UHF-GW opportunities with ALPS II and BabyIAXO

Axion infrastructures at DESY

UHF-GW Meeting, CERN, December 2023

Axel Lindner, DESY, FH-ALPS

Outline

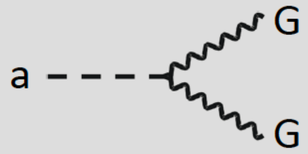
- Some experimental basics:
  - Axion- and HF-GW searches
  - Experimental approaches for axion searches
- ALPS II & BabyIAXO
- Conclusions

Axion searches

Couplings to the SM

Axions are a consequence of the Peccei-Quinn symmetry to explain θ=0.

f_a: energy scale of PQ symmetry breaking

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$ 
Mass (generic)	$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{m_\pi}{f_\pi f_a} \approx \frac{6\ \mu\text{eV}}{f_a/10^{12}\ \text{GeV}}$

A. Mirizzi, Next Frontiers in the Search for Dark Matter, 2019

Axion searches

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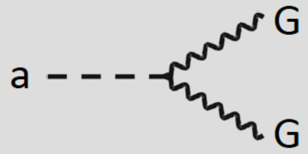
There might be more couplings to Standard Model constituents.

These couplings depend on the BSM models incorporating an "invisible axion".

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$ 
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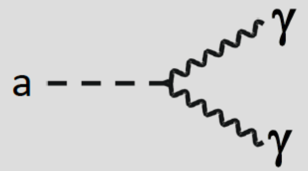
Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$ 

A. Mirizzi, Next Frontiers in the Search for Dark Matter, 2019

Axion searches

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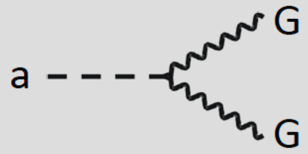
Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$ 
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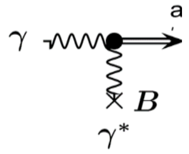
Photon coupling	In a background magnetic field: axion $\Longleftrightarrow$ photon mixing 

Many experiments exploit the axion-photon mixing:

- Axion detection:

  We know how to sense very weak photon signals.

- Axion generation:

  We know how to generate very intense light fields.

A. Mirizzi, Next Frontiers in the Search for Dark Matter, 2019

Experimental challenges exploiting photon couplings

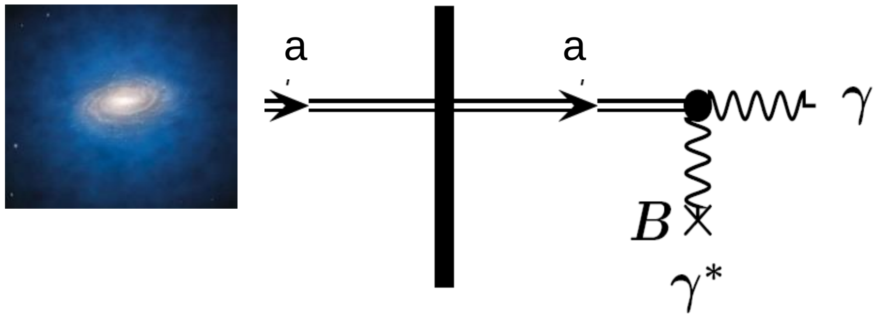
Very similar for axion and HF-GW searches

Task	Component	Critical parameters	Axion-Photon mixing	Gertsenshtein^{-1}
Generate a signal	Dipole magnets	strength, length	$(g_{a\gamma\gamma} \cdot B \cdot L)^2$	$(f \cdot h_c \cdot B \cdot L)^2$
Amplify a signal	Resonant signal amplification	Q, bandwidth	Monochromatic axions ?	Monochromatic HF-GWs ?
Measure the signal	Low flux sensing, field approach (heterodyne sensing)	Signal bandwidth, coherence time, readout bandwidth	Coherence time of weeks (LSW), O(ms) for haloscopes	?
	Low flux sensing, photon counting	Efficiency, background	Remark: 10^{-23} W for 1 keV photons corresponds to 2 counts/year.	
Pointing (for transients)	Movable magnet	Re-positioning speed	How to generate a trigger?	

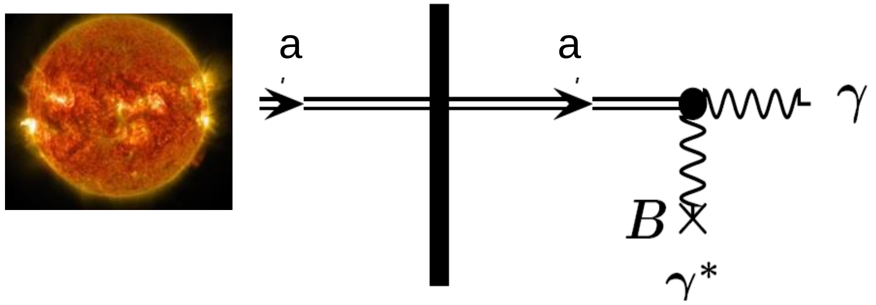
How to look: three kinds of experiments

Axion/ALP: different sources

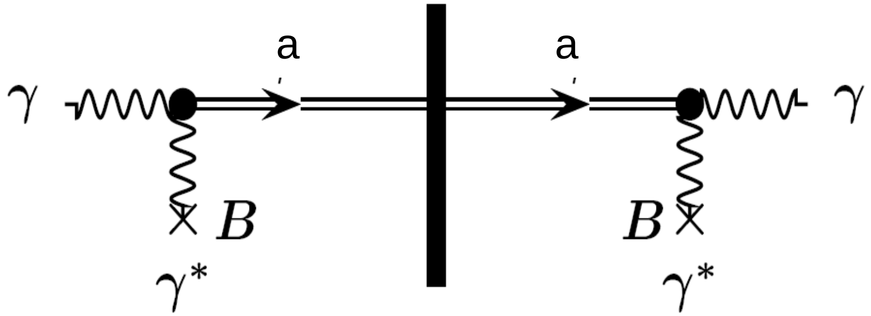
- Haloscopes
  looking for dark matter constituents,
  microwaves



- Helioscopes
  Axions emitted by the sun,
  X-rays



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



How to look: three kinds of experiments

Axion/ALP: different sources

- Haloscopes
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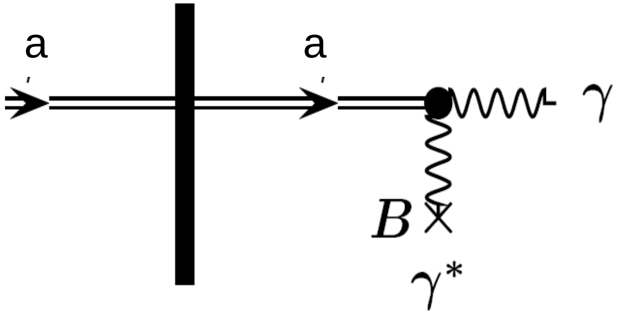
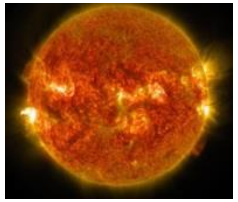
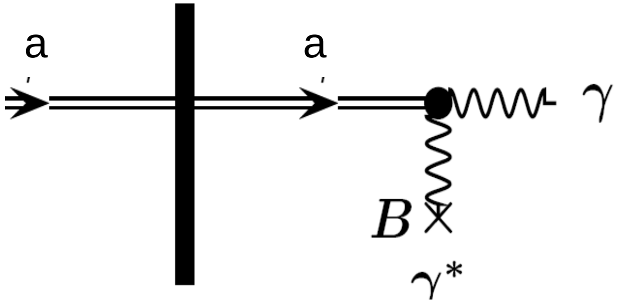
cosmological
assumptions



- Helioscopes
  Axions emitted by the sun,
  X-rays

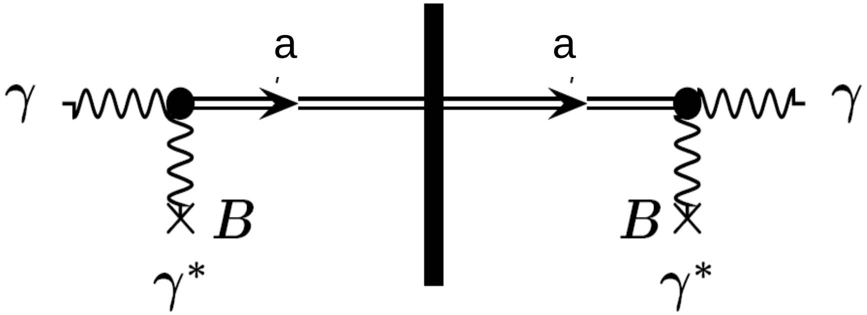
astrophysical
assumptions





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

not depending on
cosmology or
astrophysics

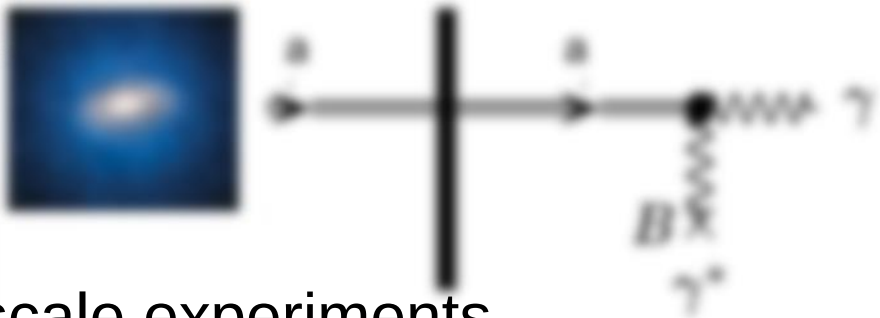


How to look: three kinds of experiments

Axion/ALP: different sources

- Haloscopes
  looking for dark matter constituents,
  microwaves

  cosmological assumptions



At some point physics asks for larger scale experiments.

- Helioscopes
  Axions emitted by the sun,
  X-rays

  astrophysical assumptions

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

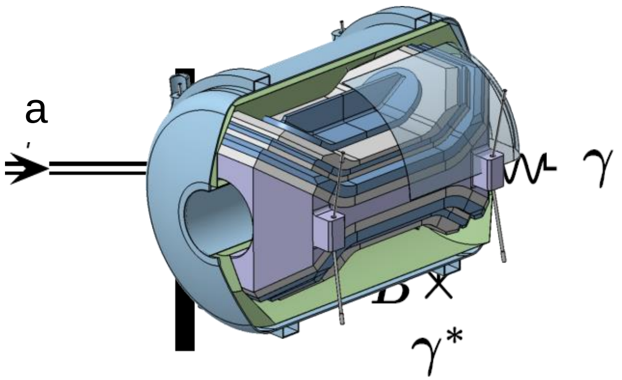
  not depending on cosmology or astrophysics

How to look: three kinds of experiments (at DESY)

Axion/ALP: different sources

- Haloscopes
  looking for dark matter constituents,
  microwaves.

MADMAX



- Helioscopes
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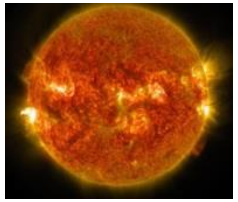
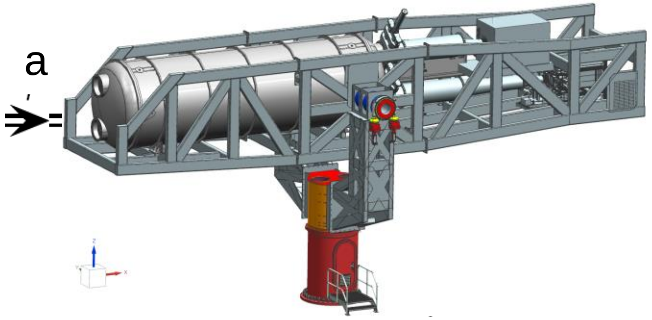
BabyIAXO





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

ALPS II

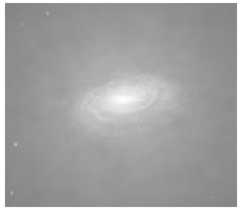
How to look: three kinds of experiments (at DESY)

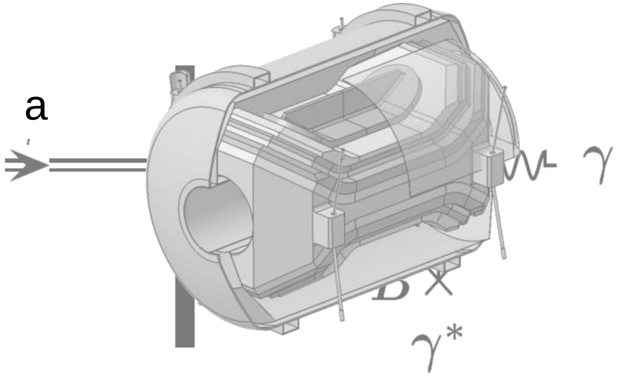
Looking for dark matter CANDIDATES

- Haloscopes
  looking for dark matter constituents,
  microwaves

MADMAX

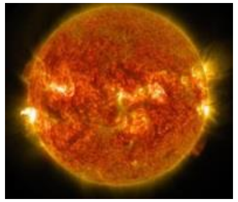
see this workshop C.A. Garcia Cely, “Axion haloscopes”, Wednesday 9:30 h

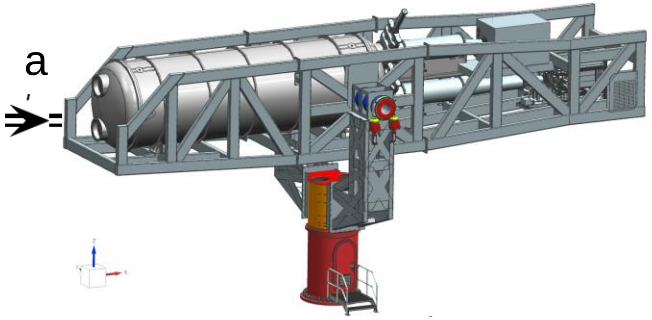




- Helioscopes
  Axions emitted by the sun,
  X-rays

BabyIAXO:
start of construction in 2024?





- Purely laboratory experiments
  “light-shining-through-walls”,
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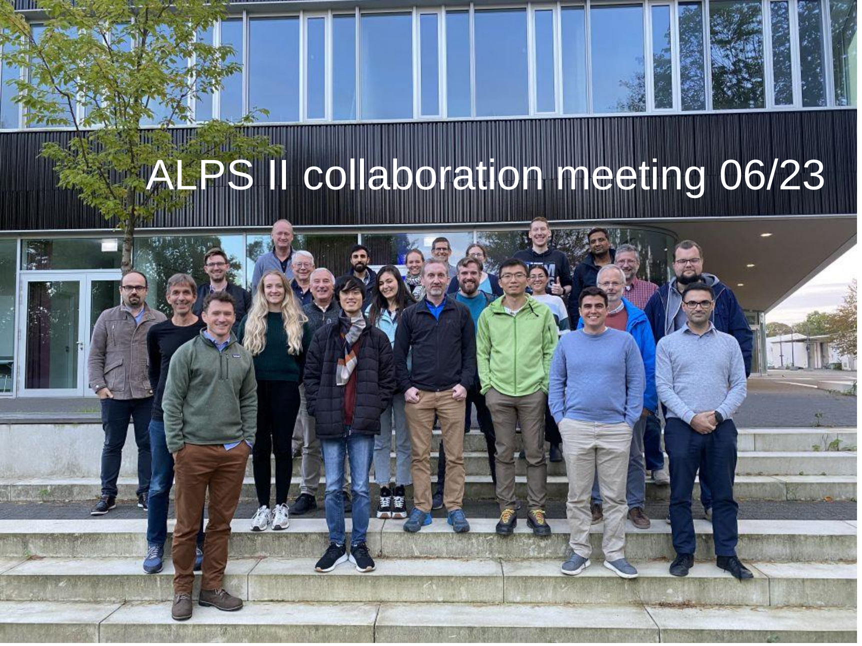
ALPS II:
1st science run started 2023.

ALPS II



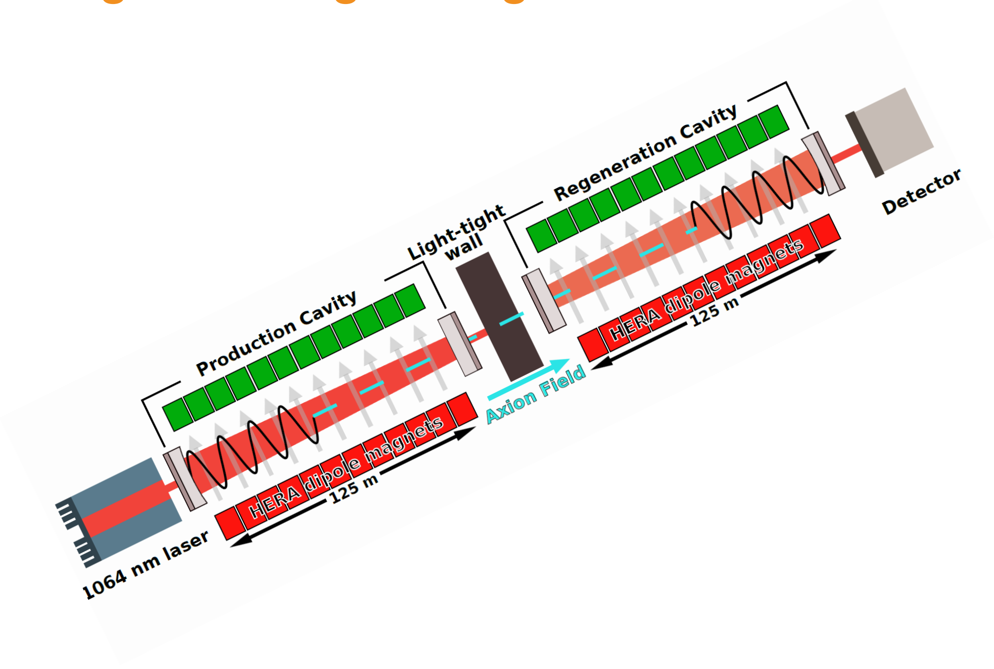
Collaboration members

ALPS II

Supported by

ALPS II in the HERA tunnel

Light-shining-through-a-wall with resonant amplification



ALPS II in the HERA tunnel

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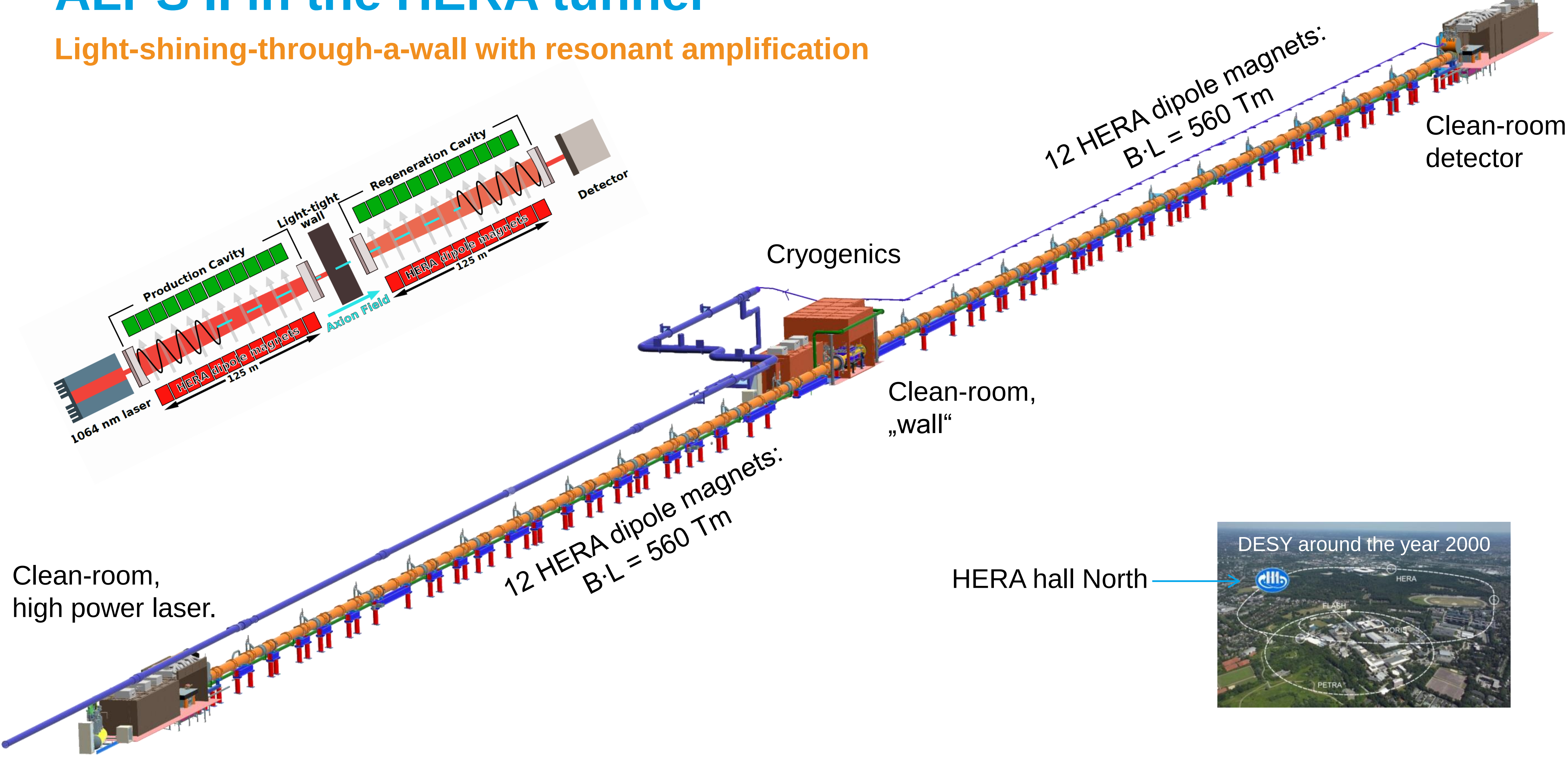
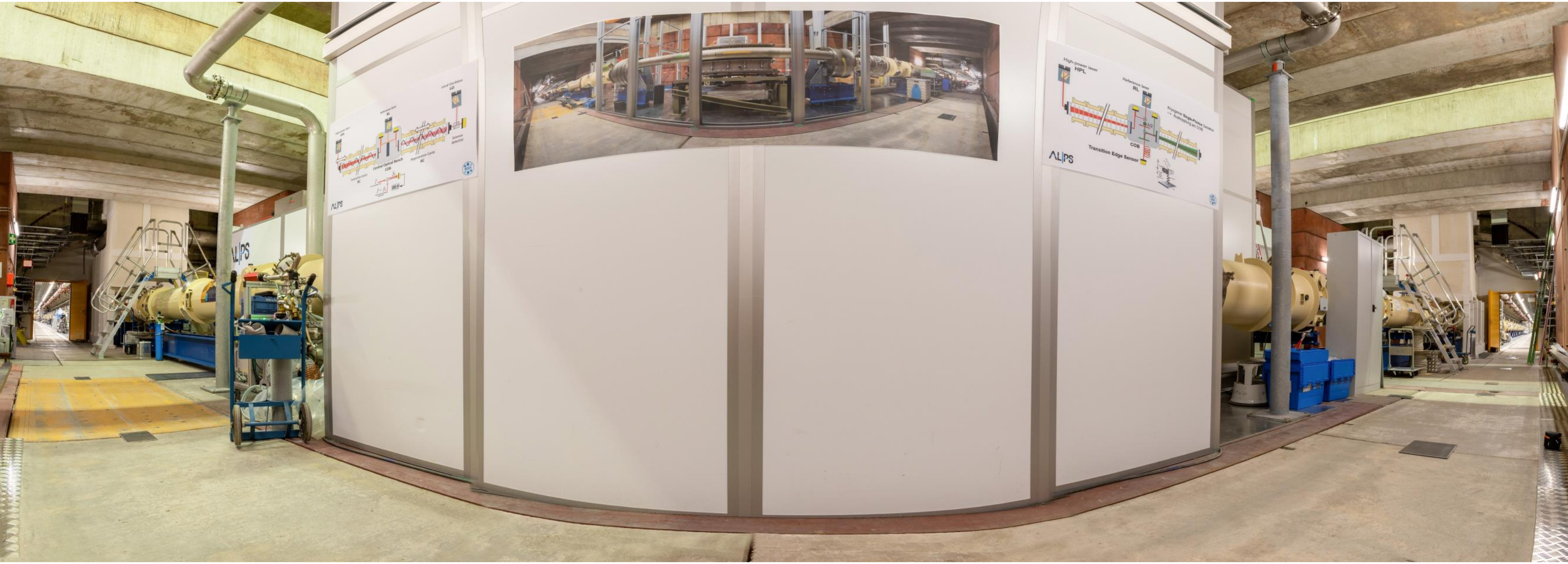
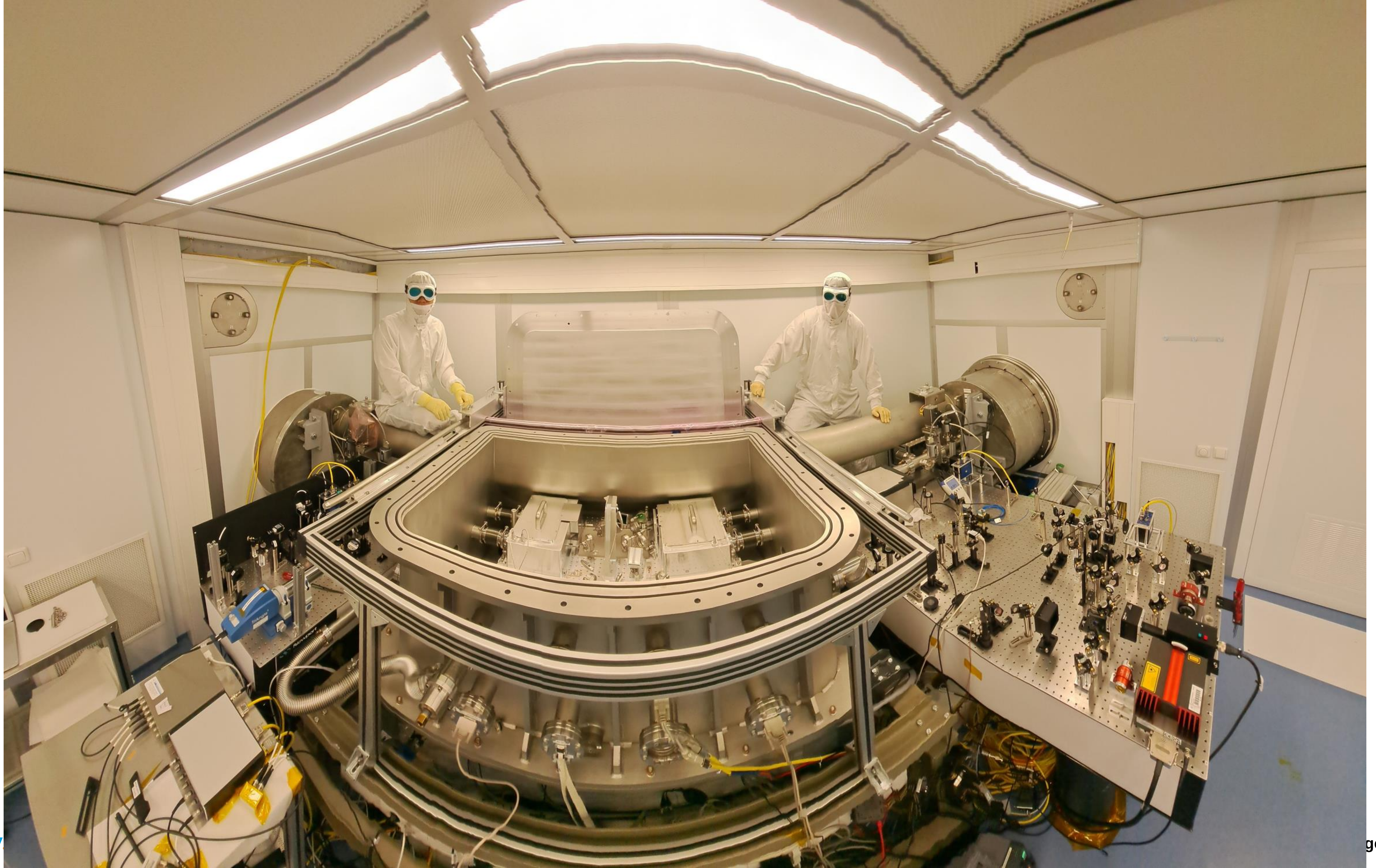
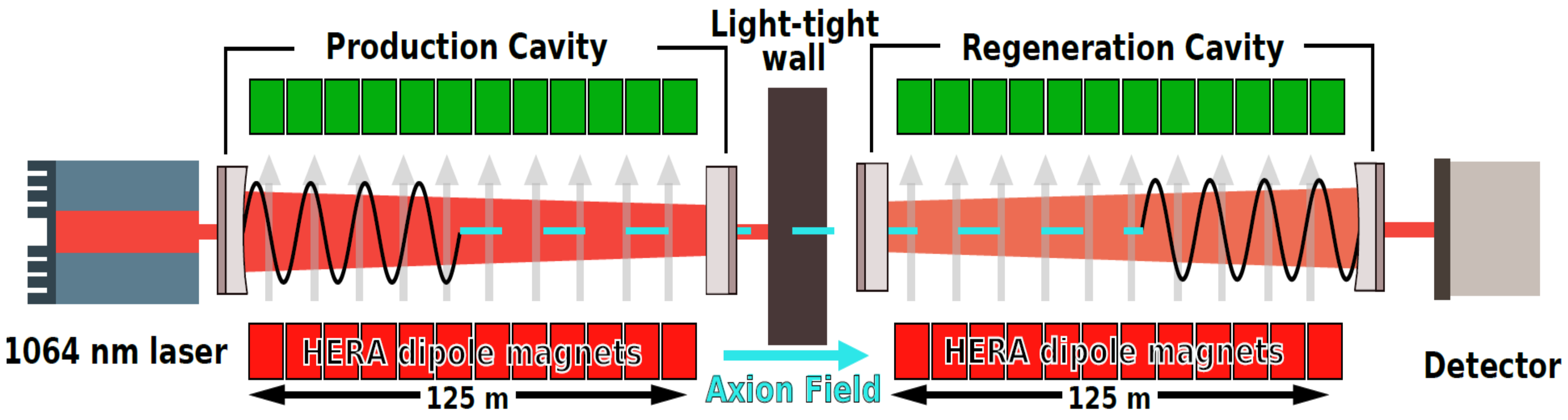



High-power laser
HPL
Reference laser
RL
Kryogener Single-Photon Detektor
→ Auskopplung am COB
COB
Transition Edge Sensor
AL|PS



ALPS II: a glimpse on the challenges

Cavities and Heterodyne Sensing



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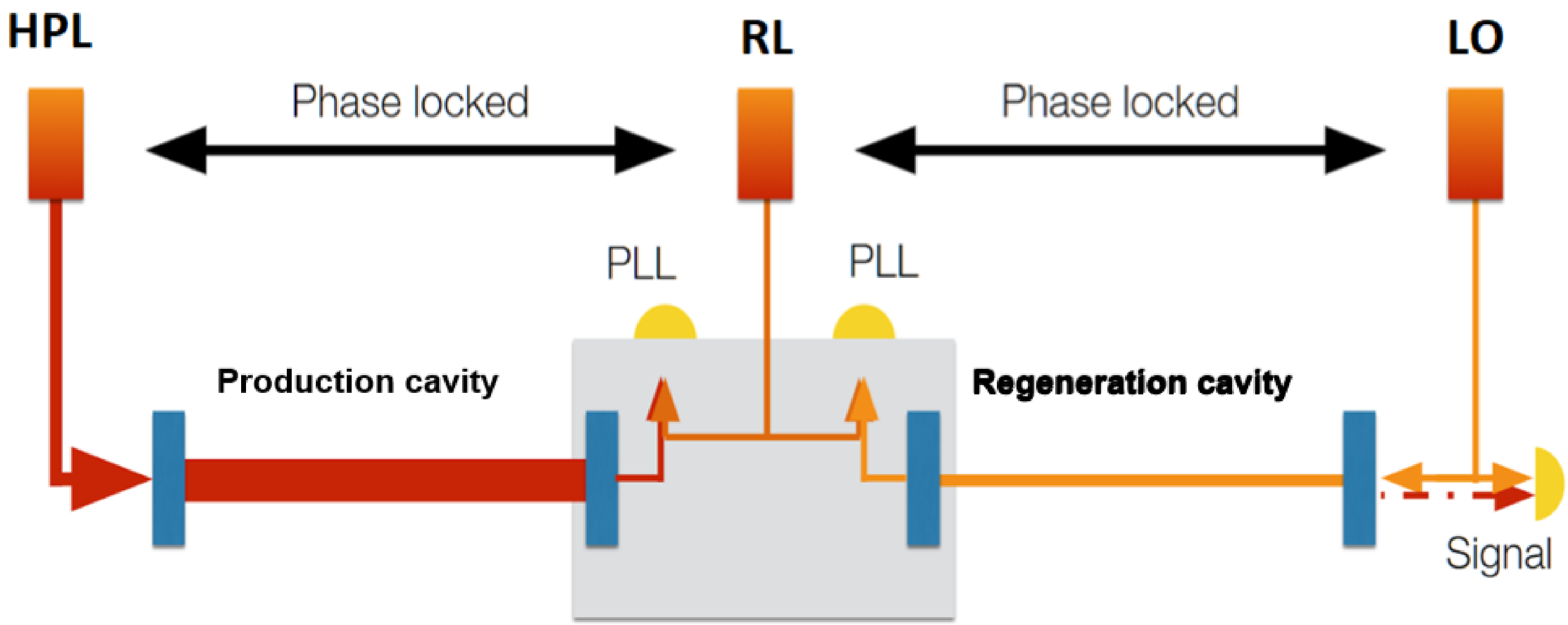


Measure P_2
and phase shift

P_1, P_2

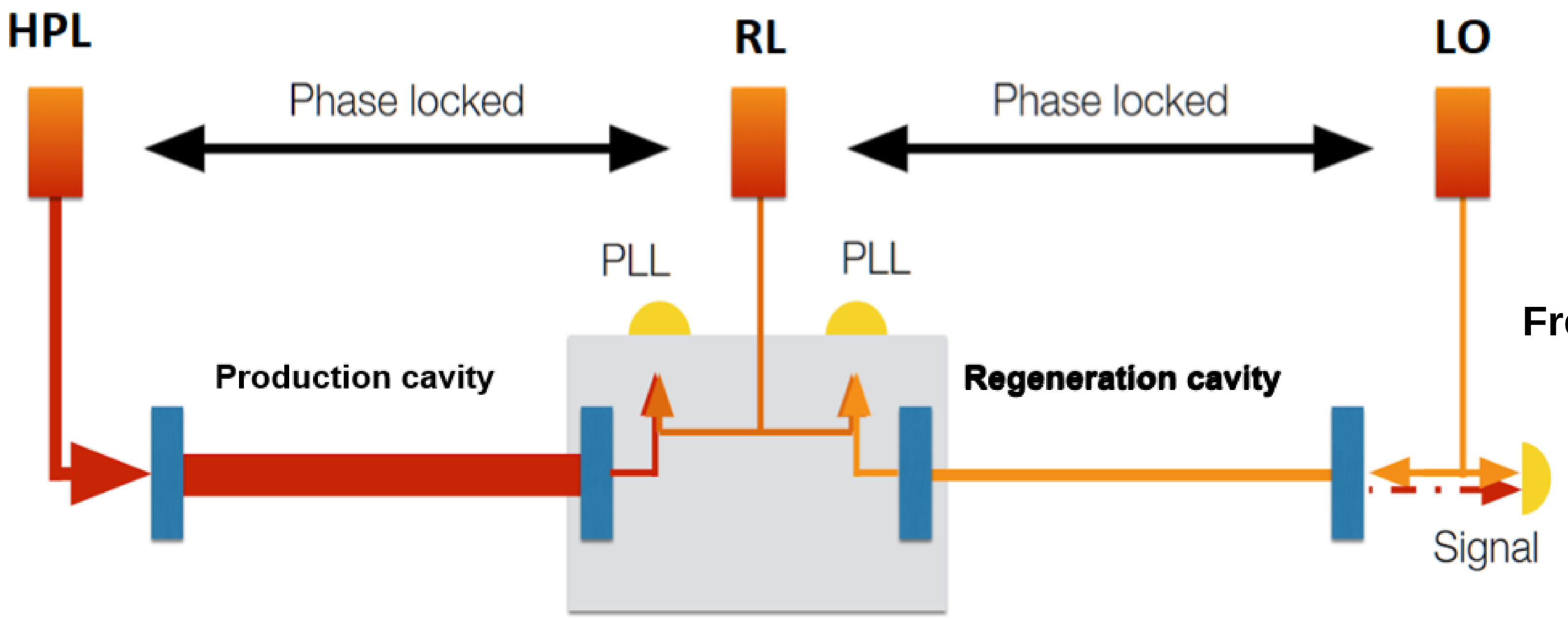
$$\left| \sqrt{\bar{P}_1} e^{i(2\pi f t + \phi_1)} + \sqrt{\bar{P}_2} e^{i[2\pi (f+f_0)t + \phi_2]} \right|^2 = \bar{P}_1 + \bar{P}_2 + 2\sqrt{\bar{P}_1 \bar{P}_2} \cos\left(2\pi f_0 t + \Delta\phi\right)$$

see this workshop A. Ejlli, “Heterodyne detection”, Monday 12:00 h

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

ALPS II: a glimpse on the challenges

Cavities and Heterodyne Sensing



Frequencies involved:

281,759,828,947,368.0 Hz
(variable to compensate seismic noise)

Difference to above: 58,659,993.2 Hz

Down-mixing for signal detection:

58,659,993.2 + 2.4 Hz
Stability requirement: 0.1 µHz

DESY News 27 October 2022

ALPS II achieves world record

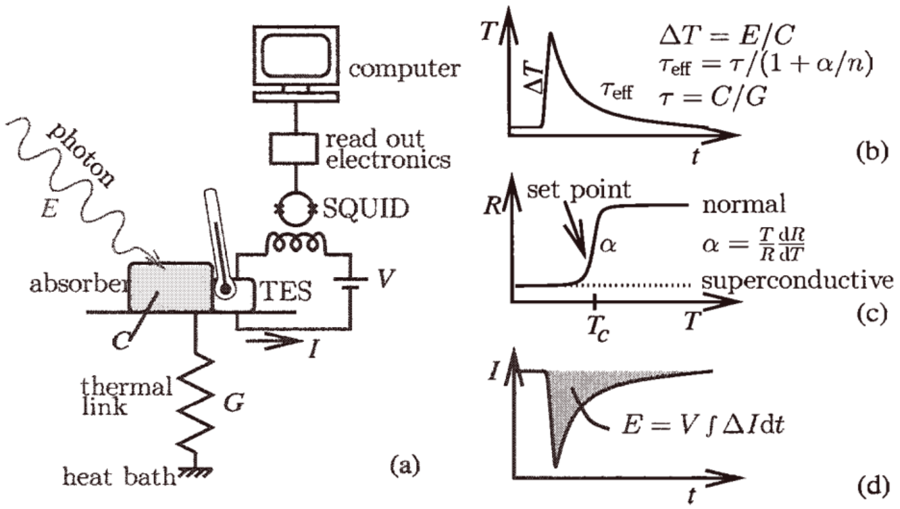
“Dark-matter experiment at DESY manages to store laser light in-between two mirrors for the longest time ever”

“DESY’s very own dark-matter experiment ALPS II – for “Any Light Particle Search” – hasn’t even started up yet, but is already breaking world records. The team, whose experiment sits in the tunnel of the former HERA accelerator and uses upcycled HERA magnets to (hopefully) send light through a wall, has managed to store laser light for 6.75 milliseconds. “We believe this a **world record for the longest amount of time laser light spends circulating between two mirrors**,“ says ALPS II researcher Todd Kozlowski, PhD student of the University of Florida.. …“

ALPS II: a second sensing scheme

Photon counting, to be implemented later

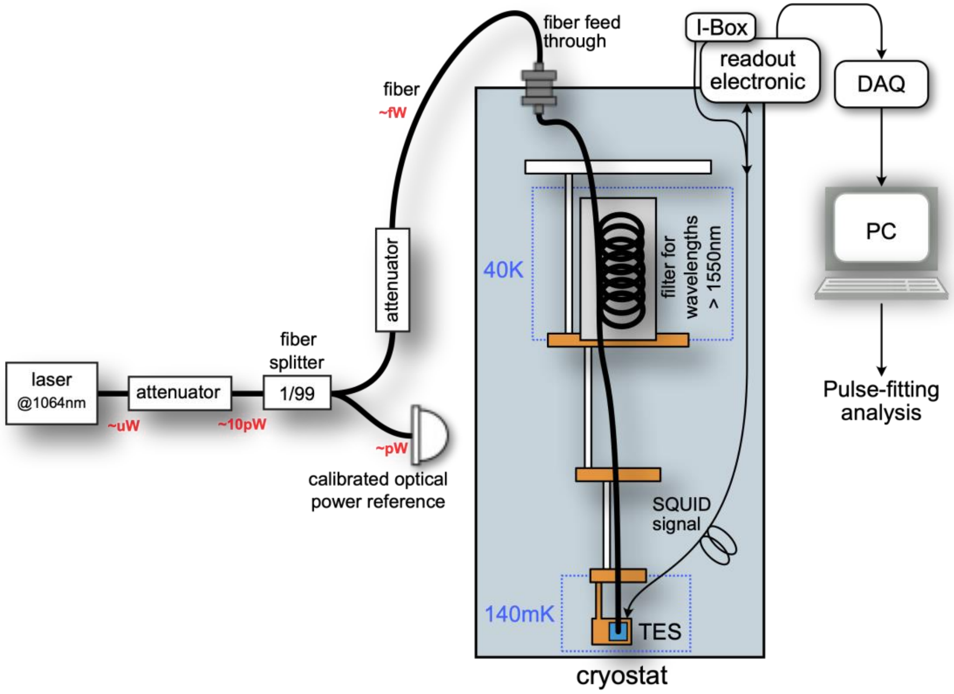
Using a superconducting transition edge sensor (TES) operated at about 100 mK.



ΔT ≈ 300 μK

ΔR ≈ 1 Ω

ΔI ≈ 70 nA



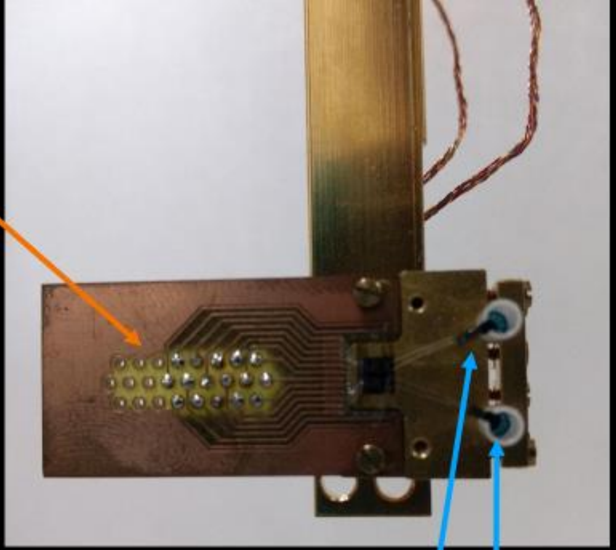
"Characterization, 1064 nm photon signals and background events of a tungsten TES detector for the ALPS experiment",
J. Dreyling-Eschweiler et al., Journal of Modern Optics, 62:14, 1132-1140

Cryostat

- Bluefors Dilution refrigerator (mixing He3/4) achieving 21mK
- Control from Bluefors (manually and remote software)
- Remote control (Windows PC)
- DOOCS Panel for remote view

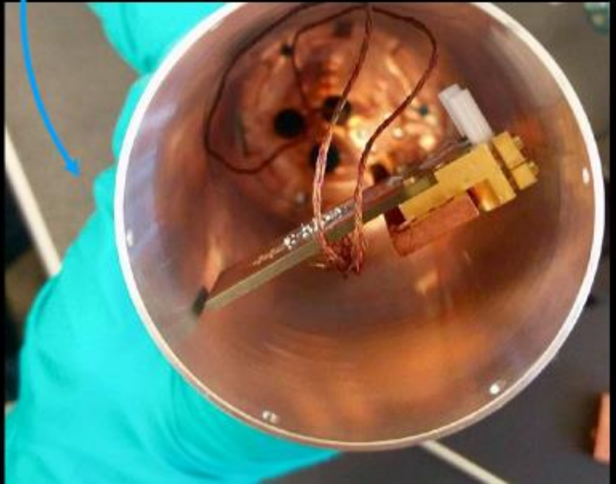
SQUID (PTB, Magnicon)

- I-Box
- Electronics from Magnicon
- IV curve measurement via Oscilloscope



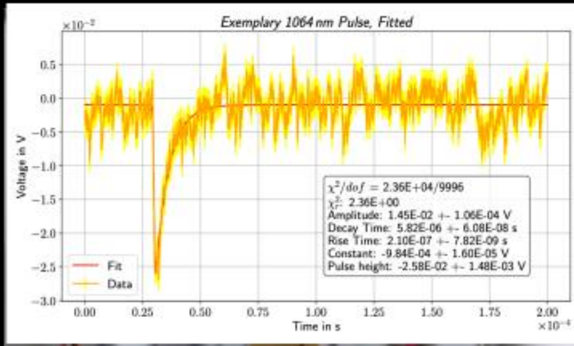
TES

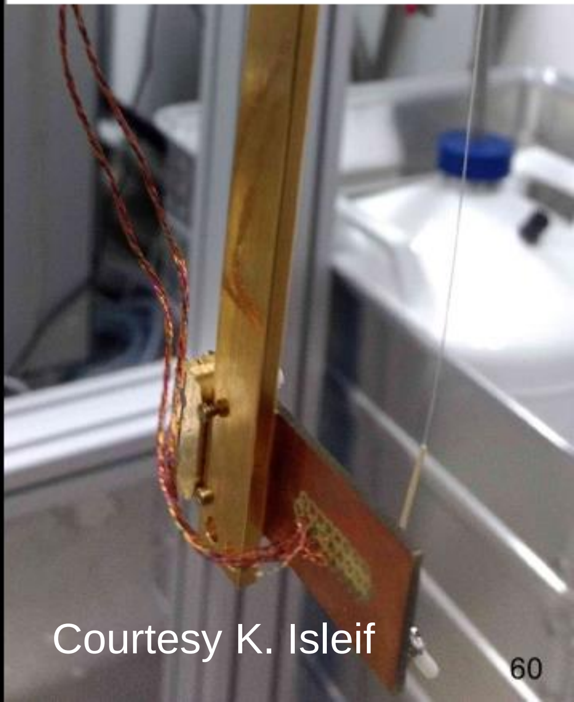
- 2 Tungsten sensors (NIST)
- High-efficient layers (>99% transmission for 1064 nm)
- Fiber coupled
- Coupled to the bath via copper
- aluminium can for shielding against magnetic, EM, BB… ?



DAQ

- Alazar ATS9626 250Ms/s via PCI on a Linux system
- GUI programmed in-house
- Triggering for different working points of TES resistance
- Different analysis lines





Courtesy K. Isleif

ALPS II: photon sensing status

Summary

Heterodyne sensing (1064 nm):

- Good prospects to reach shot-noise limitation for integration times T > 10 days.
- Good prospects to maintain coherence of signal and local oscillator for more than 10 days.

TES photon counting (1064 nm):

- Intrinsic background < 10^{-5} counts/second.
- System efficiency > 90%.
- Single photon energy resolution about 5%.

Two methods to sense $5 \cdot 10^{-24}$ W @ 1064 nm!

For signals lasting for about 20 days.

ALPS II: data taking started with the initial science run!

23 May 2023

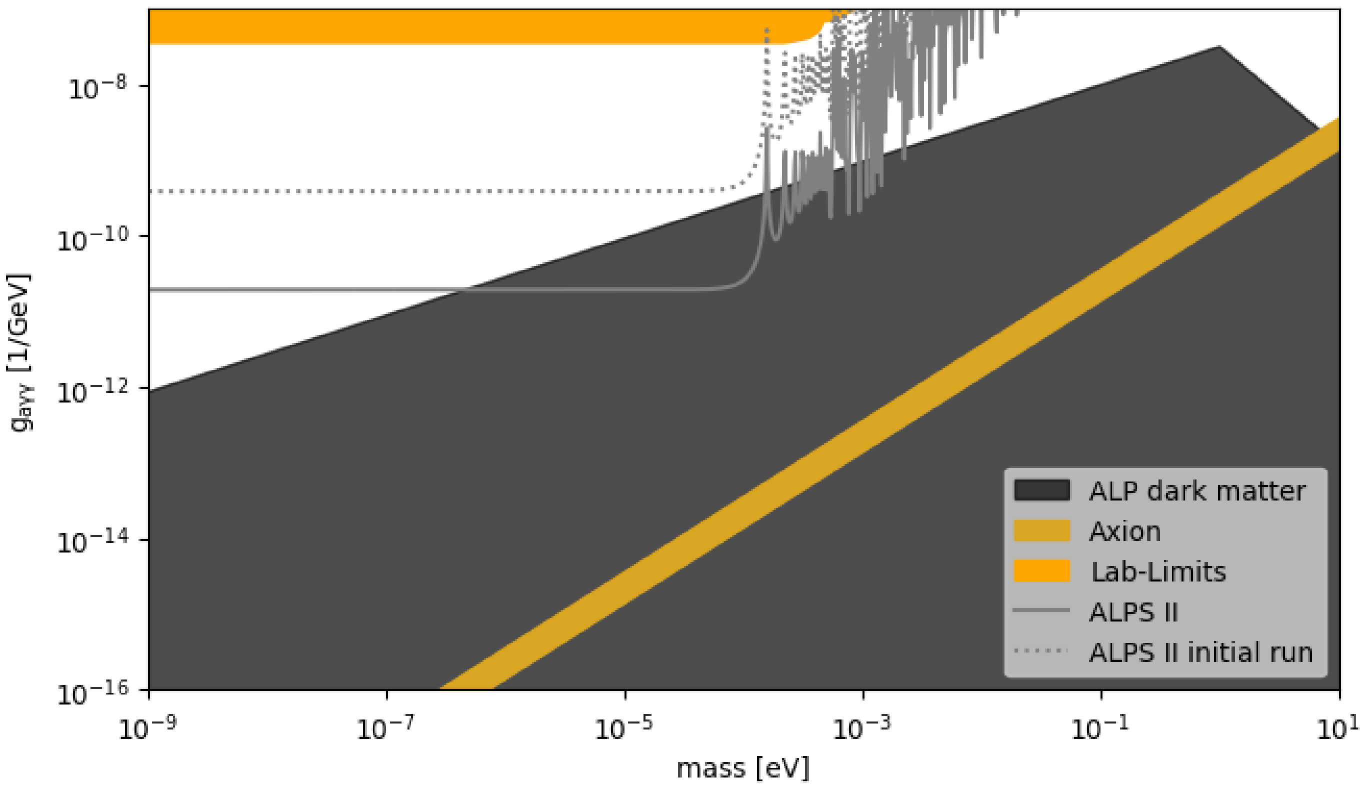
After more than 10 years of R&D and construction…

Data also by Ciaran O'Hare
https://cajohare.github.io/AxionLimits/

The ALPS II plans

Initial science run and design sensitivity

Purely laboratory based searches: model-independent results.



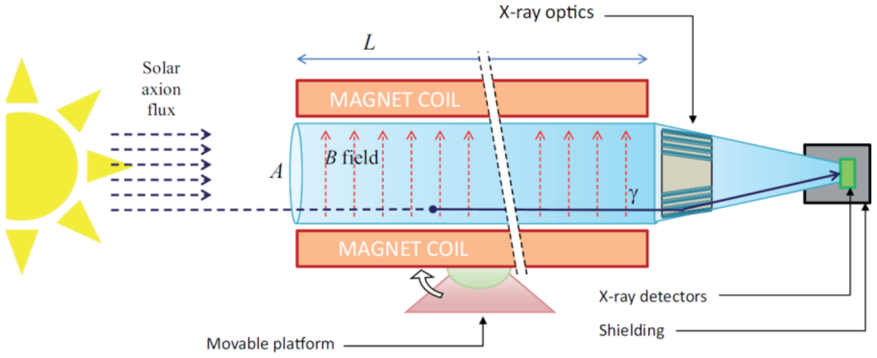
Bridging the gap with **ALPS II**:

Improve the sensitivity by $O(10^3)$!

Next steps:
- Full optics in 2024.
- Design sensitivity in 2025.

Beyond (depending on results):
- Further axion searches (TES-based?).
- Vacuum magnetic birefringence.
- High frequency gravitational waves.

Annual Review of Nuclear and Particle Science, Vol. 65: 485-514 (2015)



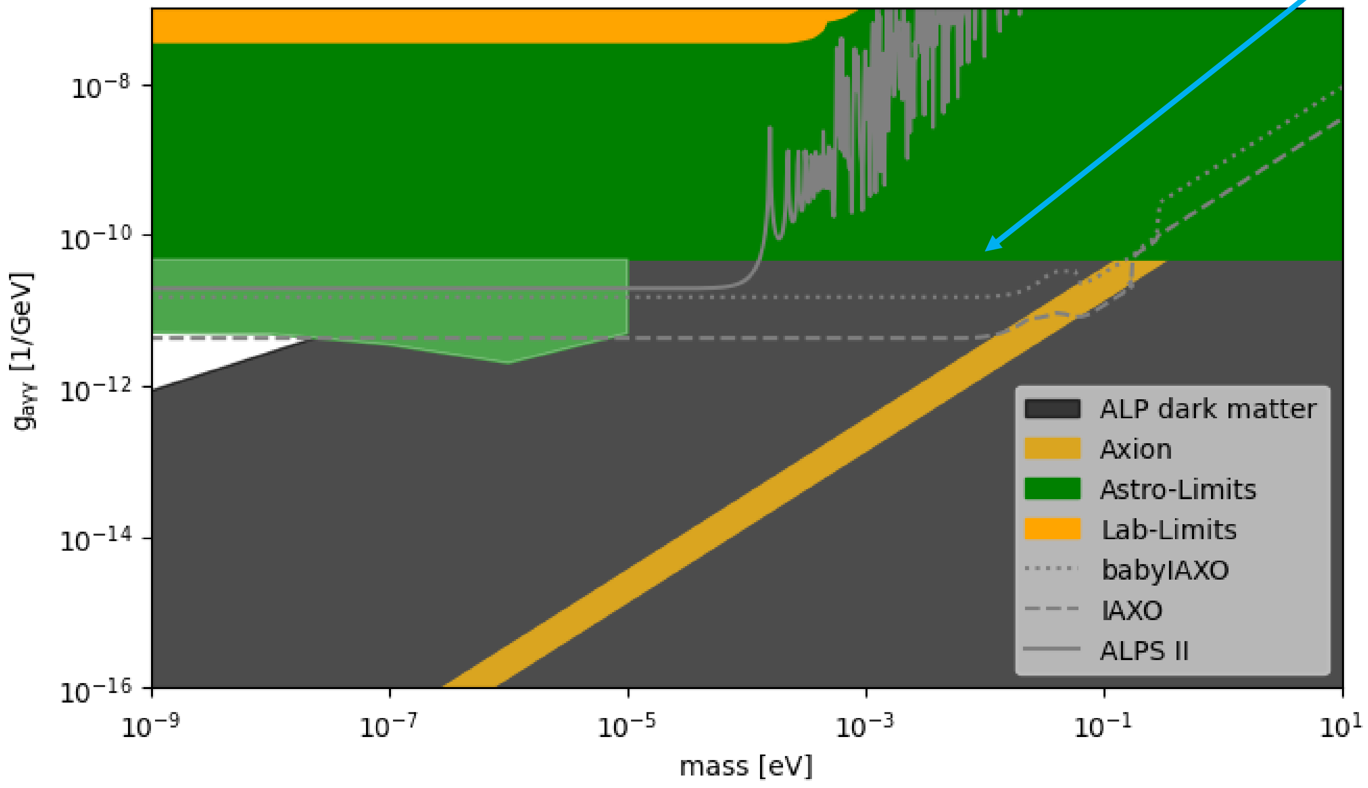
Full members: Kirchhoff Institute for Physics, Heidelberg U. (Germany) | Siegen University (Germany) | University of Bonn (Germany) | DESY (Germany) | University of Mainz (Germany) | Technical University Munich (TUM) (Germany) | University of Hamburg (Germany) | MPE/PANTER (Germany) | MPP Munich (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | INAF-Brera (Italy) | CERN (Switzerland) | ICCUB-Barcelona (Spain) | Barry University (USA) | MIT (USA) | LLNL (USA) | University of Cape Town (S. Africa) | CEFCA-Teruel (Spain) | U. Polytechnical of Cartagena (Spain)

Associate members: DTU (Denmark) | U. Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

IAXO and Baby IAXO

Looking for solar axions

Today's limit: Cern-Axion-Solar-Telescope CAST

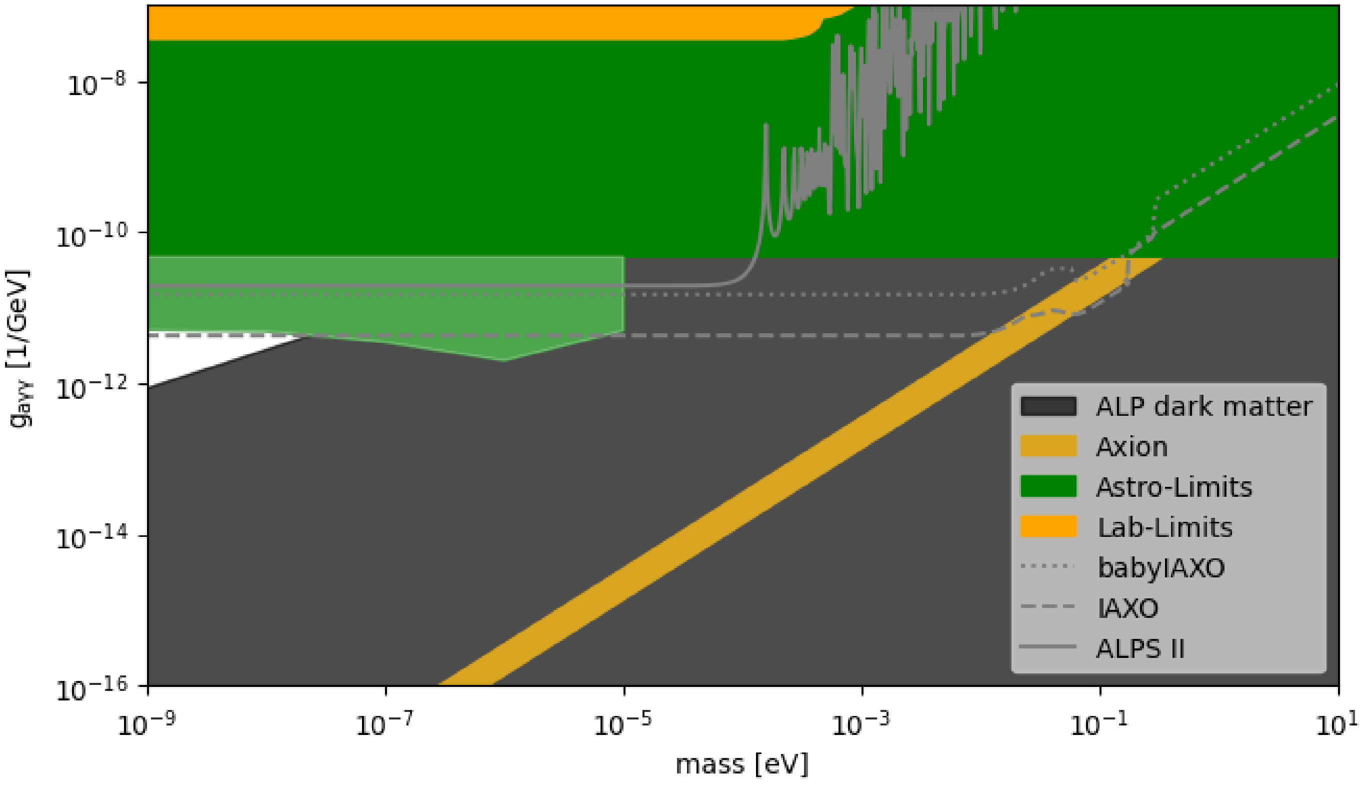


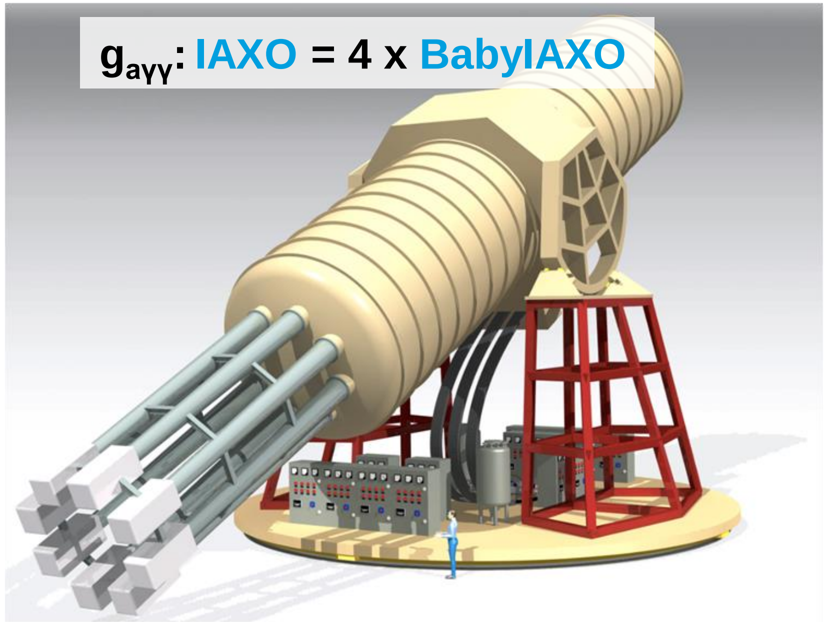
Systematic uncertainties due to unknown electromagnetic fields.

IAXO and Baby IAXO

Looking for solar axions

BabyIAXO as a full-fledged IAXO prototype with own discovery potential.





Status of BabyIAXO

Ready to start construction in 2024?

In 2022 BabyIAXO was basically ready to start construction, but experienced a serious setback after the Russian invasion into the Ukraine and the subsequent discontinuation of collaborations with Russian partner institutes.

This mainly affected the BabyIAXO magnet.

Thanks to the collaboration and engagement by CERN and DESY, the magnet seems to be in reach again!

Component / Status	Technical	Funding
Structure & Drive system	(✓)	(✓)
Vacuum & Gas System	✓	✓
Magnet	(✓)	(?)
X-ray Telescopes	✓	✓
Detectors	✓	✓

ERC-Synergy Grant DarkQuantum obtained !

- Develop quantum tech for axions
- Quantum-enhanced haloscope in BabyIAXO
- Connection with experts (cryo, quantum,…)
- Contribution to magnet

DarkQuantum

erc

I. Irastorza (U. Zaragoza), T. Kontos (École Normale Supérieure de Paris), S. Paraoanu (Aalto University), W. Wernsdorfer (KIT)

ALPS II, BabyIAXO, MADMAX

Magnet parameters

See also:
A. Ringwald et al., JCAP 03 (2021) 054a

Parameter		ALPS II	BabyIAXO	MADMAX
Dipole magnet	Strength B	5.3 T	2.5 T	4.8 T (averaged over L)
	Length L	2·12·8.8 m	10 m	6 m
	Bore diameter	5 cm	70 cm	1.25 m
$B \cdot L \cdot A^{0.5}$		2·50 Tm^2	22 Tm^2	32 Tm^2
Low frequency cutoff		5 THz	1 GHz	0.2 GHz

MADMAX magnet central part:
≈ 10 T over 2 m.

ALPS II and BabyIAXO

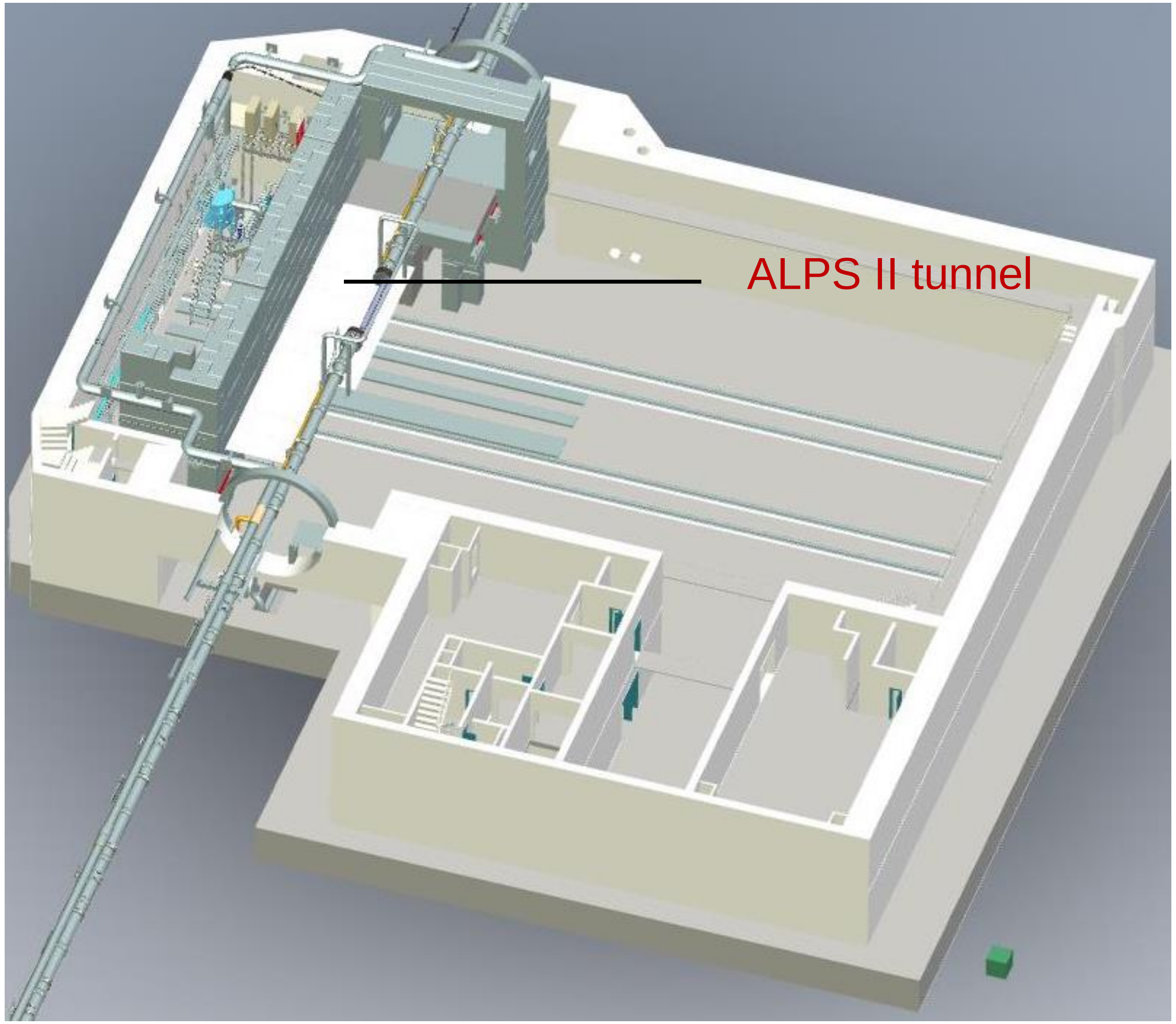
Main experimental parameters

Parameter		ALPS II	BabyIAXO
Dipole magnet	Strength B	5.3 T	2.5 T
	Length L	2·12·8.8 m	10 m
	Bore diameter	5 cm	70 cm
$B \cdot L \cdot A^{0.5}$		2·50 Tm^2	22 Tm^2
Low frequency cutoff		5 THz	1 GHz
Photon energy		1.165 eV	O(1 keV)
Signal sensing		10^{-24} W (after 20 days)	10^{-24} W (after 1 year)
Resonant amplification		up to 40,000 (power)	none

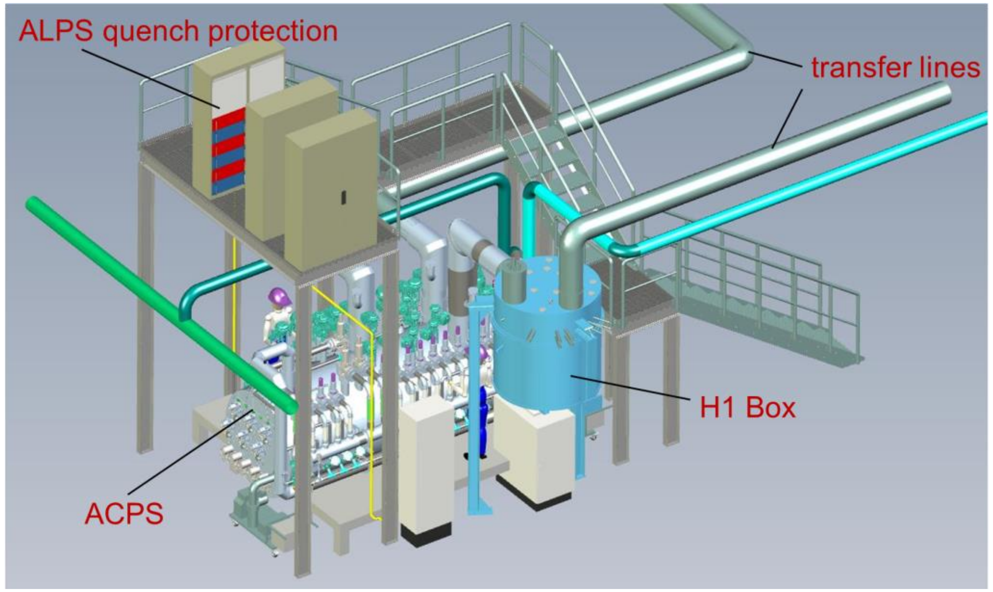
BabyIAXO sensing:
count X-ray photons essentially background-free for one year.

The new DESY cryoplatform

A general infrastructure for experiments requiring liquid He cooling



- Supplying supercritical helium as well as very high pressurized cold and warm helium gases to up to three experimental stations (one is MADMAX).
- Estimation of maximum cooling power @ 4.5 K and 3.5 bar : 500 W @ 4.5 K
- Estimation of maximum cooling power @ 40 K and 14 bar : 4400 W @ 40 K



Summary

Options for high frequency gravitational wave searches DESY

Infrastructures:

- ALPS II dipole magnet string with three cleanrooms.
- BabyIAXO dipole magnet on a movable platform.
- Cryoplatform at the HERA hall North.
- Longer-term future: MADMAX dipole magnet.

Relevant competences acquired via axion experiments:

- High precision long-baseline interferometry @ 1064 nm.
- Very weak signal sensing @ 1064 nm and X-ray energies.
- New DAQ and control schemes.
- Cryogenic competence in the particle physics group ALPS (cryoplatform, BabyIAXO/MADMAXMAGO cryostats).

Very tentative timelines for dedicates HF-GW searches:

- ALPS II: beyond 2028 ?
- BabyIAXO: beyond 2030 ?
- Cryoplatform: operational latest in 2026.

But: axion search data can also be interpreted as HF-GW searches.

In spite of long lead-times:

Due to funding discussion timelines at DESY and the Helmholtz association we should better come up with sketches of proposals in 2024.