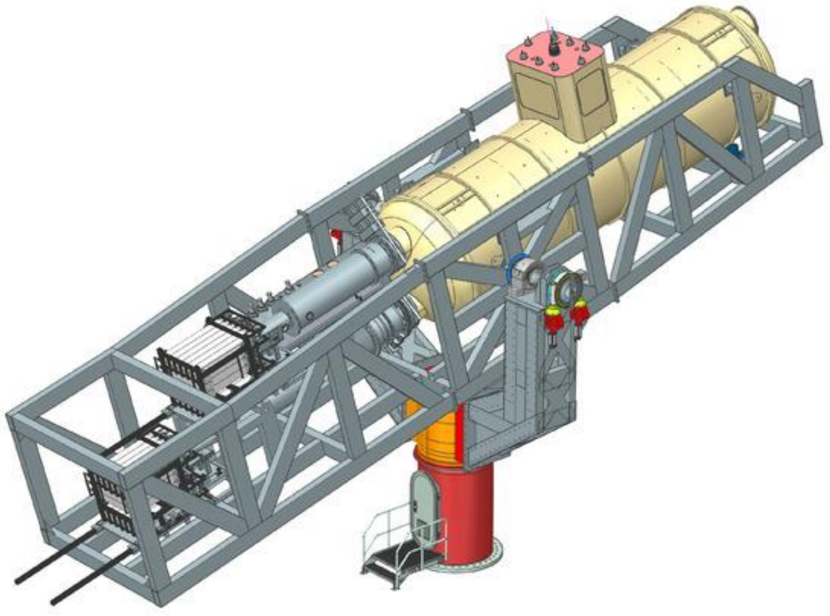
Fabricating Optics, Profiling Ovens, and Modernizing Laser Metrology for BabyIAXO

Thomas Fereday

July 30, 2026

Jooyun Woo, Kerstin Perez*

Nevis Laboratories REU 2026 · Columbia University



Baby International Axion Observatory

Agenda

- Axions and the Strong CP Problem
- IAXO and Optic Design
- Fabrication
- Scanning & IDL Data Analysis Conversion
- Results

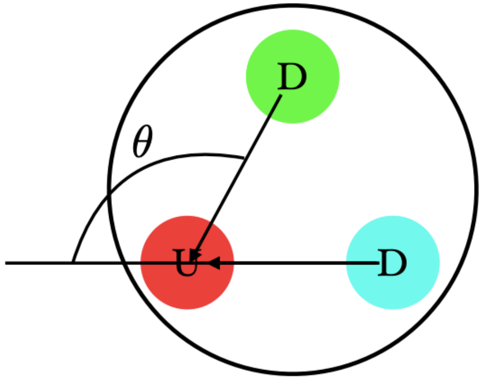
1

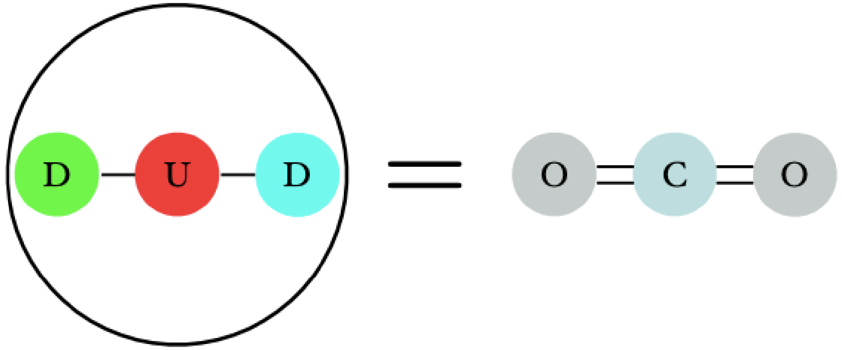
Axions and the Strong CP Problem

What is the Strong CP Problem?

- Fundamental Charge (C) and Parity (P) symmetries in Physics
- Violation discovered in weak force ~1960
- Theory expects CPV from strong force, but where?
- $\bar{\theta}$ $\rightarrow$ free parameter $[-\pi, \pi]$
- Experimental constraint $|\bar{\theta}| \leq 10^{-10}$
- Why do they disagree?
- $|\mathrm{nEDM}| \leq 10^{-26} \mathrm{e} \cdot \mathrm{cm}$

$$\mathcal{L}_{\mathrm{QCD}} \supset \bar{\theta} \frac{\alpha_s}{8\pi} G^b_{\mu\nu} \tilde{G}^{b,\mu\nu}$$

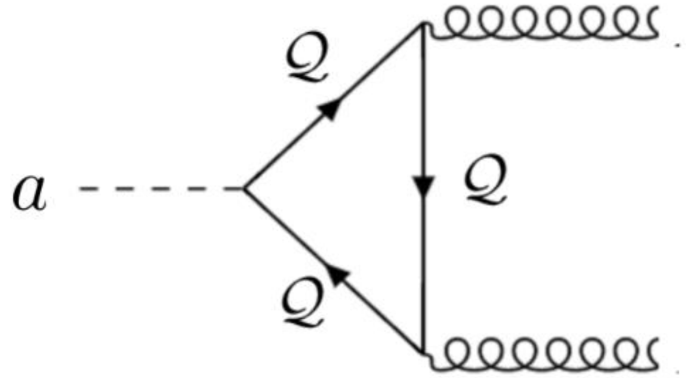




arxiv:1812.02669

Creating the Axion to Solve the Strong CP Problem

- Peccei and Quinn promote theta to a potential field
- New particle "axion" relaxes theta to near 0
- Couples to electromagnetic fields
- Low probability of photon conversion – "Primakoff Effect"



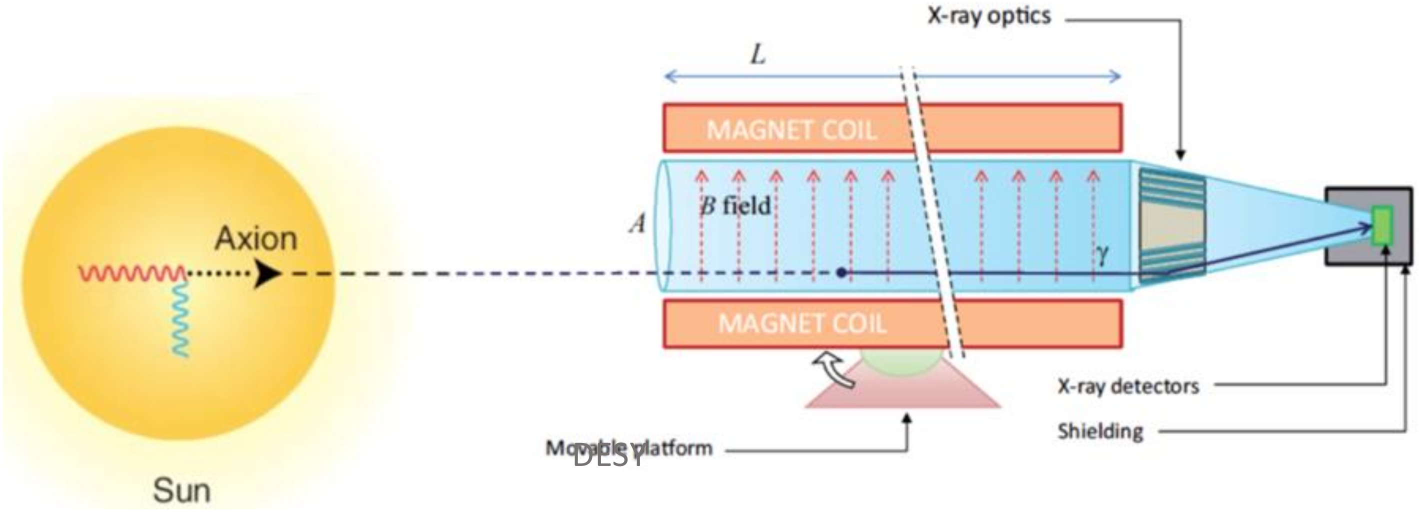
$$g_{a\gamma} \propto m_a$$

2

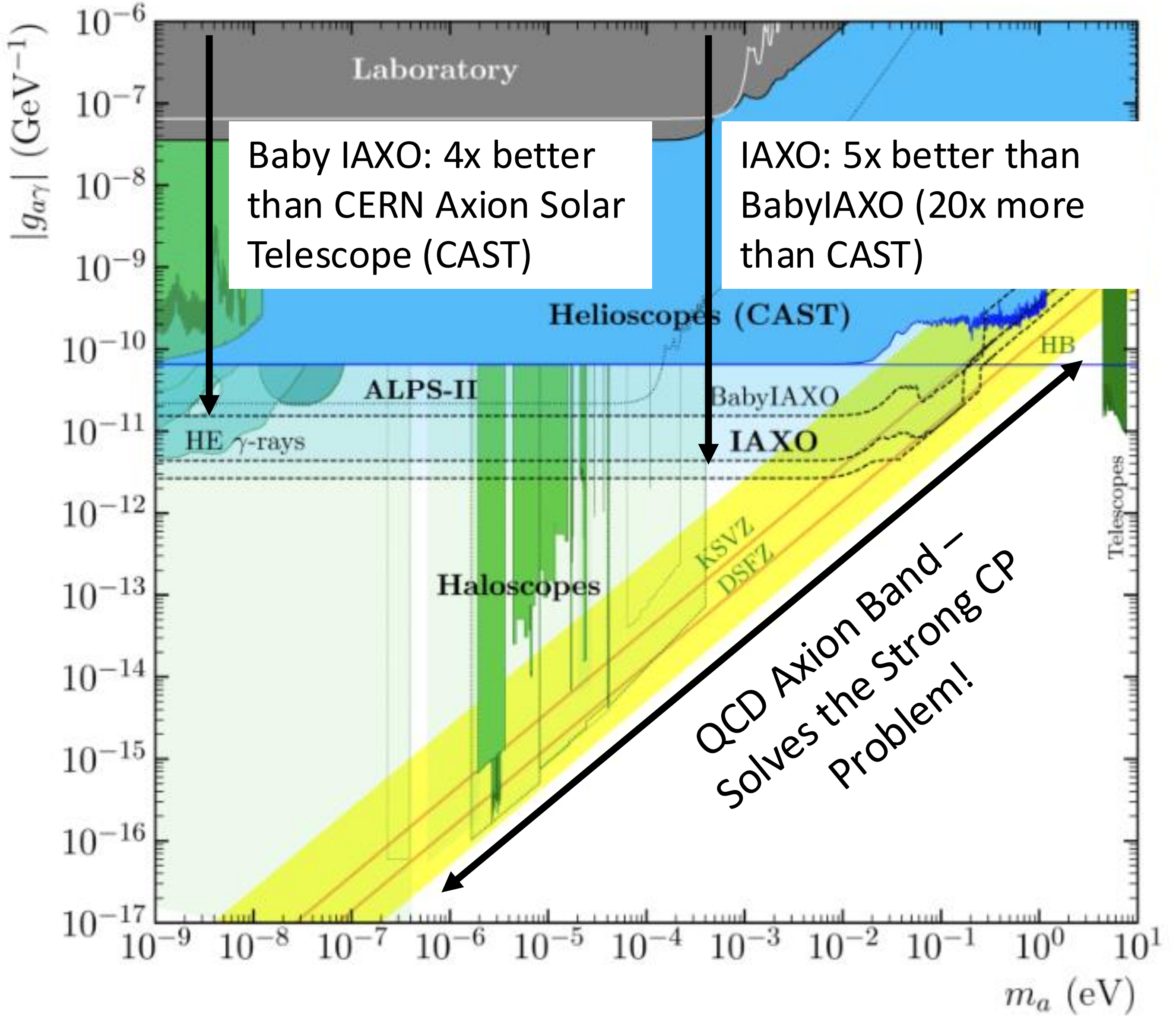
IAXO and Optics Design

How do we find the Axion?

- Where can we find them?
- Helioscopes – Our Sun
- X-Rays (1-10 keV)
- Sensitivity grows with B-field strength, length, and optic quality



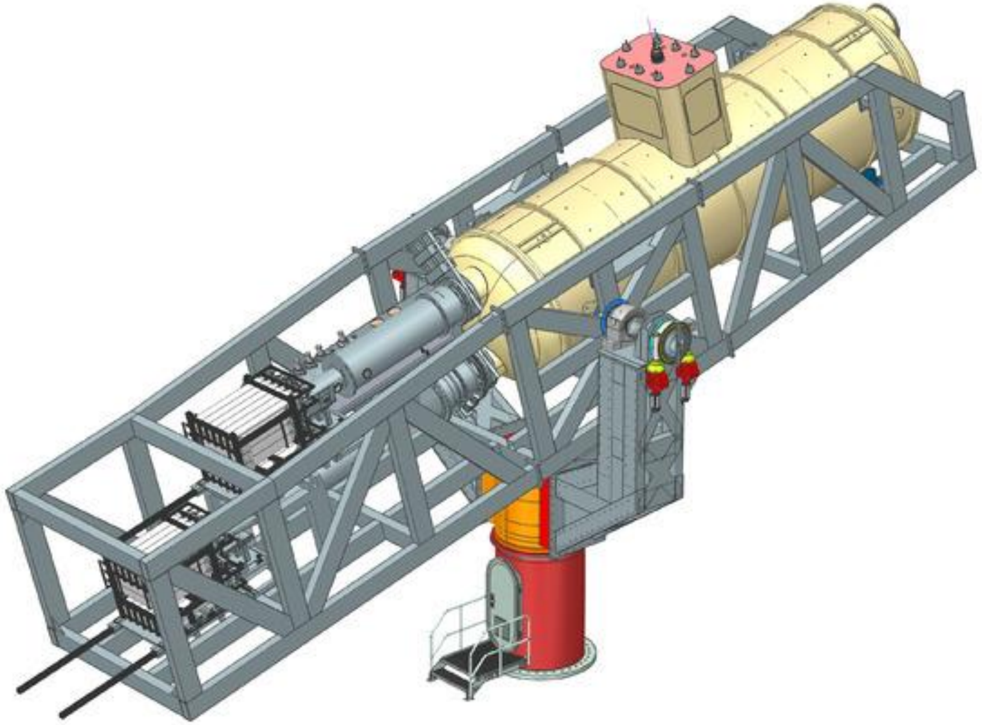
Lower coupling – harder to detect!



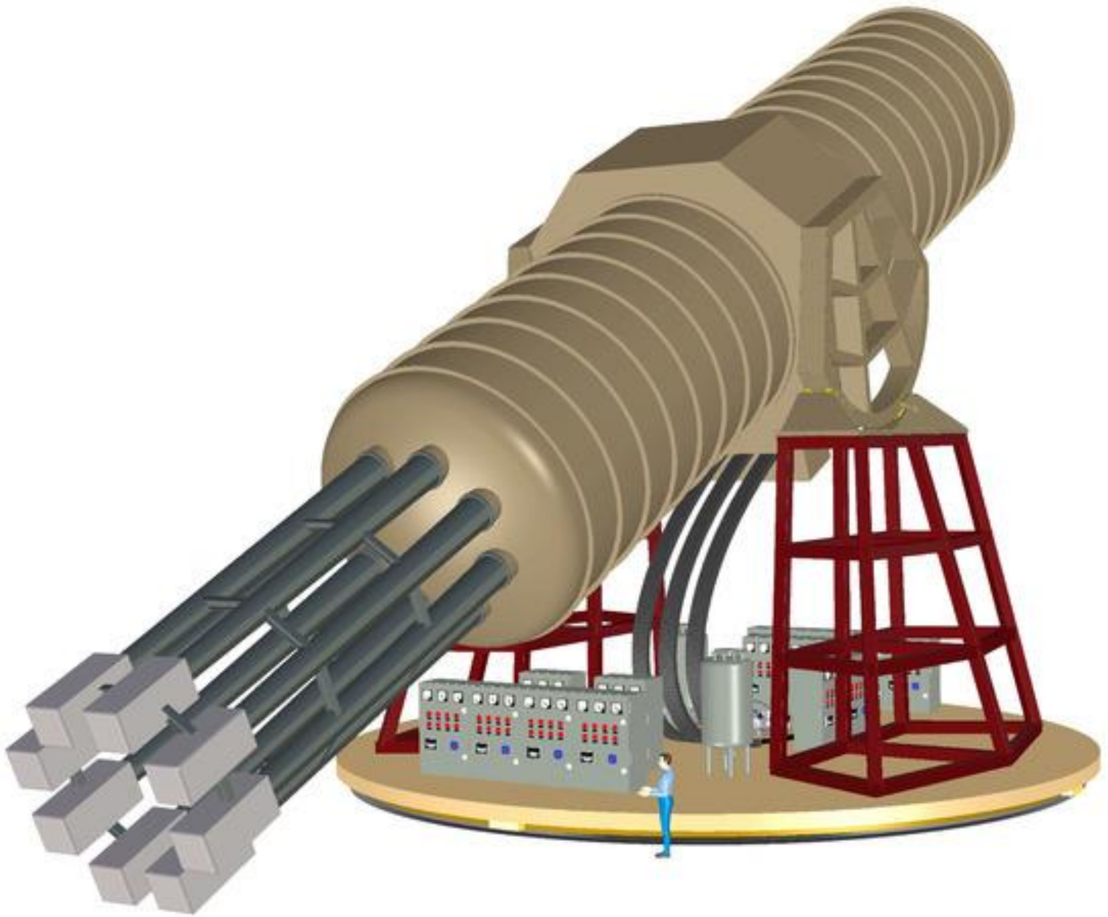
Mass of the axion

arxiv:2010.12076

Comparing IAXO Projects



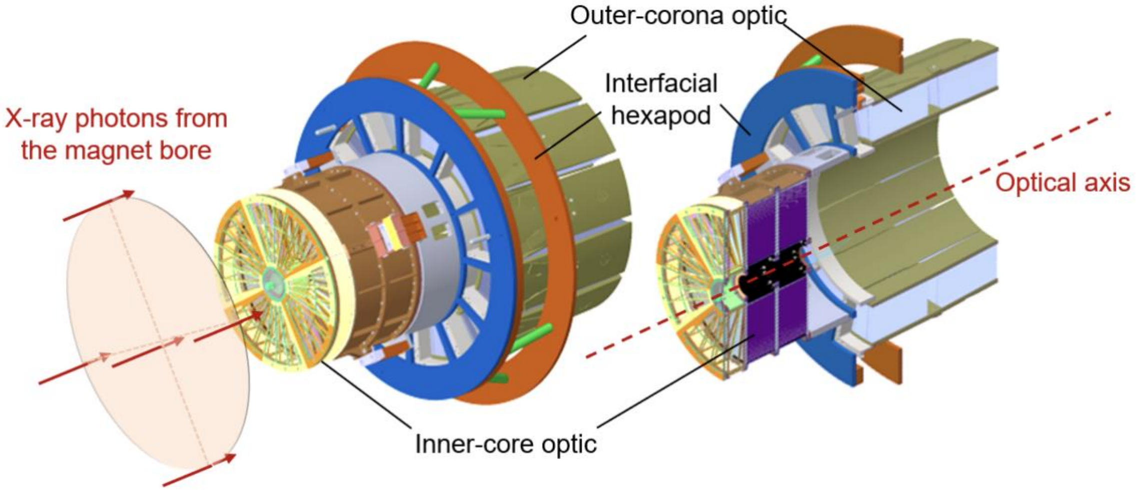
B-field: 2T
Bore Length: 10 m
Cross Section: .77 m2
X-ray optics: 2



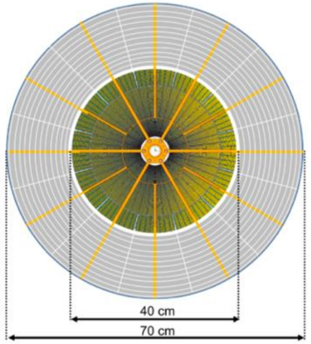
B-field: 2.5 T
Bore Length: 20 m
Cross Section: 2.3 m2
X-ray optics: 8

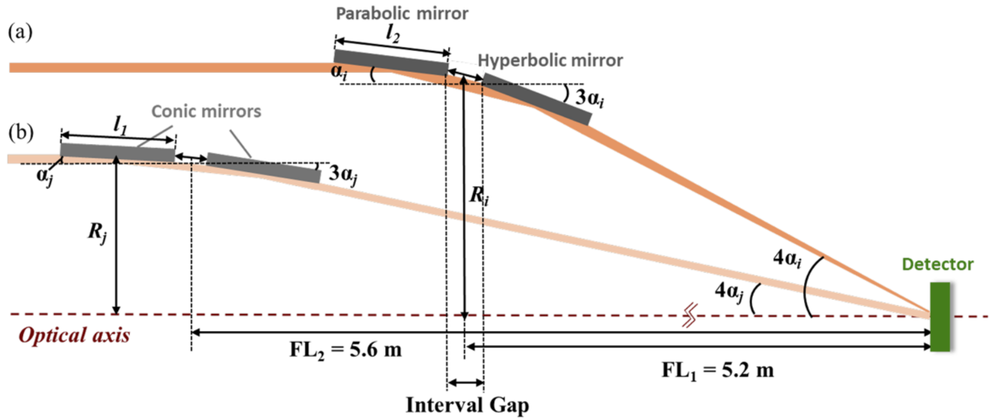
Designing the Inner X-ray Optic

- Hybrid optics: XMM-Newton Outer and Custom X-ray Inner
- Maximize signal to background ratio with small detector spot size
- Small grazing angle Wolter-1 optics
- High effective area, high resolution nested to access broad axion energy ranges
- 103 layers, 1824 total segments



arxiv:2607.20390





Yue et. al (2026)

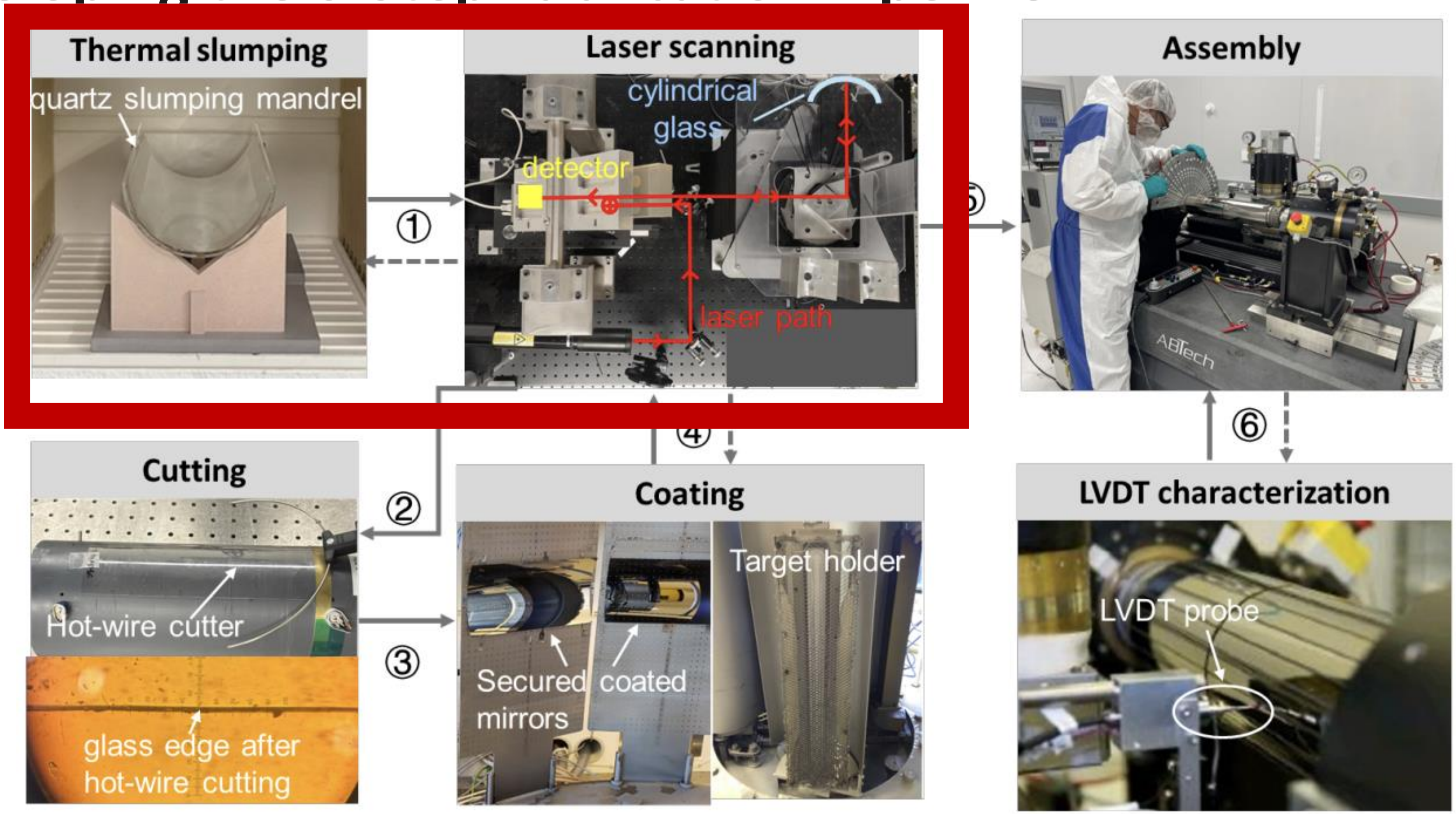
3

Fabrication

Objectives for the Summer

- Curve glass for first 10 layers of inner core optic
- Ensure quality and accuracy of glass relative to perfect cylinder
- Optimize production for consistency and efficiency for each radii (108, 110, 115, 120 and 125 mm)

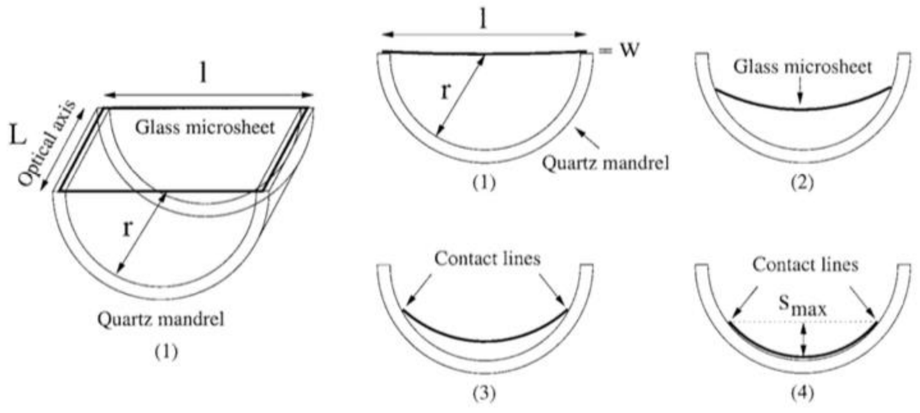
Developing the 6-Step Fabrication Pipeline



arxiv: 2607.20282

Curving flat glass into optical shapes

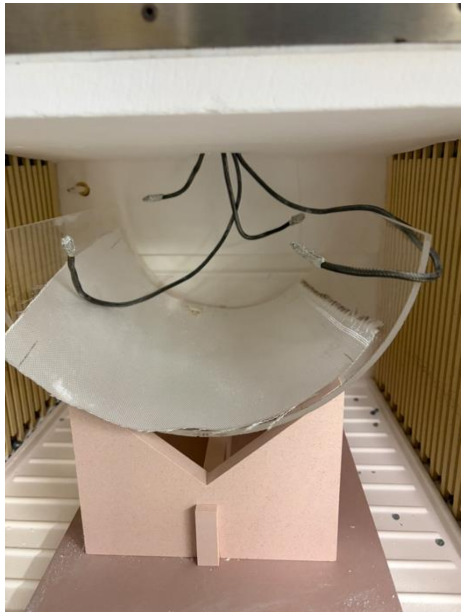
- Use smooth Schott D263 glass on quartz mandrel
- Vulcan 3-1750 furnaces lowers viscosity of glass, gravity pulls it down
- Oven and radii dependent

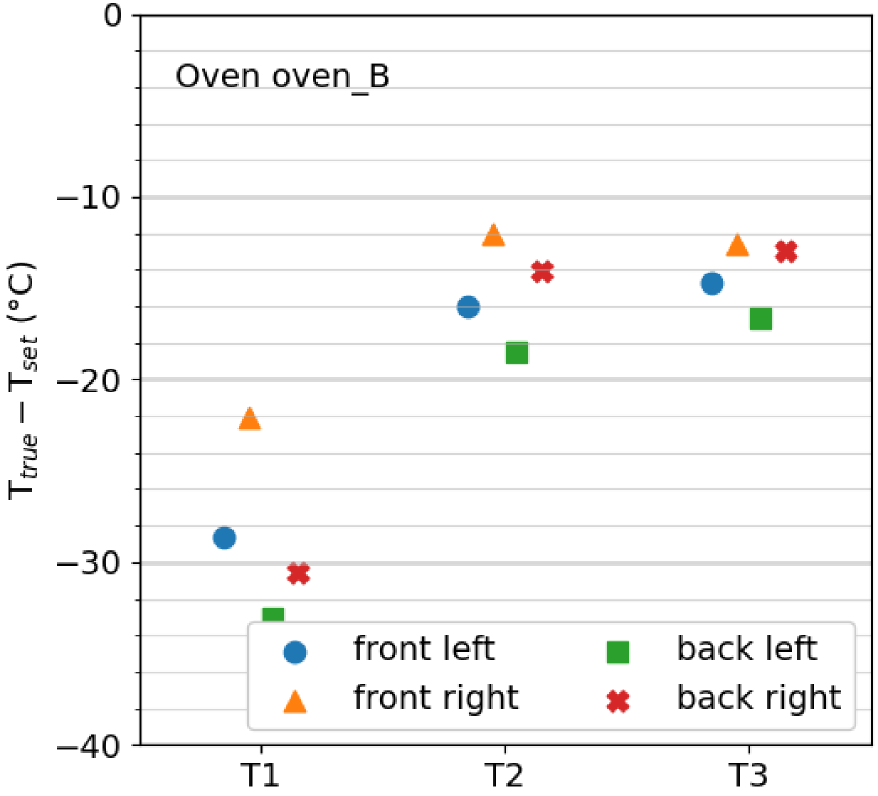


Jimenz-Garate et. al. (2003)

Discovering Spatial Temperature Differences in Ovens

- Each oven has a "personality"
- Personalities lead to defects
- Slump, scan, change settings
- Mandrel positioning
- Feedback loop based on glass quality and oven parameters
- Profile oven to make process more efficient and logic-based

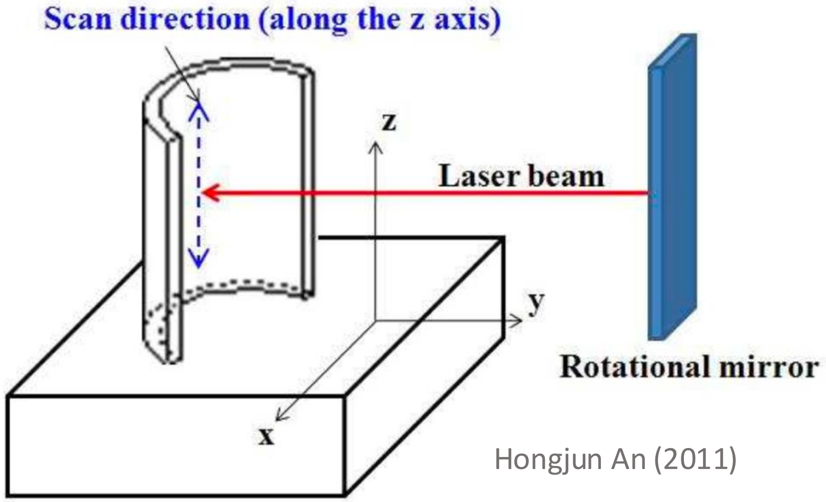




4

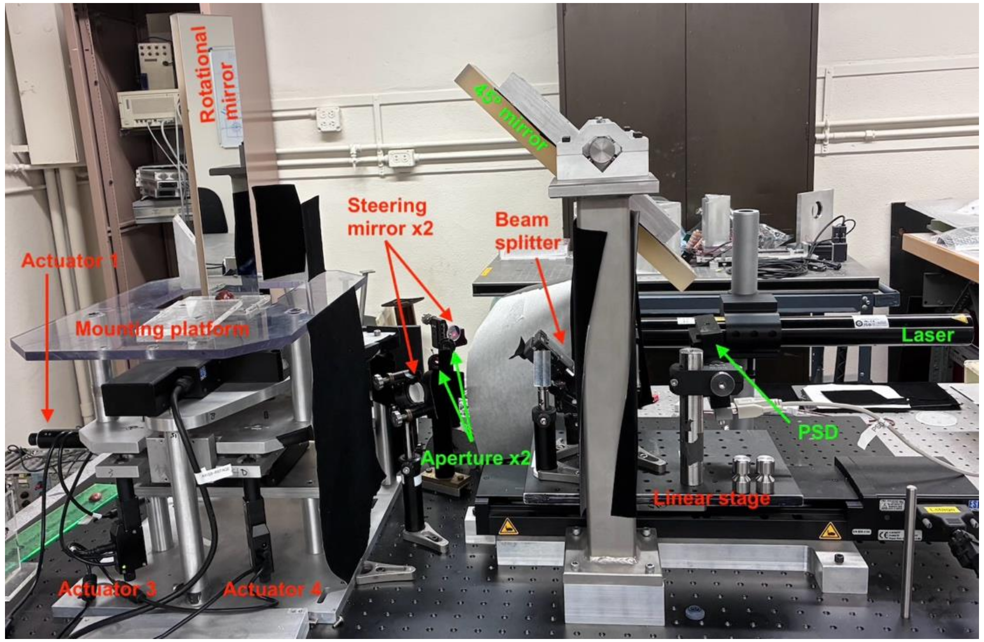
Scanning & IDL Data Analysis Conversion

Laser Scanning of Glass Segments



Hongjun An (2011)

- Laser swept across the concave surface
- Deviations from a perfect cylinder deflect the return
- Generate height map indicating quality of glass
- Occurs before and after cutting



Why Convert IDL to Python?

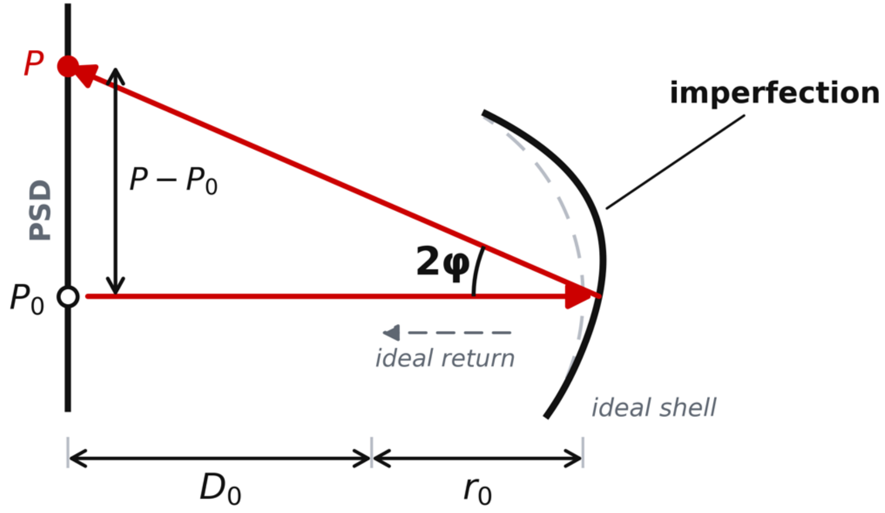
- 25-year-old IDL, heritage in HEFT and NuSTAR X-ray analysis experiments
- Licensed
- Hard to maintain
- Not version controlled
- Two goals: replicate exactly, then improve

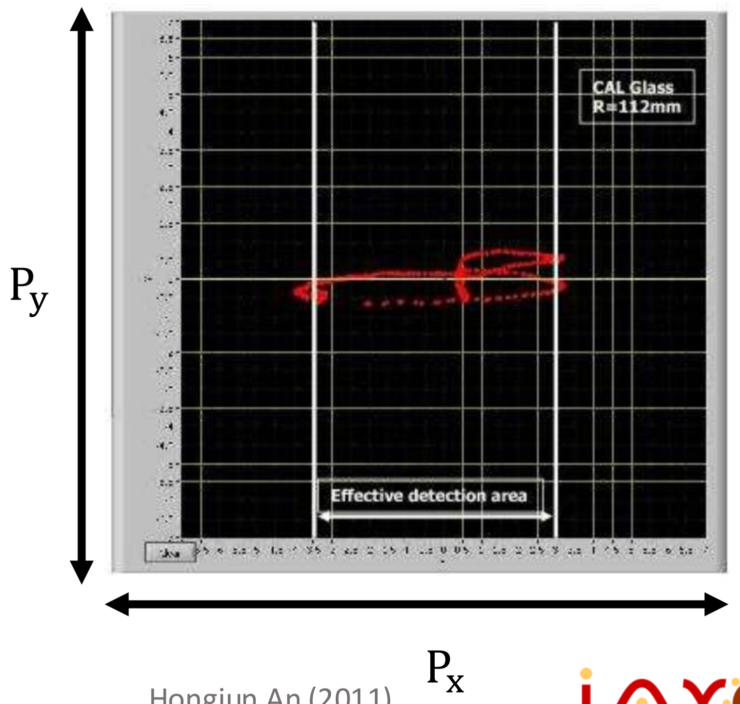
From Laser Deflection to 3D Profiles

$$\frac{\partial r}{\partial \theta} = \frac{P_x}{2\,(D_0 + r_0)}\, r_0$$

$$\frac{\partial r}{\partial z} = \frac{P_y}{2\,(D_0 + r_0)}$$

- Ingest all scan data
- Slopes from the PSD positions
- Integrate the slopes into a height map
- Strip plane, phase, and bow, and other errors



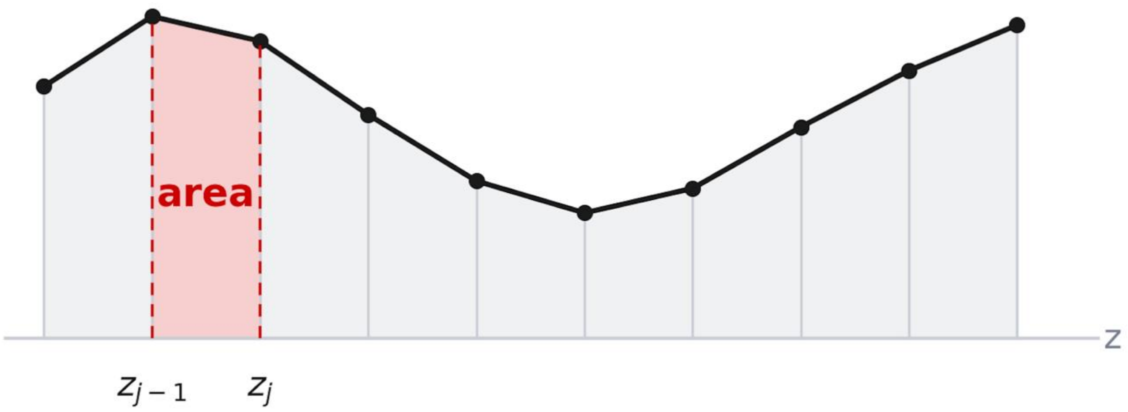


Hongjun An (2011)

Reconstructing the Surface

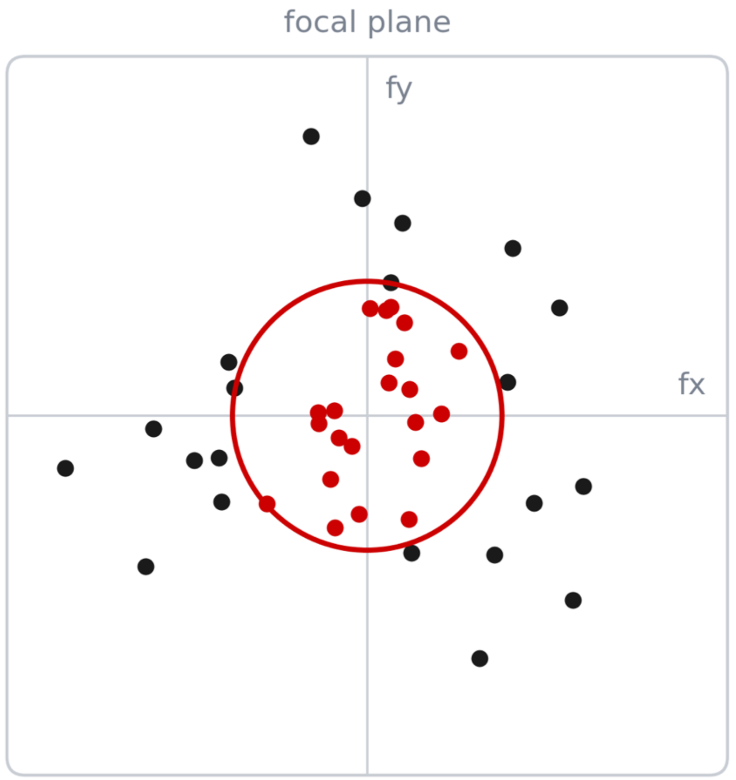
- Slope drives resolution, not height
- Two directional derivatives at every point
- Build with trapezoidal approximations
- Stitch the 31 axial scans together

$$g_{:,j} = g_{:,j-1} + \frac{\left[\left(\frac{\partial g}{\partial z}\right)_{:,j} + \left(\frac{\partial g}{\partial z}\right)_{:,j-1}\right]}{2}\Delta(z_j).$$



Computing Half Power Diameter (HPD)

- HPD – measure of glass quality (lower is better)
- Keep below 76 arcseconds
- Grid of virtual lasers, ray traced to the focal plane
- Diameter of smallest circle holding half of the landings
- Second mirror adds a $\sqrt{2}$ error multiple
- Or convolve the miss distribution with itself
- Remove skew and bow errors



5

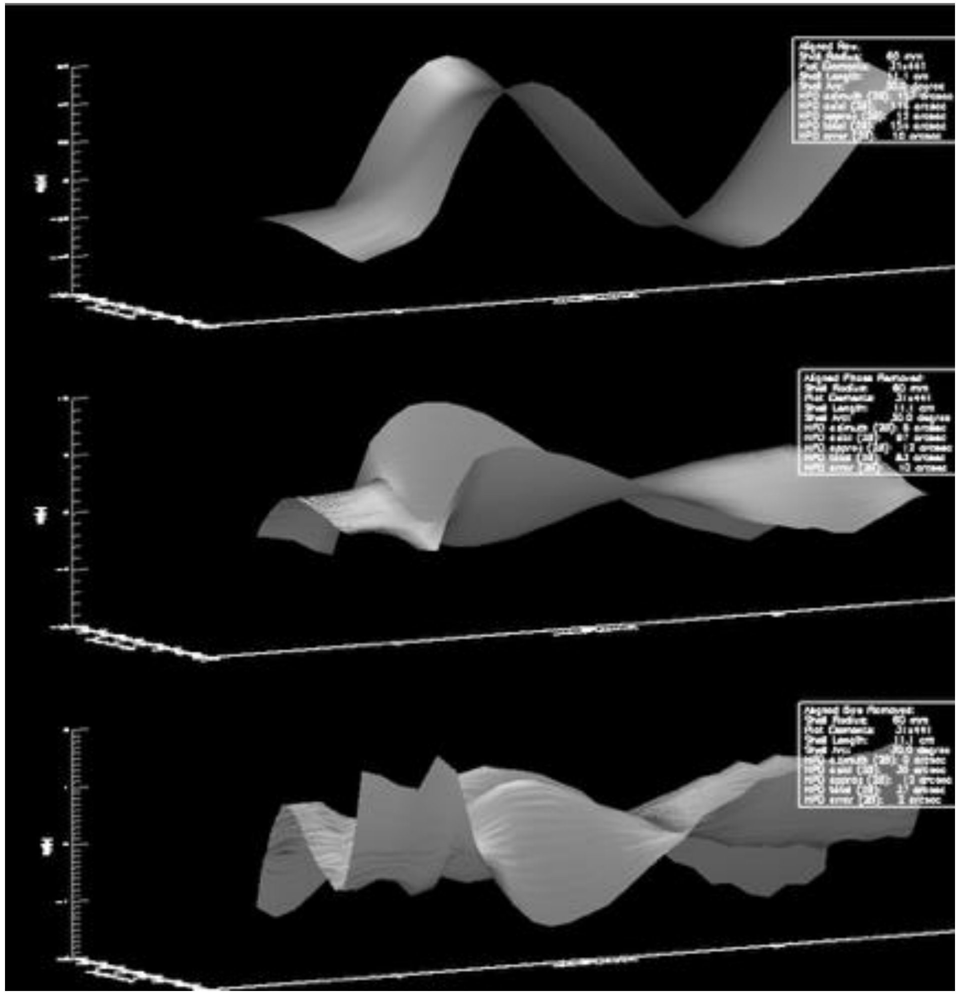
Results

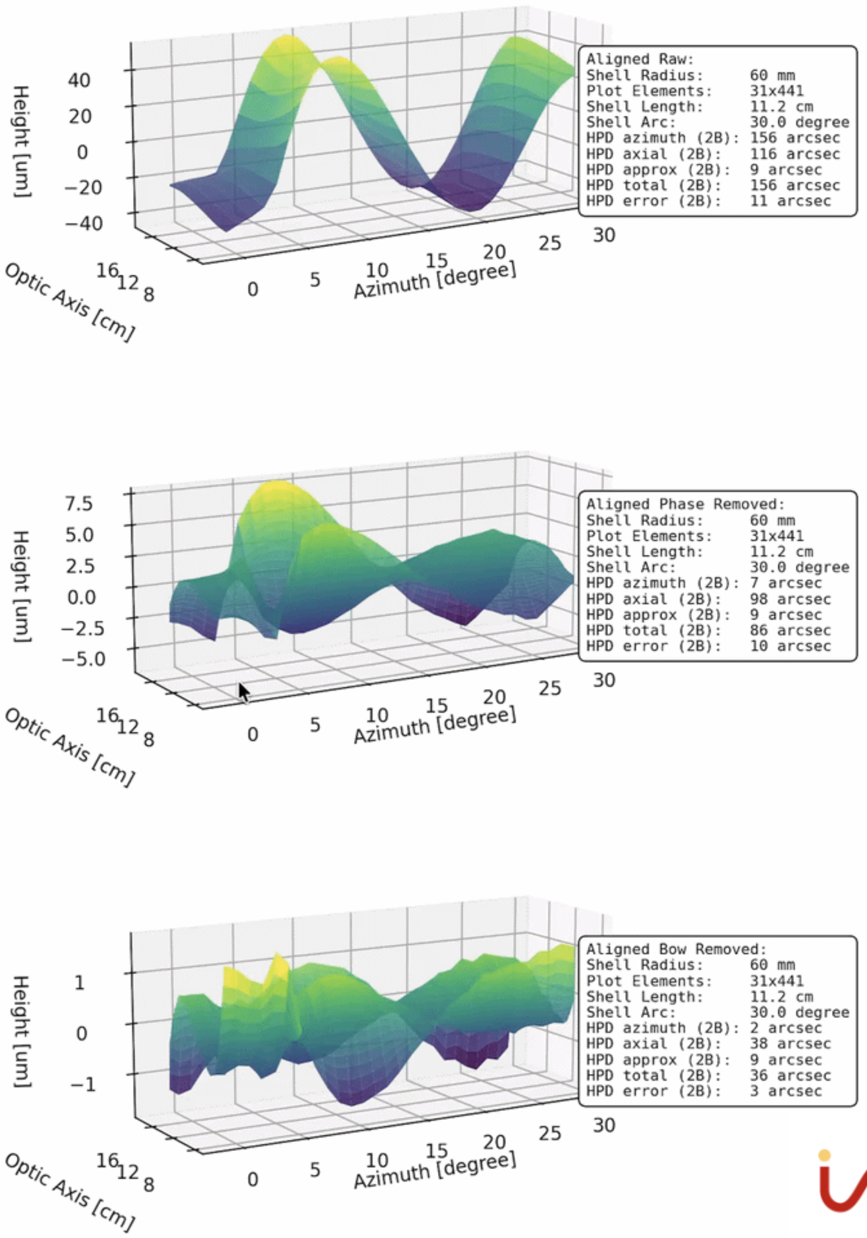
IDL vs. Python

Raw

Phase Removed

Bow Removed

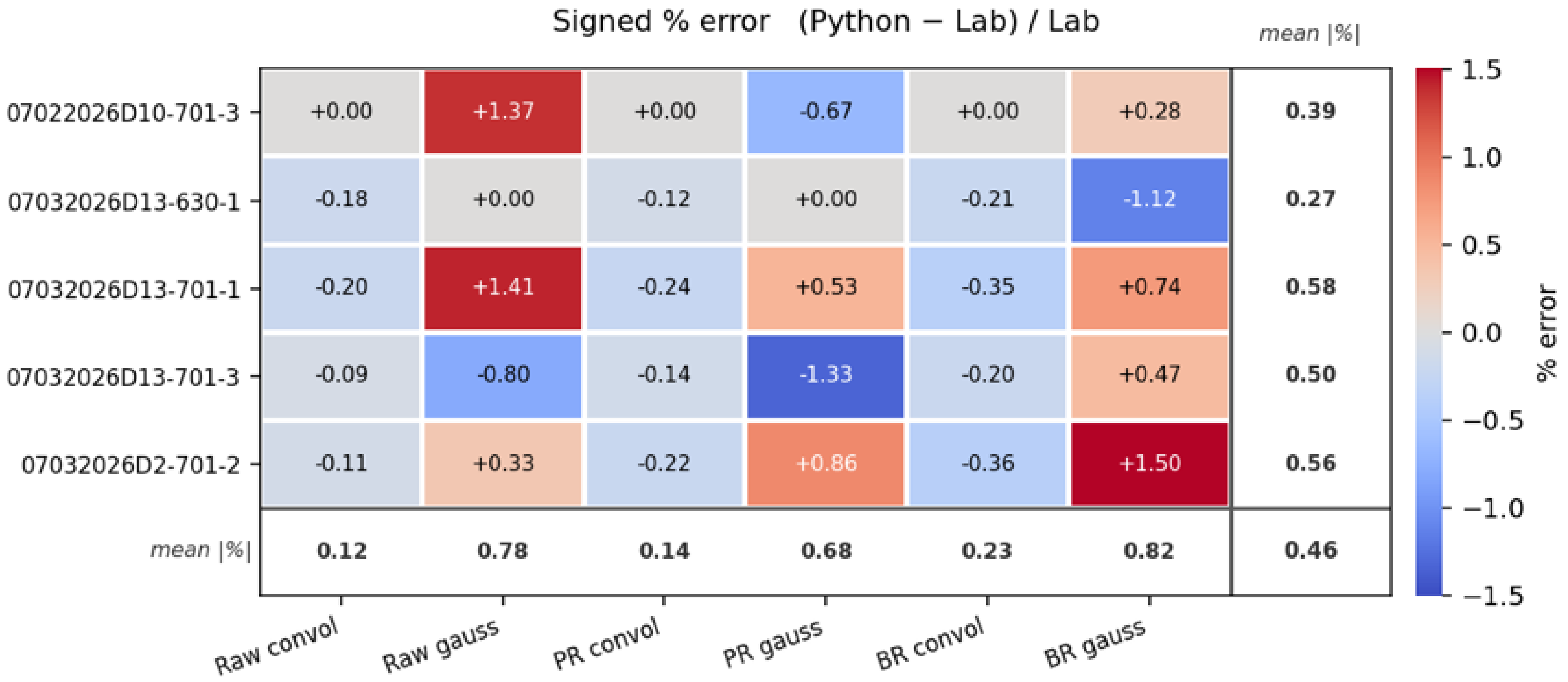




Protrusion

IDL vs. Python

Different segments



Two Different Error Calculations for Each Profile

Future Work

- Trial period running Python alongside IDL
- Test on poor-quality glass, not just good
- Profile more ovens to aid development toward the full optic

Acknowledgements

- Prof. Kerstin Perez and the Perez Lab
- Dr. Jooyun Woo and Dr. Yue Yu
- Nevis Labs REU, led by Prof. Kariogiorgi and Prof. Mukherjee

Thank You!