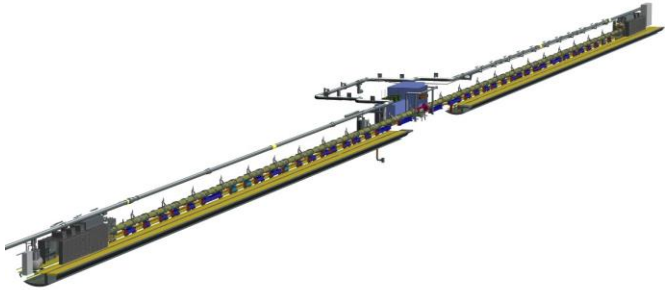
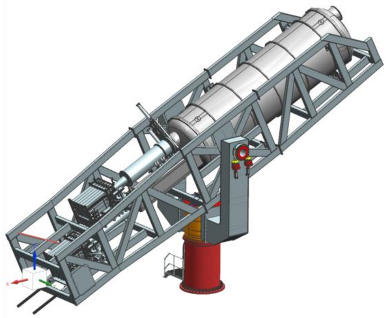


The Future of the Axion Program at DESY

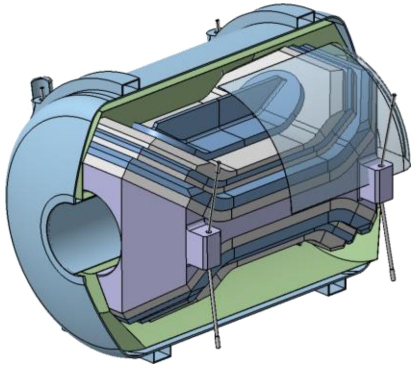
ALPS II and beyond



Friederike Januschek with many slides from **Katharina Isleif** and **Axel Lindner**

14th annual meeting of the Helmholtz alliance „Physics at the Terascale“

Hamburg, November 24th 2021



- Why axion searches?
- How axion searches?
- The Past: ALPS I
- The Present: ALPS II commissioning
- The Future: ALPS II, (Baby)IAXO, MADMAX
- Some more…

HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

PHYSICS AT THE TERASCALE Helmholtz Alliance

HELMHOLTZ GEMEINSCHAFT

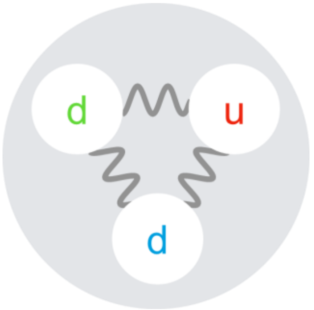
DESY.

Why to look for axions?

Axions and Axion-like particles

Axions

- Why is there **CP conservation** in QCD?
  - A new pseudo Nambu-Goldstone boson, called ***axion***, is introduced to clean the theory Peccei&Quinn (1977), Weinberg (1978)
- Axions are also viable cold **dark matter** candidates



Example: measurement of the electric dipole moment $\overline{\theta}$ of a neutron: Abel et al. 2020

$$\left.\begin{array}{l} d_{\text{neutron}}^{\text{theory}} \sim 10^{-16}\overline{\theta}\,ecm \\ d_{\text{neutron}}^{\text{exp.}} < 10^{-26}\,ecm \end{array}\right\} \overline{\theta} < 10^{-10}$$

The *QCD axion* has

- *very low mass,* that is related to QCD scale:

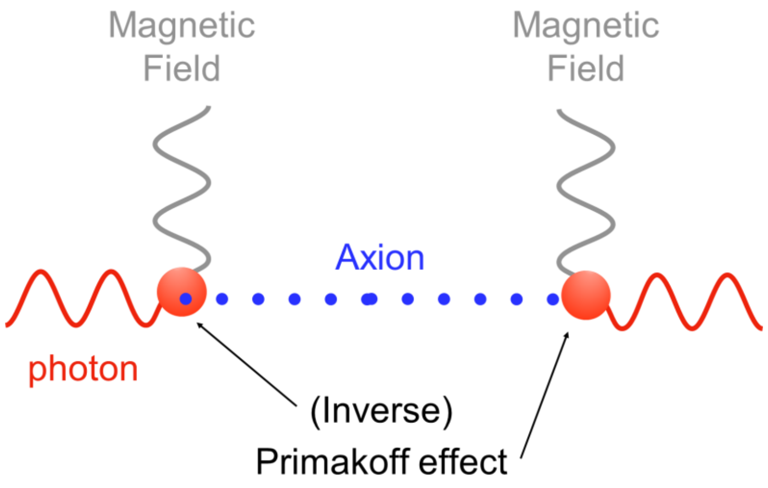
$$m_a f_a^2 \propto m_\pi^2 f_\pi^2$$

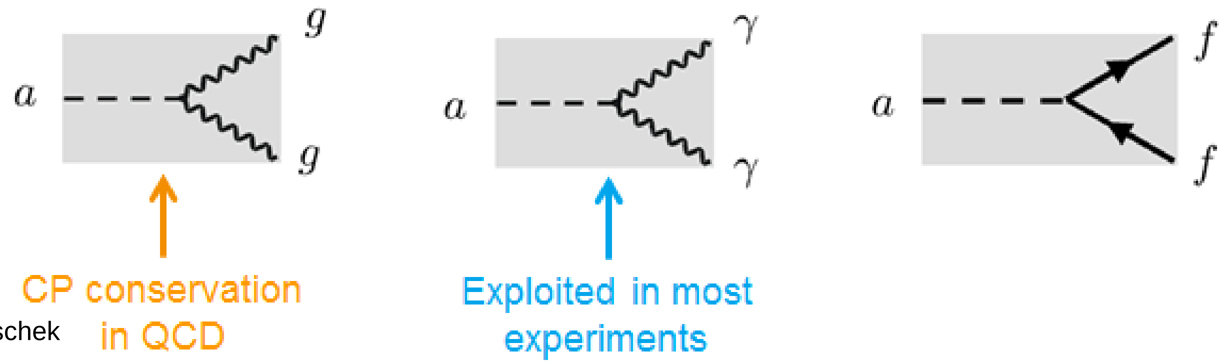
- *very weak interaction*

Axions and Axion-like particles

Axion-like particles

- Axions lead to a new class of possible BSM particles: ***Axion-like particles (ALPs).*** ***ALPs*** have similar properties as *QCD axions.*
- *They have a mass!* But it is not related to QCD scale: mass and coupling are two independent parameters.
- *Little interaction with regular matter*
- *Weak interaction with photons* ➔ Primakoff effect
- *No electric charge*
- *ALPs are WISPs*



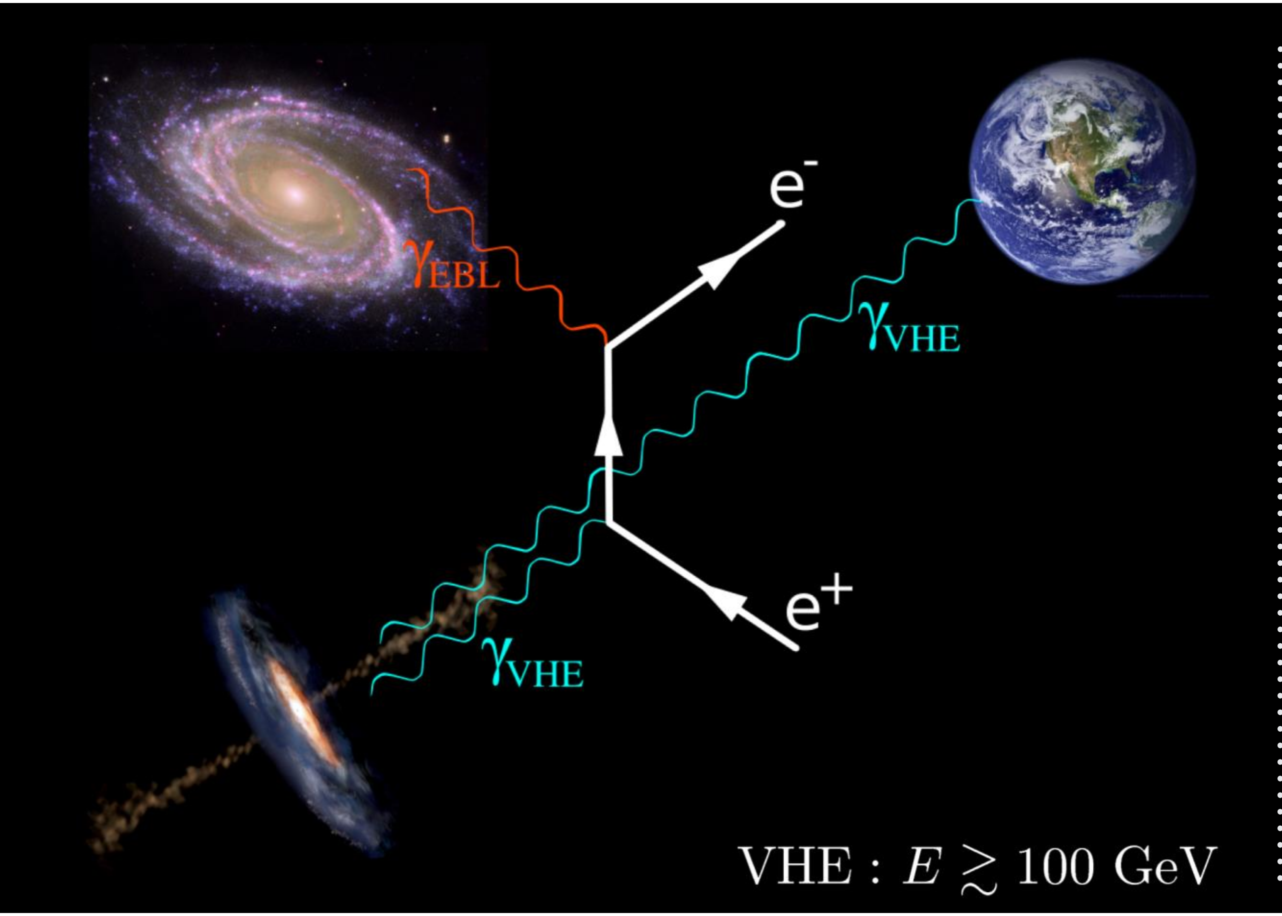


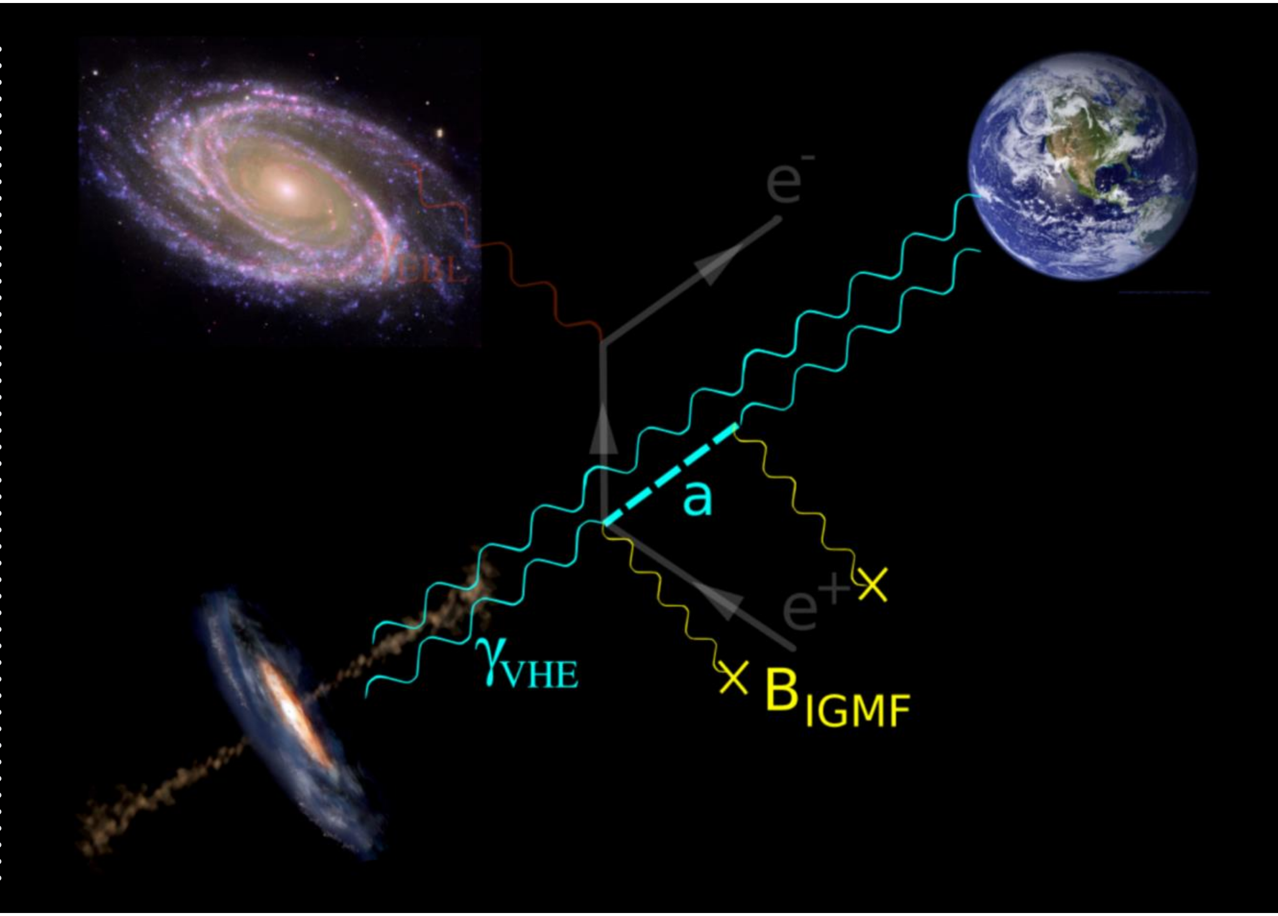
Example: Astrophysical hints for the existence of ALPs

Transparency of the Universe for very high energy (VHE) γ-rays

VHE radiation decays through electron-positron pair production if they interact with extragalactic background light (EBL).

Photons convert into ALPs in astrophysical magnetic fields. ALPs travel unhindered and reconvert close to the solar neighborhood.





pictures from M. Meyer (7th Patras Workshop, 2011)

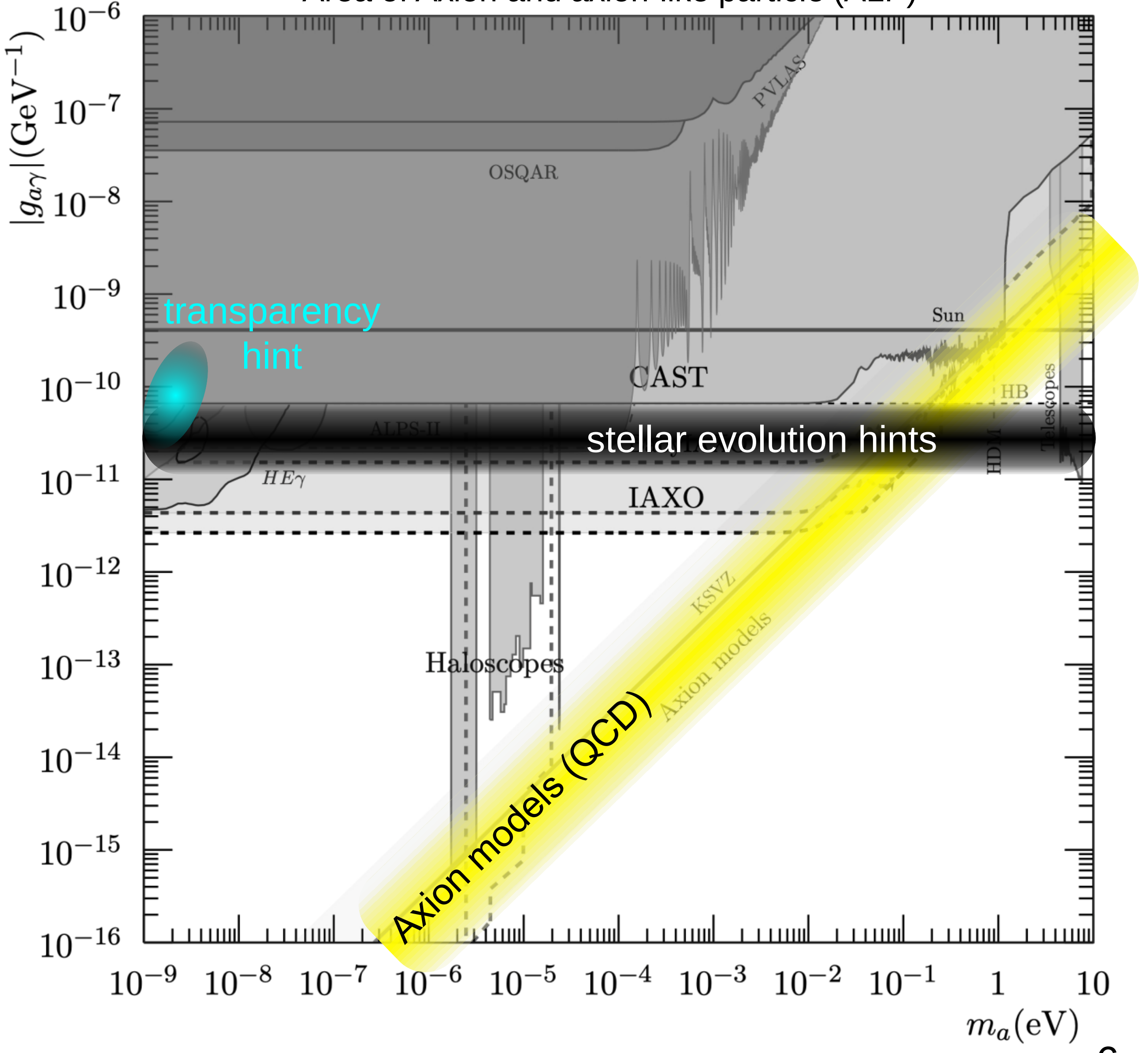
Overview axion and axion-like particle searches

Existence of *ALPs* can explain mysterious phenomena in our Universe

- TeV transparency of the Universe (extragalactic light should be suppressed)
- Stellar cooling & evolution (stars cool faster then predictions)
- (Cold) dark matter candidates (galaxy clusters, rotation of galaxies, gravitational lensing, CMB)

QCD Axion solves strong CP problem

Area of Axion and axion-like particle (ALP)

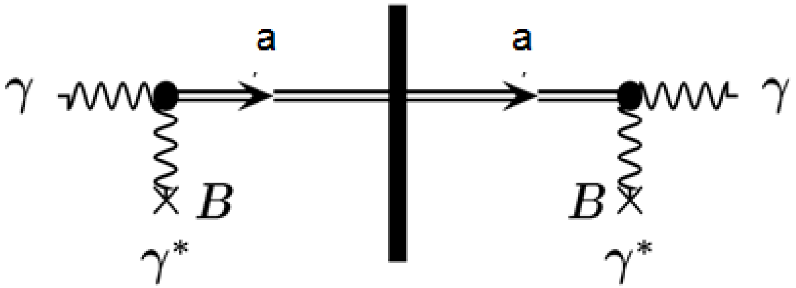


How to look for axions?

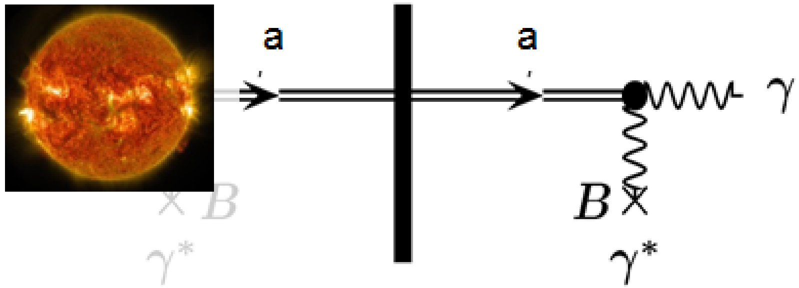
Sub-eV axions and axion-like particles (ALPs)

How to look: three kinds of axion/ALP sources

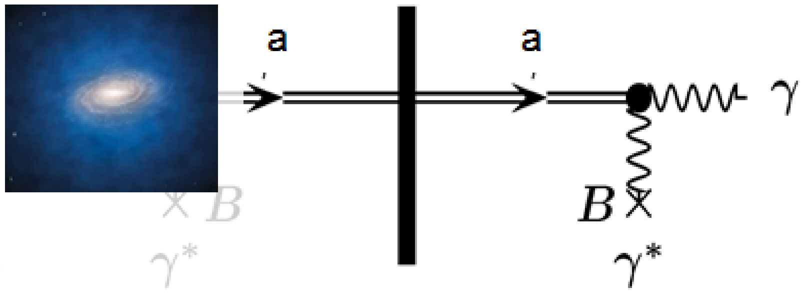
- Purely laboratory experiments
  “light-shining-through-walls”,
  optical photons



- Helioscopes
  ALPs emitted by the sun,
  X-rays



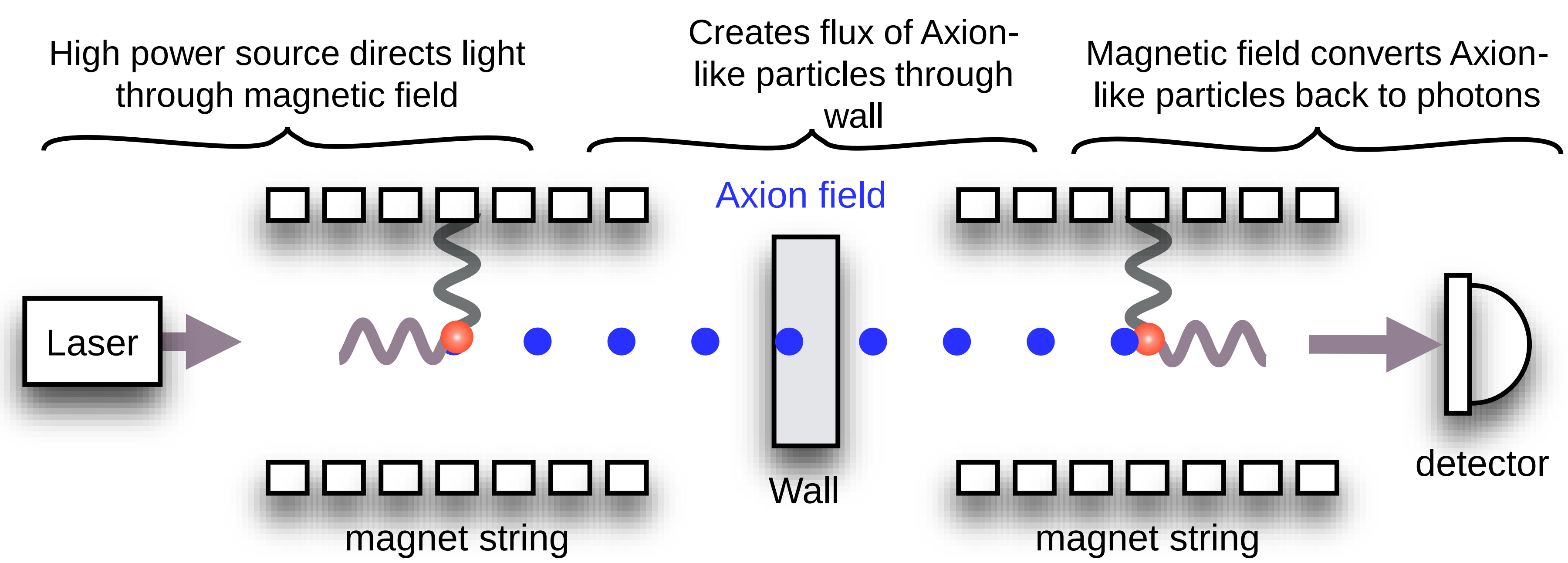
- Haloscopes
  looking for dark matter constituents,
  microwaves



Advantage lab LSW: small dependance on „other“ physics, creating and detecting WISPs in the experiment

The concept of light shining through a wall experiments

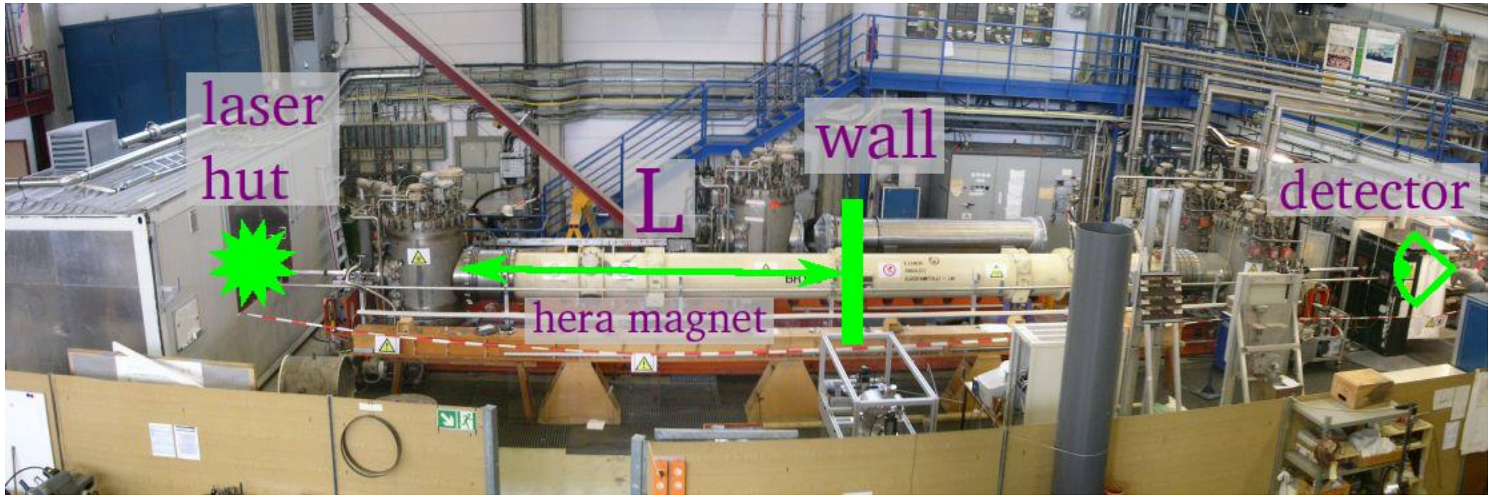
Measuring the conversion-reconversion of Axion-like particles

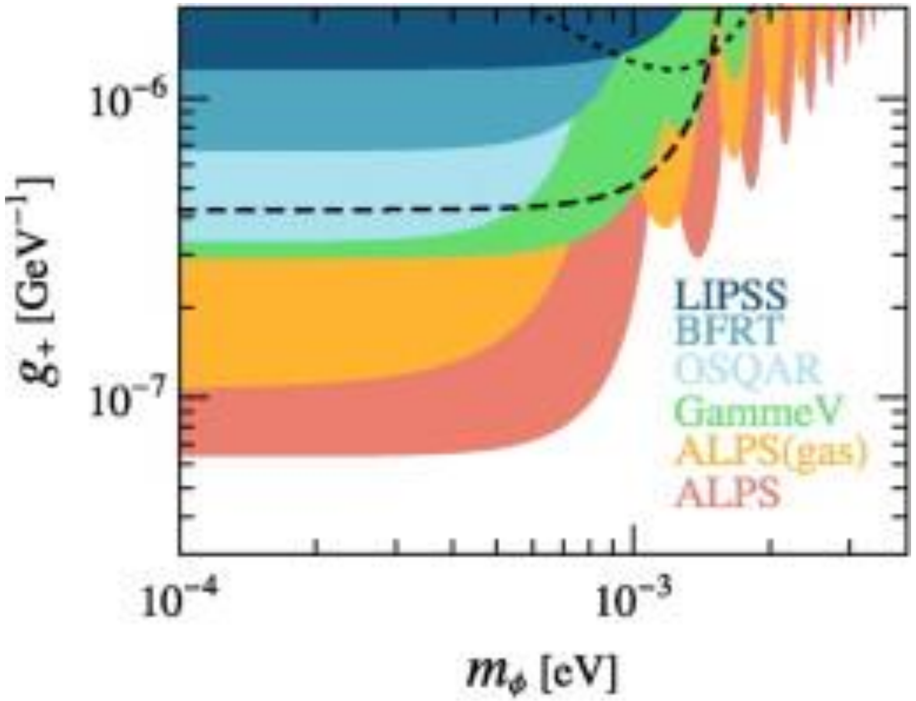


The Past:
ALPS I @ DESY

ALPS I: the first axion search at DESY

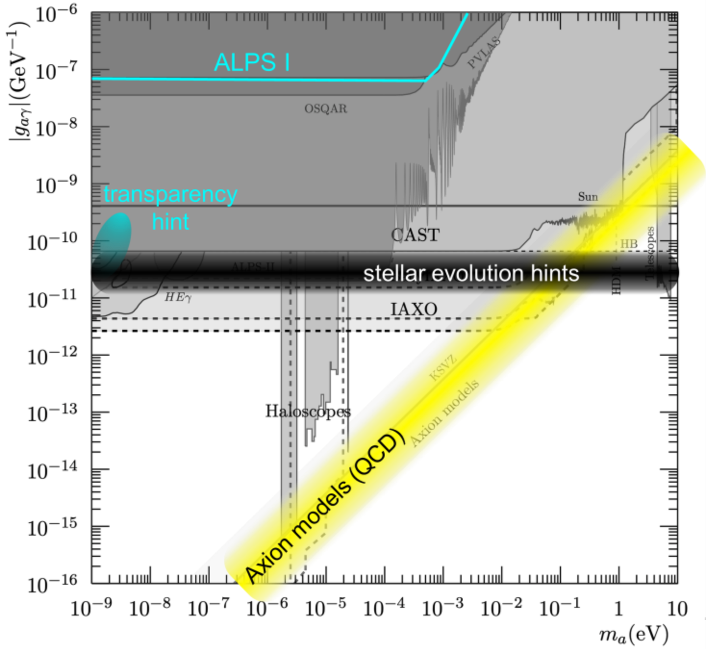
Light-shining-through-walls





ALPS I: LSW in the optical regime @ DESY

- ALPS I experiment from 2007-2010 at DESY
- Using an old HERA proton dipole magnet
- 1 kW circulating laser power (cavity), 532 nm green light
- Worldwide best laboratory limits at that time Phys.Lett. **B689** (2010) 149-15



The Present: Commissioning ALPS II @ DESY

DESY.

JG|U

UH

Leibniz Universität Hannover

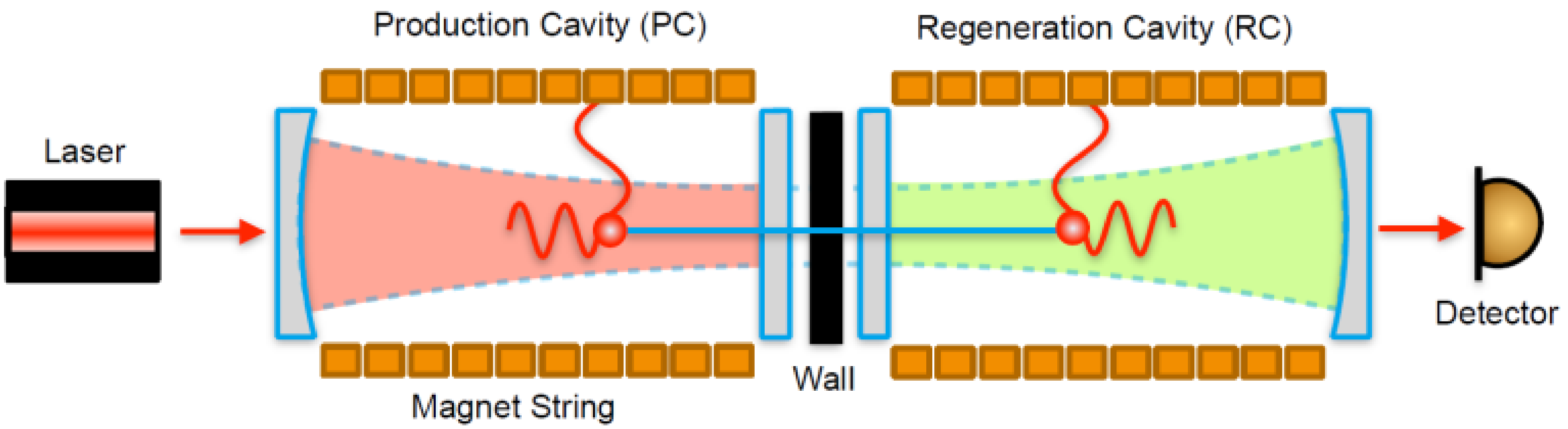
CARDIFF UNIVERSITY

UF UNIVERSITY of FLORIDA

HEISING-SIMONS FOUNDATION

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

ALPS II Design



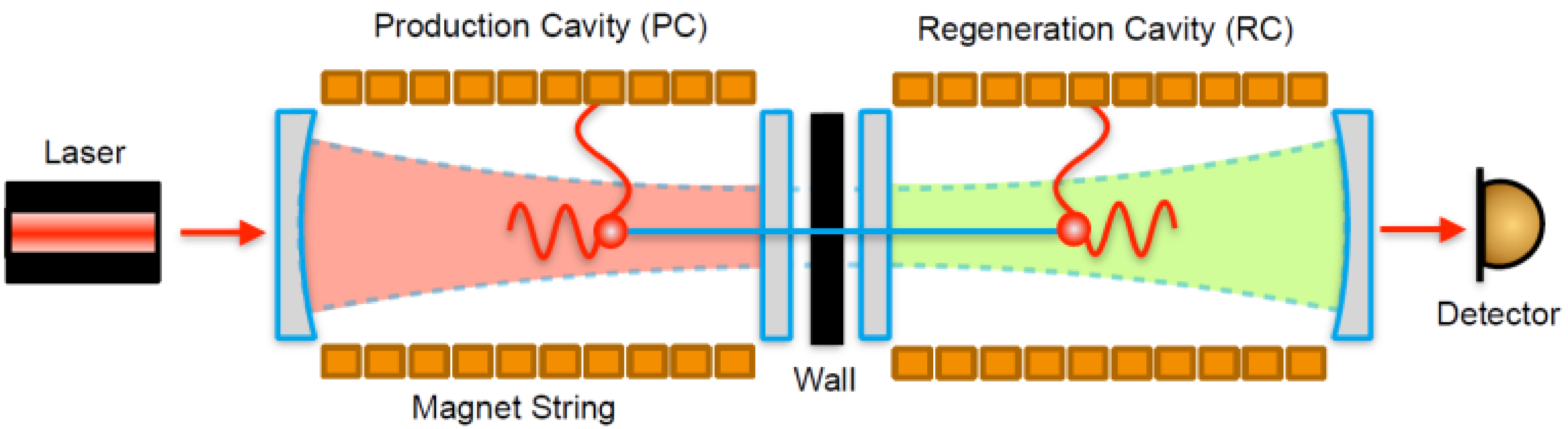
12+12 dipole magnets from the HERA proton accelerator

Production cavity and regeneration cavity, mode matched

$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot 10^{-38}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot\left(\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}\frac{B}{1\,T}\frac{l}{10m}\right)^4$$

Optics **Magnets** **Detector**

ALPS II Cavities



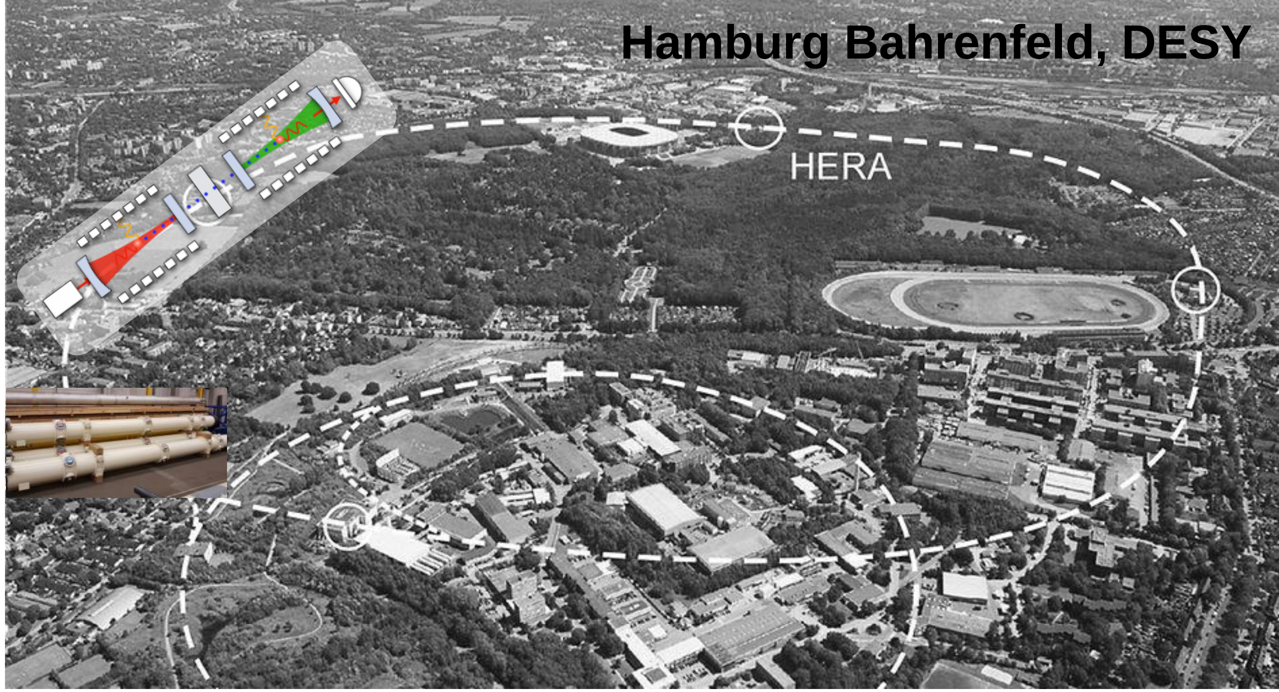
<u>Mode-matched cavities</u>:

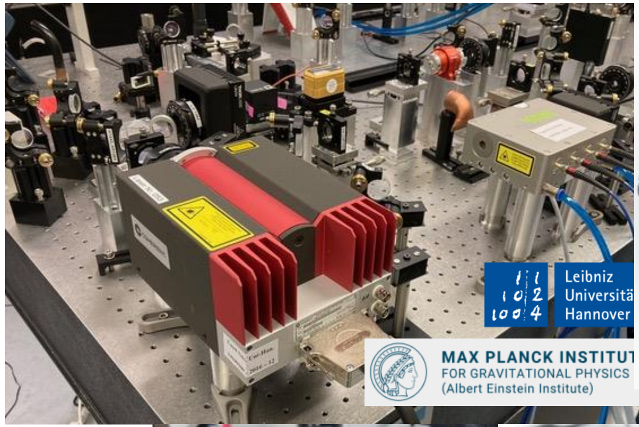
- **Production Cavity** increases circulating power before wall
- **Regeneration Cavity** resonantly enhances reconversion probability of ALPs into photons
- Assuming the coupling from the astrophysical hints of we would expect:
  - 1 photon every 200.000 years without cavities
  - 1 photon every 420 years with only the production cavity
  - 2 photons every day with production and regeneration cavity

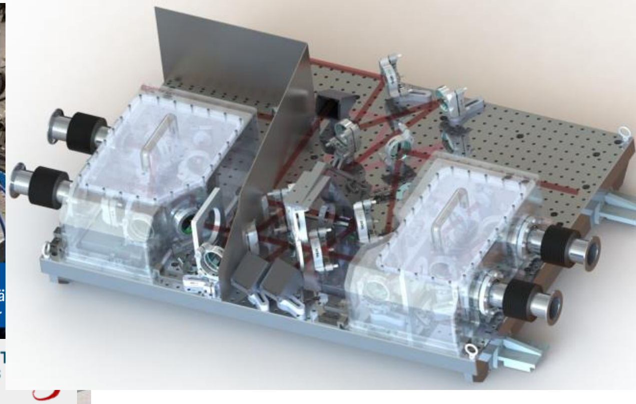
ALPS II Experiment

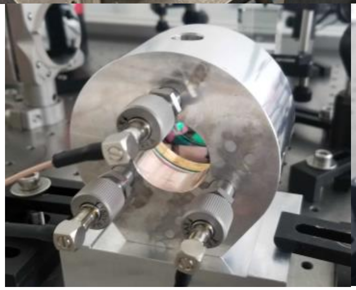
Challenges

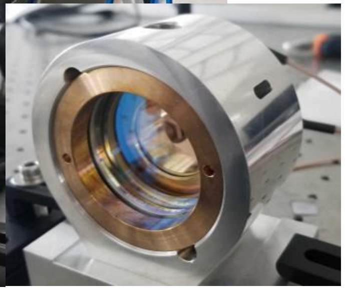
- Straight section of former HERA tunnel: 250 m limit
- 12 HERA dipole **magnets**, each 5.6 Tesla, over 120 m
  - require high power and cryogenics
  - **straightened** to have sufficient aperture
- High power **laser**, 70W, λ =1064 nm ~ 282 THz
  - Provided by AEI Hannover (LIGO laser)
- Two high-finesse **optical cavities** (PC and RC)
  - Length limited to 124.4 m each (straight section)
  - Very narrow line width of 12 Hz
  - Active and passive systems to control resonances and overlap between the cavities
- **Light tightness**: 150kW → 10^{-24}W (~1 photon/day)
- **Detector** for ultra weak signals 1 infrared photon /day ~ 10^{-5} Hz
  - Heterodyne detection (UFL, Florida)
  - Superconducting single photon detector: TES@DESY











Mirror actuators: *picometer* position accuracy required

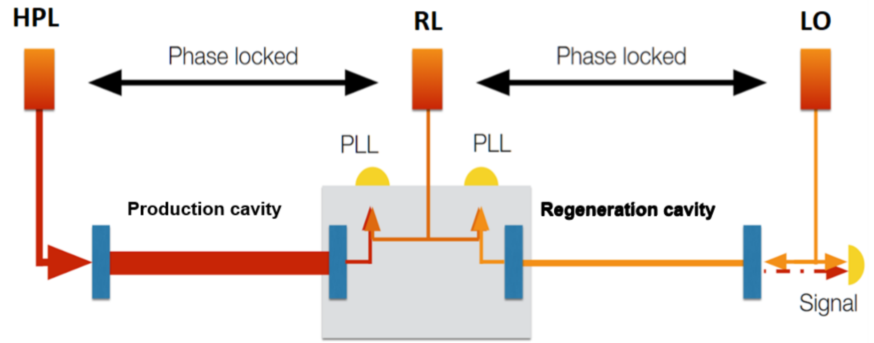
ALPS II: Heterodyne detection

"Coherent detection of ultraweak electromagnetic fields",
Z. Bush et al., Phys. Rev. D 99, 022001 (2019)

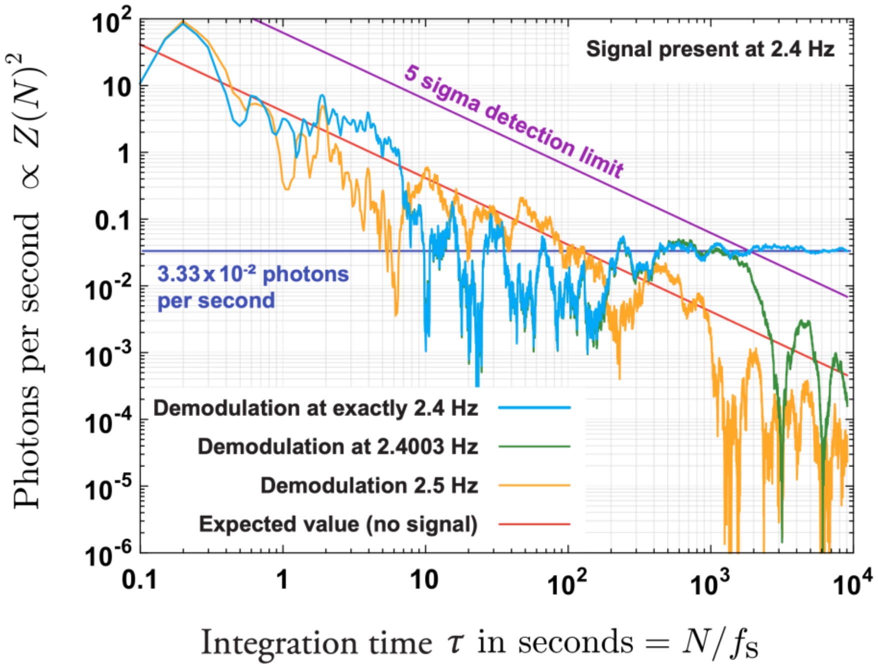
Looking for $5\cdot10^{-24}$ W @ 1064 nm

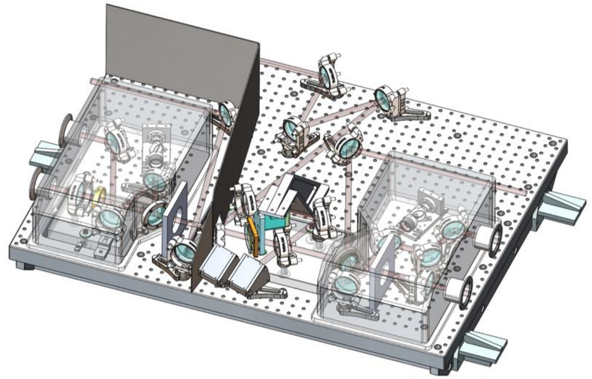
Option 1: heterodyne sensing

- Mix weak signal with a frequency f shifted local oscillator ➔ beat note signal
- Detection of a photon flux corresponding to $5\cdot10^{-21}$ W demonstrated.
- Sensitivity of 10^{-24} W demonstrated.



Heterodyne detection will be implemented first.



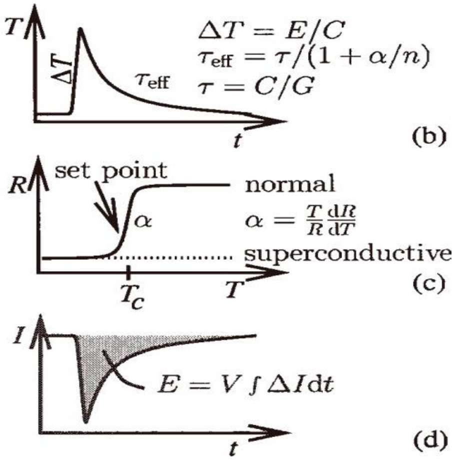


ALPS II: Transition Edge Sensor

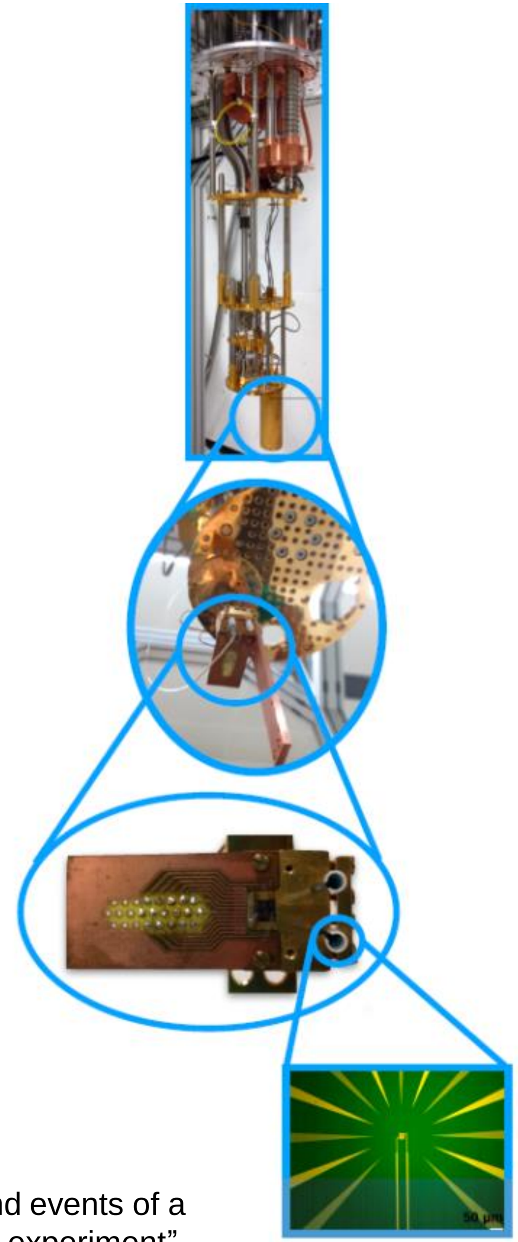
Looking for 5·10^{-24} W @ 1064 nm

Option 2: photon counting

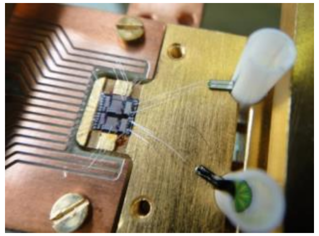
- Using a superconducting transition edge sensor (TES) operated at about 100 mK.



P.A.J. De Korte et. al., Proceedings of SPIE, pages 779-789, 2002



TES chip within the transition region at critical temperature

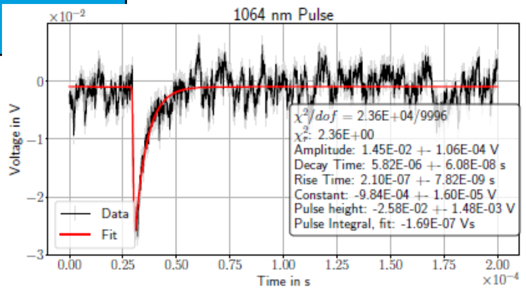


Single 1064 nm photon heats TES by ~100µK

The resistance of the TES chip increases by a few Ohm

The current changes by about 100 nA and is read out by SQUIDS

Voltage change is measured by readout electronics

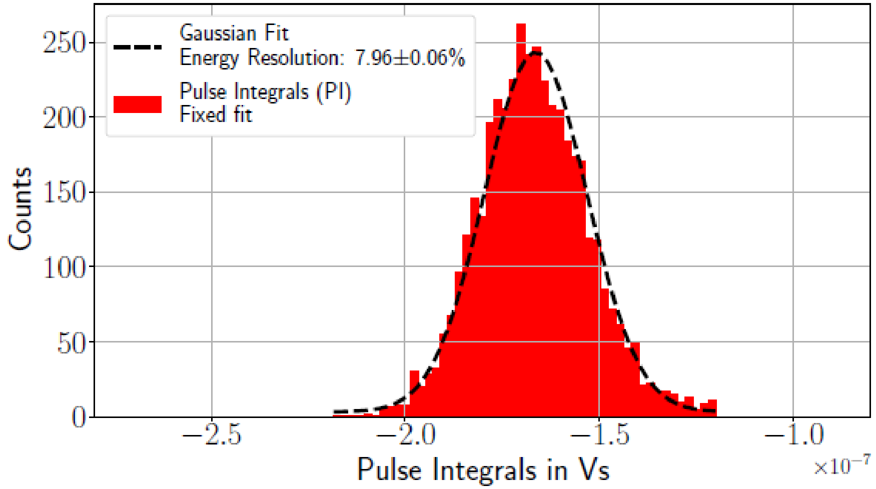


“Characterization of 1064 nm photon signals and background events of a tungsten TES detector for the ALPS experiment”, J. Dreyling-Eschweiler et al., Journal of Modern Optics, 62:14, 1132-1140

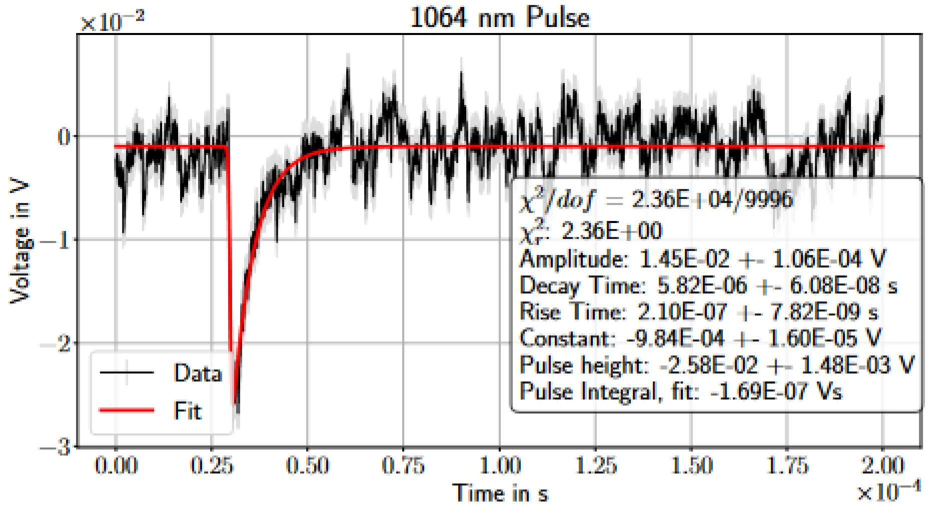
ALPS II: Characterising our TES

Excellent properties for photon counting experiments

- High quantum efficiency (QE) at wavelength of interest
- Ability to resolve single photons 1064nm ~ 1eV
- Energy resolution (≈10%), depending on method: Distinguish signal from background events
- Low dark counts ($6.9^{+5.18}_{-2.93} \cdot 10^{-6}\mathrm{Hz}$, 95% confidence level): residual background: black body, pile-ups, fluorescence; i.e. low enough for ALPS II



Submitted to JLTP

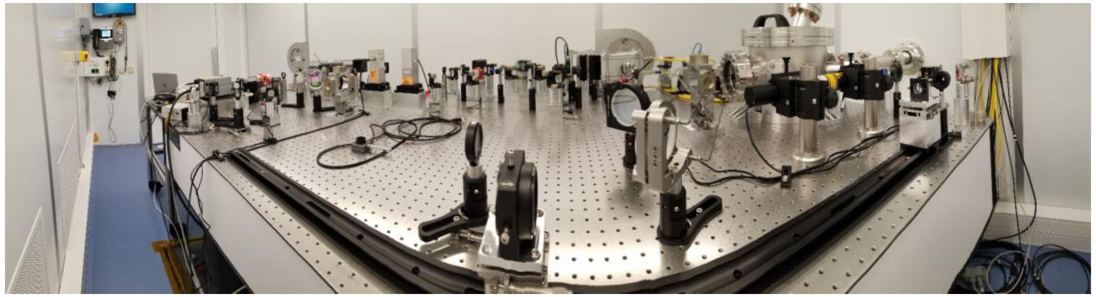


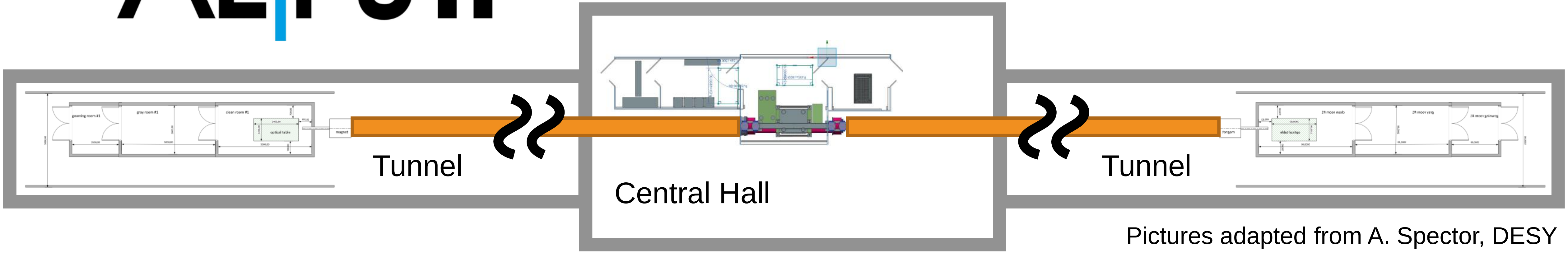
arXiv:2110.10654

Work in progress: Measurements on efficiency, background with attached fiber ongoing

ALPS II status

- First magnet installed Oct 2019, now all 24 magnets are ready
- 3 cleanrooms installed at HERA North site
- Studies with the 250m optical cavity ongoing
- Planned:
  - Cool-down of magnets started yesterday
  - First science run follows after (spring)





Pictures adapted from A. Spector, DESY

The Future:
ALPS II, (Baby-)IAXO and MADMAX

ALPS II — Any Light Particle Search II

Near future: ALPS II data taking

ALPS II will be ready to take data within 2022

ALPS II will probe the regions of

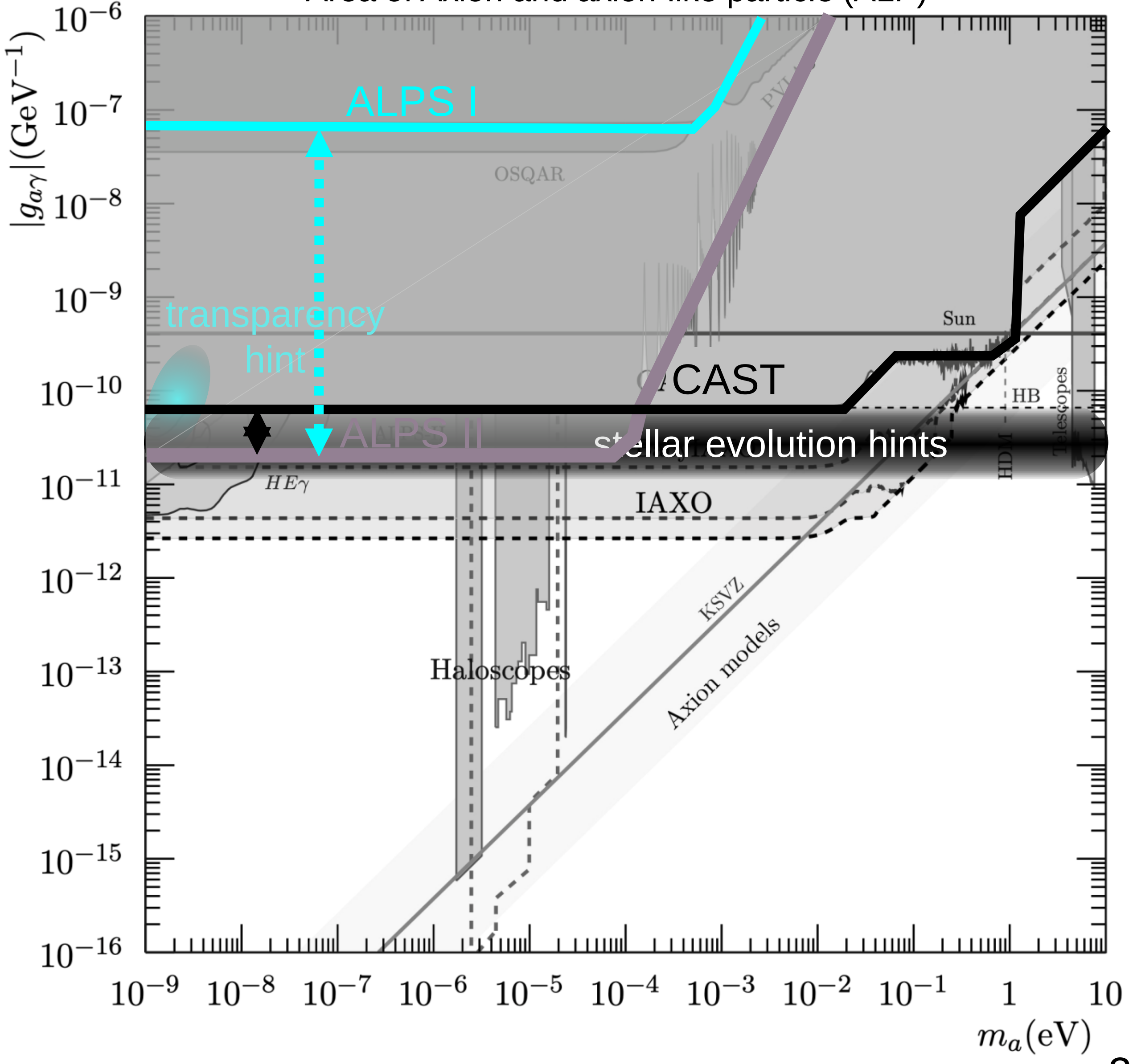
- TeV transparency hint
- Stellar cooling & evolution hints

ALPS II Target Sensitivity and Challenges

- $g_{a\gamma\gamma} = 2 \cdot 10^{-11} \mathrm{GeV}^{-1}$ and $m < 0.1 \mathrm{meV}$
- 3x better than helioscope CAST
- 1000x better than ALPS I (2007-2010)

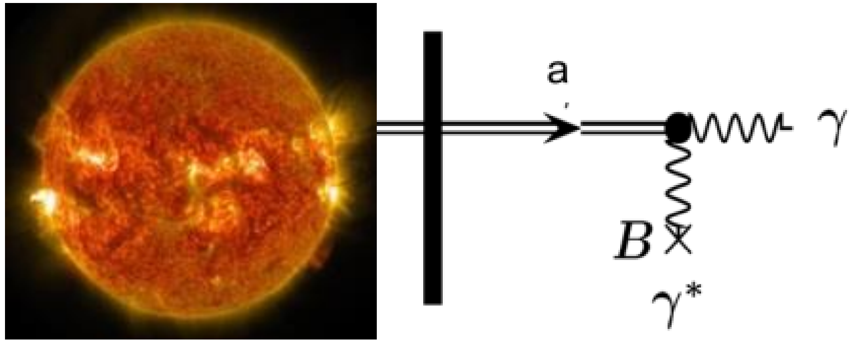
► Independent from cosmological assumptions!

Area of Axion and axion-like particle (ALP)



International Axion Observatory

Solar axions up to 1eV mass



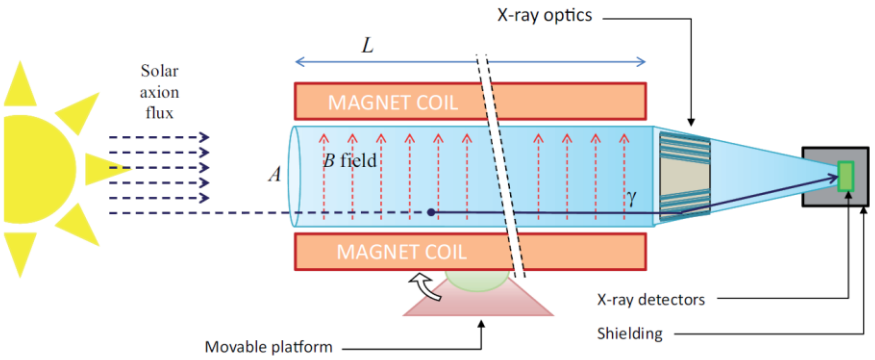
Technology:
20 m long toroidal magnet with eight 60 cm bores tracking the sun, X-ray optics to focus signal onto very low background detectors.

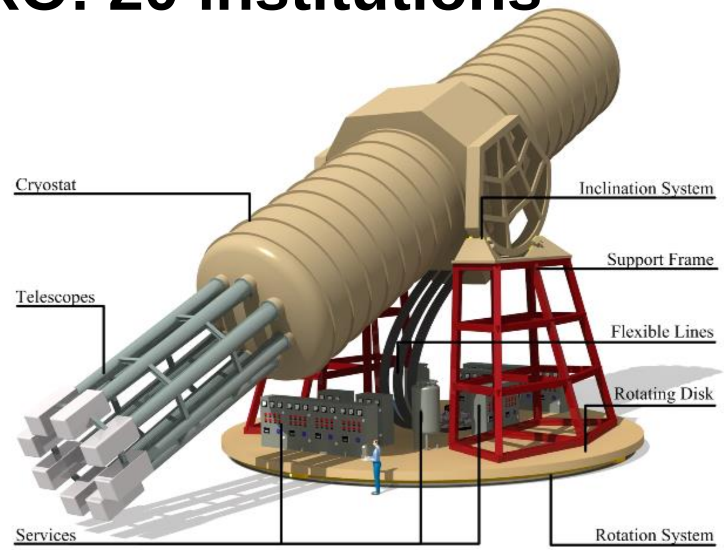
Status and schedule:

- BabyIAXO (nearly) approved
- Construction of BabyIAXO will start in 2022
- BabyIAXO could be ready for a 1st physics run in 2024 / 2025.
- IAXO could be ready in 2028.

Also sensitive to g_{ae} and g_{an}

IAXO: 20 institutions



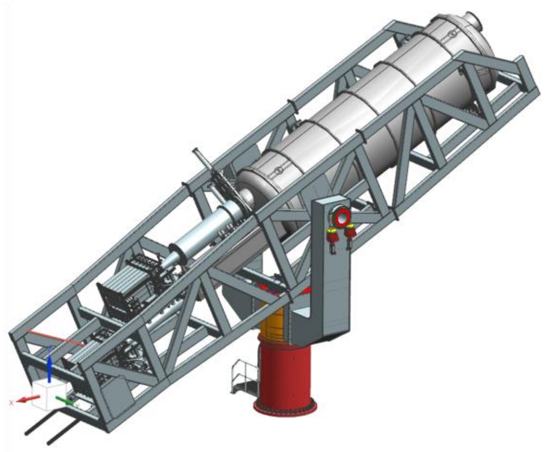


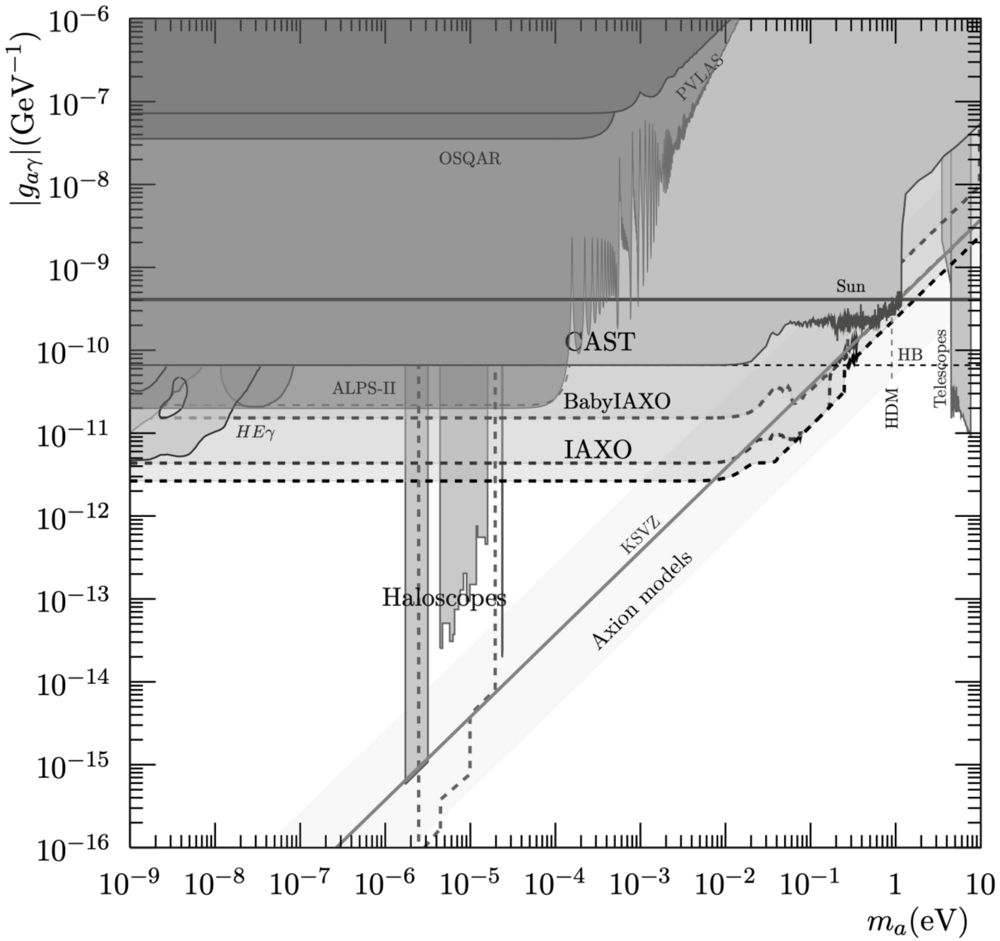
BabyIAXO

A Testbed with Physics potential

- Prototype: Intermediate experimental stage before IAXO
  - Smaller scale
  - Aim: Test and improve all systems and mitigate risk for full IAXO
  - Only two bores, but with similar dimenstions
  - Magnet will test design options

- But: BabyIAXO will already have relevant physics output, much better reach than the CAST helioscope before
- Sites:
  - BabyIAXO: HERA South hall.
  - IAXO: options on DESY campus earmarked.





MADMAX technology

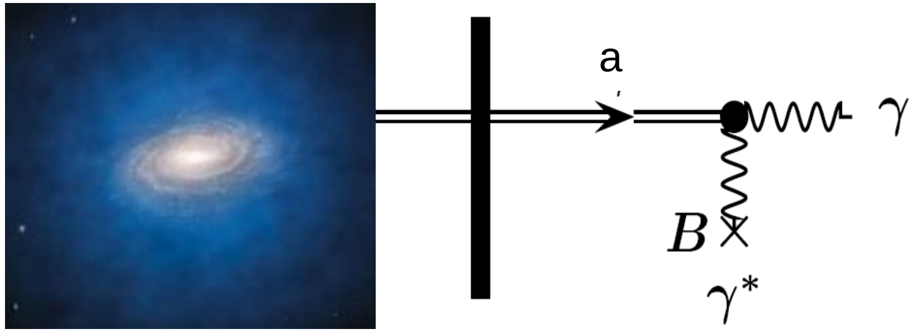
Dielectric booster …

The axion field generates a (tiny) electromagnetic field at dielectric discontinuities embedded in a magnetic field.

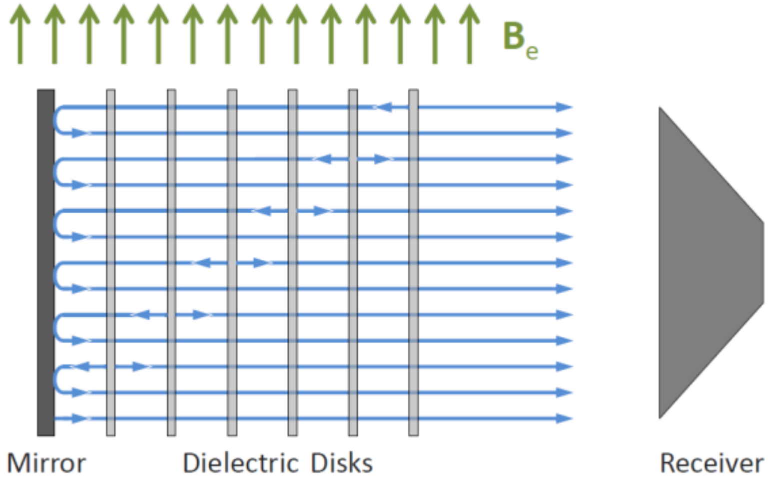
- Coherent generation of electromagnetic radiation at all surfaces as L(MADMAX) < λ (axion).
- Constructive interference results in a power boost factor β^2.
- The booster can be tuned to frequency and bandwidth by changing the disc positions.

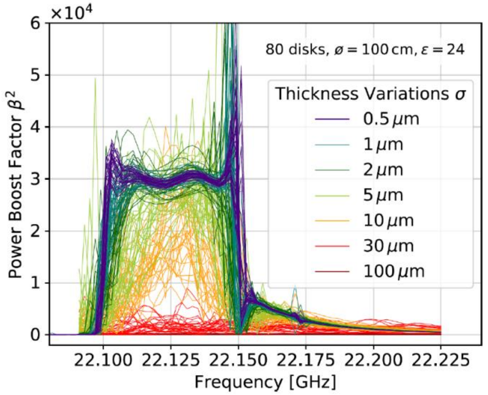
Required figures of merit:

- 80 sapphire or $LaAlO_3$ discs of 1.2 m^2 each.
- 10 T magnetic field of about 1.3 m length.



MADMAX: 9 institutions





MAgnetized Disc and Mirror Axion eXperiment MADMAX

Halo dark matter axions with masses 40 to 400 μeV

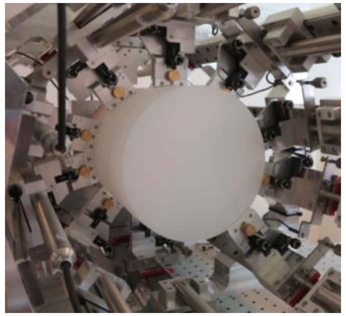
Status:

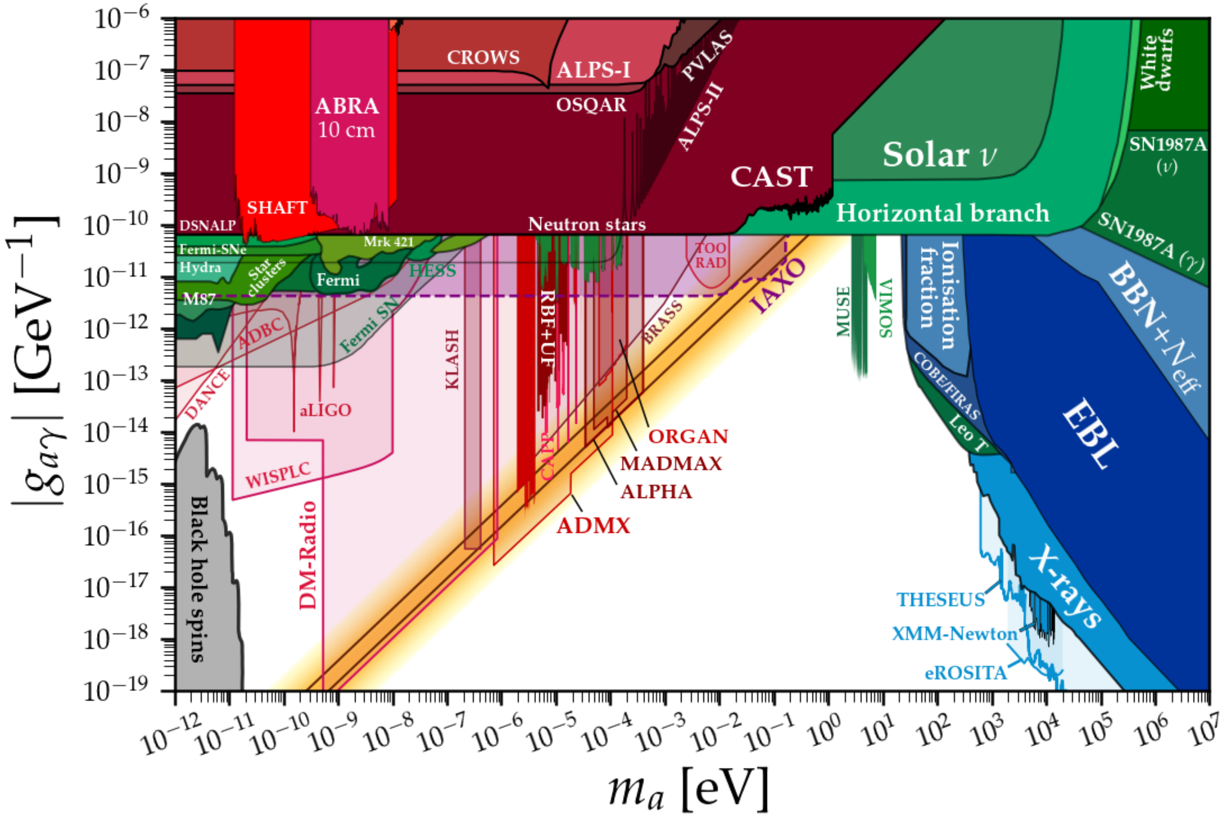
- R&D phase successfully concluded.
- Phase 2 (prototype, magnet) started.
- Prototype runs at CERN (MORPURGO) approved.

Site:

- Cryoplatform in the DESY HERA North hall (next to ALPS II).

Data taking could start in 2028.

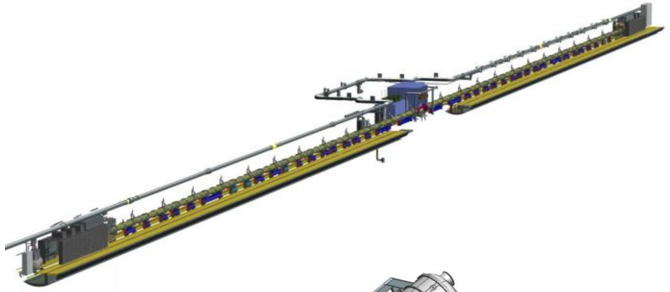




Future: three kinds of axion searches @ DESY

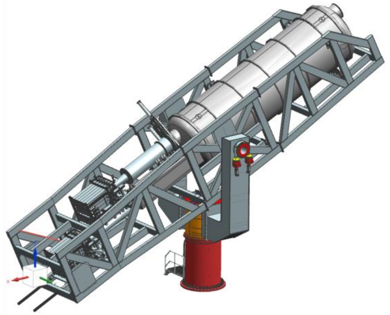
DESY as a center for axion physics

- Purely laboratory experiments
  "light-shining-through-walls",
  optical photons



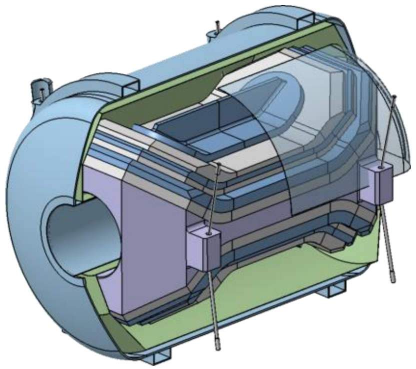
ALPS II

- Helioscopes
  ALPs emitted by the sun,
  X-rays



(Baby)IAXO

- Haloscopes
  looking for dark matter constituents,
  microwaves

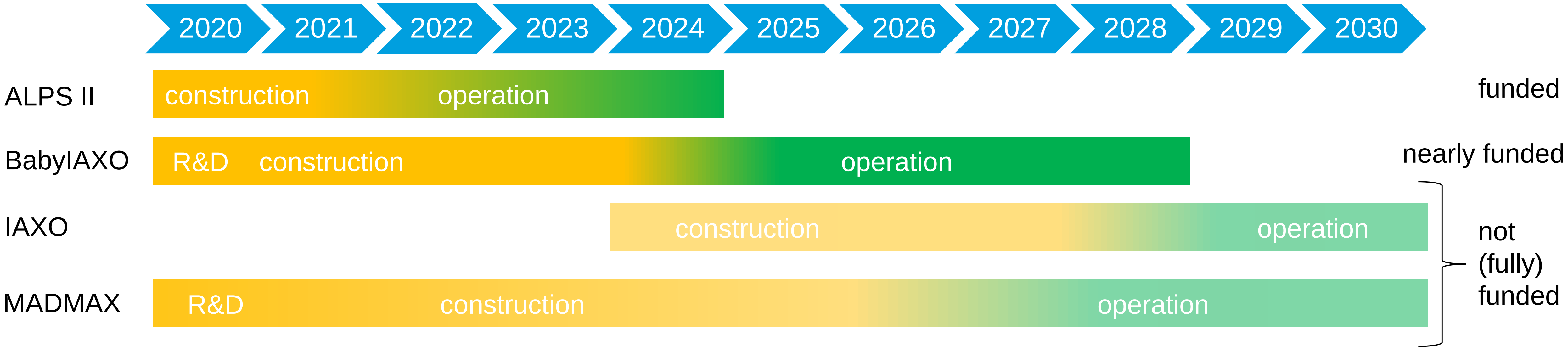


MADMAX

Timelines

ALPS II, BabyIAXO, IAXO, MADMAX

Some optimistic view (funding), assuming no surprises (axion discovery).



Program well aligned with other international axion searches.

A European Strategy Towards Finding Axions and Other WISPs

K. Desch[1], *B. Döbrich*[2], *I. Irastorza*[3], *J. Jaeckel*[4], *A. Lindner*[5], *B. Majorovits*[6], *A. Ringwald*[5],
[1]Physikalisches Institut, Uni. Bonn, Nußallee 12, D-53115 Bonn, Germany
[2]CERN, 1 Esplanade des Particules, CH-1211 Geneva 23, Switzerland
[3]Departamento de Fisica Teorica, Uni. de Zaragoza, Pedro Cerbuna 12, E-50009, Zaragoza, Spain
[4]Institut für Theoretische Physik, Uni. Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany
[5]DESY, Notkestraße 85, D-22607 Hamburg, Germany
[6]Max-Planck-Institut für Physik, Föhringer Ring 6, D-80805 Munich, Germany

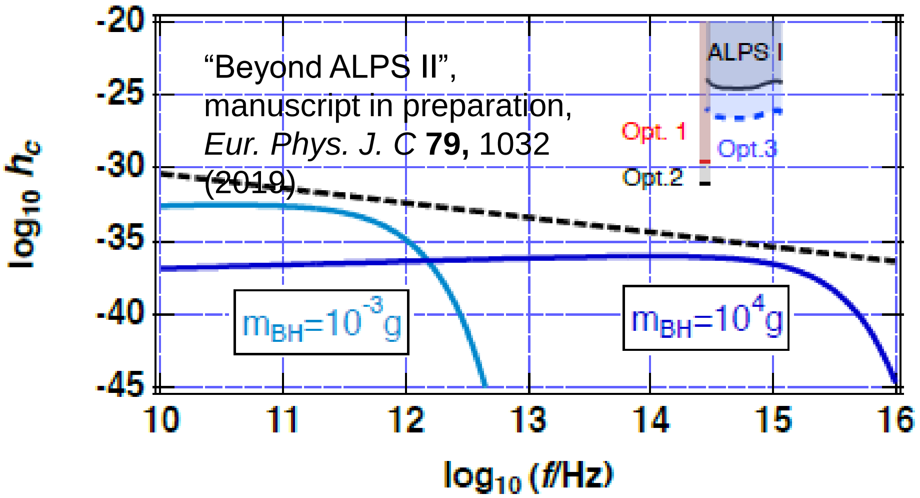
Looking beyond
- some visions

ALPS II beyond ALPS II

Assuming no surprises like axion detection …

Very tentatively, no formal decisions on any future projects beyond 2024 yet!

- 2022-2024: searching for axions with ALPS II.
- 2024-2026: measurement of **vacuum magnetic birefringence** at the ALPS II site.
- 2026-2028: data taking with ALPS II upgrades (depending also on BabyIAXO results).
- 2028 ff: dedicated **ultra high frequency gravitational wave** searches at the ALPS II site?

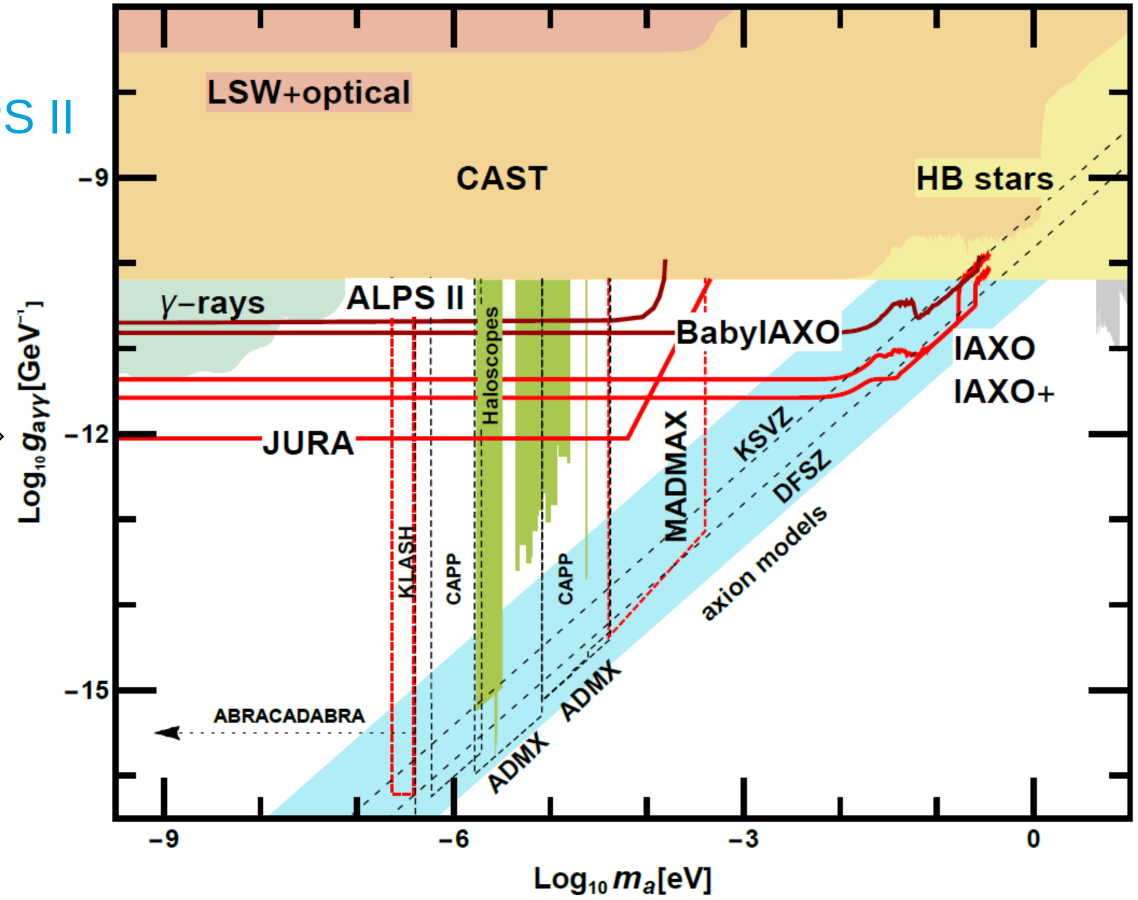


JURA

Next generation LSW experiment

- Magnetic field strength: 13 T
- Magnetic length: 426 m
- Light wavelength: 1064 nm
- Circulating light power: 2.5 MW
- Power built-up behind the wall: 10^5
- Detector sensitivity: $10^{-4}\ s^{-1}$

$\left.\begin{array}{l}\text{13 T}\\ \text{426 m}\end{array}\right\}$ 10 · ALPS II



JURA could allow to probe for very lightweight ALPs in the laboratory even beyond the IAXO reach.

It would be a (costly) about 1km long apparatus.

If ALPS II fulfills expectations, JURA should be feasible.
Dipole magnet R&D is essential.

Summary

Axions @ DESY

- Axions and ALPs are well motivated BSM particles
- ALPS II at DESY is an experiment currently being commissioned @ DESY of the light-shining-through-wall type
- ALPS II will be able to probe an interesting parameter space with astrophysical hints for ALPs
- DESY is planning two other major axion search experiments with international partners: Baby(IAXO) looking for axions from the sun and MADMAX looking for dark matter axions
- Exciting times ahead for axion searches and for DESY