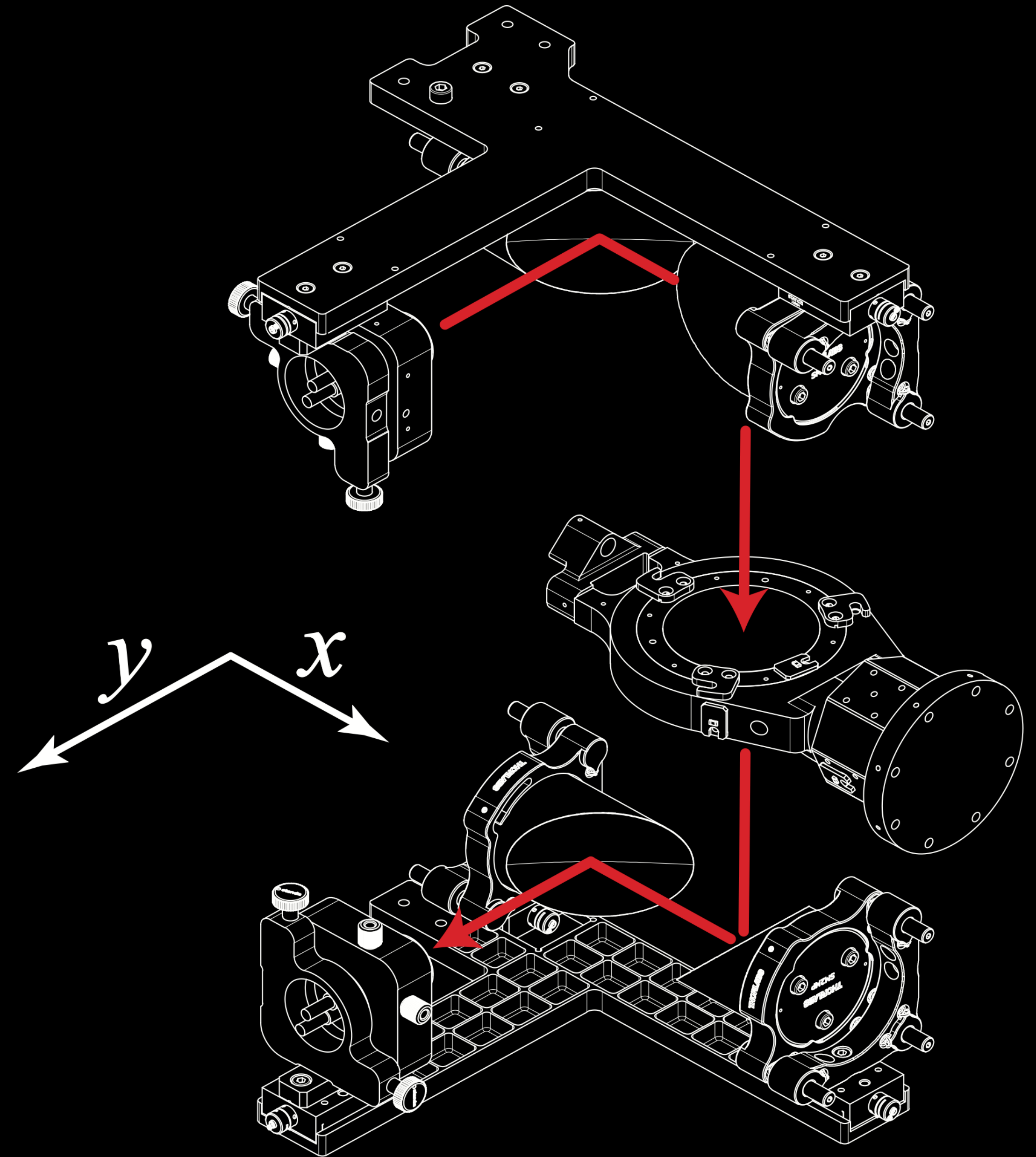
Transmission Mode



Design

Spectro - Goniometer

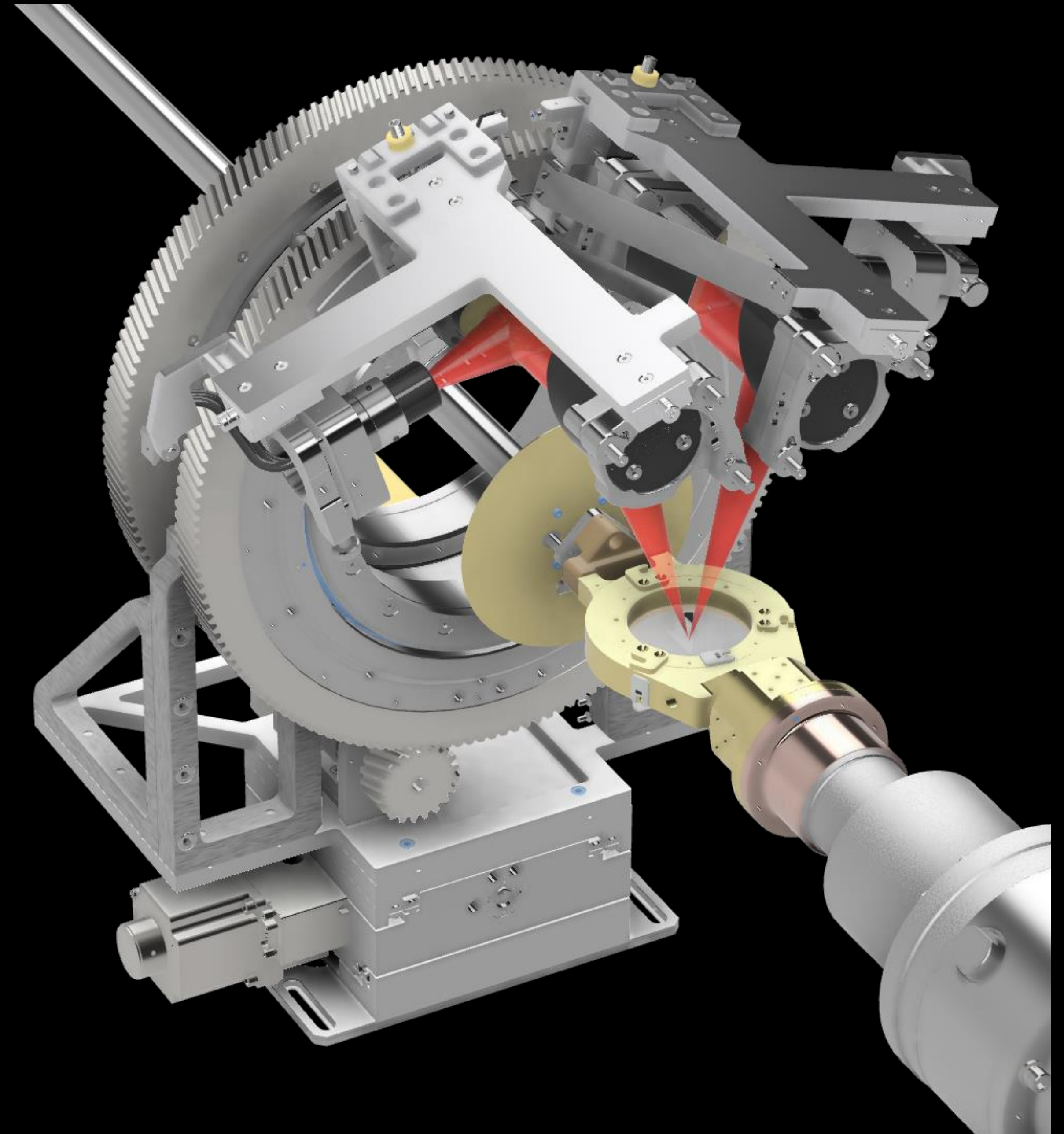
- $32^\circ - 180^\circ$, 0.5° steps
- 104 mm x 104 mm, 0.01 mm steps



Design

Spectro - Goniometer

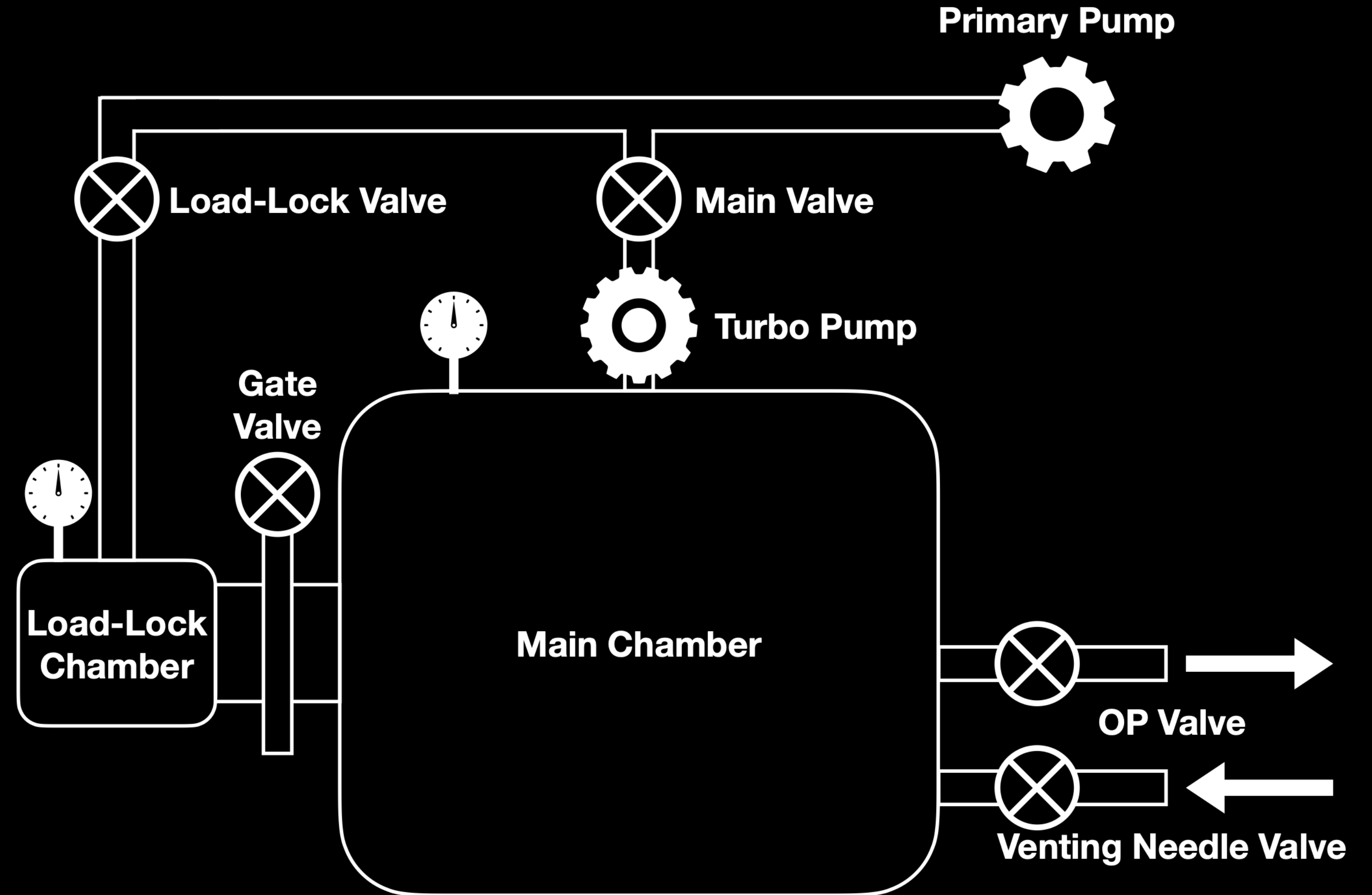
- 32° - 180° , 0.5° steps
- 104 mm x 104 mm, 0.01 mm steps



Design

Vacuum system

- Pfeiffer ACP40
- Turbo HiPace 300
- 2x PKR251



THz Time Domain Spectrometer

Toptica TeraFlash Pro

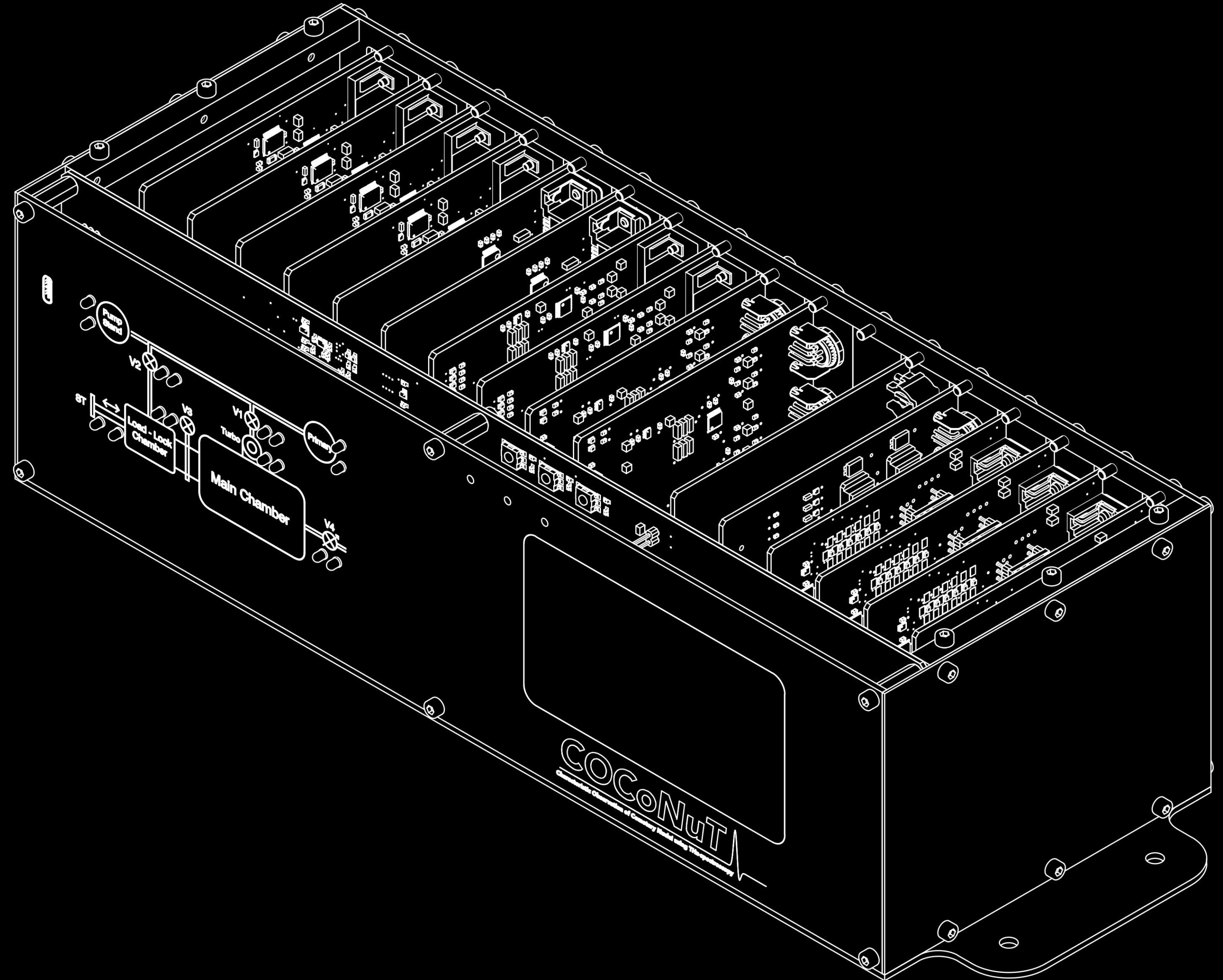
- 0.1 THz - 5.5 THz / 3 mm - 50 μm
- Pulsed fs Laser
 - 1560 nm,
 - 80 MHz rep rate
 - 30 mW
- Photoconductive Antennas
 - InGaAs/InAlAs
 - 70 μW

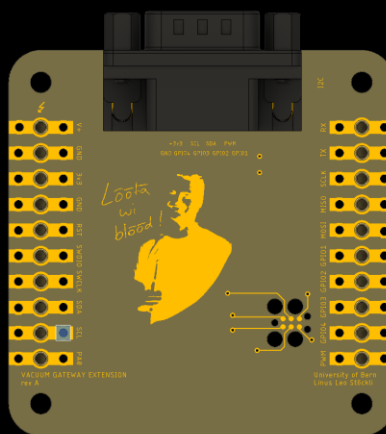
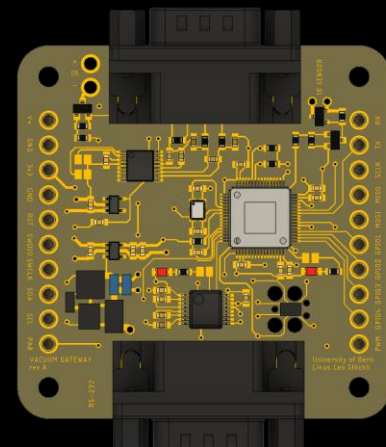
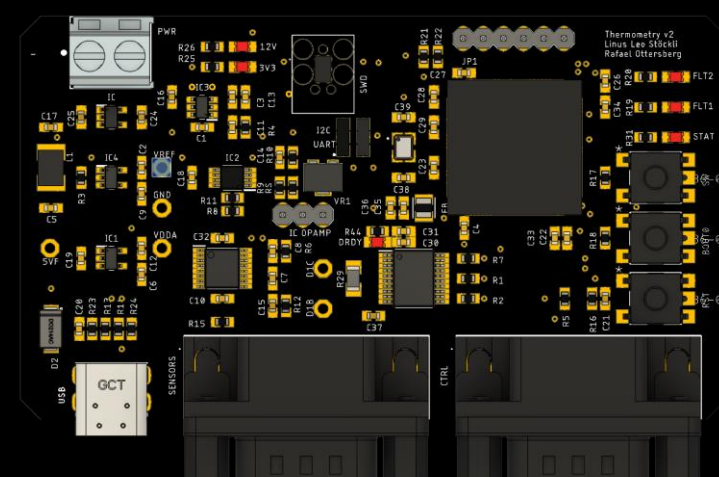
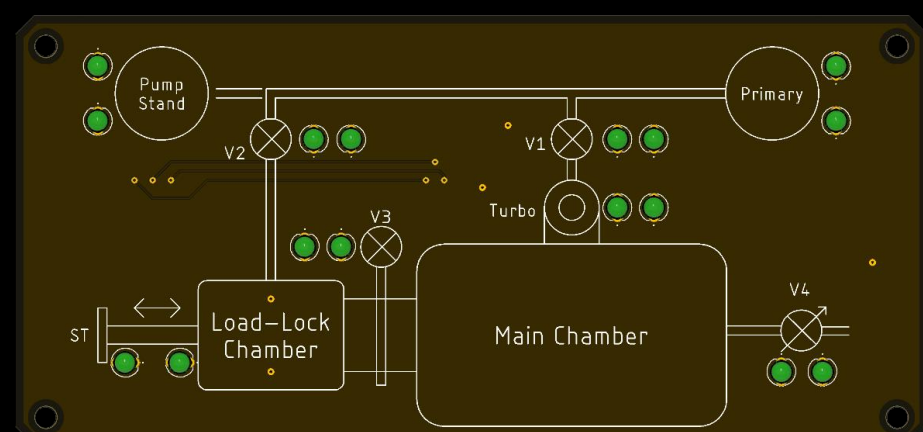
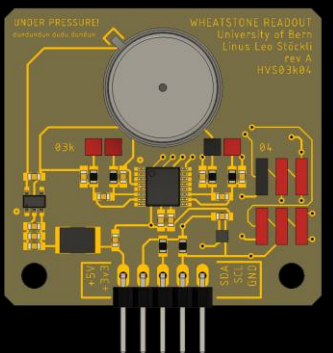
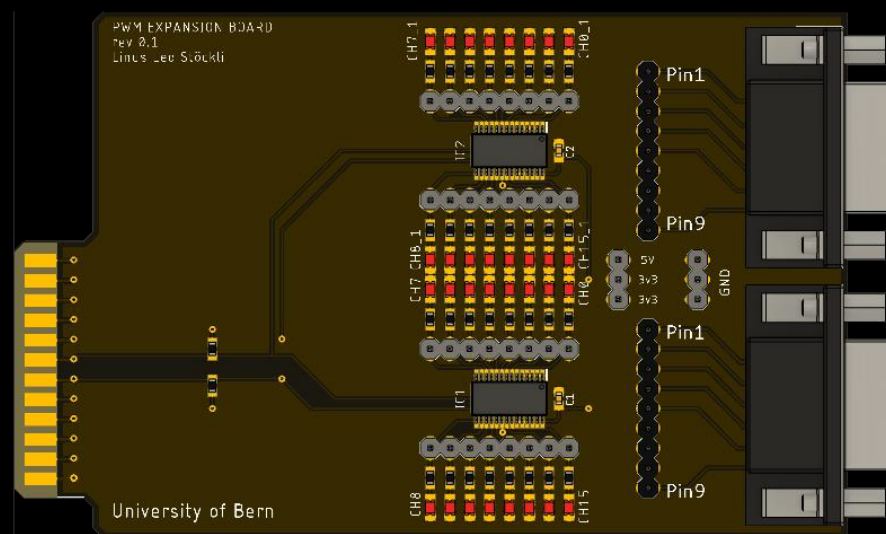
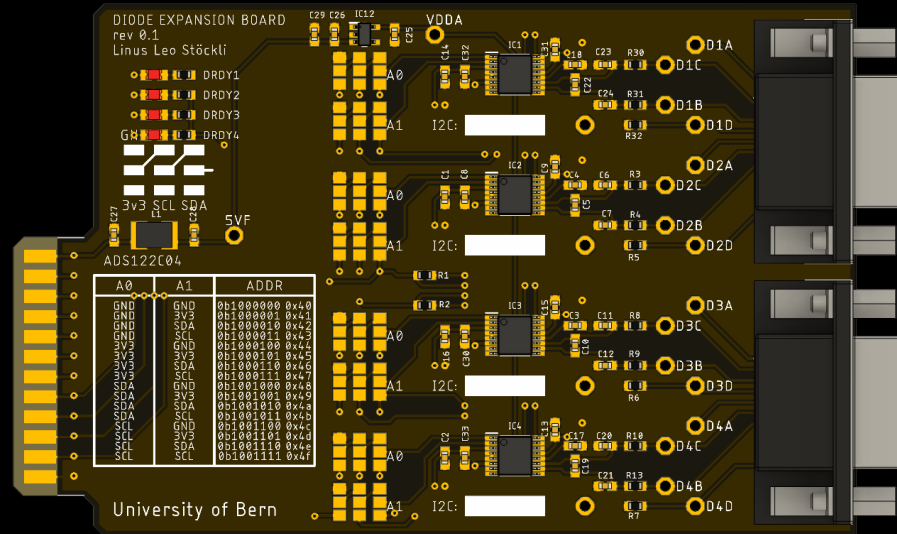
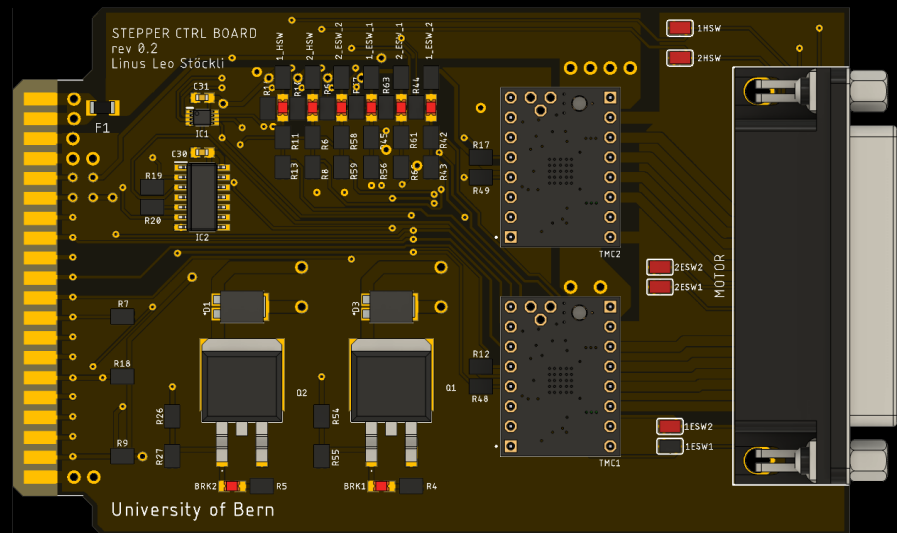
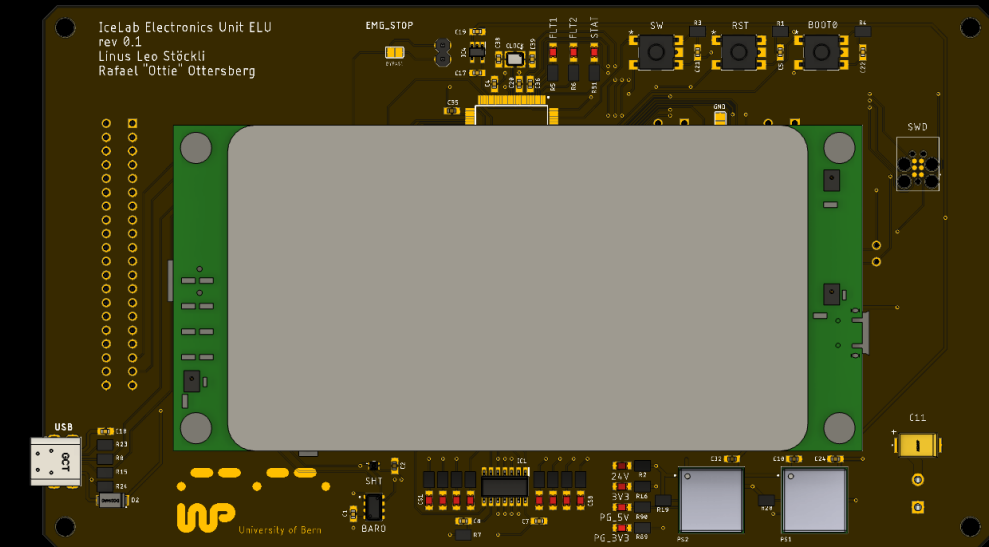
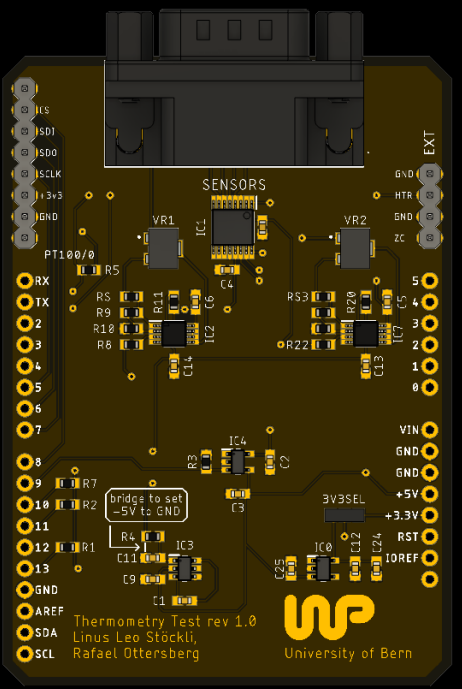
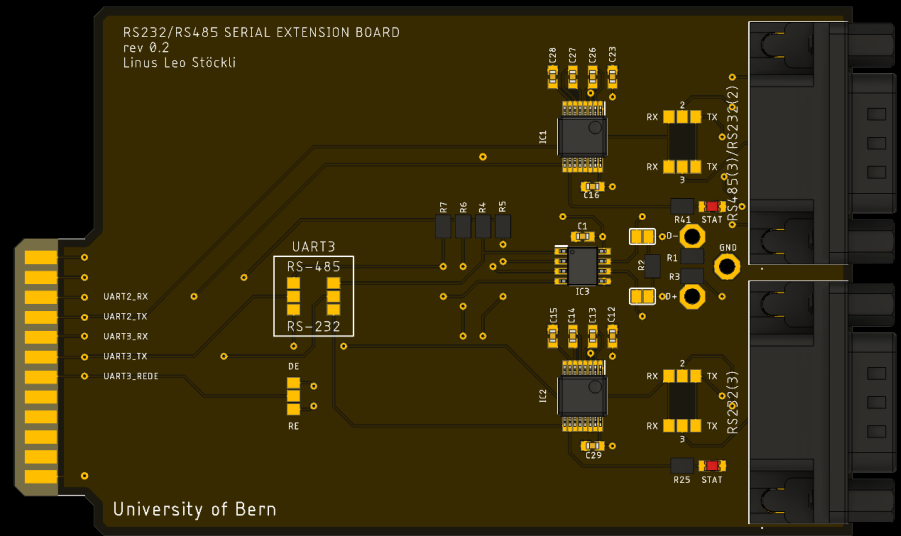
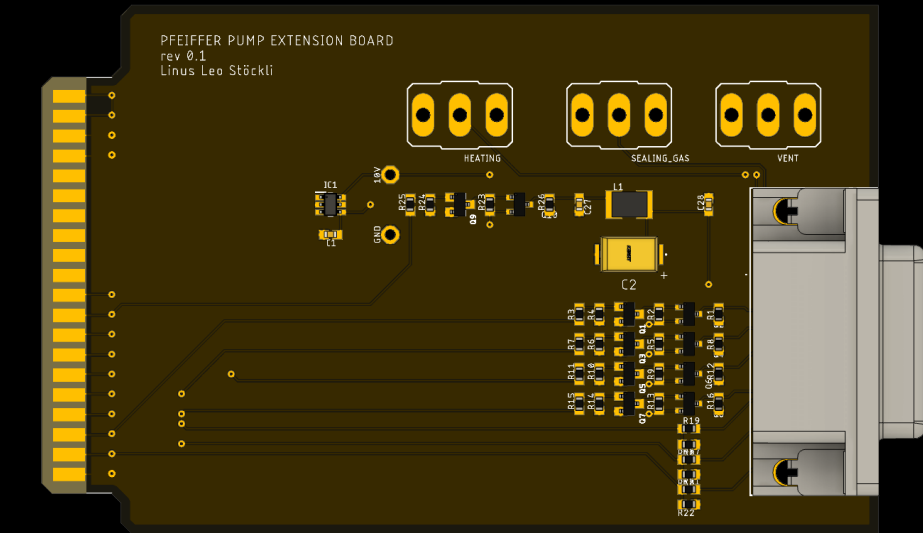
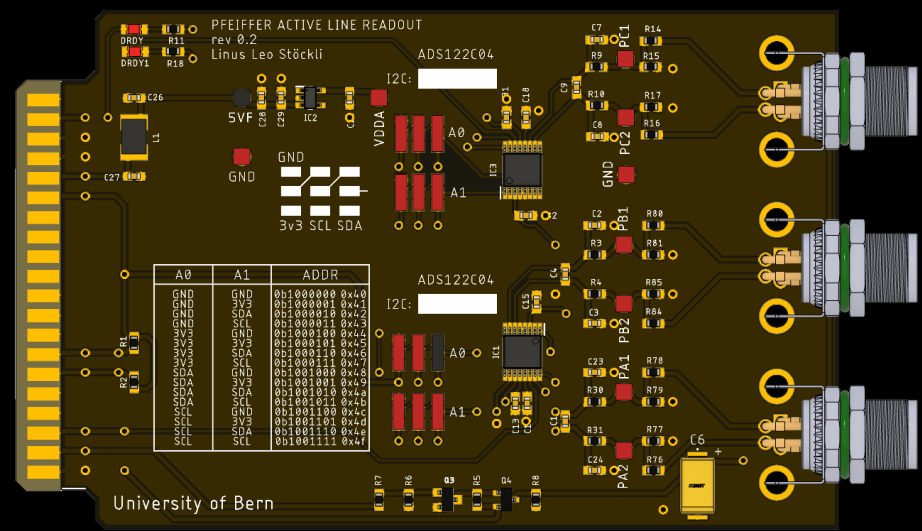
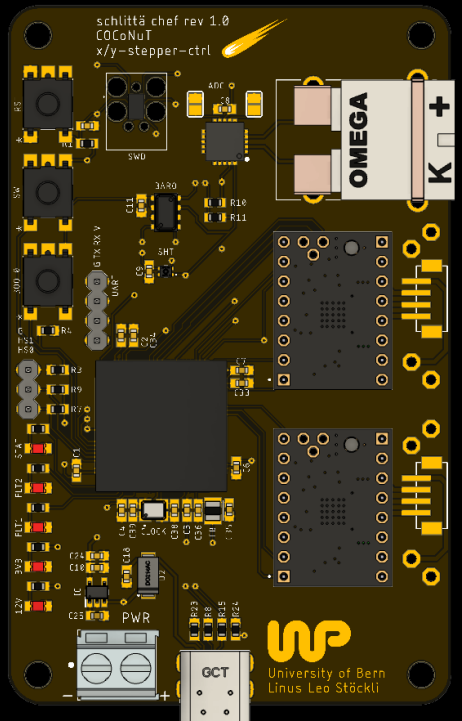
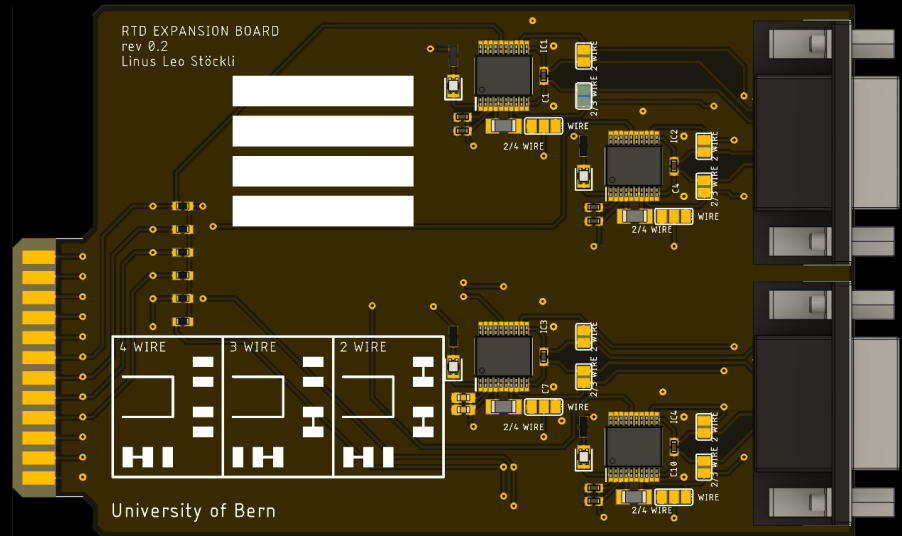
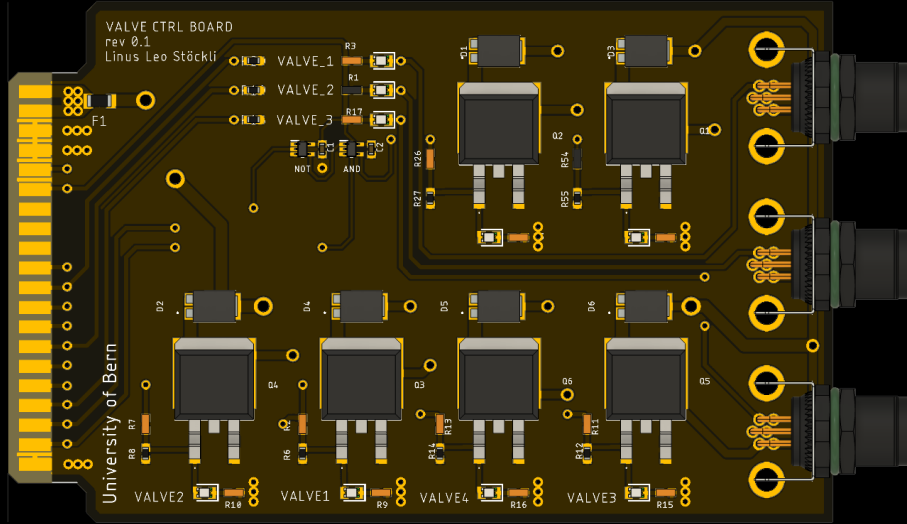
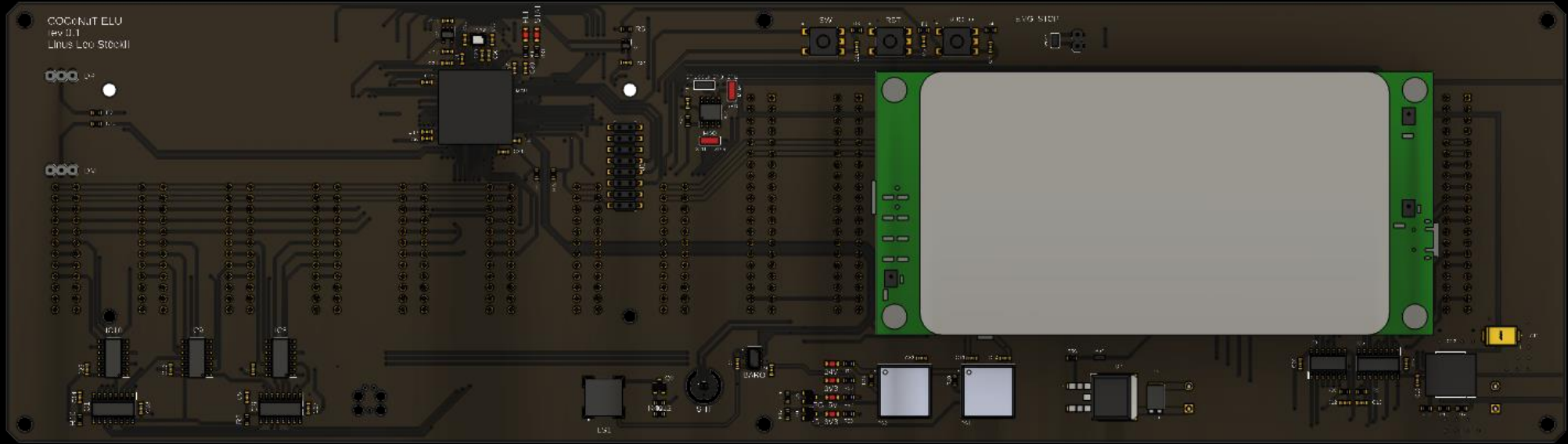


Electronics

ELU

- Modular Design
- Control of Heating, Stepper Motors, Servo Motors, Valve
- Pump Control (Pfeiffer RS-485)
- Readout of housekeeping data (PT100/PT1000, PKR251)





COCoNuT

Linus Leo Stöckli, Mathias Brändli, Daniele Piazza, Rafael Ottersberg, Antoine Pommerol, Axel Murk, Nicolas Thomas

<https://doi.org/10.1063/5.0252742>

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ARTICLE

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Design and commissioning of a THz time-domain spectro-goniometer in a cryogenic comet simulation chamber

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Axel Murk,² and Nicolas Thomas¹

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ABSTRACT

We present our newly developed laboratory setup, called COCoNuT (Characteristic Observation of Cometary Nuclei using THz-spectroscopy), consisting of a THz spectro-goniometer in a vacuum chamber along with a cryo-cooler intended for cooling down samples rich in ices expected in cometary environments. This setup allows the use of THz time domain spectroscopy on analogs including refractory materials in the spectral range from 0.1 to 5.5 THz with a spectral resolution of up to 0.005 THz. Since the optical setup is mounted on a precision controlled *x/y*-stage, imaging or spatial averaging can be performed. In this work, we present the design decisions and selection of components. Furthermore, the commissioning of the setup is described and the capabilities are shown. The system can reach pressures of 10^{−7} mbar and temperatures of 50 K. For 2D scanning, a spatial resolution of 0.3 line-pair per mm is obtained.

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I. INTRODUCTION

Comets offer a unique opportunity to gain a deeper understanding of the early evolution of our Solar System. It is widely assumed that they are remnants of the planetary formation process being proto-planetesimals that were not integrated into planets.¹ Support for the pebble accretion concept of planetary formation, in which cm-sized objects (pebbles) are brought together to produce the cores of gas giant planets, has been presented through analysis of images of cometary nuclei,² although this is controversial and disputed.^{3,4} Comets are composed mostly of volatile ices and dust; however, the exact composition is not known. To investigate the physical properties of comets in laboratory experiments, the environment can be simulated in a vacuum chamber^{5–7} where water ice⁸ and dust analogs⁹ can be analyzed. In situ comet exploration such as that conducted using the Rosetta spacecraft¹⁰ has focused on visible and infrared imaging and spectroscopy,¹¹ radar¹² observations, and mass-spectrometry. A significant part of the electromagnetic spectrum has not yet been investigated. In particular, the THz region, reaching from 100 GHz to 10 THz (3 mm–30 μm), sitting in between infrared and microwave frequencies, is relatively unexplored. While the Doppler-resolved MIRO instrument^{13,14} on-board the Rosetta mission conducted extensive measurements of the comet’s coma at 190 and 562 GHz, relatively little is known about the nucleus outside of these narrow frequency windows. Studies of THz frequencies play an increasing role in space sciences.¹⁵ We have specifically chosen THz spectroscopy because ice is sporadically seen on the surface of comets¹⁶ and THz frequencies can provide a deeper penetration into the samples than vis-IR techniques while providing a better spatial resolution than ground penetrating radar. As it has previously been established that many ices are transparent at lower THz frequencies and only have significant absorbance at higher THz frequencies,¹⁷ analyzing the nucleus with a THz spectrometer seems promising to gain knowledge about its physio-chemical structure. The non-volatile components have been shown to contain organic material,^{18–20} which can potentially be analyzed in the THz spectrum. Furthermore, as water vapor has a distinct fingerprint pattern,²¹ THz-spectroscopy

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96, 034502-1

23 December 2025 23:07:39

Characterizing the Technology

2025-10-22 22:29:58
pump_down 0

CoDA-T2

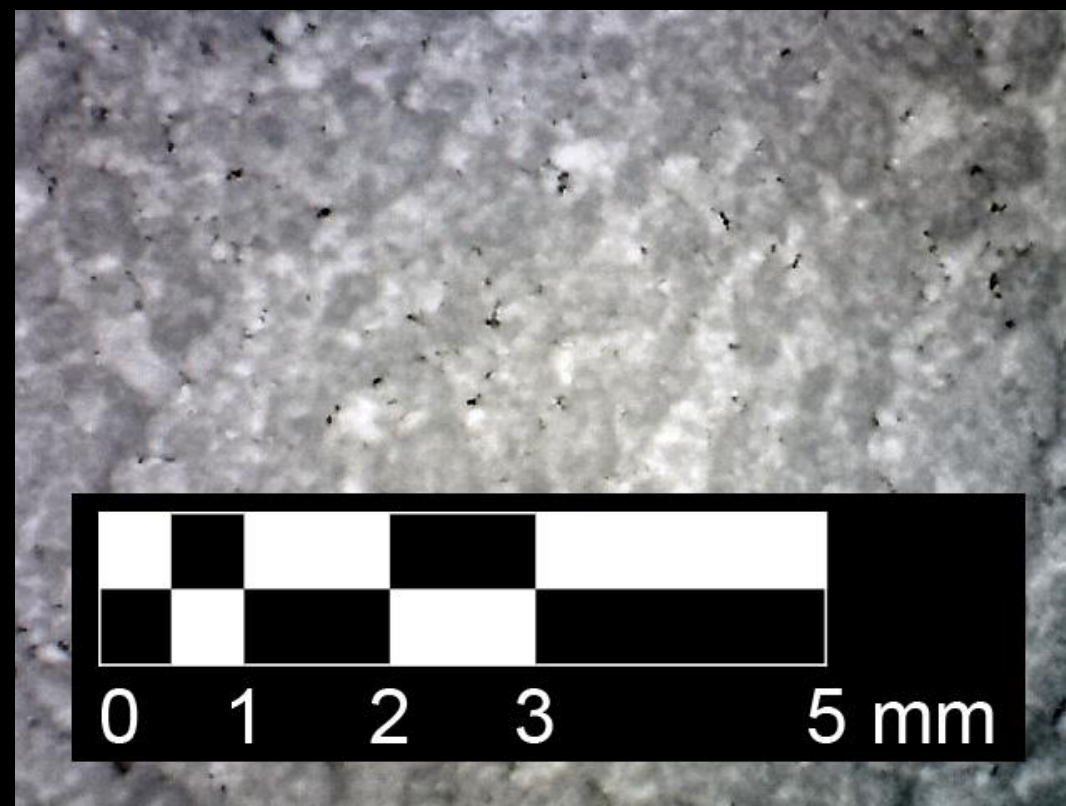
Pressure: 9.4×10^2 mbar
Temp Sample 1: 55.43 K
Temp Sample Holder: 486.08 K



Dust Analogues

Cometary Dust Analogues for THz-TDS

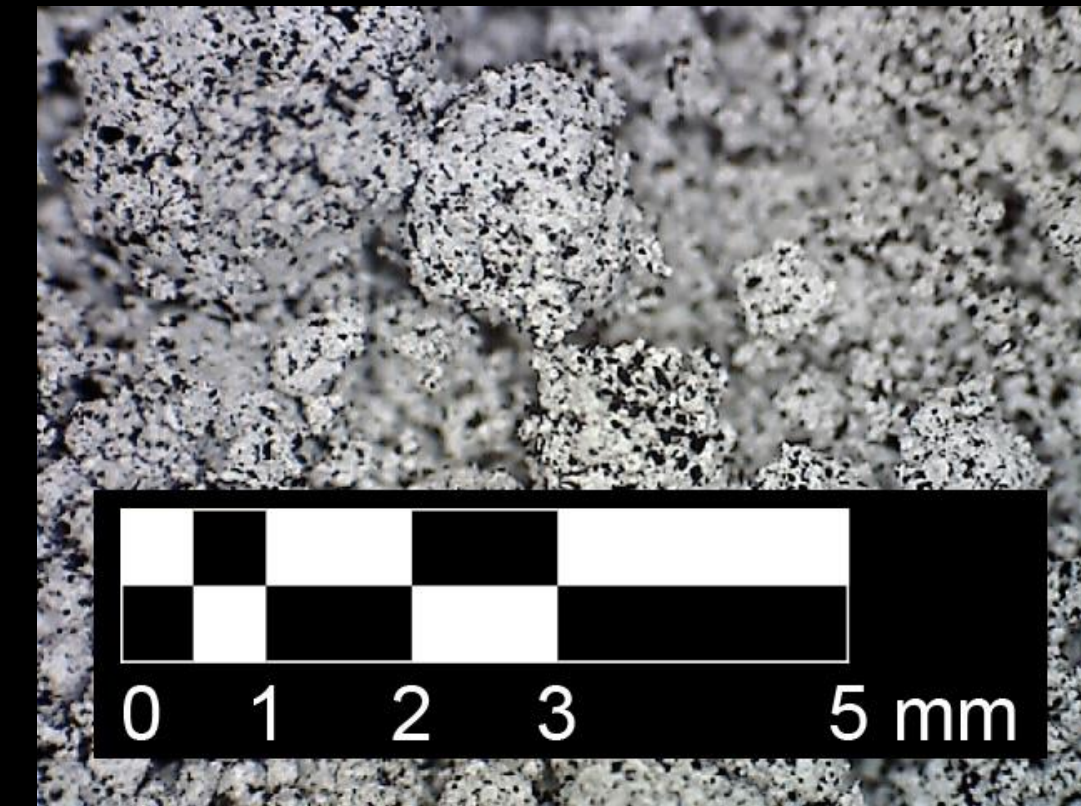
Forsterite



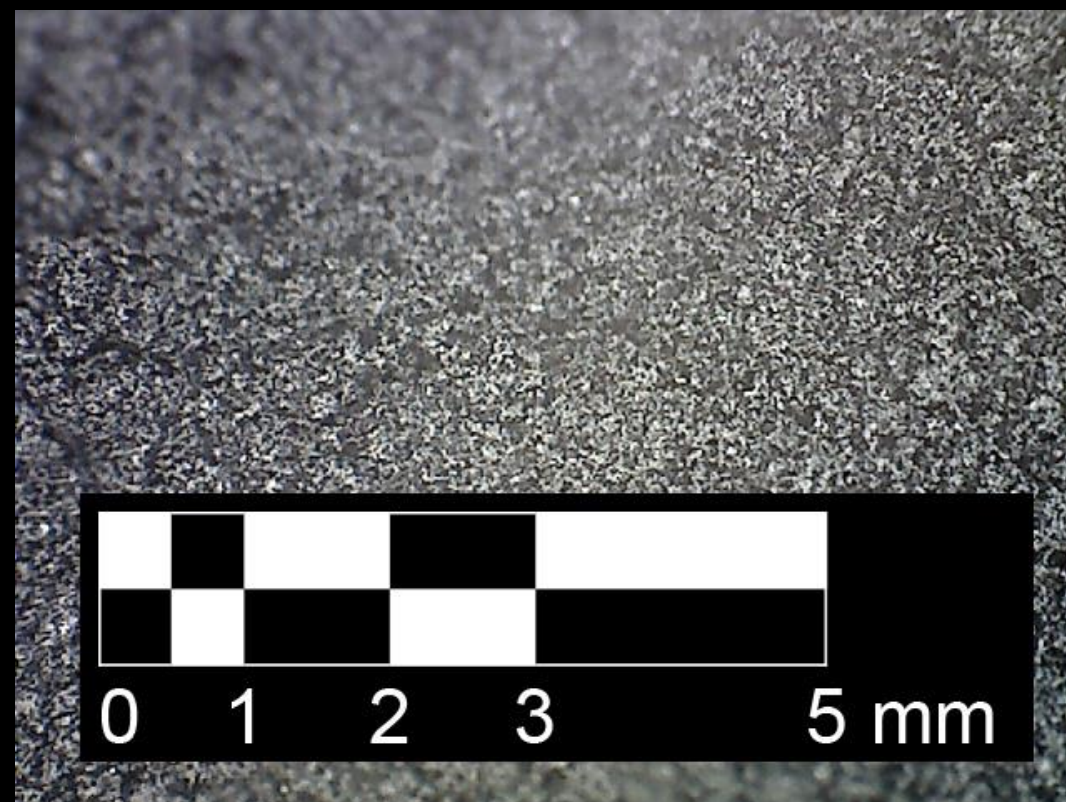
SiO₂



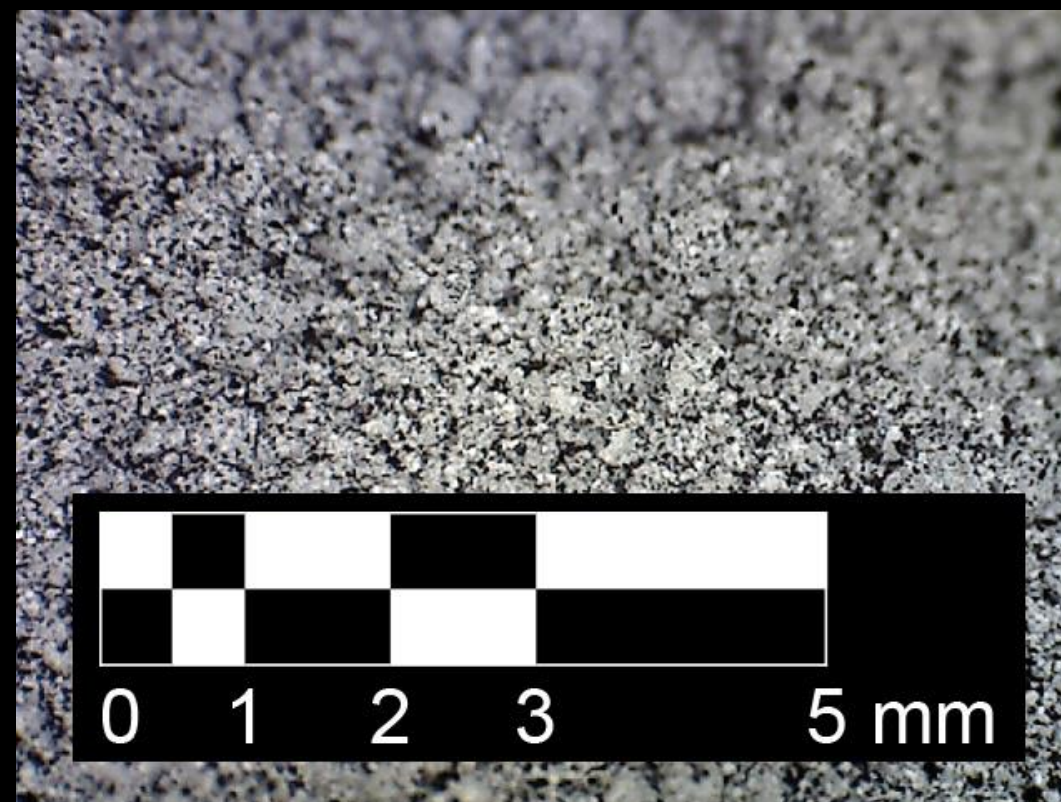
CoDA-T0



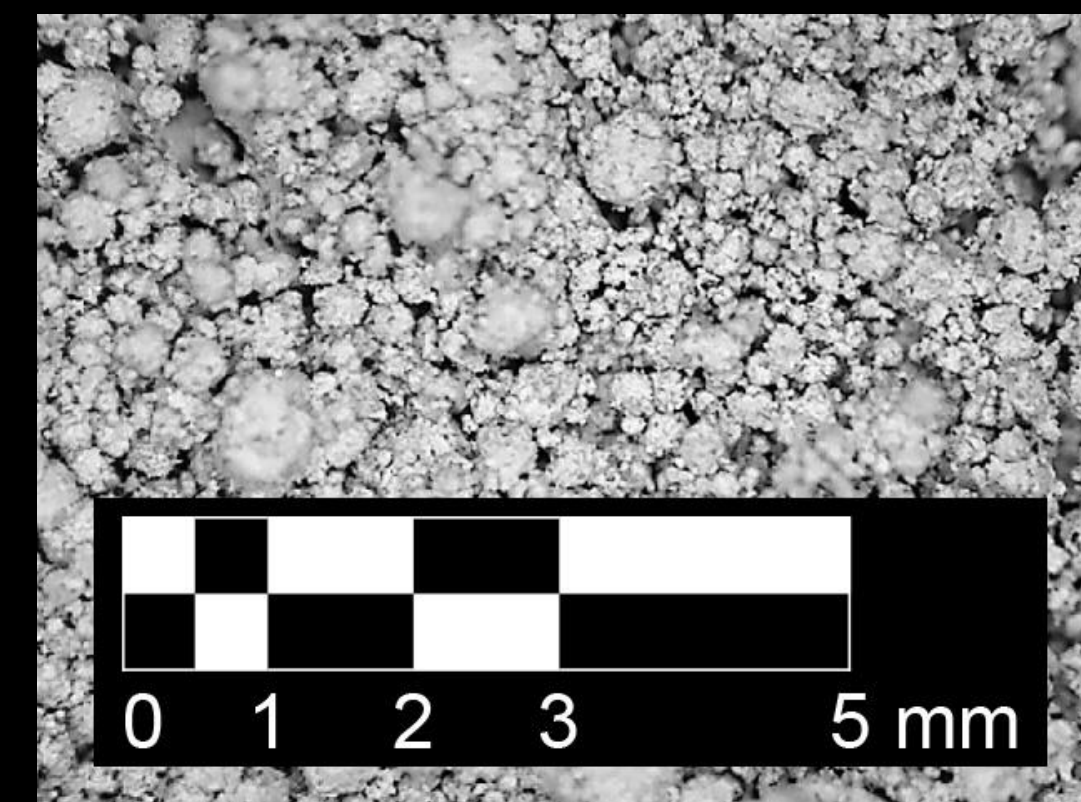
CoDA-T1



CoDA-T2



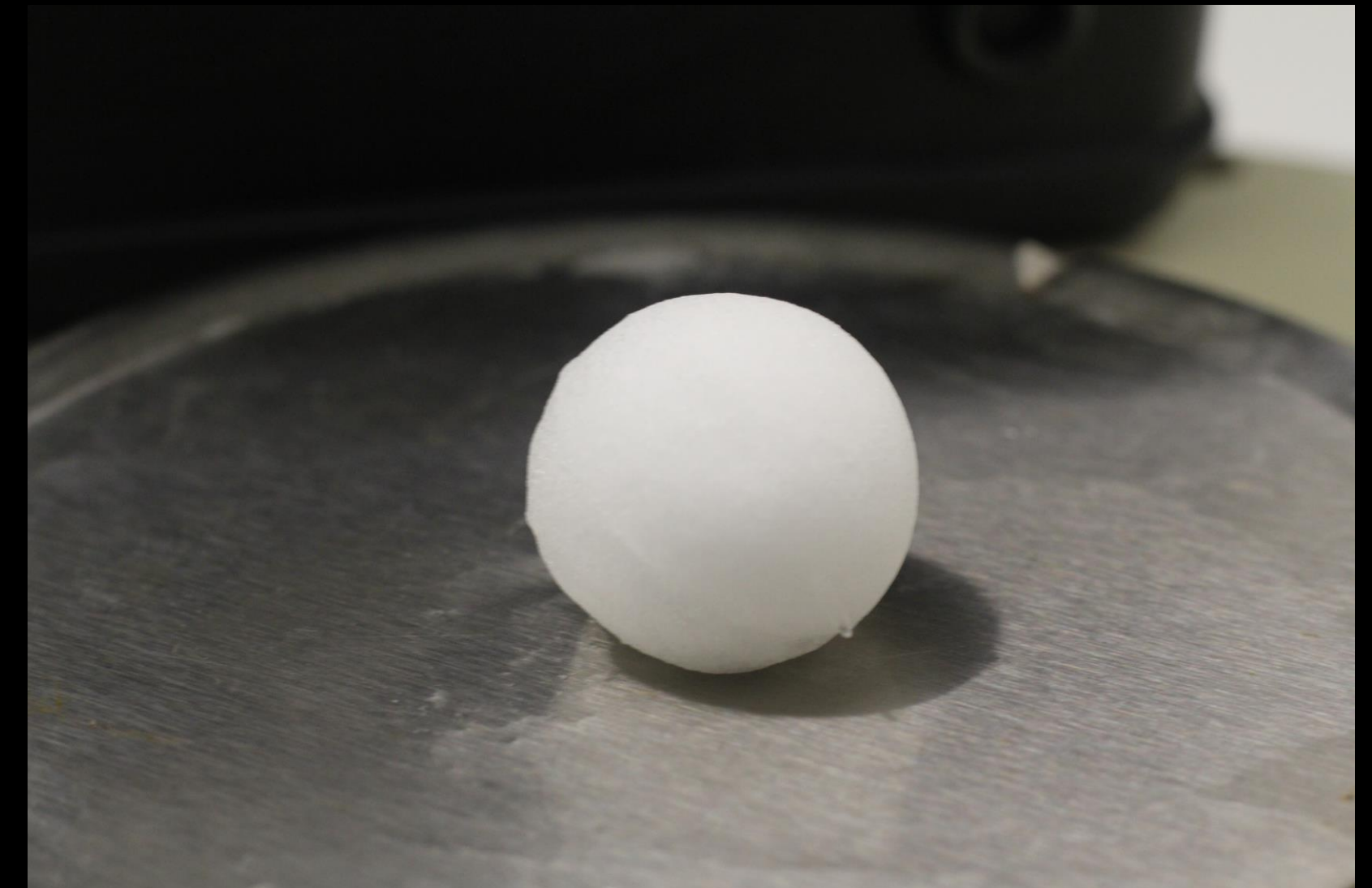
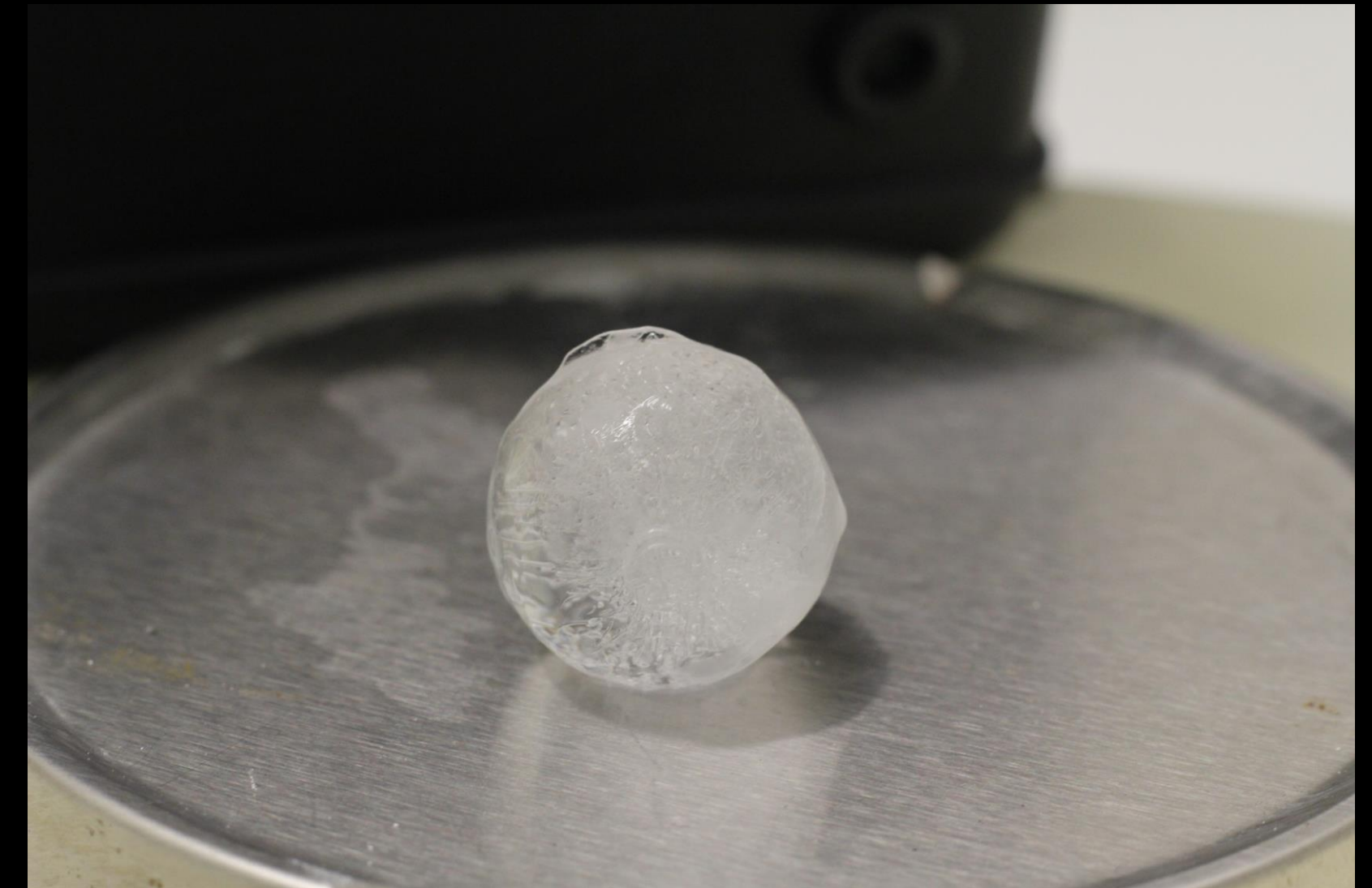
CoDA-T3



Detecting Pebbles

Surface and Sub-Surface

- Pebble simulants
 - Solid Ice
 - Porous Ice (Cometary Simulant)



Detecting Pebbles

Surface and Sub-Surface

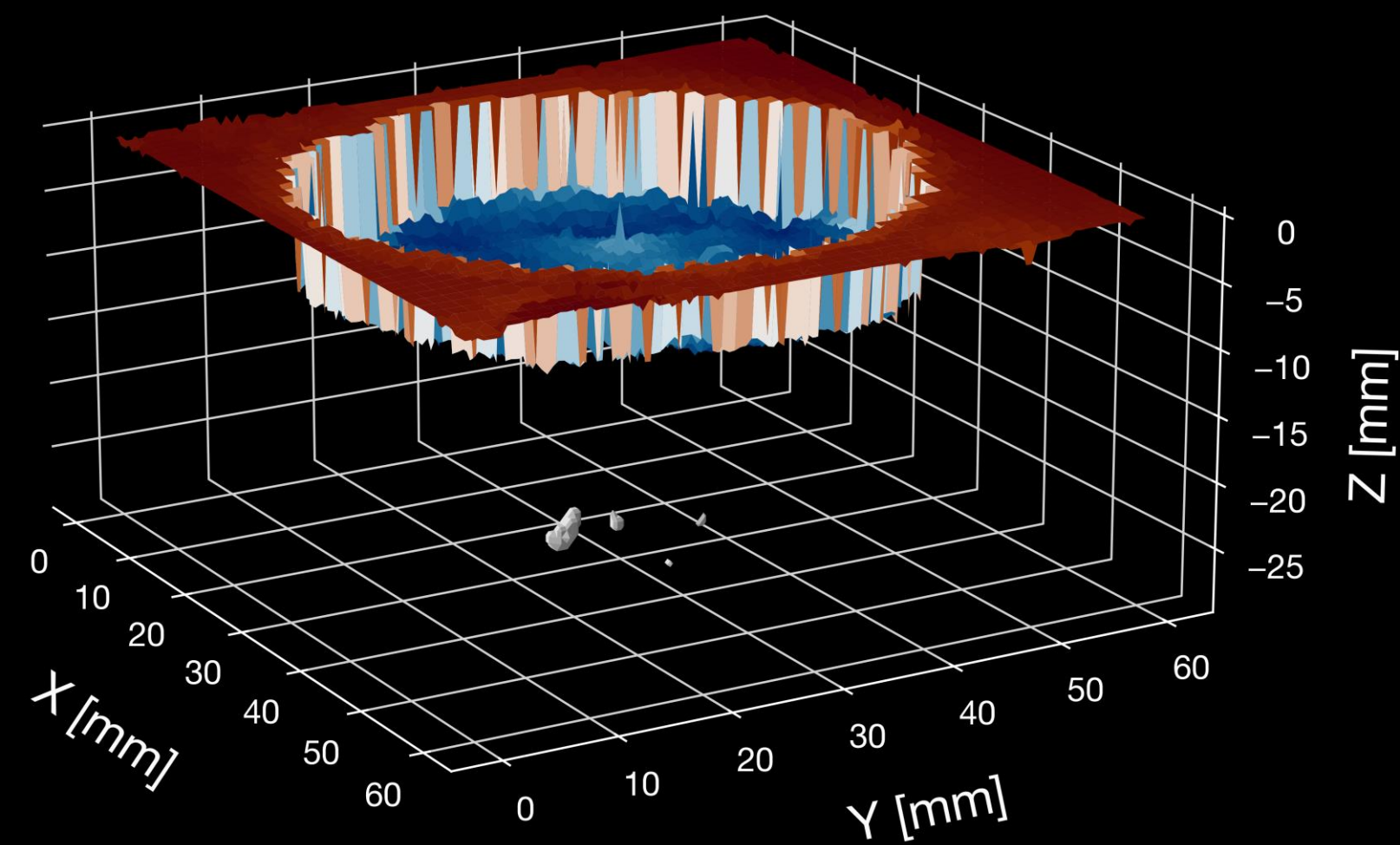
- Pebble in sample holder
- Covered with 2 - 3 mm CoDA-T3
- Transmission and reflection



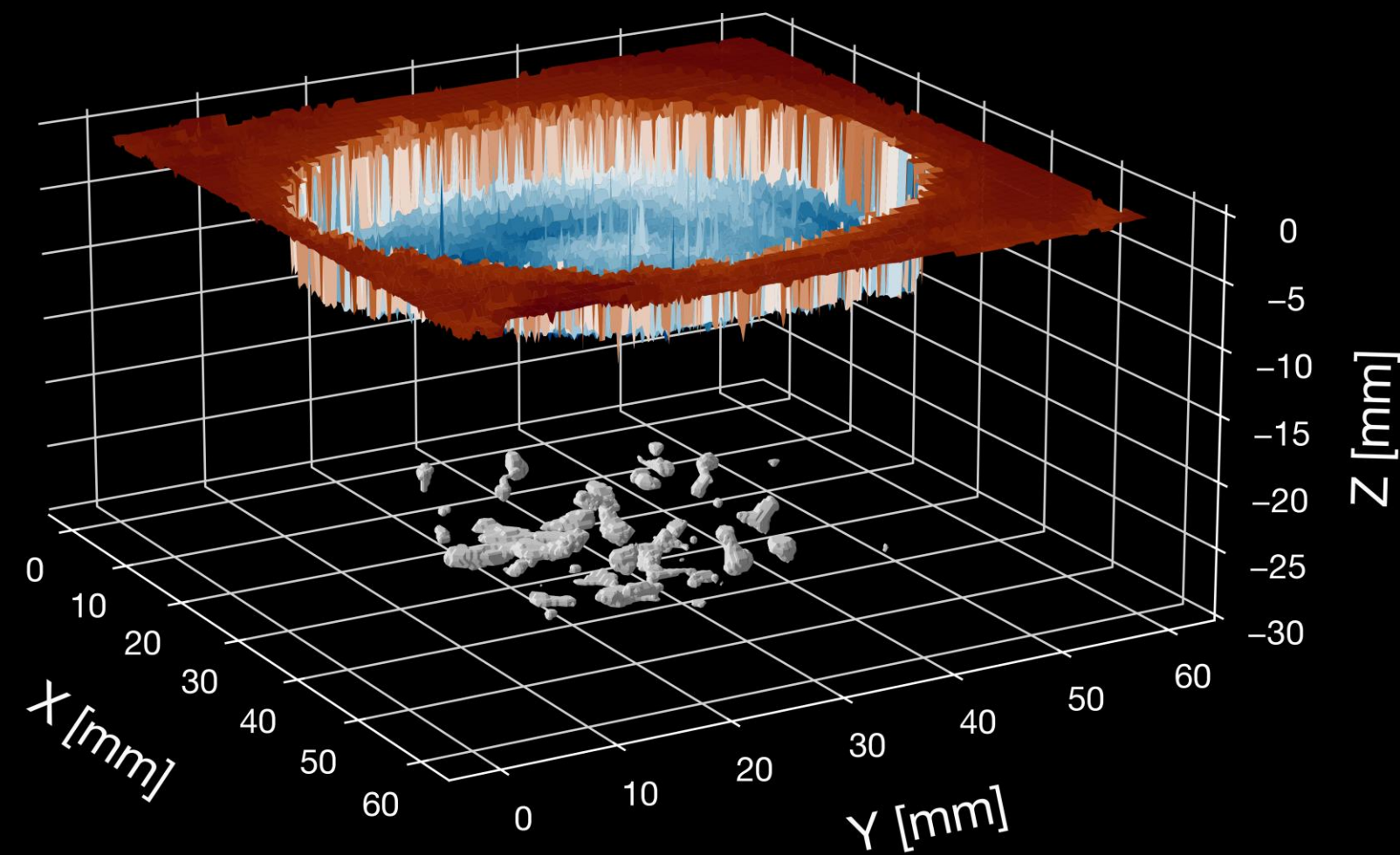
THz Tomography

Surface and Sub-Surface

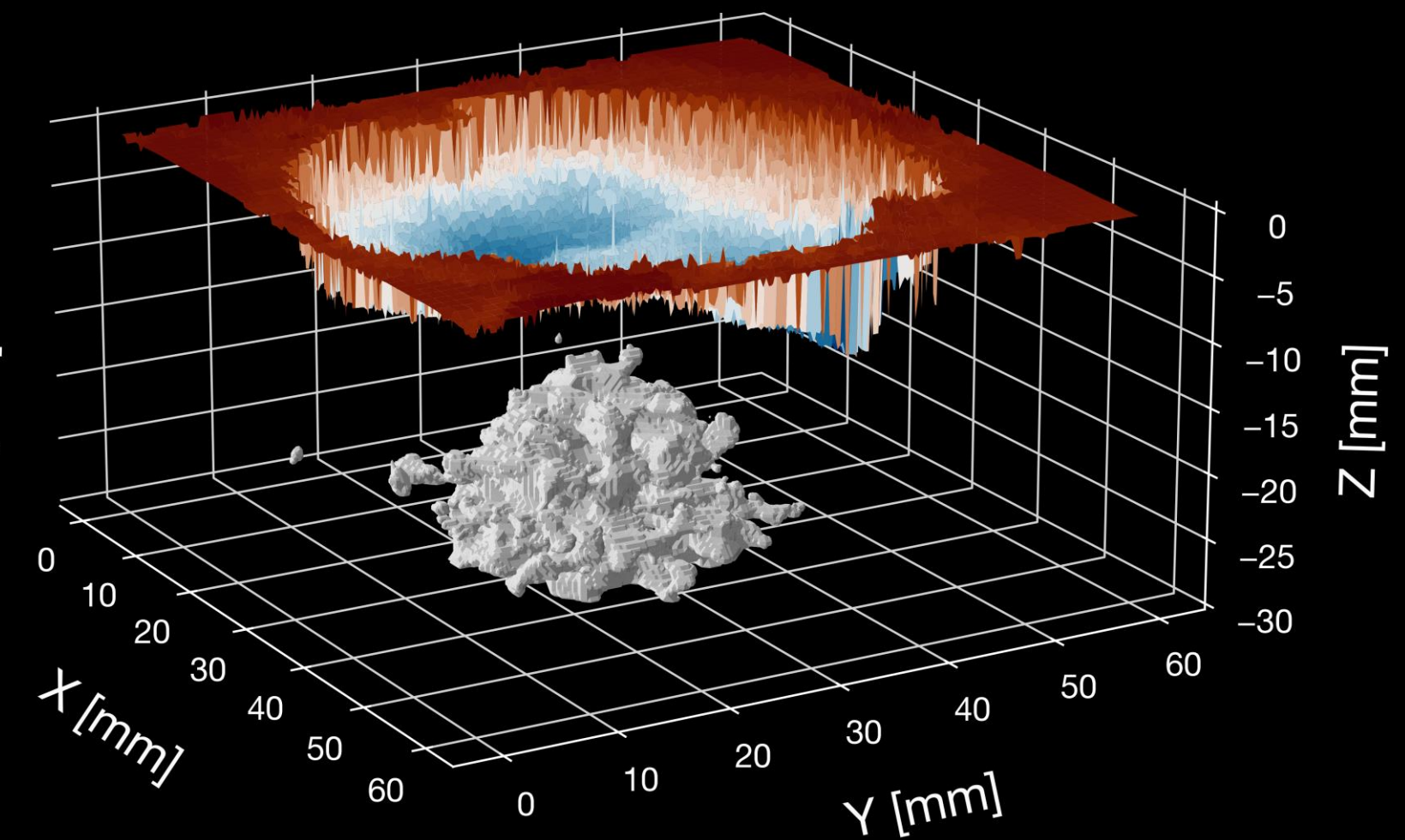
Control



SPIPA-B



Solid Ice

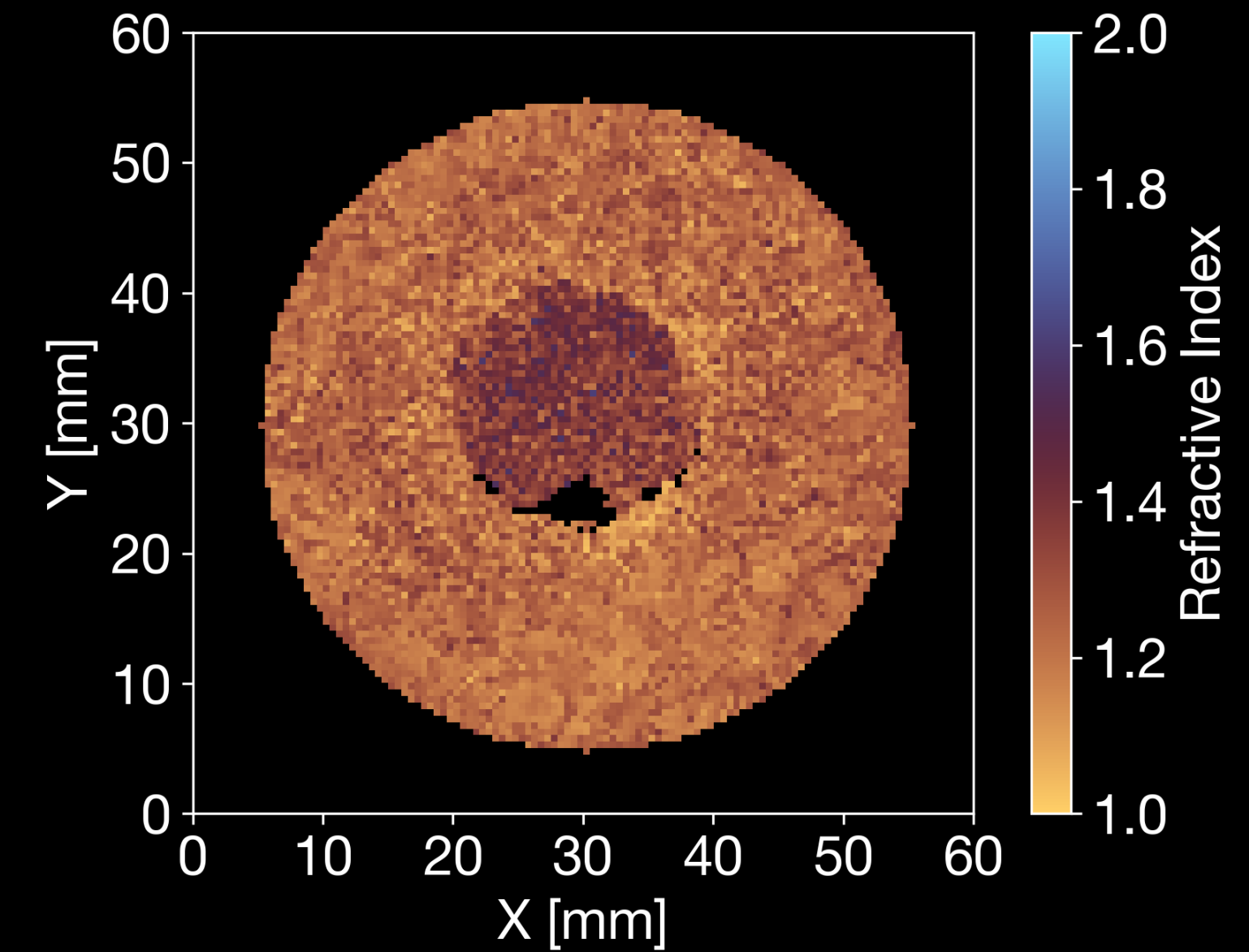


THz Tomography

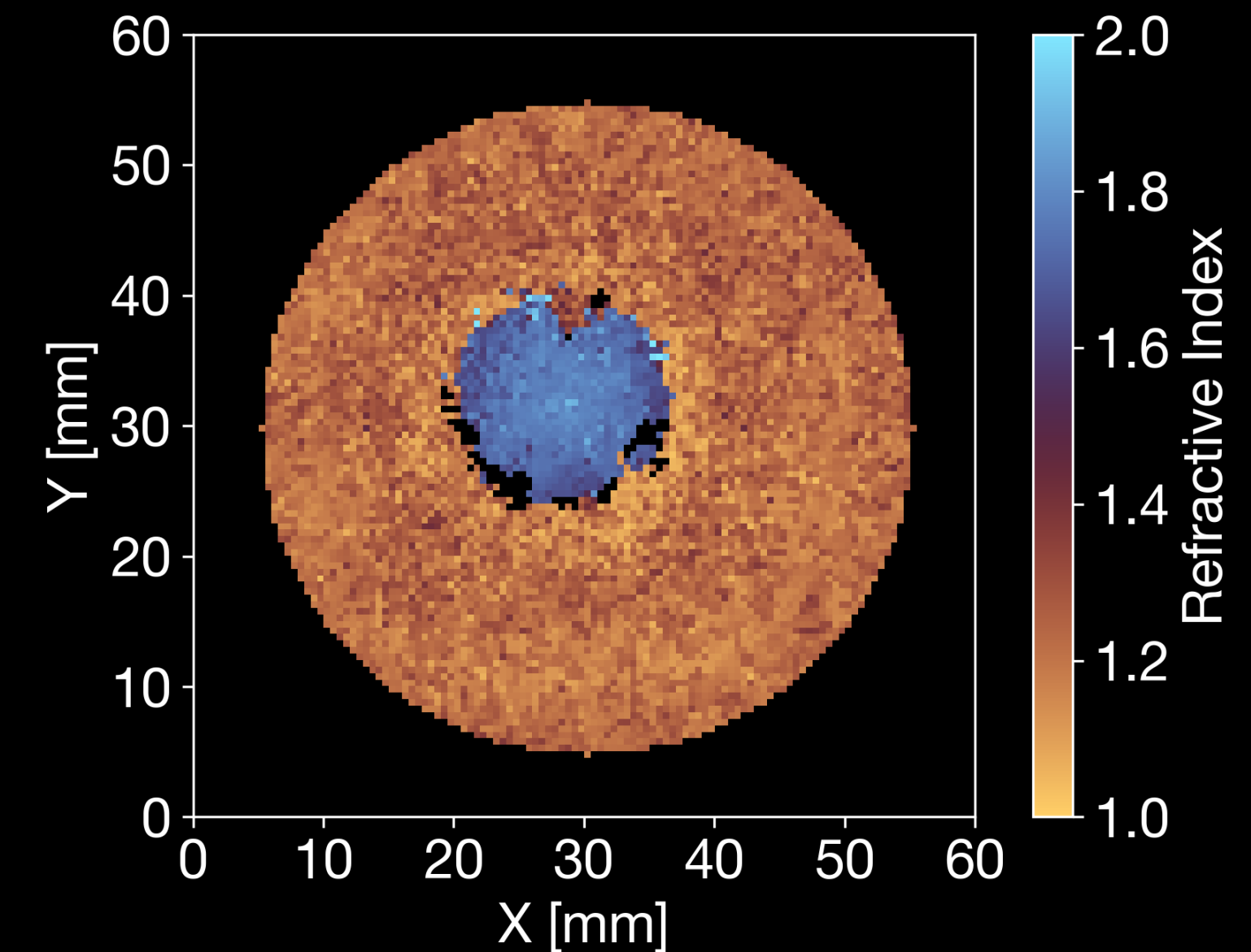
Sub-Surface

- Sub-Surface Extraction
- Transmission
- Refractive Index
 - Coupled to thickness

SPIPA-B



Solid Ice



Conclusion

We built the infrastructure to characterize THz-TDS for space applications.

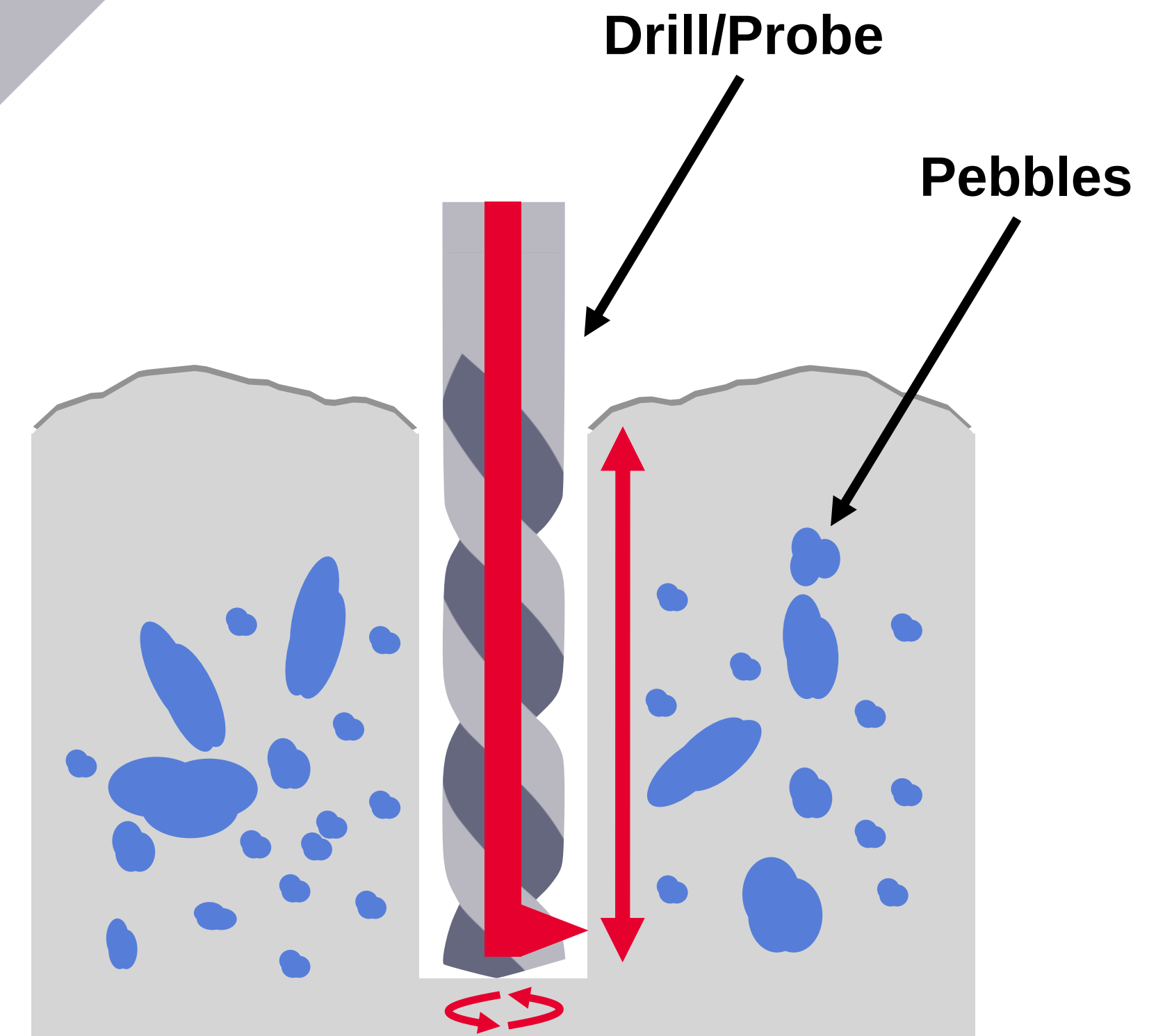
THz time domain spectroscopy in laboratory conditions

- was used to characterize cometary dust analogues at THz frequencies
- can be used to extract the surface at a resolution < 0.5 mm in reflection
- can be used to extract centimeter sized solid ice pebbles in reflection
- can be used to extract centimeter sized solid and porous ice pebbles in transmission

The absence of sub-surface pebbles on comets might well challenge the *Pebble Accretion* theory.

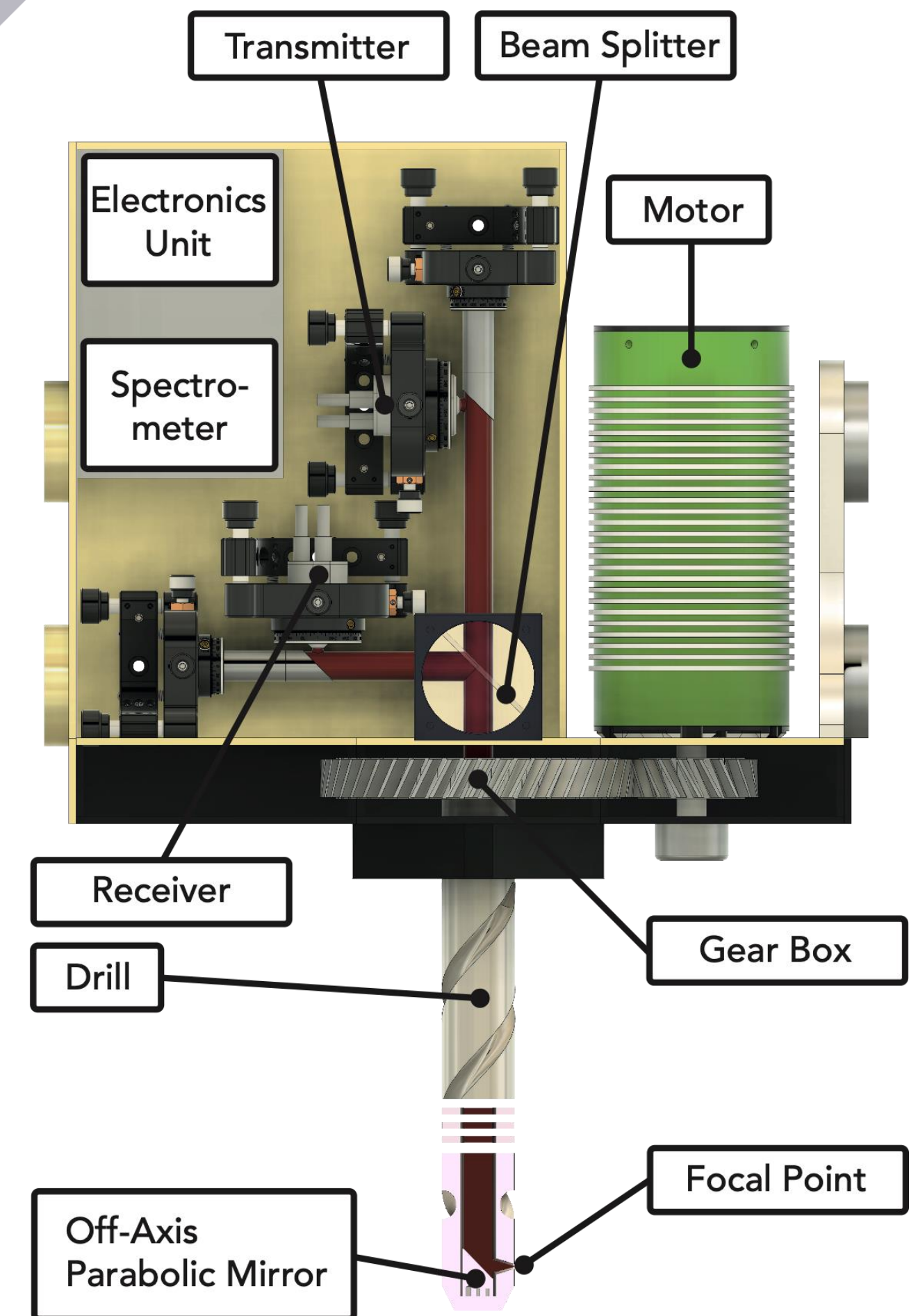
Outlook

- In-situ THz spectrometer on a Lander
- Spectrometer isolated from drill
- Drill inspired by ExoMars
 - 30 mm diameter
 - 500 mm length



Outlook

- In-situ THz spectrometer on a Lander
- Spectrometer isolated from drill
- Drill inspired by ExoMars
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Thank you!

Annabella Drewanowski
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Lukas Schneider

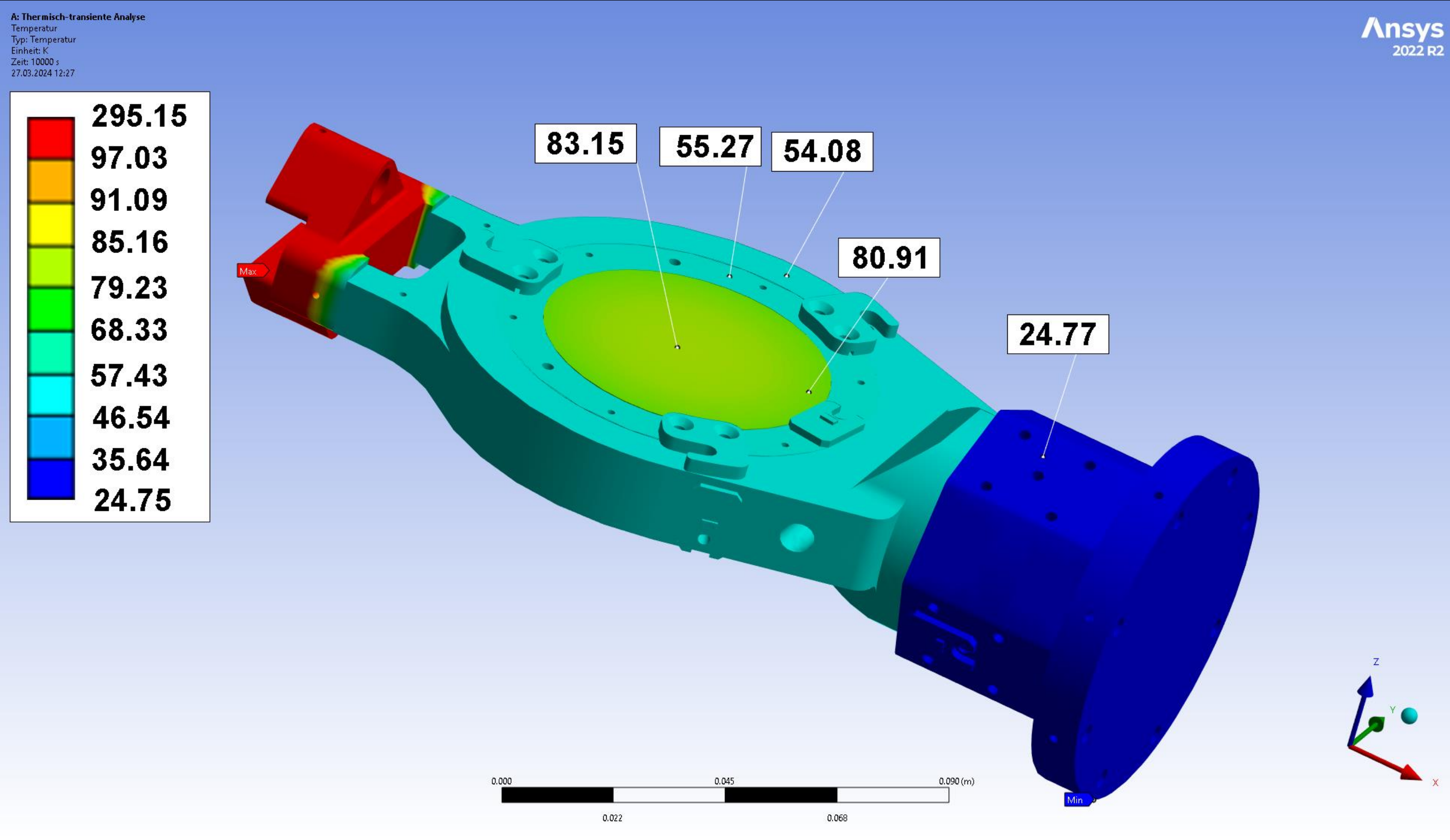


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Susanne Wampfler
Thierry De Roche
Tina Rothenbühler
Urs Geissbühler
Valentin Bickel
Valentin Meier
Yannick Zwirner

Backup Slides

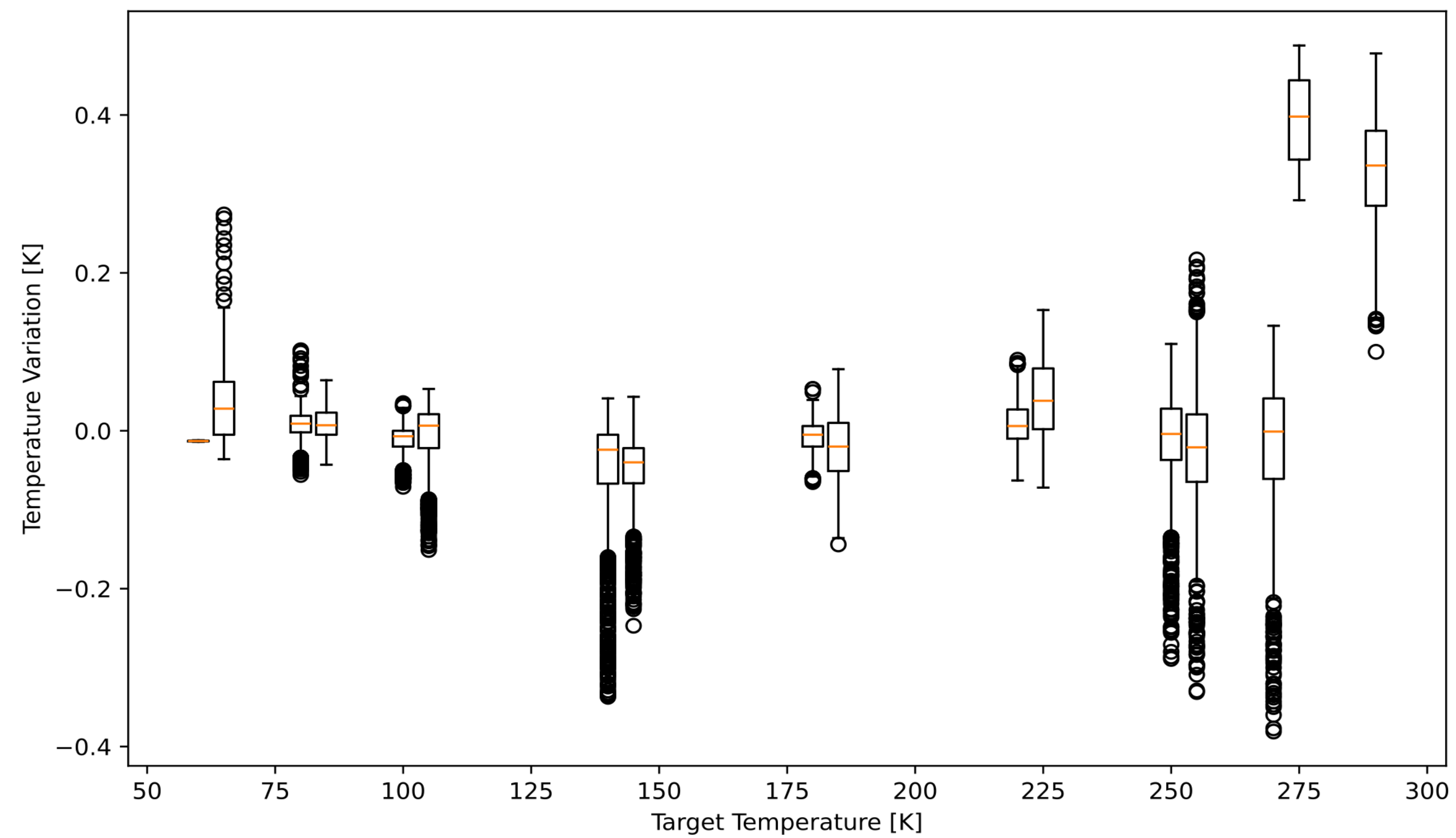
Design

Thermal Simulation



Design

PID Performance



$\vec{E}$

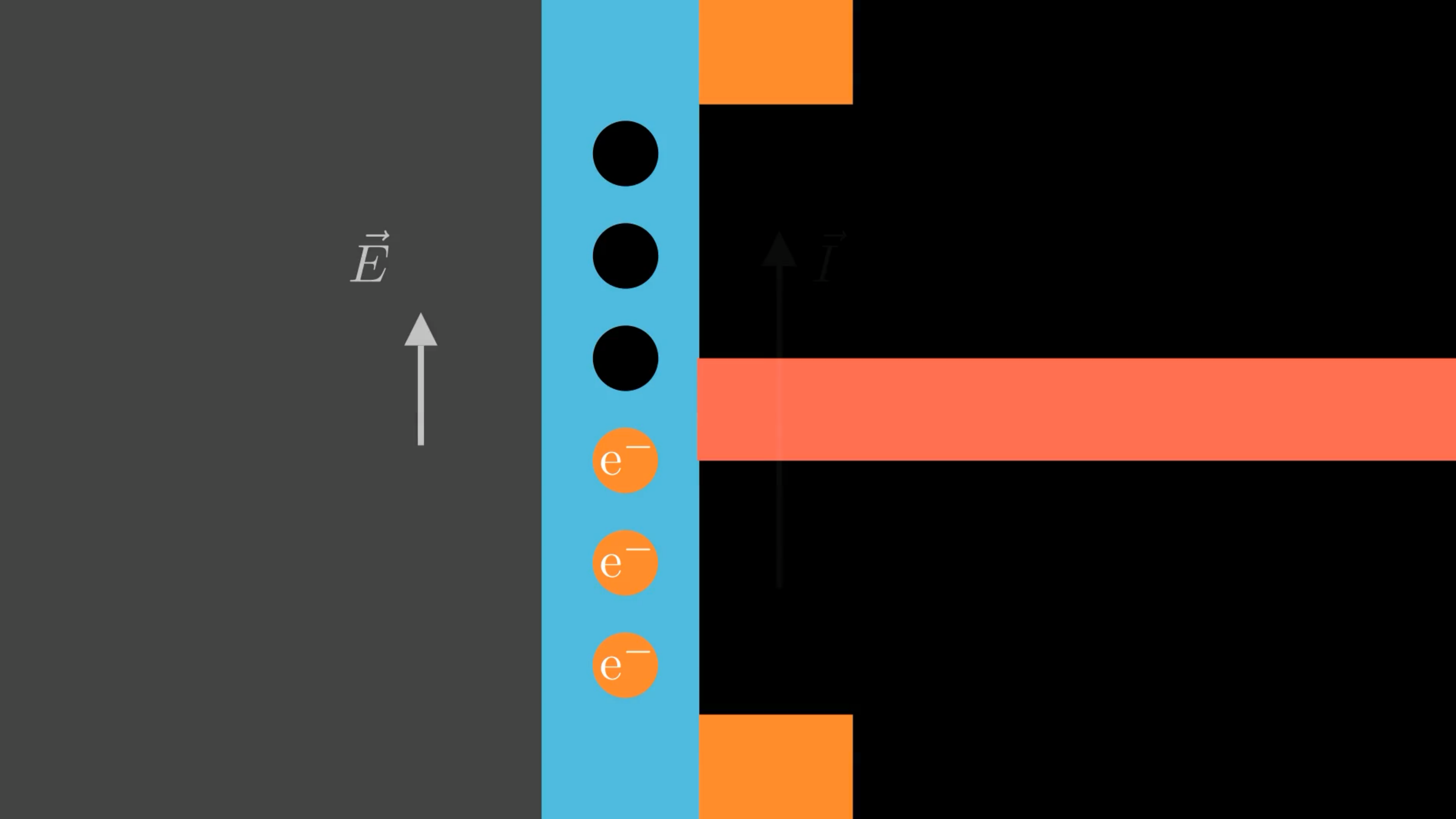
e^-

e^-

e^-







THz Spectrometer

- Pulsed Laser (fs)
- Photoconductive Antennas
- Slow Delay Line
- Fast Delay Line

