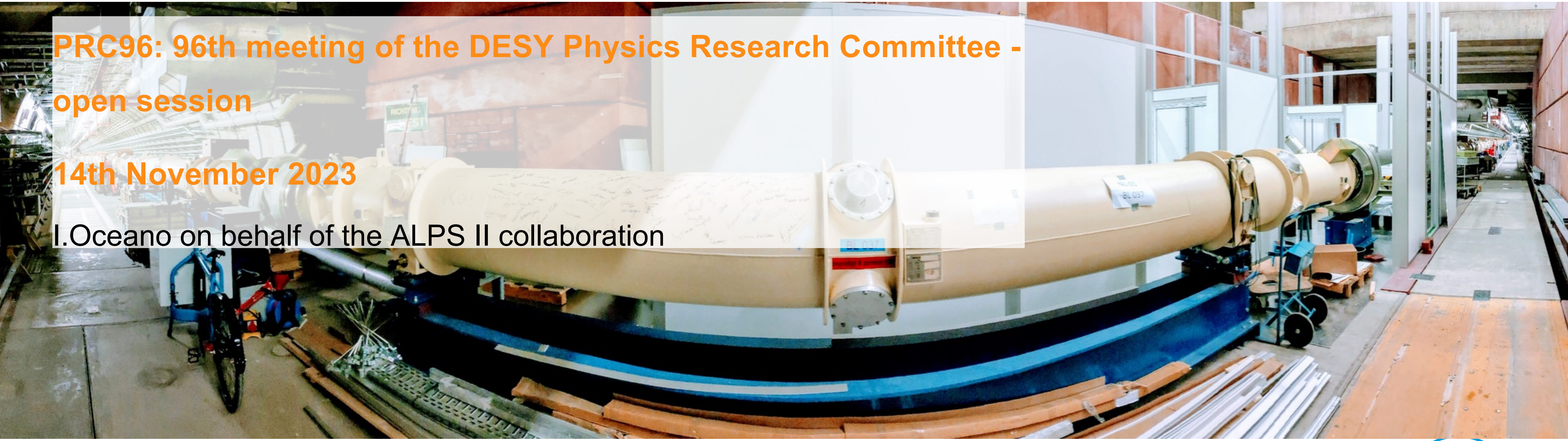
Light in the ALPS II experiment



PRC96: 96th meeting of the DESY Physics Research Committee - open session

14th November 2023

I.Oceano on behalf of the ALPS II collaboration

HELMHOLTZ

ALPS II concept

First realization of Hoogeveen idea

Arion ⇄ photon oscillations in a constant magnetic field

A. A. Ansel'm

Institute of Nuclear Physics, Academy of Sciences of the USSR, Leningrad

(Submitted 30 May 1985)
Yad. Fiz. **42**, 1480–1483 (December 1985)

Photon ⇄ arion oscil
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VOLUME 59, NUMBER 7 PHYSICAL REVIEW LETTERS 17 AUGUST 1987

Proposed Experiment to Produce and Detect Light Pseudoscalars

K. Van Bibber
Lawrence Livermore National Laboratory, Livermore, California 94550

N. R. Dagdeviren and S. E. Koonin
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

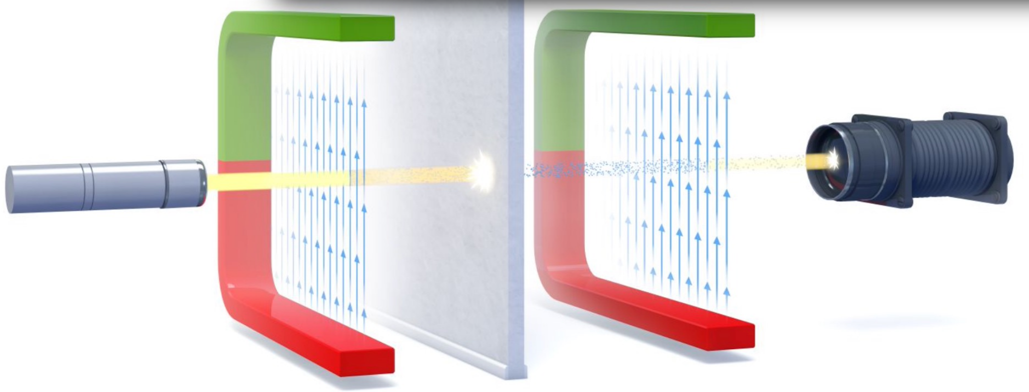
A. K. Kerman
Center for Theoretical Physics, Department of Physics, and Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

and

H. N. Nelson
Department of Physics and Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

(Received 12 May 1987)

We propose a laboratory experiment to produce and detect a light neutral pseudoscalar particle that couples to two photons. The pseudoscalar would be produced by a (real) photon from a laser beam interacting with a second (virtual) photon from a static magnetic field; it would be detected after it reconverts to a real photon in a duplicate magnetic field. The bounds on the coupling constant that could be obtained from a null result in such an experiment compete favorably with astrophysical limits and would substantially improve those from direct measurements.



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

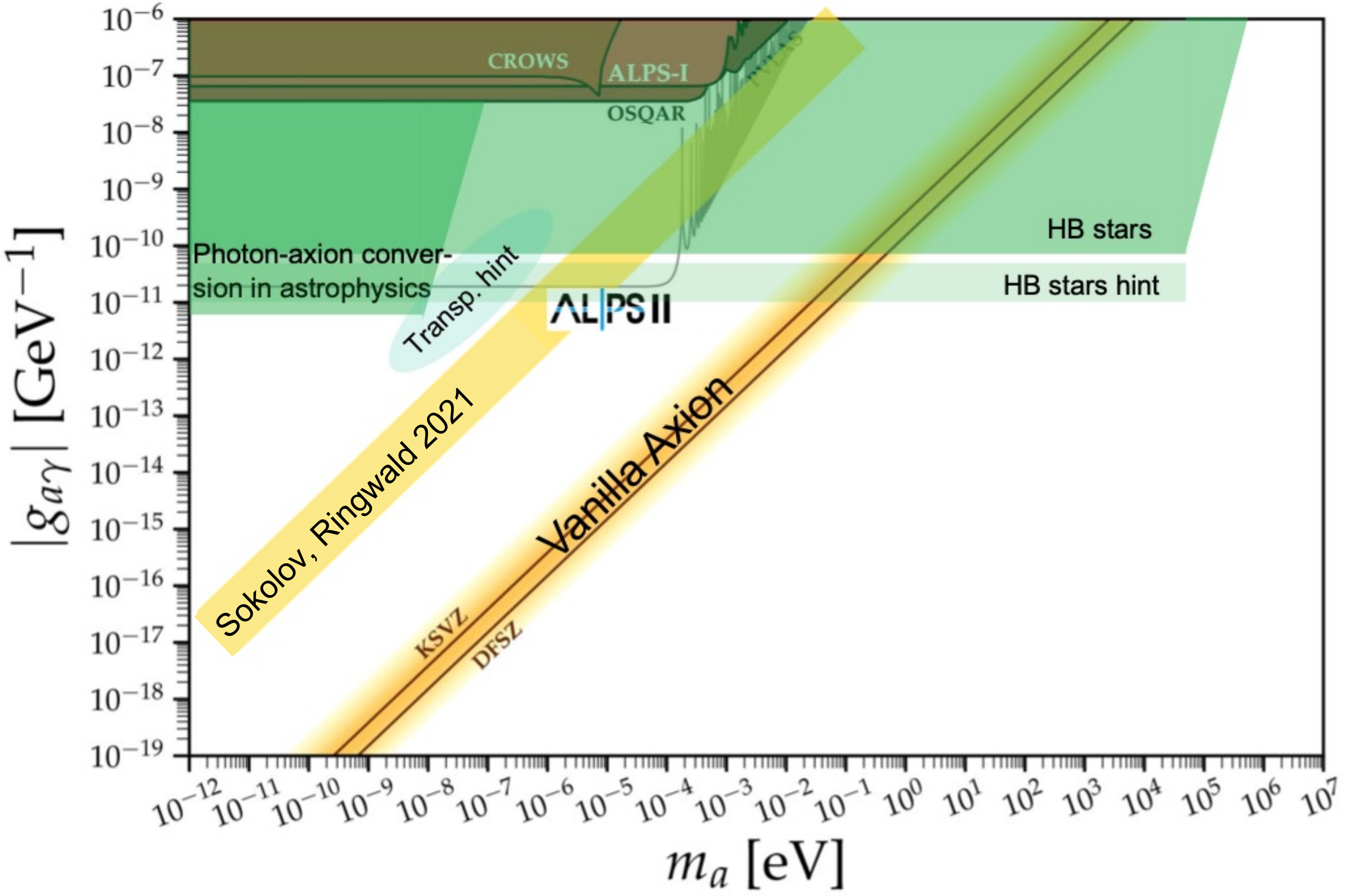
Received 13 December 1990
(Revised 22 February 1991)

Fig. 3. Axion production and detection with two optical resonators.

Any Light Particle Search II

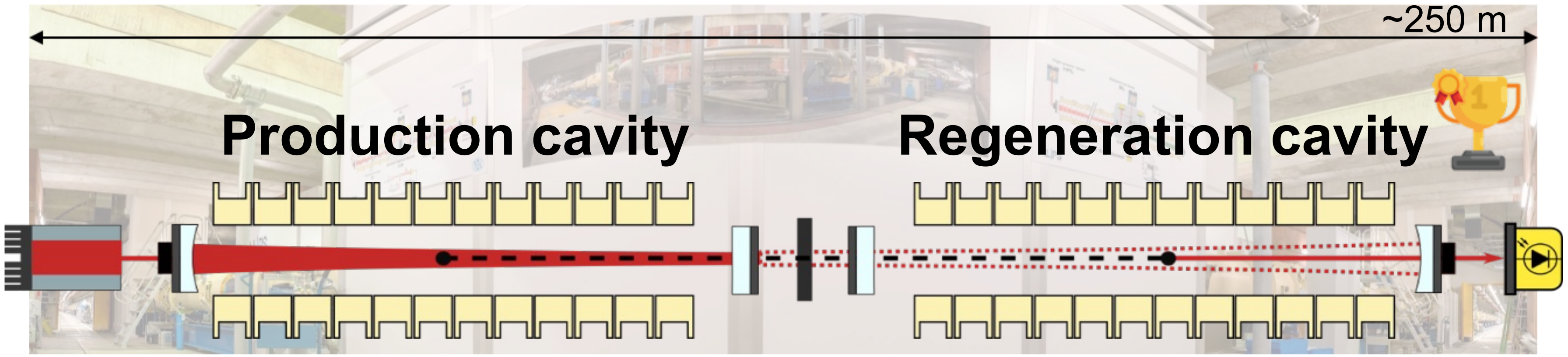
Discovery potential

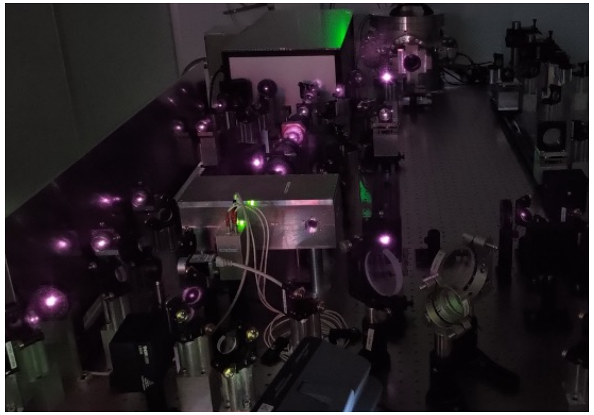
- ALPS II designed to improve sensitivity compared to ALPS I by a factor of ~3000
  - Exploring uncharted territory in parameter space, beyond astrophysical constraints
  - Checking axion explanation of astrophysical anomalies

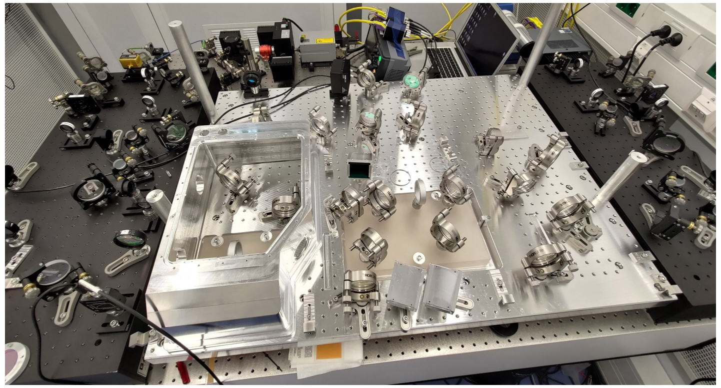


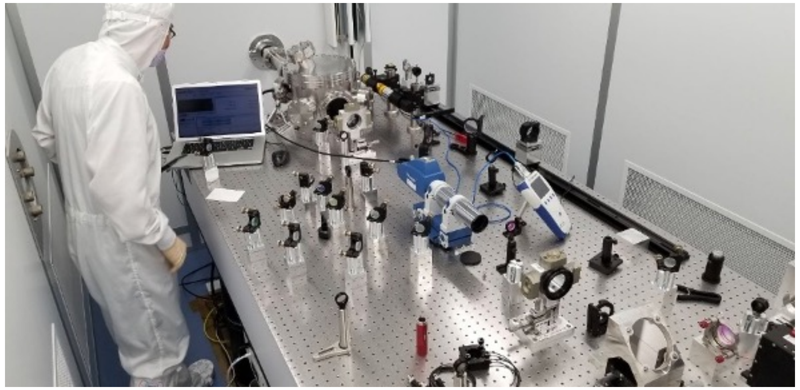
Any Light Particle Search II

The axion factory









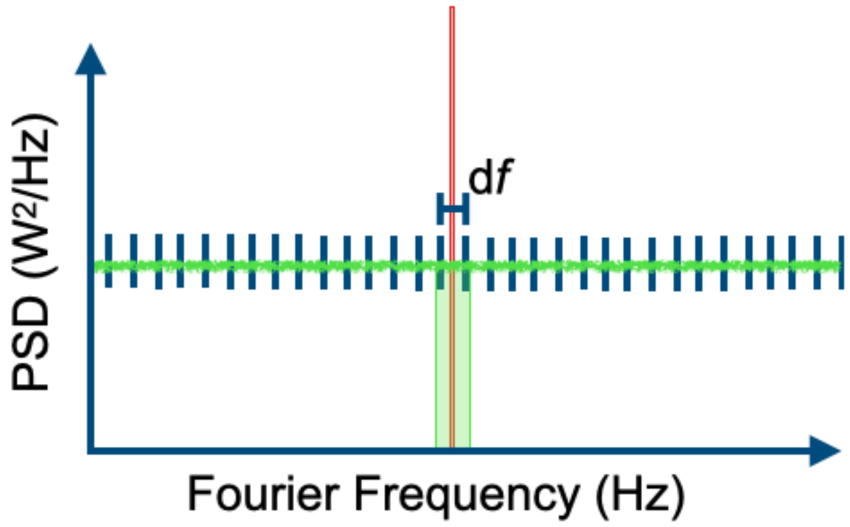
ALPS II Technology

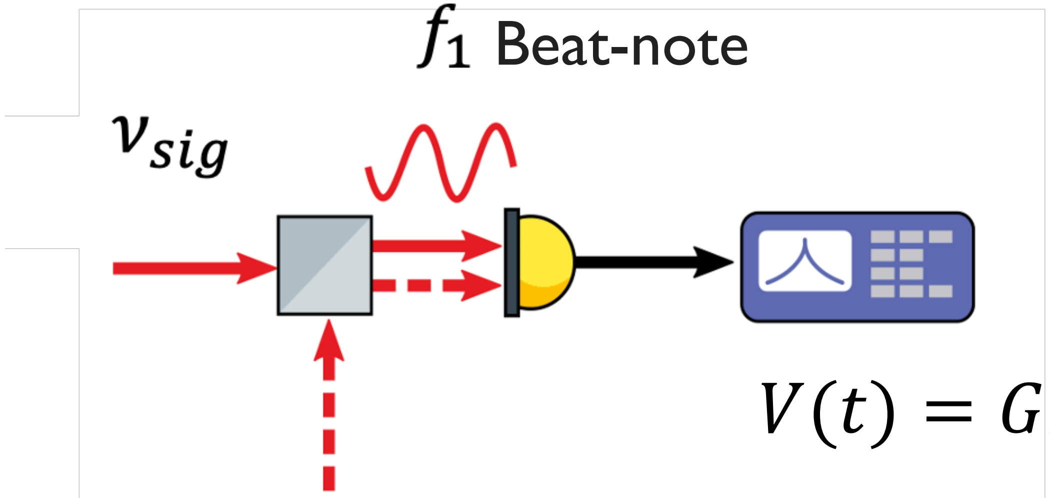
- 1. Magnets and Infrastructure
- 2. Optical Systems
- 3. Control Systems
- 4. Ultra-low power Detector

Ultra-low power detector

HETerodyne sensing

- Interfere regenerated field (ν_{sig}) with laser ($\nu_{sig} + f_1$)
- Demodulate signal at defined frequency
- Sum the amplitude of the Beat-note over a long time
- Integrate over time to shrink frequency bin





$$\nu_{LO} = \nu_{sig} + f_1$$

$$V(t) = GP_{sig} + GP_{LO} + 2G\sqrt{P_{sig}P_{LO}}\cos(2\pi f_1 t + \Delta\phi)$$

$$\Delta\phi = \phi_{sig} - \phi_{LO}$$

LO: Local Oscillator

Ultra-low power detector

Advantages, costs and difficulties

Advantages

- If the P_{LO} is large enough, the system noise is dominated by the shot-noise
  - SNR no longer depend on the LO power

$$SNR \propto \frac{\sqrt{P_{sig} P_{LO}}}{\sqrt{P_{LO}}} = \sqrt{P_{sig}}$$

Ultra-low power detector

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Costs

- Keep $\Delta\phi$ constant
- Keep f_1 constant

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Costs

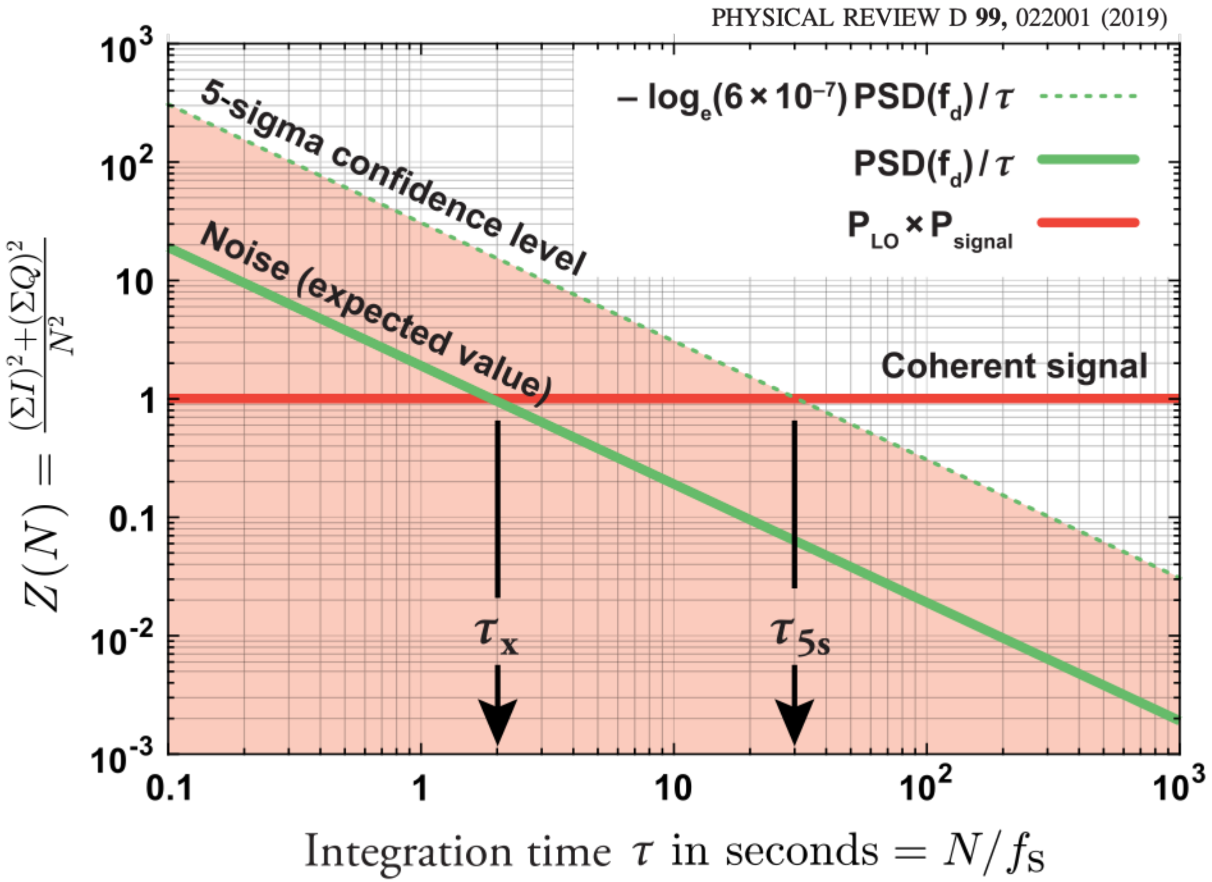
- Keep $\Delta\phi$ constant
- Keep f_1 constant

Difficulties

- Environmental Conditions: Humidity, temperature, …
  - affect the stability and accuracy of the measurements
- Mechanical Stability
  - Any vibrations, structural deformations, or movements in the setup can introduce noise and distort the measurement data.

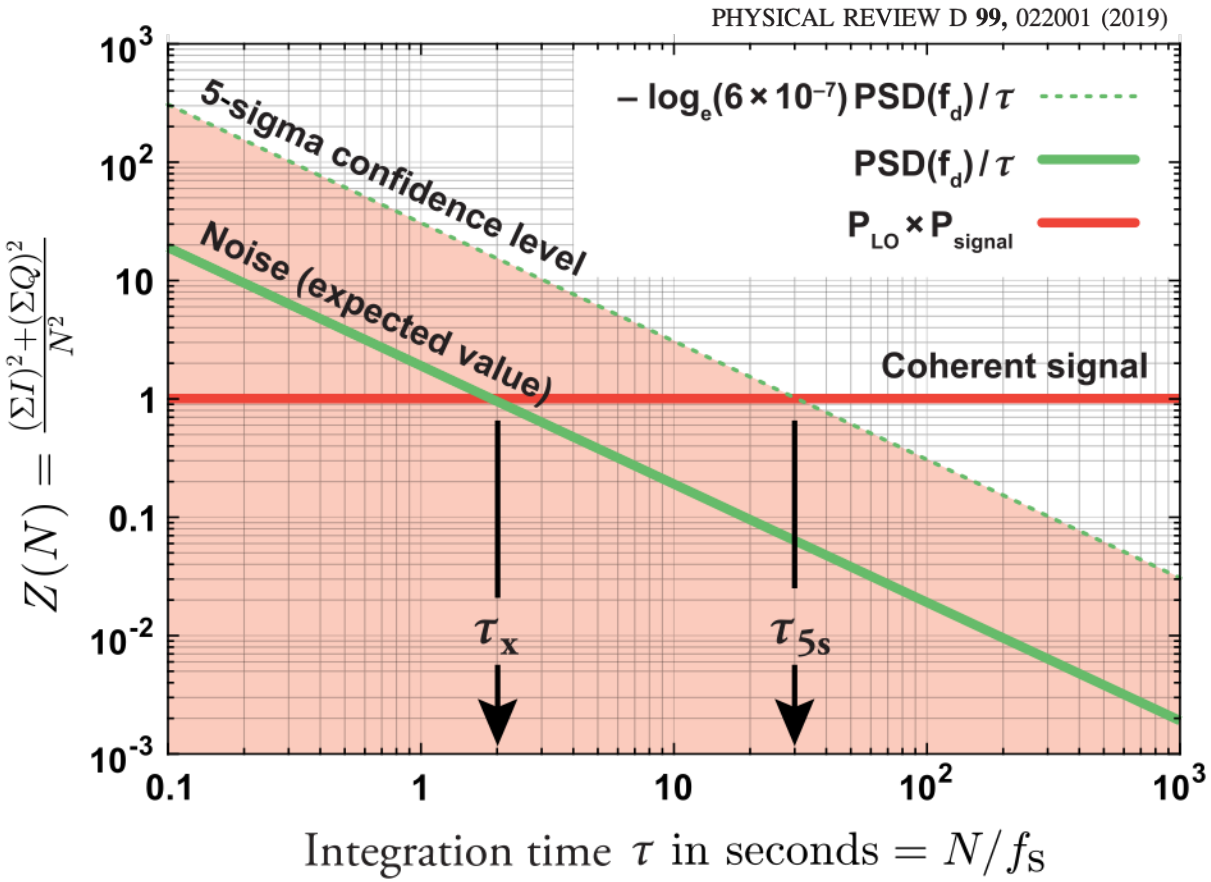
Ultra-low power detector

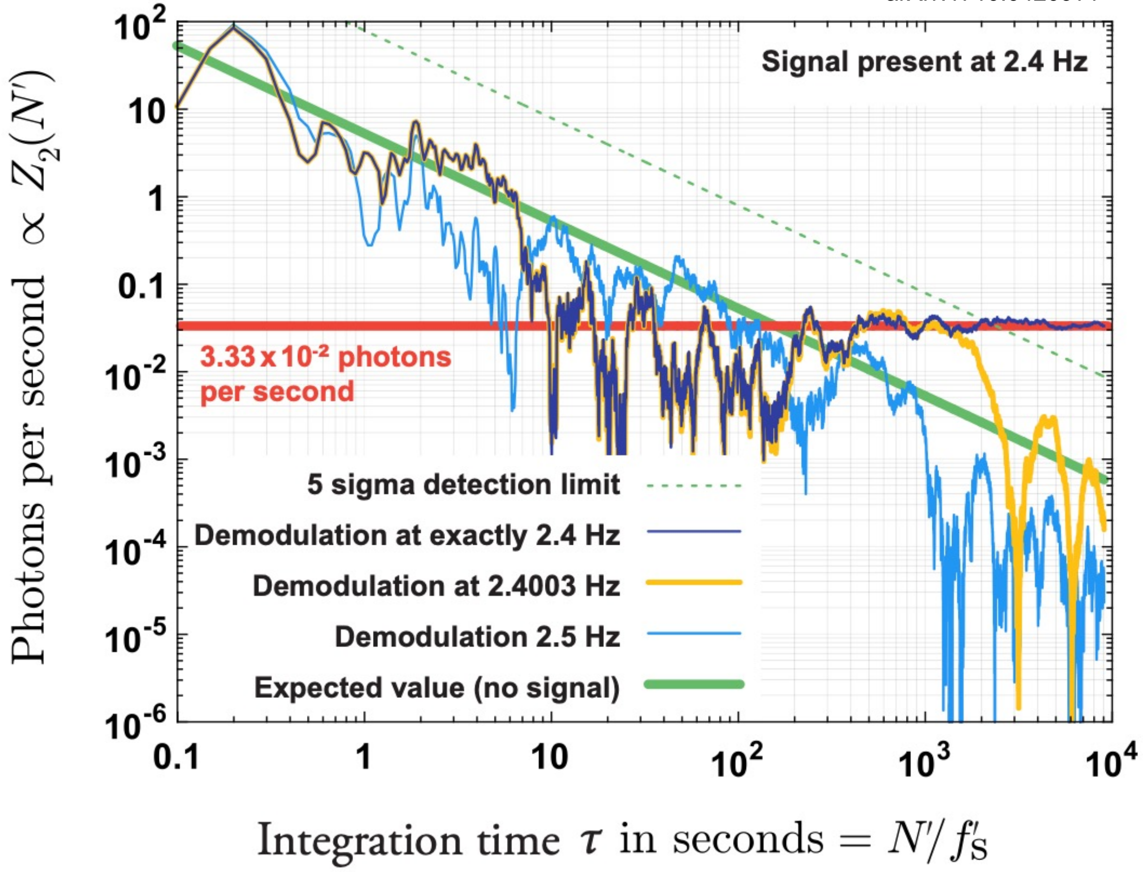
HETerodyne sensing signature



Ultra-low power detector

HETerodyne sensing signature

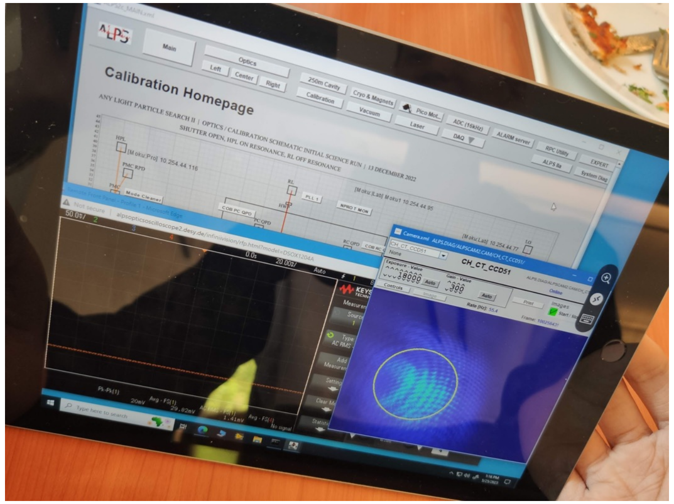




- Demonstrated $10^{-5}\gamma/s$ PHYSICAL REVIEW D **99**, 022001 (2019)
    - Limited by extrinsic noise
- ALPS II can be limited by only the intrinsic noise (shot-noise) increasing the P_{LO}

Initial science run

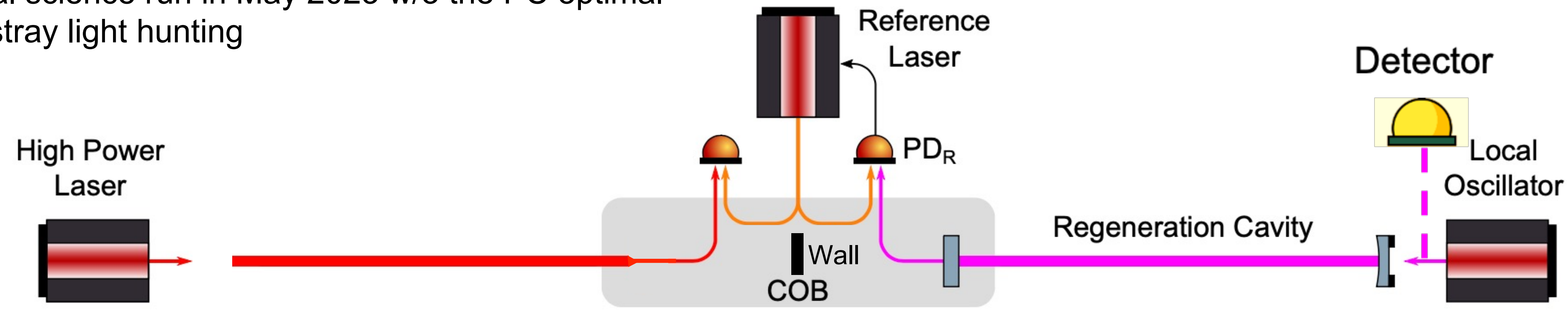
May 23rd to May 31st



Optic system

Initial science run

- Initial science run in May 2023 w/o the PC optimal for stray light hunting



Optic system

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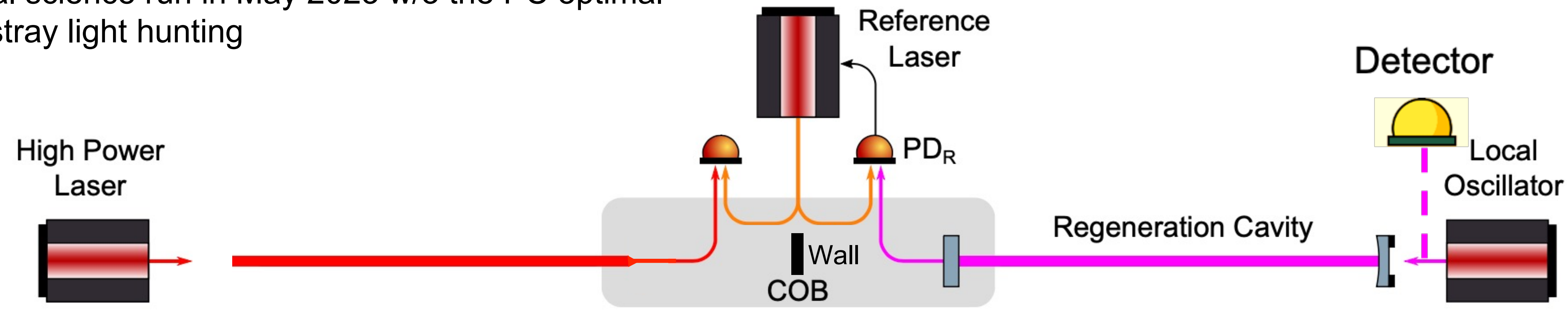


Phase stability as a **key detection point**

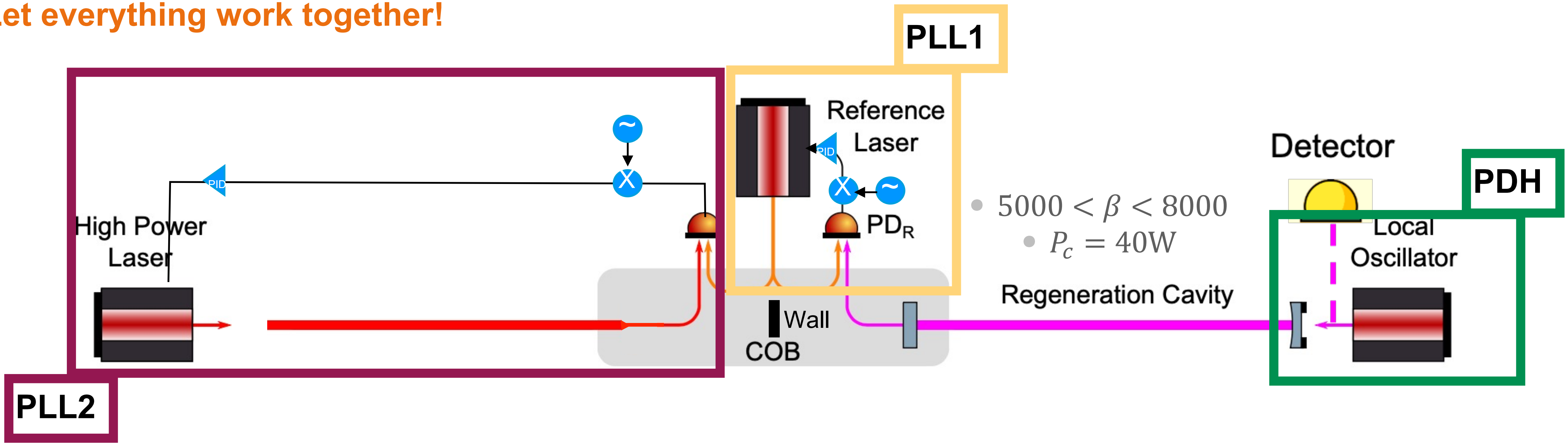
- Demodulation signal must be coherent with the measured signal
- LO must be coherent with regenerated field
  - HPL must be coherent with LO over the full run

Resonant Enhancement

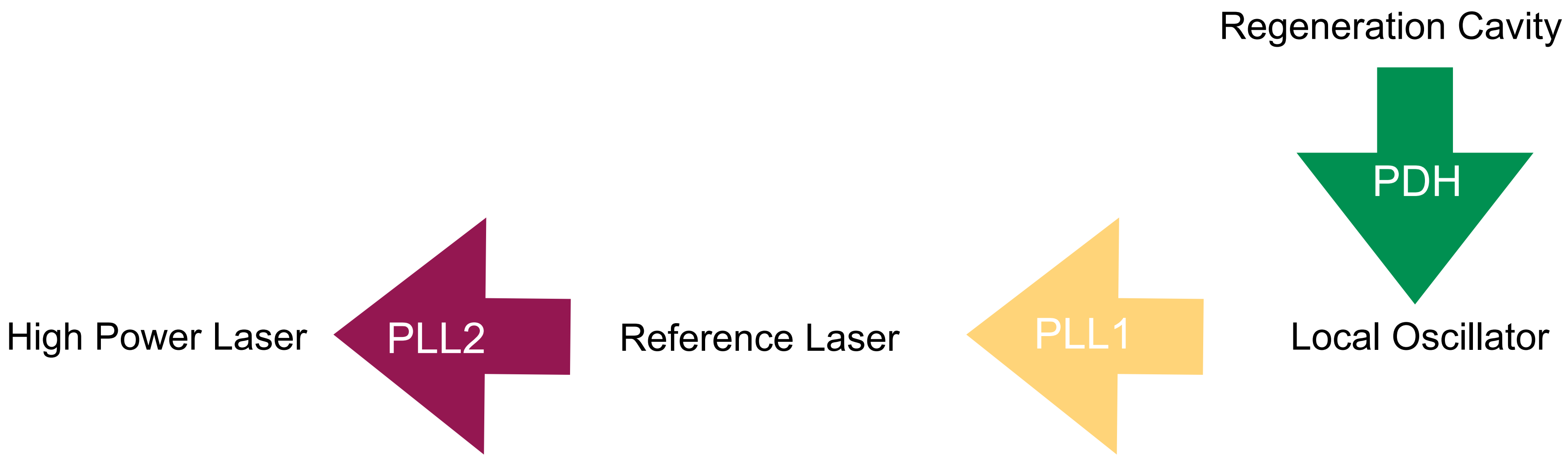
- Amplification of regeneration cavity (RC) only works if the regenerated field is resonant
- Cannot directly interfere HPL and LO fields → too much stray light!
- Use of a reference laser with cascaded phase-locked loops as a "go-between" → HPL and LO never see each other directly

Control system

Let everything work together!

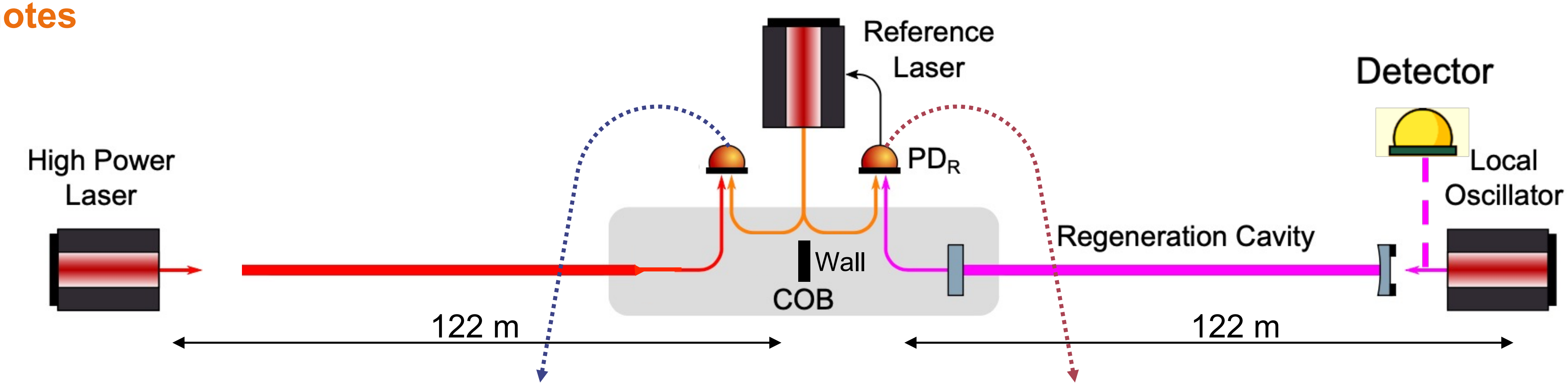


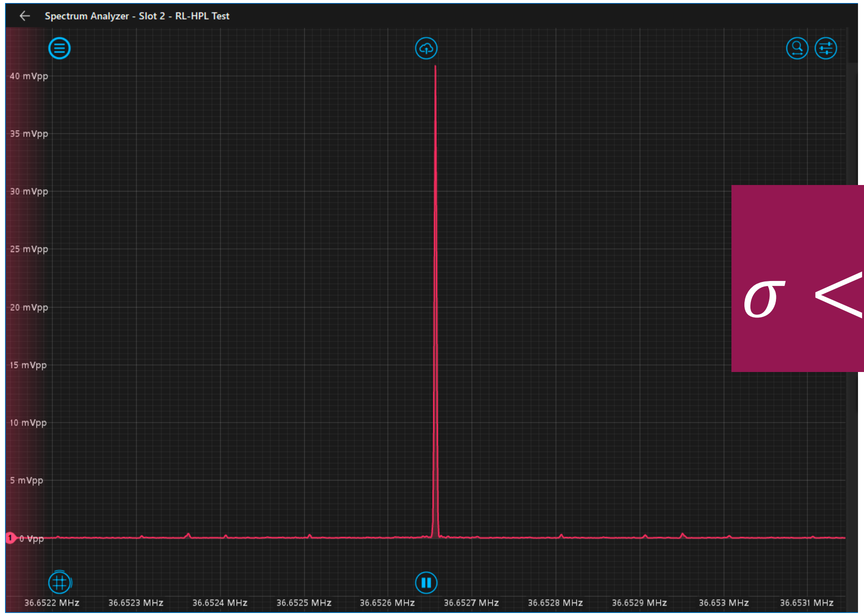
- $5000 < \beta < 8000$
  - $P_c = 40\text{W}$



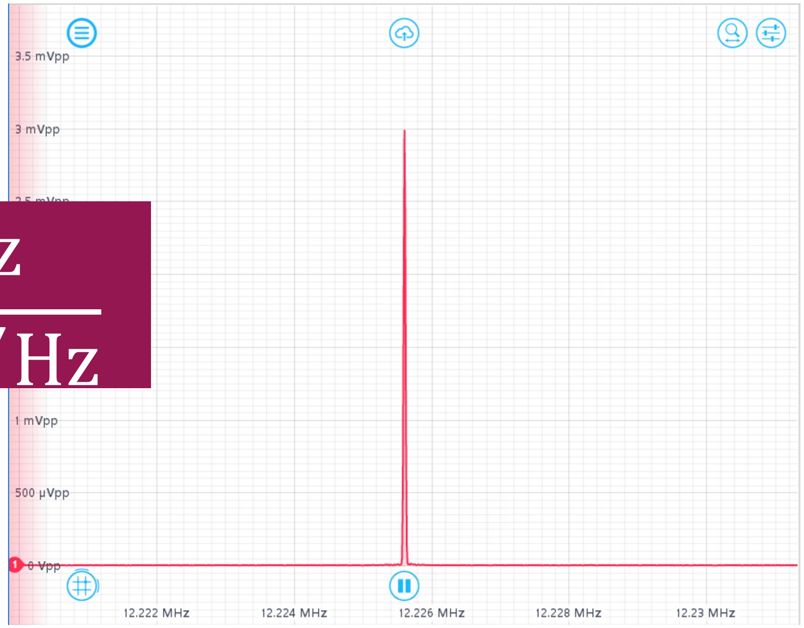
ALPS II's initial science run scheme

Beat notes





$$\sigma < \frac{\mu\text{Hz}}{\sim 10^7\,\text{Hz}}$$



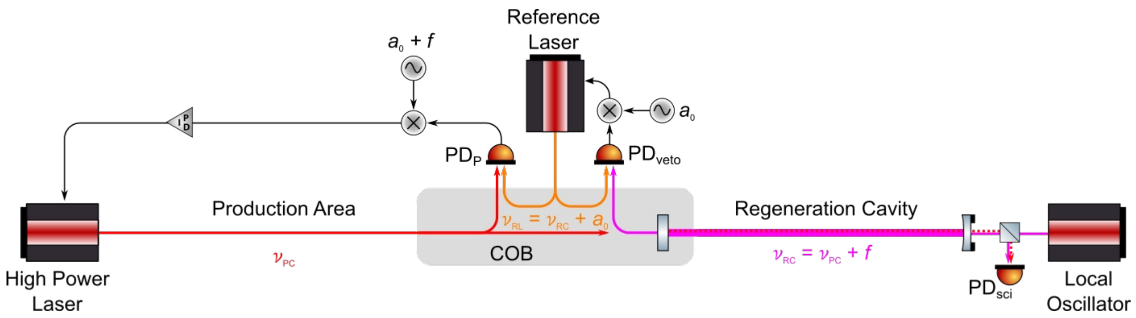
Open Shutter Runs

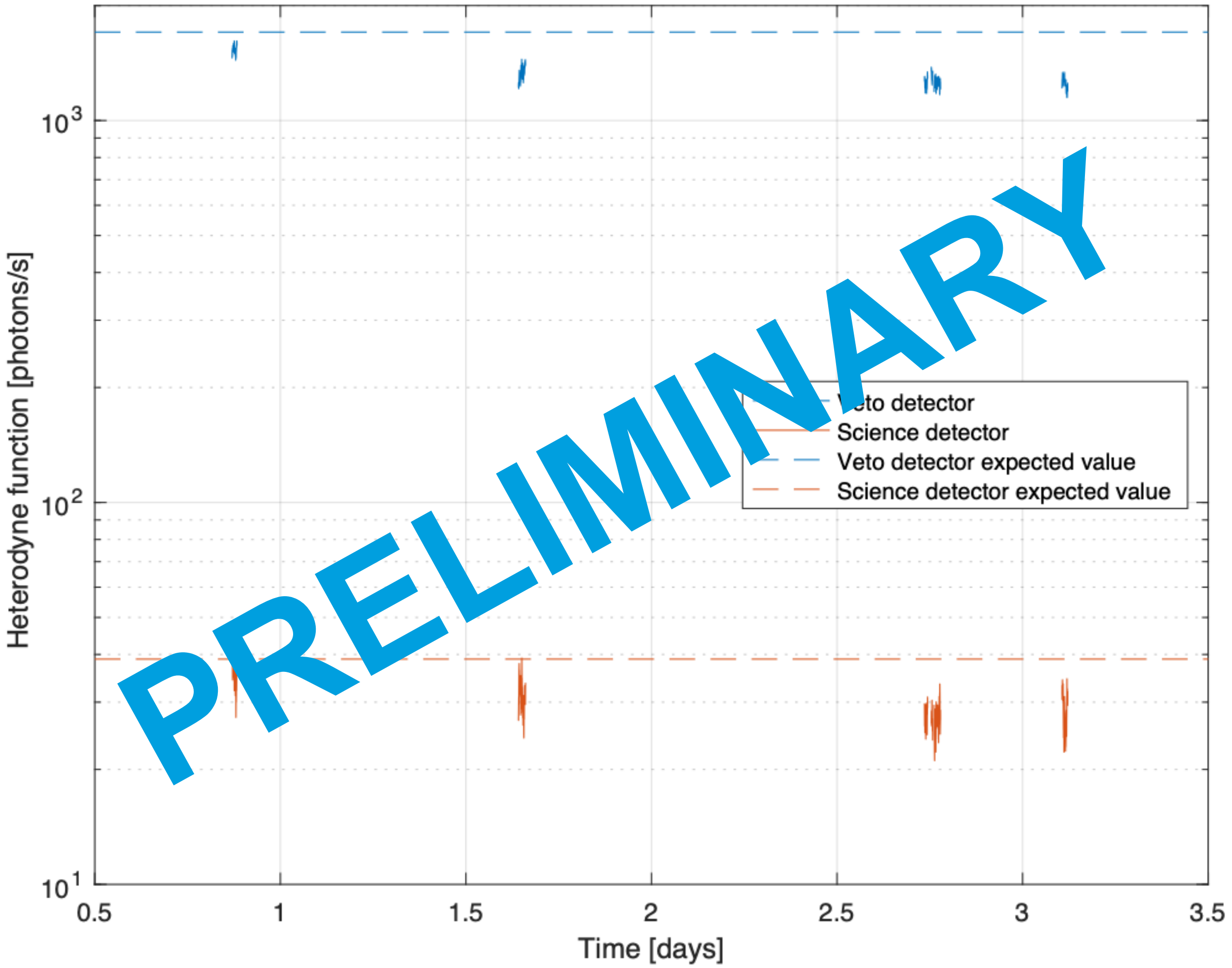
Calibrating our sensitivity

A.Spector, PATRAS 2023

Assessing the HPL-RC coupling

- Start with raw HET function data
- Scale in terms of photons/s



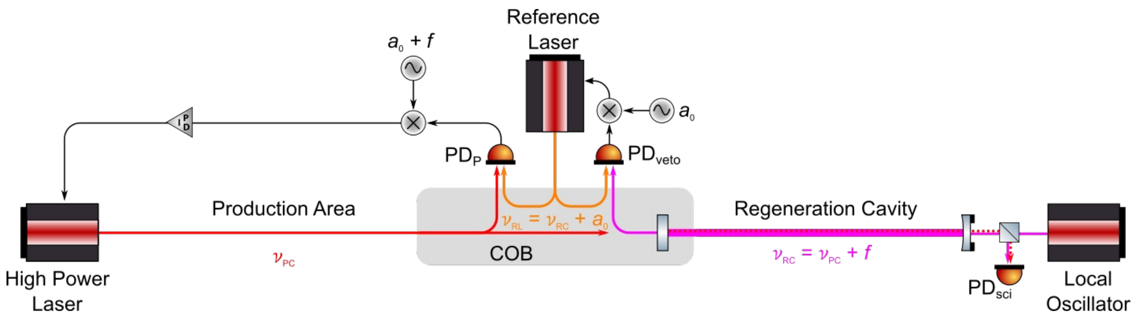


Open Shutter Runs

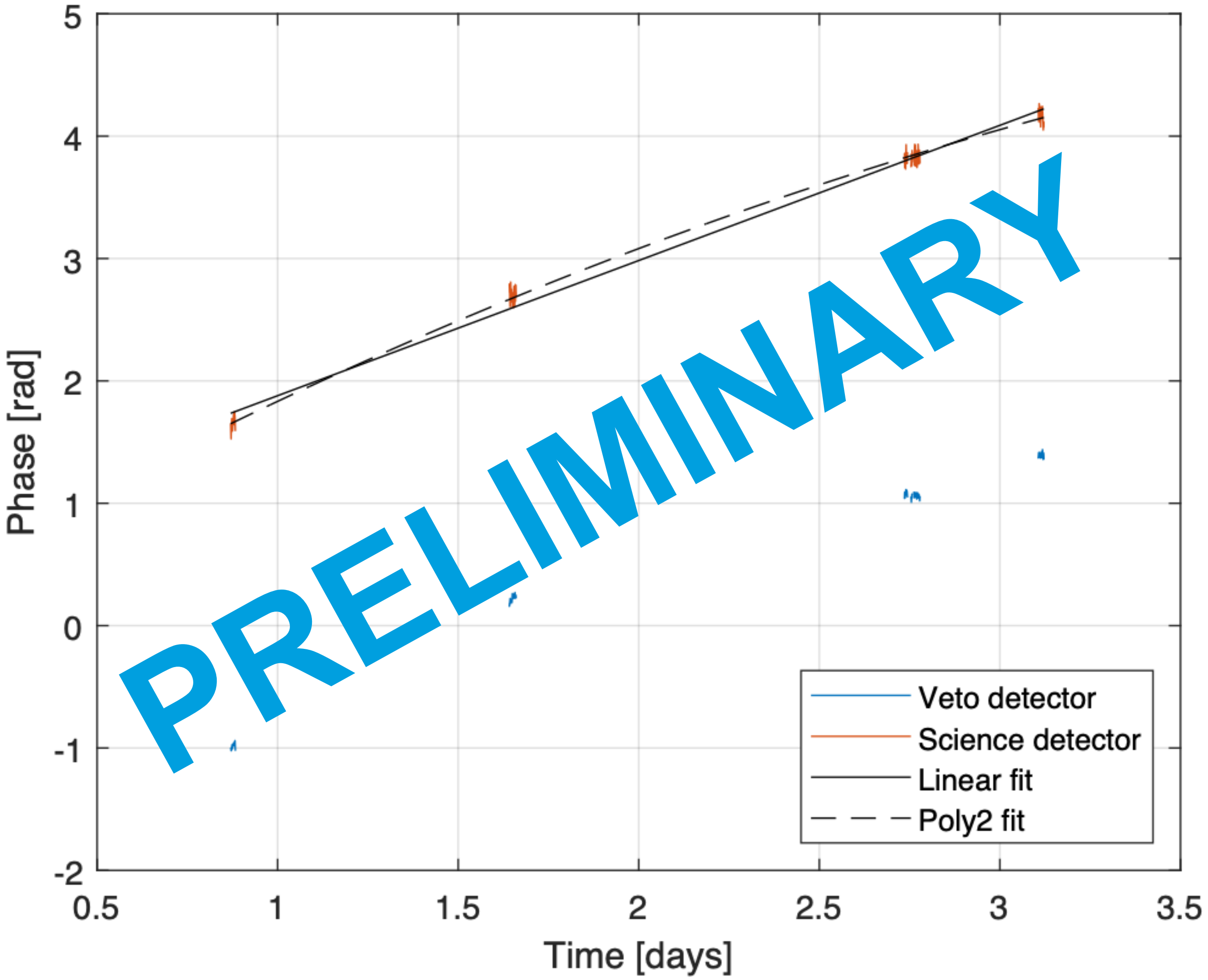
Calibrating our sensitivity

Assessing the phase evolution of the signal

- Similar phase trend in veto and science data
  - Bit depth of frequency offsets set by FPGA
- Linear and 2nd-order polynomial fits
- Linear phase trend subtracted from data

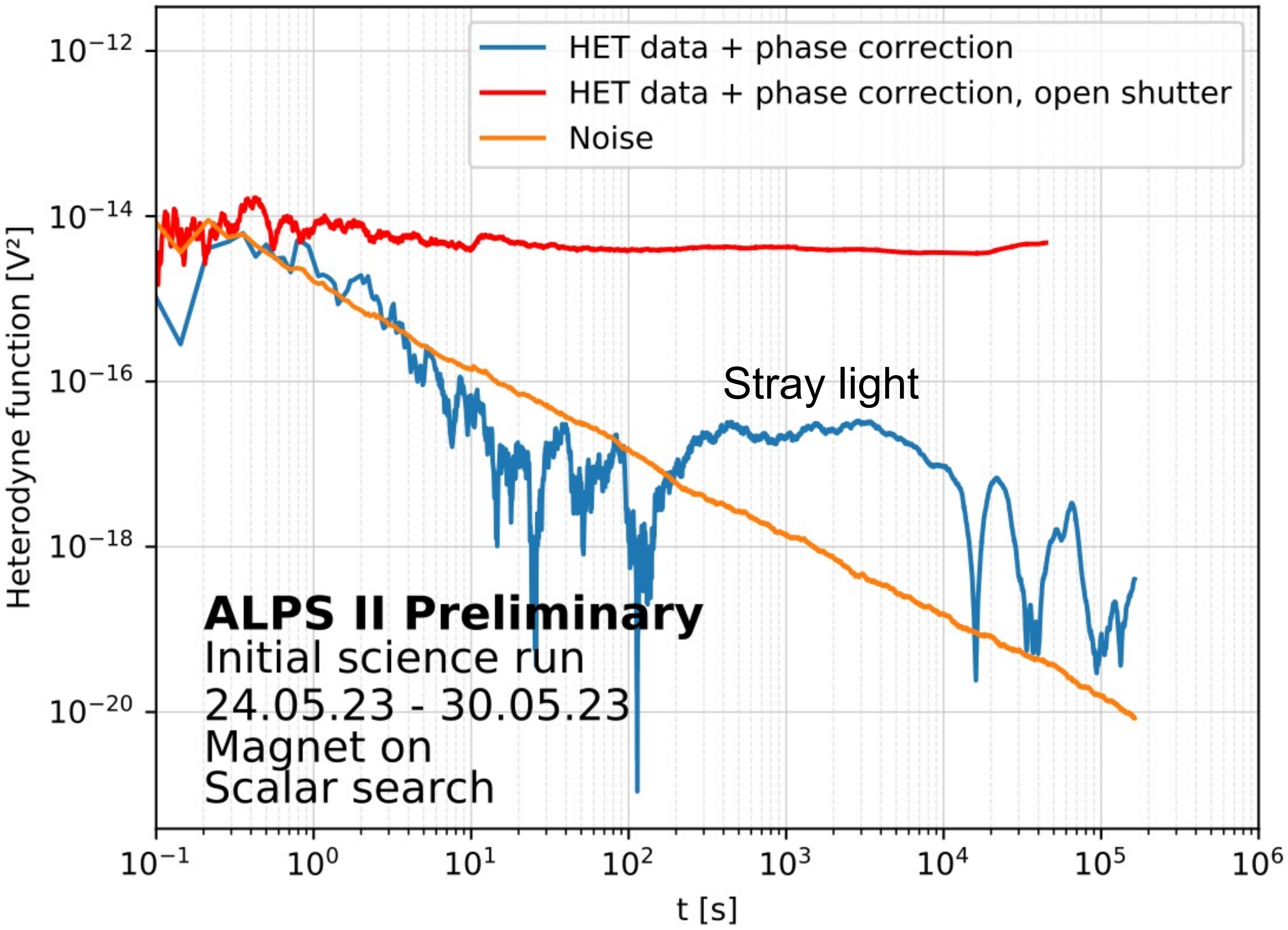


A.Spector, PATRAS 2023



Heterodyne function

Preliminary results



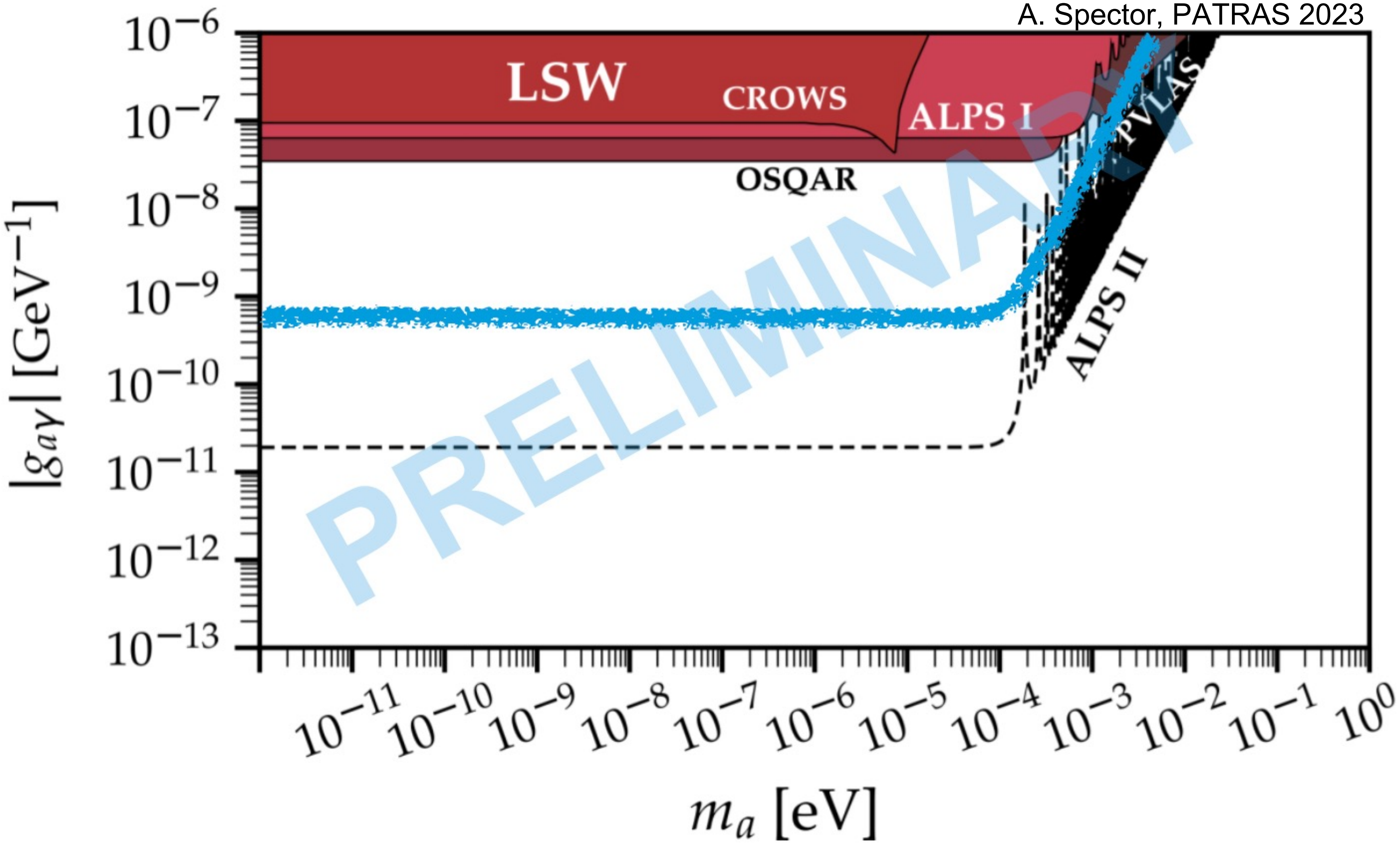
Successfully acquired data from May 23rd to 31st

- System showed very good performance
  - ~ 45 hours of high-quality data
- Open shutter periods:
  - Reliable reconstruction of phase evolution
  - Monitor for some calibration parameters

Preliminary sensitivity estimate

Preliminary results

A. Spector, PATRAS 2023



- Scalar search
- 150000 s (~45 h) integration time

ALPS II system improvements

Toward a new data taking

After the initial science run, works to

Fix the phase shift

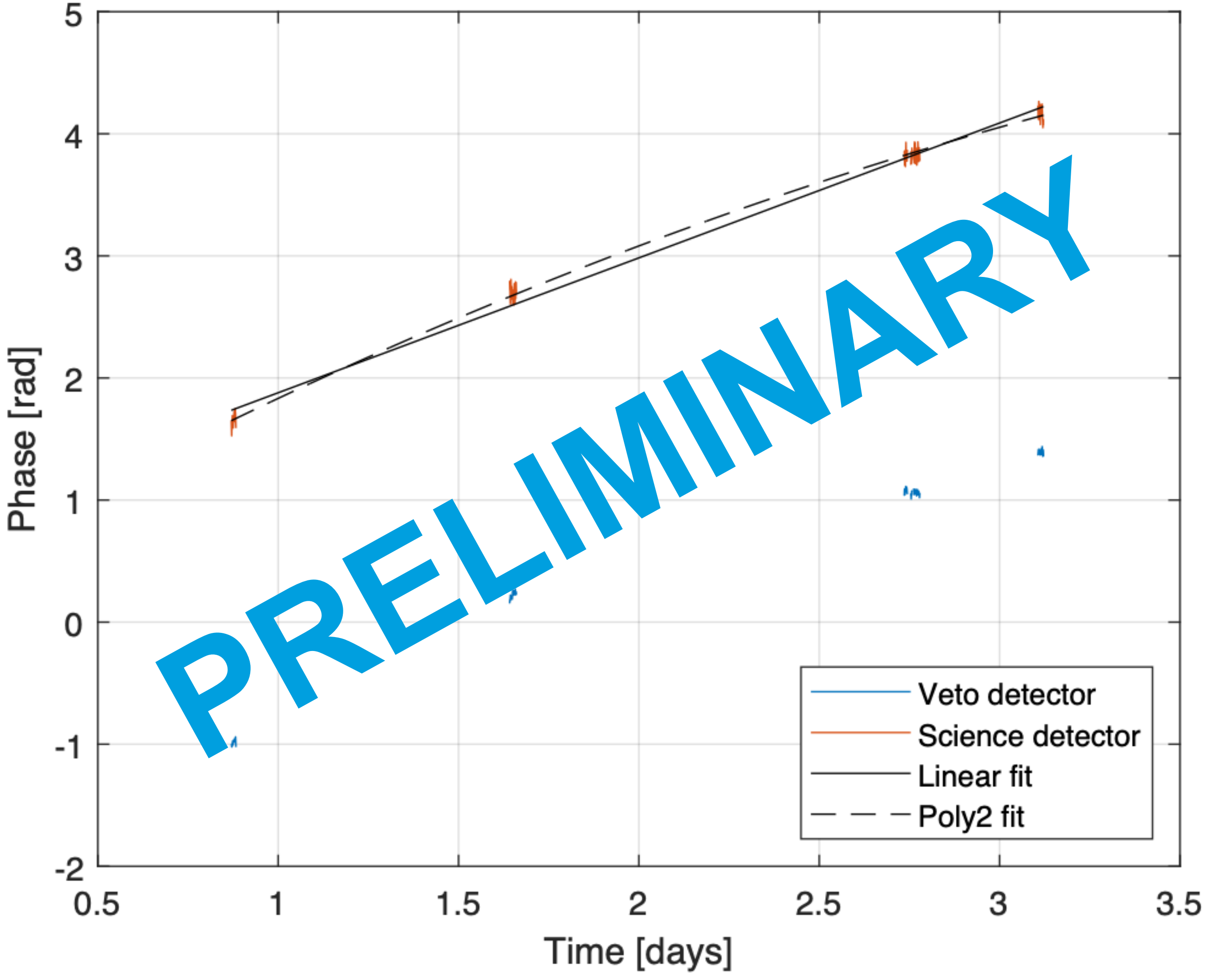
Improving the SNR
- A factor of ~2.5 adding a new LO

Automatise the locking procedure

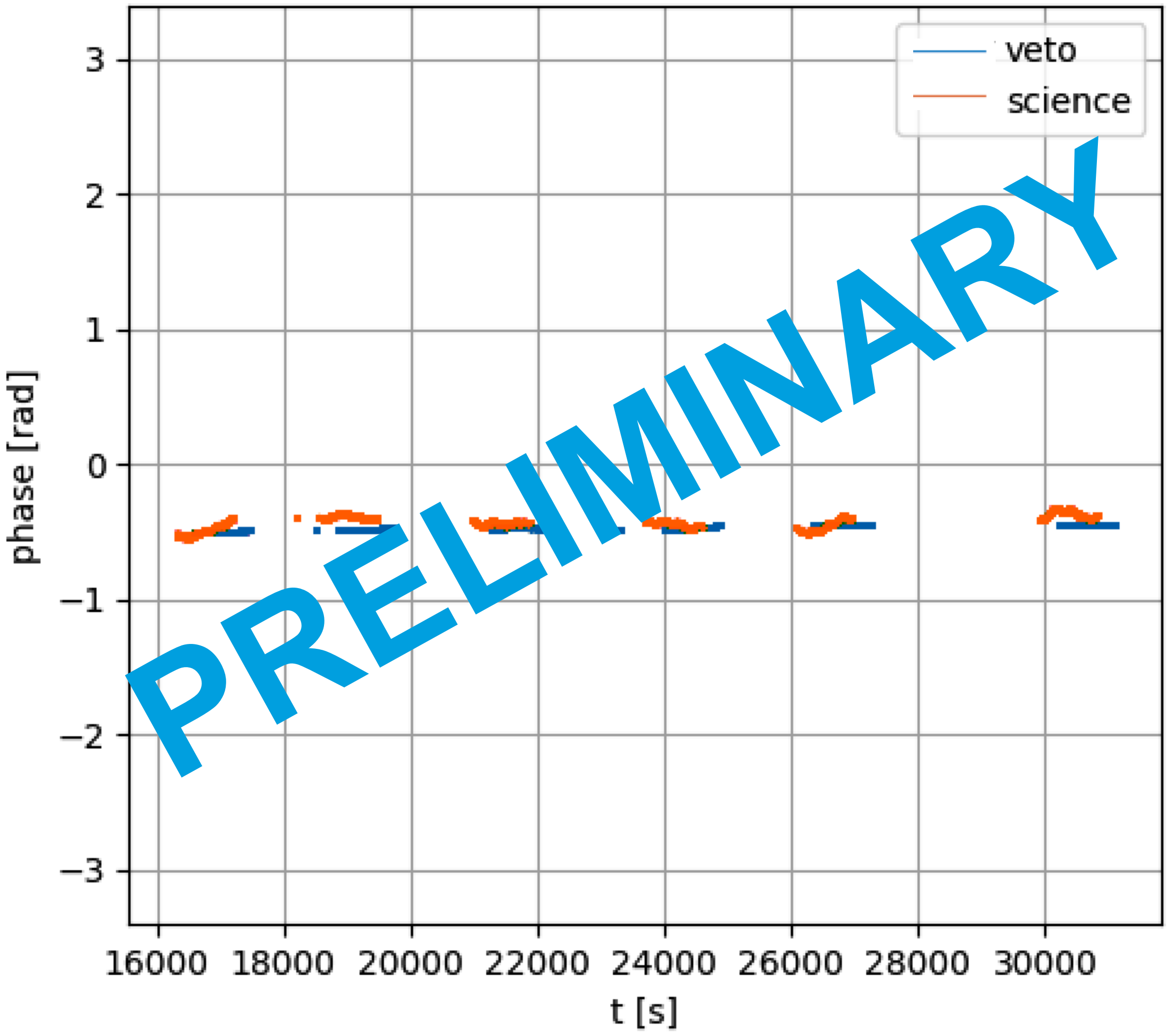
Fix the phase shift

Toward a new data taking

May 2023



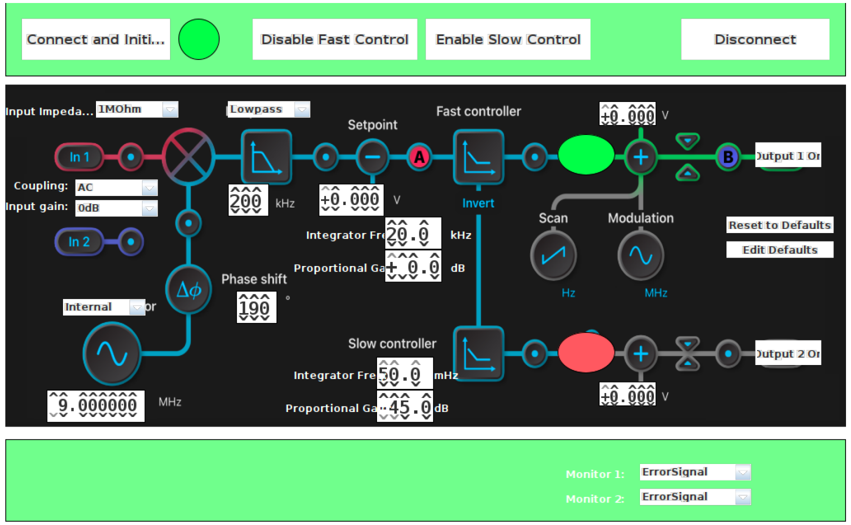
November 2023



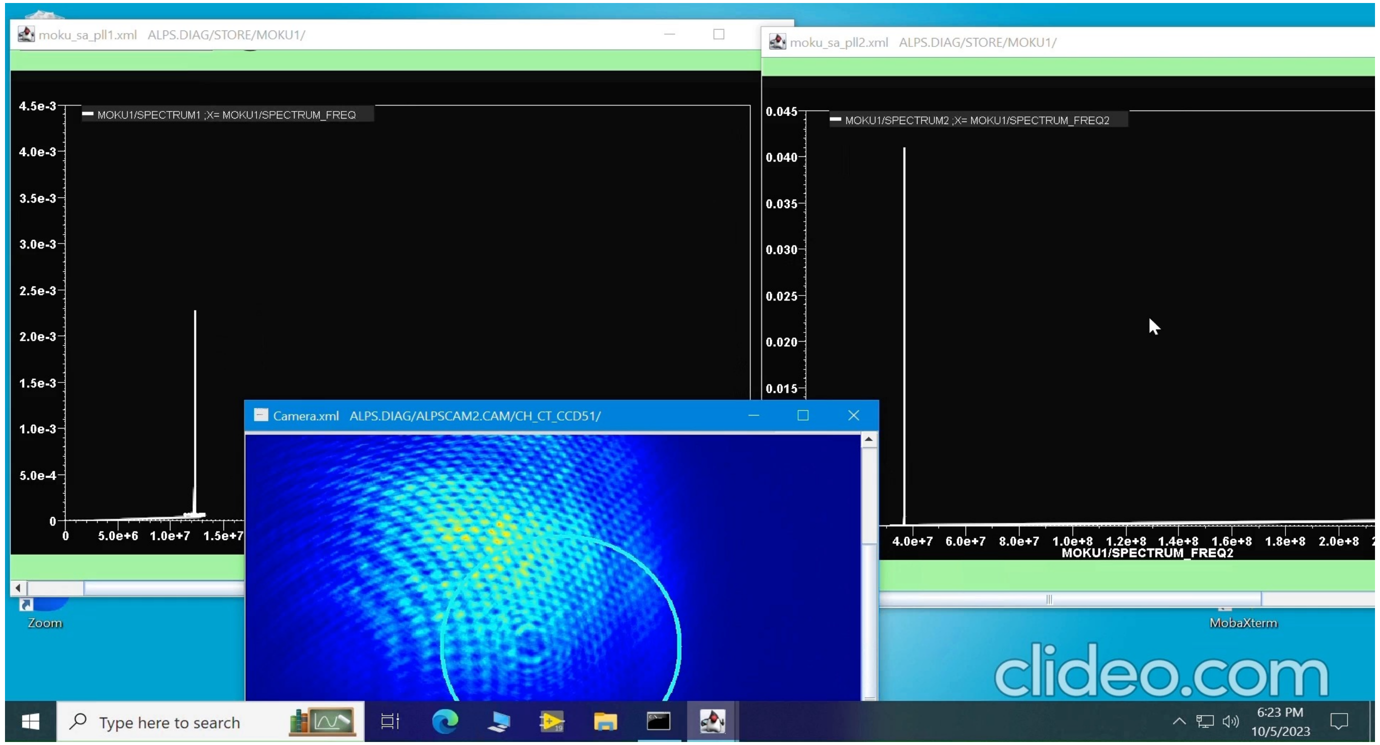
Auto-locking

Toward a new data taking

- Remote monitor of the control loops
- Less men power in monitoring
- Automatisation of the locking procedure
    - LO to the cavity
    - LO to RL
    - HPL to RL
- Continuous monitoring of calibration parameters
- Automatisation of the run procedure



24/24 h, 7/7 days beat note monitoring



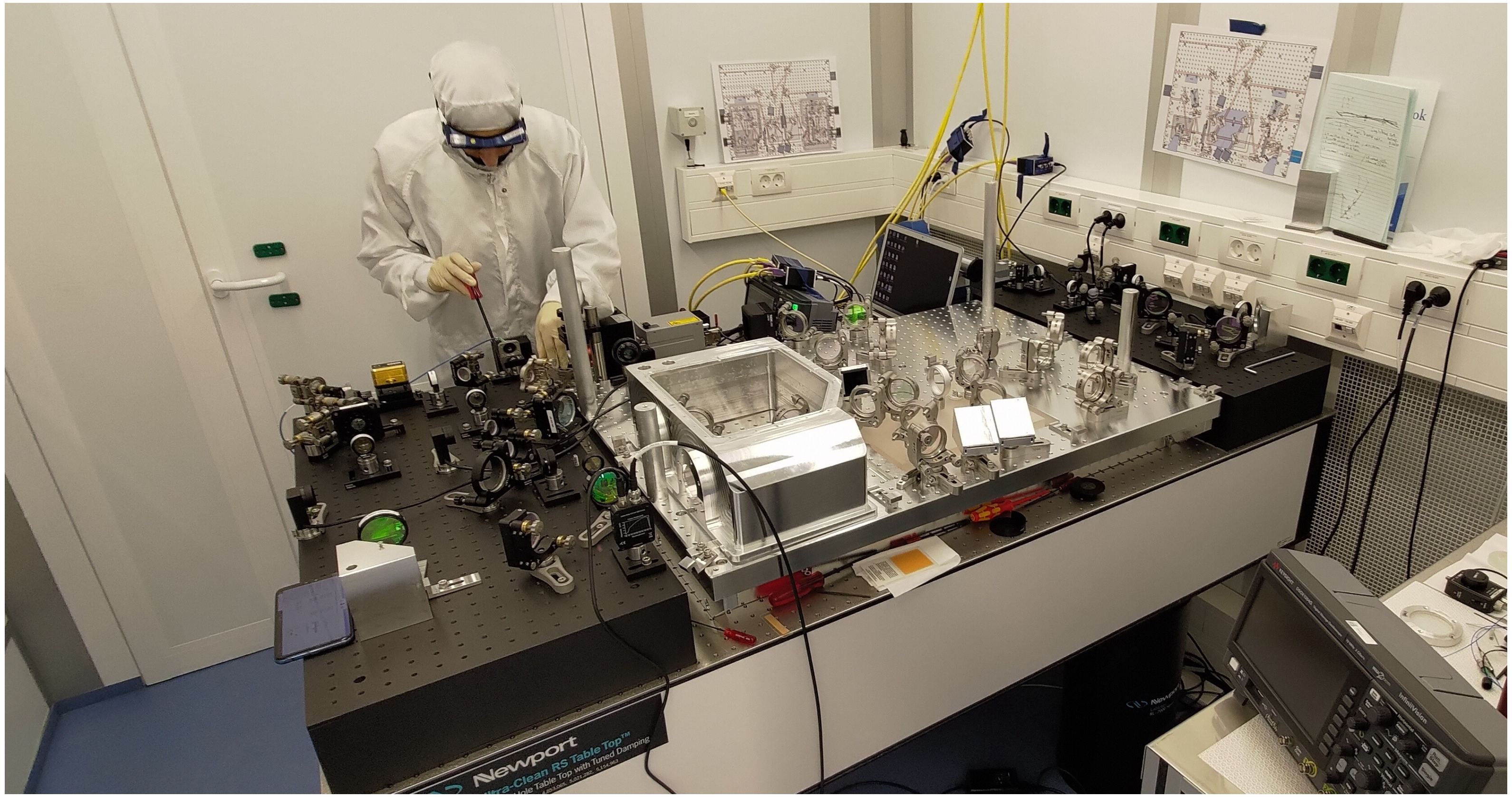
Demonstrated duty-cycle ~92%

Average locking procedure ~ 5 min

New data taking

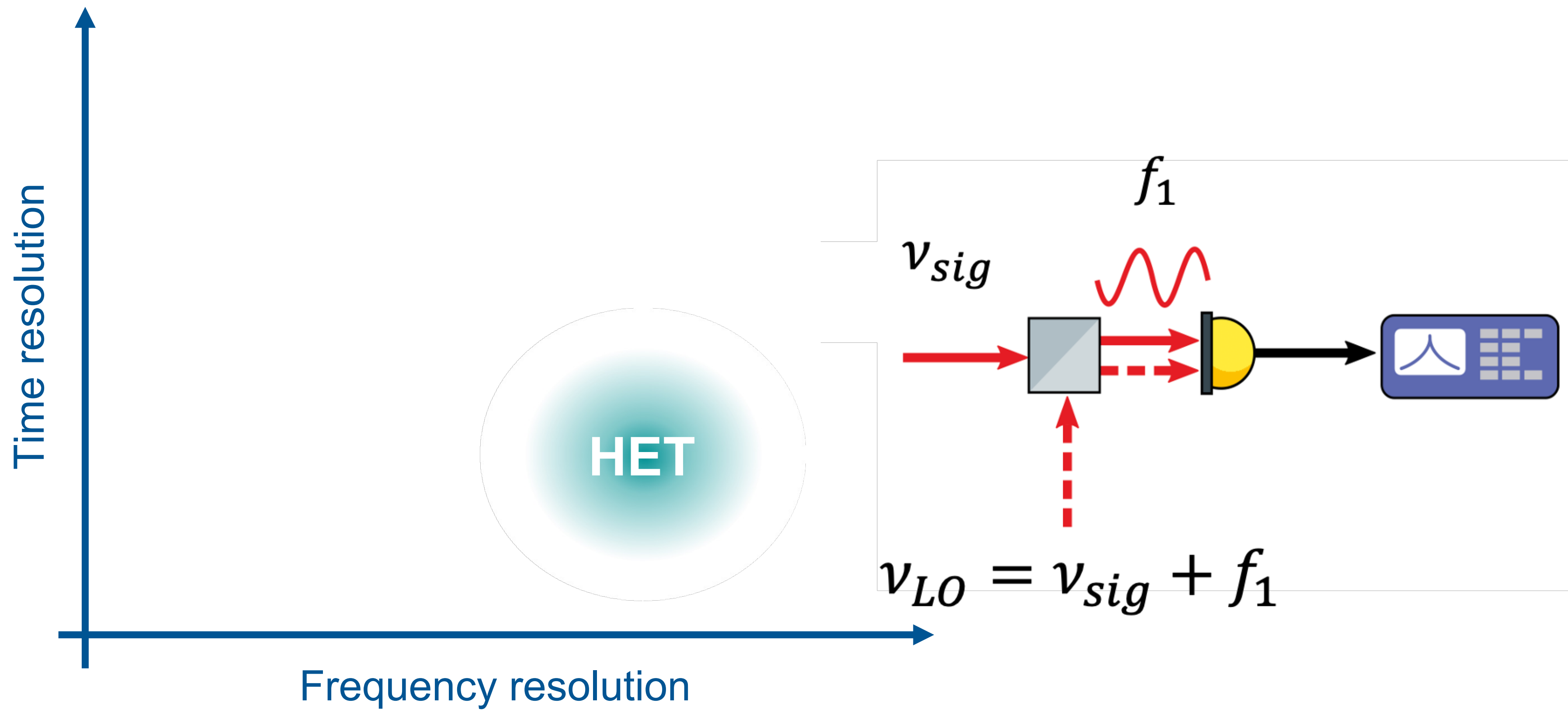
Starting from 3rd November 2023

- A new data taking with an improved system is taking place
- 1,000,000 seconds run
  - No more limited by stray-light



Regenerated photon detection

Exploiting two different techniques



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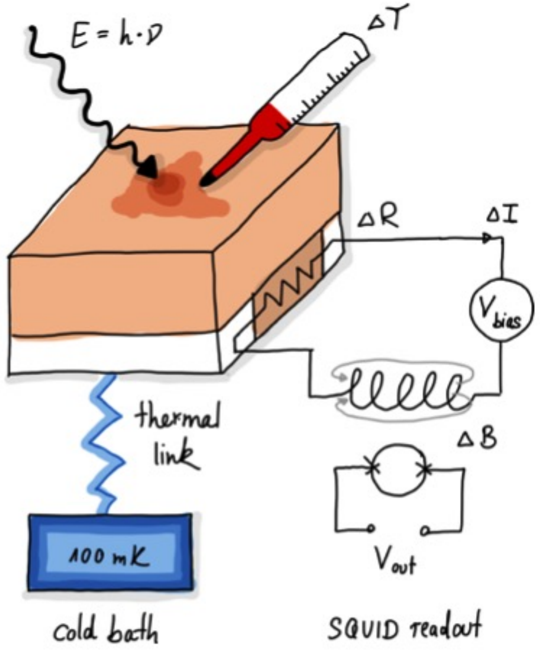
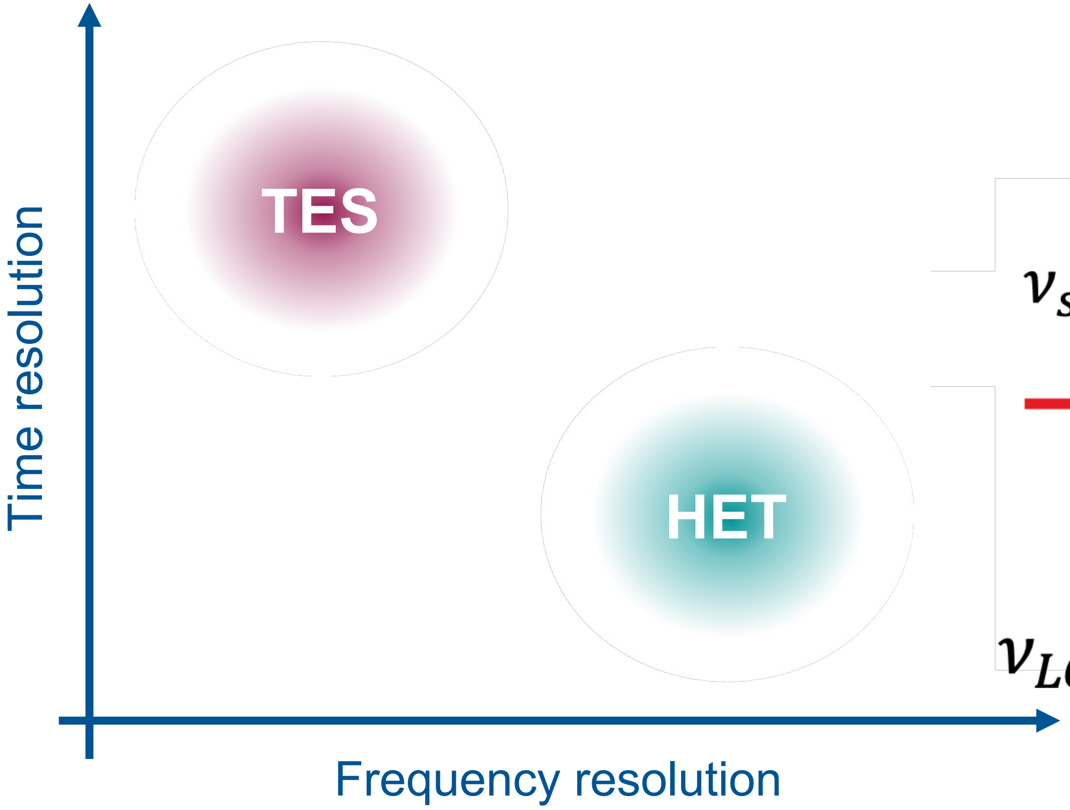
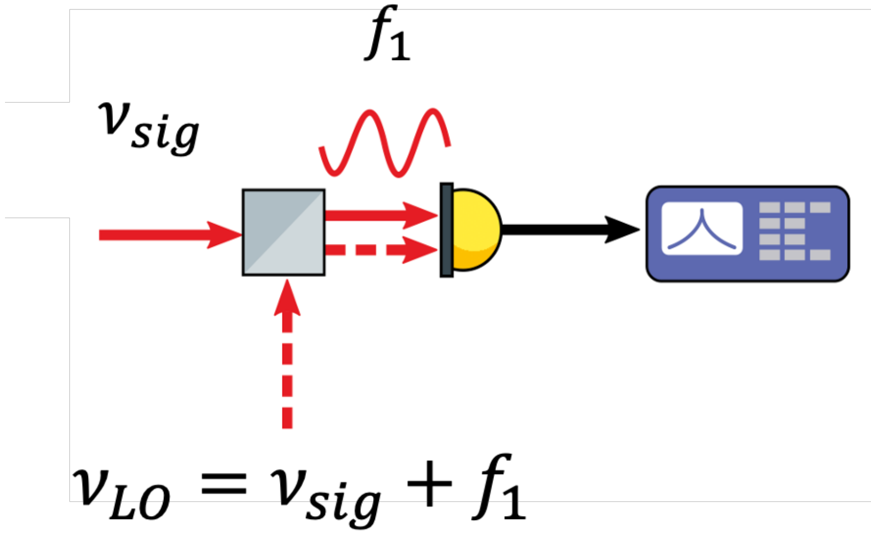






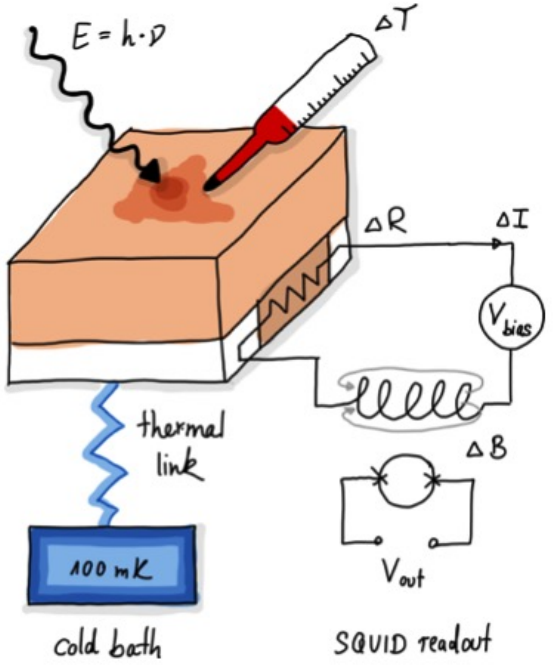
TES

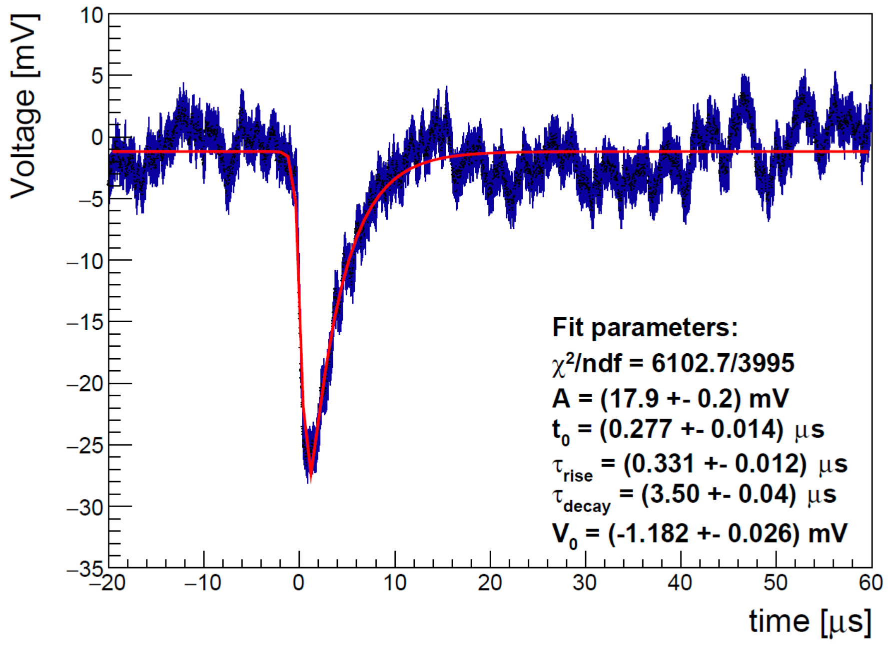
Transition Edge Sensor

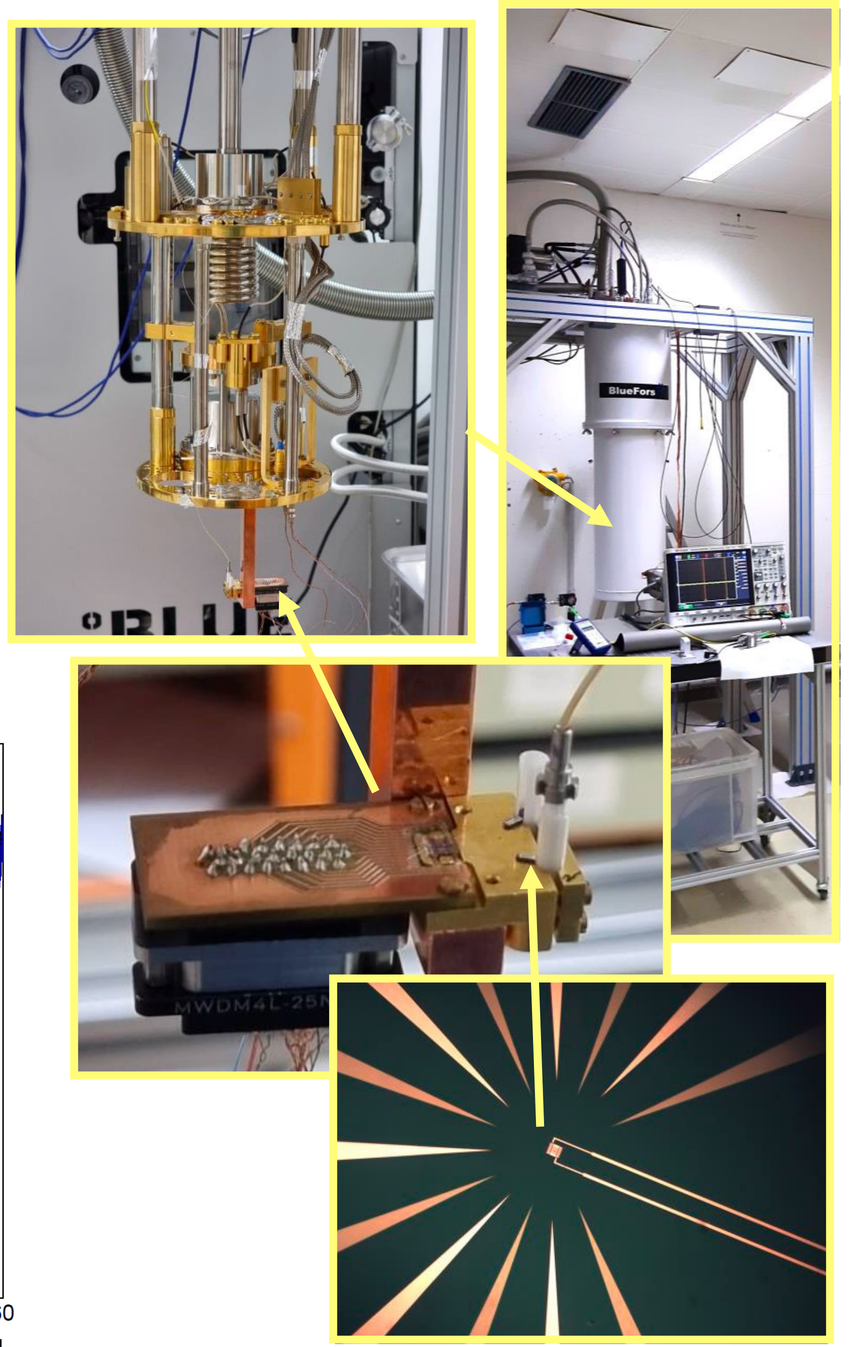
- Using a superconducting Transition Edge Sensor (TES) operated at about 100 mK.
- Already have demonstrated:
  - Low-backgrounds (μHz)
  - Good energy resolution (~10%)
  - Long-term stability (~20 days)

A tungsten microchip provided by NIST and a SQUID readout by PTB ($25\mu m \times 25\mu m \times 20nm$) operated in the transition region ($\sim 140mK$)

TES data-taking requires a different optics setup.







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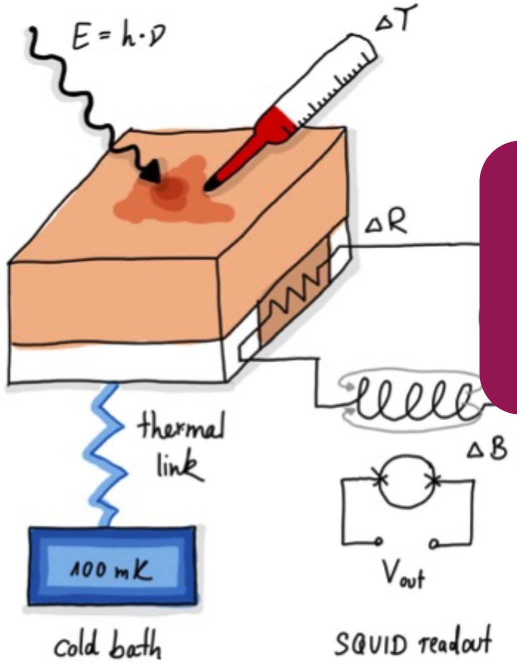
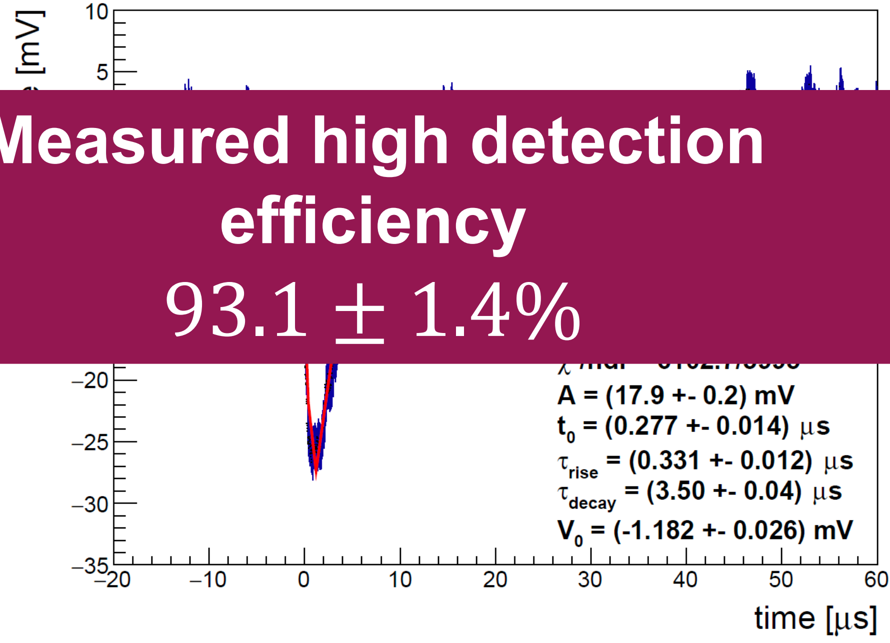
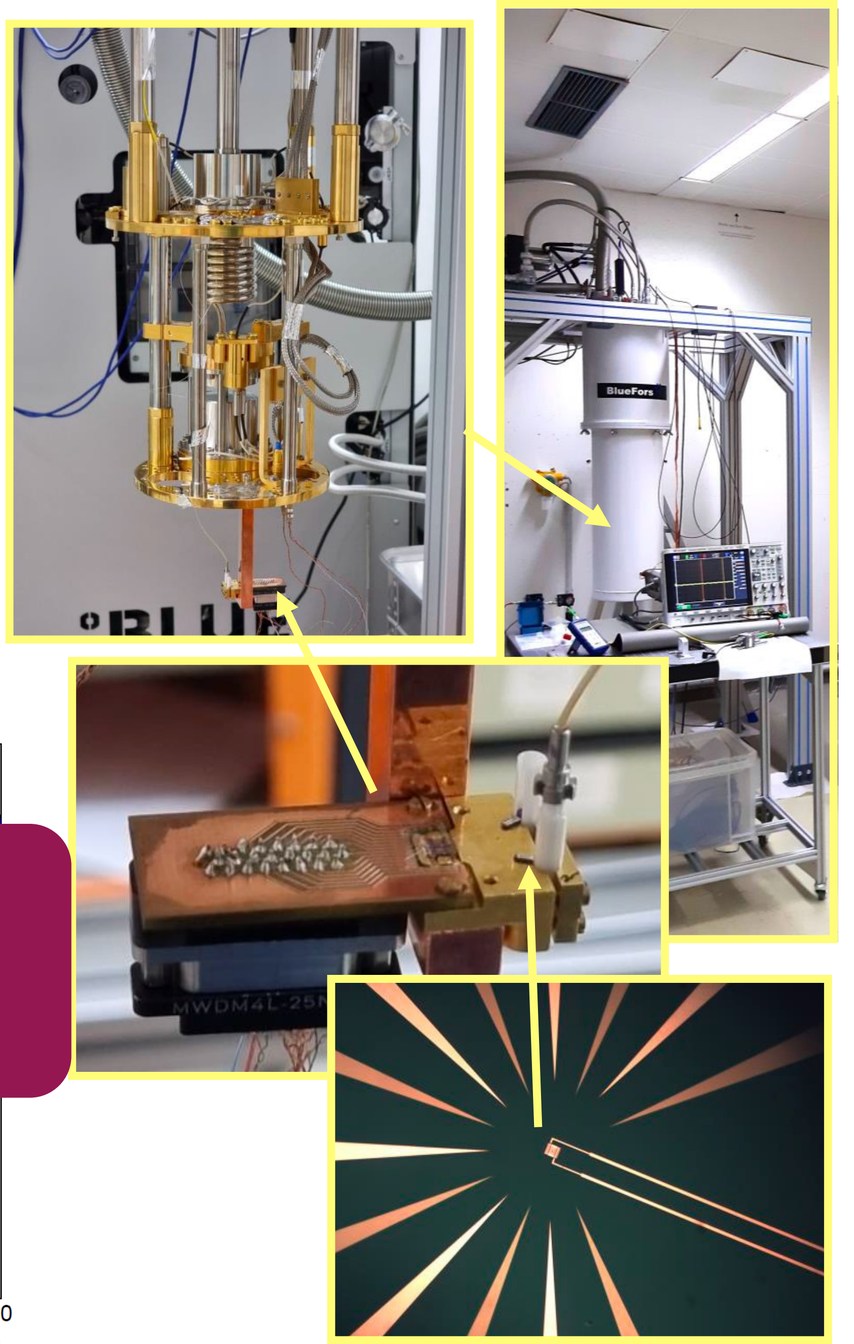


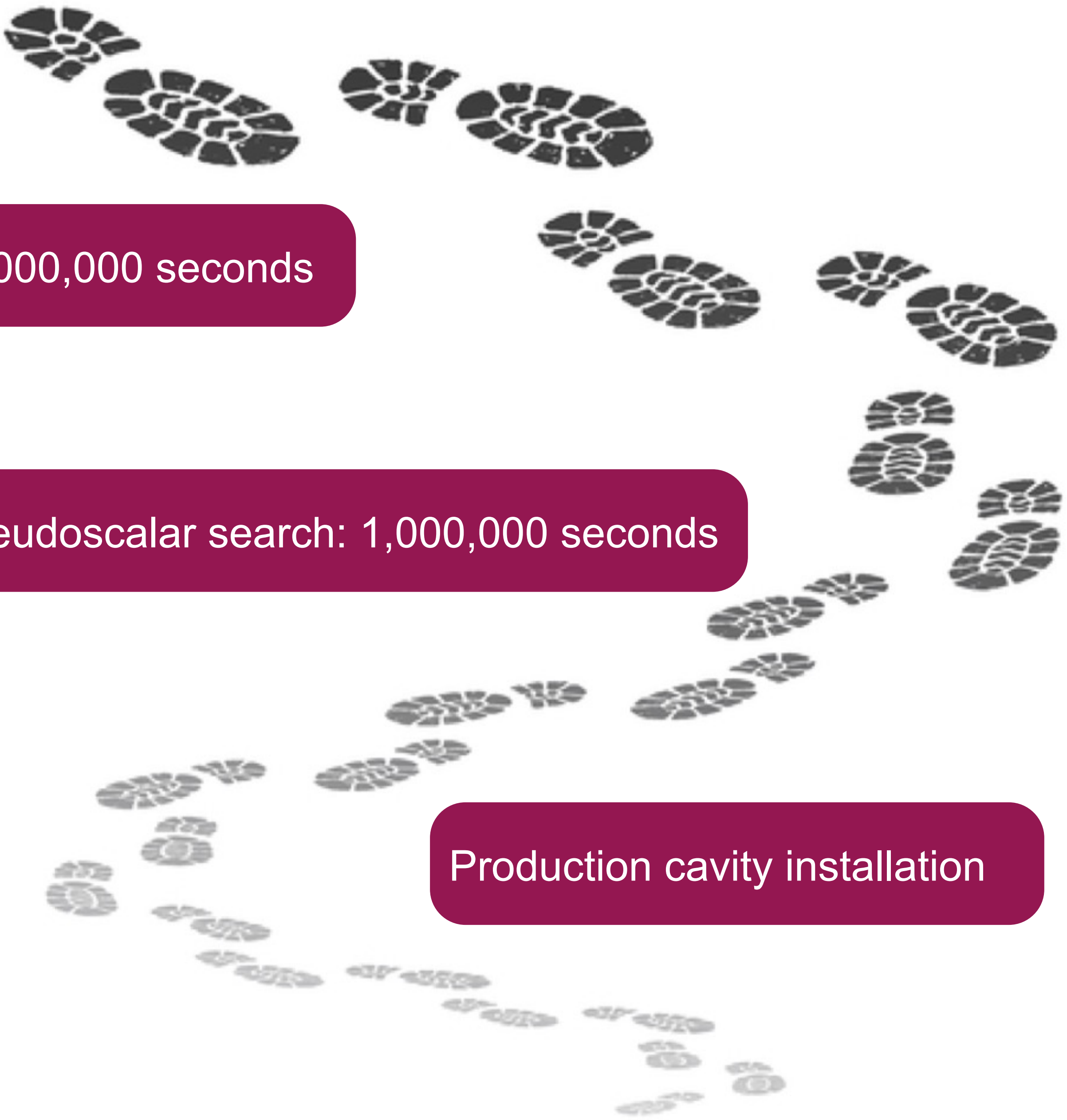


Measured high detection efficiency

$93.1 \pm 1.4\%$



Next steps



Scalar search: 1,000,000 seconds

Pseudoscalar search: 1,000,000 seconds

Production cavity installation

Conclusion

- LSW: Searching for axion and axion-like particles in a model-independent way
- During the initial run, we learned a lot:
  - Correction of the phase shift
  - Implementation of a second LO to improve the SNR
  - Full automatisation of the system
- The initial science run data improves the sensitivity by a factor of 30 to previous LSW experiments in the scalar search
- A new data taking is ongoing with an improved system
- The full setup of ALPS II will be installed in 2024, design sensitivity will be reached in 2025

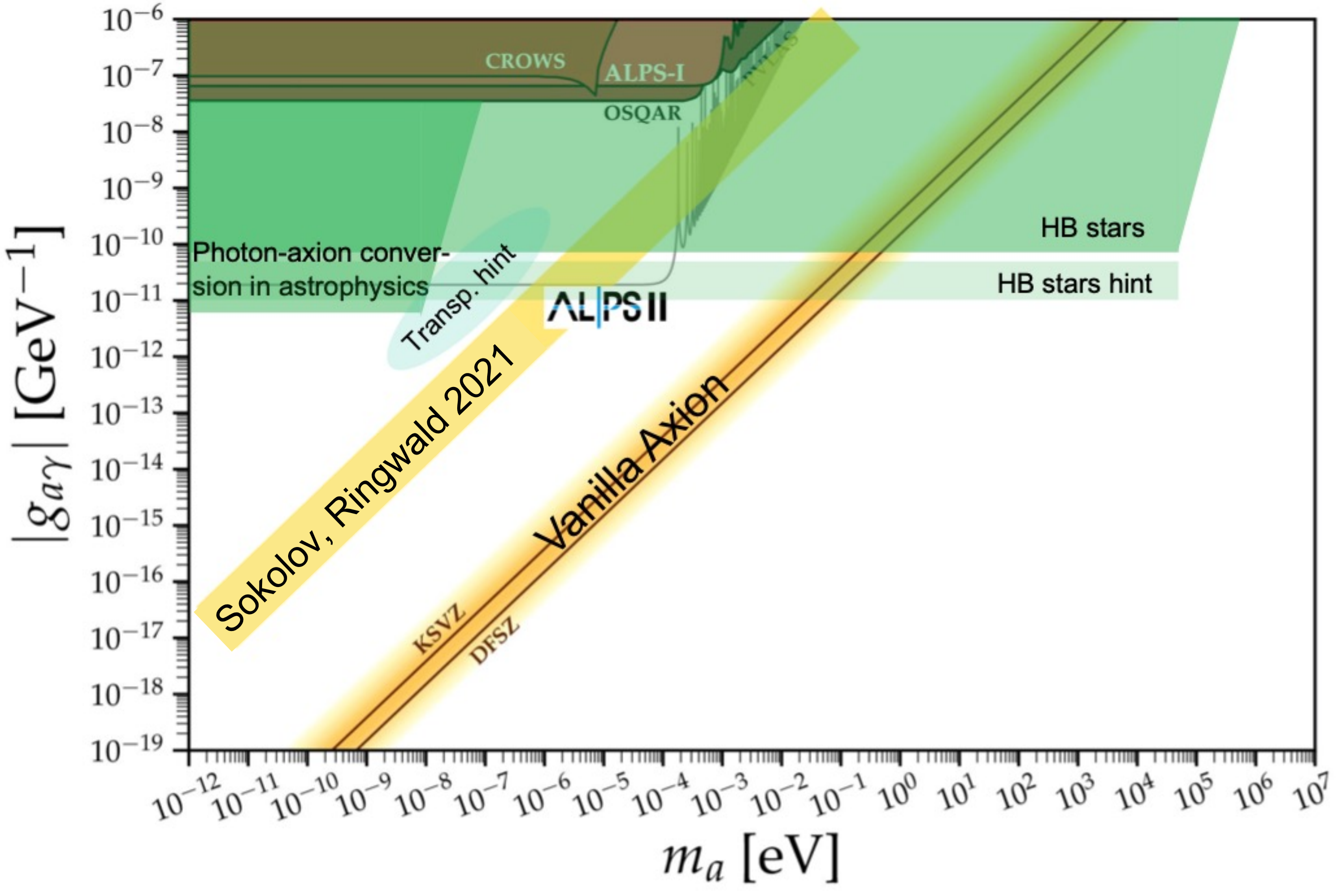
Backup

ALPS II

Strengths

ALPS IIigned to improve sensitivity compared to ALPS I by a factor of ~3000

- Exploring uncharted territory in parameter space, beyond astrophysical constraints
- Checking axion explanation of astrophysical anomalies



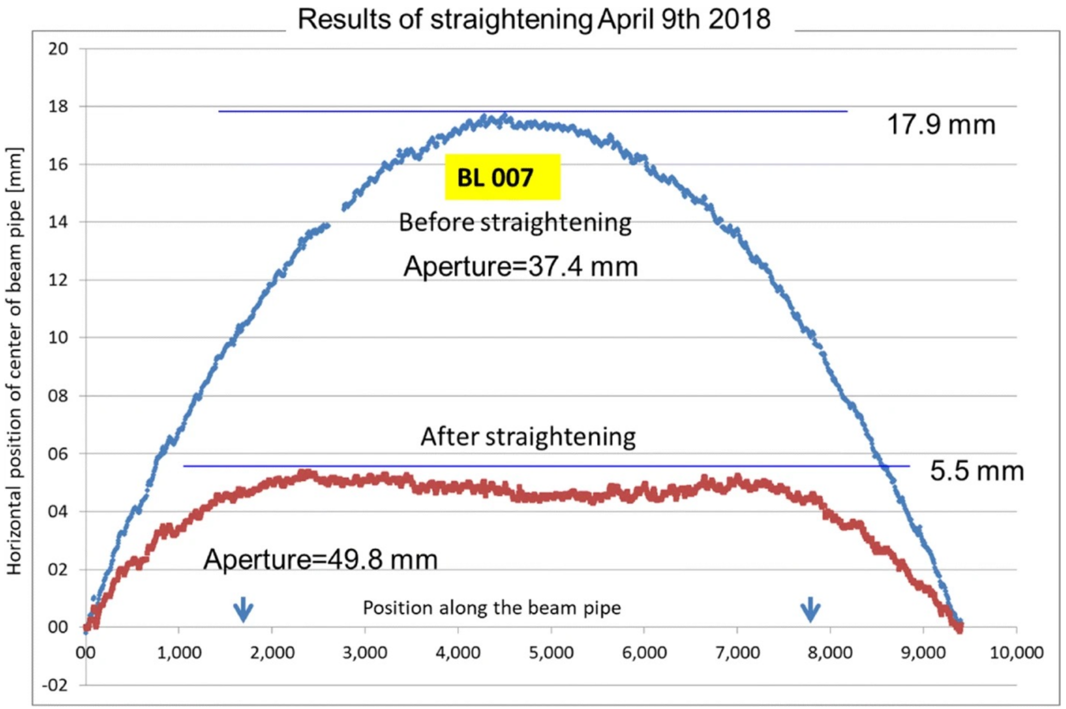
- Astrophysical constraints
  - Non-observation of BSM energy loss of Horizontal Branch (HB) stars in globular clusters
  - Non-observation of conversion photons into axions in astorophysical environments
- Astrophysical anomalies
  - Best fit of energy loss of (HB) starts hints at BSM contribution
  - Observed spectra of blazers hint at anomalous transparency of Universe from TeV photons

Magnets

The axion makers

Albrecht, C., Barbanotti, S., Hintz, H. *et al.* Straightening of superconducting HERA dipoles for the any-light-particle-search experiment ALPS II. *EPJ Techn Instrum* 8, 5 (2021).

- 24 (2 x 12) repurposed HERA dipole magnets successfully straightened, current- and quench-tested, aligned and operational
  - 5.3 T field strength at nominal 5700 A
  - Expanded beam tube aperture allows for longer optical cavities → improved sensitivity



Optimal storage time for SNR

Balancing power buildup with technical noise

Cavity impedance matching

- At ~7.8 ms no LO laser light is reflected from RC
  - Technical noise
- Ideal working point is currently at ~5.3 ms
- Additional non-resonant LO laser solves this