Post-inflationary axion dark matter search

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Max Planck Institute for Physics

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MAX-PLANCK-INSTITUT
FÜR PHYSIK

The strong CP-problem

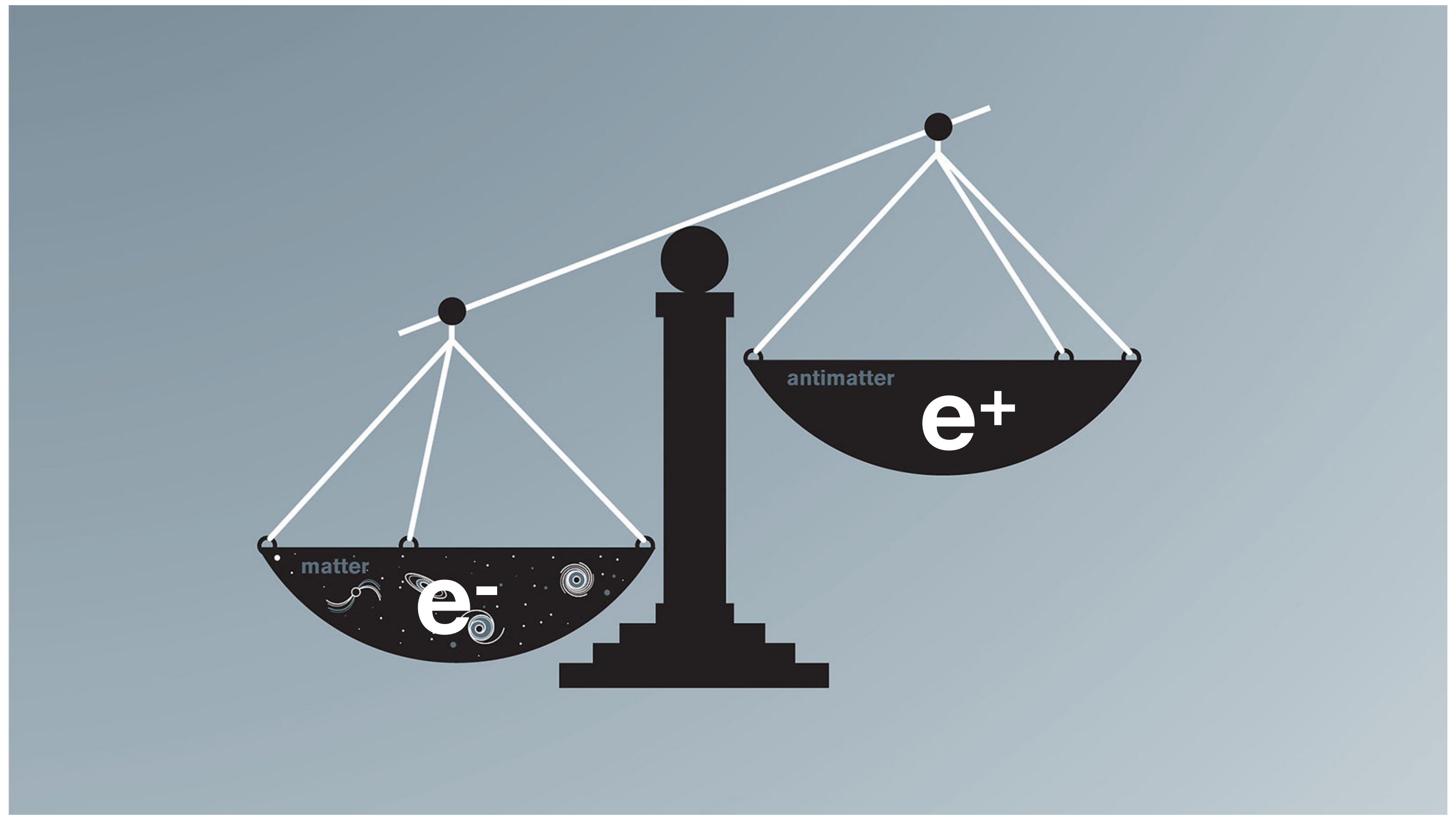
- CP symmetry appears broken.

  matter >> anti-matter

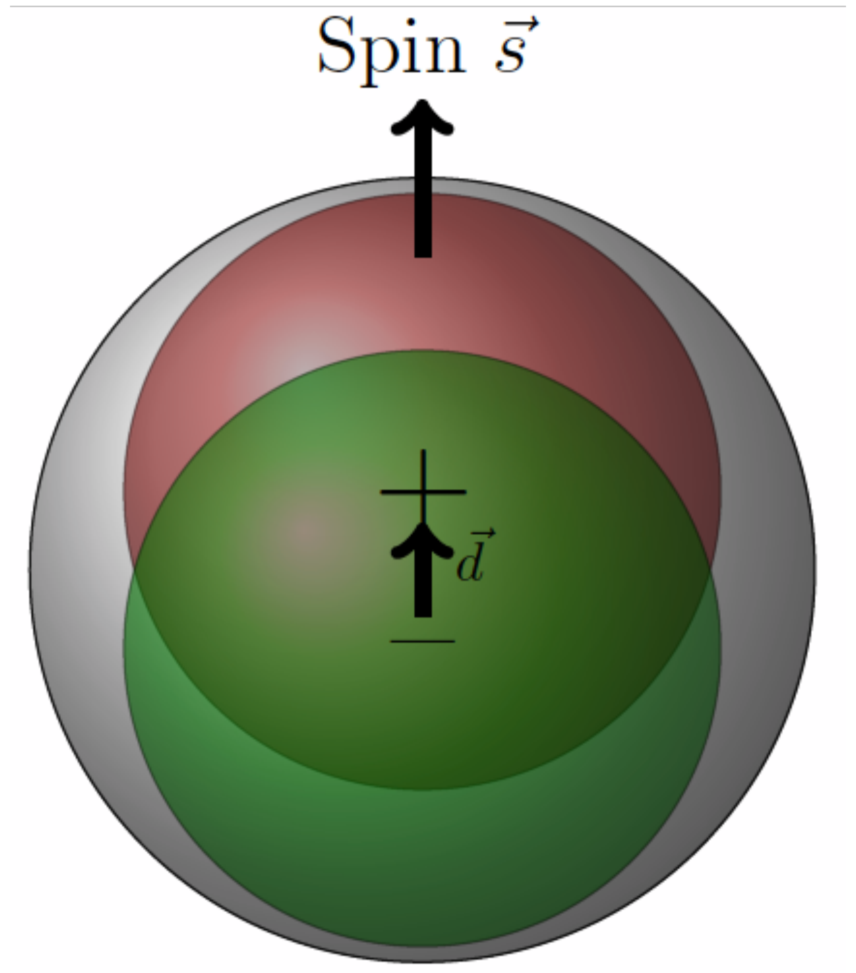
- QCD has a CP-violating term:

$$\mathscr{L} = -\theta \frac{g_s}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a, \quad -\pi < \theta < \pi$$

- However, $|\theta| < 1.3 \times 10^{-10}$
  from the neutron EDM measurement.
  PRL 97 131801 (2006)

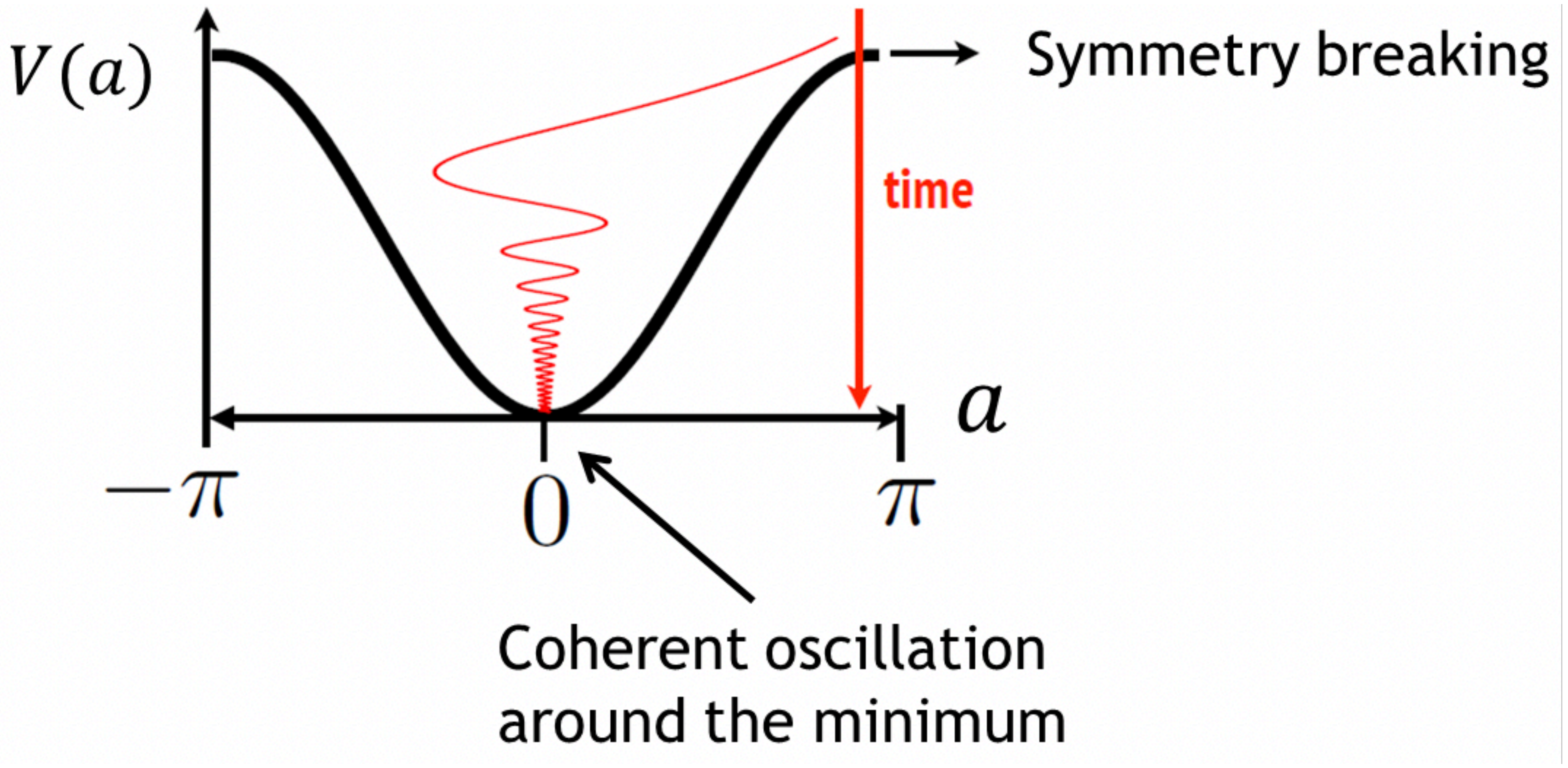


https://www.symmetrymagazine.org/sites/default/files/styles/2015_hero/public/images/standard/Matter_Antimatter_1920x1080.jpeg?itok=pal9HXXk



Peccei-Quinn mechanism

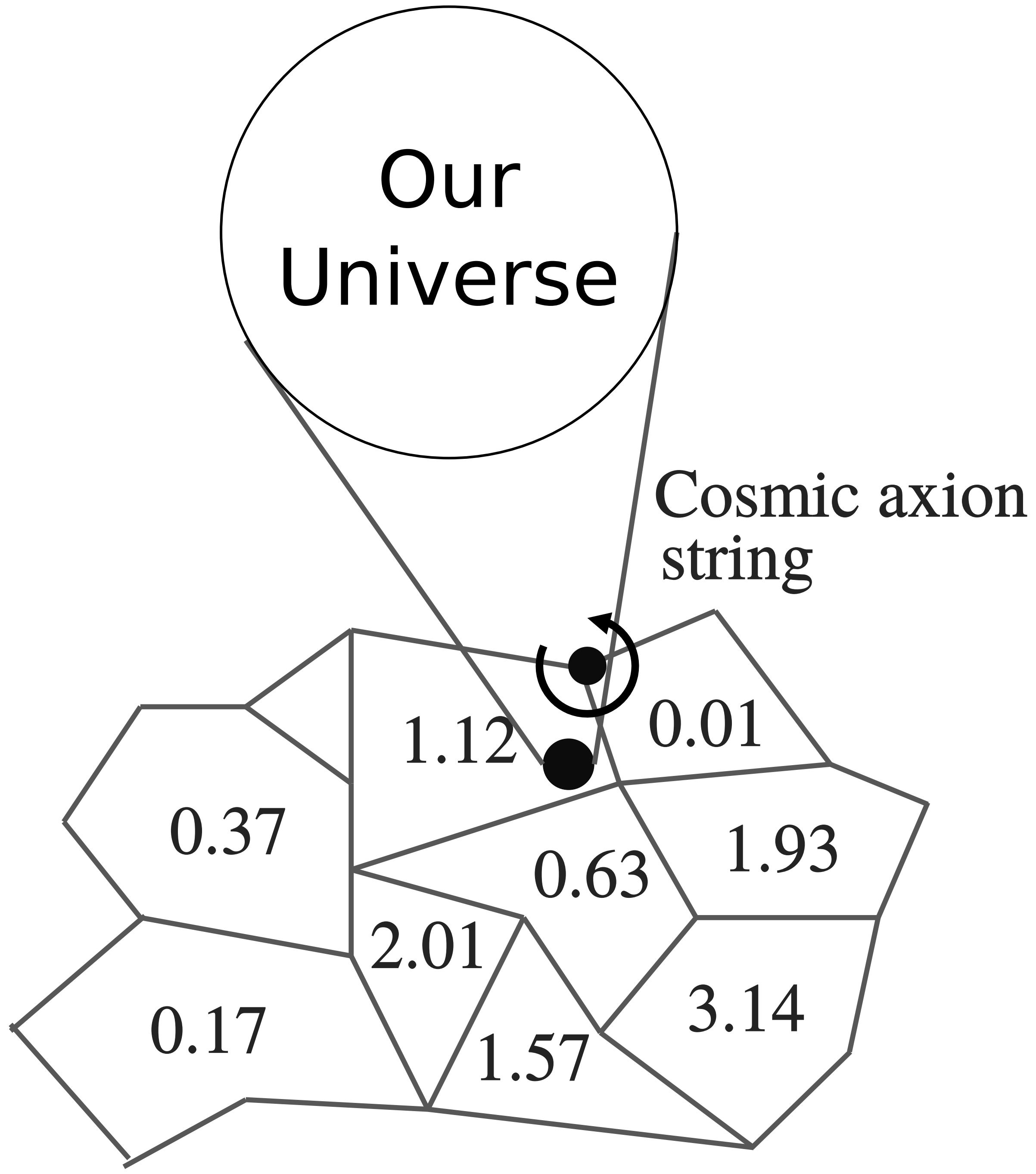
- Promote θ into a dynamic **field**: $\theta \rightarrow a(t,x)$.
  - Axion: fluctuation of a field around zero.
  - Inflation: $\theta \rightarrow 0$
- Explicit symmetry breaking by QCD at f_a: Axion acquires **mass!**
- **Relic Axion**: compelling candidate for **Cold Dark Matter.**
  - Feeble EM interaction, cold, long lifetime



http://esuhai.com/upload/fck/image/BAN%20BIEN%20TAP/bang%20tin%20kaizen/ban%20tin%2097/25.jpg

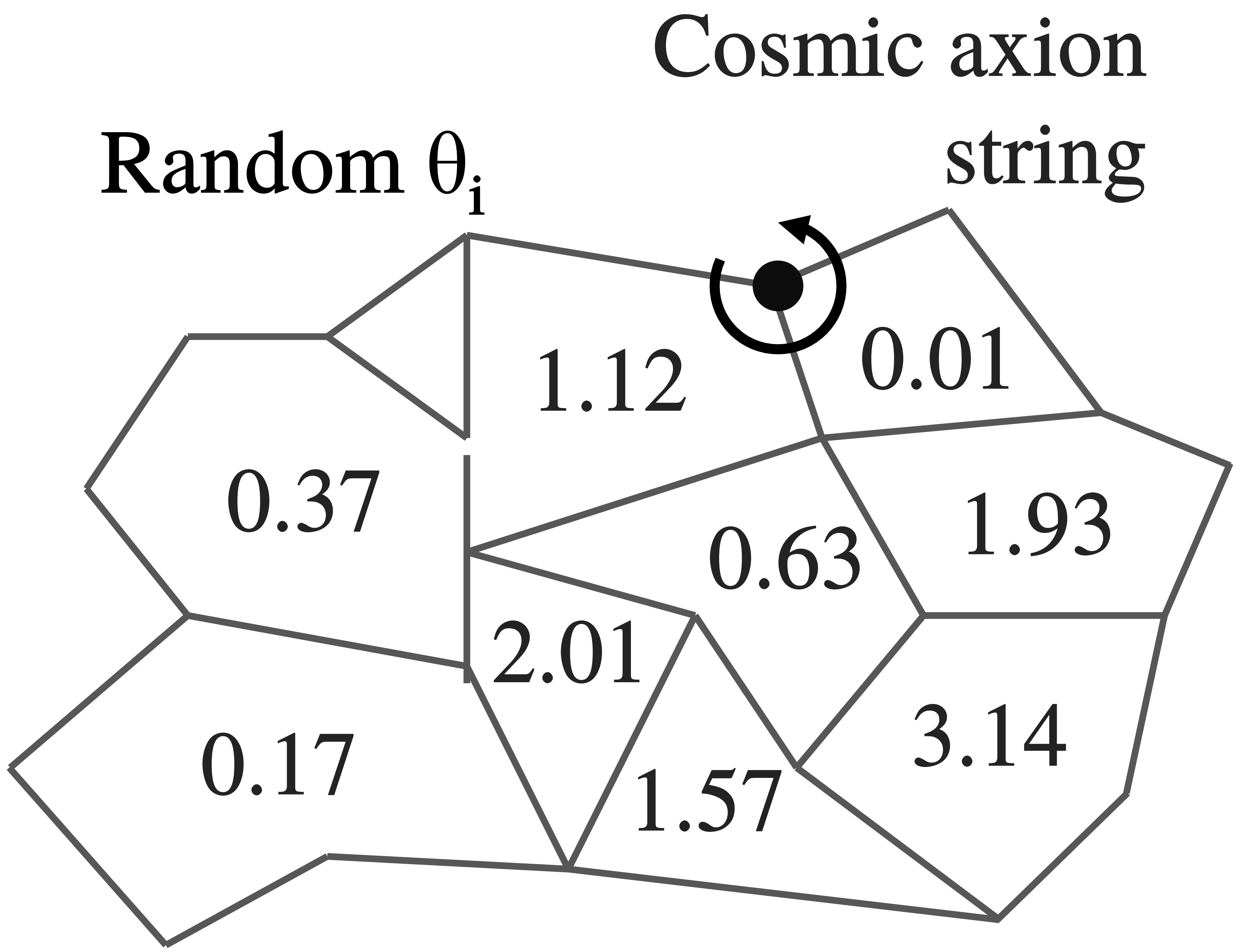
Post-Inflation

Pre-Inflation



? < m_a < ~1 meV

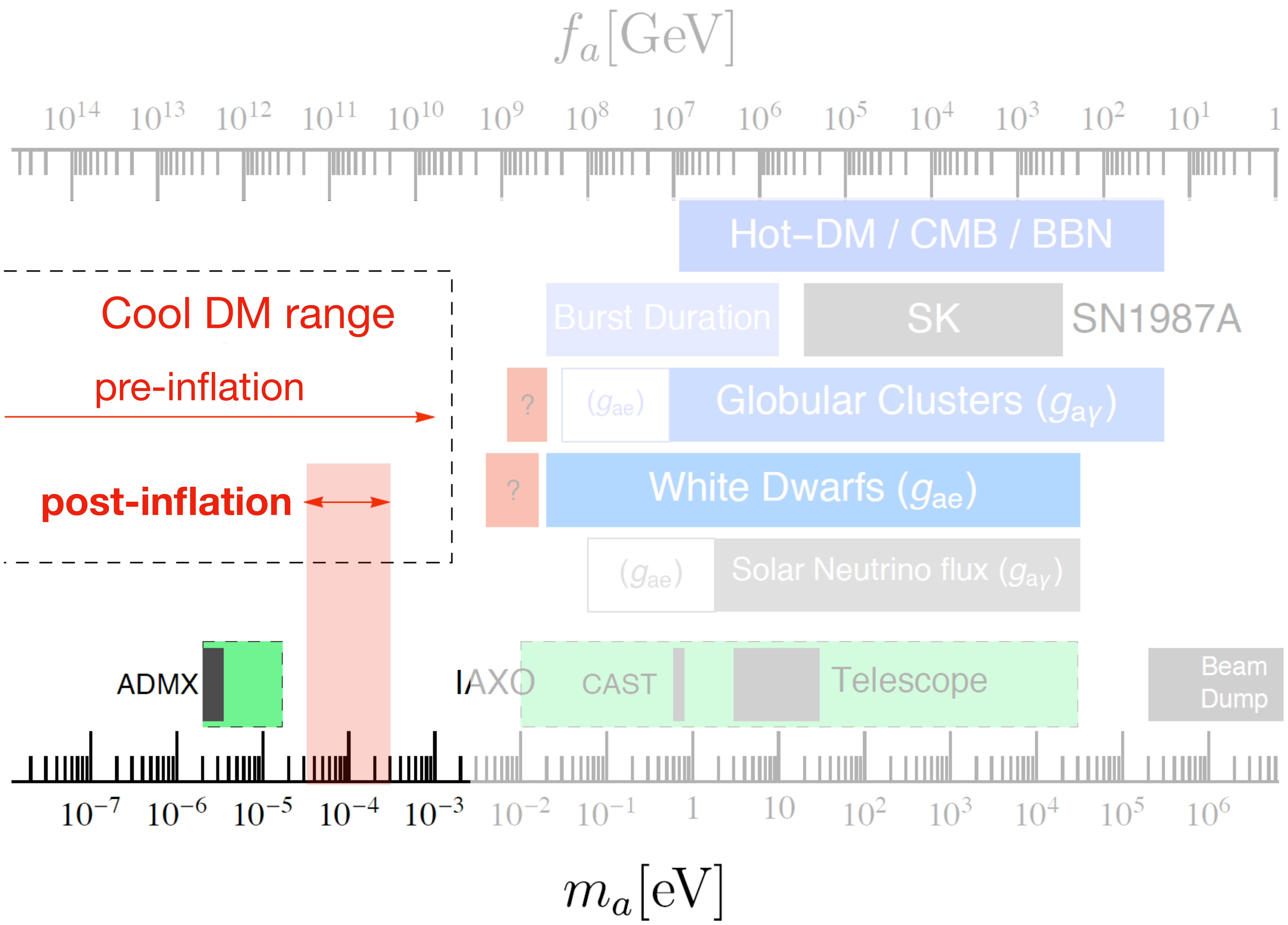
Our Universe:



PQ symmetry breaking after inflation

m_a ~ 100 μeV

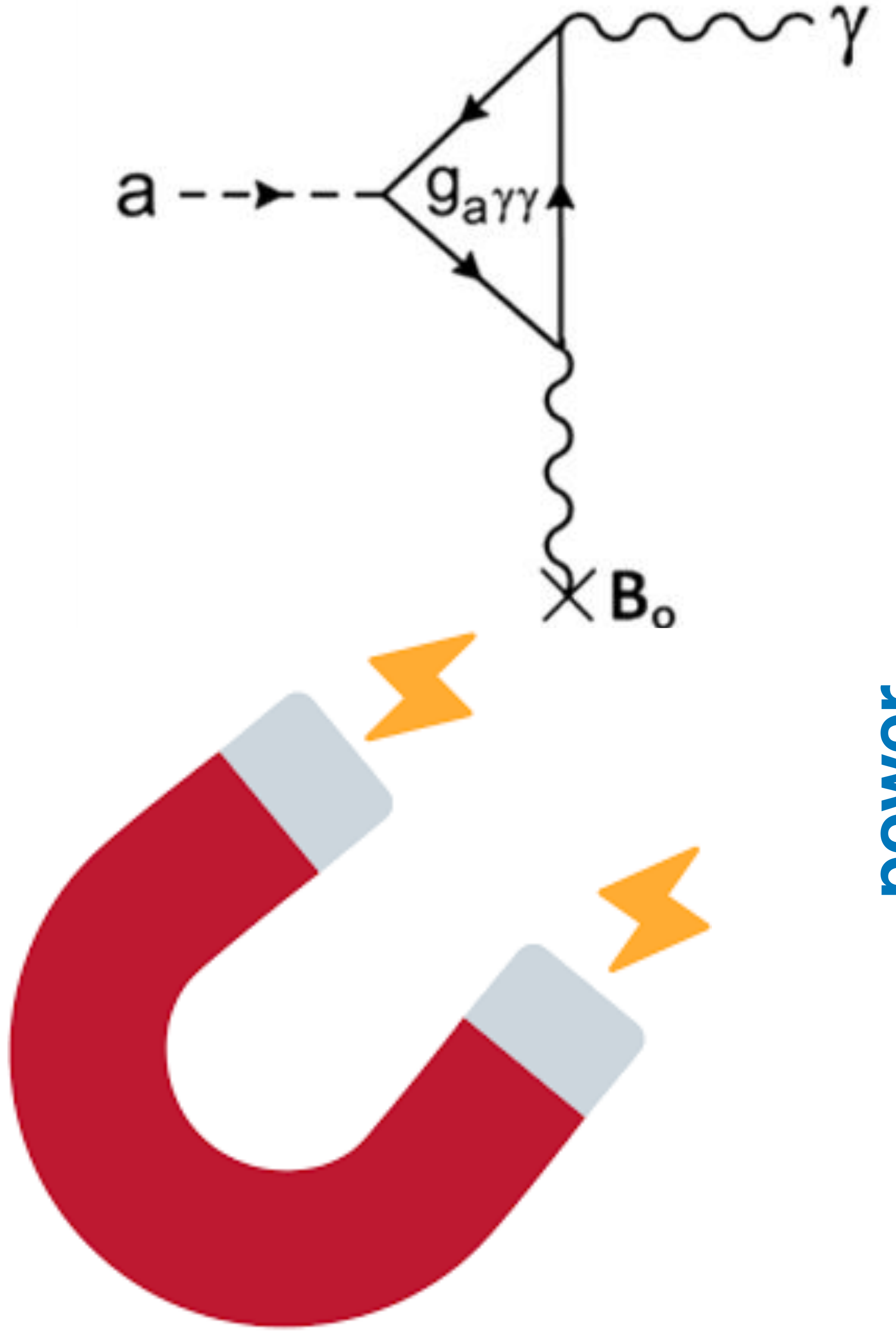
JCAP **2017,** 049–049
PRD **91**, 065014

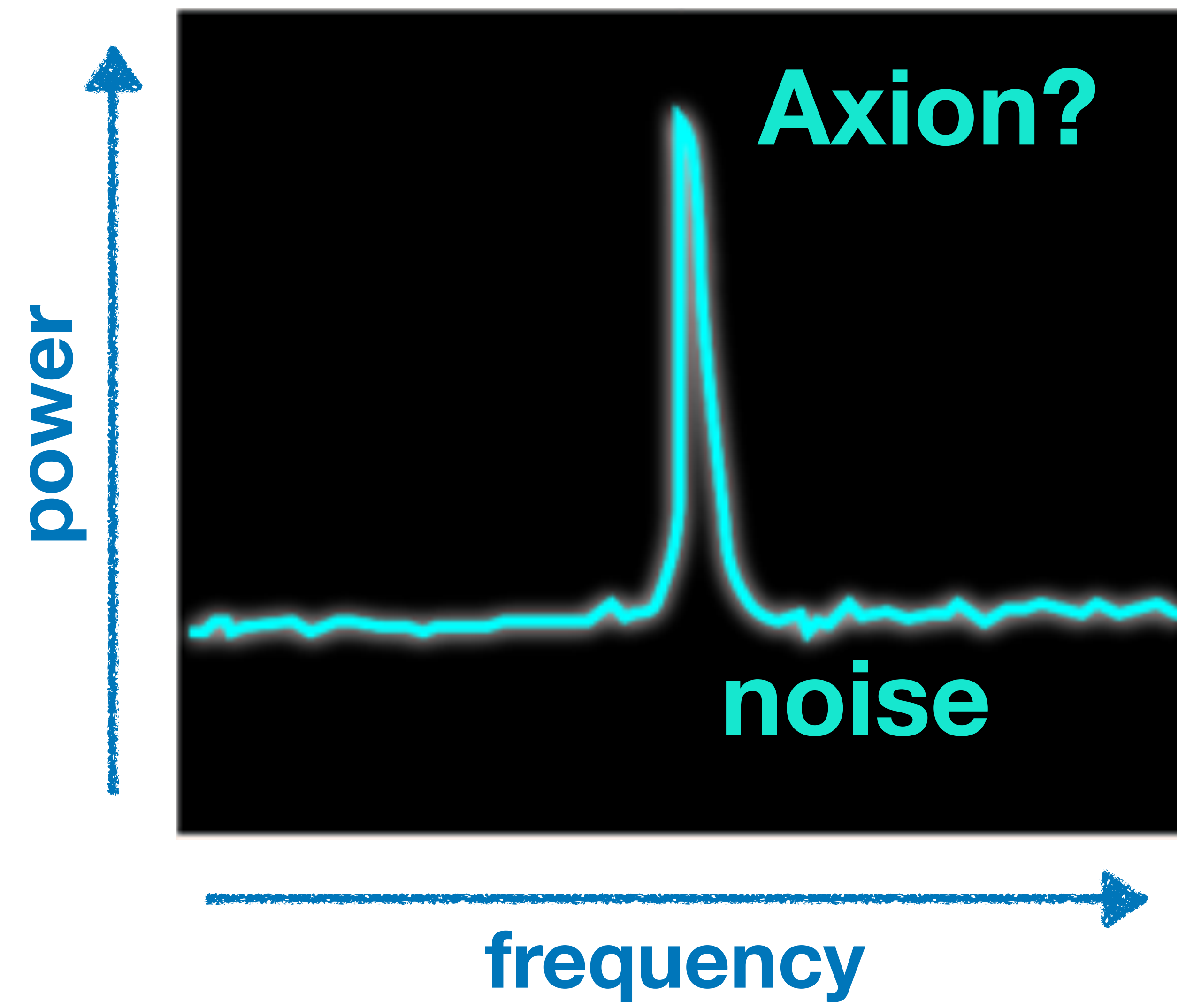

f_a[GeV]
10^{14} 10^{13} 10^{12} 10^{11} 10^{10} 10^{9} 10^{8} 10^{7} 10^{6} 10^{5} 10^{4} 10^{3} 10^{2} 10^{1} 1
Hot–DM / CMB / BBN
Cool DM range
pre-inflation
post-inflation
Burst Duration
SK
SN1987A
?
(g_{ae})
Globular Clusters ($g_{a\gamma}$)
?
White Dwarfs (g_{ae})
(g_{ae})
Solar Neutrino flux ($g_{a\gamma}$)
ADMX
IAXO
CAST
Telescope
Beam Dump
10^{-7} 10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
m_a[eV]

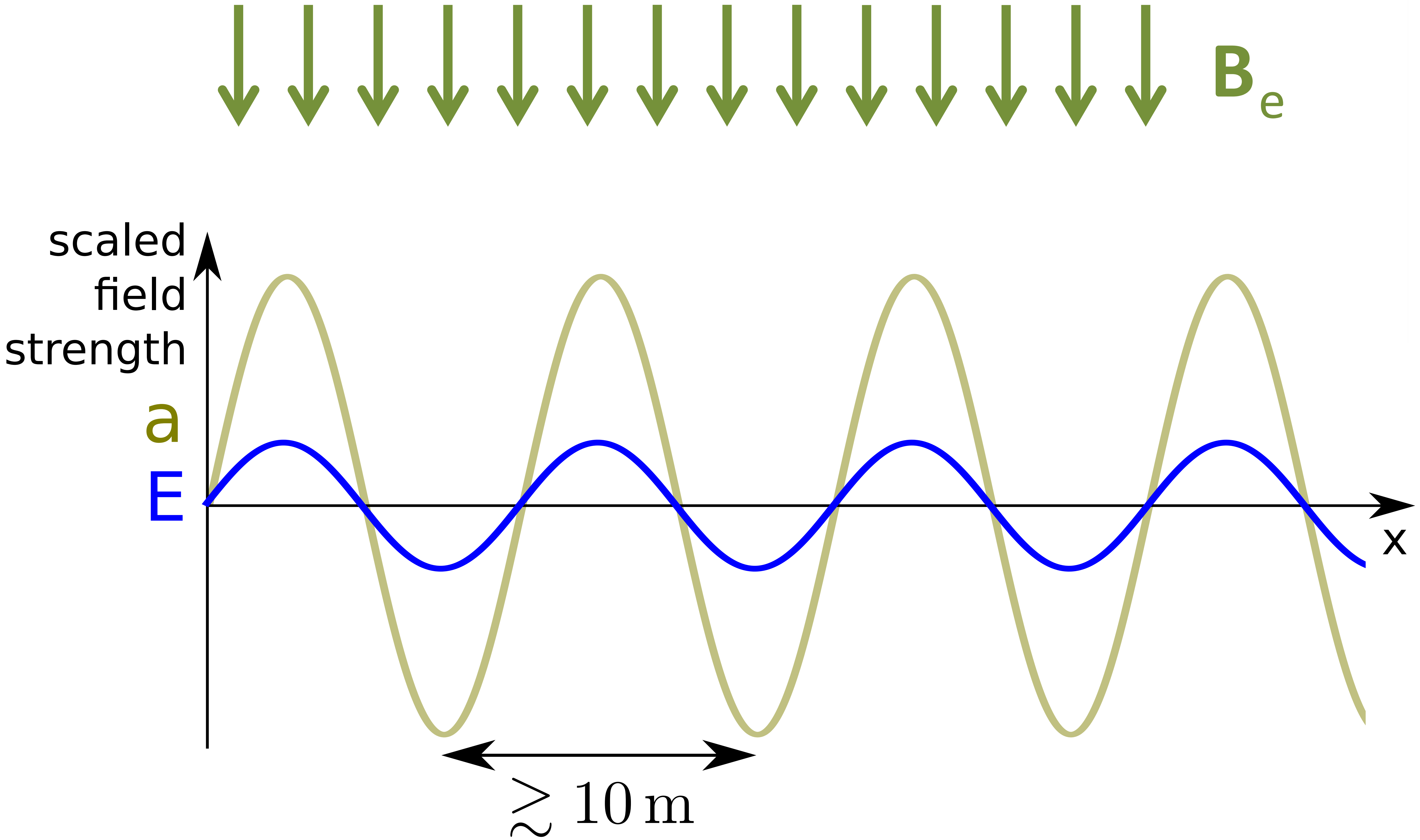
Dielectric haloscope
Principle

Primakoff interaction

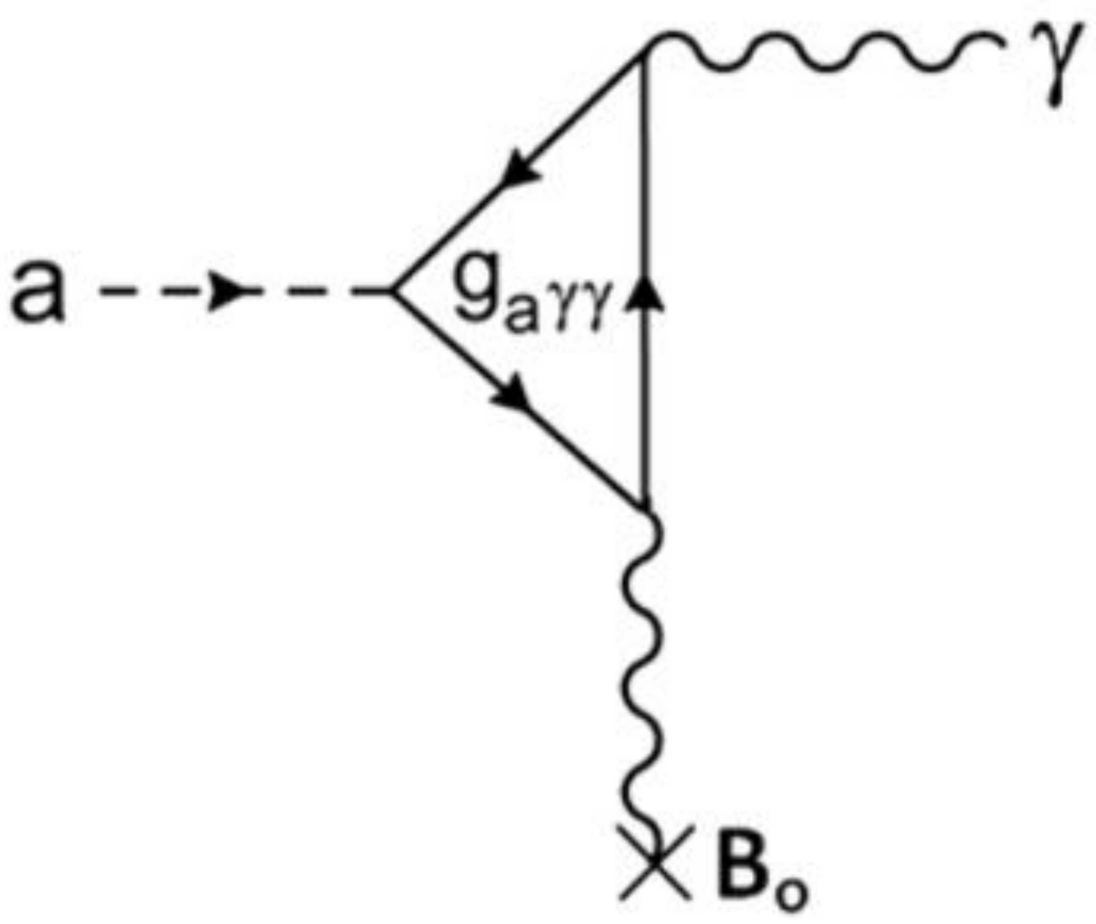
- Axion couples to a EM field:
  $\mathscr{L} = g_{a\gamma} a \vec{E} \cdot \vec{B}$
  - Axion converts into a EM field inside a magnetic field
- The product EM wave has a frequency: $\hbar\omega = m_a c^2$
  - CDM: monochromatic

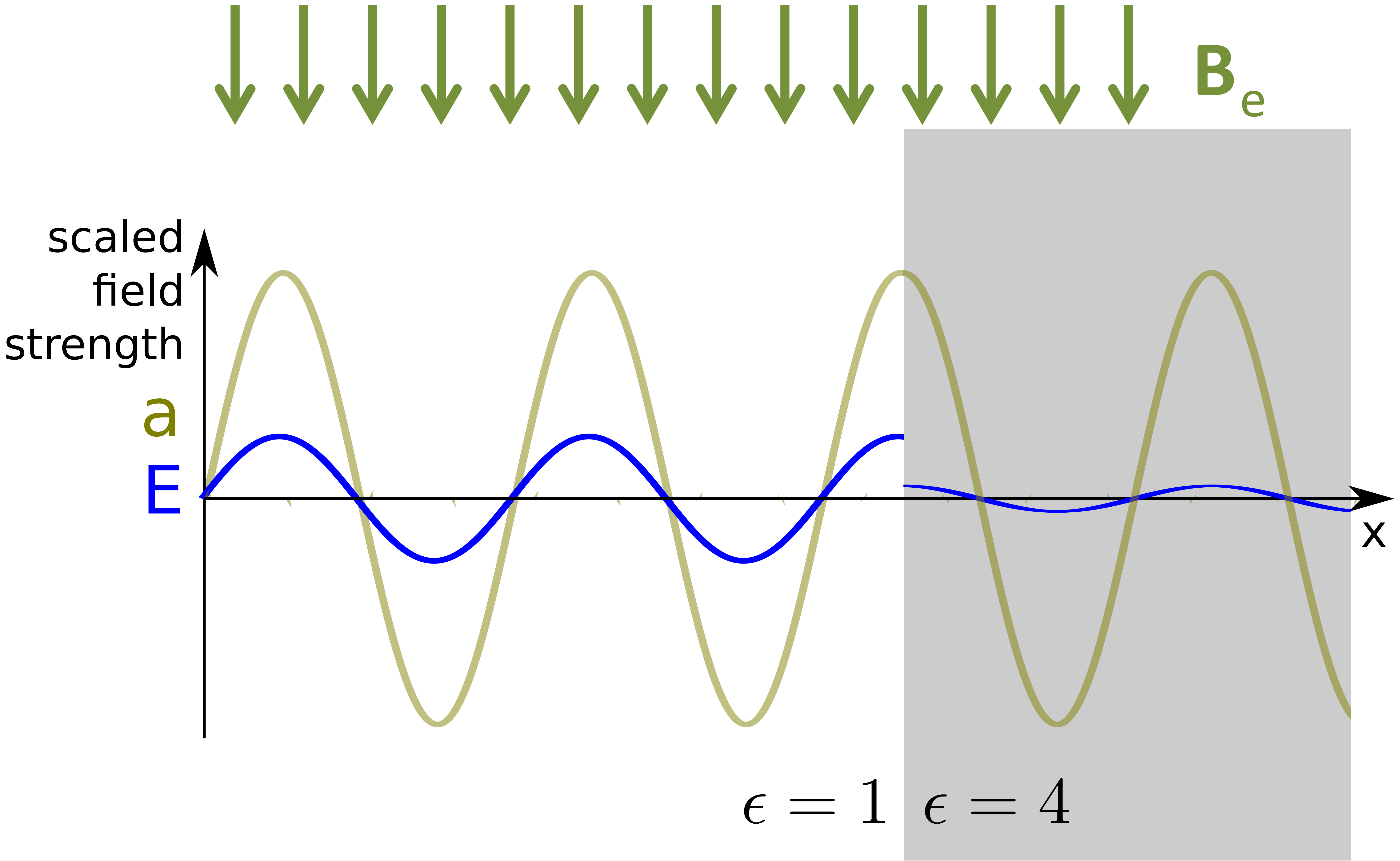




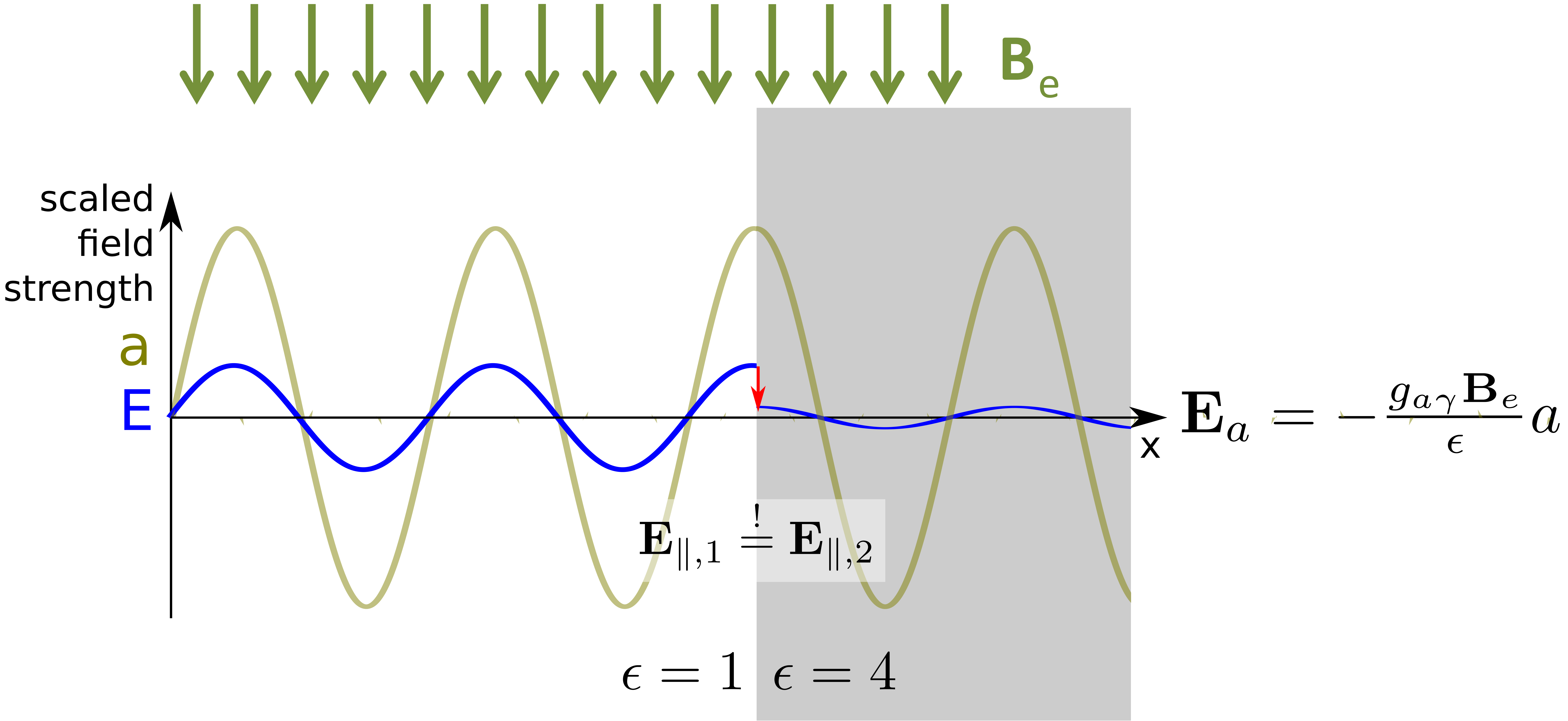


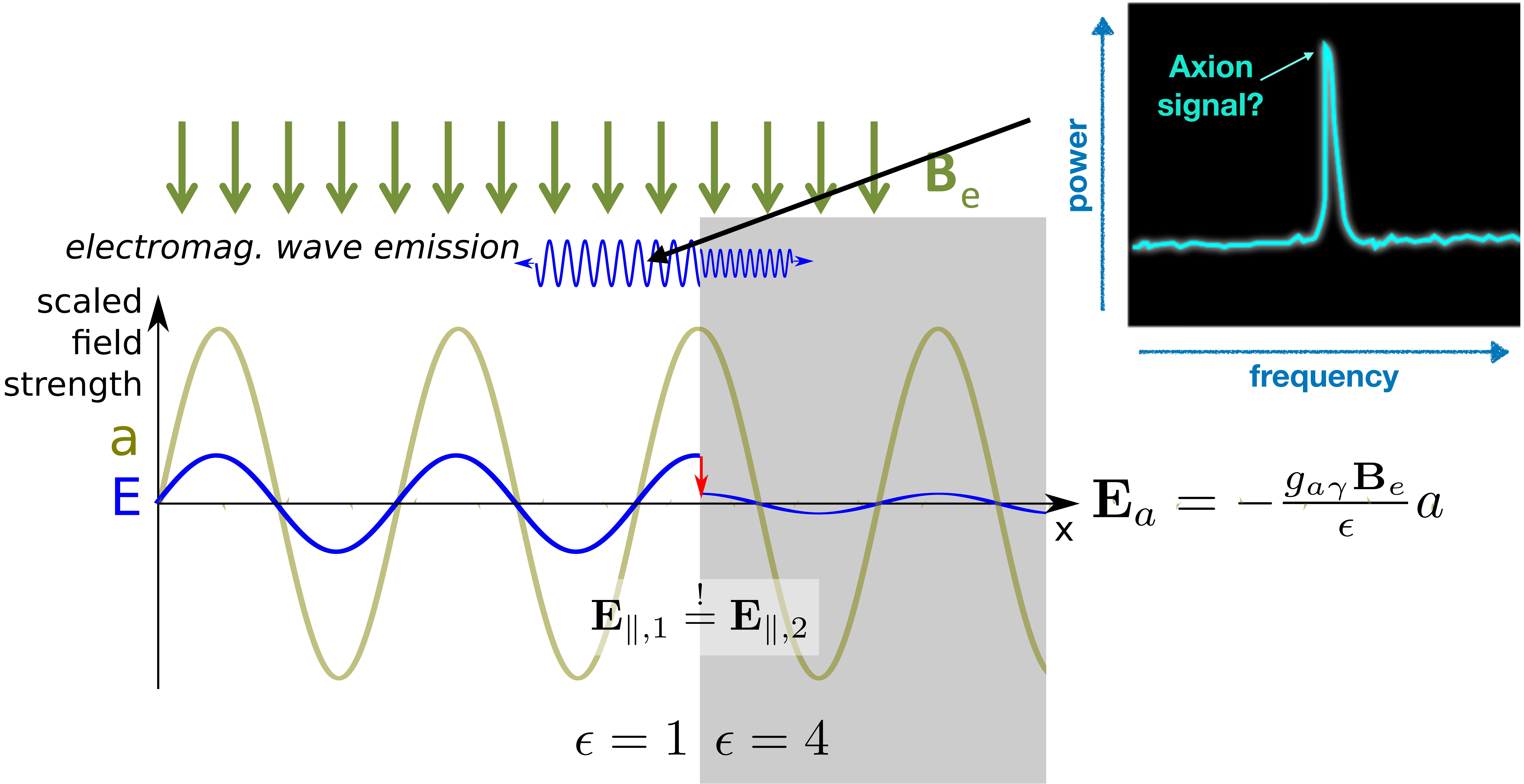
$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$





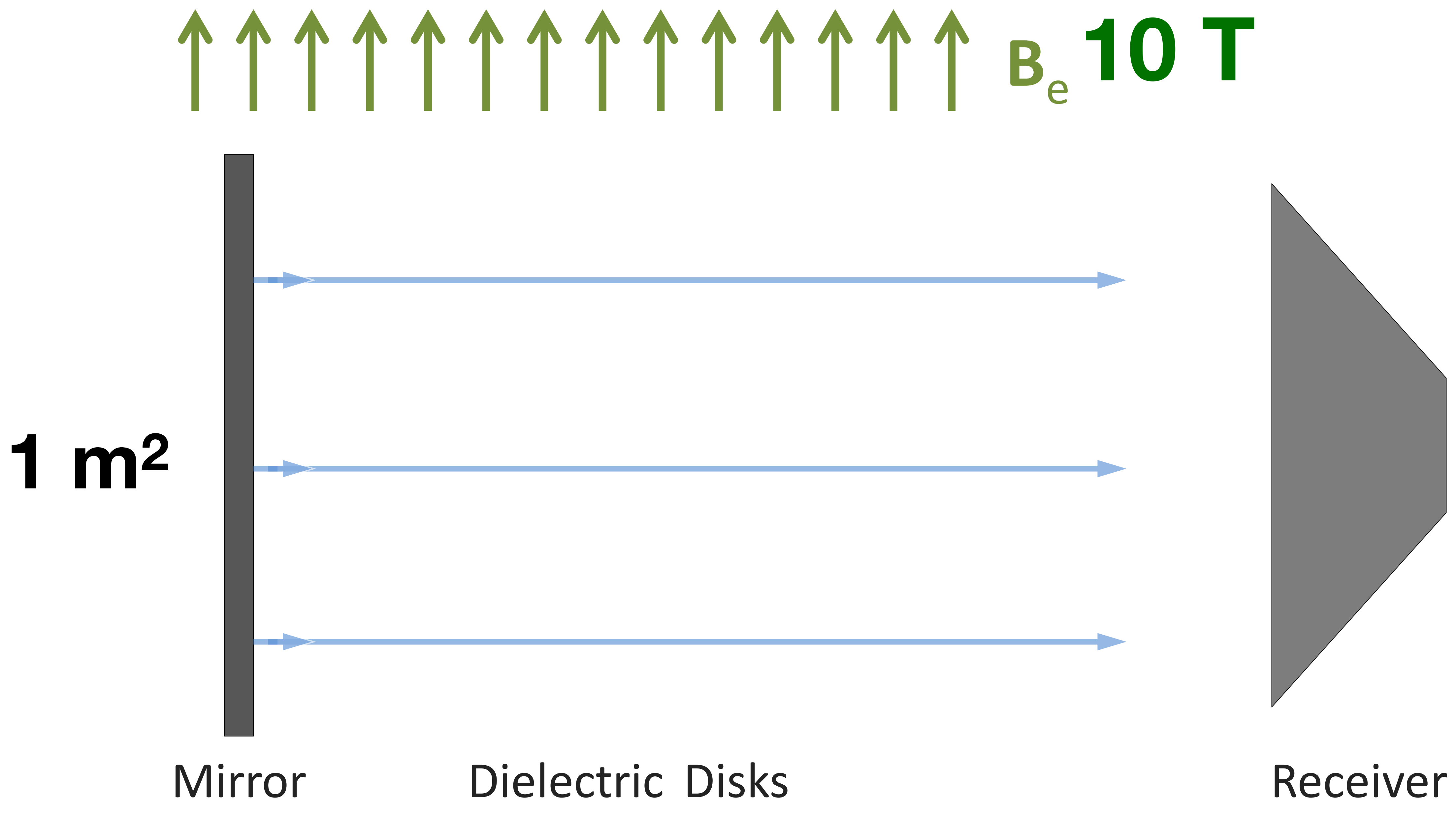
$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$


$\mathbf{B}_e$
scaled field strength
a
E
x
$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$
$\mathbf{E}_{\parallel,1} \stackrel{!}{=} \mathbf{E}_{\parallel,2}$
$\epsilon = 1$
$\epsilon = 4$



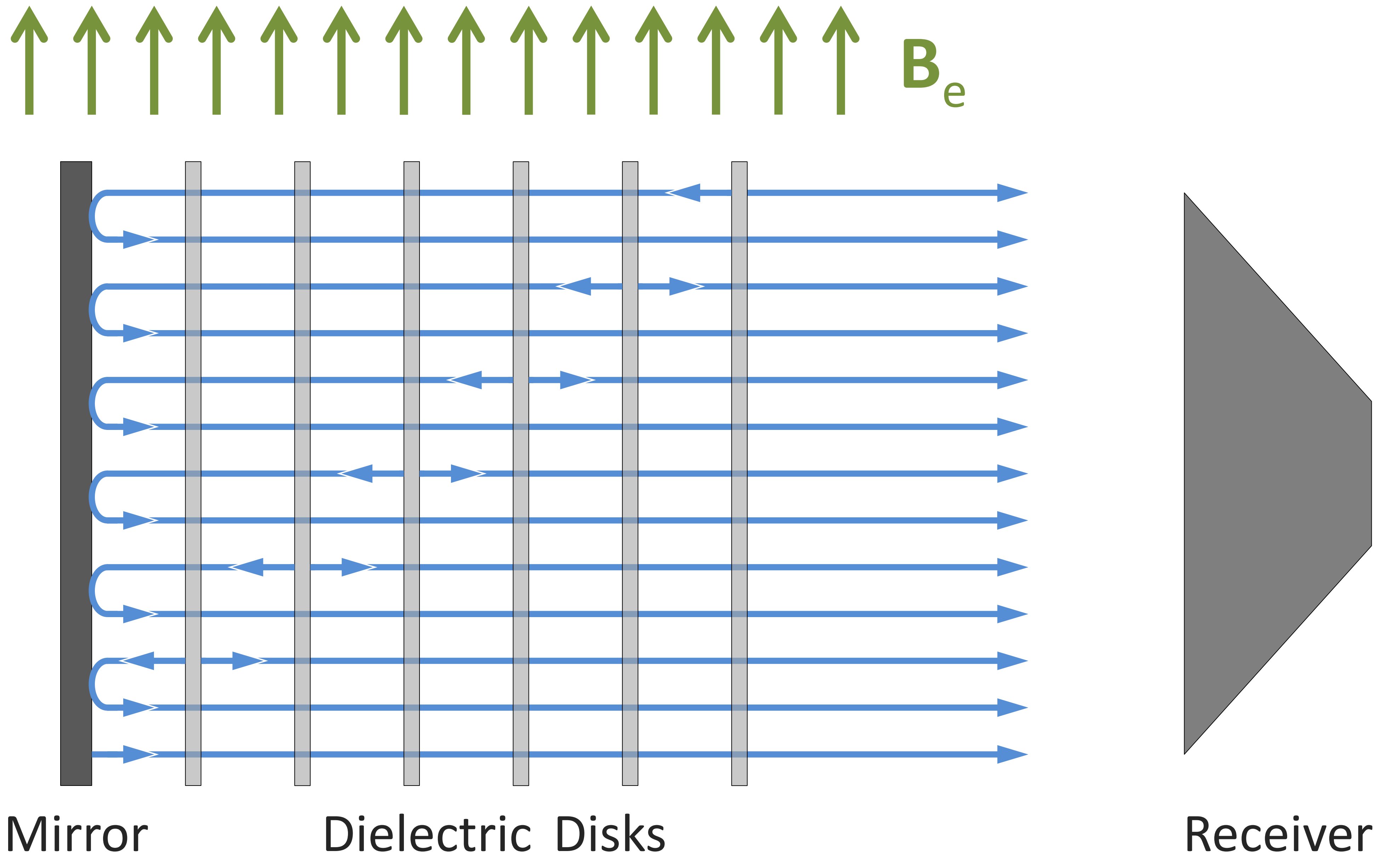
$$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon} a$$

Dielectric haloscope



- $P_0 = 10^{-27}$ W @ 10T,
  or ~2 photons / hour (@ 25 GHz). Extremely small…
- Add more dielectric disks

Dielectric haloscope



- more coherent sources + constructive interferences

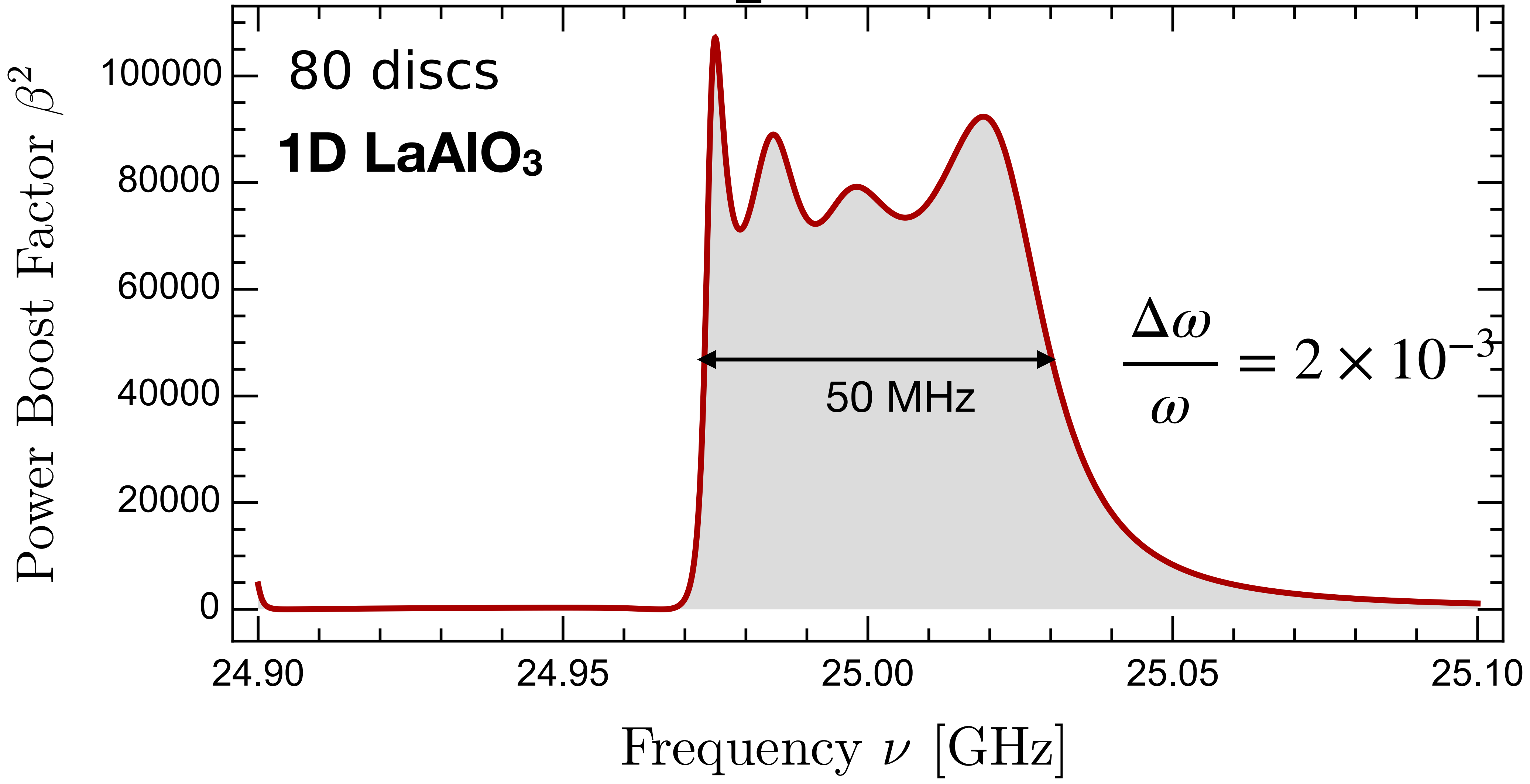
- $P_{sig} \propto B_e^2 \; A \; \beta^2$

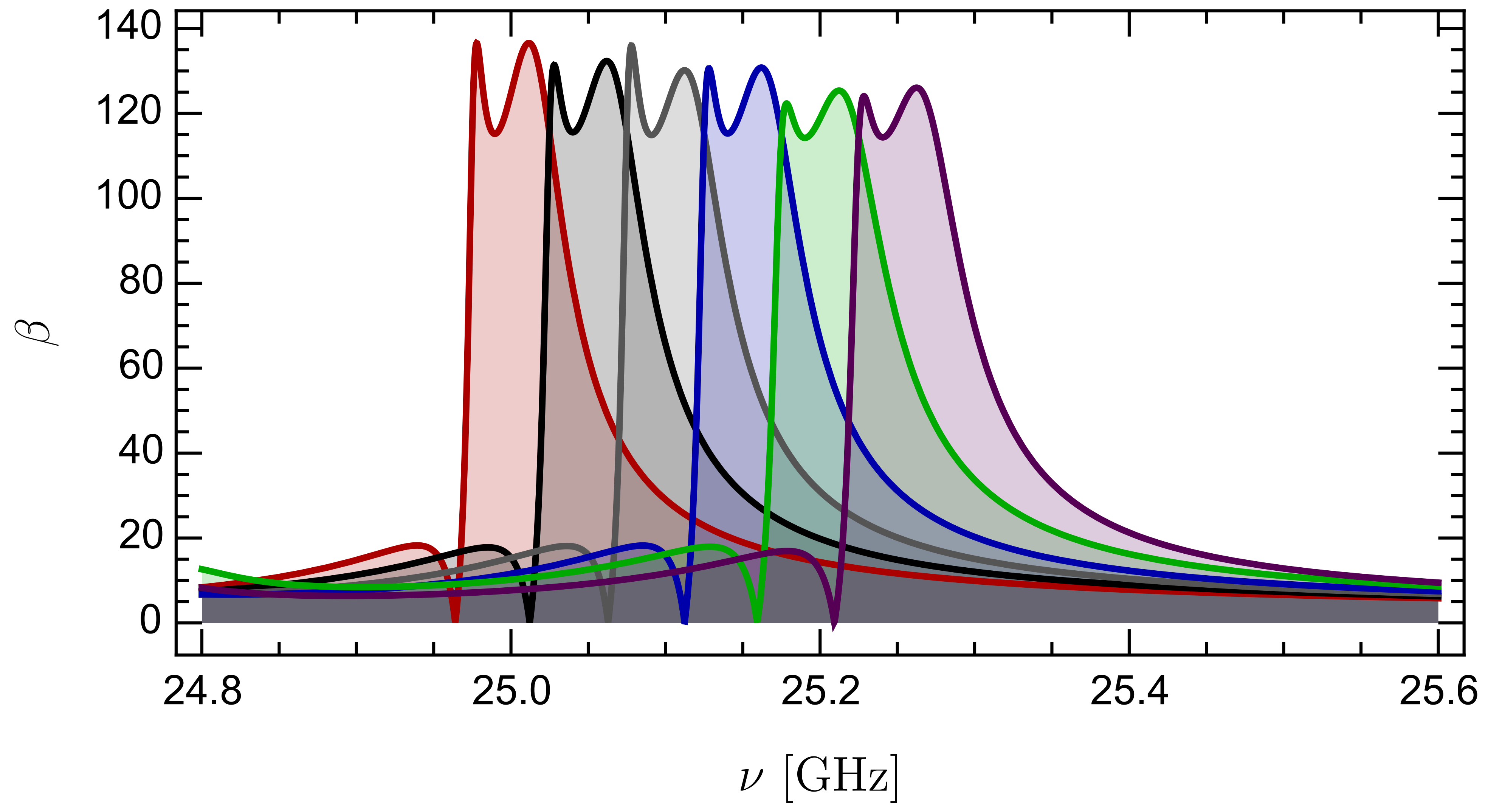
boost factor

A. J. Millar *et al* JCAP01(2017)061, Phys. Rev. Lett. 118, 091801 (2017)

Dielectric haloscope

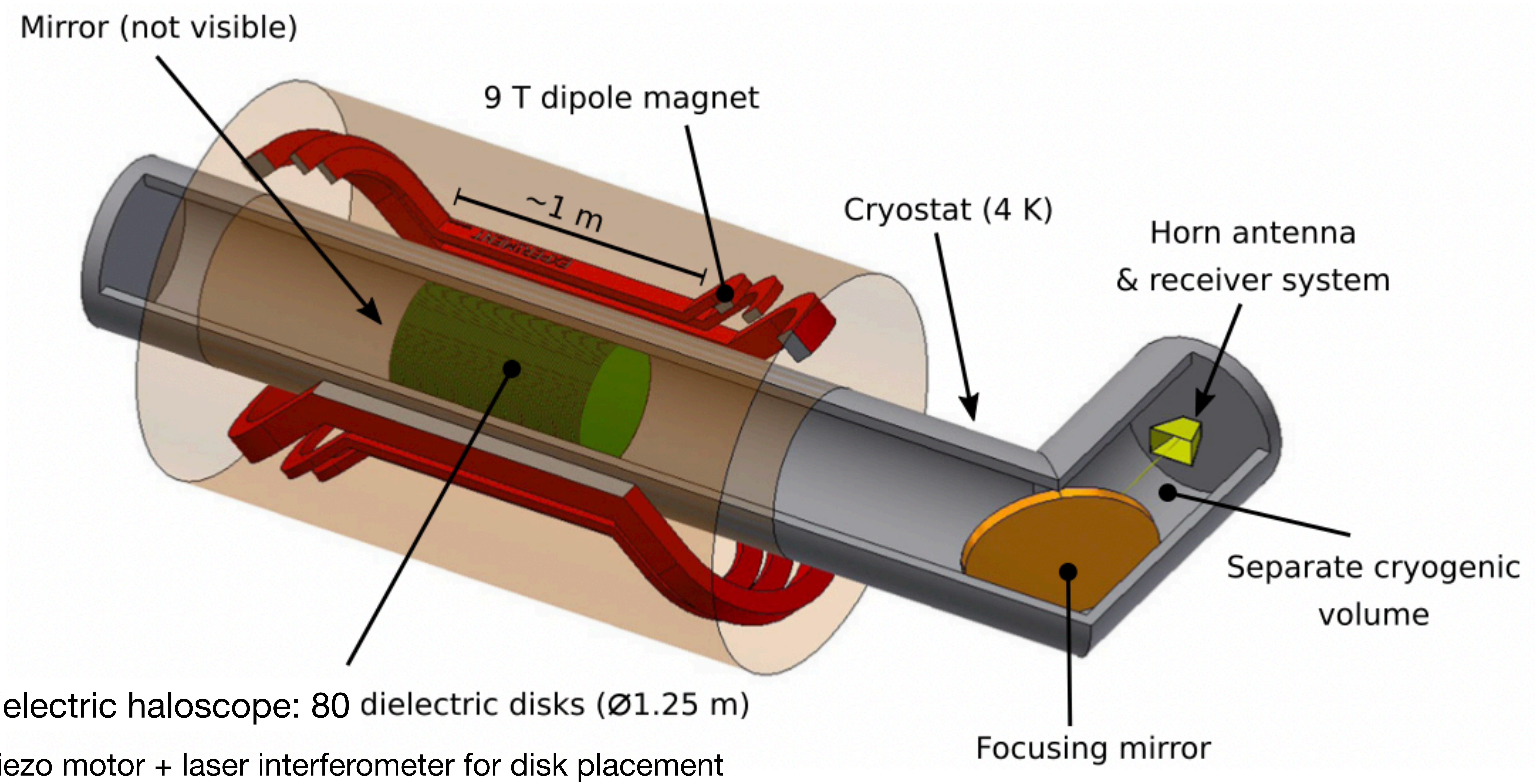
- Large **single volume**
- Approach QCD sensitivity: $\beta^2 > 20{,}000$ possible
- Frequency tuning: Disk spacings control $\beta(f)$.





RWTH Aachen, MPI for Radioastronomy, Institut NEEL, DESY,
Univ. of Hamburg, CPPM, MPI for Physics, CEA-IRFU,
Eberhard-Karls-Univ. at Tübingen, Univ. of Zaragoza,

Full MADMAX

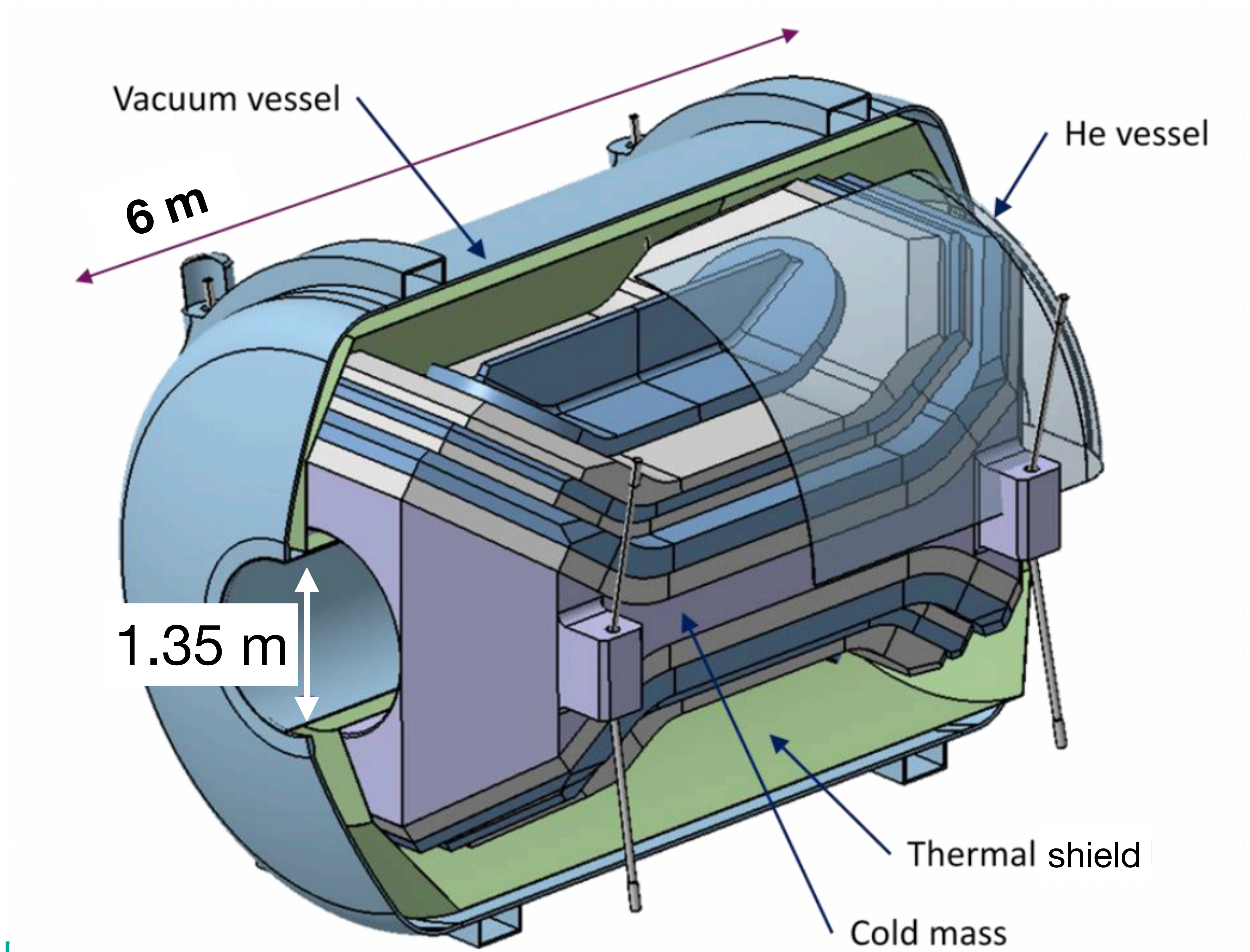


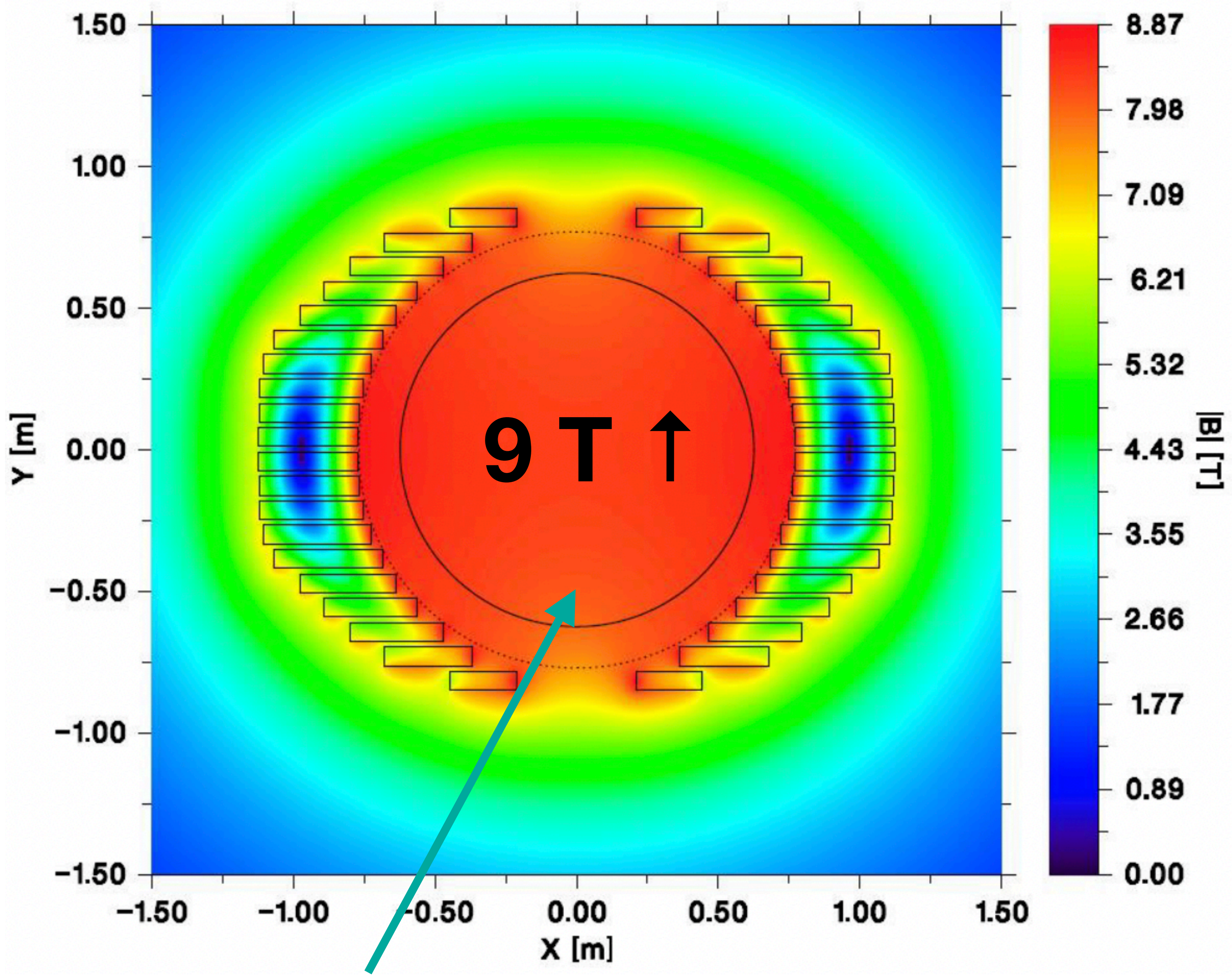
dielectric haloscope: 80 dielectric disks (Ø1.25 m)

Piezo motor + laser interferometer for disk placement

Magnet

- European Innovation partners: CEA Saclay and Bilfinger Noell
- FoM: B^2A = **100 T^2m^2**





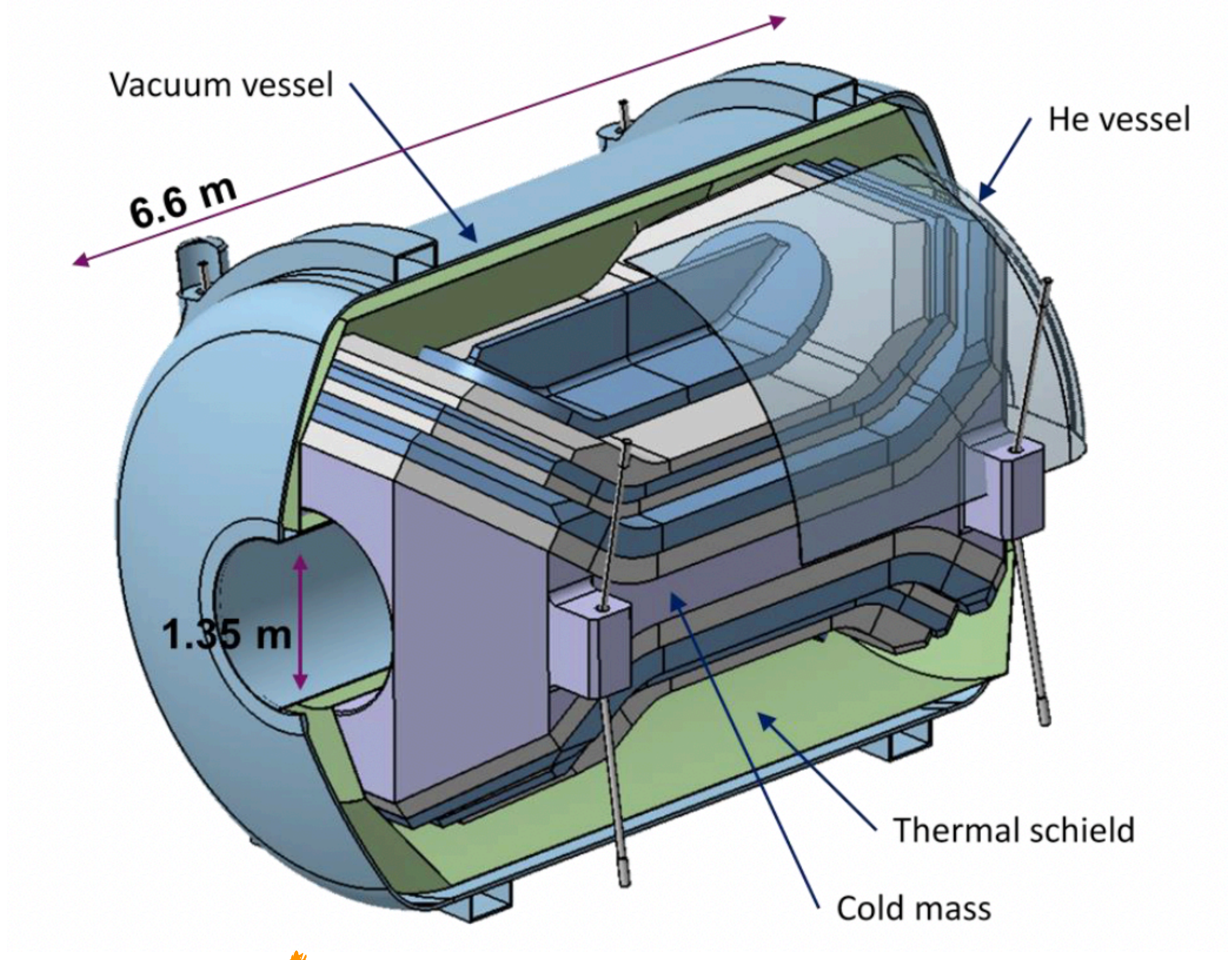
480 MJ!

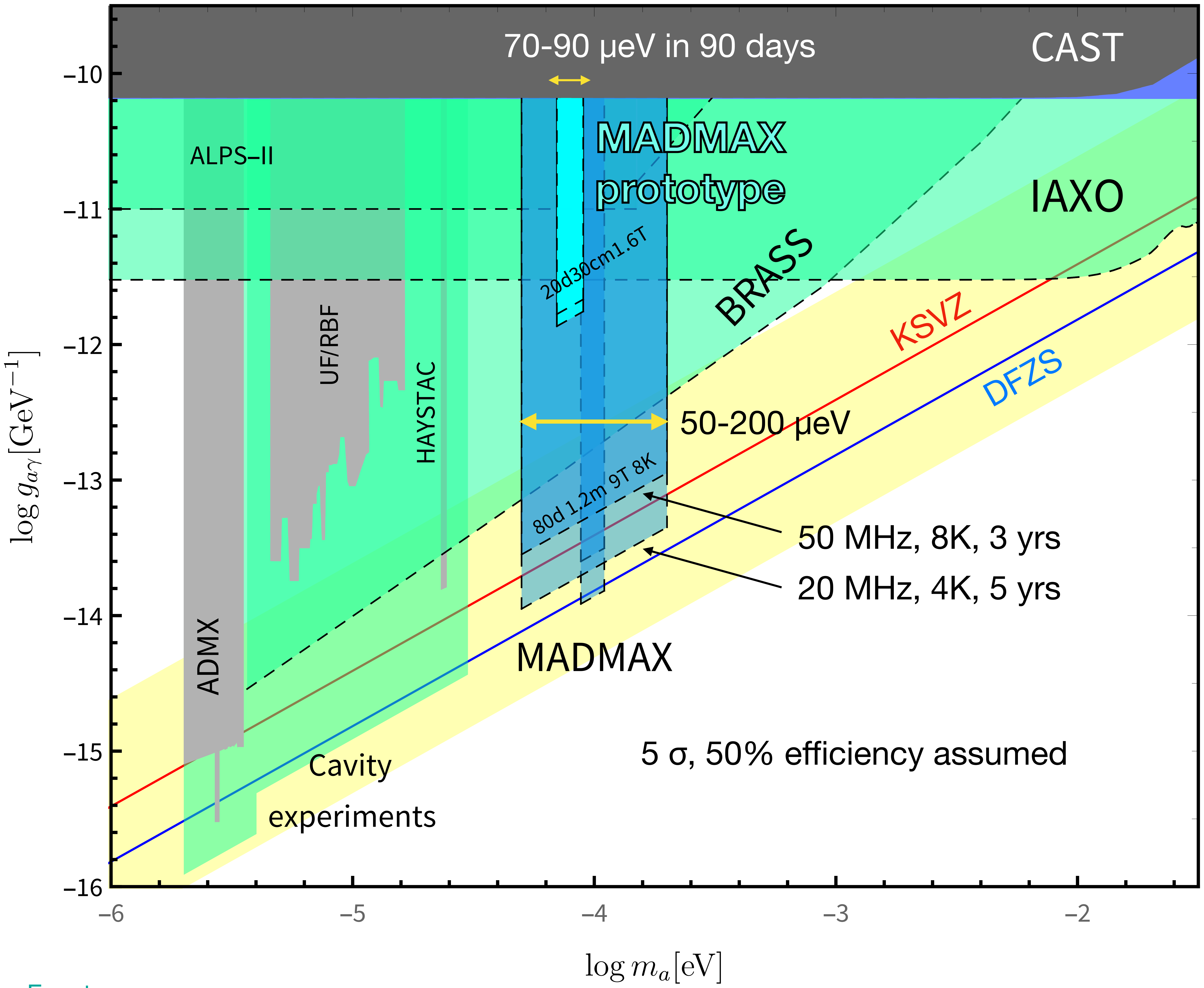
Site

- Axion experiments in DESY:
  ALPS II, IAXO, BRASS

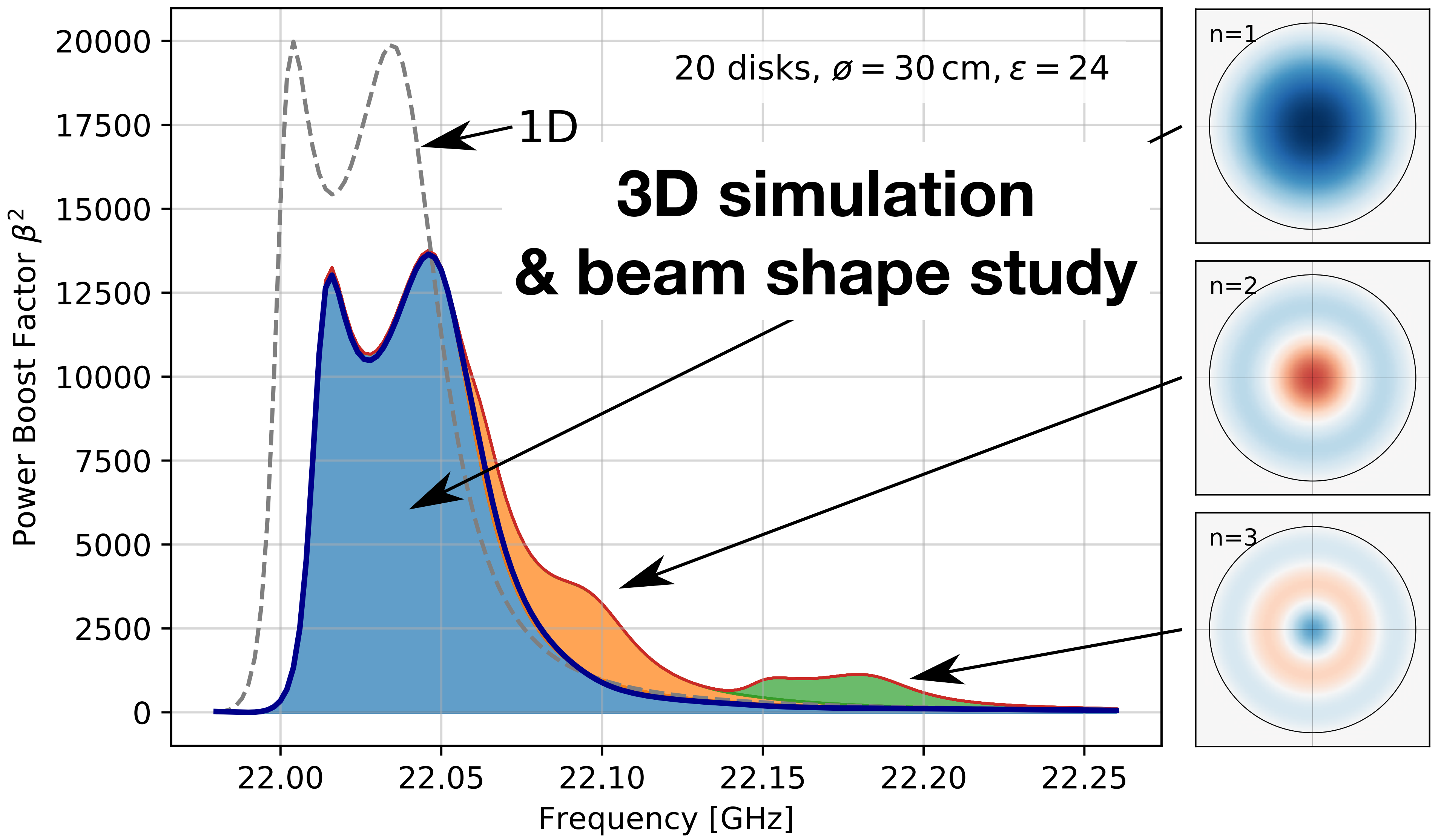
- MADMAX occupies H1 North hall
  - Existing infrastructure, H1 magnet yoke

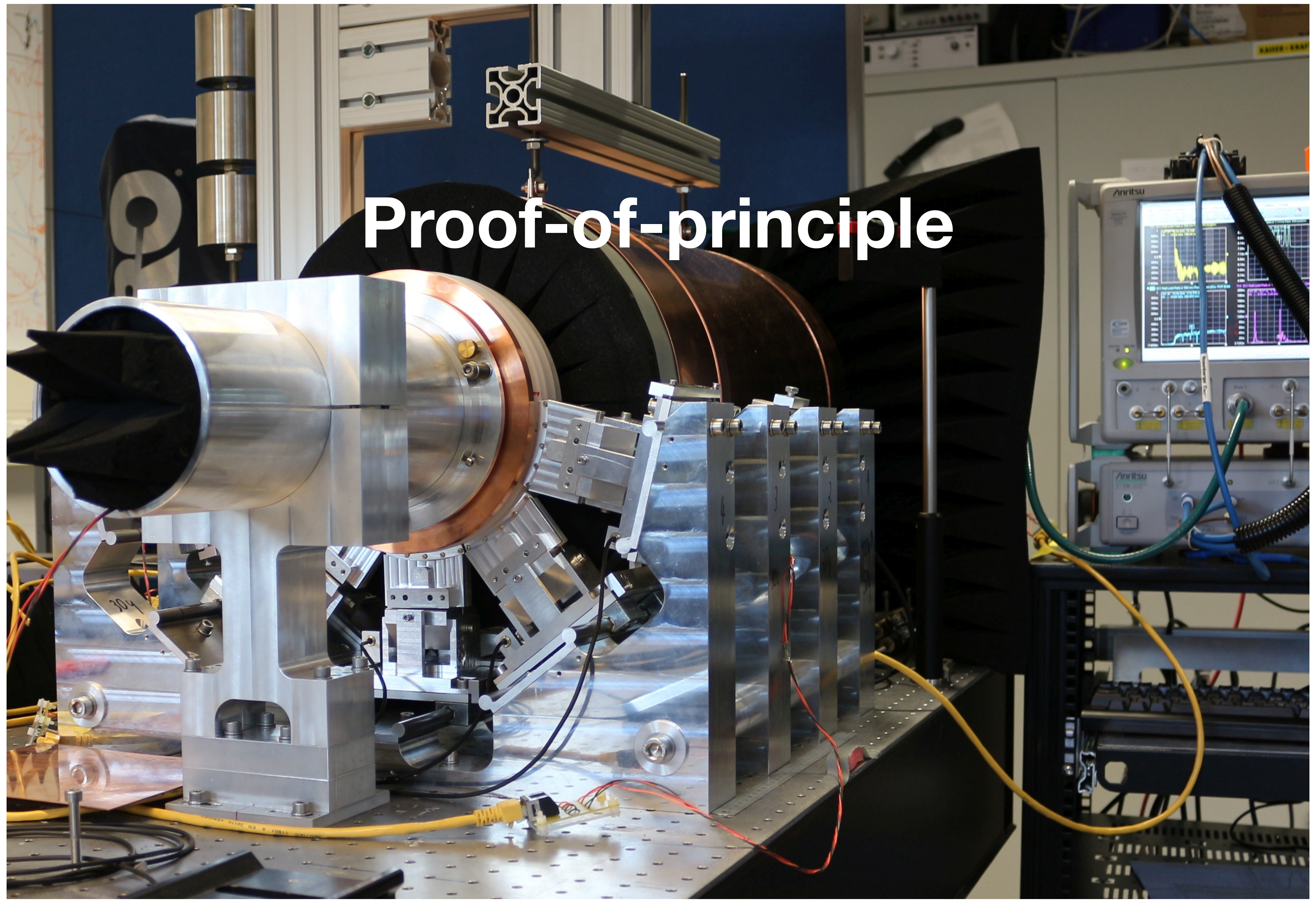
- Strong recommendation from recent DESY Physics Review Committee
  - *"The review committee enthusiastically endorses the physics goals of the MADMAX proposal… We recommend approval of the phase II of the project", Nov. 2019*

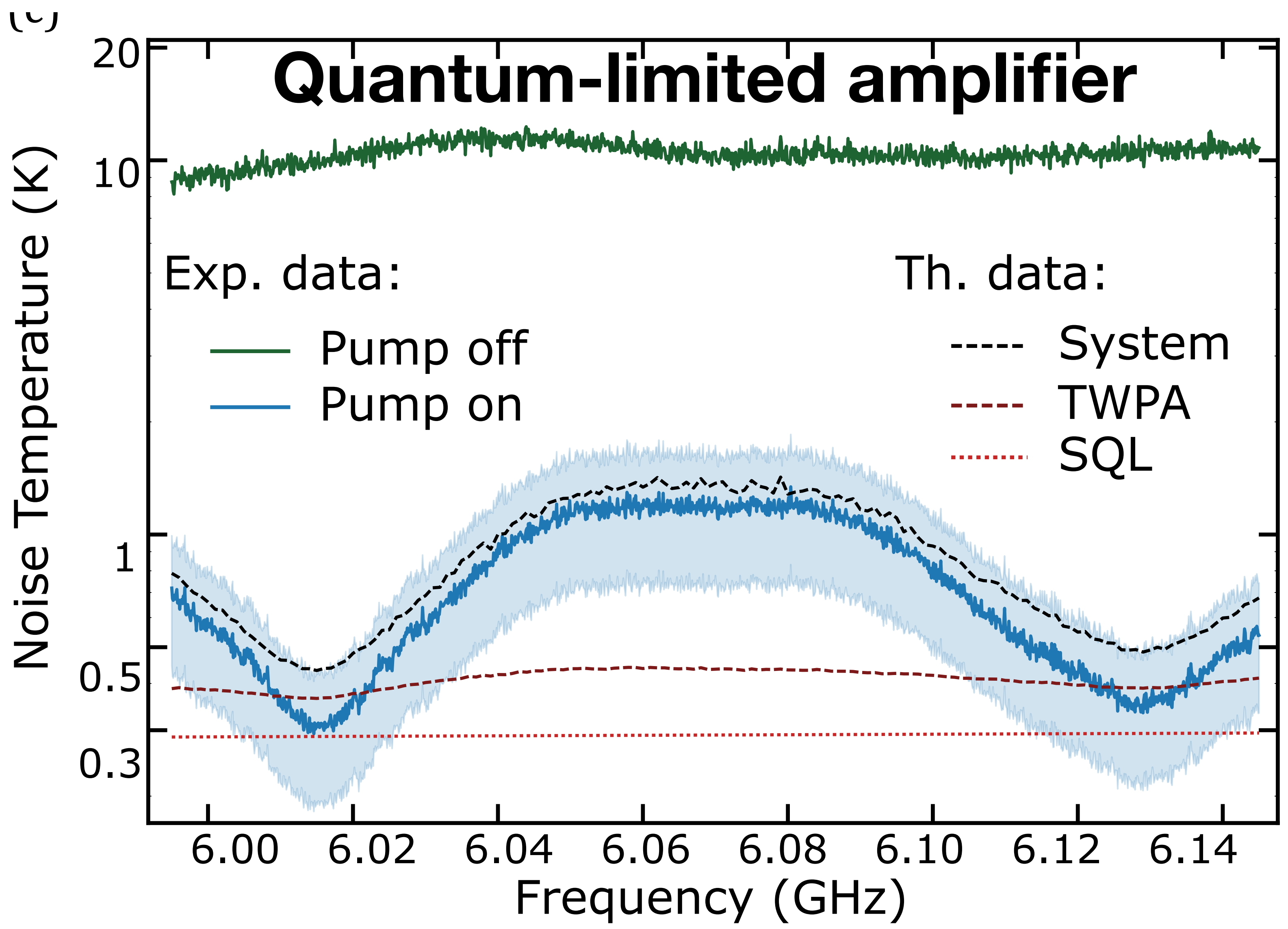


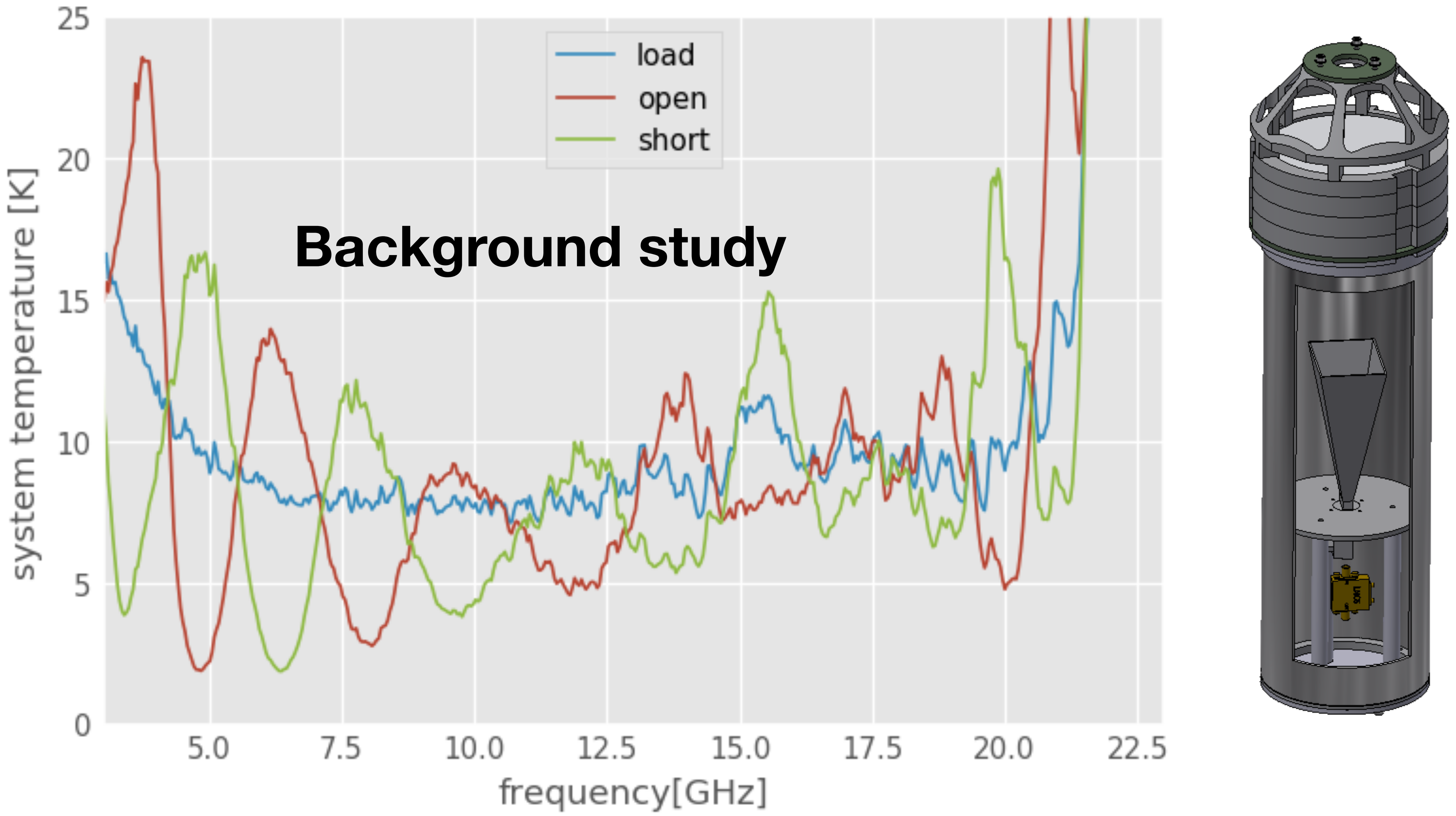

70-90 μeV in 90 days
CAST
MADMAX
prototype
ALPS–II
IAXO
20d30cm1.6T
BRASS
UF/RBF
HAYSTAC
KSVZ
DFZS
50-200 μeV
80d 1.2m 9T 8K
50 MHz, 8K, 3 yrs
20 MHz, 4K, 5 yrs
ADMX
MADMAX
5 σ, 50% efficiency assumed
Cavity
experiments
log $g_{a\gamma}[\mathrm{GeV}^{-1}]$
log $m_a[\mathrm{eV}]$
−10
−11
−12
−13
−14
−15
−16
−6
−5
−4
−3
−2

Prototype, $\Delta\nu_\beta \sim$ 50MHz (benchmark)



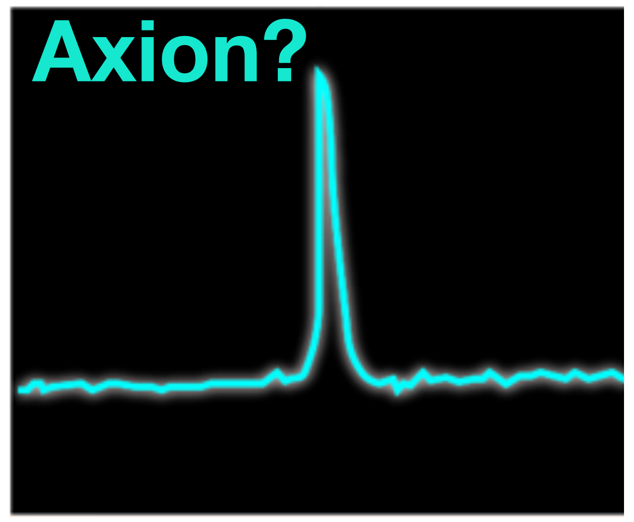






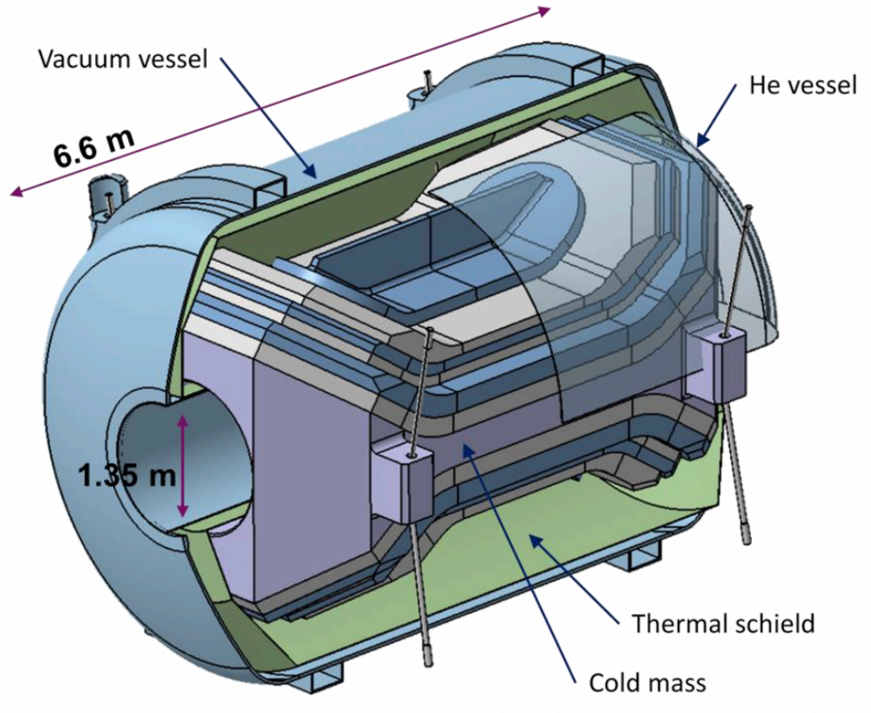
arXiv:1907.10158

Time line



1.6 T @ CERN

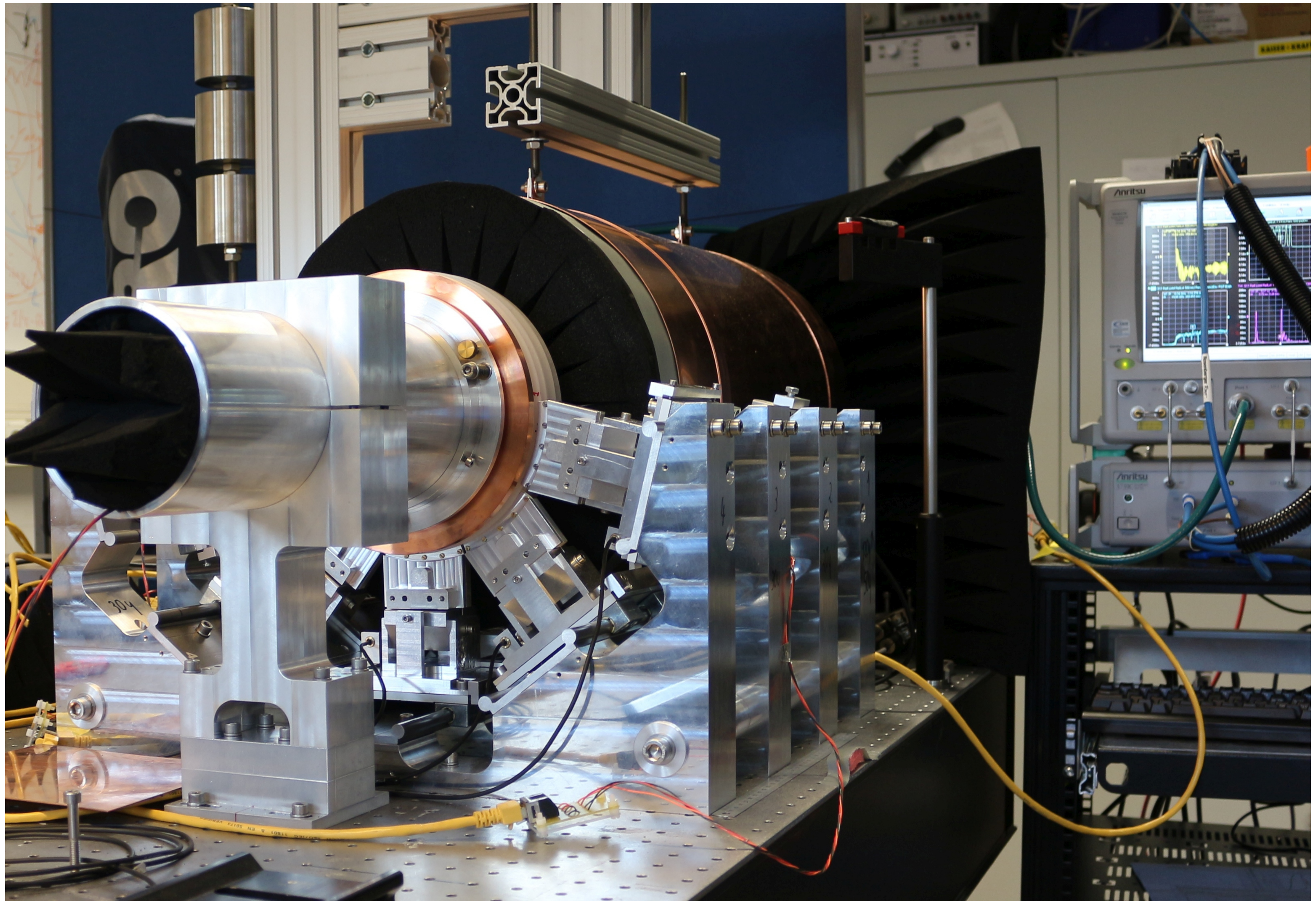
- 2020 Prototype design complete, begin fabrication
- 2021 CERN Morpurgo magnet available
- 2023 Full system design complete
- 2024 Prototype data taking
- 2025 Magnet delivered
- 2026 Full MADMAX starts



9 T @ DESY

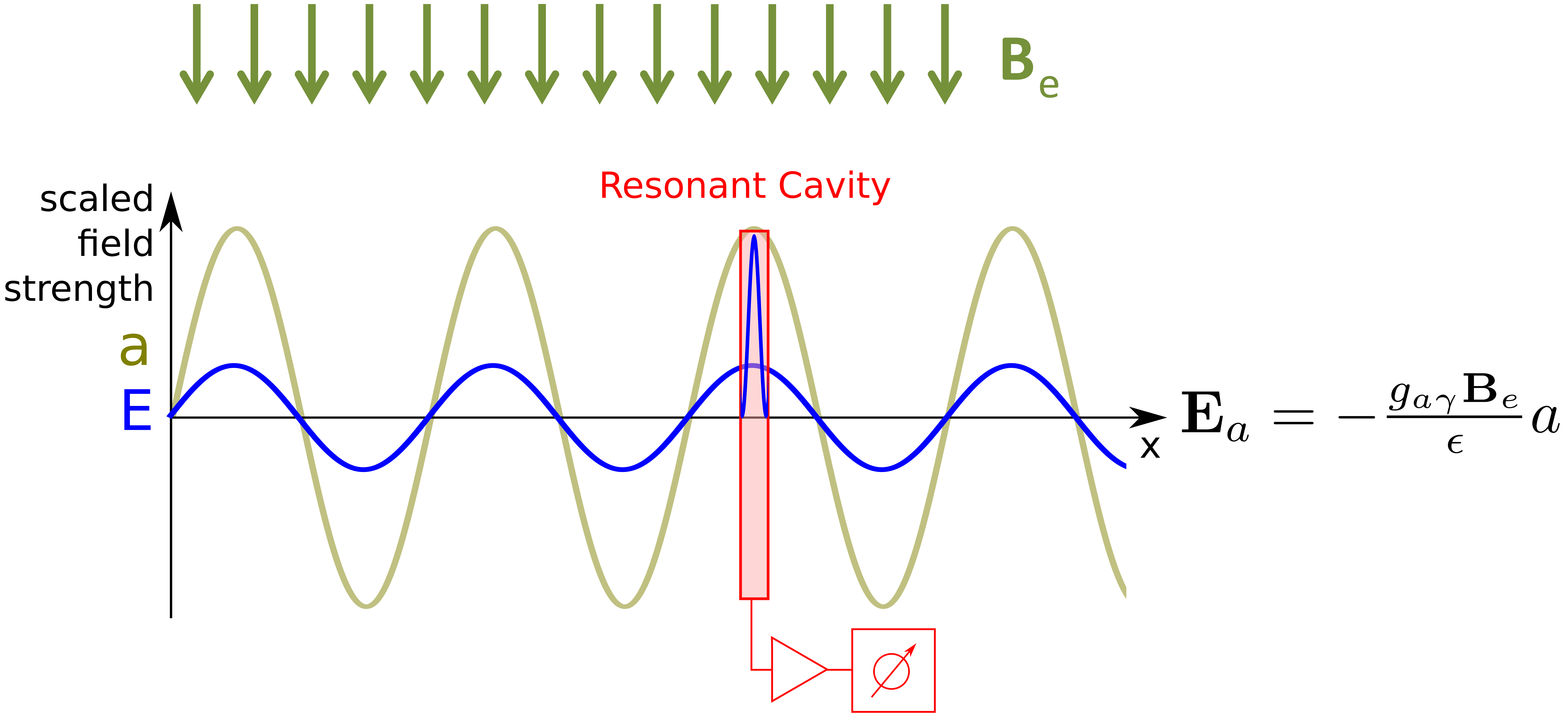
Conclusion

- Post-inflation axion around **100 μeV** is a well-motivated dark matter candidate.
- **Dielectric haloscope** is a promising technology.
- MADMAX experiment is developing.



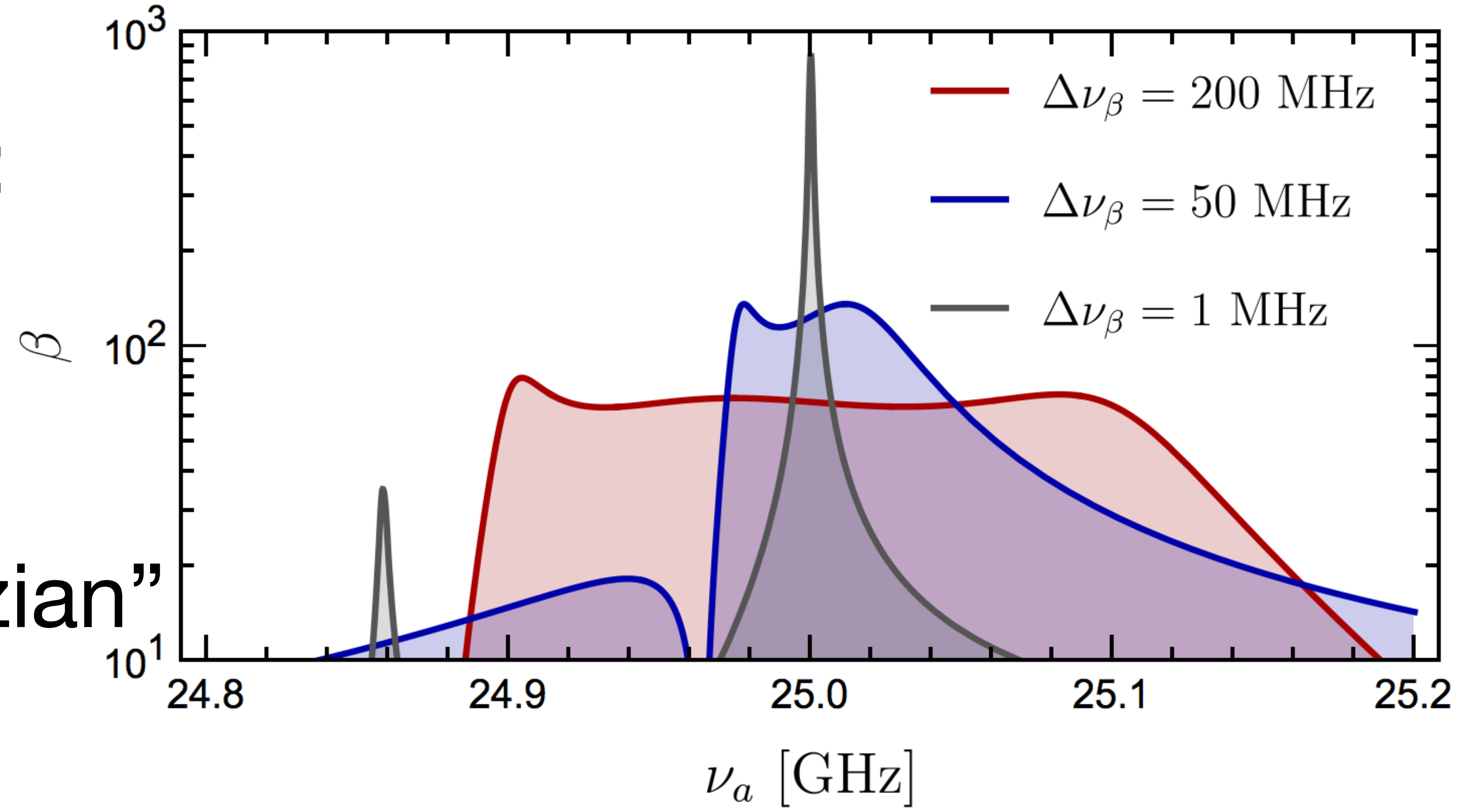
JCAP01 (2017) 061 PRL 118, 091801 (2017) EPJC (2019) 79:186


Thank you


$\mathbf{B}_e$
Resonant Cavity
scaled
field
strength
a
E
x
$\mathbf{E}_a = -\frac{g_{a\gamma}\mathbf{B}_e}{\epsilon}a$

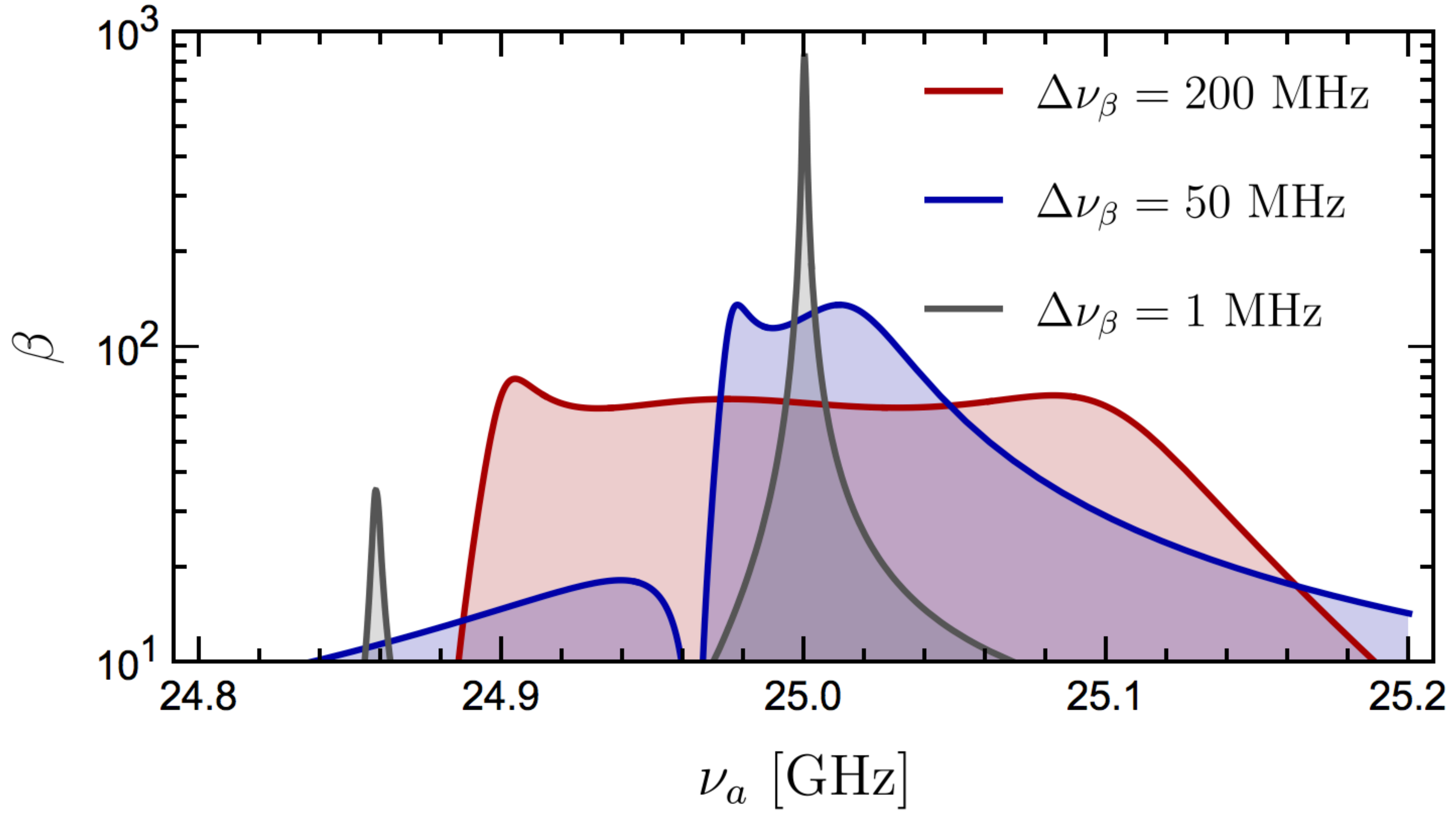
Broadband advantages

- "Resonant" setup is possible, but **not practical.**
- Broadband benefits include
  - Easier & less frequent tuning
  - Scan multiple channels: ~3,000 m_a channels
  - "Box-shape" more optimized than "Lorentzian"



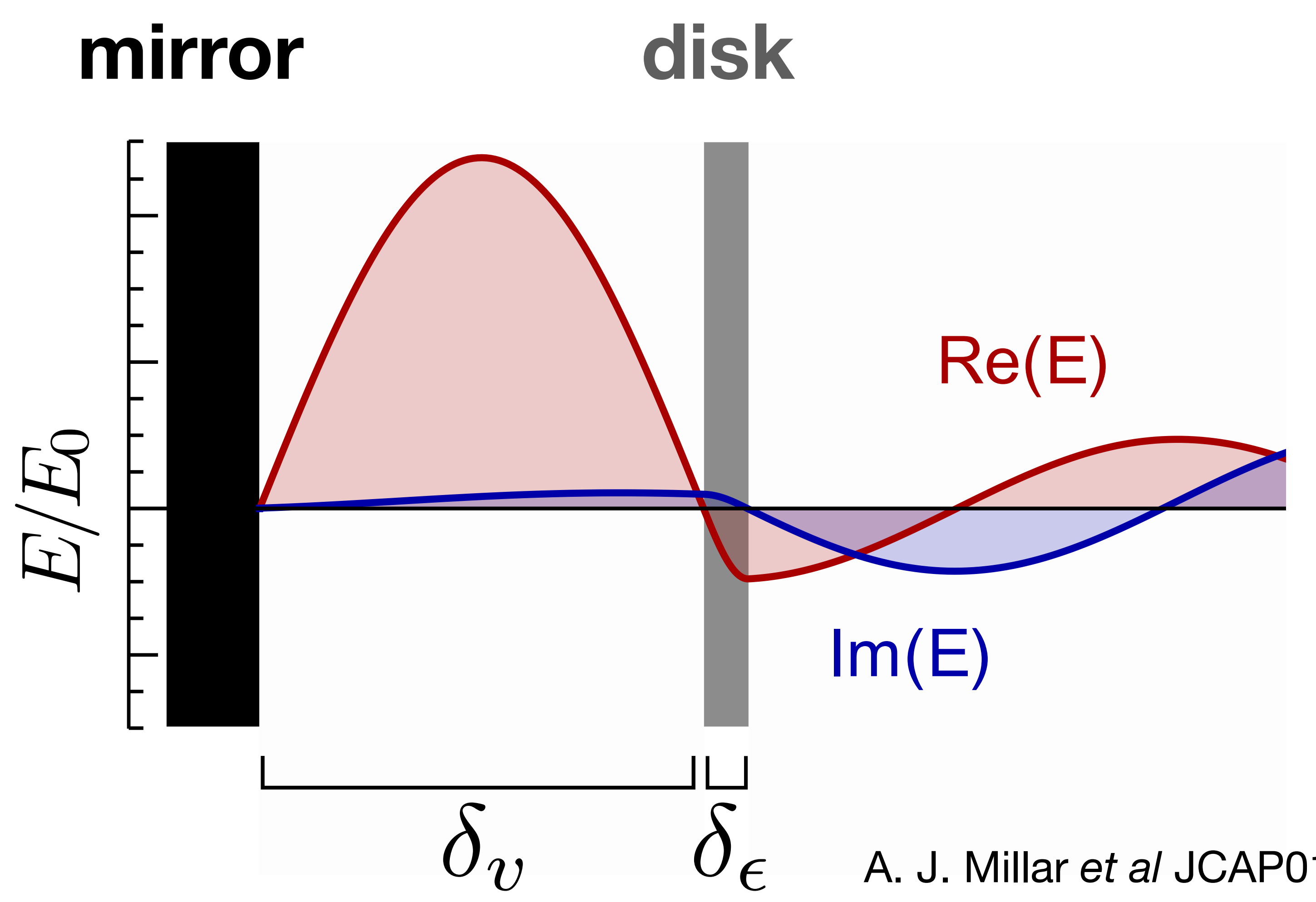
Broadband advantages

- Broadband boost factor tolerates more
  - Mechanical precision: $\delta d \propto \frac{\lambda}{Q}$.
  - ambient vibration
  - ε variation
  - Loss inside material & setup

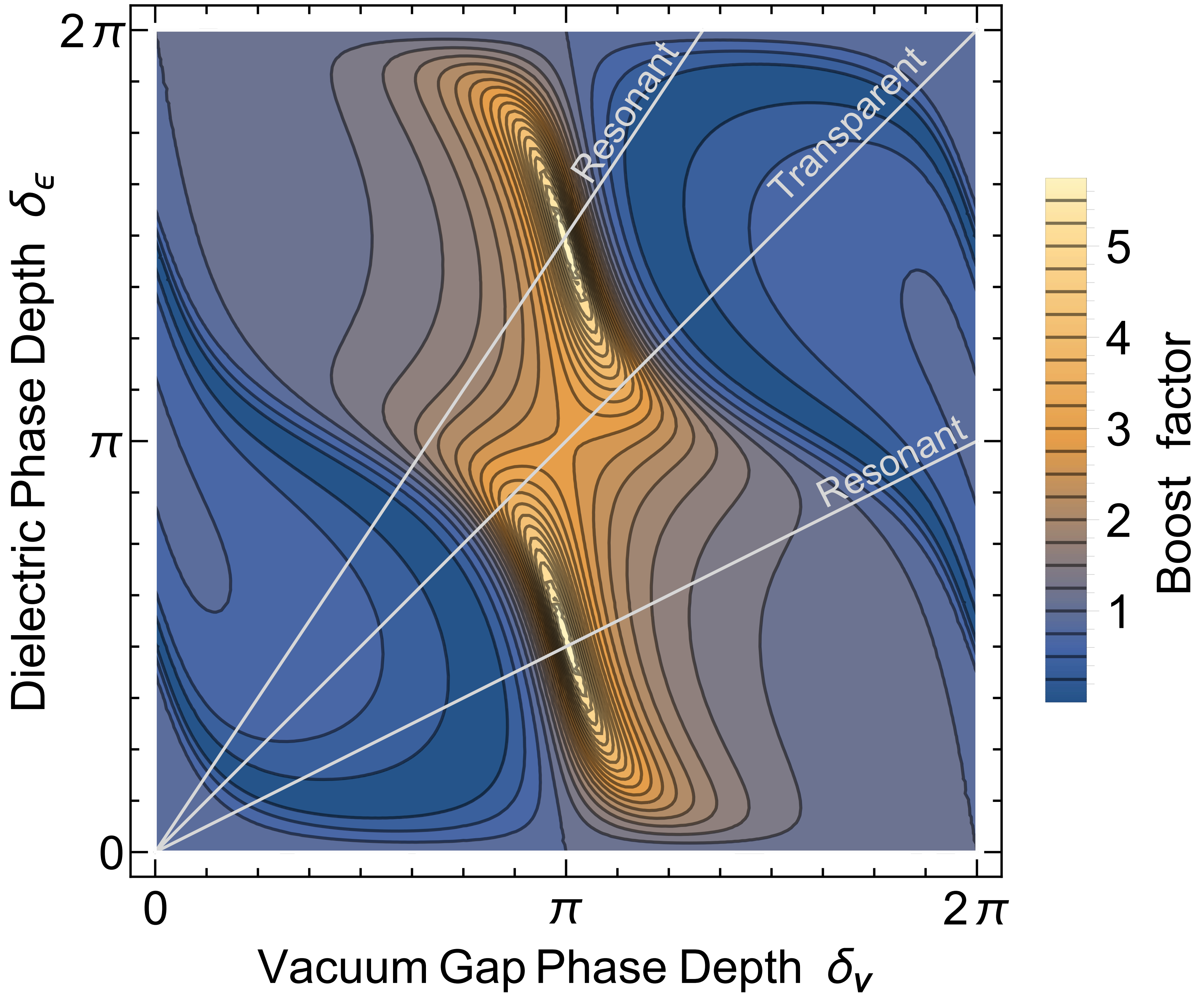


Boost

- Disks + mirror **boosts** signal by $\beta = E / E_0$
- Transparent mode: $\delta = n \times d \times \nu = \pi, 3\pi, 5\pi\ldots$ constructive interference.
- Resonant mode: $\delta = \pi/2, 3\pi/2, \ldots$ disks + mirror forms a leaky resonator.
- Combined boost from both contributions.



A. J. Millar *et al* JCAP01(2017)061



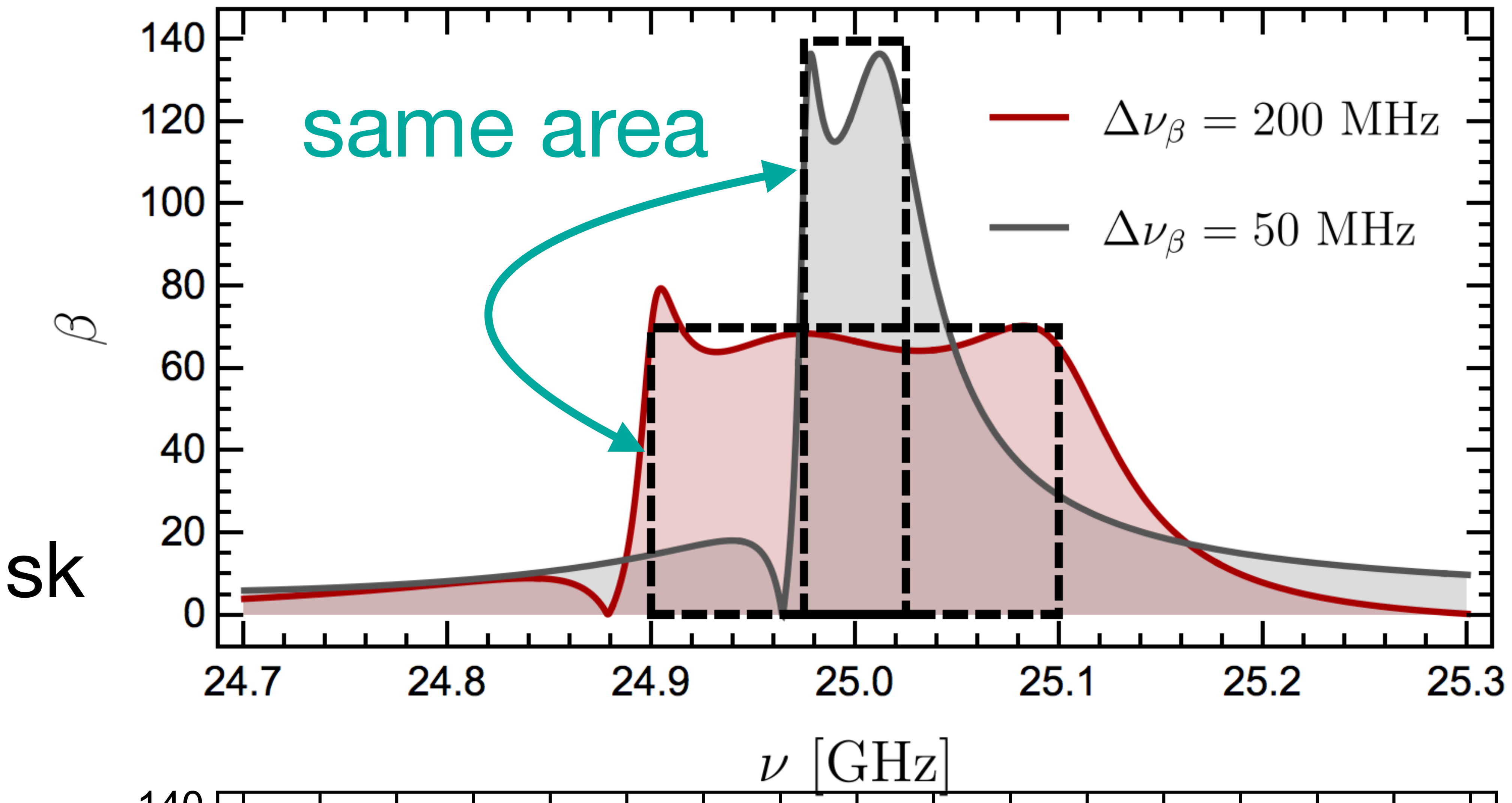
Scan strategy

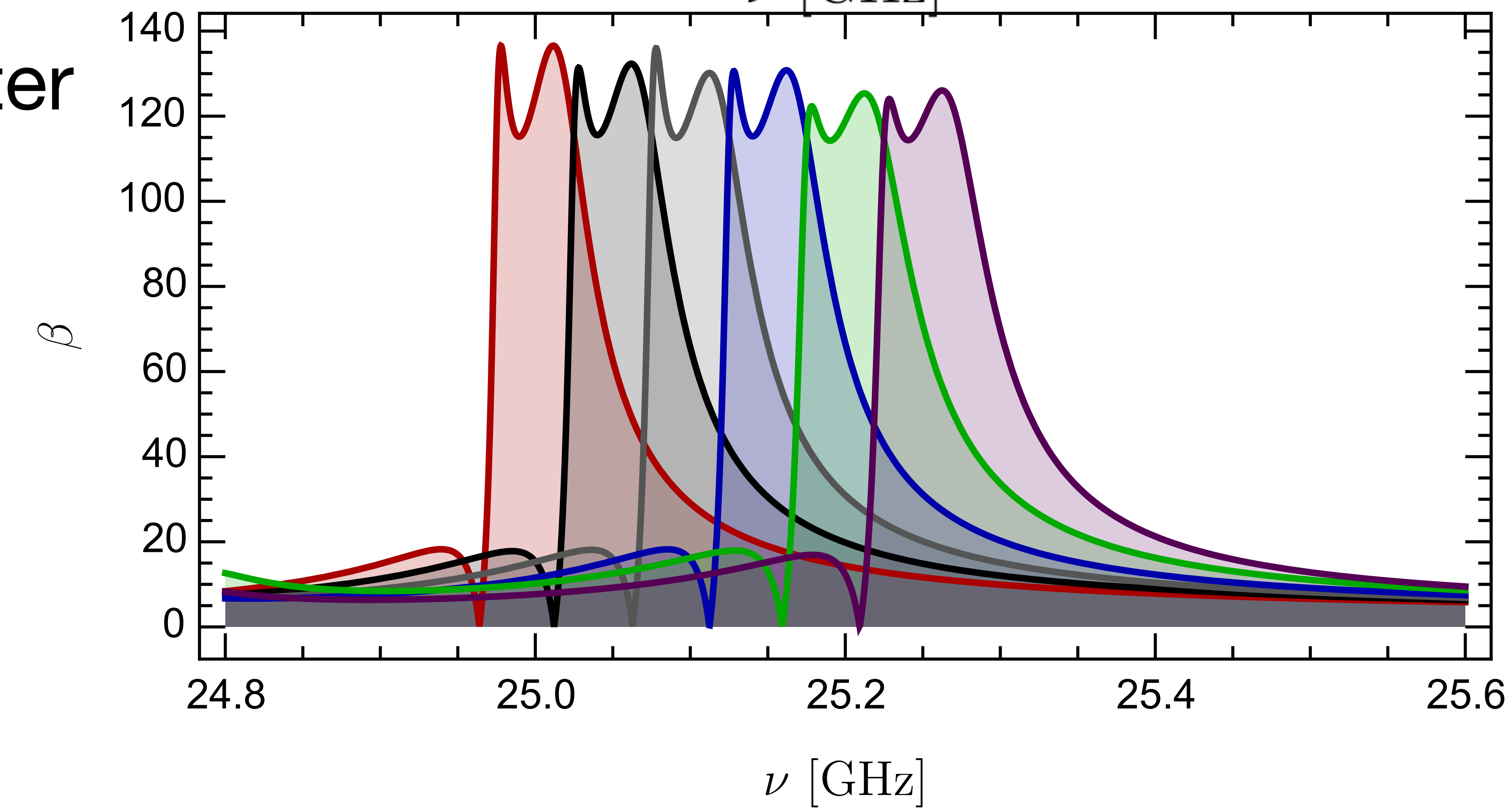
- Scan speed
  $$\frac{t_{scan}}{\Delta\nu} = \left(\frac{S}{N}\right)^2 \left(\frac{k_B T_{sys}}{P_{sig}}\right)^2$$

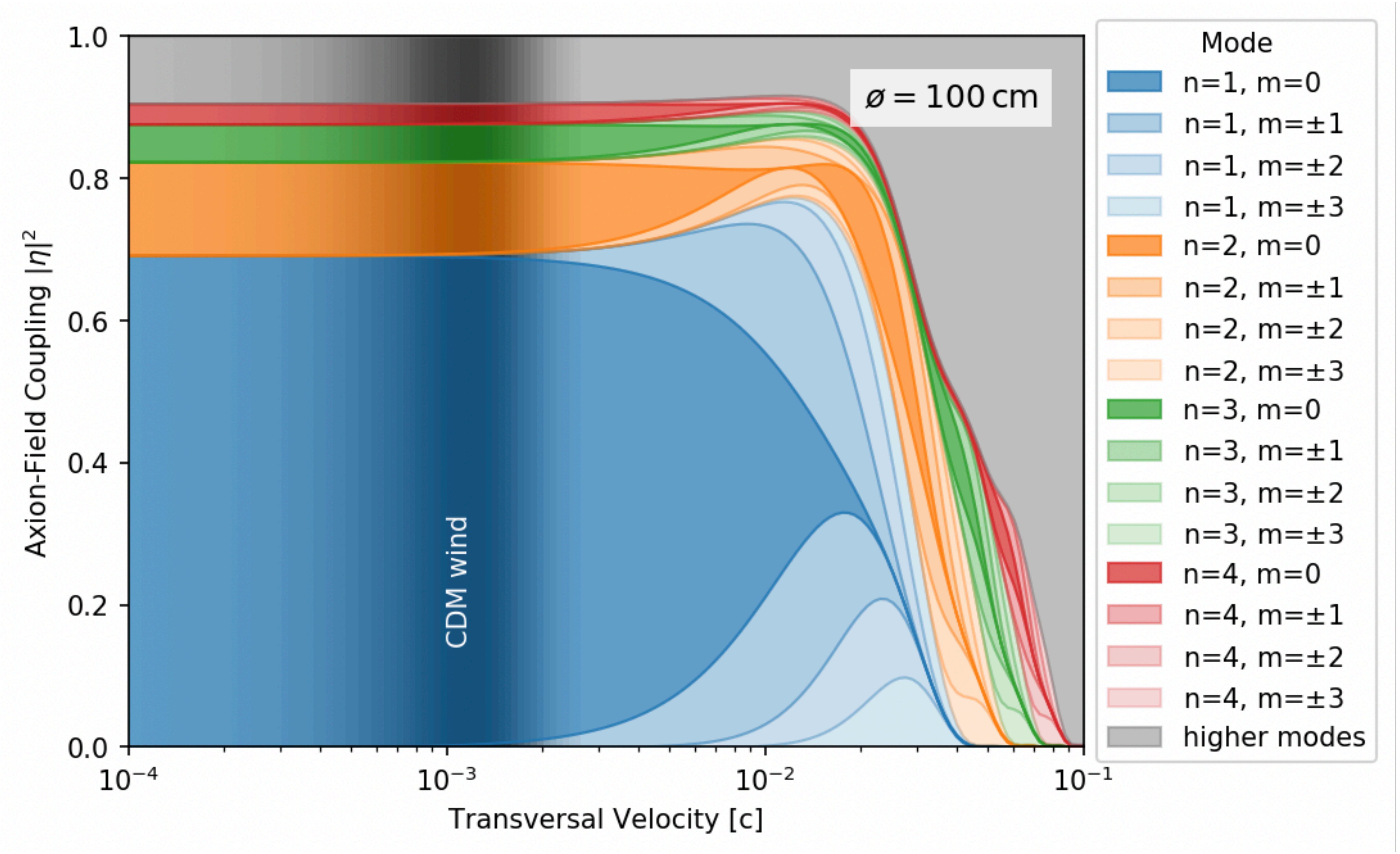
- However, **Area Law:**
  P_{sig} x $\Delta\nu$ is independent of disk spacings.

  - Narrower peak leads to faster scan.

- In practice, tuning time is significant
  $\mathbf{t_{tot\_adj} \approx t_{tot\_scan}}$.



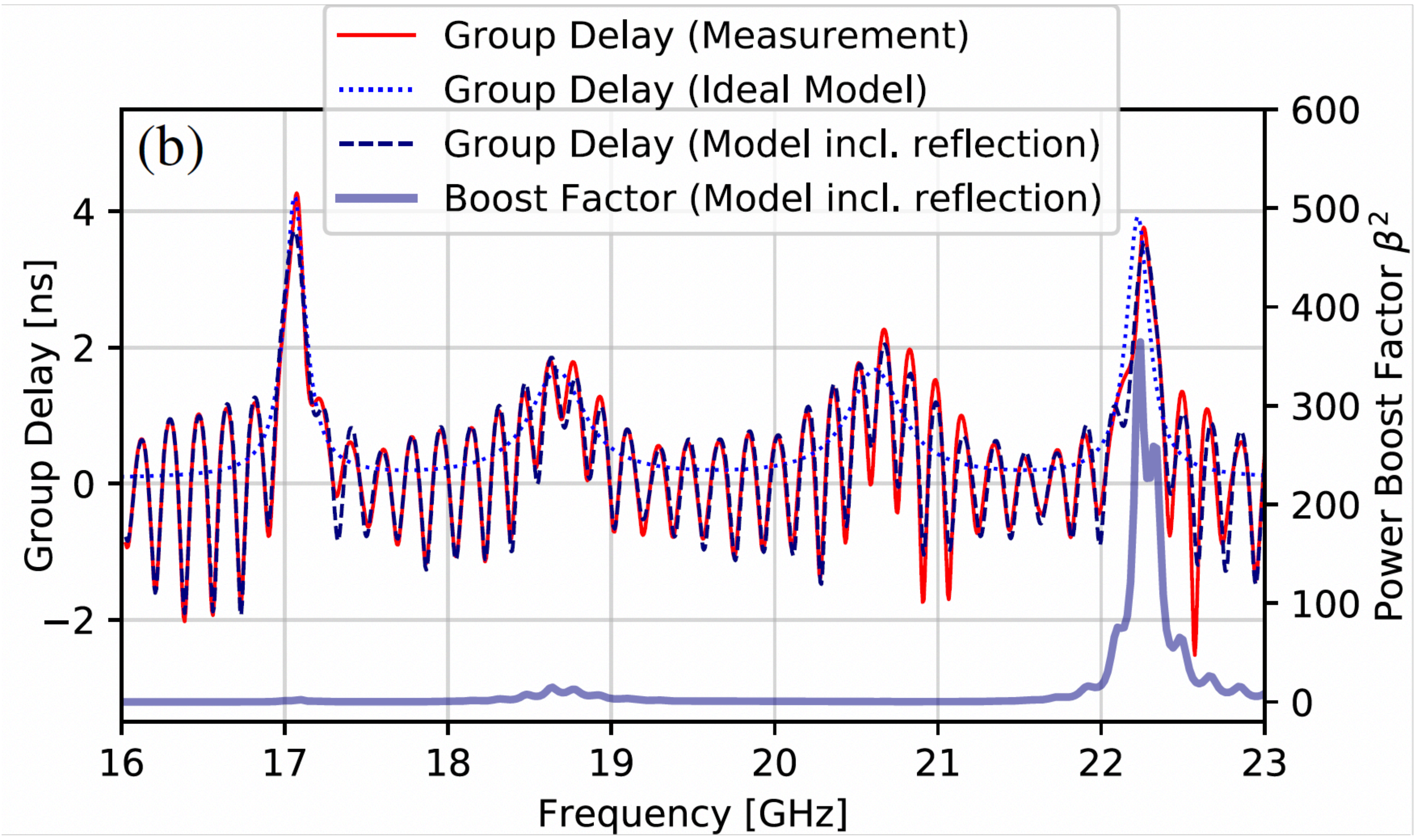




Mode
n=1, m=0
n=1, m=±1
n=1, m=±2
n=1, m=±3
n=2, m=0
n=2, m=±1
n=2, m=±2
n=2, m=±3
n=3, m=0
n=3, m=±1
n=3, m=±2
n=3, m=±3
n=4, m=0
n=4, m=±1
n=4, m=±2
n=4, m=±3
higher modes
ø = 100 cm
CDM wind
Axion-Field Coupling |η|²
Transversal Velocity [c]
1.0
0.8
0.6
0.4
0.2
0.0
10⁻⁴
10⁻³
10⁻²
10⁻¹

Disk positioning

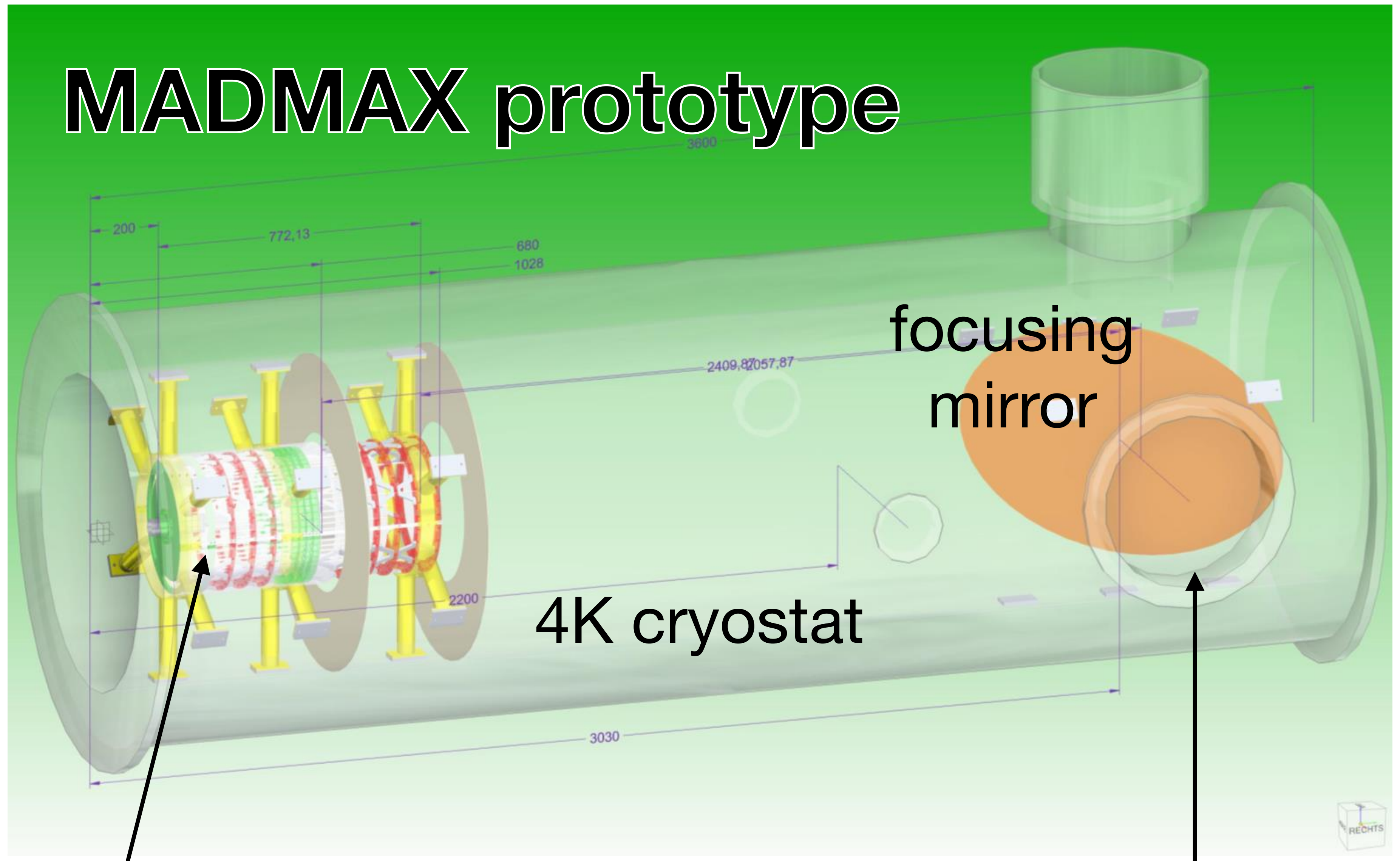
1. Bring the disks to approximate position.
2. Measure the group delay.
3. Compare 2 with the desired (simulated) group delay.
4. Minimization algorithms suggest the next moves.
5. Move the disks. Repeat 2-5.
6. Stop if the move is less than 1μm .



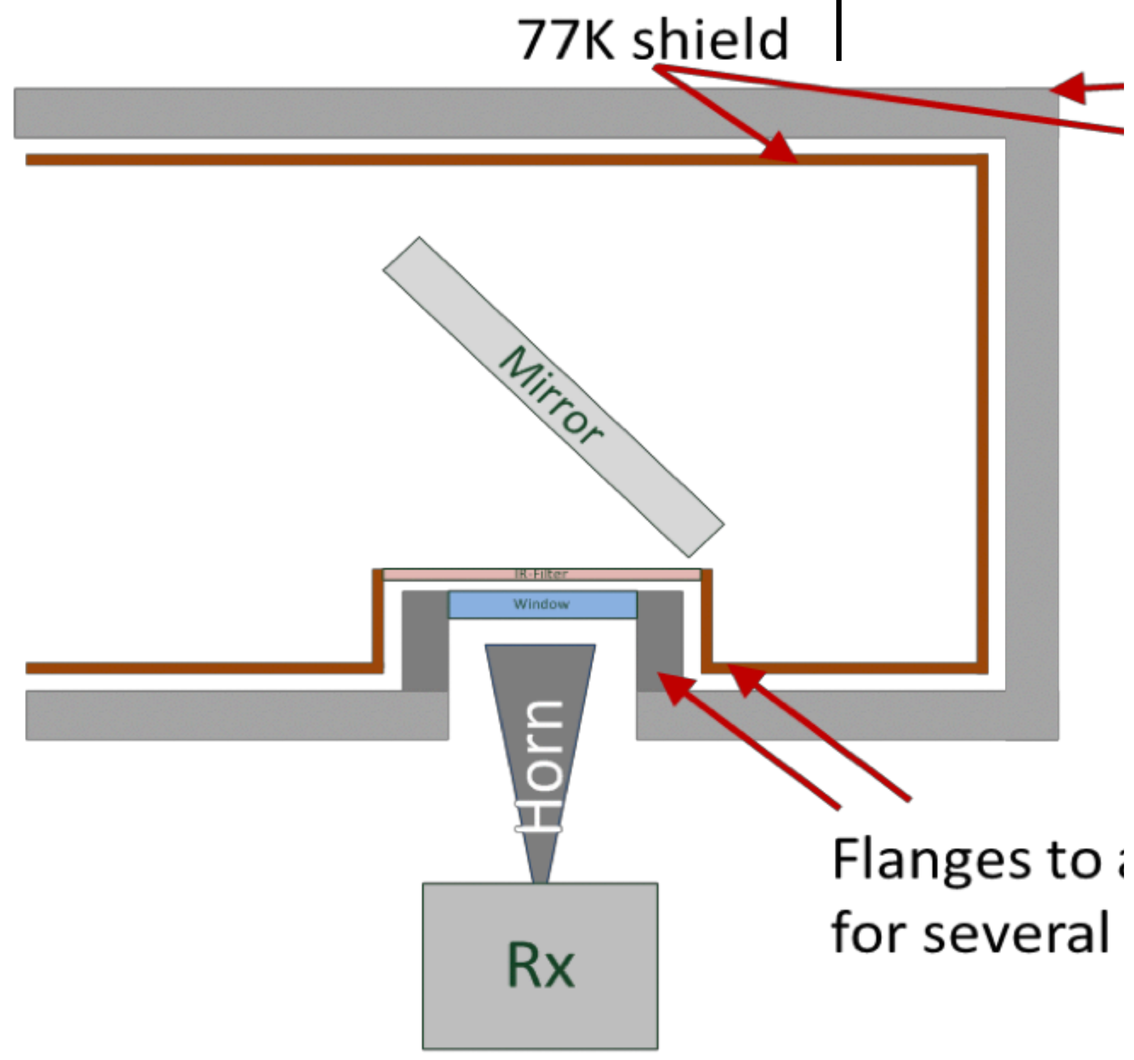
~10 min, mostly computation

More accurate than independent measurements

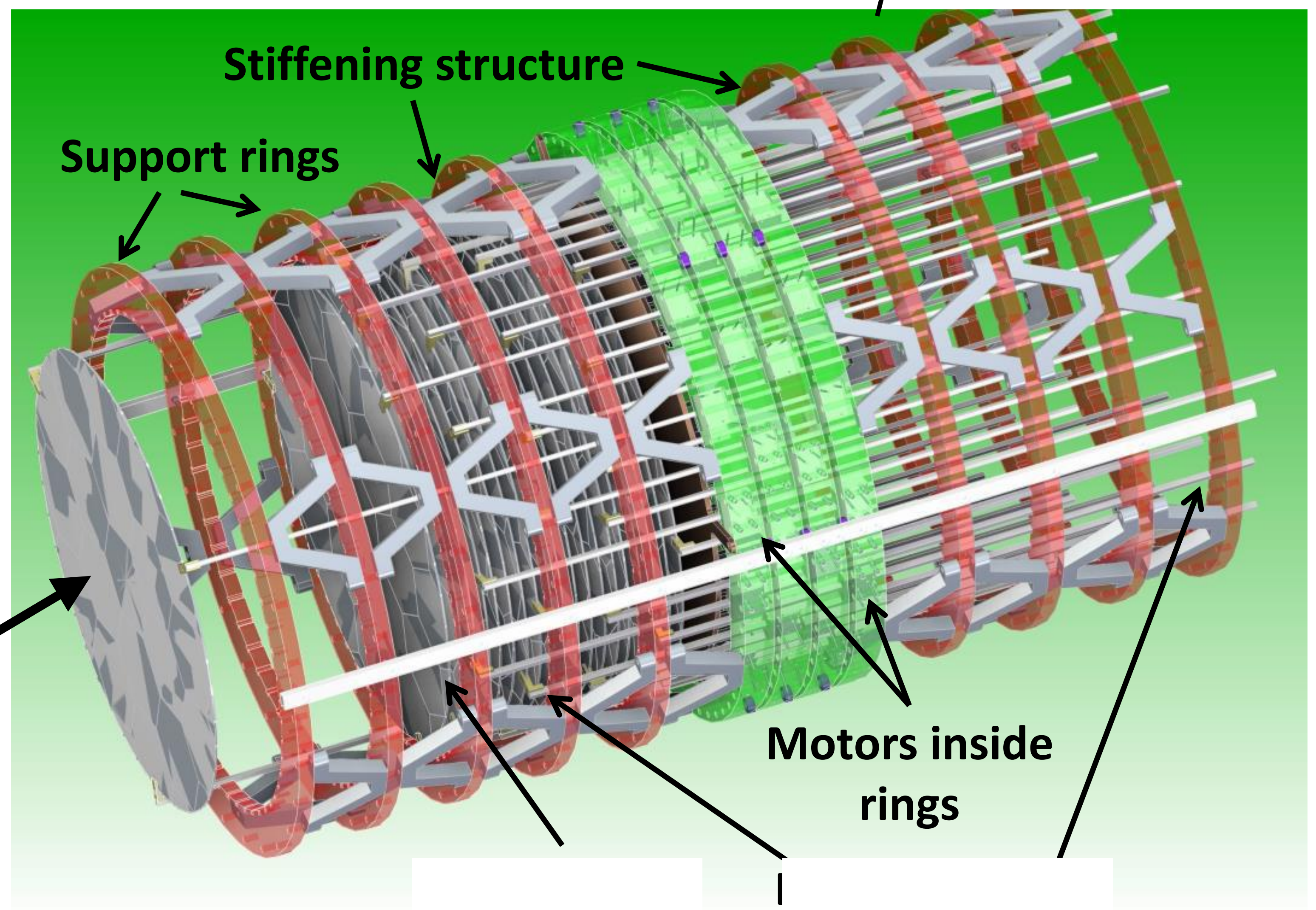
- Technological test platform
- 4 K, 1.6 T field
- ALP search ~80 μeV (10^{-12})
- LOI handed in to CERN



Receiver window

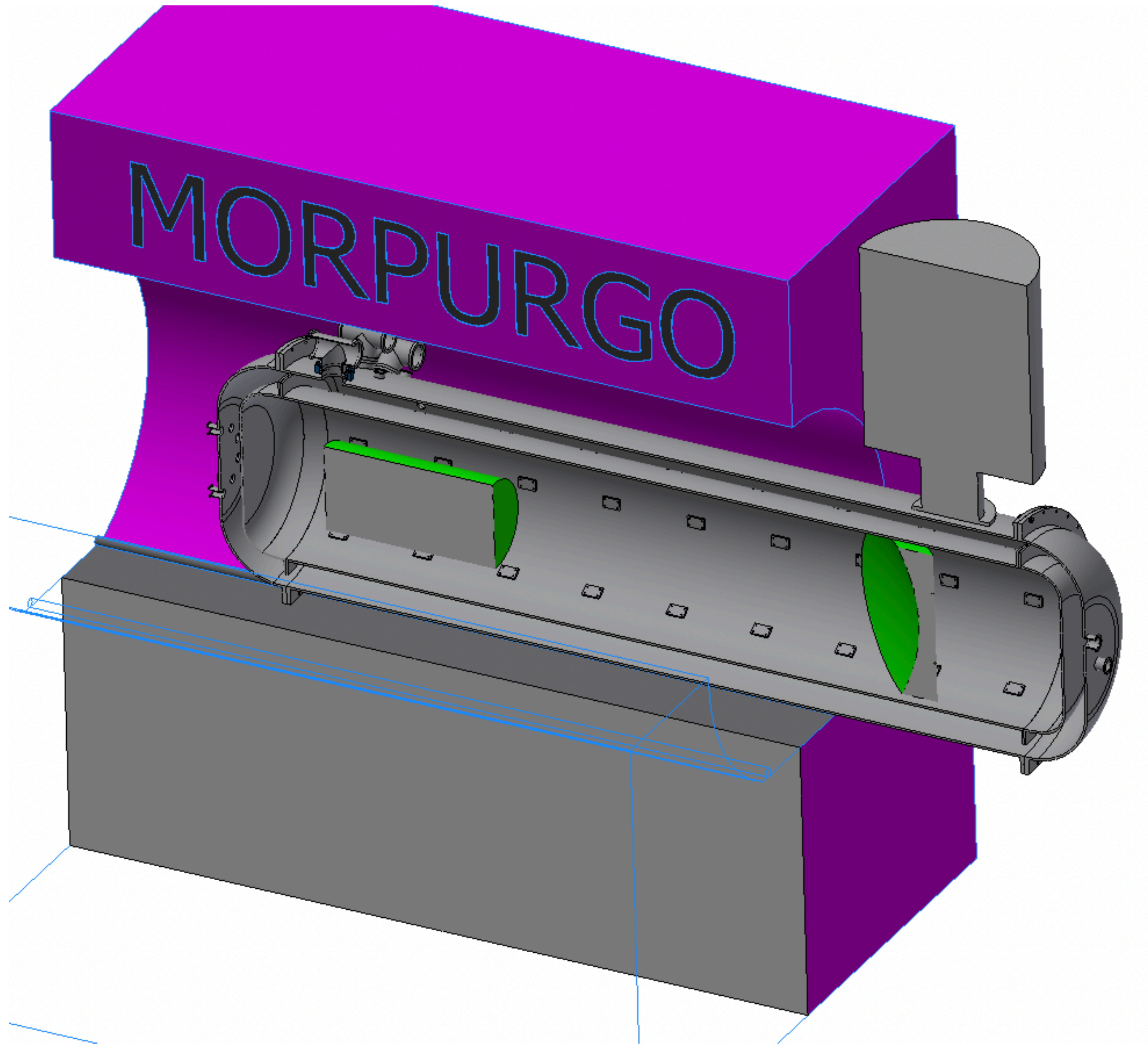


Dielectric Haloscope: 20 x ϕ30-cm sapphire disks



Prototype Magnet

- Morpurgo magnet @ CERN
- 1.6 T dipole, 1.6-m warm bore (1.45m usuable)
- Available after SPS winter shutdown from Dec. 2021 to Mar. 2022 and Dec. 2022 to Mar 2023.



Disks

- High ε, low tanδ
  Current best: $LnAlO_3$ (ε ~ 23.4)
- Single crystals have lowest tanδ, but diameter < 3 inches → tiling??
- Discontinuous ε significantly distorts the beam shape & boost factor.
- Polycrystalline $LnAlO_3$ has a higher tanδ, and can be casted.
- SiO_2 will be the default for the prototype detector