Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Detection of axion dark matter

Erika Garutti
Uni. HH

on behalf of the MADMAX collaboration

Towards the Detection of axion dark matter

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Strong CP problem

Strong force invariant under CP

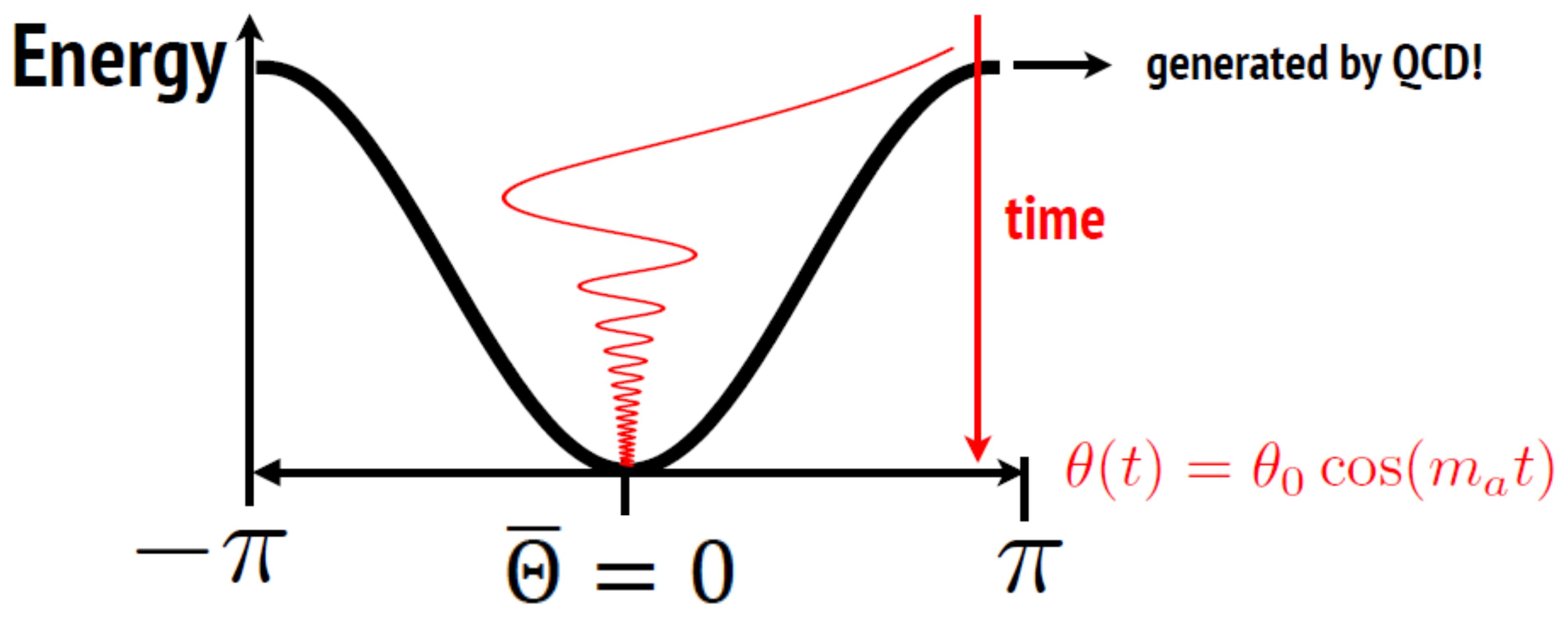
$$\mathcal{L}_{\rm QCD} = \sum_q \bar{\psi}_q(\mathrm{i}D - m_q)\psi_q - \tfrac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} - \bar{\Theta}\frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$$

➔ violates T reversal AND Parity

➔ CP violating term induces **electric dipole moment** of neutron (EDM):

$$\mathbf{d \sim \bar{\Theta} \cdot 10^{-16}\ e\ cm}$$

Peccei-Quinn symmetry breaking @ T~ f_a (very early universe, $f_a > 10^9$ GeV)



erika.garutti@physik.uni-hamburg.de

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$$\mathcal{L}_{QCD} = \sum_q \bar{\psi}_q (iD - m_q)\psi_q - \frac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} - \bar{\Theta} \frac{\alpha_s}{8\pi} G_{\mu\nu a} \tilde{G}_a^{\mu\nu}$$

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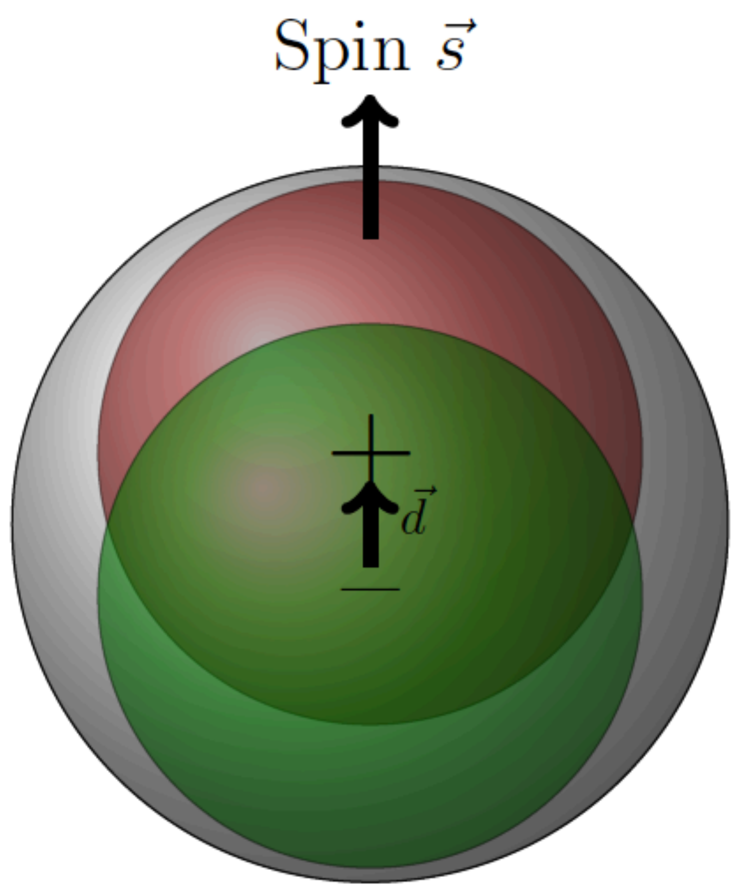

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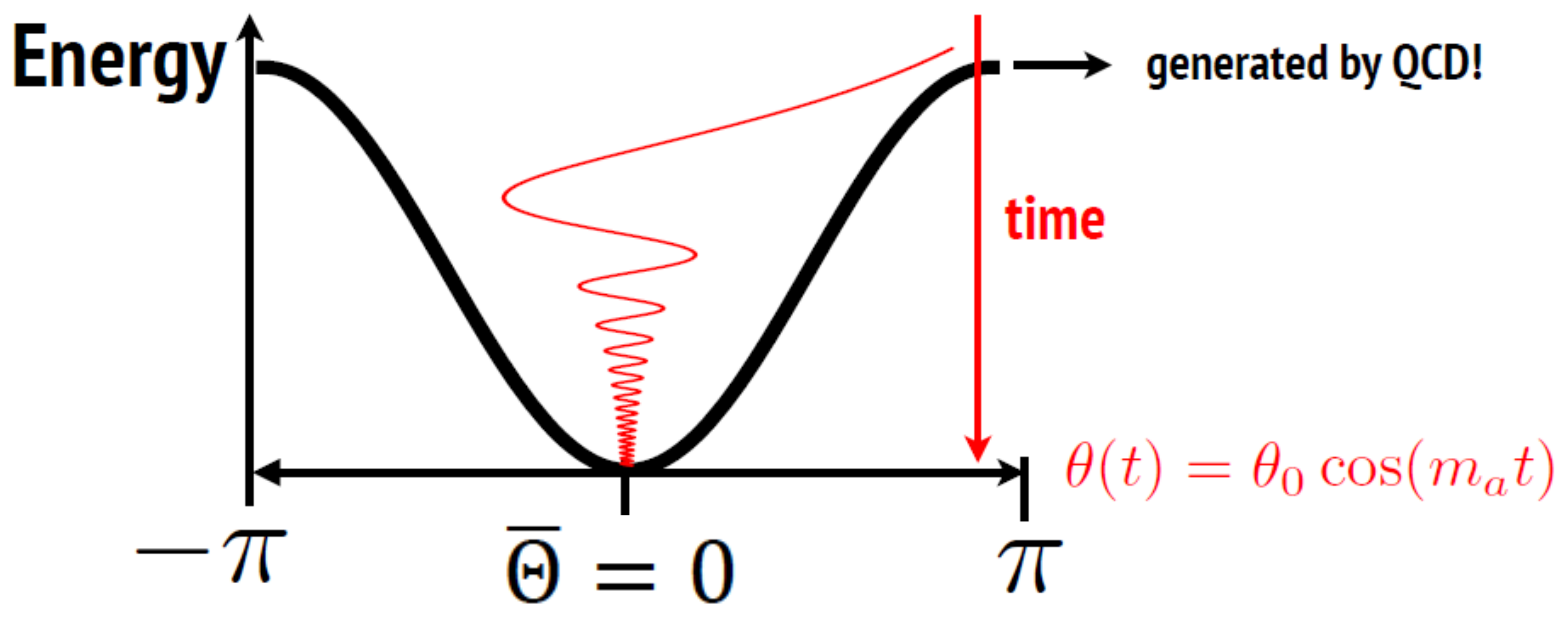

EDM:
- permanent separation of positive and negative charge
- fundamental property of particles (like magnetic moment, mass, charge)
- existence of EDM only possible via violation of time reversal T = CP symmetry
- has nothing to do with electric dipole moments observed in some molecules
- (e.g. water molecule)
- close connection to "matter-antimatter" asymmetry
- axion/ALP field leads to oscillating EDM

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Strong CP problem

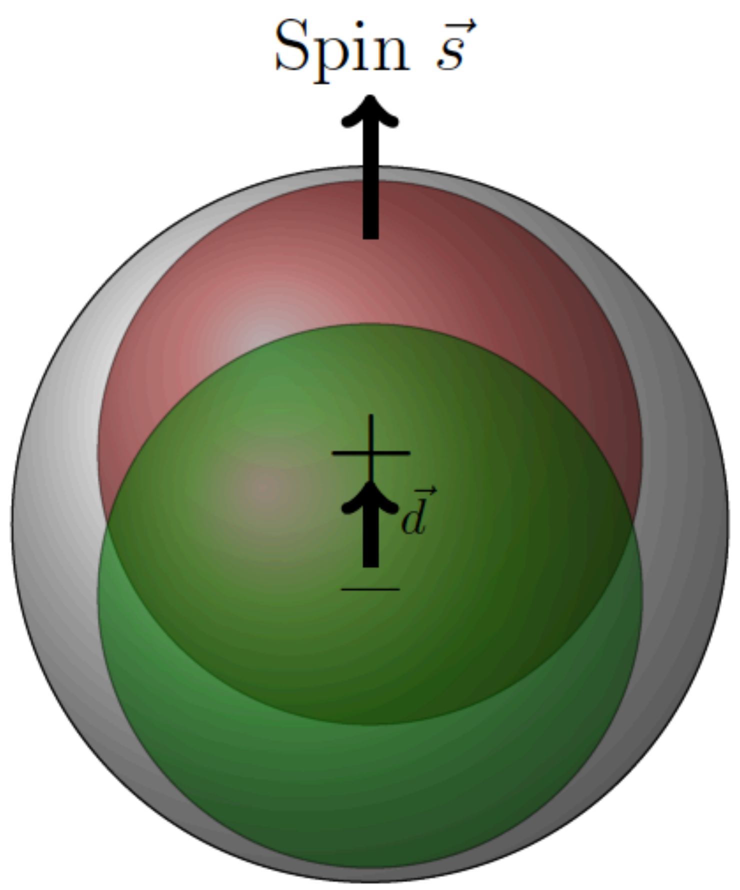
Strong force invariant under CP

$$\mathcal{L}_{QCD} = \sum_q \bar{\psi}_q (iD - m_q)\psi_q - \frac{1}{4} G_{\mu\nu a} G_a^{\mu\nu} - \bar{\Theta} \frac{\alpha_s}{8\pi} G_{\mu\nu a} \tilde{G}_a^{\mu\nu}$$

→ violates T reversal AND Parity

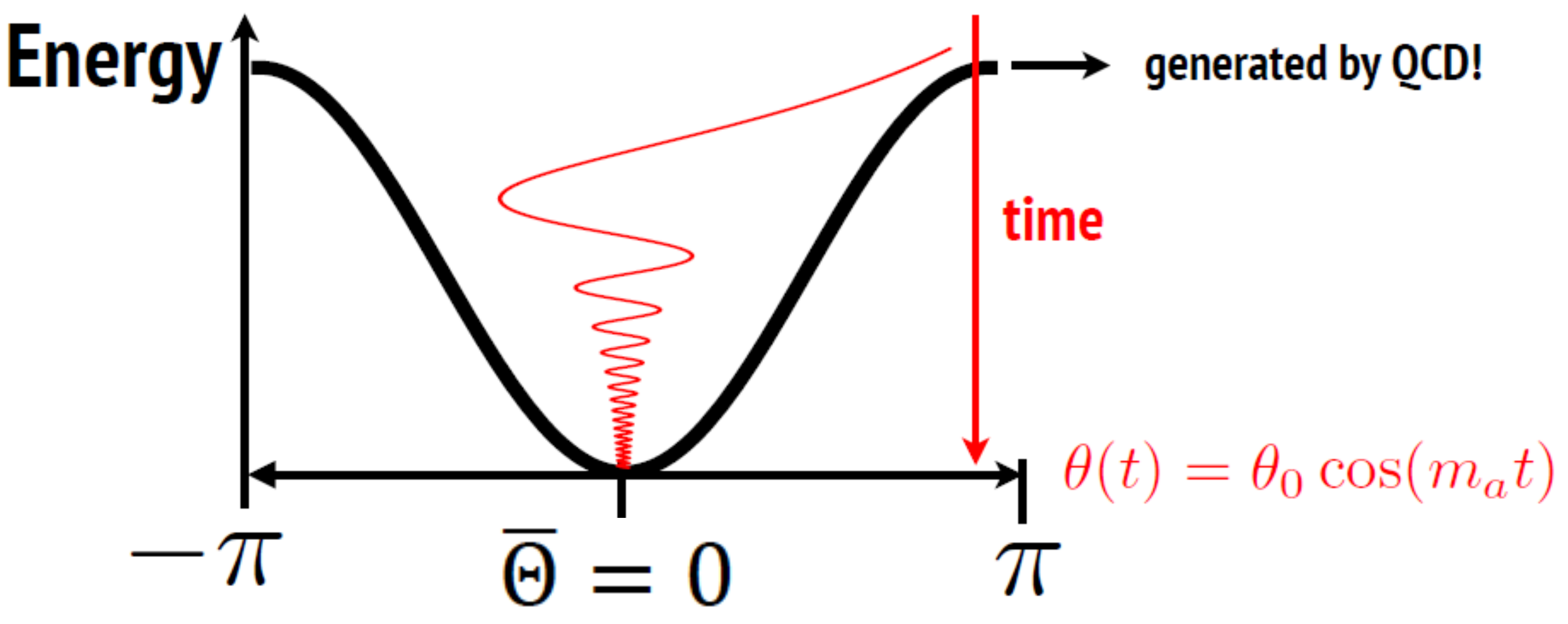
→ CP violating term induces **electric dipole moment** of neutron (EDM):

d ~ $\bar{\Theta}$ · 10^{-16} e cm



But experimentally: d < 10^{-26} e cm → $\bar{\Theta}$ < 10^{-10} **WHY SO SMALL !?!?**

Peccei-Quinn symmetry breaking @ T~ f_a (very early universe, $f_a > 10^9$ GeV)



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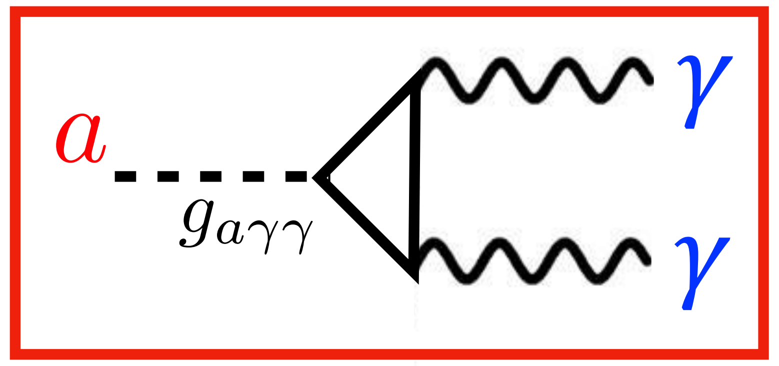
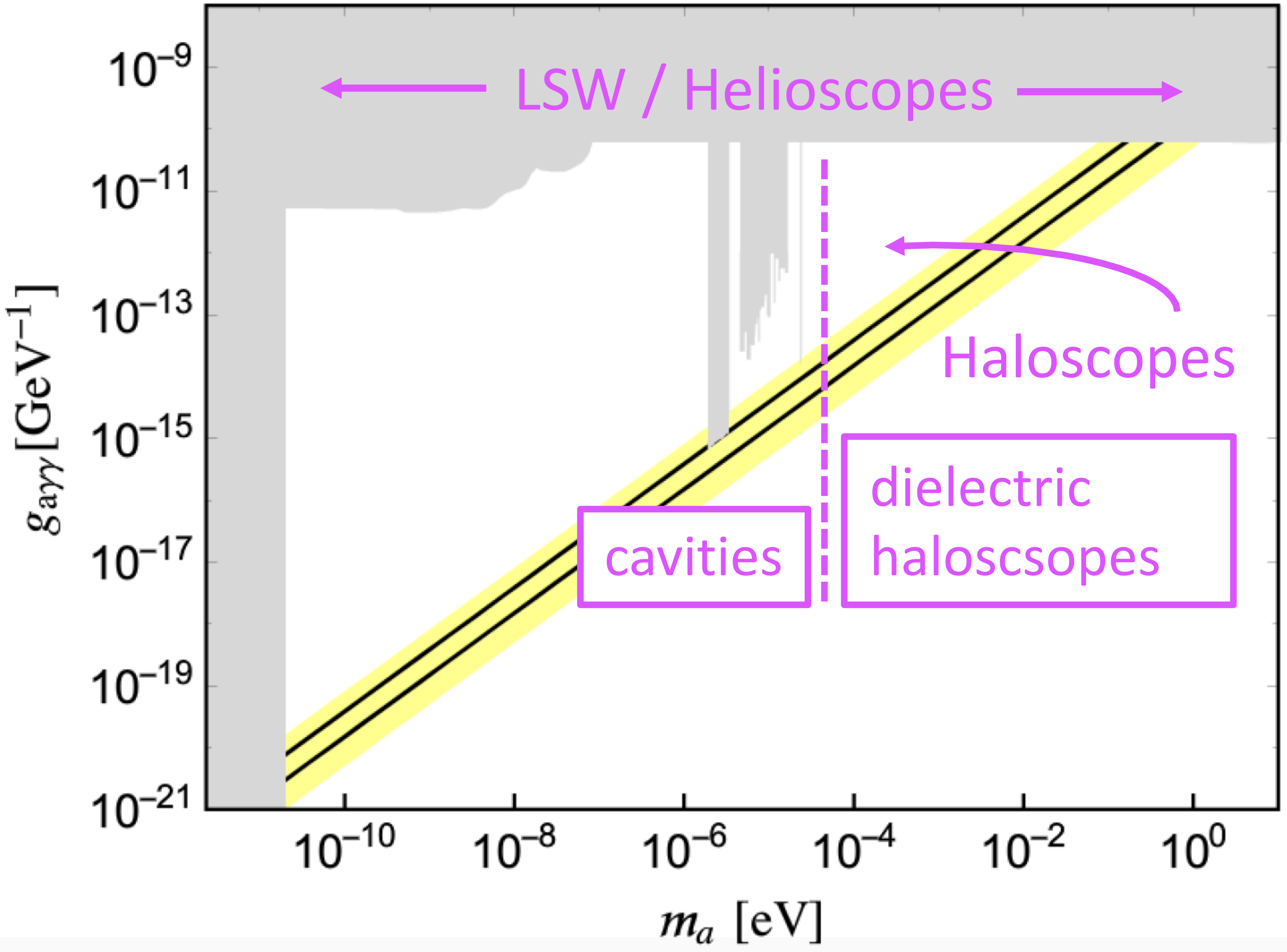
Dark matter axion search

- Axion: arises from Strong CP problem via Peccei-Quinn mechanism
- Pseudo Nambu-Goldstone boson
- Axion can couple to two photons:



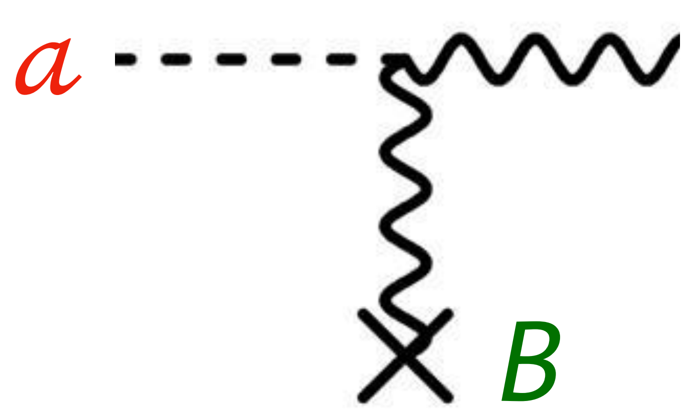
"Sikivie process"

- Axion model: $m_a \propto g_{a\gamma\gamma}$ (axion-photon coupling)
- Axion can explain (part of) Cold Dark Matter



Dielectric Haloscope

- In an external **B-field** the **axion** sources an oscillating **E-field**



$$E_a = -\frac{g_{a\gamma\gamma} B_e}{\epsilon} a$$

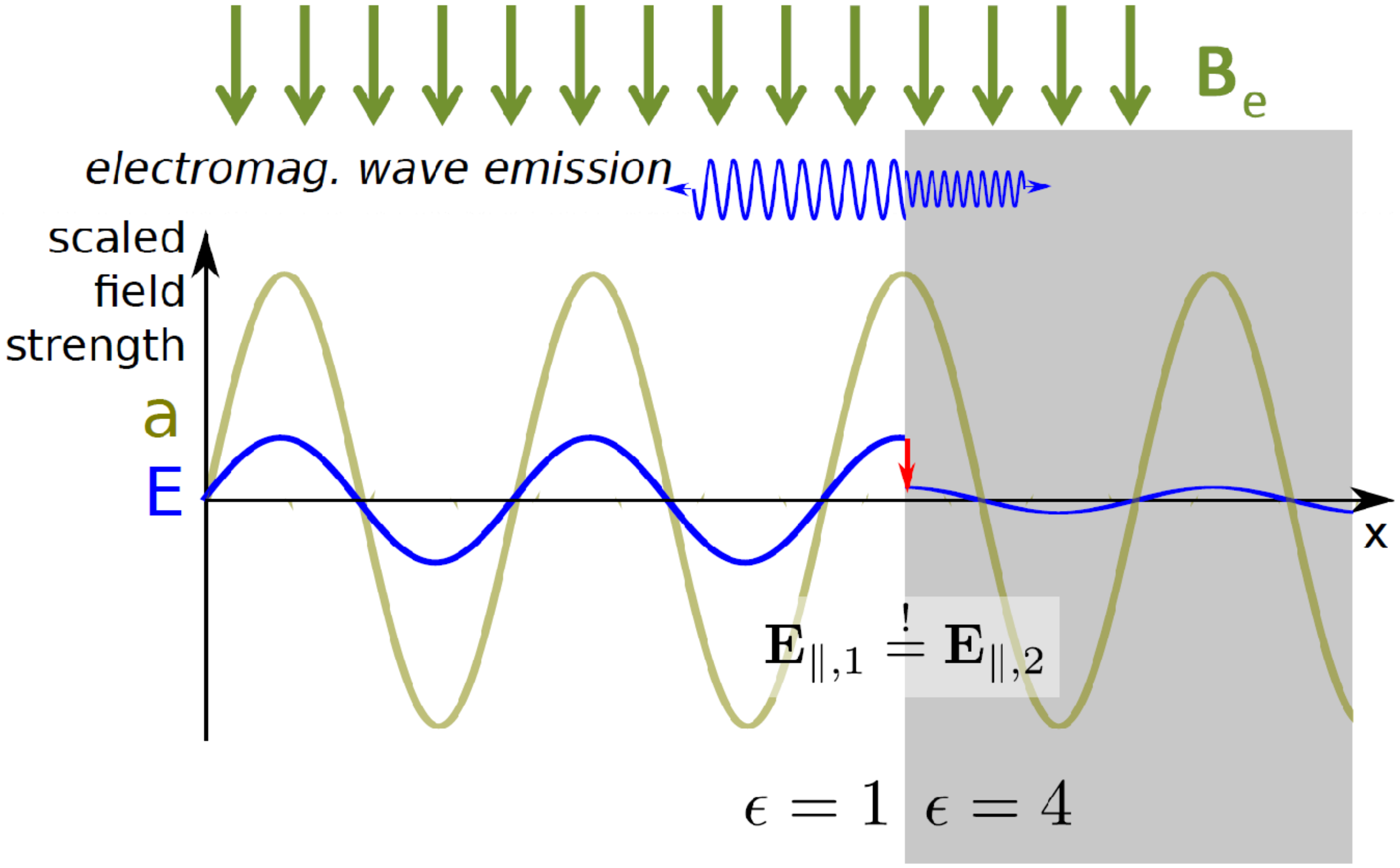
- At surfaces with transition of $\epsilon_1 \neq \epsilon_2$: E-field must be continuous
  → **Emission of photons**

Photon power :

$$\frac{P}{A} = 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} C_{a\gamma\gamma}^2 \left(\frac{B}{10\mathrm{T}}\right)^2$$

$$C_{a\gamma\gamma}^2 \propto g_{a\gamma\gamma}^2$$

$$O(C_{a\gamma\gamma}^2) = 1$$



Based on the original idea of:
D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald JCAP 1304 (2013) 016 [arXiv:1212.2970].

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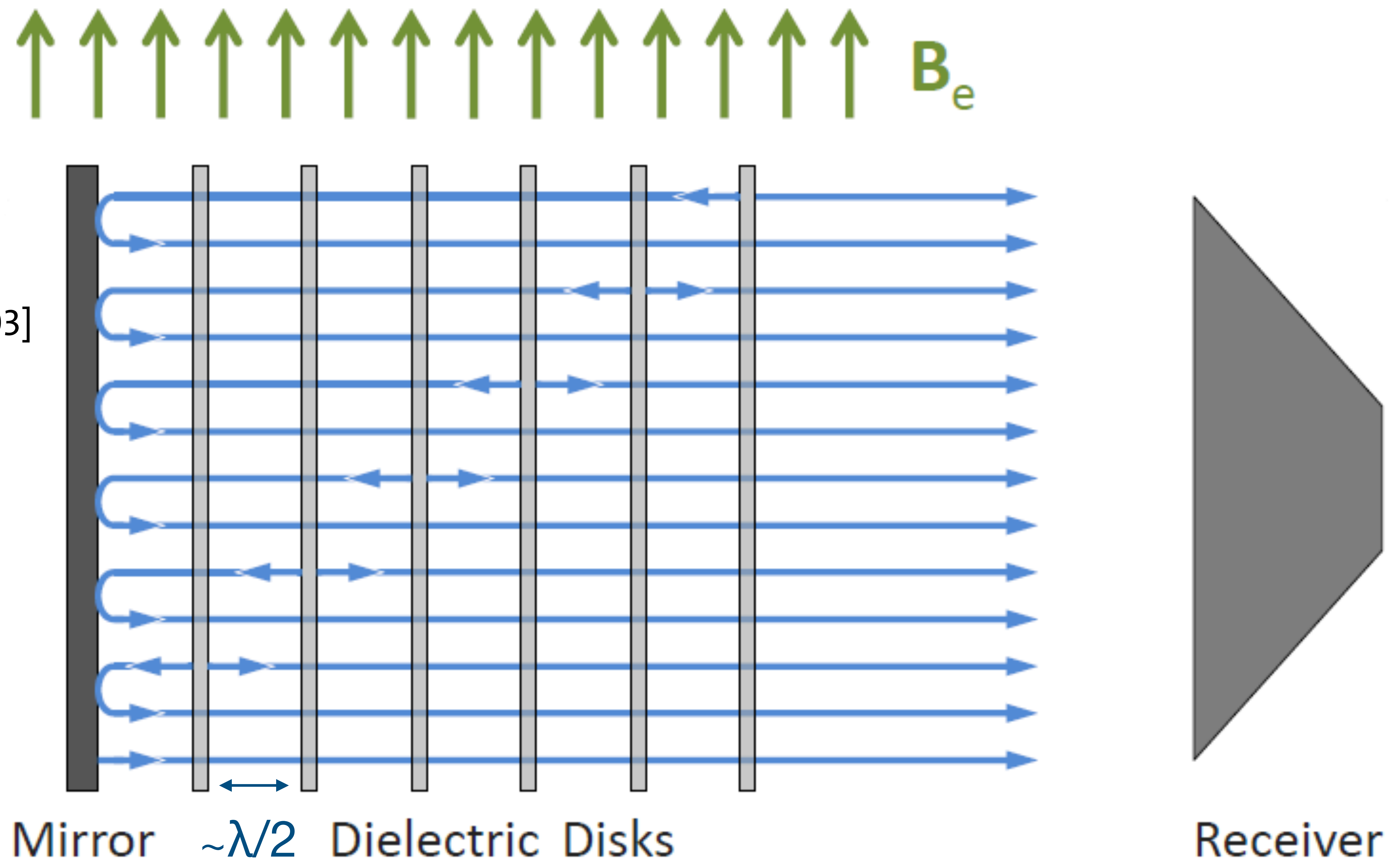
Dielectric Haloscope

- Boost the power by coherent interference of photons generated on N discs plus resonance between discs

Jaeckel and J. Redondo, Phys. Rev. D 88, 115002, (2013) [arXiv:1308.1103]



Photon power :

$$\frac{P}{A} = 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} C_{a\gamma\gamma}^2 \left(\frac{B}{10\mathrm{T}} \right)^2 |\beta|^2$$

$$\beta^2 = \frac{P_{\mathrm{Diel.Halosc.}}}{P_{\mathrm{Mirror}}}$$

Dielectric Haloscope

- Boost the power by coherent interference of photons generated on N discs plus resonance between discs

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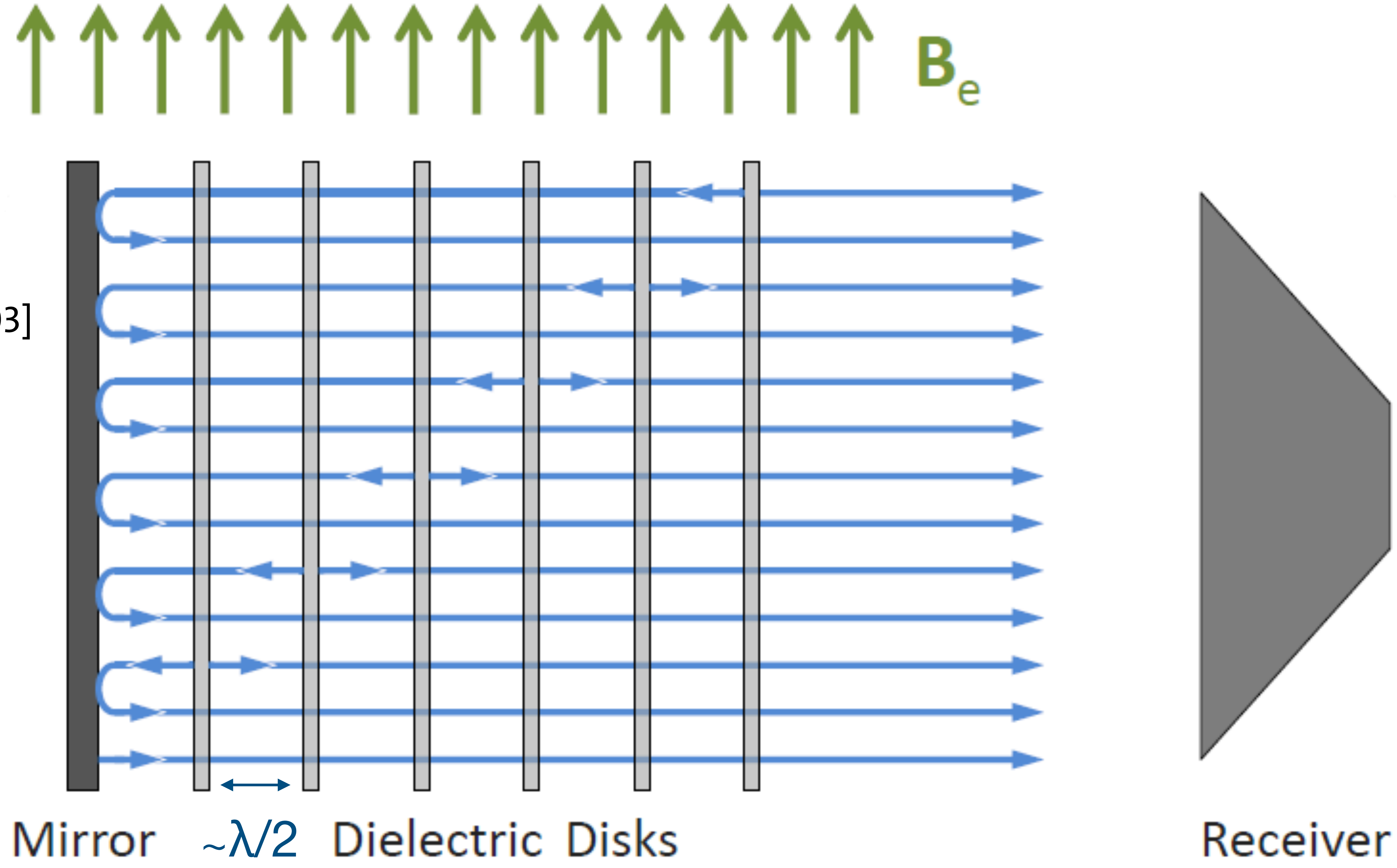

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FoM = B² m² = 100 T² m²

$$\beta^2 = \frac{P_{\text{Diel.Halosc.}}}{P_{\text{Mirror}}}$$

Dielectric Haloscope

- $|\beta|^2$ > 10^4 achievable with 80 discs of $LaAlO_3$ (ϵ = 24)

"Quasi-broadband" achieved by:

- positioning the discs with relative spacing of ~ λ/2 according to simulation prediction
- with precision better than 10 µm

Photon power :

$$\frac{P}{A} = 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} C_{a\gamma\gamma}^2 \left(\frac{B}{10\mathrm{T}}\right)^2 |\beta|^2$$

FoM = B^2 m^2 = 100 T^2 m^2

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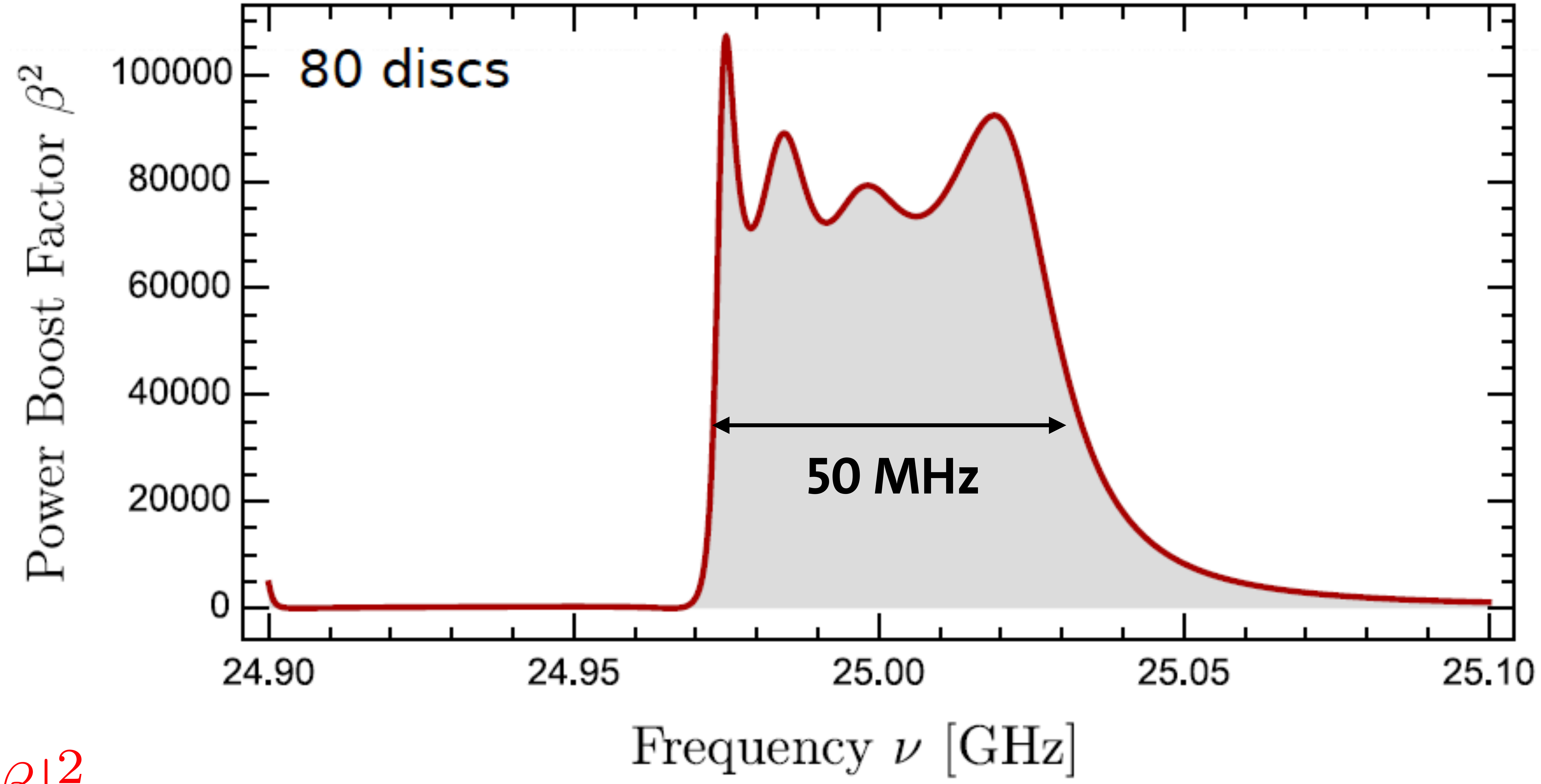
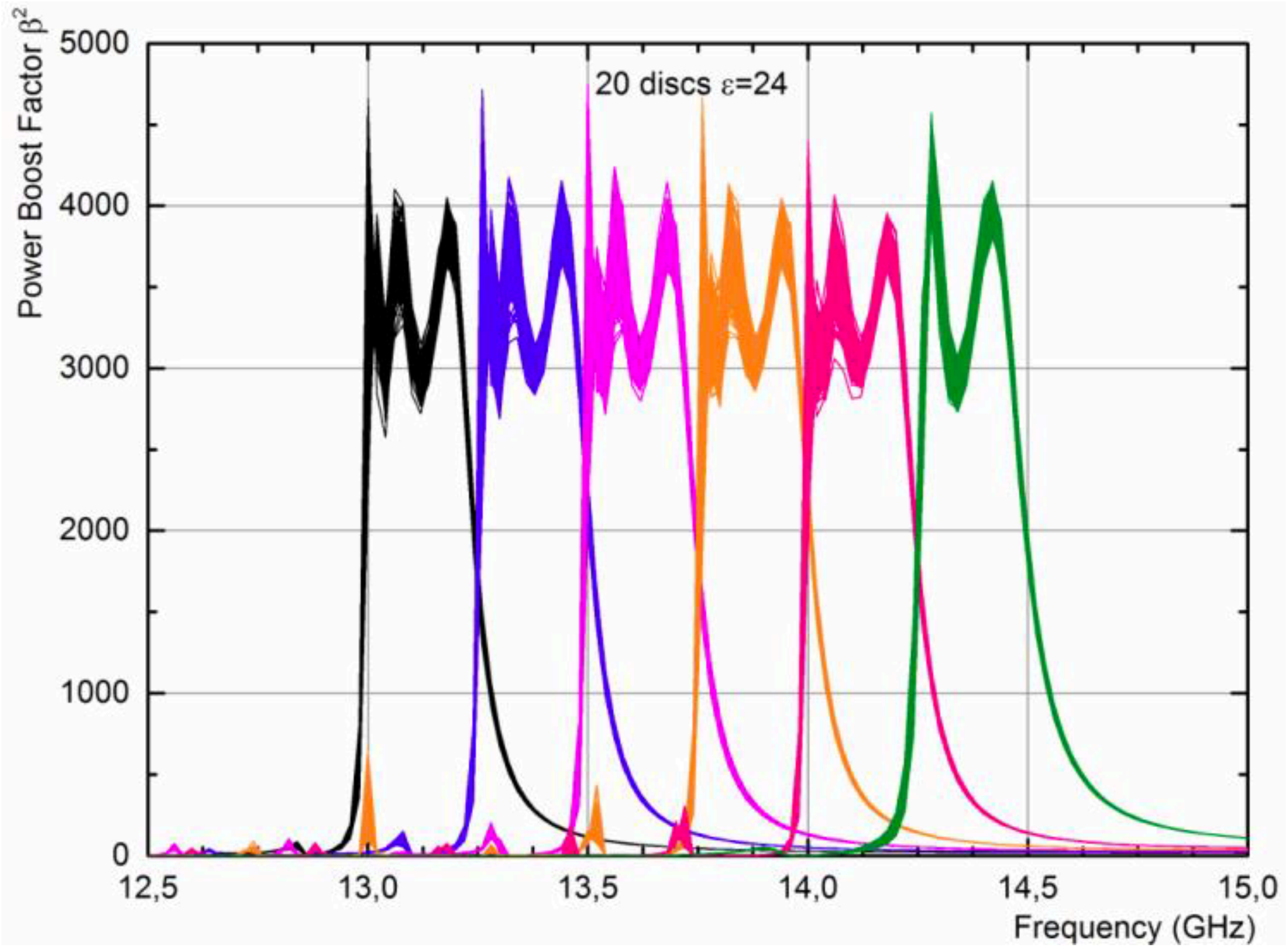


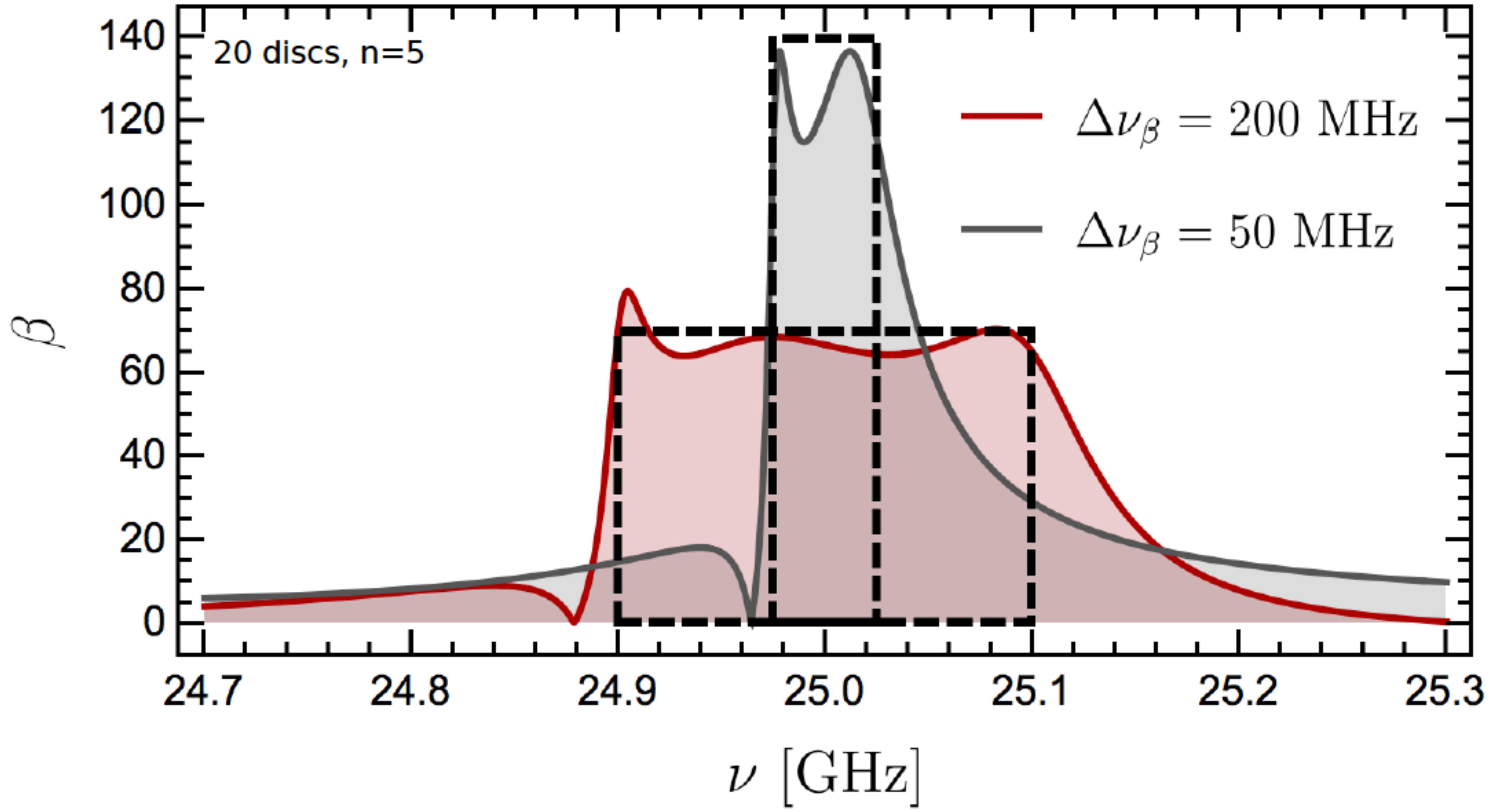
White paper: MADMAX Collaboration, Eur. Phys. J. C 79, 186 (2019), [arXiv:1901.07401]

Frequency scan concept

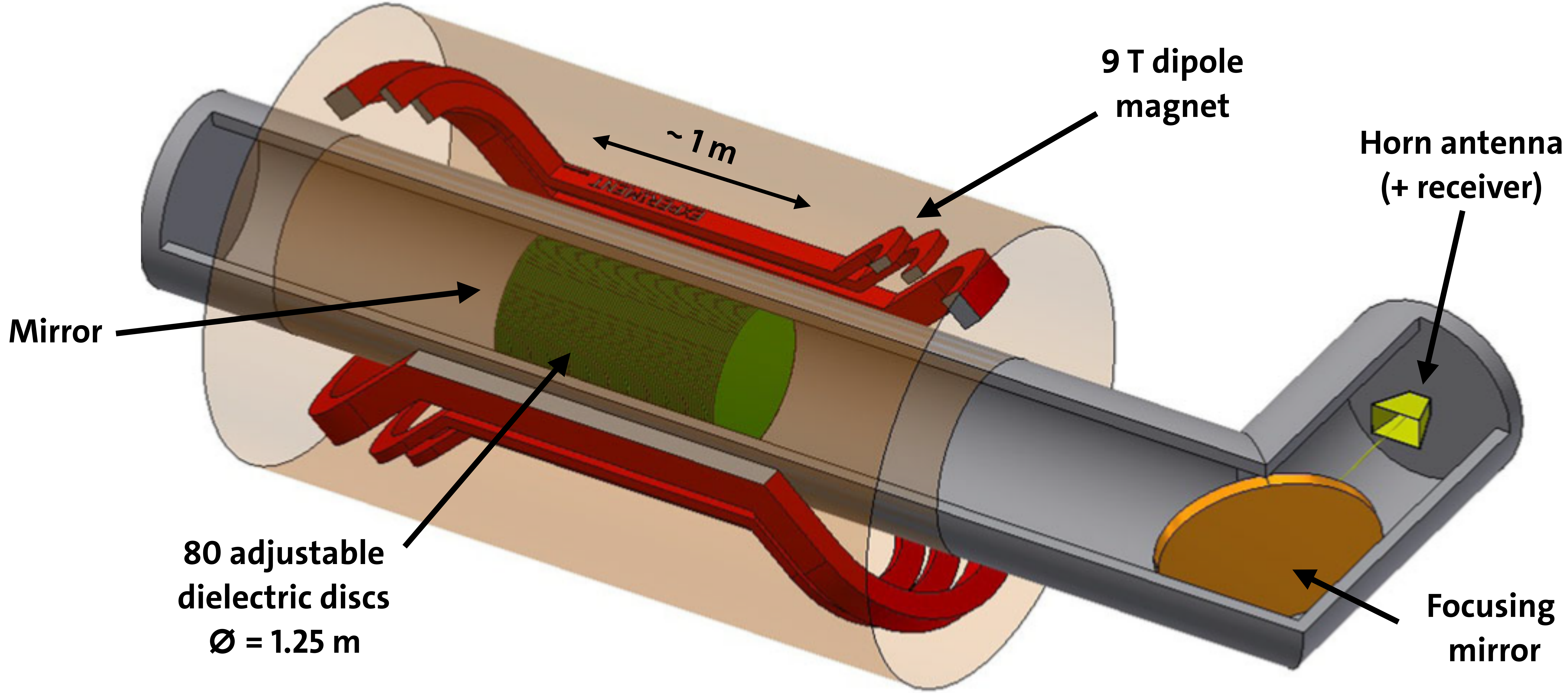
- Tuning of sensitive frequency range by adjusting disc spacing



- Area law: $\beta^2 \Delta\nu_\beta$ ~ const.
- Broad-band scan for search
- Narrow-band to confirm possible signals



MAgnetized disc and Mirror Axion eXperiment

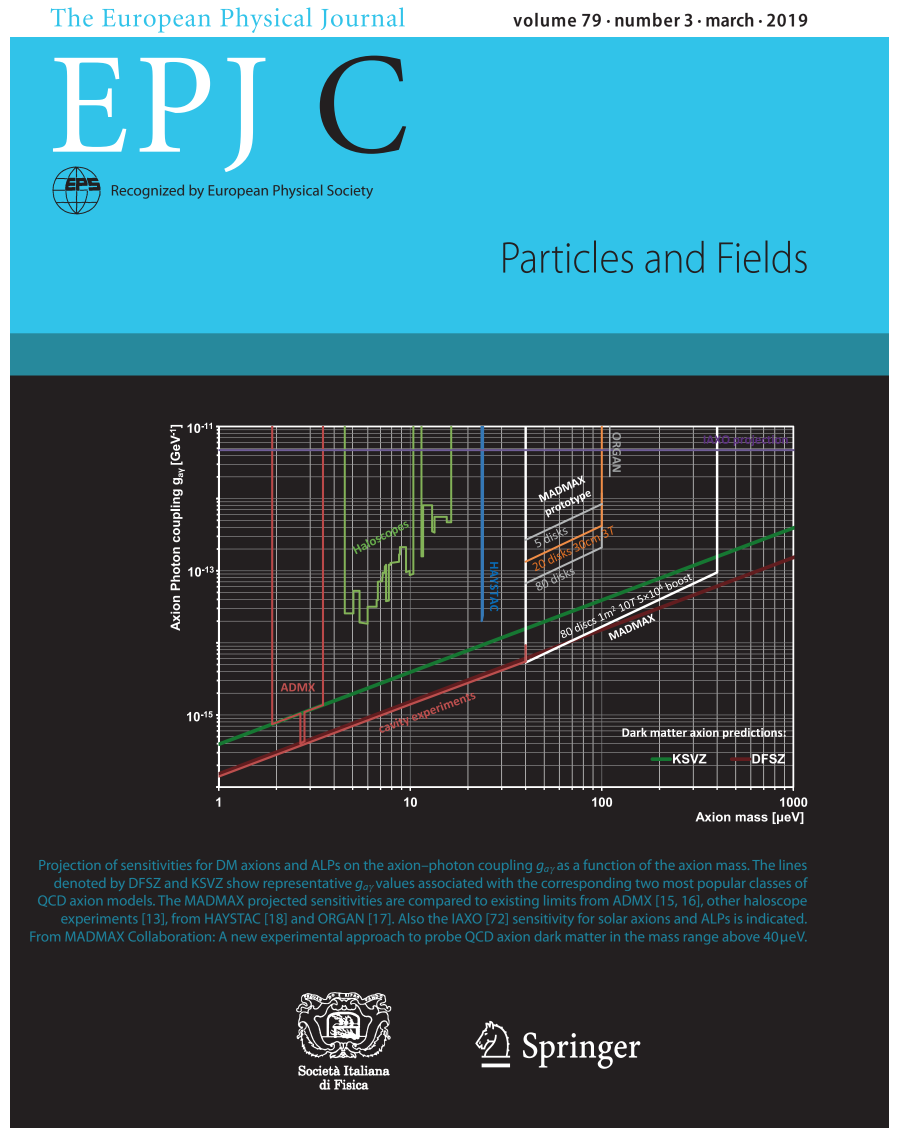


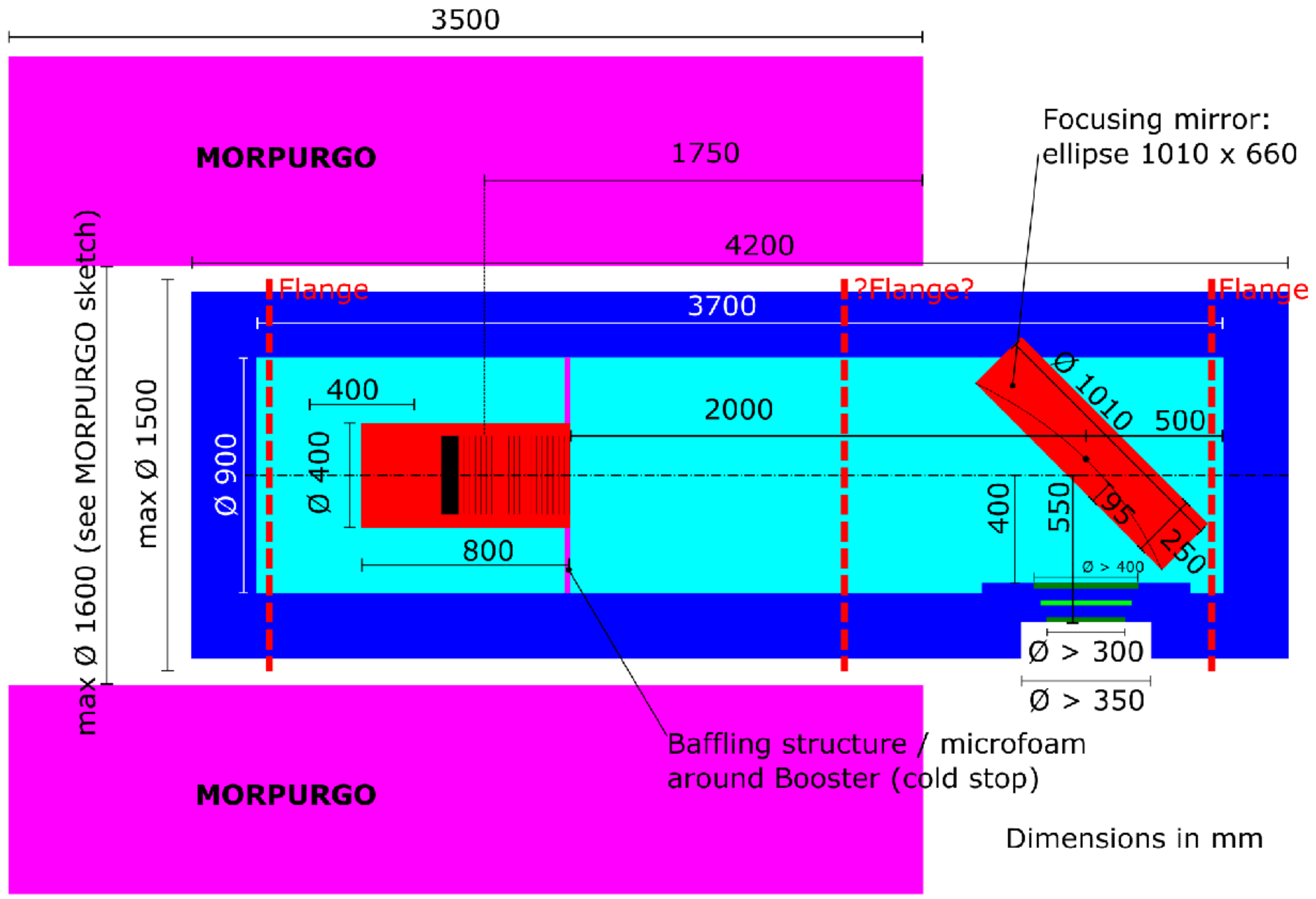
Time scale

2017 -2019	2019 -2022	2022 -2025	2025 -2035
Design	Prototype	Construction	Data taking @ DESY

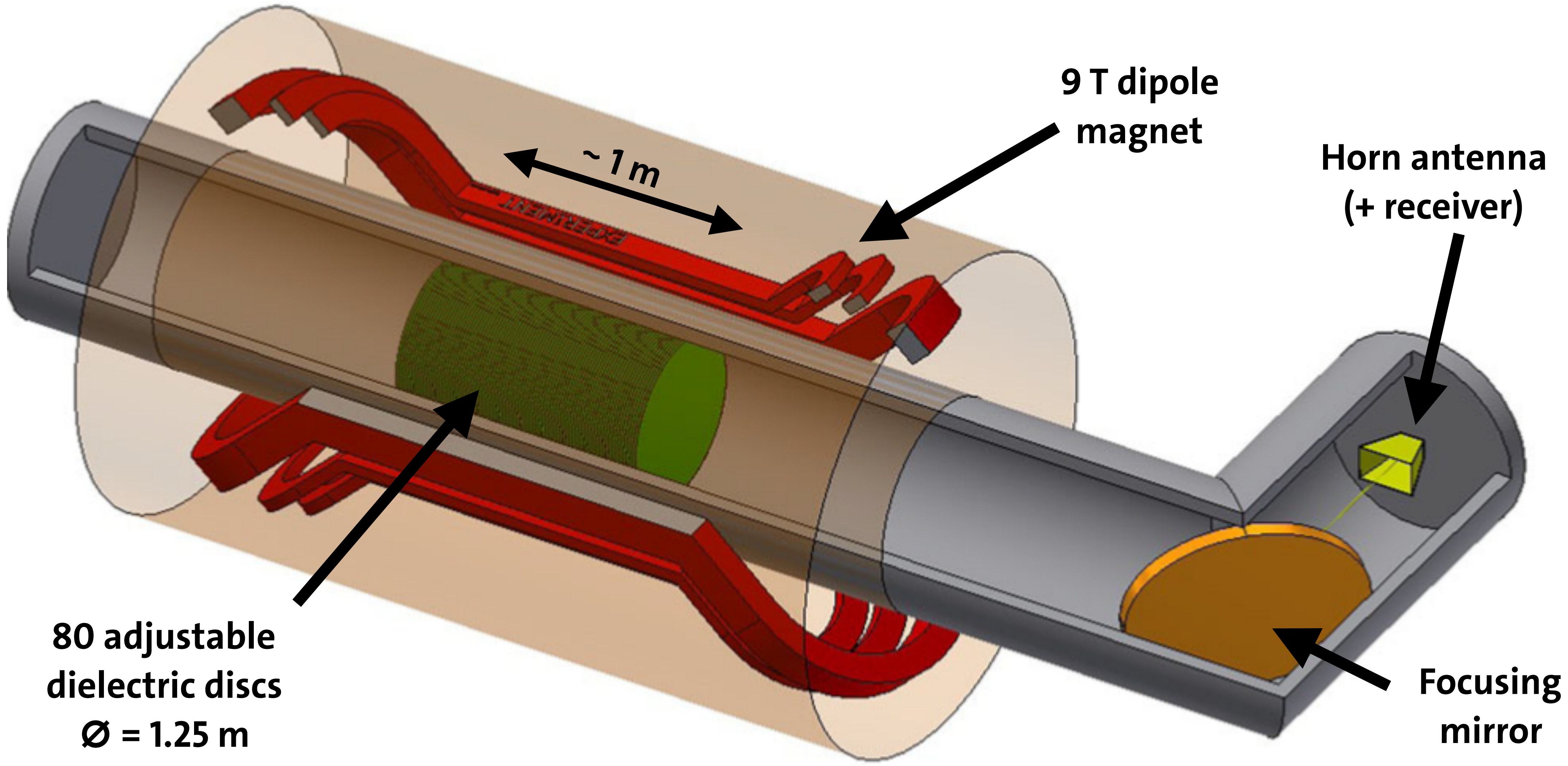
PRC 2019

First physics run @ CERN

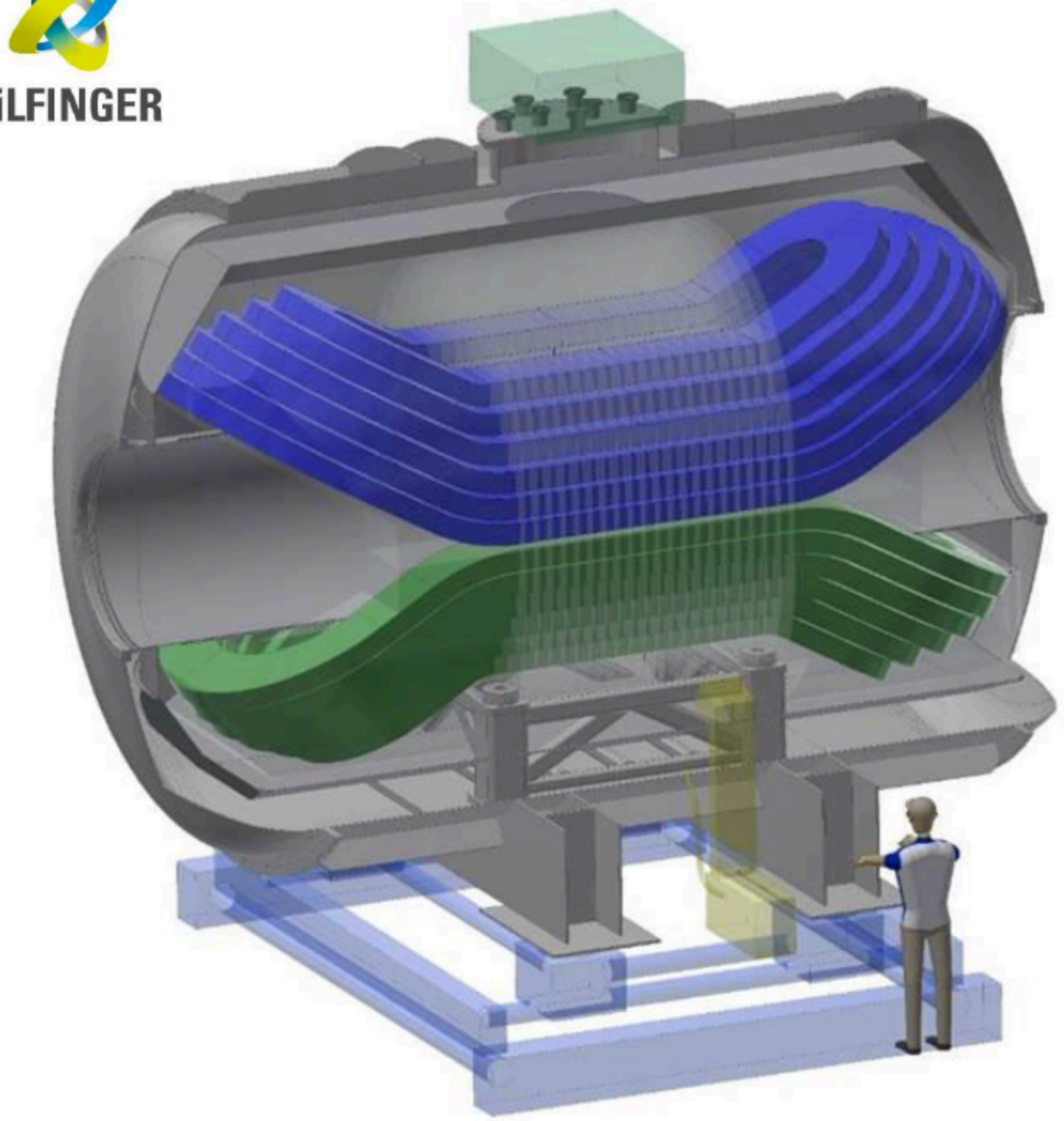


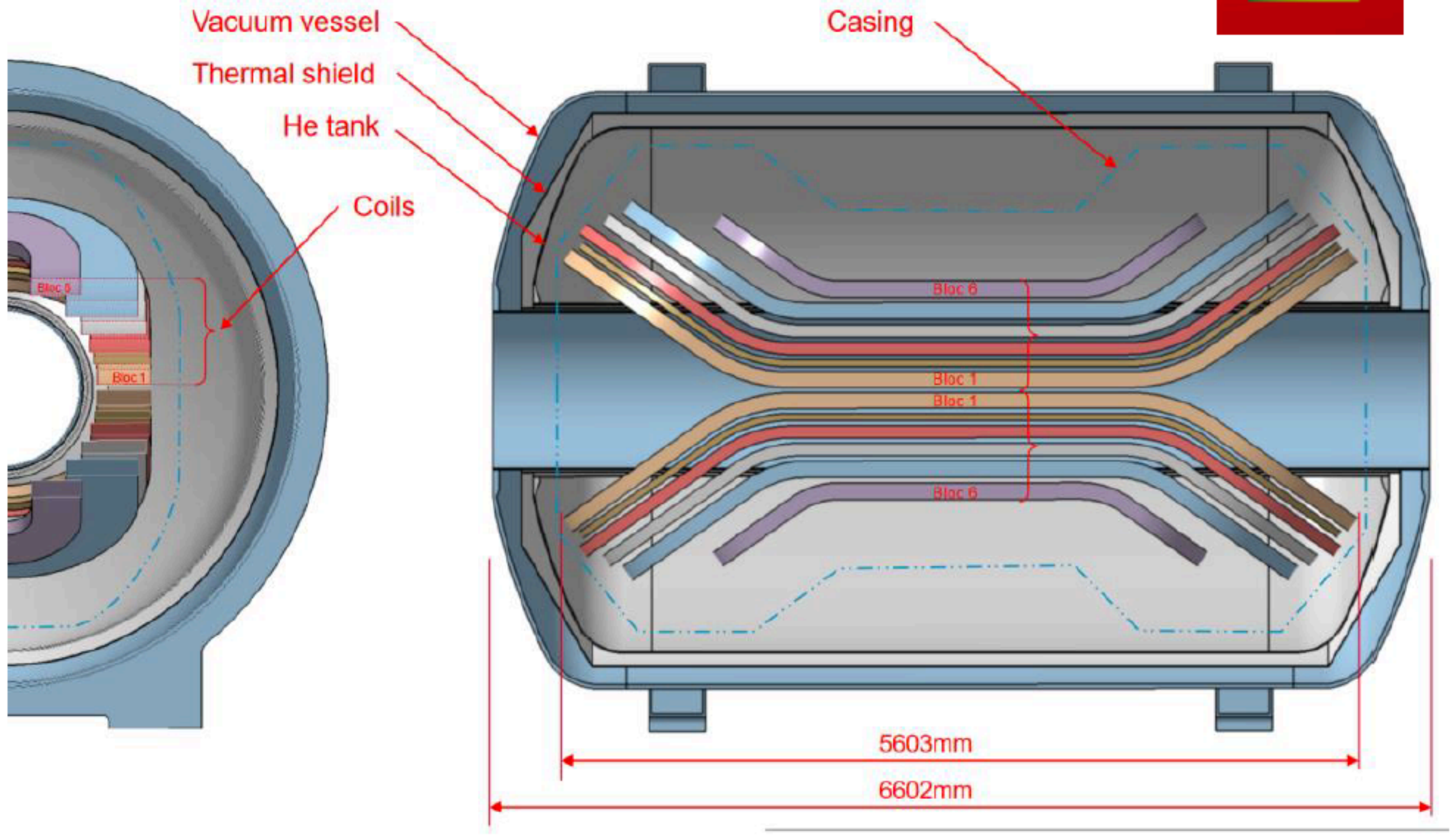


Scaling: Area 1/10 (of final experiment)
discs 1/4
B [T] 1/5



The Magnet





Block design with NbTi as superconductor

- Magnet design and construction drives the time scale of the project
- **Peak field 9 T**, homogeneity < 20%
- Magnet bore: Length ~ 1 m, **Ø ~ 1.5 m**

FoM = B^2 m^2 = 100 T^2 m^2

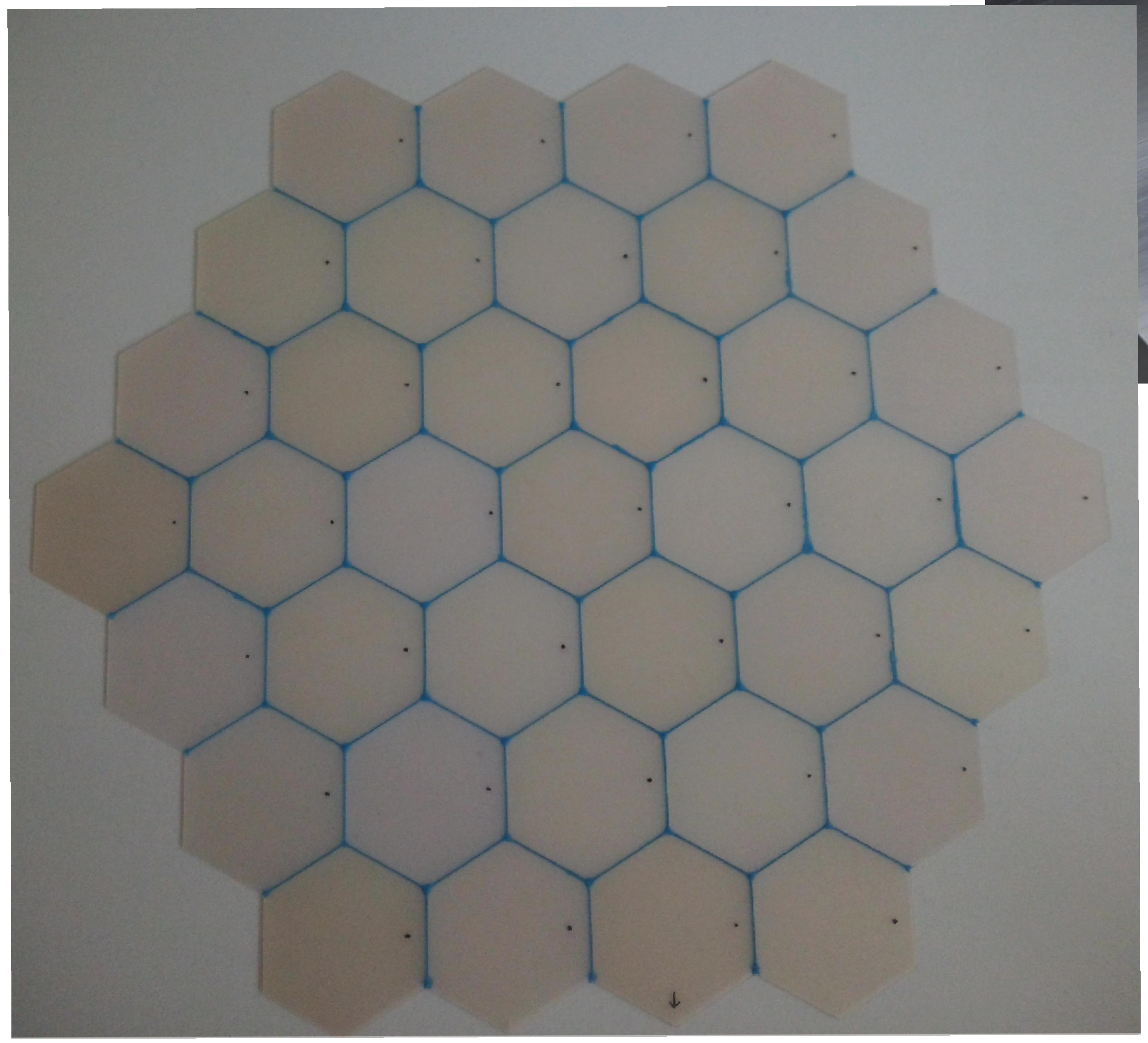
First of a kind!

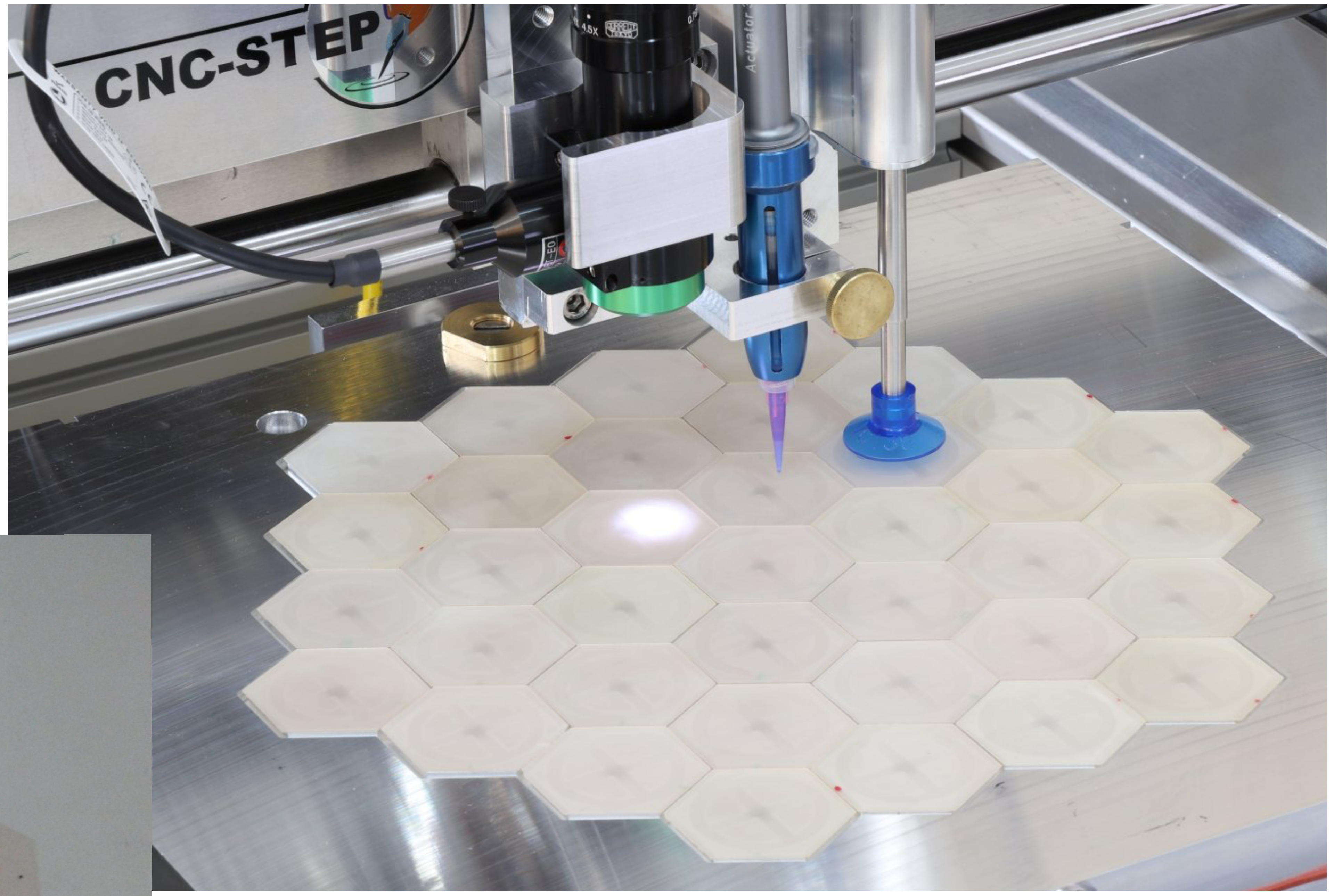
Discs

- Discs with **Ø = 1.25 m** needed for **FoM = $B^2 m^2 = 100 T^2 m^2$**
- Candidate materials:
  $LaAlO_3$ (ϵ ≈ 24, tanδ ≈ a few 10^{-5})
  Sapphire (ϵ ≈ 9, tanδ ≈ 10^{-5})
- $LaAlO_3$ grown in 3” wafers max
- Tiling necessary

- Hexagonal tiles cut by laser cutter
- Glued with Stycast Blue

- Characterisation of dielectric properties @ 4 K, f = 10 - 15 GHz ongoing



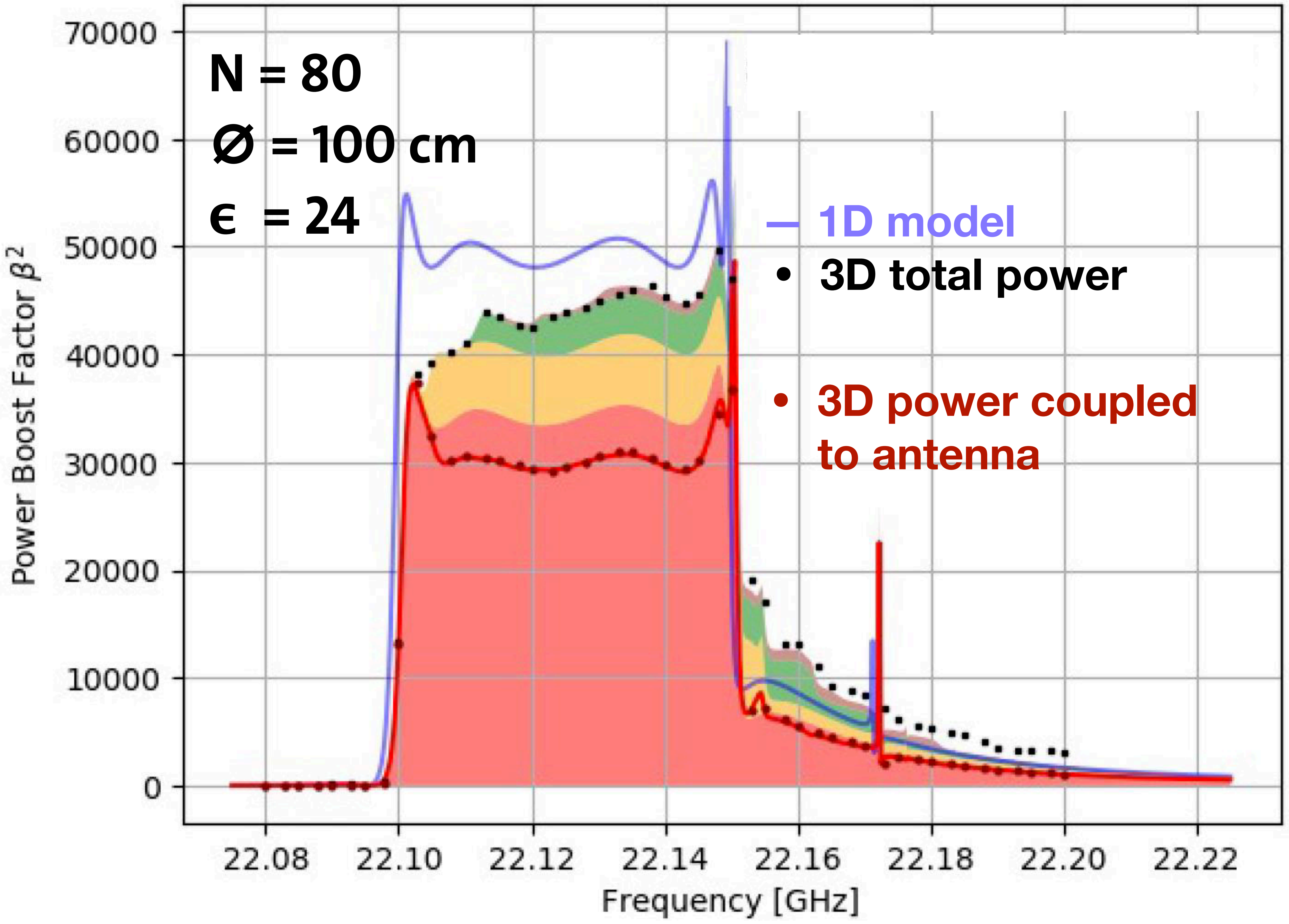


First tiled $LaAlO_3$ disc:
Ø = 30 cm
d = 1 mm
Single wafer size 2”
Scalability to Ø = 1.25 m being investigated

System design studies

Detector feasibility study and design optimisation using simulation of achievable boost factor

- **3D effects (diffraction)** ➡ ~10-20% losses
- **Coupling to antenna (beam shape)** ➡ ~10-20% losses
- Dielectric loss
- Inaccuracy (position, roughness, tilt, thickness,...)
- DM velocity dispersion
- Tiling of discs



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- **Dielectric loss** ➡ **small losses for tanδ < 10^{-4}**
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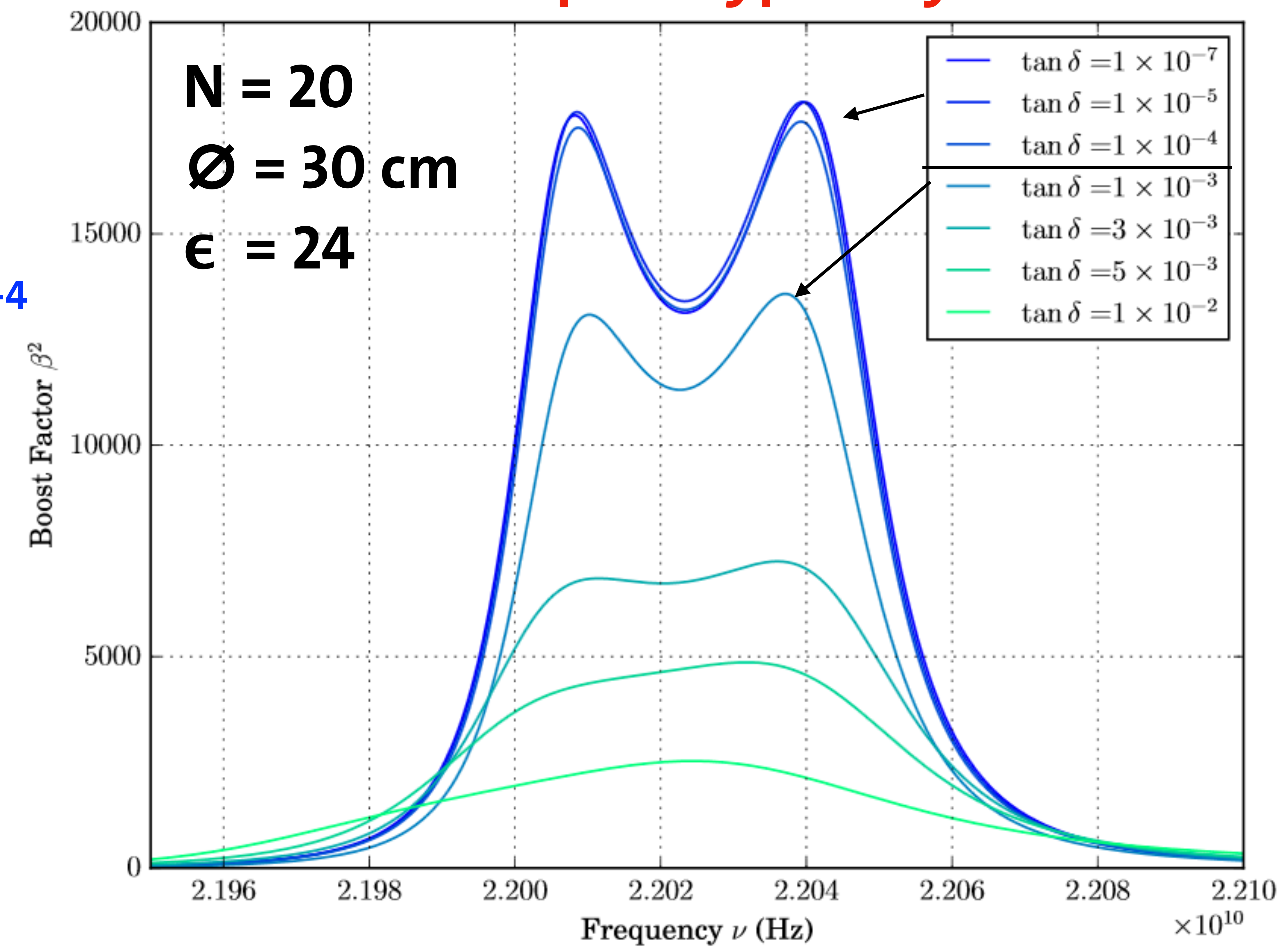
For MADMAX prototype only



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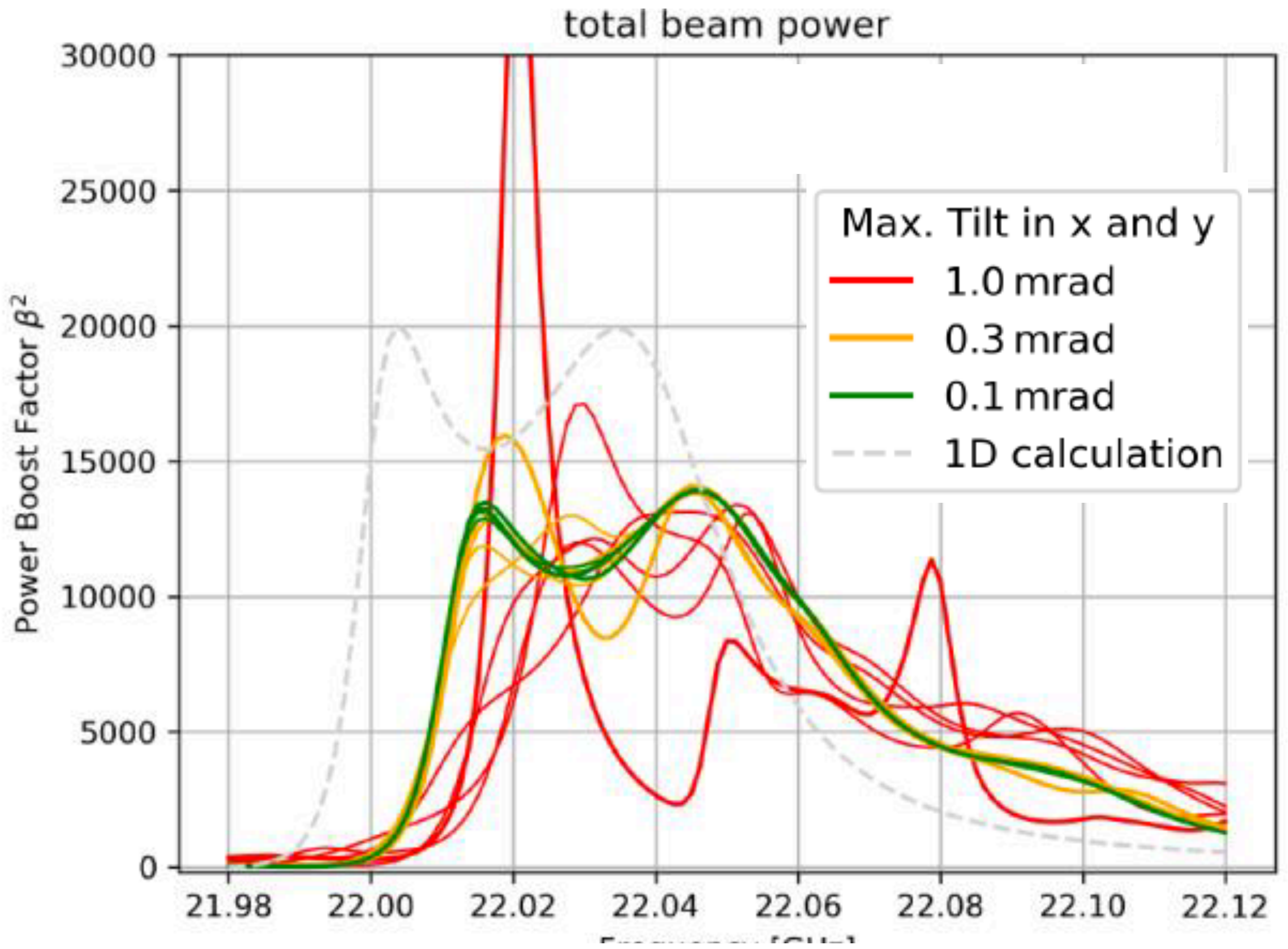
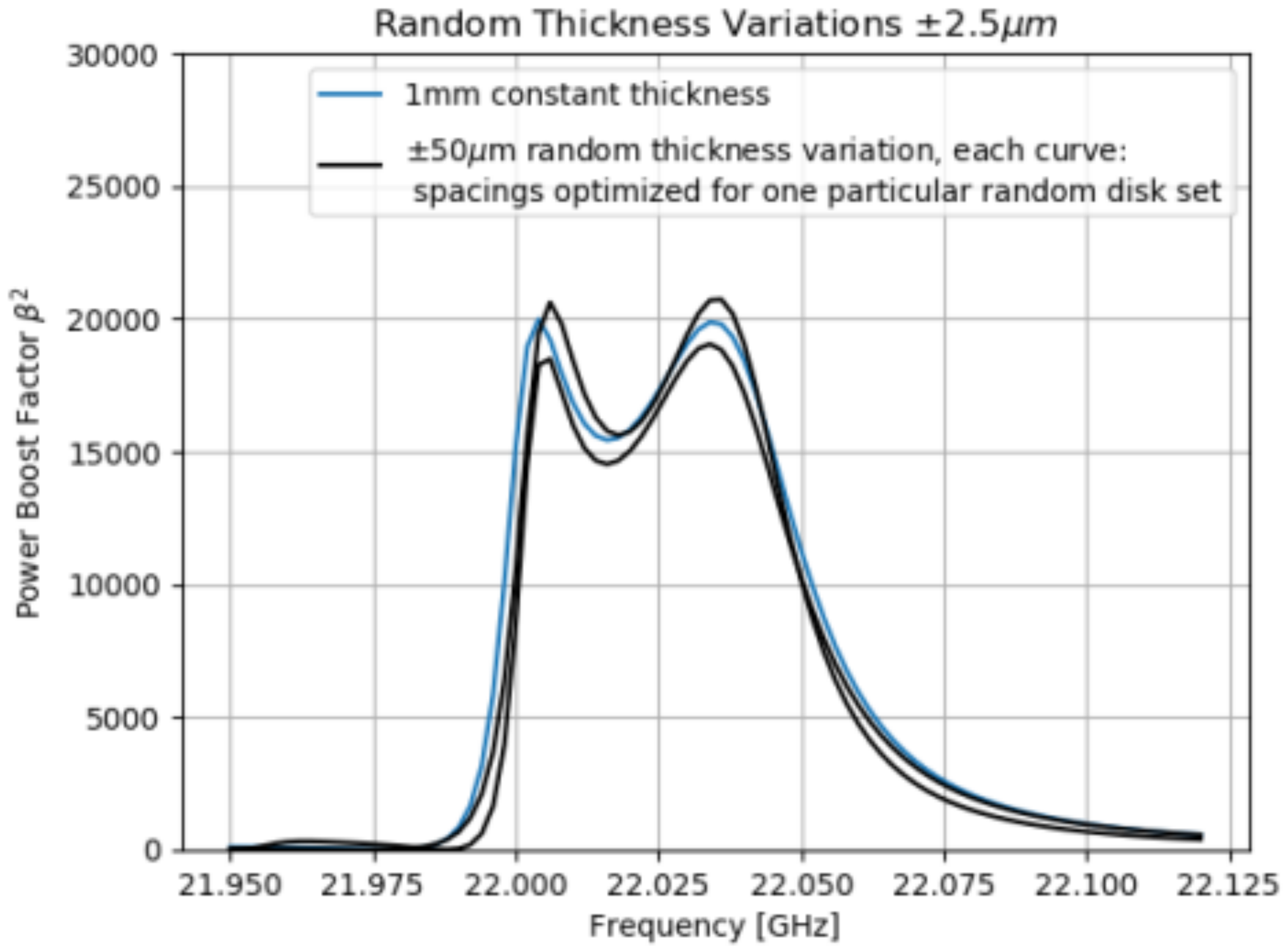
- Dielectric loss ➡ small losses for tanδ < 10^{-4}
- **Inaccuracy (position, roughness, tilt, thickness,…)** ➡ **positioning precision < 10 µm**
  roughness < 10 µm
  tilt < 0.1 mrad
  thickness measured to ± 5 µm
- DM velocity dispersion
- Tiling of discs

N = 20
Ø = 30 cm
ϵ = 24

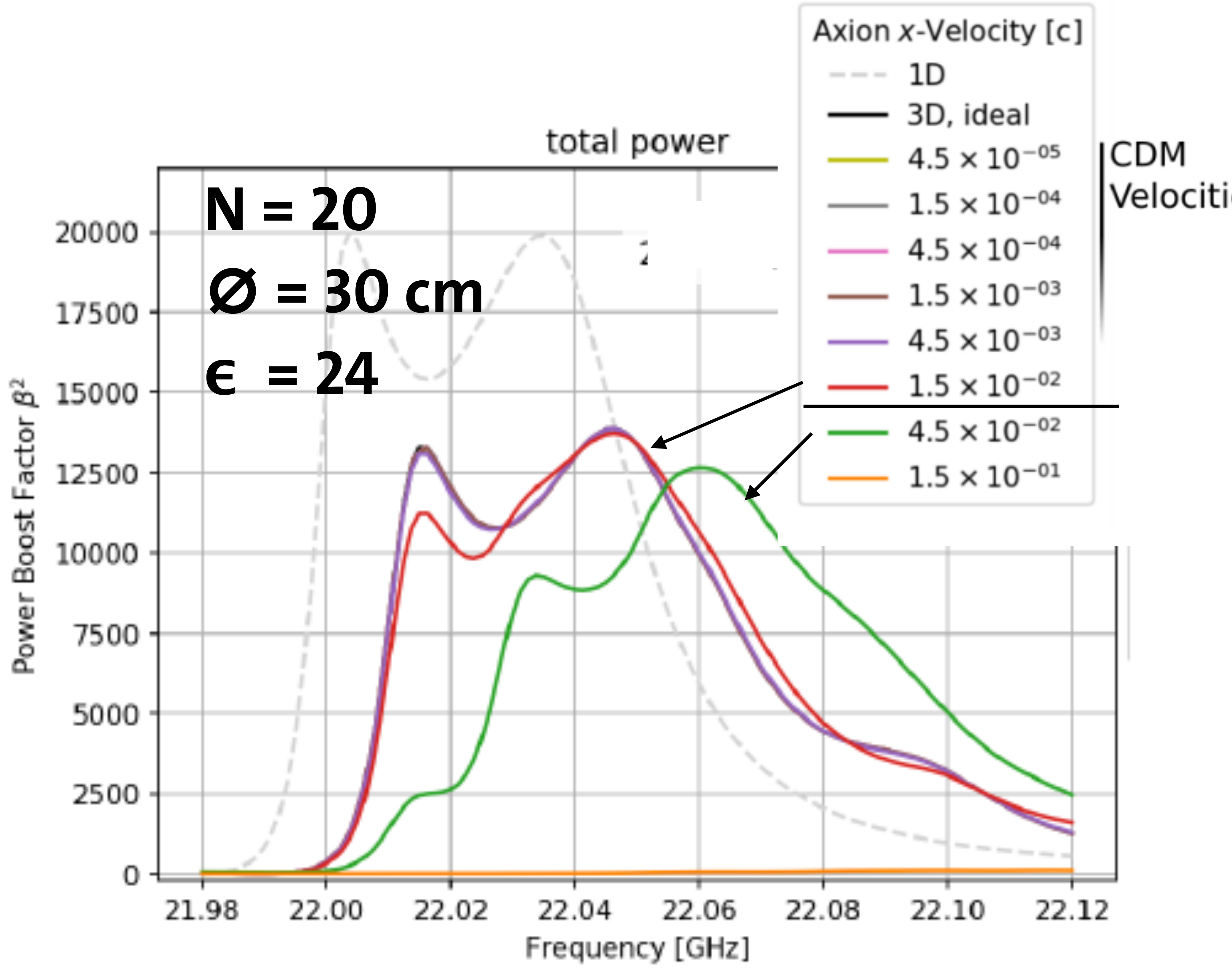




System design studies

Detector feasibility study and design optimisation using simulation of achievable boost factor

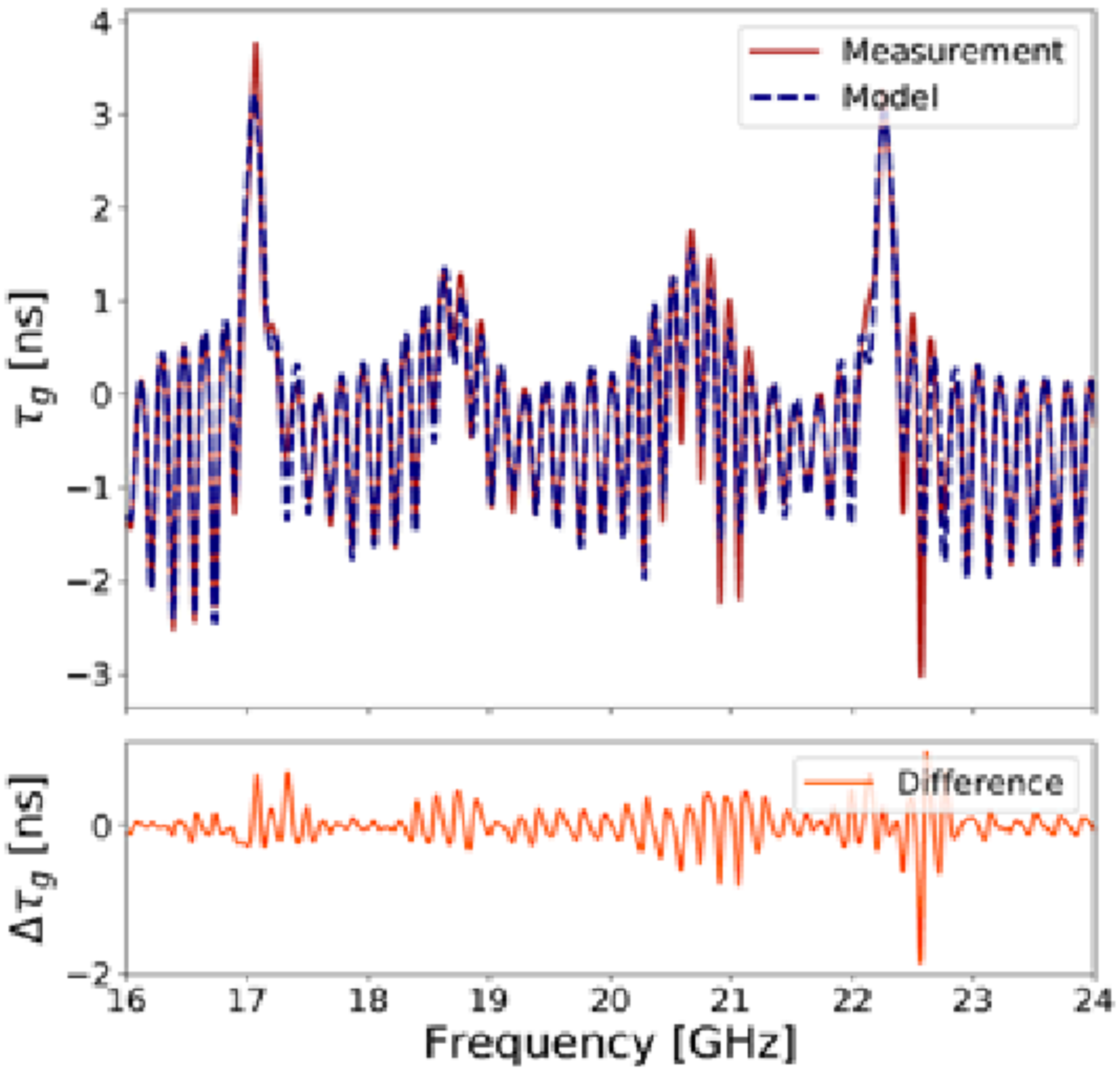
- 3D effects (diffraction) ➡ ~10-20% losses
- Coupling to antenna (beam shape) ➡ ~10-20% losses
- Dielectric loss ➡ small losses for *tanδ* < 10^{-4}
- Inaccuracy (position, roughness, tilt, thickness,…) ➡ positioning precision < 10 μm
- **DM velocity dispersion** ➡ **no significant loss if *v* < 10^{-2} c**
- Tiling of discs

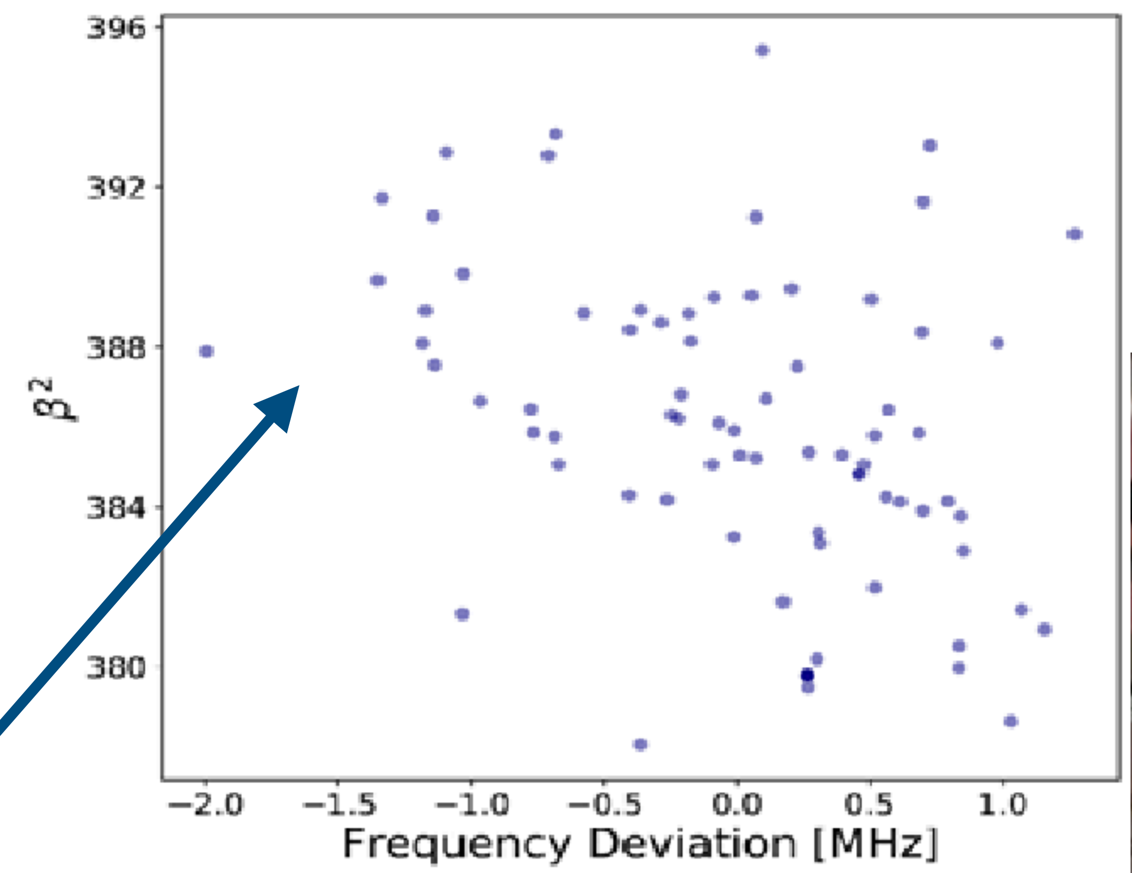


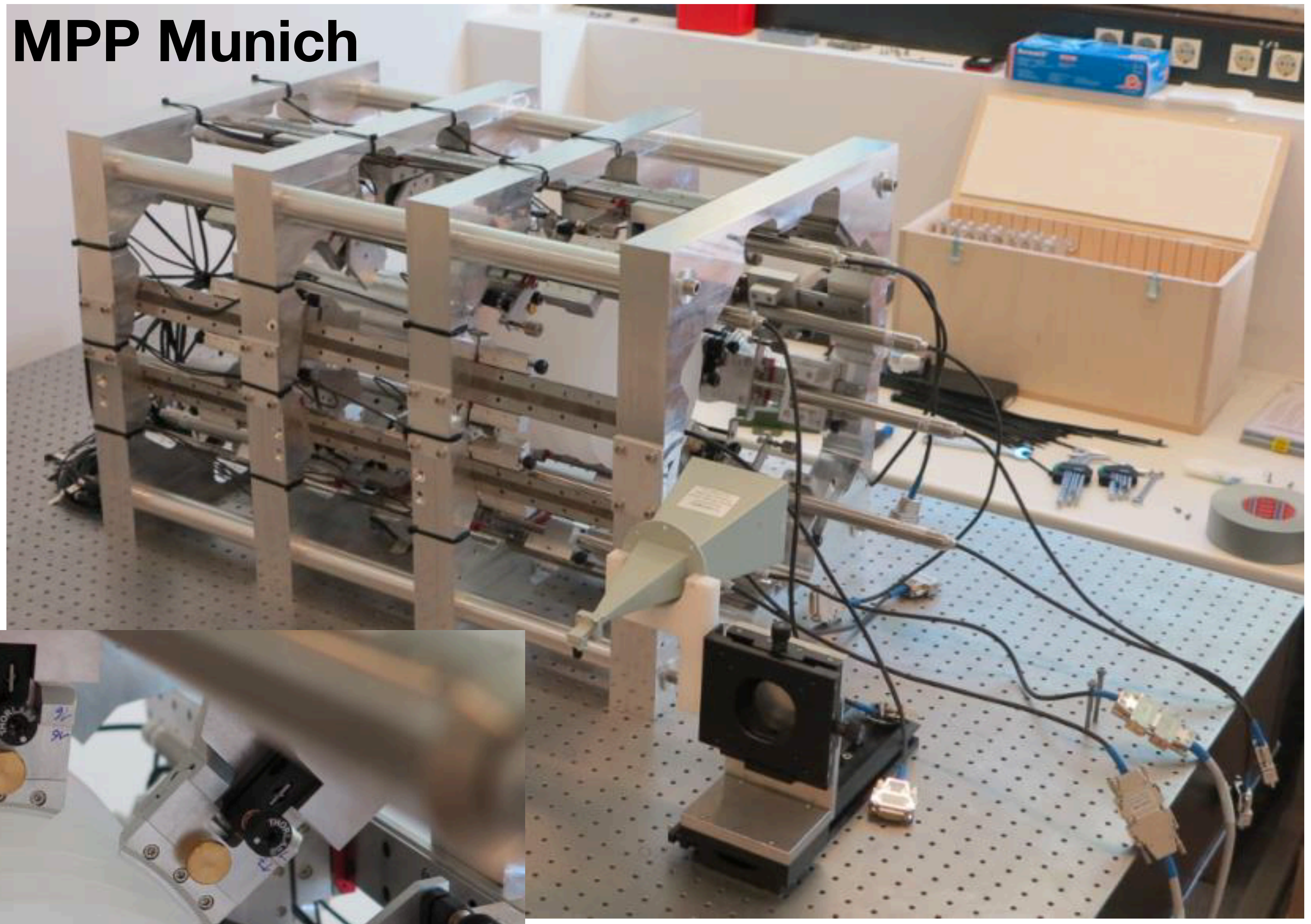
New on arxiv: 1906.02677 by Jan Schütte-Engel

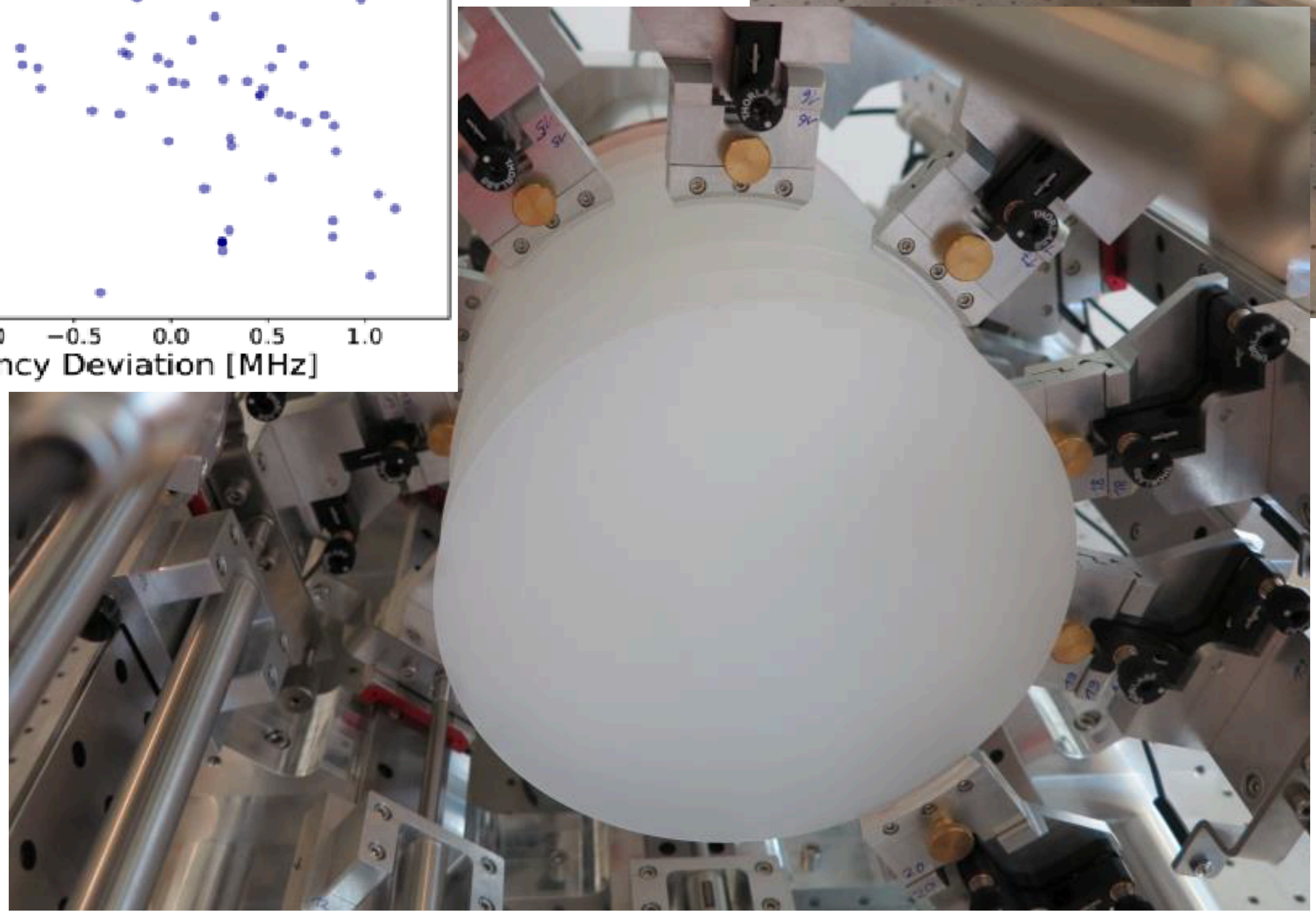
Proof of principle

- Reflectivity measurements with up to 20 discs
- Reproducibility of discs **positioning few µm**
- Achievable **boost factor** with 5 discs **reproducible within few MHz**









Proof of principle booster

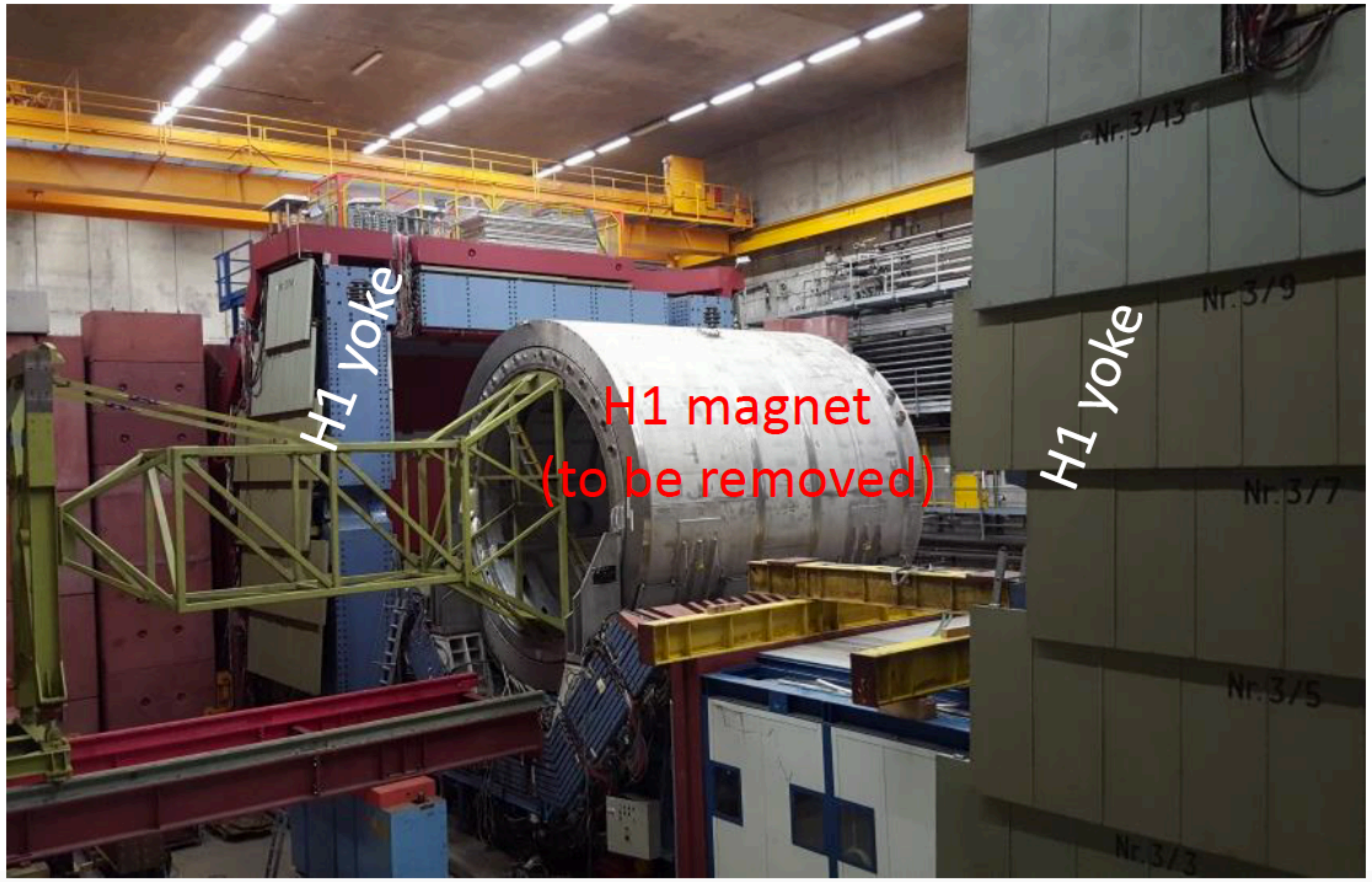
N = 20

Ø = 20 cm

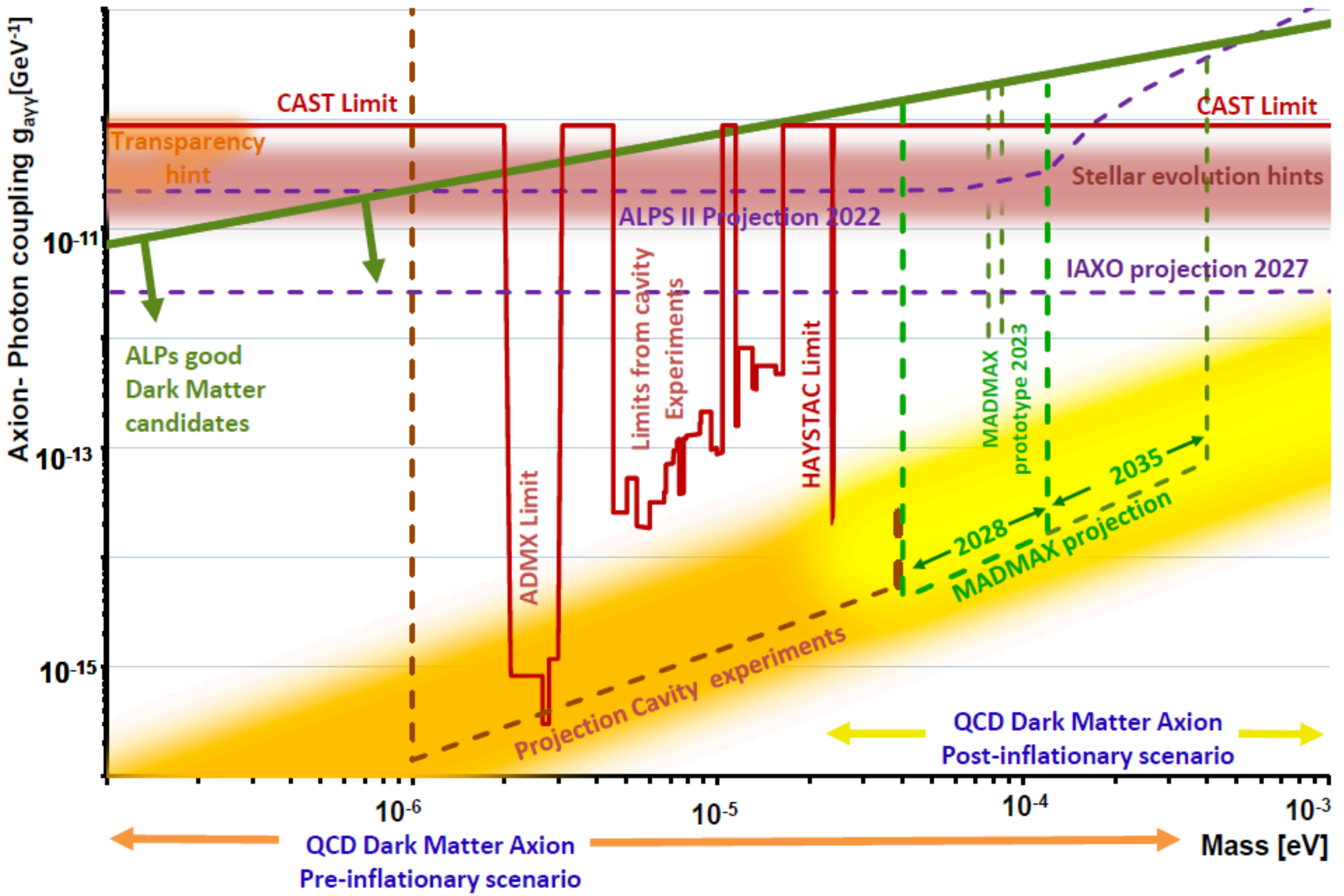
$\epsilon \approx 9$

Experimental site

- MADMAX to be built at Hera Hall North
- Make use of DESY infrastructure
- Benefit: re-use H1 yoke as magnetic shielding to reduce fringe field



Sensitivity to QCD dark matter axion



MADMAX

A = 1 m²

$B_{||}$ = 10 T

T_{sys} = 8 K

β^2 = 5 · 10⁴

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The MADMAX collaboration

RWTH AACHEN UNIVERSITY

Max-Planck-Institut für Radioastronomie

DESY

UHH Universität Hamburg DER FORSCHUNG | DER LEHRE | DER BILDUNG

Max-Planck-Institut für Physik

Irfu - CEA Saclay Institut de recherche sur les lois fondamentales de l'Univers

cea

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

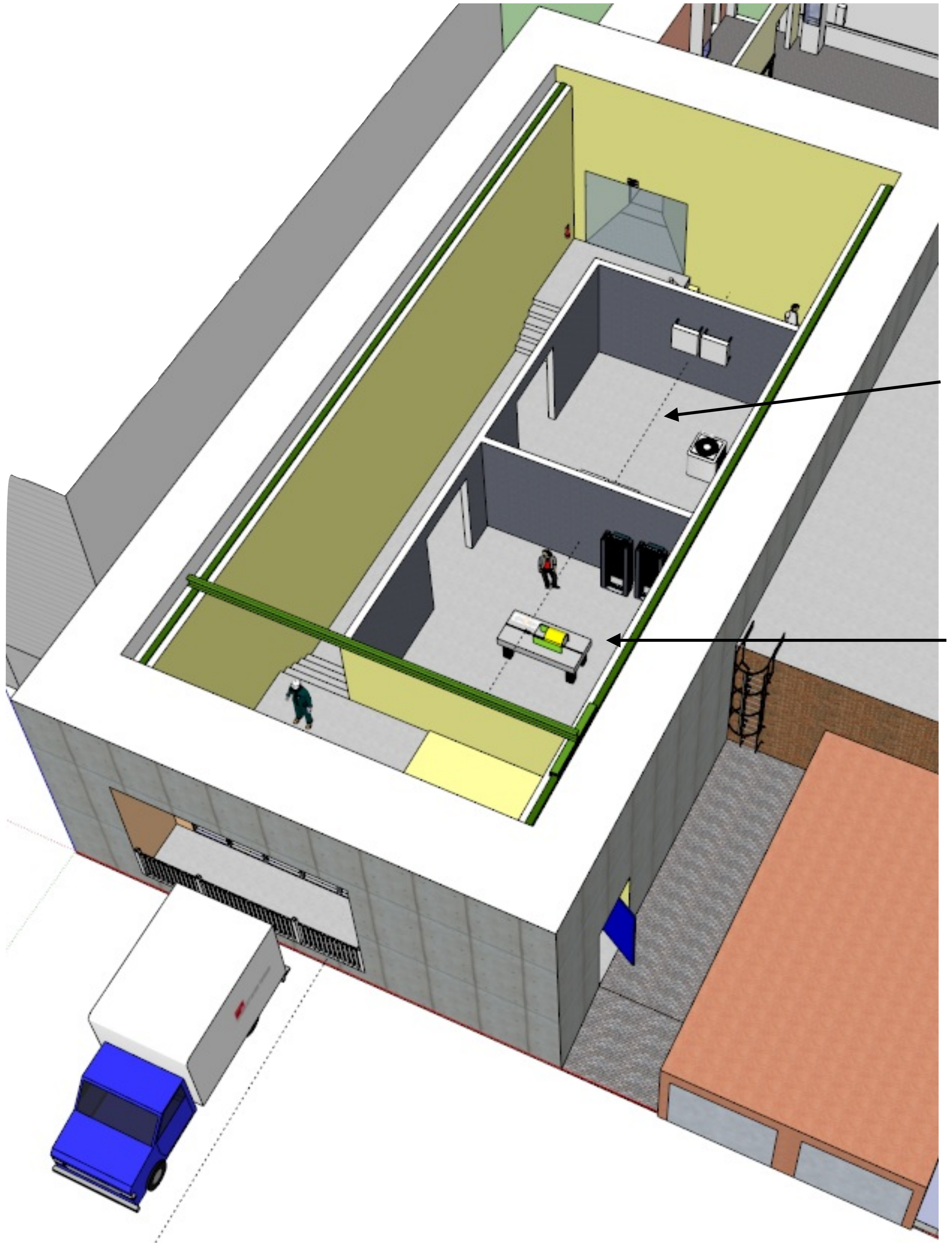
Universidad Zaragoza

associate members

NÉEL institut

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM

SHELL inauguration 08.07.19 @ 11:30



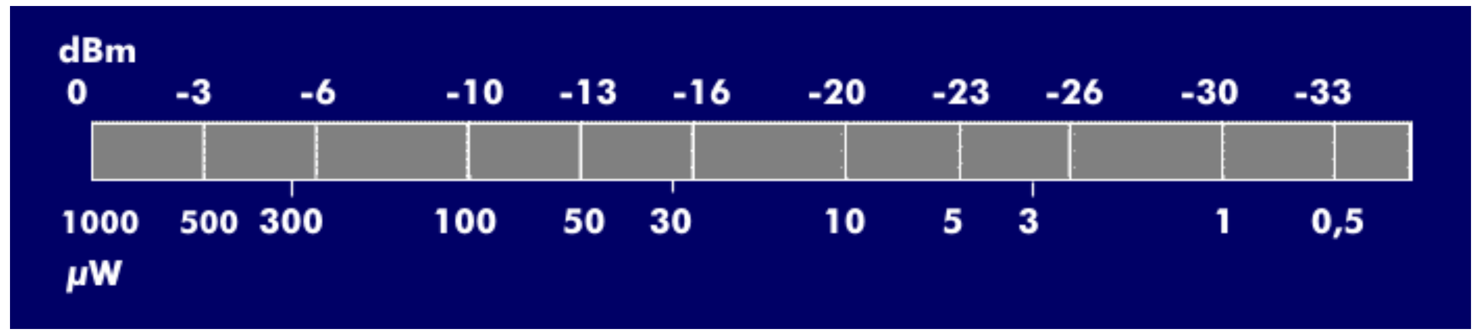
Ex-UHH synchrotron bunker
Renewed thanks to QU funds
Two RF shielded labs

< -50 dBm*, for f < 10 GHz
< -100 dBm, for f >10 GHz

BRASS

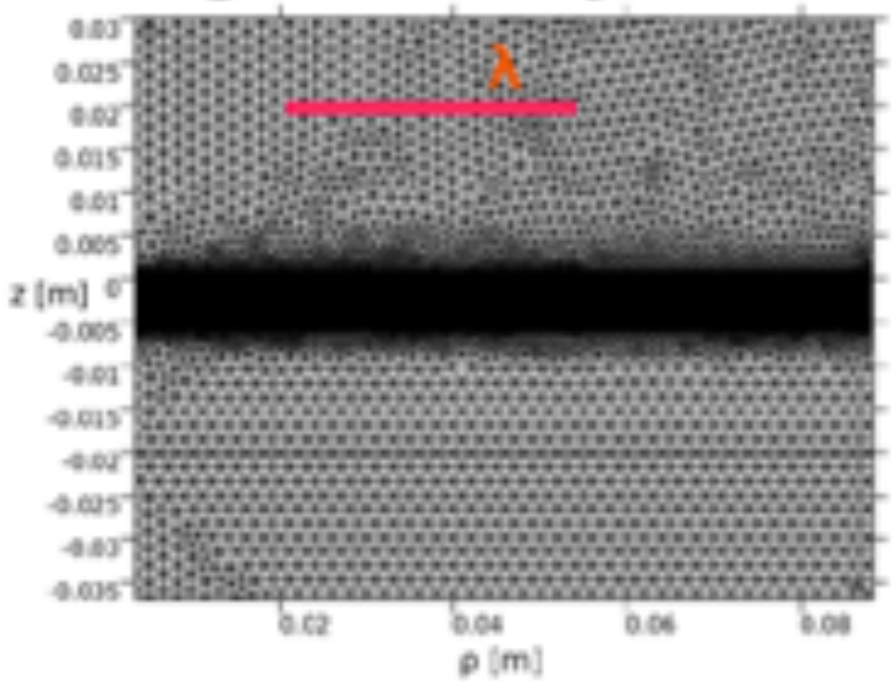
MADMAX

* dBm = Power in Decibel Milliwatt,
p = 10log(P/1 mW) [dBm]
i.e. for P = pW, p = -90 dBm



For large and many diks 3D FEM solution computationally not feasible.

Using radial symmetry in FEM

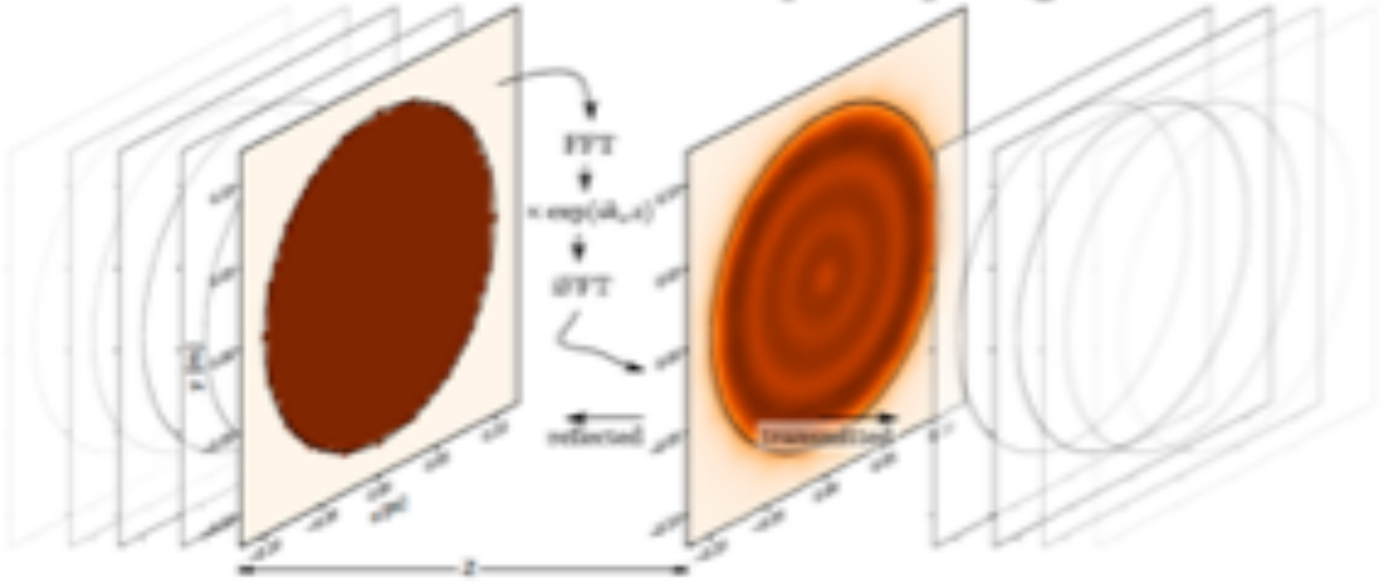


external *B*-field breaks symmetry
⇒ restore symmetry by solving two circular polarized sources

$$\nabla \times (\nabla \times \boldsymbol{E}) - k_0^2 \epsilon \boldsymbol{E} = k_0^2 \boldsymbol{f}$$

$$\boldsymbol{f}(\rho, z) = \boldsymbol{f}^{+}(\rho, \phi, z) + \boldsymbol{f}^{-}(\rho, \phi, z)$$

Recursive Fourier propagation



For each propagation use a scalar diffraction theory:

$$E_i(\boldsymbol{x}) = \int_{\mathbb{R}^2} \frac{dk_x dk_y}{(2\pi)^2} \mathcal{F}(E_i)(k_x, k_y) \times e^{i|z-z_s|\sqrt{(\omega n)^2 - k_x^2 - k_y^2}} e^{ik_x x} e^{ik_y y}$$

approaches directly applicable to other open axion haloscopes

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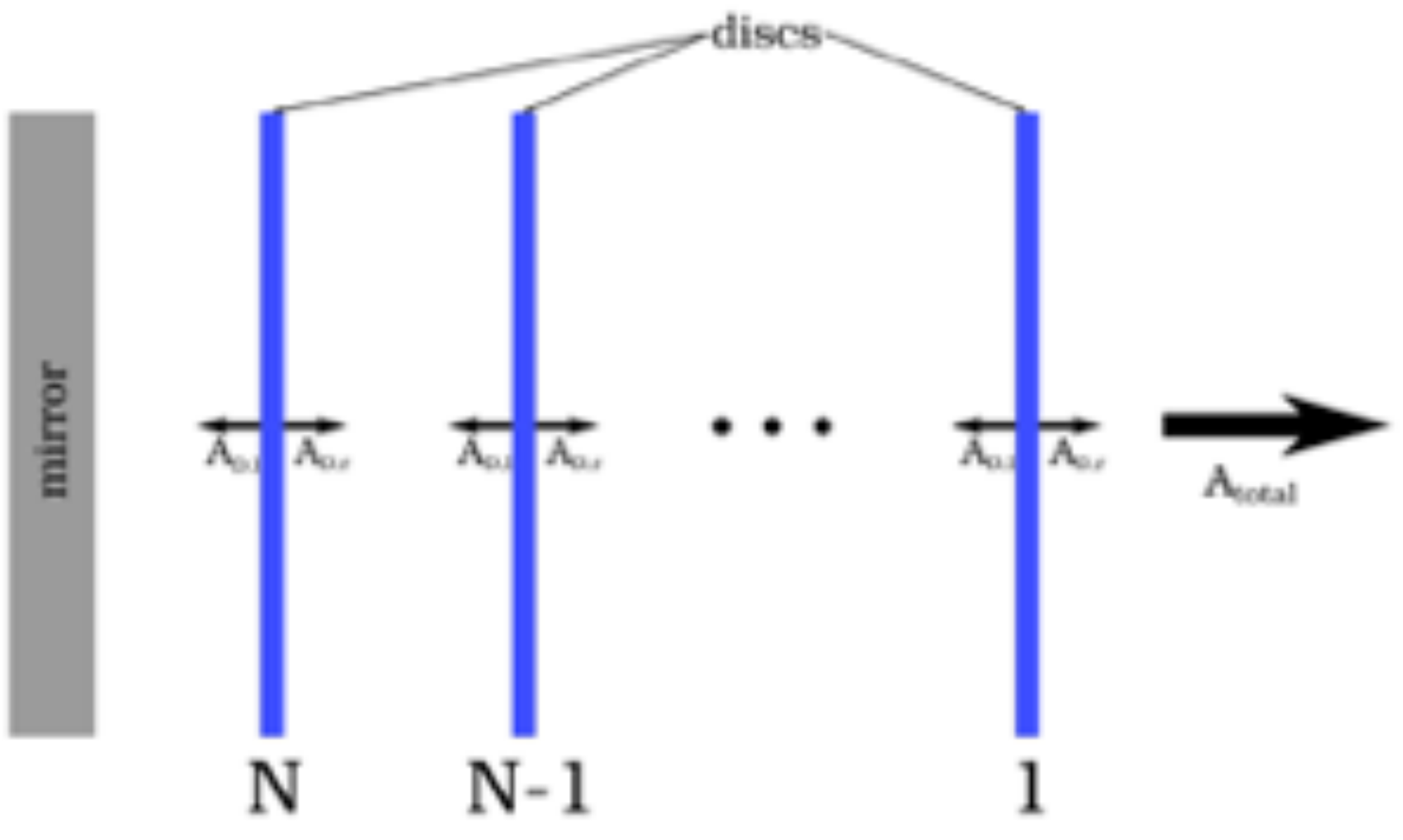
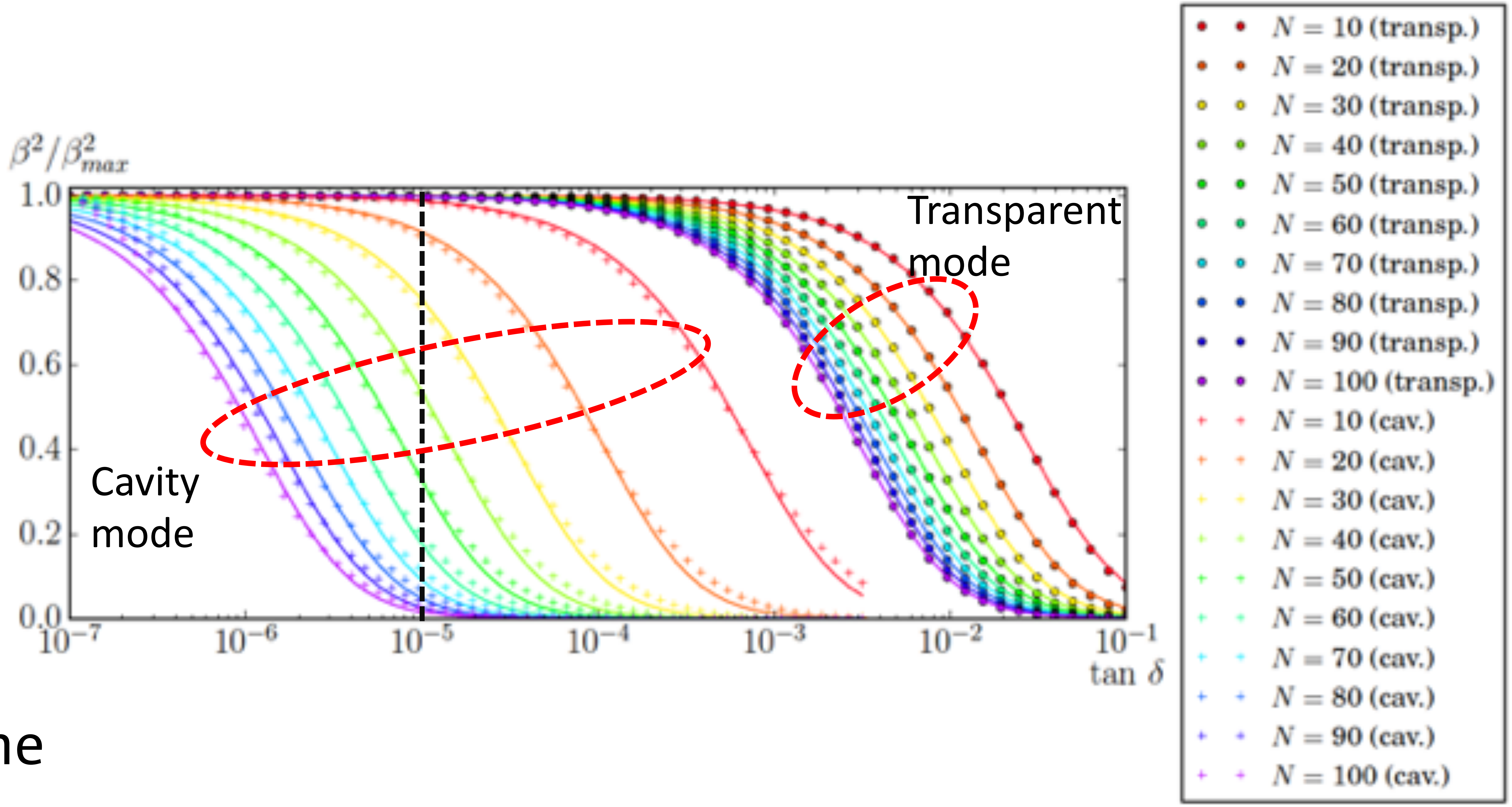
Transparent vs cavity mode





Approximate behaviour of the system with a random walk
→ $N_{eff} \sim N^2$

$\rightarrow$ cavity mode: $N_{eff} = N^a, a \approx 2.9 \pm 0.1$

Antenna and receiver

The challenges:

18-40 GHz: optimization of receiver-antenna system based on simulation results for beam shape/size **(MPIFR)**

50-100 GHz: develop a new concept for receiver **(MPIFR, NEEL)**