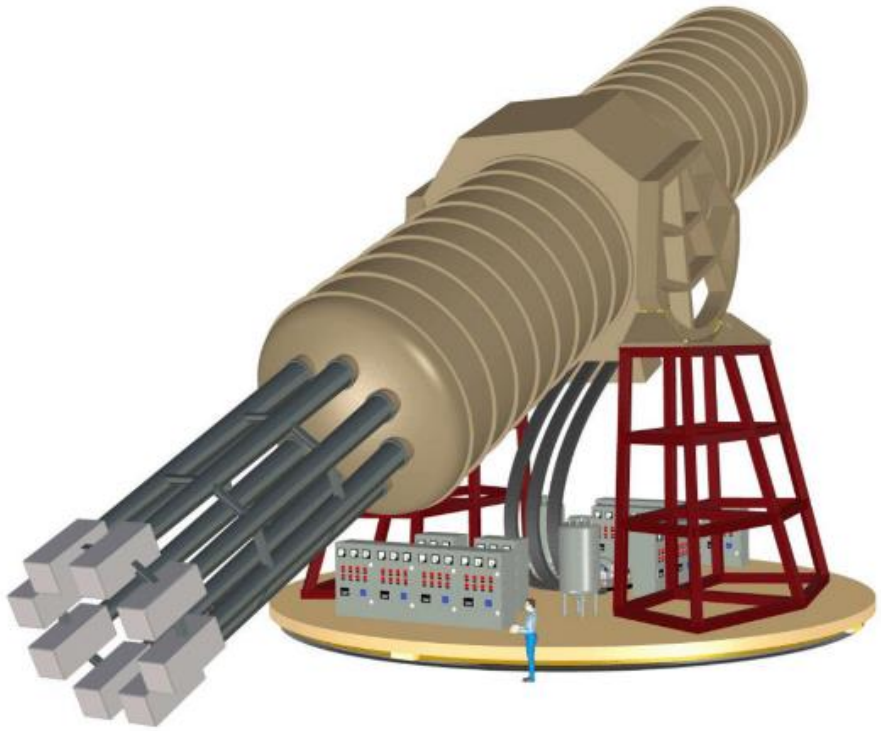
Optimizing The X-ray Optics Fabrication Process for BabyIAXO



Vyshu Sabbi

Kerstin Perez, Jooyun Woo, Yue Yu

July 31, 2025

Nevis REU 2025

International Axion Observatory

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

NEVIS LABORATORIES COLUMBIA UNIVERSITY

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Strong CP Problem

Strong CP Problem

- Charge conjugation-Parity
- Fundamental symmetry
- Part of the Standard Model

Strong CP Problem

- 3 forces covered by Standard Model
  - Strong force
  - Weak force
  - Electromagnetic force

Should **break** CP symmetry sometimes

Only one that should **conserve** CP symmetry

conjugation-Parity

- Fundamental symmetry
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Strong CP Problem

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  - Strong force
  - Weak force
  - Electromagnetic force

Should **break** CP symmetry sometimes

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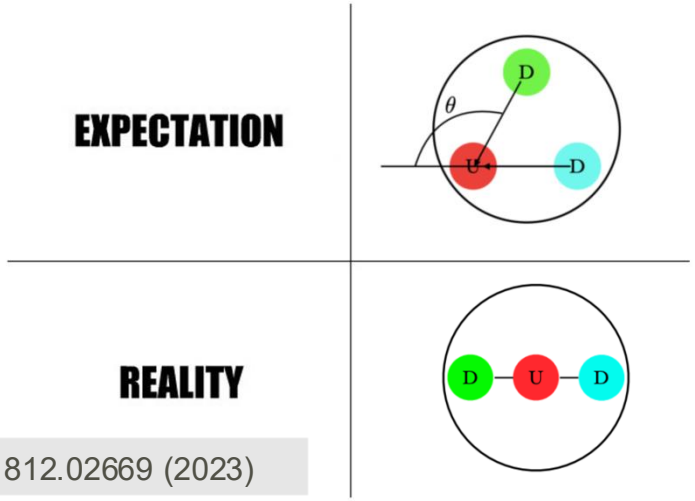
conjugation-Parity

- Fundamental symmetry
- Part of the standard model

- Neutron Electric Dipole Moment is experimentally not observed to 10^{-26} precision without any known reason??



Hook arXiv 1812.02669 (2023)

Peccei and Quinn "Clean Up" CP Problem With The Axion

R. Schude, Quanta Magazine.

QCD Axions

$< 1\ eV/c^2$

- Light, spinless particles that arise when PQ symmetry is broken
  - Feebly interact with Standard Model particles
- Purpose: extend Standard Model to "clean up" CP problem
- Why so popular?

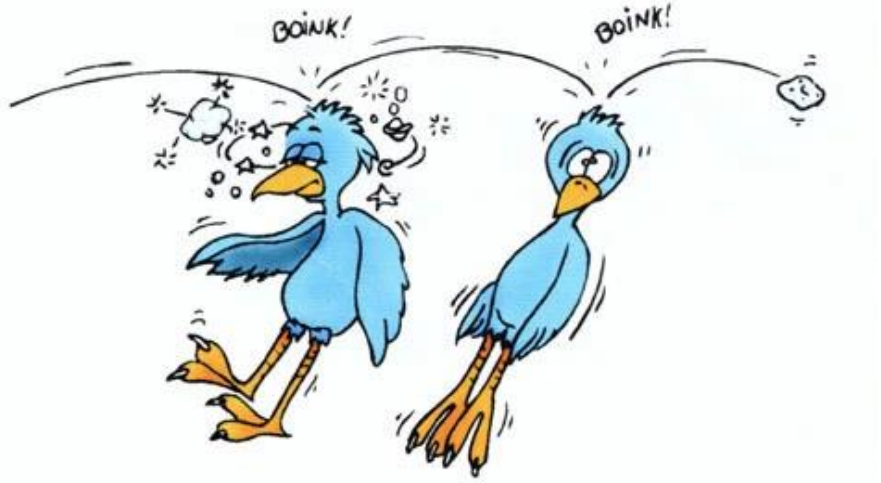
Illustration by Sandbox Studio, Chicago with Steve Shanabruch

QCD Axions

$< 1\ eV/c^2$

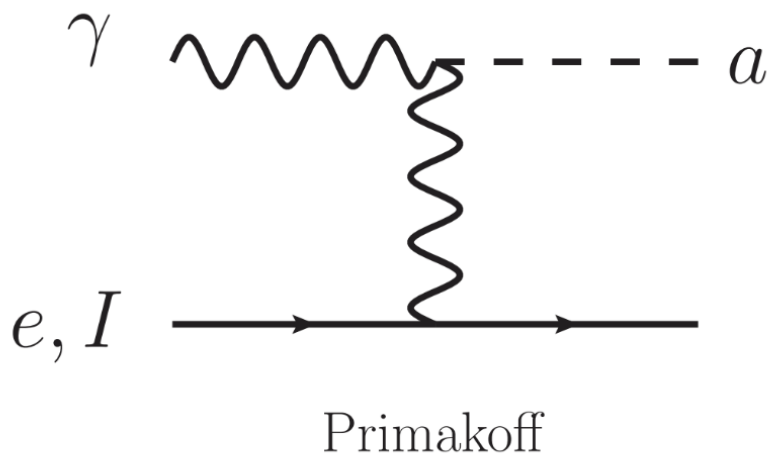
- Light, spinless particles that arise when PQ symmetry is broken
  - Feebly interact with Standard Model particles
- Purpose: extend Standard Model to "clean up" CP problem
- **Why so popular?**
  - **Solution to CP problem AND really good dark matter candidate**

Illustration by Sandbox Studio, Chicago with Steve Shanabruch



Primakoff Effect: A Way To Detect Axions

- Axion couple (interact) with photons



Redondo JCAP 1312 008 (2013)

Sandbox Studio, Chicago, Symmetry Magazine/Fermilab and SLAC

Electromagnetic field

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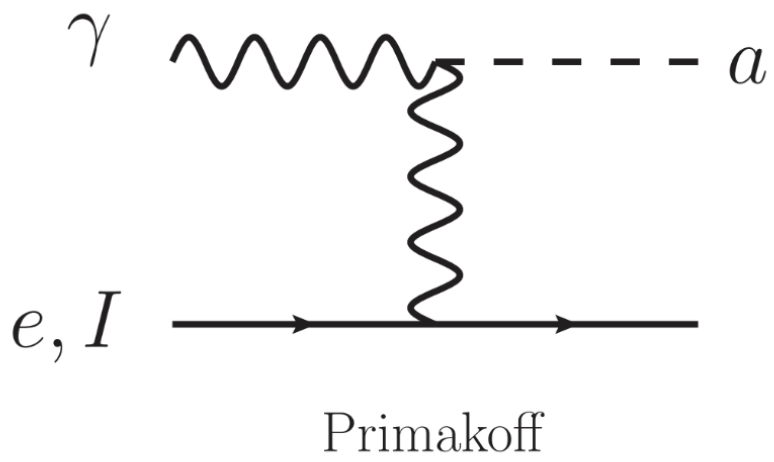
- Axion couple (interact) with photons



Primakoff

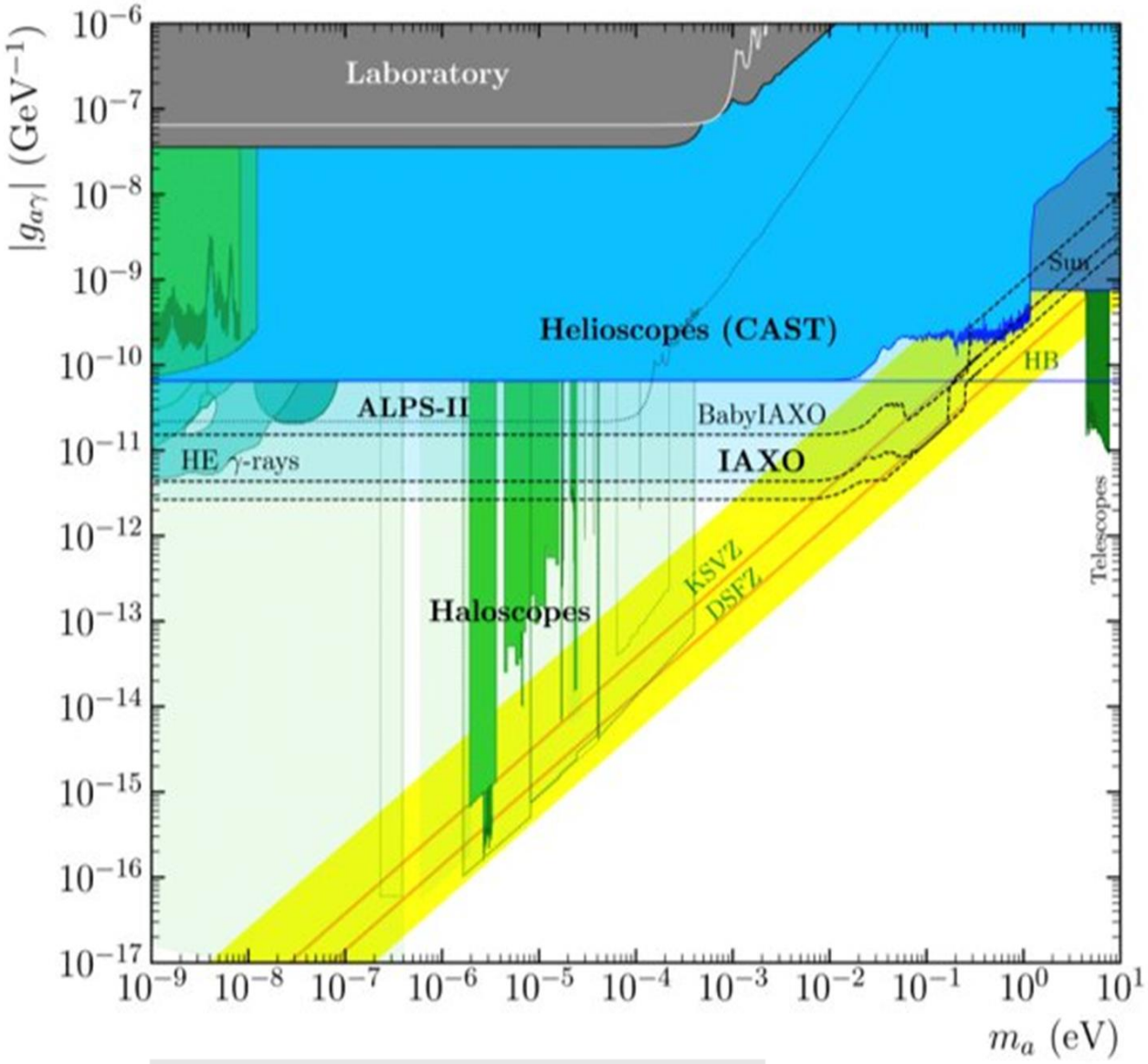
Redondo JCAP 1312 008 (2013)

Sandbox Studio, Chicago, Symmetry Magazine/Fermilab and SLAC

Why Primakoff?

Electromagnetic field

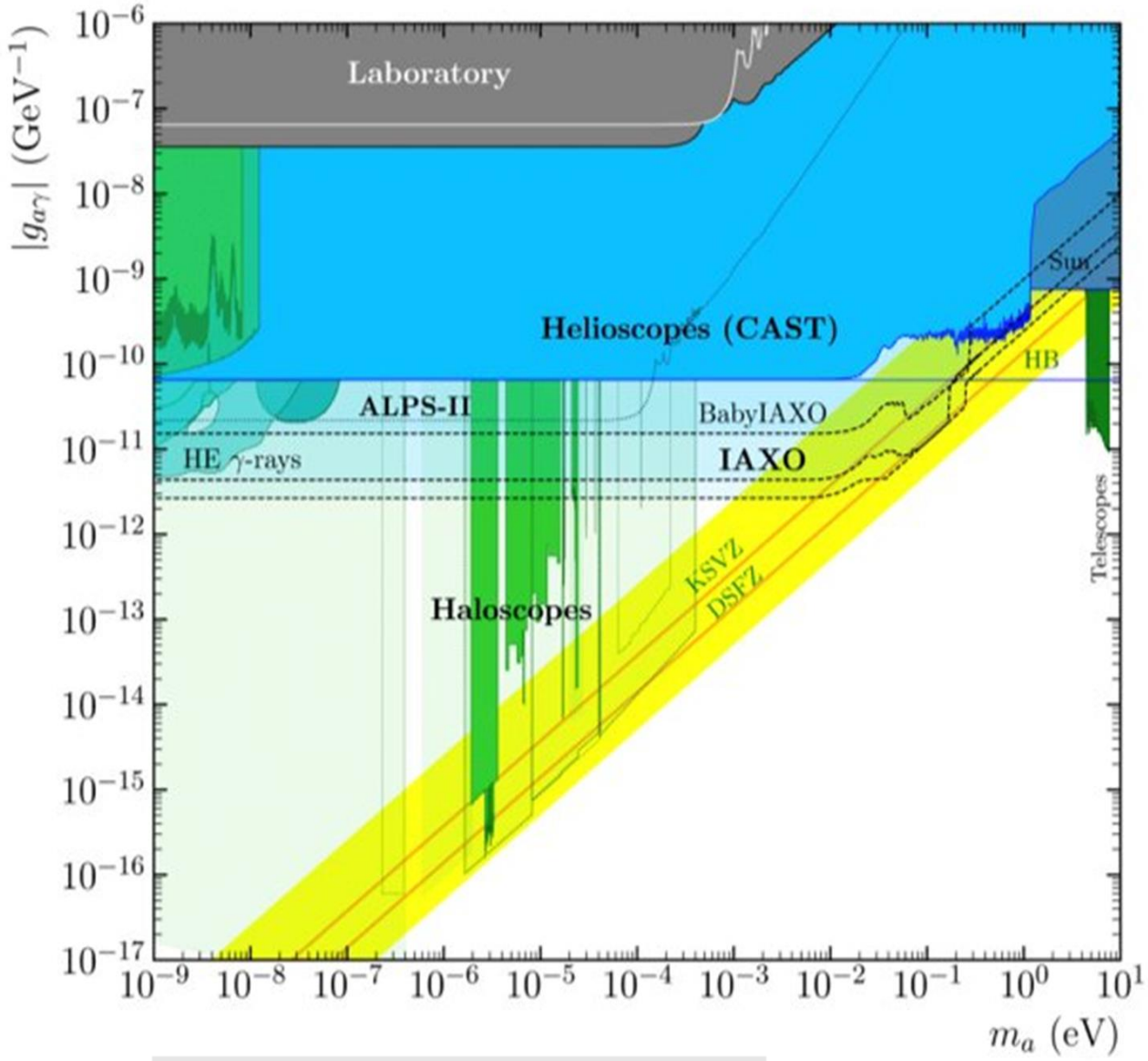
Axion-Photon Coupling Parameter Space



IAXO Collaboration, JHEP 05 (2021) 137

Axion-Photon Coupling Parameter Space

Stronger coupling to photons (*easier to find*)



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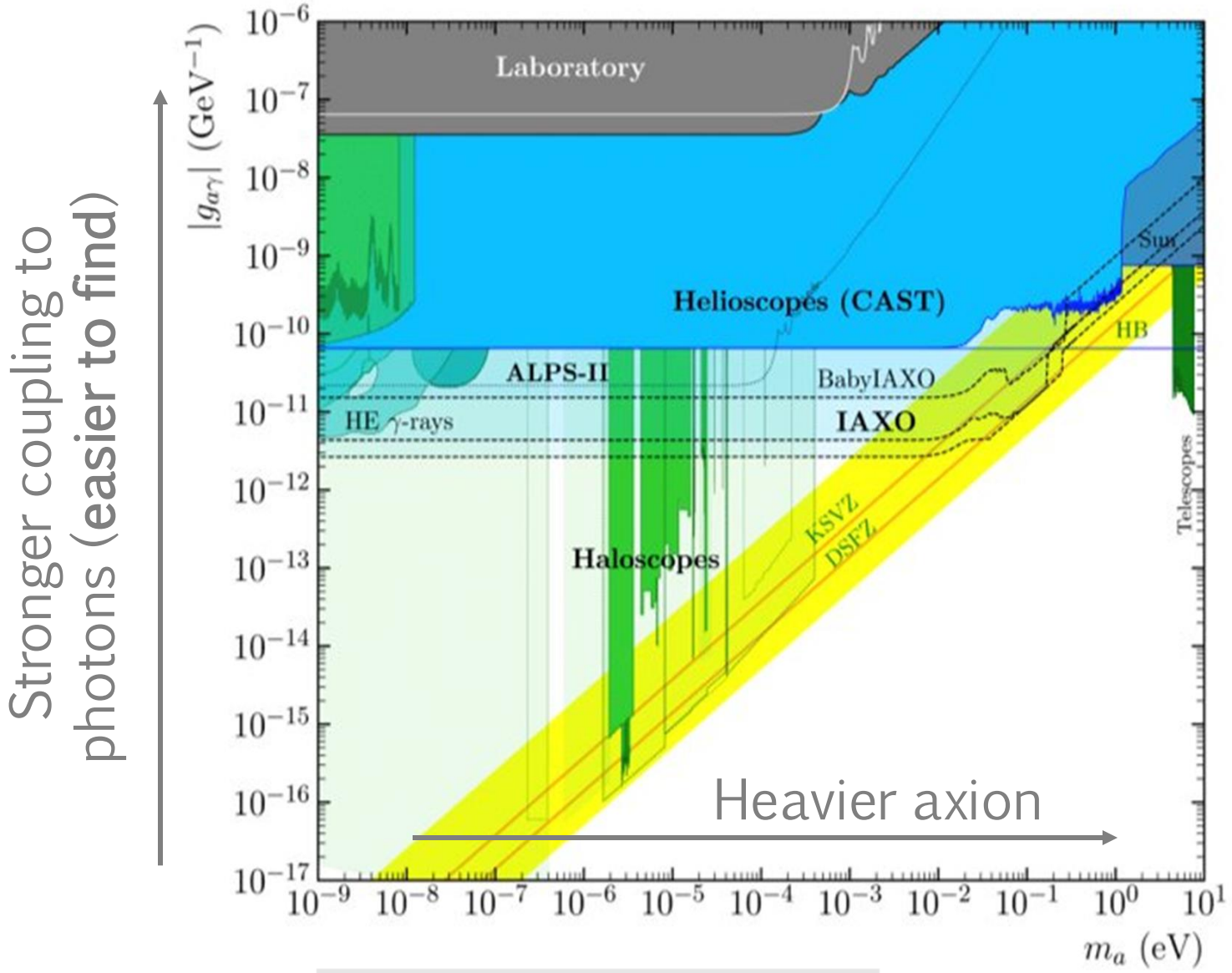

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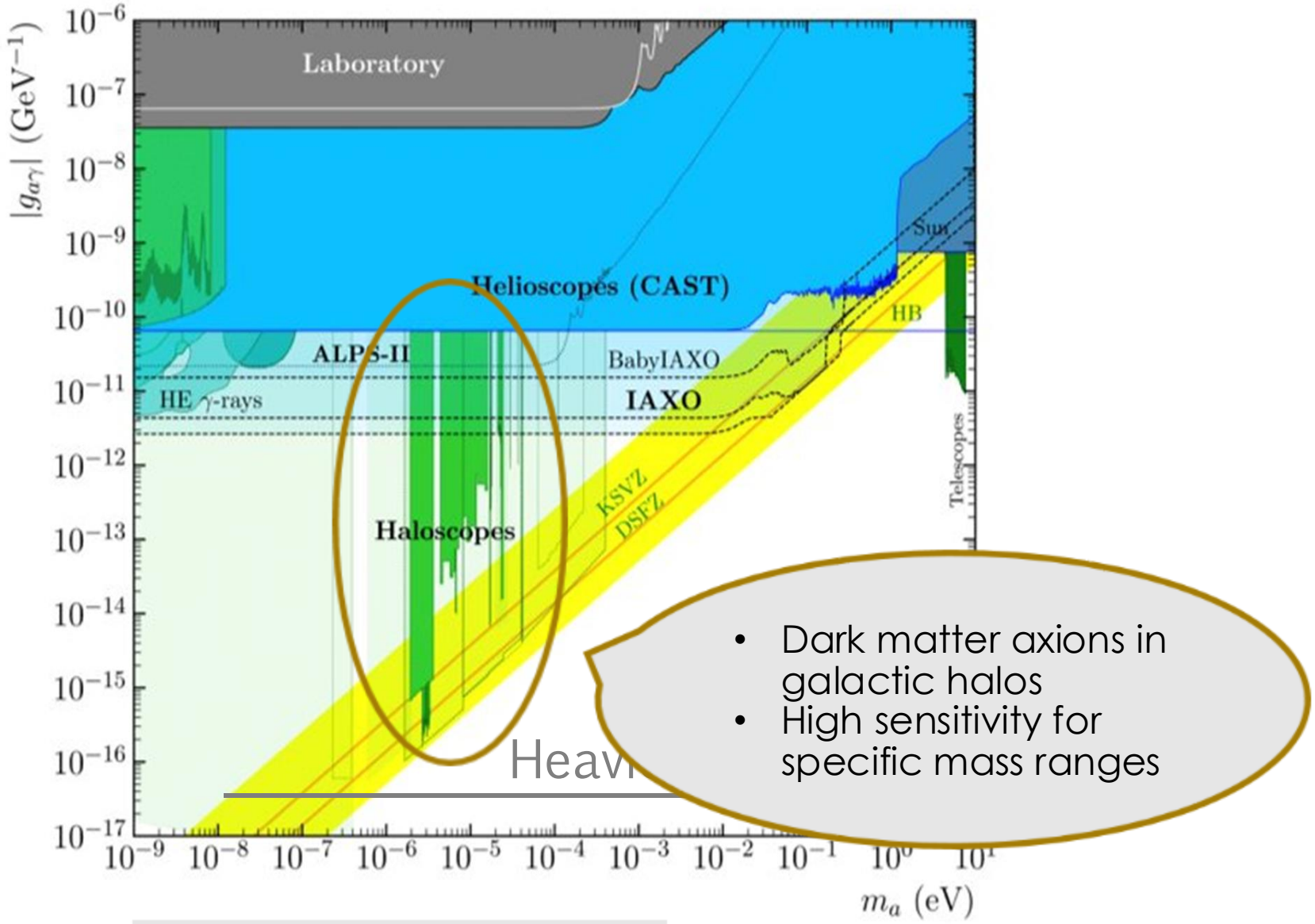
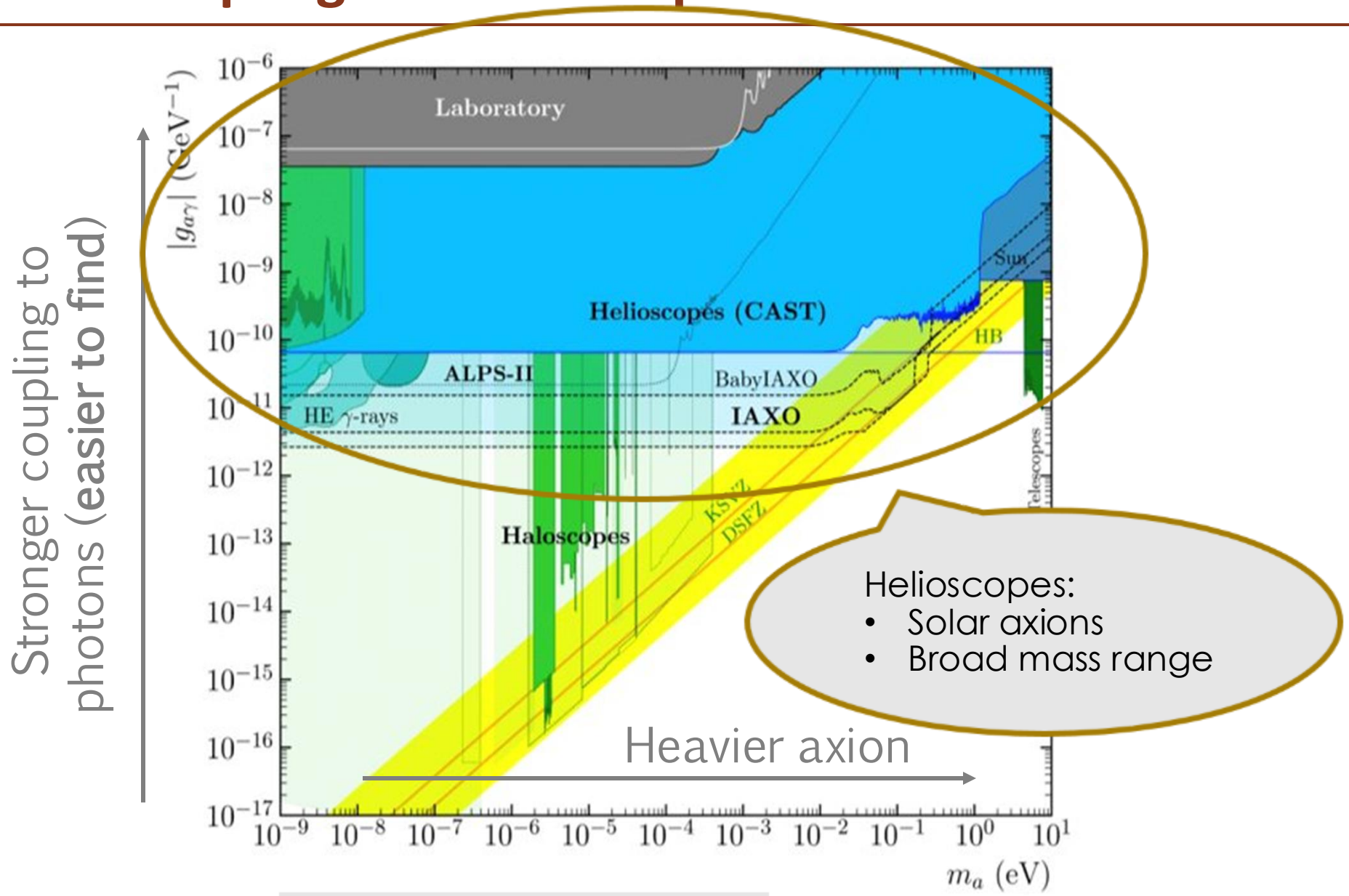


- Dark matter axions in galactic halos
- High sensitivity for specific mass ranges

IAXO Collaboration, JHEP 05 (2021) 137

Axion-Photon Coupling Parameter Space



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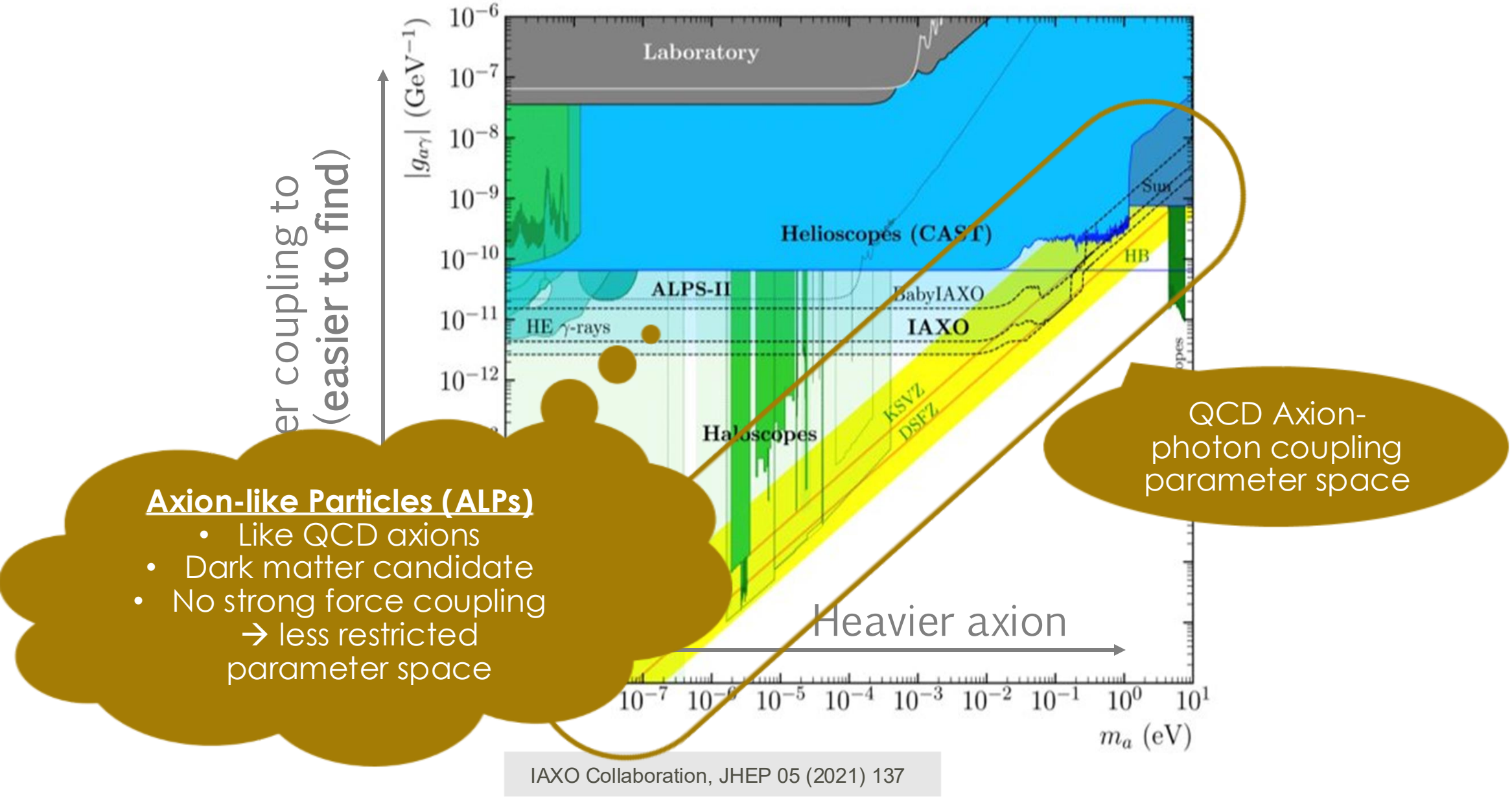

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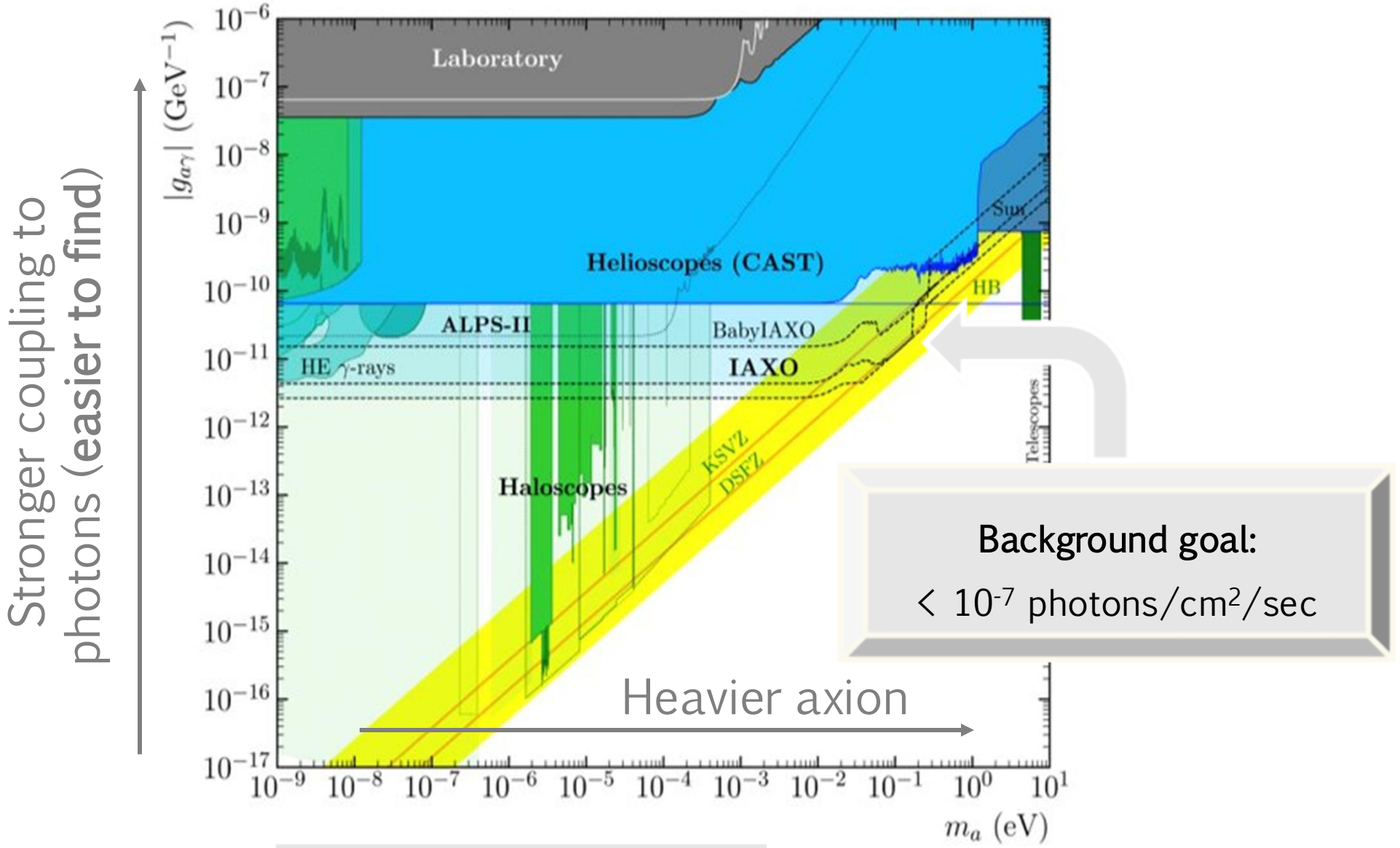

Background goal:

$< 10^{-7}$ photons/cm^2/sec

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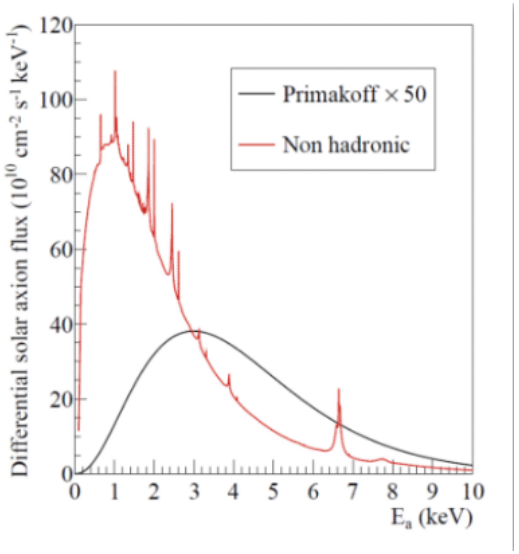
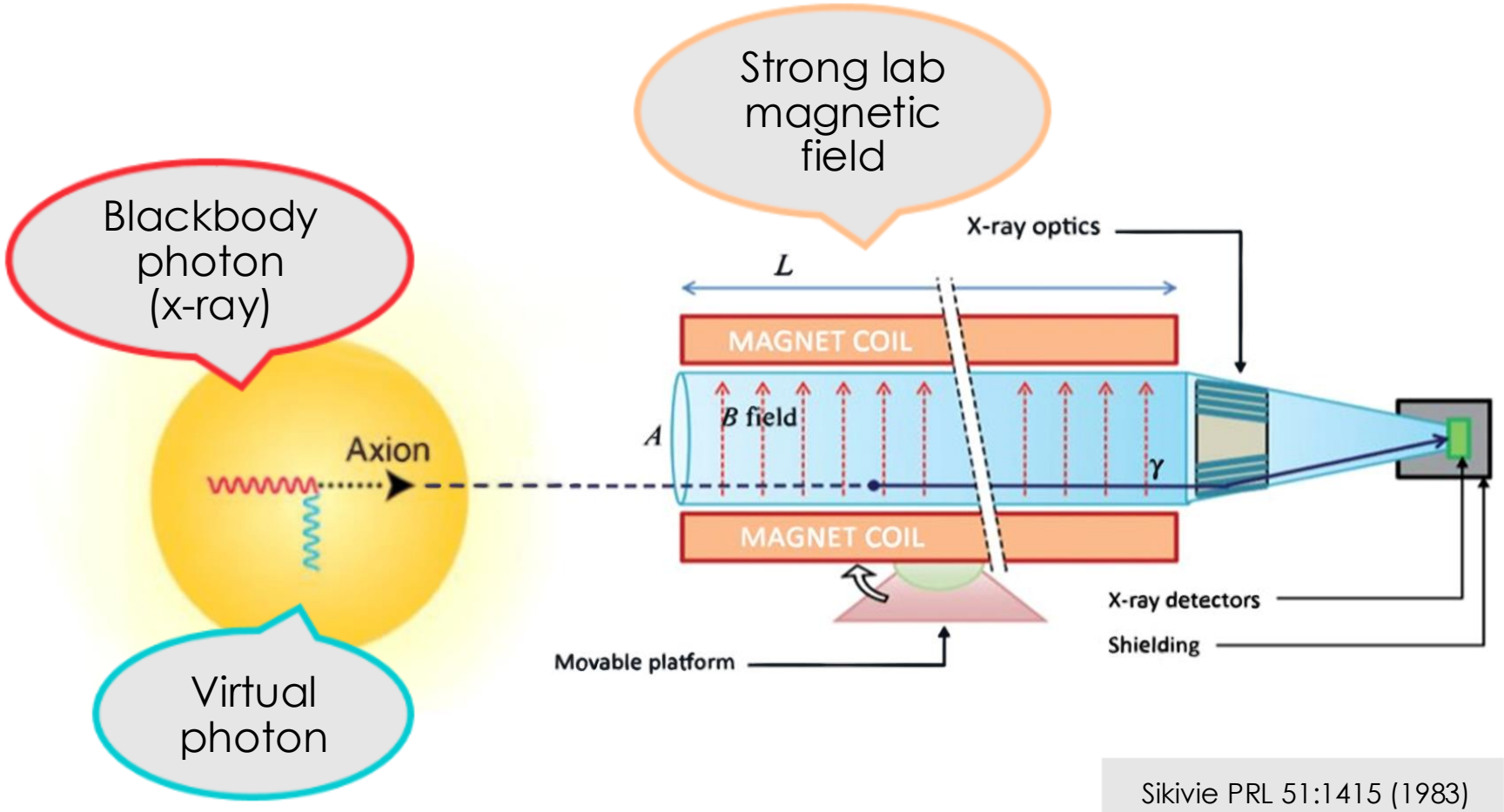
Axion Helioscope Experiment Design

Solar Axion Flux:

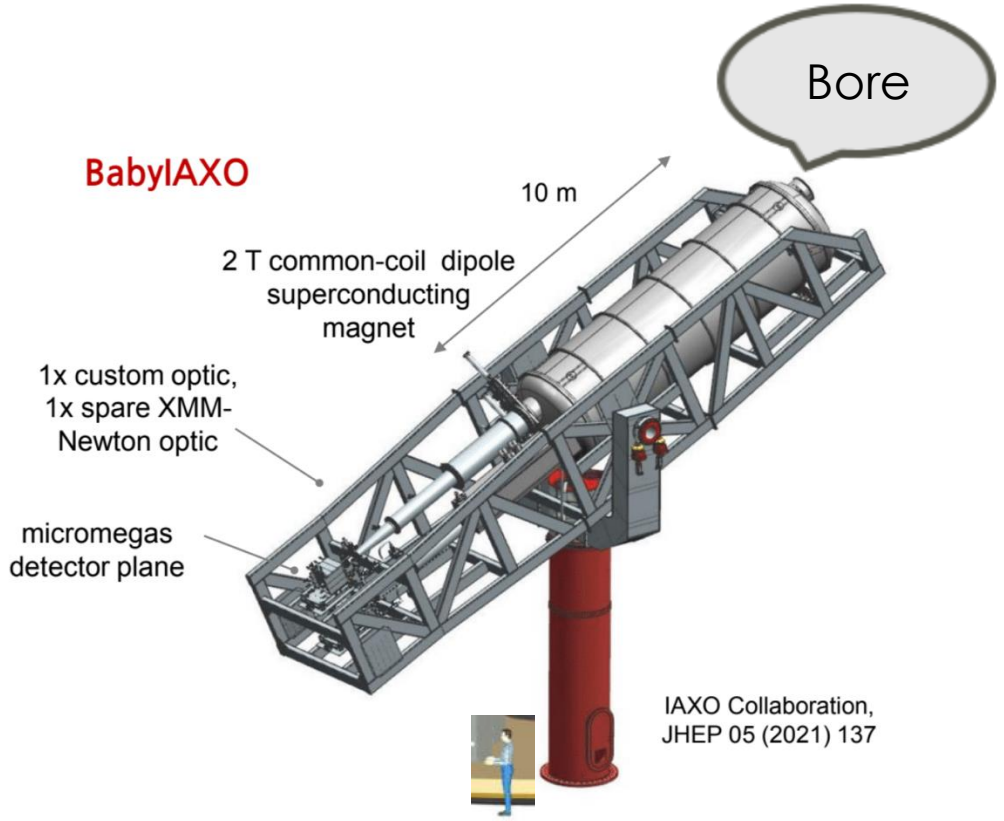


Redondo JCAP 1312 008 (2013)



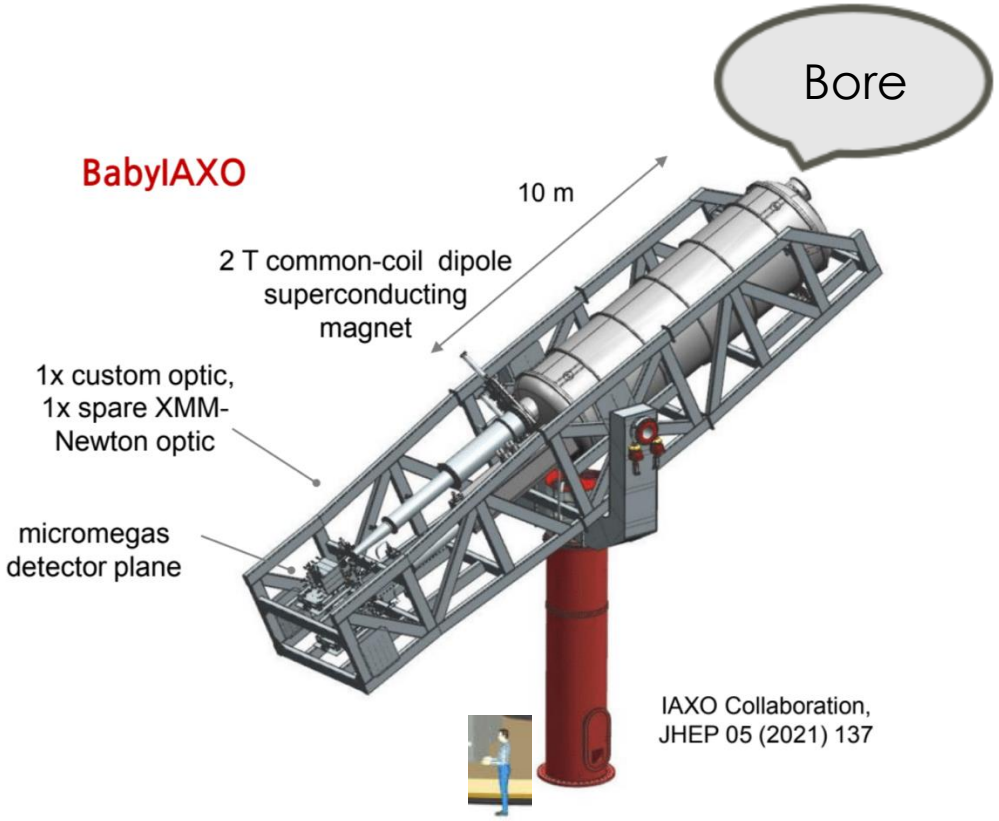
Sikivie PRL 51:1415 (1983)

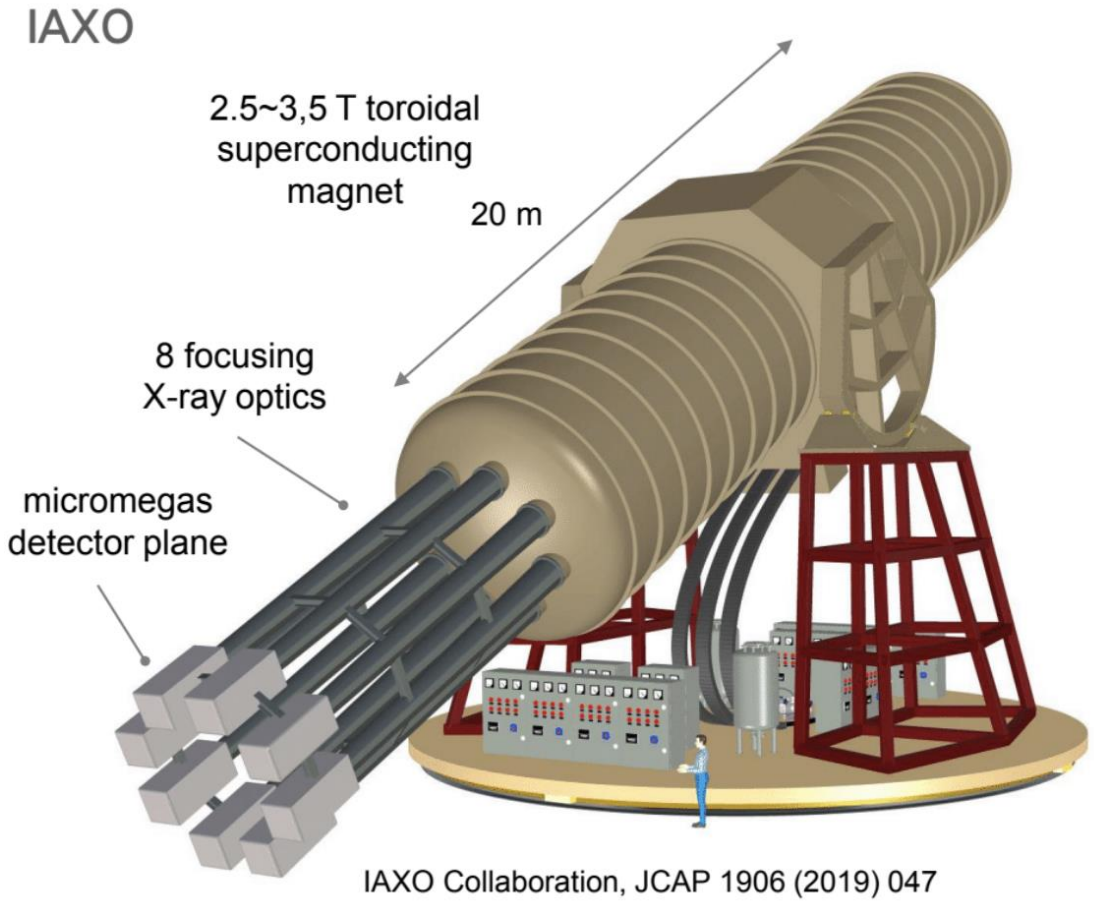
International Axion Observatory Conceptual Design



	BabyIAXO
Bore cross sectional area	.77 m^2

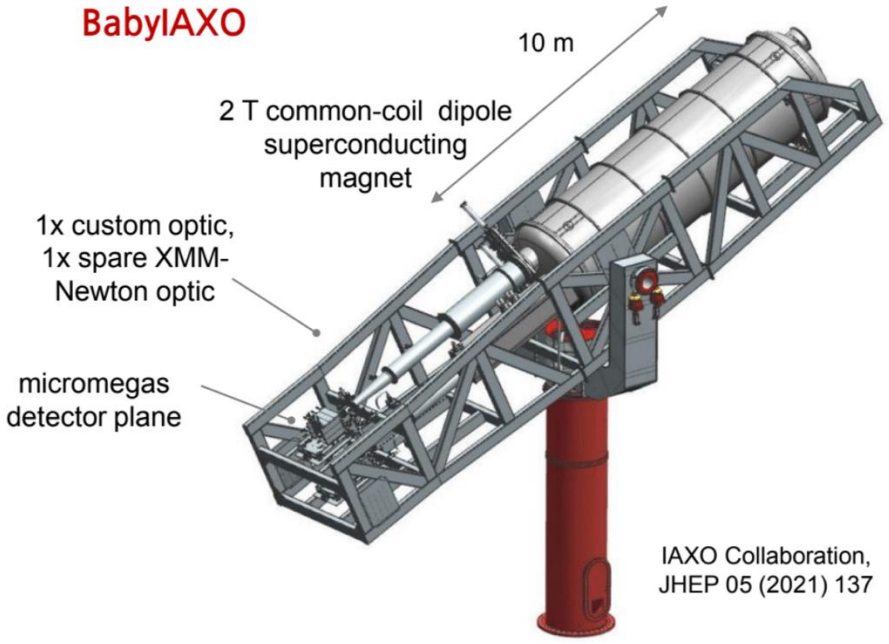
International Axion Observatory Conceptual Design





	BabyIAXO	IAXO, IAXO+
Bore cross sectional area	.77 m^2	2.3 m^2, 3.9 m^2

International Axion Observatory Conceptual Design



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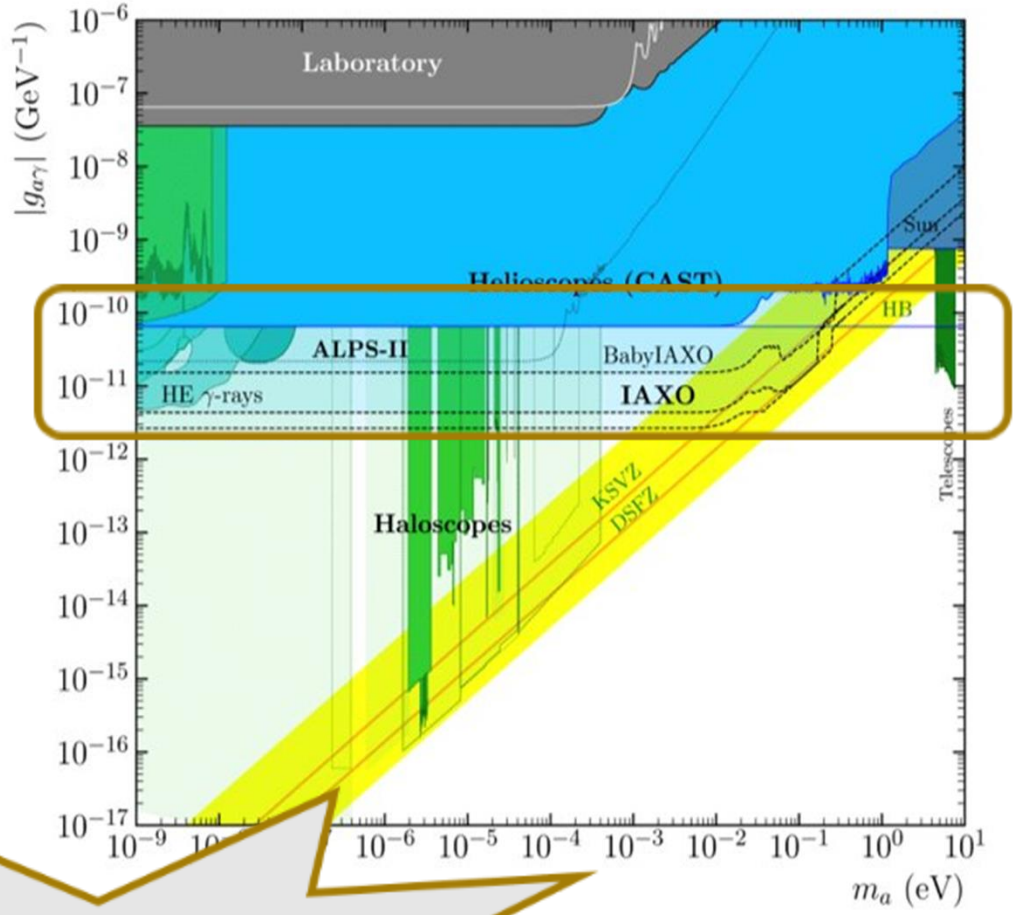
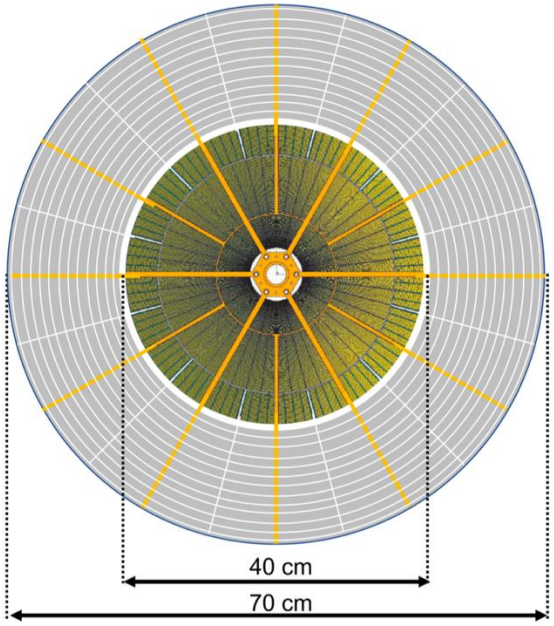


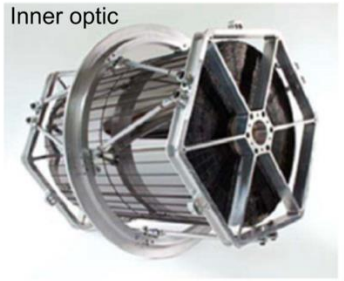
Unique sensitivity to QCD axions with $m_a > 10^{-3}$ eV

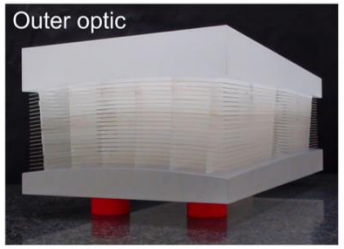
IAXO X-ray Optic

- This is what an x-ray optic has to look like:

Top view







Why?

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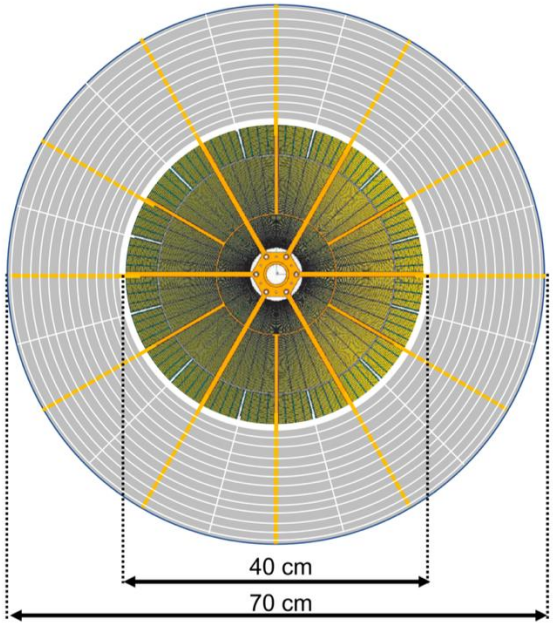

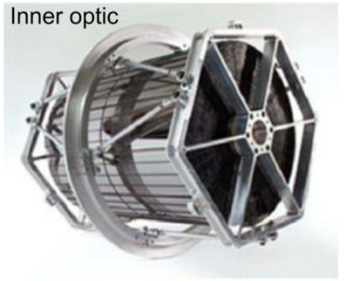

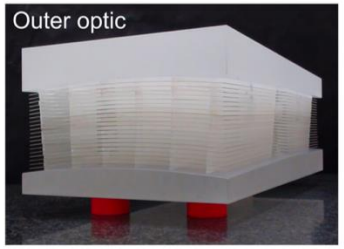

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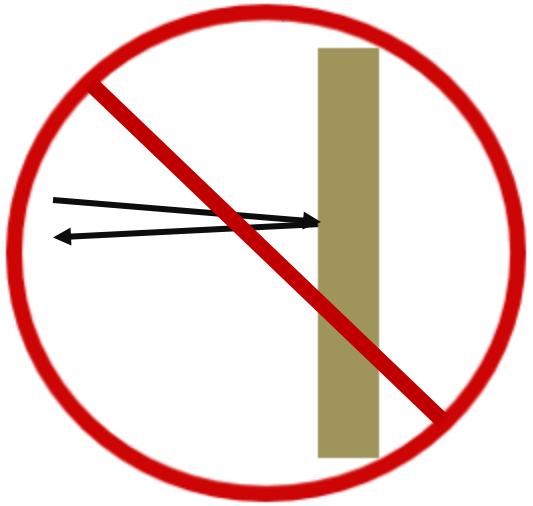
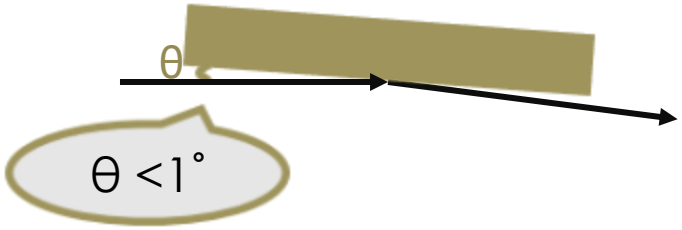


X-rays don't bounce!



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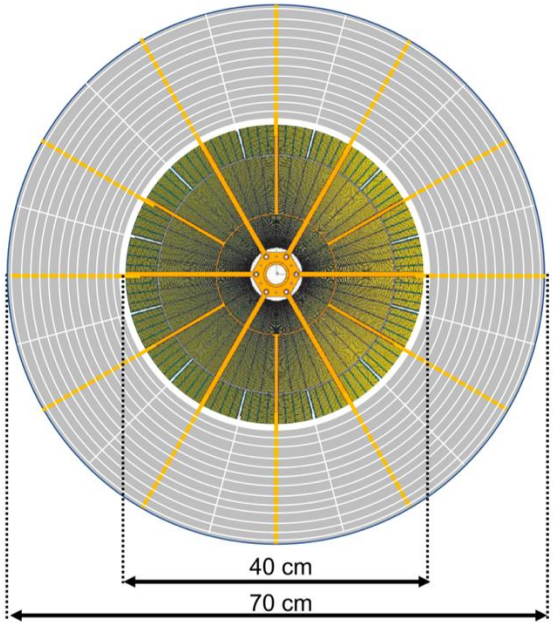

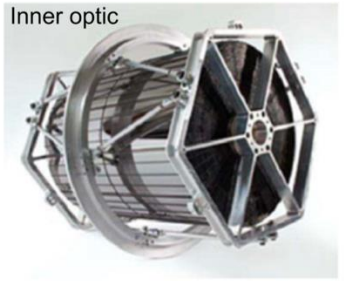

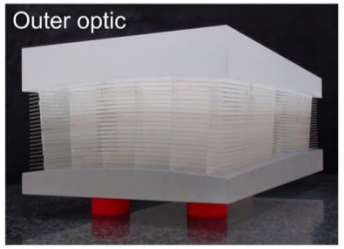

IAXO Collaboration, JHEP 05 (2021) 137

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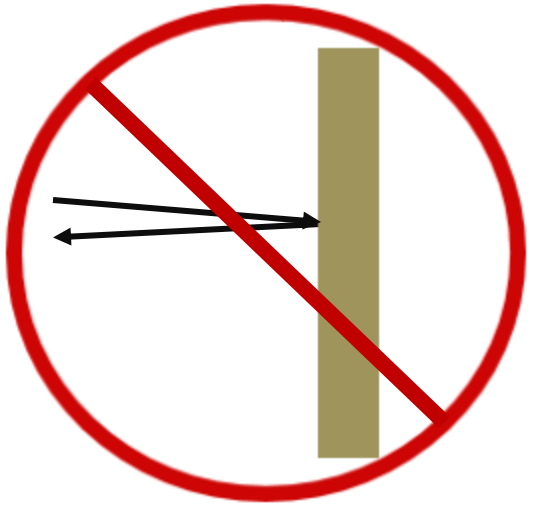
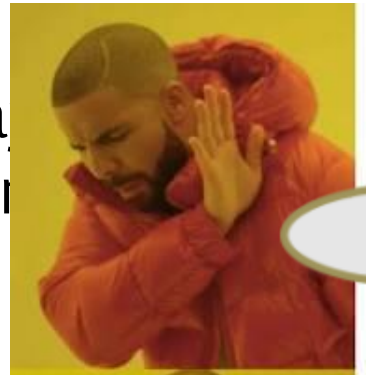
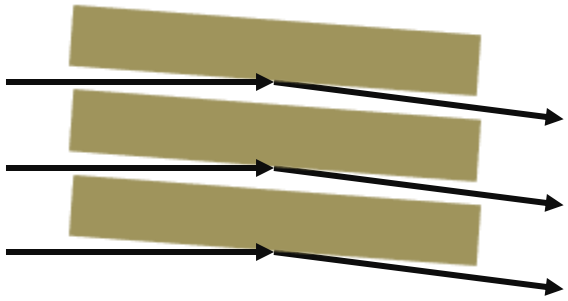


X-ra
bou

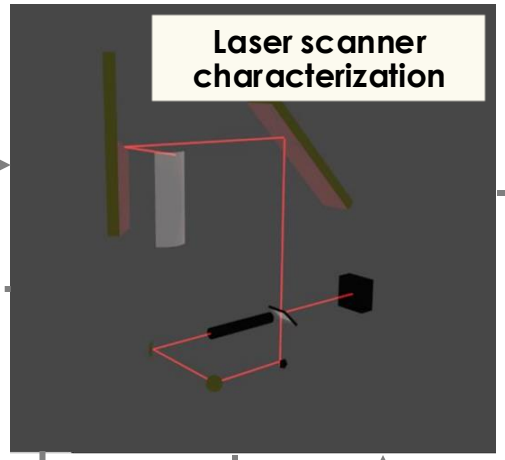


θ <1°



Optic Fabrication Process

1



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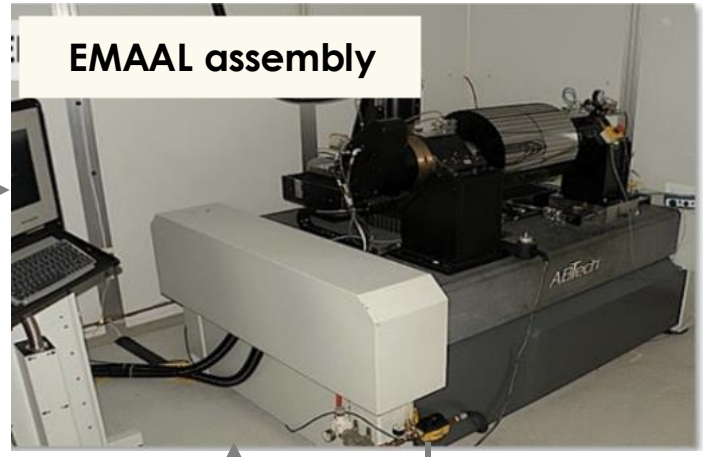
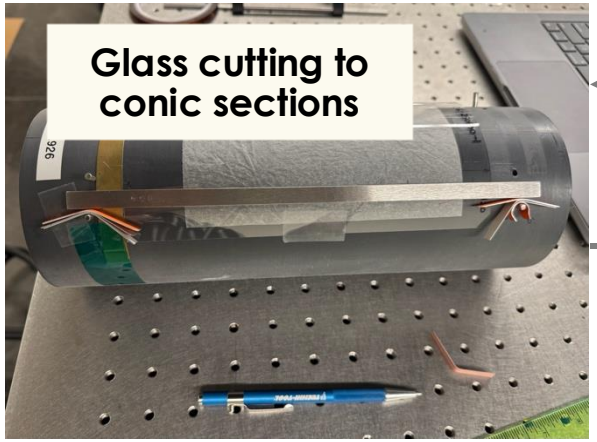


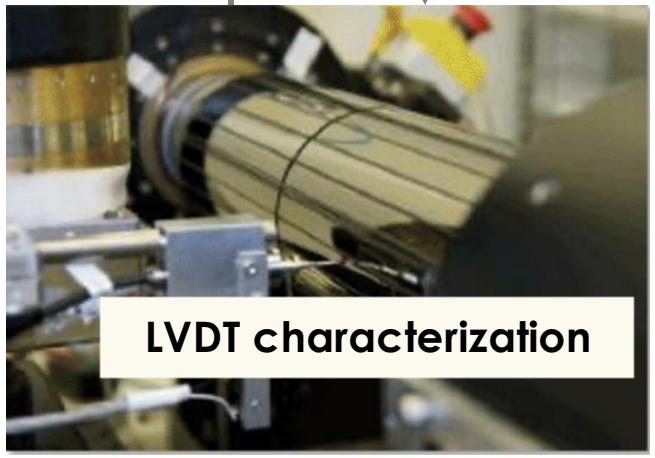
2

3

4

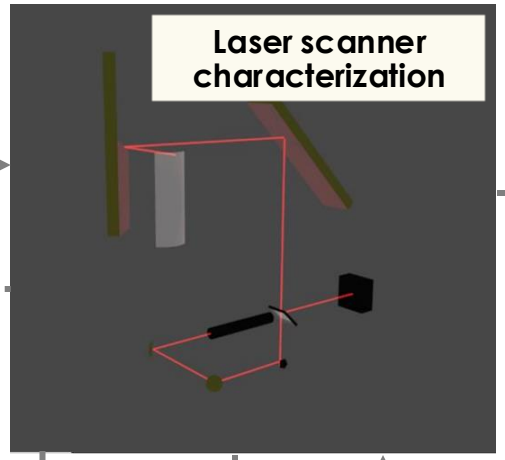
6





My Summer Goal

1



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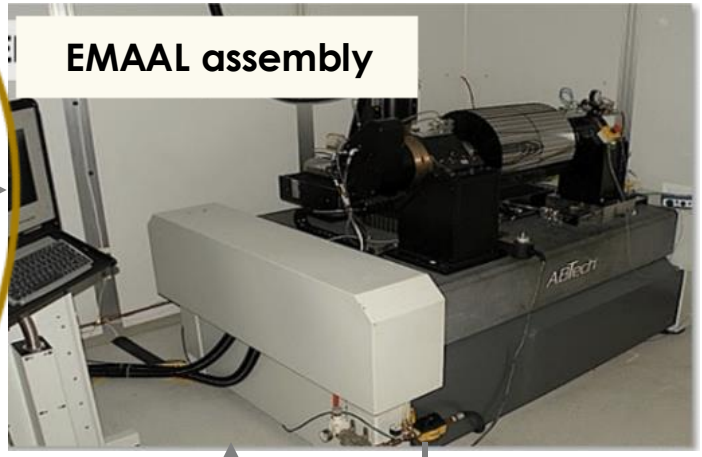

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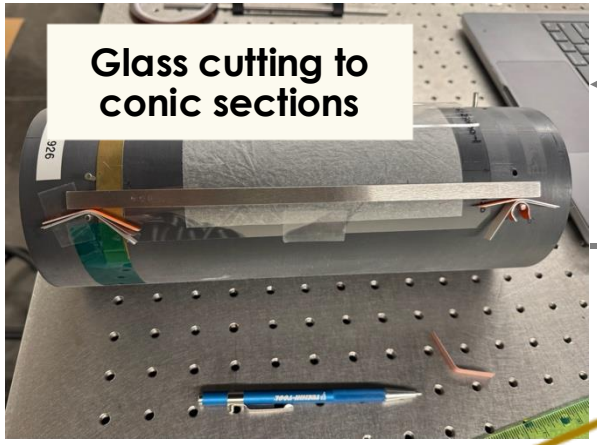

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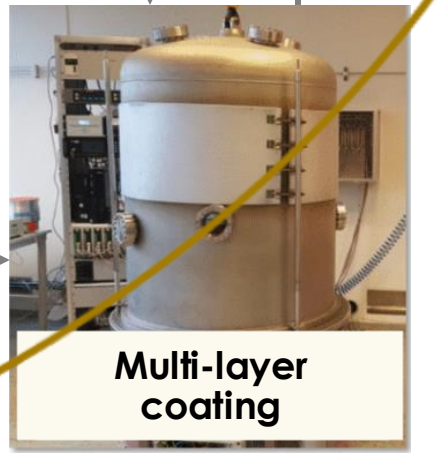

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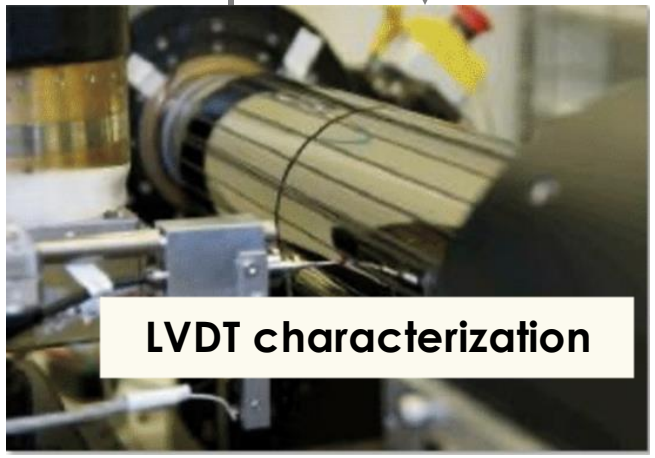
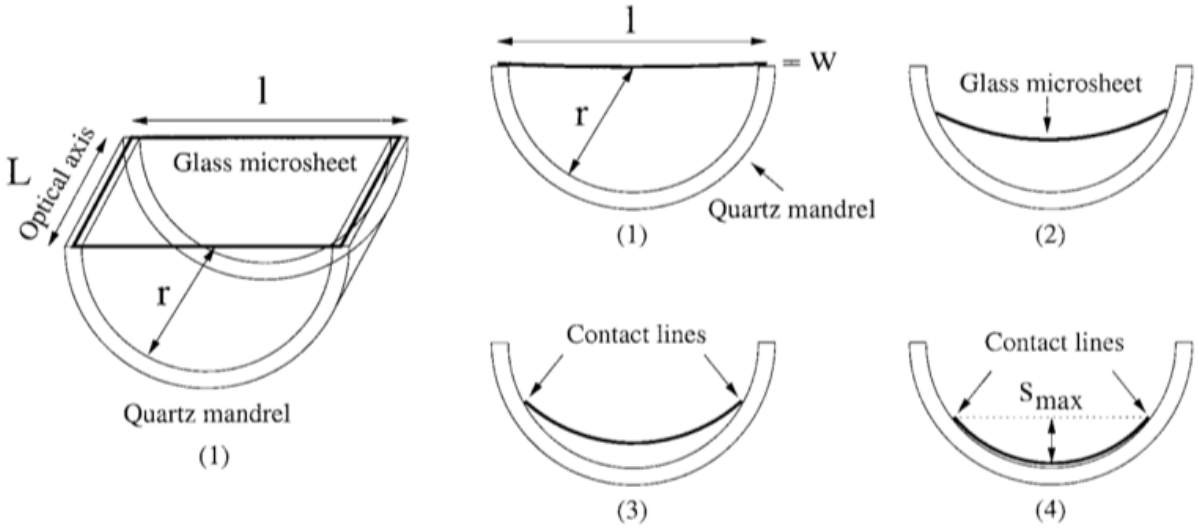
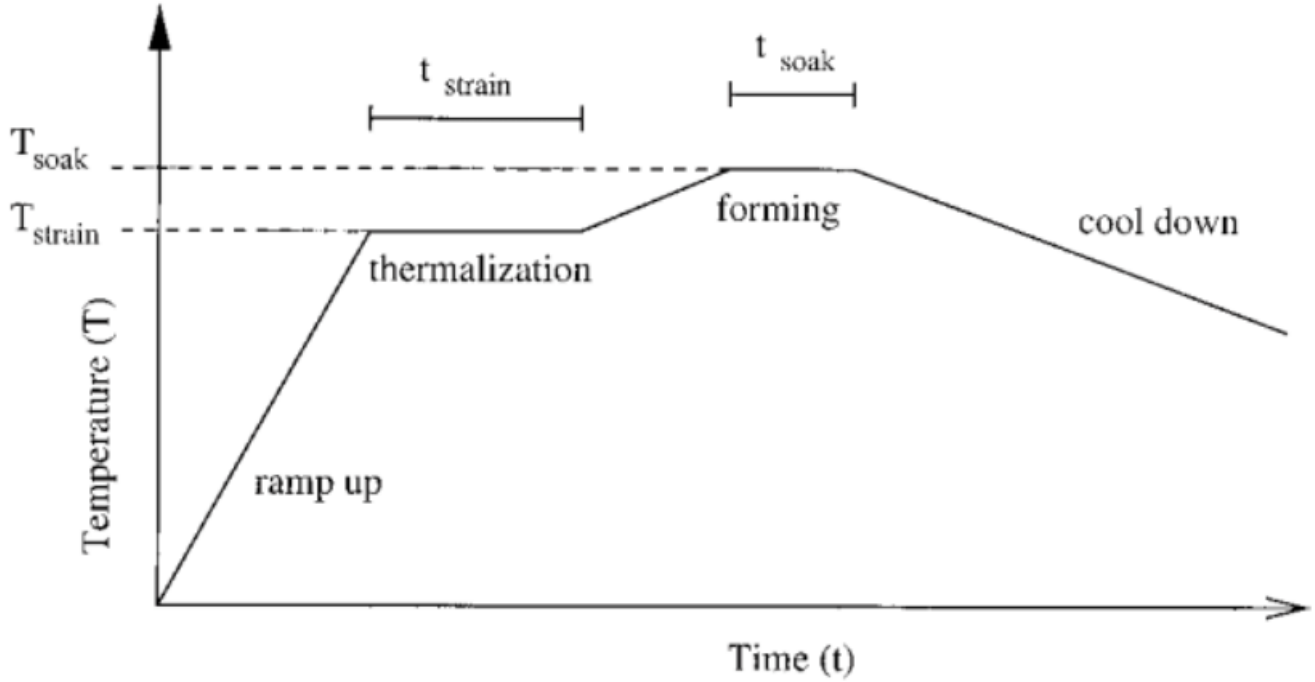


Thermal Slumping: How It Works



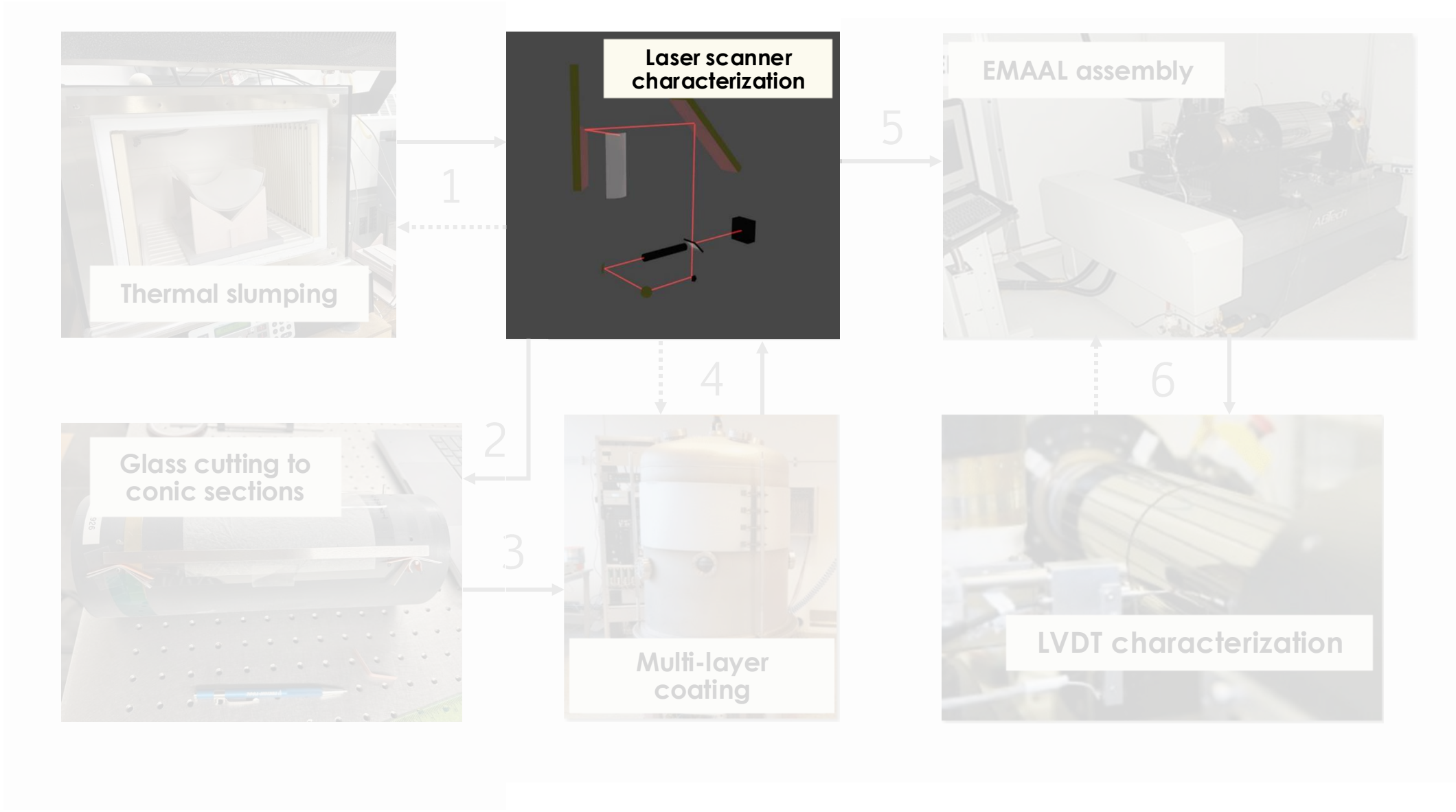


Thermal Slumping Specifications

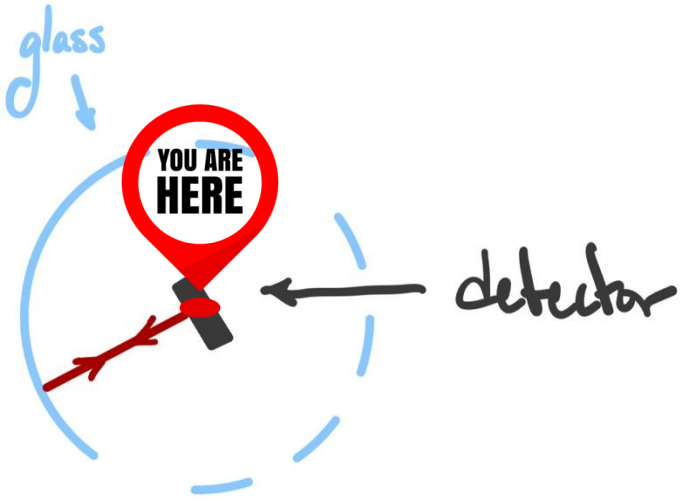
Our Oven Factory

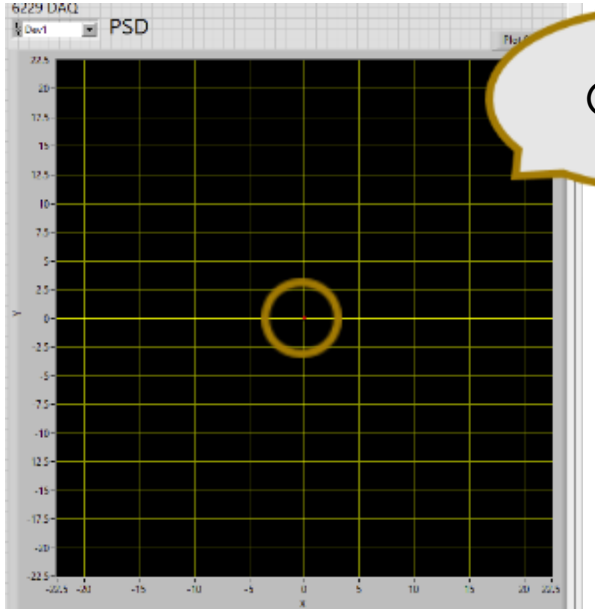
Inner 10 layers:	108-125 mm
Mirror dimensions (l x w x d)	112 mm x [ ] x .2 mm
Number of mirrors	240
Smallest mirror radius	54 mm
Biggest mirror radius	60 mm
Mirrors per shell	12

Laser Scanner Characterization

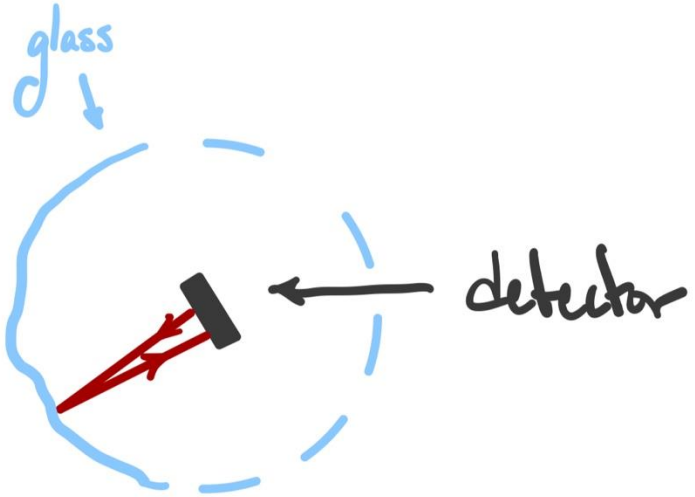


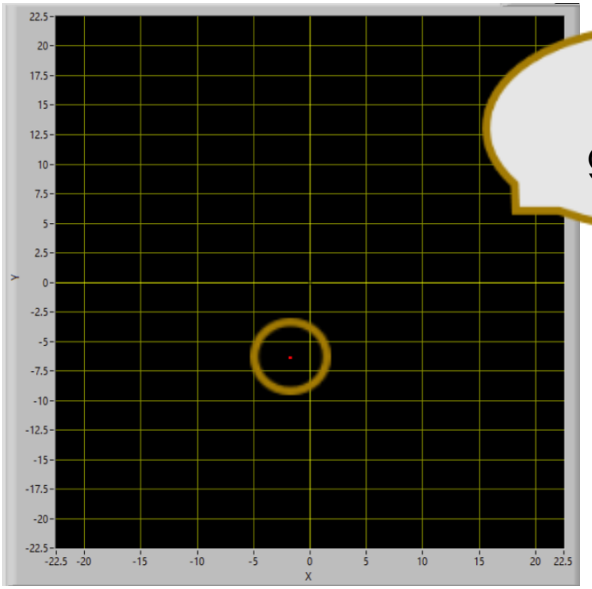
Characterizing Surface Error Using Laser Reflection





Good

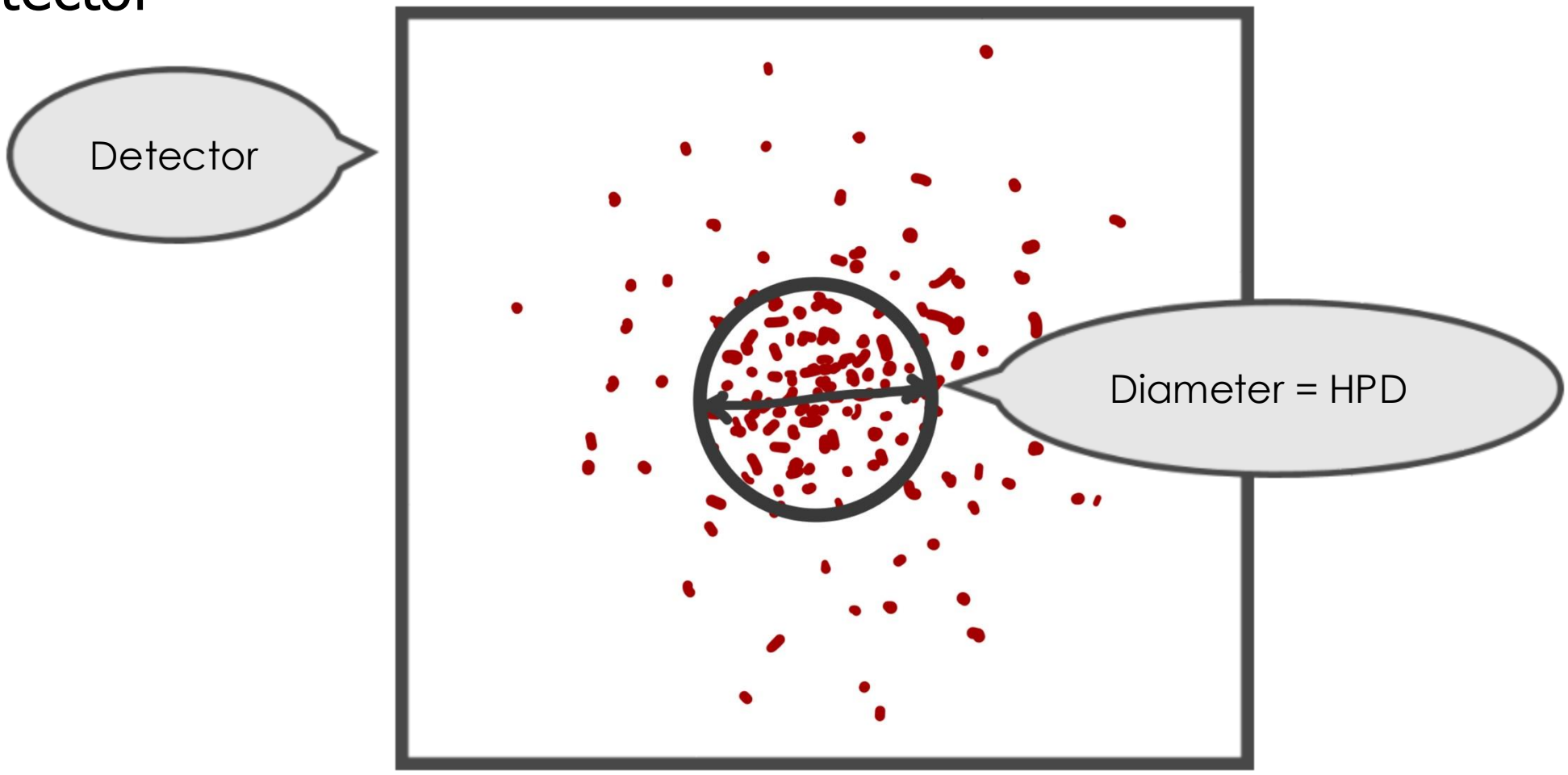




Not good

Quantifying Surface Error: Half Power Diameter

- **HPD**: diameter that encircles half of total captured energy on detector



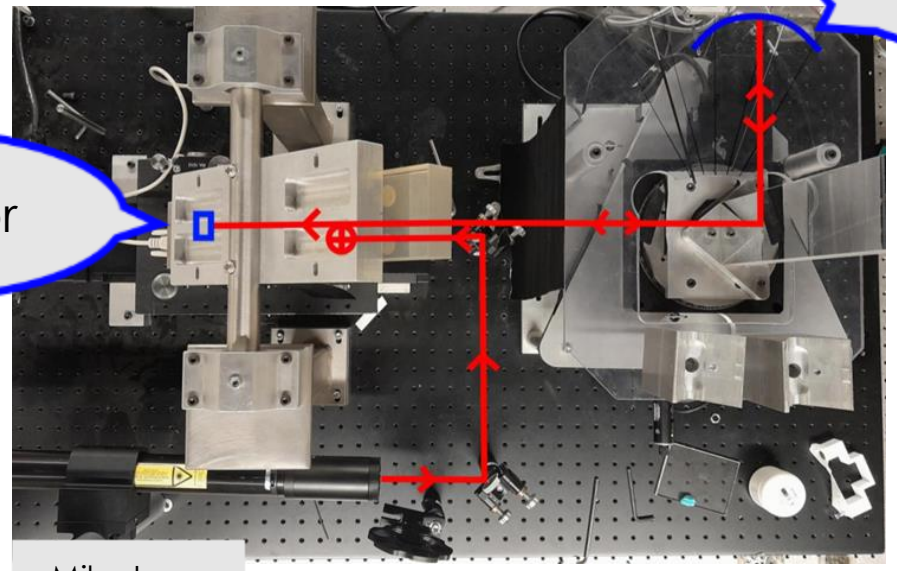
Laser Scanning Procedure

Thickens paint

- Paint back of glass with black acrylic paint mixed with sugar
  - Absorbs reflection from back glass surface
- Manually align glass so reflected laser falls on detector
- Use auto-alignment program to align glass with higher precision
- Scan!

Slumped glass

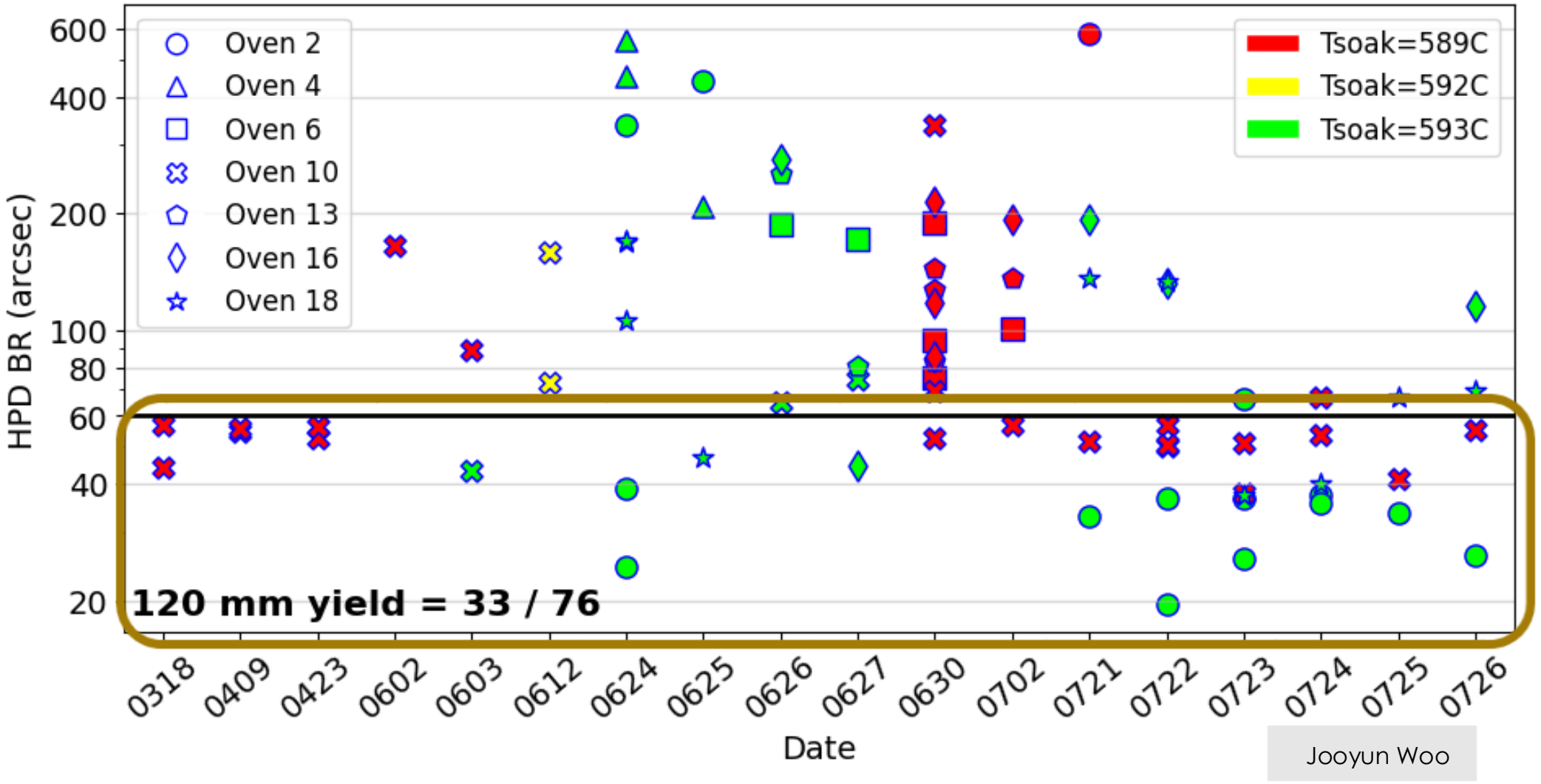
Detector



Mike Law

Jooyun Woo

Best Ovens For Different Temperatures



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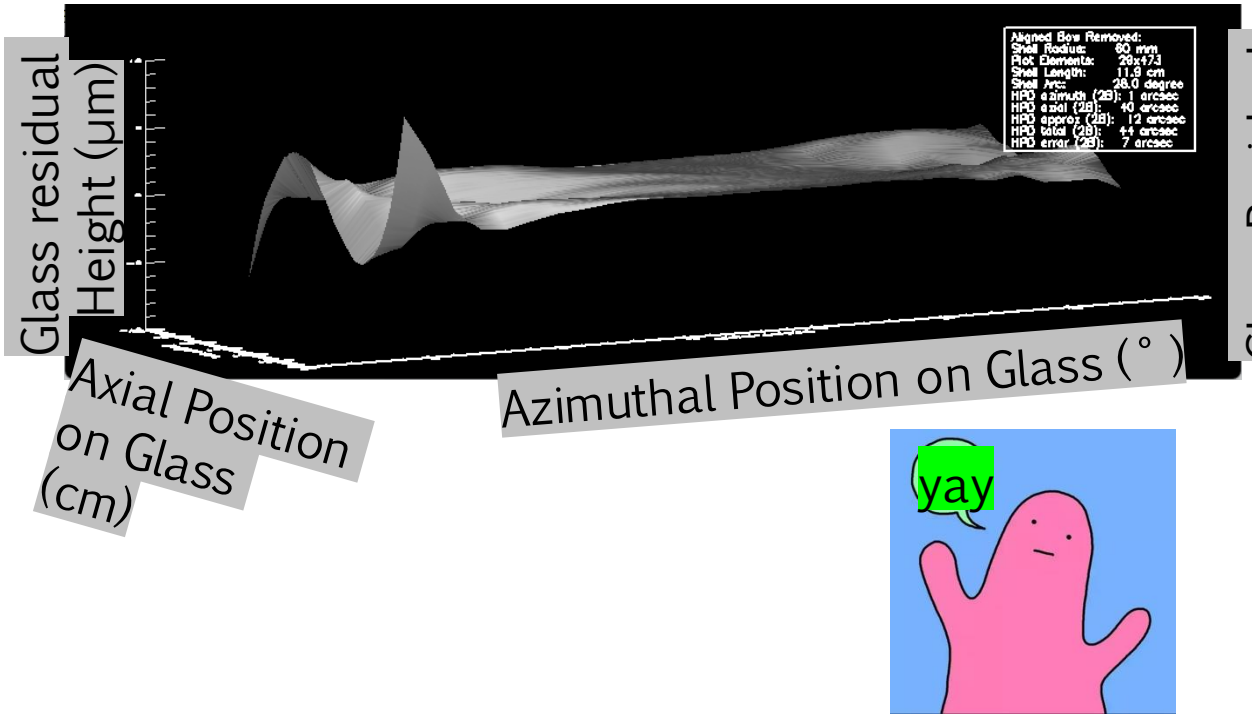
Post-Processing Scan Plots: Good Scan vs. Bad Scan

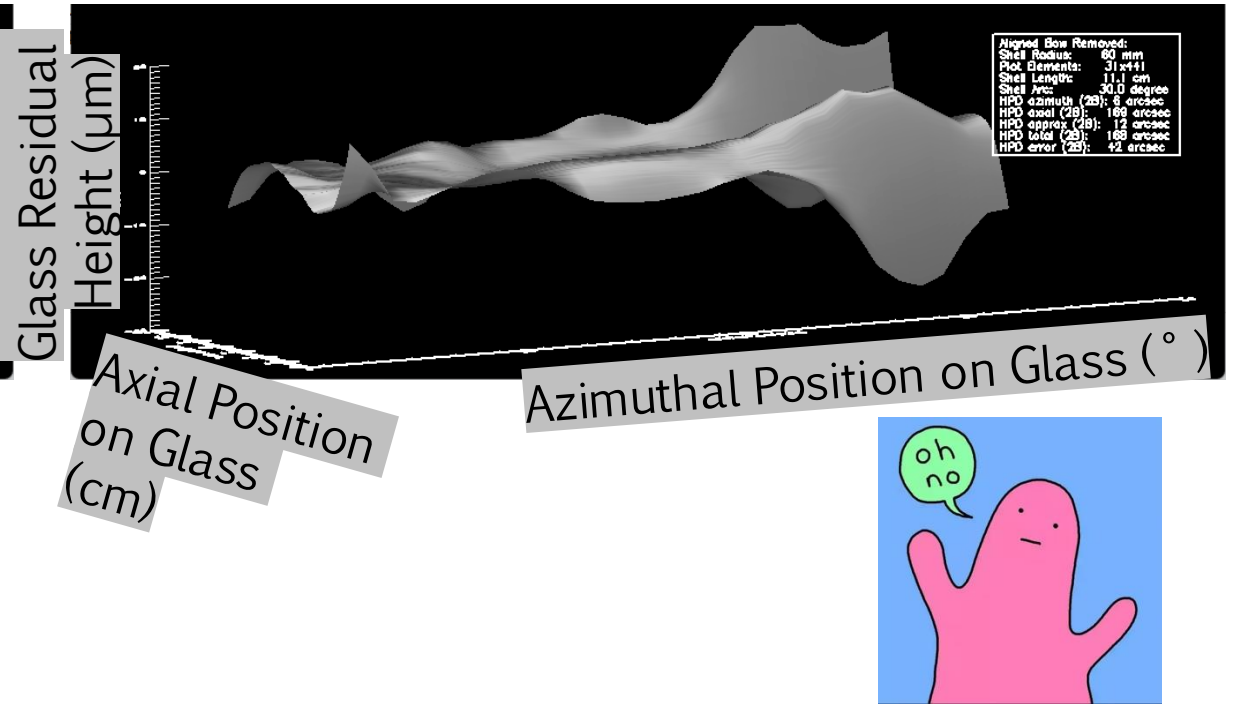
Good Scan

- 44″ HPD
- Flat = good
- Note: scale is smaller

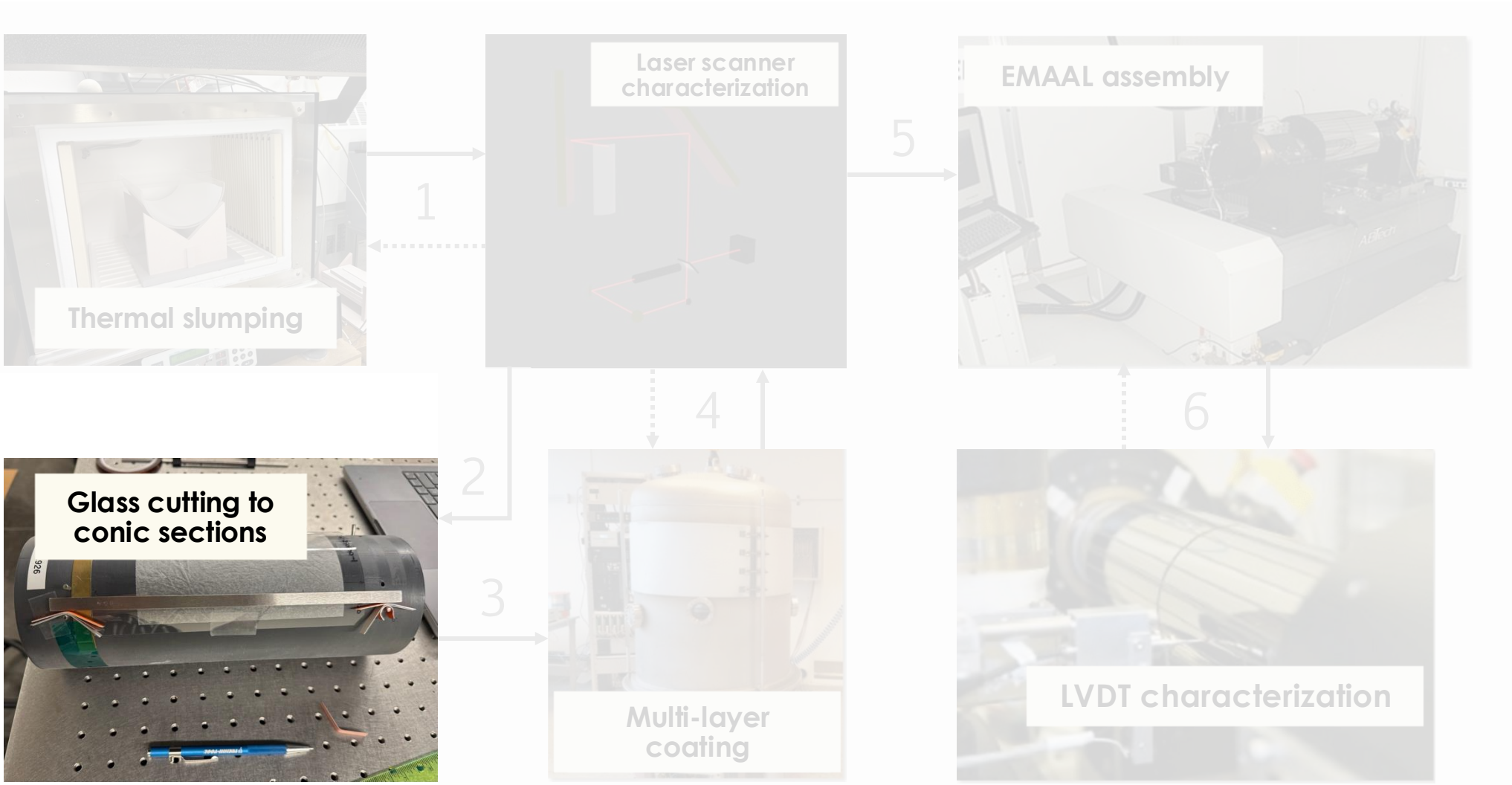


Bad Scan

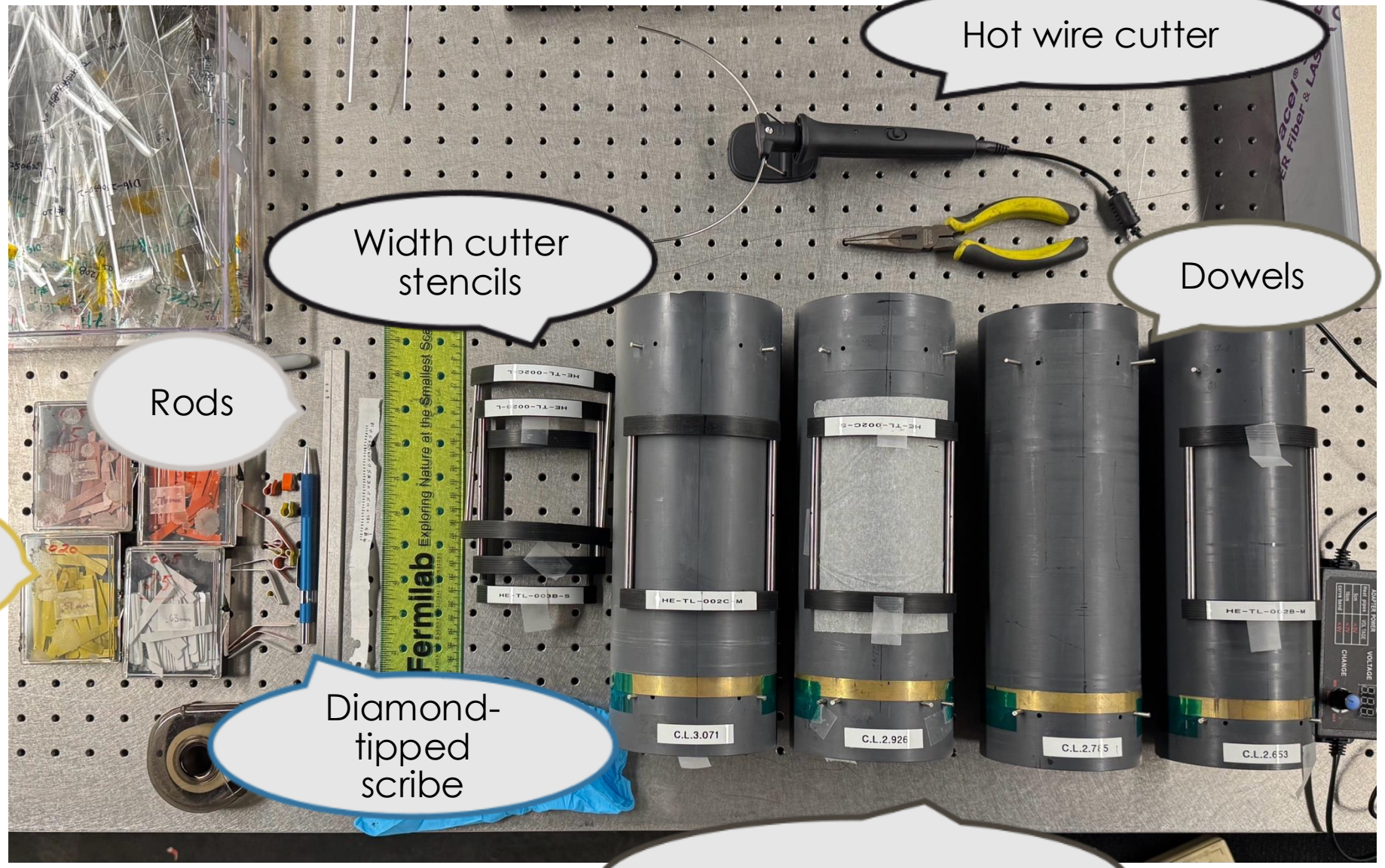
- 168″ HPD
- More variance



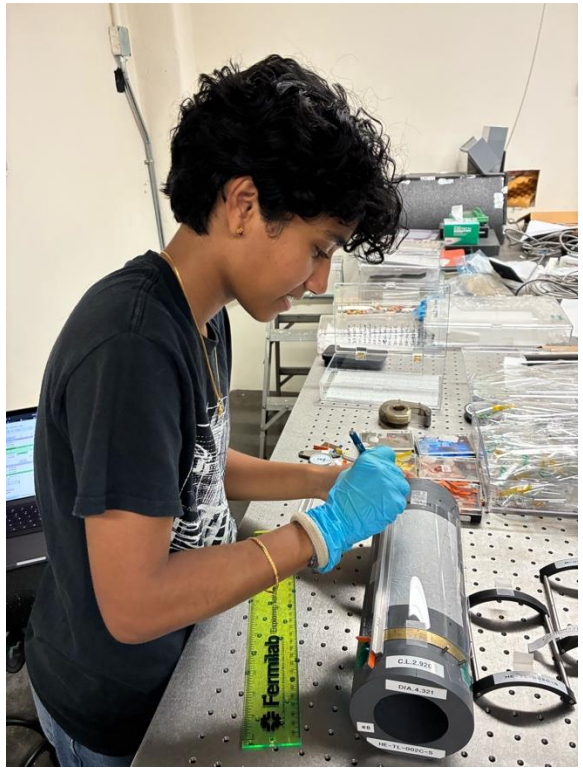
Glass Cutting



Glass Cutting Setup



Glass Cutting Process: How It Works



Align rods on dowels, score and crack lengthwise

Align width cutter, score width

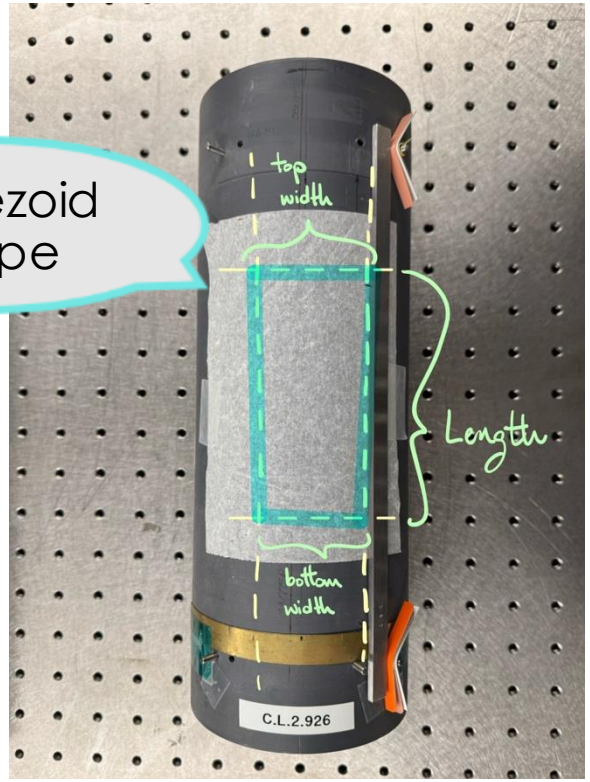
Propagate crack along width cut using hot wire cutter

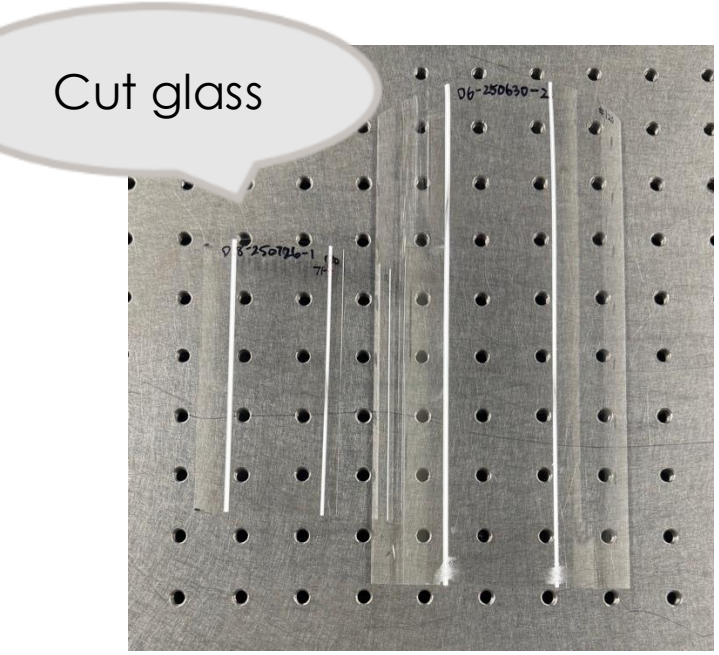
Problem With Cutting Mandrel: Wrong Shape

- Want trapezoids with specific dimensions, but have a rectangular cutting mandrels

Solution: Cutting Mandrel Modifications

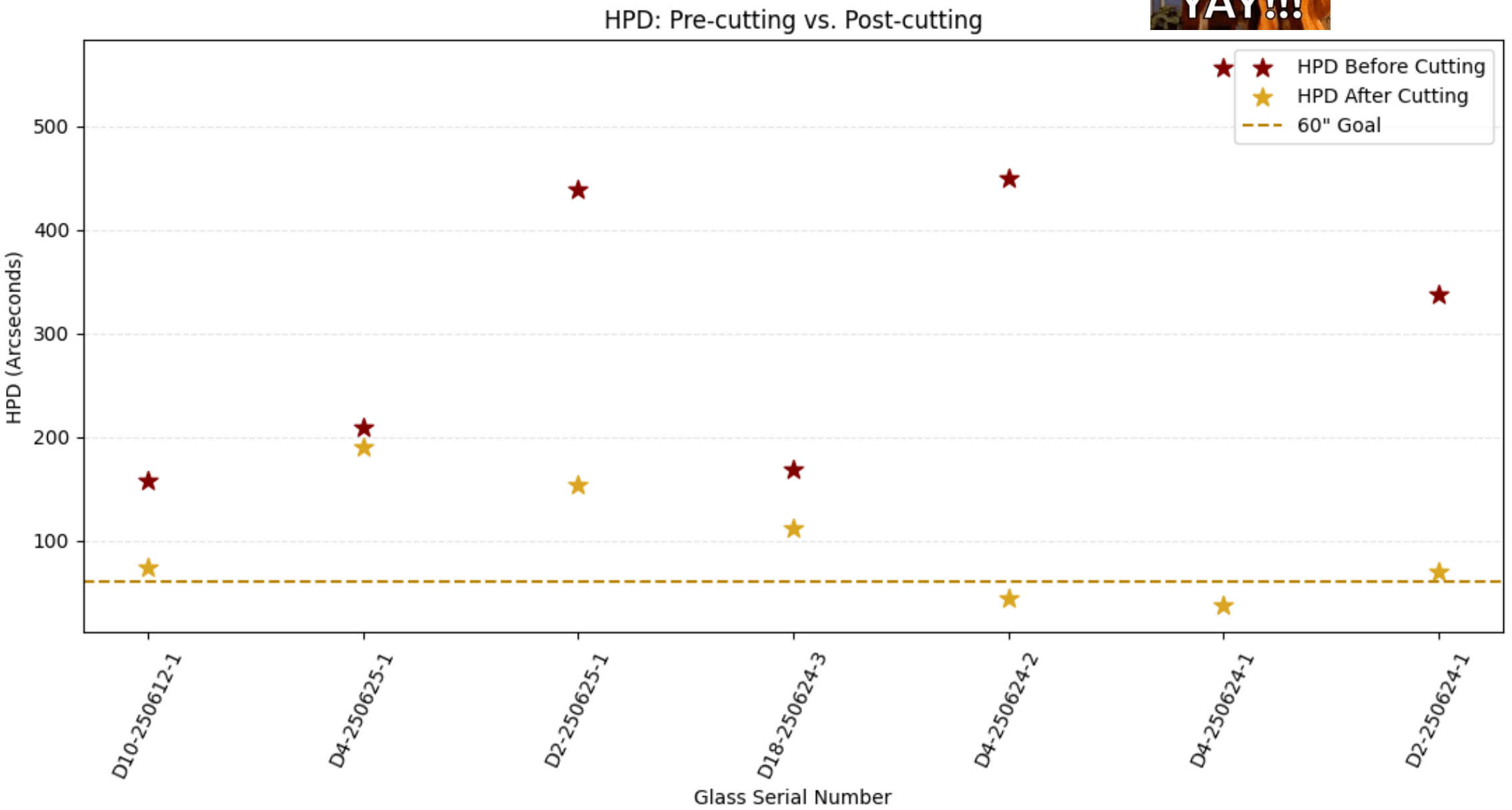
- Change rod location using shims
- Geometric solution coded into spreadsheet to give best rod & shim dimensions





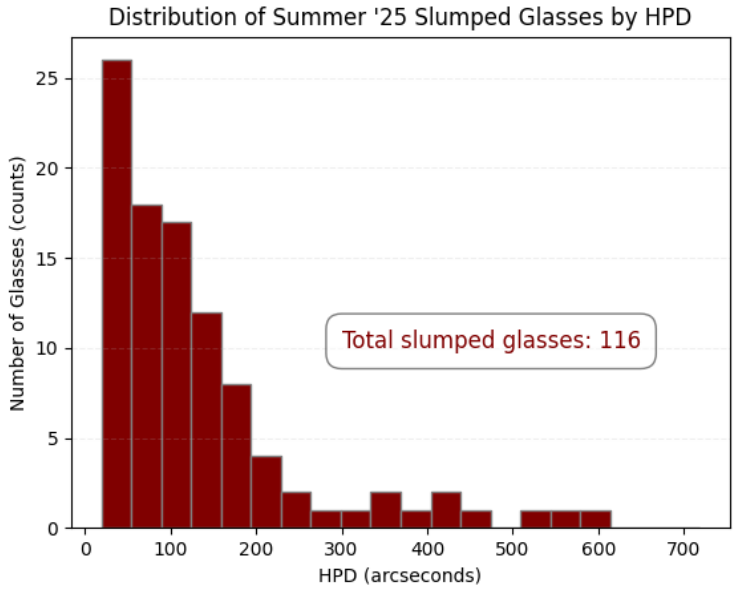
IAXO Layer	top/bottom?	top arclength of cut glass	bottom arclength of cut glass	s2-s1	e_d	a'	r	s2	s1	x	x-112
6P	T	62.06739886	61.75847558	0.6233630423	1.4	60.8	16.8	1.4	0.7766369577	967.0642969	855.0642969
6P	B	61.75847558	61.4495523	0.6233630423	1.4	60.8	16.8	1.4	0.7766369577	855.0642969	743.0642969
7P	T	62.92610085	62.61194159	0.6339285176	1.4	63.8	16.8	1.4	0.7660714824	187.5586744	75.55867439
7P	B	62.61194159	62.29778232	0.6339285176	1.4	63.8	16.8	1.7	1.066071482	182.5107961	70.51079614
7S	T	62.29778232	61.36054051	1.891220078	1.4	63.8	16.8	3	1.108779922	178.9843543	66.98435433
7S	B	61.36054051	60.4232987	1.891220078	1.4	63.8	16.8	2	0.1087799225	-52.51522305	-164.515223
8P	T	63.78480284	63.47064358	0.6339285176	1.4	63.8	16.8	1	0.3660714824	351.0891787	239.0891787
8P	B	63.47064358	63.15648431	0.6339285176	1.4	63.8	16.8	2	1.366071482	595.5962512	483.5962512
8S	T	63.15648431	62.20353454	1.922916503	1.4	63.8	16.8	2	0.07708349662	159.4273356	47.42733557
8S	B	62.20353454	61.25058477	1.922916503	1.4	63.8	16.8	2	0.07708349662	47.42733557	-64.57266443

Cutting Glass Improves Quality

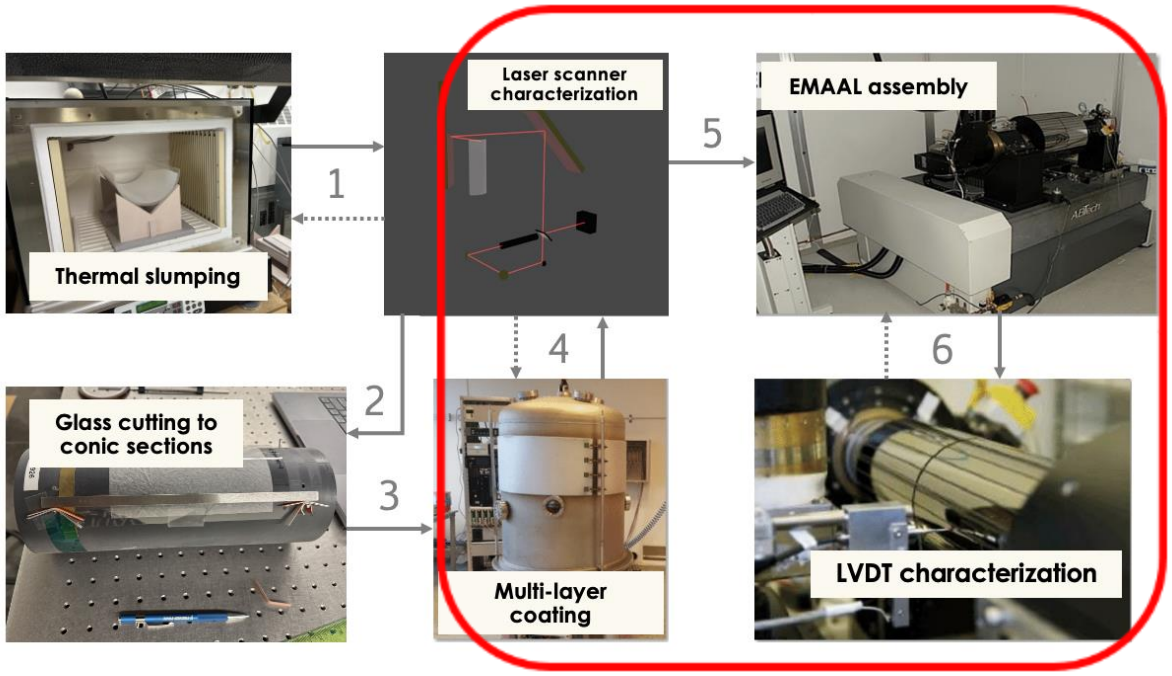


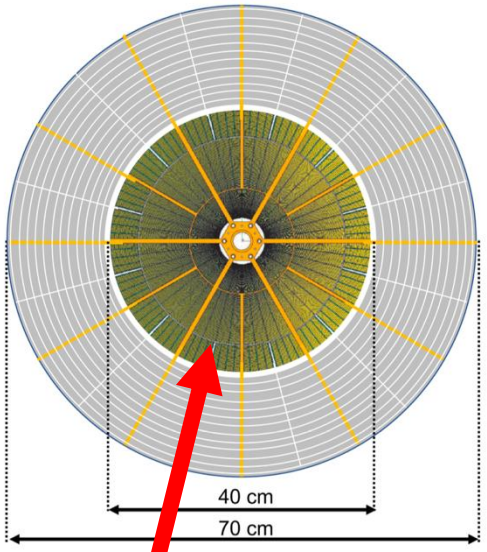
Goal Achieved ✅

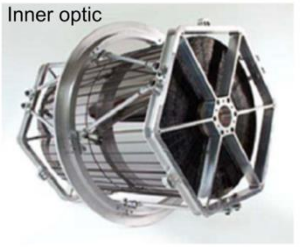
- Mastered and streamlined procedure to slump, scan, and cut glasses for inner layers of BabyIAXO optic
  - Found optimal settings for slumping high quality 120 mm diameter glass
    - Corresponding IAXO Layers: 6-8
  - Scanned slumped glasses, quantified glass quality, and provided feedback that improved slumping process
    - Slumping yield (success rate) went from 28% → 78%!
  - Established cutting procedure to accommodate different IAXO mirror geometries that can be followed to produce all the inner 10 layers
    - Cutting yield = almost 100%!
  - Proved glass quality only improves after cutting

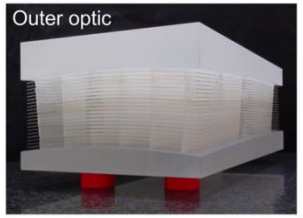


Next Steps









Optical and mechanical design locked in; Technical improvement and facility preparation ongoing

Individual techniques, materials and facilities prepared

10-layer prototype calibration; Full layer prototype assembly

Timeline

Jul. 2025

Mandrel and spider purchase starts

Mechanical engineer is urgent!

Dec. 2025-Feb. 2026

Assemble the first 10-layer prototype

Jun. 2027

Build up full layer prototype

Assume we will get funding for coating!

Thank You!!!

I'd like to acknowledge *Prof. Kerstin Perez* and the Perez Lab, the Nevis Labs REU led by *Prof. Georgia Kariogiorgi* and *Prof. Reshmi Mukherjee*, and the NSF Foundation.

Special thanks to my brilliant and supportive mentors *Dr. Jooyun Woo* and *Dr. Yue Yu*. Shoutout to my undergrad lab mate *Efi* for being my reading (and crash out) buddy.

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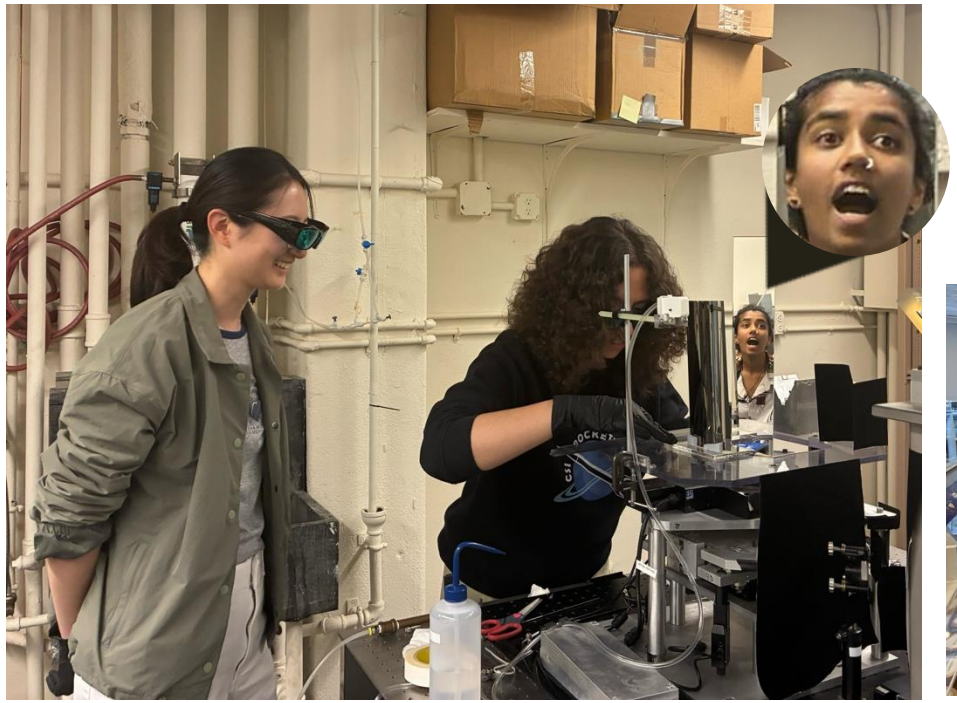

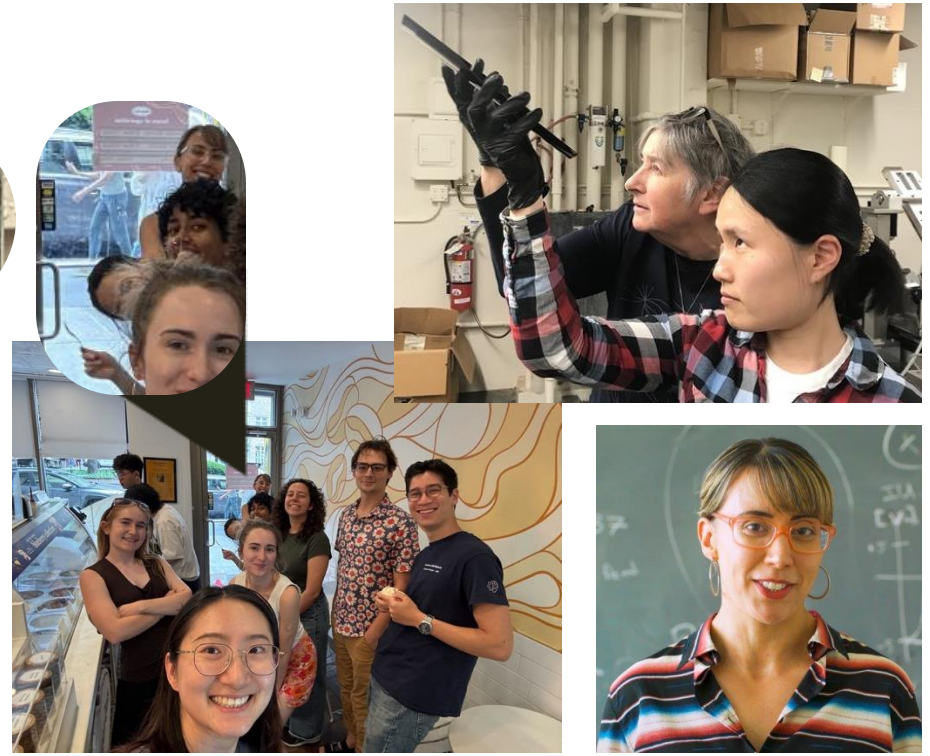

Questions?