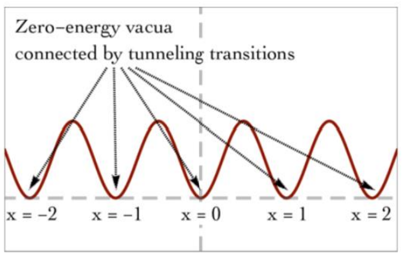
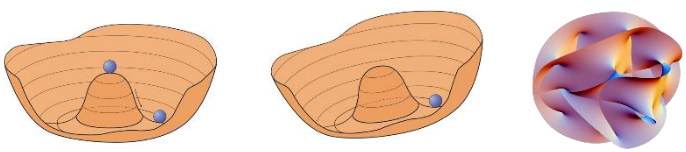
The search for axion dark matter with a dielectric haloscope: MADMAX

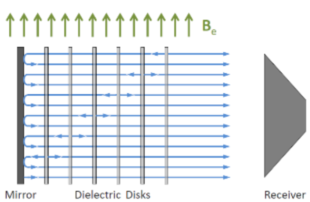
Béla Majorovits

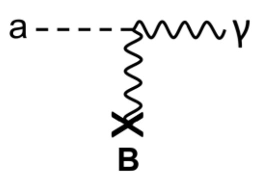
MAX-PLANCK-INSTITUT FÜR PHYSIK

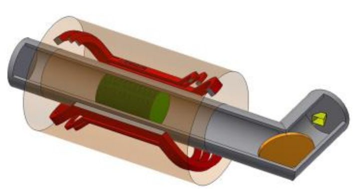
on behalf of the MADMAX collaboration











- The strong CP problem and the axion
- Axions and ALPs as dark matter
- How to detect axions
- Dielectric haloscope
- MADMAX

CP violation in the QCD vacuum

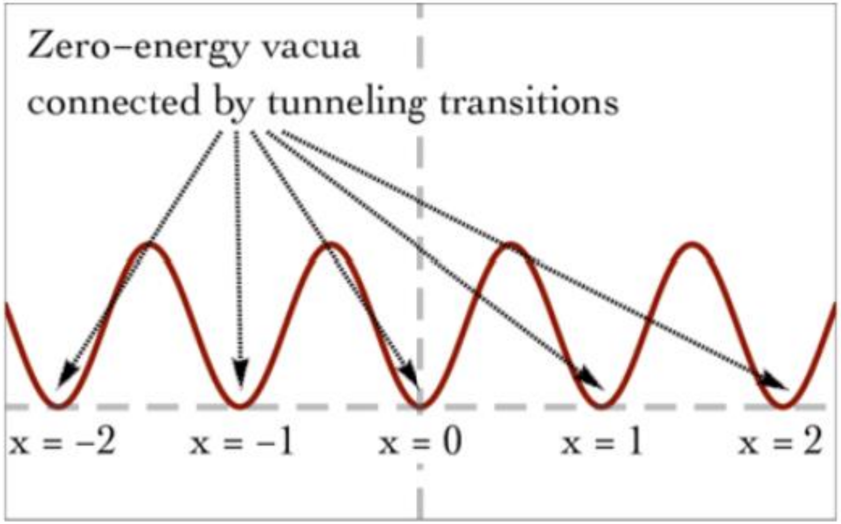
QCD SU(3) gauge group non-Abelian

gauge transformations not commutative!

→ Gauge in-equivalent zero energy states $|n\rangle$

→ Separated by potential barrier: tunneling → instantons

→ Single $|n\rangle$ not stable vacuum state



CP violation in the QCD vacuum

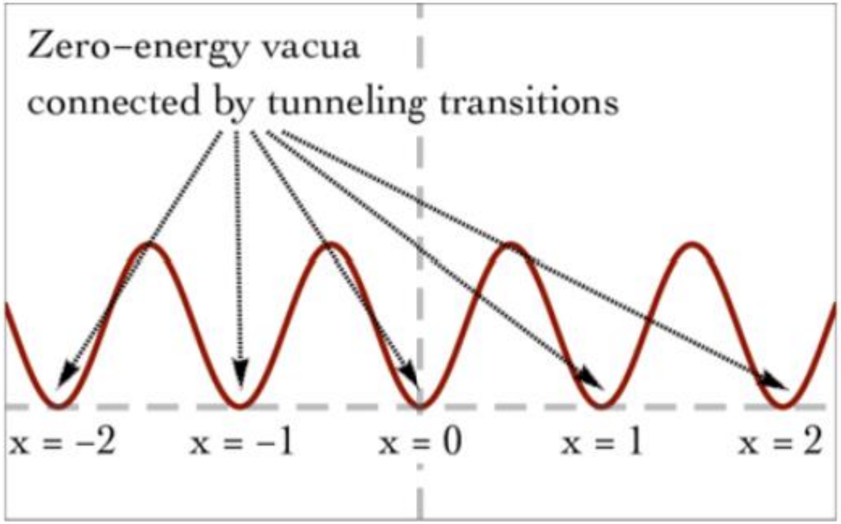
→ **Physical ground state of QCD vacuum defined by**

gauge invariant superposition of zero energy vacuum states:

θ – vacuum: $|\theta\rangle = \sum_n e^{in\theta}|n\rangle$

→ **CP violating term in QCD Lagrangian:**

$$\Theta \frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}_a^{\mu\nu}$$



CP violation in QCD

CP violating phase through CKM matrix

→ Physically observable CP violation expected:

$$\bar{\Theta} = \Theta - \arg\det M_q$$

Random phase from Θ-vacuum

phases from Yukawa coupling: CKM matrix

CP violating term in QCD Lagrangian:

$$\bar{\Theta}\frac{\alpha_s}{8\pi} G_{\mu\nu a}\tilde{G}_a^{\mu\nu} \in \mathcal{L}_{\text{QCD}}$$

CP violation in QCD - the strong CP problem

CP violating term in QCD

$$\bar{\Theta}\frac{\alpha_s}{8\pi}G_{\mu\nu a}\tilde{G}_a^{\mu\nu} \;\epsilon\; \mathcal{L}_{QCD}$$

→ induces neutron EDM:

$$d_n \sim \bar{\Theta} \cdot 10^{-16} \text{ e cm}$$

Limit on EDM of neutron:

$$d_n < 2 \cdot 10^{-26}$$

Abel et al.,
Phys. Rev. Lett. 124, 081803 (2020)

$$\bar{\Theta} < 10^{-10}$$

Two seemingly independent terms cancel each other to 1 in 10^{10}

→ Strong CP problem

The strong CP problem ?

arXiv > hep-th > arXiv:2001.07152

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High Energy Physics - Theory

[Submitted on 20 Jan 2020 (v1), last revised 28 Sep 2021 (this version, v5)]

Absence of CP violation in the strong interactions

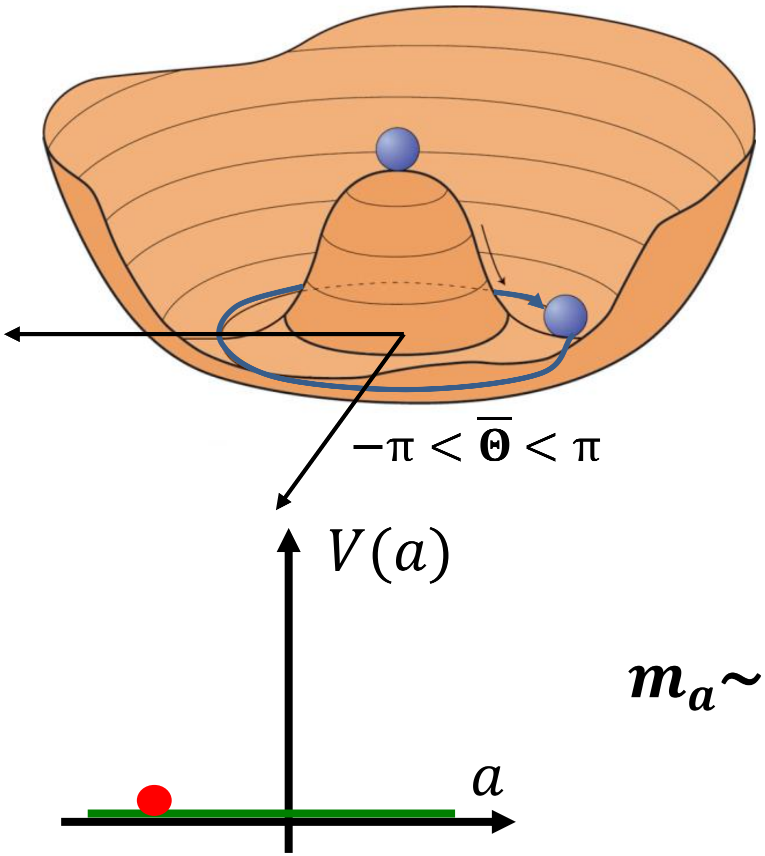
Wen-Yuan Ai, Juan S. Cruz, Bjorn Garbrecht, Carlos Tamarit

We derive correlation functions for massive fermions with a complex mass in the presence of a general vacuum angle. For this purpose, we first build the Green's functions in the one-instanton background and then sum over the configurations of background instantons. The quantization of topological sectors follows for saddle points of finite Euclidean action in an infinite spacetime volume and the fluctuations about these. For the resulting correlation functions, we therefore take the infinite-volume limit before summing over topological sectors. In contrast to the opposite order of limits, the chiral phases from the mass terms and from the instanton effects then are aligned so that, in absence of additional phases, these do not give rise to observables violating charge-parity symmetry. This result is confirmed when constraining the correlations at coincident points by using the index theorem instead of instanton calculus.

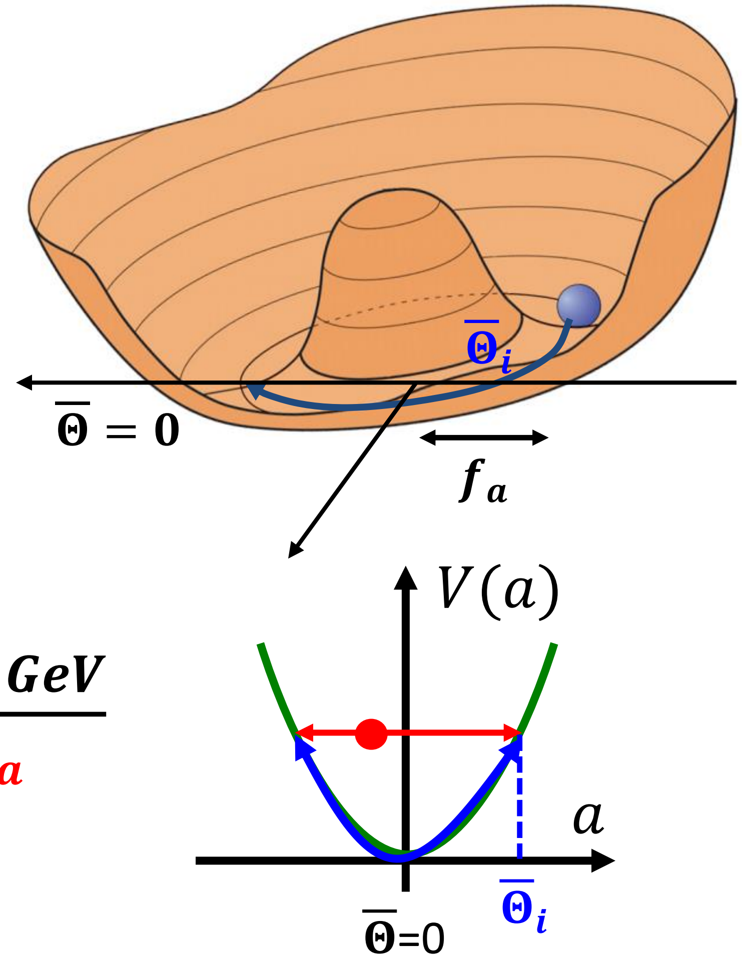
Comments:	52 pages, matches published version (except for the title that has been changed in journal) with supplementary material included
Subjects:	**High Energy Physics - Theory (hep-th)**; High Energy Physics - Phenomenology (hep-ph)
Report number:	TUM-HEP-1249/20, CP3-20-02
Cite as:	arXiv:2001.07152 **[hep-th]**
	(or arXiv:2001.07152v5 **[hep-th]** for this version)
	https://doi.org/10.48550/arXiv.2001.07152
Journal reference:	Phys.Lett.B 822 (2021) 136616
Related DOI:	https://doi.org/10.1016/j.physletb.2021.136616

Axion as solution to strong CP problem

Make $\bar{\Theta}$ dynamical → U(1) with spontaneous Peccei Quinn symmetry breaking



QCD: explicit symmetry breaking



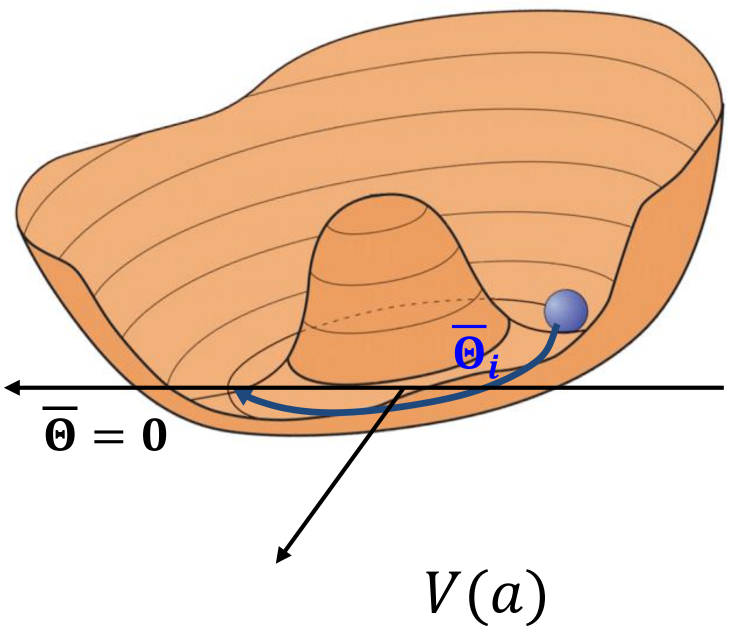
$$m_a \sim 5.7 \mu eV \frac{10^{12} GeV}{f_a}$$

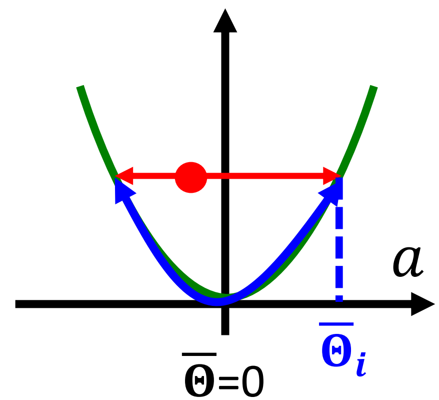
Axion as solution to strong CP problem

If axion exists:

→ Contribution to Dark Matter:

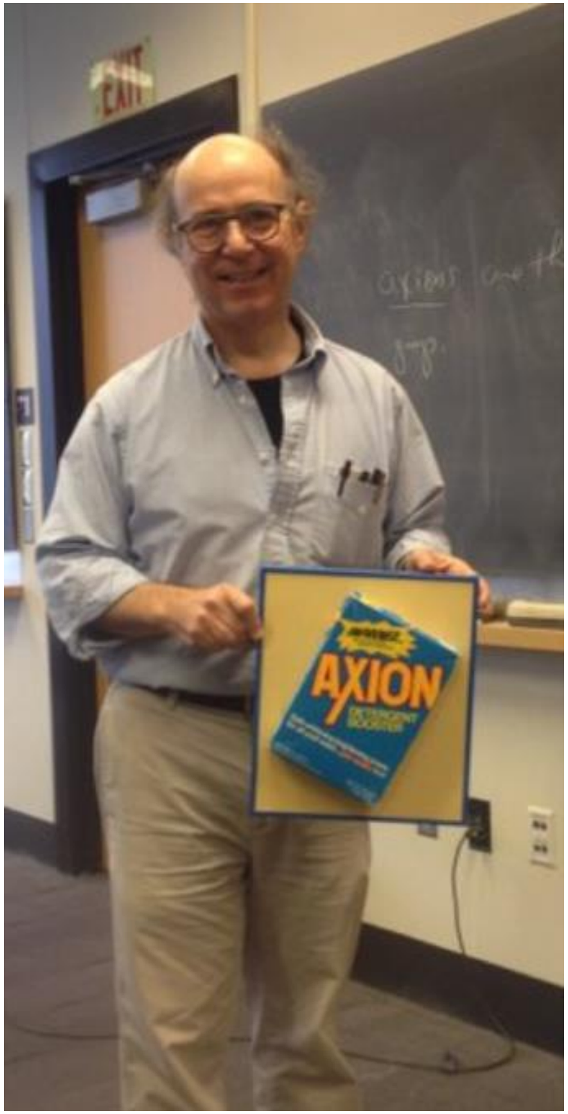
as relic oscillations of $\bar{\Theta}$ around minimum





Oscillations amplitude (particle density) damped by expansion of universe H(t)

Damping depends on ratio oscillation frequency (m_a) to H(t)



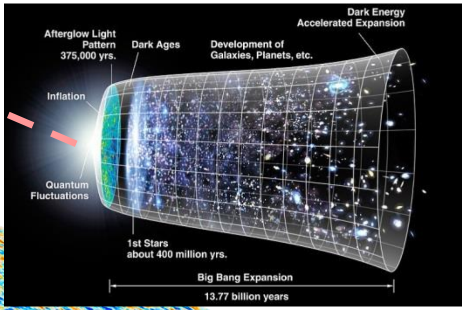
R. Peccei und *H. Quinn*,
Phys. Rev. Lett. **38**, 1440 (1977)
S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978);
F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978)

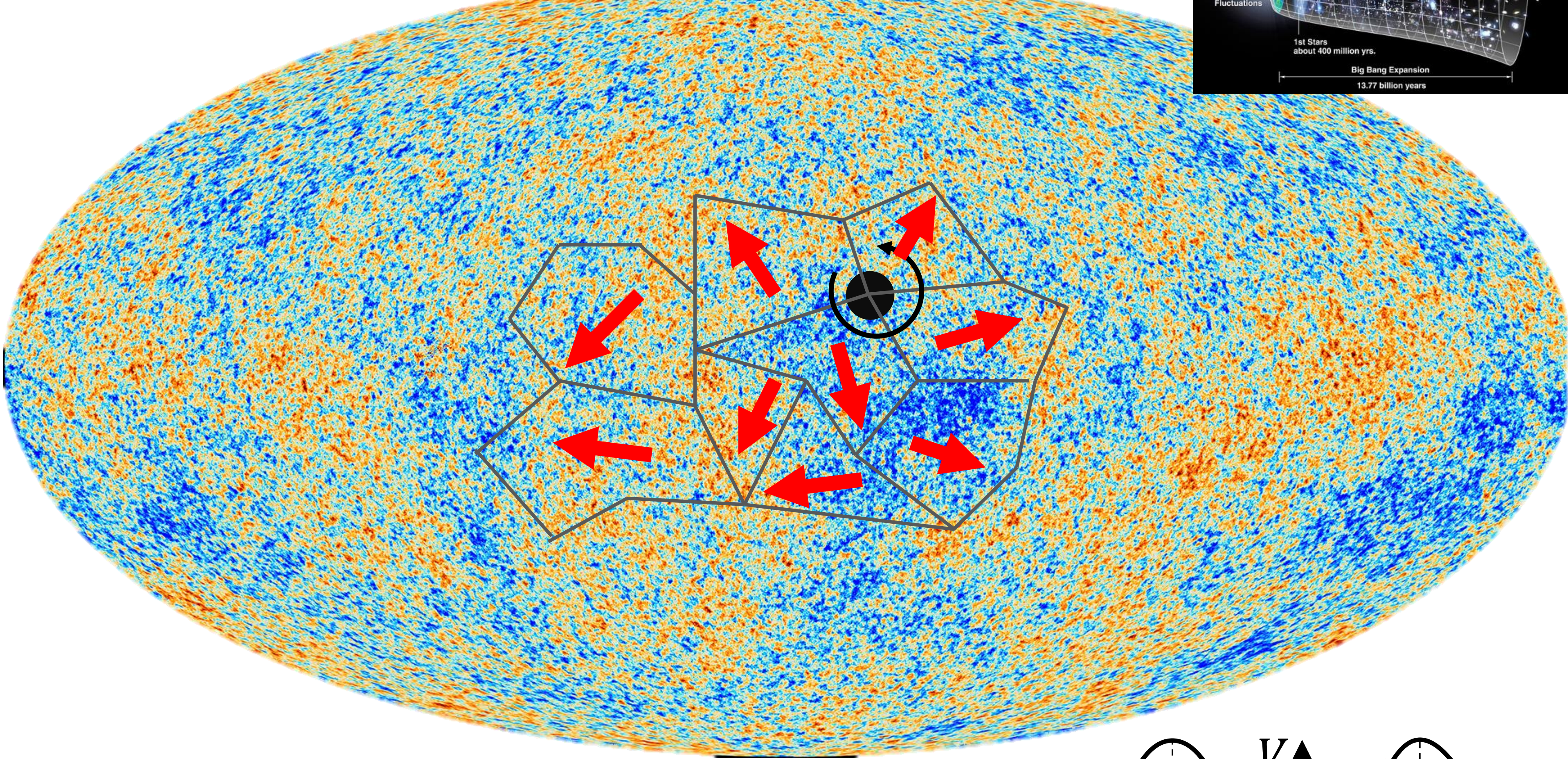
The Birth of Axions

Frank Wilczek
Institute for Advanced Study
Princeton, NJ 08540

usual, very light particle. I called this particle the *axion*, after the laundry detergent, because that was a nice catchy name that sounded like a particle and because this particular particle solved a problem involving *axial* currents.

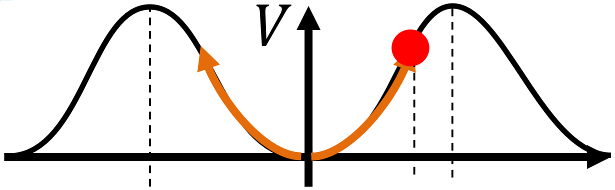
Pre-inflationary scenario





One value of $\overline{\Theta}_i$ in entire visible universe

$$0 < |\overline{\Theta}_i| < \pi$$



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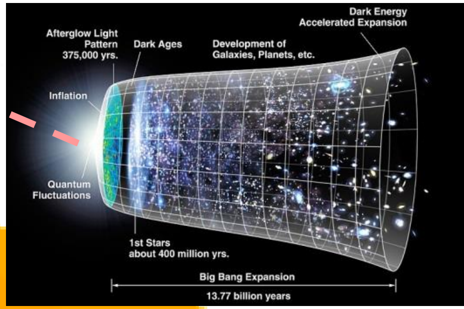
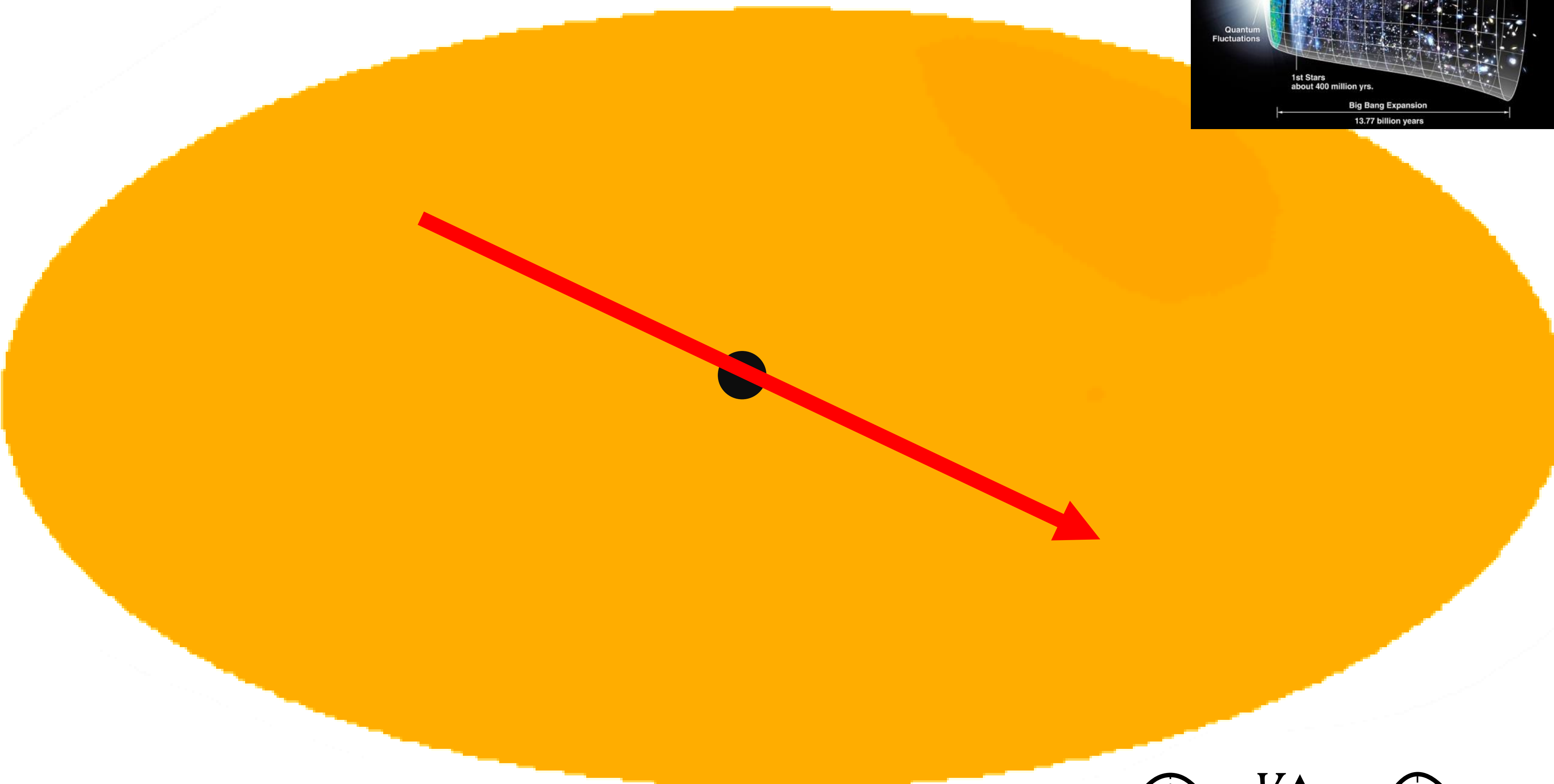
Pre-inflationary scenario





One value of $\overline{\Theta}_i$ in entire visible universe

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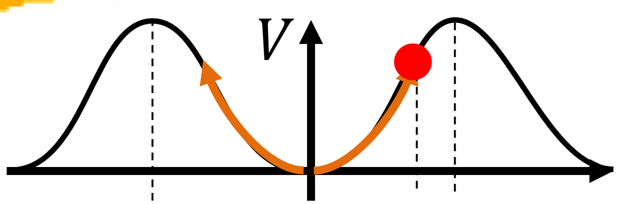
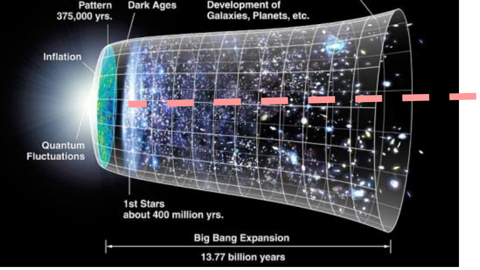
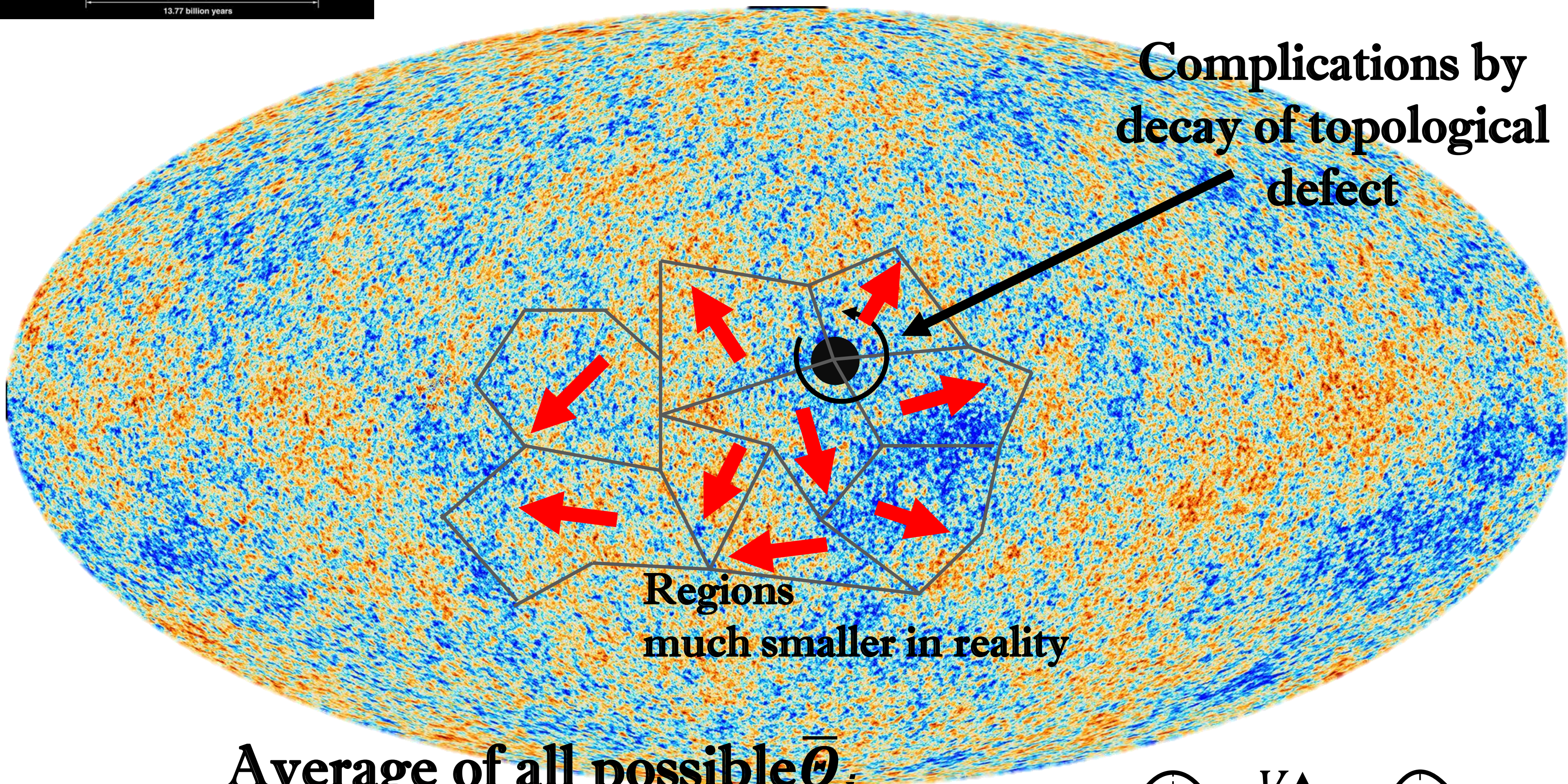


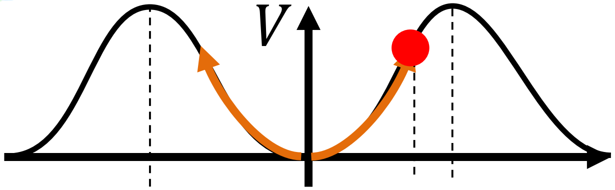


Post-inflationary Scenario

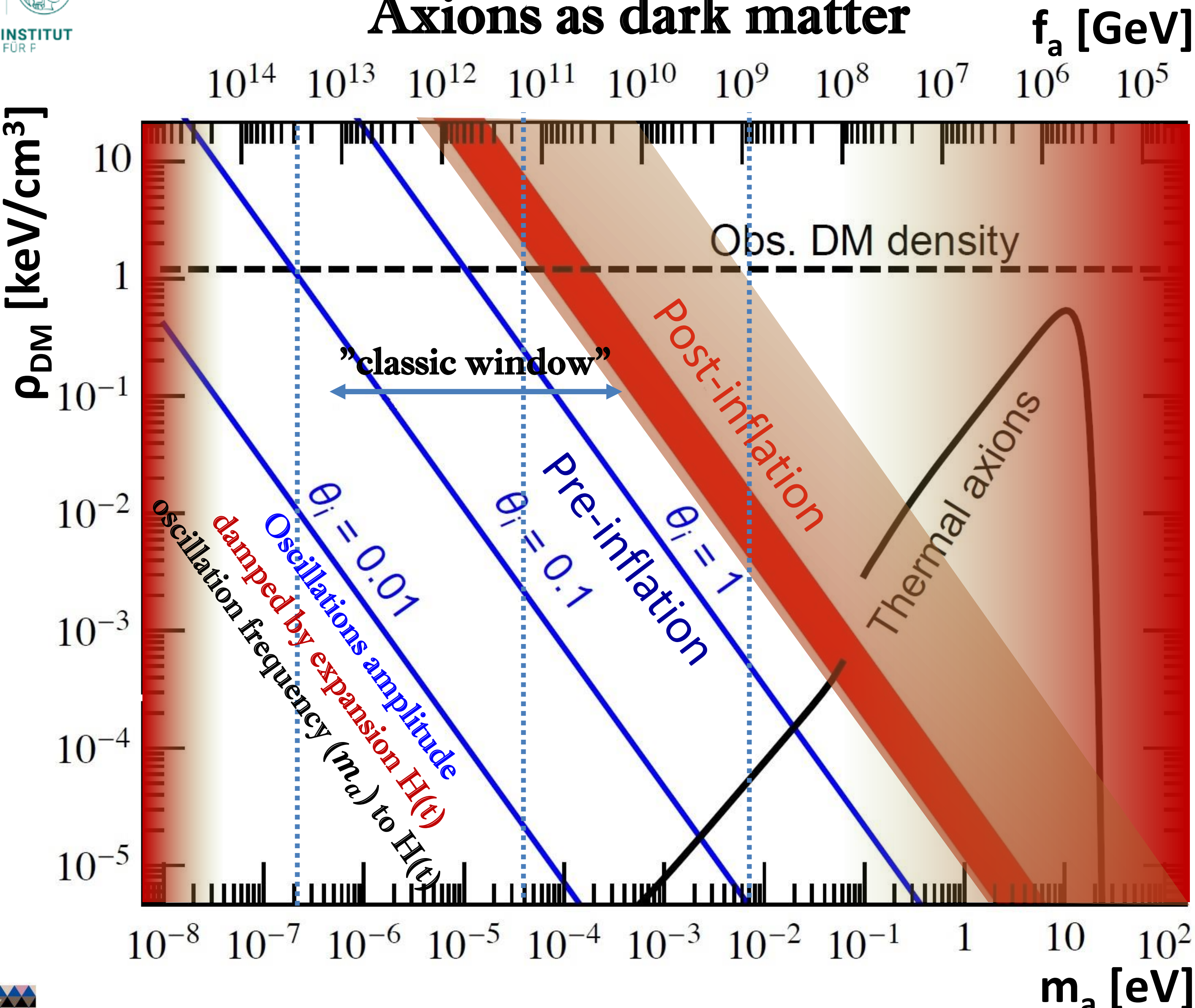


Average of all possible $\overline{\Theta}_i$

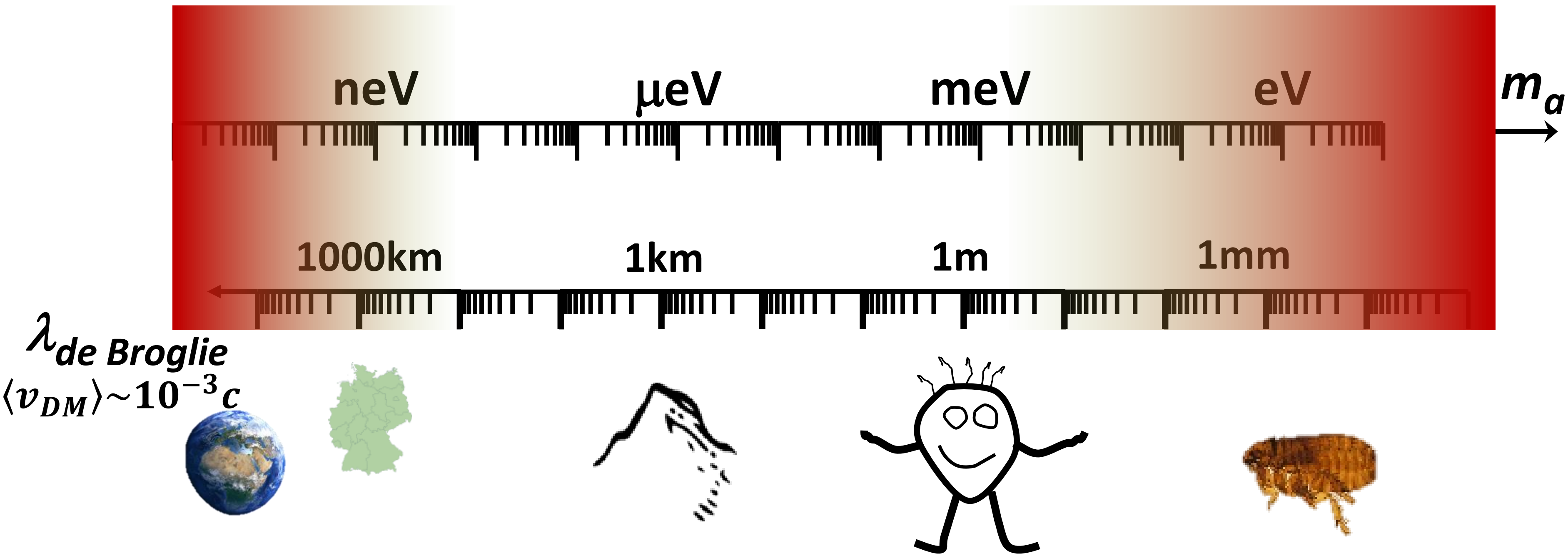
→ Prediction for overall density



Axions as dark matter



The size of DM Axions



Predictions:

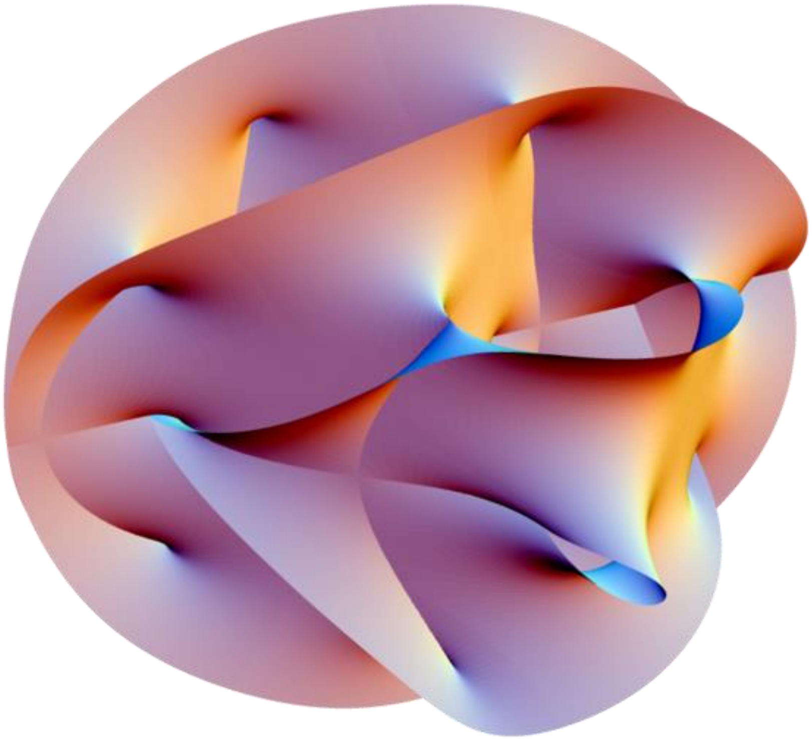
$|\Theta_i|$ arbitrary $0 - \pi$

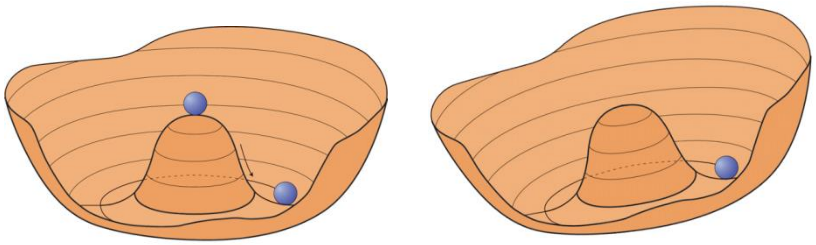
Pre-
Post-
inflationary scenario

$|\Theta_i|$ Ø of all possible values

DM axions fit into experiment!

ALPs emerging from string compactification: the Axiverse





No directe relation btw. m_{ALP} and f_{ALP}

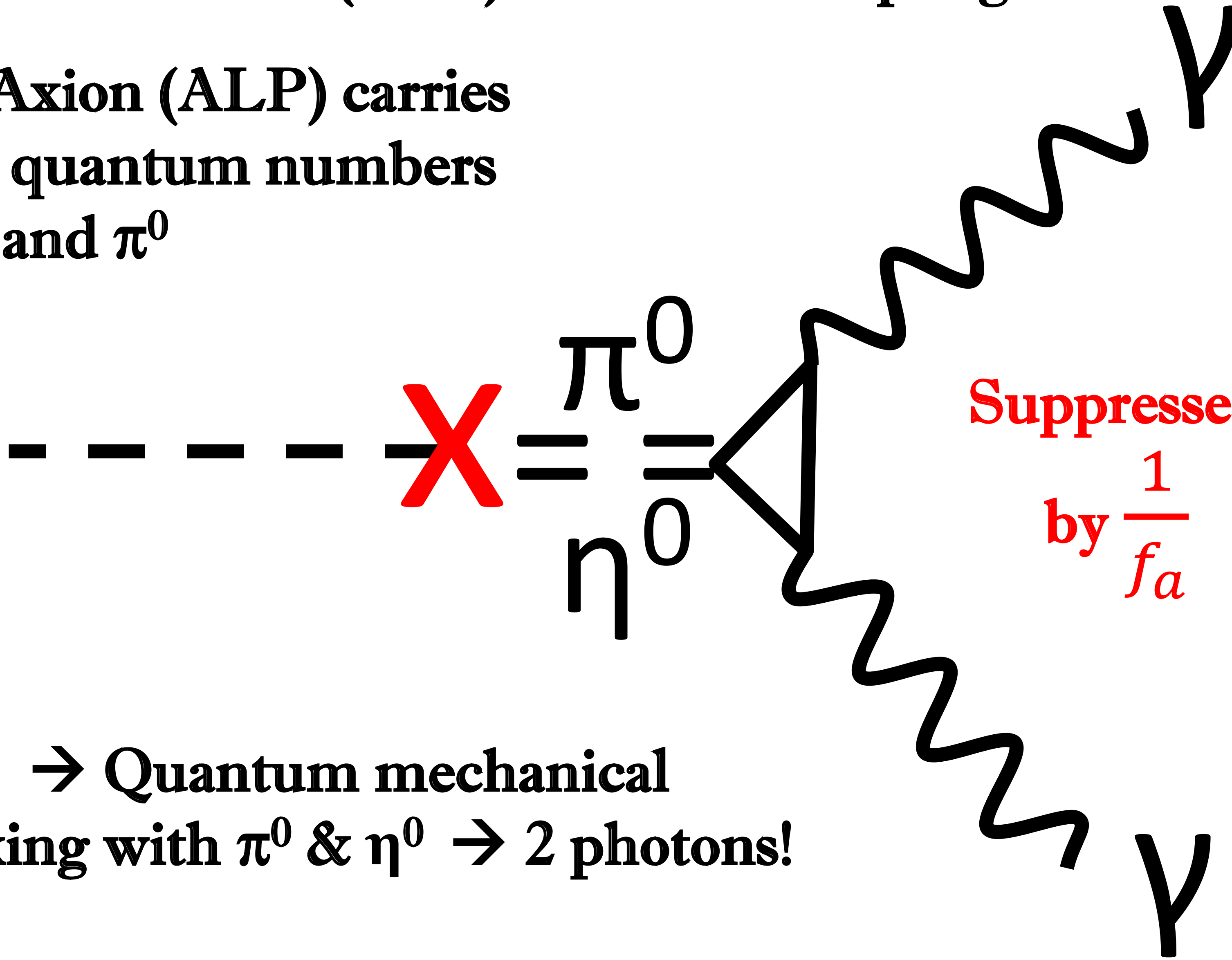
Some astrophysical inconsistencies:

- Transparency hint
- Cooling anomalies

Could be explained by ALPs

Axion (ALP) - Photon Coupling:

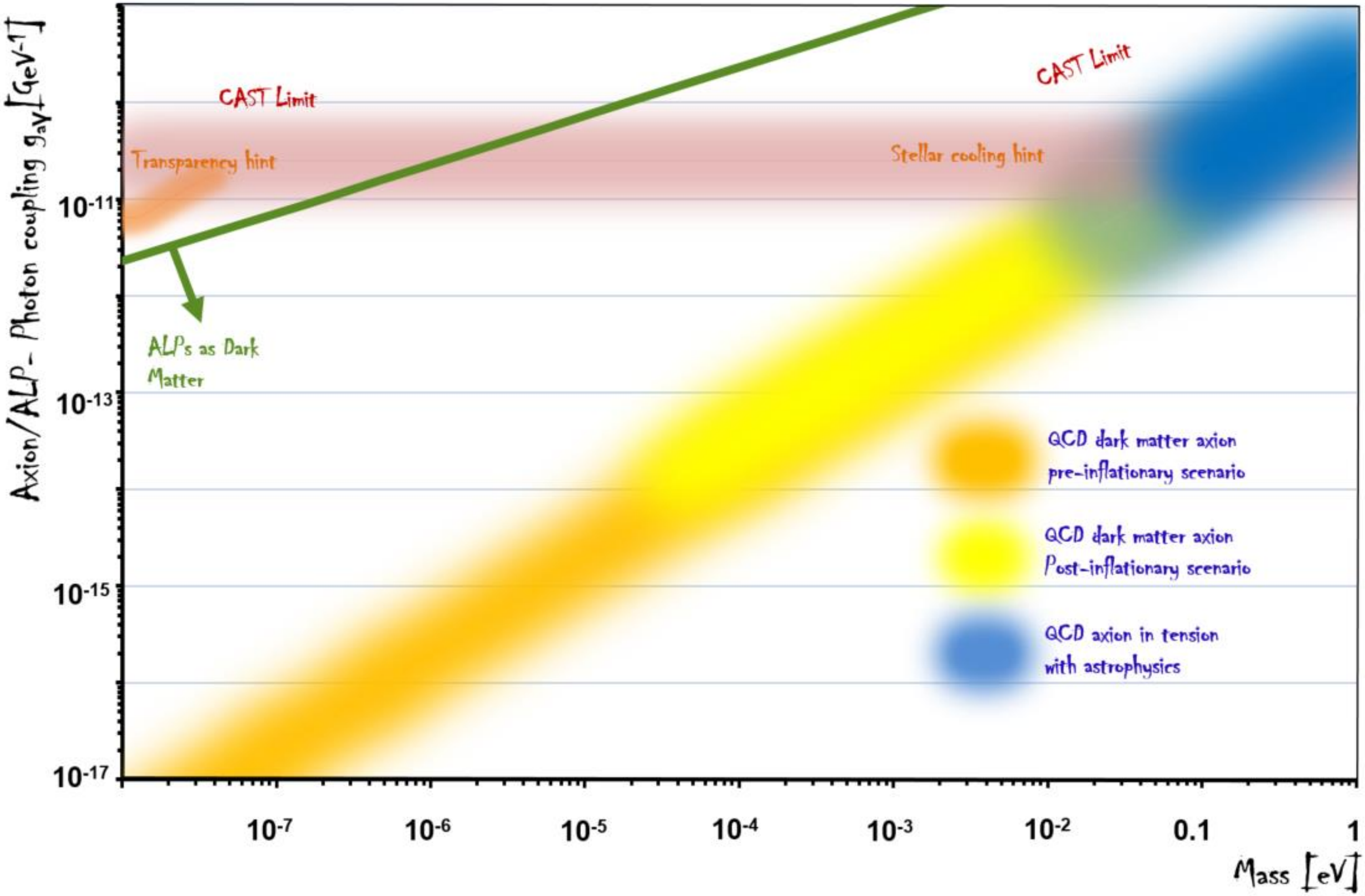
The Axion (ALP) carries same quantum numbers as η^0 and π^0



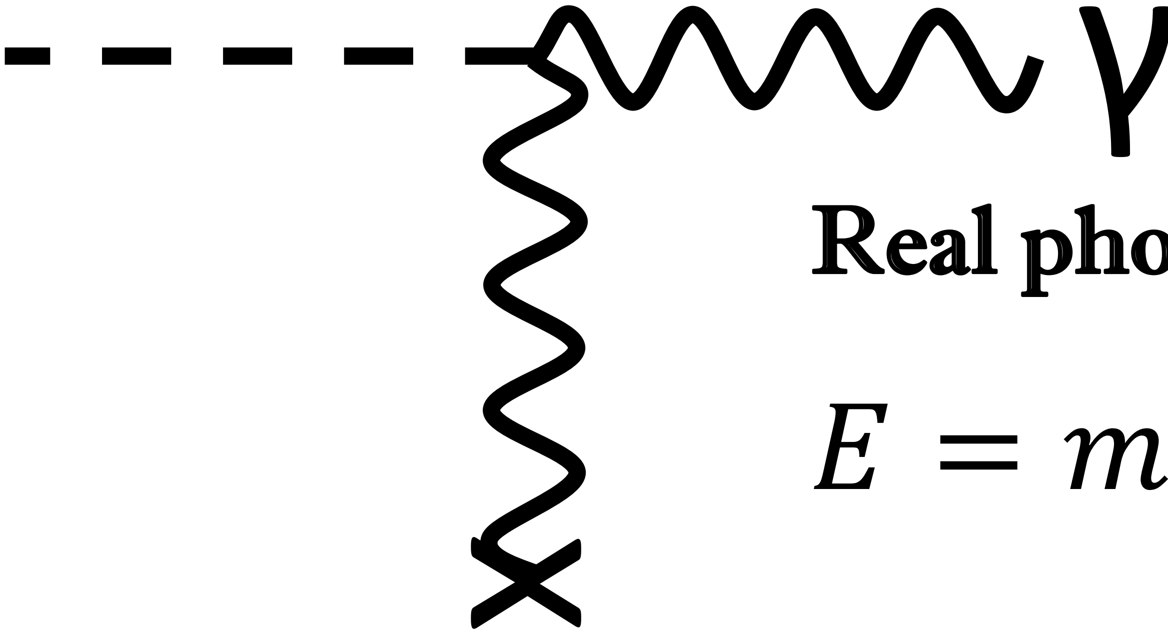
Suppressed by $\frac{1}{f_a}$

→ Quantum mechanical mixing with π^0 & η^0 → 2 photons!

Axion (ALP) - Landscape:



Axion detection: Primakoff Effect:



Real photon

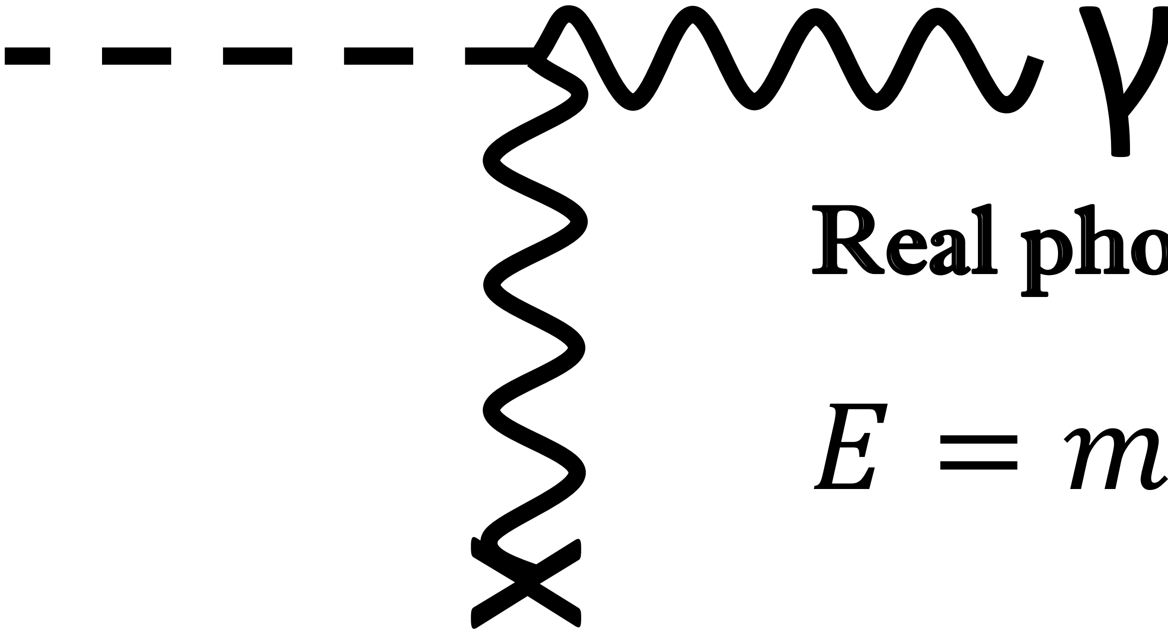
$$E = mc^2 = h\boldsymbol{\nu}$$

B-Field

Suppressed by $\frac{1}{f_a}$

$$\mathcal{L}_{a\gamma} = \frac{\alpha}{2\pi} C_{a\gamma} \frac{a(t)}{f_a} \boldsymbol{E} \cdot \boldsymbol{B}$$

Axion detection: Primakoff Effect:



Real photon

$$E = mc^2 = h\boldsymbol{\nu}$$

B-Field

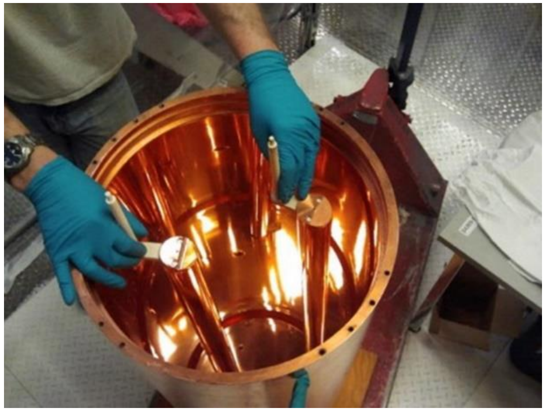
→ Axion in B-field sources E-field oscillations!

Suppressed by $\frac{1}{f_a}$

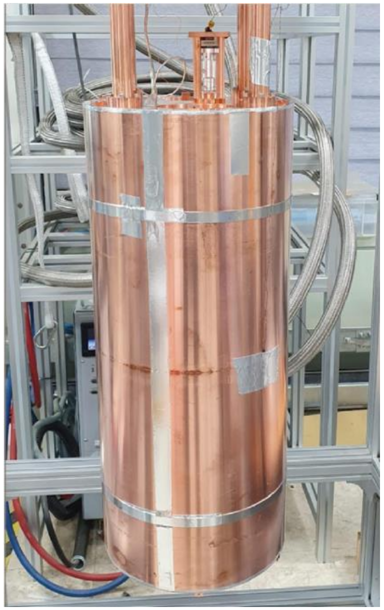
Axion detection: Cavities in B-Field:

→ Use resonator to "pump cavity"

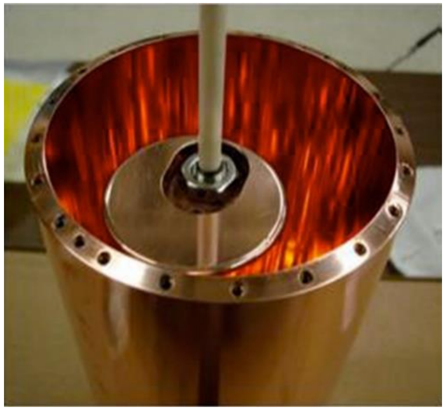
Adjusting resonance frequency: "Tuning Rod"



ADMX
U Washington, USA



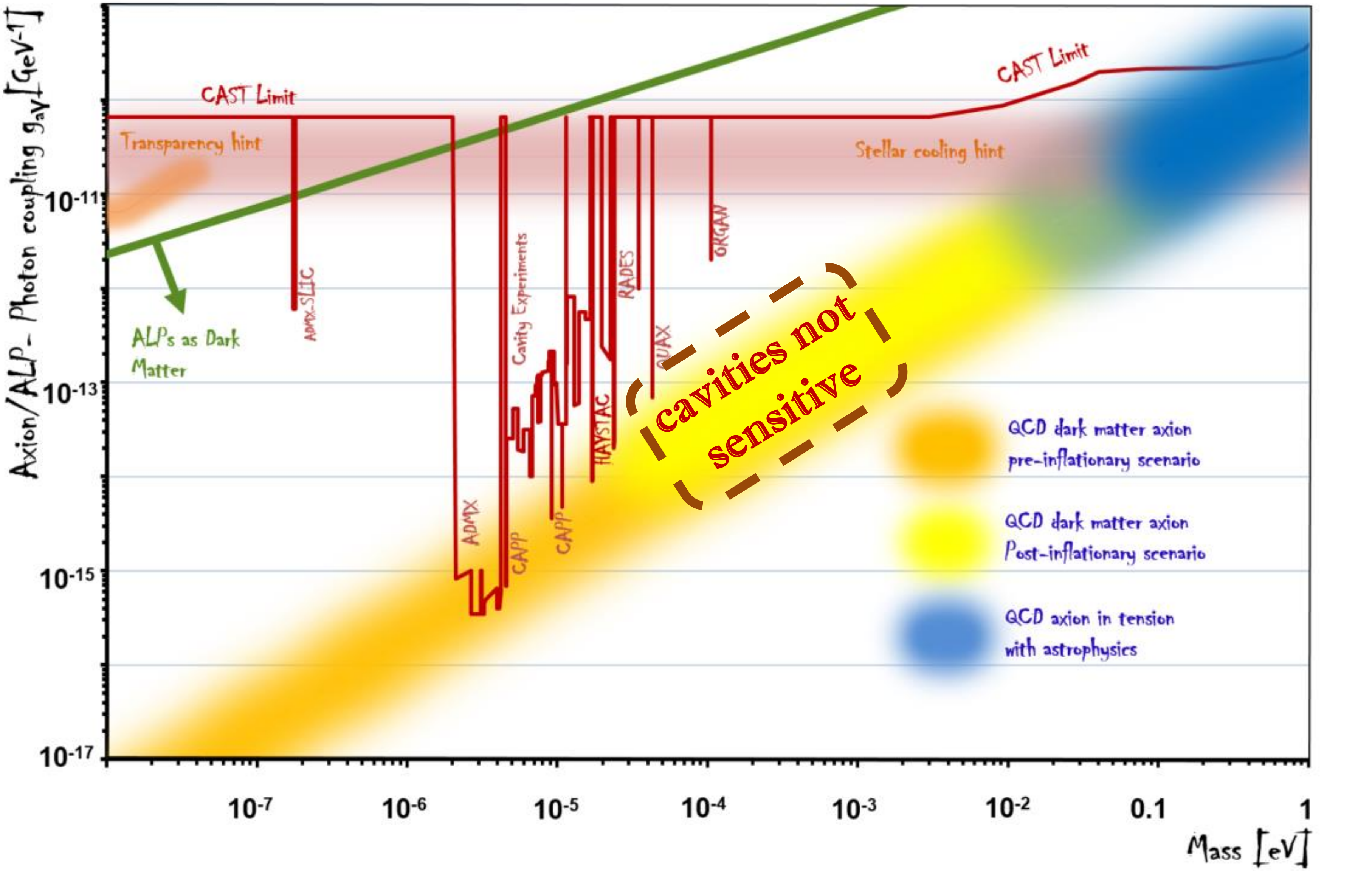
CAPP
IBS, S. Korea



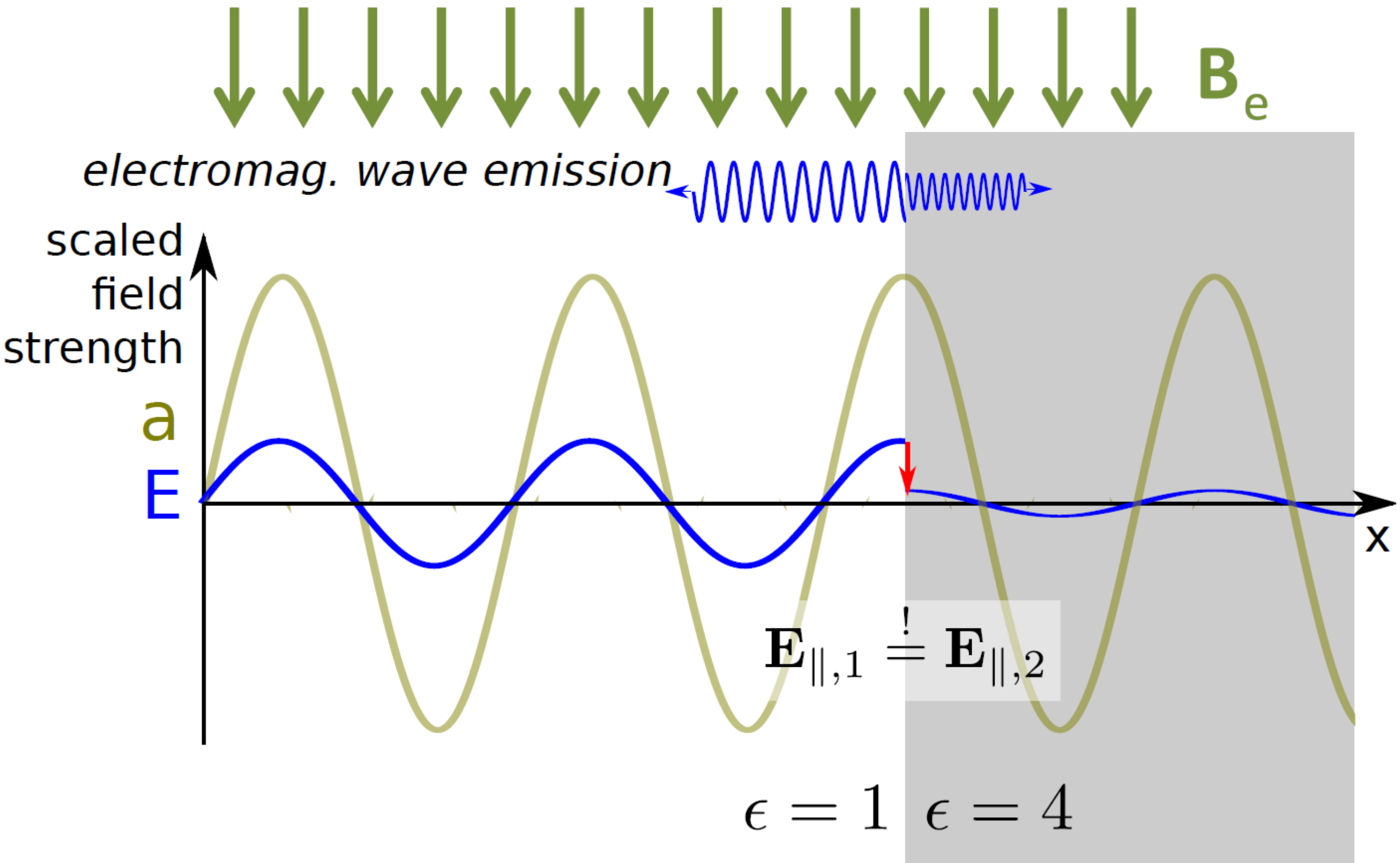
HAYSTAC
Yale University, USA

$$P_{sig} \propto B^2 V\, Q_{cav}$$

$$P_{sig}(B{=}6.8\ T,\ V{=}136\ l,\ Q{=}10^5) \sim 2 \cdot 10^{-22}\ W$$

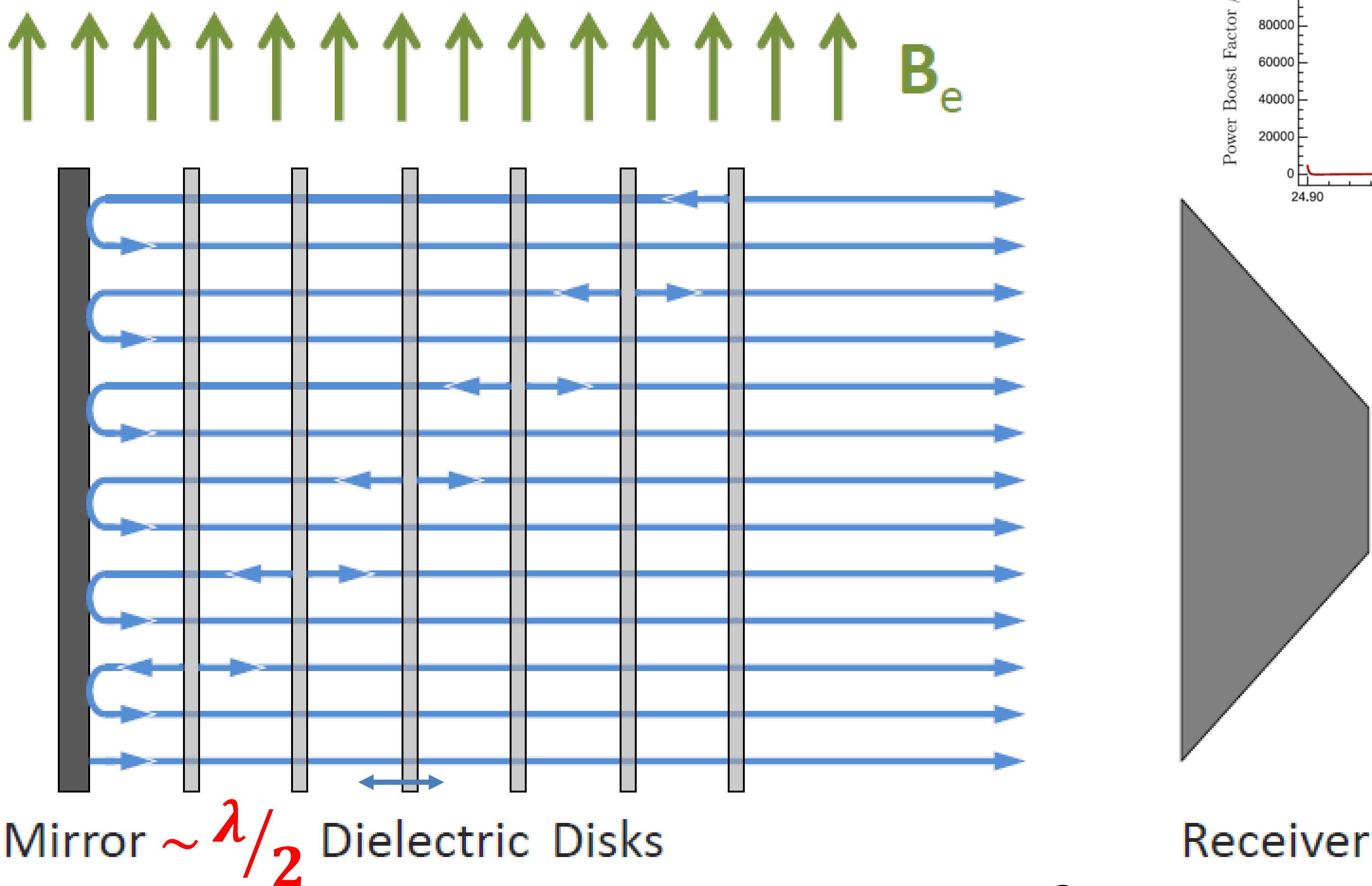

Axion/ALP- Photon coupling $g_{a\gamma}$ [GeV-1]
CAST Limit
CAST Limit
Transparency hint
Stellar cooling hint
ALPs as Dark Matter
ADMX-SLIC
Cavity Experiments
ADMX
CAPP
CAPP
HAYSTAC
RADES
QUAX
ORGAN
cavities not sensitive
QCD dark matter axion pre-inflationary scenario
QCD dark matter axion Post-inflationary scenario
QCD axion in tension with astrophysics
10-11
10-13
10-15
10-17
10-7
10-6
10-5
10-4
10-3
10-2
0.1
1
Mass [eV]

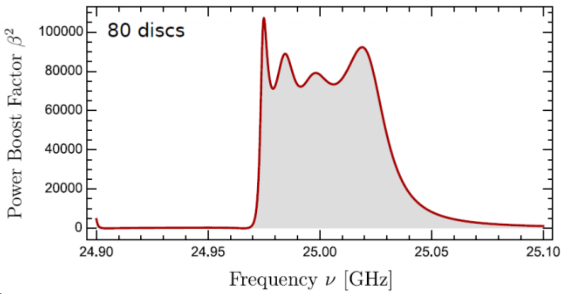
Dielectric Haloscope



$$\left(\frac{P}{A}\right)_{mirror} \sim 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_{||}}{10\ T}\right)^2 \left(g_{a\gamma\gamma} m_a\right)^2$$

Dielectric Haloscope

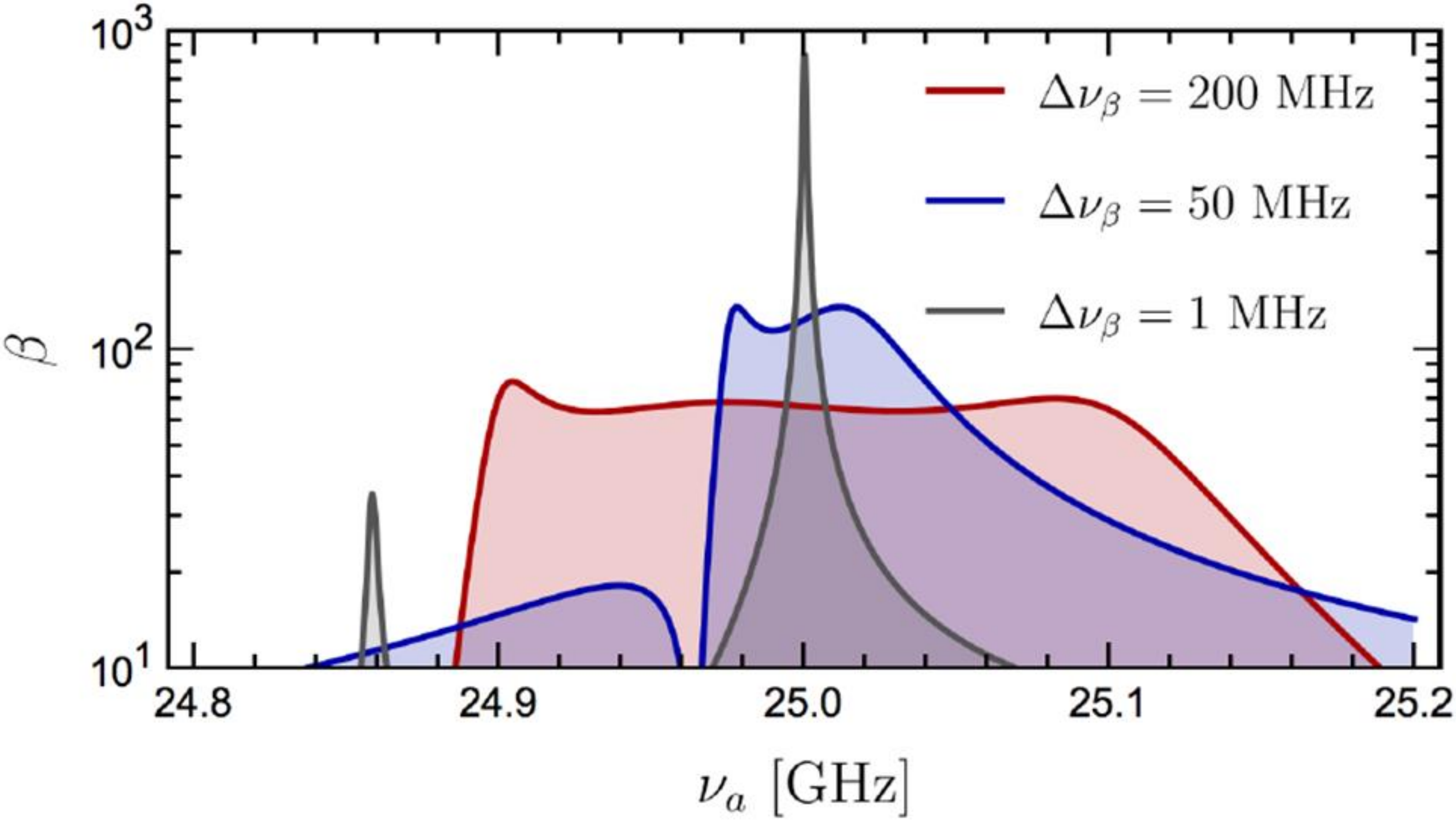




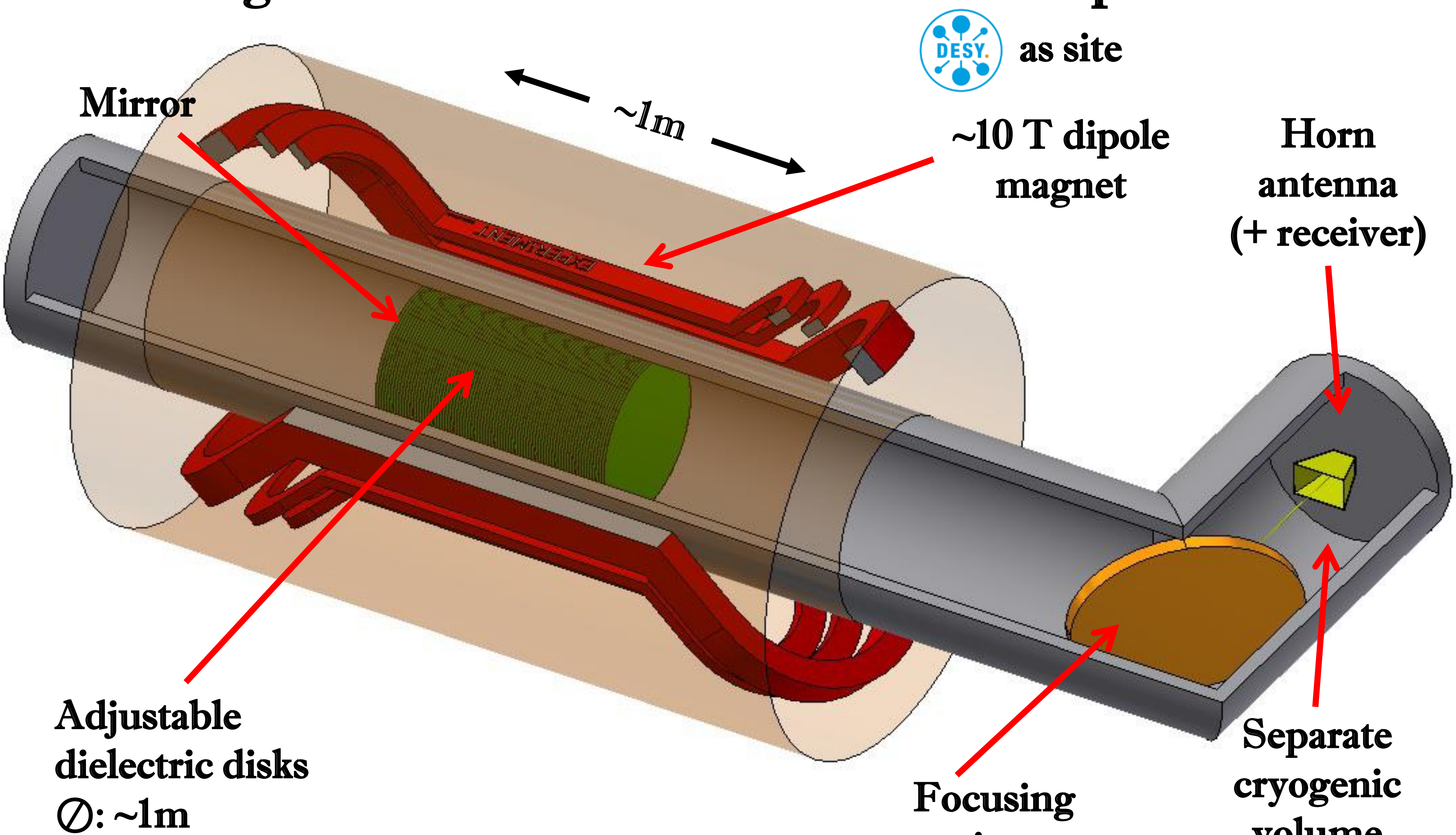
$$\beta^2 = \frac{P_{cavity}}{P_{mirror}}$$

$$\left(\frac{P}{A}\right)_{cavity} \sim 2 \cdot 10^{-27} \frac{\mathrm{W}}{\mathrm{m}^2} \left(\frac{B_{||}}{10\ T}\right)^2 \left(g_{a\gamma\gamma} m_a\right)^2 \beta^2$$

Dielectric Haloscope



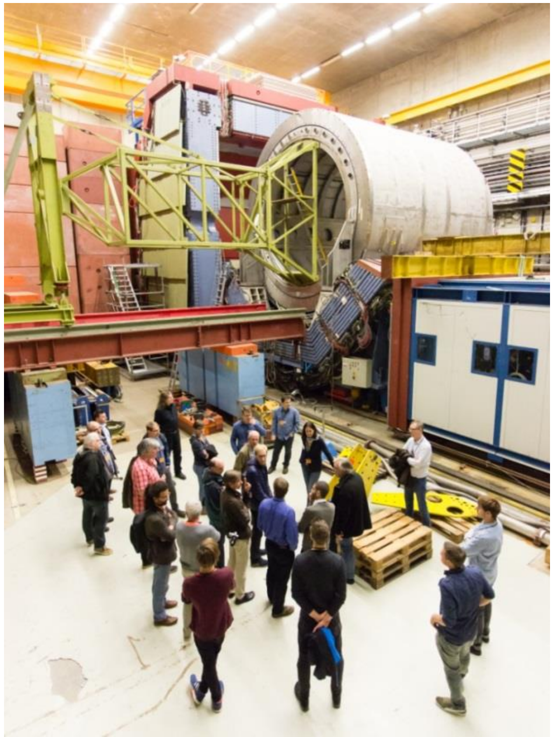
MAgnetized disk and Mirror Axion eXperiment



MADMAX

MAgnetized disk and Mirror Axion eXperiment

Collaboration forming on 18th Oct. 2017

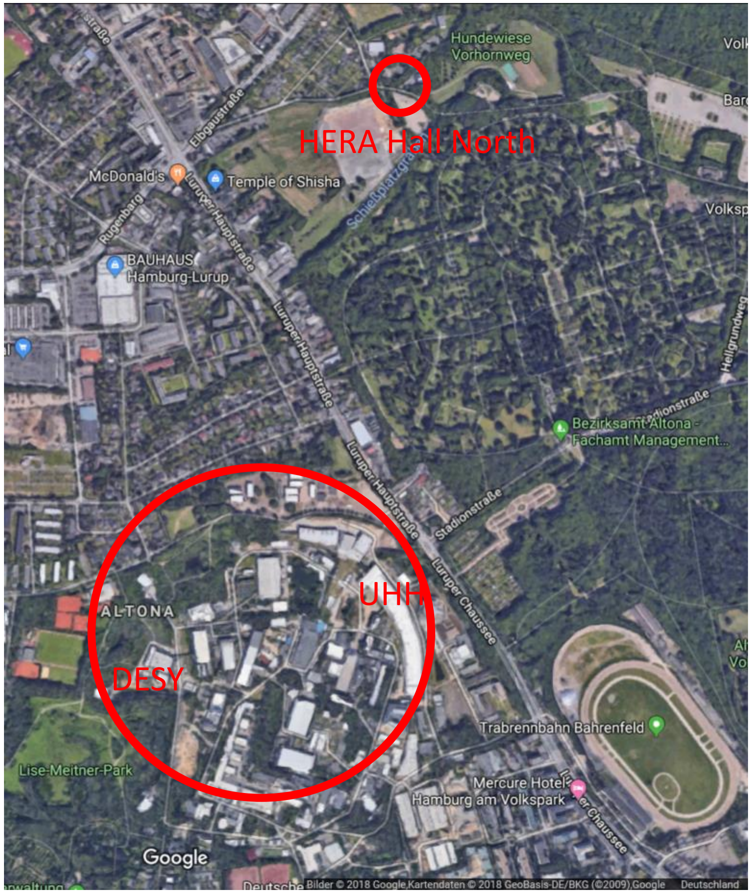


MADMAX **institutes:**

RWTH AACHEN UNIVERSITY, Max-Planck-Institut für Radioastronomie, DESY, Universität Hamburg, Max-Planck-Institut für Physik, Irfu - CEA Saclay, cea, Eberhard Karls Universität Tübingen, Universidad Zaragoza, Néel institut, CPPM

MADMAX

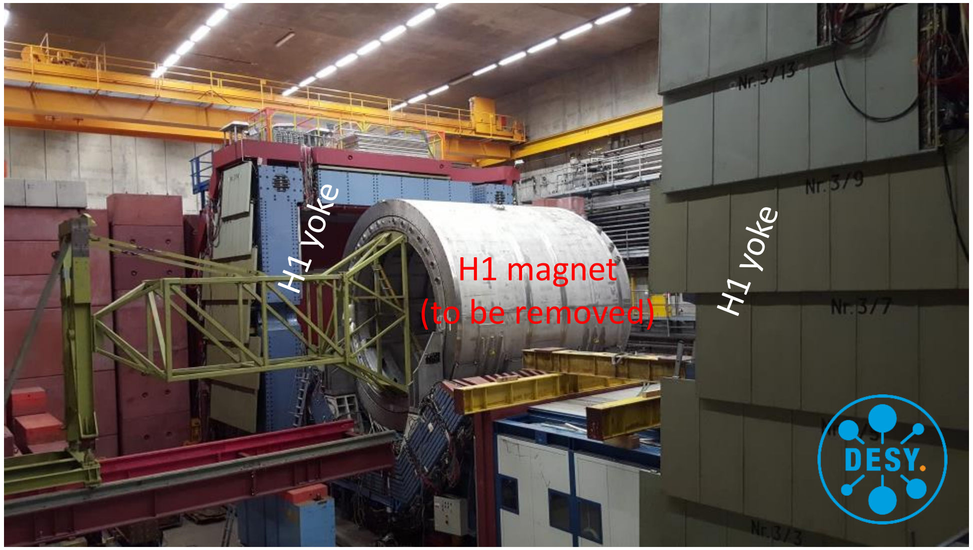
Designated Experimental Site



MADMAX to be operated at HERA Hall North

Make use of DESY infrastructure

Benefit: re-use H1 yoke as magnetic shielding to reduce fringe field and increase B field

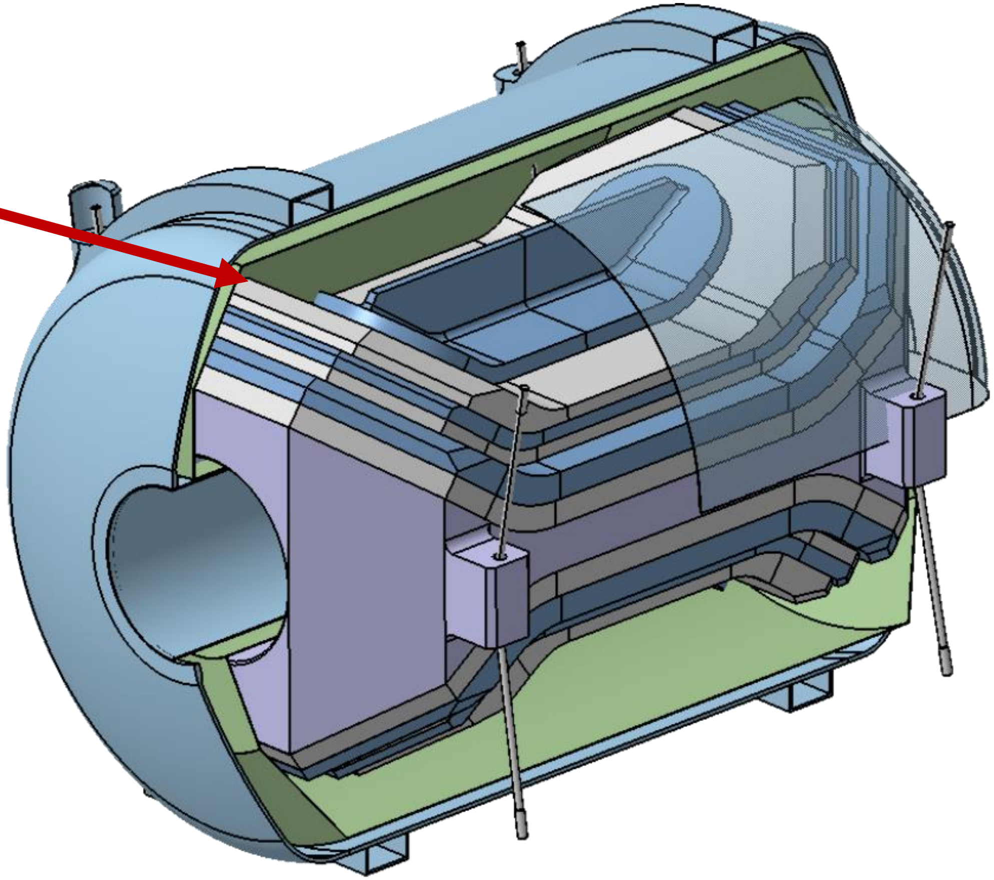


The MADMAX magnet

Design and R&D on 9T large bore dipole magnet

FoM: 100 T^2m^2 stored energy ~ 500MJ

Baseline design:
2 * 9 "skateboard coils"
with novel
copper CICC conductor



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BILFINGER BILFINGER NOELL GMBH

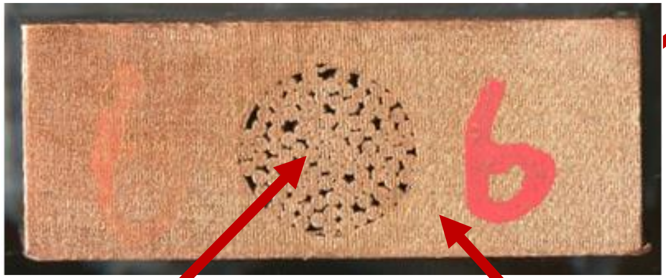
cea

The MADMAX magnet

Design and R&D on 9T large bore dipole magnet

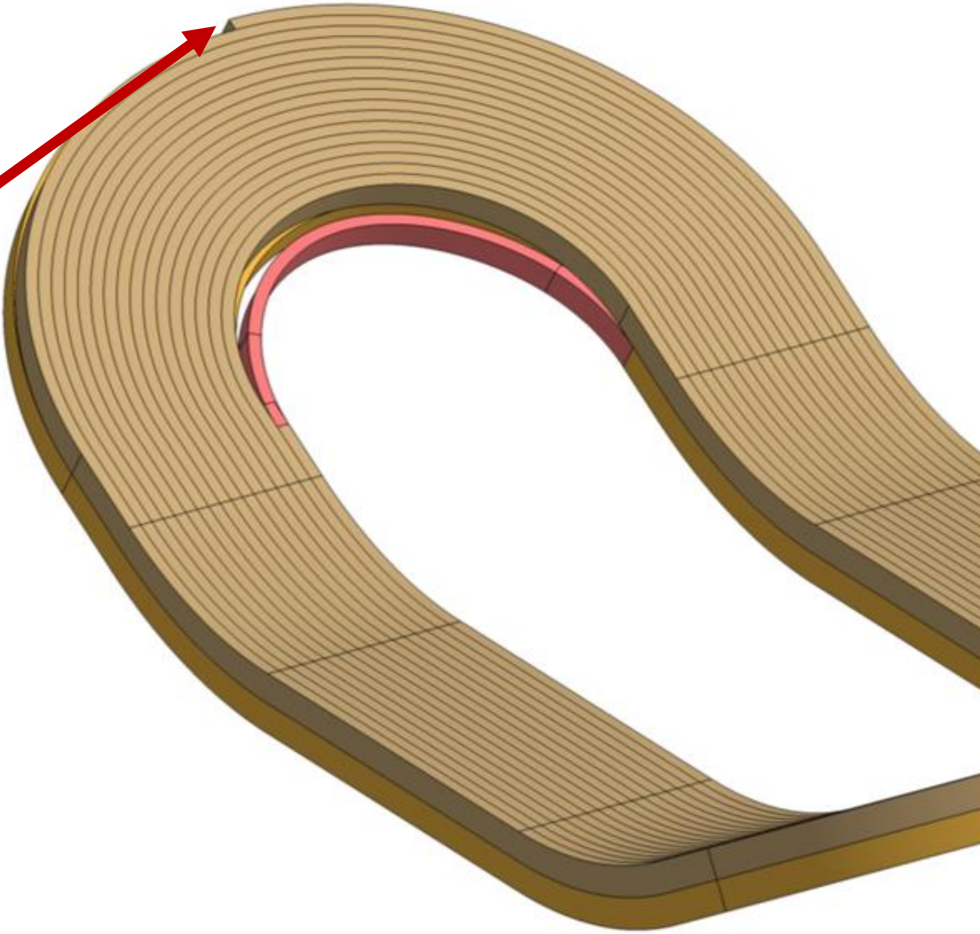
FoM: 100 T^2m^2 stored energy ~ 500MJ

Baseline design:
2 * 9 "skateboard coils"
novel copper CICC conductor



NbTi and Cu strands

Copper doncuit



- ✓ Insertion tested
- ✓ Compaction → right fill ratio
- ✓ Yield strength after cold work ok

The MADMAX magnet

Main project risk: Quench detection

Dedicated magnet:
→ characterize quench propagation

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BILFINGER NOELL GMBH

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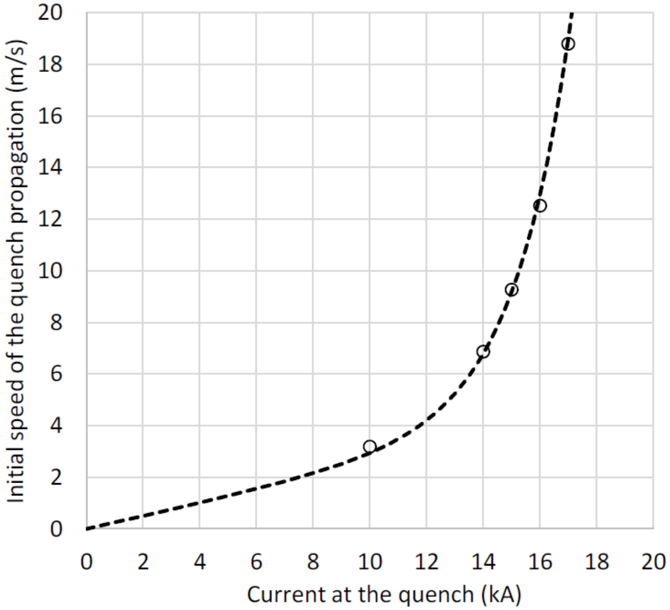
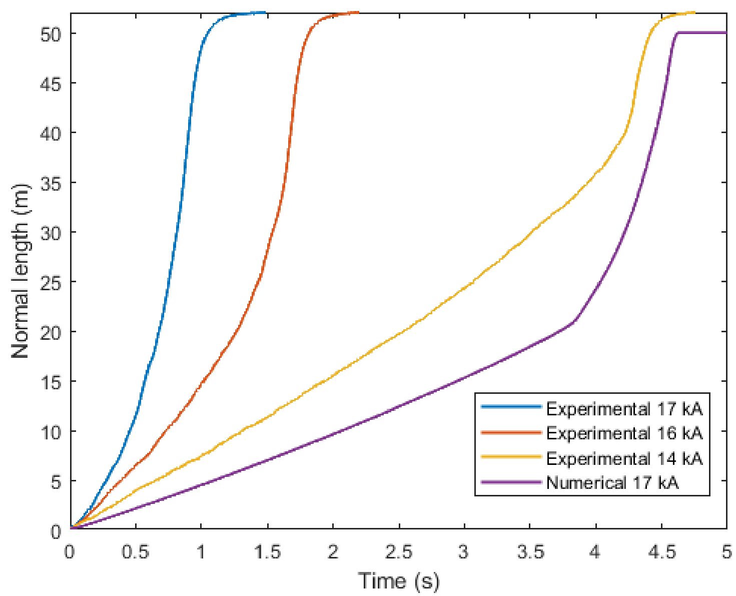
The MADMAX magnet

Main project risk: Quench detection

Quench propagation velocity:



Thermo hydraulic quenchback:

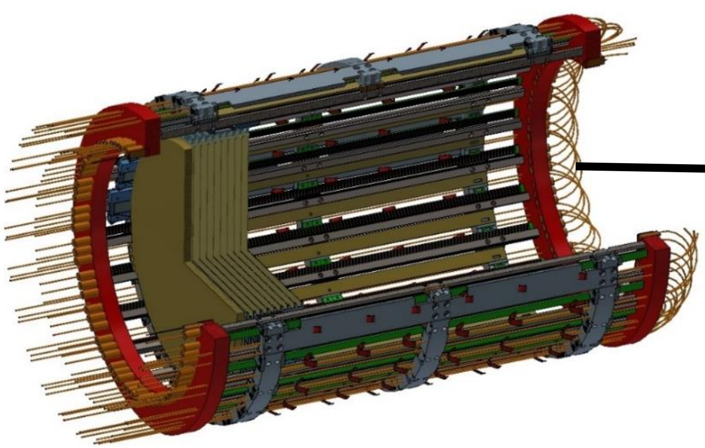


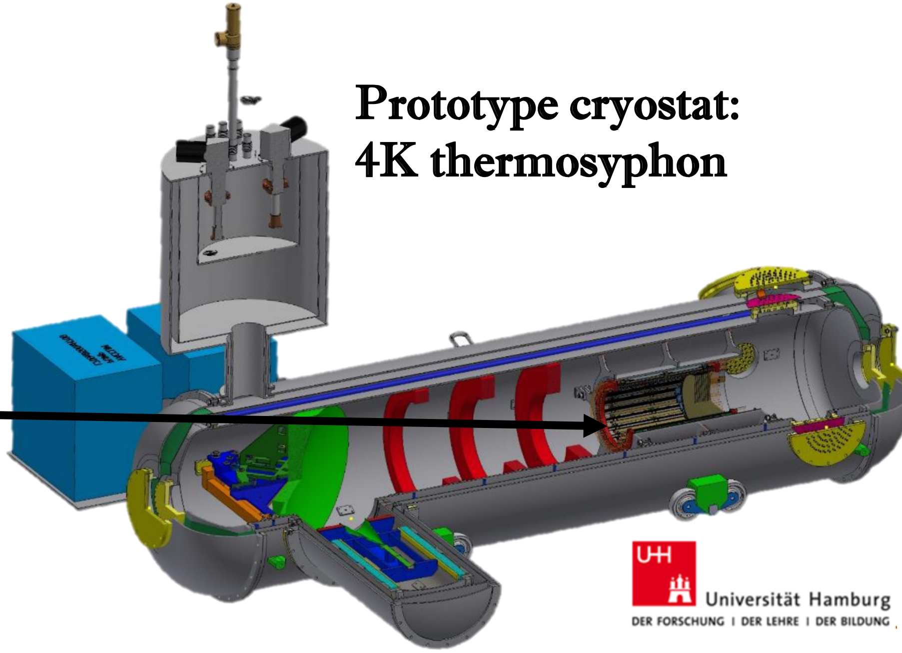
Quench propagation understood
→ Safe to operate magnet!

MADMAX prototype

Scaled down version of MADMAX:
- Reduced number of disks, 1/16 disc area (Ø:300mm)
- 1/5 magnetic field (1.6 T, MORPURGO @ CERN)

Main goals
- Demonstrating and prototyping key technologies
- Competitive ALP search

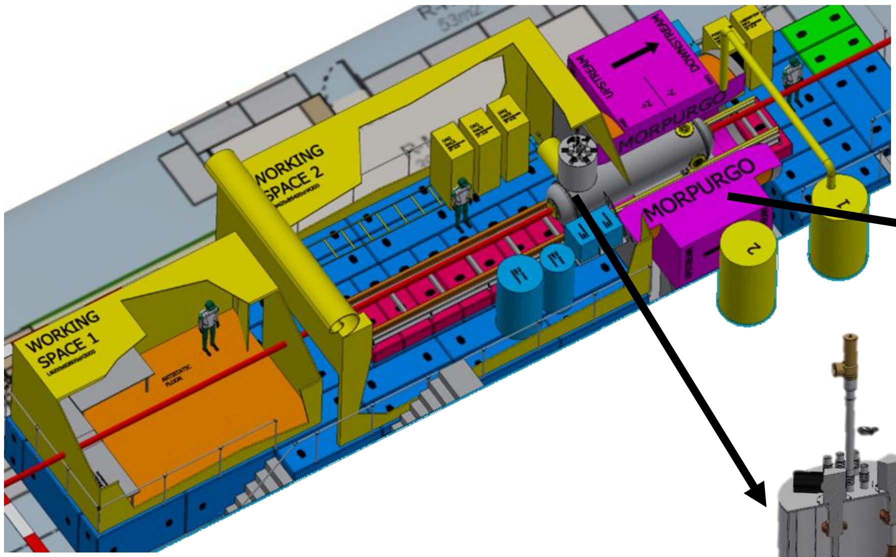


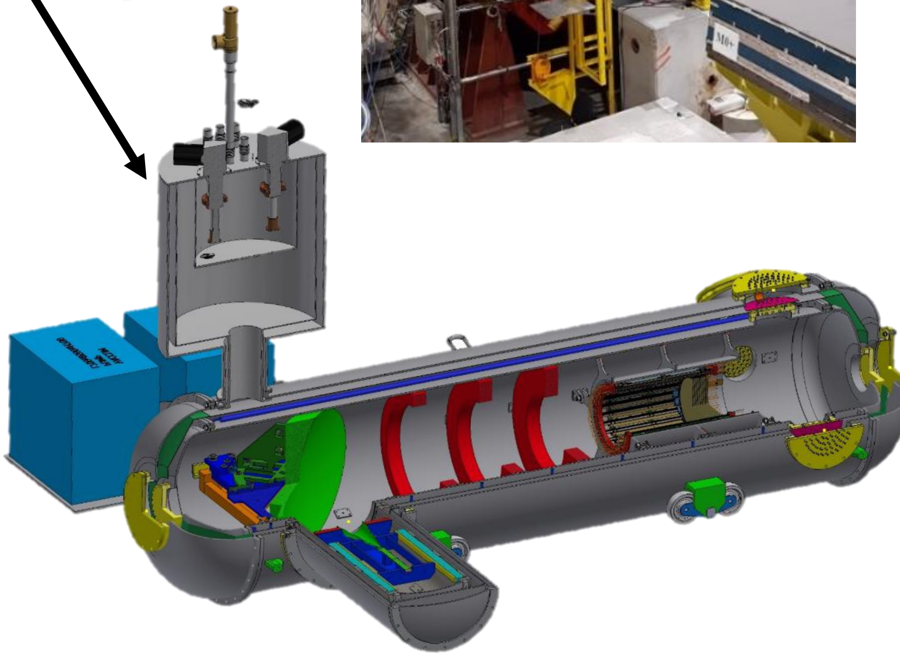


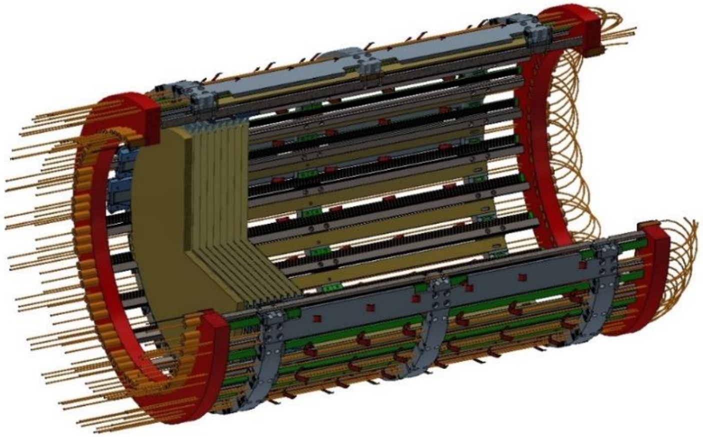
Prototype cryostat:
4K thermosyphon

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

MADMAX prototype







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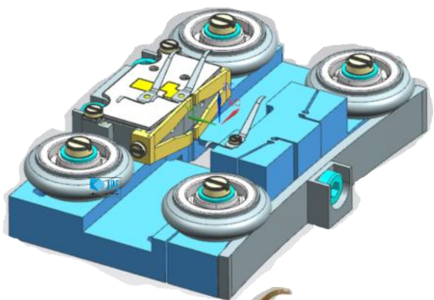
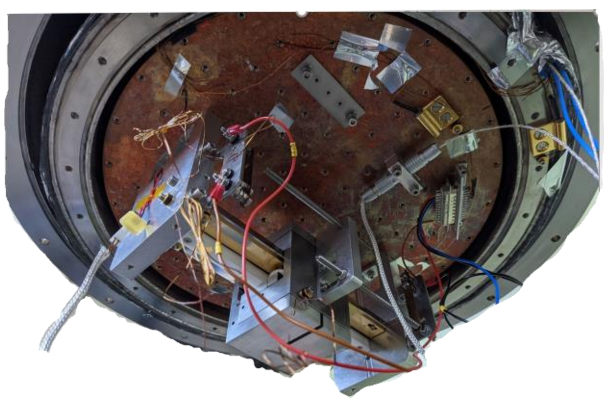
JPE Driven by Innovation

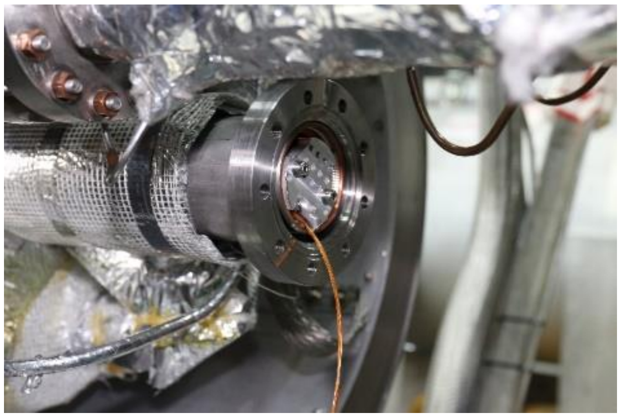
The MADMAX mechanics

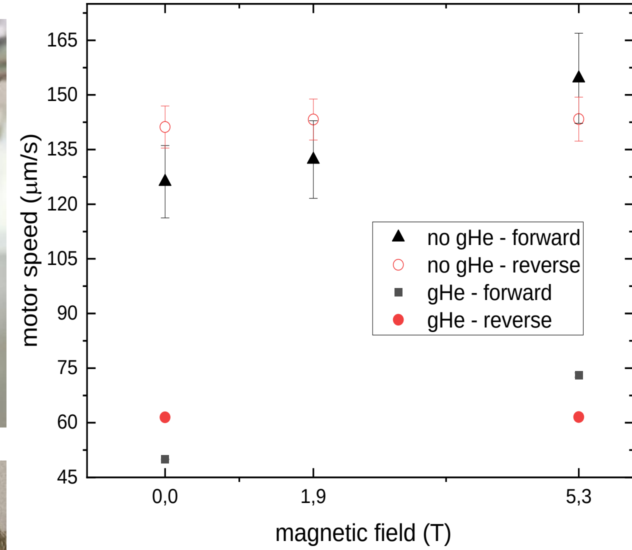


Feasibility of disc motors at 4K in strong B-field

- ✓ Developed Piezo motor drive unit
  Repeatability < 1µm
- ✓ Characterized at 4.2 K ambient temperature
  Speed > 0.1mm/sec
- ✓ Tested at 5 K in 5.3T magnet at DESY:
  Moves reliably



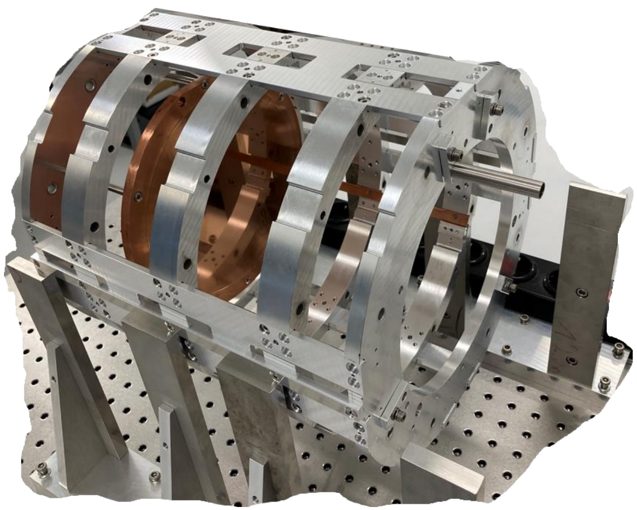




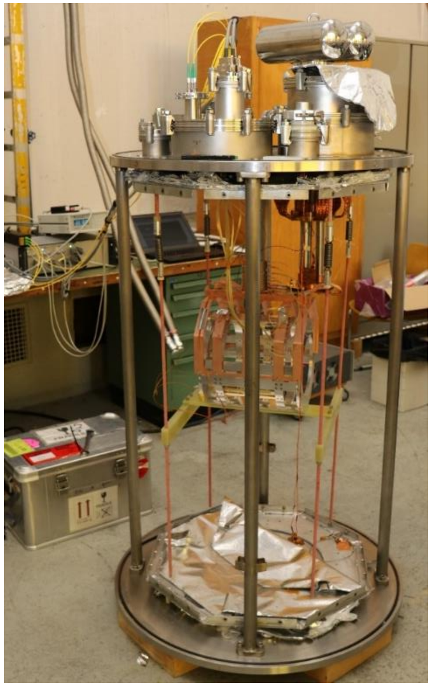
The MADMAX mechanics

Mechanical test bed:
Verify mechanical feasibility of Baseline design

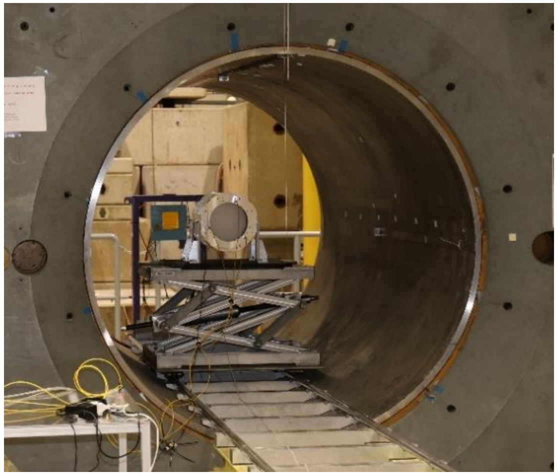
Disc movement with required accuracy at cold in high B-field



Project 200:
One disc (200mm)
In front of mirror



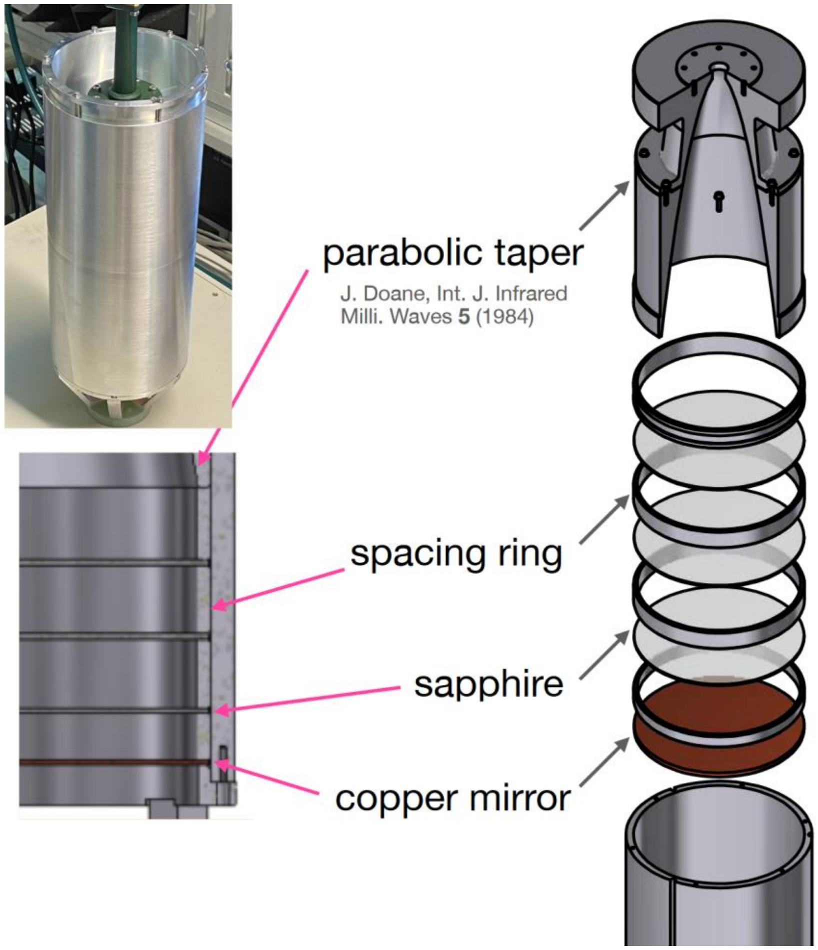
Operated in cryostat



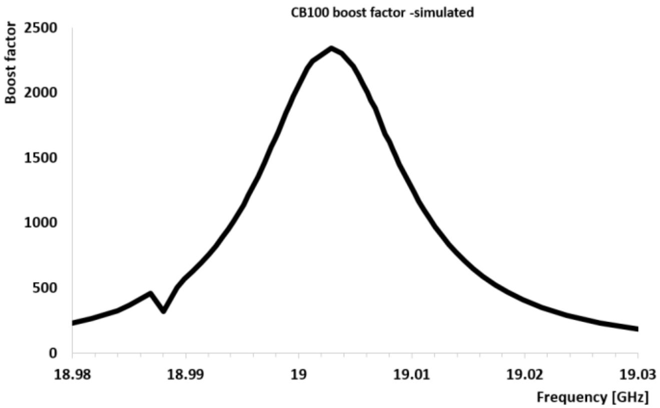
Operated in 1.6T MORPURGO magnet at CERN

The MADMAX RF response

Closed booster 100



- Three sapphire discs 100m
- Resonant configuration
- Coupling to LNA via taper

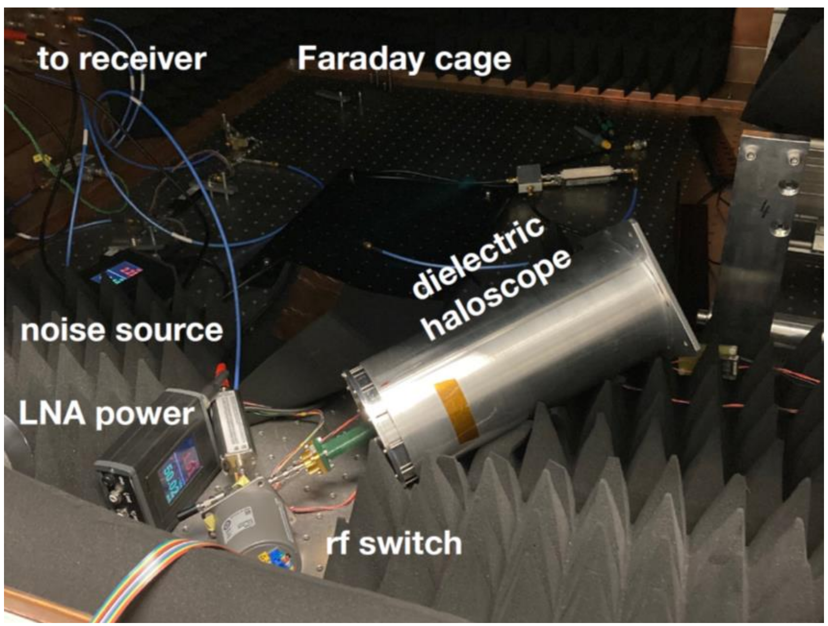


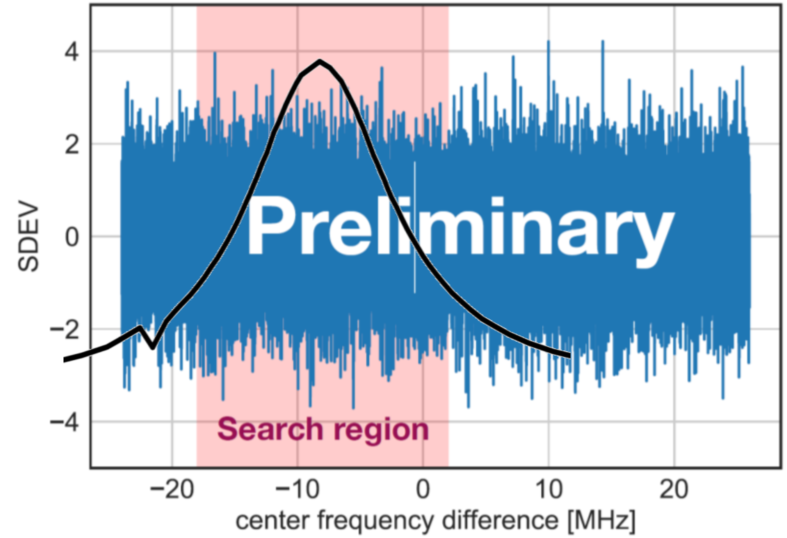
- Understand RF behavior in well defined boundary conditions
- Develop calibration procedure: reflectivity and system temperature
- First ALPS and HP measurement

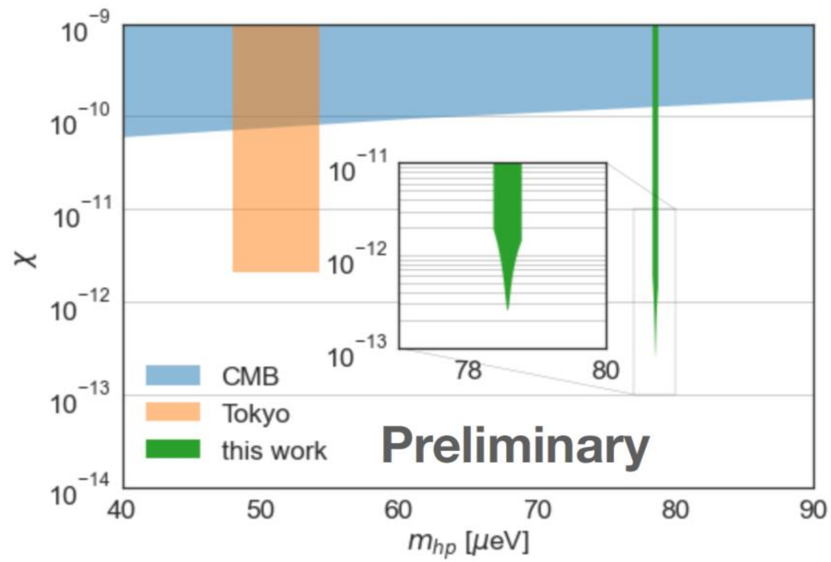
First MADMAX HP measurement

Faraday cage at MAX-PLANCK-INSTITUT FÜR PHYSIK lab

B = 0 T, t = 32 days



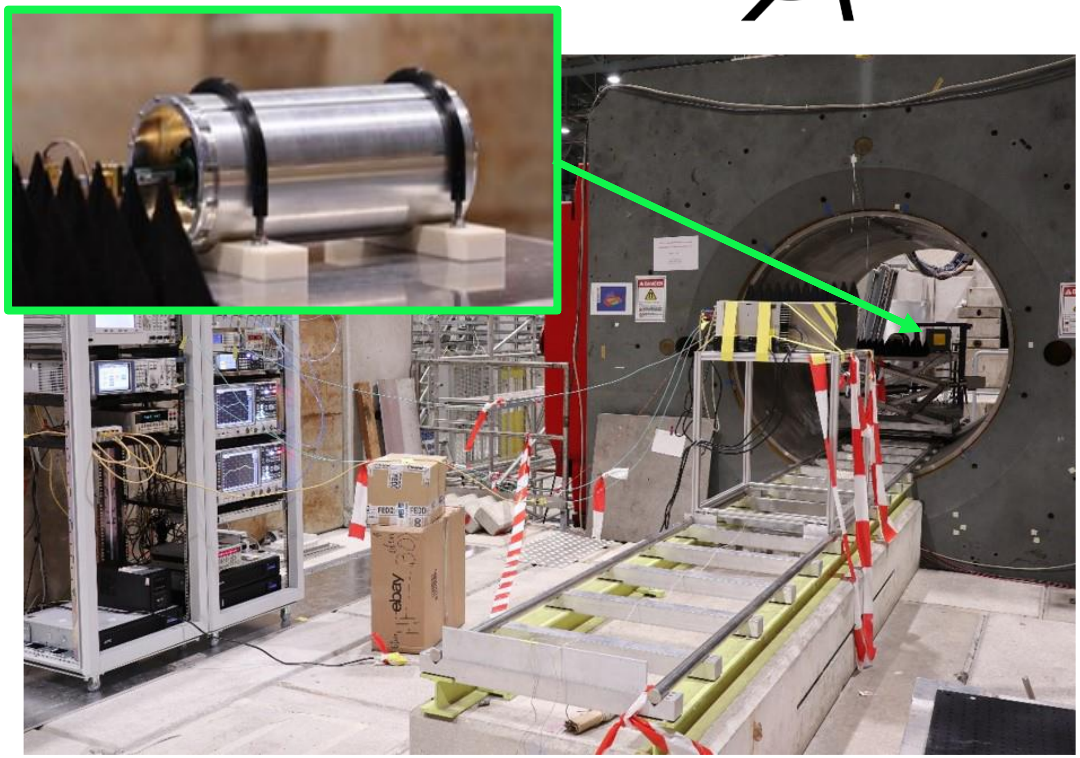


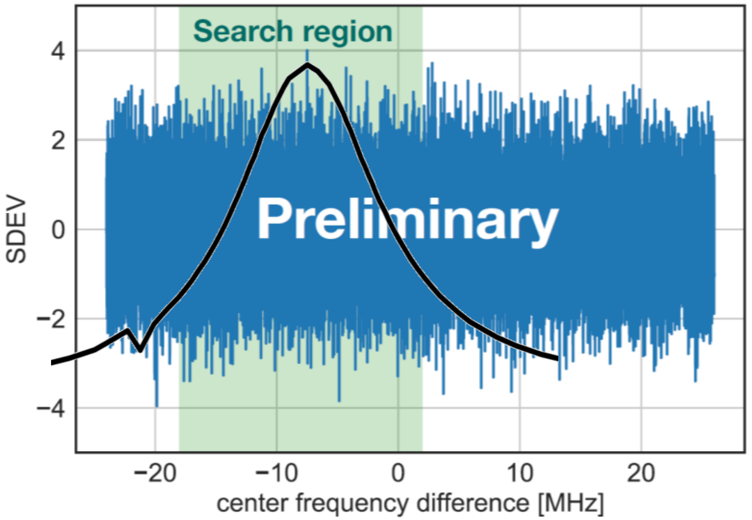


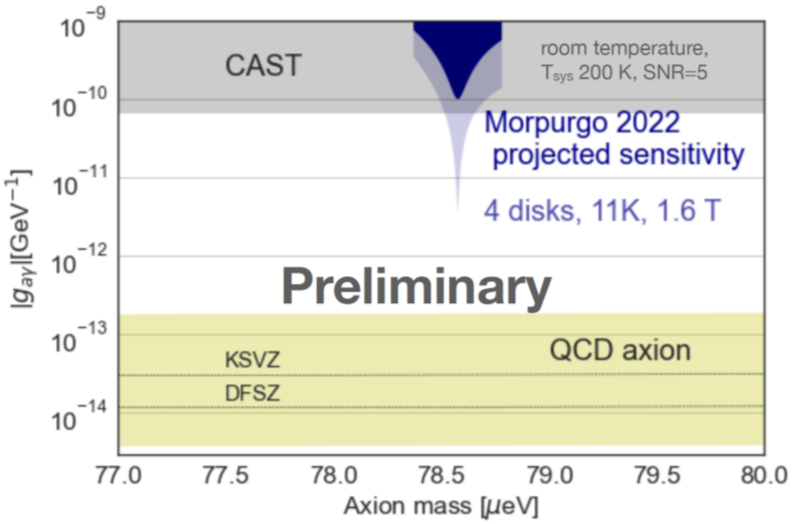
First MADMAX ALP measurement

B = 1.6 T, t = 10.5 hours

MORPURGO magnet at CERN





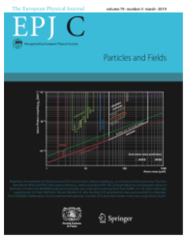


MADMAX timescale

2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | >= 2028

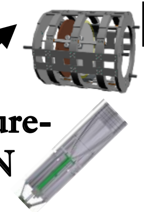
Design Phase — **Prototyping Phase** — **Construction Phase**

Foundation of MADMAX Collaboration

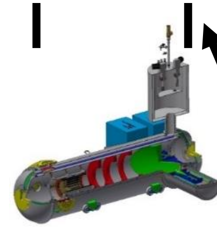


First endorsement by DESY PRC

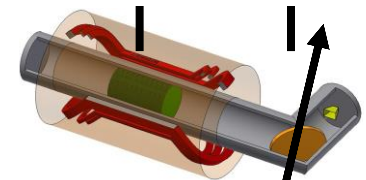
First ALP measurement at CERN



Prototype commissioning to start in 2023



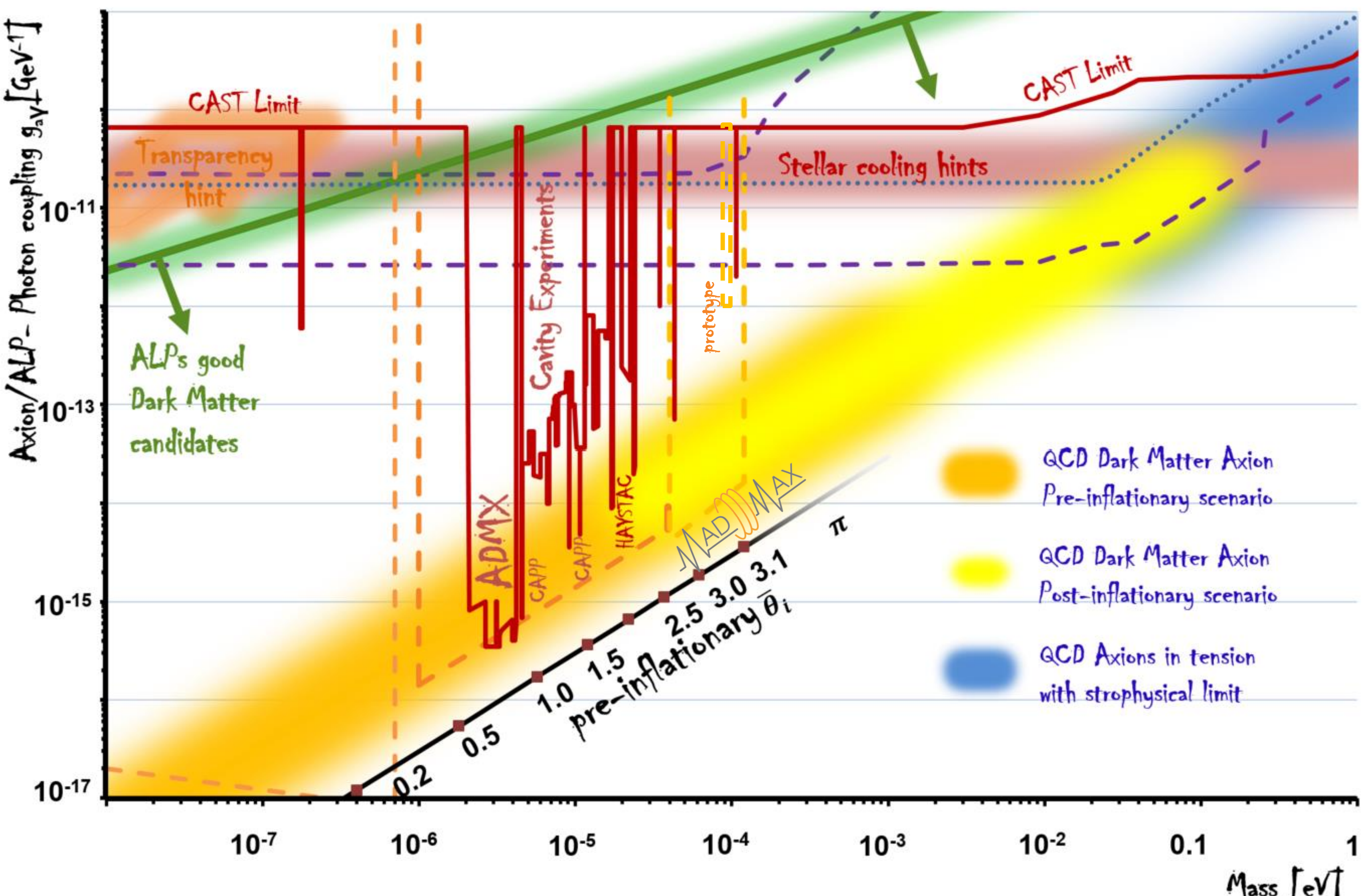
First physics data taking at cold @ CERN



Full-size MADMAX magnet commissioning
Installation at DESY

Usage of MORPURGO magnet approved by CERN Research Board for 2021-2025

The search for axion dark matter with a dielectric haloscope: MADMAX



Note: other proposals for >40 μeV detection exist:
plasma haloscope, dish antenna, …

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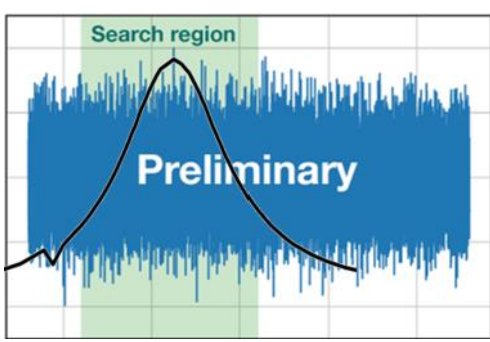
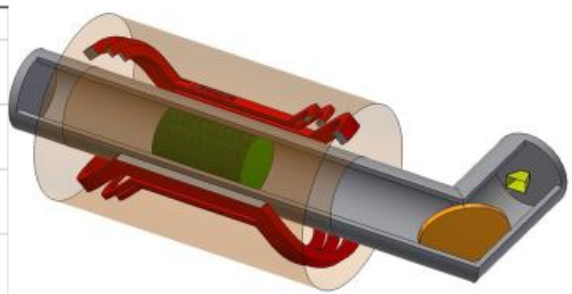
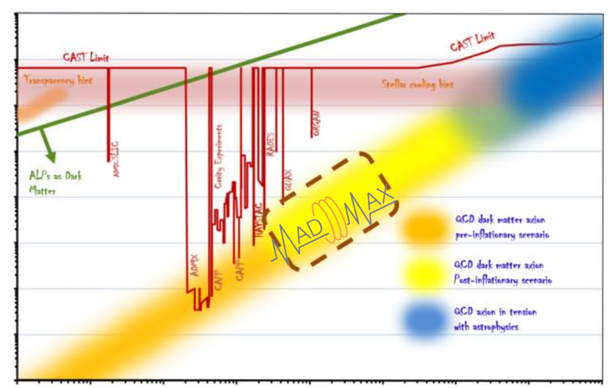
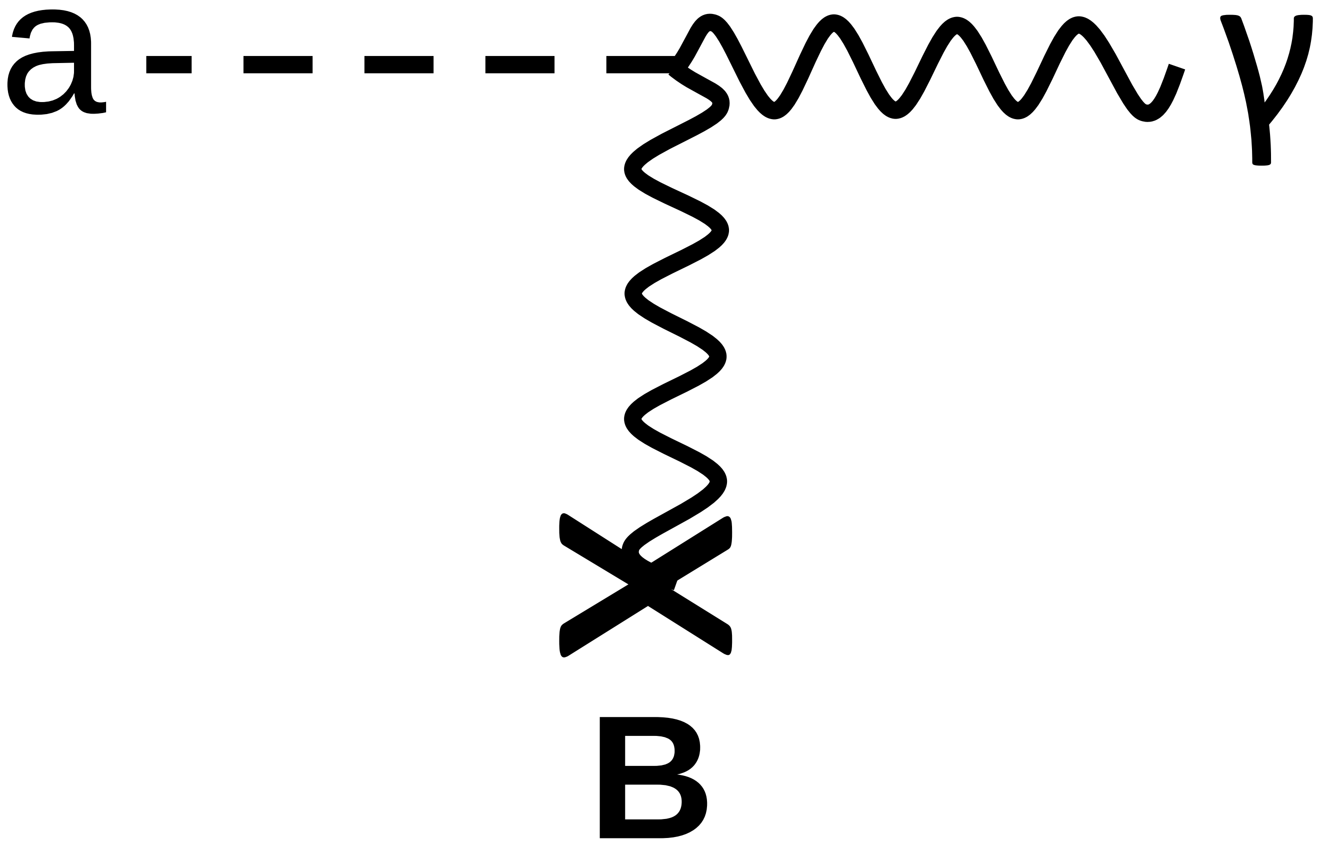
CONCLUSIONS:

- Strong CP & DM problems correlated?
  Axion could resolve both!
- Axion detection possible via conversion to γ in B-field
- Cavity experiments could detect axion any day:
  ADMX, CAPP ….
- Post inflationary scenario 100 μeV mass range not yet covered
- Dielectric haloscope could be sensitive to 100 μeV mass range
- MADMAX on the way to detect axion dark matter!



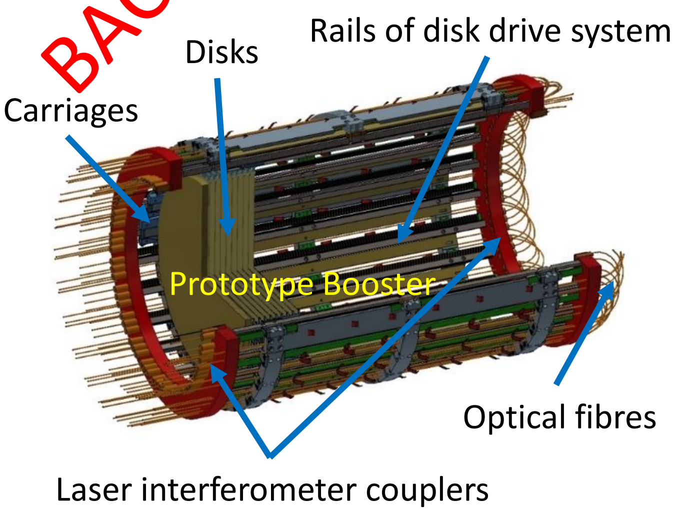


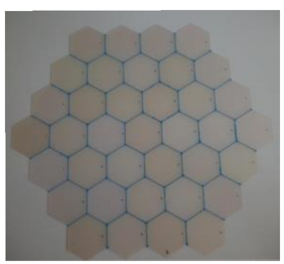



a
γ
B

The booster

BACK-UP?





- Booster is the heart of MADMAX : a mirror and several adjustable dielectric discs
- Operating conditions:
  - Cryogenic temperatures: 4 K
  - High magnetic field: up to ~10 T
  - Vacuum or cold gehe exchange gas
- Disk weight: 600 g for Ø300 mm

➢ **Piezo-driven actuator system with feedback from laser interferometer with absolute precision**

- Candidate disk materials:
  - **$LaAlO_3$ ($\varepsilon \approx 24$, tan$\delta \approx$ a few 10^{-5})**
  - Sapphire ($\varepsilon \approx 9$, tan$\delta \approx 10^{-5}$)
- $LaAlO_3$ available as 3″ wafers at maximum

➢ **Tiling necessary → Semi-automatic gluing machine**

Simulations

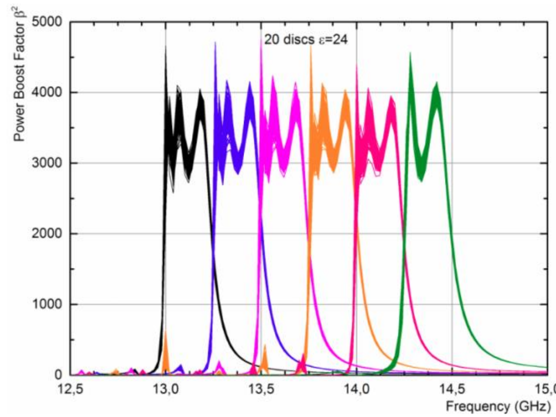
Calculations of achievable boost

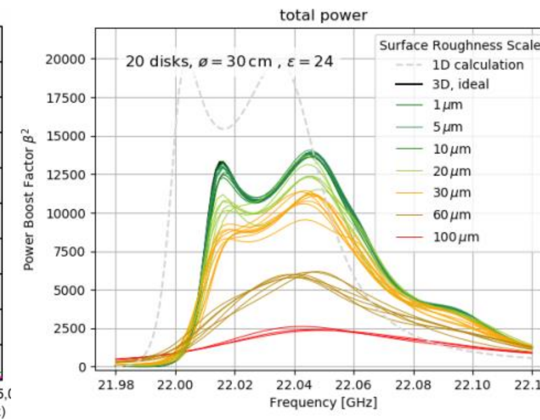
3D FEM (COMSOL+Elmer), 2D3D FEM (radial symmetry), Beam propagation

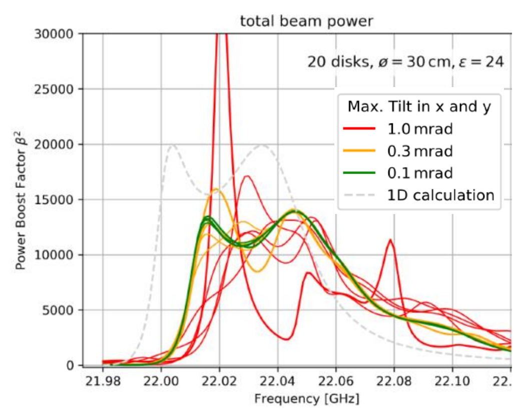
Prototype booster

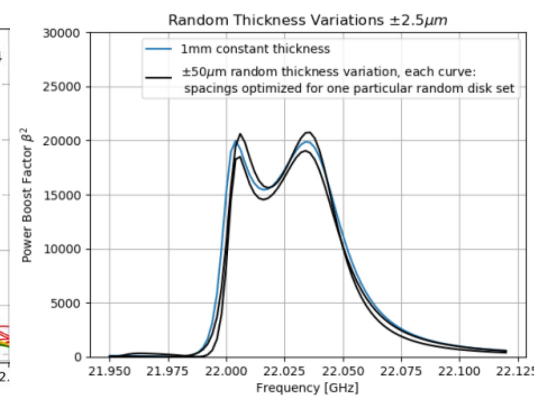
Investigated effects:

- ✓ 3D effects (diffraction)
- ✓ Dielectric loss
- ✓ Inaccuracies (positioning, roughness, tilts, thickness,…)
- ✓ DM velocity dispersion
- Tiling of disks
- Coupling to antenna, receiver
- Calibration of boost factor





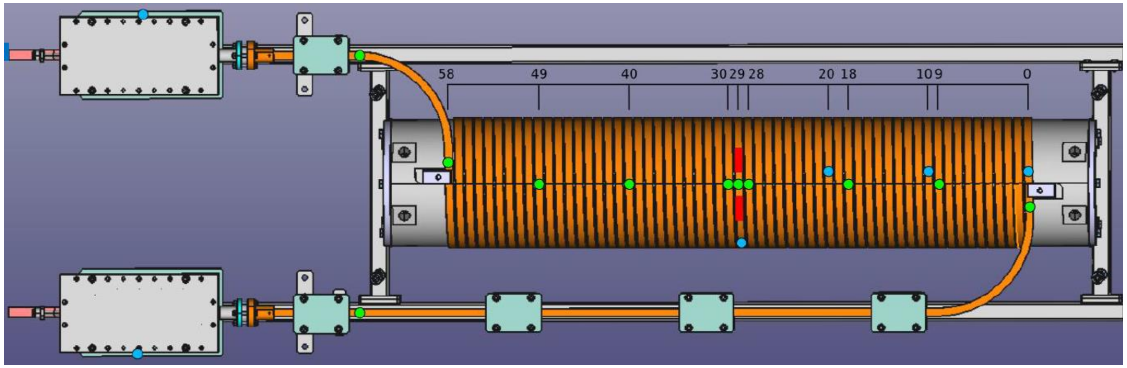




The MADMAX magnet

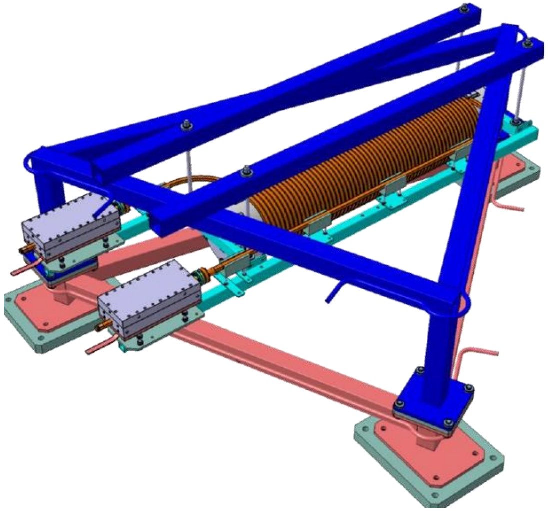
Design and R&D on 9T large bore dipole magnet

Quench protection: demostrator magnet "MACQU"



Production at NOELL, integration at CEA

Design in cooperation between CEA and NOELL



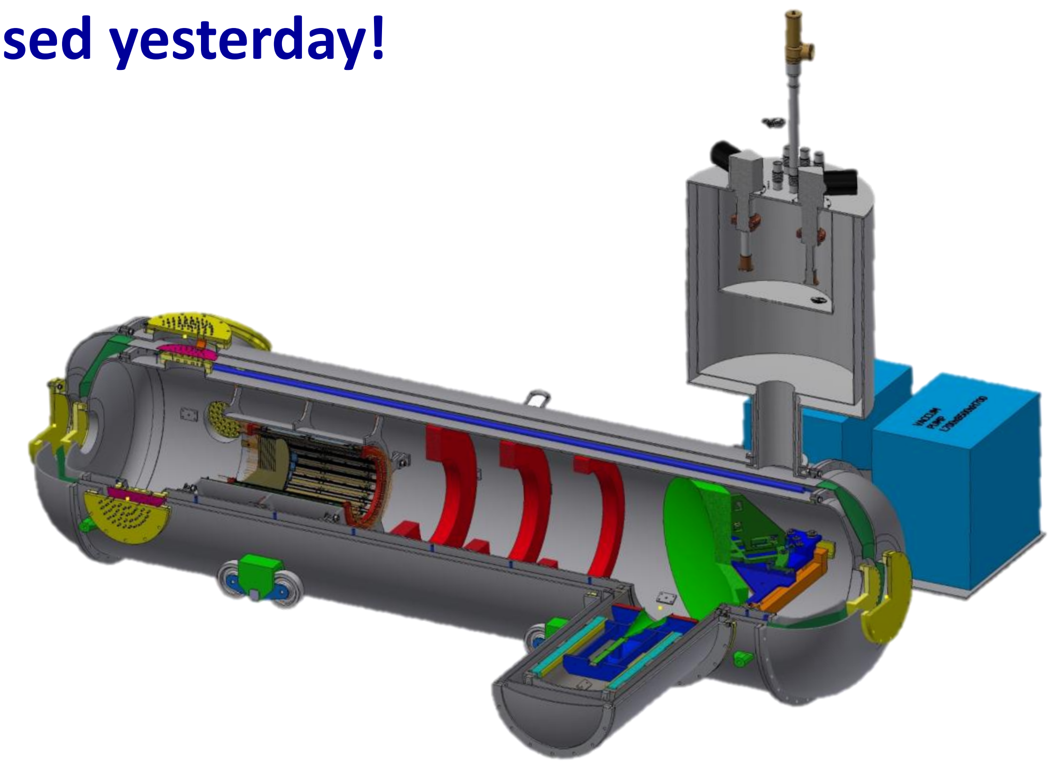
R&D on mechanical feasibility

Cryostat for prototype (2024 MORPURGO run)

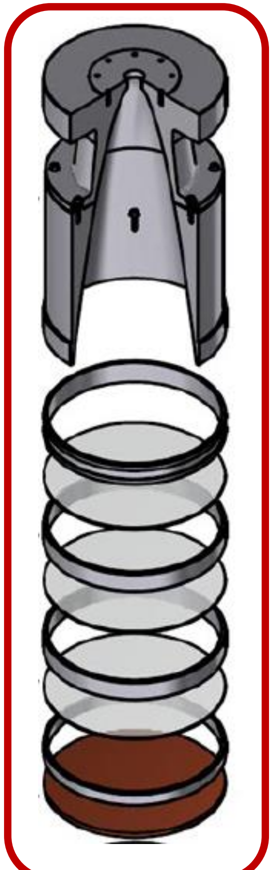
Financing of cryostat secured!
Tender ongoing:
application deadline passed yesterday!

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

→ More news from C. Krieger



Closed Booster



Name	acronym	disc diameter [mm]	Nr. of discs	Availability
Closed booster 100	CB100	100	3	2021
Closed booster 200	CB200	200	≥3	2022
Project 200	P200	200	1	2021
Reduced booster	r-booster	300	≥3	2023
Prototype booster	P-booster	300	20	2024
Final booster		1250	80	>2025

CB100 RT tests with HEMT preamp in 2022:

Quantification of system temperature

Work in progress!

CB100 4K tests with VNA

Reflectivity behavior at 4K according to specs

Very good time stability

Work in progress!

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→ More news from O. Reimann

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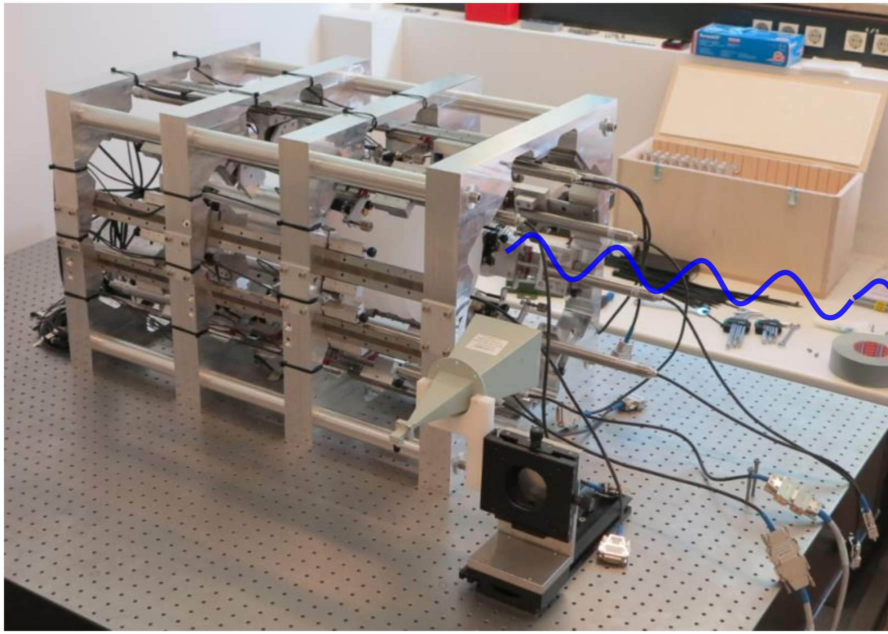
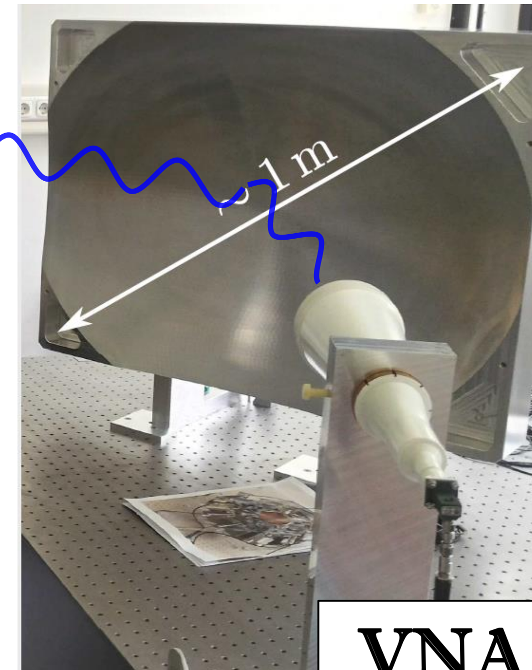
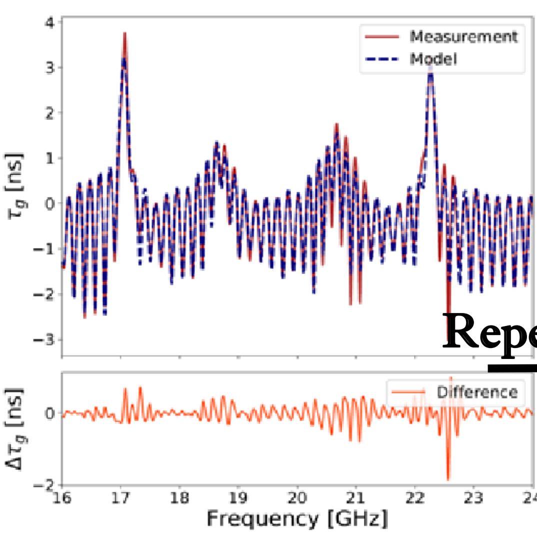
MADMAX Proof of Principle Setup

Verification of experimntal feasibility:

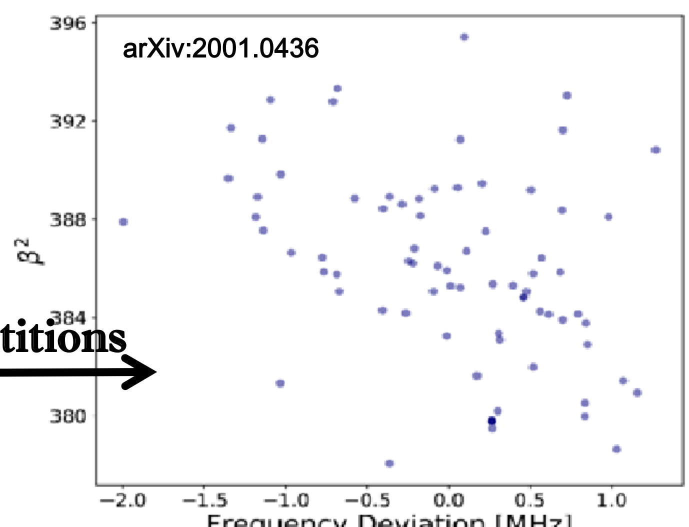




VNA



Repetitions →



- Reproducibility
- Correlations
  reflectivity vs. boost
- Positioning algorithm