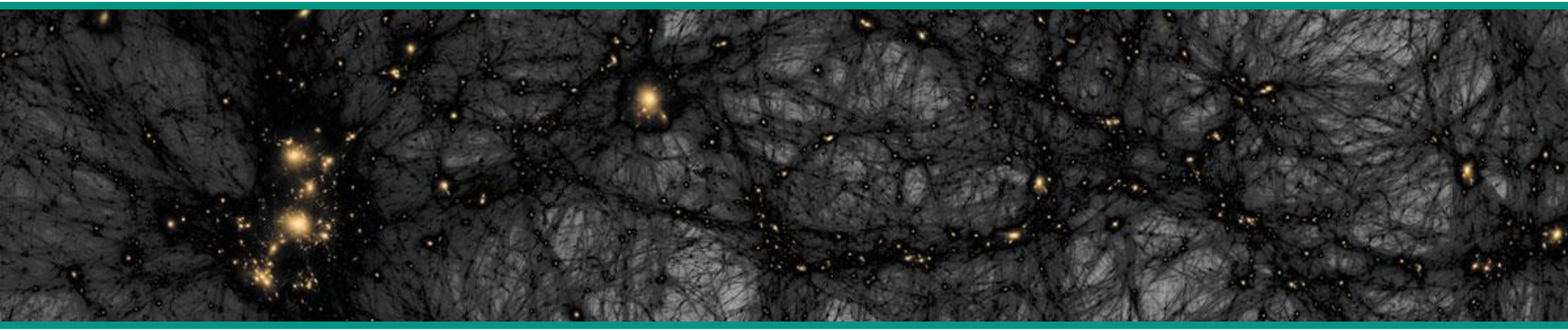
Astroparticle physics I – Dark Matter

Winter term 23/24 Lecture 22 Feb. 14, 2024



Recap of Lecture 21

- $\boldsymbol{Axion}$ **detection in haloscopes** & **helioscopes**

  - **detection**: based on $\boldsymbol{Primakoff}$ **effect** using virtual photons in strong $\boldsymbol{B}-$ field

  - $\boldsymbol{axion}$ **plot**: limits & expectations for $\boldsymbol{axion}$ **mass** $\boldsymbol{m_a}$ & **coupling** $\boldsymbol{g_{a\gamma\gamma}}$

  - $\boldsymbol{QCD - axions}$: allowed band ($\boldsymbol{KSVZ}$ & $\boldsymbol{DFSZ}$) & astrophysical limits

  - $\boldsymbol{axion}$ **searches**: **3** methods – **haloscopes** – **helioscopes** & $\boldsymbol{LSW}$ **experiments**

  - **haloscopes**: $\boldsymbol{DM}$ –´radio´ in **resonance** cavity surrounded by $\boldsymbol{B}-$ field ($\boldsymbol{ADMX}$)

  - **helioscopes**: convert $\boldsymbol{keV}$ –scale solar $\boldsymbol{axions}$ into $\boldsymbol{X}$ –rays via dipole ($\boldsymbol{CAST}$,…)

$BabyIAXO$ – a helioscope for the nearer future

- Expected start of construction phase at $DESY$: 2025

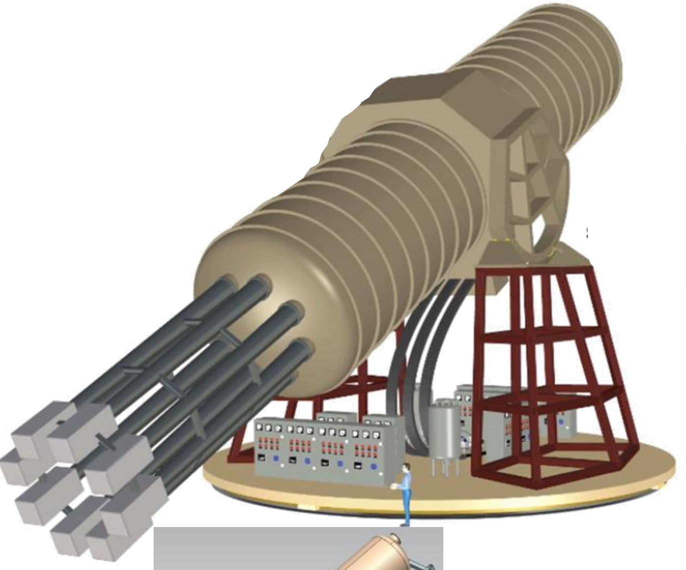
- figure–of–merit: $\sim B^2 \cdot L^2 \cdot A$

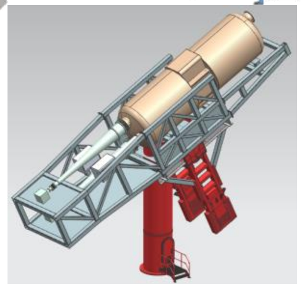
  - $CAST$: $21\ T^2\ m^4$
  - $BabyIAXO$: $\sim\ 230\ T^2\ m^4$
  - $IAXO$: $\sim 6000\ T^2\ m^4$

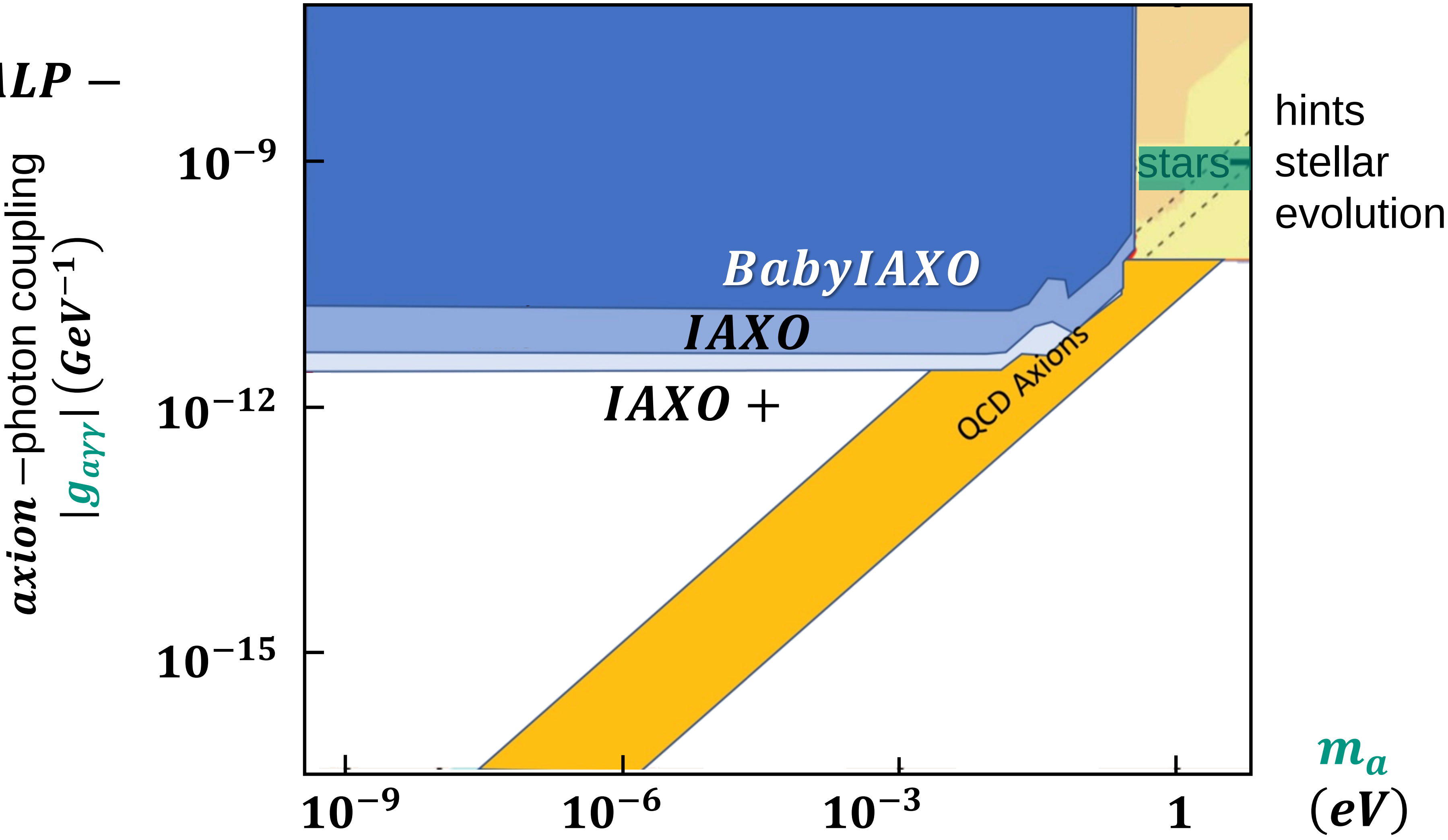
*$IAXO$ – International AXion Observatory

Helioscopes – expected sensitivities

- $IAXO, BabyIAXO$: improvments for $ALP-$ parameters







Helioscopes & LSW experimental searches

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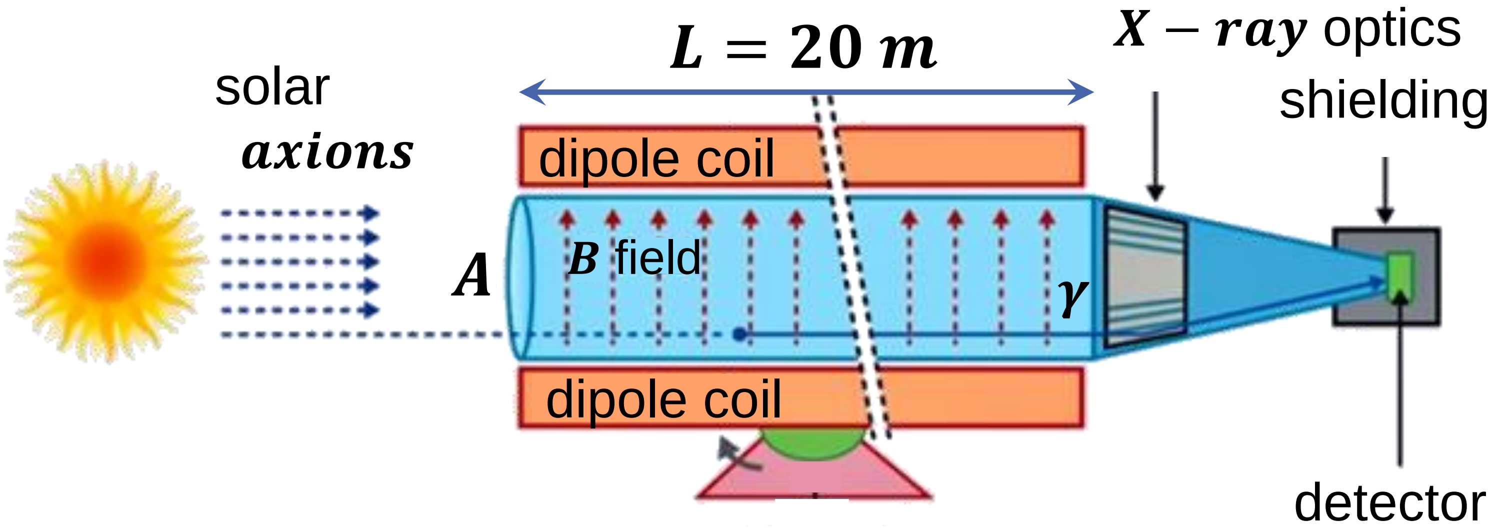
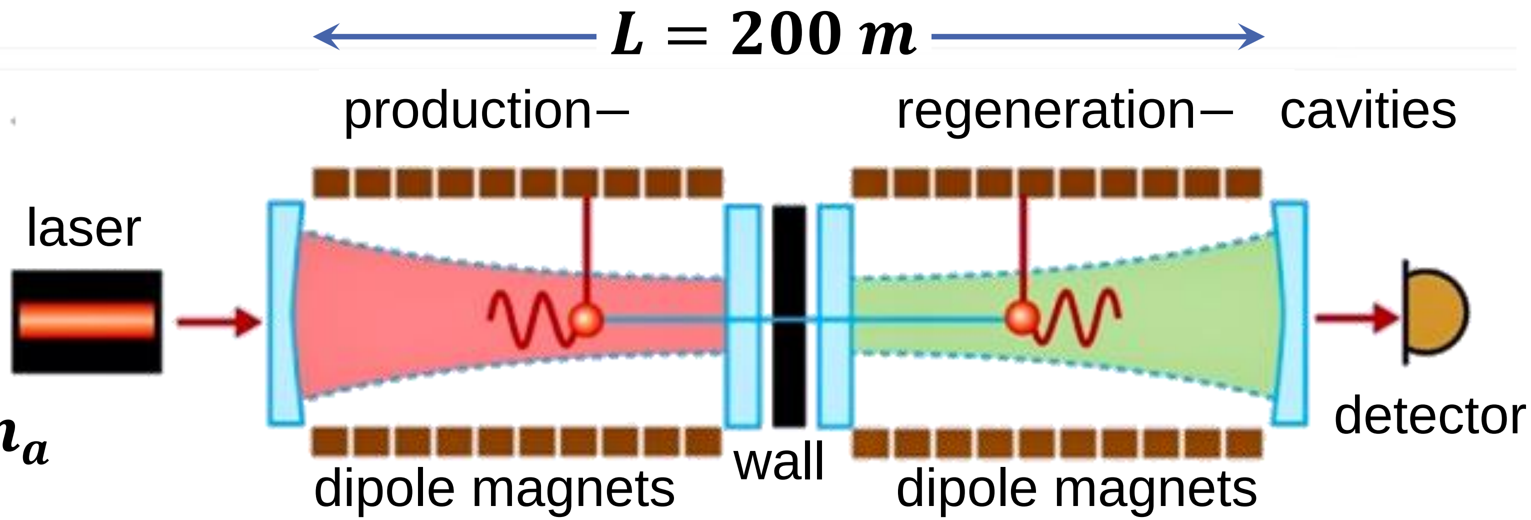
■ Experimental setups

- ´ultra–relativistic´ $\boldsymbol{axions}$ from solar plasma convert energy to X –ray photons, **no** sensitivity to mass m_a



- $\boldsymbol{axions}$ produced via laser in optical cavity: $\boldsymbol{axions}$ propagate through wall, γ – regeneration in 2^{nd} cavity, **no** sensitivity to mass m_a



$Axion$ searches: Light–Shining–through–Walls

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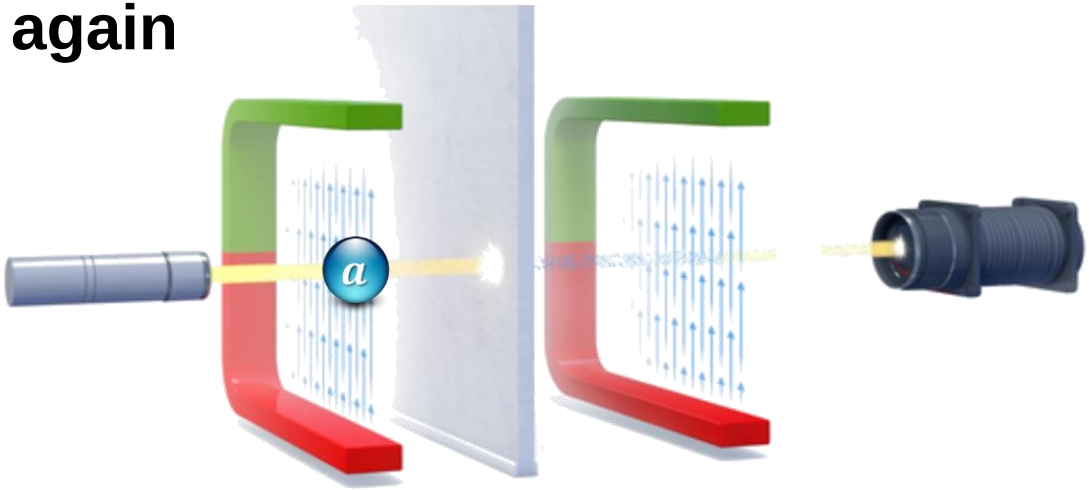
- **Converting a $photon$ to an $axion$ & back again**



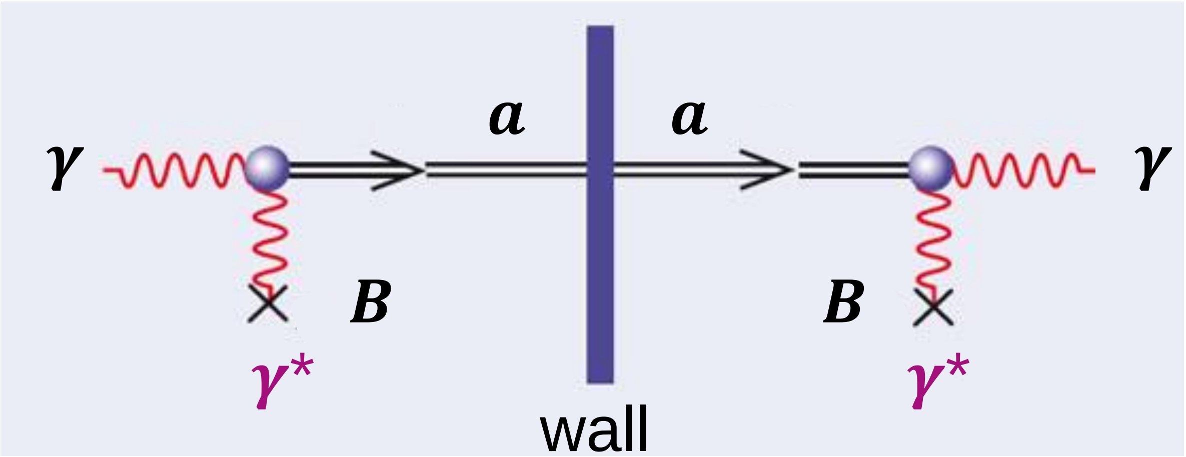
- applying the $\boldsymbol{Primakoff}$ **effect** **twice** to transmit light through a wall

laser light passes transversal $\boldsymbol{B}$ – field

conversion into $\boldsymbol{ALP}$s / $\boldsymbol{axions}$

$\boldsymbol{ALP}$s / $\boldsymbol{axions}$ can pass the wall

identical $\boldsymbol{B}$ – field: back–conversion



- disadvantage: **second** order weak effect

RECAP: Light Shining through the Universe

- **Surprisingly large range of TeV – gammas: conversion to $axions/ALPs$?**

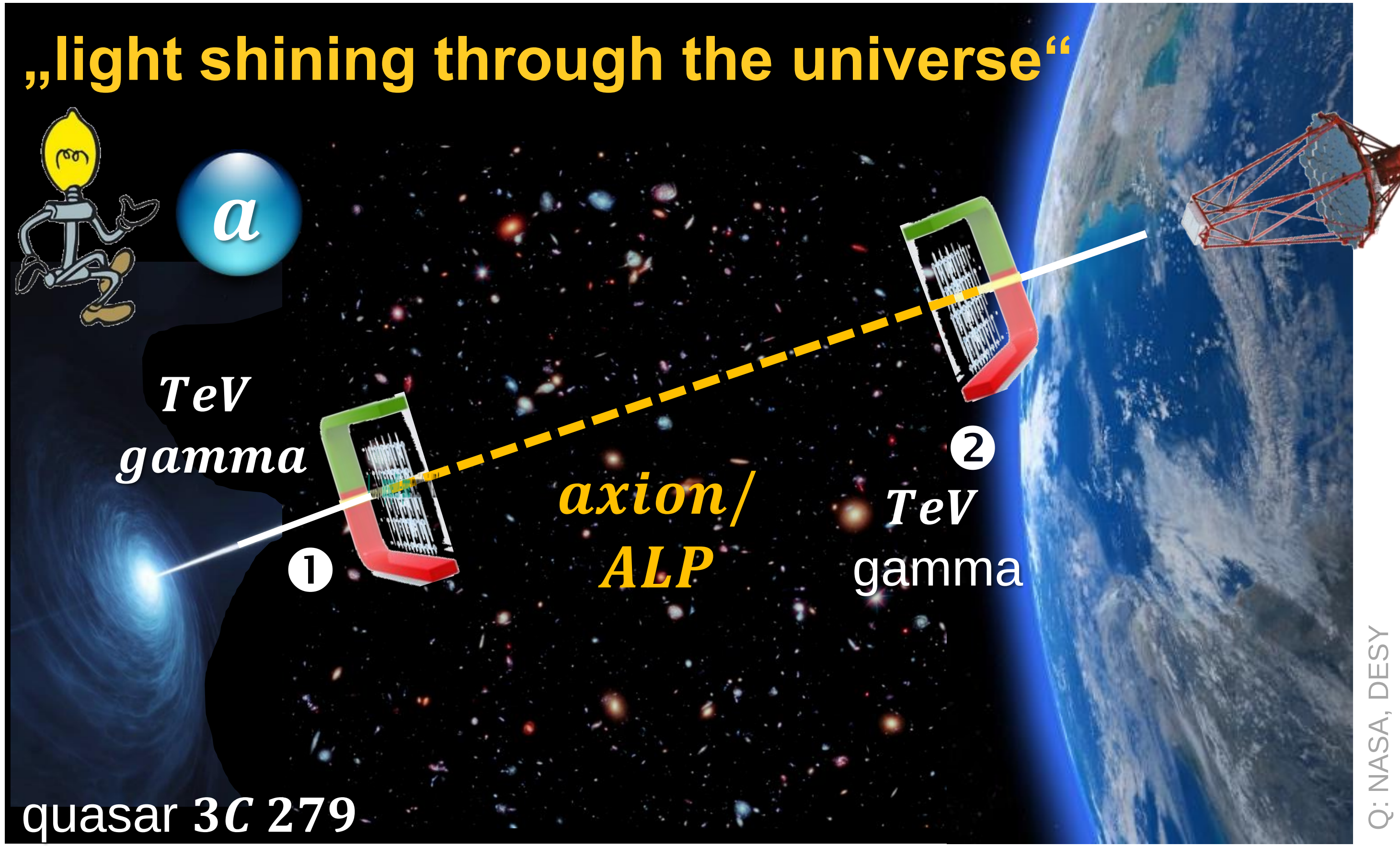
- key observation* of TeV – **gamma astronomy**:

- we detect $TeV - \gamma$´s from great distances d , despite limited range of γ´s due to IR – light

- **hypothesis**:

  ❶ $TeV - \gamma$ converts close to its source to an $axion$ / ALP

  ❷ galactic B – field: $axion$ / ALP converts back to $TeV - \gamma$



Q: NASA, DESY

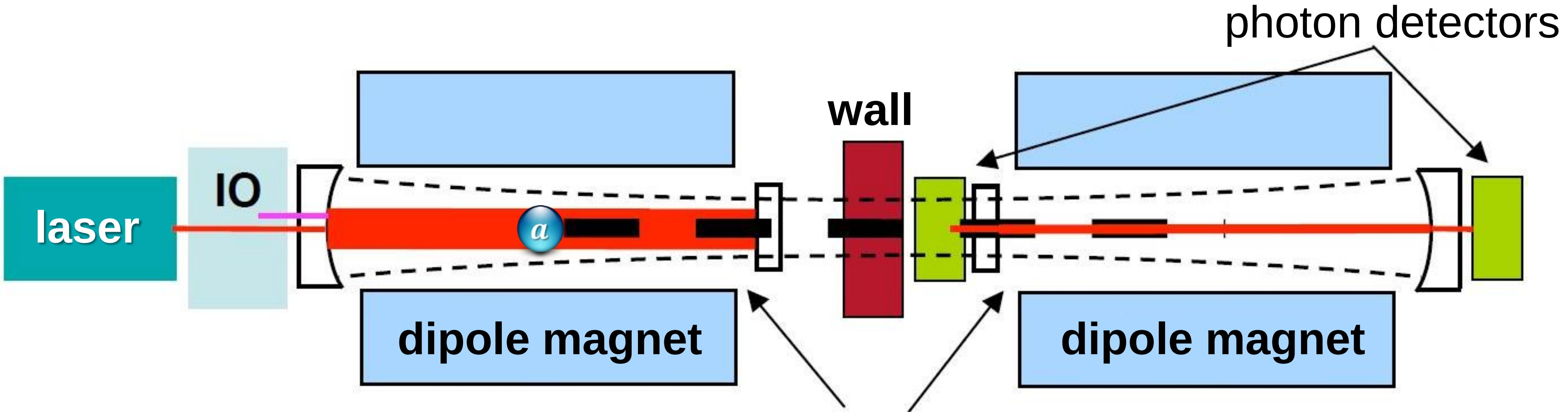
*see lecture #2

$Axion$ searches: Light–Shining–through–Walls

- **Converting a $photon$ to an $axion$ & back again: Primakoff effect 2^{nd} order**

  - **optical cavities (*Fabry–Perot*)** enhance light intensity by huge factor

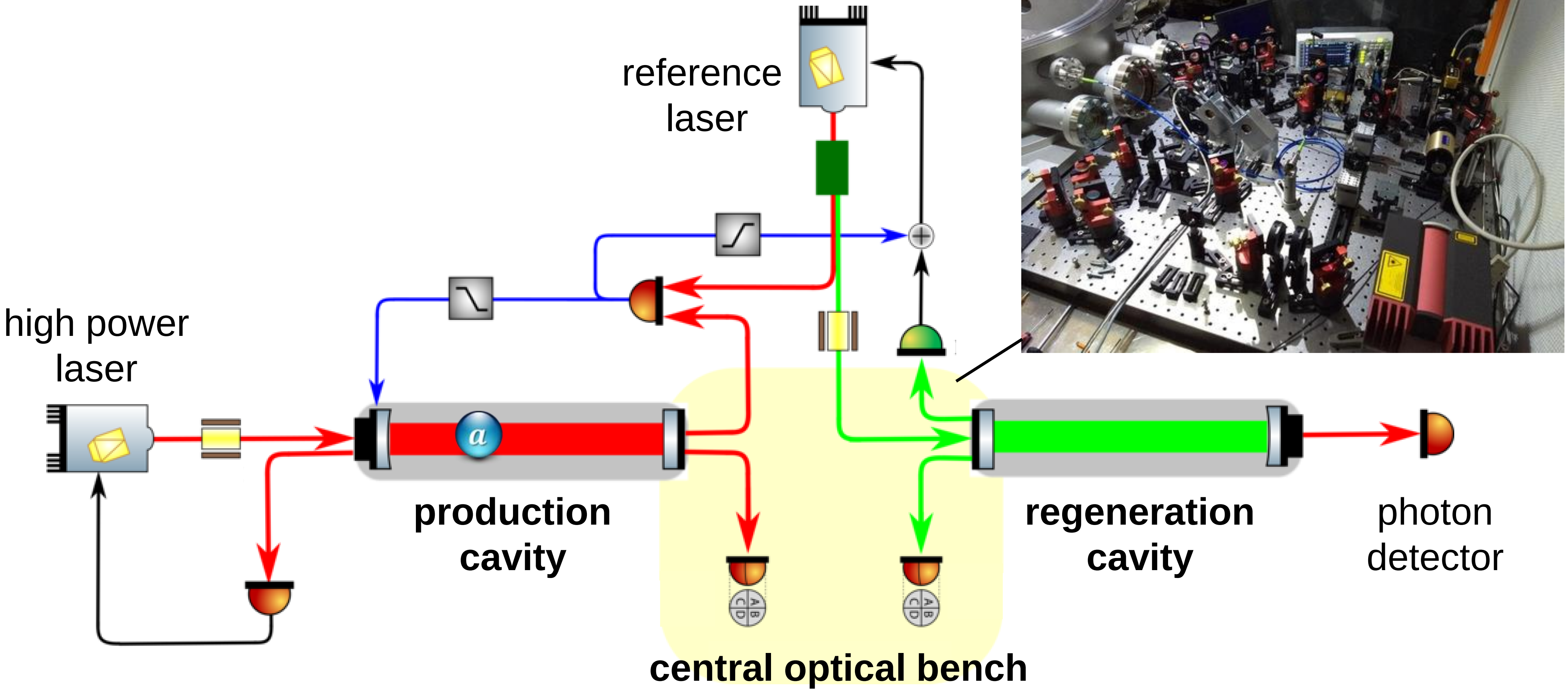
  - cavities surrounded by dipole magnets: **laser light** → $axion\ /ALP$ → **photon**



matched ***Fabry–Perot*** cavities

LSW experiments: *ALPS – II*

- **Optical system with two long cavities at *DESY***



LSW experiments: $ALPS-II$

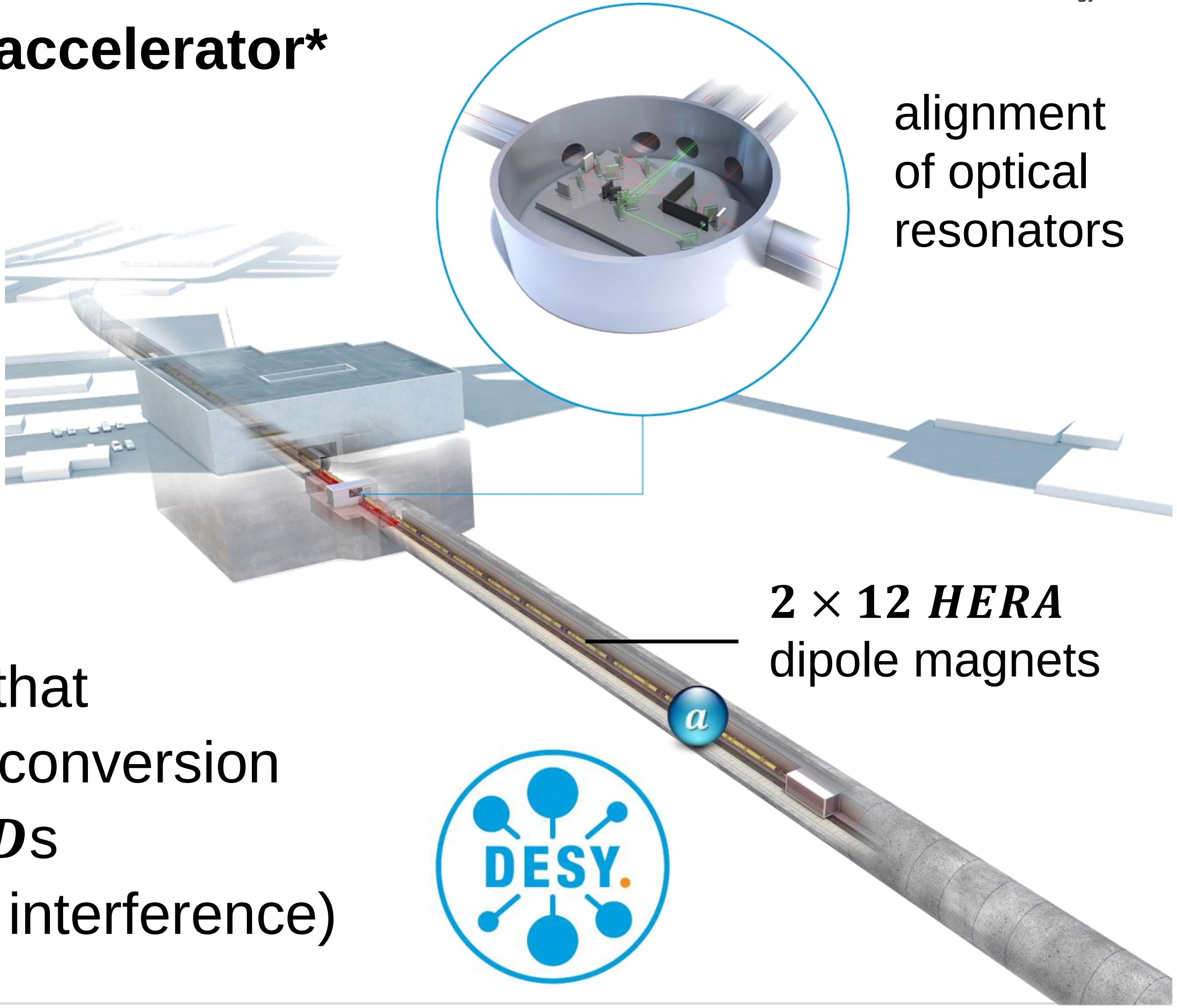
■ **Using existing dipoles from $HERA$ accelerator***

- laser ($\lambda = 1064\,nm$) power in $FP-$ cavity: $P = 150\,kW$

- length of optical cavity: $2 \times 124\,m$

- magnets: 2×12 dipoles ($2 \times 106\,m$) with $B = 5.3\,T$ (straigthened)

- detect very small number of photons that have coupled into other cavity due to conversion & back–conversion via special $SQUID$s (Fabry–Perot operated at destructive interference)



*Hadron Elektron Ring Anlage

LSW experiments: $ALPS - II$

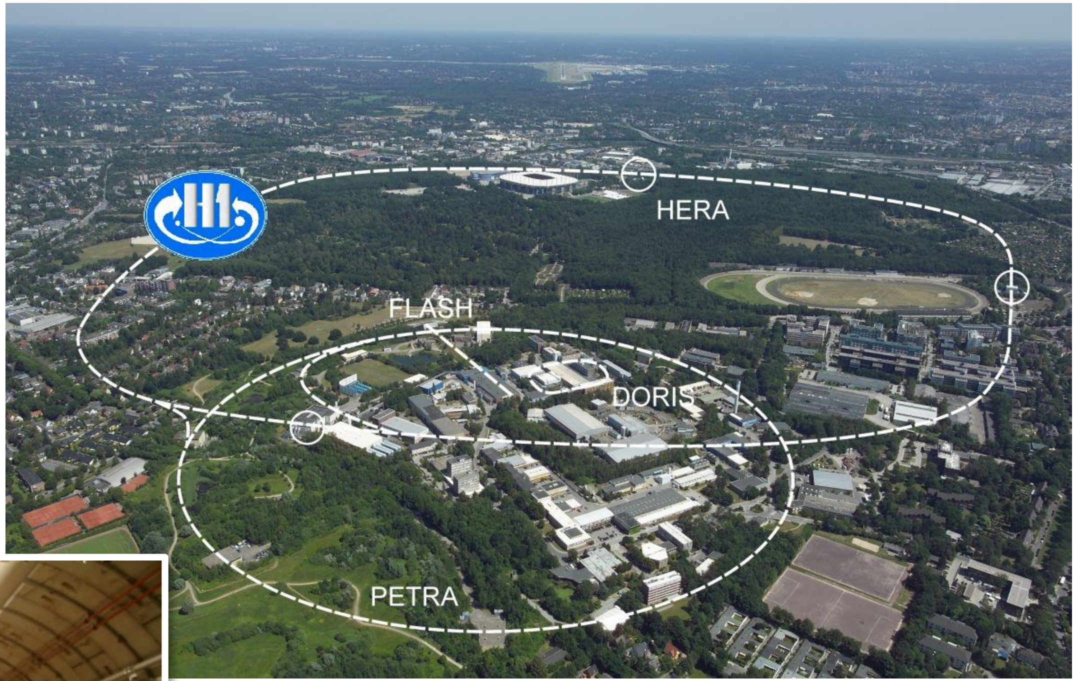
- **RECAP: $HERA$ accelerator to study electron$-$proton collisions**

  - accelerator with circumference $\mathbf{6.3}\ km$,
    $\sqrt{s} = \mathbf{320}\ GeV$, in operation: $\mathbf{1992} \ldots \mathbf{2007}$

  - electron ($E = \mathbf{27.5}\ GeV$) collisions
    with protons ($E = \mathbf{920}\ GeV$): $H1, ZEUS, \ldots$

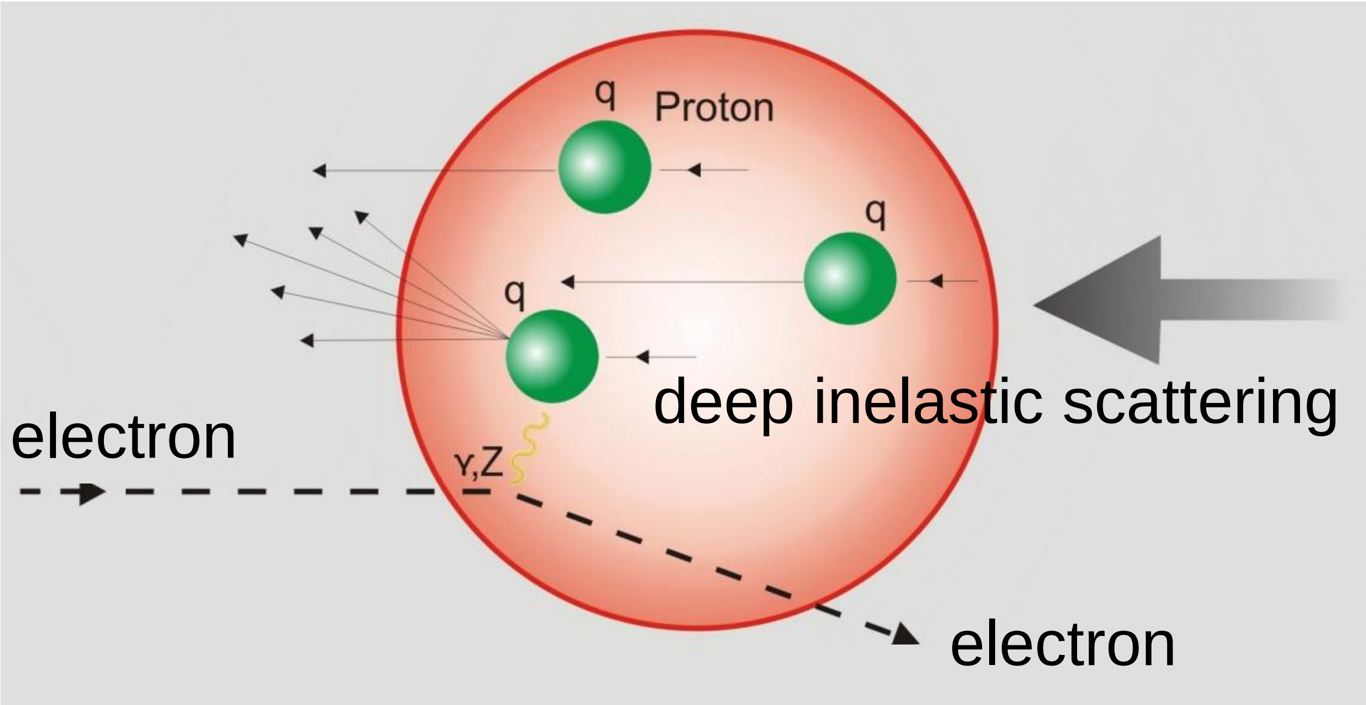
  - investigations of inner structure (**parton distributions**) of $proton$

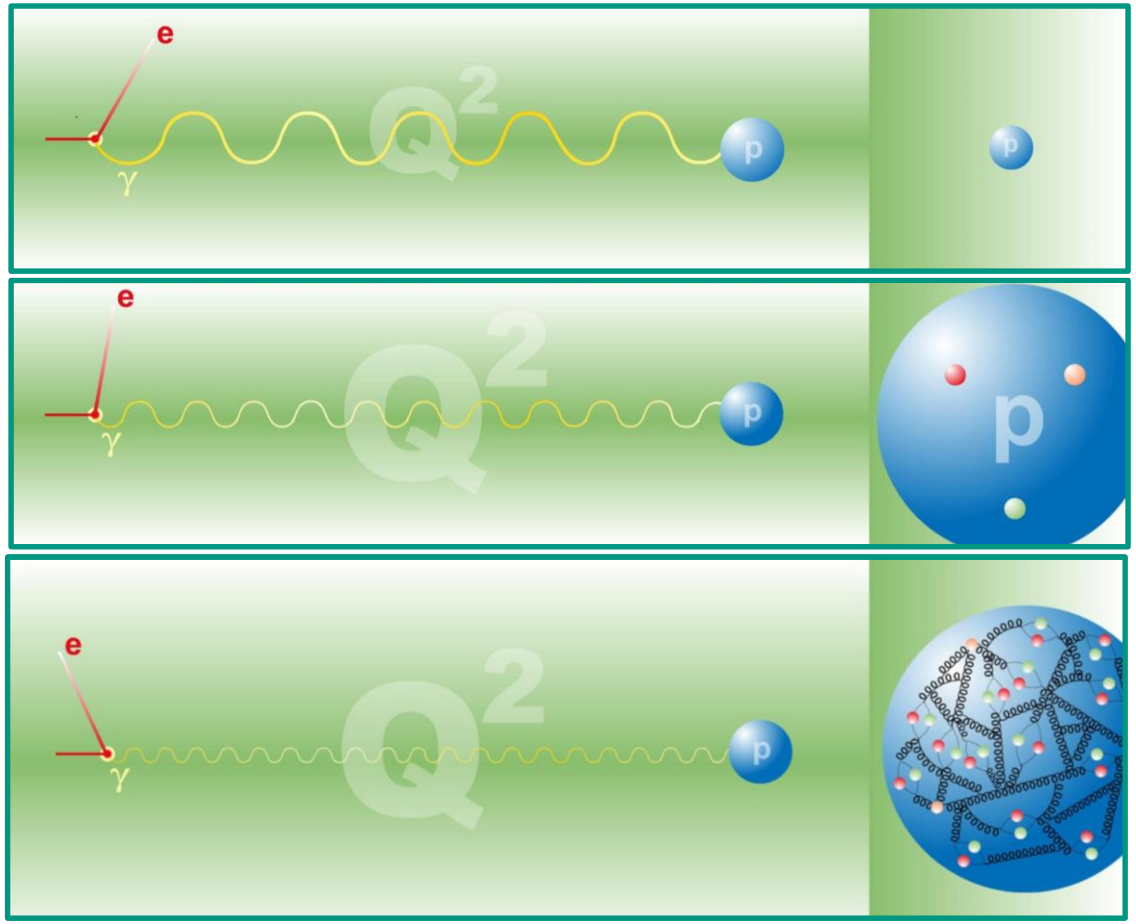
  - many $s.c.$ **dipole magnets** were available (had to be straigthened, see $CAST$)



LSW experiments: $ALPS-II$

- **RECAP: $HERA$ accelerator to study electron−proton collisions**

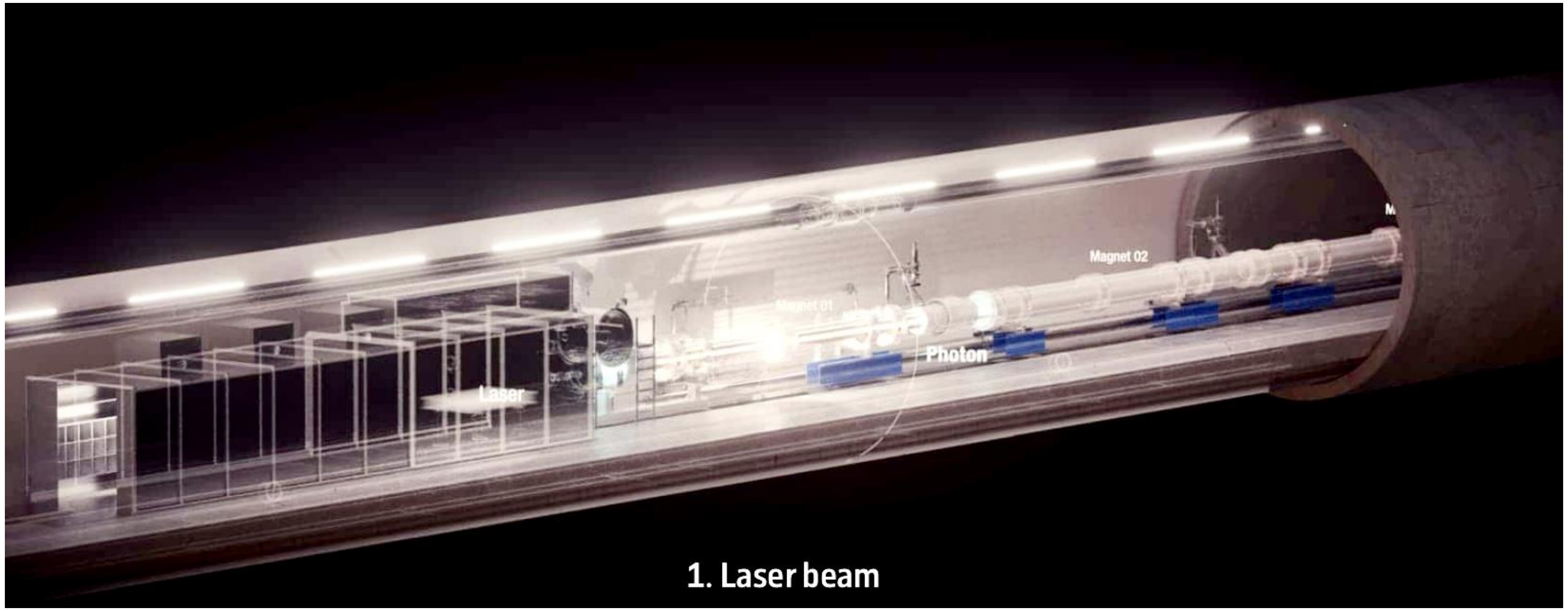


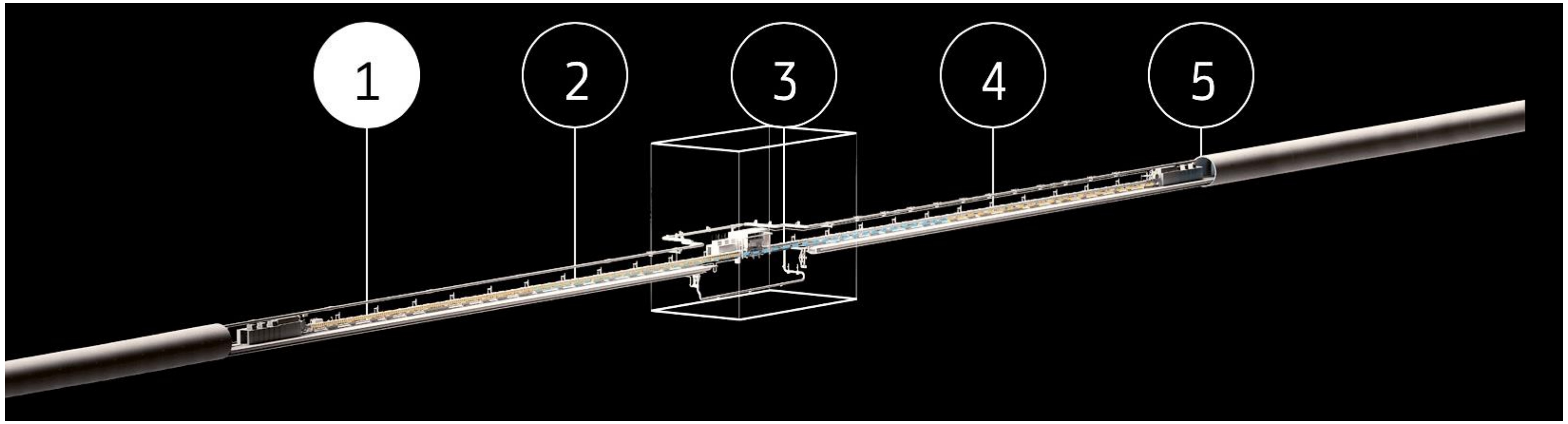


LSW experiments: $ALPS-II$

- **Principle**

- light from the laser beam gets amplified in the **optical cavity** (basically a huge **´mirror chamber´**)

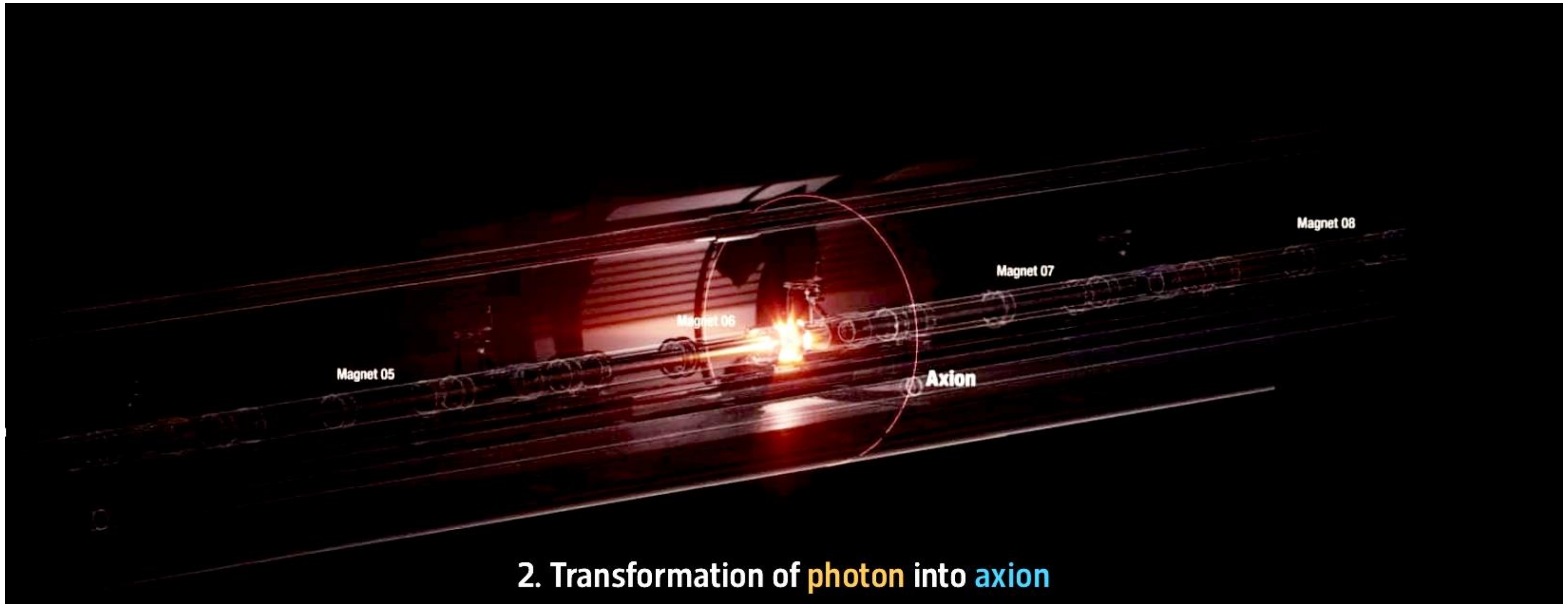


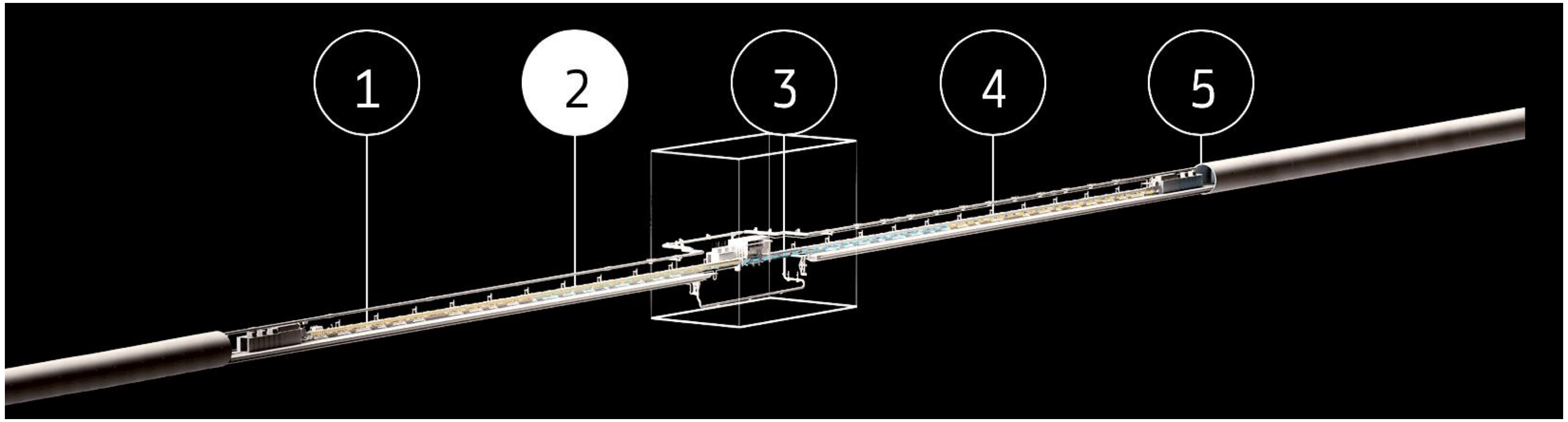


LSW experiments: $ALPS - II$

- **Principle**

- light from the laser beam passes through a strong $\boldsymbol{B}$ – field by $\mathbf{12}\ \boldsymbol{s.c.}$ dipoles photons can thus transform into $\boldsymbol{axions}$ with very small $\boldsymbol{P \sim 1 : 10^{14}}$





LSW experiments: $ALPS - II$

Principle

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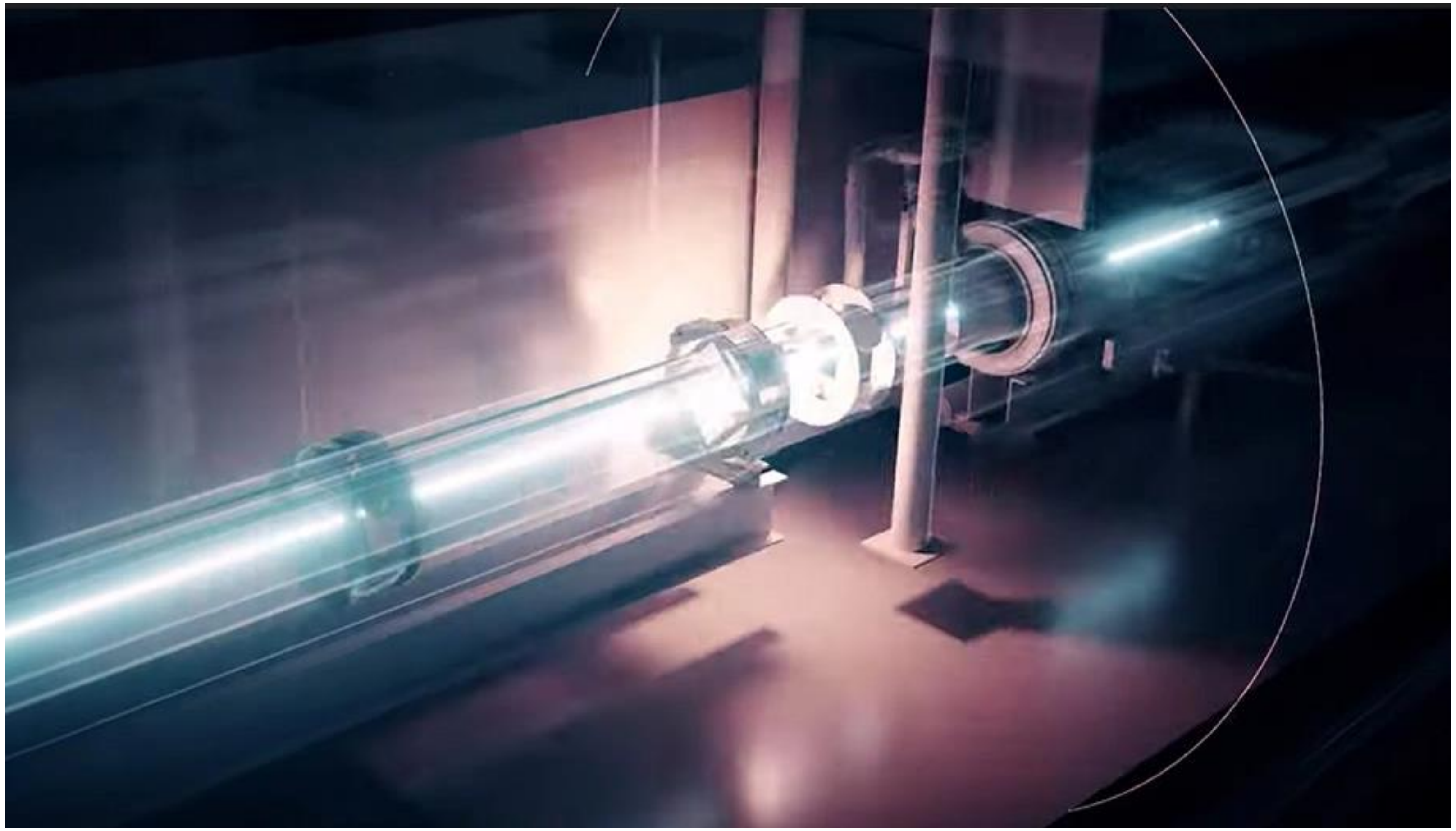
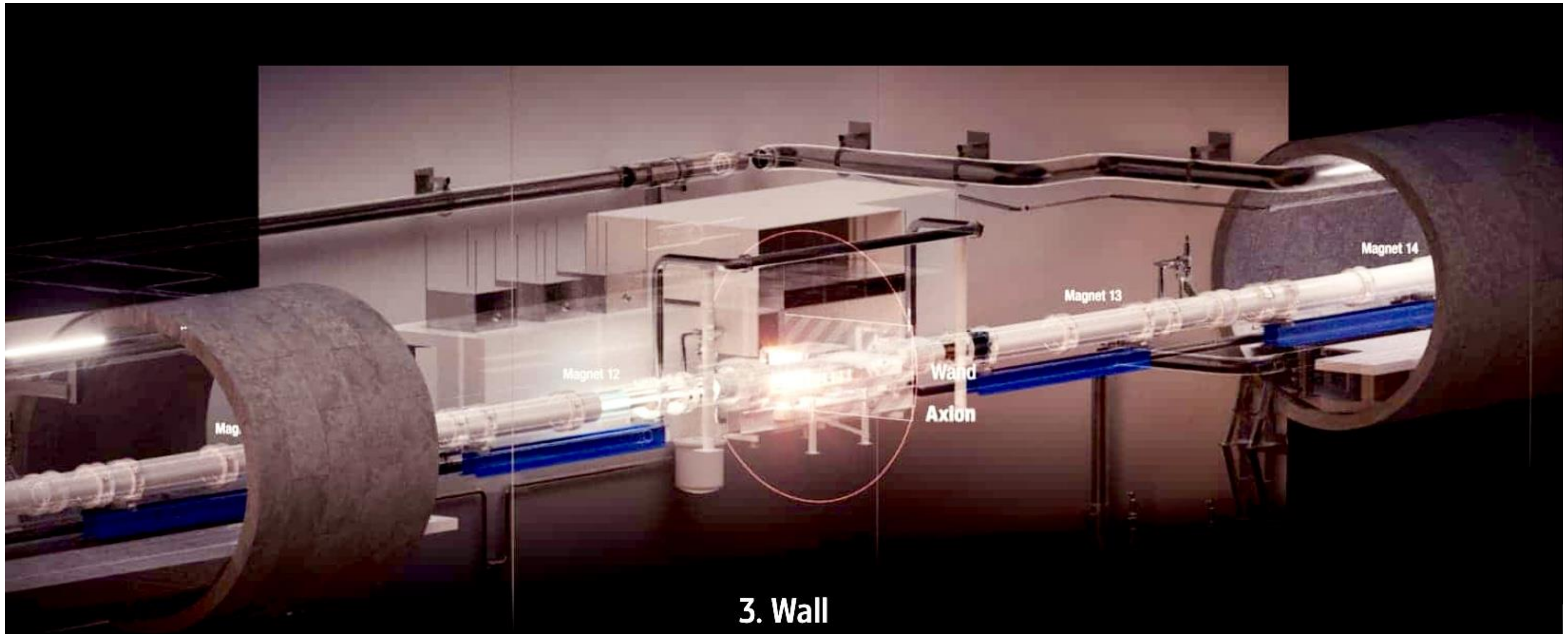
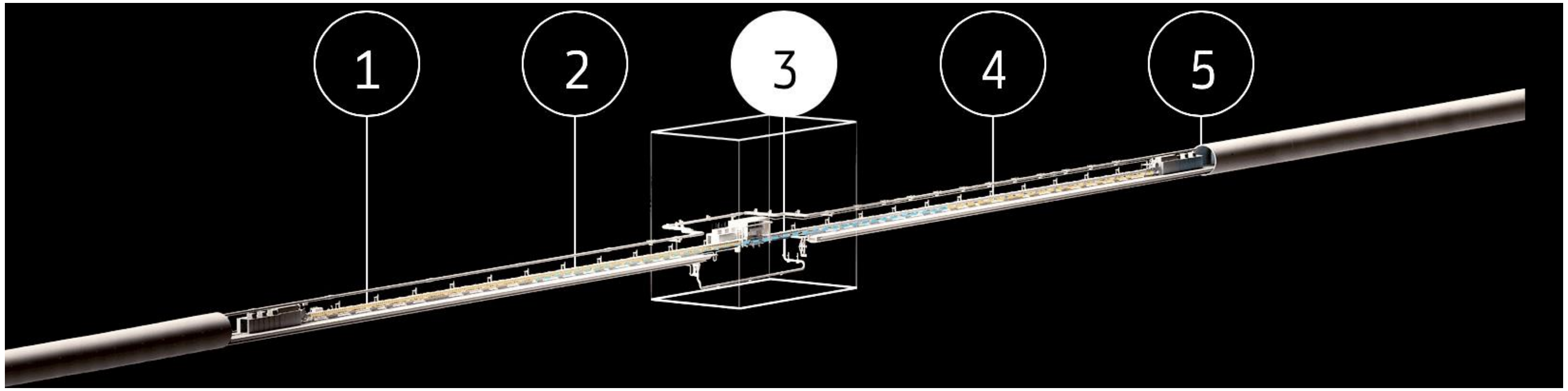


LSW experiments: $ALPS - II$

- **Principle**

- light from the laser beam is stopped by the wall. $\boldsymbol{Axions}$ will simply pass through the wall ($\boldsymbol{LSW}$ principle)

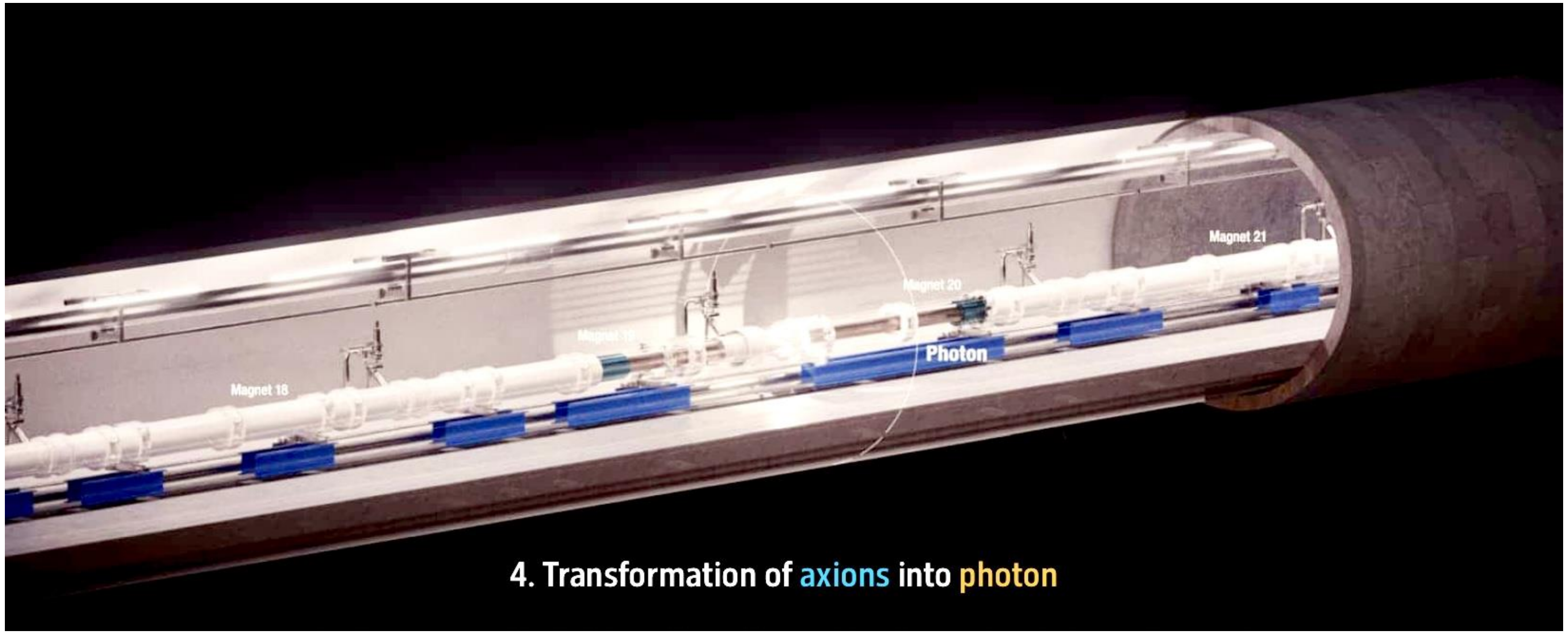


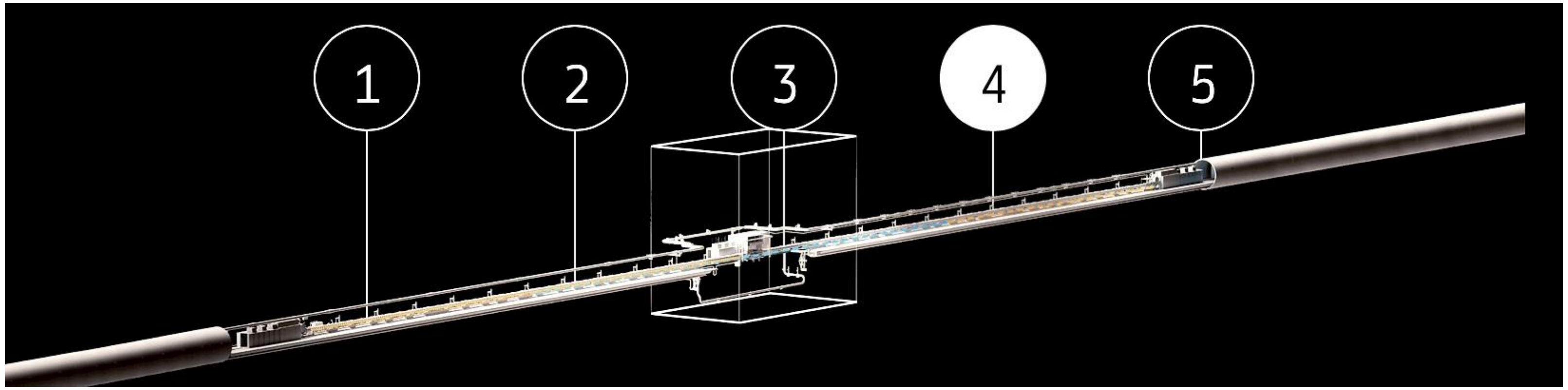


LSW experiments: $ALPS-II$

- **Principle**

  \- in the B –field on the other side (**regeneration cavity**) $axions$ will be transformed back into photons



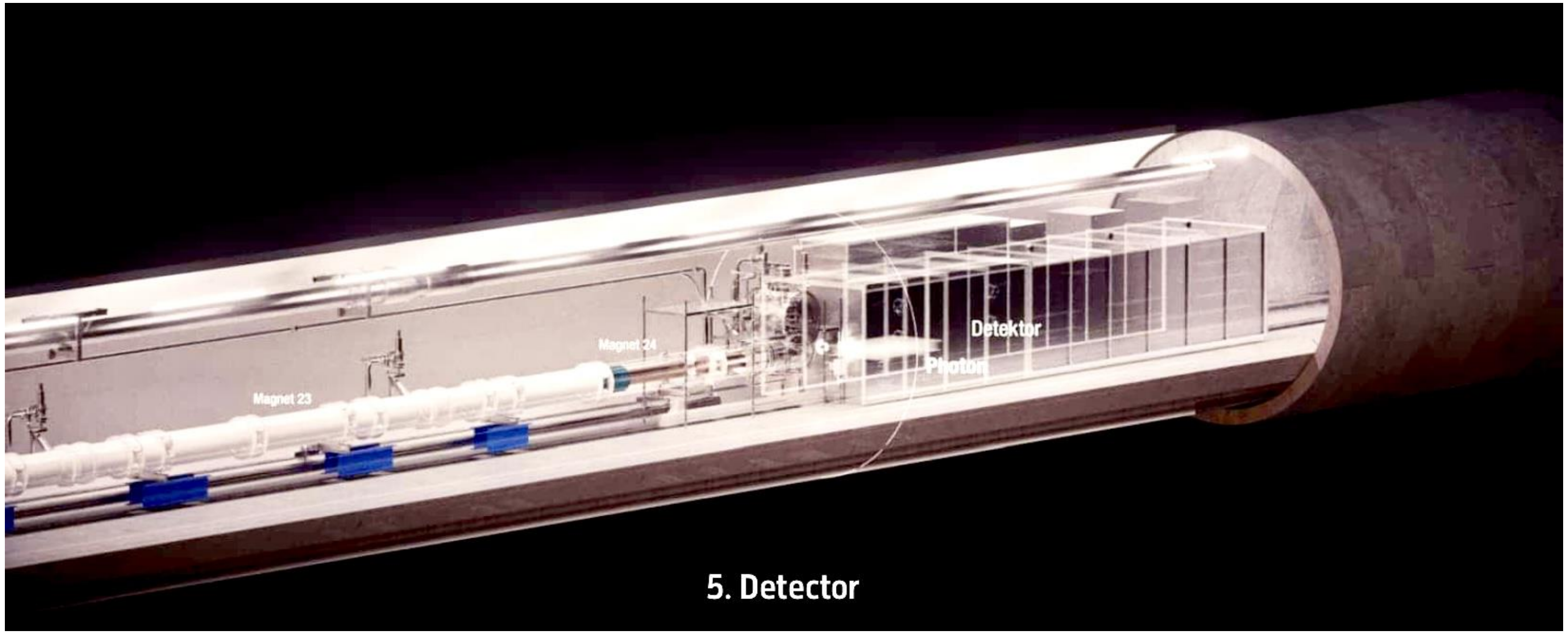


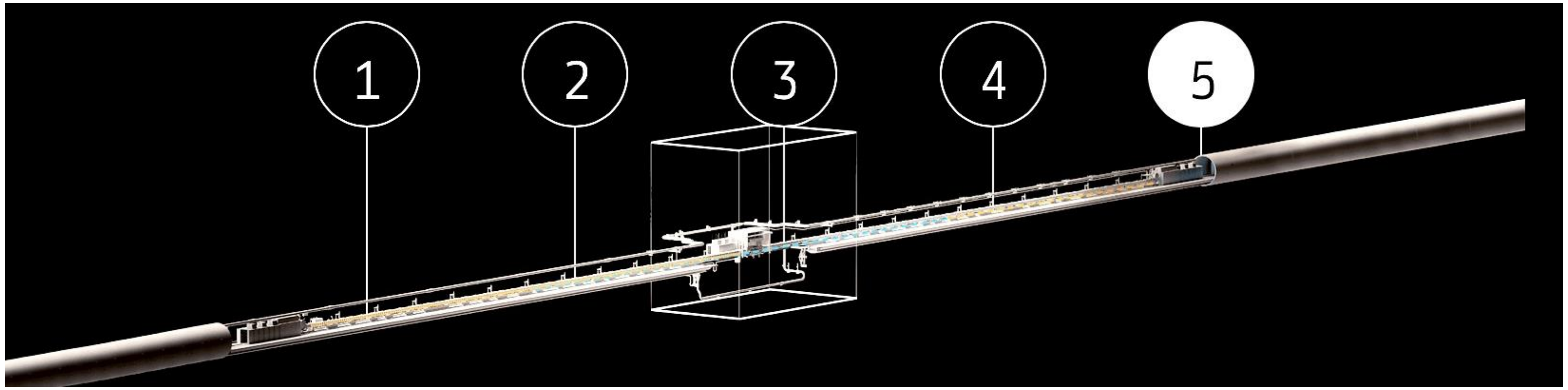
ALPS

LSW experiments: $ALPS - II$

- **Principle**

- as the principle involves a weak effekt to second order, also the detector must really be extremely sensitive to photons (has to **detect a few $\gamma\acute{}s \,/\, day$**)



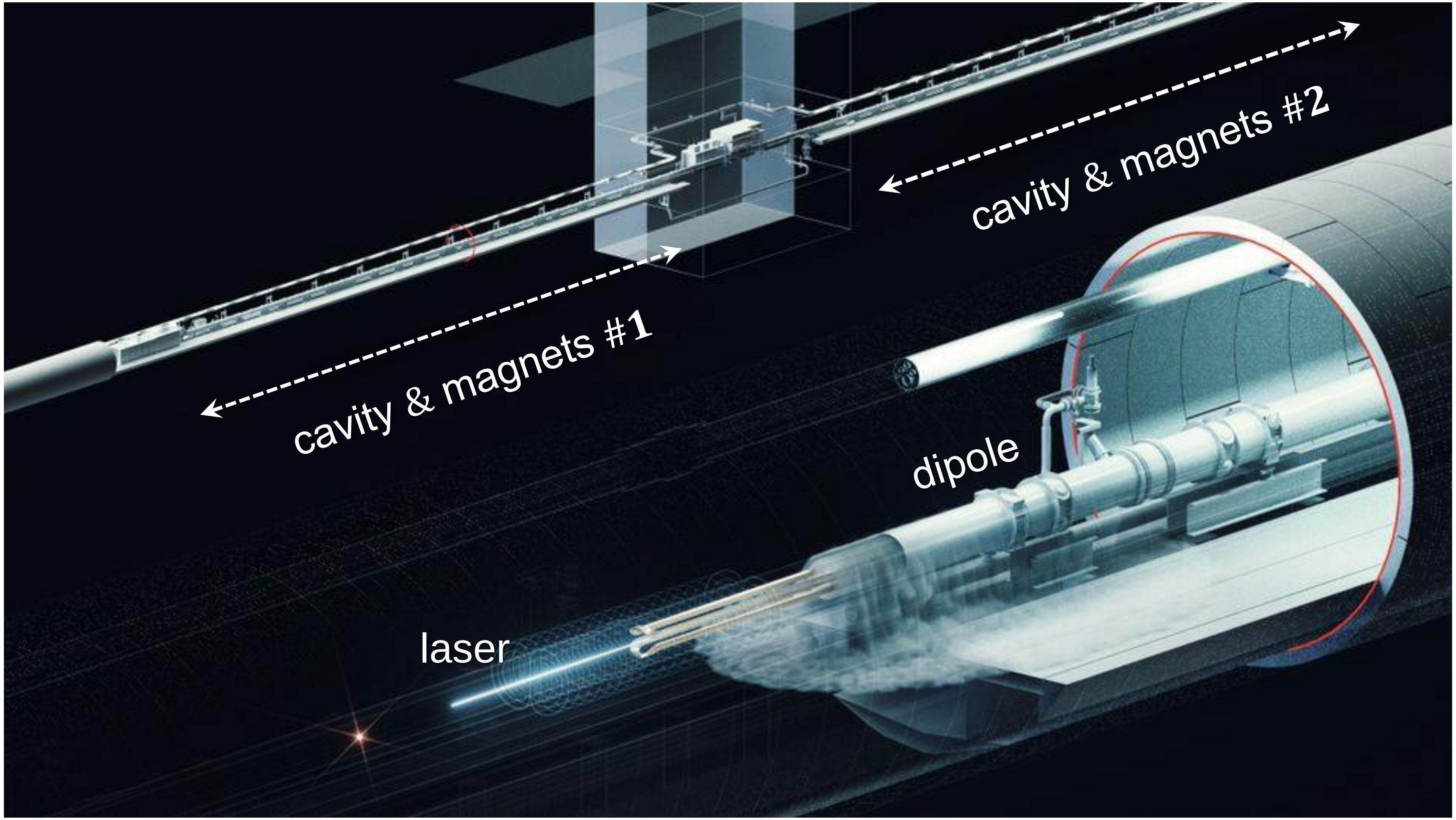


LSW experiments: $ALPS-II$

- **Status @ $DESY$**

- magnets are all powered up

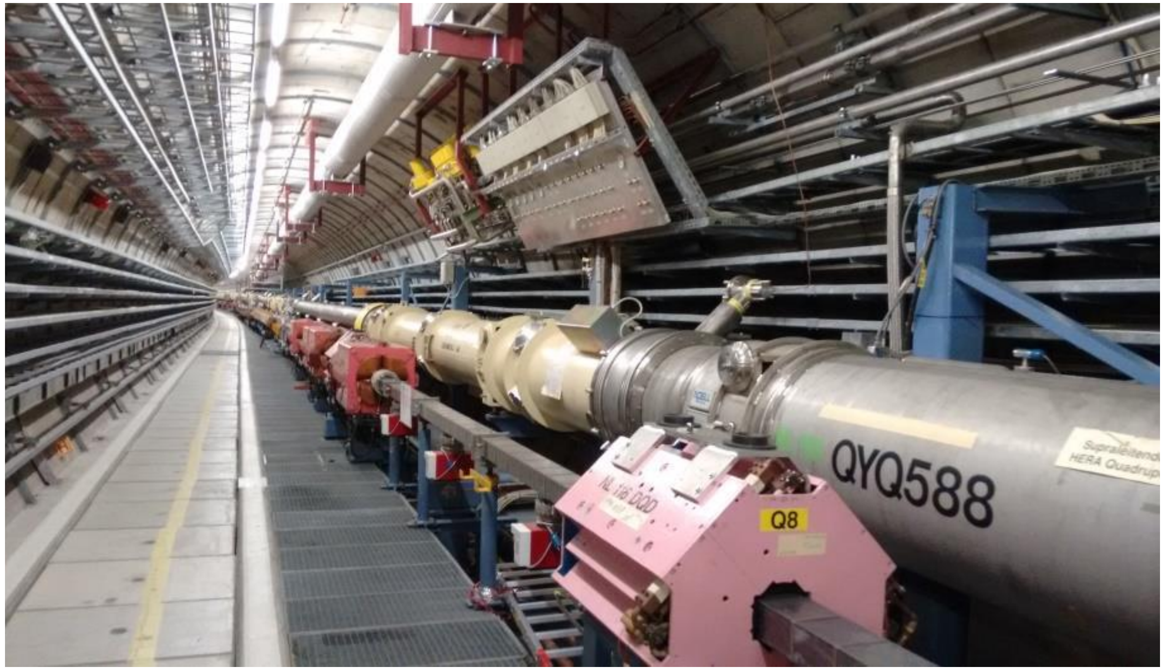
- optical cavities store laser light for $t = 6.75\,ms$ (world–record!)



LSW experiments: $ALPS-II$

- **Impressions during installation phase**

  - dismanteling of the $\boldsymbol{HERA}$ accelerator



- dipoles of the former $\boldsymbol{HERA}$ accelerator: ready for installation

LSW experiments: $ALPS-II$

- **Impressions during installation phase**

  - construction works:

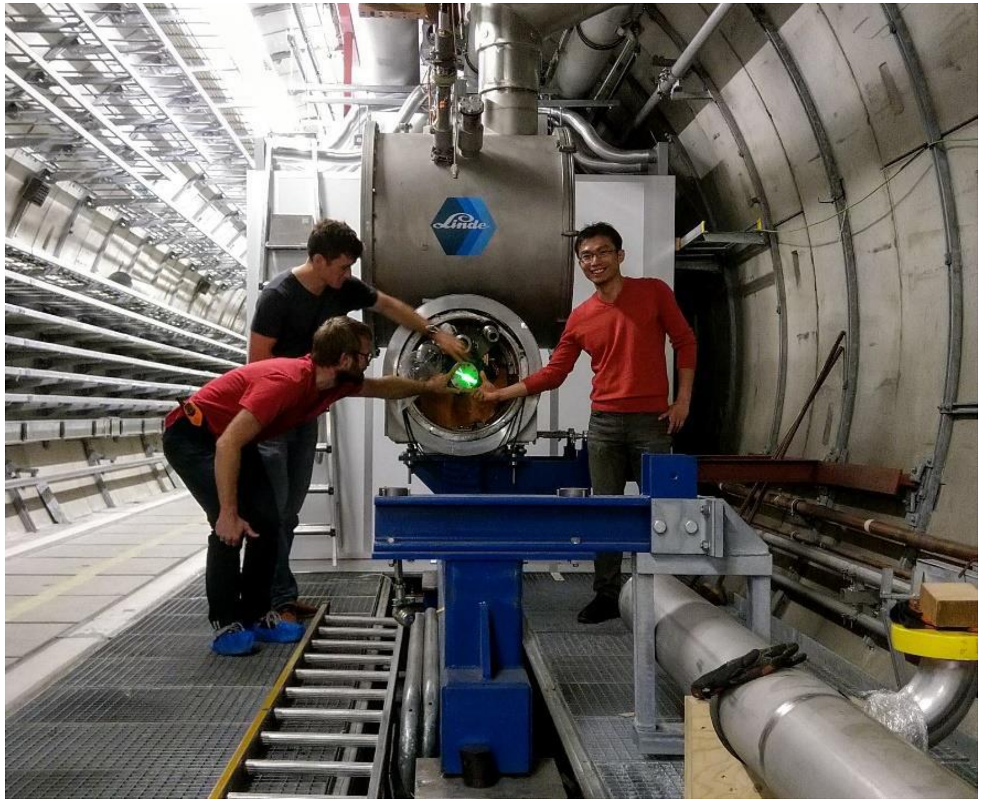
    integration of the **optical cavities** into the magnet bores

    connecting the $\mathbf{12}$ dipoles

LSW experiments: $ALPS - II$

- **Impressions during installation phase**

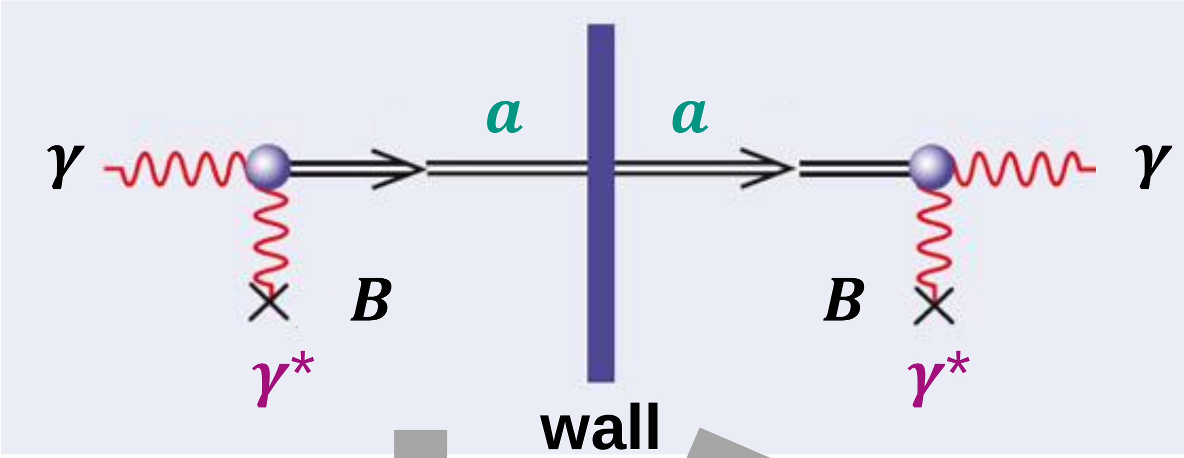
  - construction works $\mathbf{2019 - 2023}$

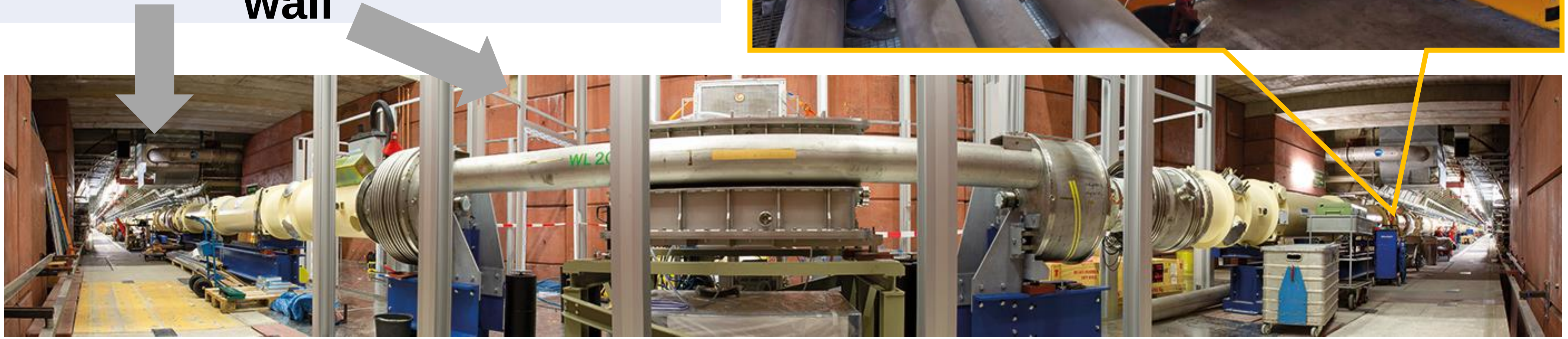


- **first light** through the magnets

LSW experiments: $ALPS - II$

- **Impressions during installation phase**





LSW experiments: $ALPS - II$

- May $23, 2023$: start of measurements!

'Light shining through a wall' experiment ALPS starts searching for dark matter

World's most sensitive instrument of its kind is to produce axions

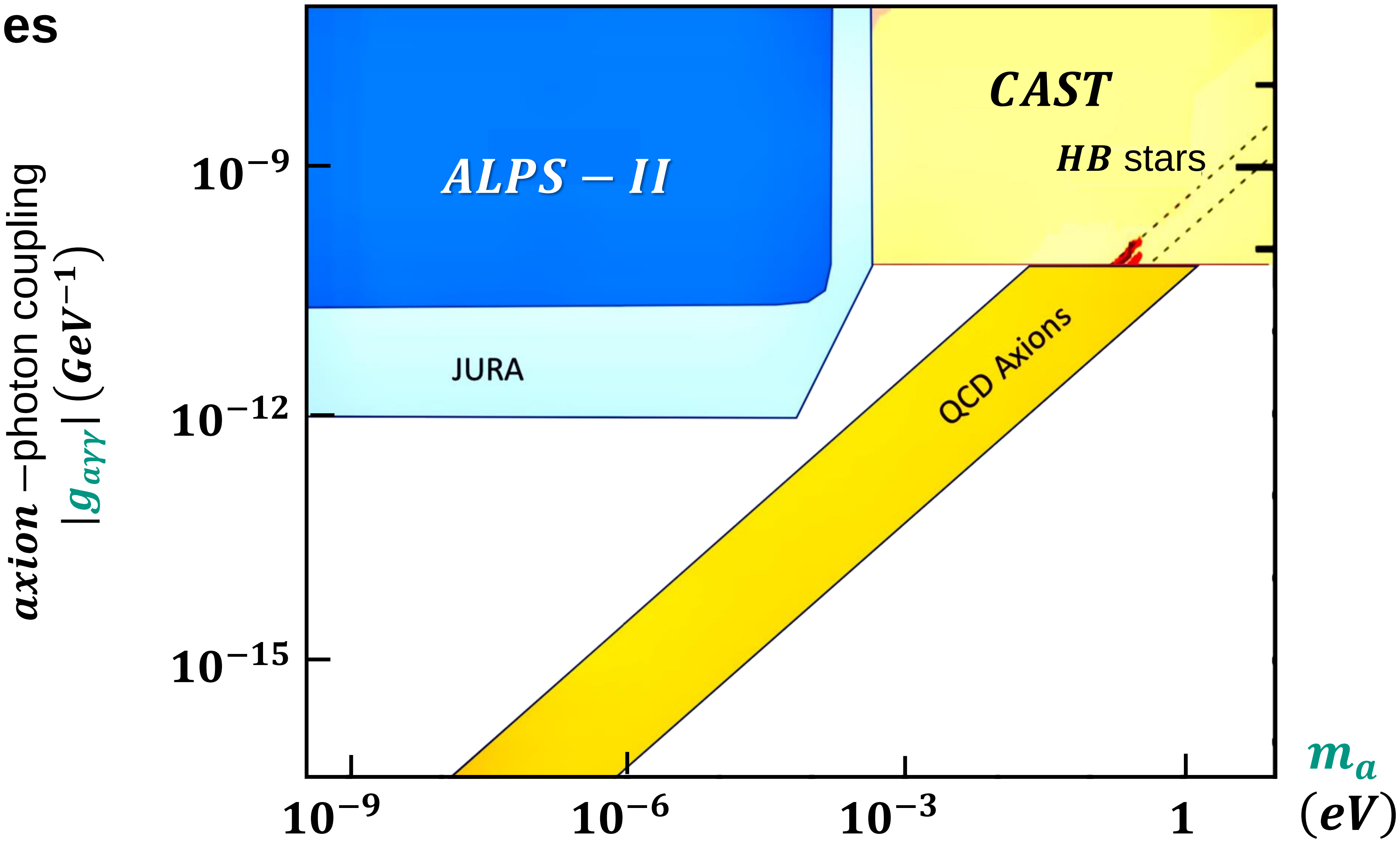
The world's most sensitive model-independent experiment to search for particularly light particles, of which dark matter might be composed, starts today at DESY in the form of the 'light shining through a wall' experiment ALPS II. Scientific calculations predict that this ominous form of matter should occur five times as often in the universe as normal, visible matter. Until now, however, no one has been able to identify particles of this substance; the ALPS experiment could now furnish such evidence.

LSW experiments: $ALPS-II$

■ **Expected sensitivities**

- only sensitive to $ALPs$ with mass $m_a < meV$ – scale & large coupling values $g_{a\gamma\gamma}$

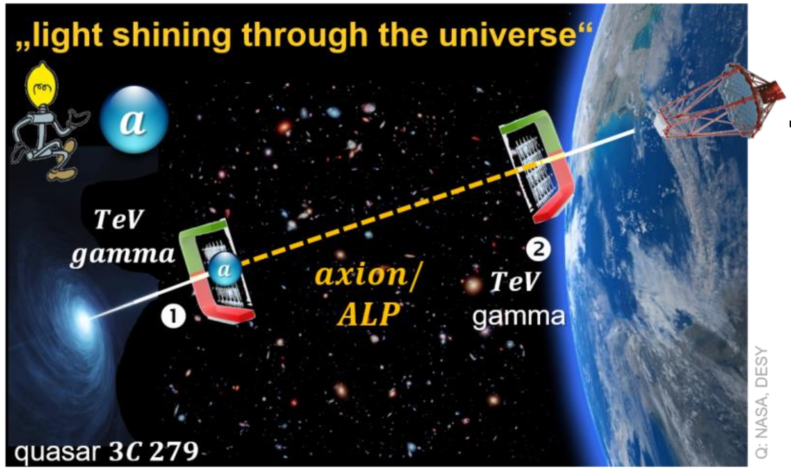
- not sensitive to the parameter region of $QCD - axions$

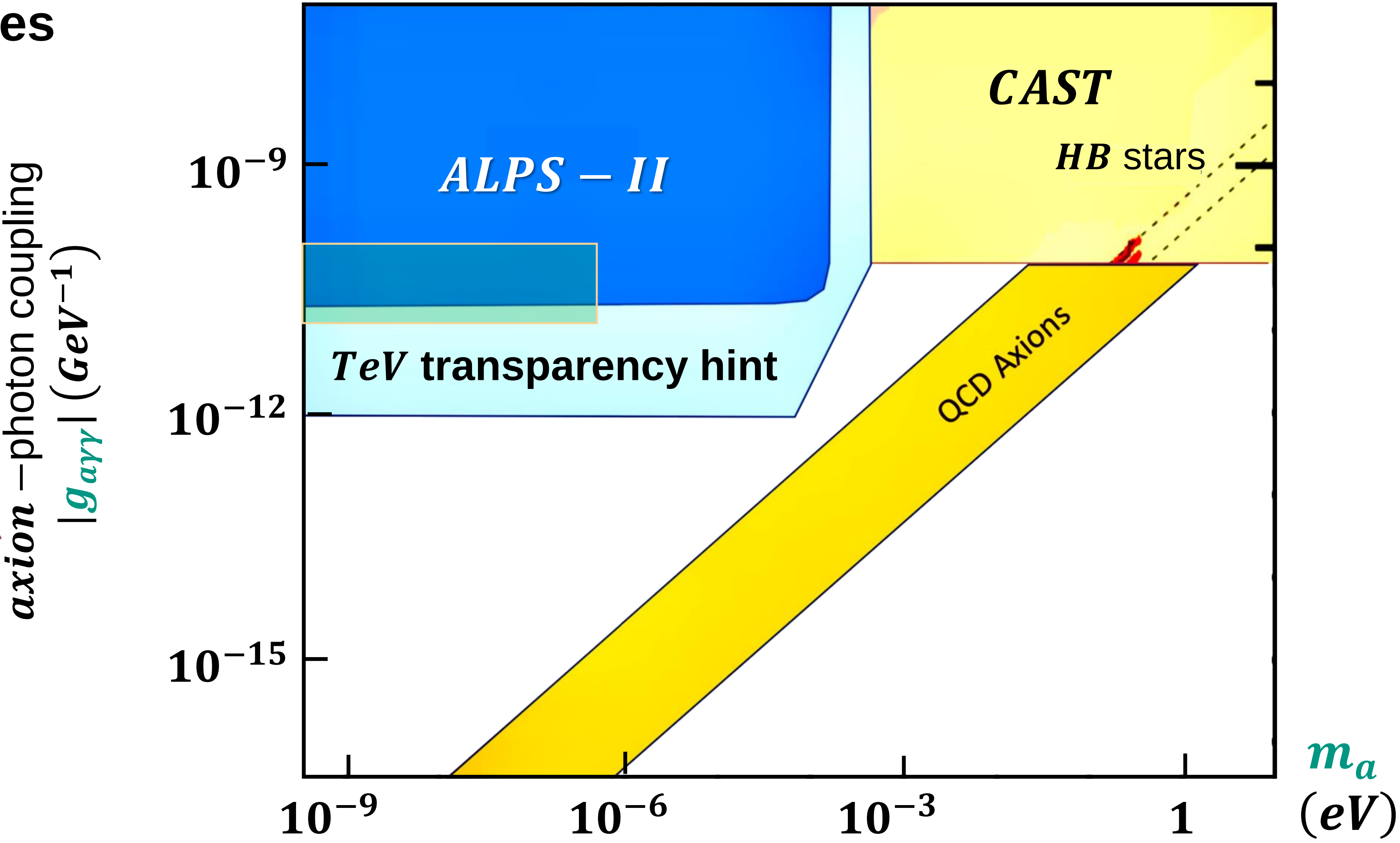


LSW experiments: $ALPS-II$

Expected sensitivities

- sensitive to ALPs with mass parameters to explain $TeV-\gamma$ data of $IACTs$

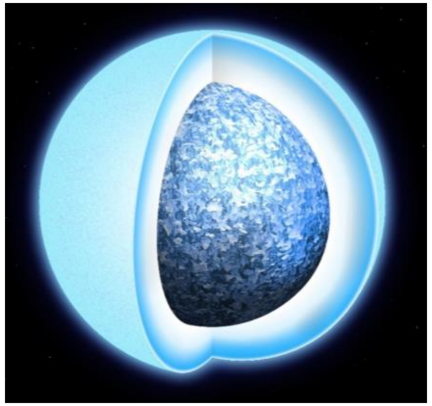


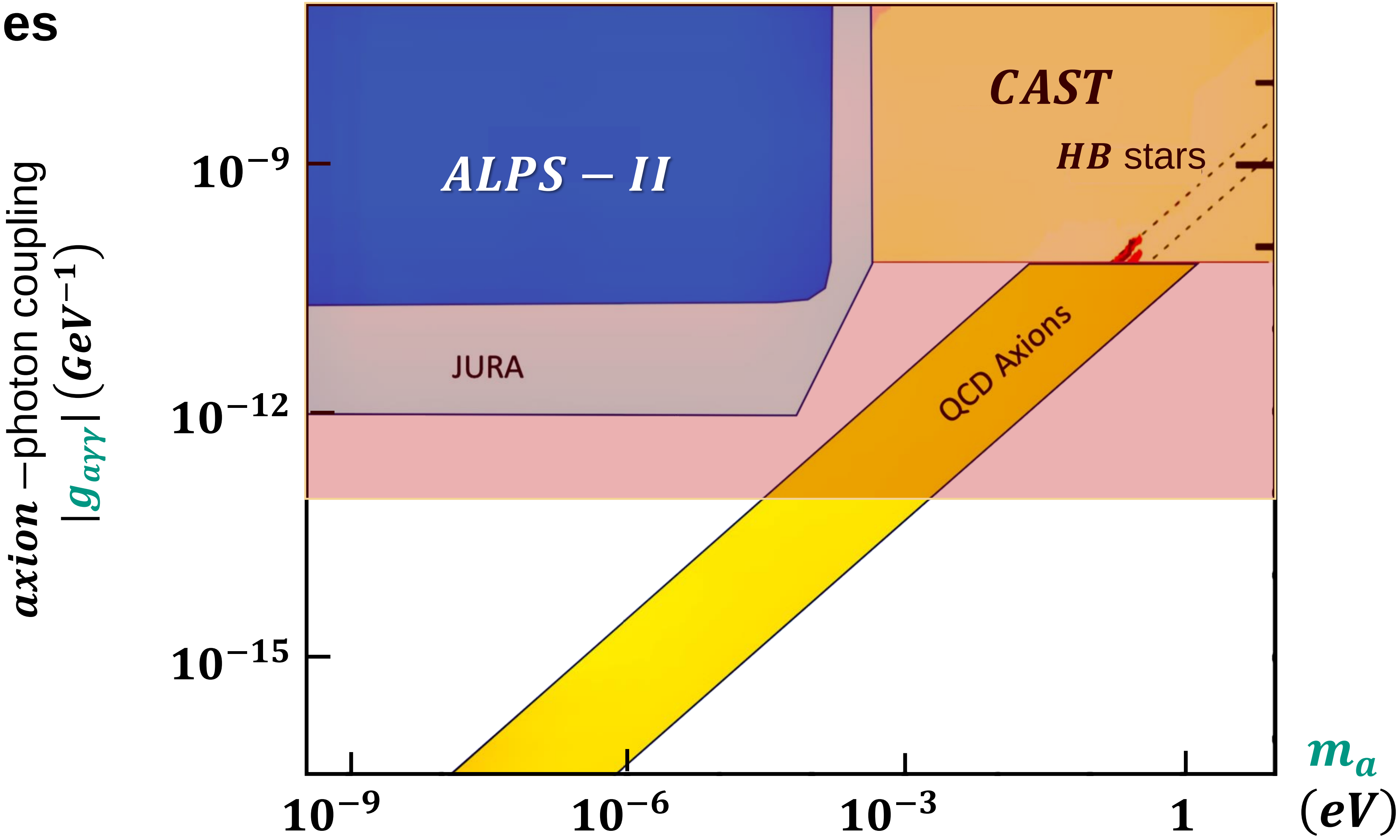


LSW experiments: $ALPS-II$

- **Expected sensitivities**

- very strong **astrophysical limits** on $ALPs$ from the cooling process of **White Dwarf** stars ($ATP-II$)



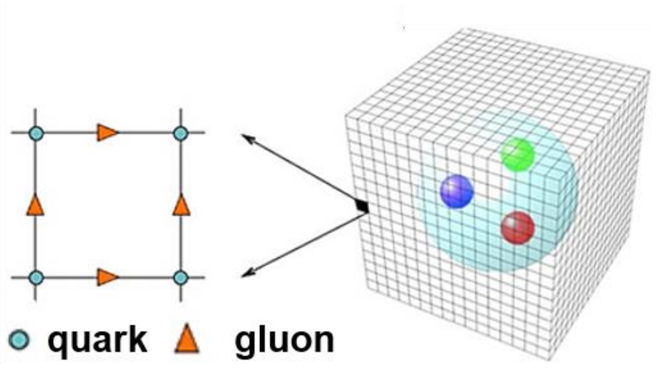


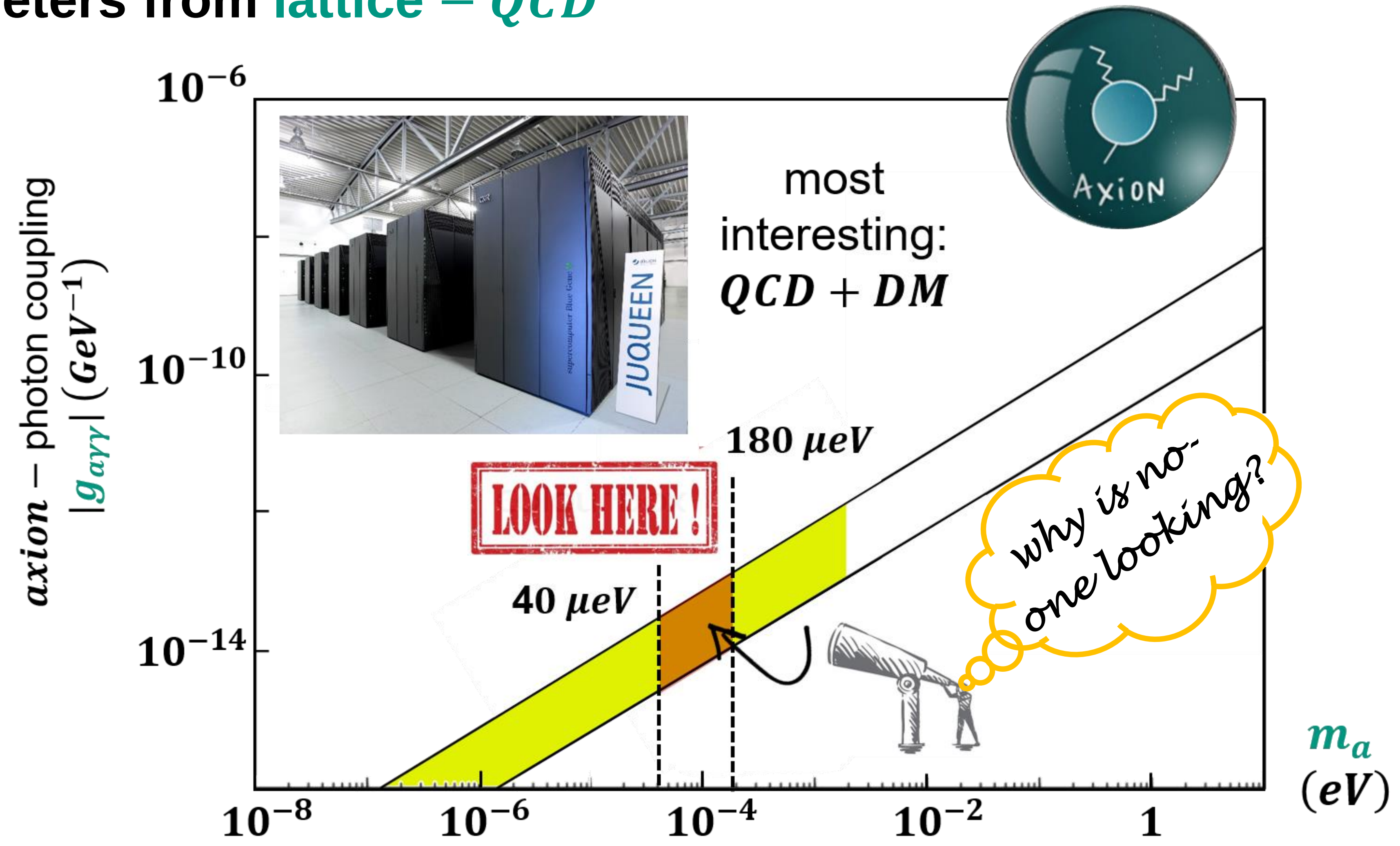
Detection of ´true´ $CDM\ axions$ from halo

■ **RECAP:** $axion$ **parameters from lattice** $-\ QCD$

- we expect $\boldsymbol{CDM/QCD-axions}$ with mass $\boldsymbol{m_a \sim 40 \ldots 180\ \mu eV}$

- we expect $\boldsymbol{CDM/QCD-axions}$ with small **couplings**





Detection of ´true´ CDM $axions$ from halo

- RECAP: $axion$ searches with cavities ⇨ resonant $TM01$ – mode

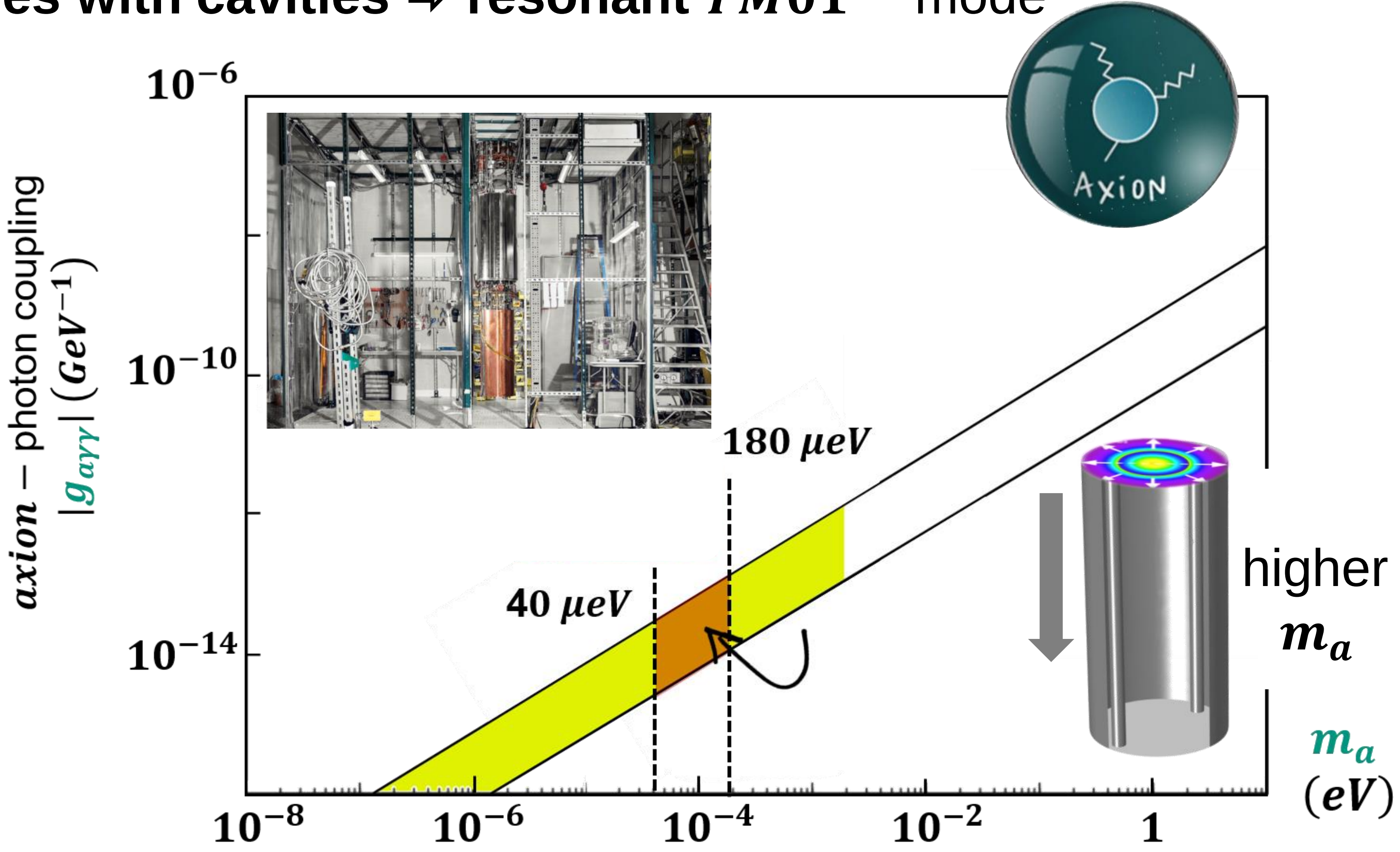
- **cavities*** have to be tuned to a **specific** $axion$ **mass** m_a

$E_a = m_a \cdot c^2$

$E_\gamma = h \cdot f_{res}$

$m_a = 10\ \mu eV$ ⇔
$f_{res} = 2.4\ GHz$

$m_a = 100\ \mu eV$ ⇔
$f_{res} = 24\ GHz$



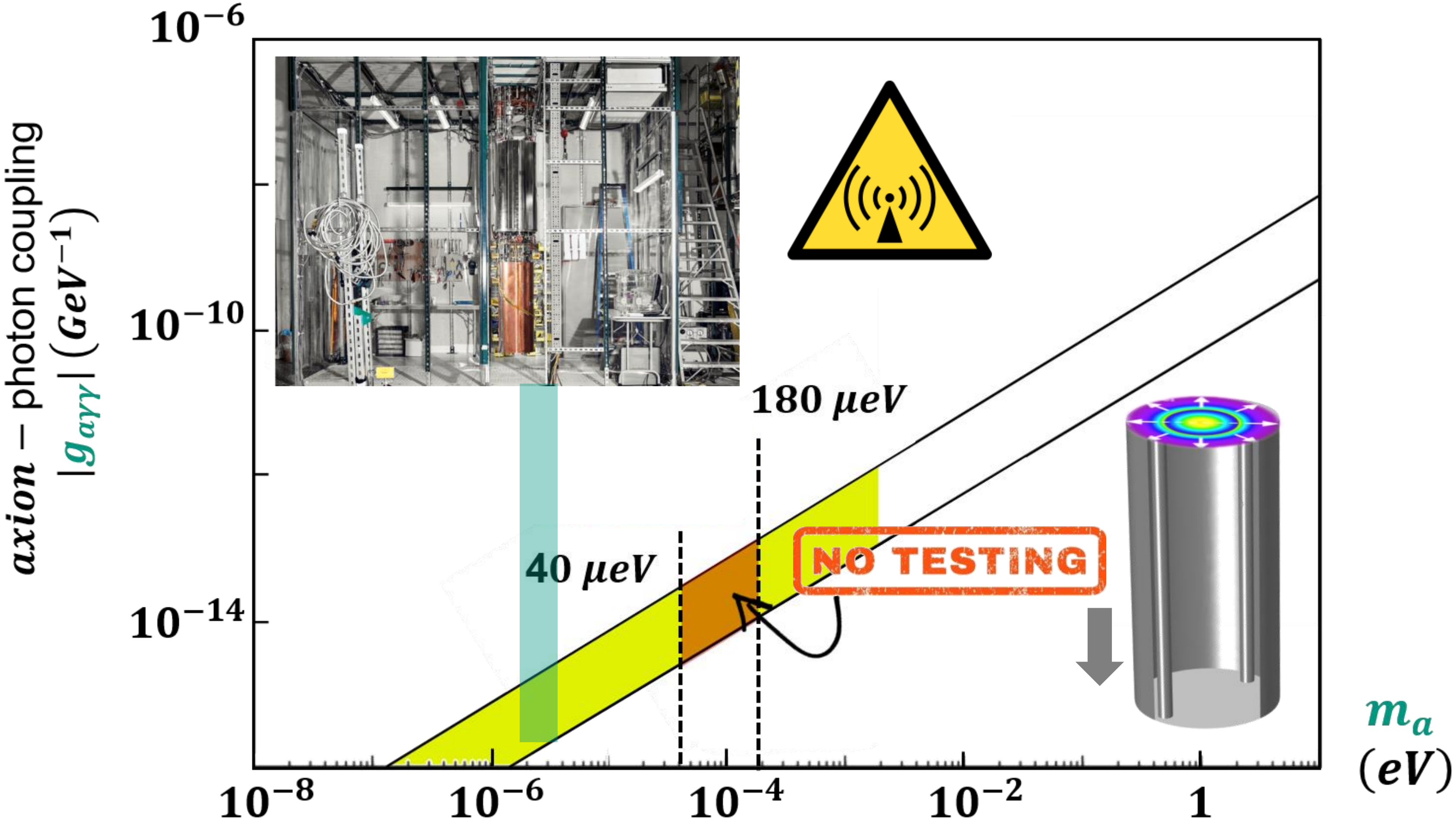
*see Lect. #21: $ADMX$

Detection of ´true´ $CDM\ axions$ from halo

- **RECAP: $axion$ searches with cavities ⇨ resonant $TM01$** – mode

- **resonant cavities:**
  not suitable for
  higher mass range
  $m_a = 40 \ldots 180\ \mu eV$

- **cavity power P:**
  scales as $P \sim$ volume V
  ⇨ the tuning volume*
  $V \sim \lambda_{a,Compt}^3$
  to obtain resonance
  gets **too small**!



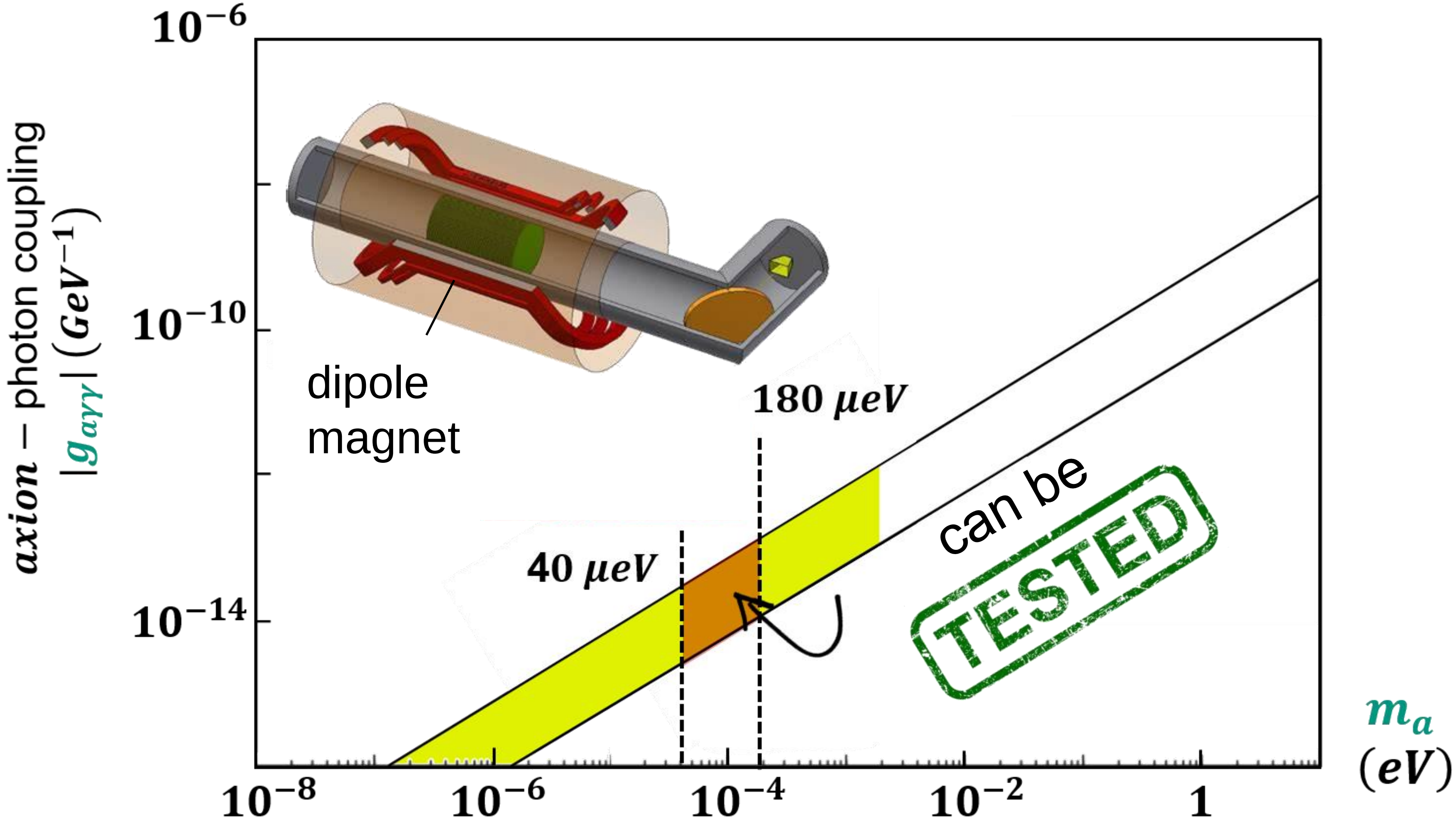
*with $\lambda_{a,Compt} \sim 1/m_a$ (see $p.\,34$)

Detection of wave–like $axions$ at $m_a \sim 10^{-4}\ eV$

- $axion$ searches with dielectric haloscopes: a novel technique

- the $axion$ **field** oscillates over the **de Broglie wavelength λ_a**

- idea: place **dielectric discs** (large ε_R) in a strong magnetic dipole field ⇨ **coherent** emission of radio waves at surfaces of circular discs



Detection of wave−like $axions$

- $axion$ searches with dielectric haloscopses: what about $\lambda_{a,de\ Br}$?

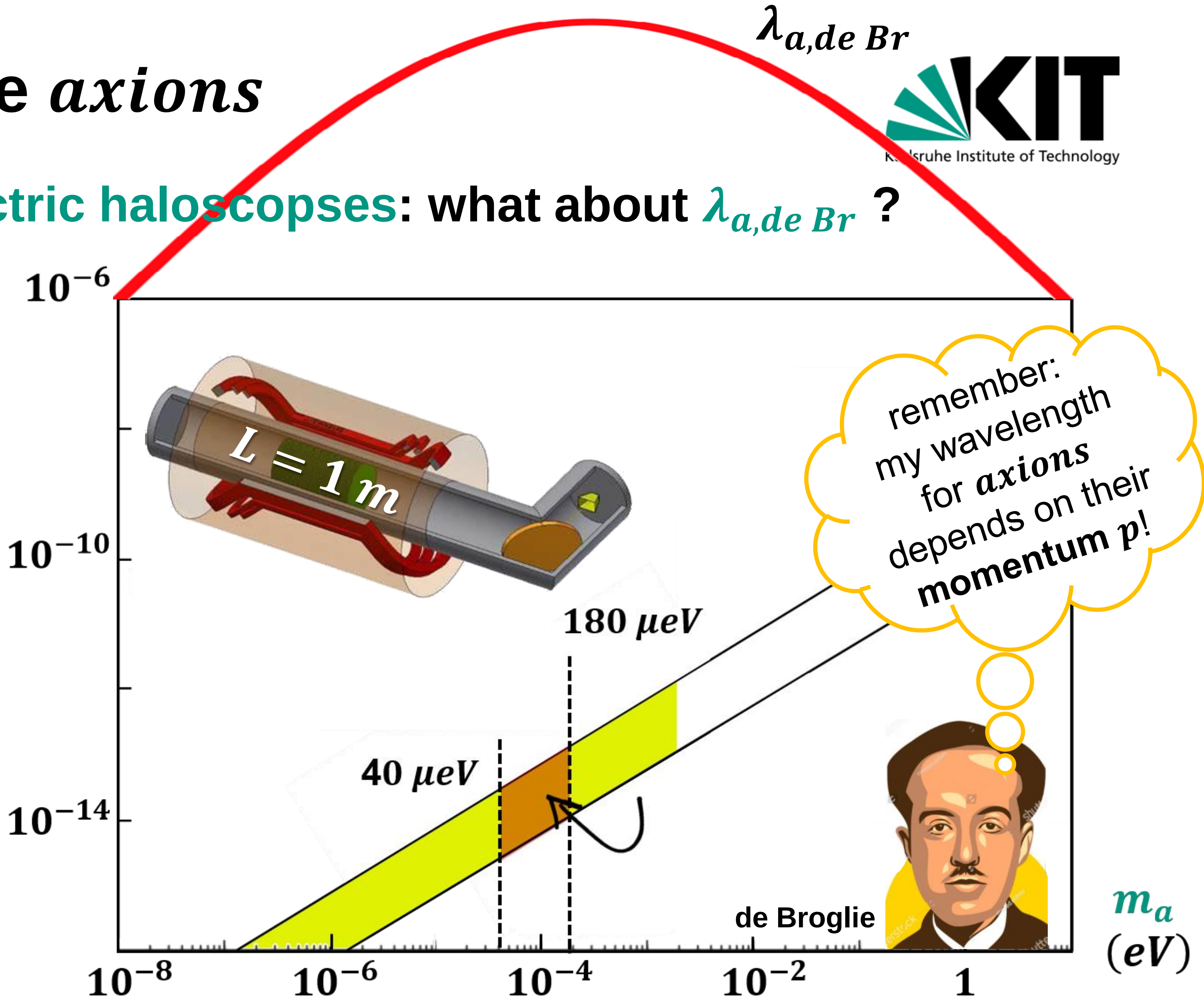
- the $\boldsymbol{axion}$ **de Broglie** wavelength* is

$$\lambda_{a,de\ Br} \approx \frac{2\pi}{m_a \cdot v_{gal}} =$$

$$12.4\ m \cdot \frac{100\ \mu eV}{m_a}$$

- for $m_a = 40 \ldots 180\ \mu eV$ we still fulfill condition for the size L of our setup

$$\lambda_{a,de\ Br} > L$$



$^{*}v_{gal} = 300\ km/s$

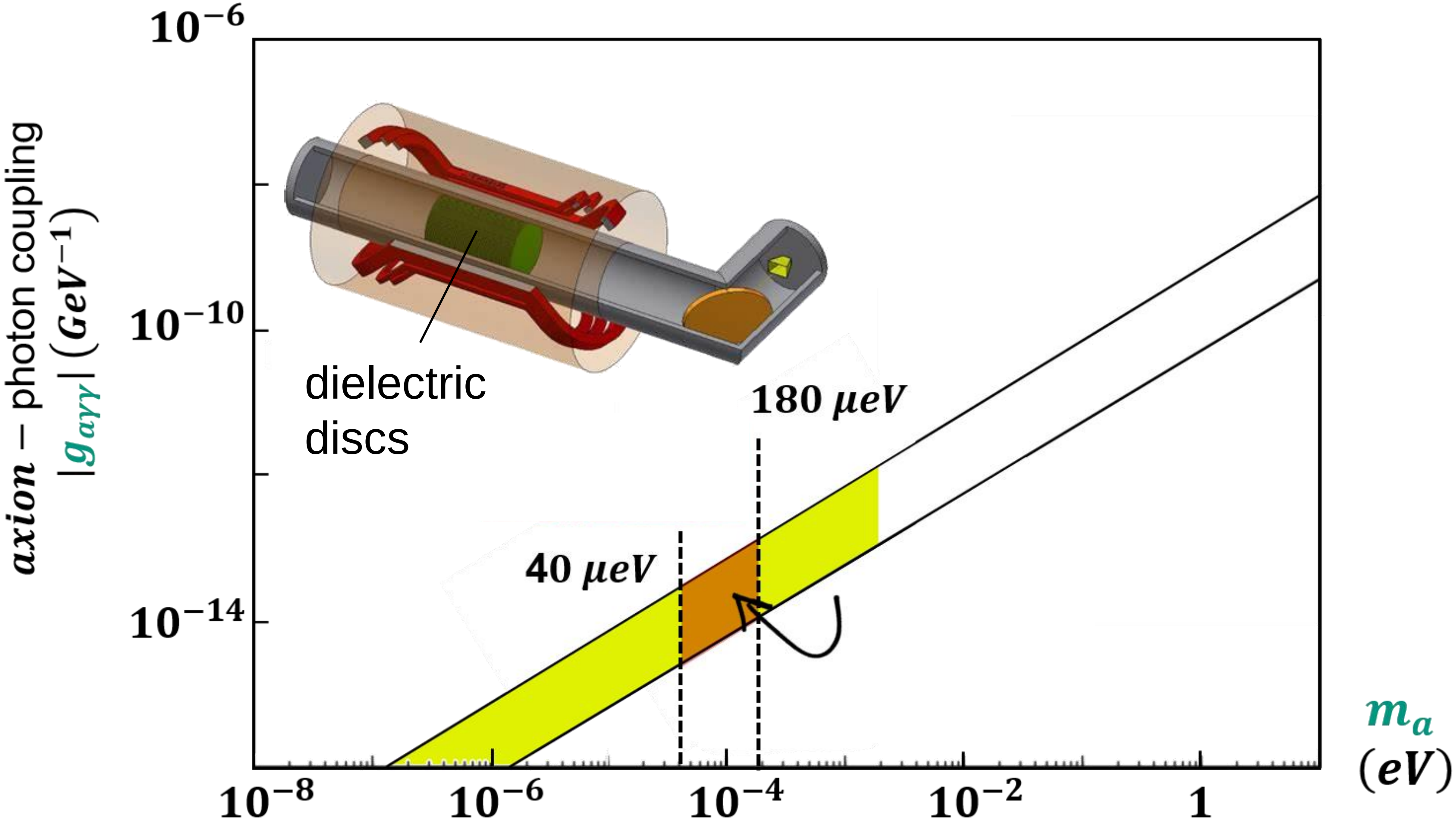
Detection of wave–like $axions$

- $axion$ searches with dielectric haloscopes: what about the signal?

- ⇨ $axion$ behaves as a homogeneous & mono–chromatic & **classical oscillating field**

⇨ induces a really tiny oscillating electric field $E_a(t)$

⇨ emission of **radio waves** at discontinuity between media with ε_R



Detection of wave–like *axions* by radio waves

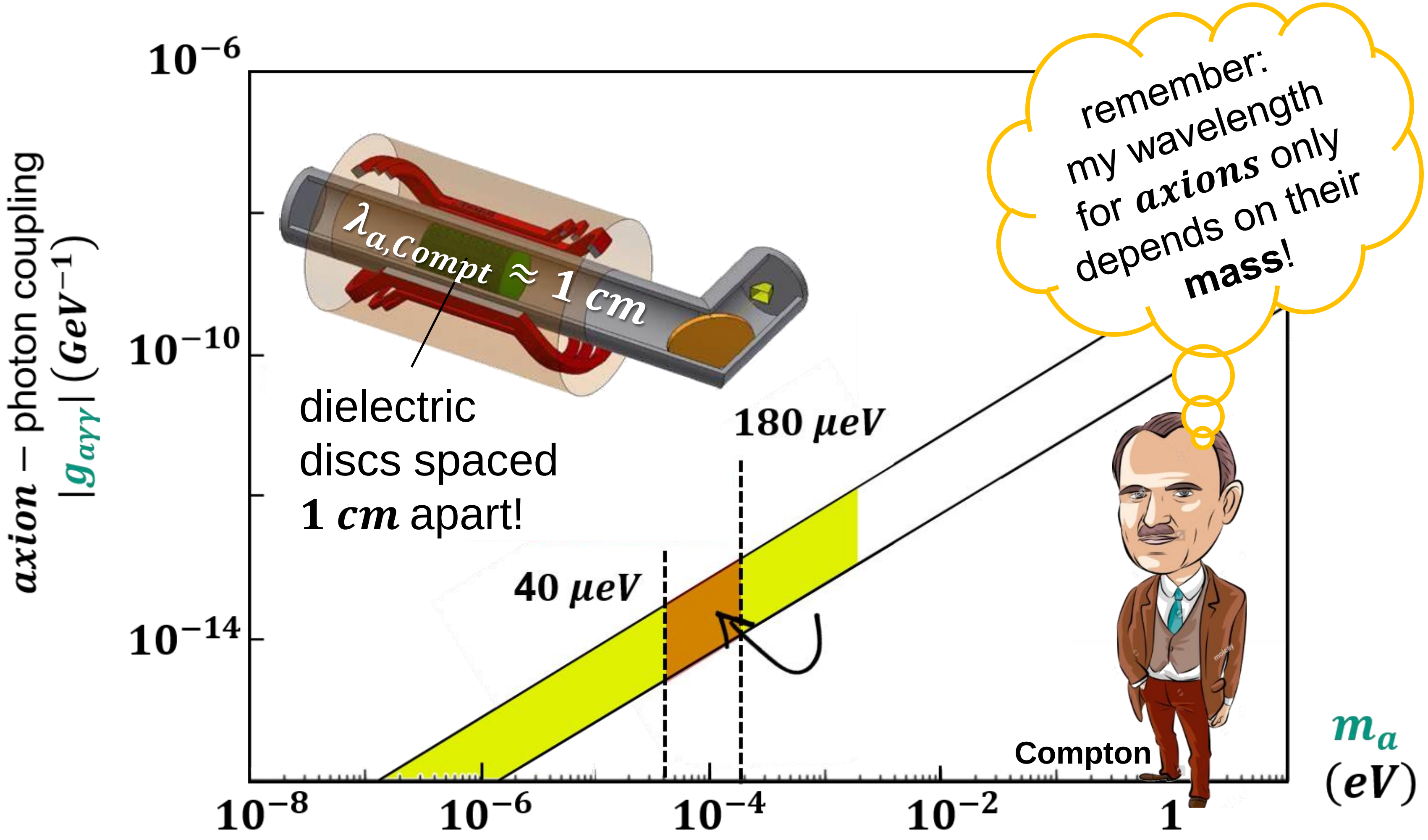
■ ***axion*** **searches with dielectric haloscopes: what about the radio waves?**

- $\boldsymbol{axions}$ $(m_a = 100\ \mu eV)$ cause the emission of **radio** waves, why?

$$\lambda_{a,Compt} \approx \frac{h}{m_a \cdot c}$$

$$\approx 1\ cm$$

- $\boldsymbol{axion}$ as $\boldsymbol{CDM}$ particle*: Compton wavelength $\lambda_{a,Compt} \approx 10^{-3} \cdot \lambda_{a,de\ Br}$



$^*v_{gal} = 10^{-3} \cdot c$

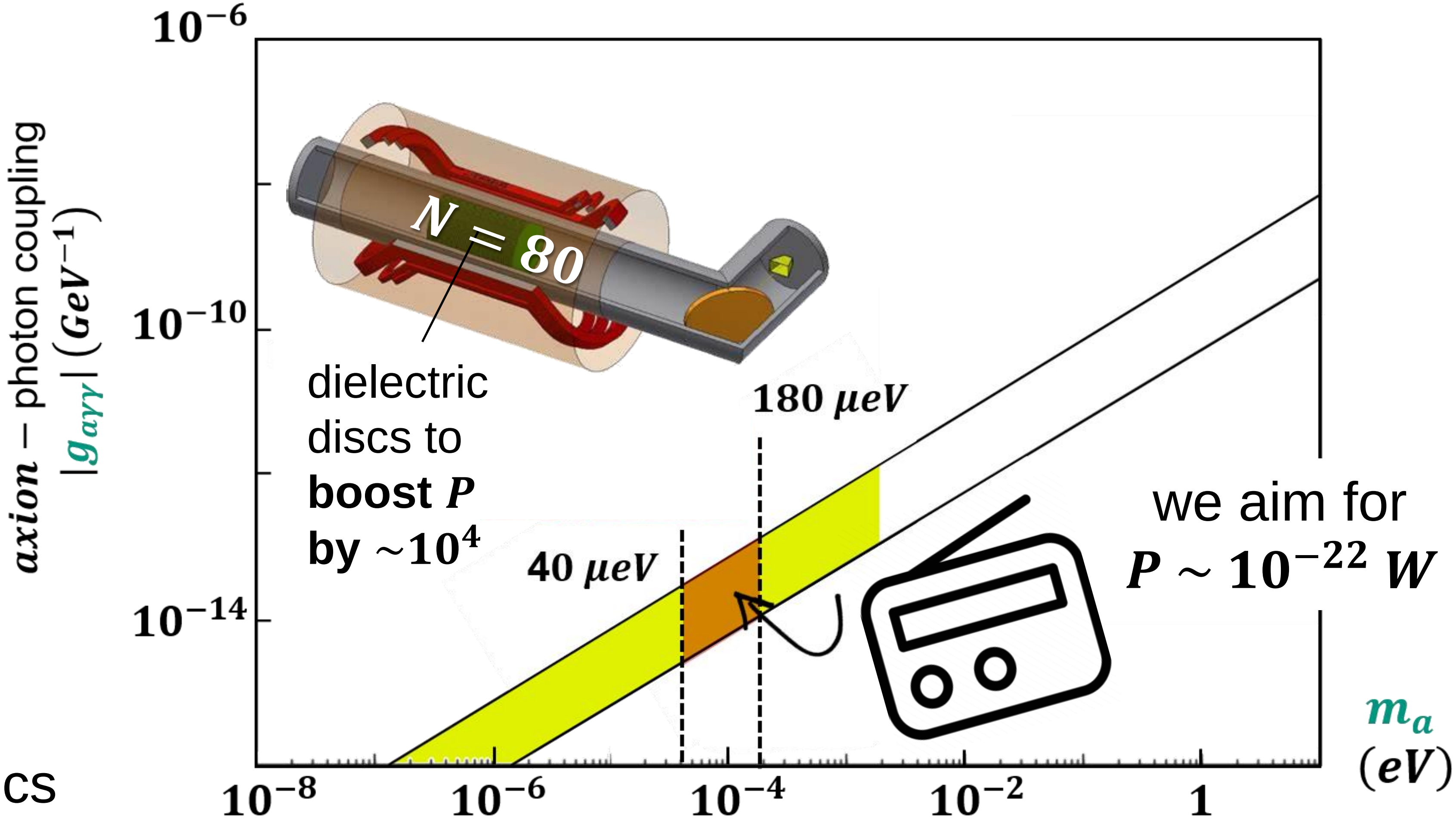
Detection of wave–like $axions$

- $axion$ searches with dielectric haloscopes: what about the radio power?

- the $axion$ – induced power of radio waves ($\mathbf{1}$ dielectric disc)

$$P = 2.2 \cdot 10^{-27}\, W \cdot \left(\frac{A}{1\, m^2}\right)^2 \cdot \left(\frac{B_{ext}}{10\, T}\right)^2$$

⇨ **boost** by many ($\mathbf{80}$) discs



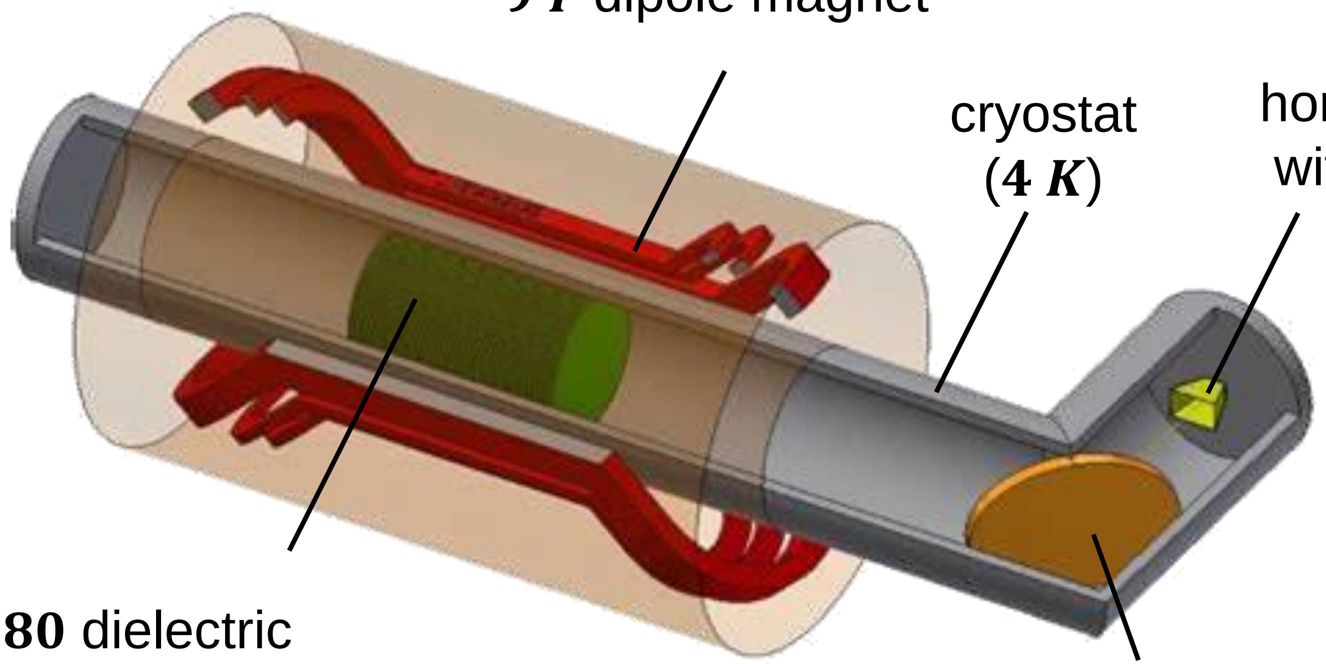
we aim for $P \sim 10^{-22}\, W$

$^*v_{gal} = 300\ km/s$

Dielectric haloscopes: enter $\boldsymbol{MADMAX}$*

- **Central element: large dielectric discs in $\boldsymbol{B}$ – field**

  - searching for $\boldsymbol{CDM - axions}$ with mass $\boldsymbol{m_a \approx 100\ \mu eV}$



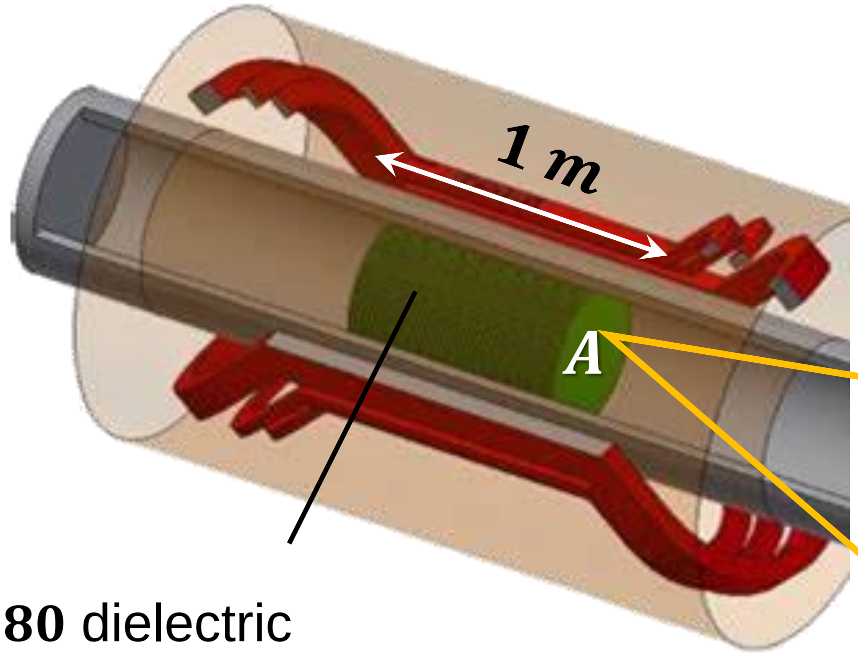
*$\boldsymbol{MA}$gnetized $\boldsymbol{D}$isc and $\boldsymbol{M}$irror $\boldsymbol{A}$xion E$\boldsymbol{X}$periment

Dielectric haloscopes: disks of $MADMAX$

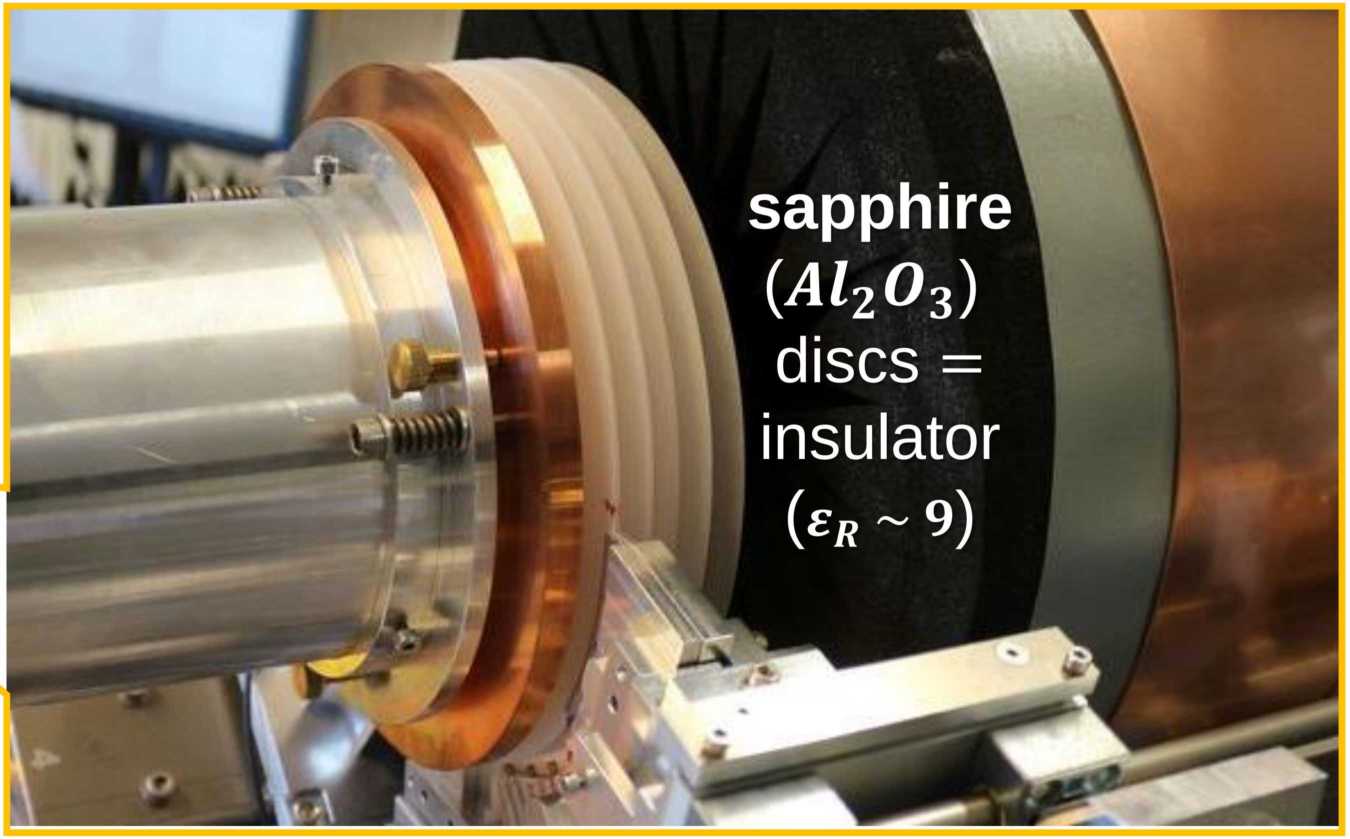
- A ´booster array´ of many large dielectric sapphire discs in strong B – field

  - $\boldsymbol{axion}$ sensitivity scales as $\sim (B^2 \cdot A) \times$ **coherence boost** (10^4) from many discs

    ⇨ goal: $B^2 \cdot A = 100\ T^2 m^2$



$\mathbf{80}$ dielectric plates ($\varnothing\ =\ \mathbf{1.25}\ m$)

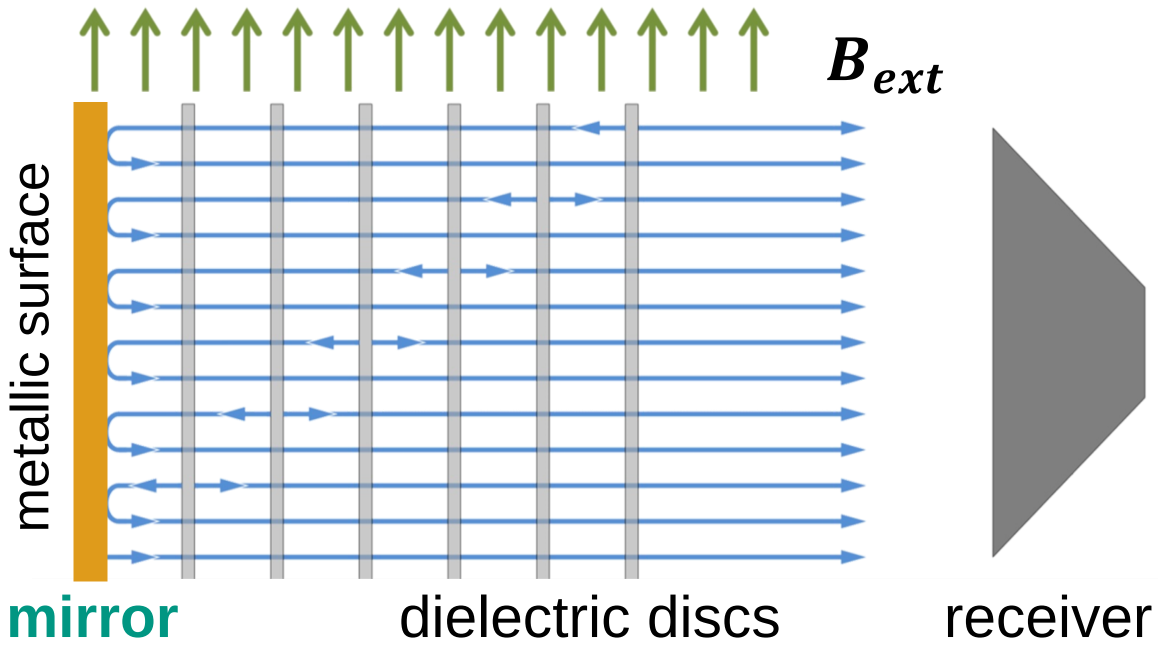


Dielectric haloscopes: principle of $MADMAX$

- $Axion$ **field induces electromagnetic field at surfaces of dielectric discs**

  - **surface of one dielectric disc**: discontinuity of $\boldsymbol{axion}$ – induced electromagnetic oscillations (⇨ emission of radio waves)

  - **many** dielectric plates: ⇨ **coherent emission** (**constructive** interference)



- expected $\boldsymbol{axion}$ signal power:
  1 disc with $\boldsymbol{A = 1\,m^2}$ in $\boldsymbol{B_{ext} = 10\,T}$
  ⇨ $\boldsymbol{P = 10^{-27}\,W}$ (much too small...)

- solution:
  large number of dielectrics & **1 mirror**
  ⇨ **coherence boosts signal by** $\boldsymbol{> 10^4}$

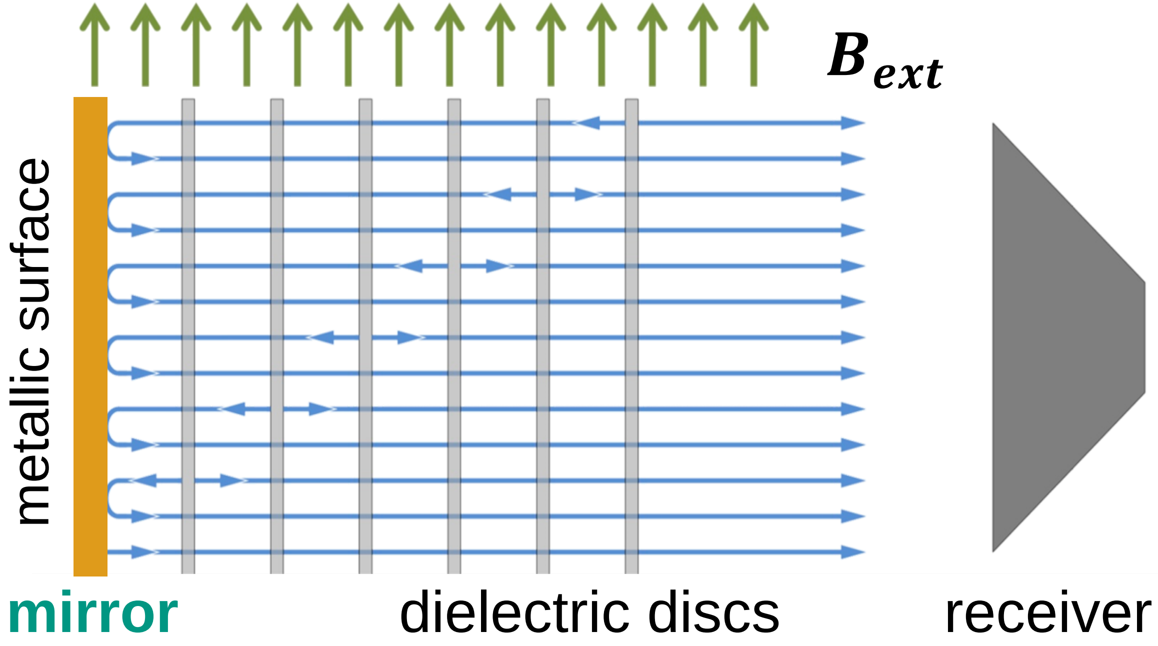
Dielectric haloscopes: principle of $MADMAX$

Karlsruhe Institute of Technology

- $Axion$ **field induces electromagnetic field at surfaces of dielectric discs**

  - constructive interference of emitted radio waves: requires **extremely precise positioning** (μm – **scale!**) of large, heavy dielectric discs in strong B – field!

  - variation of **distance d** between discs allows to scan $axion$ **mass range m_a**

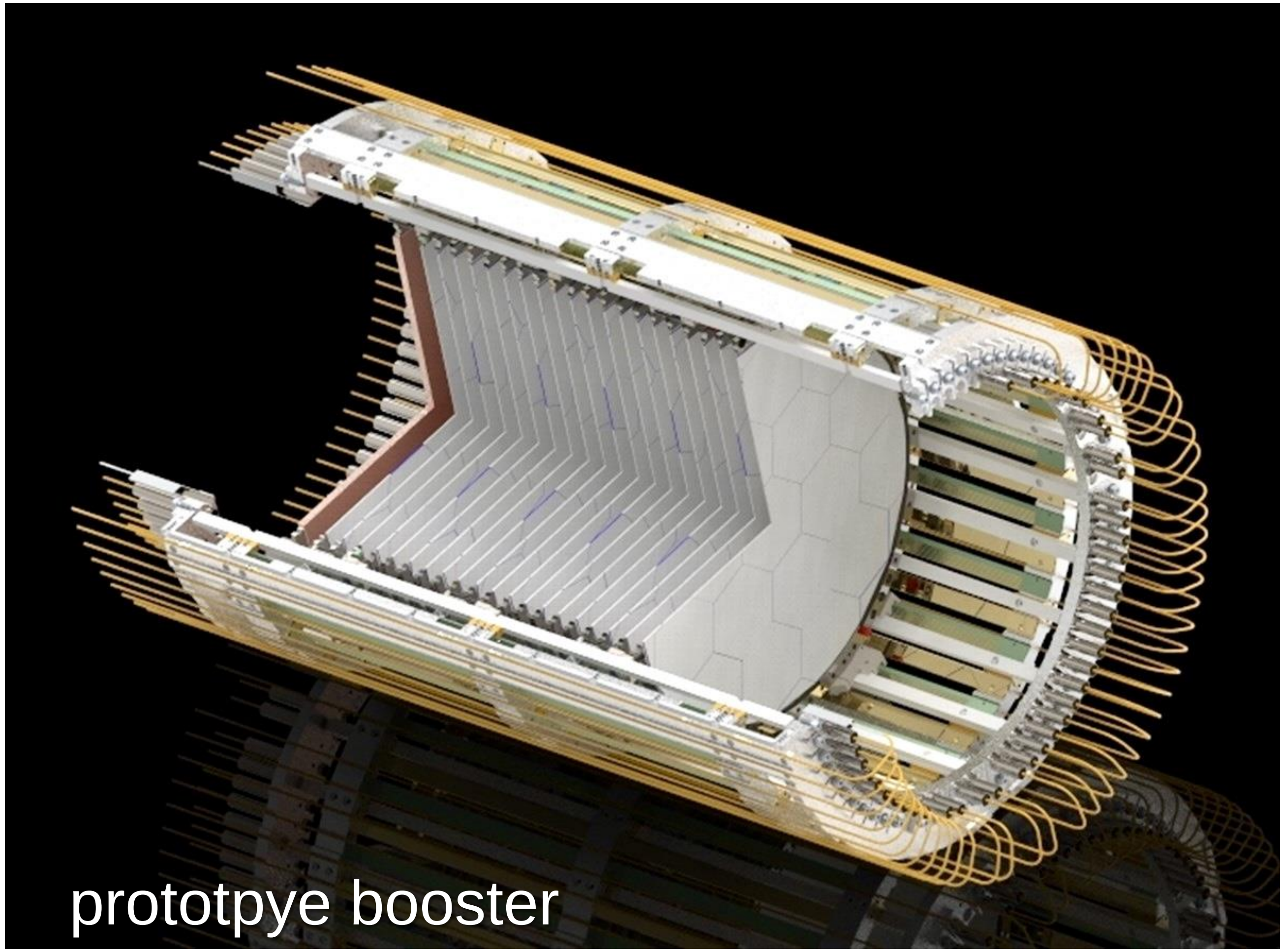


- dielectric discs made of lanthanum aluminate $LaAlO_3$ with $\epsilon_r = 24$
  ⇨ generation of **radio waves**

- **boosting of signal power**: many resonant transitions of ϵ_r at surfaces
  ⇨ reasonable band–width in $axion$ scans

Dielectric haloscopes: discs of $MADMAX$

- $Axion$ **field induces electromagnetic field at surfaces of dielectric discs**



prototpye booster

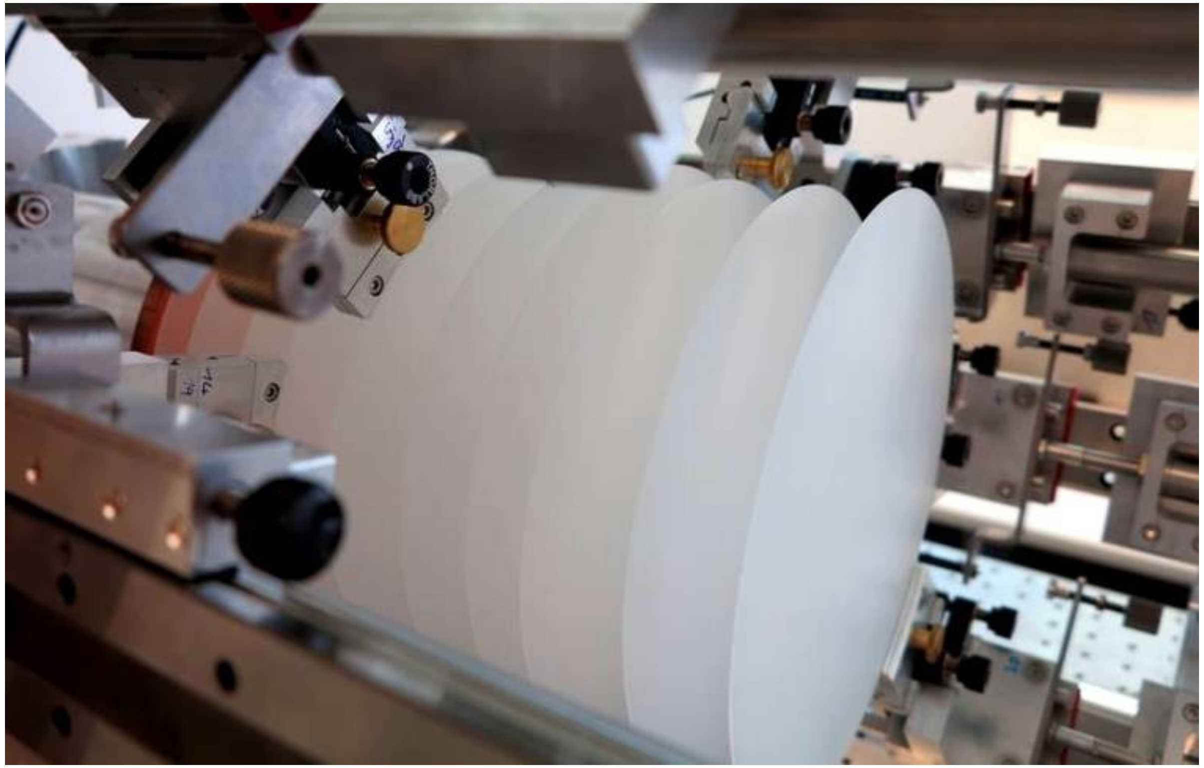
- dielectric discs have to operate
  at cryogenic $\boldsymbol{T = 4\ K}$
  in strong dipole fields $\boldsymbol{B_{ext} = 10\ T}$
  over many years during scans

- highly accurate positioning of discs
  via piezo−driven **actuators** to
  a) maximise the coherence of all
  $\mathbf{80}$ disks
  b) to scan the $\boldsymbol{axion}$ mass range
  by adjusting the disc distance $\boldsymbol{d}$

Dielectric haloscopes: disks of $MADMAX$

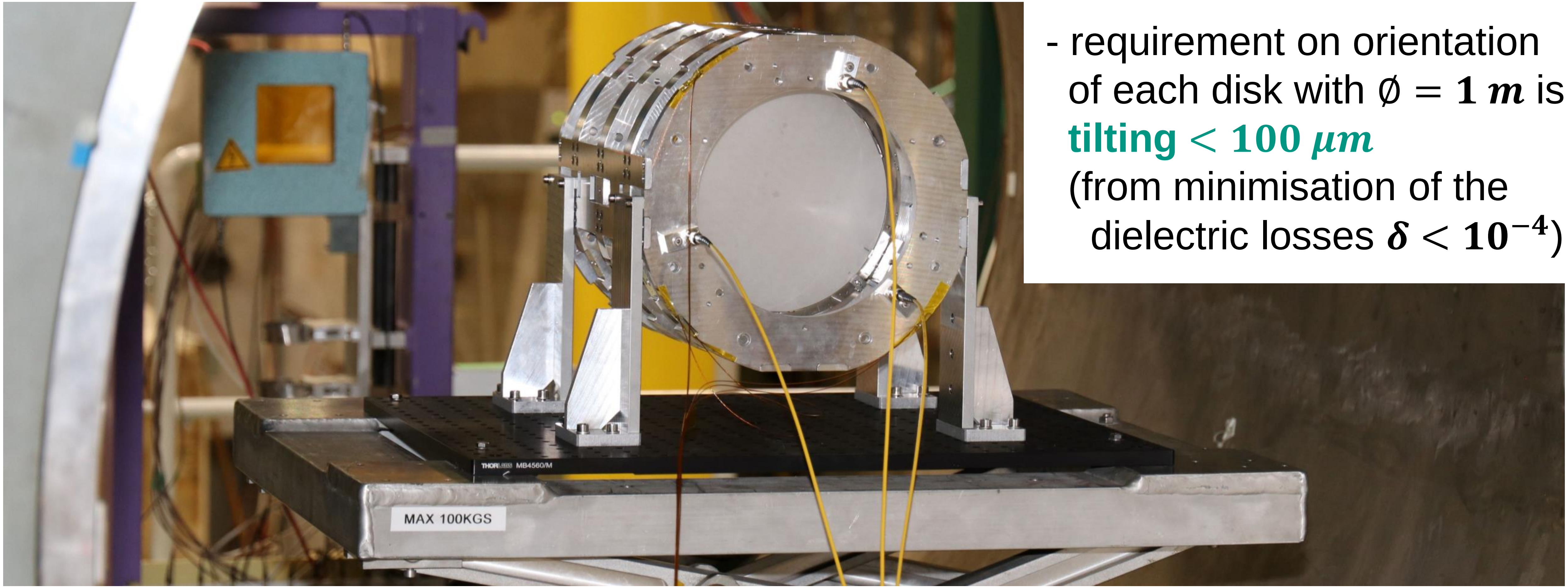
- $Axion$ **field induces electromagnetic field at surfaces of dielectric discs**

- dielectric discs: broad $R\&D$ works
  required flatness $< 2\ \mu m$



Dielectric haloscopes: disks of $MADMAX$

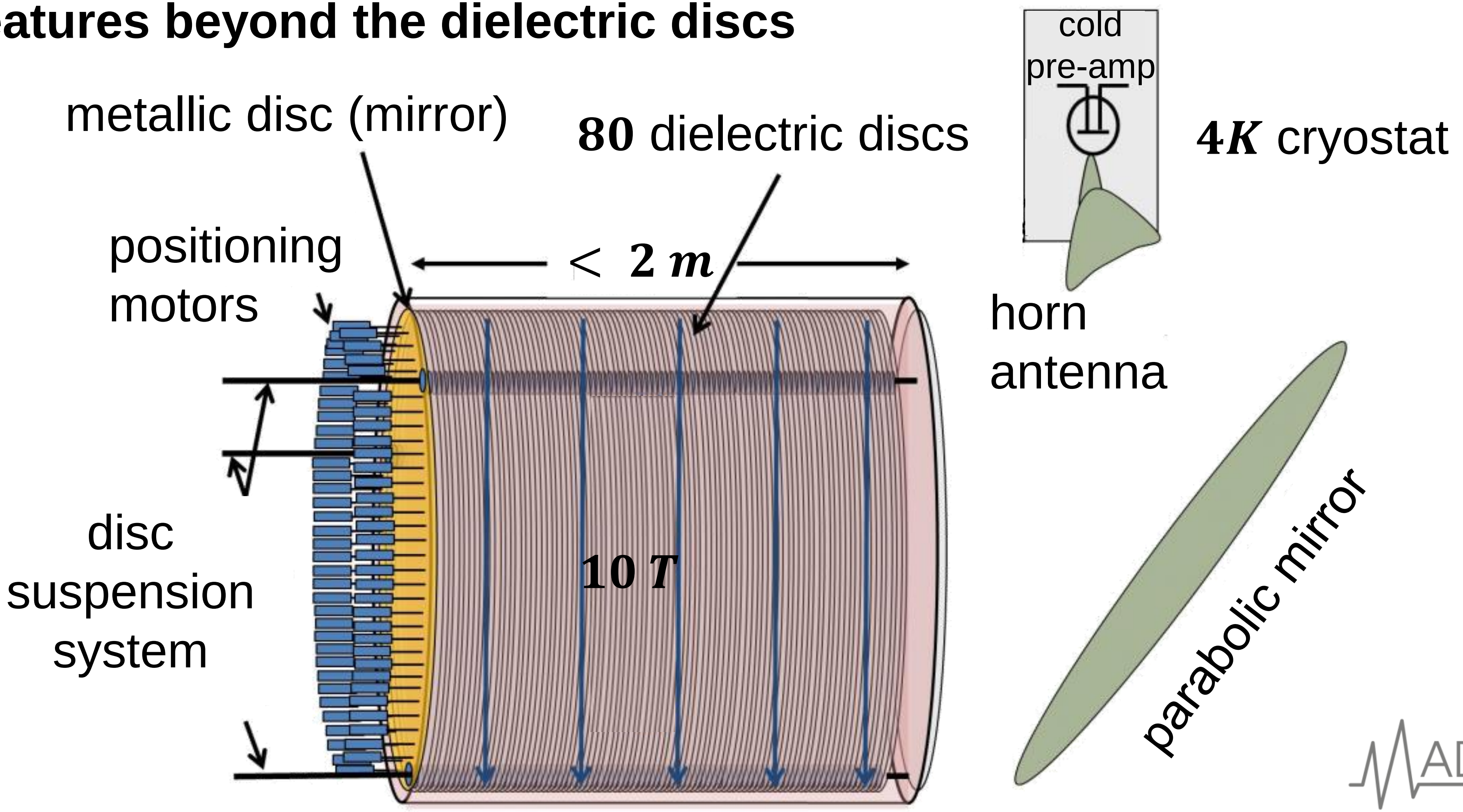
- Ongoing tests at different laboratories



- requirement on orientation of each disk with $\emptyset = \mathbf{1}\,\boldsymbol{m}$ is **tilting $< \mathbf{100}\,\boldsymbol{\mu m}$** (from minimisation of the dielectric losses $\boldsymbol{\delta} < \mathbf{10^{-4}}$)

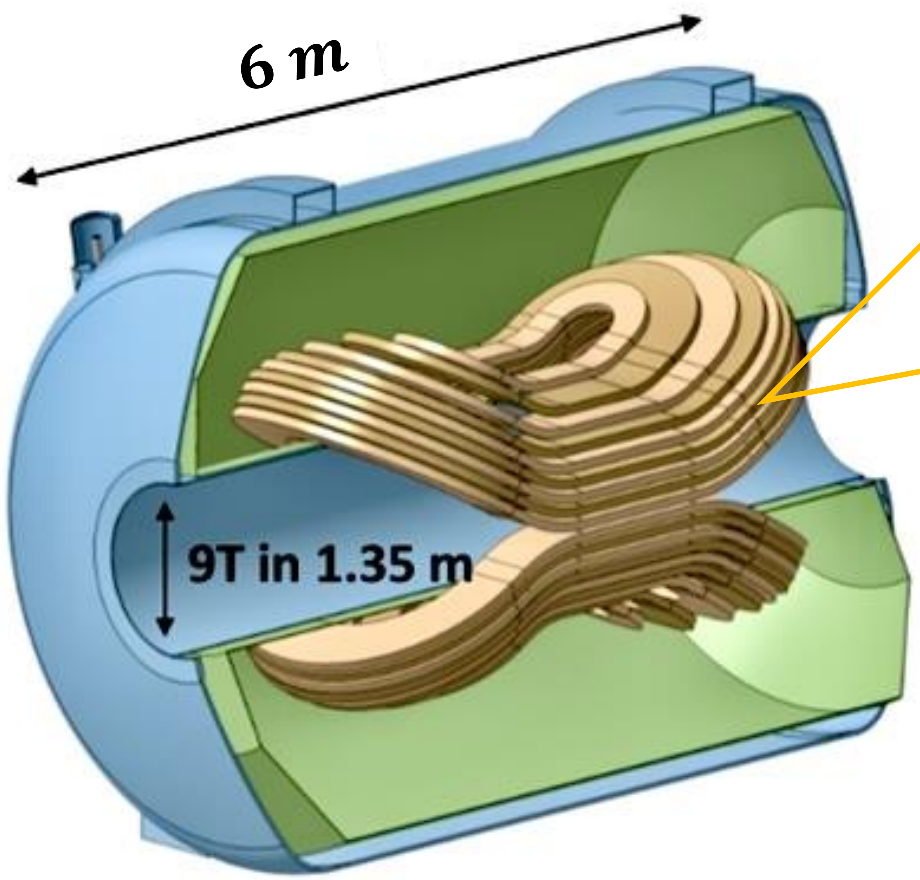
Dielectric haloscopes: principle of $MADMAX$

- **Key features beyond the dielectric discs**



Dielectric haloscopes: setup of $MADMAX$

- Key features of $s.c.$ dipole: ongoing studies by leading magnet companies



Parameter	Results
J_E	50 A/mm²
By (0,0,0)	-8.82 T
Bpeak (x,y,0)	9.85 T
Bpeak	**9.87 T**
Overfield (B_{peak}/B_0)	11.8 %
FoM	**94.4 T²m²**
H+ / H- (Z = 0.0 m)	-0.9 % / 5.0 %
Energy	**482 MJ**
Volume	**4.435 m³**
Length	**5.0 m**

BILFINGER NOELL GMBH

Dielectric haloscopes: testing of $\boldsymbol{MADMAX}$

Karlsruhe Institute of Technology

■ **MADMAX and CERN's Morpurgo magnet**

$\boldsymbol{Project\ 200}$

- measurements with test set–up at $\mathbf{40}\ \boldsymbol{yr}$ – old ´$\boldsymbol{Morpurgo}$´ magnet ($\boldsymbol{B = 1.6\ T}$) at $\boldsymbol{CERN}$

- **$\mathbf{2022}$: testing the positioning accuracy in a strong $\boldsymbol{B}$ – field**

The Morpurgo magnet, located in the North Area on the Prévessin site, will provide a magnetic field of up to 1,6 Tesla for the MADMAX prototype (Image: CERN)

MADMAX is preparing for a stopover at CERN from 2022. Mel Gibson, his artillery and quest for revenge will not be there, but instead a handful of physicists armed with an aged magnet will be searching for dark matter in CERN's North Area (not to be confused with a post-apocalyptic wasteland).

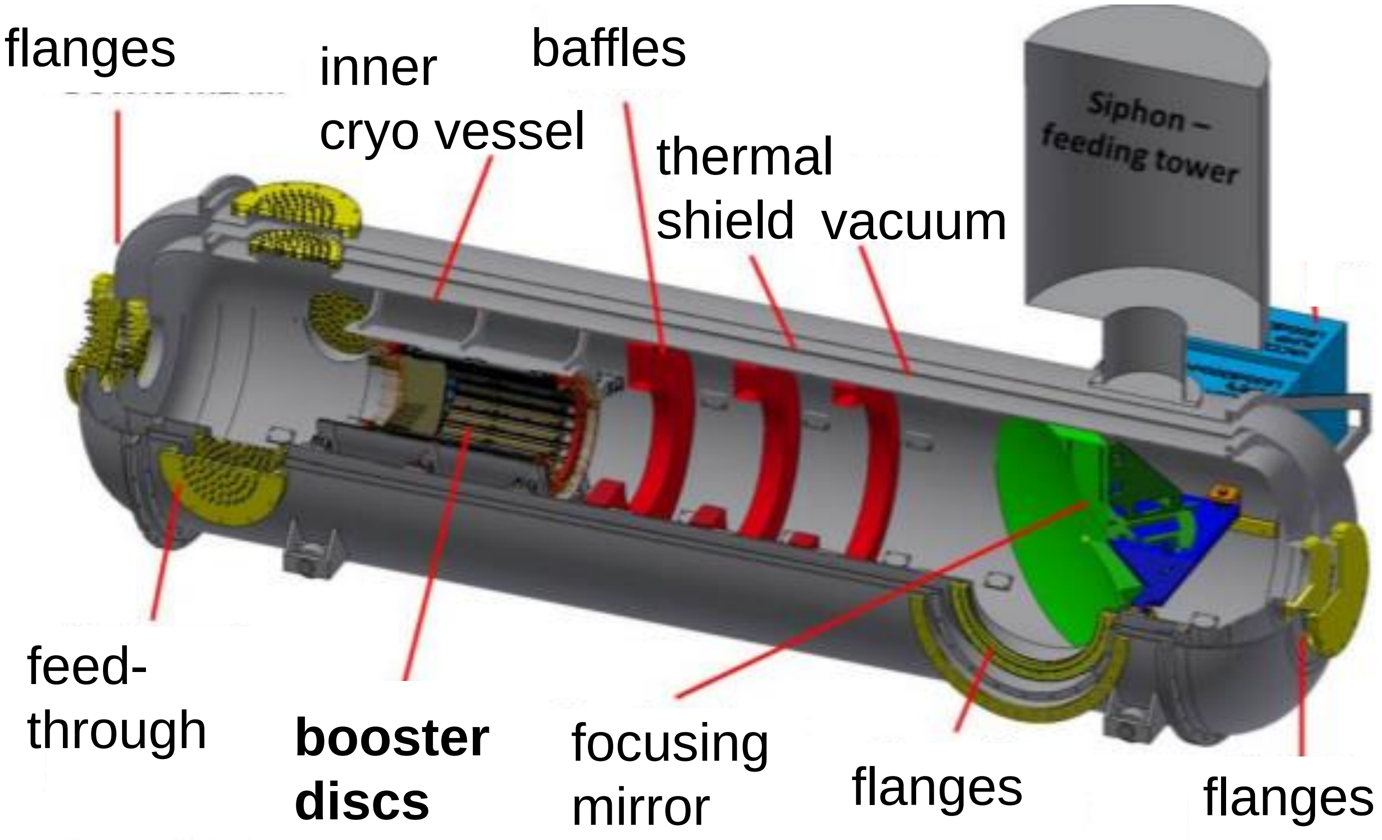
Dielectric haloscopes: prototyping for $MADMAX$

- **Setup of $CB100$: a physics prototype experiment at $CERN$**

- prototype built at $DESY$ and shipped to $CERN$

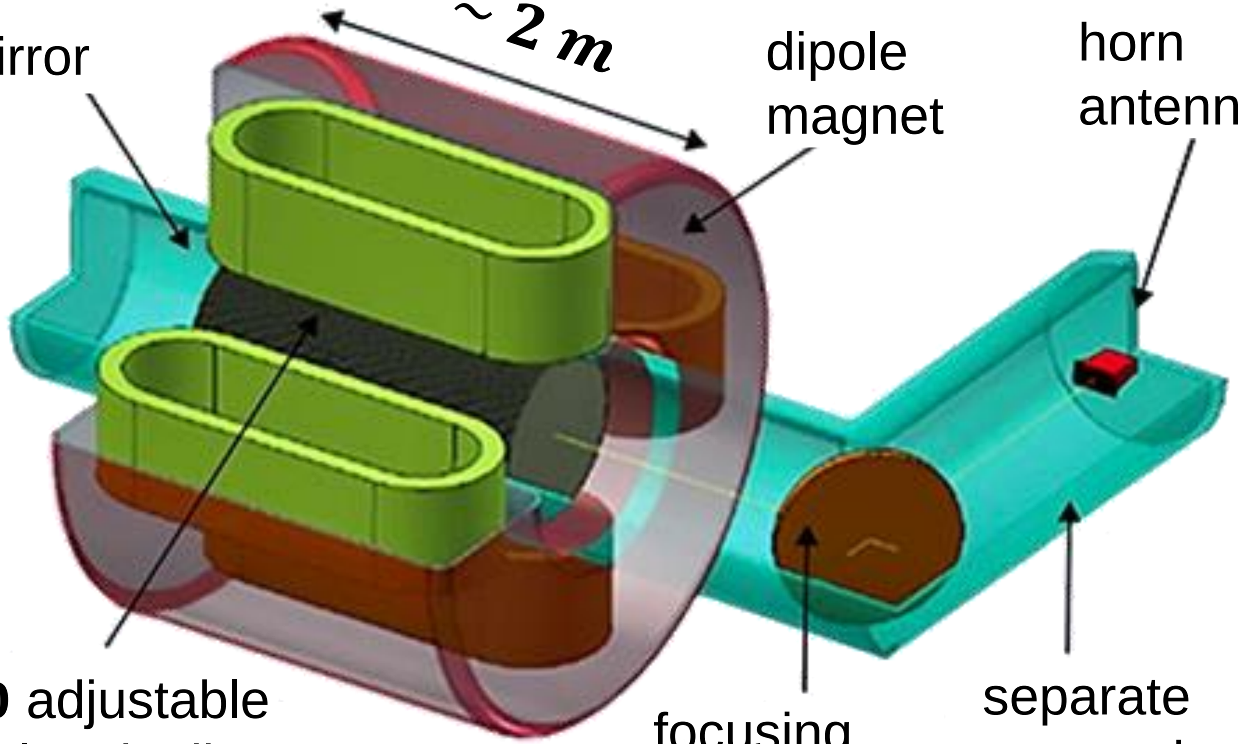
- prototype cryostat with a **booster** of $\mathbf{20}$ discs of $\emptyset = 30\ cm$

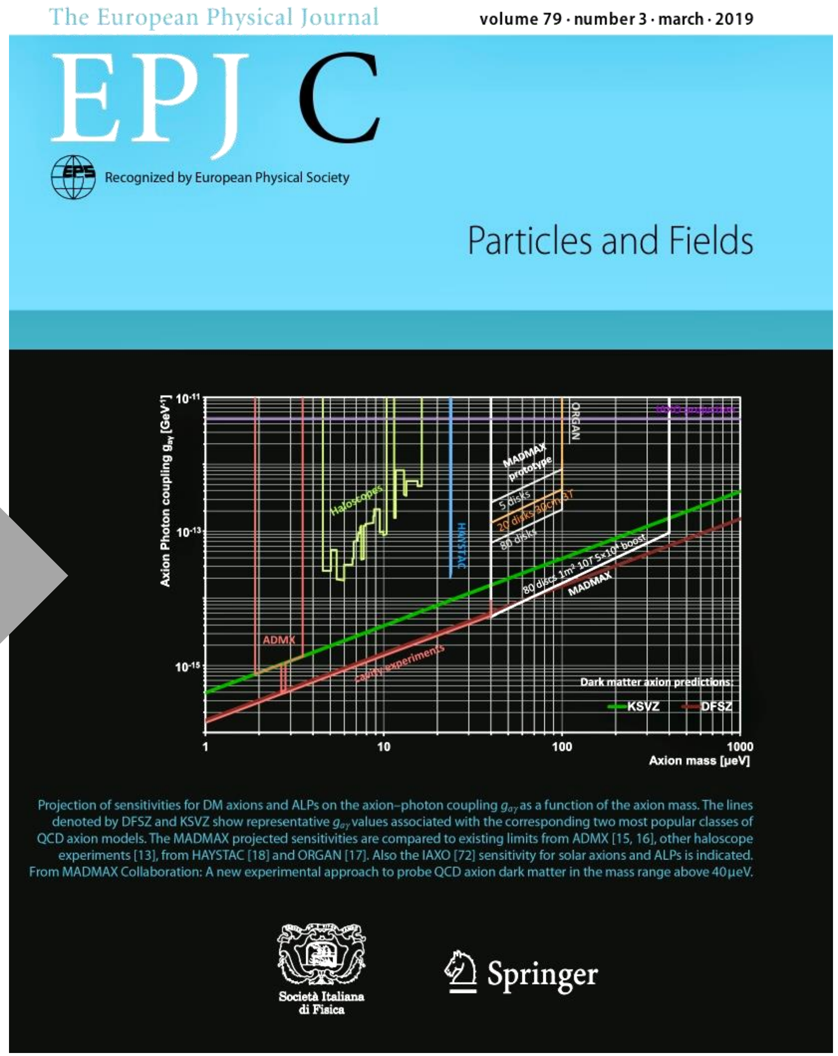
- if prototype is well understood: obtain first competitive limits on $ALPs$ at $m_a = 100\ \mu eV$ (if a noise temperature $T = 8\ K$ is reached) after $\mathbf{90}$ days of scans



Dielectric haloscopes: final setup of $MADMAX$

■ **Optimizing the final experiment**





Comparison of experimental sensitivities

- **Dielectric haloscopes & others**