Post-inflationary axion dark matter search with a dielectric haloscope

Axions beyond Gen 2, Jan 28th 2021

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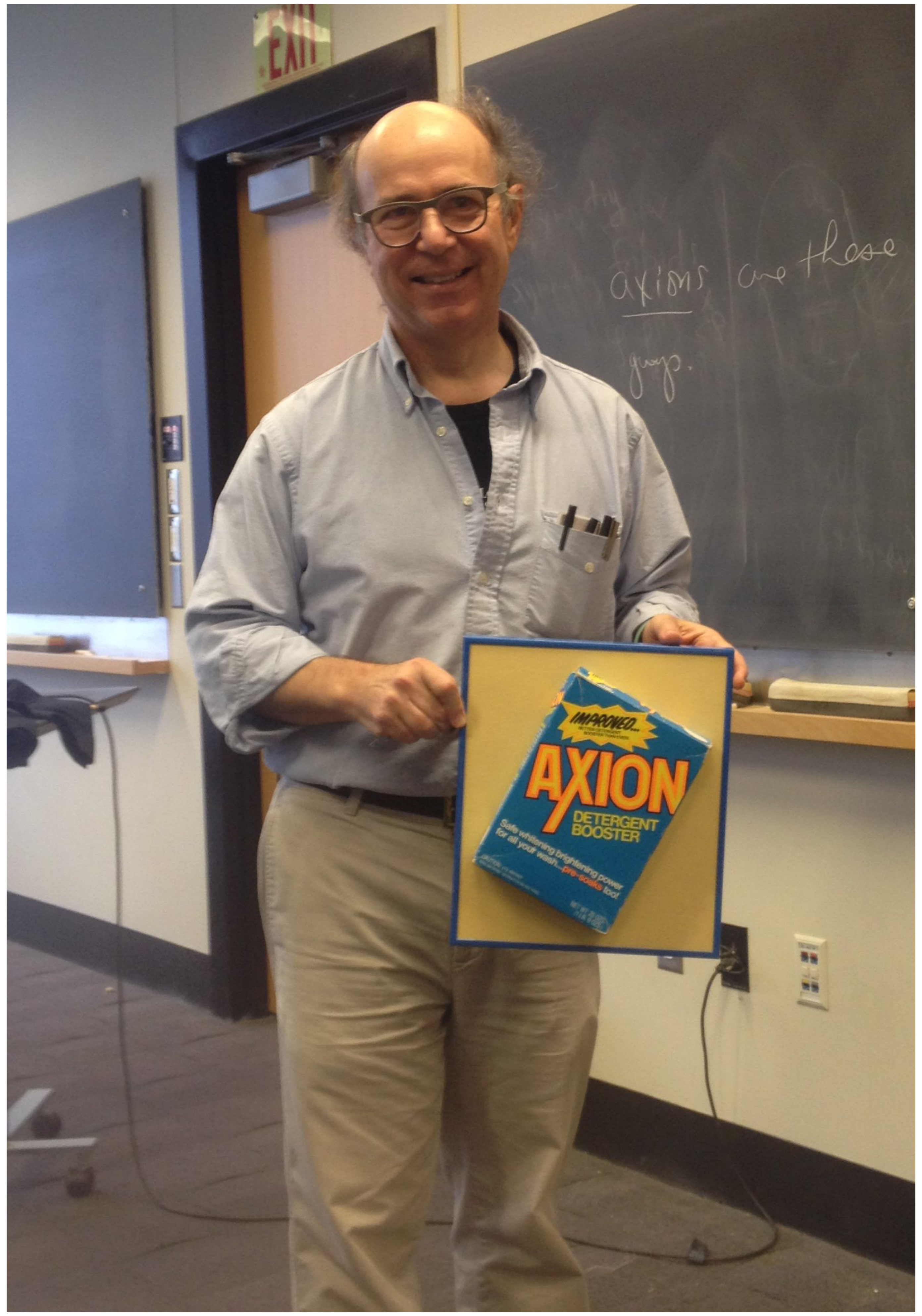
MAX-PLANCK-INSTITUT FÜR PHYSIK

Overview

- Theoretical motivations
- Scale-up & challenges
- Dielectric haloscope
- MADMAX experiment
- Proof-of-principle setup: 100mm setup in LHe
- Conclusion

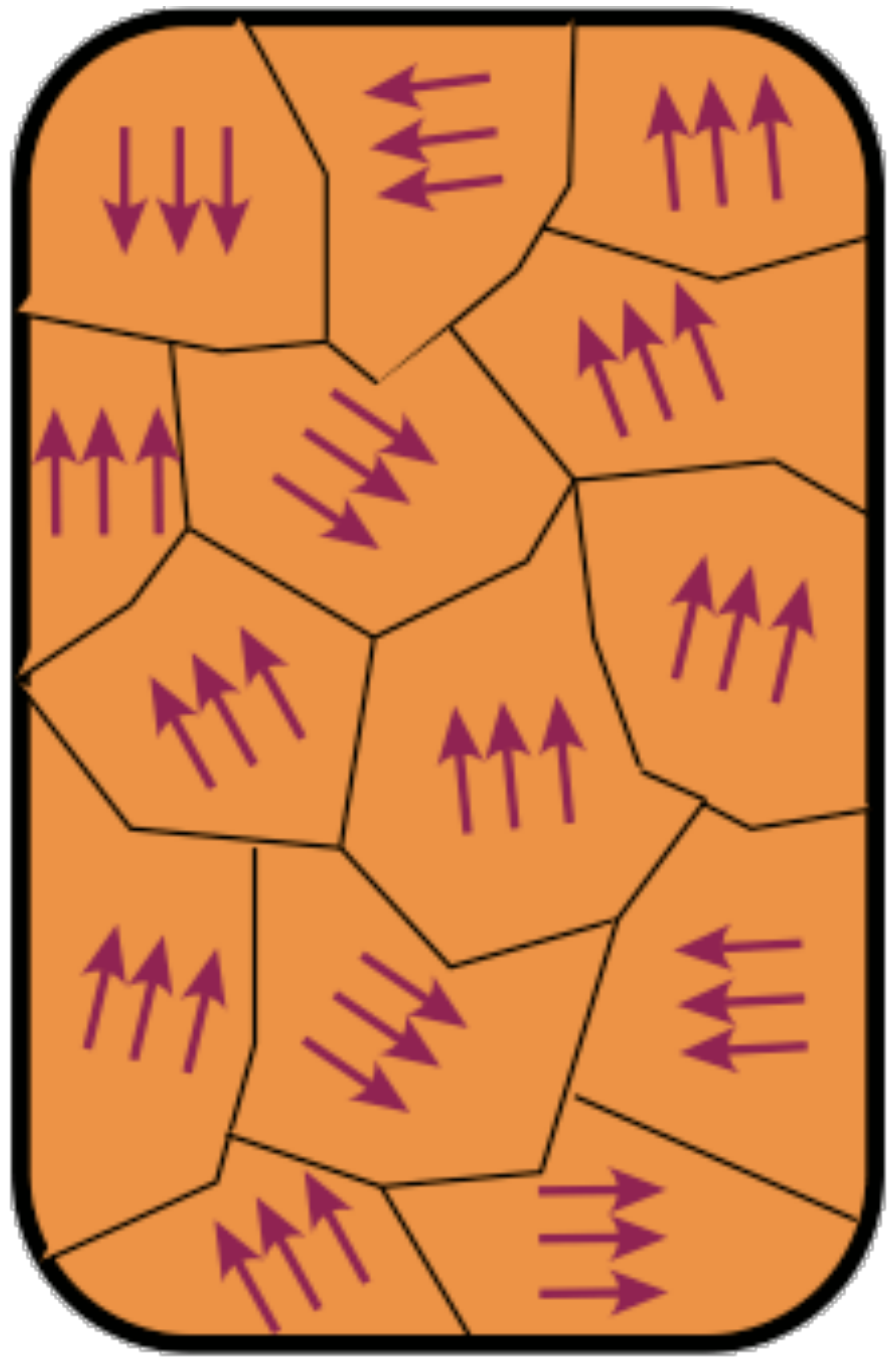


"The box is empty... OR IS IT?"

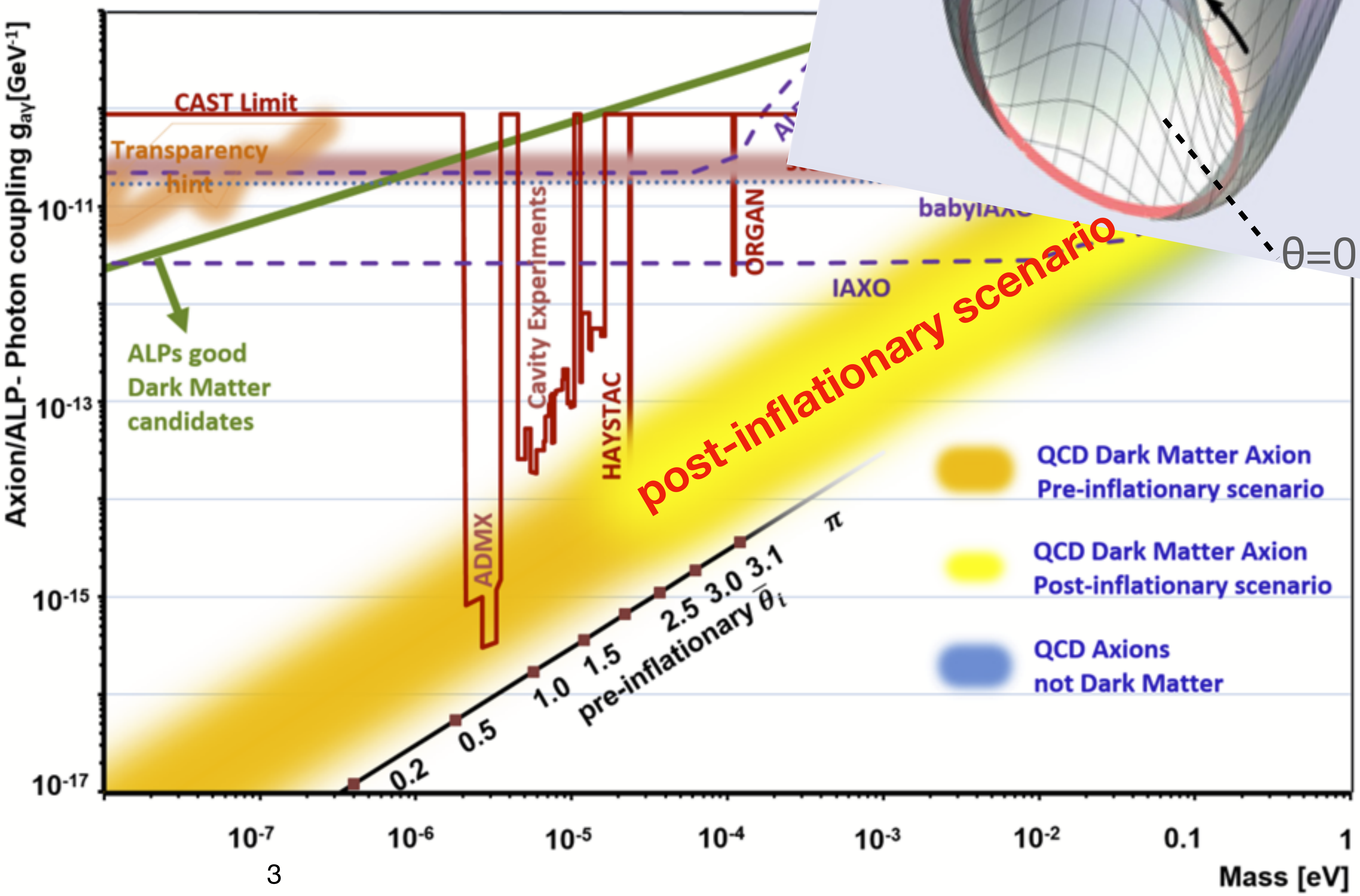
from Twitter@FrankWilczek

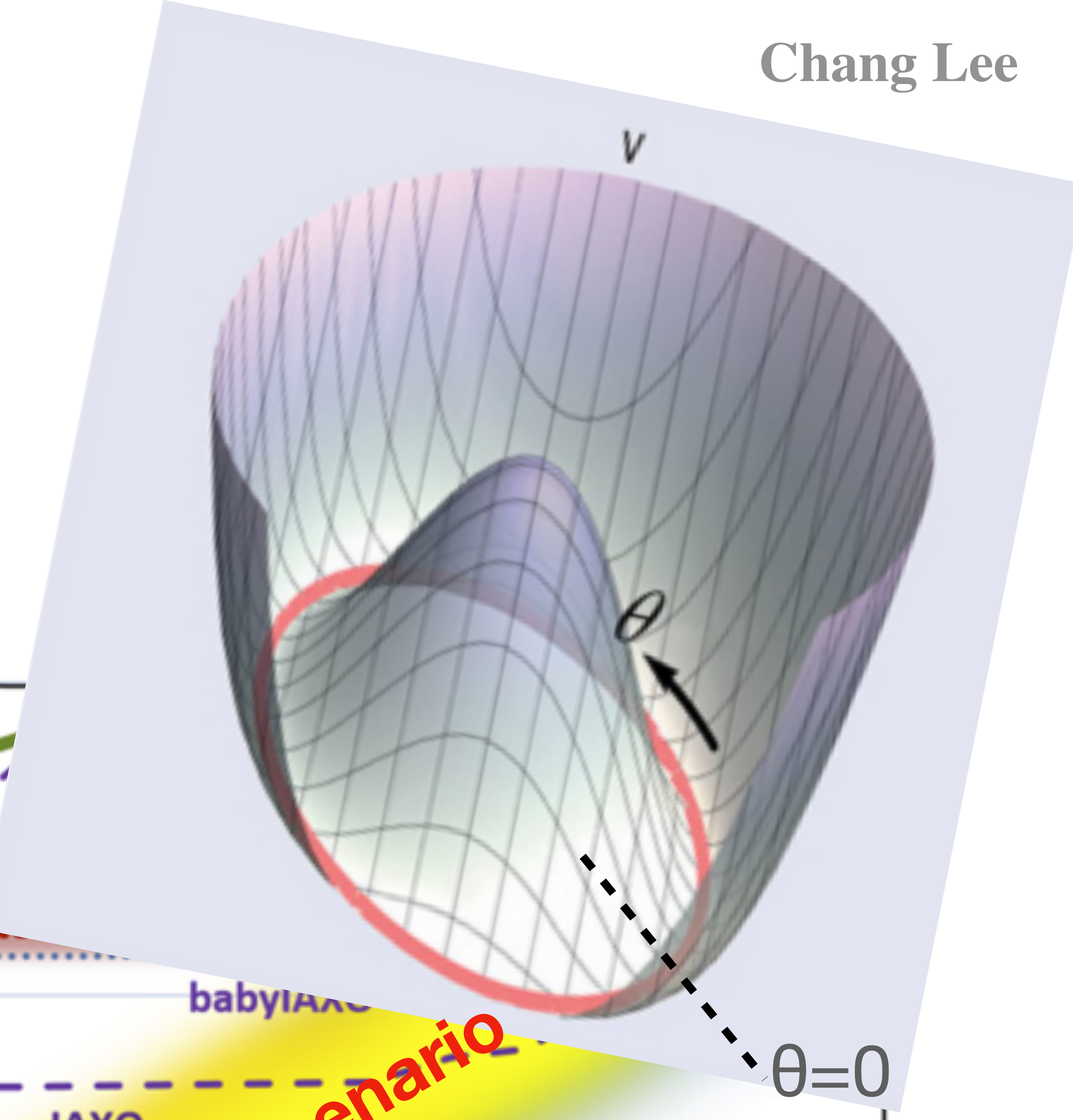
Post-inflation scenario

"Terra incognita"



http://physicstuff.com/how-do-magnets-work/





M. Kawasaki et al., Phys. Rev. D 91, 065014 (2015)

T. Hiramatsu, et al., Phys. Rev. D 85, 105020 (2012)

S. Borsanyi, et al., Nature 539, 69 (2016)

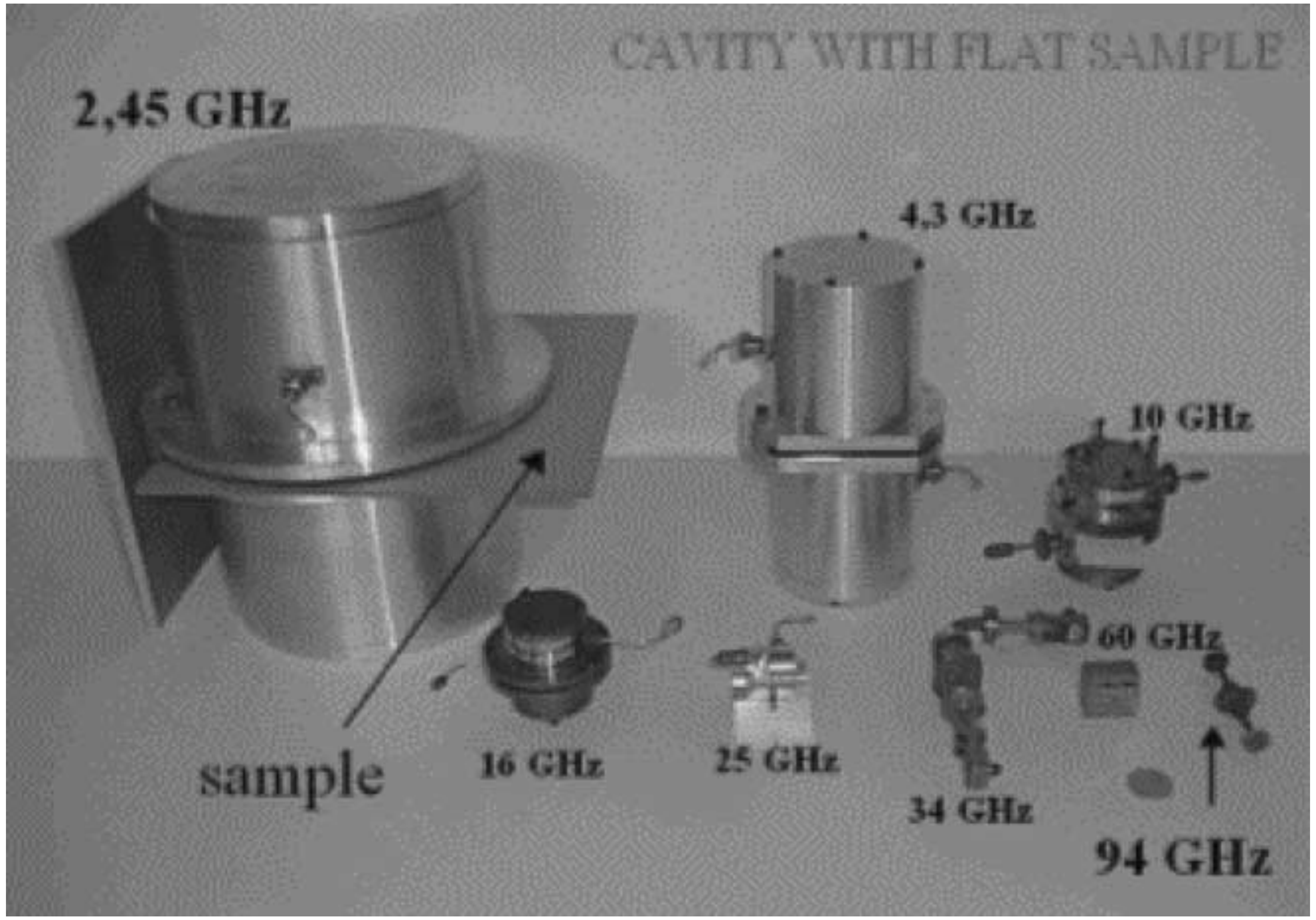
V. B. Klaer and G. D. Moore, J. Cosmol. Astropart. Phys. 2017 (11), 049

R. T. Co, et al., Phys. Rev. Lett. 124 , 251802 (2020)

High frequency challenge

How to be sensitive above 10 GHz

- $P_{\text{sig}} \propto QV$.
- Single-mode resonator shrinks rapidly at high frequency.
- Q also decreases with higher skin loss
- How to reach QCD above 10 GHz?



1 GHz cavity

image from Wikipedia: O’zapft is!

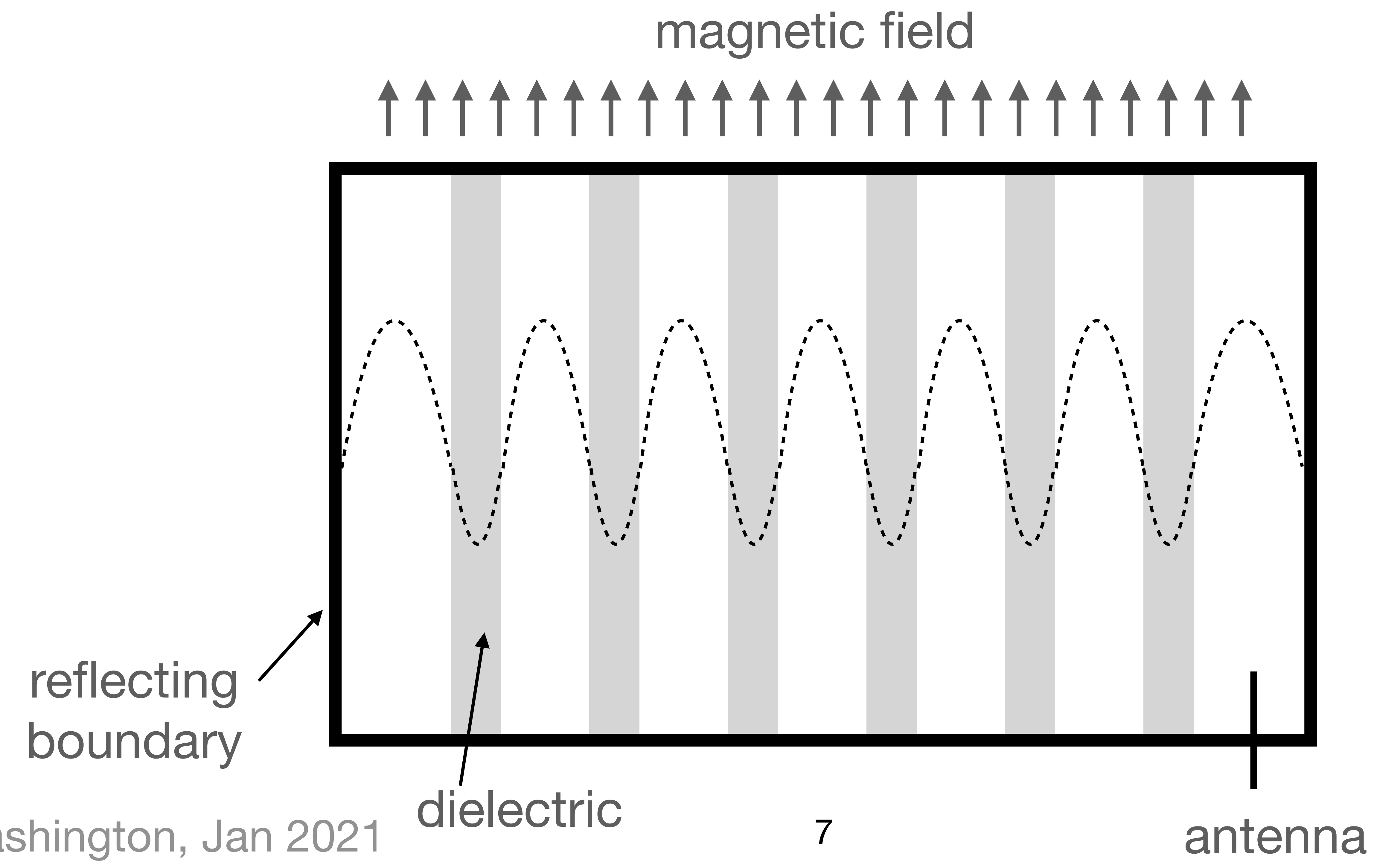
10 GHz cavity

Scale-up & challenges

https://abeautifulmess.com/how-to-build-a-champagne-tower/

Dielectric-loaded resonator

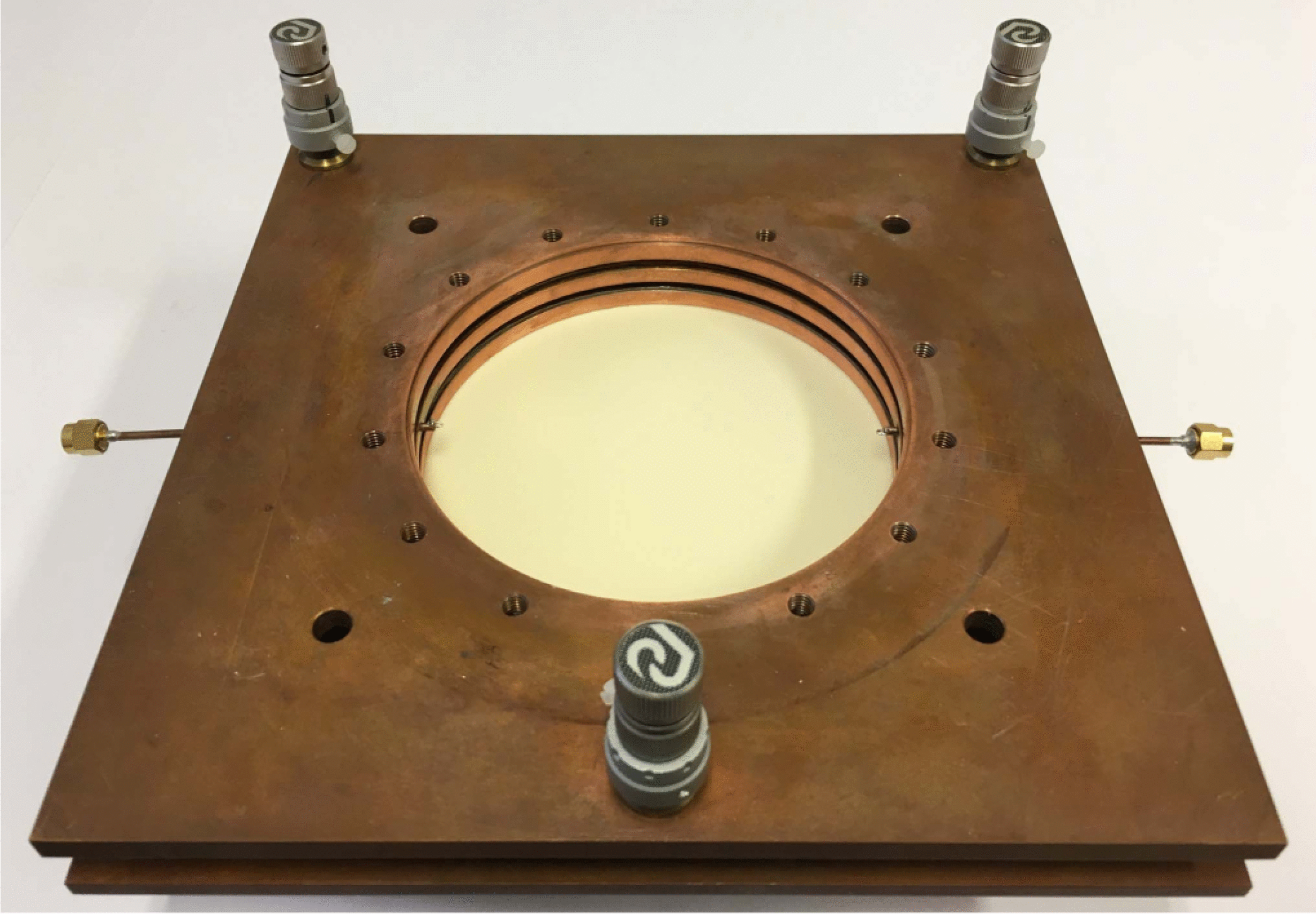
- Resonant cavity loaded with dielectric to maximize overlap with E_a.
  - Concept already used by ORPHEUS and ORGAN.



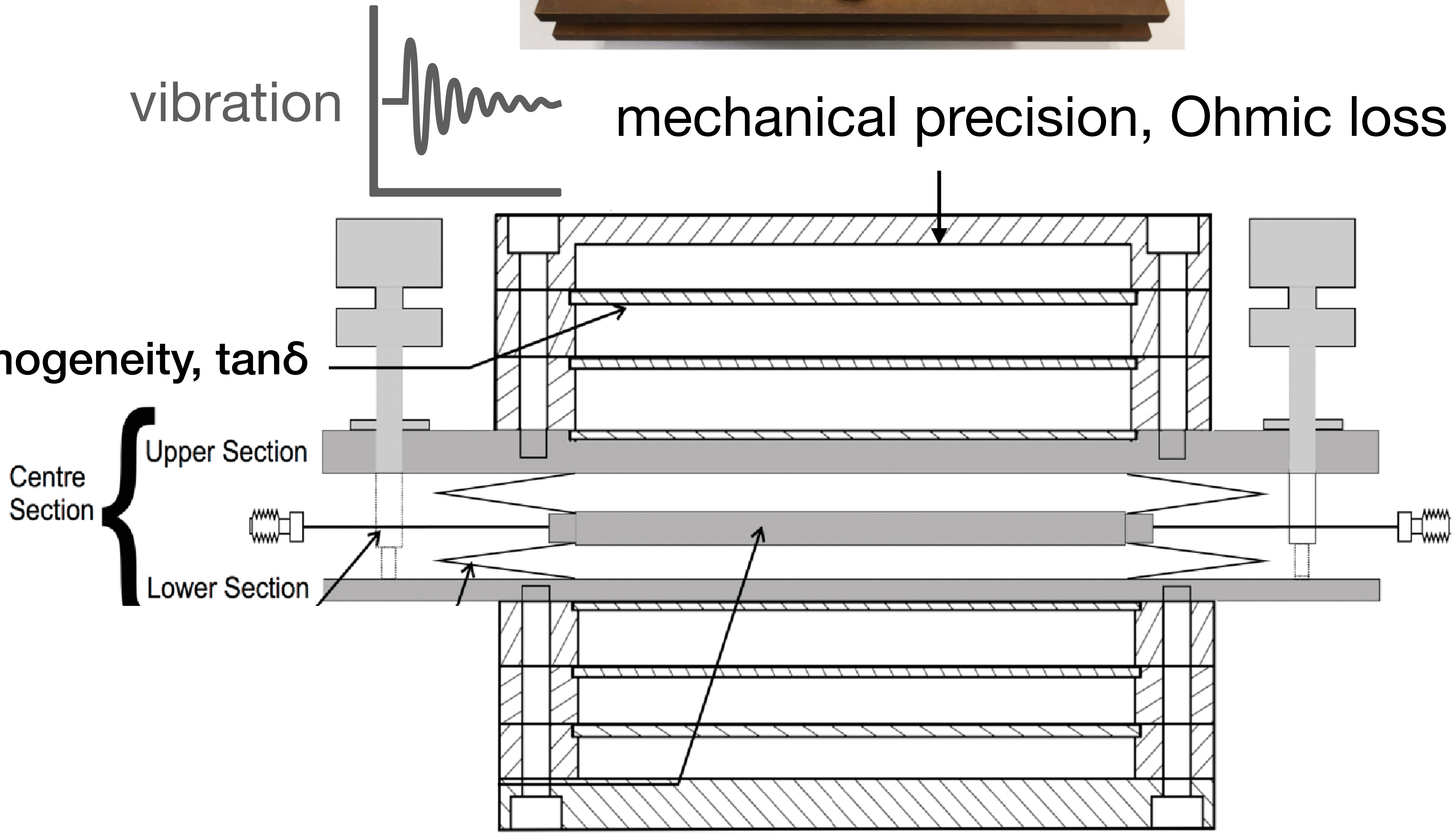
ORPHEUS: 3rd Workshop on Microwave Cavities and Detectors for Axion Research, Aug. 2018 LLNL, ORGAN: arXiv:1706.00209

Increasing Q-factor

Quality front



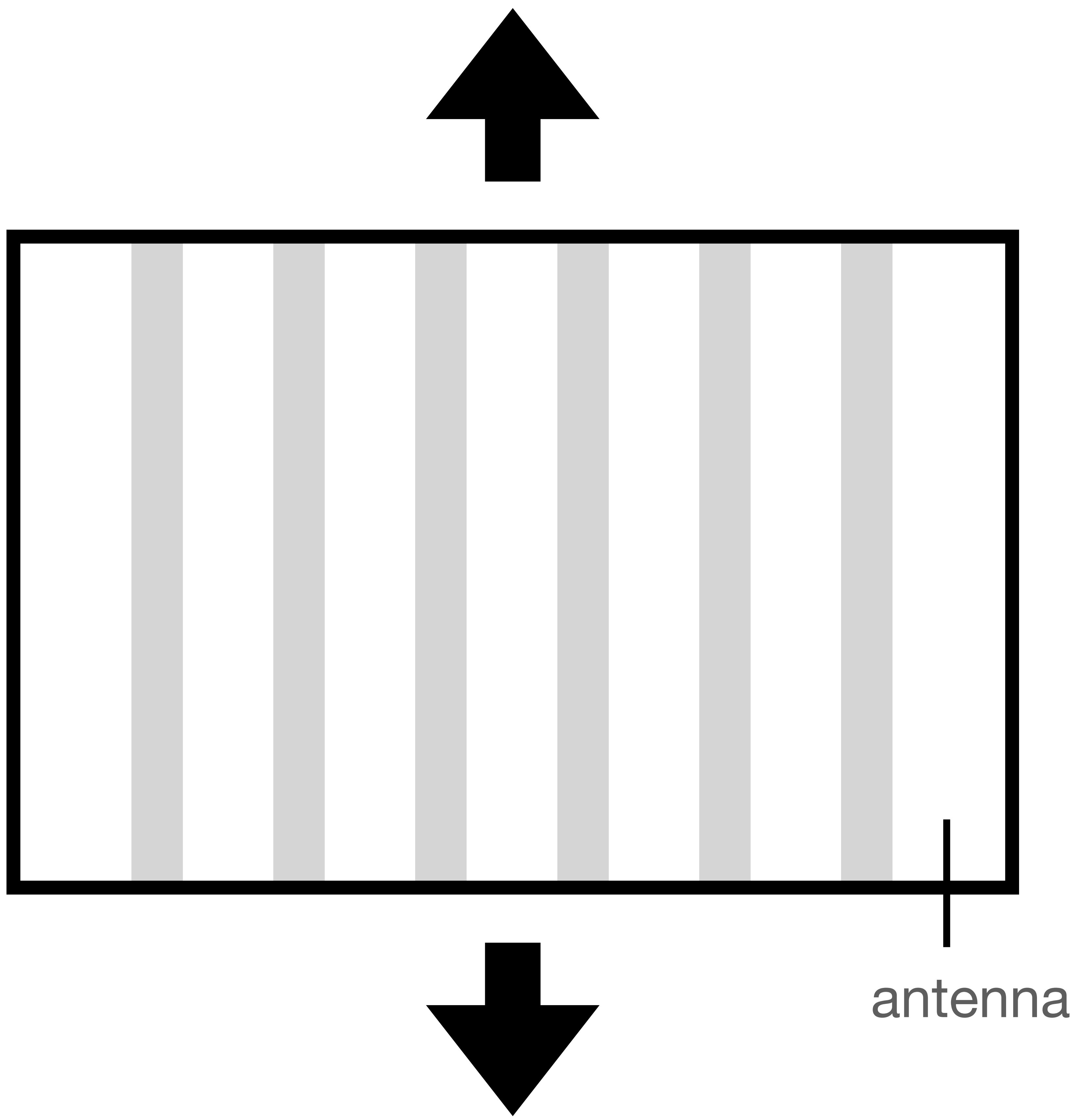
- Example: Bragg resonator: Q_0 ~100k @ TE01
- Q > 100k is challenging, especially with
  - complicated structures
  - cryogenic temp
  - Tuning



J. Bale *et al.*, *IEEE Trans. Ultrason, Ferroelectr, and Freq Control*, vol. 65, pp. 281, 2018

Increasing volume

- Large volume: large magnet & cryostat
  - Expensive, but solutions exist
- Increase the transverse dimension:
  - Over-moded system:
    Mode-crowding, mode-crossing loss, coupling ambiguity

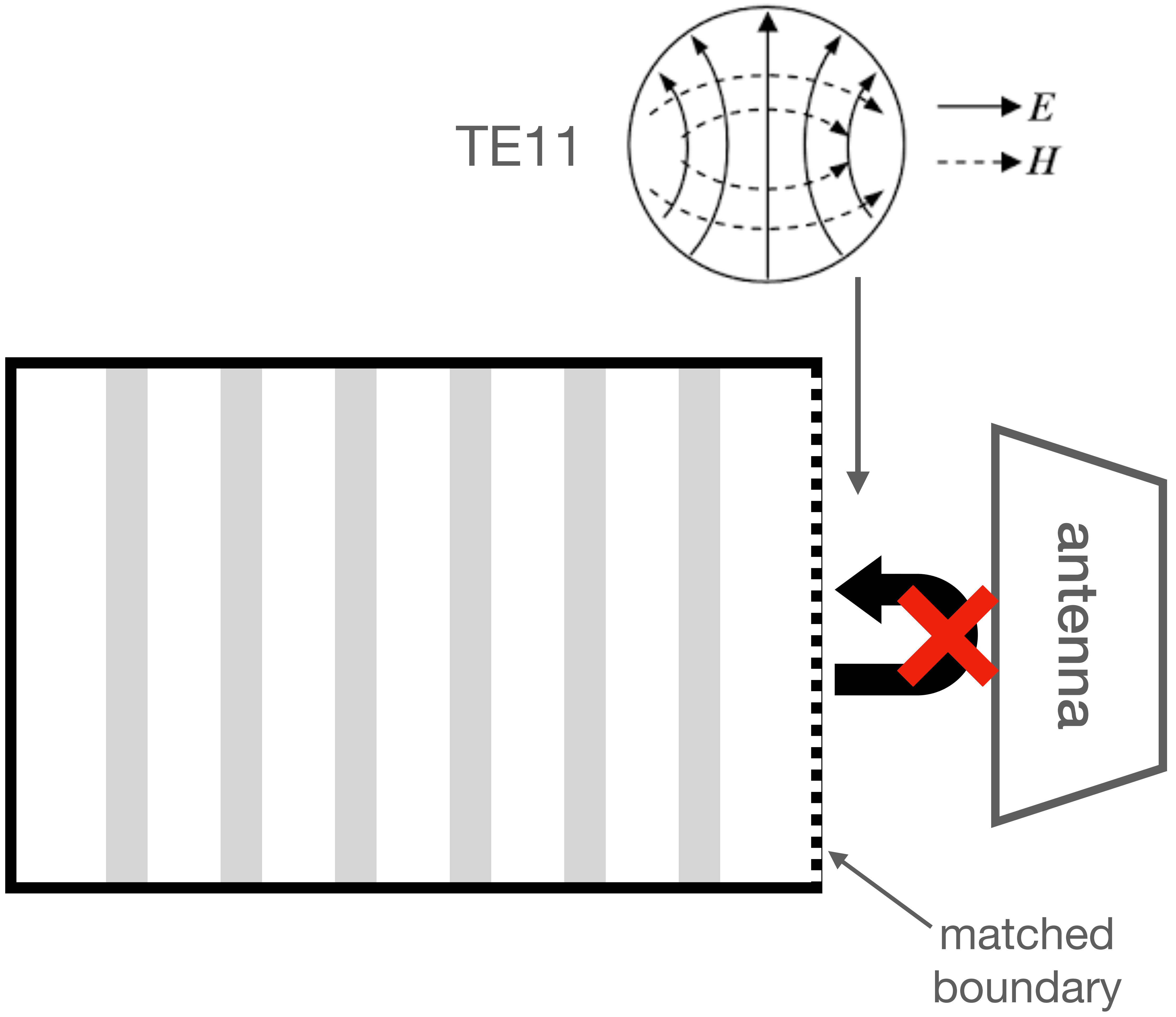


Increasing volume

longitudinal dimensions

- Matched boundary (antenna, taper):
  - No longitudinal modes
  - Detect **Traveling wave** instead of standing wave modes.
  - Lower Q (or boost factor), but Q increases with many disks
- Reflected beam ≠ axion induced beam

image Int. J. Electr. Eng. Inform. **3**, 3, (2011)



Without lateral walls

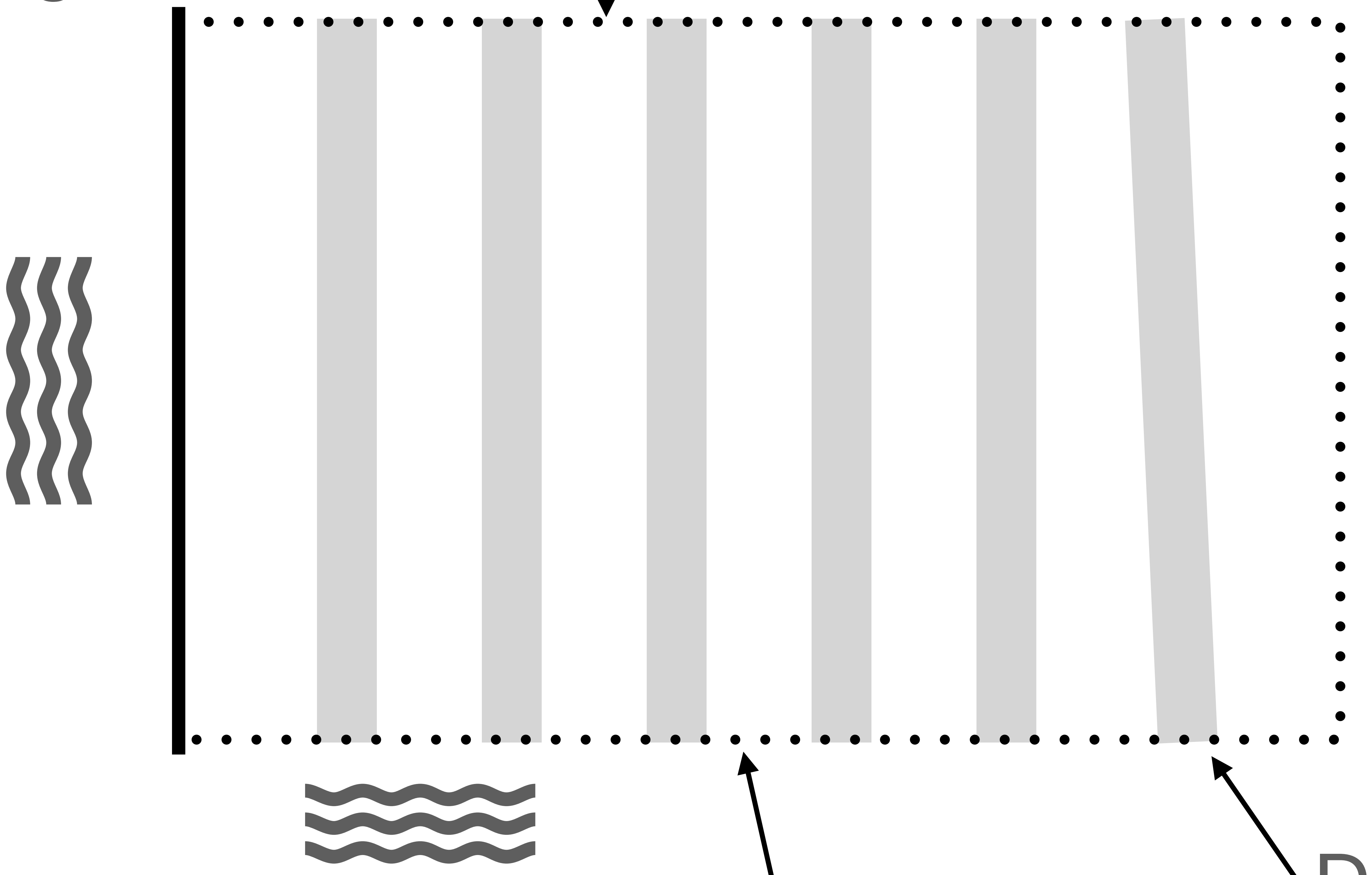
"open" system

1. less mode-crowding

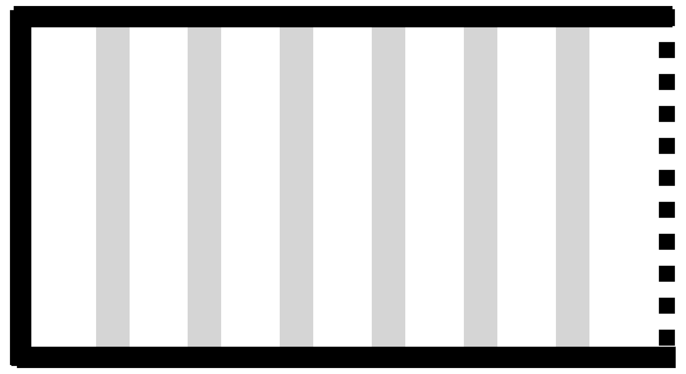
2. no Ohmic loss

3. diffraction loss → 0 for $R \gg \lambda$ or curved mirror

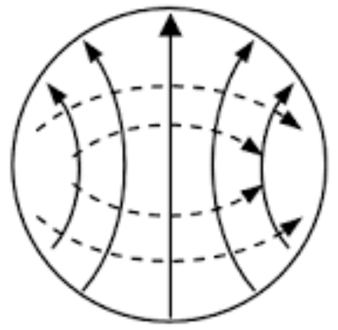
A. radiation loss via surface current



approx. gaussian beam



"closed" system



TE11

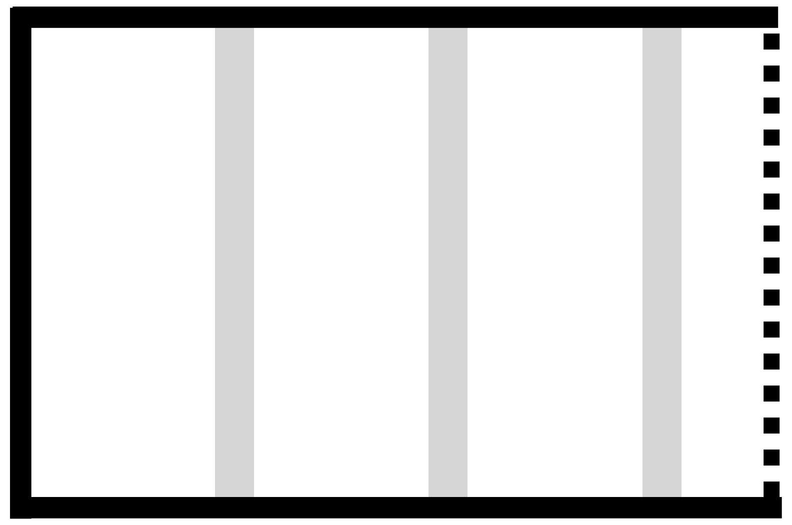
B. radiation loss on sides

C. Z, k_{trans}? ex) reflection off cryostat

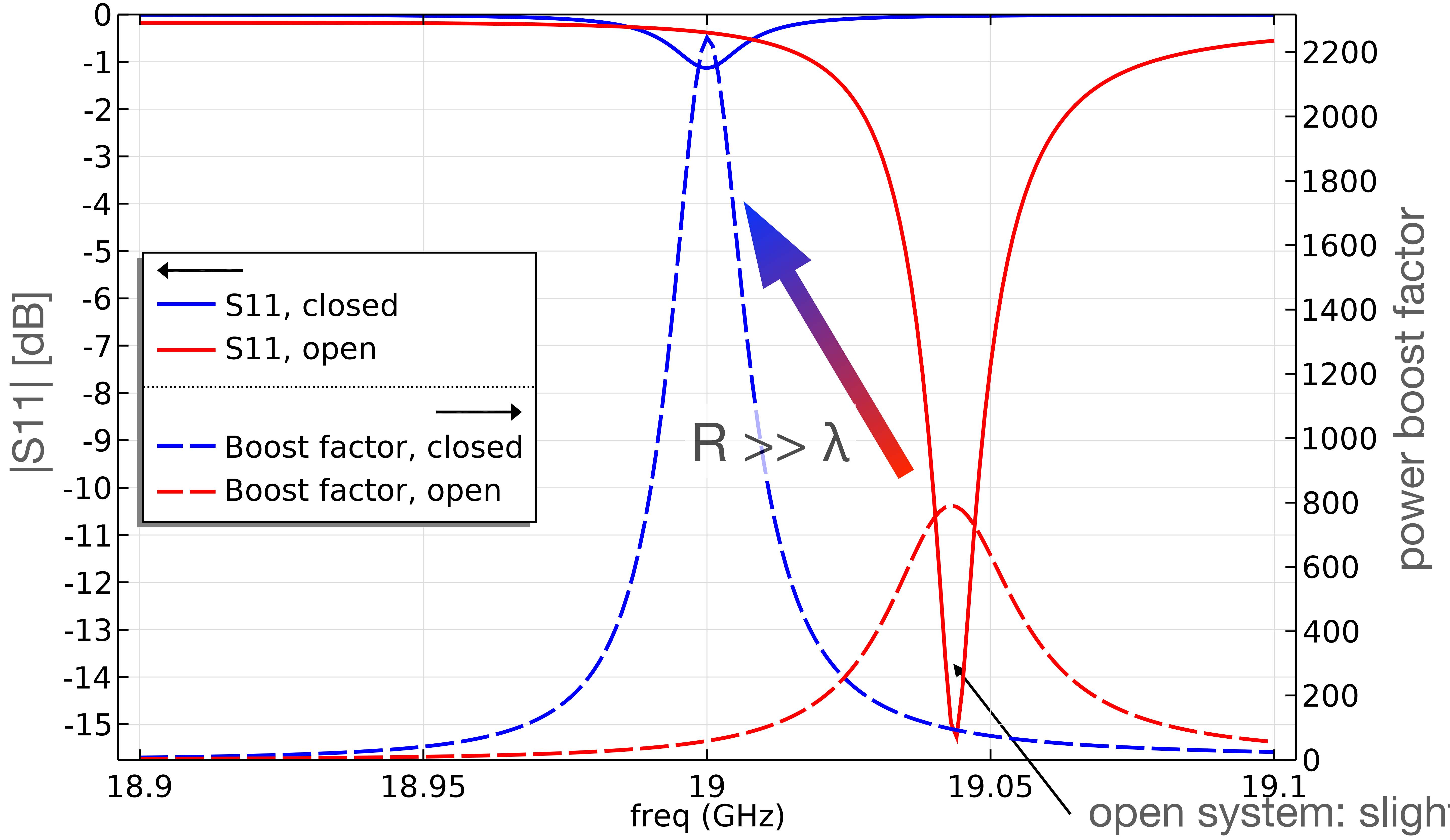
D. misalignment

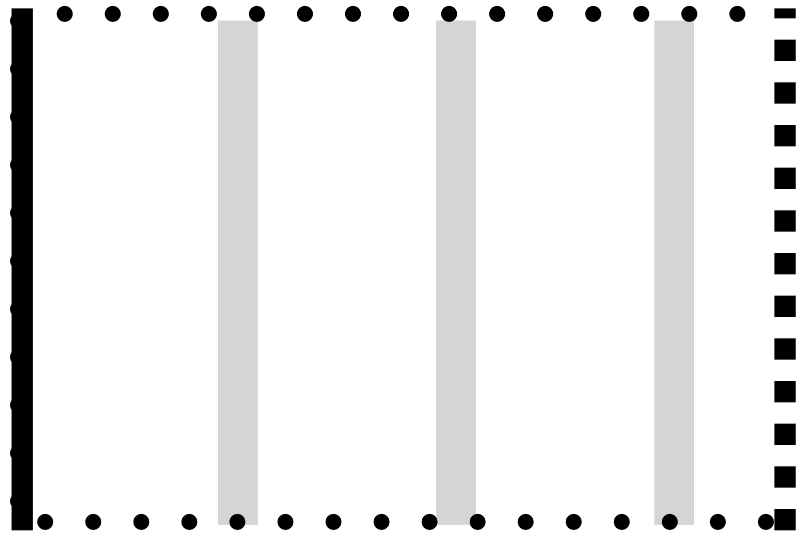
Open vs. closed systems

- Example: simulation of 3 x ϕ100mm sapphire disks tuned @ 19 GHz.



closed

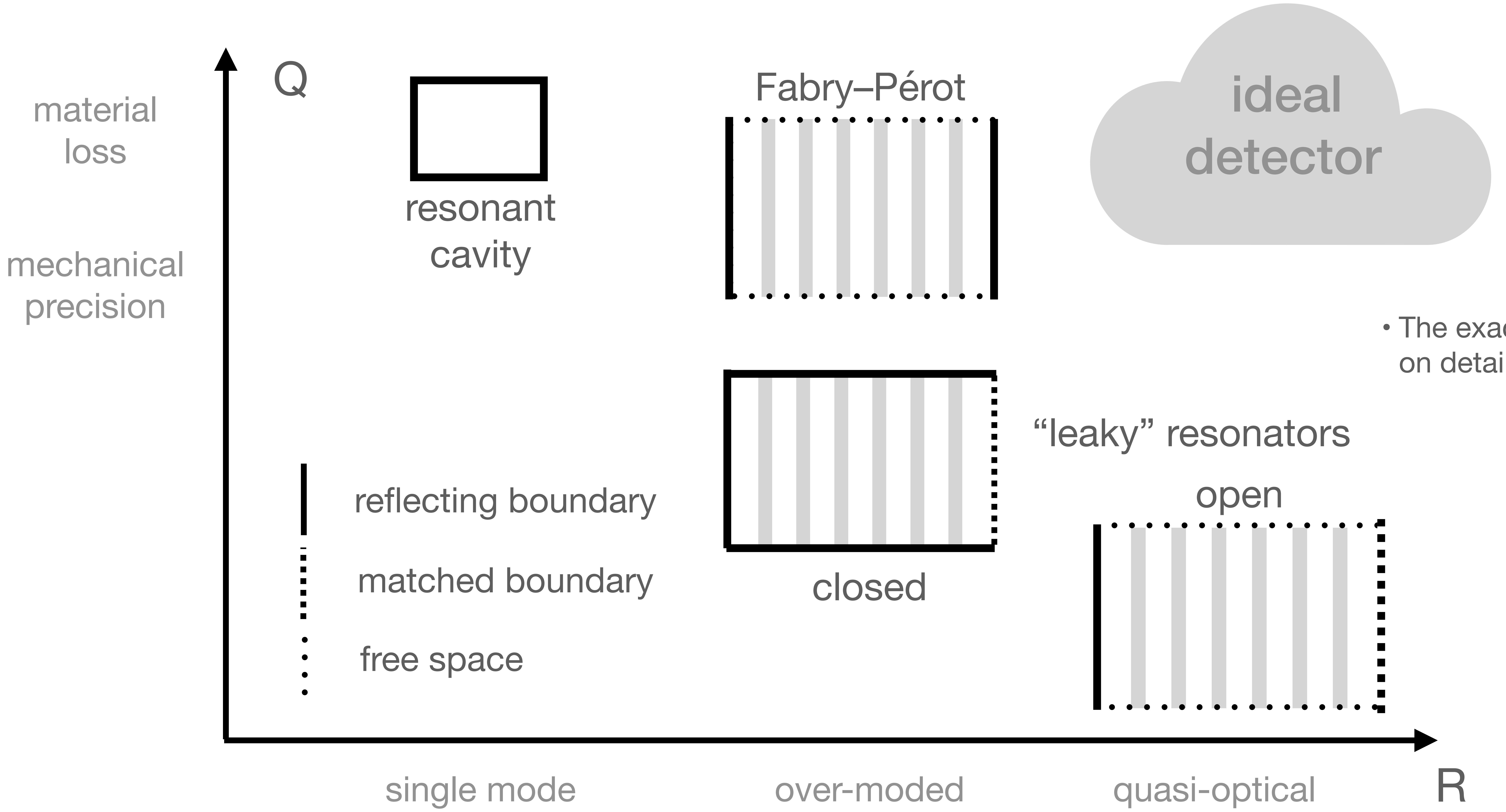




open

open system: slightly higher transverse momentum

Scale-up challenges overview



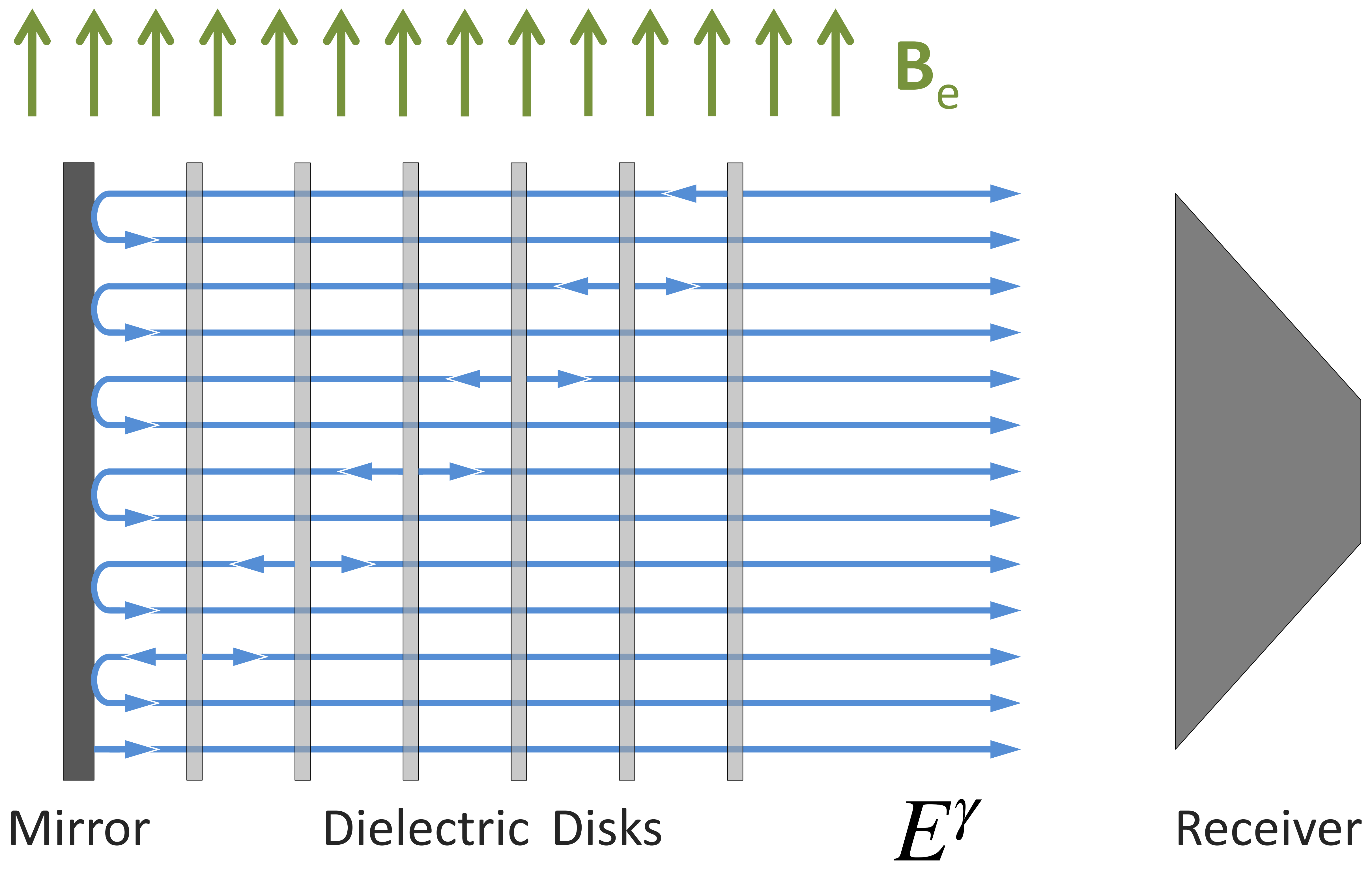
- The exact location depends on details of the systems

Dielectric haloscope

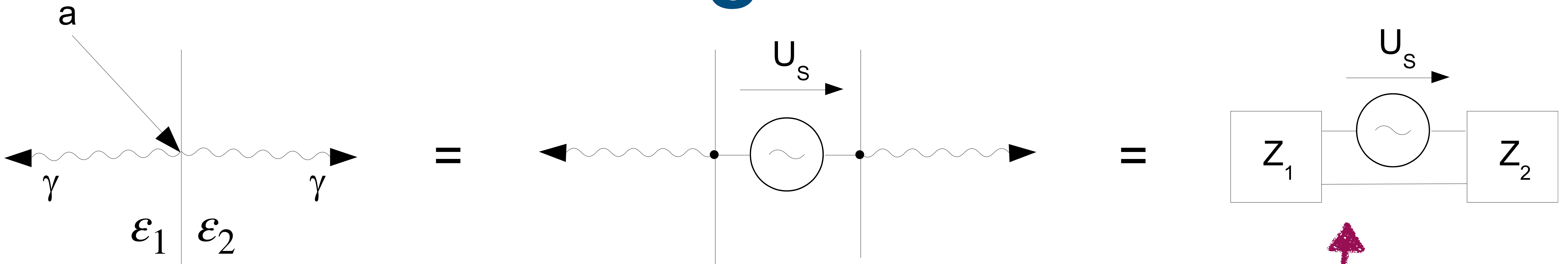
Dielectric haloscope

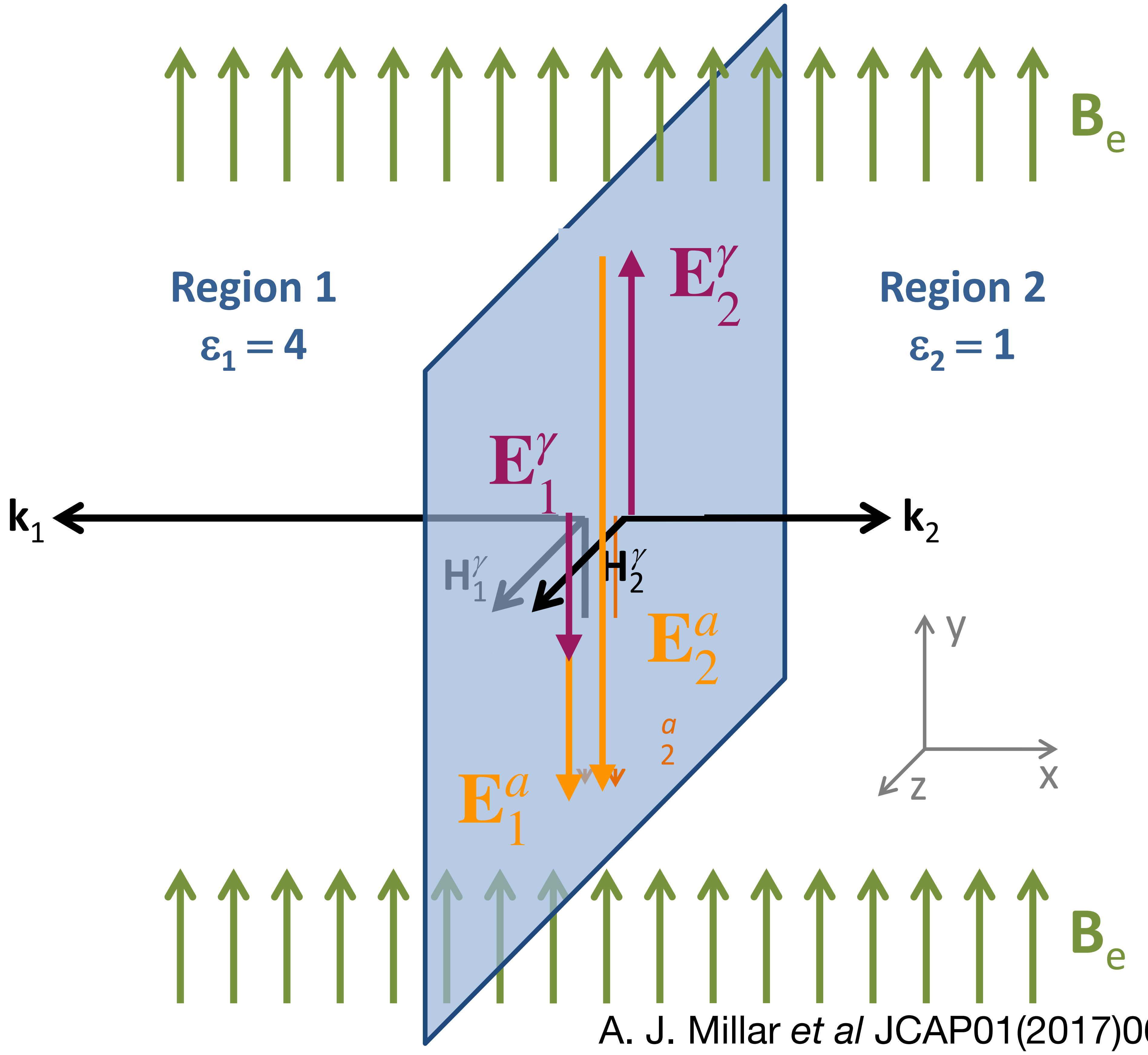
A. Caldwell, et al., *PRL*, *118*(9), 091801.

- Large, over-moded, **leaky resonator**
  - **Matched boundary** on one end. Open / closed boundary on sides
- Boost factor: $\beta = \dfrac{E^\gamma}{E_0}$.
  - $P_{\text{sig}} \propto \beta^2 A$ (equivalent to *QV* for cavities).



Axion-induced traveling wave





A. J. Millar *et al* JCAP01(2017)061

- $$E^{\alpha}_{1,2} = -\frac{g_{a\gamma} B_e}{\varepsilon_{1,2}} a$$
- $$E_1^\gamma = \frac{Z_1}{Z_1 + Z_2}\left(E_2^\alpha - E_1^\alpha\right)$$ (traveling wave)

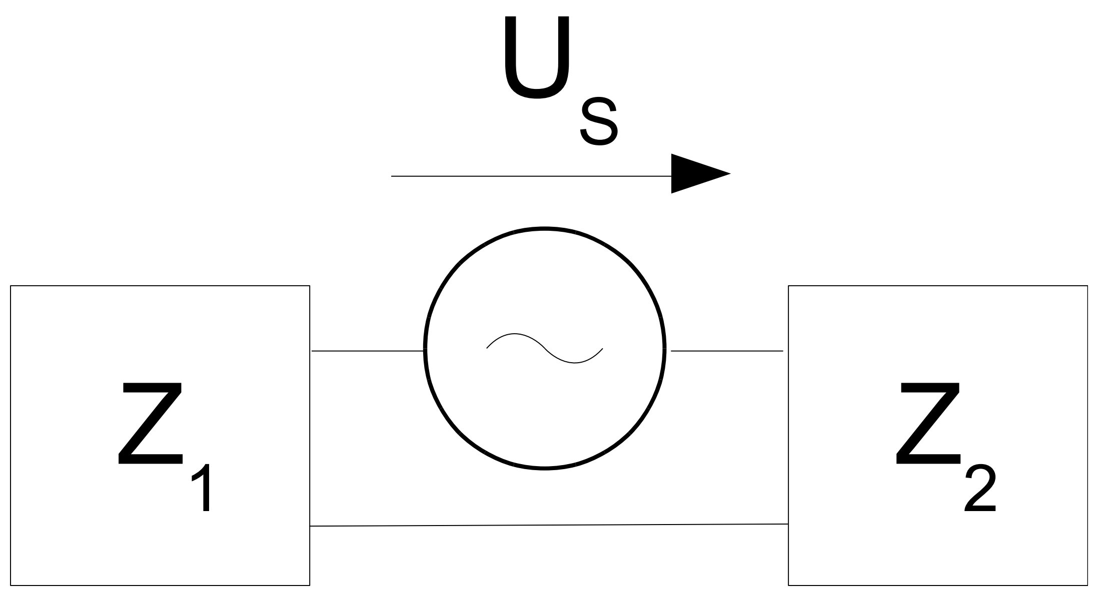
voltage divider!

characteristic impedance

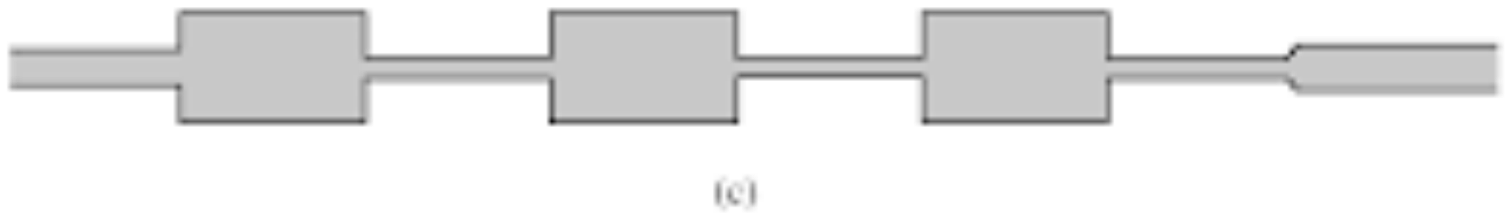
- Modify Z to increase the radiation?

Disk spacing

Resonant case



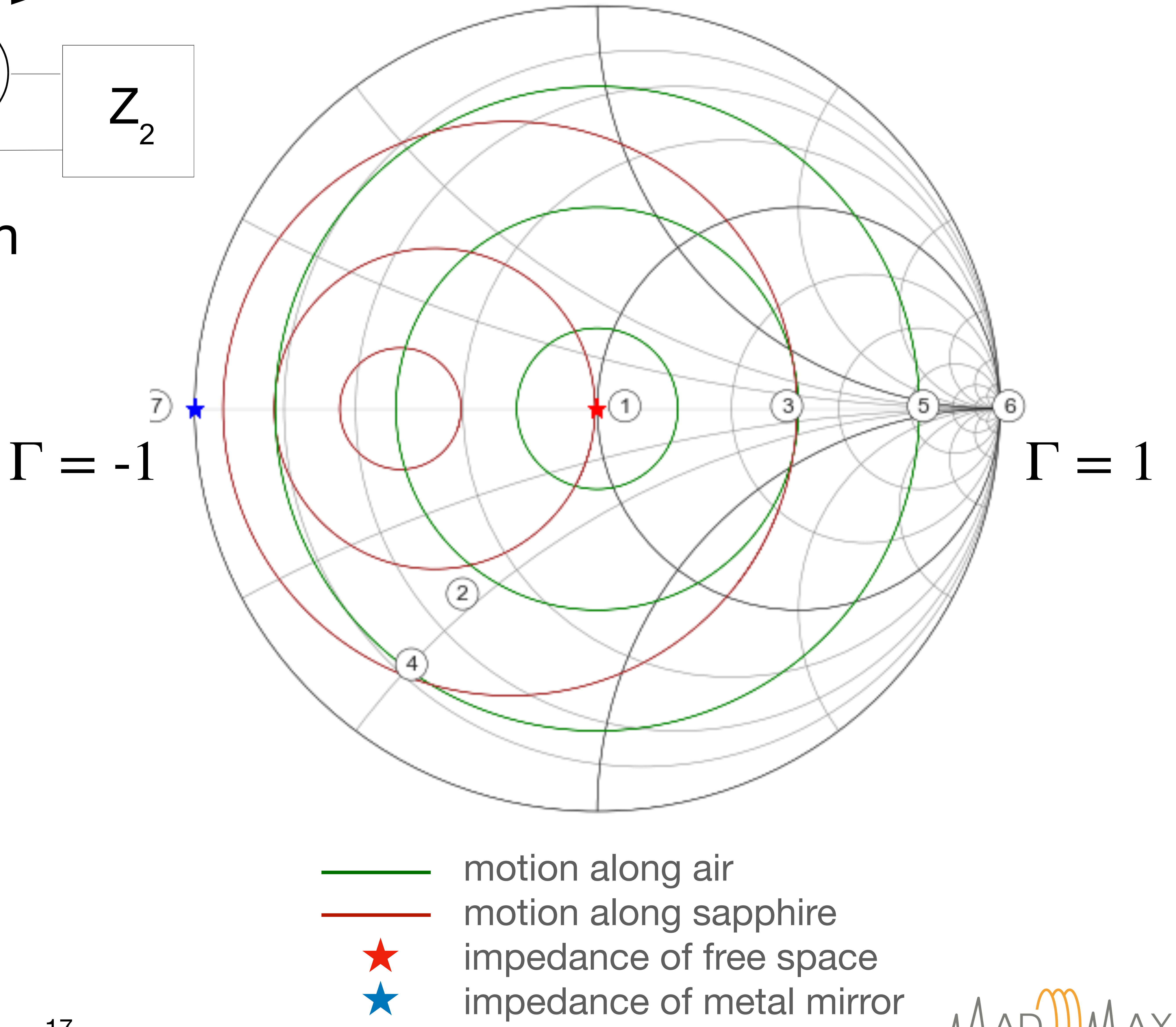
- Maximize the axion-induced radiation from the metal surface
  - Impedance transform: $Z_0 \to 0$.
  - A special case of stepped-impedance filters, or generalized Bragg resonator



- Limitation: not considering emission from most disks, disk # < ~5

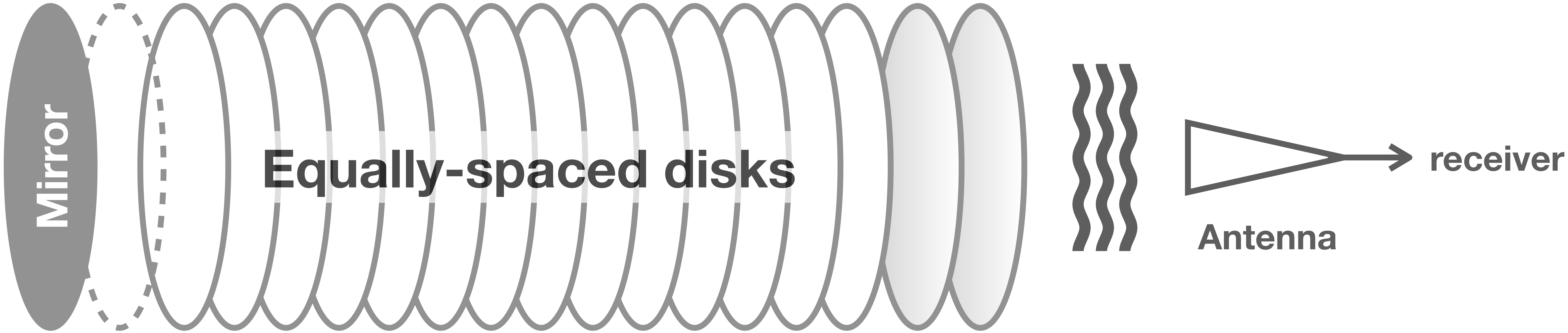
"Smith Chart Calculations", The ARRL Antenna Book 21st ed.

Normalized to $Z_0 = 377\Omega$



Disk spacing

"Waveguide structure"

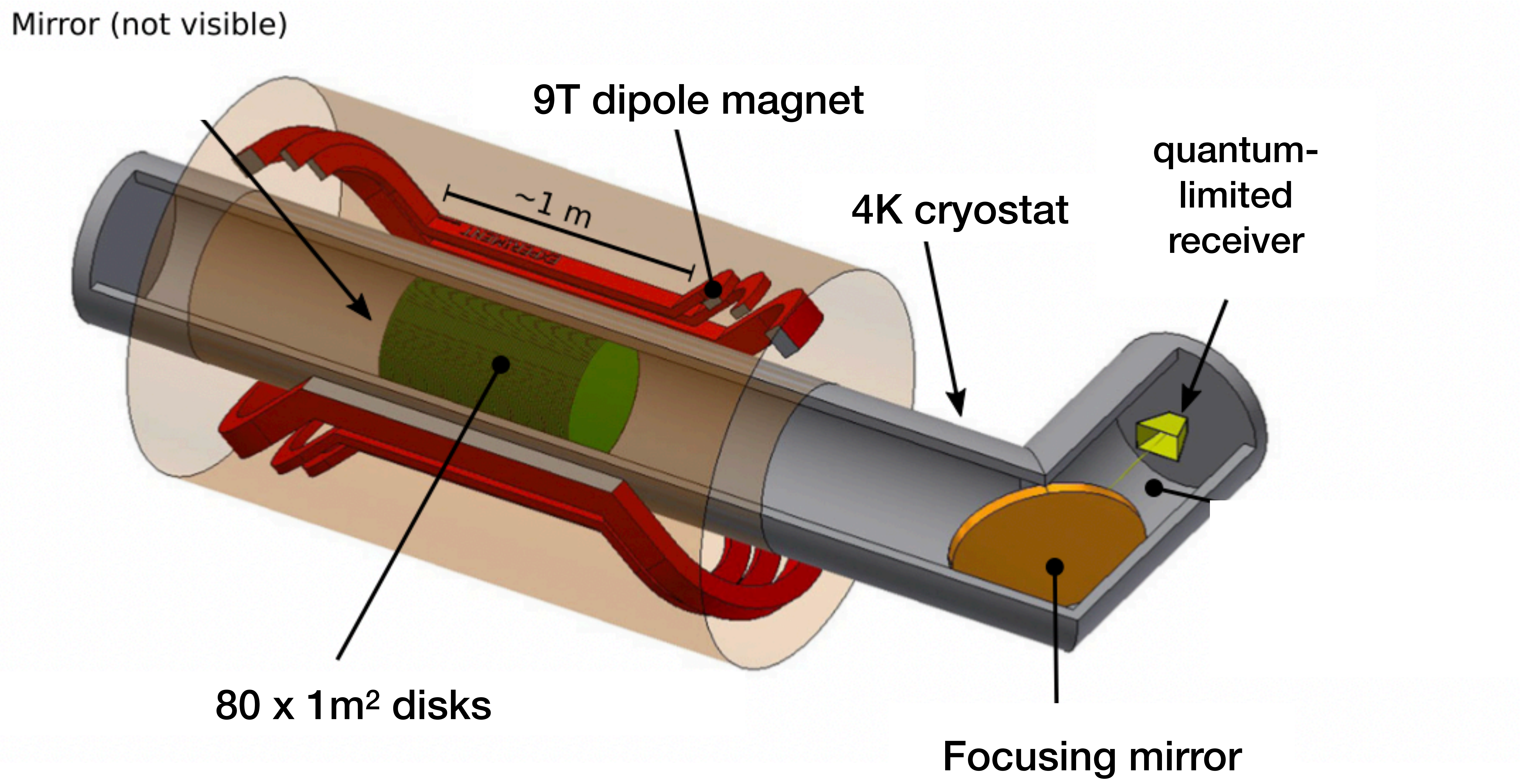


	Mirror matching	equally-spaced disks	free space matching
impedance	0 to Z_c	characteristic impedance (Z_c)	Z_c to Z_0
air gap length	$\sim \lambda/4^*$	from **Bloch impedance**	impedance transform
# of disks	0~1	>2	1~2

✳ Distance to the first unit cell, not disk.

Ultimate dielectric haloscope

Sensitive to post-inflationary QCD-axion

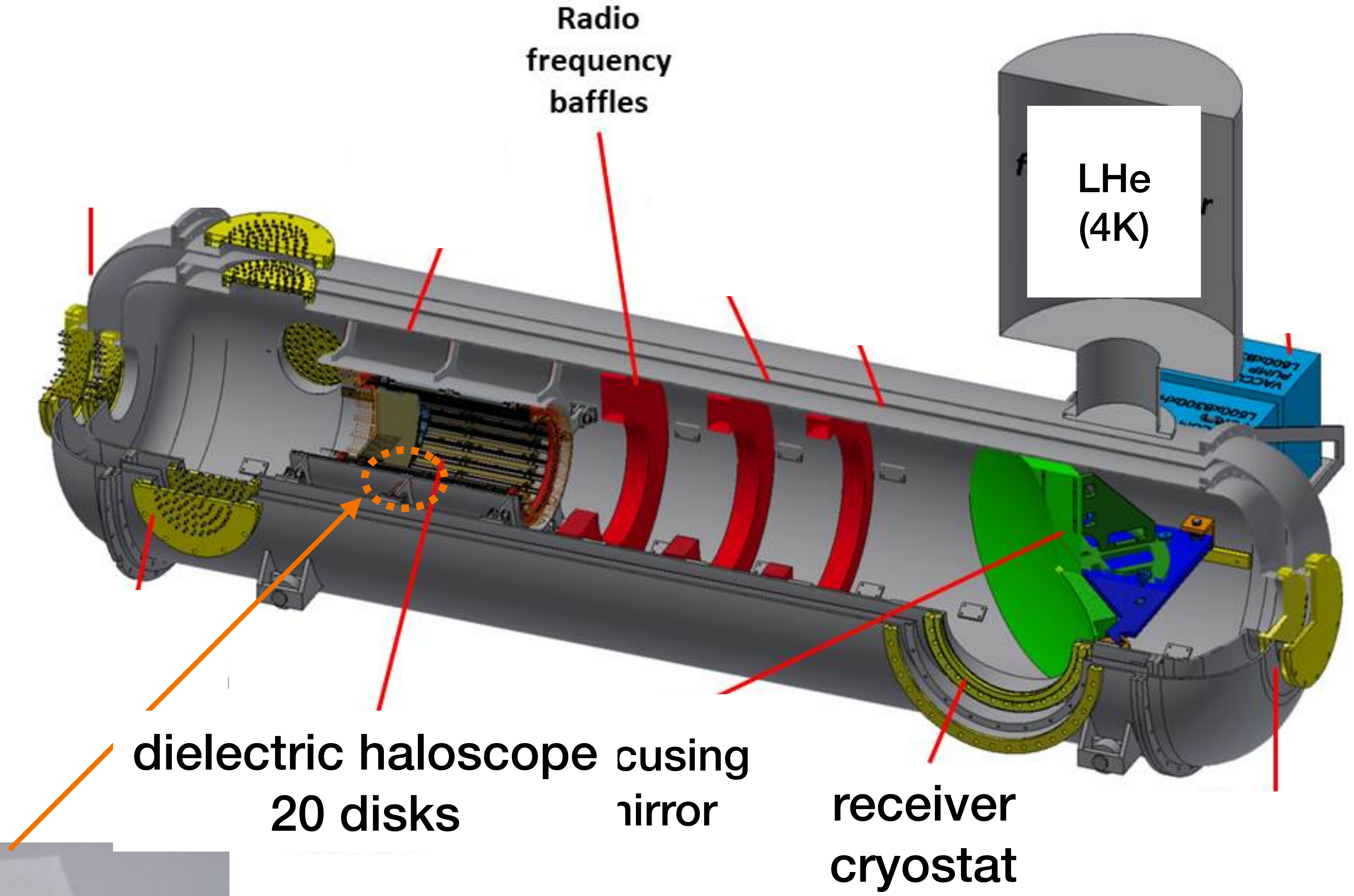


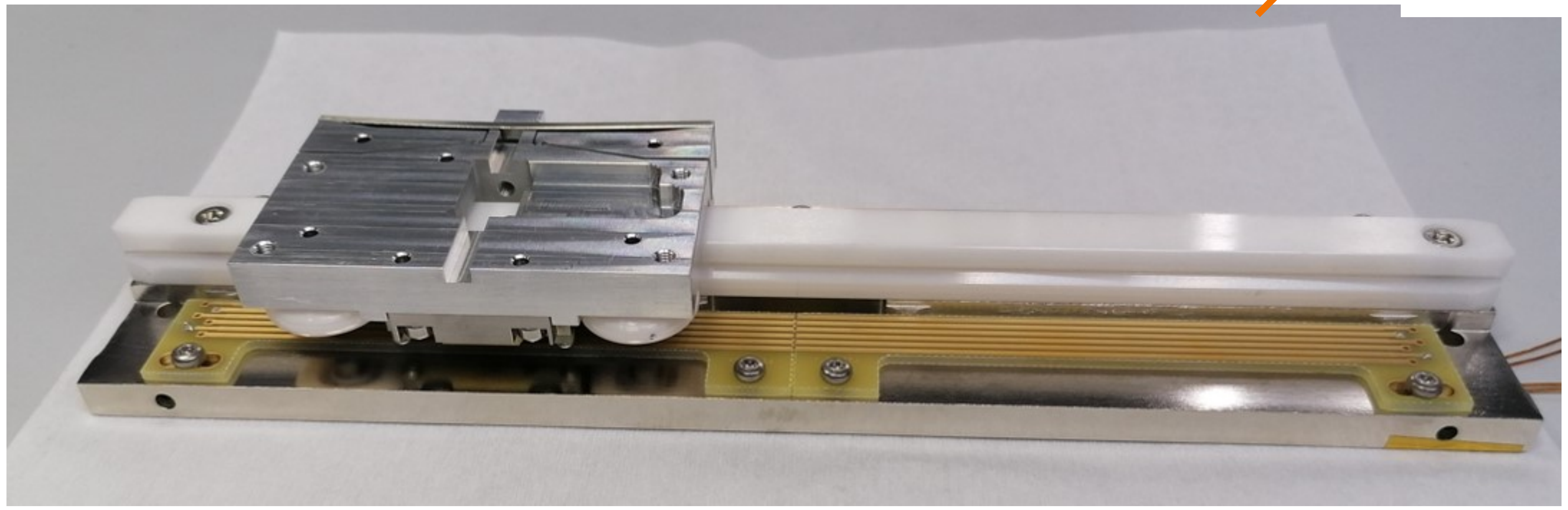
MADMAX collaboration

Max-Planck-Institut für Radioastronomie

Prototype

- R&D platform
- Cryostat design fixed
- ALPs / HP search





Cryogenic piezo positioner &
laser interferometer assembly

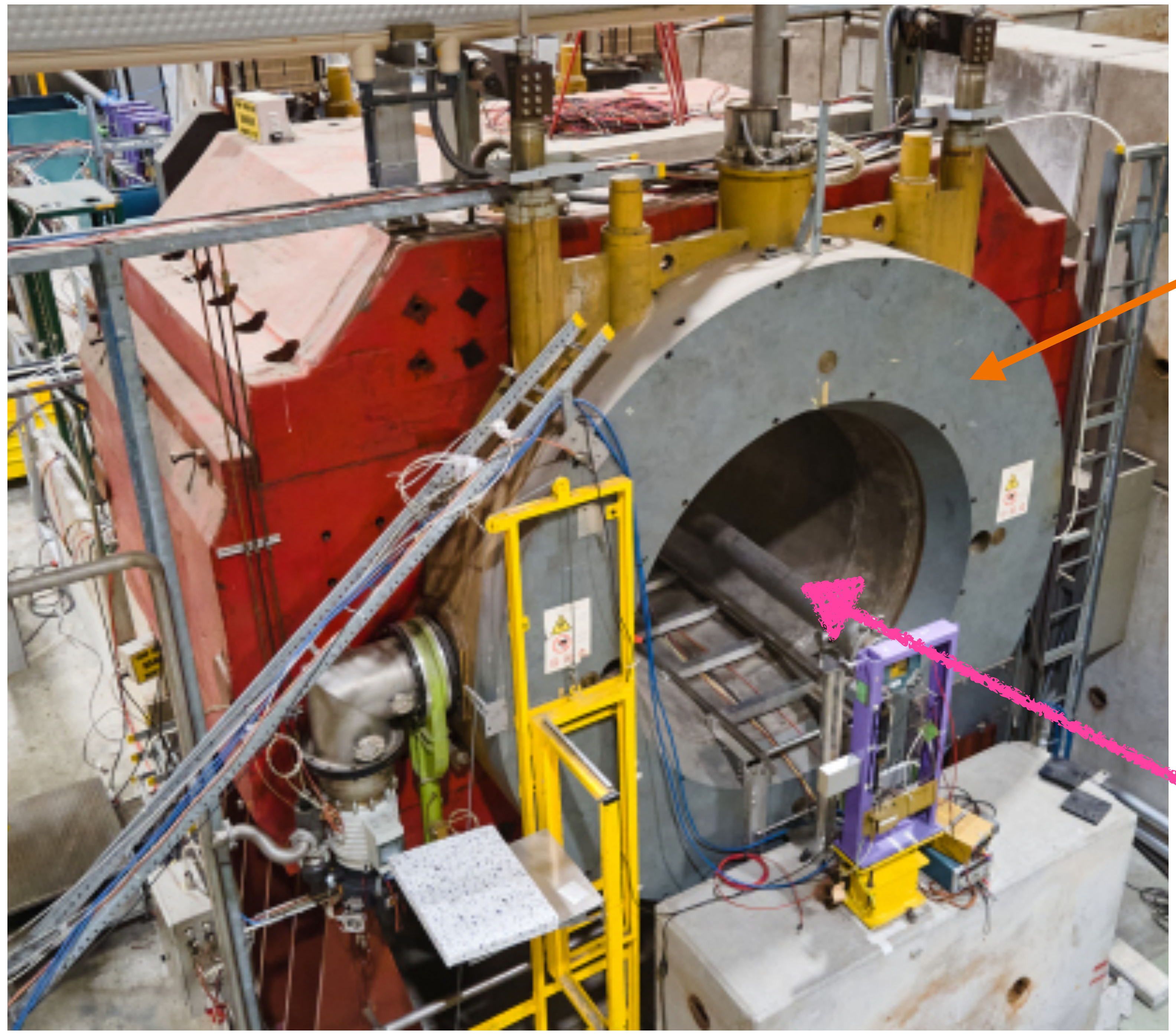
MADMAX and CERN's Morpurgo magnet

A new collaboration, MADMAX, will seize the chance to use a CERN magnet named Morpurgo to test their dark-matter prototype

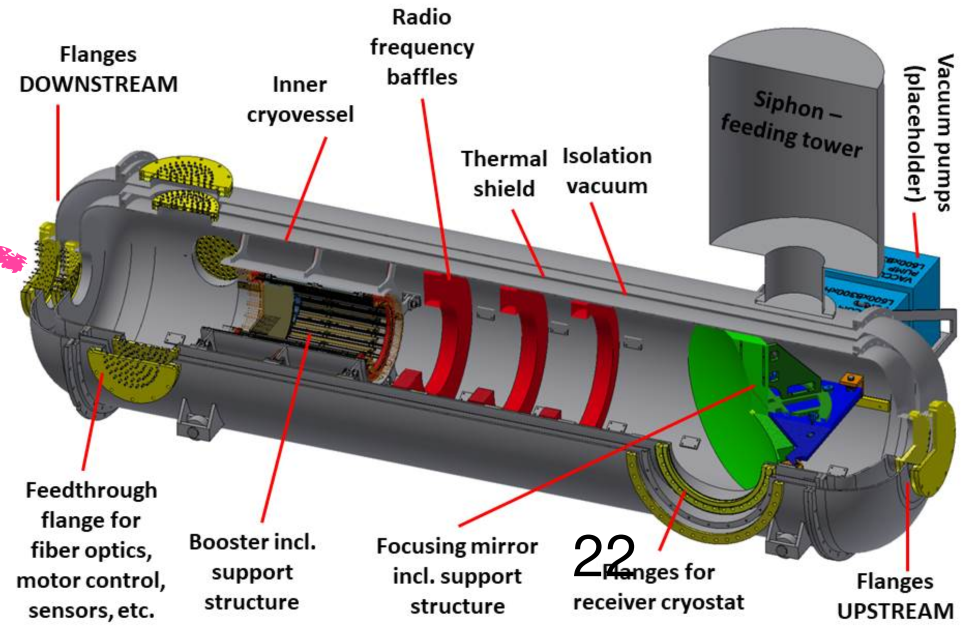
CERN Bulletin
https://home.cern/news/news/experiments/madmax-and-cerns-morpurgo-magnet

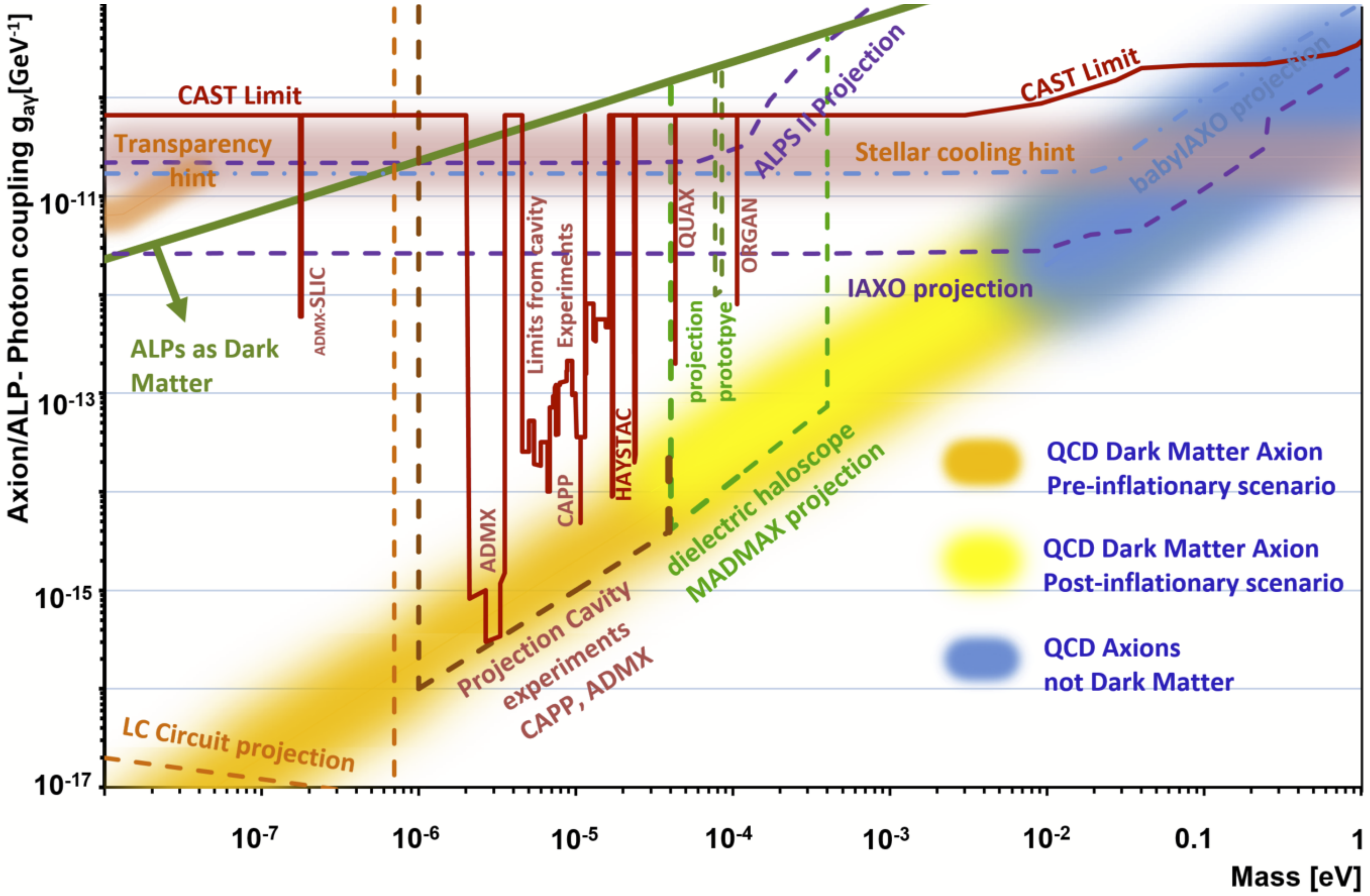
10 NOVEMBER, 2020 | By Thomas Hortala

- Test of the components in B-field during the SPSS shut down



1.6 T dipole

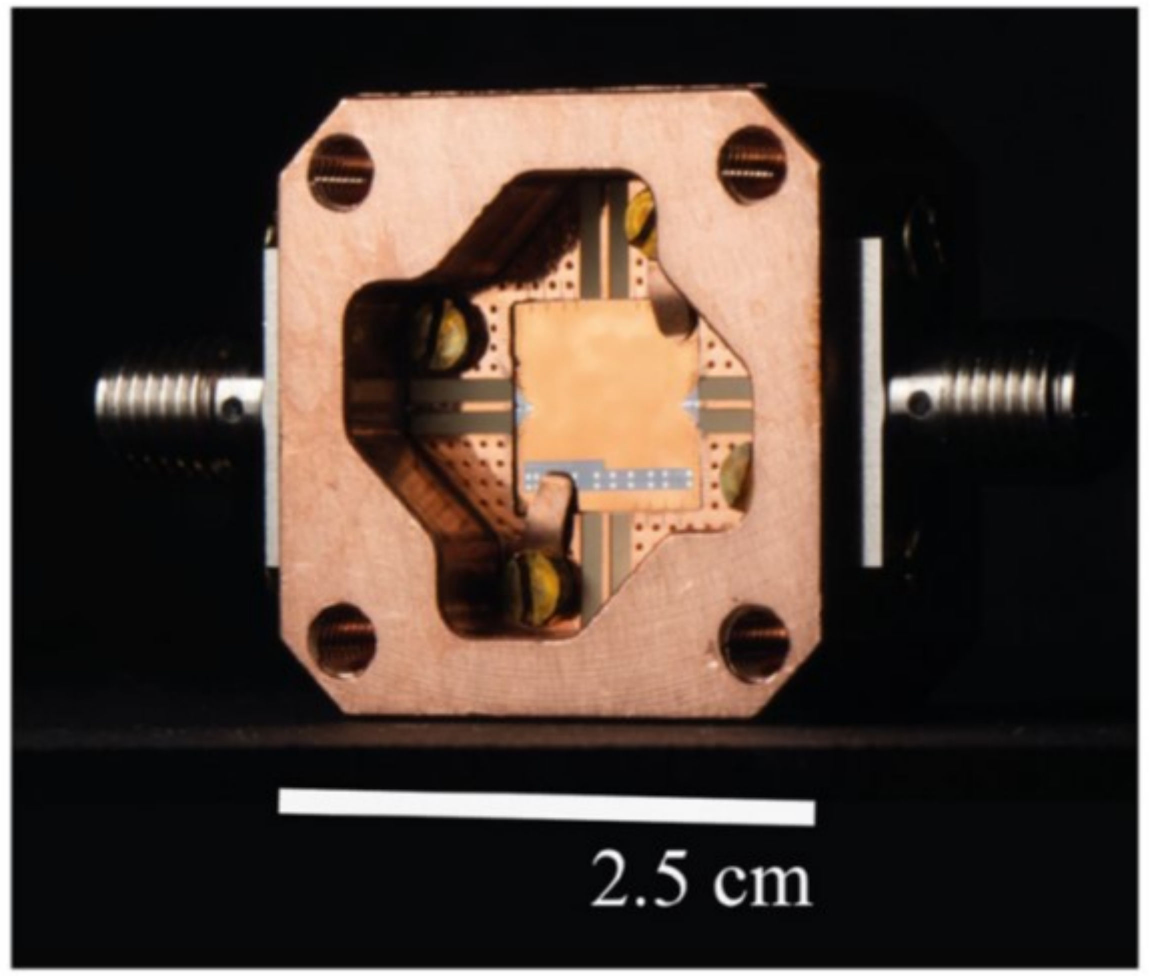


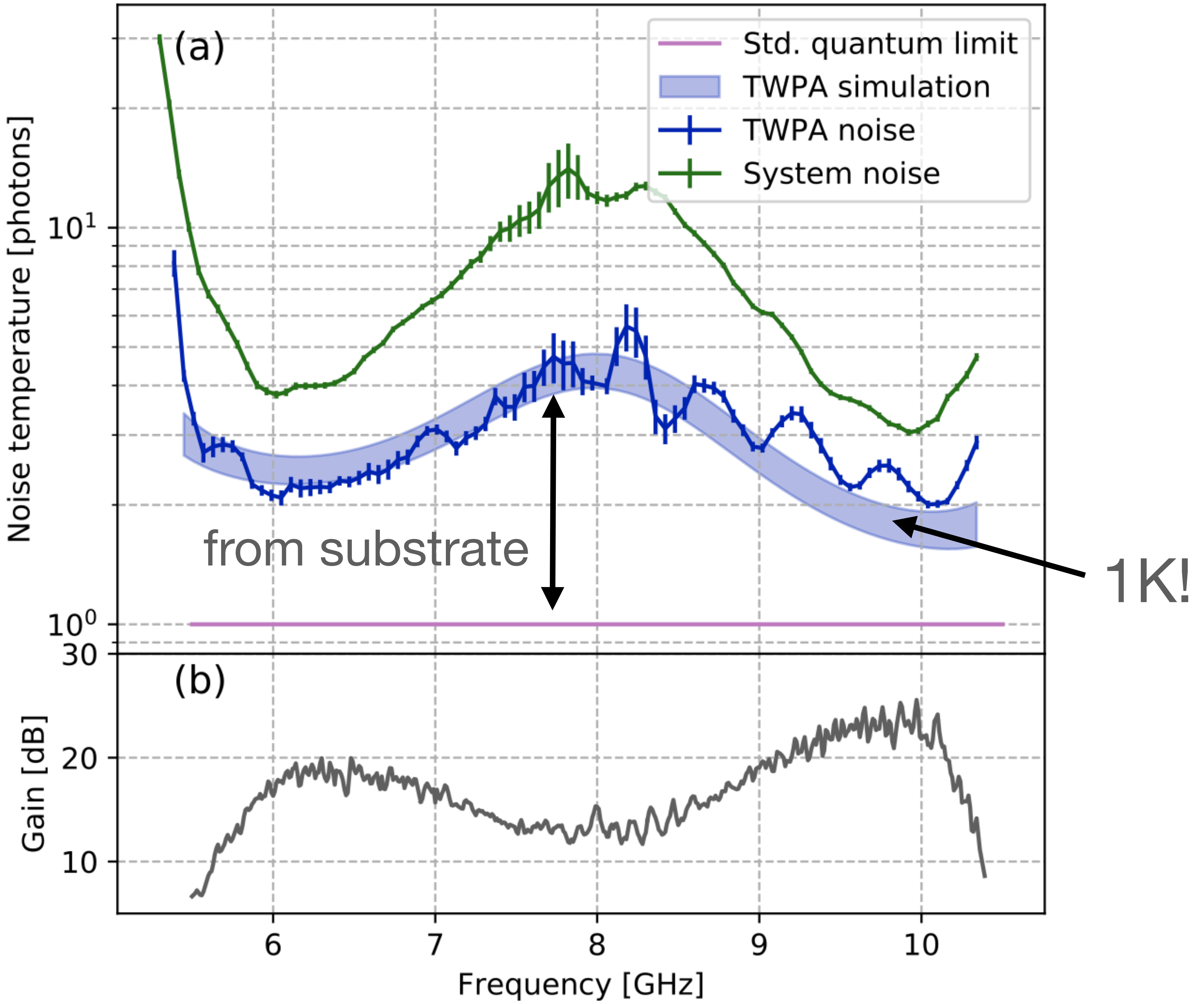


Quantum-limited amplifier

Traveling wave parametric amplifier (TWPA)

- **First 10 GHz TWPA** produced.
  PRX **10**, 021021
- 1K noise temp, 20 dB gain @ 10 GHz.
- Future development to 30 GHz.





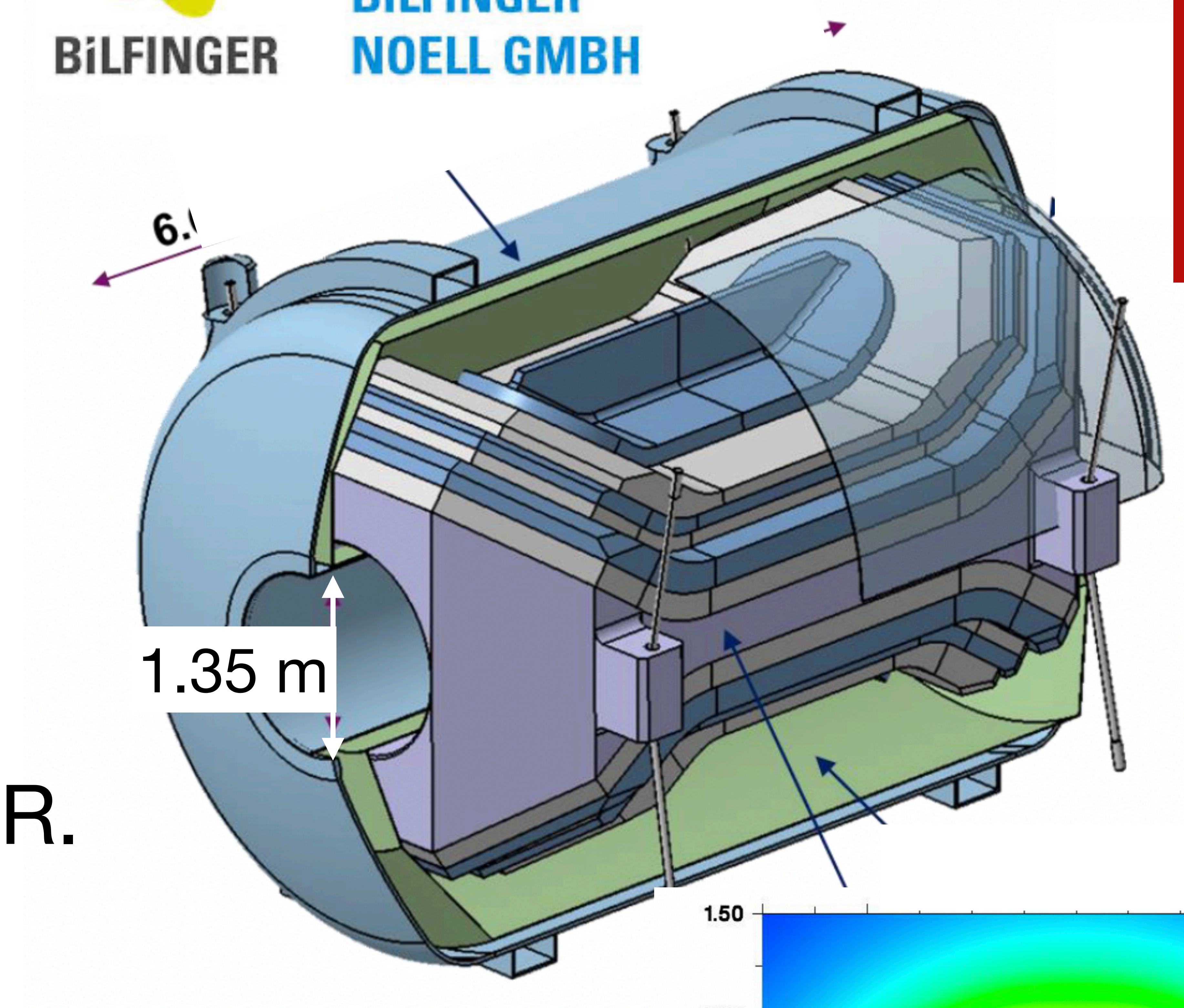
Reversed Kerr TWPA arXiv:2101.05815

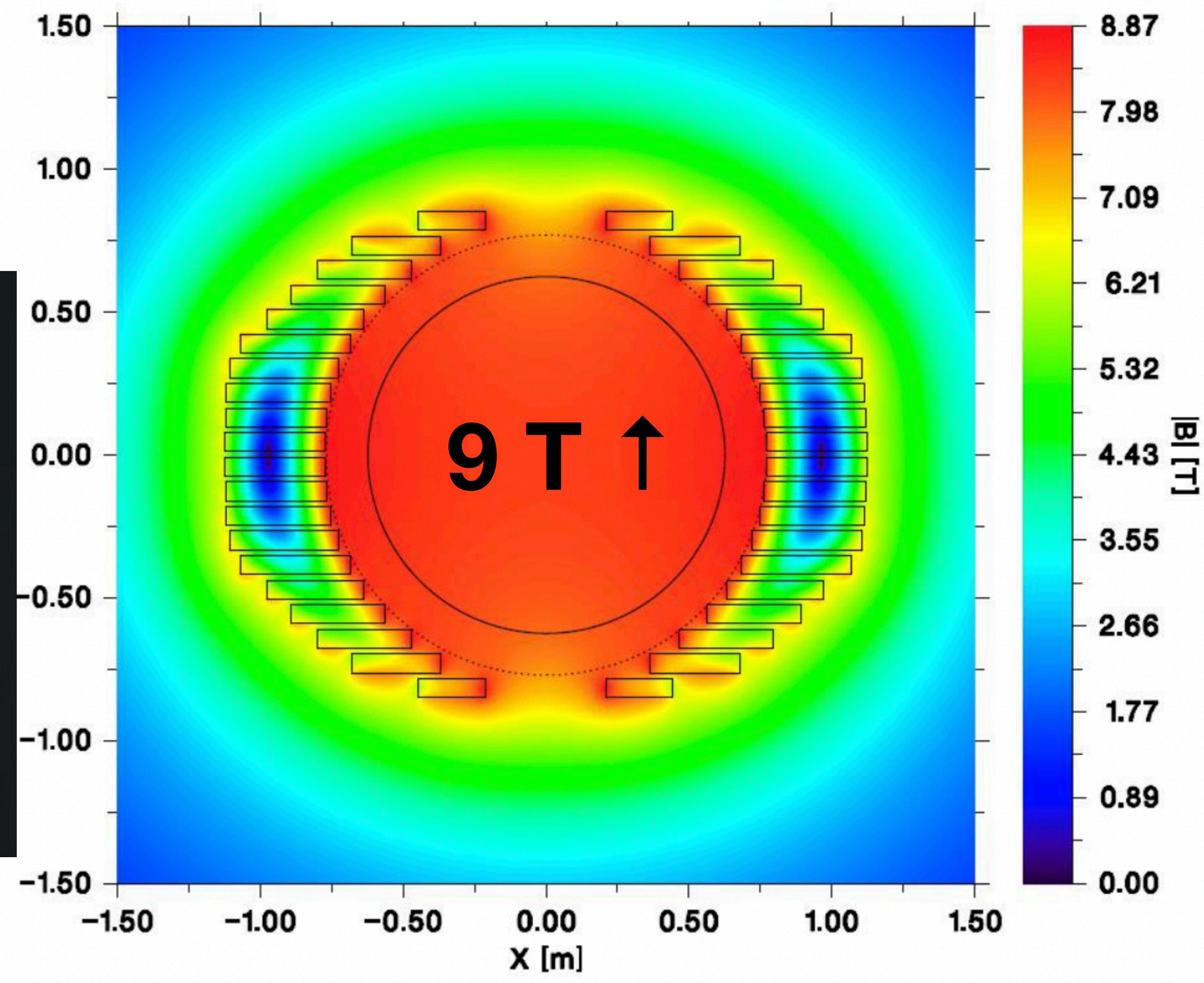
Magnet development

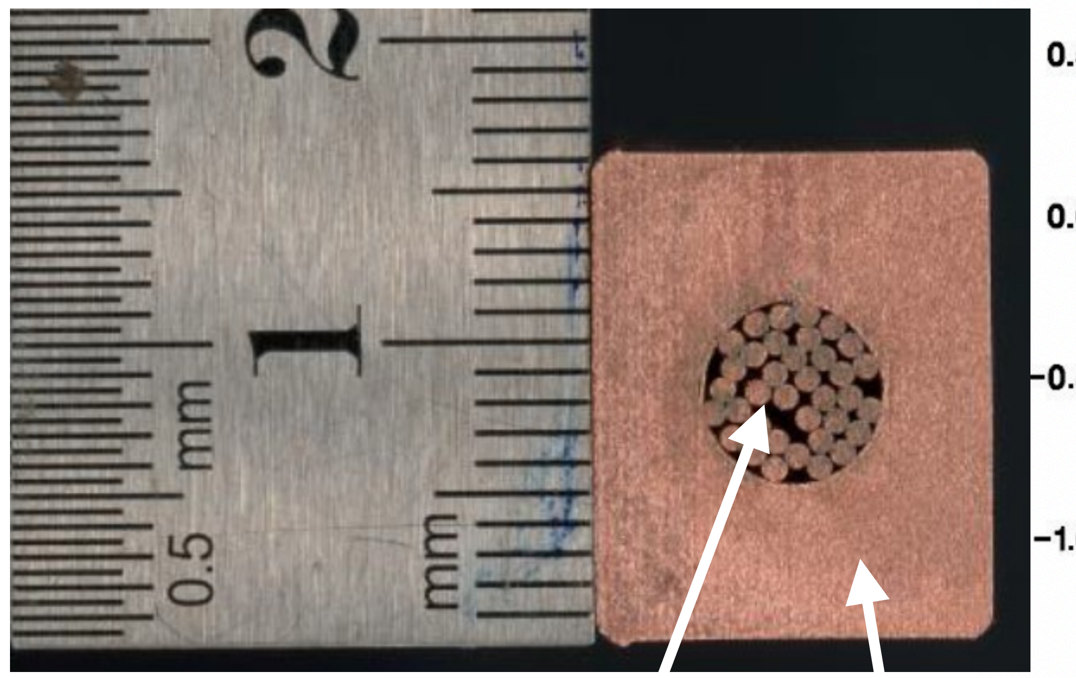
Full scale MADMAX magnet

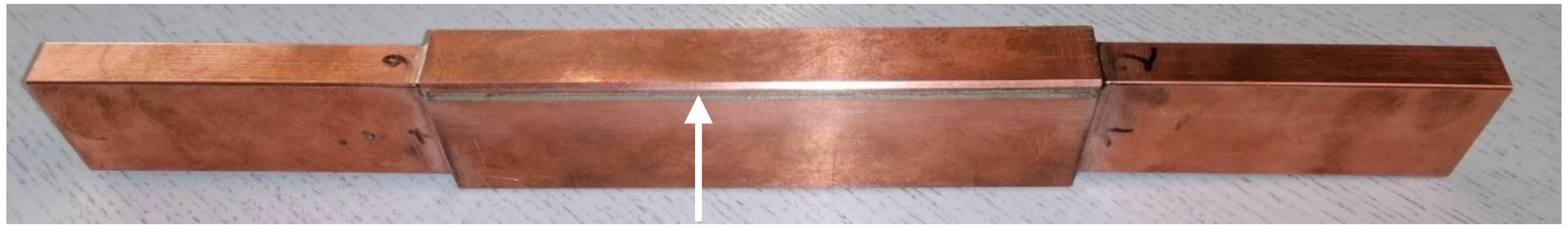
- 9T, 1.35-m warm bore **dipole** magnet
- Superconducting CICC w/ Cu jacket
  - experience and infrastructure from ITER.
  - Quench test: 1/2 size mockup coil

BILFINGER NOELL GMBH

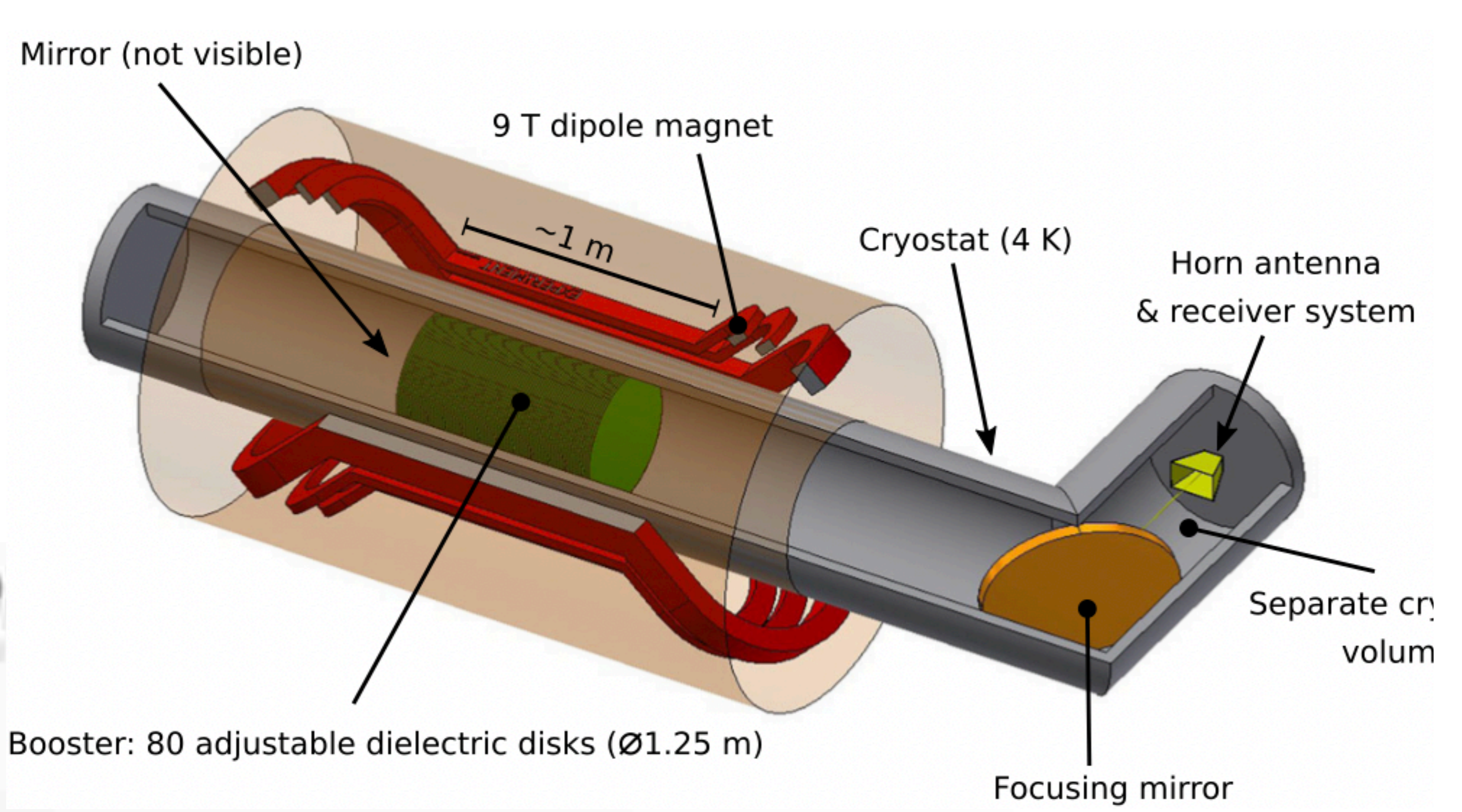






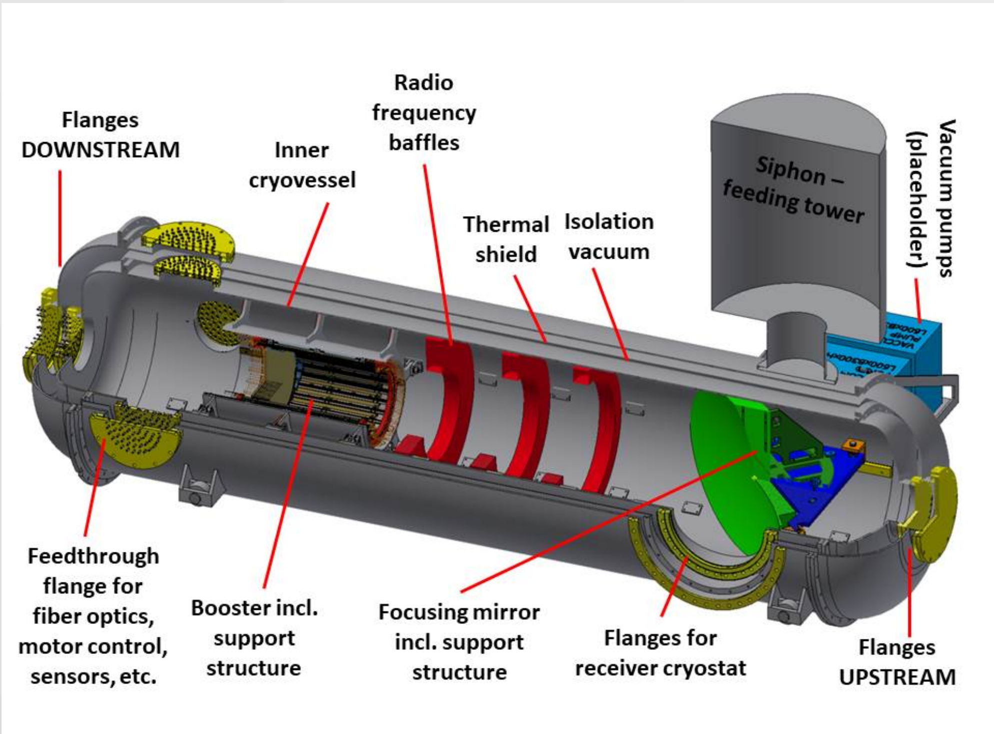


laser welding



Timeline

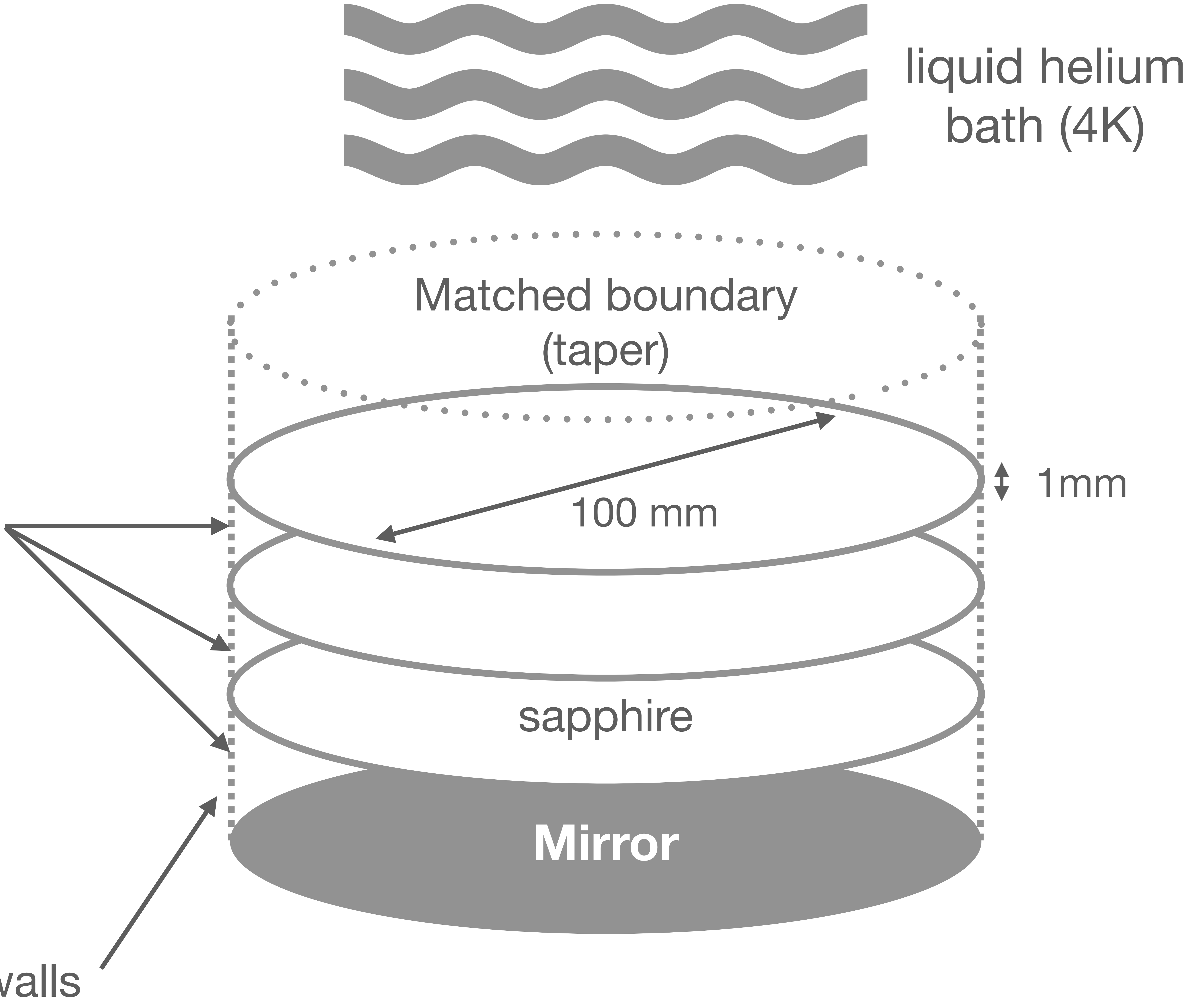
- **2028?** Full MADMAX physics run
- **2028** Full MADMAX magnet commission
- **2024** Prototype Physics run
- **2022** Prototype commission
- **2020** CERN Morpurgo magnet approved



100mm LHe setup

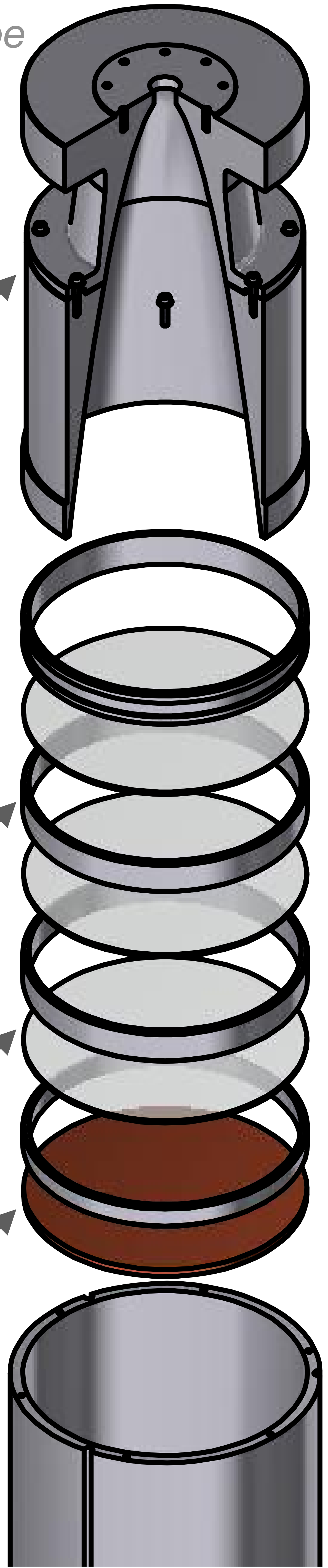
Overview

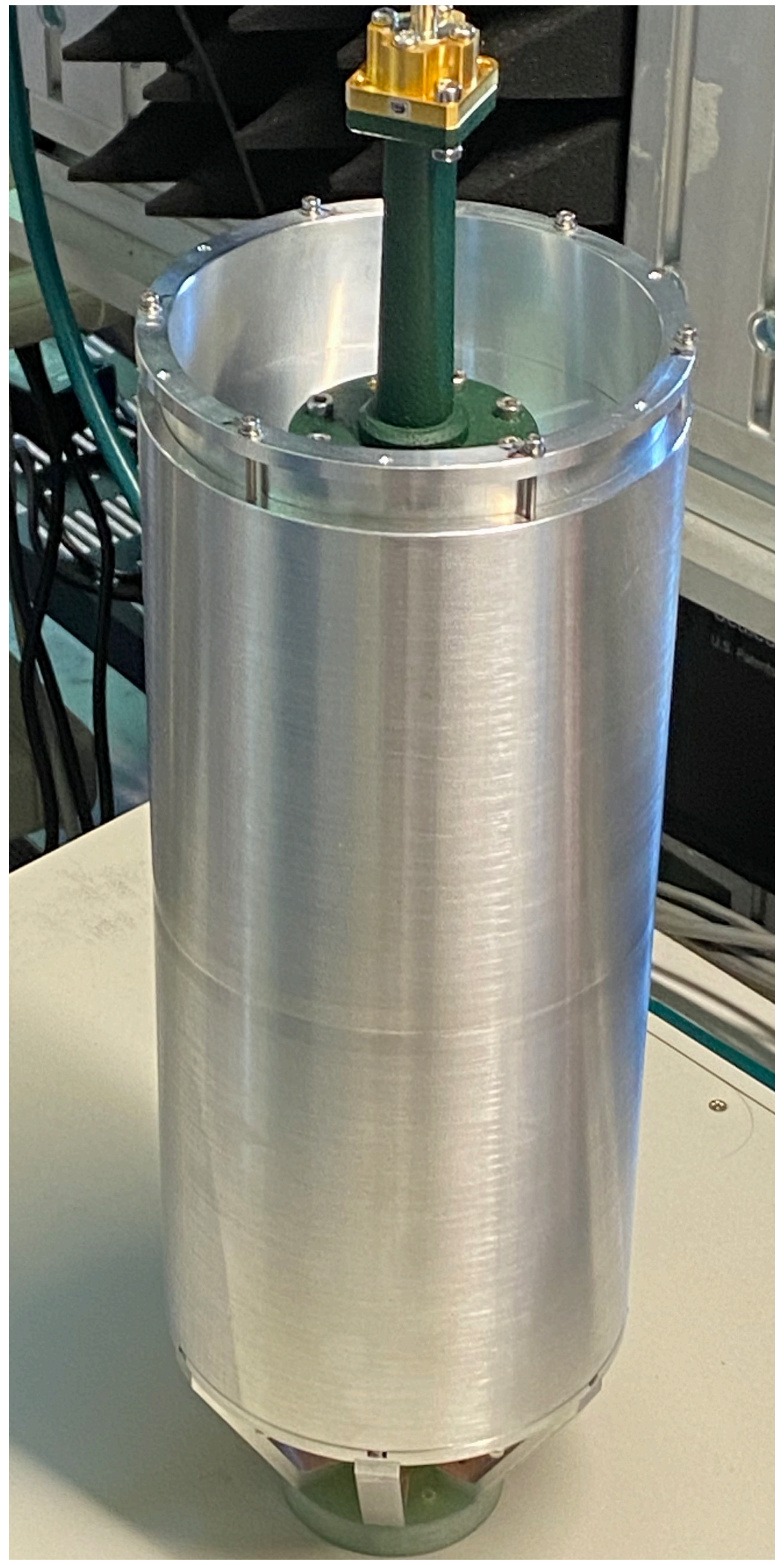
- Proof-of-principle
- Resonance @ 19 GHz
  - Air gaps from impedance matching
- Closed system w/ taper



Construction

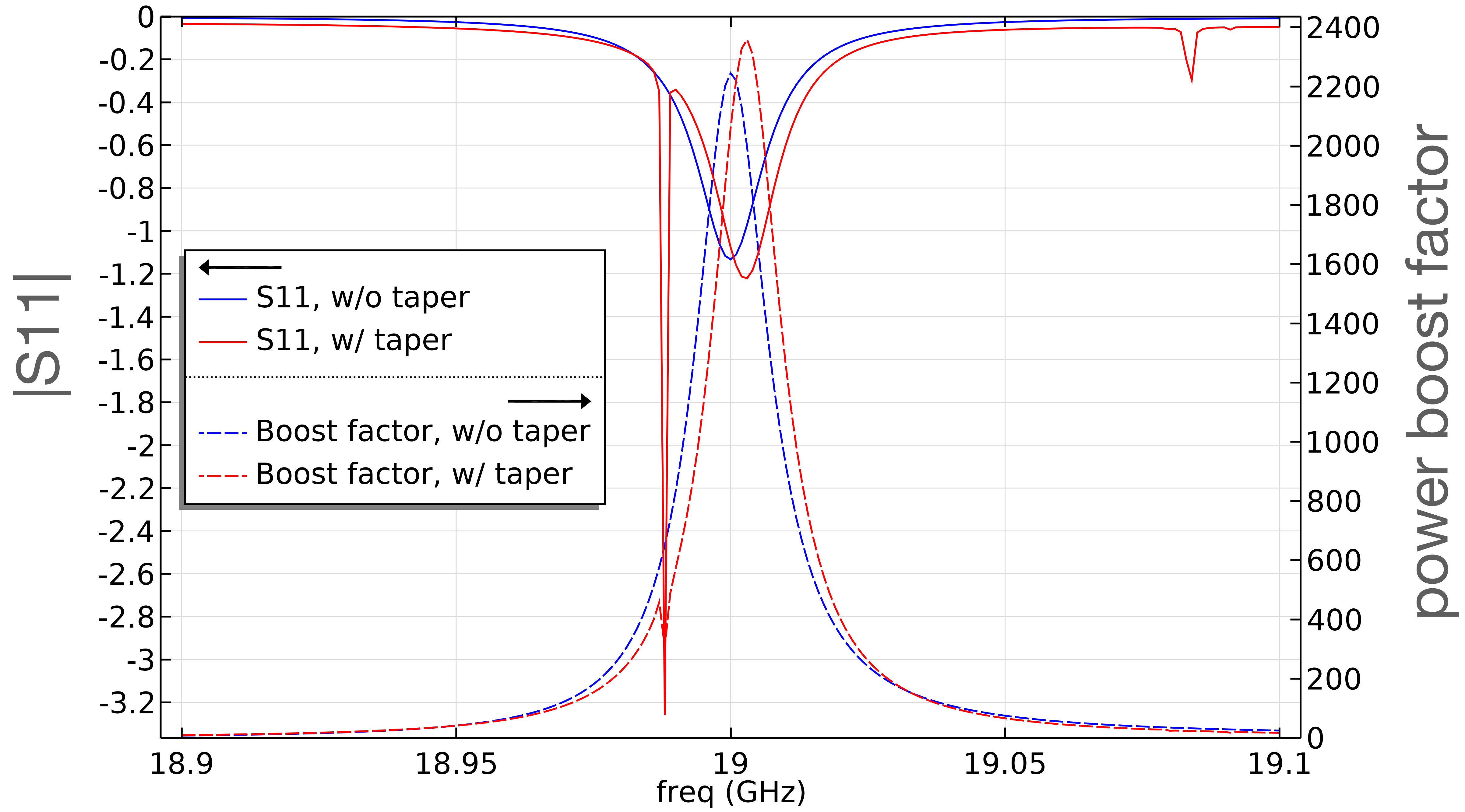
- Reproducible, modular structure



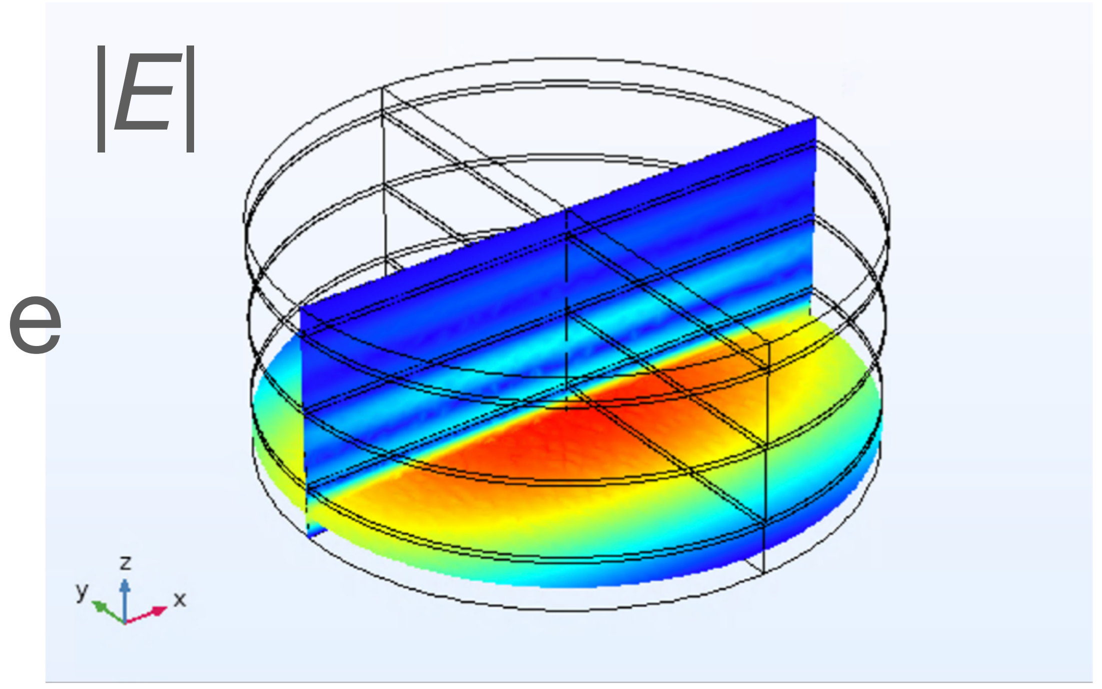


Simulation

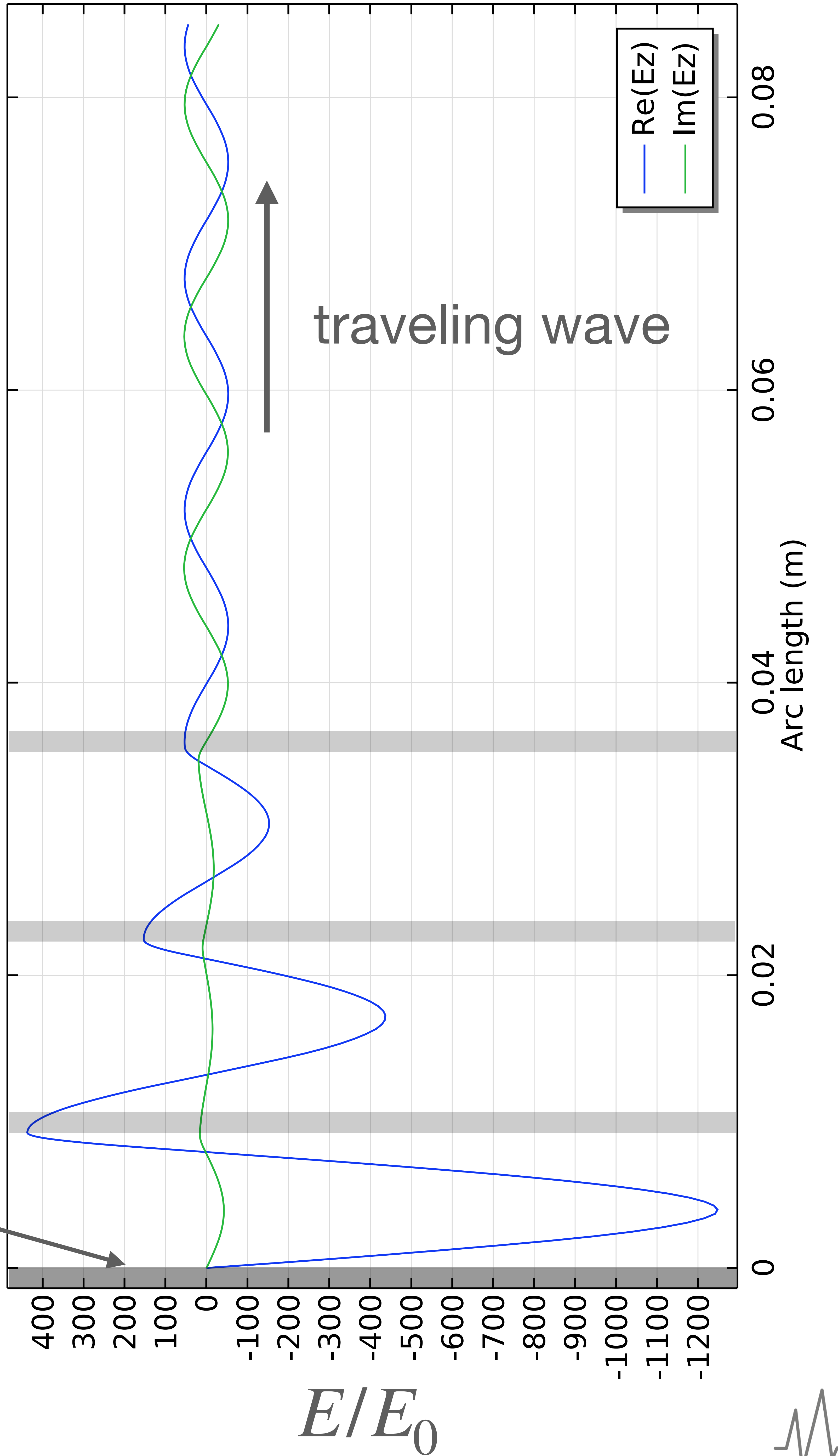
Dielectric haloscope EM response



(quasi) TE11 mode

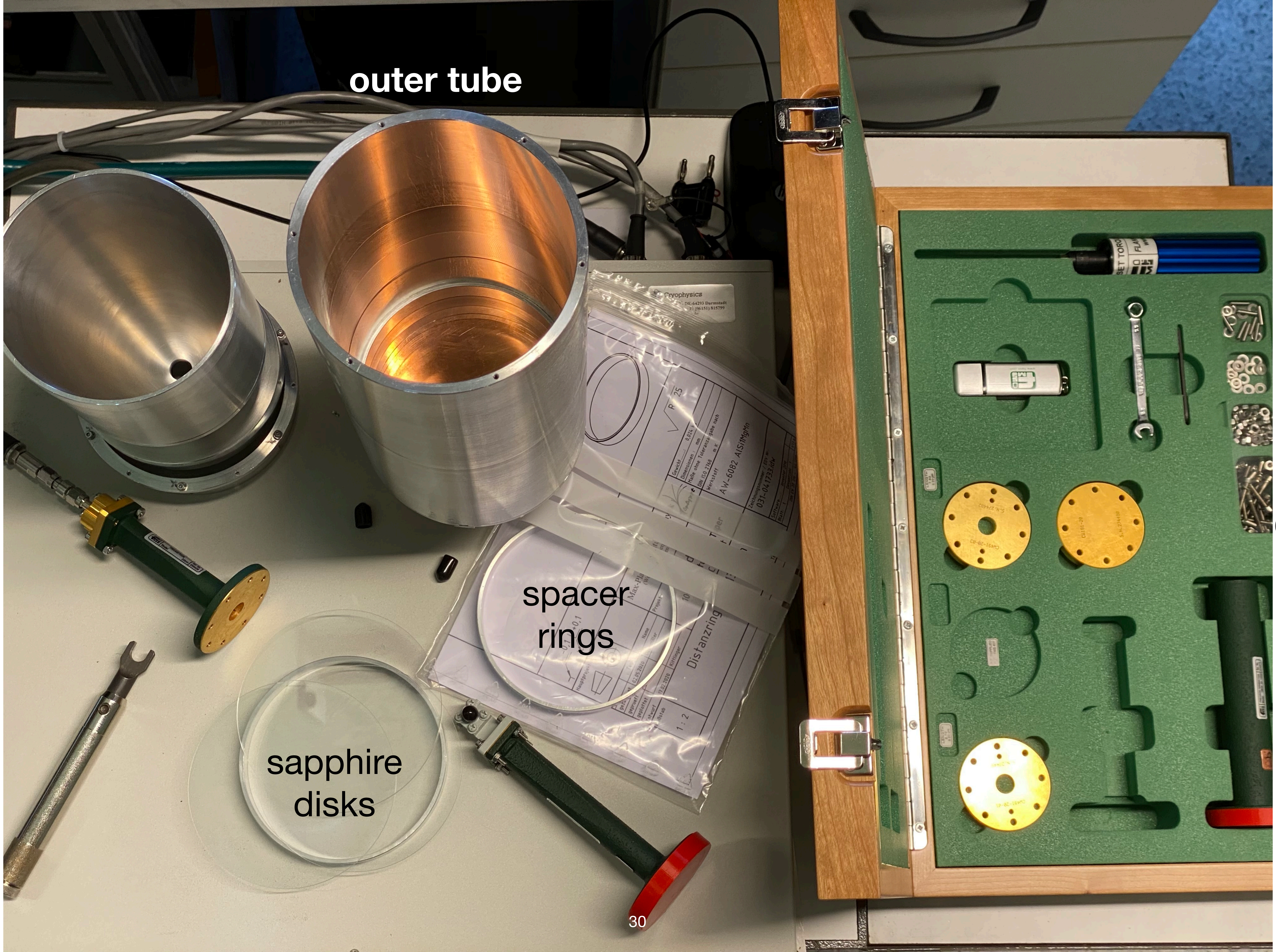


Major loss @ Cu mirror



parabolic taper

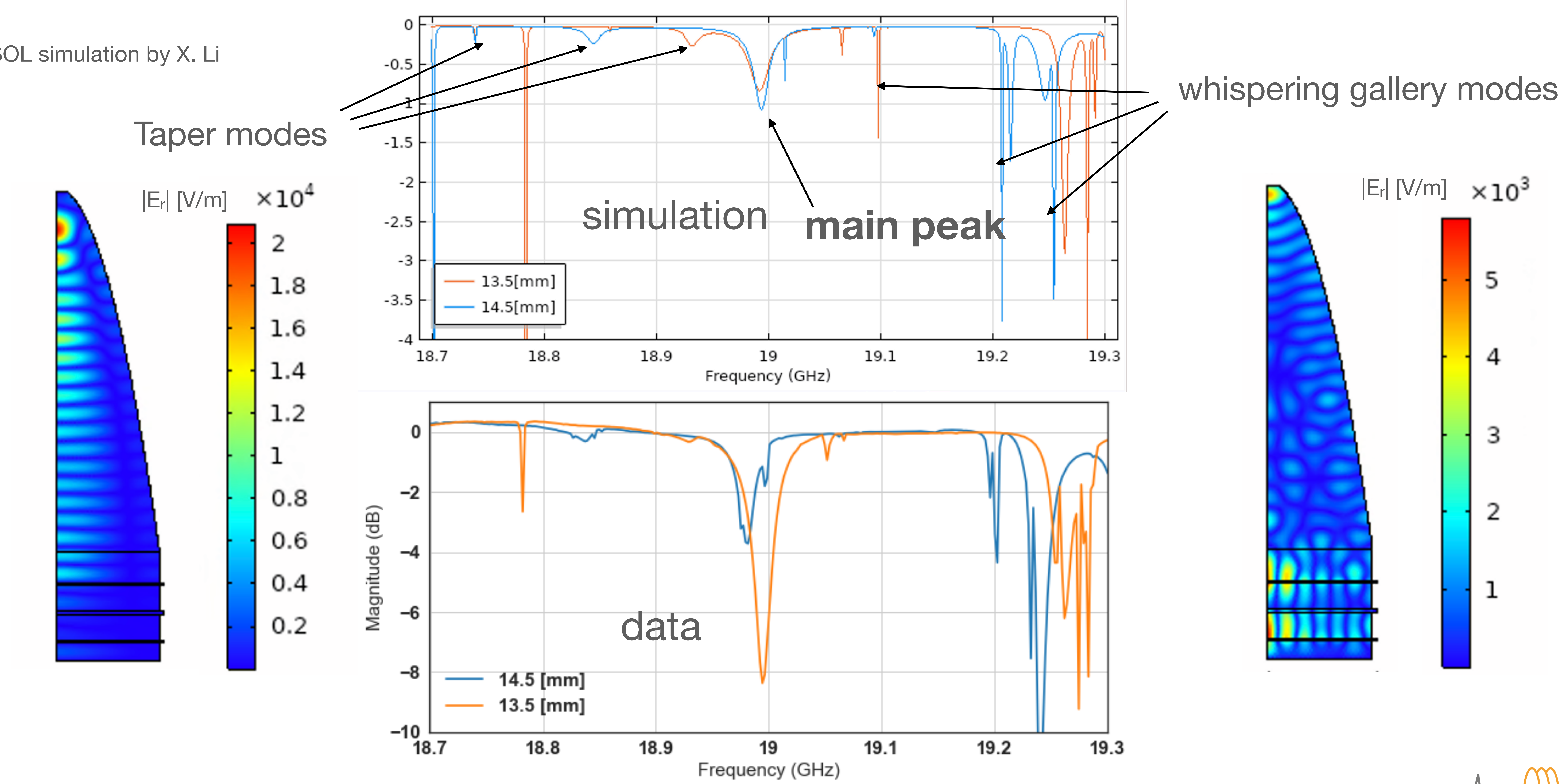
circular-rectangular WG transition



circular WG calibration kit (custom!)

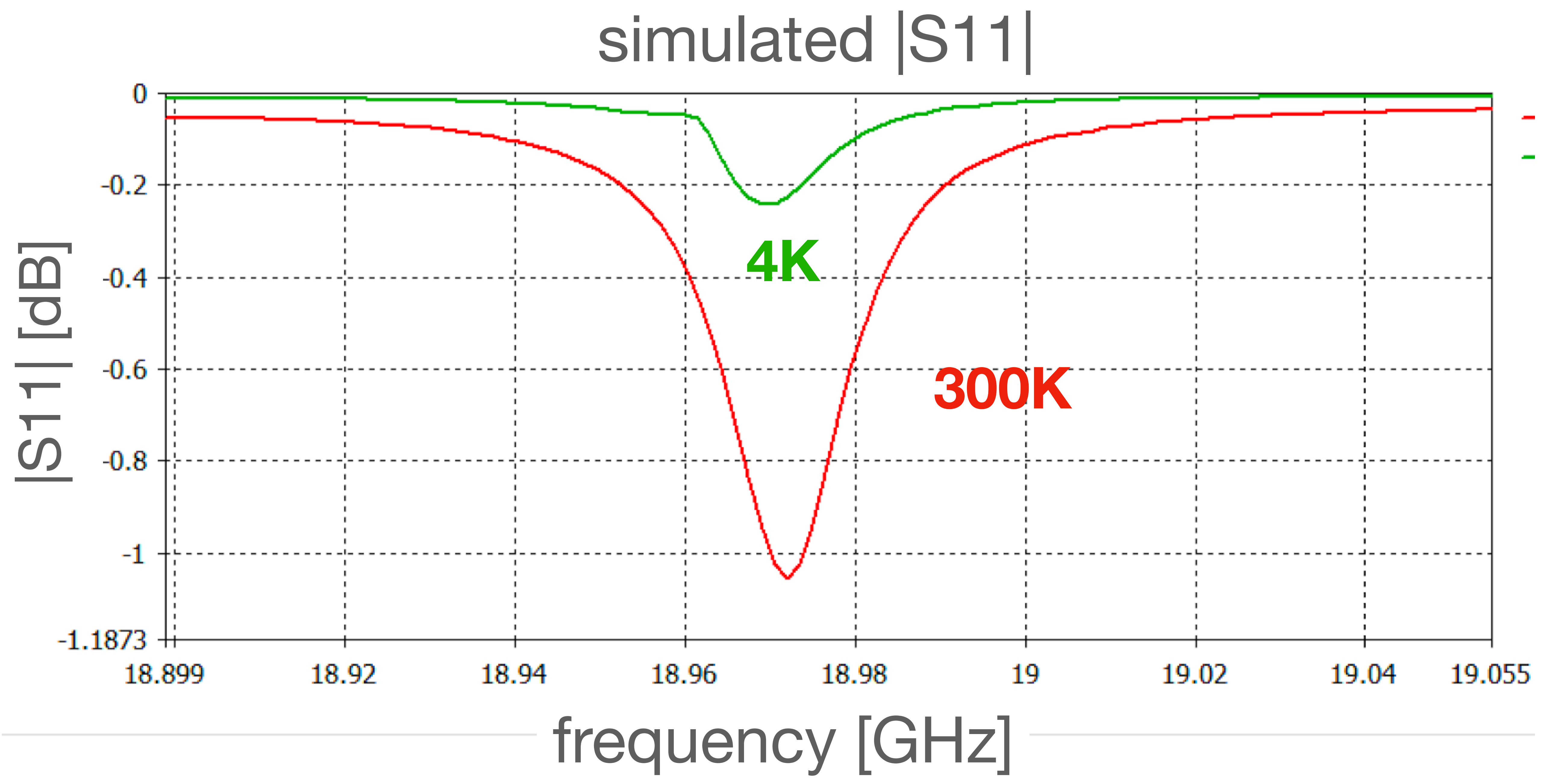
Room temperature reflectivity

COMSOL simulation by X. Li



Cryogenic operation

- Cryostat is ready.
- RF calibrated down to circular WG at 4K

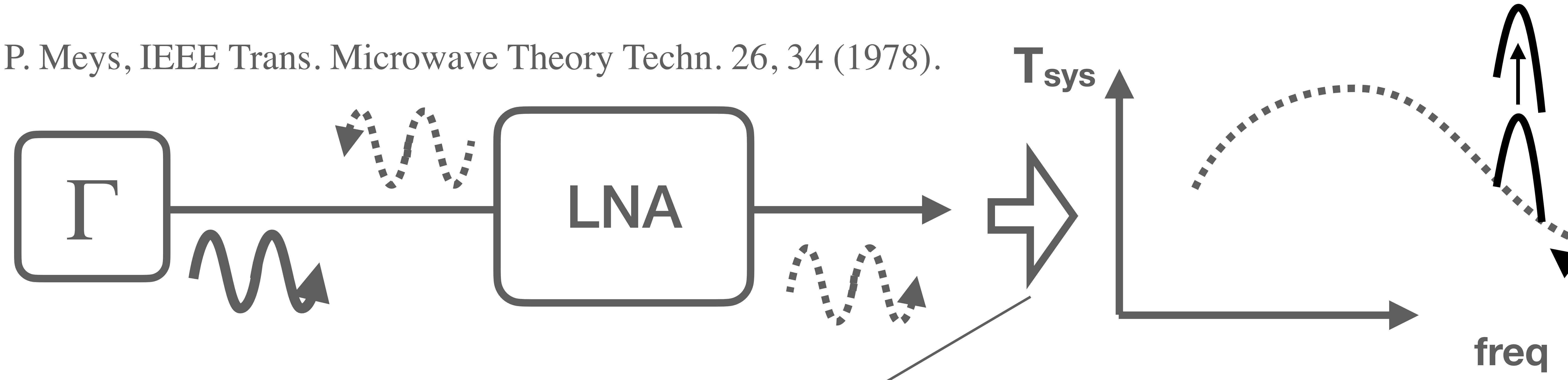


LHe bath cryostat

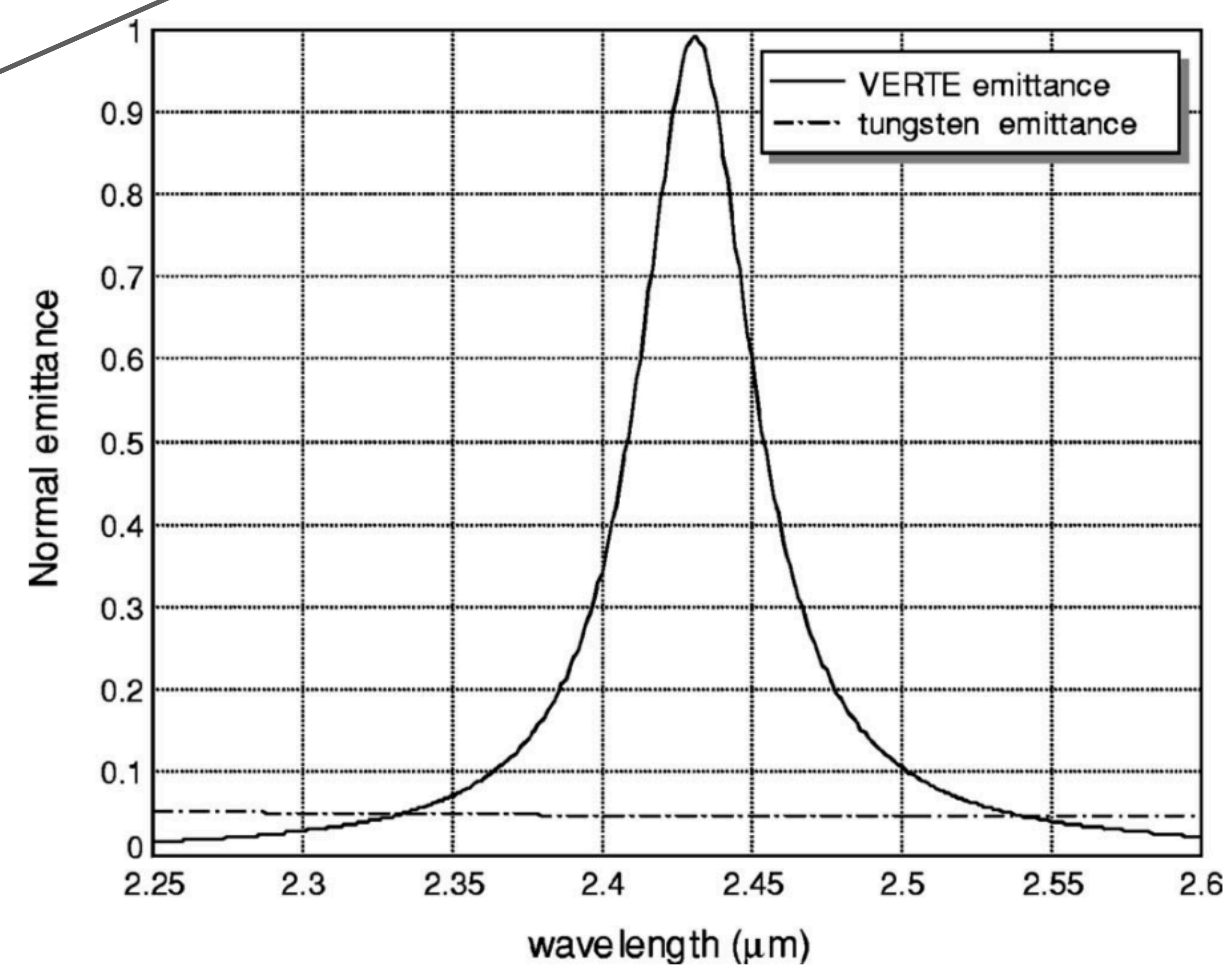
Background noise

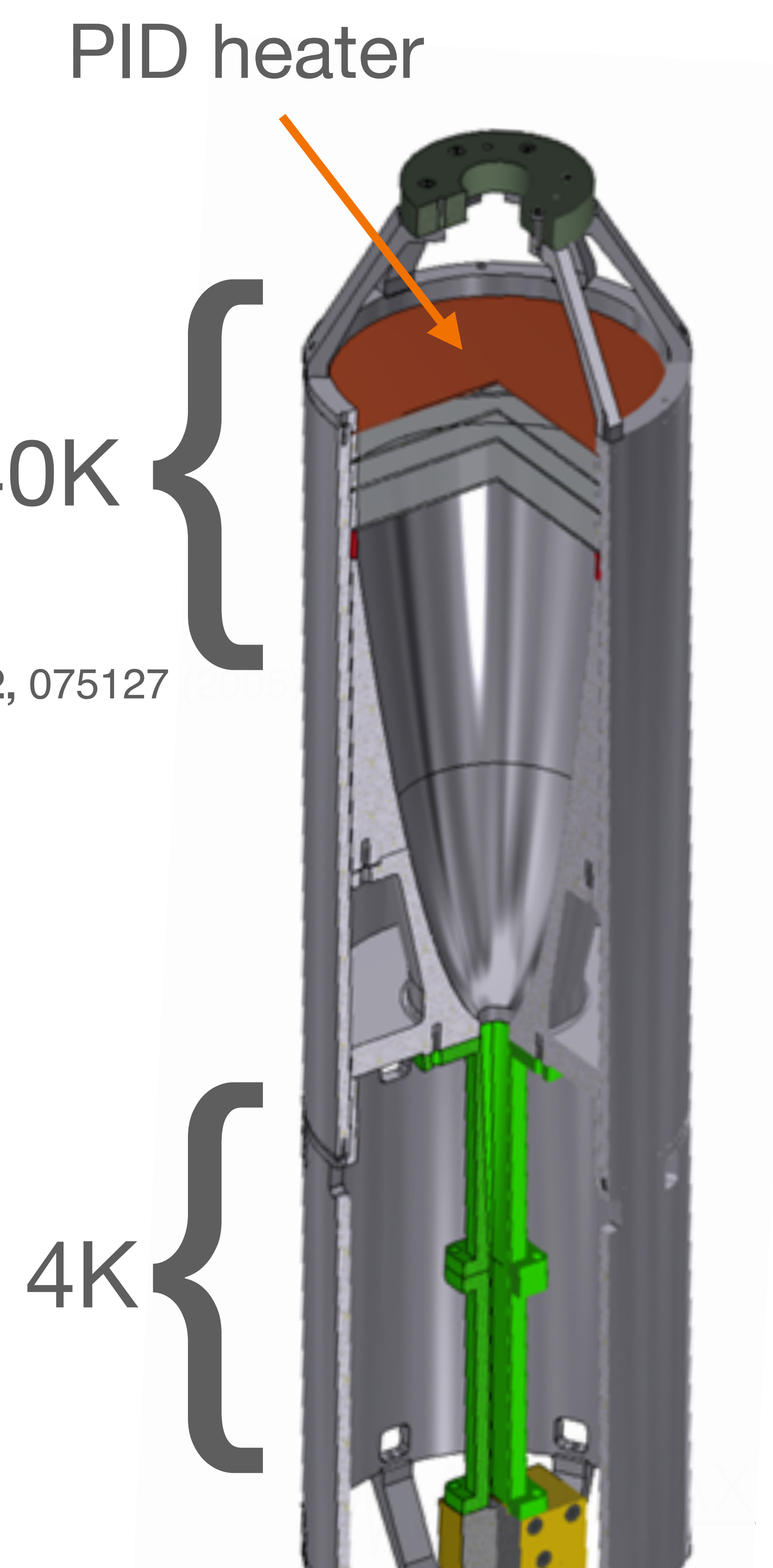
- Thermal noise can be enhanced if the mirror is heated.

R. P. Meys, IEEE Trans. Microwave Theory Techn. 26, 34 (1978).



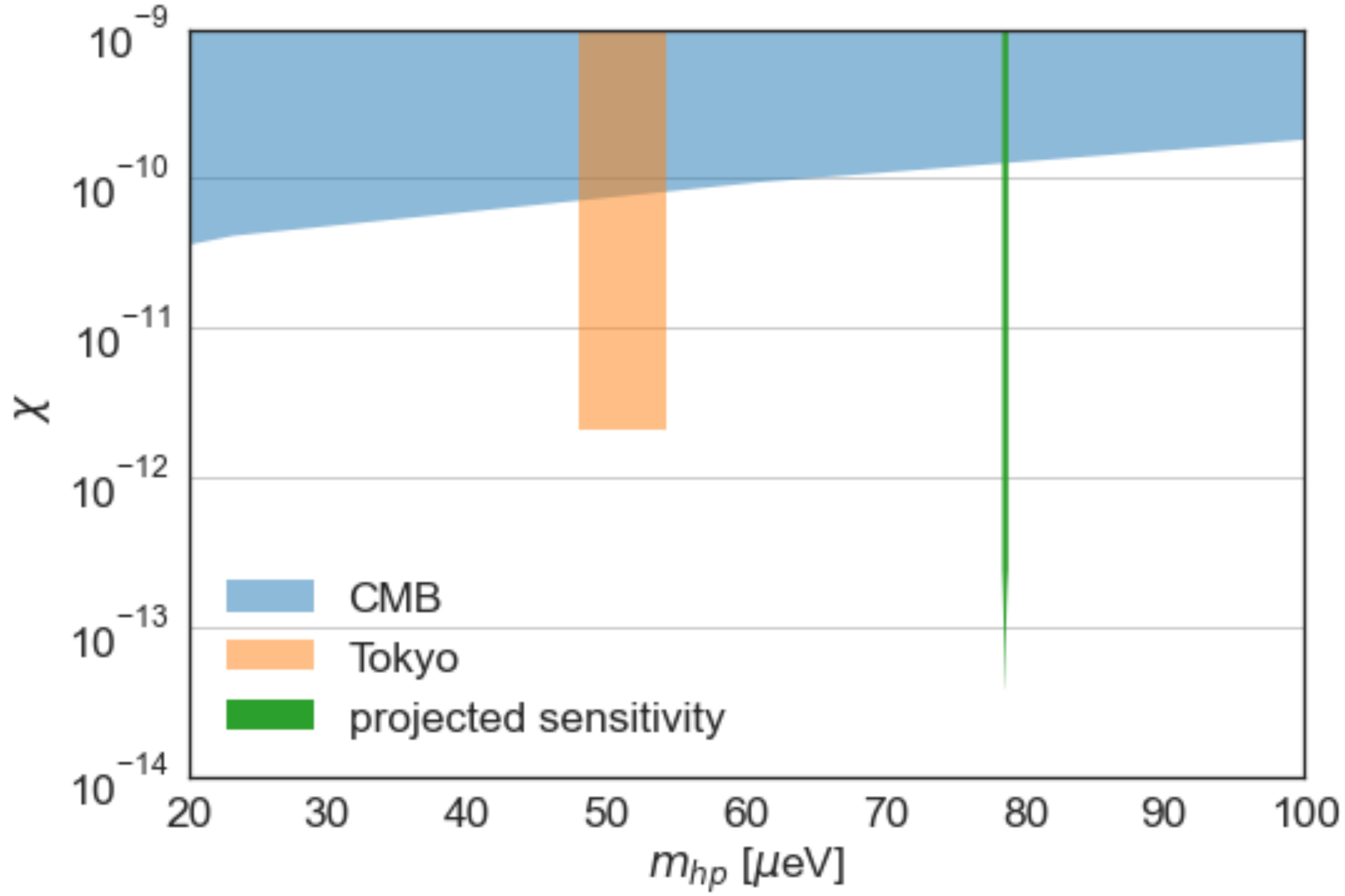
I. Celanovic *et al.*, *Phys. Rev. B* **72,** 075127





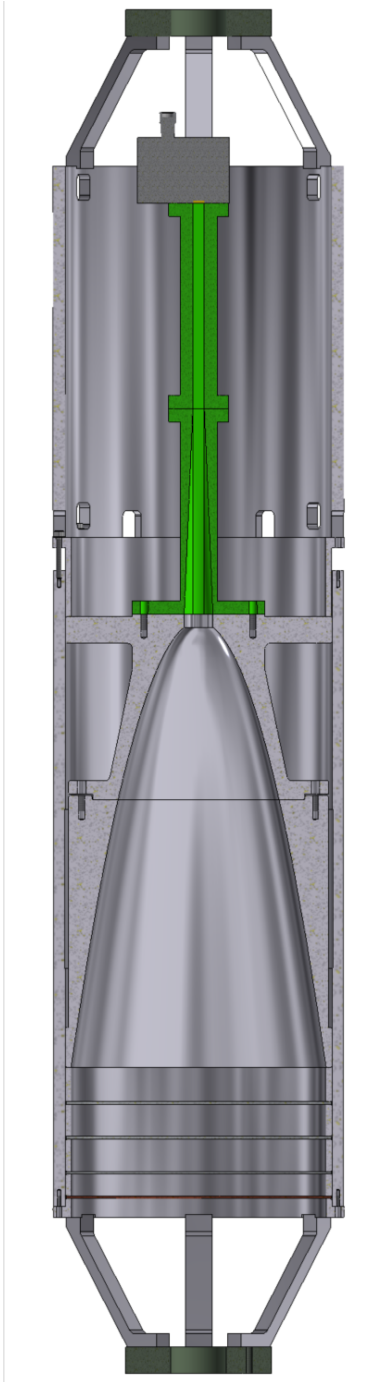
Hidden photon search

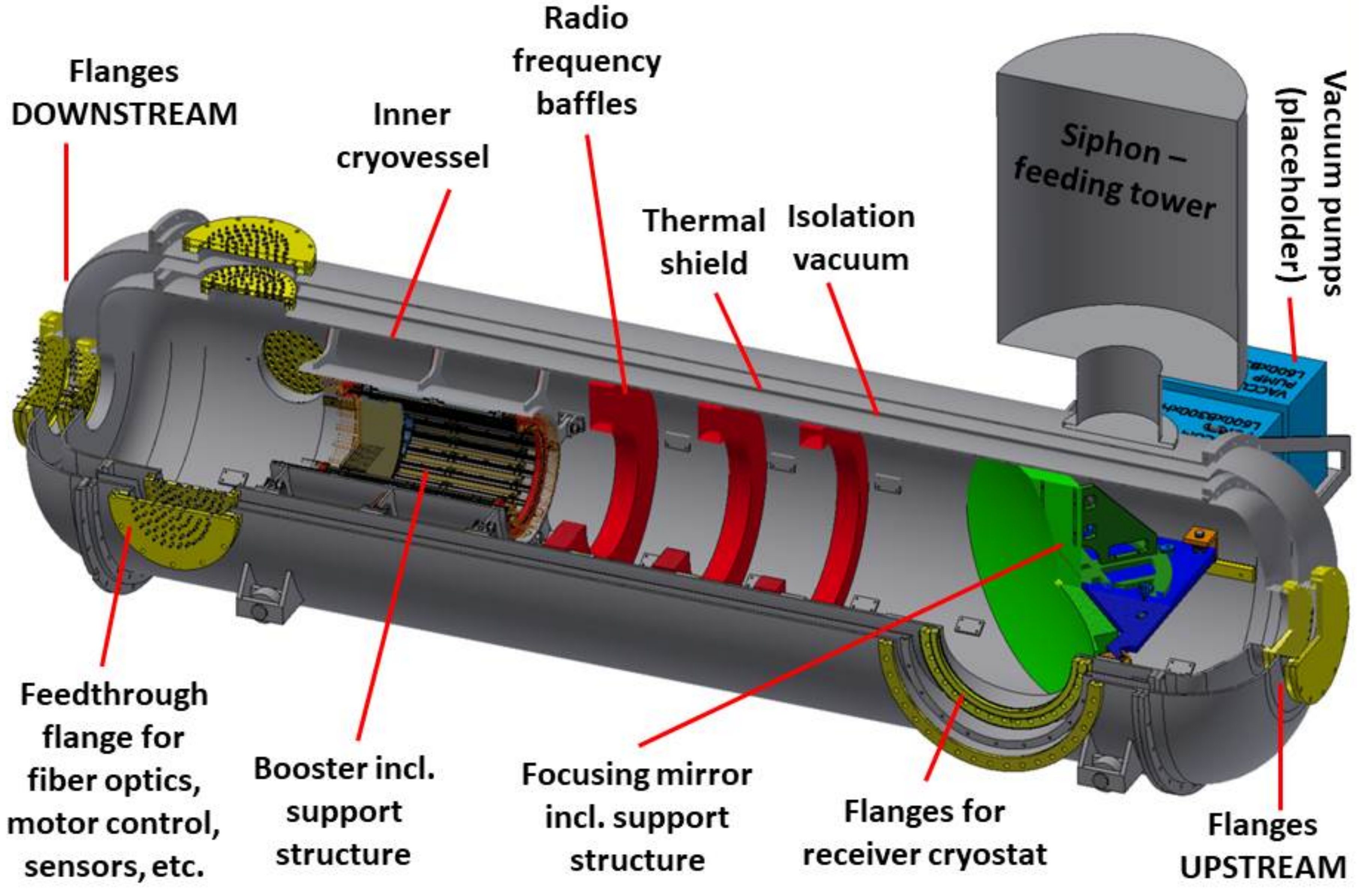
- $\chi = 4.5 \times 10^{-9} \left(\frac{P_{\text{sens}}}{10^{-13}\ \text{W}}\right)^{\frac{1}{2}} \left(\frac{1\ \text{m}^2}{A_{\text{mirror}}}\right)^{\frac{1}{2}} \left(\frac{1}{\beta^2}\right)^{\frac{1}{2}} \left(\frac{1}{\eta}\right)^{\frac{1}{2}} \left(\frac{0.45\ \text{GeV/cm}^3}{\rho_{\text{HPDM}}}\right)^{\frac{1}{2}}$
- 11K T_{sys}, 7 days data taking, 90% efficiency, S/N 5
- Δf ~ 20 MHz, χ ~ 1e-13

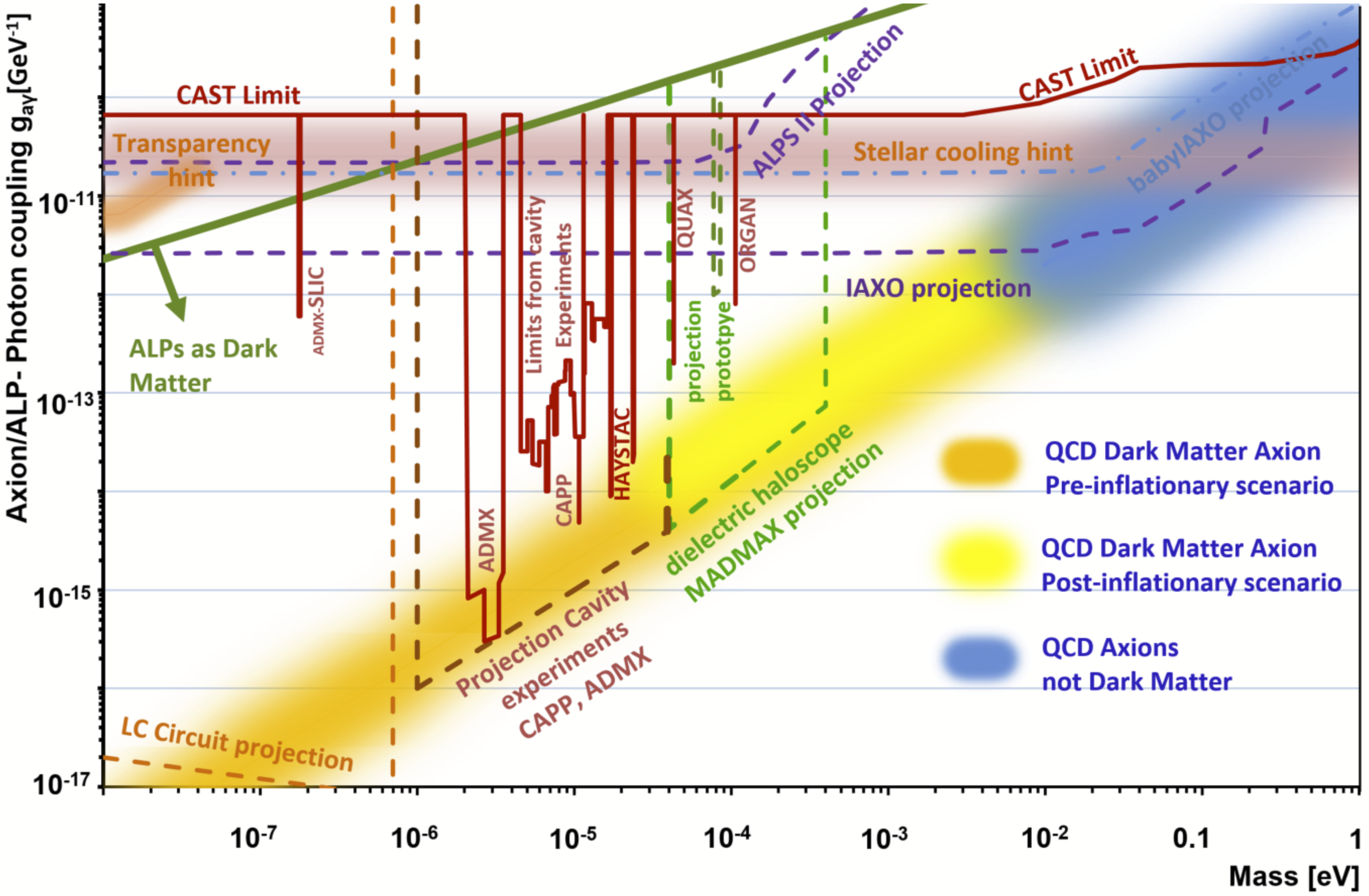


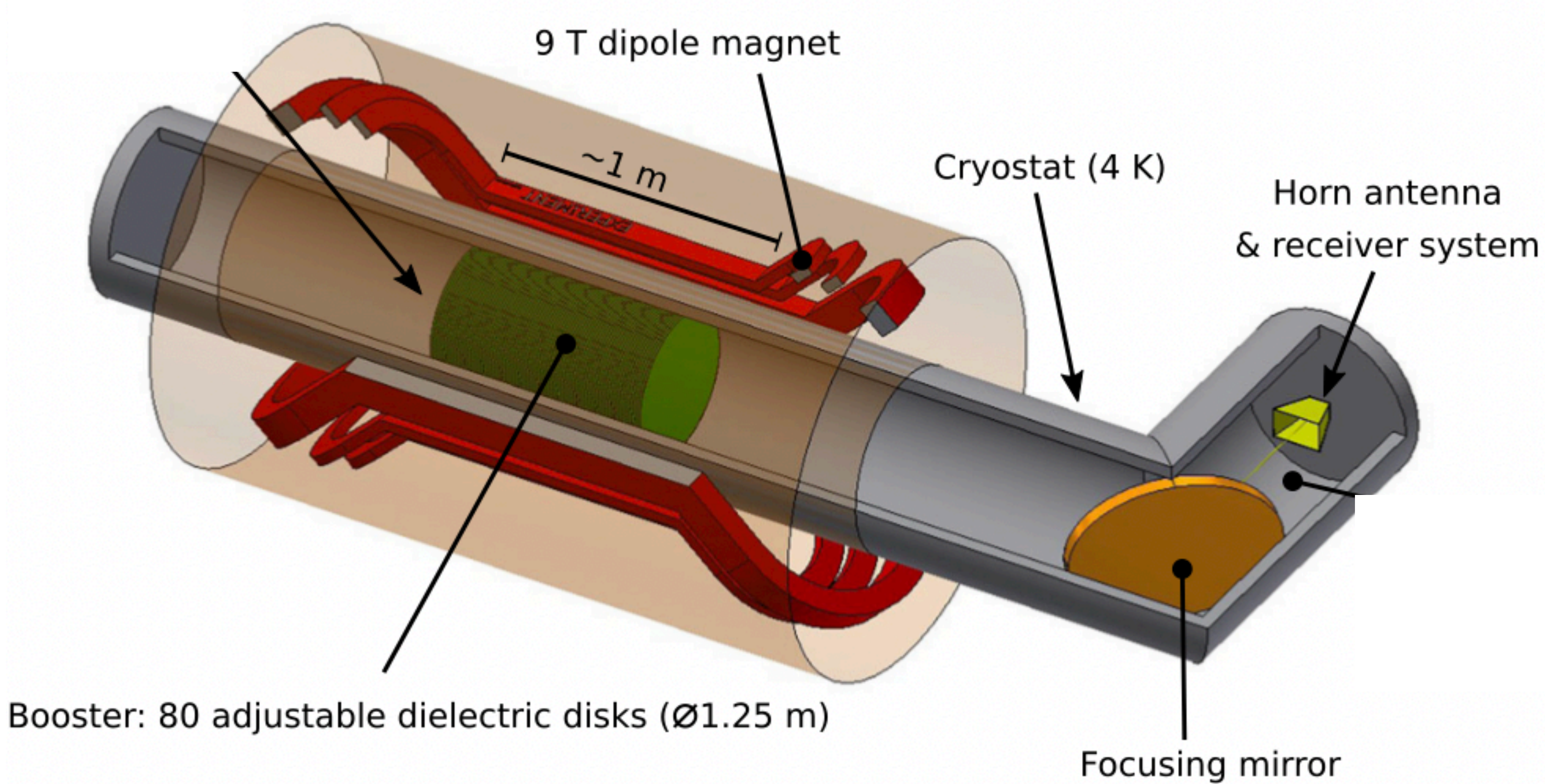
Conclusion

- Dielectric haloscope is an ingenious approach to probe post-inflationary QCD axion dark matter







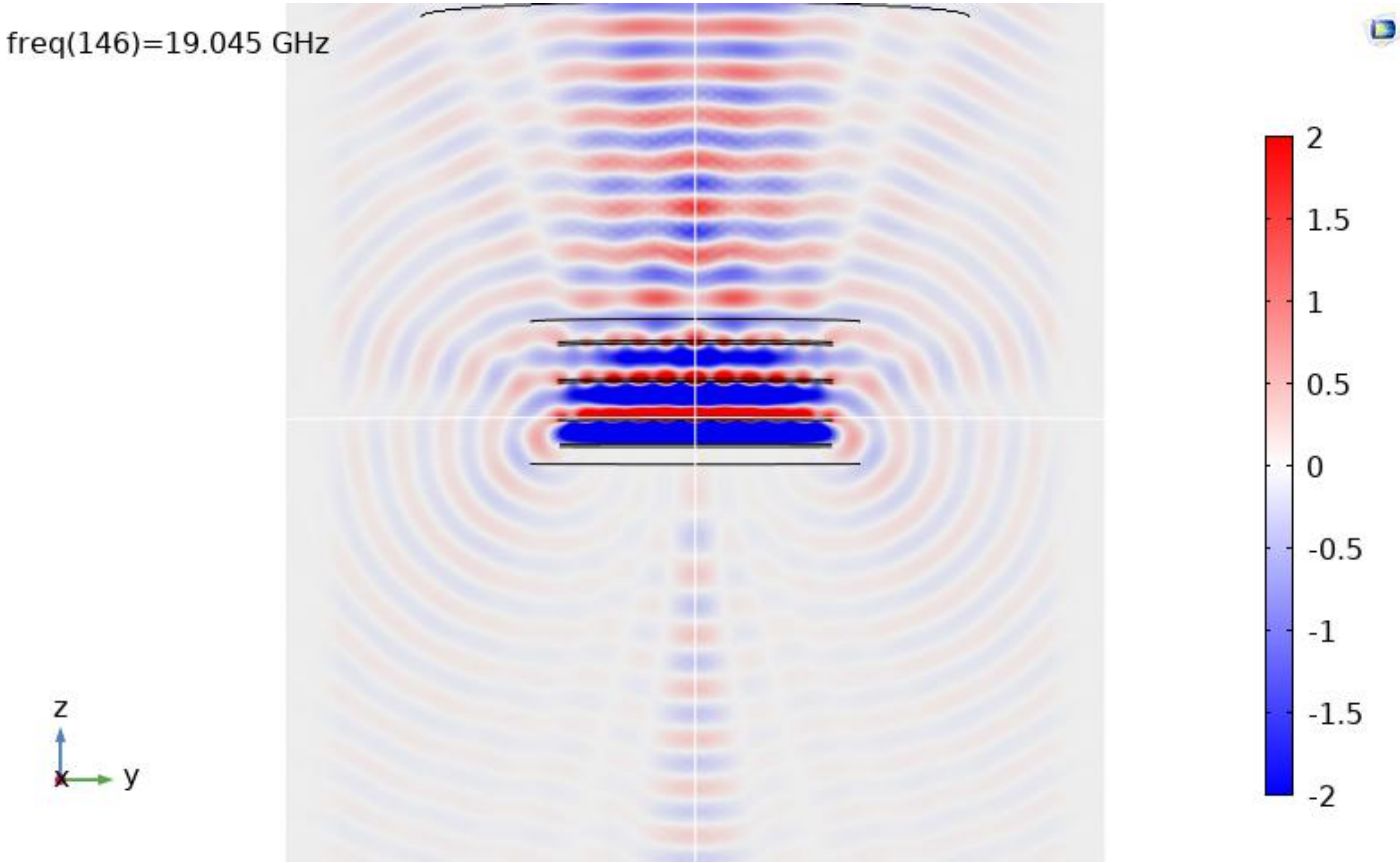


Thank you

Stay tuned!

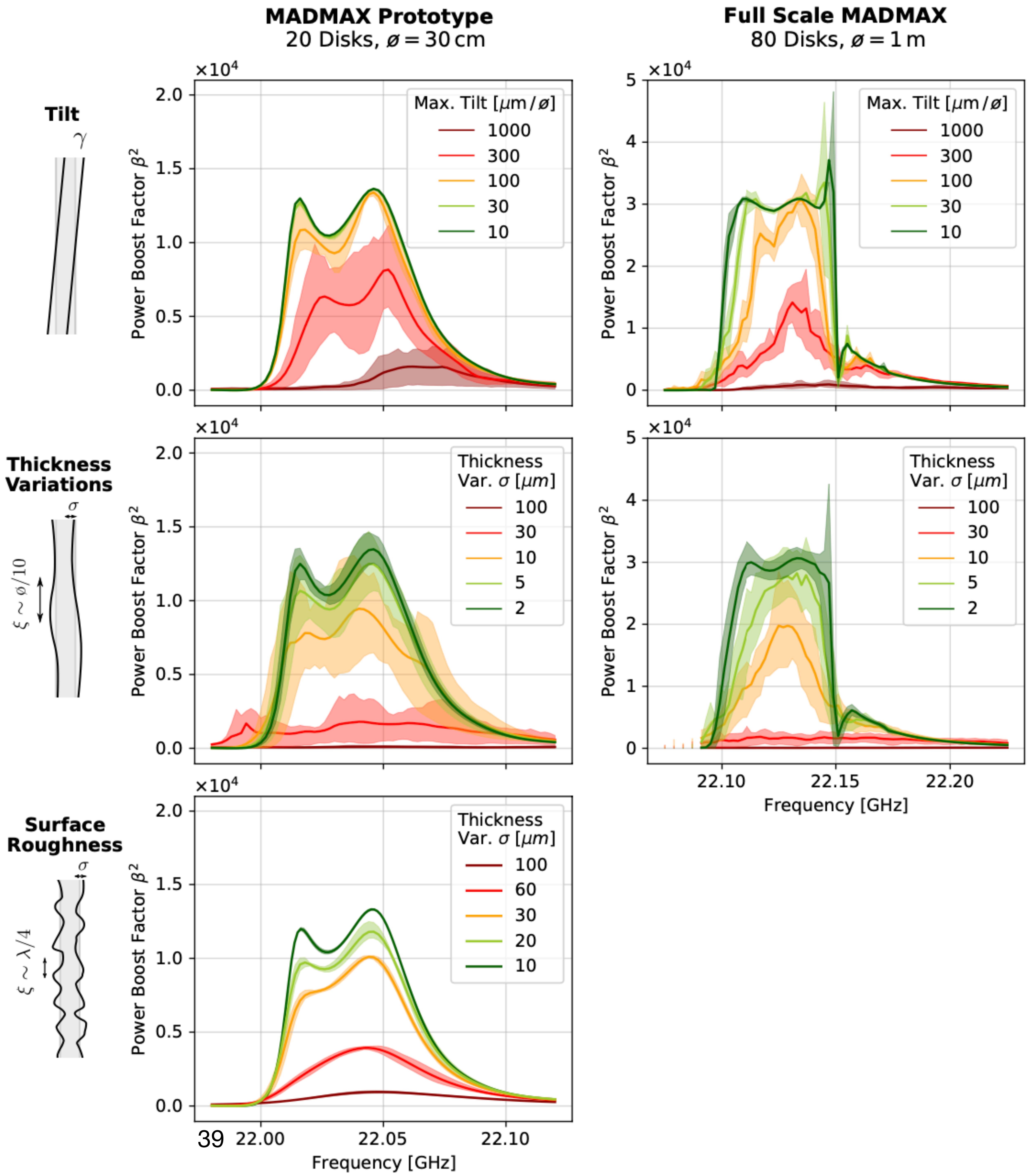
Back-up

Radiation from open booster

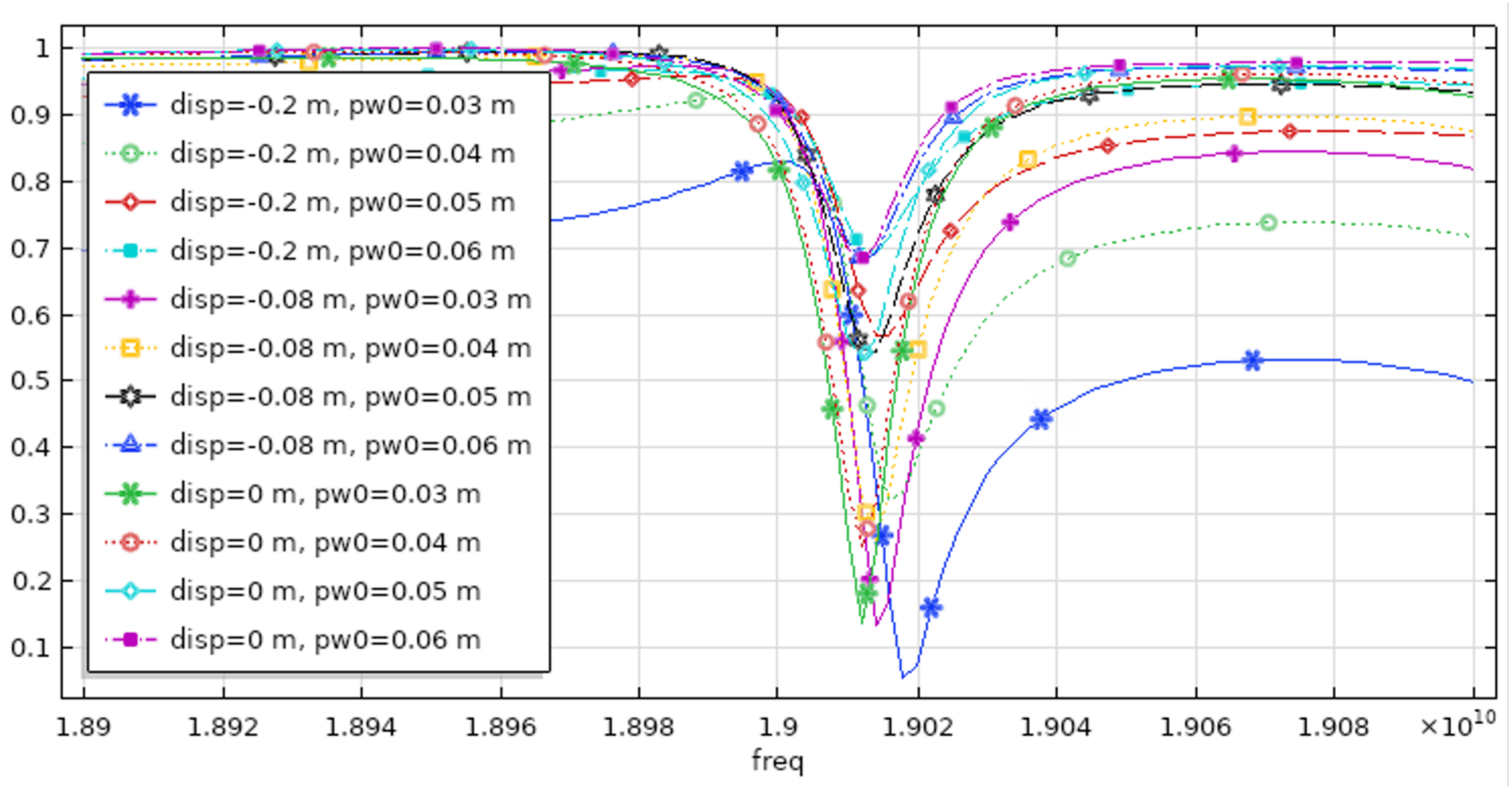


Mechanical precision study

Simulation paper in preparation



Reflectivity vs. beam waist for open system



Transfer matrix formalism

A. J. Millar *et al.*, JCAP01 (2017) 061

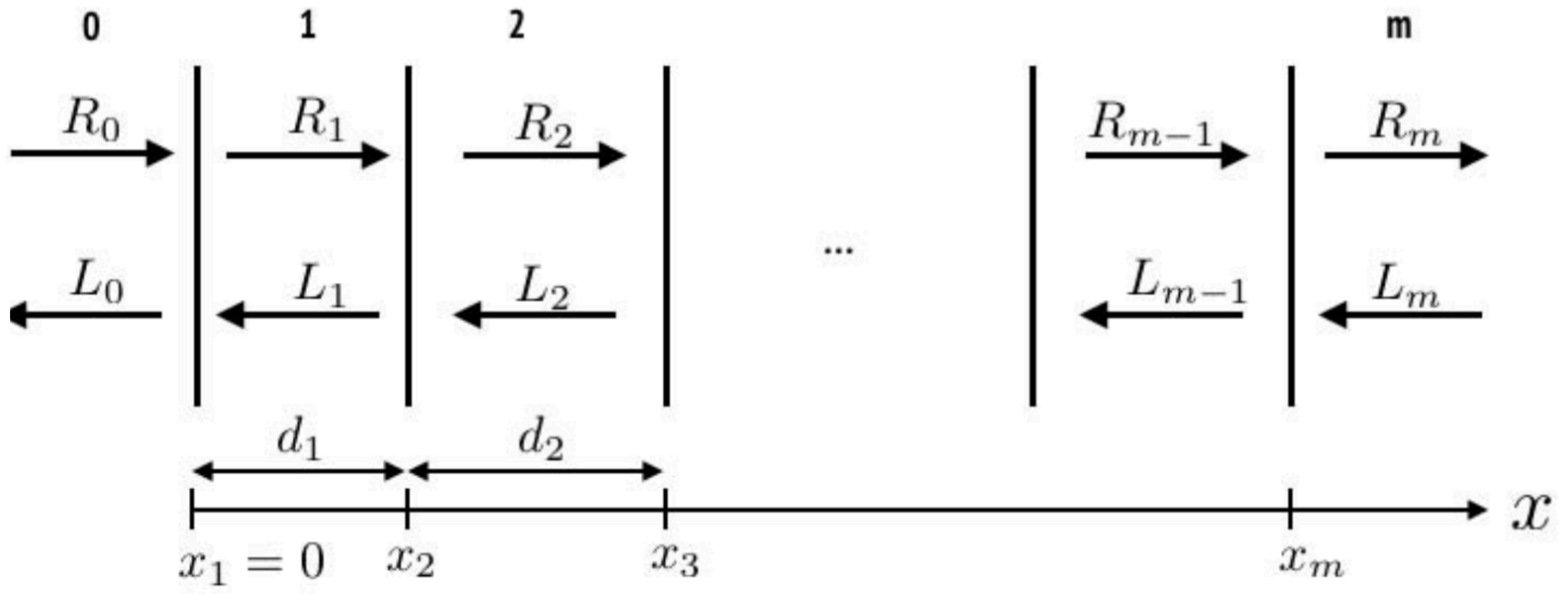
- Exact calculation of axion-induced traveling wave from give geometry

$$\begin{pmatrix} R_{r+1} \\ L_{r+1} \end{pmatrix} = \mathsf{G}_r \mathsf{P}_r \begin{pmatrix} R_r \\ L_r \end{pmatrix} + E_0\, \mathsf{S}_r \begin{pmatrix} 1 \\ 1 \end{pmatrix},$$

reflection $$\mathsf{G}_r = \frac{1}{2n_{r+1}} \begin{pmatrix} n_{r+1}+n_r & n_{r+1}-n_r \\ n_{r+1}-n_r & n_{r+1}+n_r \end{pmatrix},$$

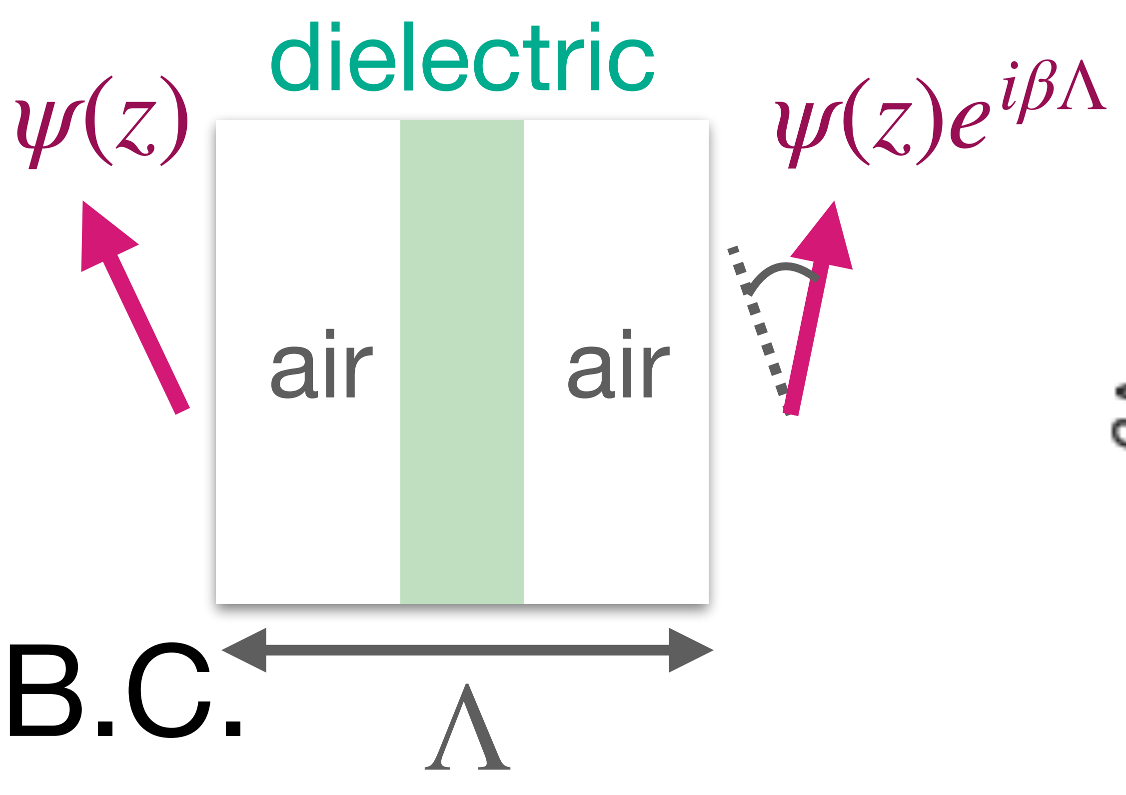
propagation $$\mathsf{P}_r = \begin{pmatrix} e^{+i\delta_r} & 0 \\ 0 & e^{-i\delta_r} \end{pmatrix},$$

source $$\mathsf{S}_r = \frac{A_{r+1} - A_r}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$

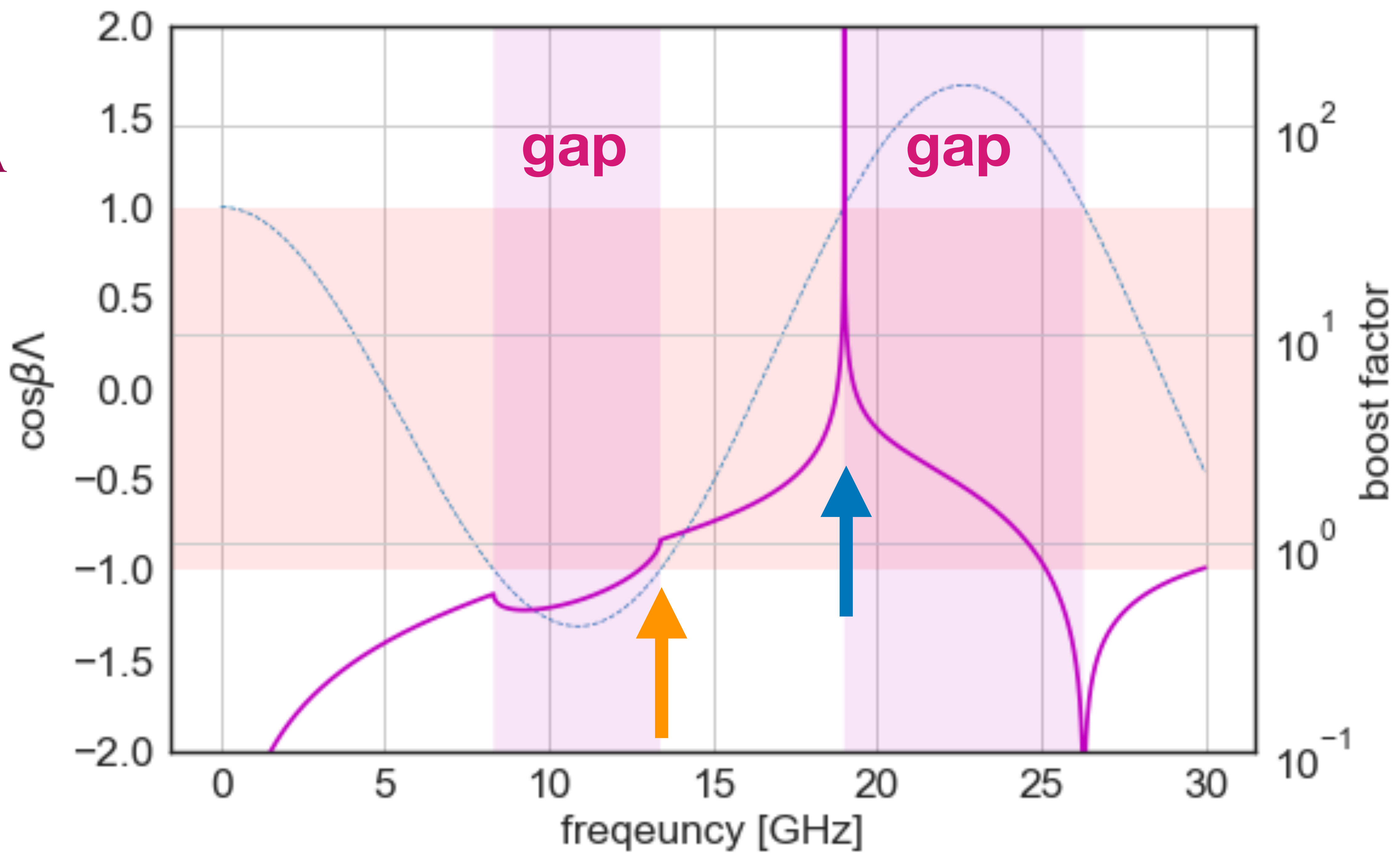


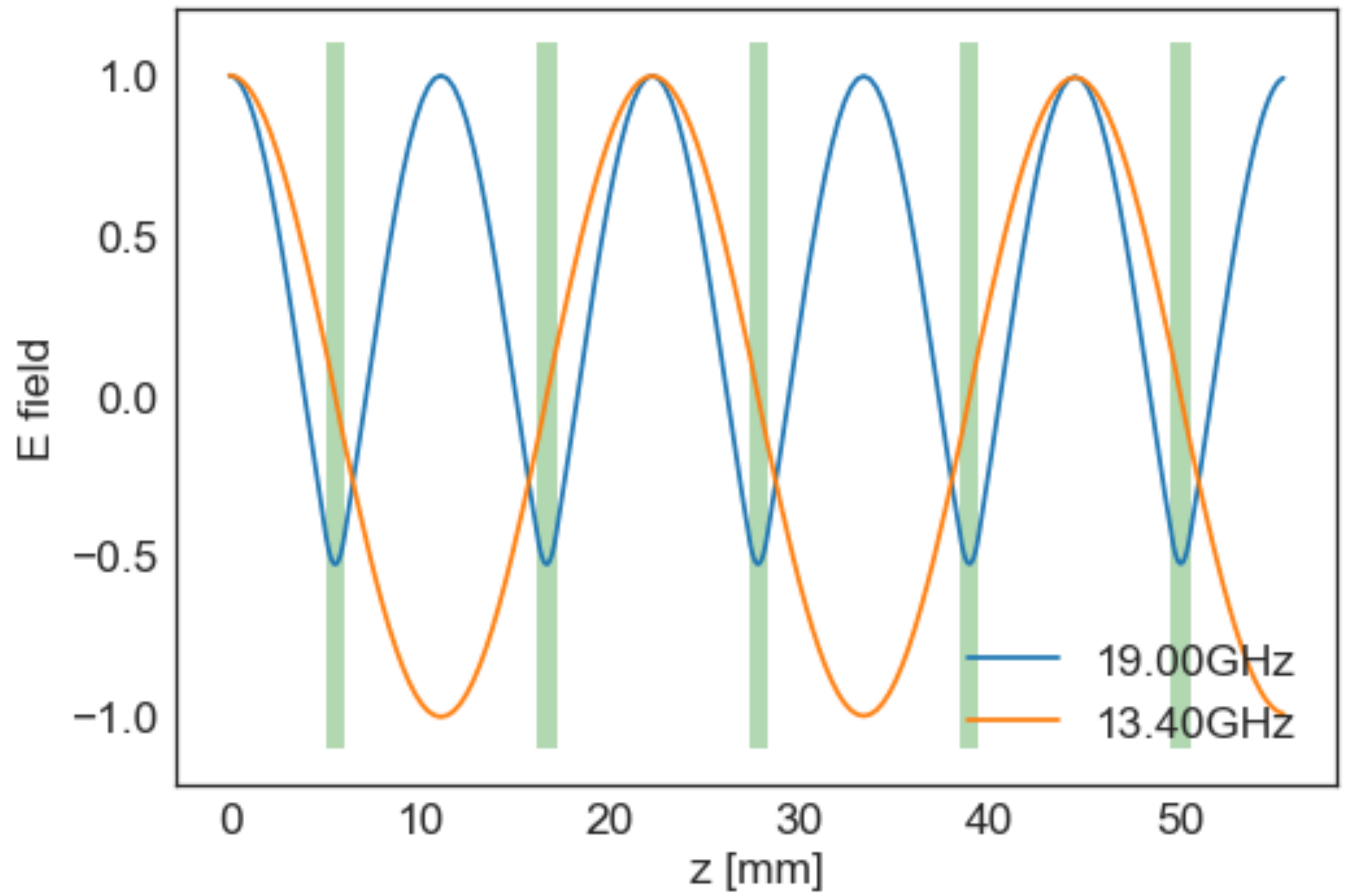
Disk spacing

"infinite booster"



- Dispersion from Bloch B.C.
    - "Band" structure
- Boost factor maximum
  @ the **boundary of 2nd pass/stop band**
    - Disk spacing for the boundary can be analytically calculated.
- Bloch impedance (Z_B): characteristic impedance of the periodic structure.

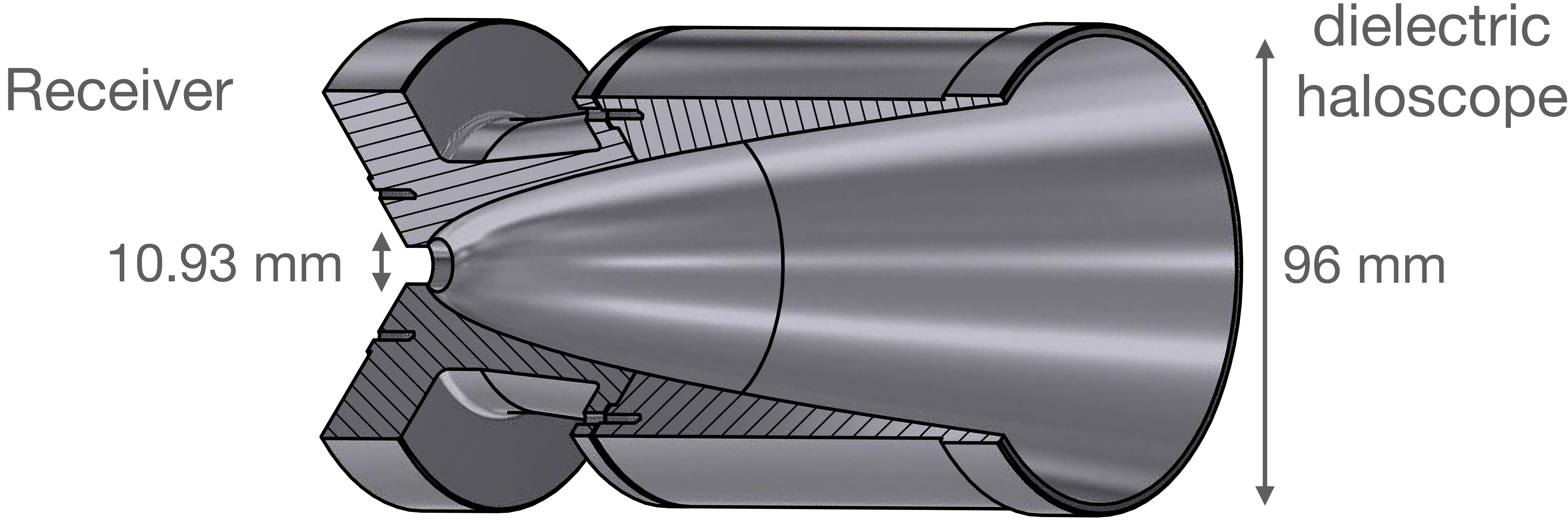


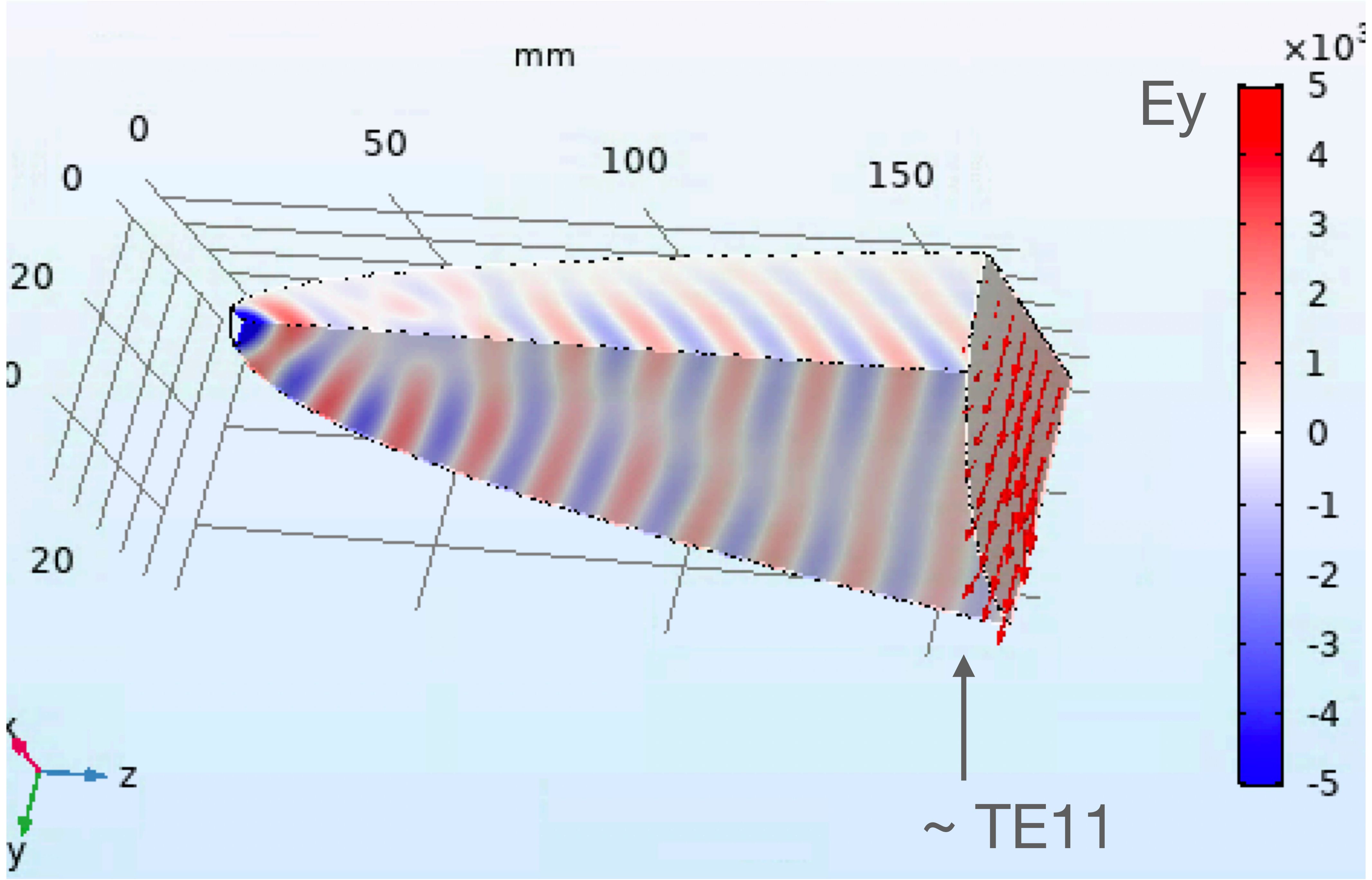


Simulation

parabolic taper

- “Matched” boundary
- RL > 20dB
- TE11 mode at the ports
- Additional gap btw. taper and booster.
- J. Diane, Int. J. Infrared Milli. Waves **5** (1984)





Chang Lee

Loss

- Simulation ~ 1dB vs. data > 6 dB
- Surface current leakage:
  solution: indium or EMI gasket
- Radiation leakage thru dielectric rims:
  solution: EMI gasket, metal sputtering