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

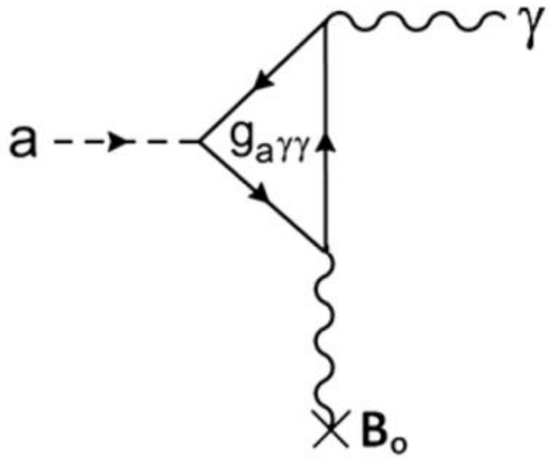
Outline

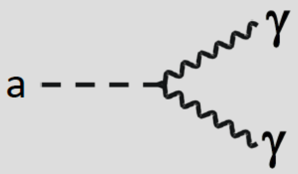
- Light-shining-through-a-wall — Axel
    - 3 different kinds
- Any-light-particle search: the ALPS II experiment — Axel
- A Transition Edge Sensor (TES) for ALPS II — Jose
- More Dark Matter Searches with a TES — Christina
- Summary

Axions

Photon coupling and Maxwell 1864

Exploited by many experiments as relatively “simple”.

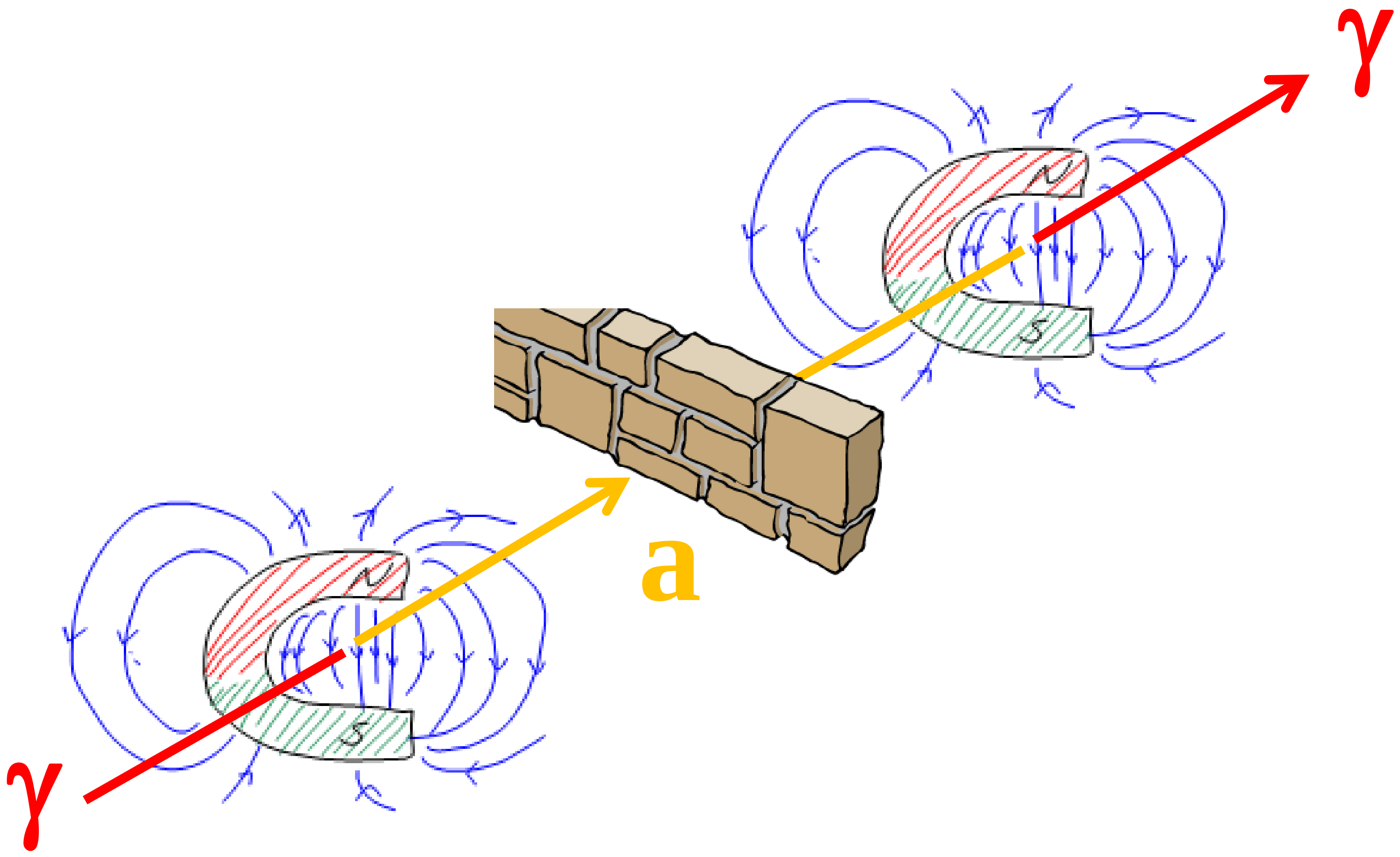


Photon coupling	$\mathcal{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F\tilde{F}a = g_{a\gamma}\, \mathbf{E}\cdot\mathbf{B}\, a$ $g_{a\gamma} = \frac{\alpha}{2\pi f_a}\left(\frac{E}{N} - 1.92\right)$	

Photon-axion mixing in a background magnetic dipole filed

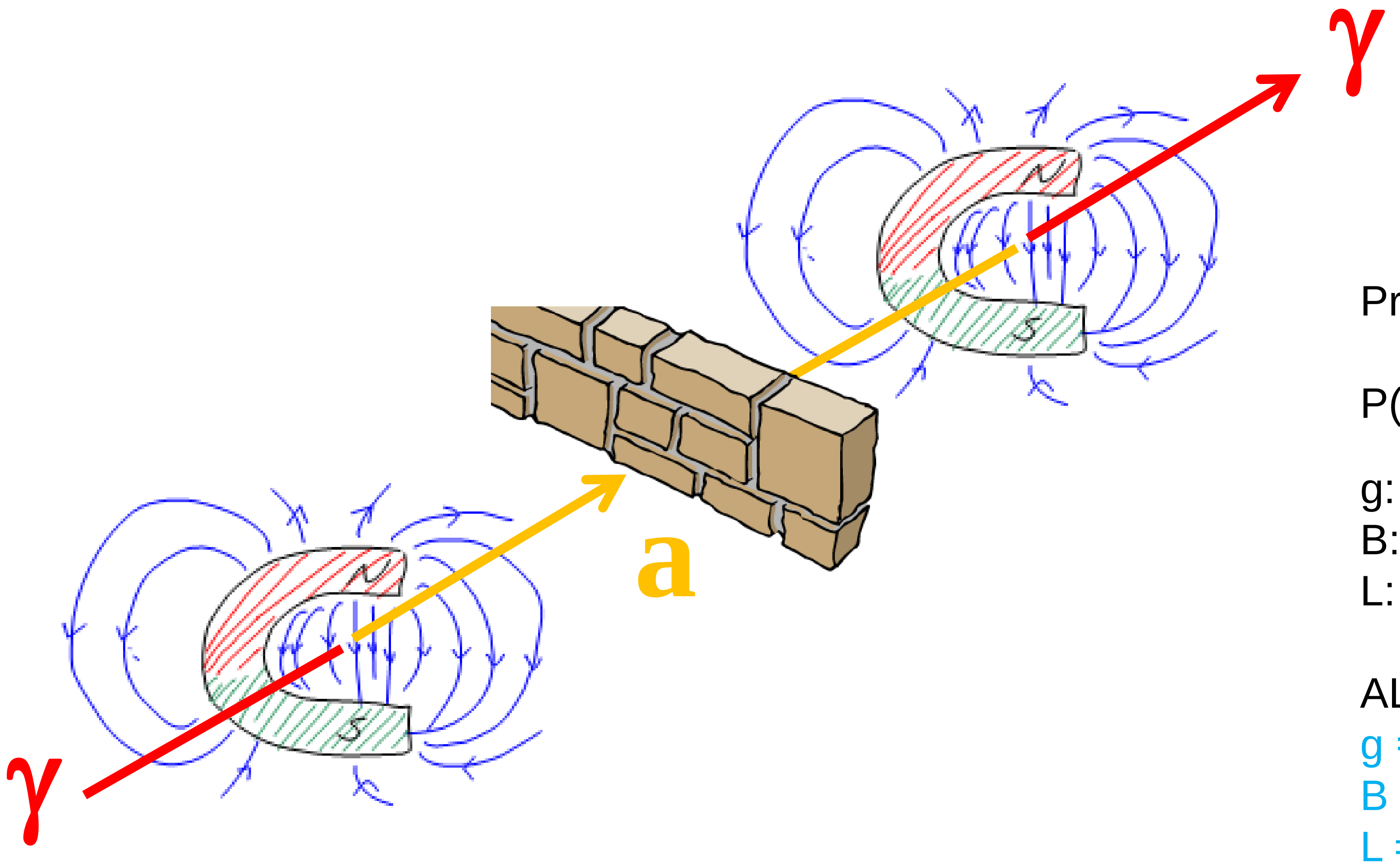
The concept

Light-through-a-wall



The challenge

Any-Light-Particle-Search ALPS II



Probability:

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

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

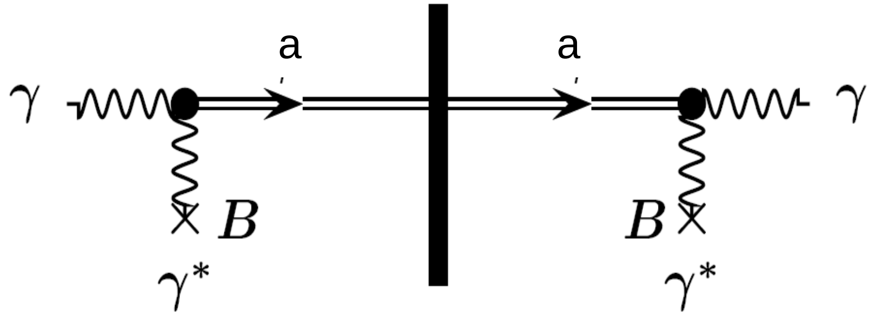
ALPS II:
$g = 2 \cdot 10^{-11}$ 1/GeV (astrophysics)
B = 5.3 T
L = 105.6 m
$P(\gamma \rightarrow a \rightarrow \gamma) = 5 \cdot 10^{-34}$

Still invisible?

How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

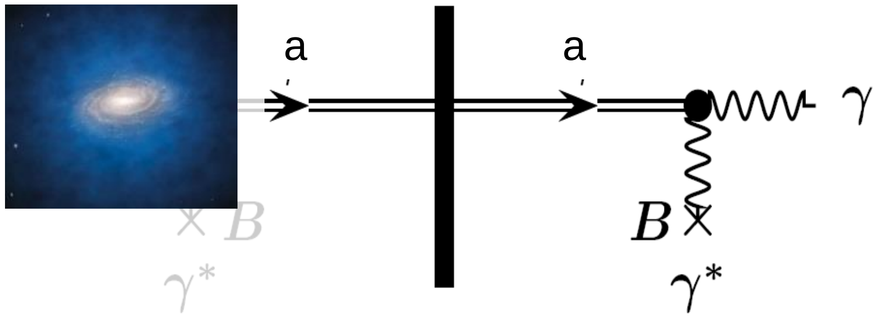
- Purely laboratory experiments "light-shining-through-walls", optical photons



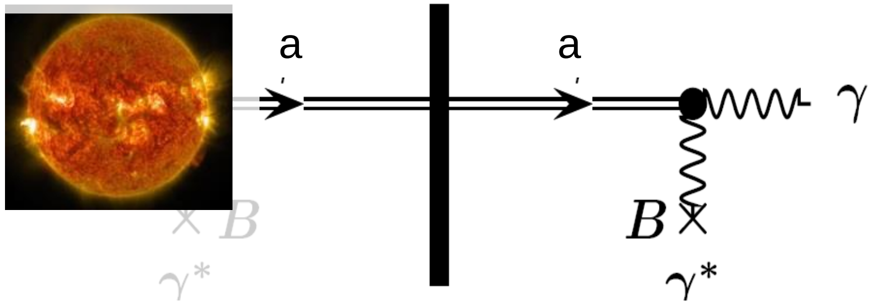
How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

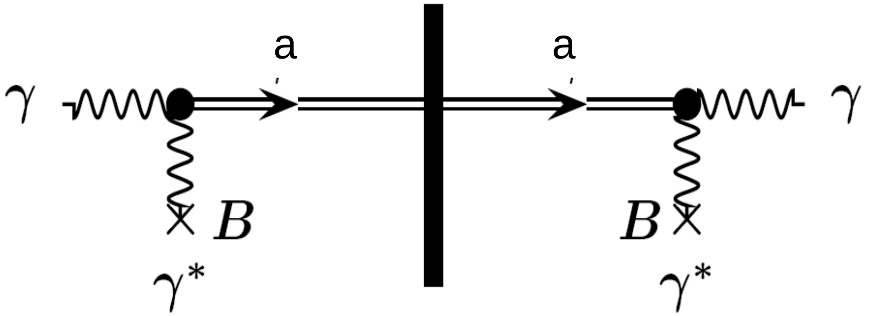
- Haloscopes
  looking for dark matter constituents,
  microwaves



- Helioscopes
  Axions emitted by the sun,
  X-rays



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

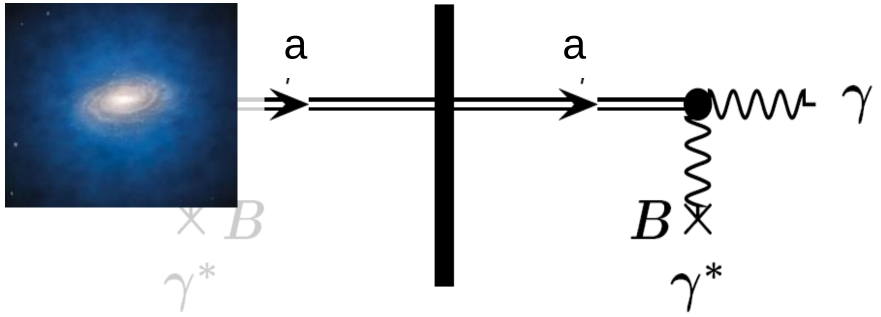


How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

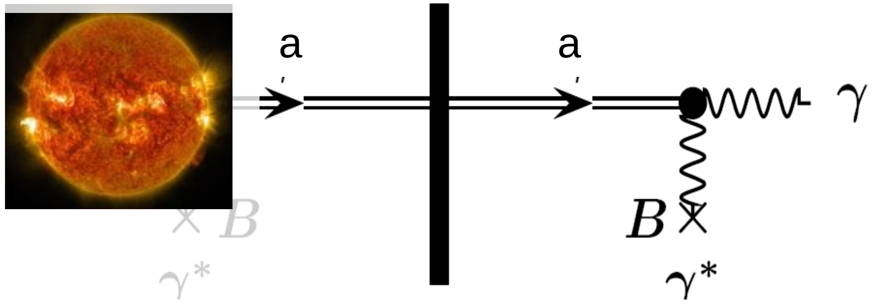
- Haloscopes
  looking for dark matter constituents,
  microwaves.

non-relativistic axions, "monochromatic" photons



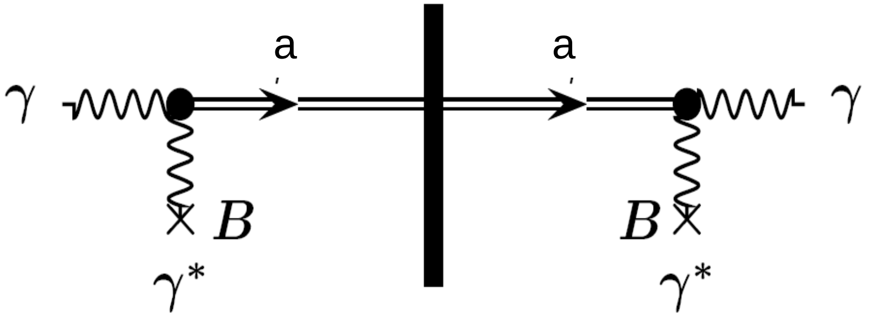
- Helioscopes
  Axions emitted by the sun,
  X-rays

relativistic axions, thermal photon spectrum



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

relativistic axions, monochromatic photons

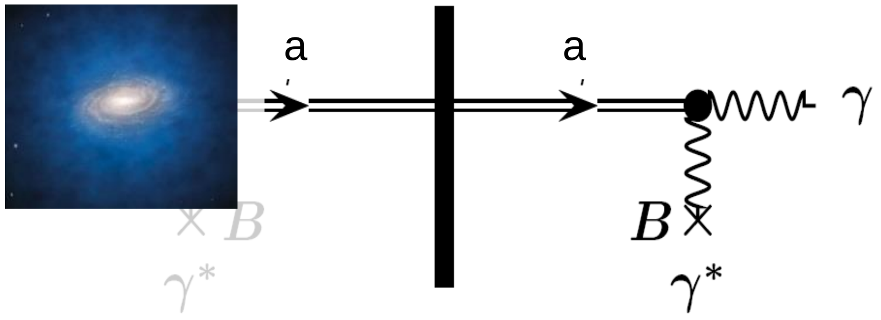


How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

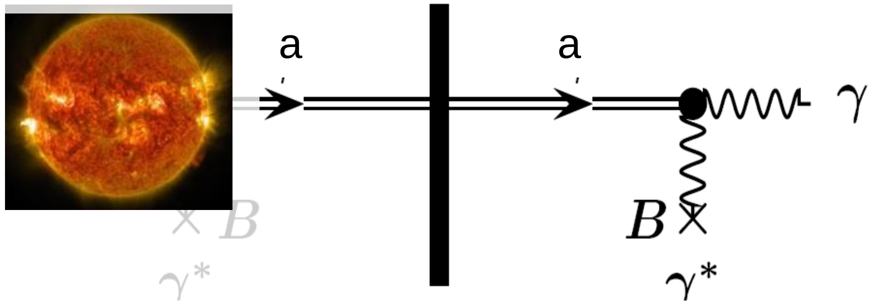
- Haloscopes
  looking for dark matter constituents,
  microwaves.

10^{-23} W
exploit resonant
detection



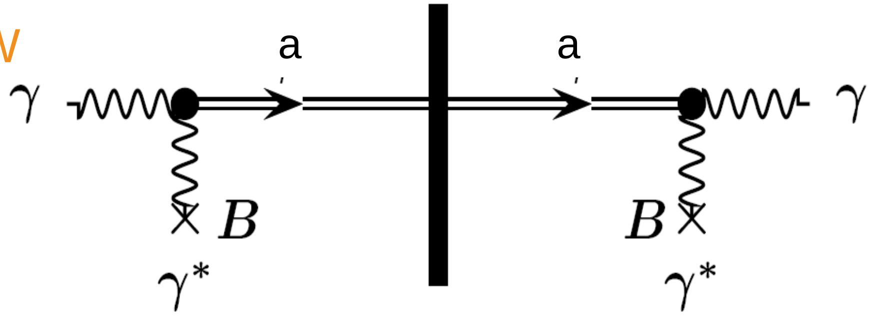
- Helioscopes
  Axions emitted by the sun,
  X-rays

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



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

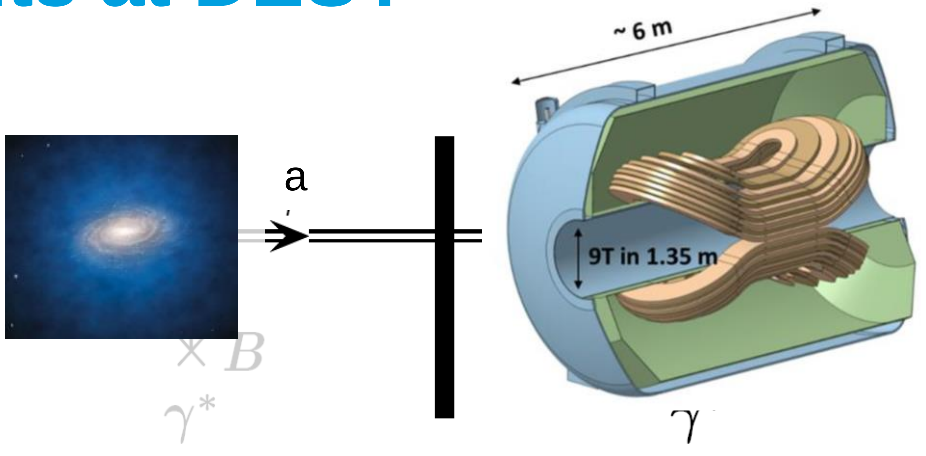
1 photon/day, 5·10^{-24} W
exploit resonant
detection



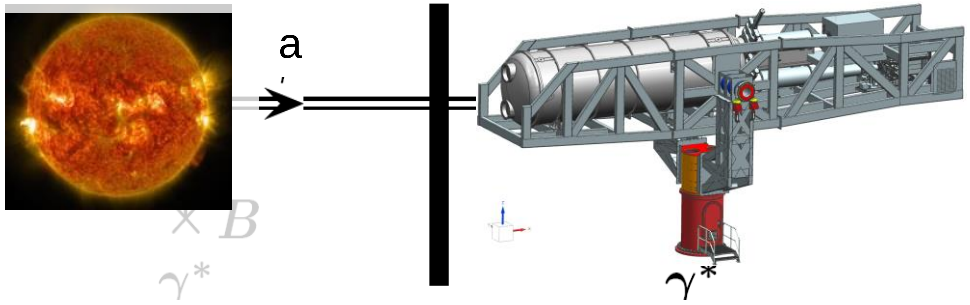
How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

- Haloscopes
  looking for dark matter constituents, microwaves. — MADMAX



- Helioscopes
  Axions emitted by the sun, X-rays — BabyIAXO



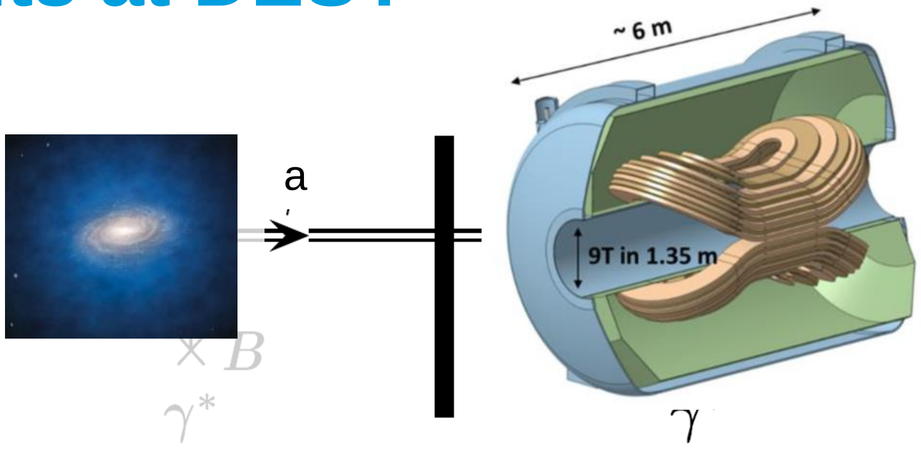
- Purely laboratory experiments
  "light-shining-through-walls", optical photons — ALPS II

How to look: three kinds of experiments at DESY

Axion/ALP photon mixing in magnetic fields

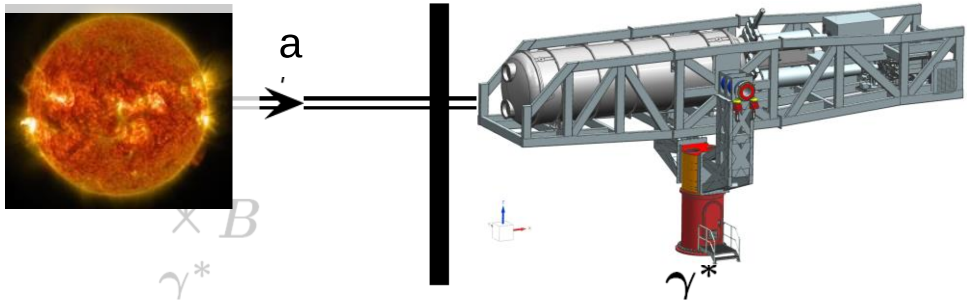
- Haloscopes
  looking for dark matter constituents, microwaves.

MADMAX



- Helioscopes
  Axions emitted by the sun, X-rays

BabyIAXO

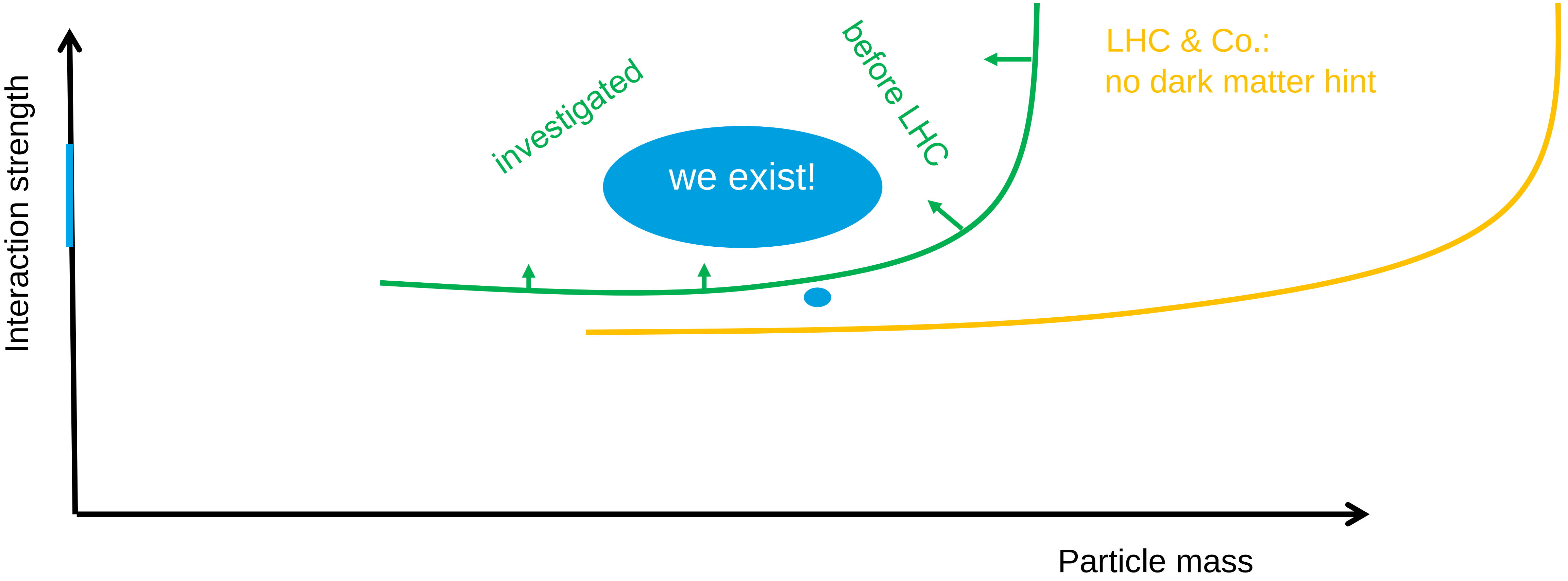


- Purely laboratory experiments
  “light-shining-through-walls”, optical photons

ALPS II
1st science run just started!

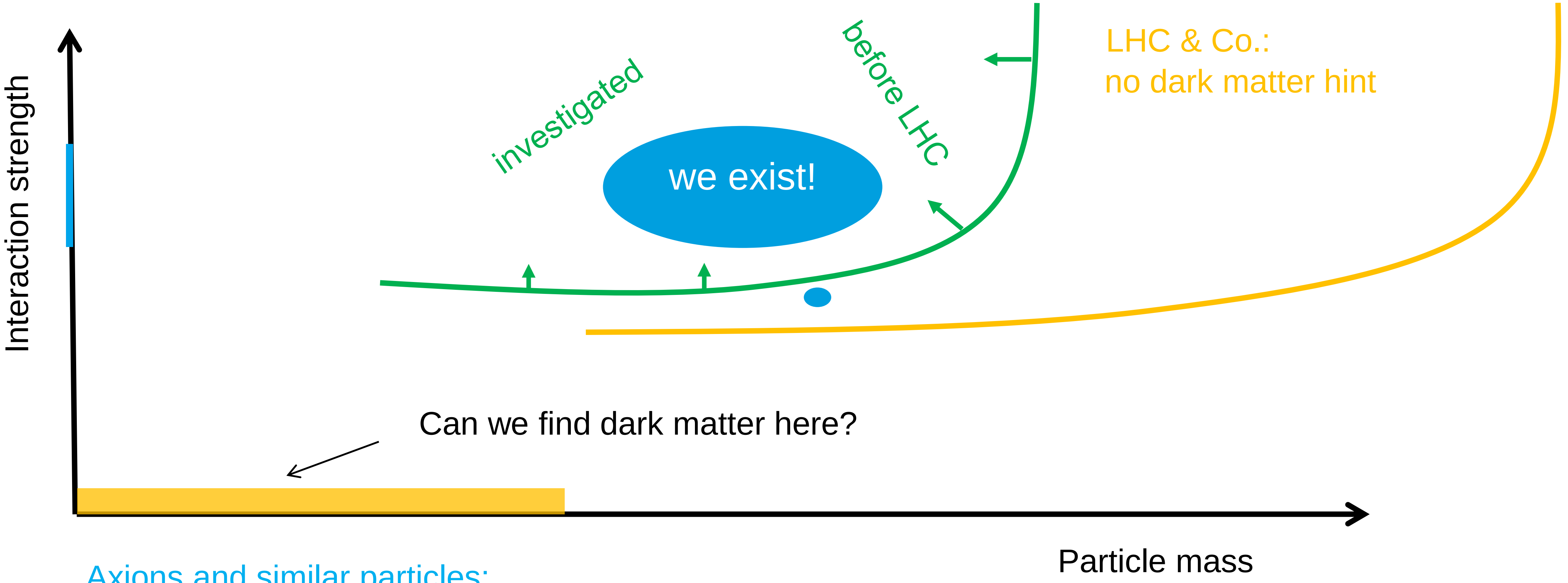
Context: particle physics at colliders

A very simplified picture



Particle physics beyond colliders

Axions and other Weakly Interacting Slim Particles (WISPs)



Axions and similar particles:
interact much too weakly to be seen at colliders.

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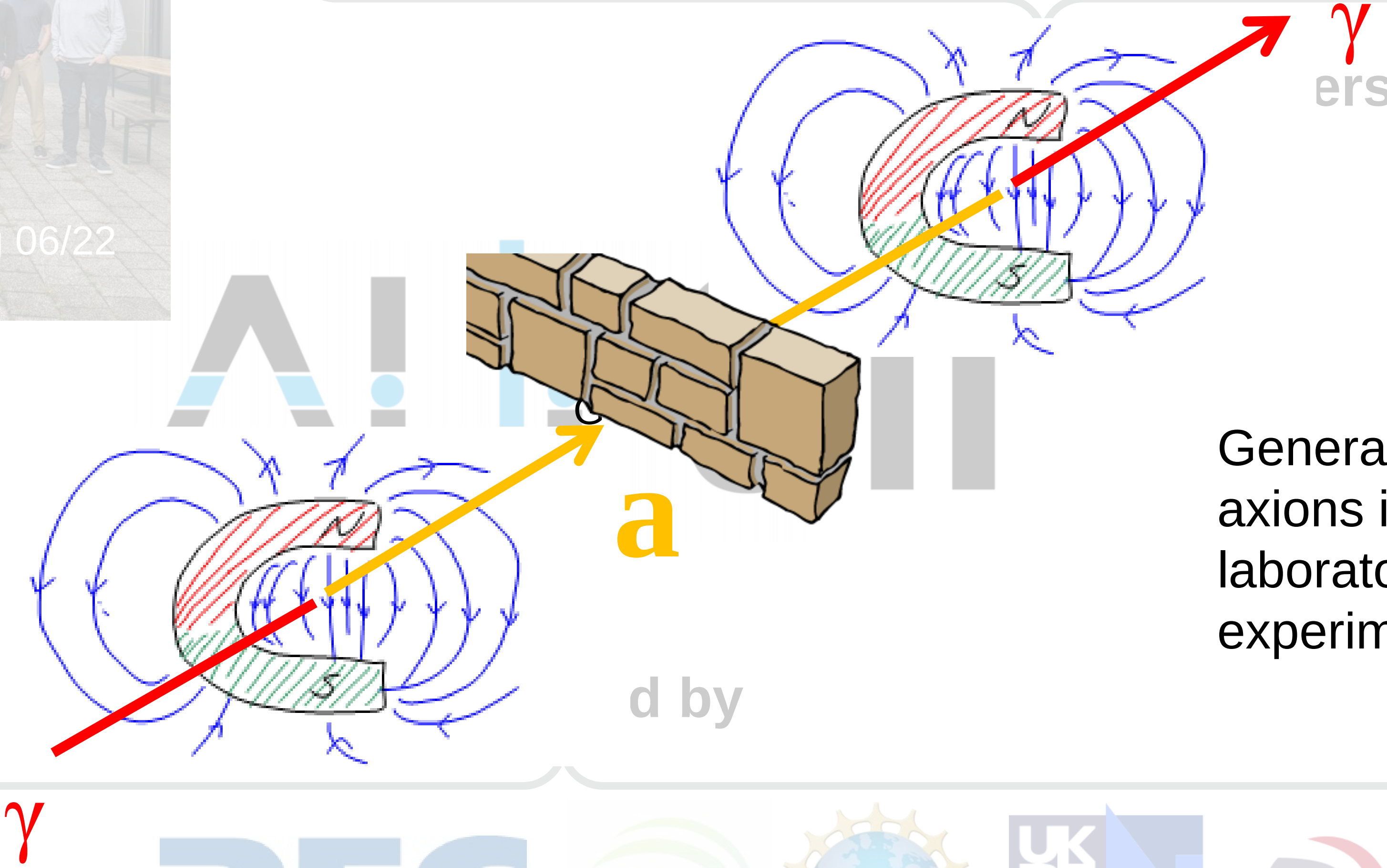
Collaboration members

ALPS II

Supported by

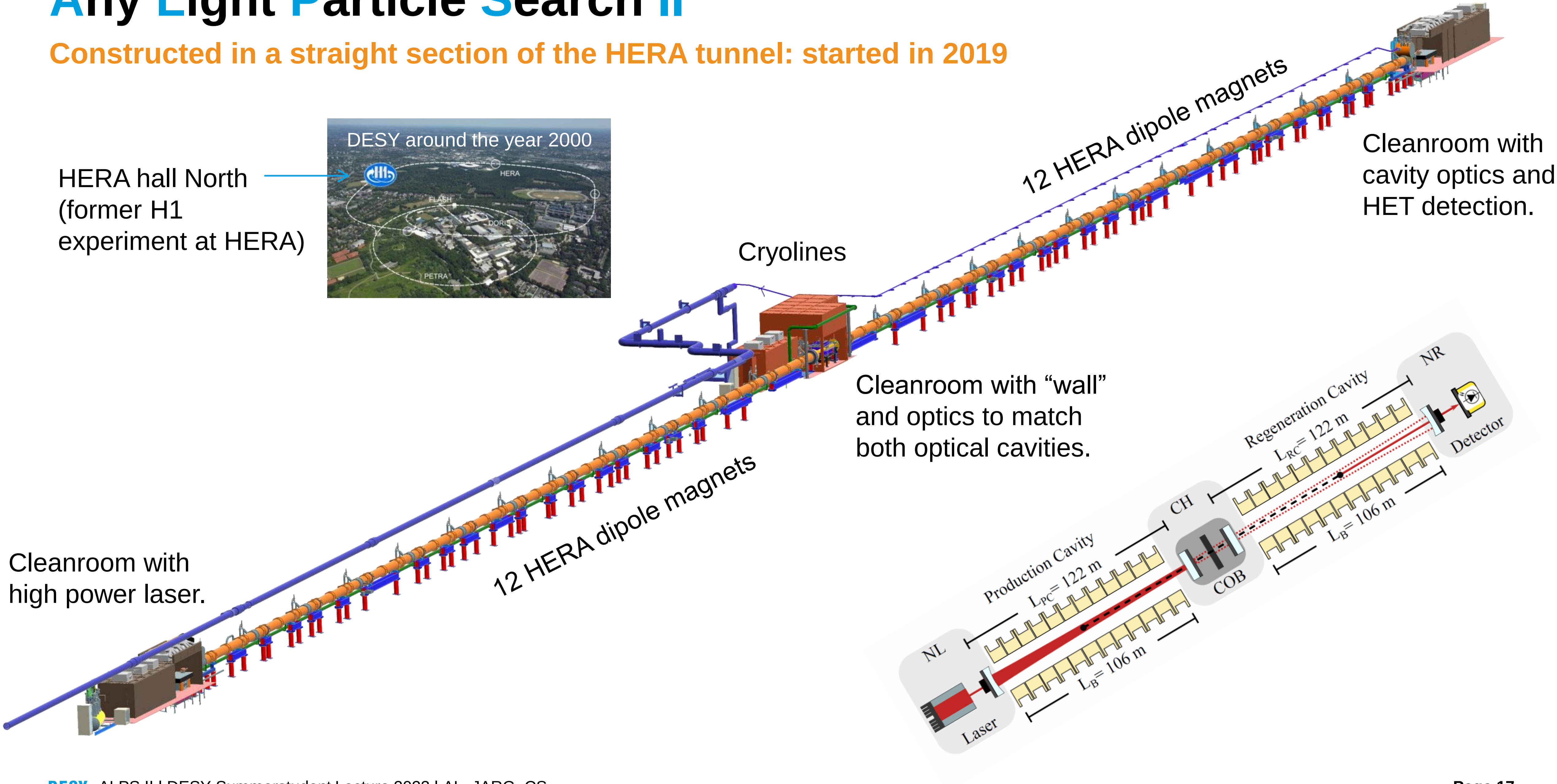


Generate and detect axions in a purely laboratory-based experiment.

Any Light Particle Search II

Constructed in a straight section of the HERA tunnel: started in 2019

HERA hall North
(former H1
experiment at HERA)



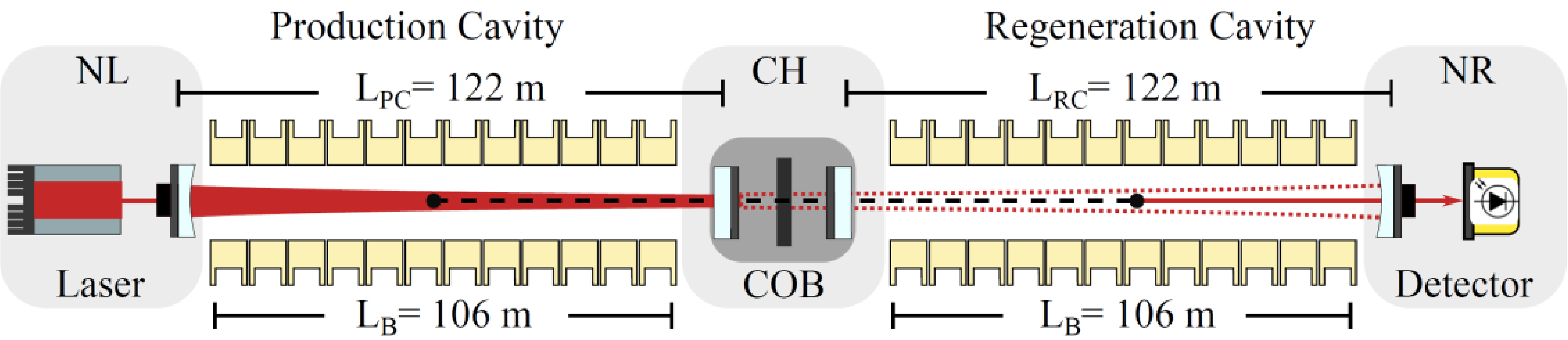
Cleanroom with
cavity optics and
HET detection.

Cleanroom with “wall”
and optics to match
both optical cavities.

Cleanroom with
high power laser.

Any Light Particle Search II

Exploiting mode matched optical cavities



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

$= 10^{-25}$

5,000   40,000   0.2   5.3   10.56

Motivated by astrophysics

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

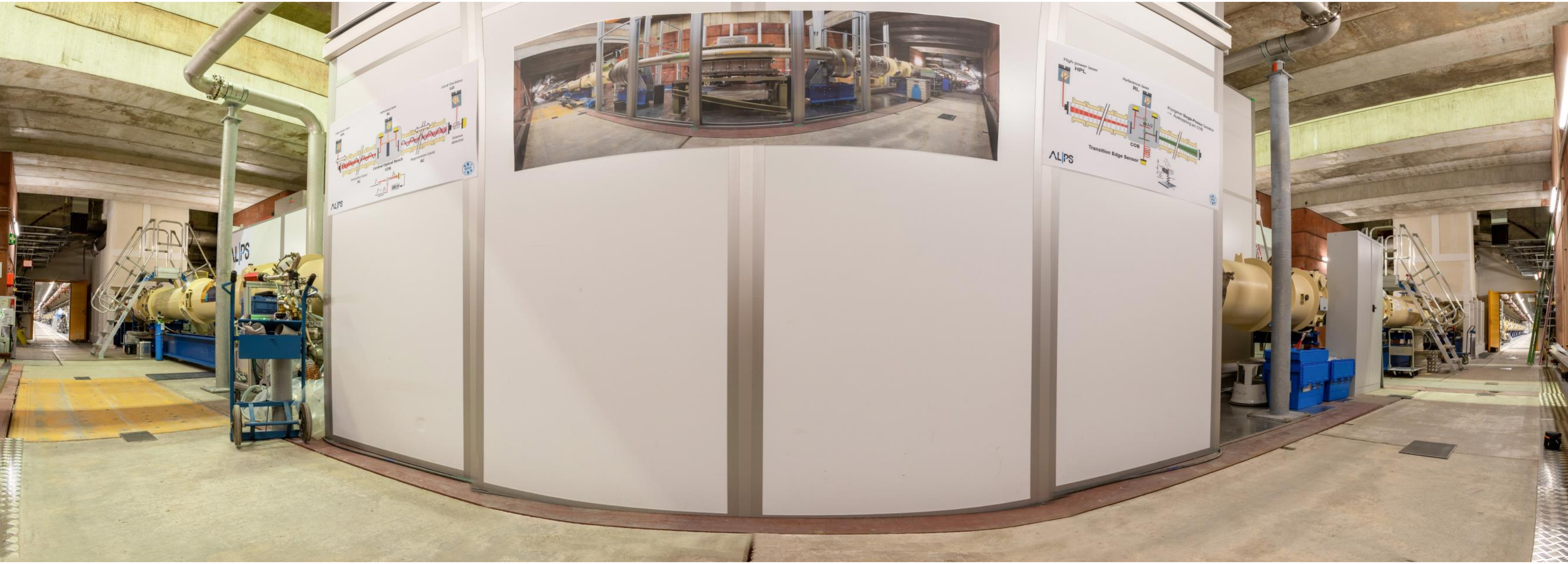
30 W cw Laser 1064 nm: $3\cdot 10^{-5}$ Photonen / s ($5\cdot 10^{-24}$ W).

Any Light Particle Search II

Autumn 2020

Any Light Particle Search II

Autumn 2022: all components ready for operation



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

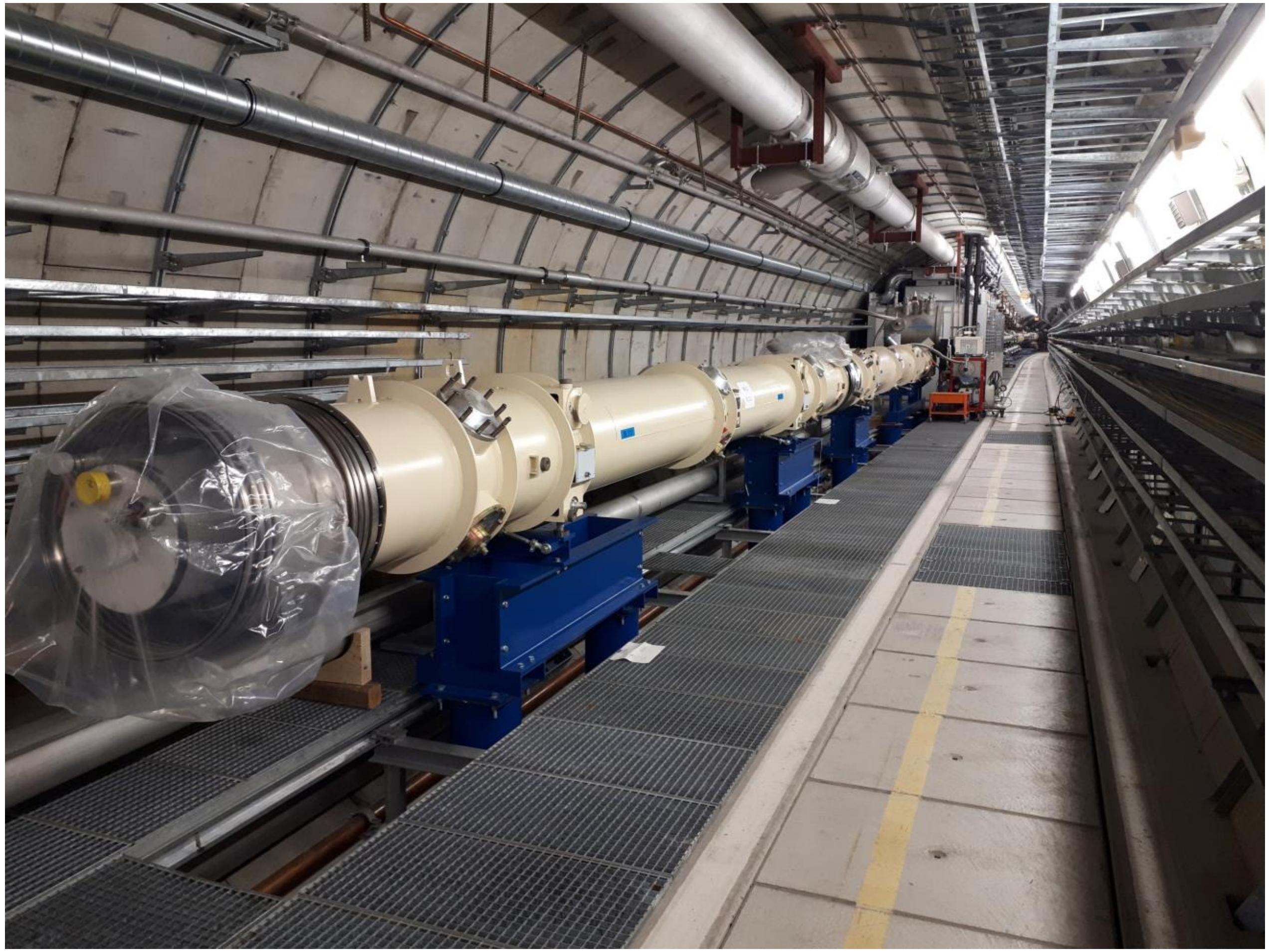
More magnets

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

inlovewithflight

Any Light Particle Search II

Technologies

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

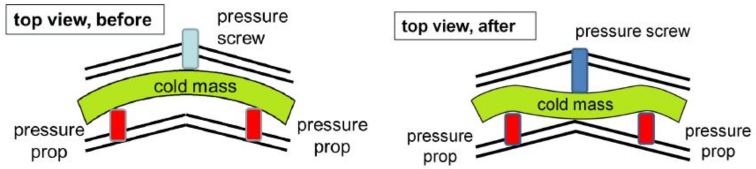
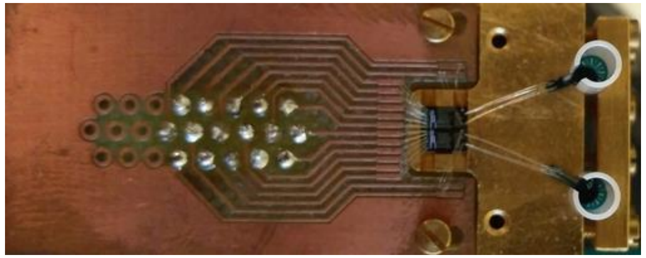


Figure 9: *Schematics of straightening. Left: Before applying the deforming force, Right: The deformation forces the pipe to develop two 'camel humps,' exaggerated in the figure for better illustration. This deformation yields the largest achievable horizontal aperture.*

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

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

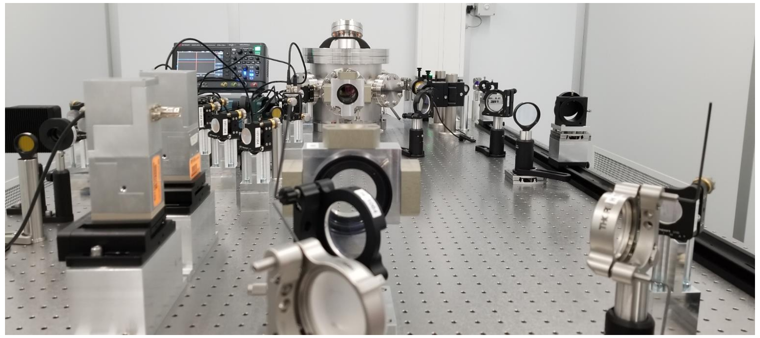
- Extremely low 1064 nm photon flux detection:
  10^{-24} W sensitivity with heterodyne sensing and
  a superconducting transition edge sensor (TES).



Phys.Dark Univ. 35 (2022), 100914

PoS EPS-HEP2021 (2022), 801

- Optics:
  long baseline precisions interferometry based on
  GEO600 and aLIGO experience,
  10^{-12} m precision!



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

ALPS II improvements

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

ALPS I in 2010
OSQAR in 2015

magnets: 24

optics: 49

photon detection: 3

ALPS II

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

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

ALPS II improvements

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

ALPS I in 2010
OSQAR in 2015

magnets: 24

optics: 49

photon detection: 3

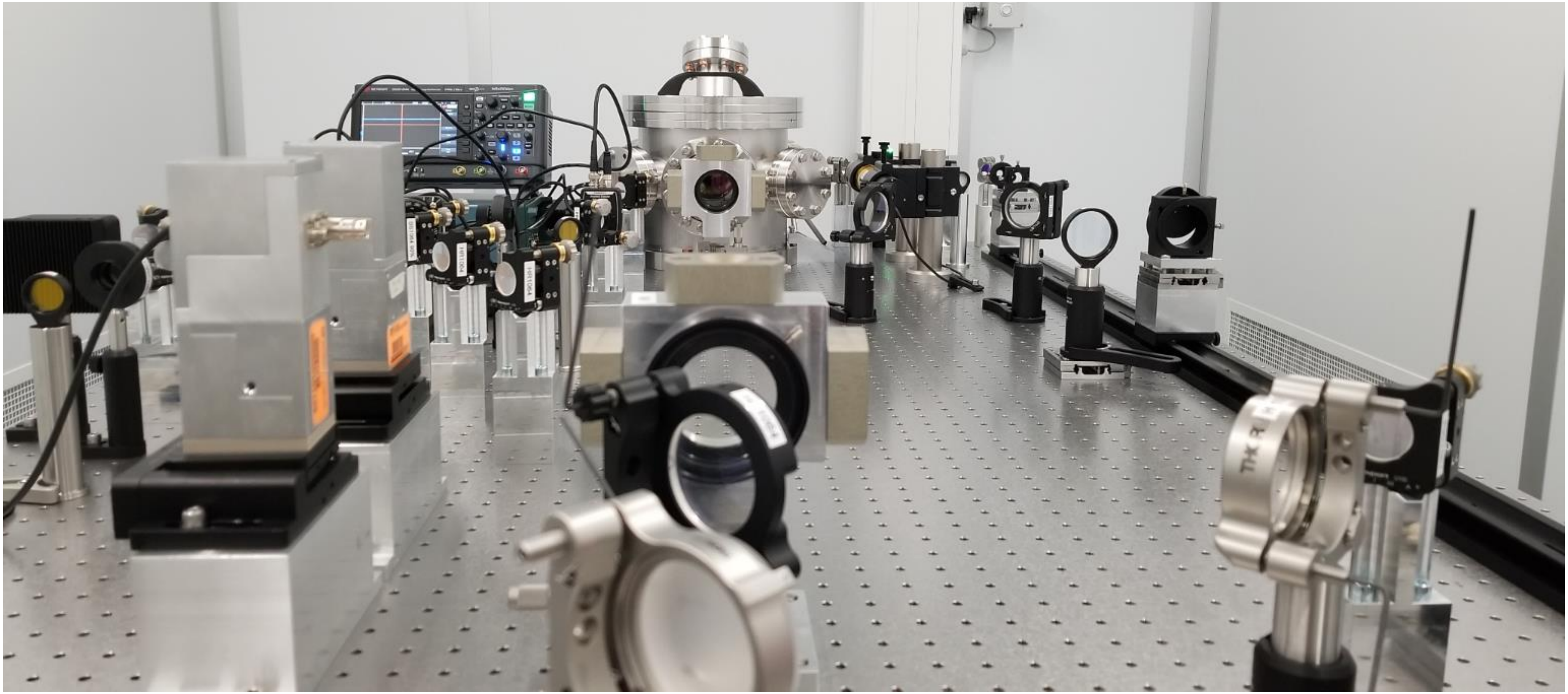
ALPS II

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

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

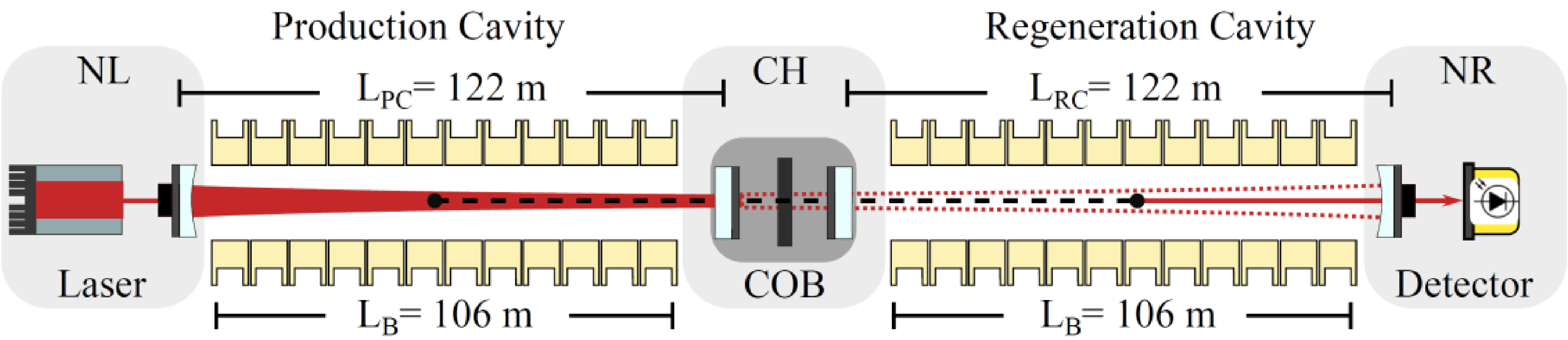
ALPS II optics

Strongly benefiting from GEO600 and aLIGO

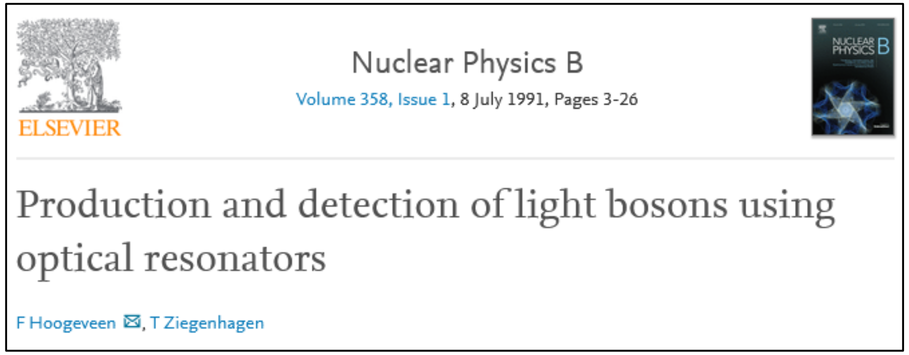


ALPS II optics

Based optical resonators



Proposed already in 1991!


ELSEVIER

Nuclear Physics B

Volume 358, Issue 1, 8 July 1991, Pages 3-26

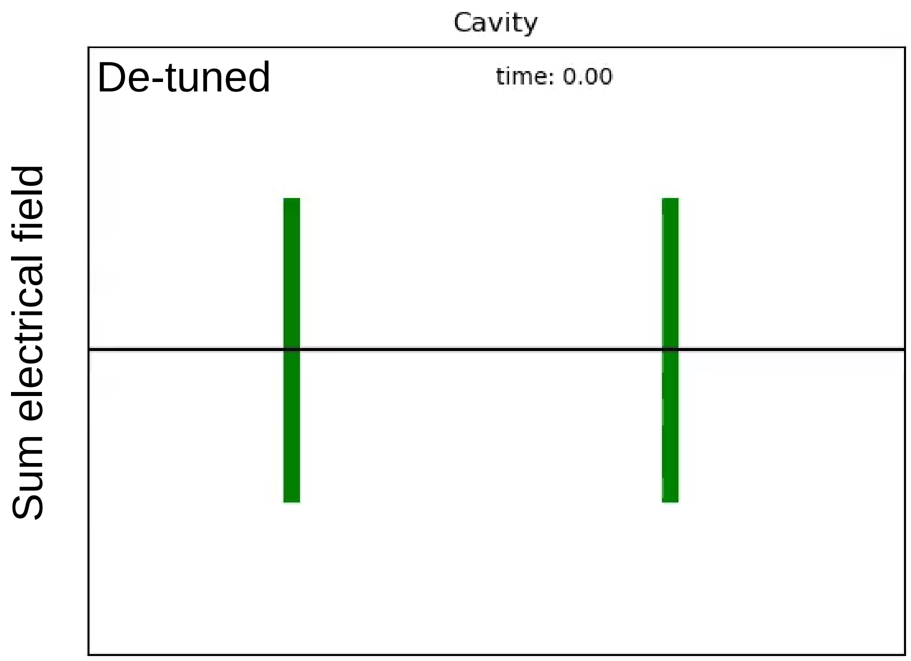
Production and detection of light bosons using optical resonators

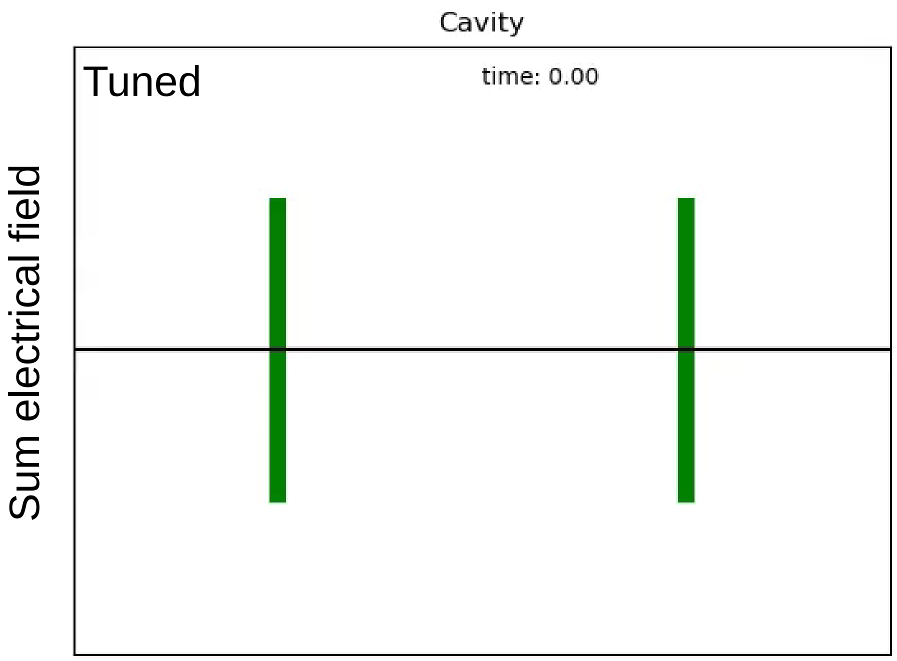
F Hoogeveen, T Ziegenhagen

ALPS II Optics

Based on optical resonators

Set-up: two semi-transparent mirrors with 80% reflection (in this toy example).





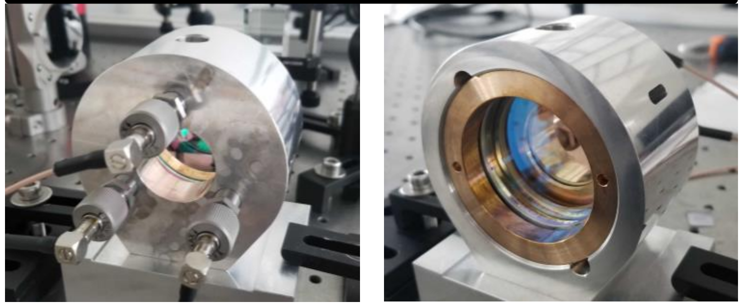
Tuned:

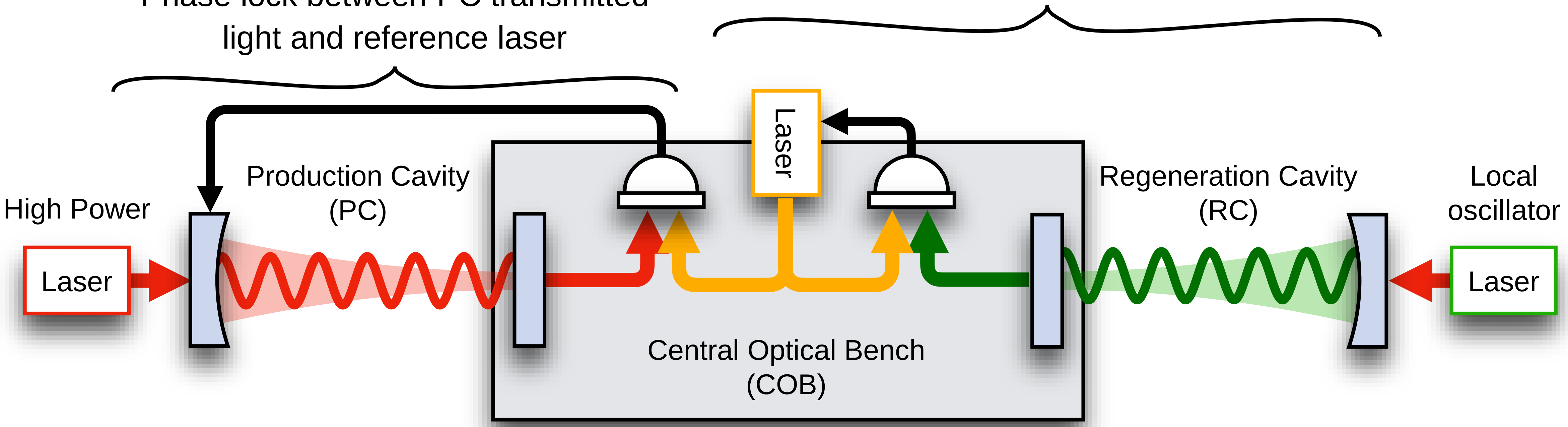
- The mirror system becomes transparent.
- The power in between the mirrors gets amplified. 80% reflectivity: factor 5.

Any Light Particle Search II

Optics "locking" scheme to overcome seismic noise

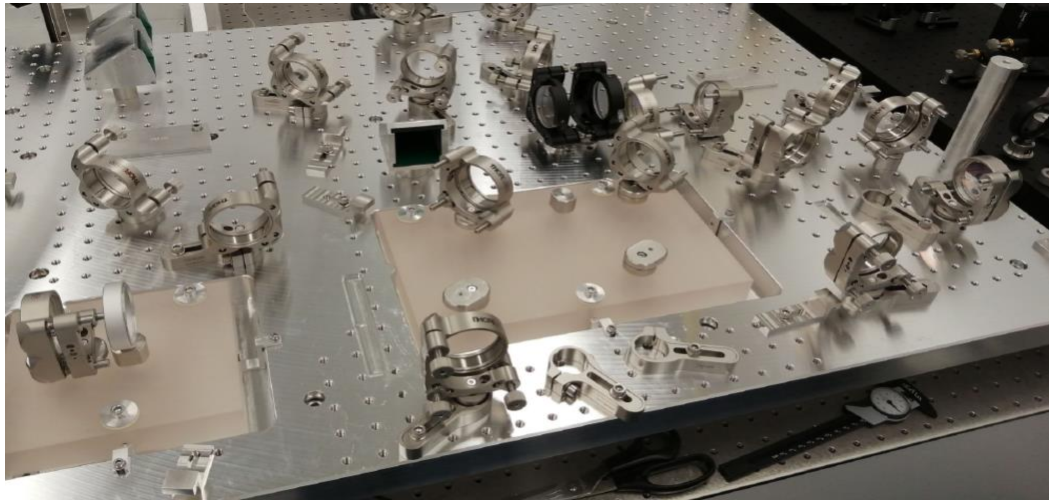
Actuators: *picometer* position accuracy required

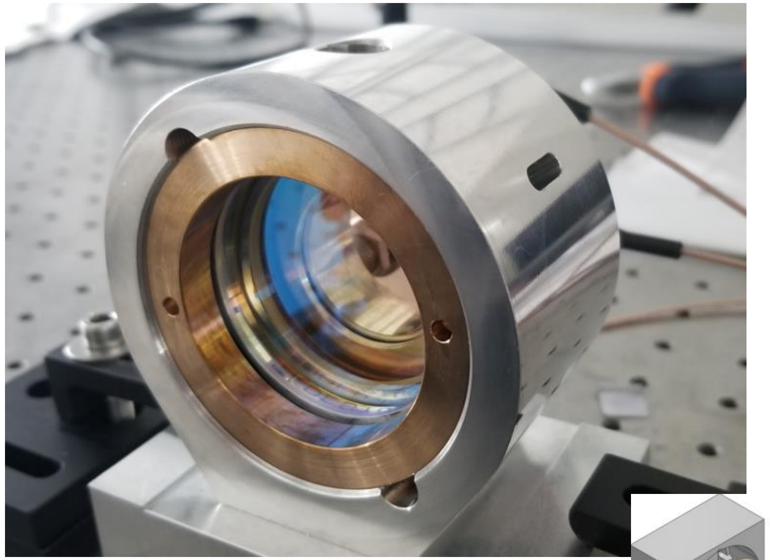


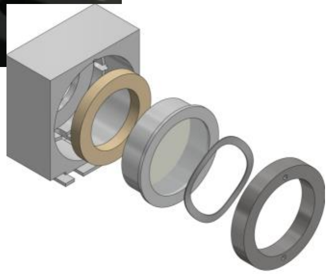


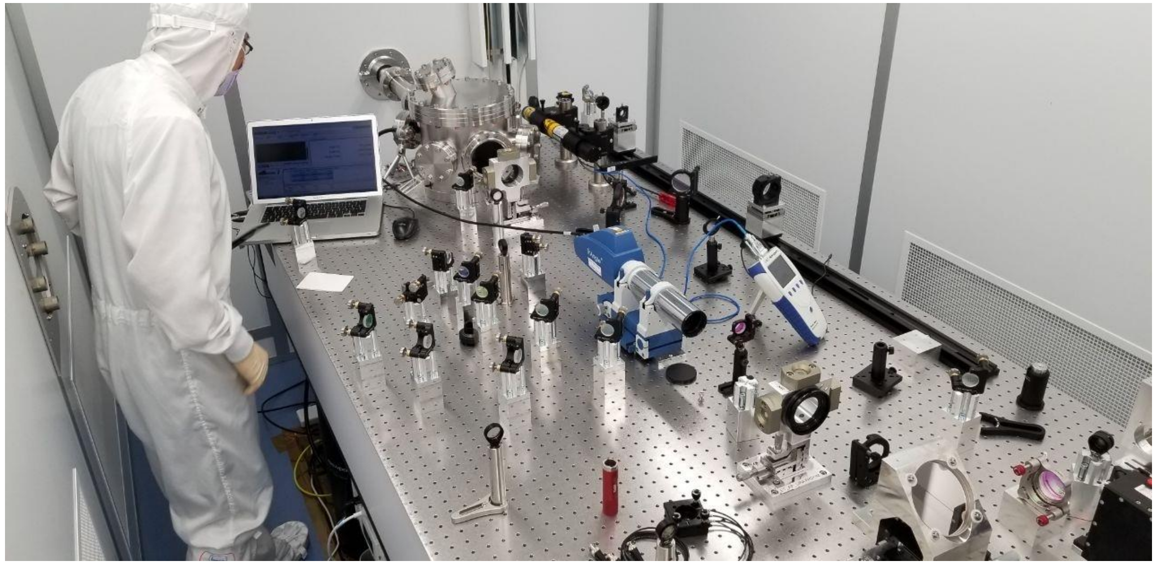
Any Light Particle Search II

Complex optics









Any Light Particle Search II

Challenging working conditions

DESY News 27 October 2022

ALPS II achieves world record

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

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

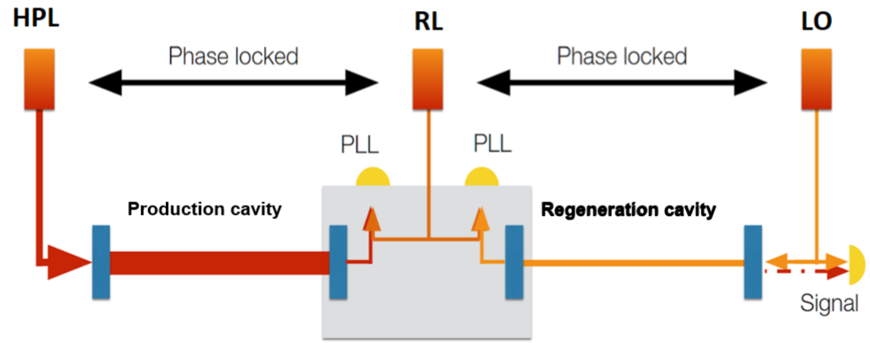
Any Light Particle Search II

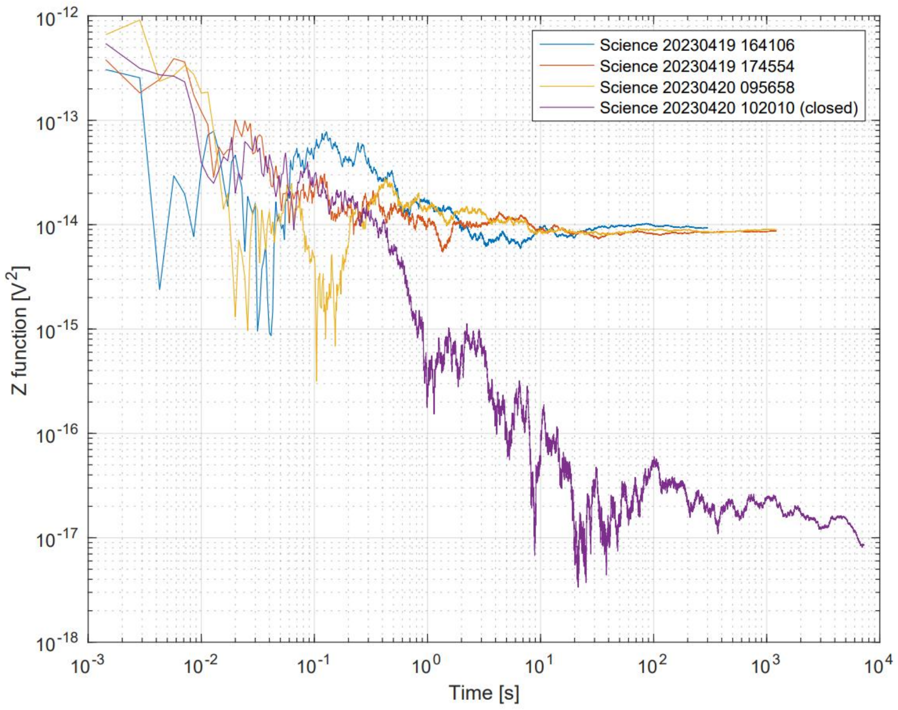
Looking for $5 \cdot 10^{-24}$ W @ 1064 nm

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

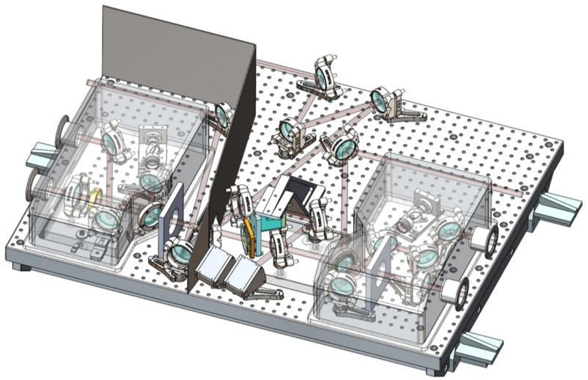
Option 1: heterodyne sensing

- Mix weak signal with a frequency f shifted local oscillator and demodulate at f.
- Detection of a photon flux corresponding to $5 \cdot 10^{-21}$ W demonstrated.
- Sensitivity of 10^{-24} W demonstrated.





The first science runs of ALPS II will use heterodyne sensing.



ALPS II initial science run

Started 23 March 2023

Magnets ramping up 24 May 2023

ALPS II initial science run

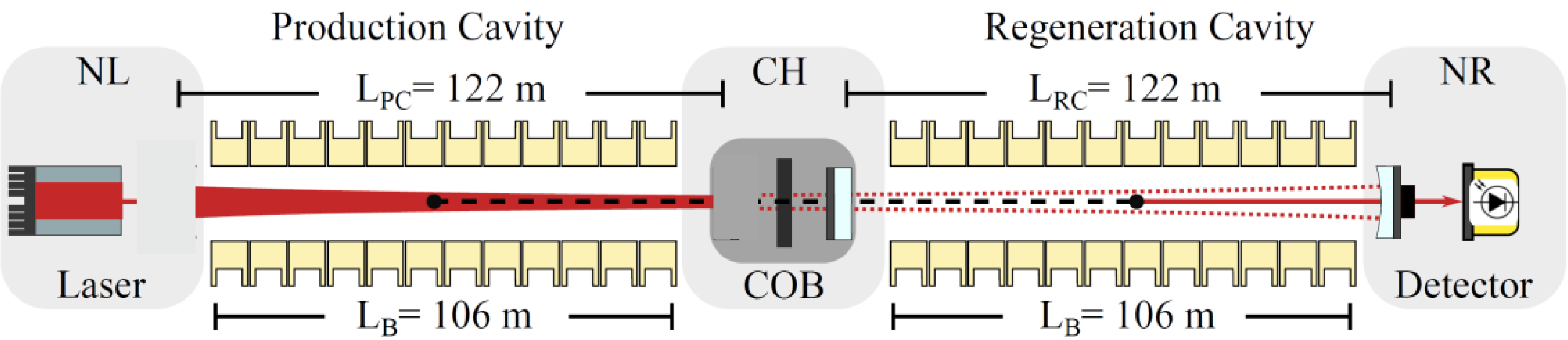
ALPS II Fest 30 May 2023: 20 years after discussing the first axion search ideas at DESY

ALPS II initial science run

ALPS II initial configuration

Initial science run:

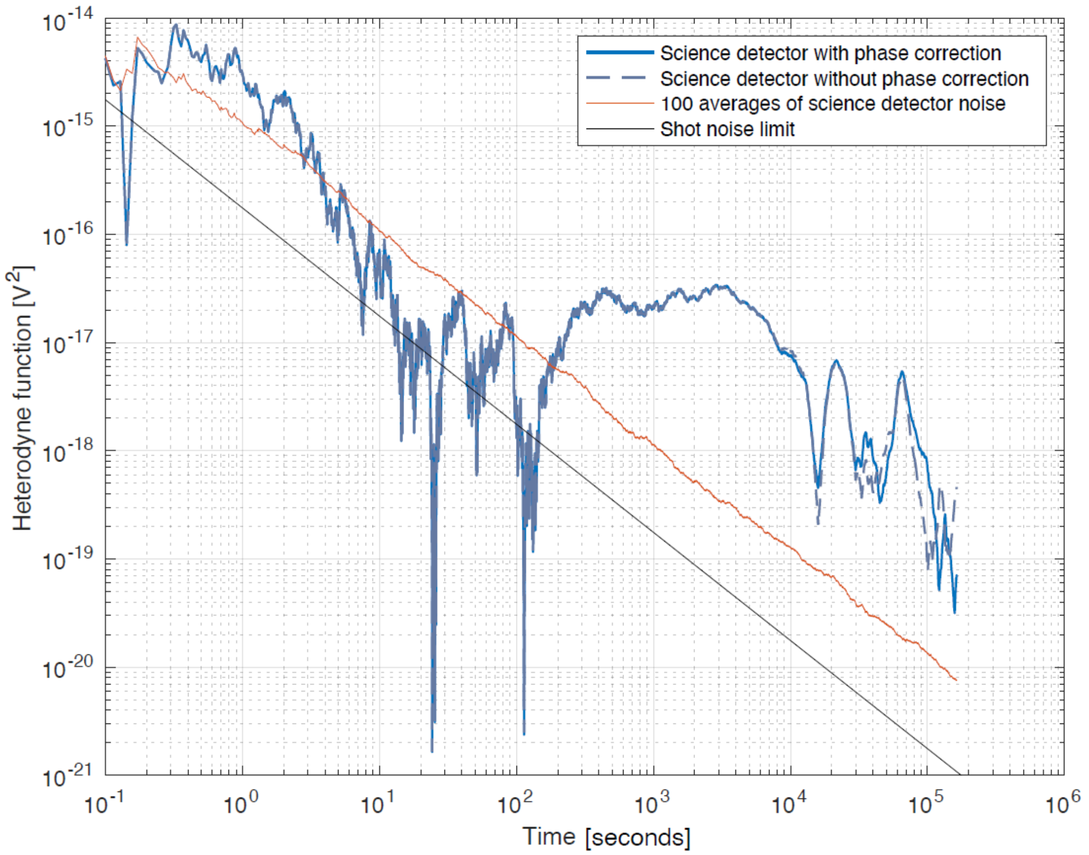
- No “production cavity” to optimize for stray-light searches.
- About 100-fold improvement on the axion-photon coupling. The last factor of about 10 will come with the production cavity.



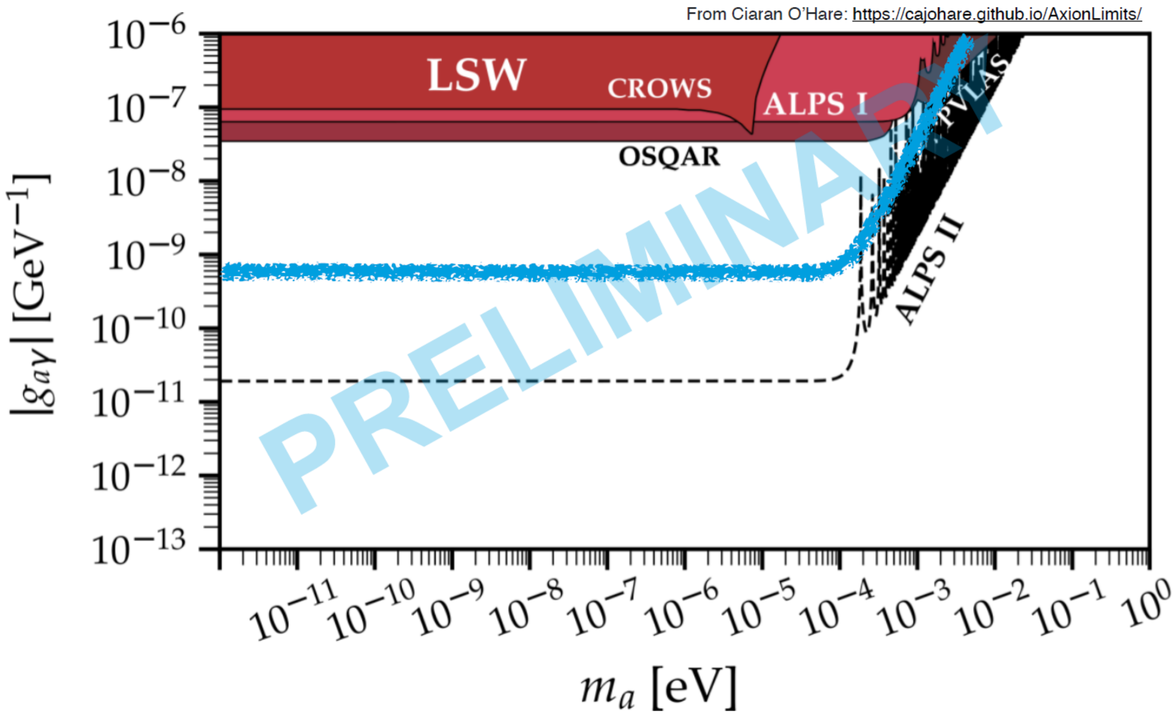
ALPS II initial science run

Sensitivity reached with 1.9 days of good data (preliminary)

The “signal channel”:



Sensitivity reached by now:



Already about 100 times more sensitive than previous experiments!

Outline

Jose

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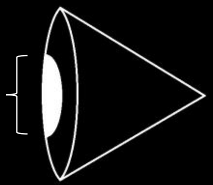
$800\ lm$

23% of power converted to light

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

Narrow pupil
$2\ mm$ diameter

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



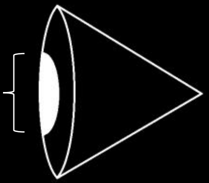
$1\ m$

$800\ lm$

23% of power converted to light

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

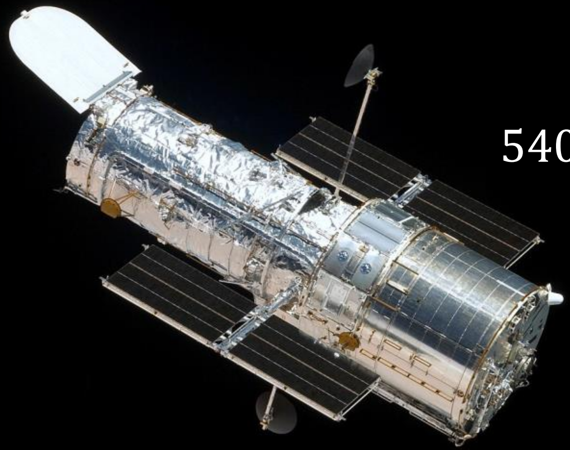
Narrow pupil
$2\ mm$ diameter



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

$1\ m$

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



$540\ km$

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

DESY.

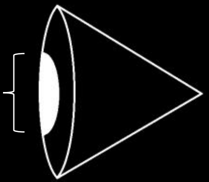
$800\ lm$

23% of power converted to light

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

Narrow pupil

$2\ mm$ diameter

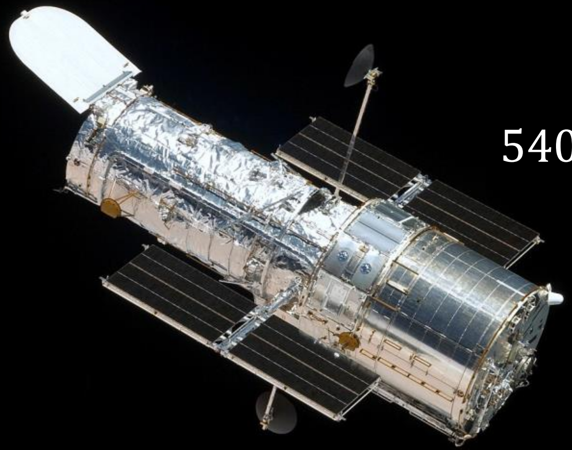


$4.8 * 10^{12}\ \gamma/s$

$1\ m$

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

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



$540\ km$

$3.84 * 10^{5}\ km$

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

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

DESY.

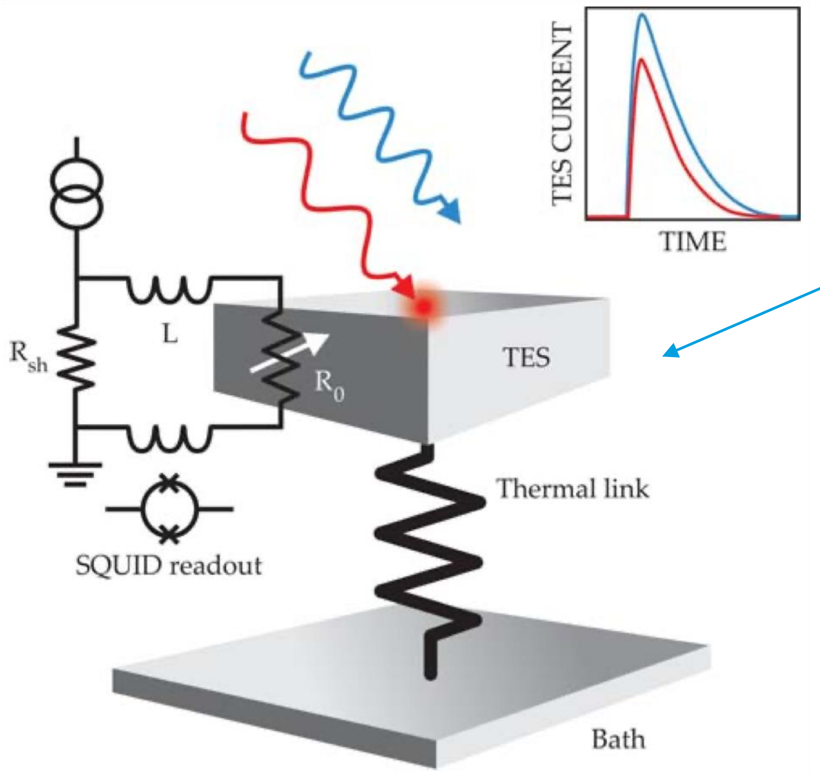
Single photon detector

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: $< 7.7 \cdot 10^{-6} \mathrm{cps} \sim 1 \text{ photon } (1064\mathrm{nm} - \text{like}) \text{ every } 2 \text{ days}.$
- 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

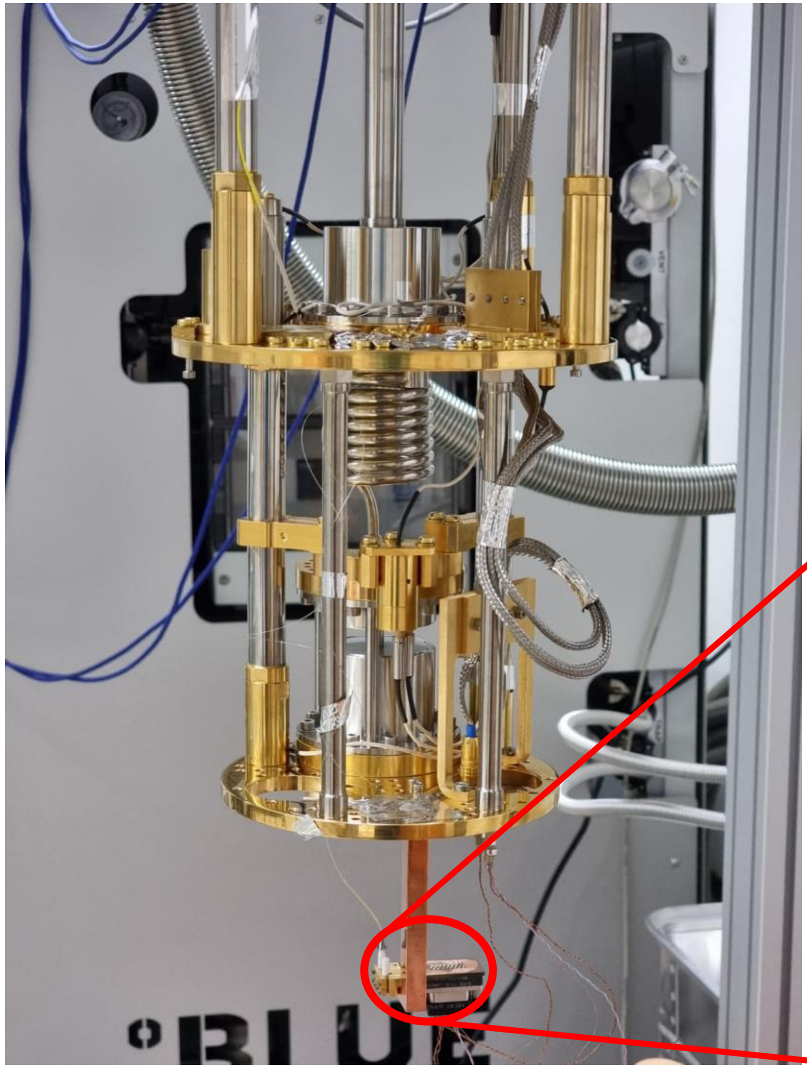
⬋

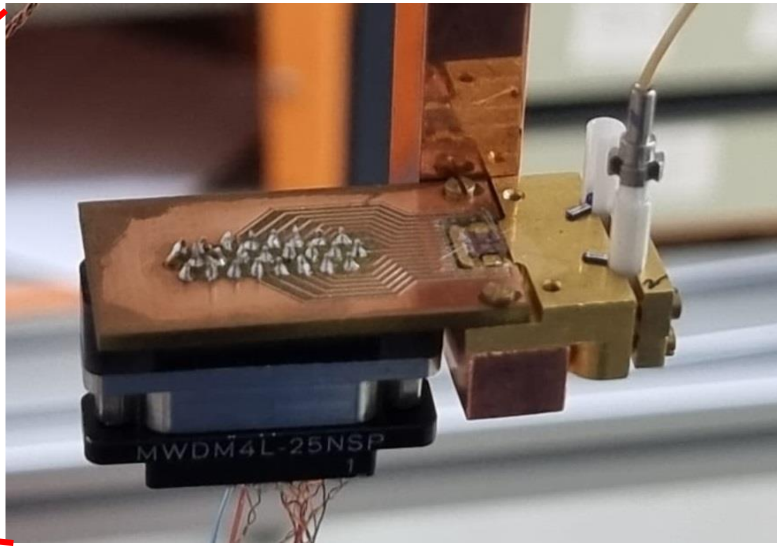
Current change (voltage-biased circuit)

Schematic adapted from Katharina-Sophie Isleif.

Transition Edge Sensor (TES)

$\sim 1\ m$





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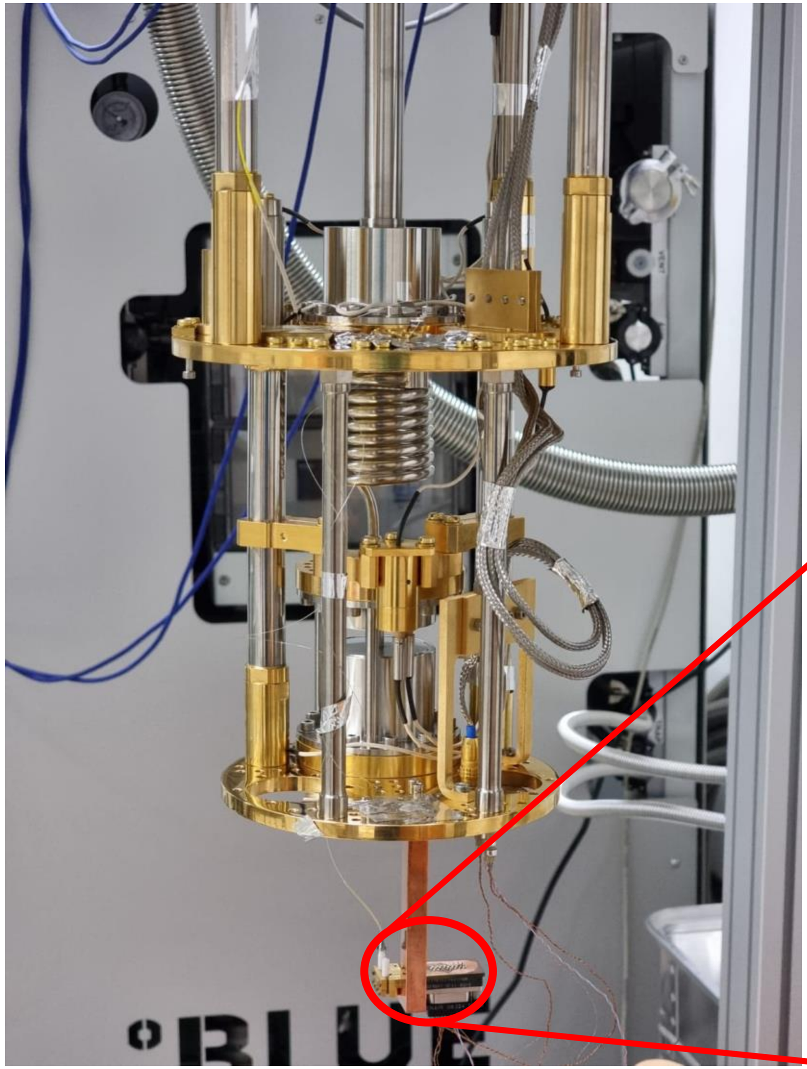
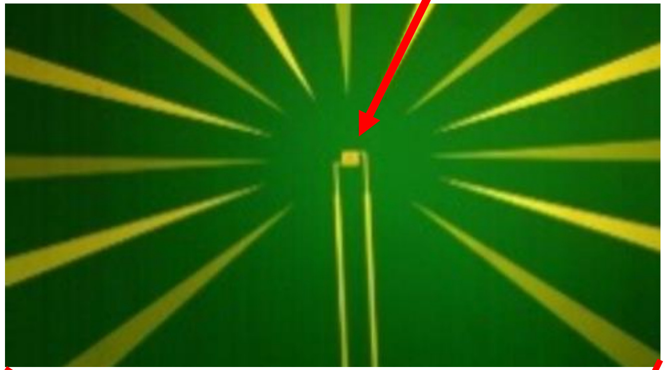
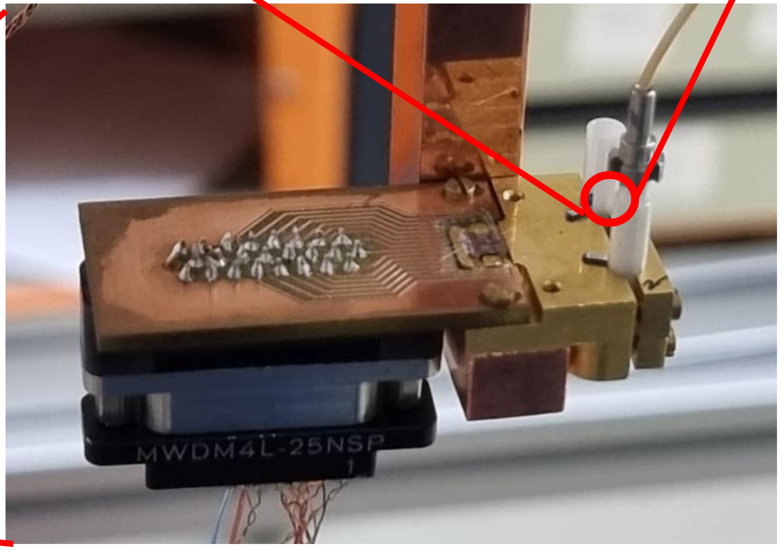


$25\ \mu m \times 25\ \mu m \times 20\ nm$





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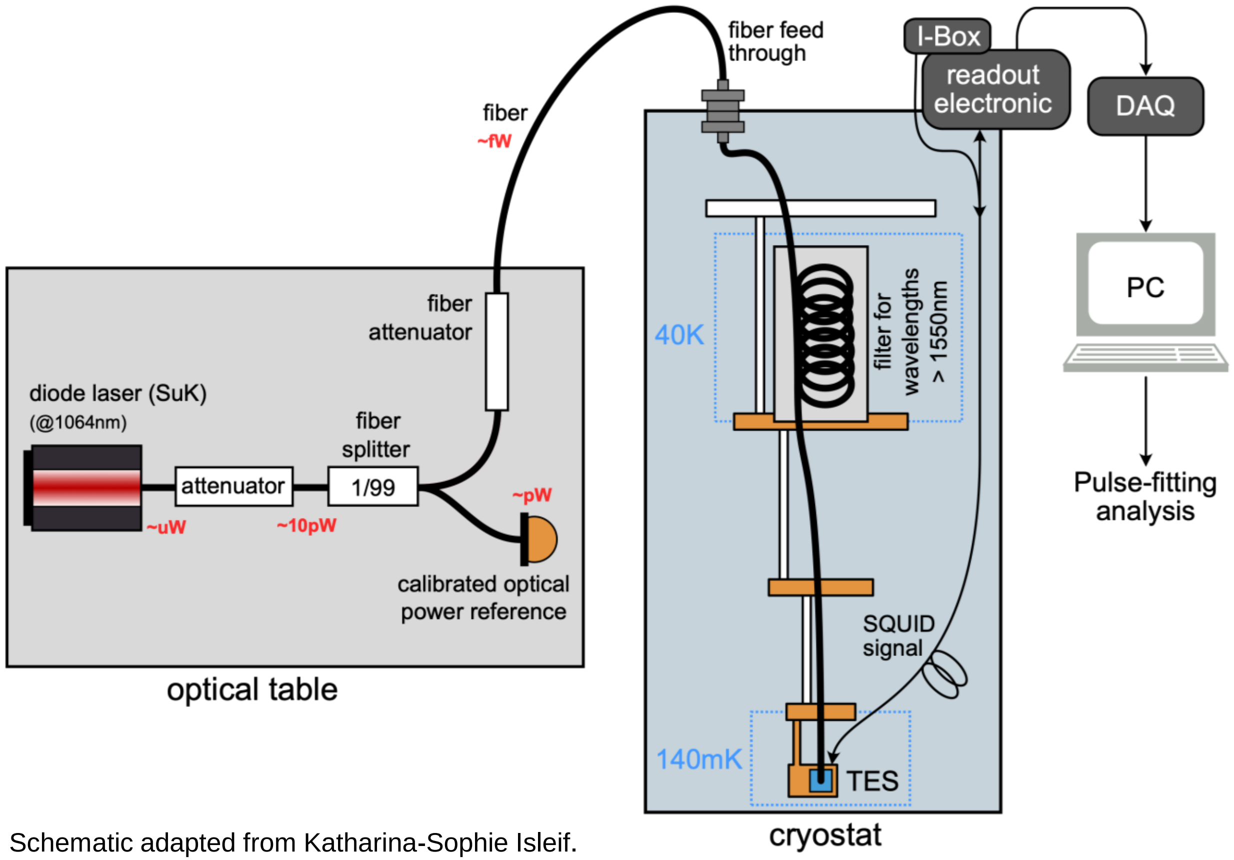

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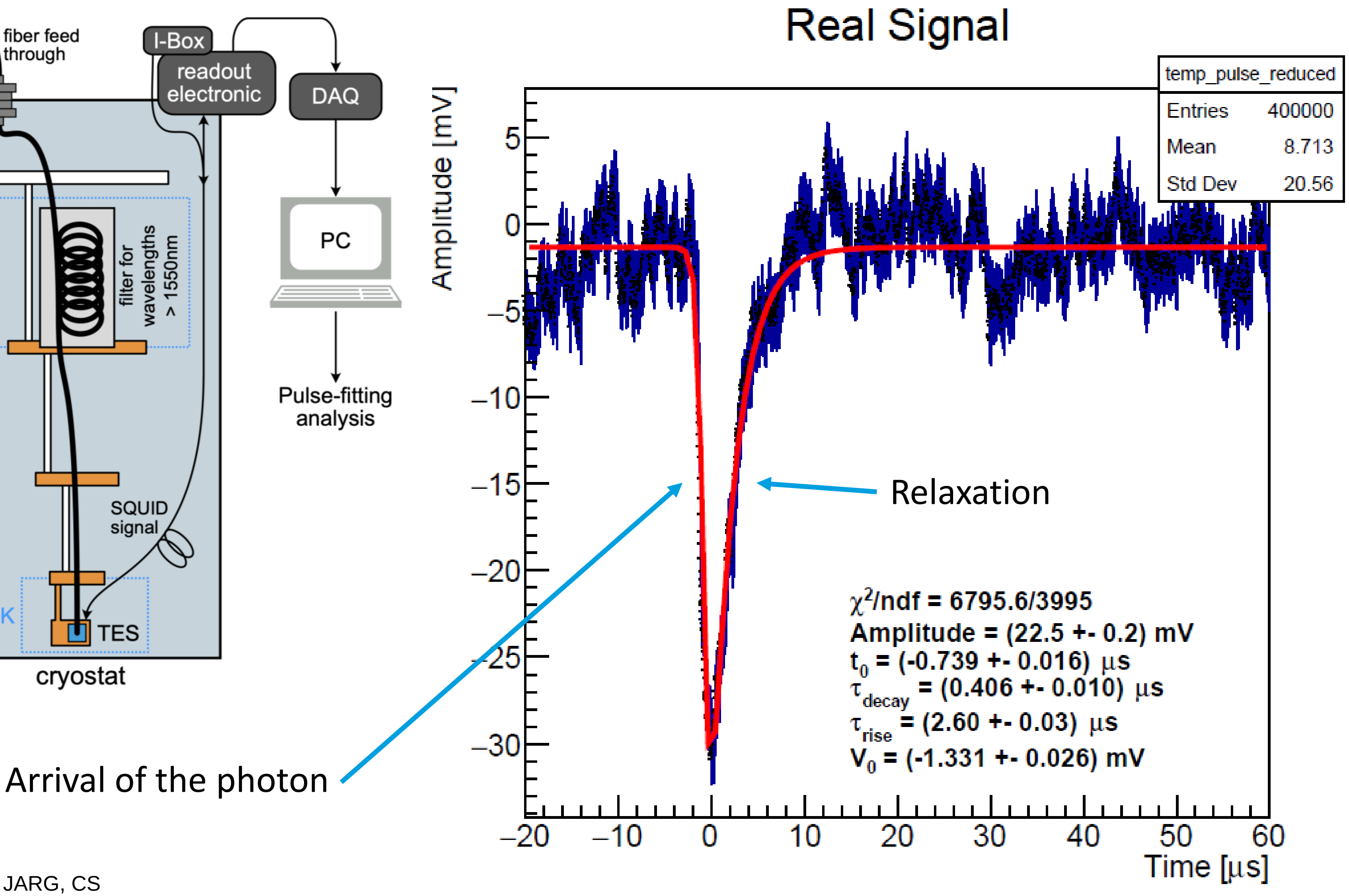

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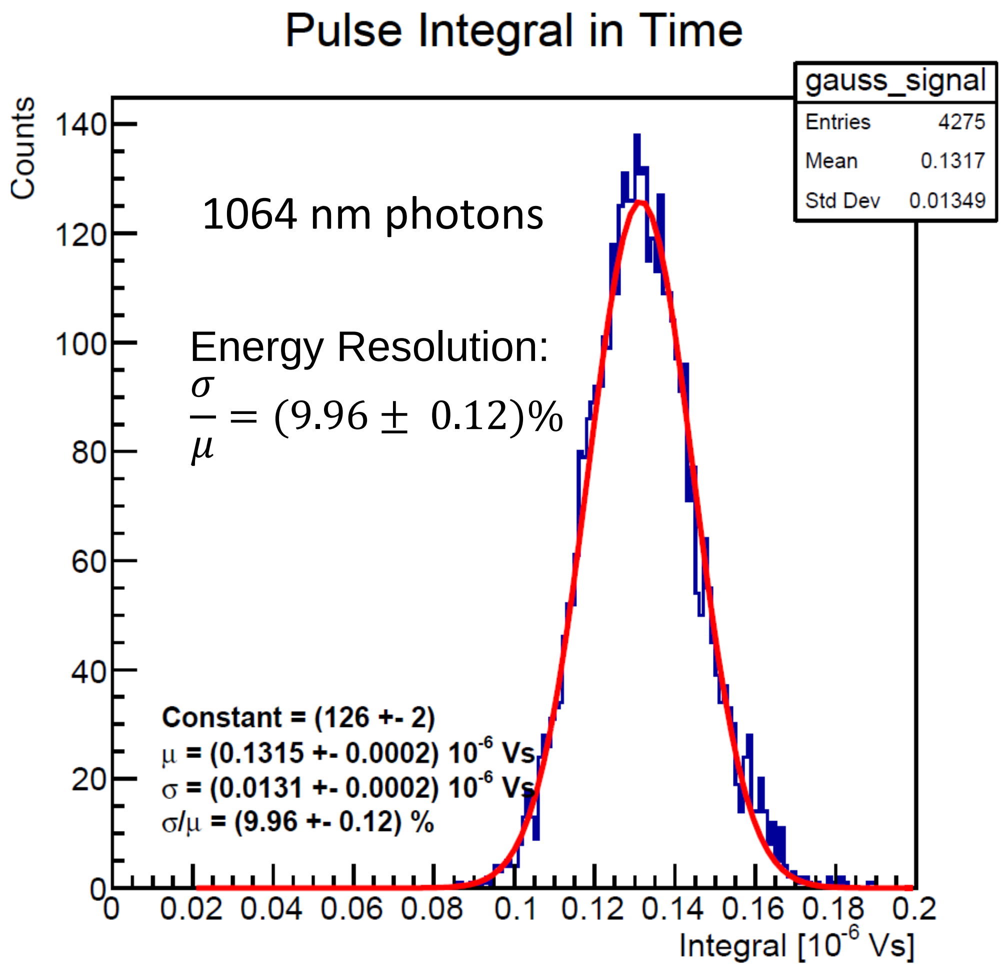
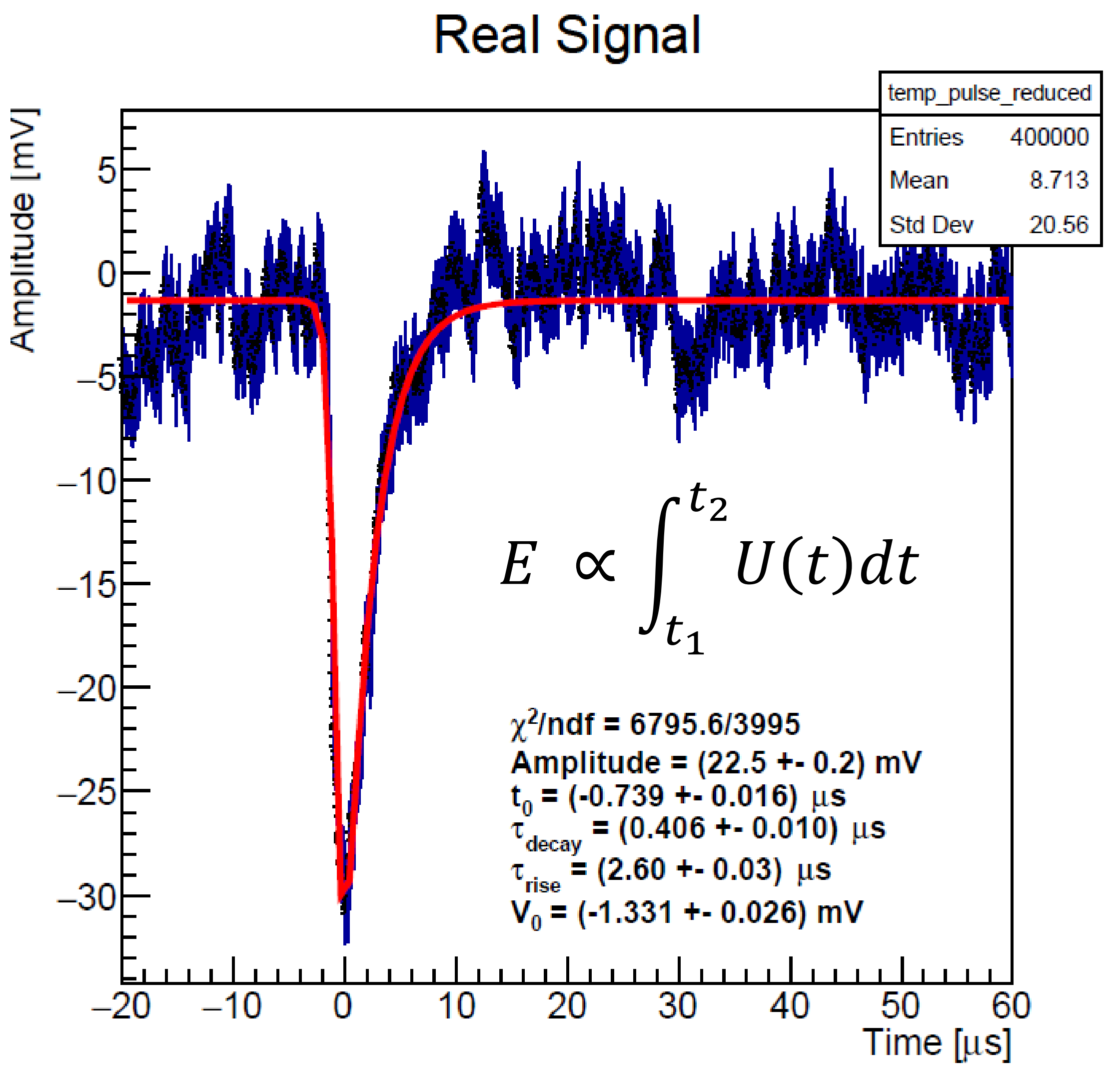
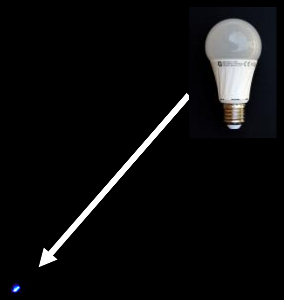
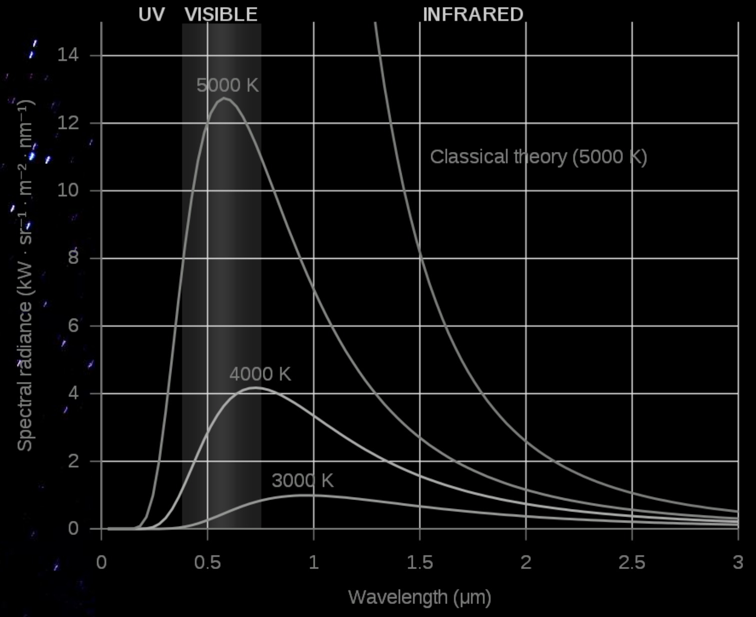


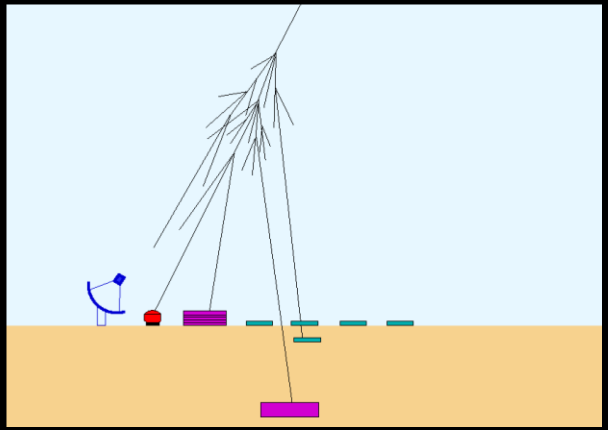




Low background rate: $< 7.7 \cdot 10^{-6}$cps

~ 1 photon (1064nm – like) every 2 days.





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

A PhD thesis outline

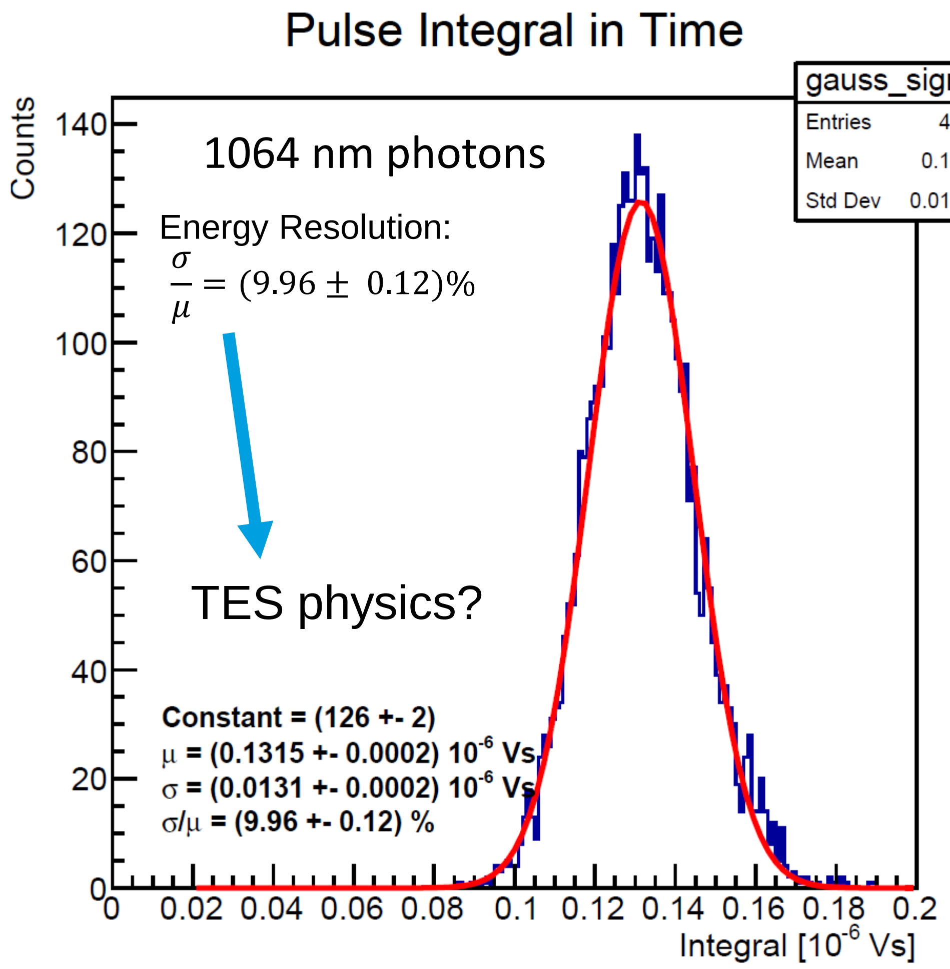
Optimizing a Transition Edge Sensor detector system for low flux infrared photon measurements at the ALPS II experiment

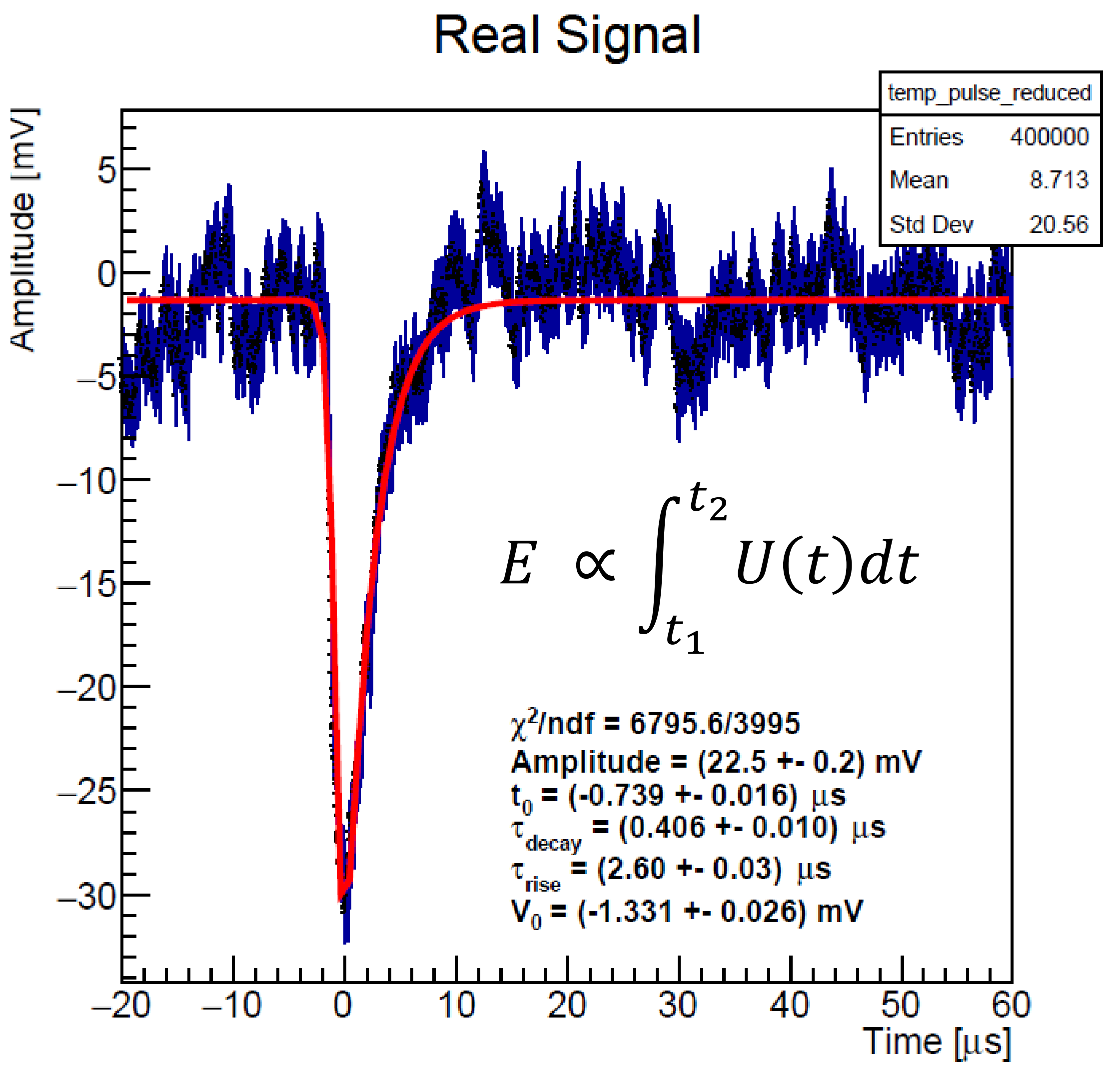
A PhD thesis outline

Optimizing a Transition Edge Sensor detector system for low flux infrared photon measurements at the ALPS II experiment

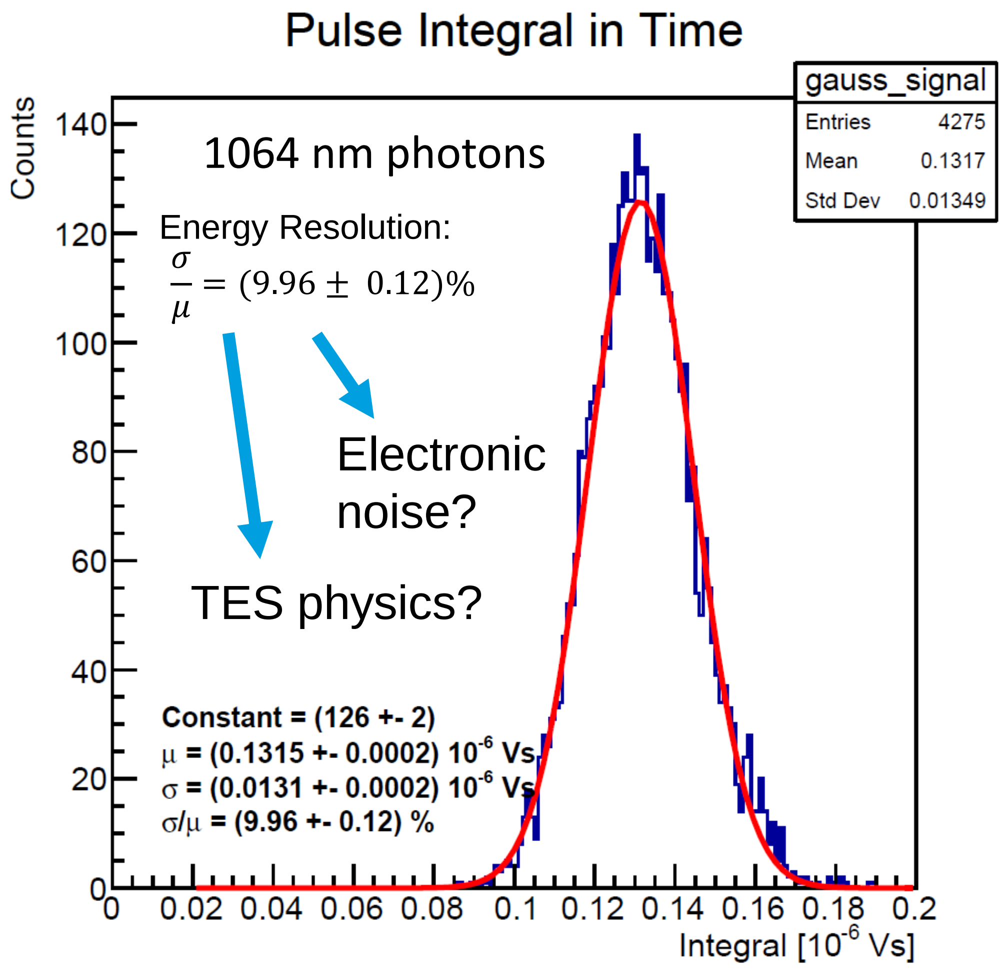
Understanding the signal

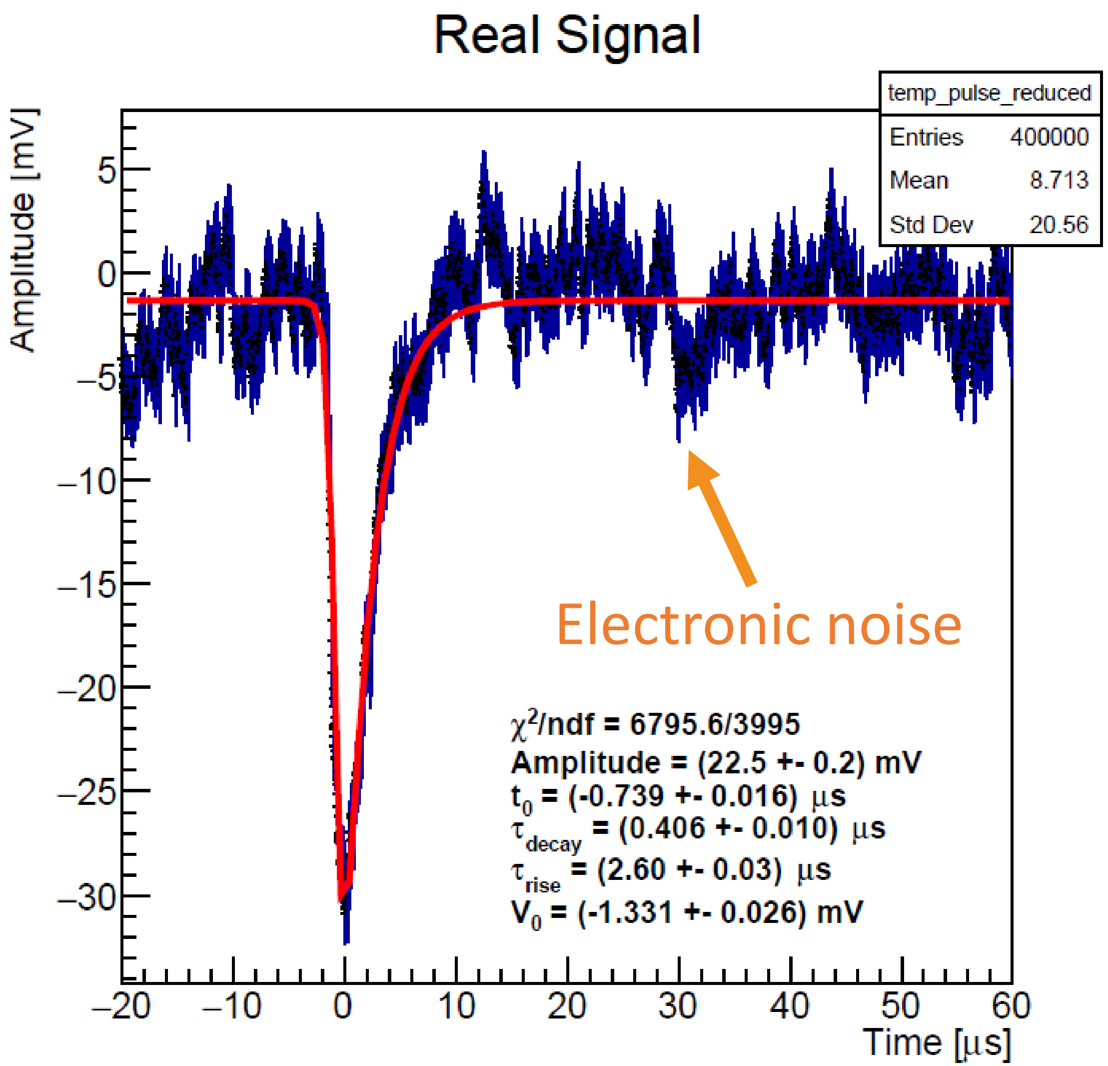
Understanding the signal



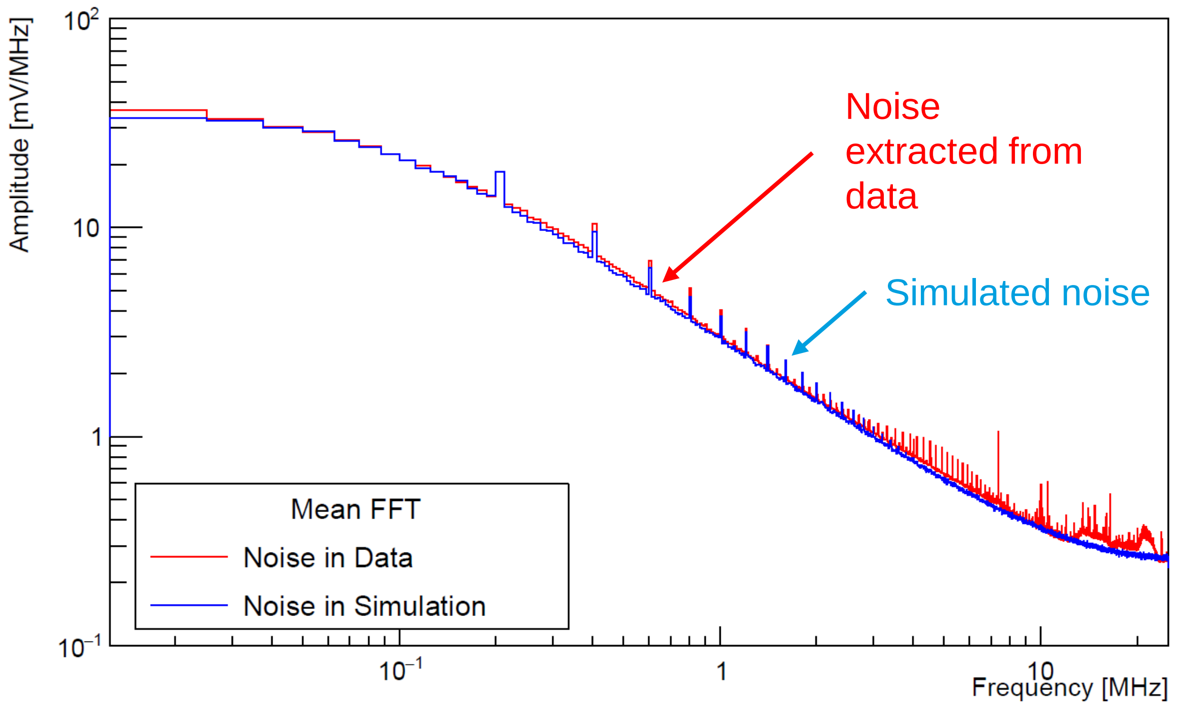


Understanding the signal





Simulation of electronic noise



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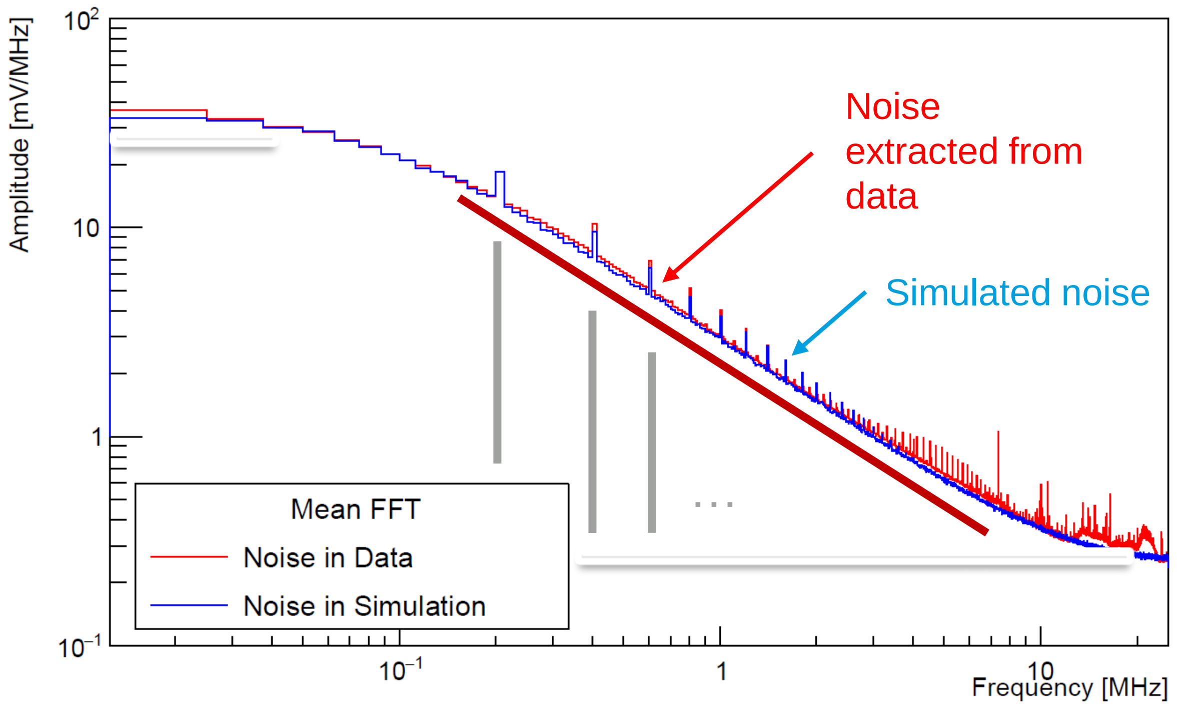
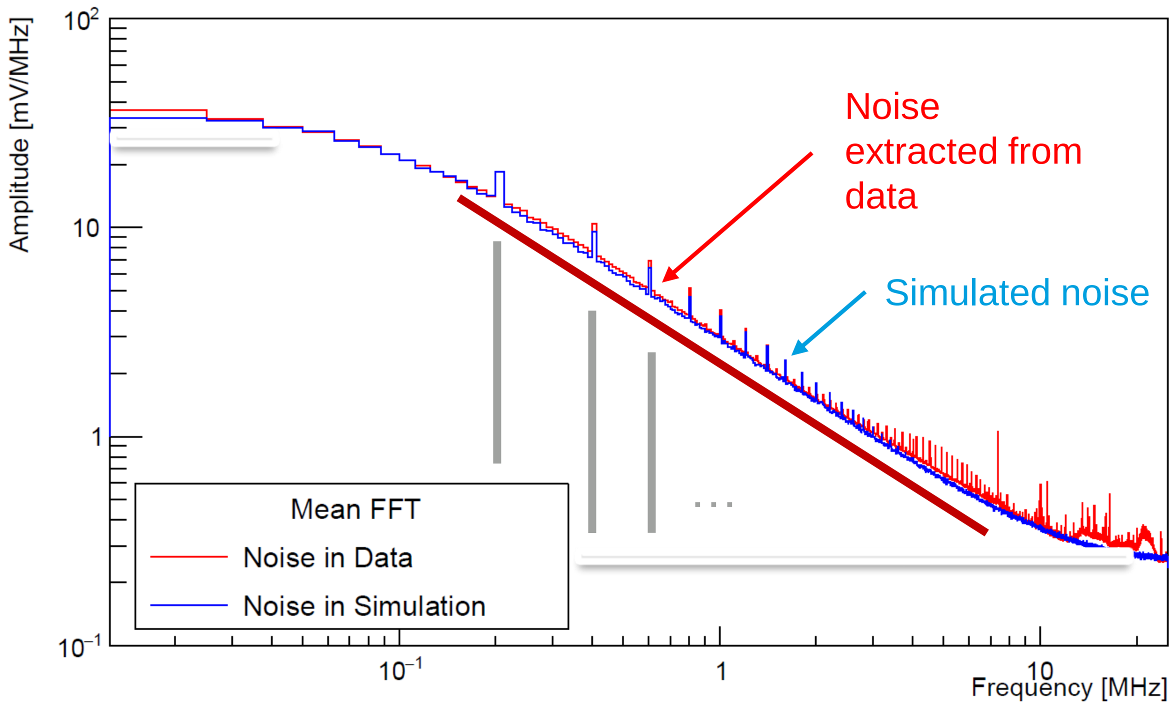
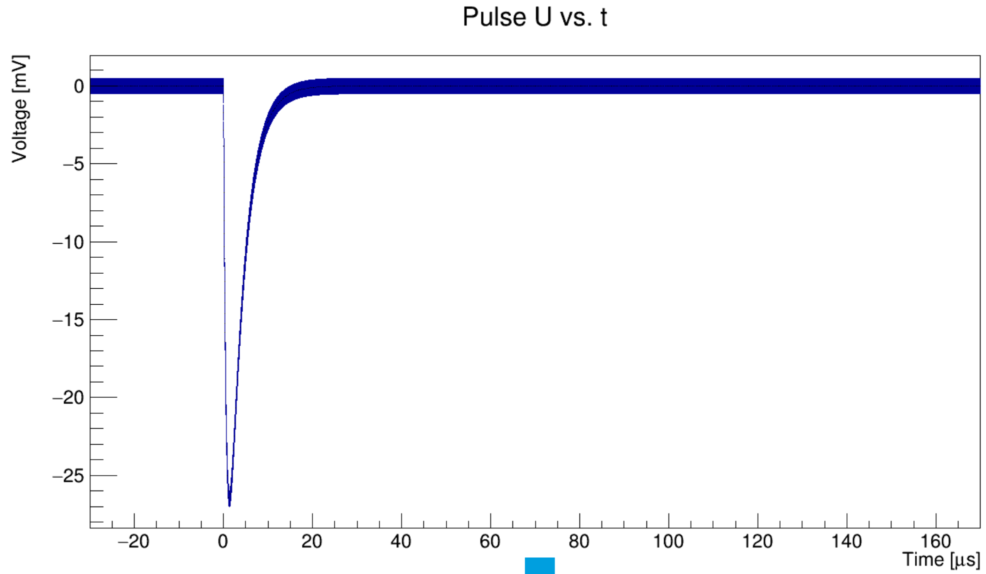


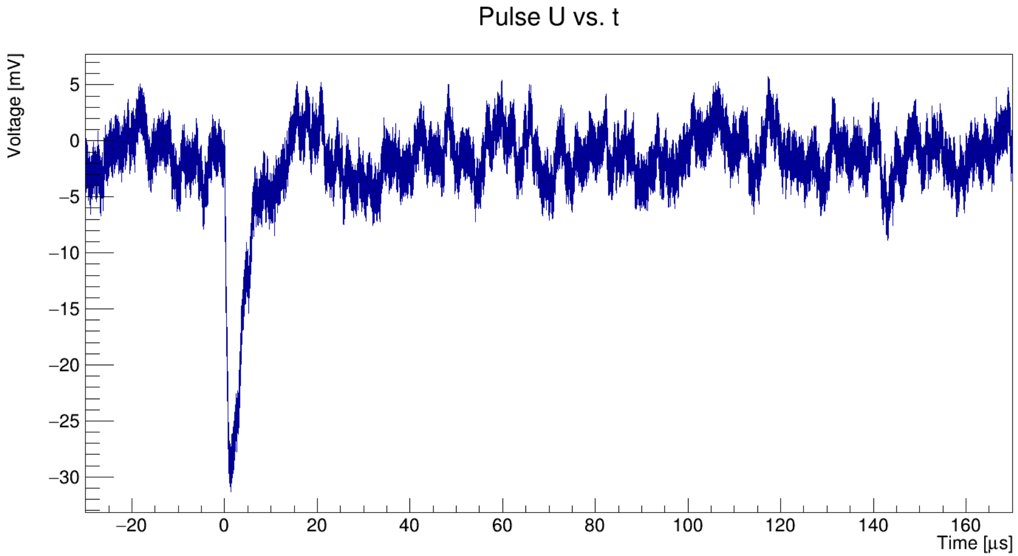
- $200\ kHz$ harmonics
- White noise
- Brownian noise

Simulation of electronic noise



+





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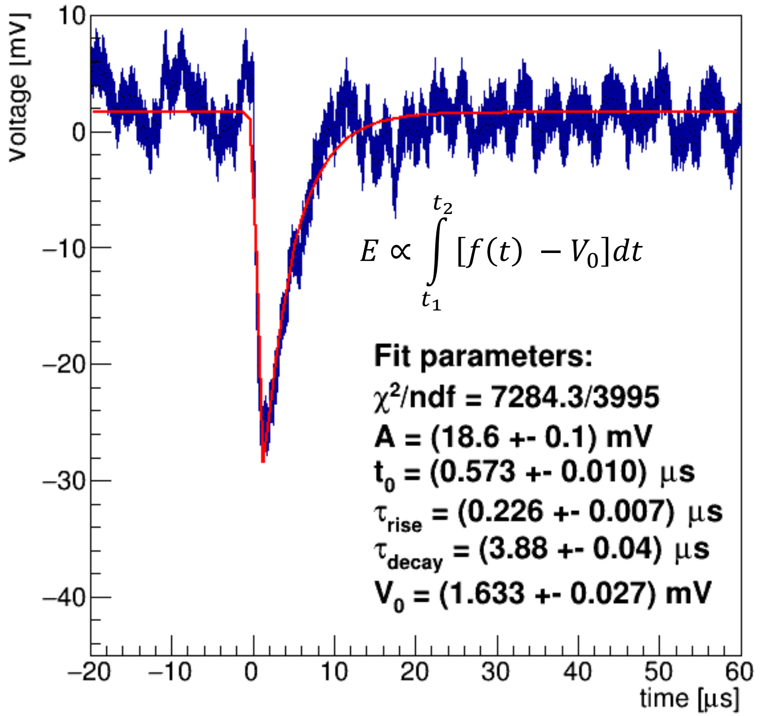
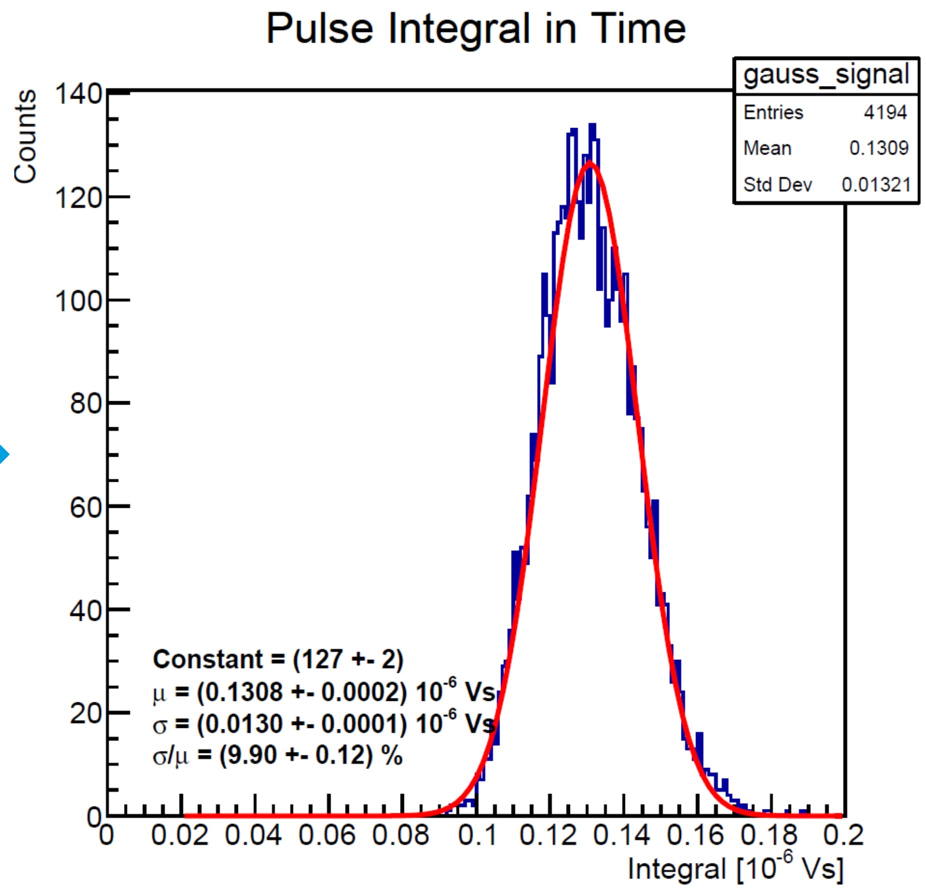




Data Analysis:
Energy Resolution
$(9.96 \pm 0.12)\%$

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.

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: $< 7.7 \cdot 10^{-6}\text{cps} \sim 1\ \text{photon}\ (1064\text{nm} - \text{like})\ \text{every 2 days.}$ Yes, for intrinsics
- High detection efficiency. Yes: Preliminary >80% efficiency
- Long term stability ($\sim 20\ days$). ✓

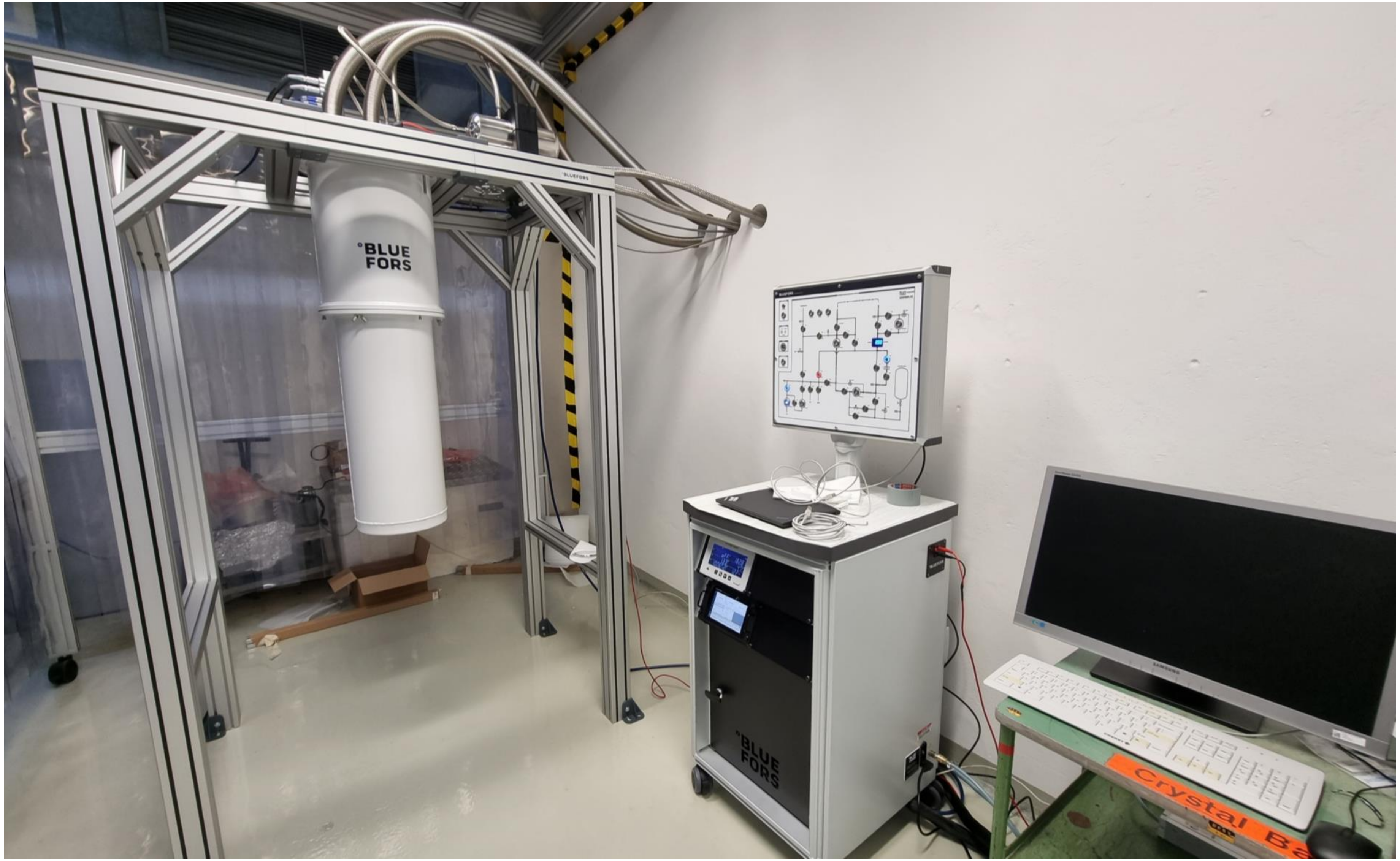
Characterizing a cryogenic, low-background, low energy single photon detector – Doctoral thesis by Rikhav Shah

And also … first results on simulating our system

new cryostat for R&D

studying feasibility of the TES for direct dark matter detection

New cryostat for R&D



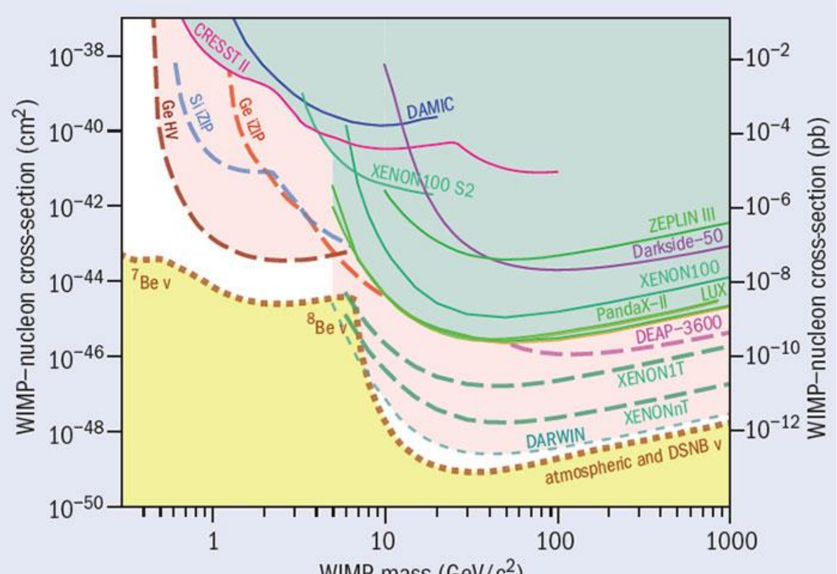
Outline

Christina

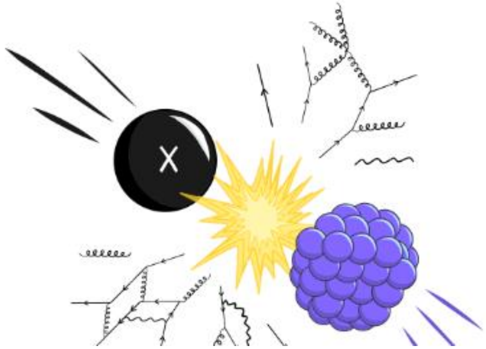
- Light-shining-through-a-wall
  - 3 different kinds
- Any-light-particle search: the ALPS II experiment
- A Transition Edge Sensor (TES) for ALPS II
- More Dark Matter Searches with a TES
- Summary

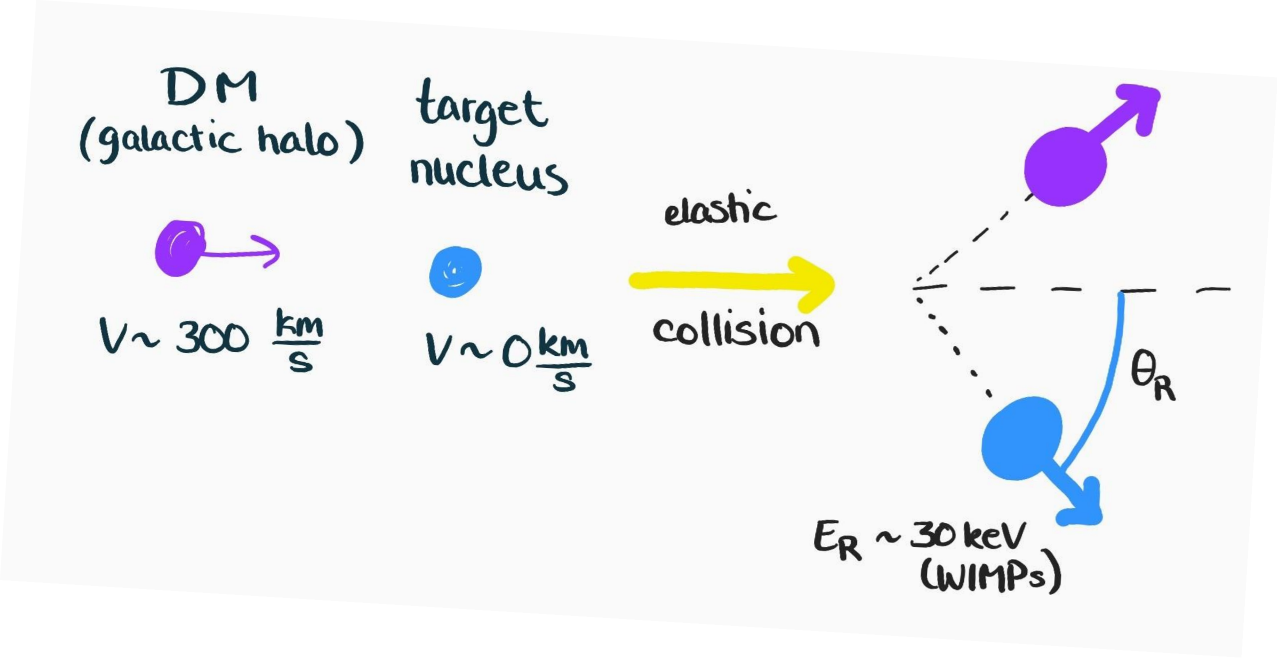
Sub-GeV dark matter?

Limits of nuclear recoil experiments



Cern Courier (2017)

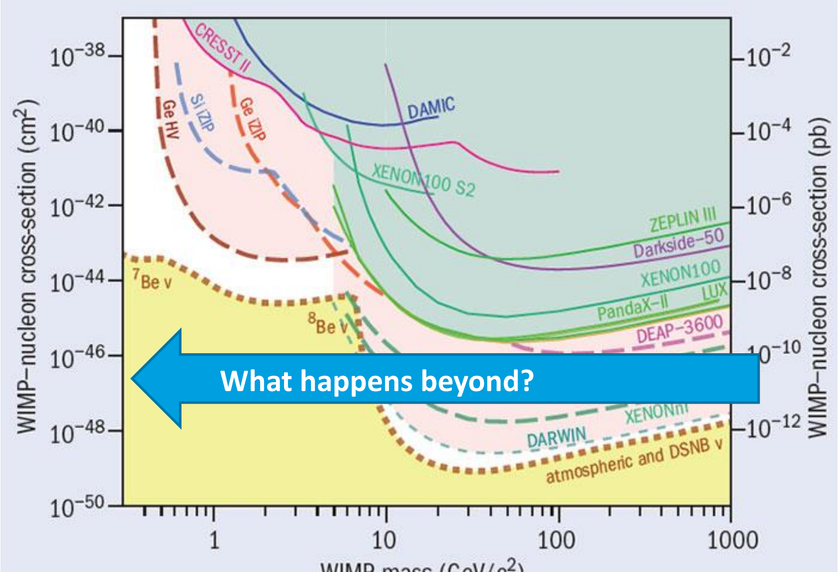




Sketch adapted from Benjamin V. Lehman

Sub-GeV dark matter?

Limits of nuclear recoil experiments



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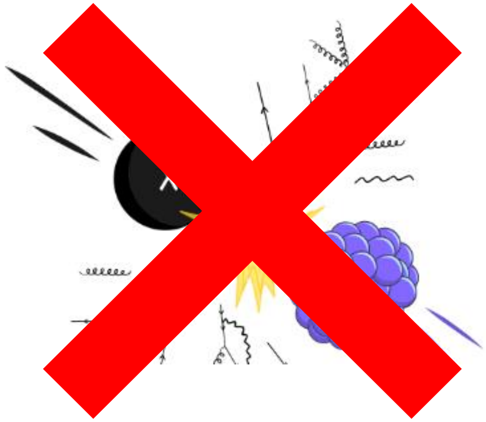

DM mass: m_χ, target mass: m_T

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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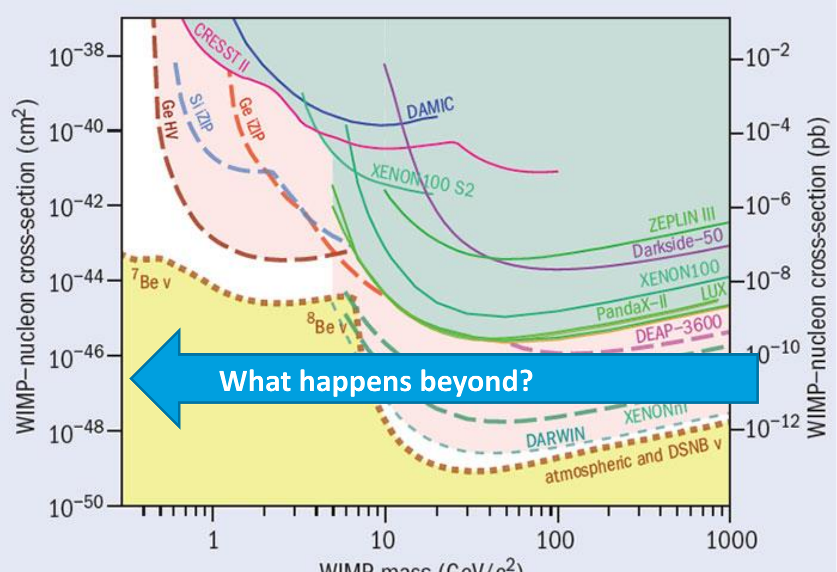
Sub-GeV dark matter?

Limits of nuclear recoil experiments



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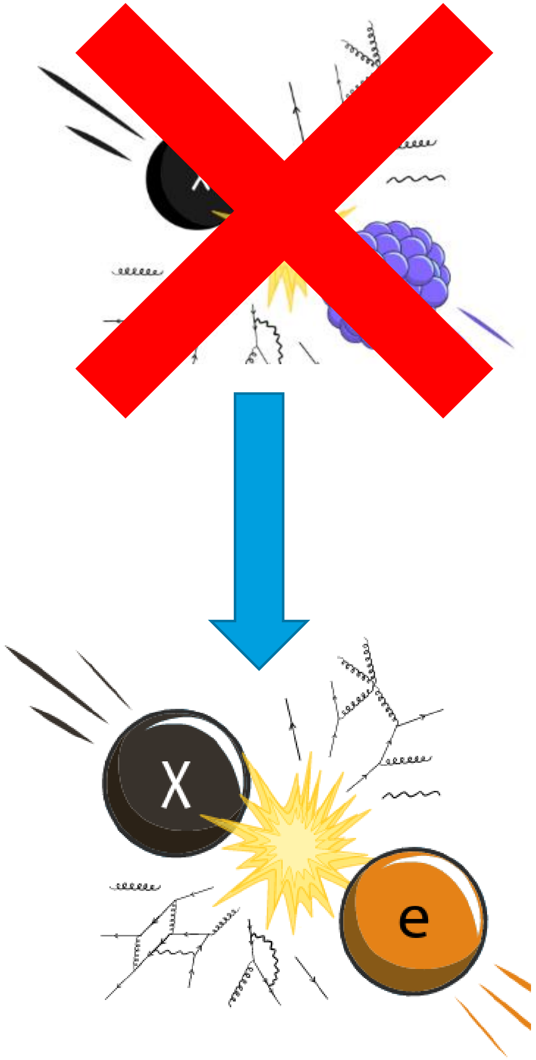

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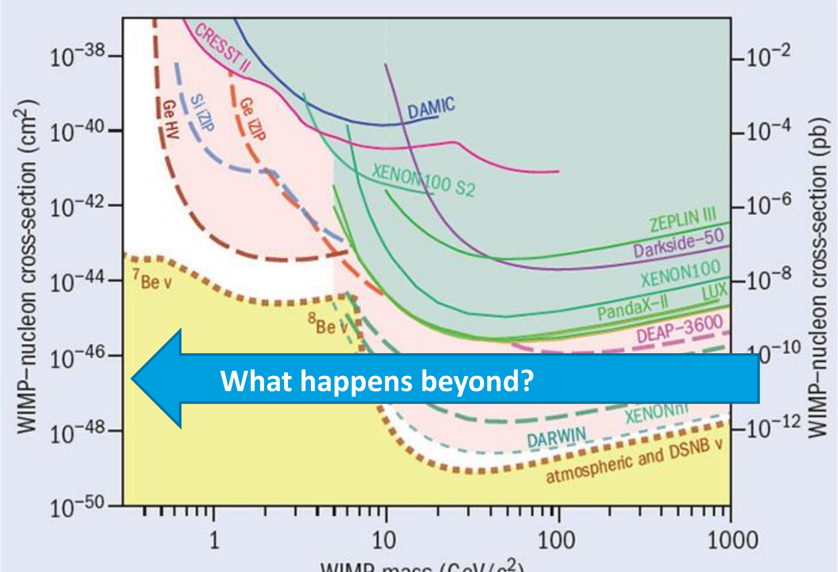
Sub-GeV dark matter?

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:

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

Sub-GeV dark matter?

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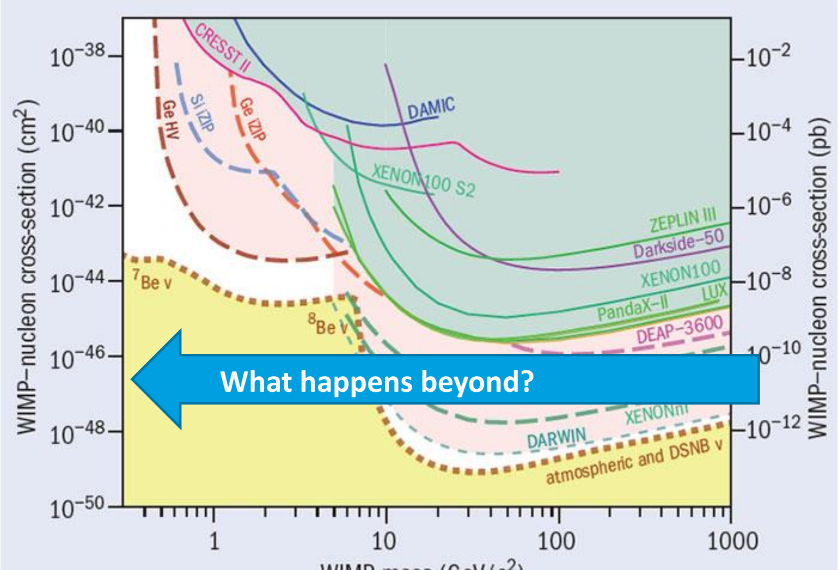

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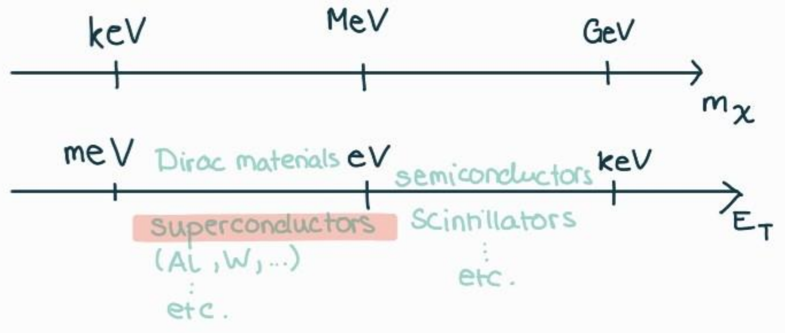
Energy range for given mass range:



Sub-GeV dark matter?

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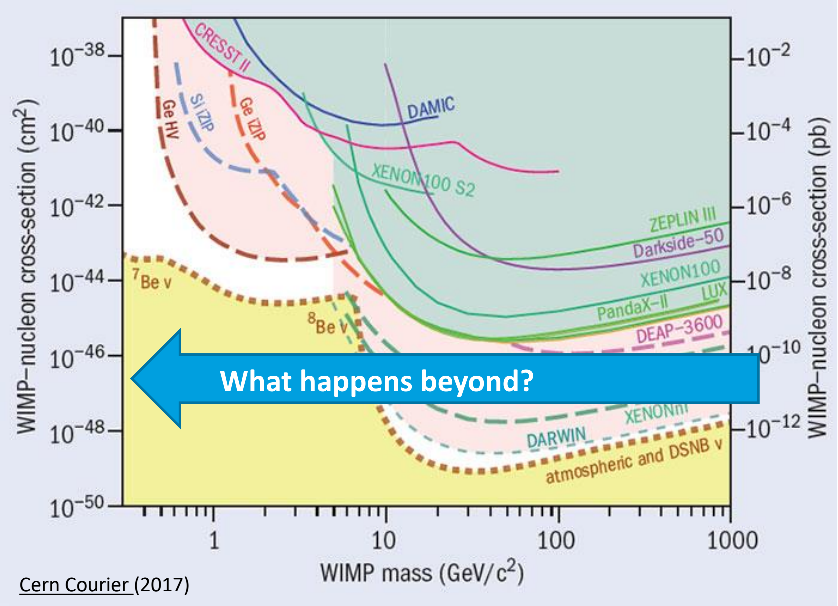

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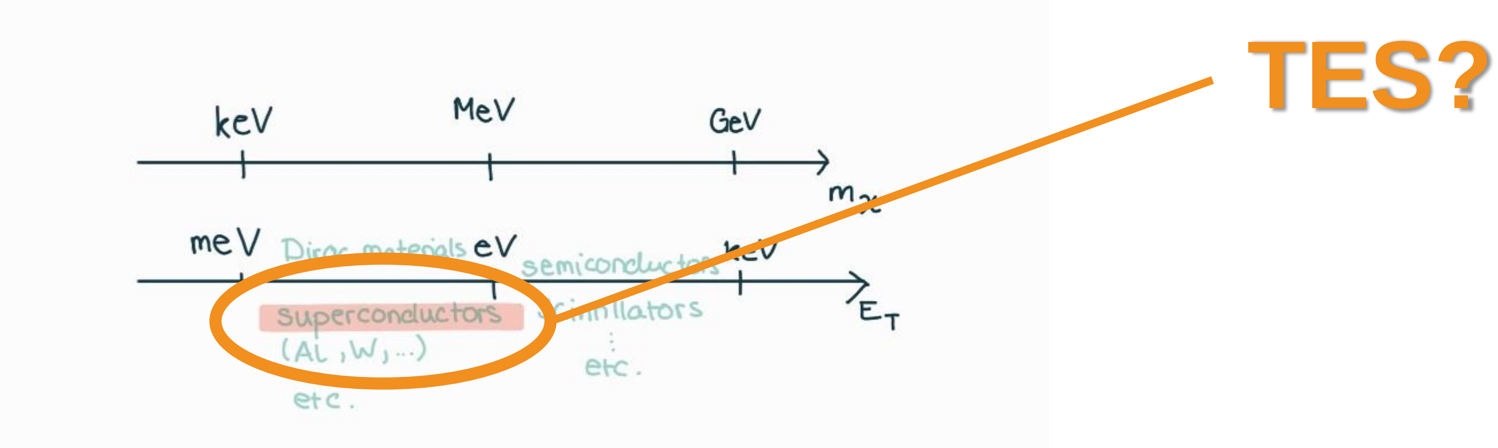


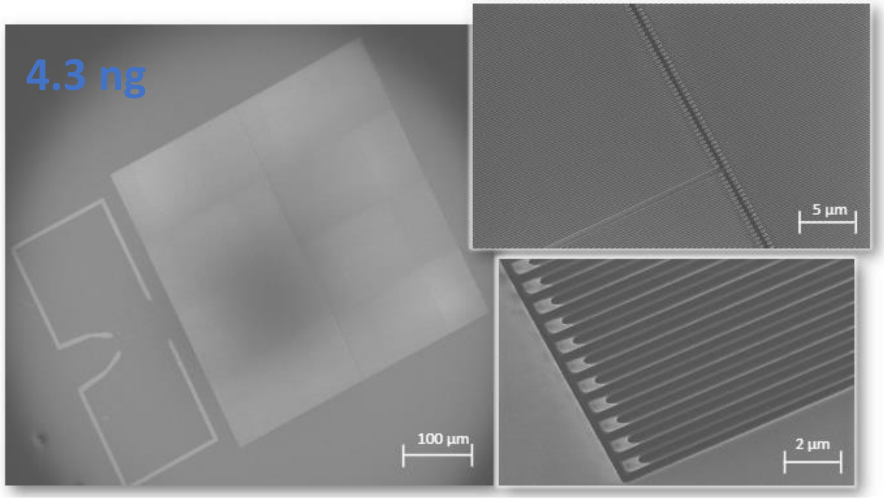
Direct DM detection

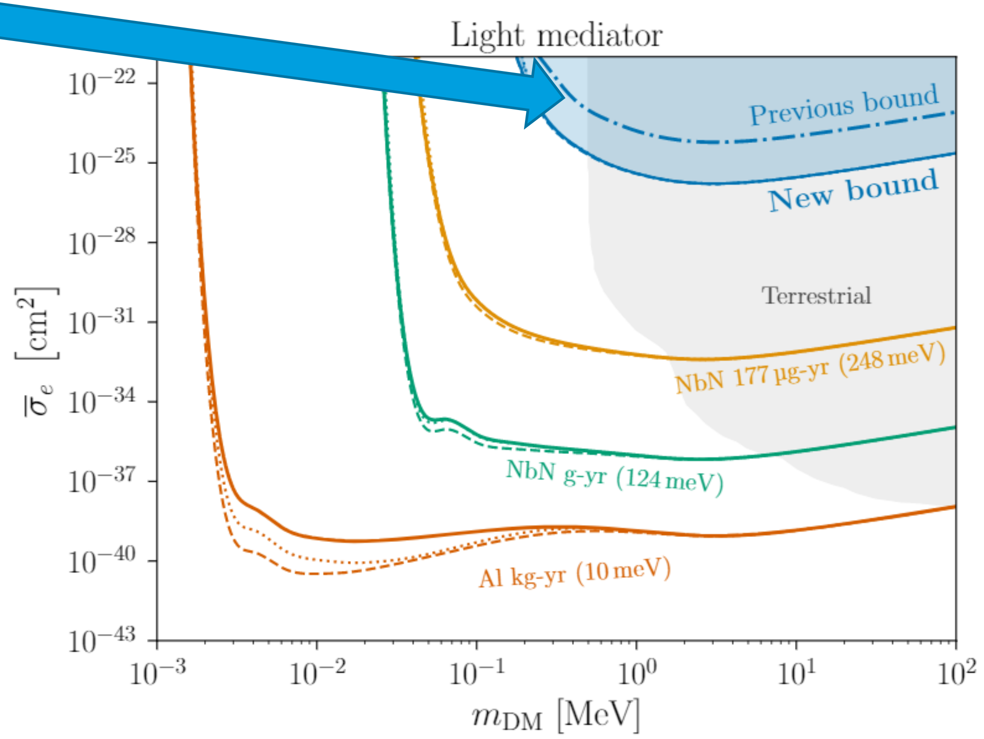
Suitable devices

- 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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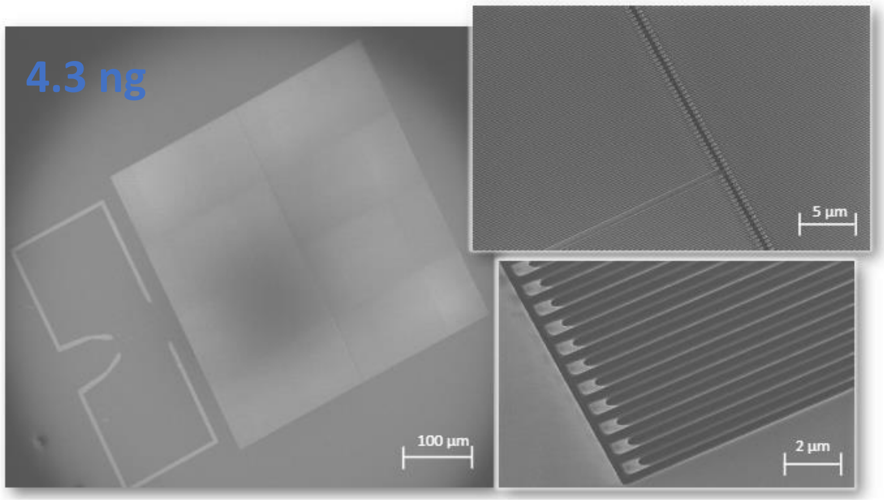

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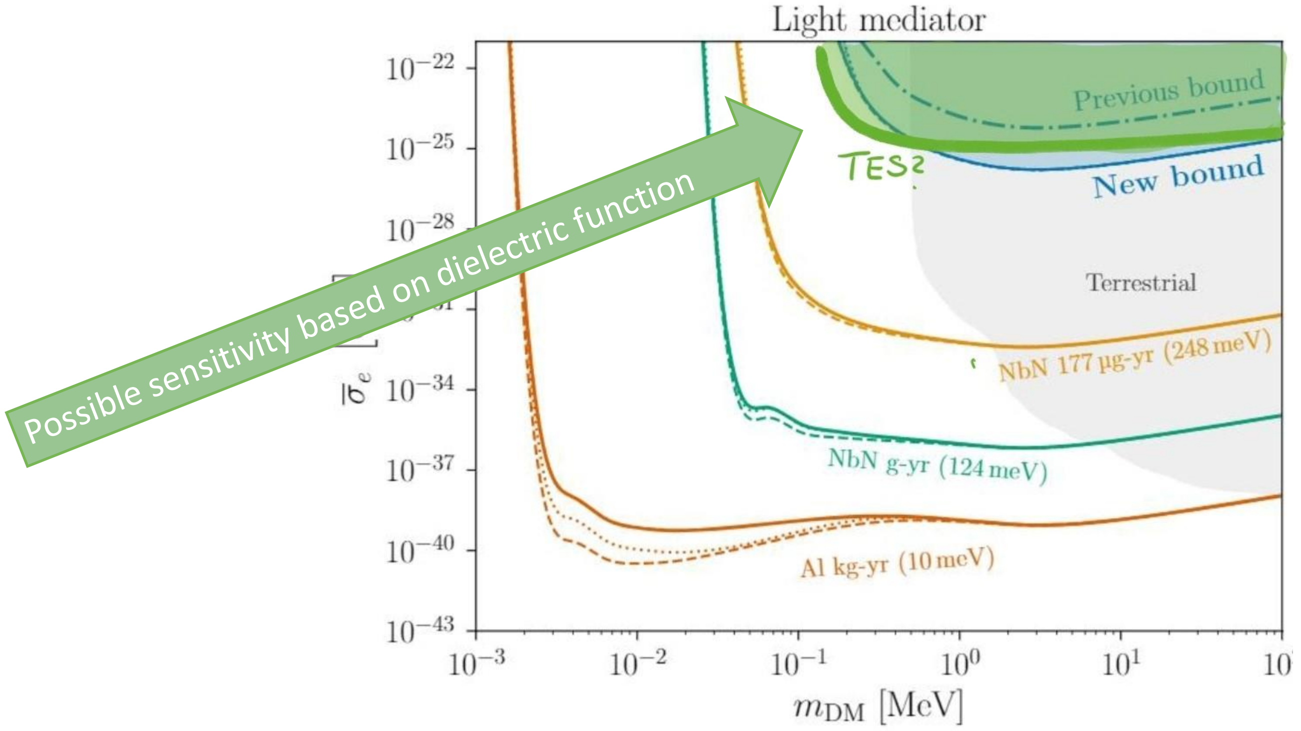
Proposal: Apply same idea to TES!

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



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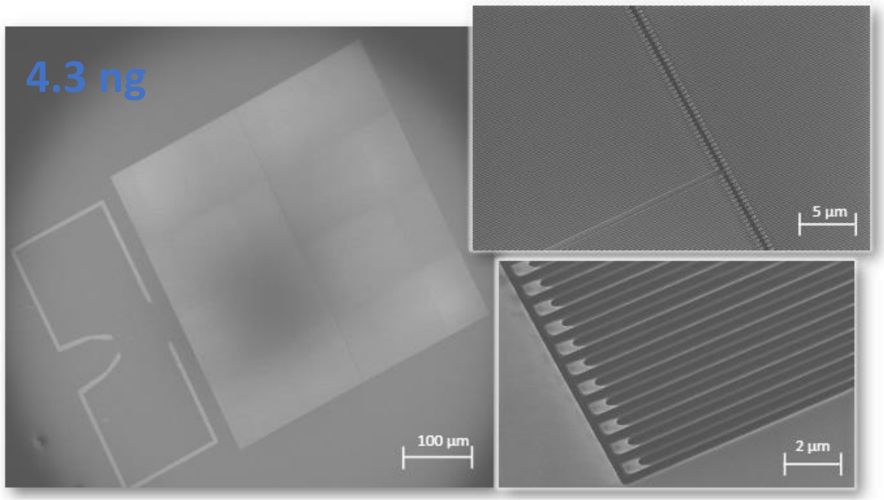

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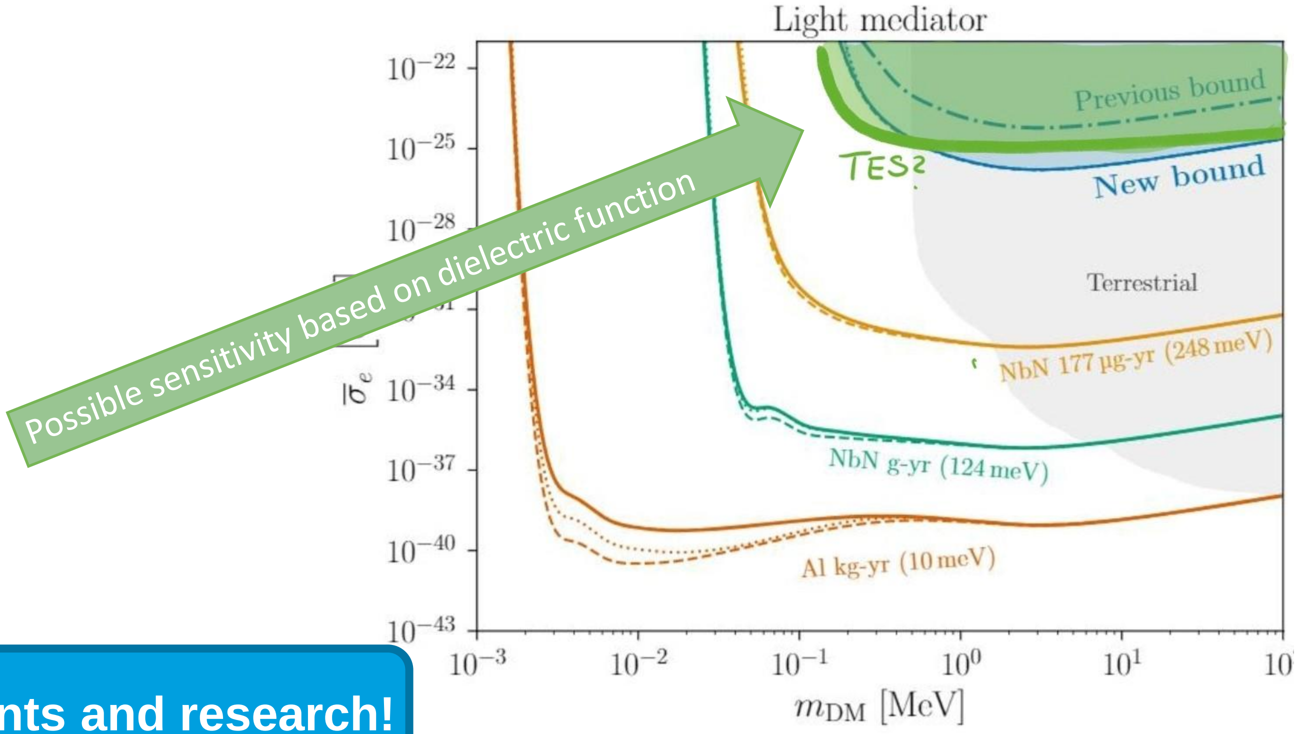

Ongoing measurements and research!

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

Outline

Axel

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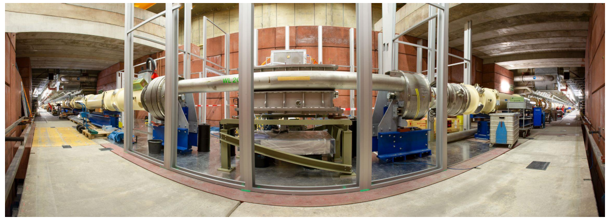
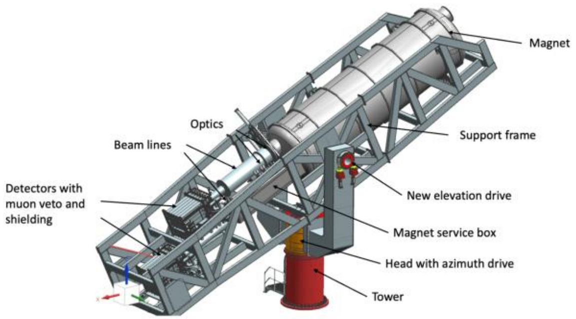
Instead of a summary

A dream



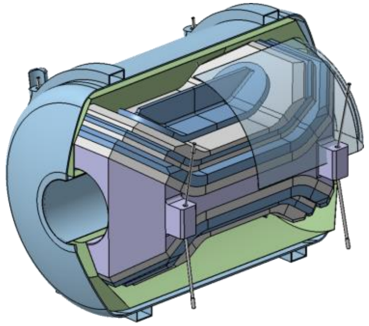
ALPS II, first data taking in 2023:

- Determine the axion-photon coupling model-independently.



IAXO, first data taking of BabyIAXO in 2028 ?

- 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.

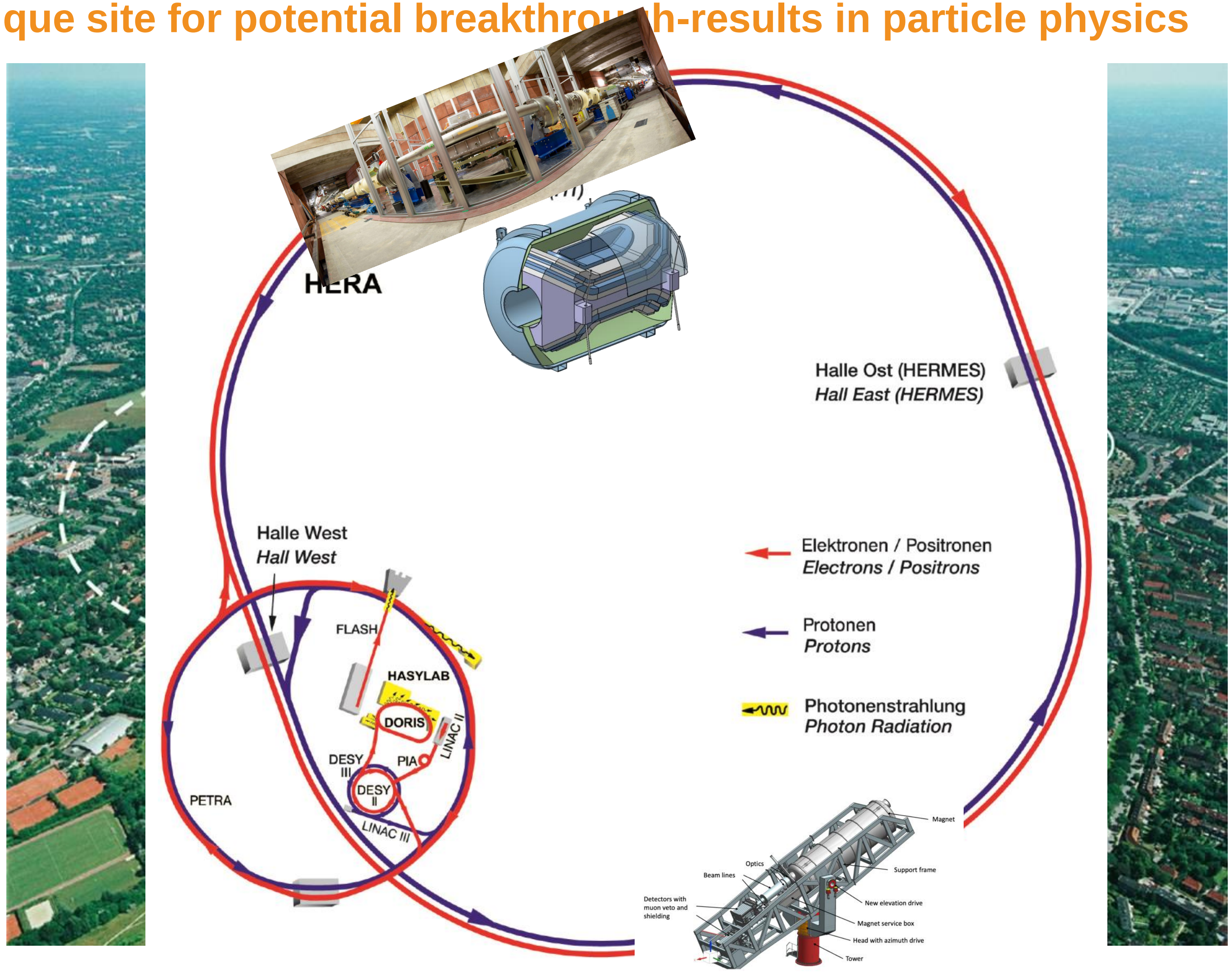


MADMAX, first data taking in 2030 ?

- 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 breakthrou h-results in particle physics



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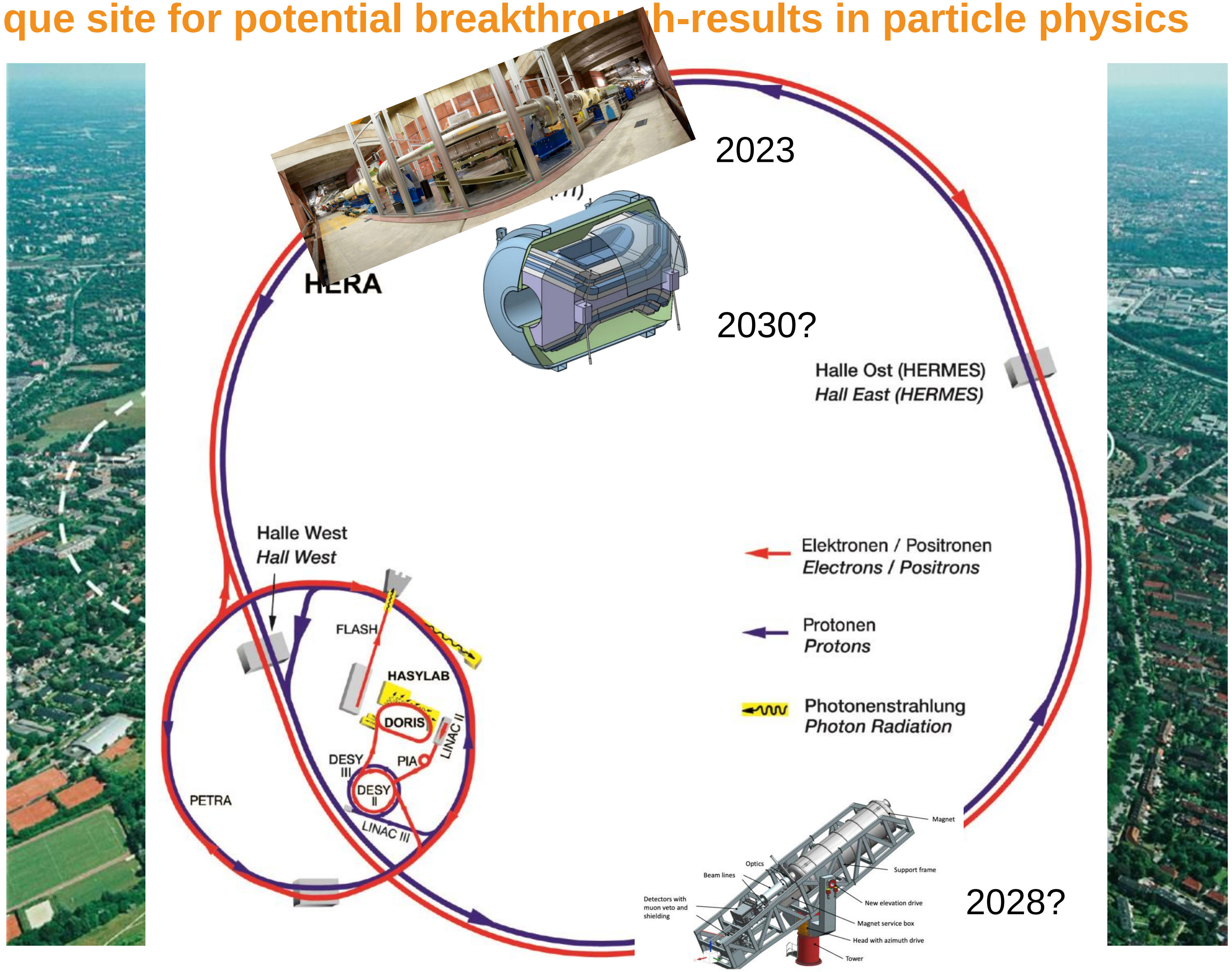

Many thanks to the enthusiastic colleagues at DESY and world-wide for realizing the “impossible” to find the “invisible”!

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Axel Lindner, Jose Alejandro Rubiera Gimeno, Christina Schwemmbauer

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