Dark Matter and more: Axion Searches at DESY

First results, plans and visions

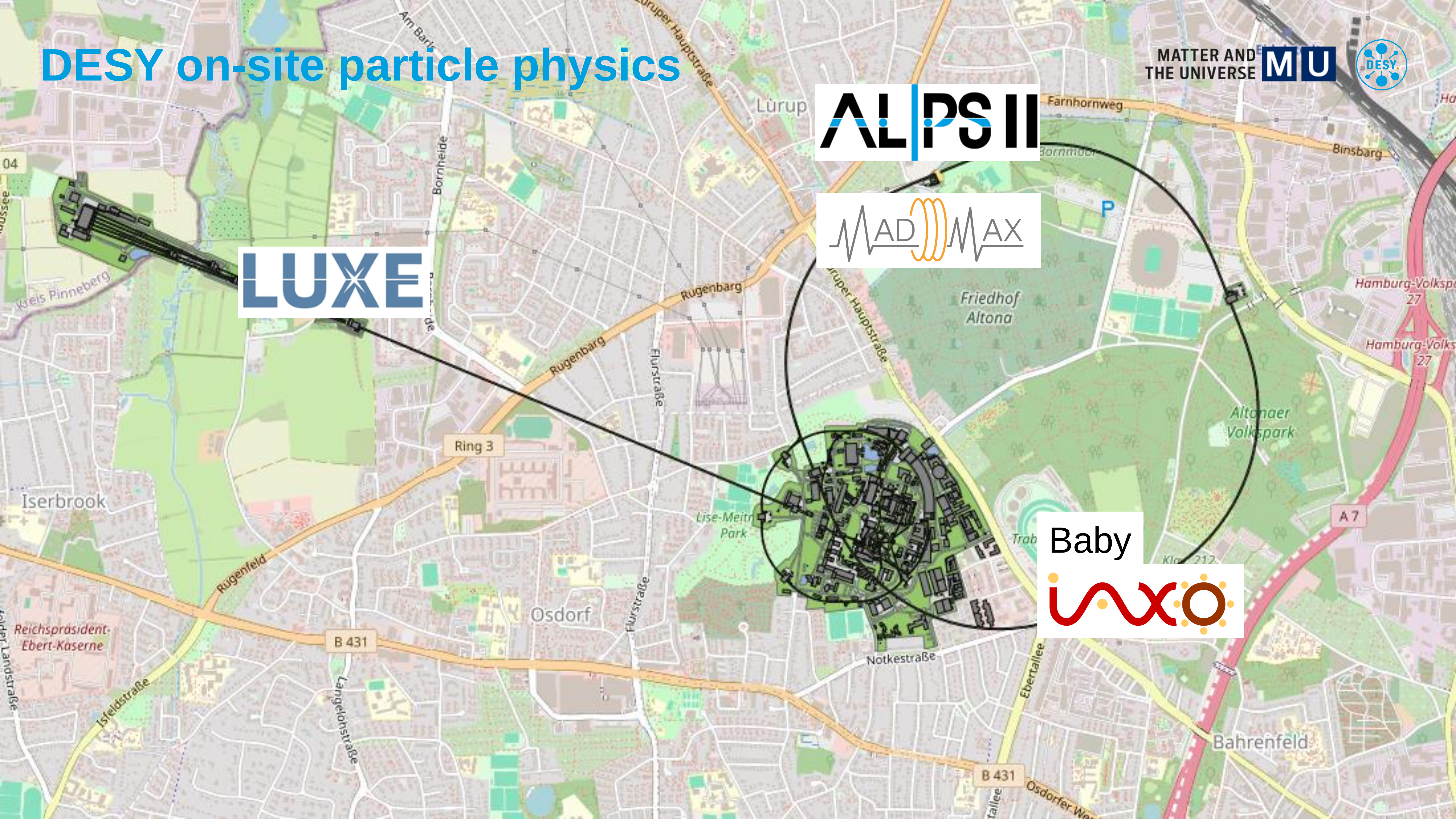
DESY-Pforta Week 2025

4 June 2025
Axel Lindner, DESY

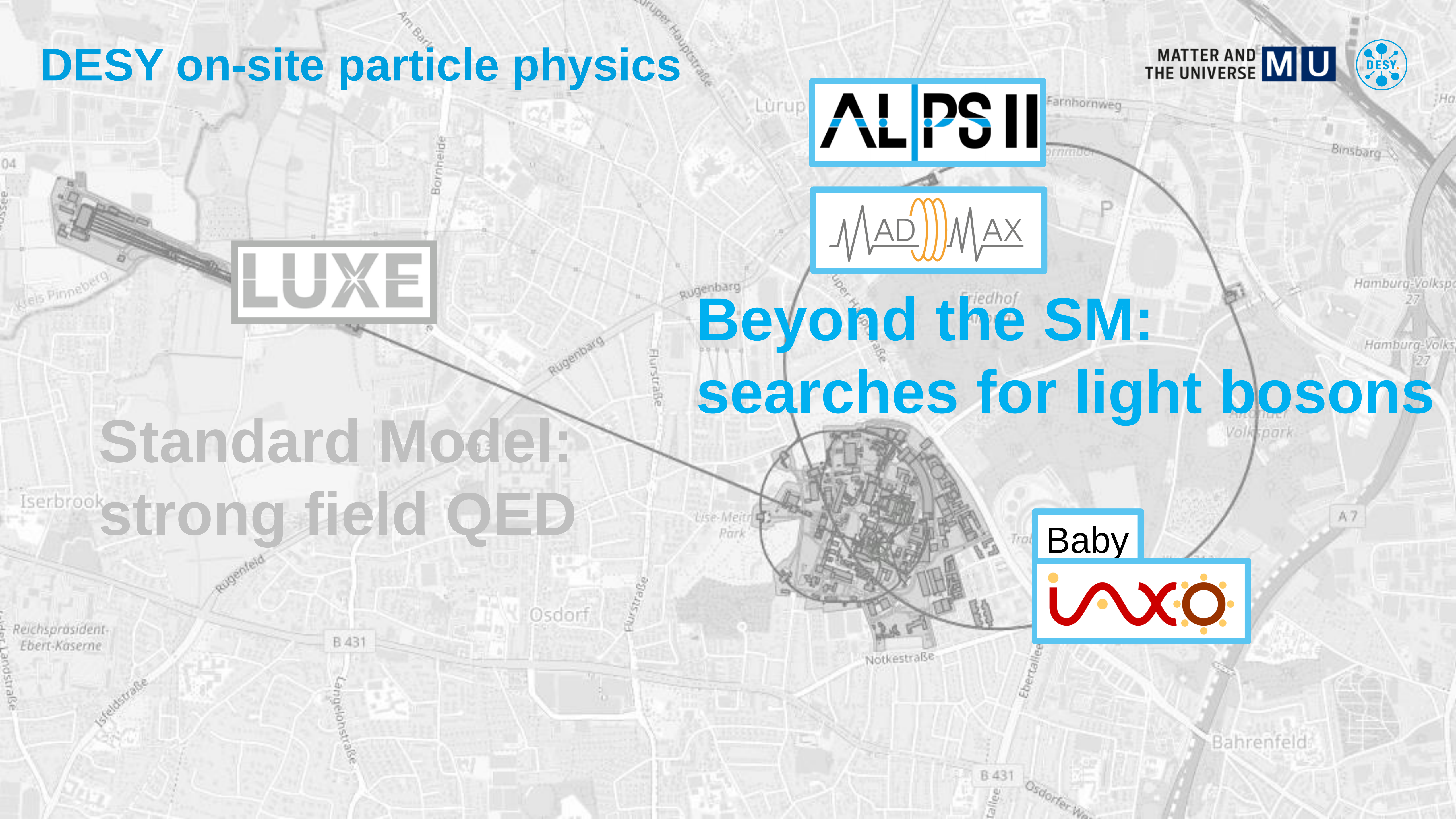

AL|PS
PAULANER
PUKY

DESY on-site particle physics

MATTER AND THE UNIVERSE MU



DESY on-site particle physics



Standard Model: strong field QED

Beyond the SM: searches for light bosons

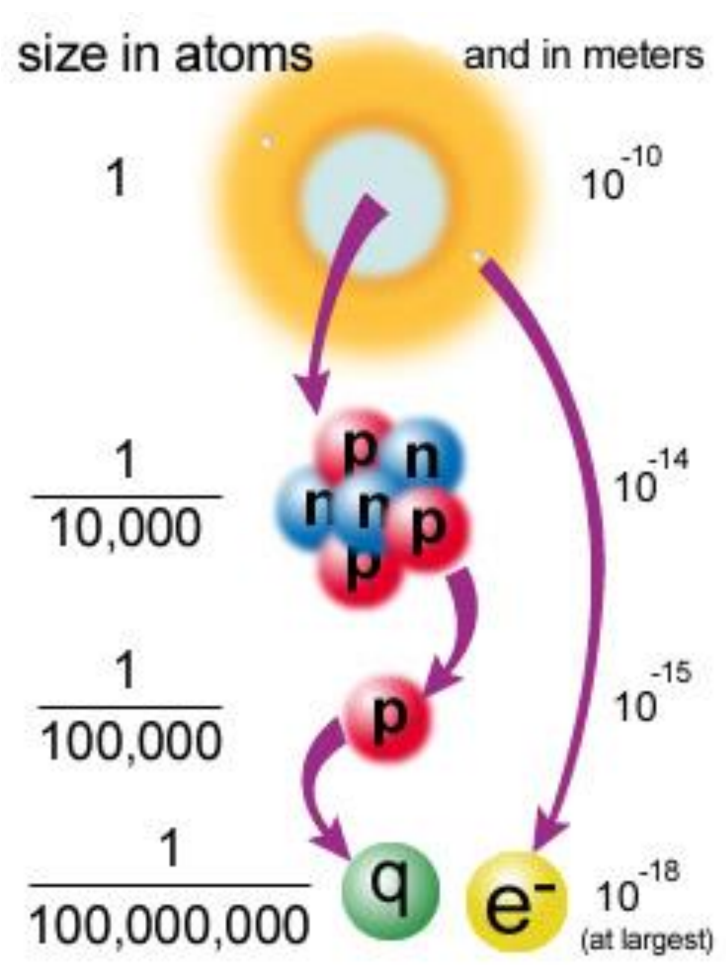
Outline

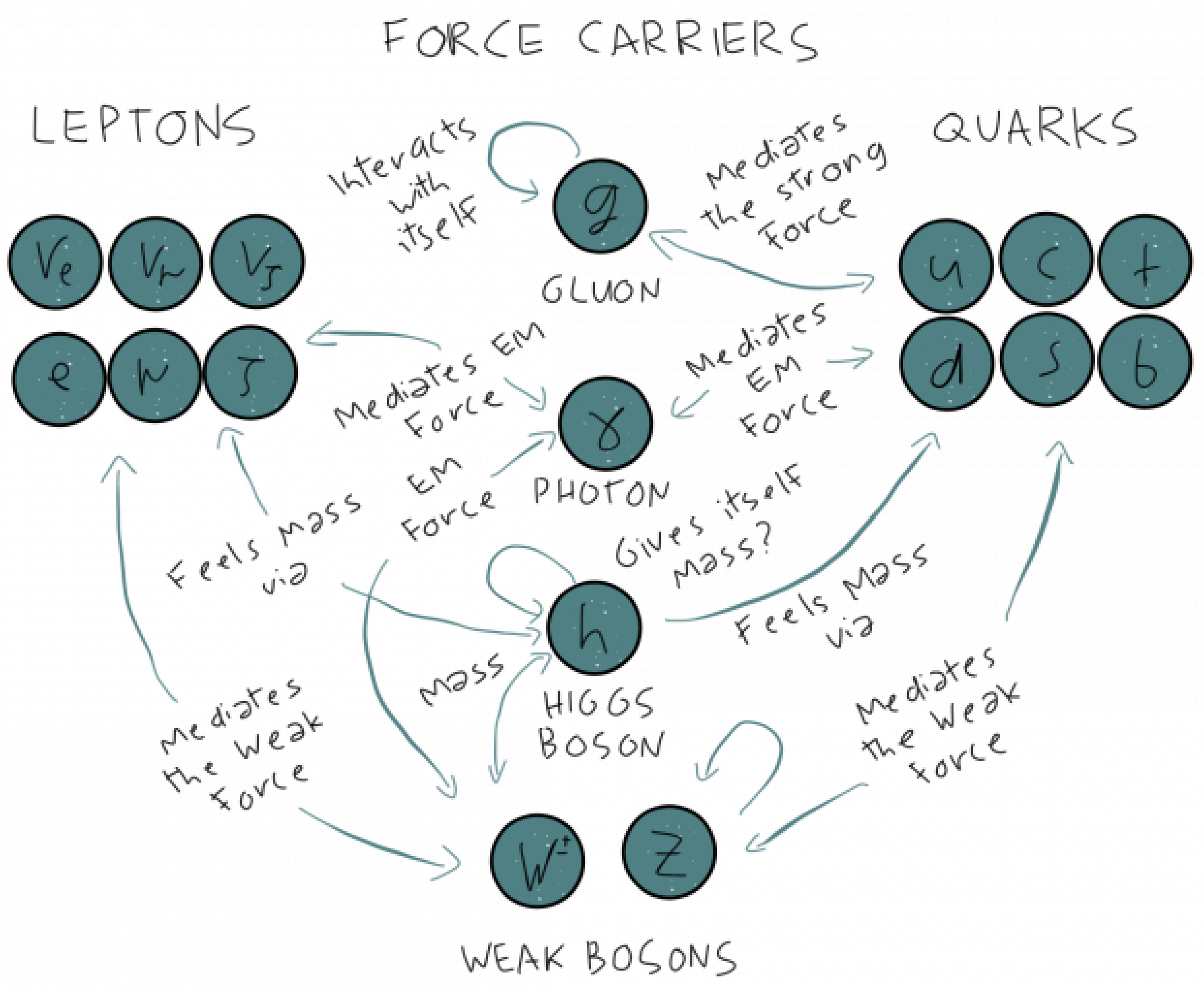
- A primer on the physics case
- Designing ALPS II
- Building ALPS II
- Understanding ALPS II
- First results and next steps
- Beyond ALPS II: BabyIAXO and MADMAX

A tremendous success story: understanding smallest scales

The Standard Model of particle physics

https://www.physics.louisville.edu/cldavis/phys299/notes/ap_scale.jpg

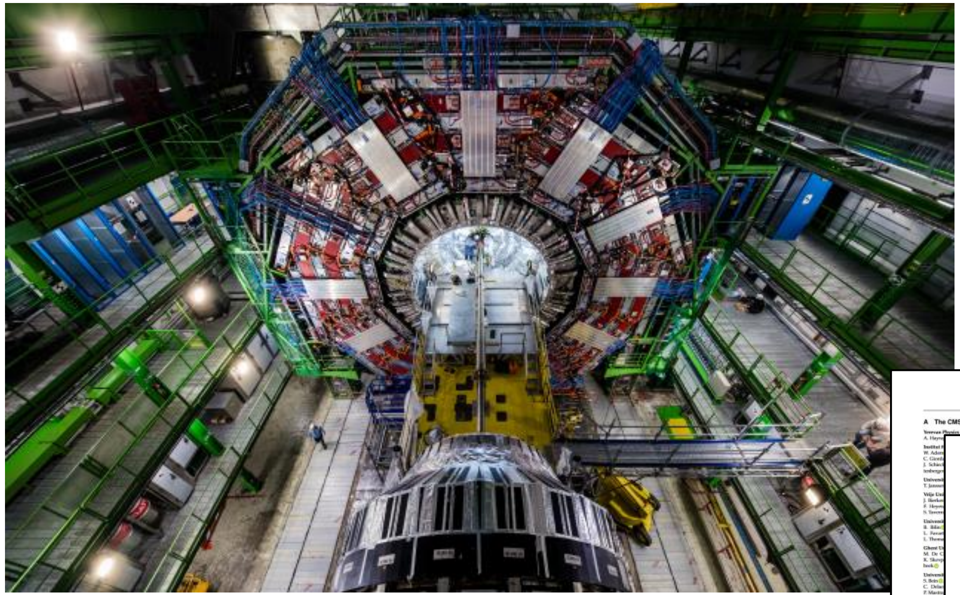


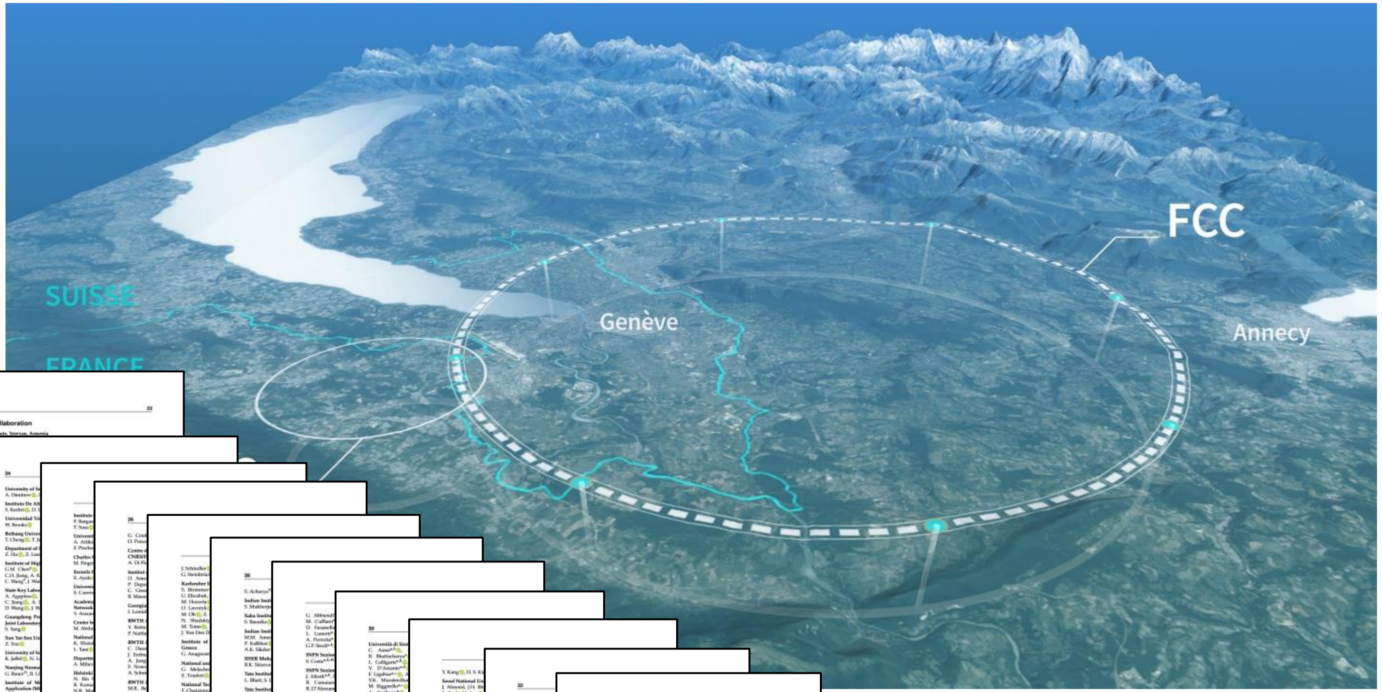


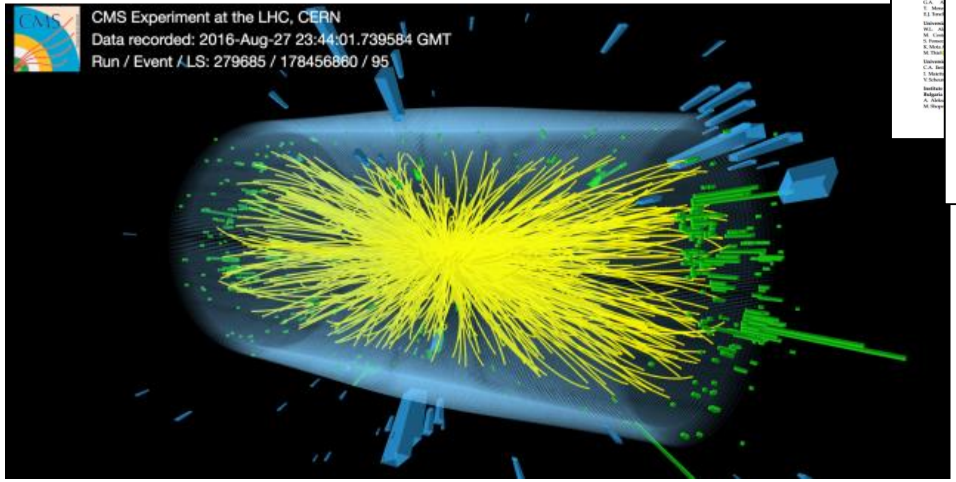
https://physicstravelguide.com/_media/models/paper.journal.40.png

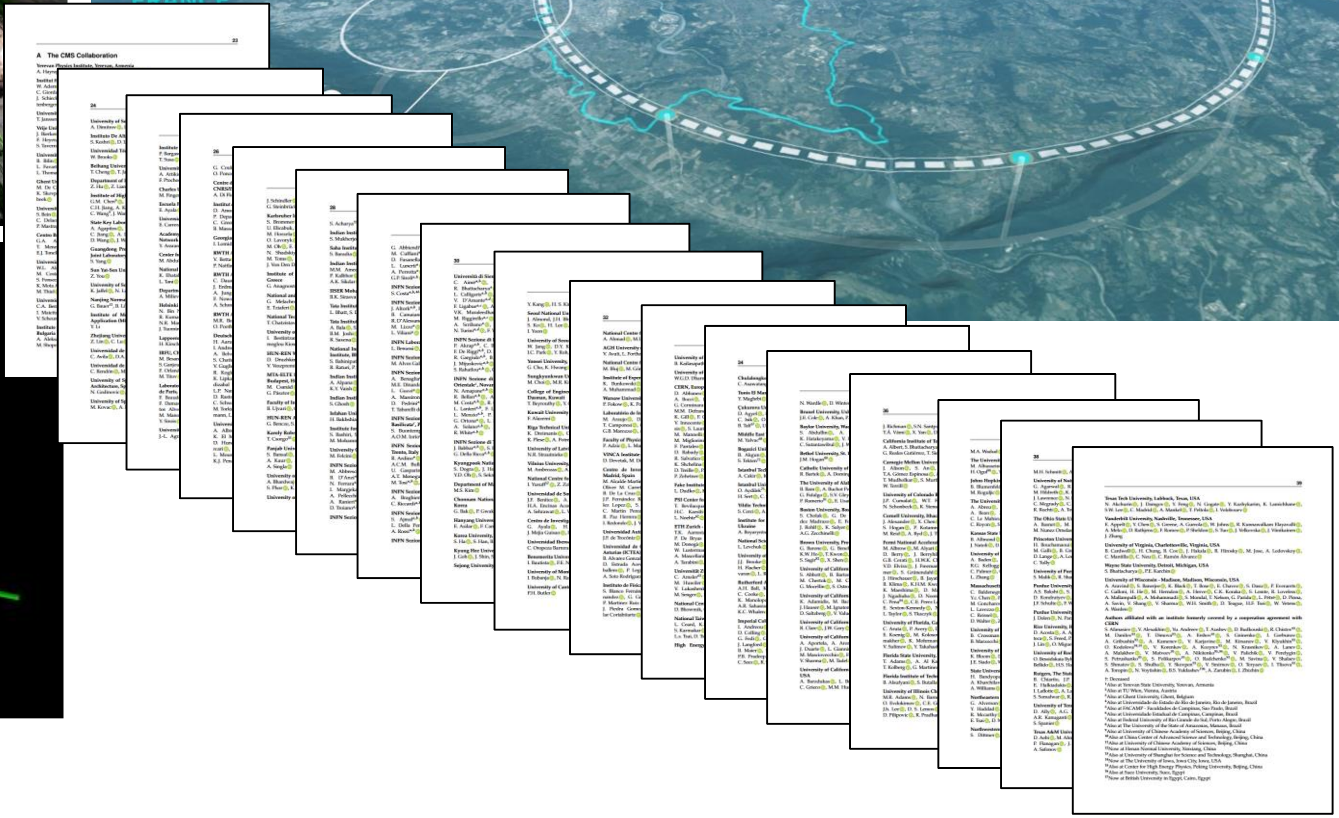
A tremendous success story: understanding smallest scales

Large facilities and world-wide collaboration



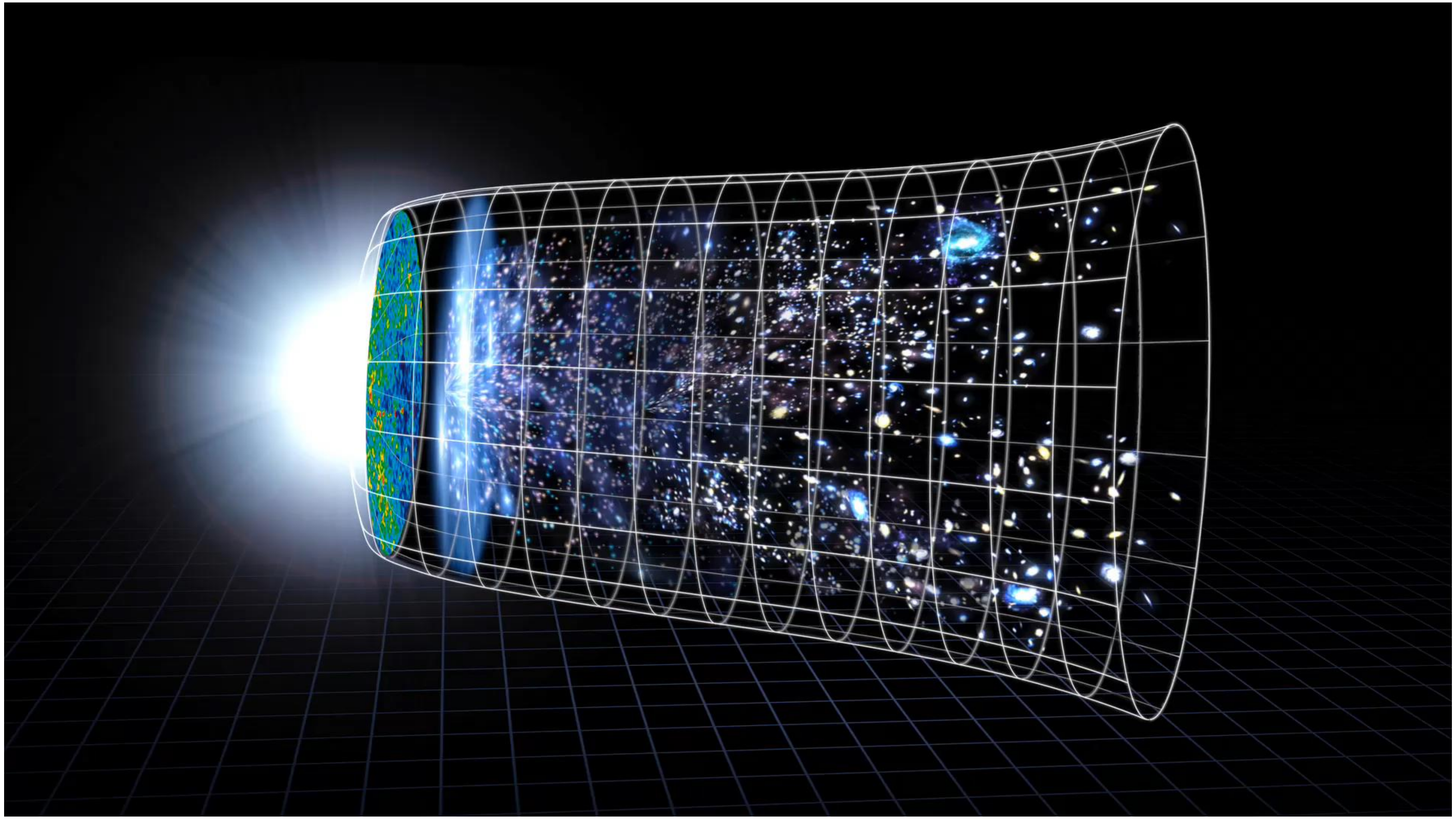






A tremendous success story: understanding smallest scales

Enables to understand the largest scales!

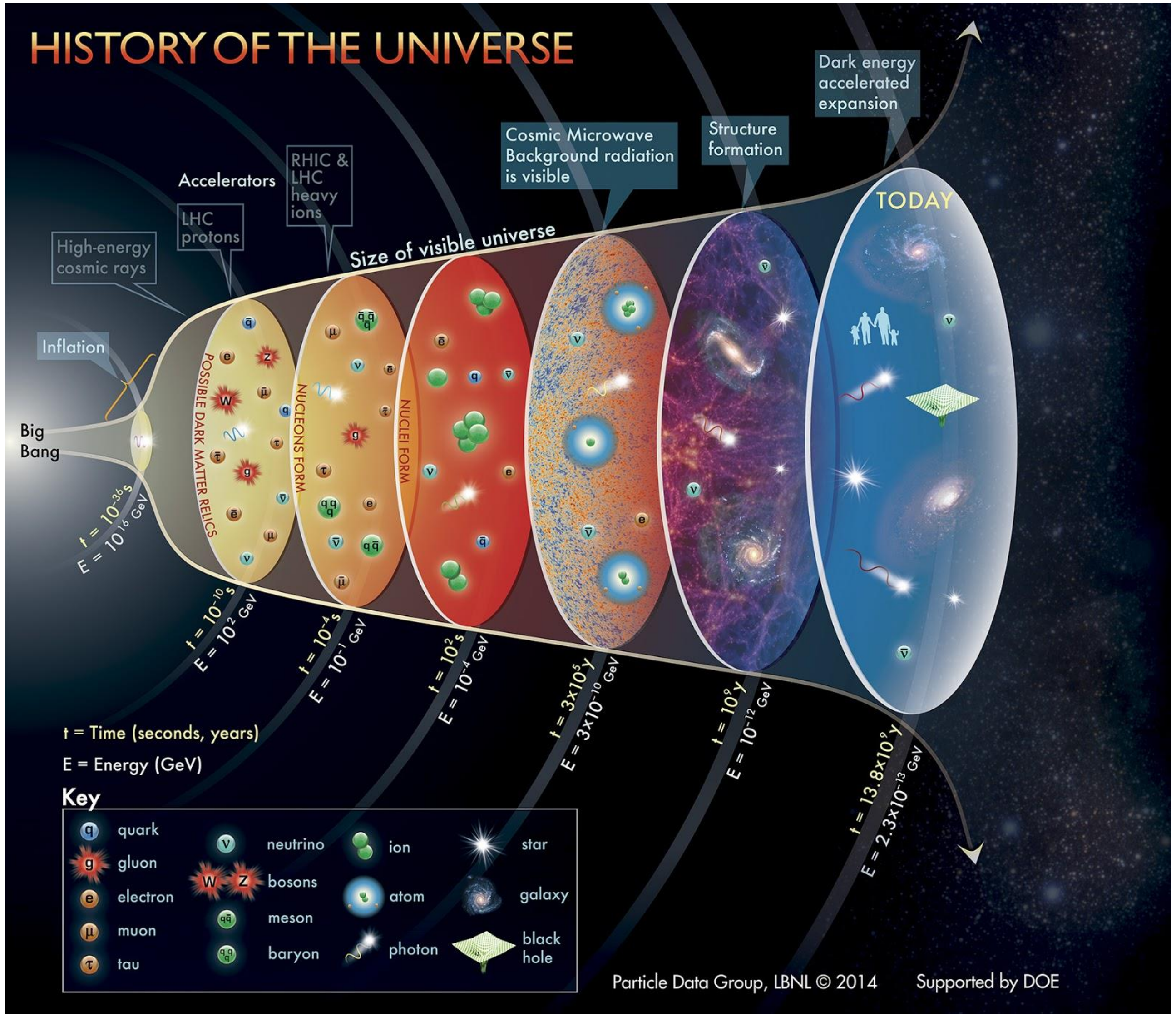


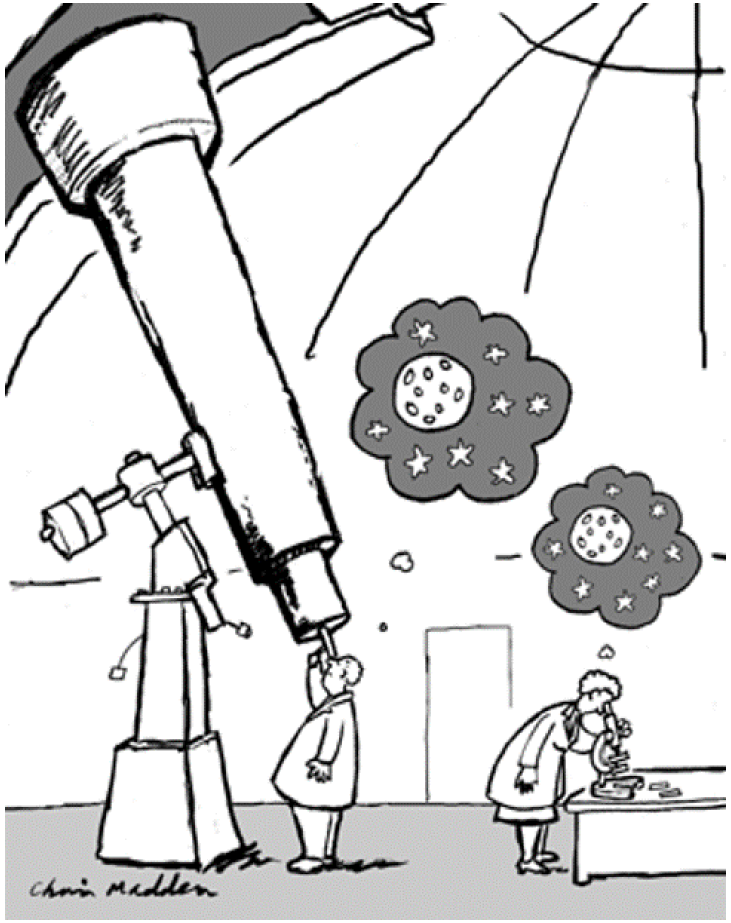
High energy particle colliders simulate the earliest moments of the universe!

We also have a standard model of cosmology.

Linking largest and smallest scales

The standard model of cosmology



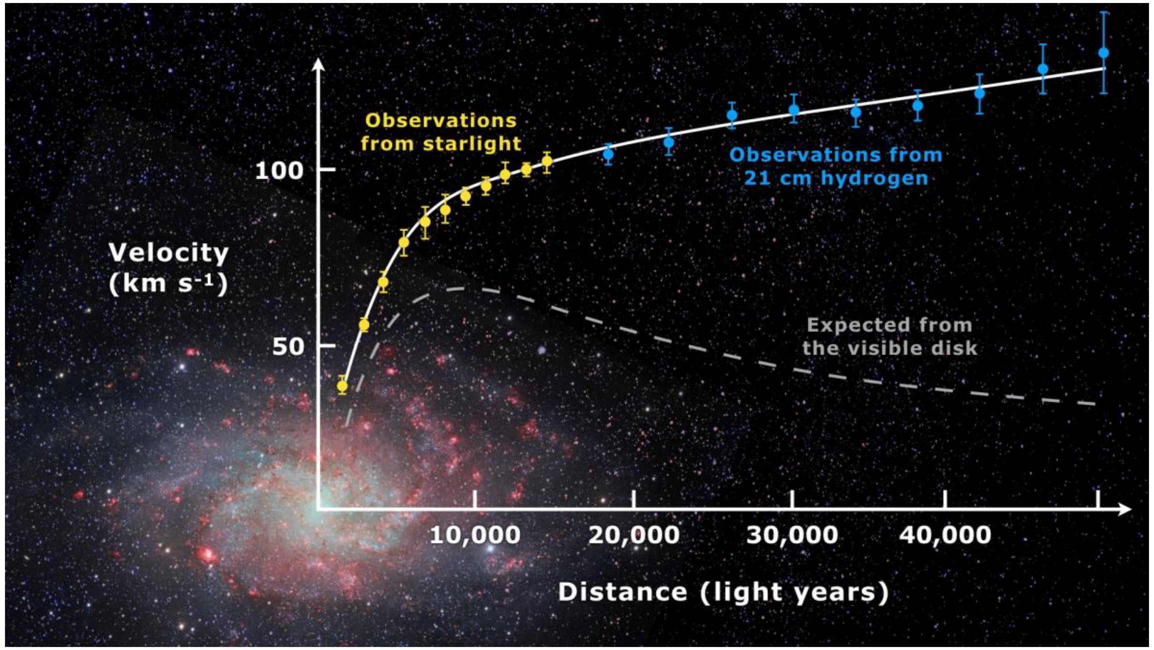


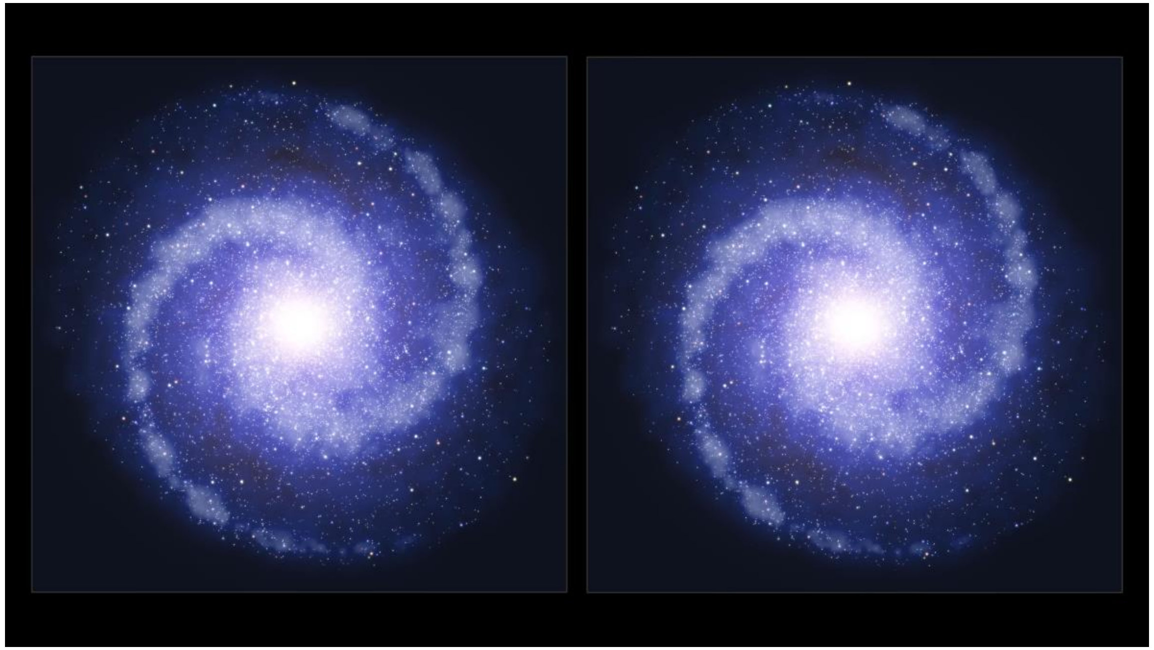
Linking largest and smallest scales

… points at unknown particle physics “Beyond the Standard Model” (BSM)

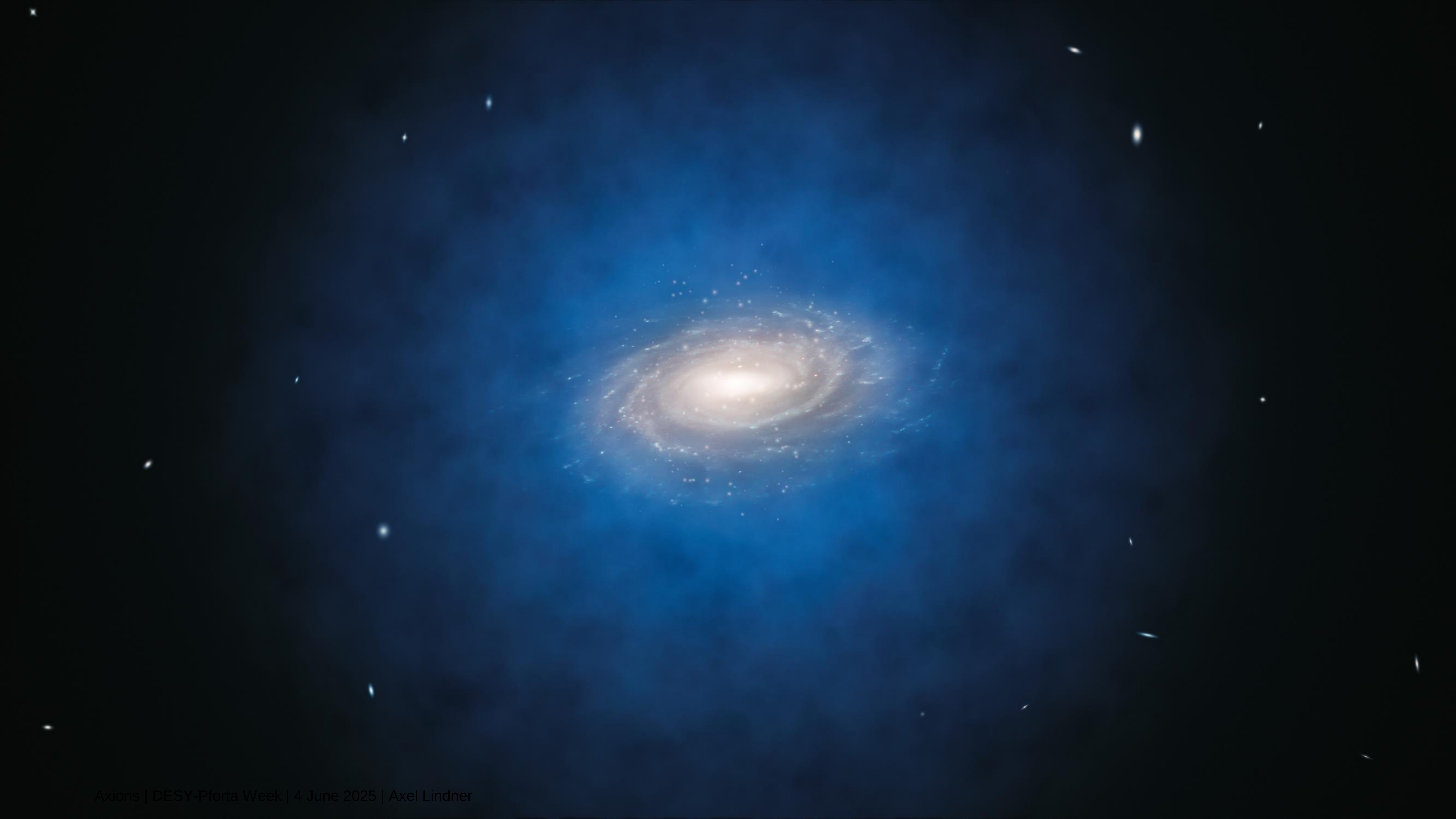
Most striking:

- We need extra “dark” matter to explain structure and dynamics of the universe on all scales larger than about 1,000 lightyears.
  This matter is not made out of stuff we know.





M33, https://en.wikipedia.org/wiki/Galaxy_rotation_curve



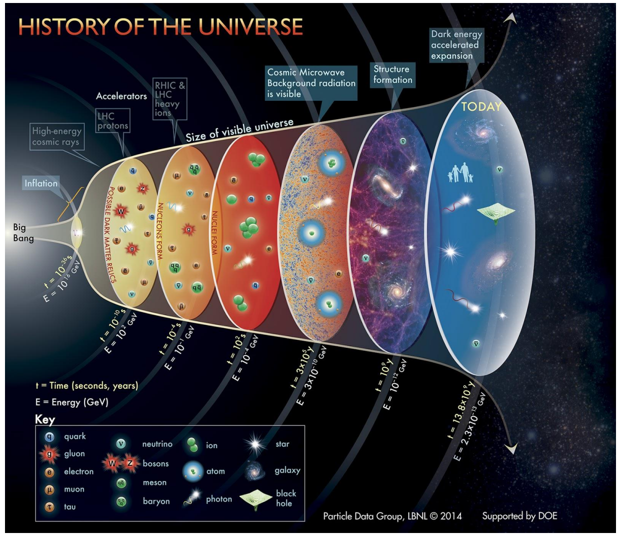
Tamas Szalay,
Volker Springel,
Gerard Lemson

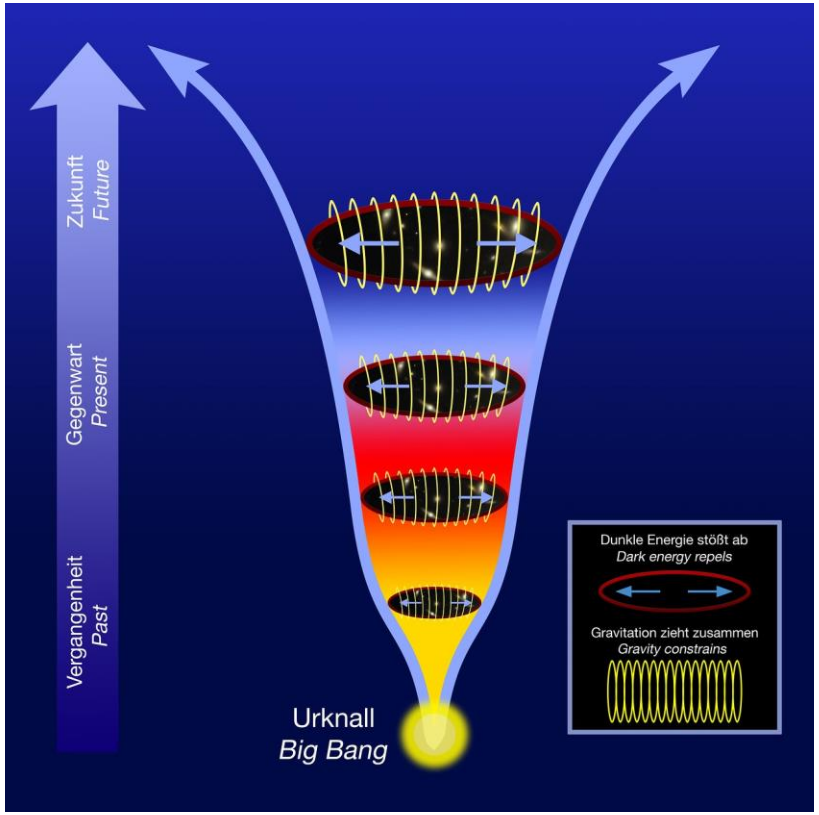
Linking largest and smallest scales

… points at unknown particle physics “Beyond the Standard Model” (BSM)

Most striking:

- We need extra “dark” matter to explain structure and dynamics of the universe on all scales larger than about 1,000 lightyears.
  This matter is not made out of stuff we know.
- At present, the universe is expanding with accelerating speed, driven by a “dark energy”.
  This energy is not made out of stuff we know.



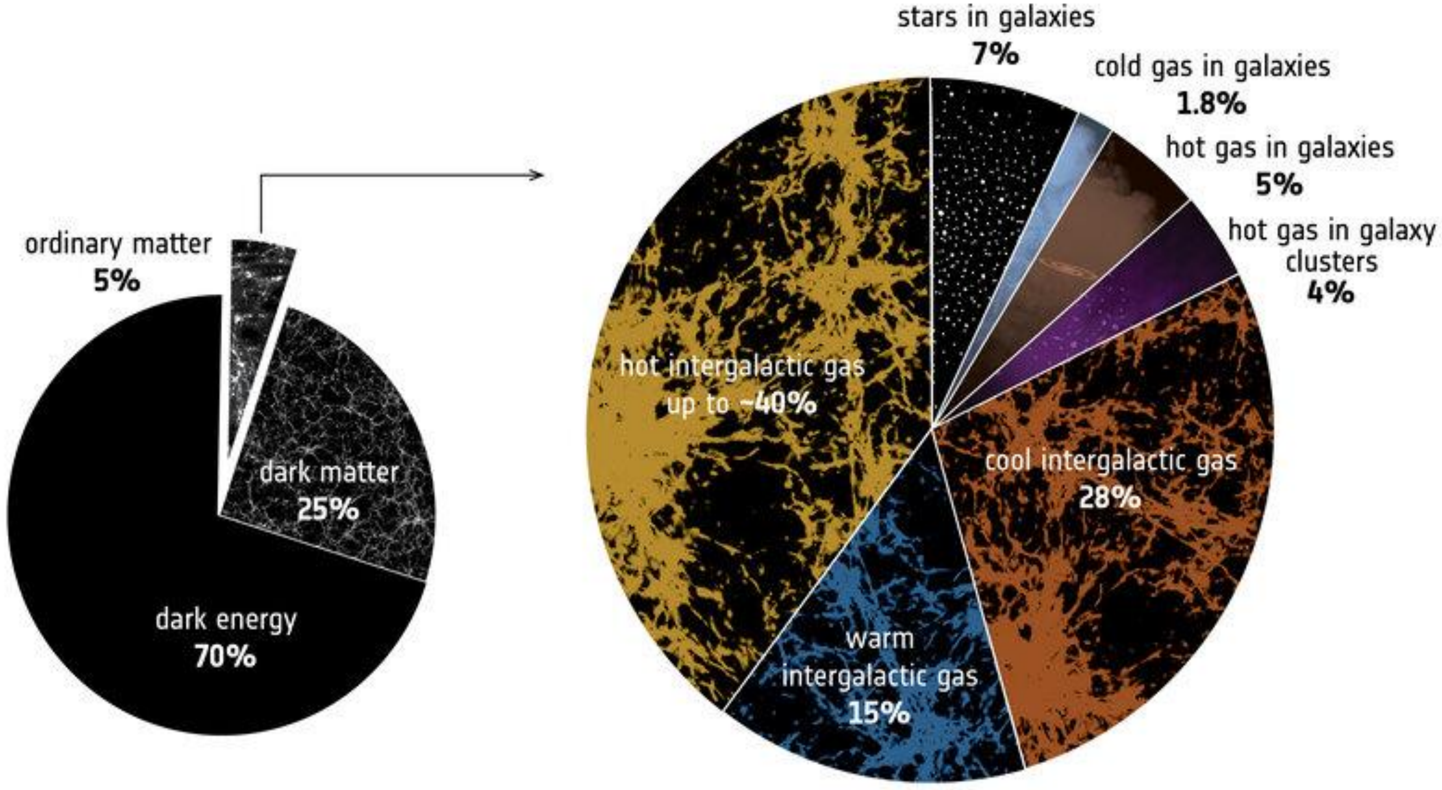


Linking largest and smallest scales

… points at unknown particle physics “Beyond the Standard Model” (BSM)

Most striking:

- The standard model of particle physics explains about 5% of the universe only.

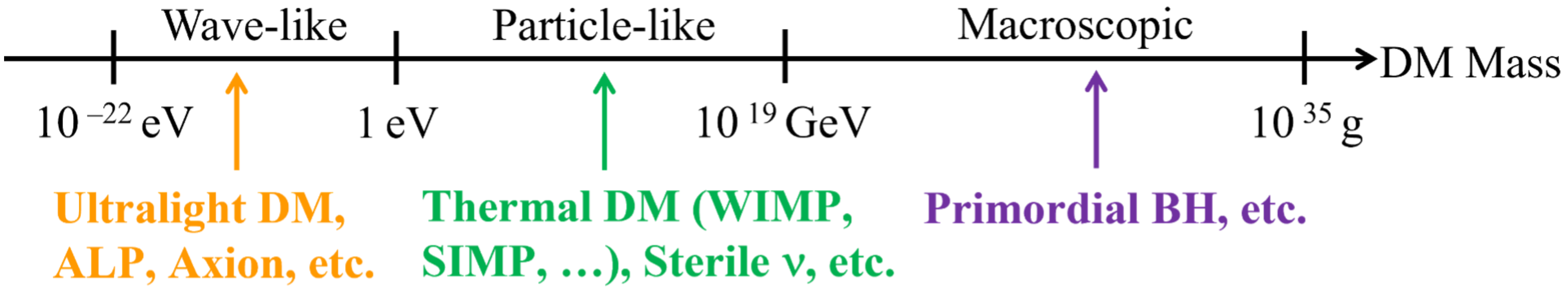



DARK MATTER
GRAVITINO
PROTON
PHOTON
e
e
e-
AXION
AXION
NEUTRALINO
NEUTRINO
DARK ELECTRONS
MUON
NEUTRON
QUARK
VISIBLE MATTER
Wimp
DARK NEUTRON

Dark matter candidates

A huge candidate parameter region!

https://member.ipmu.jp/shigeki.matsumoto/index.html



De Broglie wavelength: $\lambda = h/p$

with v=250 km/s

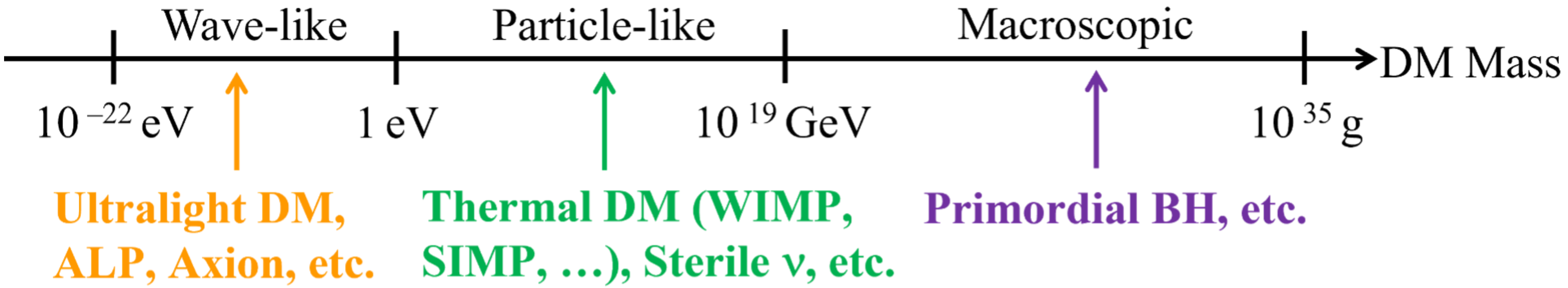
λ(m=1GeV) = $1.5 \cdot 10^{-12}$ m
λ(m=1eV) = 1.5 mm
λ(m=10^{-22} eV) = 1500 lightyears

λ(m=$1.6 \cdot 10^{-30}$ eV) = $93 \cdot 10^{9}$ lightyears (diameter of the observable universe)
λ(m=$6.5 \cdot 10^{-33}$ eV) = $23 \cdot 10^{12}$ lightyears (diameter of the universe?)

Lightweight dark matter candidates

Mass < 1eV

https://member.ipmu.jp/shigeki.matsumoto/index.html



This presentation:

- Axions and
  axion-like particles (ALPs).
- No general introduction and overview on other activities elsewhere.
- Not much on theory. Sorry!

Remark:

Most of the axion / ALP searches are also sensitive to other light bosons like dark photons.

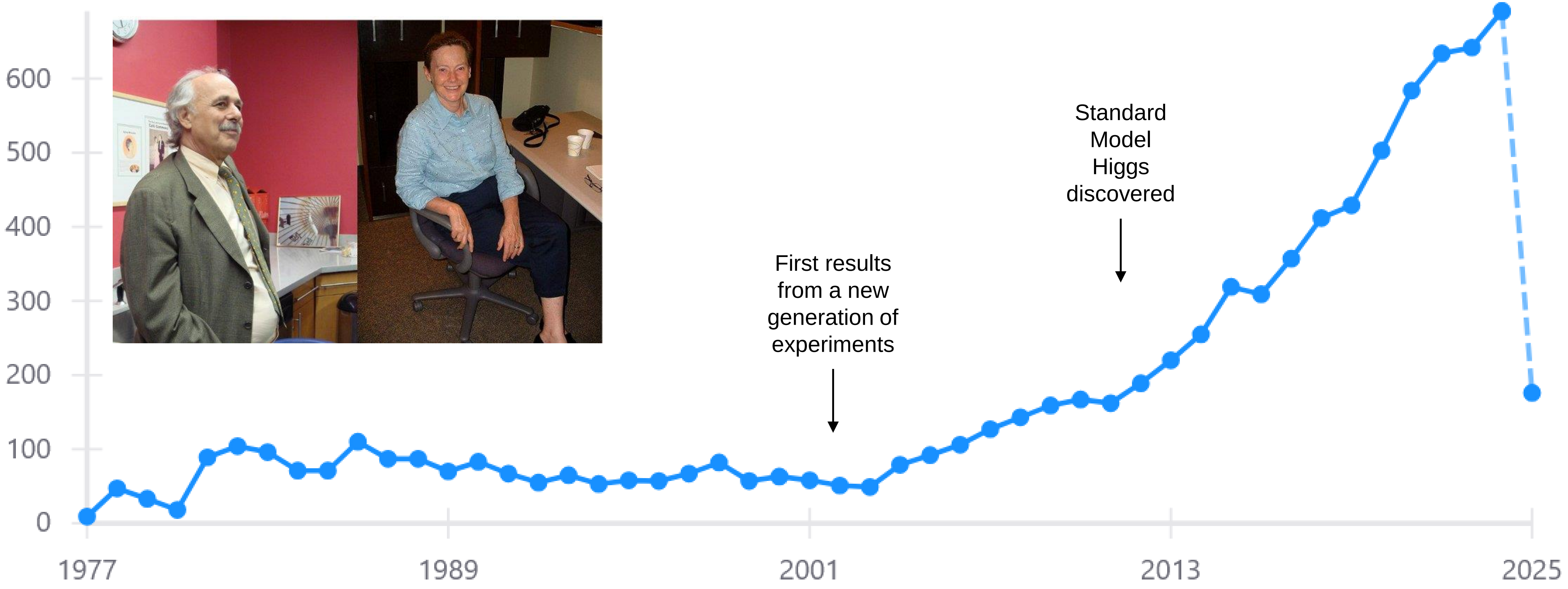
To confuse you:
ALPS is an experiment searching (also) for ALPs.

Word-wide interest in axions …

… ever rising!

https://inspirehep.net as of 26 April 2025

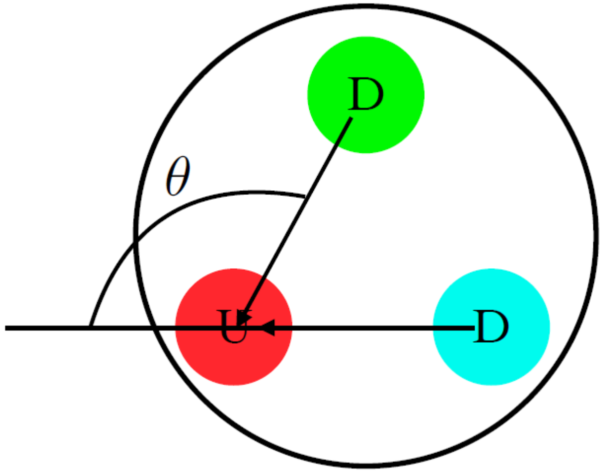
Citations per year of “CP Conservation in the Presence of Instantons” (Peccei, Quinn)



Axions

Particle physics motivation

- Axions: to solve the riddle of CP-conservation in QCD or
  the missing static electric dipole moments (EDM) of nucleons.



https://arxiv.org/abs/1812.02669

Theory: $EDM_{neutron} = \theta \cdot 3{\cdot}10^{-16}$ e·cm

Experiments: $EDM_{neutron} < 3{\cdot}10^{-26}$ e·cm; $\theta < 10^{-10}$

QCD conserves CP!

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https://arxiv.org/abs/1812.02669

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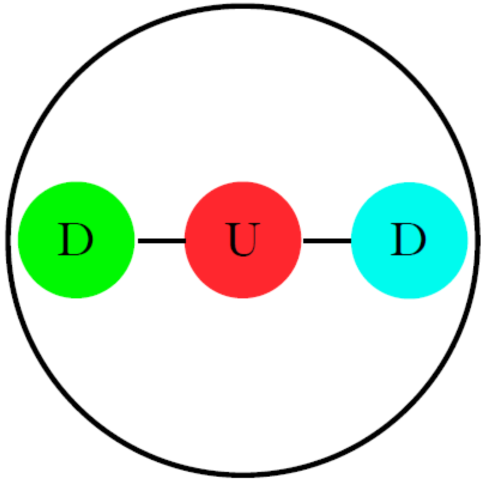
Experiments: $EDM_{neutron} < 3{\cdot}10^{-26}$ e·cm; $\theta < 10^{-10}$

QCD conserves T symmetry!

The three quarks are perfectly aligned!



Peccei-Quinn symmetry …

… and a new elementary particle!

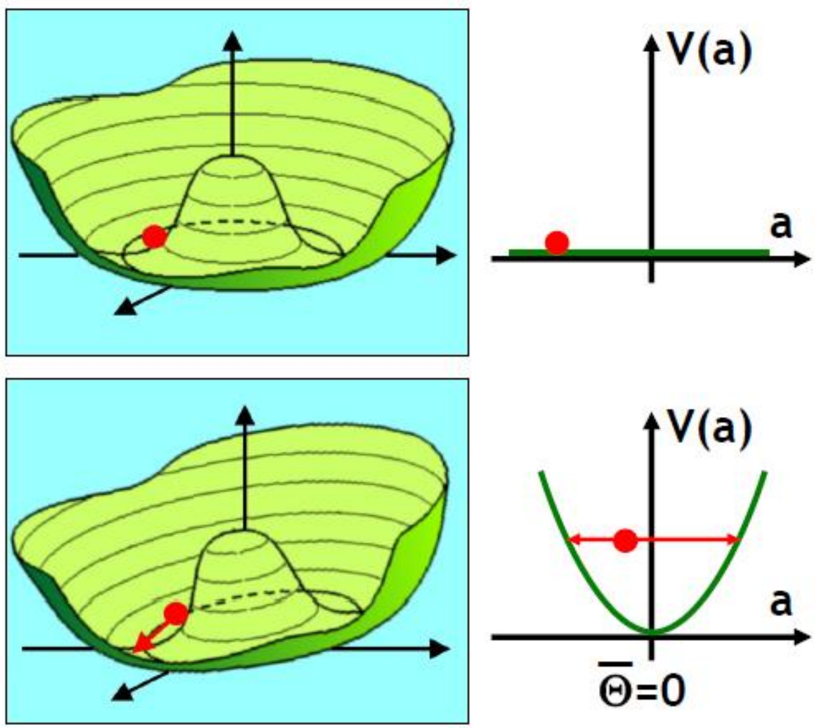
Idea: if θ is not a fixed value, but an evolving field, it relaxes to zero by QCD instanton effects.

Peccei-Quinn symmetry:

- Global U(1), complex scalar field.
- Spontaneously broken at very high energies: a massless Goldstone boson should exist. This is the axion.
- QCD instanton effects explicitly break the axion (a) symmetry, so that it becomes inexact at QCD energies. The axion acquires mass.

  If θ = 0 by the Peccei-Quinn mechanism, an axion should exist!

- The Peccei-Quinn symmetry breaking should have happened also in the early universe potentially producing dark matter axions.



S. Hannestad, presentation at 5th Patras Workshop 2009

Word-wide interest in axions …

… due to a unique physics case.

The discovery of an axion could

- solve fundamental questions of particle physics,
- solve the riddles of cosmological dark matter and/or dark energy,
- relax tensions in modelling star evolutions and the propagation of high energy photons in the universe.

Axions and axion-like particles are expected

- by string-theories (uniting particle physics and gravitation),
- to provide insight into particle physics at highest energies
  beyond the reach of any colliders.

Axions and axion-like particles could serve as new probes

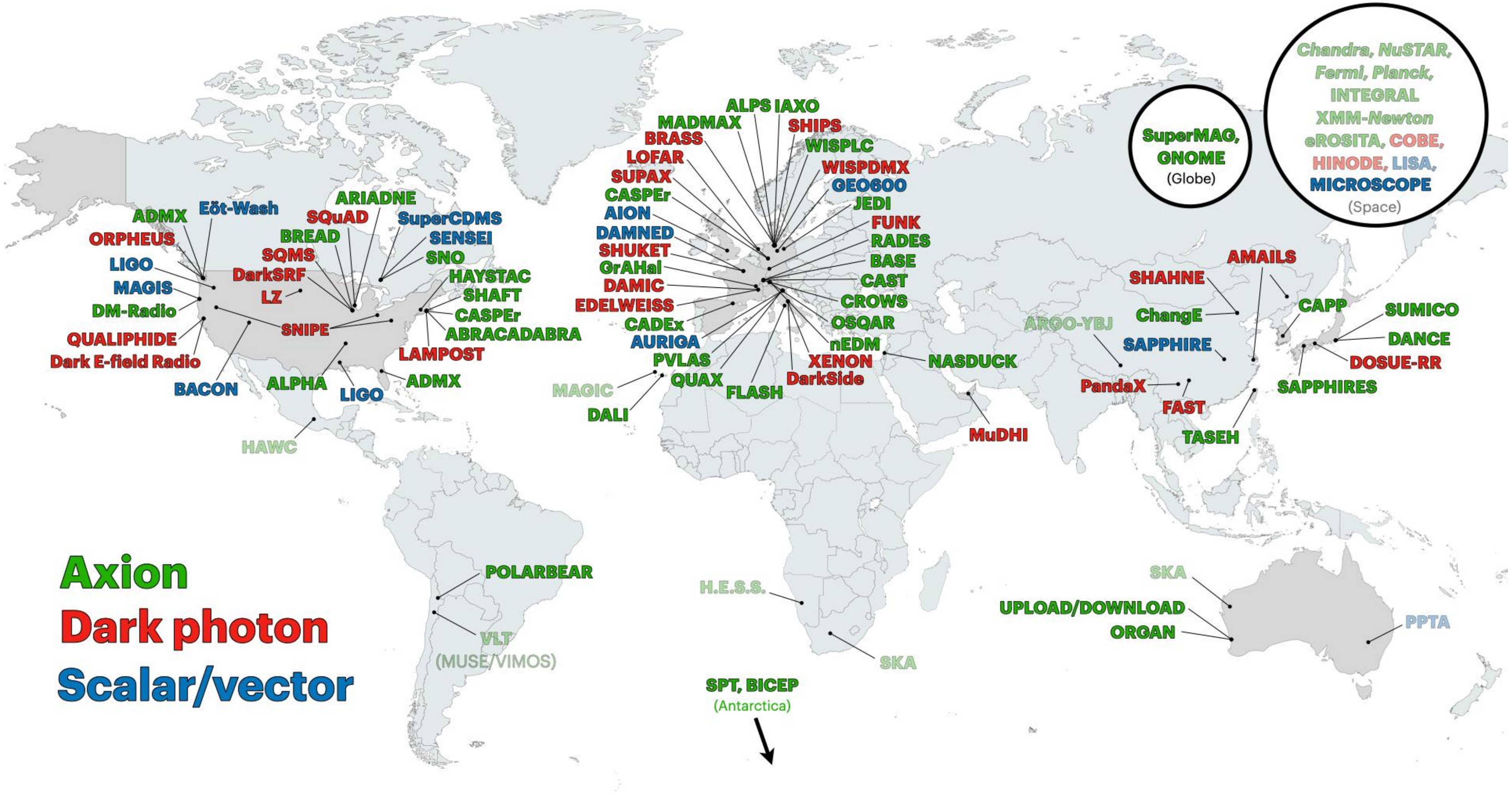
- to understand the Sun, supernovae and/or the history of the milky way.

Word-wide interest in axions …

… due to new experimental technologies.

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

more experiments to be added …

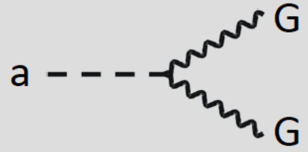


Axions

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)	$m_a = \frac{\sqrt{m_u m_d}}{m_u + m_d} \frac{m_\pi}{f_\pi^{-1} f_a} \approx \frac{6\ \mu\mathrm{eV}}{f_a/10^{12}\ \mathrm{GeV}}$

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

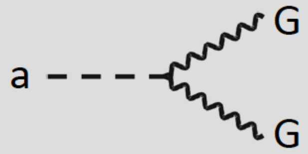
Axions

Couplings to the SM

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

There might be more couplings to Standard Model constituents.

These couplings depend on the BSM models incorporating an "invisible axion".
Also axion-like particles (ALPs) could show photon couplings.

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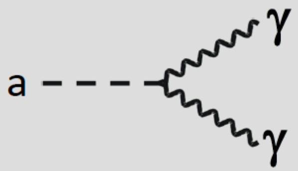
Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$ 

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

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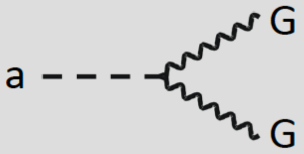
Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
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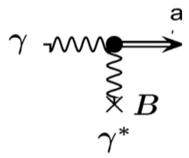
Photon coupling	In a background magnetic field: axion⟺ photon mixing	

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

Axions

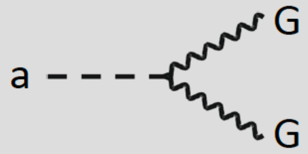
Couplings to the SM

Axions are a consequence of the Peccei-Quinn symmetry to explain $\theta=0$.

There might be more couplings to Standard Model constituents.

These couplings depend on the BSM models incorporating an “invisible axion”.
Also axion-like particles (ALPs) could show photon couplings.

Pion, nucleon and/or electron couplings depend on the specific axion models (and might give a handle to discriminate between models).

Gluon coupling (generic)	$\mathcal{L}_{aG} = \frac{\alpha_s}{8\pi f_a} G\tilde{G}a$	
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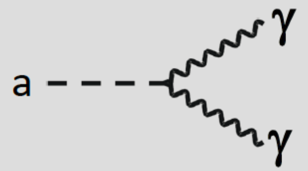
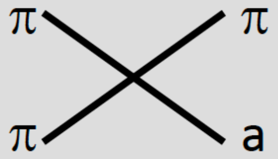
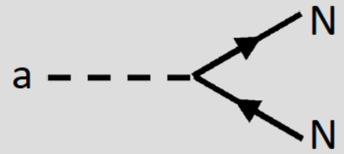
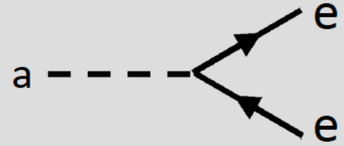
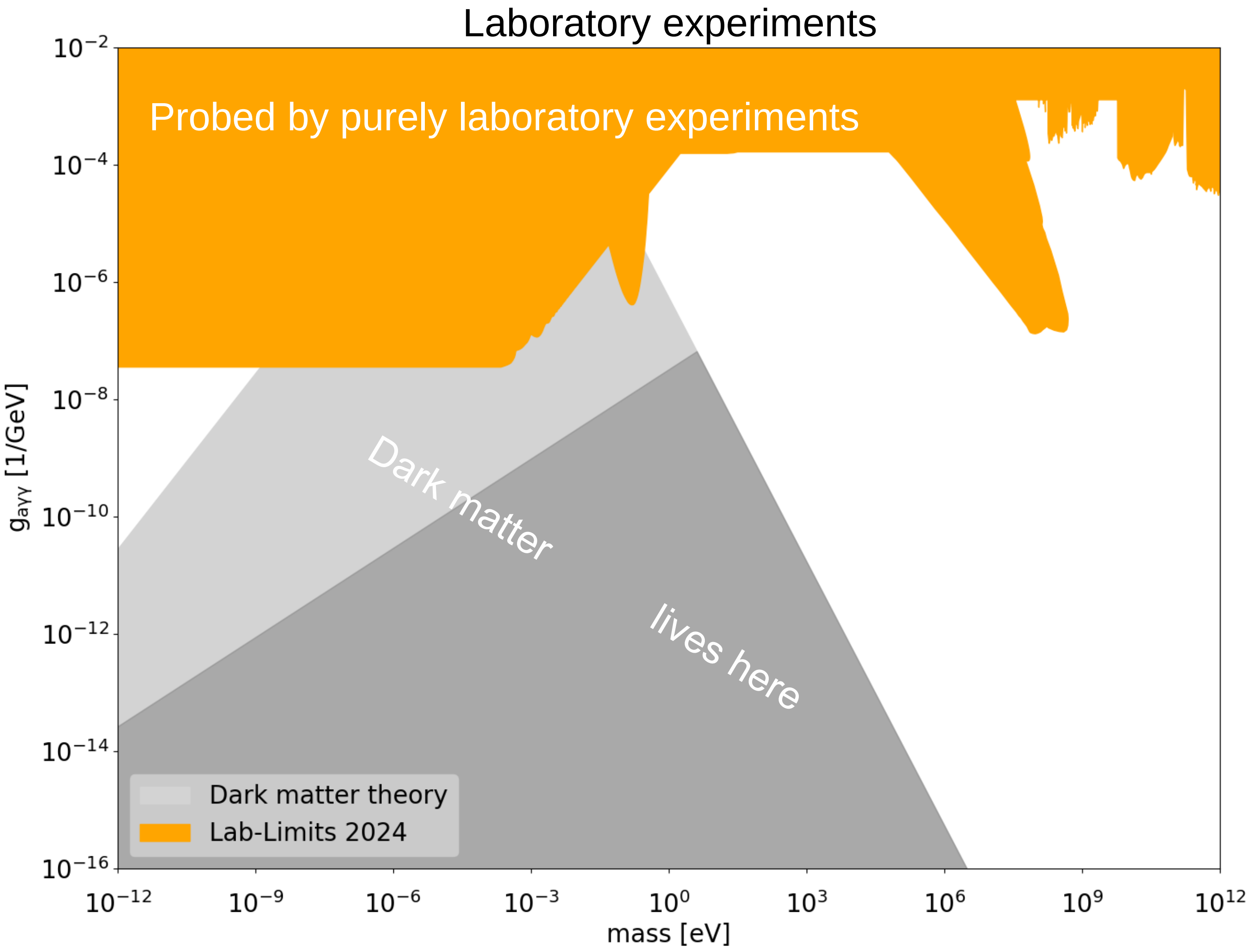
Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\,\mathbf{E}\cdot\mathbf{B}\,a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	
Pion coupling	$\mathcal{L}_{a\pi} = \frac{C_{a\pi}}{f_\pi f_a}(\pi^0\pi^+\partial_\mu\pi^- + \cdots)\partial^\mu a$	
Nucleon coupling (axial vector)	$\mathcal{L}_{aN} = \frac{C_N}{2f_a}\bar{\Psi}_N\gamma^\mu\gamma_5\Psi_N\partial_\mu a$	
Electron coupling (optional)	$\mathcal{L}_{ae} = \frac{C_e}{2f_a}\bar{\Psi}_e\gamma^\mu\gamma_5\Psi_e\partial_\mu a$	

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

Hypothetical light bosons for BSM physics



Axion and axion-like particle dark matter:

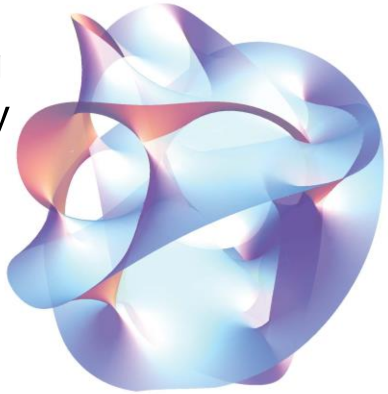
Group G. Servant:
ALP dark matter from kinetic fragmentation
JCAP 10 (2022) 053

Group A. Ringwald:
WISPy cold dark matter
JCAP 06 (2012) 013

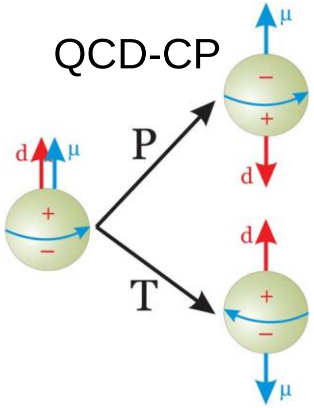
Hypothetical light bosons for BSM physics

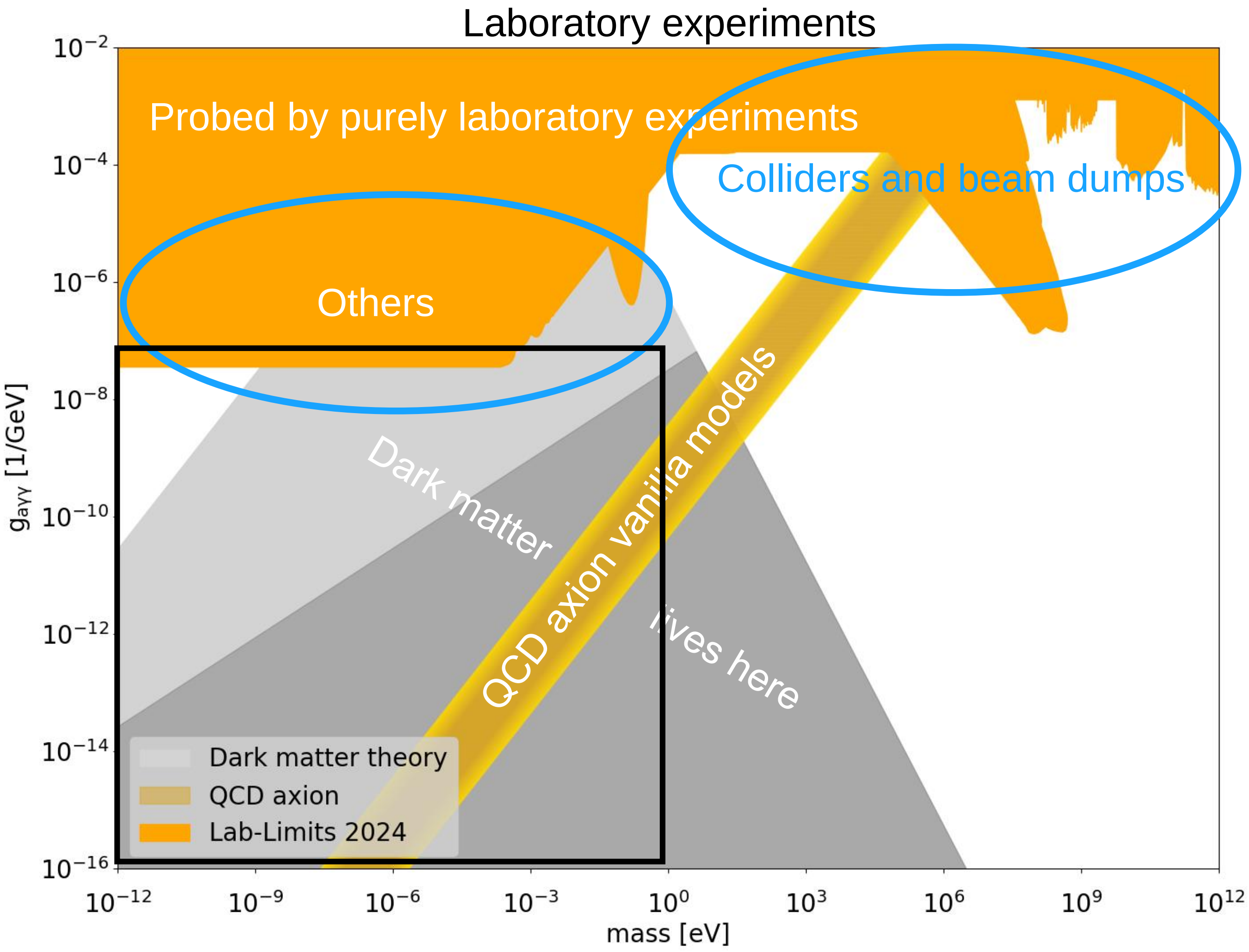
Most interesting parameter space out of reach at colliders

String theory



QCD-CP





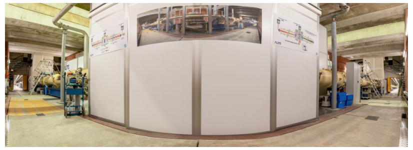
The DESY strategy

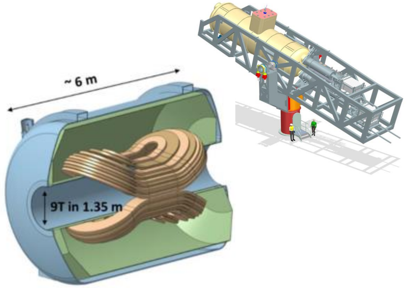
Hypothetical light bosons for BSM physics

Mass range < 1 eV.

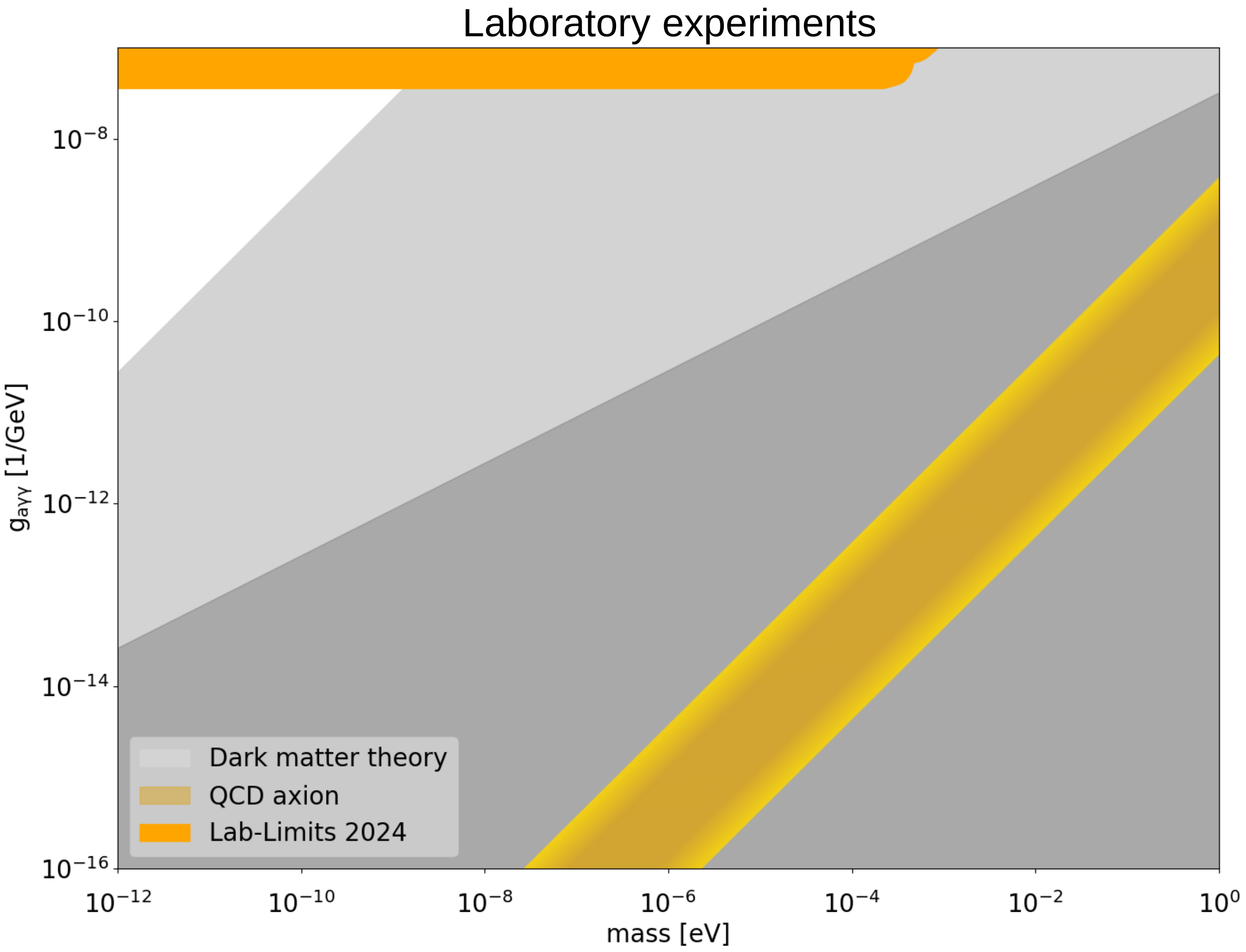
Three different experiments @ DESY:

- ALPS II
- BabyIAXO
- MADMAX





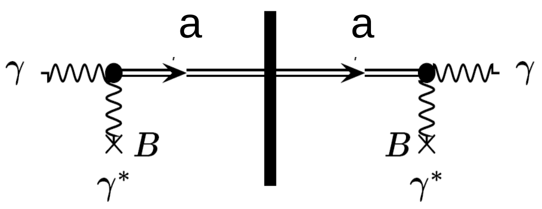
Two new experimental platforms:
- Cryoplatform
- Cryogenic quantum sensing



The DESY strategy

Complementing approaches … and a dream for the next decade

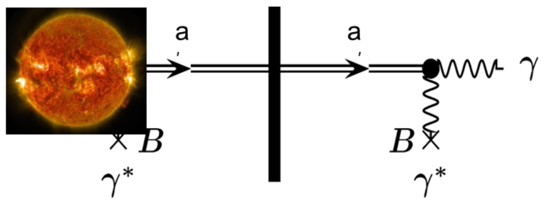
1. Probe for axions / ALPs **without additional assumptions**:



Establish the existence of light bosons beyond the SM, measure $g_{a\gamma\gamma}$.

World-wide lead

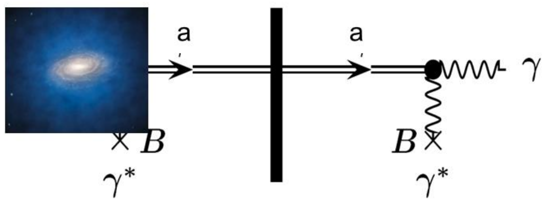
2. Probe for axions with minimal additional assumptions, **increase the reach**:



Measure the sun‘s axion luminosity (knowing $g_{a\gamma\gamma}$) and narrow done on the BSM theory.

World-wide lead

3. Probe for **axions as dark matter constituents** in a mass range not accessible by current experiments:



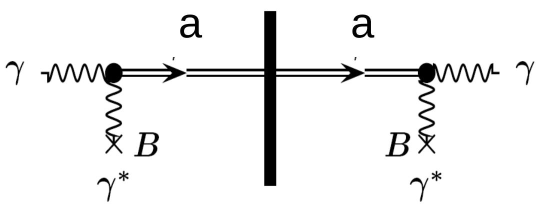
Light bosons make up the dark matter in our galaxy.

Complementing the mass reach of other experiments

Why at DESY?

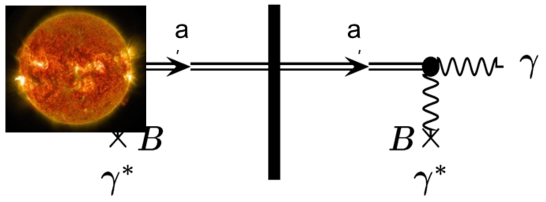
Existing infrastructure and cutting edge technologies

1. Probe for axions / ALPs **without additional assumptions**:



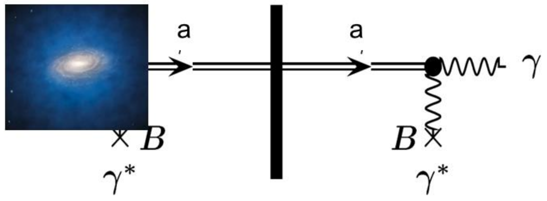
HERA tunnel, magnets, cryogenics + high-precision long-baseline interferometry

2. Probe for axions with minimal additional assumptions, **increase the reach**:



HERA hall, CTA-MST prototype + new magnet design, X-ray optics, extremely low-noise detectors

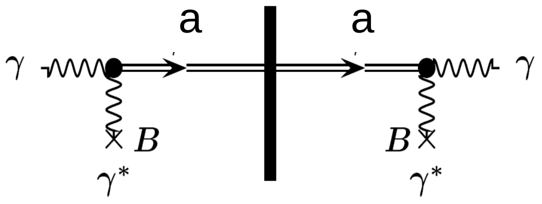
3. Probe for **axions as dark matter constituents** in a mass range not accessible by current experiments.



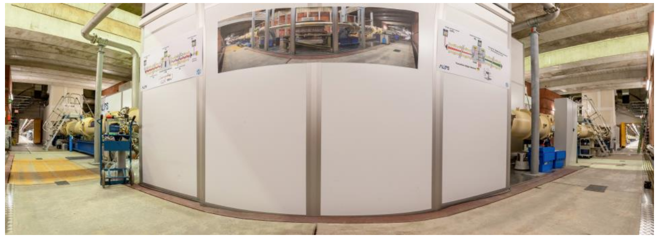
HERA hall, H1 iron yoke, cryogenics + new magnet design, new detector concept

The DESY strategy
Complementary on-site experiments

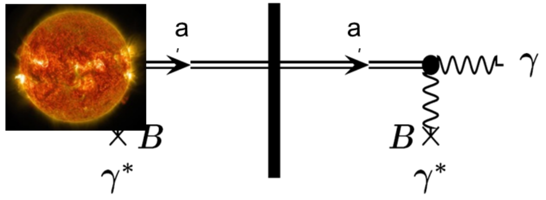
1. Probe for axions / ALPs without additional assumptions:



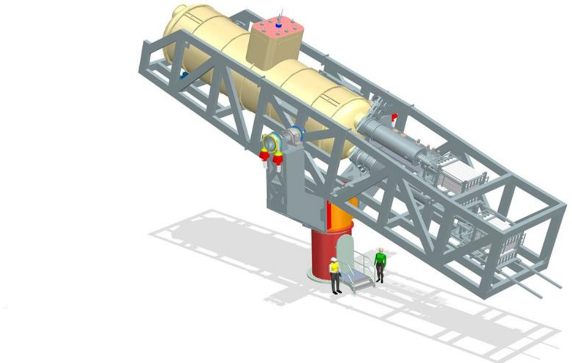
ALPS II
taking data



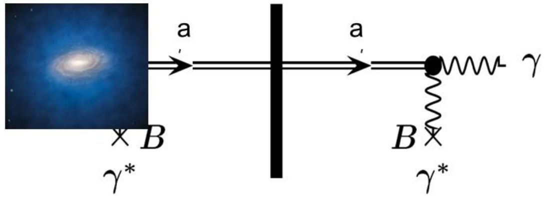
2. Probe for axions with minimal additional assumptions, increase the reach:



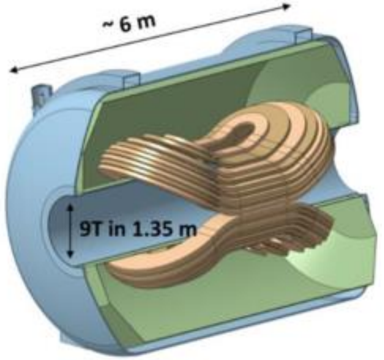
BabyIAXO
(nearly) ready to start construction



3. Probe for axions as dark matter constituents in a mass range not accessible by current experiments.



MADMAX
physics results from prototypes



The DESY strategy

Complementary on-site experiments

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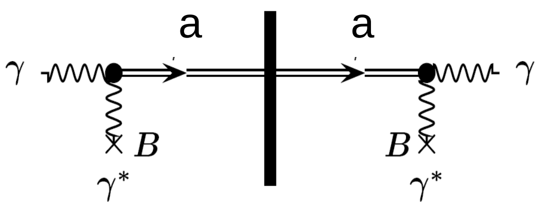
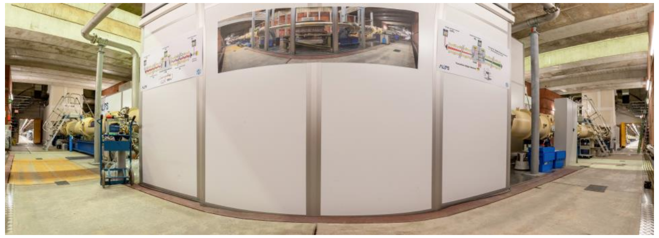


ALPS II
taking data



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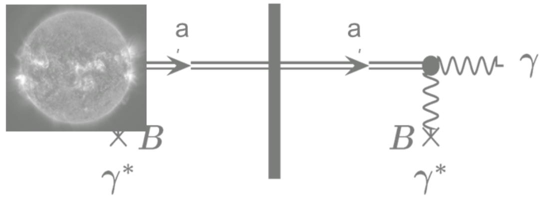

BabyIAXO
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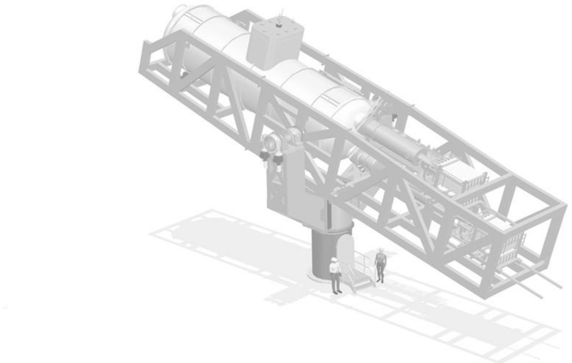
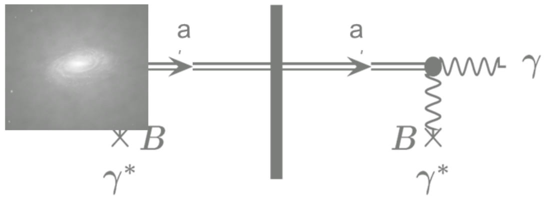
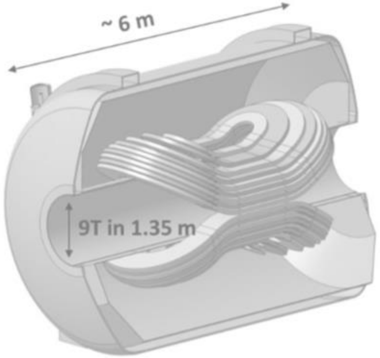


3. Probe for axions as dark matter constituents in a mass range not accessible by current experiments.

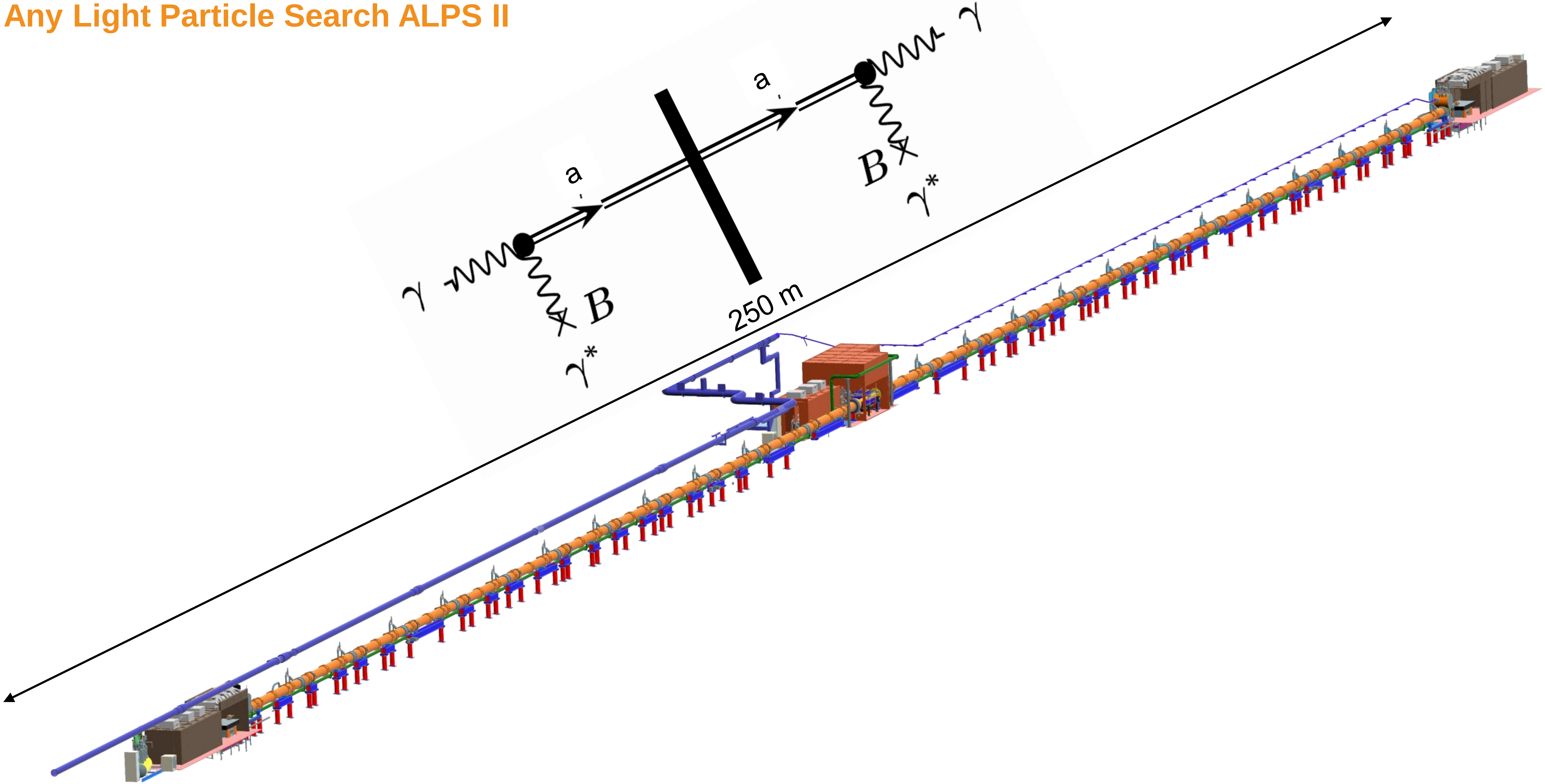


MADMAX
physics results from prototypes



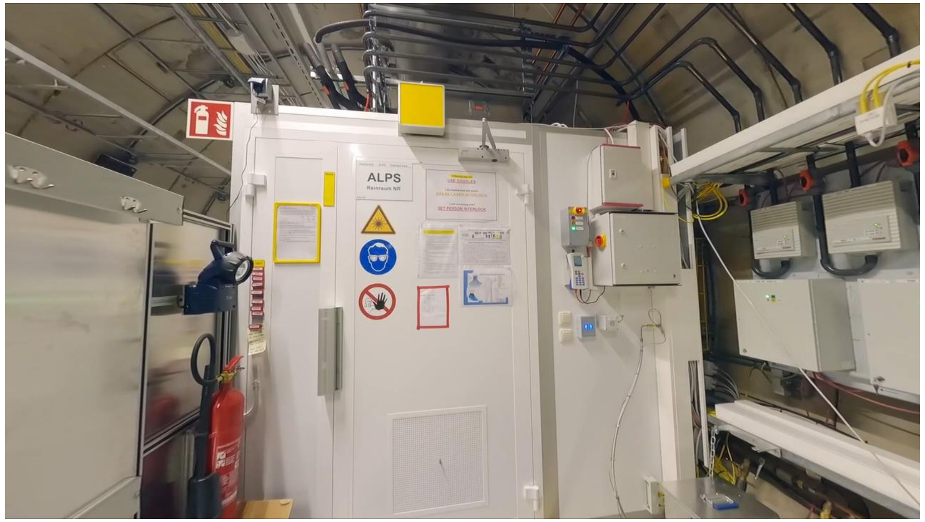
Generate and detect dark matter bosons

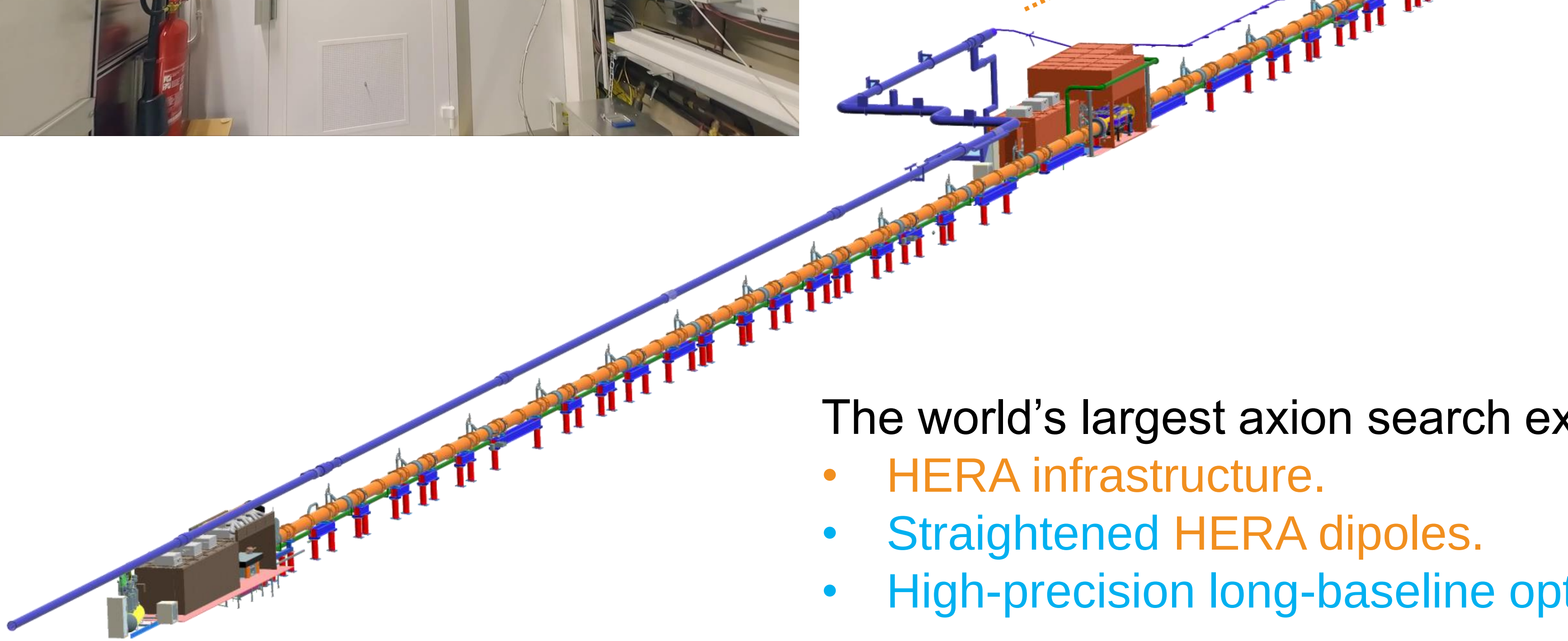
Any Light Particle Search ALPS II



Generate and detect dark matter bosons

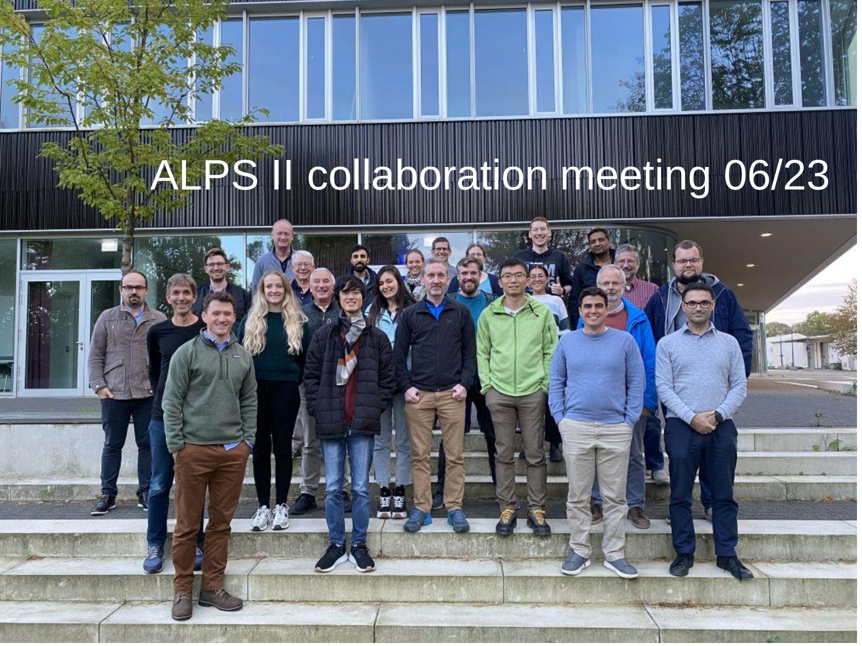
Any Light Particle Search ALPS II





The world's largest axion search experiment:

- HERA infrastructure.
- Straightened HERA dipoles.
- High-precision long-baseline optical interferometry.



Collaboration members

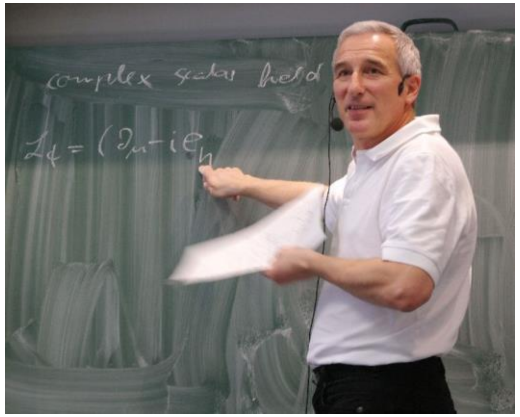
ALPS II

Supported by

Any Light Particle Search II

Founding father (among others)

Andreas Ringwald sparked the interest for new local particle physics experiments at DESY.



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Physics Letters B 569 (2003) 51–56

PHYSICS LETTERS B

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Production and detection of very light bosons in the HERA tunnel

A. Ringwald

Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

Received 17 June 2003; accepted 3 July 2003

Editor: P.V. Landshoff

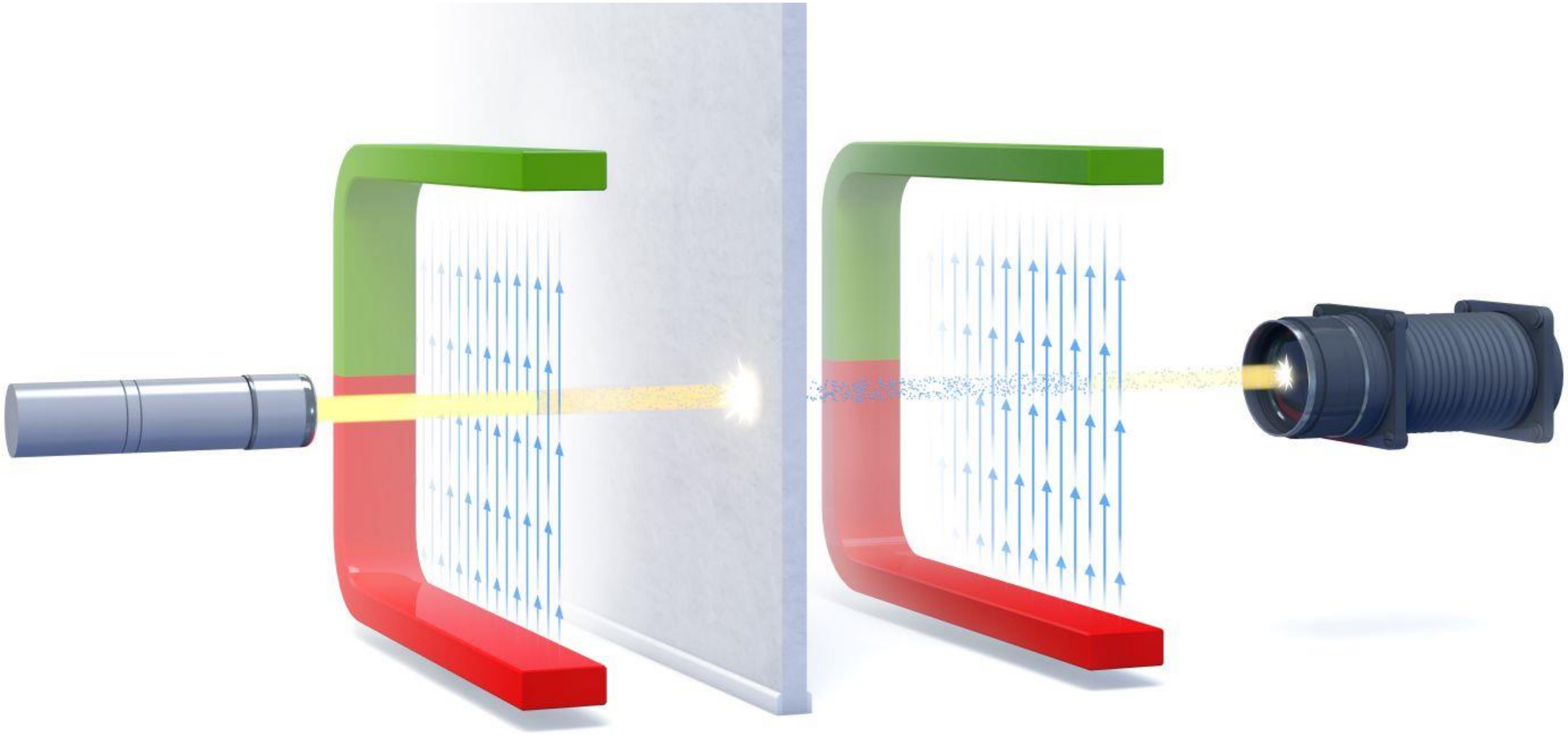
Abstract

There are strong theoretical arguments in favour of the existence of very light scalar or pseudoscalar particles beyond the Standard Model which have, so far, remained undetected, due to their very weak coupling to ordinary matter. We point out that after HERA has been decommissioned, there arises a unique opportunity for searches for such particles: a number of HERA's four hundred superconducting dipole magnets might be recycled and used for laboratory experiments to produce and detect light neutral bosons that couple to two photons, such as the axion. We show that, in this way, laser experiments searching for photon regeneration or polarization effects in strong magnetic fields can reach a sensitivity which is unprecedented in pure laboratory experiments and exceeds astrophysical limits from stellar evolution considerations.

In a later stage, one may think on deploying all 400 decommissioned HERA dipole magnets ($2\ell \approx 4000$ m) in the 4 km long TESLA XFEL tunnel at DESY, in which after 2010 a superconducting linear accelerator will run to provide high-quality electron bunches for the X-ray free electron lasers (XFELs) in a dedicated laboratory [24] (cf. Fig. 4). The corresponding sensitivity, $g_{A\gamma} \lesssim 9 \times 10^{-12}$ GeV^{-1} for $m_A \lesssim 3 \times 10^{-5}$ eV (labelled "Laser in XFEL tunnel" in Fig. 1), has so far been only probed by microwave cavity searches for axions, under the assumption that they are the dominant part of the galactic cold dark matter (cf. Fig. 1).

Designing ALPS II

Axion-Photon mixing ($\Phi \leftrightarrow \gamma$)



Designing ALPS II

Axion-Photon mixing (Φ↔γ)

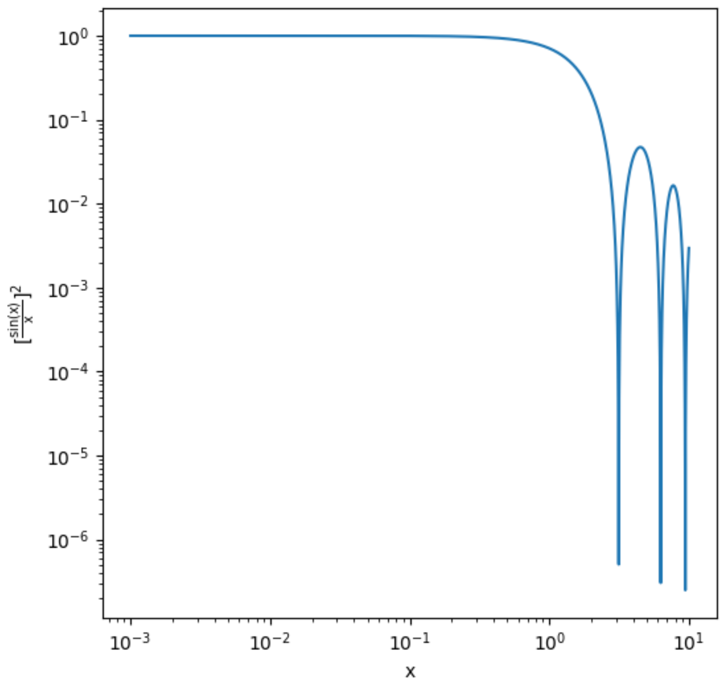
In a constant background magnetic dipole field (see https://inspirehep.net/literature/870931):

With $k_\phi = \sqrt{\omega^2 - m_\phi^2}$ $\quad q = n\omega - \sqrt{\omega^2 - m_\phi^2} \approx \omega(n-1) + \frac{m_\phi^2}{2\omega}$

$$P_{\gamma\to\phi} = P_{\phi\to\gamma} = \frac{1}{4}\frac{\omega}{k_\phi}(gBL)^2\,|F(qL)|^2$$

For a single dipole magnet: $|F_{\text{single}}(qL)| = \left|\frac{2}{qL}\sin\left(\frac{qL}{2}\right)\right|$

De-coherence between axions and light fields limits mass reach



Designing ALPS II

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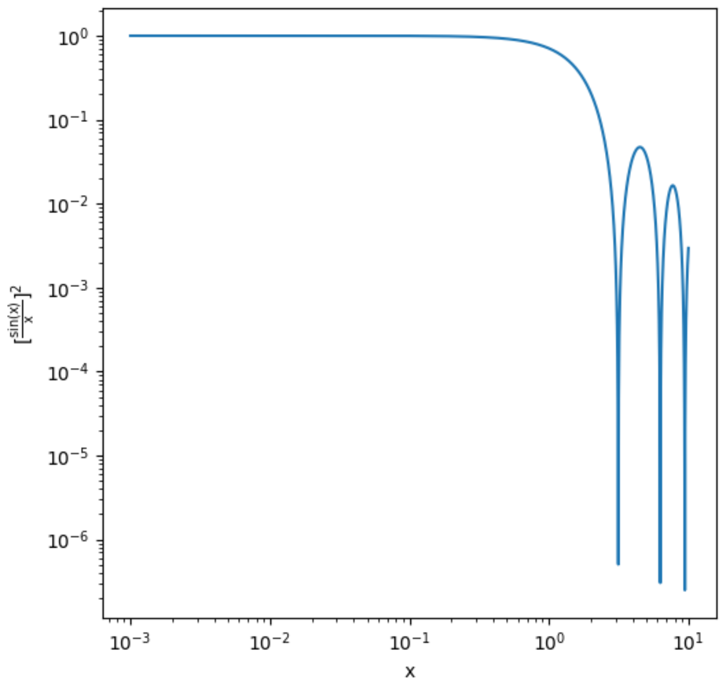


Note:

For light-shining-through-a-wall P(LSW) ~ g^4

ALPS II: strives to improve S/N by 12 orders of magnitude.

Designing ALPS II

Photon-Axion-Photon mixing

In numbers, low-mass limit (*F*=1):

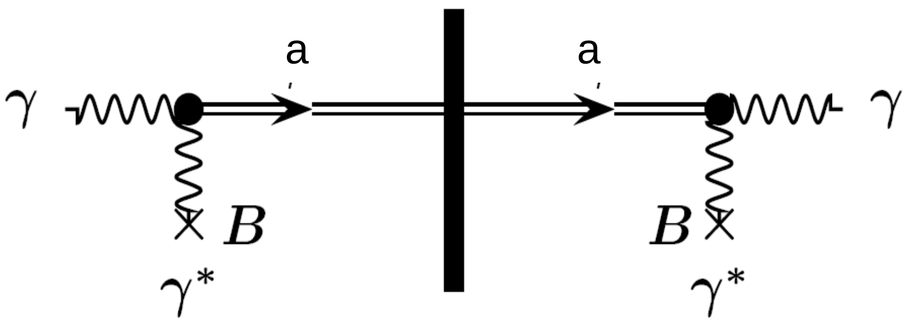
P(LSW) = (g[10^{-10} GeV^{-1}] · B[T] · L[m])^4 · $6\cdot10^{-42}$

With:

- B = 5.3 T
- L = 12 · 8.8 m
- g = $2\cdot10^{-11}$ 1/GeV

P(LSW) = 10^{-33}

Absurdly small!

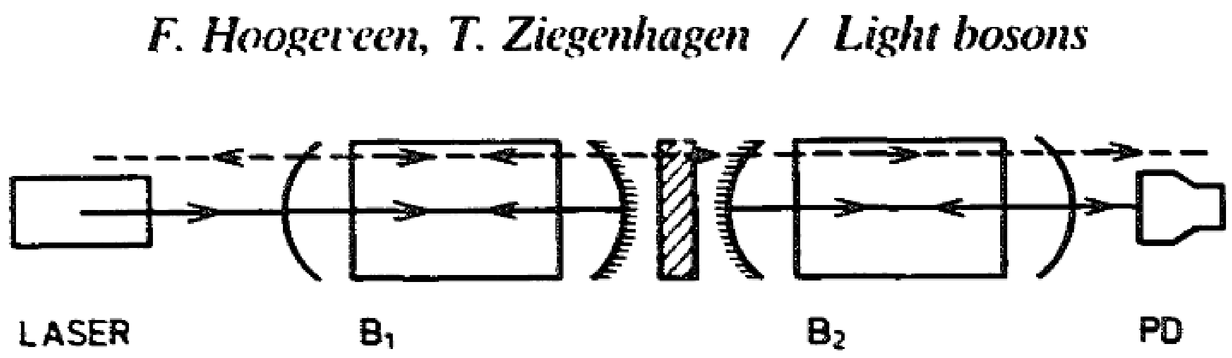


Assume a cw laser of 70 W:
one photon through the wall each 90,000 years.

Designing ALPS II

Photon-Axion-Photon mixing boosted

Resonant enhancement:



The optics concept was invented three times independently:

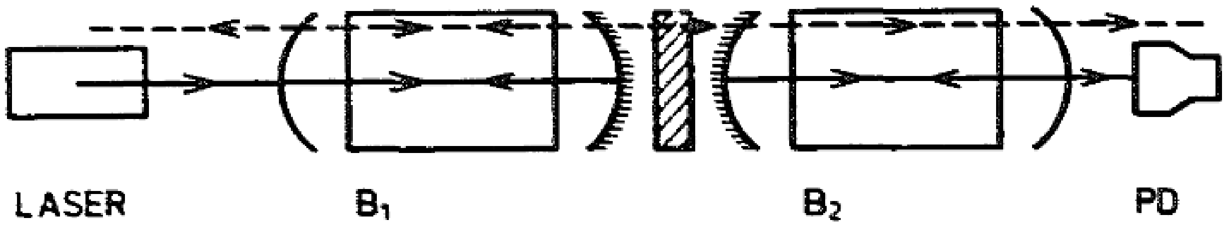
- *Hoogeveen F, Ziegenhagen T., Nucl. Phys. B358:3 (1991)*
- *Fukuda Y, Kohmoto T, Nakajima Si, Kunitomo M., Prog. Cryst. Growth Charact.Mater. 33:363 (1996)*
- *Sikivie P., Tanner D.B., van Bibber K., Phys.Rev.Lett. 98 (2007)*

Designing ALPS II

Photon-Axion-Photon mixing boosted

Resonant enhancement.

F. Hoogeveen, T. Ziegenhagen / Light bosons



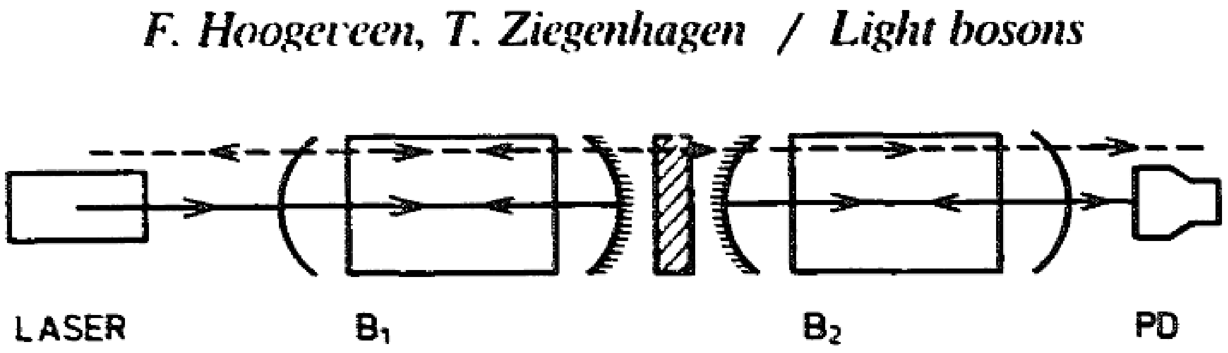
$$\frac{N_{\gamma\ \mathrm{out}}}{N_{\gamma\ \mathrm{in}}} = \frac{\Omega^2}{\Omega^2 - m_a^2}\left(\frac{g^2 B_1 B_2 L_1 L_2}{4}\right)^2 |F_1(q)|^2 F_2(q)|^2 |G_1|^2 |G_2|^2$$

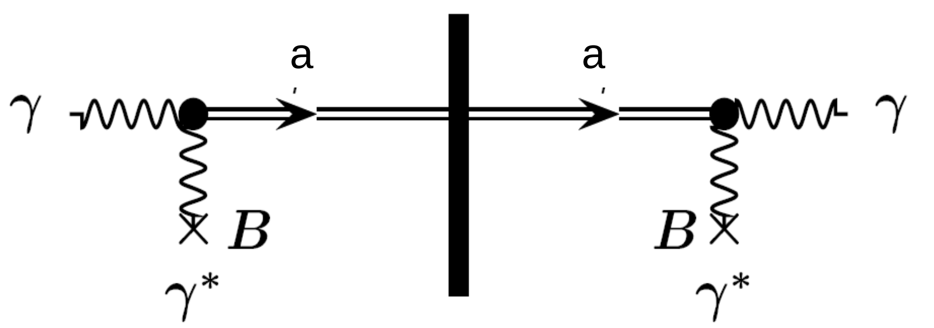
Could be $O(10^3)$ to $O(10^4)$ each!

Designing ALPS II

Photon-Axion-Photon mixing boosted

Resonant enhancement.





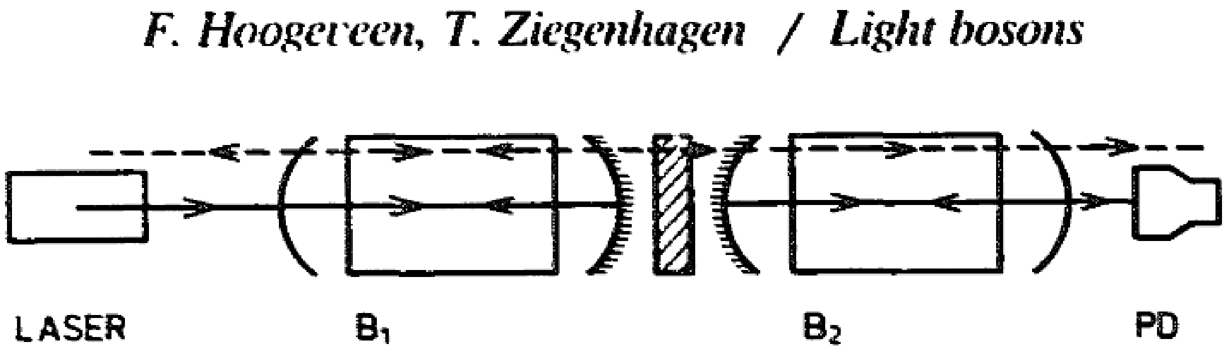
One photon through the wall each 90,000 years
boosted by 1,000·10,000
equals 0.3 photons per day!

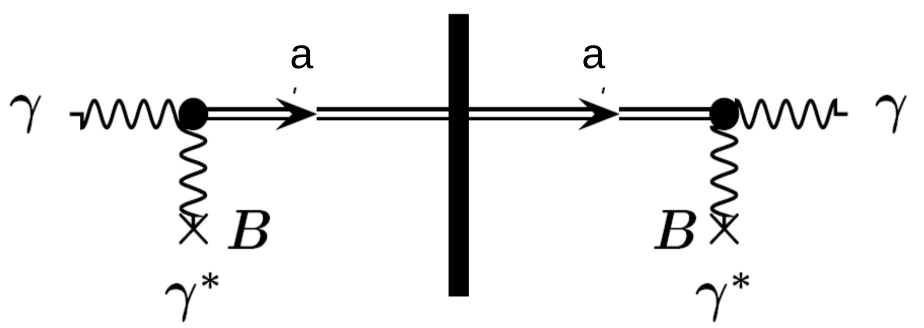
We have a plan!

Designing ALPS II

Photon-Axion-Photon mixing boosted

Resonant enhancement.





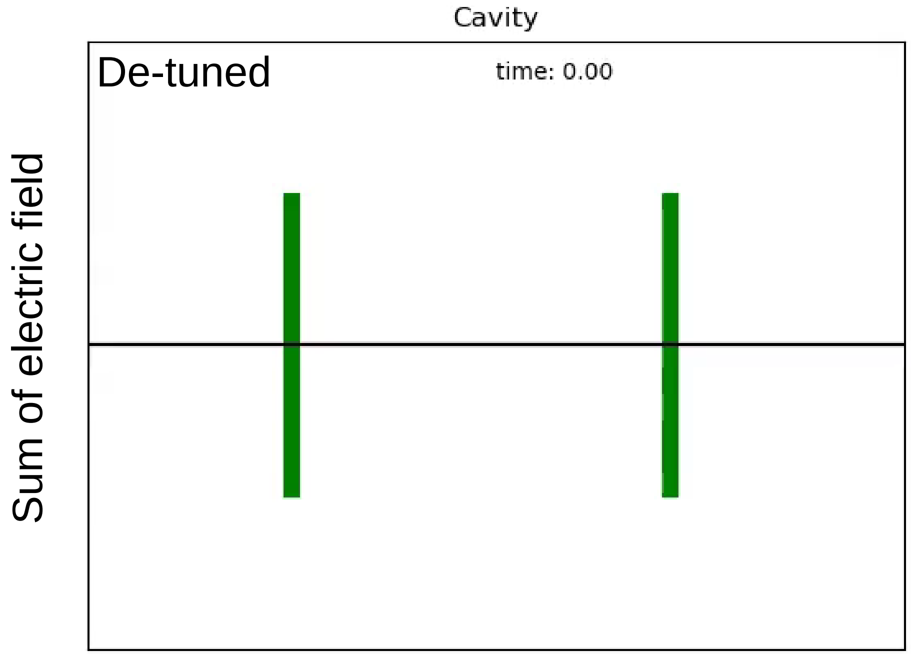
One photon through the wall each 90,000 years
boosted by 1,000·10,000
equals 0.3 photons per day!

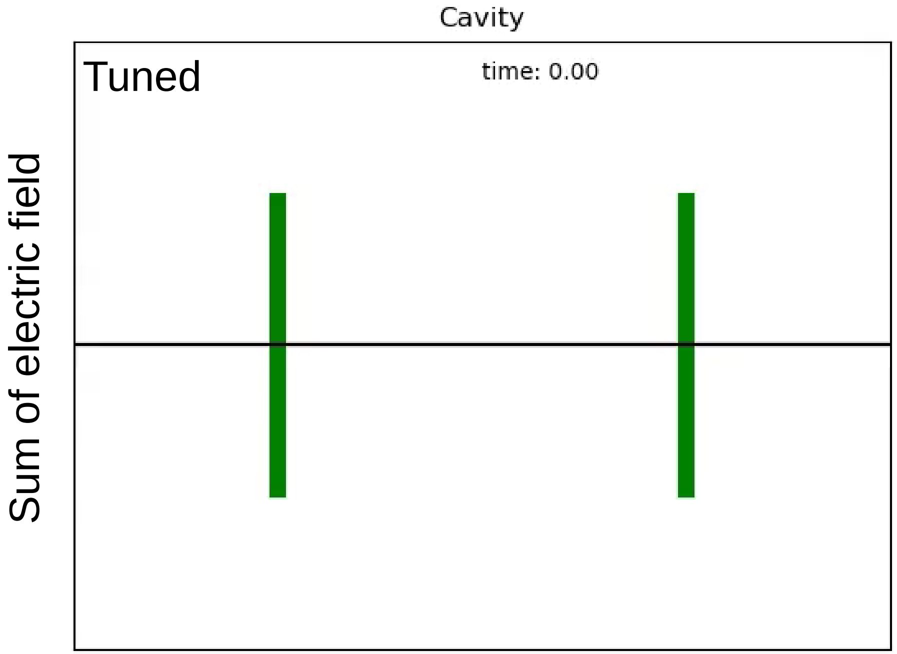
Maybe there is a reason why this has not been realized since 1991 …

ALPS II Optics

Optical resonators

Two semitransparent mirrors, 80% reflection in the animation.





Tuned:

- The electric field is amplified between the mirrors.
- ALPS II: power build-up factor up to 40,000, requiring pm length control.

ALPS II technologies

Challenges all over

- 12+12 superconducting dipole magnets
  built for the former HERA proton accelerator,
  needed to straighten the cold mass.

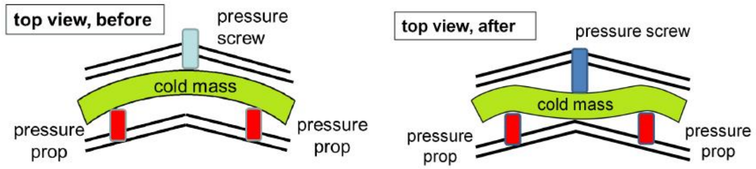
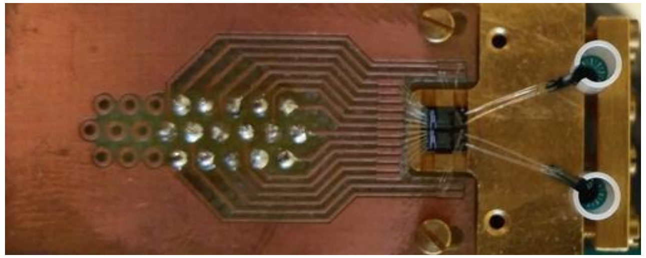


Figure 9: *Schematics of straightening. Left: Before applying the deforming force, Right: The deformation forces the pipe to develop two 'camel humps,' exaggerated in the figure for better illustration. This deformation yields the largest achievable horizontal aperture.*

Physics Letters B
Volume 689, Issues 4–5, 31 May 2010

Figure 10: *Outer pressure prop parts (left) and prop inserted into the cryostat (right).*

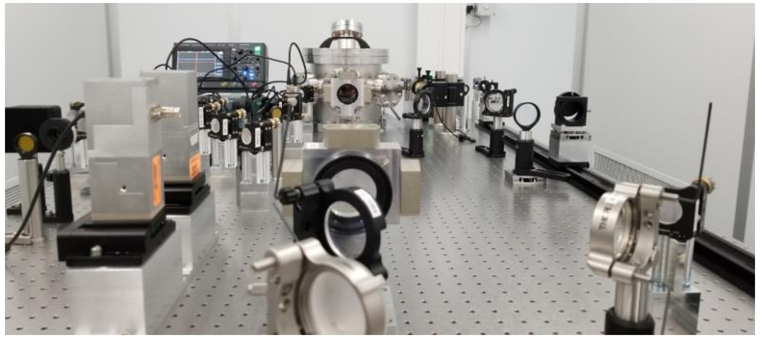
- Extremely low 1064 nm photon flux detection:
  heterodyne sensing and
  superconducting transition edge sensor (TES)



Phys.Dark Univ. 35 (2022), 100914

PoS EPS-HEP2021 (2022), 801

- Optics:
  long baseline precisions interferometry based on
  GEO600 and aLIGO experience.



Design of the ALPS II optical system,
Phys.Dark Univ. 35 (2022), 100968

Designing ALPS II

Sensitivity increase for the axion-photon coupling $g_{a\gamma\gamma}$

ALPS I in 2010
OSQAR in 2015

magnets: 24

optics: 49

photon detection: 3

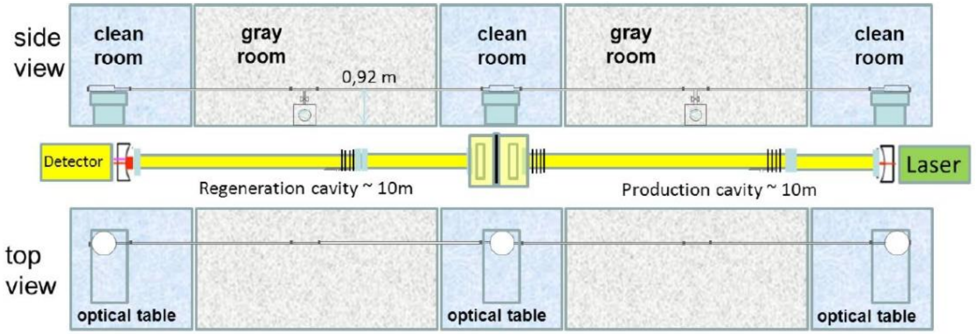
ALPS II will increase the sensitivity by three orders of magnitude.

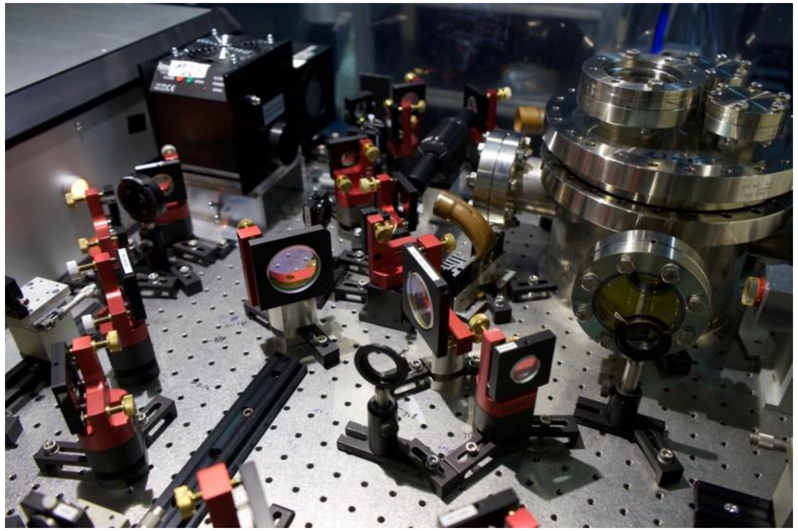
Signal-to-noise will improve by 10^{12}!

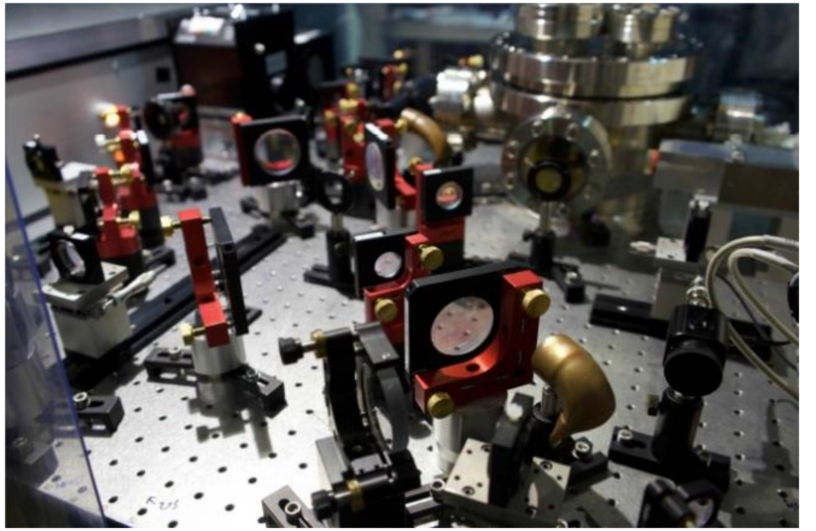
ALPS II

Optics for ALPS II

R&D in a dedicated 20 m optics lab started 2012.







- Concept heavily based on aLIGO and GEO600 experience with additional challenges:
  - Spatial coupling of any generated axion field with regeneration cavity mode.
  - Light-tightness between PC and RC.

Any Light Particle Search II

Demounting HERA: mid 2018 to mid 2019

Any Light Particle Search II

Foundations for the optics

First Magnet Fest 28 October 2019

Any Light Particle Search II

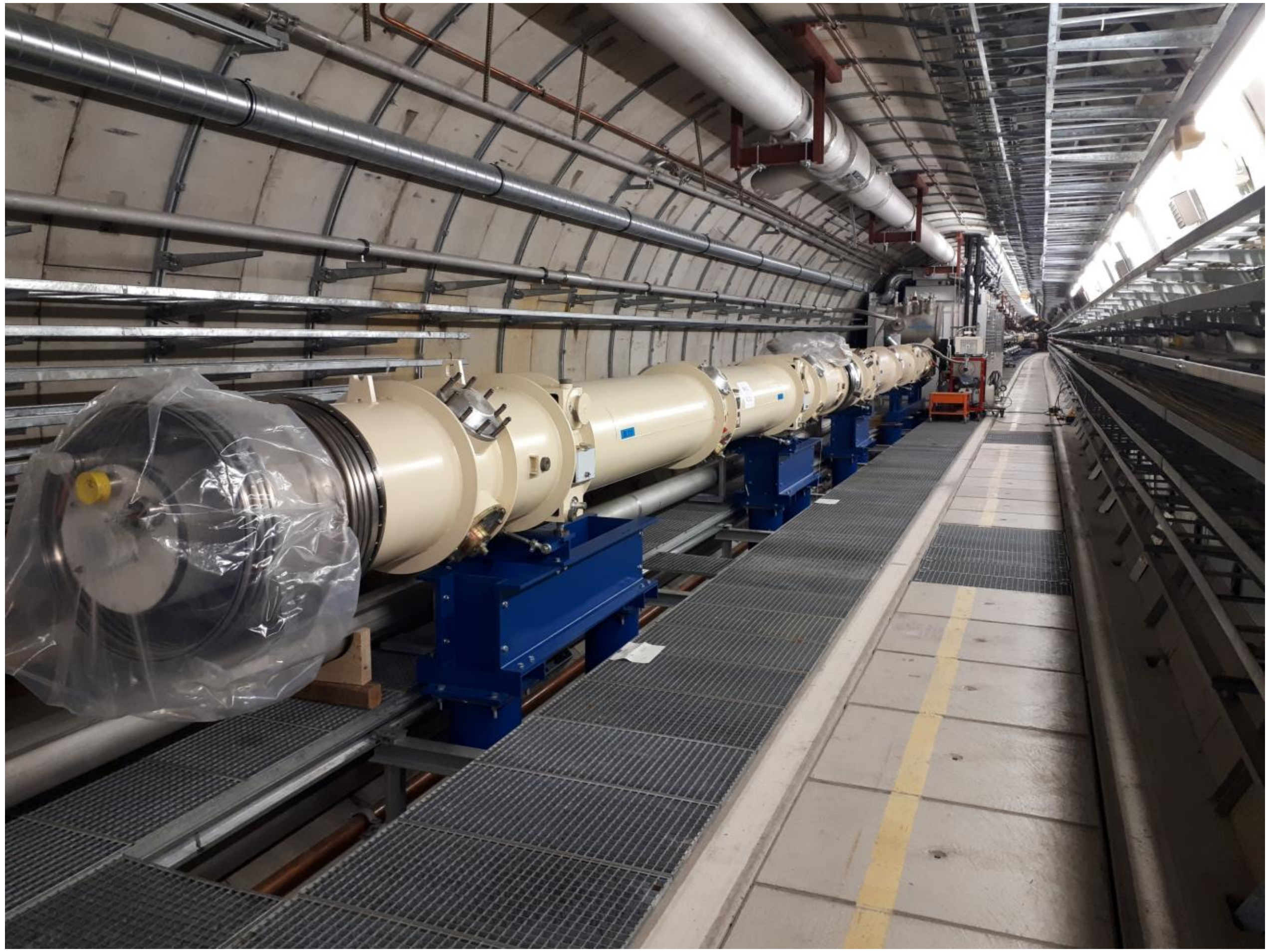
More magnets

Any Light Particle Search II

More magnets

Any Light Particle Search II

More magnets



Any Light Particle Search II

More magnets

Any Light Particle Search II

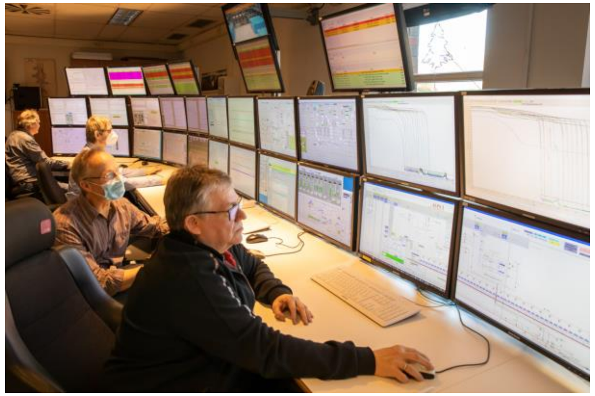
22 October 2020: last magnets installed!

Joachim Mnich,
Director for
particle physics
(now at CERN)

Wim Leemans,
Director for
accelerators

Any Light Particle Search II

Further construction milestones



- Spring 2021: start of optics installation.
- June 2021: lock of 250 m long optical resonator, characterization of optics and seismic noise studies.
- September 2021: all magnets connected.
- December 2021: magnet string reaches operation temperature of 4 K.
- March 2022: magnet string reaches full operation current of 5.7 kA.
- May 2022: regeneration cavity test-installation and -lock.
- June 2022: world-record cavity storage time.
- September 2022:
installation of central optical bench for first science run.

125 m regeneration
cavity storage time:
6.75 ms! (world record).
Now 7.2 ms.

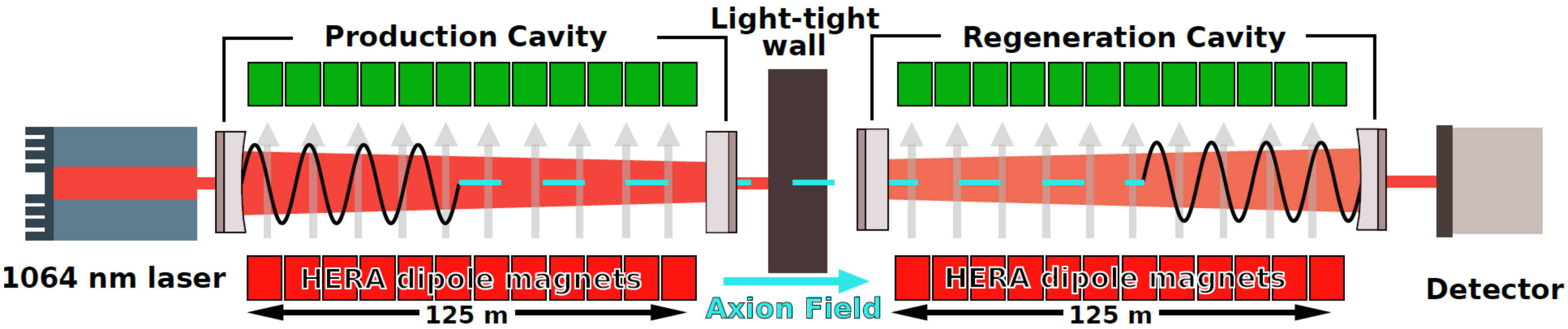
ALPS II start-up

23 May 2023

After more than 12 years of preparation.

Understanding ALPS II

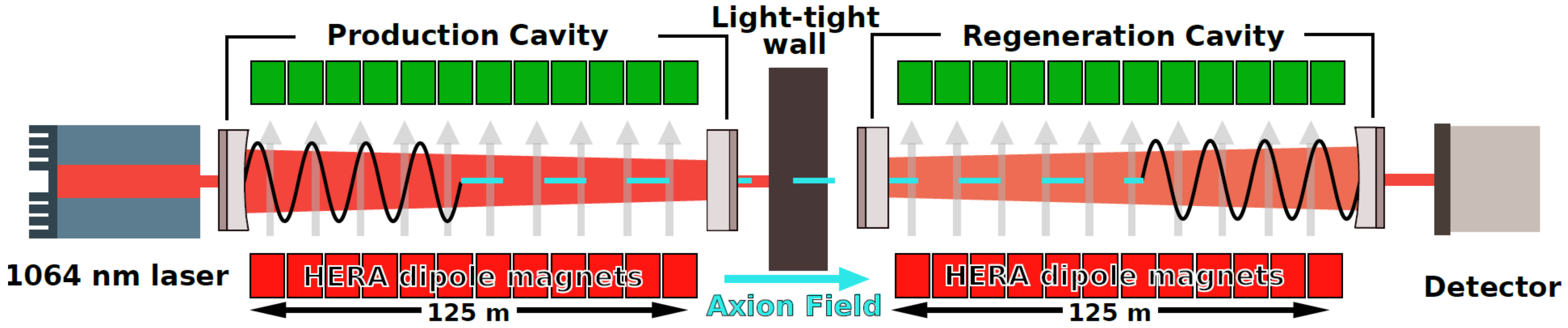
No standard model physics signal for calibration



- Careful characterization of the system.
  - Exclude any fake signals.
  - Ensure detection, if an ALP is in reach.
- Crucial tool: open a shutter in the light-tight wall
  - Monitor 1064 nm laser light storage in regeneration cavity.

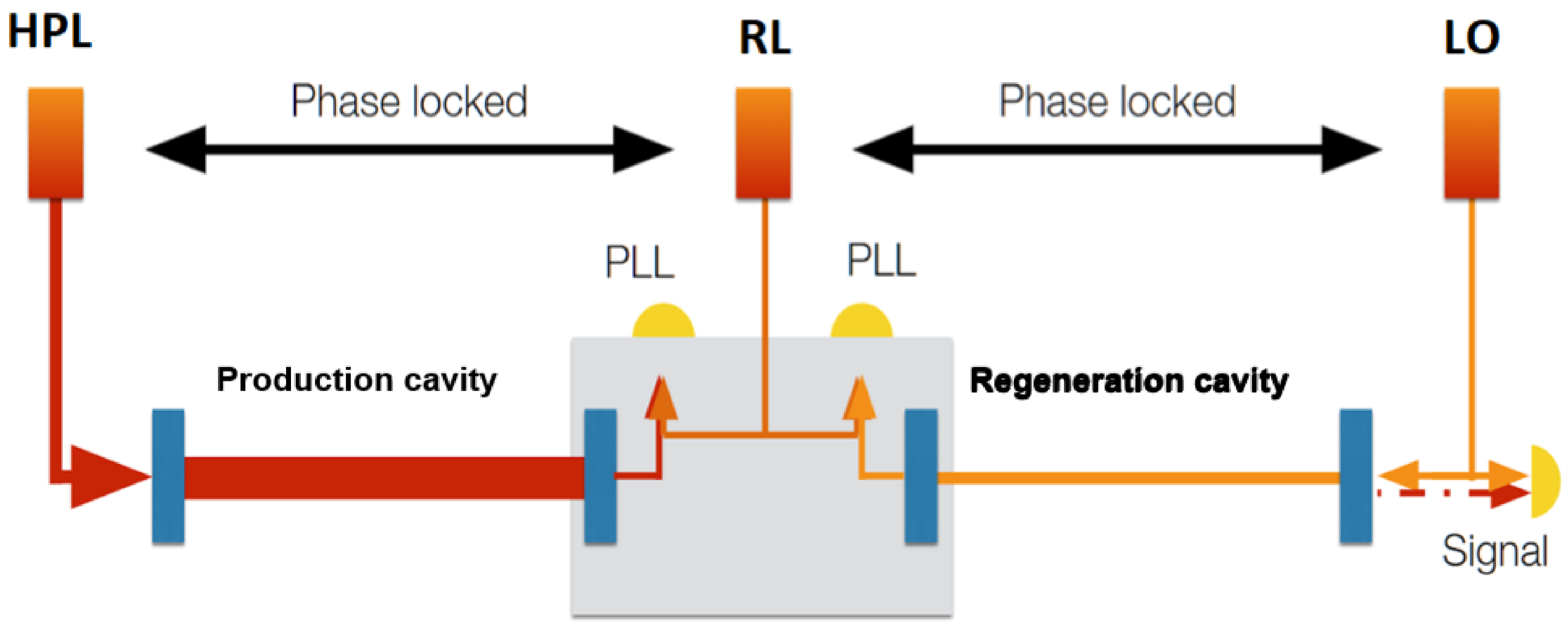
ALPS II: a glimpse on the challenges

Cavities and Heterodyne Sensing



ALPS II: a glimpse on the challenges

Cavities and Heterodyne Sensing



Problem:
Light in regeneration cavity required to sense mirror motions to maintain resonance condition for light from axion reconversion.

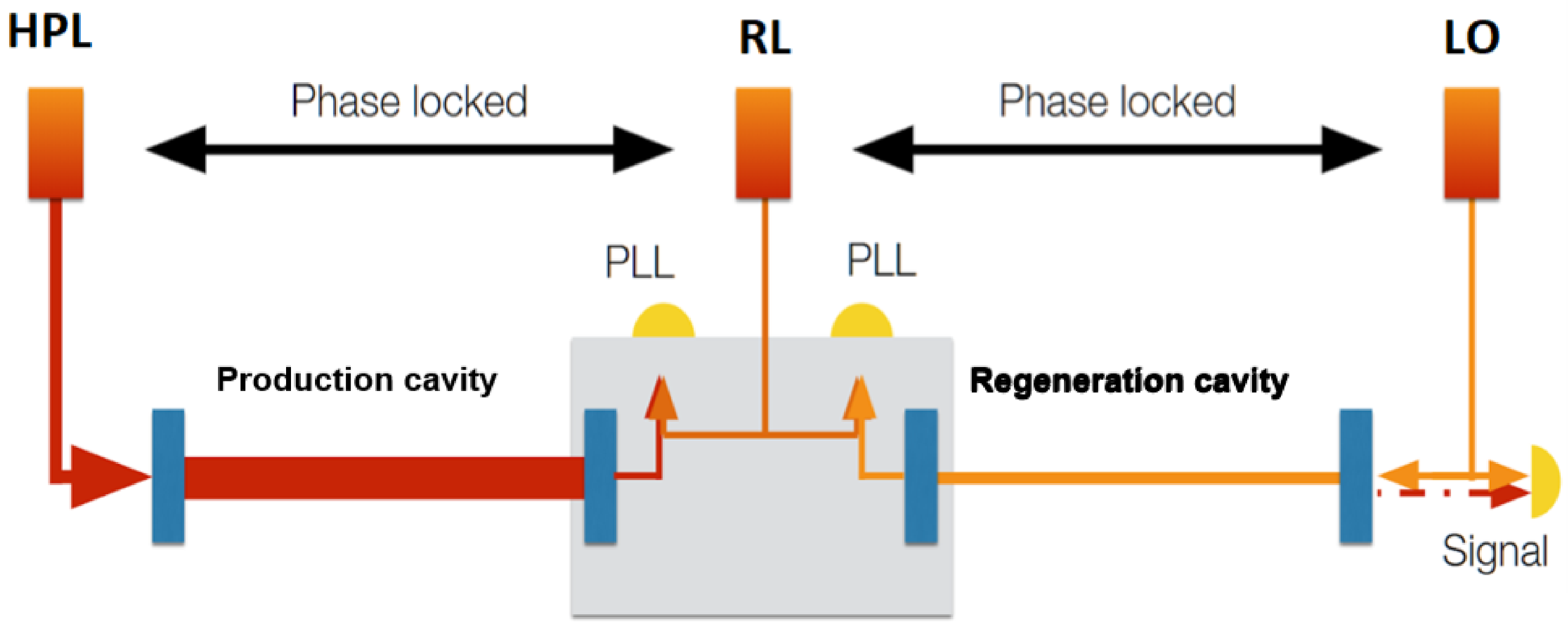
From a problem to a benefit:
Maintain a constant

- frequency difference and
- phase difference

between sensing light and "axion-light".
Superpose both light fields and look for the beat-signal (heterodyne sensing).

ALPS II: a glimpse on the challenges

Cavities and Heterodyne Sensing



Measure P_2
and phase shift

P_1, P_2

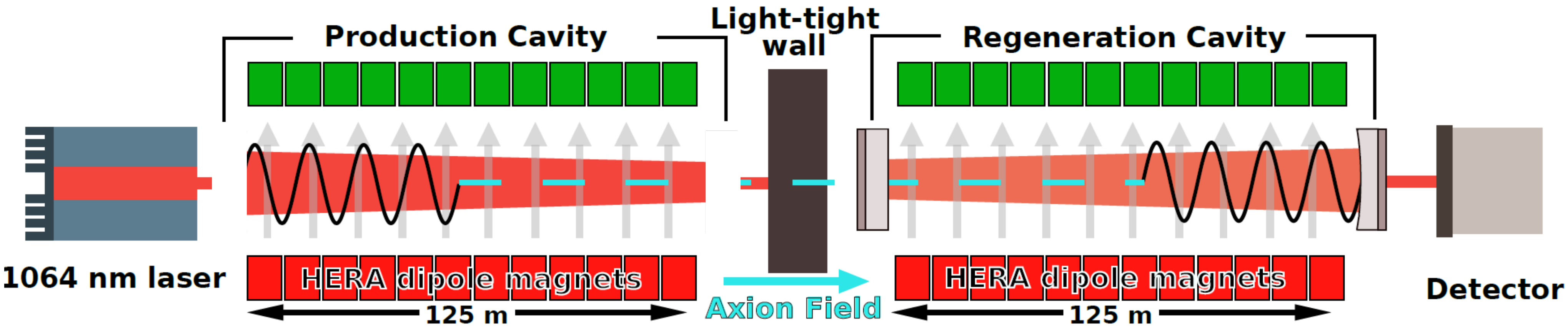
$$\left| \sqrt{\bar{P}_1} e^{i(2\pi f t + \phi_1)} + \sqrt{\bar{P}_2} e^{i[2\pi (f + f_0) t + \phi_2]} \right|^2 =$$

$$\bar{P}_1 + \bar{P}_2 + 2\sqrt{\bar{P}_1 \bar{P}_2} \cos\left(2\pi f_0 t + \Delta\phi\right)$$

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

ALPS II initial configuration

No optical cavity in front of the wall

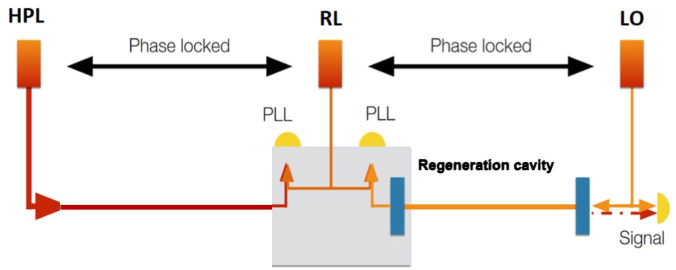


Prime motivations:

- Understand the (simpler) system.
- Demonstrate stable data taking.
- Characterize and mitigate stray-light reaching the detector:
  40-fold enhancement without the production cavity.

ALPS II: a glimpse on the challenges

Cavities and Heterodyne Sensing



Blog-Eintrag / 2024 / Juni / 10 Bearbeiten Favorit Beobachtung Teilen

10.06.2024 exact demodulation frequency pseudoscalar run (review)

Daniel Cai Brotherton posted on 10. Jun. 2024 17:38h - last edited by Daniel Cai Brotherton on 10. Jun. 2024 17:45h

The Moku:Lab frequency resolution is 1 GHz / 2^48.

The desired demodulation frequency is 2.4 Hz.

The FSR was measured before the run to be 1222632.33 Hz and based on this, the reference frequencies set on the Mokus are:

PLL2: 52546866.89 Hz

Science: 14603135.51 Hz

Veto: 40346869.29 Hz

Additionally, there are the reference frequencies:

PLL1: 12200000 Hz

PLL3: 54950000 Hz

The calculated demodulation frequencies are:

Science: 2.40000019222498 Hz

Veto: 2.40000020712614 Hz

FSR: 1.22 MHz
free spectral range, difference between cavity resonances

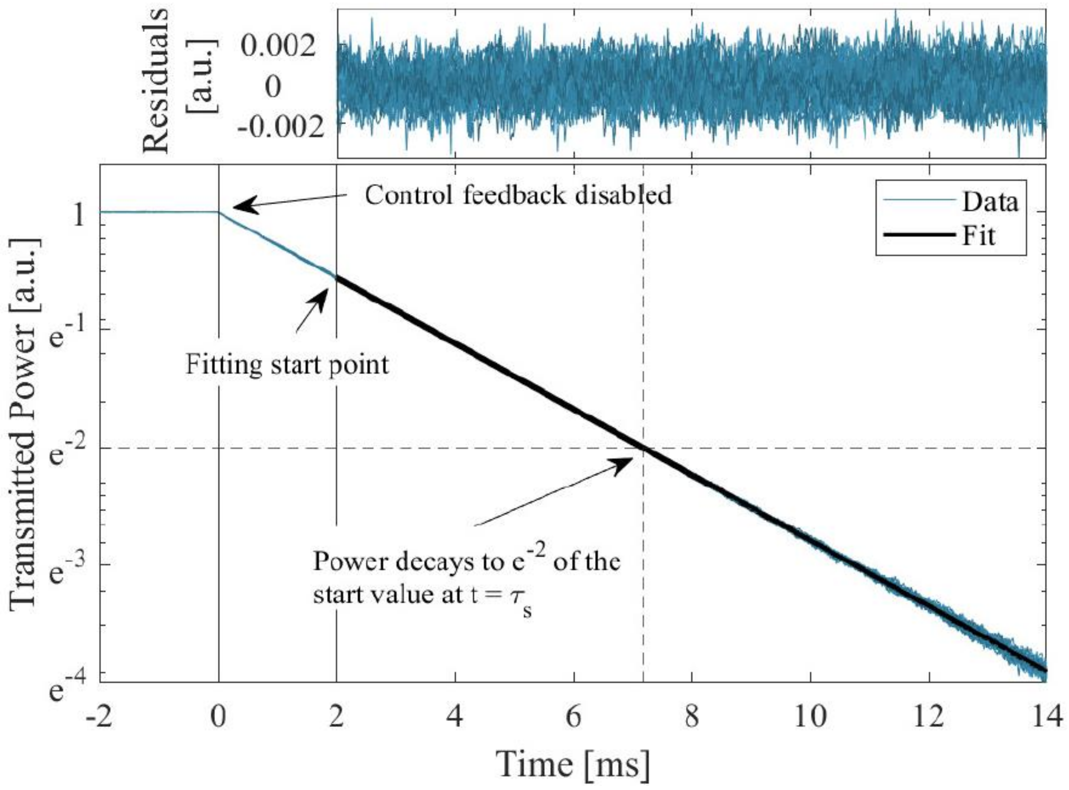
Linewidth of resonances: 44 Hz

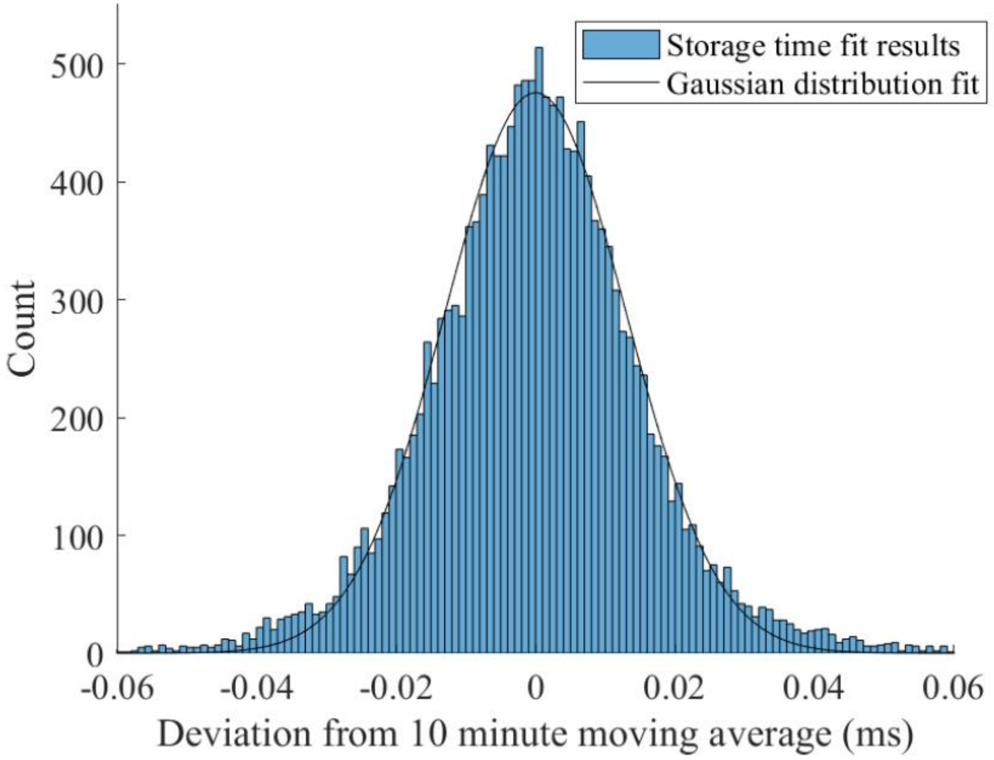
Phase stability required: 0.1 rad

sub-µHz precision needed for 280 THz infrared light!

ALPS II systematics (example)

Regeneration cavity light storage time





Storage time (7.17 ± 0.01) ms. World record!

ALPS II systematics (example)

Regeneration cavity light storage time: do we understand the results?

Measure mirror reflectivity and losses by scanning a cavity resonance :

$$\mathcal{R}(\Delta\nu) \equiv \frac{E_{\mathrm{ref}}}{E_i} \approx 1 - \frac{T_{\mathrm{input}}}{\frac{1}{2}A - 2\pi i \frac{\Delta\nu}{f_0}}$$

E_i : injected light (E-field)
E_{ref} : reflected light (E-field)
T_{input}: transmission of mirror
A : total loss in cavity per round-trip

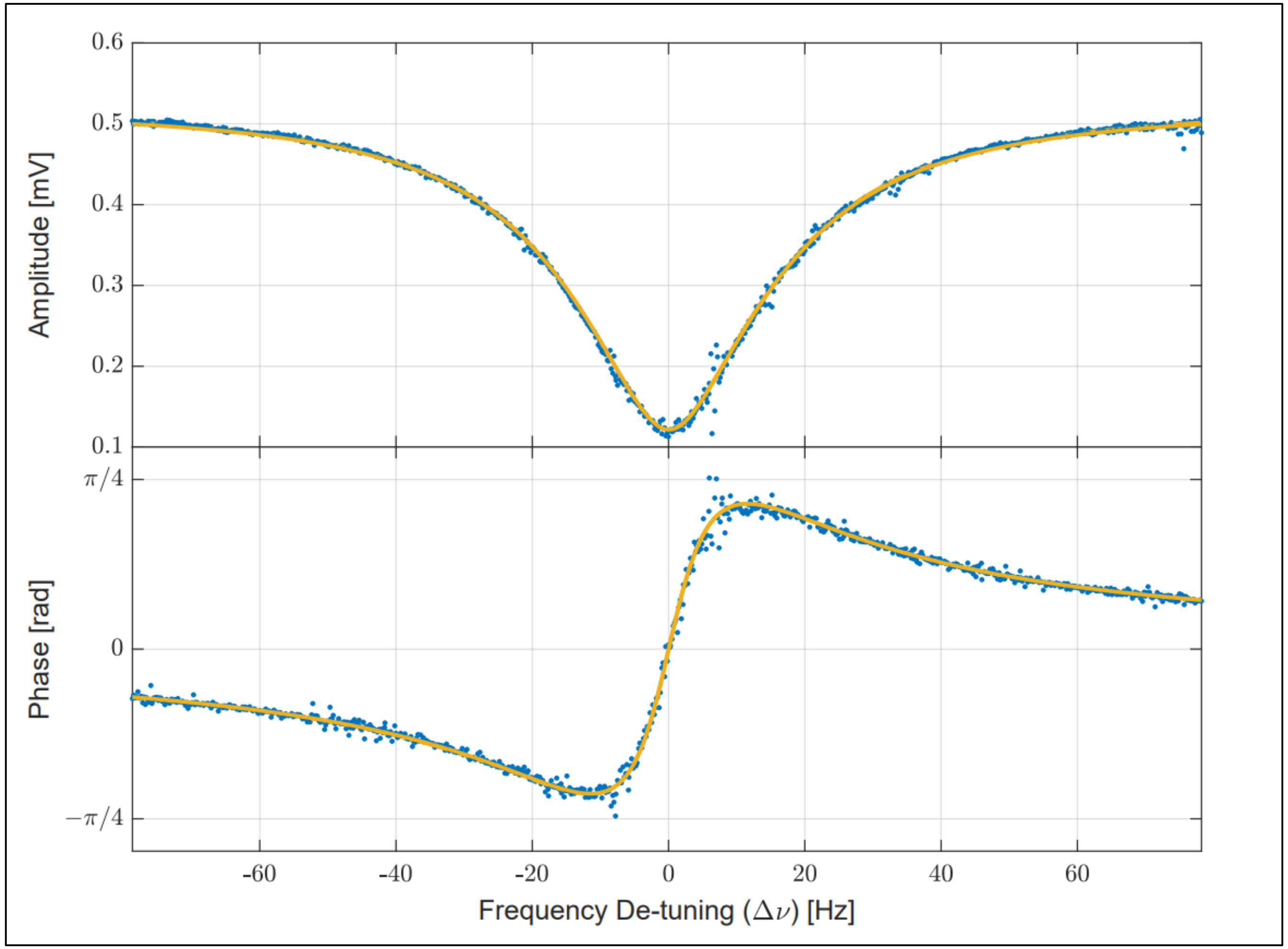
Optical cavity characterization with a mode-matched heterodyne sensing scheme

Aaron D. Spector * [1] and Todd Kozlowski[1]

[1]Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany

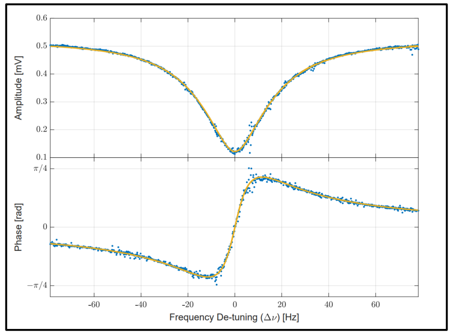
April 12, 2024

https://inspirehep.net/literature/2776450



ALPS II systematics (example)

Regeneration cavity light storage time: do we understand the results?



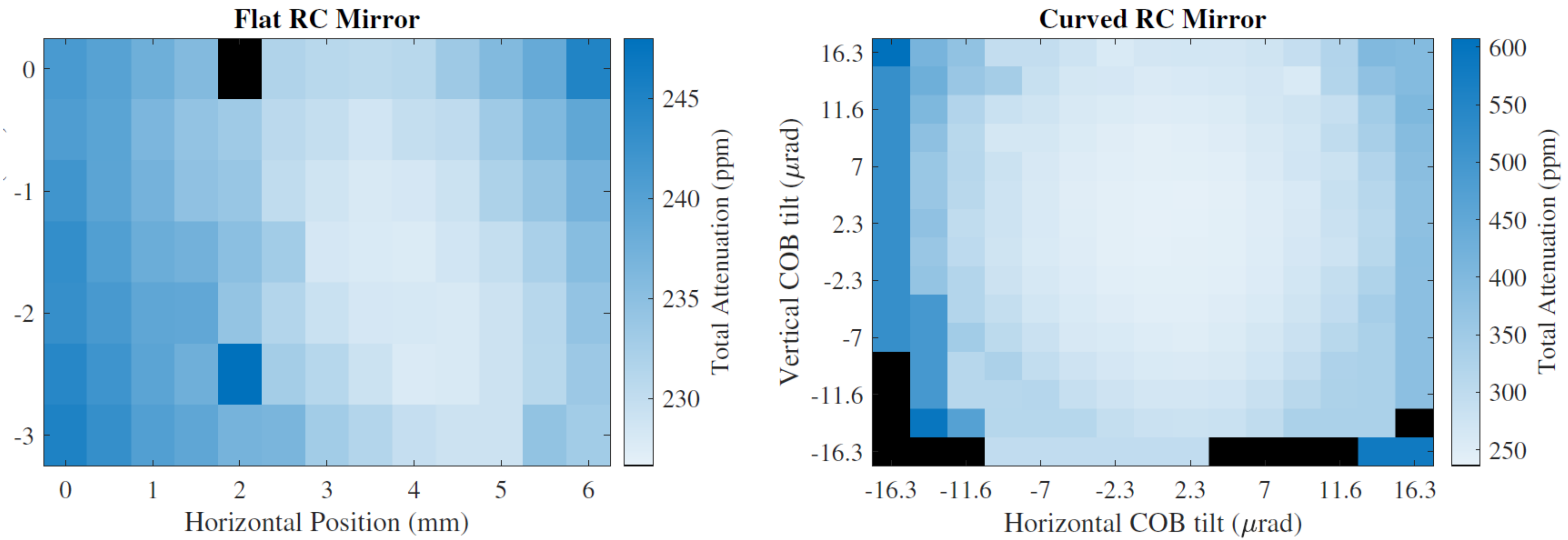
Preliminary results:

Cavity parameter	Complex Reflectivity (Operational)	Ring-down (Operational)	Ring-down (Lowest loss)
Length (L_{RC})	122.60122 m	–	–
Finesse ($\mathcal{F}$)	25850 ± 50	25650 ± 20	27550 ± 40
Flat Mirror Transmissivity (T_2)	5.1 ± 0.5 ppm	–	–
Curved Mirror Transmissivity (T_1)	95.7 ± 0.5 ppm	96^{+1}_{-4} ppm	99^{+1}_{-4} ppm
Round-trip Attenuation (A)	243 ± 0.5 ppm	245.0 ± 0.2 ppm	228.1 ± 0.3 ppm
Round-trip Losses (l)	142 ± 1 ppm	144^{+4}_{-1} ppm	124^{+4}_{-1} ppm
Resonant Enhancement (β)	6480 ± 50	6400^{+60}_{-270}	7610^{+75}_{-300}

ALPS II systematics (example)

Regeneration cavity light storage time: do we understand the results?

Measure mirror reflectivity and losses by walking the beam across the mirror surfaces at resonance:

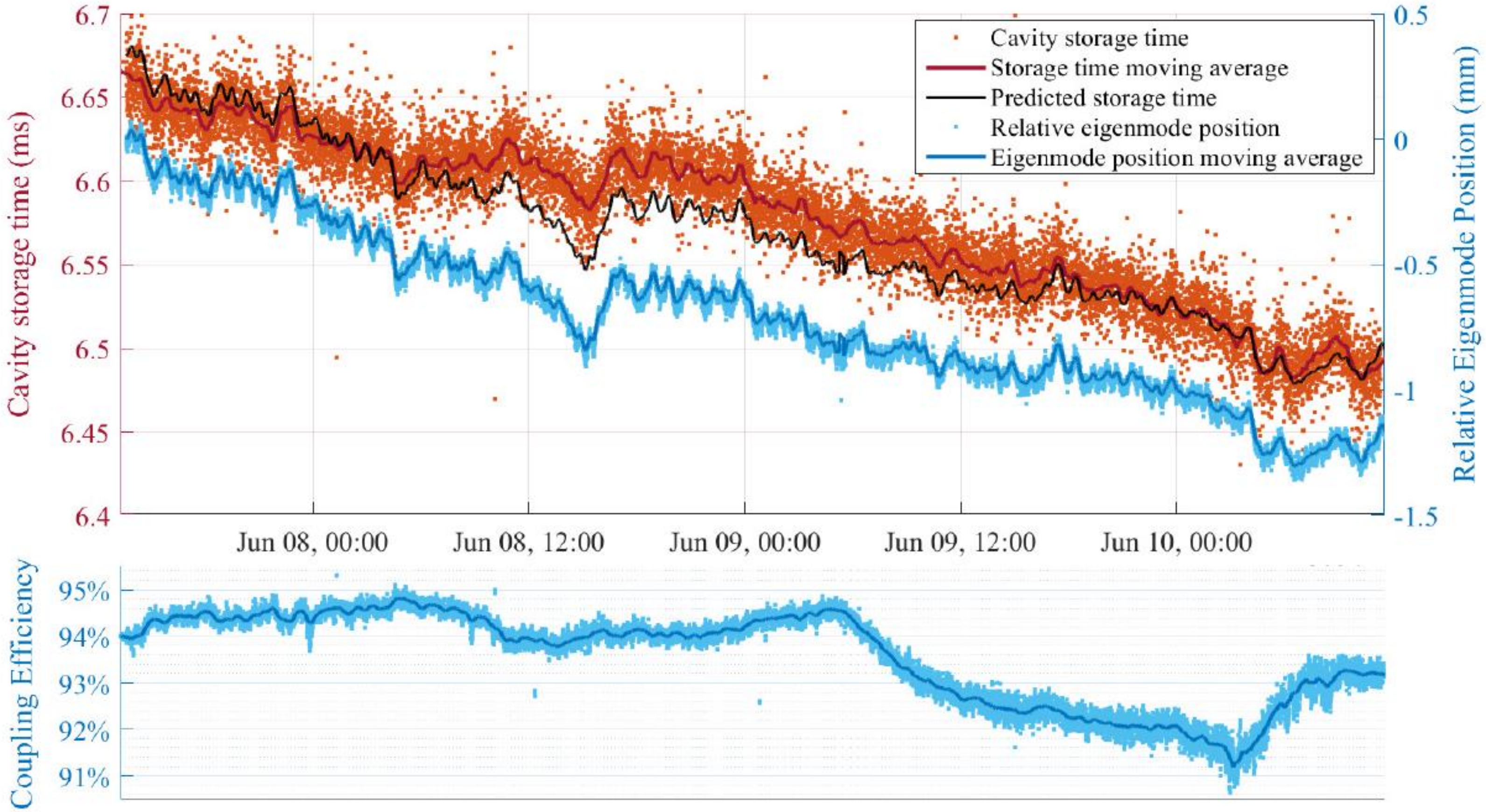


Large losses at large tilts due to aperture limitations.

ALPS II systematics (example)

Regeneration cavity light storage time: we understand the results!

Predictions from mirror characterization match very well with storage time measurements.
Drift explained by beam position drift on mirrors.



No correlation with spatial alignment of laser beam and cavity axis.

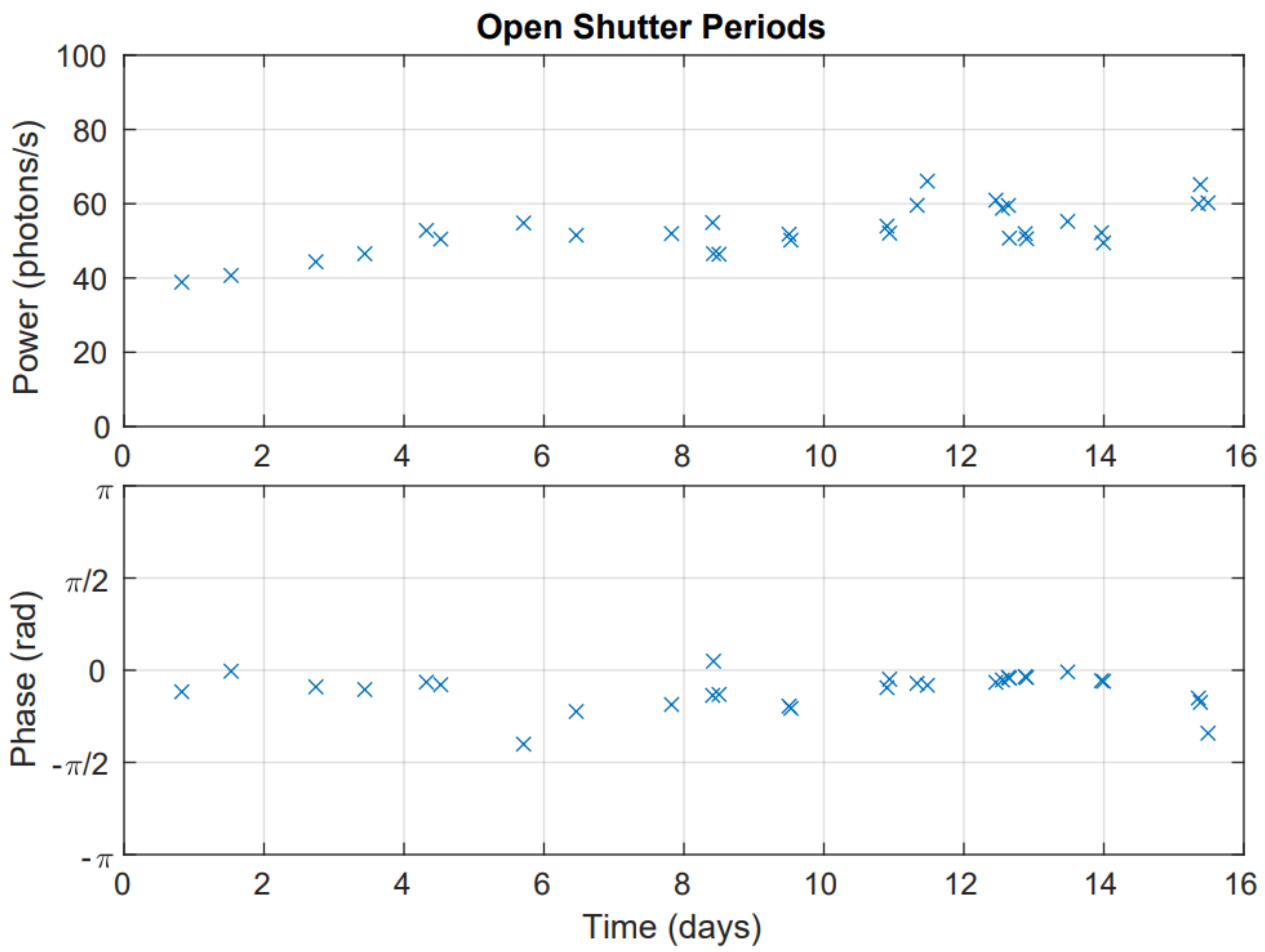
ALPS II systematics (example)

Can we maintain phase stability?

Open a shutter in the wall and measure the high-power laser light in the regeneration cavity.

50 photons/s = 10^{-17} W

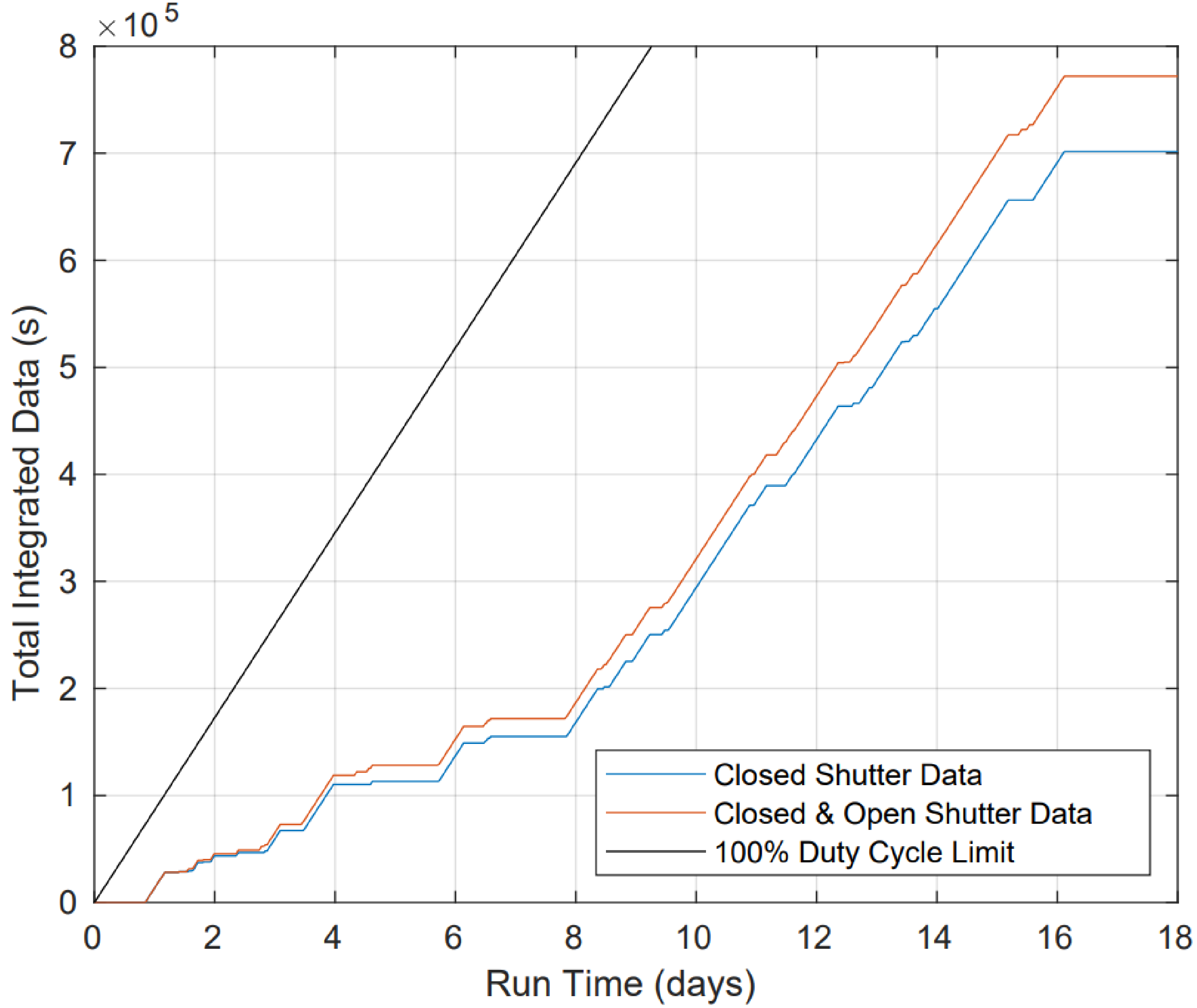
Phase stability is maintained, measurements even allow to correct for the drift.



ALPS II systematics (example)

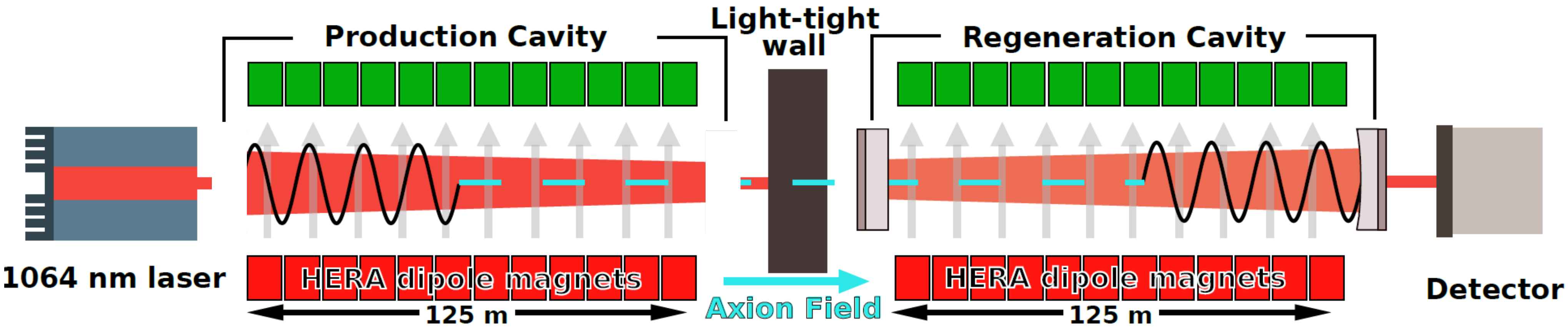
Can we operate the whole system?

Yes, after some learning curve!



ALPS II initial configuration

No optical cavity in front of the wall

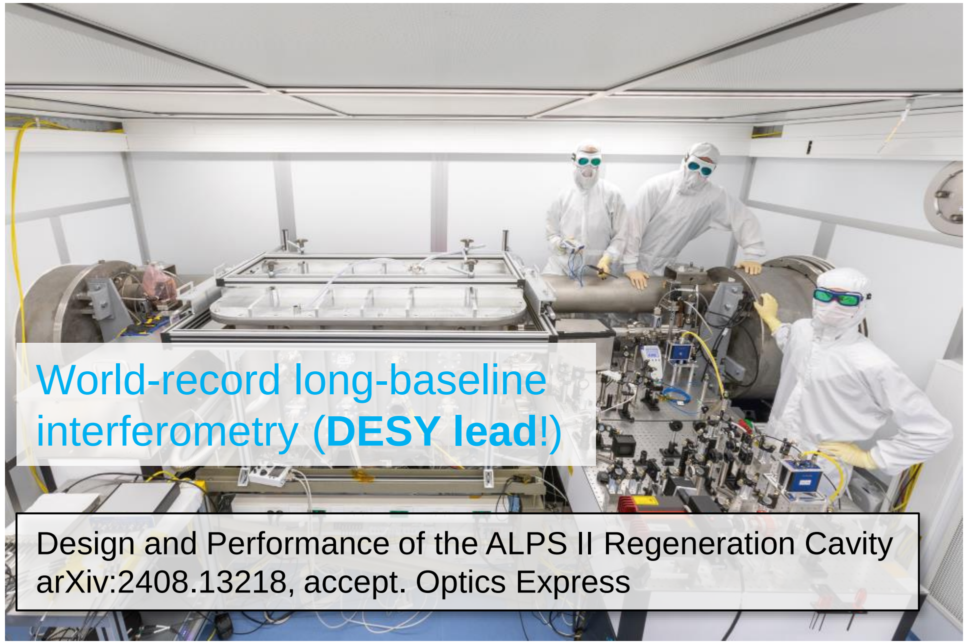


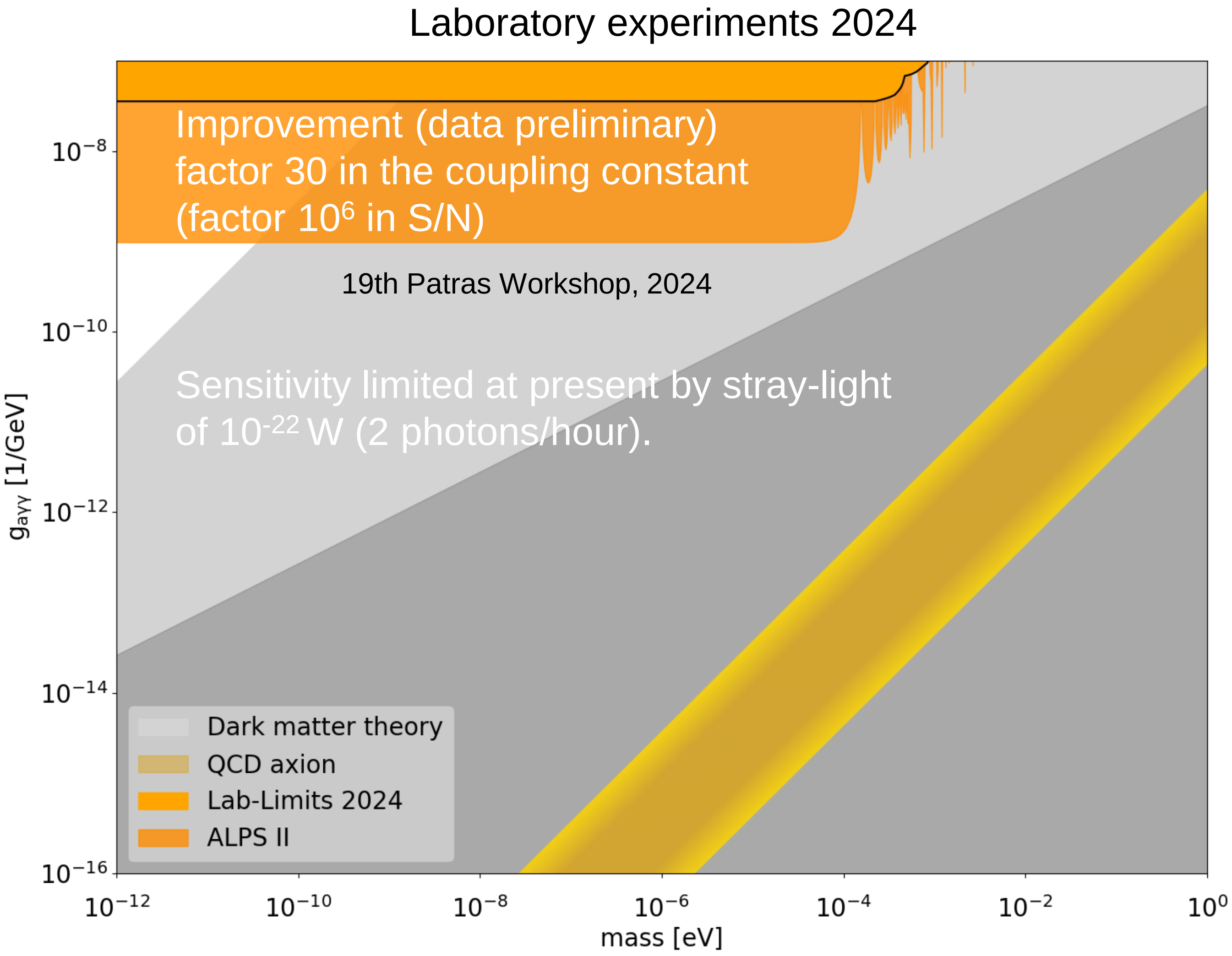
Prime motivations:

- Understand the (simpler) system. ✓
- Demonstrate stable data taking. ✓
- Characterize and mitigate stray-light reaching the detector: ✓
  40-fold enhancement without the production cavity. ✓

ALPS II: key achievements

A world-record and first results





First run 05/2023 to 05/2024.

What if …

… we a see a signal?

There is only one ALPS II world-wide!

Plan:

Switch from heterodyne sensing (“interference effect”) to photon counting.

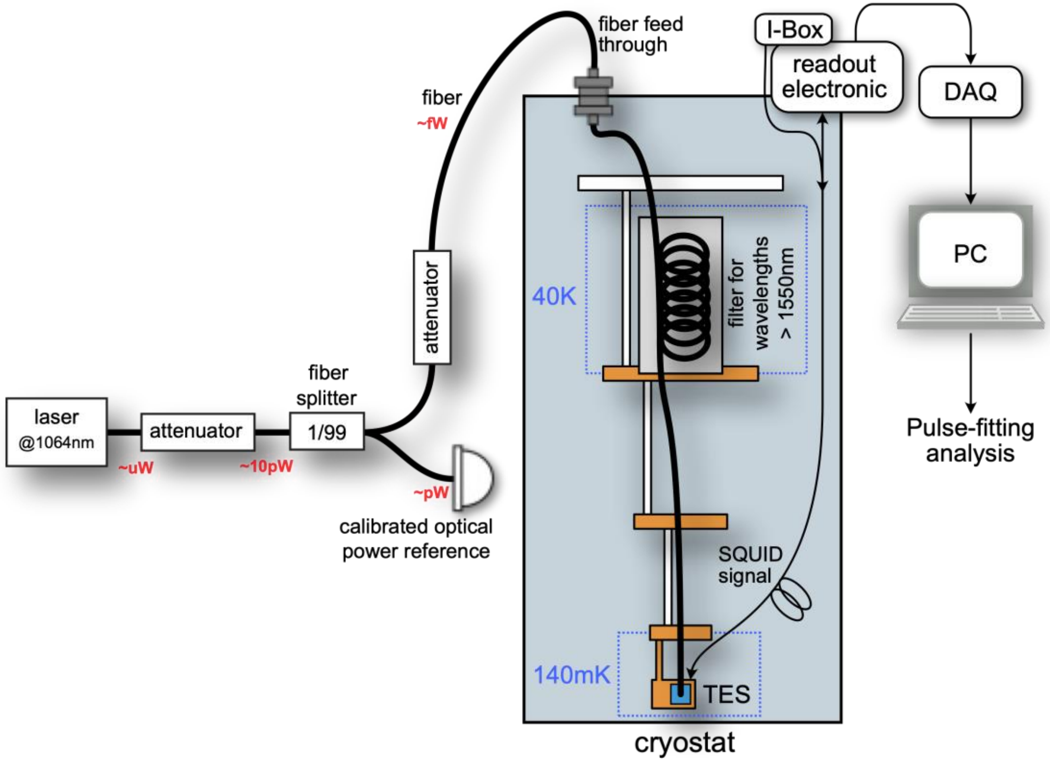
- Pro:
  Very different systematic uncertainties.
- Con:
  Need to construct a revised optics concept with a new central optical bench.

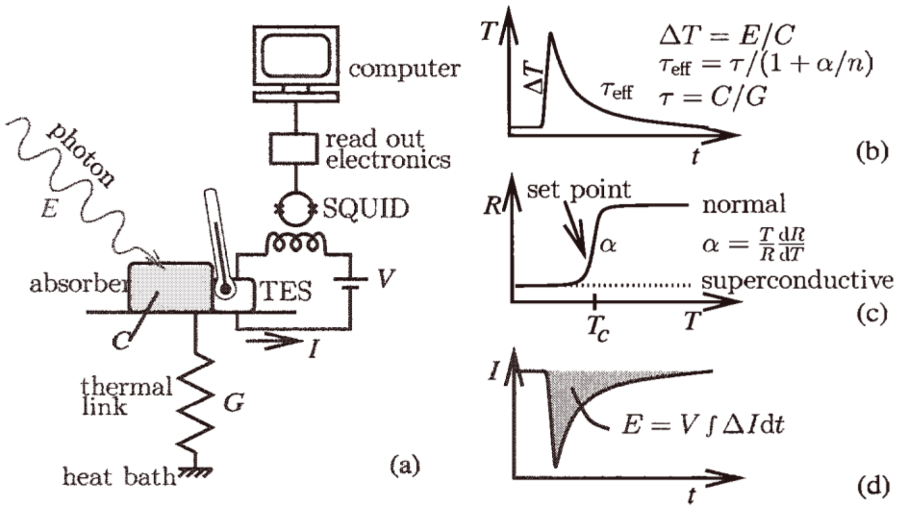
Need to develop a photon counting system capable of detecting few 1064 nm photon per day ($5 \cdot 10^{-24}$ W)!

ALPS II: TES detectors for an alternative LSW sensing

Counting photons with $5 \cdot 10^{-24}$ W @ 1064 nm and <10% single photon energy resolution

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





ΔT ≈ 300 µK

ΔR ≈ 1 Ω

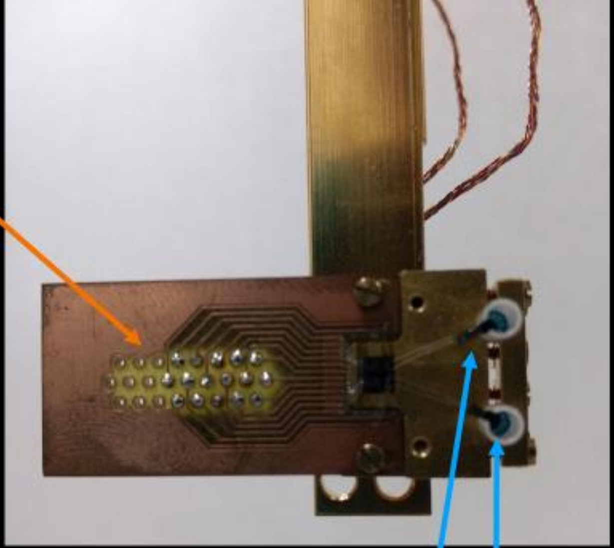
ΔI ≈ 70 nA

- Two dilution refrigerators available.
- TES for direct dark matter searches?
- TES for squeezed light photon statistics?

Status:
https://inspirehep.net/literature/2751657

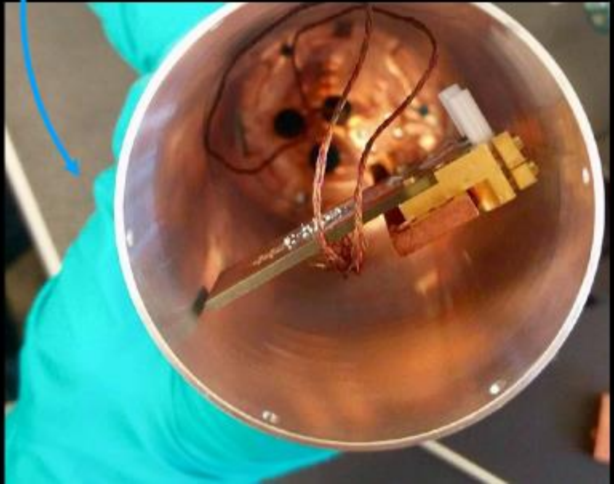
SQUID (PTB, Magnicon)

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



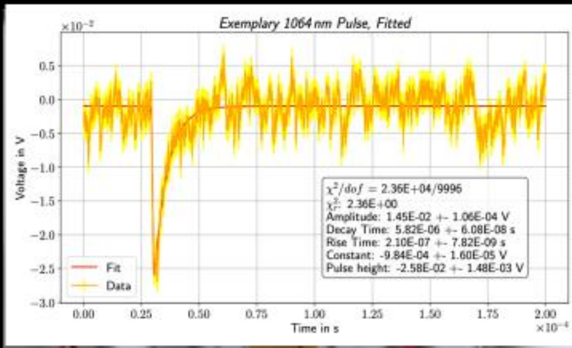
TES

- 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

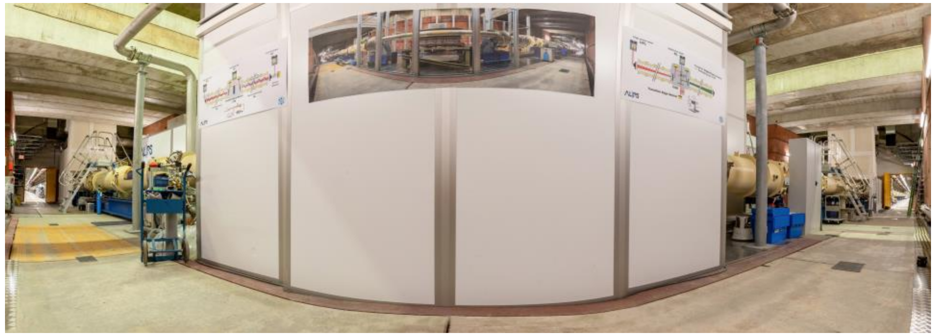


Cryostat

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

ALPS II: key goals

Reach target sensitivity, going beyond CAST and astrophysics

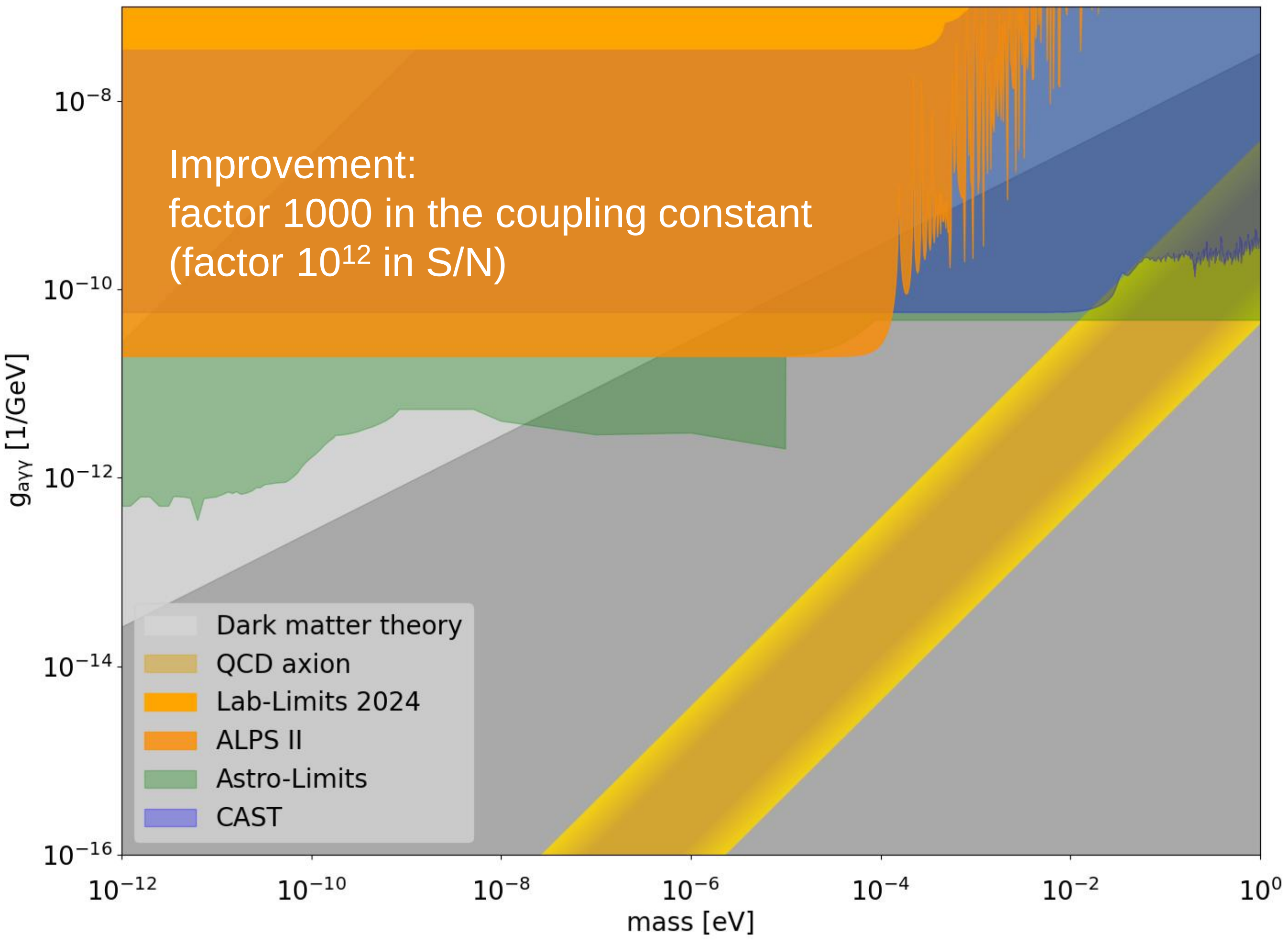


Purely laboratory based searches

Solar axion searches (CAST@CERN)

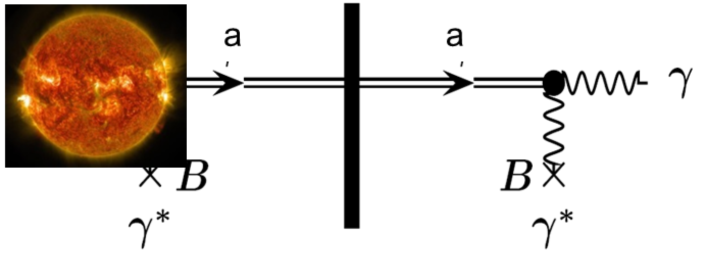
Astrophysical searches

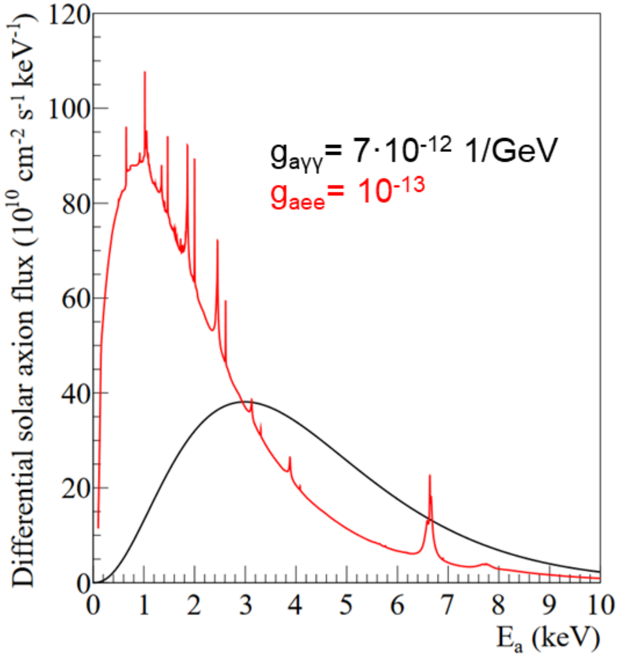
Laboratory experiments and astrophysics 2027



Measure the Sun’s dark luminosity

International AXion Observatory IAXO



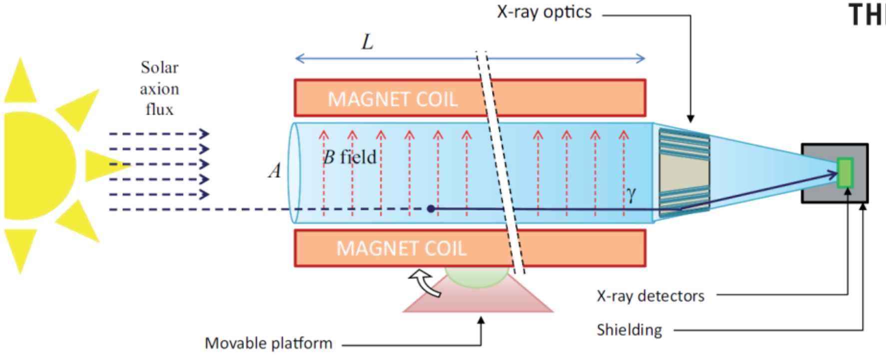


Solar axions generated via couplings to photons, electrons and nuclear transitions (i.e. 14.4 keV).

JCAP01(2016)034

BabyIAXO located in the hall HERA South (option).

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)

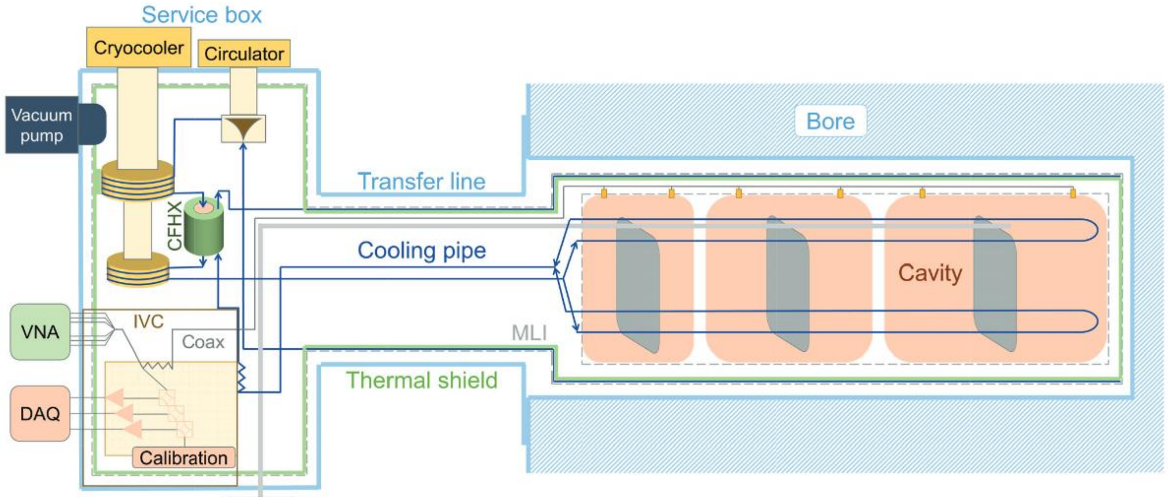
BabyIAXO achievements

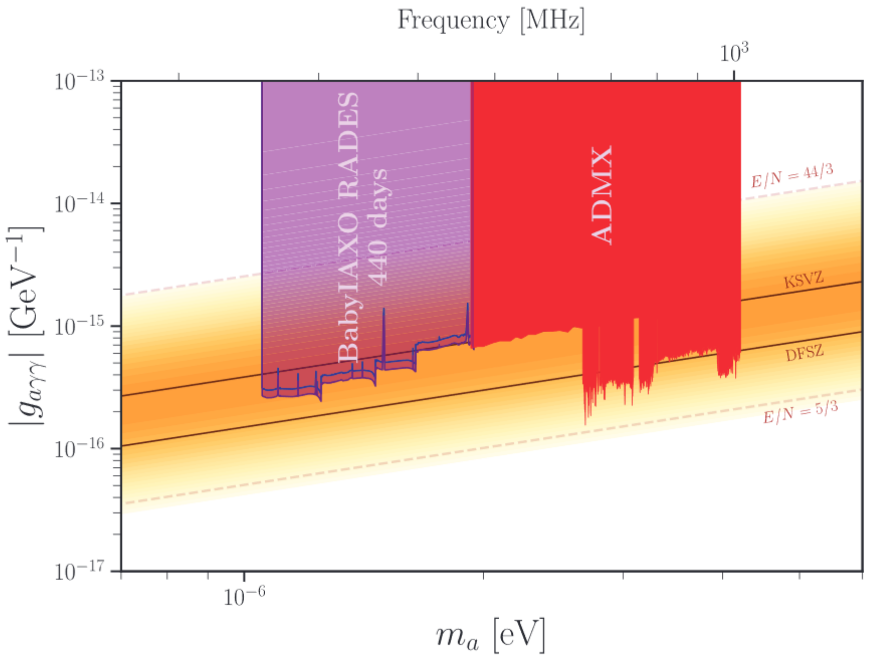
Ready to start construction

Key achievements:

- Magnet CDR and TDR (2025), recovered from suspension of Russia in February 2022.
- Promising funding scenario.

- Extensions of the science case:
    - Direct dark matter searches with RADES.





Look for axion dark matter below the ADMX mass reach.

Annalen Phys. 535 (2023) 12, 2300326

BabyIAXO achievements and goals

Ready to start construction - reach sensitivity beyond ALPS II

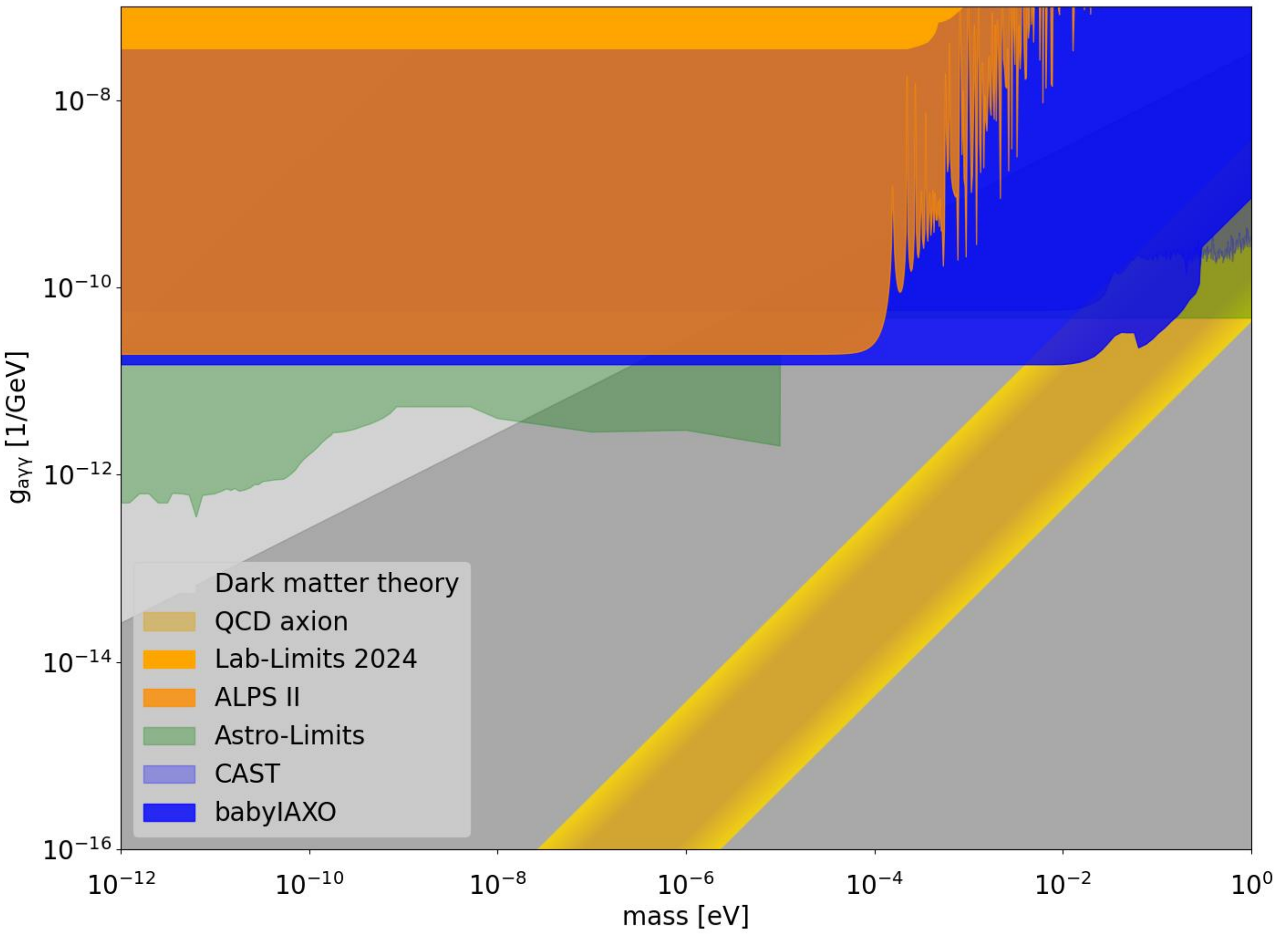
Key achievements:

- Magnet CDR and TDR (2025), recovered from suspension of Russia in February 2022.
- Promising funding scenario.

- Extensions of the science case:
  - Direct dark matter searches with RADES.
  - Supernova axions.

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

Laboratory experiments and astrophysics 2035



BabyIAXO achievements and goals

Ready to start construction - reach sensitivity beyond ALPS II

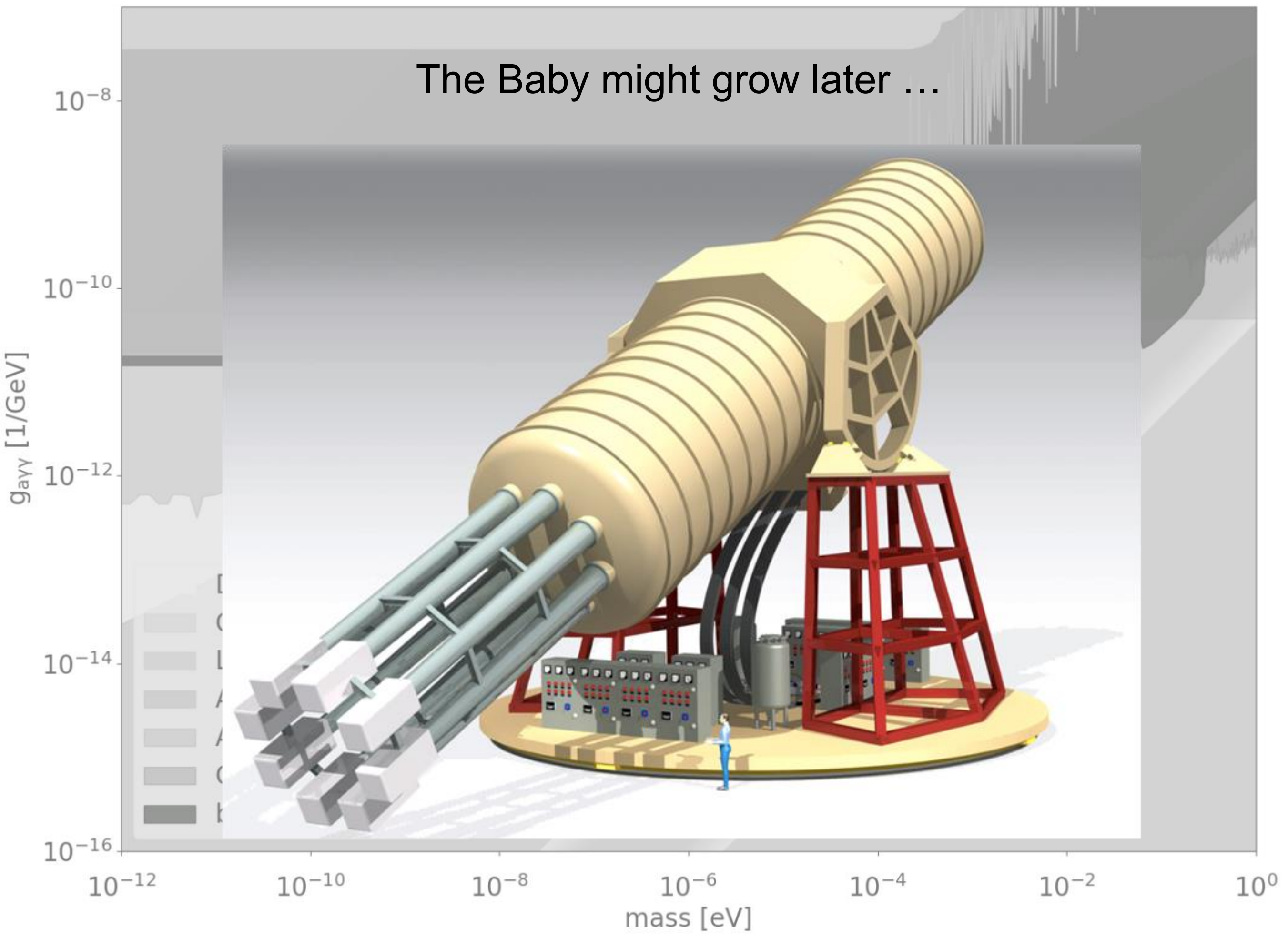
Key achievements:

- Magnet CDR and TDR (2025), recovered from suspension of Russia in February 2022.
- Promising funding scenario.

- Extensions of the science case:
  - Direct dark matter searches with RADES.
  - Supernova axions.

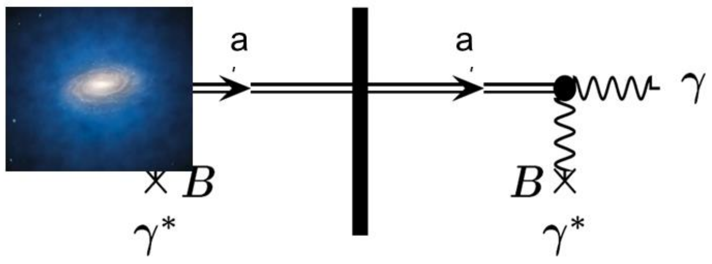
Component / Status	Technical	Funding
Structure & Drive system	(✓)	(✓)
Vacuum & Gas System	✓	✓
Magnet	(✓)	(?)
X-ray Telescopes	✓	✓
Detectors	✓	✓

Laboratory experiments and astrophysics 2035



Finding ambient dark matter

MAgnetized Disc and Mirror Axion eXperiment

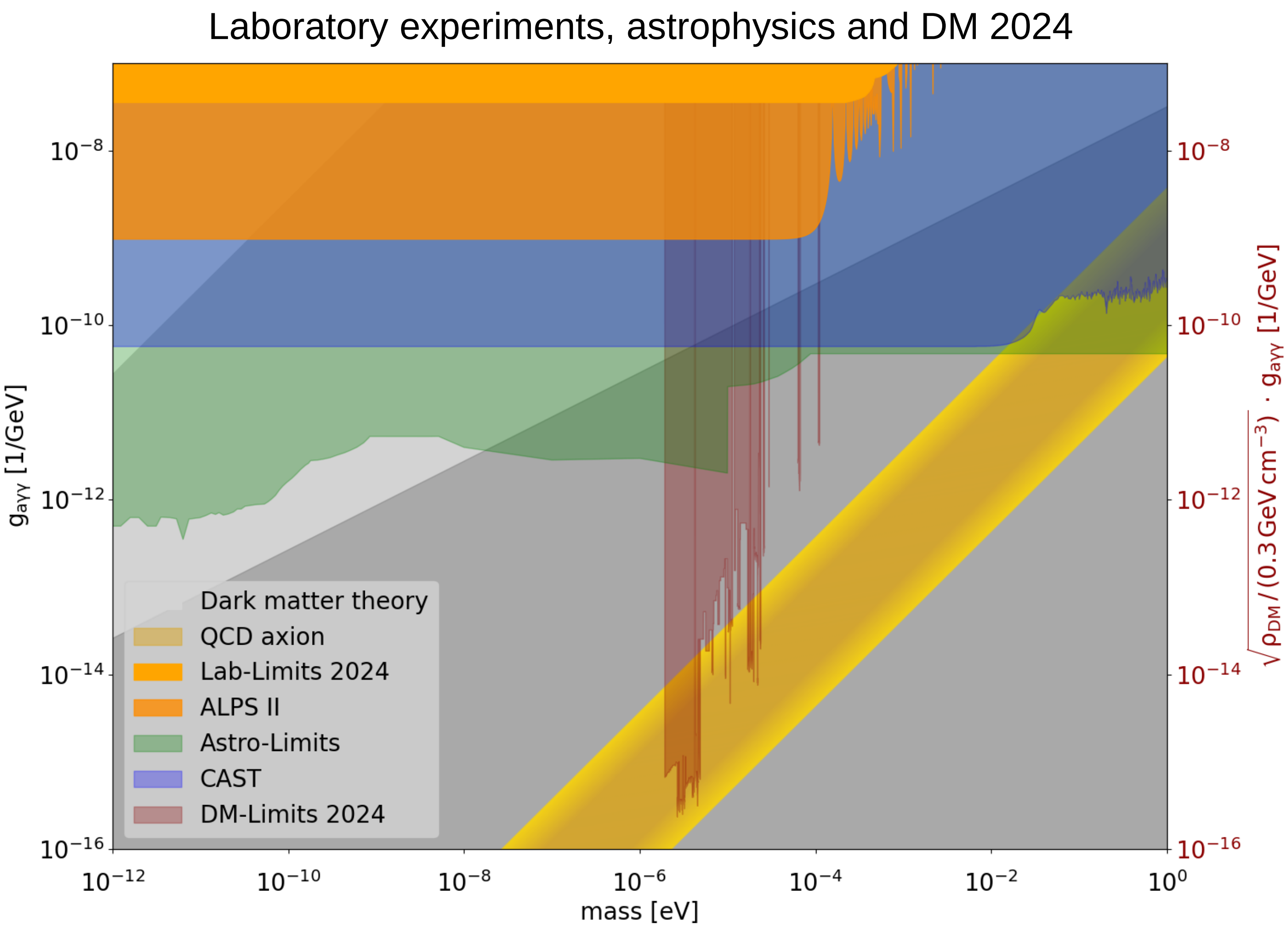


Purely laboratory based searches

Solar axion searches (CAST@CERN)

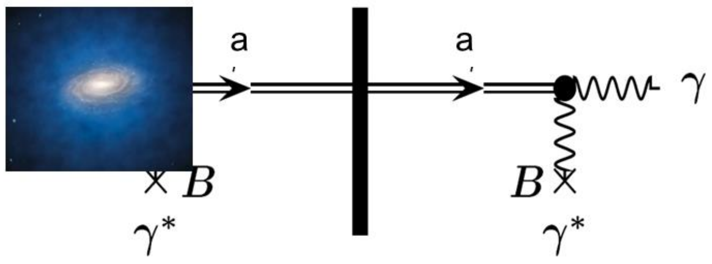
Astrophysical searches

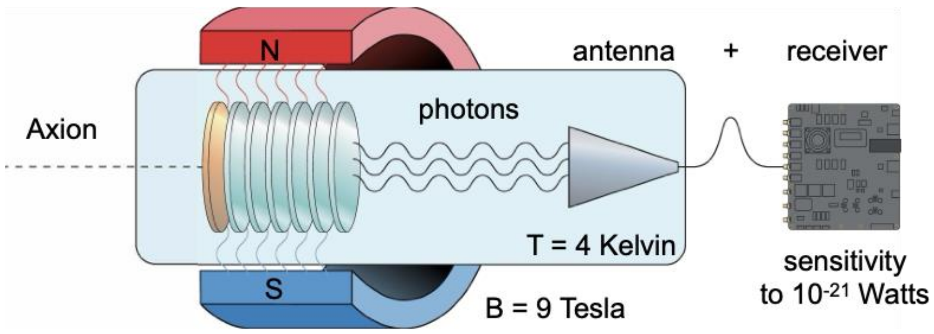
Direct dark matter searches (ADMX@FNAL)

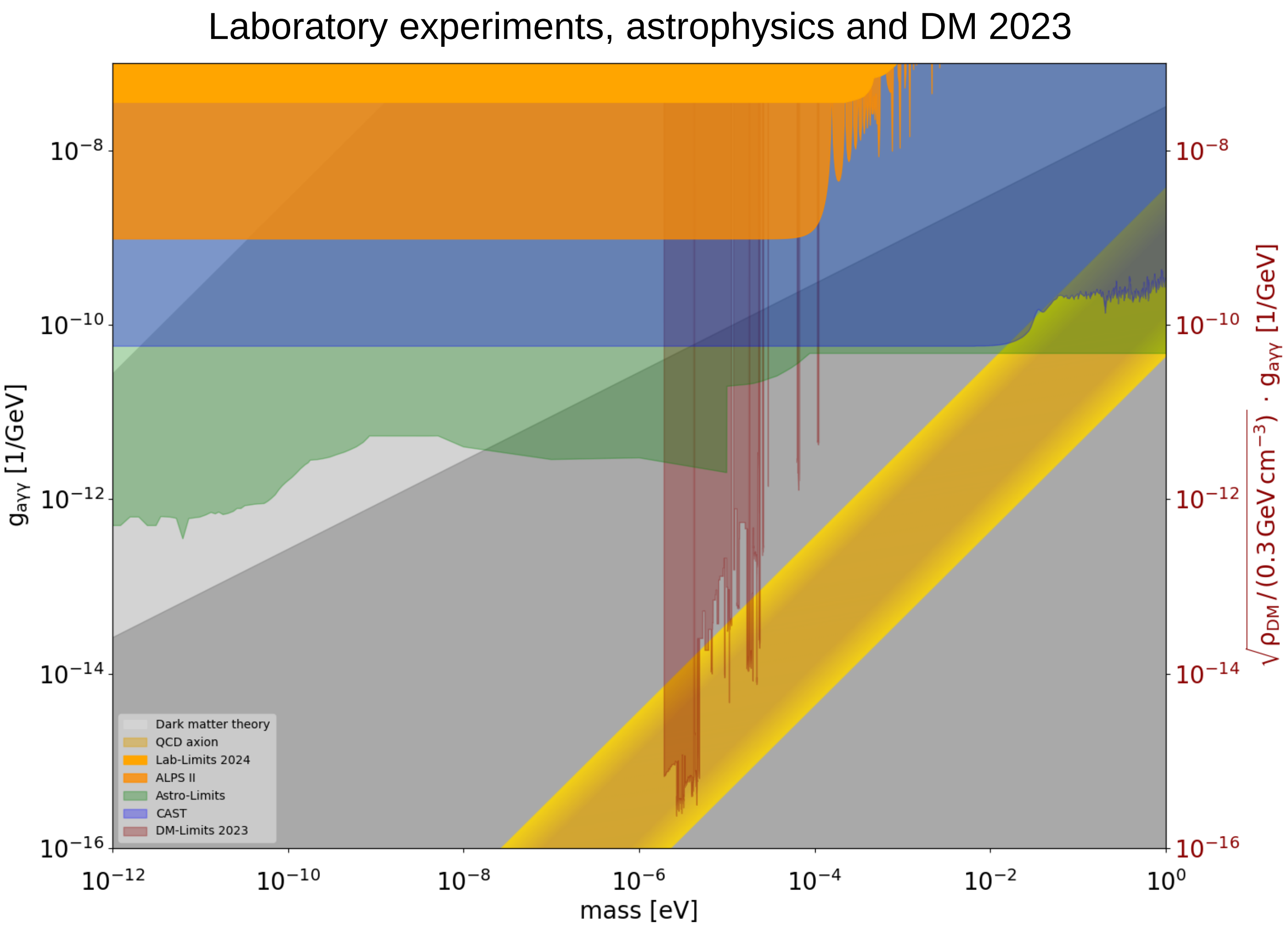


Finding ambient dark matter

MADMAX: new technologies to search for 10-100 µeV axions







MAgnetized Disc and Mirror Axion eXperiment

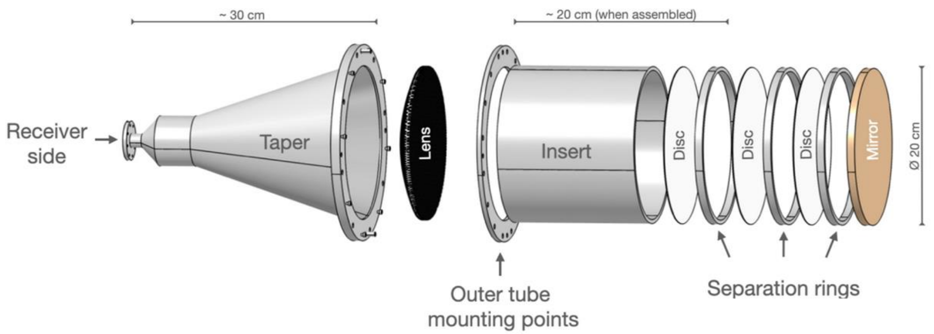
https://madmax.mpp.mpg.de/

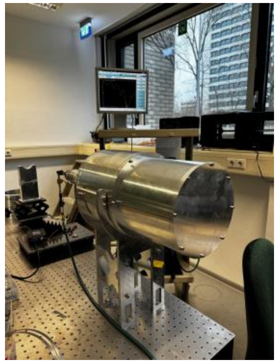
- CPPM, France
- DESY Hamburg, Germany
- Néel Institute, Grenoble, France
- **MPI für Physik, Munich, Germany**
- MPI für Radioastronomie, Bonn, Germany
- RWTH Aachen, Germany
- University of Hamburg, Germany
- University of Tübingen, Germany
- University of Zaragoza, Spain

MADMAX achievements

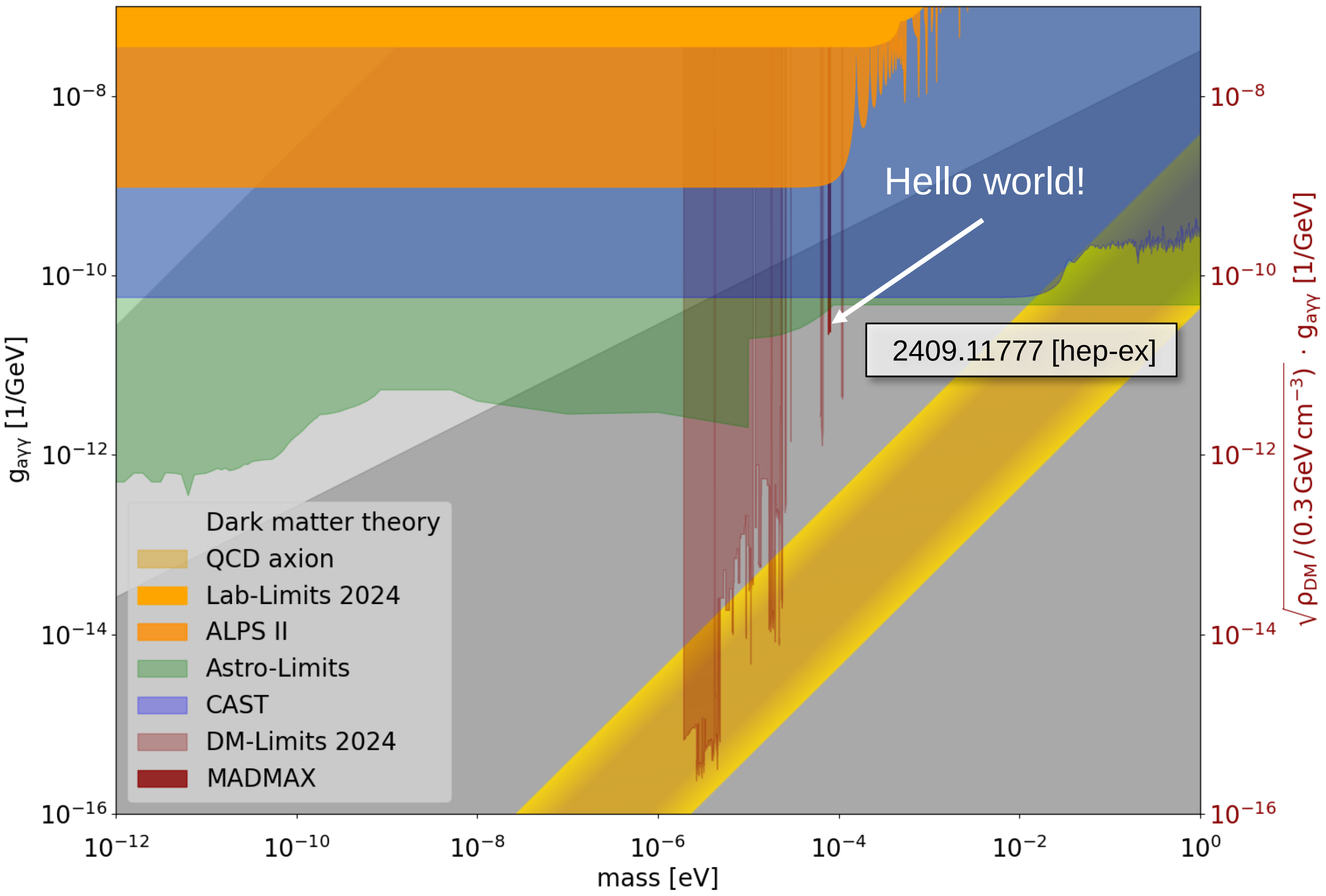
Science results on axion and dark photon searches

Technical feasibility demonstrated!





Laboratory experiments, astrophysics and DM 2024

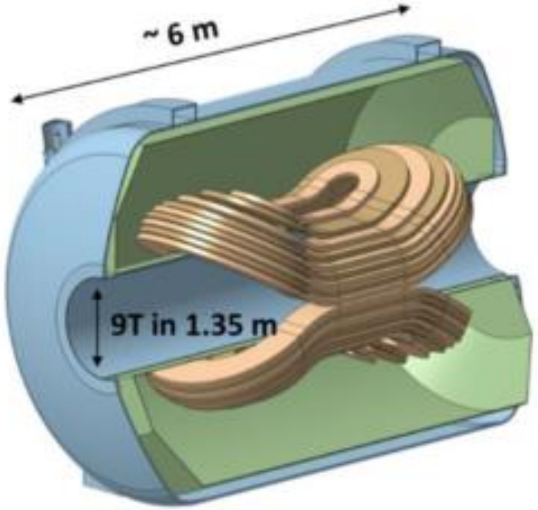


MADMAX goals

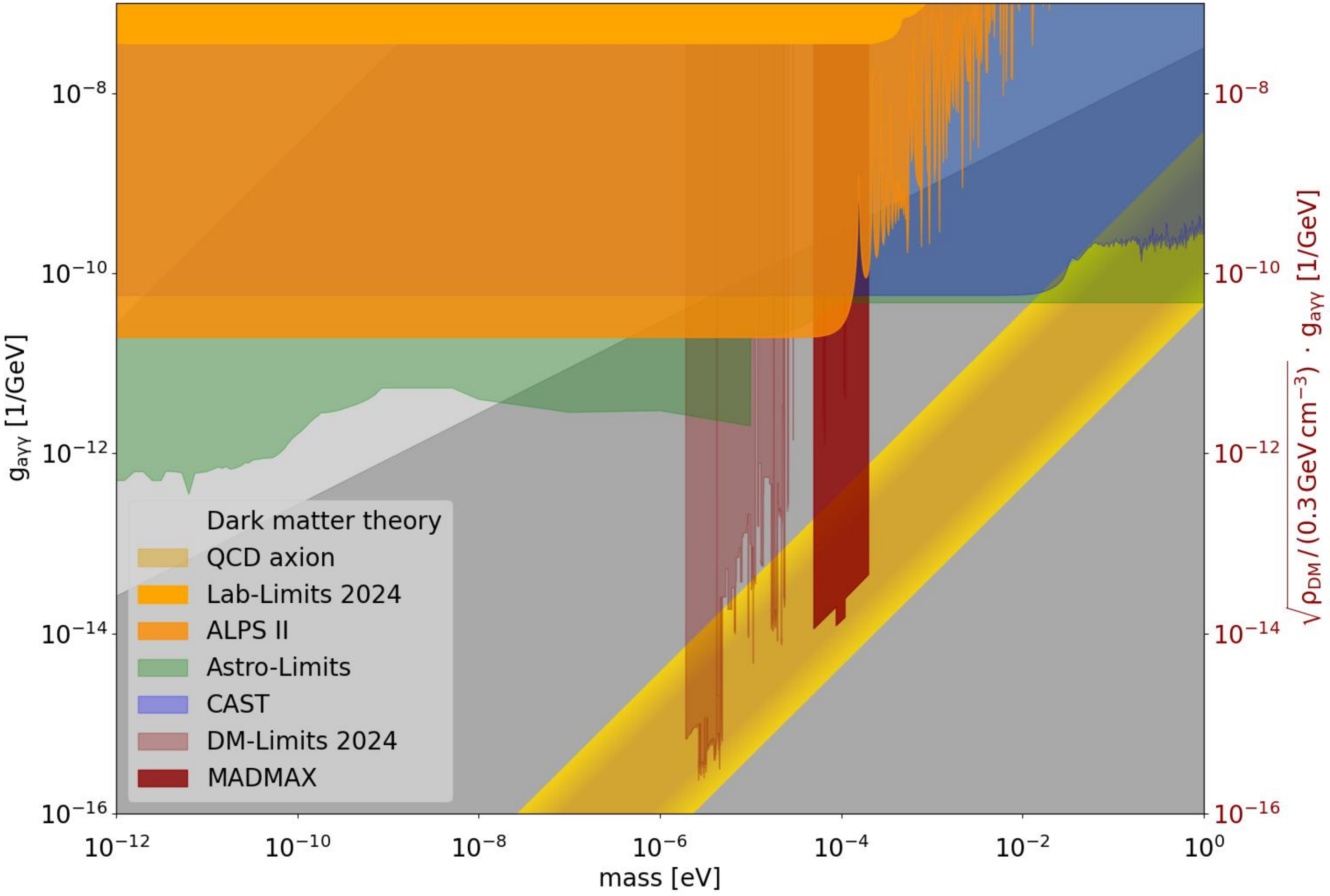
Reach out for vanilla QCD axions

Key activities:

- Scaling up the “booster”, cryogenic: further prototype measurements @ CERN.
- 10^{-24} W RF sensing.
- Building a huge dipole magnet.



Laboratory experiments, astrophysics, MADMAX 2035/40



Hypothetical light bosons for BSM physics

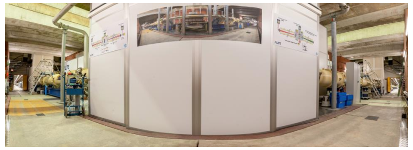
DESY ambition: a world-leading axion site

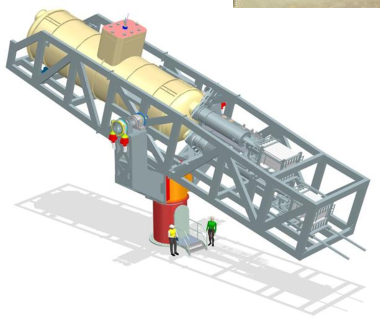
ALPS II target sensitivity

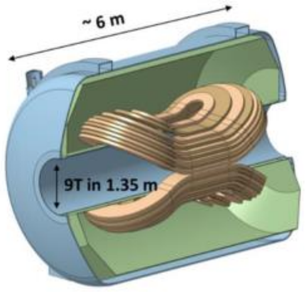
MADMAX target sensitivity

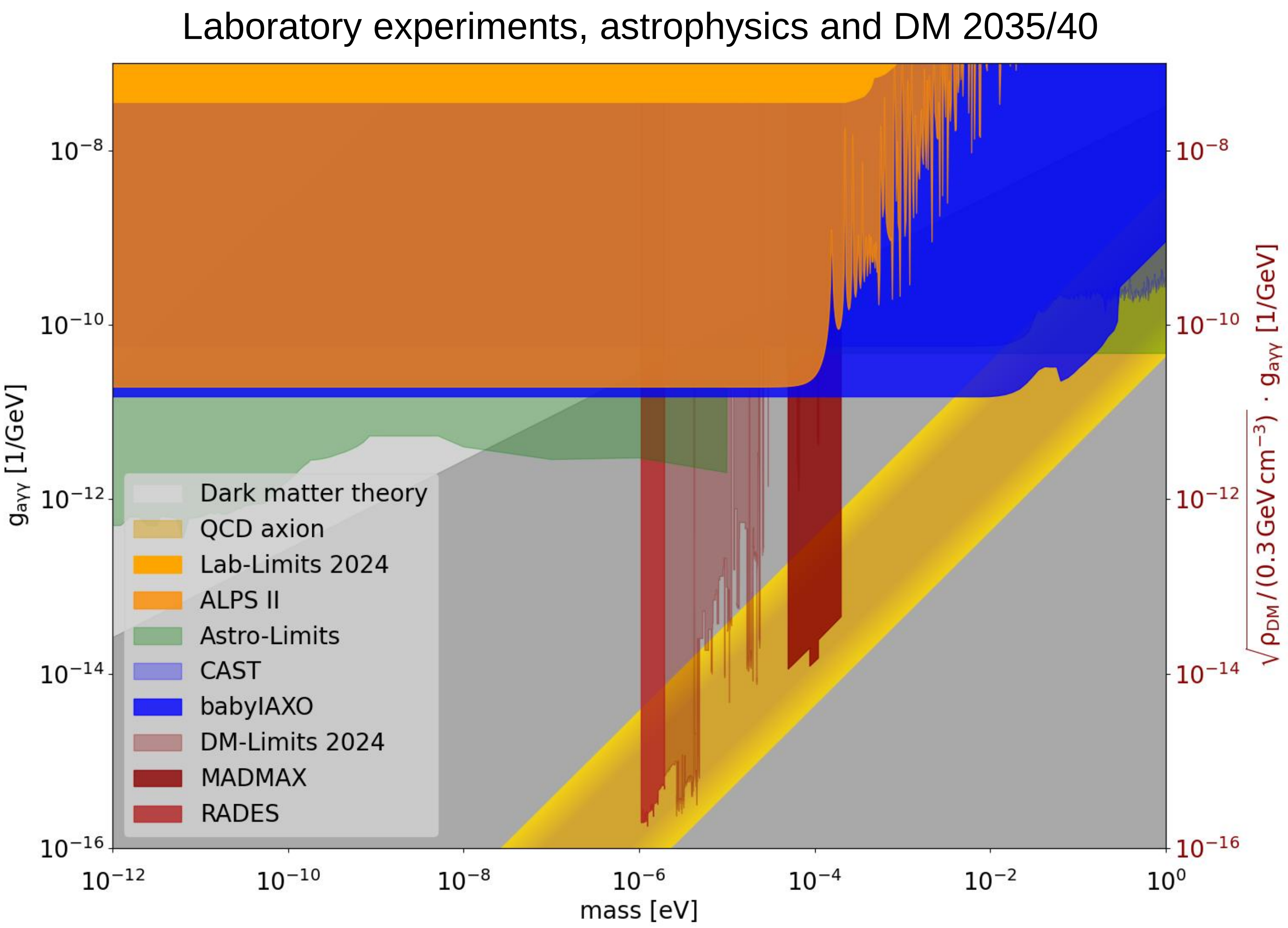
RADES target sensitivity (using the BabyIAXO magnet)

BabyIAXO target sensitivity





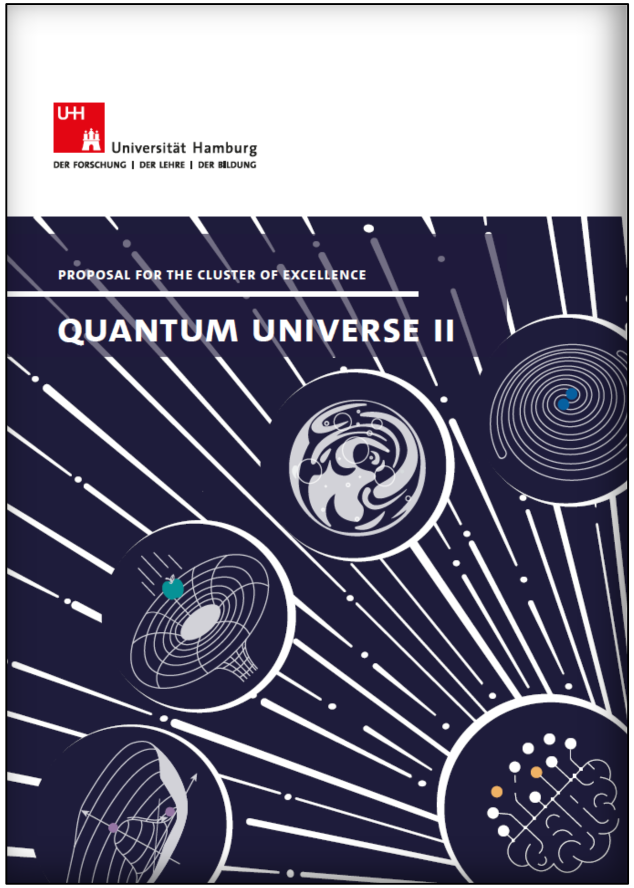




DESY searches for hypothetical light bosons:

driving a coherent strategy for the whole campus, embedded in quantum sensing R&D

DESY and Hamburg University:
towards world-leading axion cluster.



DESY is partner in the ERC synergy grant
“DarkQuantum” (lead by I. Irastorza, Zaragoza)

News

News from the DESY research centre

2023/10/26

Back

ERC project to provide quantum detectors for DESY dark matter experiment

European Research Council (ERC) Synergy project to develop quantum sensors and apply them in dark matter experiments

The European Research Council (ERC) has bestowed a prestigious Synergy grant that will develop novel quantum sensors for experiments searching for dark matter. The DarkQuantum project, which is coordinated by the University of Zaragosa in Spain, has been funded with almost 13 million euros. The aim of which is the development of new quantum sensors and their application in experiments to search for axions, hypothetical particles that could make up dark matter. One of the experiments benefitting from this effort is the experiment BabyIAXO, a dark matter observatory under construction at DESY.

Download [3.0 MB, 2032 x 1530]
A visualisation of the BabyIAXO experiment in the underground chamber where it will be located. The quantum detectors that will be developed through DarkQuantum will be installed within this experiment. (Picture: IAXO Collaboration)

The ERC's “Synergy” projects aim to bring together the expertise of several principal investigators (between 2 and 4) to tackle very ambitious research, which could not be carried out individually. The researcher Igor García Irastorza, professor of physics at the University of Zaragoza and leader of the DESY-based International Axion Observatory (IAXO), will lead the DarkQuantum project. The project is based on the Irastorza's extensive experience with this type of experiment, exploiting recent innovations in the field of quantum technologies. In addition to Irastorza, three other international experts in different aspects of quantum technologies are contributing, namely Takis Kontos of the École Normale Supérieure de Paris, Sorin Paraoanu of Aalto University in Finland, and Wolfgang Wernsdorfer of the Karlsruhe Institute of Technology.

DarkQuantum will develop new photon sensors based on recent advances, similar to those that now make it possible to build the quantum bits (or “qubits”) that make up the first quantum computers. Subsequently, these sensors will be installed in two experiments that will search for dark matter axions with a sensitivity never seen before. One of them is planned to be installed in the Canfranc Underground Laboratory, and will be the first experiment of its kind underground. The second will be installed inside the BabyIAXO magnet at DESY. BabyIAXO, a smaller preliminary version of the IAXO experiment, already received ERC funding in 2018.

Among other topics: quantum noise limited cryogenic amplifiers for RADES.

Axion technologies for more physics

Beyond hypothetical boson searches

Vacuum magnetic birefringence:
- High-precision long-baseline interferometry
- ALPS II magnet string

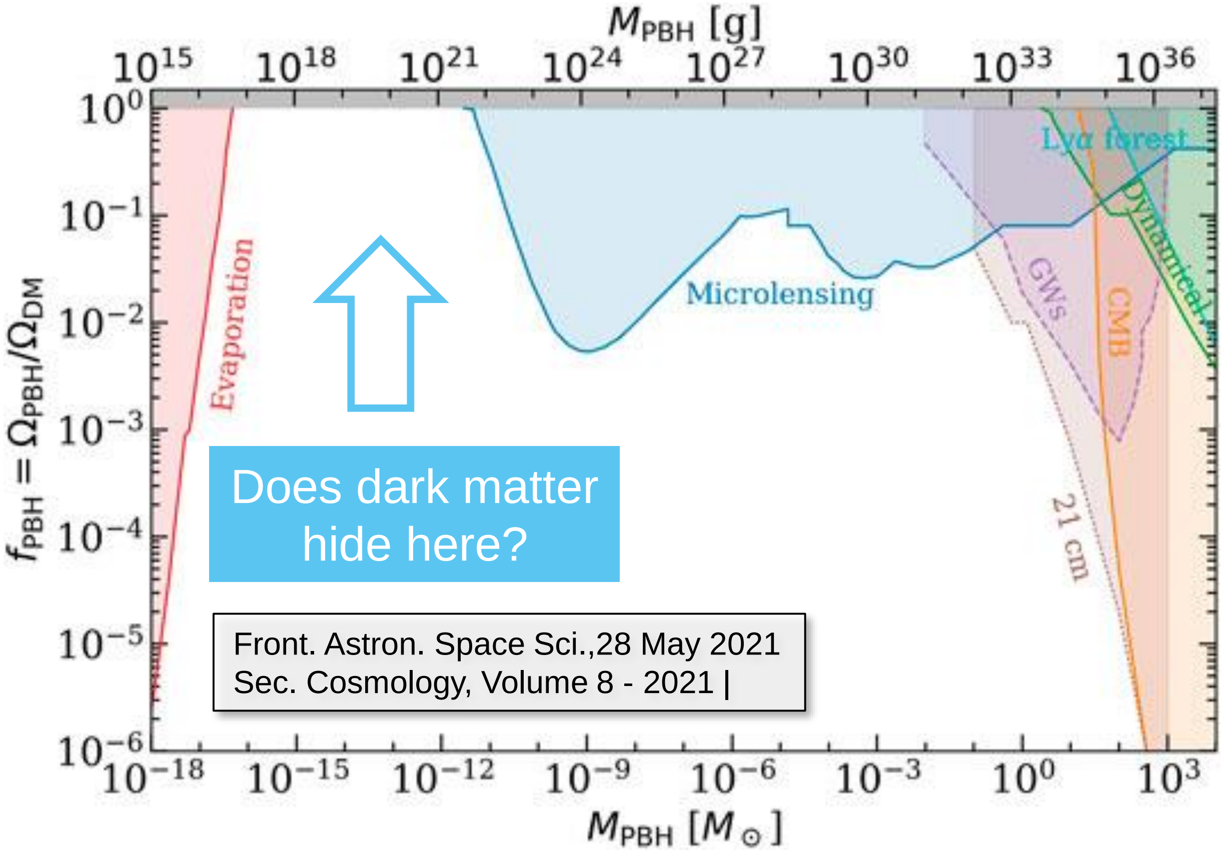
$\Delta n = 4 \cdot 10^{-24} \cdot B\ [T]$

Sub-MeV dark matter searches:
- Quantum sensing

Axion dark matter searches without magnets:
- High-precision long-baseline interferometry

High-frequency gravitational waves:
- High-precision long-baseline interferometry
- Magnets of ALPS II, BabyIAXO, MADMAX
- Quantum sensing.

…



ECRs and media attention

Successes beyond physics and technologies

Early careers at ALPS II

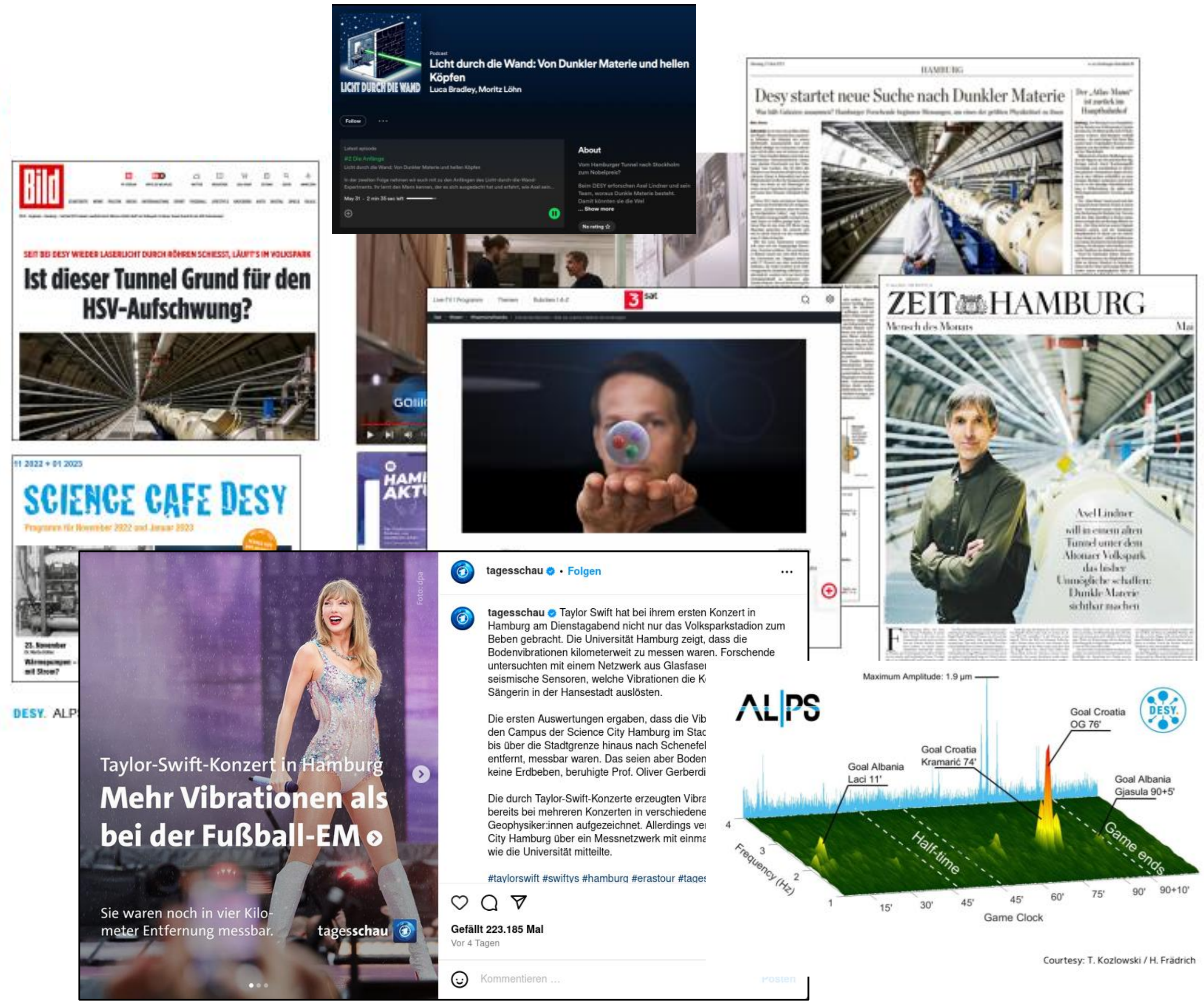
ALPS II doctoral researchers:

- 14 dissertations in experimental physics.
- 1 dissertation in engineering.
- At least 4 theses still to come.

Former ALPS II DESY fellows:

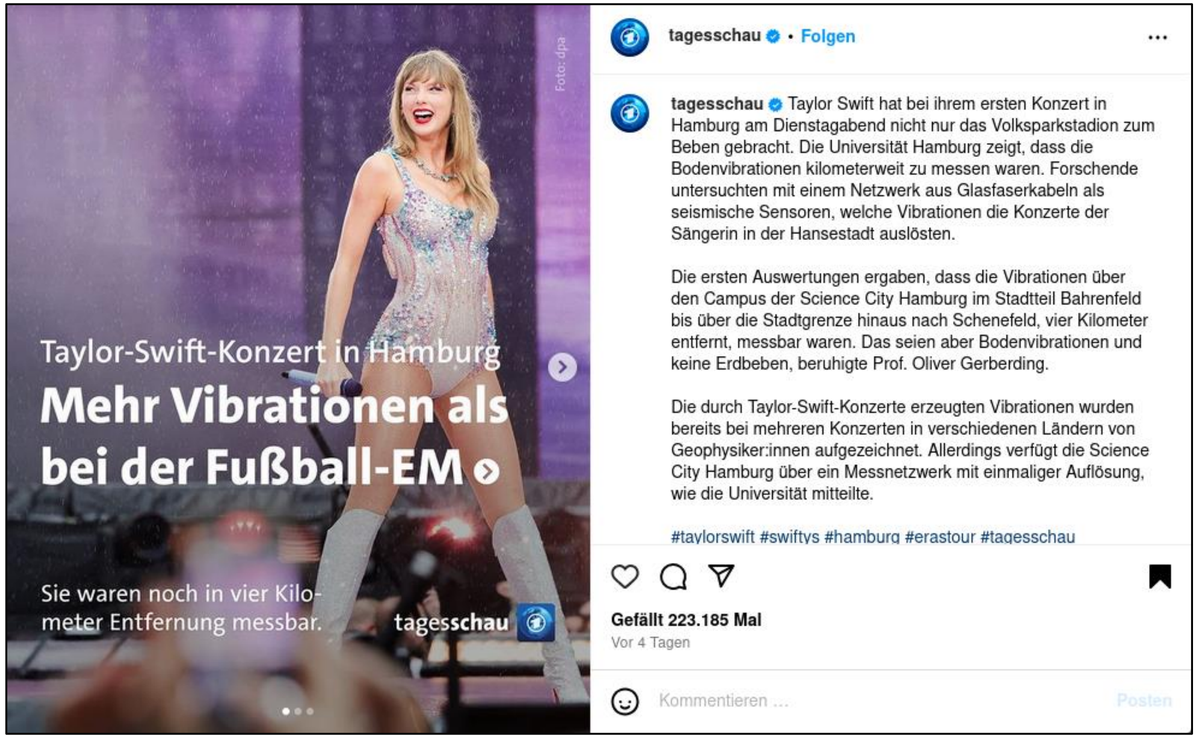
- 5 permanent positions in academia.
- 1 junior professorship.
- 3 left for other postdoc positions.
- 2 left to industry.

Media on the ALPS II

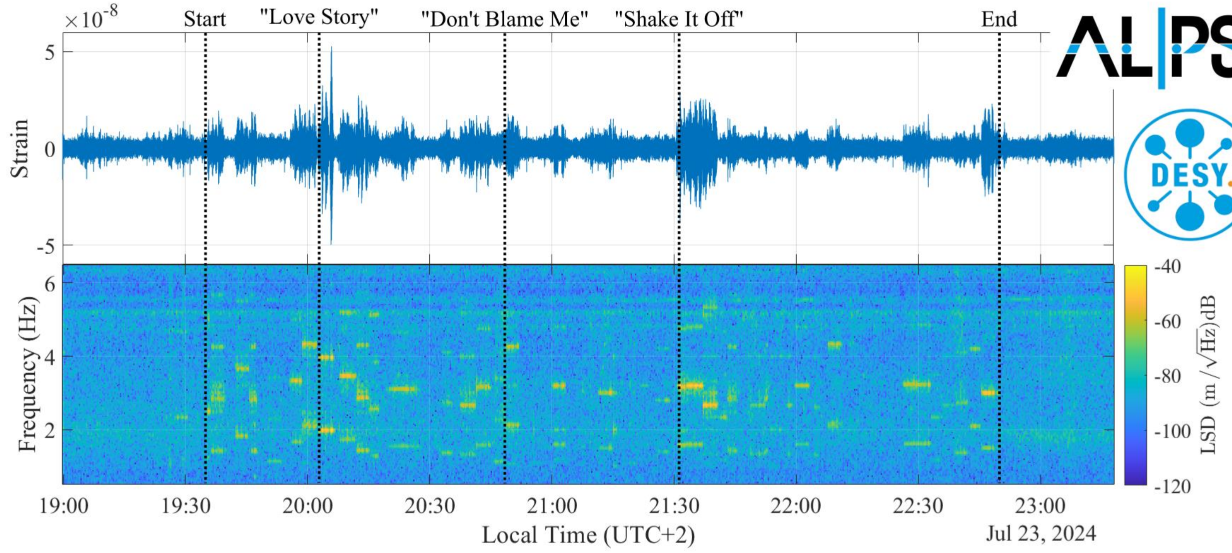


Taylor Swift @ ALPS II

Jumping crowds cause length changes of the regeneration cavity



https://www.instagram.com/p/C90CNVgiIXN/



Particle physics experiments are back at DESY!

ALPS II

MADMAX

LUXE

Baby IAXO

Science drivers:
Word-wide outstanding opportunities for QED tests and axion searches.

Achievements:
- ALPS II science results
- MADMAX prototype science results
- Cryogenic quantum sensing lab established

Future:
- Science with LUXE, BabyIAXO, MADMAX
- Cryoplatform

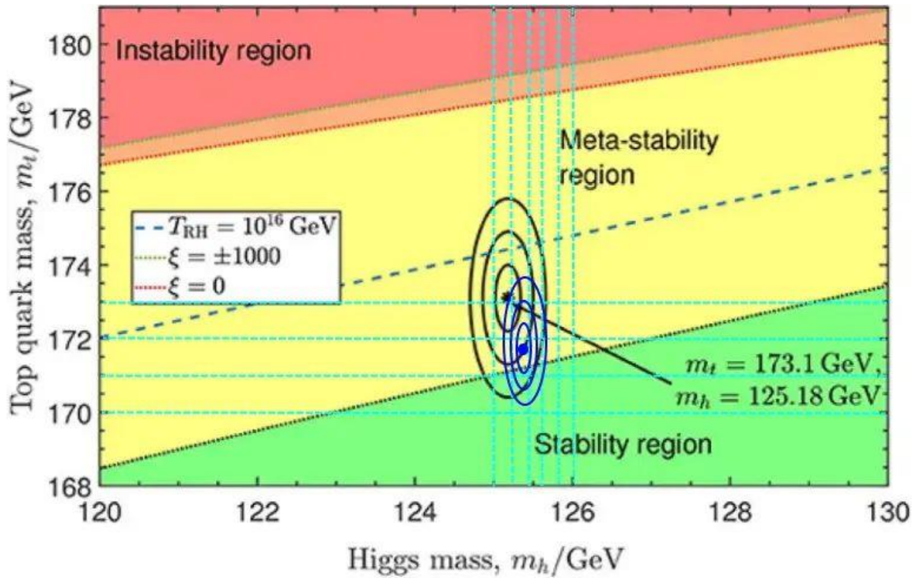
Enabled by combining existing infrastructure and new cutting edge technologies.

Where to find particle physics beyond the standard model?

The next relevant energy scale might be out of reach at accelerators

QCD (1 GeV) ⟶ Electroweak (174 GeV, LHC) ⟶ Planck 10^{19} GeV (10^{15}·LHC)

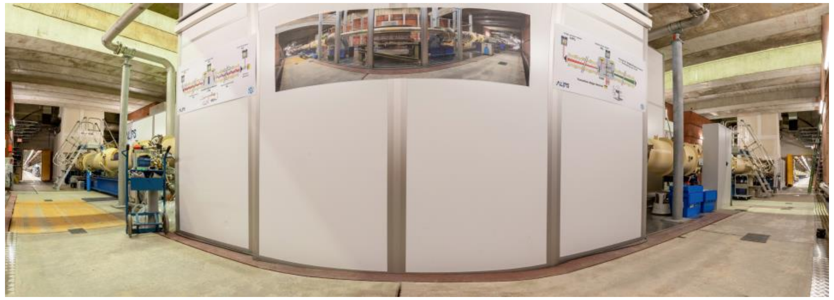
There is no hint for a “new physics energy scale” from accelerator based particle physics.



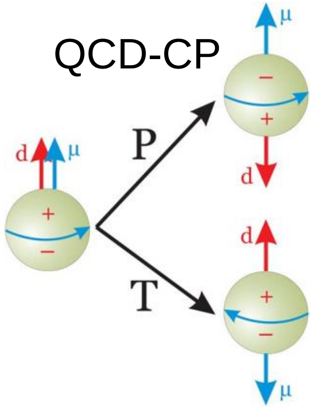
https://bigthink.com/starts-with-a-bang/universe-fundamentally-unstable/
https://arxiv.org/pdf/1809.06923

Axions might provide the key to understand “everything”

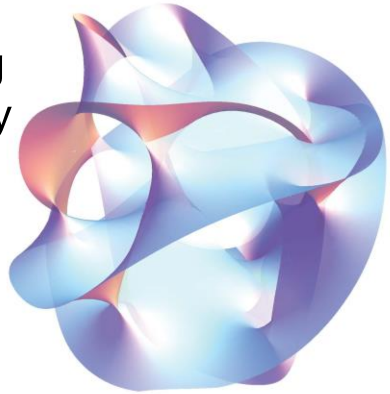
Cosmology, particle physics, unification of quantum mechanics and general relativity

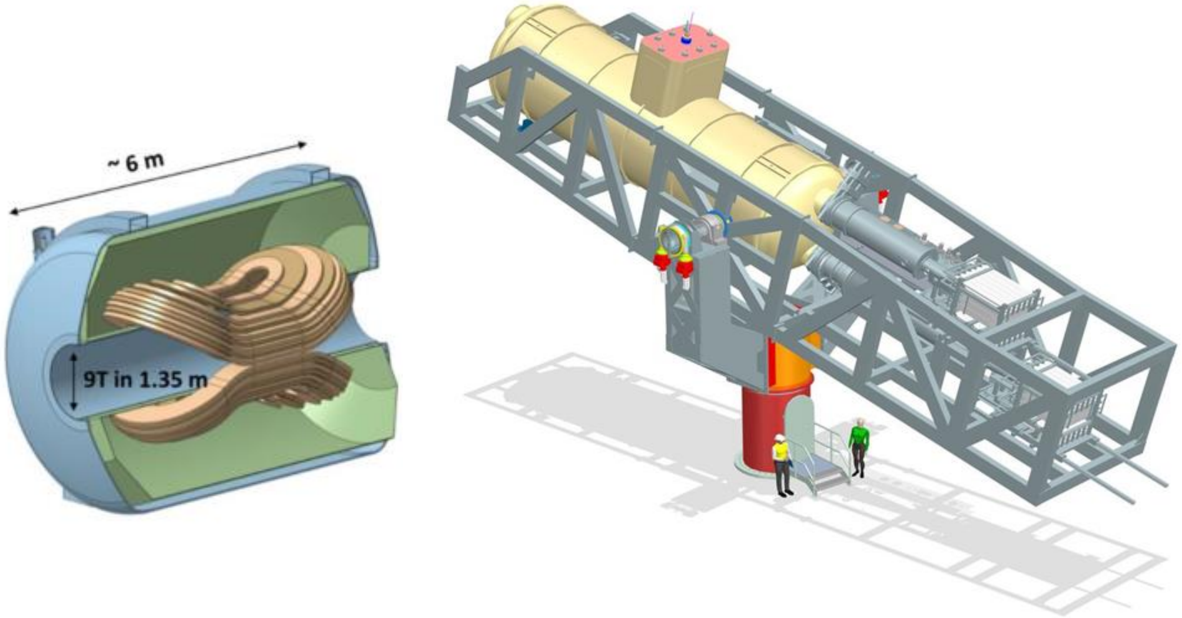


QCD-CP



String theory





Experiments will tell!

Thank you

…. any my many colleagues for their engagement in trying to make the invisible visible ….

Contact

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