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

Stefan Knirck*
for the MADMAX collaboration

CEA-IRFU, Saclay, France
* Max-Planck-Institut für Physik, Munich, Germany
University of Hamburg, Hamburg, Germany
Max-Planck-Institut für Radioastronomie, Bonn, Germany
DESY, Hamburg, Germany
University of Zaragoza, Spain

MAX-PLANCK-GESELLSCHAFT

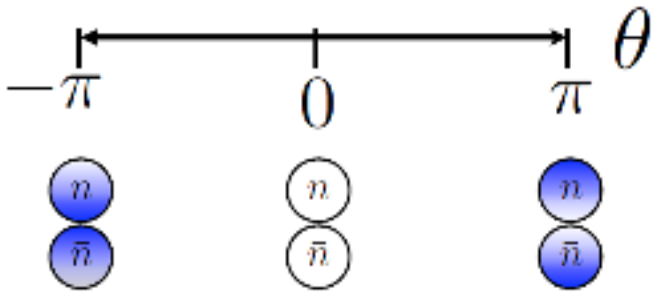
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

The Strong CP-Problem

QCD allows for a term

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

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

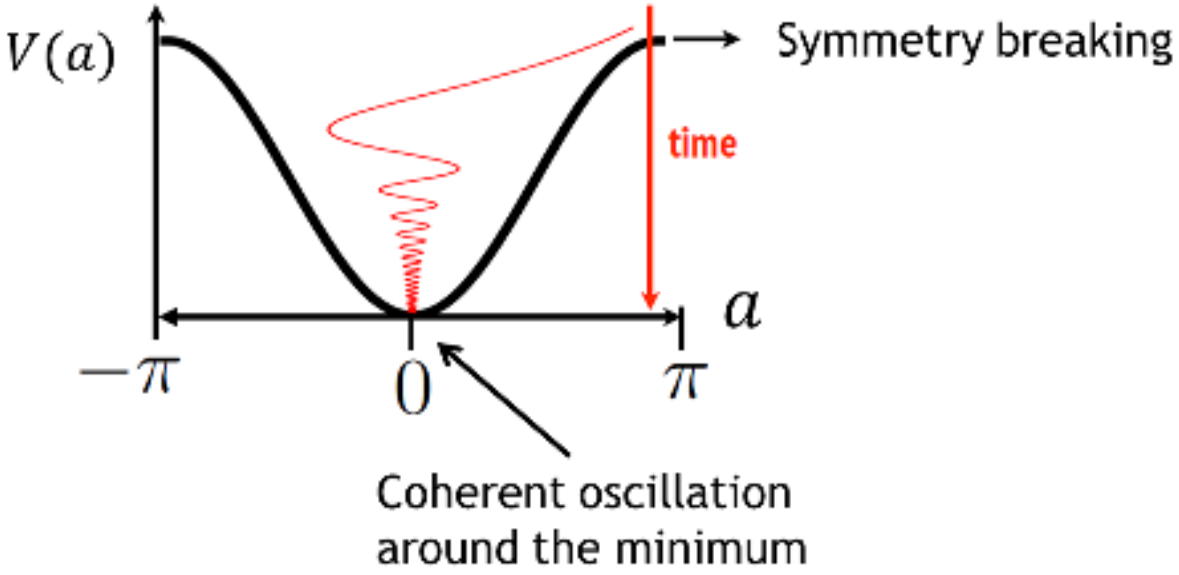


The Strong CP-Problem

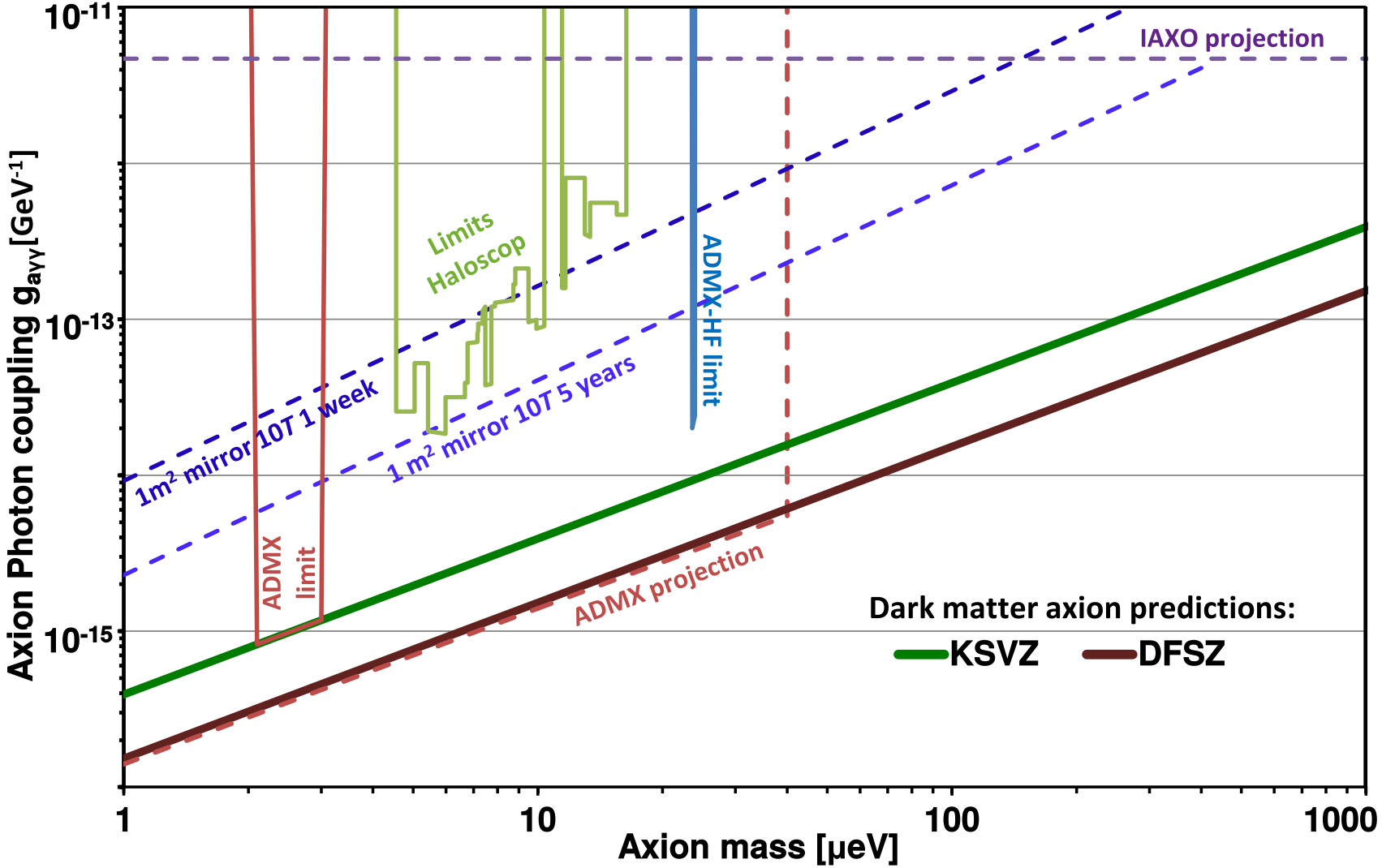
make θ a dynamic field: $\theta \to a(t;\mathbf{x})$ (Pecci-Quinn 1977)

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

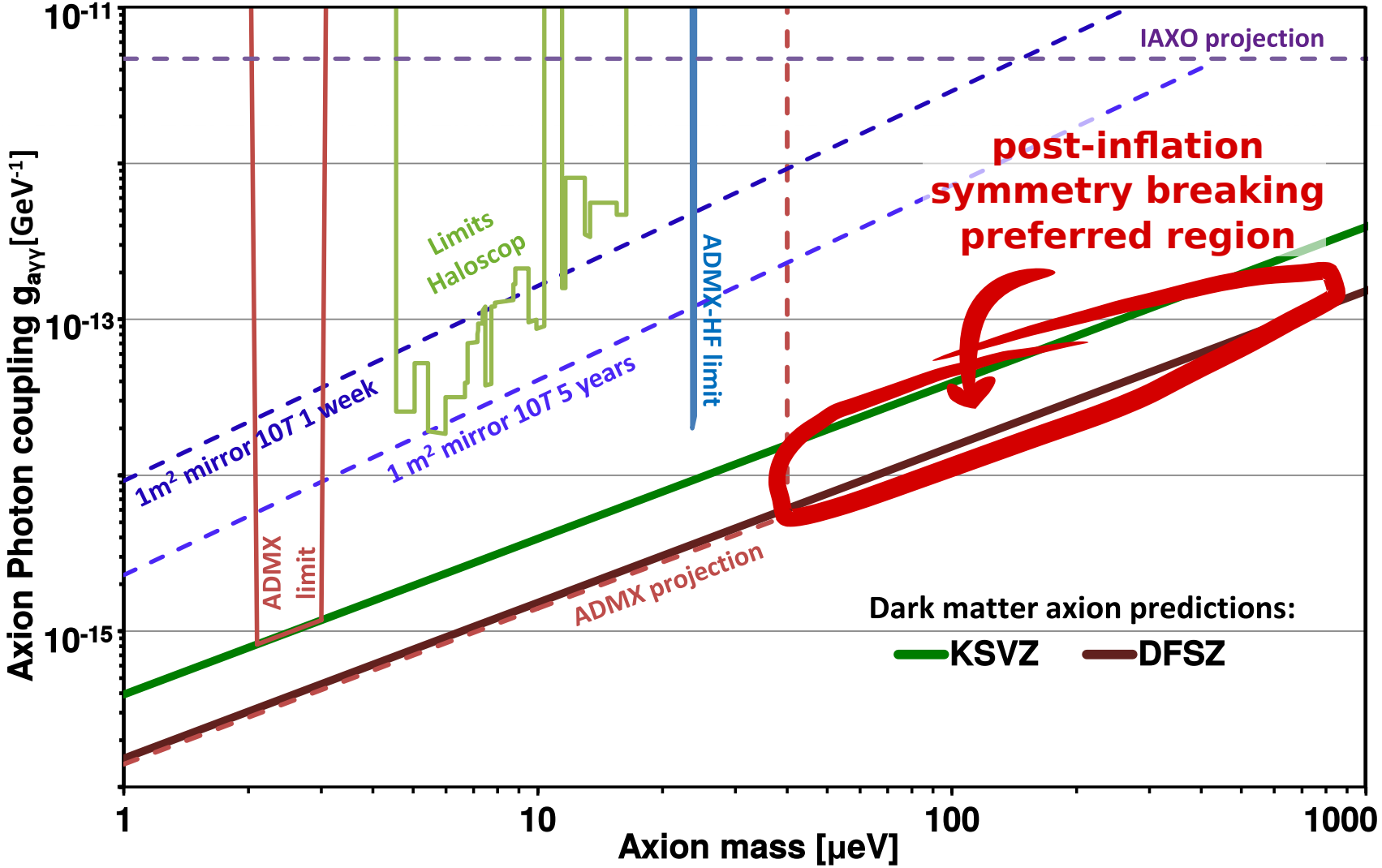
rolldown to CP conserving limit:



The Axion - Parameterspace

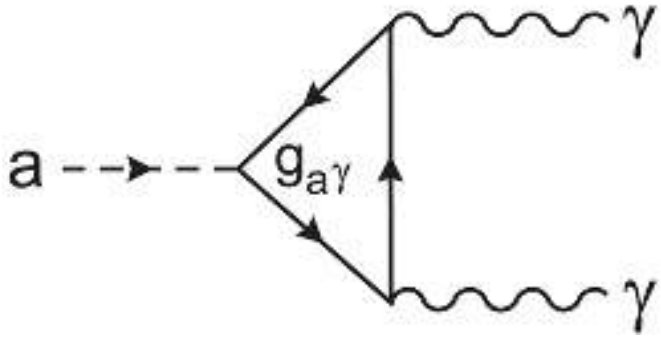


The Axion - Parameterspace



Axion Electrodynamics

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



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

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

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

$m_a \sim 30\,\mu\text{eV}$, non-relativistic

$$\Rightarrow \lambda_{\text{DB}} = \frac{2\pi}{p} \sim \frac{2\pi}{10^{-3}m_a} \sim 10\,\text{m}$$

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 $\mathbf{B}_e$:

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

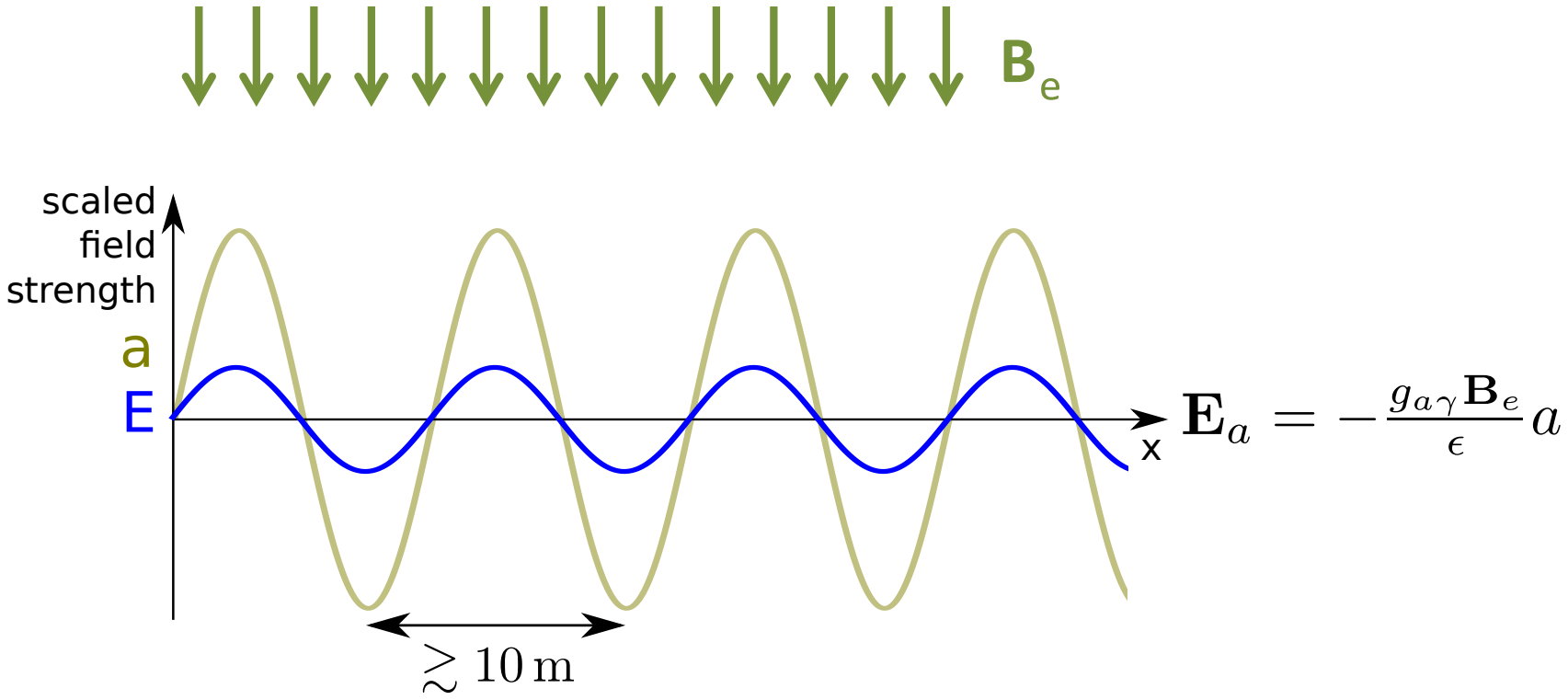
$$\nabla\times\mathbf{H} - \dot{\mathbf{E}} = \mathbf{J} + g_{a\gamma}\mathbf{B}_e\dot{a}$$

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

Axion induced electric field:

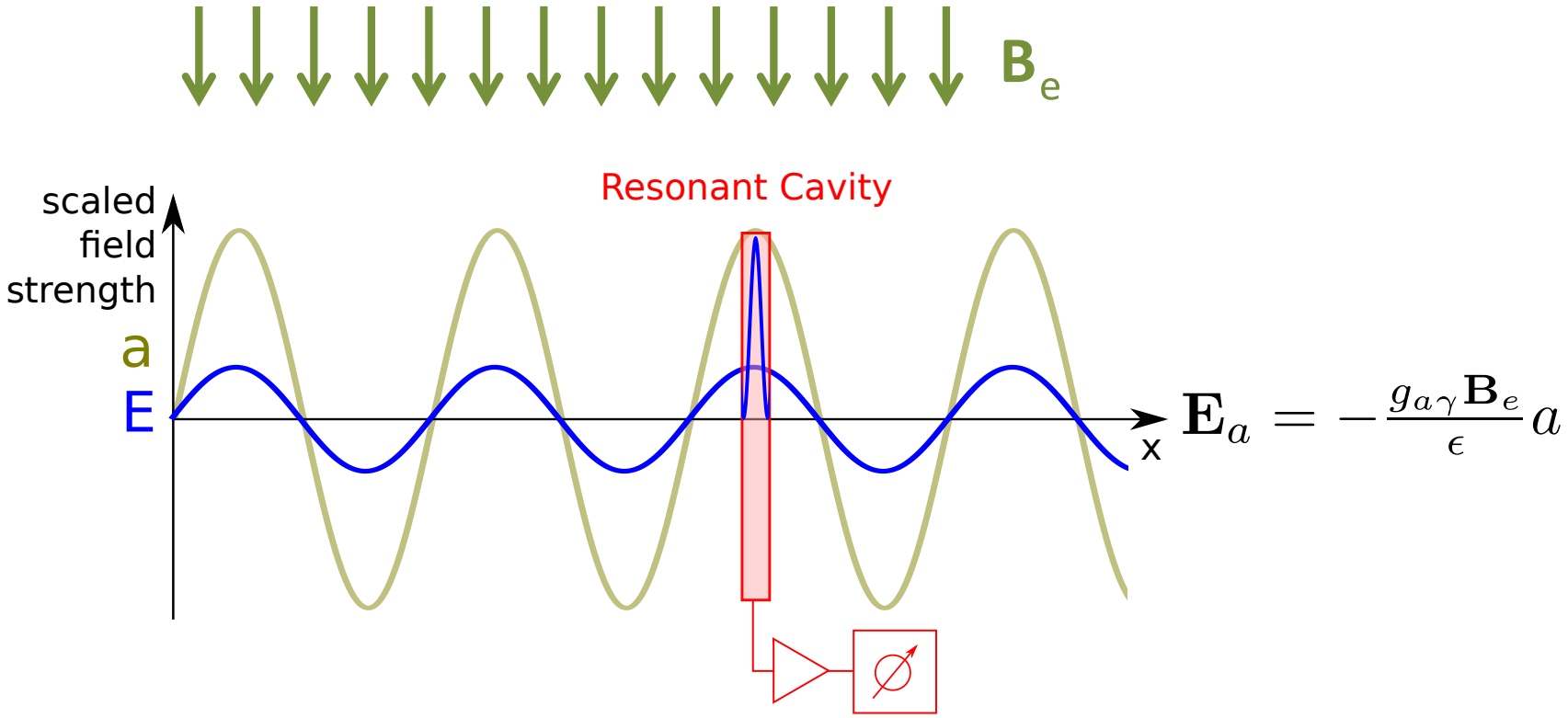
$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a = 1.3\times10^{-12}\,\mathrm{V\,m^{-1}}\times\left(\frac{B_e}{10\,\mathrm{T}}\right)\frac{C_{a\gamma}f_{DM}^{1/2}}{\epsilon}$$

Axion - Photon Mixing



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

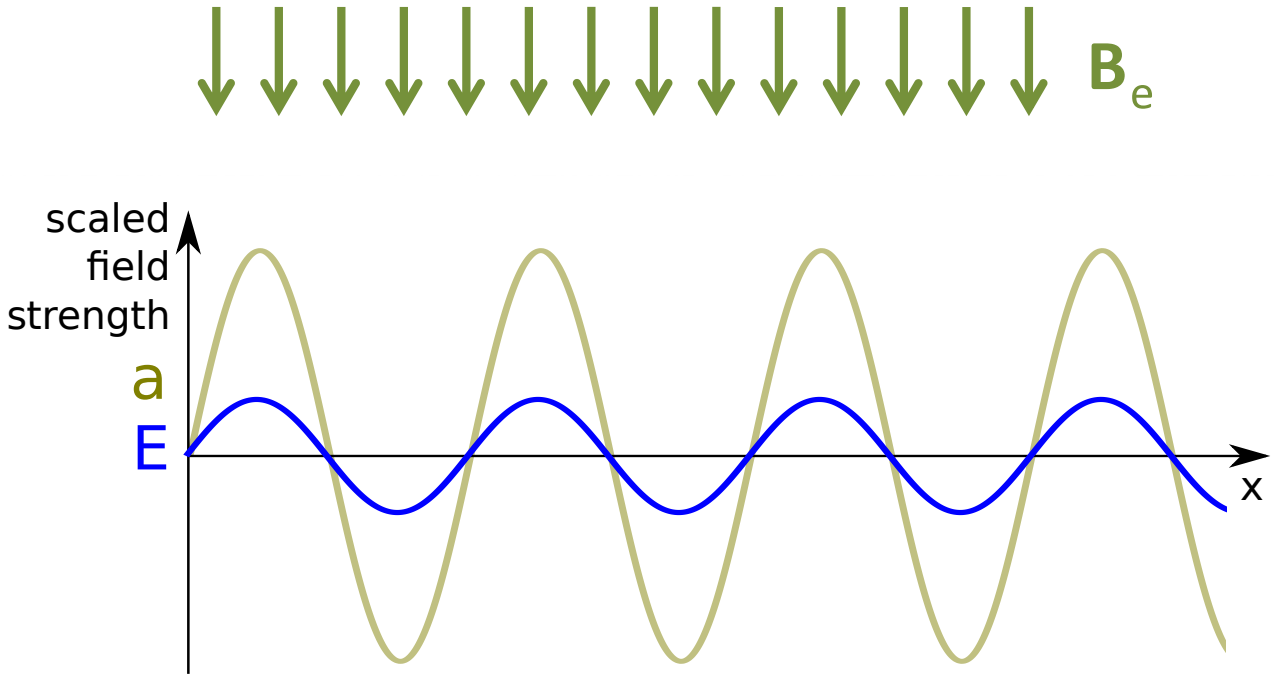
Axion - Photon Mixing



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

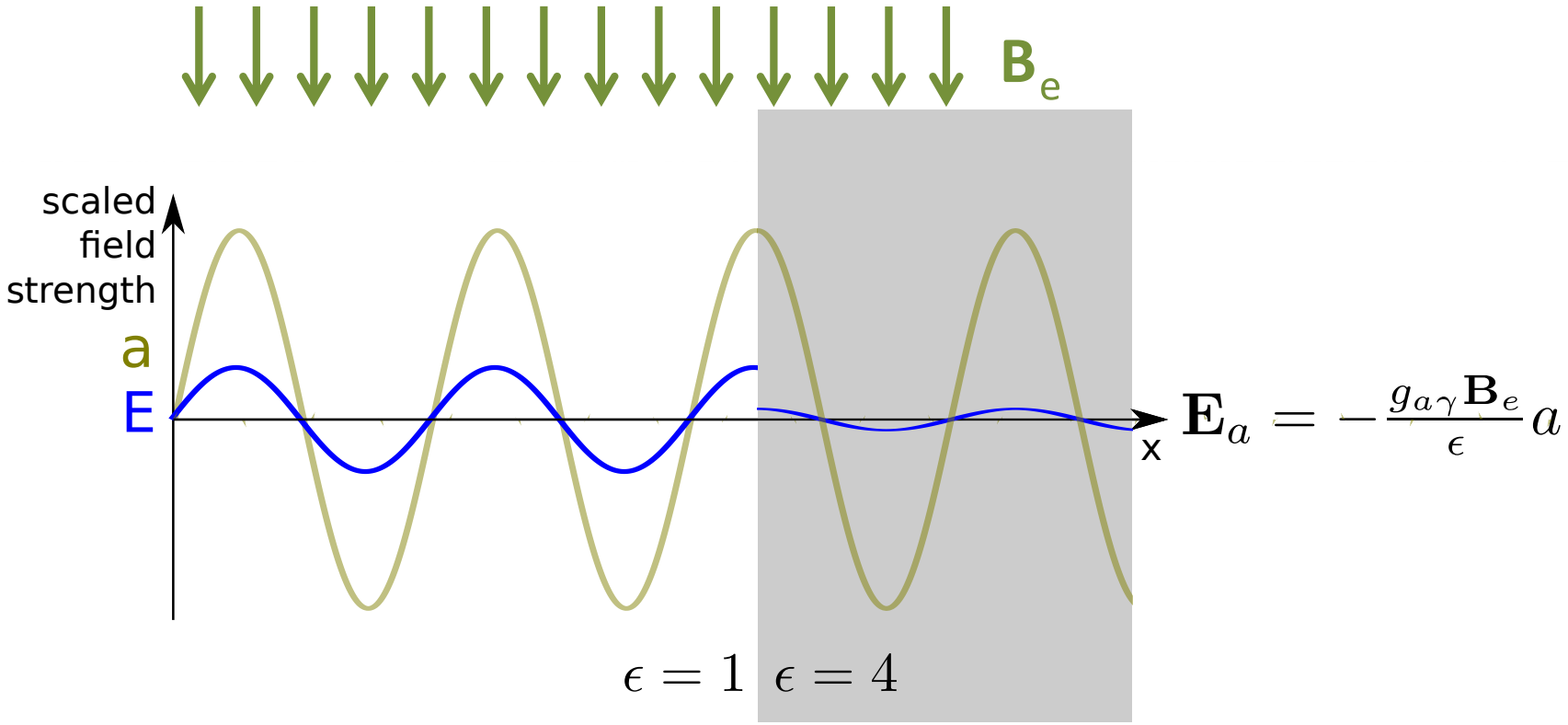
Q: Quality Factor, C_{nml}: mode factor

Axion - Photon Mixing

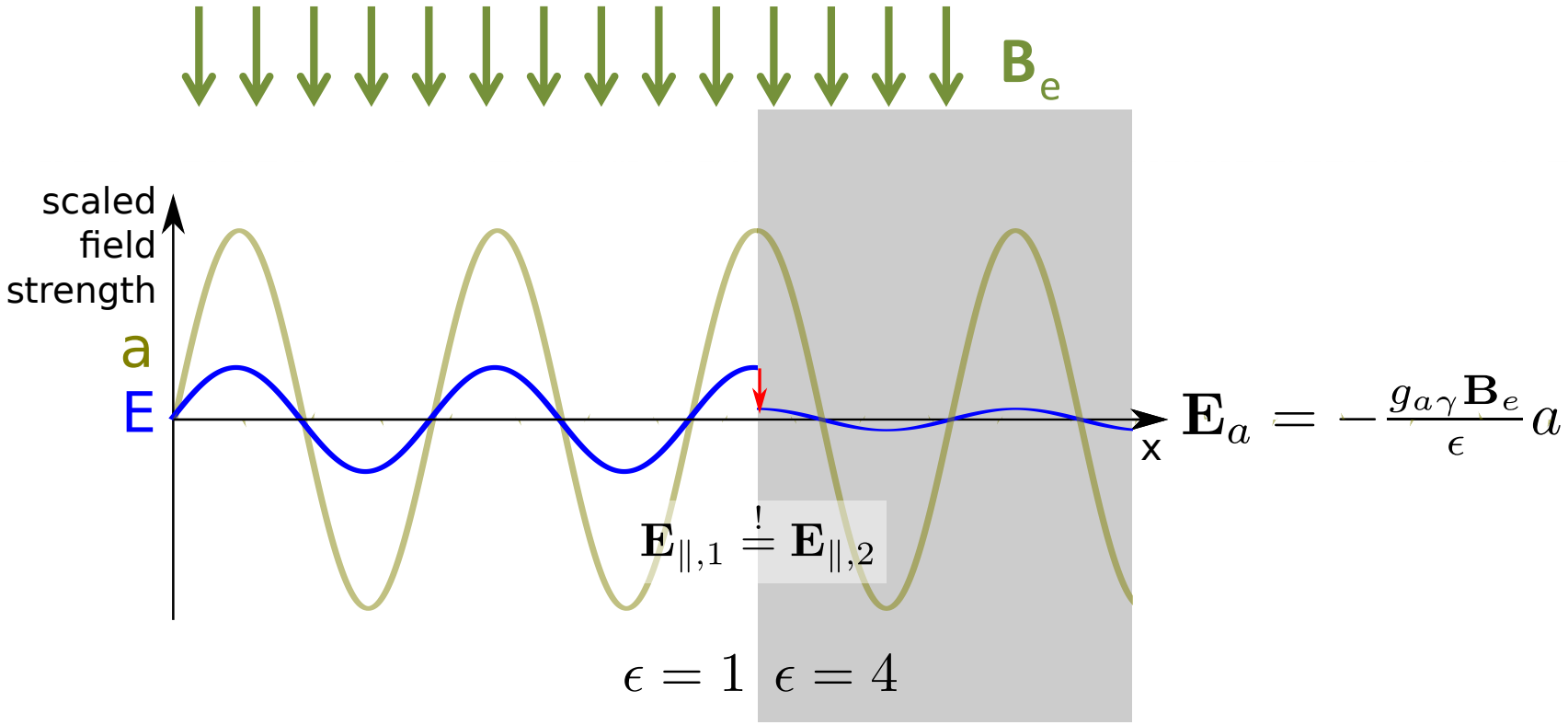


$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$

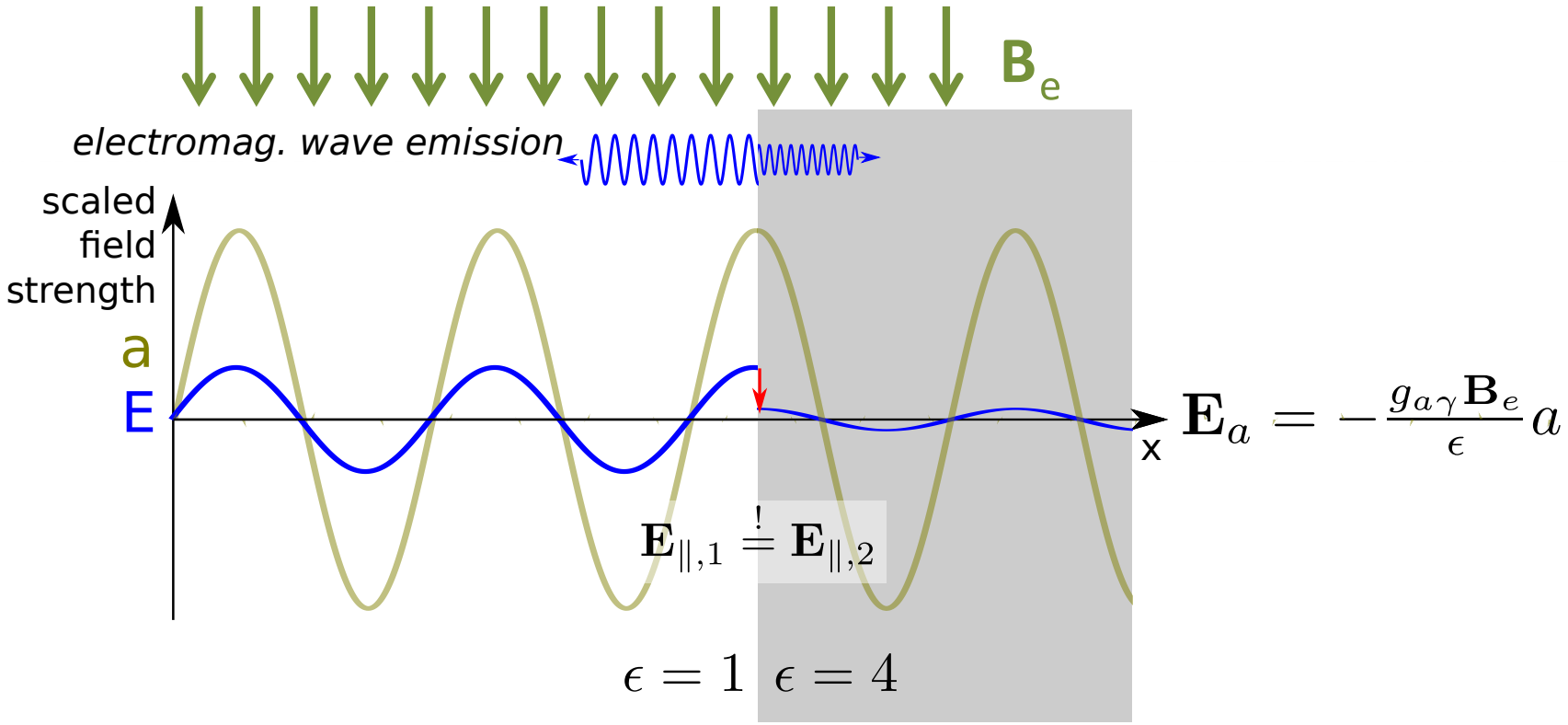
Axion - Photon Mixing



Axion - Photon Mixing

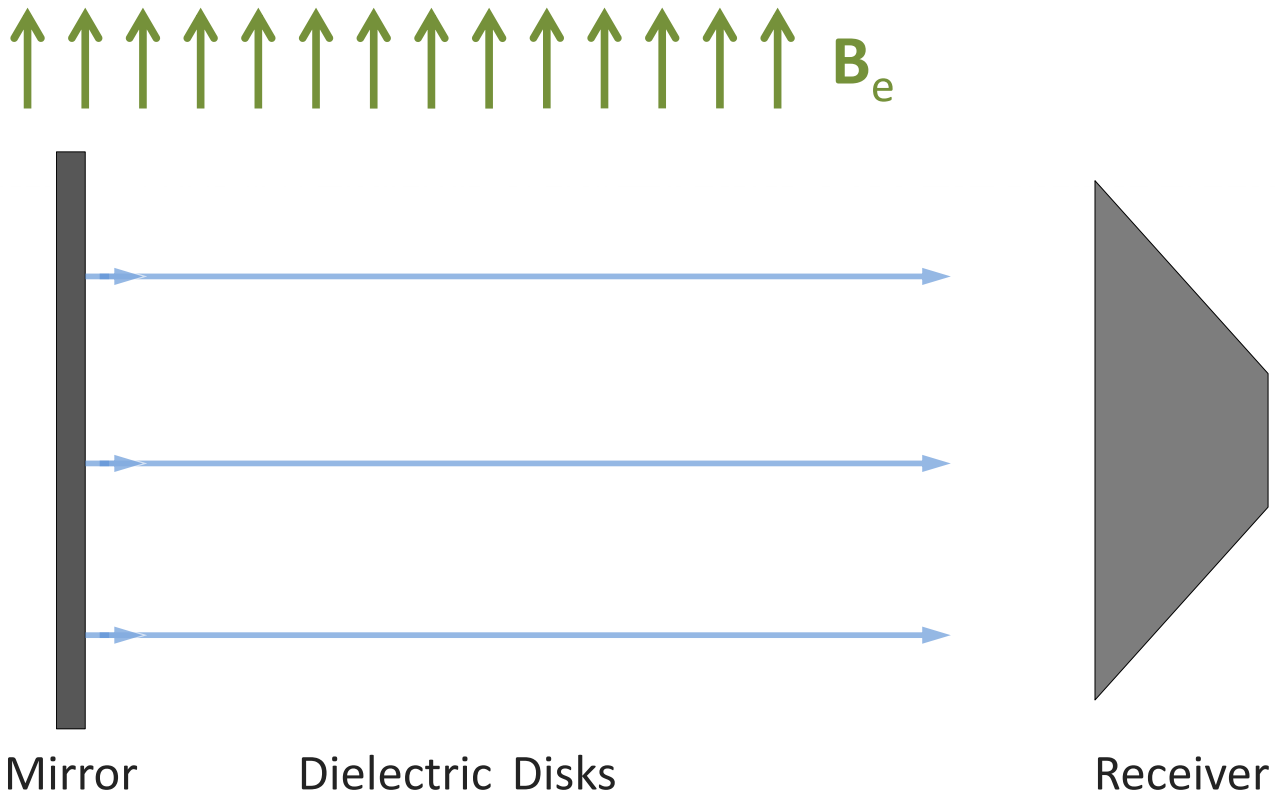


Axion - Photon Mixing



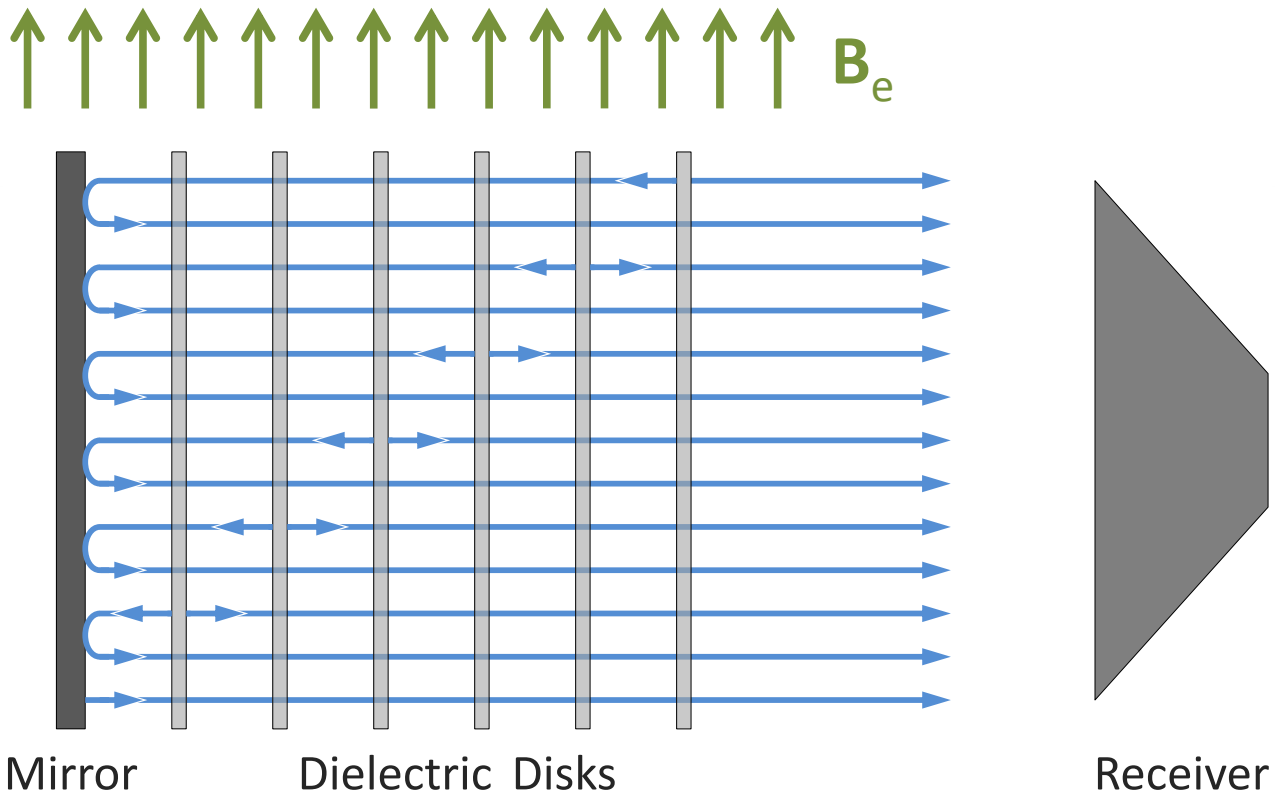
$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 {C_{a\gamma}}^2 \cdot f(\epsilon_1, \epsilon_2)$$

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

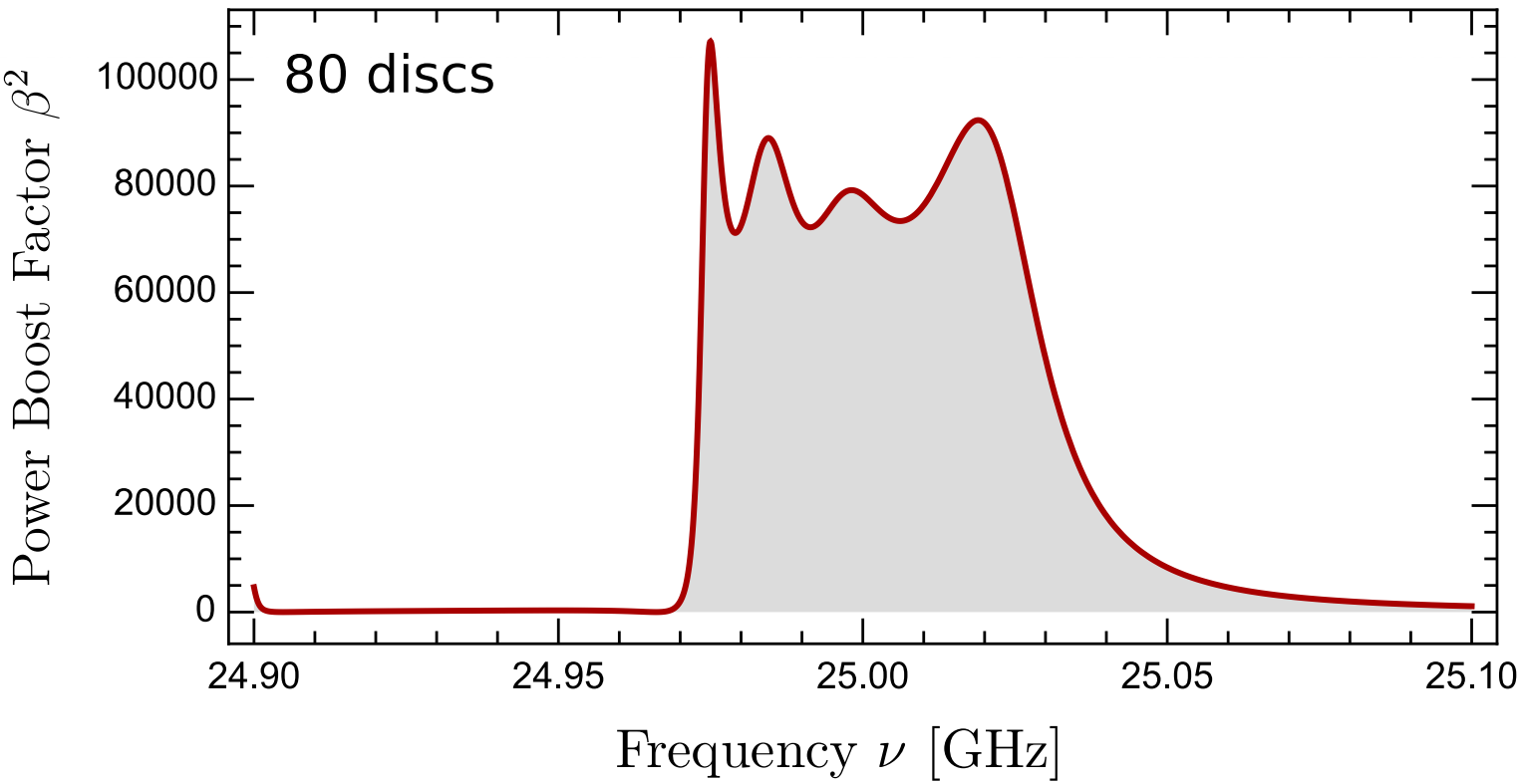


$$P/A = 2.2 \times 10^{-27}\,\mathrm{W\,m^{-2}} \left(\frac{B_e}{10\,\mathrm{T}}\right)^2 {C_{a\gamma}}^2 \cdot \beta^2$$

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

Power Boost Factor β^2 –

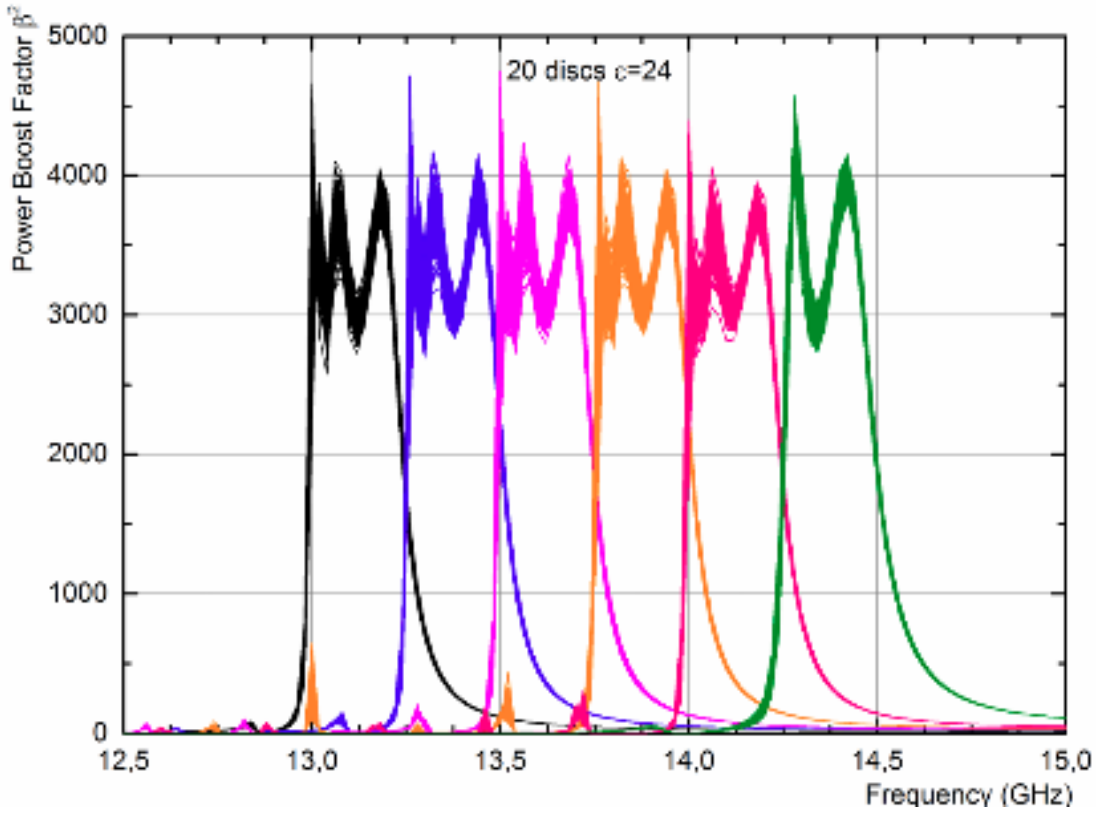
adjust disc spacings:



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

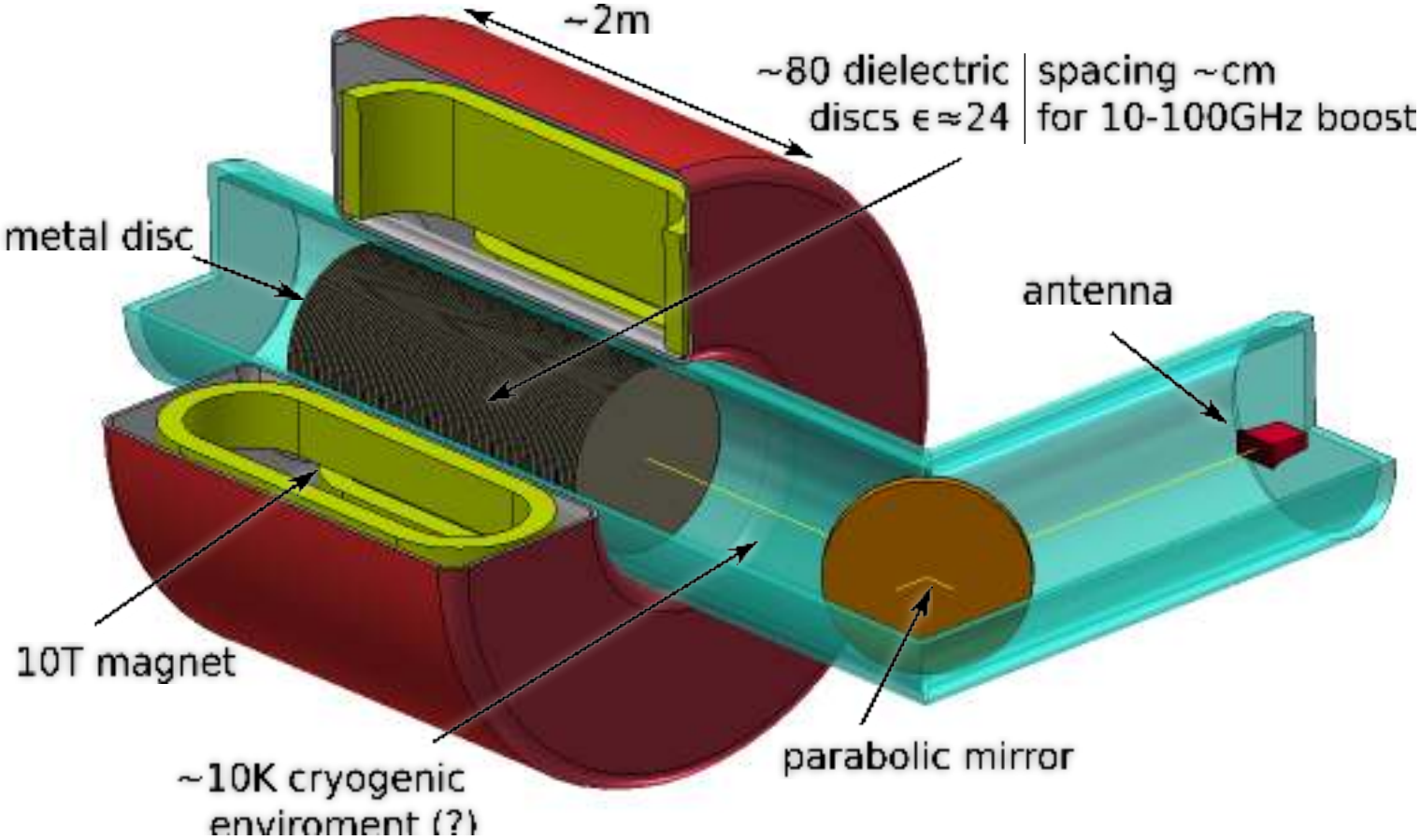
Power Boost Factor β^2

adjust disc spacings:

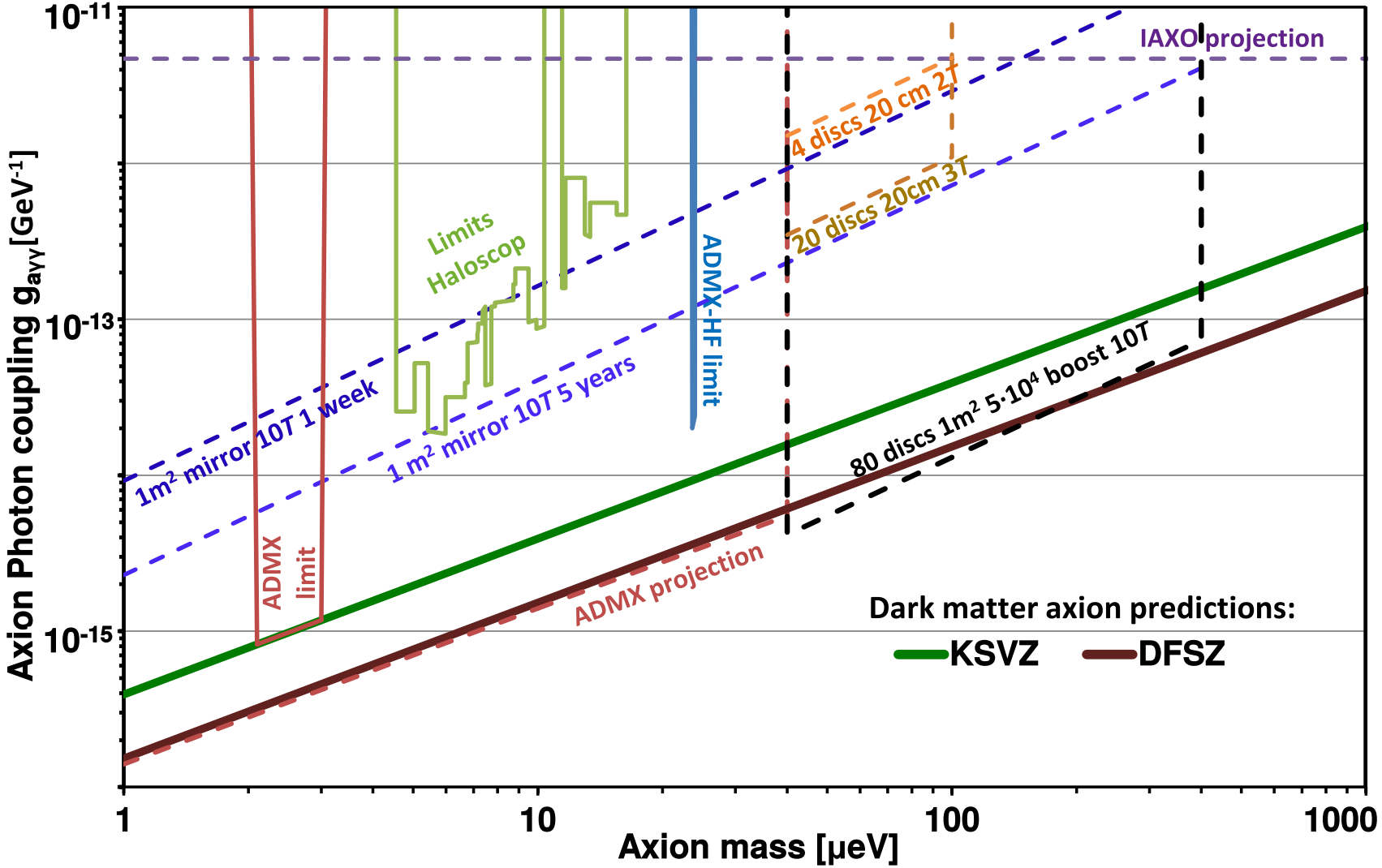


Frequency Band Tunable

The Vision

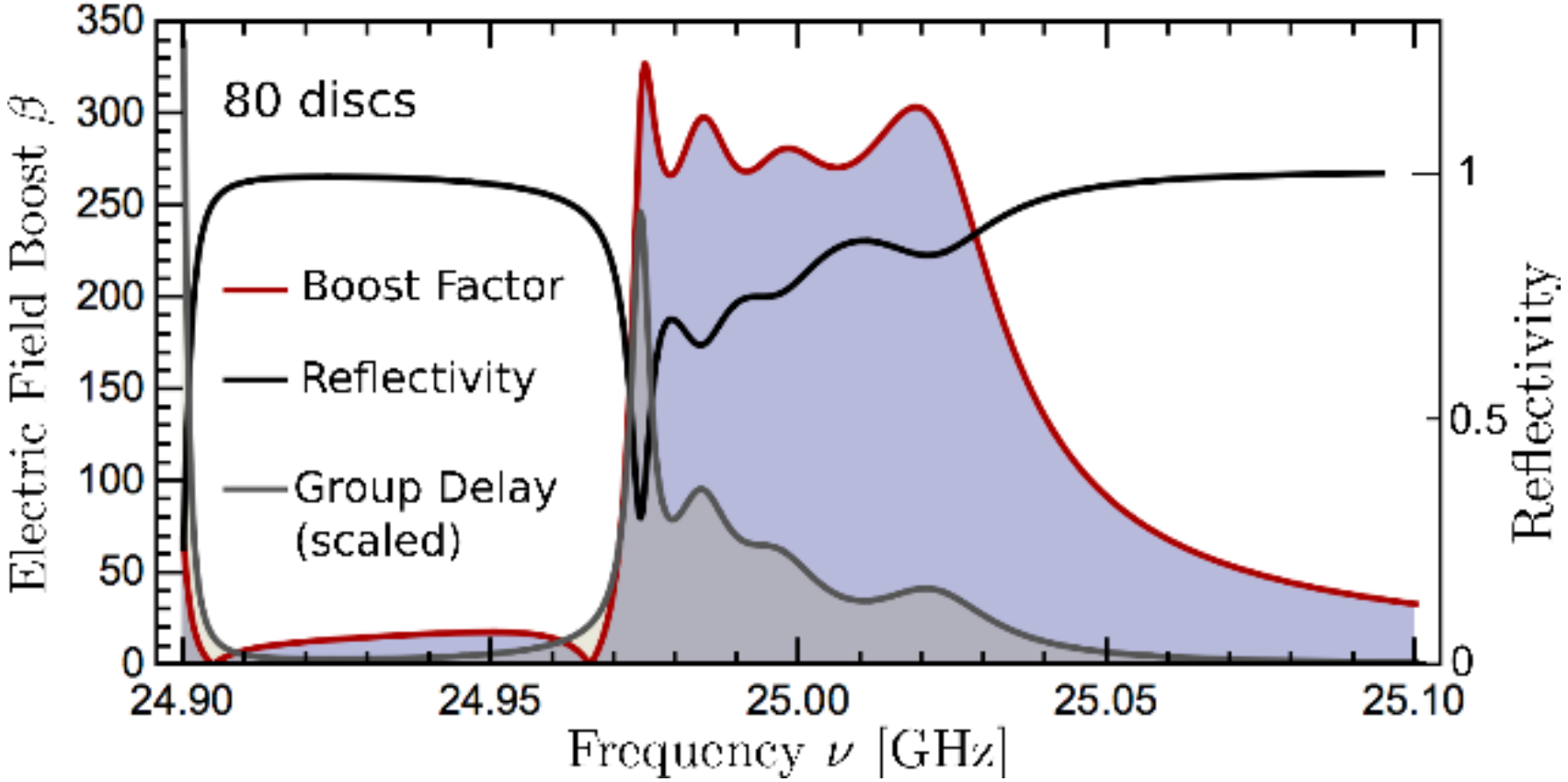

~2m
~80 dielectric discs ϵ≈24
spacing ~cm for 10-100GHz boost
metal disc
antenna
10T magnet
~10K cryogenic enviroment (?)
parabolic mirror

Sensitivity



Let's do it...

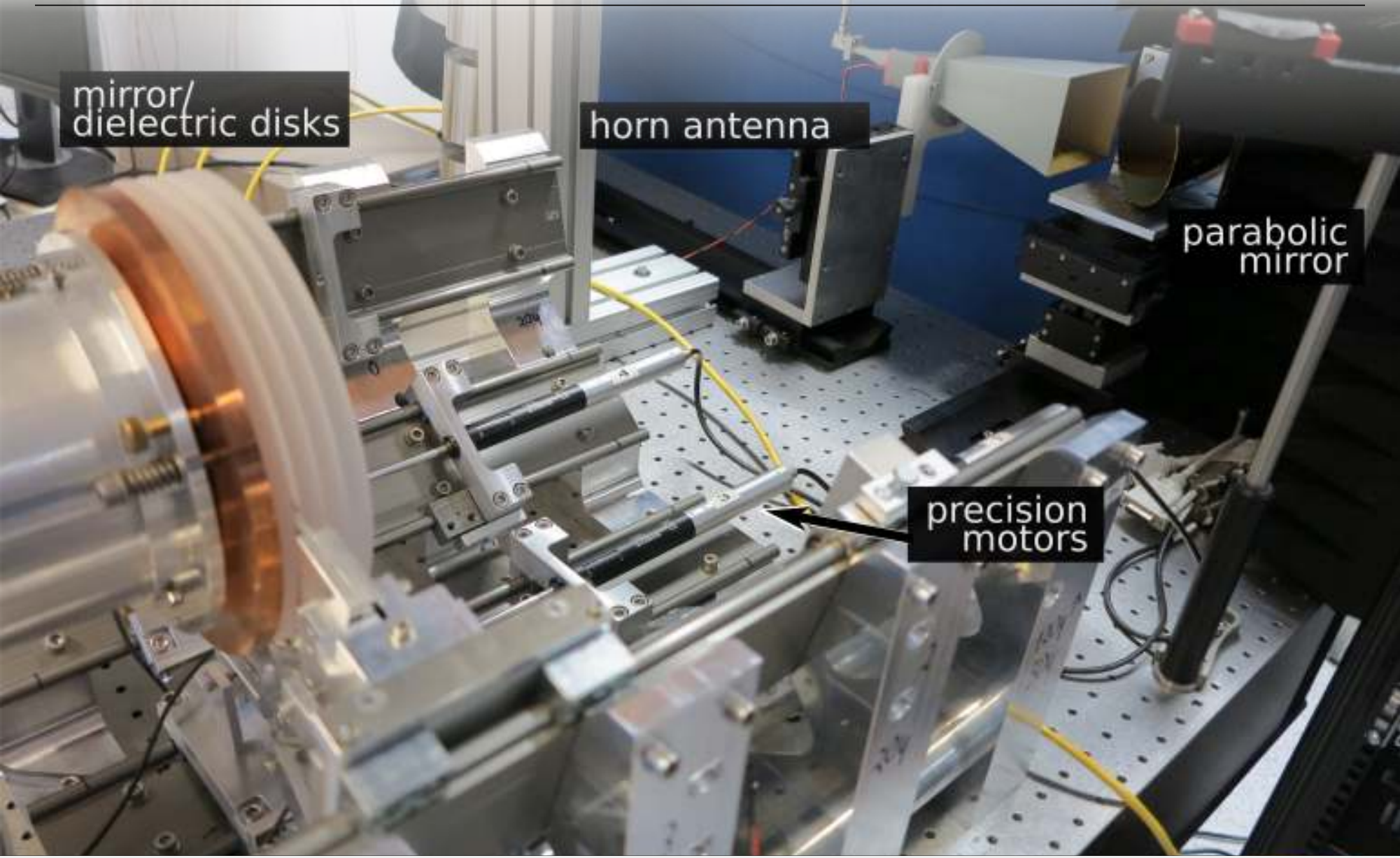
Probing the Boost Factor – Idea



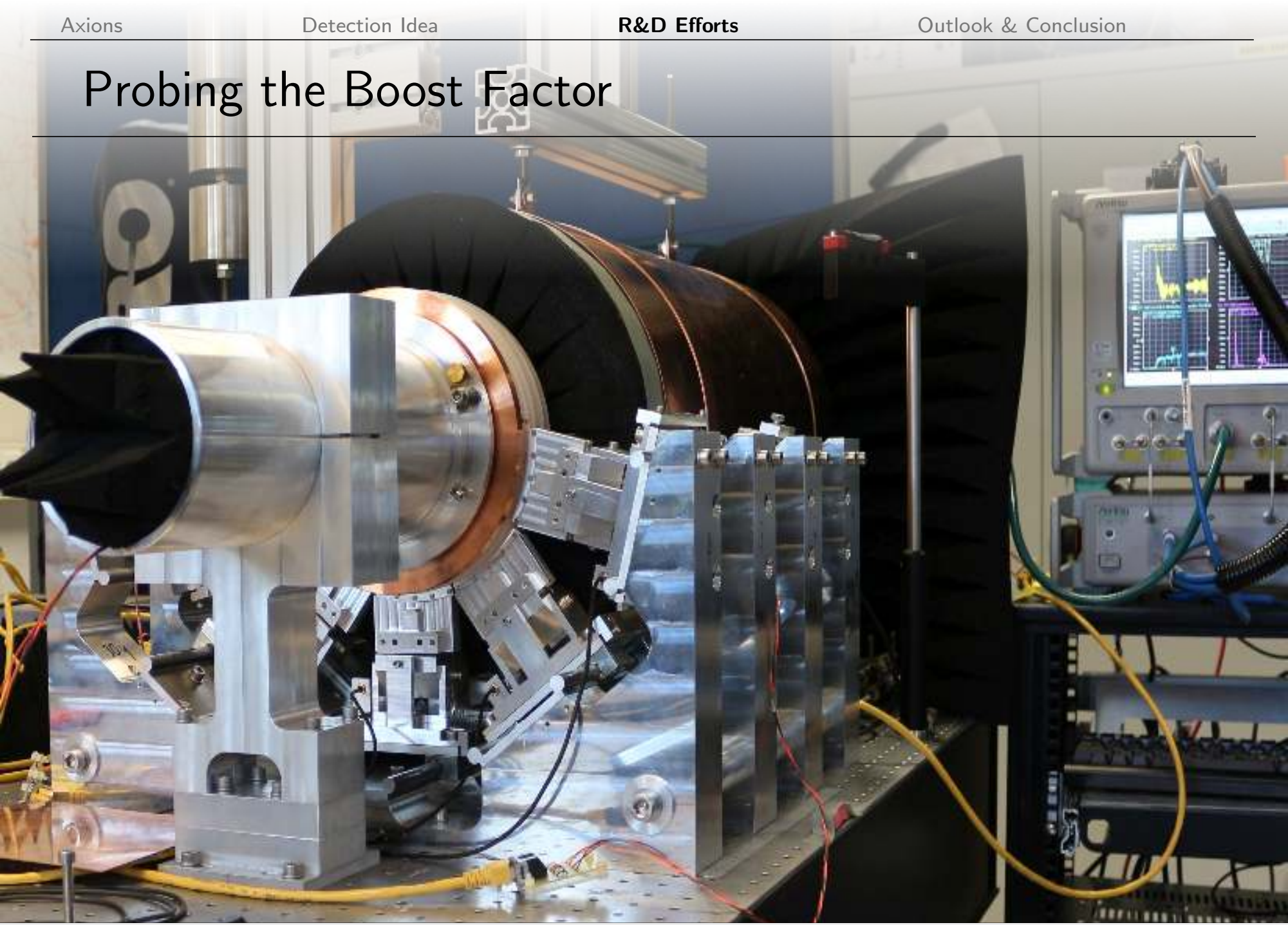
Boost Factor $\leftrightarrow$ Reflectivity / Group Delay Corellation

Probing the Boost Factor

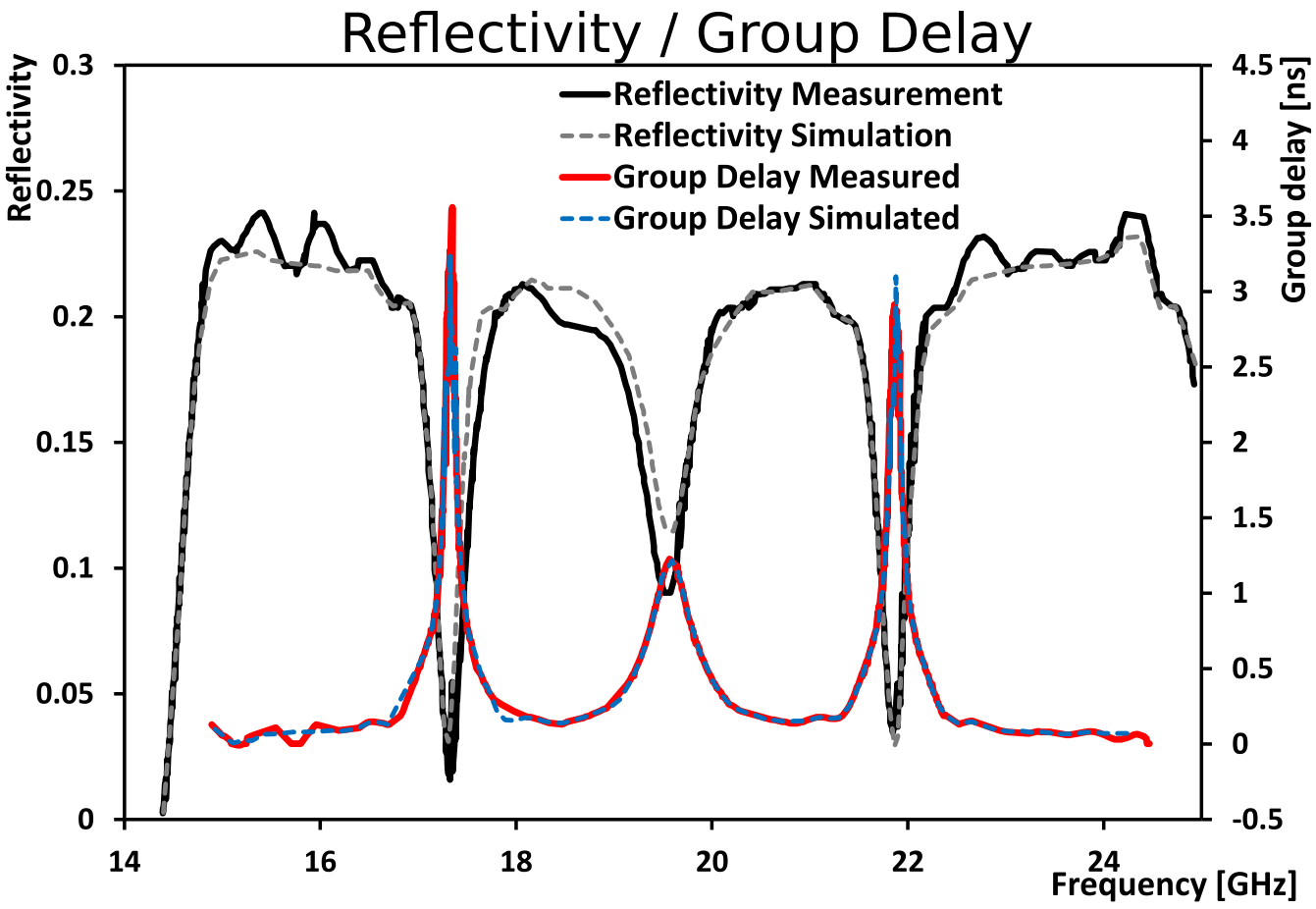
partially funded by Excellence Cluster Universe



Probing the Boost Factor

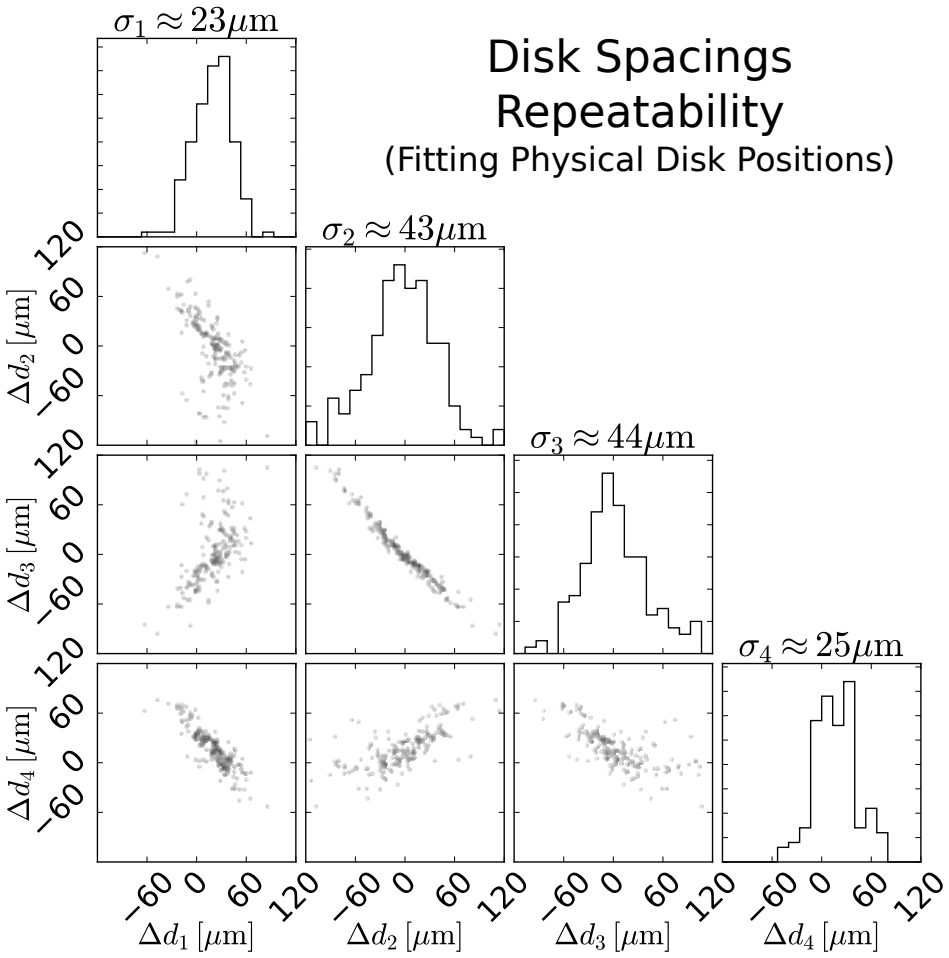


Probing the Boost Factor – Preliminary Results



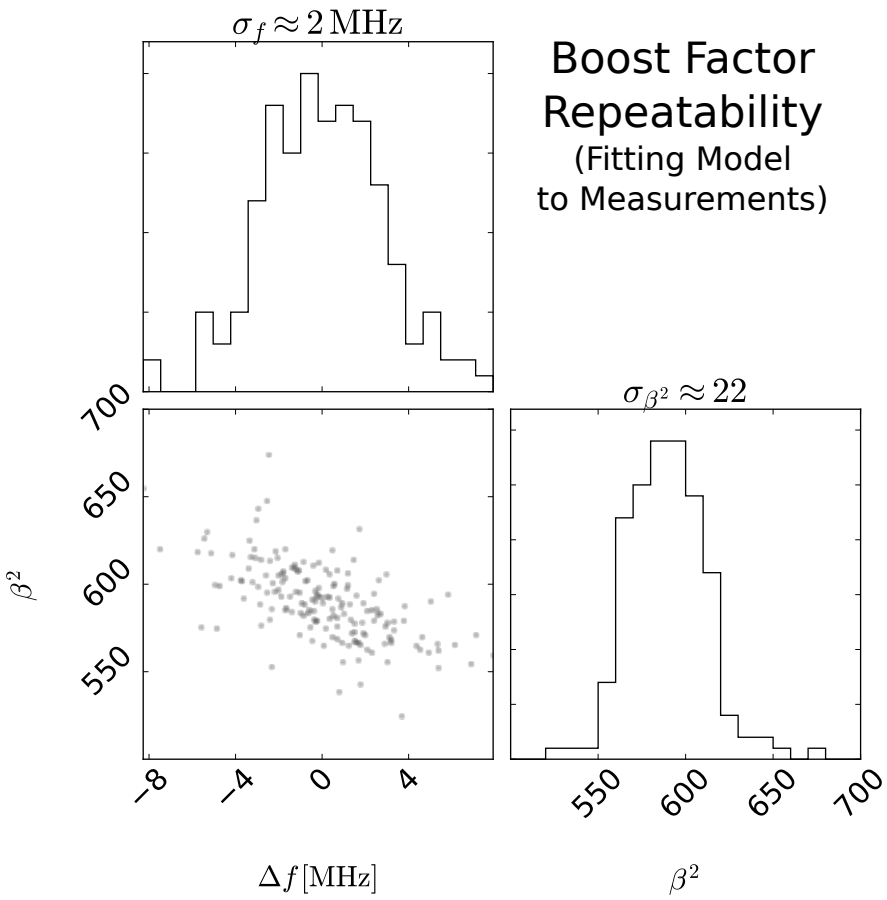
Predicted Electromagnetic Response Demonstrated

Probing the Boost Factor – Preliminary Results



Predicted Electromagnetic Response Demonstrated

Probing the Boost Factor – Preliminary Results



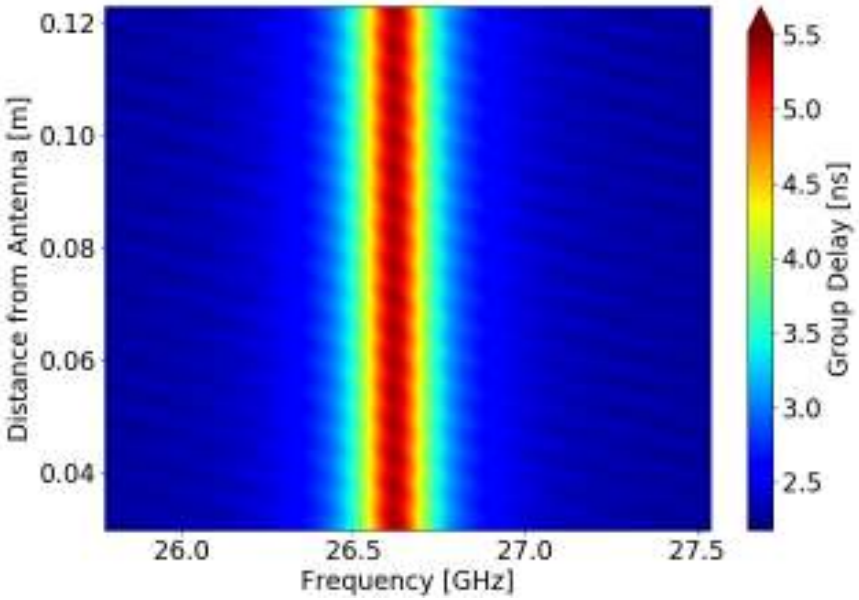
Predicted Electromagnetic Response Demonstrated

Probing the Boost Factor – Systematics

Unwanted Reflections:

single disk and mirror, $d \approx 5\,\mathrm{cm}$

+ slightly mismatched antenna



Displace Group Delay Peak

Losses

Diffraction

Tilts

Surface Imperfections

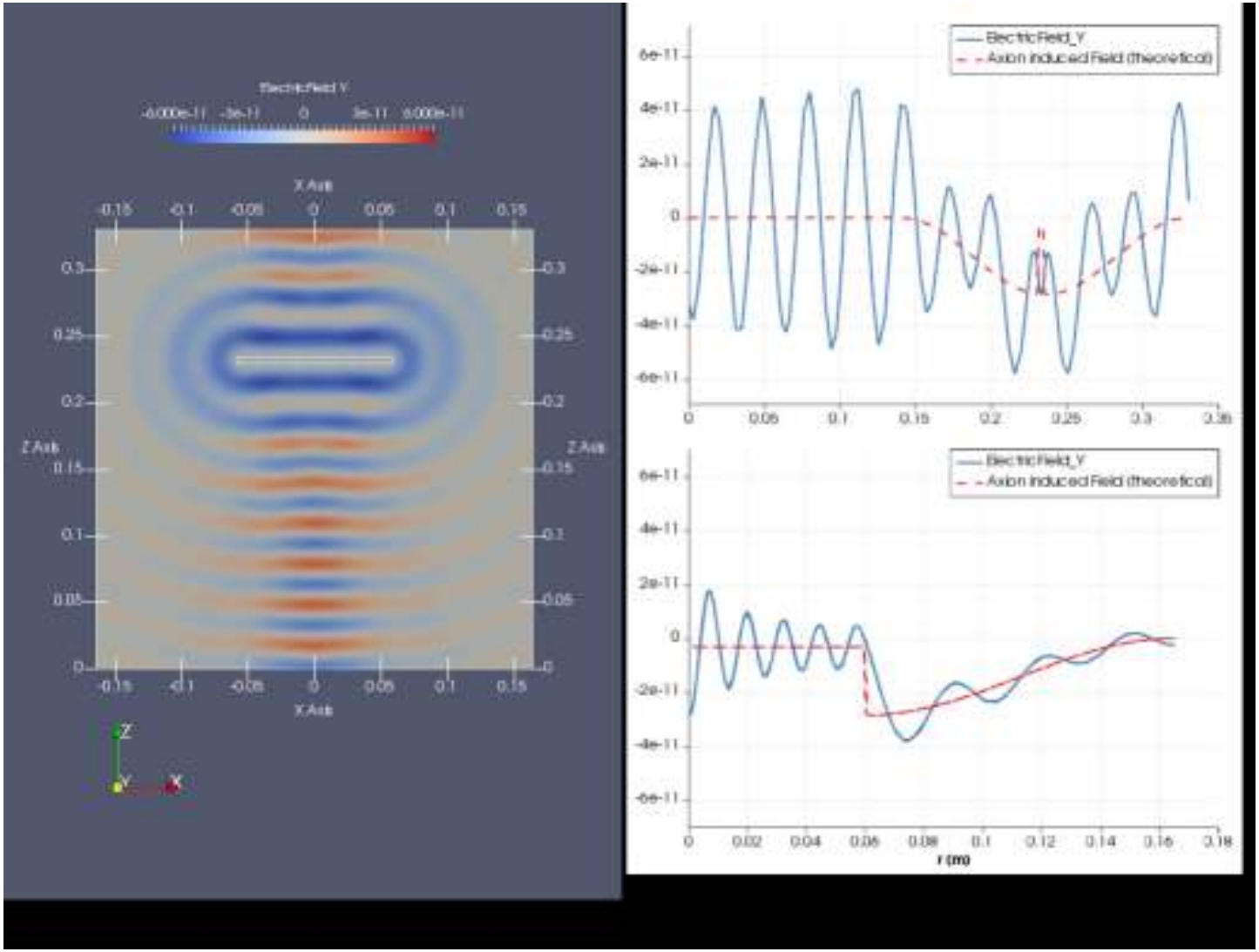
Near Fields

...

Physical Understanding / Modeling Needed

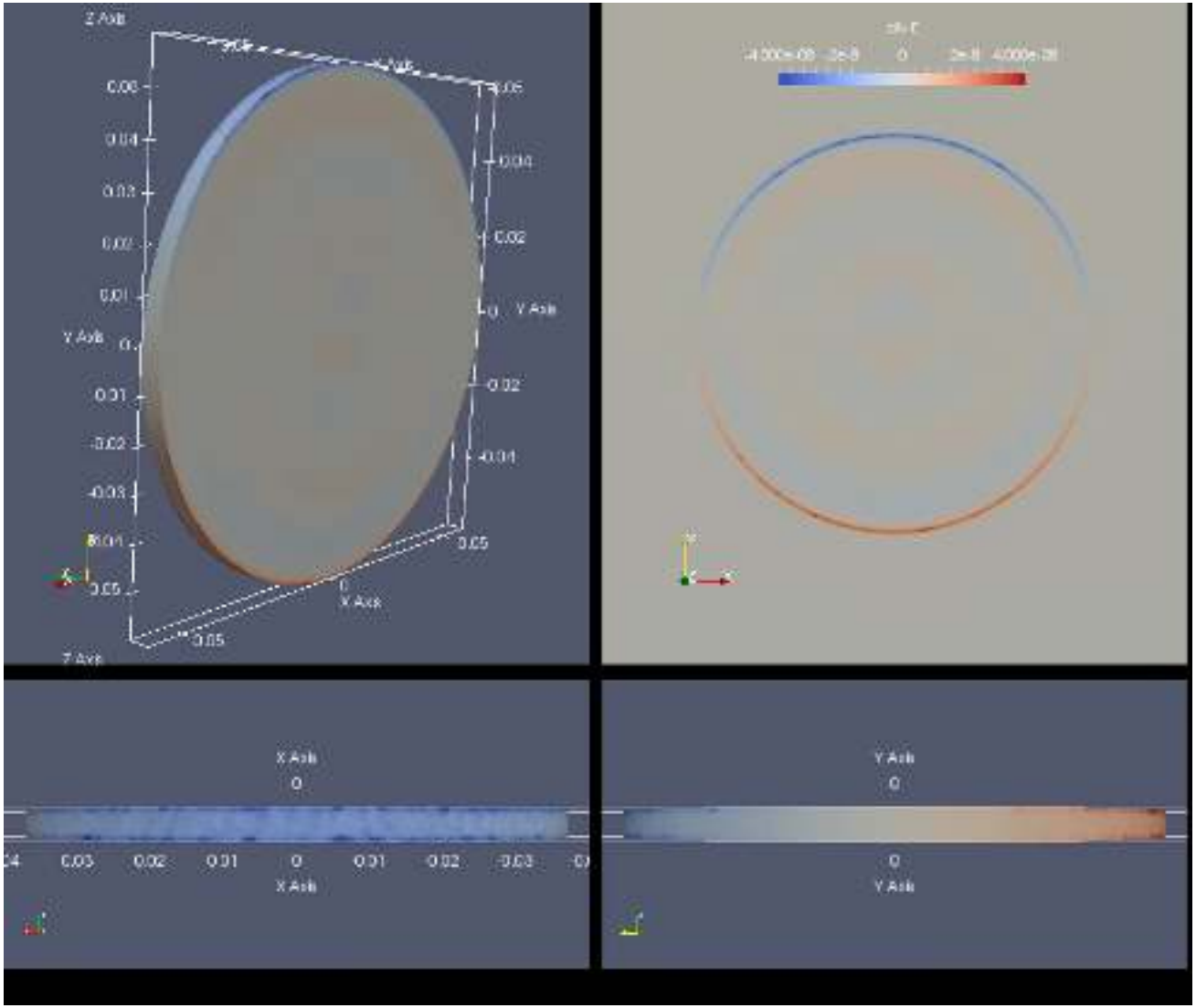
20 Disc Setup

Simulations



Simulations

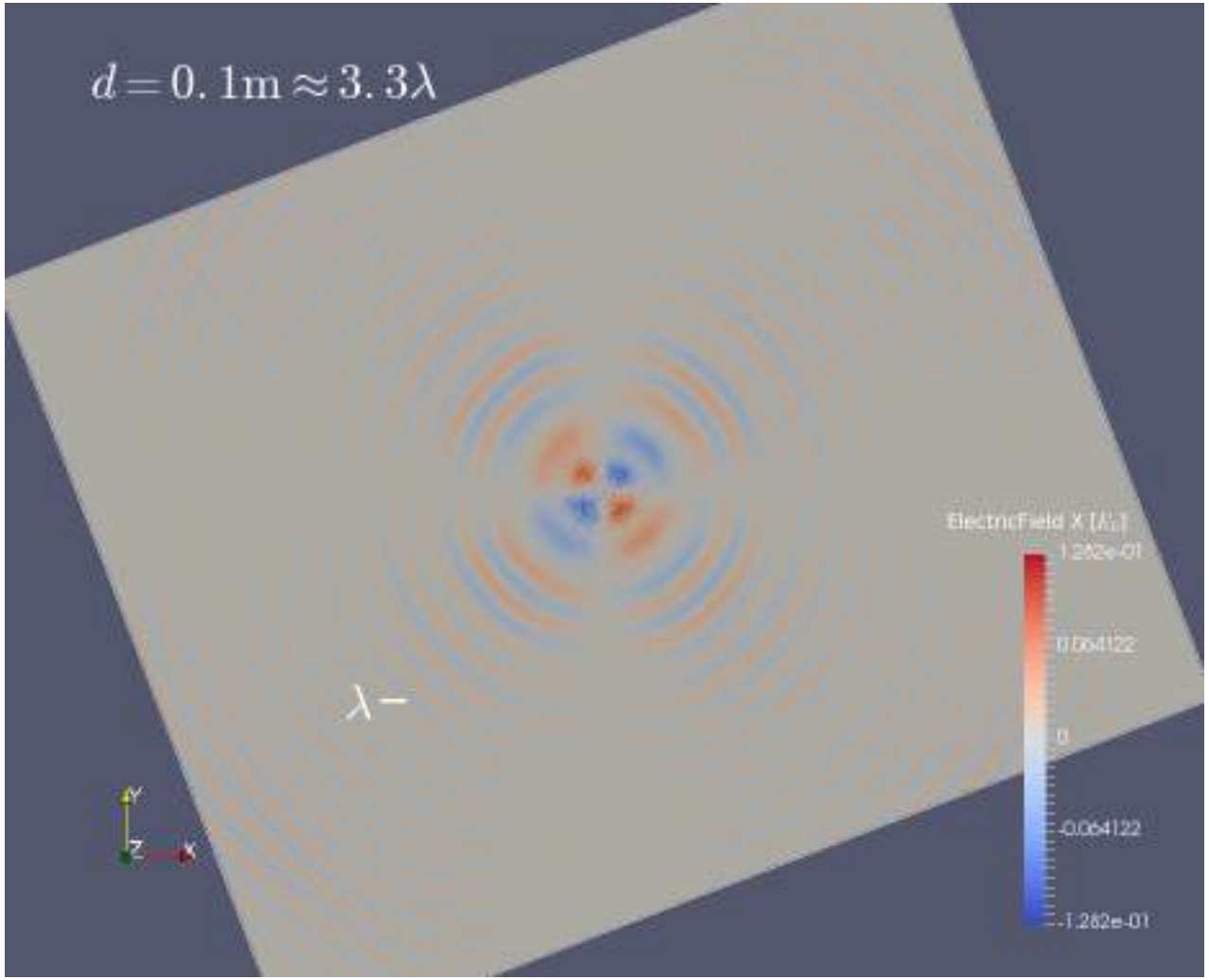
$\nabla \cdot \mathbf{E} = \rho$ on sapphire plate



Simulations

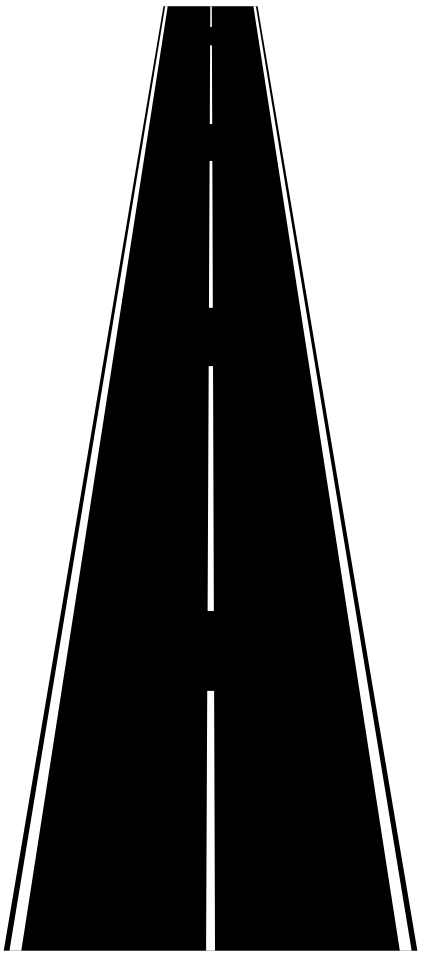
$$\nabla \cdot \mathbf{E} = \rho \quad \text{on sapphire plate}$$

$$\Rightarrow \text{Near Fields}$$



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

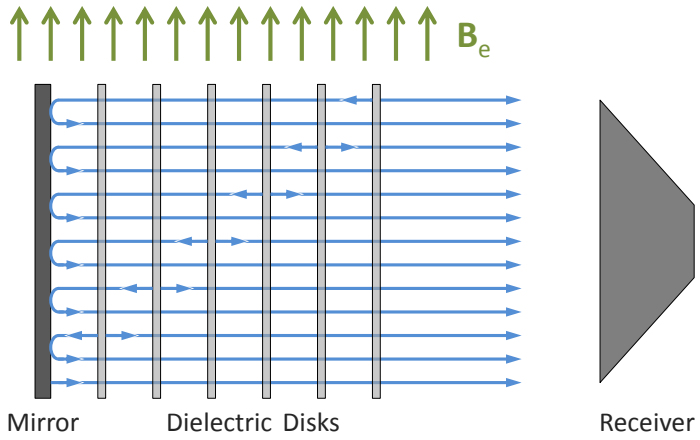
in 2-4 years:

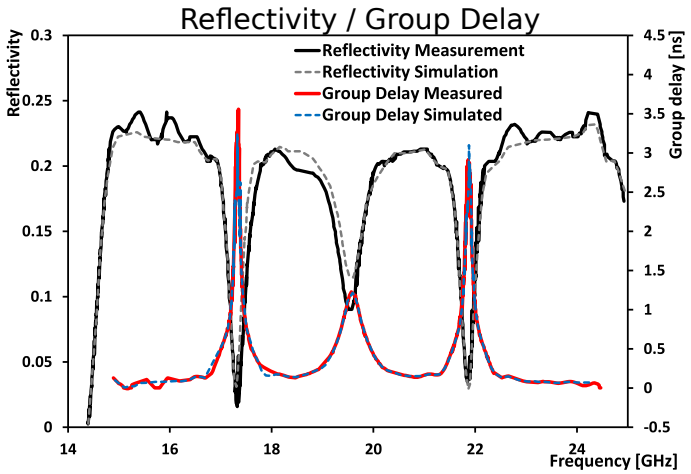
20 disc prototype: $\varnothing_{\mathrm{disc}} \approx 30\,\mathrm{cm}$, $B = 3 - 4\,\mathrm{T}$
$\Rightarrow$ first physics results

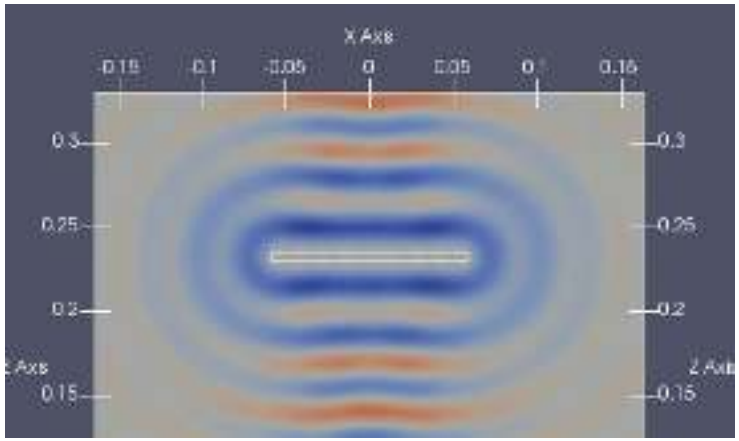
afterwards (2022?):

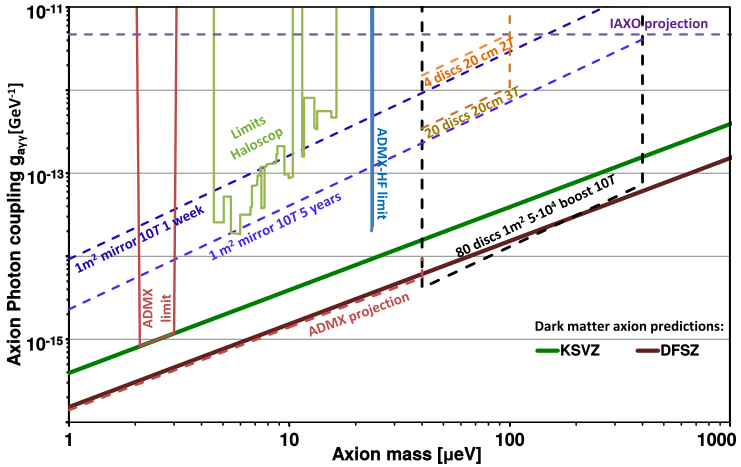
full scale experiment

Conclusions







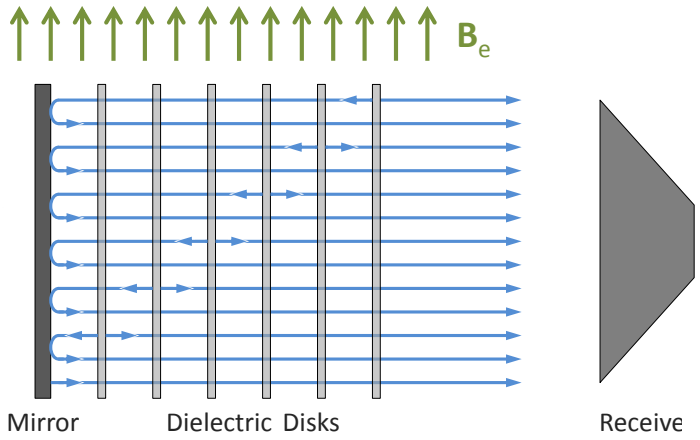


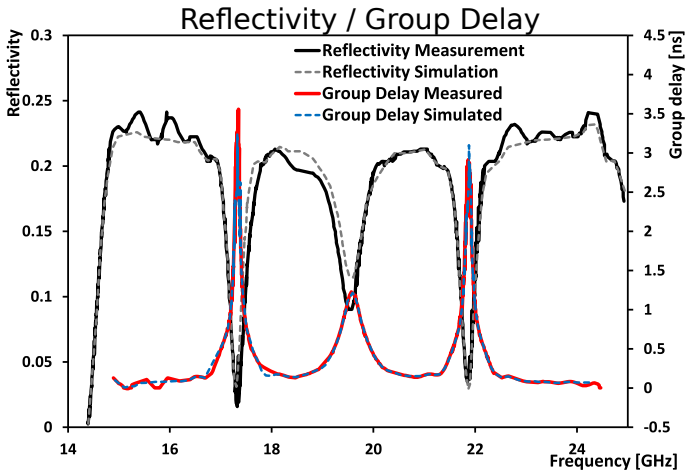
for more information:

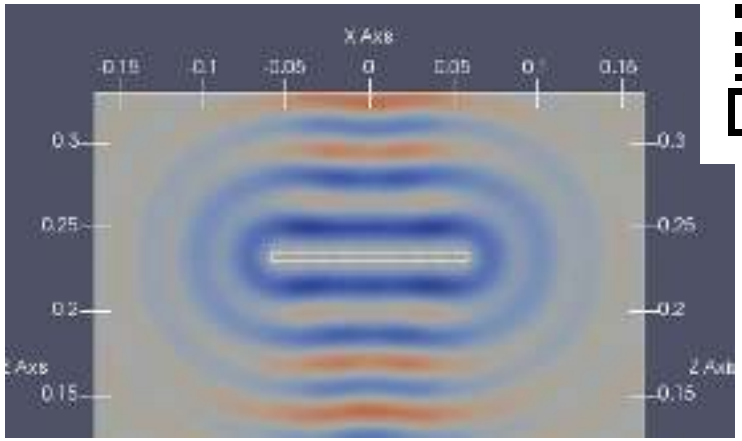
MADMAX collaboration white paper,

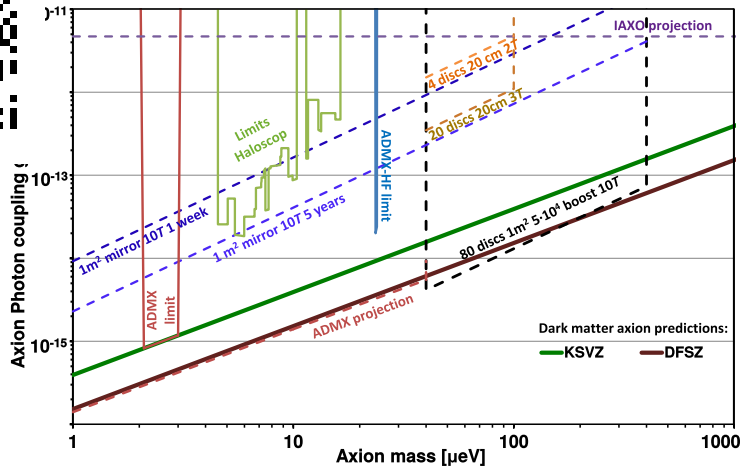
Phys. Rev. Lett. 118, 091801, **JCAP** 1701:061,2017

Thank You very much









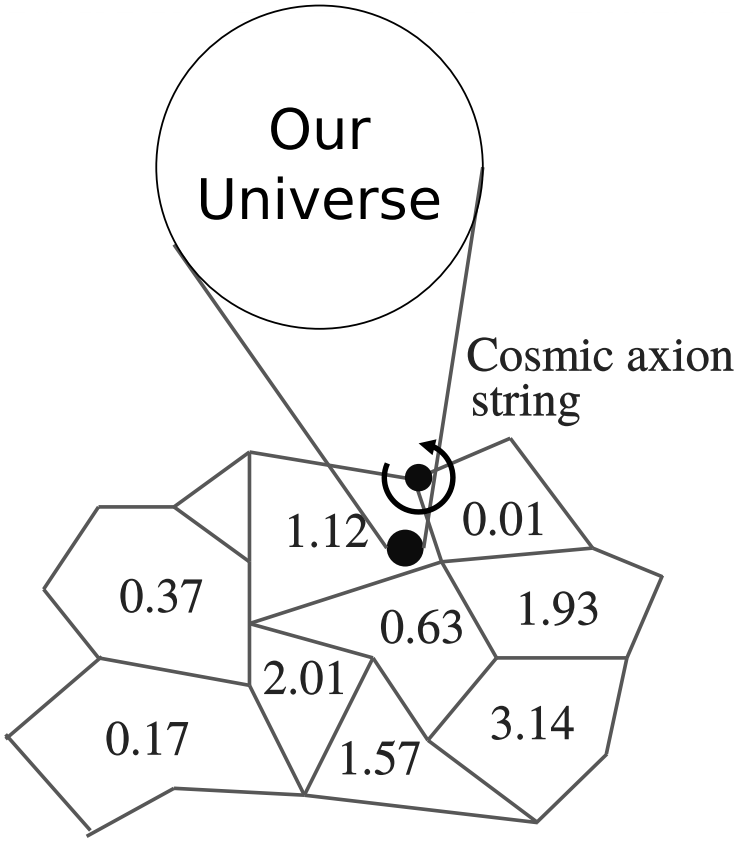
for more information:

MADMAX collaboration white paper,

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

Pecci-Quinn Symmetry Breaking...

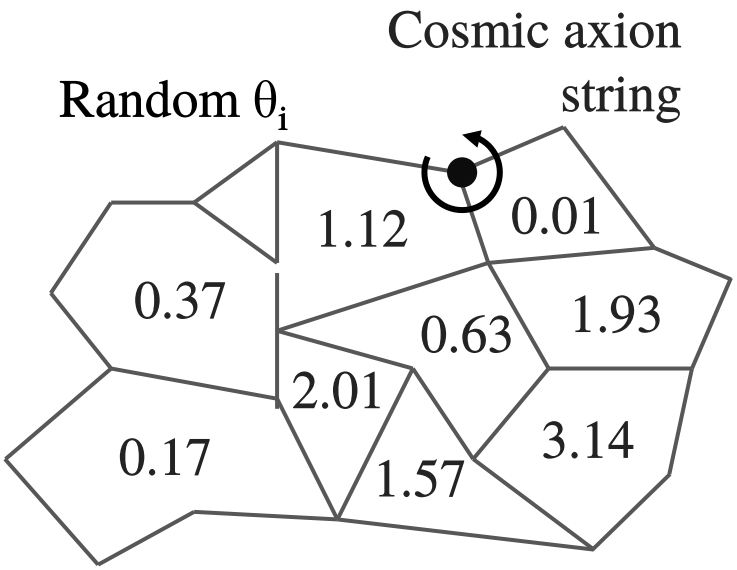
before inflation:



$m_A \lesssim$ meV

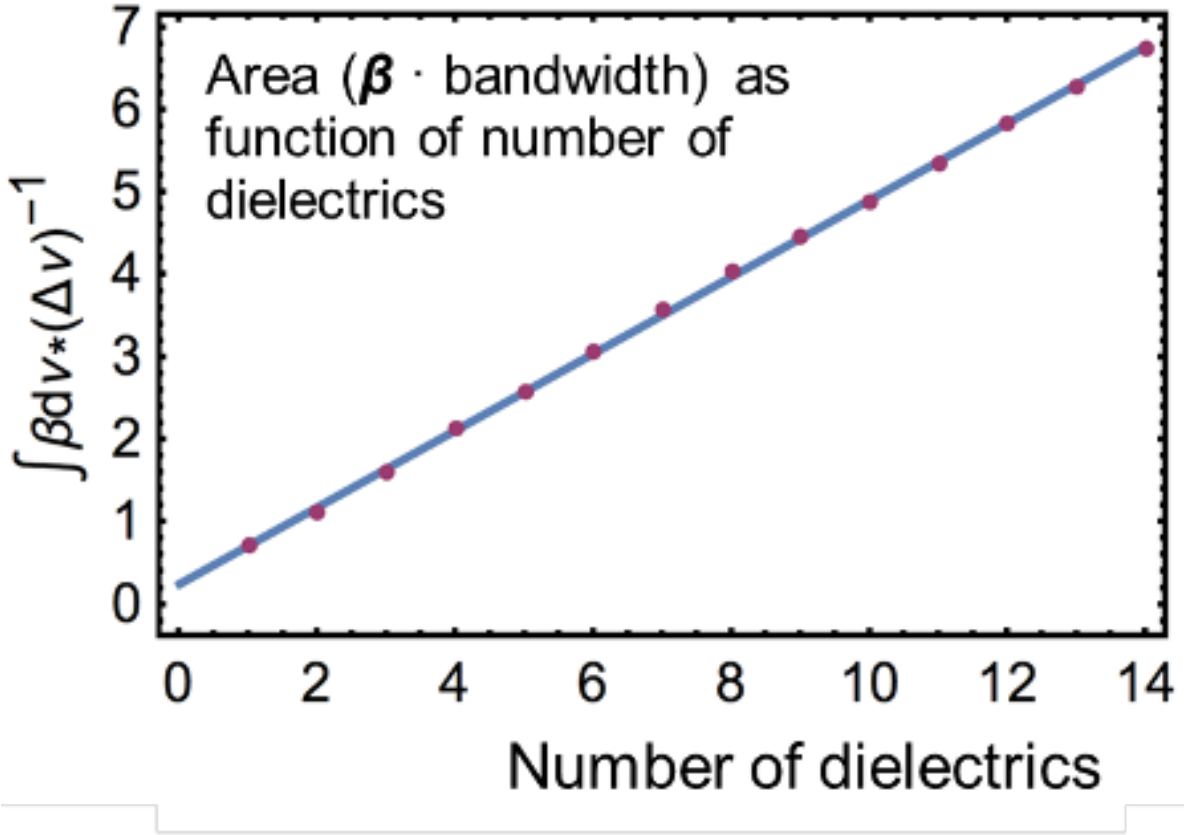
after inflation:

Our Universe:



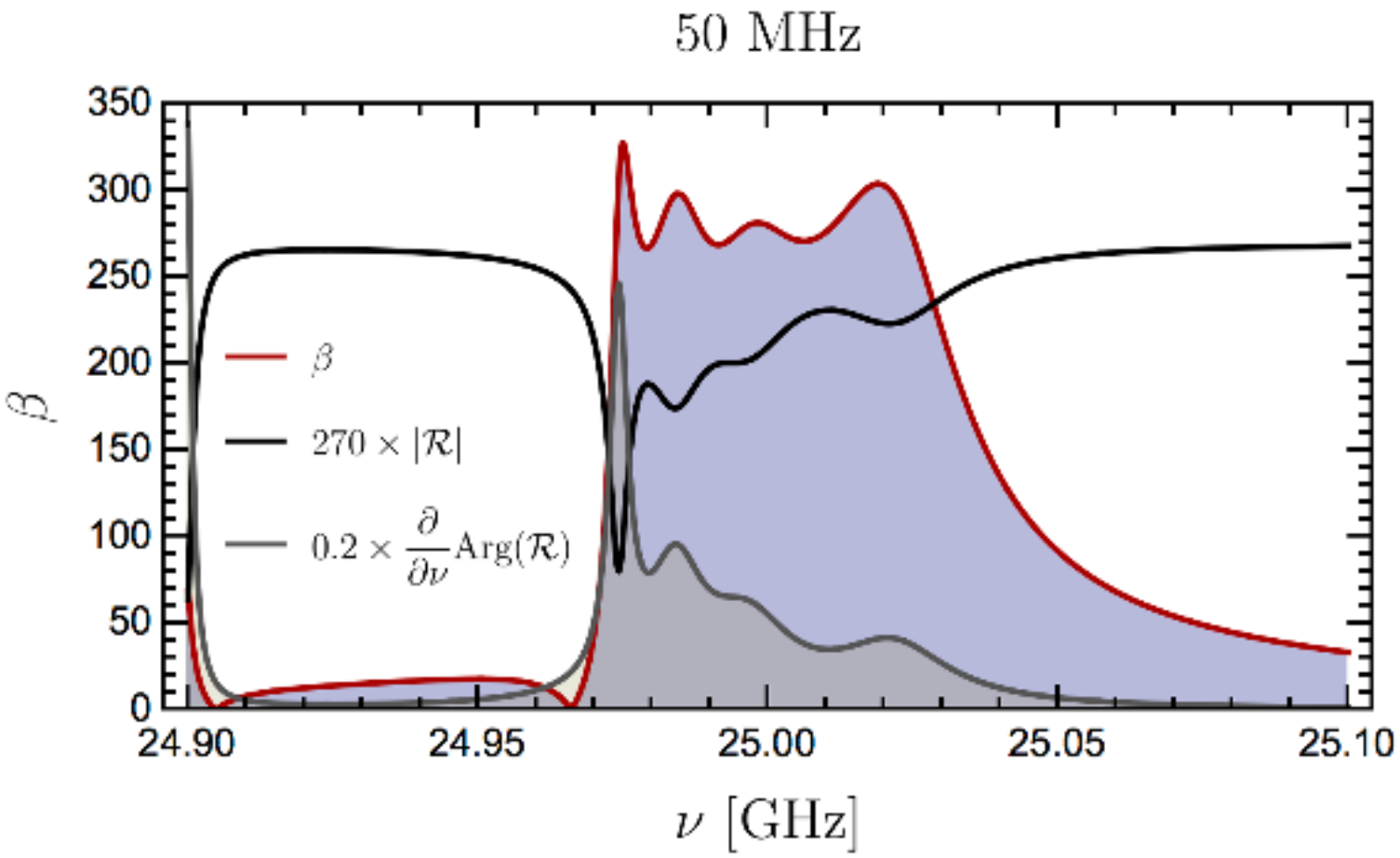
$m_A \sim 100\,\mu$eV

Boost Factor and Disc Number



Boost Factor Corellation

80 discs



Dielectric Materials

Chose dielectric material:

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

→ Sapphire (Al_2O_3) @ 300K, 10 GHz:

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

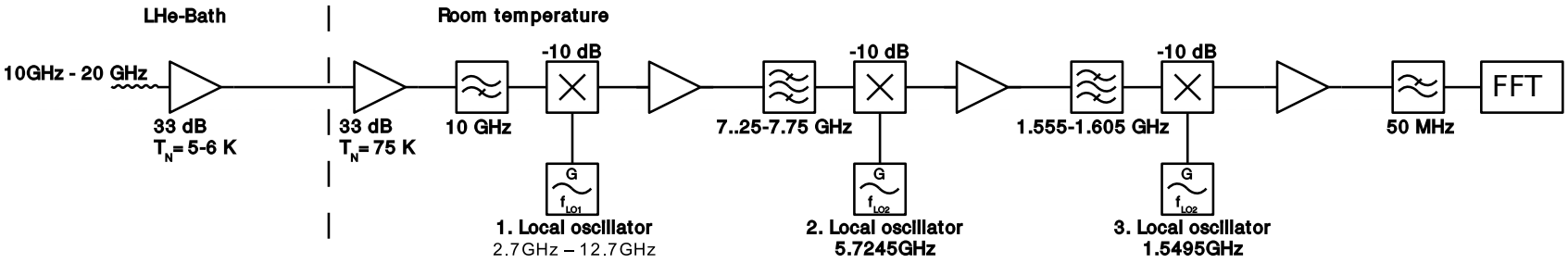
→ Lanthanide Aluminate ($LaAlO_3$) @ 77K

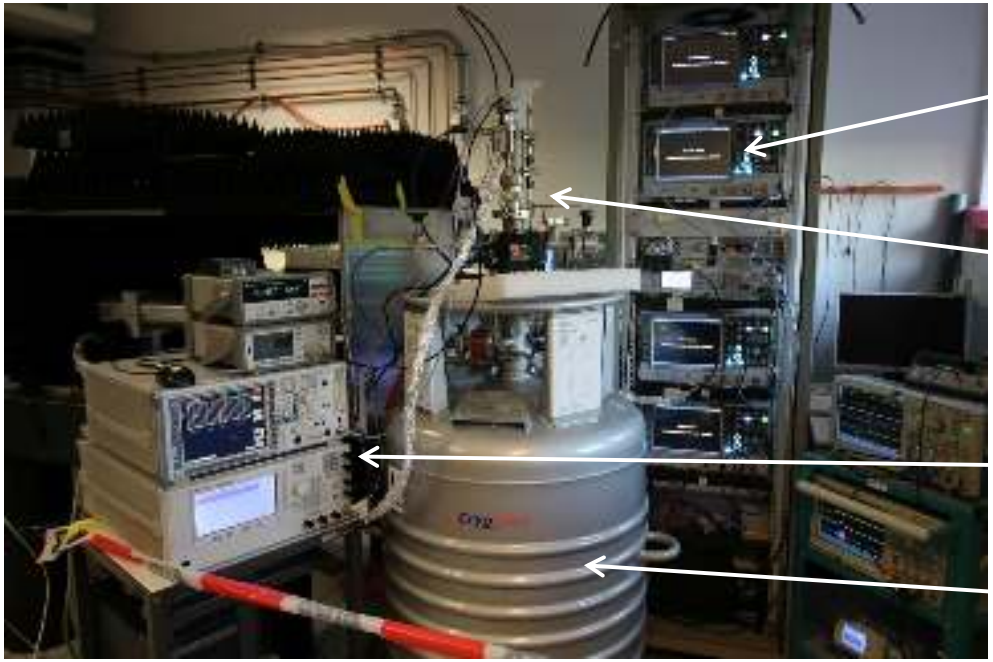
$$\varepsilon \sim 24; \qquad \tan\delta \sim 3 \cdot 10^{-5}$$

→ Titanium dioxide – Rutil (TiO_2)

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

Receiver System





signal analyzer
(4 samplers, 1.4% dead time)

front end mixers
and amps

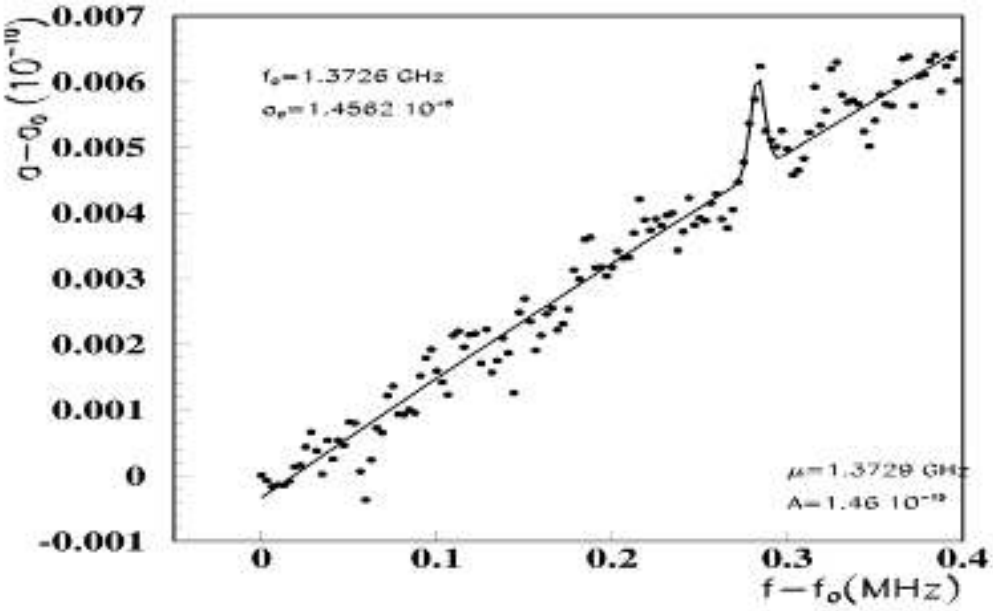
"Fake Axion"

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

Receiver System

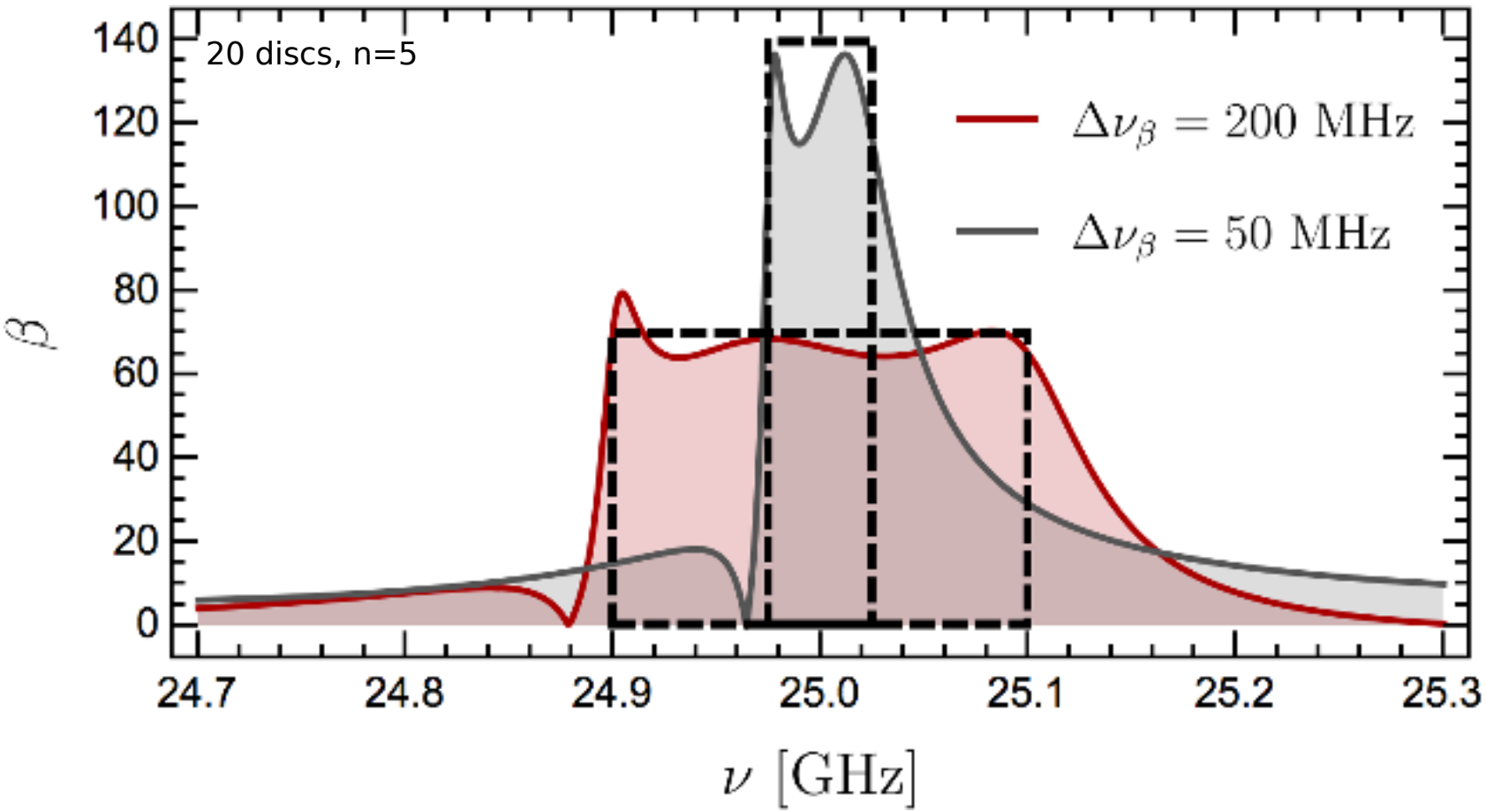
typical one week measurment

(with higher input signal)



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

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: