MADMAX

introduction and status

Chang Lee on behalf of the **MADMAX** collaboration
MPI for Physics

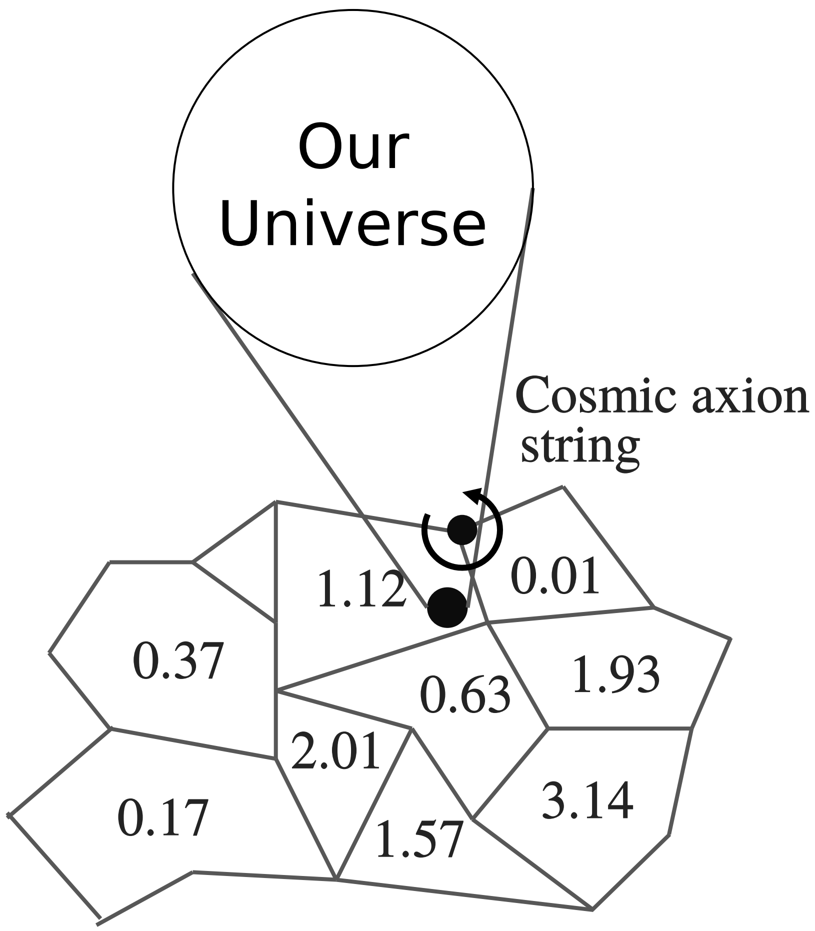
3rd Workshop on Microwave cavities and detectors for Axion Research
Aug 24th, Livermore, CA, USA

MAX-PLANCK-GESELLSCHAFT

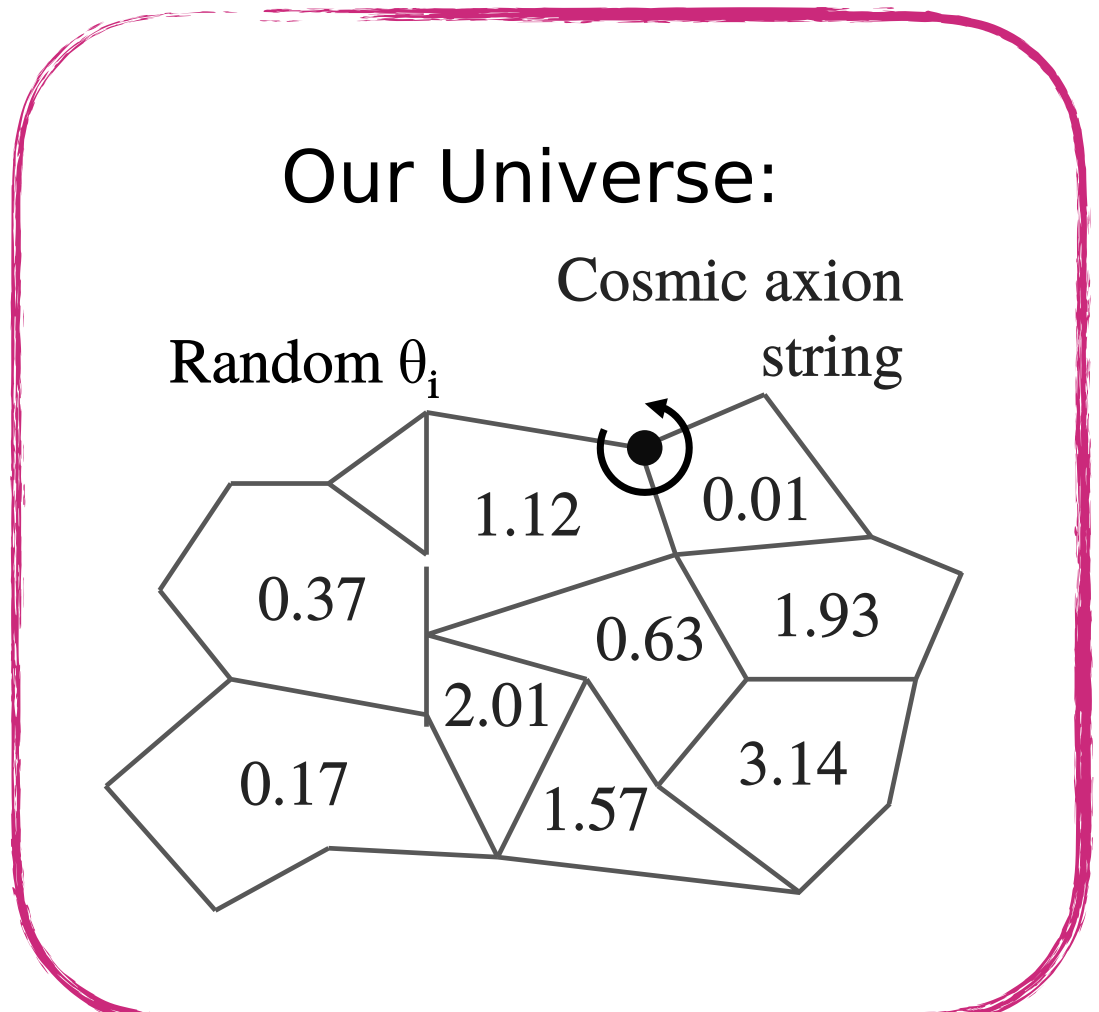
$\Delta p \cdot \Delta q \geq \frac{1}{2}\hbar$

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

Post-inflation axion



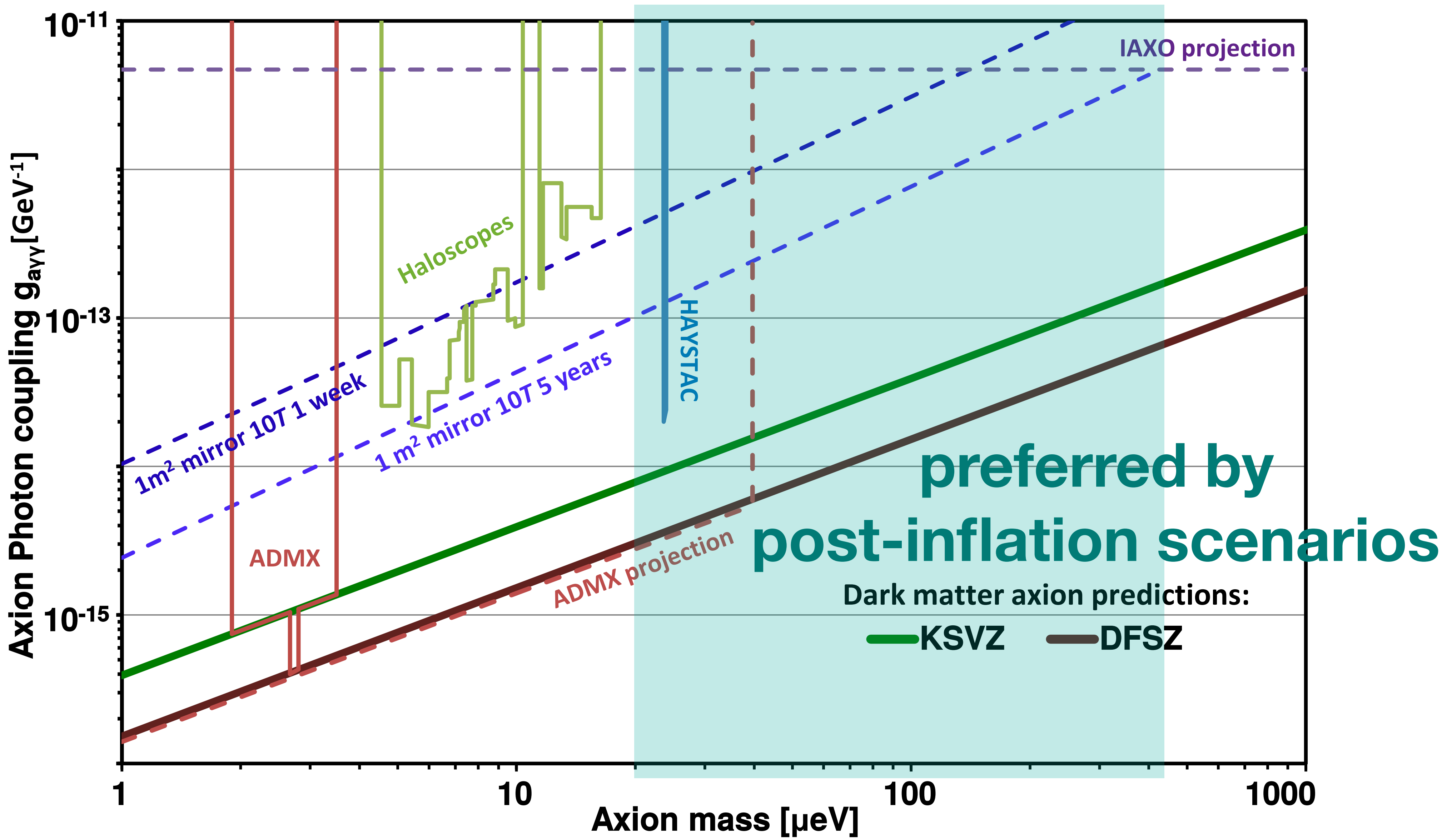
m_a < 10 meV



PQ symmetry breaking after inflation

m_a ~ 100 µeV

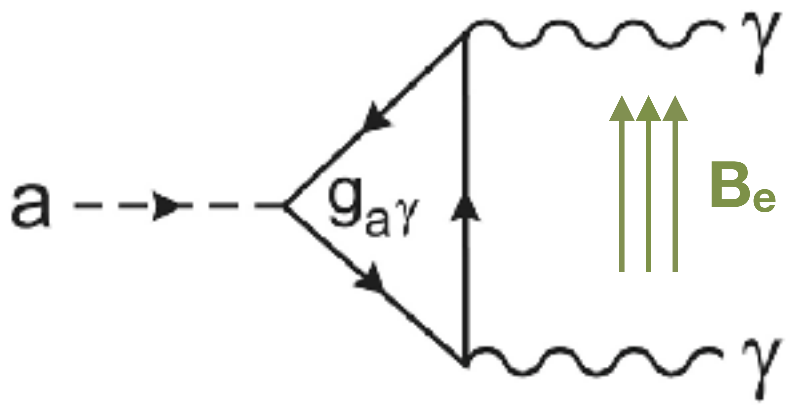
High-mass challenge



- 40—400μeV (10—100 GHz): Challenging for traditional resonant cavity due to smaller volume, lower Q

Axion signal

- Inverse-Primakoff in matter



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

- **Discontinuity of *ε*** or *B*e generates propagating **EM field.**

$$E_{\parallel,1} = E_{\parallel,2} \quad H_{\parallel,1} = H_{\parallel,2}$$

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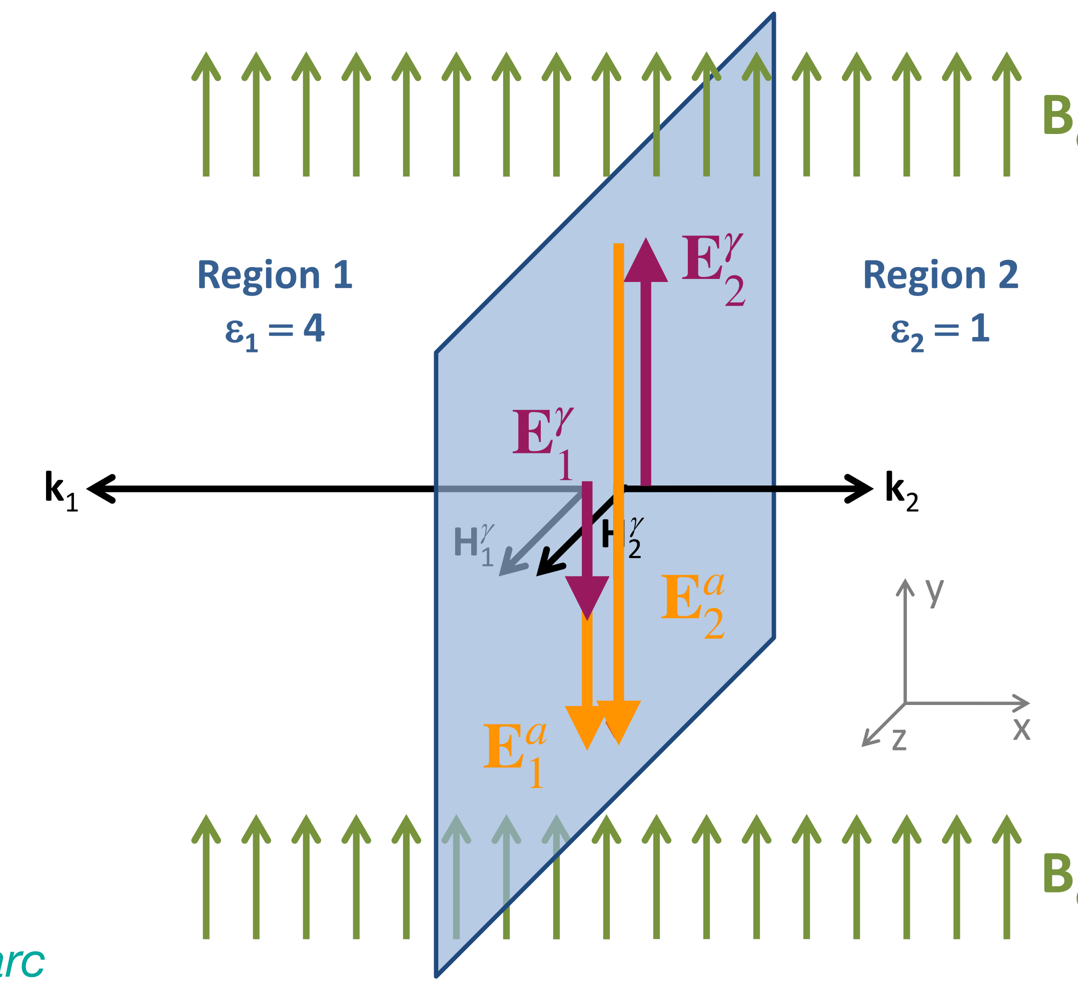
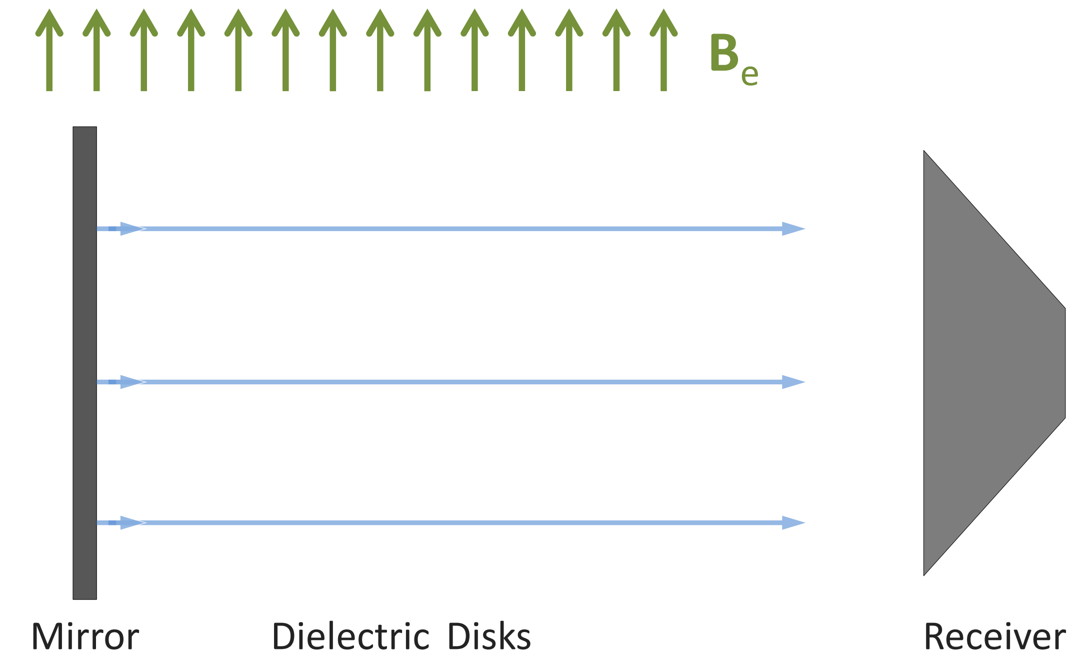


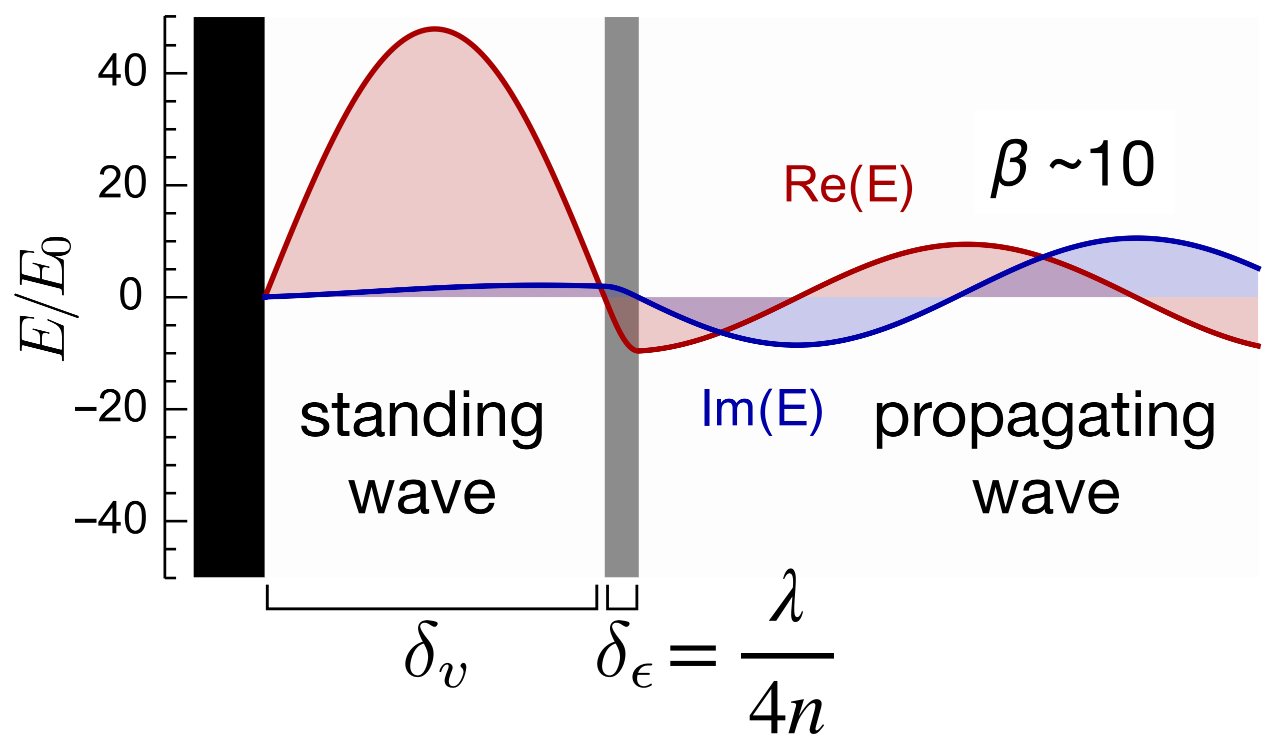
signal power



- Simplest: a metallic mirror ($\varepsilon = \infty$)

$$E_0 = 1.3 \times 10^{-12}\ [V/m] \times \left(\frac{B_e}{10T}\right)$$

~12 photons / day / m² (@ 25 GHz)



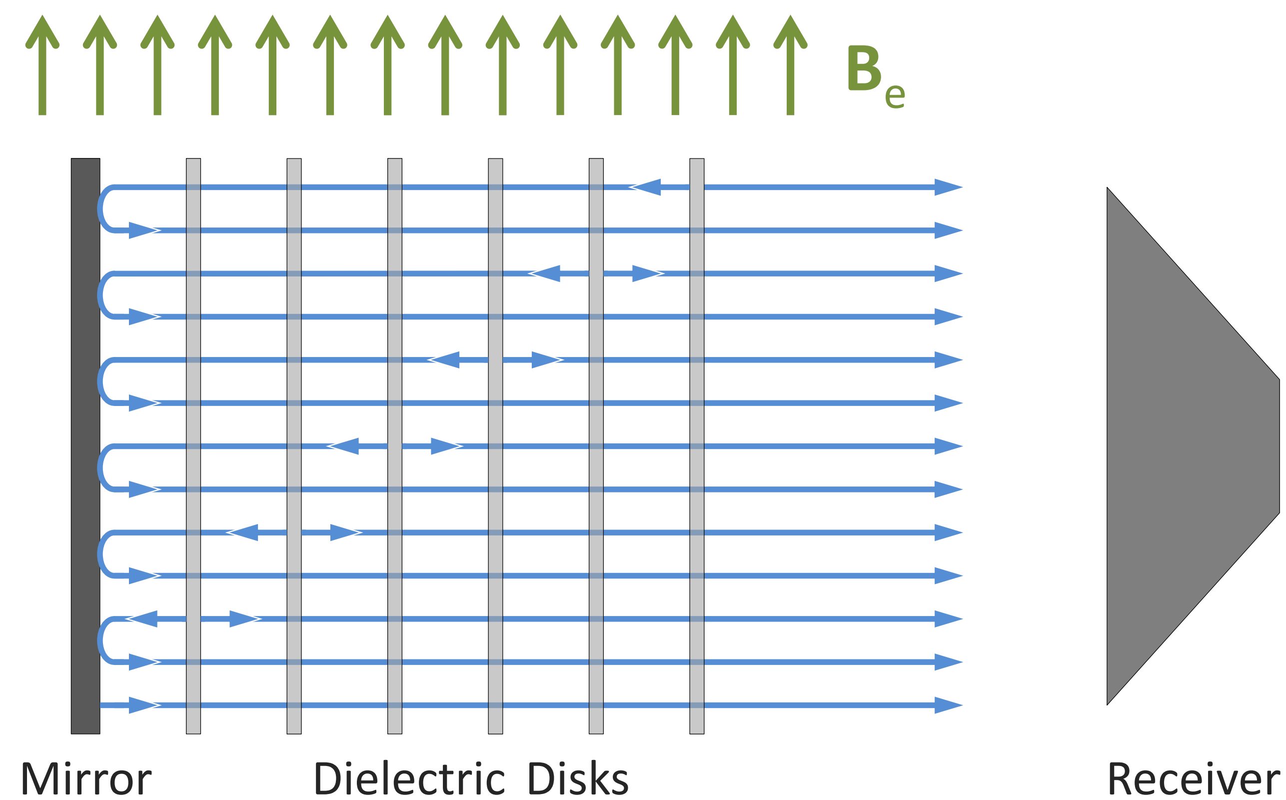
- Mirror + dielectric: $Q \propto \varepsilon$
  Leaky resonator, $\beta = E/E_0$
  boost factor:

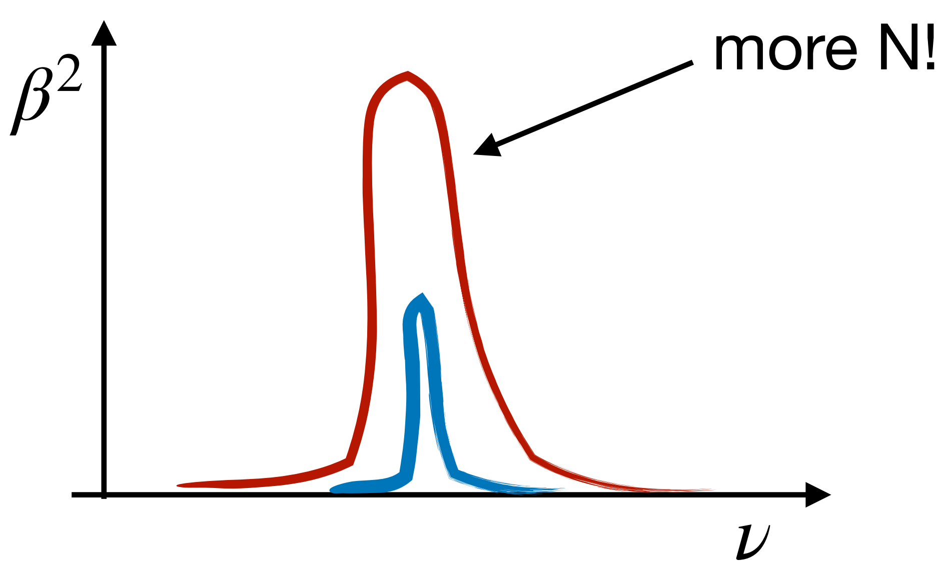
$$P \propto E^2 \propto \beta^2$$

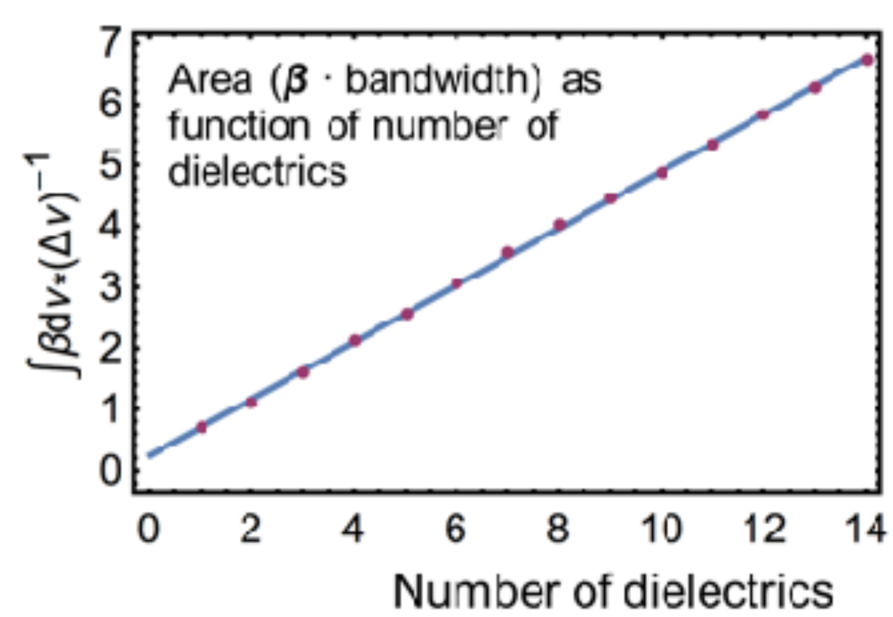
- Add more dielectric disks…

Dielectric haloscope

- more sources + coherent interferences
- Boost

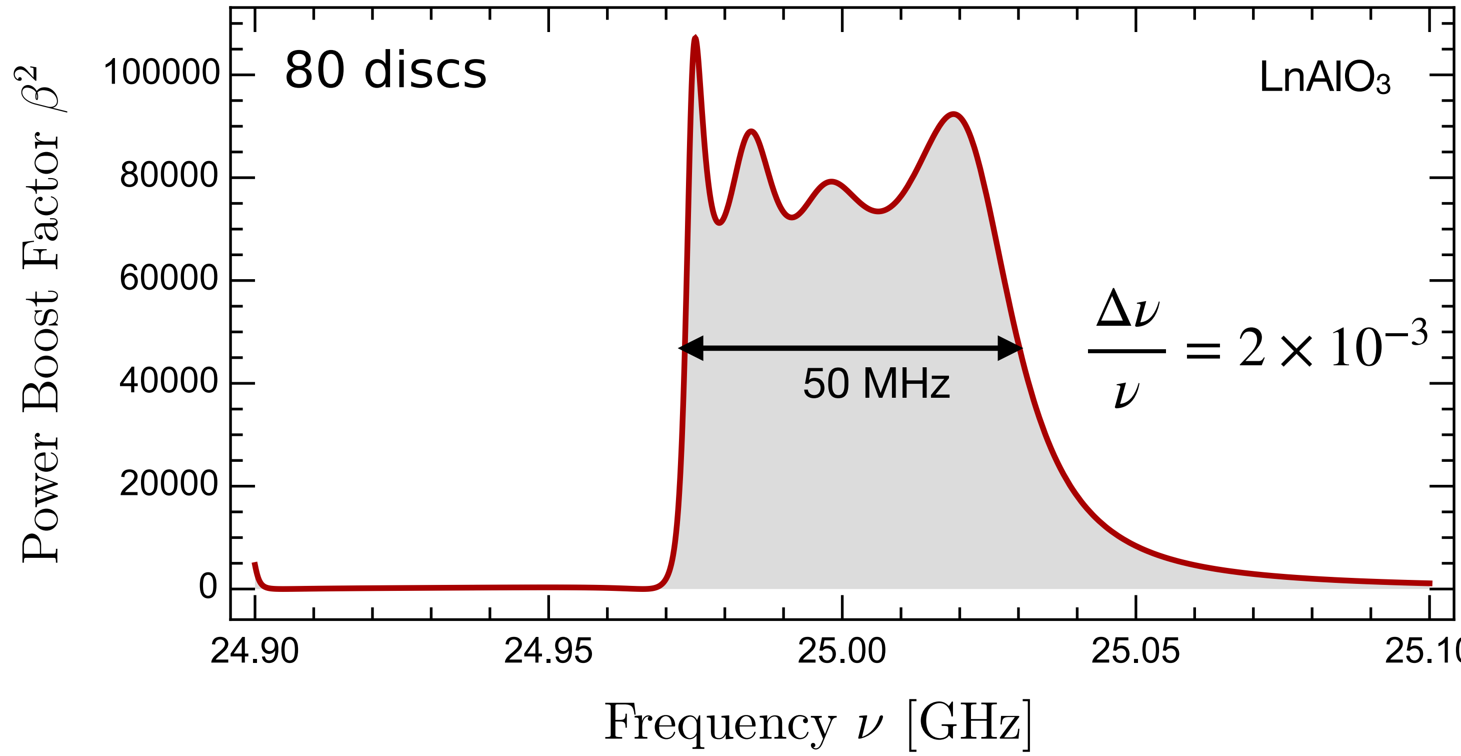




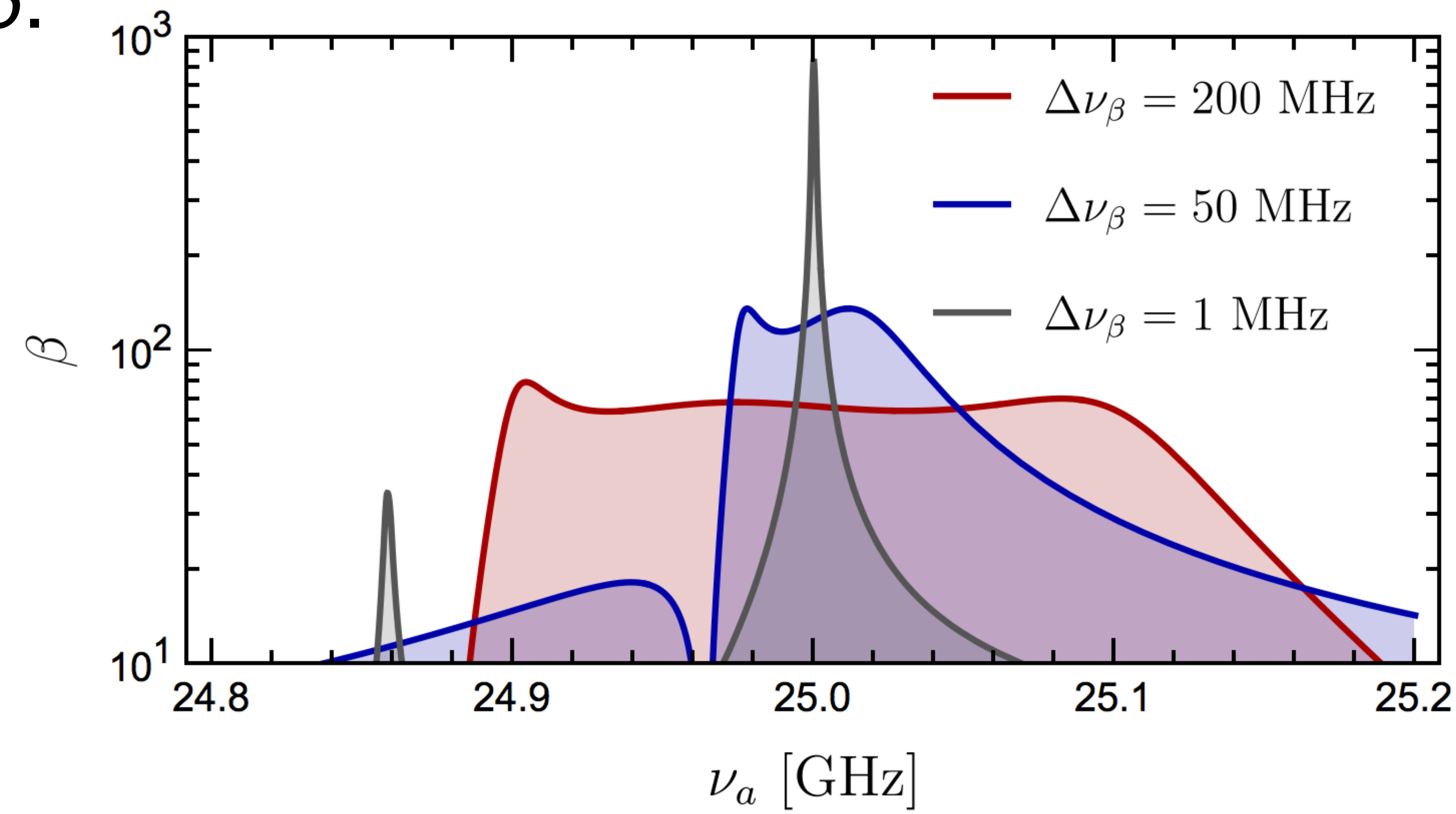


Boost

- $\beta^2 > 60{,}000$ possible with ~80 disks.

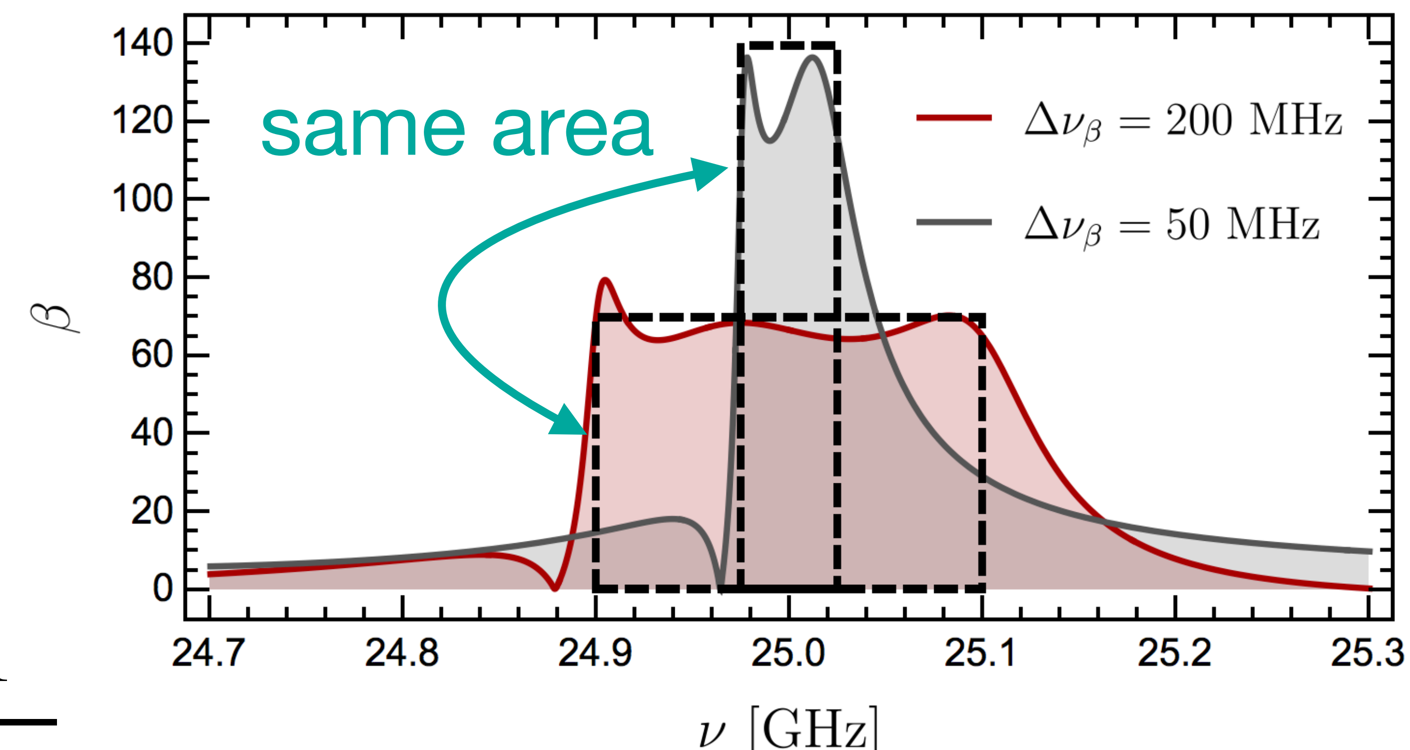


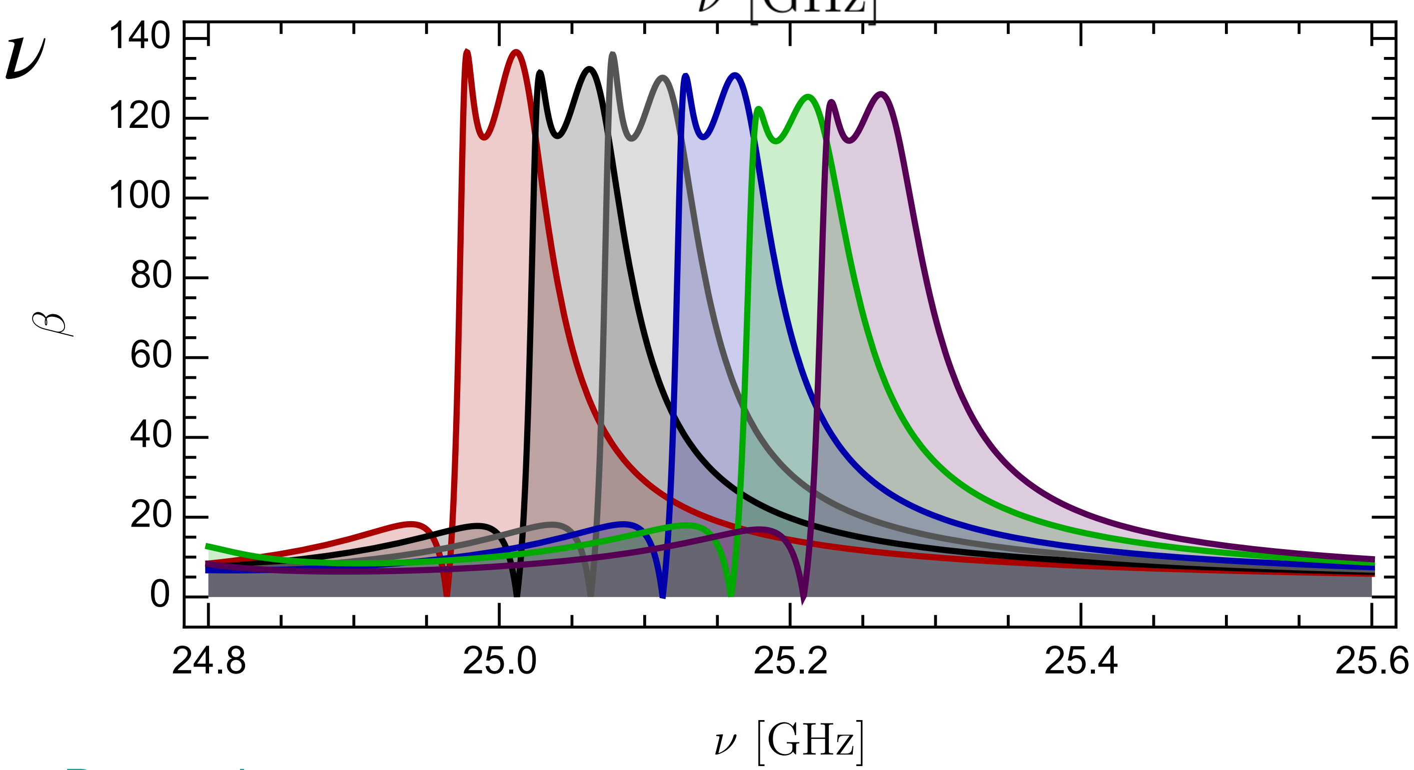
- Disk spacings tune β.
  - Broad band for coverage
  - higher β for confirmation



Scan strategy

- **Area Law:** P_{sig} x $\Delta\nu$ is independent of disk spacings.
- $$\frac{t_{scan}}{\Delta\nu} = \left(\frac{S}{N}\right)^2 \left(\frac{k_B T_{sys}}{P_{sig}}\right)^2$$
  $$P_{sig} \propto \; B_0^2,\ \beta^2,\ n,\ A,\ N,\ \frac{1}{\Delta\nu}$$
  - Narrower peak leads to faster scan.
- In practice, **$t_{tot\_adj} \approx t_{tot\_scan}$.**



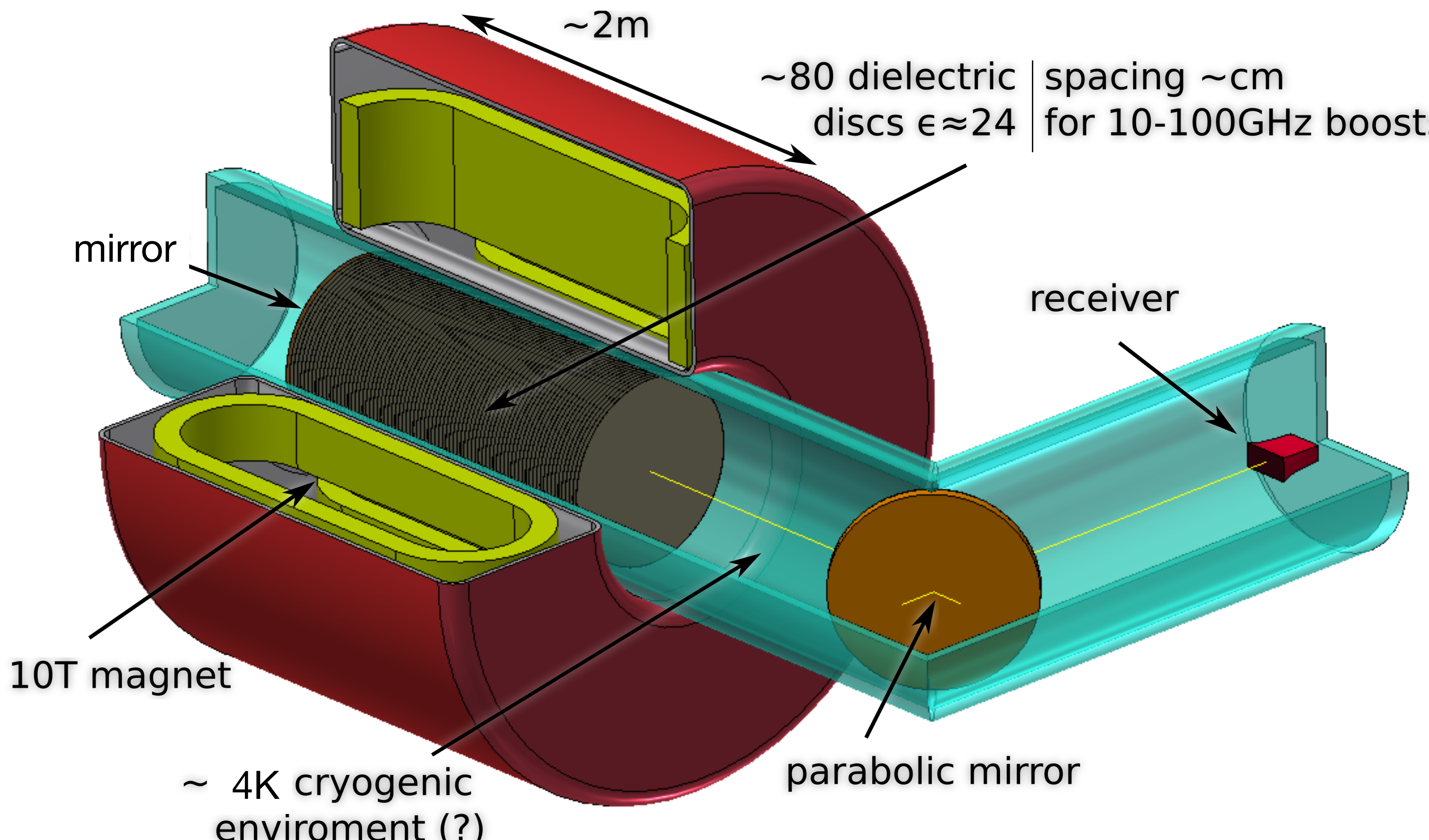


MADMAX collaboration

MAgnetized **D**isk-and-**M**irror **A**xion e**X**periment

DESY, Univ. of Hamburg, CEA-IRFU, MPI for Radioastronomy,
RWTH Aachen, Univ. of Zaragoza, MPI for Physics

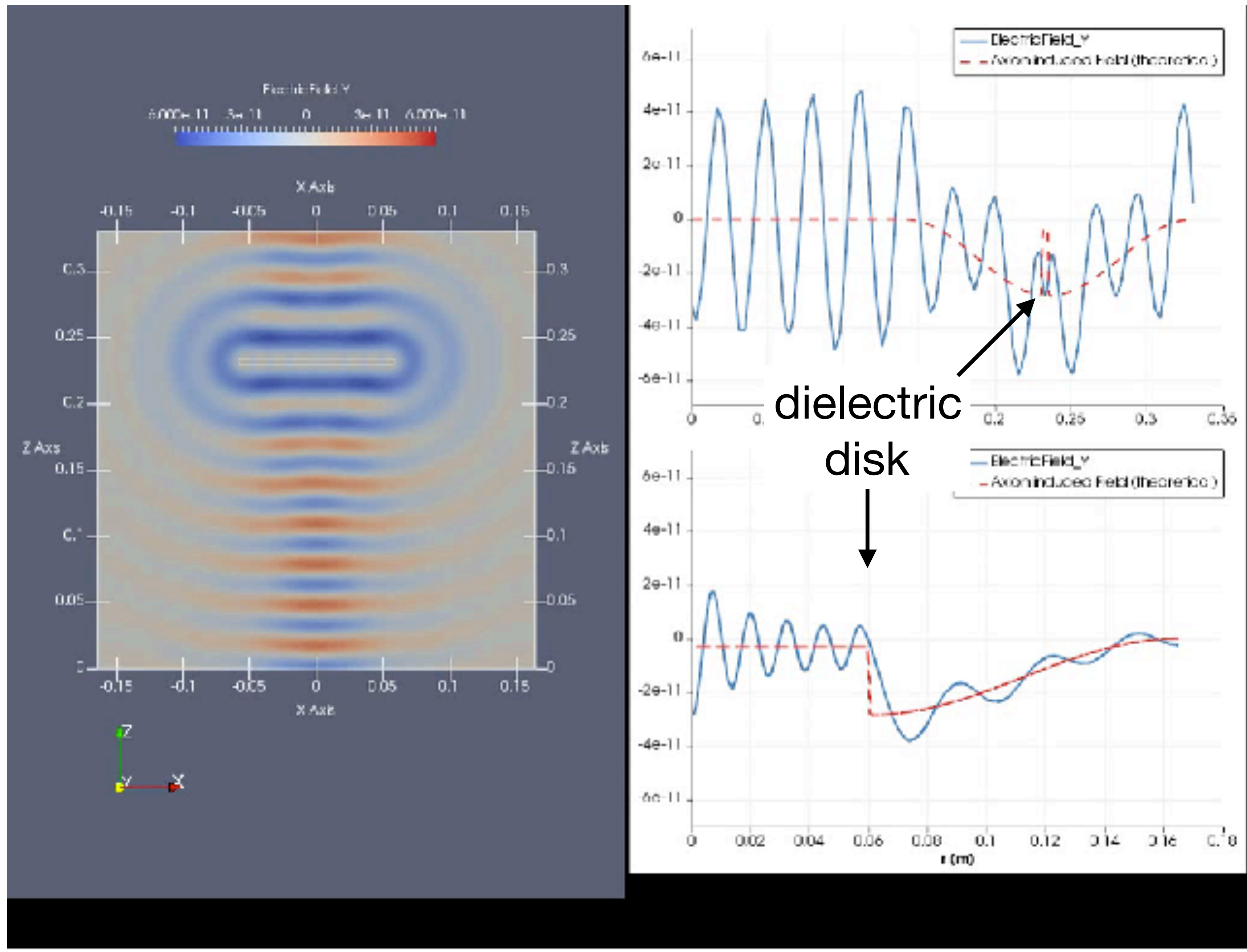
Instrument



Cover the QCD axion @ 10—100 GHz

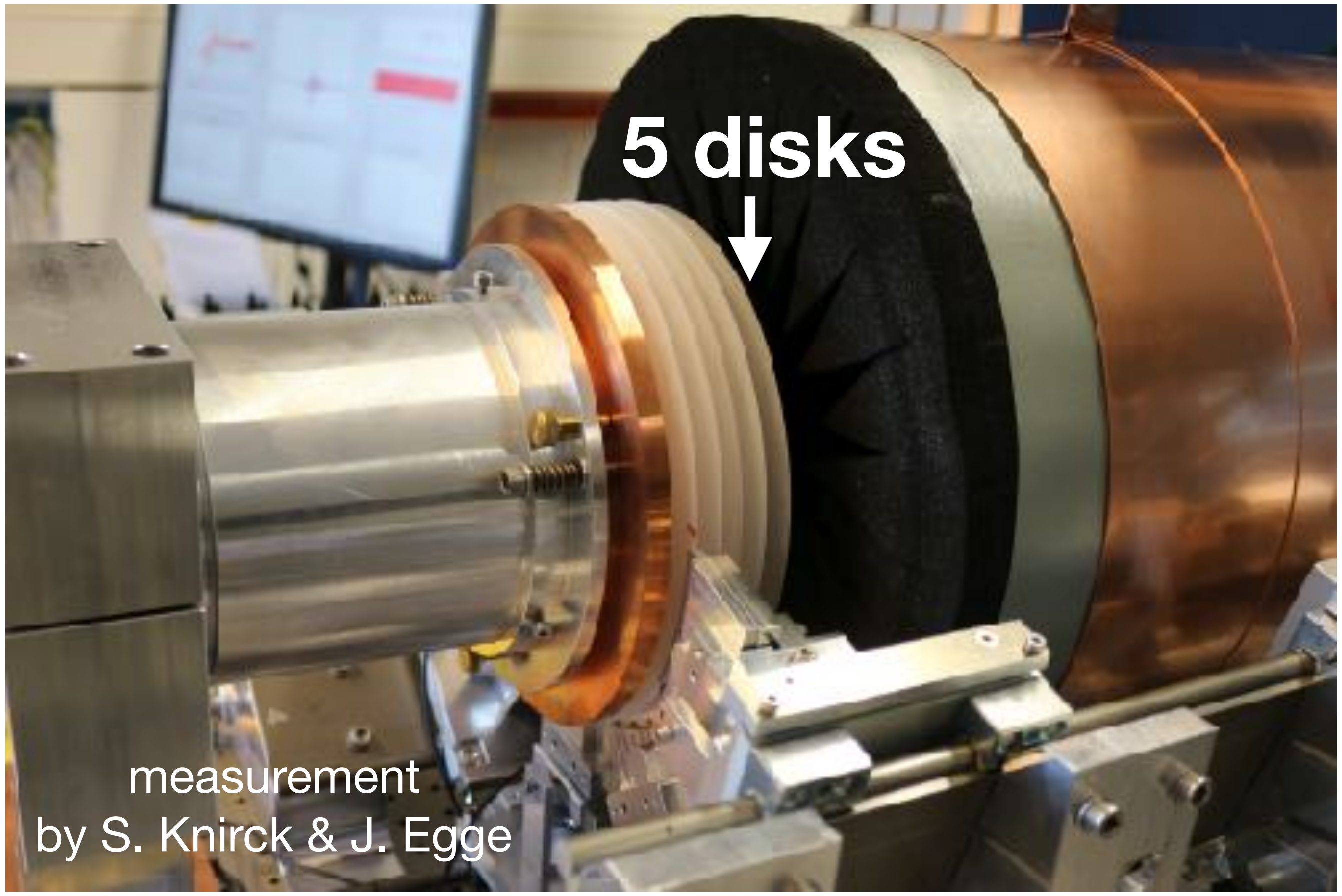
Simulation

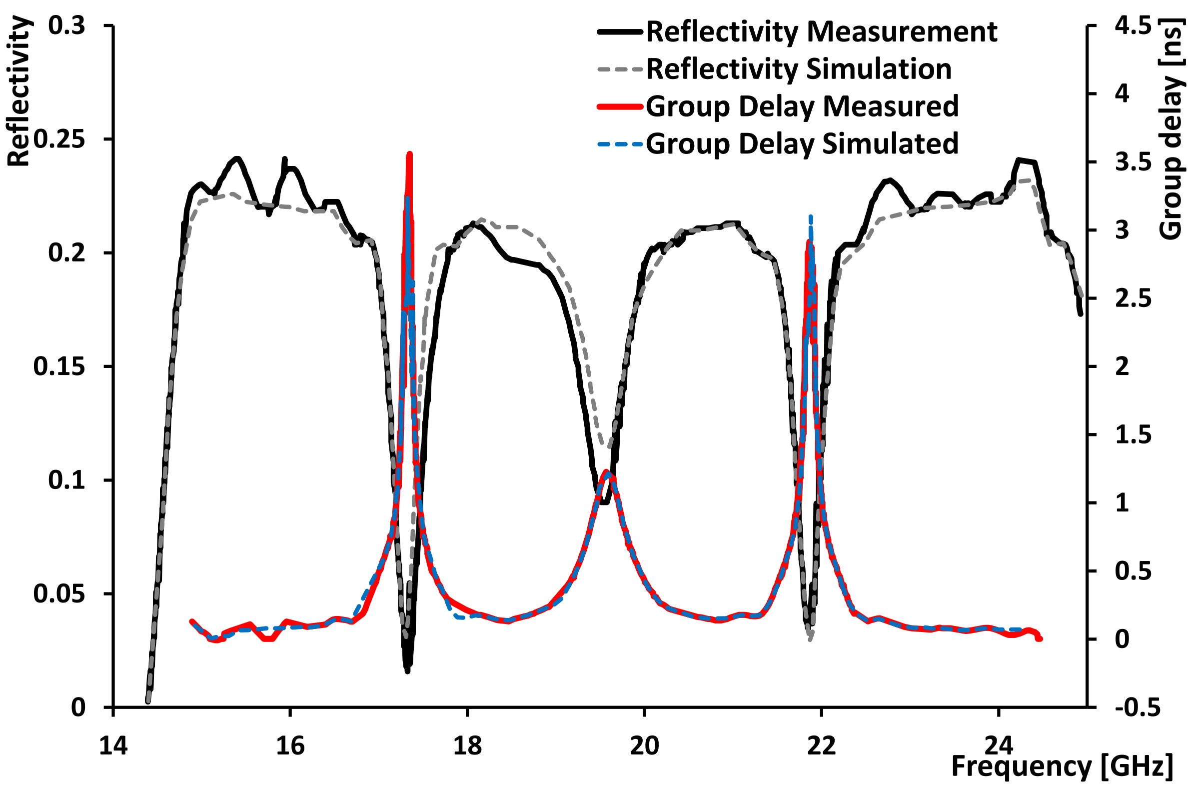
- Maxwell-Axion equation solved by analytic, FEM, ray tracing, and other methods.
- 1D calculations confirmed.
- Latest topics: 3D effects, boundary loss, diffraction

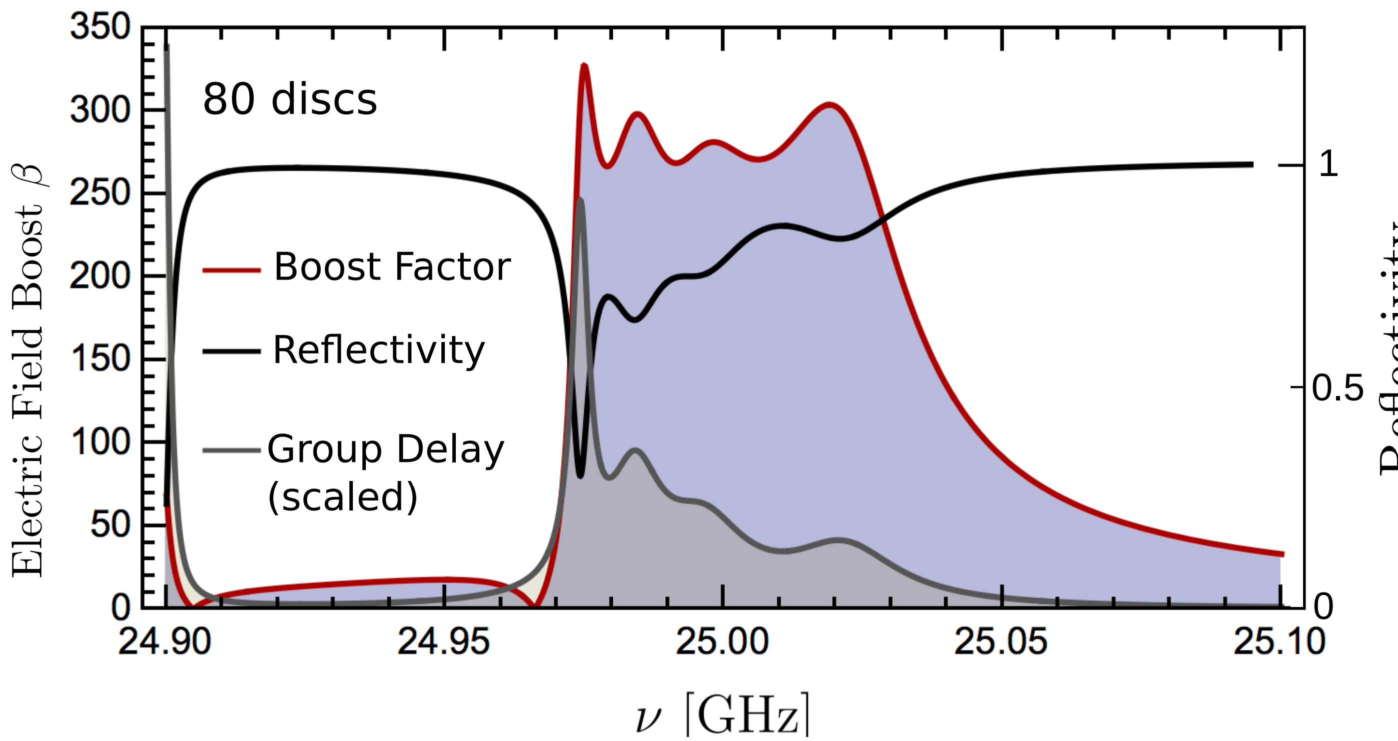


Boost measurement

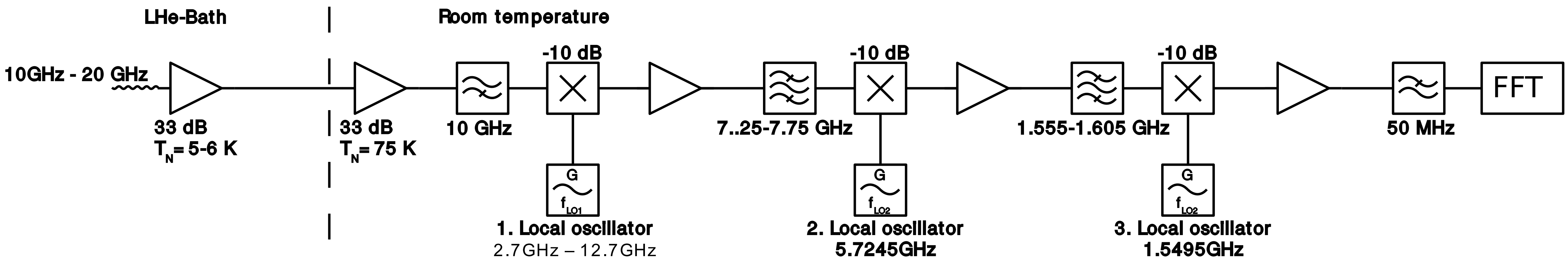
- Boost factor is indirectly confirmed by the reflectivity and **group delay** measurements.

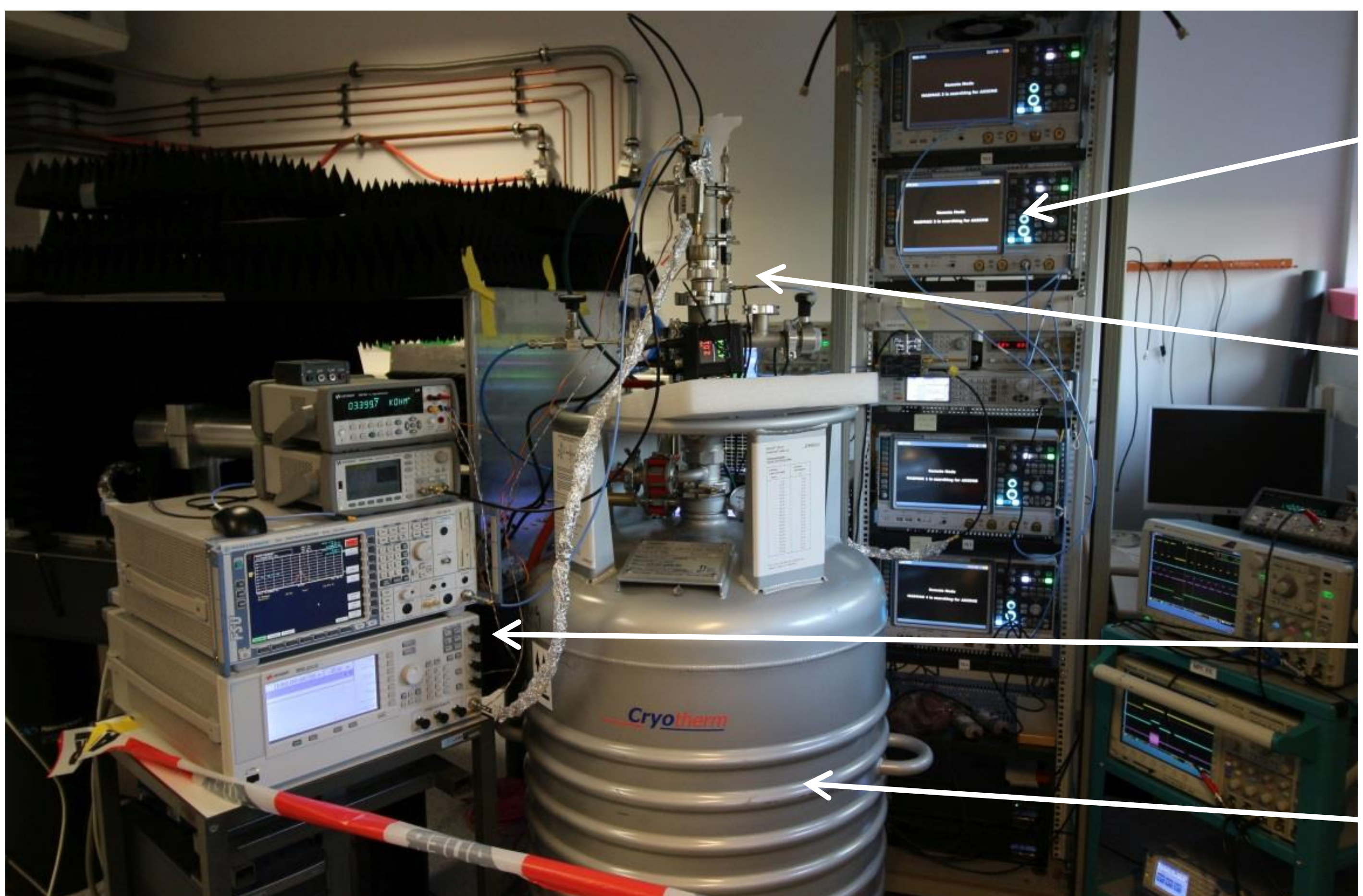






receiver chain





signal analyzer
(4 samplers, 1.4% dead time)

front end mixers
and amps

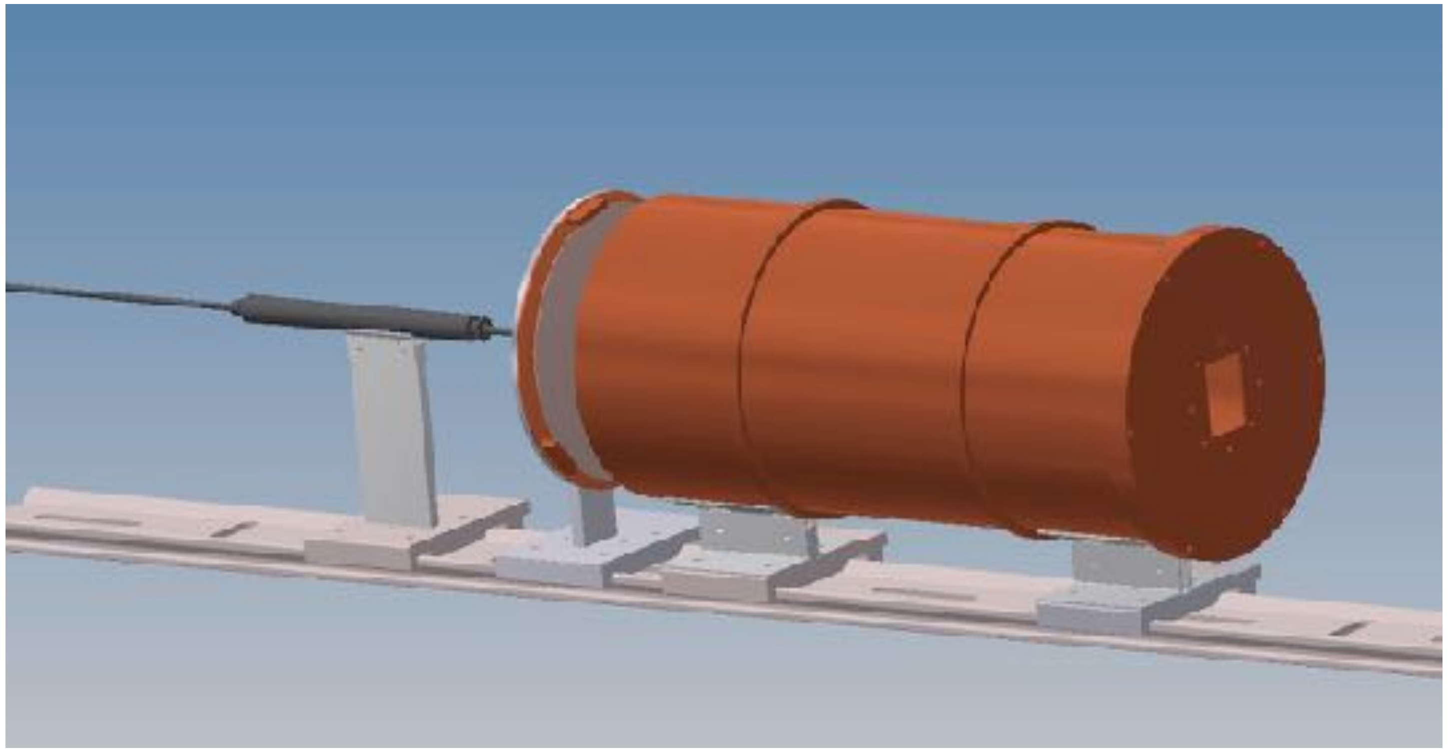
“Fake Axion” (signal generator)

LHe bath
→ $4K\ T_{He} + 5.5K\ T_{Amp} \approx 9.5K\ T_{Sys}$

- 10^{-23} W detected in a week

System temperature

- Thermal emissivity of the internal parts to be measured.
  goal: ΔT < 0.5 K
- Bottleneck: ~5 K noise temperature from HEMT
  - Quantum noise: ~0.48K @ 20 GHz
  - Latest options (JPA, TWPA, …) to be considered



$$\frac{t_{scan}}{\Delta\nu} \propto T_{sys}^2, T_{sys} = \underbrace{T_{bg}}_{< 4K} + \underbrace{T_{amp}}_{5\sim6K}$$

Mechanical design

- Baseline design by M. Matysek & D. Kittlinger
  - 80 disks at cryogenic temp.
  - Each moves 1.5—30mm w/ < 60μm precision for β ~1000.
- Piezo motor for moving disks
  - test @ cryogenic + high magnetic field
  - Hysteresis, accuracy measurement at varying loads

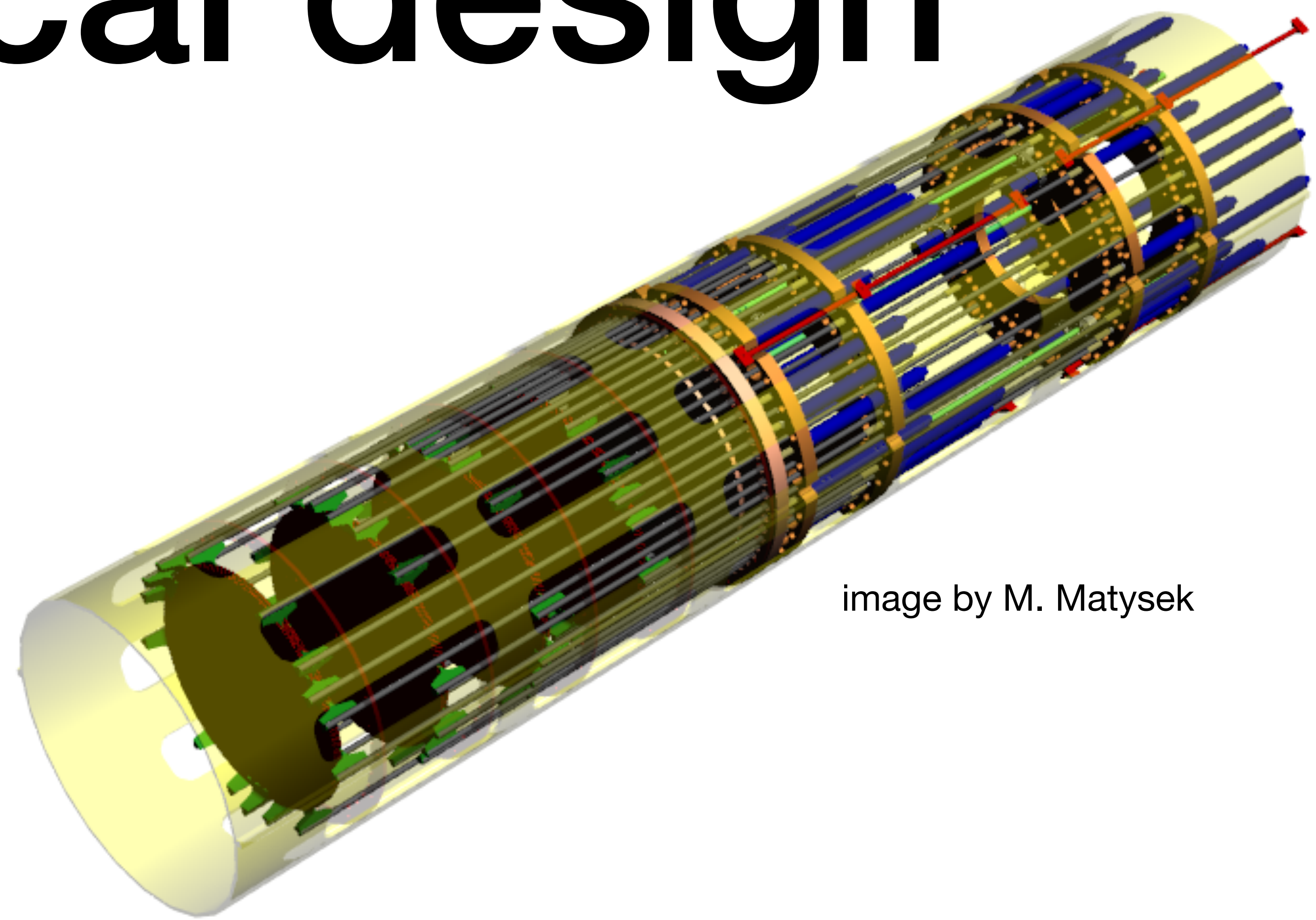
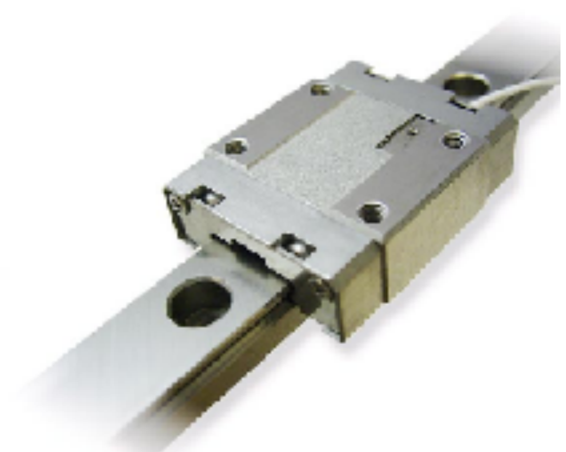
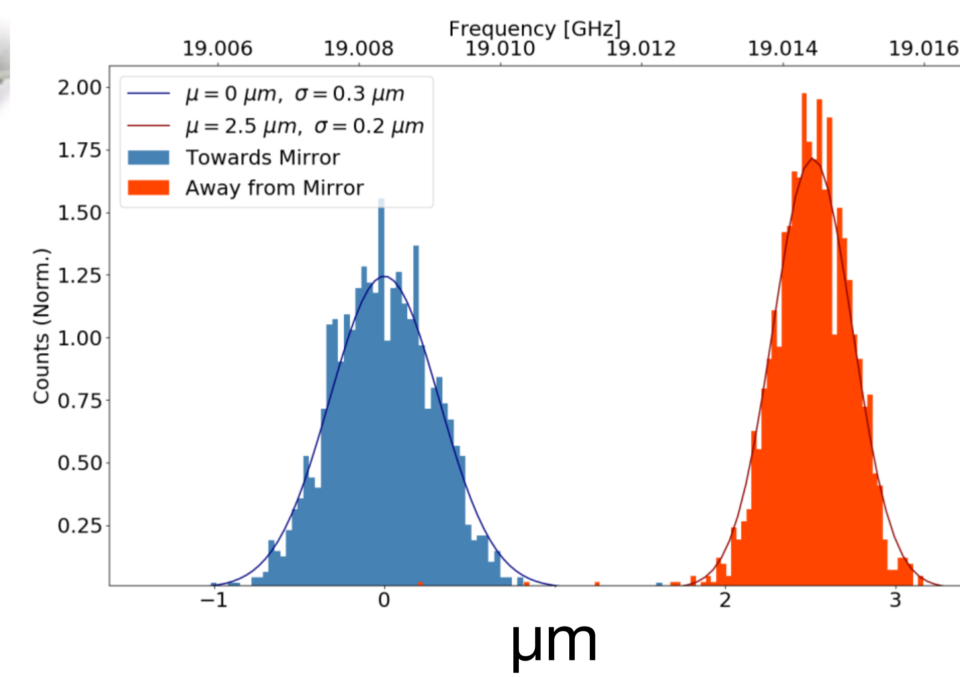


image by M. Matysek



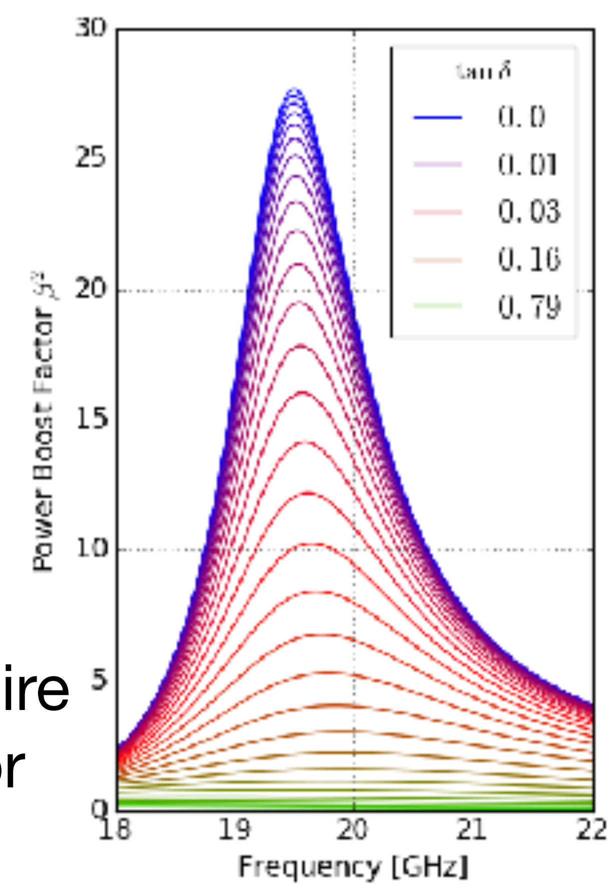


Dielectric study

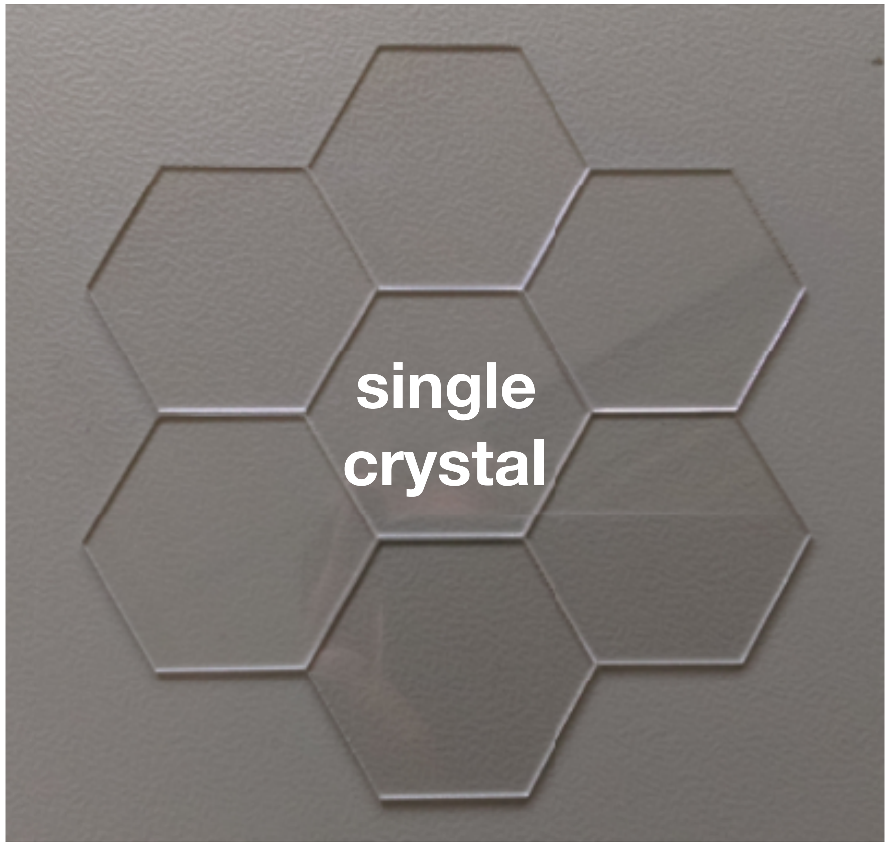
$$\beta^{max} = 2n - \frac{1}{n}$$

for 1 mirror + 1 disk setup
at resonance

1 Sapphire
+ mirror



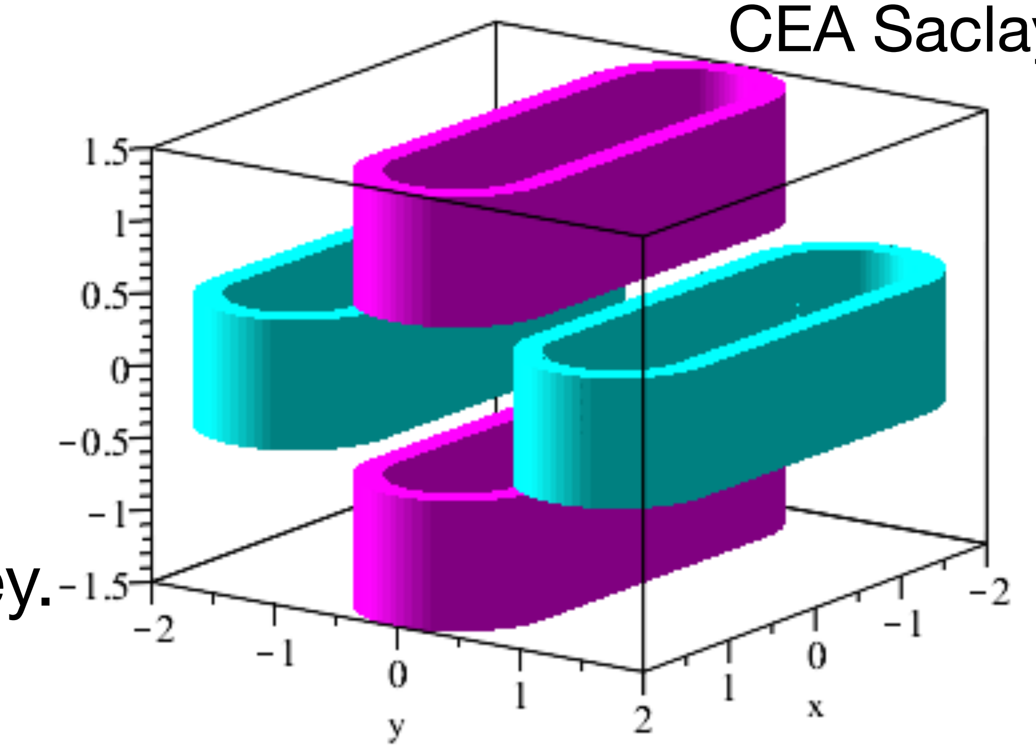
dielectrics	$\varepsilon = n^2$	tanδ
Al_2O_3	10	10^{-5}
$LaAlO_3$	24	3×10^{-5}
TiO_2	100	3×10^{-5}



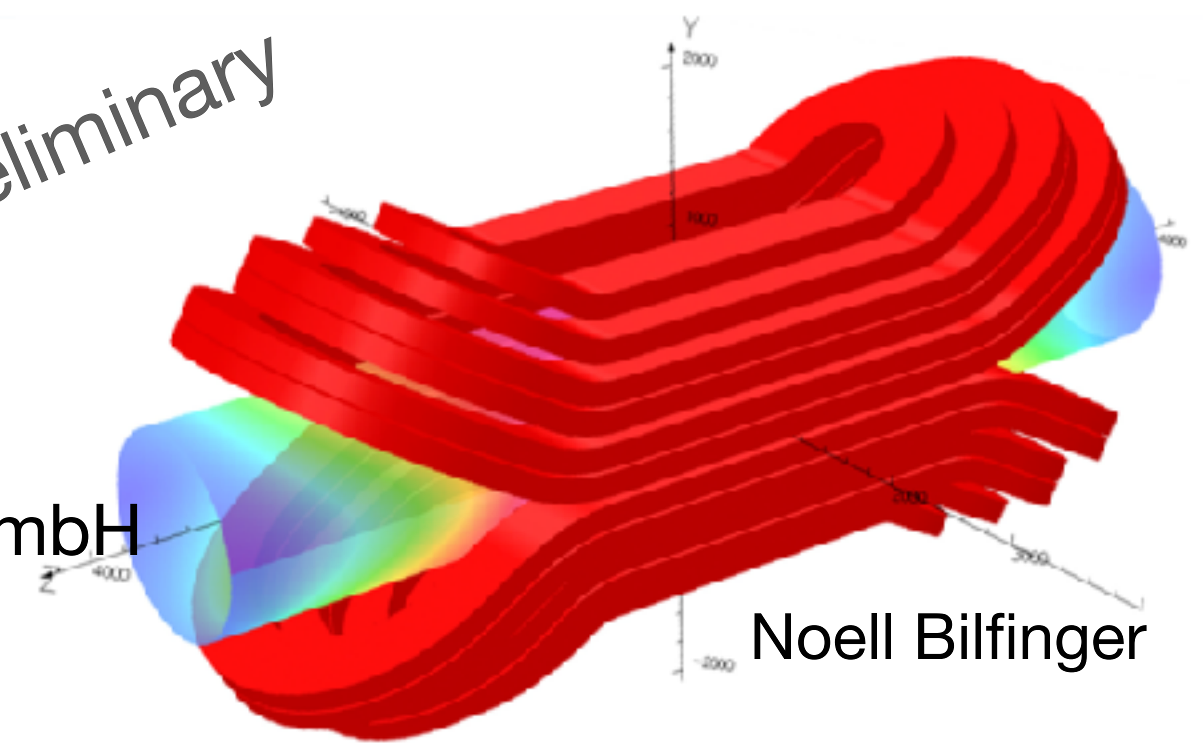
Magnets

- Prototype magnets for R&D (2~3 years)
  - 3-4 T, ~400mm bore
  - Used magnets at Saclay under survey.
- Final setup (> 5 years)
  - 10T dipole, B^2A: ~100 T^2m^2, ~400 MJ stored in 2m x $1m^2$
  - Two independent design studies by CEA Saclay & Bilfinger Noell GmbH

CEA Saclay



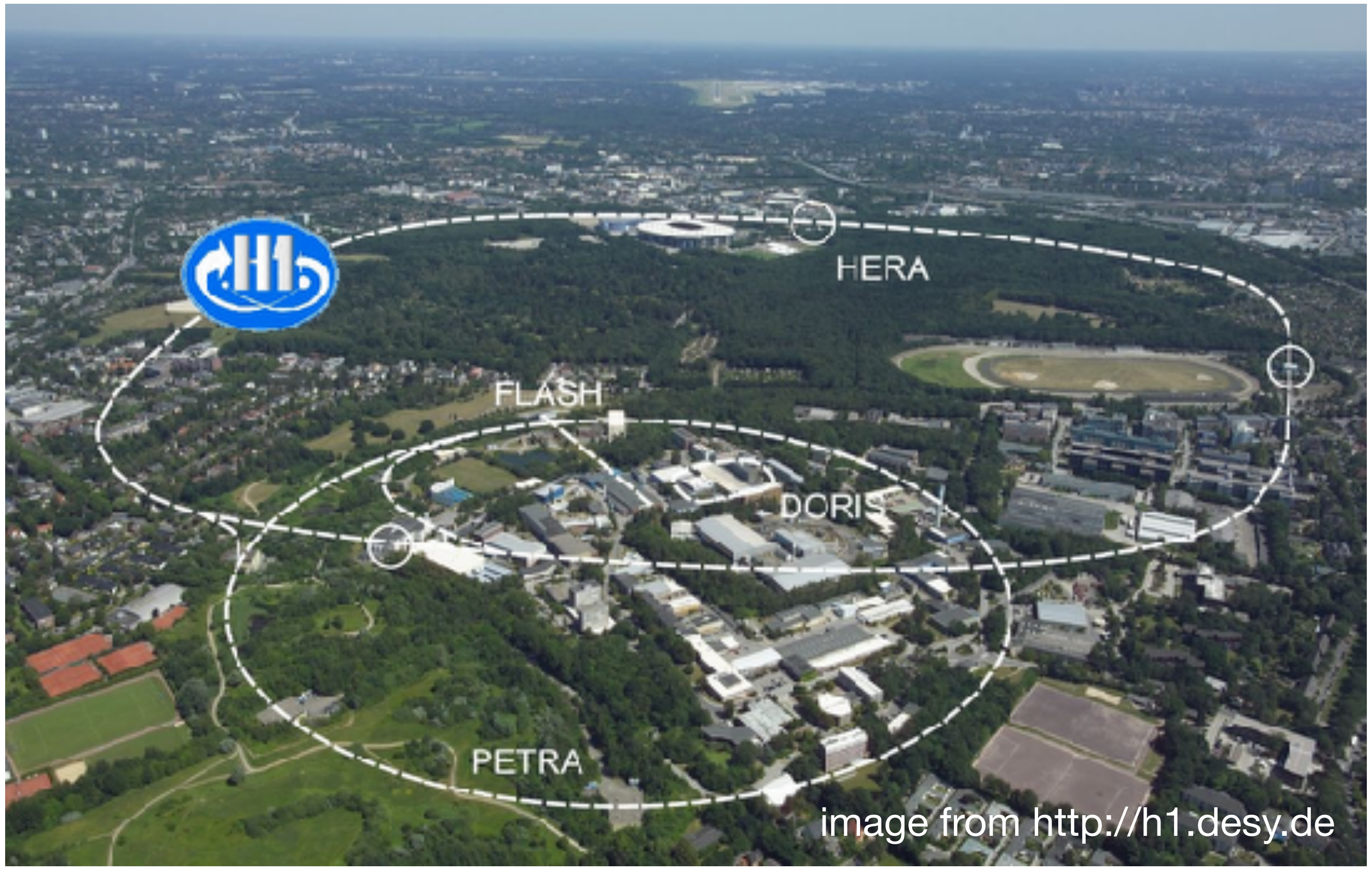
Preliminary



Noell Bilfinger

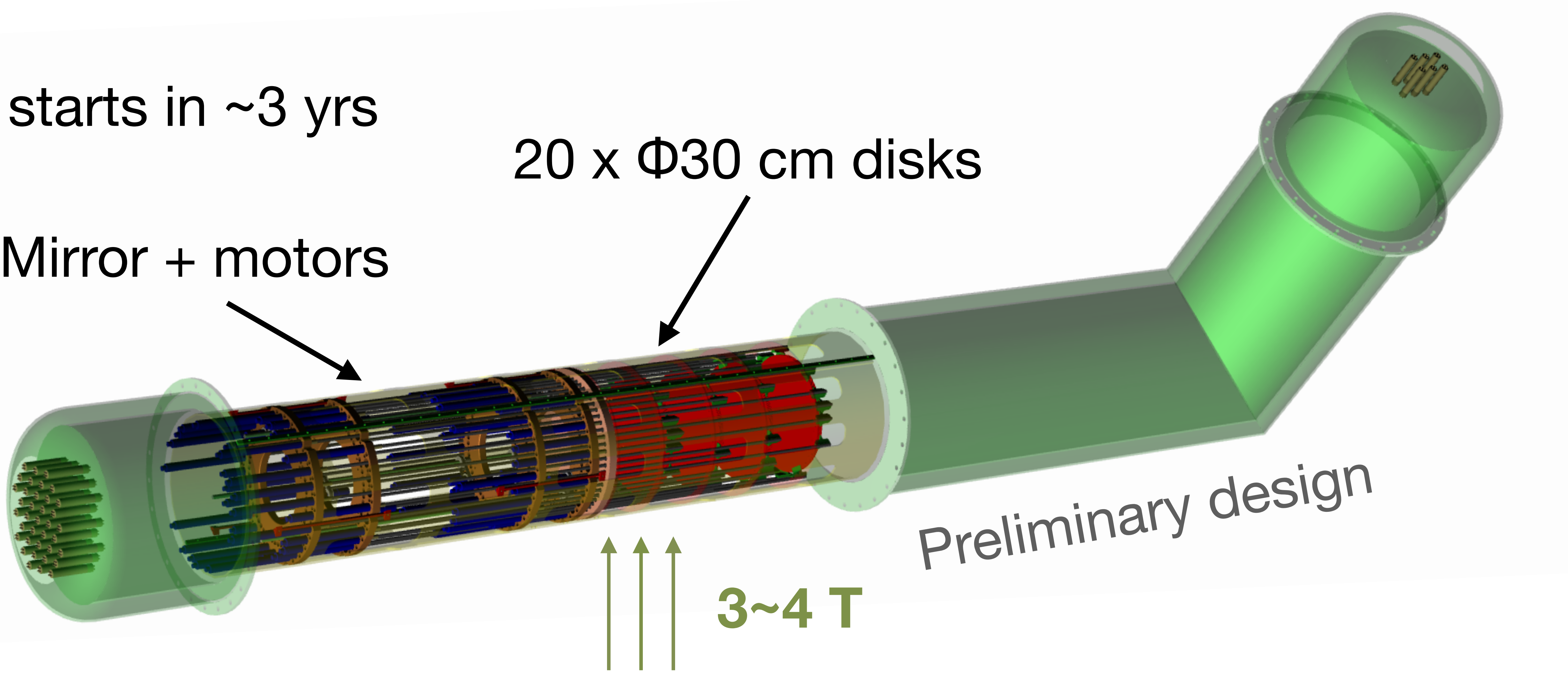
Site & infrastructure

- DESY offered HERA north hall (H1)
- Large supply of LHe for magnets
- Support for magnets' weight (~150 tons)



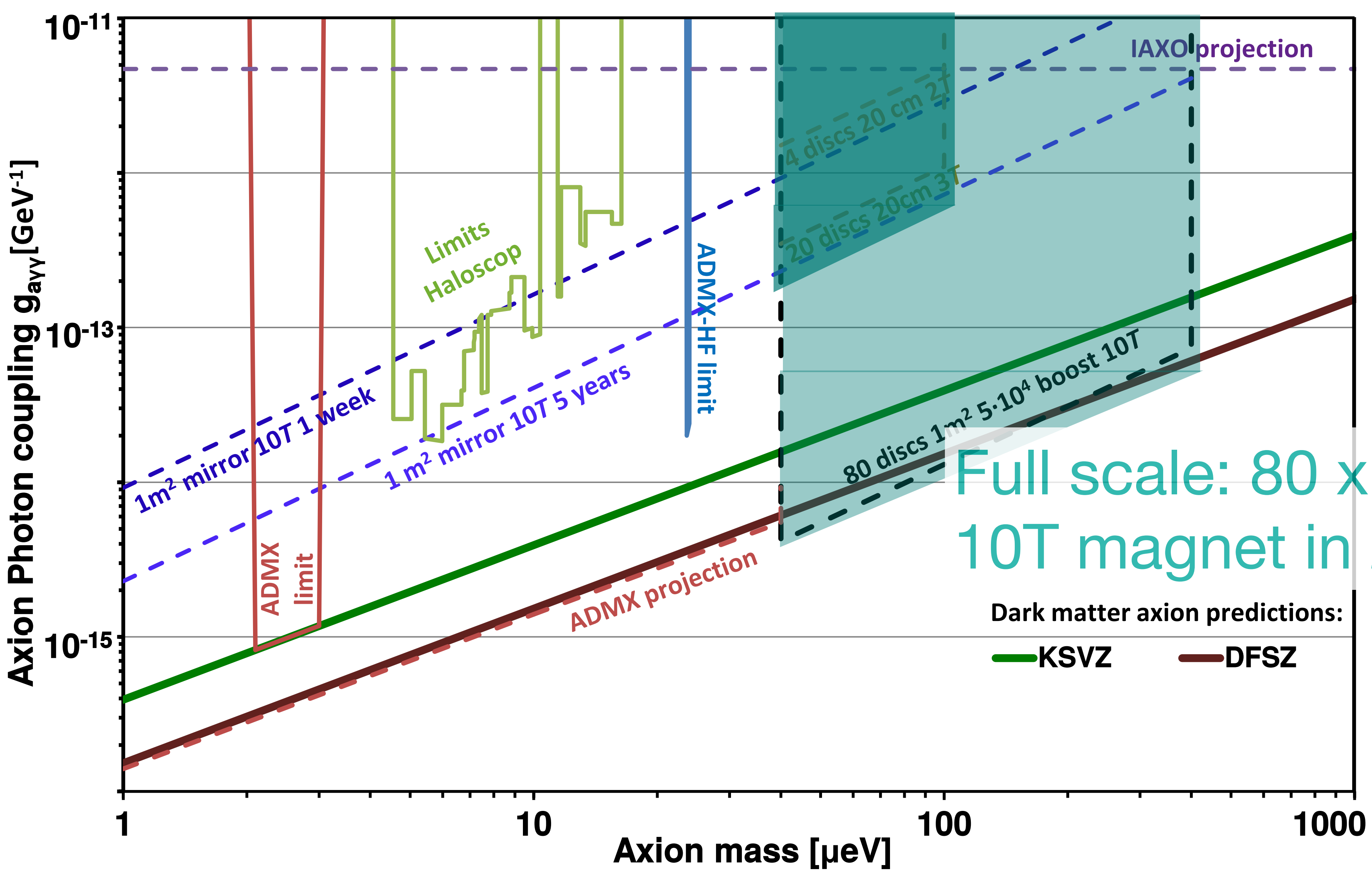
Prototype

- Feasibility test & First scientific data
- starts in ~3 yrs



Future perspective

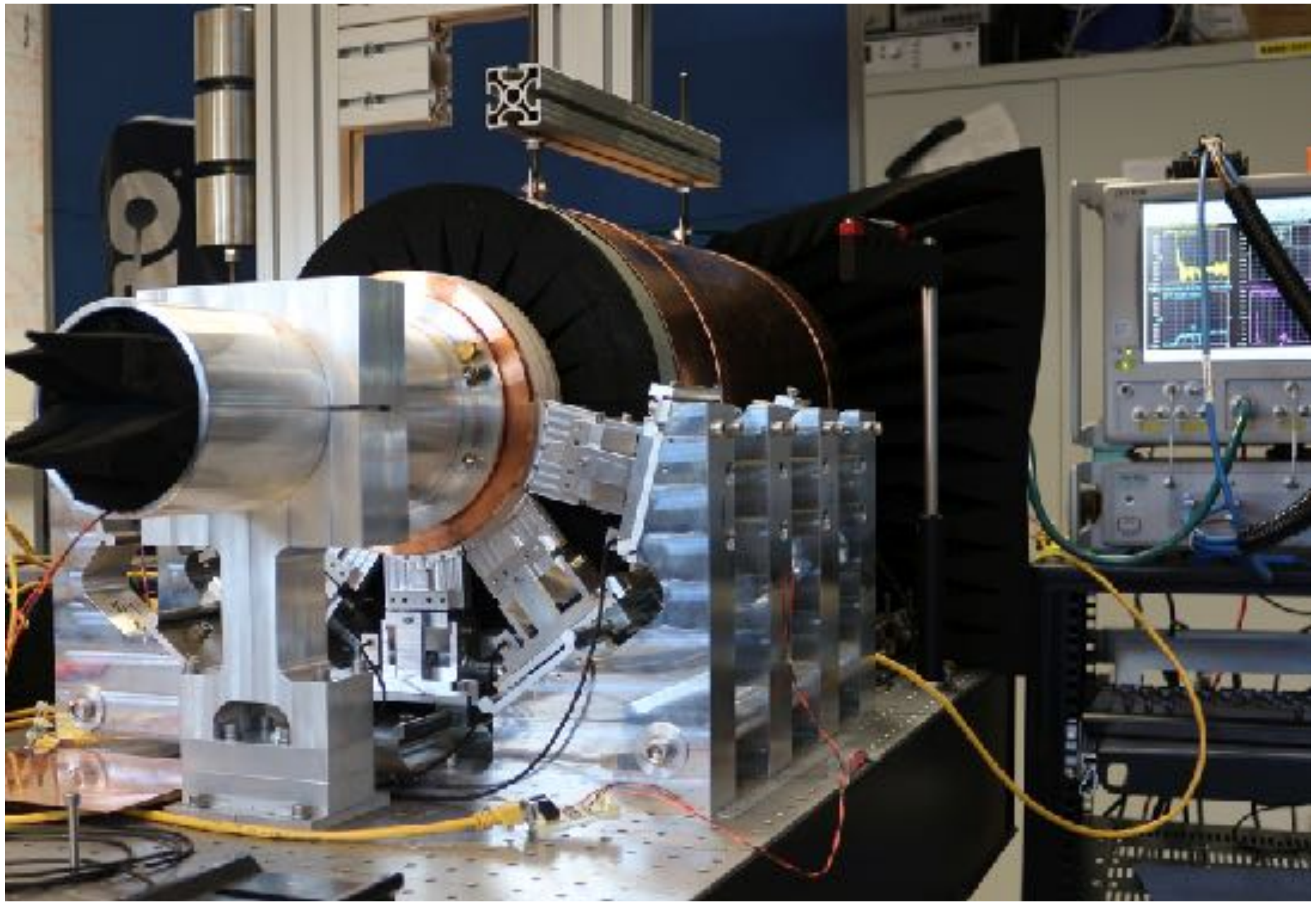
Prototype



Full scale: 80 x 1m² disks, 10T magnet in 202x?

Summary

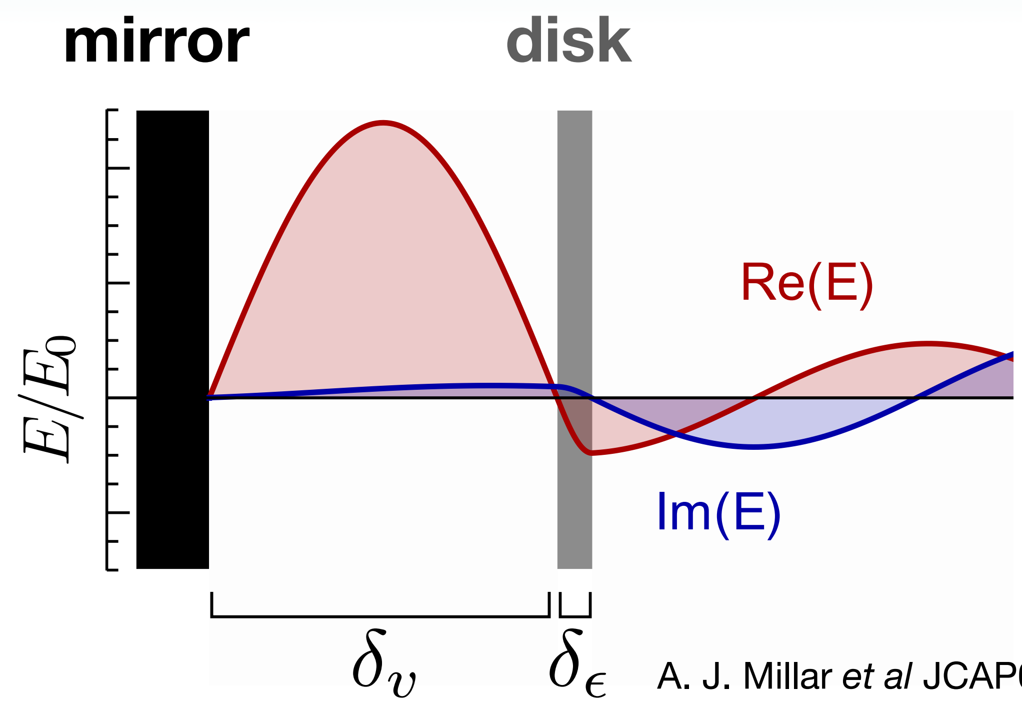
- **40—400 μeV** is an interesting target for post-inflation QCD axion search.
- **Dielectric haloscope** is a promising technique.
- MADMAX is developing, aiming to cover the parameter space.
- PRL **118** 091801
  JCAP01 (2017) 061
  MADMAX white paper



Back-up slides

Boost

- Disks + mirror **boosts** signal by $\beta = E / E_0$
- Transparent mode: $\delta = n \times d \times \nu = \pi, 3\pi, 5\pi\ldots$ constructive interference.
- Resonant mode: $\delta = \pi/2, 3\pi/2, \ldots$ disks + mirror forms a leaky resonator.
- Combined boost from both contributions.



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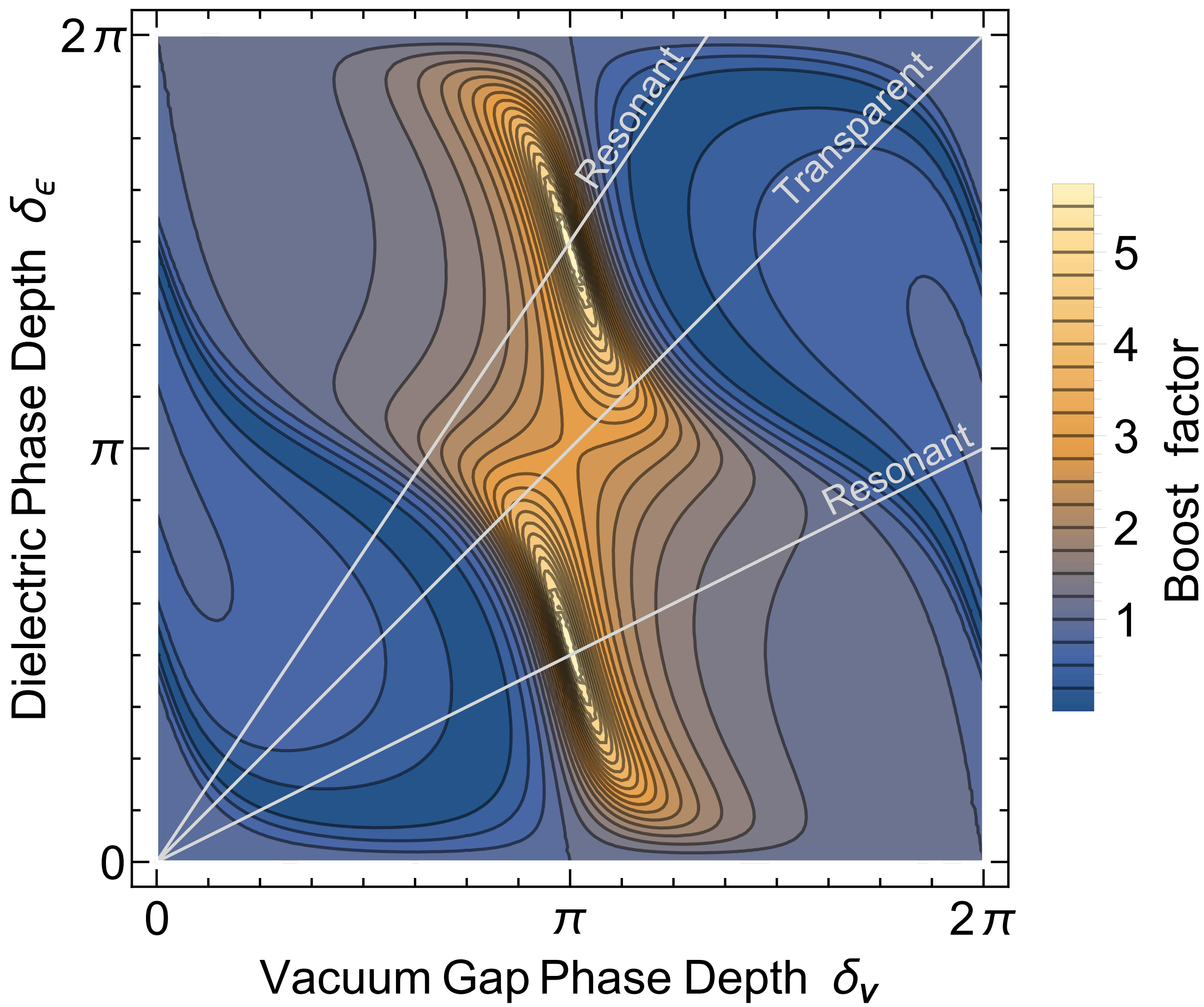
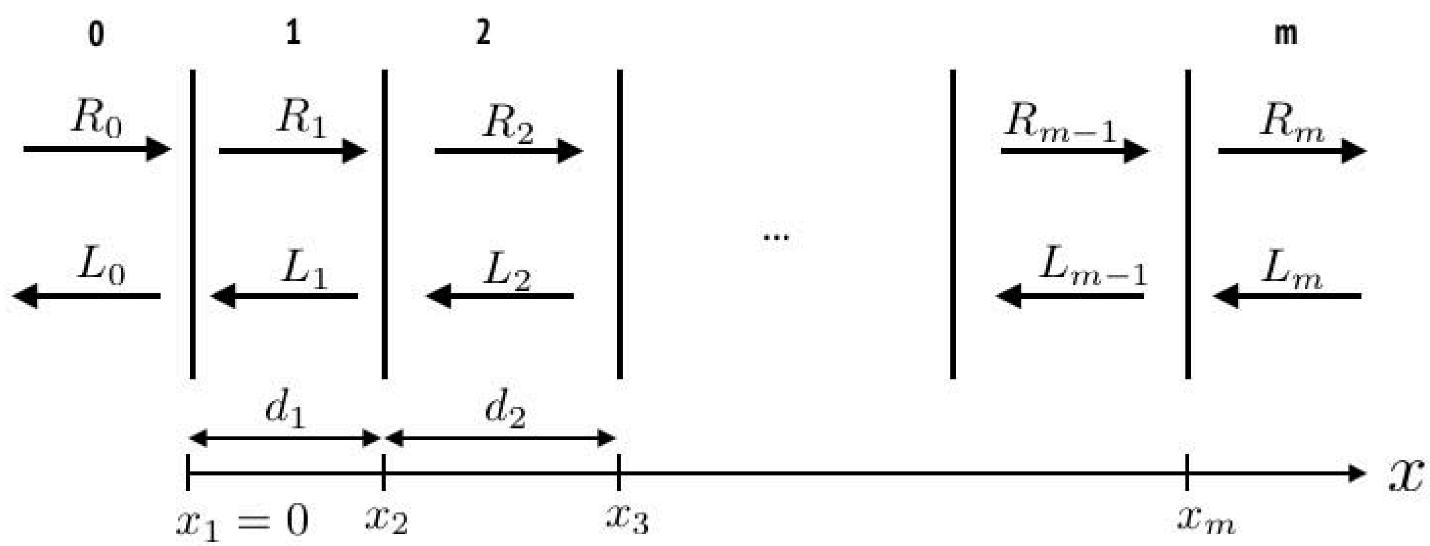


Transfer matrix

- Transfer matrix formalism w/ boundary conditions



$$E_{\parallel,1} = E_{\parallel,2} \quad H_{\parallel,1} = H_{\parallel,2}$$

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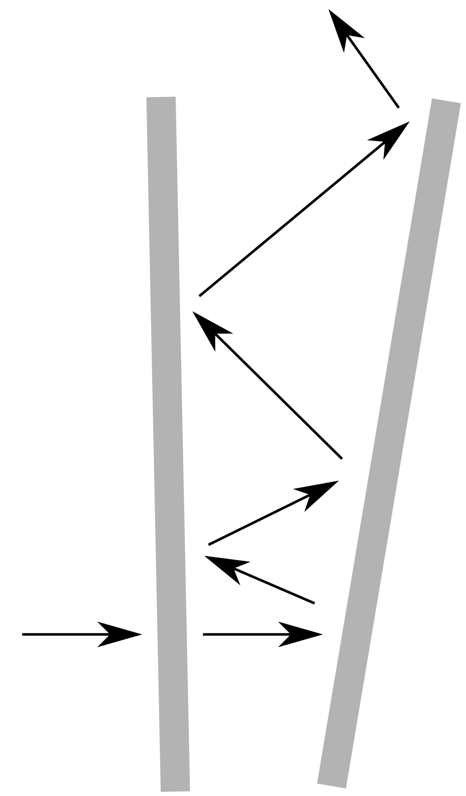
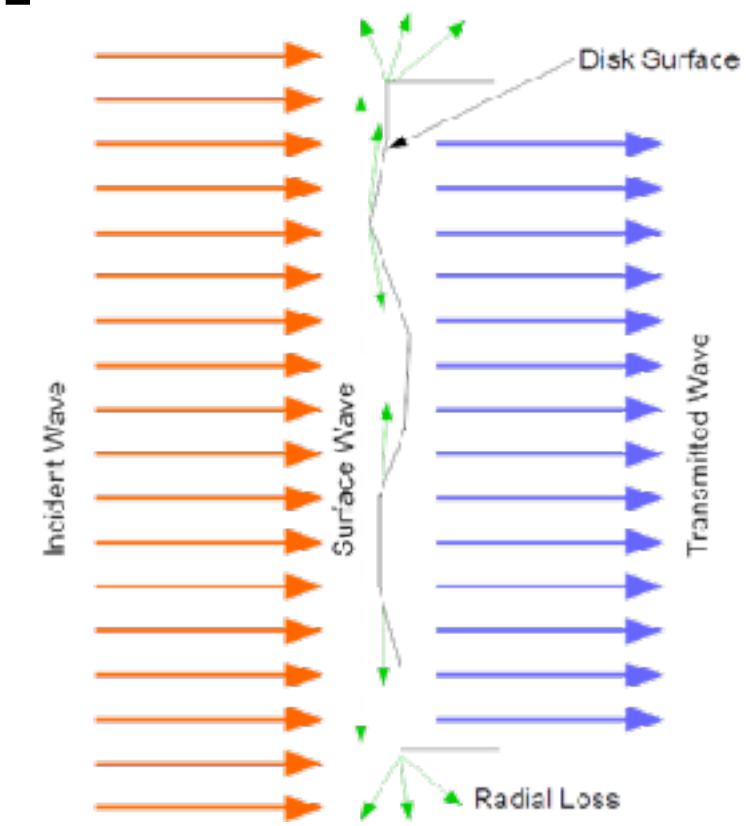
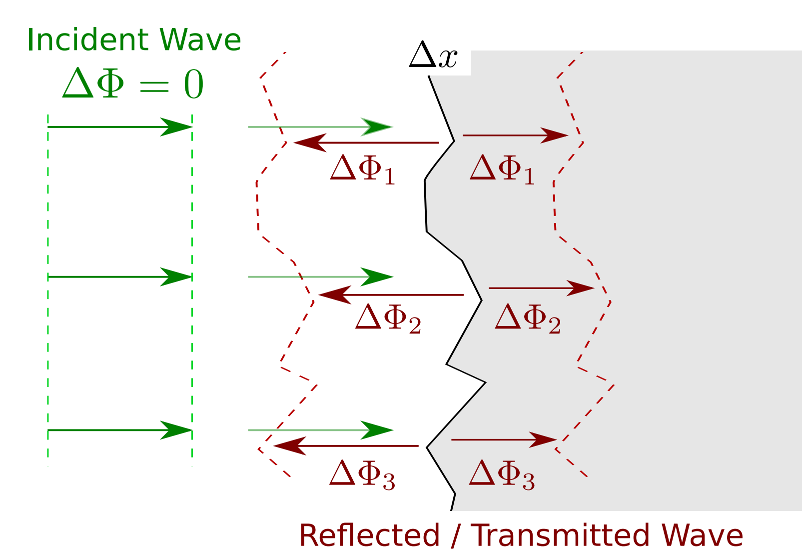
list of show-stoppers

- Unexpected losses
  - High tanδ, tilt, 3D loss, diffraction
- Components incompatible with high B field
- Mechanical precision too difficult.







Dielectric width

- For a set of dielectric disk with width d, how wide frequency can we cover?
    - 1mm 15—30GHz
    - 3mm 5—15GHz ($LaAlO_3$)

Fine-tuning search