MAX-PLANCK-GESELLSCHAFT

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

DIELECTRIC HALOSCOPE AND THE MADMAX EXPERIMENT

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FEB. 18, 2020

THE STRONG CP PROBLEM

- The QCD Lagrangian contains a CP-violating term:

$$\mathscr{L}_{QCD} = \ldots + \frac{\alpha_s}{8\pi}\,\bar{\theta}\,G_{\mu\nu a}\tilde{G}_a^{\mu\nu}, \qquad \bar{\theta} = \theta_{QCD} + \theta_{Yukawa} \in [-\pi, \pi] \sim \mathscr{O}(1)$$

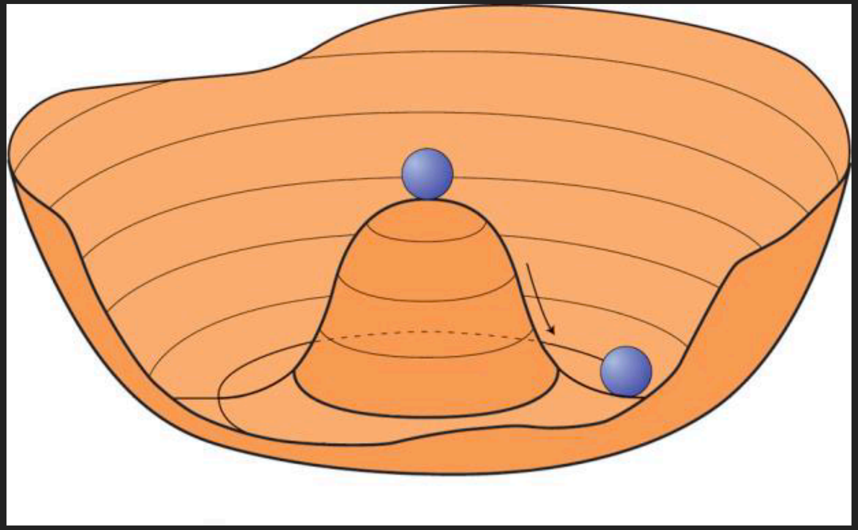
- Neutron electric dipole moment

$$d_N \sim 10^{-16}\,\bar{\theta}\,e\text{-cm} < 3 \times 10^{-26}\,e\text{-cm} \Rightarrow \bar{\theta} < 3 \times 10^{-10}$$

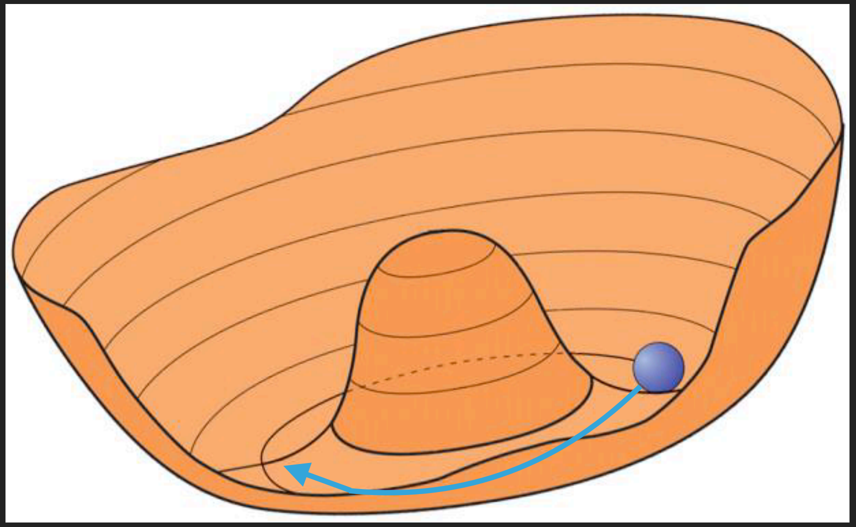
- The Standard Model does not provide a reason for why $\bar{\theta}$ is so tiny, i.e. the strong CP problem.
- The Peccei-Quinn mechanism provides a reason for the value of $\bar{\theta}$ and predicts a light neutral pseudoscalar boson – the axion.

THE PECCEI-QUINN MECHANISM

- Peccei-Quinn introduces a global $U(1)_{PQ}$ symmetry which spontaneously breaks at $T = f_a \gg \Lambda_{QCD}$

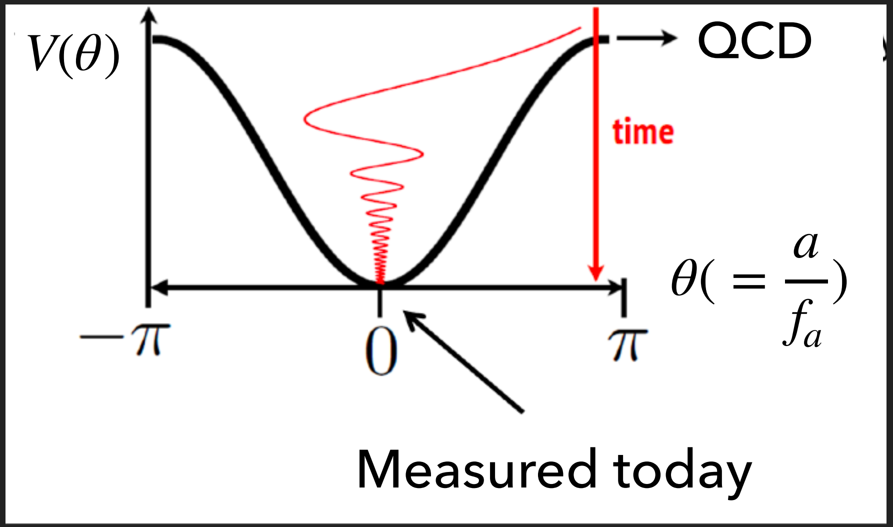


1 GeV $< T < f_a$ (PQ symmetry breaking)

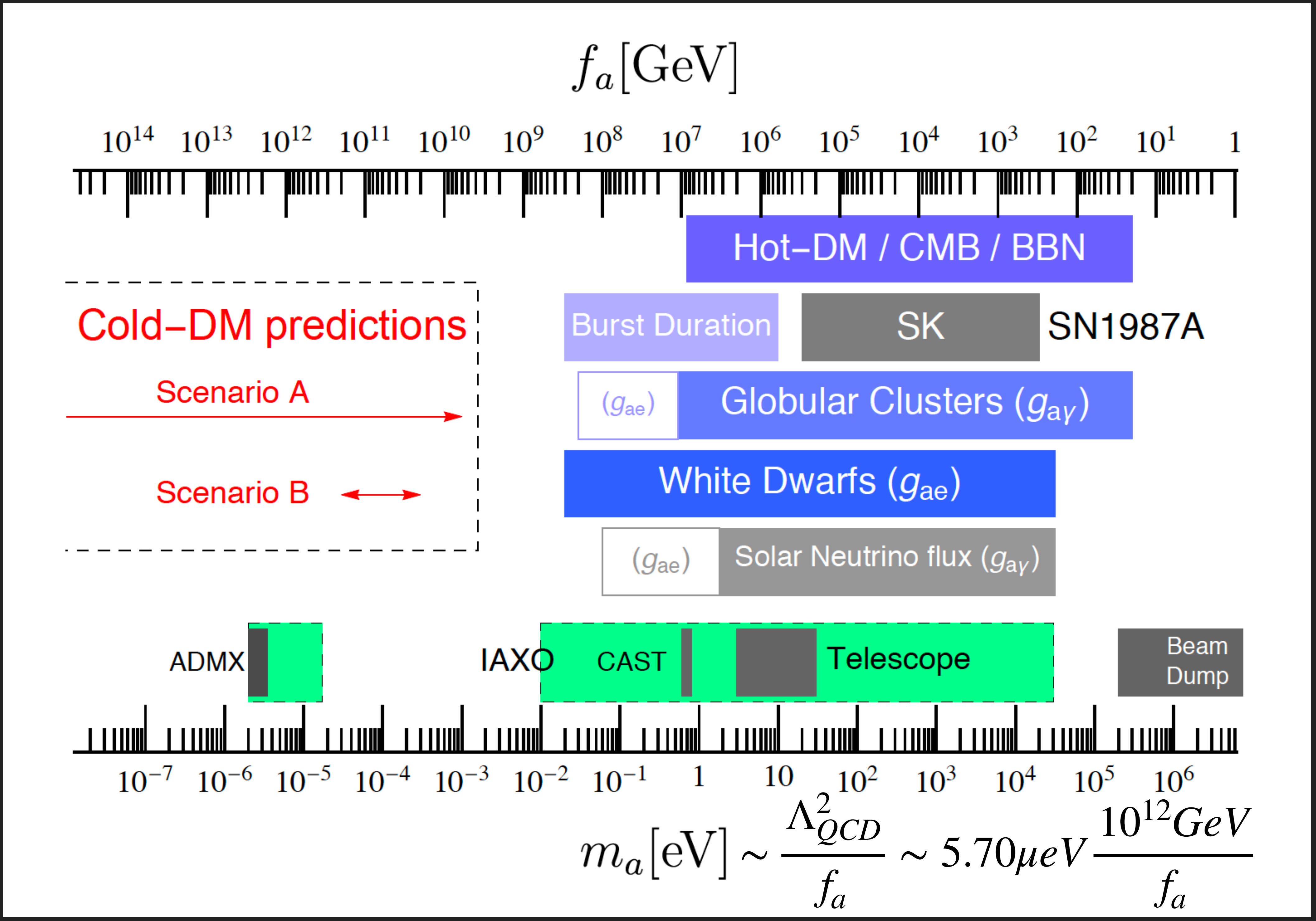


$T < 1$ GeV (QCD phase transition)

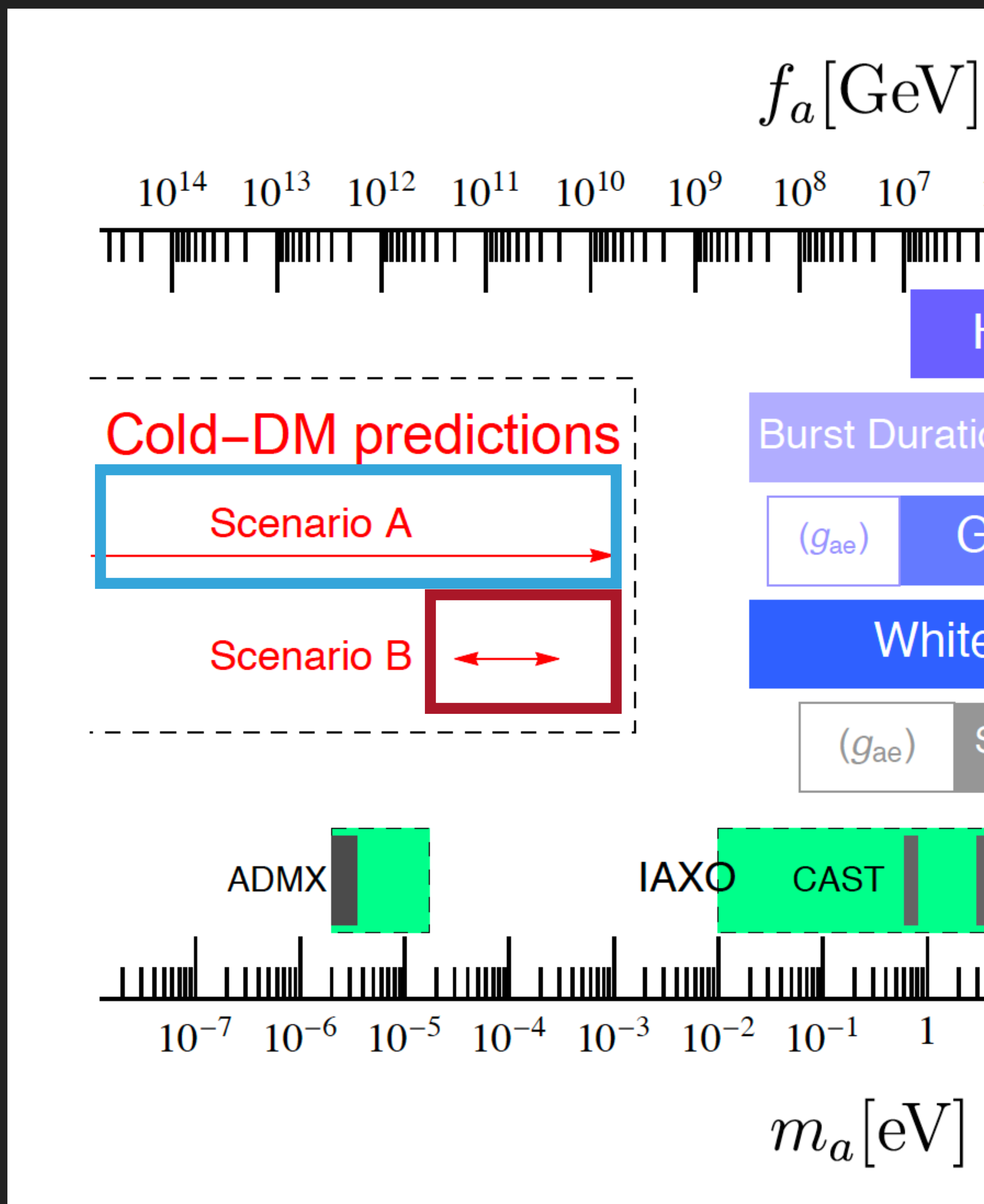
- $\mathscr{L} = \ldots + \bar{\theta}\frac{\alpha_s}{8\pi}G_{\mu\nu a}\tilde{G}_a^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$
- Axion potential $V_a\left(a/f_a\right)$ is minimized at $\bar{\theta} + \frac{a}{f_a} = 0$
- The axions produced by the "misalignment" mechanism are a good CDM candidate



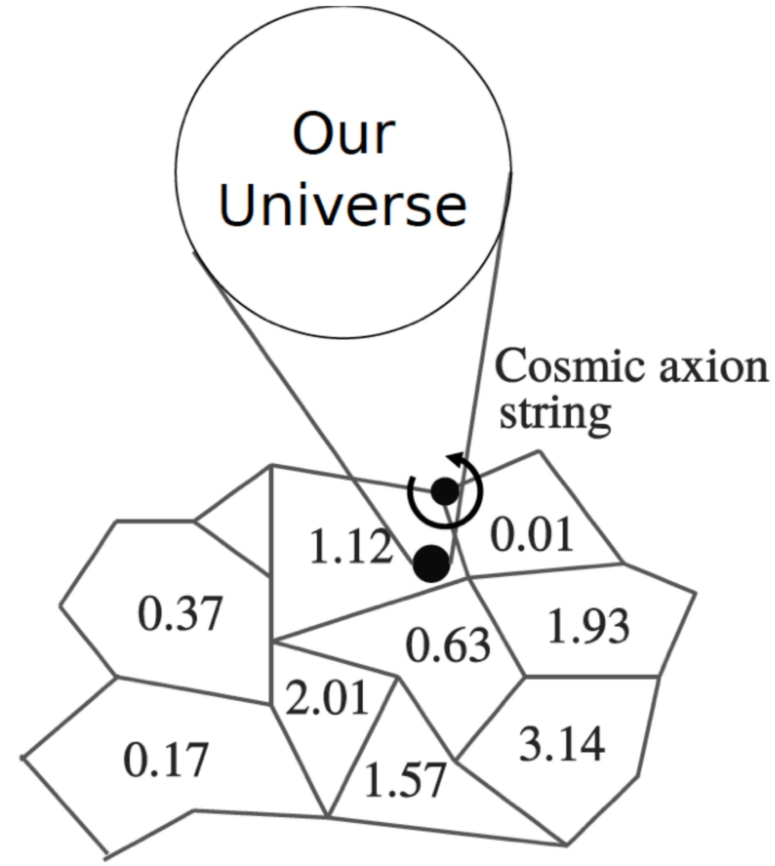
CONSTRAINTS ON QCD AXION MASS



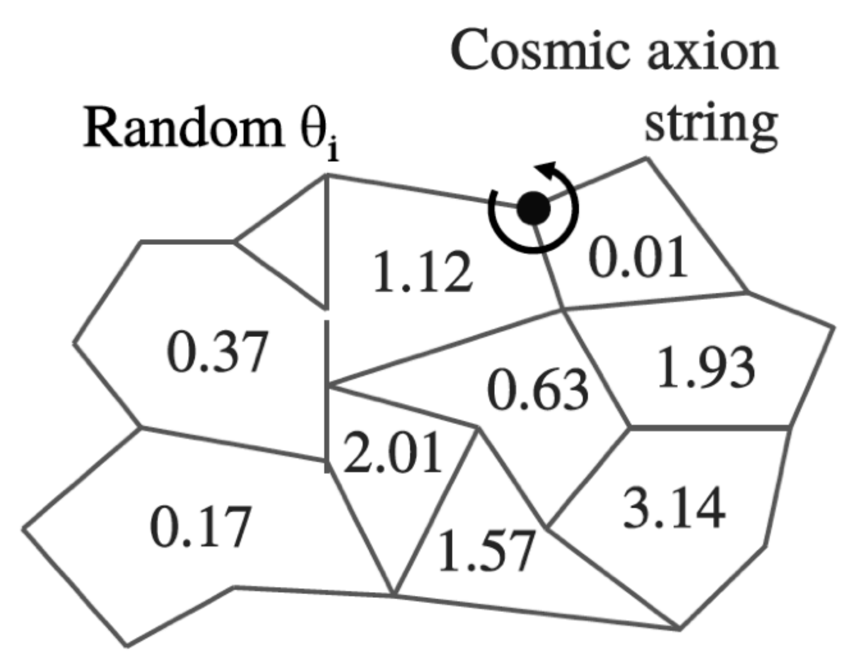
CONSTRAINTS ON QCD AXION MASS



Scenario A: PQ symmetry breaking happens **before** inflation

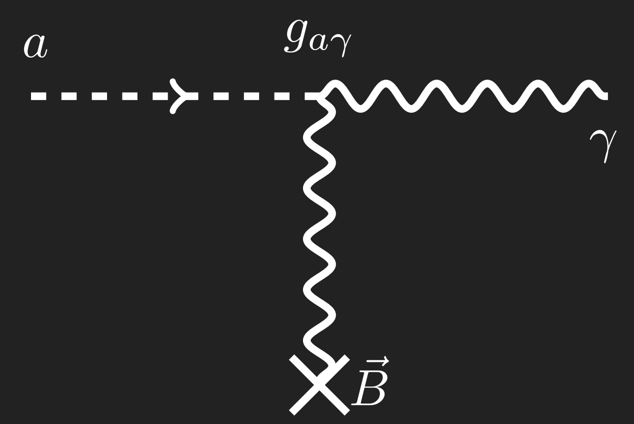


Scenario B: PQ symmetry breaking happens **after** inflation



CDM AXION DIRECT-DETECTION

- Axion-photon interaction:



$$\mathscr{L}_{a\gamma\gamma} = C_{a\gamma}\frac{\alpha}{2\pi f_a} a F^{\mu\nu}\tilde{F}_{\mu\nu}$$

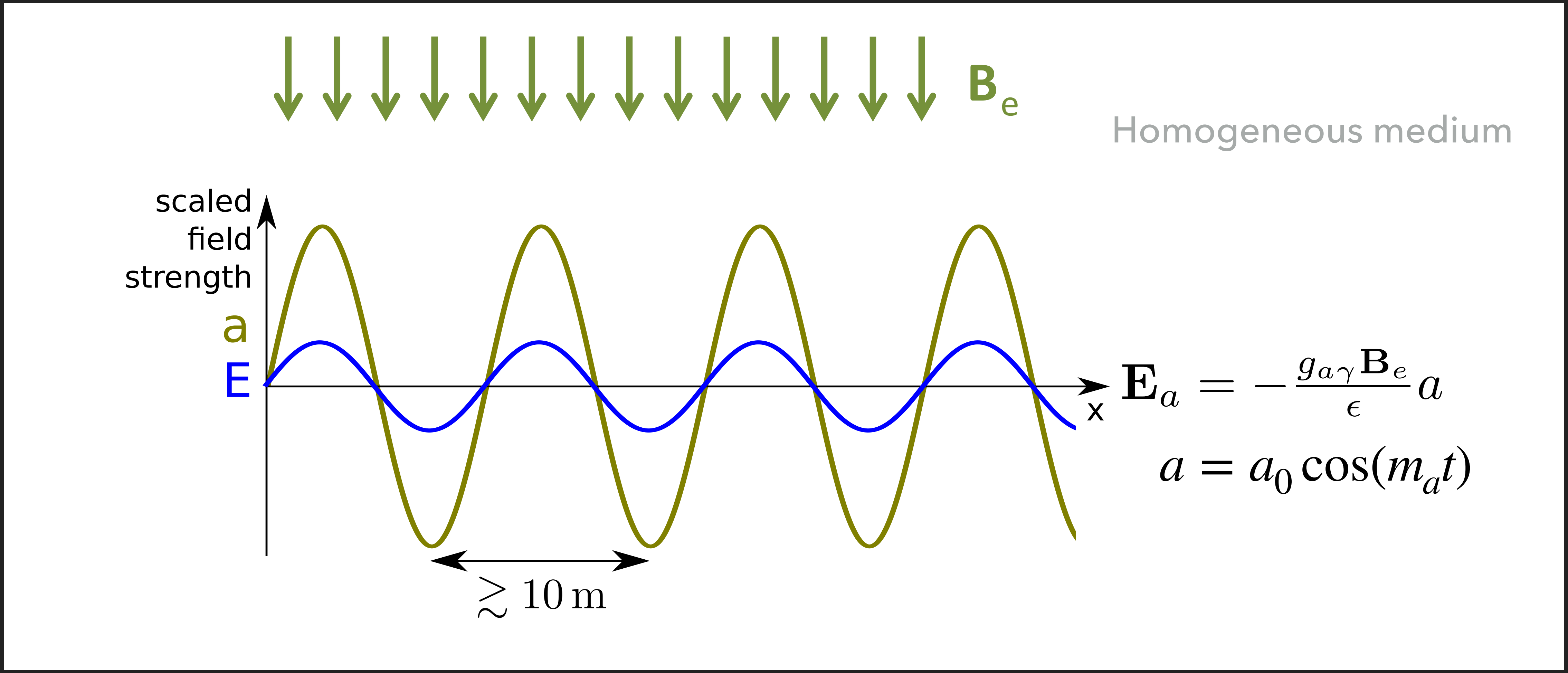
$$\downarrow$$

$$g_{a\gamma} = 2.04(3)\times 10^{-16}\text{GeV}^{-1}\frac{m_a}{\mu\text{eV}}C_{a\gamma}$$

- CDM axions behave like a **classical wave**: $a/f_a = \theta = \theta_0\cos(m_a t)$
  - E.g. $m_a \sim 100\ \mu$eV, local galactic axion density $\rho_a = (f_a m_a)^2\theta_0^2/2 = 0.45$ GeV/cm^3
    - Axion de Broglie wavelength: $\lambda_a = \dfrac{2\pi}{m_a v_a} \gtrsim 10$ m $\ (v_a \approx 10^{-3}c)$
    - Axion phase-space occupancy: $\mathscr{N}_a \sim n_a\lambda_a^3 = (\rho_a/m_a)\lambda_a^3 \sim 10^{22}$
- **Macroscopic** axion-Maxwell equation under external B-field:

$$\begin{cases} \nabla\cdot\mathbf{D} = \rho_f - g_{a\gamma}\mathbf{B}_e\cdot\nabla a \\ \nabla\times\mathbf{H} - \dot{\mathbf{D}} = \mathbf{J}_f + g_{a\gamma}\mathbf{B}_e\dot{a} \end{cases}$$

AXION HALOSCOPE



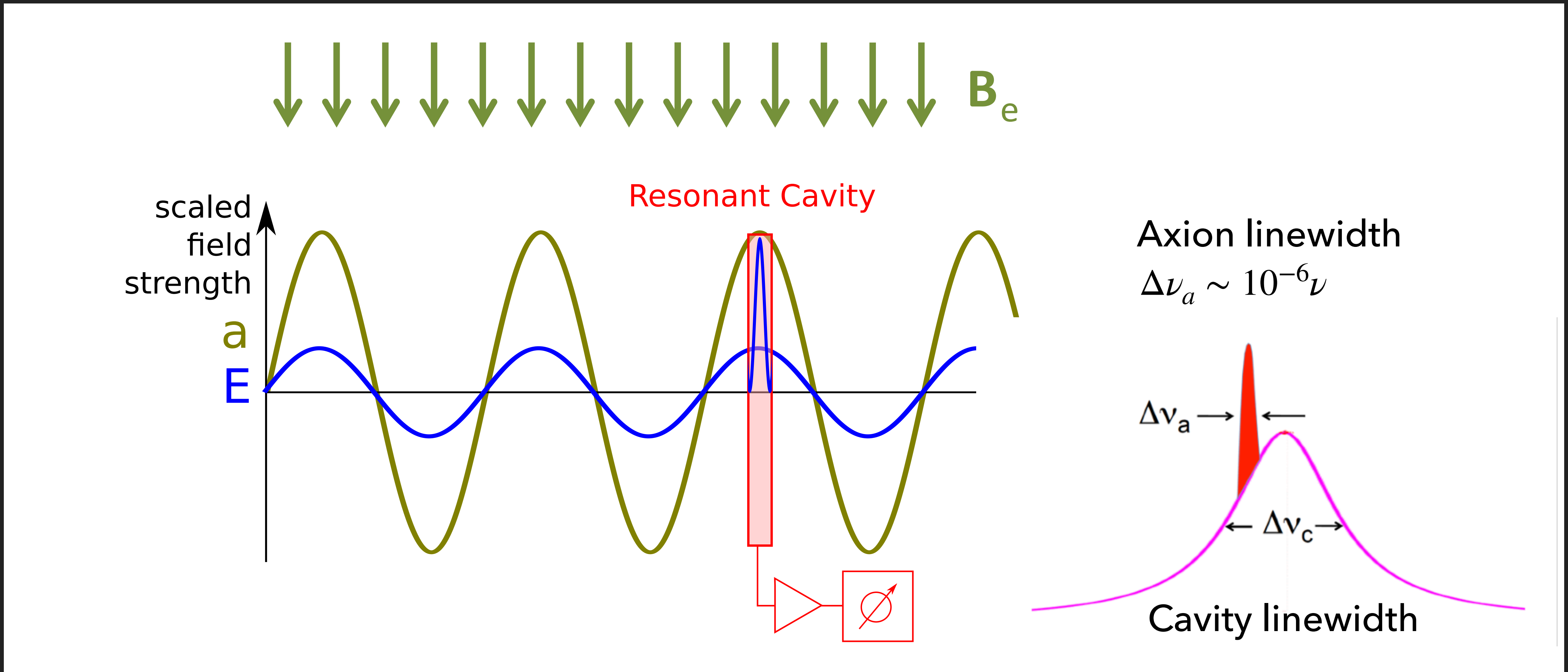
- Axion induced electric field:

$$|\mathbf{E}_a| = \left| -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a \right| = 1.3 \times 10^{-12}\,\mathrm{Vm}^{-1} \times \left(\frac{B_e}{10\,\mathrm{T}}\right) \left(\frac{\rho_a}{300\,\mathrm{MeV/cm}^3}\right)^{1/2} \frac{C_{a\gamma}}{\epsilon}$$

Local axion DM density (ρ_a)

Dielectric constant (ϵ)

CAVITY HALOSCOPE



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

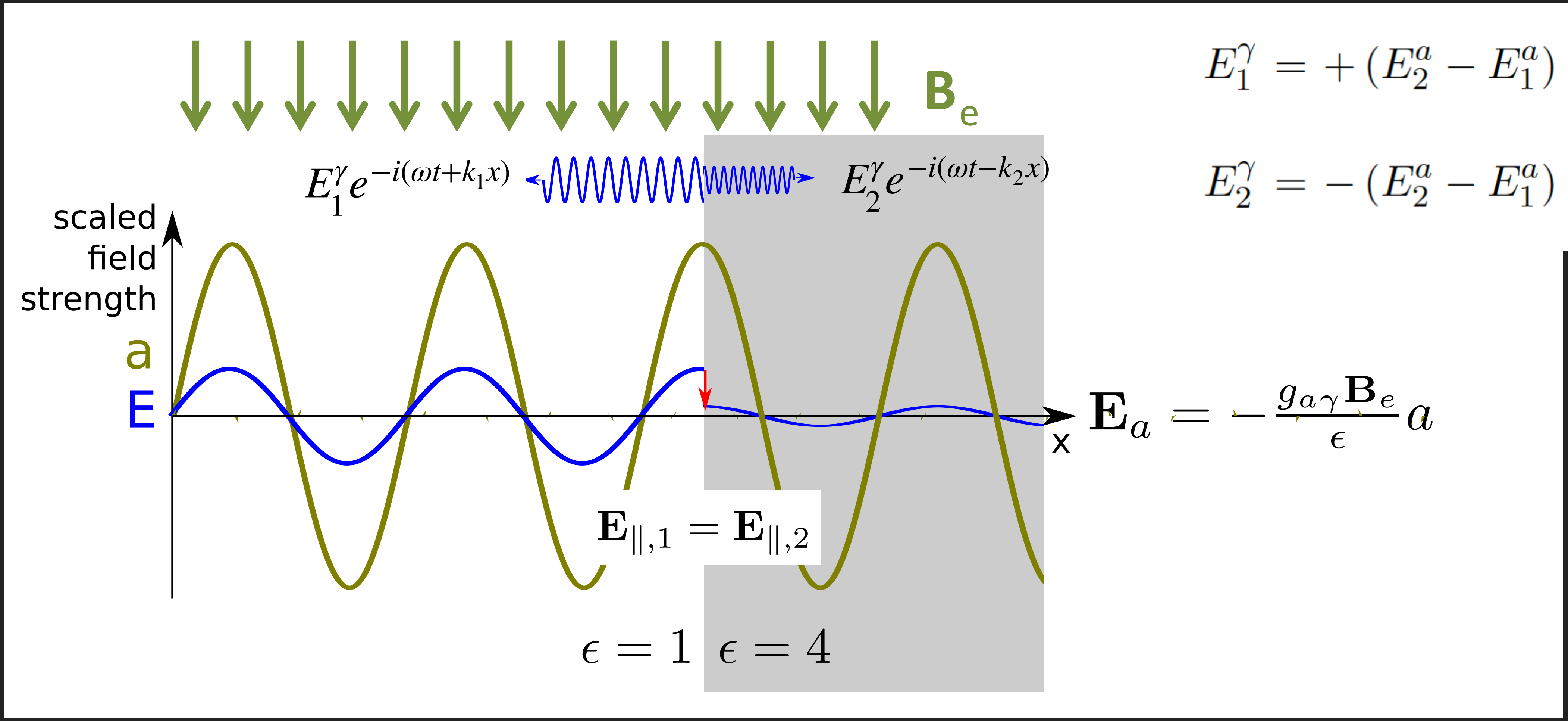
Cavity volume, scaled by f^{-3}

Cavity form factor

Cavity Quality factor

- At higher frequencies, cavities are increasingly difficult to build

DIELECTRIC HALOSCOPE (1)



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

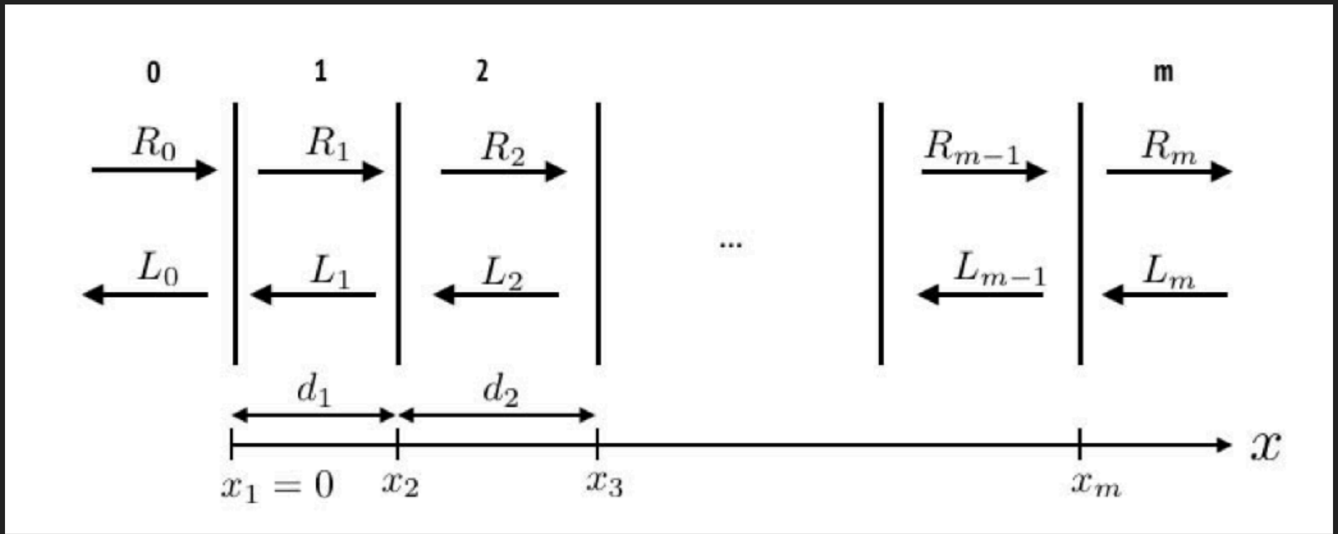
$$E_2^\gamma = -(E_2^a - E_1^a)\,\frac{\epsilon_1 n_2}{\epsilon_1 n_2 + \epsilon_2 n_1}$$

- Power emitted at a vacuum-to-perfect-conductor interface:

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

"*Axion-photon conversion caused by dielectric interfaces: quantum field calculation*", A. N. Ioannisian, N. Kazarian, A. J. Millar, G G. Raffelt, DOI: 10.1088/1475-7516/2017/09/005

DIELECTRIC HALOSCOPE (2)



- In the r^{th} domain

$$E_a^r = -A_r E_0 \,,$$

where $A_r = \dfrac{1}{\epsilon_r}\dfrac{B_{e,r}}{B_{e,max}}$,

$$E_0 = g_{a\gamma} B_{e,max} a_0$$

- Continuity conditions at each boundary

$$\begin{pmatrix} R_{r+1} \\ L_{r+1} \end{pmatrix} = G_r P_r \begin{pmatrix} R_r \\ L_r \end{pmatrix} + E_0 S_r \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \text{ where}$$

$$G_r = \frac{1}{2n_r + 1}\begin{pmatrix} n_{r+1} + n_r & n_{r+1} - n_r \\ n_{r+1} - n_r & n_{r+1} + n_r \end{pmatrix},$$

$$P_r = \begin{pmatrix} e^{i\delta_r} & 0 \\ 0 & e^{-i\delta_r} \end{pmatrix},$$

$$S_r = \frac{A_{r+1} - A_r}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Transfer matrix between in and out EM waves

Axion source terms

$$\begin{pmatrix} R_m \\ L_m \end{pmatrix} = T \begin{pmatrix} R_0 \\ L_0 \end{pmatrix} + E_0 M \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \text{ where}$$

$$T_a^b = G_{a-1}P_{a-1}G_{a-2}P_{a-2}\ldots G_{b+1}P_{b+1}G_bP_b,$$

$$T = T_0^m \text{, and}$$

$$M = \sum_{s=1}^{m} T_s^m S_{s-1}$$

A. Millar, G. Raffelt. J. Redondo, F. Steffen, JCAP 1701 (2017) no.01, 061

DIELECTRIC HALOSCOPE (3)

- A perfect mirror on the left

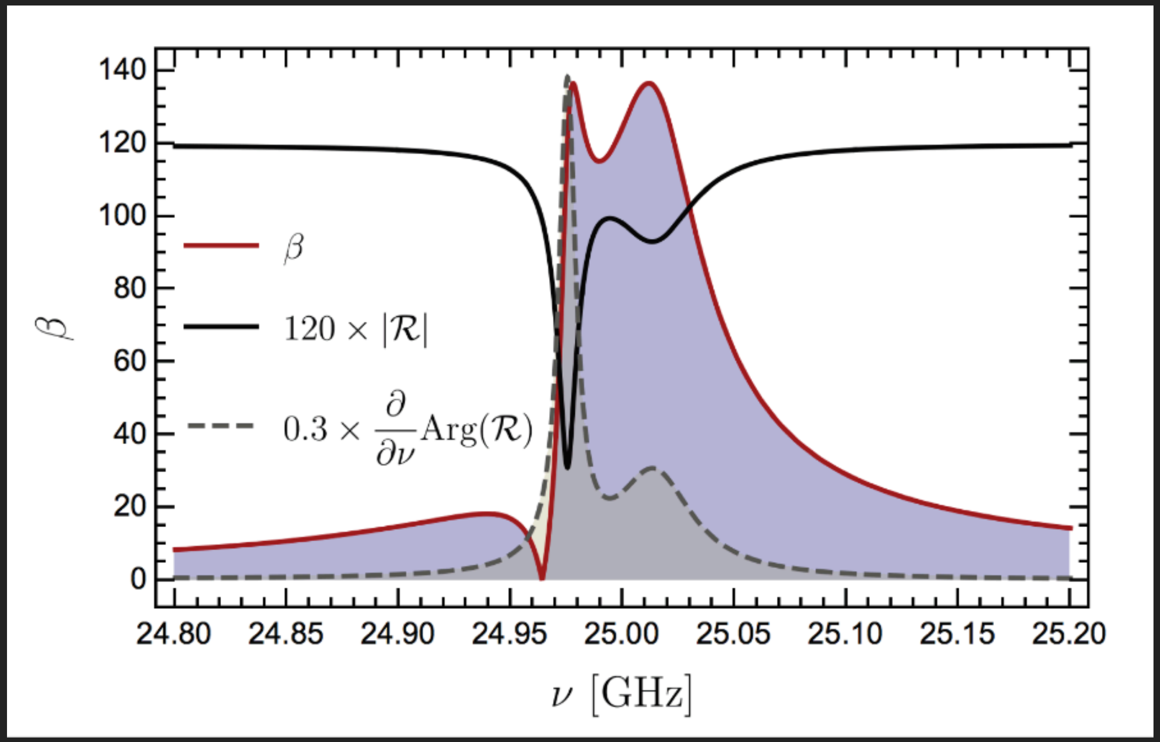
$$\text{Reflectivity } R_R = \left.\frac{R_m}{L_m}\right|_{R_0=0} = \frac{T[1,2]}{T[2,2]},$$

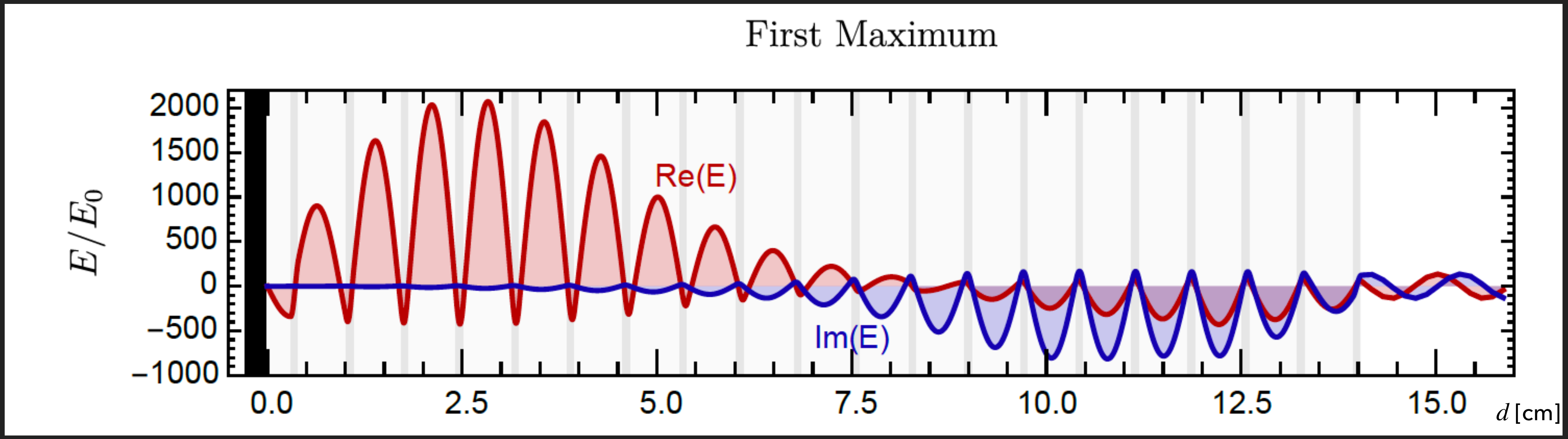
$$\text{Boost } \beta = \frac{R_m}{E_0} = M[1,1] + M[1,2]$$

- Tolerance to disc positioning inaccuracy:

$$\sigma \ll 200\mu\text{m} \left(\frac{10^2}{\beta}\right)^{1/2} \left(\frac{100\mu\text{eV}}{m_a}\right)$$

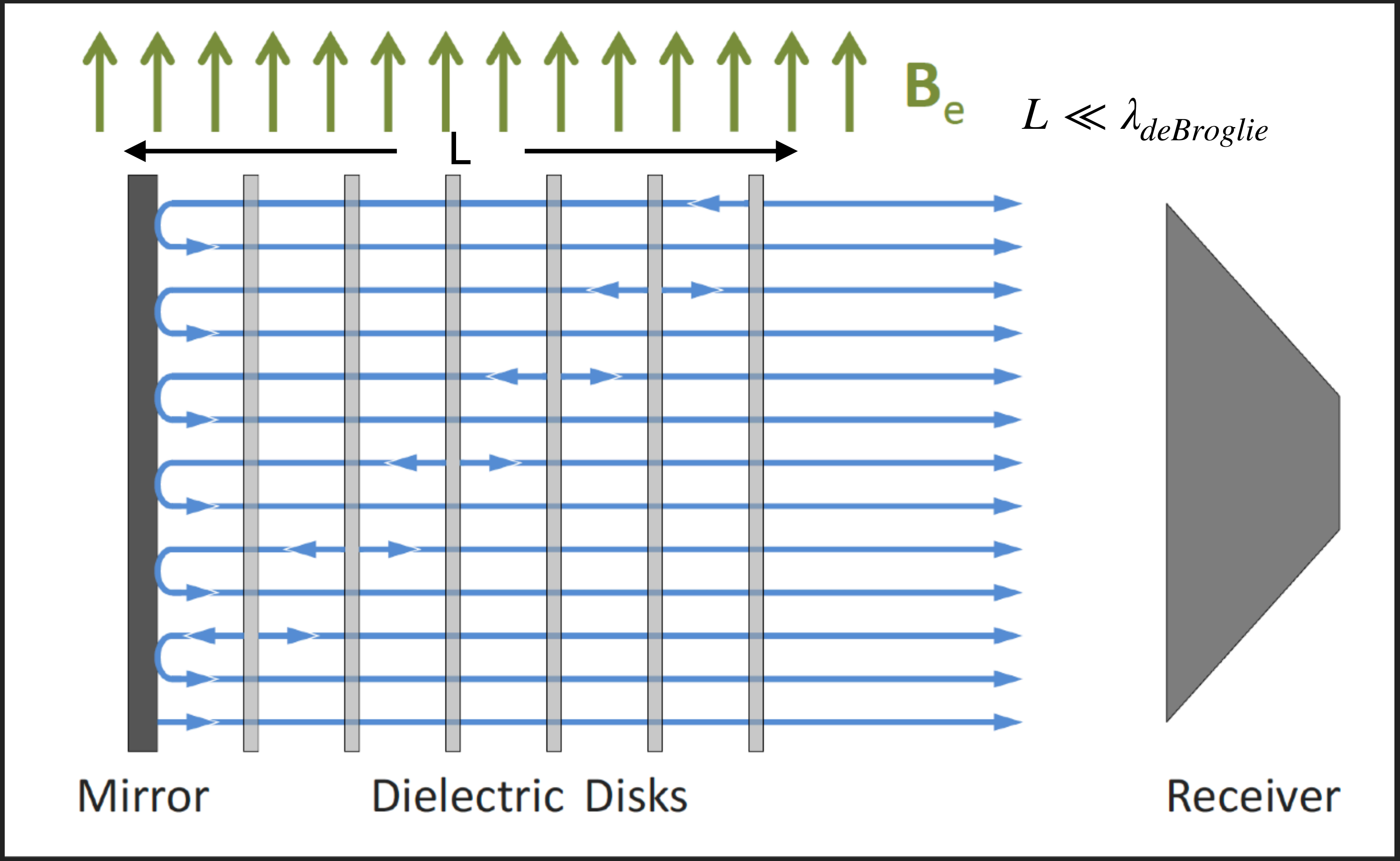
20 discs, $d = 1$ mm, $n = 5$





MAgnetized Disc and Mirror Axion eXperiment (MADMAX)

Cryogenic environment



- Power enhancement from coherent emission from and resonances between interfaces

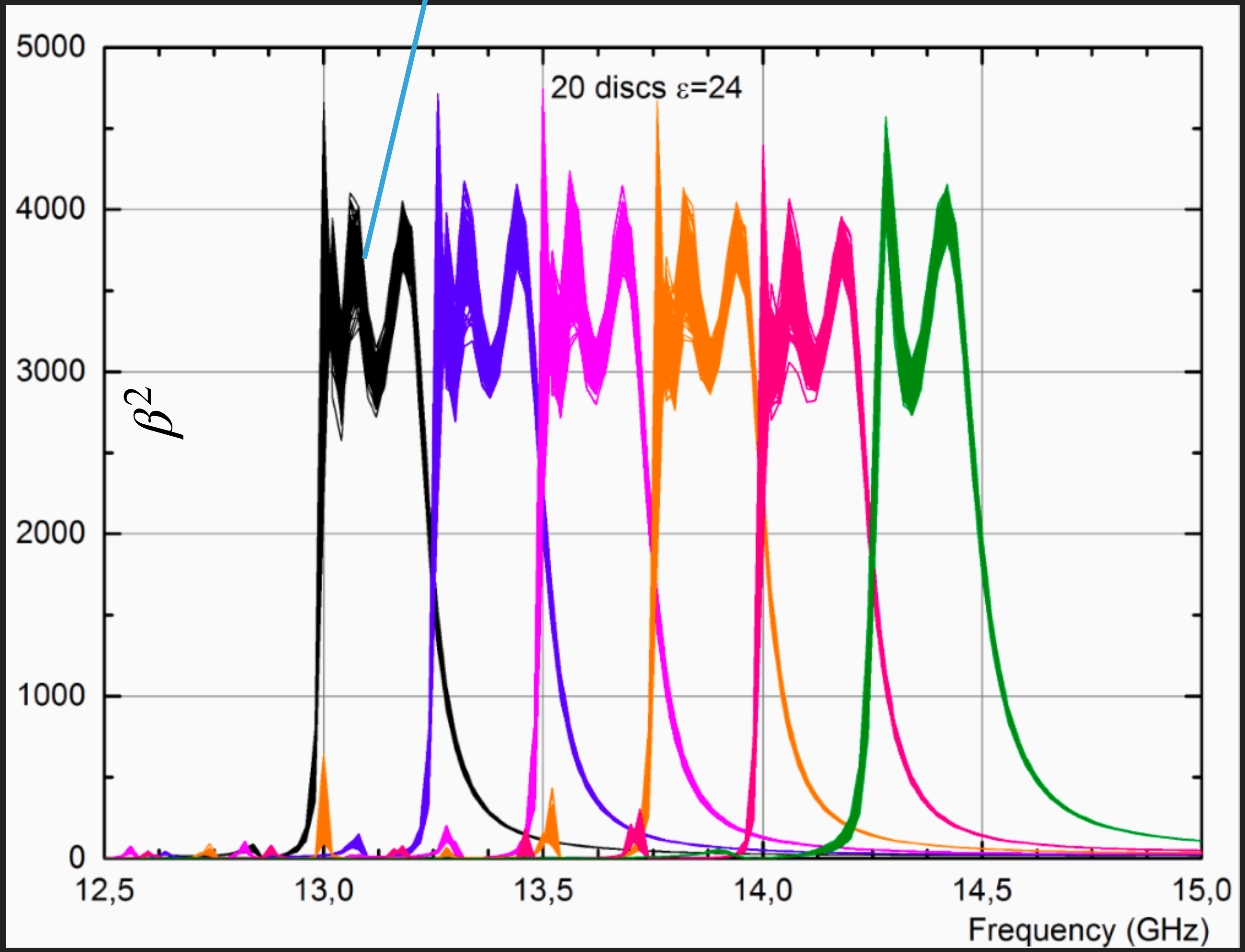
$$\frac{P^{\gamma}_{sig}}{A} = 2.2 \times 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 C^2_{a\gamma} \cdot \beta^2 \longrightarrow \text{Boost factor } \beta^2 \geq 10^4 \text{ achievable}$$

~m²

MADMAX BOOST FACTOR

- Frequency tuning possible

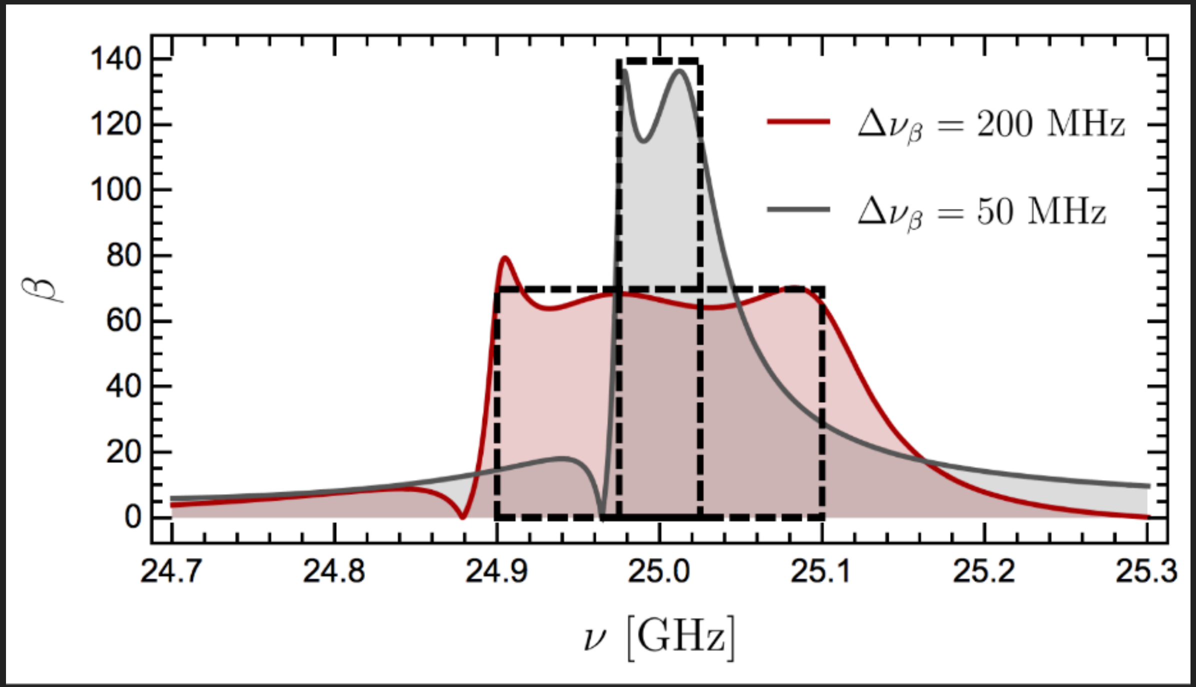
Disc positions randomly varied by $\sigma = 15\ \mu m$



Frequency is tuned by changing disc positions

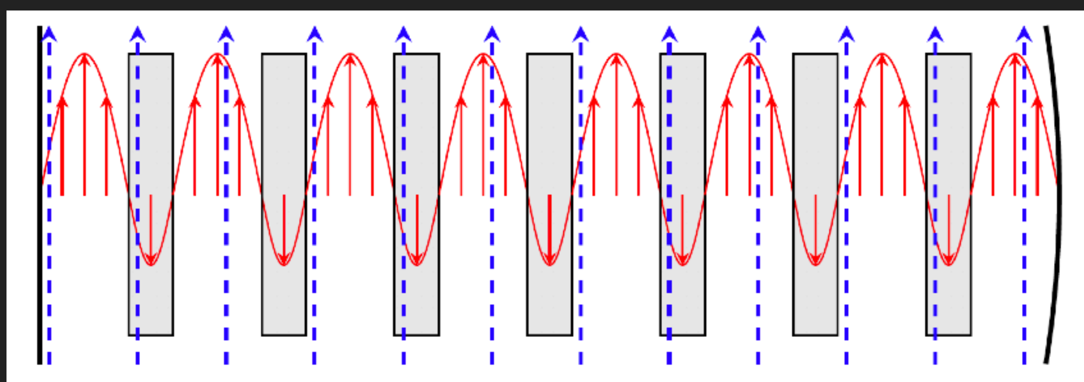
- Area law: $\int |\beta(\nu)|^2 \, d\nu \propto N$

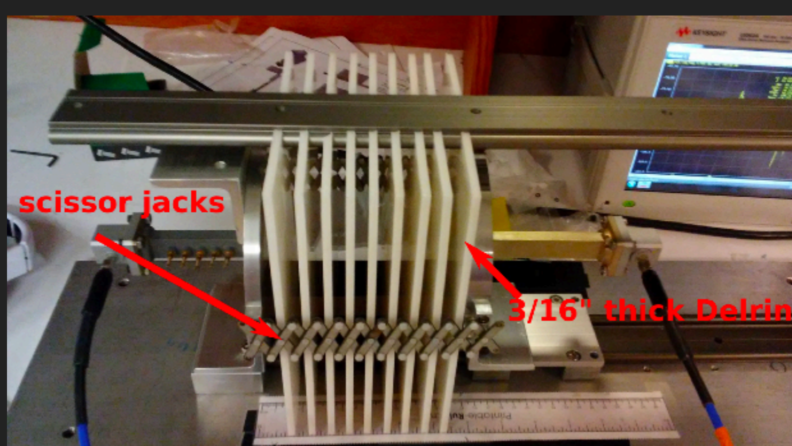
- Options for broadband and narrowband scans



OTHER DIELECTRIC HALOSCOPES

ADMX Orpheus

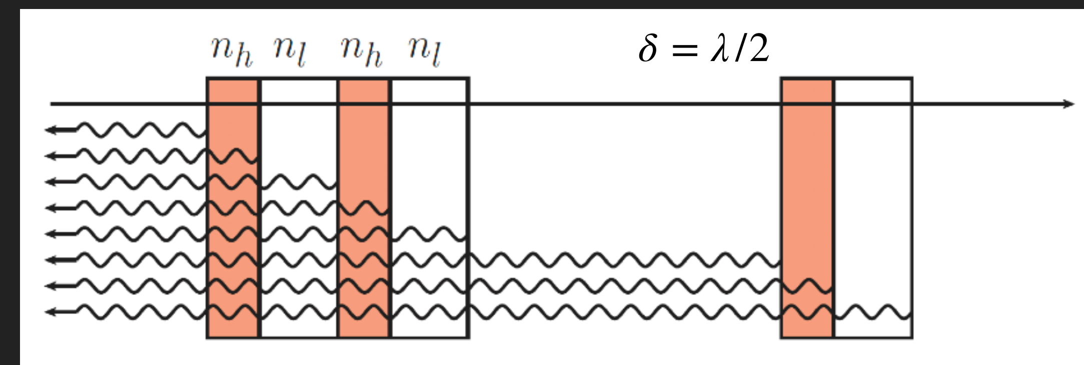




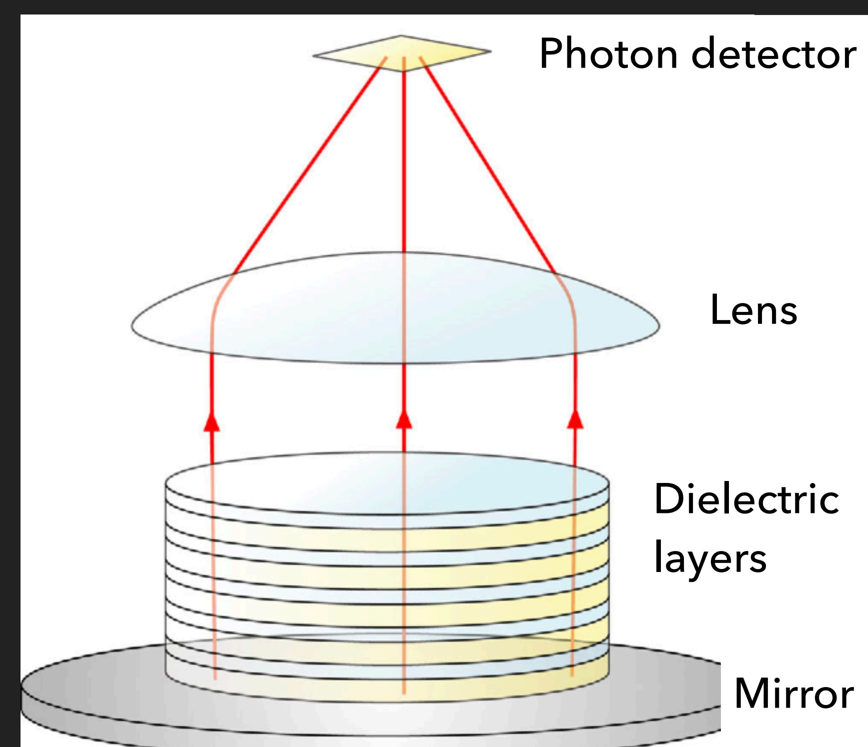
15-18 GHz

- Open cavity with evenly spaced dielectrics
- Dielectric media compresses wavenumber and prevent the form factor integral from dropping to zero

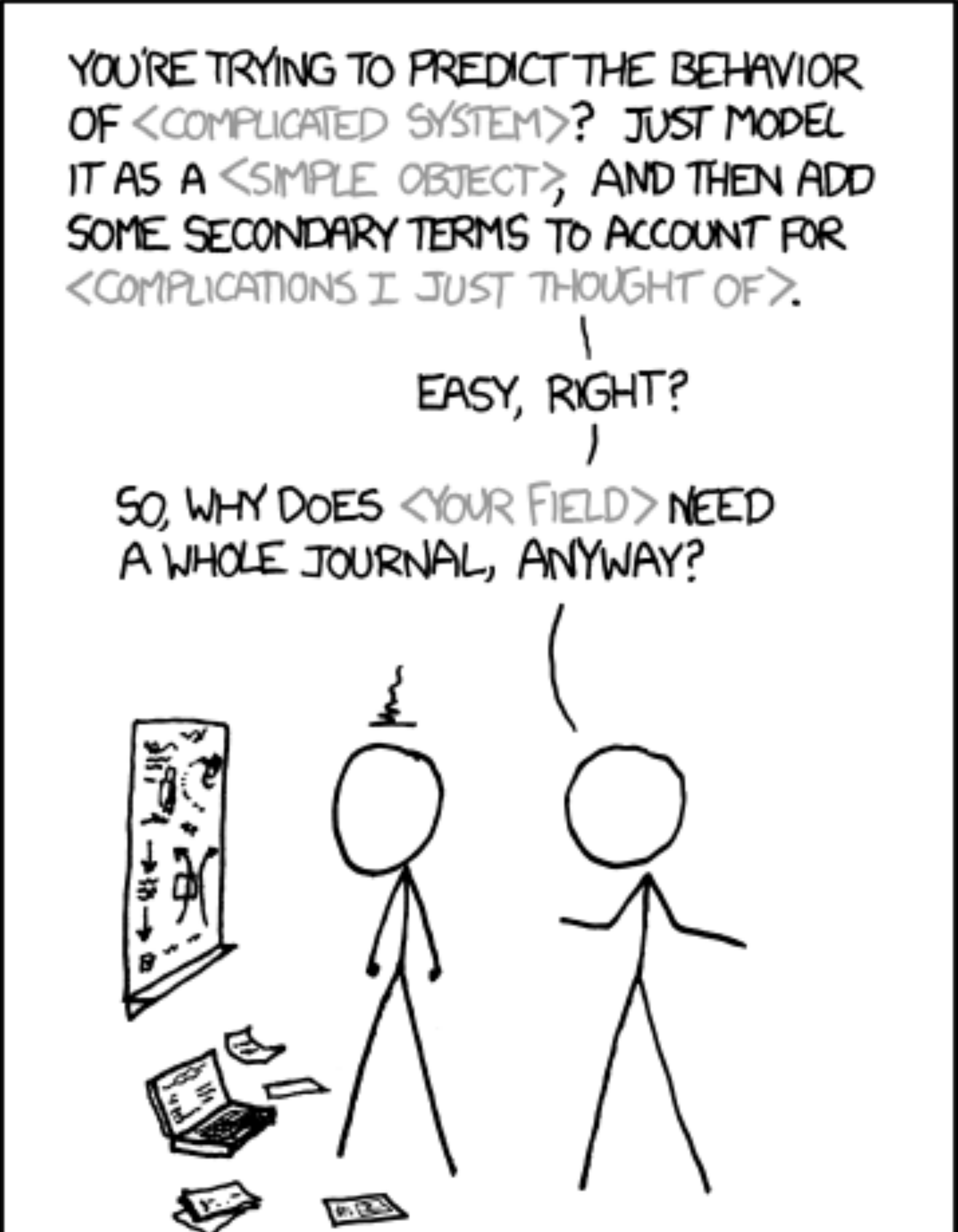
J. Jaeckel, J. Redondo, DOI:10.1103/PhysRevD.88.115002



M. Baryakhtar, J. Huang, R. Lasenby, PRD 98, 035006 (2018)



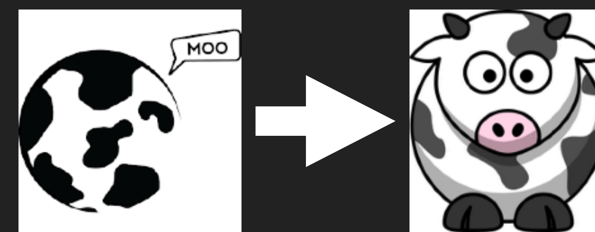
Infrared to ultraviolet



xkcd.com

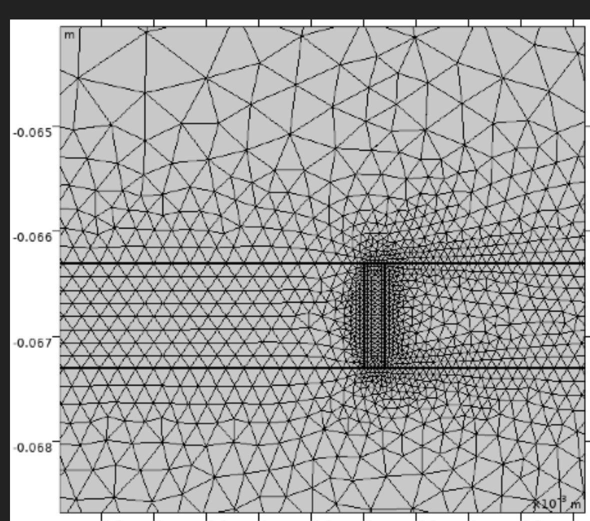
- More realistic simulations
- Frequency tuning in reality
- RF signal detection
- Other engineering challenges

3D SIMULATION (1)

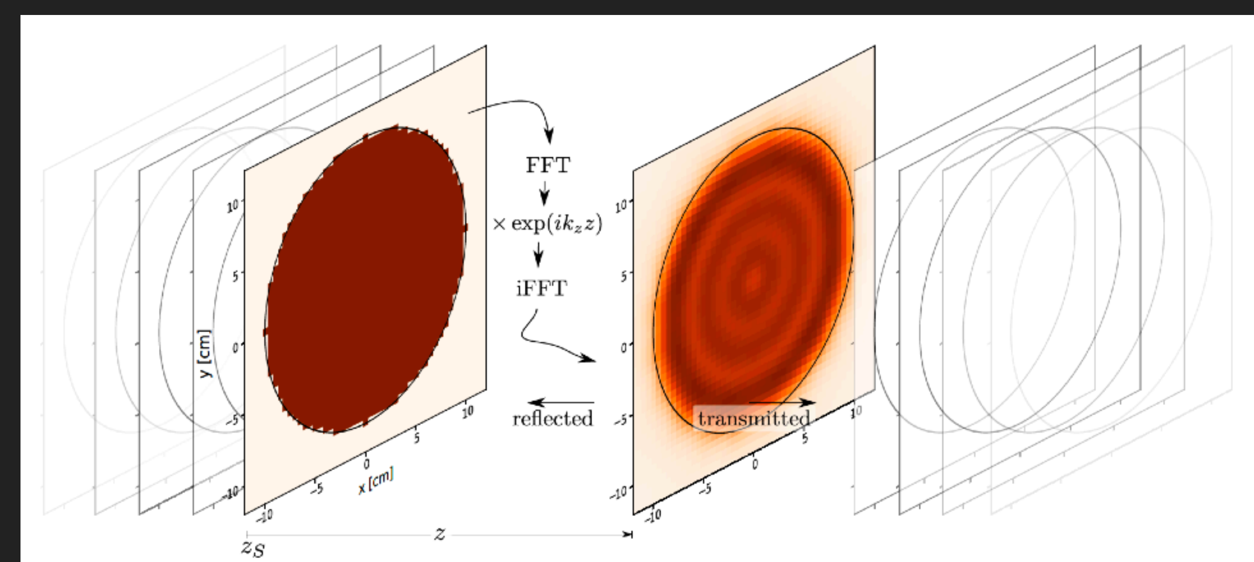


S. Knirck, J. Schütte-Engel, *et. al.*
DOI: 10.1088/1475-7516/2019/08/026

A. Finite element method (FEM) w/ Comsol Multiphysics ® and Elmer
   - Axion-induced E field is implemented as an external current density: $\mathbf{J}_a(t) = g_{a\gamma}\mathbf{B}_e\dot{a}(t)$
   - Fewer underlying assumptions but time-consuming

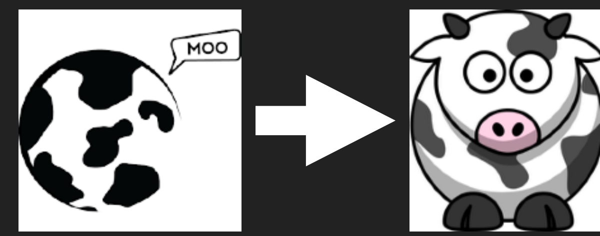


B. Recursive Fourier propagation method
   - Assumption: no charge accumulation, i.e. $\nabla \cdot \mathbf{E} = 0$



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

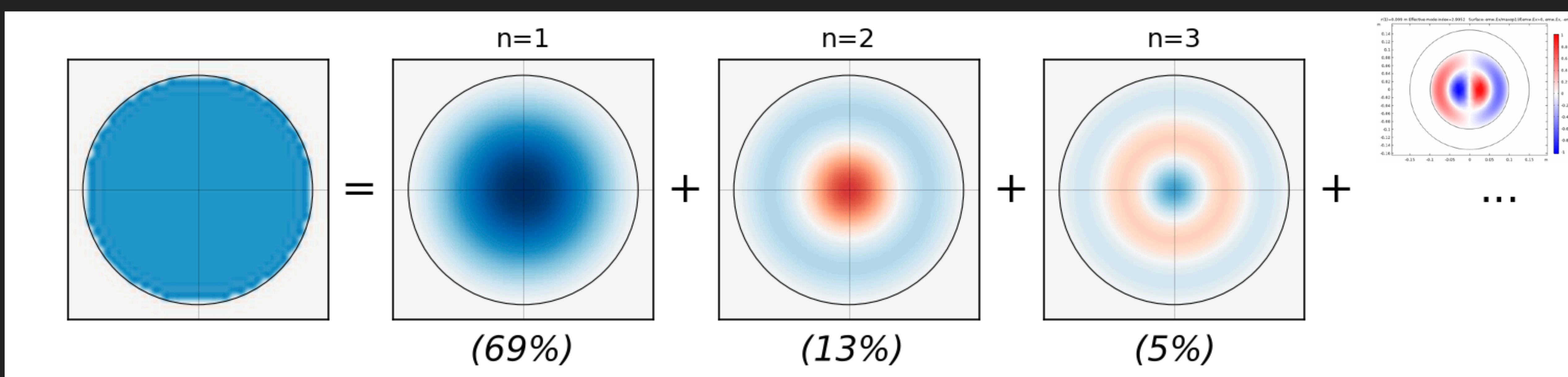
3D SIMULATION (2)



C. Mode matching

- If the booster mechanics have negligible effects, the booster can be regarded as similar to a dielectric waveguide

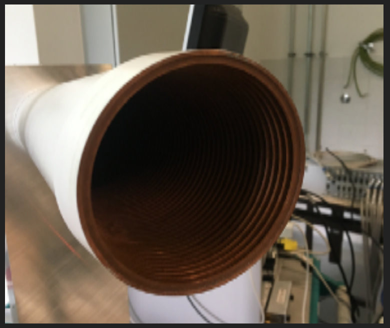
Eigenmodes w/ different field patterns and propagation constant

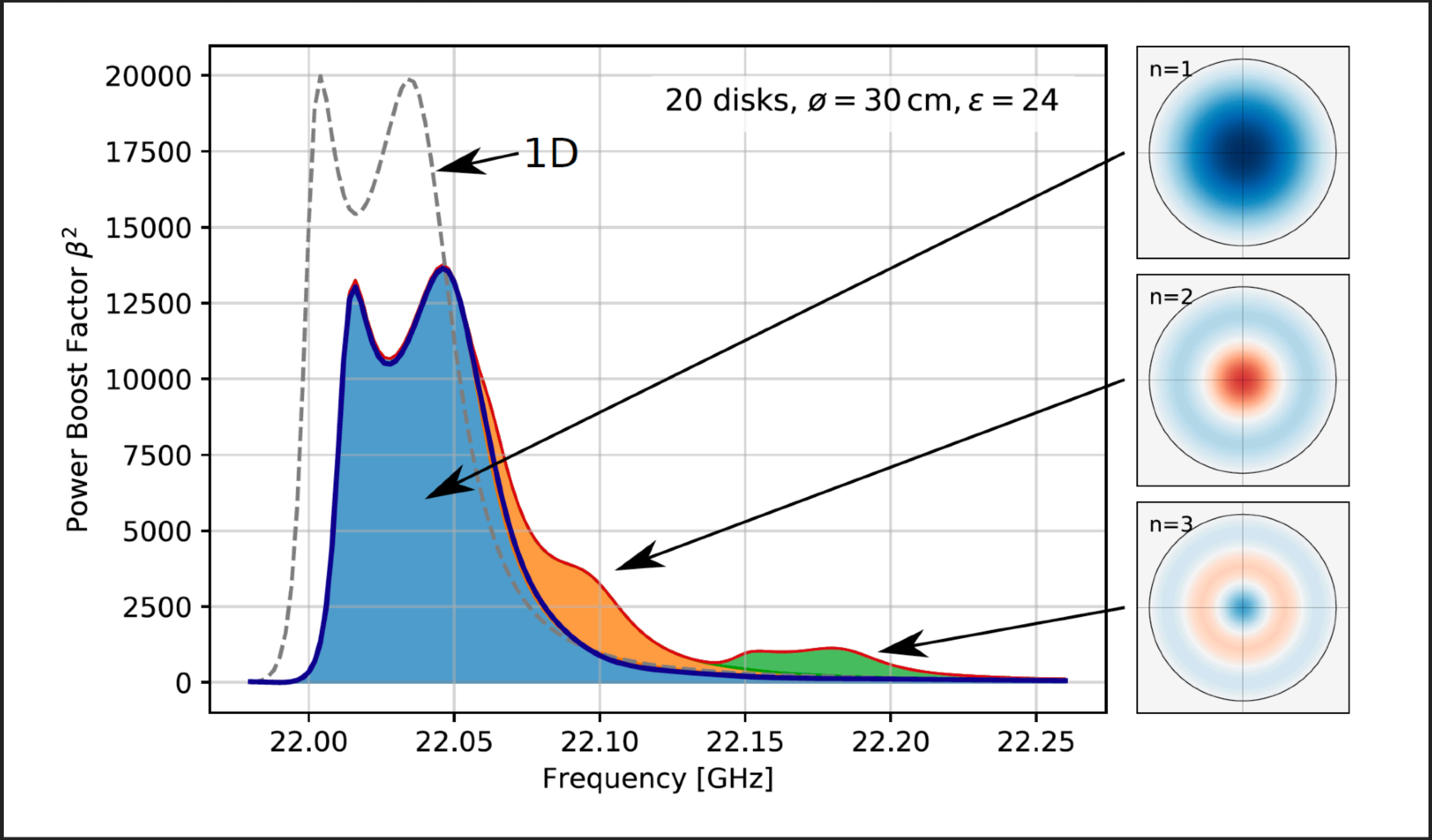


- Mode mixing can happen due to diffraction, tilted disc, etc.

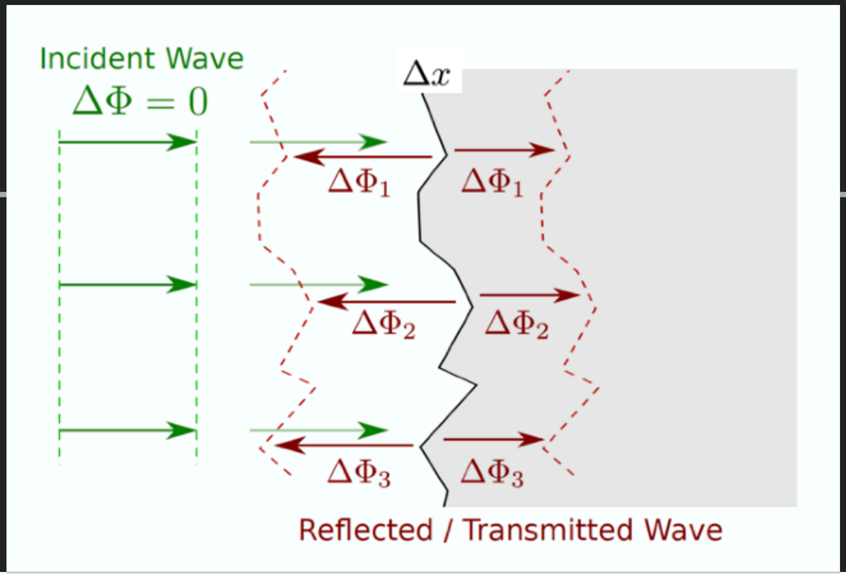
- Three methods yield consistent results where comparison is possible

3D SIMULATION (3)

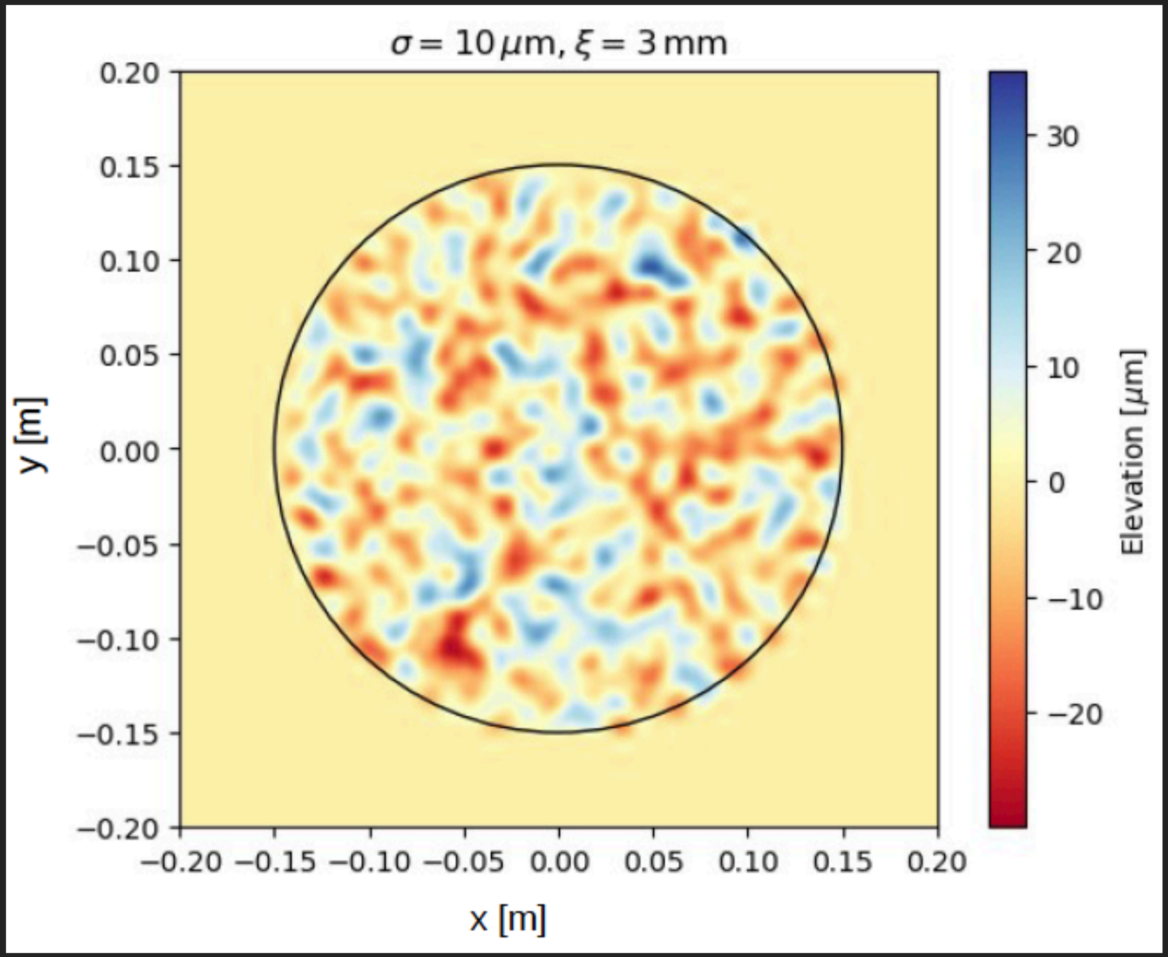




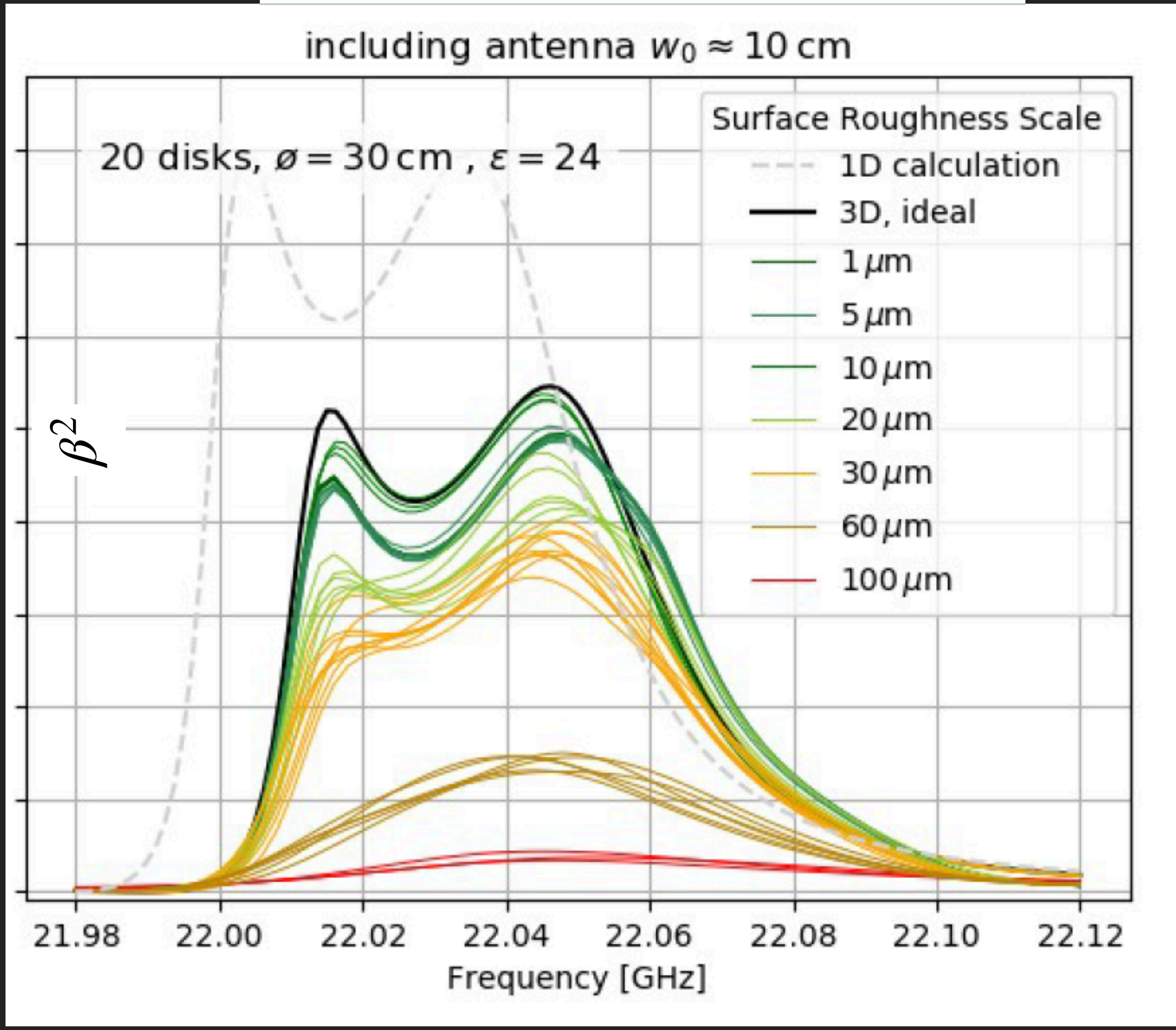
CRITICAL DESIGN PARAMETERS (1)



- Disc surface roughness



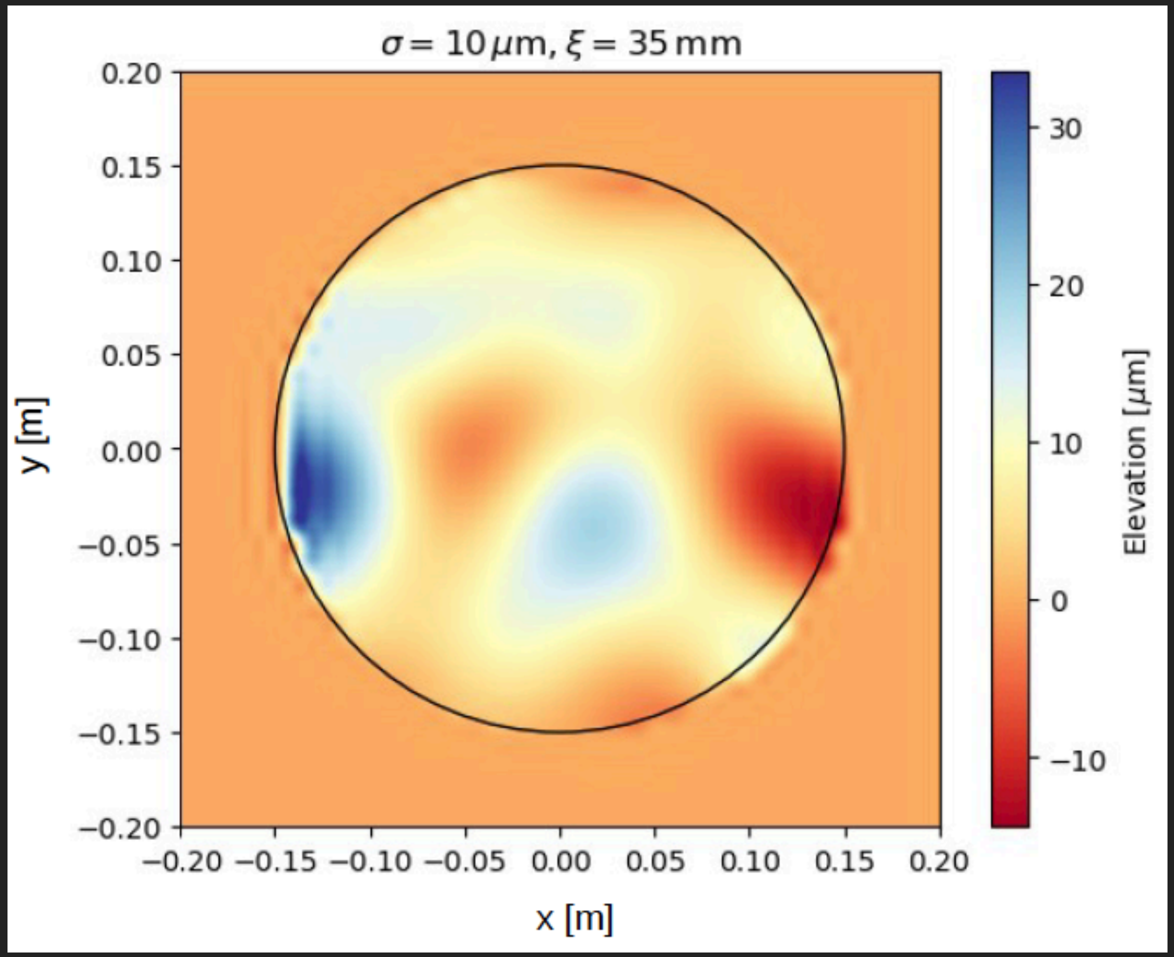
Correlation length 3 mm



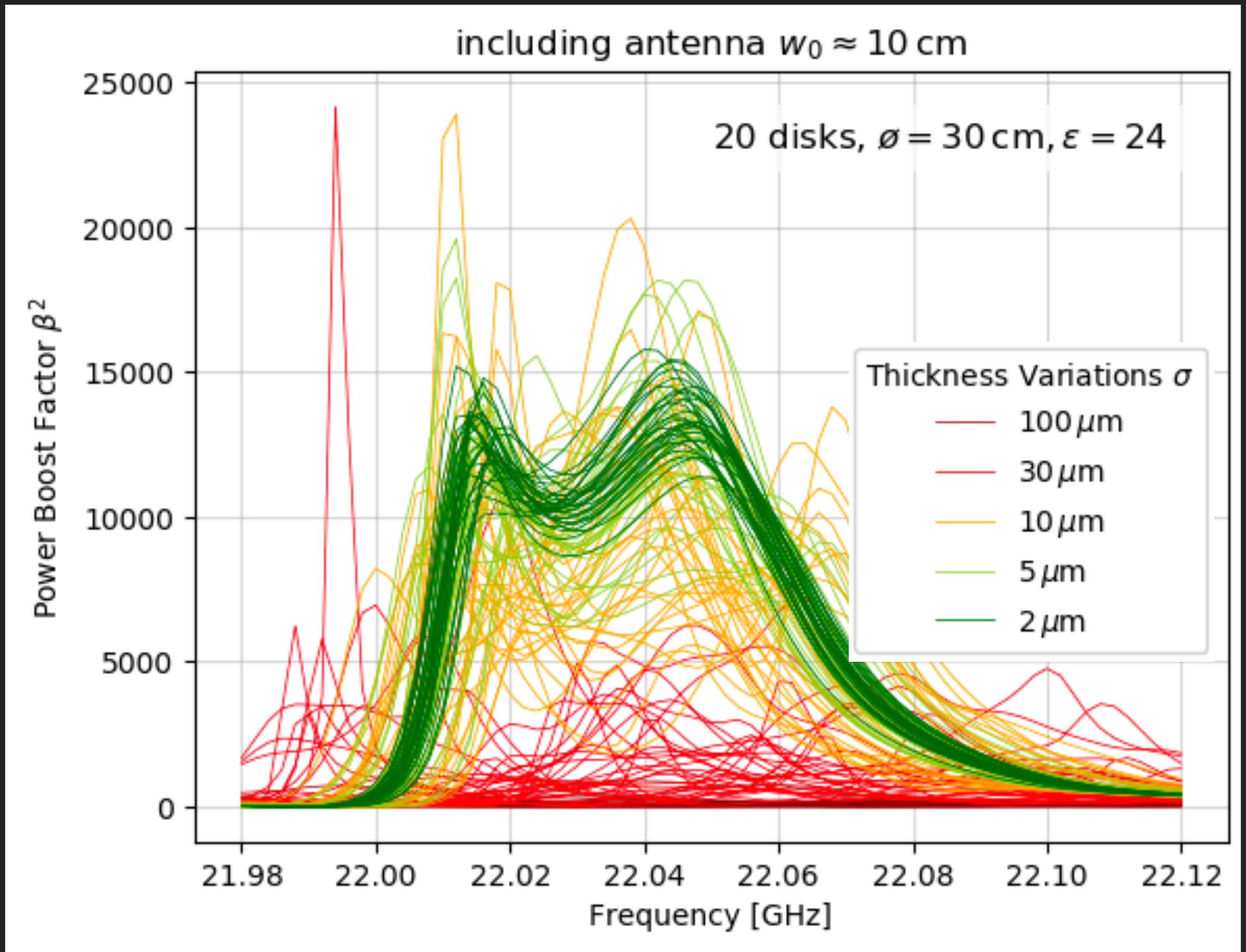
- Booster is forgiving to small-scale roughness

CRITICAL DESIGN PARAMETERS (2)

- Disc thickness variation

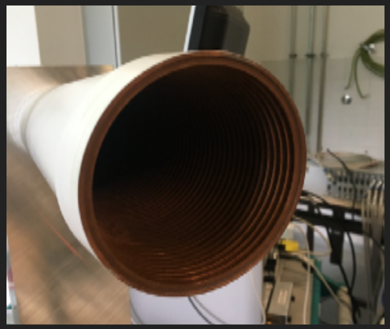


Correlation length 35 mm

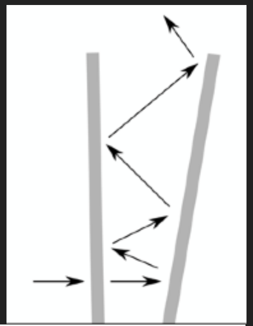


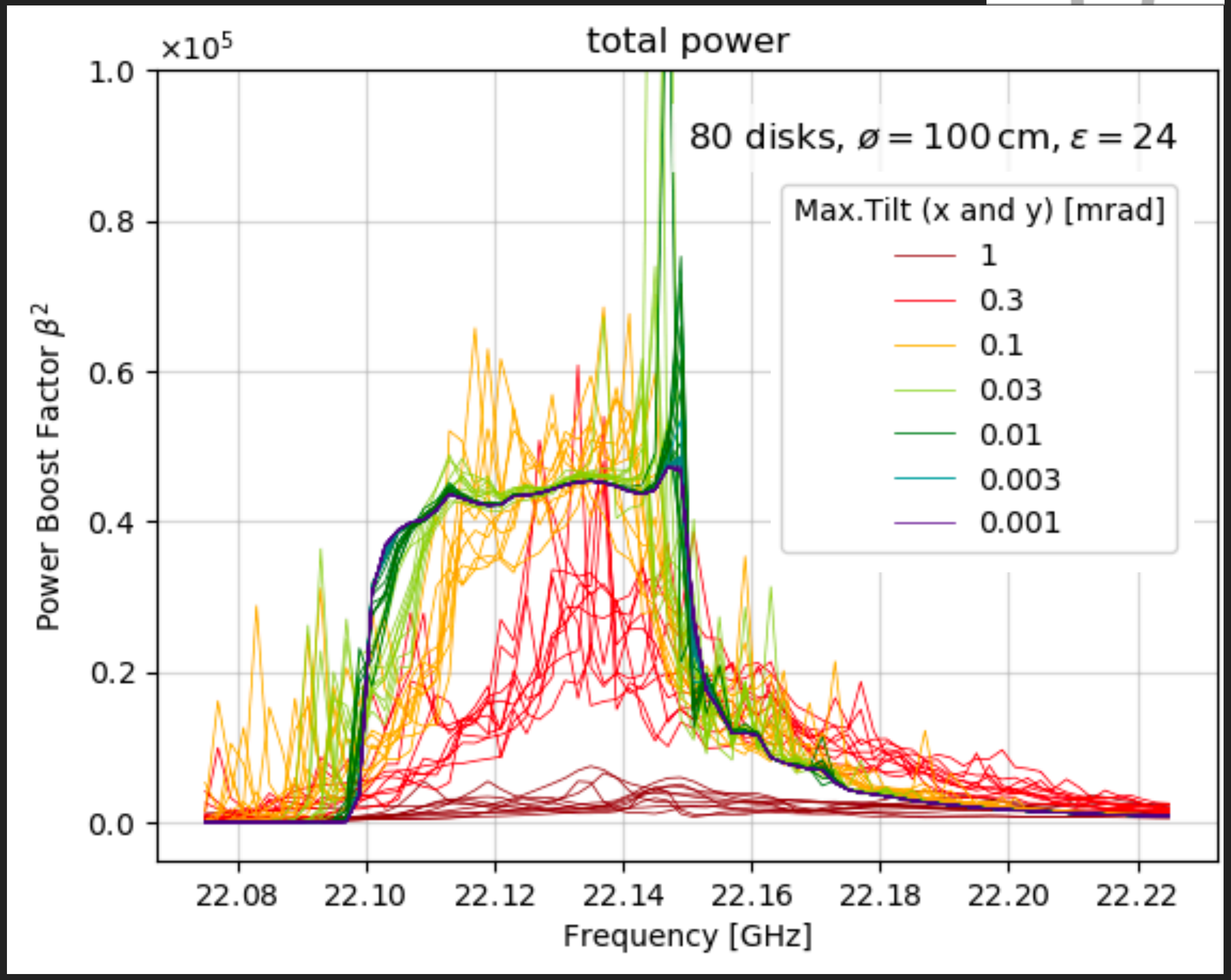
- Disc flatness better than $5\ \mu m$ is desirable; $10\ \mu m$ is critical
- Effects on boost factor may be mitigated through measurement-based tuning

CRITICAL DESIGN PARAMETERS (3)



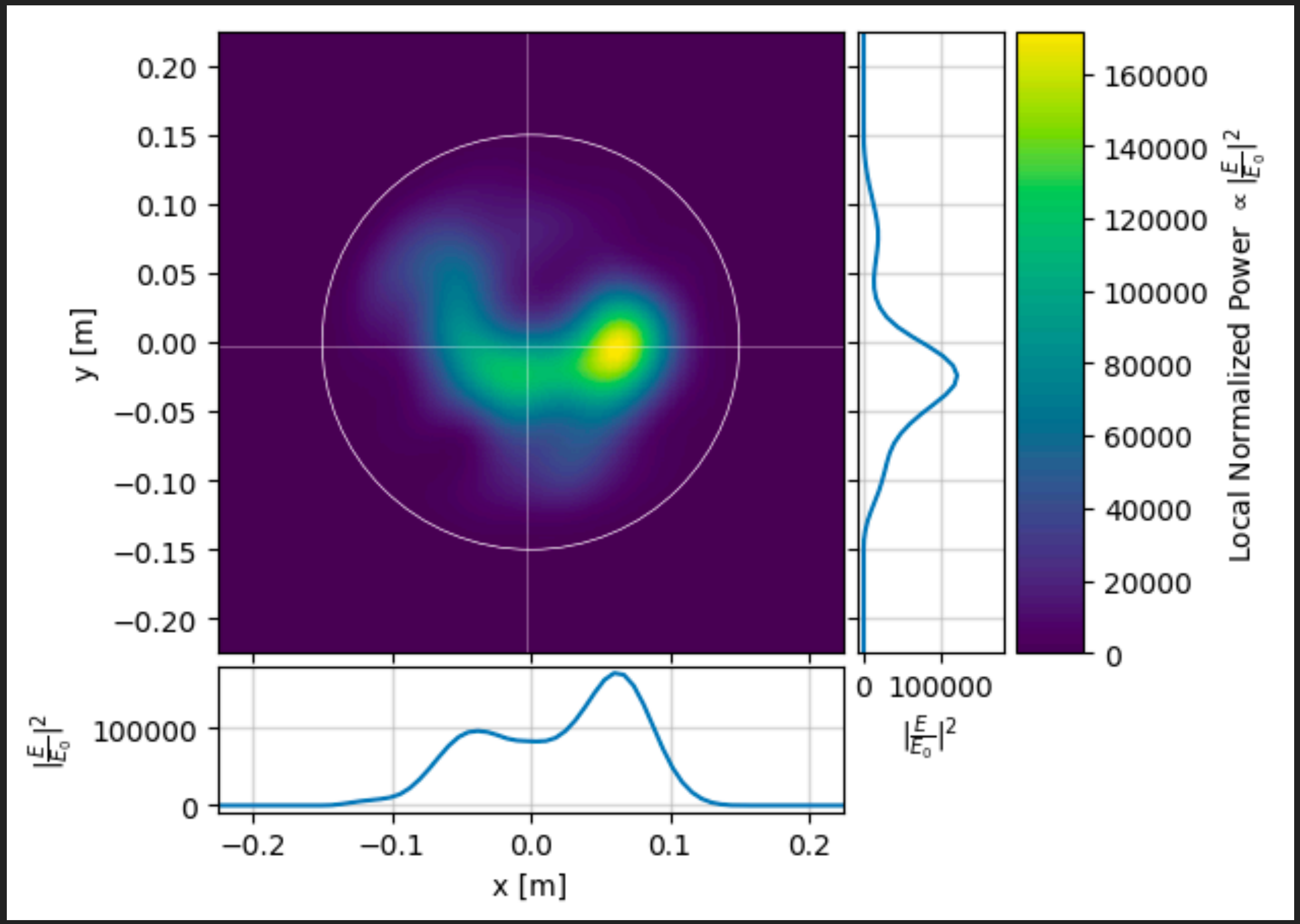
- Disc tilting





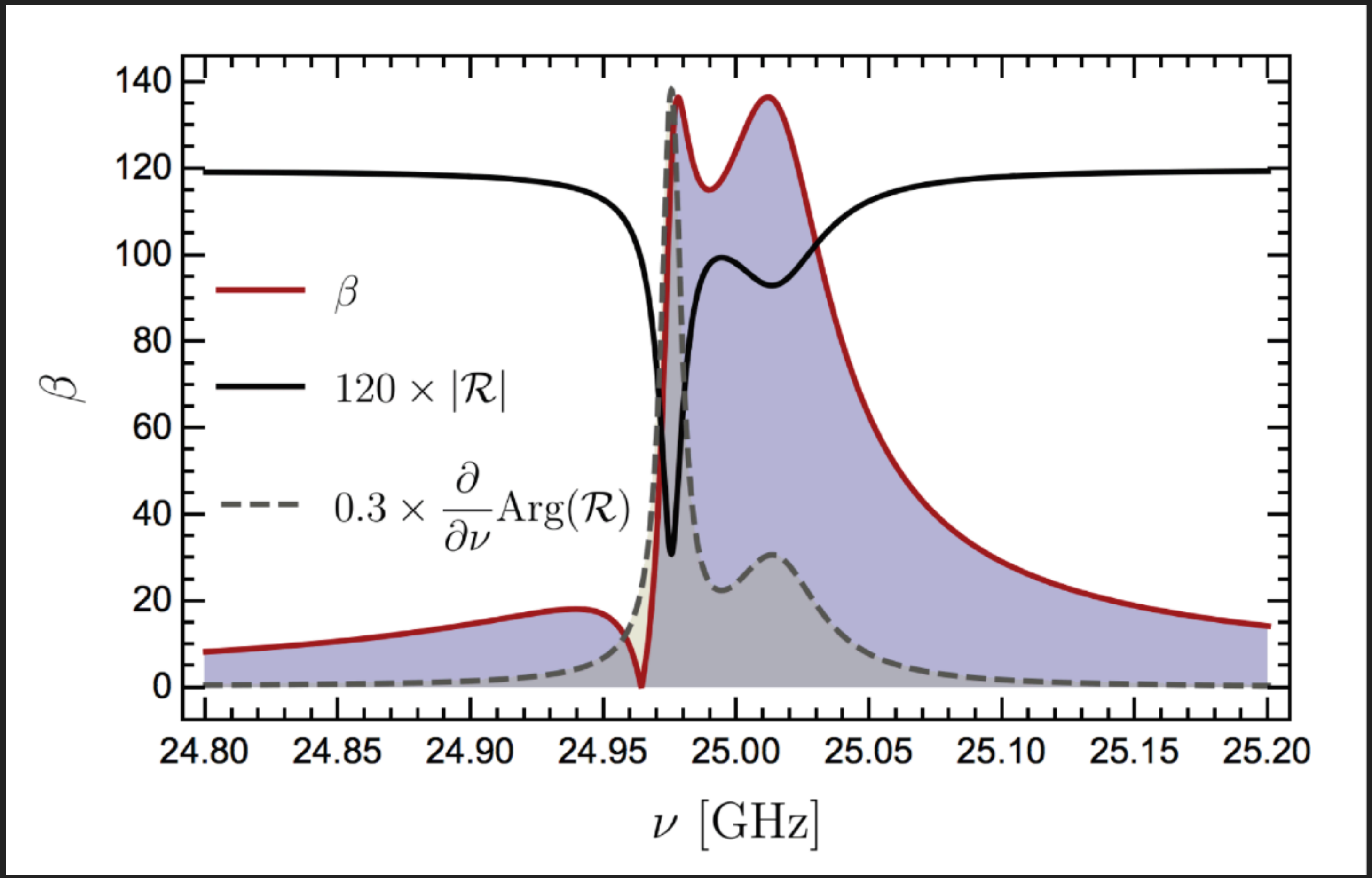
- For 1-m discs, disc tilting should be less than 0.1 mrad ($100\ \mu$m)

- Non-ideal discs result in irregular beam shapes
  - How to efficiently couple such a beam into the receiver is under study



FREQUENCY TUNING

- Boost factor cannot be measured experimentally
- It can be inferred from measurements of the electromagnetic response such as the reflectivity, as it is strongly correlated with the boost factor

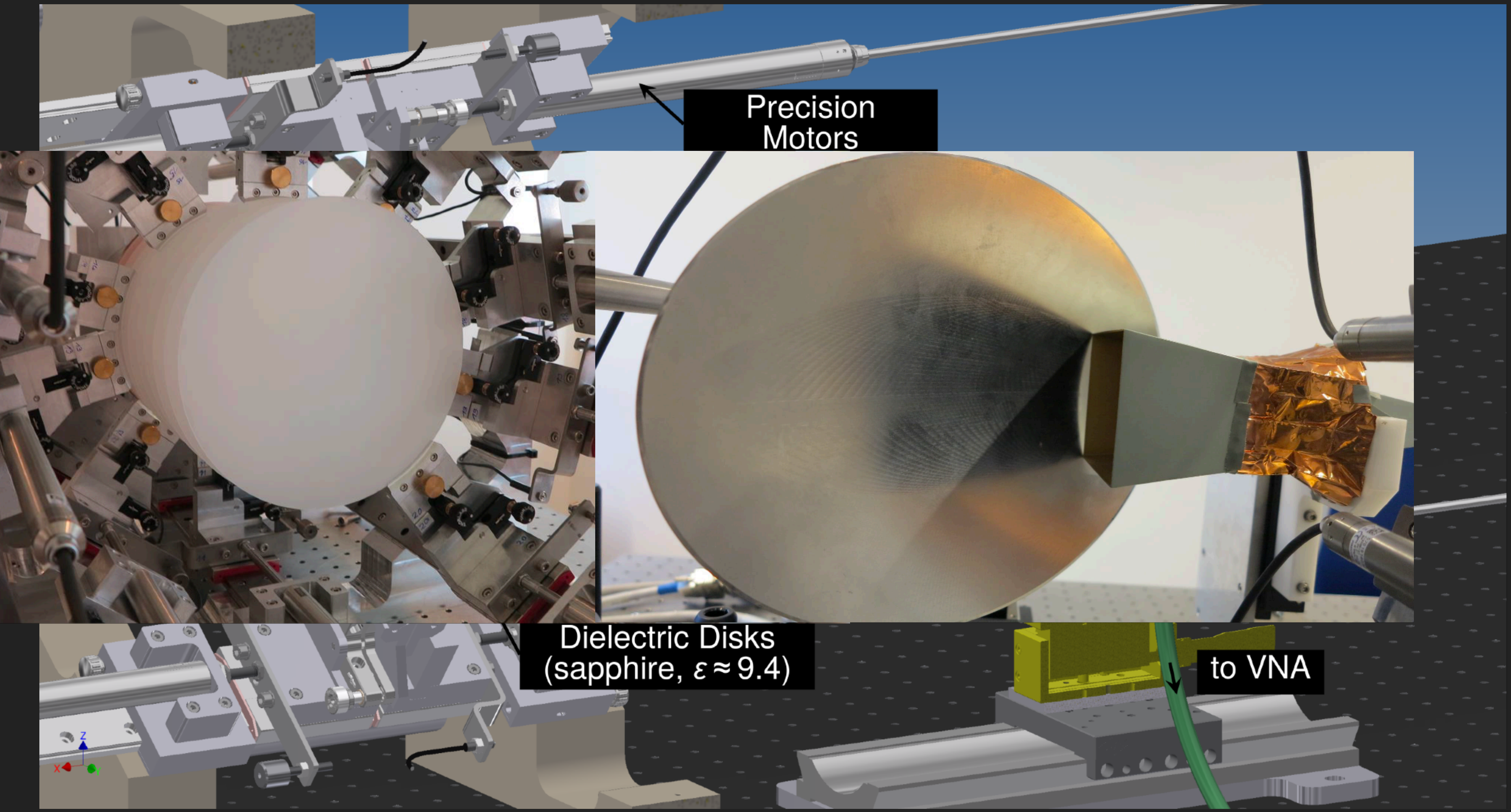


20 discs, 1 mm-thick, $\epsilon = 25$

- ***Group delay*** $\frac{\partial}{\partial\nu}\arg\left(\mathscr{R}\right)$ maps out the resonances within the booster
  - Near frequencies that experience a large number of internal reflections, the phase of the reflected radiation changes rapidly.

PROOF-OF-PRINCIPLE SETUP

J. Egge, S. Knirck, *et. al.* arXiv:2001.04363



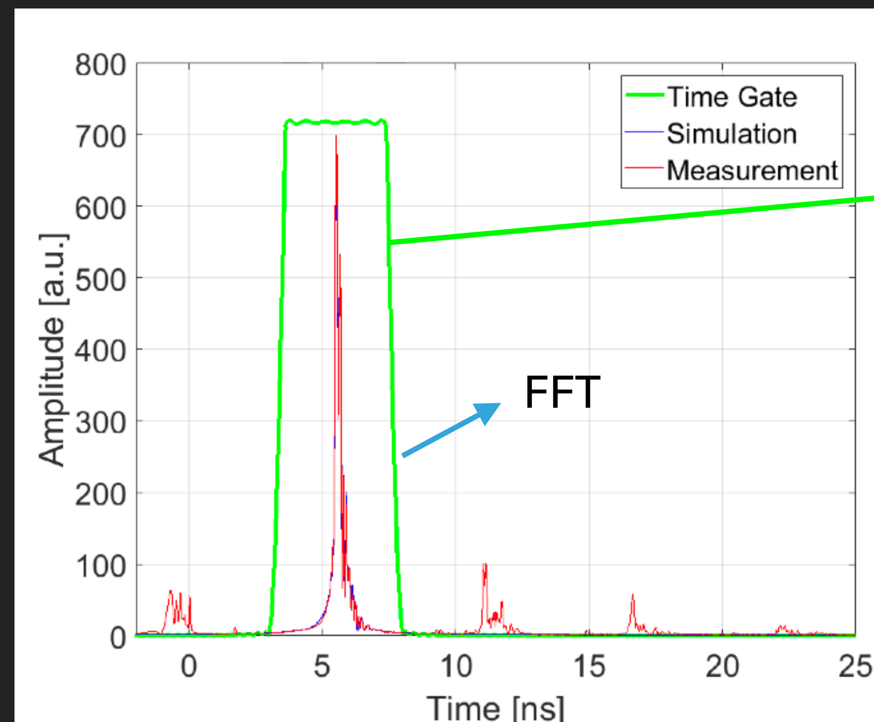
ANTENNA EFFECTS

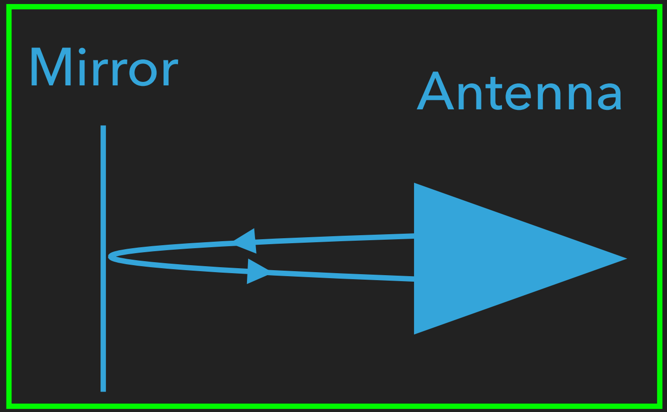
- Antenna-mirror efficiency

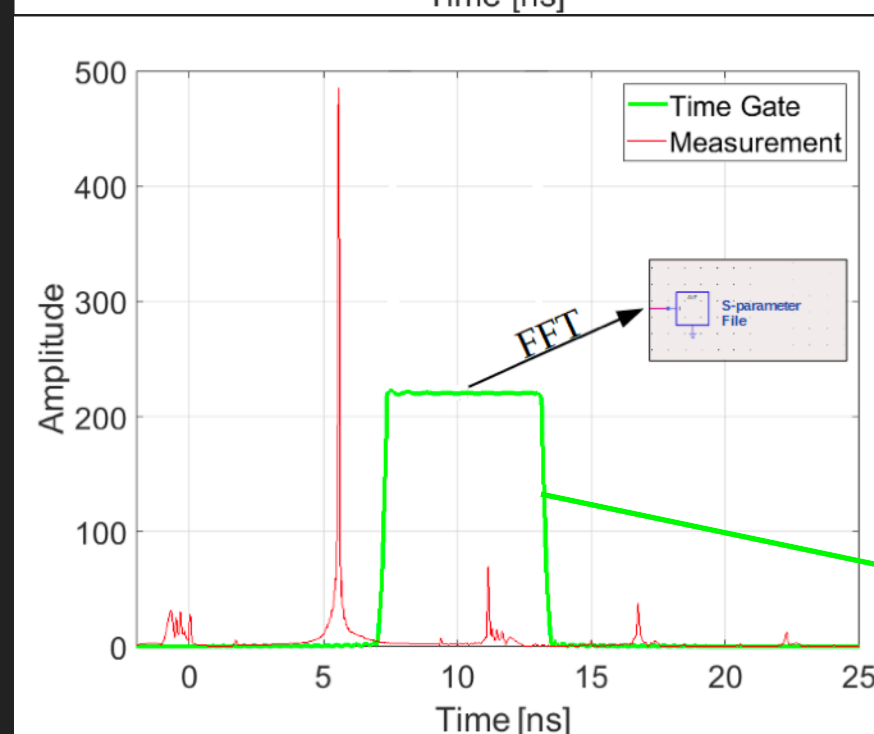
Assumption: adding discs does not significantly alter the beam shape

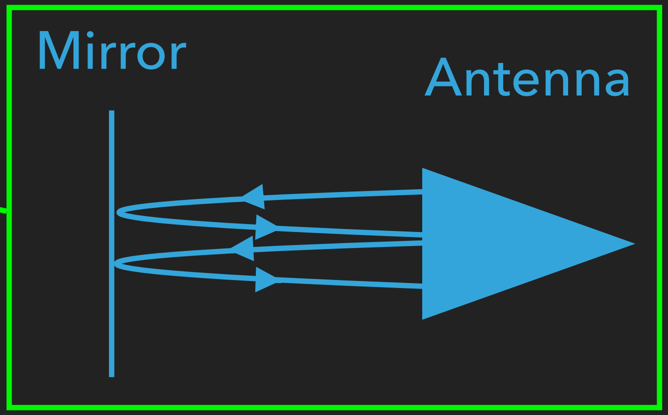
- Impedance mismatch between the antenna and free space
  - Included in simulation

Reflectivity of the antenna-mirror system in time domain





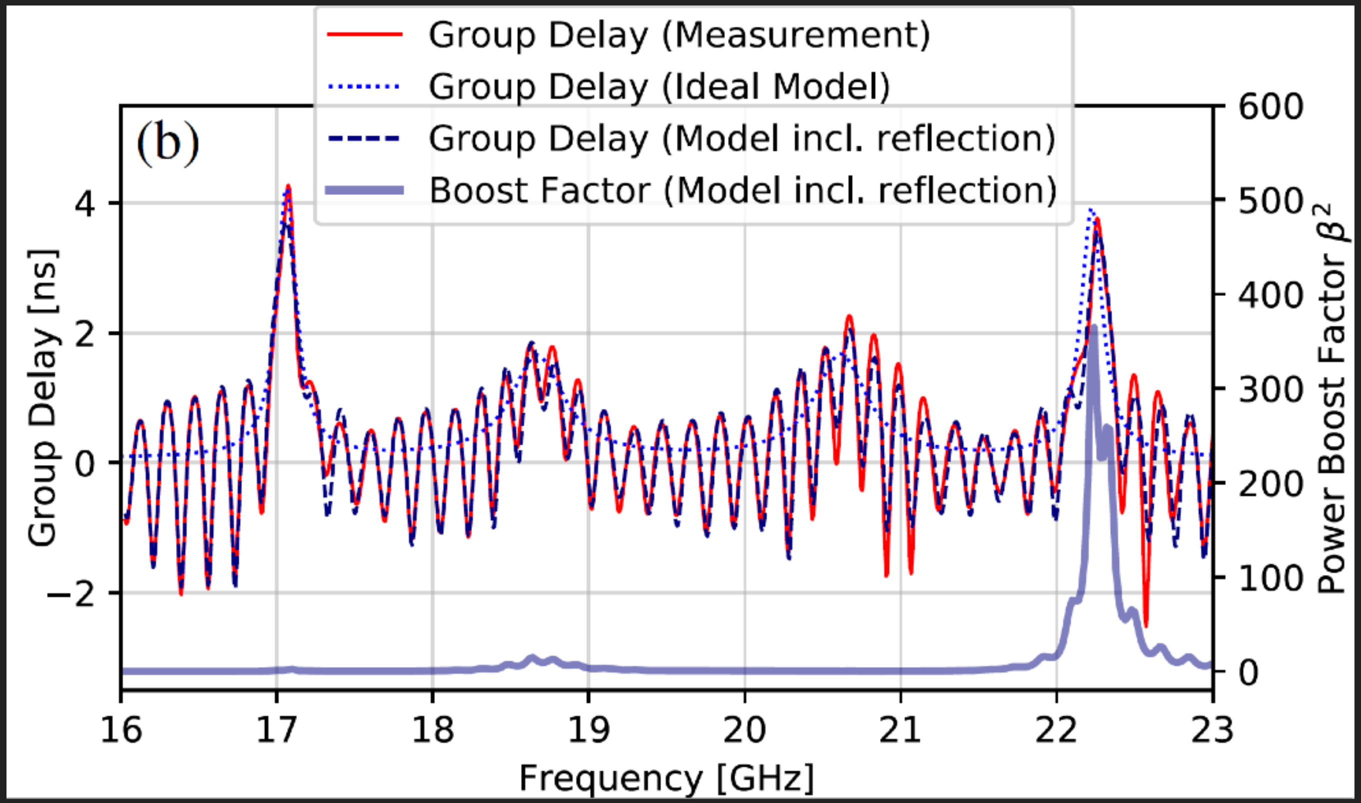




More sophisticated antenna model is needed

REFLECTIVITY MEASUREMENT AND FREQUENCY TUNING

Proof-of-principle setup with 4 discs

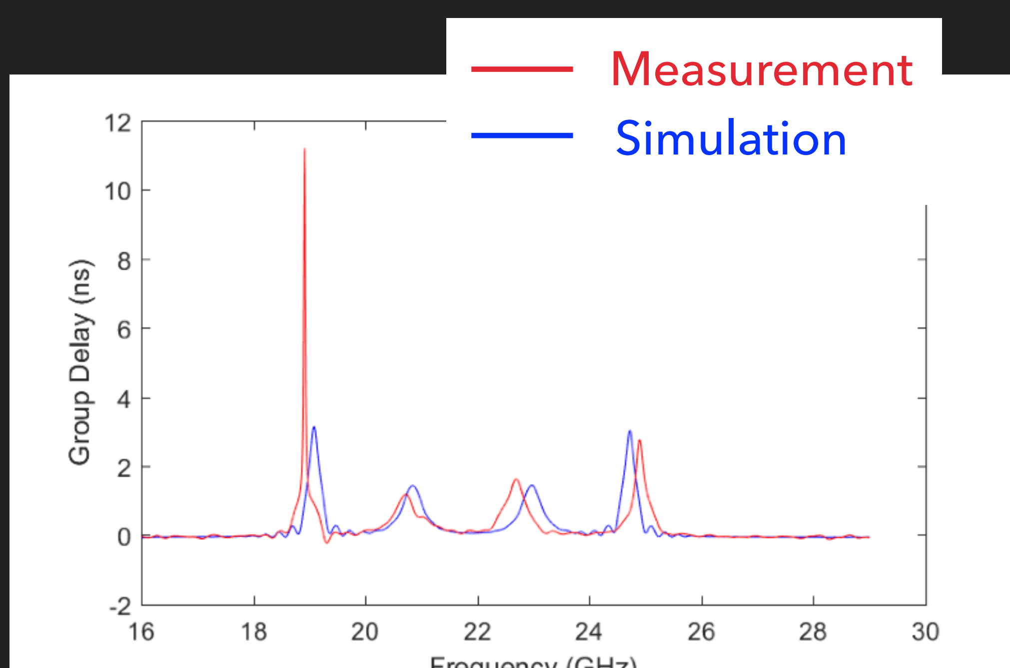


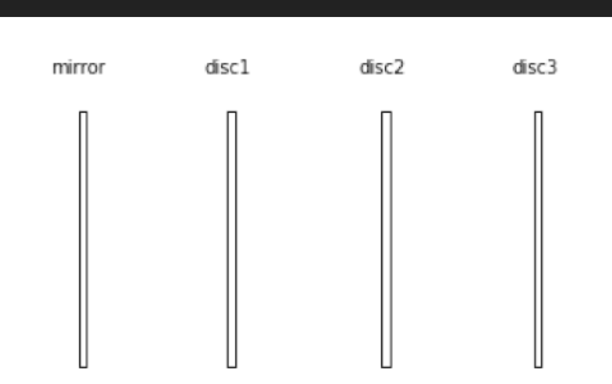
- 1D model is used
- Ripples due to the impedance mismatch at antenna aperture

- Challenges for frequency tuning
  - Absolute disc positions are not known
  - Key booster parameters such as the dielectric constant are difficult to measure precisely
  - Perfect simulation does not exist
- Theses issues can be mitigated by a ***measurement-based tuning procedure***

DISC TUNING PROCEDURE

1. Adjust the disc spacings in the **simulation** to obtain the desired boost factor
   - Calculate the reflectivity, in particular the group delay, with the same configuration with calibrated antenna reflections included
2. Adjust the disc positions in the setup until the measured group delay matches that given by the simulation



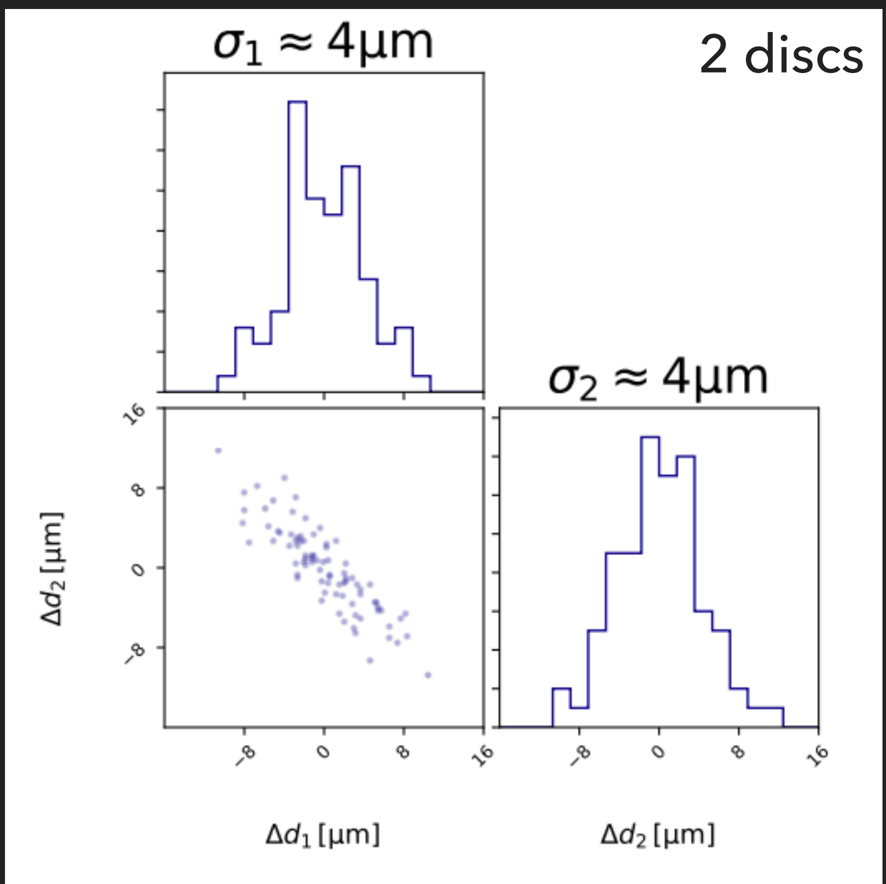


The movement is guided by an algorithm

Move discs in the setup

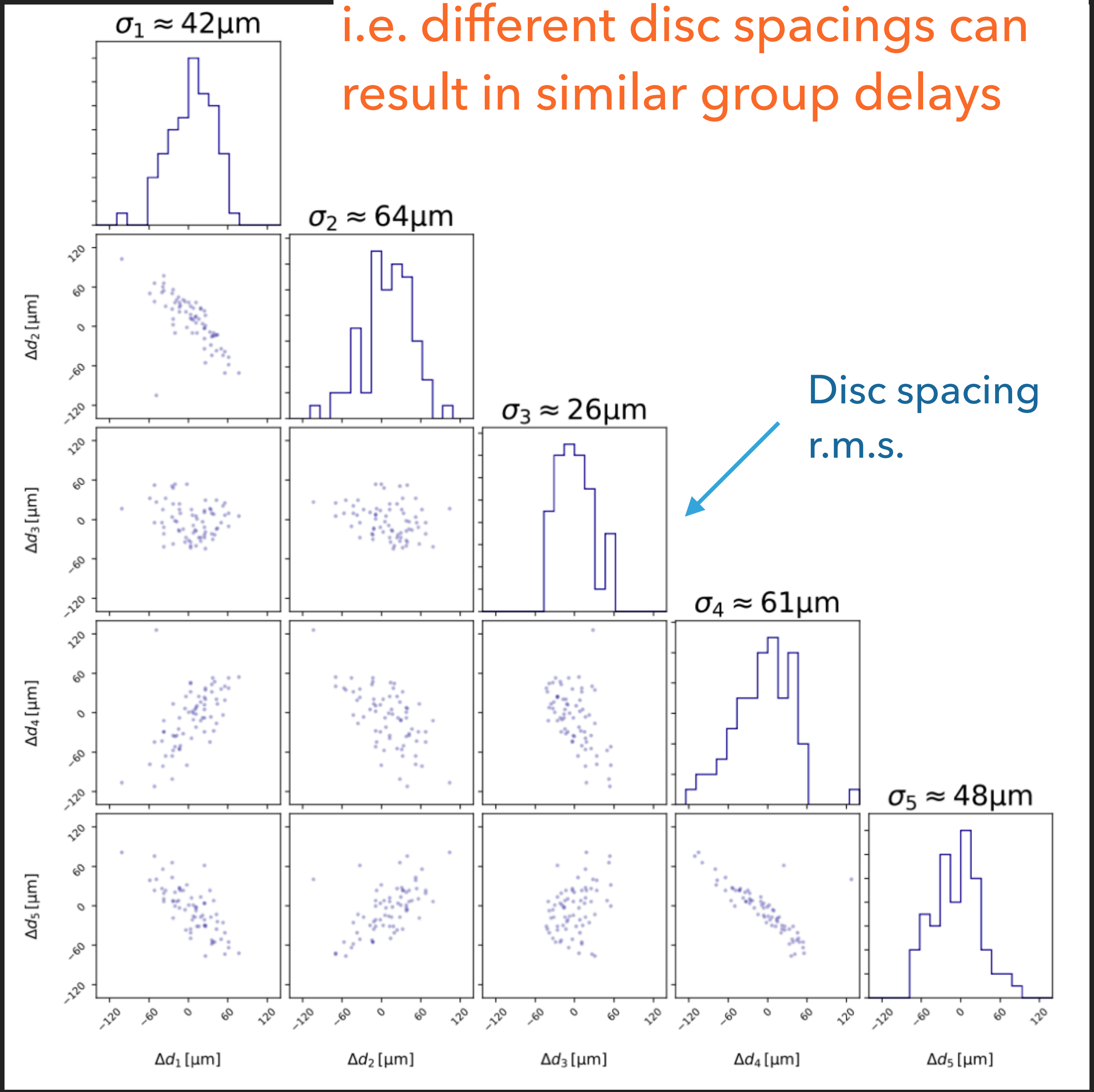
DISC TUNING RESULTS

- In order to quantify the disc spacing repeatability, repeat step 2 with different random starting positions ~200 times



5 discs

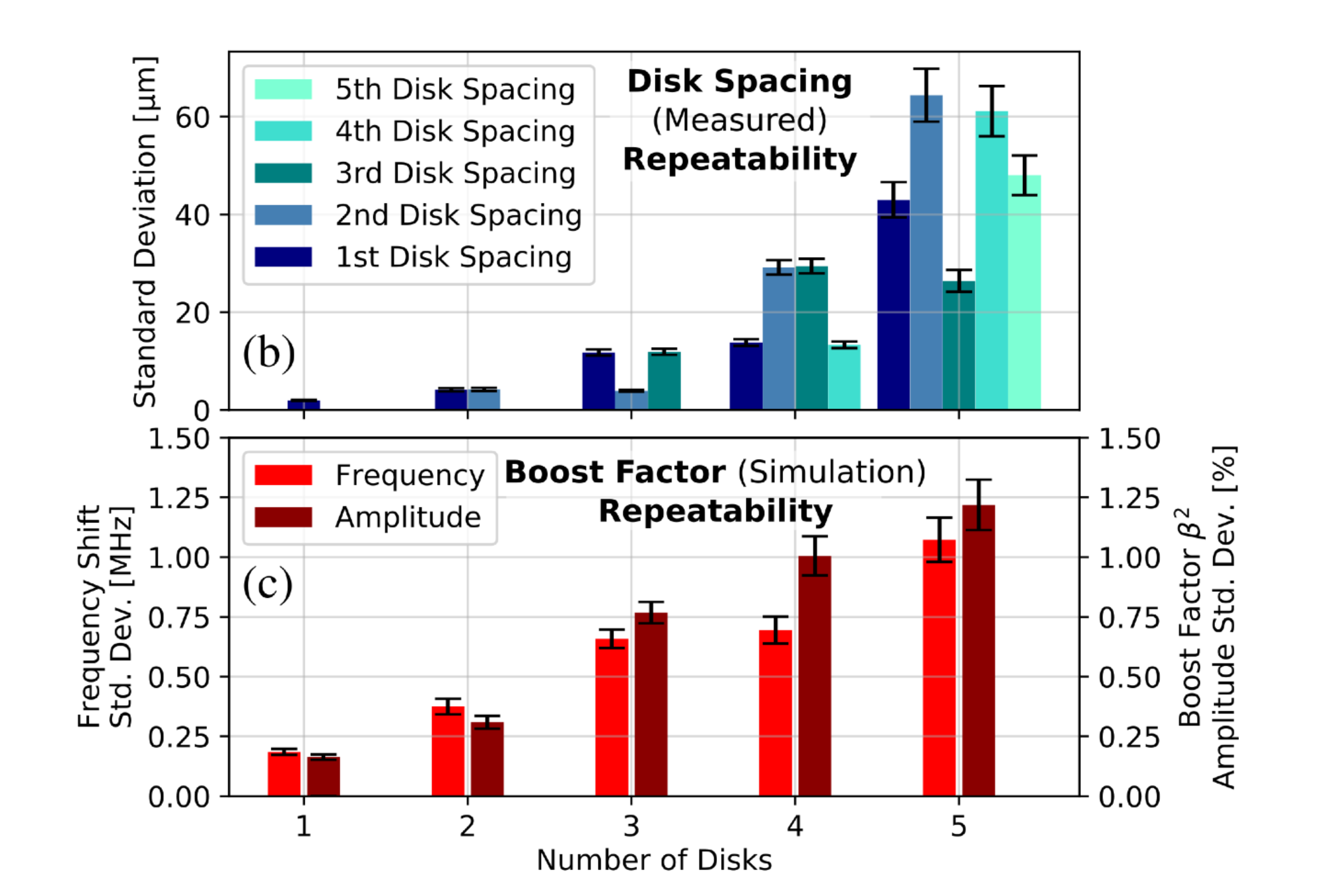
Disc spacings are degenerate, i.e. different disc spacings can result in similar group delays

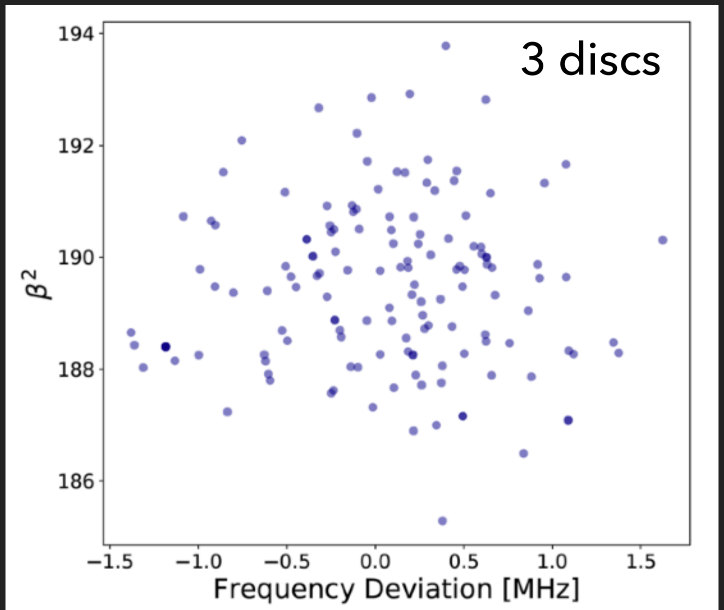


Disc spacing r.m.s.

UNCERTAINTY OF THE BOOST FACTOR DUE TO TUNING

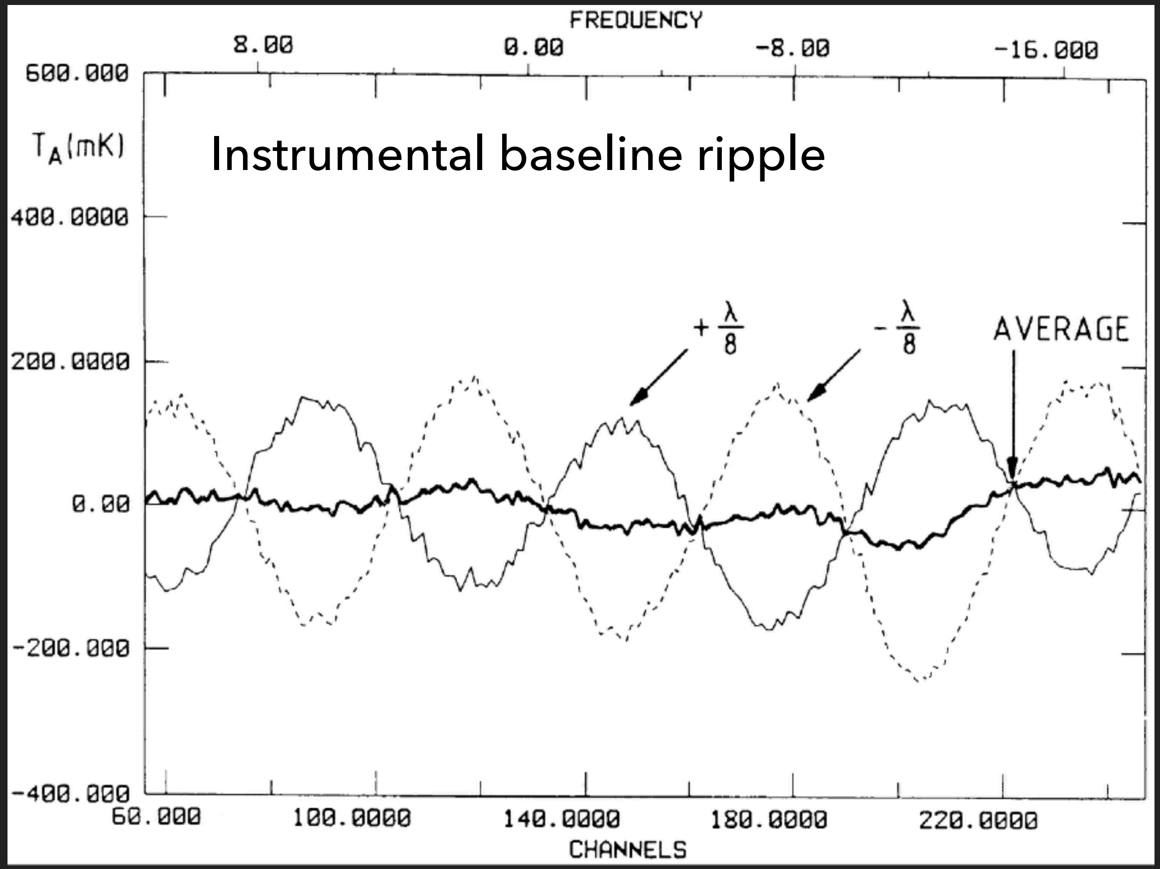
- Degenerate disc spacings → uncertainties on the boost factor





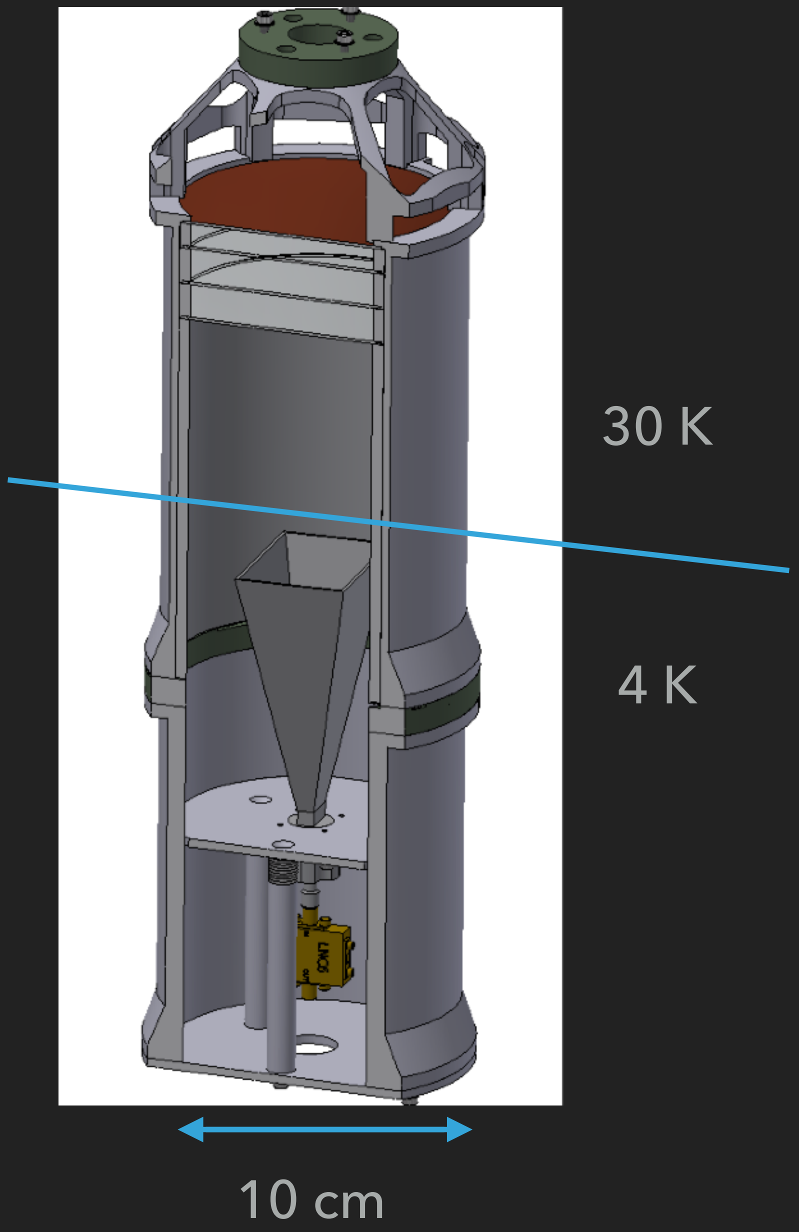
SYSTEM NOISE TEMPERATURE

- $\text{SNR} = \frac{P_{sig}}{k_B T_{sys}} \sqrt{\frac{t_{scan}}{\Delta\nu}}$, where $T_{sys} = T_{rec} + T_{booster}$
- T_{rec} depends on receiver noise temperature and frequency



"*Tools of Radio Astronomy*", T.L. Wilson, K. Rohlfs, S. Hüttermeister, Fifth edition

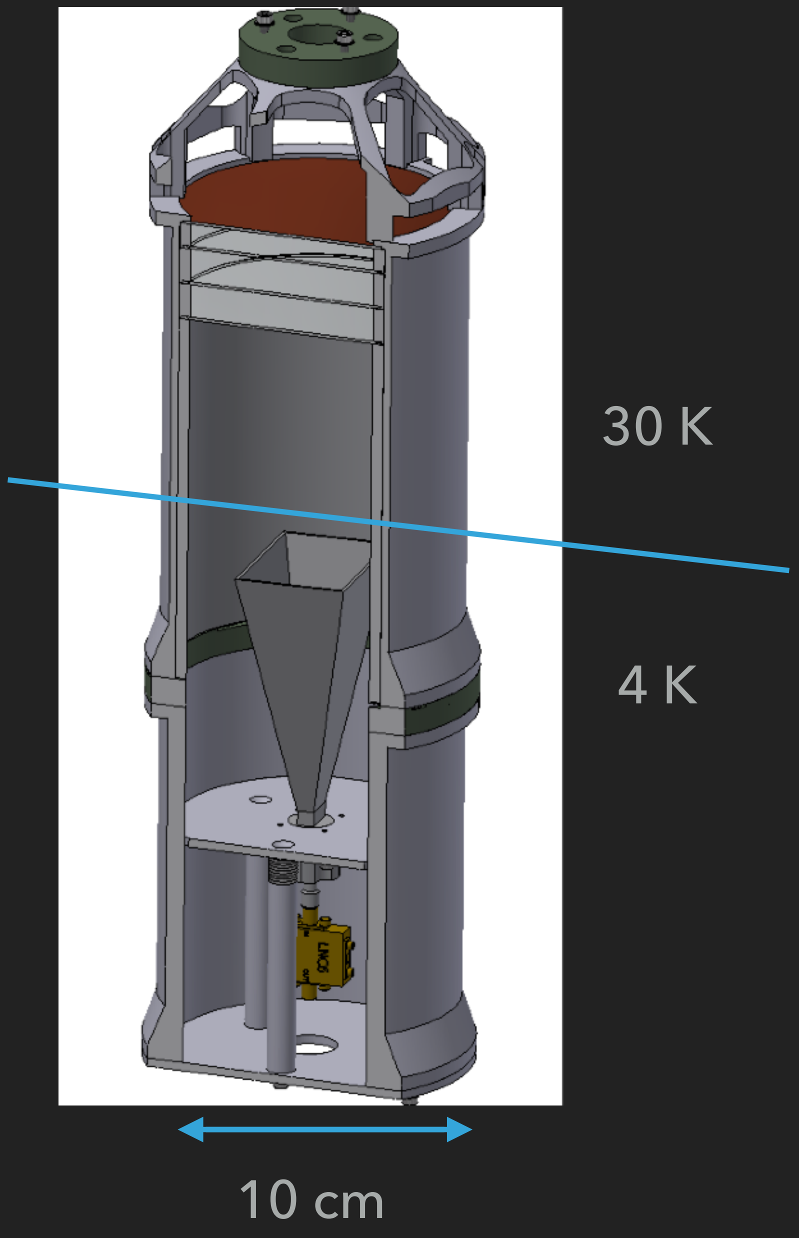
Cold measurement of system noise temperature ongoing



SYSTEM NOISE TEMPERATURE

- SNR $= \frac{P_{sig}}{k_B T_{sys}} \sqrt{\frac{t_{scan}}{\Delta\nu}}$, where $T_{sys} = T_{rec} + T_{booster}$
- T_{rec} depends on receiver noise temperature and frequency
- Kirchhoff theorem: $T_{booster} = \epsilon \cdot T_{physical}$
  - Emissivity $\epsilon = 0$ for perfect electrical conductor, $\epsilon = 1$ for perfect blackbody
  - ϵ can be reduced by choosing low $\tan\delta$ loss material for the discs and low loss metal for the mirror
  - Booster ϵ has frequency dependence

Cold measurement of system noise temperature ongoing

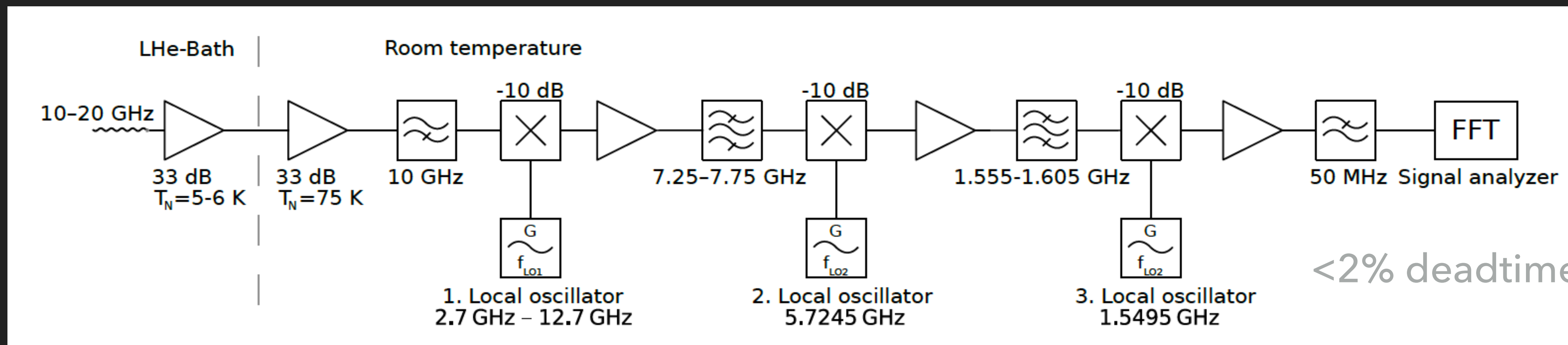


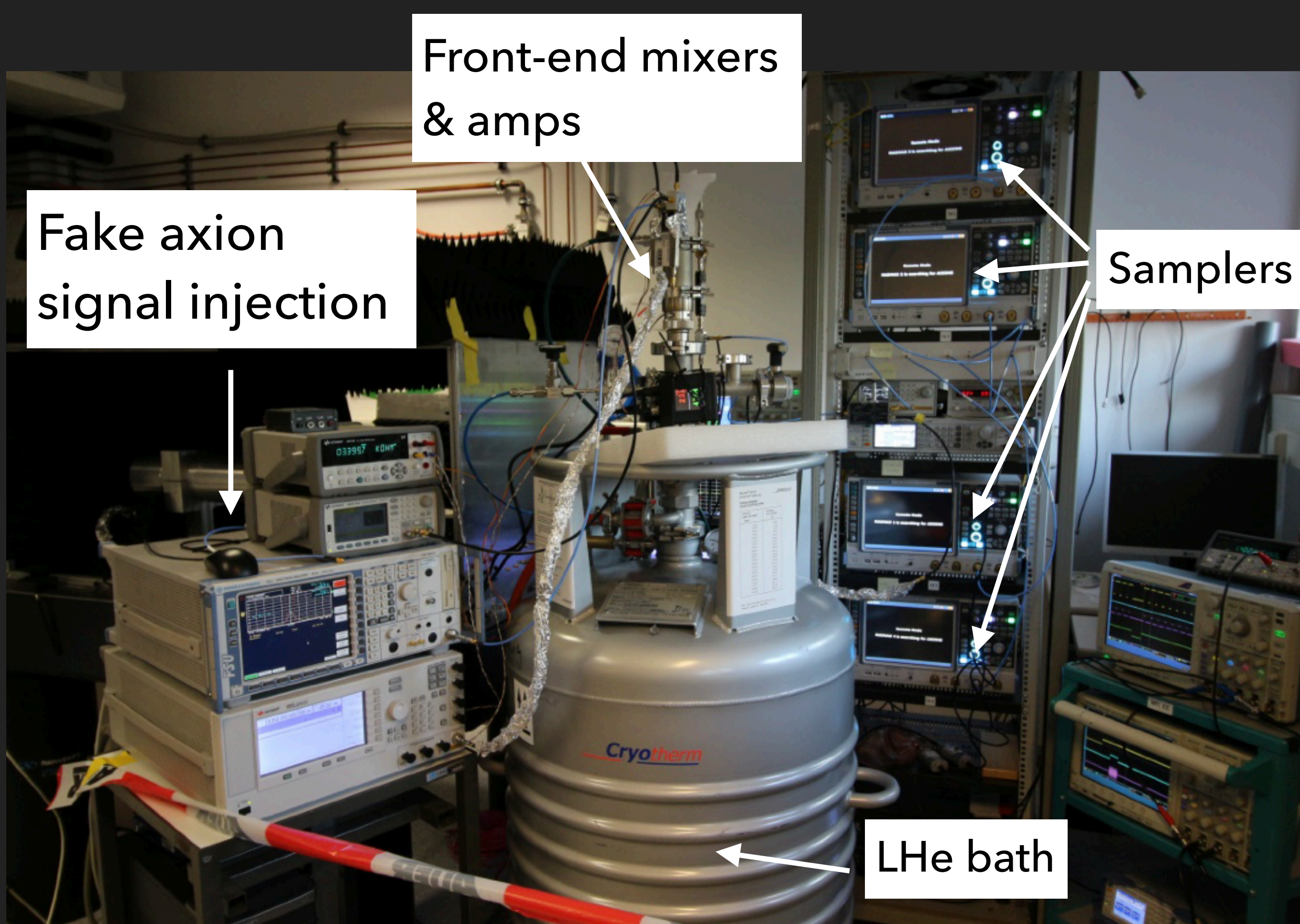
RECEIVER CHAIN

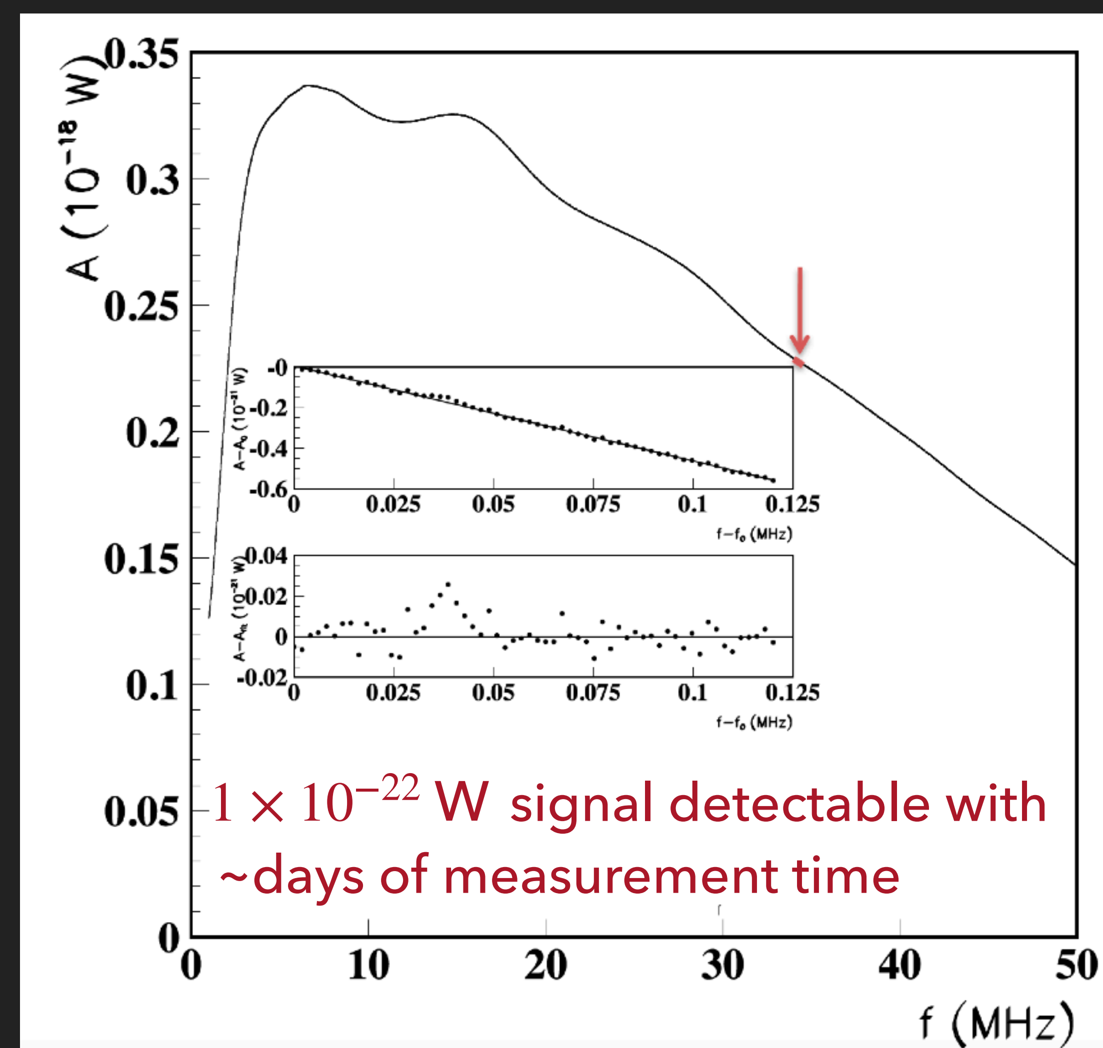
- Below 40 GHz linear amplifier most suitable

HEMT amplifier from Low Noise Factory

$T_{rec} = 5 - 6$ K





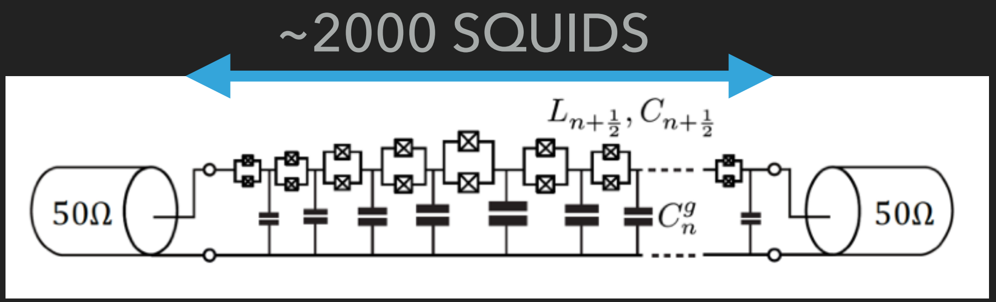


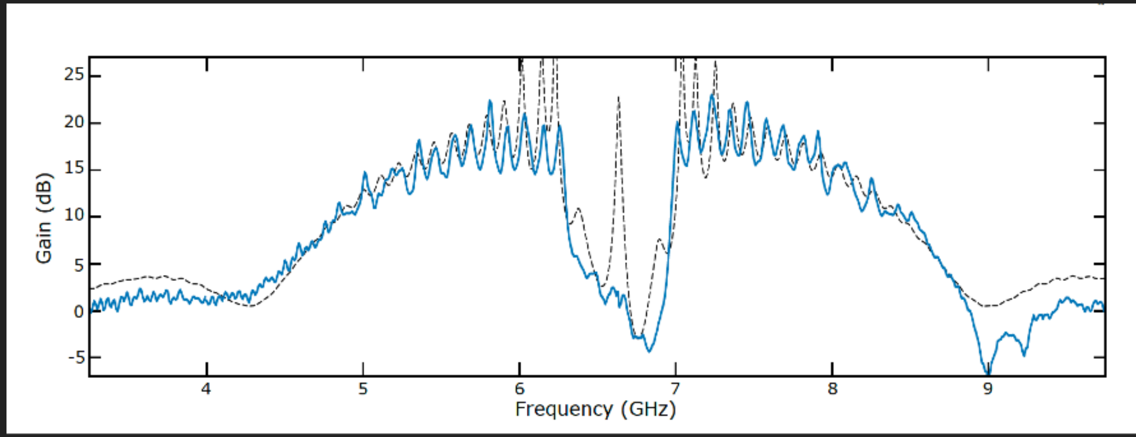
TRAVELING WAVE AMPLIFIER

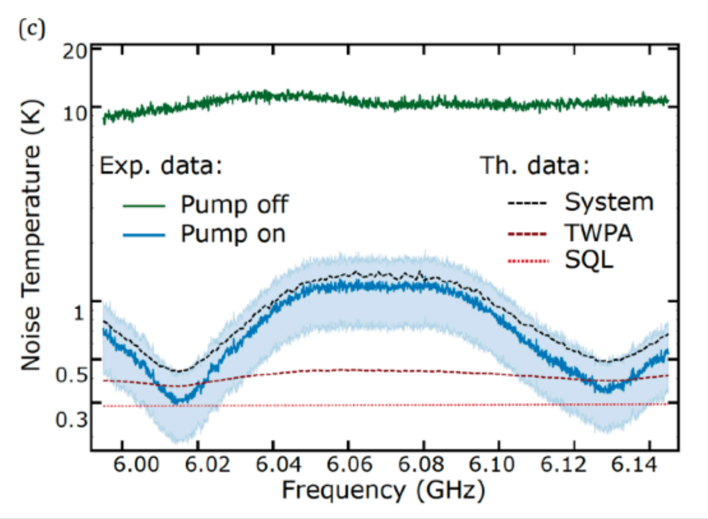
- Quantum limit of coherent detectors:

$$k_B T_{rec} = h\nu N_A, \text{ where } N_A \geq \frac{1}{2}$$

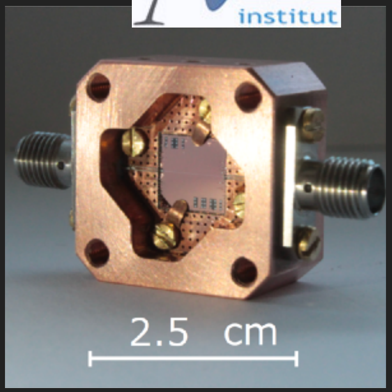
- Broadband traveling wave JPA could potentially halve system noise temperature for MADMAX
    - Josephson junction nonlinear inductance
    - GHz bandwidth
    - High 1-dB compression point
    - No need to tune frequently
    - 10-40 GHz possible with the current fabrication technology
- Testing of ~12 GHz device this summer







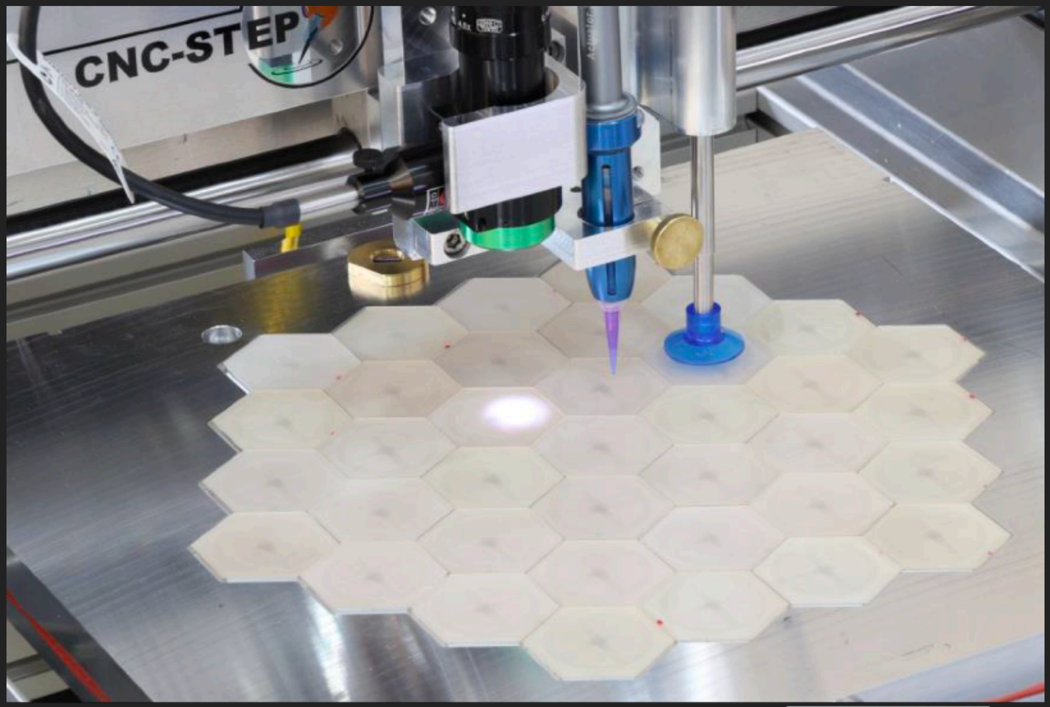
NÉEL institut



L. Planat, *et. al. arXiv:1907.10158*

DIELECTRIC DISC

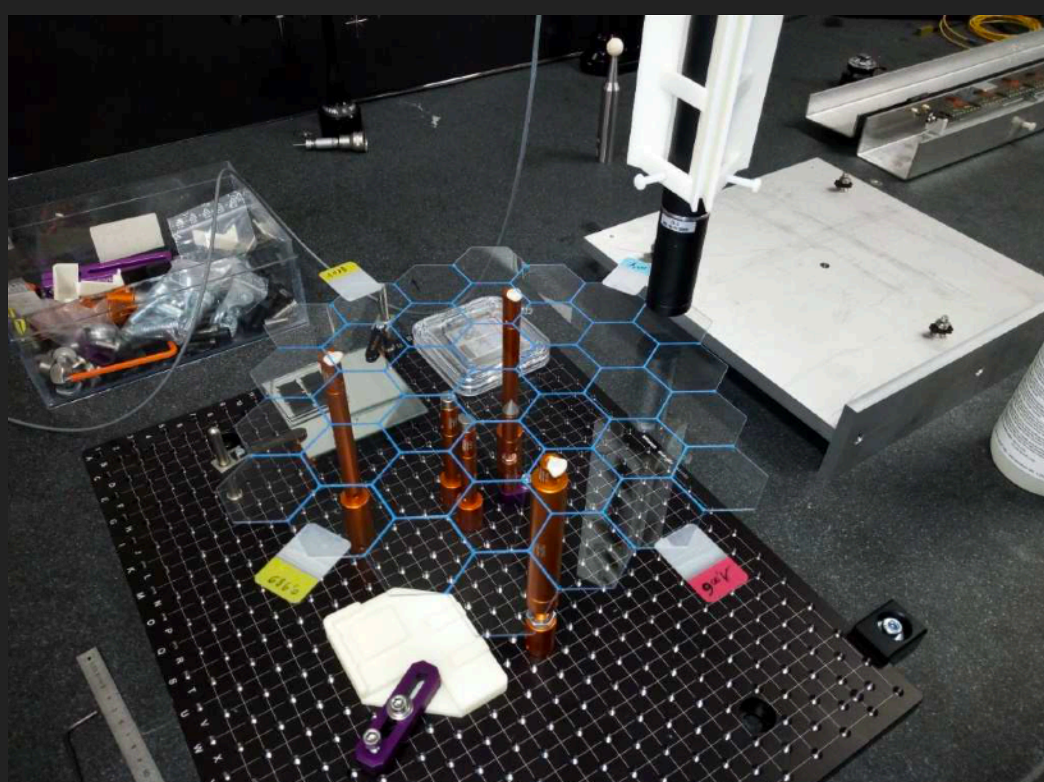
- Discs are 1.25 m in diameter and 1mm in thickness
- Candidate materials:
  - $LaAlO_3$
    - $\epsilon \approx 24$
    - $\tan\delta =$ a few $\times 10^{-5}$
    - Only grown on 3" wafer; tiling needed for 1 m^2 discs
  - Sapphire
    - $\epsilon \approx 9$ (C-cut)
    - $\tan\delta \approx 10^{-5}$
    - Up to 20"
- Other possible candidate materials are being explored



First tiled $LaAlO_3$ disc ($\phi = 30$ cm)

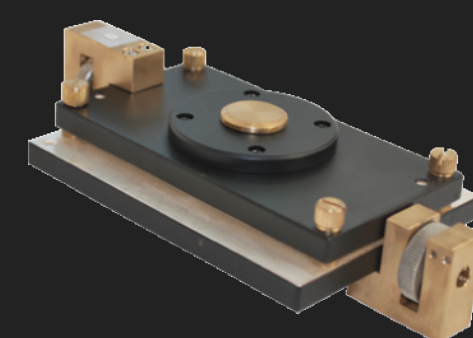
DISC CHARACTERIZATION

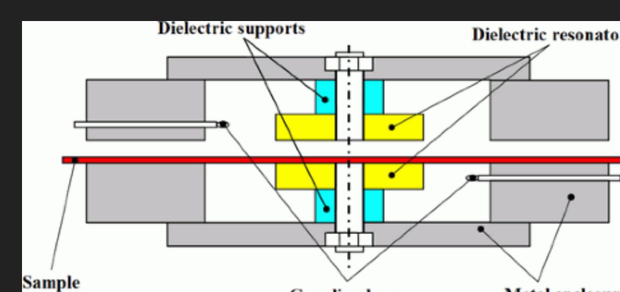
- Tiled disc surface is measured
  - Feedback to tiling process



CPPM Marseille

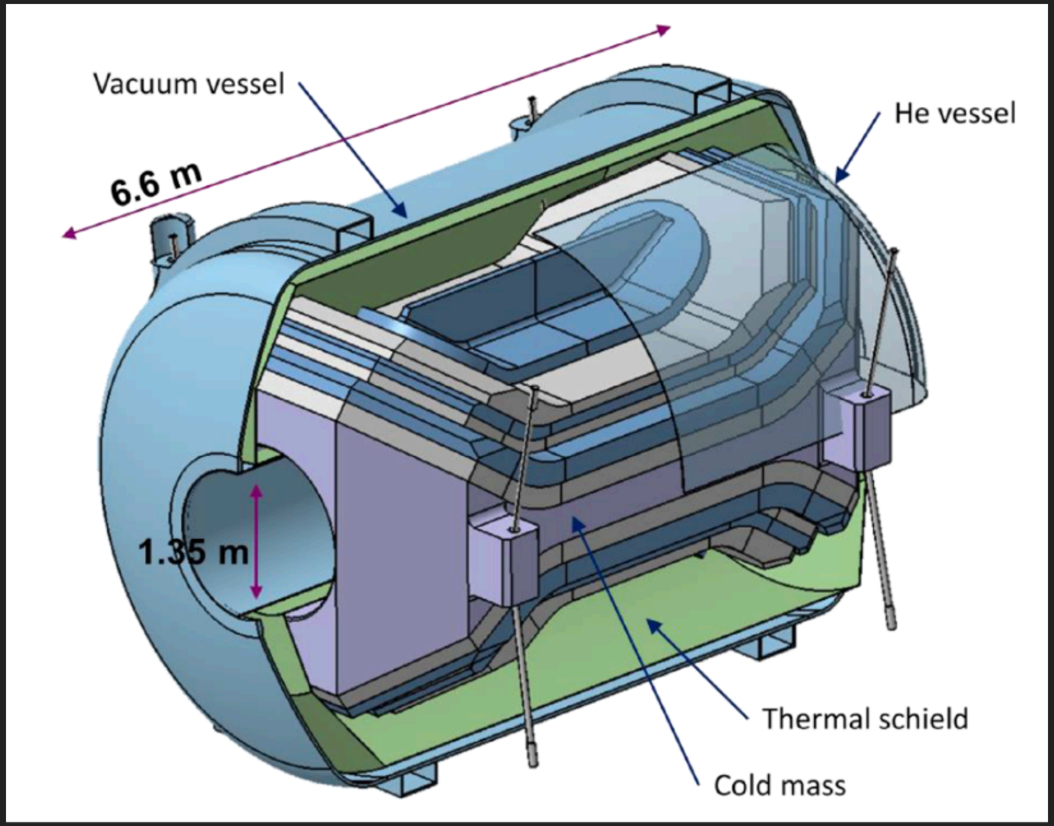
- Literature values for $LaAlO_3$ not available at 10 to 100 GHz and/or not down to 4 K
- Highly dependent on manufacturing process

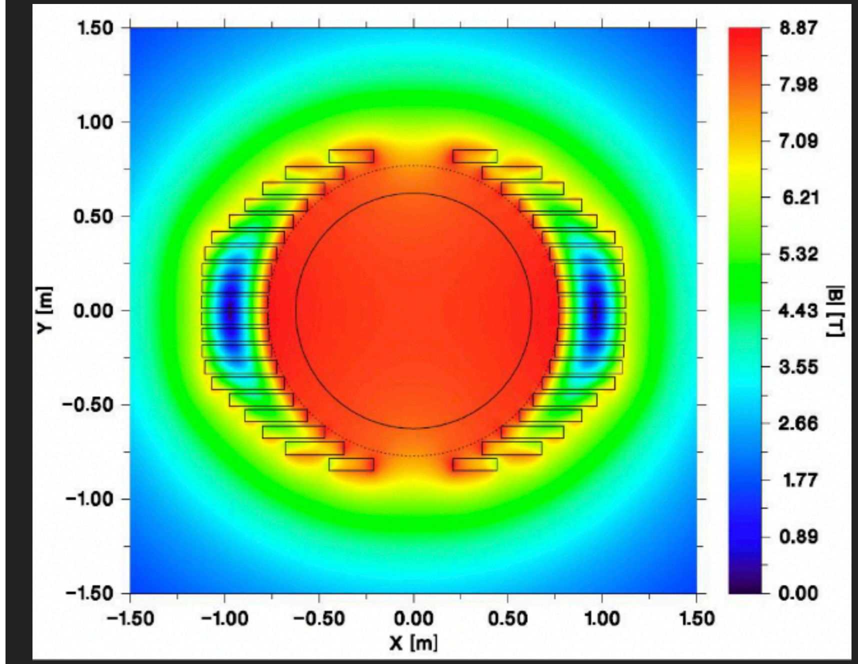




ϵ and $\tan\delta$ measurements @ UHH

MAGNET DESIGN STUDIES

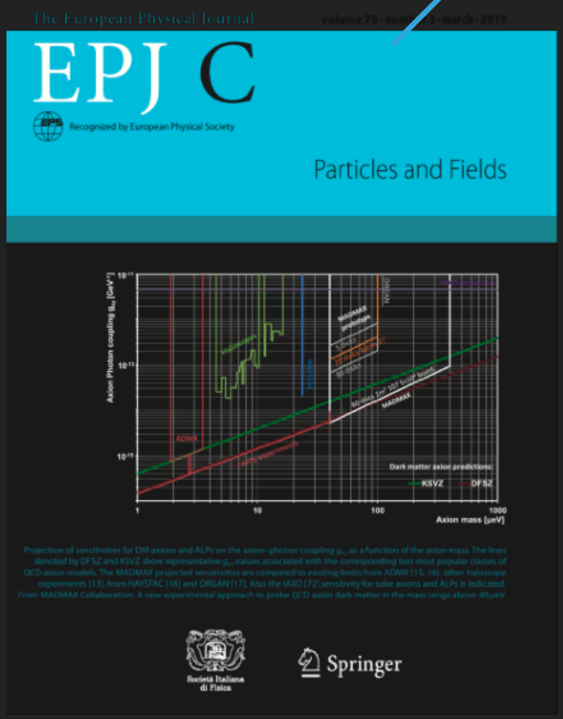




- $B^2 \cdot A \sim 100\ \mathrm{T}^2\mathrm{m}^2$ magnet has never been built before
- Working with innovation partners and an expert committee
  - NbTi coil, 9 T field, 1.25 m^2 aperture, ~5% inhomogeneity, 480 MJ stored energy
- Conceptual design available since 2019; the first coil may be delivered by 2021; full magnet to be commissioned by 2025

TIMELINE OF MADMAX (with abundant optimism)

2017-2019	2019-2022	2022-2025	2025-2035
DESIGN	PROTOTYPING	DETECTOR CONSTRUCTION	DATA TAKING @ DESY



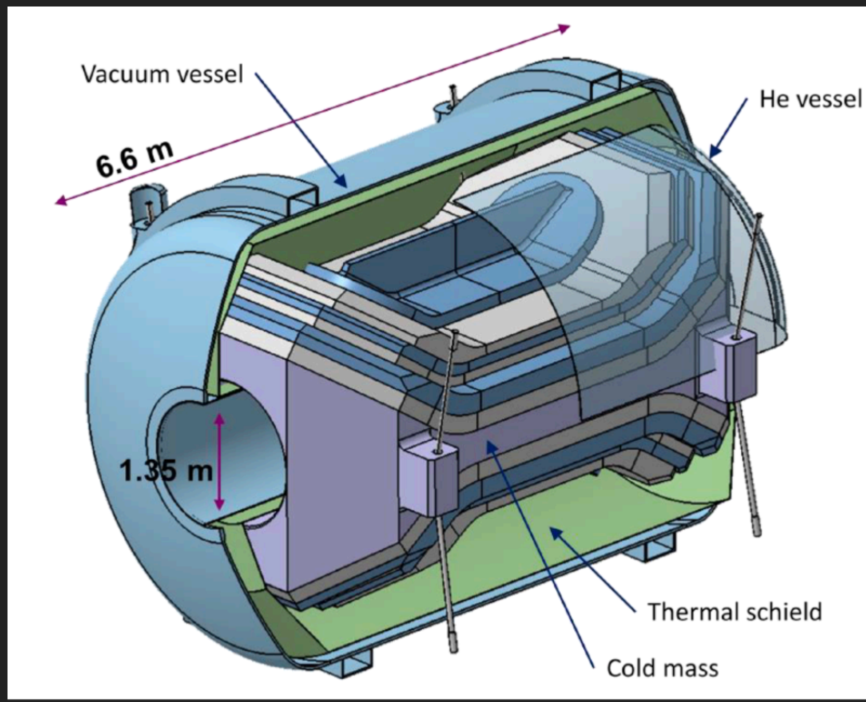
MADMAX white paper

Eur. Phys. J. C (2019) 79: 186

RF lab SHELL
@ UHH

MORPURGO magnet
@ CERN up to 1.6 T

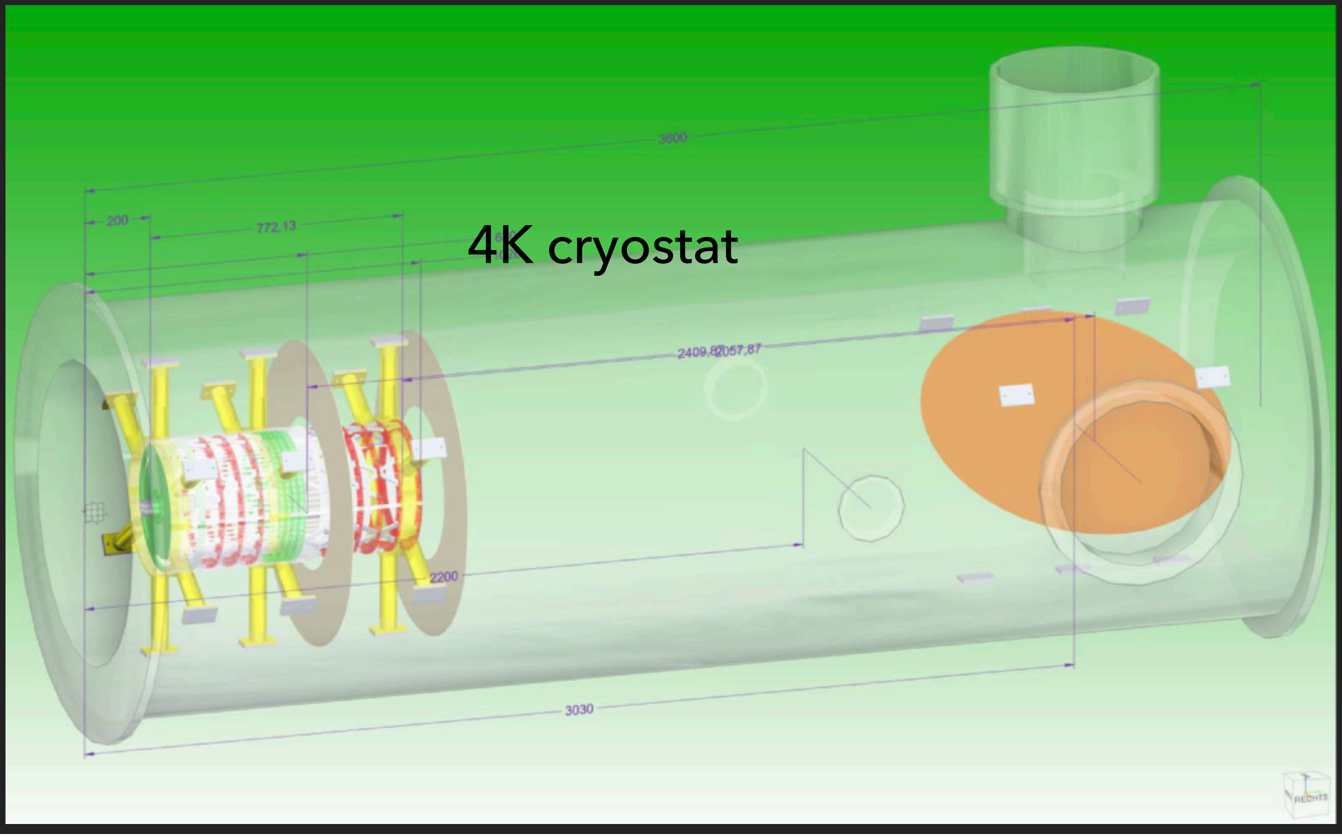
Prototype detector data taking

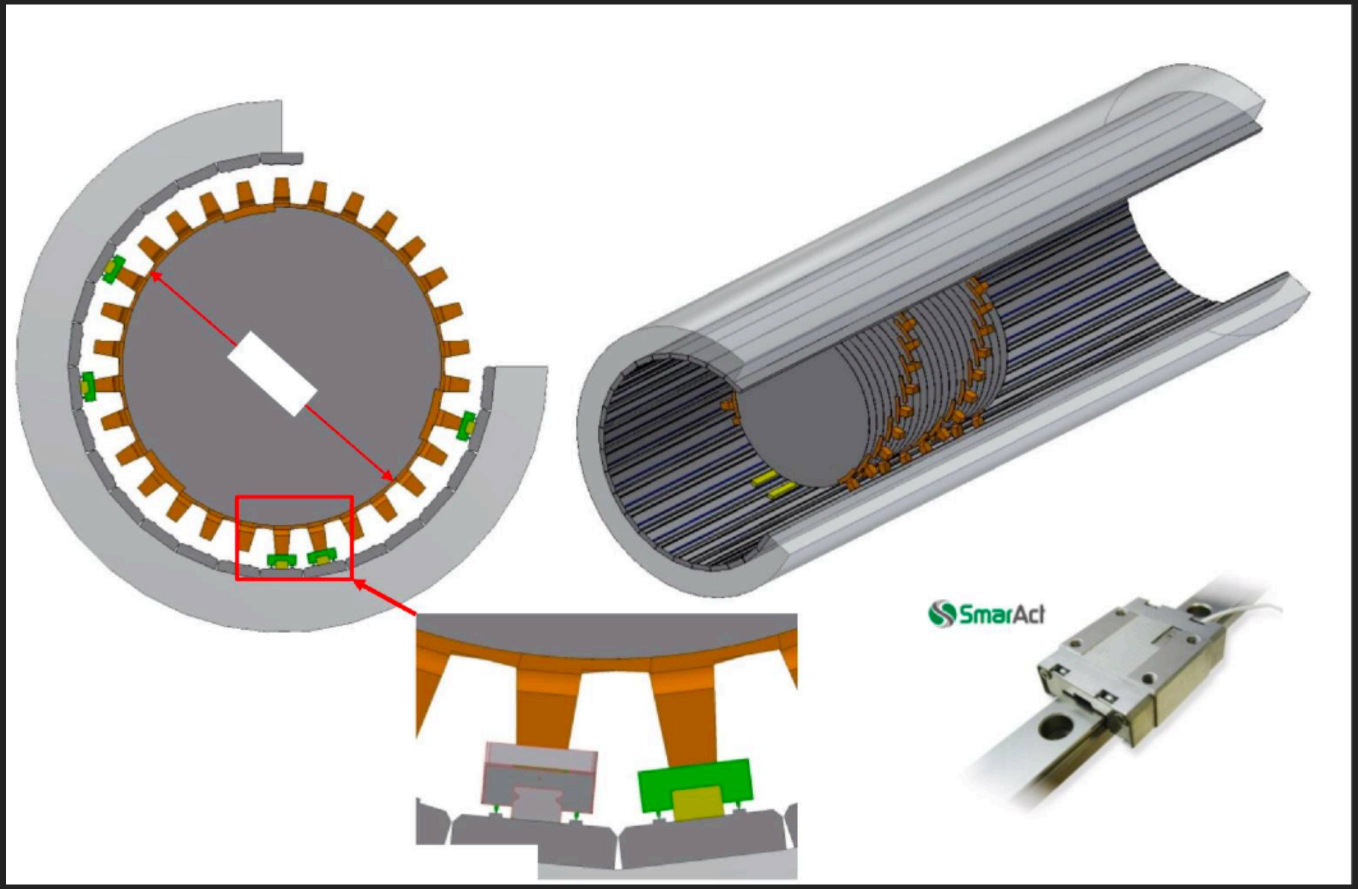


Full-size detector

PROTOTYPE

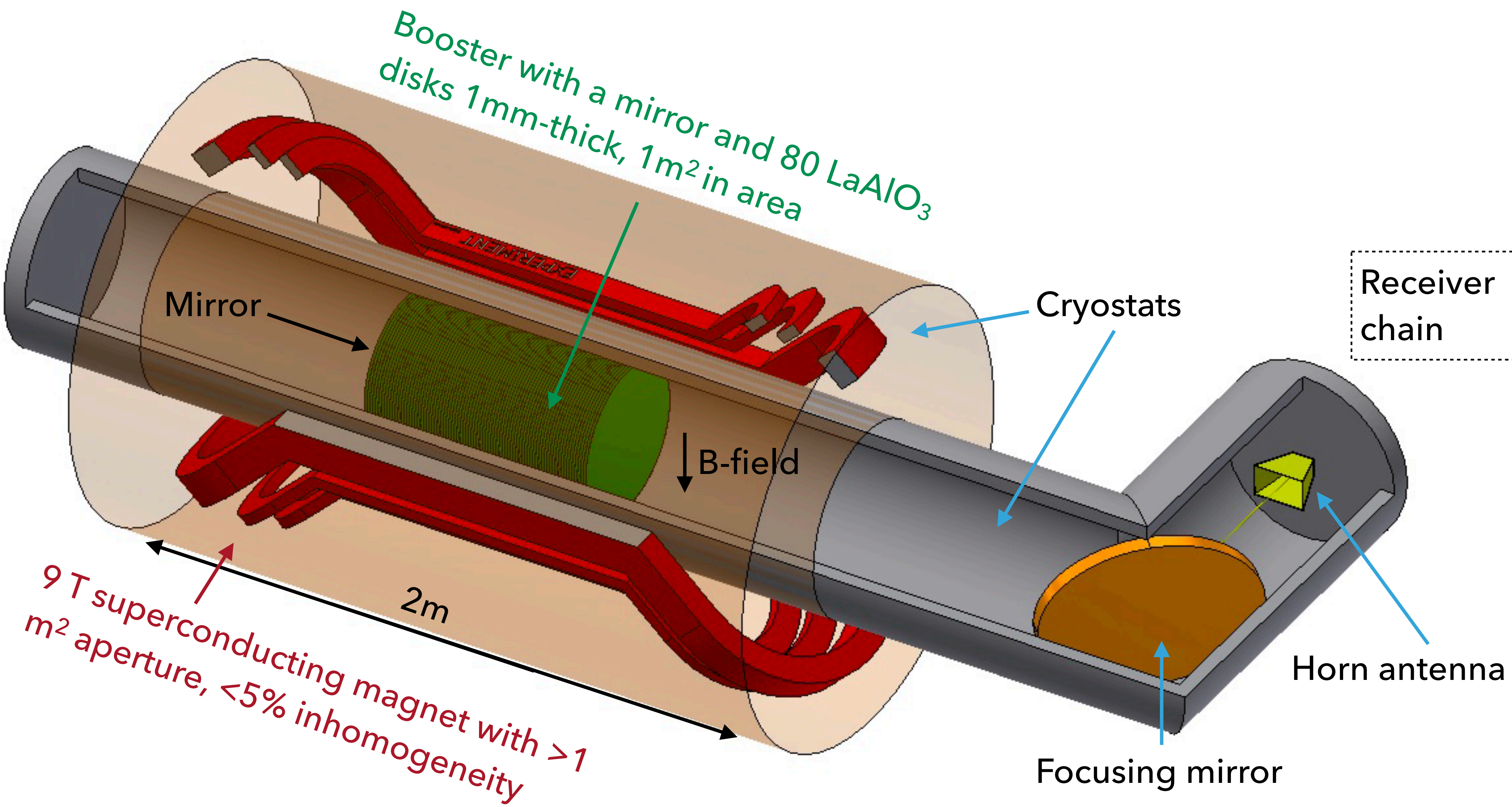
- Aim to construct and commission prototype booster by 2022
  - 20 $LaAlO_3$ discs with 30cm diameter; laser interferometer incorporated
  - Hammer out the mechanical design
  - Hidden photon/ALP search $\sim 80\ \mu$eV
- Development and testing of piezo motors are ongoing
  - 4 K, ~9 T, long travel range, 6 kg load bearing





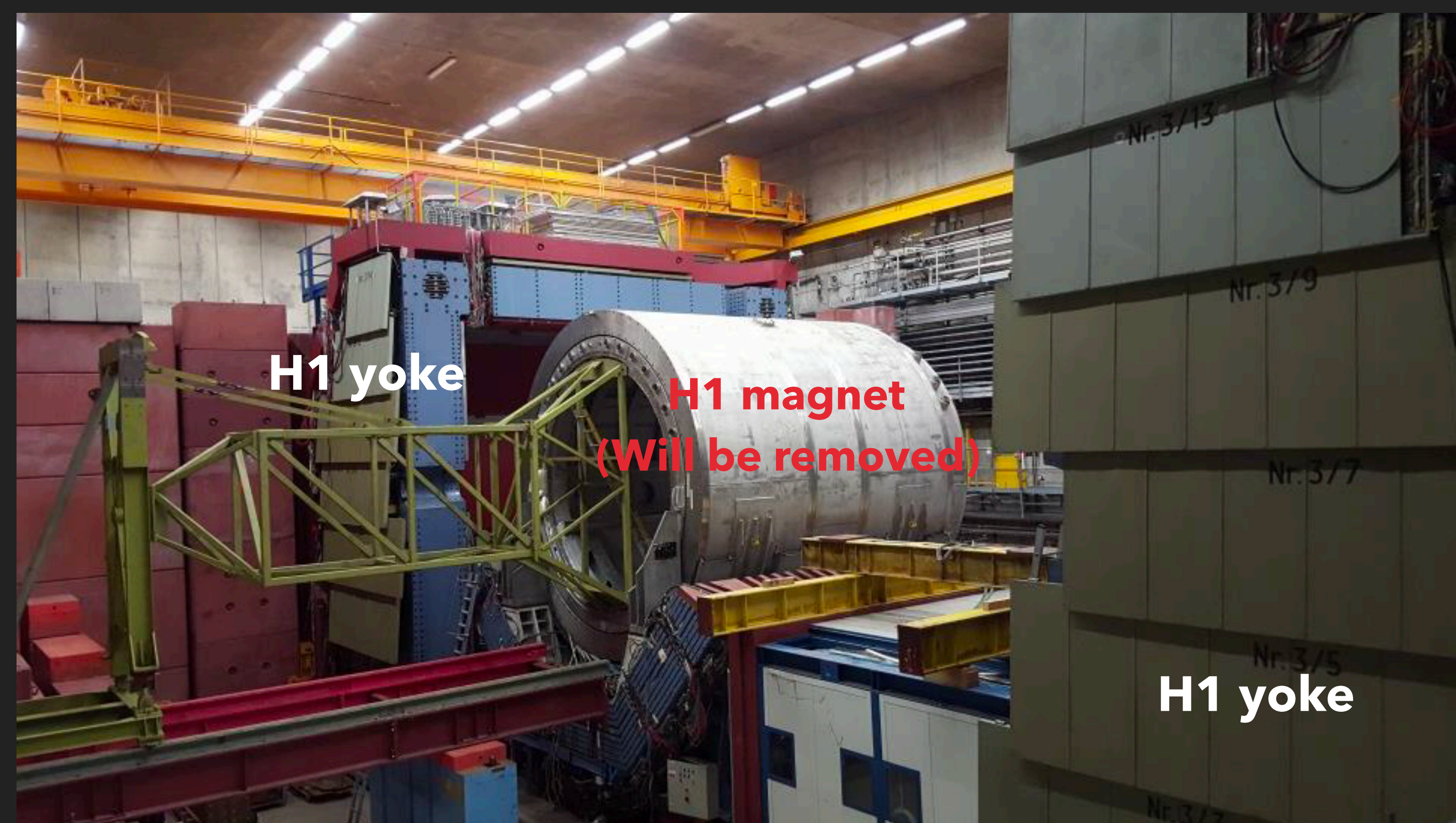
MADMAX BASELINE DESIGN

Full-scale detector

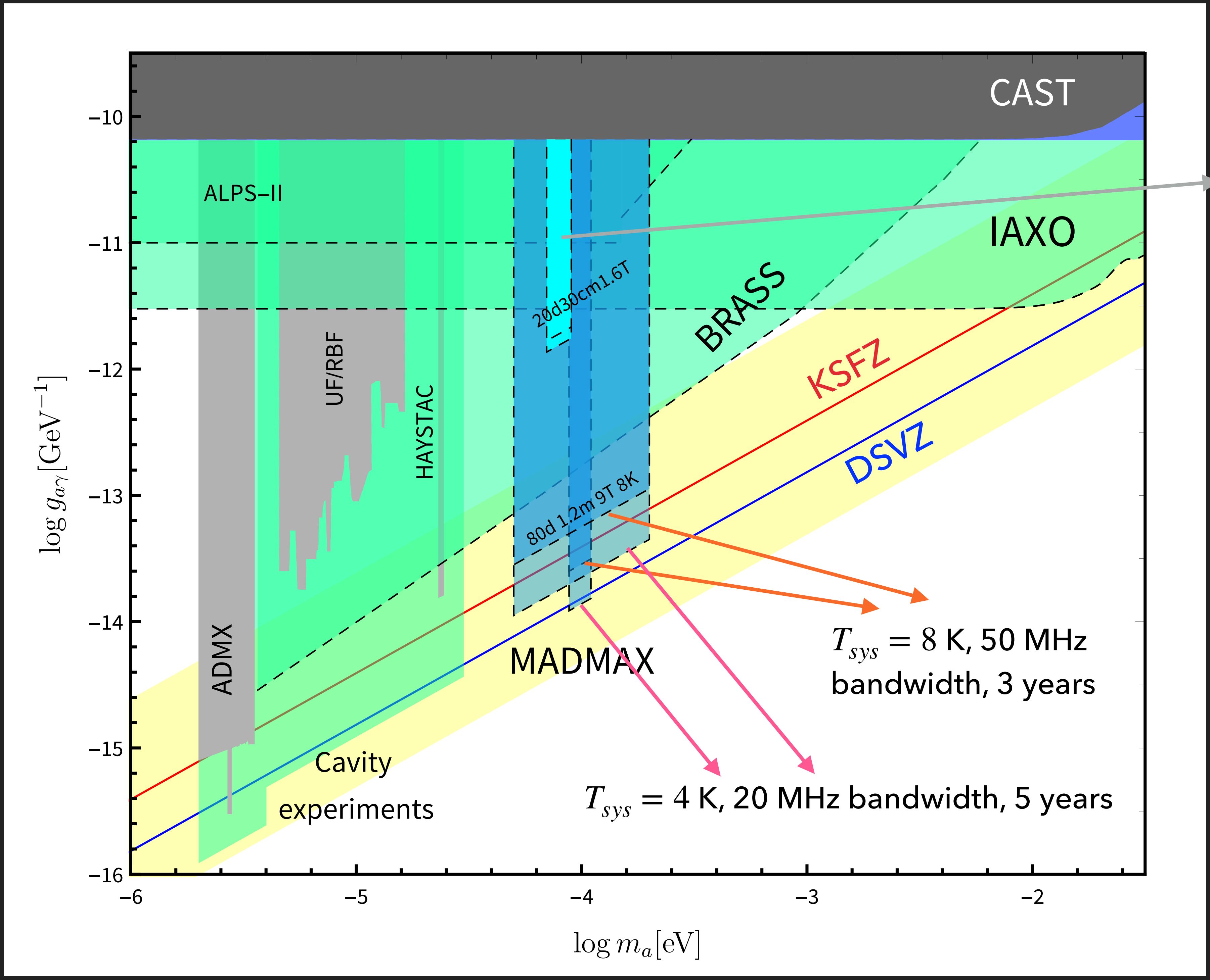


DESY SITE

- Final MADMAX detector will be located at HERA Hall North
- Make use of DESY infrastructure
- Reuse H1 yoke



MADMAX SENSITIVITY



Prototype detector
3 months

Assuming 50% of obtainable power from 1D simulation is received; 5σ detection level

SUMMARY AND FUTURE PROSPECT

- The MADMAX experiment aims to search for QCD axions in the form of local CDM in the well-motivated mass range of $40 \sim 400\ \mu$eV
  - Microwave signal at $10 \sim 100$ GHz
  - Novel dielectric haloscope to boost axion signal to a detectable level
  - Design R&D and simulation studies are on going
  - Aim for data-taking in 2025

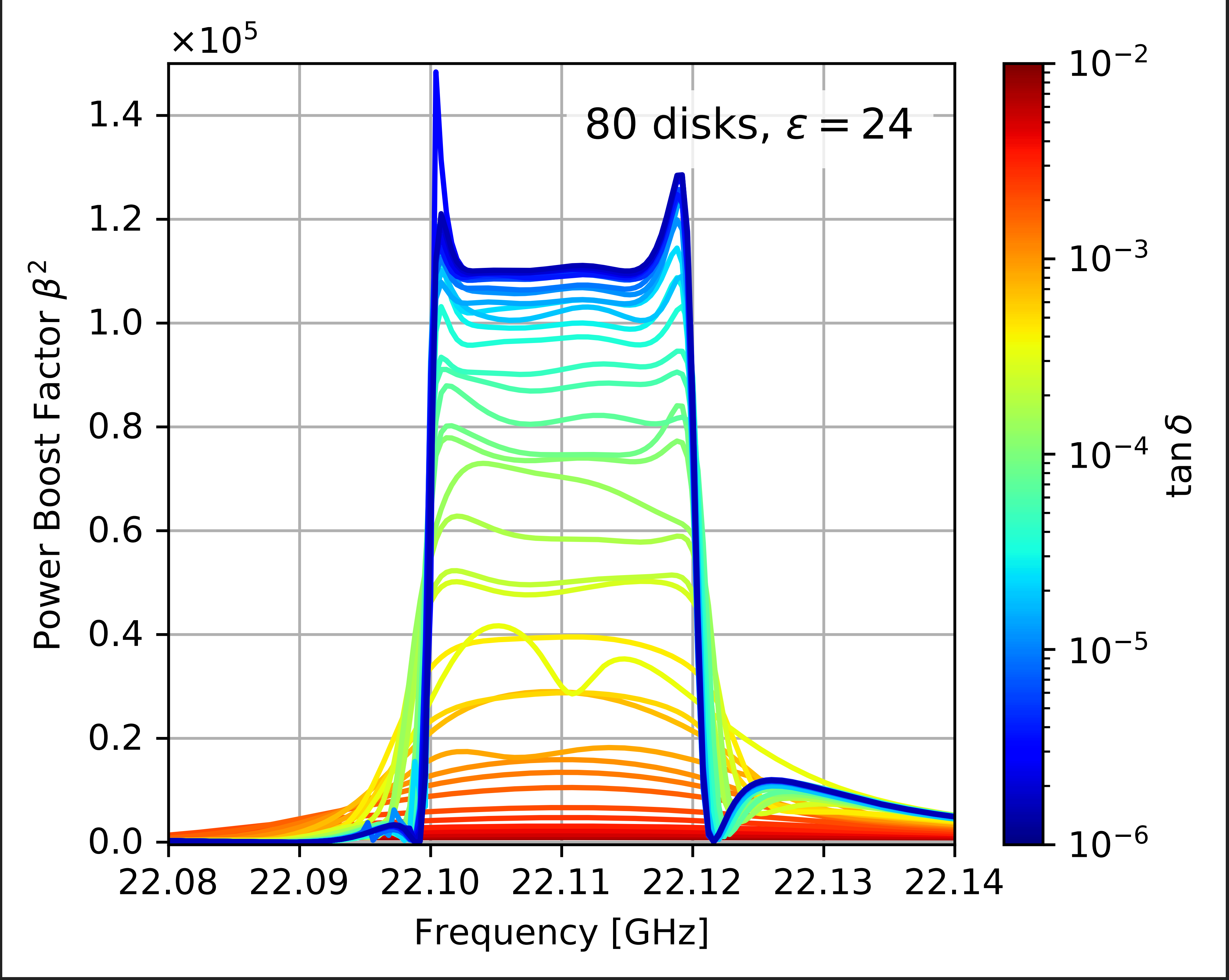
THE CHALLENGES

- Booster physics
  - Realistic simulations of axion signal and EM measurements
  - System noise temperature
  - Coupling of axion signal to receiver via antenna or taper
  - Other EM measurements to constrain boost factor?
- Frequency tuning of 80 discs
- Implementation of quantum limited amplifier below ~40 GHz
- Novel detection technology needed above ~40 GHz
- Engineering challenges
  - 100 T^2m^2 dipole magnet
  - Disc driving mechanism at 4K, 9 T, ~1 m driving distance, μm precision, 6 kg load bearing
  - Large dielectric discs with sufficient flatness, high ϵ, low $\tan\delta$

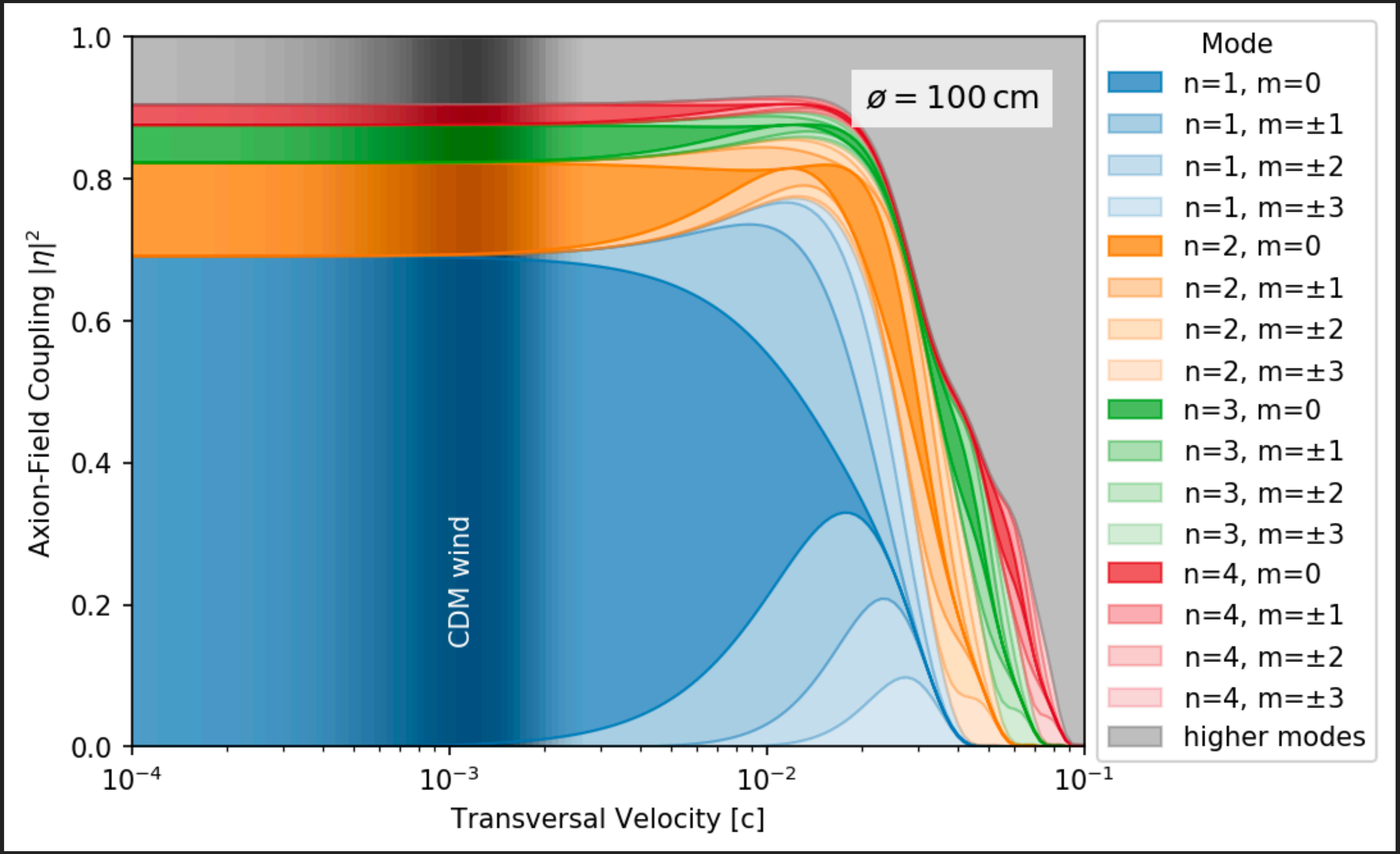
MADMAX COLLABORATION

RWTH AACHEN UNIVERSITY · Max-Planck-Institut für Radioastronomie · DESY · 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 · CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE CPPM · NÉEL institut

DIELECTRIC LOSS

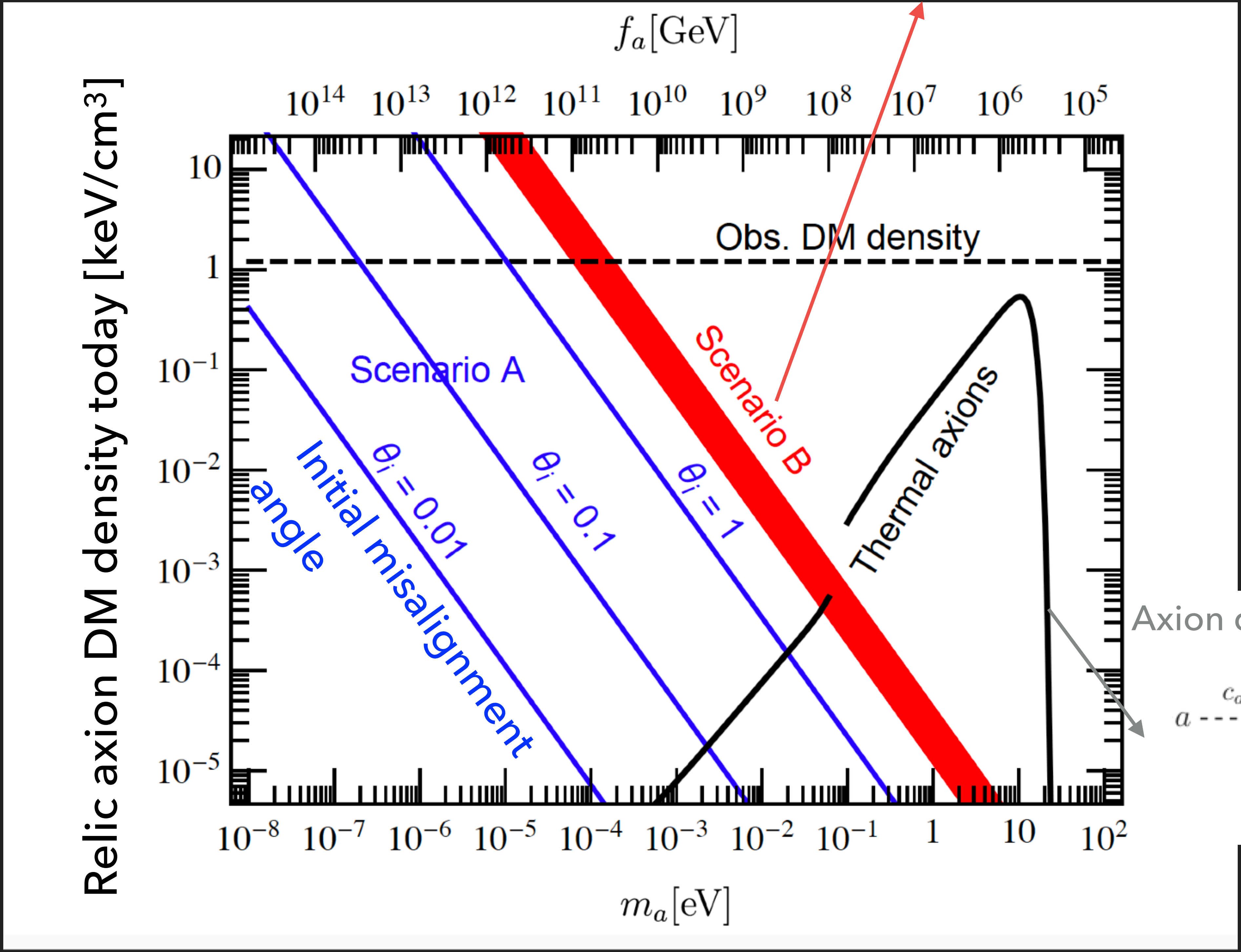


AXION VELOCITY EFFECT

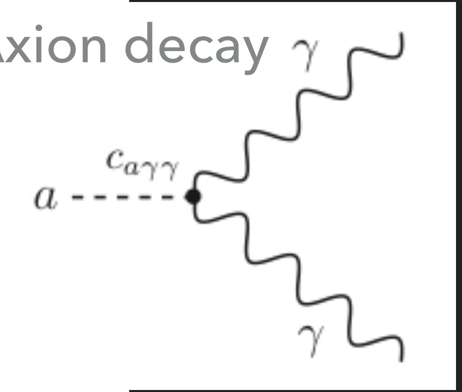


DM AXION DENSITY

Cosmic string +
Domain walls



Axion decay

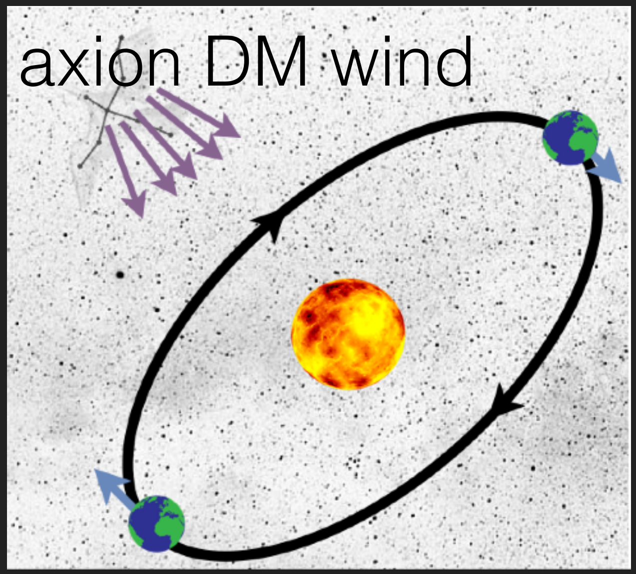


FROM AXION SEARCHES TO AN AXION TELESCOPE

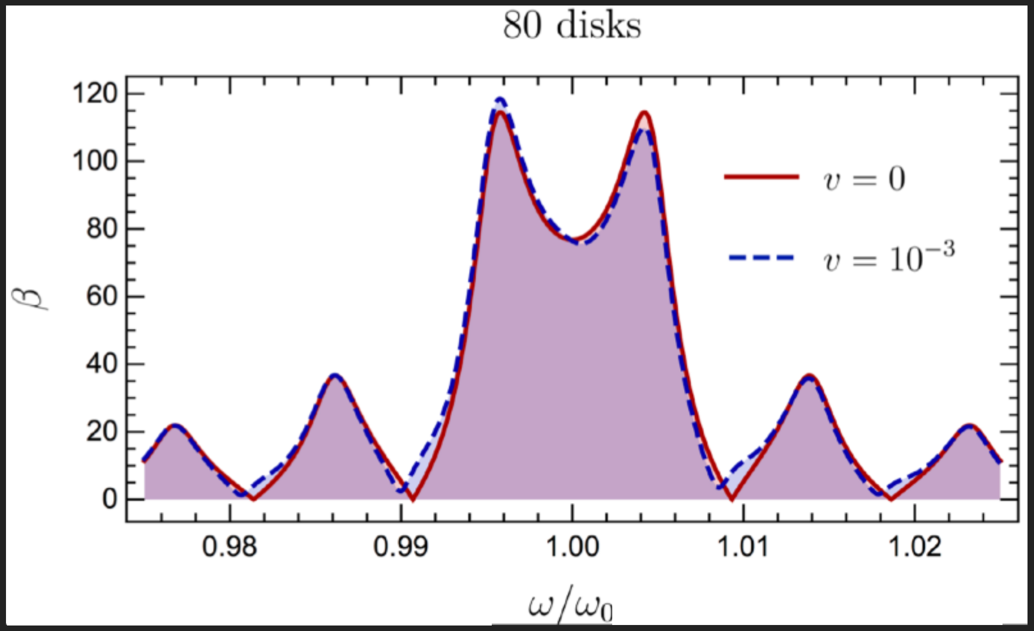
Axion DM field $$a(\mathbf{x},t) \approx \frac{\sqrt{2\rho_a}}{m_a}\cos(\omega t - \mathbf{p}\cdot\mathbf{x} + \alpha)$$

$$\omega = m_a\left(1 + \frac{v^2}{2}\right)$$

$$\mathbf{p} = m_a \mathbf{v}$$

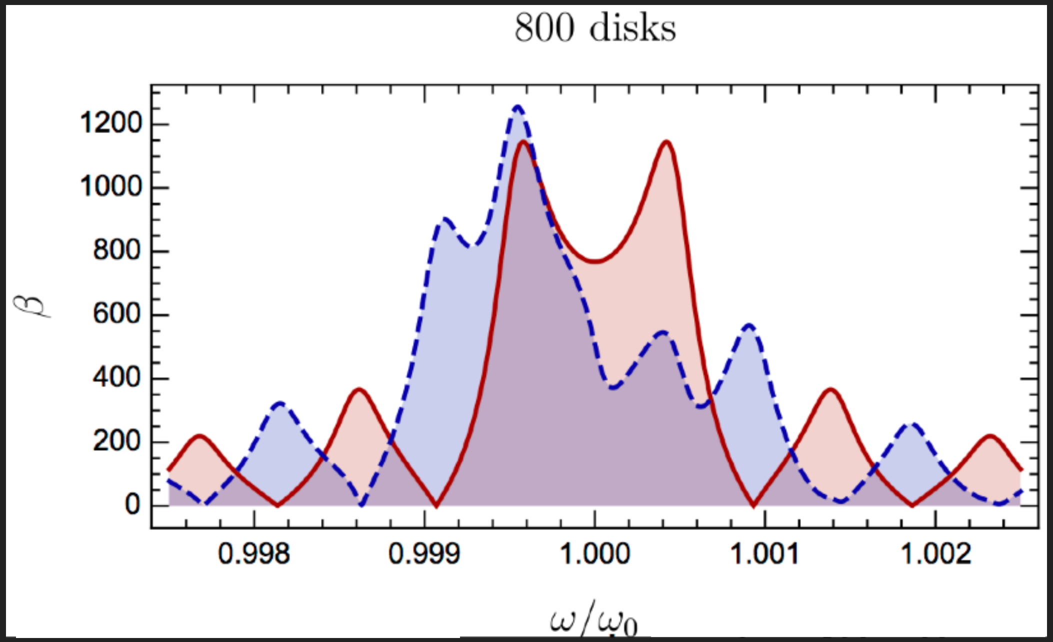


Axion search experiment



No *v* sensitivity

Axion telescope



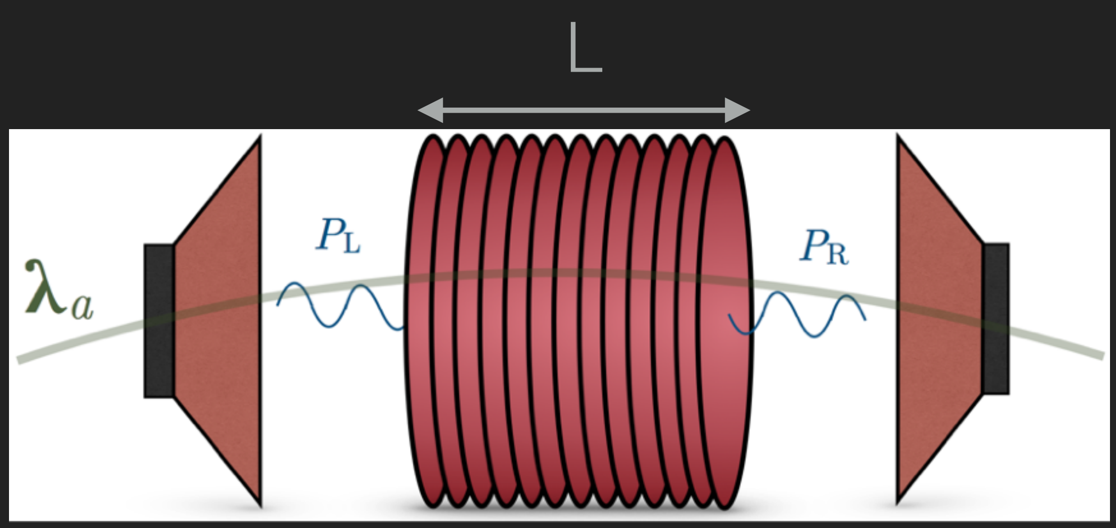
Directional *v* effect

[A.J.Millar, J.Redondo, F.D.Steffen, JCAP1710, 006, arXiv:1707.04266]

A VISION FOR THE FAR FUTURE: AXION ASTRONOMY

Key: axion phase differences across large exp. + rotation of the Earth

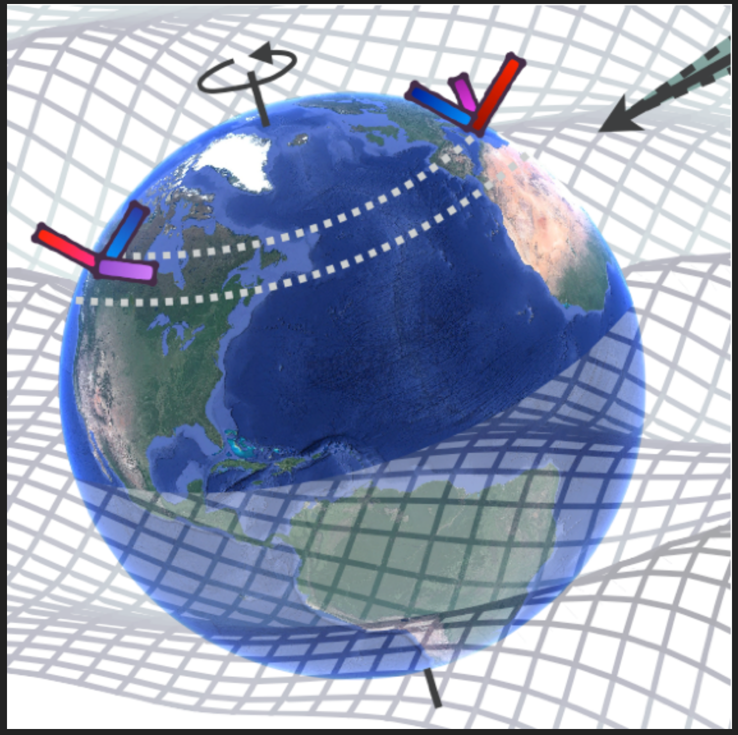
MADMAX-XXXL in 3 directions = axion telescope



400 disks
B_e=15 T
A =1 m²

$$L \sim \lambda_a = \frac{2\pi}{m_a \sigma_v} \simeq 12.4\ \mathrm{m} \left(\frac{100\ \mu\mathrm{eV}}{m_a}\right)$$

Axion DM wind



- measure the daily and annual modulation (and solar velocity)
- measure the anisotropy of the DM halo
- measure a stream (and mini cluster streams)

[S.Knirck, A.J.Millar, C.A.J.O'Hare, J.Redondo, F.D.Steffen, JCAP1811, 051, arXiv:1806.05927]