A new QCD Dark Matter Axion search using a dielectric resonant cavity

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- **Motivation: QCD Dark Matter Axions**
- **The experimental idea**
- **First simulations & measurements, expected sensitivity**
- **Proposed magnet and prototype setup at MPI**
- **Further plans**

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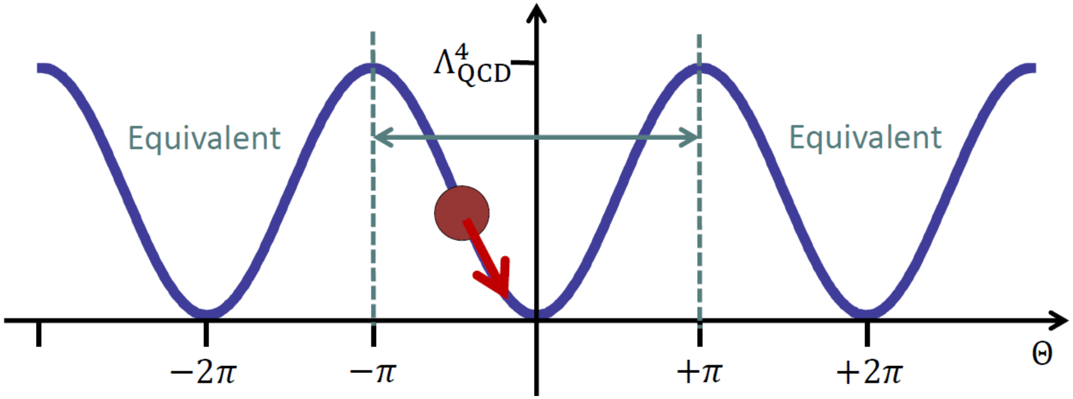
Dec. 1st 2015, München

Motivation: solution to strong CP problem

Neutron EDM very small

→Strong force (nearly?) invariant under CP while weak force CP violating

QCD vacuum energy $V(\Theta)$



Peccei Quinn mechanism:
Add dynamical, spontaneously broken field

→New pseudoscalar particle: Axion
(oscillation around minimum)

Motivation: QCD axions as cold dark matter

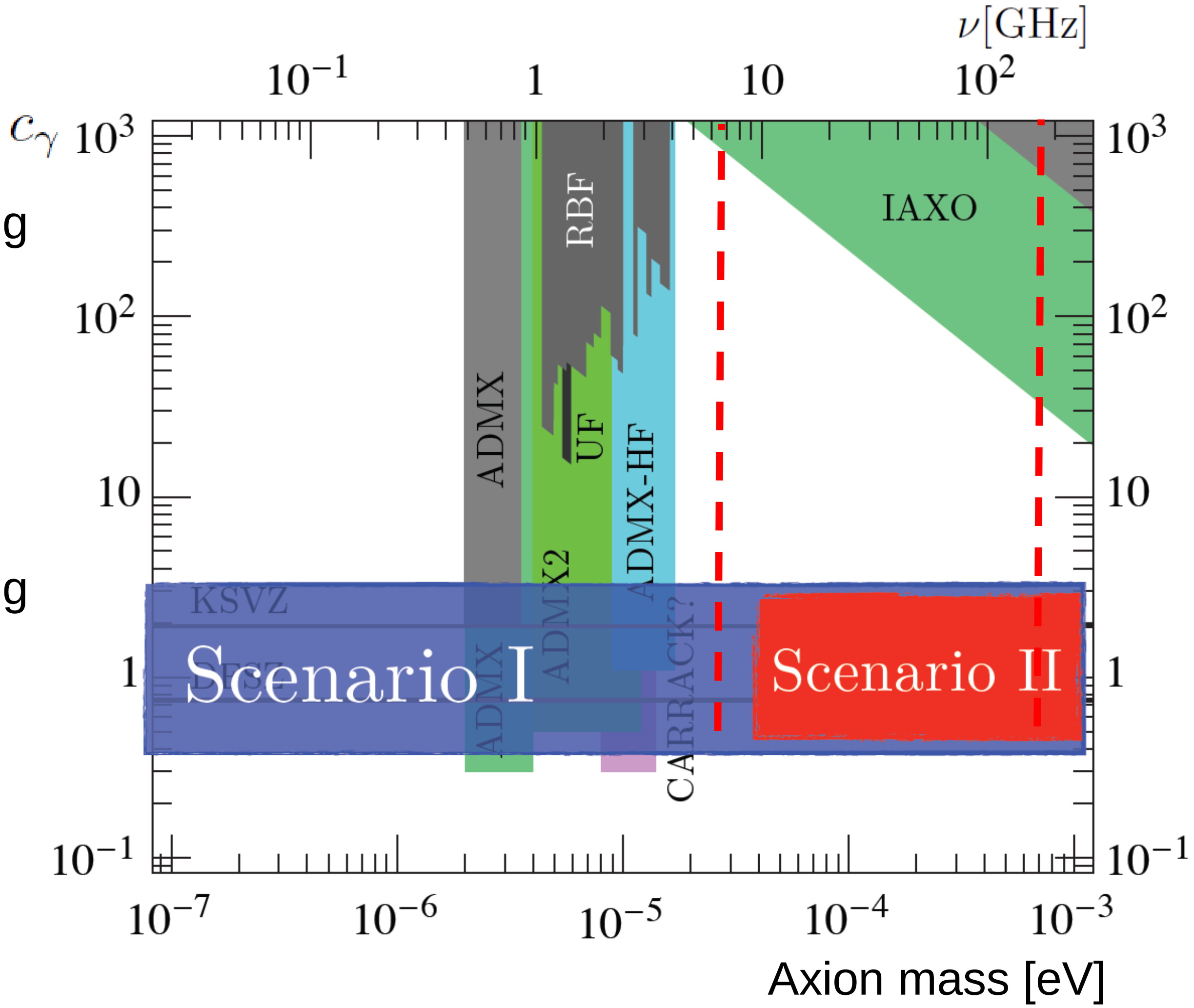
QCD Axions could also explain dark matter!

Scenario I:
Prediction for symmetry breaking before inflation

Being experimentally covered

Scenario II:
Prediction for symmetry breaking after inflation: decay of strings and domain walls

Experimentally not covered

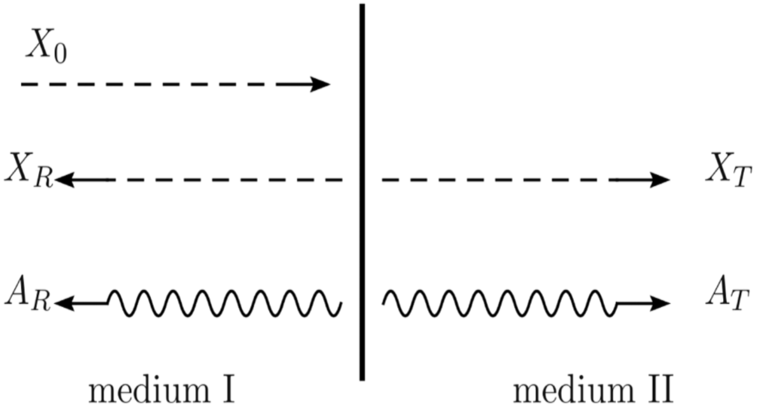


Experimental idea

Axion field mixes with photon field in a static B-field

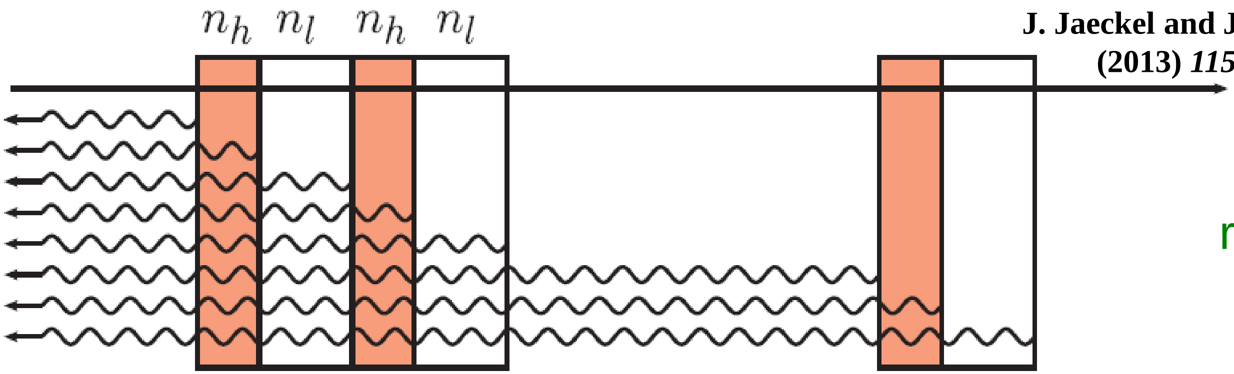
At surfaces (reflecting or change in refractive index): emission of photons in both directions

D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald JCAP 1304 (2013) 016 *[arXiv:1212.2970]*.



$$(P/A)_{\text{single surface}} \sim 2 \cdot 10^{-27}\ \text{W/m}^2 \cdot (B_{\|}/5\text{T})^2 \cdot (c_\gamma/2)^2$$

Many surfaces → resonator→ “photon boost”



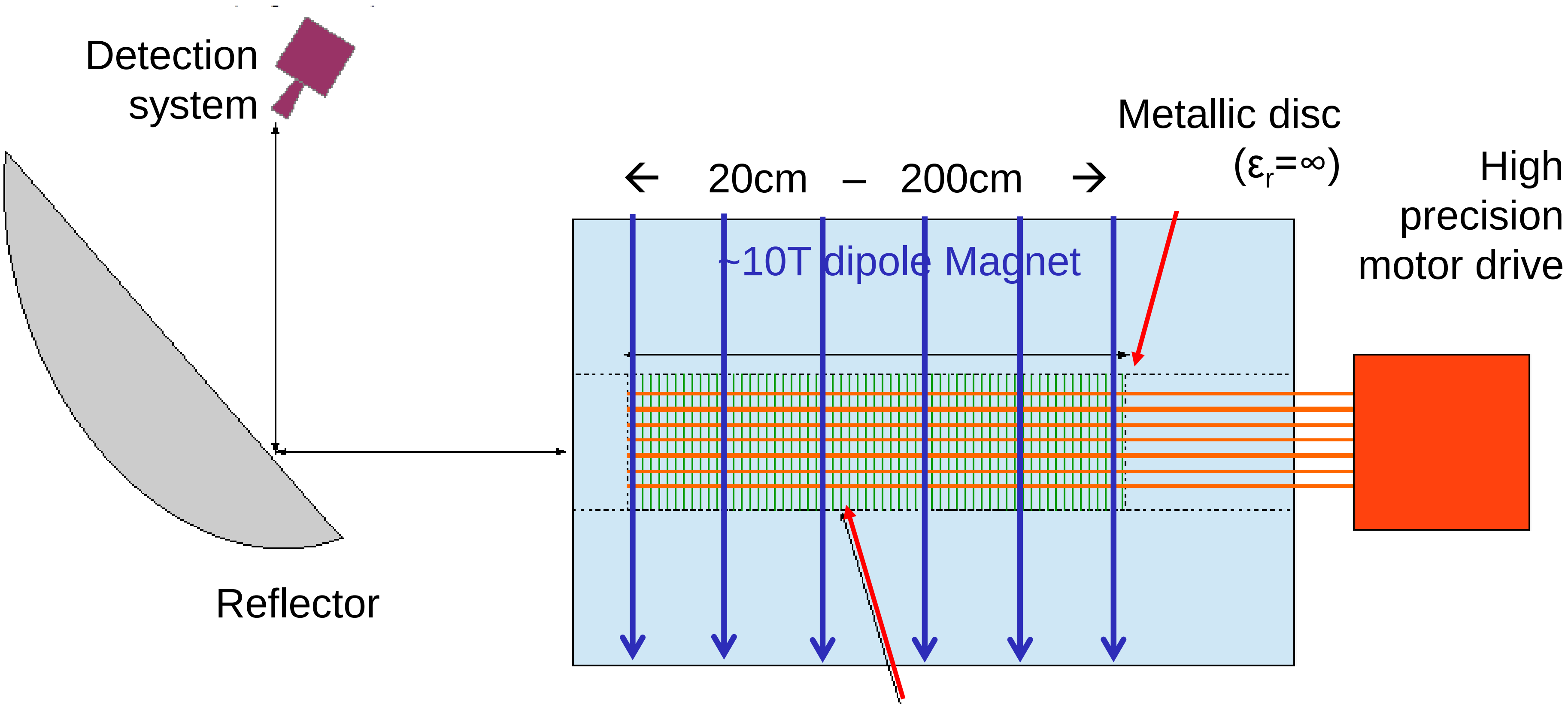
J. Jaeckel and J. Redondo, Phys. Rev. D 88 (2013) *115002 [arXiv:1308.1103]*

Boost factor: power generated in resonator/power generated on single metallic ($\varepsilon_r=\infty$) surface

$$(P/A)_{\text{resonant cavity}} \sim 2 \cdot 10^{-27}\ \text{W/m}^2 \cdot (B_{\|}/5\text{T})^2 \cdot (c_\gamma/2)^2 \cdot (\text{Boost factor})$$

Boost depends on: frequency, ε of materials, number of surfaces, displacement between surfaces, etc.

Experimental idea



Detection system

Metallic disc ($\varepsilon_r=\infty$)

← 20cm – 200cm →

High precision motor drive

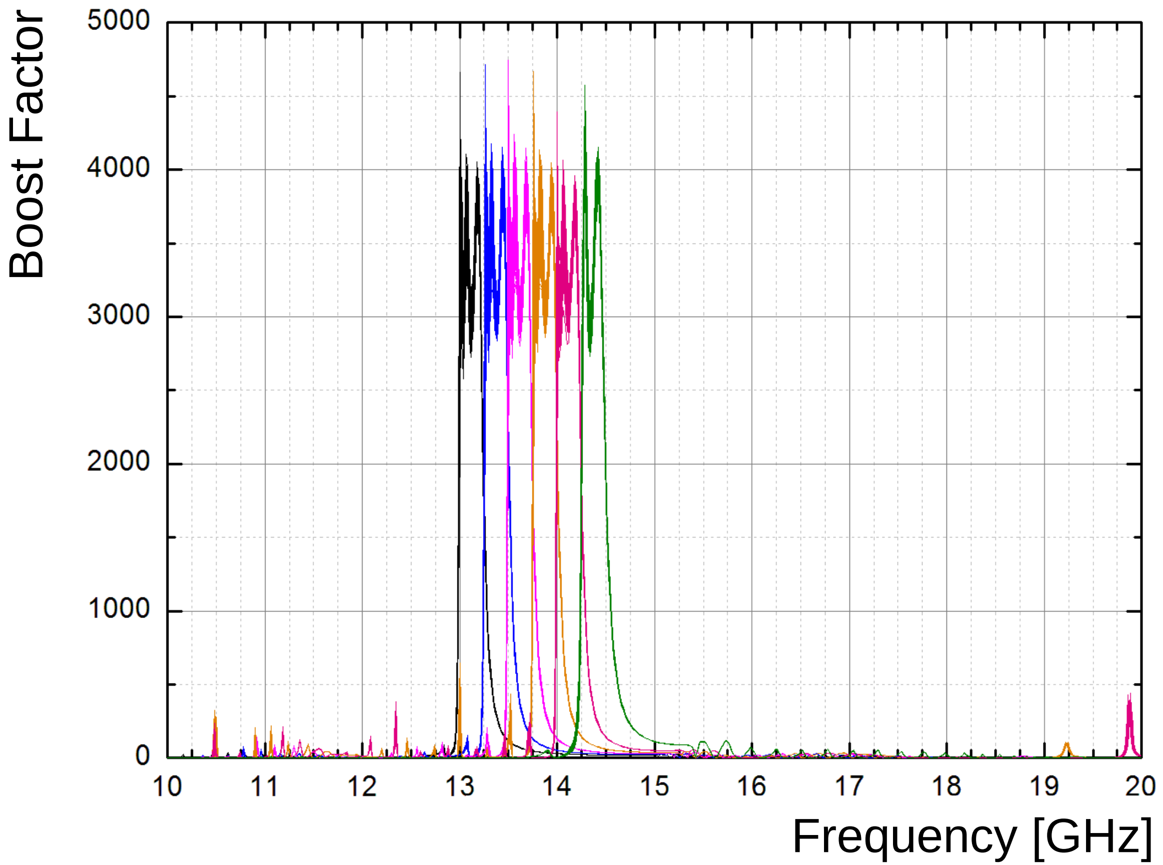
~10T dipole Magnet

Reflector

Resonator with 80 high ε plates, spacing ~mm to cm range for boost in the frequency band 10 to 100 GHz

First simulations: the boost factor

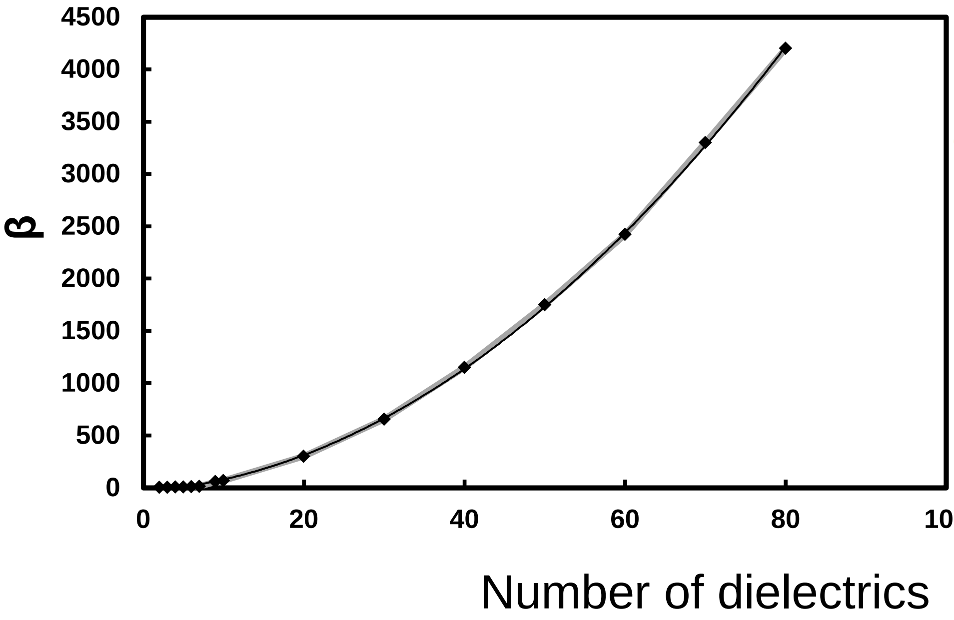
20 plates with $\varepsilon_r = 24$ ($LaAlO_3$)

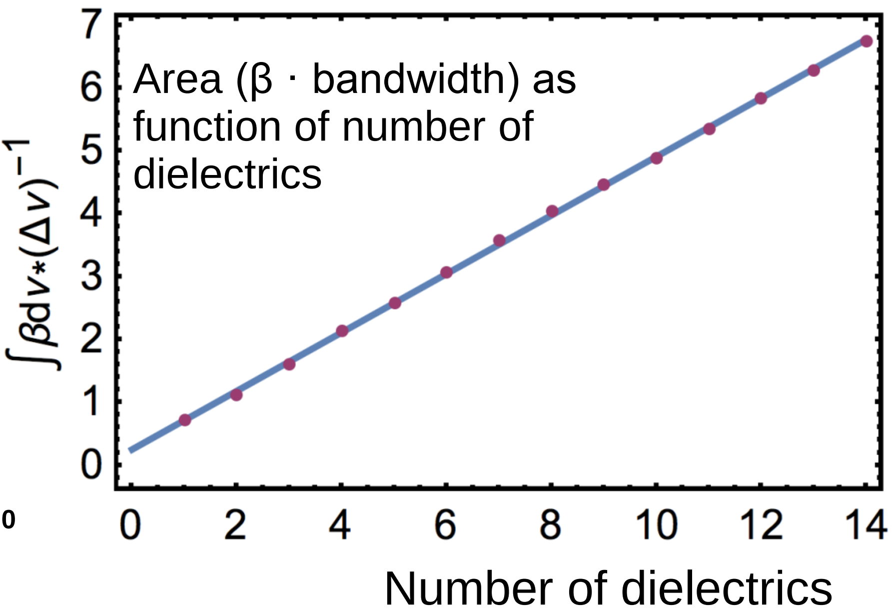


Bandwidth per setting: ~250MHz

Precision of placement of high ε plates needed: ~few μm

First simulations: the boost factor





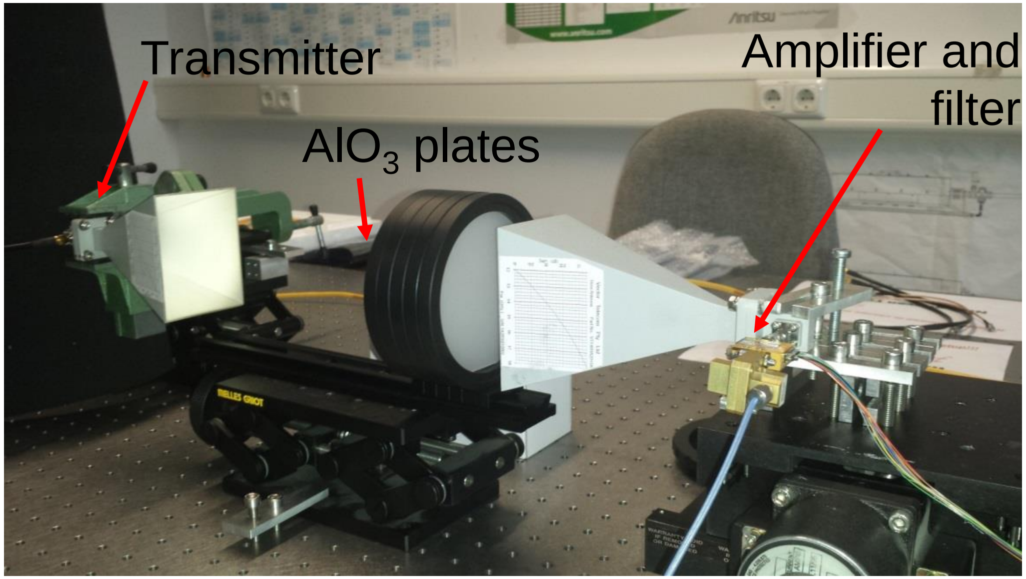
Area (β · bandwidth) as function of number of dielectrics

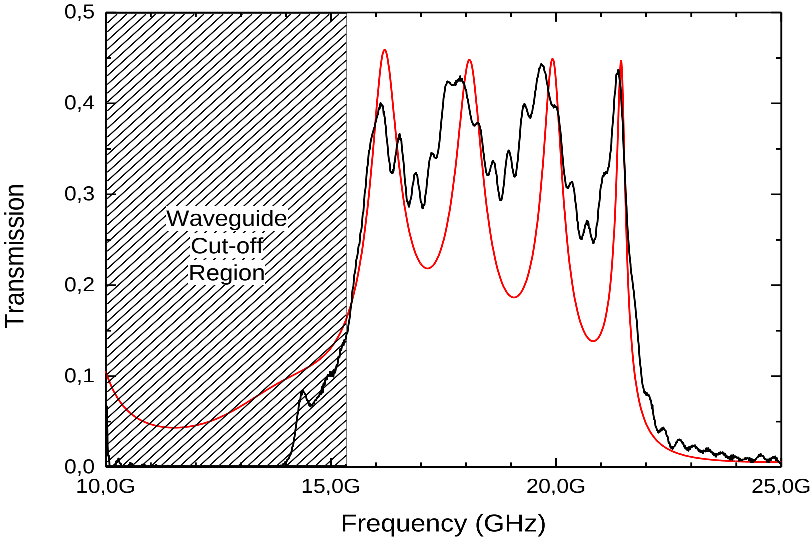
- Maximum boost factor scales ~quadratically with number of discs
  - Area of boost peak scales ~linearly with number of discs

Simulations suggest: disc placement (80 discs) with precision of few µm is enough to achieve β~10^5 with a bandwidth of tens of MHz

Boost factor can be probed by reflectance and transmittance measurements

First measurements: transmission

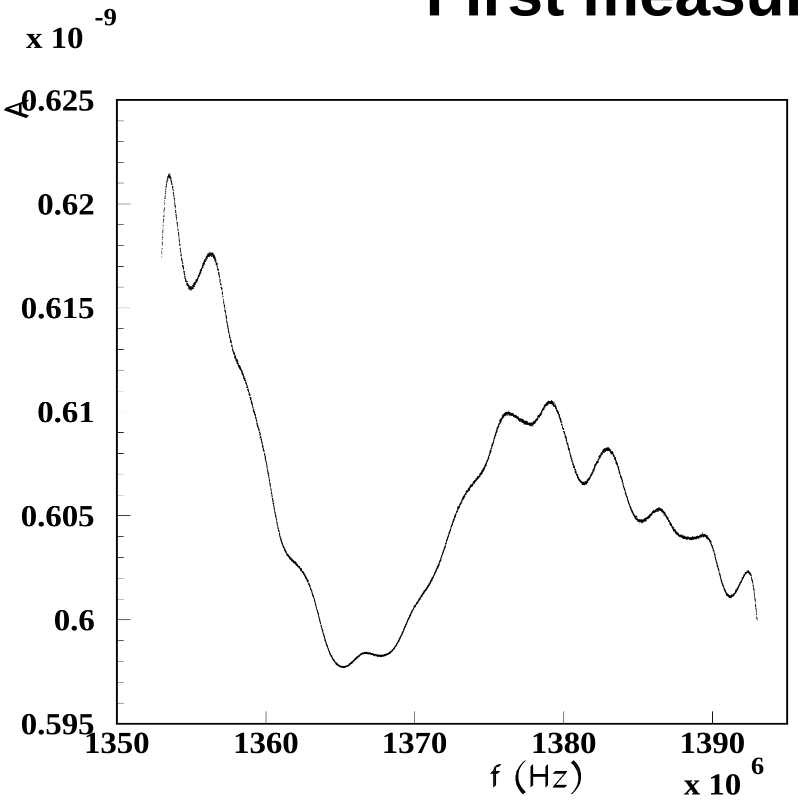


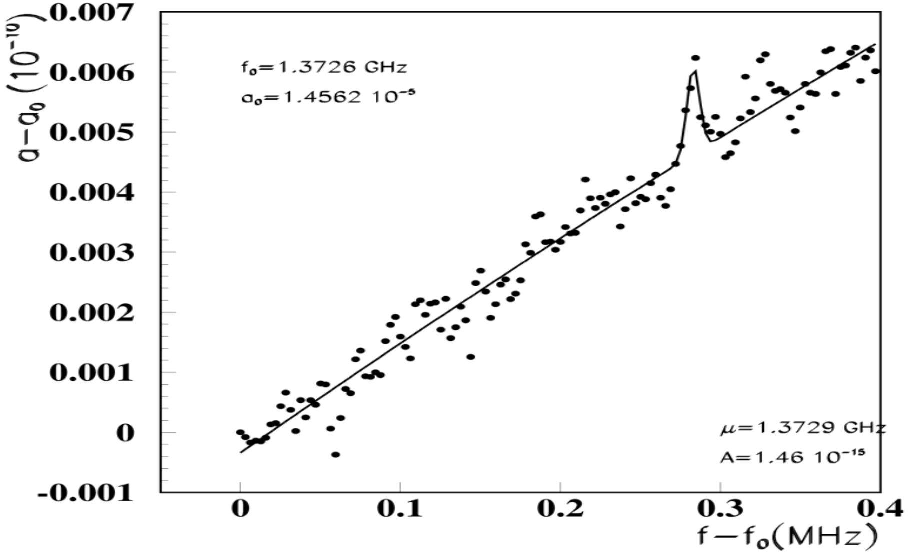


- 5 AlO$_3$ discs with diameter 100mm positioned within uncertaintiy ~ 1mm
- Disc positions determines **transmission, reflection** and **boost factor** (**β**) curves
- Prediction (red) fits measurement (black) well.

→ Verification of boost by transmission measurement!

First measurements: sensitivity





- Inject fake axion signal with **$3{\cdot}10^{-21}$** W power
- Mesurement for one week (integrate signal): Receiver at Room Temp.

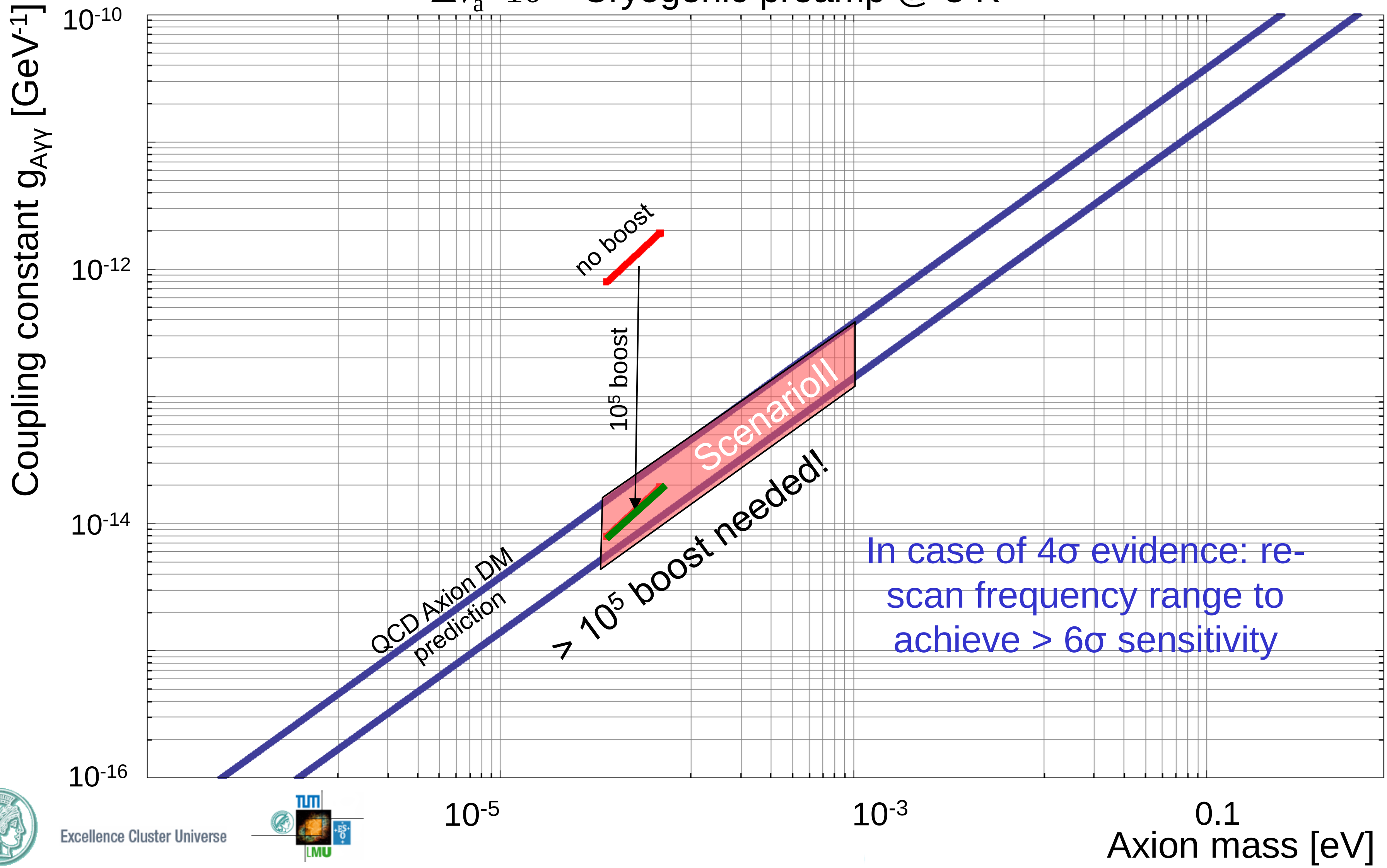
→ Independent „blind“ analysis
→ found > 6σ signal succesfully

→ At LHe: noise level factor 100 better
→ Sensitivity at the level of 10^{-23} W expected

First measurements: sensitivity

Expected 4σ detection sensitivity with and without boost

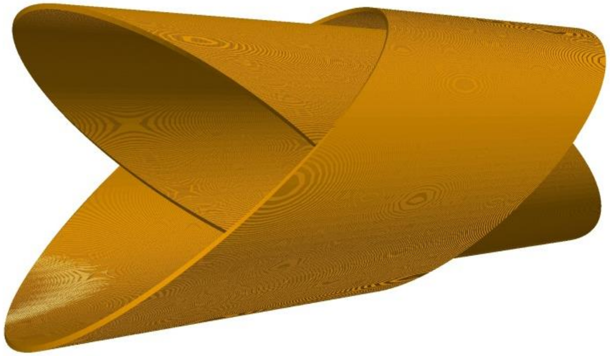
for 80 discs, 1m^2 surface, 10T B-field, τ=200h, 50MHz boost andwidth, $\Delta\nu_a = 10^{-6}$; Cryogenic preamp @ 8 K



In case of 4σ evidence: re-scan frequency range to achieve > 6σ sensitivity

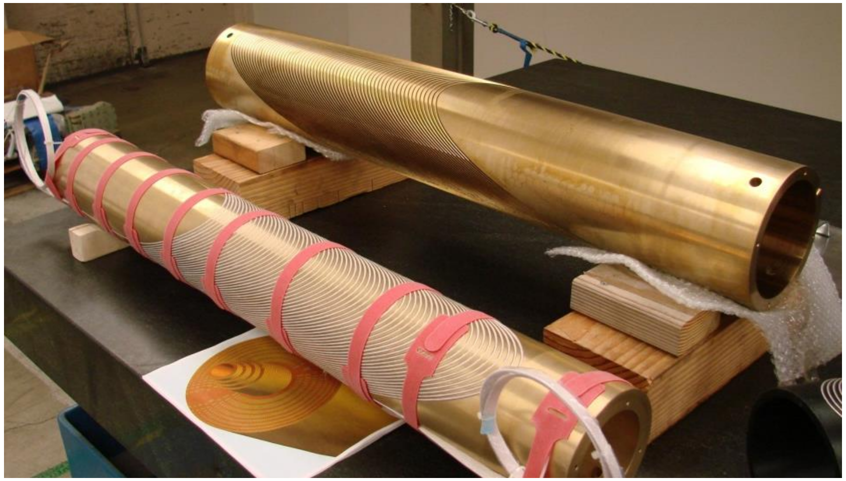
Idea for ~10T magnet

The Canted-Cosine-Theta of the Superconducting Magnet Group of the Lawrence Berkeley National Laboratory

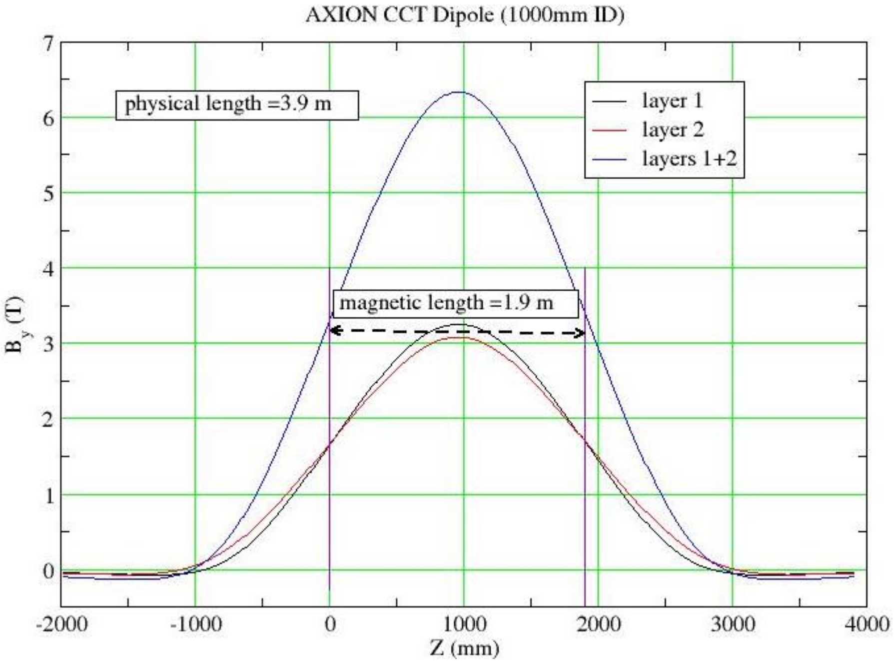


Two superimposed coils, oppositely skewed, achieve a pure cosine-theta field and eliminate axial field.

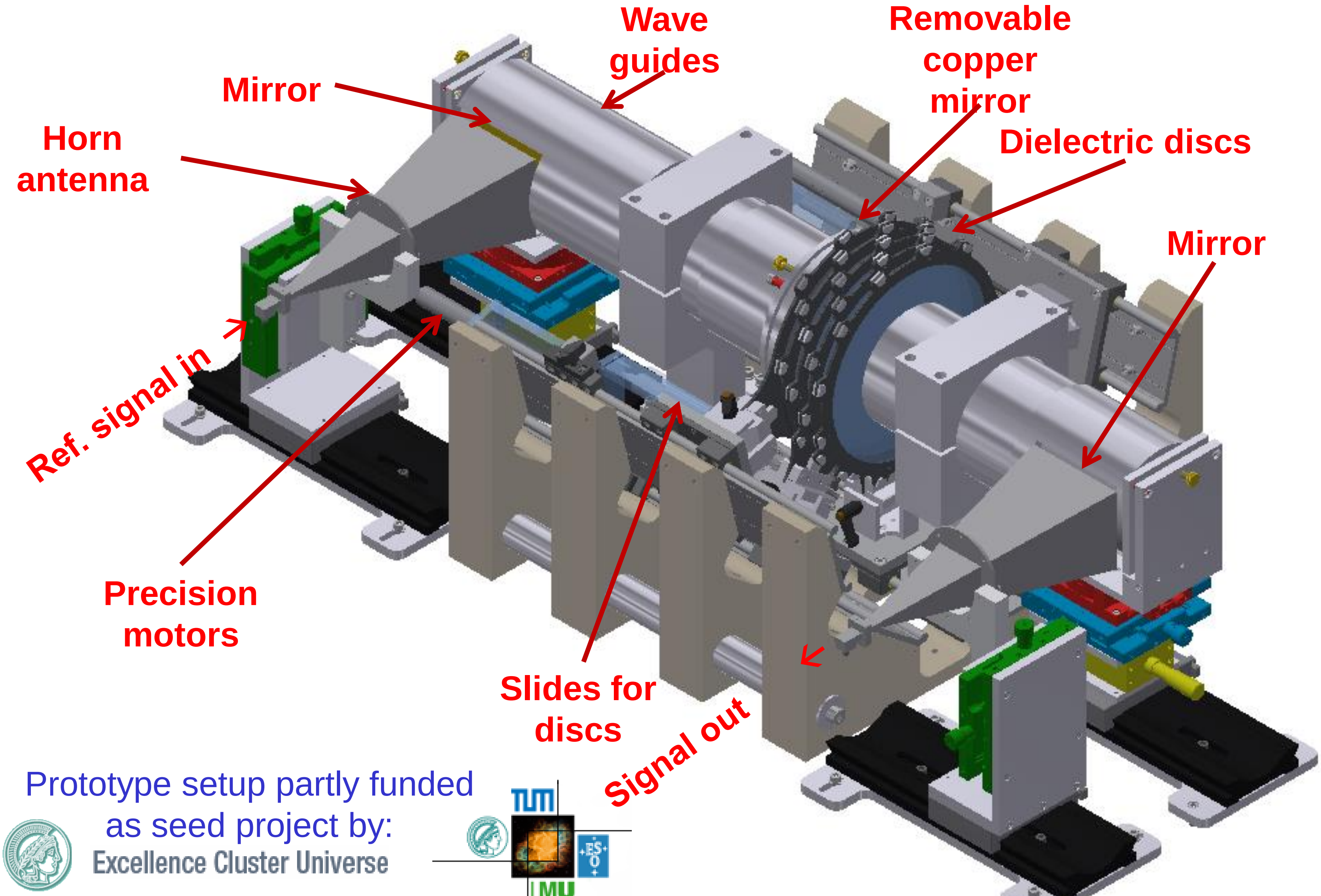
Inner coil structure



Mandrels integrate windings and structure, assemble poles and are part of the reaction and impregnation tooling.



First prototype setup at MPI



Prototype setup partly funded as seed project by:
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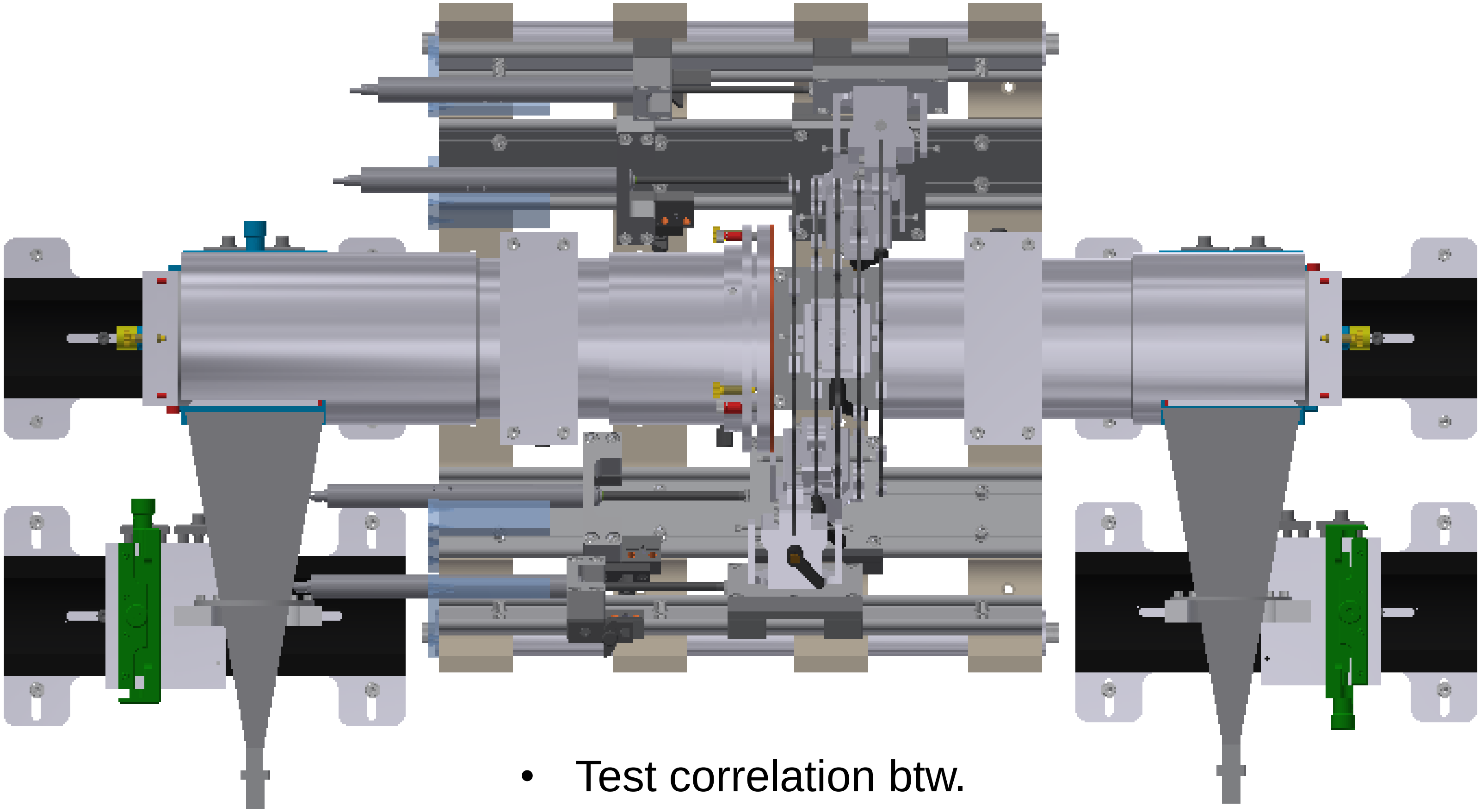
First prototype setup at MPI



- Test correlation btw. transmission and boost factor
- Test needed disc prescision
- Evaluate uncertainties
- R&D on tiling

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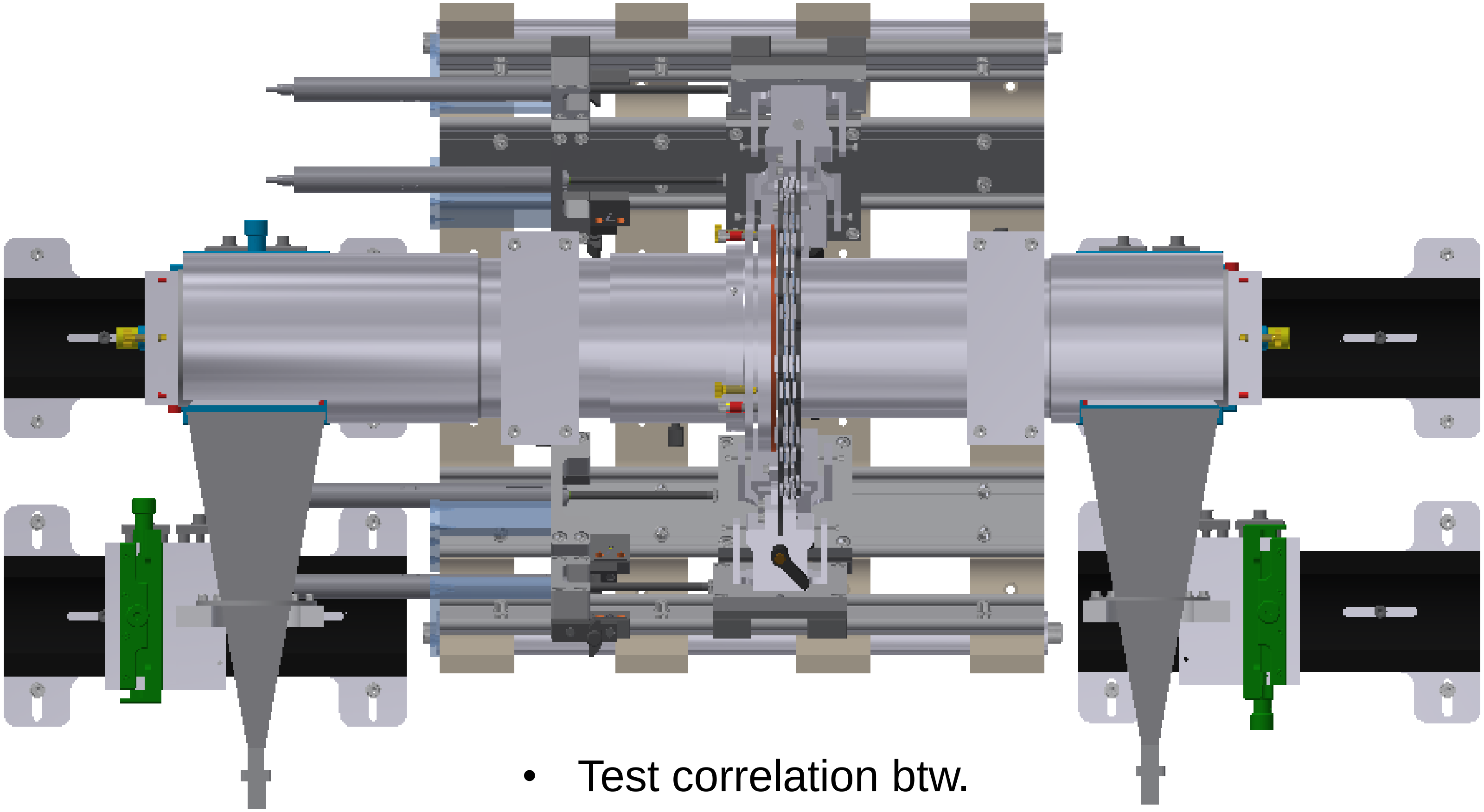
First prototype setup at MPI



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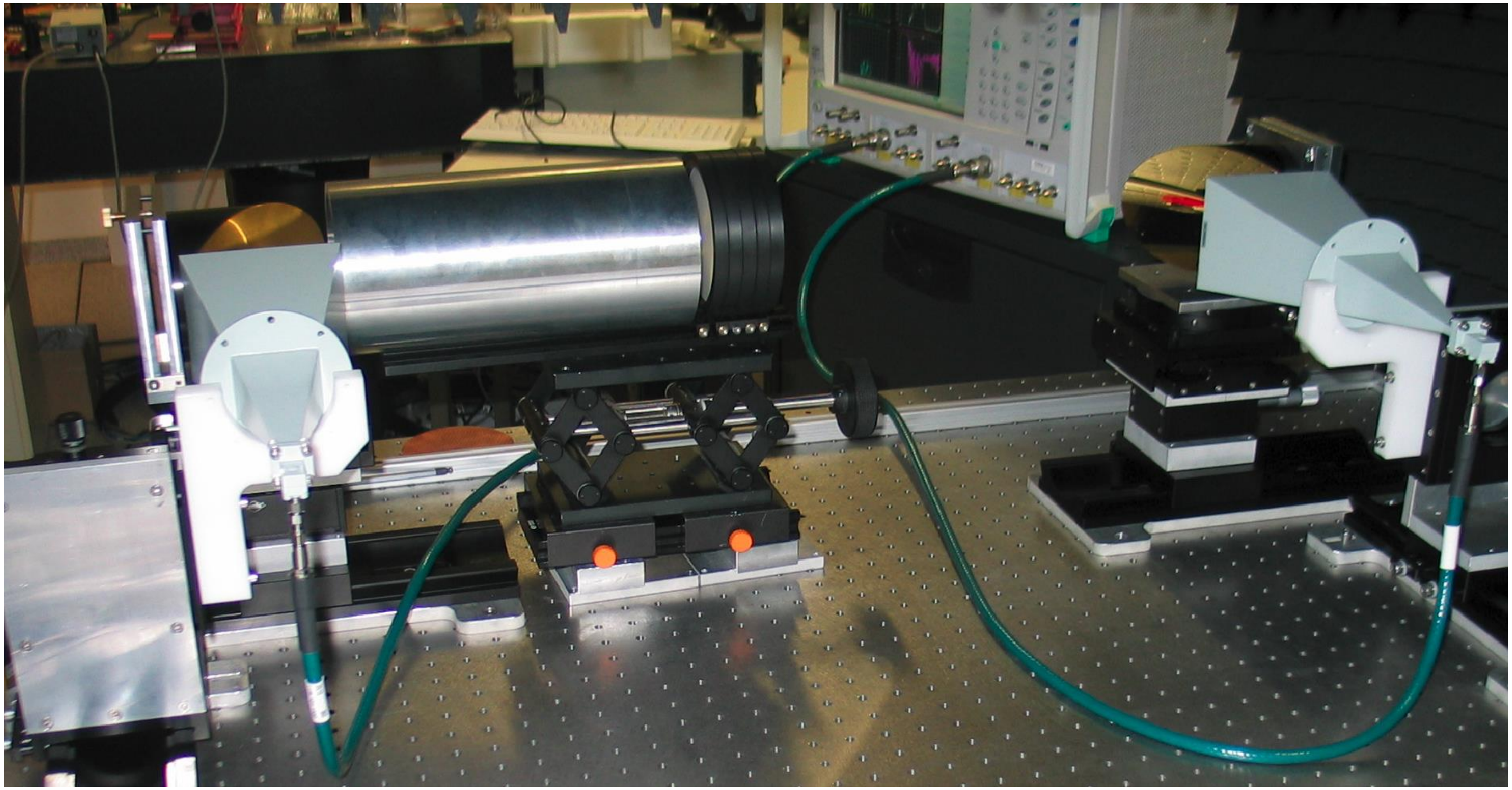

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Further plans

2016:

- Finish first test measurements at room temperature at MPI
- Test noise of preamplifier at LHe temperature
- Find additional collaborators for specific parts of project
- Start design of 10T magnet
- Develope technique to cover frequencies above 30 GHz
- R&D on production of large diameter high-ε discs

2017-2018:

- Demonstrate low noise performance, operation with many discs, scalability to 1m diameter, work in ~10 T environment
- Build prototype with preamp in LHe in cryostat and resonator in magnetic field

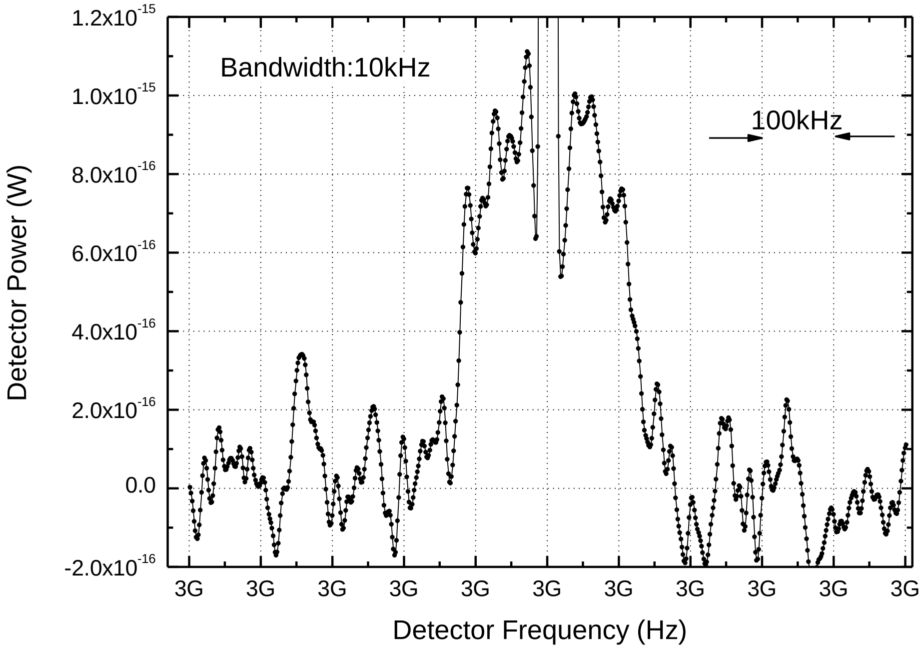
2019:

- Start building full scale experiment

CONCLUSIONS

- Axions in the mass range tens to hundres of µeV could solve strong CP problem AND Dark Matter
- Open dielectric resonator with 80 discs might boost axion to photon conversion rate by 5 orders of magnitude
- First measurements with low noise preamp promising: With 80 big enough discs in 10 T B-field: sensitivity enough to probe models
- 10 T dipole magnet with 1m inner hole „very doable“
- Proof of principle setup being produced

Preparations: detectable power

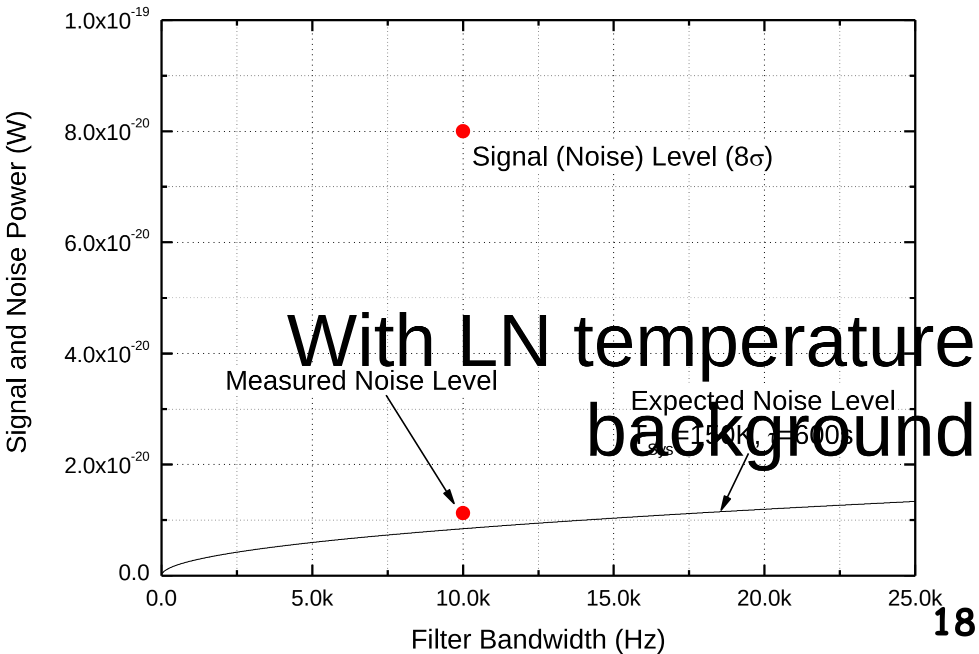


Attenuated signal (70dB in LN) detected with 8σ significance

→ Proved that detection system can be operated at the physical limit

Extrapolation of sensitivty for cryo detector at 8K:

10^{-20} W/Hz$^{1/2}$ (NEP)



With LN temperature background

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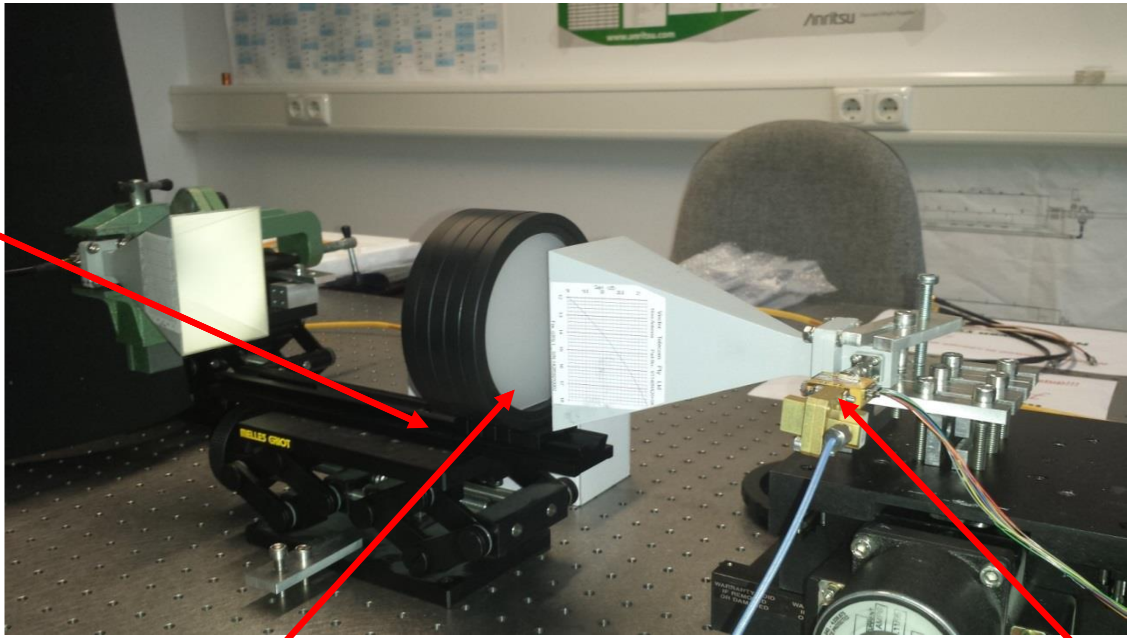
Proposed seed project

Significant improvement of existing setup necessary:

High precision motors to test ~µm precision of relative plate positioning



Different high ε plates with diameter 200mm to test transmission behavior for different ε:

→ cross check simulations, ε dependence, tiling of plates, precision of geometries

Cryogenic low noise amplifier for reference measurements