Radiation **I**mpact on **S**uperconducting **Q**ubits **2024**

– Recent progress from the Pyle group at UCB

RISQ 2024
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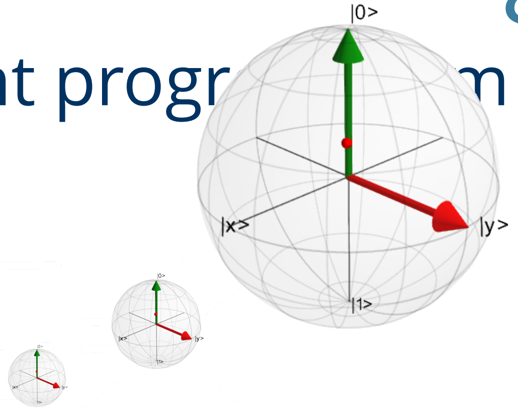
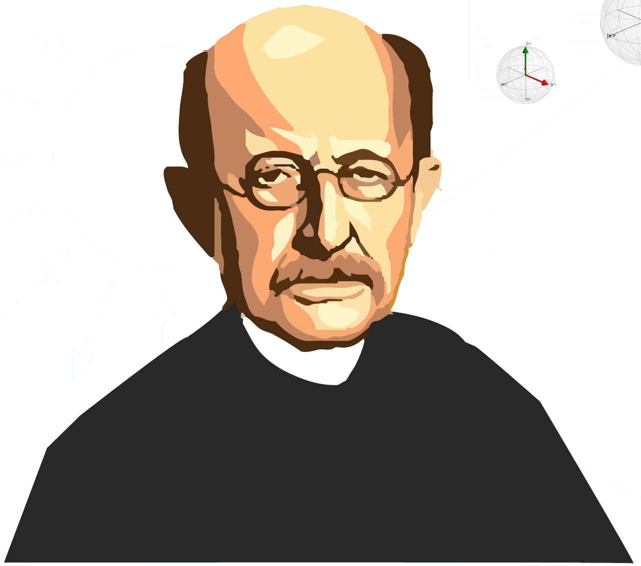
May 30, 2024

Blackbody Radiation Impact on Superconducting Qubits 2024

– Recent progr


m the Pyle group at UCB



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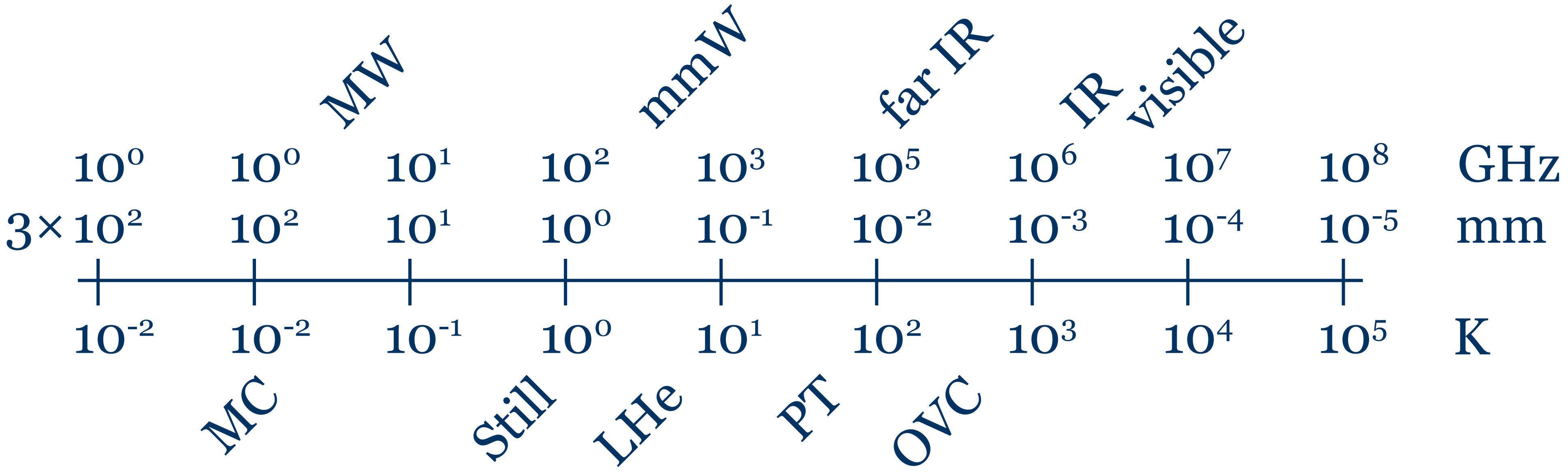
Outline

- Blackbody radiation (BBR).
  – Terminology & order-of-magnitude argument.
- Tight-fitted device box doesn't shield BBR.
  – An analytical waveguide model.
- Filter BBR as micro/millimeter-wave (MW/mmW).
  – A novel MW BBR filter.
- The filter works!
  – The experiment.
- More exciting progress from the Pyle group.

Blackbody radiation impact p1

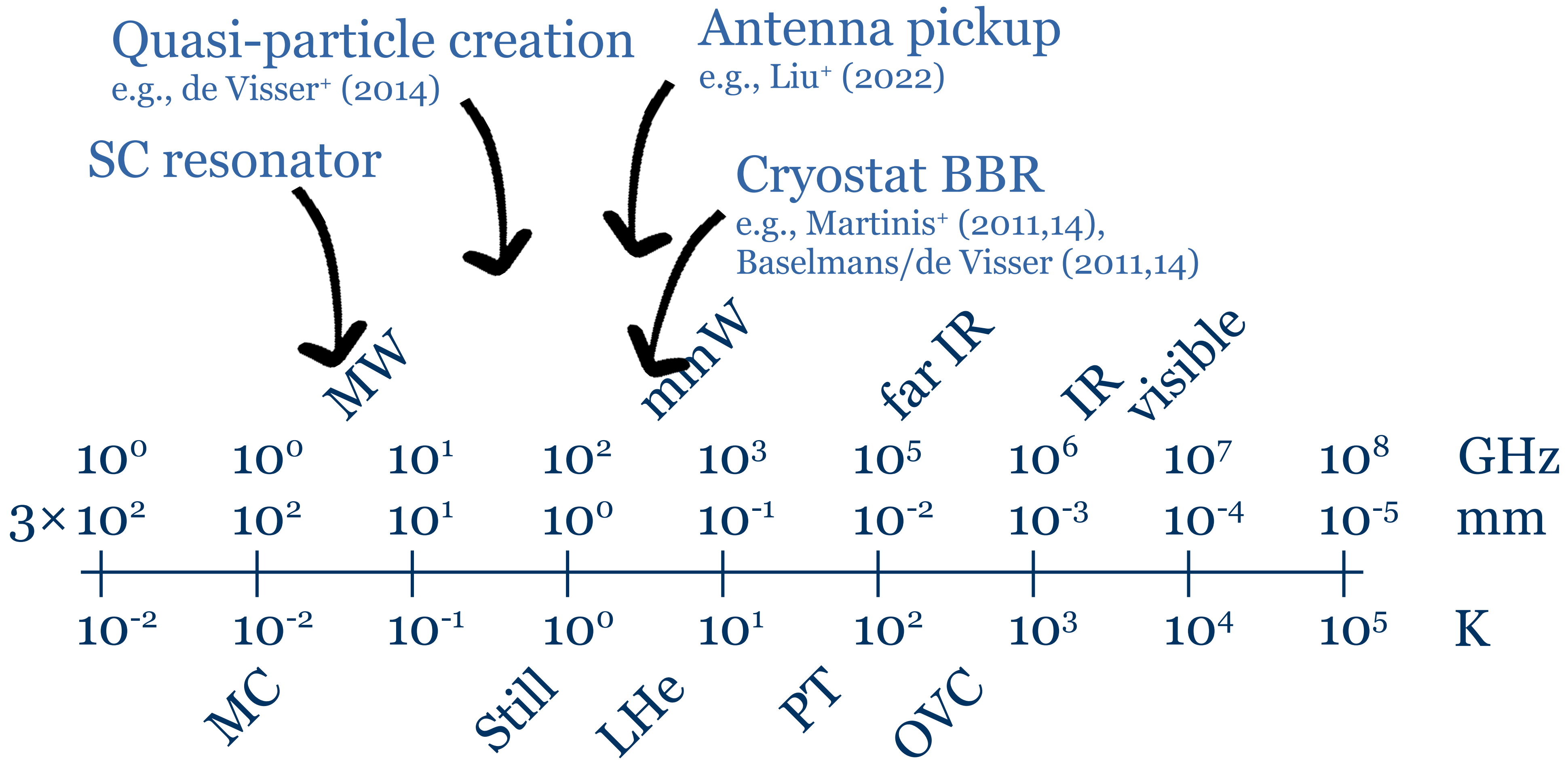
- 1 K BBR: $\lambda_{peak} \approx 3$ mm, $f_{peak} \approx 100$ GHz.
- Q~$\mathcal{O}(1)$ wide spectrum.
- "IR" is a misguiding name for the issue.

BBR for us is more of a millimeter/micro-wave.



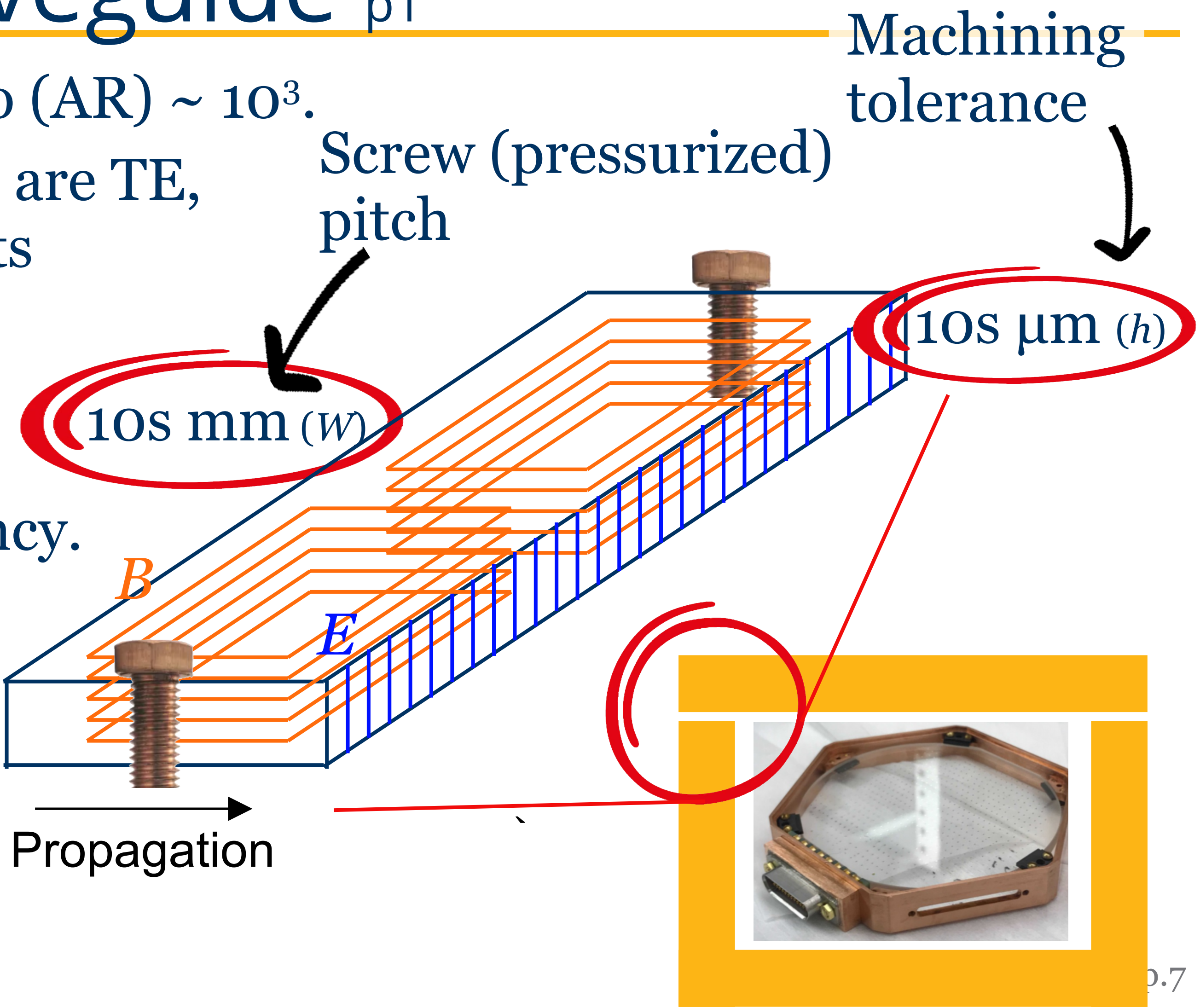
I. Blackbody radiation

Blackbody radiation impact p2

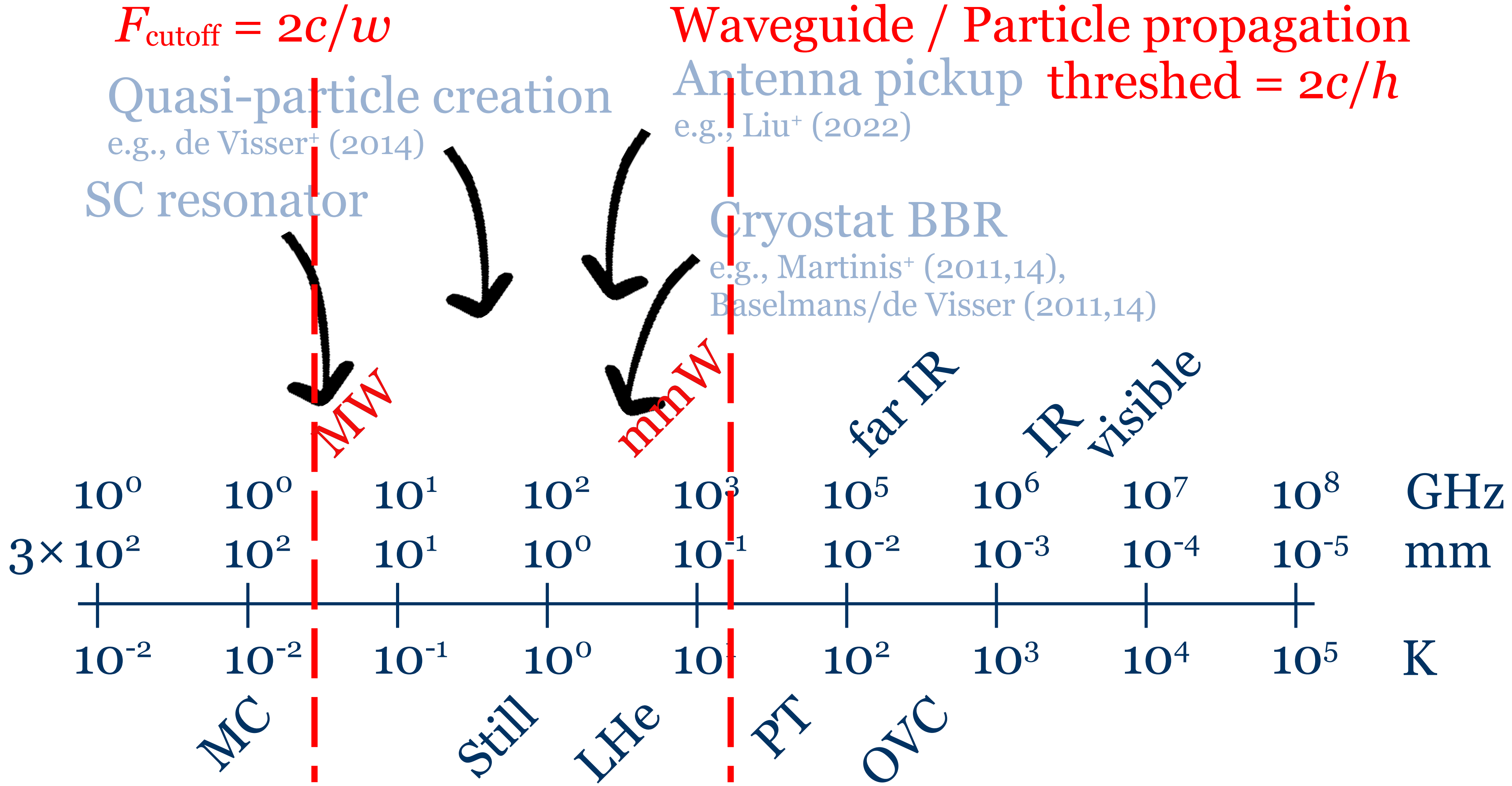


Rectangular waveguide p1

- Cross section aspect ratio (AR) ~ 10^3.
- All low-frequency modes are TE, with non-TM components suppressed by $\mathcal{O}$(AR).
  → Approximately TEM.
- Screw pitch determines waveguide cutoff frequency.
- Machining tolerance determines unbounded propagation (particle-like).

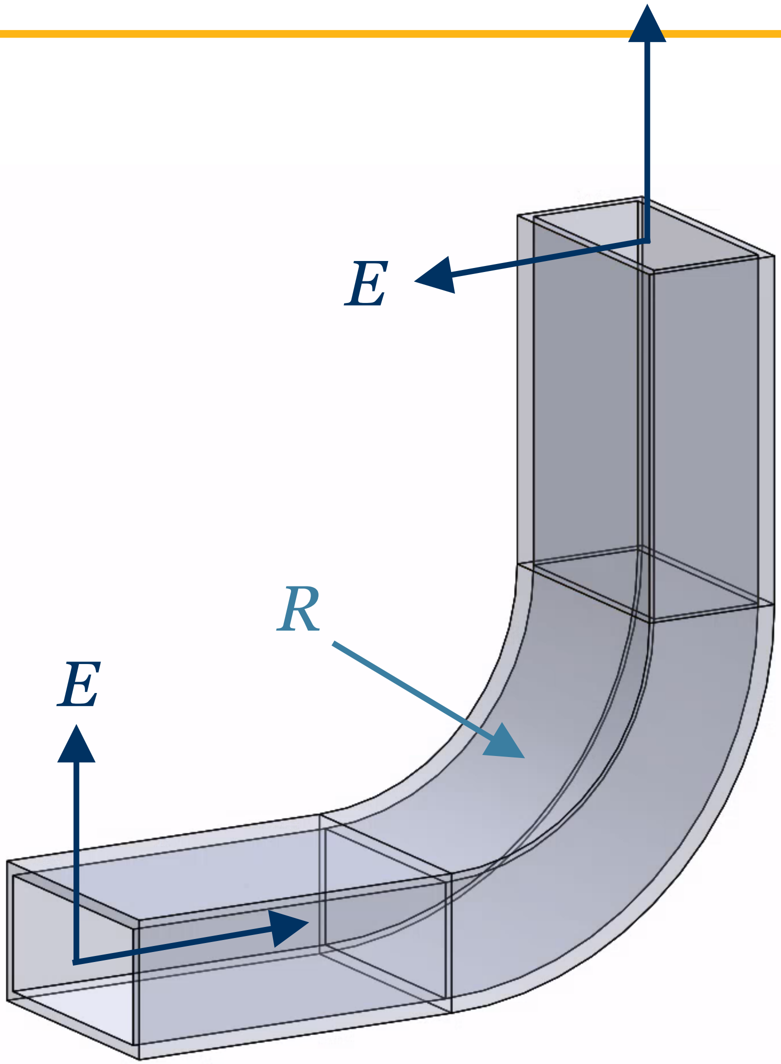


Rectangular waveguide p2



E-bend p1

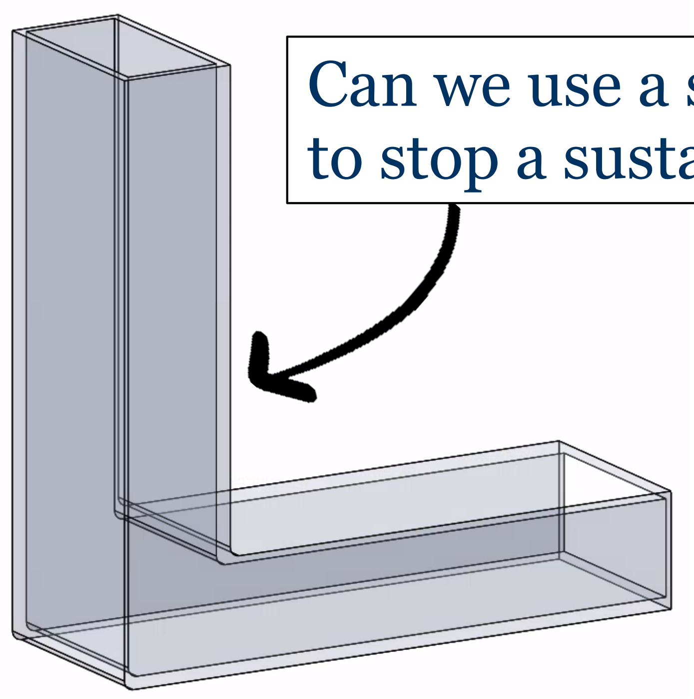
- E-bend: Bending the TE mode direction.
- Convention: $R > 2\lambda$ to avoid reflection.

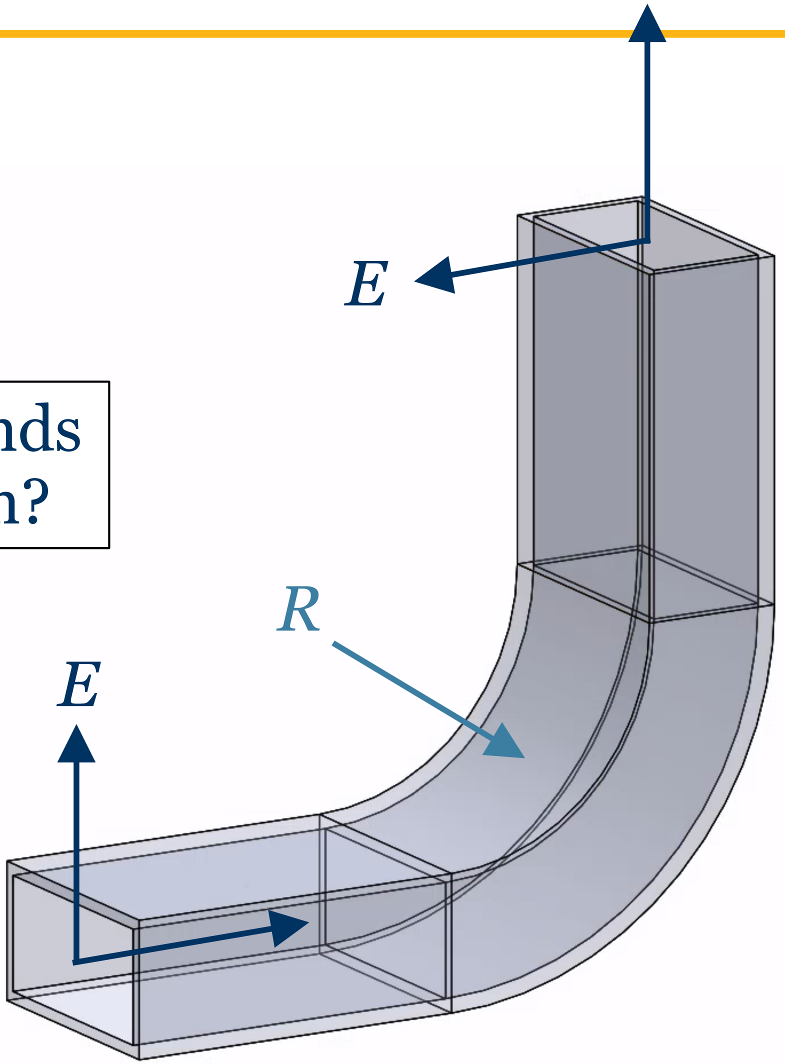


E-bend p2

- E-bend: Bending the TE mode direction.
- Convention: $R > 2\lambda$ to avoid reflection.

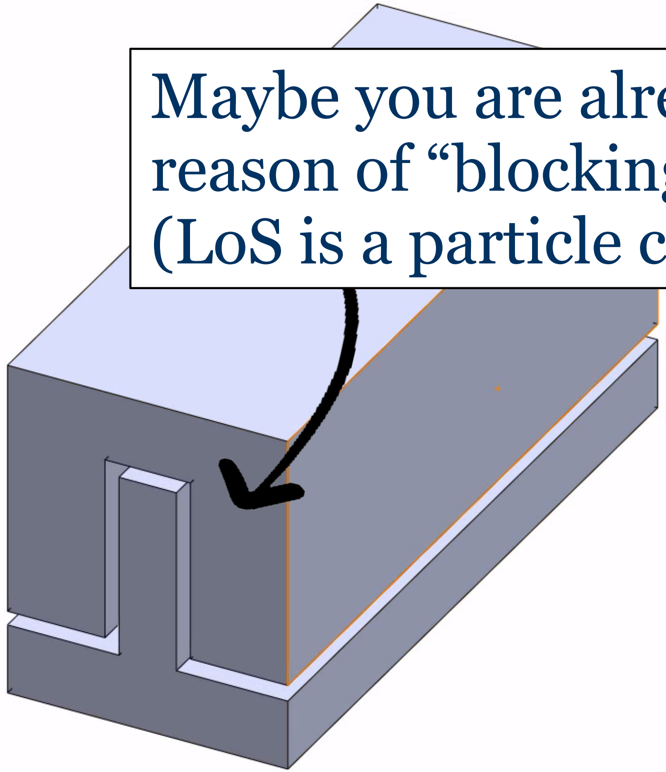
Can we use a series of sharp bends to stop a sustained transmission?



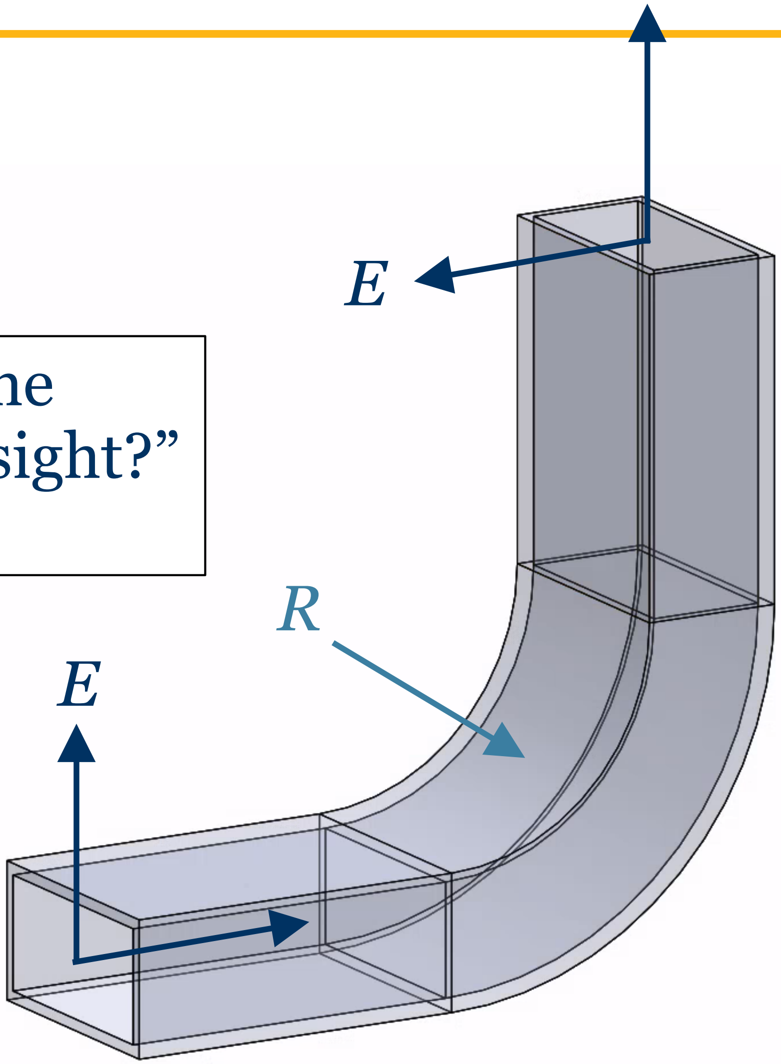


E-bend p3

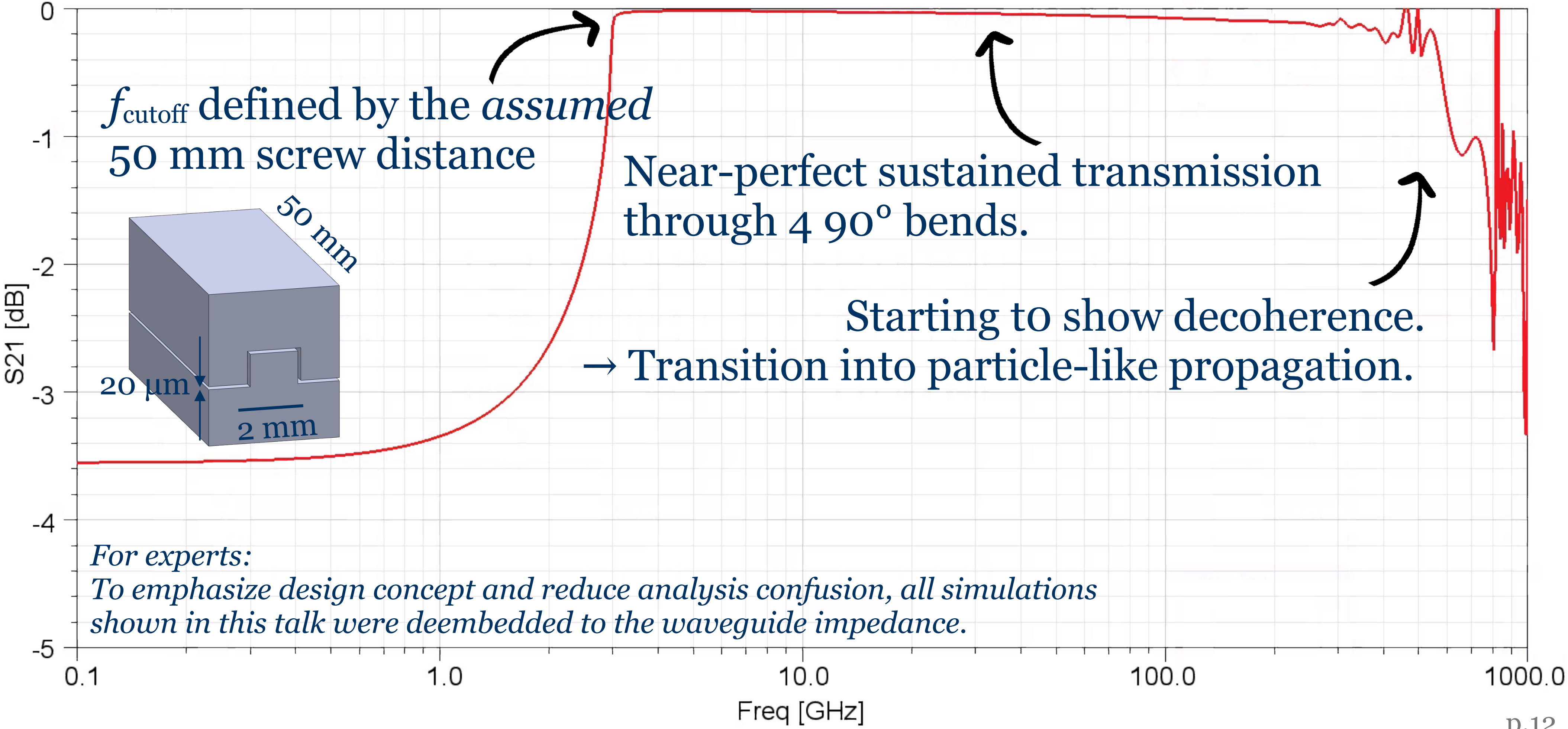
- E-bend: Bending the TE mode direction.
- Convention: $R > 2\lambda$ to avoid reflection.



Maybe you are already doing it for the reason of “blocking straight line-of-sight?” (LoS is a particle concept.)

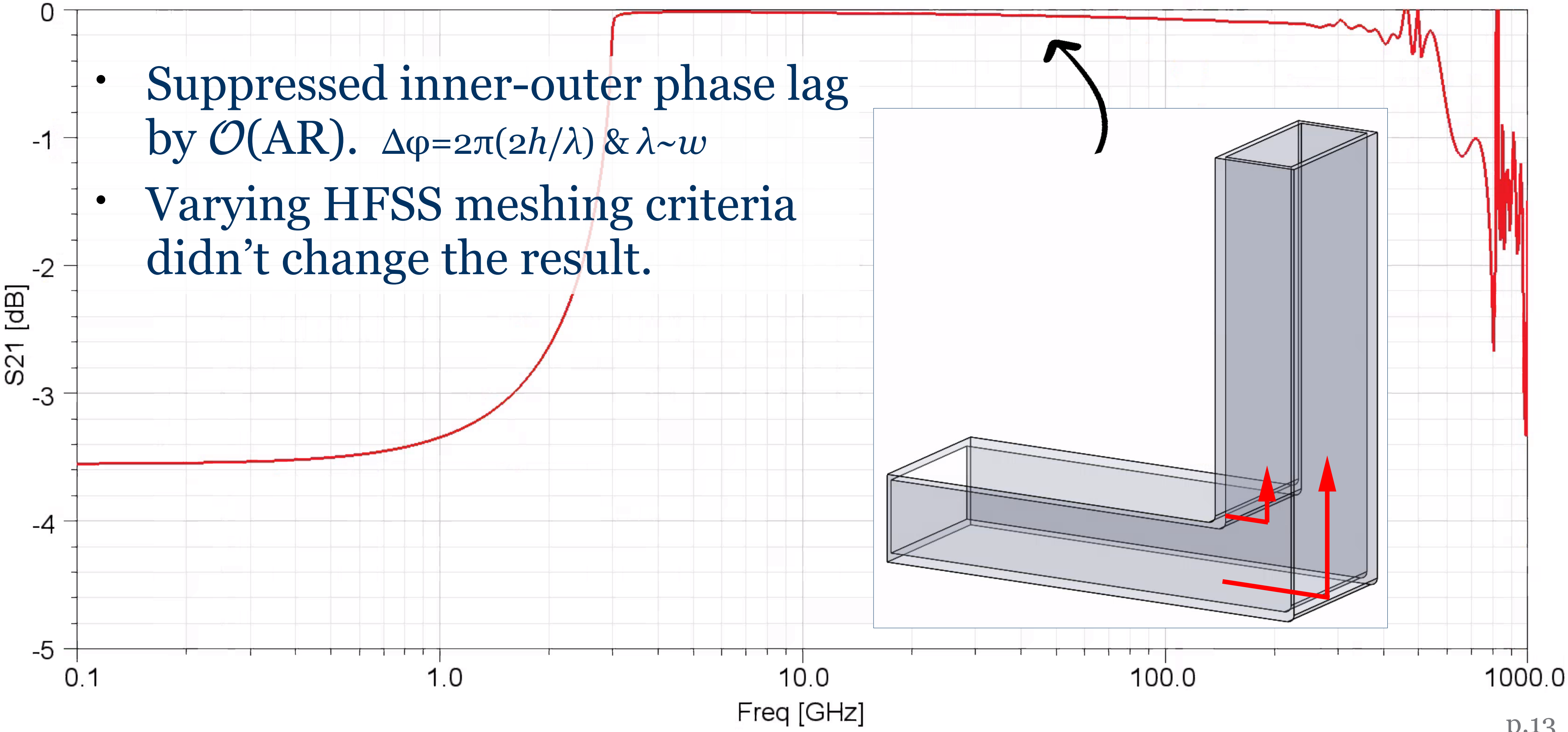


E-bend simulation p1



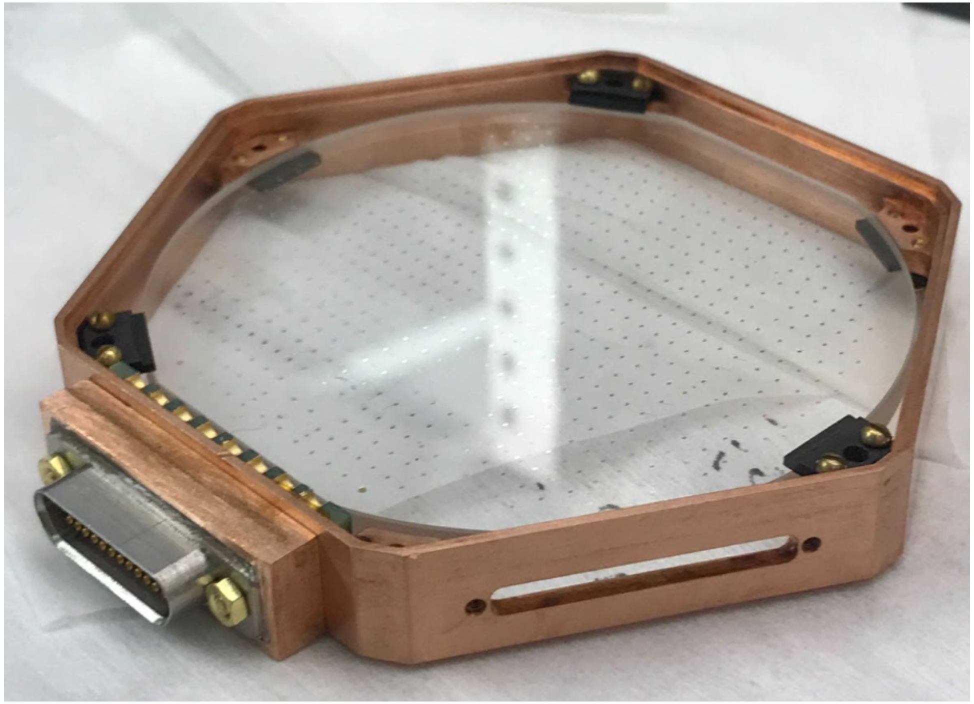
E-bend simulation p2

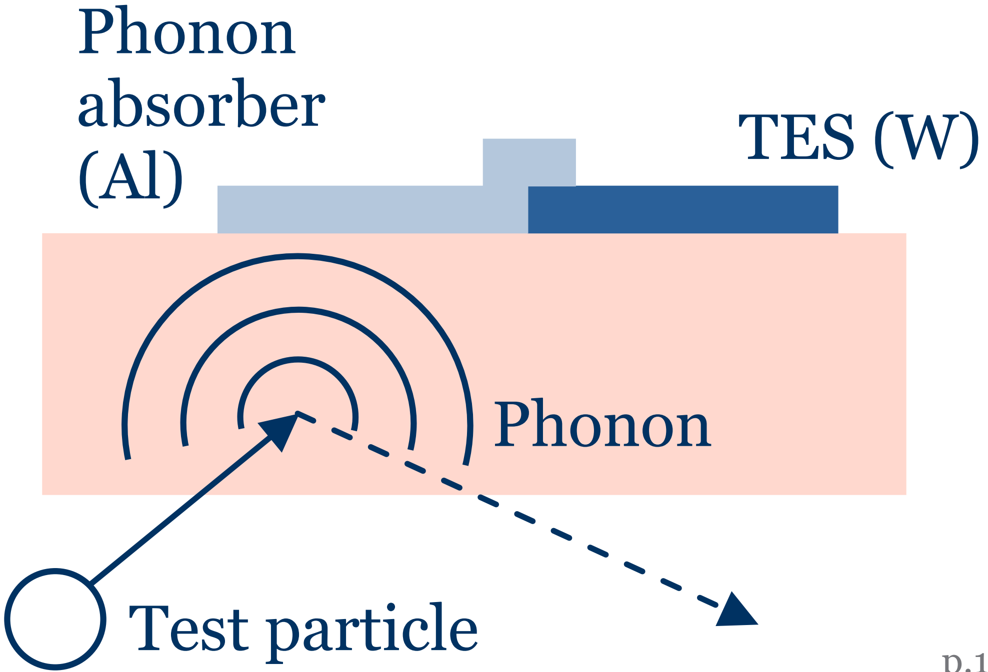
- Suppressed inner-outer phase lag by $\mathcal{O}$(AR). $\Delta\varphi=2\pi(2h/\lambda)$ & $\lambda \sim w$
- Varying HFSS meshing criteria didn't change the result.



TES-based radiation detector

- 3” phonon-mediated sapphire radiation detector.
- Transition edge sensor (TES)-based phonon sensor.

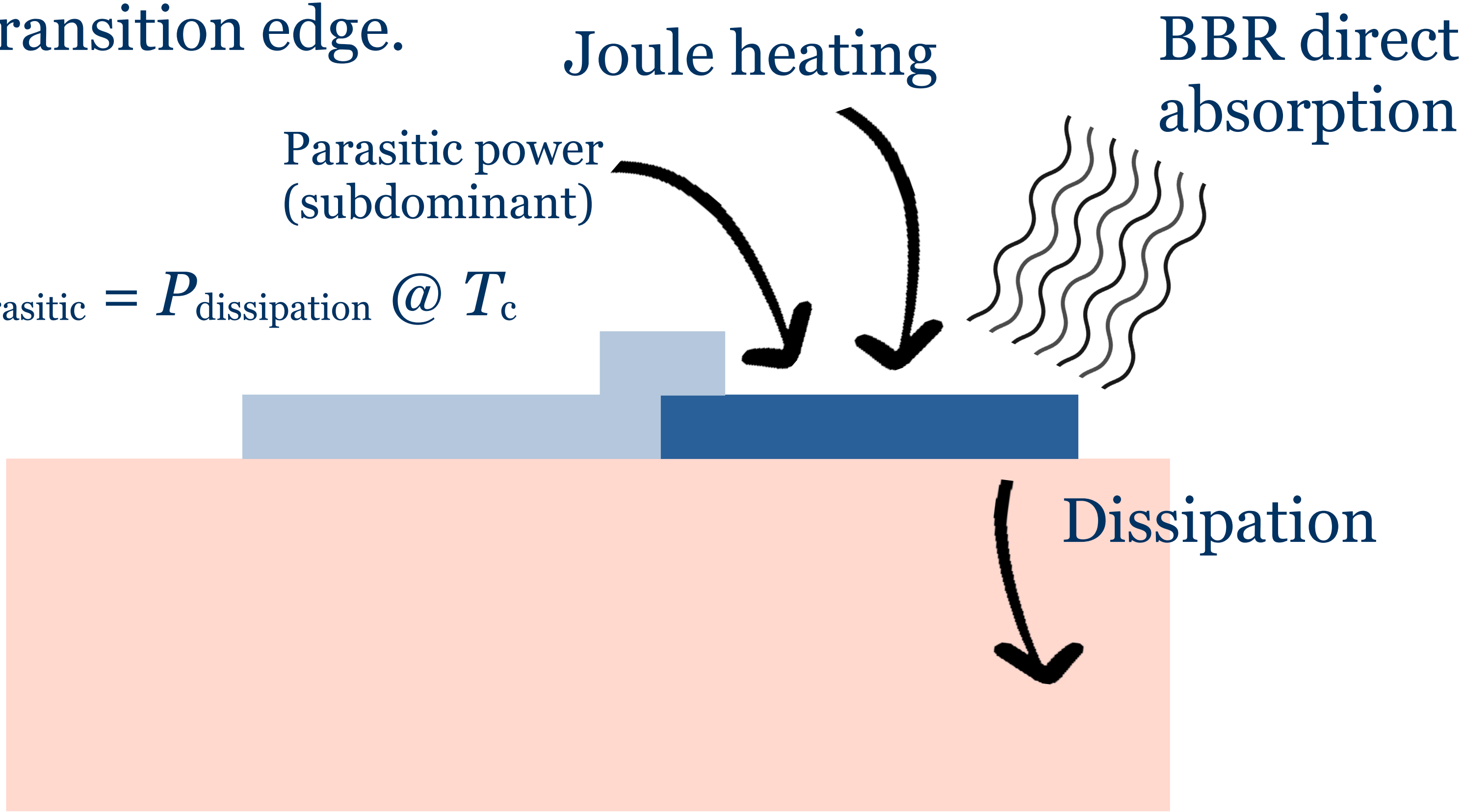




“Parasitic” power measurement p1

- Total received power
  = Dissipation to substrate
  = Constant at transition edge.

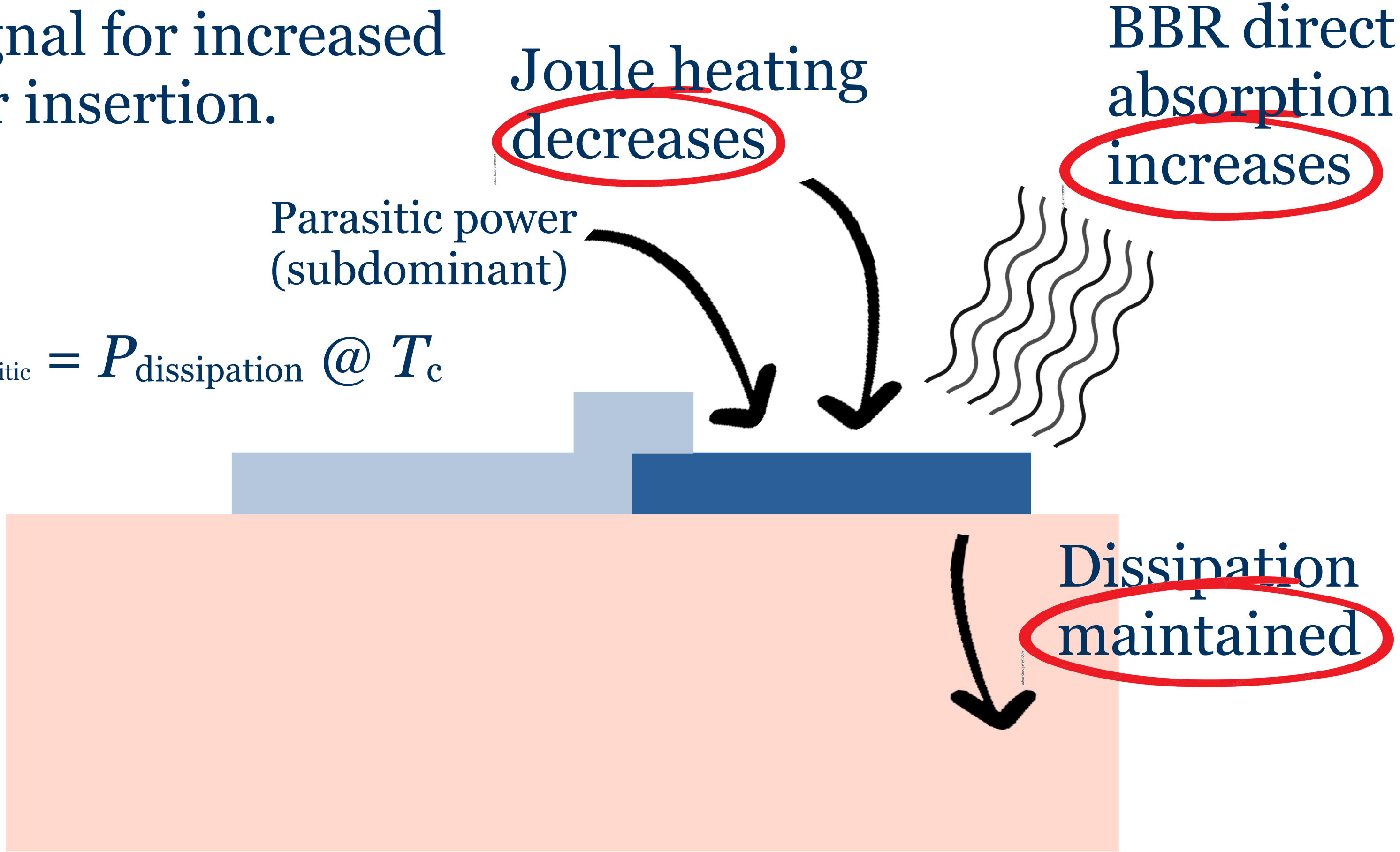
$$P_{\mathrm{BBR}}+P_{\mathrm{Joule}}+P_{\mathrm{parasitic}} = P_{\mathrm{dissipation}} \ @ \ T_{\mathrm{c}}$$



"Parasitic" power measurement p2

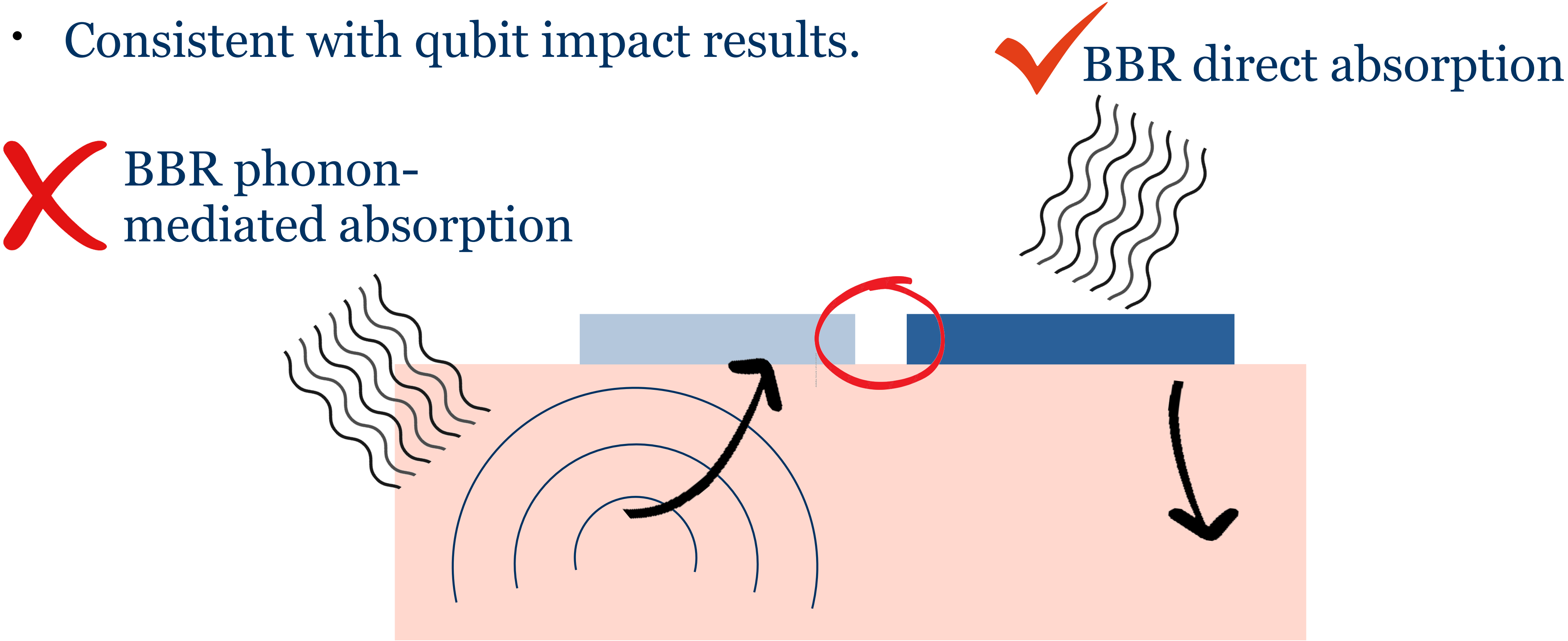
- Measured suppressed manual heating as a signal for increased parasitic power insertion.

$$P_{\mathrm{BBR}}+P_{\mathrm{Joule}}+P_{\mathrm{parasitic}}=P_{\mathrm{dissipation}} \ @ \ T_c$$



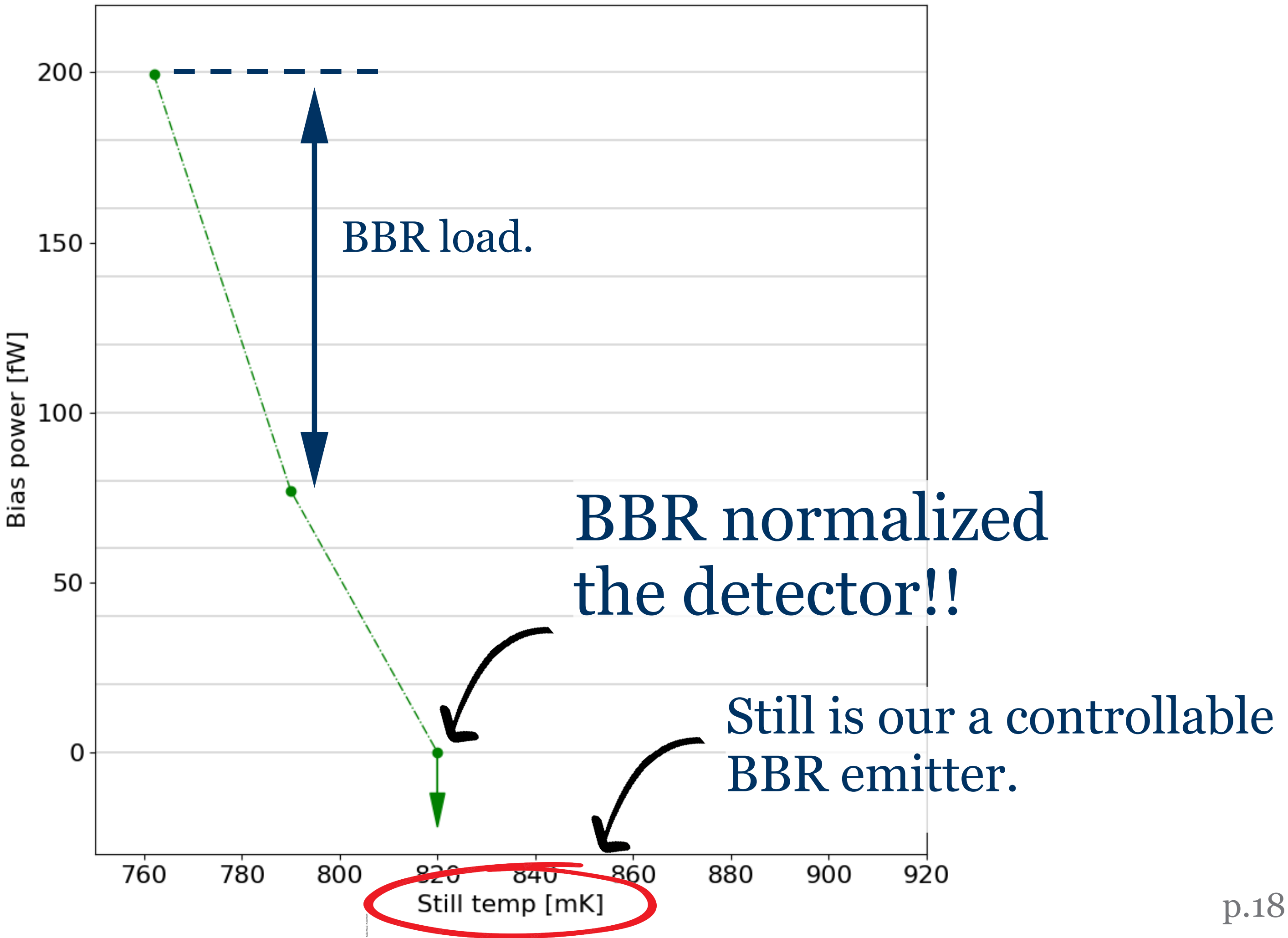
"Parasitic" power measurement p3

- Detaching phonon absorber did not affect signal size.
  → Dominated by direct SC feature absorption.
- Consistent with qubit impact results.



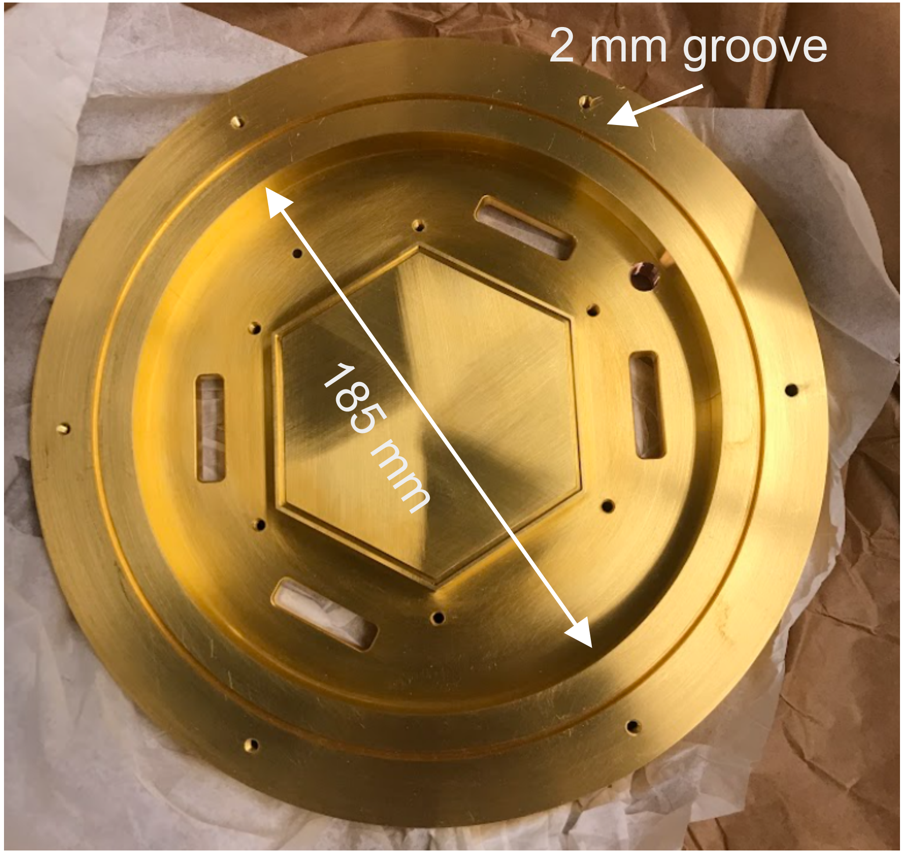
"Parasitic" power measurement p4

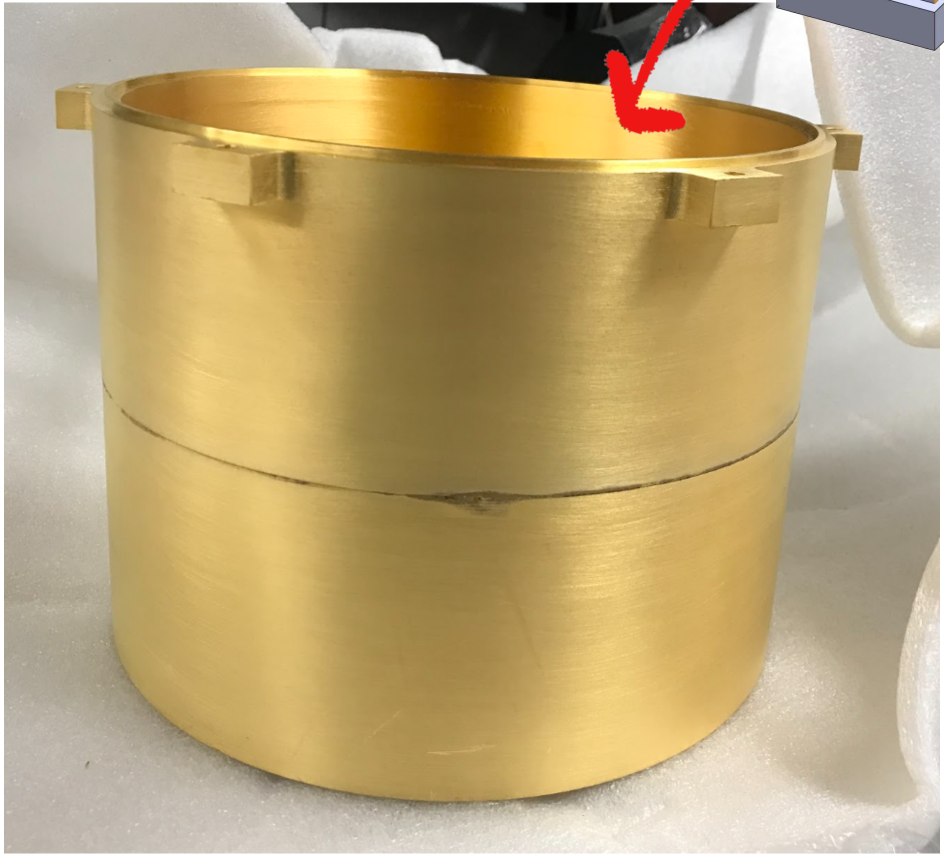
BBR impact w/o any shielding strategy:



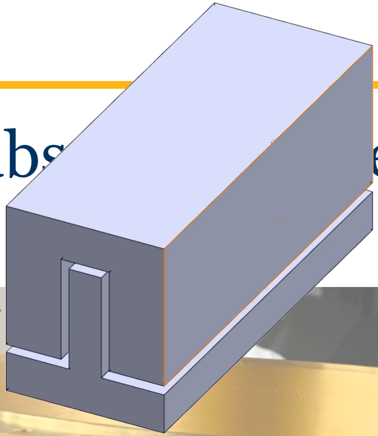
Coated double shield p1

- Qubit community's double shield with absorber strategy.
  e.g., Barends[+], 1105.4642.

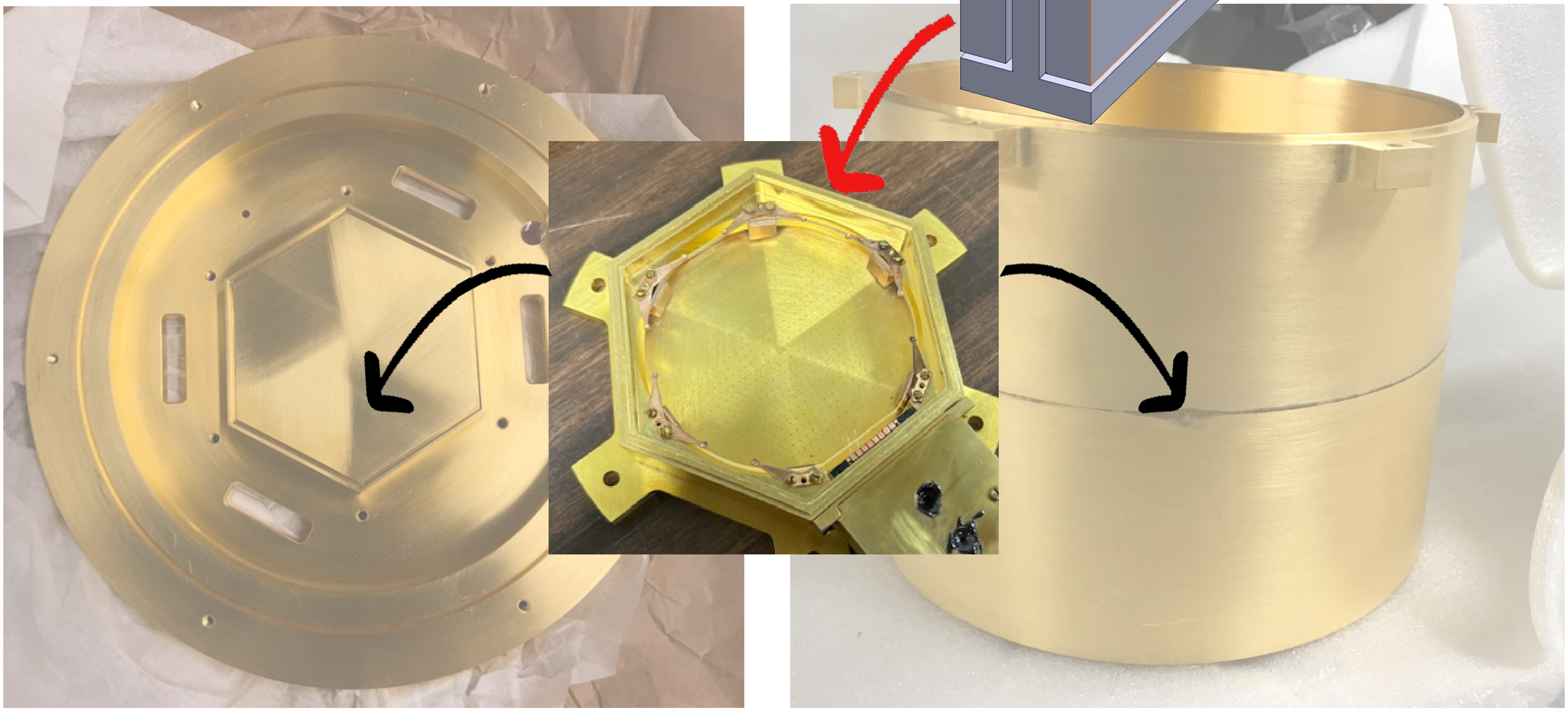




Coated double shield p2

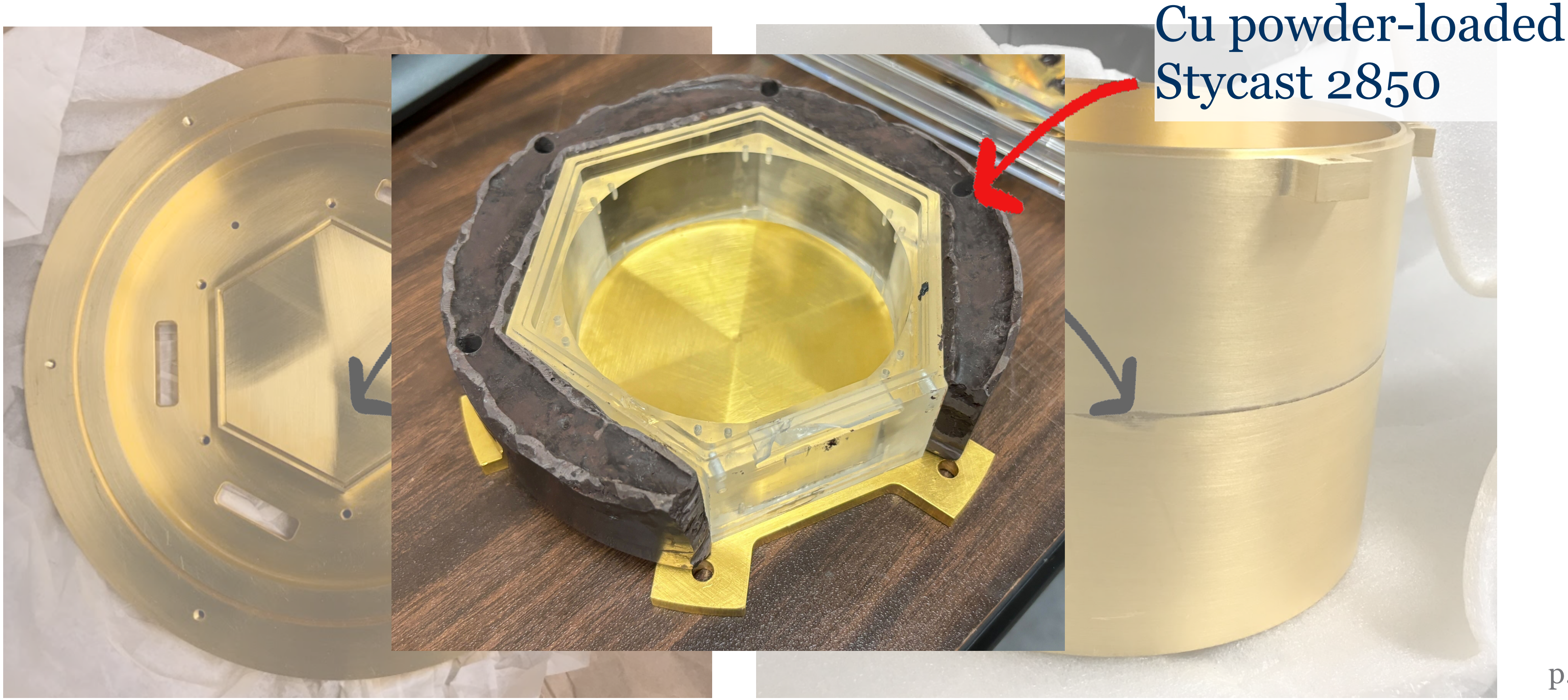


- Qubit community's double shield with abs egy.
  e.g., Barends+, 1105.4642.



Coated double shield p3

- Qubit community's double shield with absorber strategy.
  e.g., Barends+, 1105.4642.



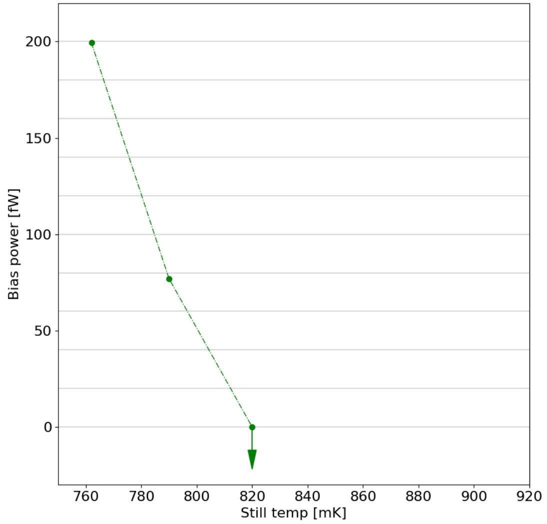
4-bend flange penetration p1

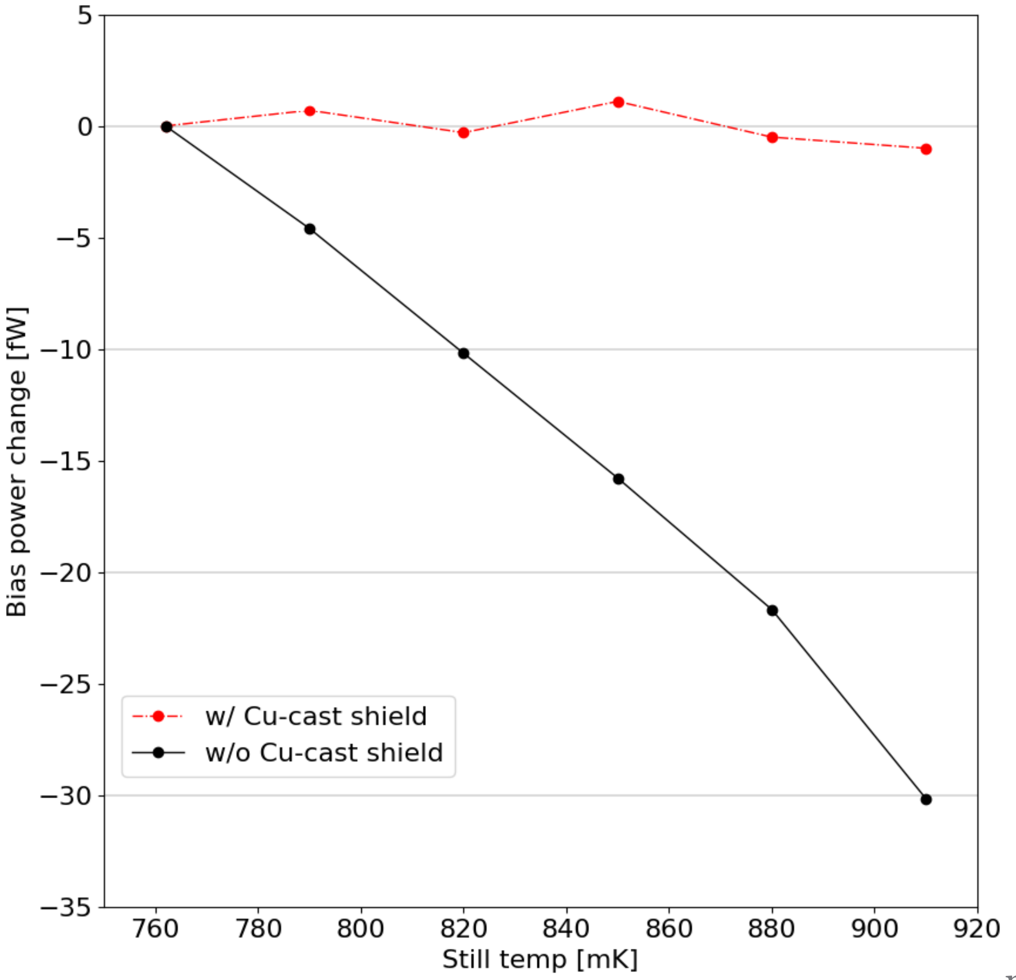
- More than 15 orders-of-magnitude *visible light* attenuation.
  - Iterated mechanical design until no light leak signal in long-exposure photos.
  - More stringent than our frequency range of interest due to shorter wavelengths.

4-bend flange penetration p2

- Suppressed all BBR, consistent with non-wiring-transmitted penetration.

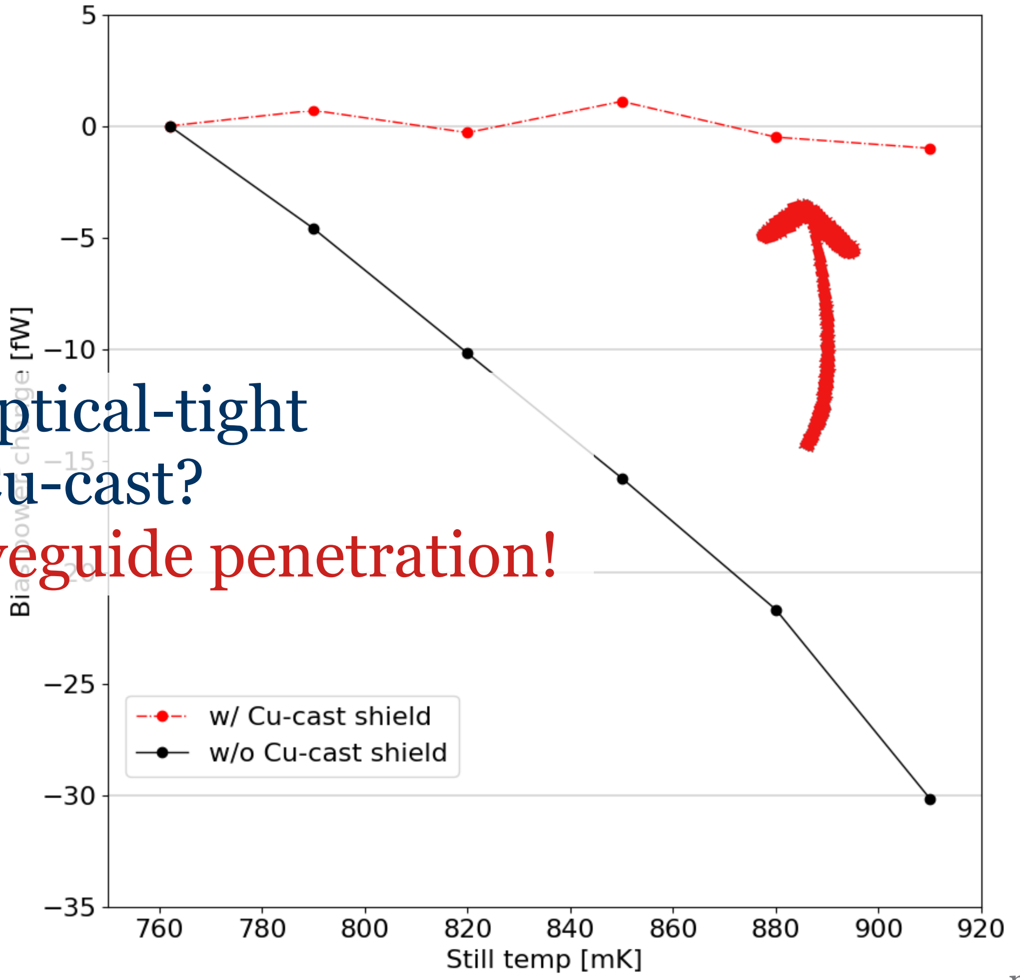
Recall: Normalized with this shield.





4-bend flange penetration p3

- Suppressed all BBR, consistent with non-wiring-transmitted penetration.



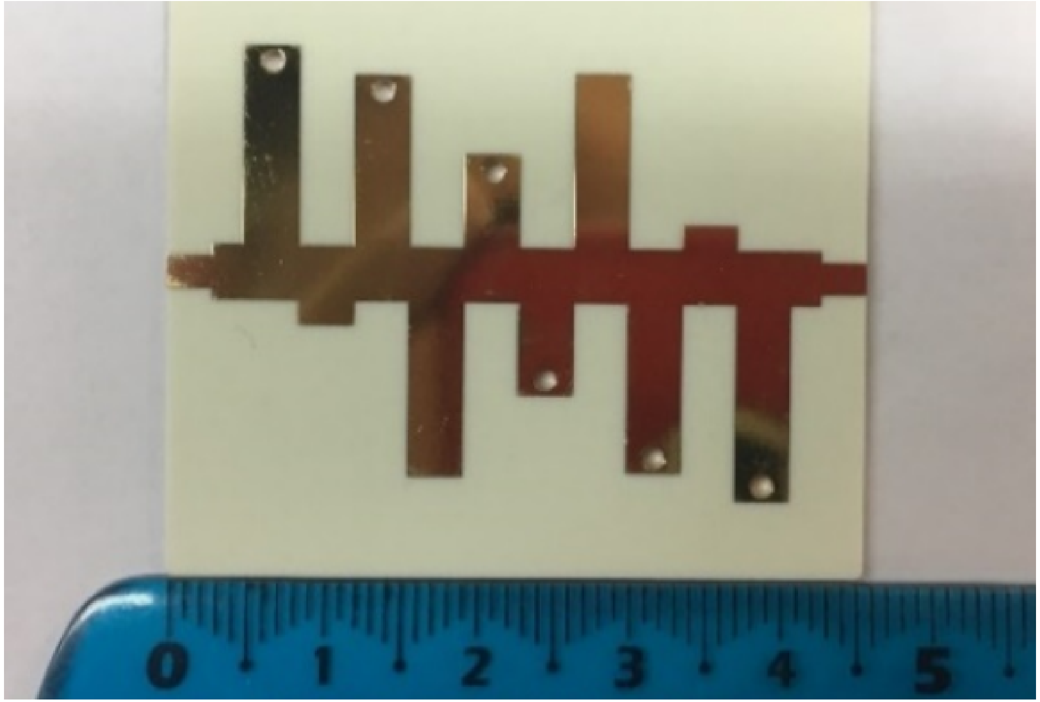
Q: What penetrated the 150-dB optical-tight 4-bend slit and get absorbed by Cu-cast?

A: It's consistent with the slit waveguide penetration!

II. A microwave filter for blackbody radiation

Microwave stub filter

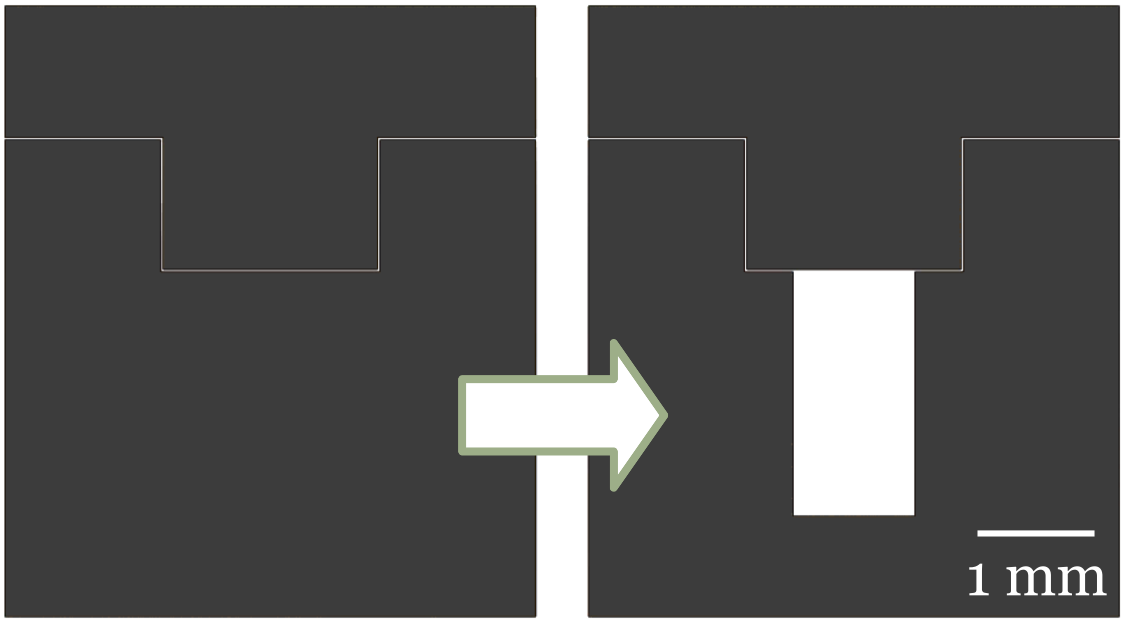
- Stubs on the transmission line create
  1) Impedance mismatch below f_{cutoff} – lumped element limit,
  2) Off-resonance reflection above f_{cutoff} – sustained wave.



[Y. Ma+ (2018)]

Stub filter adaptation p1

- Practical fabrication, can be retrofitted.

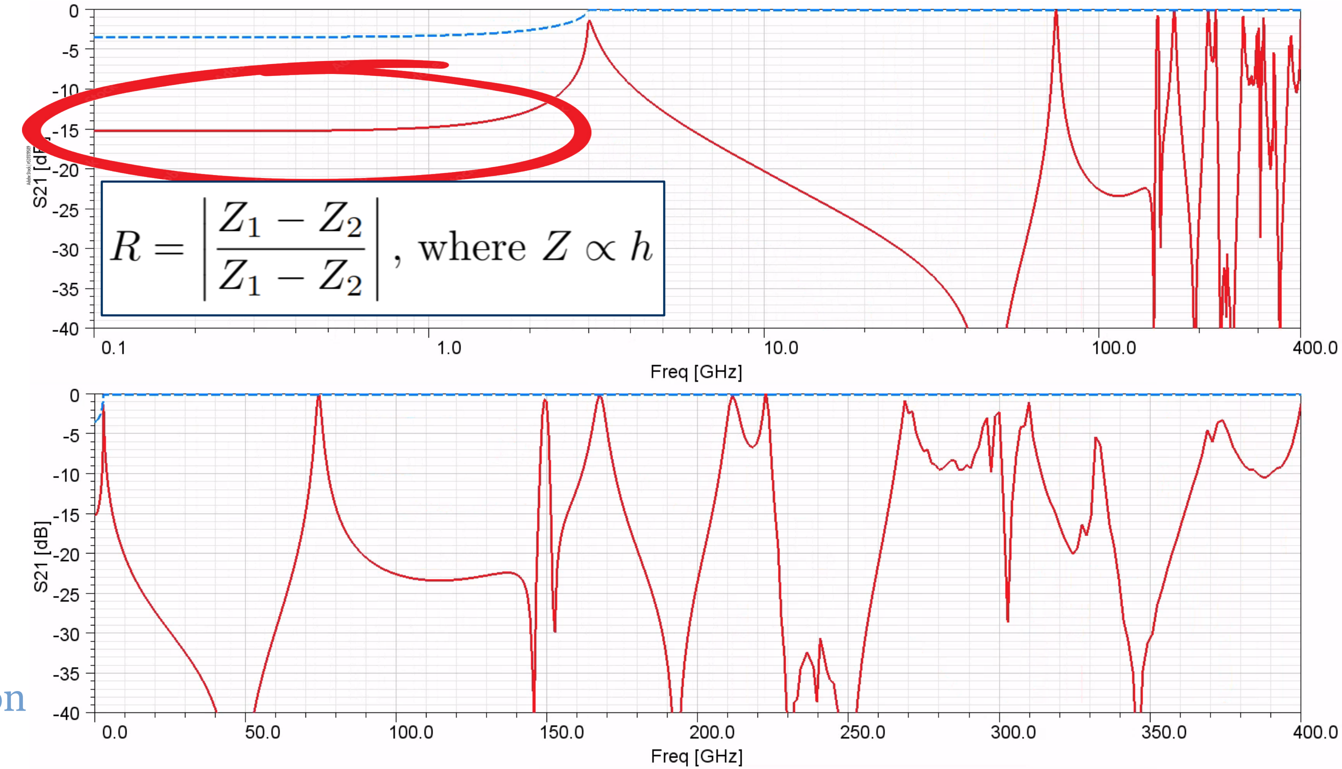


Stub filter adaptation p2

- Practical fabrication, can be retrofitted.

BBR stub filter p1

- Analogous to (continuing p.28 design)
  – Below f_{cutoff}: A transmission line with impedance continuities.



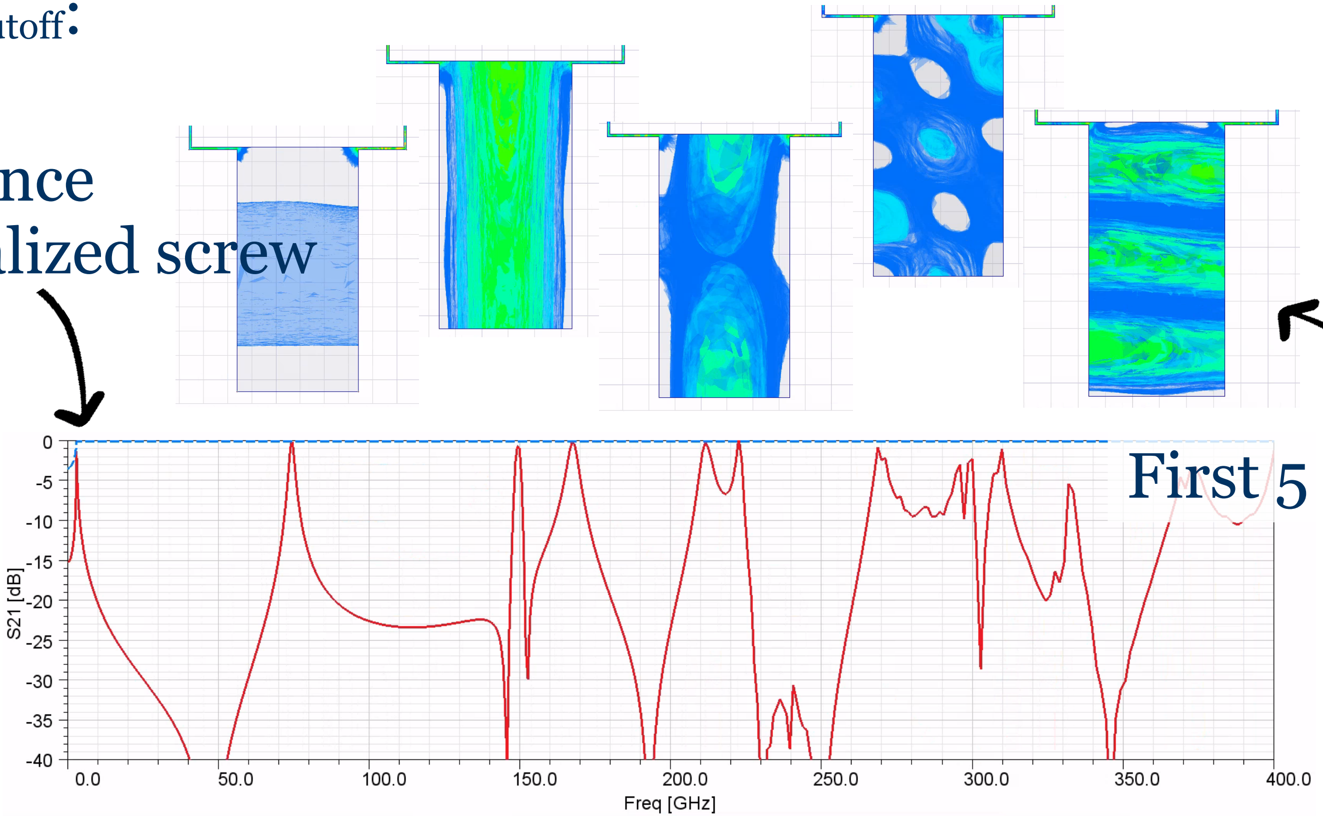
$$R = \left| \frac{Z_1 - Z_2}{Z_1 - Z_2} \right|, \text{ where } Z \propto h$$

Red solid:
After modification
Blue dashed:
Before modification

BBR stub filter p2

- Analogous to (continuing p.28 design)
  - Below f_{cutoff}: A transmission line with impedance continuities.
  - Above f_{cutoff}:

f_{cutoff}: Resonance between idealized screw boundaries.

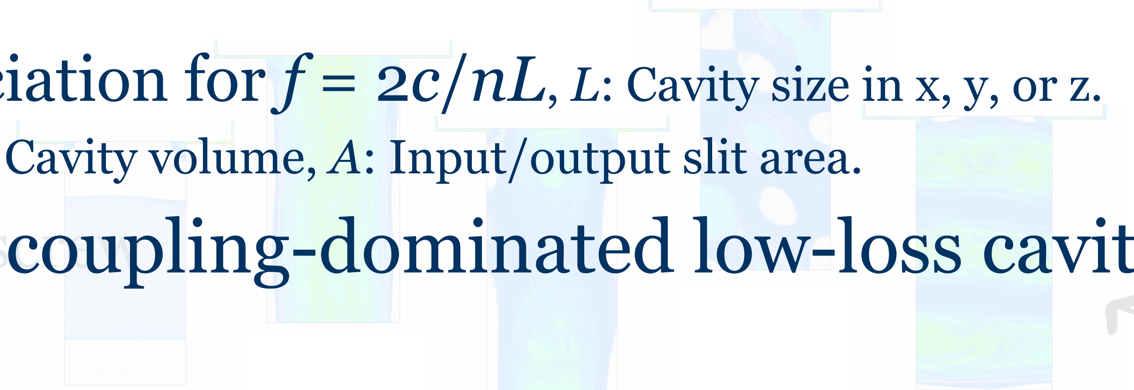


First 5 resonances

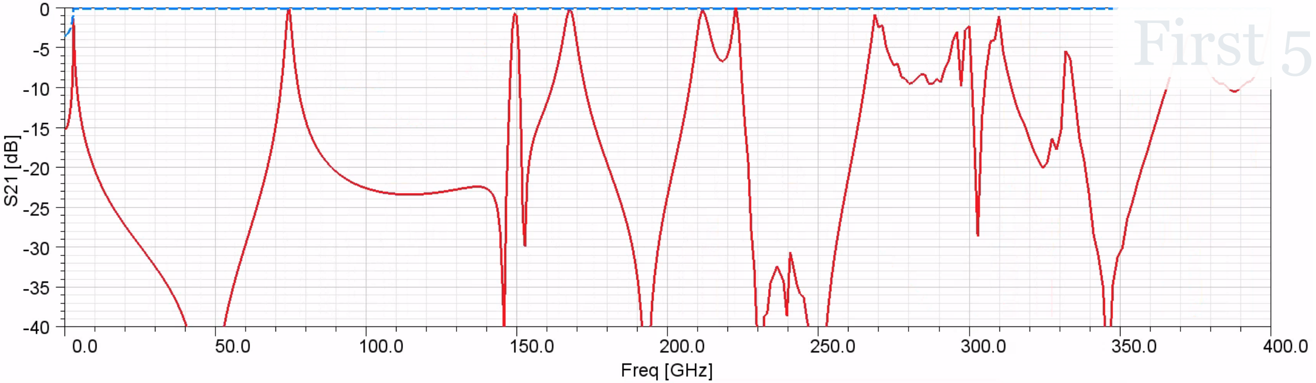
Red solid: After modification
Blue dashed: Before modification

BBR stub filter p3

- Analogous to (continuing p.28 design)
  - Below f_{cutoff}: A transmission line with impedance continuities.
  - Above f_{cutoff}:
    1) Exact association for $f = 2c/nL$, L: Cavity size in x, y, or z.
    2) $Q \propto V/A$, V: Cavity volume, A: Input/output slit area.



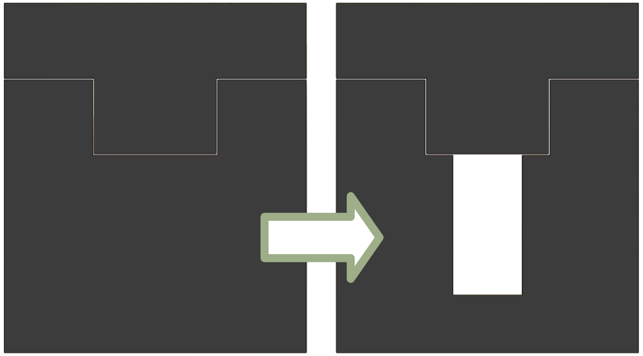
A near-ideal coupling-dominated low-loss cavity

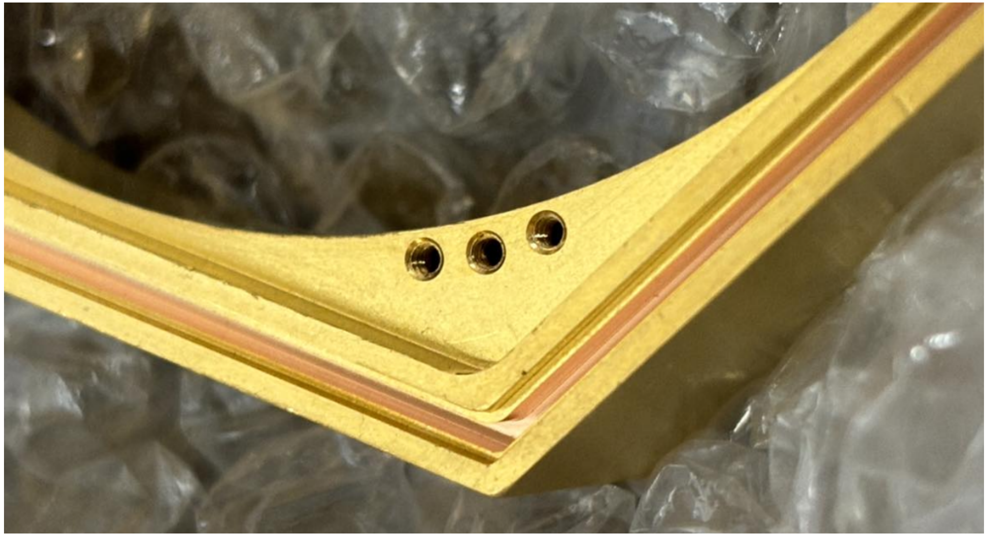


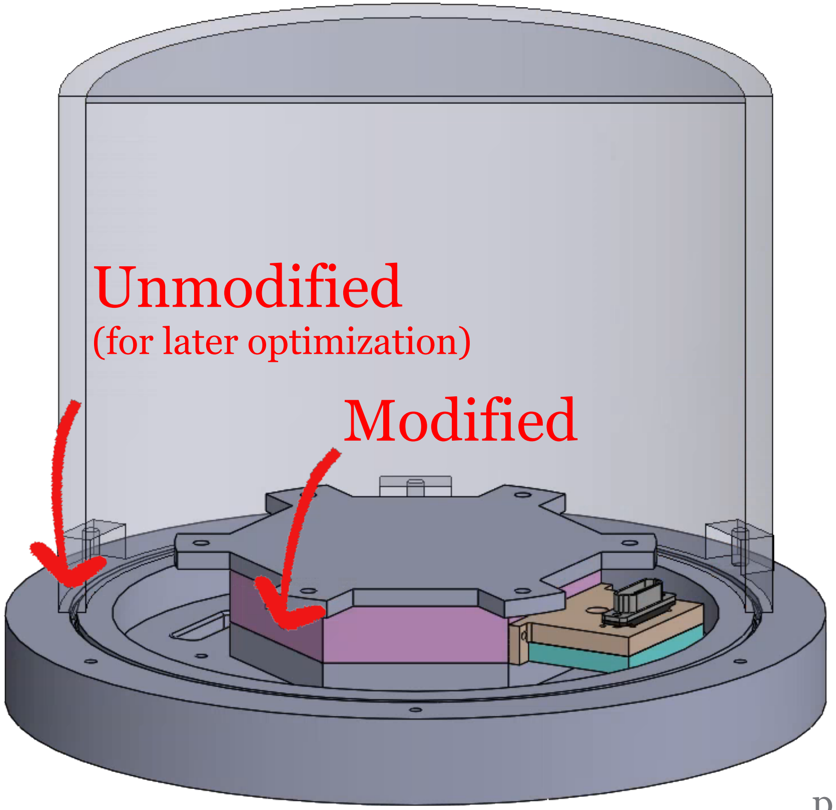
Red solid:
After modification
Blue dashed:
Before modification

Proof-of-principle experiment p1

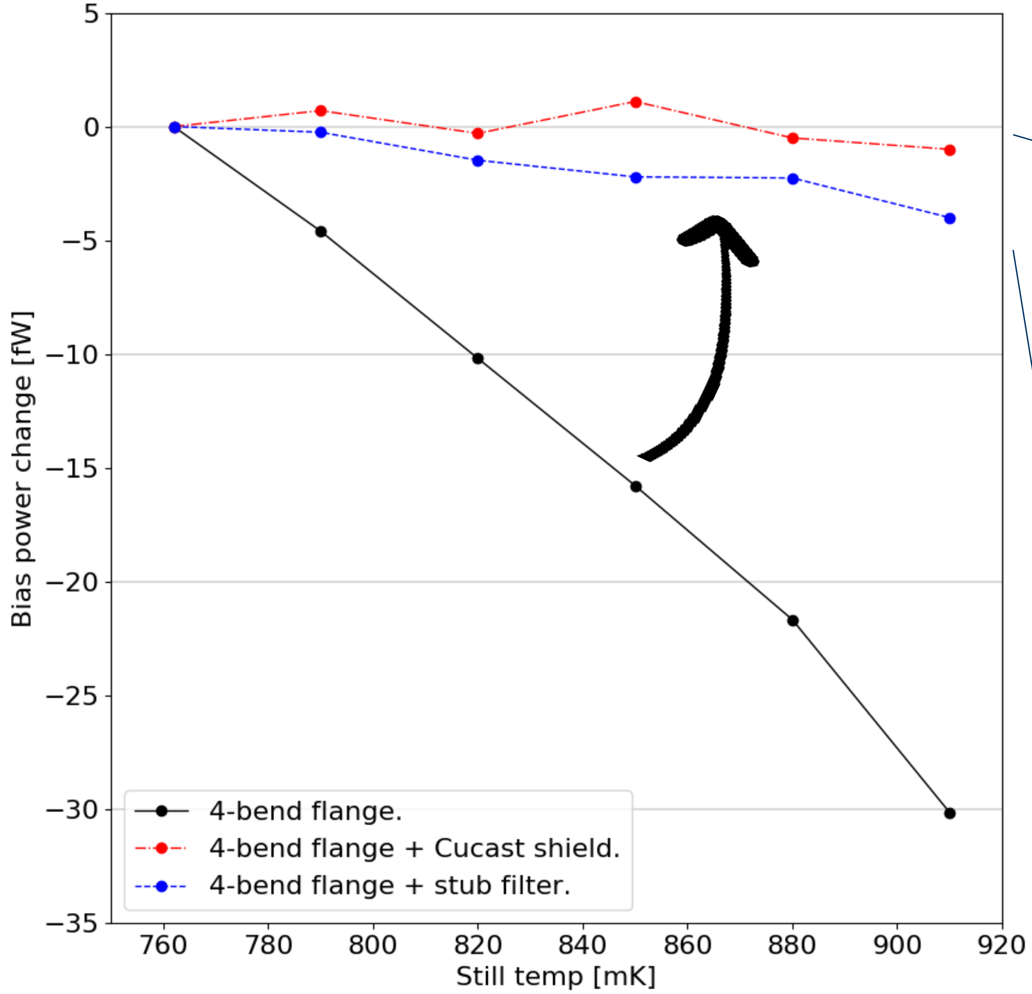
- Retrofitted an 1×2 mm groove into detector housing's tight flange.





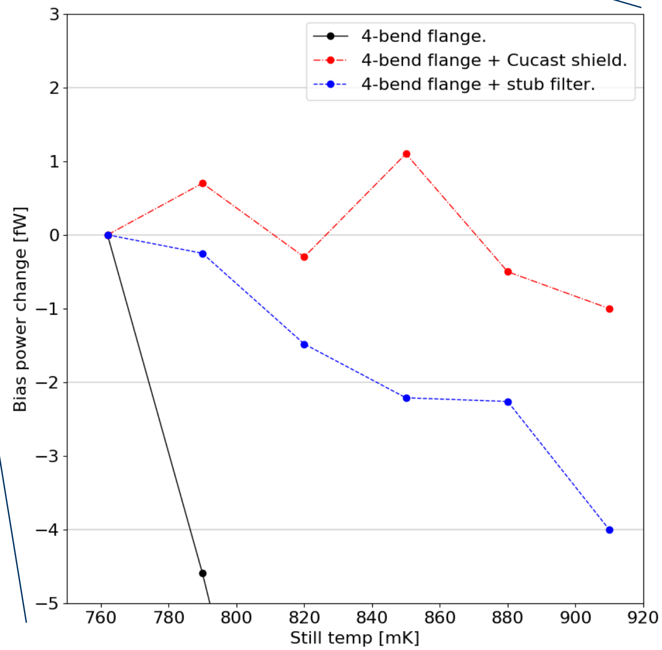


Proof-of-principle experiment p2



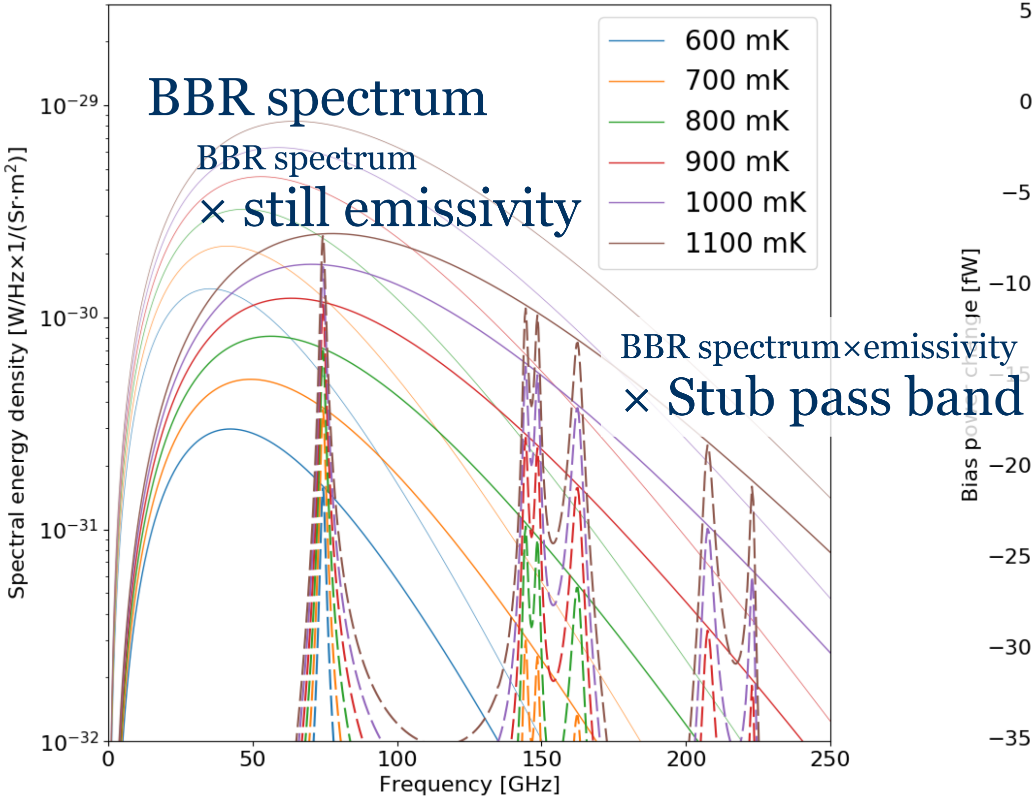
Single-stub BBR filter significantly decreased BBR leakage!

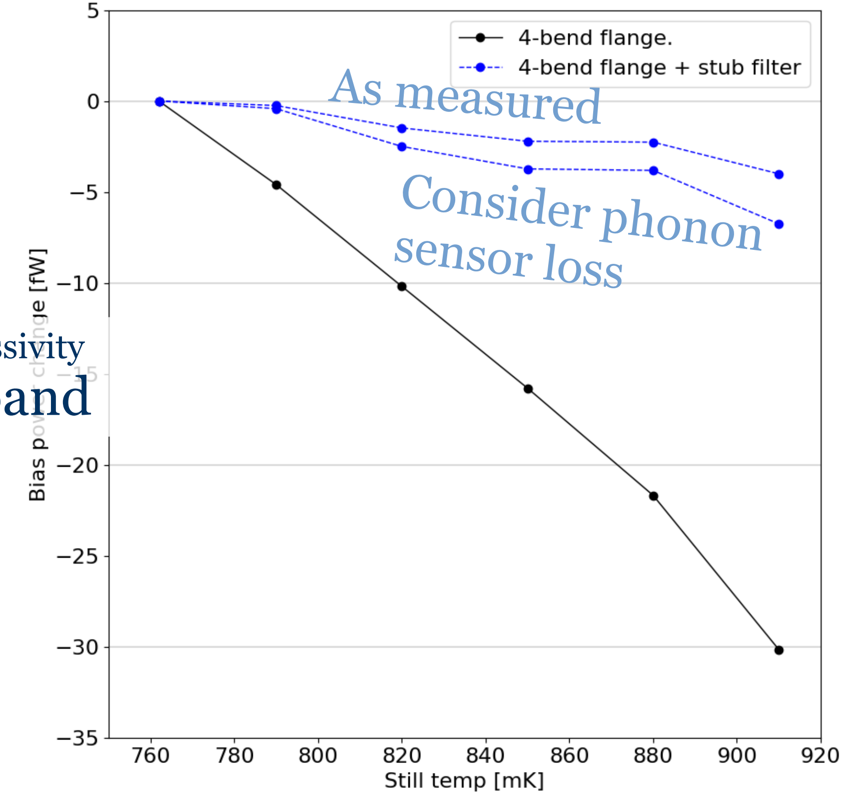
(We can only set upper limit for how good Cu-cast is.)



Proof-of-principle experiment p3

- Consistent with the calculated integrated BBR power.
- MC can radiation recycle efficiency dominated uncertainty.





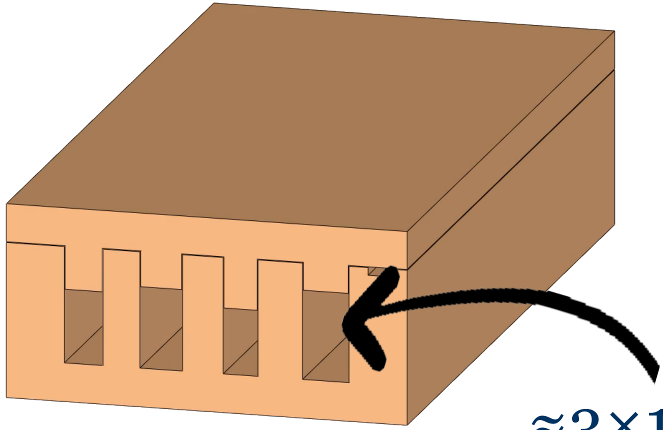
Benefit of stub filter shielding

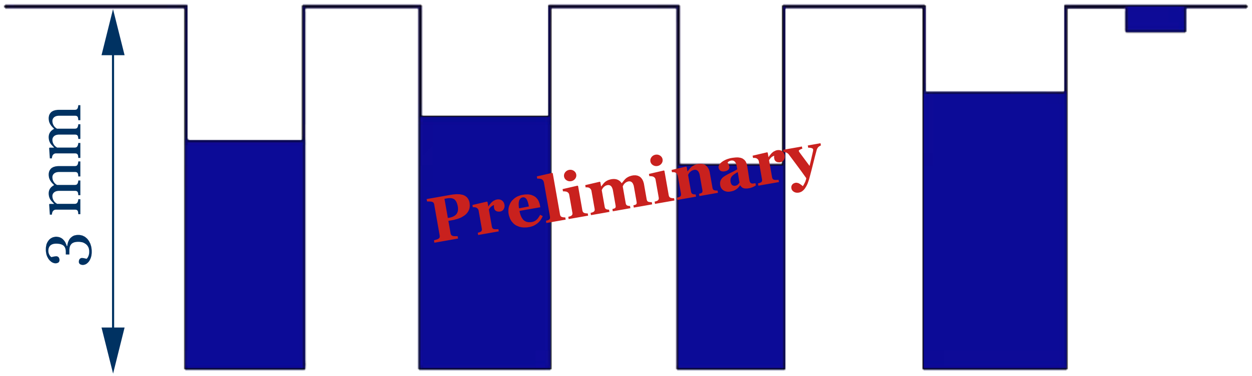
- High design flexibility & accuracy.
- Compatible with commercial fabrication.
- Can be retrofitted & integrated with exiting shielding strategies, e.g., w/ BBR absorber.
- It's pure copper!
  - No magnetic material, e.g., Eccosorb, ferrite.
  - Easy to use, e.g., v.s. indium,
  - Easy to integrate with existing infrastructure.

<u>A complementary BBR shielding technique with unique advantages.</u>

Toward an optimal design p1

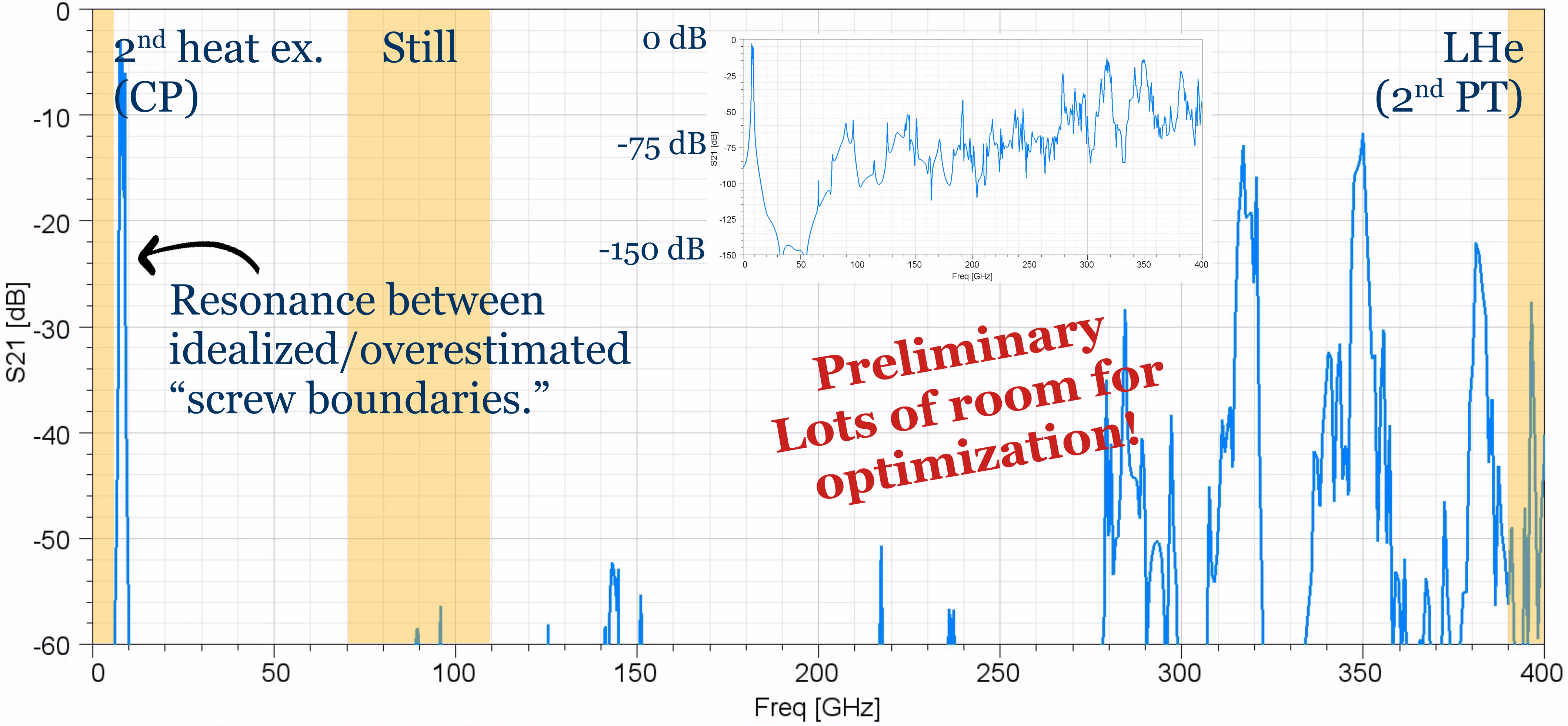
- Goals
  - Compatible with commercial fabrication.
  - Place resonance pass bands to filter each other.
    – As close as possible to push common resonances to high freq. ($2c/L$)
    – Sufficiently separated to avoid beat generation. (Q)
  - Narrow sections = transmission line: Be careful of $\lambda/4$ pass!
  - >1 cm bendy slit to suppress particle-like penetration.





≈3×1.2 mm grooves

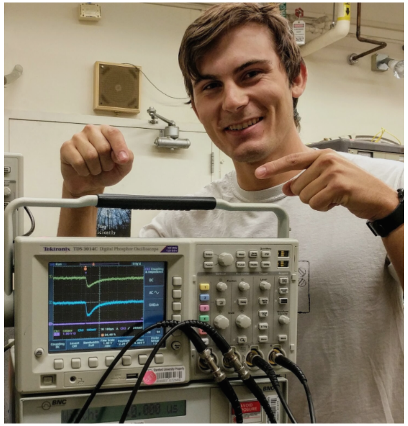
Toward an optimal design p2



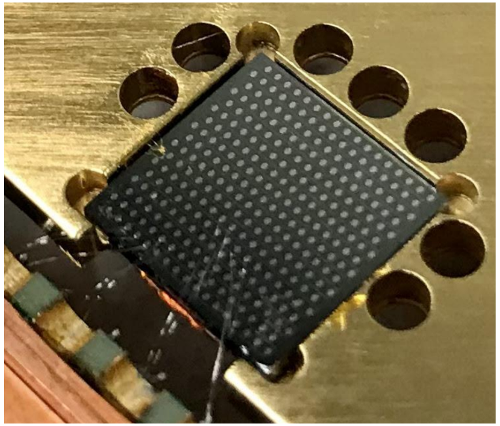
III. More from our group

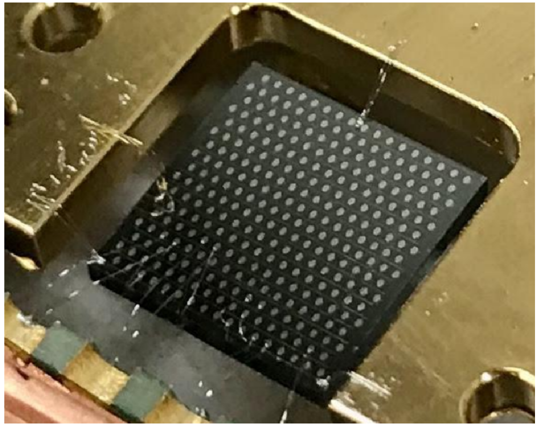
Stress-generated phonon QP poisoning

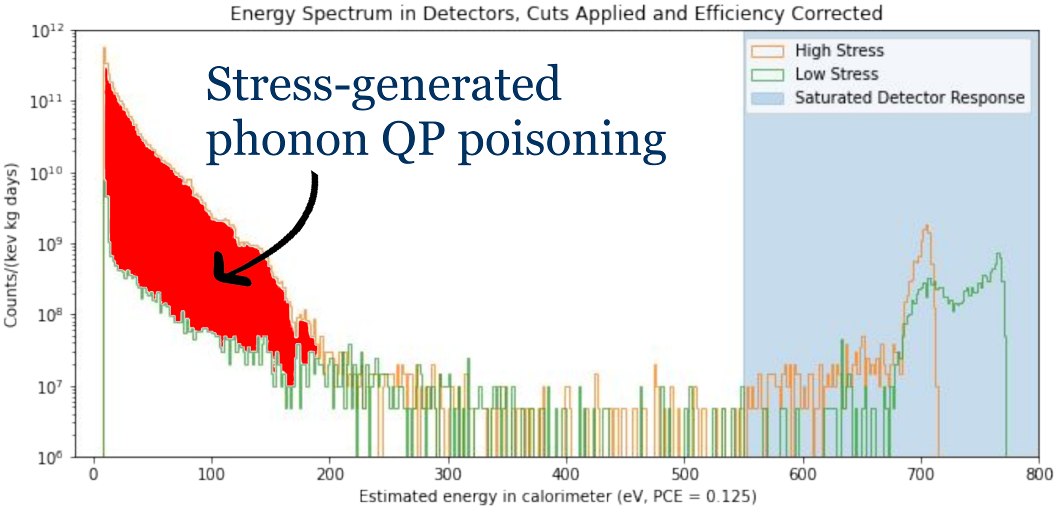
- Poster: ***Quasiparticle Posioning, the Low-Energy Excess and Stress Relaxation***
- Identified stress as a source of phonon QP poisoning.
- A "thermal cycle-recharged" effect that relaxes at a time scale of days.



R. Romani



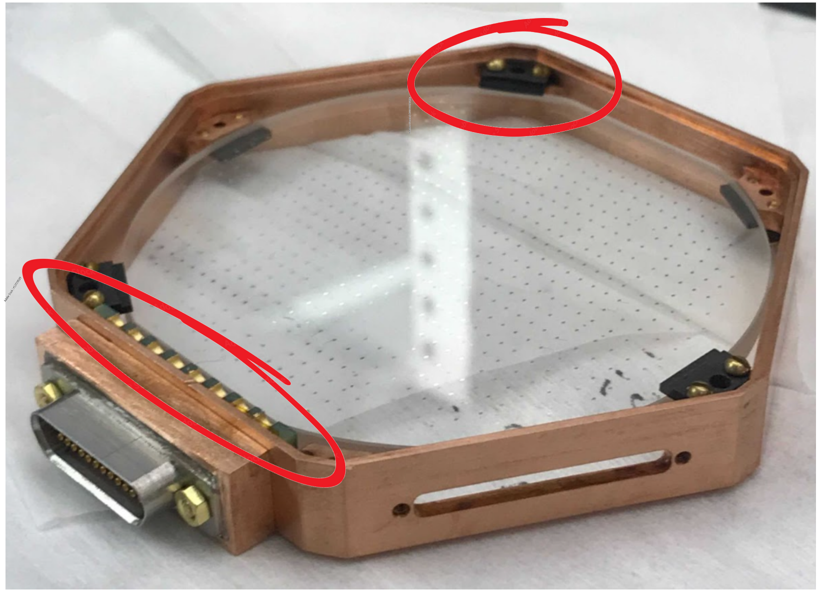


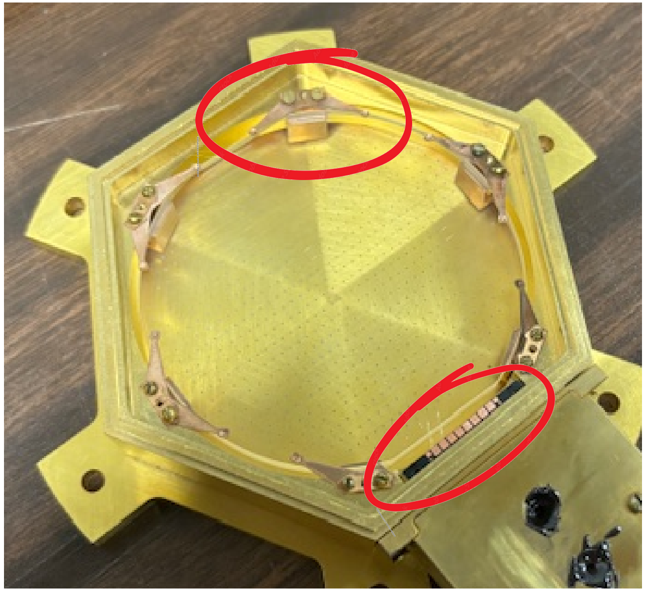


Low-background housing

- Removed all dielectrics to suppress scintillation.
- Optimized spring clamp to suppress stress & vibration noise.
- Low-BBR leak "copper-cast" feedthrough mechanics.

M. Reed





Summary

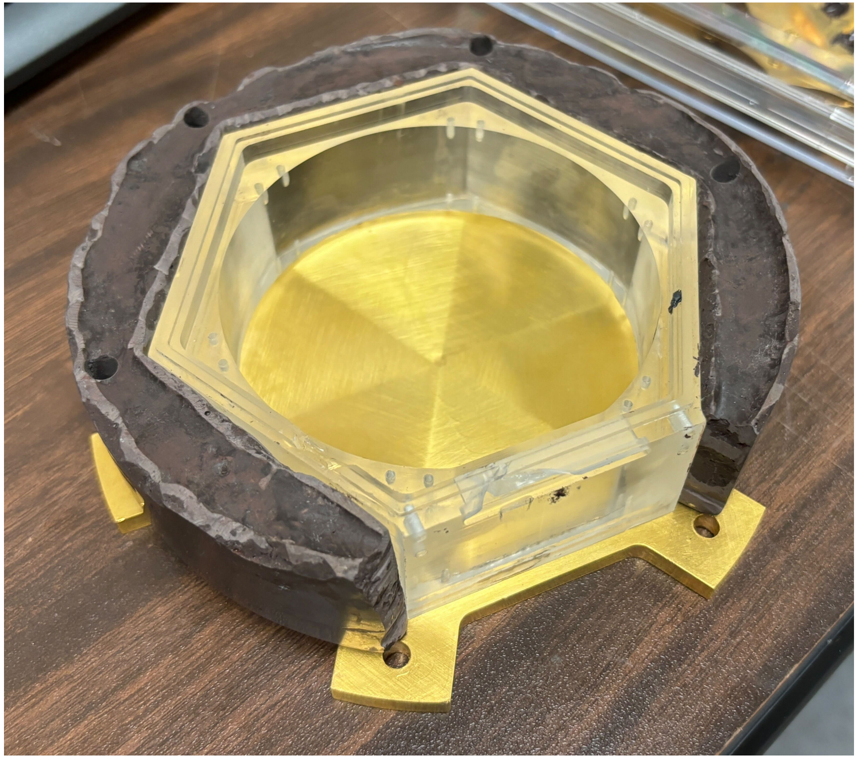
- After reasonable shielding, blackbody radiation impacts quantum devices primarily as micro/millimeter-wave.
- Line-of-sight-based strategies fail to shield sustained wave penetration.
- We propose a novel adaptation of the microwave stub filter for designing blackbody radiation shields.
- Our blackbody radiation filter is practical, can be retrofitted, and free from undesirable radiation sources.
- We understand the working principles of the BBR stub filter and can optimize the design based them.
- We identify stress as a phonon poisoning source.

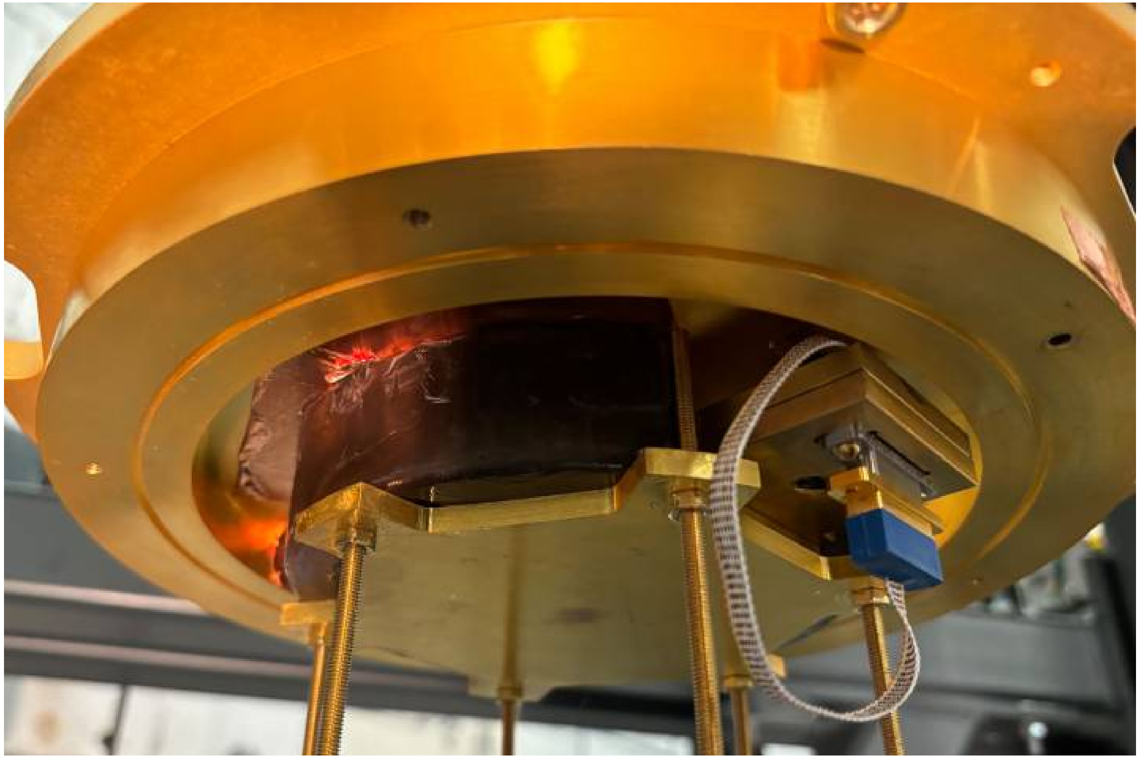
Thank you!

Backup

Copper-cast shield

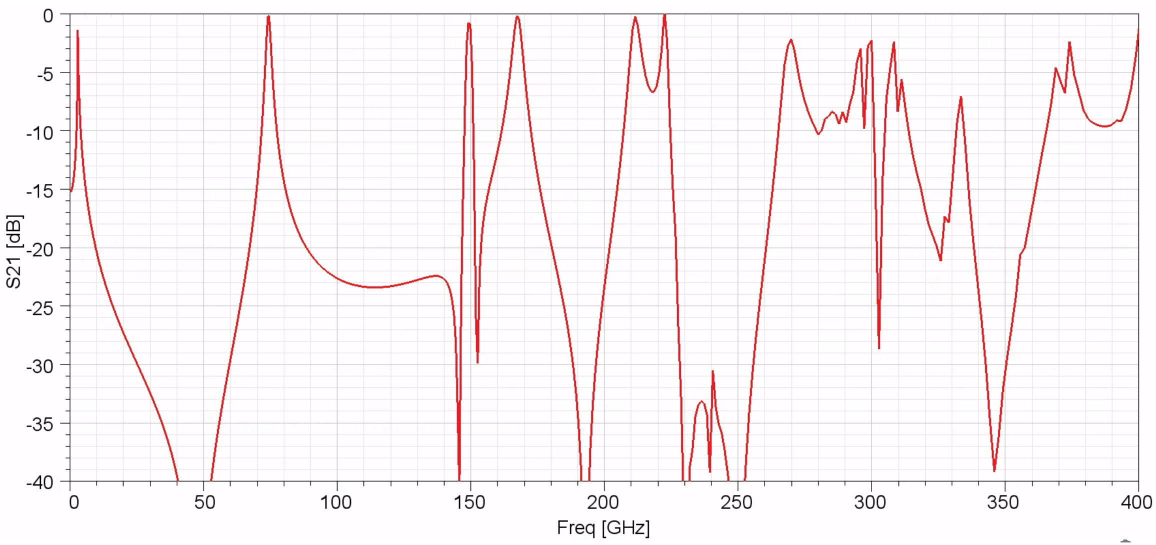
- 400-mesh Cu powder + Stycast 2850, 1:1 Cu:Stycast part A by weight.



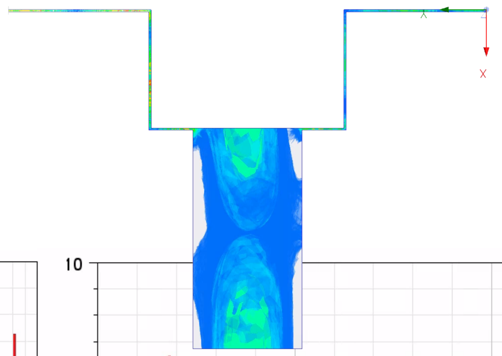


Analysis ingredient

- Radiation equilibrium inside the MC can, $P_1 = A_1 S_{21,1} / \Sigma A_i S_{21,i}$.
  - High-reflectivity, low-leak limit.
  - A: Antenna aperture, unknown but ∝ slit length.
- Phonon sensor loss, R_n: 198→334 mΩ .
- Still surface emissivity, $\sqrt{8\varepsilon_0\omega/\sigma}$.
- HFSS-simulated pass band:

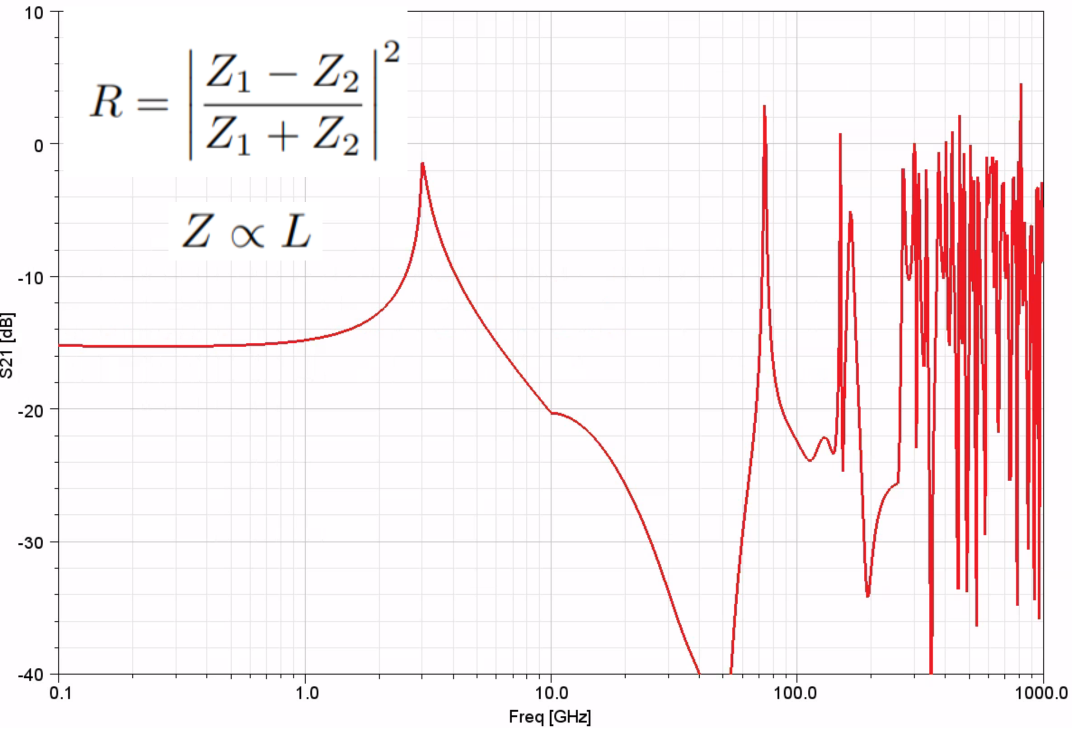


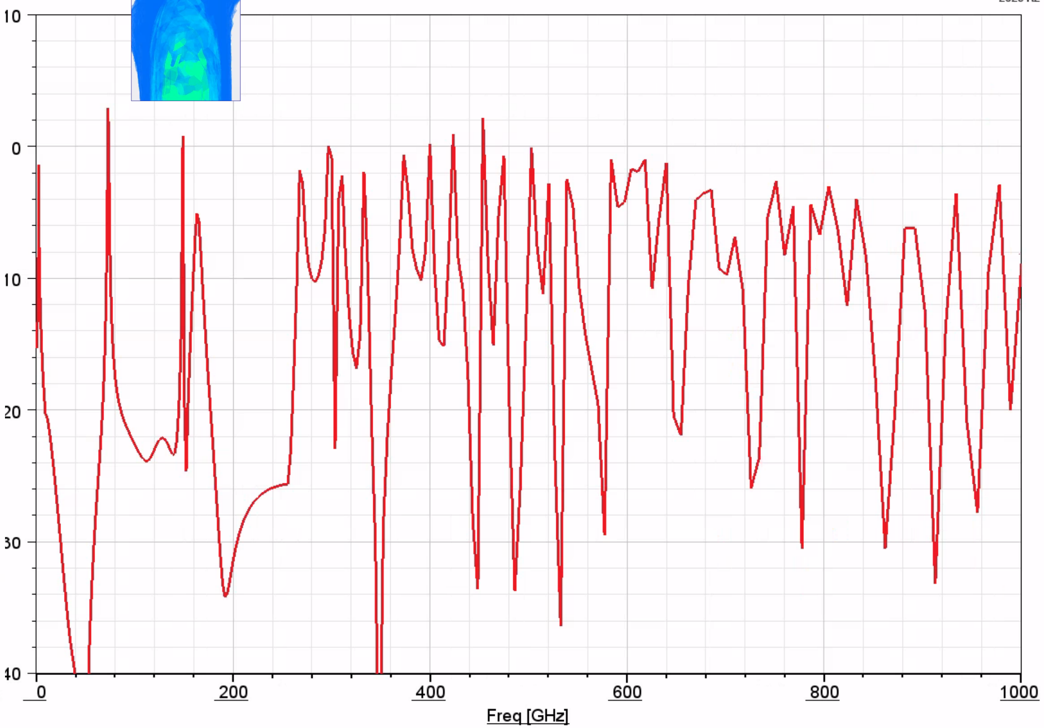
Single stub physics



$$R = \left| \frac{Z_1 - Z_2}{Z_1 + Z_2} \right|^2$$

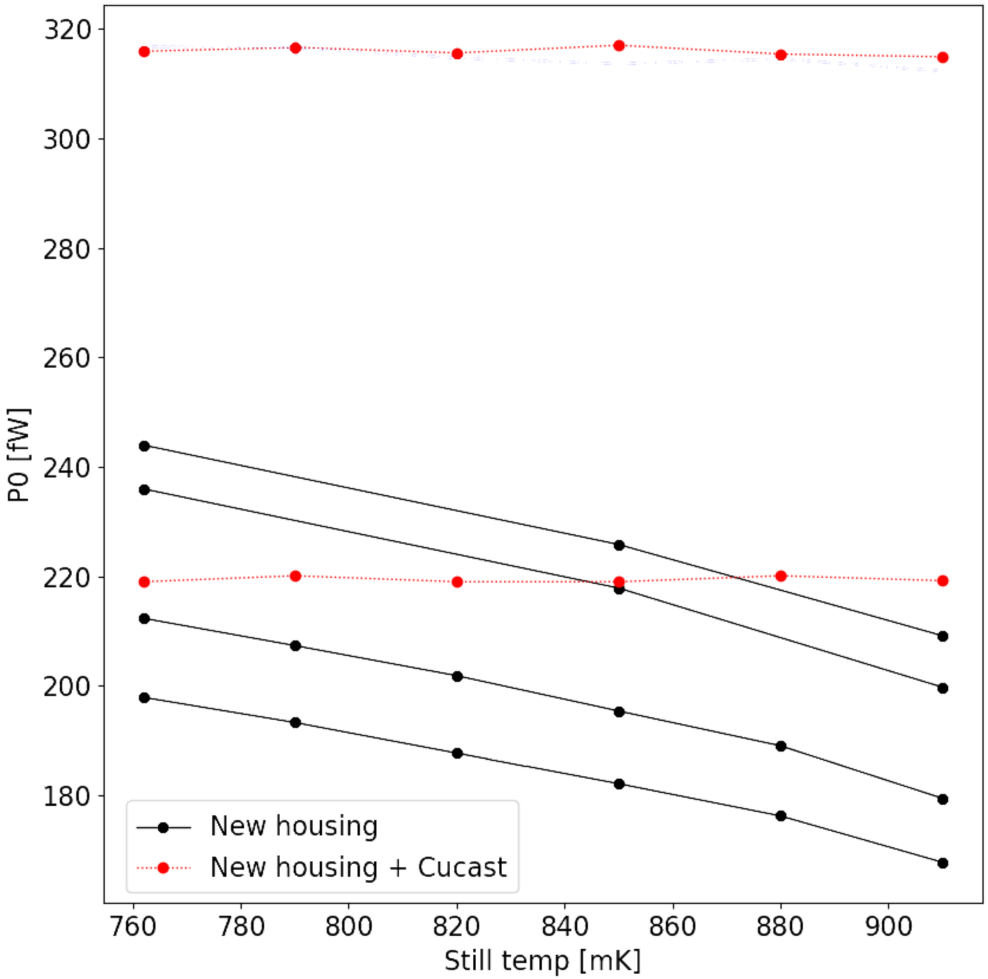
$$Z \propto L$$





Stress relaxation

- Relaxed at 2 fW/hr for 5 days regardless of BBR load.



Particle-vs-wave penetration p2

- Photon-leaky vs -tight detector housing.

Flat edge