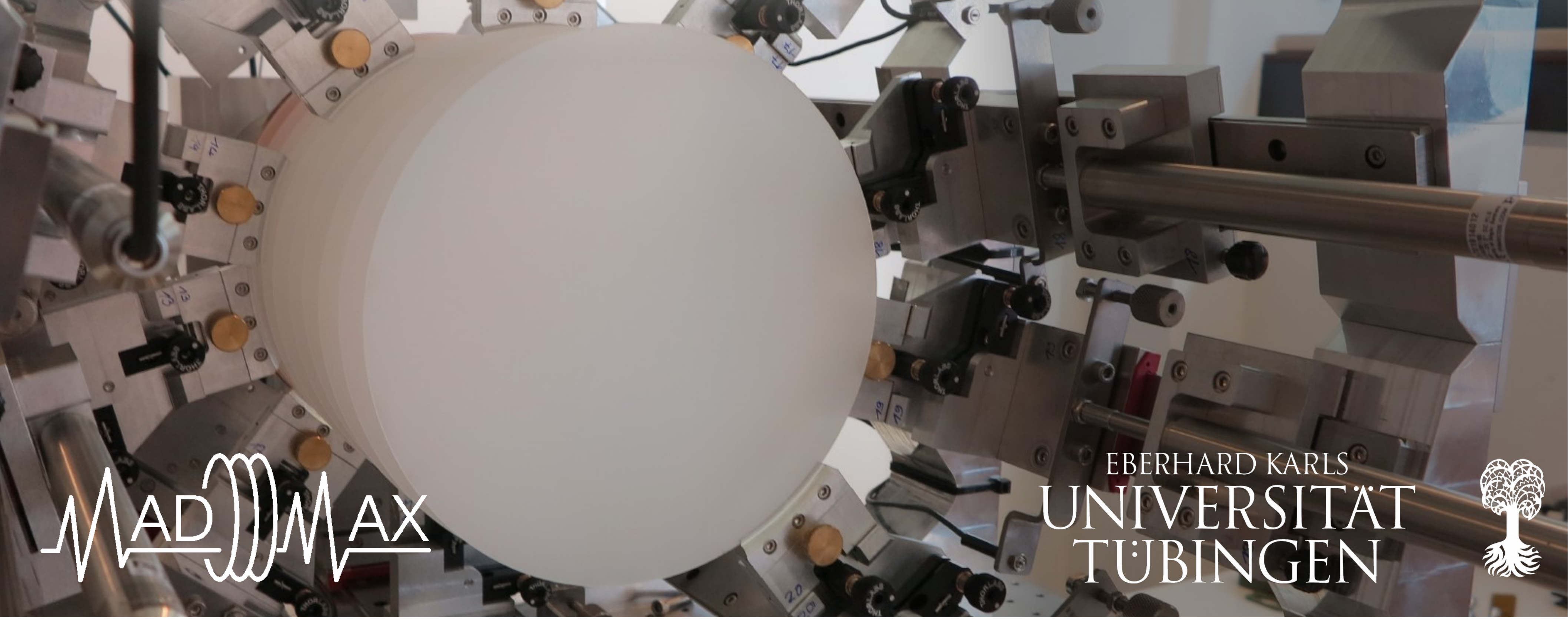

MADMAX

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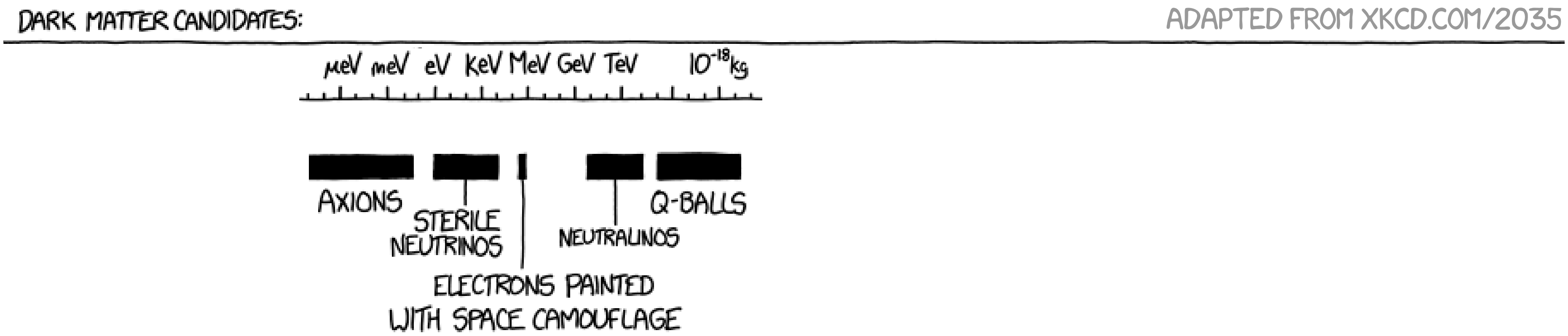
Search for Dark Matter Axions with MADMAX

Dark Side of the Universe, Buenos Aires 15-19/07/19

Christian Strandhagen

Dark Matter Candidates



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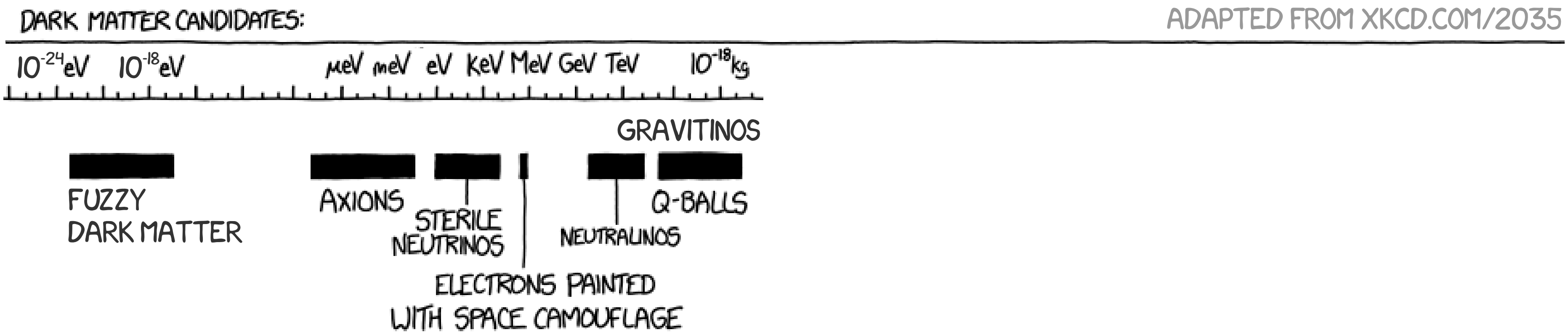

ADAPTED FROM XKCD.COM/2035

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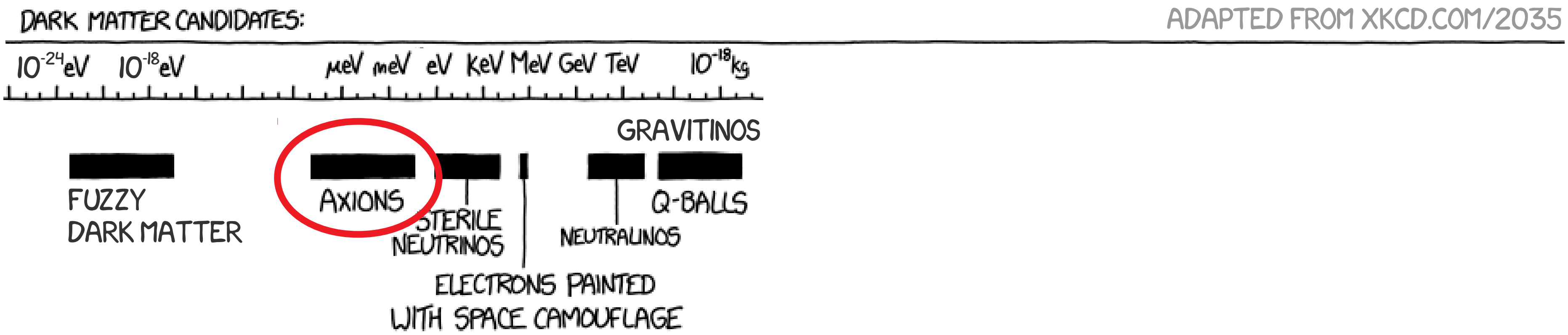

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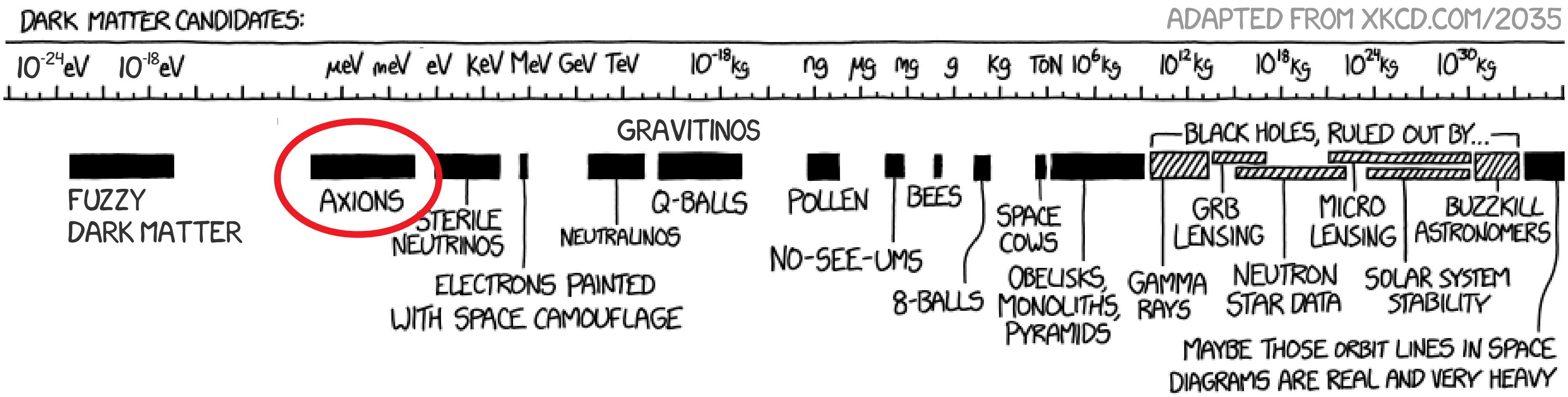



AXION
Castrol EDGE
Castrol EDGE
selú
Tiffany
ANTEPRIMA

The QCD Axion

The QCD Lagrangian contains a **CP-violating** term

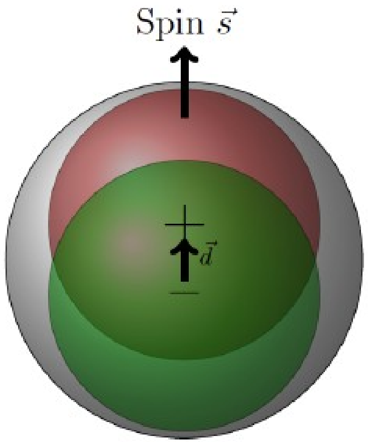
$$\mathcal{L}_{QCD} = \ldots + \frac{\alpha_S}{8\pi}\bar{\theta} G_{\mu\nu a}\tilde{G}^{\mu\nu}_{a}, \bar{\theta} = \theta_{QCD} + \theta_{Yukawa} \in [-\pi, \pi] \sim \mathcal{O}(1)$$

→ violates **T** and **P** and thus **CP**

→ induces **electric dipole moment** (EDM) of neutron $d \sim \bar{\theta} \cdot 10^{-16} e\mathrm{cm}$

experimentally:

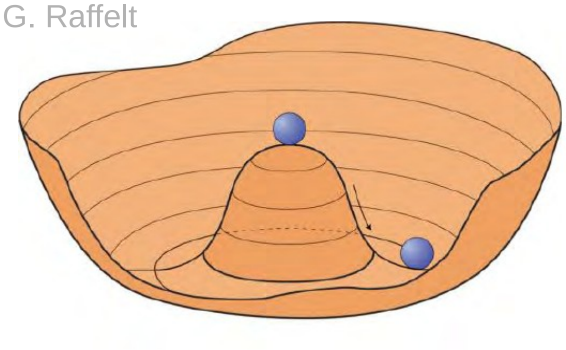
$d < 10^{-26} e\mathrm{cm} \rightarrow \bar{\theta} < 10^{-10}$

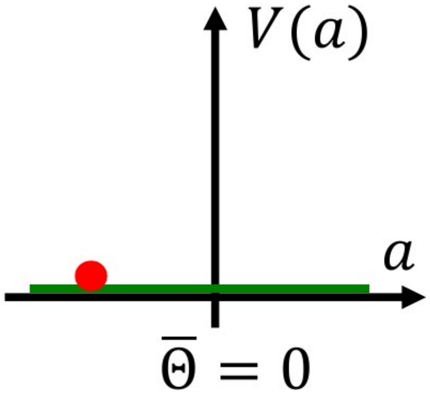


Why is θ so small? → **Strong CP problem**

The QCD Axion

The solution: make θ a dynamical parameter by introducing a scalar field by adding a new $U(1)_{PQ}$ symmetry (Peccei-Quinn)


G. Raffelt



$U(1)_{PQ}$ spontaneously broken at high energy scale f_a

θ minimum is degenerate → arbitrary value chosen

The QCD Axion

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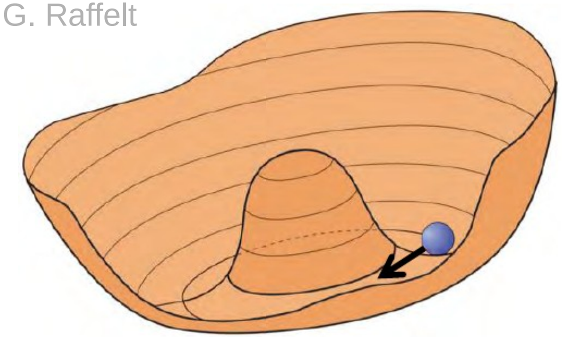
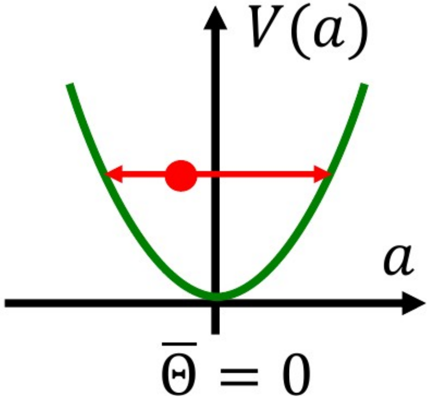
G. Raffelt





potential gets tilted during
QCD phase transition (T < 1 GeV)

field starts oscillating
→ axion acquires mass

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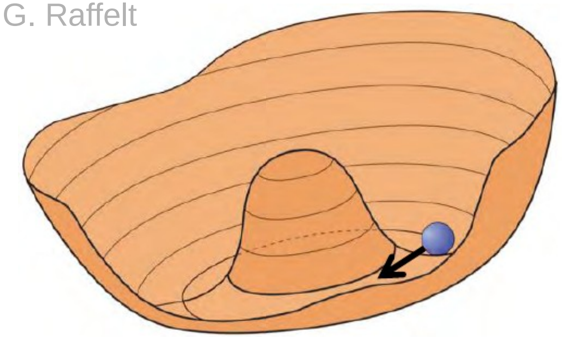
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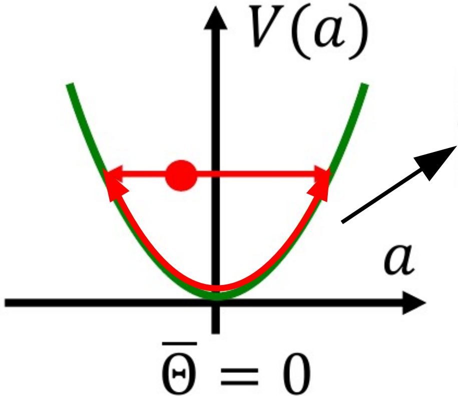


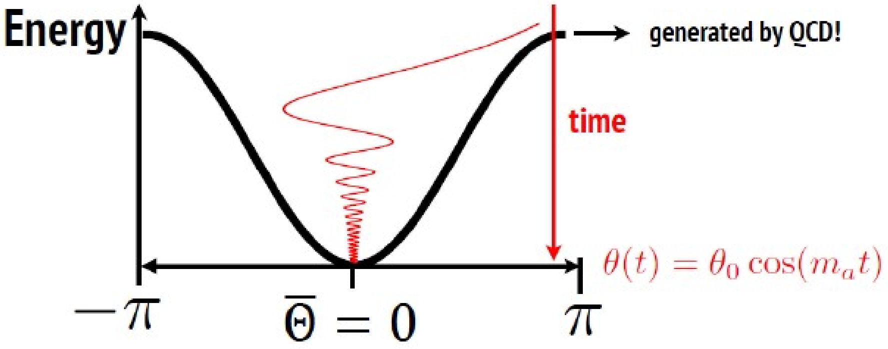
$$m_a \approx 6\mu eV \left(\frac{10^{12}\mathrm{GeV}}{f_a}\right)$$

potential gets tilted during QCD phase transition (T < 1 GeV)

field starts oscillating
→ axion acquires mass

QCD Axion Dark Matter

Axions created in early universe through **initial misalignment** are good candidate for **cold dark matter**



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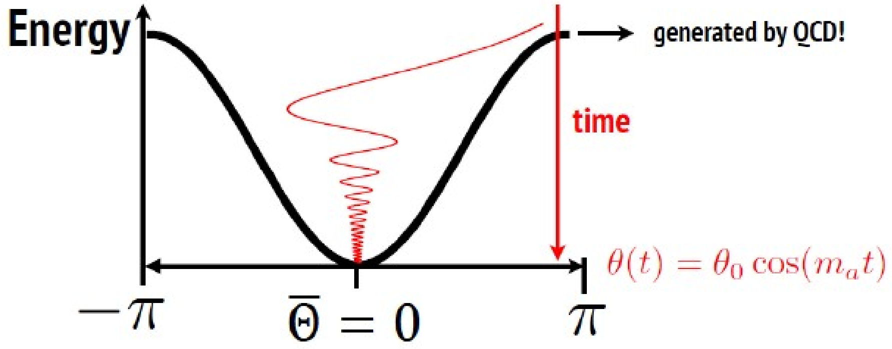

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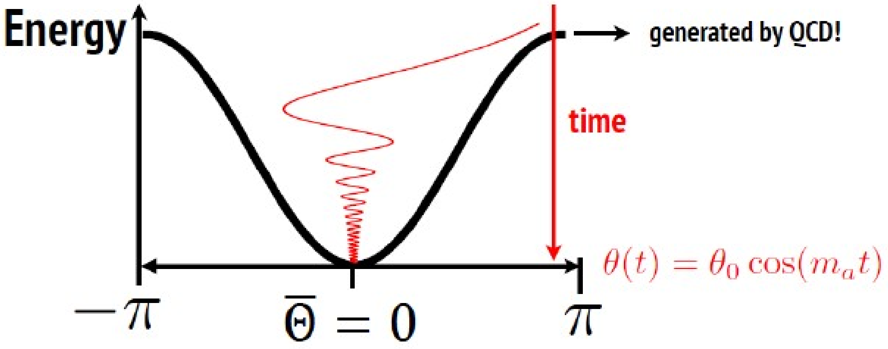

astrophysical bounds

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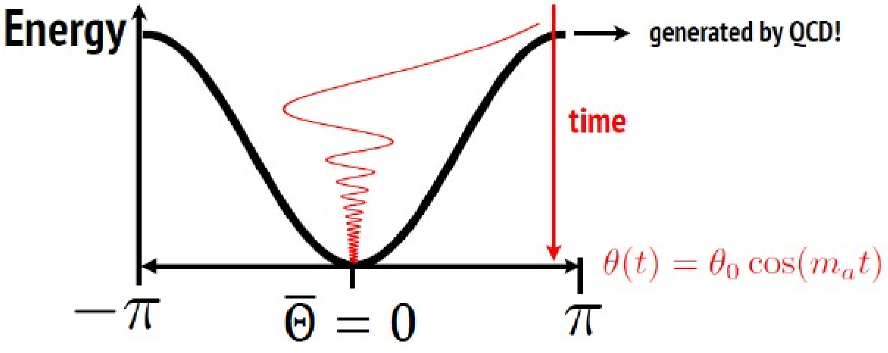

too much dark matter*

astrophysical bounds

*depends on the actual cosmology

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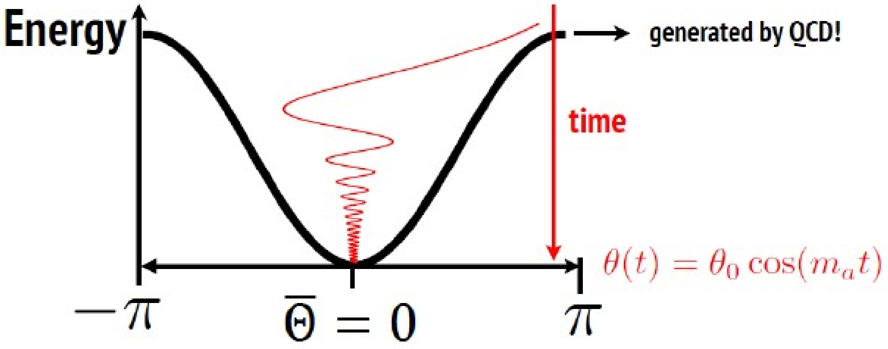

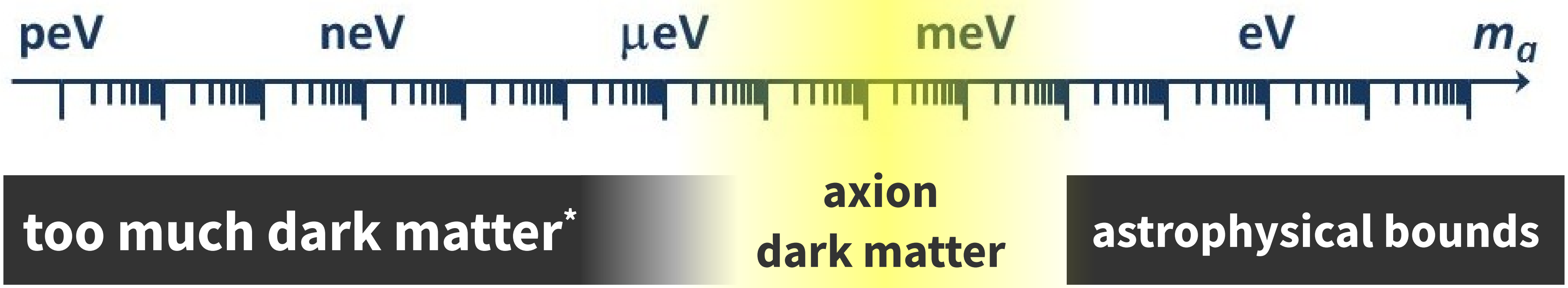

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axion dark matter

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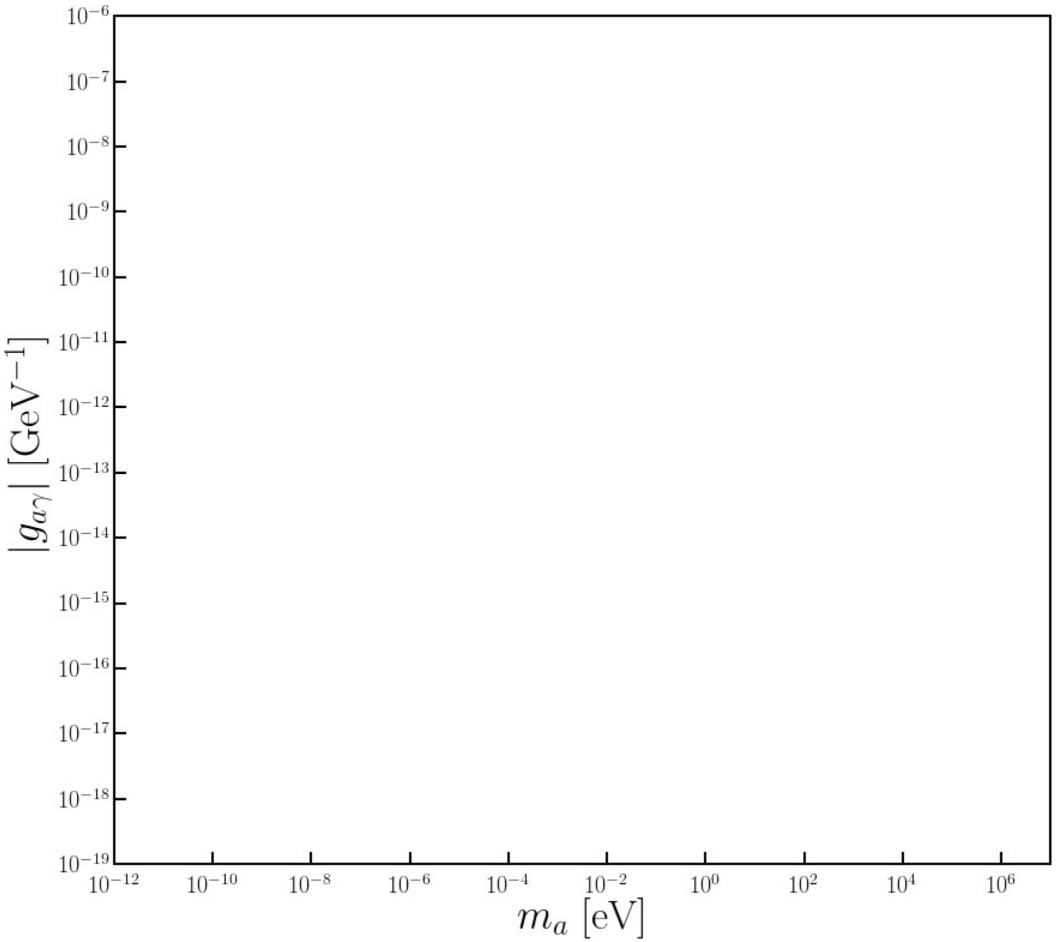
Axion Landscape

coupling strength (to photons)



github.com/cajohare/AxionLimits

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Axion Landscape

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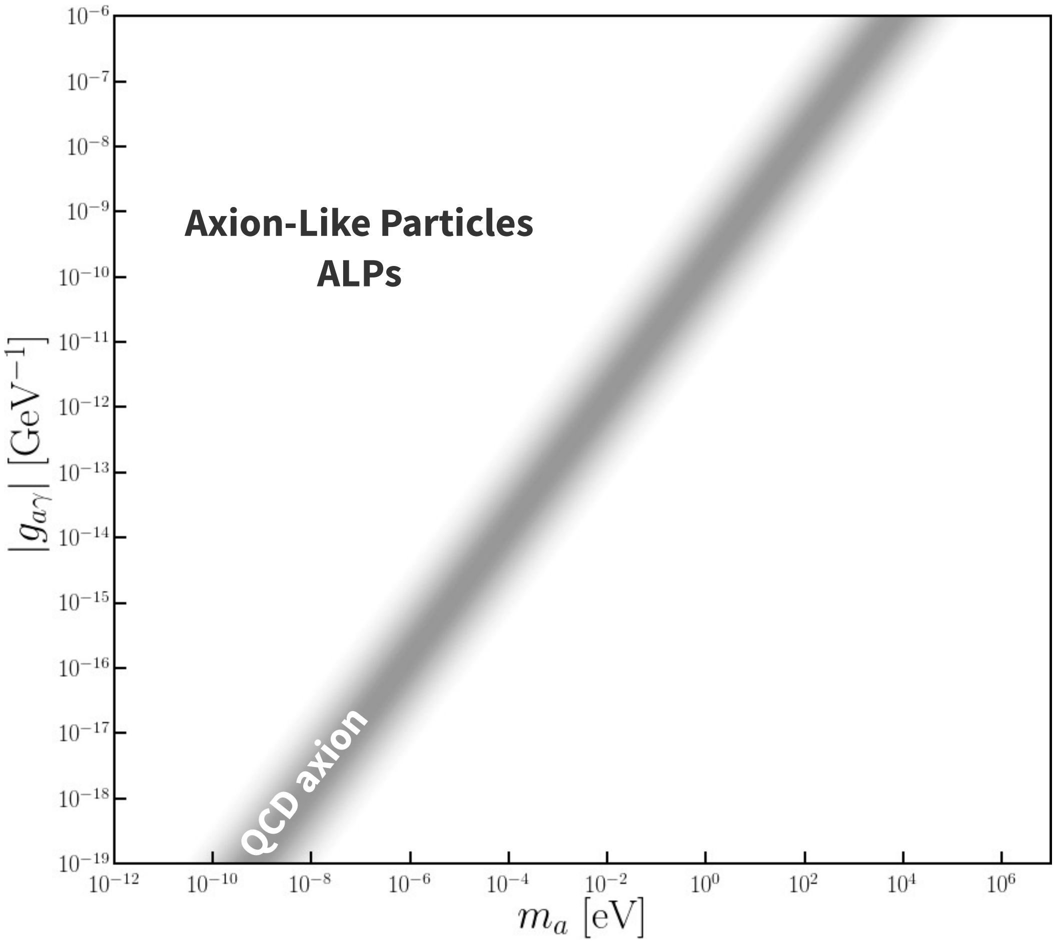

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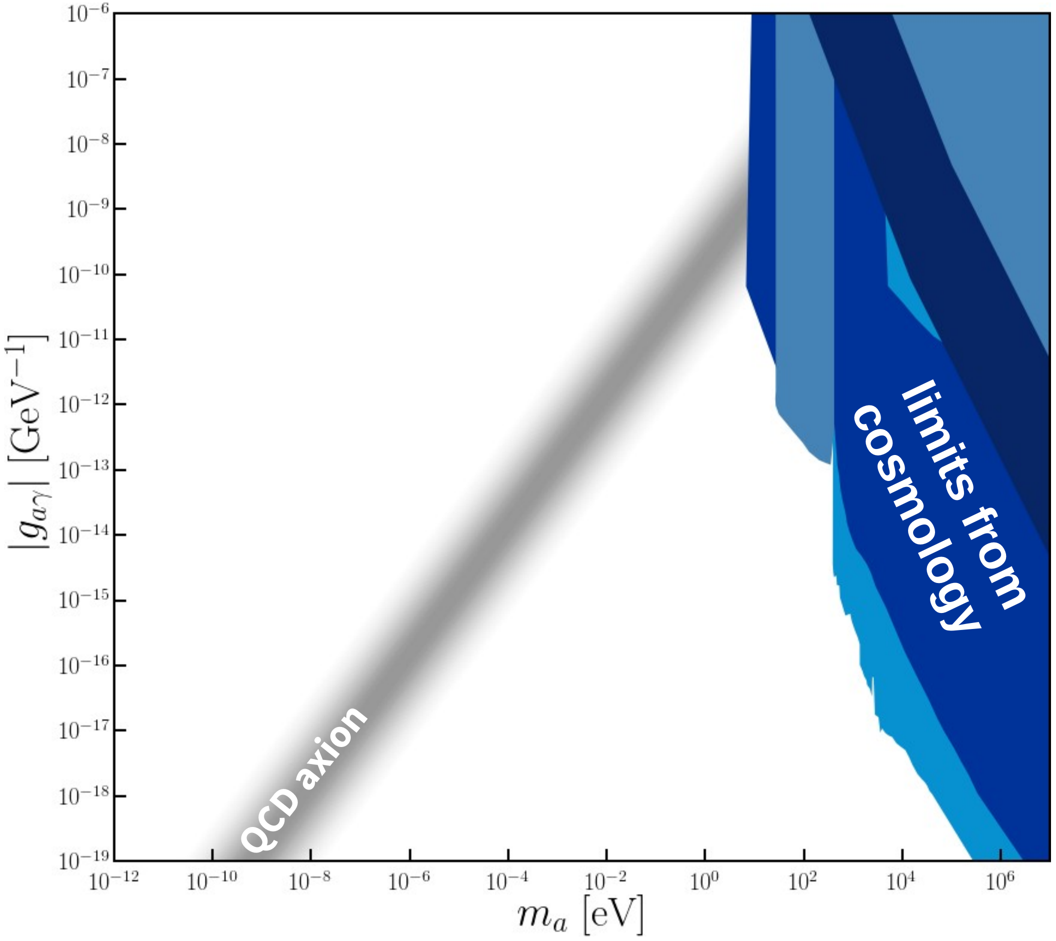

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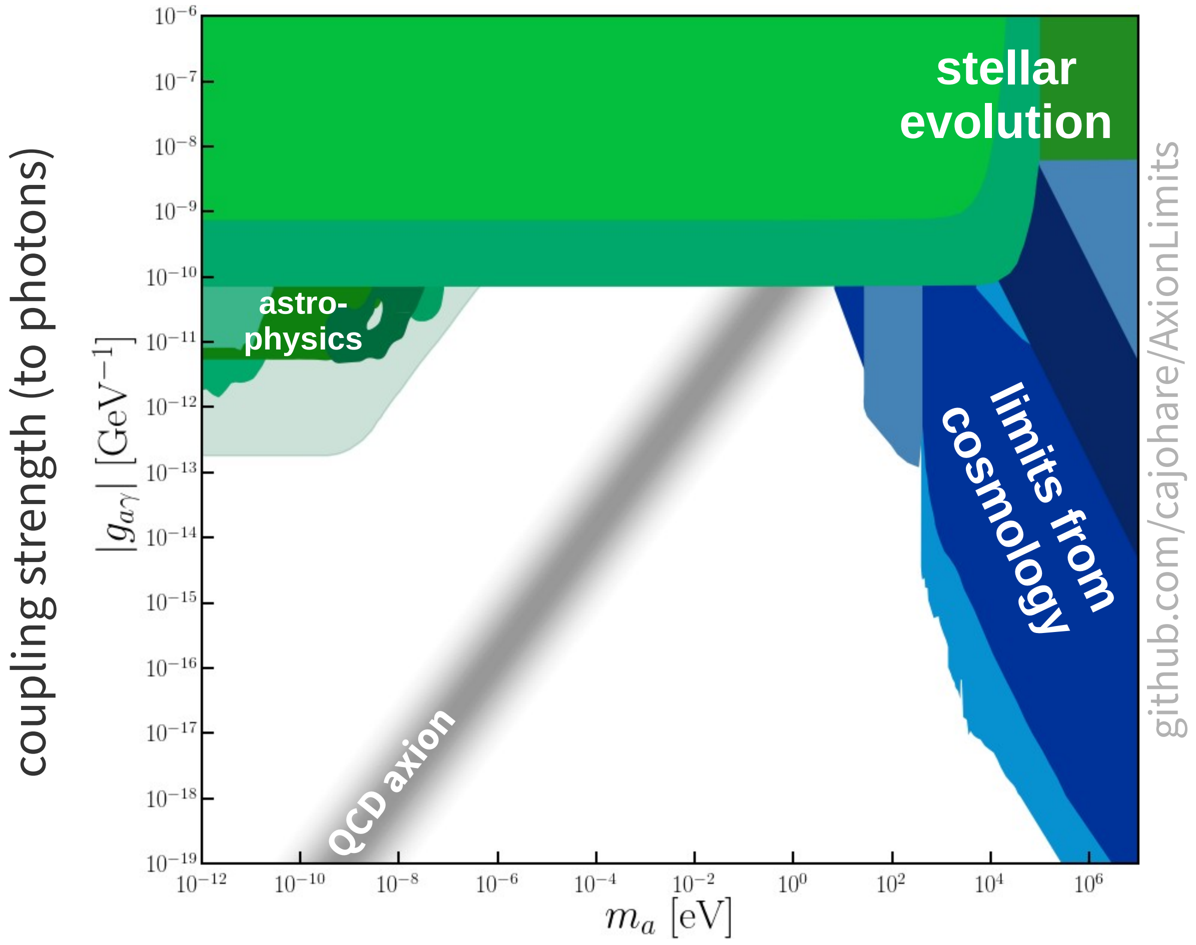

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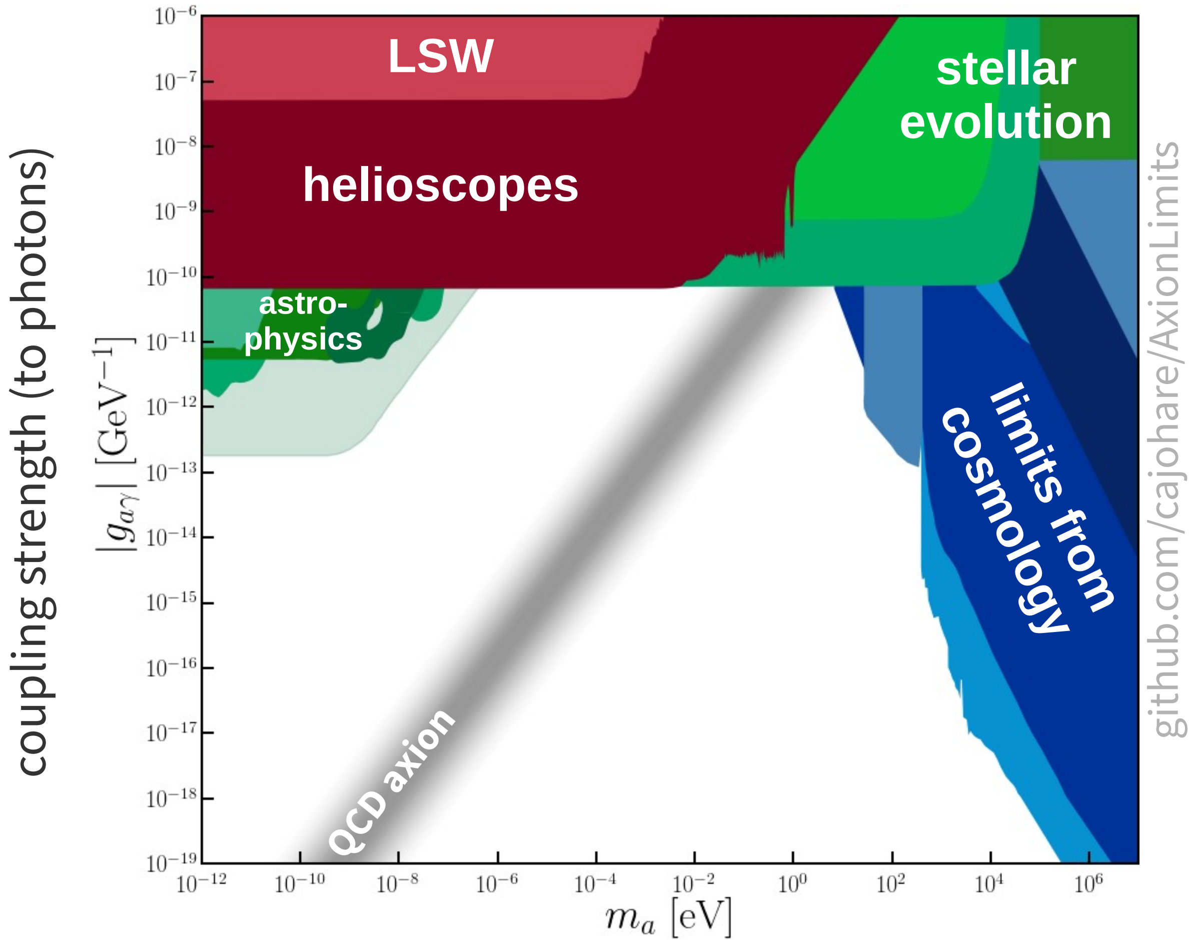

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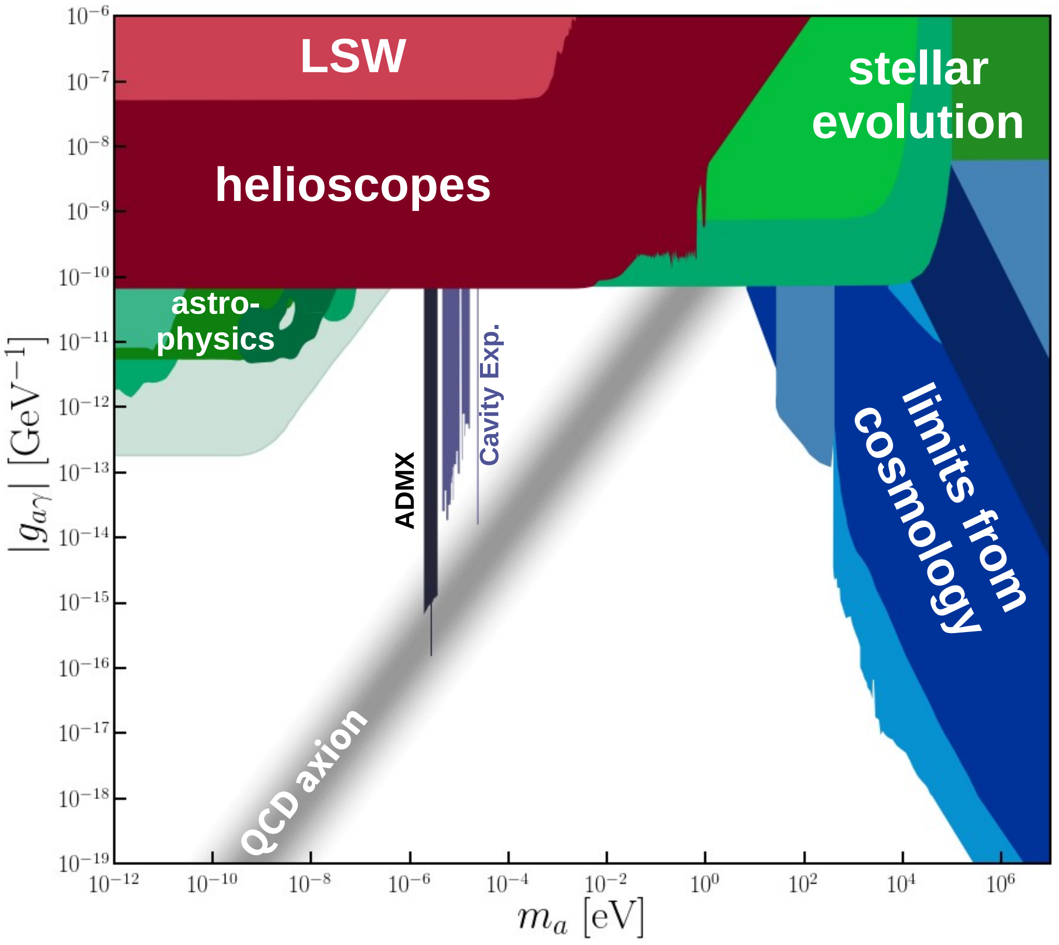

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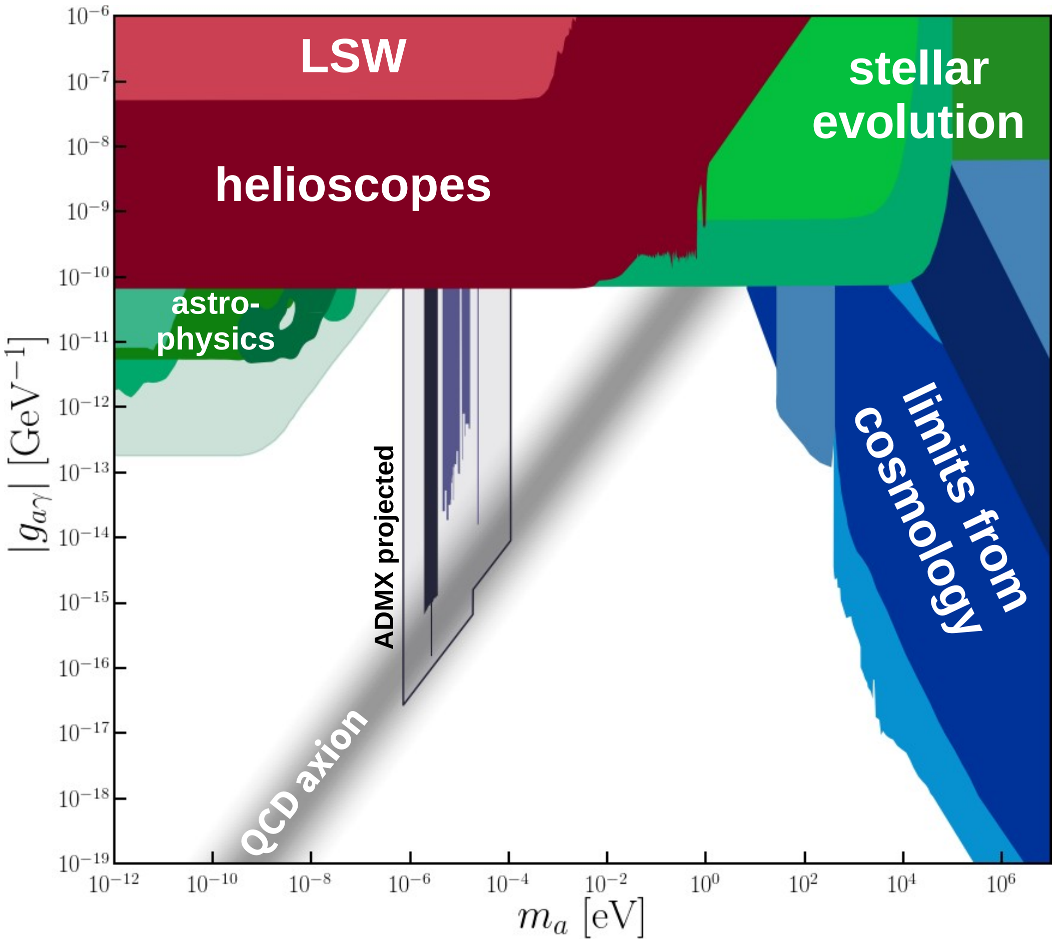

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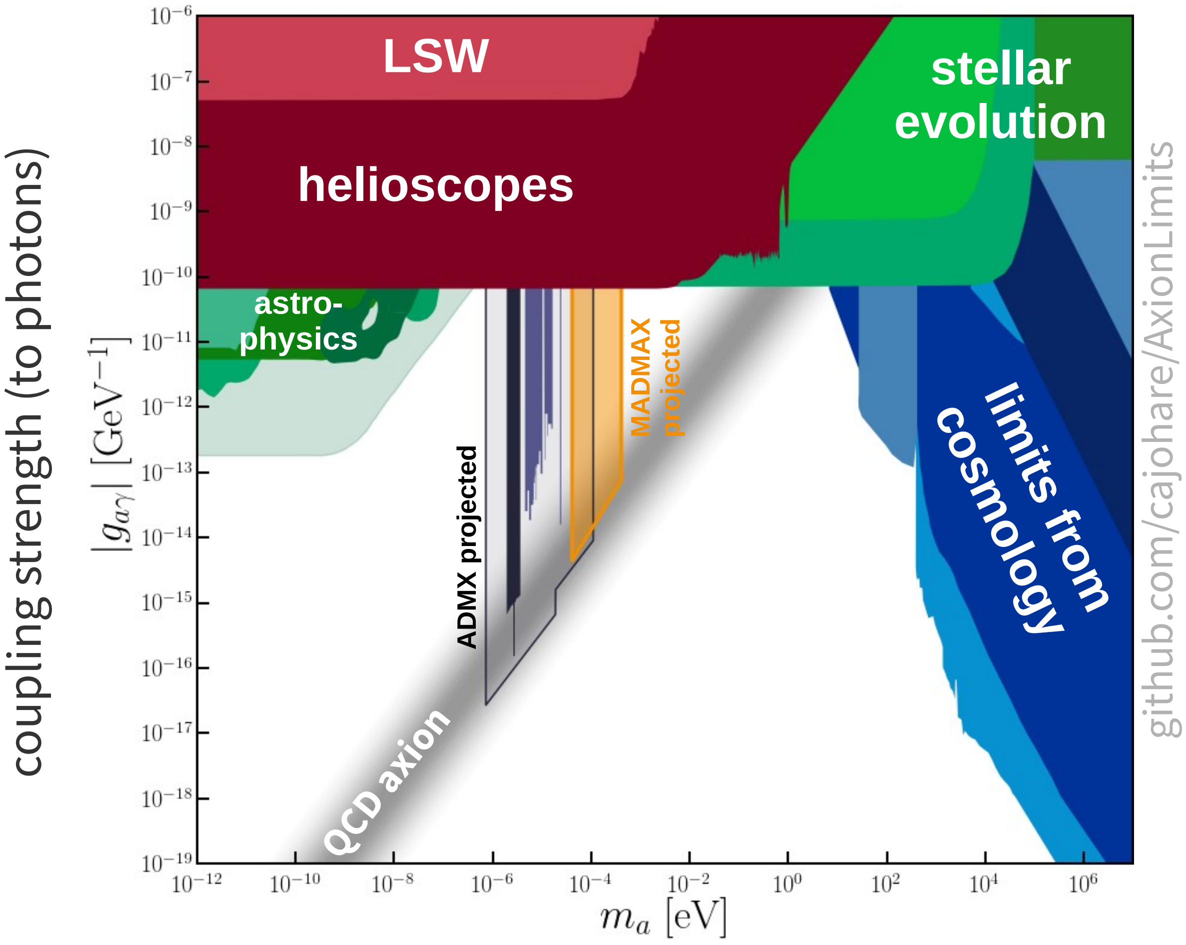

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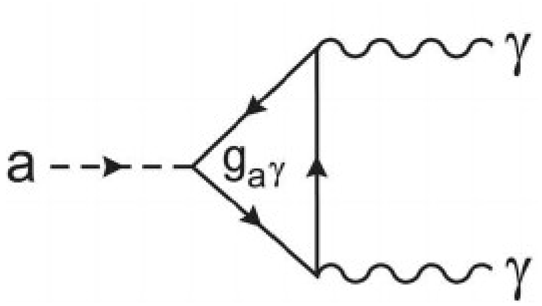
How to Detect Axions

- axions are **pseudo-scalar bosons** (like pions) and have a **2-photon-coupling**:

$$g_{a\gamma} = 2\cdot 10^{-16}\mathrm{GeV}^{-1}\frac{m_a}{\mu eV}|C_{a\gamma}|, C_{a\gamma}\sim\mathcal{O}(1)$$



- their de Broglie wavelength is large (O(m))

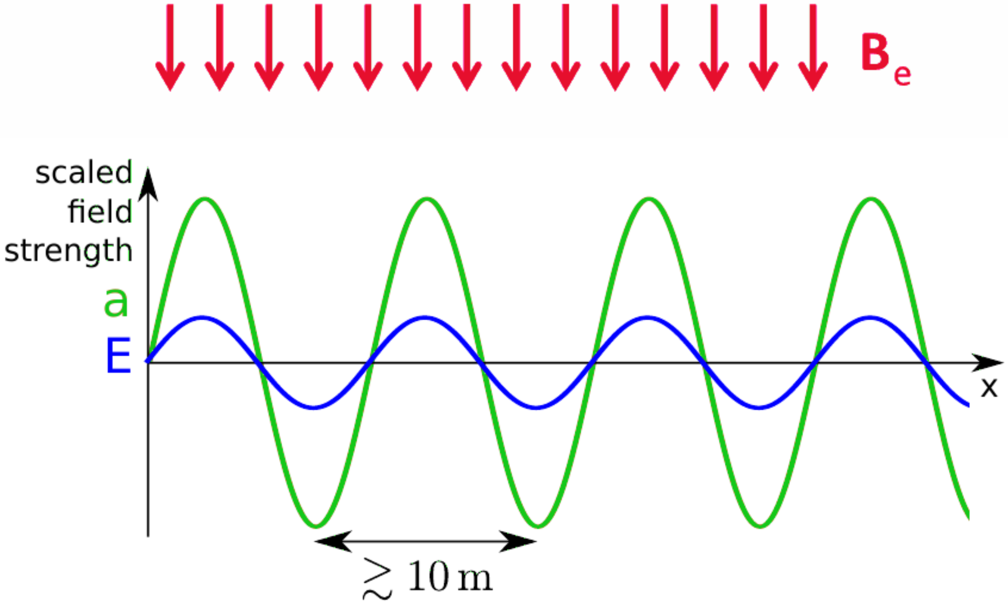
  → we can treat them as **classical wave**

  → axions appear as a source term in Maxwell's equations

$$\nabla\cdot\boldsymbol{D} = \rho - g_{a\gamma}\boldsymbol{B_e}\cdot\nabla\boldsymbol{a}$$

$$\nabla\times\boldsymbol{H} - \dot{\boldsymbol{D}} = \boldsymbol{J} + g_{a\gamma}\boldsymbol{B_e}\dot{\boldsymbol{a}}$$

How to Detect Axions



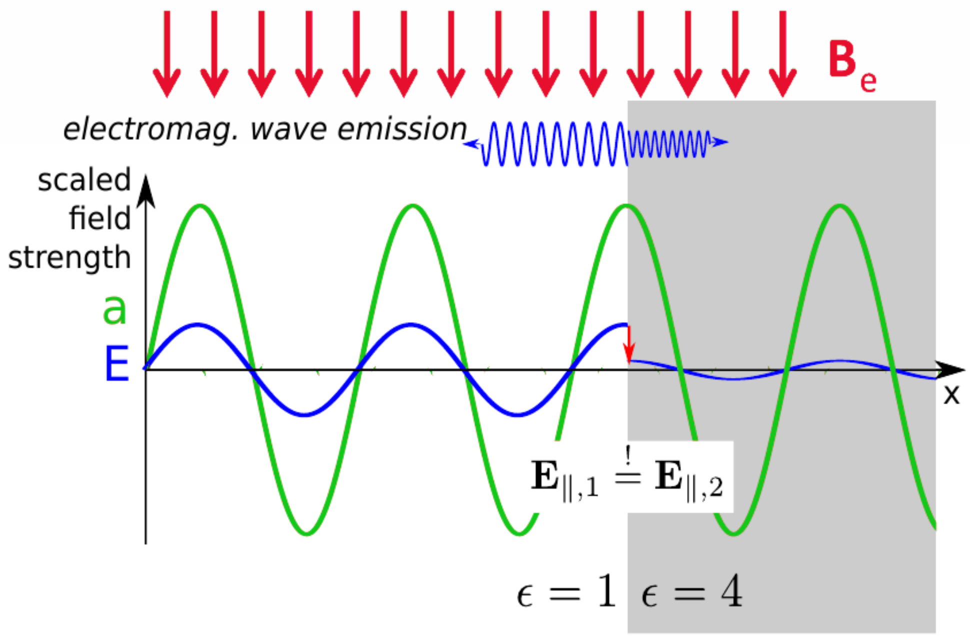
In an external **B field B_e** the **axion field a(t)** sources an oscillating **E field E_a**

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

$$a = a_0 \cos(m_a t)$$

axion-induced electric field: $|E_a| = |\frac{-g_{a\gamma}B_e}{\epsilon}a| = 1.3 \cdot 10^{-12}\mathrm{Vm}^{-1}\left(\frac{B_e}{10\mathrm{T}}\right)\left(\frac{\rho_a}{0.3\mathrm{GeV\ cm}^{-3}}\right)^{1/2}\frac{|C_{a\gamma}|}{\epsilon}$

Dielectric Haloscope



In an external **B field B_e** the **axion field a(t)** sources an oscillating **E field E_a**

E_a is different in materials with different ε

At the surface, $E_{||}$ must be continuous
→ emission of electromagnetic waves

Phys. Rev. D **88**, 115002 (2013)

power emitted from single interface: $$\frac{P_{\mathrm{mirror}}}{A} = 2.2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_e}{10\mathrm{T}} \right)^2 C_{a\gamma}^2$$

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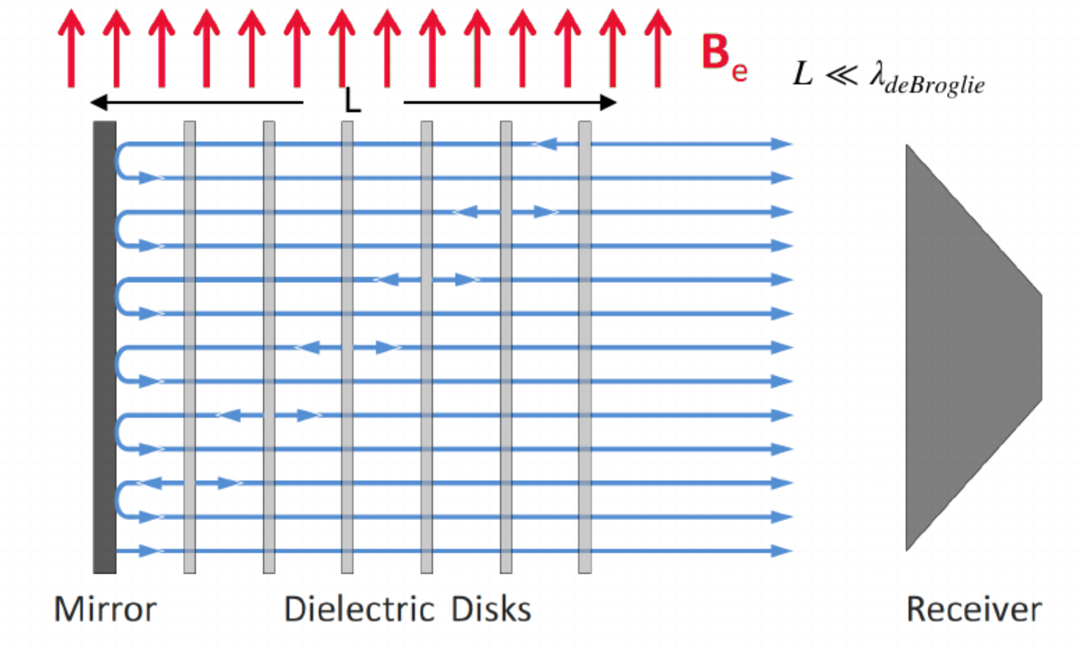
Dielectric Haloscope



- boost emitted power through
  - coherent emission from multiple interfaces
  - resonance effects
- power boost factor

$$\beta^2 = \frac{P_{\rm tot}}{P_{\rm mirror}}$$

PRL **118**, 091801 (2017)

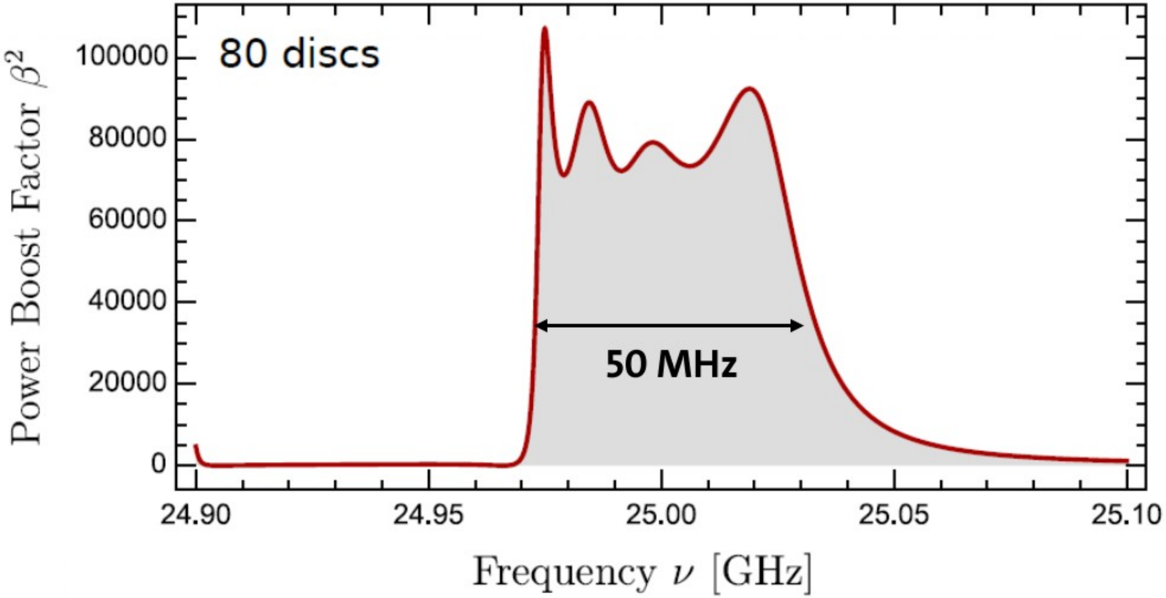
power emitted from all interfaces:

$$\frac{P_{\rm tot}}{A} = 2.2 \cdot 10^{-27} \frac{\rm W}{\rm m^2} \left(\frac{B_e}{10{\rm T}}\right)^2 C_{a\gamma}^2 |\beta^2|$$

Dielectric Haloscope

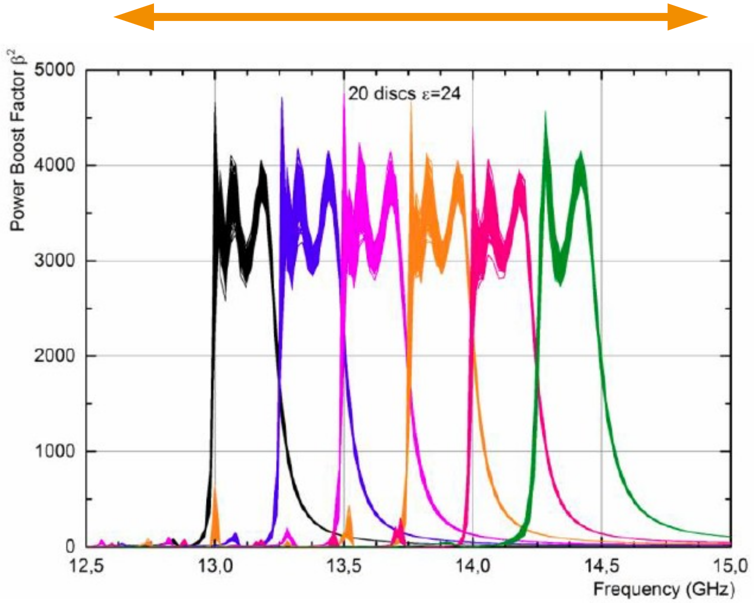
- $|\beta|^2 > 10^4$ achievable with 80 disks and $\varepsilon = 24$
- non-uniform disk spacing of ~ $\lambda/2$ can achieve “broadband” response
- precision required for disk spacing < 10 µm

JCAP **061** (2017); arXiv:1612.07057



Boost Factor

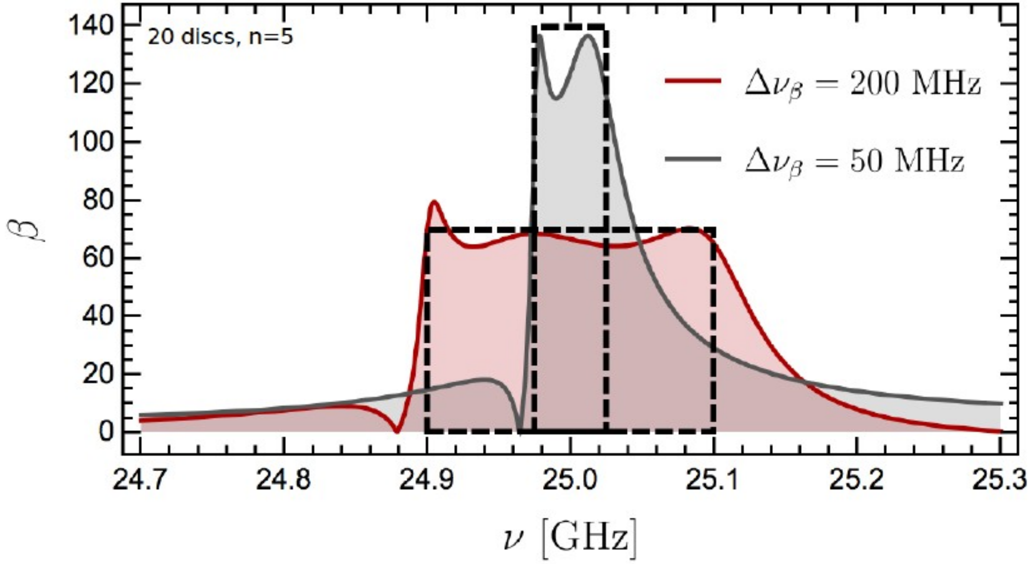
frequency is tuned by adjusting disk spacings



area law: $\beta^2 \cdot \Delta\nu_\beta \sim \text{const.}$

→ broad-band scan for search

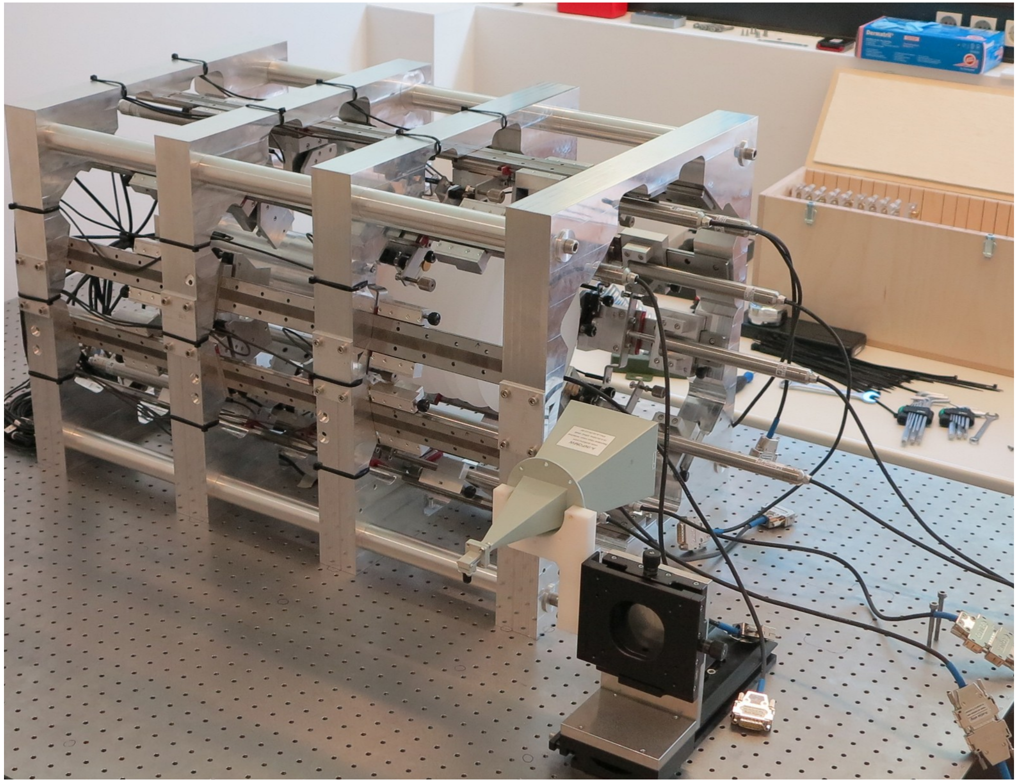
→ narrow-band to check signal candidates



Proof of Principle Setup

Test setup at MPP Munich

- up to **20 disks** (Ø = 20 cm, ε ≈ 9)
- reproducibility of positioning **~ µm**



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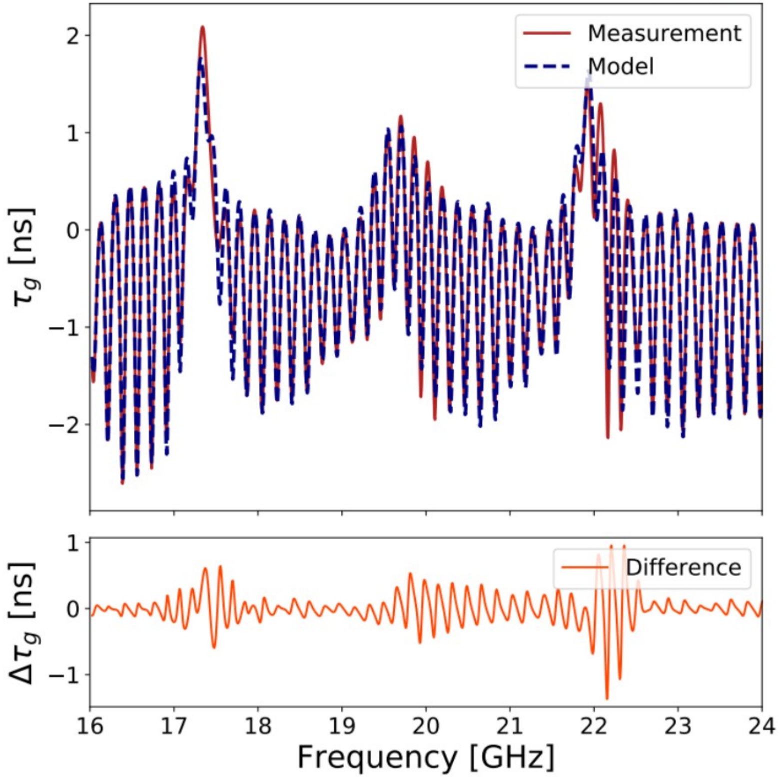
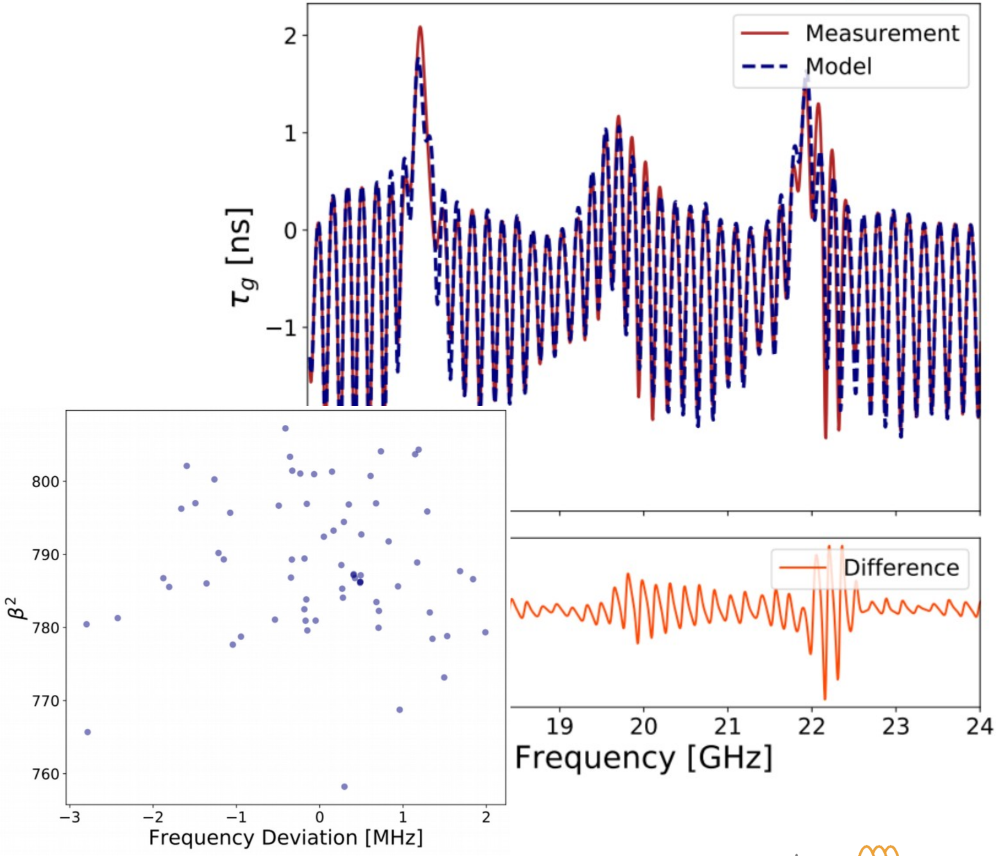
- compare reflectivity measurements to model calculations



Proof of Principle Setup

Test setup at MPP Munich

- up to **20 disks** (Ø = 20 cm, ε ≈ 9)
- reproducibility of positioning **~ µm**
- compare reflectivity measurements to model calculations
- **boost factor** reproducible within **few MHz** for 5 disks



The MADMAX Collaboration

CENTRE DE PHYSIQUE DES PARTICULES DE MARSEILLE
CPPM

DESY.

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

Max-Planck-Institut
für Radioastronomie

RWTH AACHEN UNIVERSITY

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

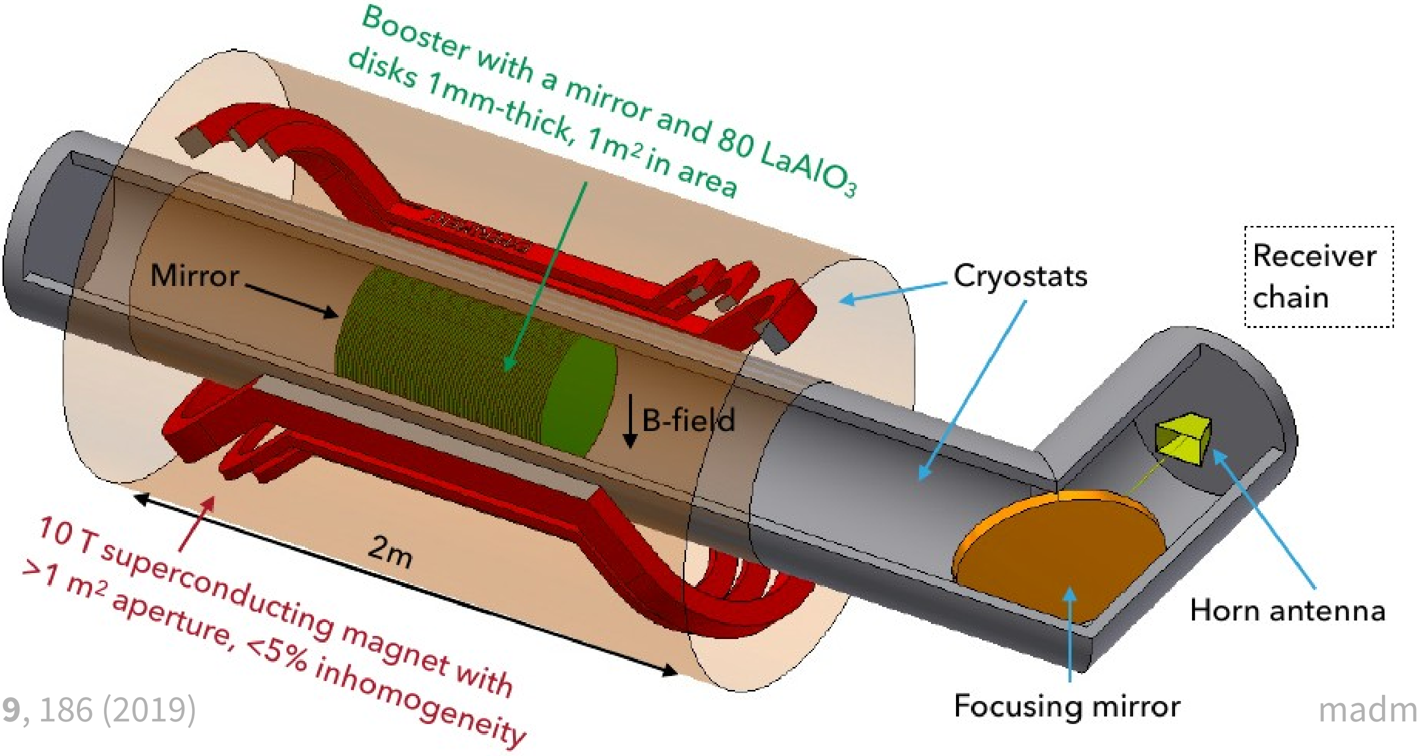
DE LA RECHERCHE À L'INDUSTRIE
cea

UH
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Universidad
de Zaragoza

MADMAX

MAgnetized **D**isk and **M**irror **A**xion E**X**periment



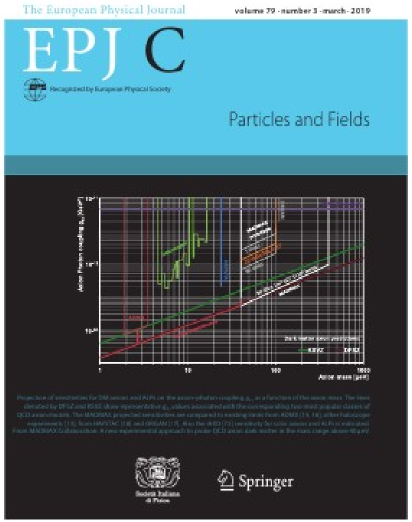
EPJ C **79**, 186 (2019)

madmax.mpp.mpg.de

MADMAX Timeline

2017 – 2019

Design



The European Physical Journal

volume 79 · number 3 · march · 2019

EPJ C

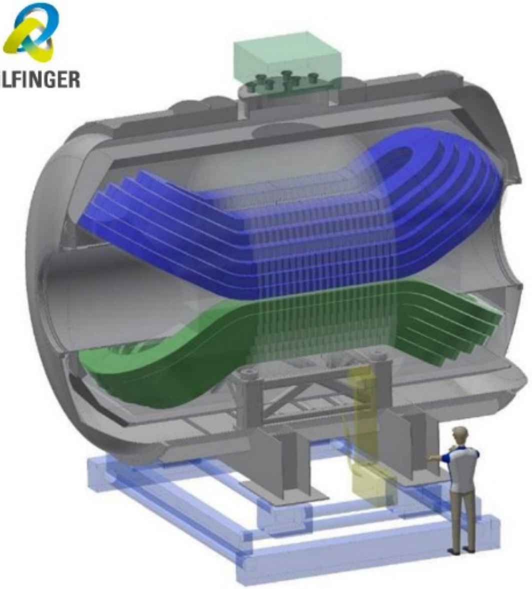
Recognized by European Physical Society

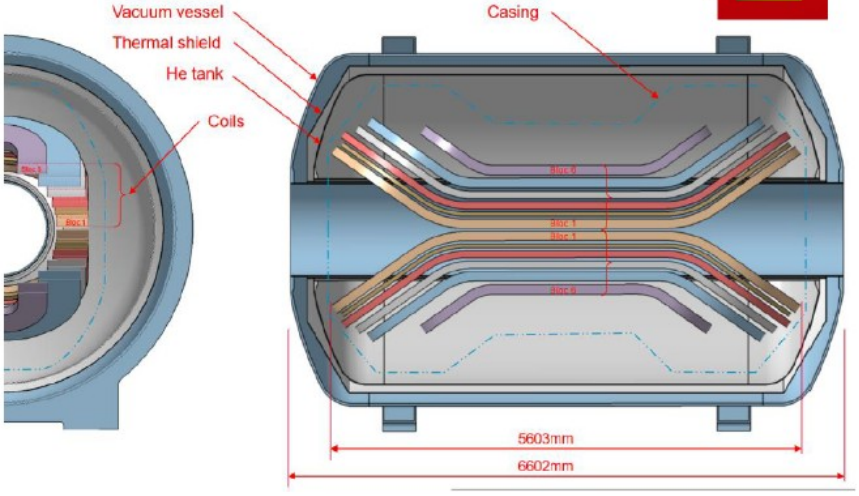
Particles and Fields

Springer

EPJ C **79**, 186 (2019)

Magnet

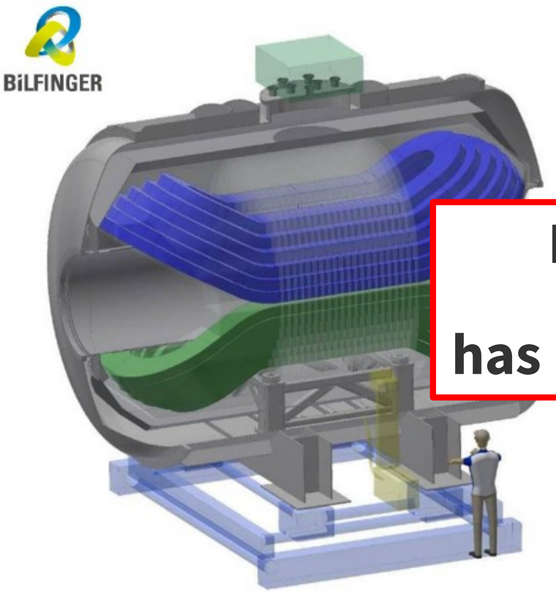


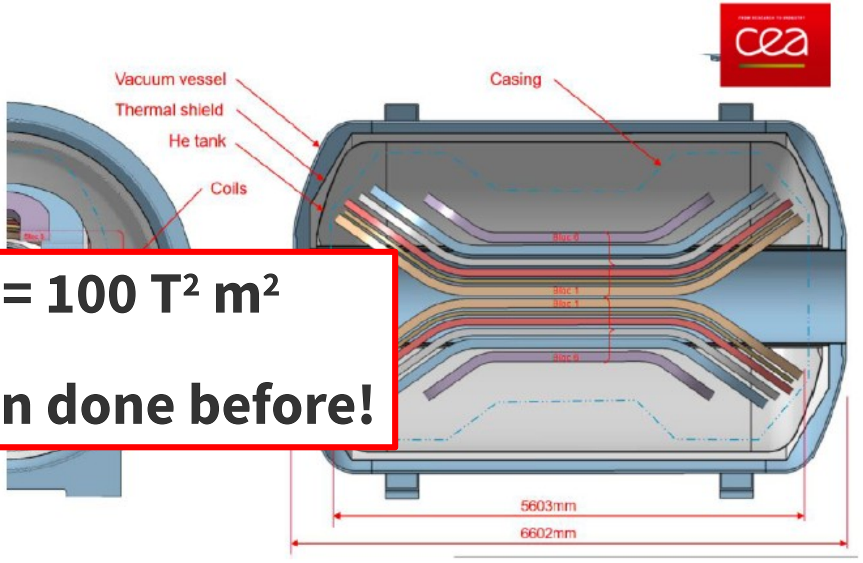


block design with NbTi superconductor

- design and construction of magnet drives time scale of project
- **peak field ~ 9 T**, homogeneity < 20 %
- dimensions of bore: length ~ 1 m, **diameter ~ 1.5 m**

Magnet





$\mathrm{FoM} = B^2A = 100\ \mathrm{T}^2\ \mathrm{m}^2$

has never been done before!

block design with NbTi superconductor

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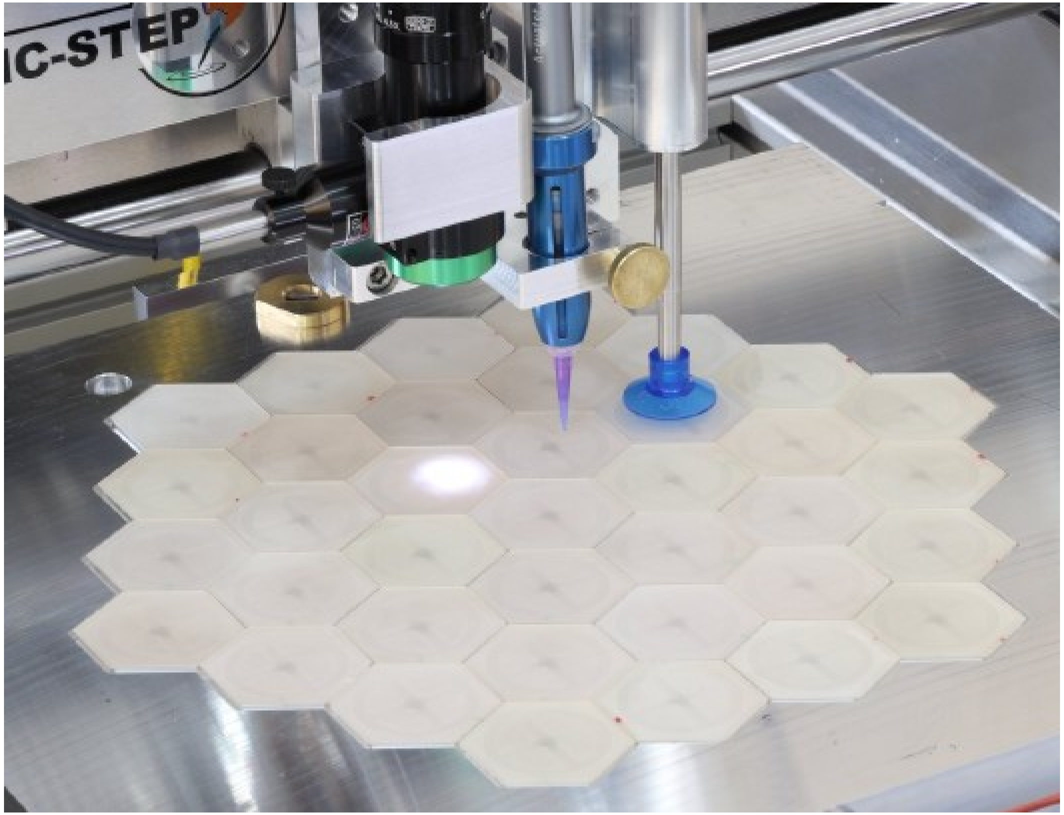
Disks

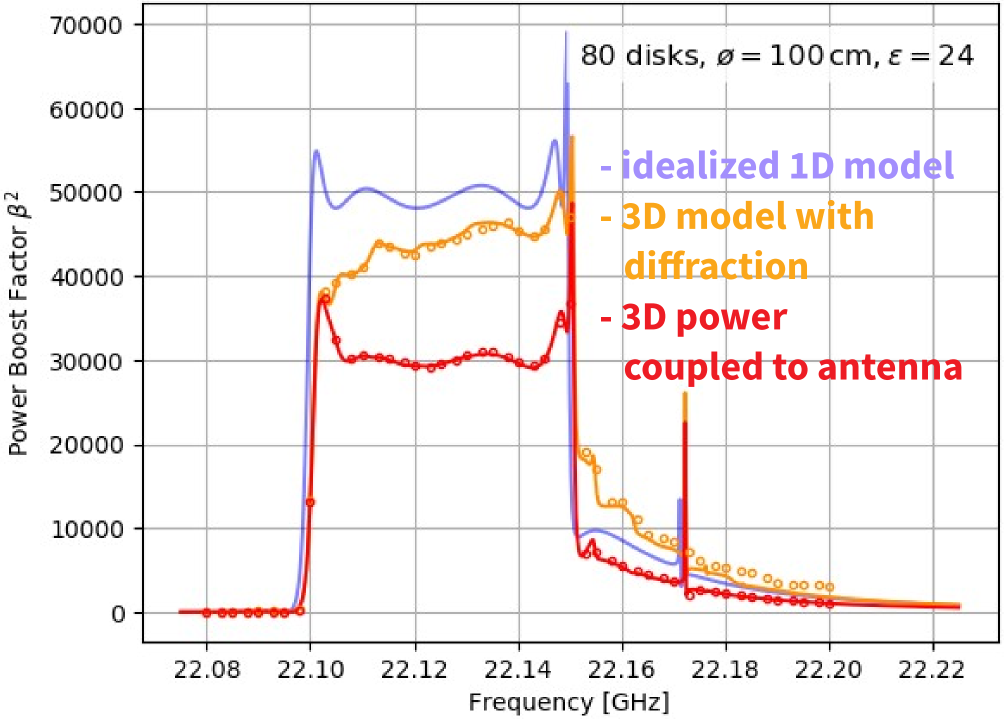
- requirements: high ε, low loss (tan δ)
  → candidate materials:
  - **LaAlO3 (ε ≈ 24, tan δ ≈ few 10^{-5})**
  - Sapphire (ε ≈ 9, tan δ ≈ 10^{-5})
- Ø = 1.25 m needed for 100 T^2 m^2
  → tiling necessary
- characterisation of dielectric properties @ 4K, f = 10-15 GHz ongoing



Booster Simulation Studies

Study achievable boost factor using different simulation methods to optimize design

- **3D effects (diffraction)** → ~30% loss (combined)
- **coupling to antenna (beam shape)**
- dielectric loss
- inaccuracies (positioning, surface roughness, thickness)
- effects due to tiling
- …



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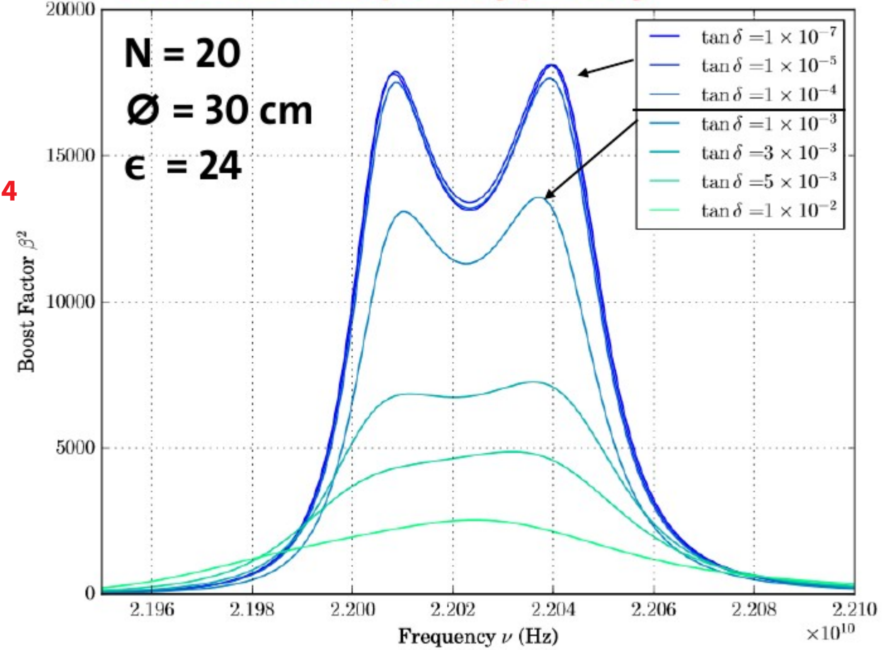
For MADMAX prototype only



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  thickness ± 5 µm
  sourface roughness < 10 µm
  positioning < 10 µm
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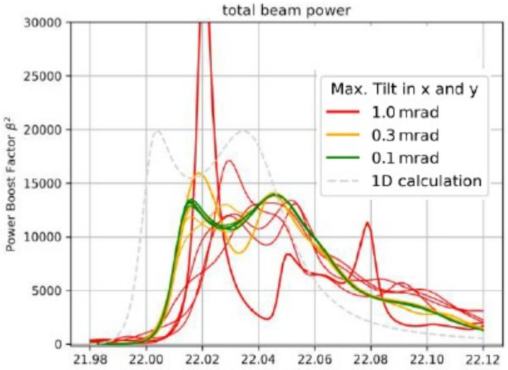
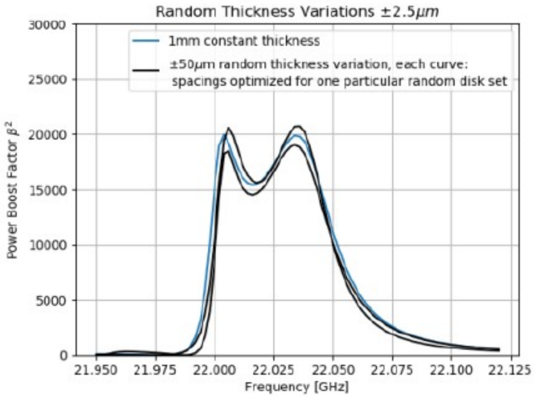
- …





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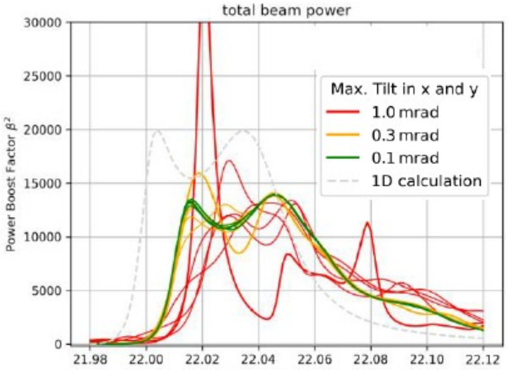
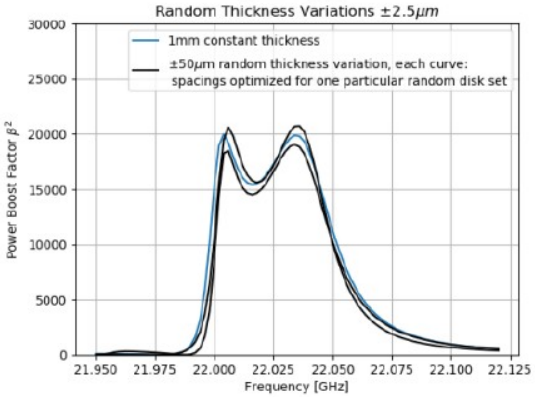
- effects due to tiling
- …

More on the methods: arXiv:1906.02677

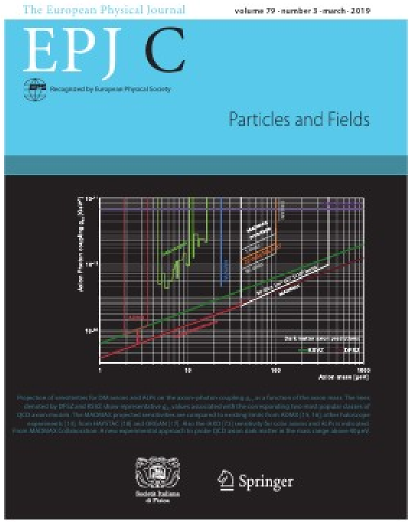




MADMAX Timeline

2017 – 2019
Design

2019 – 2022
Prototype



The European Physical Journal

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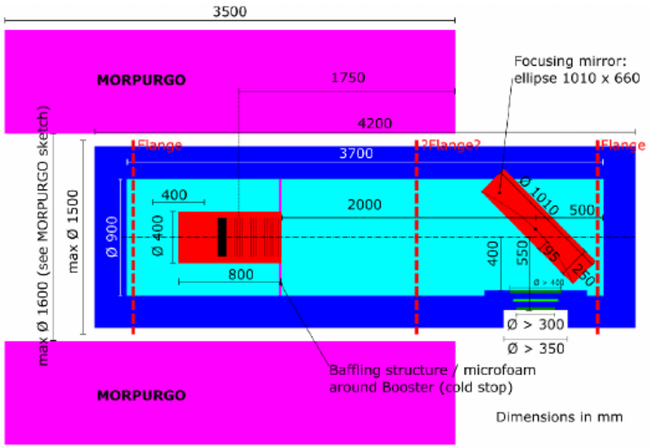
Particles and Fields

Springer

EPJ C **79**, 186 (2019)



first steps:

- build an intermediate-scale prototype of booster to test mechanics, receiver, …
- put it in an existing magnet
- do some physics

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

Prototype Sensitivity - ALPs

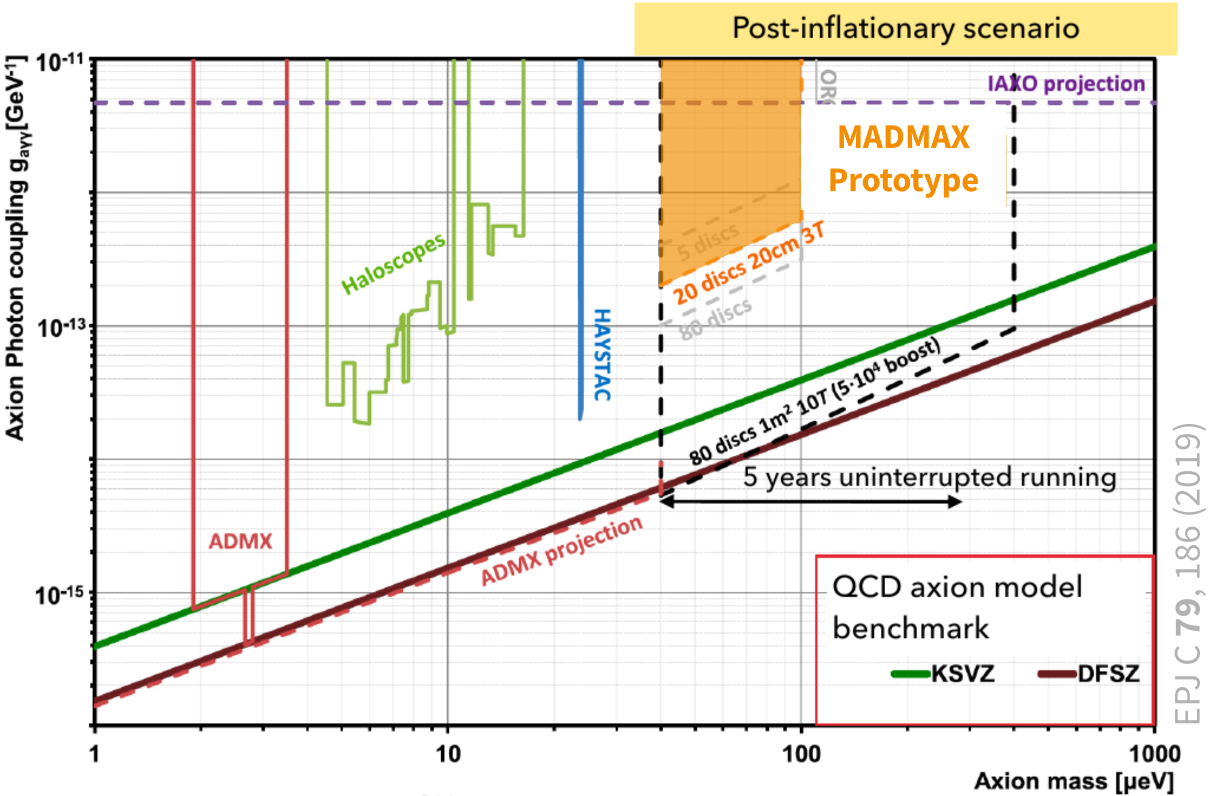
Axion-like Particle Search:

with less and smaller disks and lower B-field (~ 3T)

→ don’t reach QCD axion sensitivity

but

explore new parameter space for ALPs



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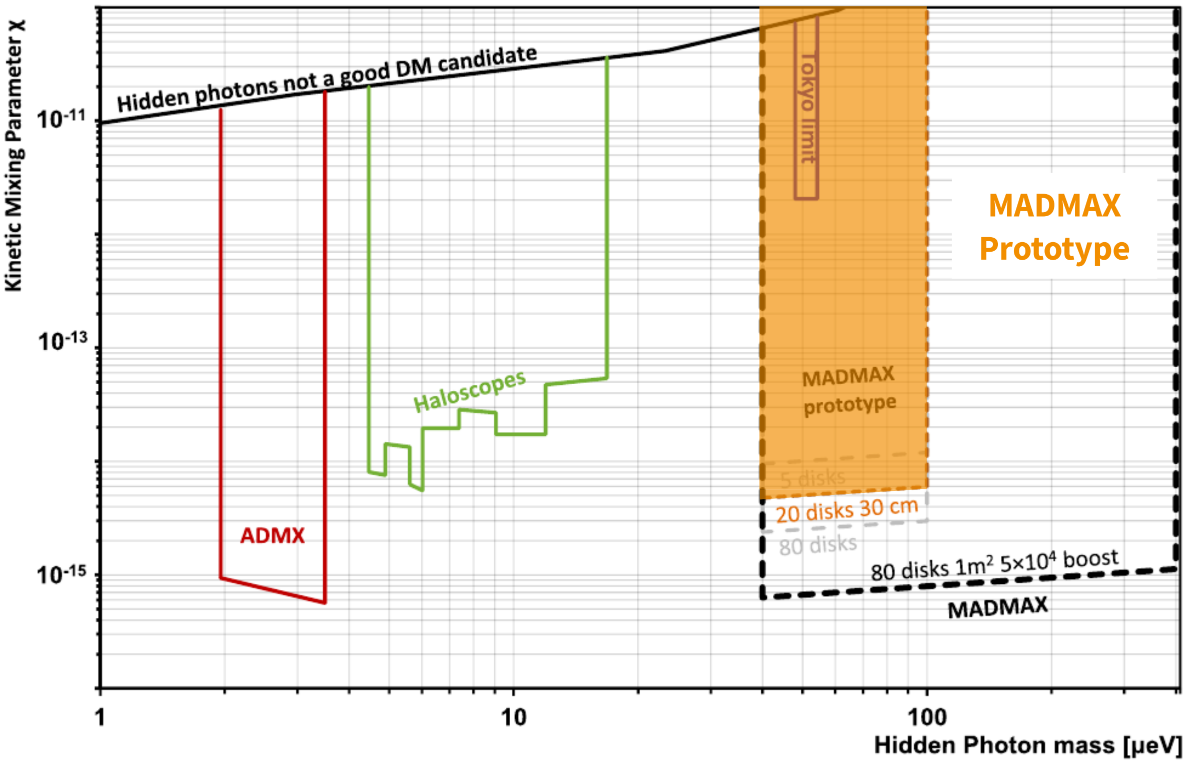
* assuming system temperature ~8K

Sensitivity – Hidden Photons

Hidden photon search

hidden photon mixes with normal photon

→ conversion doesn't require magnetic field



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MADMAX Timeline

2017 – 2019	2019 – 2022	2022 – 2025	2025 – 2035
Design	**Prototype**	**Construction**	**Data taking**

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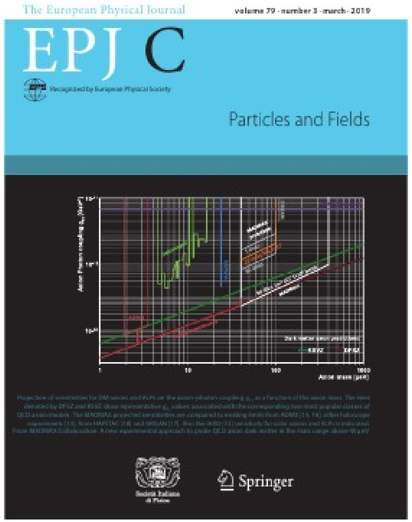

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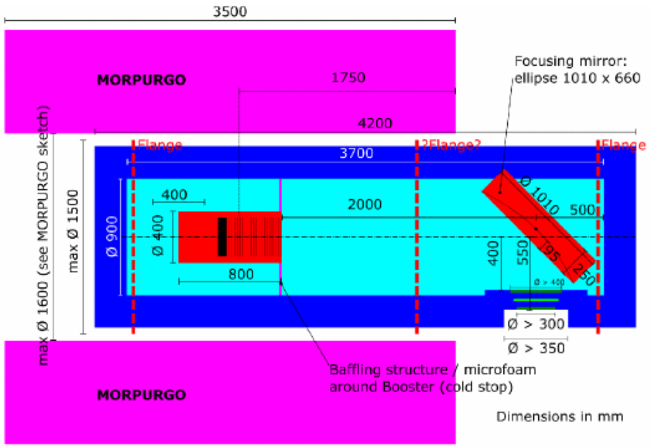
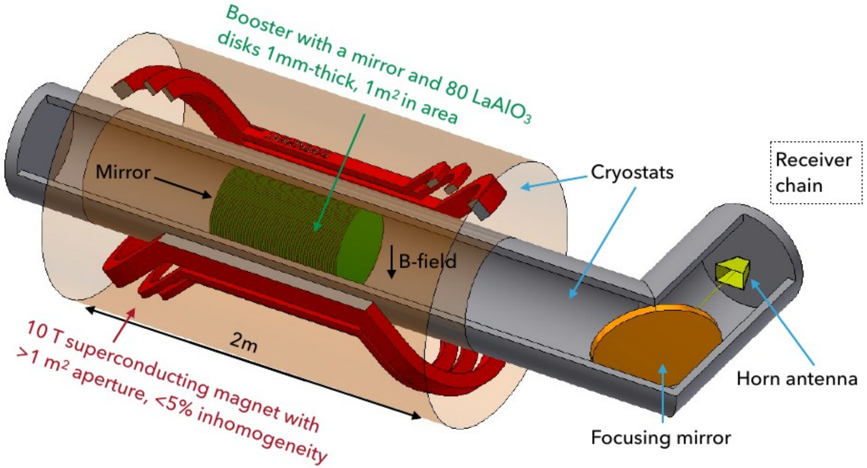


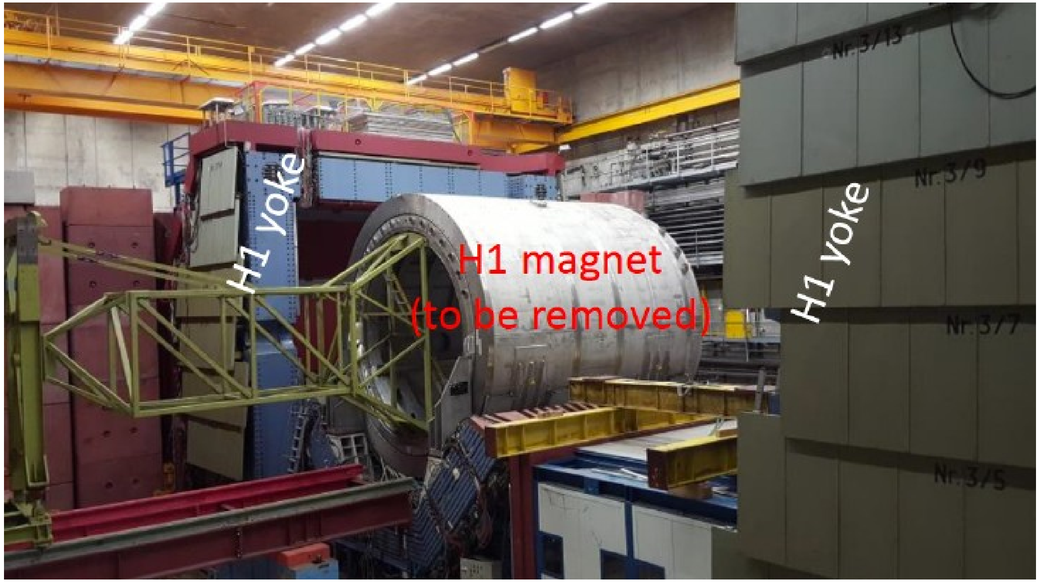


Experimental Site

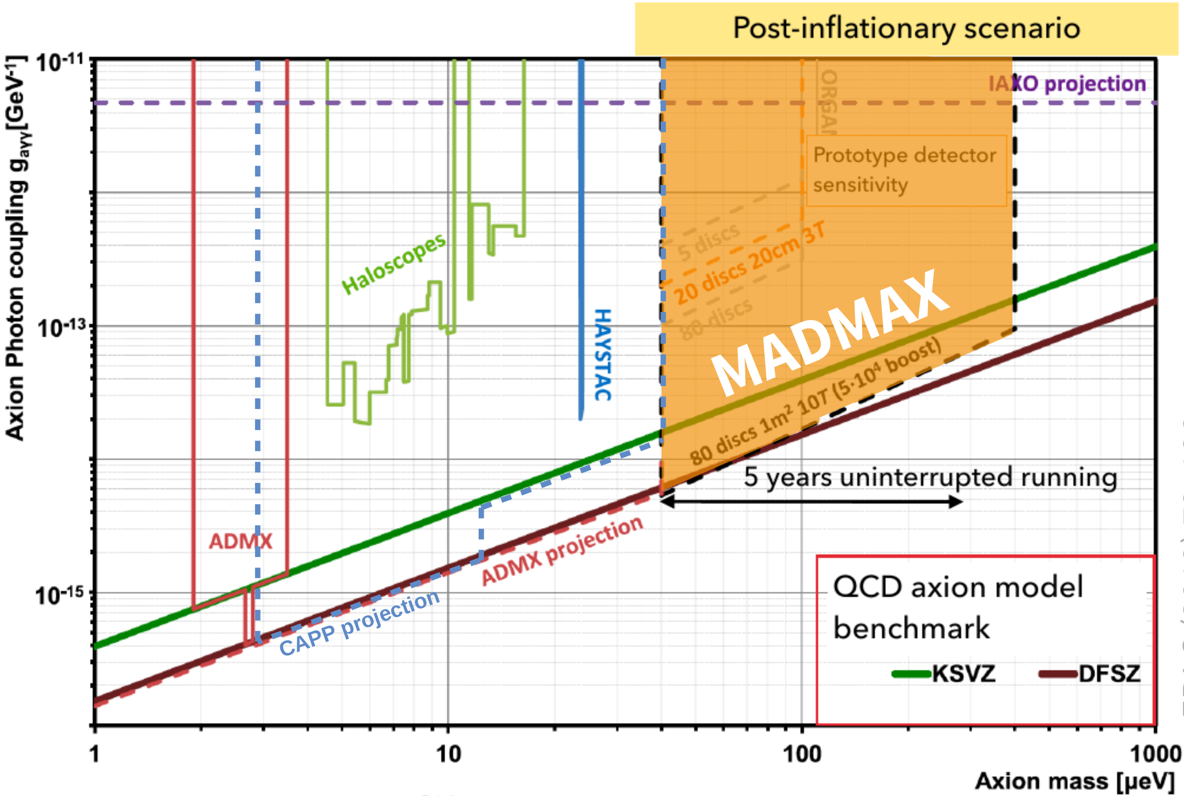
planned to be built at **DESY** in HERA Hall North

→ use existing cryogenic infrastructure

→ option to re-use H1 yoke to shield magnet



Projected Sensitivity



EPJ C (2019) 79: 186

* assuming system temperature ~8K