National Institute of Standards and Technology U.S. Department of Commerce [1]

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Complex permittivity measurements of substrates and thin films at millimeter-wave frequencies

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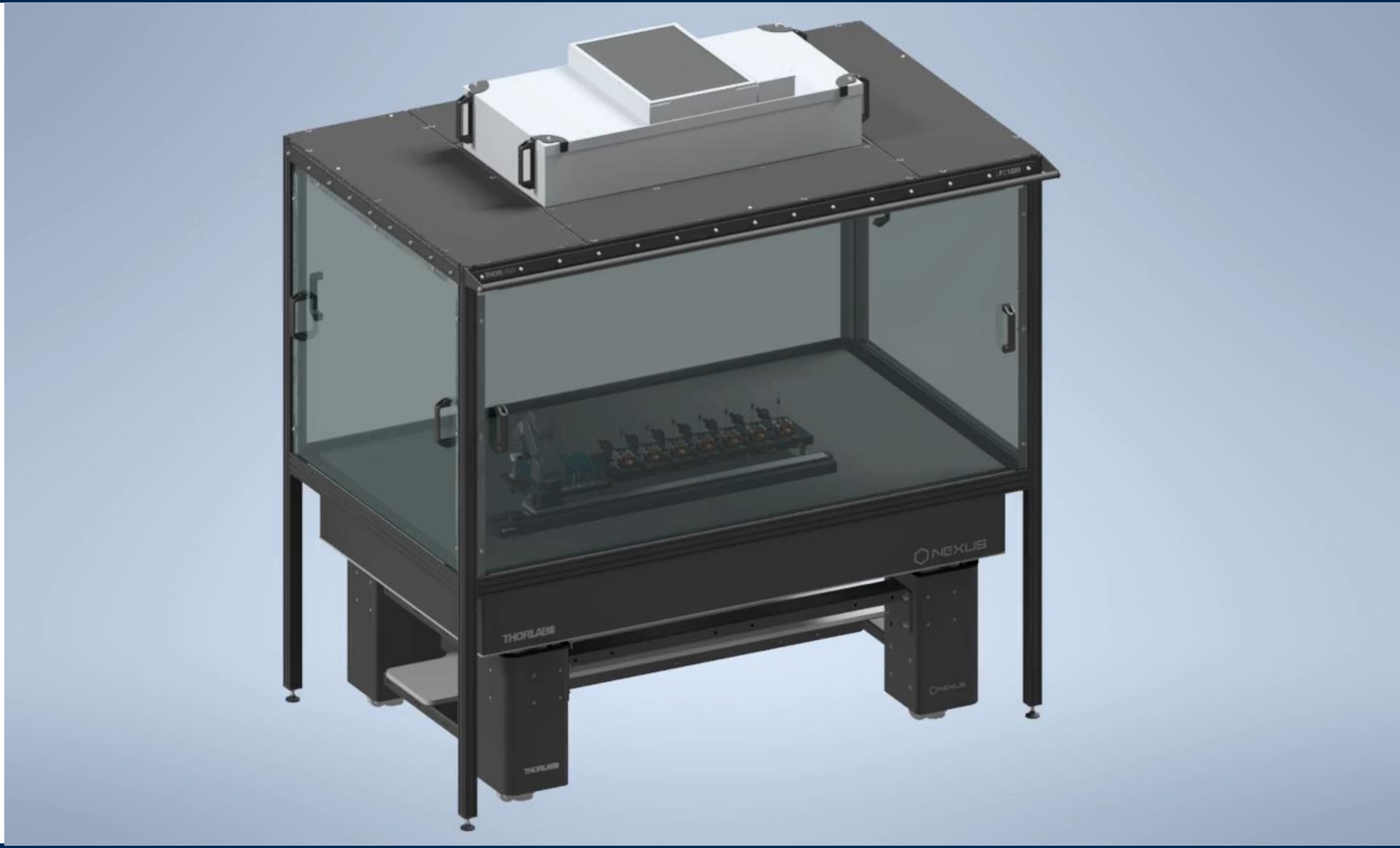
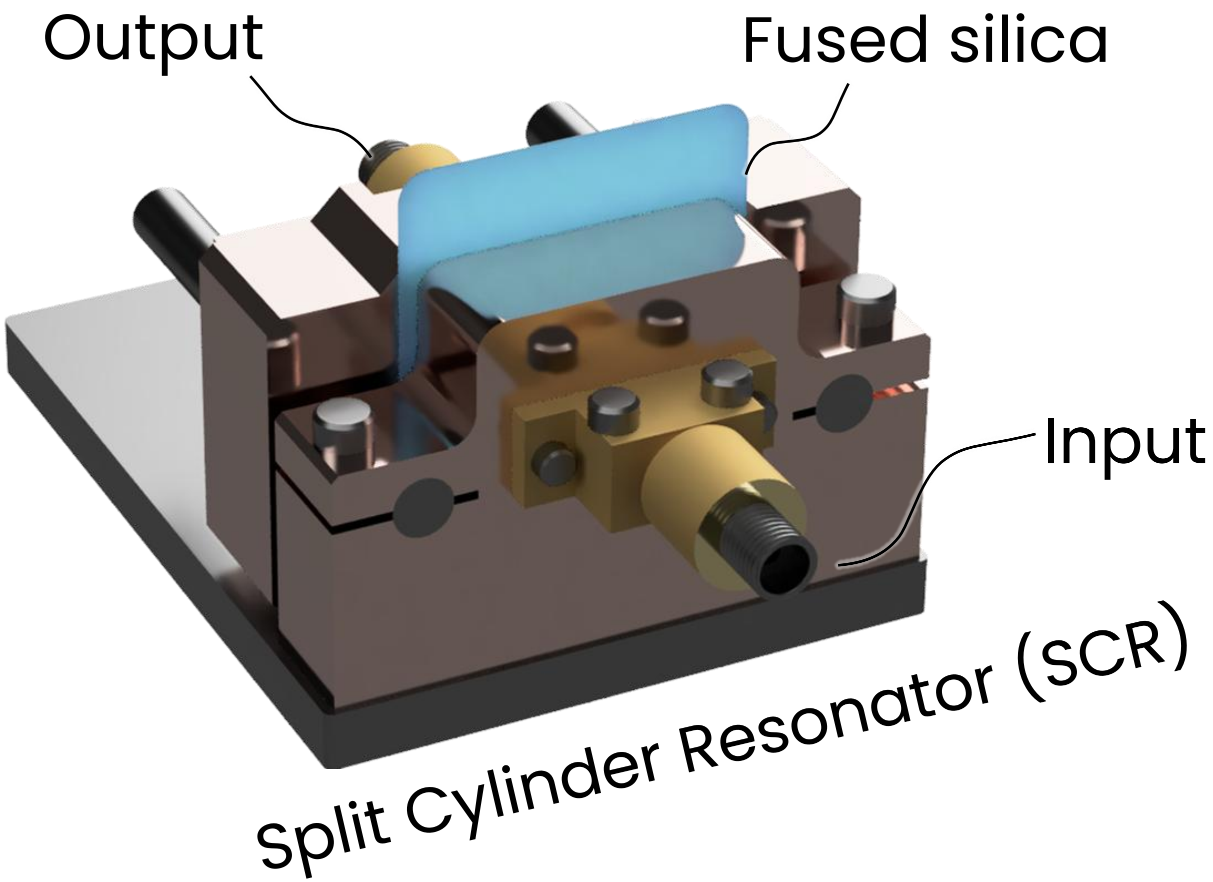
We made a standard for relative permittivity

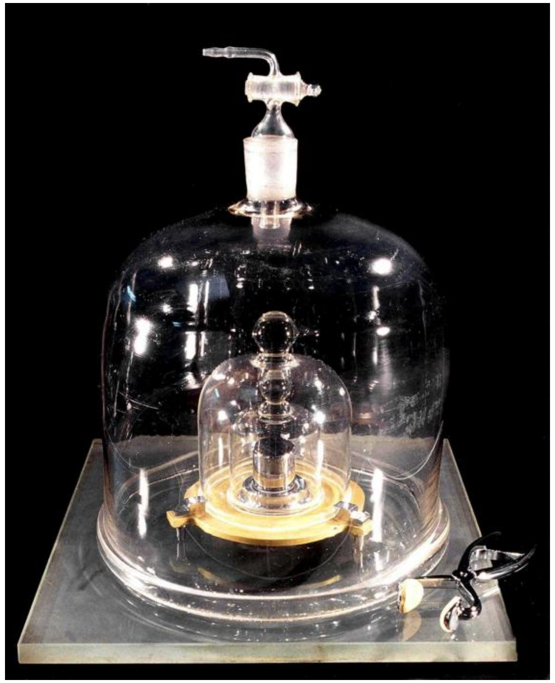


Industry collaborators helped a ton along the way

It's relatively straightforward to measure substrates



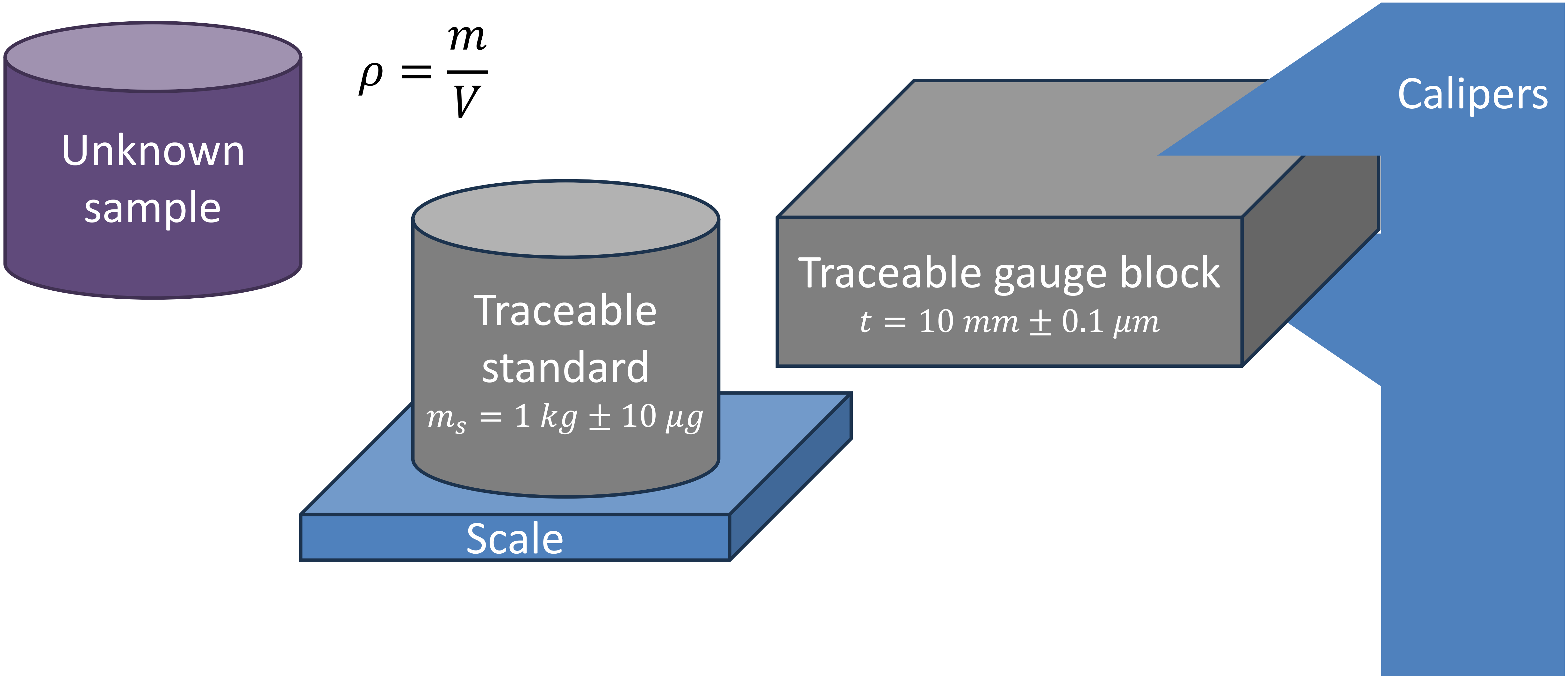
We measure **resonance frequency**, **quality factor**, and **sample thickness** to get ϵ_r' and ϵ_r''



https://www.nist.gov/si-redefinition/kilogram-introduction

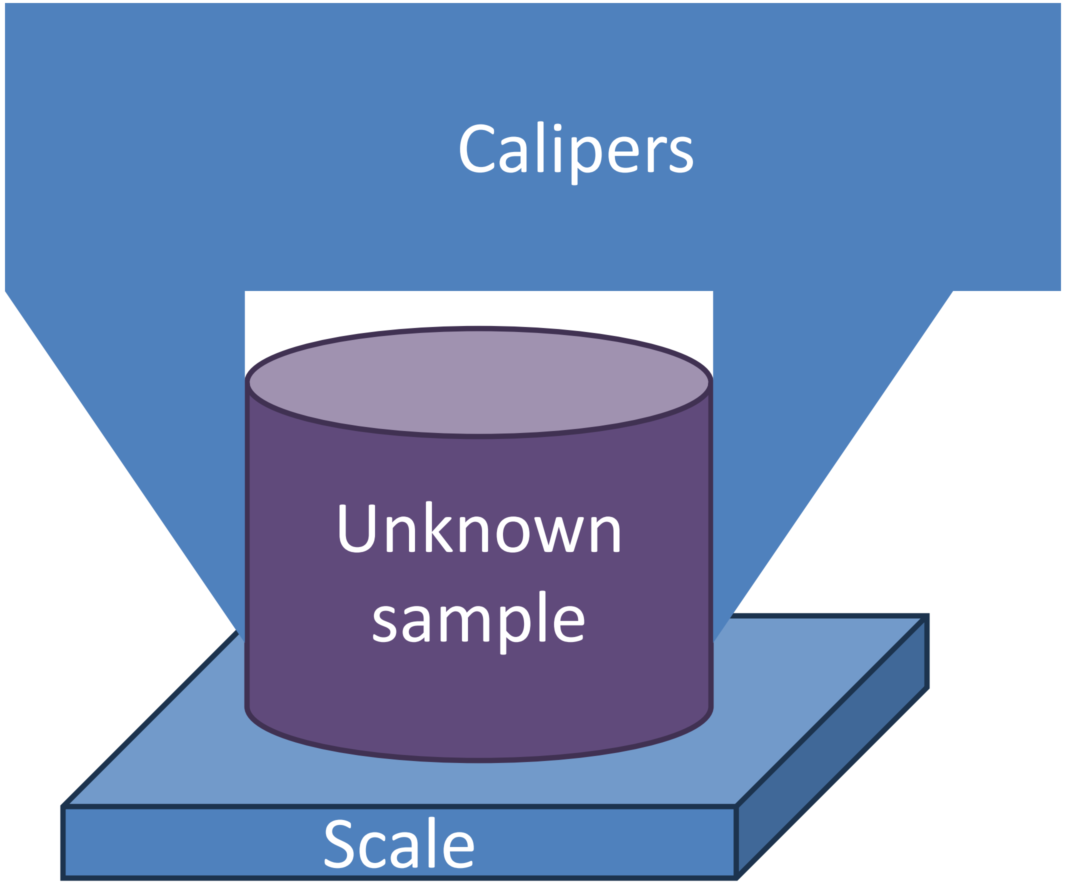
It's harder to measure substrates traceably

Density as an example of traceability



Let’s apply this back to our problem

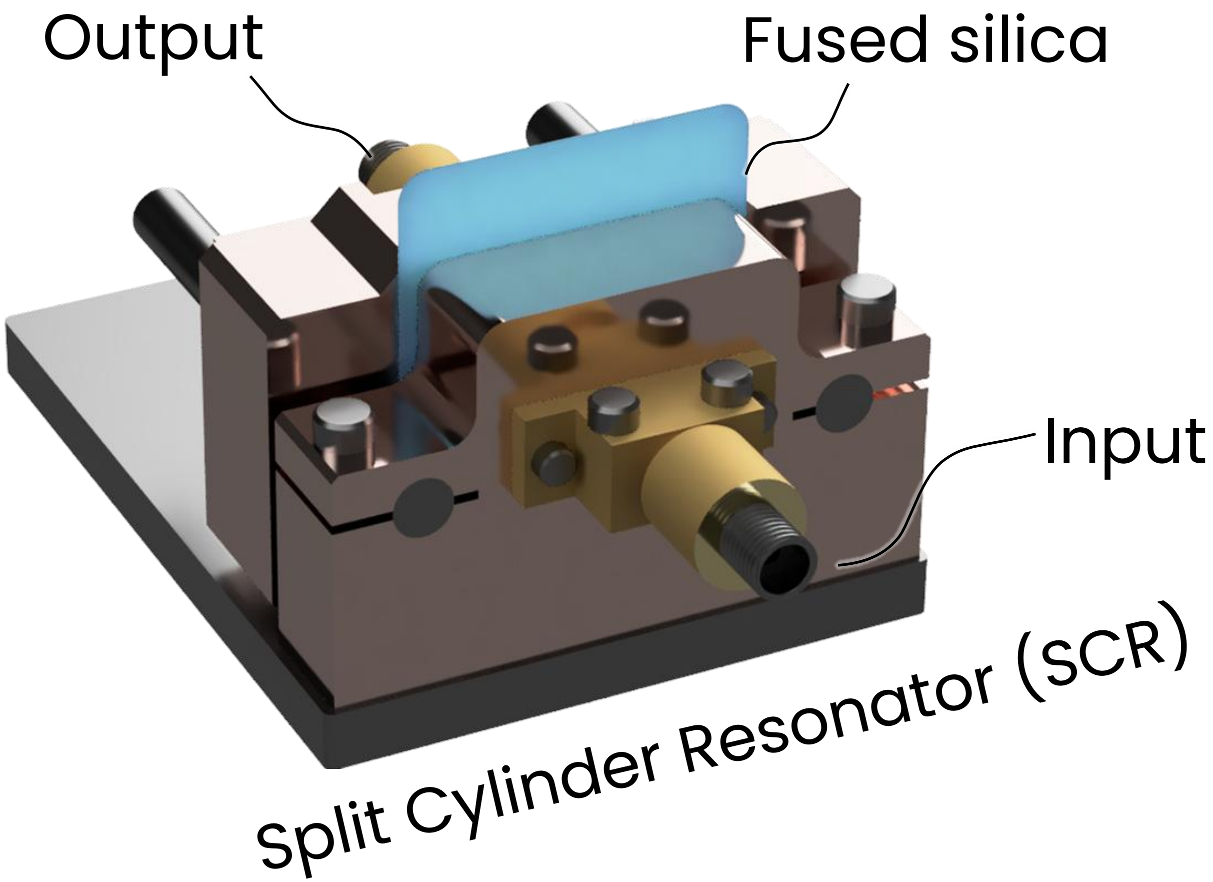
Density as an example of traceability

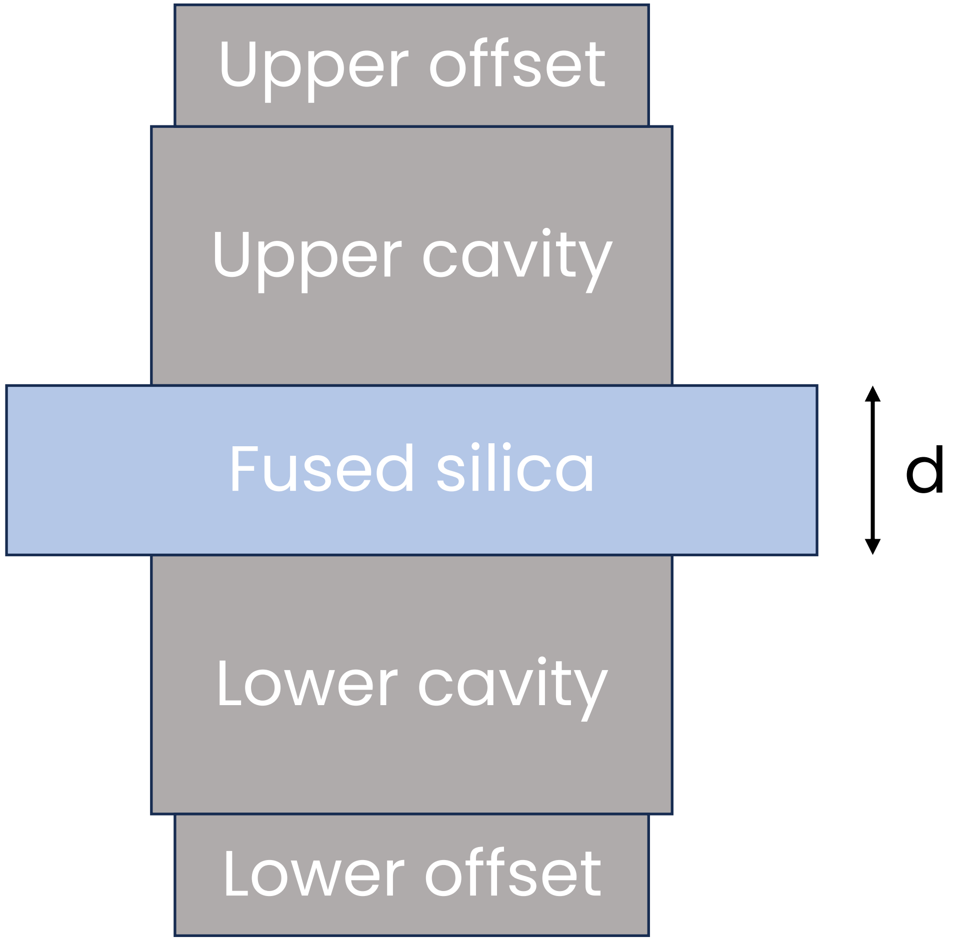


$$\rho \pm \delta\rho = \frac{m \pm \delta m}{V \pm \delta V}$$

Let's apply this back to our problem

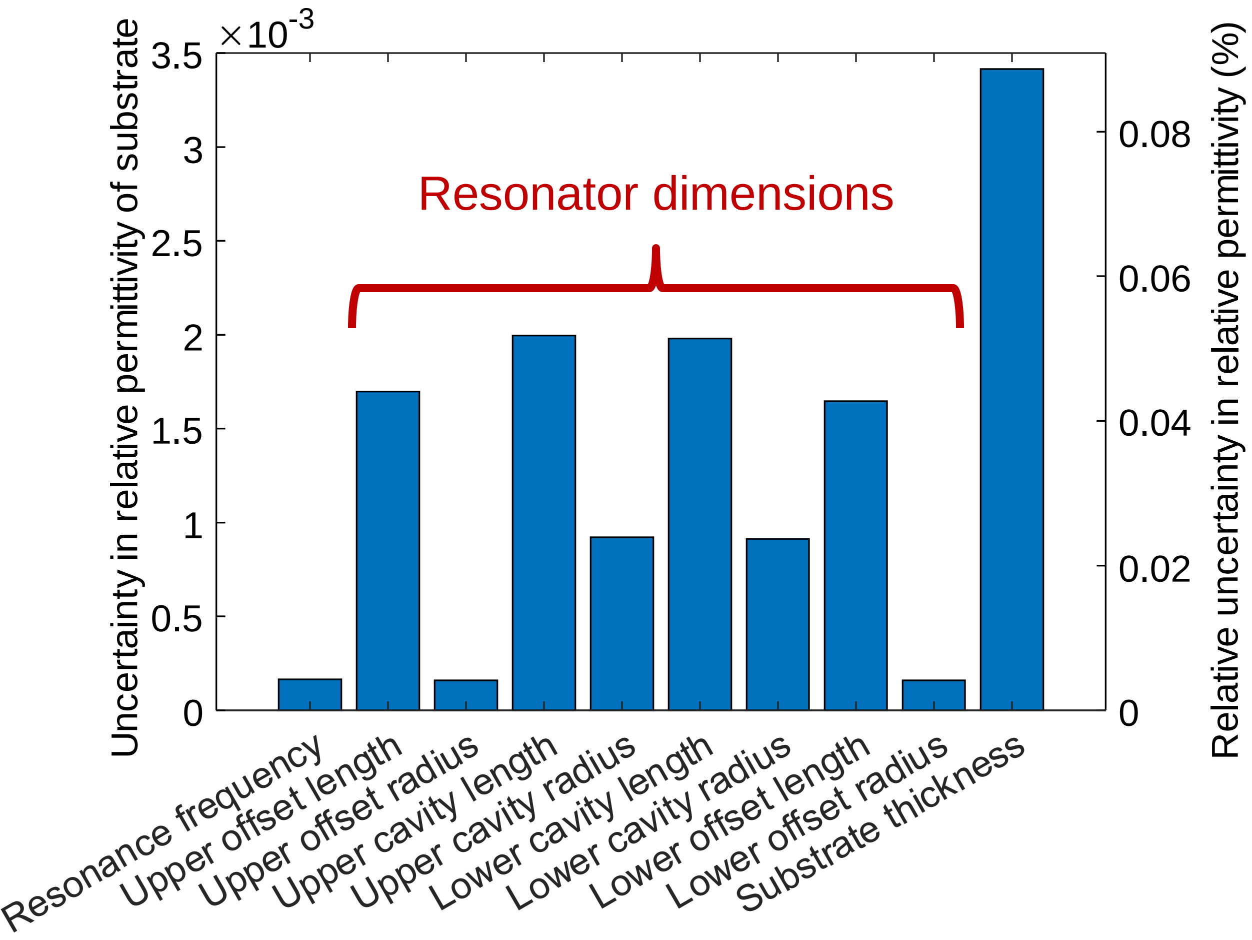
To get SI-traceable uncertainties, we use mode-matching

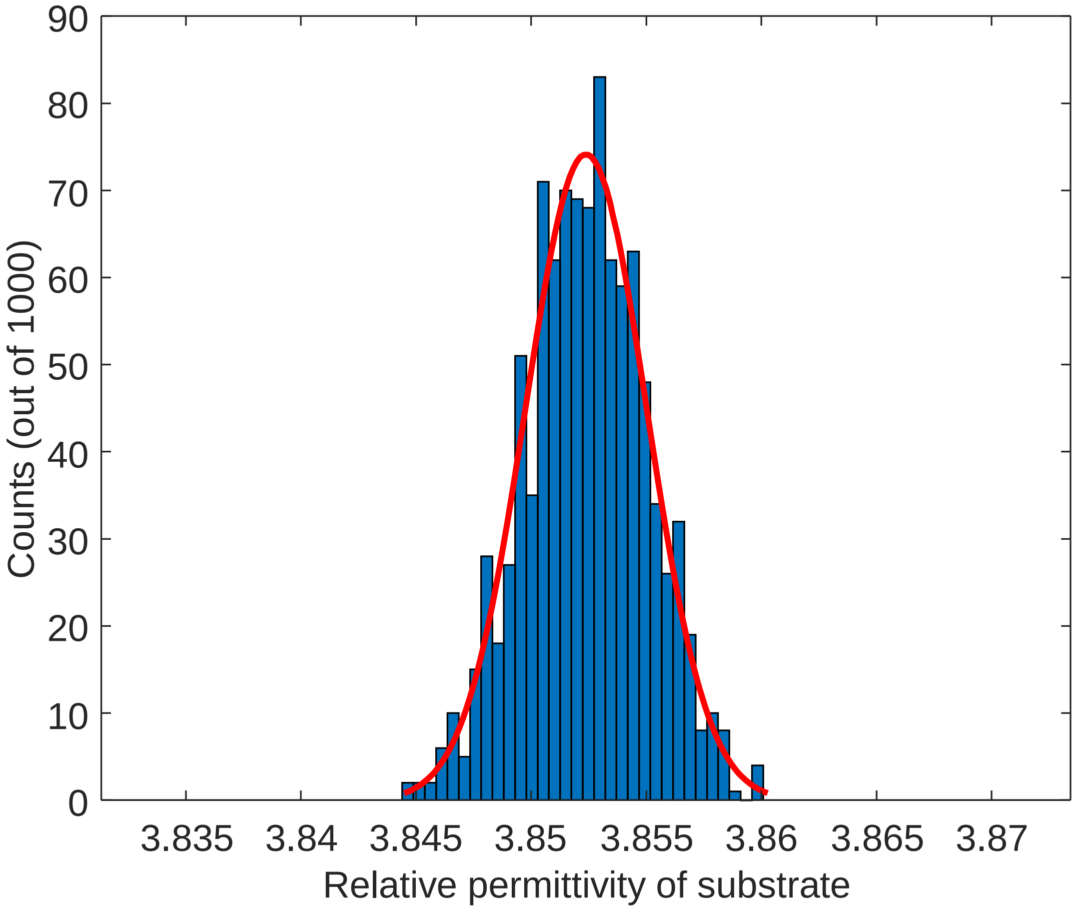




This analytical theory maps measurements to properties

We can vary the input parameters to analyze uncertainty

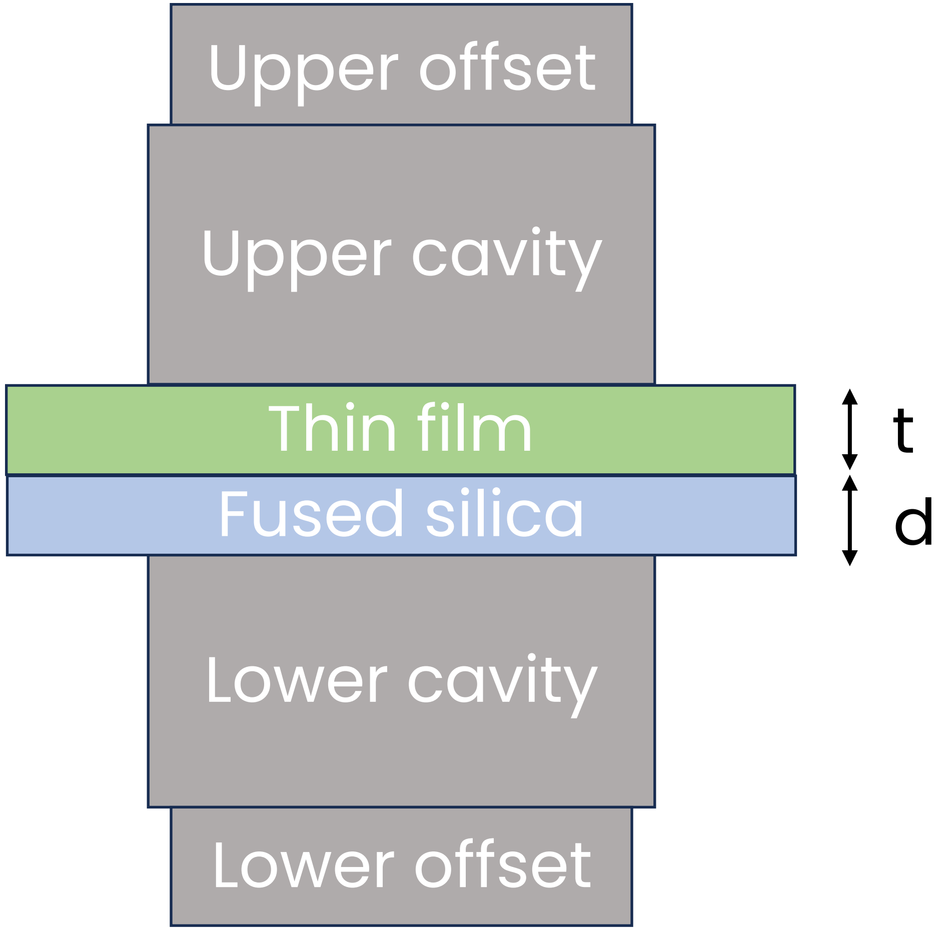




Uncertainty budget

Combined uncertainty

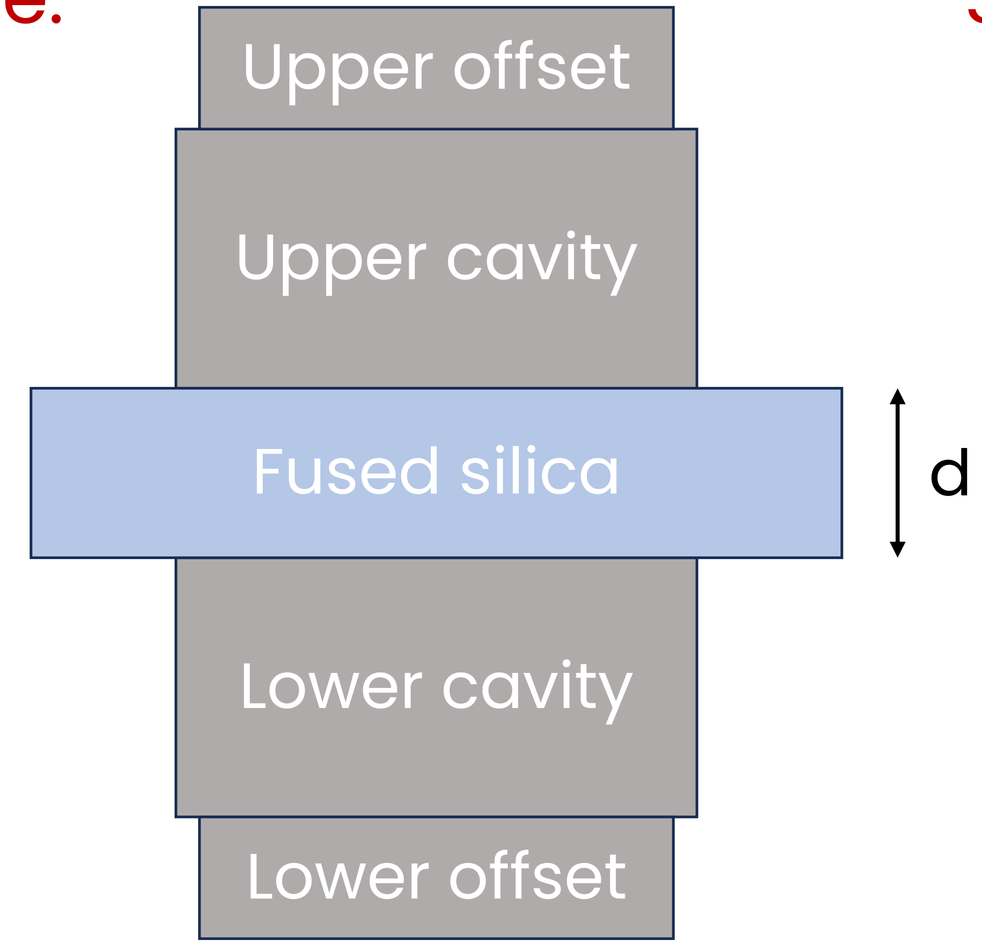
We can add cylinders to that same analytical theory



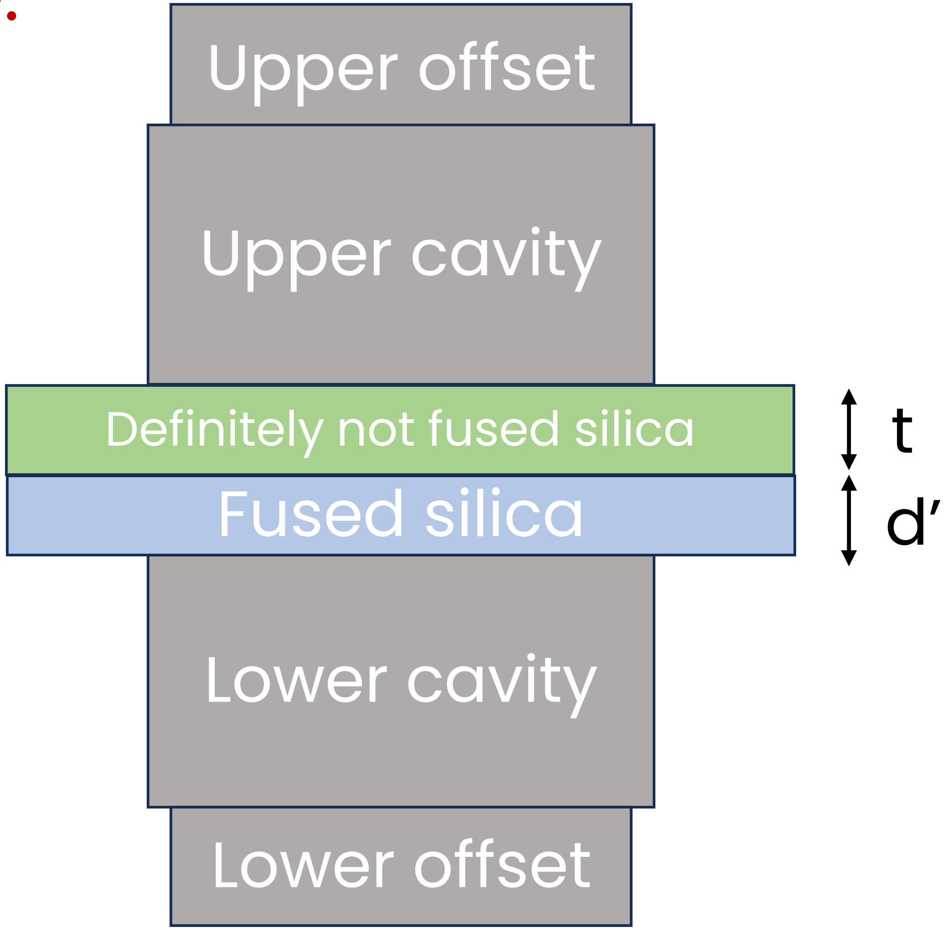
Knowing the substrate properties, we can measure a thin film

Validating this is tricky

Measure:



Solve:

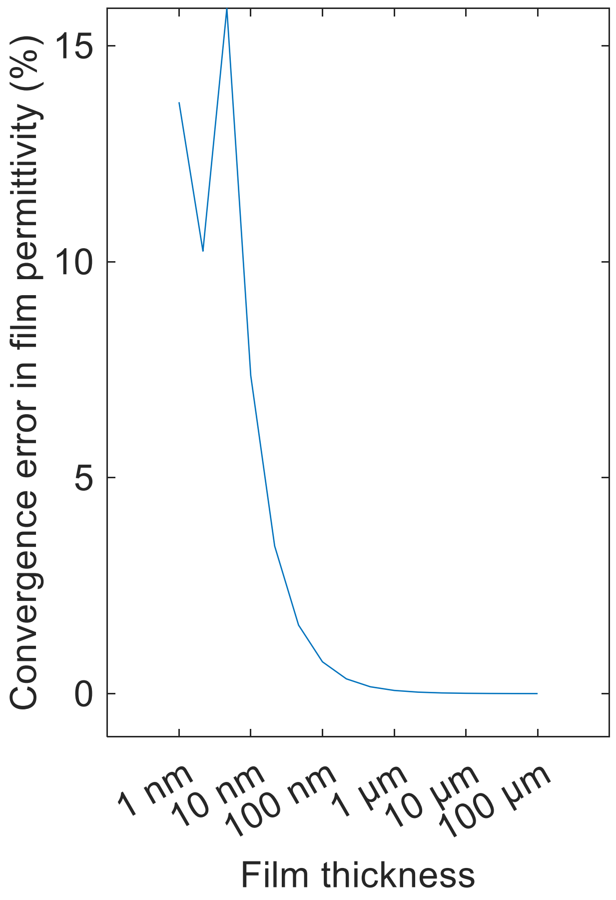


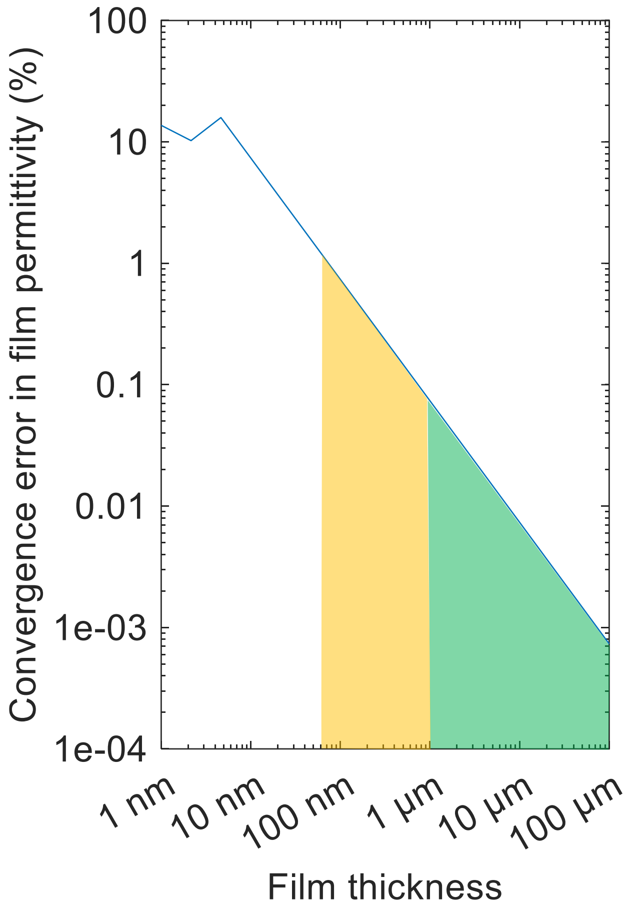
Lying to our analysis code gives us a target

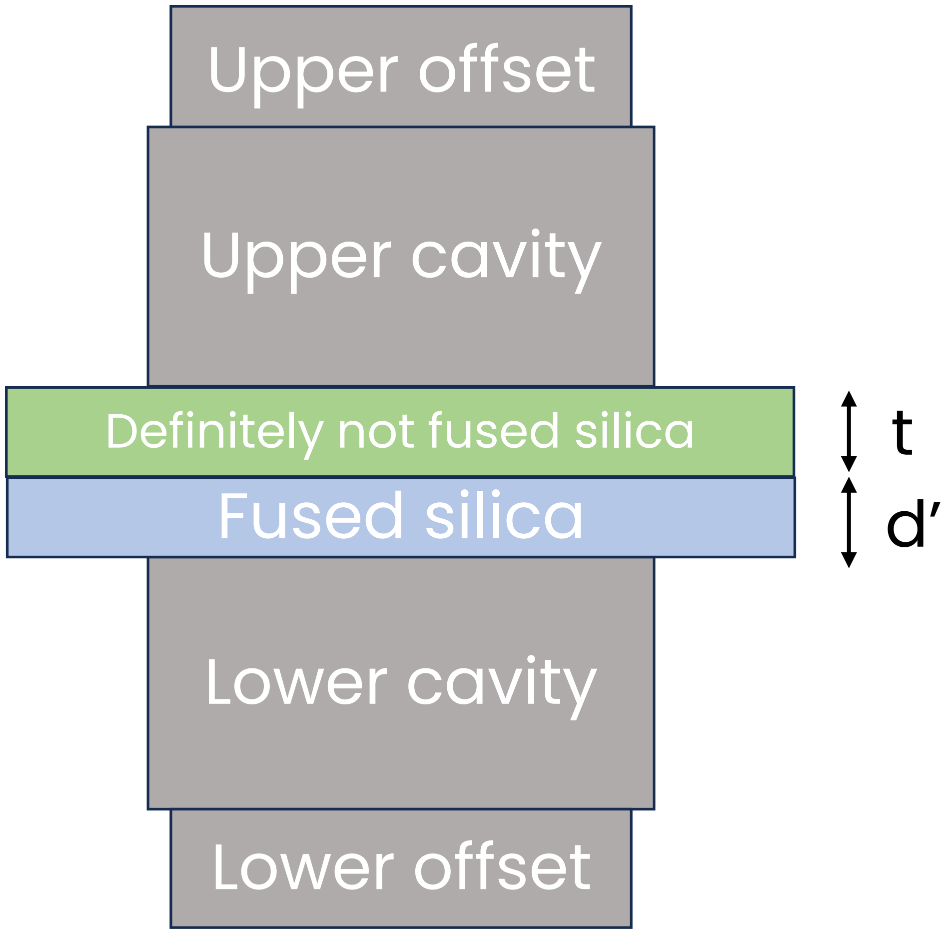
We can analyze the error from that target

Fused silica

$\epsilon_r' = 3.8381 \pm 0.0042$

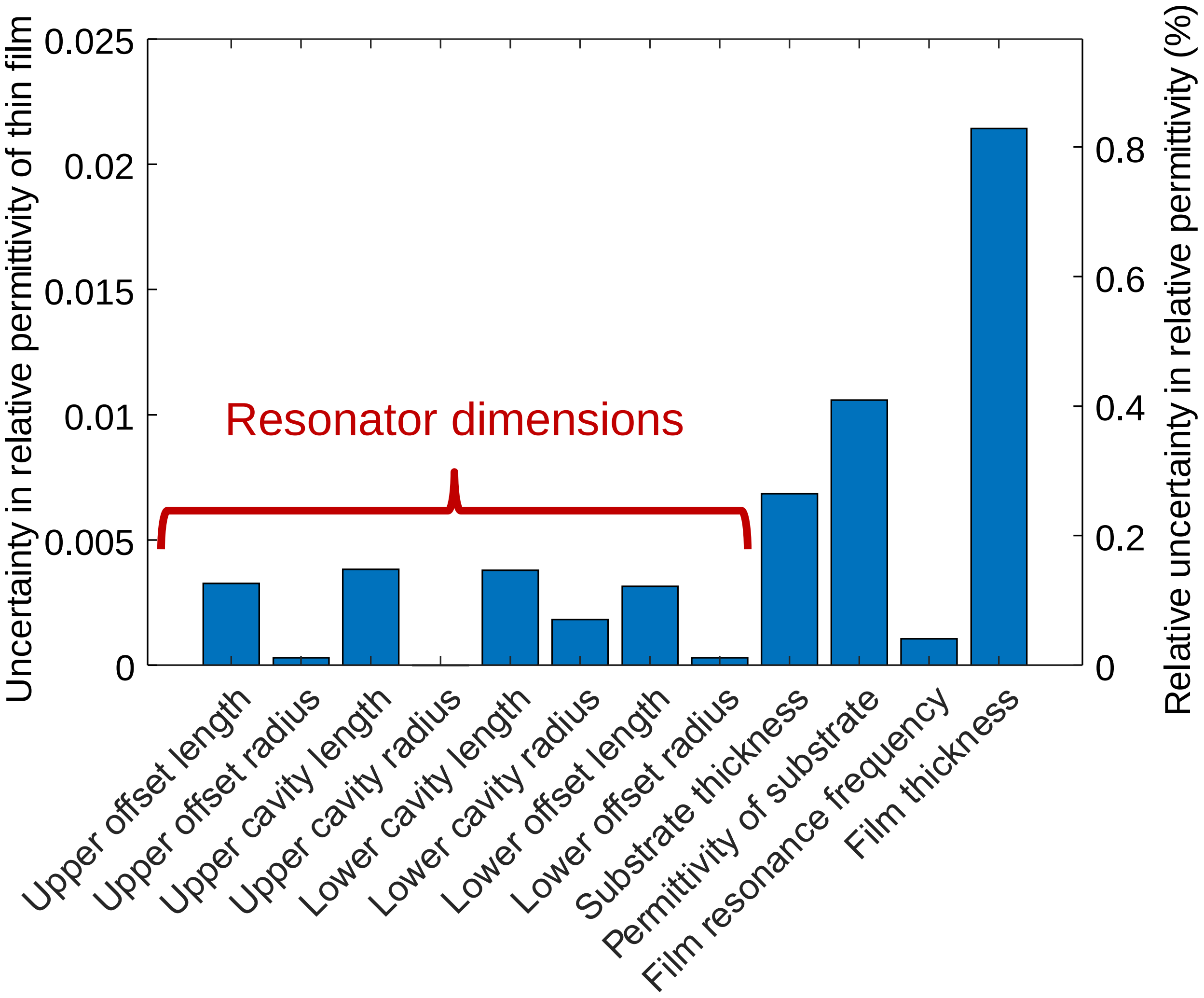


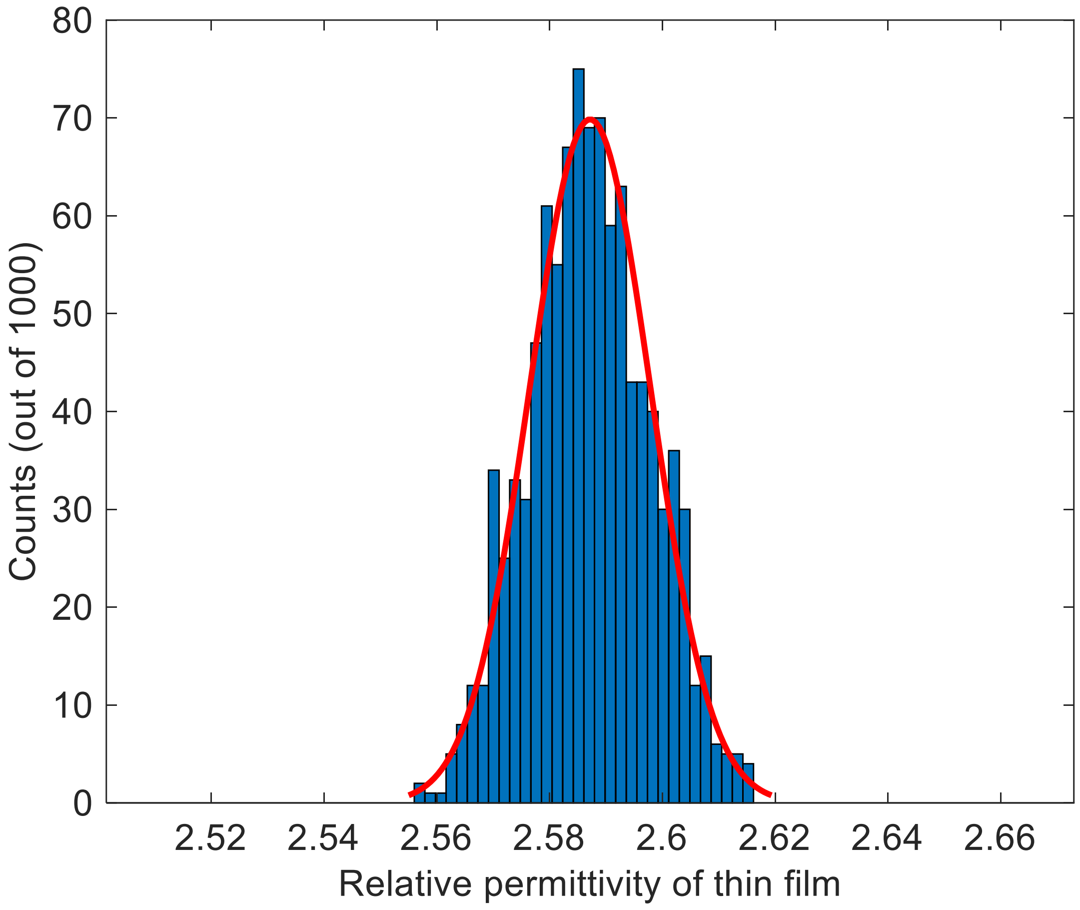




This convergence error bounds the films we can measure

We do a similar uncertainty analysis for the thin film case





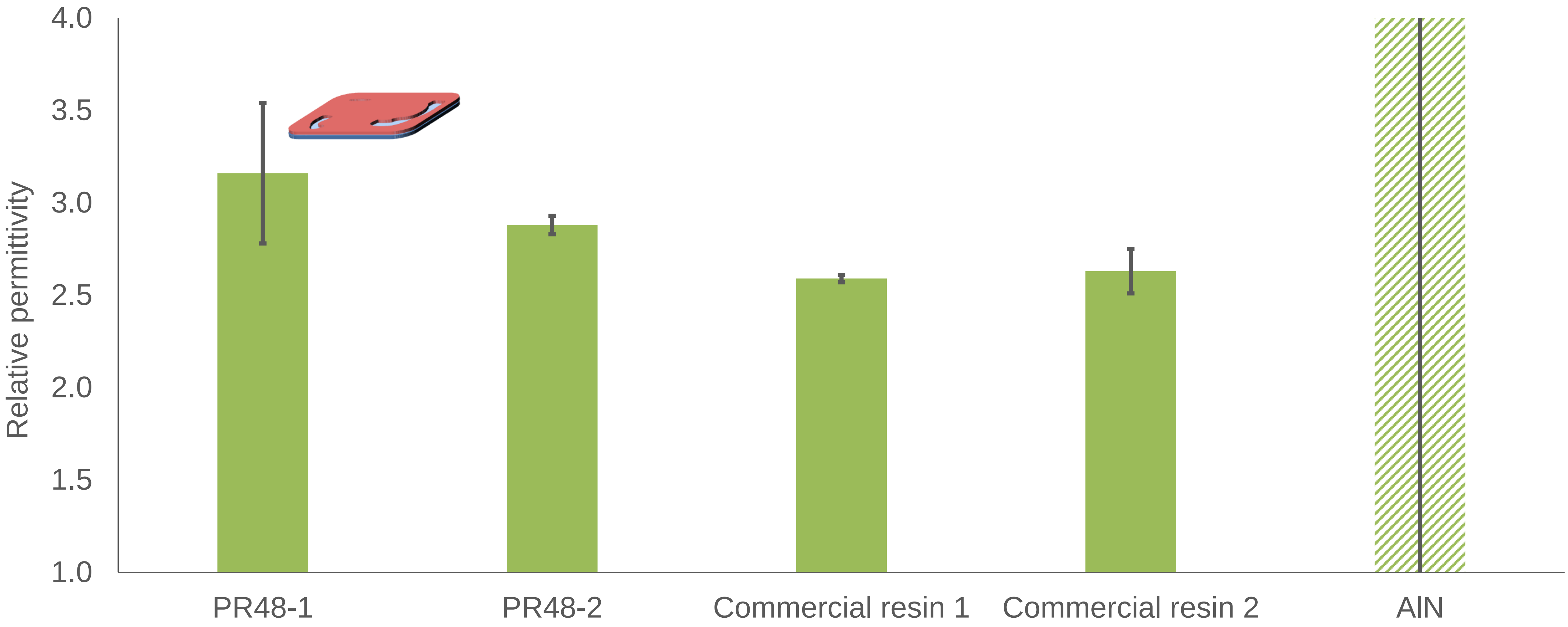
Film thickness is a huge source of uncertainty

So we can measure a whole bunch of films

Fused silica substrate		Thin film		
Thickness	**Relative permittivity**	**Material**	**Thickness**	**Relative Permittivity**
105.97 µm ± 0.27 µm	3.85 ± 0.02	PR48	20.02 µm ± 3.41 µm	3.16 ± 0.38
106.46 µm ± 0.17 µm	3.85 ± 0.02	PR48	19.60 µm ± 0.45 µm	2.88 ± 0.05
105.81 µm ± 0.12 µm	3.85 ± 0.02	Commercially available high frequency resin 1	52.70 µm ± 0.64 µm	2.59 ± 0.02
106.52 µm ± 0.15 µm	3.85 ± 0.02	Commercially available high frequency resin 2	26.55 µm ± 1.80 µm	2.63 ± 0.12
146.71 µm ± 0.17 µm	3.84 ± 0.01	AlN	*0.25 µm ± 0.1 µm*	-

We are typically bounded by film thickness uncertainties

Some key findings



And some lingering questions

There is still plenty of work to do

Objective: Split-cylinder resonator measurements of thin films

Key idea: Build on standards (mode-matching theory lets us add cylindrical regions).

Next steps: Find a better way to measure the thin film thickness. Reduce systematic convergence error.

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Thanks!