Wicked Windows and Abominable Anti-reflection Coats for Hellish High Frequencies

Or: the Cursed Development Cycle of the BA220/270 Thin Window

Presented by Miranda Eiben

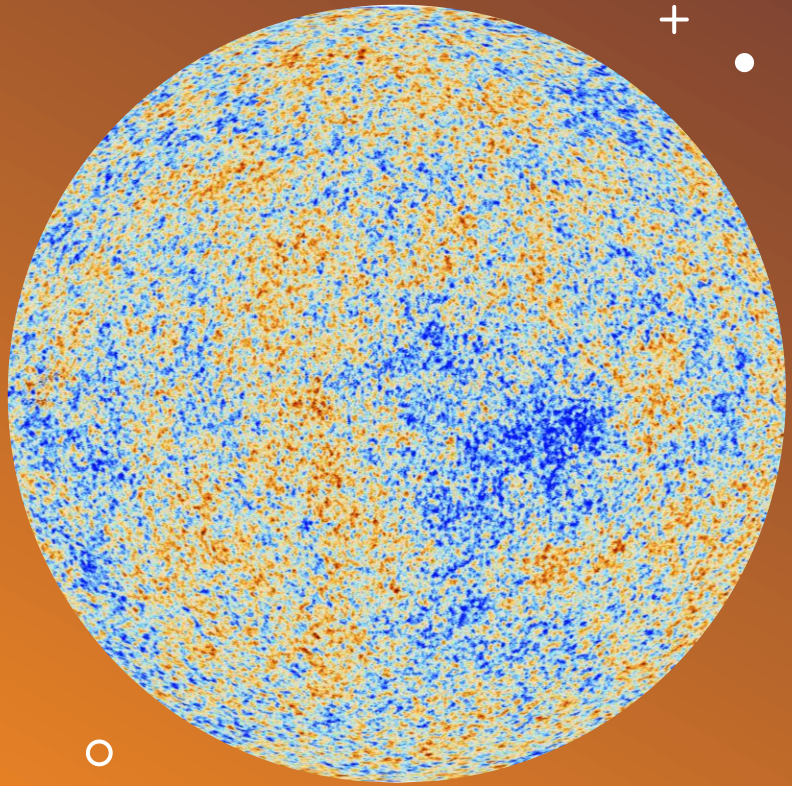
Happy Halloween!

We made *three* BA220/270 windows

Coded for clarity*:

- 1st window: 🎃
- 2nd window: 💀
- 3rd window: 🕸️

* We'll be skipping around in the timeline a bit



AGENDA*

Hellish High Frequencies

Wicked Windows

Abominable Anti-reflection Coats

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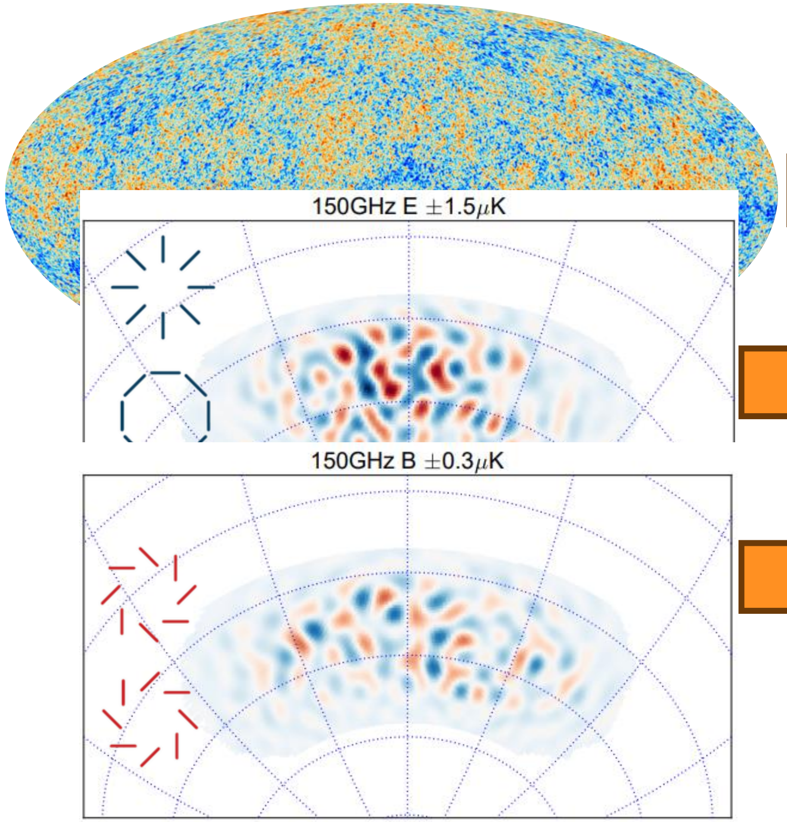
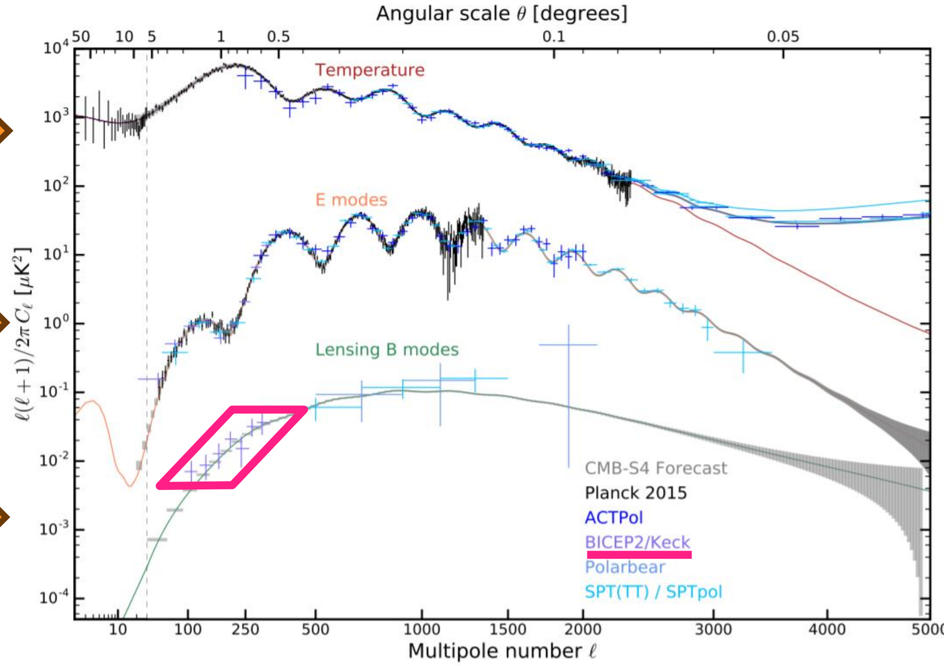
Background

HELLISH HIGH FREQUENCIES

Physics from the CMB

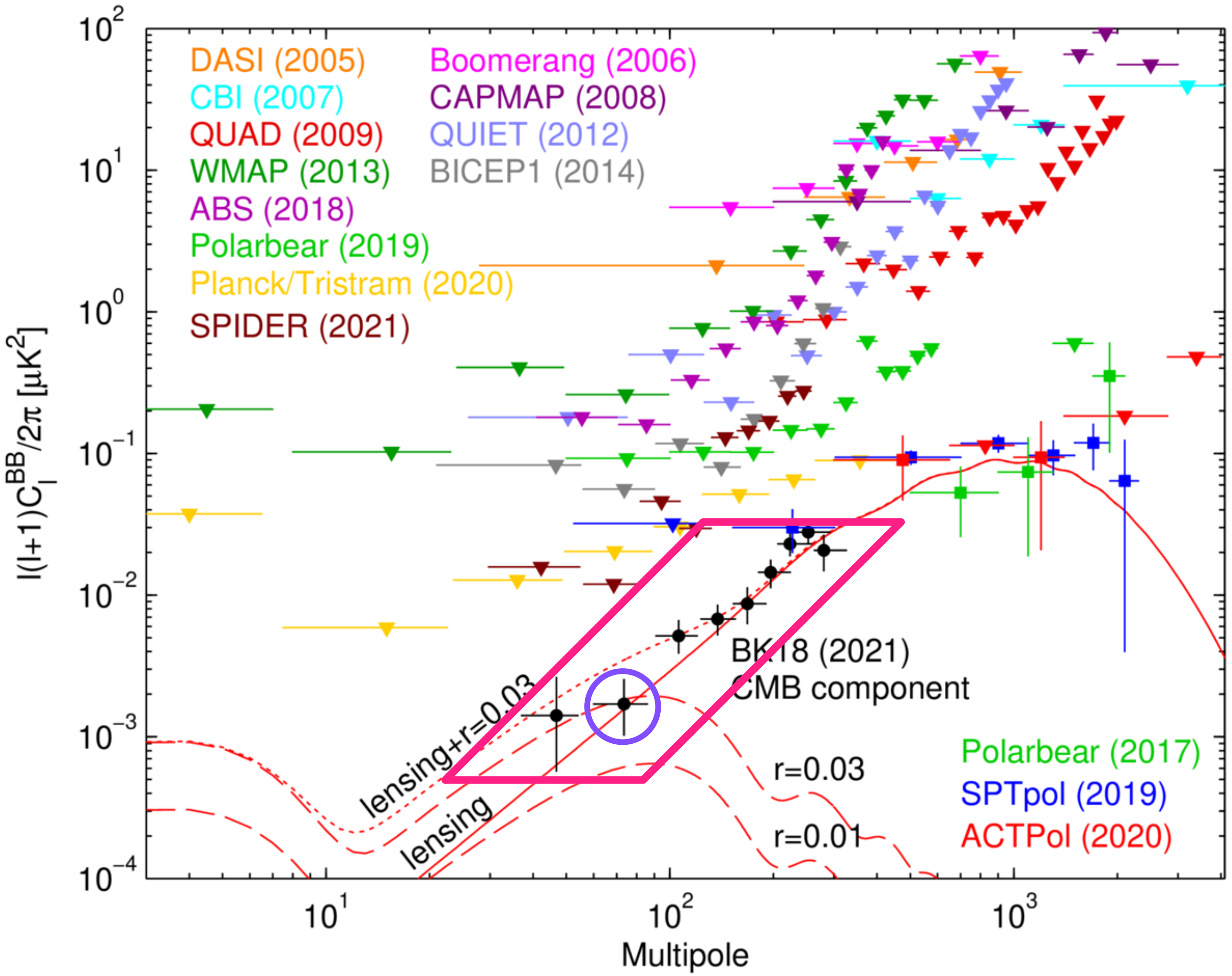




https://www.cosmos.esa.int/web/planck/picture-gallery
arXiv:2110.00483

arXiv:1610.02743

Current Constraints



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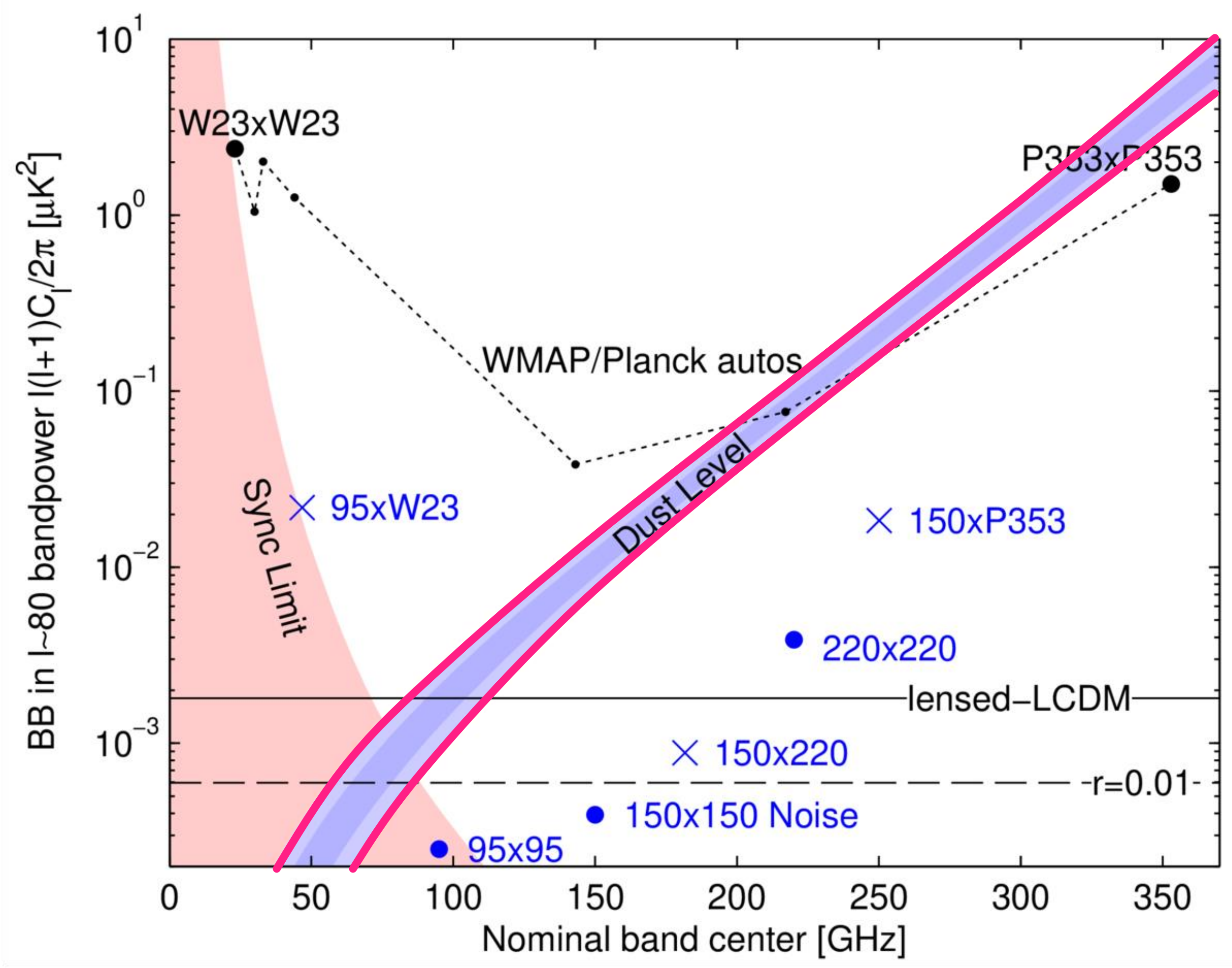
Other Sources of Spectral Power



arXiv:2110.00483

Observe at multiple frequencies

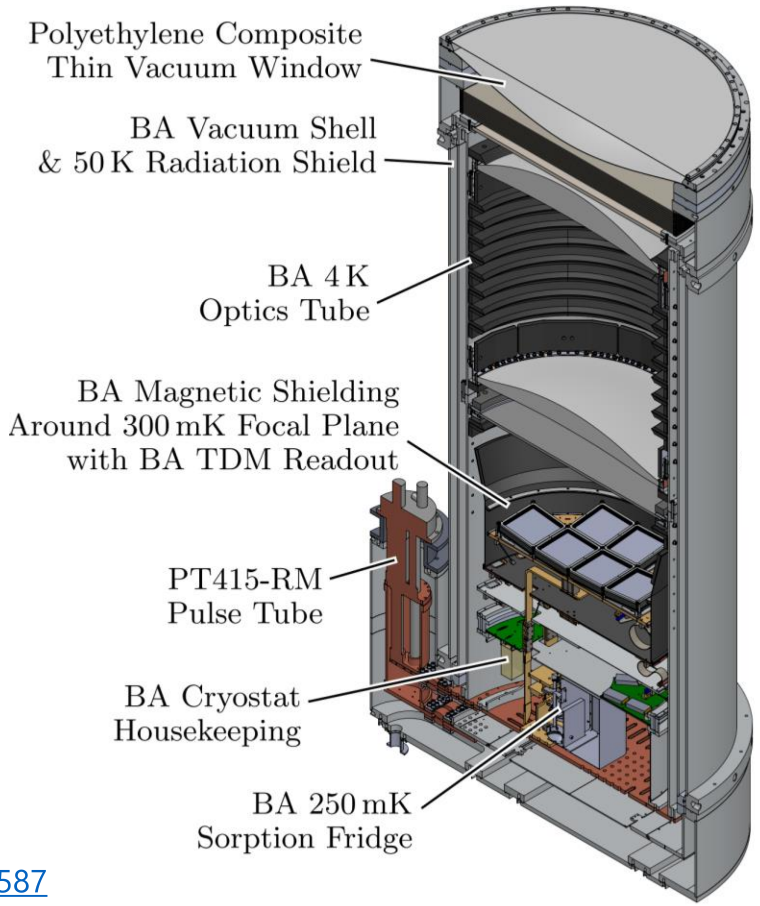
(for component separation)

Limit noise

(to reduce survey time)

But there are some problems…

Problems With High Frequency

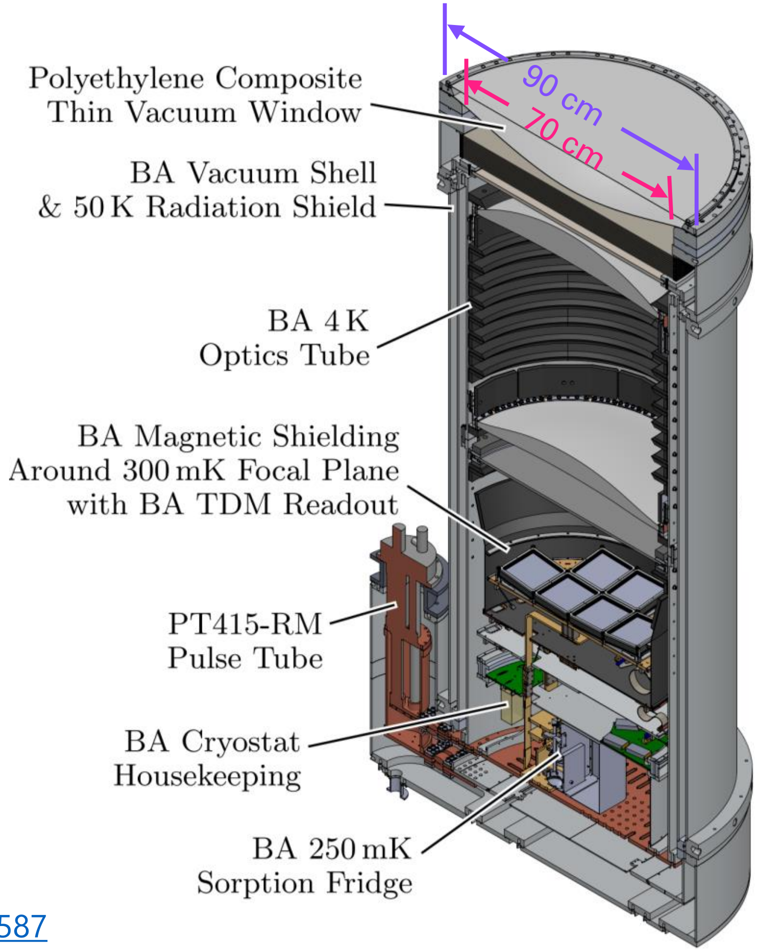


1) Absorption/Emission

- Power emitted scales with absorption like:
  - $p(\nu, \alpha, \boxed{T, t}) = \frac{h\nu\,(1-\exp[-\alpha t])}{\exp\left(\frac{h\nu}{kT}\right)-1}$

arXiv:2406.13587

Problems With High Frequency



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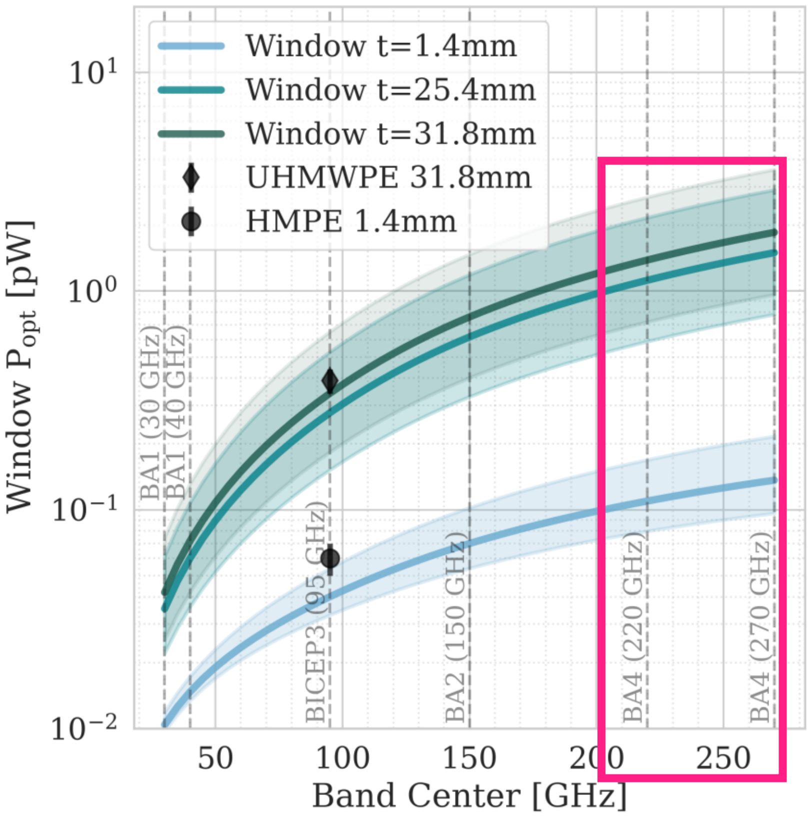
Component	Power to Det (pW) [220/270 GHz]
CMB	0.04/0.02
Atmosphere	2.87/4.40
Forebaffle	0.62/0.70
Window	1.43/2.25
Cold Optics	0.37/0.42

arXiv:2406.13587

Problems With High Frequency



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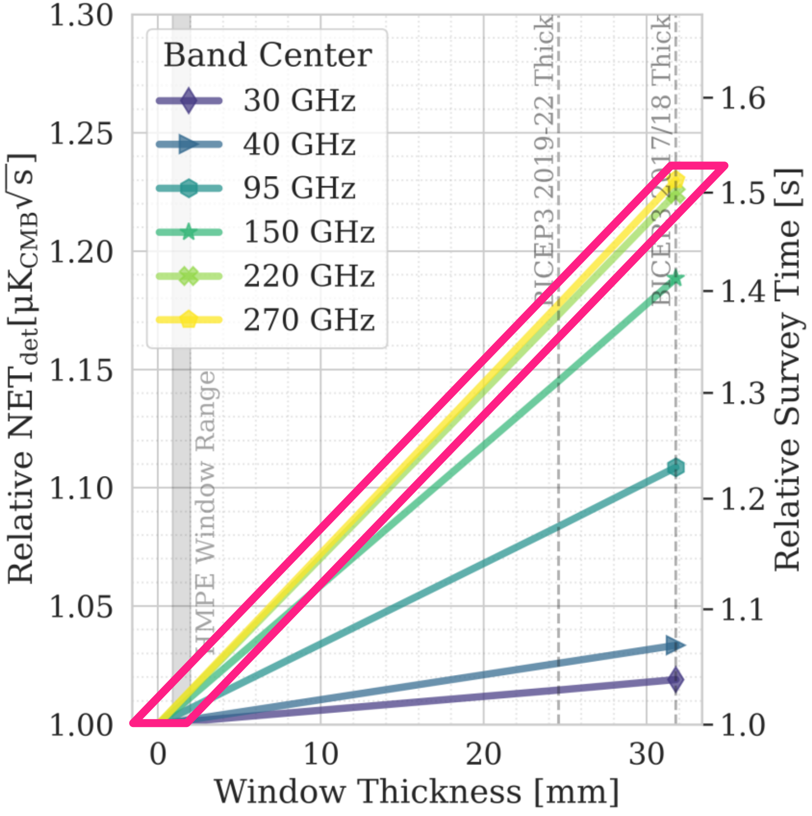
- For the vacuum window, there is only one parameter that is controllable: t

Problems With High Frequency



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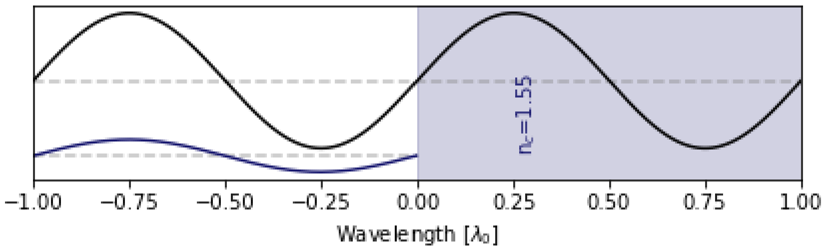
- Power emitted scales with absorption like:
  - $p(\nu, \alpha, T, t) = \frac{h\nu\,(1-\exp[-\alpha t])}{\exp\left(\frac{h\nu}{kT}\right)-1}$
- For the vacuum window, there is only one parameter that is controllable: t (thickness)
- This also sharply reduces the expected noise on a detector

Problems With High Frequency

2) Anti-reflection Coats

- Change in impedance into a material will reflect power



Problems With High Frequency

2) Anti-reflection Coats

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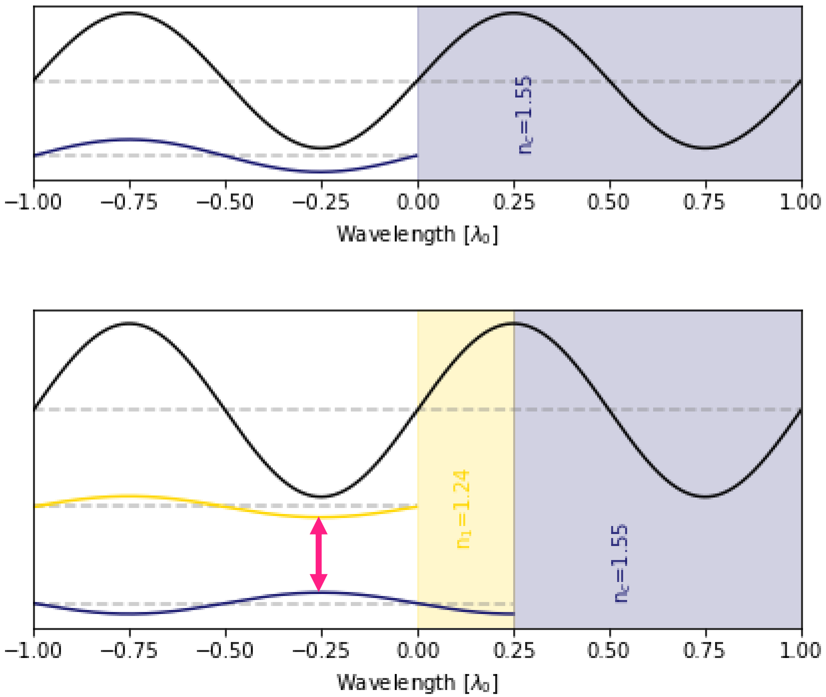
  - Requires a coating that causes destructive interference (1/4 λ)



Problems With High Frequency

2) Anti-reflection Coats

- Change in impedance into a material will reflect power
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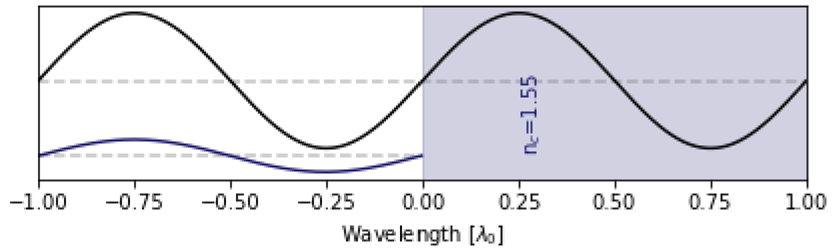
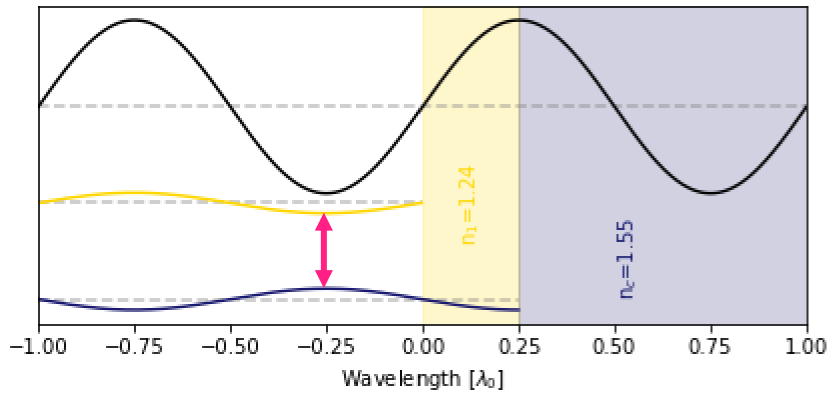
- 1/4 λ at 250 GHz = 0.24 mm
  - Needs to be a consistent thickness over ~70 cm diameter

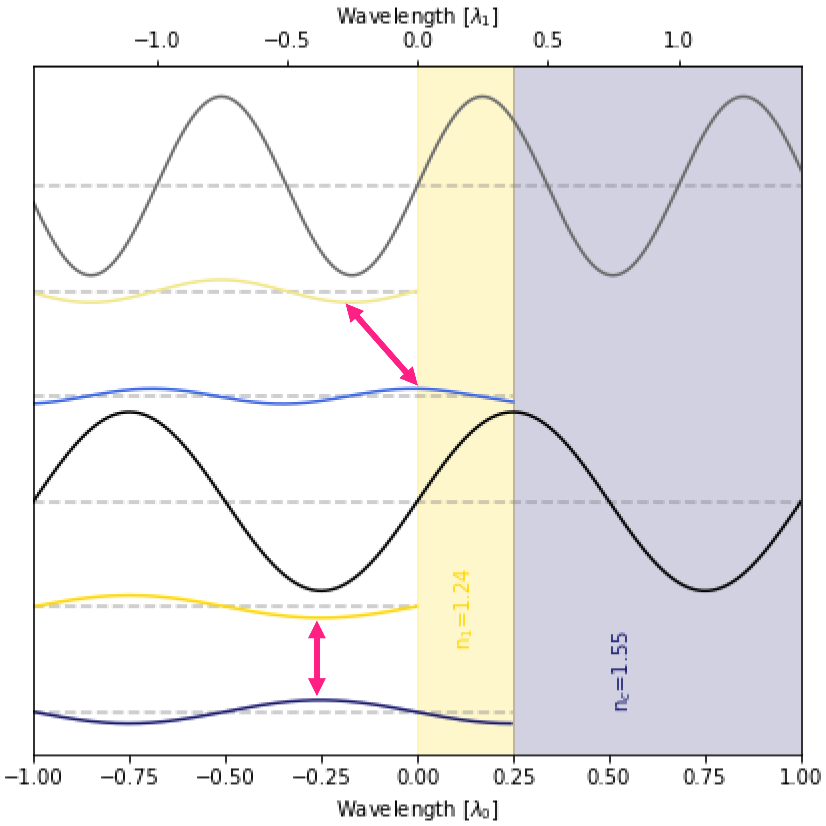




Problems With High Frequency

2) Anti-reflection Coats

- Change in impedance into a material will reflect power
  - Requires a coating that causes destructive interference (1/4 λ)
- 1/4 λ at 250 GHz = 0.24 mm
  - Needs to be a consistent thickness over ~70 cm diameter
  - Also: broad bandwidths reduce efficacy of AR
    - 220/270 fractional bandwidth ~ 0.4



Problem #1

WICKED WINDOWS

Window Material

Typical window materials compared

Window Material	Ultimate Tensile Strength (MPa)	Elastic Modulus (GPa)	Thickness for Safety Factor of 3 (mm)
HDPE	20-25	0.9	12.7-17.7
UHMWPE	22-40	0.7	5.5-13.6
HMPE Laminate	120-135	1.1-1.3	1.2-1.4

Window Material

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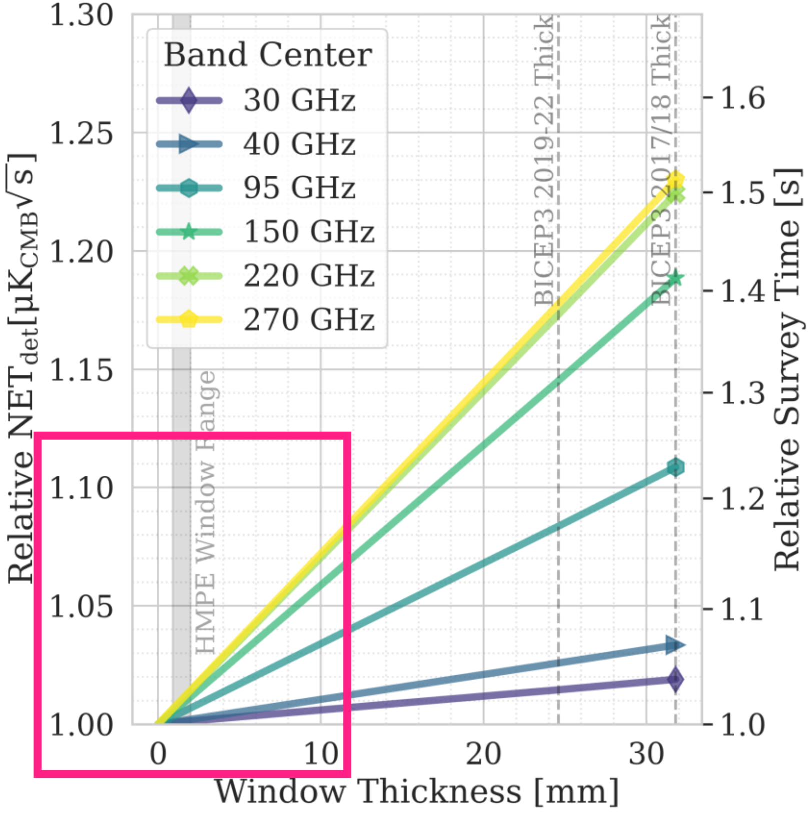
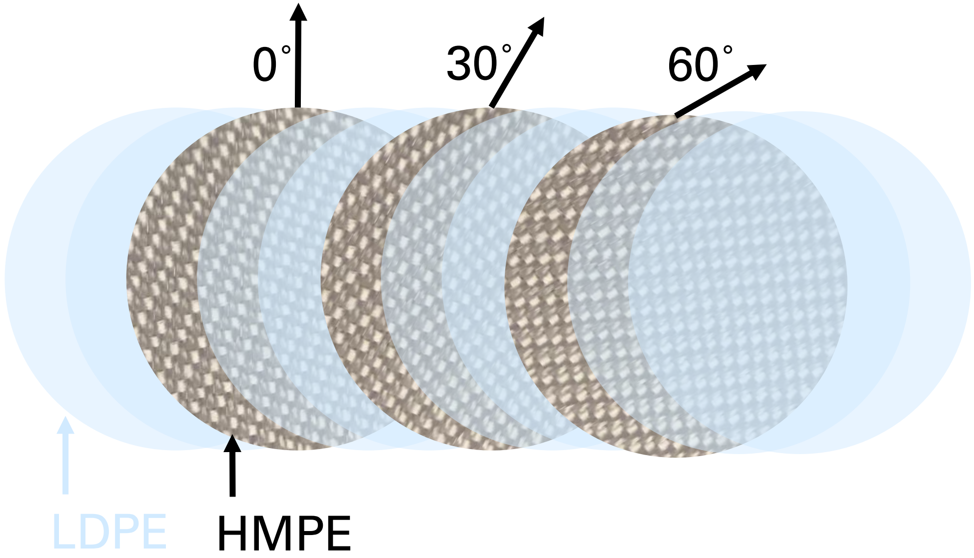


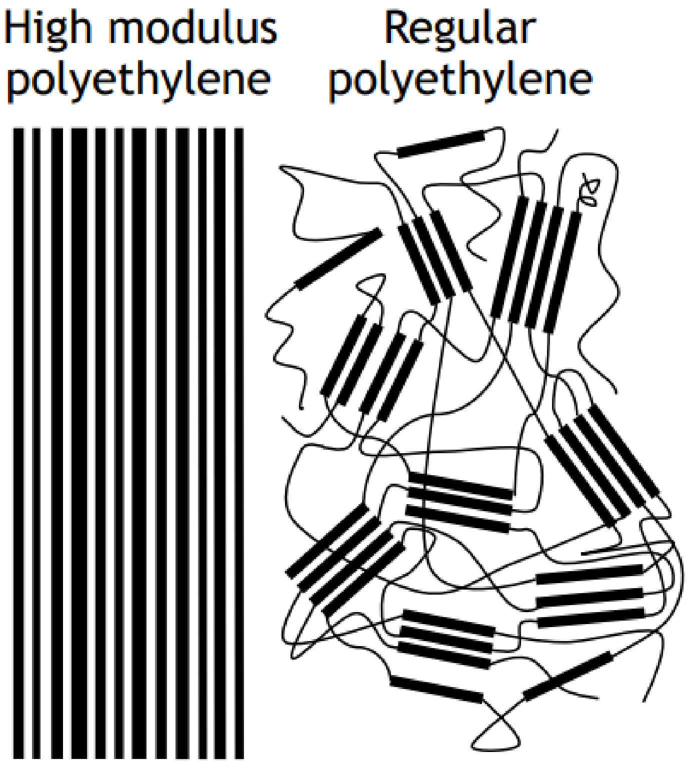
sile	Elastic Modulus (GPa)	Thickness for Safety Factor of 3 (mm)
	0.9	12.7-17.7
	0.7	5.5-13.6
	1.1-1.3	1.2-1.4

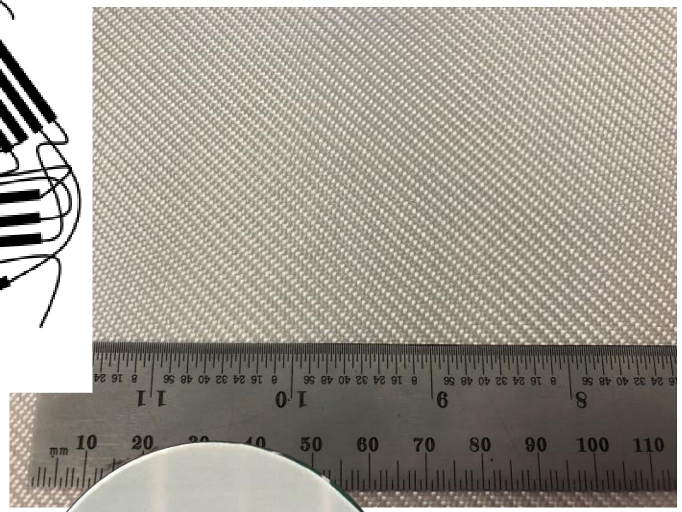
What is HMPE?

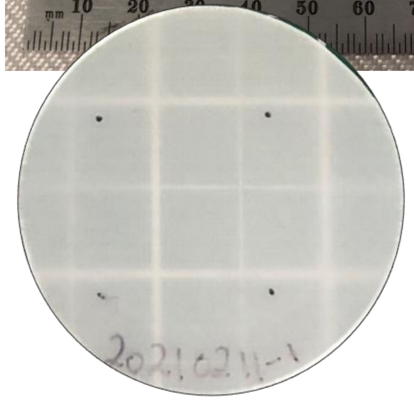
High Modulus Polyethylene (HMPE, commercial name Dyneema)

- Long aligned strands
- Very high density
- Very high strength



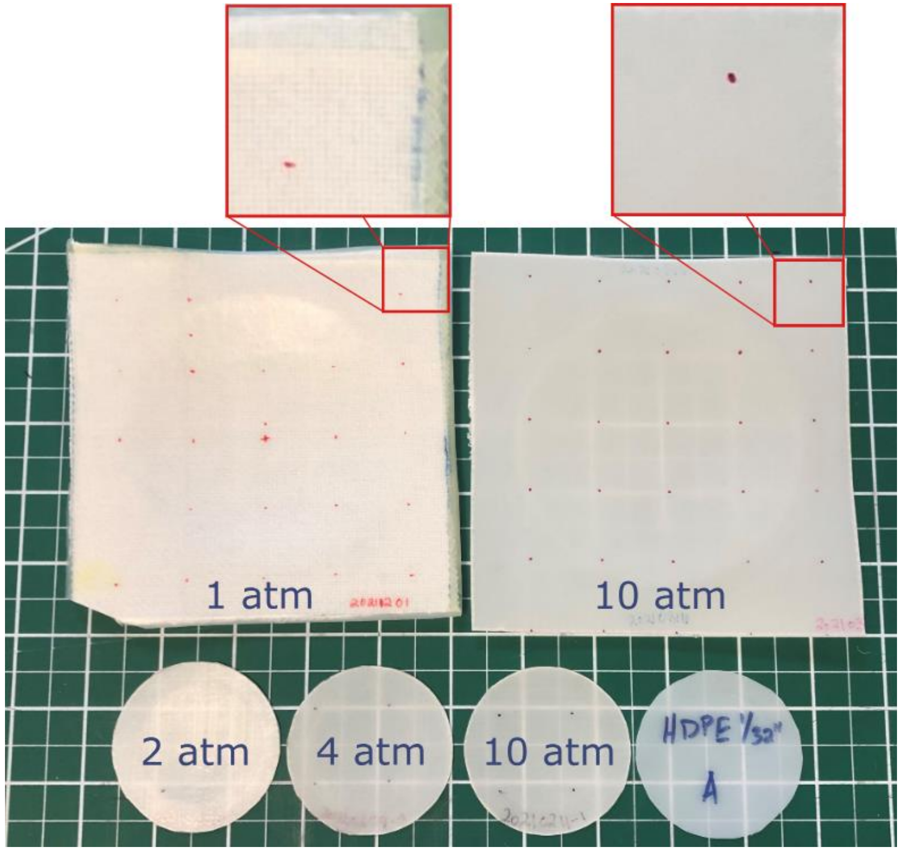


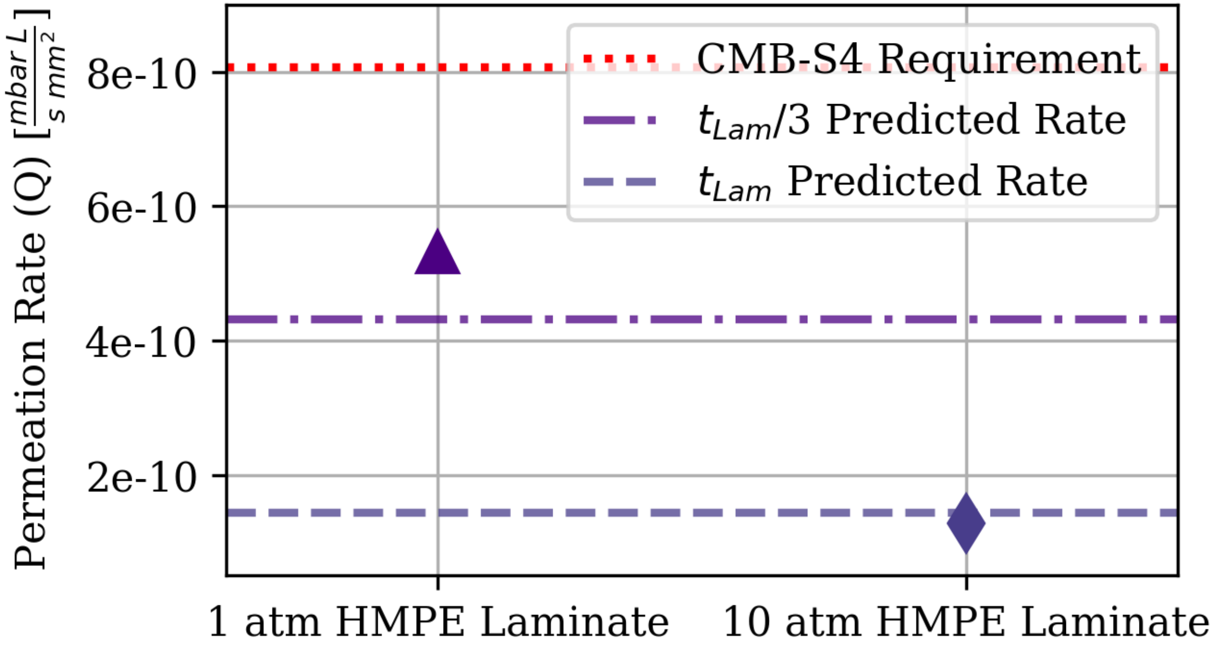




Window Compression

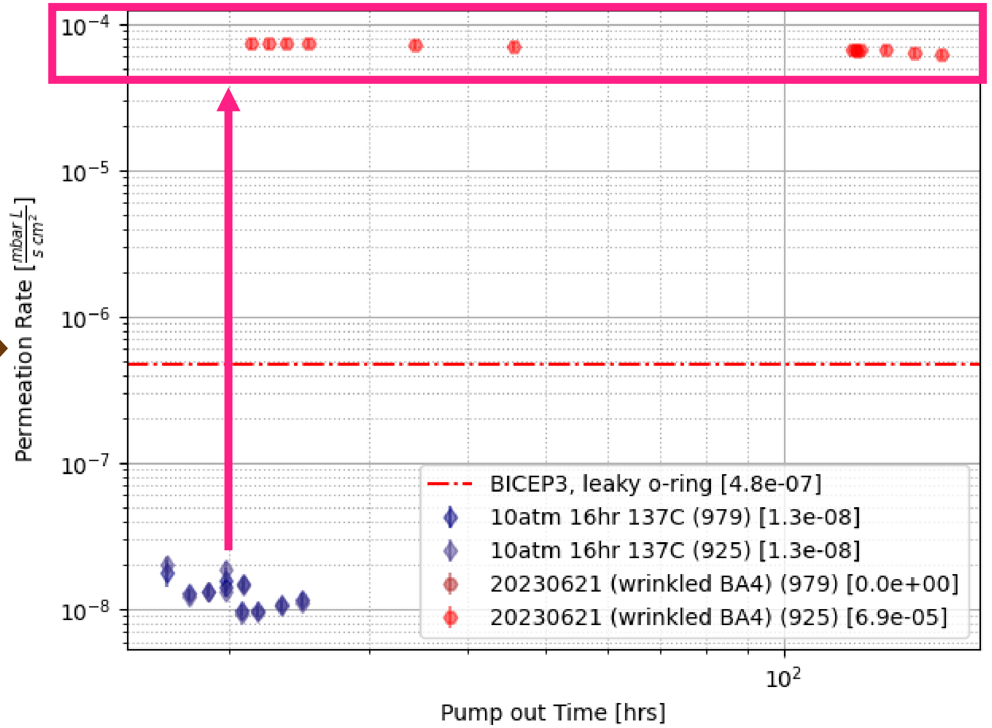
Windows need to be compressed to reduce permeation rate

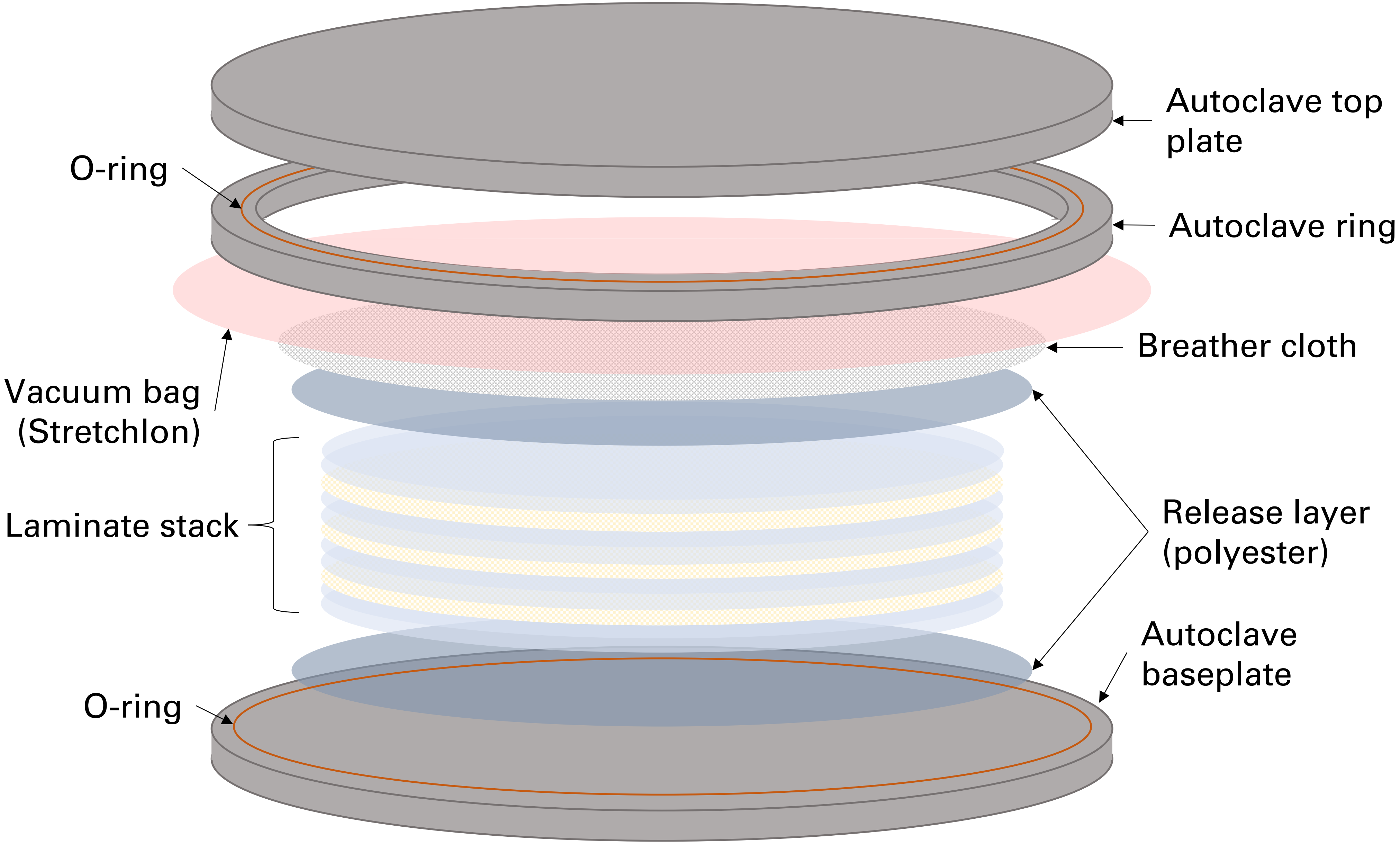


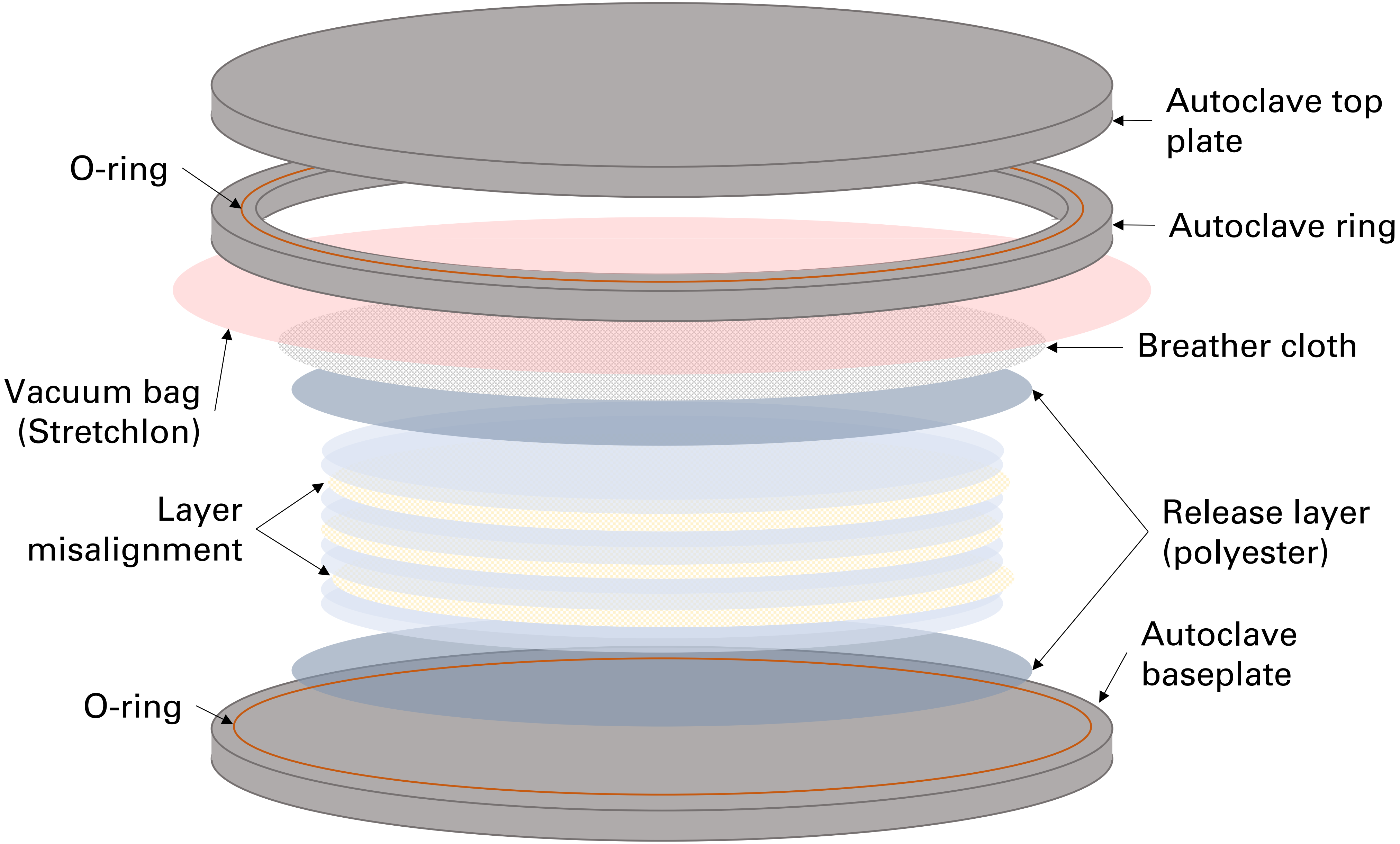


When Lamination Goes Wrong

1st window



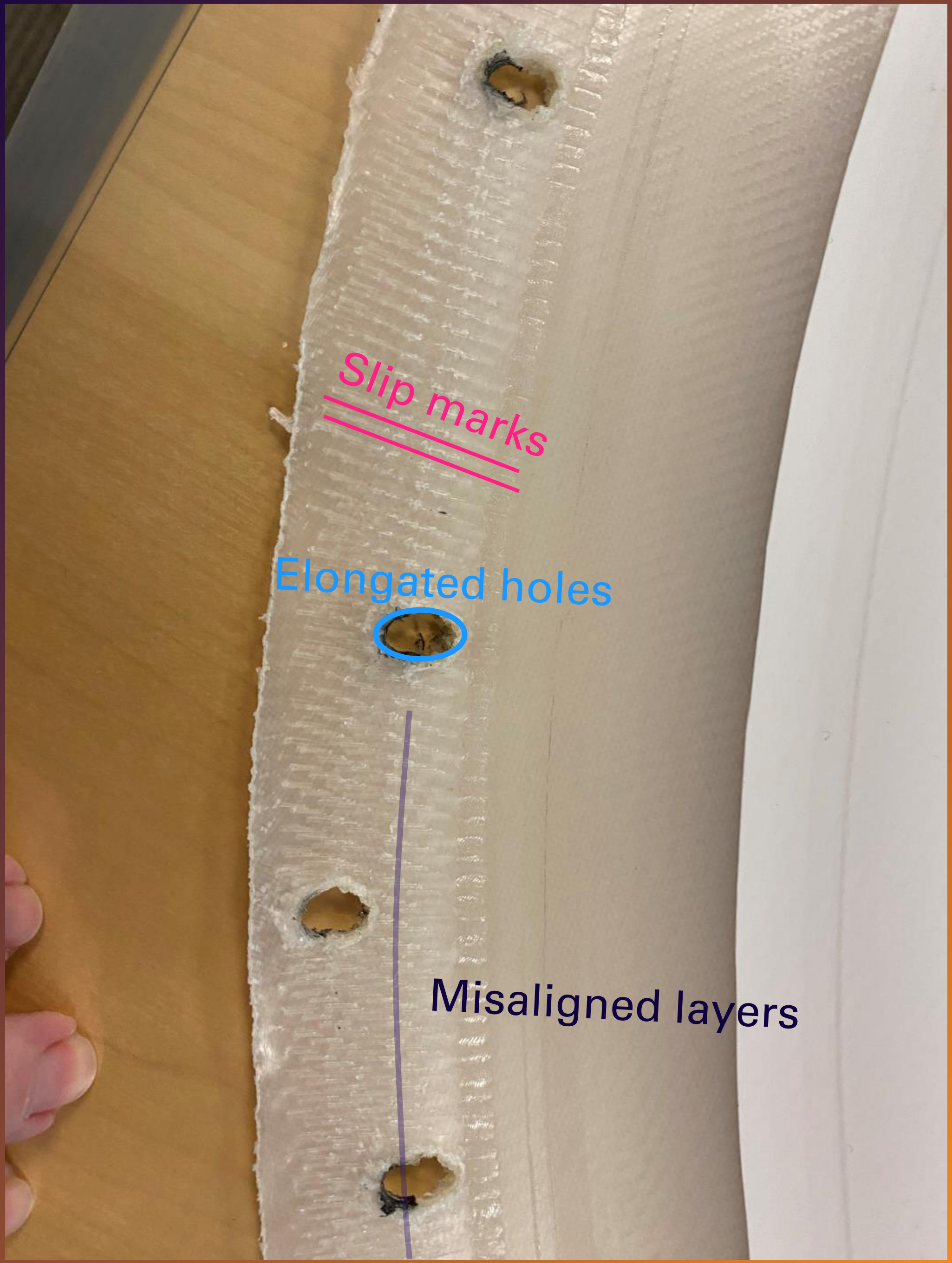

Autoclave top plate
O-ring
Autoclave ring
Breather cloth
Vacuum bag (Stretchlon)
Laminate stack
Release layer (polyester)
Autoclave baseplate
O-ring


Autoclave top plate
O-ring
Autoclave ring
Breather cloth
Vacuum bag (Stretchlon)
Layer misalignment
Release layer (polyester)
Autoclave baseplate
O-ring

Layer Misalignment And Slipping

One edge was thinner than the others

- This allowed the window to slip in the clamping mechanism



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- This caused a pinched o-ring, and caused the window to fail its initial permeation checks

Layer Misalignment And Slipping

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- This allowed the window to slip in the clamping mechanism
- This caused a pinched o-ring, and caused the window to fail its initial permeation checks
- Fixed by bulking up thickness of edge with tape

Mechanical Difficulties Led to Improved Testing

Previous quality assurance testing:

- Pre-deflection in-band S11 measurement
- Deflection
- Gas accumulation rate

New quality assurance testing:

- Pre-deflection in-band S11 measurement
- Deflection
- Initial/final pump out pressure
- Gas accumulation rate
- Post-deflection in-band S11 measurement
- Edge helium leak check
- Helium diffusion rate

3rd window has passed all these tests!

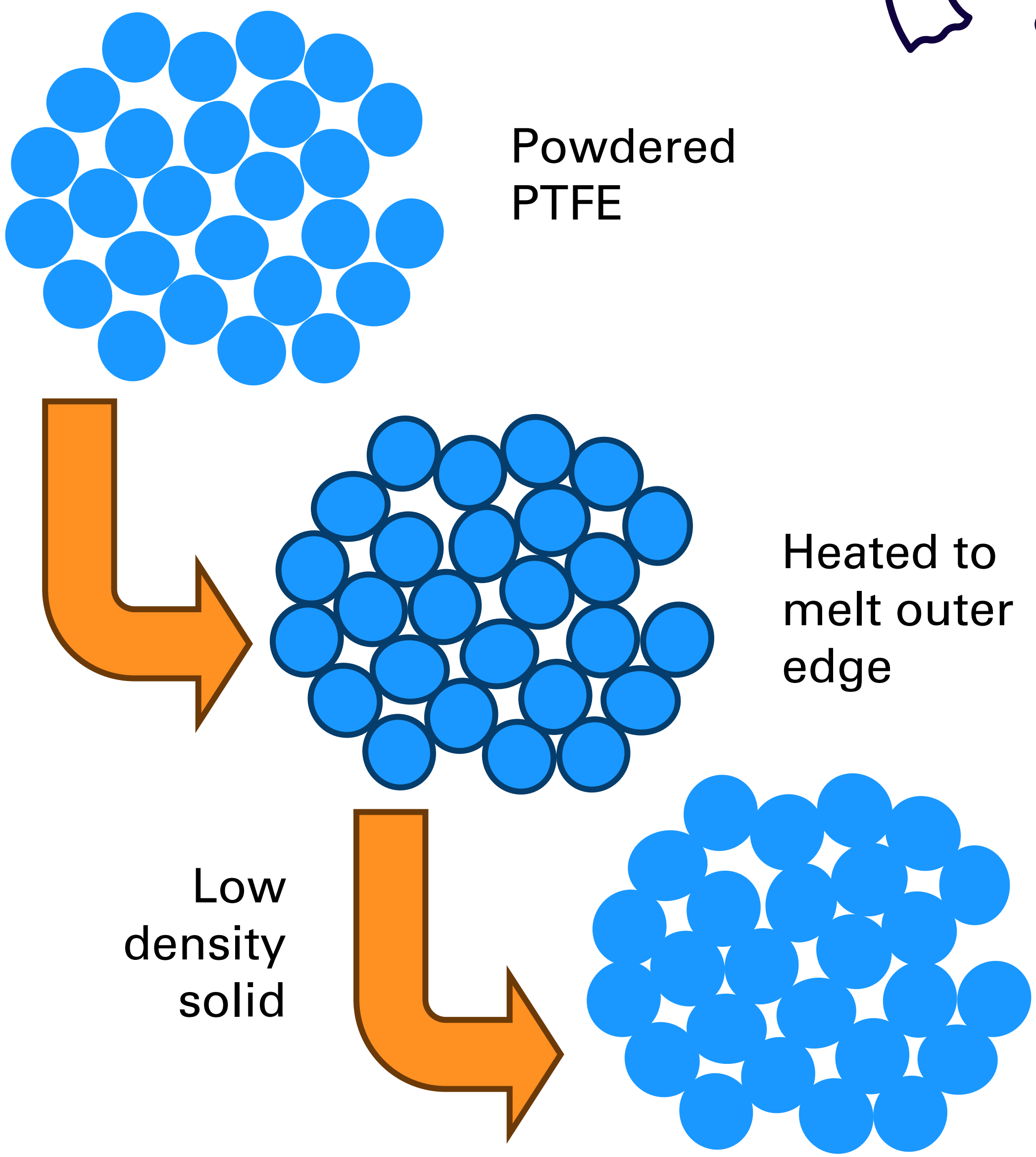
Problem #2

ABOMINABLE ANTI-REFLECTION COATS

Previous AR Coats

Sintered PTFE (sPTFE)

- Commercial names Porex/Zitex
  - Manufacturing:
    - A cylinder (billet)
    - Skive (cut) a thin membrane



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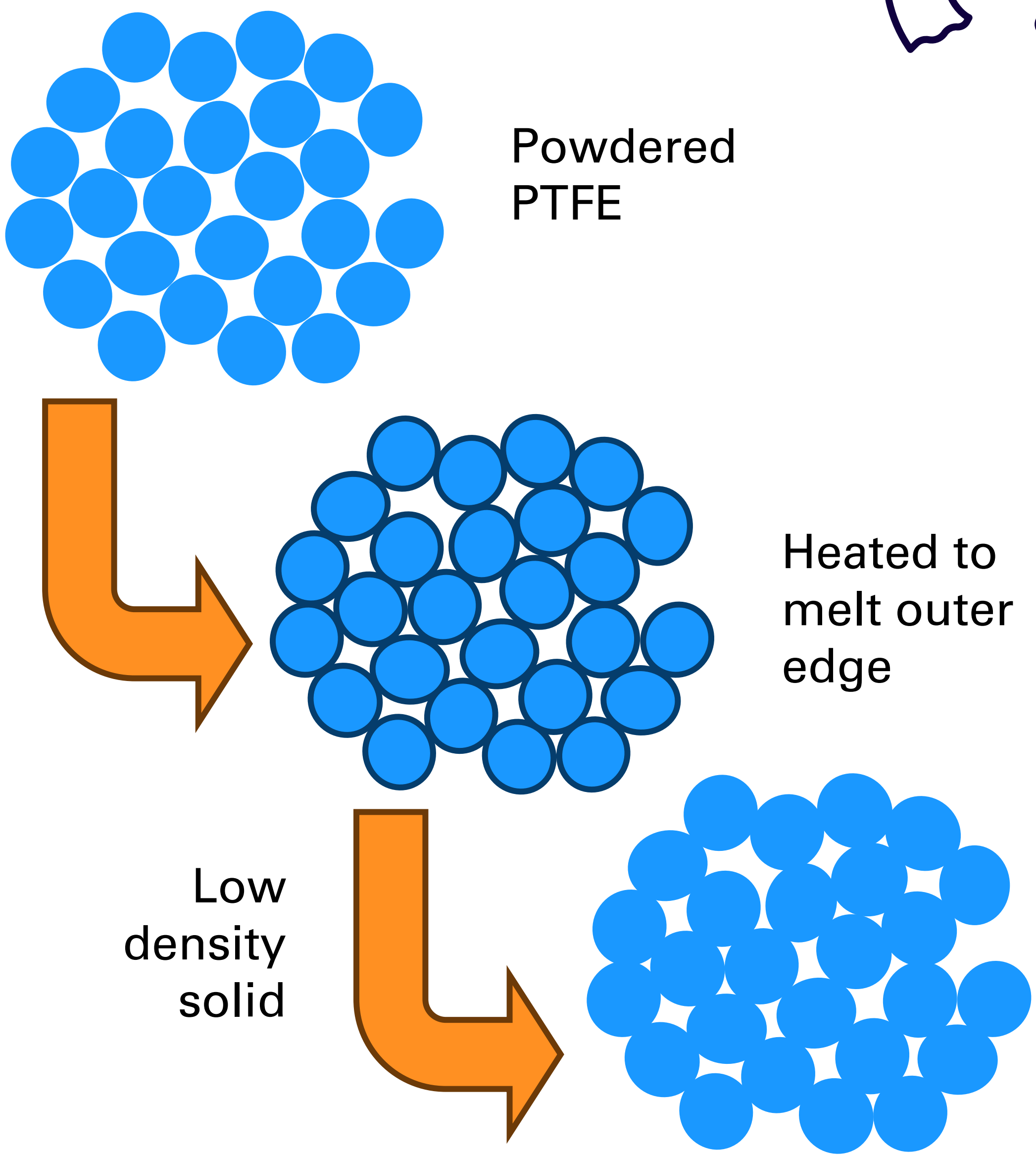
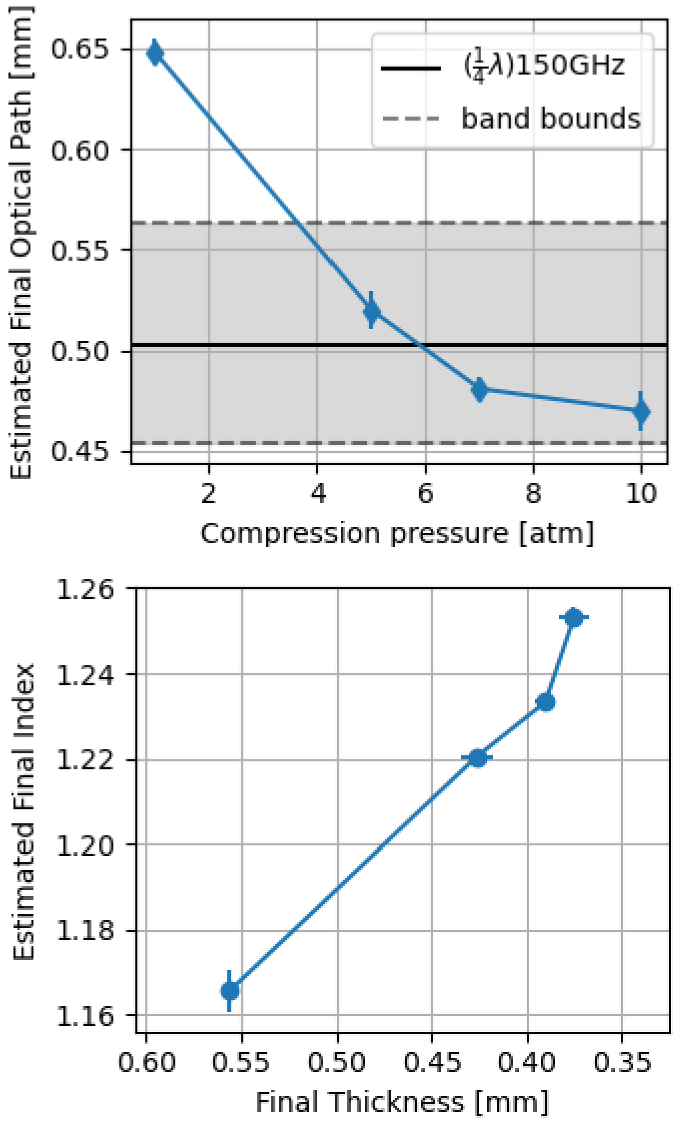
- Commercial names Porex/Zitex
  - Manufacturing:
    - A cylinder (billet)
    - Skive (cut) a thin membrane
  - Large scale difficulties
    1. Ideal density is difficult to manufacture
    2. Ideal thickness difficult to skive



Previous AR Coats

Expanded PTFE (ePTFE)

- Previously used Teadit (30/40, 95, 150 GHz)
  - Manufacturing:
    - Resin extruded then stretched



arXiv:2208.01088

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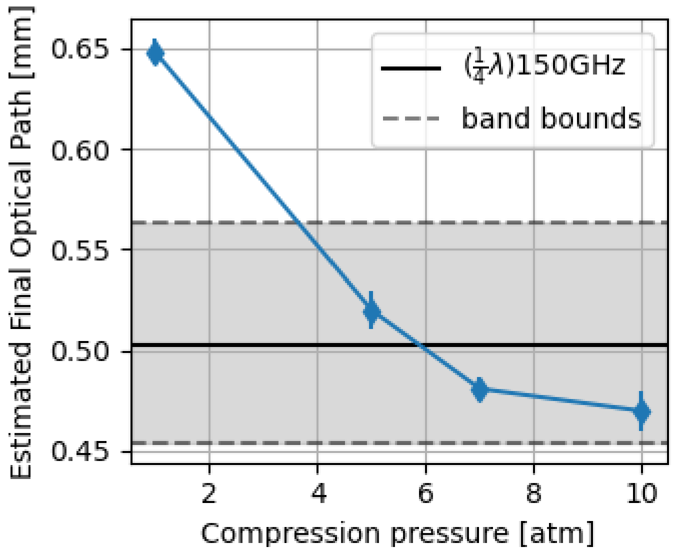
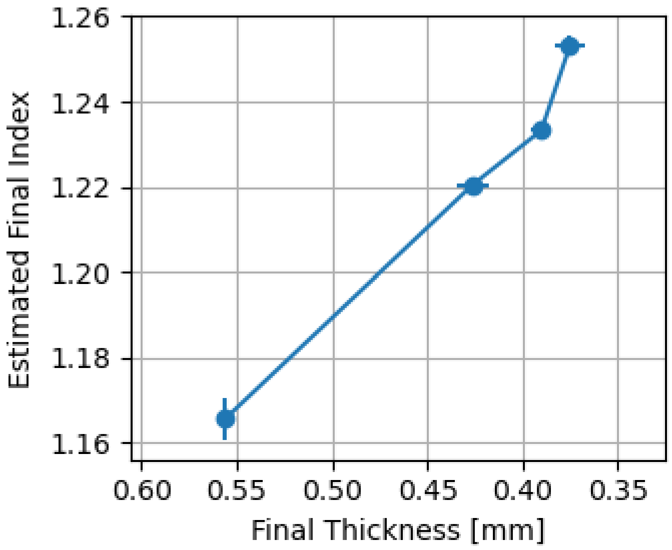
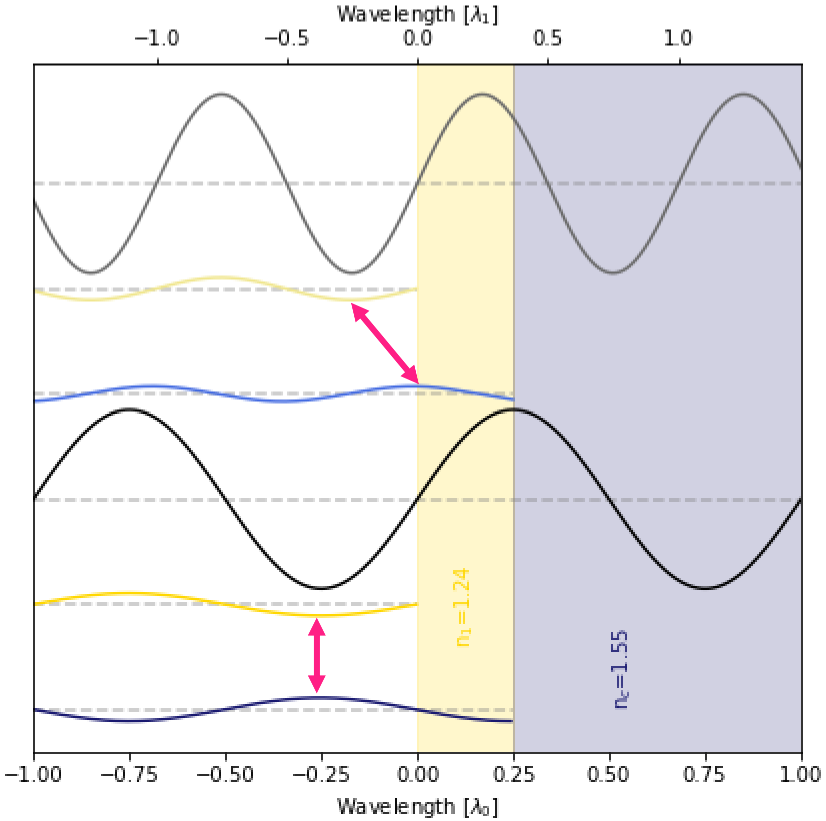
- Previously used Teadit (30/40, 95, 150 GHz)
  - Manufacturing:
    - Resin extruded then stretched
  - Large scale difficulties
    1. Ideal thicknesses difficult to make
    2. Consistency of parameters
       - Thickness and density tends to vary across a sheet

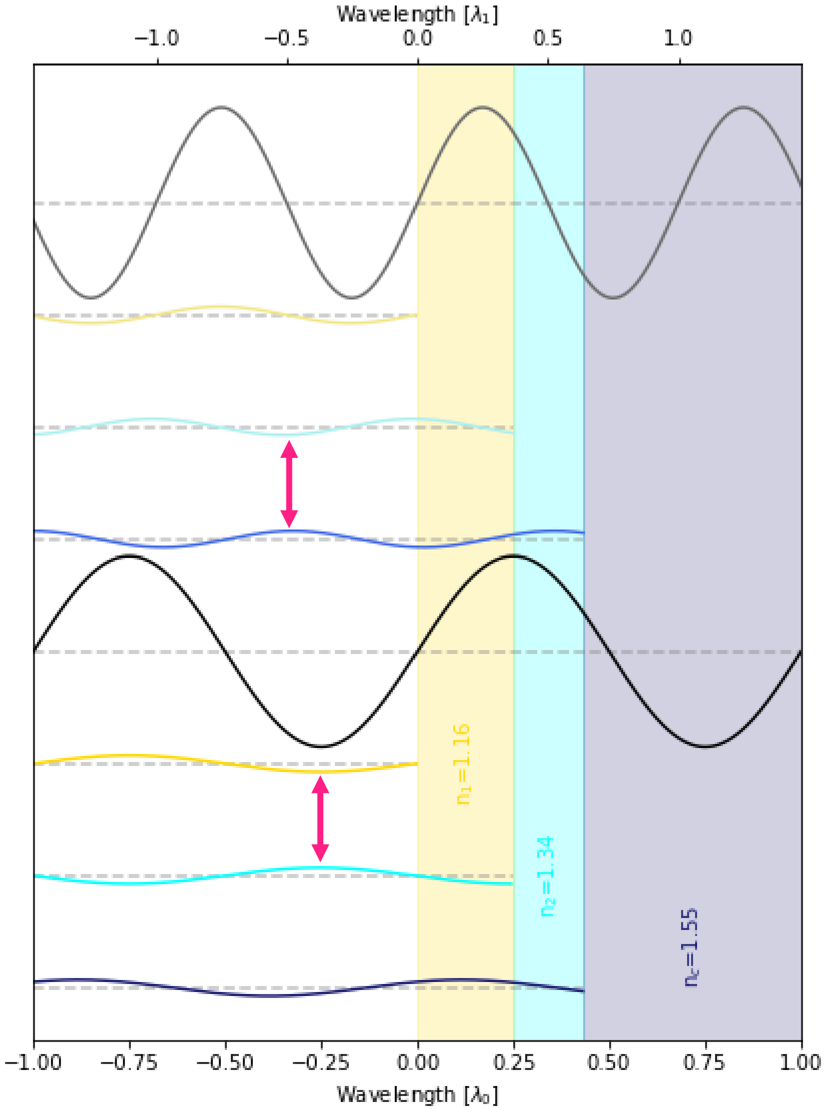




arXiv:2208.01088

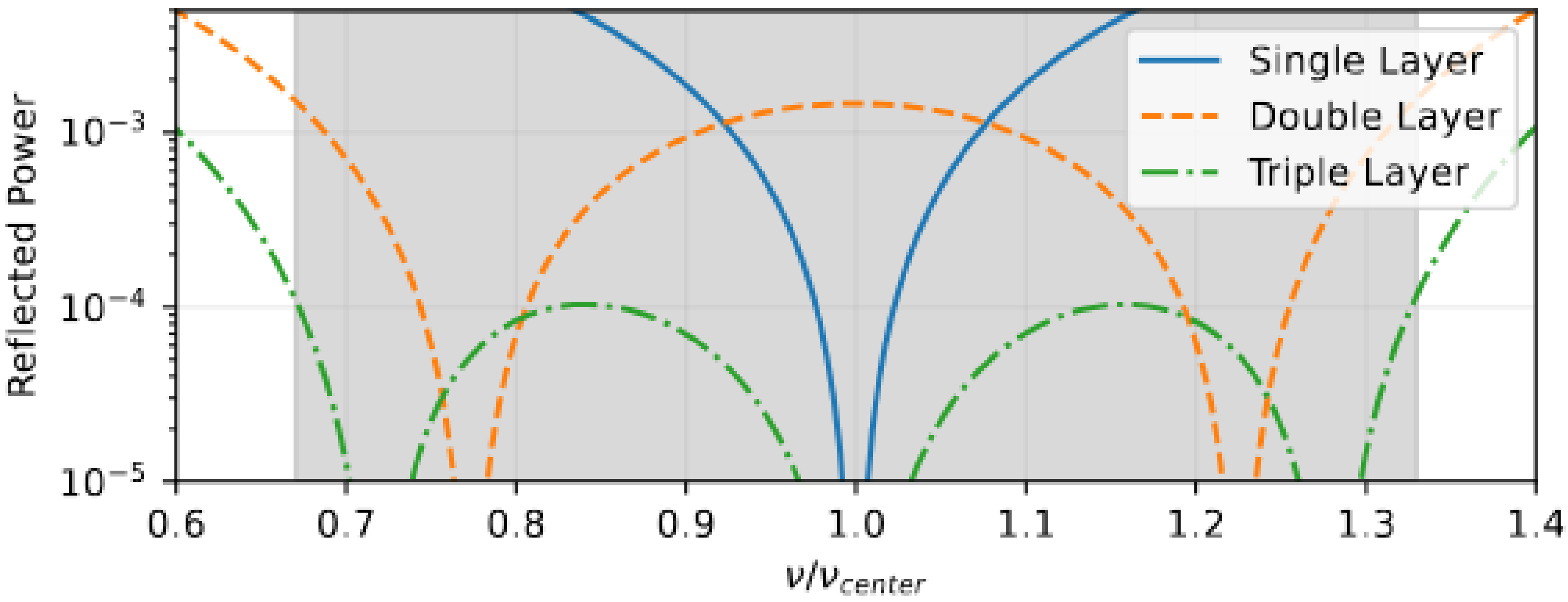
Multi-layer AR Coats





Chebyshev Anti-reflection Coats

Uses Chebyshev polynomials to calculate ideal multilayer anti-reflection coats over a broad bandwidth



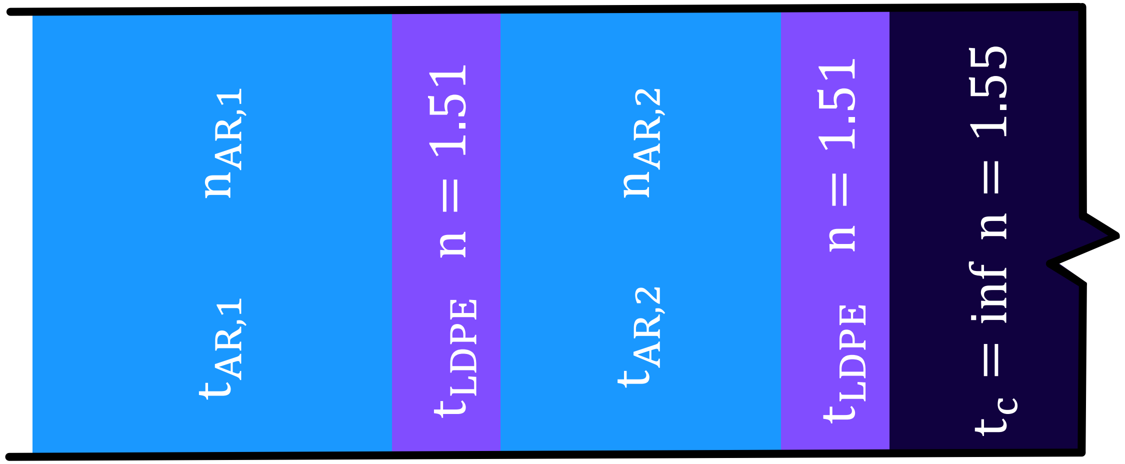
arXiv:2407.17604

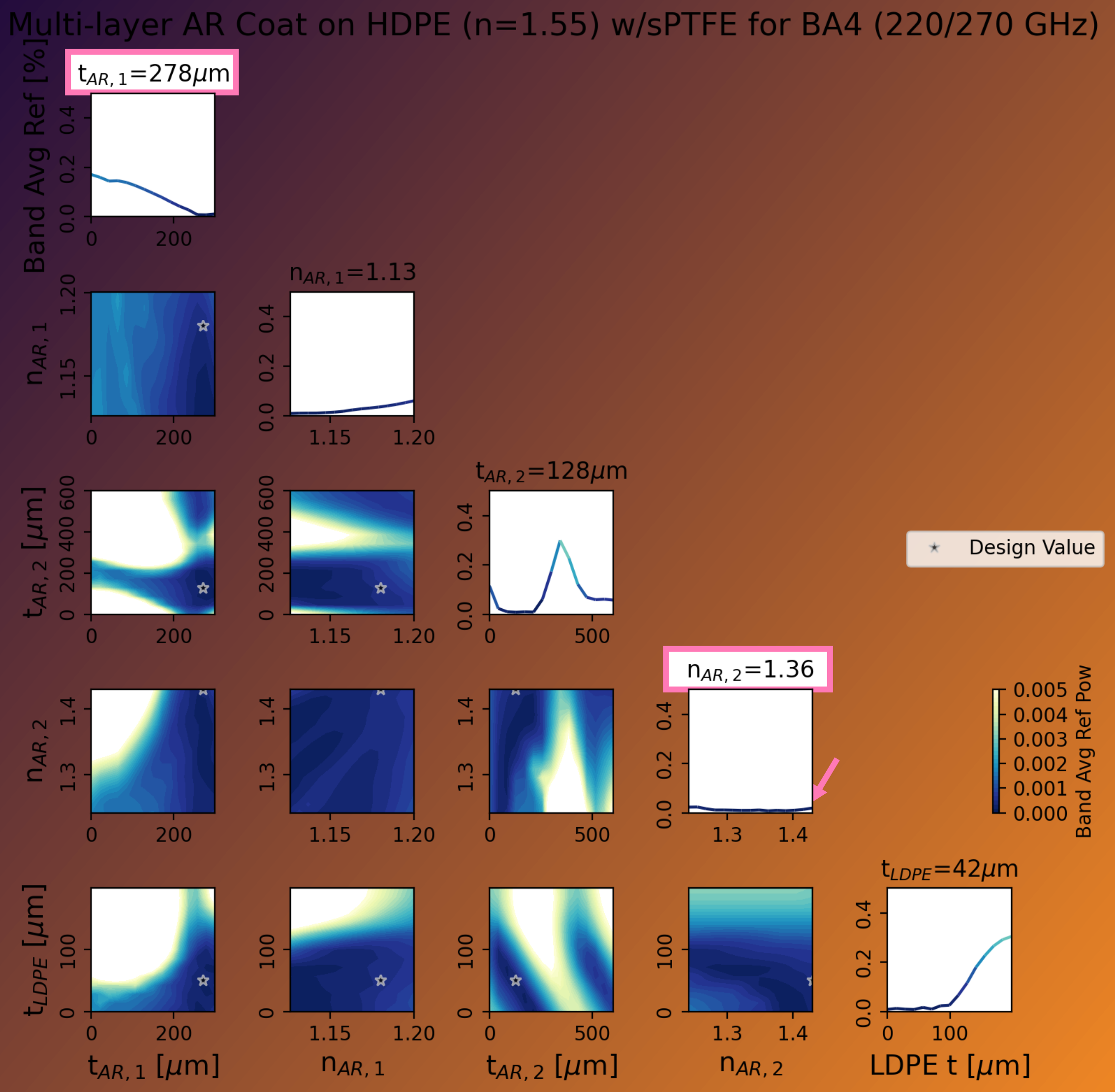
DeWAL

Extremely thin ePTFE – t ~ 70 μm

Extremely low density – n~1.05-1.2

Extremely… stackable?





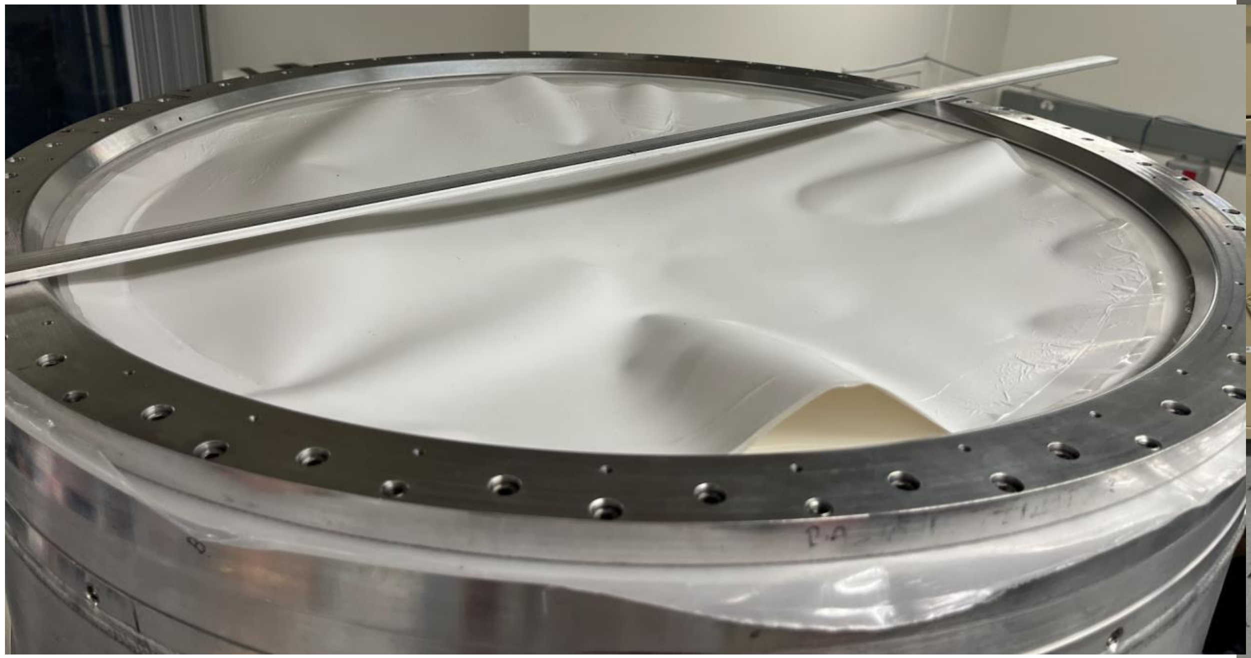
1st window

arXiv:2407.17604

Problems with DeWAL

First window anti-reflection coat

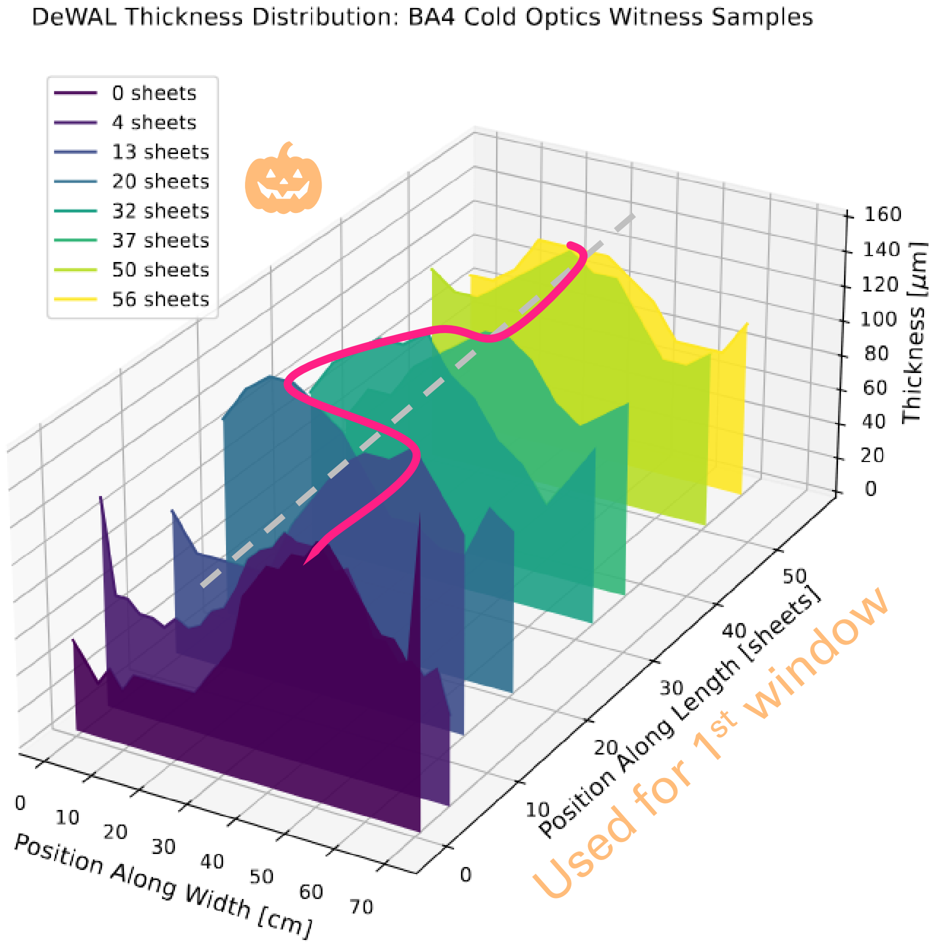
- Don’t use bulk PTFE on the windows



1st window

Problems with DeWAL

Thickness variation across roll



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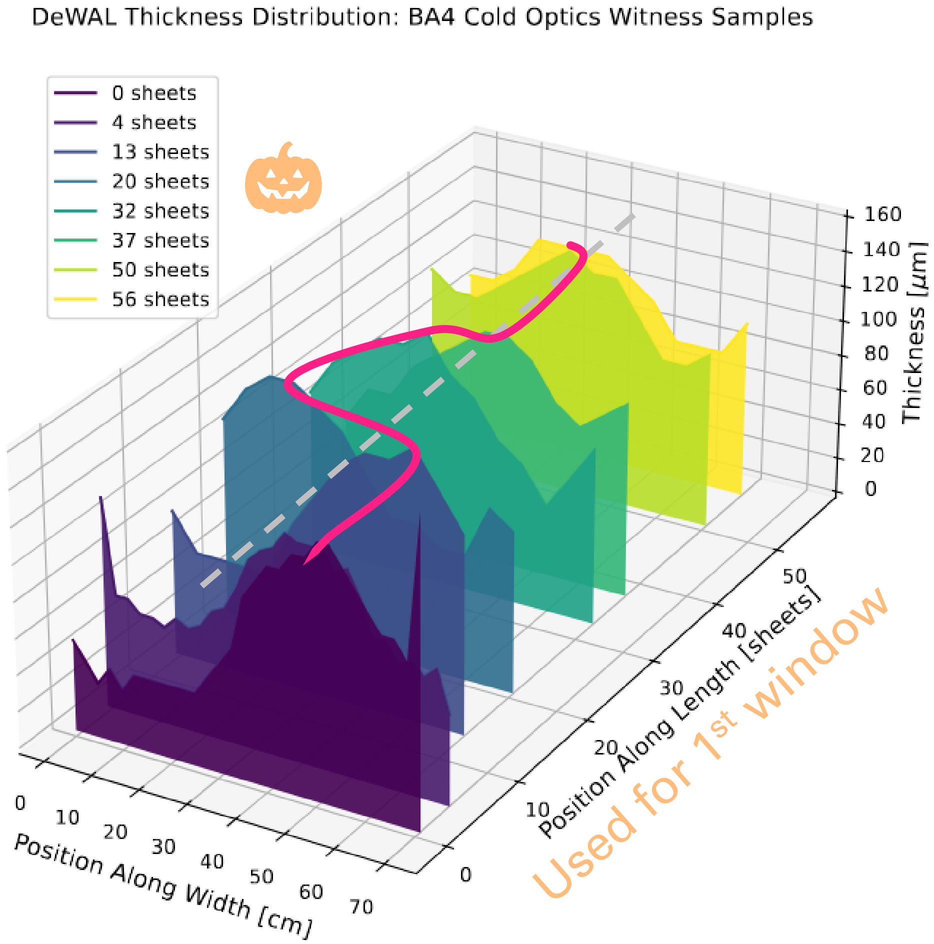
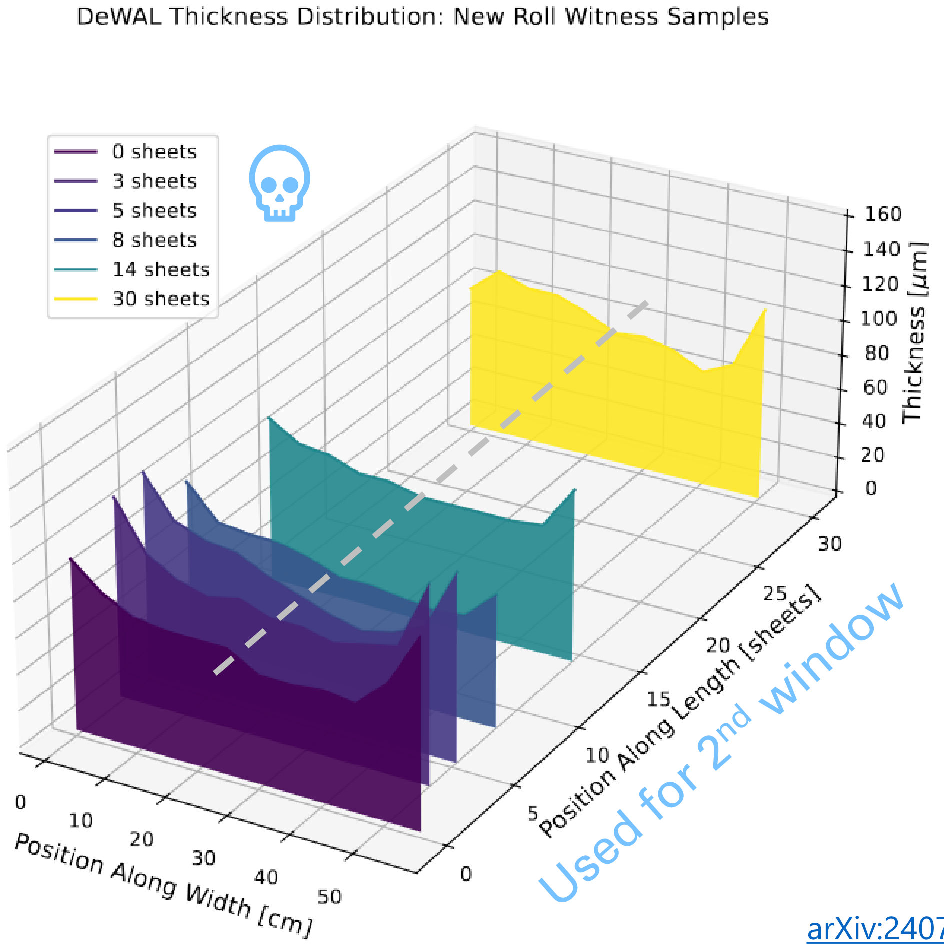
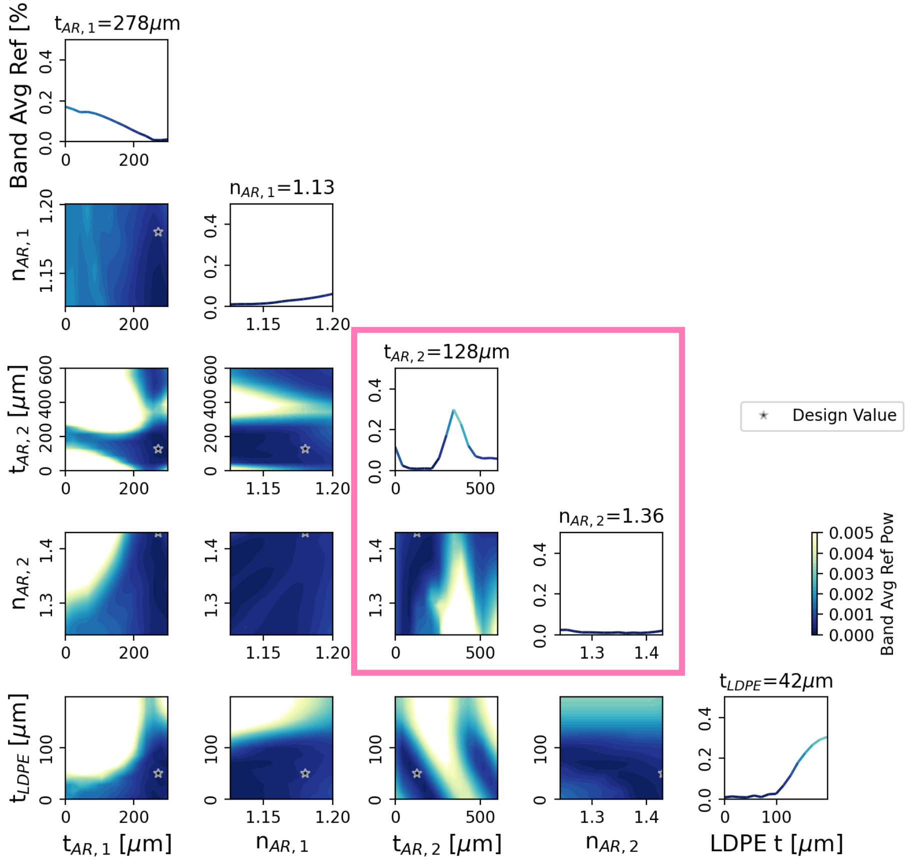




[arXiv:2407.17604](https://arxiv.org/abs/2407.17604)

Redesigned DeWAL Only AR

Multi-layer AR Coat on HDPE (n=1.55) w/sPTFE for BA4 (220/270 GHz)



1st window

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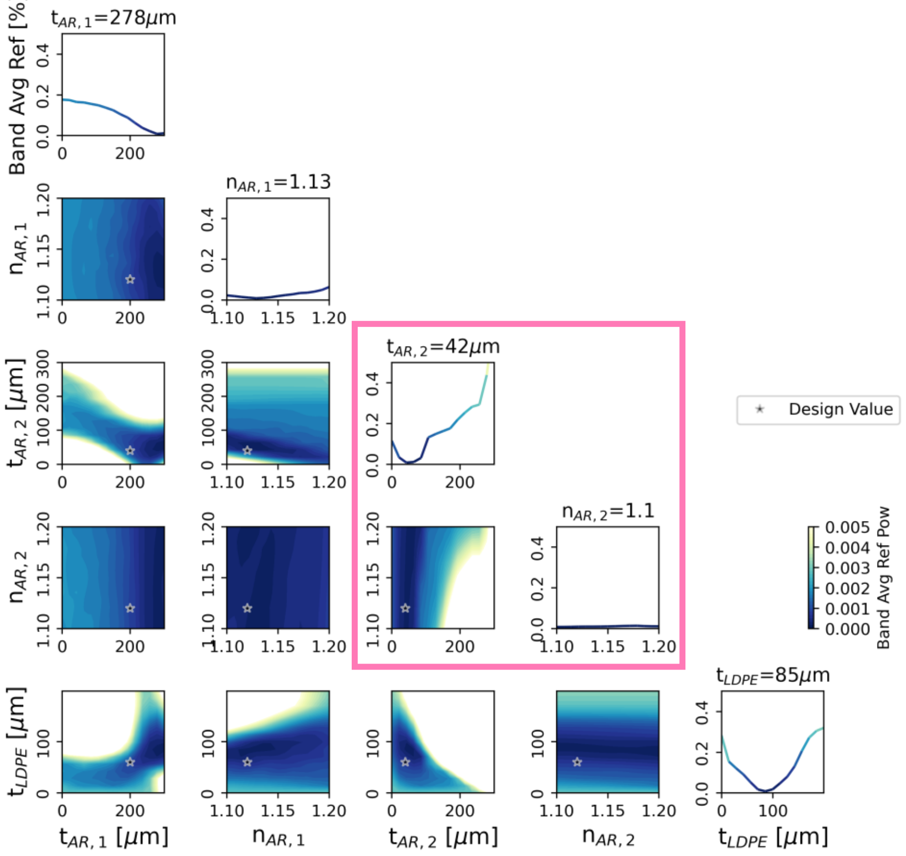


2nd window; 3rd window

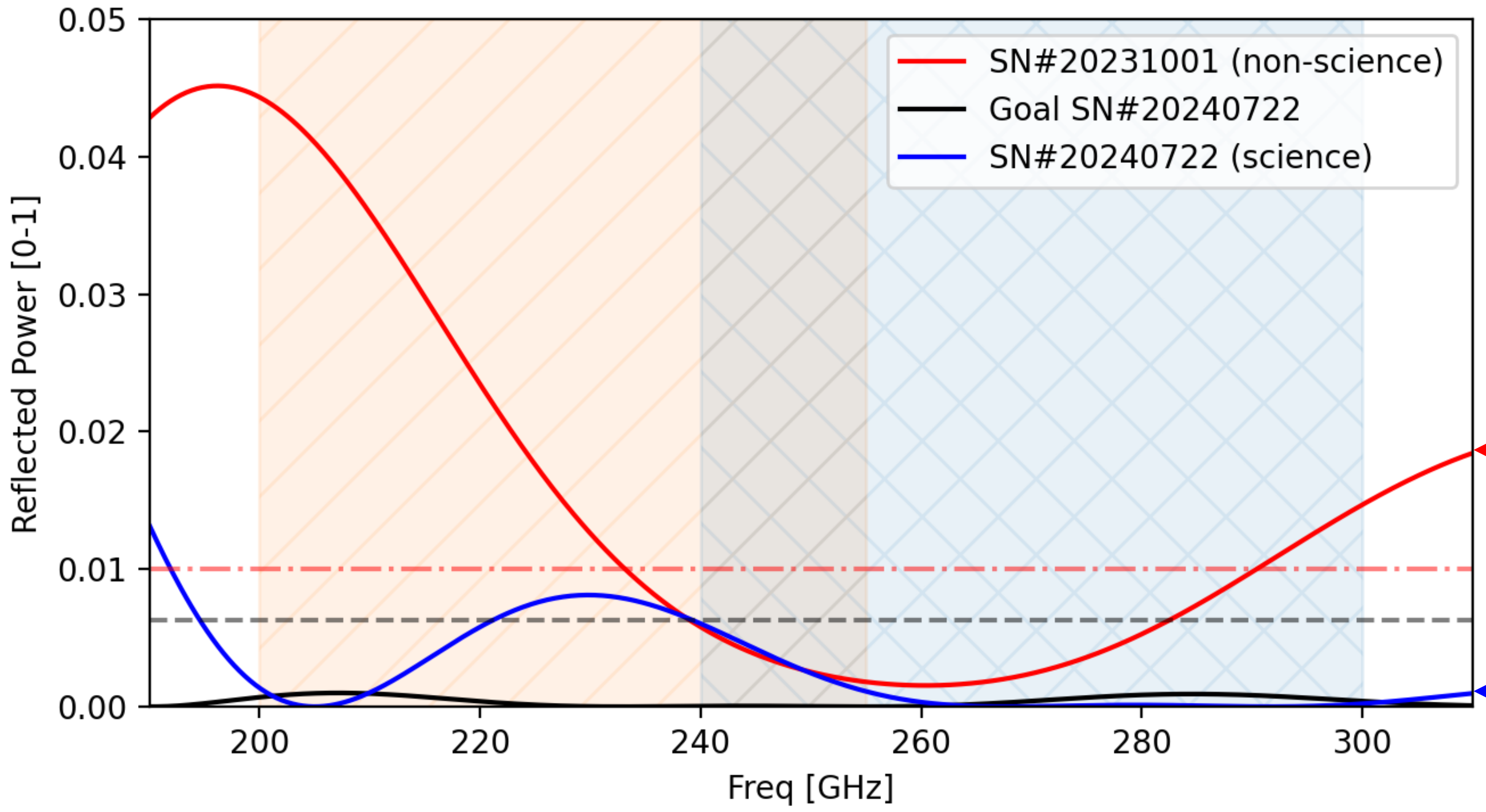
Problems with DeWAL

Second window anti-reflection coat

- Can’t add layers to a compressed stack

Problems with DeWAL

Difficulty controlling final parameters



2nd window

3rd window

CONCLUSIONS

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- We have successfully made a thin window for a large aperture high frequency BICEP Array receiver!
- Updated quality assurance testing for final thin windows
- For more information:
  - About Chebyshev or DeWAL AR coats
    - [arXiv:2407.17604]
  - About Thin HMPE windows
    - Full paper coming soon!

3rd window

This work was made possible by many people, including Keara Carter (above), Mike Echter, Brodi Elwood, Robert Kimberk, John Kovac, Paul Grimes, Matthew Miller, Matthew Petroff, Annie Polish, and Clara Vergès