MADMAX: A new way of probing QCD Axion Dark Matter with a Dielectric Haloscope

Foundations

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for the MADMAX interest group

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

The Strong CP-Problem

QCD allows for a term

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

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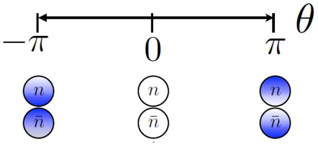
but experimentally: $|\theta| < 10^{-9}$ (neutron electric dipole moment)

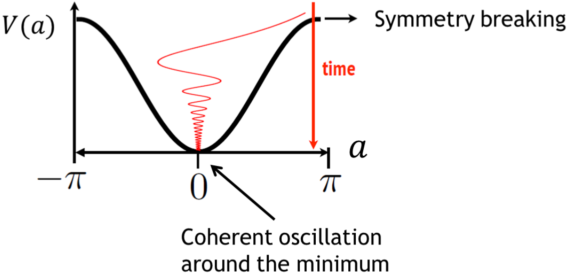


The Strong CP-Problem

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

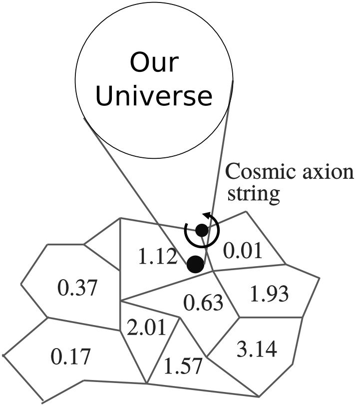
$$\mathcal{L} = -\, a\frac{g_S}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a \; + \; \frac{1}{2}\,\partial_\mu a\,\partial^\mu a$$

rolldown to CP conserving limit:



Pecci-Quinn Symmetry Breaking...

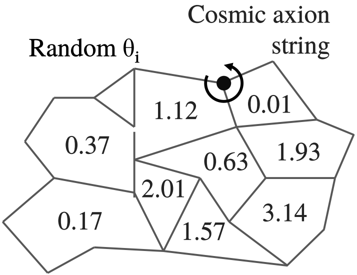
before inflation:



$m_A \lesssim \mathrm{meV}$

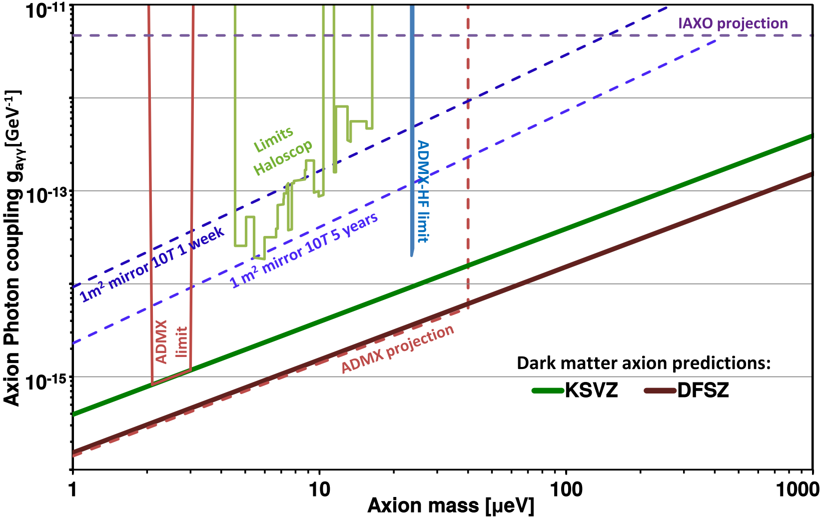
after inflation:

Our Universe:

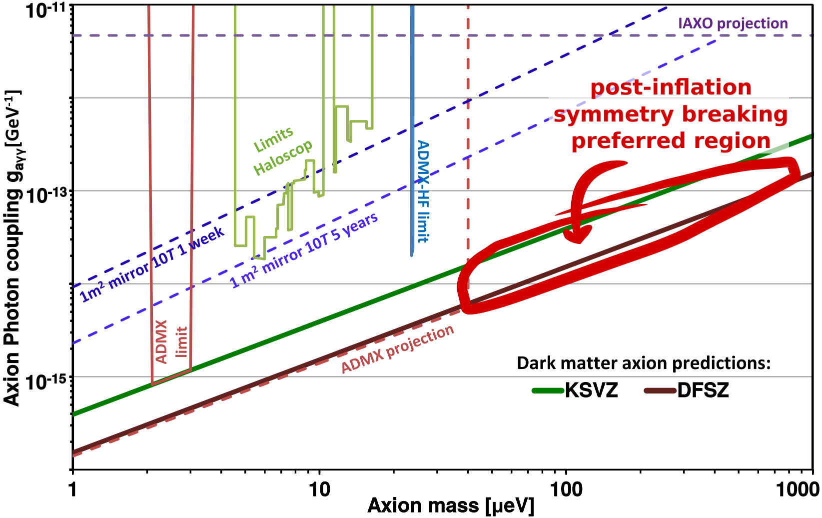


$m_A \sim 100\,\mu\mathrm{eV}$

The Axion - Parameterspace

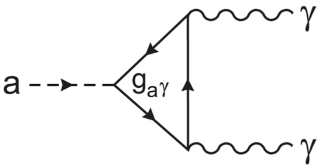


The Axion - Parameterspace



Axion Electrodynamics

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



$$m_a = 5.70(7)\,\mu\text{eV}\,\frac{10^{12}\text{GeV}}{f_a}\,,$$

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a}C_{a\gamma} = 2.04(3)\times 10^{-16}\ \text{GeV}^{-1}\,\frac{m_a}{\mu\text{eV}}\,C_{a\gamma}\,,$$

$$C_{a\gamma} = \frac{E}{N} - 1.92(4)\,,$$

Axion Electrodynamics

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

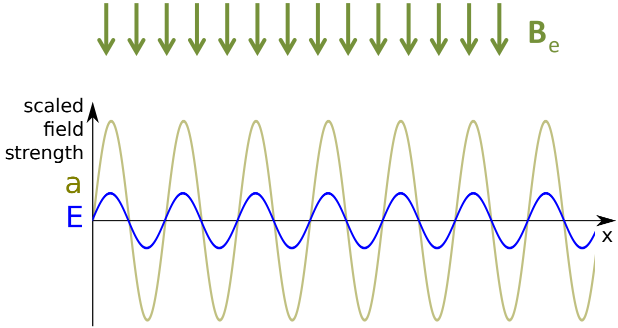
Solve EOM under external magnetic field $\mathbf{B}_e$:

$$\begin{aligned} \epsilon\nabla\cdot\mathbf{E} &= \rho - g_{a\gamma}\mathbf{B}_e\cdot\nabla a \\ \nabla\times\mathbf{H} - \dot{\mathbf{E}} &= \mathbf{J} + g_{a\gamma}\mathbf{B}_e\dot{a} \\ \ddot{a} - \nabla^2 a + {m_a}^2 a &= g_{a\gamma}\mathbf{E}\cdot\mathbf{B}_e \end{aligned}$$

Axion induced electric field:

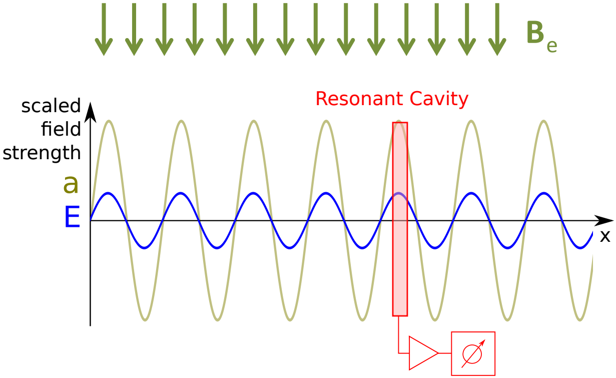
$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a = 1.3\times10^{-12}\,\mathrm{V\,m^{-1}}\times\left(\frac{B_e}{10\,\mathrm{T}}\right)\frac{C_{a\gamma}f_{DM}^{1/2}}{\epsilon}$$

Axion - Photon Mixing



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

Axion - Photon Mixing

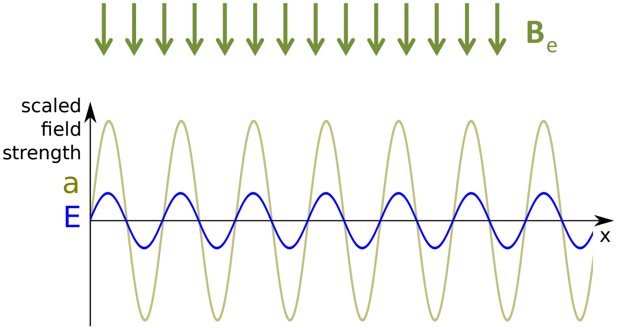


$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$

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

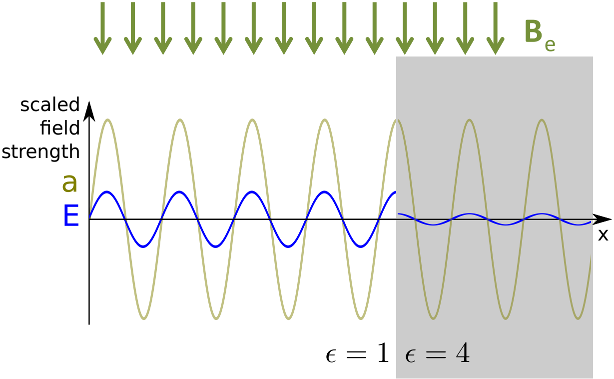
Q: Quality Factor, C_{nml}: mode factor

Axion - Photon Mixing



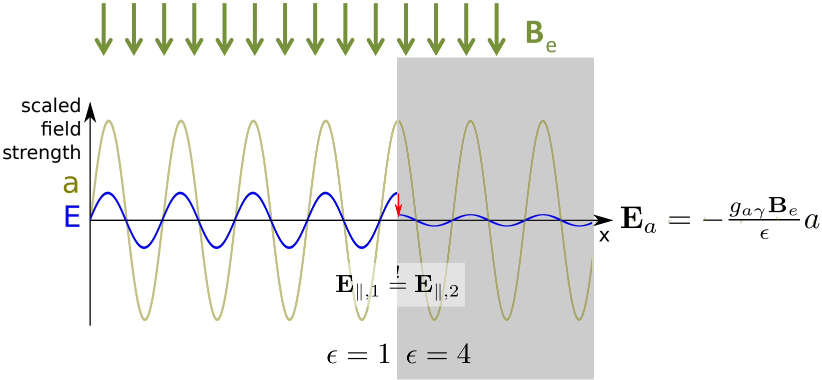
$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$$

Axion - Photon Mixing



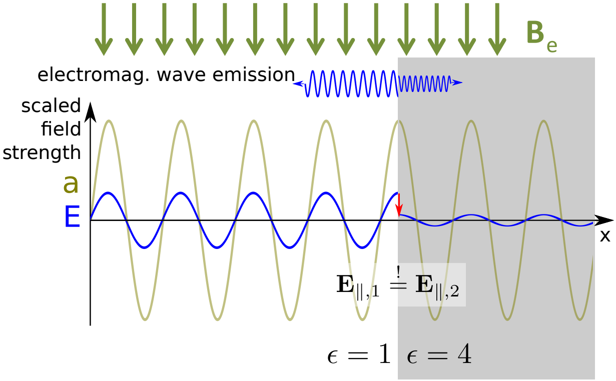
$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$$

Axion - Photon Mixing



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

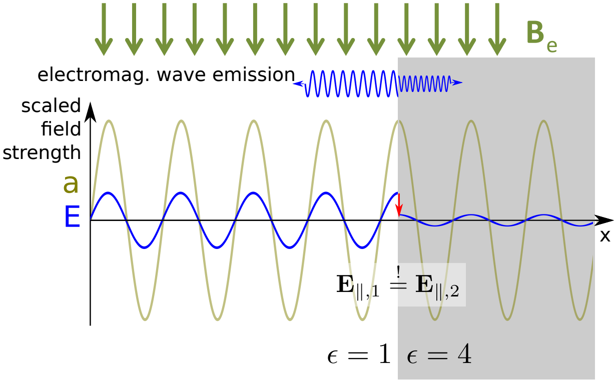
Axion - Photon Mixing



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

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

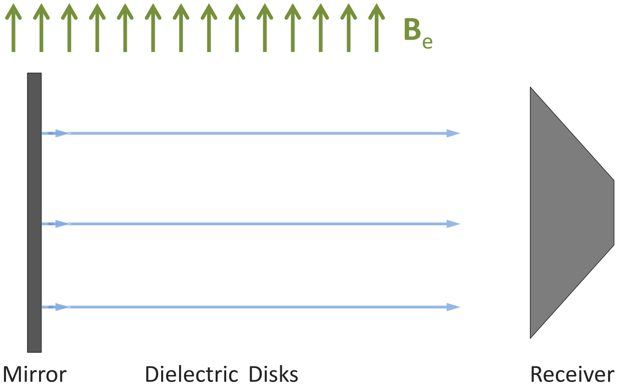
Axion - Photon Mixing



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

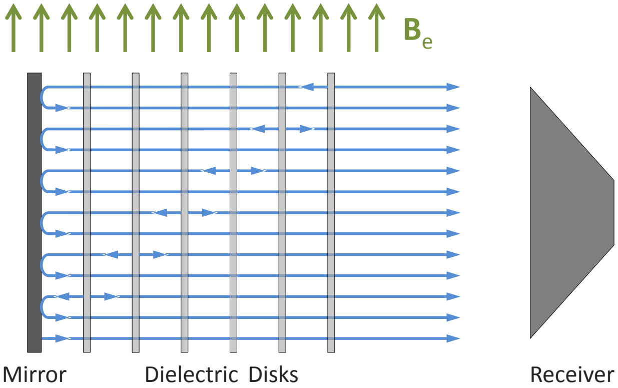
$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 {C_{a\gamma}}^2 \cdot f(\epsilon_1, \epsilon_2)$$

The MADMAX Idea



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

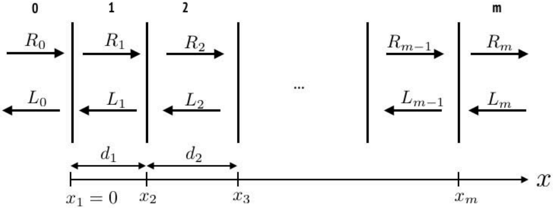
The MADMAX Idea



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

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

Calculating β - Transfer Matrices [arXiv:1612.07057]

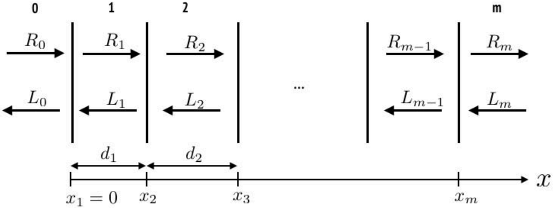


Reflection / Transmission: $$\mathrm{G}_r = \frac{1}{2n_{r+1}} \begin{pmatrix} n_{r+1}+n_r & n_{r+1}-n_r \\ n_{r+1}-n_r & n_{r+1}+n_r \end{pmatrix}$$

Phase Propagation: $$\mathrm{P}_r = \begin{pmatrix} e^{+i\delta_r} & 0 \\ 0 & e^{-i\delta_r} \end{pmatrix}$$

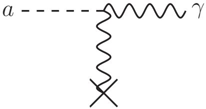
Axion Induced Fields: $$\mathrm{S}_r = \frac{A_{r+1} - A_r}{2} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

Calculating β - Transfer Matrices [arXiv:1612.07057]



$$\begin{aligned}
\begin{pmatrix} R_m \\ L_m \end{pmatrix} &= \mathsf{G}_{m-1}\mathsf{P}_{m-1}\begin{pmatrix} R_{m-1} \\ L_{m-1} \end{pmatrix} + E_0 \mathsf{S}_{m-1}\begin{pmatrix} 1 \\ 1 \end{pmatrix} \\
&= \dots \\
&= \mathsf{T}_0^m \begin{pmatrix} R_0 \\ L_0 \end{pmatrix} + E_0 \sum_{s=1}^{m} \mathsf{T}_s^m \mathsf{S}_{s-1} \begin{pmatrix} 1 \\ 1 \end{pmatrix} .
\end{aligned}$$

Calculating β - QFT Calculation [arXiv:1707.00701]



Primakoff process

decay rate:

$$\Gamma_{a\to\gamma} = 2\pi \sum_{\mathbf{k}} |\mathcal{M}|^2 \, \delta(\omega_a - \omega_{\mathbf{k}})$$

matrix element:

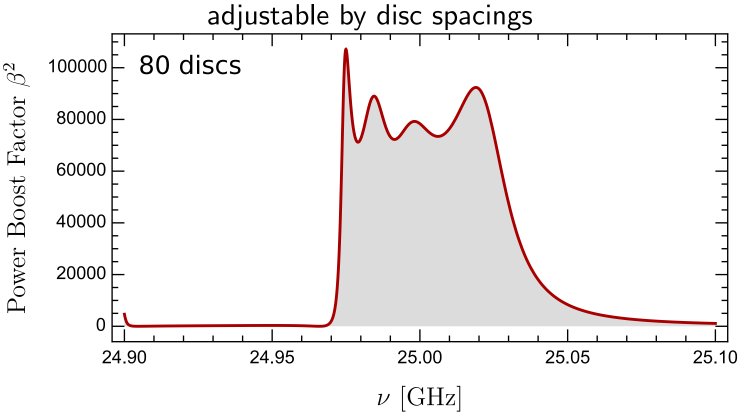
$$\mathcal{M} = \langle \mathrm{f} | H_{a\gamma} | \mathrm{i} \rangle = \frac{g_{a\gamma}}{2\omega V} \int d^3\mathbf{r} \, e^{i\mathbf{p}\cdot\mathbf{r}} \, \mathbf{B}_{\mathrm{e}}(\mathbf{r}) \cdot \mathbf{E}^*_{\mathbf{k}}(\mathbf{r})$$

Haloscope (layers) breaks translational invariance:

$$\Rightarrow \mathcal{M} = i \, \frac{g_{a\gamma} \, \epsilon \cdot \mathbf{B}_{\mathrm{e}}}{2V} \int_{-\infty}^{+\infty} dx \, A_\omega(x) \qquad A_\omega : \text{Garibian wave functions}$$

confirms classical results

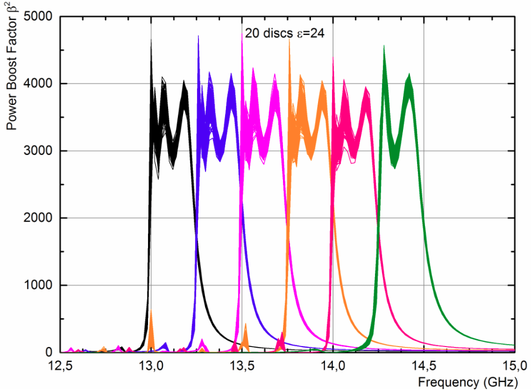
Power Boost Factor β^2



Wide Bandwidth Boost Factor of $10^4 - 10^5$ possible

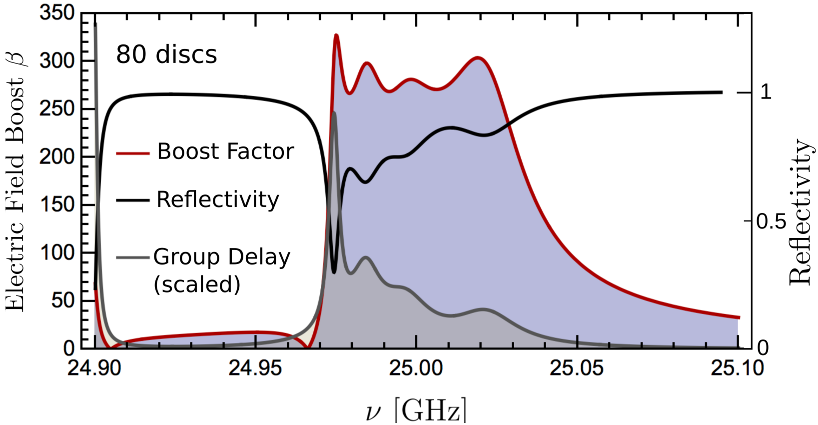
Power Boost Factor β^2

adjustable by disc spacings



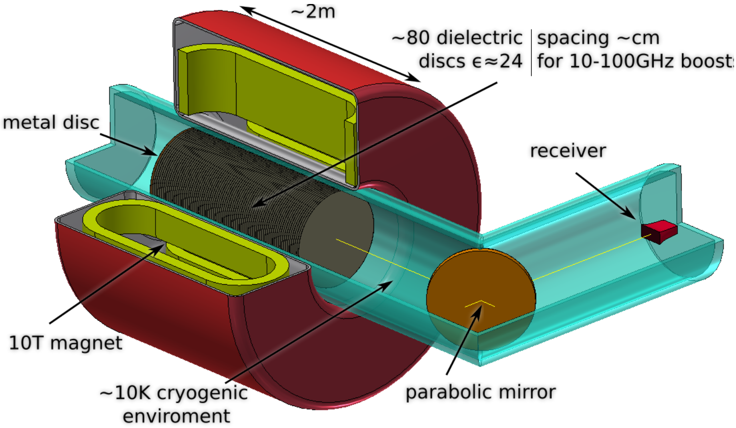
frequency band tunable

Probing the Boost Factor



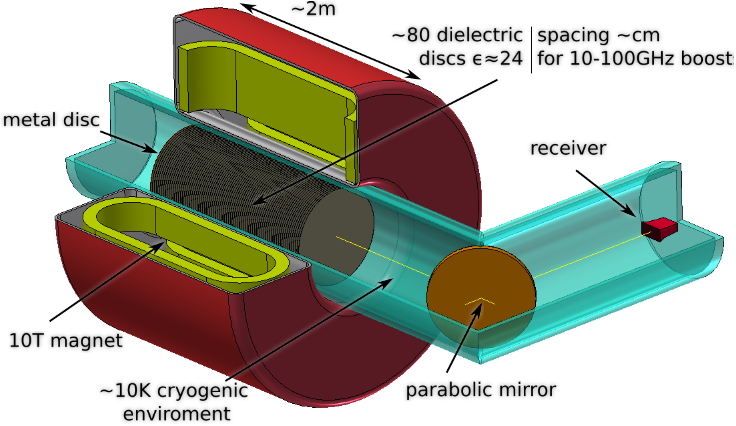
Boost Factor ↔ Reflectivity / Group Delay Corellation

Outlook: Experiment



White paper of the MADMAX interst group available:
https://www.mpp.mpg.de/en/research/astroparticle-physics-and-cosmology/madmax-searching-for-axion-dark-matter/

Thank You very much



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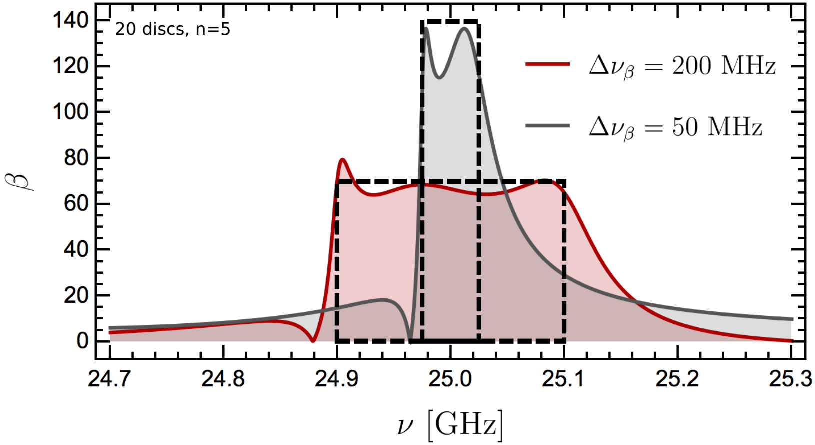
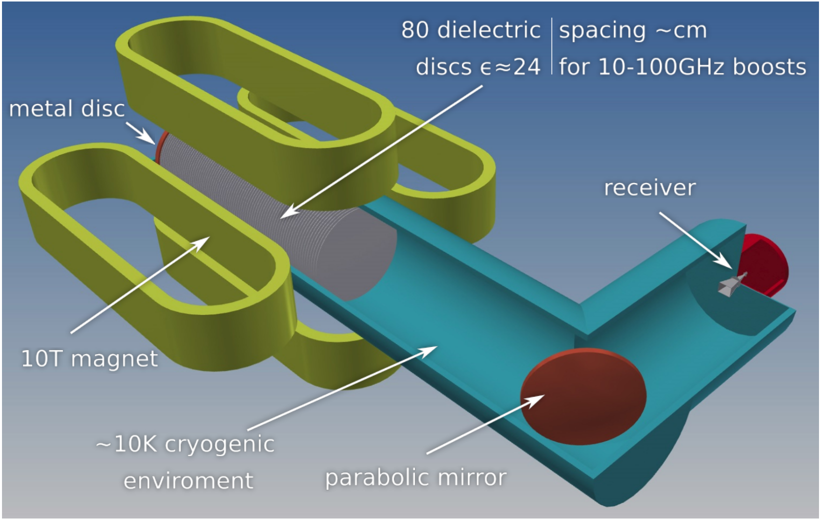
Optimizing the Boost Factor

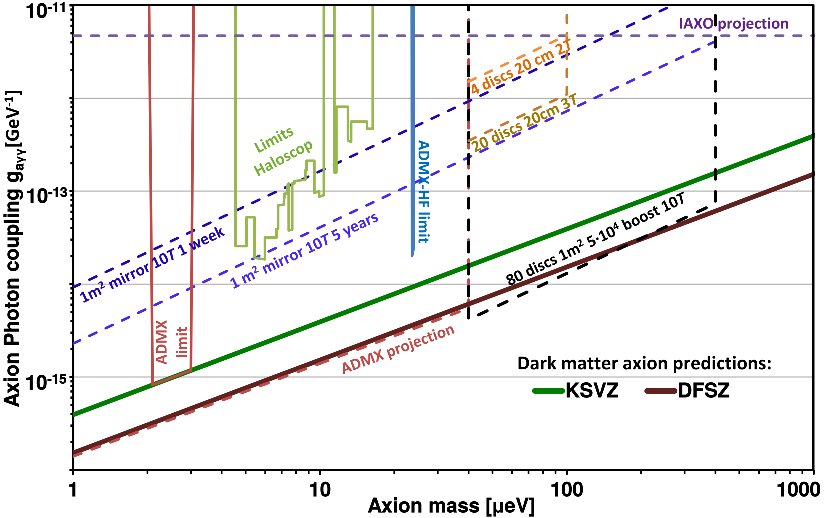


Area under Boost Factor curve approximately conserved

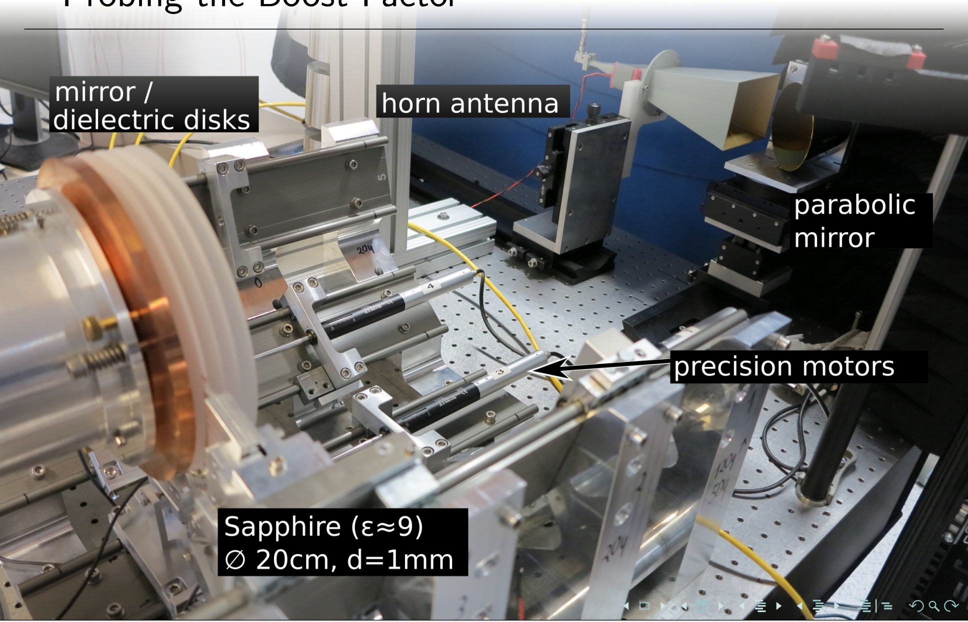
Proposed Setup



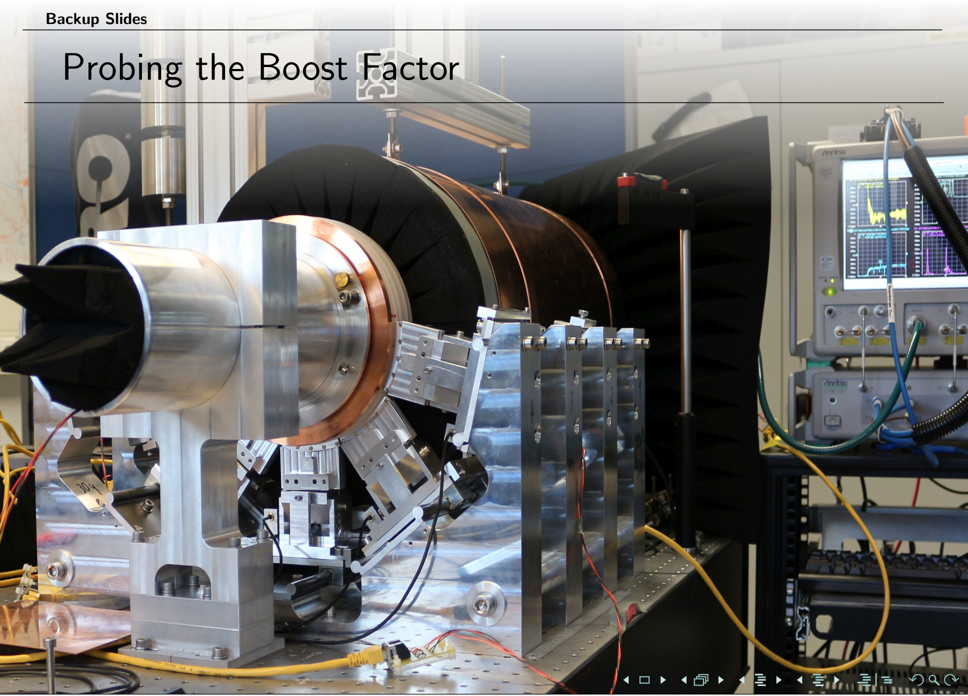
Sensitivity



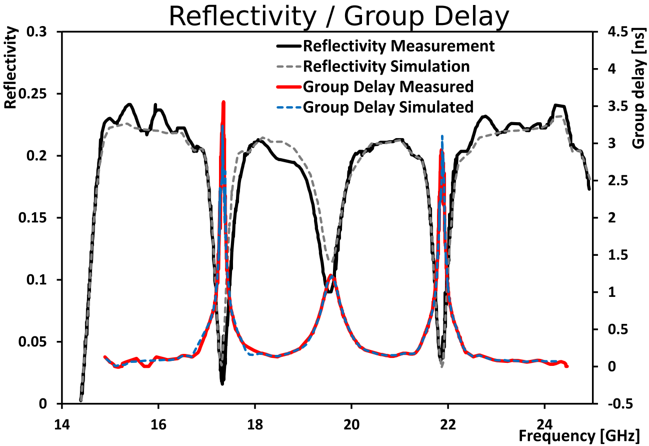
Probing the Boost Factor



Probing the Boost Factor

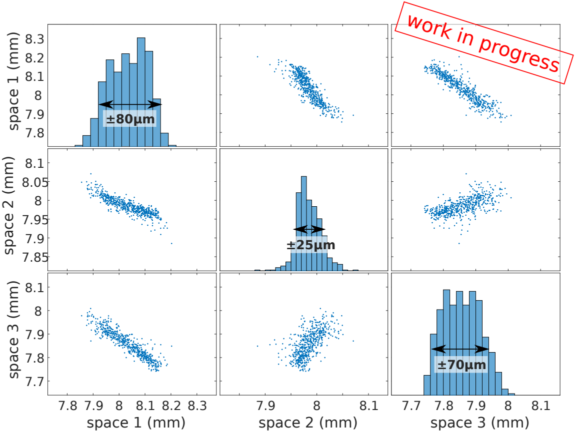


Probing the Boost Factor

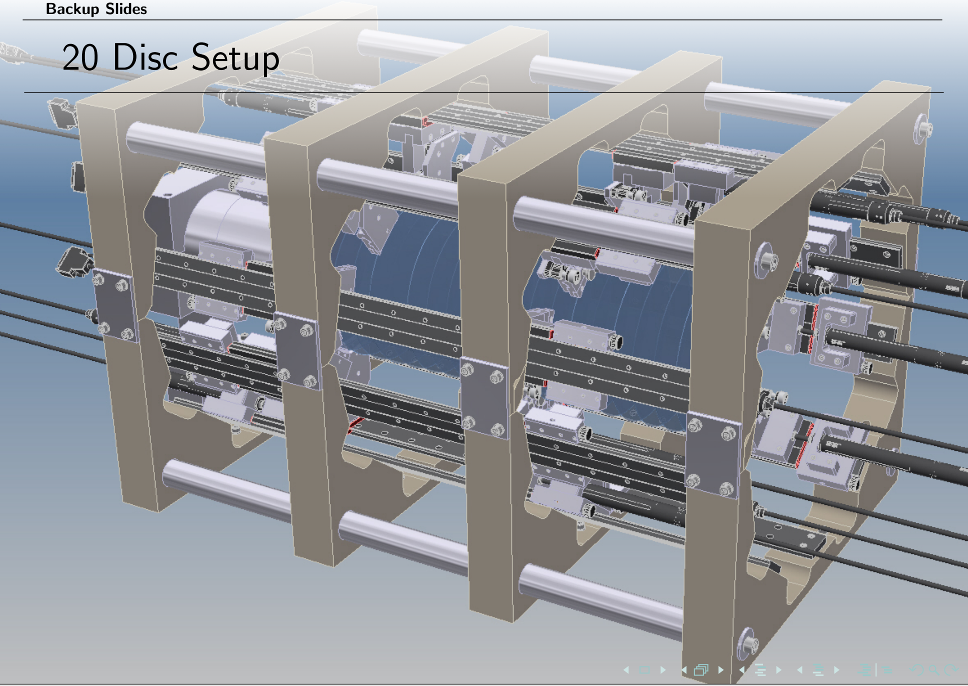


Align Discs to Match Group Delay

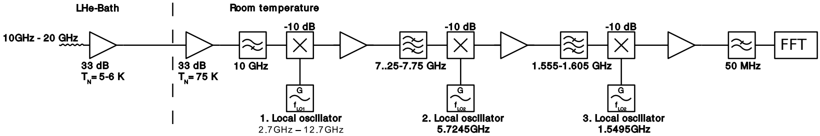
E.g. Spacings Reproducibility for 3 equidistant discs:

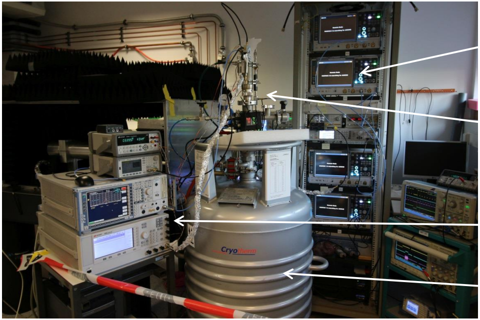


20 Disc Setup



Receiver System





signal analyzer
(4 samplers, 1.4% dead time)

front end mixers
and amps

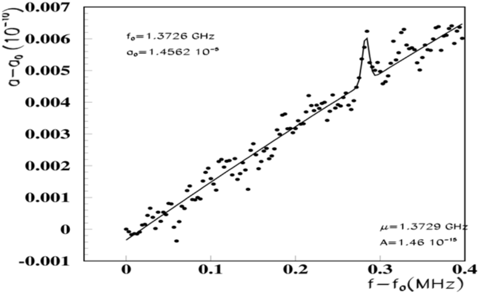
“Fake Axion”

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

Receiver System

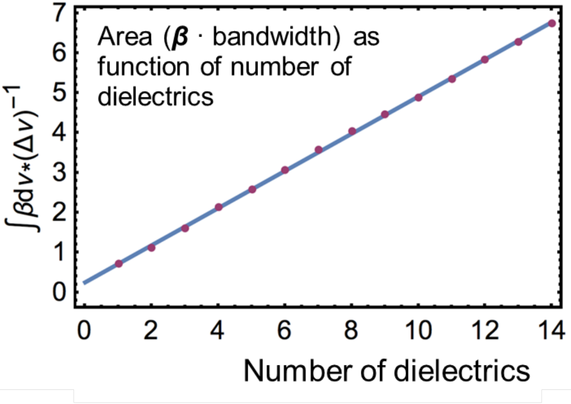
typical one week measurment

(with higher input signal)



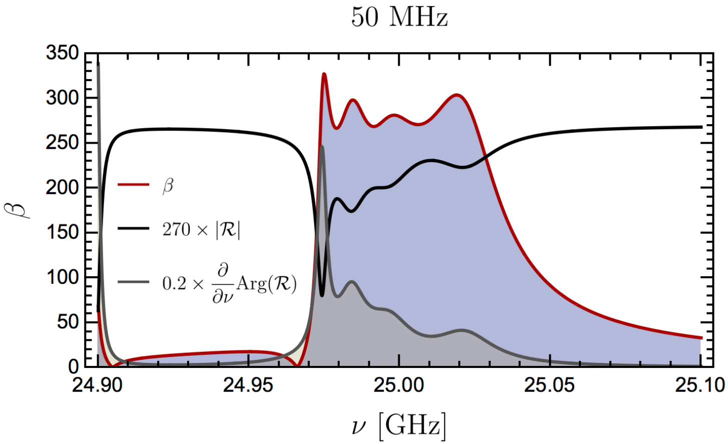
with preamp @ 4K:
signal down to $\sim 10^{-23}\,\mathrm{W}$ **detected**

Boost Factor and Disc Number



Boost Factor Corellation

80 discs



Dielectric Materials

Chose dielectric material:

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

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

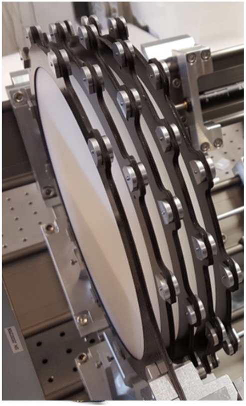
$$\varepsilon \sim 10; \qquad \tan\delta \sim few \cdot 10^{-5}$$

→ **Lanthanide Aluminate ($LaAlO_3$)** @ 77K

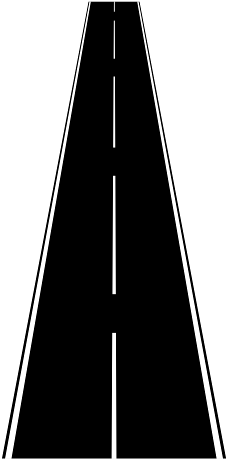
$$\varepsilon \sim 24; \qquad \tan\delta \sim 3 \cdot 10^{-5}$$

→ **Titanium dioxide – Rutil (TiO_2)**

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



Roadmap



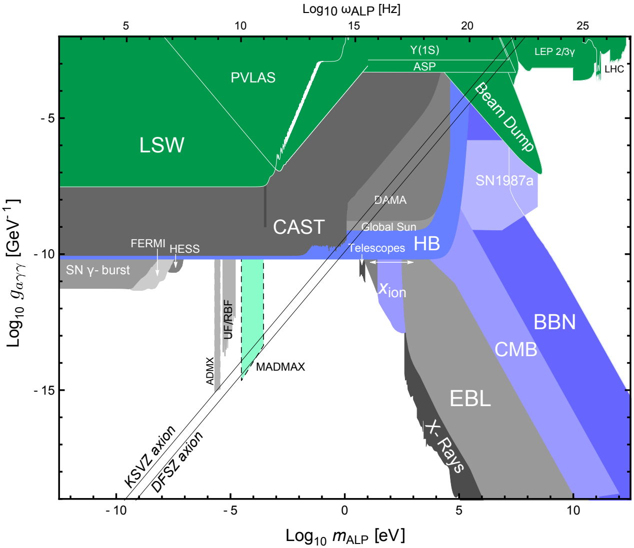
collaboration forming:
DESY; Univ. of Hamburg; CEA-IRFU, Saclay; MPI für Radioastronomie, Bonn; Univ. of Zaragoza

near future:
magnet design studies $B^2A \approx 100\,\mathrm{T}^2\,\mathrm{m}^2$
(two independent partners)
20 disc seed setup reflectivity & transmissivity
R&D on $\mathrm{LaAlO_3}$ dielectric plates, meachanics, noise contribution of booster

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

Sensitivity



Sensitivity