# MADMAX: **MA**gnetised **D**isk-and-**M**irror **A**xion e**X**periment

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for the MADMAX collaboration

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DESY, Hamburg, Germany
University of Zaragoza, Spain

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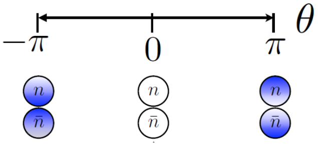
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

# The Strong CP-Problem

QCD allows for a term

$$\mathcal{L} = -\,\theta \frac{g_S}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a, \qquad \theta = -\pi \ \dots\ \pi$$

**but experimentally:** $|\theta| < 10^{-10}$ (neutron electric dipole moment)

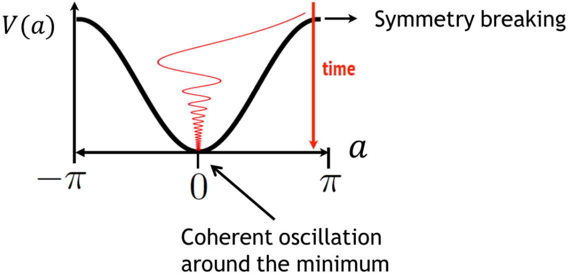


# The Strong CP-Problem

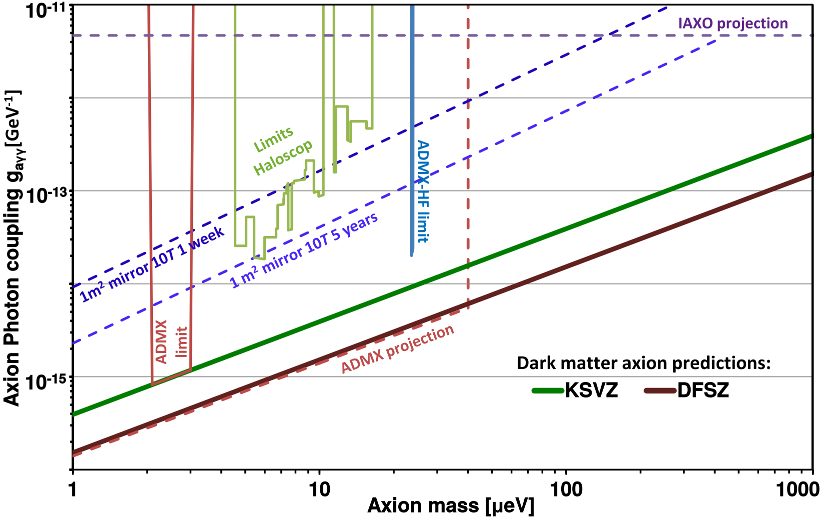
make $\theta$ a dynamic field: $\theta \to a(t;\mathbf{x})$ (Pecci-Quinn 1977)

$$\mathcal{L} = -\, a\frac{g_S}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a + \frac{1}{2}\partial_\mu a\, \partial^\mu a$$

rolldown to CP conserving limit:



# The Axion - Parameterspace



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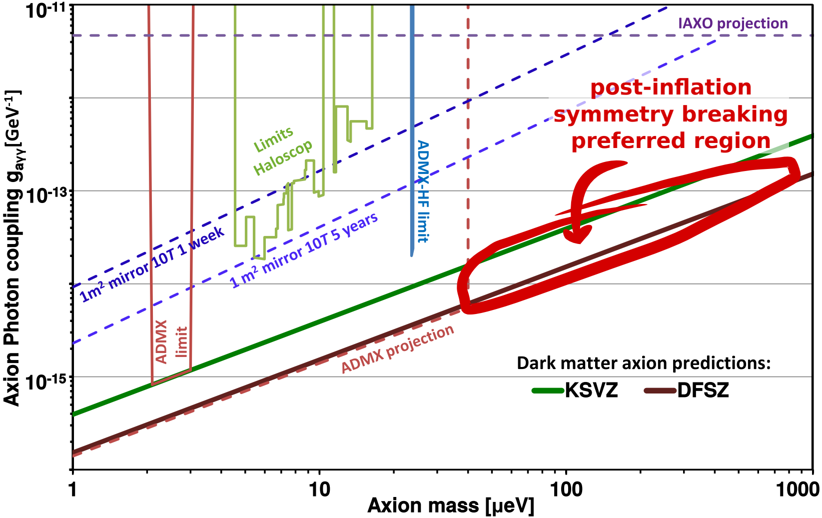


# Axion Electrodynamics

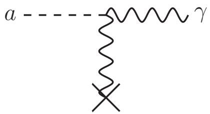
$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - j^{\mu} A_{\mu} + \frac{1}{2} \partial_{\mu} a \, \partial^{\mu} a - \frac{1}{2} {m_a}^2 a^2 \quad - \quad \frac{g_{a\gamma}}{4} a \; F_{\mu\nu} \tilde{F}^{\mu\nu}$$

Solve EOM under external magnetic field $\mathbf{B}_e$:

$$\epsilon \nabla \cdot \mathbf{E} = \rho - g_{a\gamma} \mathbf{B}_e \cdot \nabla a$$

$$\nabla \times \mathbf{H} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma} \mathbf{B}_e \dot{a}$$

$$\ddot{a} - \nabla^2 a + {m_a}^2 a = g_{a\gamma} \mathbf{E} \cdot \mathbf{B}_e$$

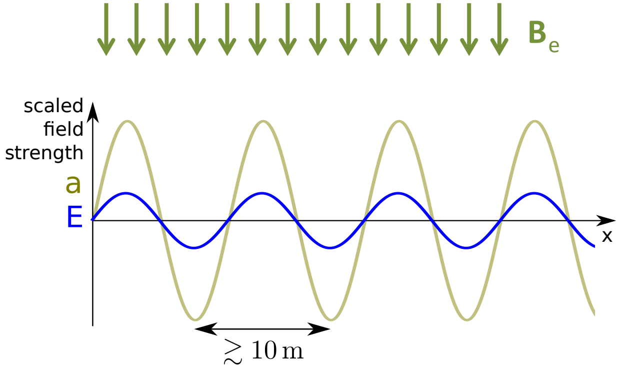



Primakoff process

Axion induced electric field:

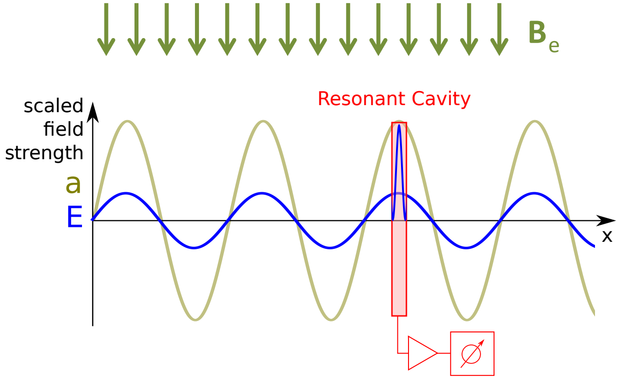
$$\mathbf{E}_a = -\frac{g_{a\gamma} \mathbf{B}_e}{\epsilon} a = 1.3 \times 10^{-12} \, \mathrm{V\,m^{-1}} \times \left( \frac{B_e}{10\,\mathrm{T}} \right) \frac{C_{a\gamma} f_{DM}^{1/2}}{\epsilon}$$

# Axion - Photon Mixing




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

# Axion - Photon Mixing

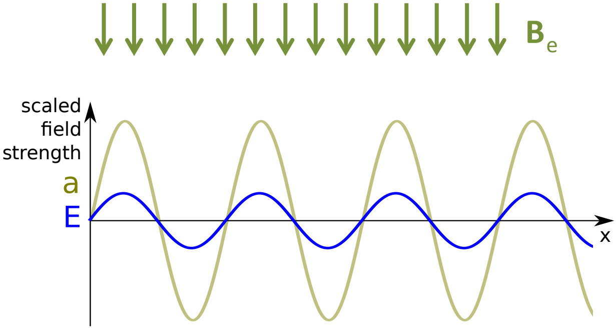



$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$

$$P_{\rm sig} = \left(B^2 Q\ V\ C_{nml}\right)\left({g_{a\gamma\gamma}}^2 m_a \rho_a\right)$$

$Q$: Quality Factor, $C_{nml}$: mode factor

# Axion - Photon Mixing




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

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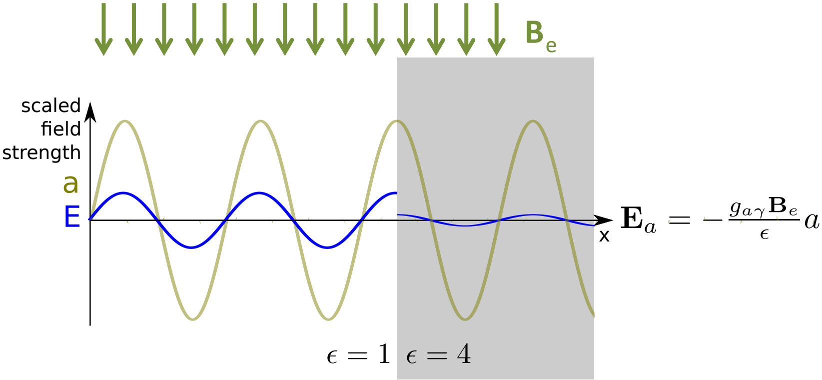

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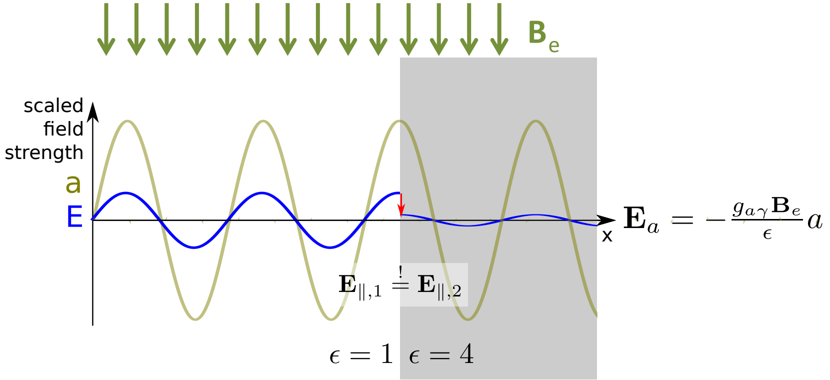

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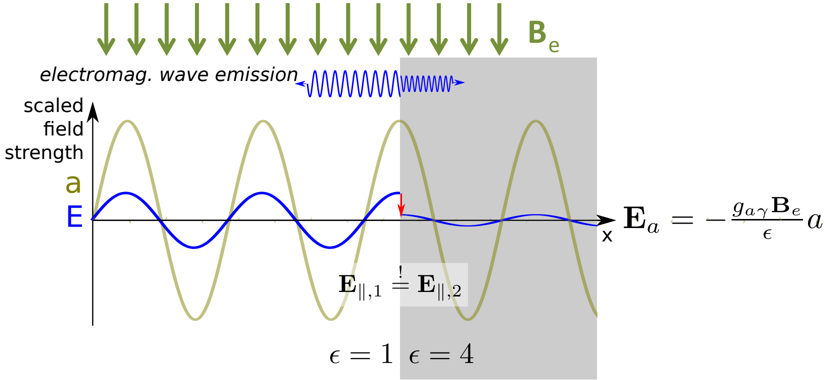
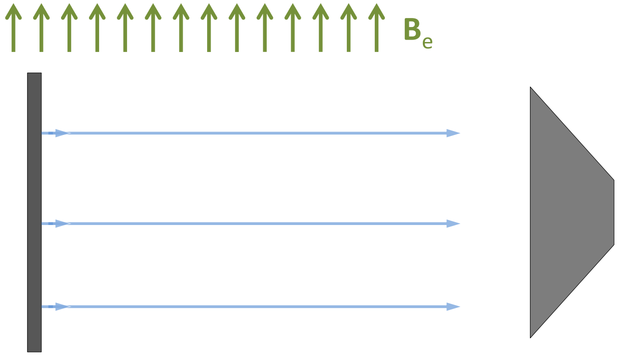


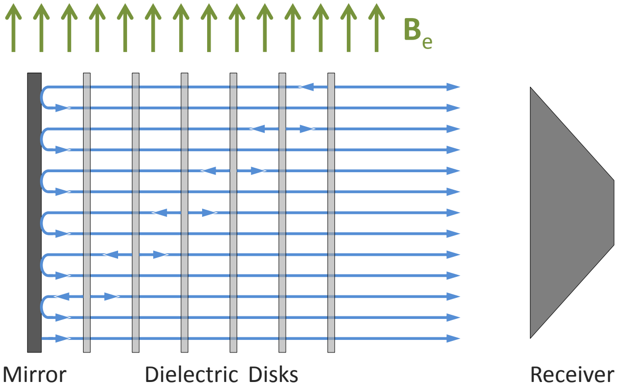

$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 {C_{a\gamma}}^2 \cdot f(\epsilon_1, \epsilon_2)$$

# The MADMAX Idea




$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 {C_{a\gamma}}^2 \cdot 1$$

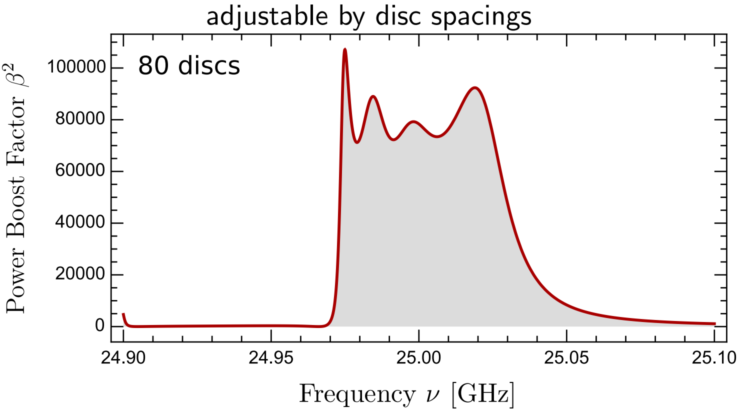
# The MADMAX Idea




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

$\beta^2$: power emitted by booster / power emitted by single mirror ($\epsilon = \infty$)

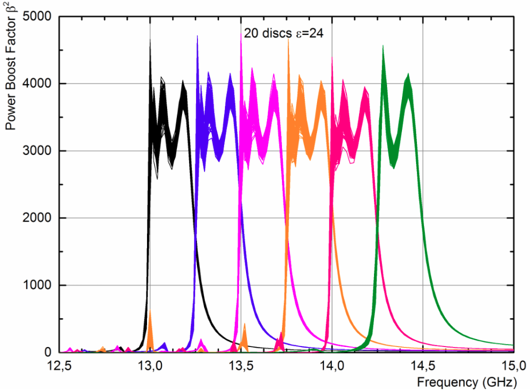
# Power Boost Factor $\beta^2$




**Wide Bandwidth Boost Factor of $10^4 - 10^5$ Possible**

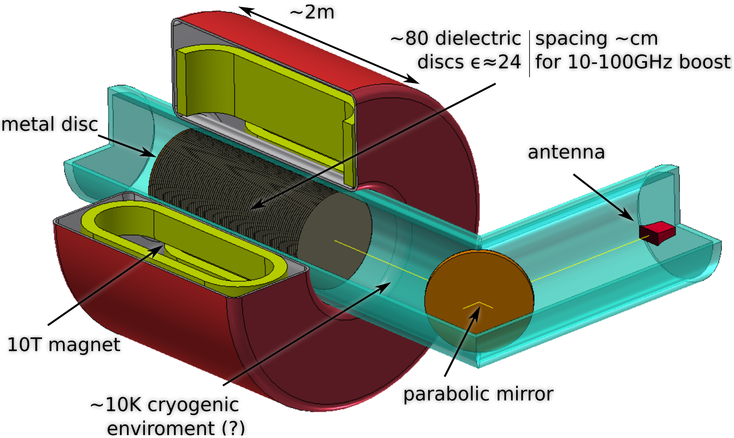
# Power Boost Factor $\beta^2$

adjustable by disc spacings

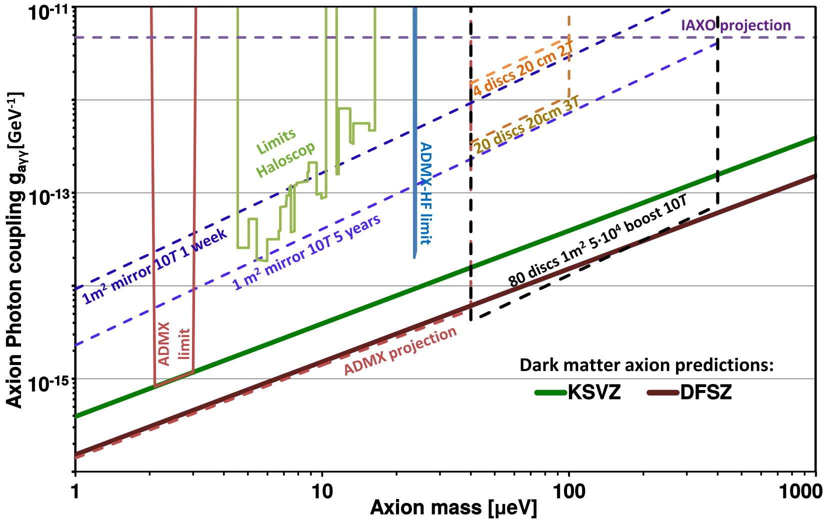



**Frequency Band Tunable**

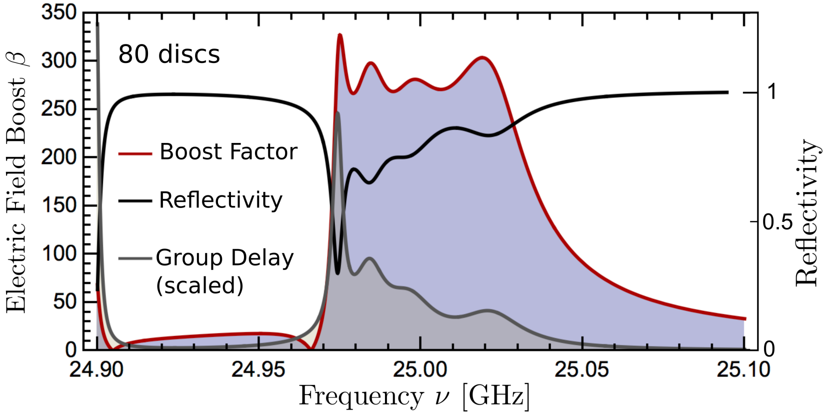
# The Vision


~2m
~80 dielectric discs ϵ≈24
spacing ~cm for 10-100GHz boost
metal disc
antenna
10T magnet
~10K cryogenic enviroment (?)
parabolic mirror

# Sensitivity



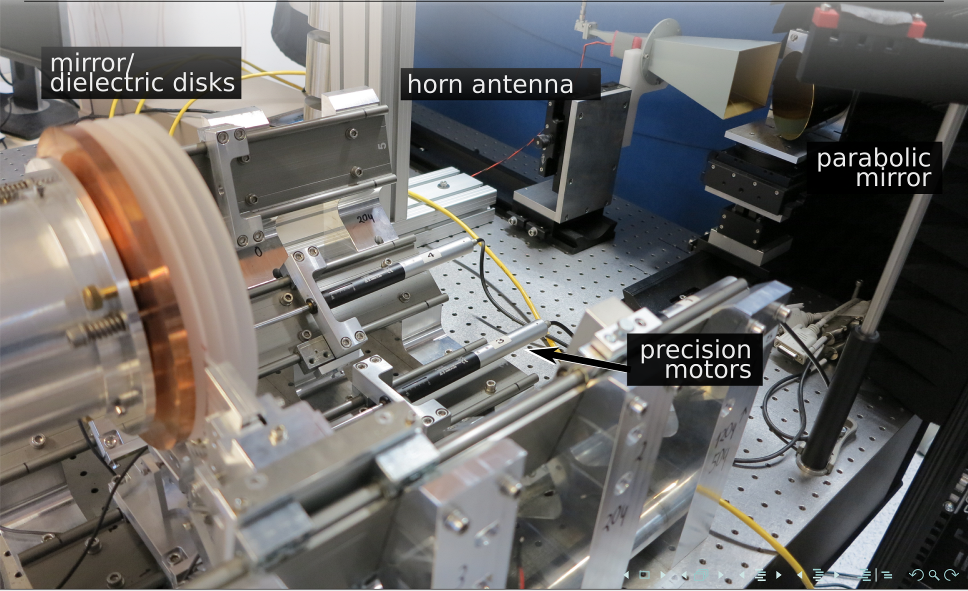
# Probing the Boost Factor




**Boost Factor $\leftrightarrow$ Reflectivity / Group Delay Corellation**

# Probing the Boost Factor

partially funded by Excellence Cluster Universe



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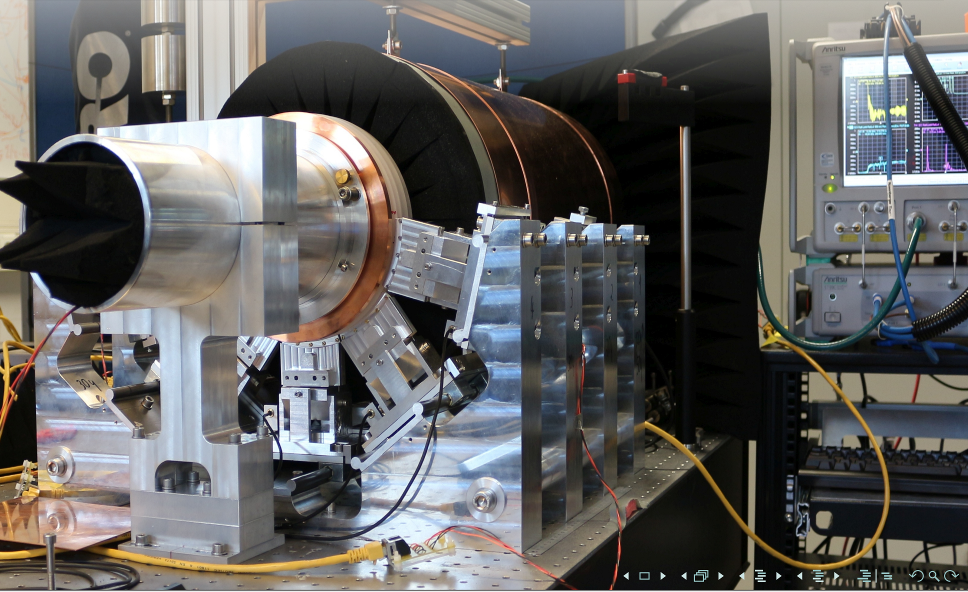

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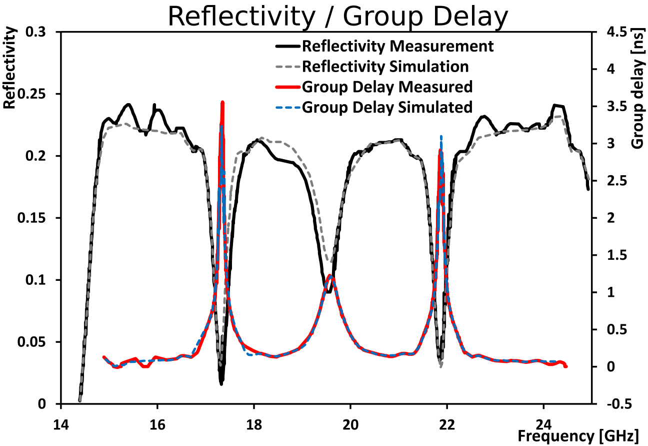
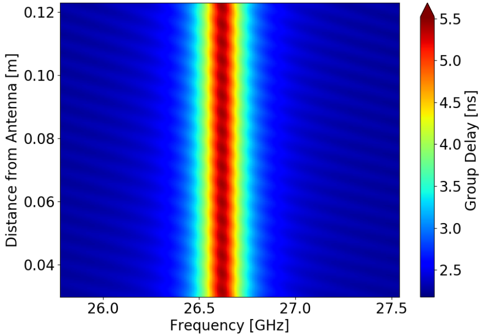



**Predicted Electromagnetic Response Demonstrated**

# But: Systematics

e.g. **Unwanted Reflections:**
single disk and mirror, $d \approx 5\,\mathrm{cm}$
$+$ slightly mismatched antenna




**displace Group Delay Peak**

other effects:

**Diffraction**,

**Losses**,

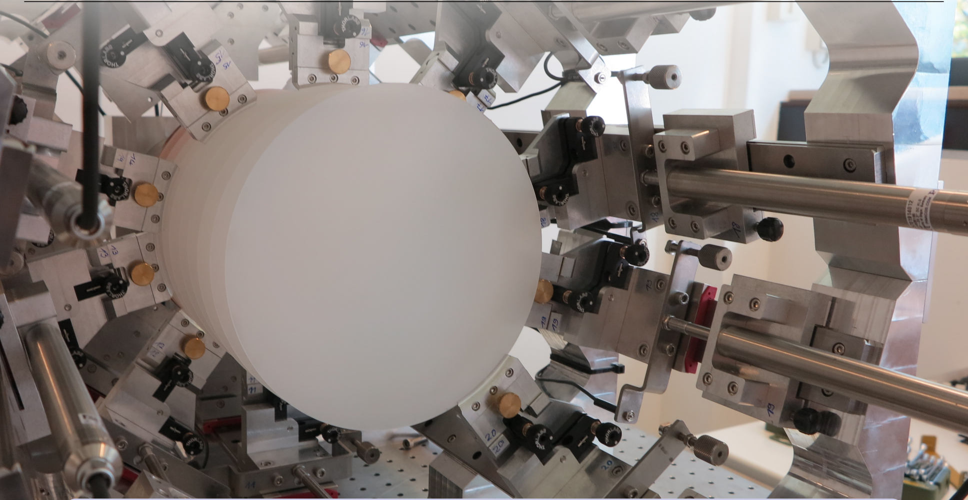
**Tilts / Surface Imperfections**,

**Near Fields**

…

**Physical Understanding / Modeling Needed**

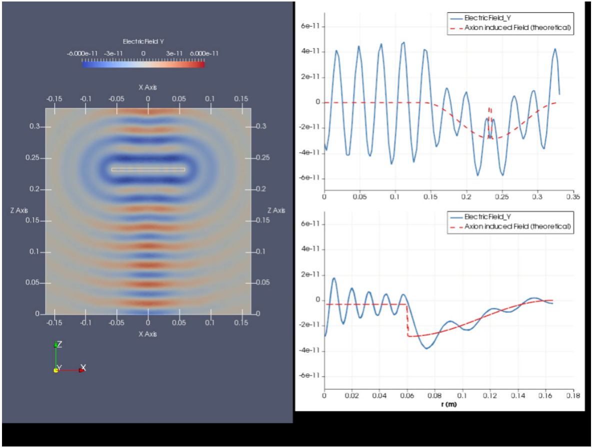
# 20 Disc Setup



more c.f. talk by Jacob Egge, Thu, 18:30; T 93.9

*Demonstrating EM Properties of a MADMAX Prototype Booster*

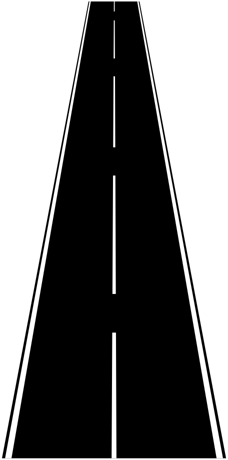
# Simulations




more c.f. talk by Jan Schütte-Engel, Mo, 17:05; T 6.5,
*Simulation Studies for Axion Direct Detection Experiments*

# Newly Founded MADMAX collaboration

# Roadmap



19 Oct 2017 collaboration forming:
DESY; Univ. of Hamburg; CEA-IRFU, Saclay; MPI für Radioastronomie, Bonn; Univ. of Zaragoza

ongoing:

**magnet design studies** $B^2 A \approx 100\,\mathrm{T}^2\,\mathrm{m}^2$ (two independent partners)

**R&D** on mechanics, $\mathrm{LaAlO_3}$ dielectric plates, noise contribution of booster, receiver

**booster studies** 20 disc seed setup, 3D simulations

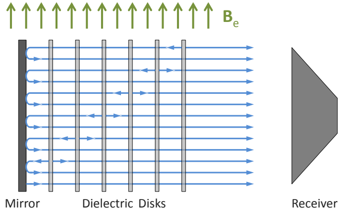
in 2-4 years:

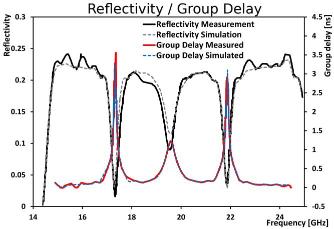
**20 disc prototype:** $\varnothing_{\mathrm{disc}} \approx 30\,\mathrm{cm}$, $B = 3 - 4\,\mathrm{T}$
$\Rightarrow$ **first physics results**

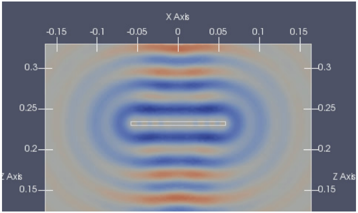
afterwards (2022?):

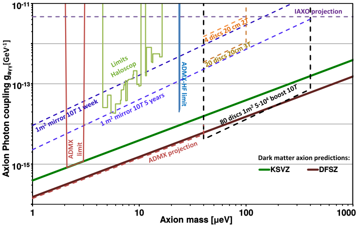
**full scale experiment**

# Conclusions



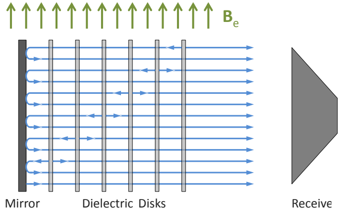



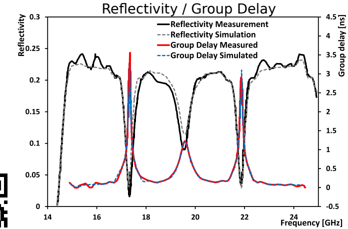

for more information:

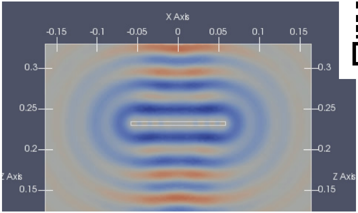
MADMAX collaboration white paper,

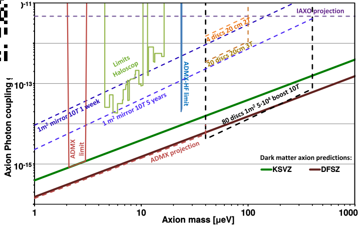
**Phys. Rev. Lett.** 118, 091801, **JCAP** 1701:061,2017

# Thank You very much

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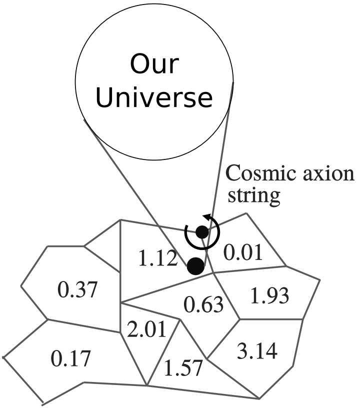
# Pecci-Quinn Symmetry Breaking...

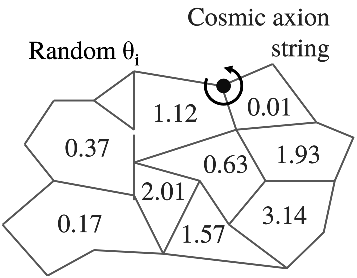
**before inflation:**




$m_A \lesssim$ meV

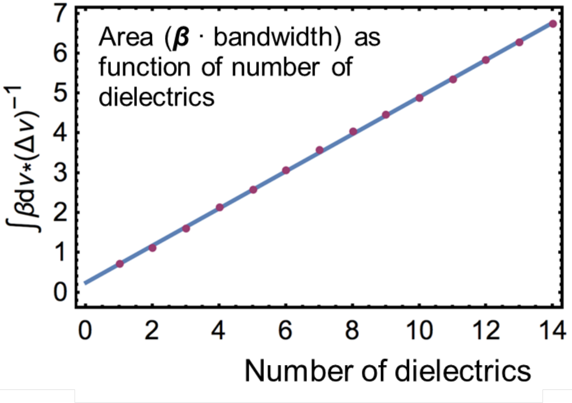
**after inflation:**

Our Universe:



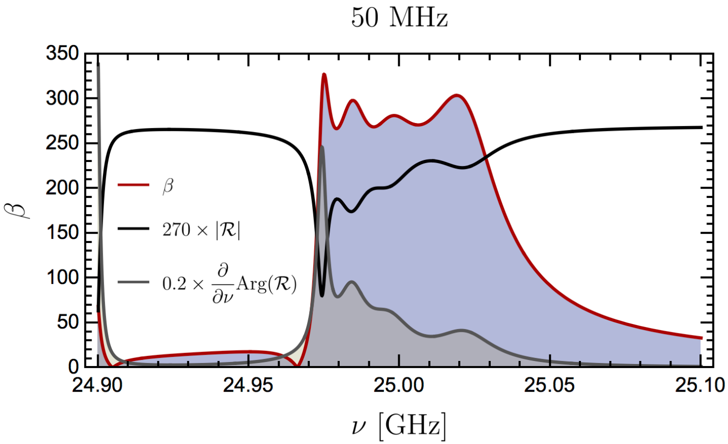

$m_A \sim 100\,\mu$eV

# Boost Factor and Disc Number



# Boost Factor Corellation

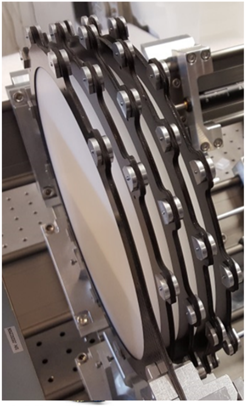
80 discs



# Dielectric Materials

**Chose dielectric material:**

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



→ Sapphire ($Al_2O_3$) @ 300K, 10 GHz:

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

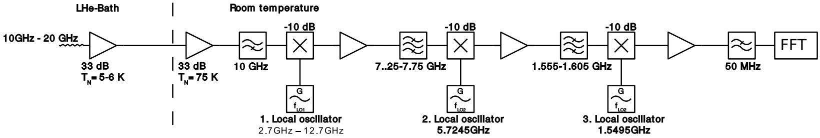
→ Lanthanide Aluminate ($LaAlO_3$) @ 77K

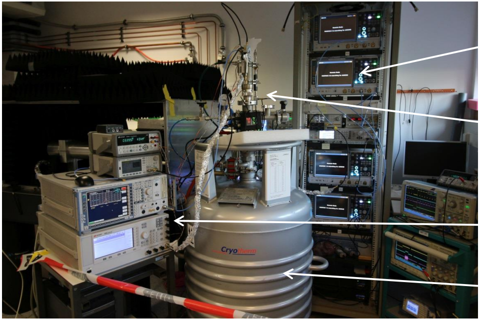
$$\varepsilon \sim 24; \qquad \tan\delta \sim 3 \cdot 10^{-5}$$

→ Titanium dioxide – Rutil ($TiO_2$)

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

# Receiver System



signal analyzer
(4 samplers, 1.4% dead time)

front end mixers
and amps

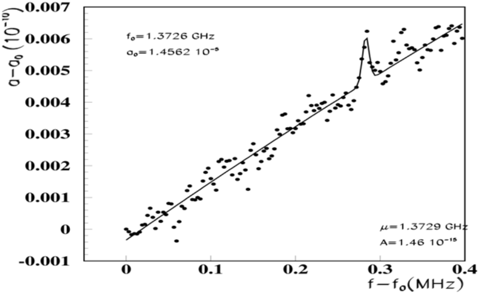
“Fake Axion”

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

# Receiver System

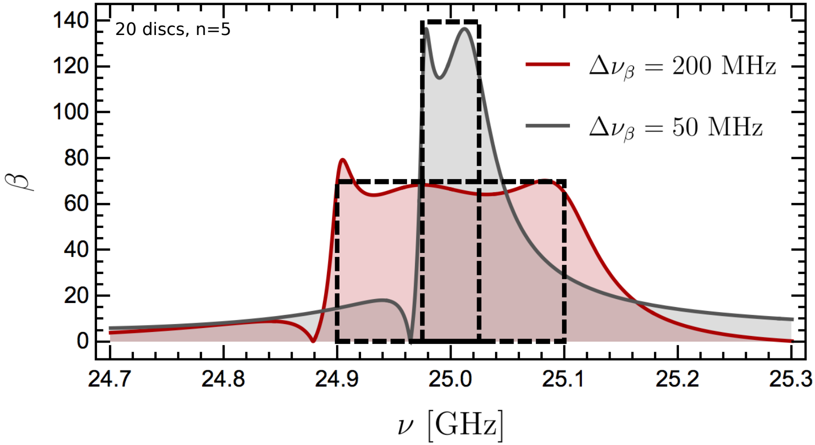
**typical one week measurment**

(with higher input signal)




with preamp @ 4K:
**signal down to** $\sim 10^{-23}\,\mathrm{W}$ **detected**

# Optimizing the Boost Factor




**Area under Boost Factor curve approximately conserved**

# Align Discs to Match Group Delay

E.g. Spacings Reproducibility for 3 equidistant discs: