Search for Dark Matter Axions with the MADMAX experiment

Alexander Schmidt (RWTH Aachen)
for the MADMAX collaboration

- Acknowledgements:
  - many plots taken from Javier Redondo, Stefan Knirck, Jan Schütte-Engel, Frank Steffen, Olaf Reimann, Alex Millar, Georg Raffelt, Bela Majorovits, …

axions

AXION
energy

axion electrodynamics

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - J^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\partial^{\mu}a - \frac{1}{2}m_a^2a^2 - \frac{g_{a\gamma}}{4}F_{\mu\nu}\widetilde{F}^{\mu\nu}a,$$

axion DM modifies maxwell equations:

- new equations:

$$\begin{aligned} \boldsymbol{\nabla}\cdot\mathbf{E} &= \rho - g_{a\gamma}\mathbf{B}\cdot\boldsymbol{\nabla}a\,, \\ \boldsymbol{\nabla}\times\mathbf{B} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma}\left(\mathbf{B}\,\dot{a} - \mathbf{E}\times\boldsymbol{\nabla}a\right) \\ \boldsymbol{\nabla}\cdot\mathbf{B} &= 0\,, \\ \boldsymbol{\nabla}\times\mathbf{E} + \dot{\mathbf{B}} &= 0\,, \\ \ddot{a} - \boldsymbol{\nabla}^2a + m_a^2a &= g_{a\gamma}\mathbf{E}\cdot\mathbf{B}\,. \end{aligned}$$

axion electrodynamics

- zero-velocity limit (axion at rest):

$$a(t) = a_0 e^{-im_a t}$$

- with frequency

$$\omega = m_a$$

- dark matter density:

$$\rho_a = \frac{m_a^2 |a_0|^2}{2} = f_{\rm DM} \frac{300\ {\rm MeV}}{{\rm cm}^3}$$

- the homogeneous axion-induced E field can be derived as

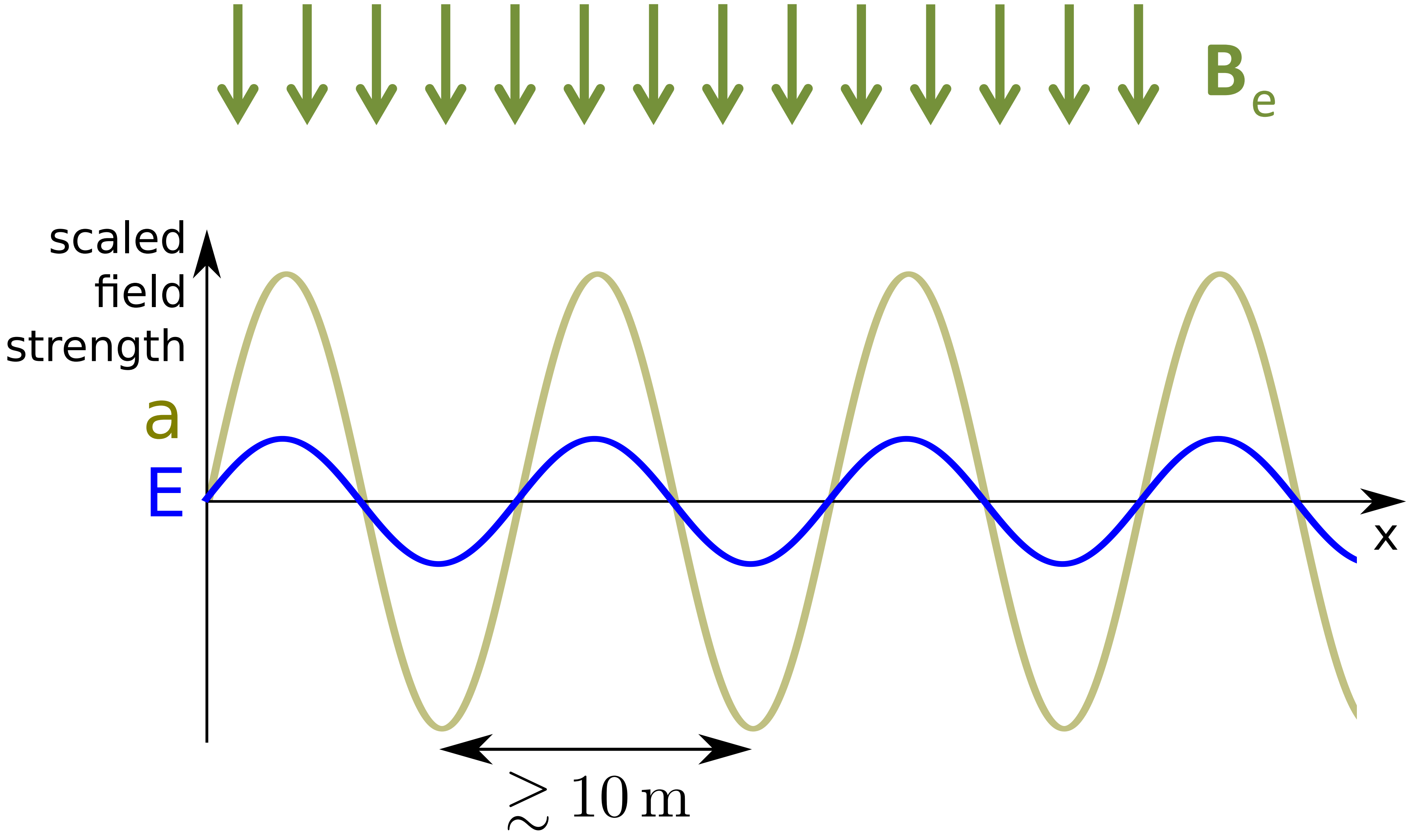
$$\mathbf{E}_a(t) = -\frac{g_{a\gamma}\mathbf{B}_{\rm e}}{\epsilon} a(t)$$

- with

$$\mathbf{E}_a(t) = -\frac{\mathbf{E}_0}{\epsilon} e^{-im_a t}$$

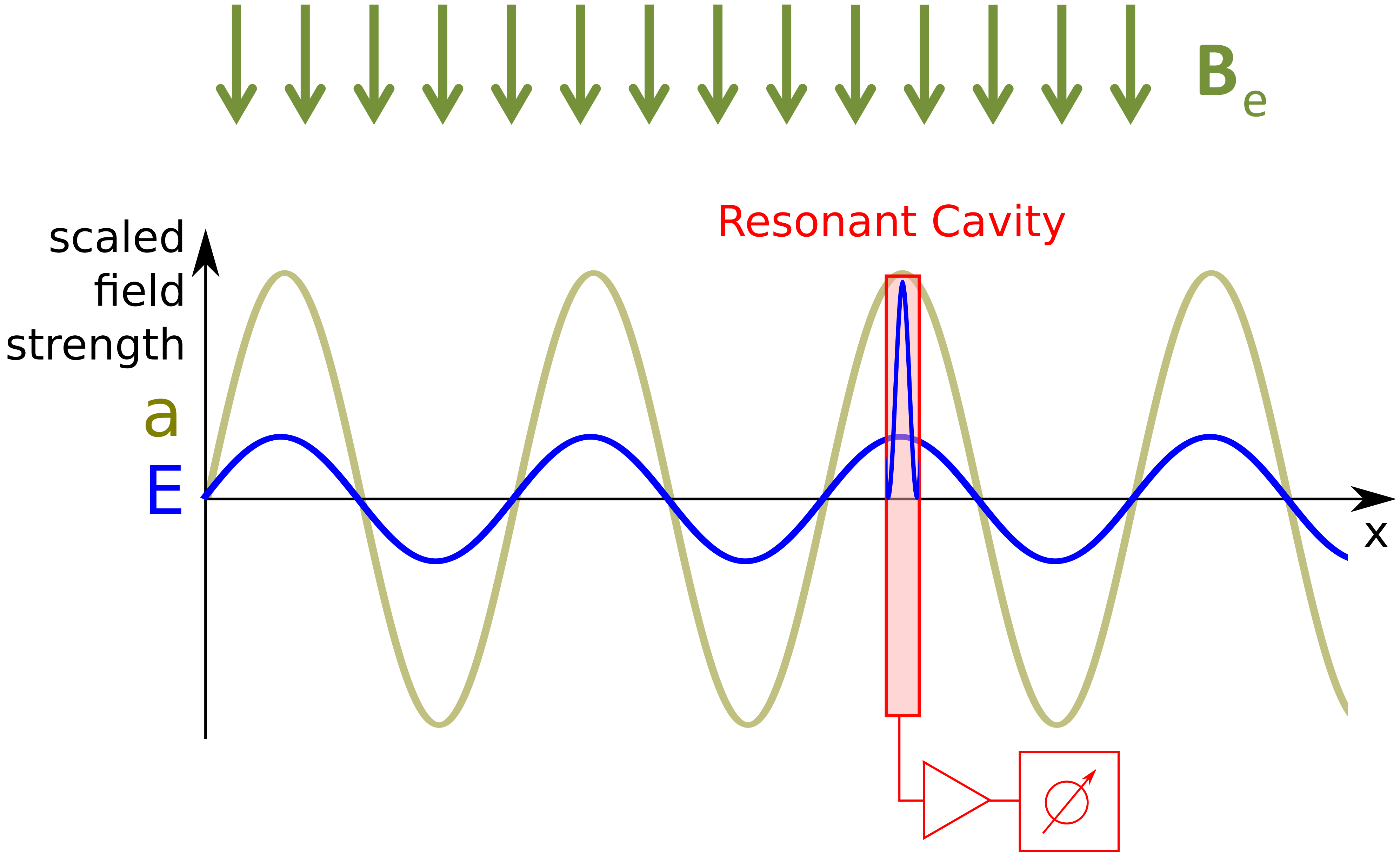
$$E_0 = 1.3 \times 10^{-12}\ {\rm V/m}\ \frac{B_{\rm e}}{10\ {\rm T}}\ |C_{a\gamma}| f_{\rm DM}^{1/2}$$

axion electrodynamics



$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$$

axion electrodynamics



$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$$

challenges for ADMX-like experiments

emitted power from cavity

arXiv:1804.05750

$$P_{\mathrm{axion}} = 1.9 \times 10^{-22}\mathrm{W} \left(\frac{V}{136\ l}\right) \left(\frac{B}{6.8\ \mathrm{T}}\right)^2 \left(\frac{C}{0.4}\right) \left(\frac{g_\gamma}{0.97}\right)^2 \left(\frac{\rho_{\mathrm{a}}}{0.45\ \mathrm{GeV\ cm^{-3}}}\right) \left(\frac{f}{650\ \mathrm{MHz}}\right) \left(\frac{Q}{50,000}\right)$$

needs to scale with f^{-3}

is expensive

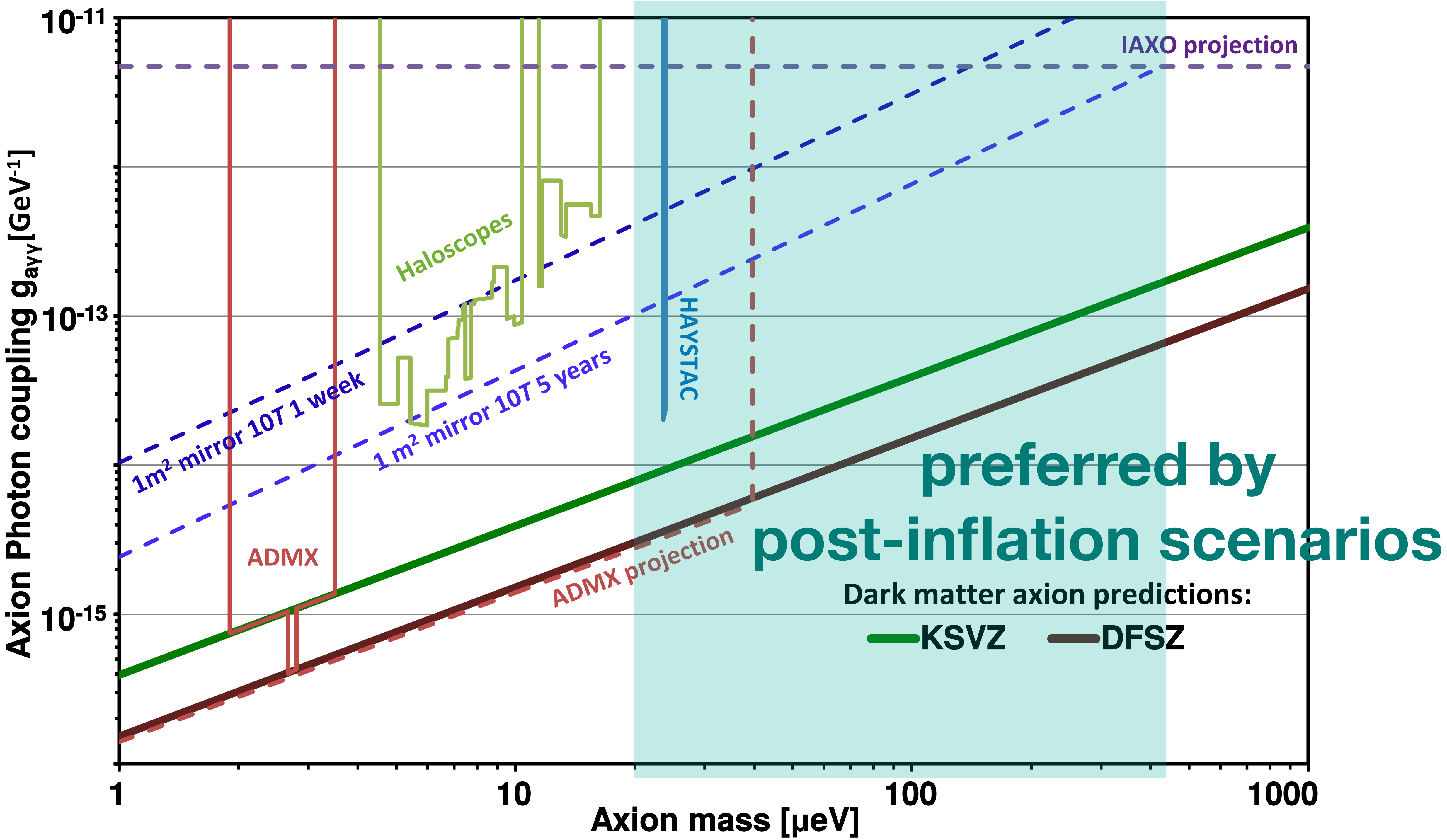
given by nature

scan this

technical limitations, decreases with larger *f*

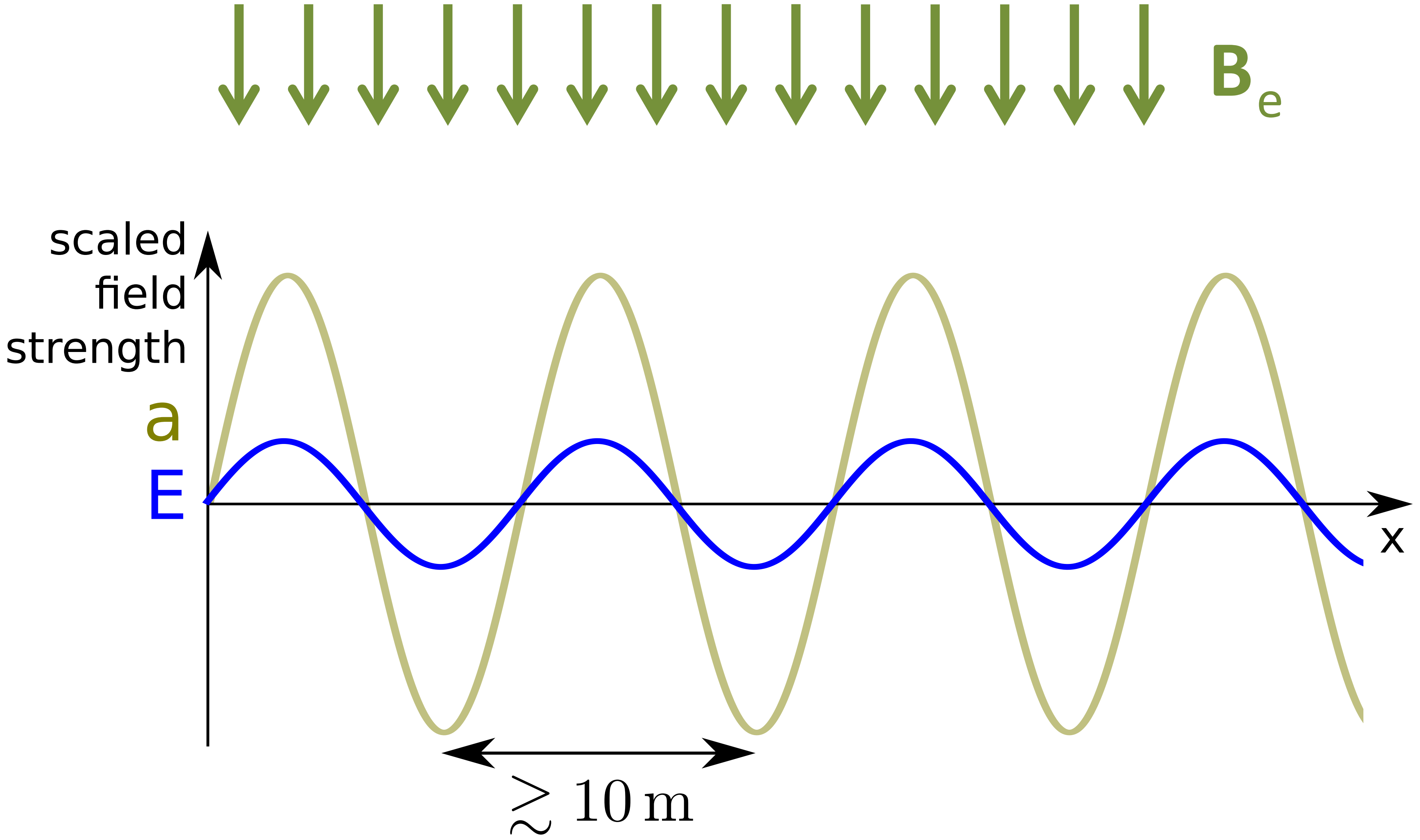
reach of cavity haloscope limited for higher frequency (mass)

ADMX reach



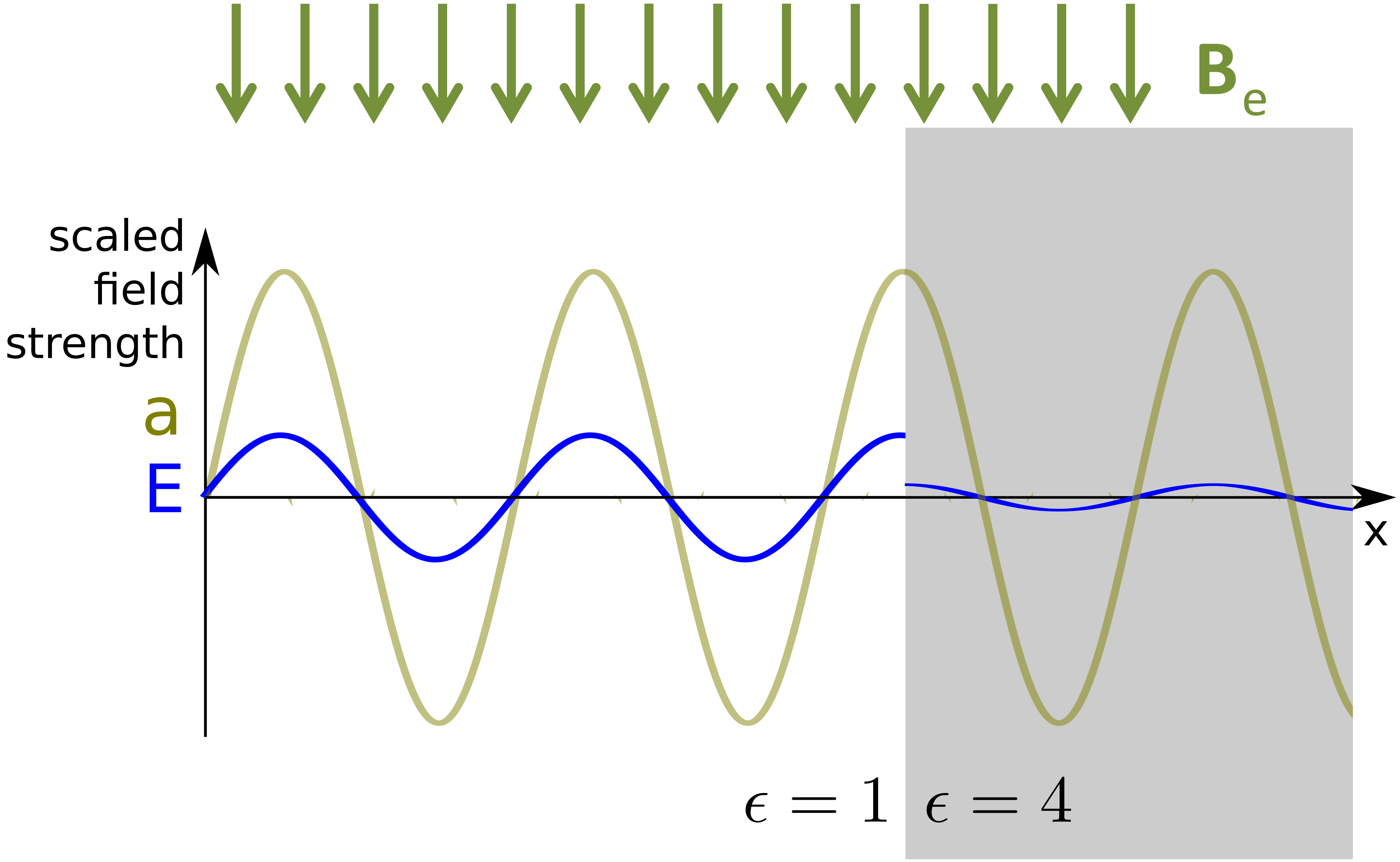
10^{-11}
10^{-13}
10^{-15}
Axion Photon coupling $g_{a\gamma\gamma}$[GeV^{-1}]
IAXO projection
Haloscopes
HAYSTAC
1m² mirror 10T 1 week
1 m² mirror 10T 5 years
ADMX
ADMX projection
preferred by
post-inflation scenarios
Dark matter axion predictions:
KSVZ
DFSZ
1
10
100
1000
Axion mass [μeV]

dielectric haloscope



$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\boxed{\epsilon}}a$$

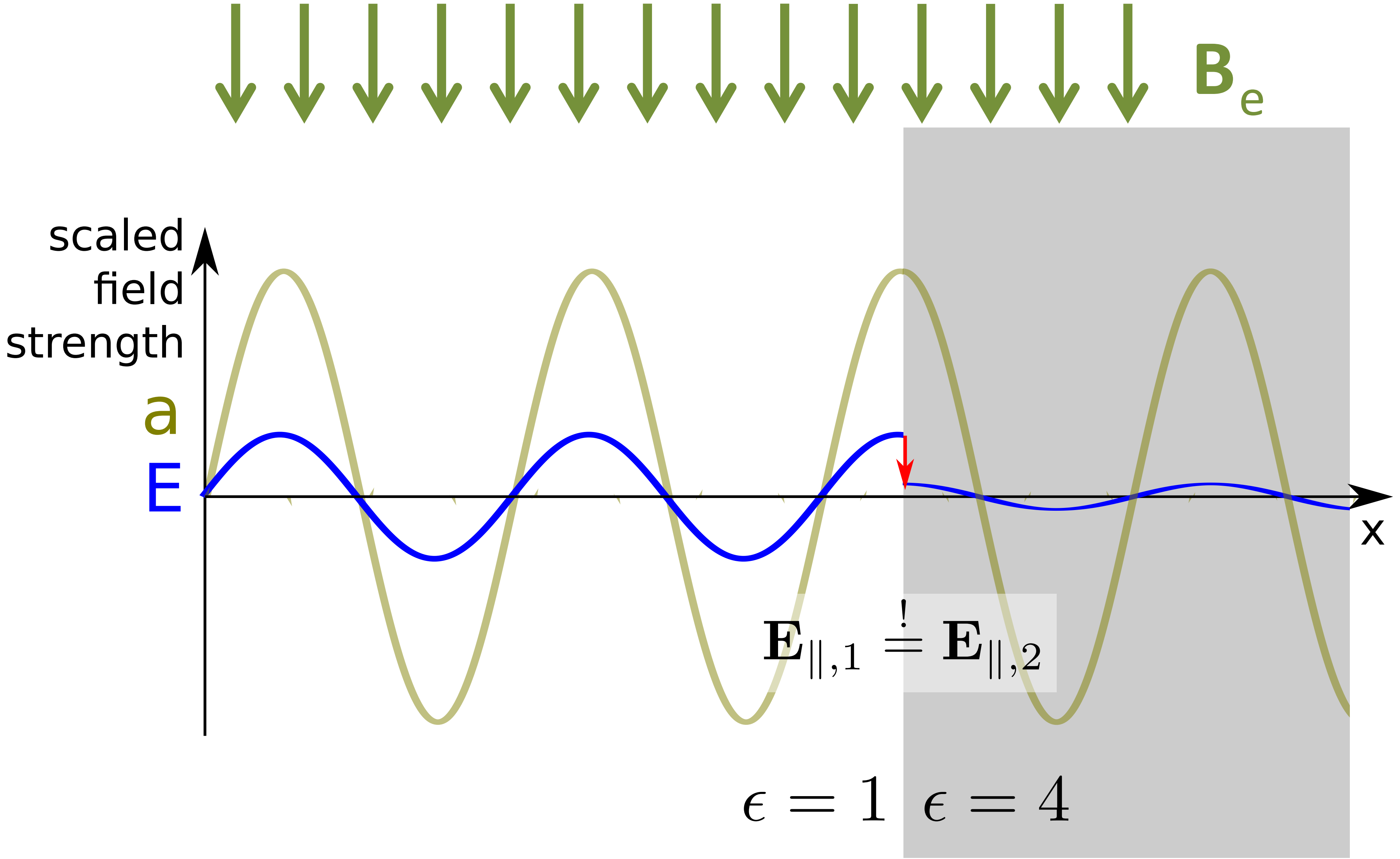
dielectric haloscope



$\epsilon = 1$ $\epsilon = 4$

$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$$

dielectric haloscope

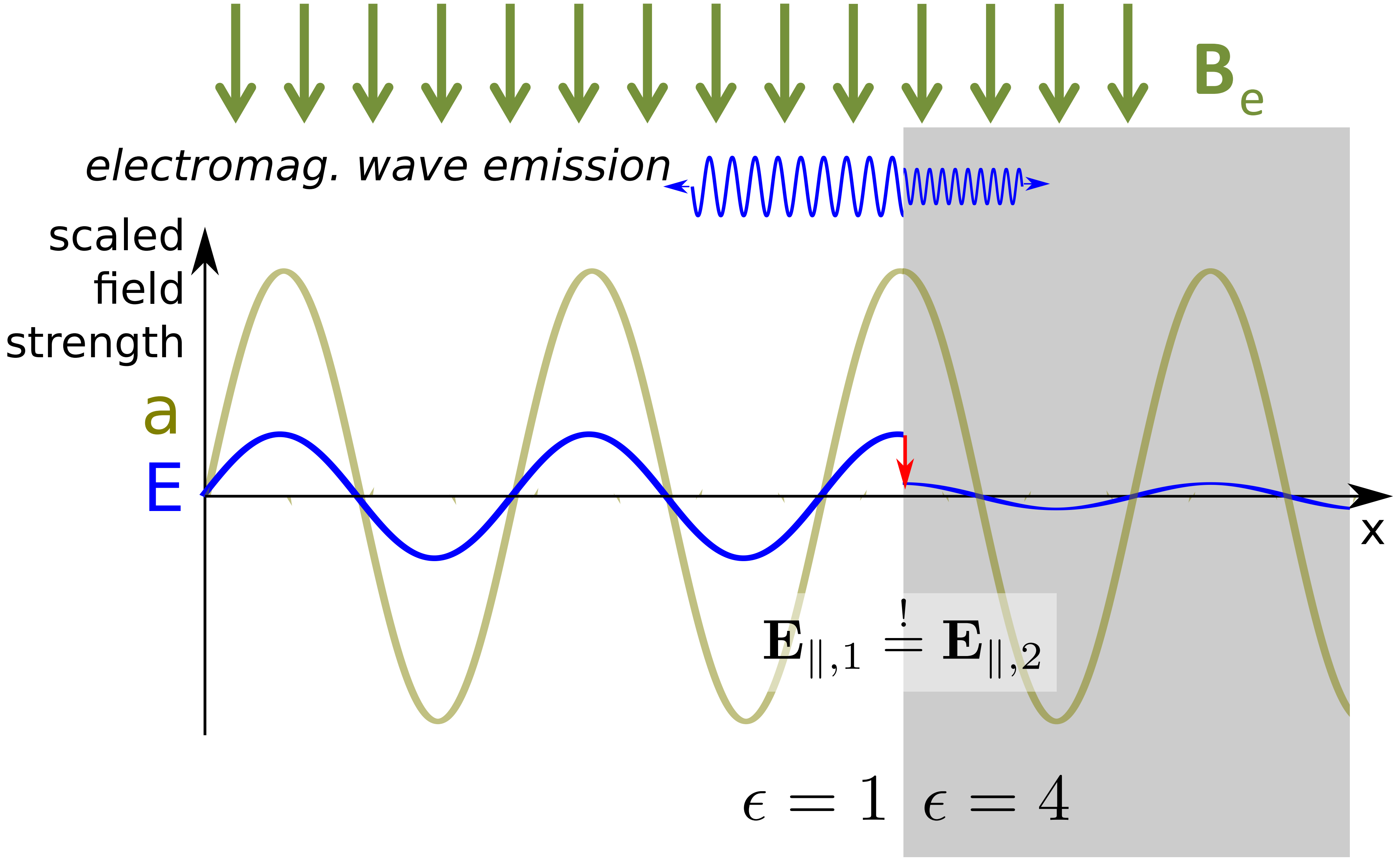


$$\mathbf{E}_{\parallel,1} \overset{!}{=} \mathbf{E}_{\parallel,2}$$

$\epsilon = 1$ $\epsilon = 4$

$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$$

dielectric haloscope



$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$

radiation at an interface

- continuity:

$$\mathbf{E}_{\|,1} = \mathbf{E}_{\|,2} \quad \text{and} \quad \mathbf{H}_{\|,1} = \mathbf{H}_{\|,2}$$

Continuity of $\mathbf{E}_{\|}$

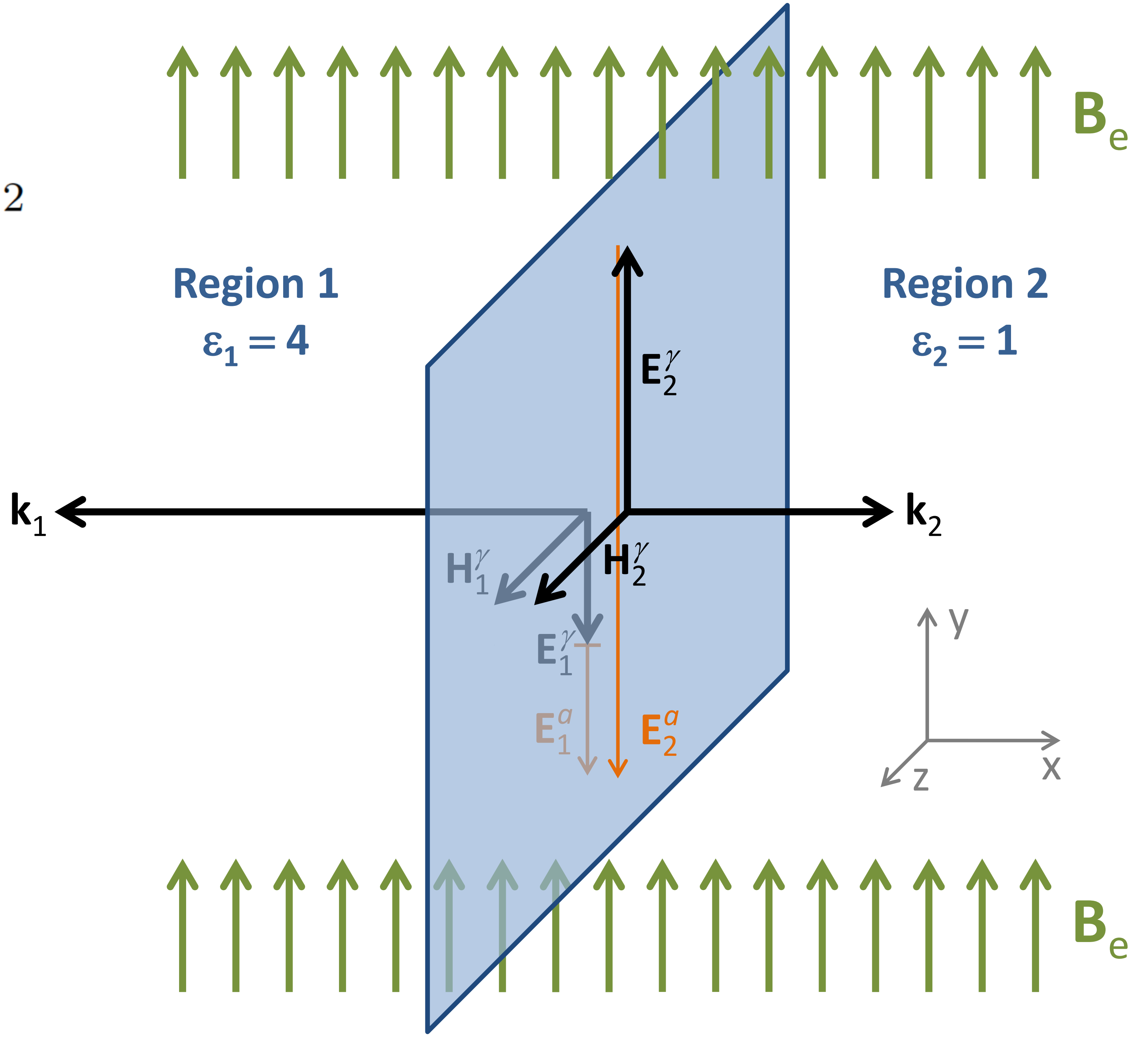
$$E_1^\gamma + E_1^a = E_2^\gamma + E_2^a$$

Continuity of $\mathbf{H}_{\|}$

$$-\frac{\epsilon_1}{n_1} E_1^\gamma = \frac{\epsilon_2}{n_2} E_2^\gamma$$

because Maxwell eq:

$$\mathbf{k} \times \mathbf{H}_\gamma + \omega\epsilon\mathbf{E}_\gamma = 0$$



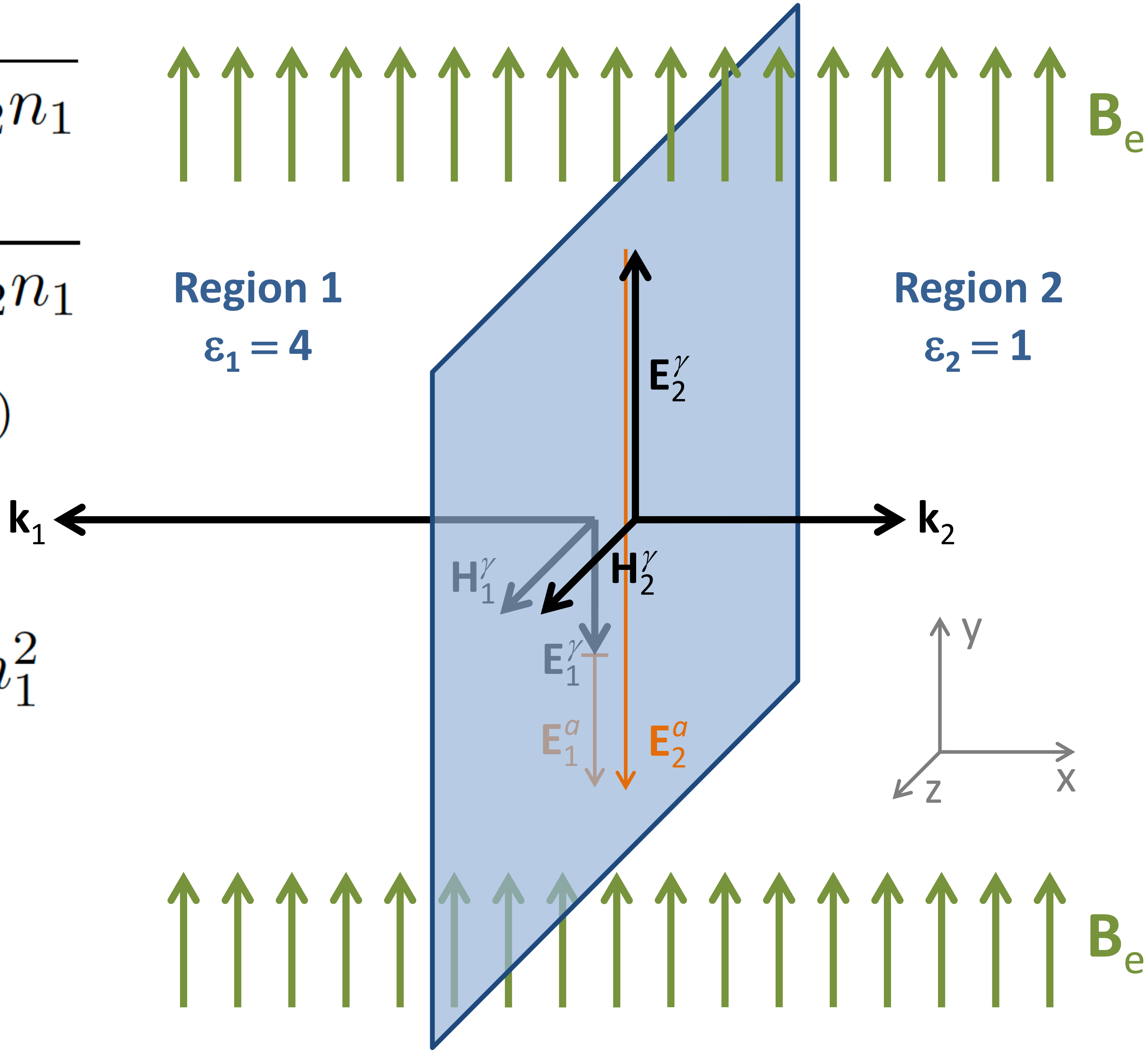
radiation at an interface

we get for the propagating fields:

$$E_1^\gamma = +\left(E_2^a - E_1^a\right)\frac{\epsilon_2 n_1}{\epsilon_1 n_2 + \epsilon_2 n_1}$$

$$E_2^\gamma = -\left(E_2^a - E_1^a\right)\frac{\epsilon_1 n_2}{\epsilon_1 n_2 + \epsilon_2 n_1}$$

$$E_{1,2}^a\, e^{-i\omega t}\,, \qquad E_{1,2}^\gamma\, e^{-i(\omega t - k_{1,2}x)}$$



assume:

$$\mu_1 = \mu_2 = 1 \text{ so that } \epsilon_1 = n_1^2$$

with the *E_a* field discontinuity:

$$E_2^a - E_1^a = -(\epsilon_2^{-1} - \epsilon_1^{-1})E_0$$

result:

$$E_1^\gamma = -\frac{E_0}{n_1}\left(\frac{1}{n_2} - \frac{1}{n_1}\right)$$

radiation at an interface

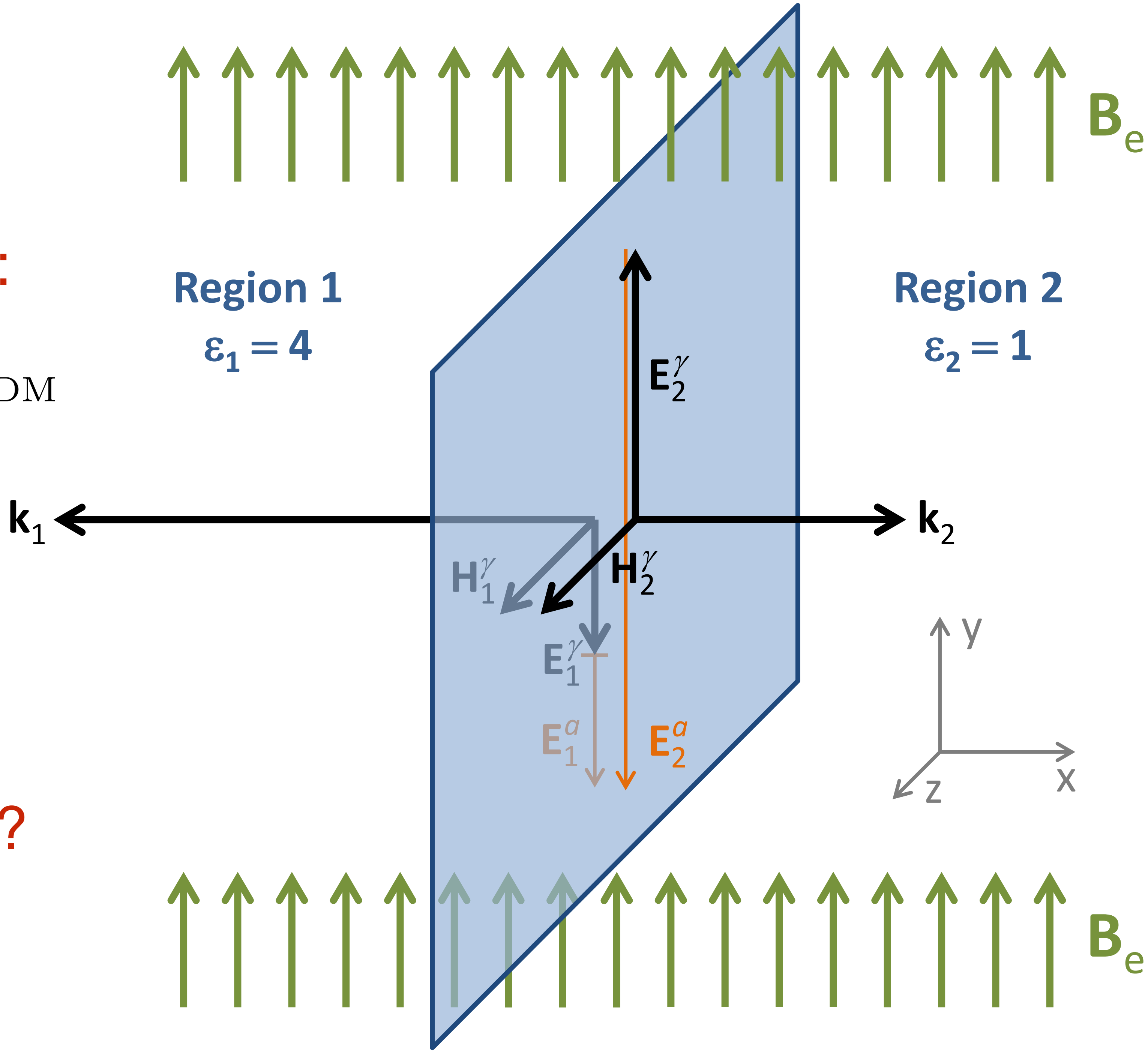
arXiv:1612.07057

- power emission by interface:

$$\frac{P}{A} = 2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\mathrm{T}}\right)^2 C_{a\gamma}^2 f_{\mathrm{DM}}$$

- too small to detect
- stronger B field? larger area?

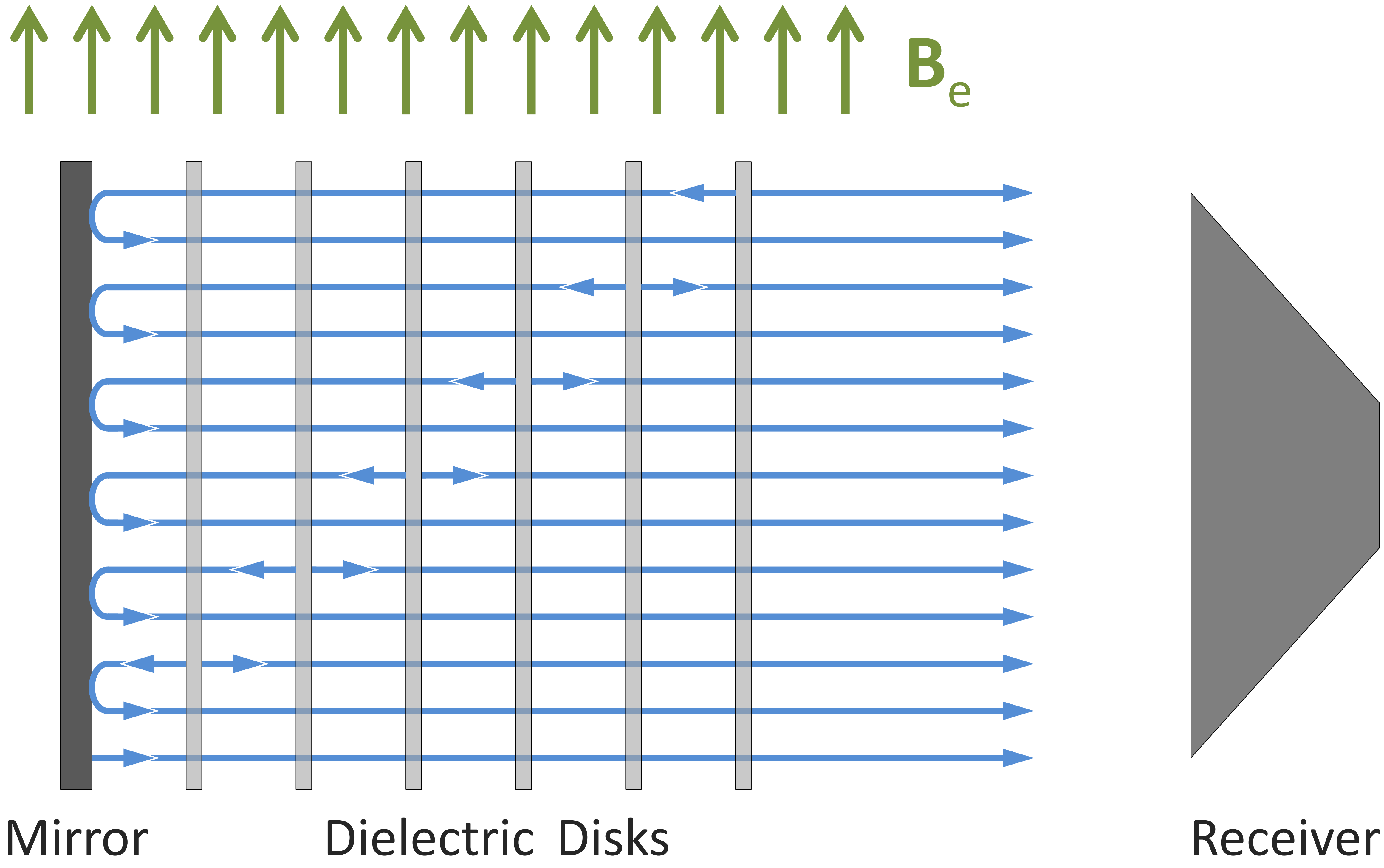
➡resonator



dielectric haloscope

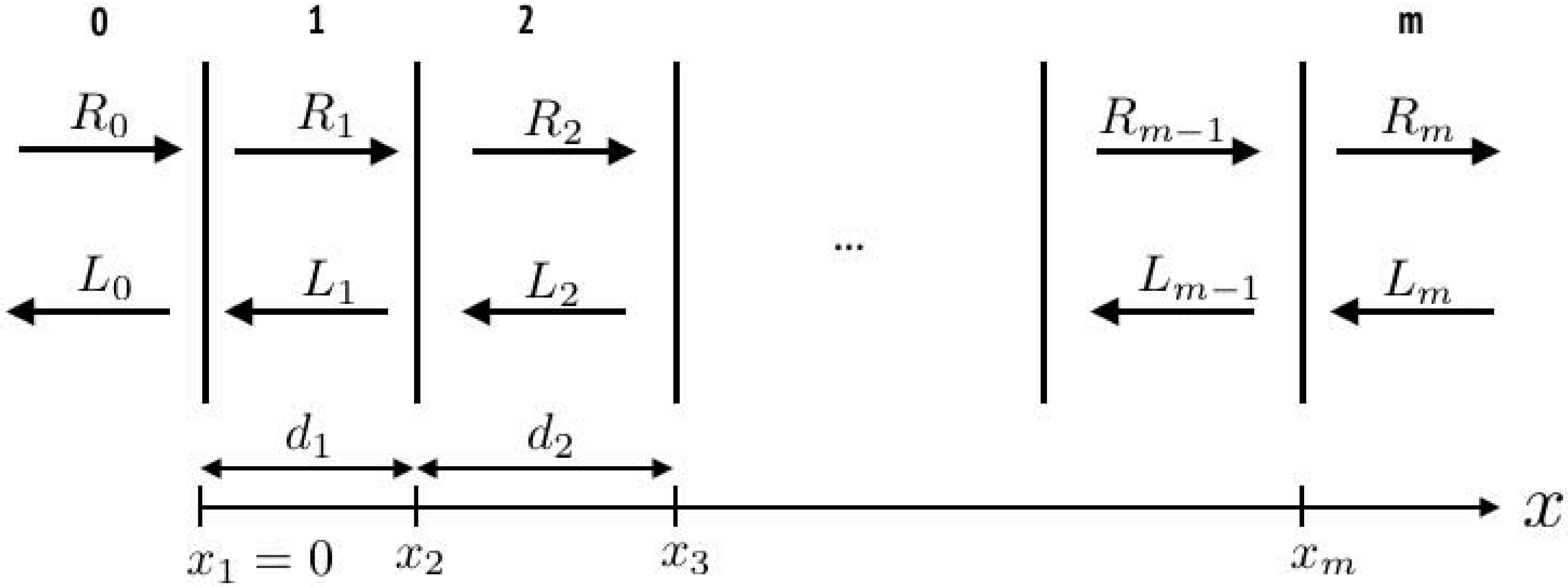
arXiv:1612.07057

- resonator: multiple layers



dielectric haloscope

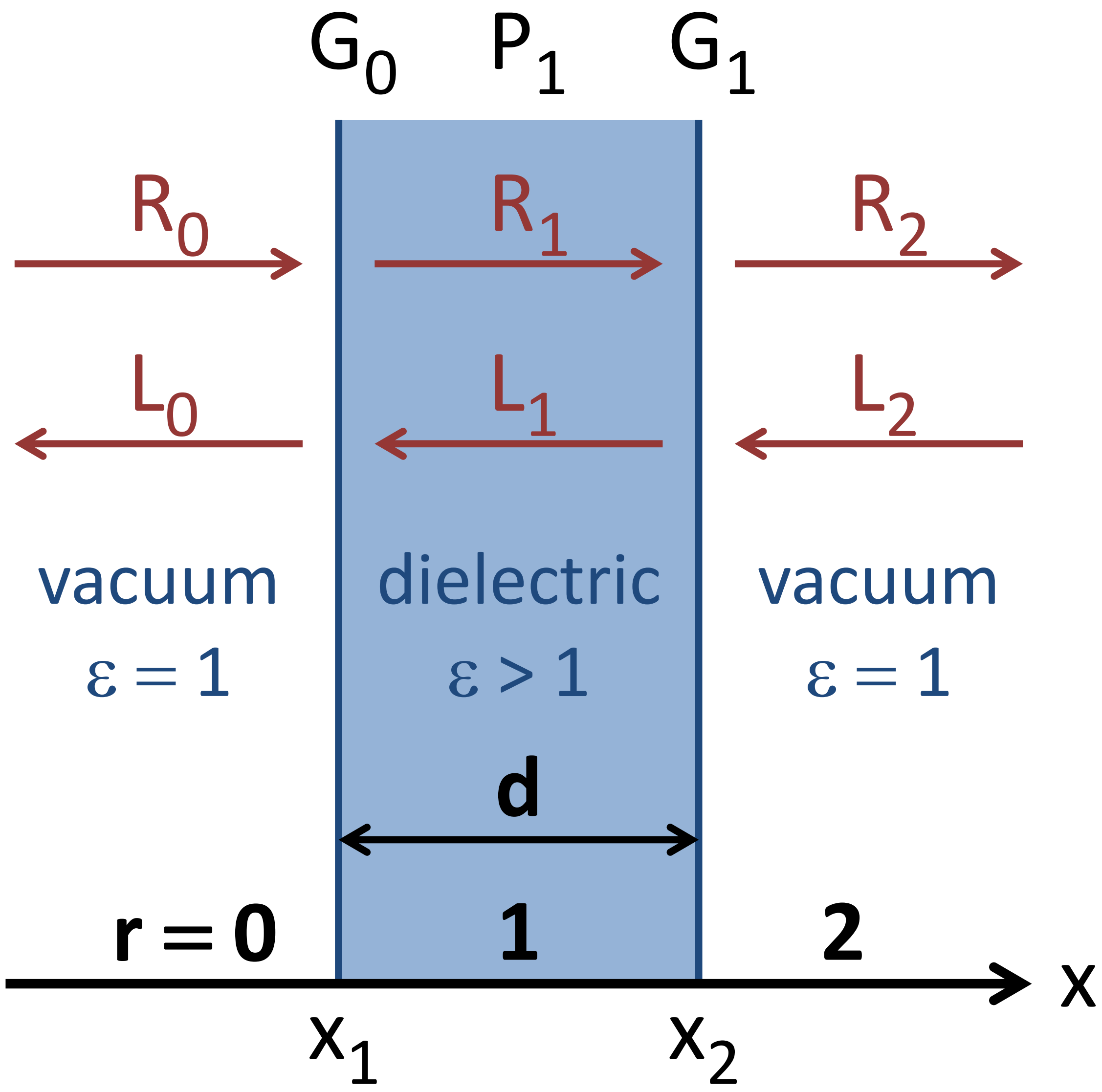
- coherent superposition of amplitudes produced at all interfaces



- each layer transmits and reflects
- EM waves moving left and right
- transfer matrix formalism to relate amplitudes (skip here)
- can act as forced oscillator
- EM radiation escapes at open end

special case: 1 disc

- simple case: one single disc with two interfaces



transmissivity:

$$\mathcal{T}_\mathrm{D} = \frac{i\,2n}{i\,2n\cos\delta + (n^2+1)\,\sin\delta}$$

reflectivity:

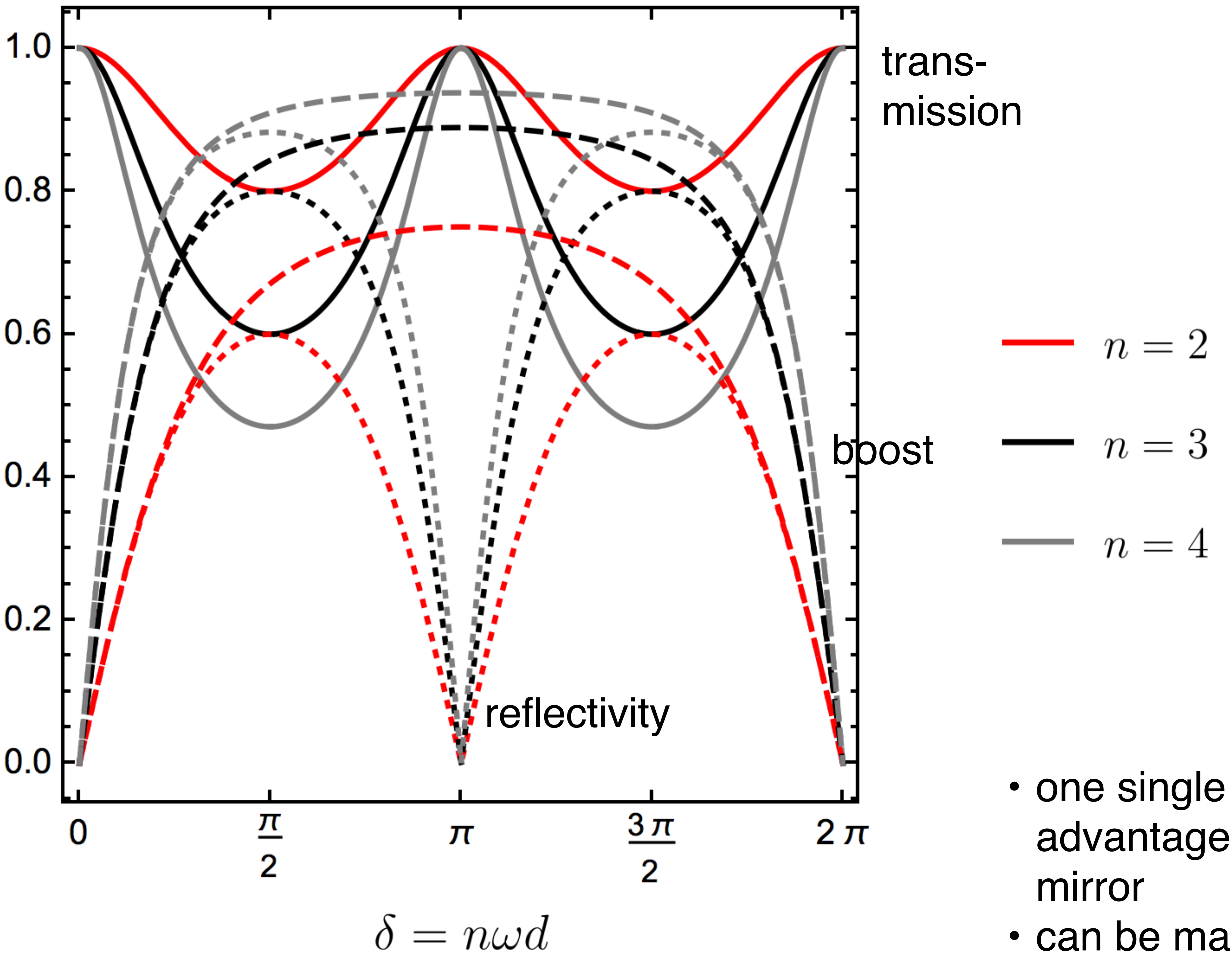
$$\mathcal{R}_\mathrm{D} = \frac{(n^2-1)\,\sin\delta}{i\,2n\cos\delta + (n^2+1)\,\sin\delta}$$

boost (amplitude in units of E_0):

$$\mathcal{B}_\mathrm{D} = \frac{(n^2-1)\sin(\delta/2)}{n^2\sin(\delta/2) + i\,n\cos(\delta/2)}$$

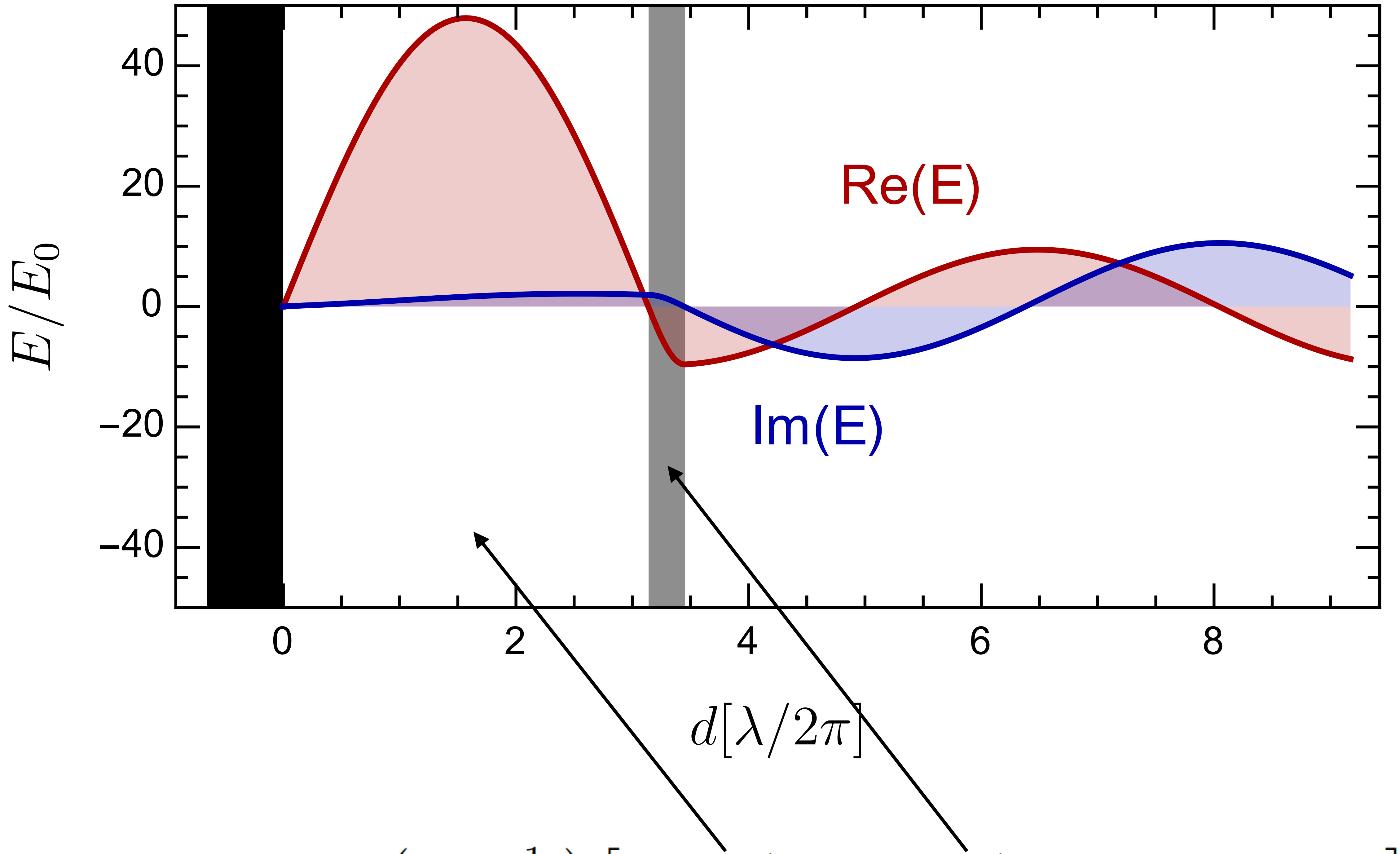
$$\text{Boost factor:} \qquad \beta = |\mathcal{B}|$$

special case: 1 disc



- one single disc has no advantage over single mirror
- can be made completely transparent

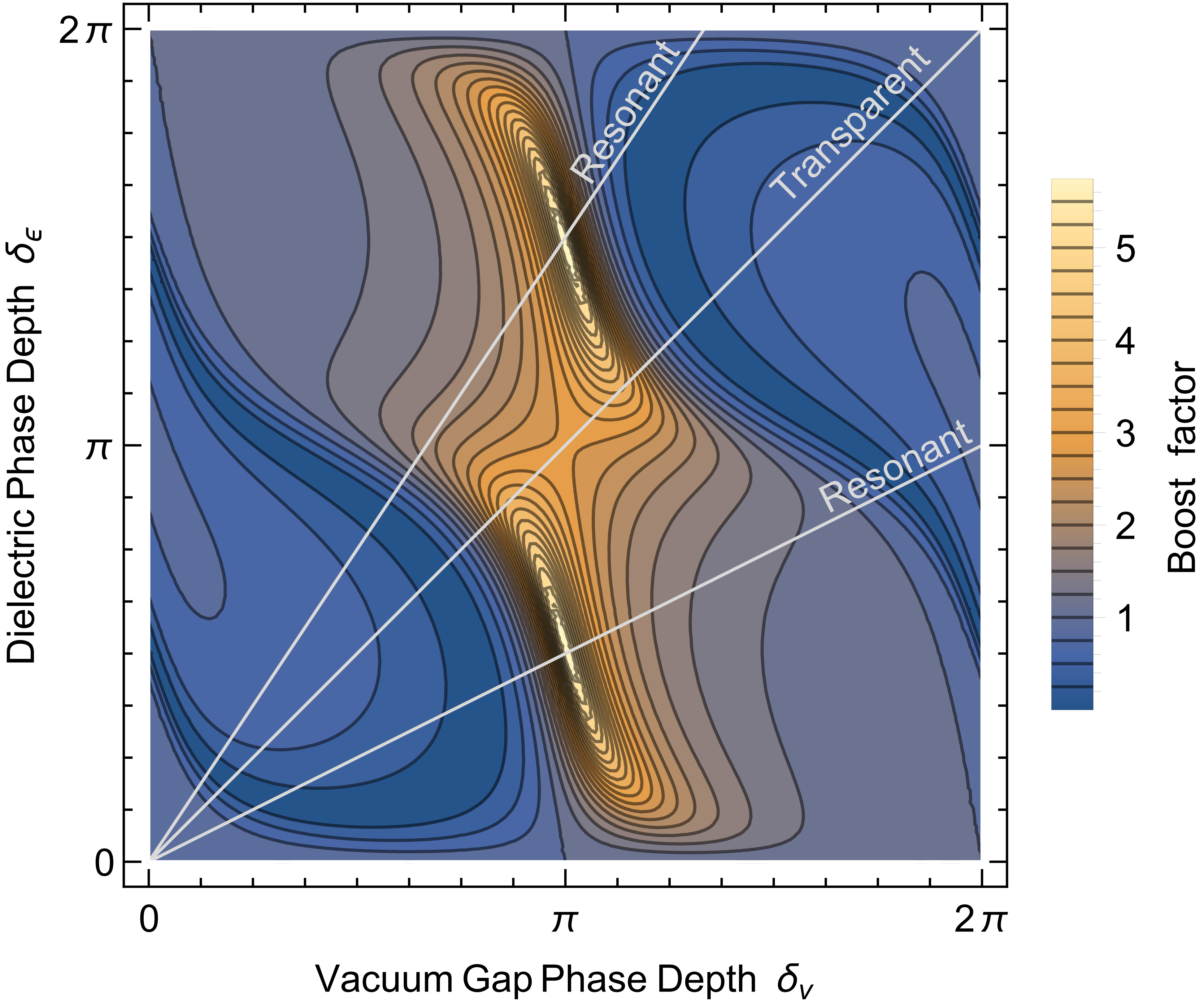
special case: mirror with 1 disc



boost

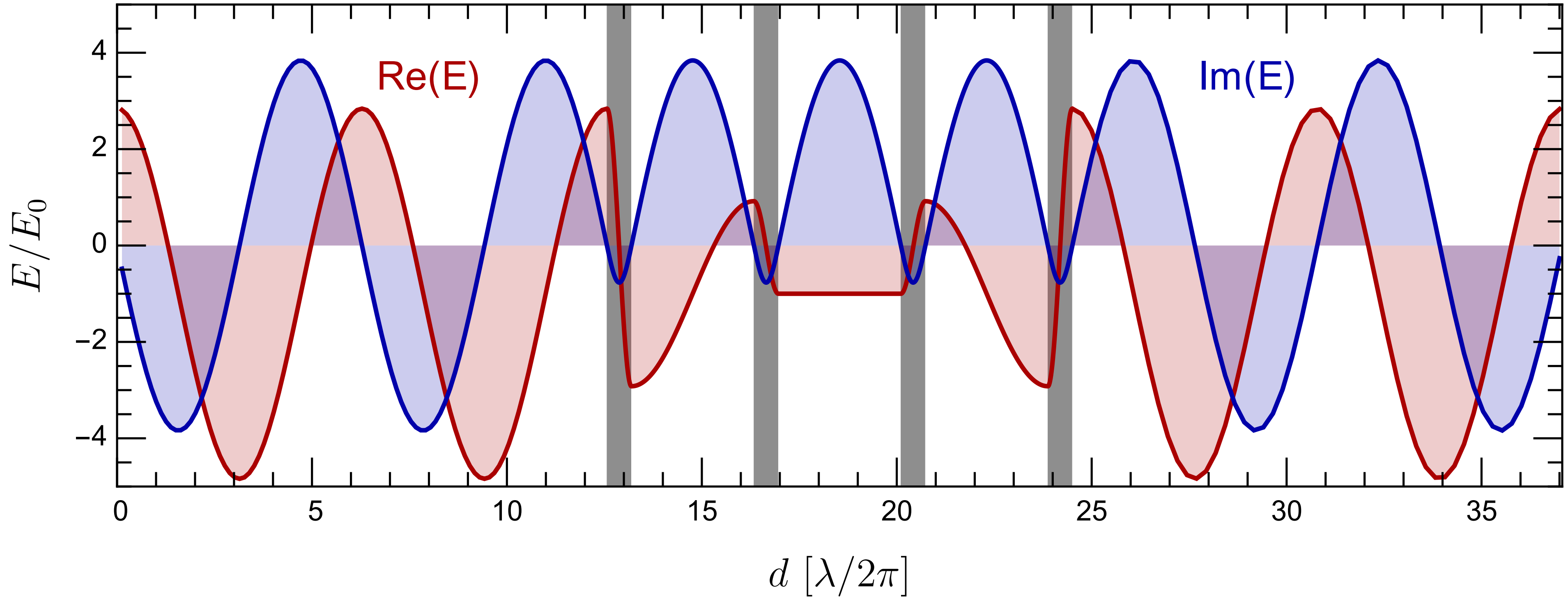
$$\mathcal{B}_\mathrm{C} = \frac{1-\left(1-\frac{1}{n^2}\right)\left[\cos\delta_v(1-\cos\delta_\epsilon)+n\sin\delta_\epsilon\sin\delta_v\right]}{e^{-i\delta_v}\cos\delta_\epsilon-\sin\delta_\epsilon\left(\frac{i}{n}\cos\delta_v+n\sin\delta_v\right)}$$

special case: mirror with 1 disc

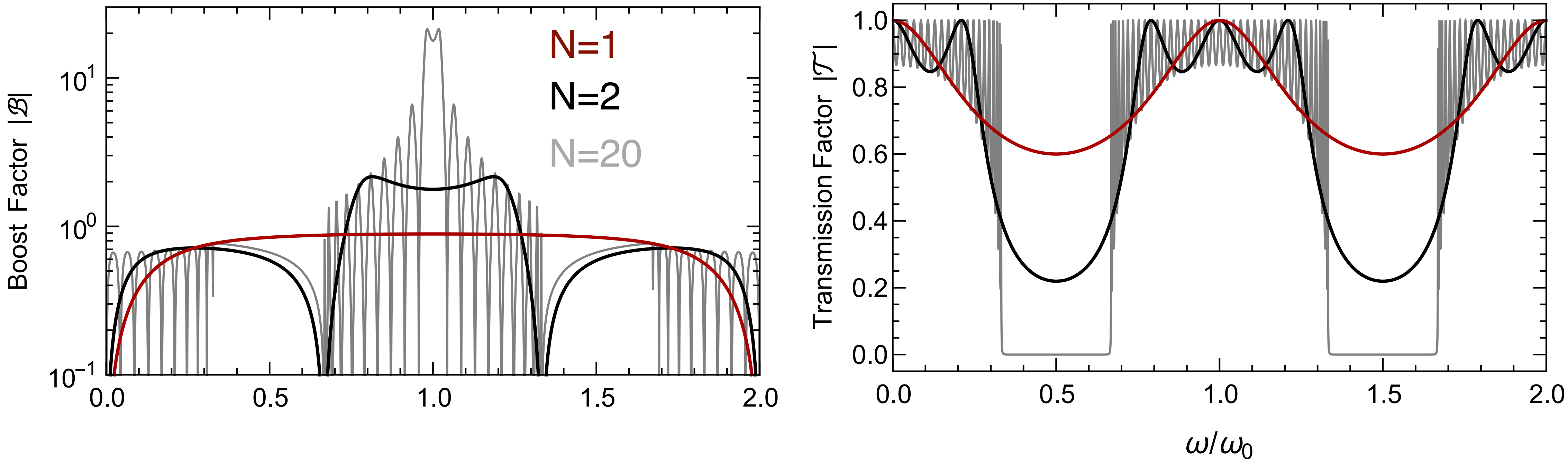


some other setups

4 discs, transparent, n=5



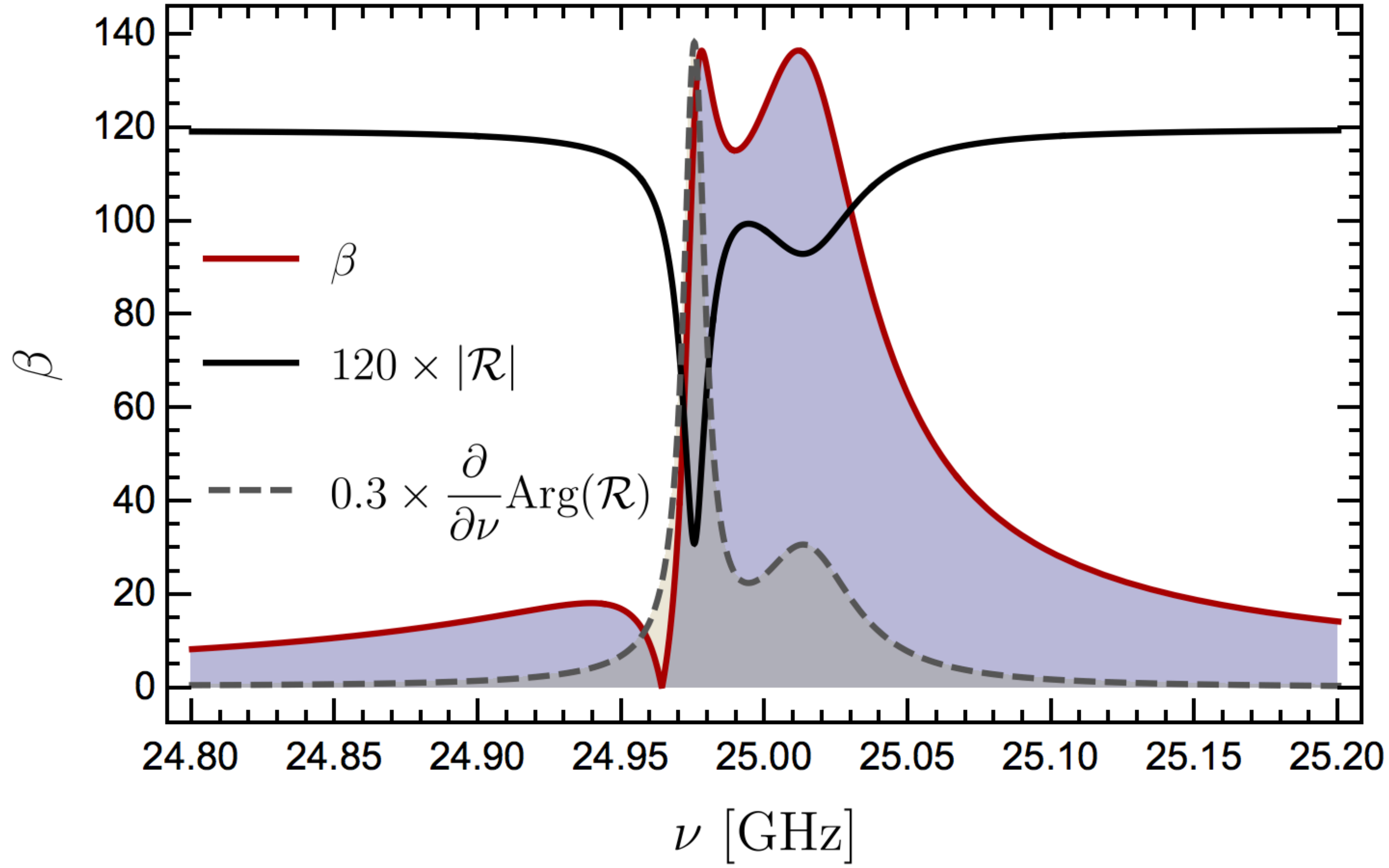
N discs, n=3, $d_\epsilon = \pi/n\omega_0$



- peak gets larger (with N) and narrower (1/N)

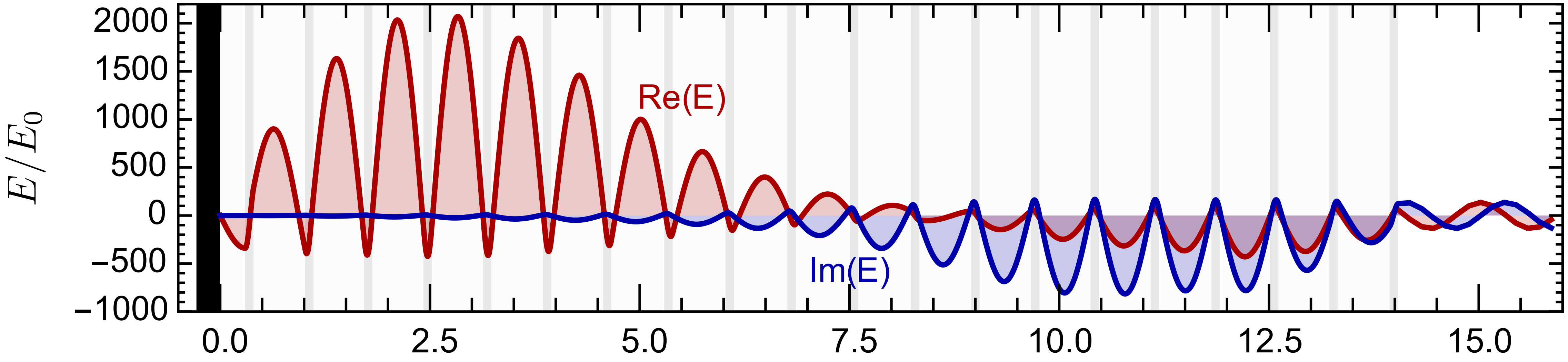
broadband response

20 discs with mirror, n=5



- desired bandwidth 50MHz
- find optimal disc positions by random walk in 20 dim param space

First Maximum

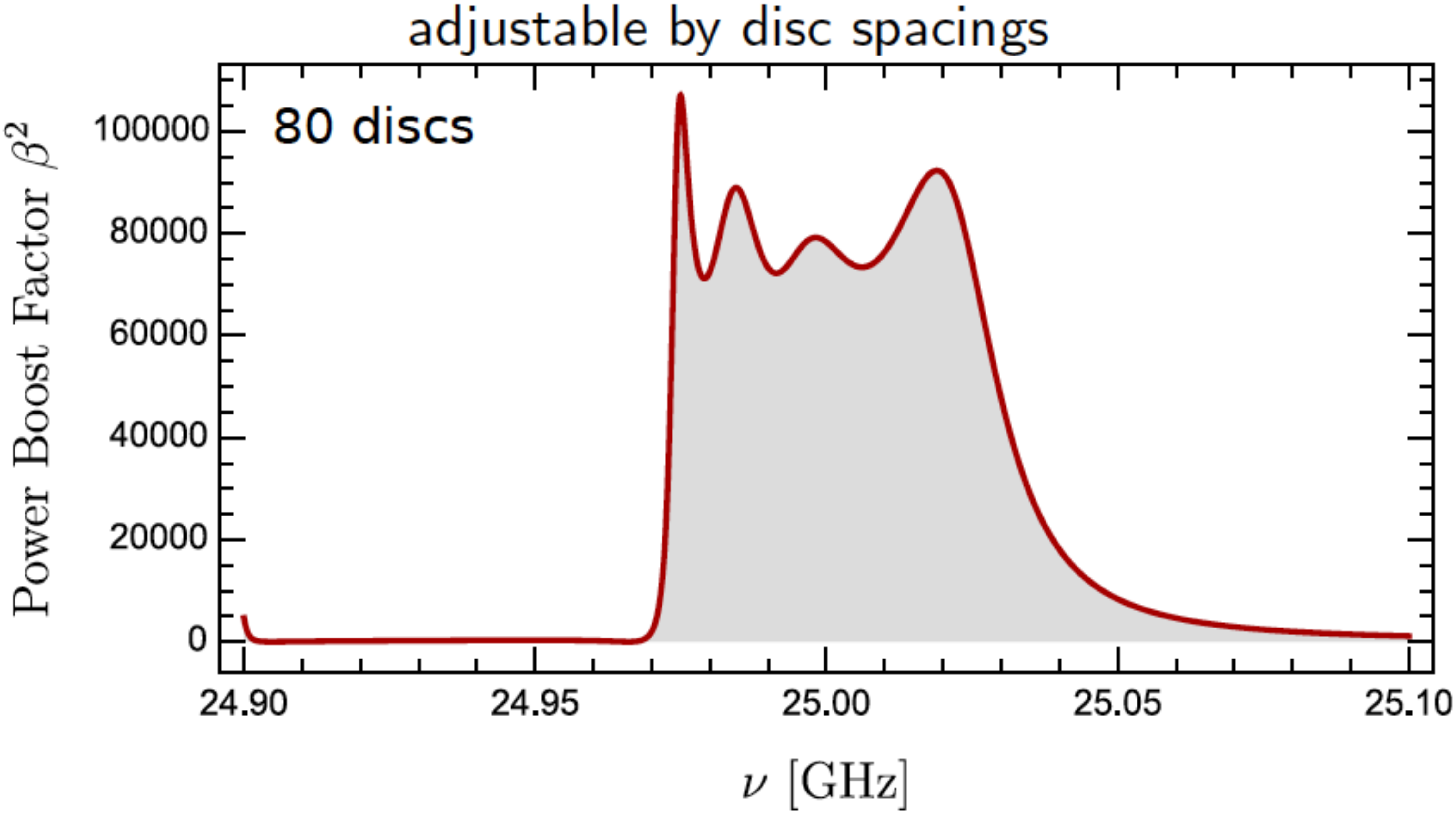


- miracle:
  - axion-photon conversion can be boosted by appropriate disc placement
  - emitted power goes with boost^2

$$\frac{P}{A} = 2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\mathrm{T}} \right)^2 C_{a\gamma}^2 f_{\mathrm{DM}} \bullet \beta^2$$

broadband response

- boosted power emission by 80 layers:



strategy

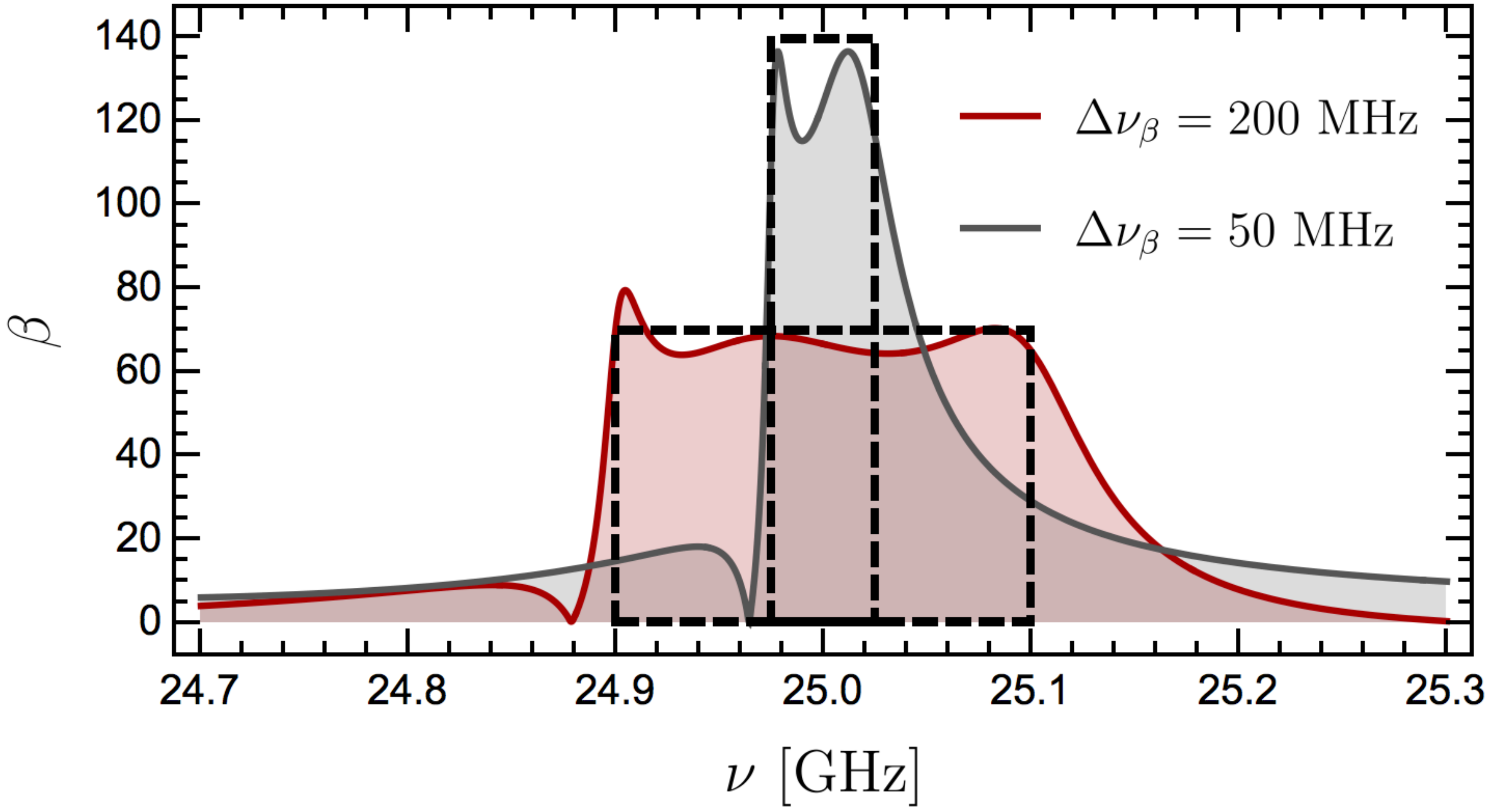
arXiv:1612.07057

operating principles

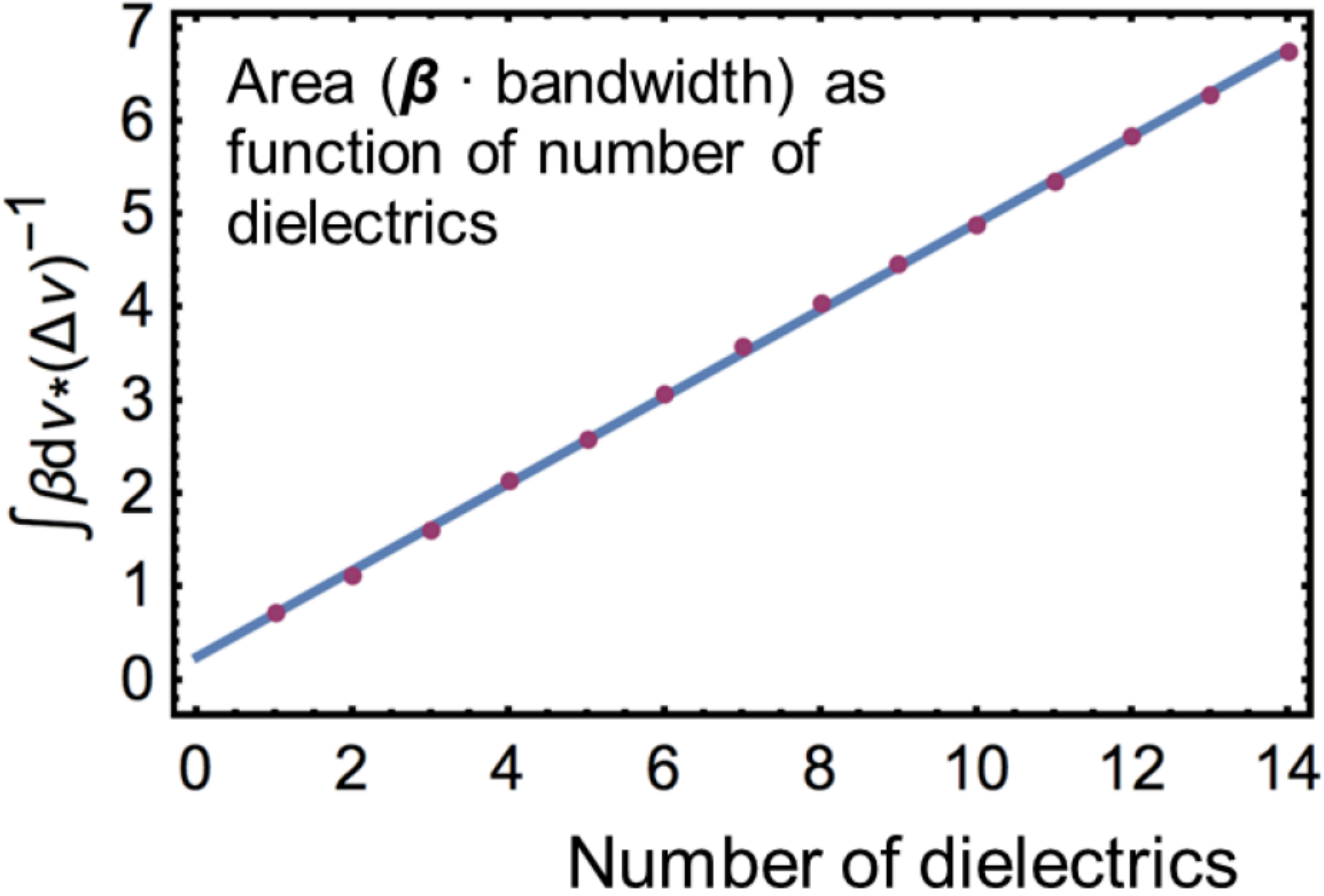
- equidistant layers:
  - large boost, good S/N
  - narrow frequency range
  - frequent disk -repositioning required
- slight misalignment of layers:
  - smaller boost, worse S/N
  - broad frequency range
  - less repositioning

→trade-off for optimal sensitivity

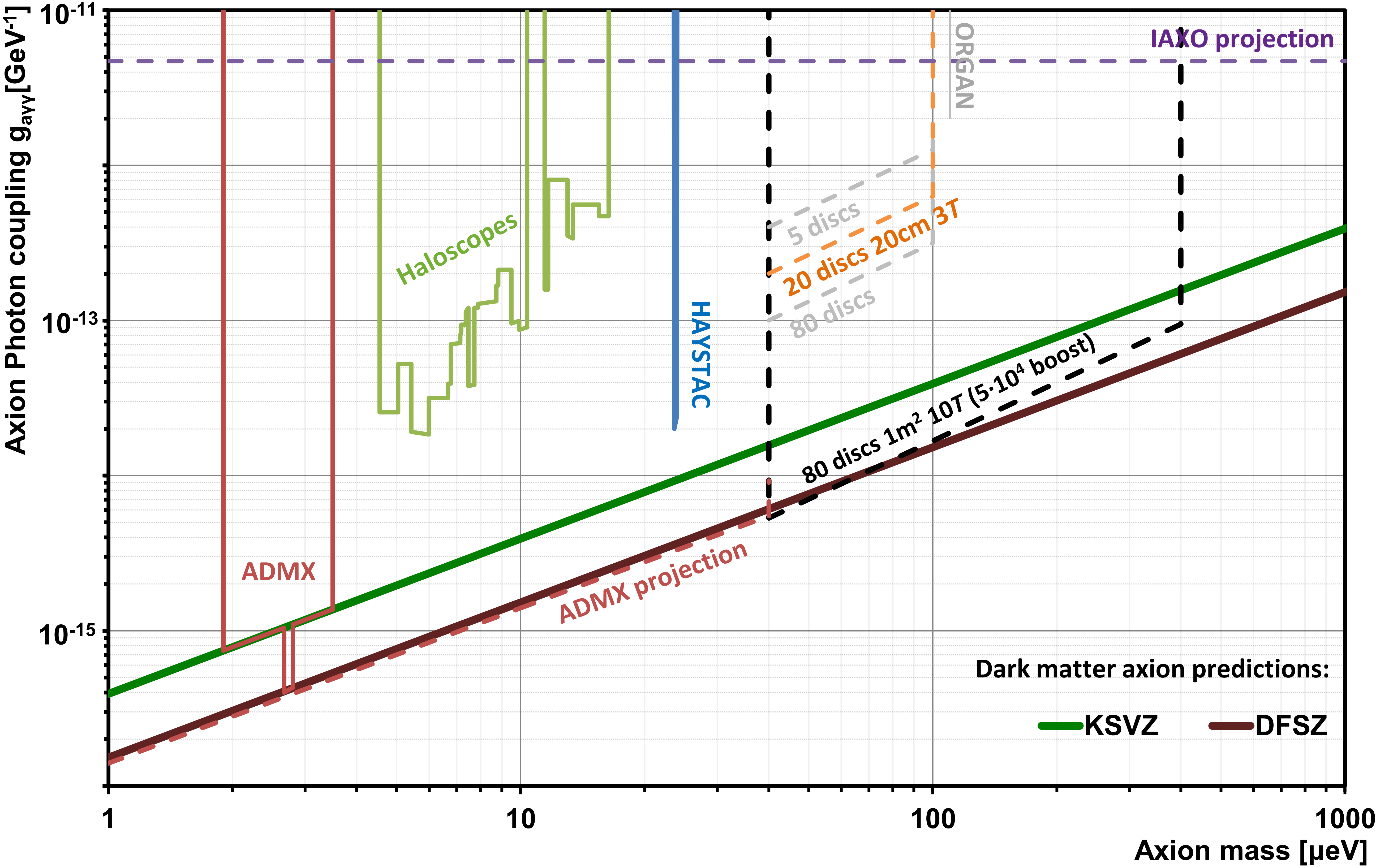
- all disks need individual high-precision adjustment



area law

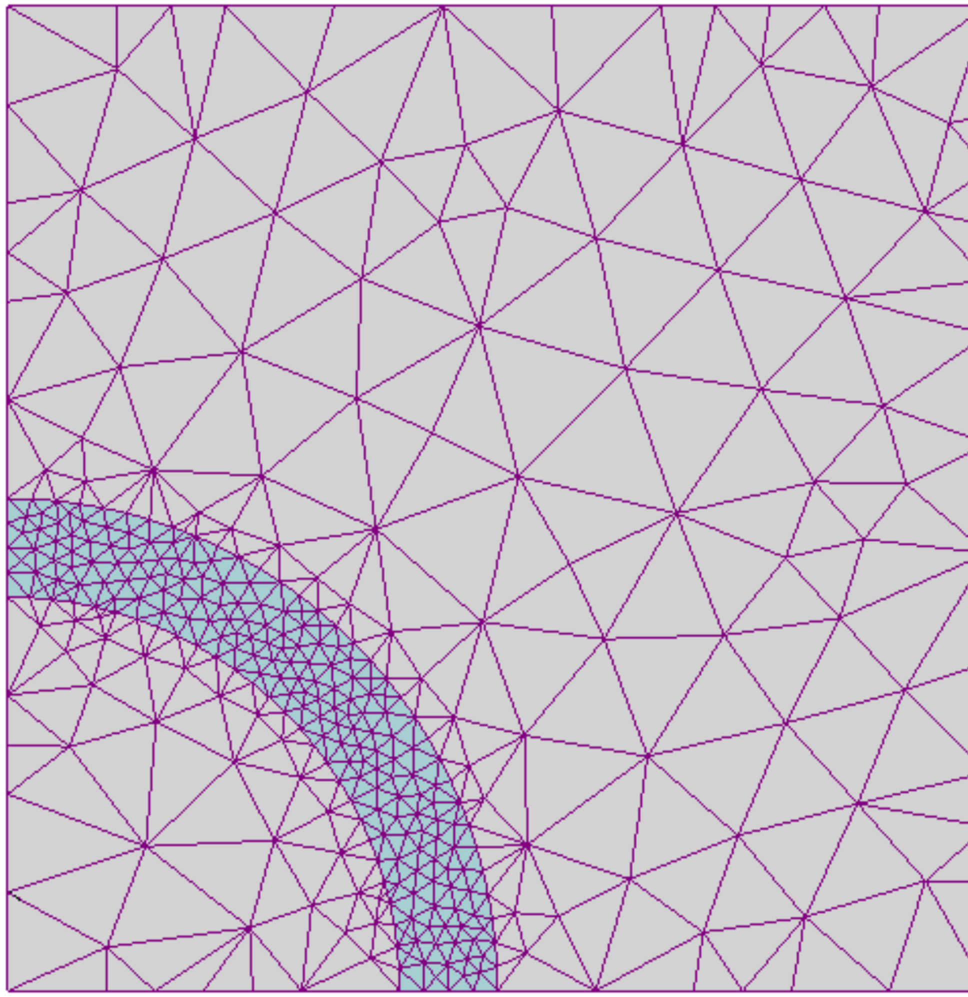

Area ($\boldsymbol{\beta}$ · bandwidth) as function of number of dielectrics
$\int \beta dv_*(\Delta v)^{-1}$
0
1
2
3
4
5
6
7
0
2
4
6
8
10
12
14
Number of dielectrics

sensitivity calculation



simulation

- all of previous slides was for an idealized 1D calculation
- realistic situations include: diffraction, dielectric loss, tilts, surface roughness
- investigated with finite element simulations (FEM)
  - yields approximate values of the unknowns at discrete number of points over the simulation domain
  - subdivides a large problem into smaller, simpler parts (called finite elements)
  - simple equations that model these finite elements are then assembled into a larger system of equations that models the entire problem

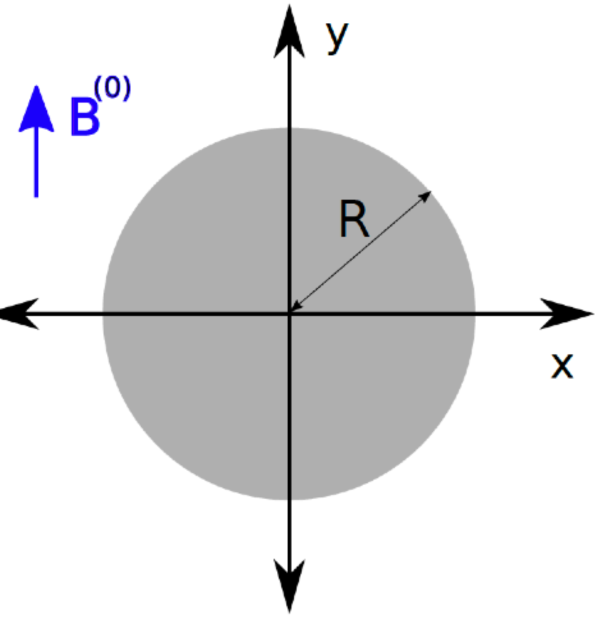


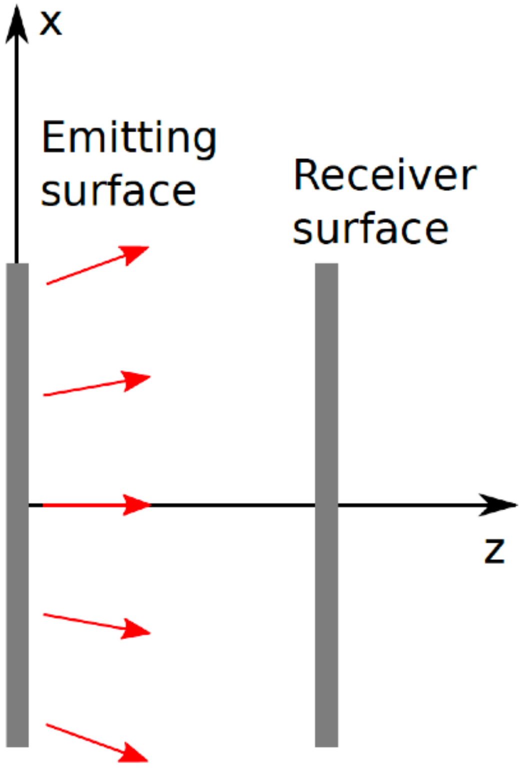
FEM simulation

- PDE to solve

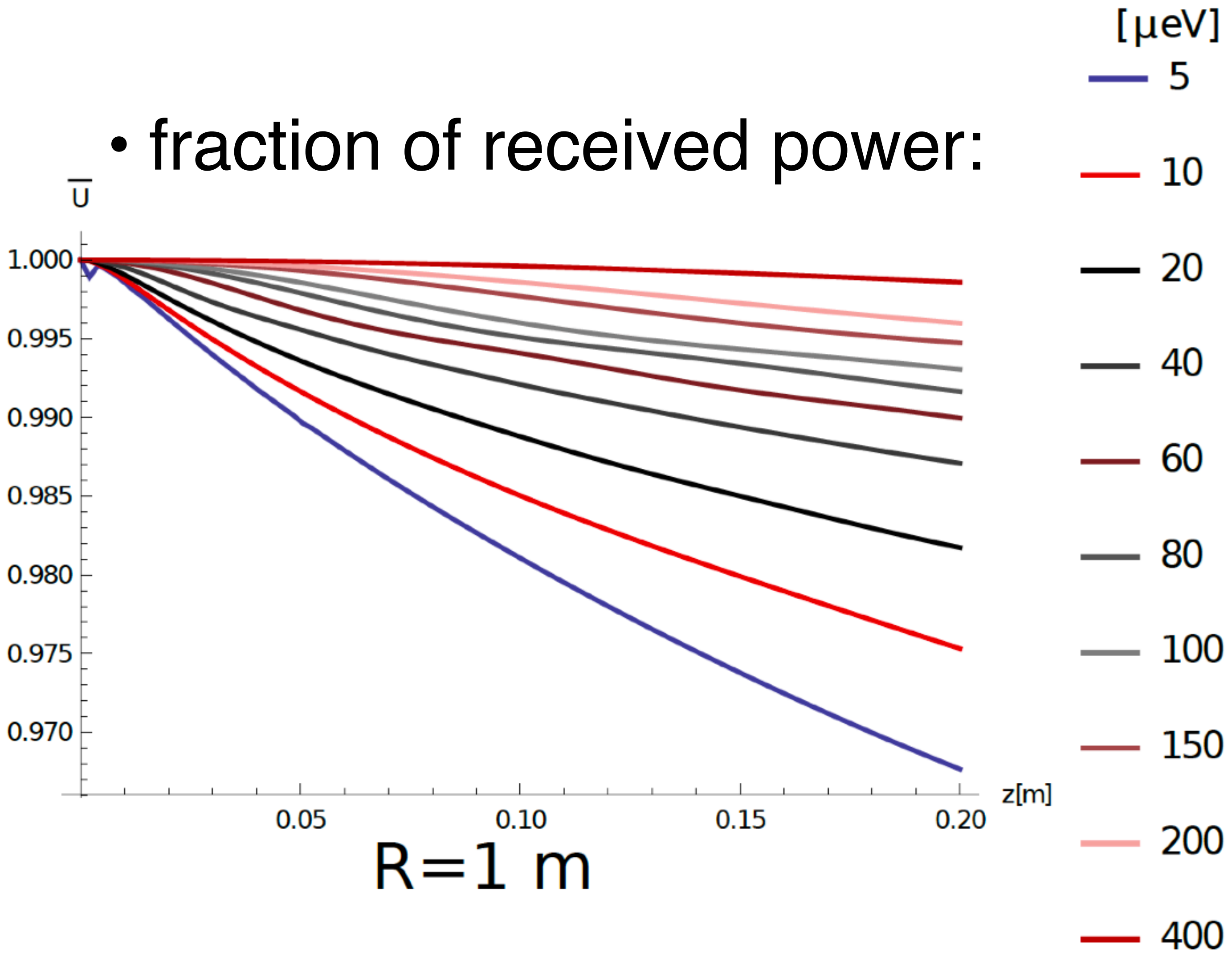
$$\nabla \times (\mu^{-1} \nabla \times \boldsymbol{E}) - m_a^2 \epsilon \boldsymbol{E} - m_a \boldsymbol{B}^{(0)} a^{(0)} = 0,$$

- verify simple cases:





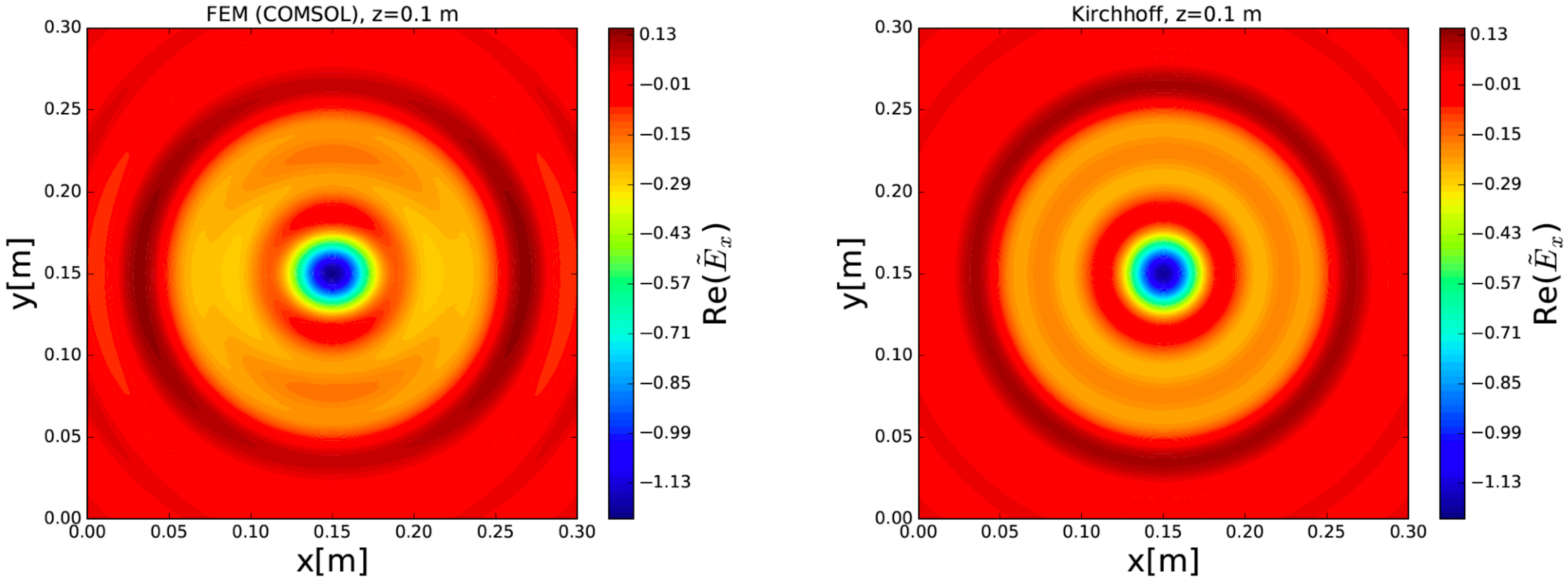
- fraction of received power:



- find that power is lost through diffraction
- loss is larger for smaller axion masses

FEM simulation

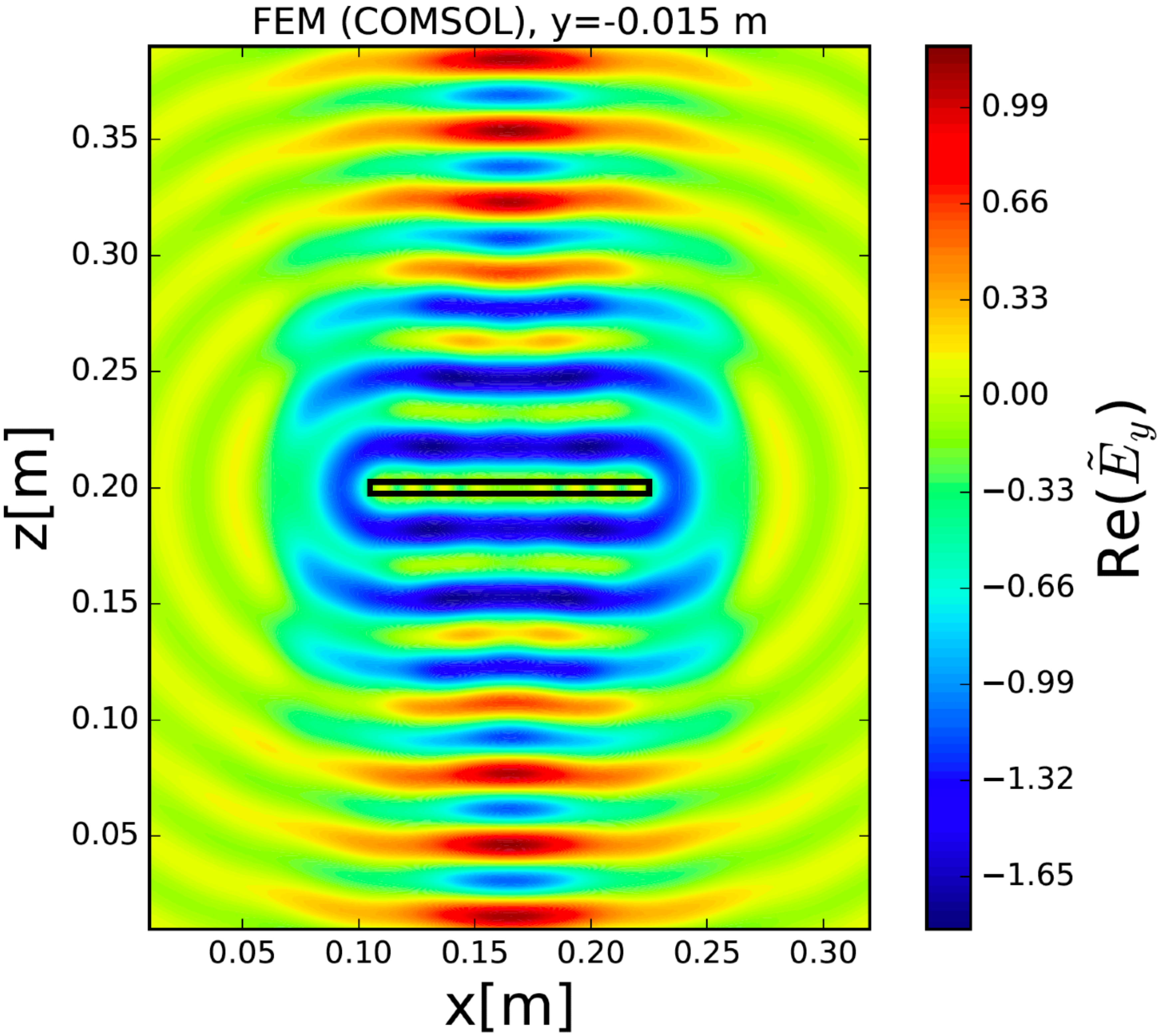
- compare FEM to Kirchhoff calculation:



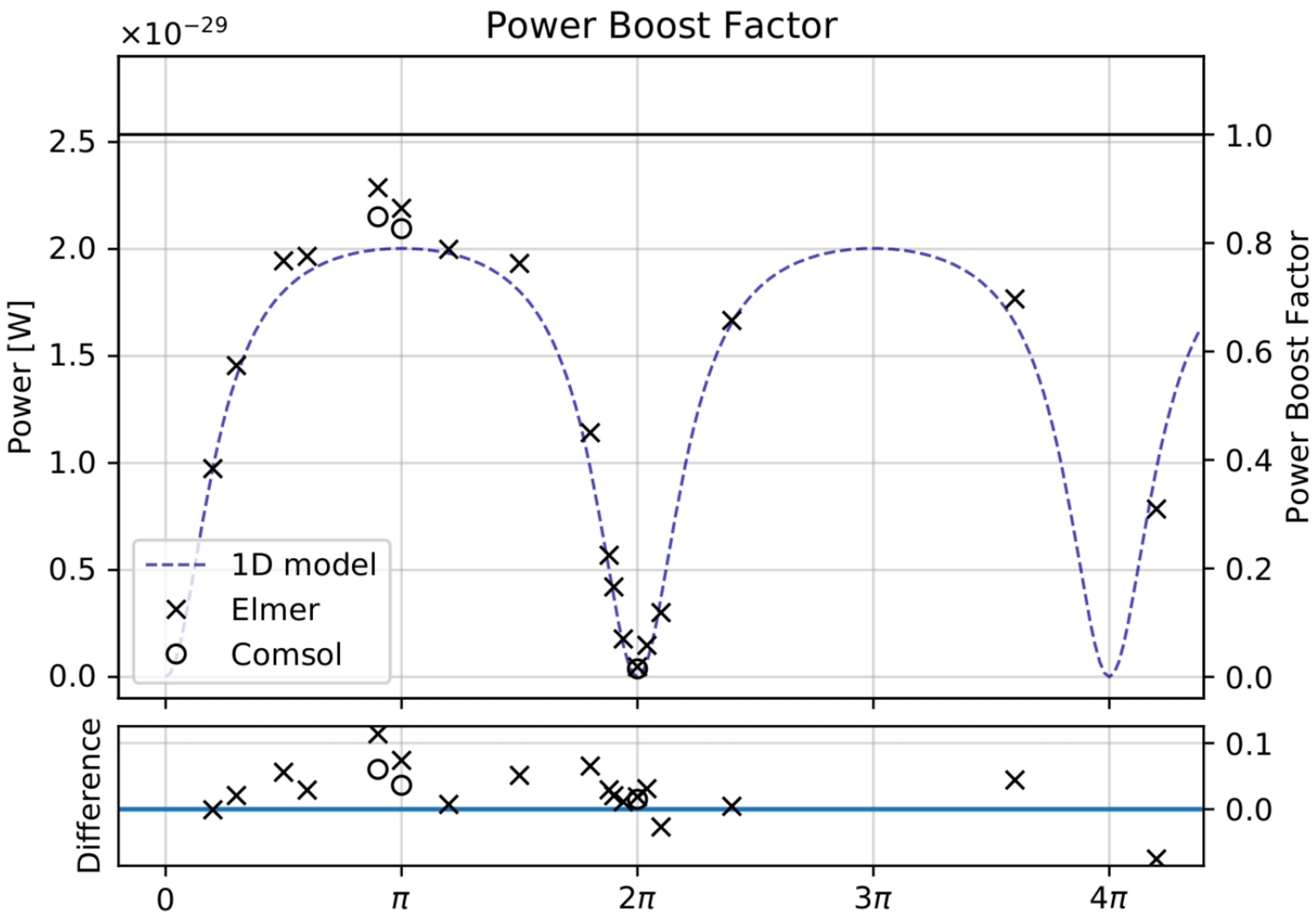
- can reproduce analytical results as far as available

FEM simulation

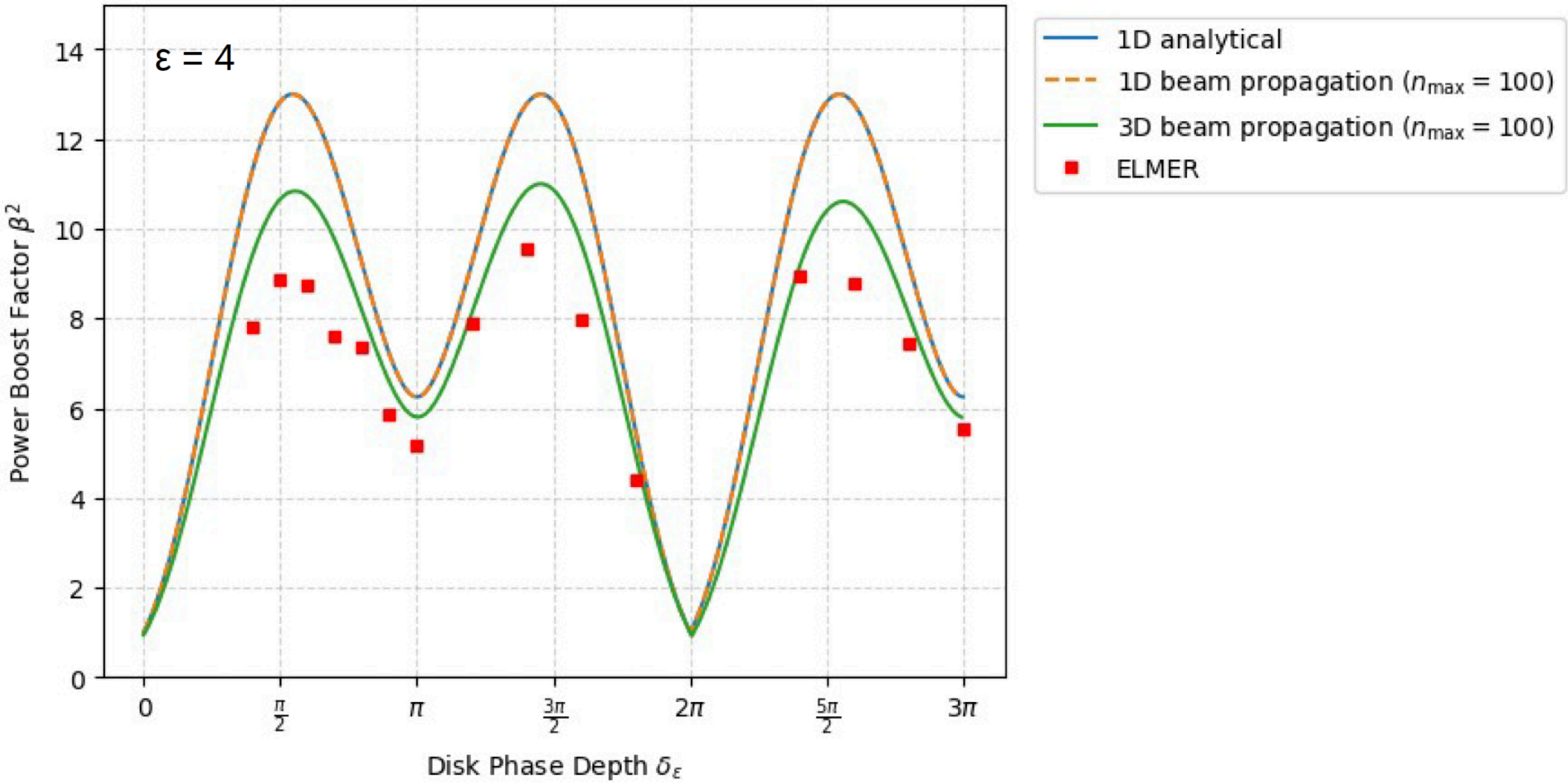
- single dielectric disc:



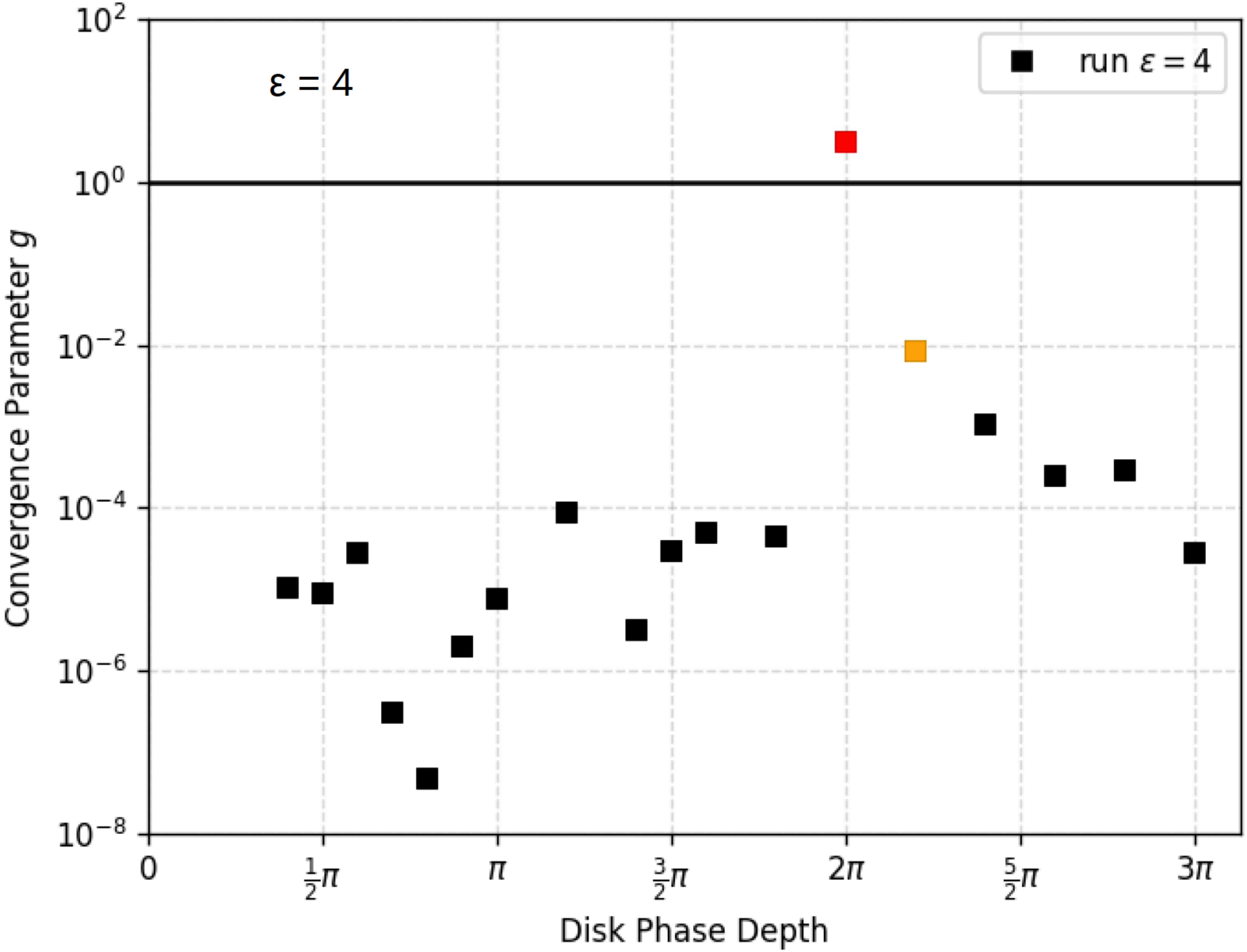
comparison single disk



comparison disk plus mirror



disk plus mirror: convergence



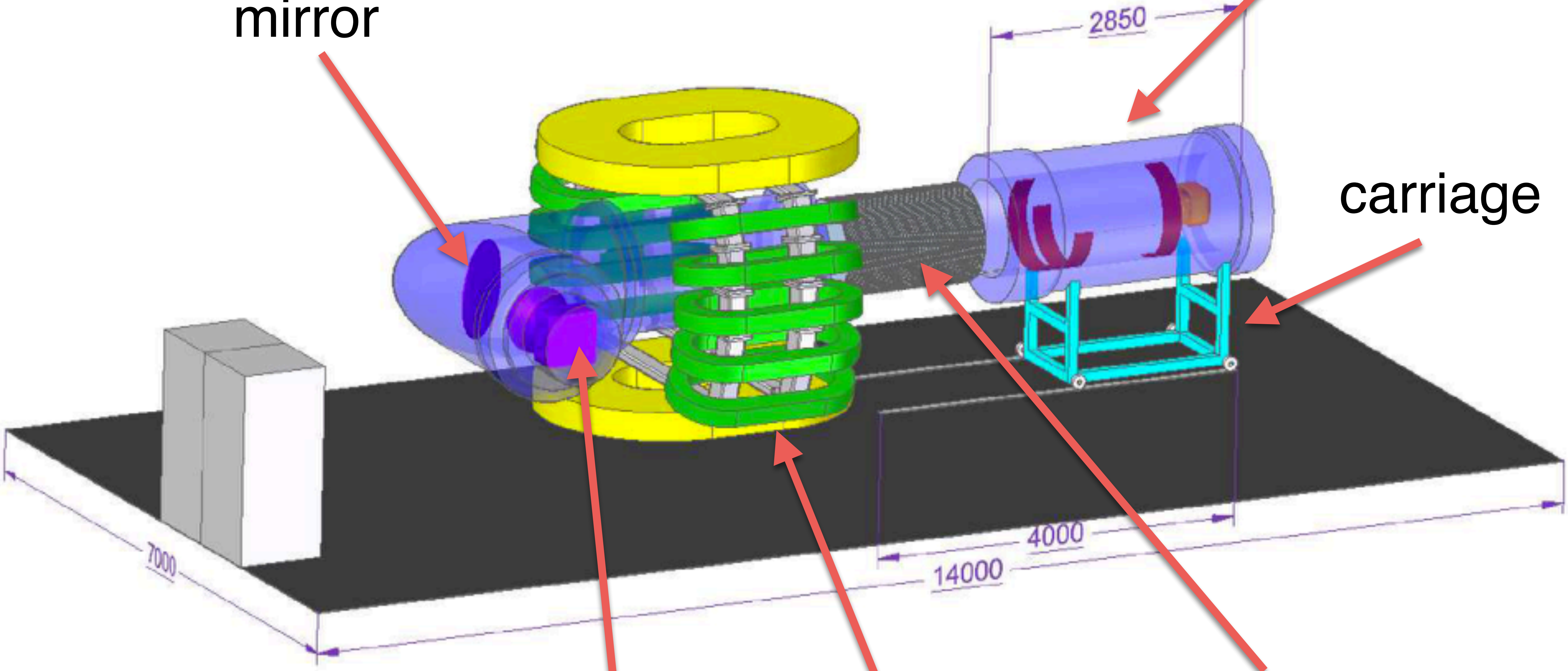
MADMAX simulation

- convergence is an issue for FEM solvers, even in simple cases (mirror plus very few disks)

- impossible to fully simulate 3D model of full experiment:
  - convergence
  - too much CPU
  - too much memory

- in the process of developing custom “fast” simulation
  - could be based on 1D calculations with “fudge” factors applied

MADMAX sketch



vacuum,
cryo enclosure

mirror

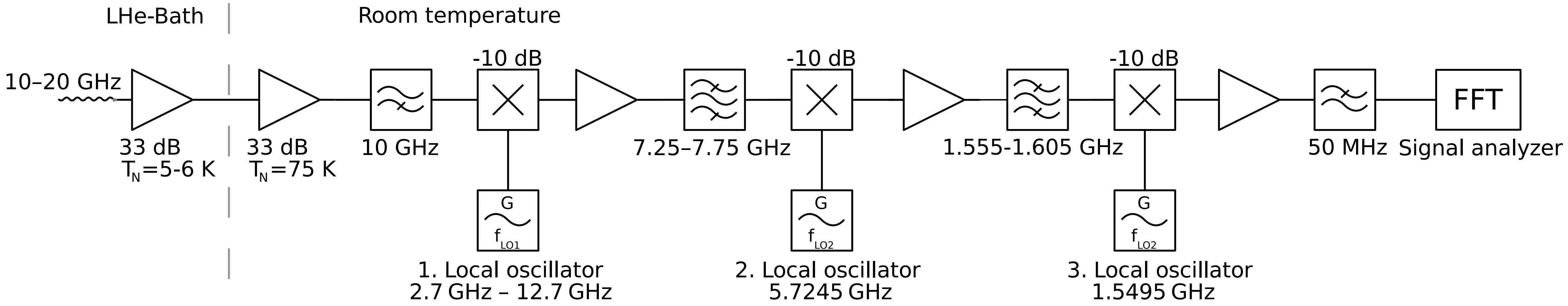
carriage

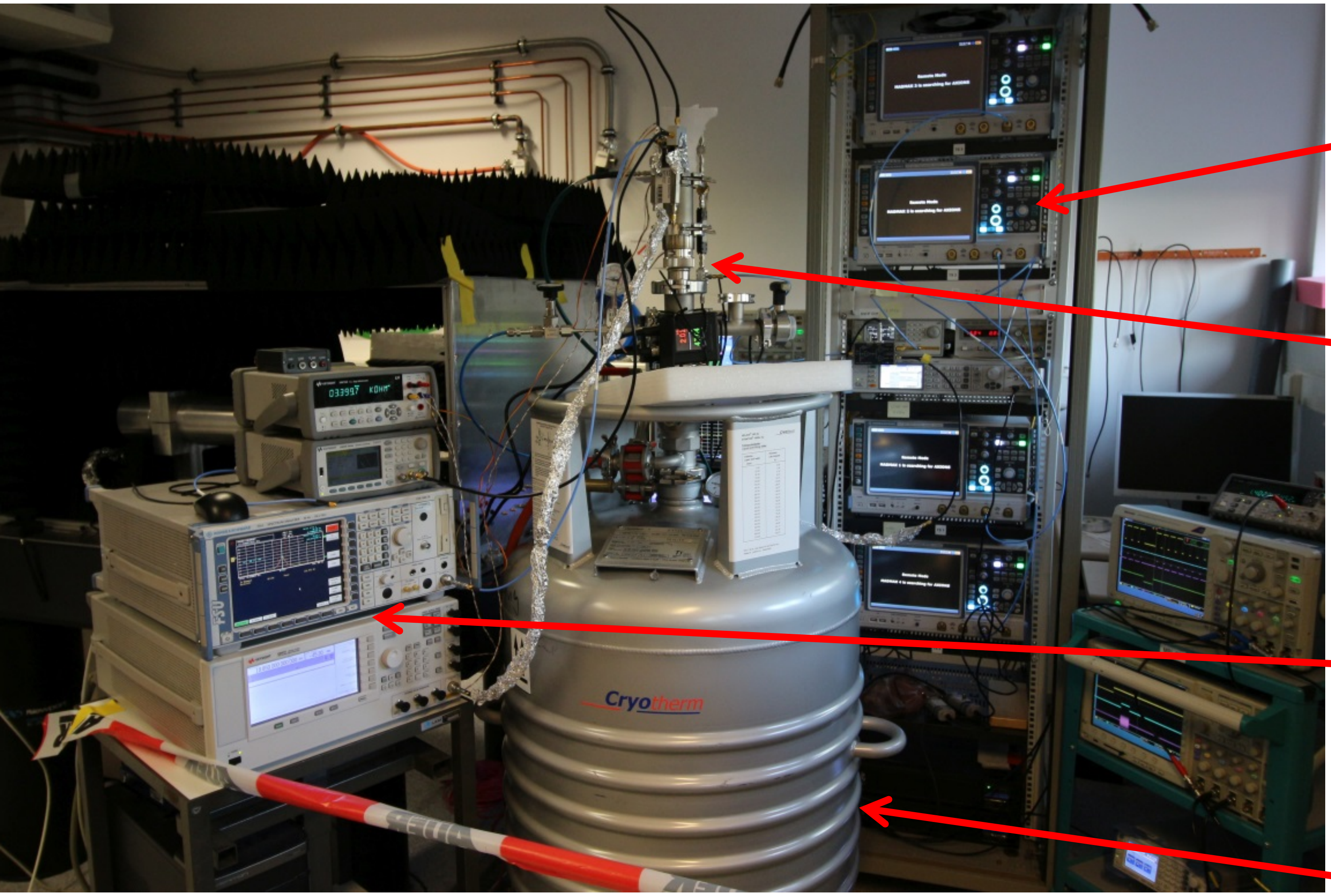
microwave
receiver

magnet

booster (movable
dielectric layers)

receiver test





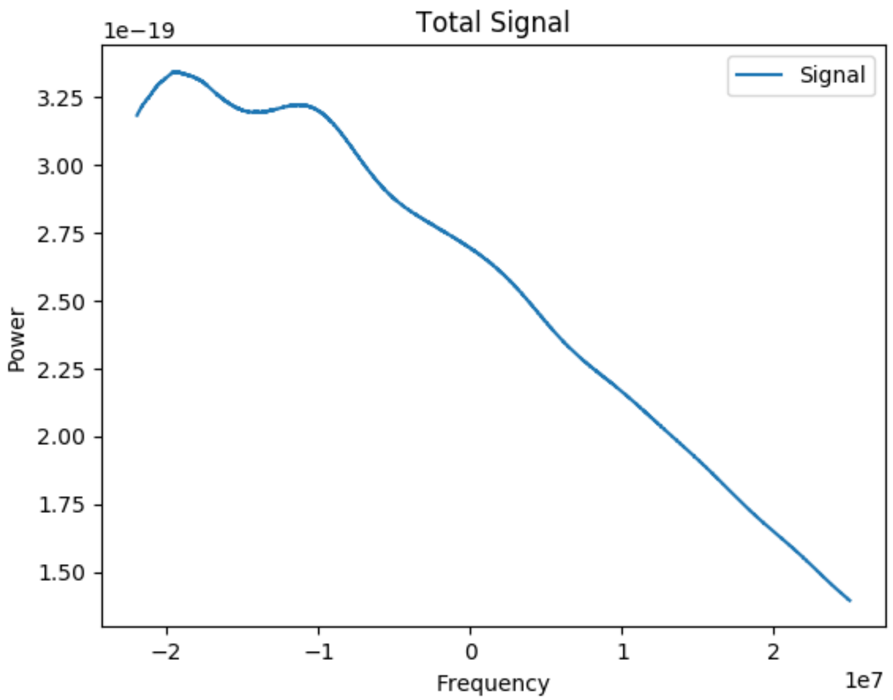
Signal analyzer (4 samplers, 1.4% dead time)

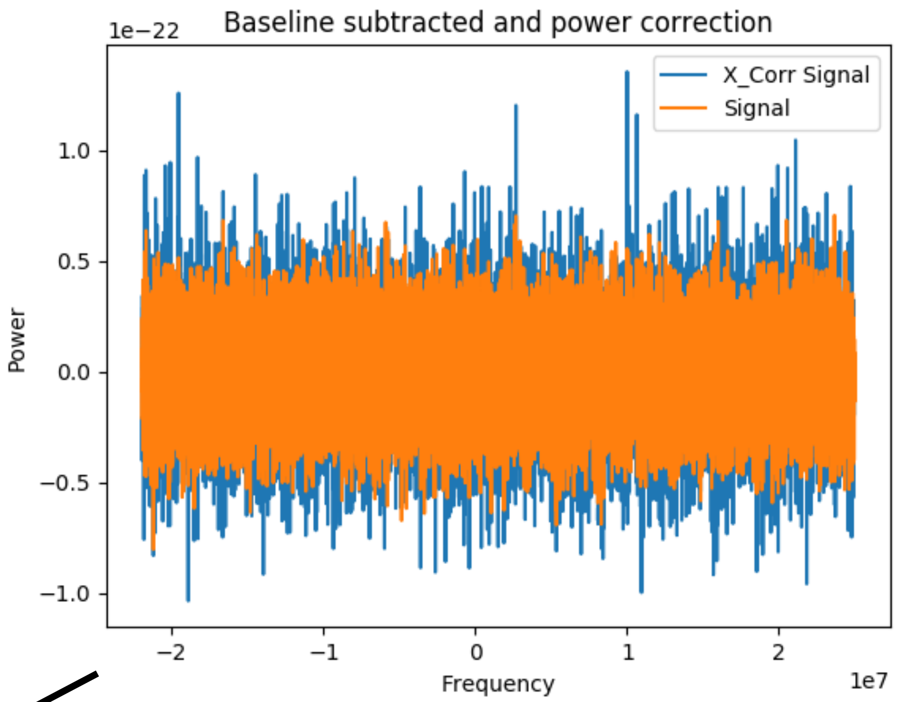
Front end mixers and amps

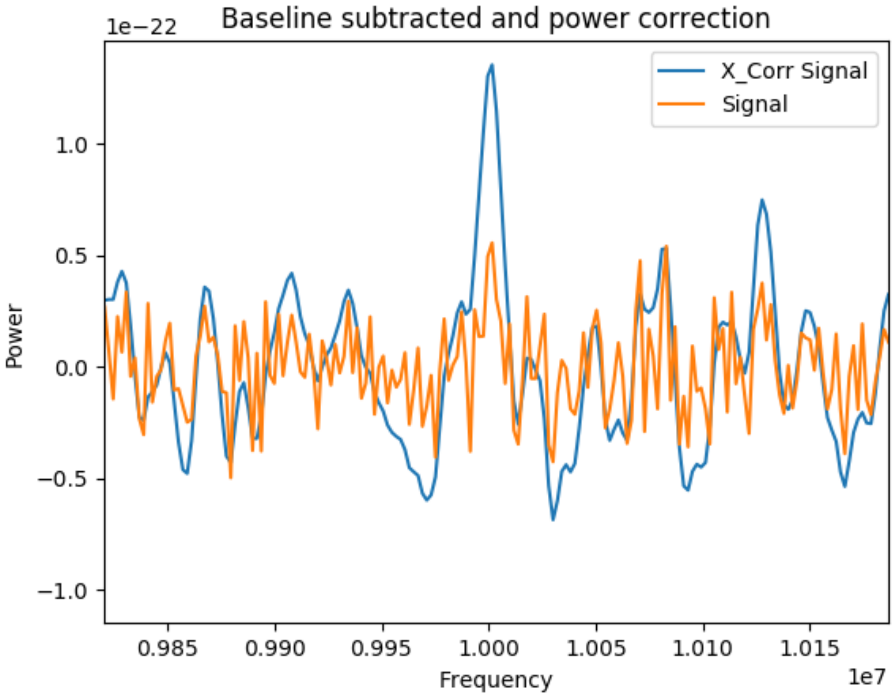
Fake axion

LHe bath
→ 4K T_{He} + 5.5K T_{Amp}
= 9.5K T_{Sys}

receiver test





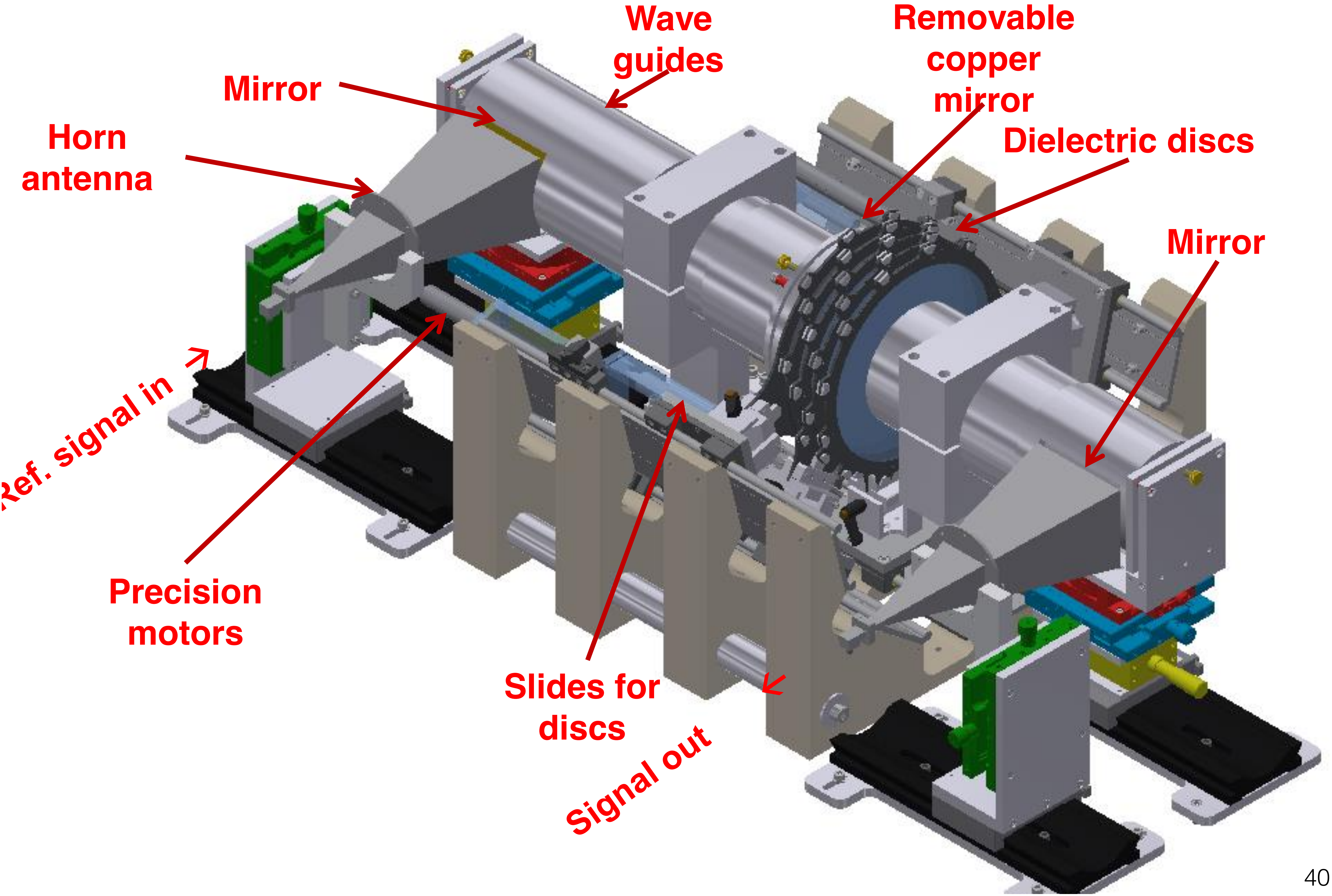


- **Inject fake 18GHz axion signal with 10^{-22} W power**
- **Measurement for 28 hours (integrate signal): Receiver at LHe temp.**

→ Cross correlation analysis (8kHz Lorentz shaped)
→ found ~5σ signal succesfully

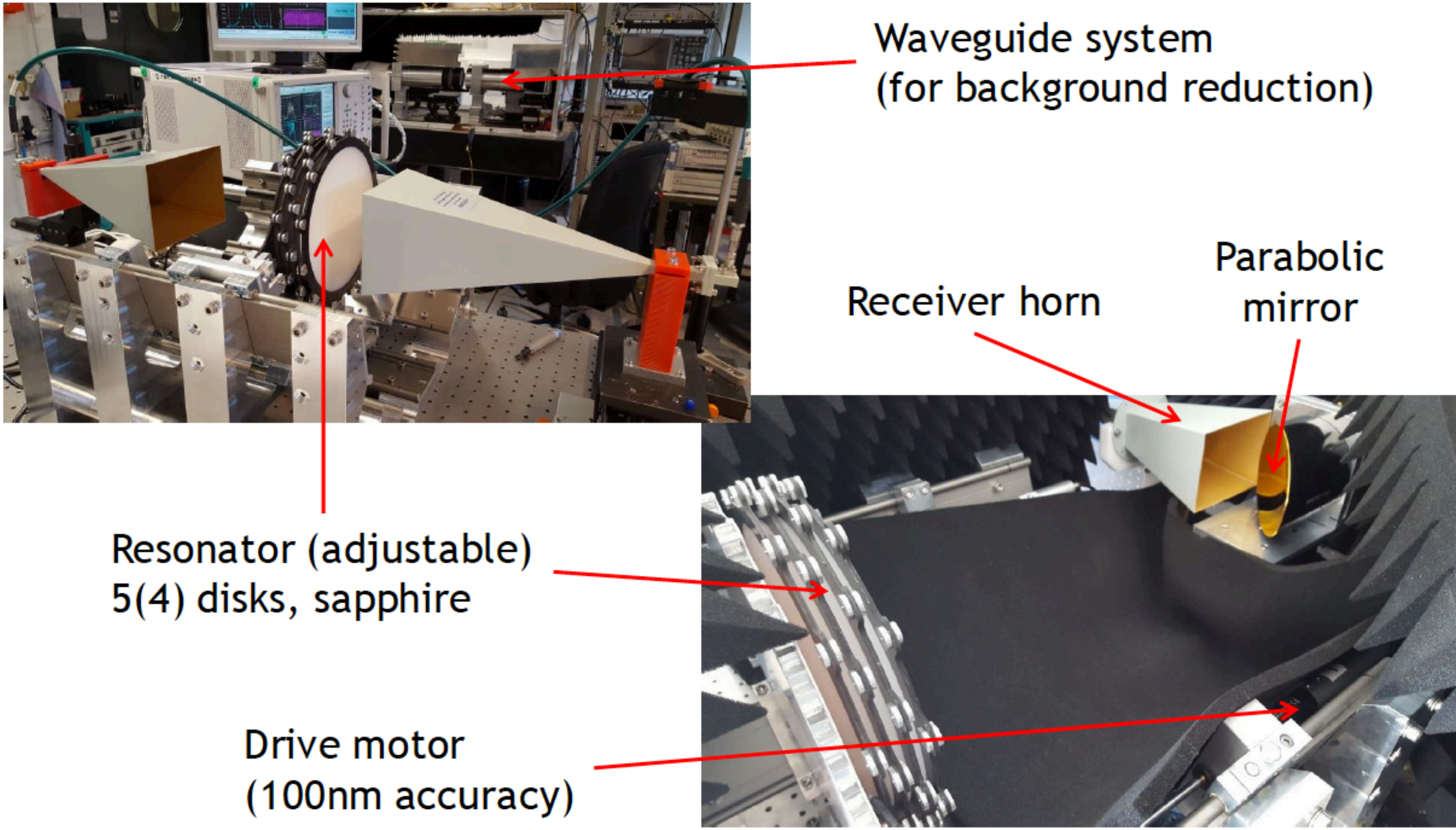
→ For 1 week measurement:
Sensitivity at the level of ~ few 10^{-23} W

MADMAX test setup



test setup in Munich

- The real device (200mm sapphire disks):



Waveguide system
(for background reduction)

Receiver horn

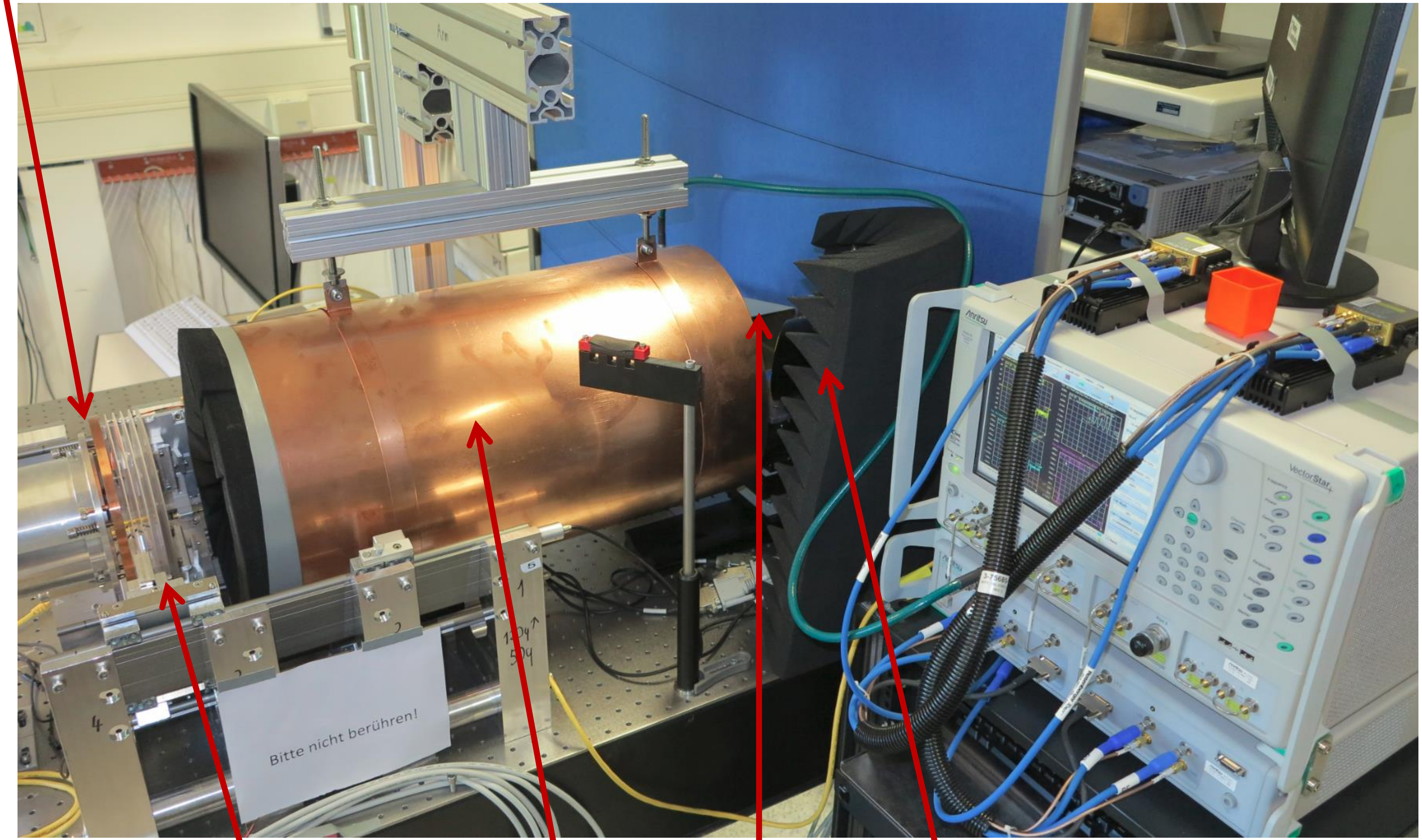
Parabolic
mirror

Resonator (adjustable)
5(4) disks, sapphire

Drive motor
(100nm accuracy)

MADMAX prototype

Removable
copper mirror



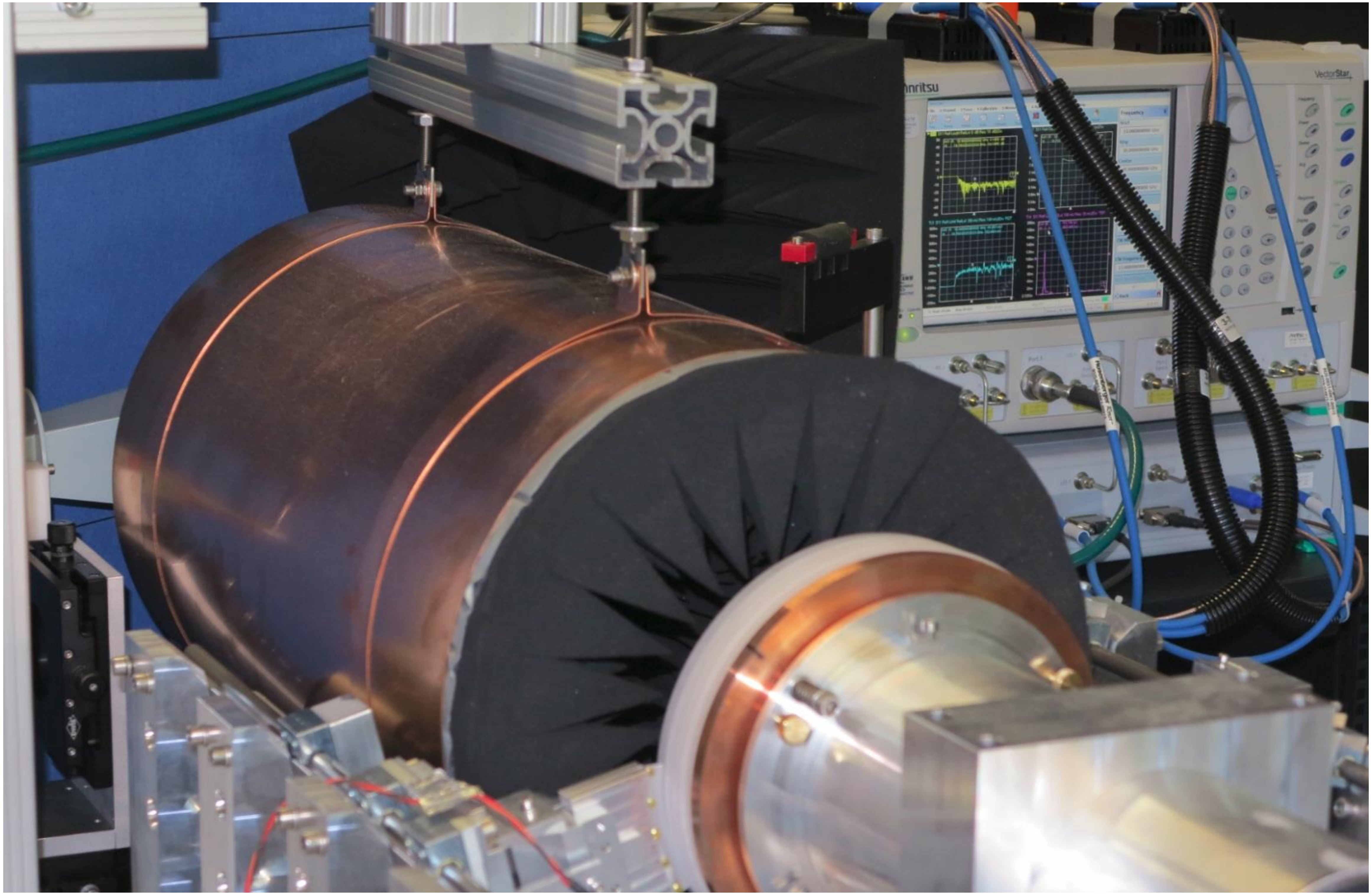
Dielectric discs
(Saphire)

„Wave
guide“

Horn
antenna

Mirror

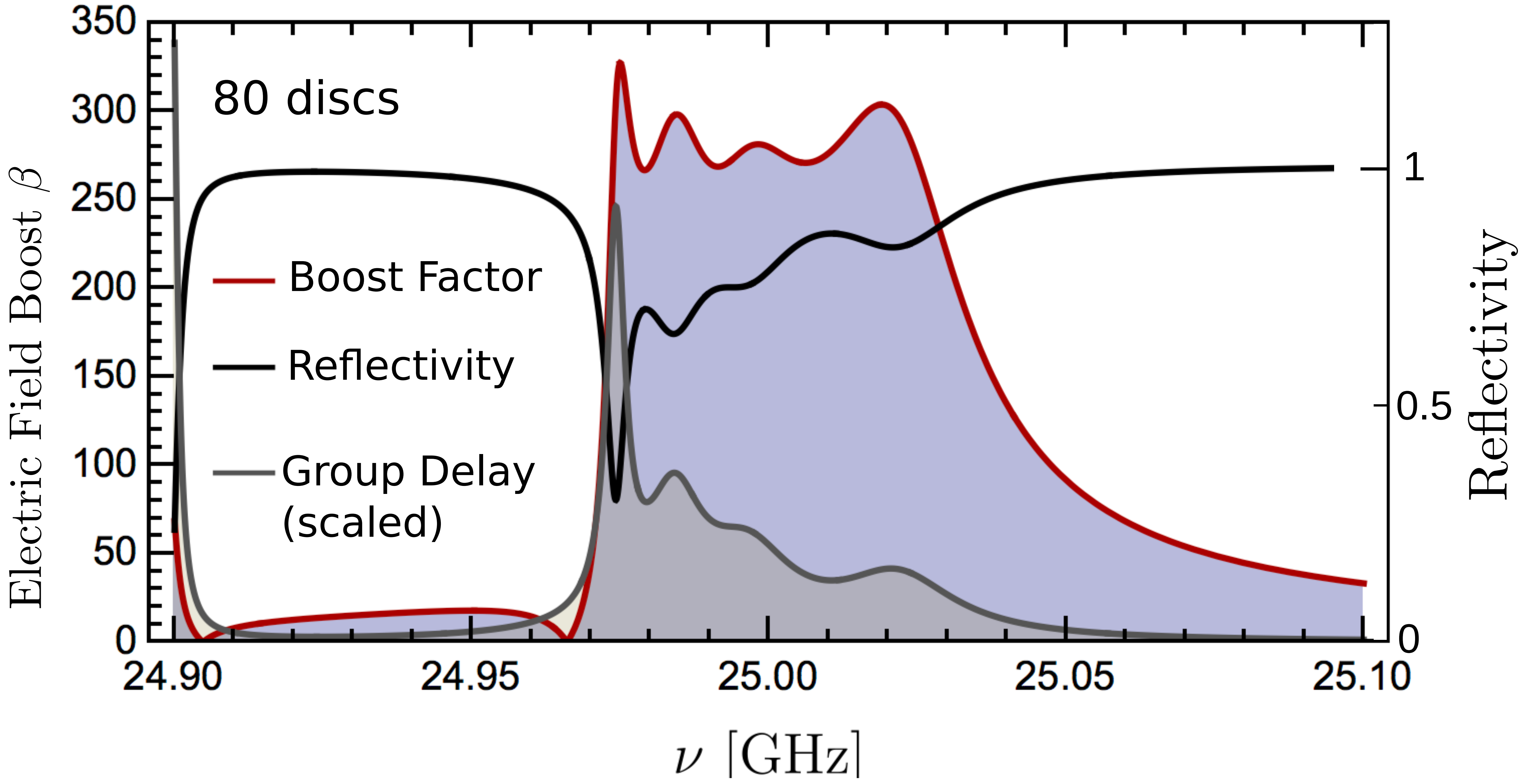
MADMAX prototype



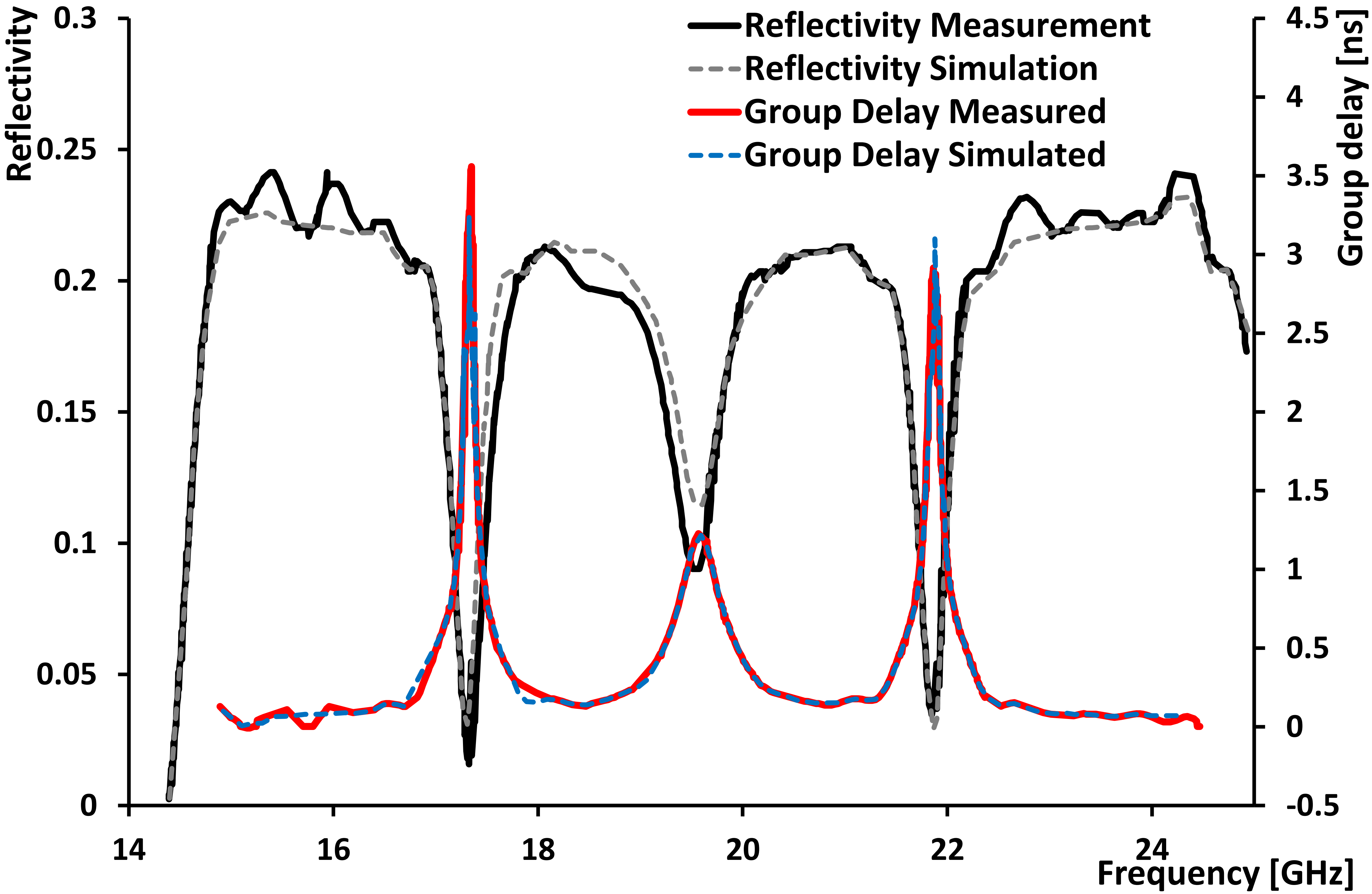
probing the boost factor

arXiv:1612.07057

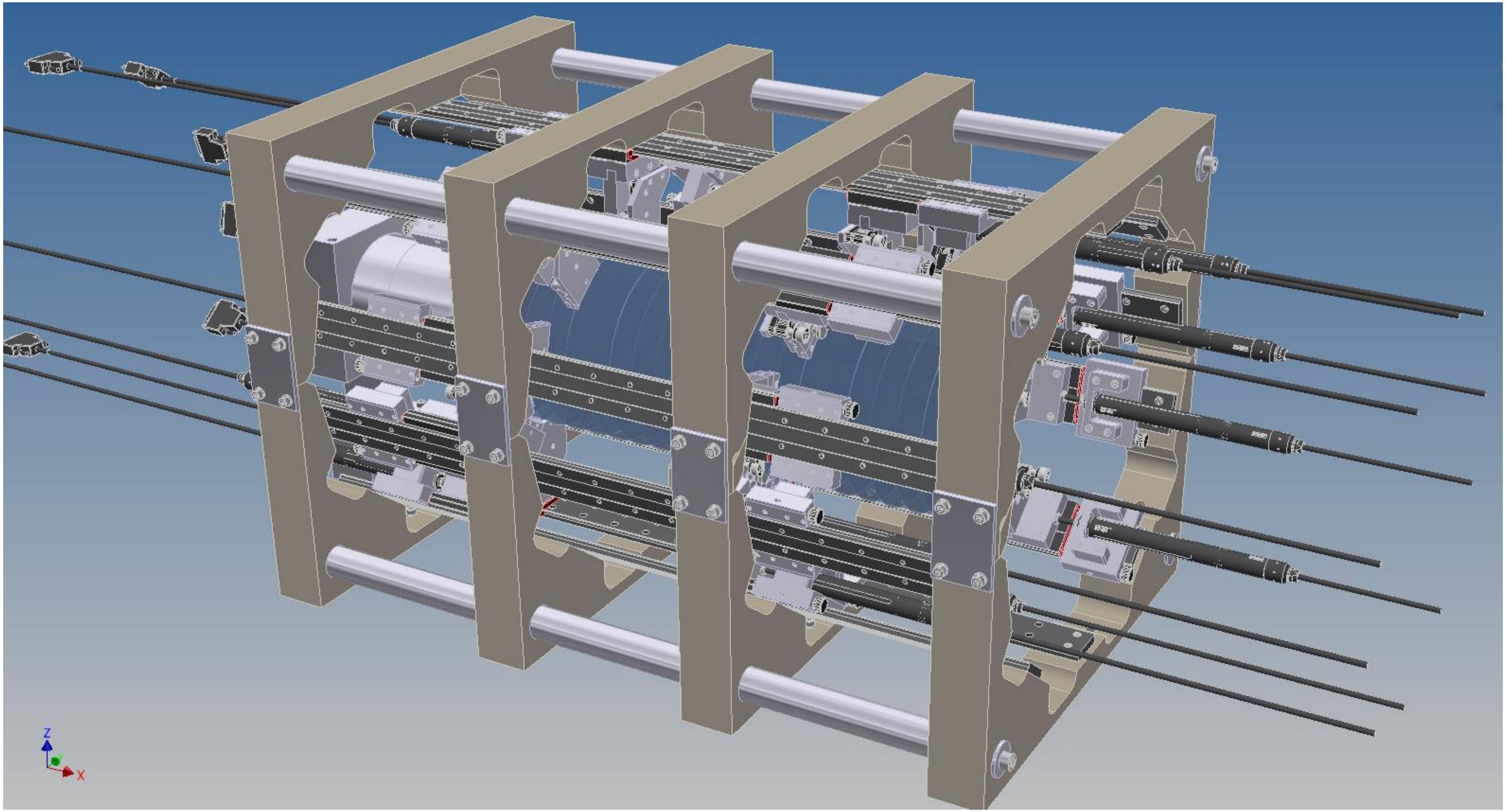
- boost factor cannot be measured directly
  - exploit correlation with observable quantities



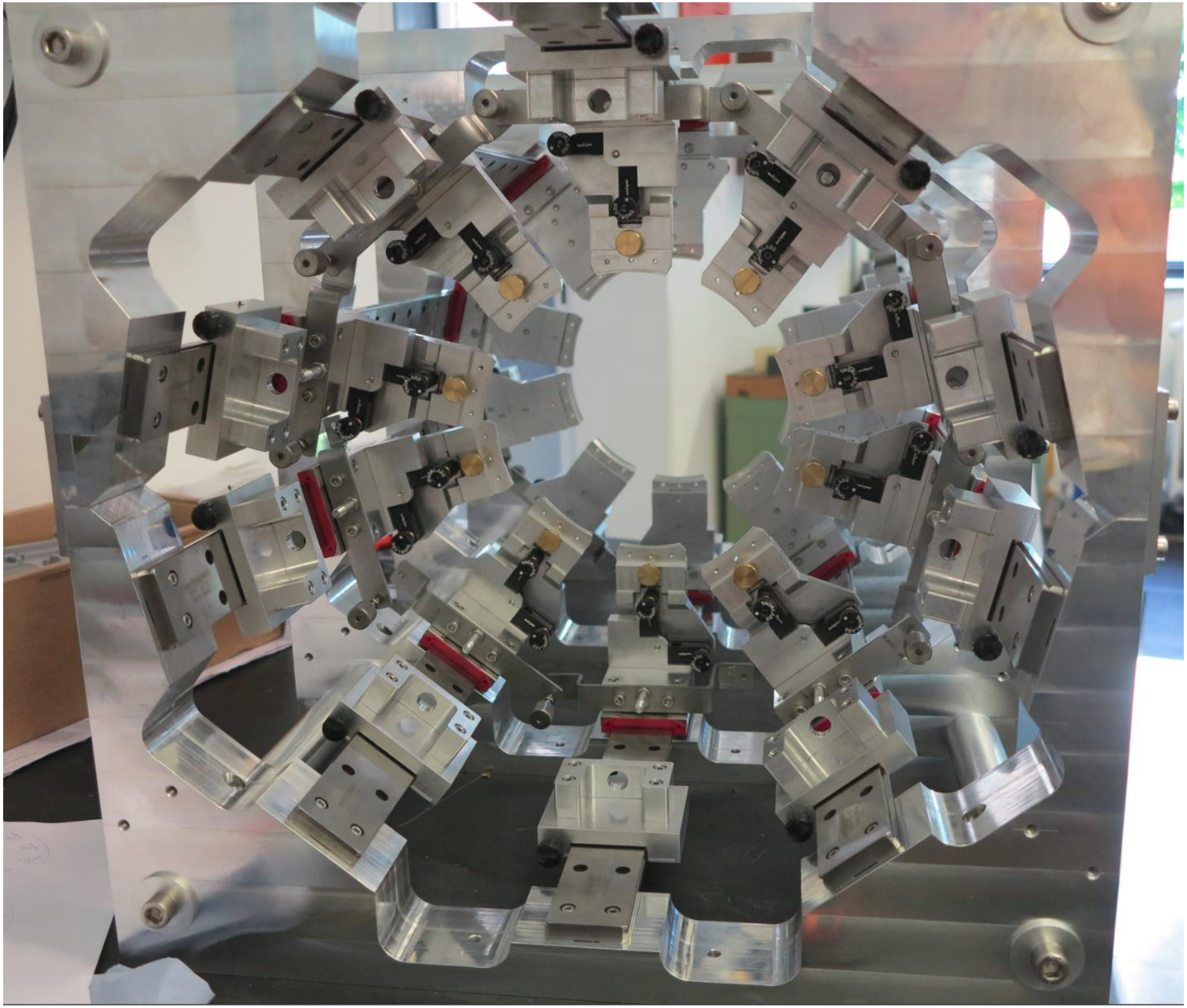
measurement at test setup



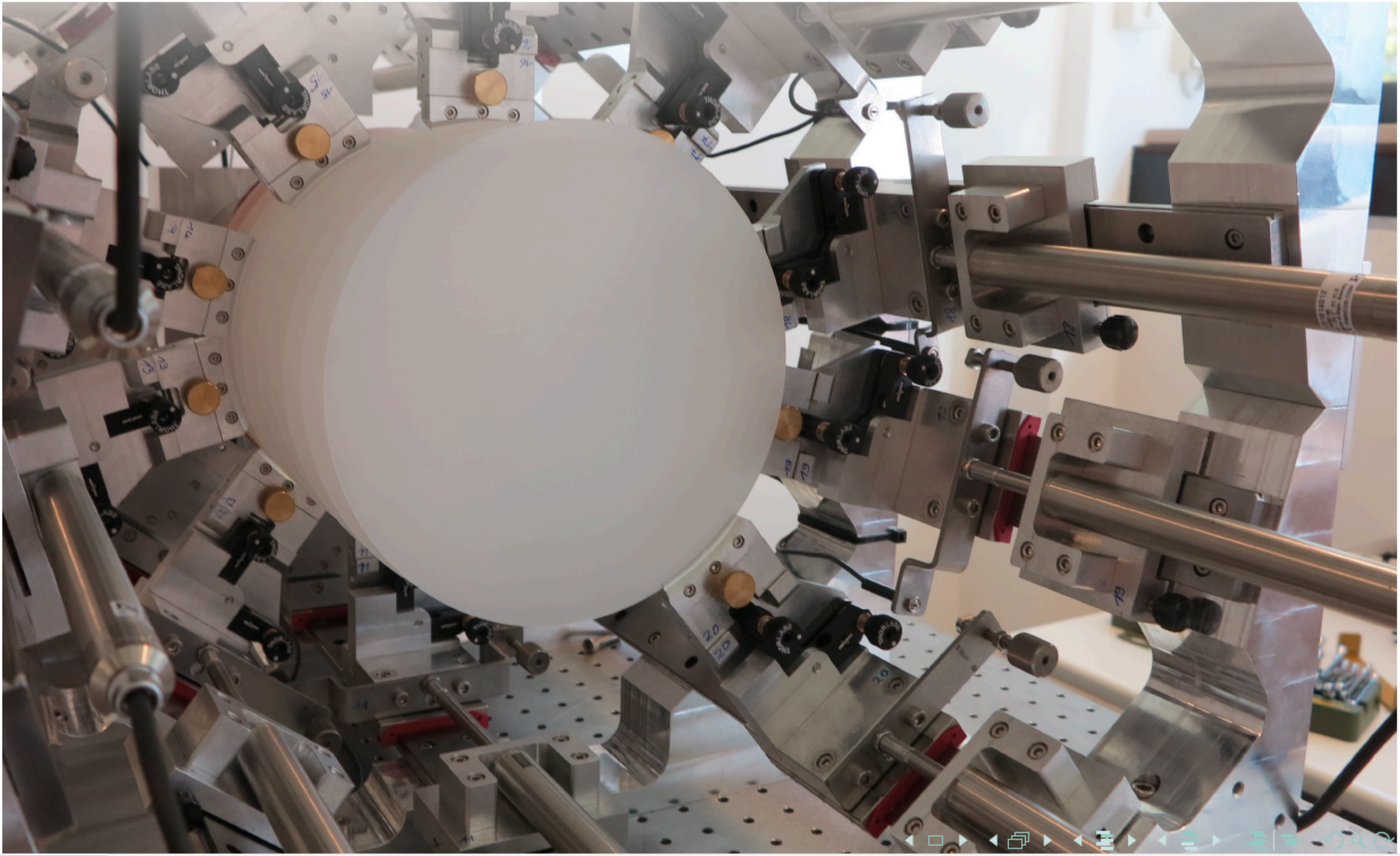
next step: 20 disc setup



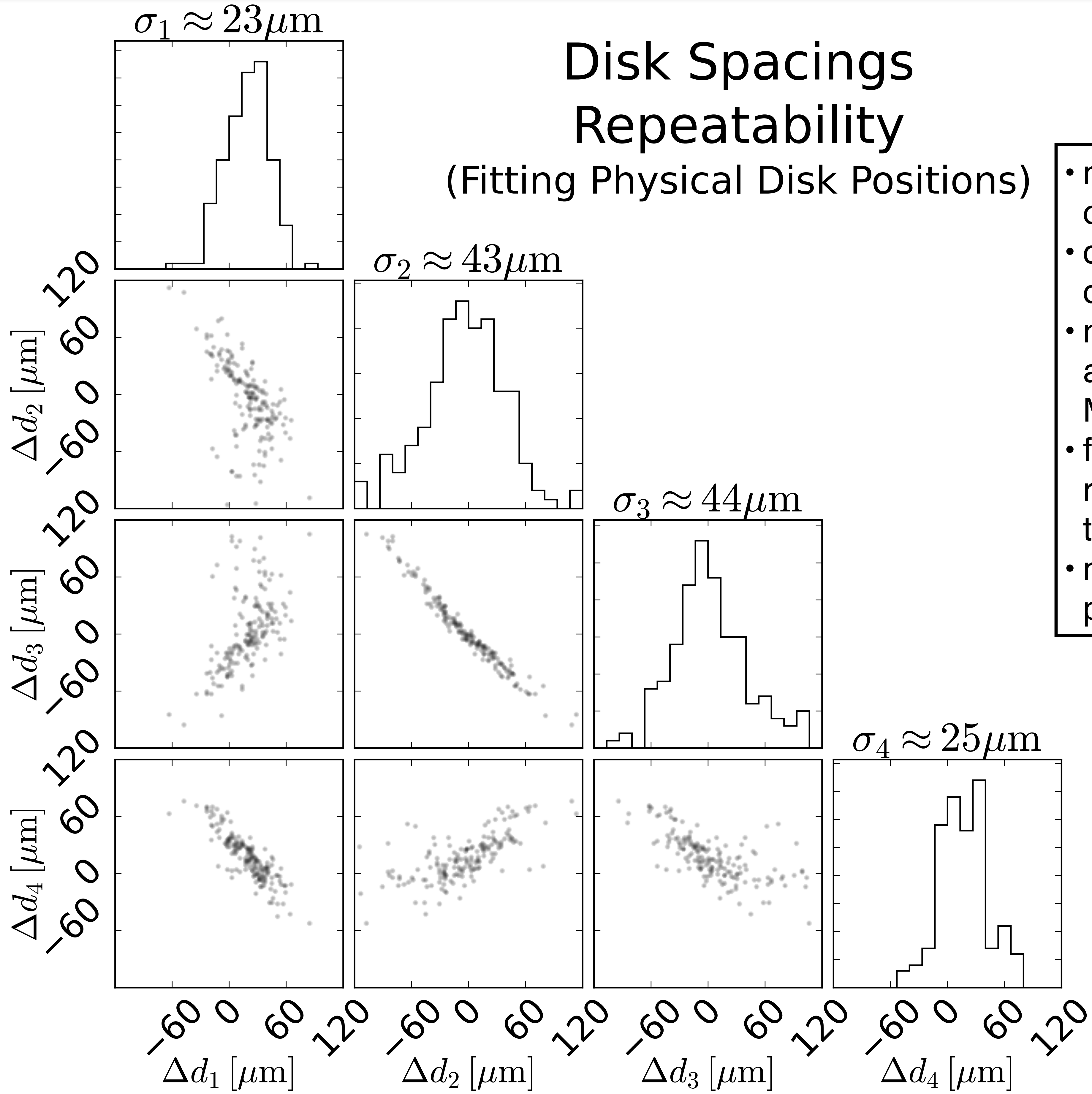
next step: 20 disc setup



next step: 20 disc setup



disc positioning

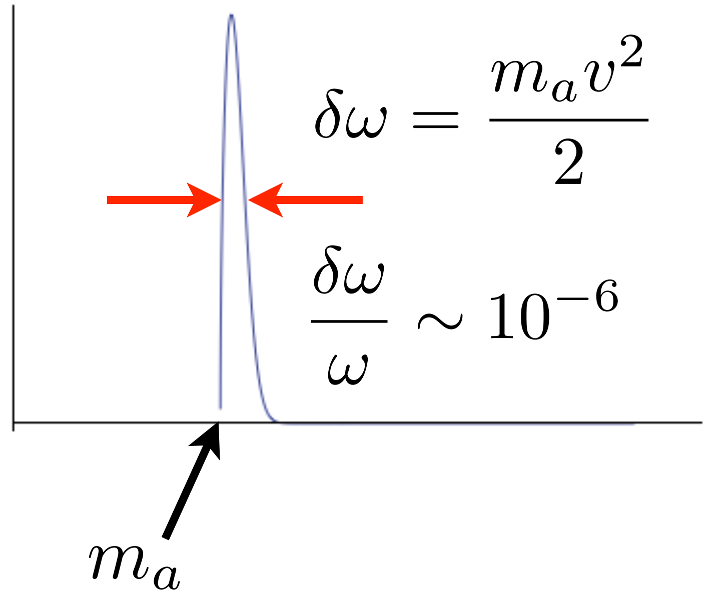

Disk Spacings Repeatability (Fitting Physical Disk Positions)

- match group delay to prediction of the 1D model
- discs are physically moved during fit
- movement done through special algorithms (genetic, Nelder-Mead,…)
- figure shows positions after repeating procedure multiple times
- note that there is degeneracy in positions

MADMAX experiment

- challenges:
  - huge and strong magnet 10 T (never built before)
  - large, thin dielectric media 1m^2, to be moved around with high precision (in vacuum, cold, strong field)
  - tiny signal, unknown frequency
  - (is DM located here or elsewhere?)
  - coherence:

$$\omega \simeq m_a(1 + v^2/2 + ...)$$



$$\delta\omega = \frac{m_a v^2}{2}$$

$$\frac{\delta\omega}{\omega} \sim 10^{-6}$$

coherence length

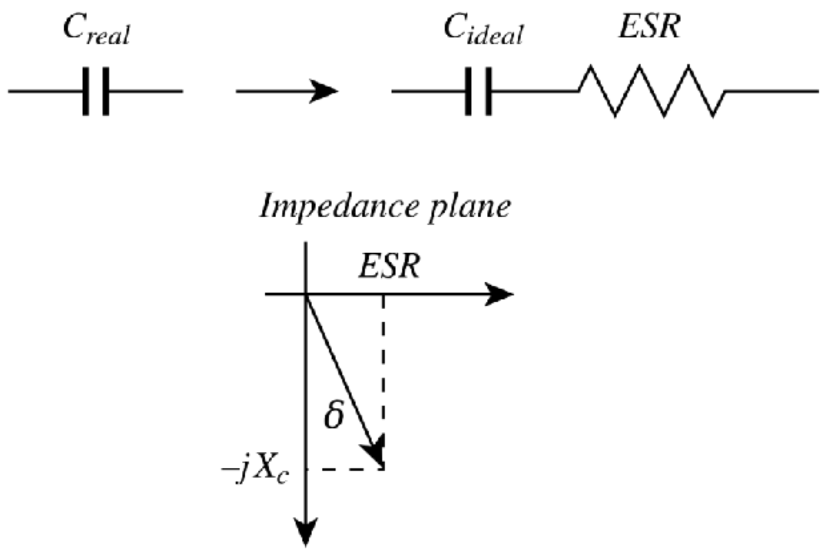
$$\boxed{\delta L \sim \frac{1}{\delta p} \sim 20\mathrm{m}\left(\frac{10^{-5}\mathrm{eV}}{m_a}\right)}$$

dielectric material

- **Problem**: find the ideal dielectric material to obtain
  - high boost factors
  - over a large surface

- ideal dielectric has:
  - High dielectric constant ($\varepsilon > 10$) for large axion/photon conversion factor
  - Low loss ($\tan \delta < 10^{-5}$) in order to reduce photon loss

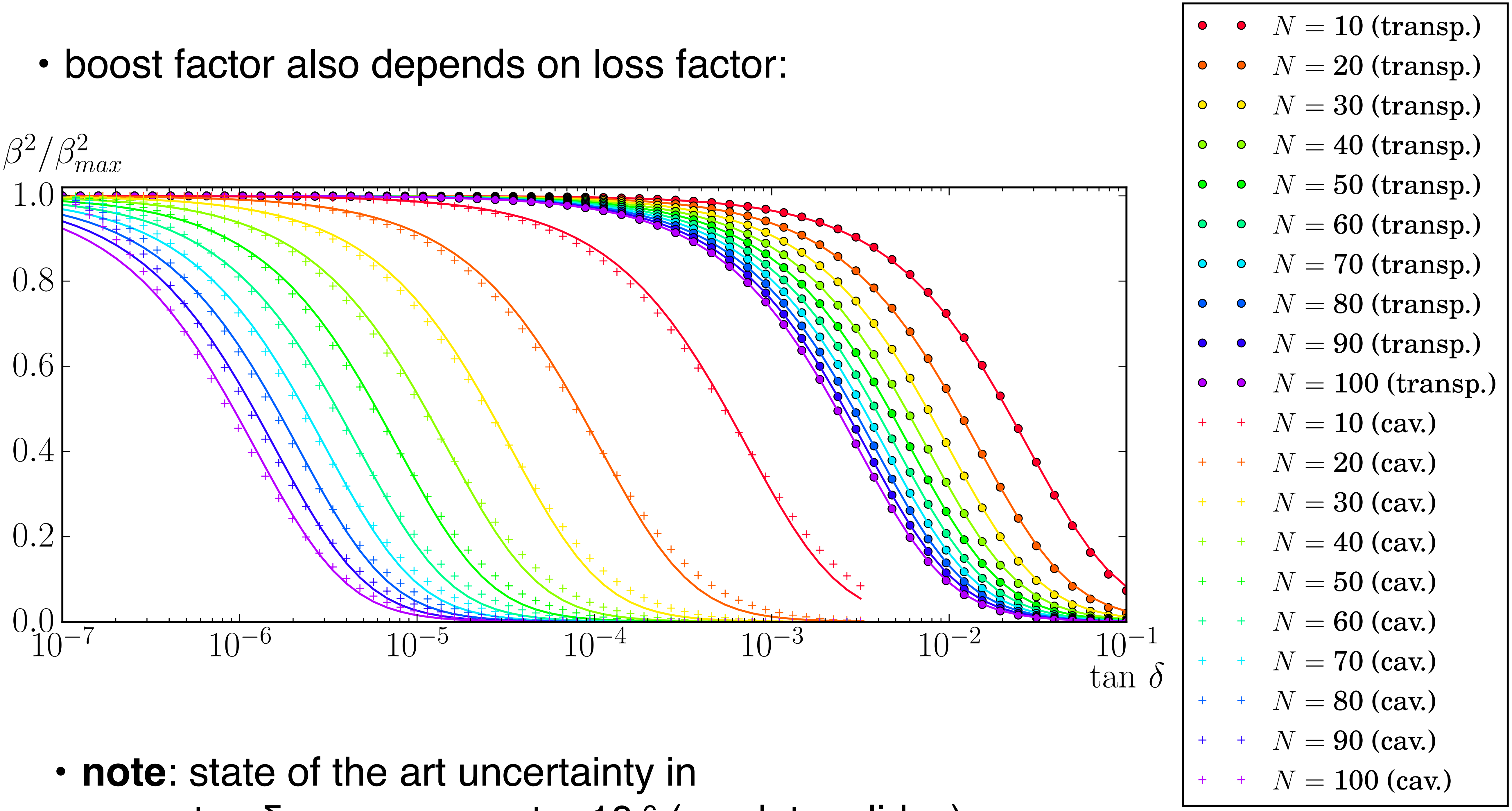
real dielectric = ideal capacitor + equivalent series resistance (ESR)



ESR should be minimum, i.e. tan δ should be small

dielectric material

- boost factor also depends on loss factor:



- **note**: state of the art uncertainty in
  tan δ measurement: ~10^{-6} (see later slides)
- 10^{-6} can make a significant difference in boost factor

dielectric material

$$\mathbf{E}_a(t) = -\frac{\mathbf{E}_0}{\epsilon} e^{-im_a t}$$

Chose dielectric material:

- High dielectric constant ε (for large boost & conversion)
  - Low loss → low tan δ (reduce photon losses)
    - Stable
    - Cheap

$$\mathbf{E}_0 \equiv g_{a\gamma} \mathbf{B}_\mathrm{e} a_0$$

→ Sapphire (Al_2O_3) @ 300K, 10 GHz:

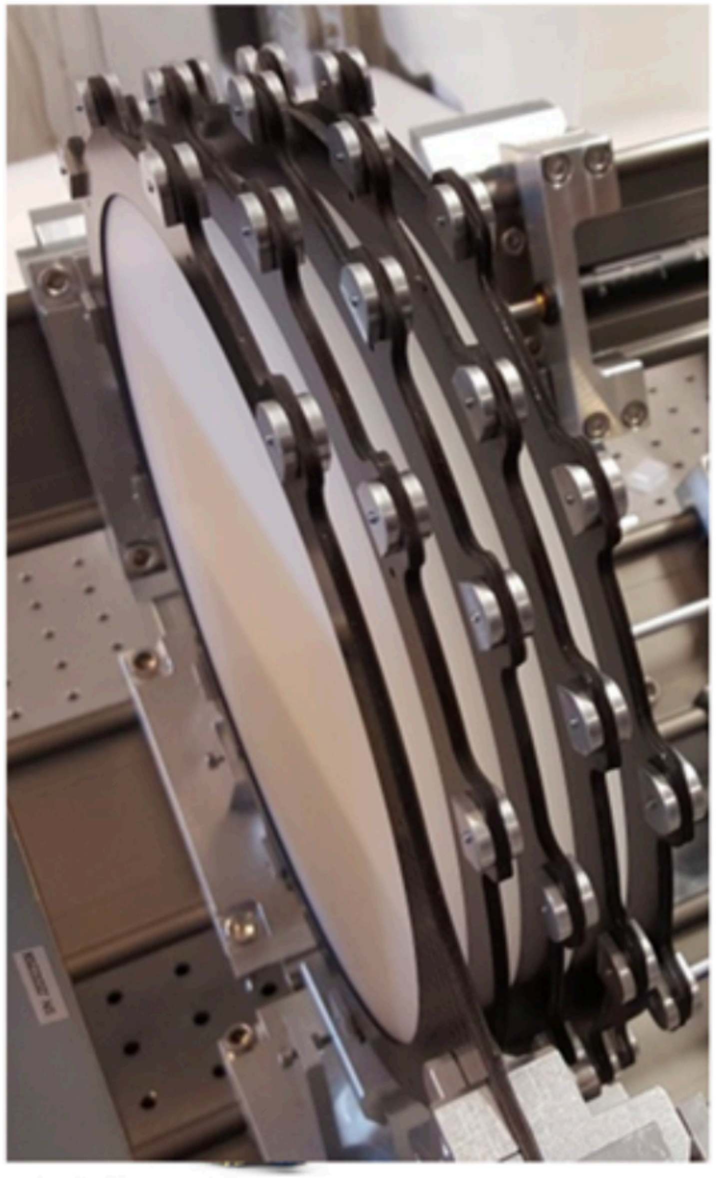
$$\varepsilon \sim 10; \qquad \tan\delta \sim few \cdot 10^{-5}$$

→ Lanthanide Aluminate ($LaAlO_3$) @ 77K

$$\varepsilon \sim 24; \qquad \tan\delta \sim 3 \cdot 10^{-5}$$

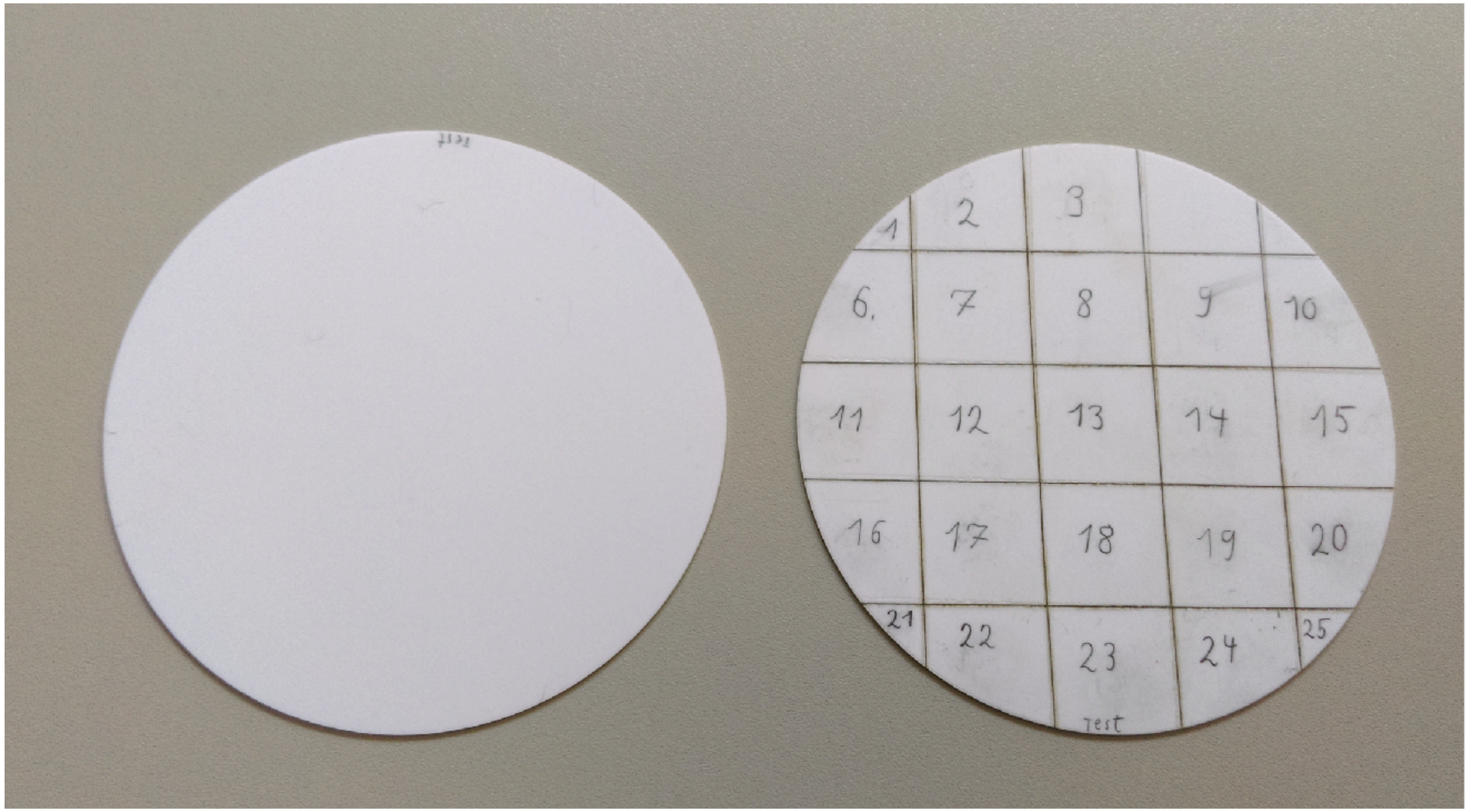
→ Titanium dioxide – Rutil (TiO_2)

$$\varepsilon \sim 100; \qquad \tan\delta \sim ???$$

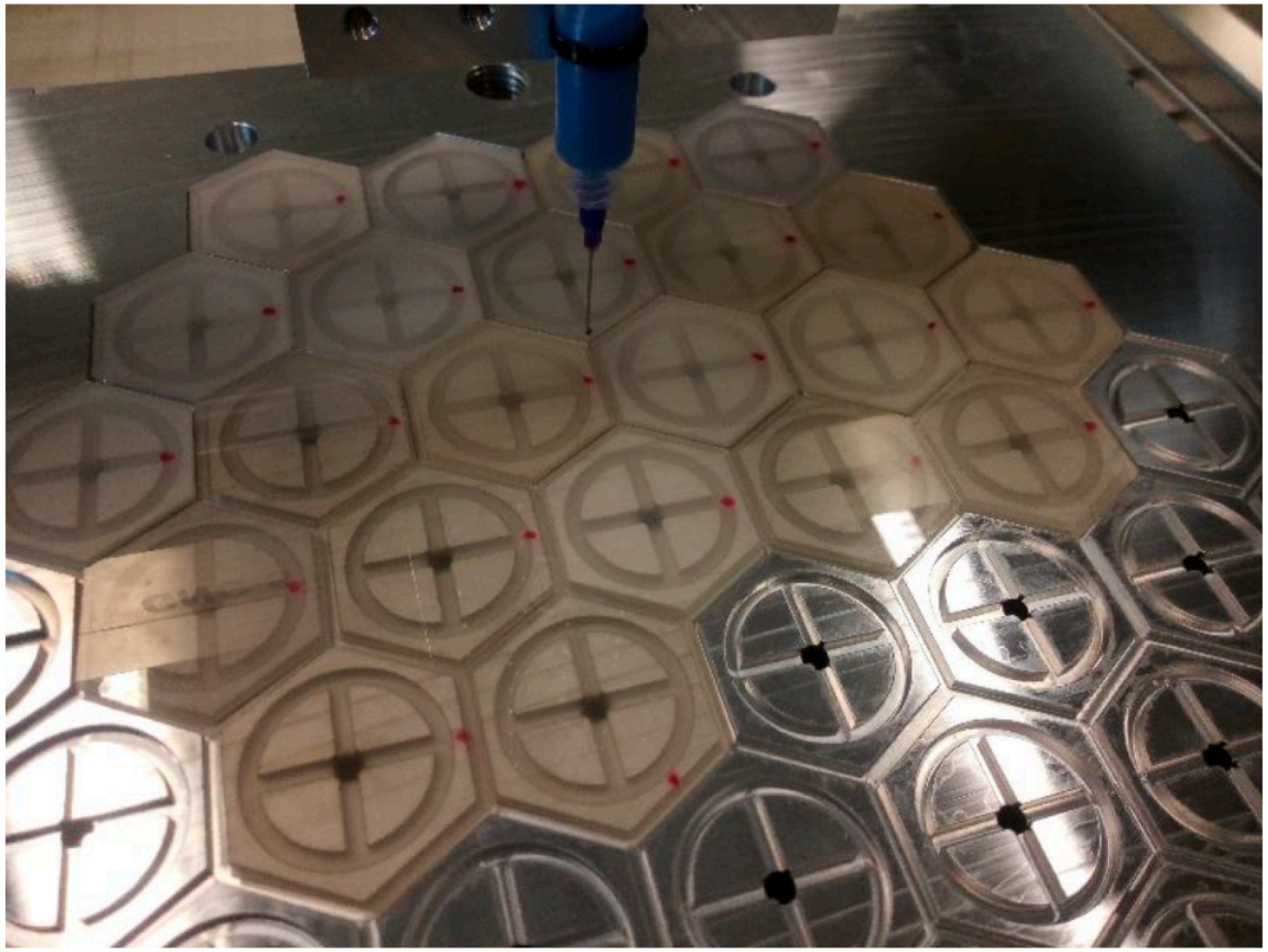


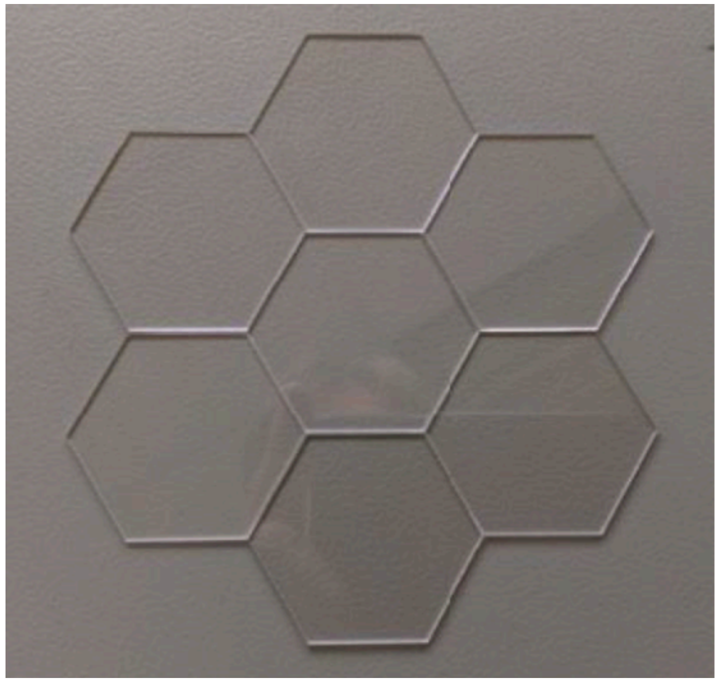
test of dielectric disk tiling

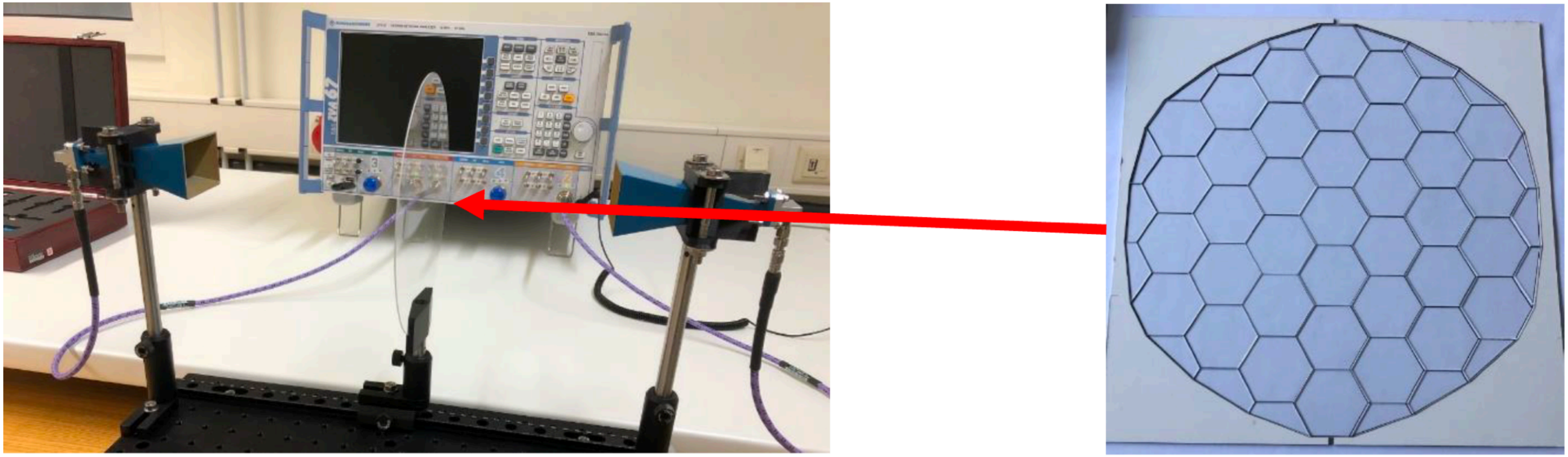
- 1 m^2 dielectric crystals cannot be grown (today)
- Solution: tiling
  - how to cut dielectric crystals ? (bridle)
  - how to glue ?
  - how to test dielectric properties after glueing ?



test of dielectric disk tiling



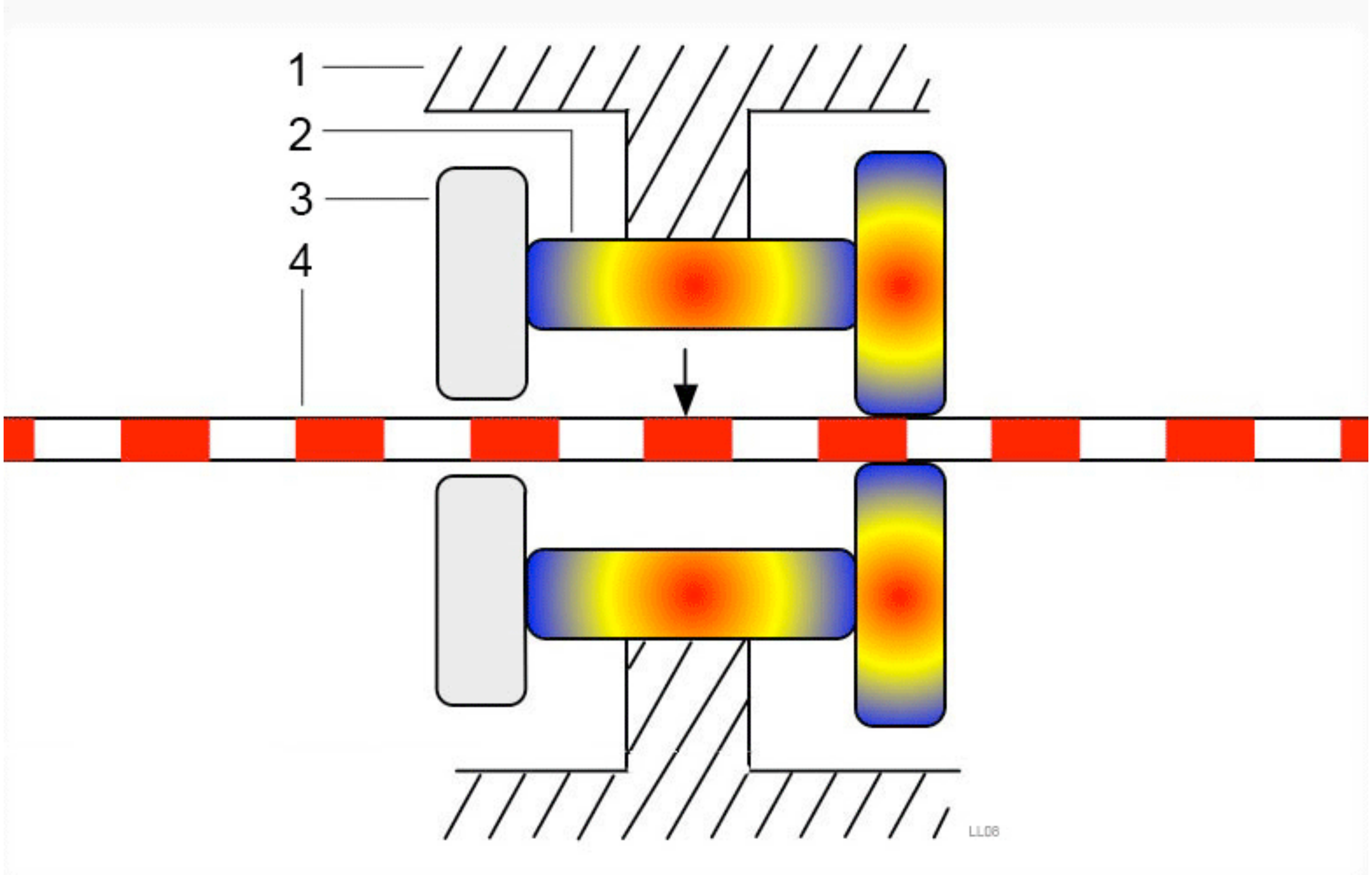




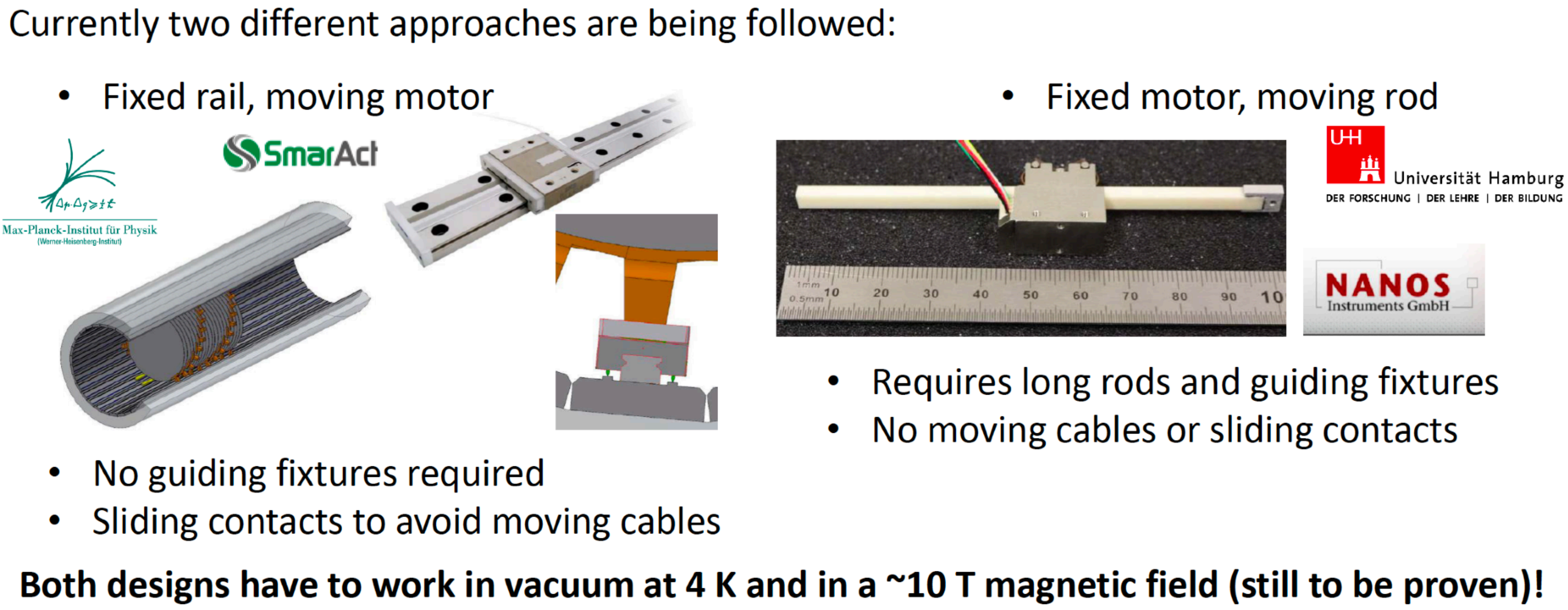
disc positioning system

- Discs have to be positioned with relative distances between 2 and 20 mm with few µm precision

- currently investigating piezo motor technique:



disc positioning system



Currently two different approaches are being followed:

- Fixed rail, moving motor
  - No guiding fixtures required
  - Sliding contacts to avoid moving cables
- Fixed motor, moving rod
  - Requires long rods and guiding fixtures
  - No moving cables or sliding contacts

Both designs have to work in vacuum at 4 K and in a ~10 T magnetic field (still to be proven)!

- commerically available piezo motors have been tested, failed at cold temperature

magnet

$B^2 \cdot A \gtrsim 100\ \mathrm{T^2m^2}$ over 2m

European Innovation Partnerships

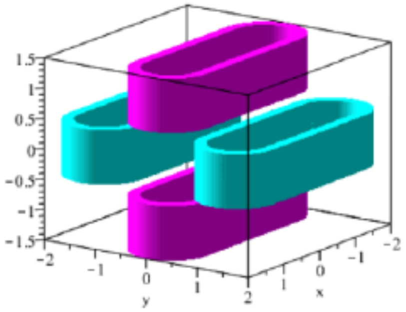
European Innovation Partnerships (EIPs) are a new approach to EU research and innovation.

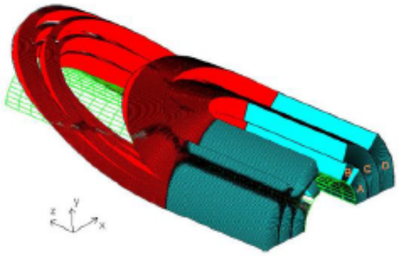
EIPs are challenge-driven, focusing on societal benefits and a rapid modernisation of the associated sectors and markets.

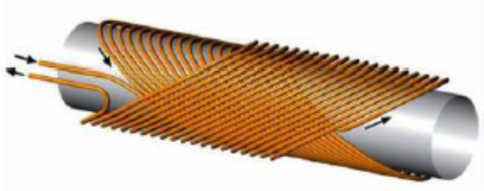
first dipole of that size has never been produced:

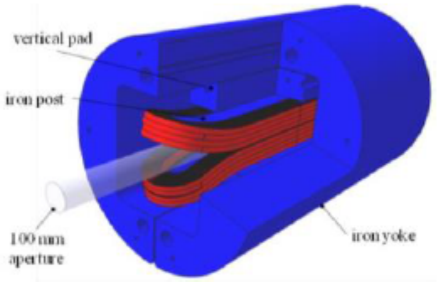
- design studies by innovation partners
- from prototype to full scale magnet

magnet





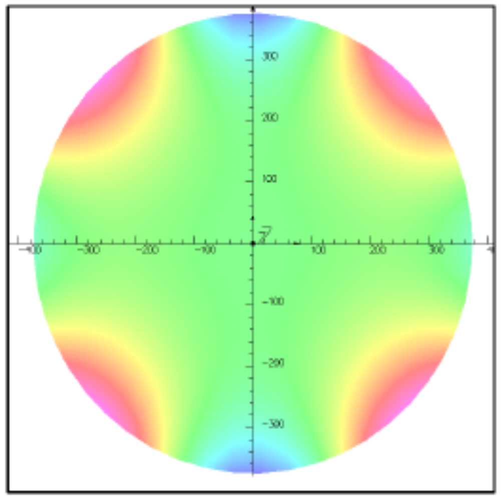
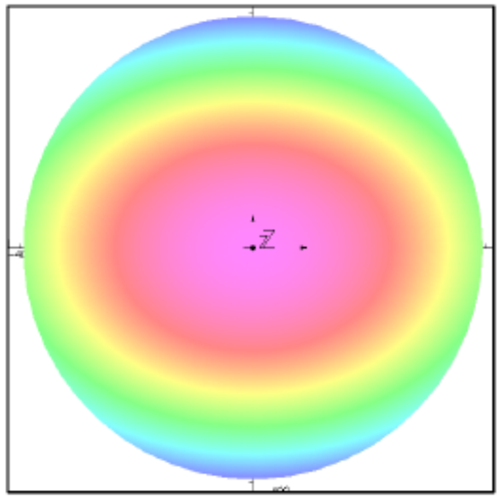
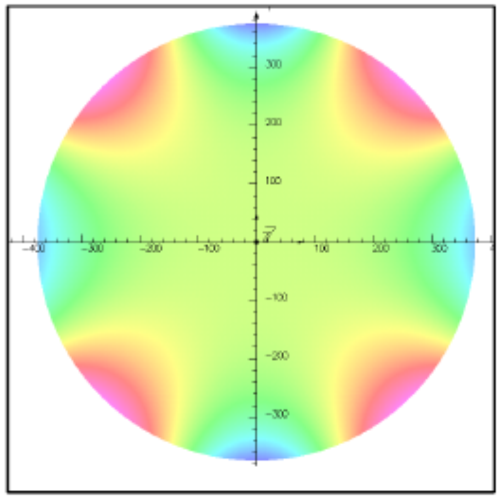
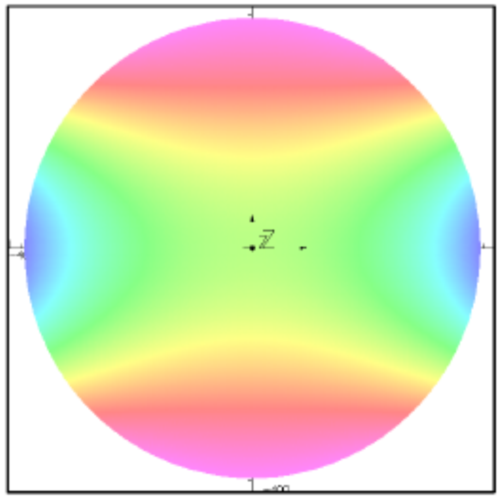




Field specification	+ +	+ +	- -	+ +
Peak field	-	++	+	++
Stress analysis	+	- -	- -	+
Conductor design	+	- -	- -	+
Mechanical layout	+ +	- -	+ +	- -
Superconductor	-	+ +	+	+ +
Stray field	+ +	- -	- -	- -
Compatibility H1 yoke	- -	+ +	-	+ +
Magnet volume	+	+ +	- -	+ +
First order conclusions that will be confirmed by further detailed studies	**Encouraging solution that has to be optimized if shielding is required**	**Seems not feasible due to technological limits (conductor , layers, …)**	**Seems not feasible due to design, techno and cost limits (field, cond, vol)**	**Encouraging solution if the H1 yoke fits with the stray field requirements**

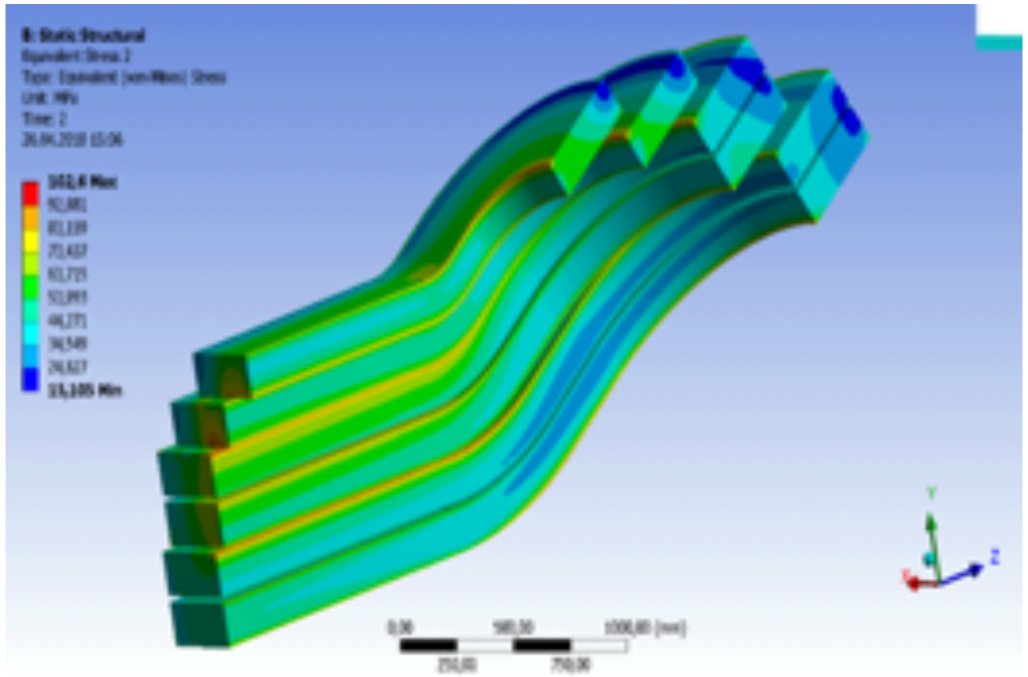
Comparison

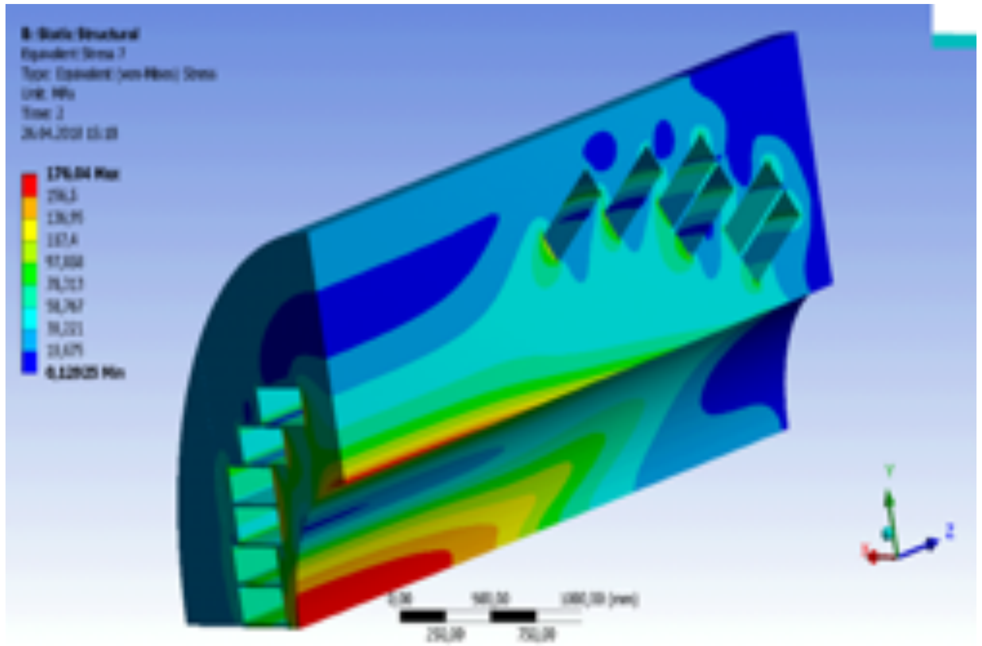
Preparing for the next step

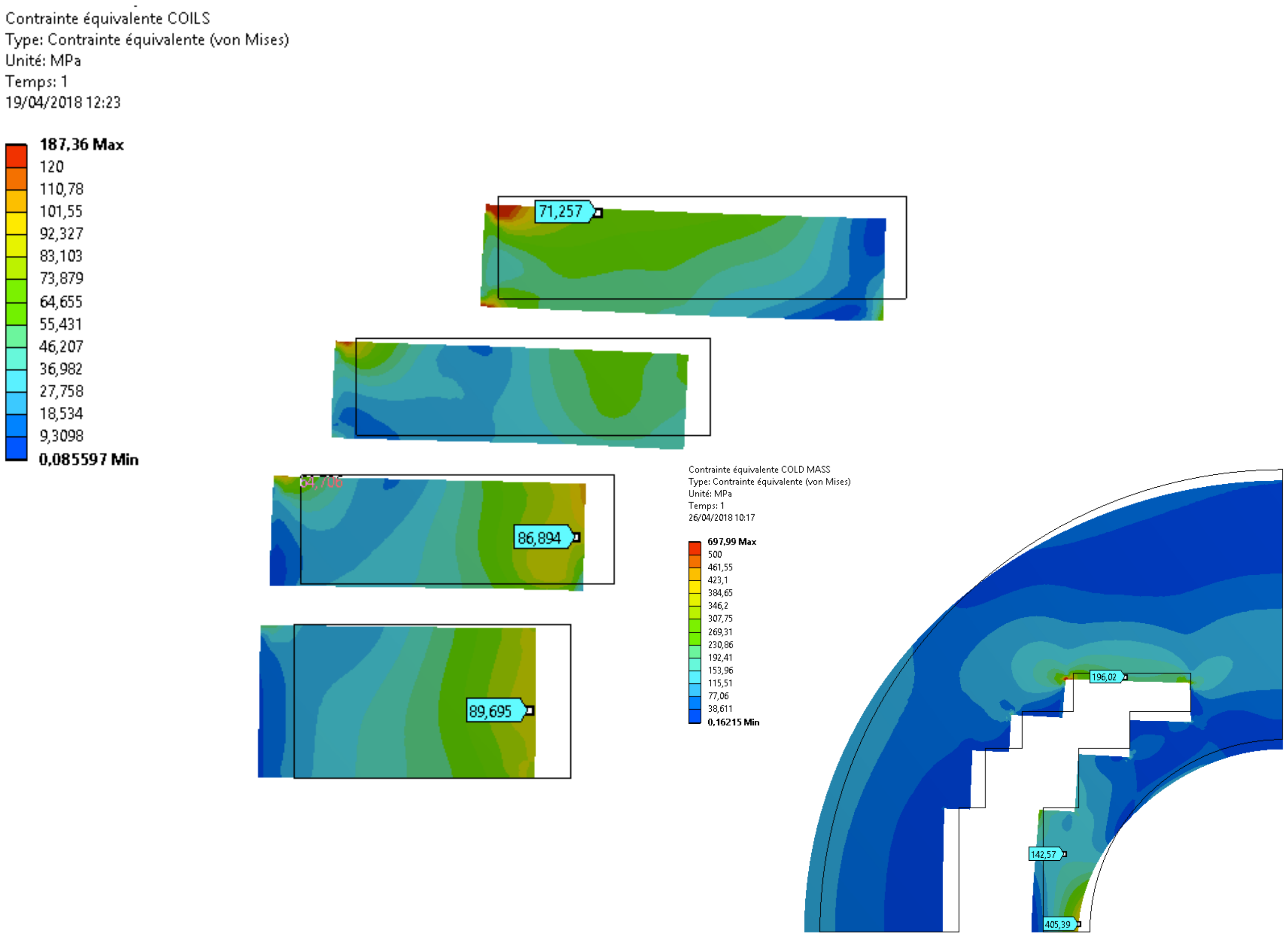
Cosine Theta	CCT	Block design	Racetrack	Helmholtz pair
				
Traditional design Extensive exp. Good homogeneity Small cross section	Easy to optimize High potential Easy to produce Good homogeneity	Easier to manufacture than cos theta Flat or cc cable Harder to optimize		Short setup solution Lots of space Low homogeneity

magnet

The Forces







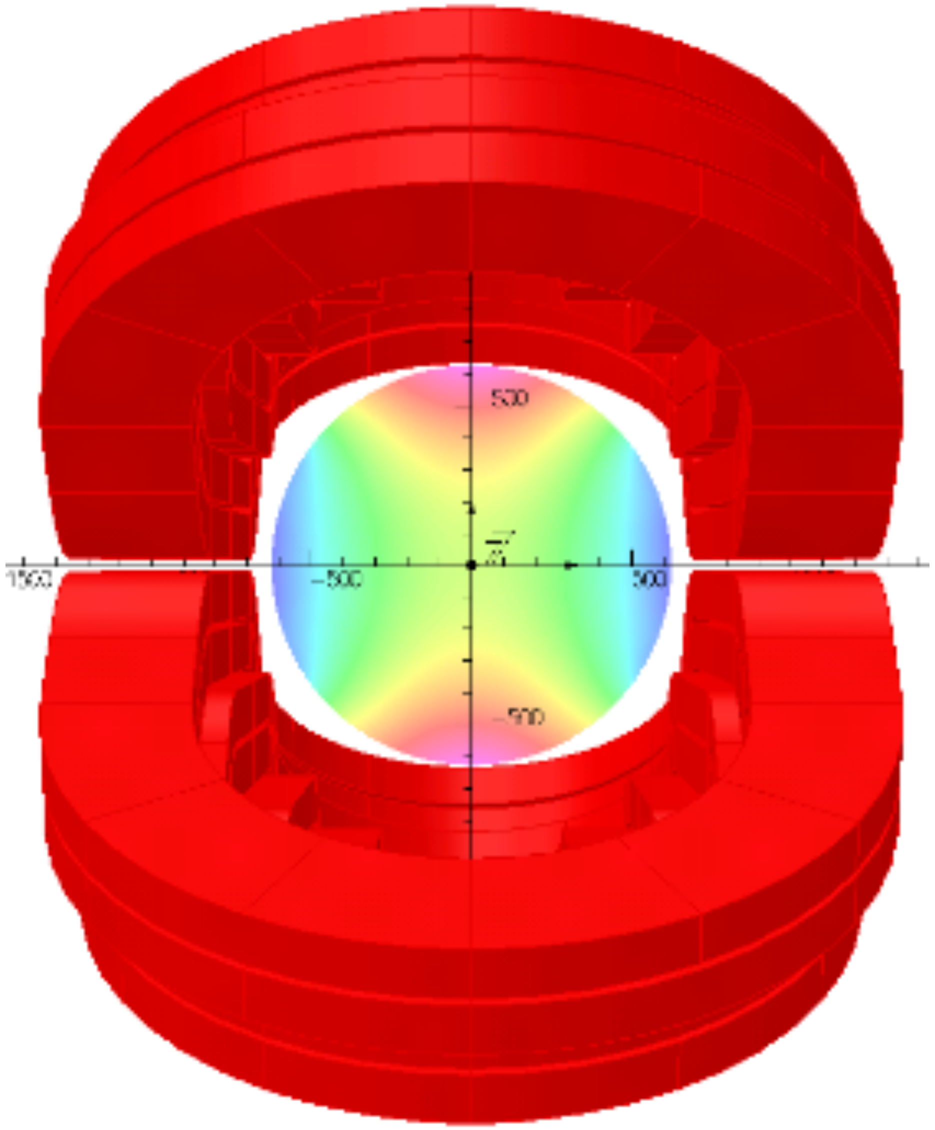
<200 Mpa Ppeak stress in conductor

<300 Mpa peak stress in yoke

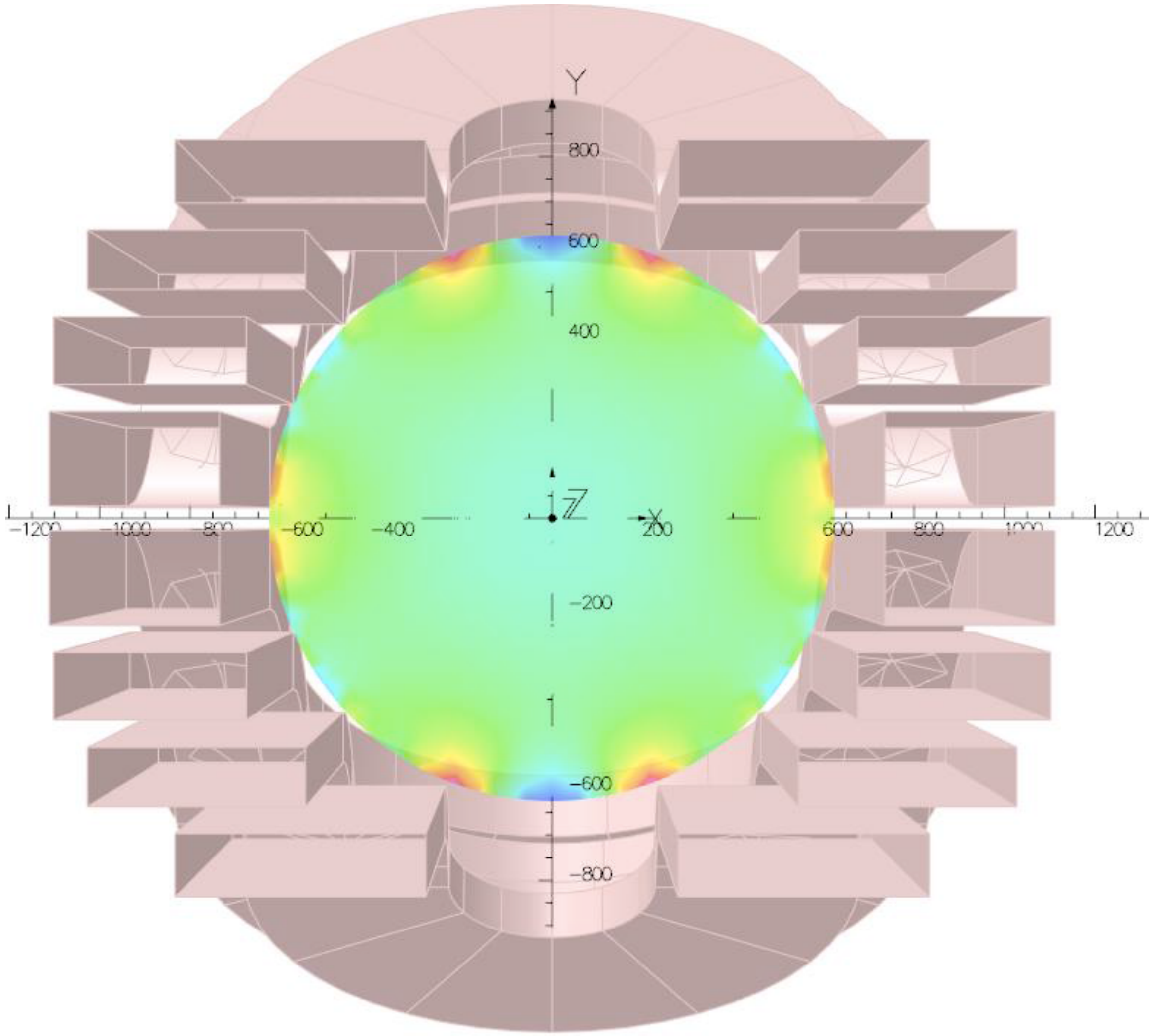
→ Accepatble!

magnet

Homogeneity



+ 2.4 % / -3.0 %



+ 4.6 % / -1.7 %

magnet

BiLFINGER

Weight: < 200.000 Kg

Length: 6900 mm

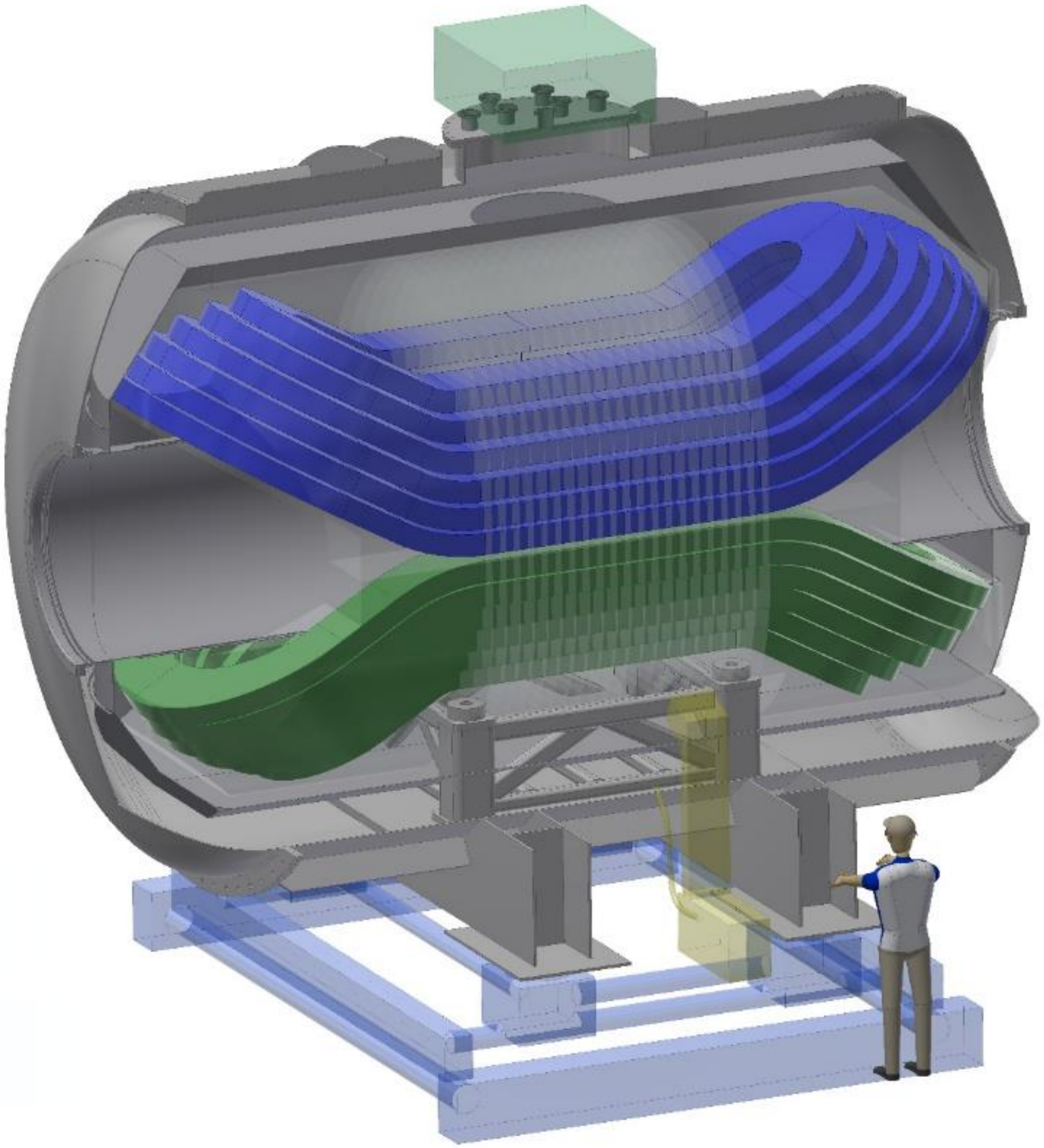
Diameter: 4400 mm

Warm bore: 1350* mm

Superconducting cable: 35.000 m

Superconducting wire: > 700.000 m NbTi

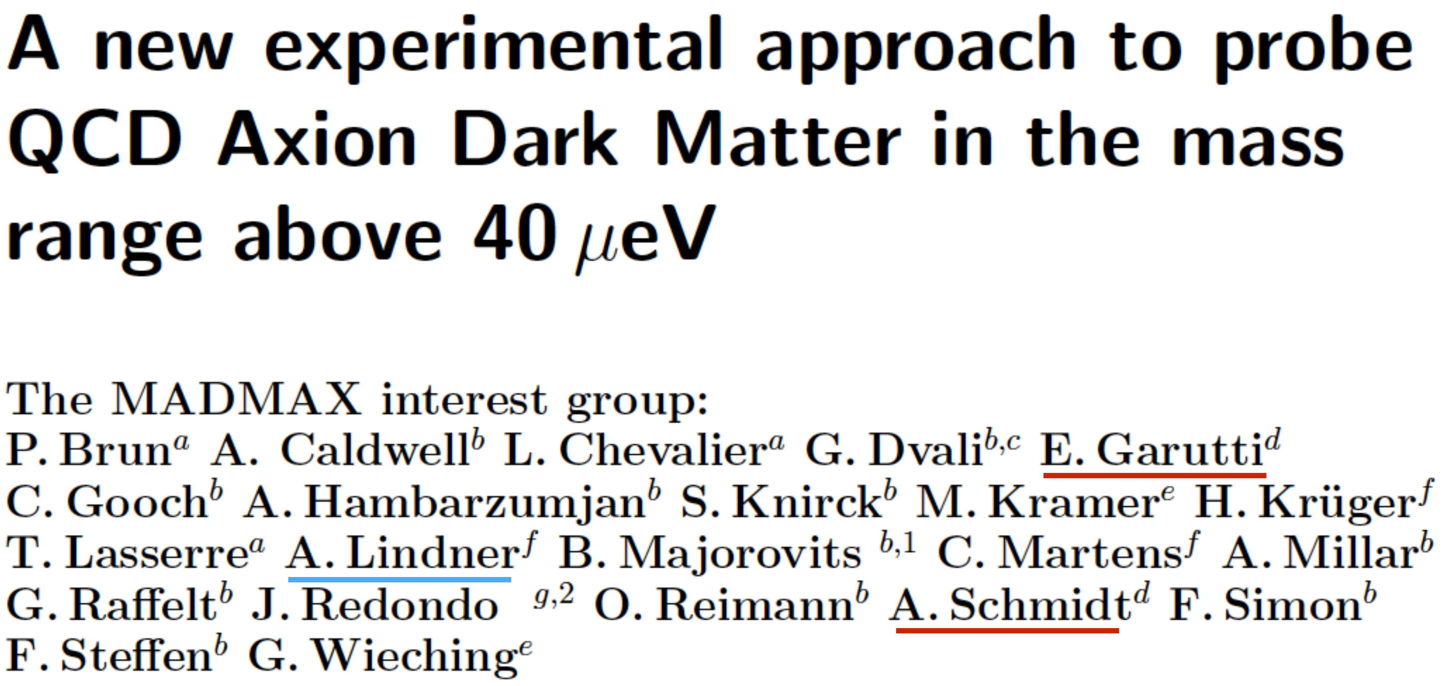
Operating temperature: ~2 K



So far no show stoppers, the show goes on!

MADMAX white paper

- MADMAX white paper:



A new experimental approach to probe QCD Axion Dark Matter in the mass range above 40 μeV

The MADMAX interest group:
P. Brun[a] A. Caldwell[b] L. Chevalier[a] G. Dvali[b,c] E. Garutti[d]
C. Gooch[b] A. Hambarzumjan[b] S. Knirck[b] M. Kramer[e] H. Krüger[f]
T. Lasserre[a] A. Lindner[f] B. Majorovits [b,1] C. Martens[f] A. Millar[b]
G. Raffelt[b] J. Redondo [g,2] O. Reimann[b] A. Schmidt[d] F. Simon[b]
F. Steffen[b] G. Wieching[e]

- madmax website:

https://www.mpp.mpg.de/forschung/astroteilchenphysik-und-kosmologie/madmax-suche-nach-axionen-als-dunkler-materie/

MADMAX collaboration

- MADMAX collaboration formed on 18. October 2017
  - MPI Munich
  - MPIfR Bonn
  - RWTH Aachen
  - Universität Hamburg
  - Universität Tübingen
  - Universidad de Zaragoza
  - CEA-IRFU Saclay
  - DESY Hamburg

MADMAX site

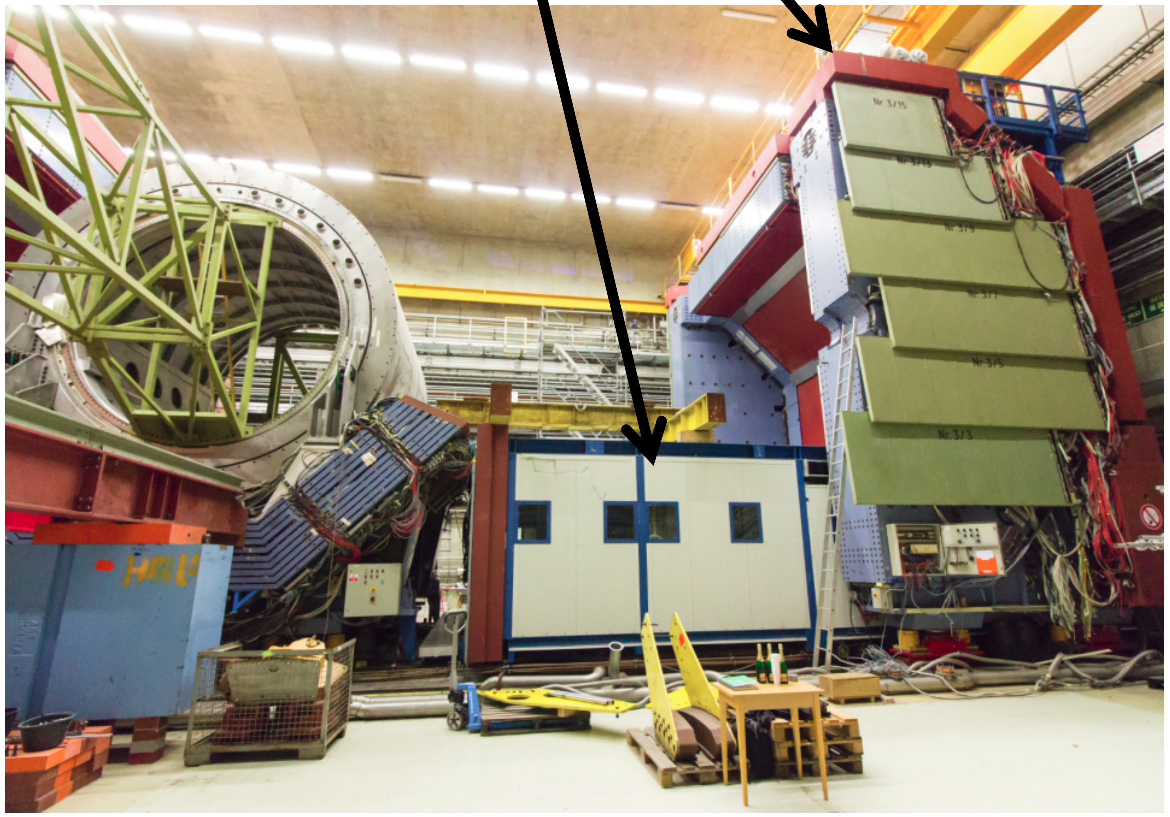
- DESY Hamburg (underground hall HERA-north)
  - excellent infrastructure (cryogenic supply)
  - location of ALPS-II
  - low EM noise environment
  - support from DESY

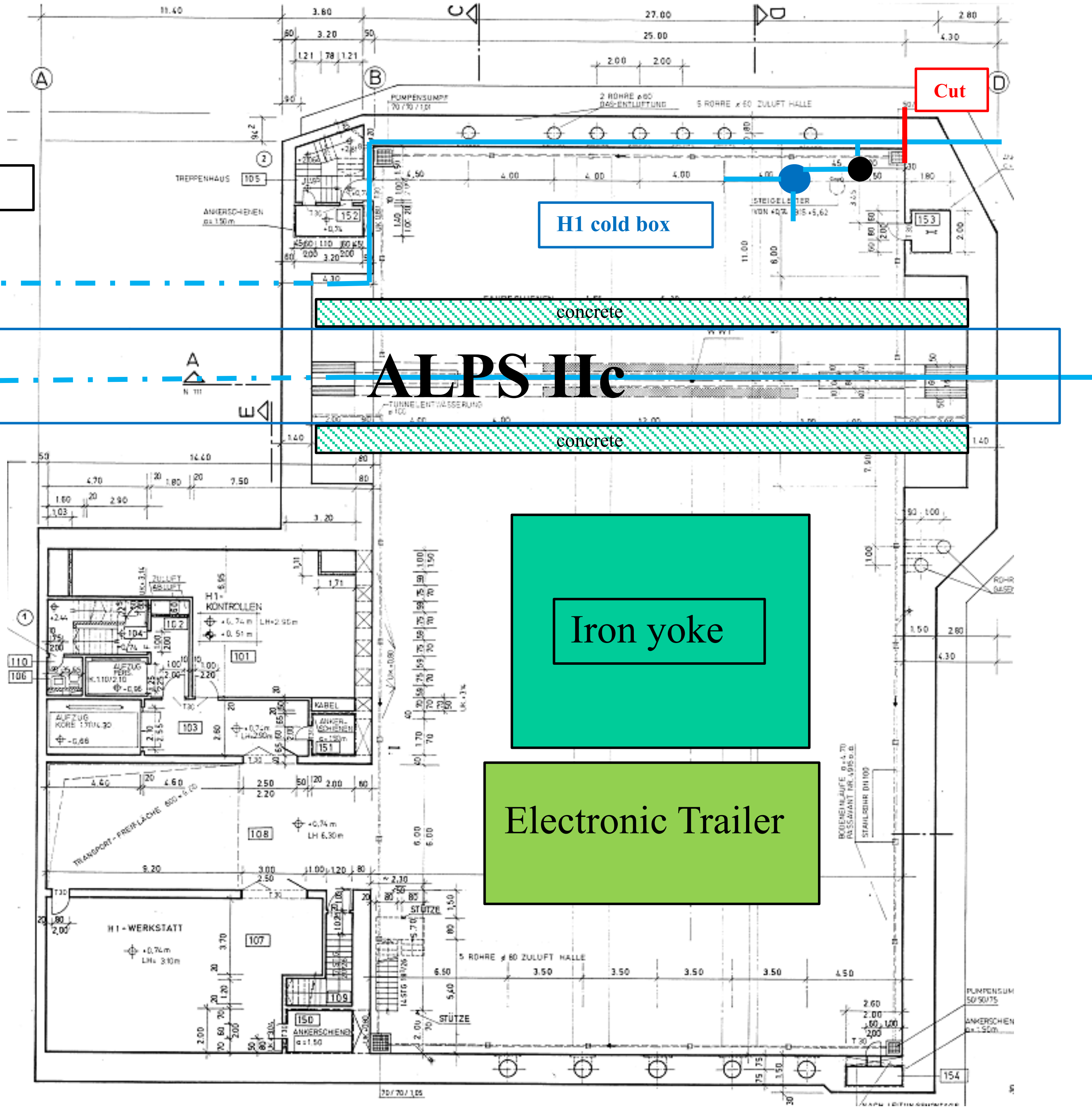
HERA north hall

@ DESY HERA hall north

offered to host MADMAX

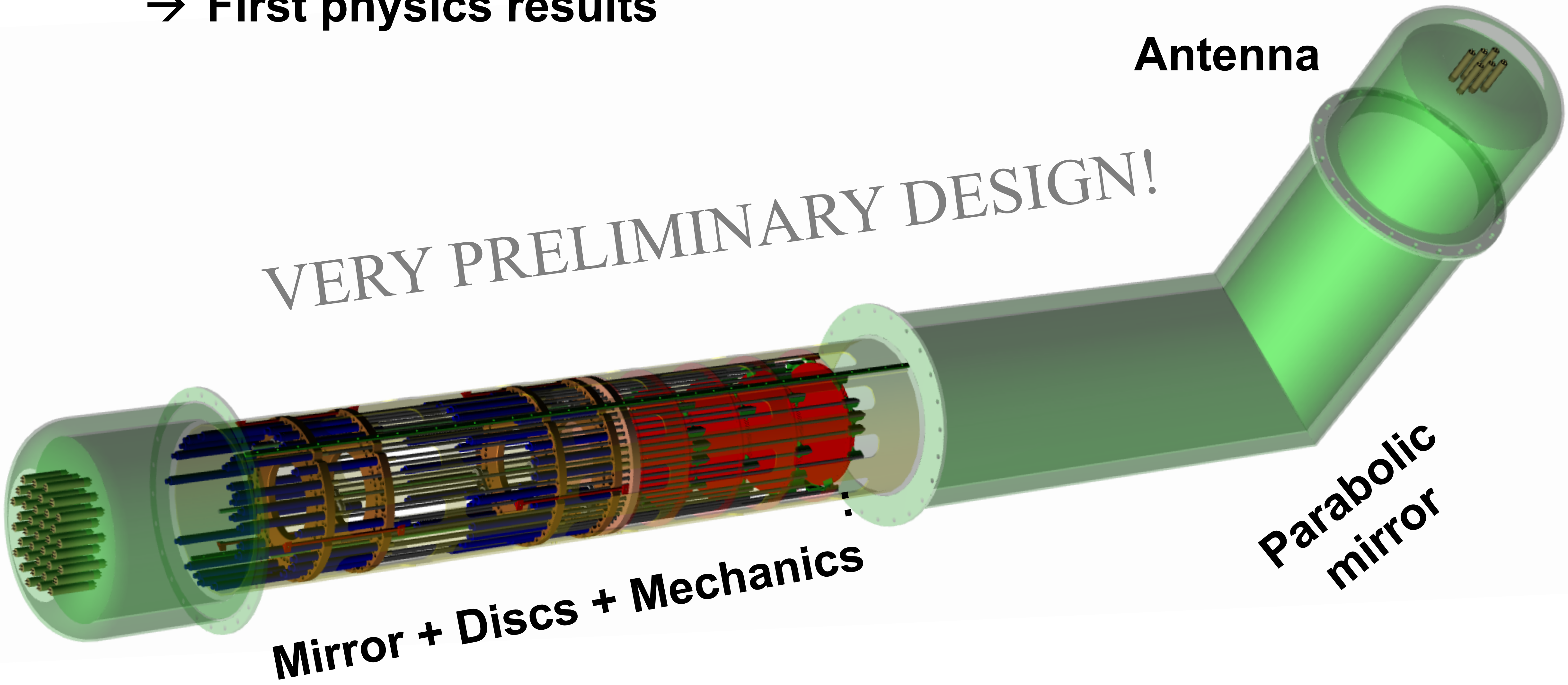
HERA yoke and control room available



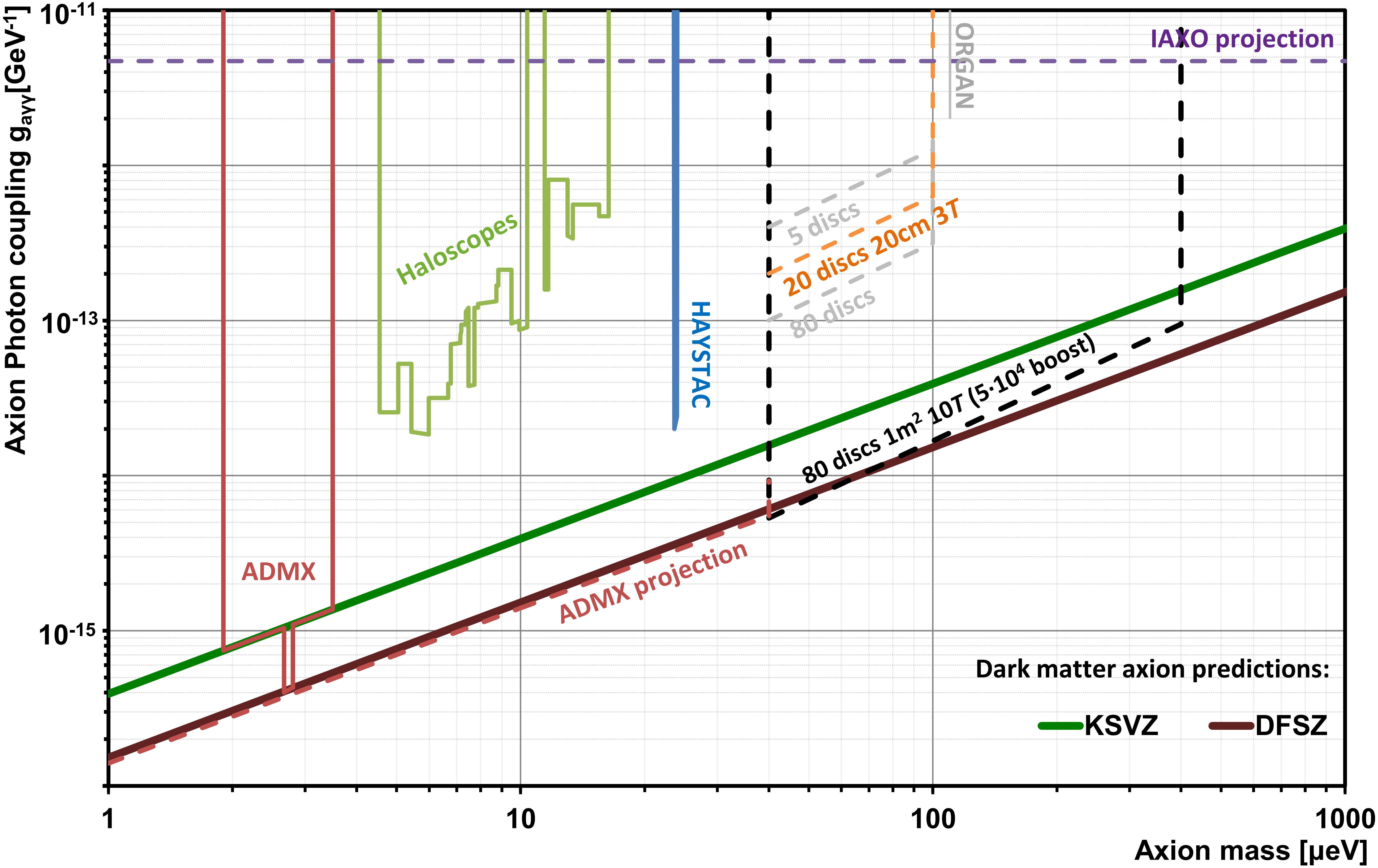


prototype

Build prototype with 20 discs, 30cm diameter
Use inside prototype (few T) magnet:
→ Test feasibility of 1m² booster
→ First physics results

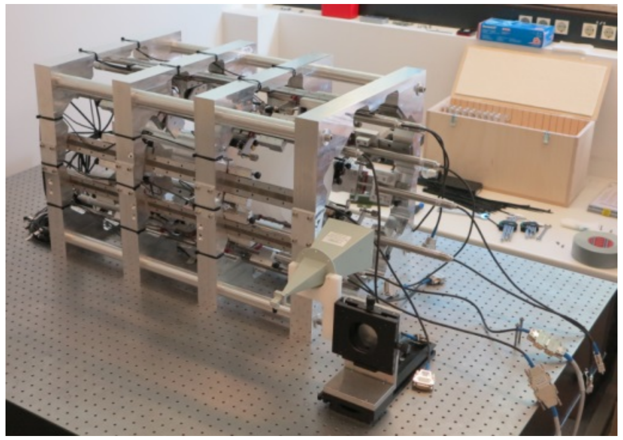


sensitivity calculation

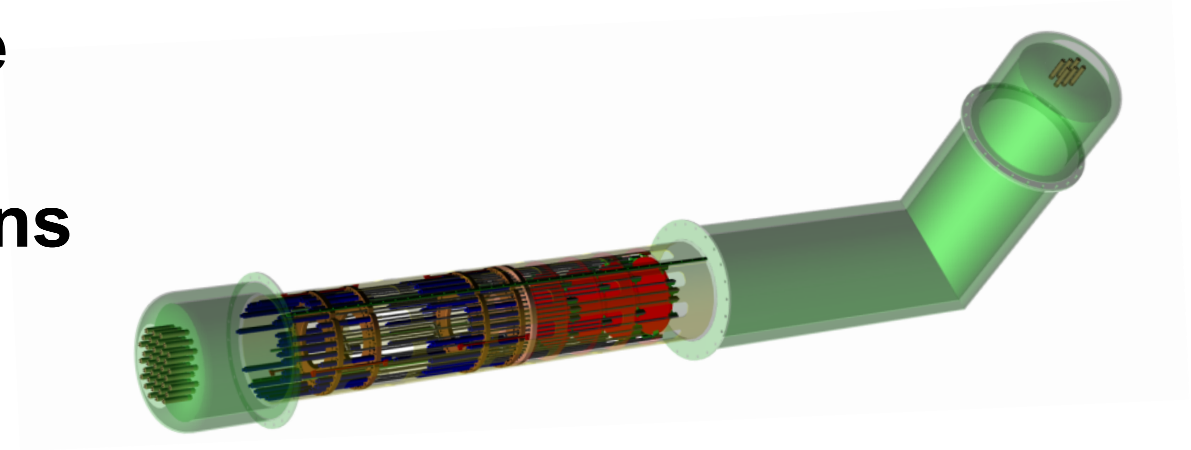


time line

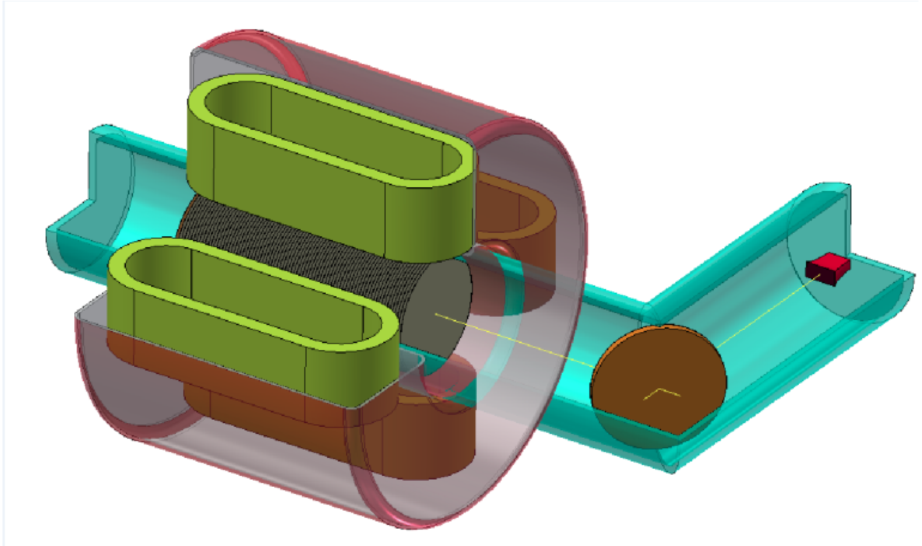
2018-2020
Finish Proof of principle phase,
full understanding of 3D effects



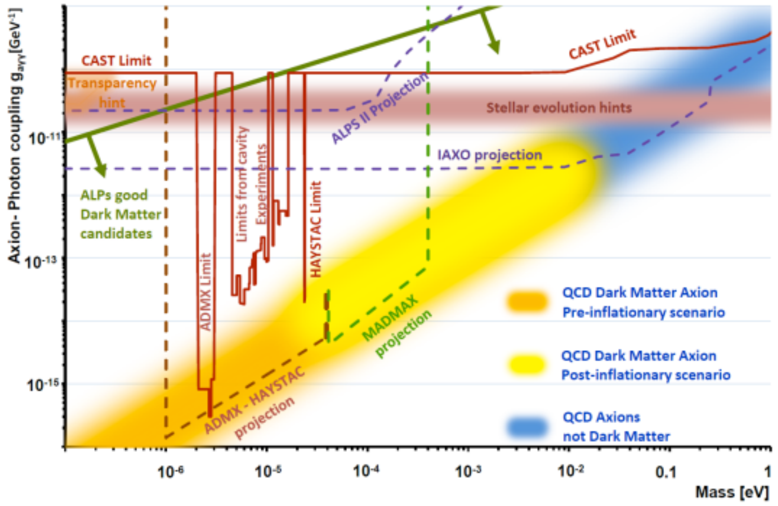
2018-2022
Prototype magnet & booster available
→ Integration, first physics runs,
search for ALPs and hidden photons

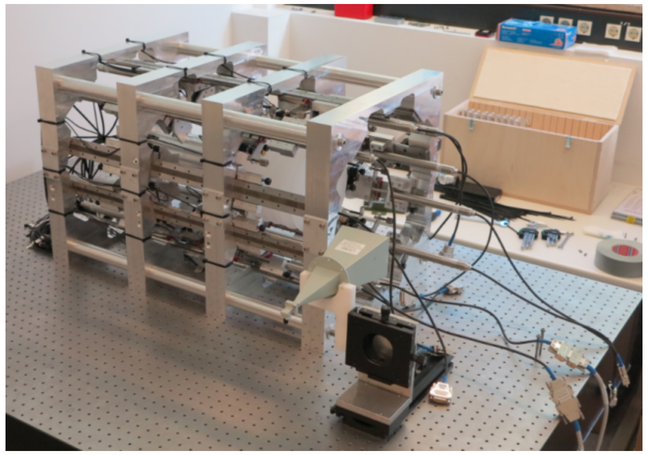


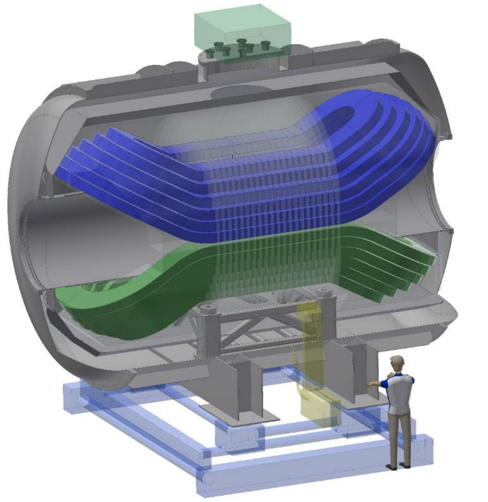
Afterwards:
Build final magnet
Build final booster
→ Start scanning 10-30GHz
(40-120 µeV) range



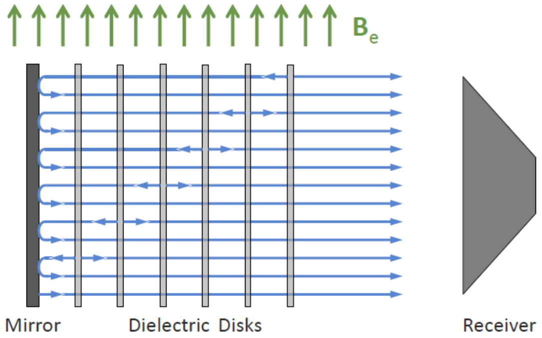
summary



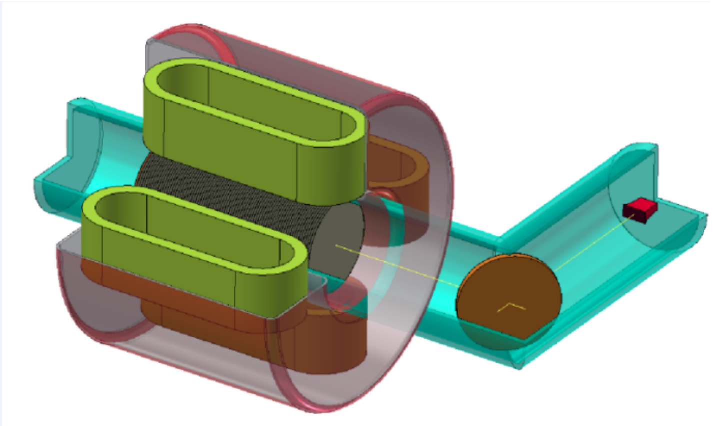




CONCLUSION

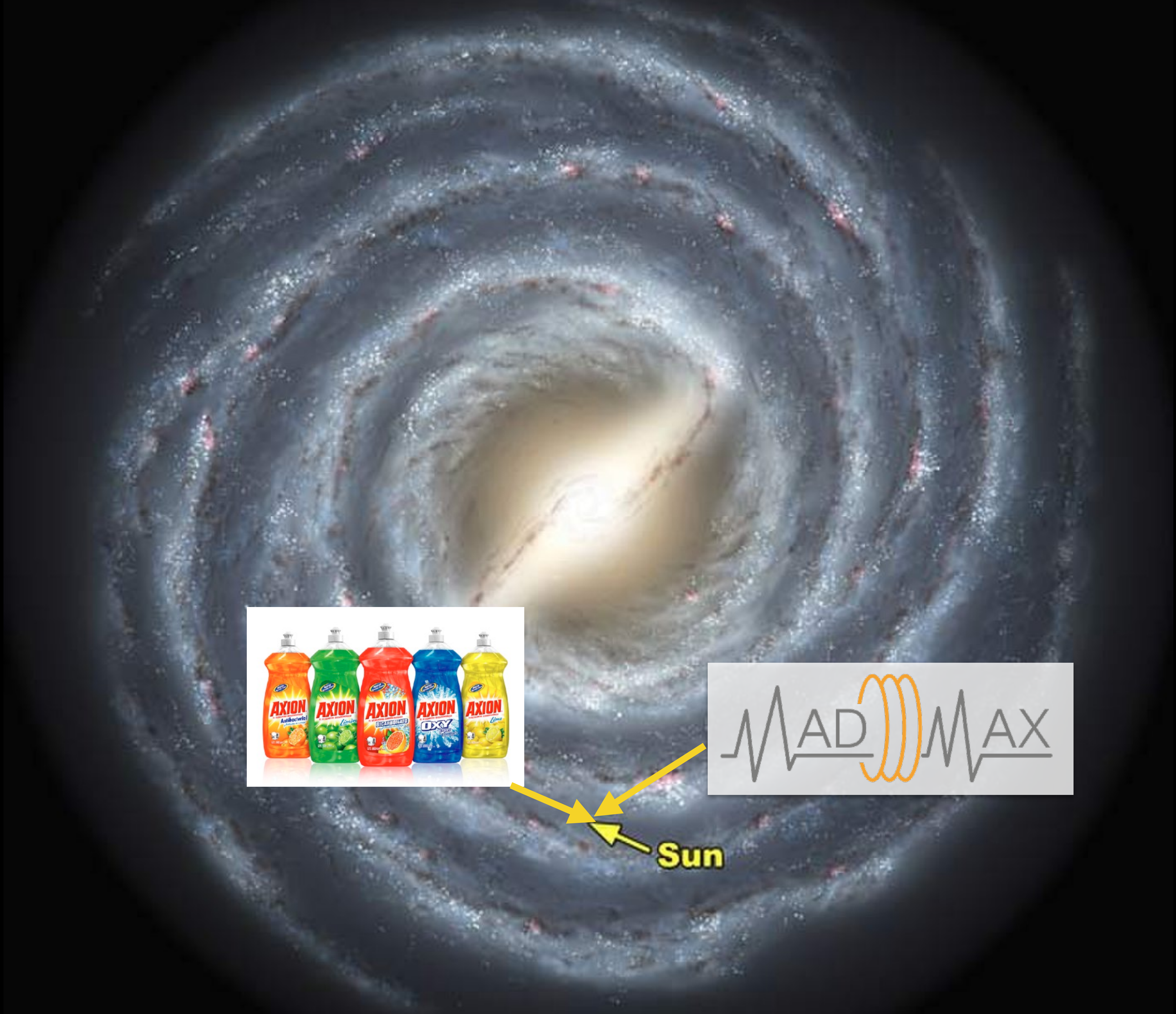


- Axions could solve strong CP and DM problems
- ALPs could solve astrophysical inconsistencies
- Mass range 40-400 µeV very well motivated, previously no experimental concepts!
- Dielectric haloscope could cover ~40-400 µeV axion/ALP mass rang
- MADMAX collaboration formed in Oct. 2017
- Magnet seems feasible
- So far no show stoppers found
- MADMAX: to be continued!



- Acknowledgements:
  - many plots taken from Javier Redondo, Stefan Knirck, Jan Schütte-Engel, Frank Steffen, Olaf Reimann, Alex Millar, Georg Raffelt, Bela Majorovits, …

backup


AXION
MADMAX
Sun