Outline

- Light-shining-through-a-wall
  - 3 different kinds
- Any-light-particle search: the ALPS II experiment
- A Transition Edge Sensor (TES) for ALPS II
- More Dark Matter Searches with a TES
- Summary

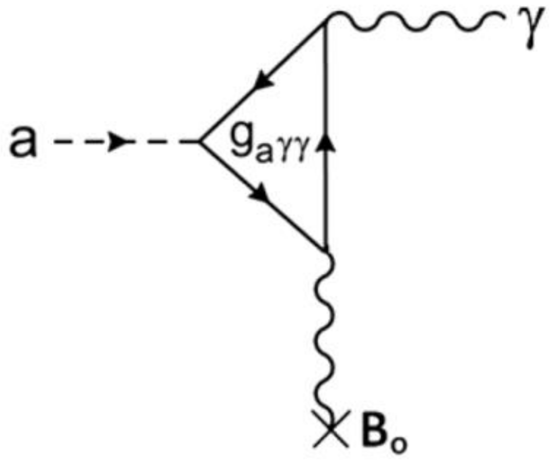
Outline

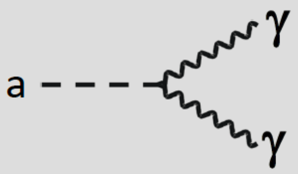
- Light-shining-through-a-wall — Axel
  - 3 different kinds
- Any-light-particle search: the ALPS II experiment — Axel
- A Transition Edge Sensor (TES) for ALPS II — Jose
- More Dark Matter Searches with a TES — Christina
- Summary

Axions

Photon coupling and Maxwell 1864

Exploited by many experiments as relatively “simple”.

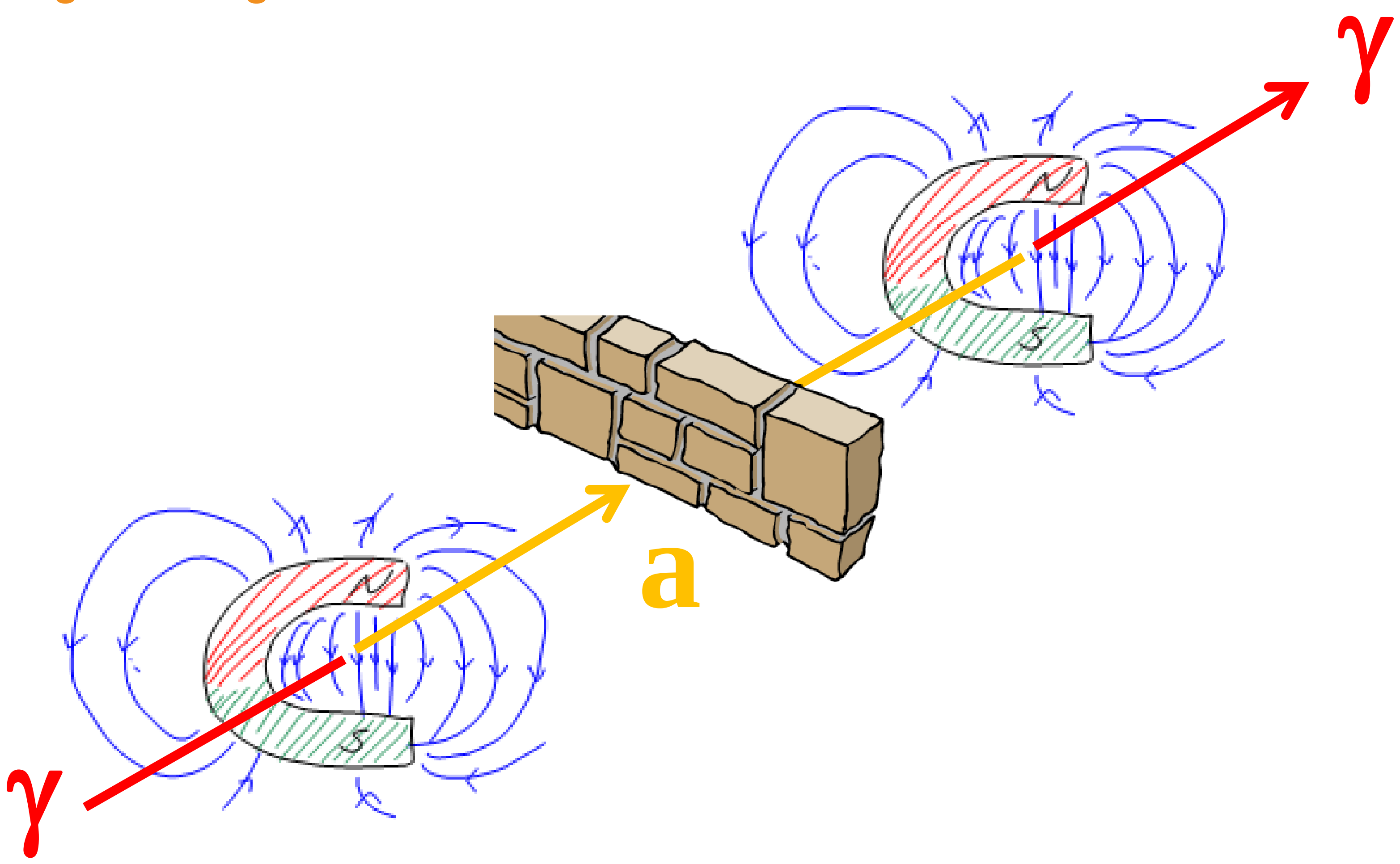


Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$ 

Photon-axion mixing in a background magnetic dipole filed

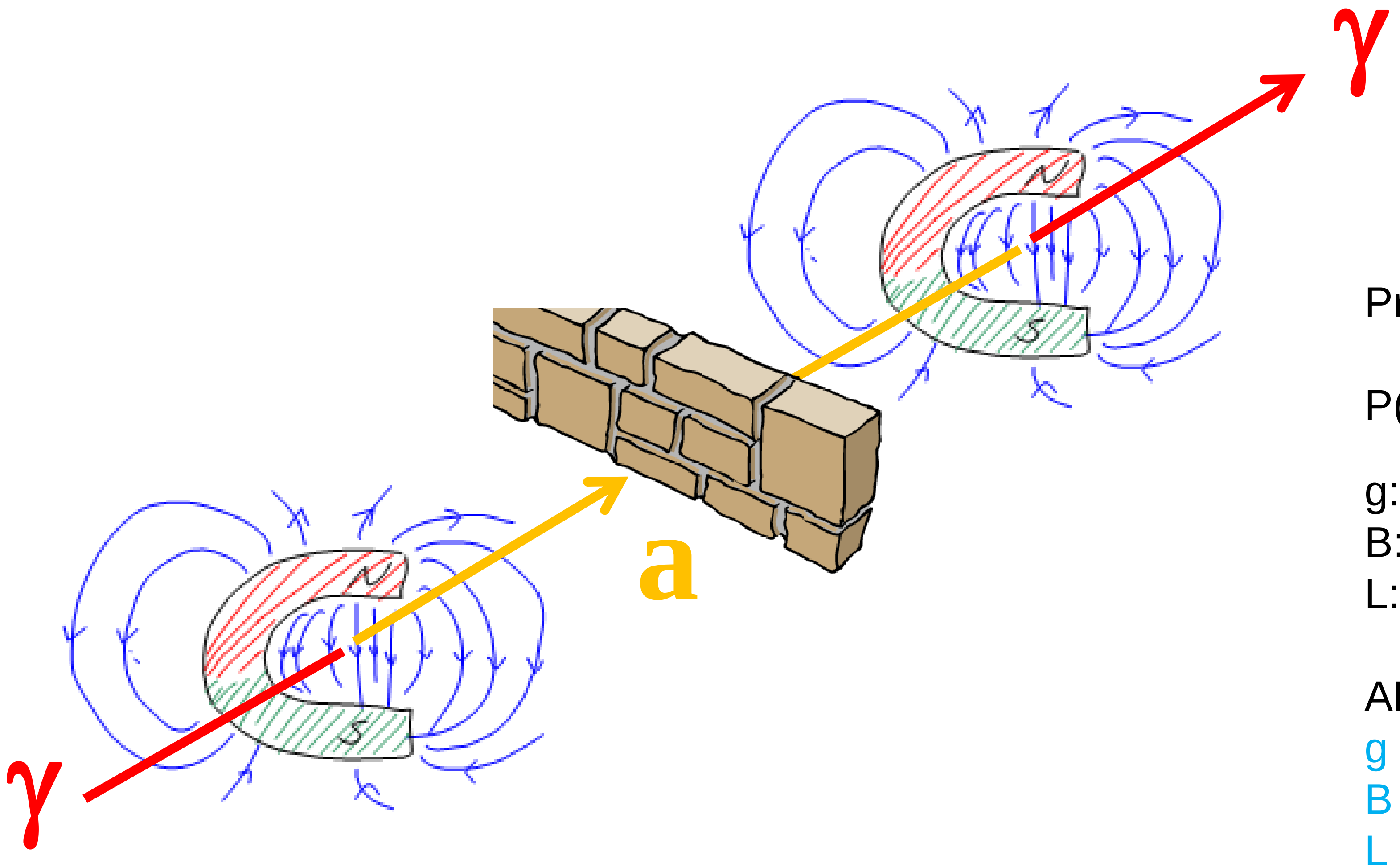
The concept

Light-through-a-wall



The challenge

Any-Light-Particle-Search ALPS II



Probability:

$P(\gamma \to a \to \gamma) \sim (g \cdot B \cdot L)^4$

g: axion-photon mixing (particle physics)
B: strength of the magnetic field
L: length of the magnetic field

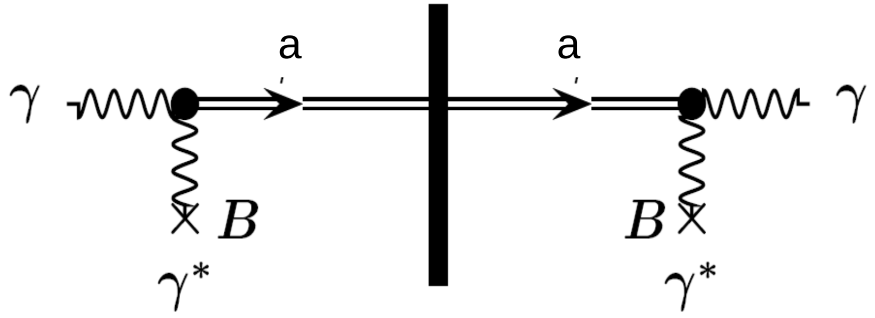
ALPS II:
$g = 2 \cdot 10^{-11}$ 1/GeV (astrophysics)
B = 5.3 T
L = 105.6 m
$P(\gamma \to a \to \gamma) = 5 \cdot 10^{-34}$

Still invisible?

How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

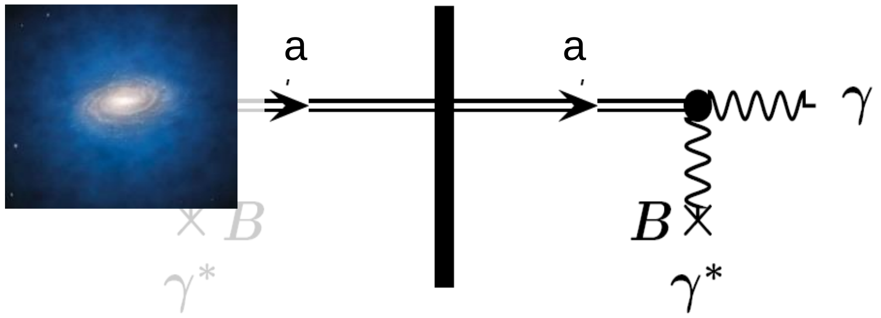
- Purely laboratory experiments "light-shining-through-walls", optical photons



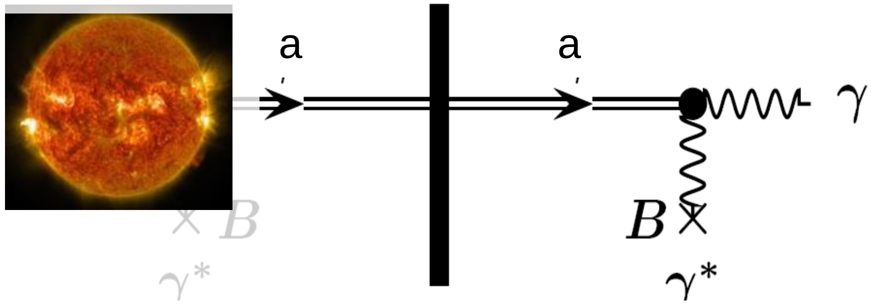
How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

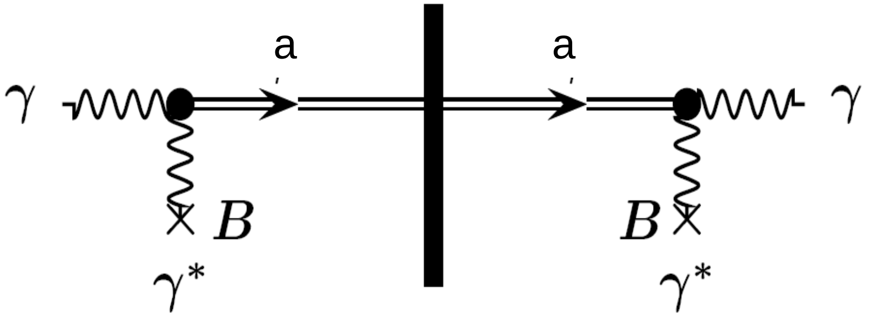
- Haloscopes
  looking for dark matter constituents,
  microwaves



- Helioscopes
  Axions emitted by the sun,
  X-rays



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

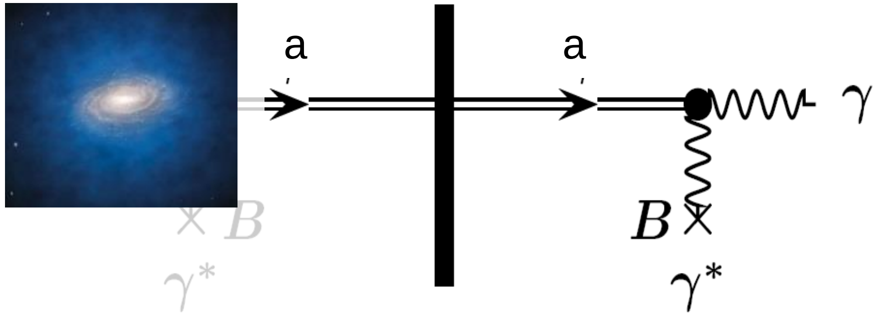


How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

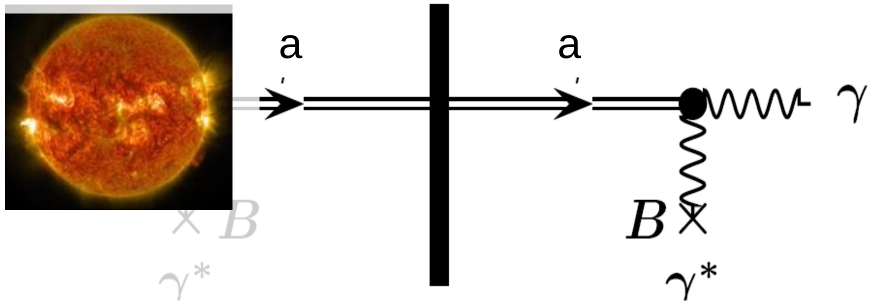
- Haloscopes
  looking for dark matter constituents,
  microwaves.

non-relativistic axions, “monochromatic” photons



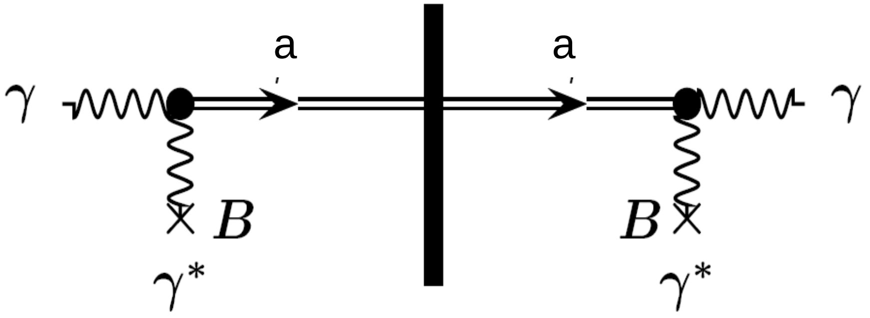
- Helioscopes
  Axions emitted by the sun,
  X-rays

relativistic axions, thermal photon spectrum



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

relativistic axions, monochromatic photons

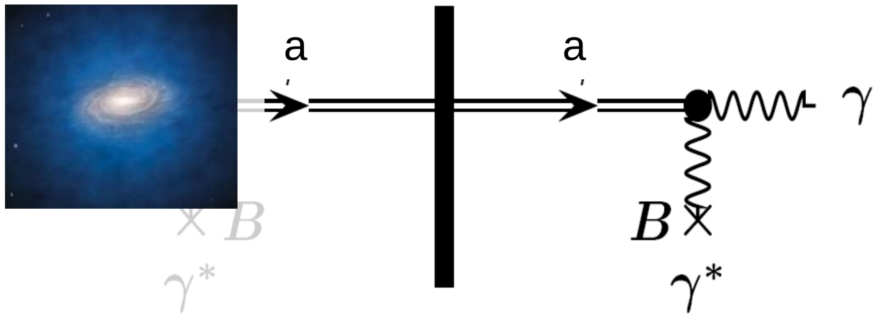


How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

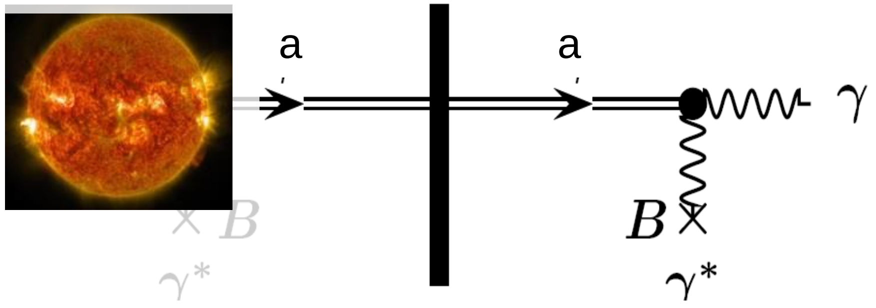
- Haloscopes
  looking for dark matter constituents,
  microwaves.

  10^{-23} W
  exploit resonant
  detection



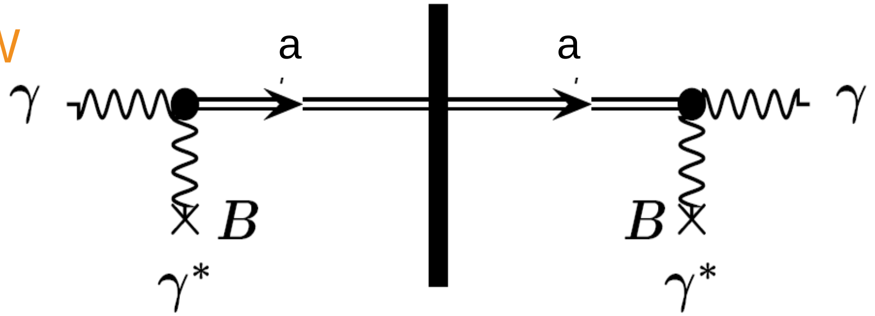
- Helioscopes
  Axions emitted by the sun,
  X-rays

  1 photon/year
  (10^{-23} W)



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

  1 photon/day, $5 \cdot 10^{-24}$ W
  exploit resonant
  detection

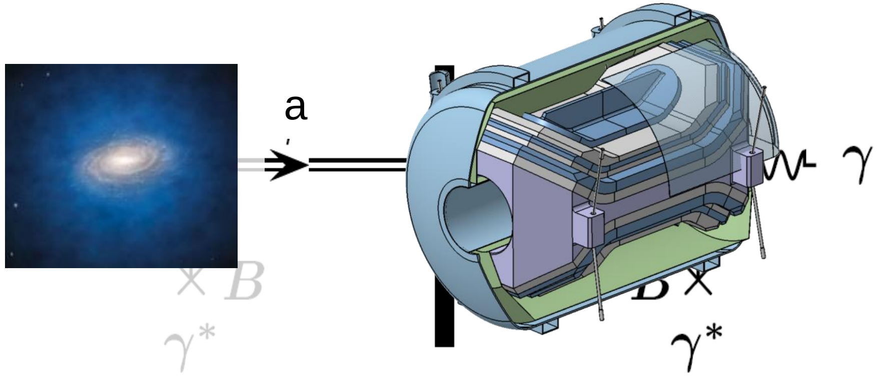


How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

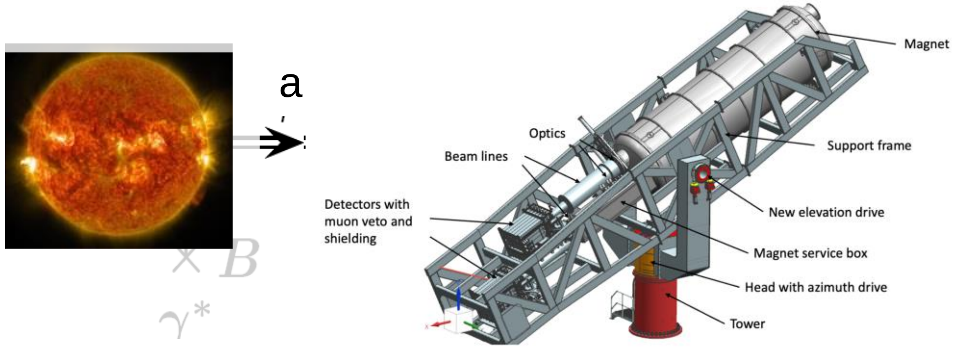
- Haloscopes
  looking for dark matter constituents,
  microwaves.

MADMAX



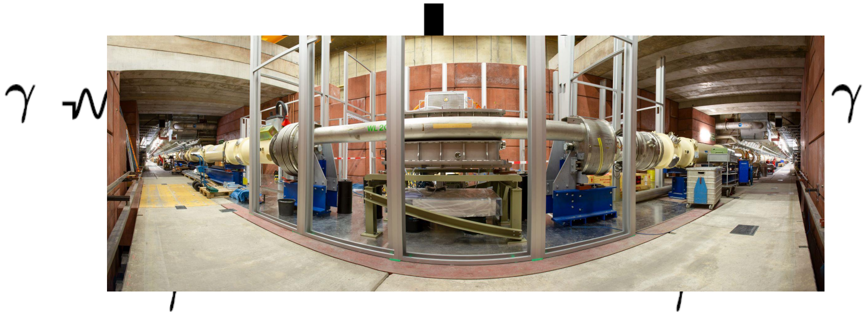
- Helioscopes
  Axions emitted by the sun,
  X-rays

BabyIAXO



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

ALPS II

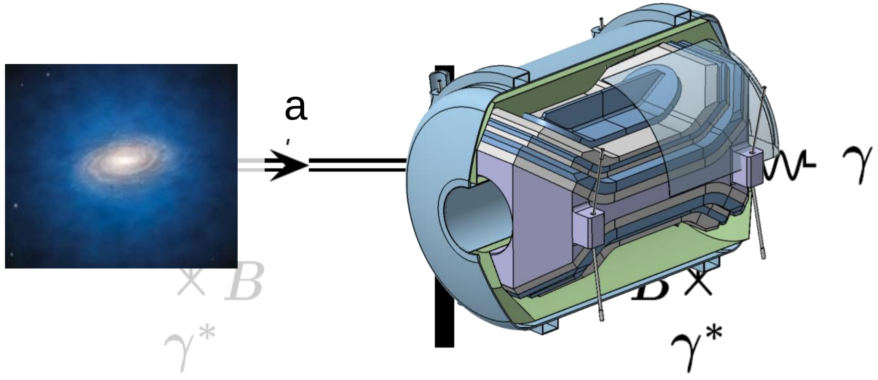


How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

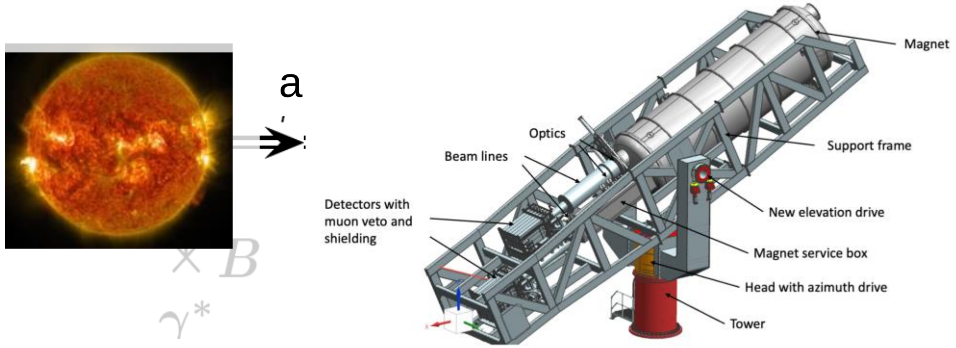
- Haloscopes
  looking for dark matter constituents, microwaves.

MADMAX



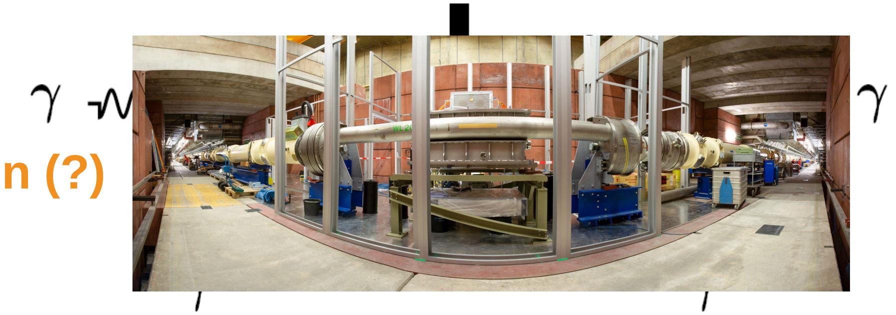
- Helioscopes
  Axions emitted by the sun, X-rays

BabyIAXO



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

ALPS II
1st science run soon (?)



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ALPS II collaboration meeting 06/22

Collaboration members

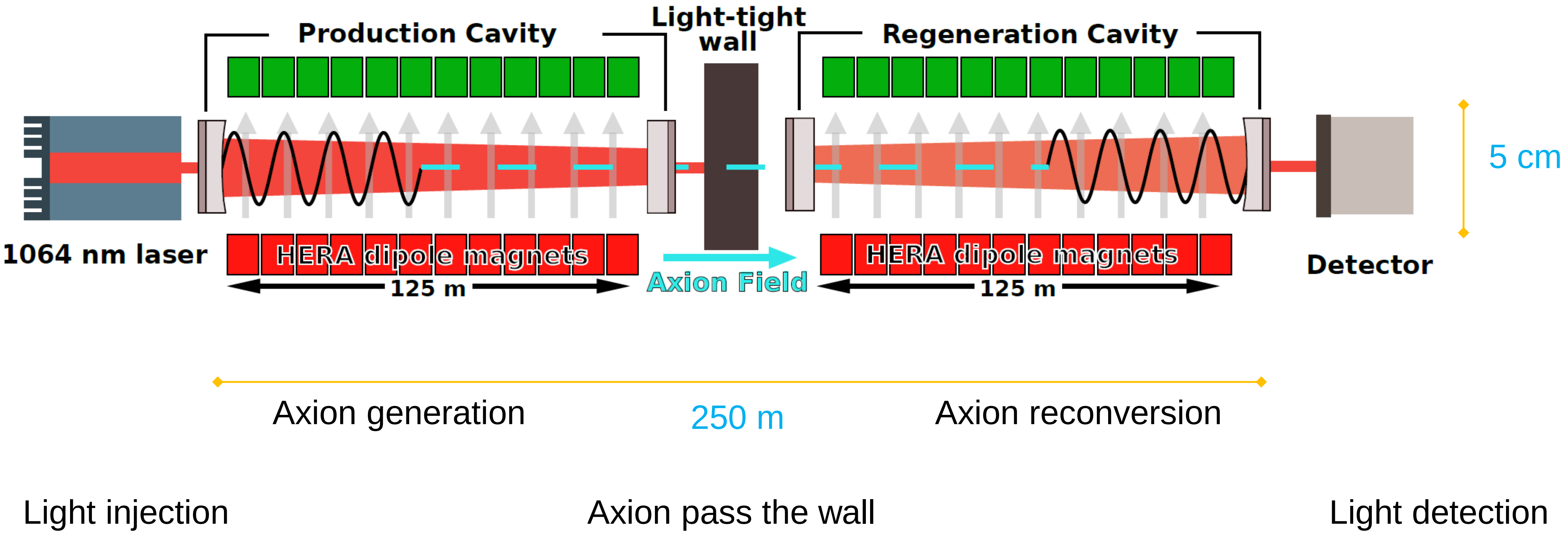
ALPS II

Supported by

Any Light Particle Search II

Light-through-a-wall

Probing axion-photon couplings model independently.

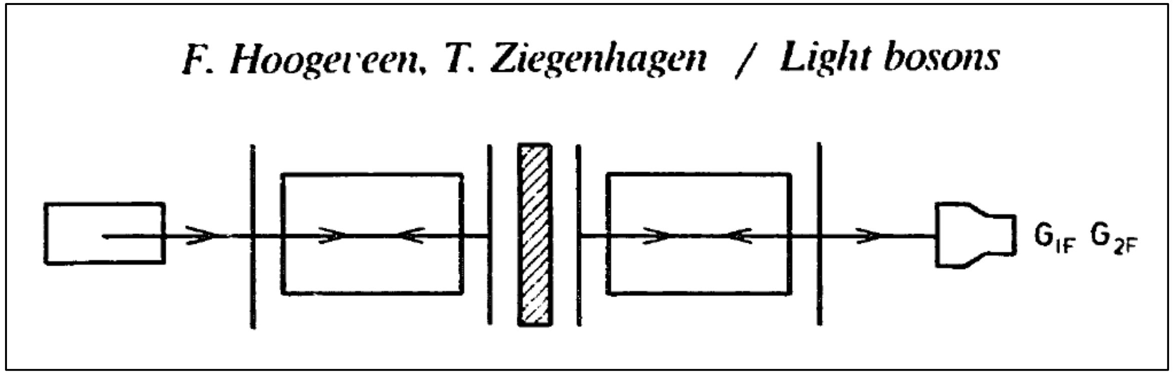


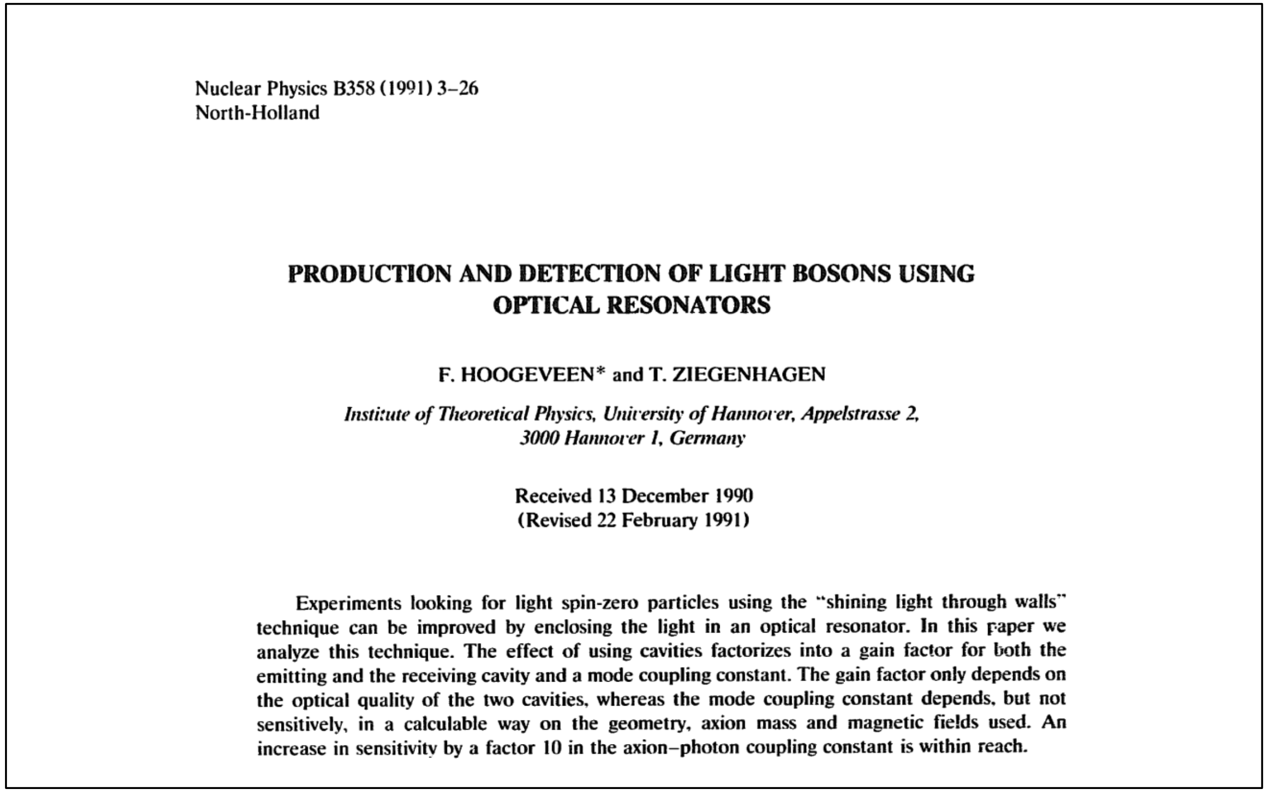
Any Light Particle Search II

Founding fathers (among others)

The light-shining-through-a-wall approach exploiting optical resonators was already proposed in 1991.

And later re-invented (at least) twice.





Nuclear Physics B358 (1991) 3–26
North-Holland

PRODUCTION AND DETECTION OF LIGHT BOSONS USING OPTICAL RESONATORS

F. HOOGEVEEN* and T. ZIEGENHAGEN

Institute of Theoretical Physics, University of Hannover, Appelstrasse 2, 3000 Hannover 1, Germany

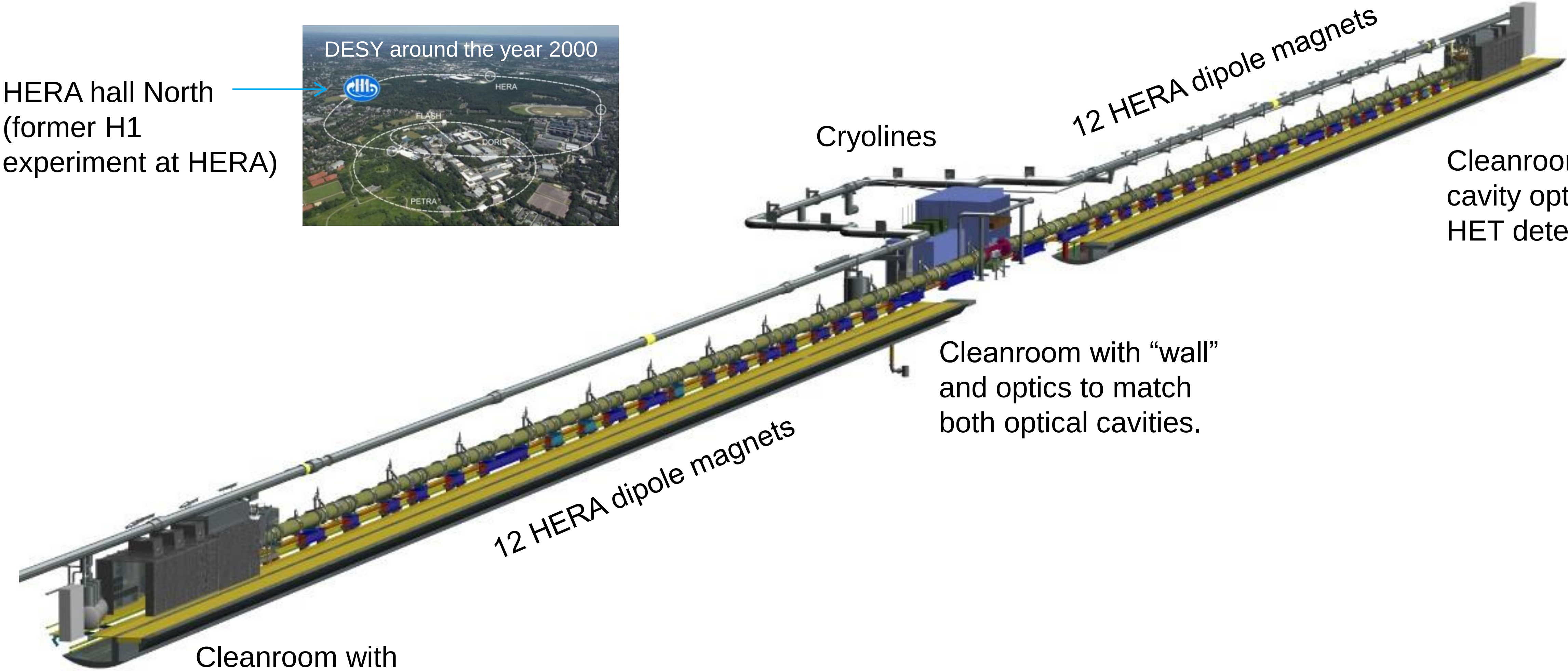
Received 13 December 1990
(Revised 22 February 1991)

Experiments looking for light spin-zero particles using the "shining light through walls" technique can be improved by enclosing the light in an optical resonator. In this paper we analyze this technique. The effect of using cavities factorizes into a gain factor for both the emitting and the receiving cavity and a mode coupling constant. The gain factor only depends on the optical quality of the two cavities, whereas the mode coupling constant depends, but not sensitively, in a calculable way on the geometry, axion mass and magnetic fields used. An increase in sensitivity by a factor 10 in the axion–photon coupling constant is within reach.

Any Light Particle Search II

Constructed in a straight section of the HERA tunnel

HERA hall North
(former H1
experiment at HERA)



Any **L**ight **P**article **S**earch **II**

Status of autumn 2020

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

Magnets going underground

Any Light Particle Search II

More magnets

Any Light Particle Search II

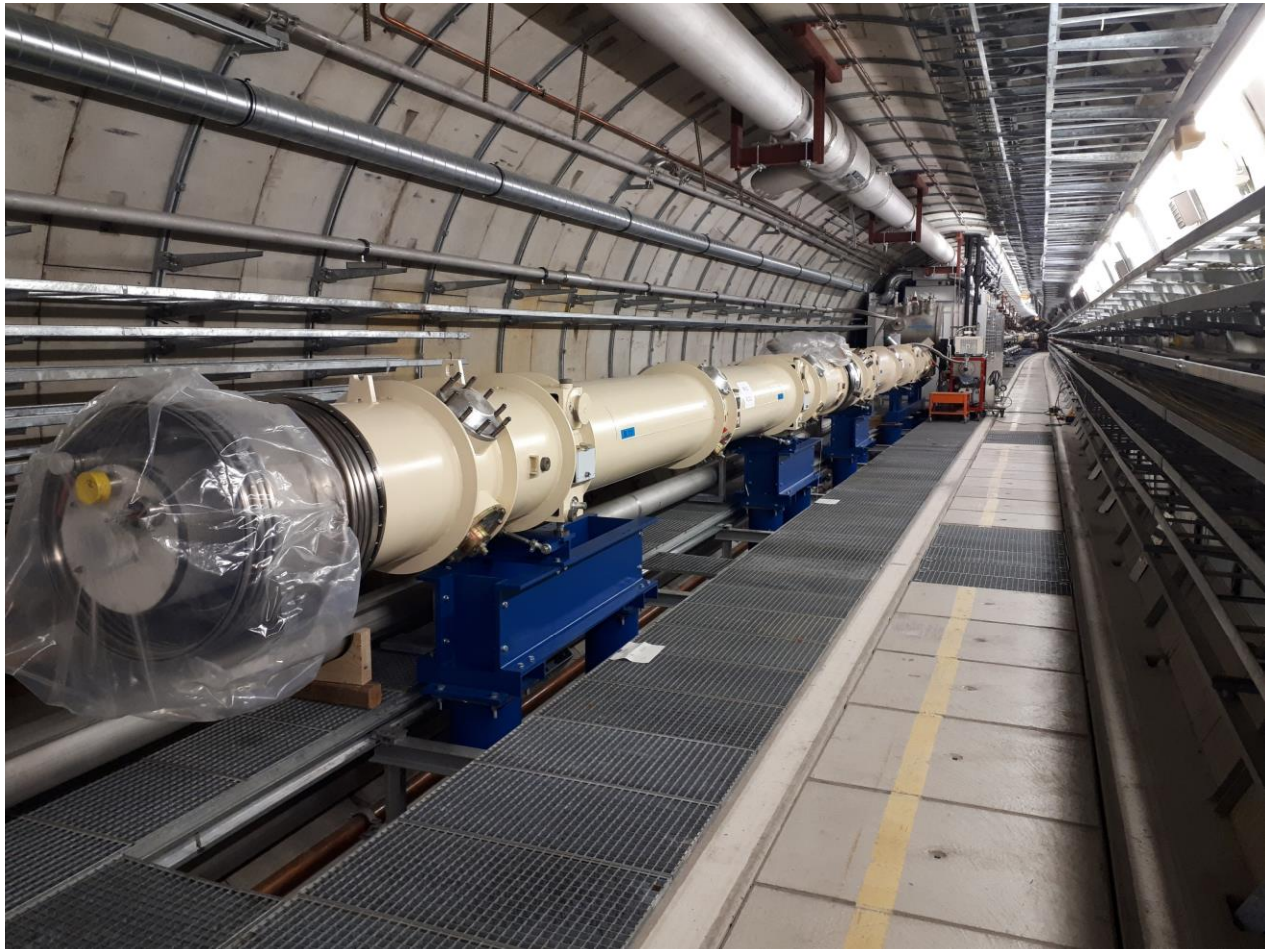
More magnets

Any Light Particle Search II

More magnets

Any Light Particle Search II

More magnets



Any Light Particle Search II

More magnets

Any **L**ight **P**article **S**earch **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

July 2021

Any Light Particle Search II

Technologies

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

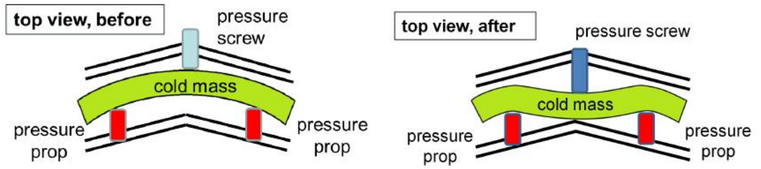
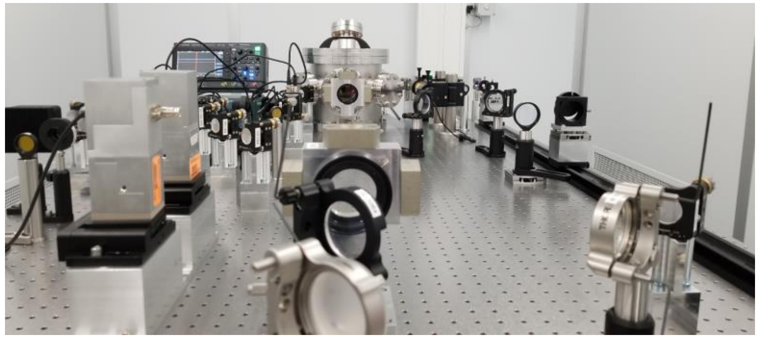


Figure 9: *Schematics of straightening. Left: Before applying the deforming force, Right: The deformation forces the pipe to develop two 'camel humps,' exaggerated in the figure for better illustration. This deformation yields the largest achievable horizontal aperture.*

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

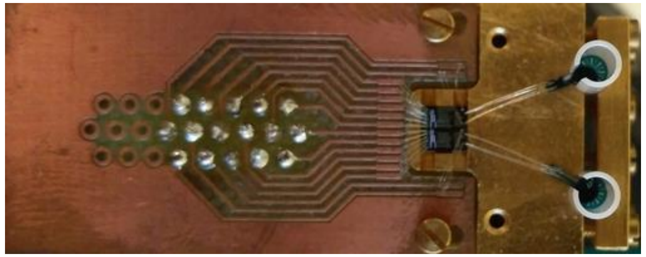
Figure 10: *Outer pressure prop parts (left) and prop inserted into the cryostat (right).*

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



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

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



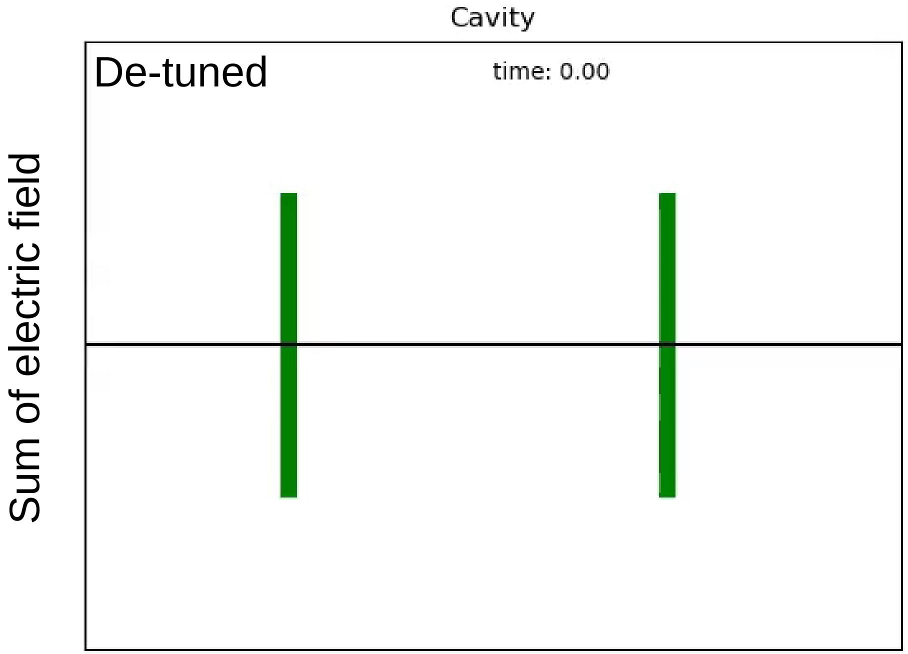
Phys.Dark Univ. 35 (2022), 100914

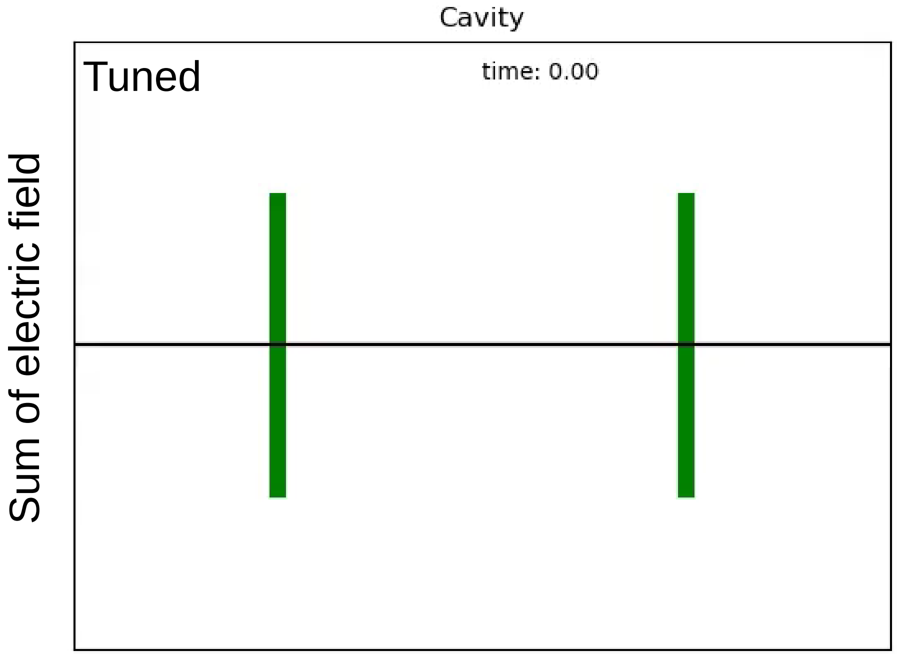
PoS EPS-HEP2021 (2022), 801

ALPS II Optics

Optical resonators

Two semitransparent mirrors, 80% reflection in the animation.



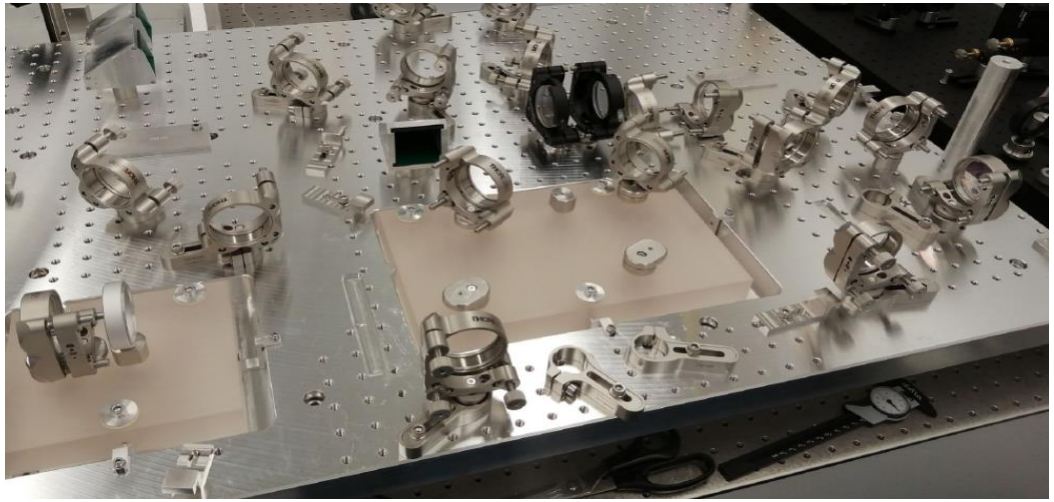


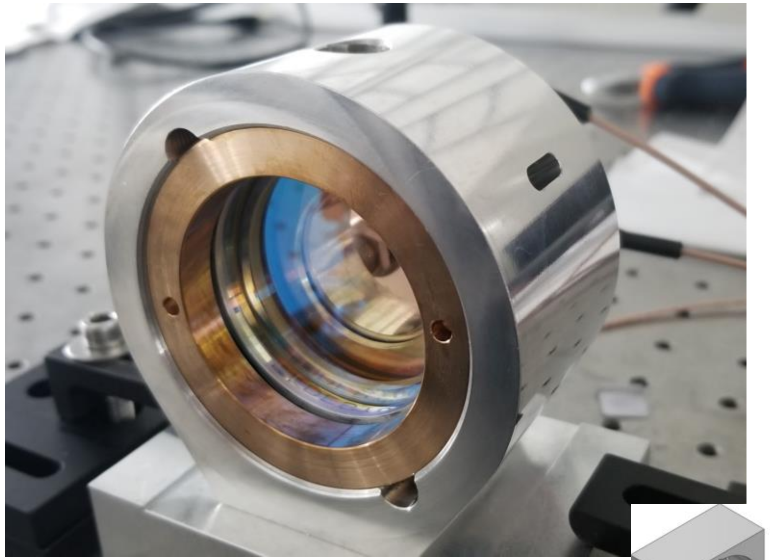
Tuned:

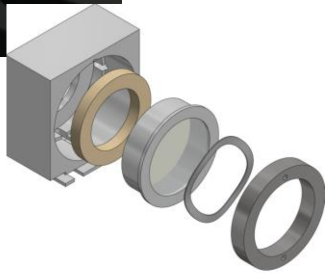
- The mirror system becomes transparent, the electric field is amplified between the mirrors.
- ALPS II: power built-up factor up to 40,000, requiring sub-pm length control.

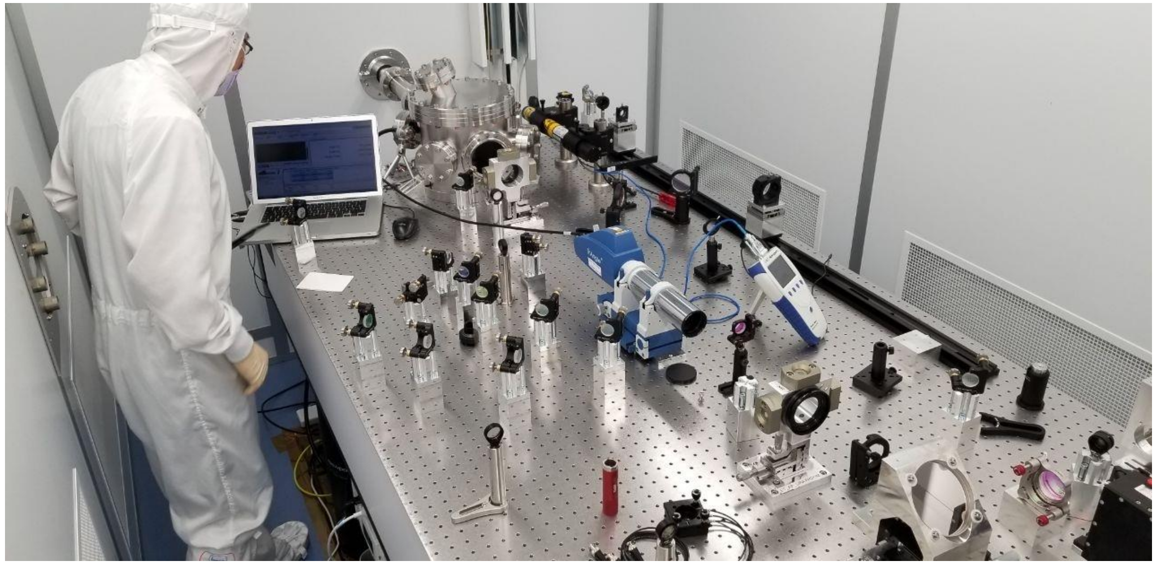
Any Light Particle Search II

Optics





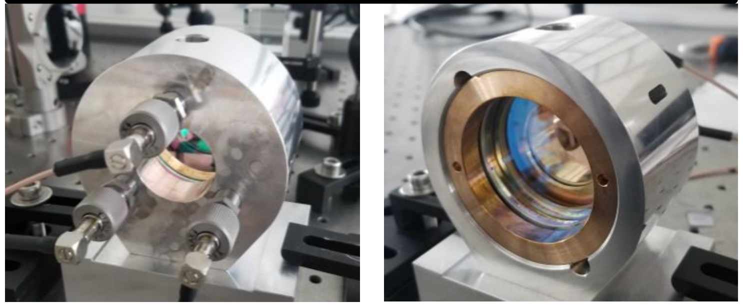




Any Light Particle Search II

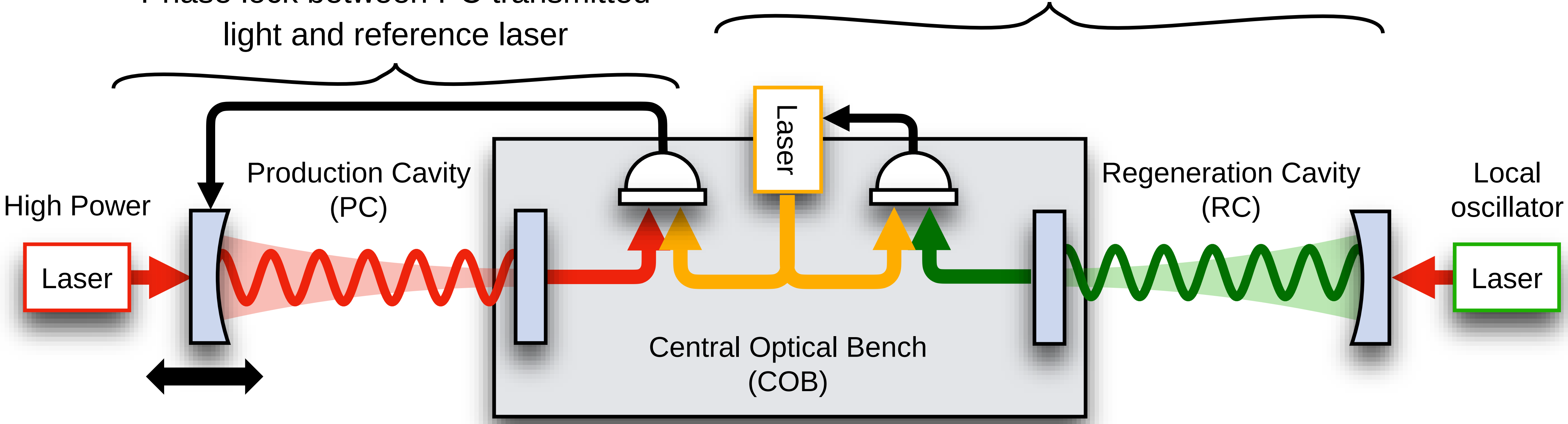
Optics “locking” scheme to overcome seismic noise

Actuators: *picometer* position accuracy required



Phase lock between PC transmitted light and reference laser

Additional reference laser coupled to RC length



Any Light Particle Search II

Optics requirements for the first full science run

RC resonant enhancement (β_{RC})	> 10 000
RC absolute length changes (ΔL_{RC})	~ 15 µm
RC linewidth (HWHM)	15 Hz
PC circulating power	> 150 kW
PC relative power noise (RMS)	< 0.1%
Axion Coupling to RC (η)	> 90%
Coherence ($\eta_{\Delta f}$)	> 95%
Dynamic phase noise ($\Delta\varphi$)	< 0.2 rad
Static frequency offset (Δf)	< 1.5 Hz
Spatial overlap (η_T)	> 95%
Angular alignment ($\Delta\theta$)	< 5.7 µrad
Transversal shift (Δx)	< 1.2 mm
Detector sensitivity	> 2×10^{-24} W for 20 days
Environmental temperature conditions	< 0.1 K
Stray light mitigation	< 1 photon / 10 days

15 Hz out of $3{\cdot}10^{14}$ Hz

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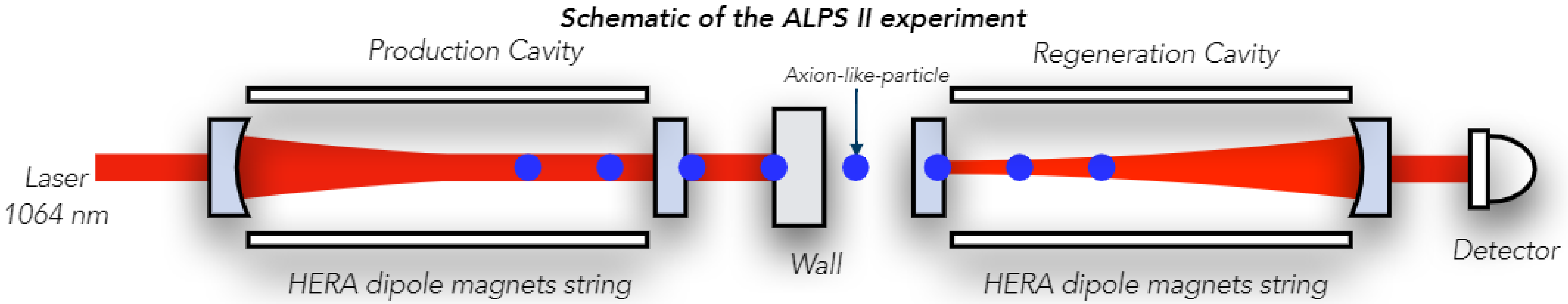
ALPS II



$$P_{\gamma\to\phi\to\gamma} = \frac{1}{16}\cdot\mathcal{F}_{PC}\mathcal{F}_{RC}\cdot(g_{a\gamma\gamma}Bl)^4 = 6\cdot10^{-38}\cdot\underbrace{\mathcal{F}_{PC}}_{5000}\underbrace{\mathcal{F}_{RC}}_{40000}\cdot\left(\underbrace{\frac{g_{a\gamma\gamma}}{10^{-10}GeV^{-1}}}_{0.2}\underbrace{\frac{B}{1T}}_{5.3}\underbrace{\frac{l}{10m}}_{105.6}\right)^4$$

$$P_{\gamma\to\phi\to\gamma} = 1.9 * 10^{-25}$$

$$\boxed{g_{a\gamma} = (0.29 \pm 0.18)\times 10^{-10}\ \mathrm{GeV}^{-1}}$$

$\text{PC: } 30\ W \longrightarrow RC: 5.7 * 10^{-24}\ W$

$\sim 3.5 * 10^{-5} Hz \approx 3\ photons\ per\ day$

Schematic adapted from Rikhav Shav

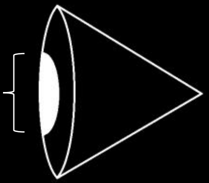
$800\ lm$

23% of power
converted to light

$2.3\ W \rightarrow 6.24 * 10^{18}\ \gamma/s$

Narrow pupil
$2\ mm$ diameter

$4.8 * 10^{12}\ \gamma/s$



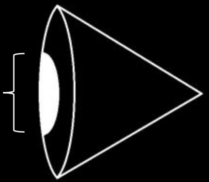
$1\ m$

$800\ lm$

23% of power
converted to light

$2.3\ W \ \rightarrow 6.24 * 10^{18}\ \gamma/s$

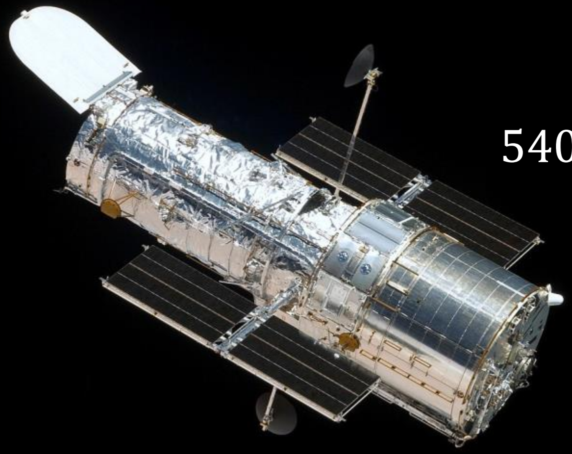
Narrow pupil
$2\ mm$ diameter



$4.8 * 10^{12}\ \gamma/s$

$1\ m$

$1\ \gamma/s \longrightarrow 2.19 * 10^{3}\ km$



$540\ km$

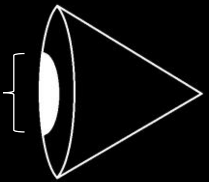
https://en.wikipedia.org/wiki/File:HST-SM4.jpeg

$800\ lm$

23% of power converted to light

$2.3\ W \rightarrow 6.24 * 10^{18}\ \gamma/s$

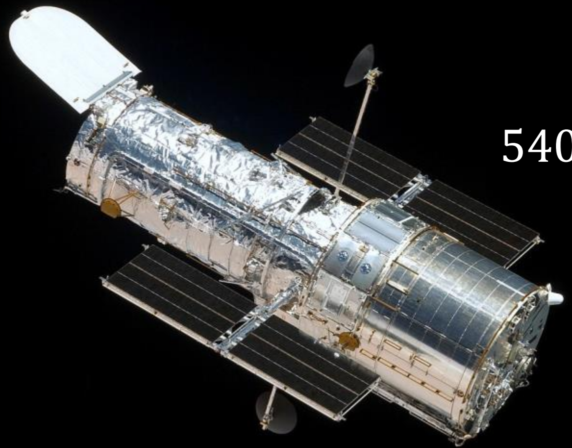
Narrow pupil
$2\ mm$ diameter



$4.8 * 10^{12}\ \gamma/s$

$1\ m$

$1\ \gamma/s \longrightarrow 2.19 * 10^{3}\ km$



$540\ km$

$10^{-5}\ \gamma/s \longrightarrow 6.92 * 10^{5}\ km$

$3.84 * 10^{5}\ km$

https://en.wikipedia.org/wiki/File:HST-SM4.jpeg

https://en.wikipedia.org/wiki/Moon#/media/File:FullMoon2010.jpg

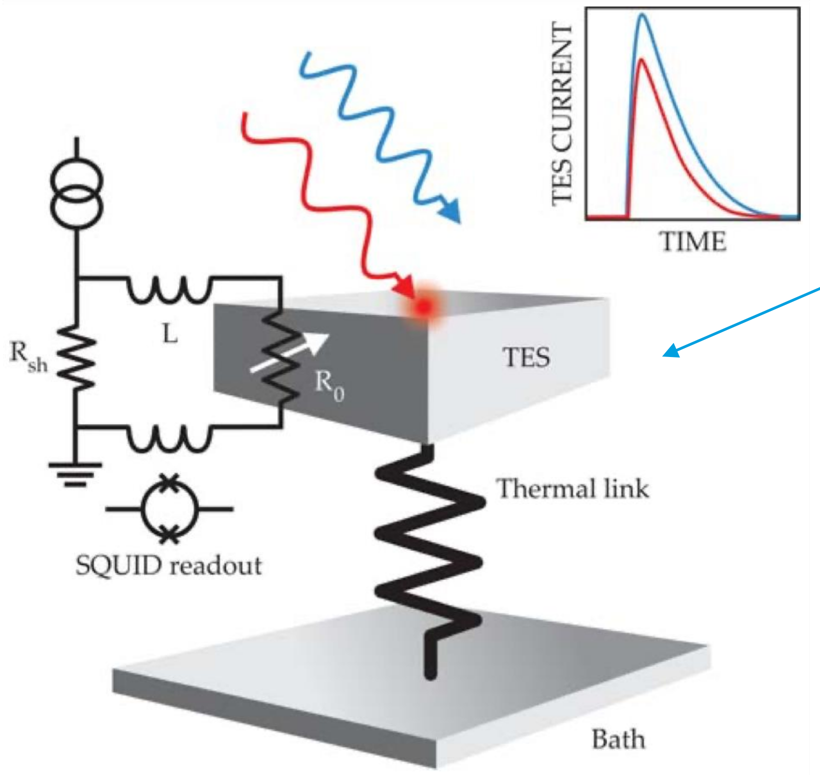
Single photon detector

Requirements for ALPS II:

- Sensibility to very low rates (1-2 photons a day).
- Low energy photon detection (1064 nm equivalent to 1.16 eV).
- Low background rate: $< 7.7 \cdot 10^{-6}\mathrm{cps} \sim 1\ \mathrm{photon}\ (1064\mathrm{nm} - \mathrm{like})\ \mathrm{every}\ 2\ \mathrm{days}$.
- High detection efficiency.
- Long term stability ($\sim 20\ days$).

The Transition Edge Sensor (TES) could meet these requirements.

Transition Edge Sensor (TES)



Tungsten microchip at critical transition region ($\sim 140\ mK$)

Temperature increase: Single photon ($1064nm \approx 1.16eV$) heats TES by $\sim 100\ \mu K$

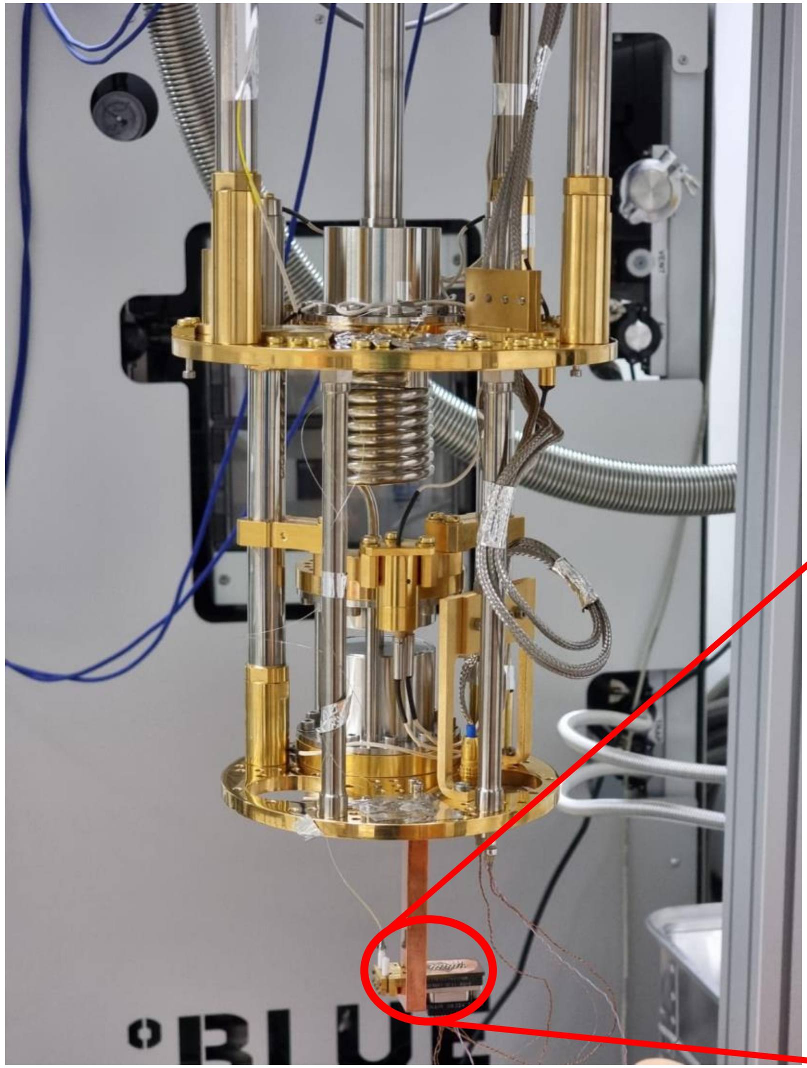
$\sim 6.6\ \Omega$ resistance increase: from superconducting to normal conducting

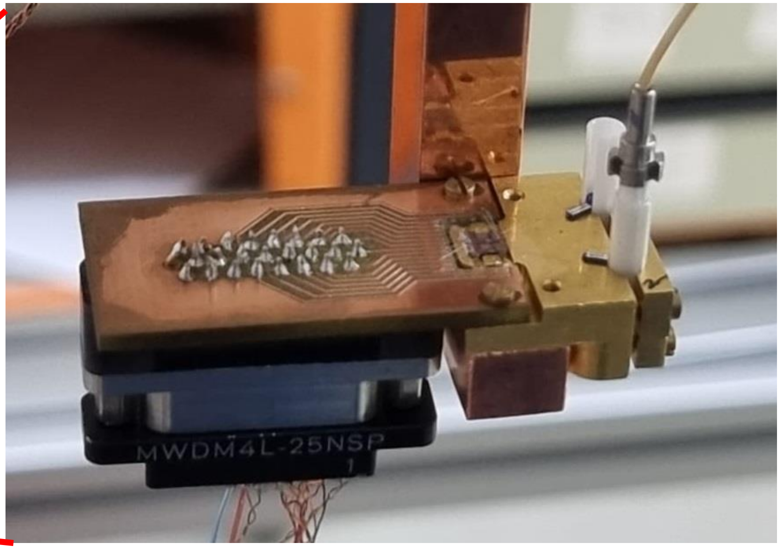
Current change (voltage-biased circuit)

Schematic adapted from Katharina-Sophie Isleif.

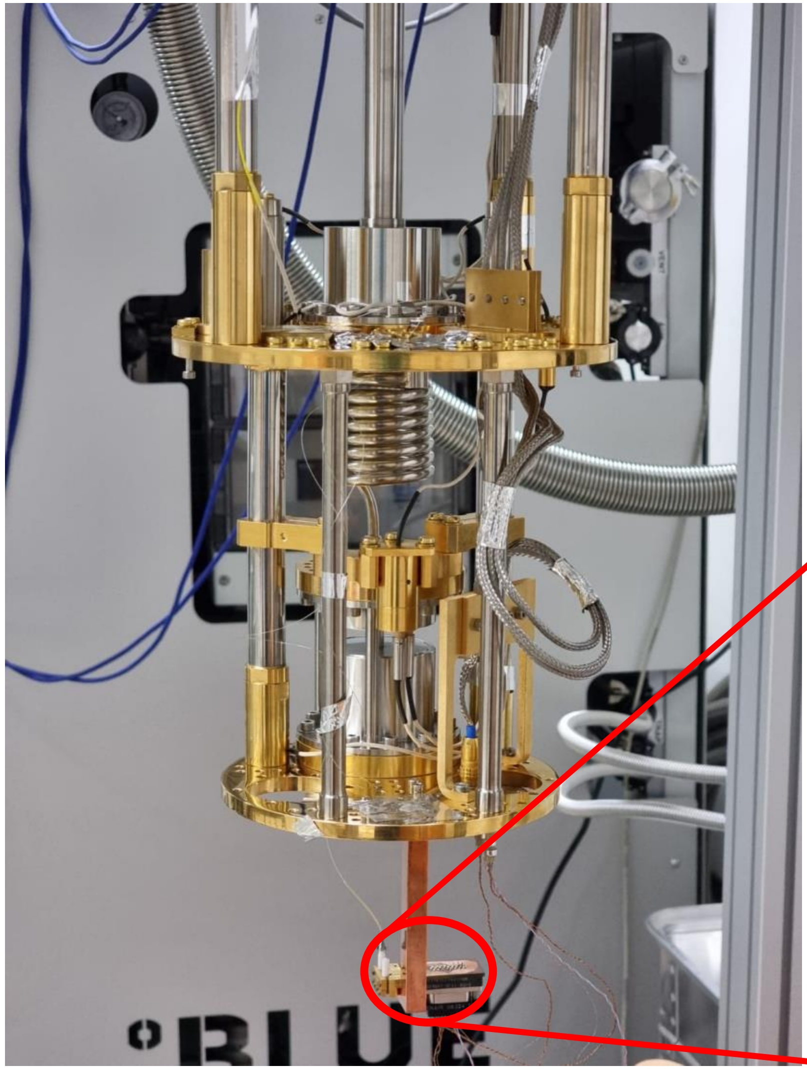
Transition Edge Sensor (TES)

$\sim 1\ m$

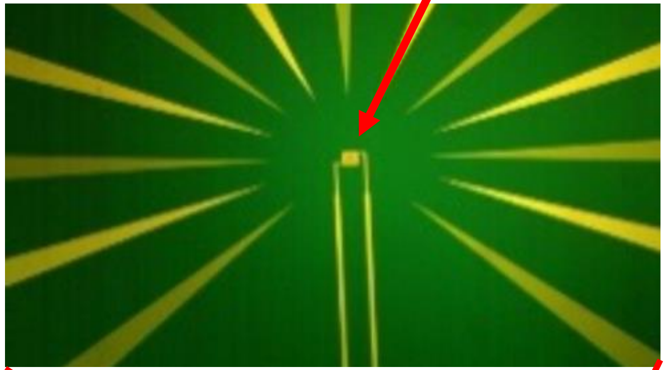


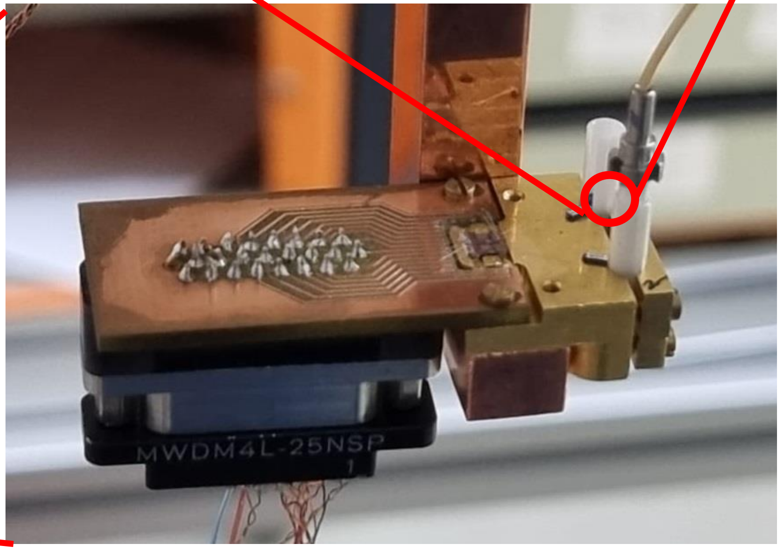


Transition Edge Sensor (TES)



$25\ \mu m \times 25\ \mu m \times 20\ nm$





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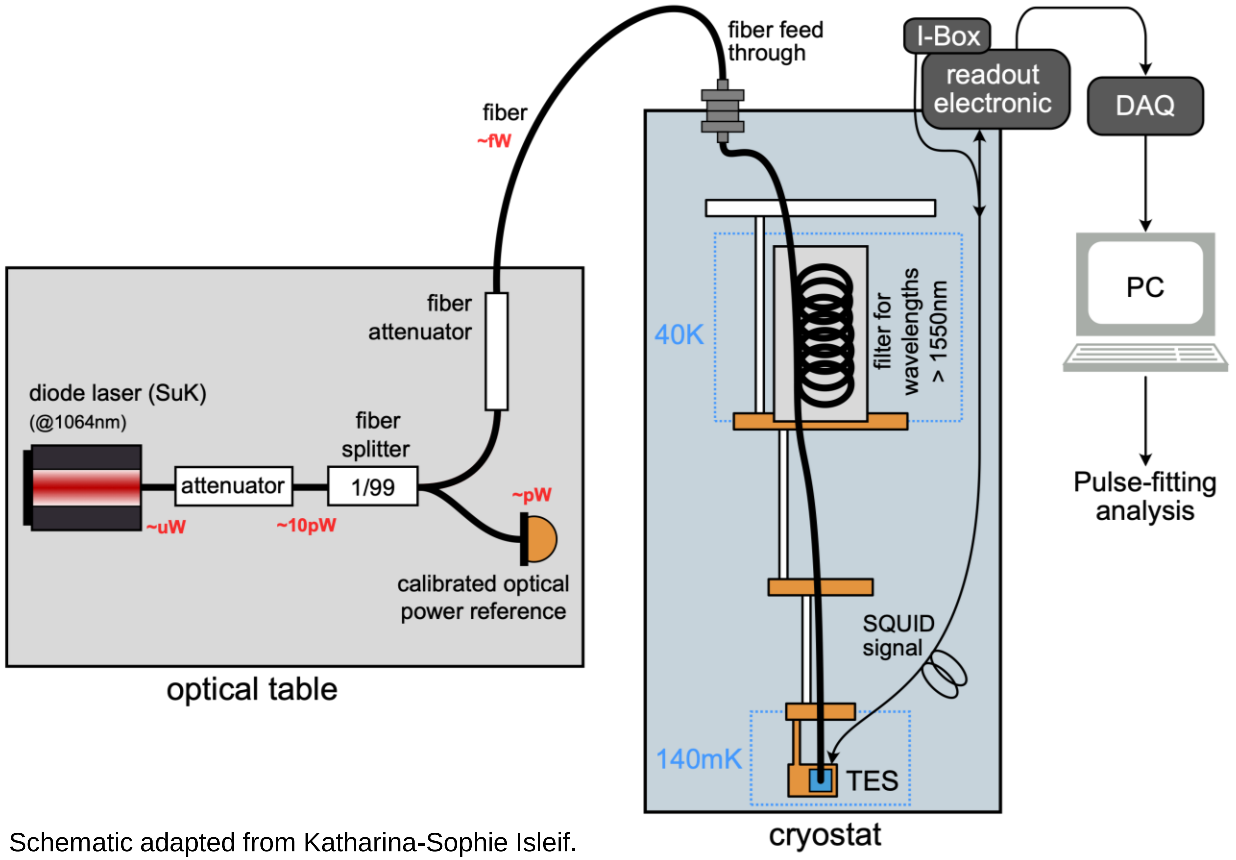
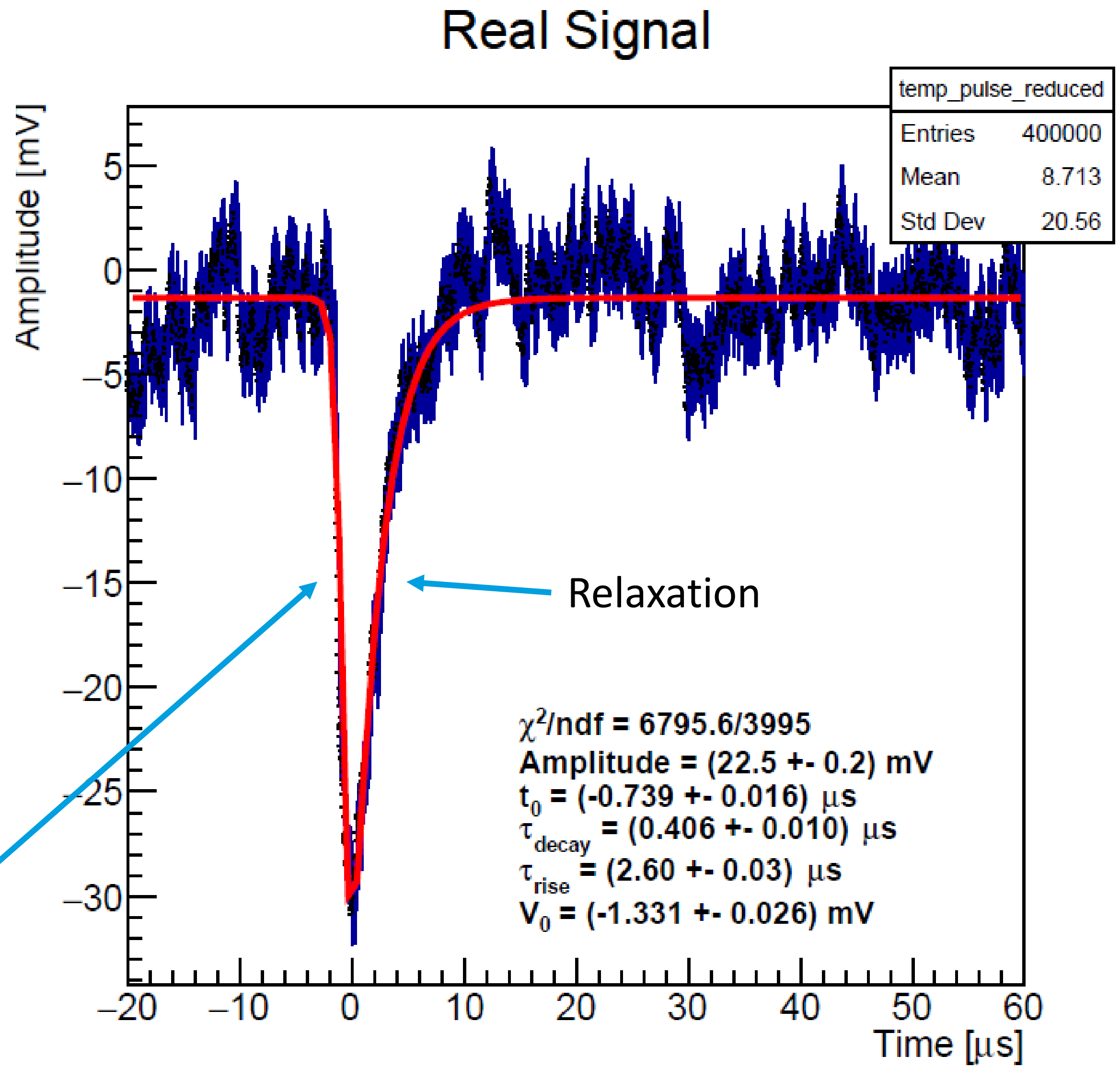
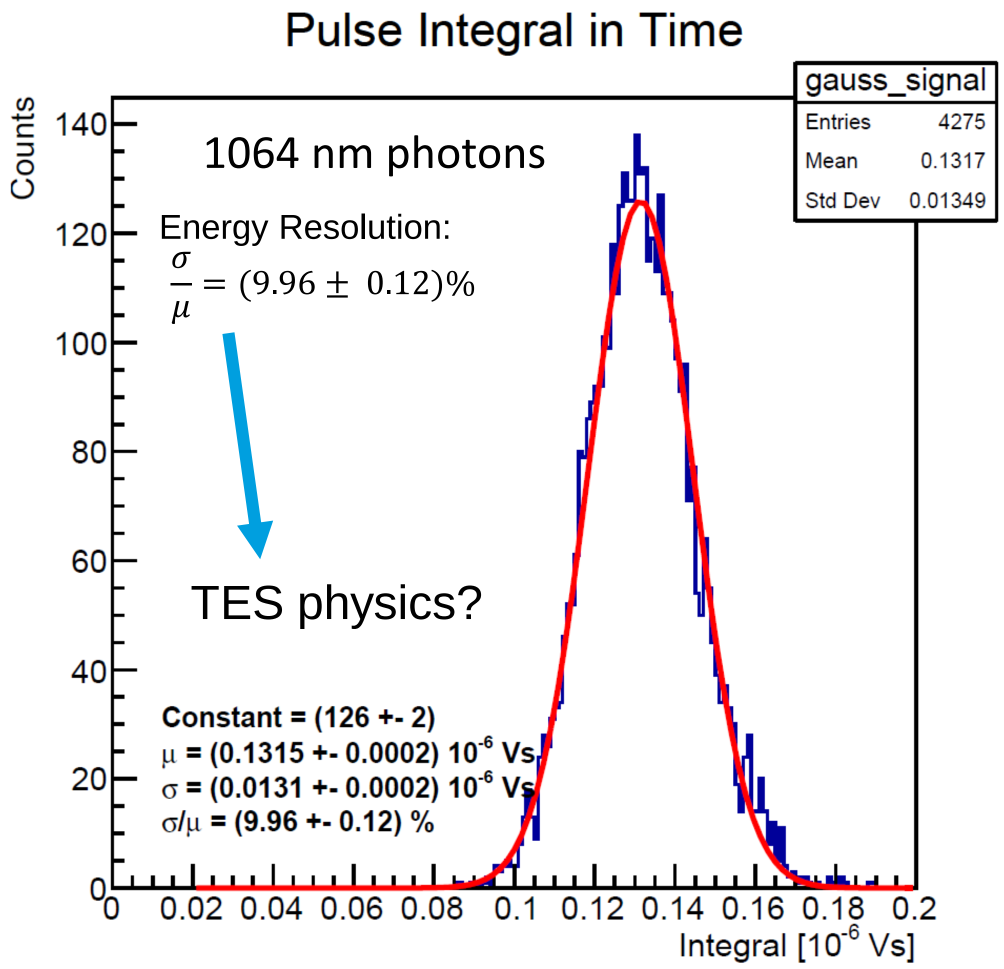


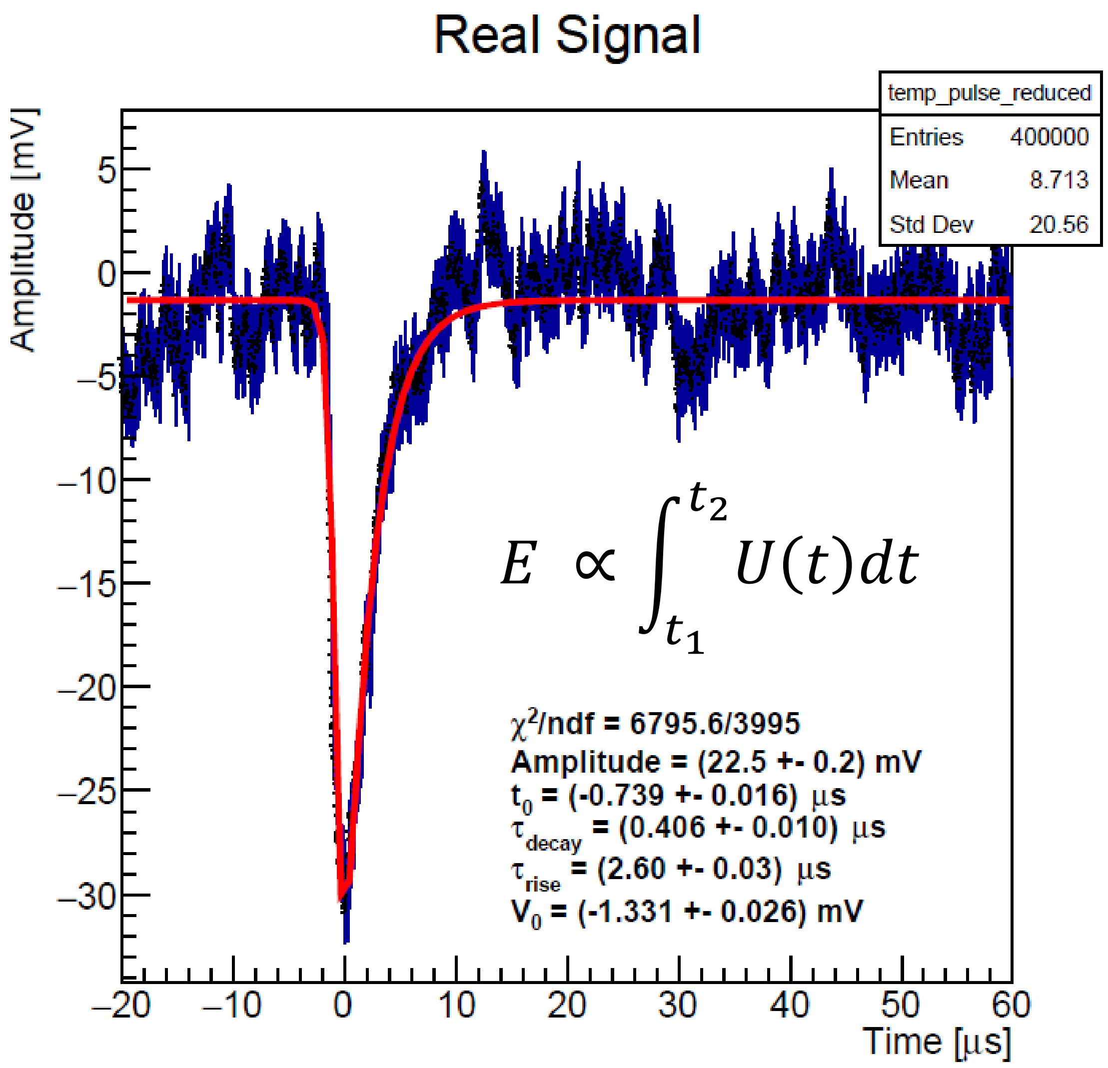
Schematic adapted from Katharina-Sophie Isleif.



Arrival of the photon

Understanding the signal





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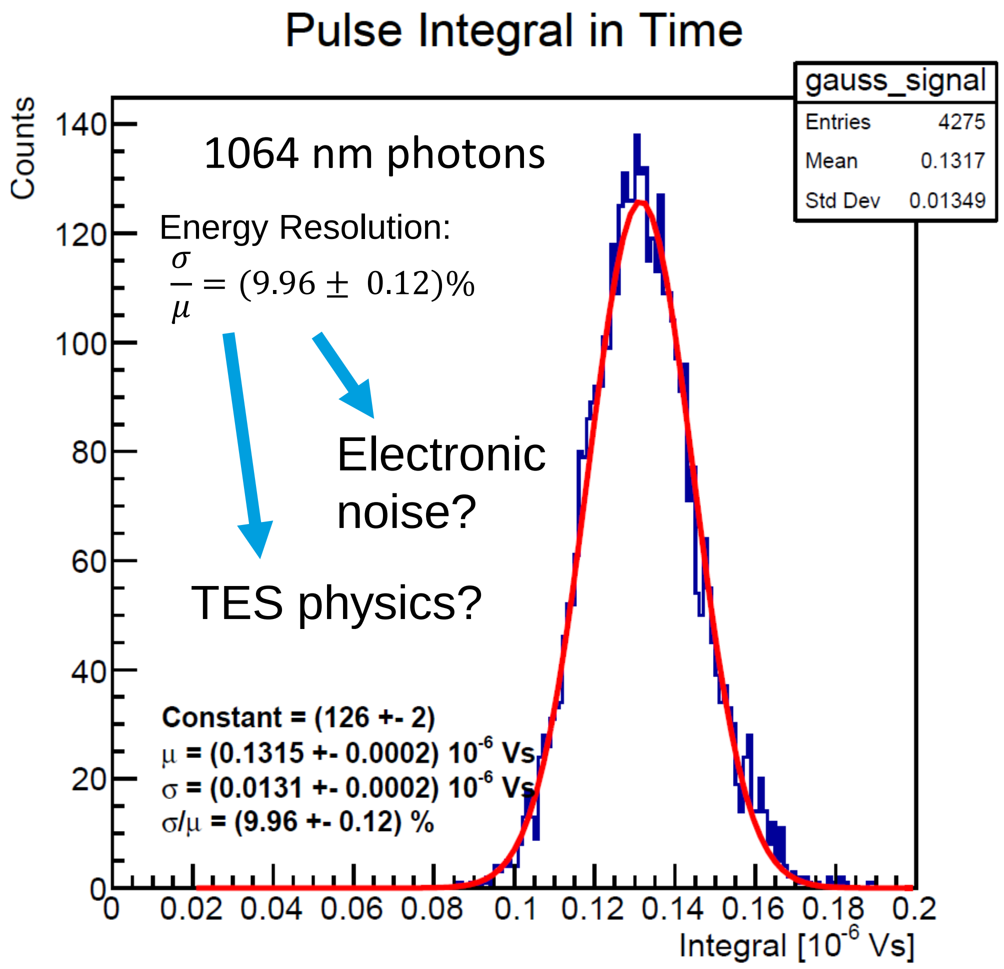
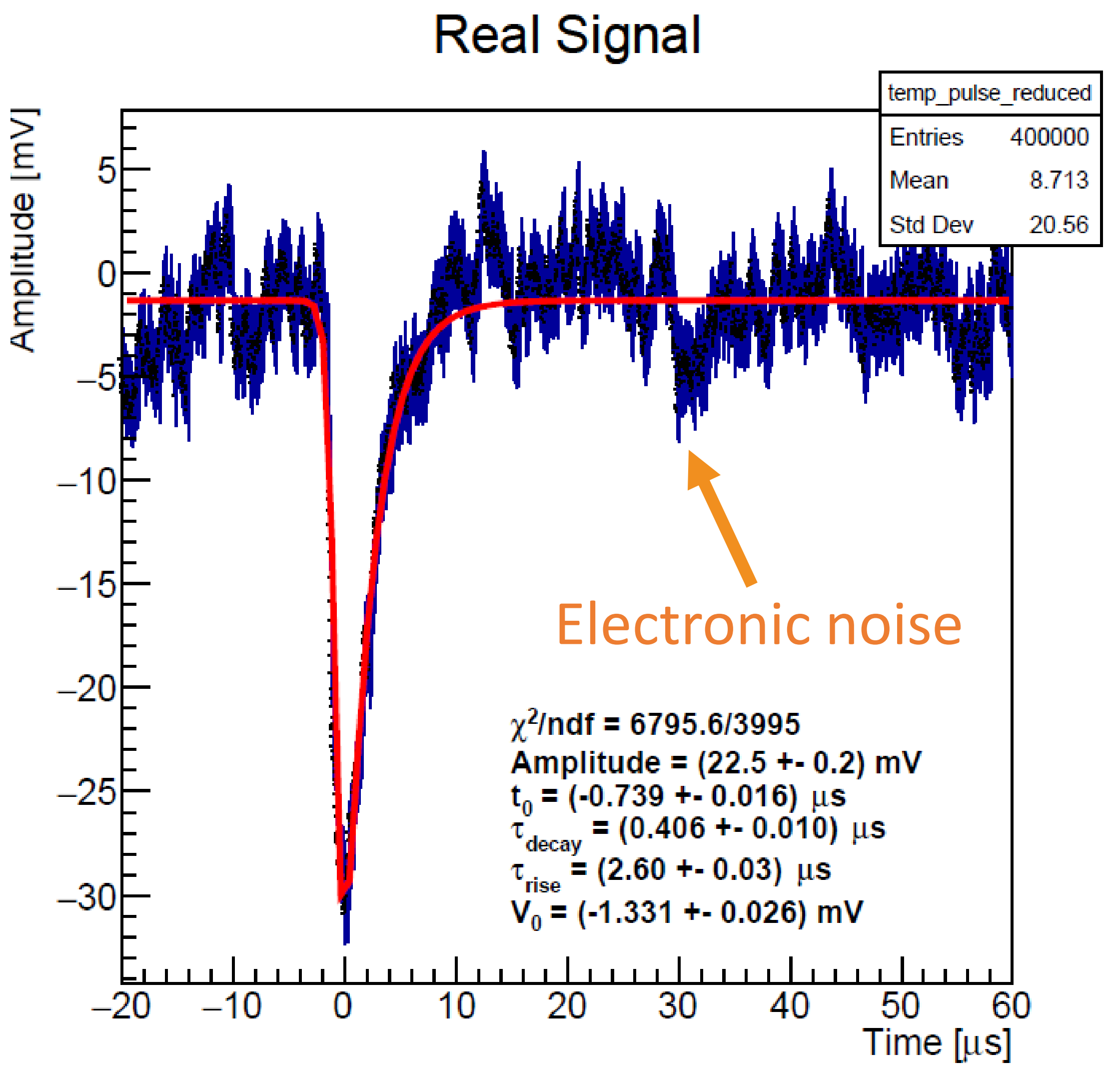
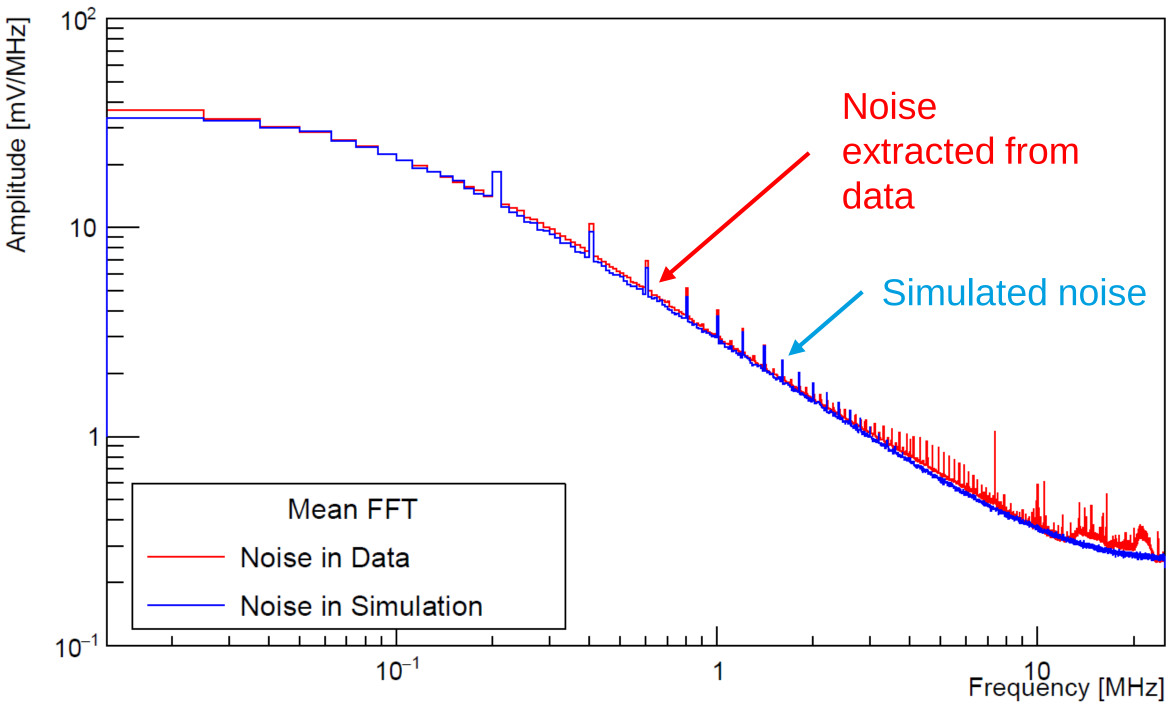




Simulation of electronic noise



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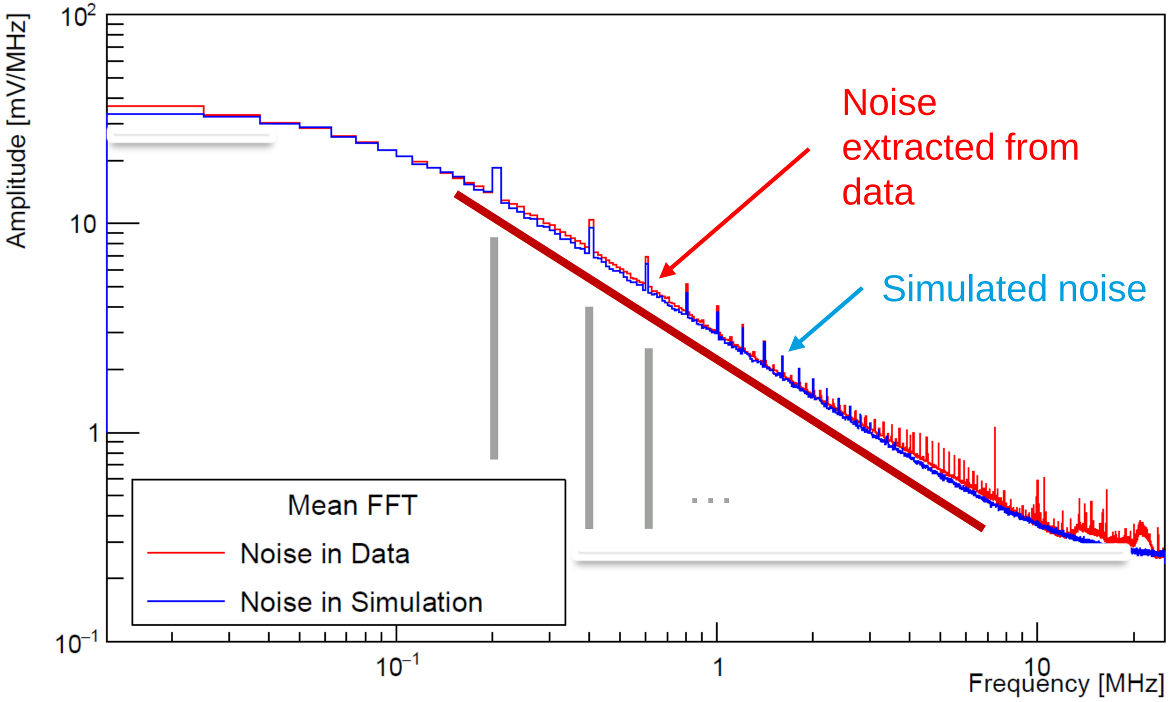
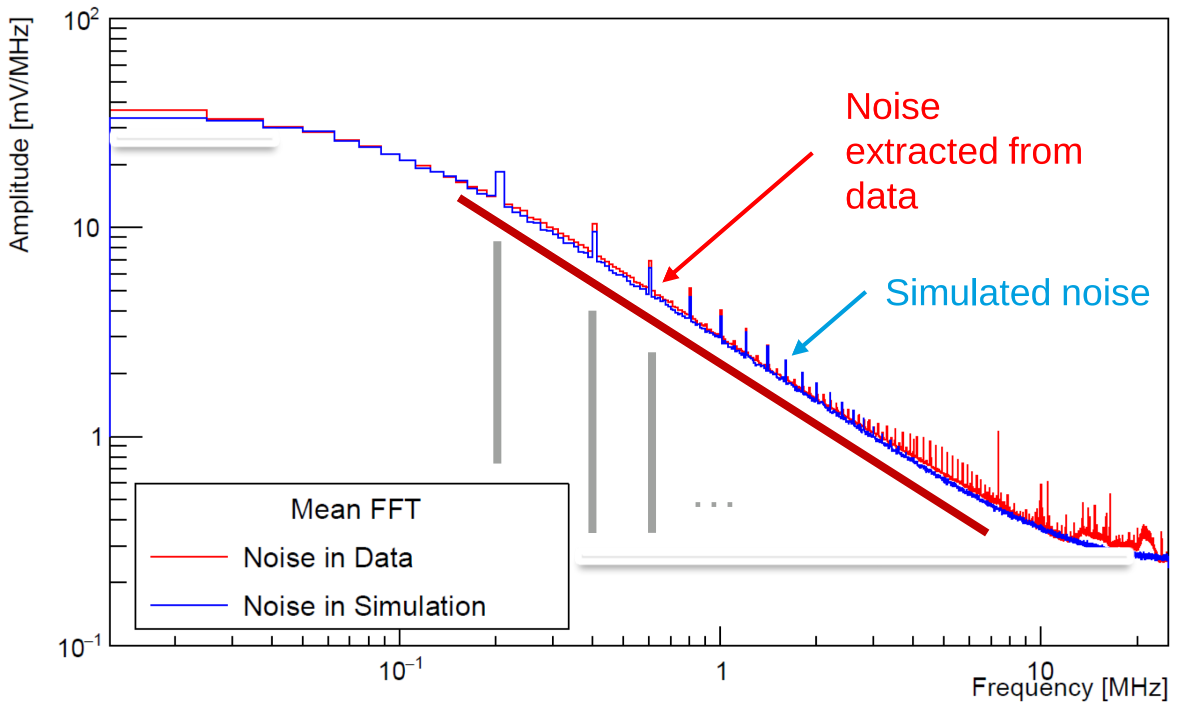
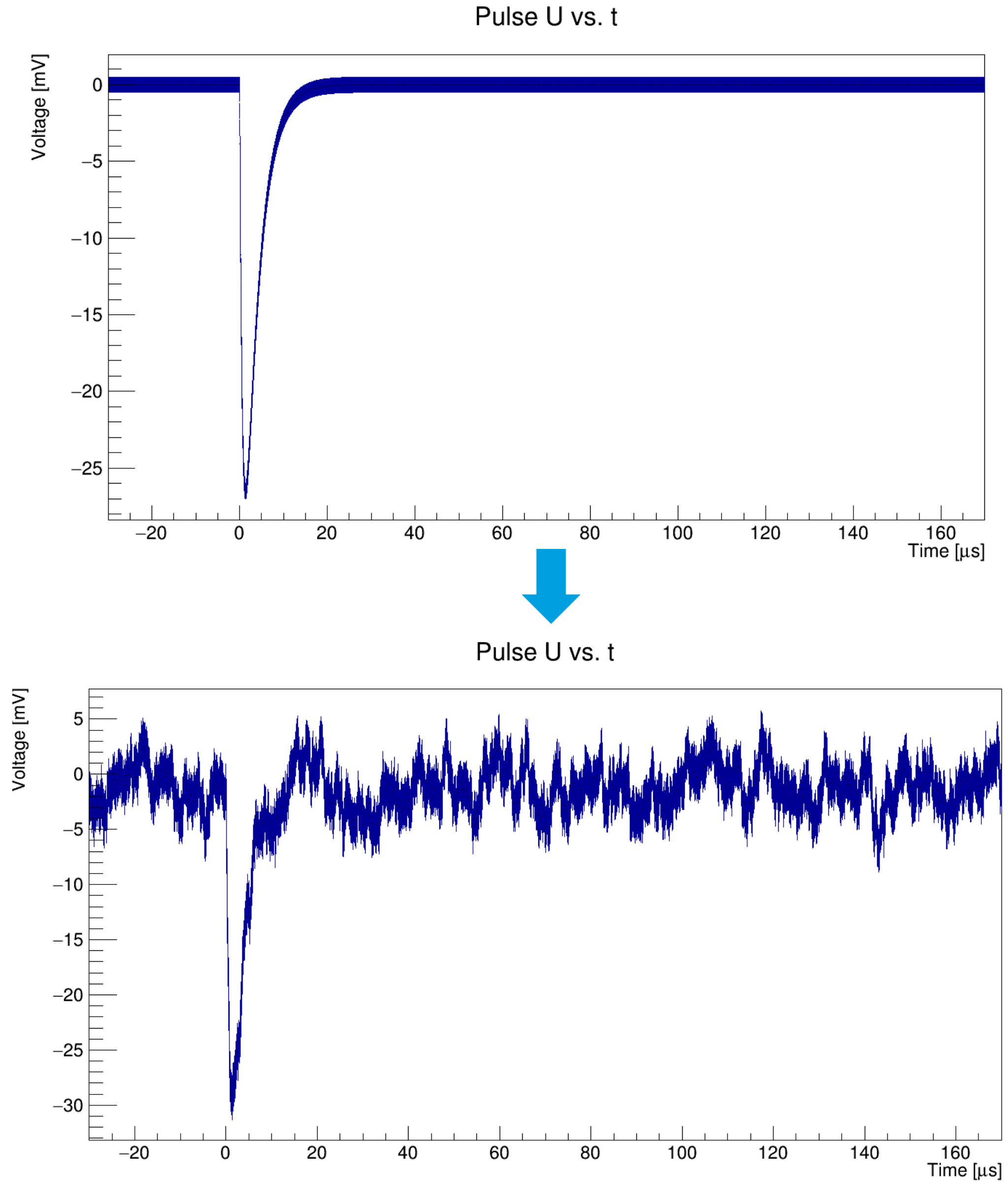


- $200\ kHz$ harmonics
- White noise
- Brownian noise

Simulation of electronic noise



+



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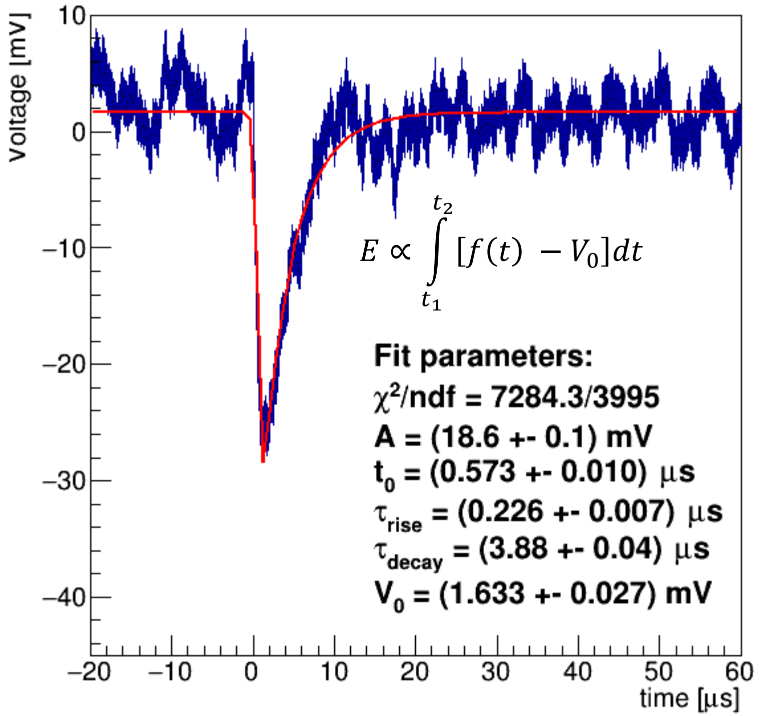
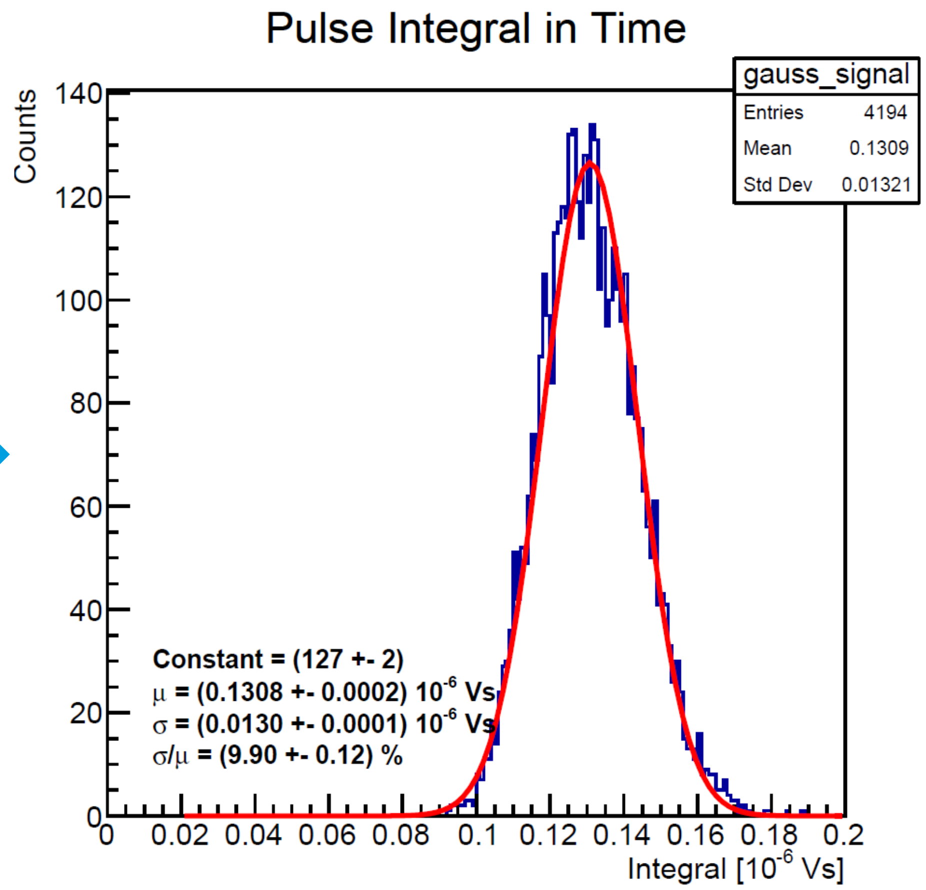


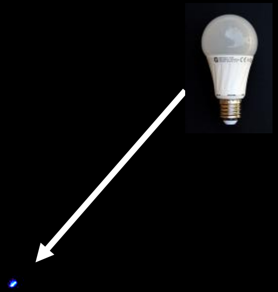


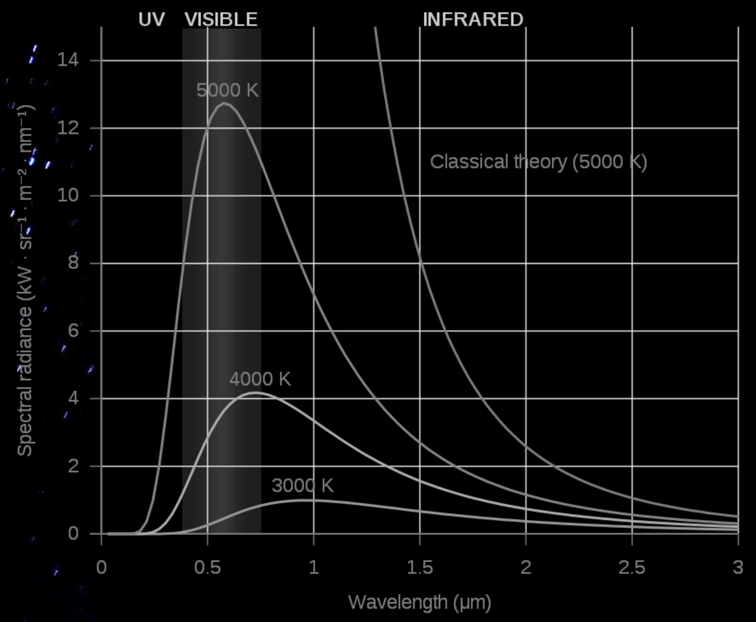
Data Analysis:
Energy Resolution
$(9.96 \pm 0.12)\%$

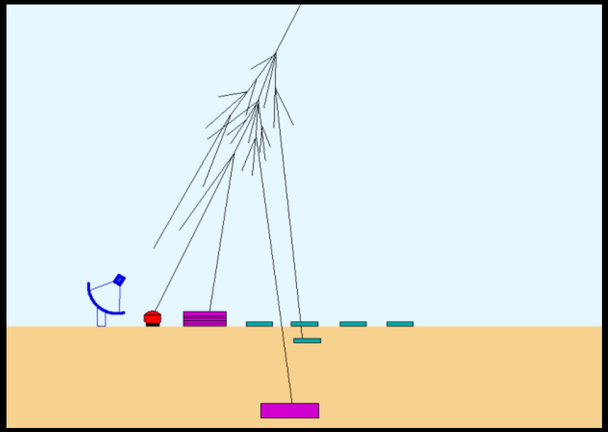
Simulation:
Energy Resolution
$(9.90 \pm 0.12)\%$

Studying other phenomena
- Rejection of pileup
- DAQ trigger efficiency.

Energy resolution can be explained by the electronic noise.





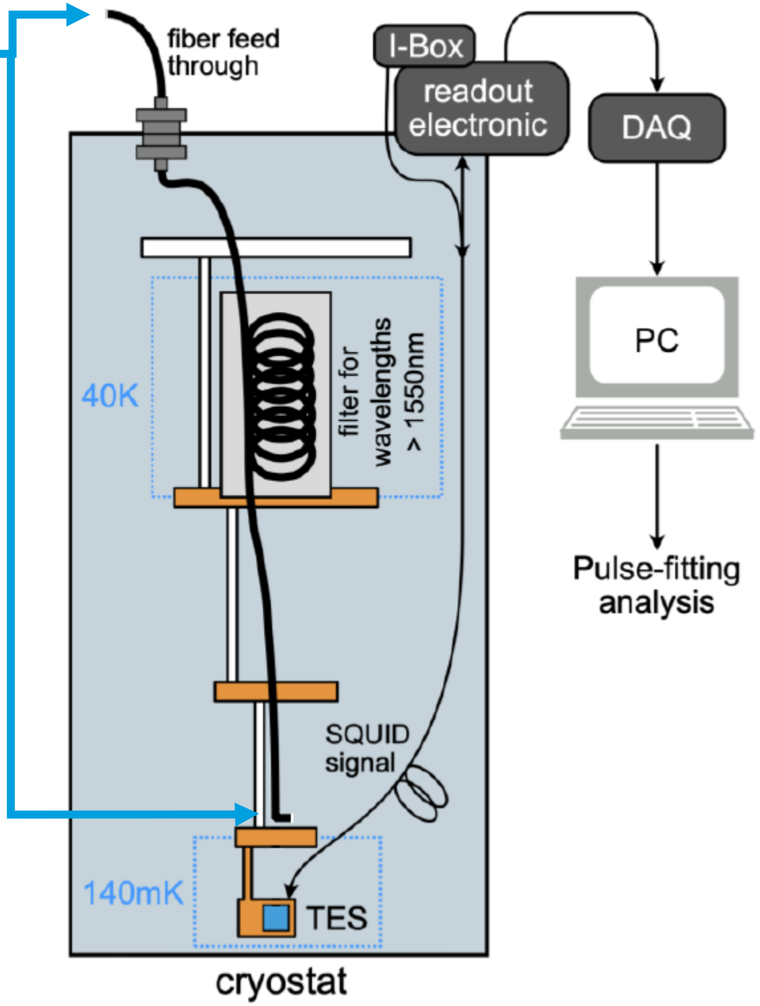


https://upload.wikimedia.org/wikipedia/commons/a/ae/Auvergne%2C_d%C3%A9cembre_2018_%E2%80%94_29.jpg

Intrinsics background

Intrinsic background (no fiber connected)

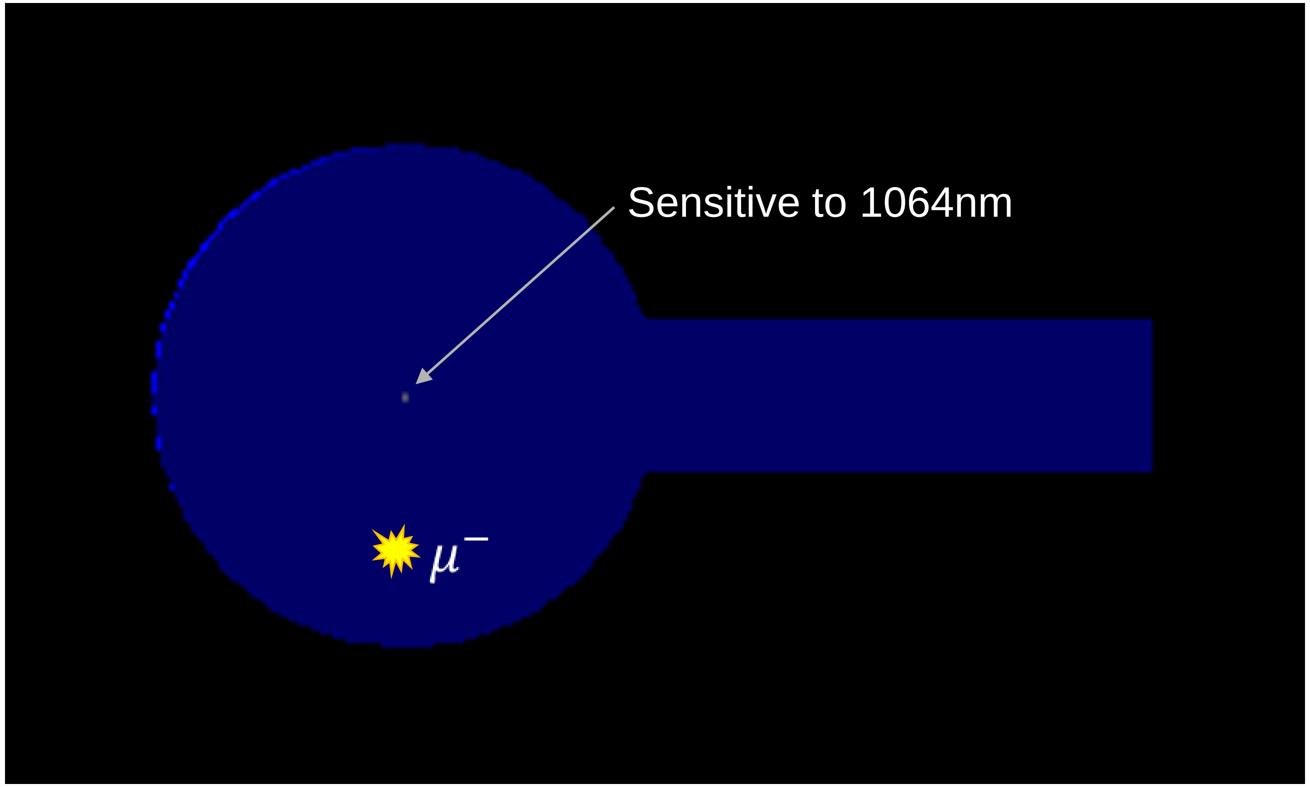
The accepted rate of events is in the order of $10^{-2}\ cps$ (same trigger as light samples).



Possible contributions:

- Cosmic Rays (Muons)
- Radioactivity (Surrounding materials)

Understanding background



Geant4 simulation

Possible contributions:

- Cosmic Rays (Muons)
- Radioactivity (Surrounding materials)

Particles could produce a signal indirectly in the sensor.

Single photon detector

Requirements for ALPS II:

- Sensibility to very low rates (1-2 photons a day). ✓
- Low energy photon detection (1064 nm equivalent to 1.16 eV). ✓
- Low background rate: $< 7.7 \cdot 10^{-6}\mathrm{cps} \sim 1\ \mathrm{photon}\ (1064\mathrm{nm} - \mathrm{like})\ \mathrm{every}\ 2\ \mathrm{days}.$ Yes, for intrinsics
- High detection efficiency. Yes, demostrated for similar systems
- Long term stability ($\sim 20\ days$). ✓

Outline

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  - 3 different kinds
- Any-light-particle search: the ALPS II experiment
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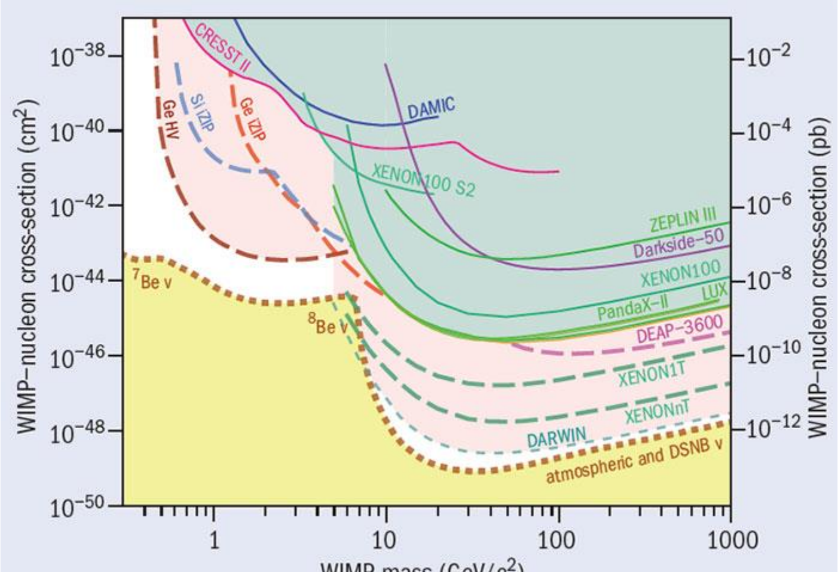
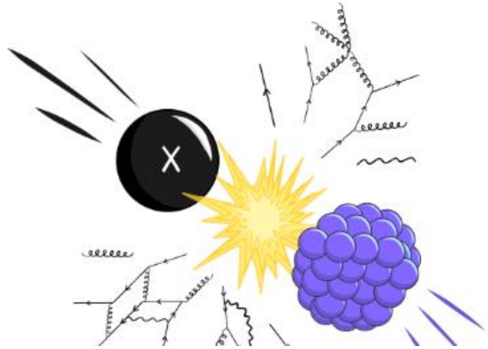
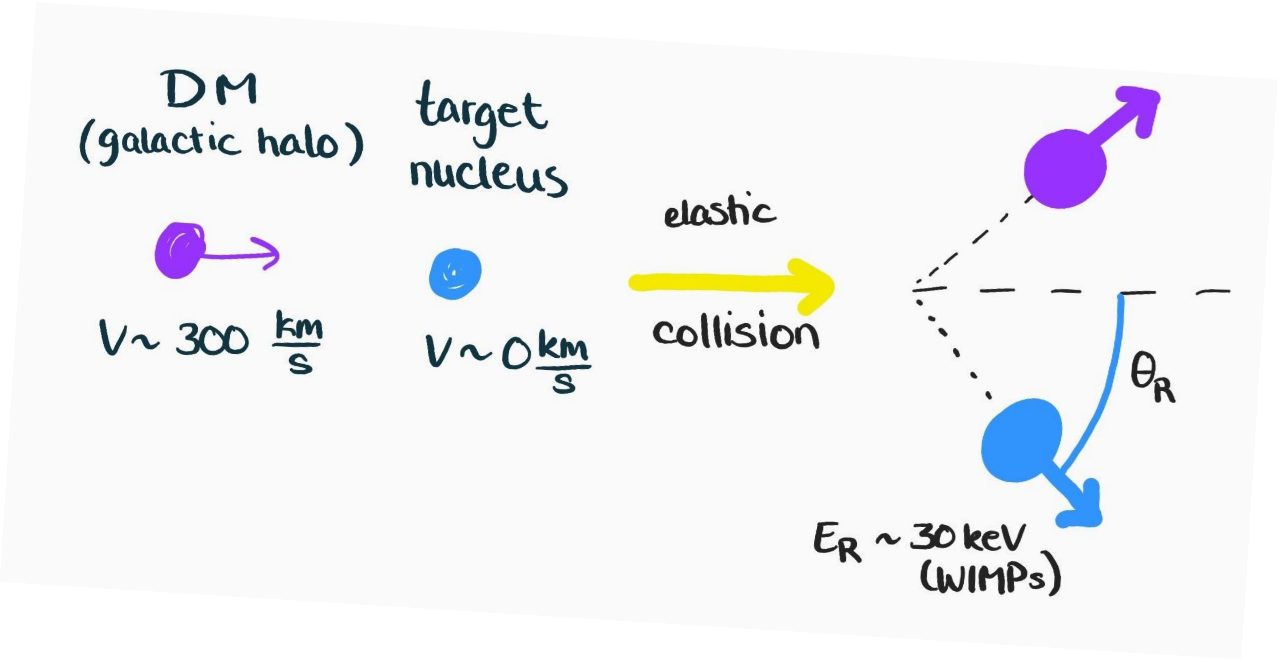
Sub-GeV dark matter?

Limits of nuclear recoil experiments



Cern Courier (2017)





Sketch adapted from Benjamin V. Lehman

Sub-GeV dark matter?

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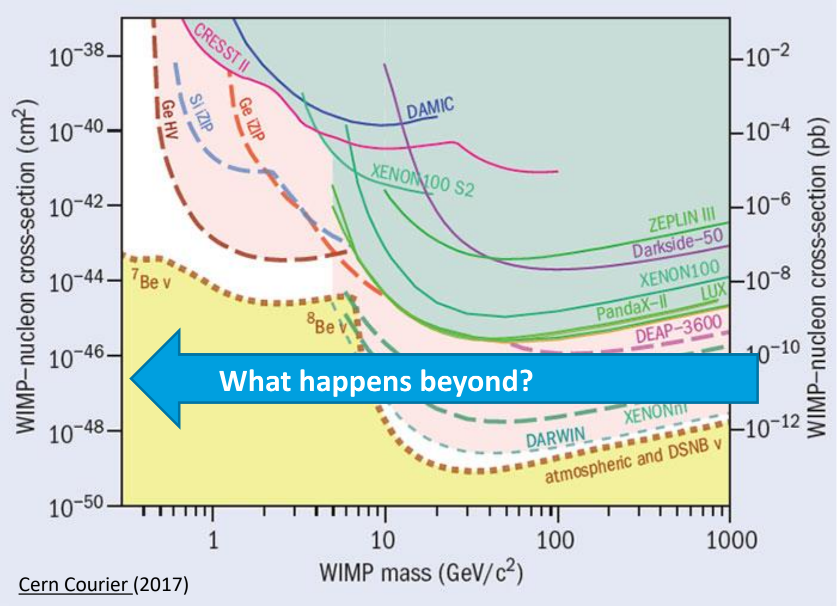

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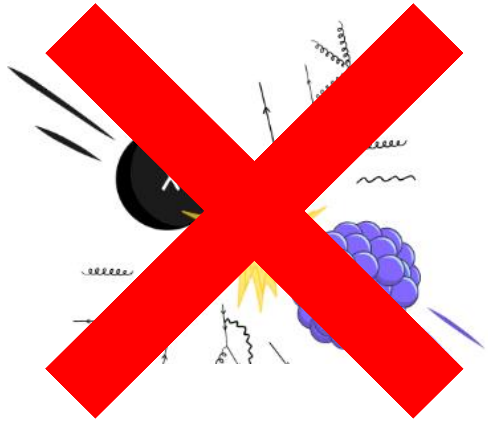

DM mass: m_χ, target mass: m_T

reduced mass: $\mu = \frac{m_\chi m_T}{m_\chi + m_T}$

recoil energy: $E_R = \frac{|q|^2}{2m_T} = \frac{\mu^2 v^2}{m_T}(1 - \cos(\theta_R))$

For $m_\chi \ll m_T$: $\mu \approx m_\chi$

$\rightarrow E_R \sim \frac{m_\chi^2}{m_T}$

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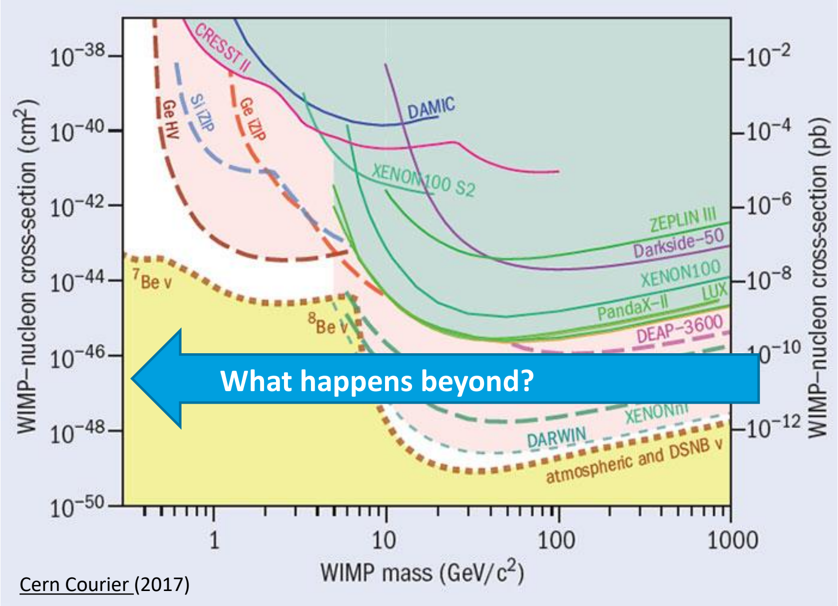

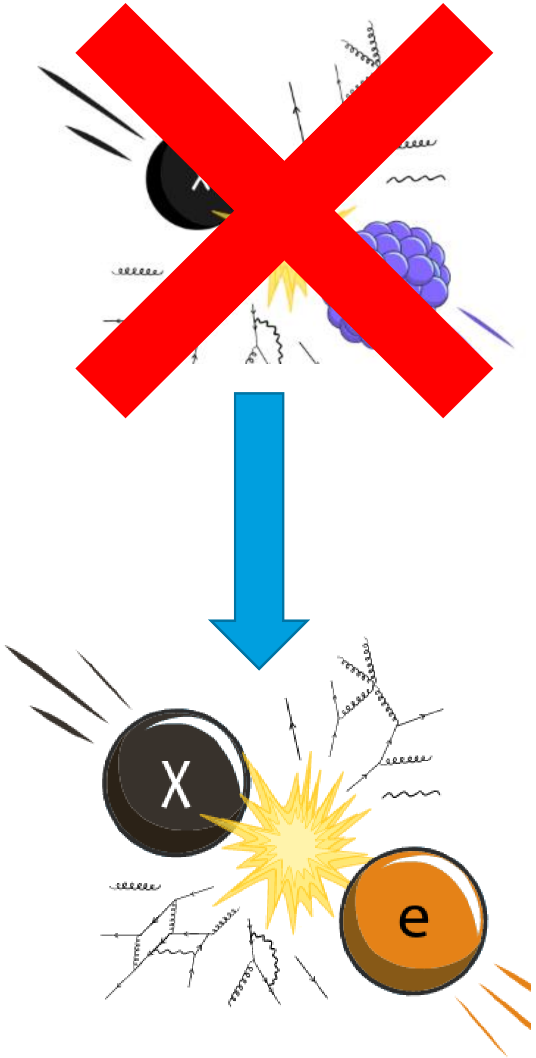

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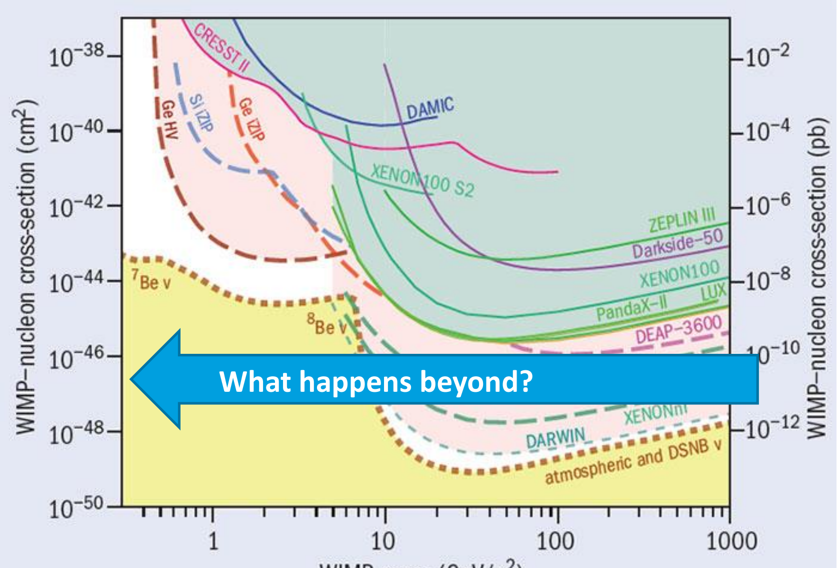
Sub-GeV dark matter?

DM – electron scattering



Cern Courier (2017)

Assume:

- Characteristic DM halo velocity $v_\chi \sim 10^{-3}$
- Scattering via mediator (heavy or light) coupling to EM charges (e.g. dark photon as massless, light mediator)

Maximum Energy transfer E_T in scattering event is entire kinetic energy of DM particle with mass m_χ:

$$E_{T_{\mathrm{max}}} = E_{\mathrm{kin}} \sim m_\chi v^2 \sim 10^{-6} m_\chi$$

Sub-GeV dark matter?

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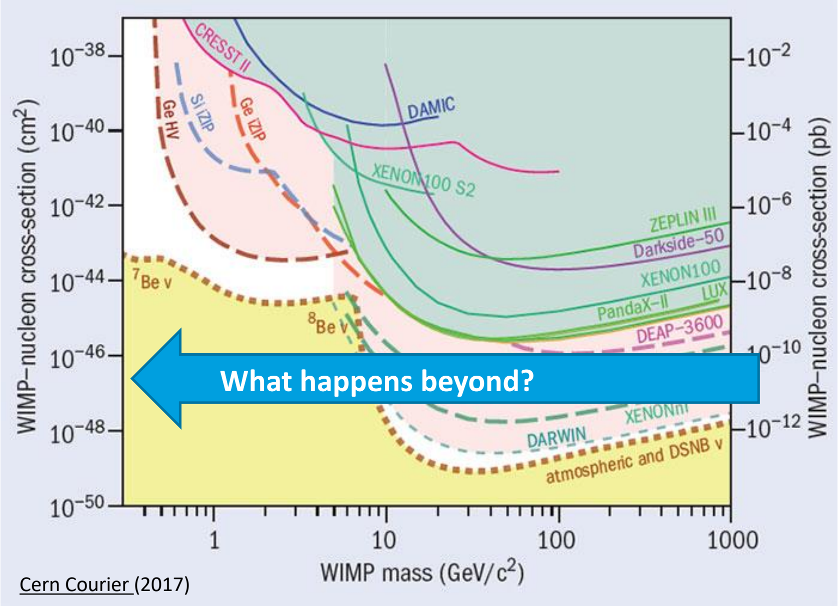

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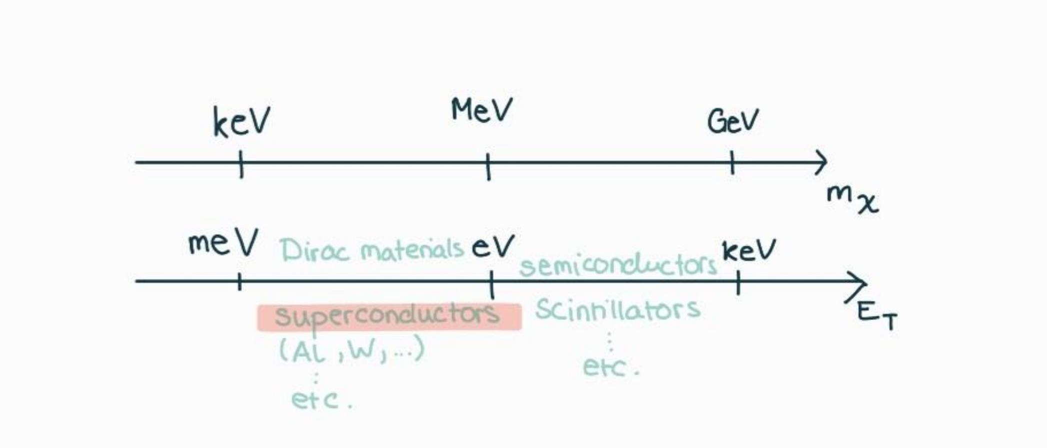
Energy range for given mass range:



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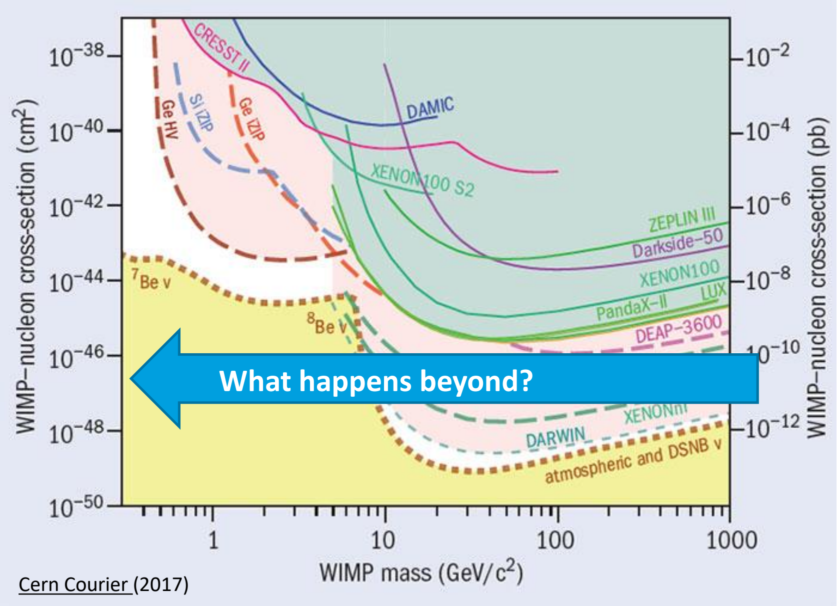

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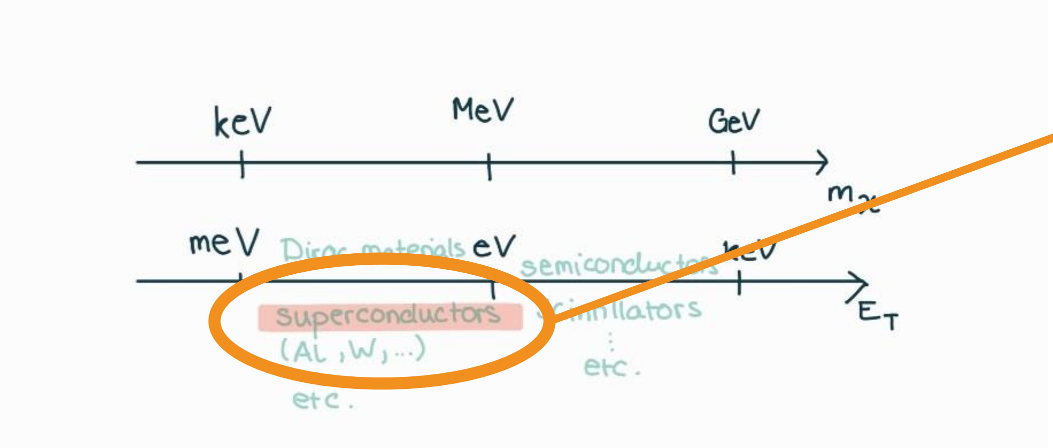


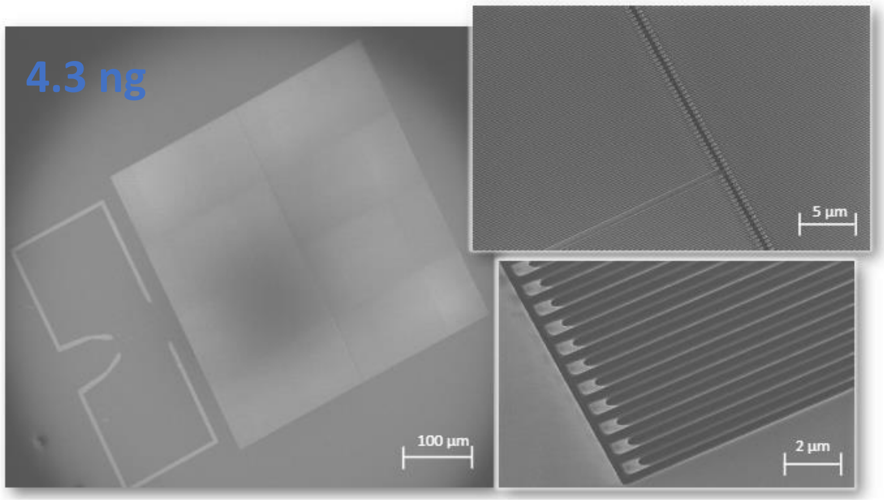
TES?

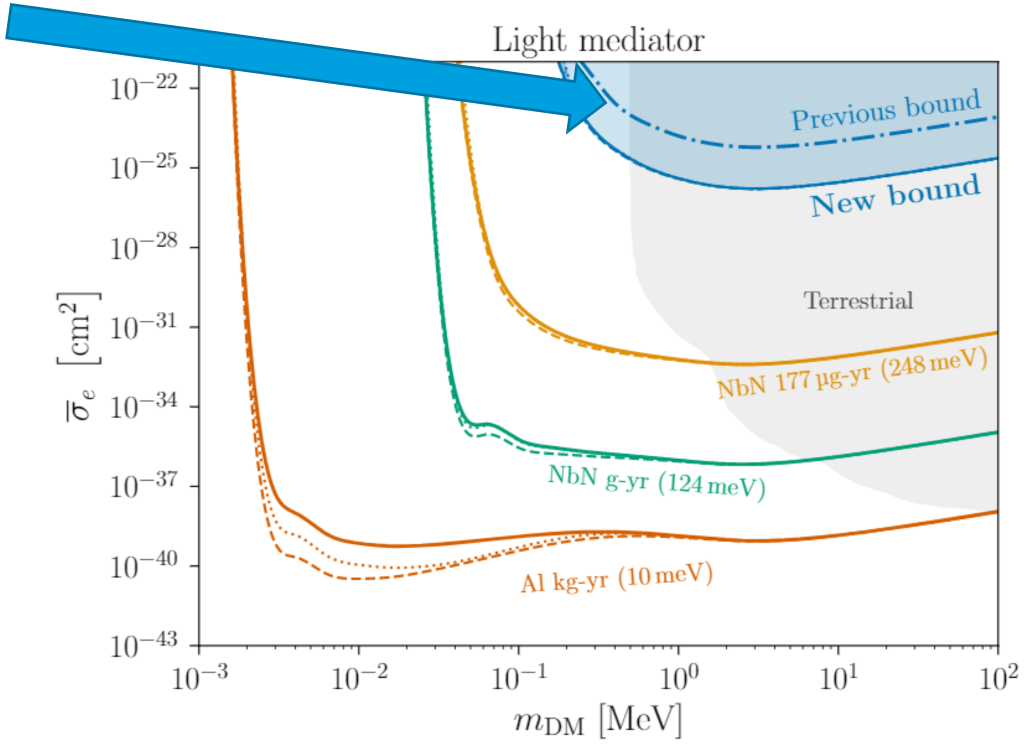
Direct DM detection
Suitable devices

- Low noise
- 'Large' target mass

Example: principle proven for SNSPDs (**S**uperconducting **N**anowire **S**ingle **P**hoton **D**etector)

Were able to set new bounds on parameter space with only one 3hr measurement (no background signals, 0.76 eV energy threshold)





Hochberg, Y. et al. arXiv:2110.01586 (2021)

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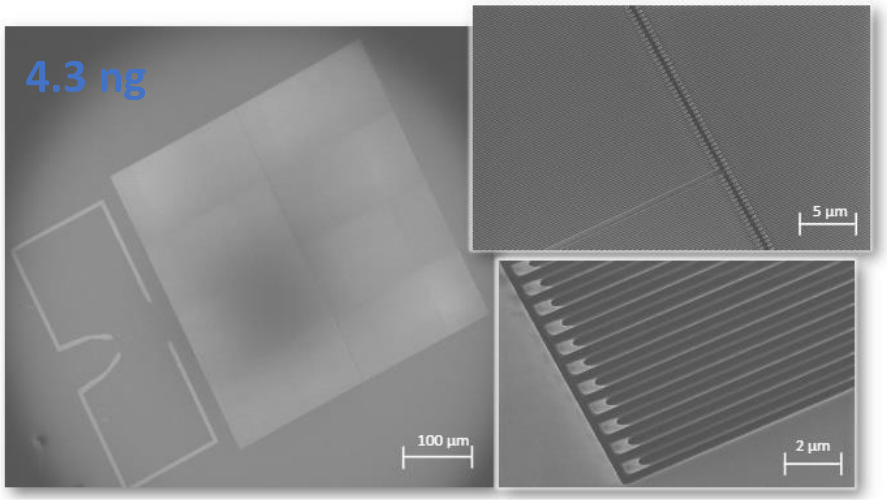

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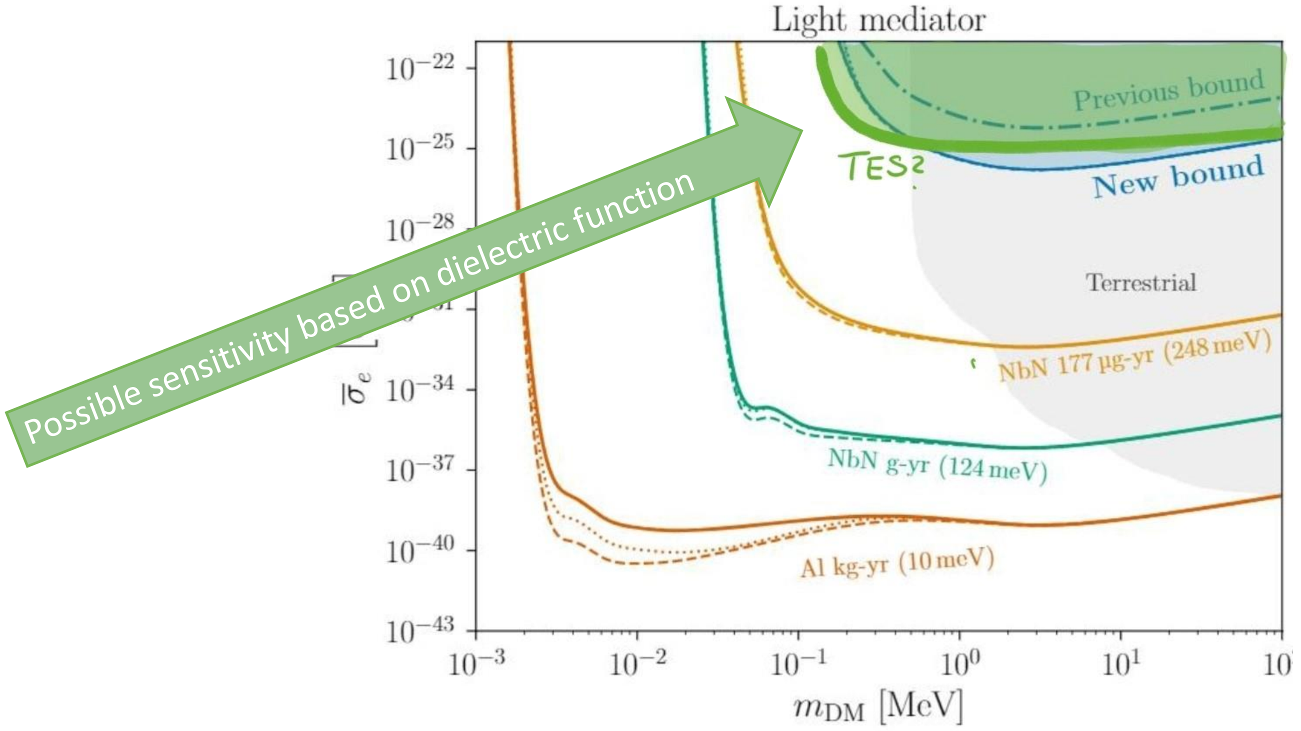
Proposal: Apply same idea to TES!

✓ Superconductor
✓ Low noise
✓ Energy resolution
✓ Lower energy threshold
X Lower mass (0.2 ng)
X Smaller target area



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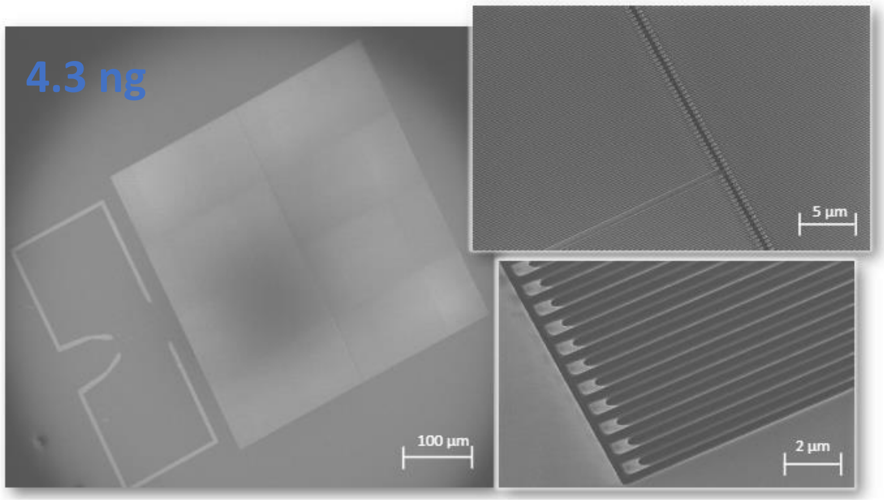

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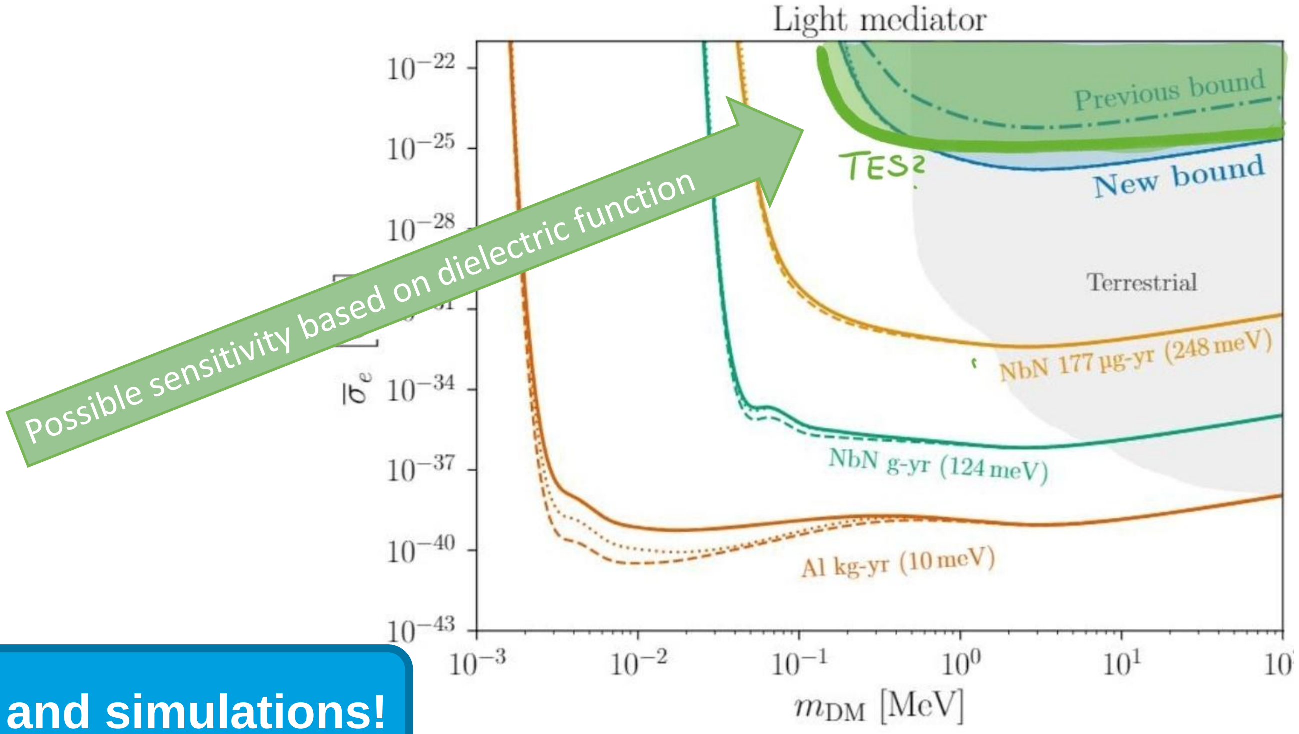

Ongoing research and simulations!

Hochberg, Y. et al. arXiv:2110.01586 (2021)

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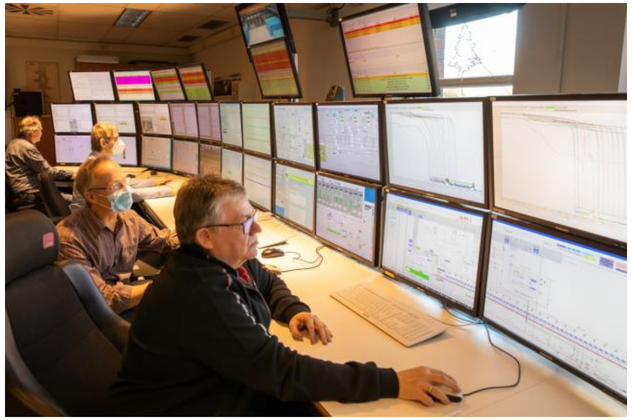
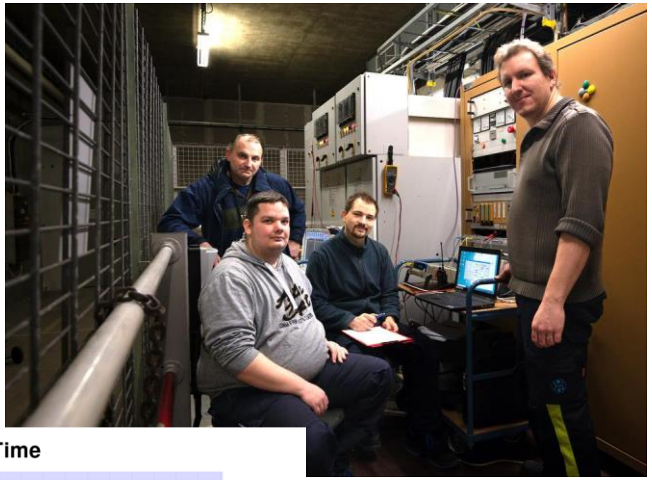
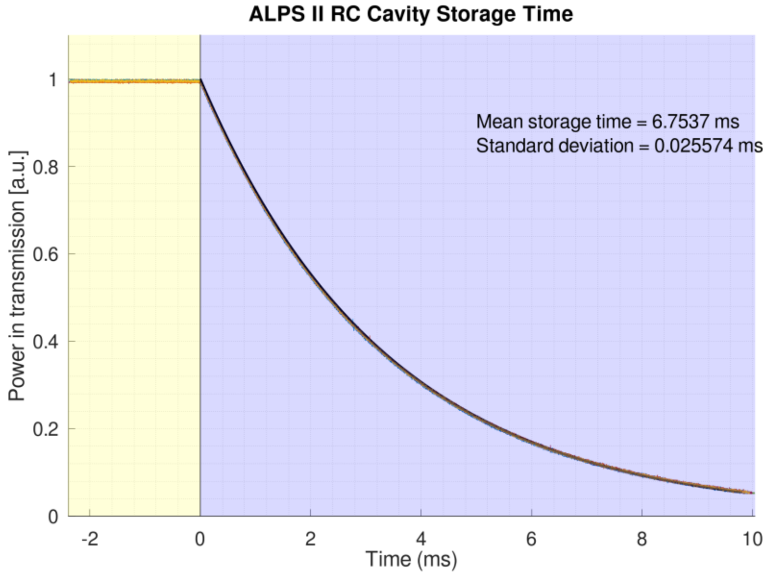
Any Light Particle Search II

Recent 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 aligned and 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.
- Late 2022: first science run (hopefully)!







125 m regeneration cavity storage time: 6 ms! (world record)

More achievements since 2012

PhDs and DESY fellows

PhDs:

- 11 dissertations in experimental physics.
- 1 dissertation in engineering.
- At least 6 theses still to come.

Former DESY fellows:

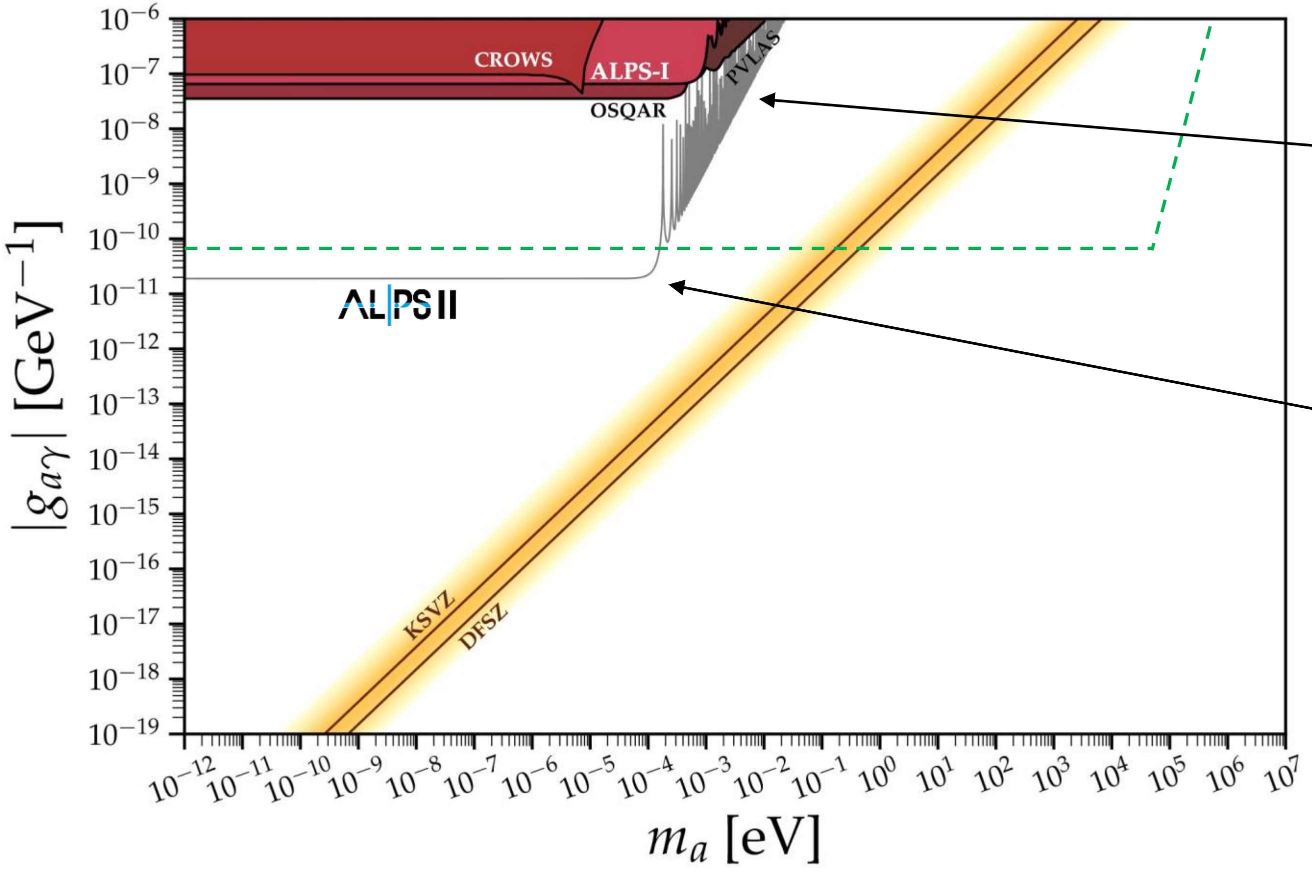
- 5 permanent positions in academia.
- 1 junior professorship.
- 1 left for family reasons to another postdoc position.
- 2 left to industry.

Axion searches at DESY

In context

ALPS II, model independent searches:

- Improve sensitivity on axion-photon coupling by a factor of ≈ 1,000, going beyond astrophysics limits.



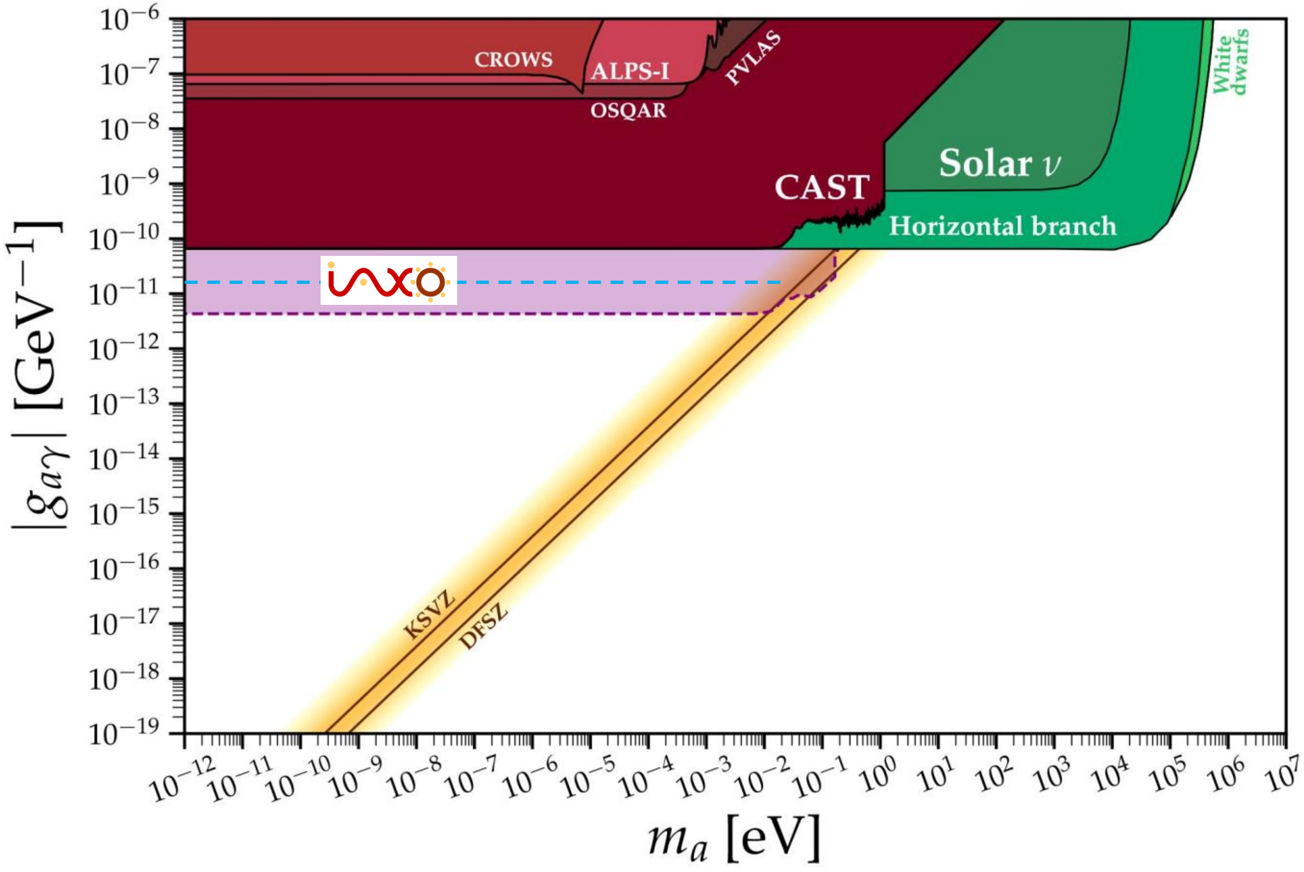
https://github.com/cajohare/AxionLimits

Axion searches at DESY

In context

IAXO, solar axion searches:

- Improve sensitivity on axion-photon coupling by a factor of ≈ 15 (BabyIAXO ≈ 4).



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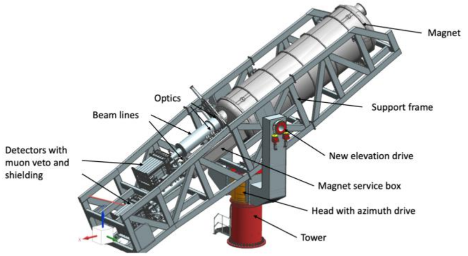
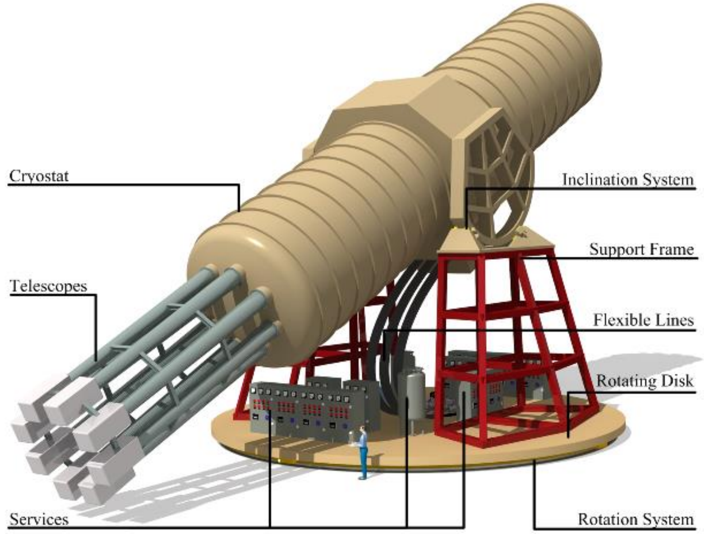


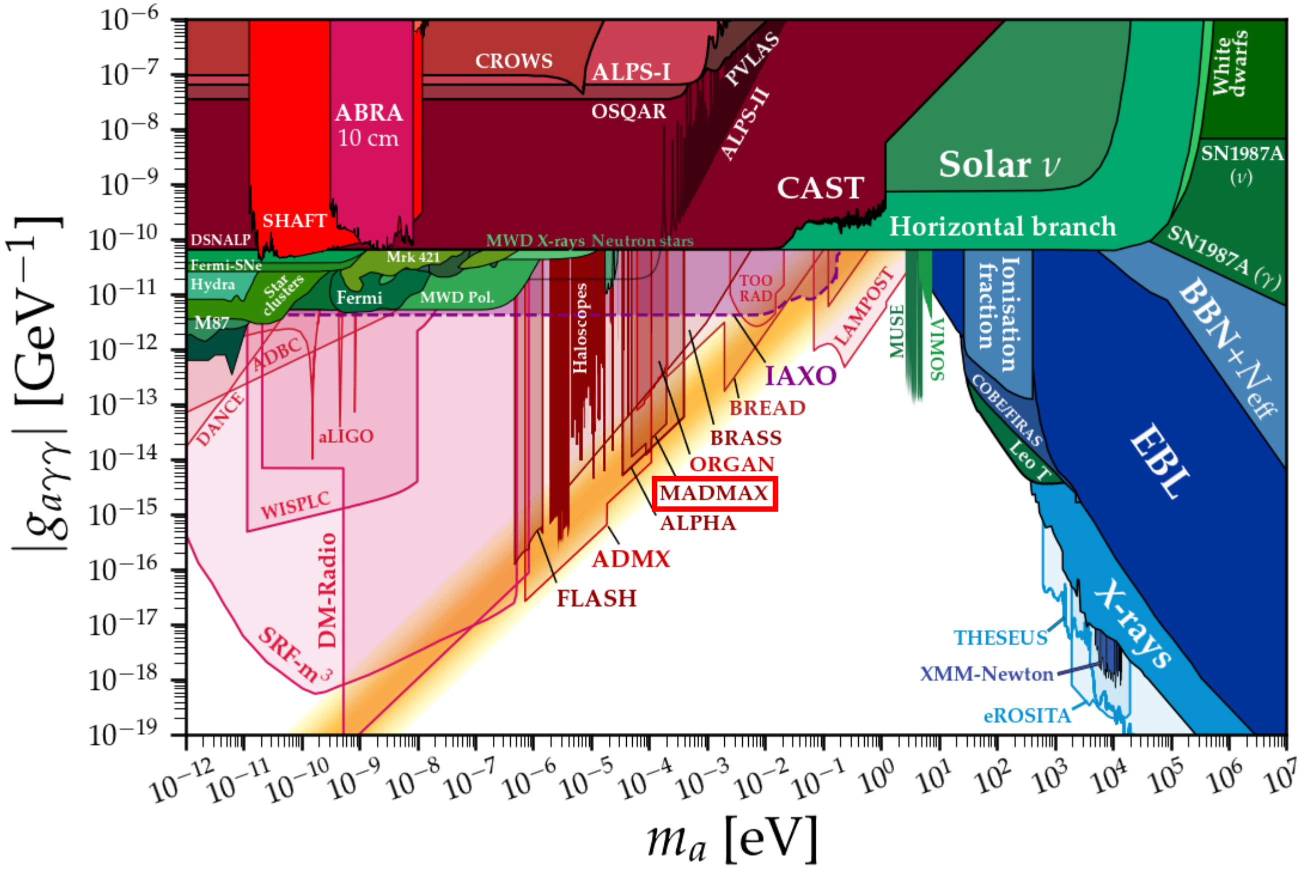


Axion searches at DESY

In context

MADMAX, dark matter axion searches:

- Probe the mass region between 40 and 400 µeV.



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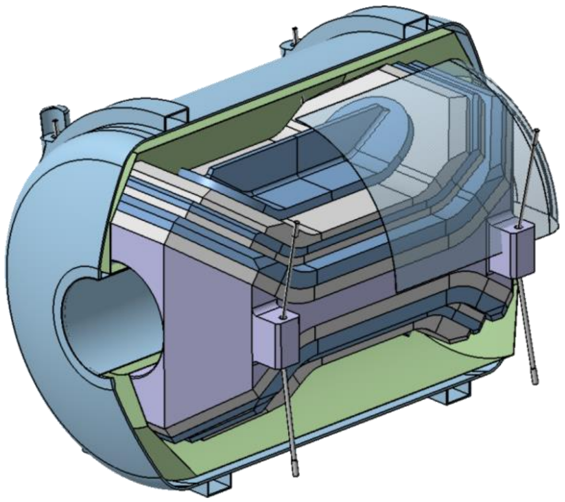


Instead of a summary

A dream

ALPS II, first data taking in 2022:

- Determine the axion-photon coupling model-independently.

IAXO, first data taking of BabyIAXO in 2026 ?

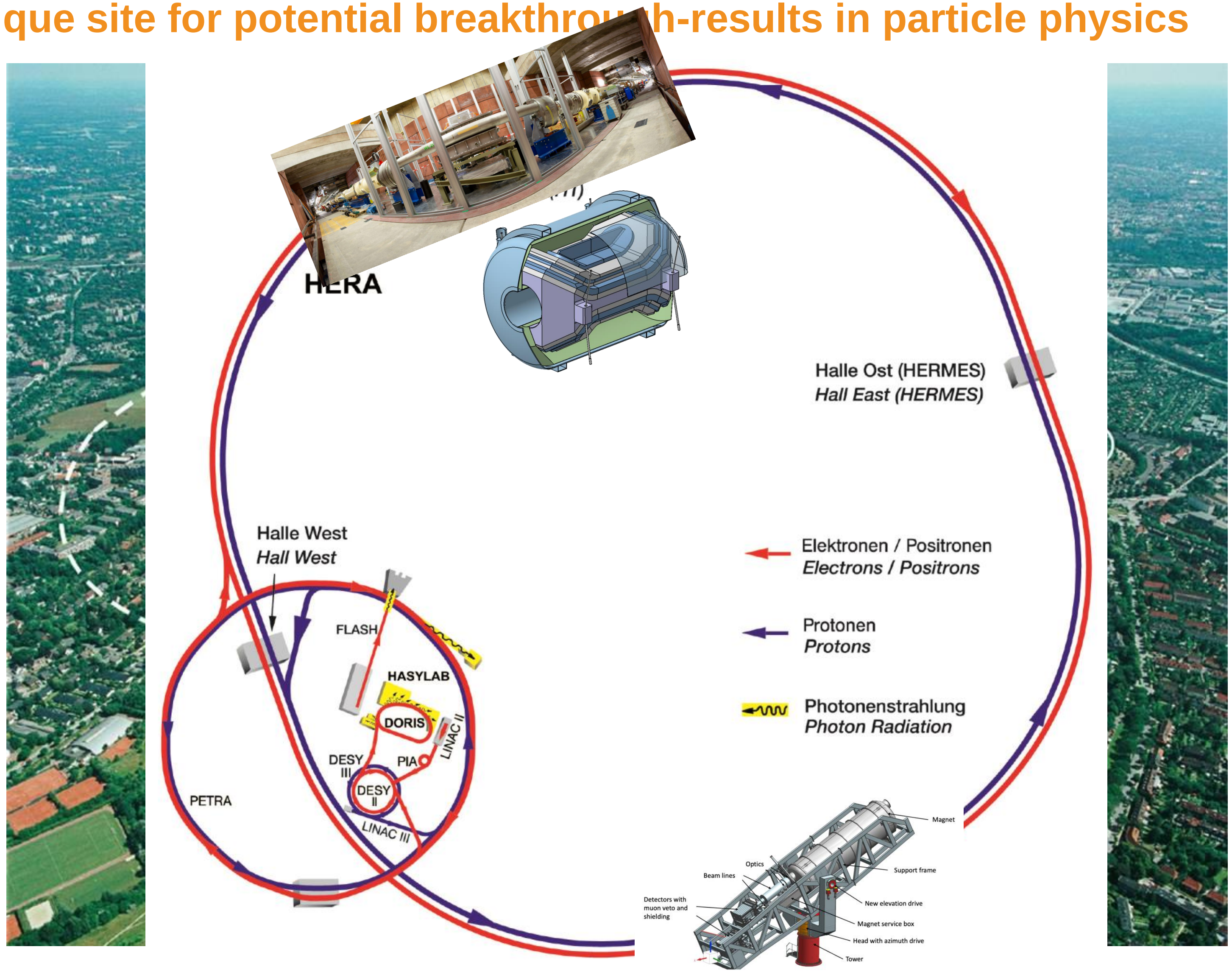
- Determine the absolute solar axion flux using the ALPS II result.
    - Do axion-photon mixings differ in vacuum and dense plasmas?
- Measure the axion-electron and axion-nucleon couplings.

MADMAX, first data taking in 2028 ?

- Axions make up the dark matter in our universe.
- Precisely measure the axion mass and the dark matter velocity distribution.

DESY in Hamburg in the 2020-ties

HERA: still a unique site for potential breakthrough-results in particle physics



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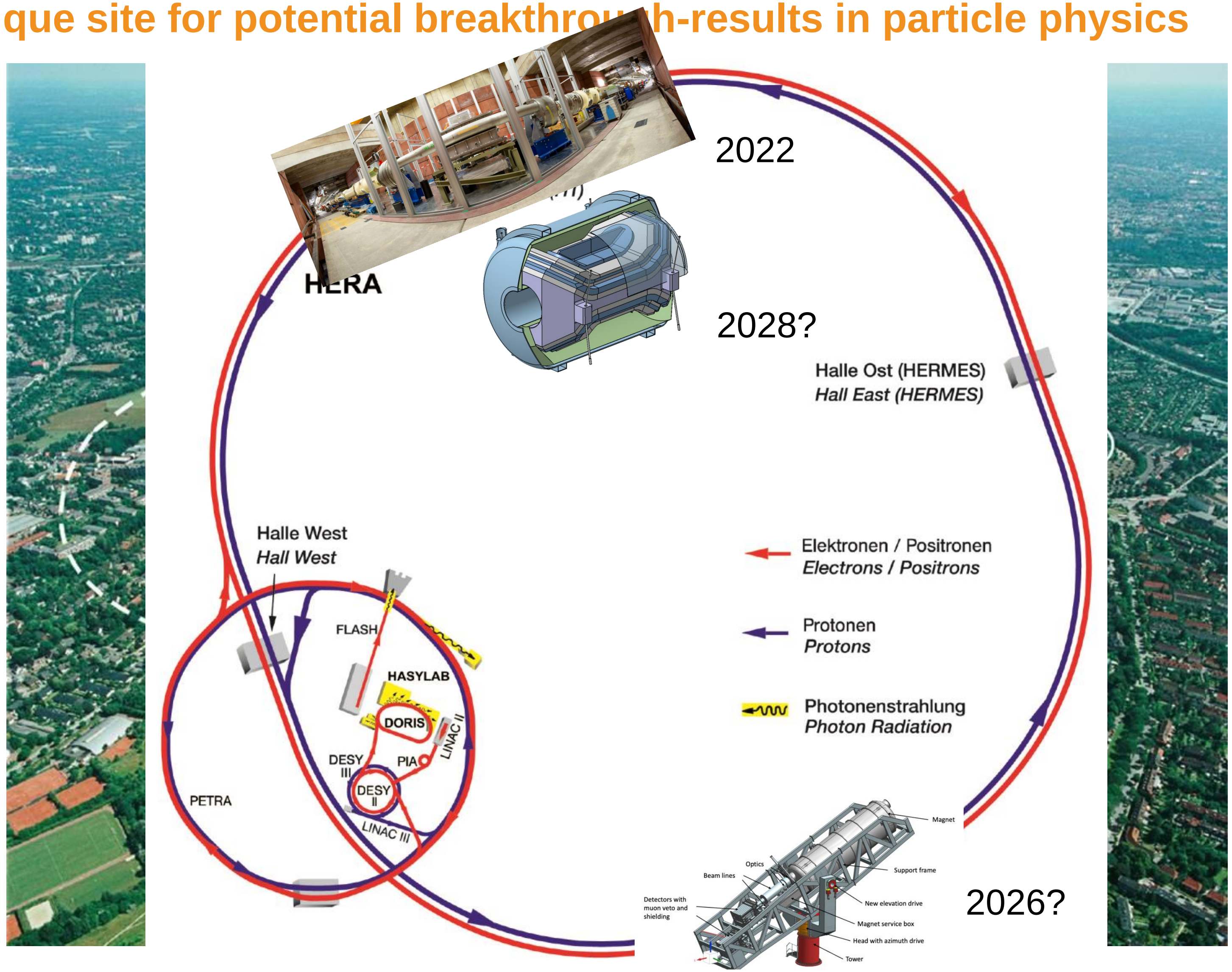

Many thanks to the enthusiastic colleagues at DESY and world-wide for realizing the “impossible” to find the “invisible”!

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Axel Lindner, Jose Alejandro Rubiera Gimeno, Christina Schwemmbauer

FH-ALPS
axel.lindner@desy.de
+49 40 8998 3525