



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

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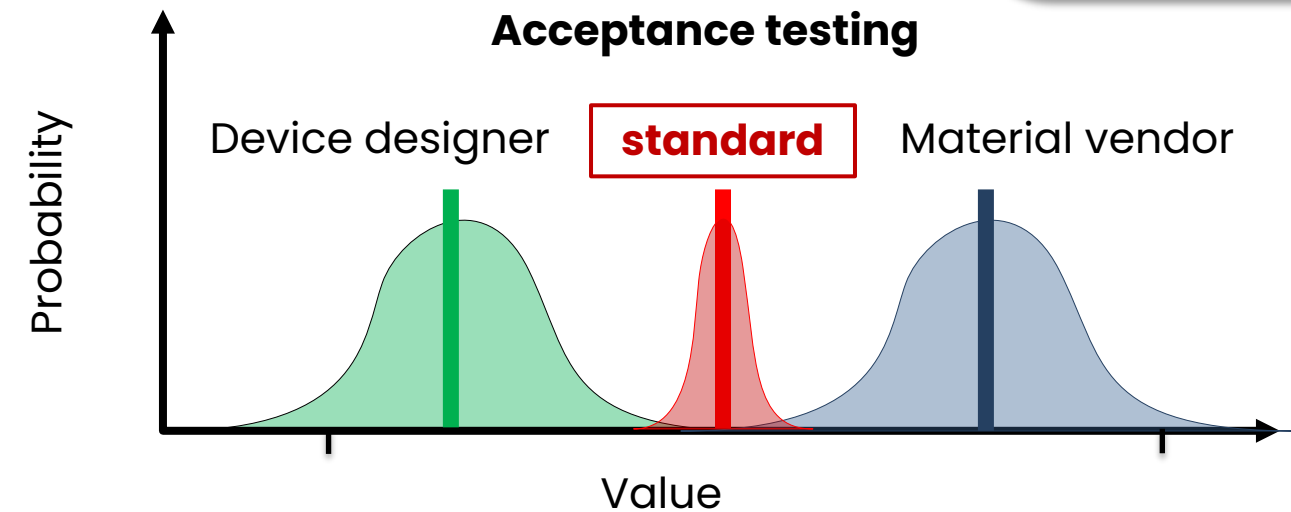
Companies need to understand their materials



iNEMI mmWave materials and rest roadmap:

“Circuit designers need dielectric property data for materials at millimeter-wave (mmWave) frequencies to optimize device performance of new hardware and for quality assurance.

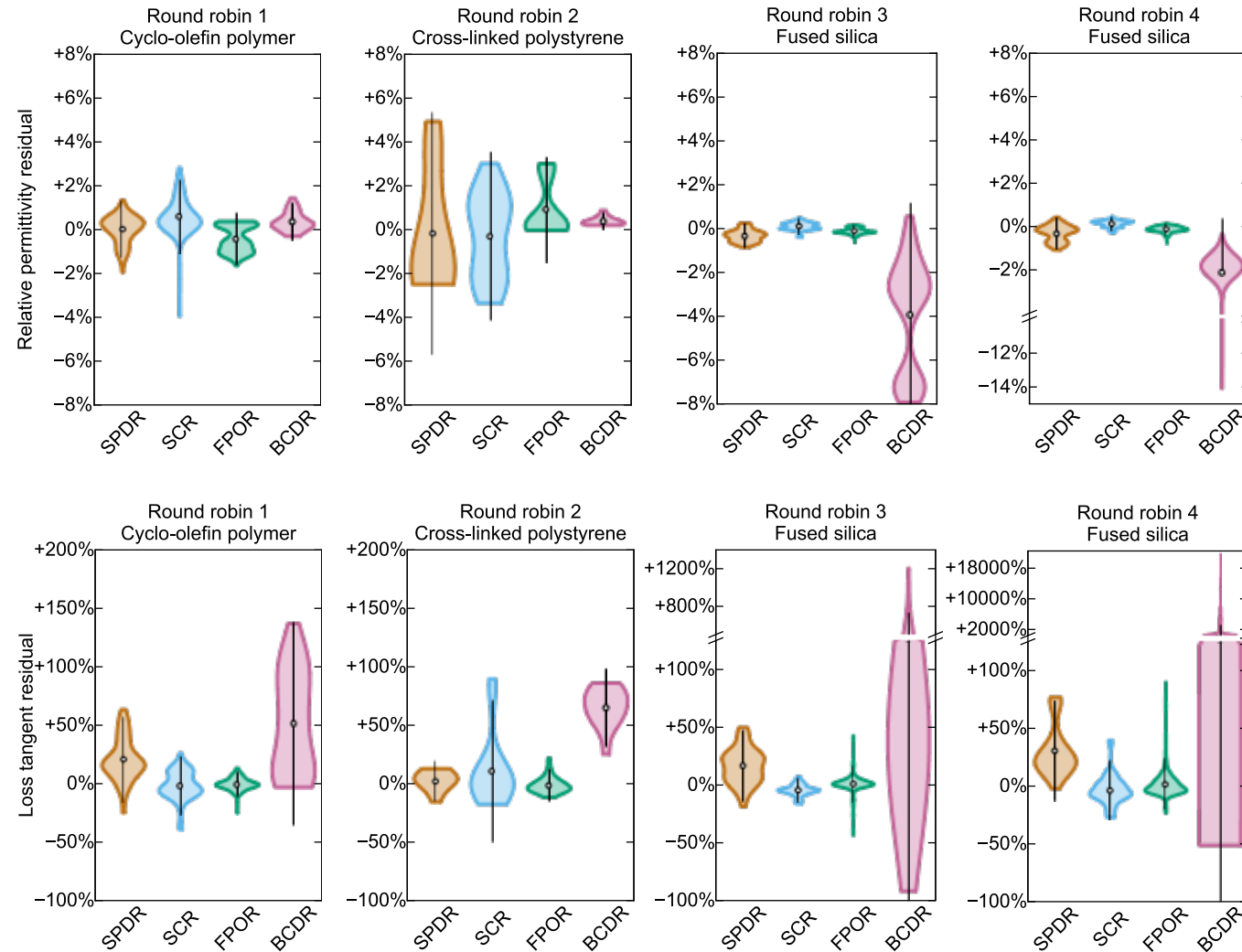
However, **there are no standard traceable reference materials or even agreed upon characterization test methods** for materials at mmWave frequencies.”



Understanding materials means understanding measurements



We can compare to the consensus



This outlined material and measurement requirements

How to make a standard in five(ish) steps

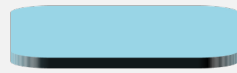
0

Incorporate
industry
feedback



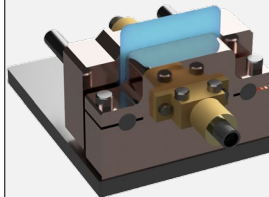
1

Choose
material



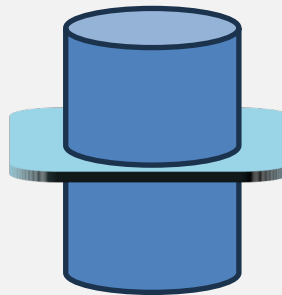
2

Choose
method



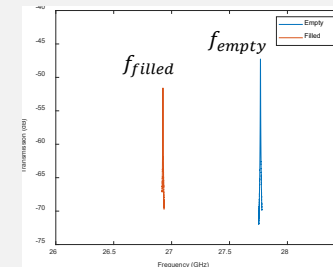
3

Use theory
to map to
permittivity



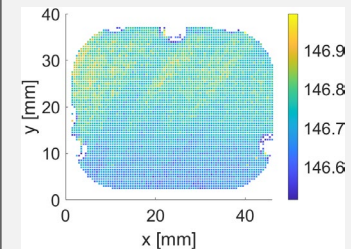
4

Measure
Scattering
parameters



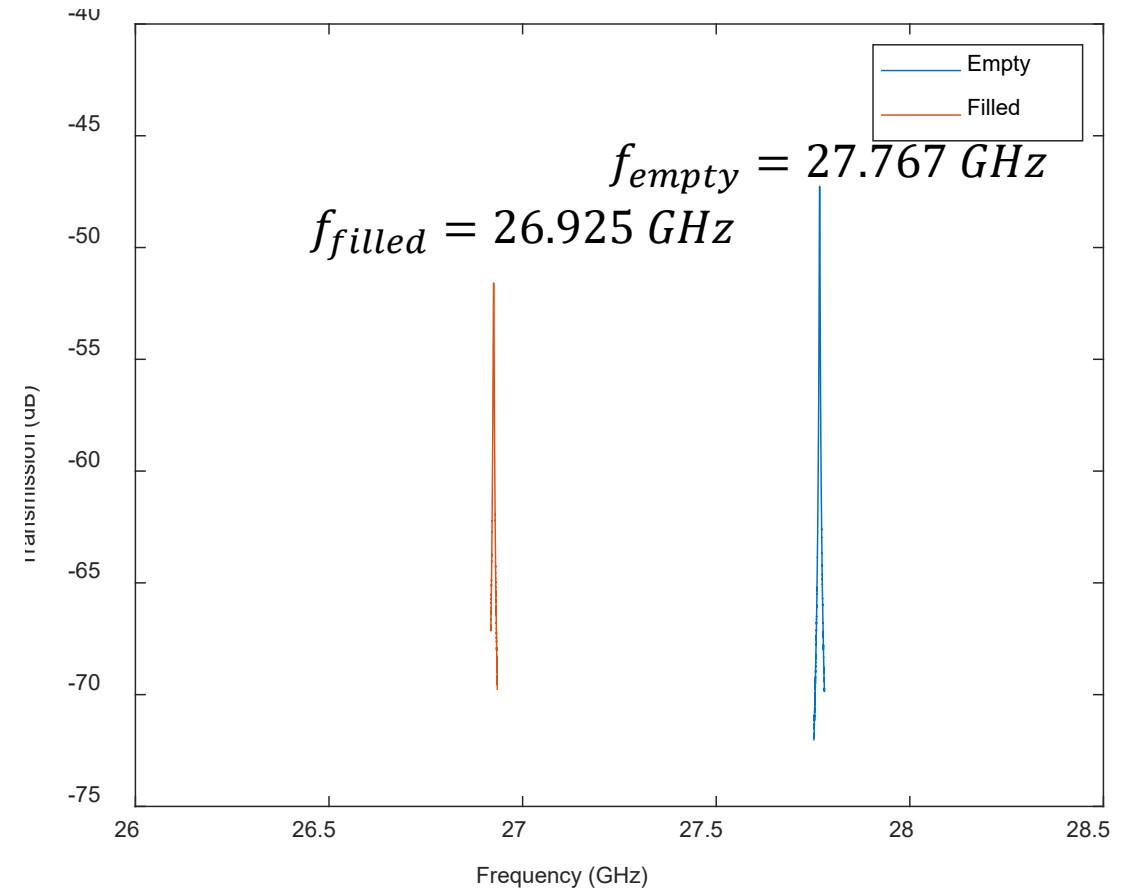
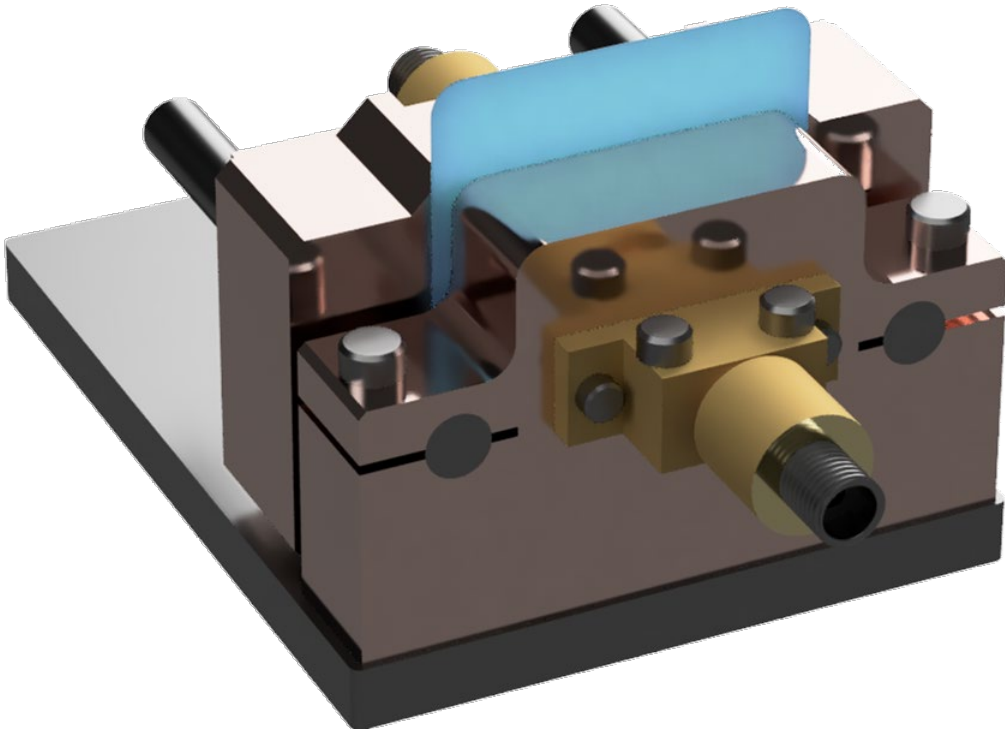
5

Measure
dimensions

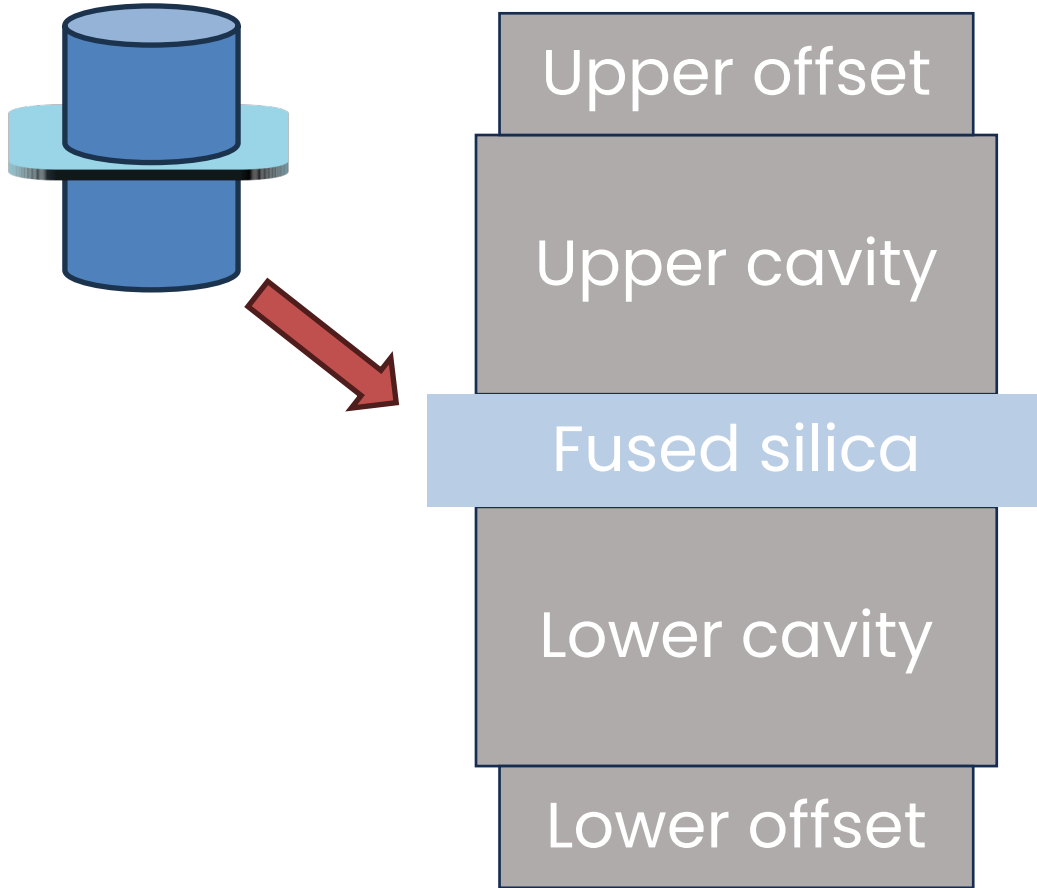


I will quickly highlight a few of the finer points

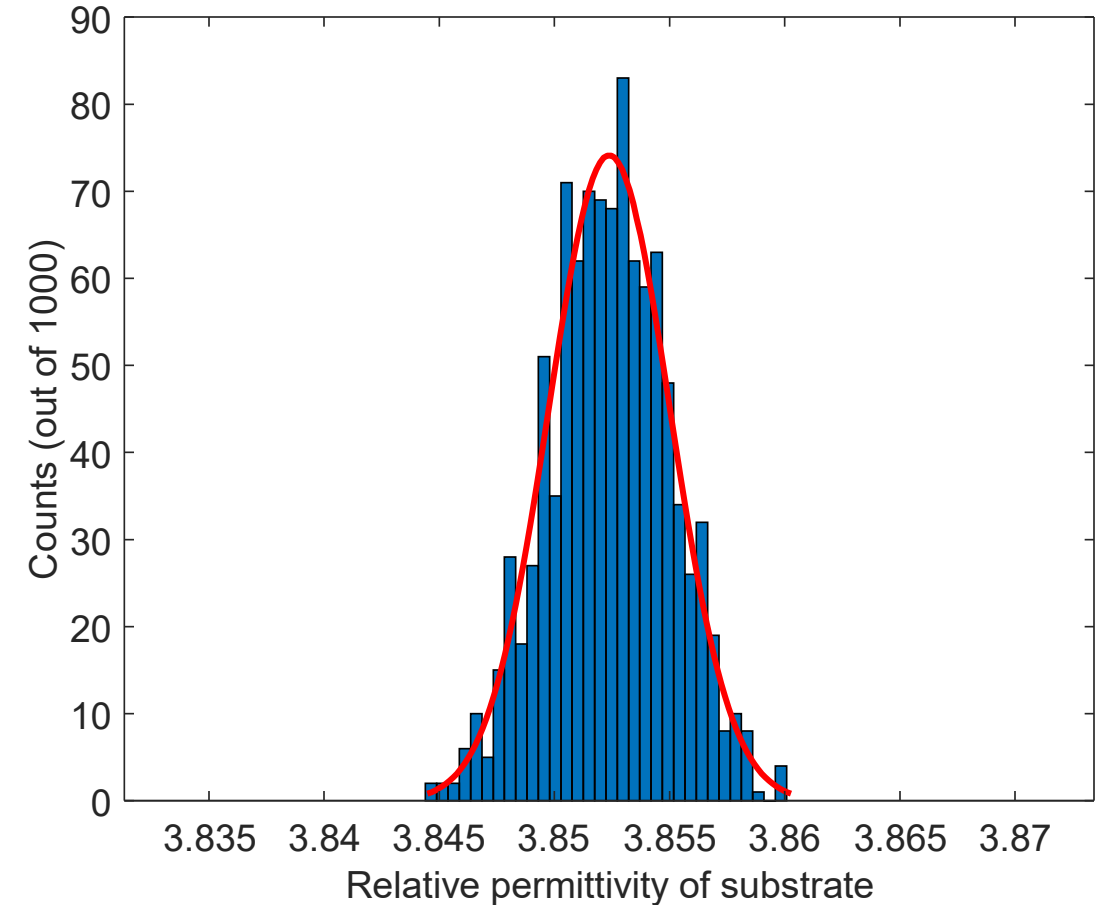
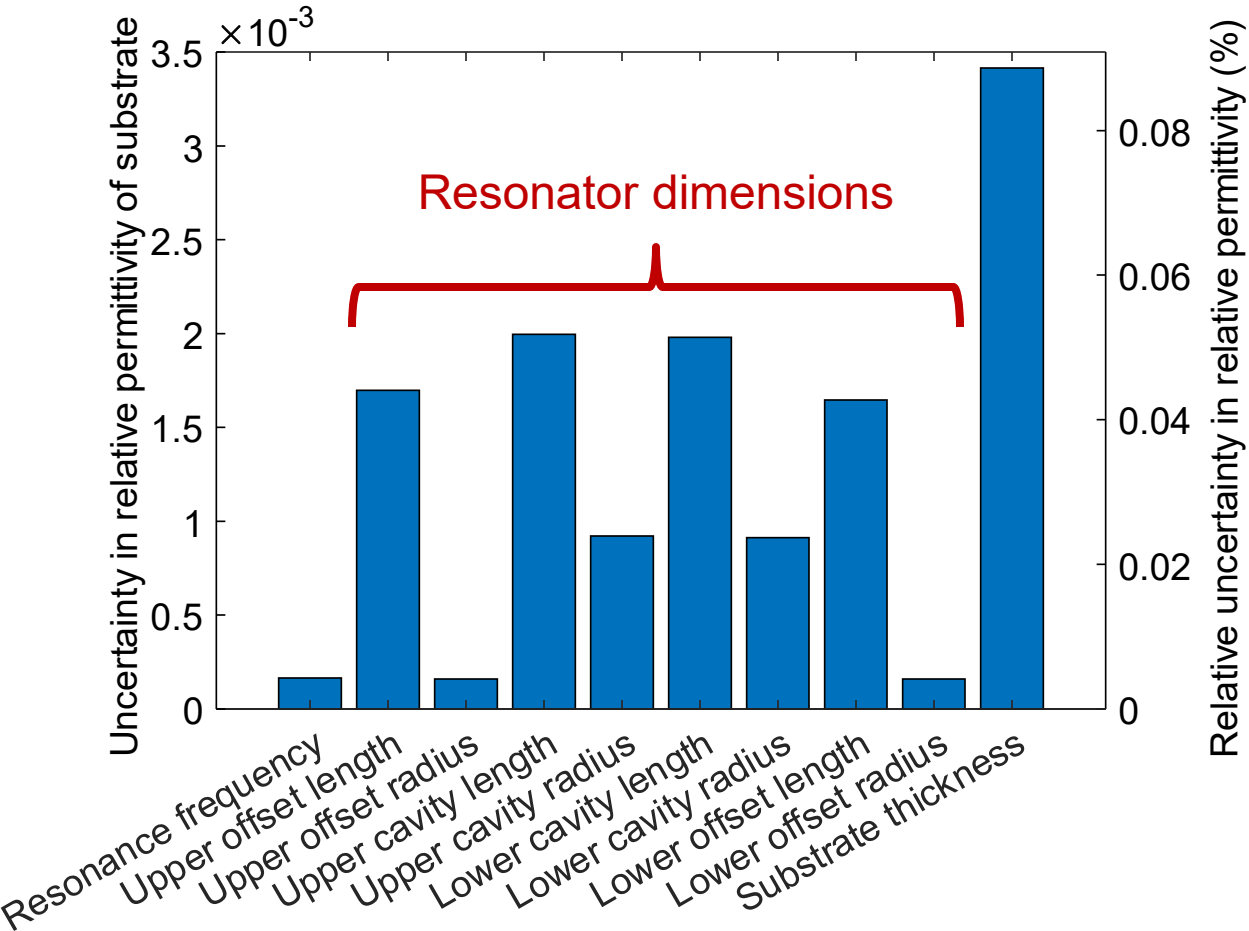
Measuring the resonance tells us material properties



Mode-matching maps the measurements to properties



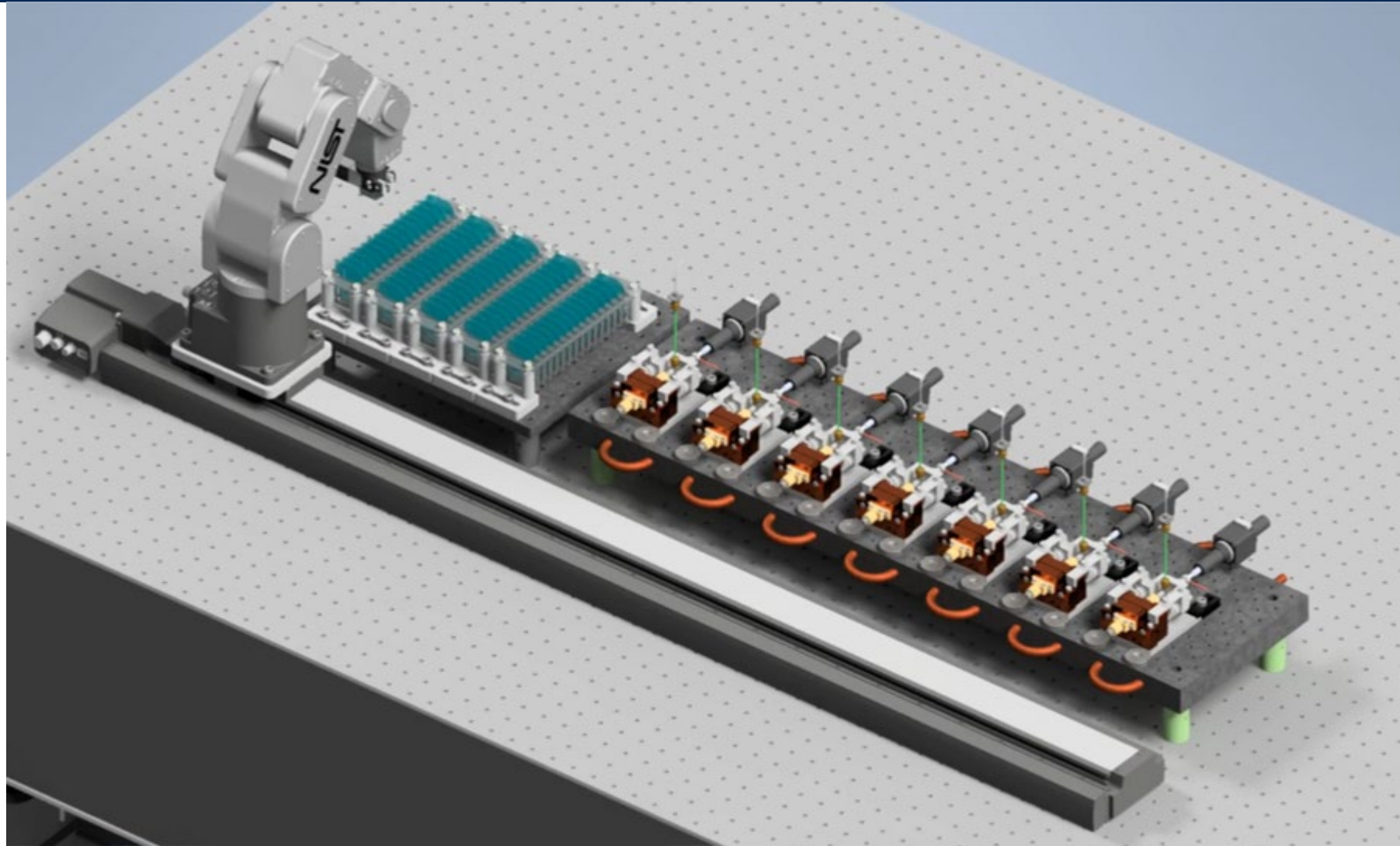
We can vary the input parameters to analyze uncertainty



Uncertainty budget

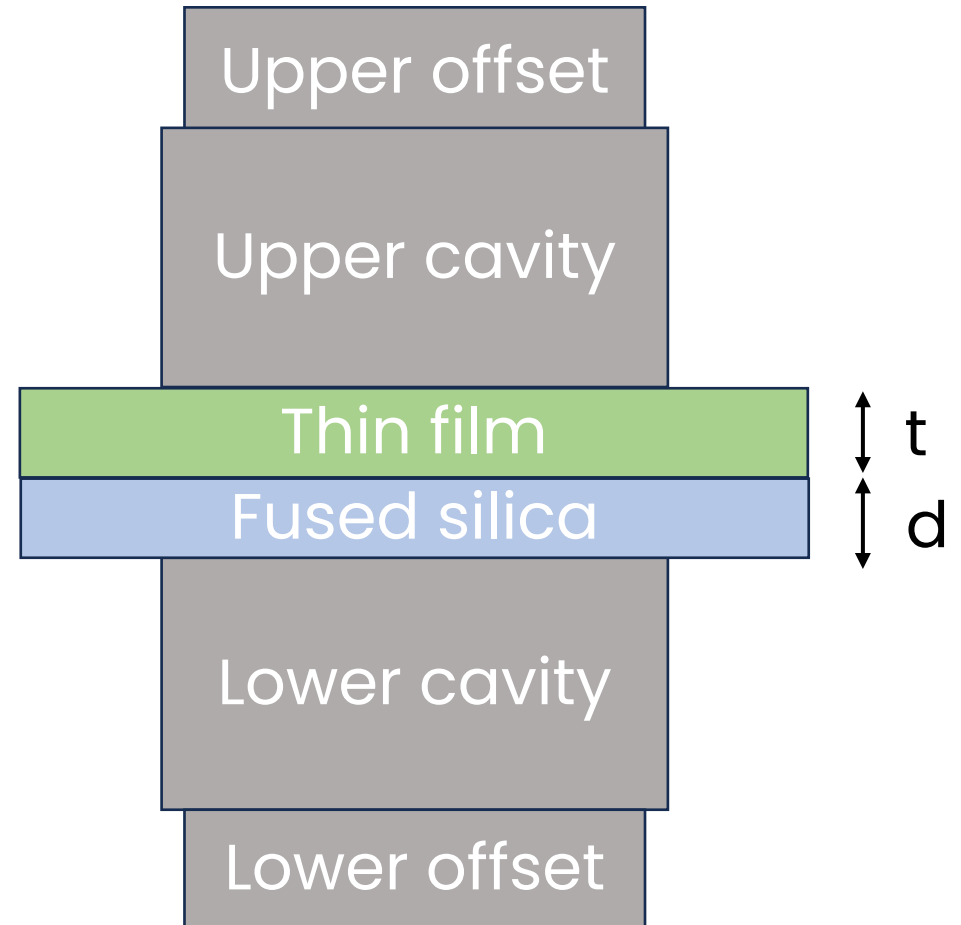
Combined uncertainty

We made a standard for relative permittivity



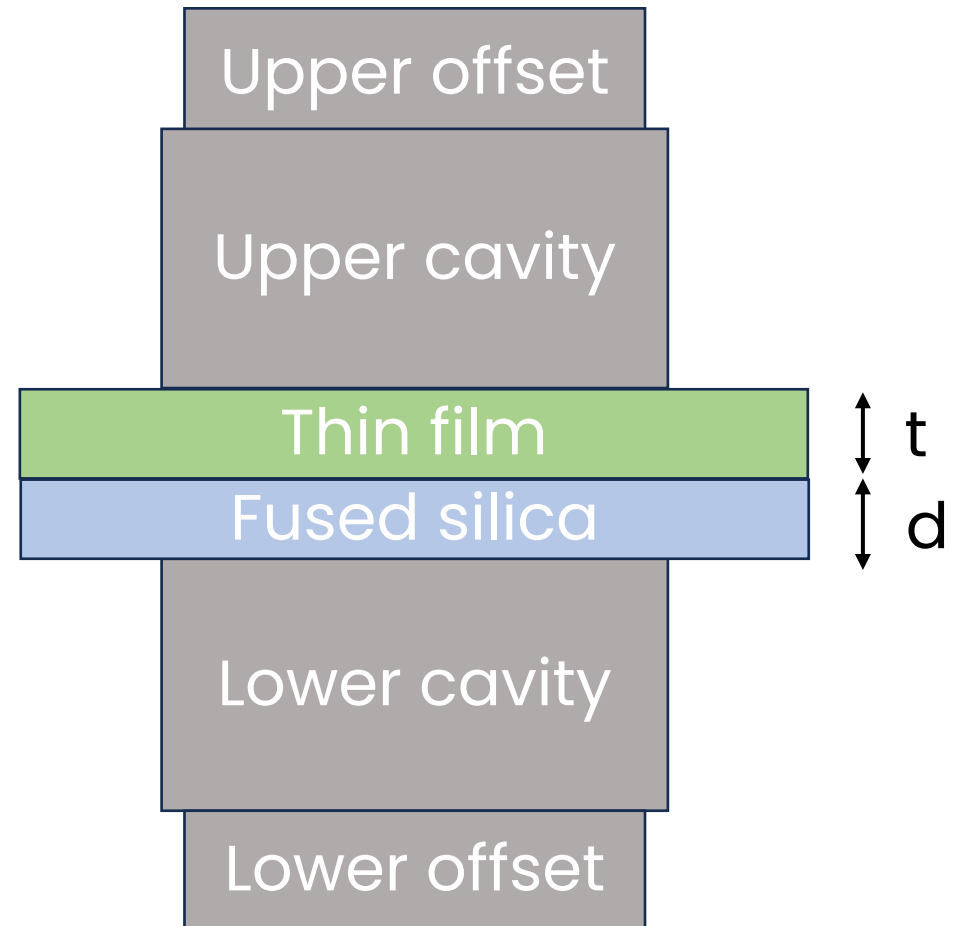
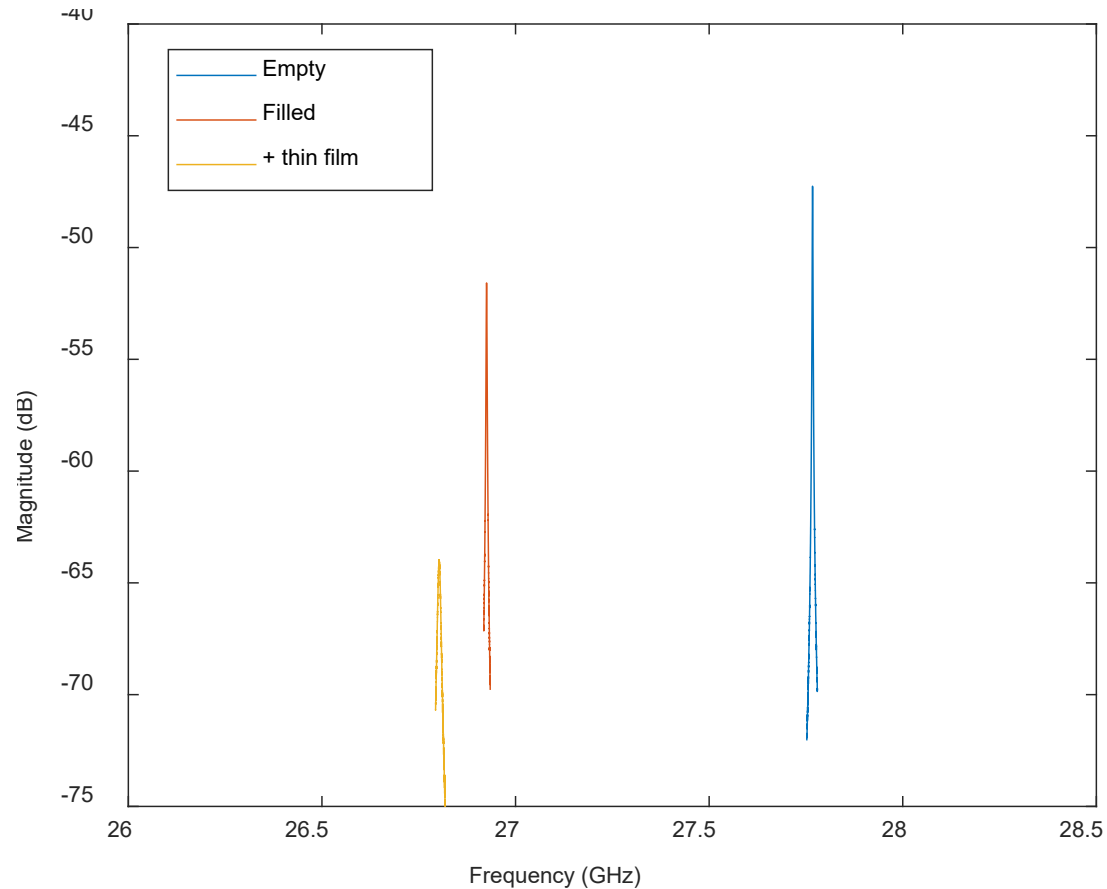
Industry collaborators helped a ton along the way

We can add cylinders to that same analytical theory



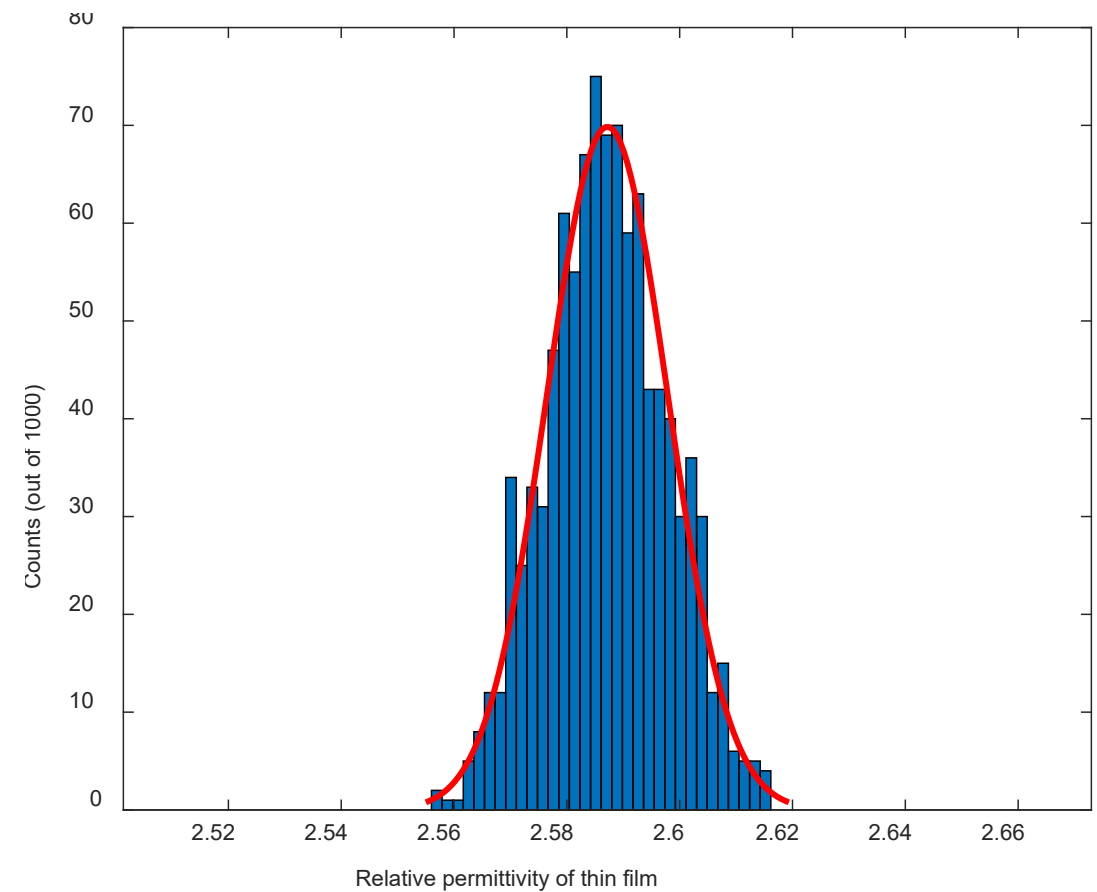
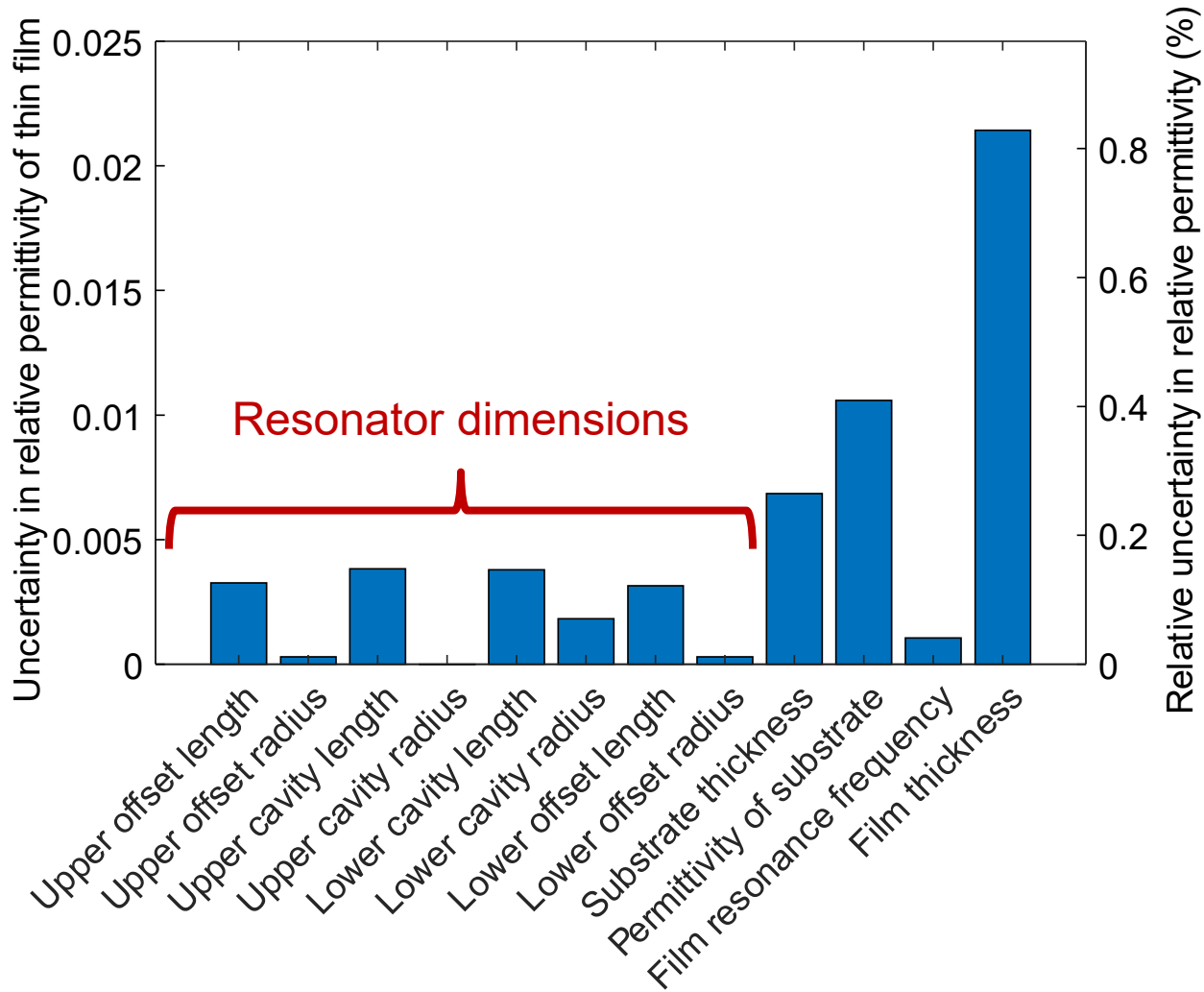
Knowing the substrate properties, we can measure a thin film

We can add cylinders to that same analytical theory



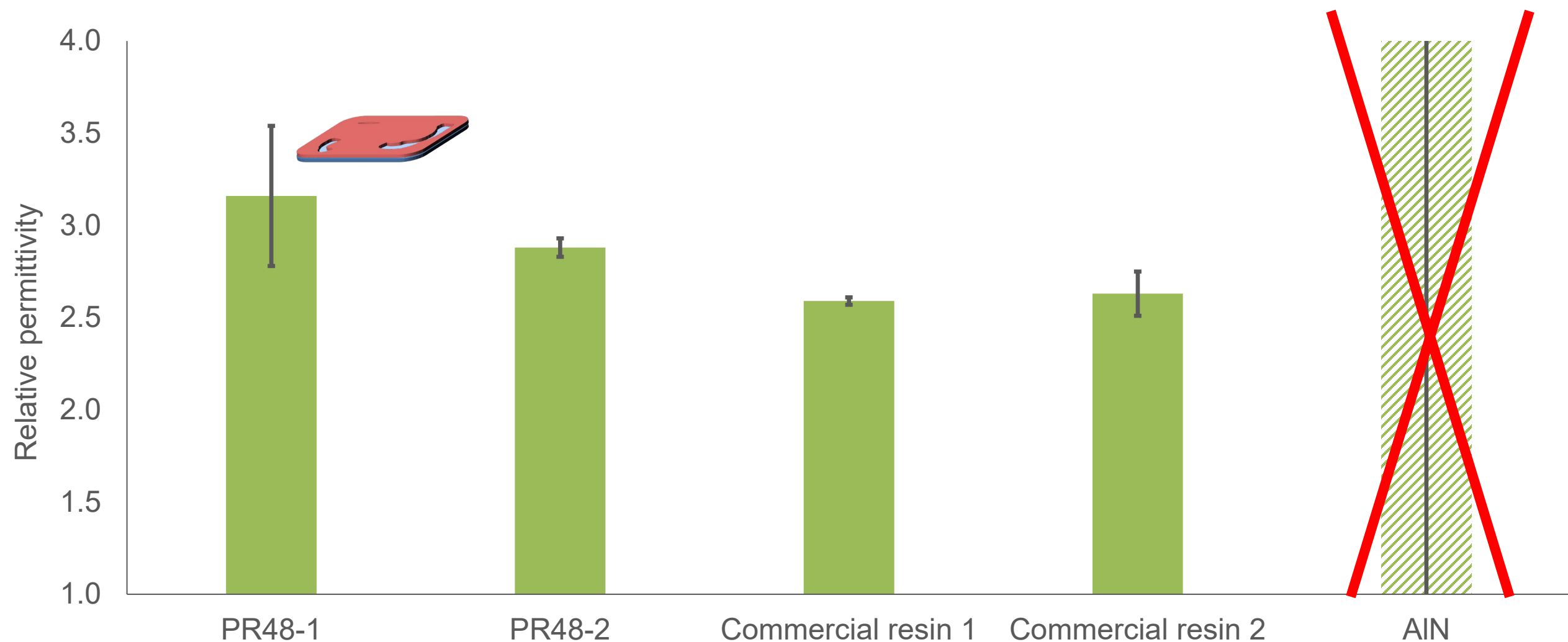
Knowing the substrate properties, we can measure a thin film

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



But some are still problematic

There is still plenty of work to do

Objective: Split-cylinder resonator measurements of substrates and thin films

Key idea: SI-traceable measurements → **standards**
Then, build on those standards

Next steps: Publishing background work, finishing touches on standards, refining analysis,...



Thanks!

So, we can measure a whole bunch of films

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

We are typically bounded by film thickness uncertainties