A new way to search for QCD Axion Dark Matter with a Dielectric Haloscope

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for the MADMAX collaboration

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RWTH Aachen University, Aachen, Germany
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University of Zaragoza, Spain

MAX-PLANCK-GESELLSCHAFT

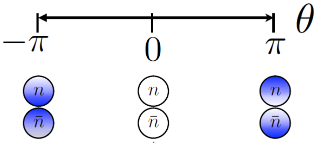
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

The Strong CP-Problem

QCD allows for a term

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

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

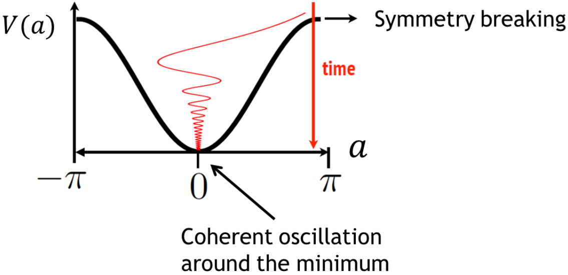


The Strong CP-Problem

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

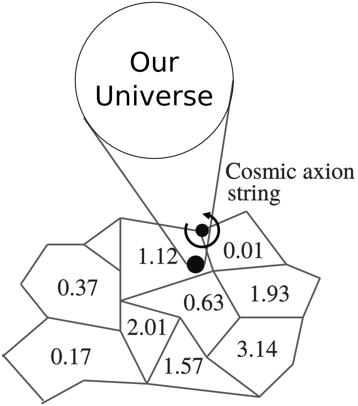
$$\mathcal{L} = -\, a \frac{g_S}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \; + \; \frac{1}{2}\, \partial_\mu a \, \partial^\mu a$$

rolldown to CP conserving limit:



Peccei-Quinn Symmetry Breaking...

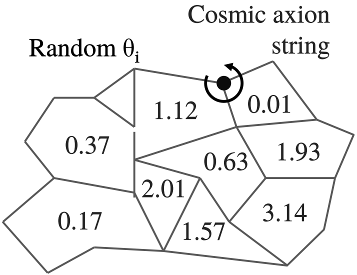
before inflation:



$m_A \lesssim$ meV

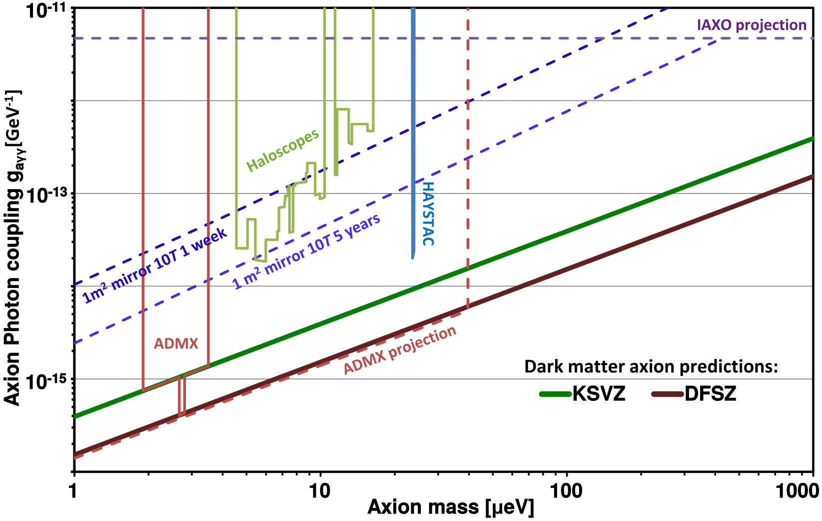
after inflation:

Our Universe:



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

The Axion - Parameterspace



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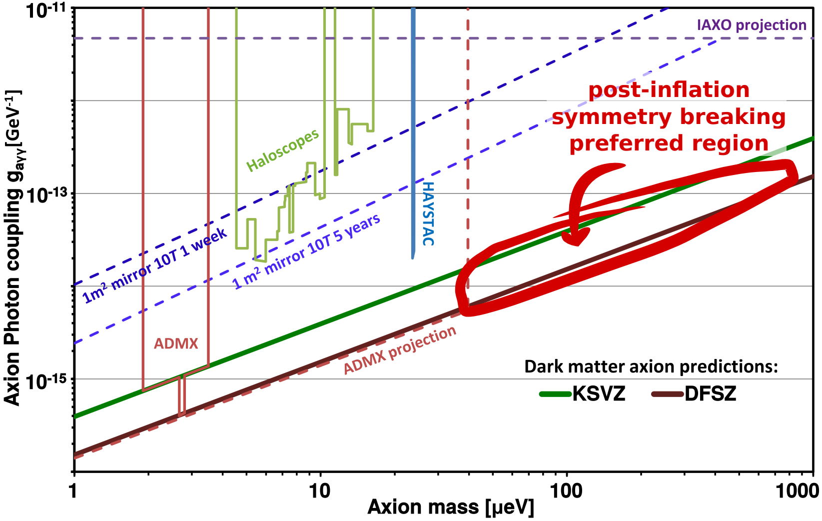


Axion Electrodynamics

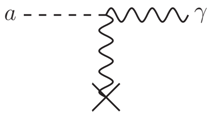
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - j^{\mu}A_{\mu} + \frac{1}{2}\partial_{\mu}a\,\partial^{\mu}a - \frac{1}{2}{m_a}^2a^2 - \frac{g_{a\gamma}}{4}a\,F_{\mu\nu}\tilde{F}^{\mu\nu}$$

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

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

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

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

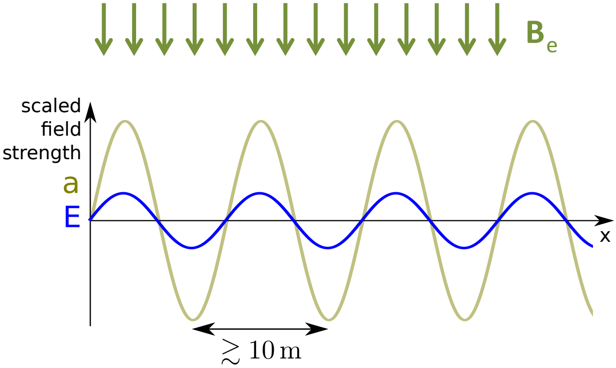


Primakoff process

Axion induced electric field:

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

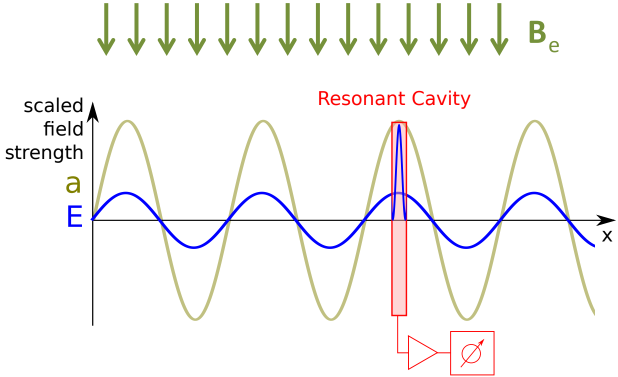
Axion - Photon Mixing

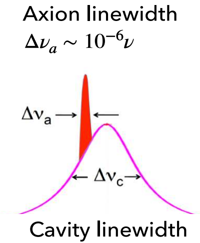


$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$

$$a \propto \cos(m_a t)$$

Axion - Photon Mixing

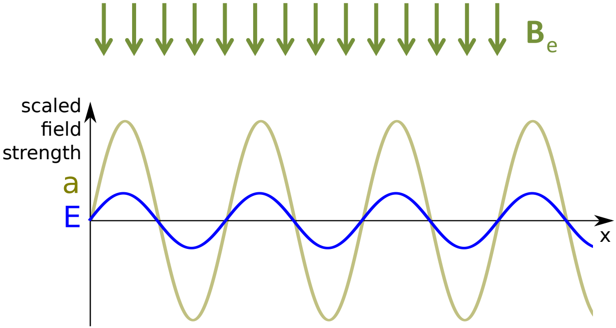




$$P_{\rm sig} = \left(B^2 Q\ V\ C_{nml}\right)\left(g_{a\gamma\gamma}{}^2 m_a \rho_a\right)$$

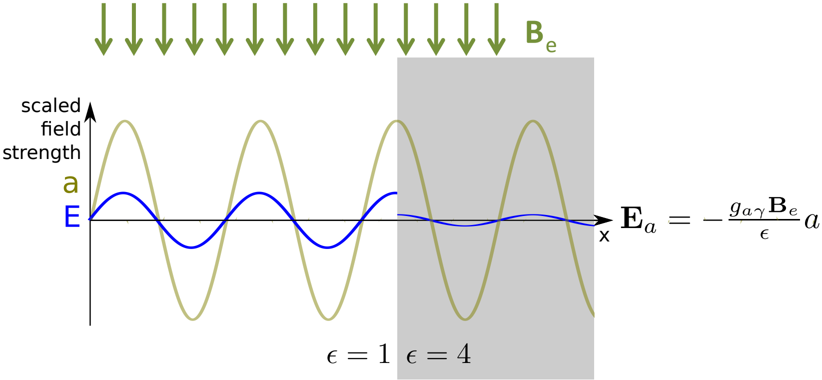
Q: Quality Factor, C_{nml}: mode factor

Axion - Photon Mixing

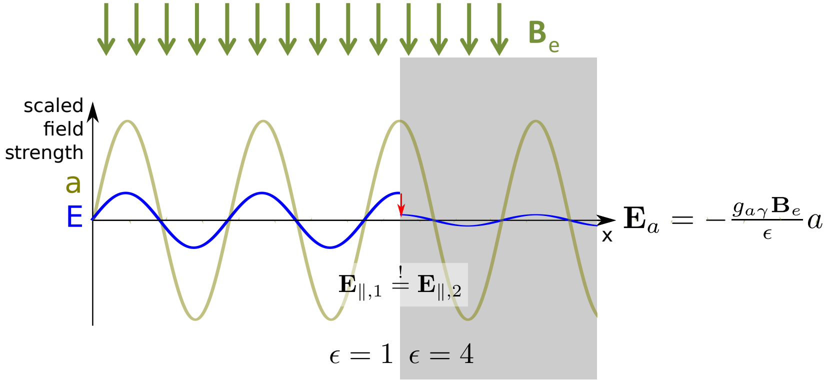


$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$$

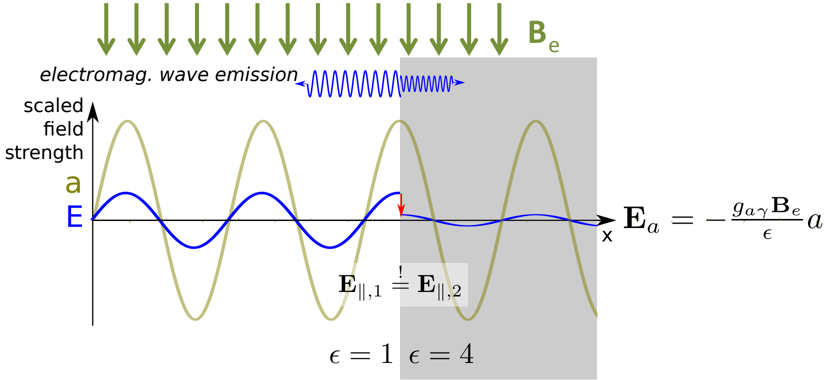
Axion - Photon Mixing



Axion - Photon Mixing

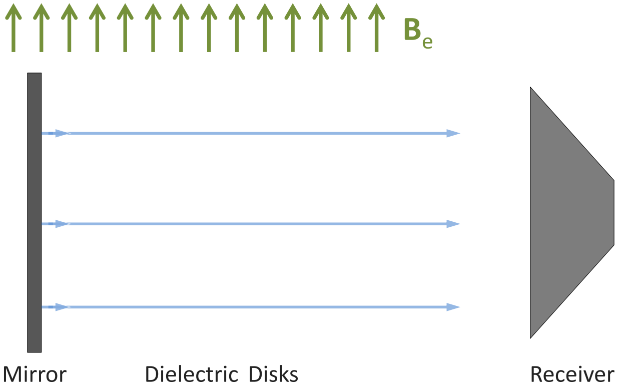


Axion - Photon Mixing



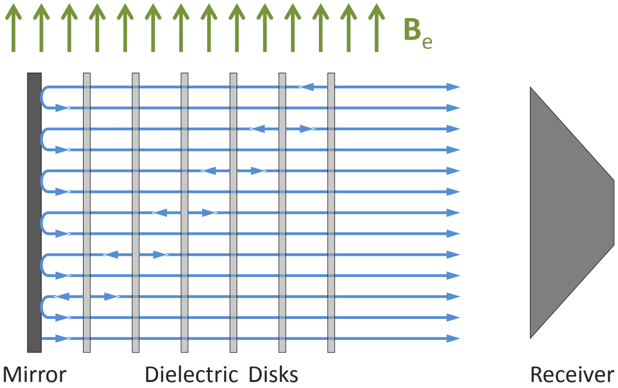
$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 {C_{a\gamma}}^2 \cdot f(\epsilon_1, \epsilon_2)$$

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

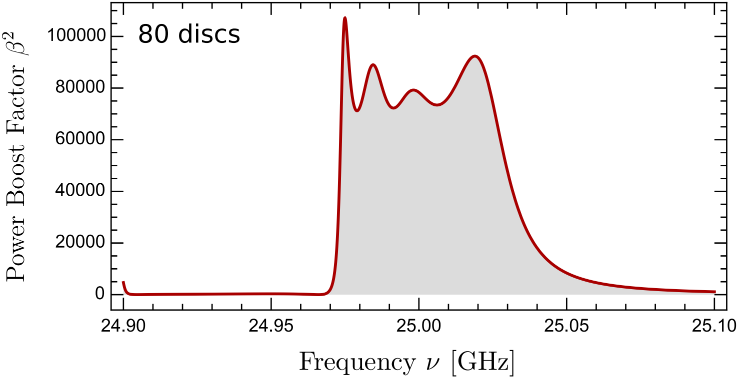


$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 C_{a\gamma}{}^2 \cdot \beta^2$$

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

Power Boost Factor β^2

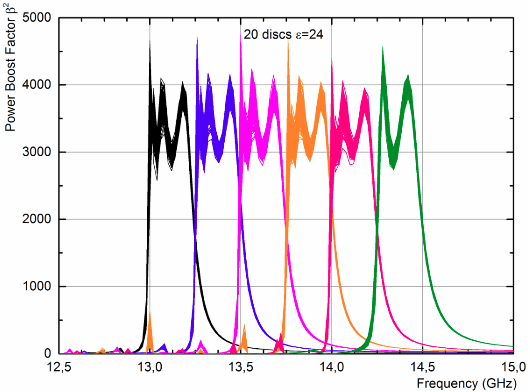
adjust disc spacings:



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

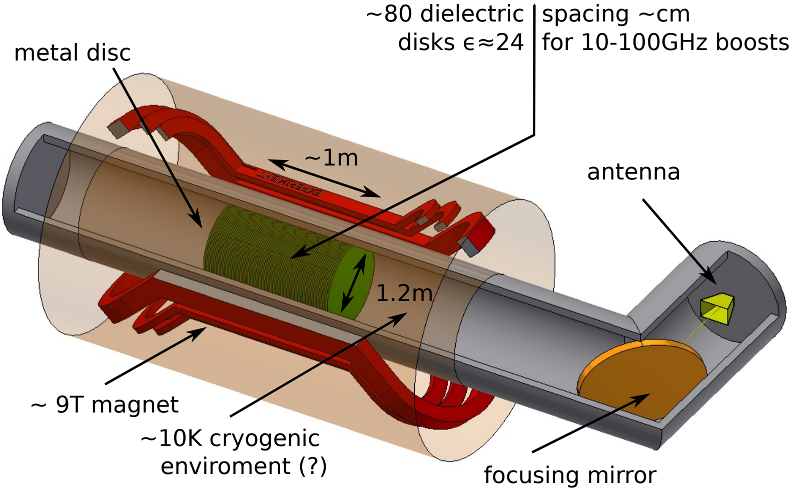
Power Boost Factor β^2

adjust disc spacings:

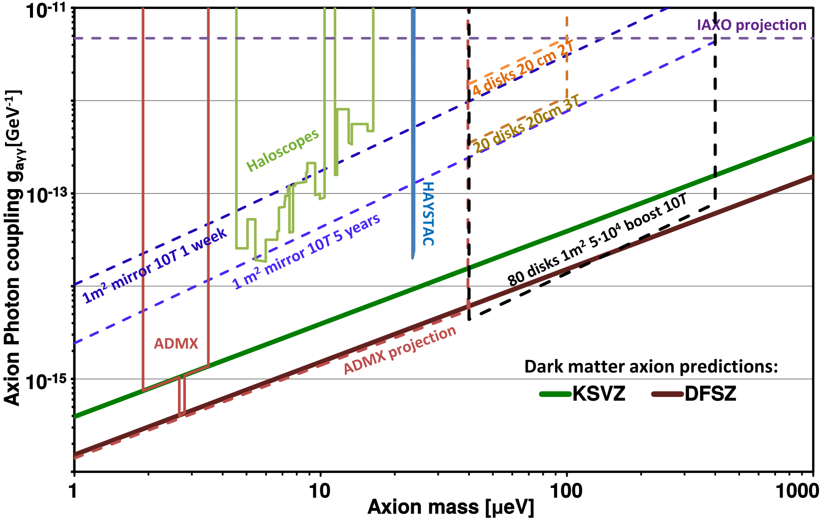


Frequency Band Tunable

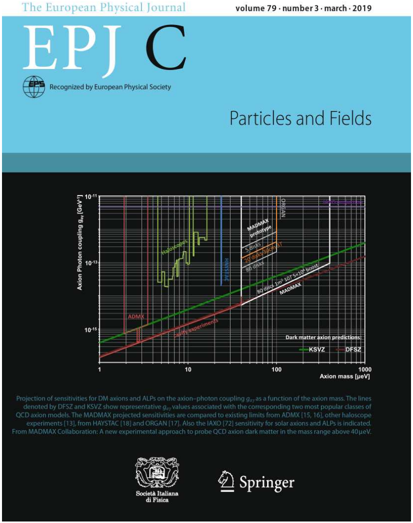
The Vision


~80 dielectric disks ϵ≈24
spacing ~cm for 10-100GHz boosts
metal disc
~1m
antenna
1.2m
~ 9T magnet
~10K cryogenic enviroment (?)
focusing mirror

Sensitivity

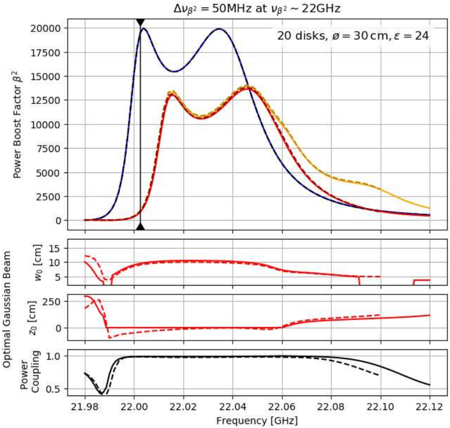


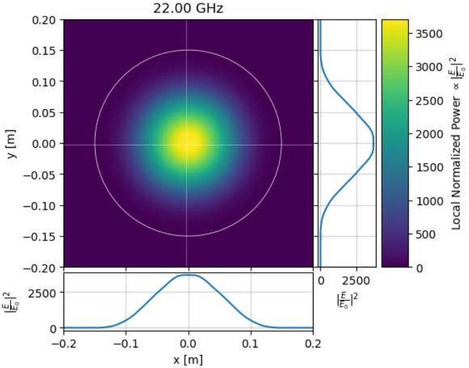
Sensitivity



3D Simulations – Beam Shape

methods see arXiv:1906.02677

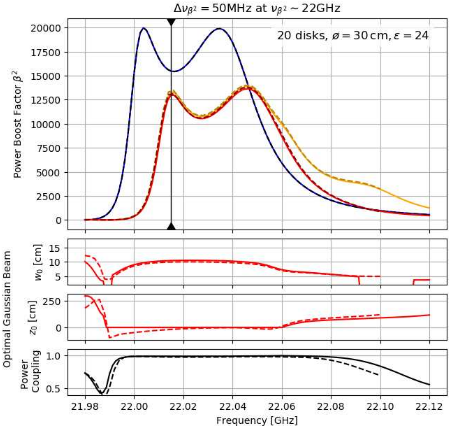


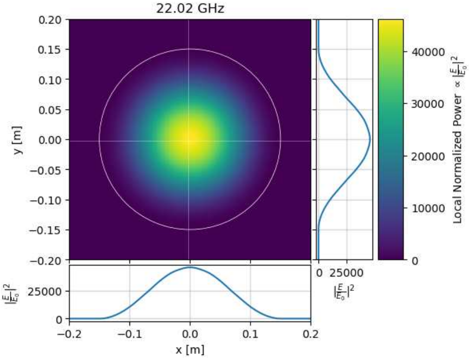


well matched to Gaussian beam $w_0 \approx 10\,\text{cm}$

3D Simulations – Beam Shape

methods see arXiv:1906.02677





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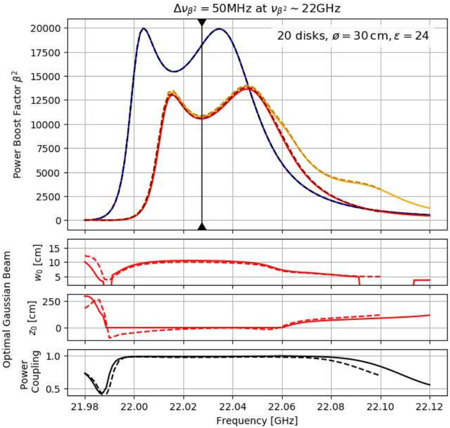

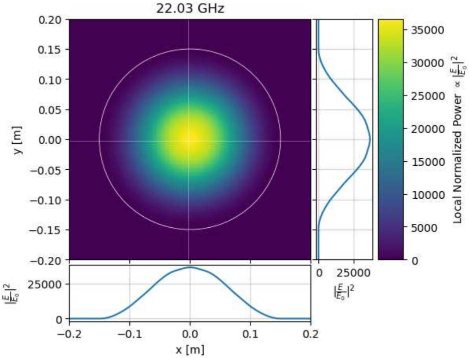

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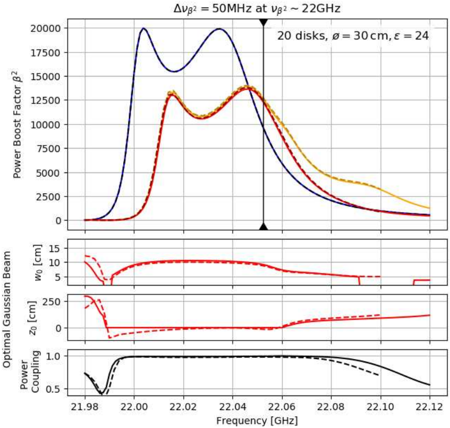

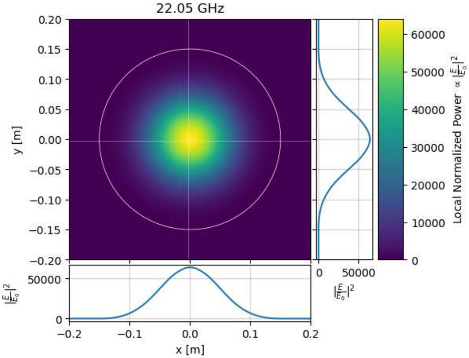

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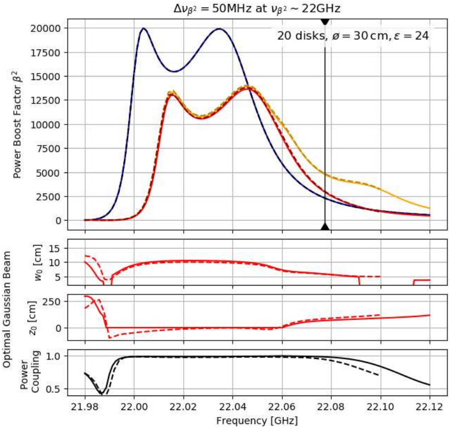

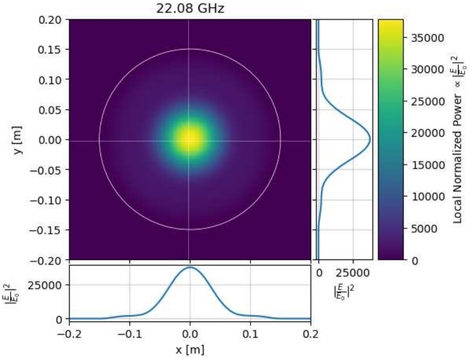

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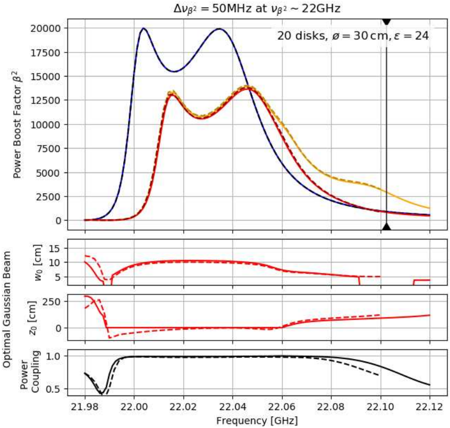
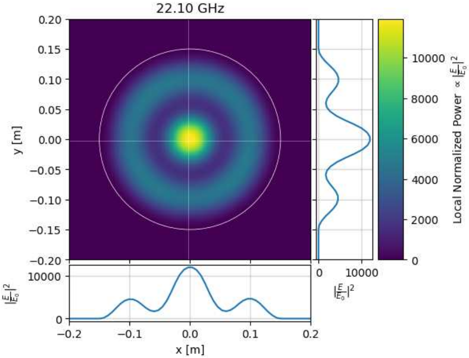
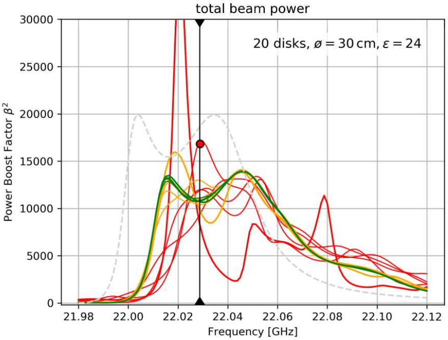
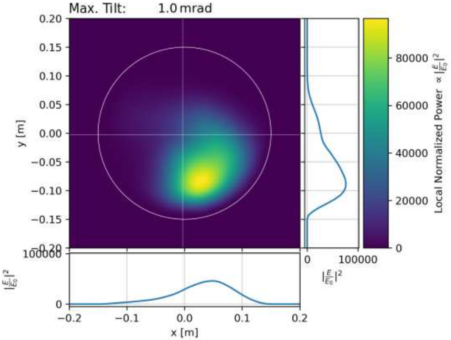




well matched to Gaussian beam $w_0 \approx 10$ cm

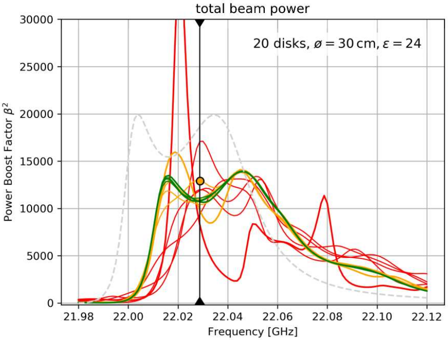
3D Simulations – Tilts

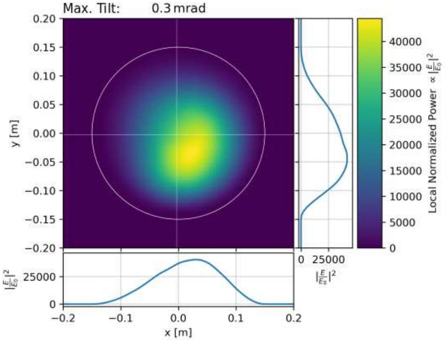




tilts better than 0.1 mrad ≈ 30 μm/30 cm **required**

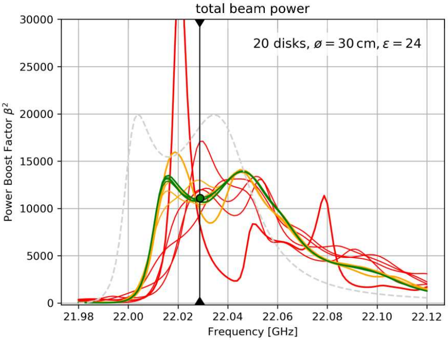
3D Simulations – Tilts

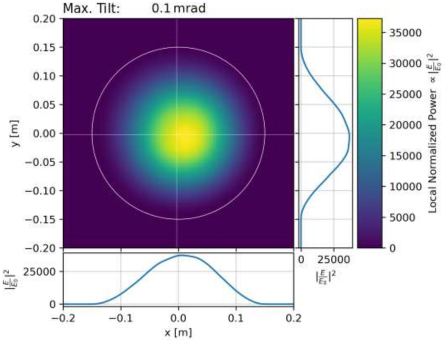




tilts better than $0.1\,\text{mrad} \approx 30\,\mu\text{m}/30\,\text{cm}$ **required**

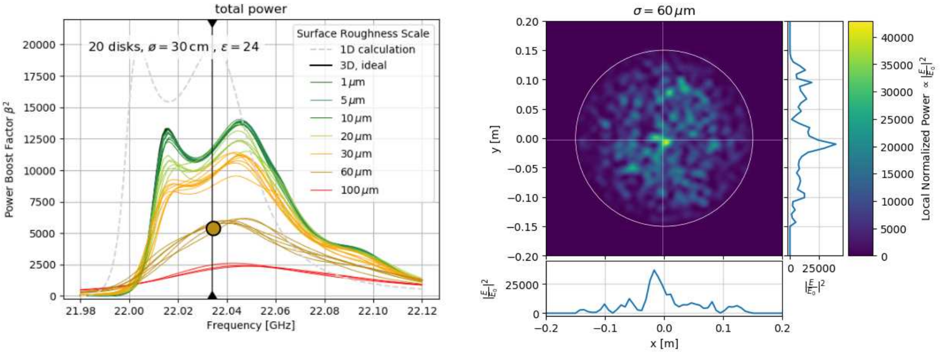
3D Simulations – Tilts





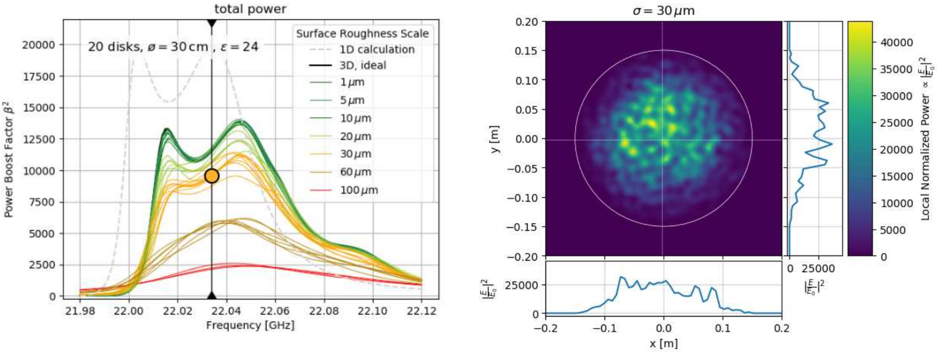
tilts better than 0.1 mrad ≈ 30 µm/30 cm **required**

3D Simulation – Surface Roughness



$10\,\mu\mathrm{m}$ **unproblematic**

3D Simulation – Surface Roughness



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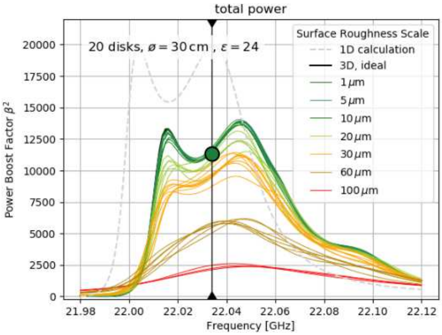
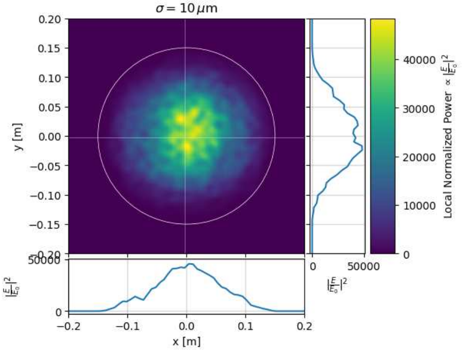
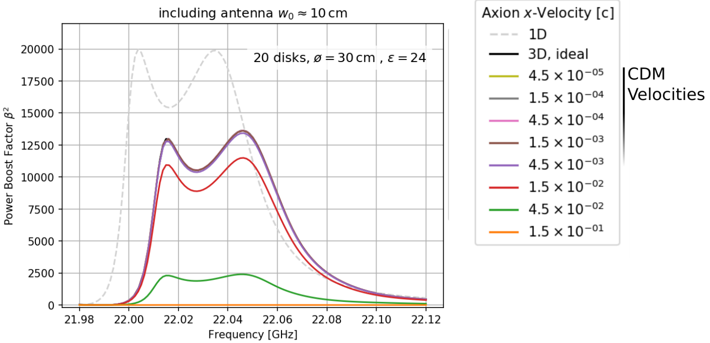




10 µm unproblematic

3D Simulations – Axion Velocity

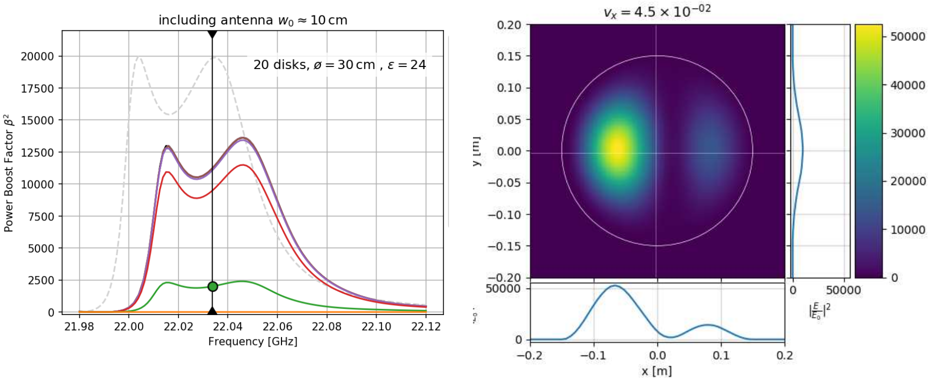
each disk: tilted emission with angle v_x



CDM velocities: **unproblematic**

3D Simulations – Axion Velocity

each disk: tilted emission with angle v_x



CDM velocities: unproblematic

3D Simulations – Axion Velocity

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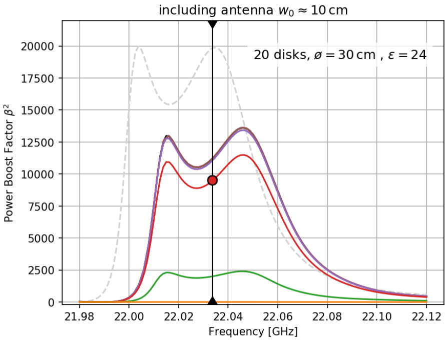

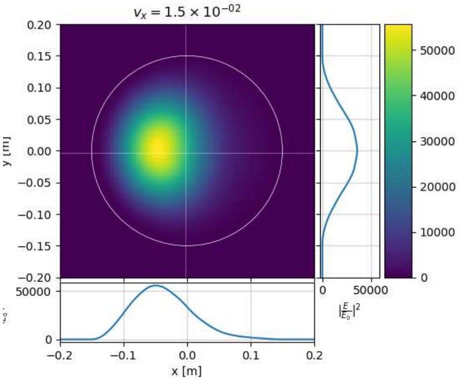

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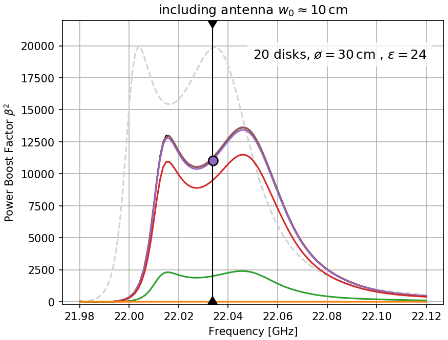
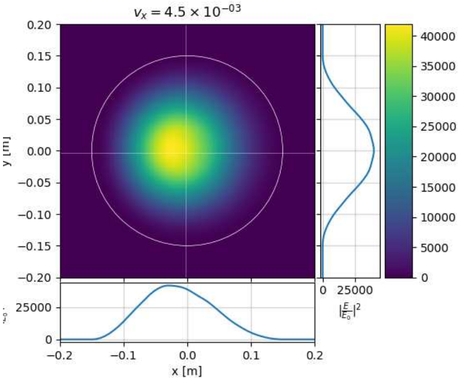
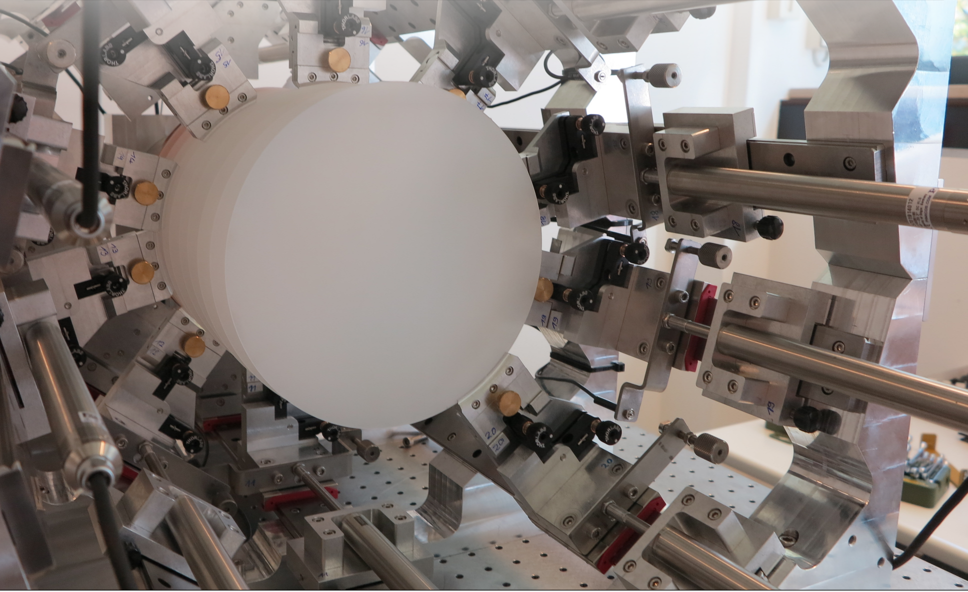


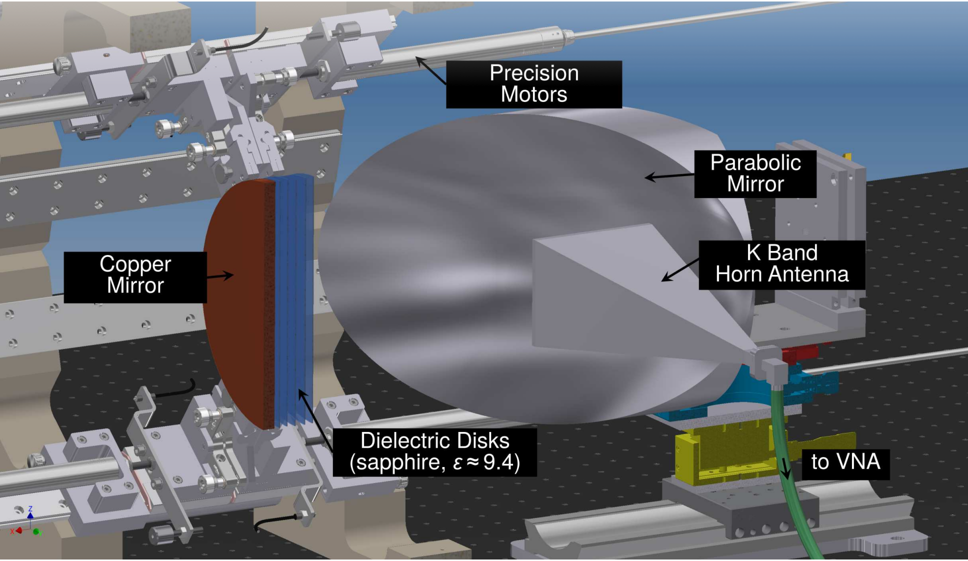


CDM velocities: unproblematic

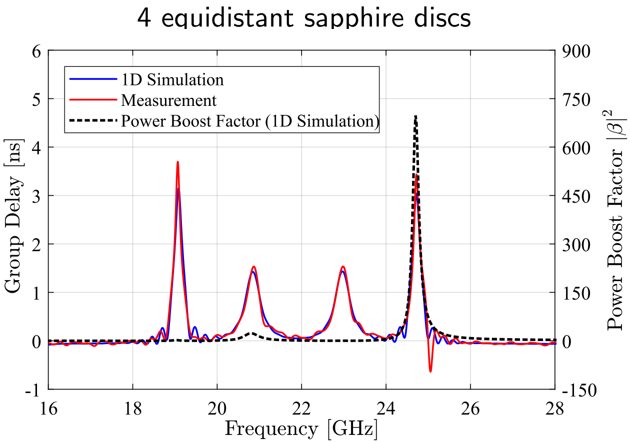
Proof of Principle Setup



Proof of Principle Setup



Probing the Boost Factor see also Eur. Phys. J. C (2019) 79: 186



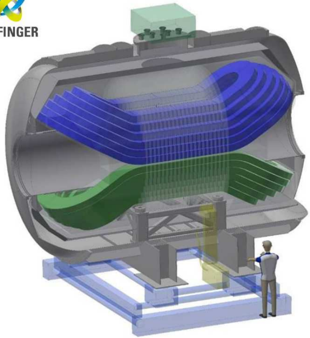
predicted electromagnetic response demonstrated

ongoing: comparison with 3D simulation, more discs

Further Challanges...

9 T **Magnet**

BiLFINGER

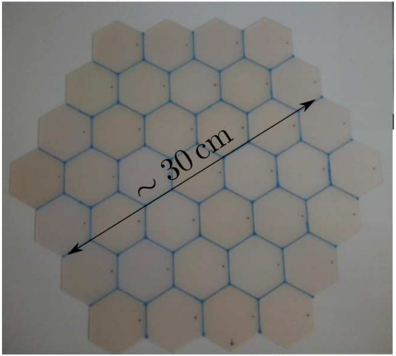


similar design also by cea

$B^2 A \sim 100\,\mathrm{T}^2\mathrm{m}^2$,
$\varnothing \sim 1.5\,\mathrm{m}, \ell \sim 1\,\mathrm{m}$; NbTi

Dielectric Discs

$\epsilon \approx 24, \tan\delta \sim \text{few} \times 10^{-5}$



U. Hamburg

Motor R&D (e.g. Piezo)

MADMAX collaboration

cea

DESY.

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

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

Max-Planck-Institut
für Radioastronomie

Universidad de Zaragoza

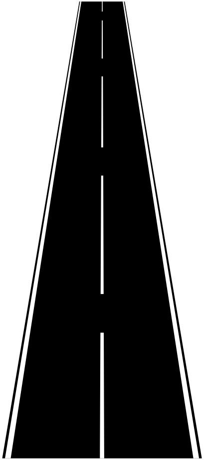
RWTH AACHEN UNIVERSITY

EBERHARD KARLS UNIVERSITÄT TÜBINGEN

NÉEL institut

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

Roadmap



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

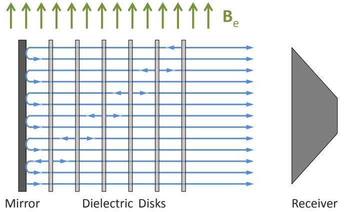
in 1-3 years:

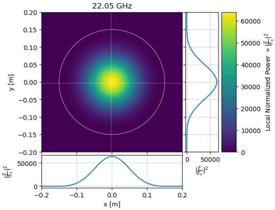
20 disc prototype: $\varnothing_{\mathrm{disc}} \approx 30\,\mathrm{cm}$, $B = 3 - 4\,\mathrm{T}$
$\Rightarrow$ first physics results

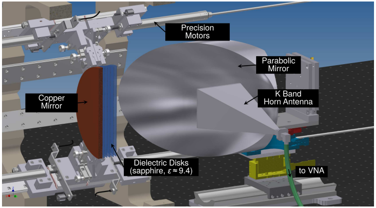
afterwards (2025?):

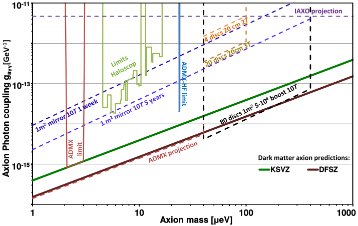
full scale experiment

Conclusions







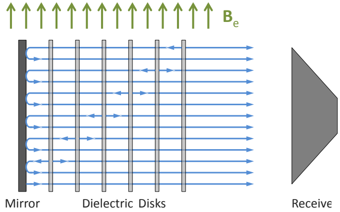


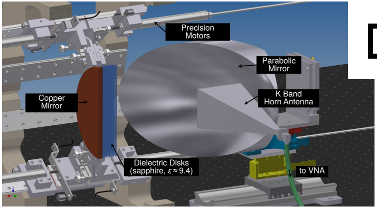
for more information:

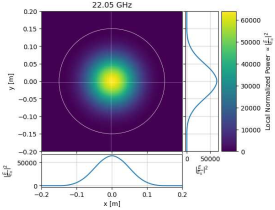
MADMAX collaboration white paper,

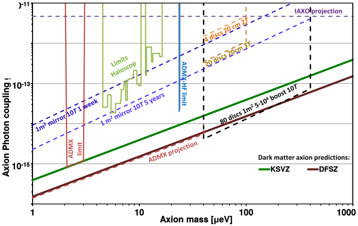
Phys. Rev. Lett. 118, 091801, **JCAP** 1701:061,2017

Bedankt voor uw aandacht









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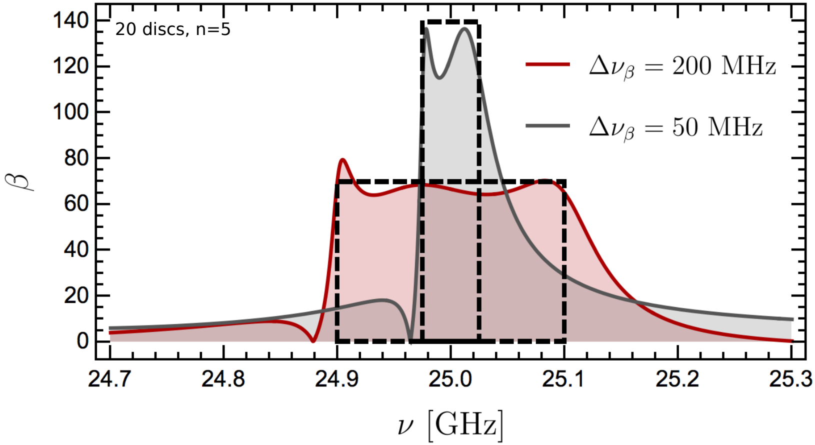
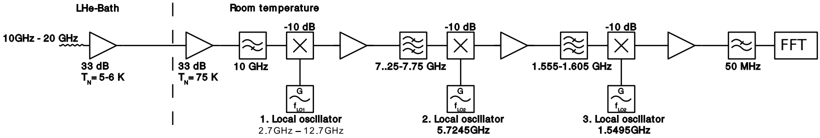
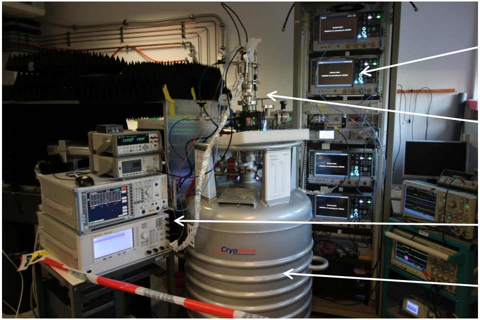
Optimizing the Boost Factor



Area under Boost Factor curve approximately conserved

Receiver System





signal analyzer
(4 samplers, 1.4% dead time)

front end mixers
and amps

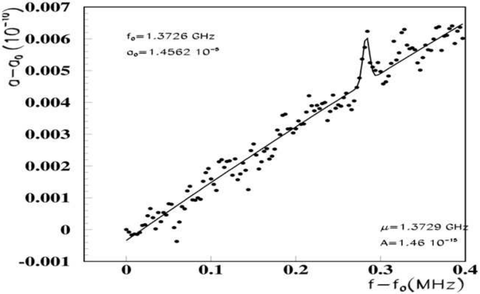
“Fake Axion”

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

Receiver System

typical one week measurment

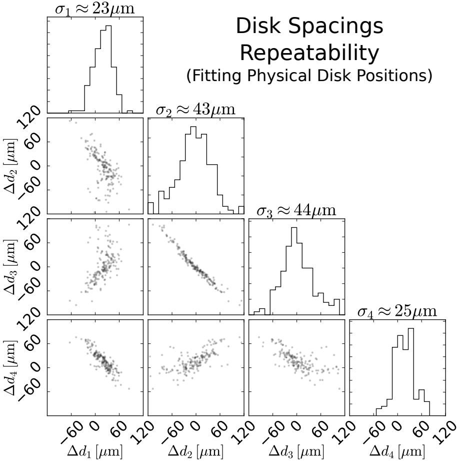
(with higher input signal)



with preamp @ 4K:

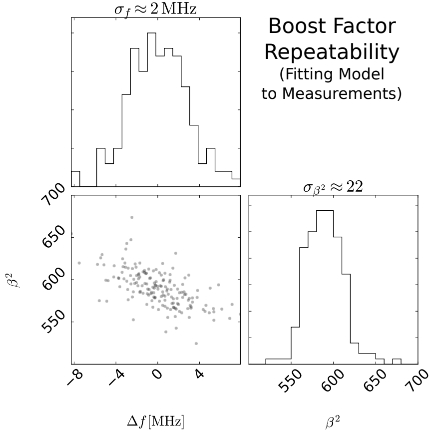
signal down to $\sim 10^{-23}$ W **detected**

Probing the Boost Factor – Results



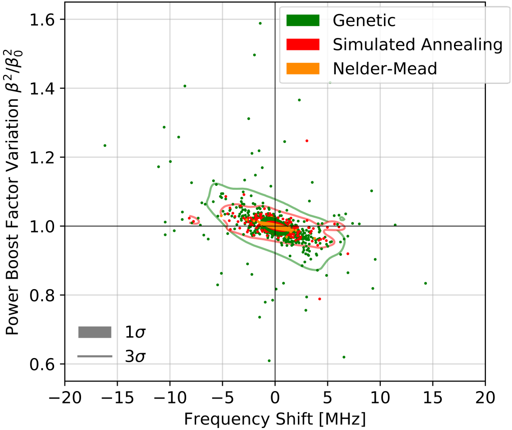
Predicted Electromagnetic Response Demonstrated

Probing the Boost Factor – Results



Predicted Electromagnetic Response Demonstrated

Boost Factor Repeatability



errors on boost factor under control