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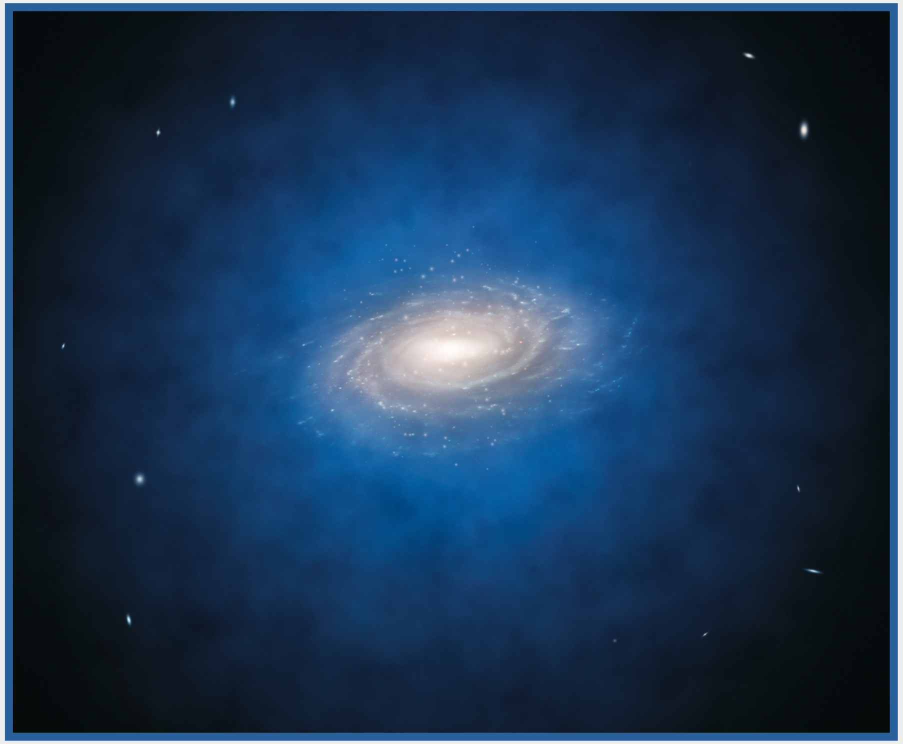
Towards the first open dielectric haloscope

Current efforts on MADMAX in Hamburg

Jacob Egge
University of Hamburg

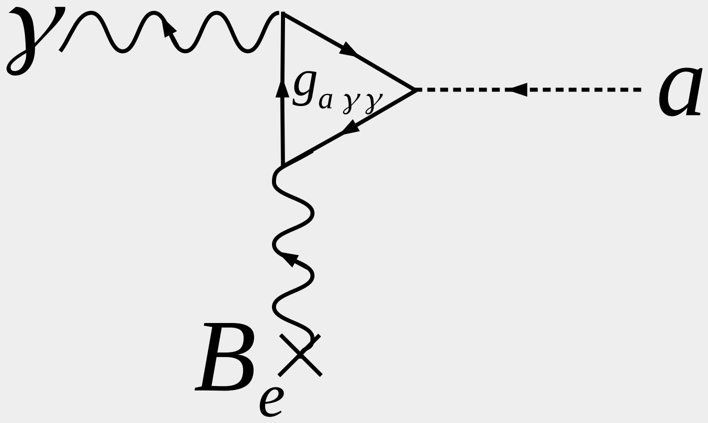
What is a haloscope?



Credit: ESO/L. Calçada

- Detect dark matter from the galactic halo
- Earth should be surrounded by dark matter
- Detection scheme depends on particle nature of dark matter

Axion



- The Axion is a hypothetical particle well suited to be dark matter
- Can be produced non-thermally in sufficient abundance in the early universe
- Lightweight and weakly interacting
- Can convert into a photon inside a magnetic field

Strong CP problem

$$\mathscr{L}_{QCD} \supset \theta \frac{g^2}{32\pi^2} F_{\mu\nu} \tilde{F}^{\mu\nu}$$

$$g_{a\gamma} \approx -2\times 10^{-16}\, GeV^{-1} \left(\frac{m_a}{1\,\mu eV}\right) C_{a\gamma}$$

- QCD Lagrangian is, in principle, CP violating
- No CP violations are observed (θ~0)
- Peccei-Quinn mechanism naturally leads to θ → 0
- Comes with an extra particle, the axion
- Axion mass proportional to coupling

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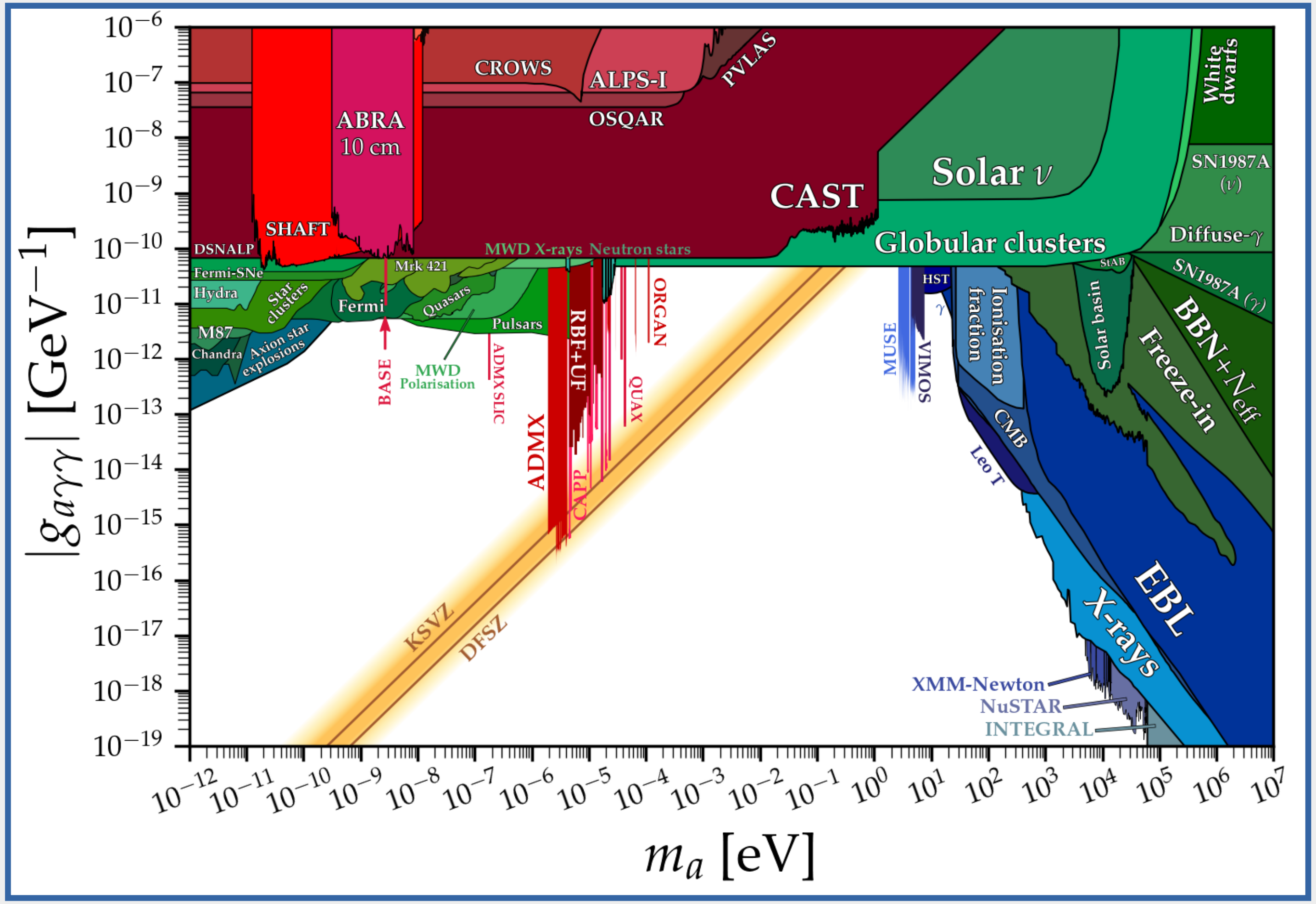
MADMAX

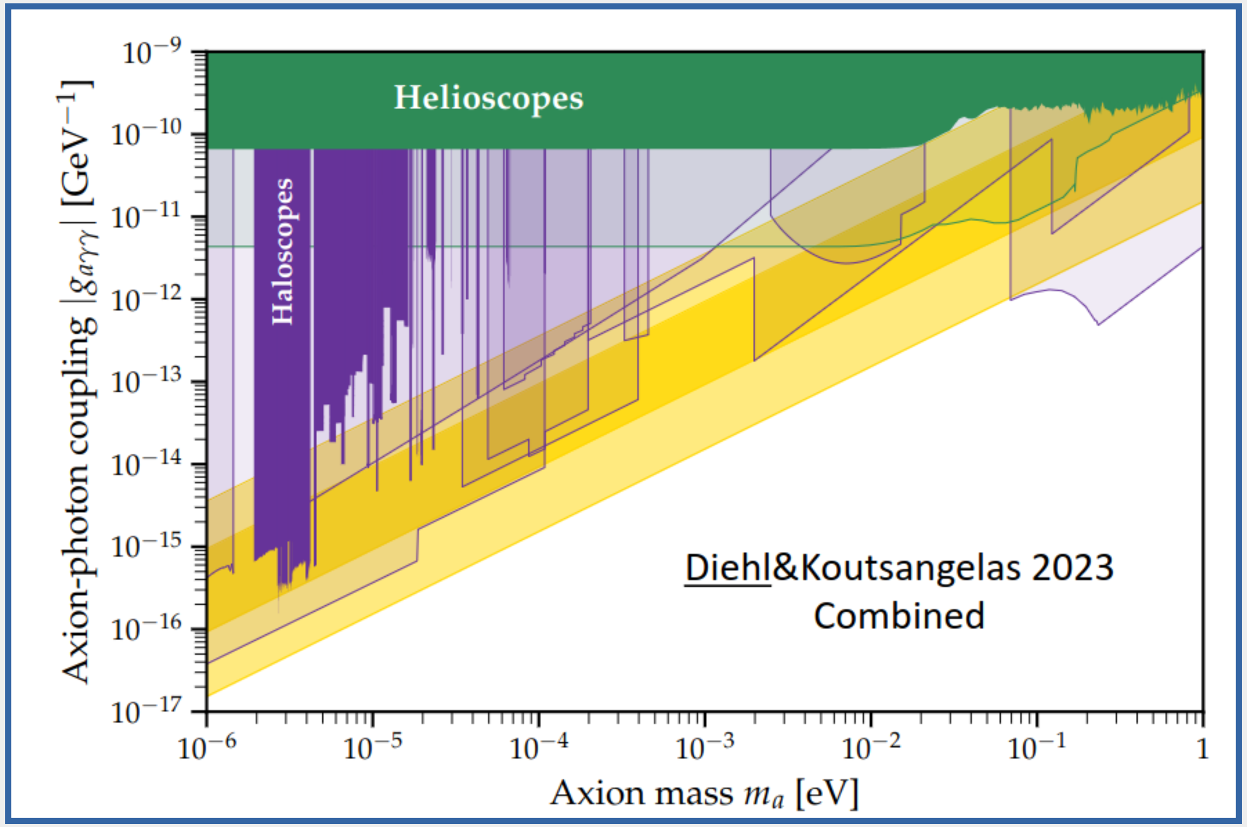
- Coupling to photons is model-dependent
- KSVZ and DFSZ have become benchmark models
- (non-minimal) extensions widen the possible range

$$g_{a\gamma} \approx -2\times 10^{-16}\, GeV^{-1} \left(\frac{m_a}{1\,\mu eV} \right) C_{a\gamma}$$



Axion models

- Non-minimal extensions
  - KSVZ: add ≤ 28 heavy Quarks
  - DFSZ: add ≤ 8 Higgs doublets
- Other extensions relax mass-coupling relation further
- Axion-like particles:
  - No mass-coupling relation
  - don't solve strong CP problem



Diehl et al: https://doi.org/10.1103/PhysRevD.107.095020

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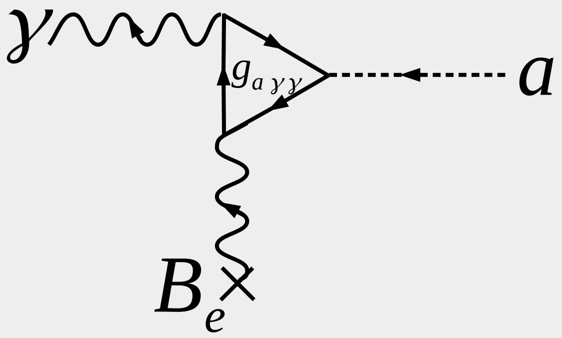
Axion-Maxwell



$$\nabla \times \boldsymbol{H} + i\omega \boldsymbol{D} = \boldsymbol{J}_f - i g_{a\gamma} \omega a \boldsymbol{B}_e$$

- Dark matter axion field can be treated classically
- Axion-photon coupling modifies Maxwell's equations
- Homogeneous axion field and external magnetic field
- Uniform effective current density oscillating with axion compton frequency
- Oscillating currents produce electromagnetic radiation

How to build a haloscope

$\boxed{i\omega g_{a\gamma\gamma} a \boldsymbol{B}_e}$ Effective axion current

$\downarrow$ Suitable geometry

$\boxed{\boldsymbol{E}_a, \boldsymbol{H}_a}$ Axion-induced radiation

$\downarrow$ Receive with antenna

$\boxed{\boldsymbol{J}_R}$ Induces current in receiver

$\downarrow$ Further amplficiation

$\boxed{P_{\text{sig}}}$ Signal power

How to build a haloscope

$\boxed{i\omega g_{a\gamma\gamma} a \boldsymbol{B}_e}$ Effective axion current

$\uparrow$ Suitable geometry

$\boxed{\boldsymbol{E}_R, \boldsymbol{H}_R}$ Reflection-induced radiation

$\uparrow$ Transmit with antenna

$\boxed{\boldsymbol{J}_R}$ Drive current in receiver

$\uparrow$ Further amplficiation

$\boxed{P_{\text{sig}}}$ Signal power

- Reciprocity approach
  - Allows switching source and load
- Signal power expressed in measurable fields!

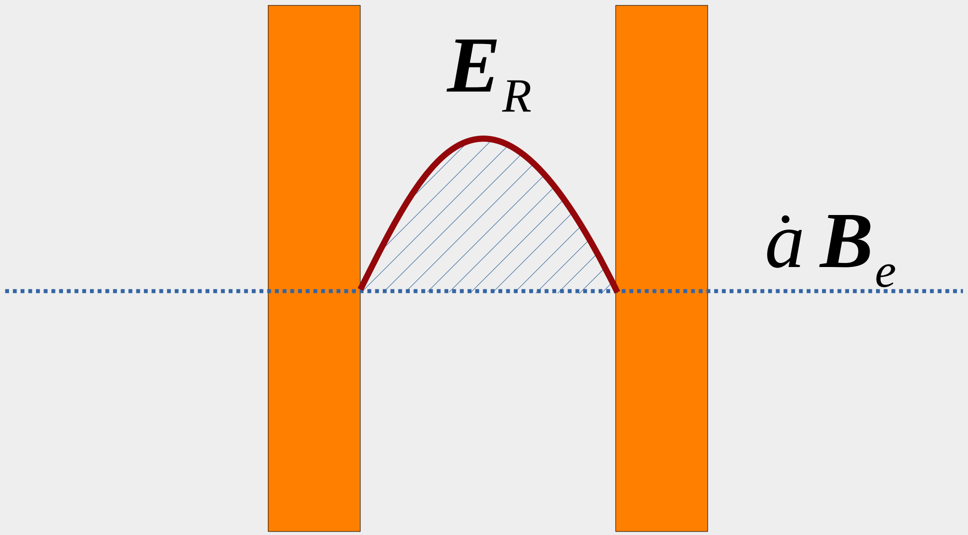
$$\boxed{P_{sig} = \frac{g_{a\gamma\gamma}^2}{16 P_{\text{in}}} \left| \int_{V_a} dV\, \boldsymbol{E}_R \cdot \dot{a} \boldsymbol{B}_e \right|^2}$$

J.E JCAP04(2023)064

How to build a haloscope

$$P_{sig} = \frac{g_{a\gamma\gamma}^2}{16 P_{\text{in}}} \left| \int_{V_a} dV \, \boldsymbol{E}_R \cdot \dot{a} \boldsymbol{B}_e \right|^2$$

Cavity

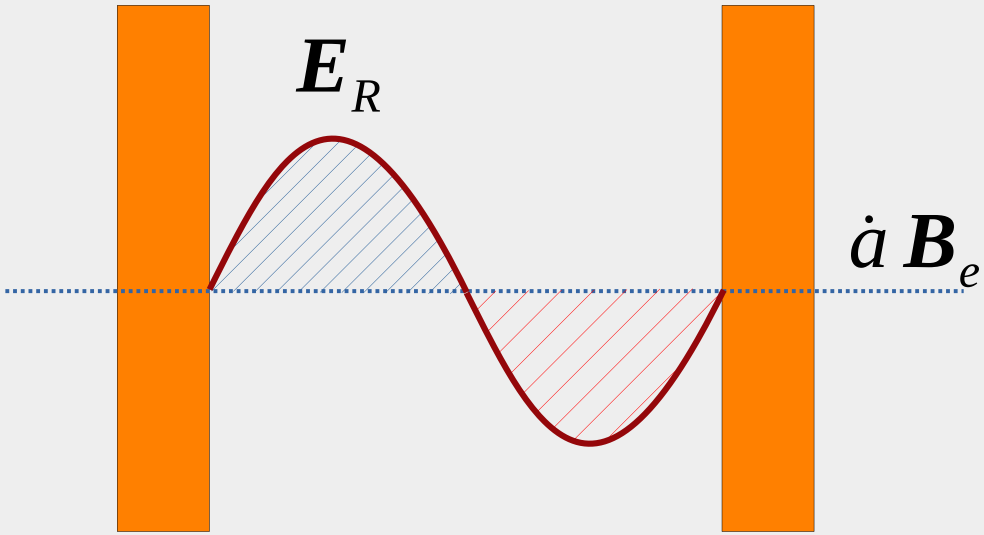


- Strong E_R on resonance
- Good overlap with uniform axion current
- Size directly proportional to wavelength

How to build a haloscope

$$P_{sig} = \frac{g_{a\gamma\gamma}^2}{16\,P_{\text{in}}} \left| \int_{V_a} dV\, \boldsymbol{E}_R \cdot \dot{a}\,\boldsymbol{B}_e \right|^2$$

Cavity

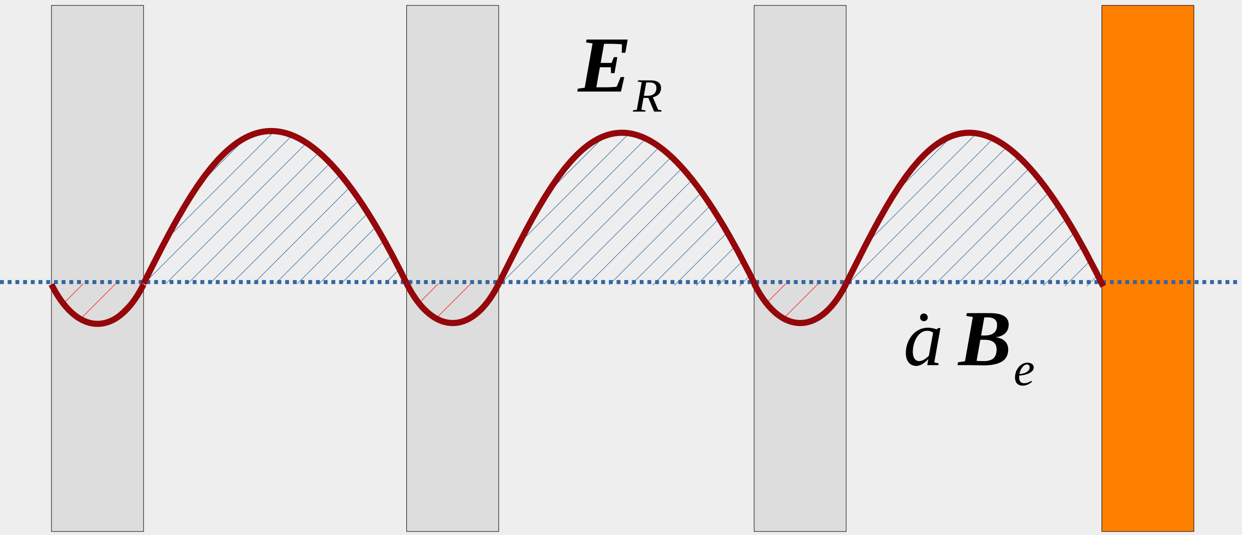


- Strong E_R on resonance
- Bad overlap with uniform axion current
- Size directly proportional to wavelength

How to build a haloscope

$$\boxed{P_{sig} = \frac{g_{a\gamma\gamma}^2}{16\,P_{\text{in}}} \left| \int_{V_a} dV\, \boldsymbol{E}_R \cdot \dot{a}\,\boldsymbol{B}_e \right|^2}$$

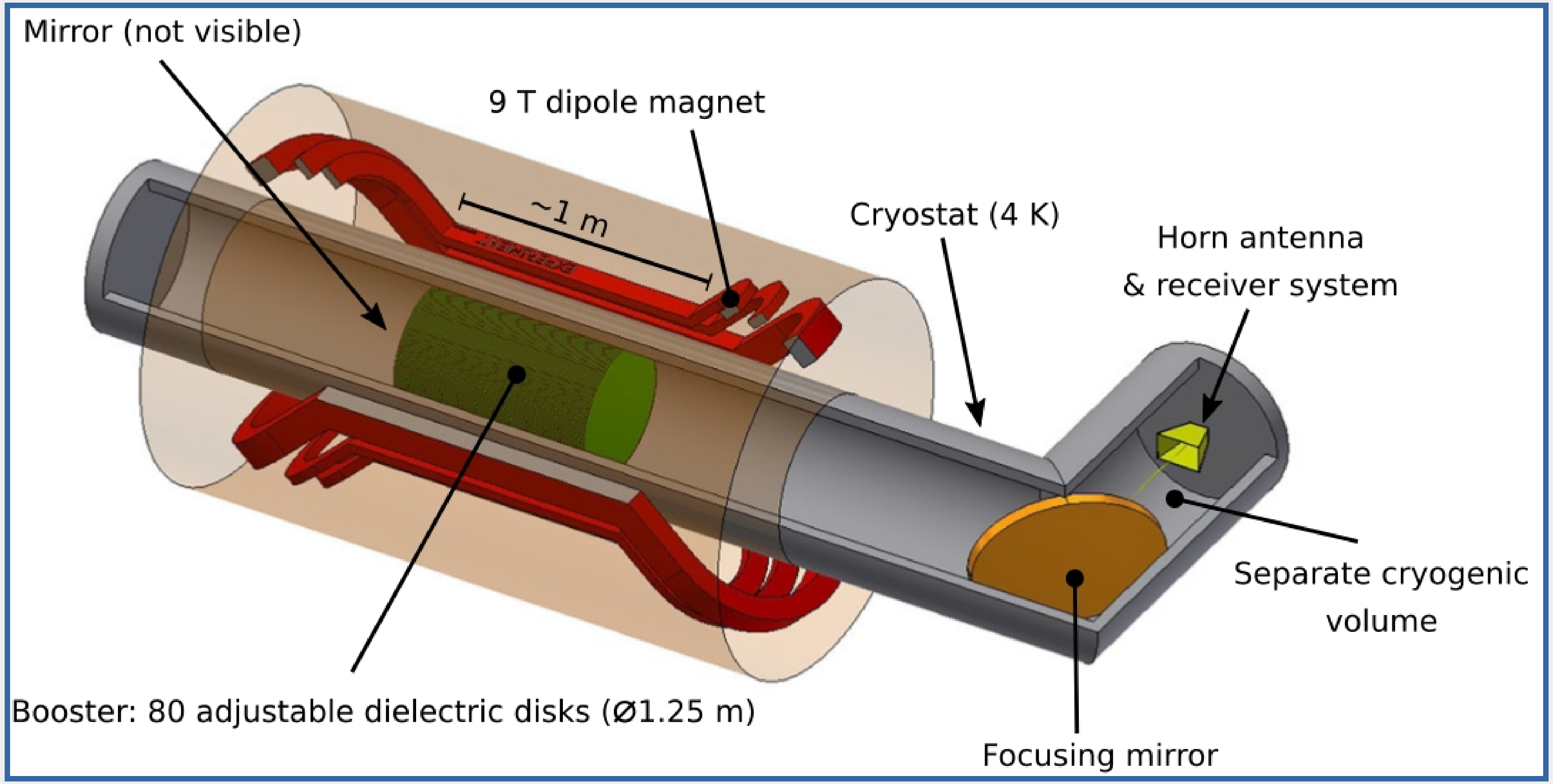
Dielectric haloscope



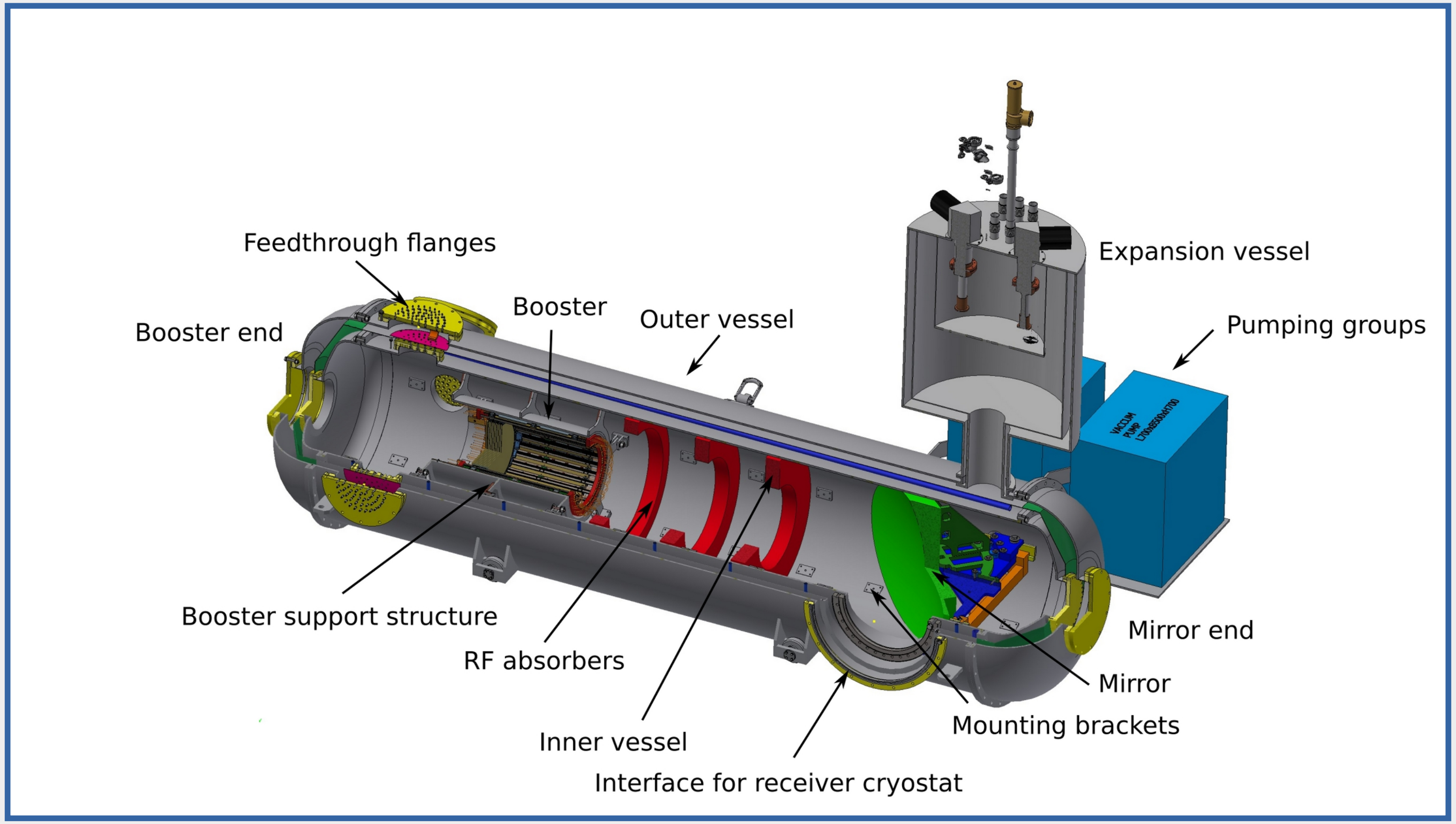
- Suppress negative lobes by placing dielectric disks
- Size independent of wavelength
- Still good overlap with uniform axion current
- Resonances can still happen and increase E_R
- Move disks to tune frequency

MADMAX

Magnetized disk and mirror axion experiment

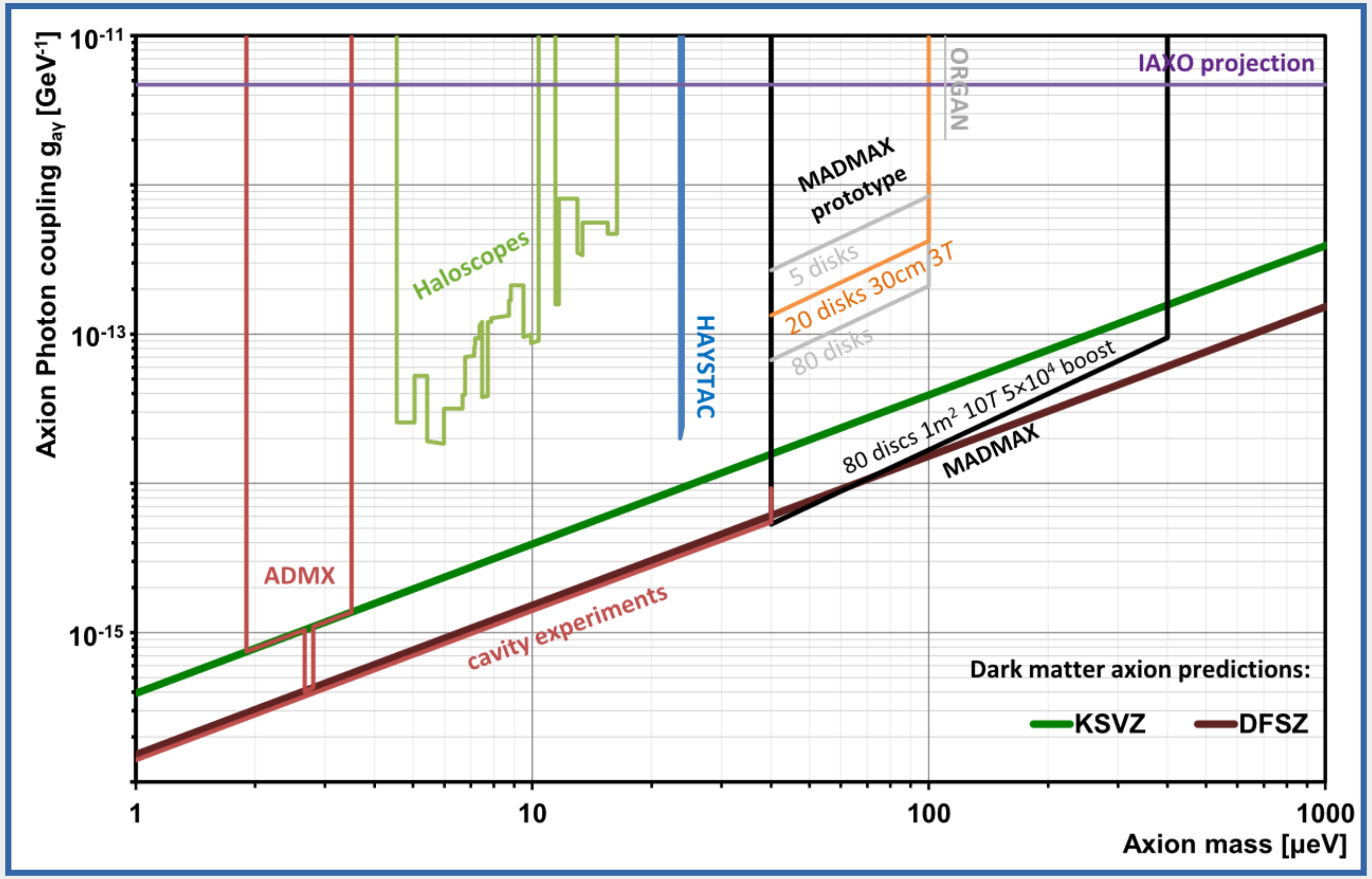


Prototype

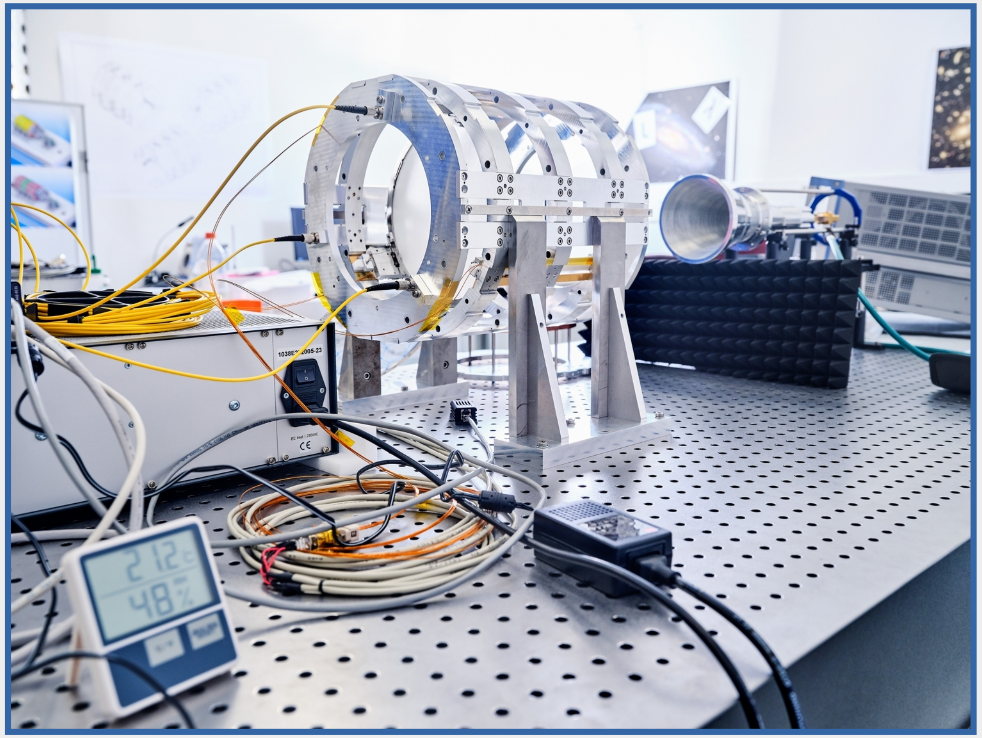


- Up to 20 disks with 300 mm diameter
- 4K cryostat (ready spring next year)
- Fits into a 1.6 T magnet at CERN
- 18-26.5 GHz

Parameter space



Open booster



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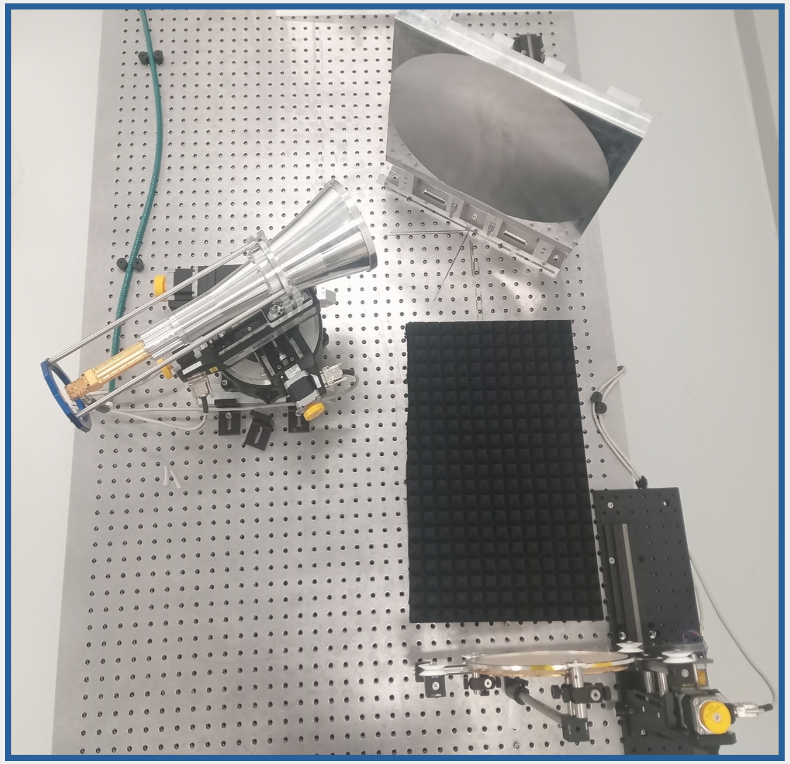
- Cavities are closed system:
  - Easy to simulate (size~wavelength)
  - Discrete set of modes
- MADMAX is an open optical system:
  - Necessary to move disks
  - Transverse dimension independent of wavelength
  - Harder to simulate
  - Continuous set of modes

Open booster



$$P_{sig} = \frac{g_{a\gamma\gamma}^2}{16\,P_{in}} \left| \int_{V_a} dV\, \boldsymbol{E}_R \cdot \dot{a}\, \boldsymbol{B}_e \right|^2$$

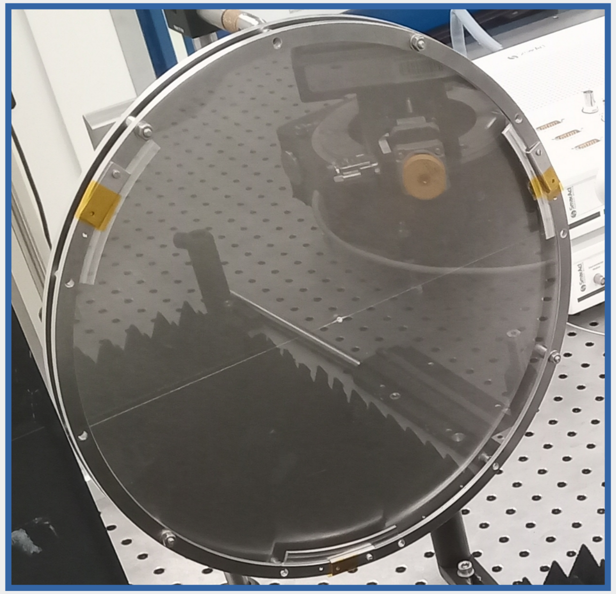
Electric field excited by reflection measurement

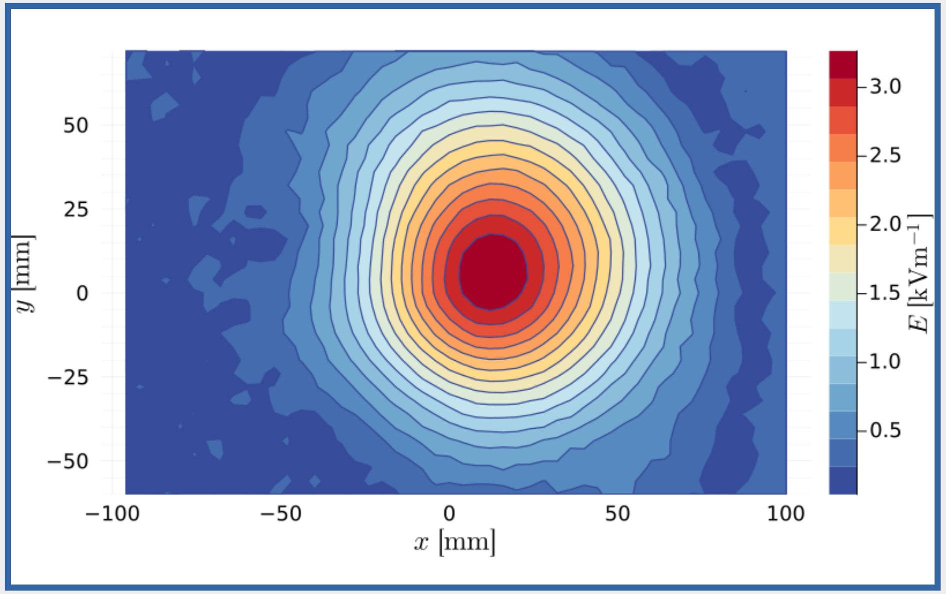
$$\boldsymbol{E}_R^2 = \frac{4\,P_{in}}{\alpha_e\,\omega} \Delta\Gamma$$

- Aim: Calculate potential signal power via the reciprocity approach
- No need to simulate
- Measure E_R with bead-pull method

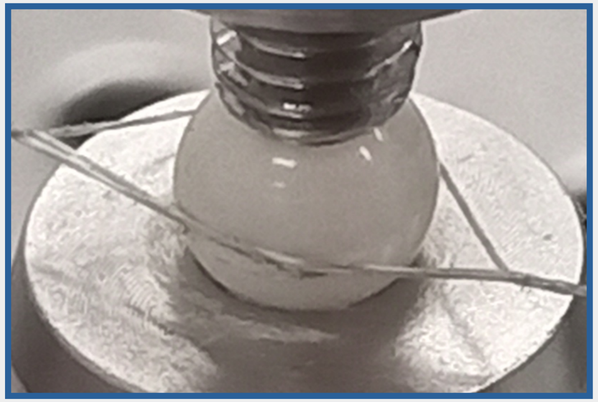
Bead-pull

$$\boxed{E_R^2 = \frac{4P_{\text{in}}}{\alpha_e \omega} \Delta\Gamma}$$

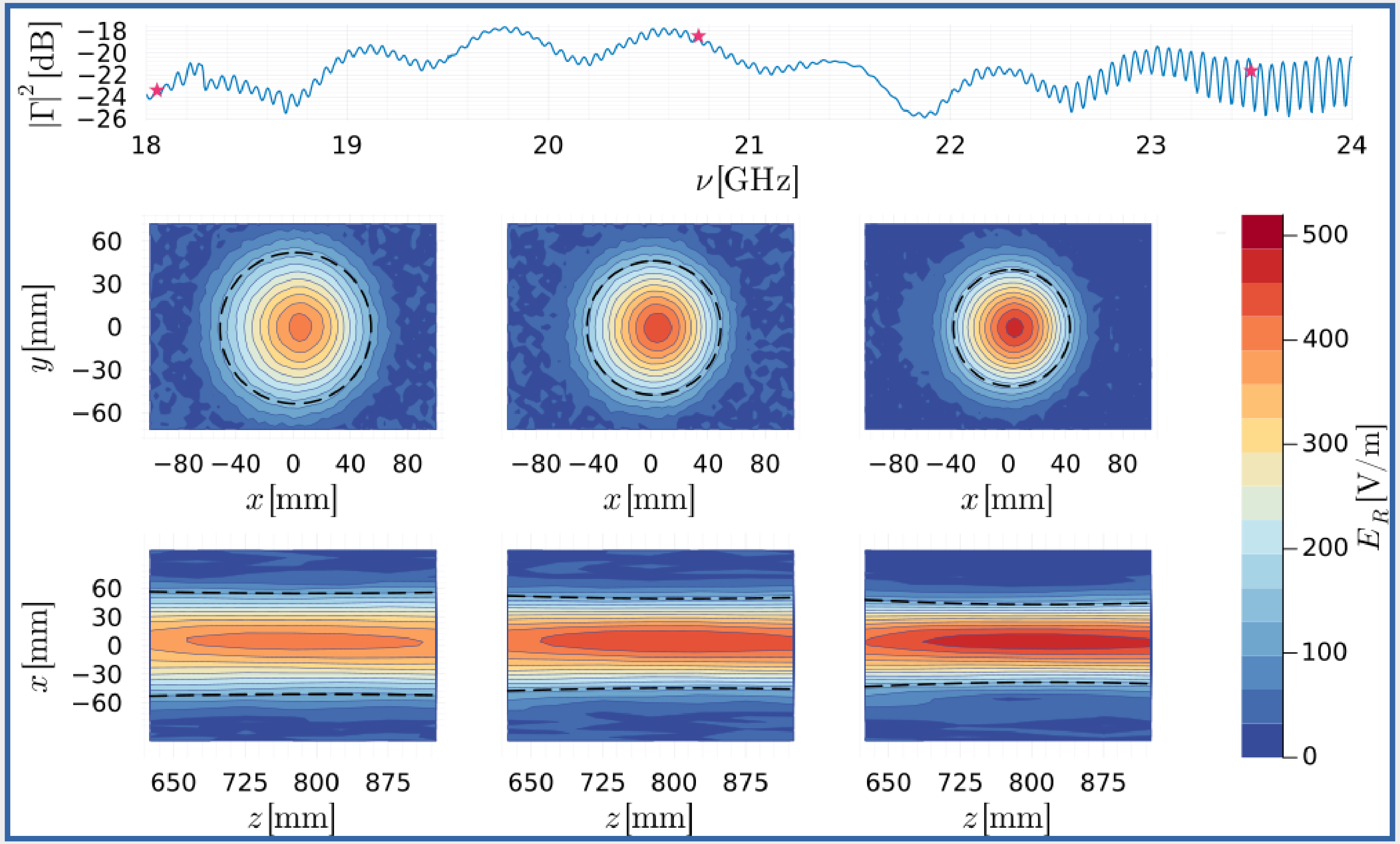


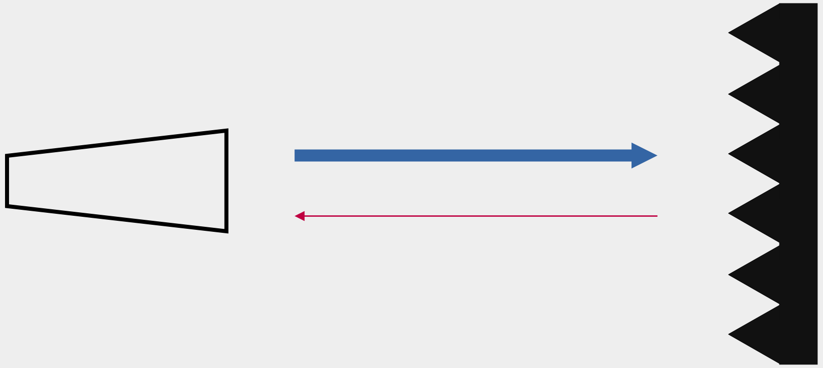


- Measure $\mathbf{E}_R$ with bead pull method



Antenna beam





- Put RF absorbers instead of booster
- Measure just the antenna beam
- Matches expectation: Gaussian beam

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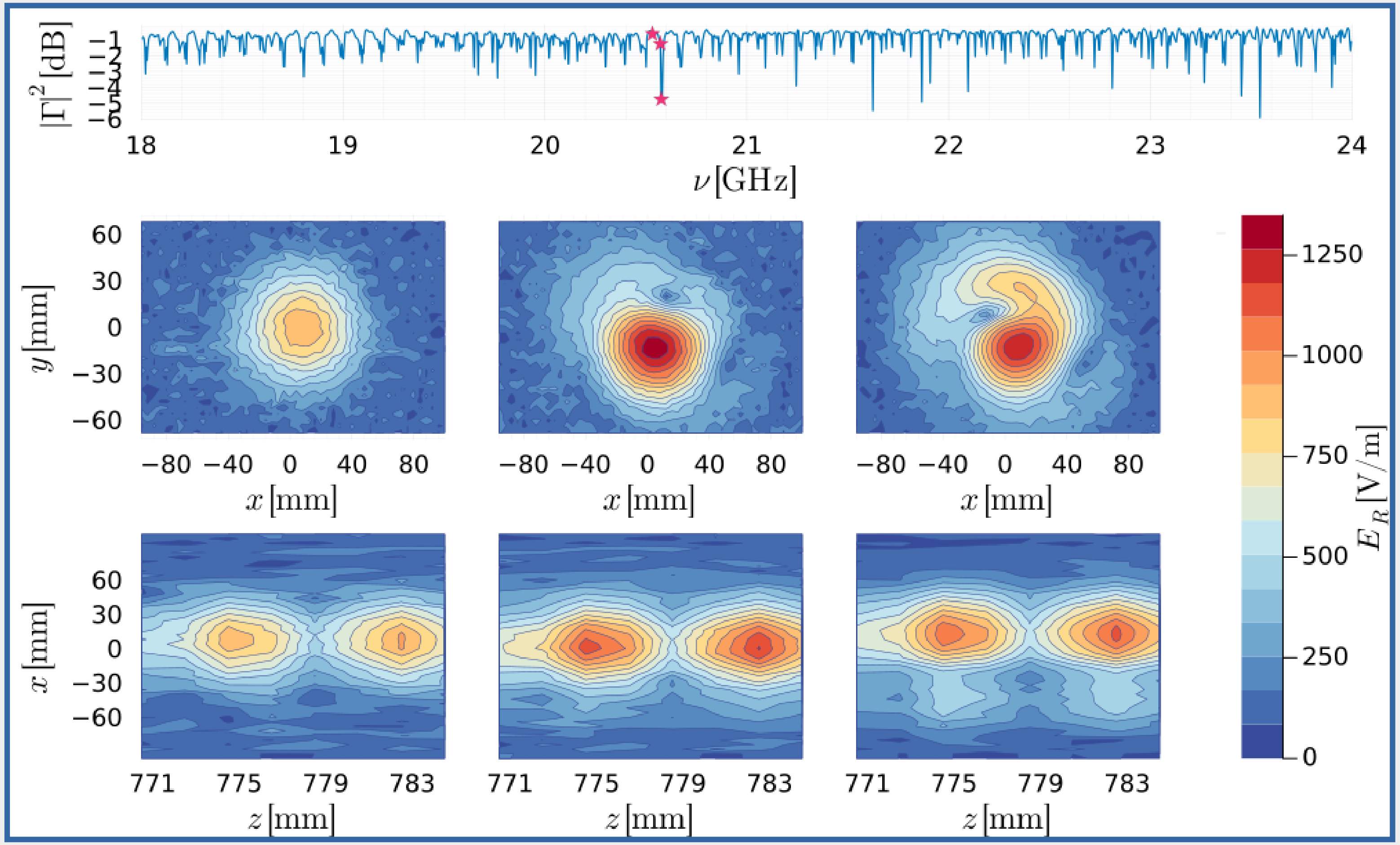
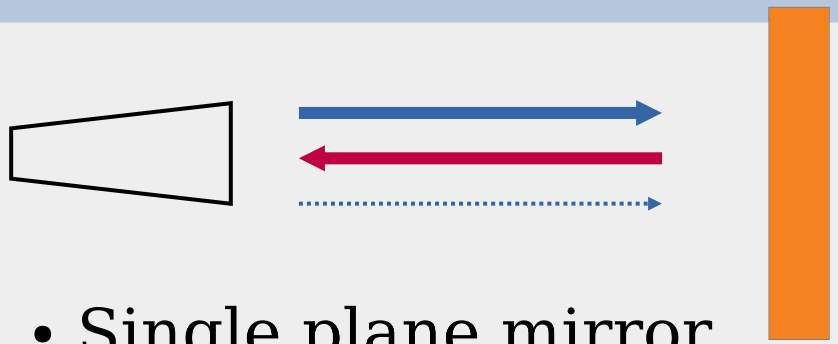
Dish antenna

MADMAX



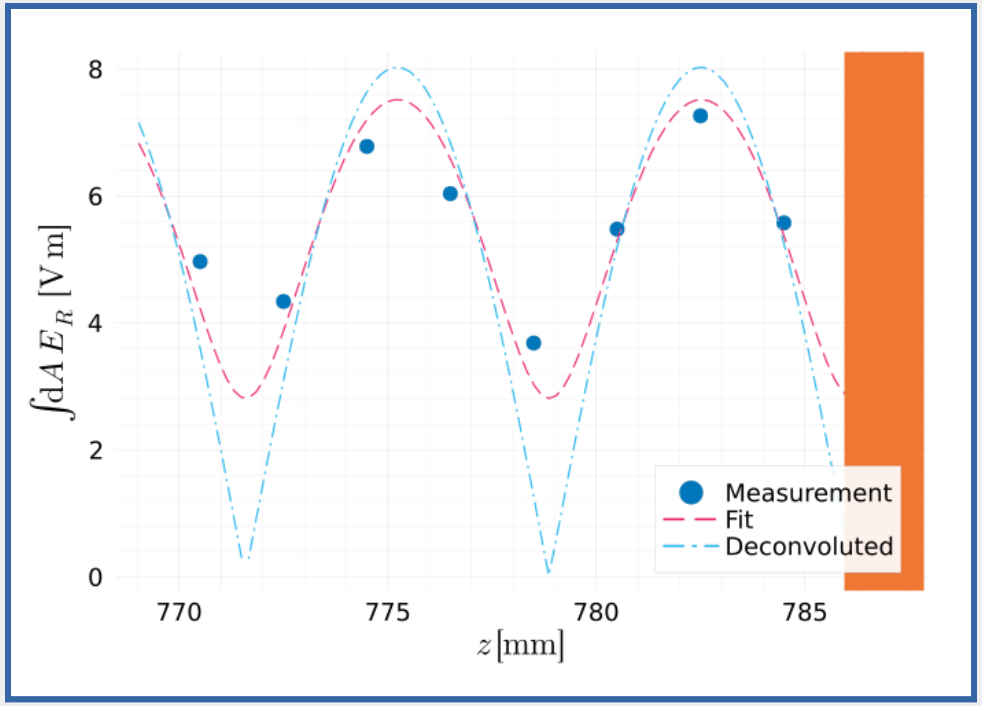


- Single plane mirror as booster
- Beam perturbations lead to unwanted reflections
- Would be very hard to simulate
- We just need to integrate!

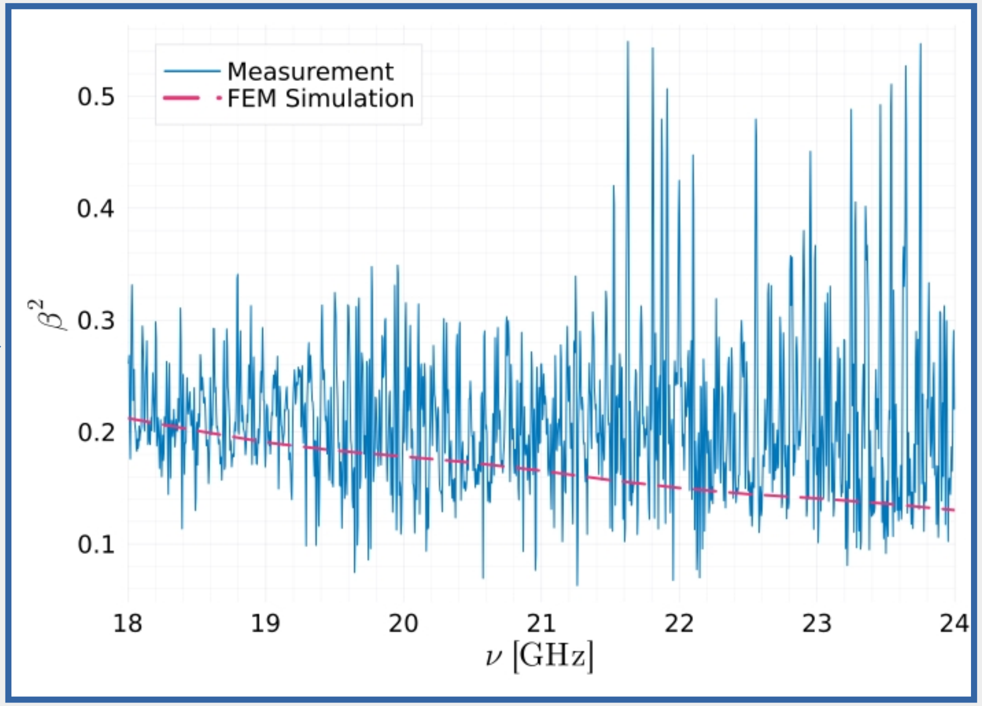
Dish antenna

Integrate dA

$$P_{sig} \sim \left| \int dz \int dA\, E_R \right|^2$$



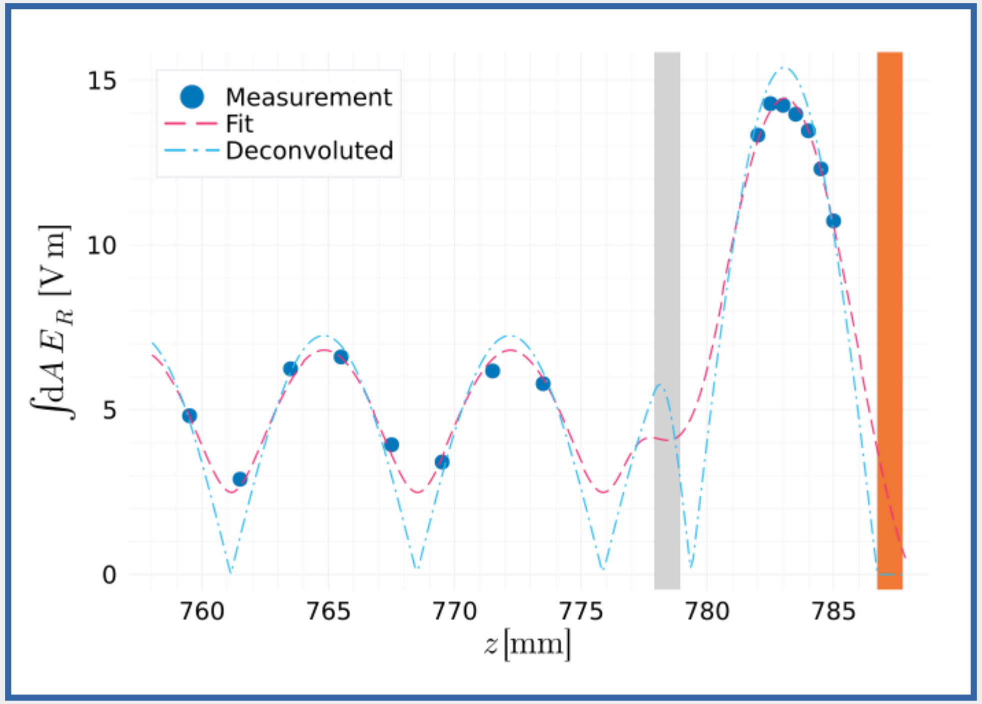
Integrate dz



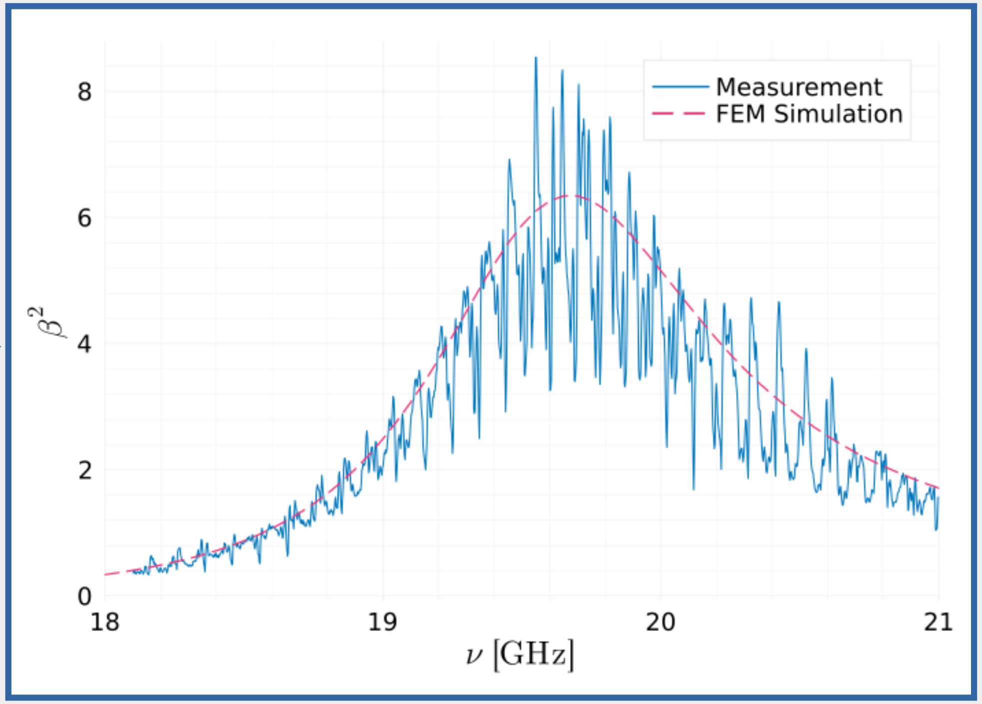
Dielectric haloscope

Integrate dA

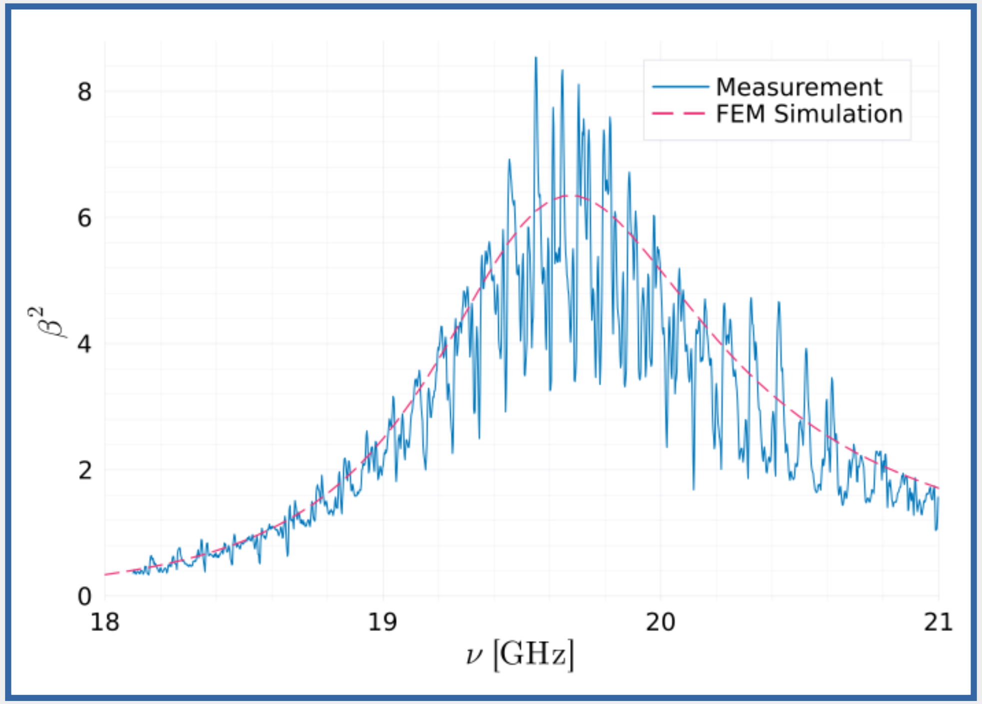
$$P_{sig} \sim \left| \int dz \int dA\, E_R \right|^2$$



Integrate dz

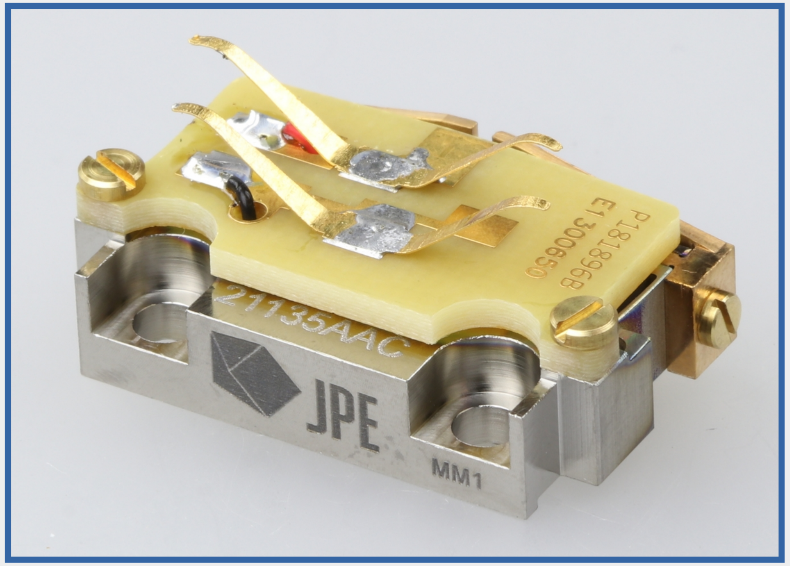


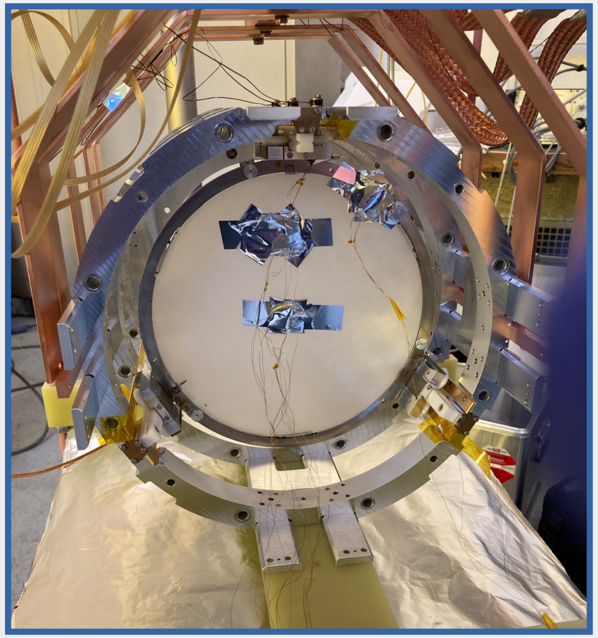
Dielectric haloscope



- Model-independent method to obtain signal power
- Baseline matches expectation
- Beam perturbations have significant effect
- Can be accounted for

Mechanics

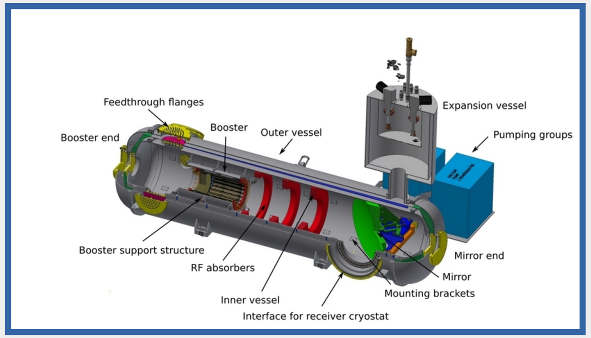


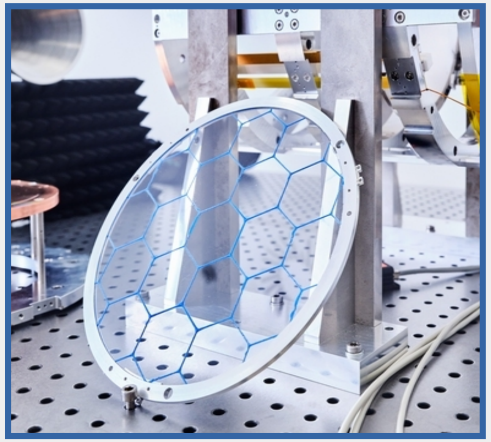


- Successful operation of booster test setup at 4K and magnetic field
- Mechanical show-stoppers seem to be eliminated
- Build prototype booster next

Next steps

- Simple setup nearly fully understood
- Extend to more complex setups:
  - More disks
  - Tiled disks

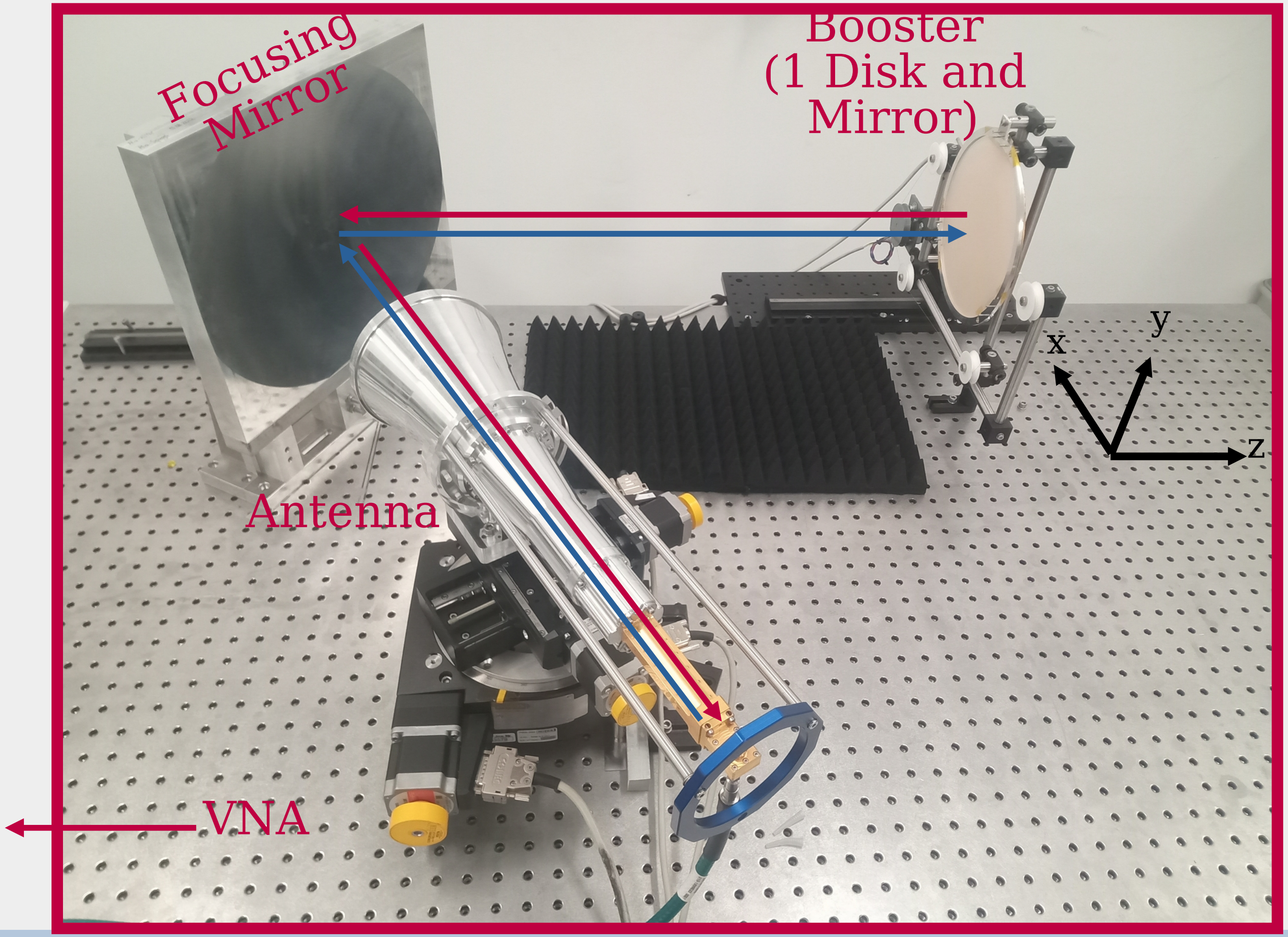




- Cryostat delivered soon (go cold!)
- Set up simple RF receiver chain end of this year
- First science runs with open booster

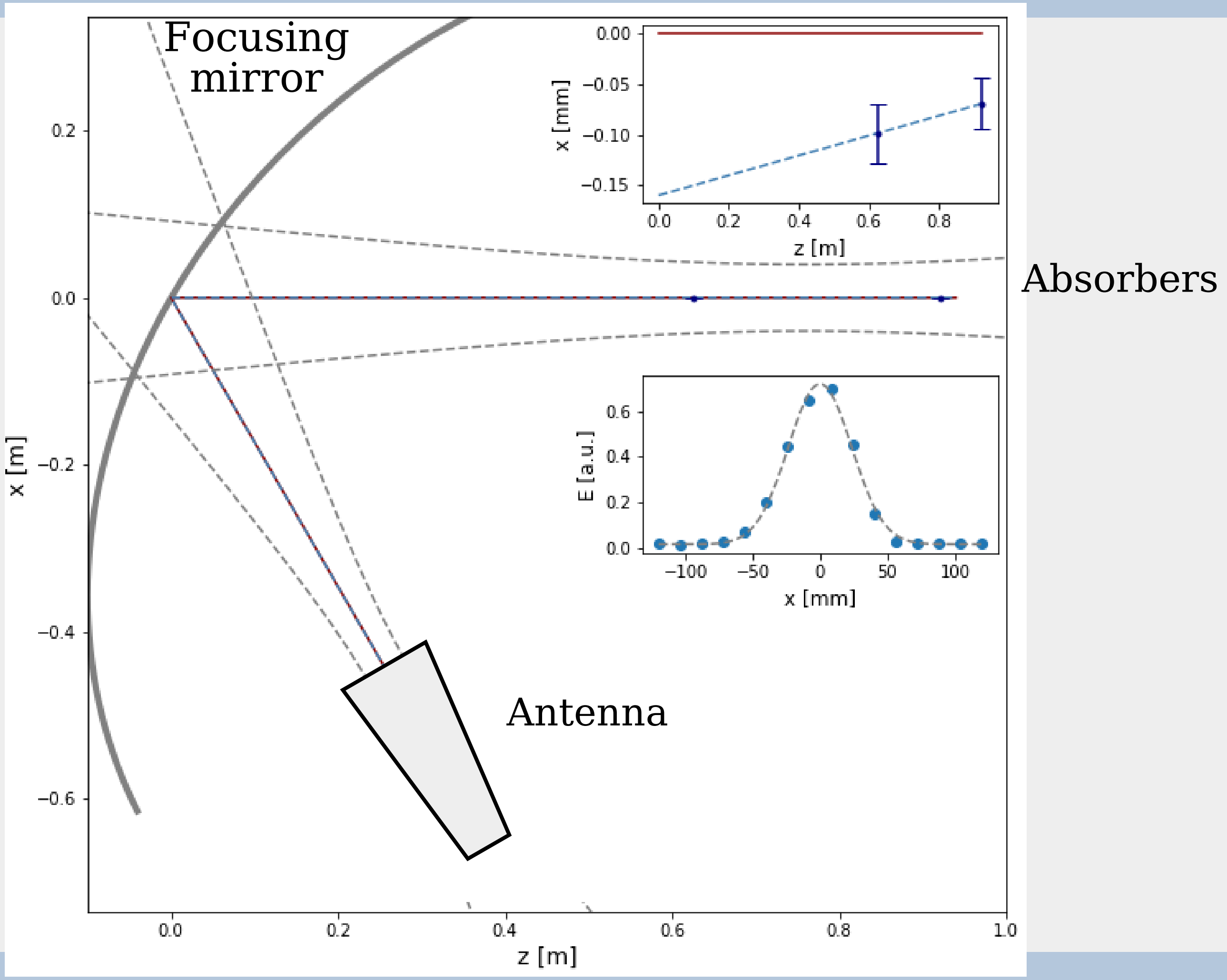
Backup

Backup



Reflection coefficient
a.k.a. reflectivity, S11

$$\Gamma = \frac{refl\,.\,amplitude}{input\ amplitude}$$



Focusing mirror
Absorbers
Antenna
x [m]
z [m]
x [mm]
E [a.u.]