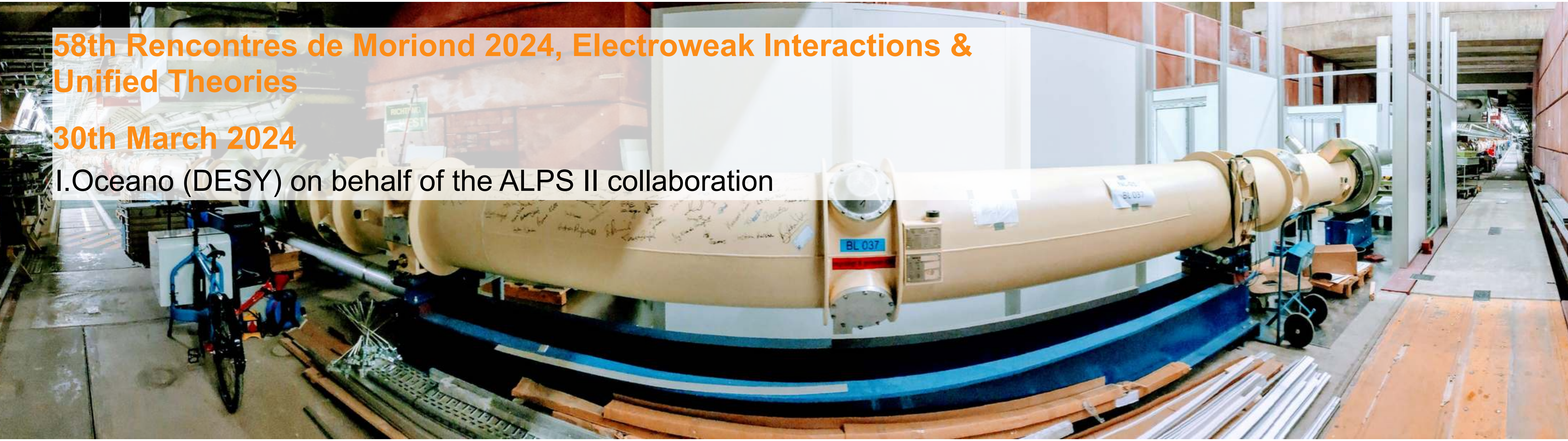
ALPS II experiment first results



58th Rencontres de Moriond 2024, Electroweak Interactions & Unified Theories

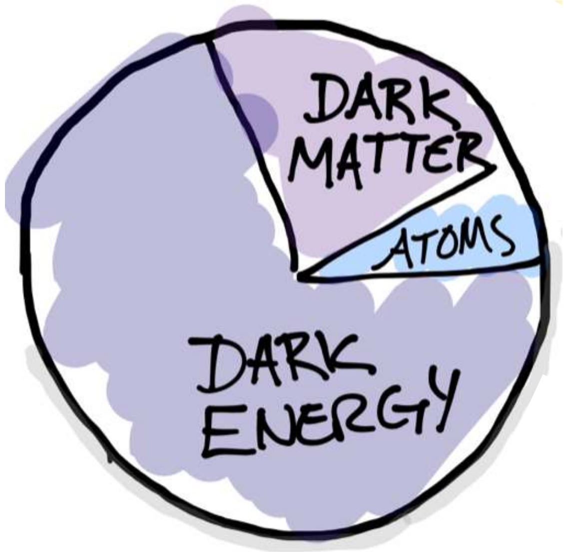
30th March 2024

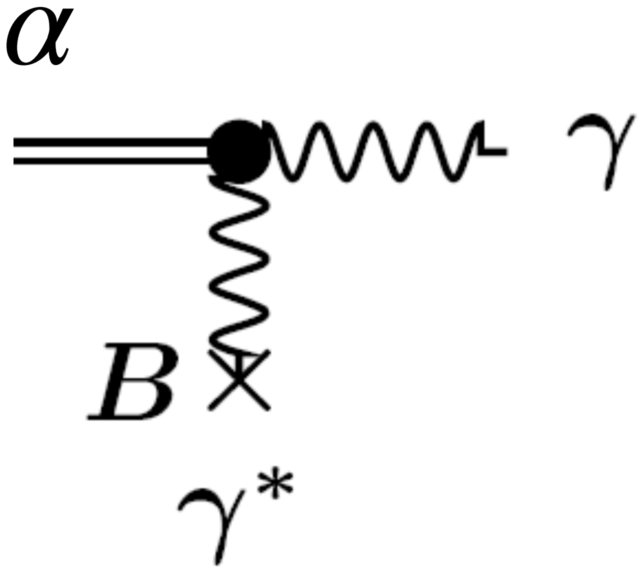
I.Oceano (DESY) on behalf of the ALPS II collaboration

Axion and Axion-Like particles

Motivation

- Solution for SM unsolved questions:
  - What is the nature of dark matter (DM)?
  - Why is the electric dipole moment of the neutron so tiny?
    - Axions are a consequence of the Peccei-Quinn symmetry to explain θ=0.





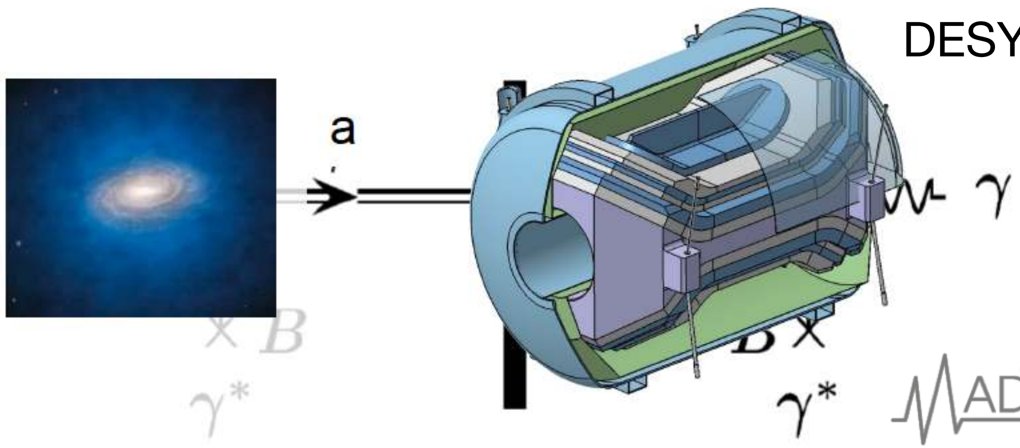
Sikivie effect

$$P(\alpha \to \gamma) \propto (g_{\alpha\gamma\gamma} B_0 L)^2$$

Axion and Axion-Like particles

Searches strategy

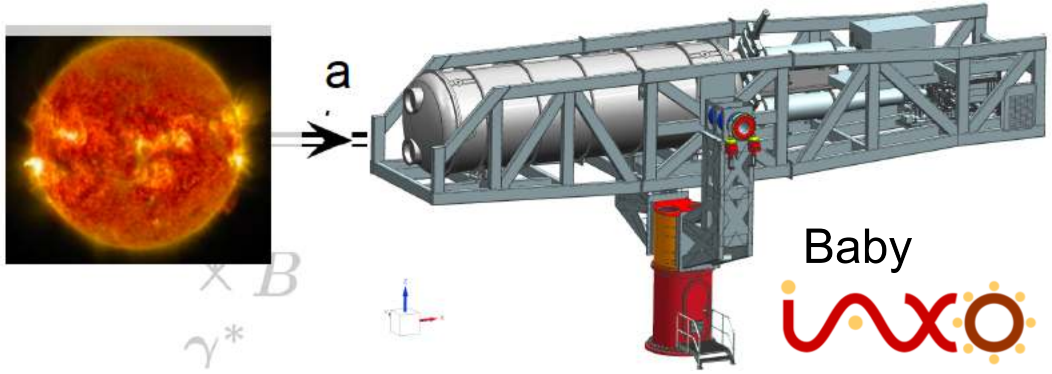
- Haloscopes



DESY

MADMAX

- Helioscopes

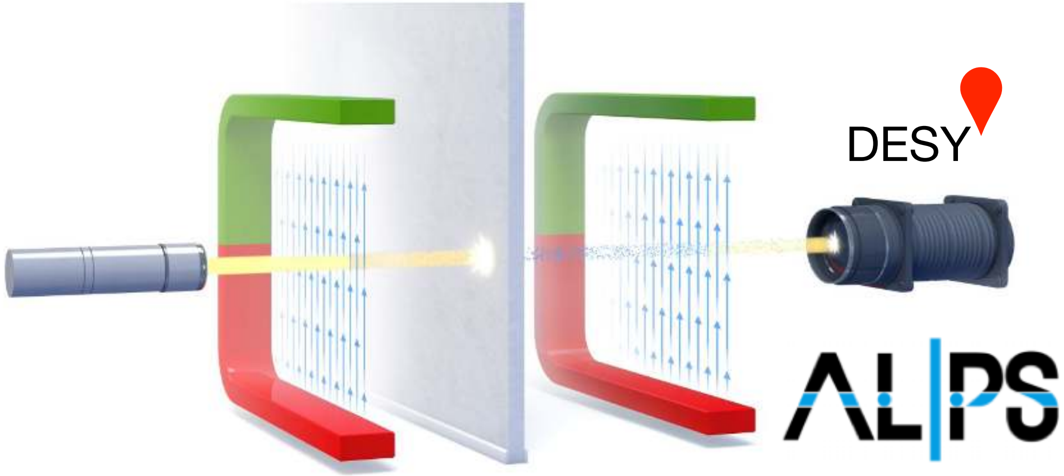


DESY

Baby IAXO

- **Light-shining-through-walls**

Not requiring cosmological or astrophysical assumption



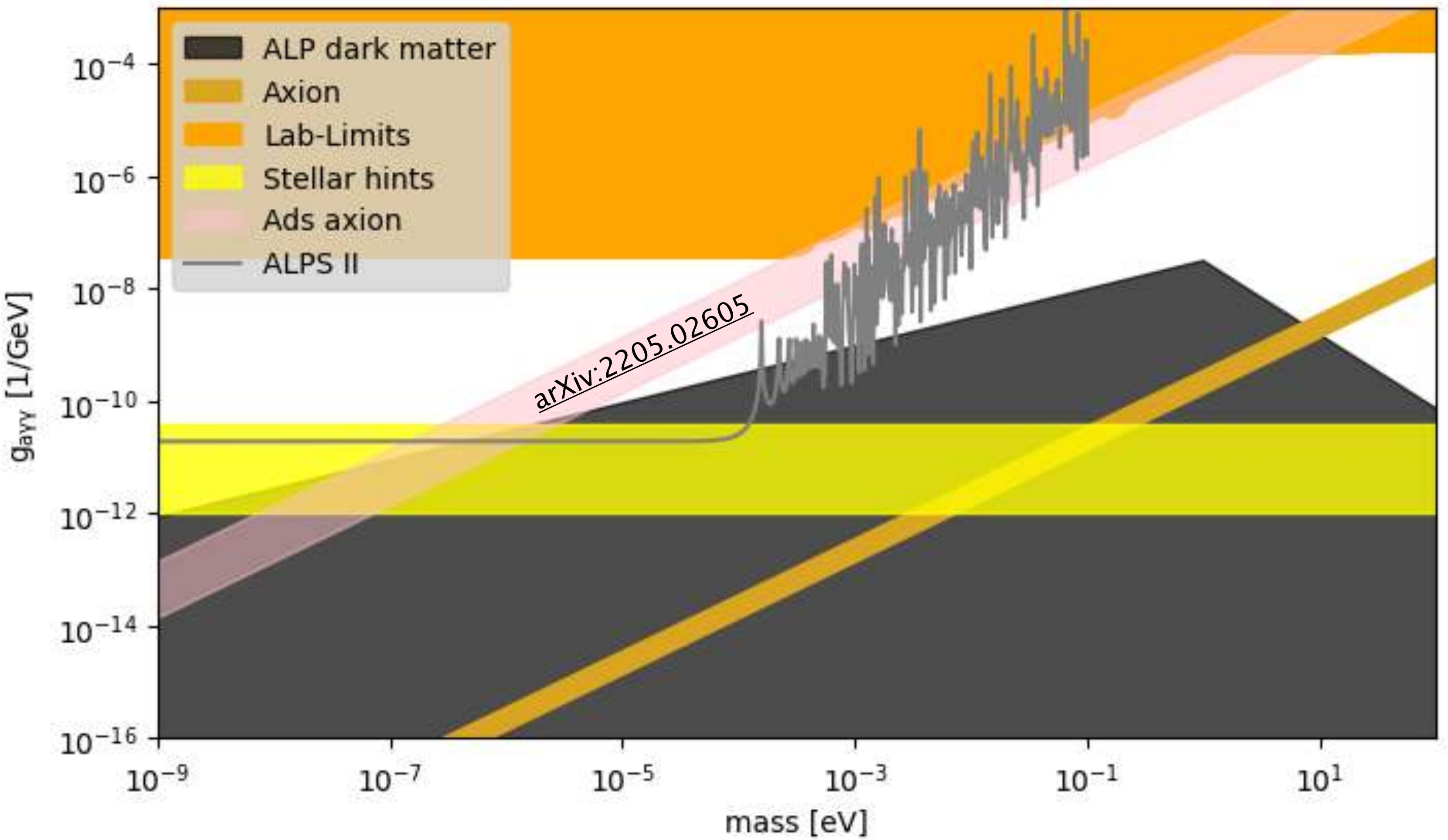
DESY

ALPS II

Axions: Light Shining through the Wall experiments

Model-independent search

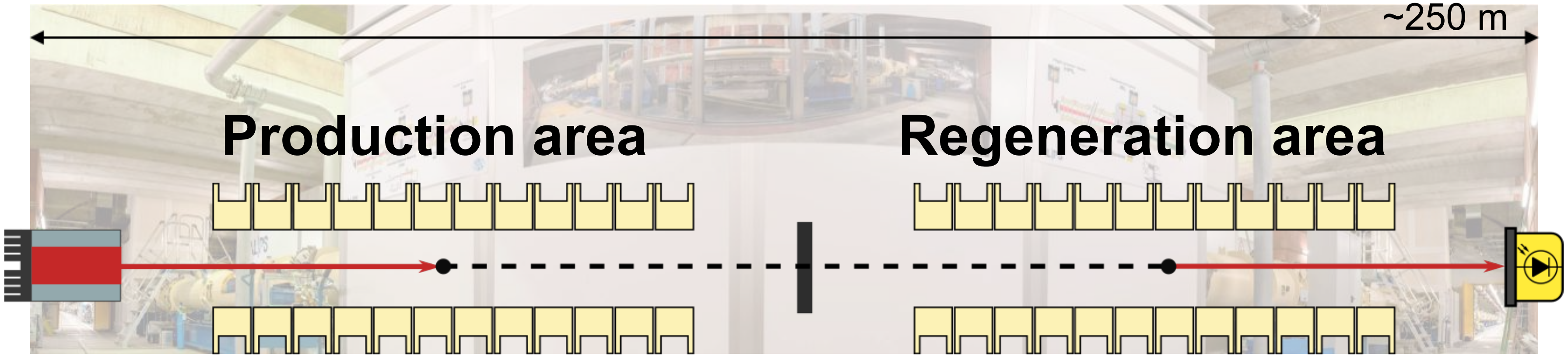
- ALPS II designed to improve sensitivity compared to ALPS I by a factor of ~3000
  - Exploring uncharted territory in parameter space, beyond astrophysical constraints
  - Checking axion explanation of astrophysical anomalies



arXiv:2205.02605

Any Light Particle Search II

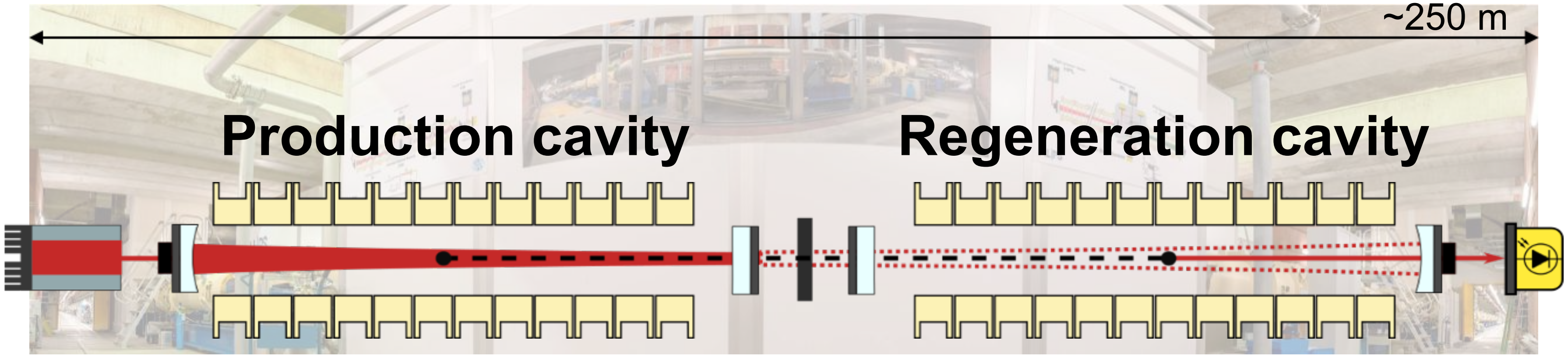
The axion factory



$$n_{\text{signal}} \approx \frac{1\ \text{photon}}{115{,}000\ \text{yr}} \cdot \left(\frac{P_{\text{laser}}}{50\ \text{W}}\right)\left(\frac{g_{a\gamma\gamma}}{2{\times}10^{-11}\ \text{GeV}^{-1}}\right)^4\left(\frac{B}{5.3\ \text{T}}\right)^4\left(\frac{L}{106\ \text{m}}\right)^4$$

Any Light Particle Search II

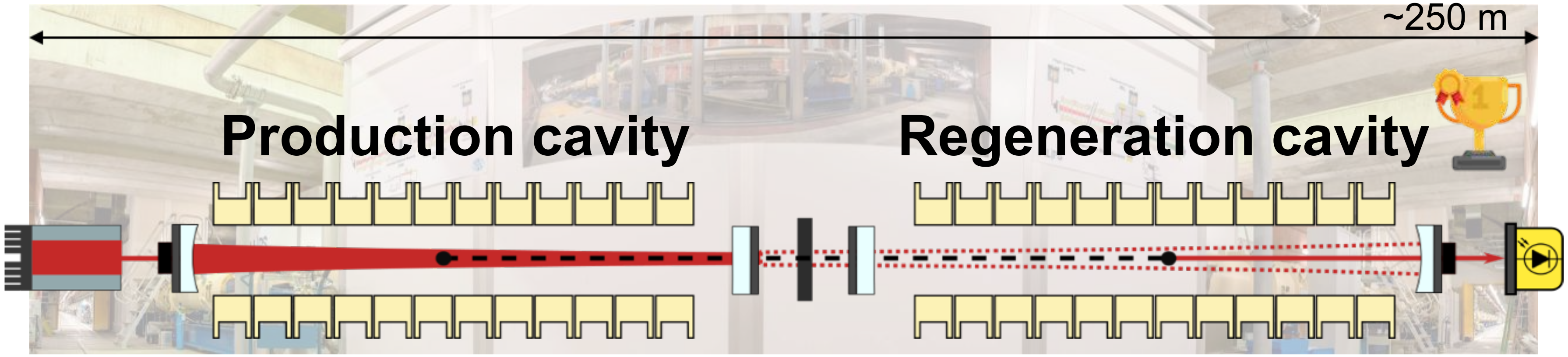
The axion factory



$$n_{\text{signal}} \approx \frac{1\ \text{photon}}{37\ \text{hours}} \cdot \left(\frac{P_{\text{PC}}}{150\ \text{kW}}\right)\left(\frac{\beta_{\text{RC}}}{10{,}000}\right)\left(\frac{\eta}{0.9}\right)\left(\frac{g_{a\gamma\gamma}}{2\times 10^{-11}\ \text{GeV}^{-1}}\right)^4\left(\frac{B}{5.3\ \text{T}}\right)^4\left(\frac{L}{106\ \text{m}}\right)^4$$

Any Light Particle Search II

The axion factory



- HETerodyne interferometer
- Transition Edge Sensor

ALPS II Technology

1. Magnets and Infrastructure

2. Optical Systems

3. Control Systems

4. Ultra-low power Detector

ALPS II technology

Optical system

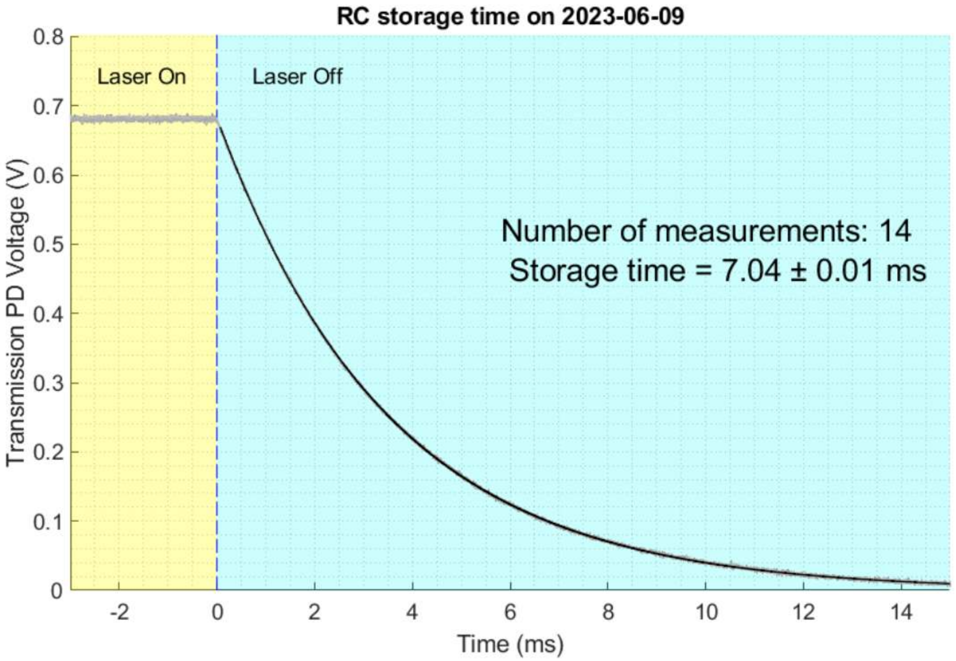
1. Magnets and Infrastructure

2. Optical Systems

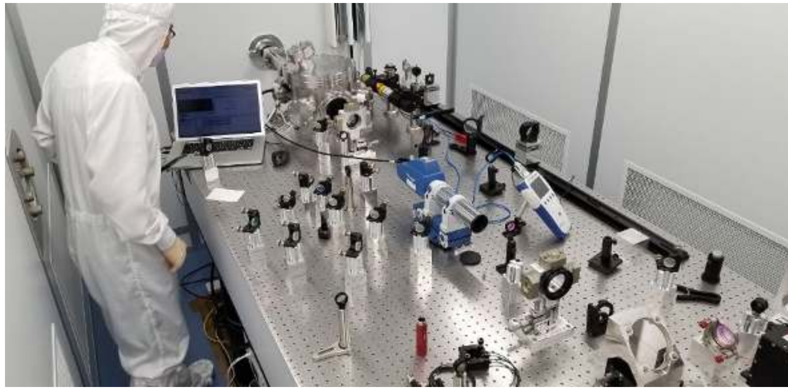
3. Control Systems

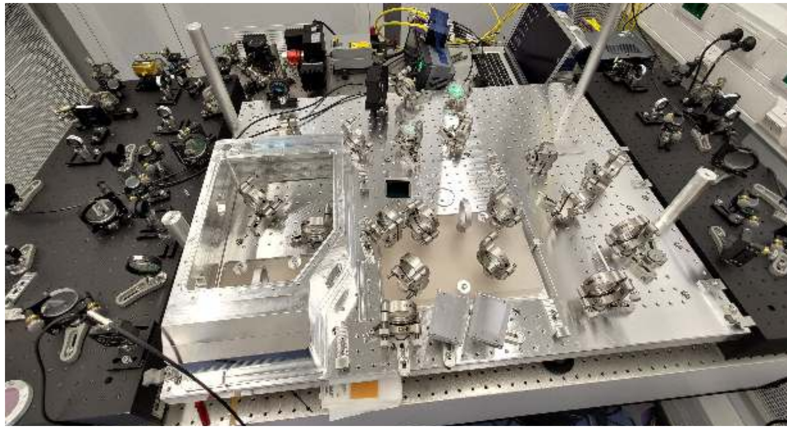
4. Ultra-low power Detector

- Longest storage time Fabry Perot cavity ever!
- Length: 124.6m, FSR: 1.22 MHz
- Storage time: **7.04 ms**


RC storage time on 2023-06-09

Leading precision interferometry!





ALPS II technology

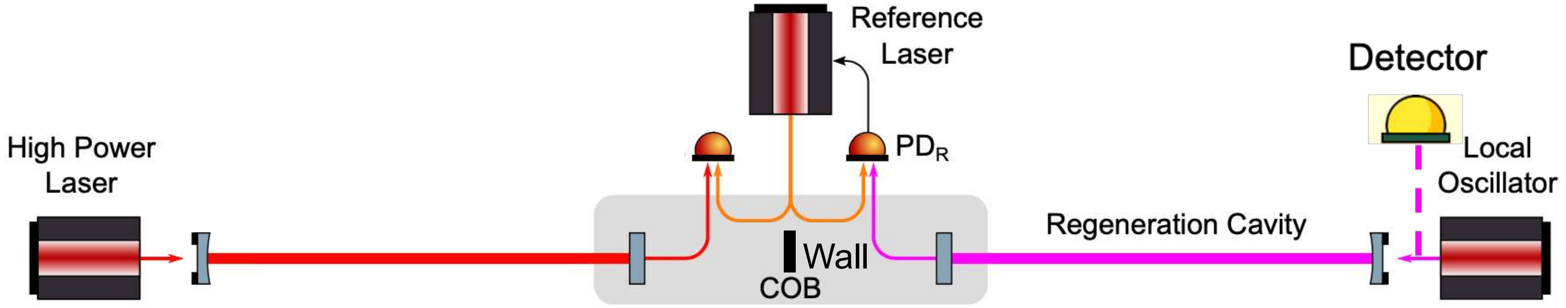
Control system

1. Magnets and Infrastructure

2. Optical Systems

3. Control Systems

4. Ultra-low power Detector



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

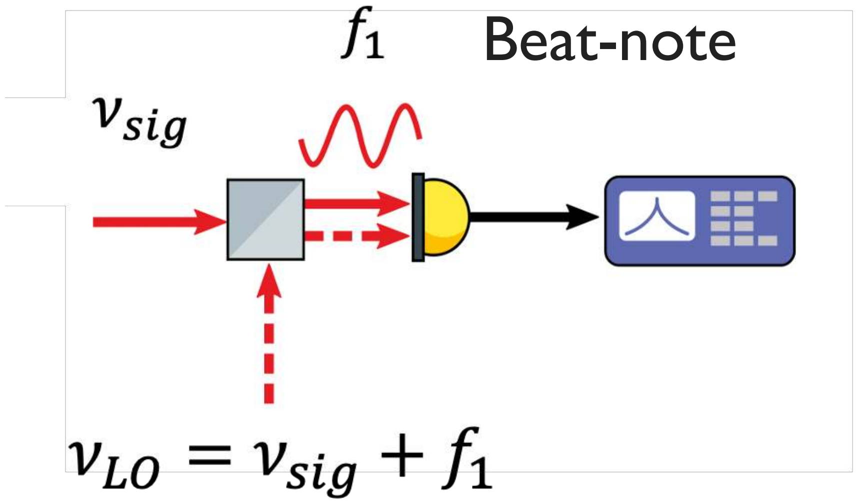
- Amplification of regeneration cavity (RC) only works if the regenerated field is resonant
- Cannot directly interfere HPL and LO fields → too much stray light!
- Use of a reference laser with cascaded phase-locked loops as a “go-between” → HPL and LO never see each other directly

ALPS II technology

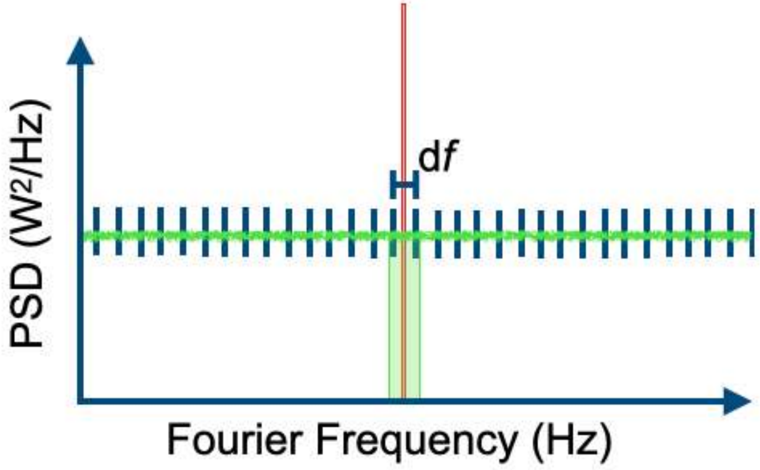
Ultra-low power detector

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

- 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



LO: Local Oscillator



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

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

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

Advantages, costs and difficulties

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

Challenges

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

Ultra-low power detector

Advantages, costs and difficulties

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Challenges

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

Solution

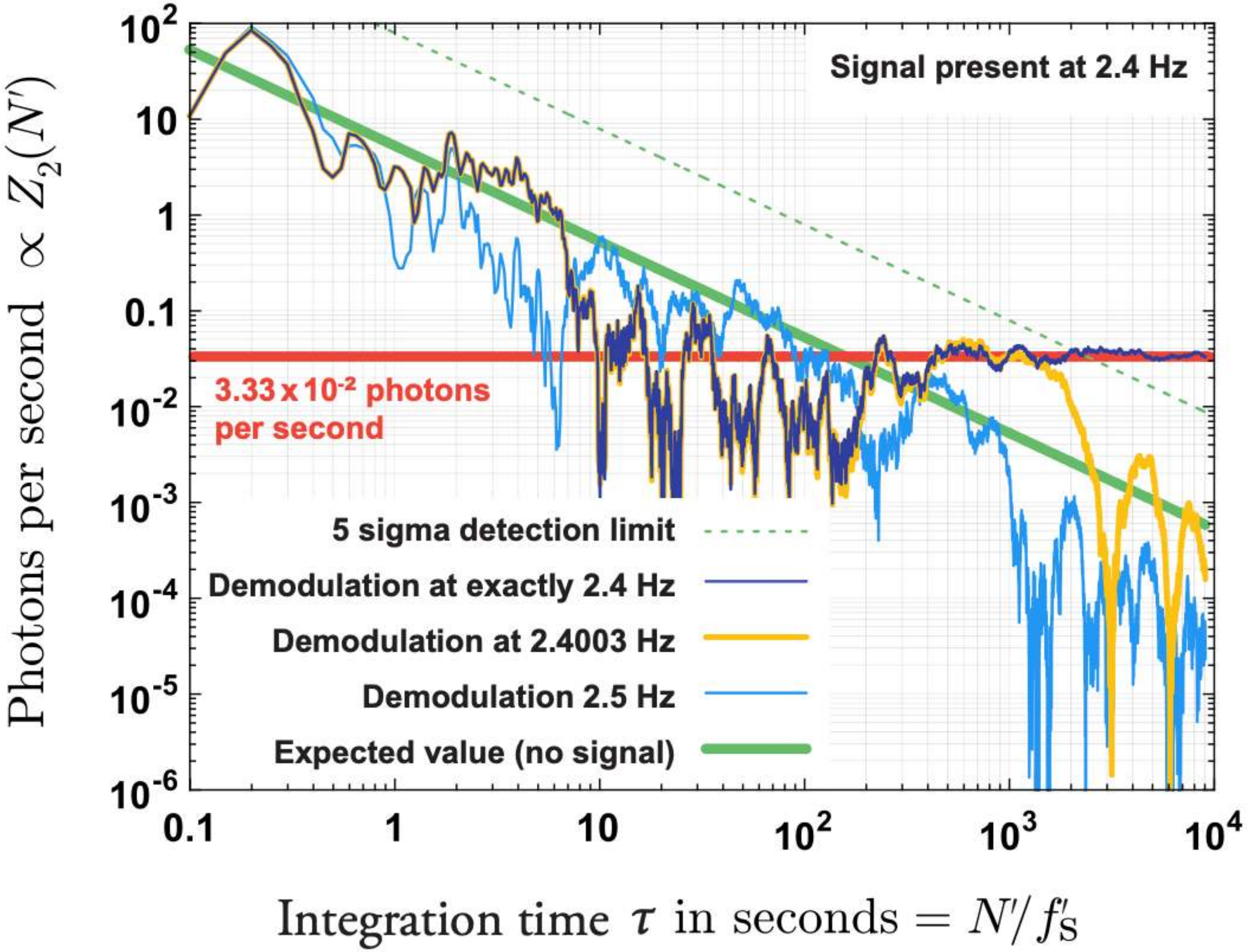
Control system must compensate for

- 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

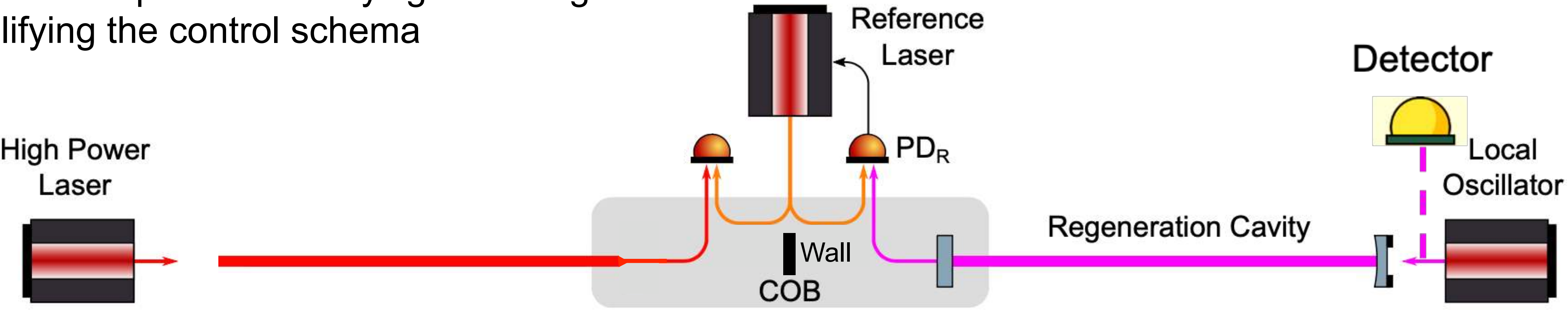
arXiv:1710.04209v4



Optic system

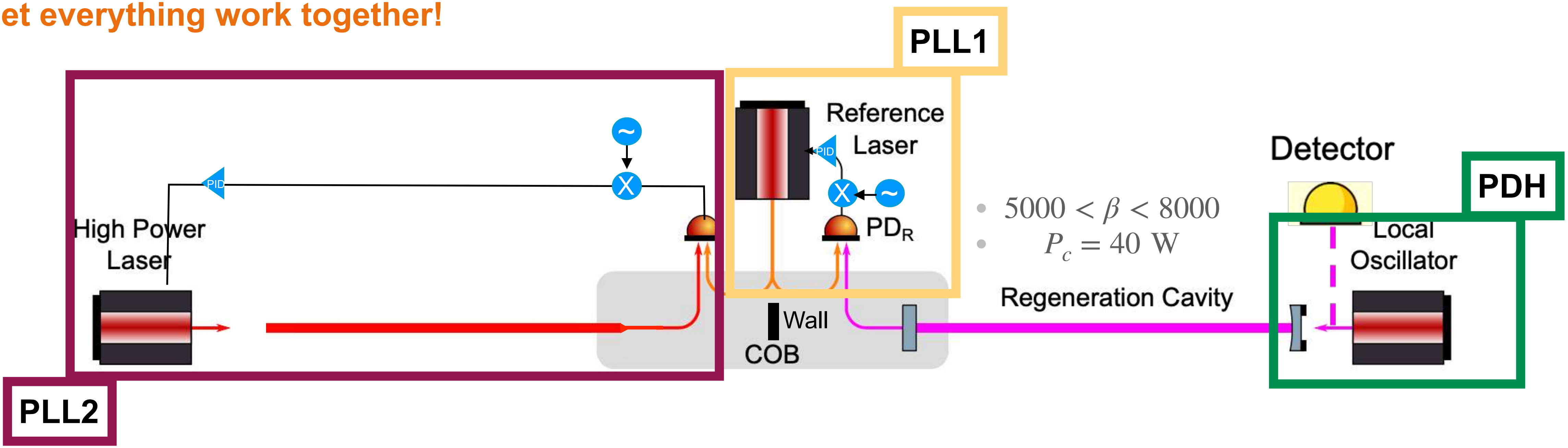
Initial science run

- w/o the PC optimal for stray light hunting and simplifying the control schema

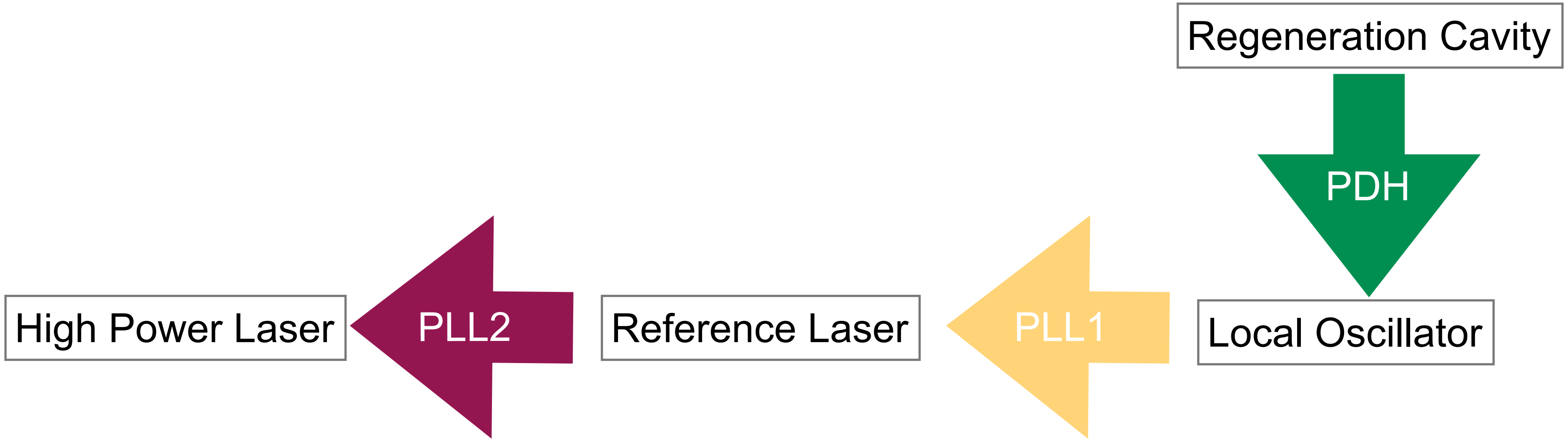


Control system

Let everything work together!



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



ALPS II data taking

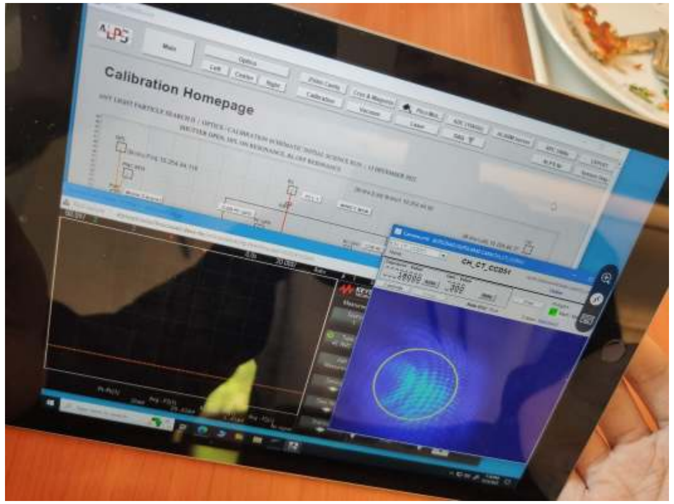
2023 2024 2025

May January April July …

- Engineering run
  - ~150k s integration time

Initial science run

Starting May 2023



ALPS II data taking

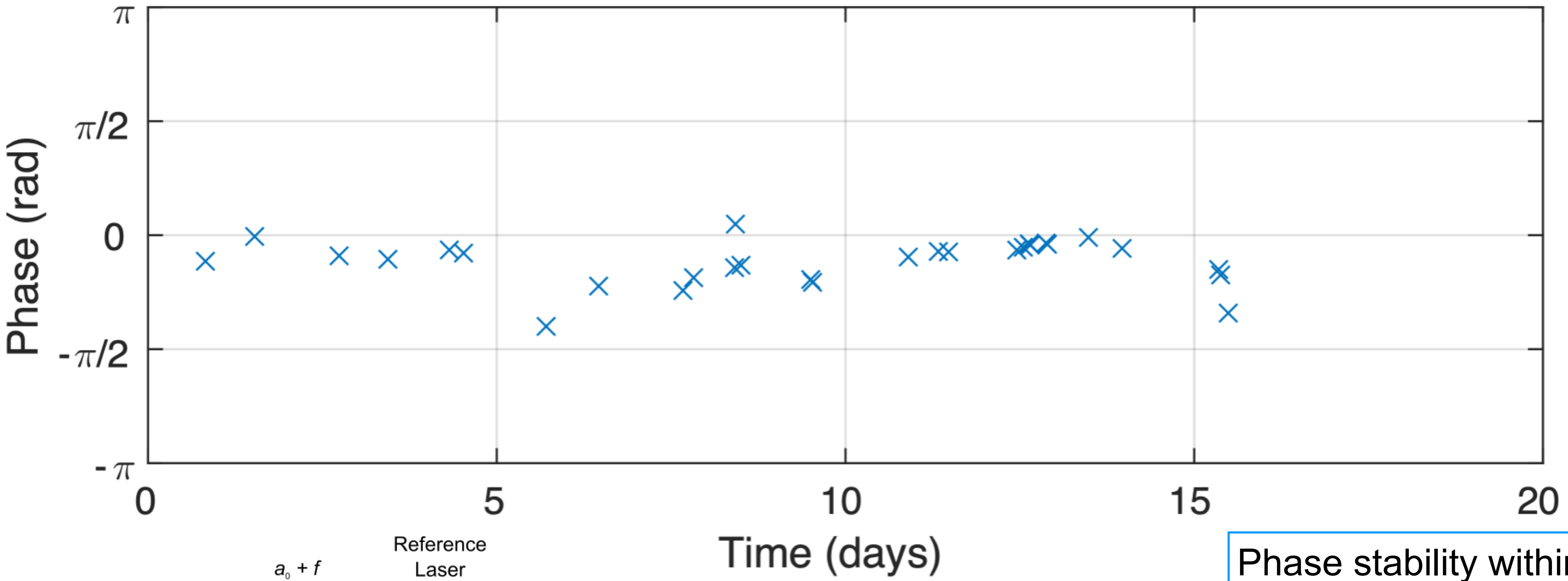
2023 | 2024 | 2025

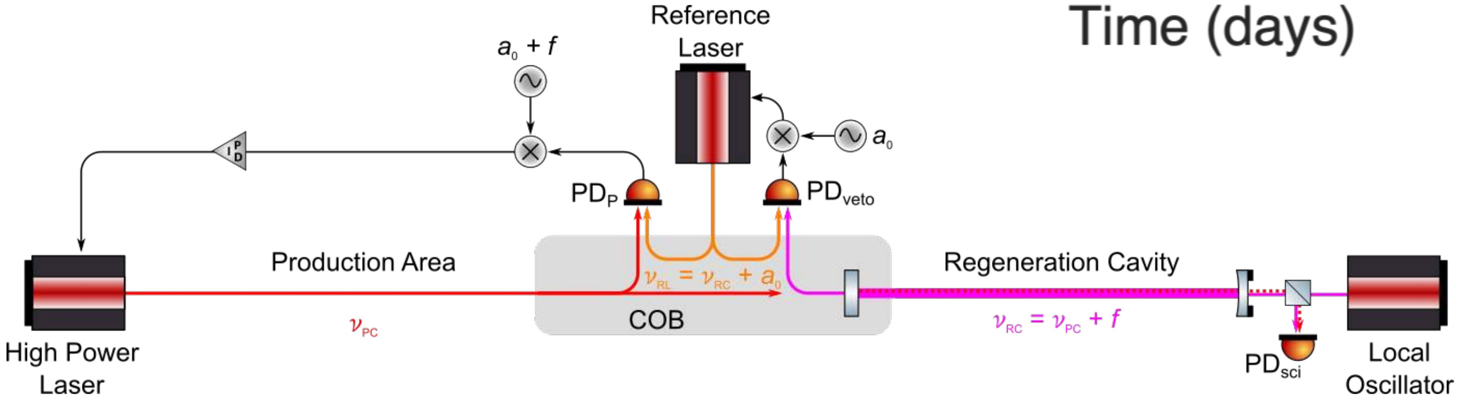
May | January | April | July | …

- Engineering run
  - ~150k s integration time
- Fix problems and improve stability
- Scalar search
  - ~800k s integration time

Open Shutter Runs

Phase stability





Phase stability within 0.33 rad over 16 days

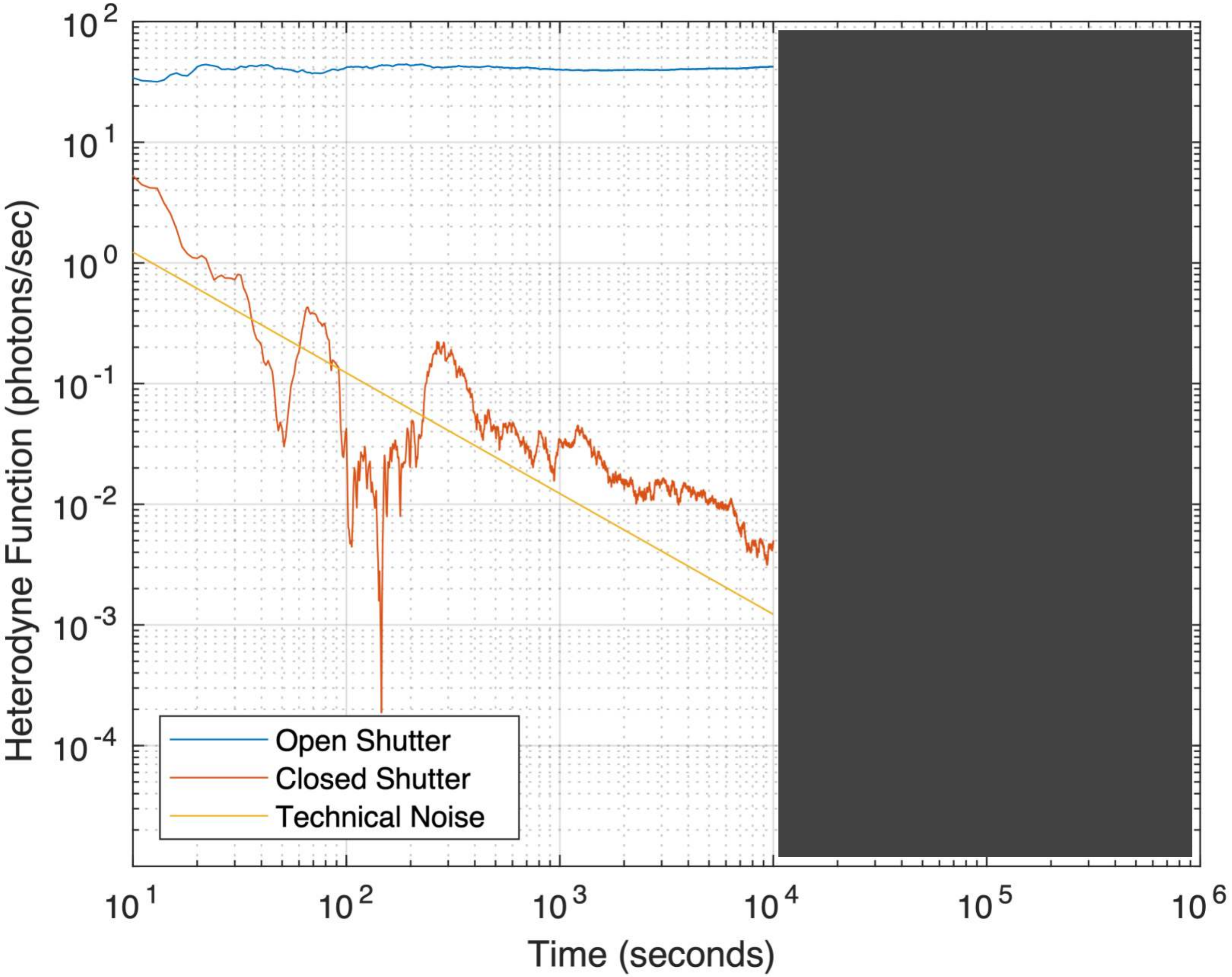
- <10% signal loss

Preliminary results

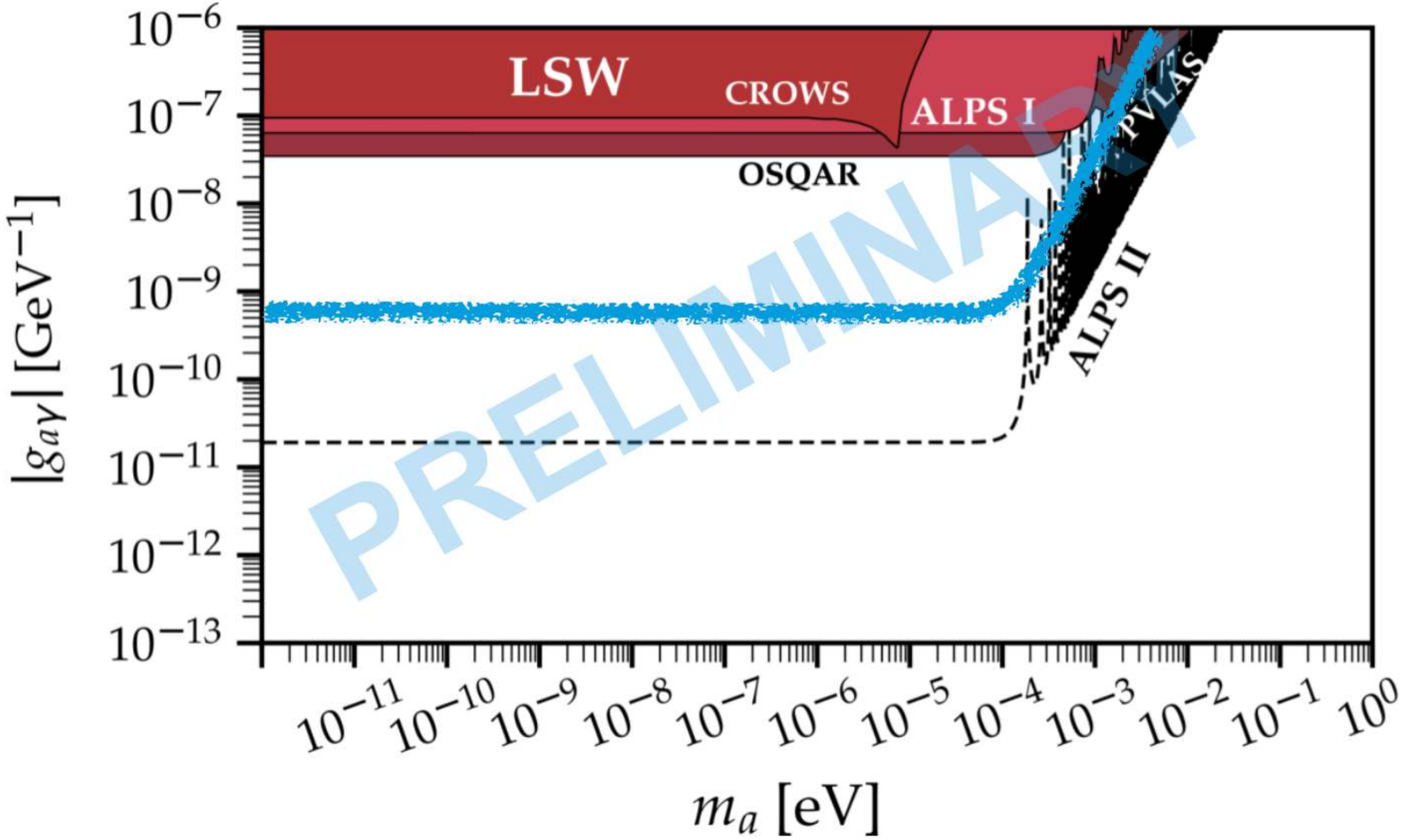
HET function

Successfully acquired data for the scalar search

- System showed very good performance
  - ~ 10 days of high-quality data
- Open shutter periods:
  - Reliable reconstruction of phase evolution
  - Monitor for some calibration parameters



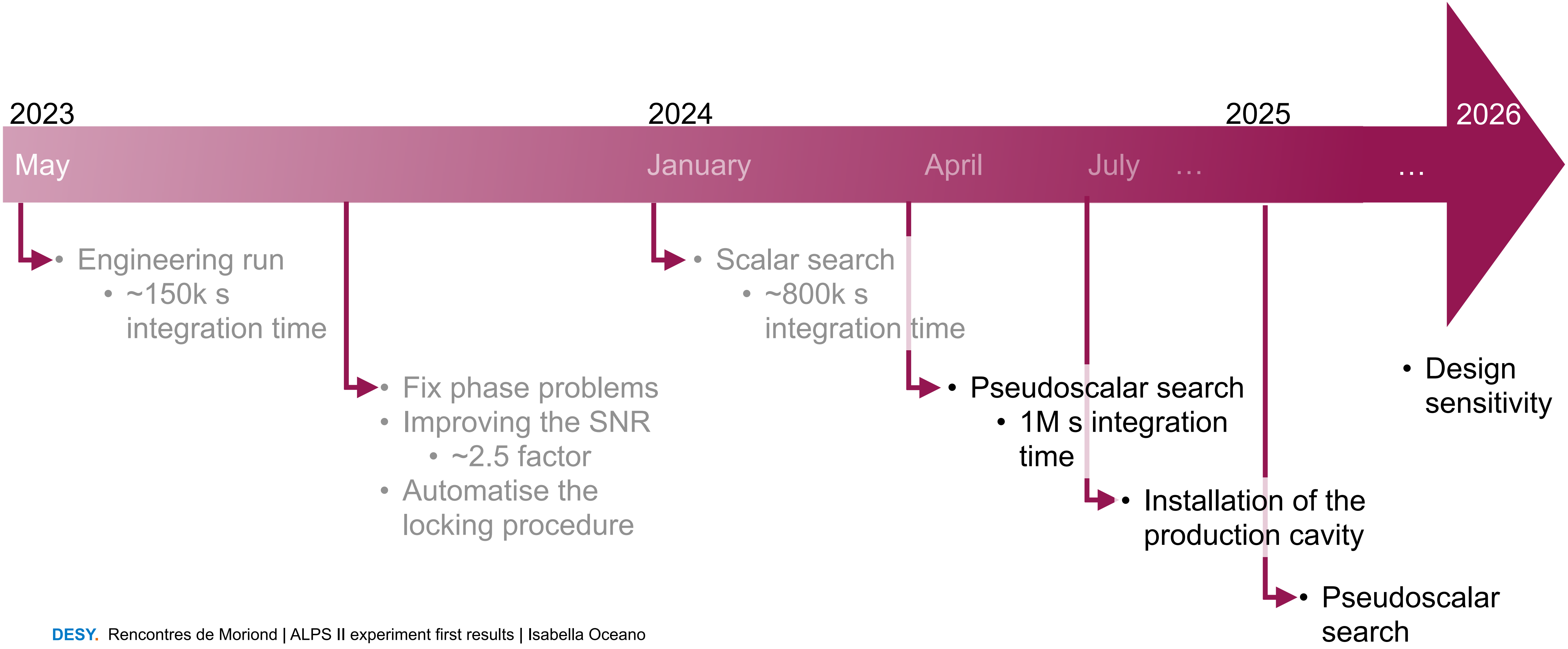
Preliminary sensitivity estimate



Scalar search

ALPS II data taking

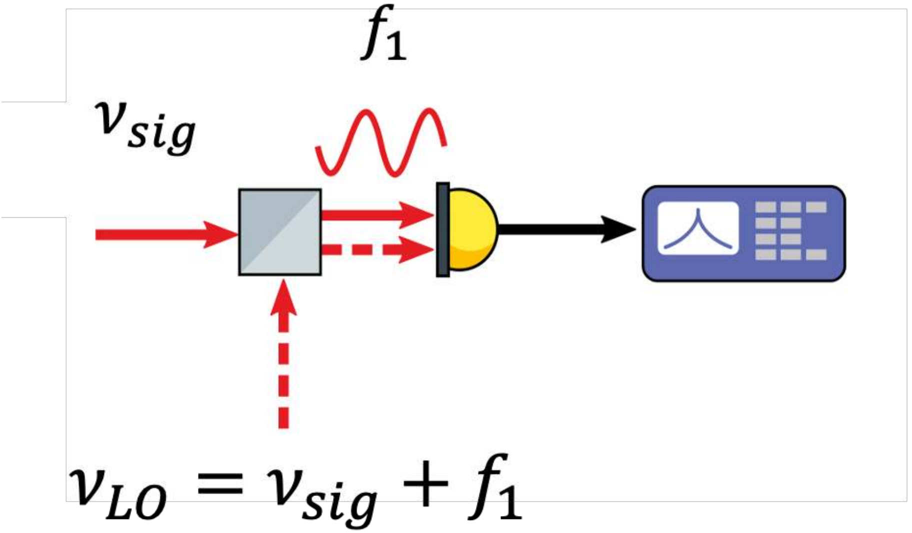
Next steps



- Engineering run
  - ~150k s integration time
- Fix phase problems
- Improving the SNR
  - ~2.5 factor
- Automatise the locking procedure
- Scalar search
  - ~800k s integration time
- Pseudoscalar search
  - 1M s integration time
- Installation of the production cavity
- Pseudoscalar search
- Design sensitivity

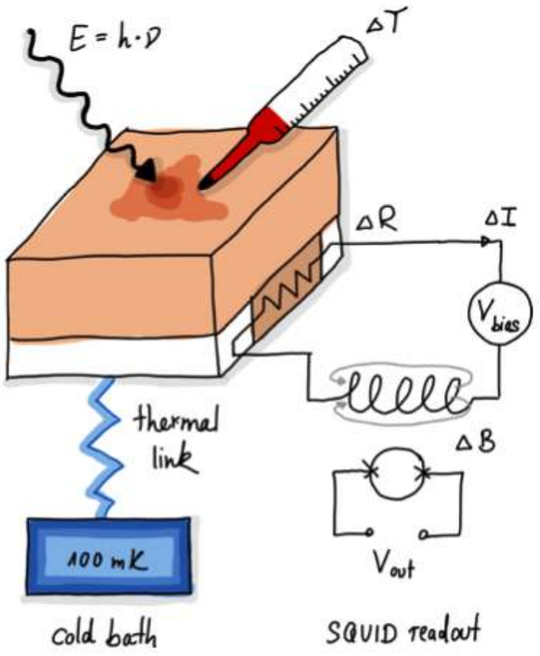
Regenerated photon detection

Exploiting two different techniques



HET

TES

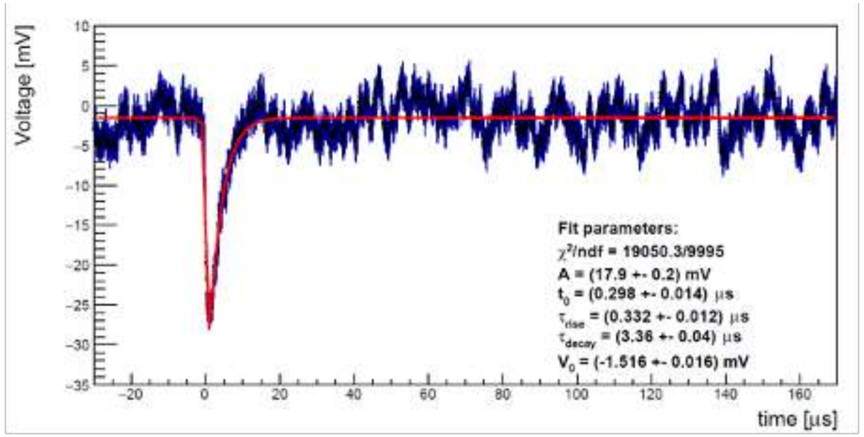


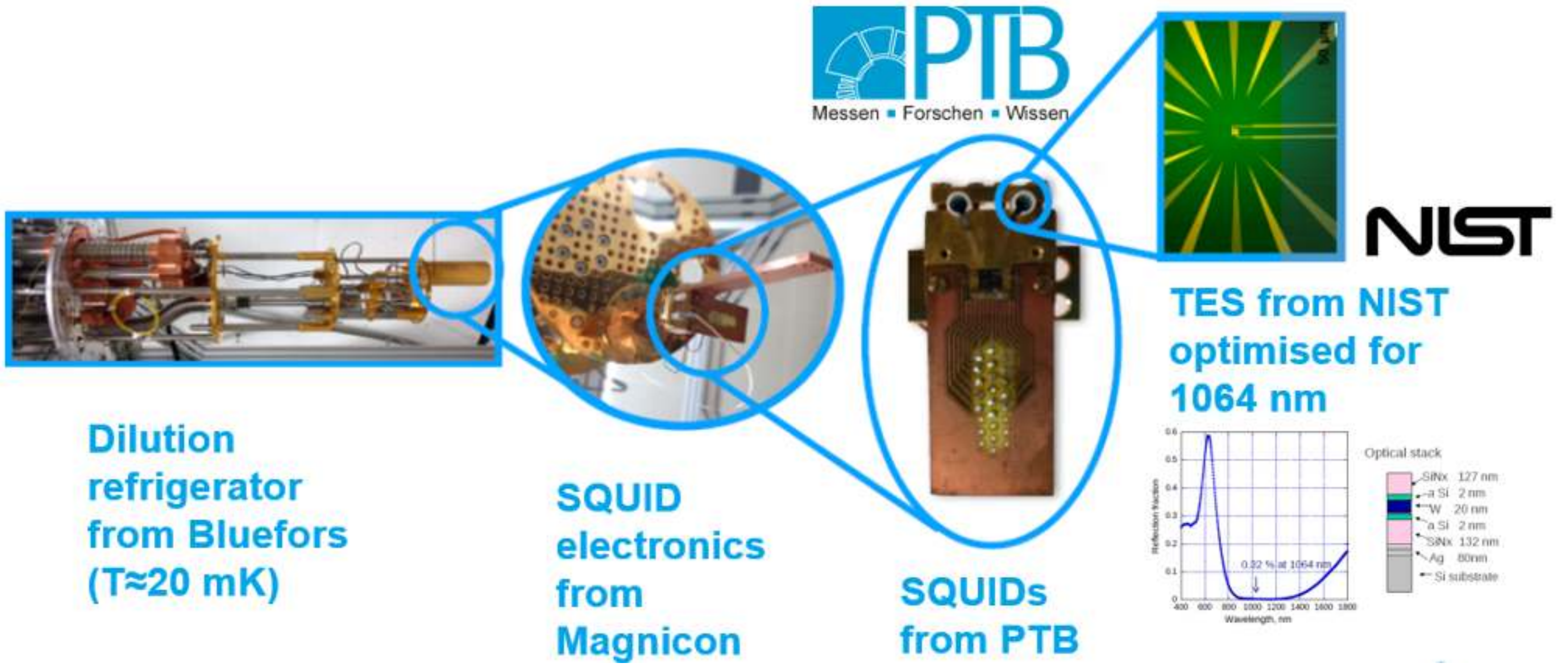
Photon Counting with a Cryogenic Transition Edge Sensor

Photon counting @ 1064 nm with low dark counts and high efficiency

Using a superconducting Transition Edge Sensor (TES) operated at about 50 mK

- Qualified TES for ALPS II
  - Low **intrinsic dark counts** $(6.9^{+5.18}_{-2.93} \times 10^{-6}$ Hz, 95% CL) shown
  - High efficiency of TES system reached
    - η = 0.931 ± 0.015
  - Energy resolution below 10%





Dilution refrigerator from Bluefors (T≈20 mK)

SQUID electronics from Magnicon

SQUIDs from PTB

TES from NIST optimised for 1064 nm

Conclusion

Successful start of ALPS II

- LSW: Searching for axion and axion-like particles in a model-independent way

- During the initial run, we learned a lot and reached stable operation

- The scalar search data improves the sensitivity by a factor of 30 to previous LSW experiments

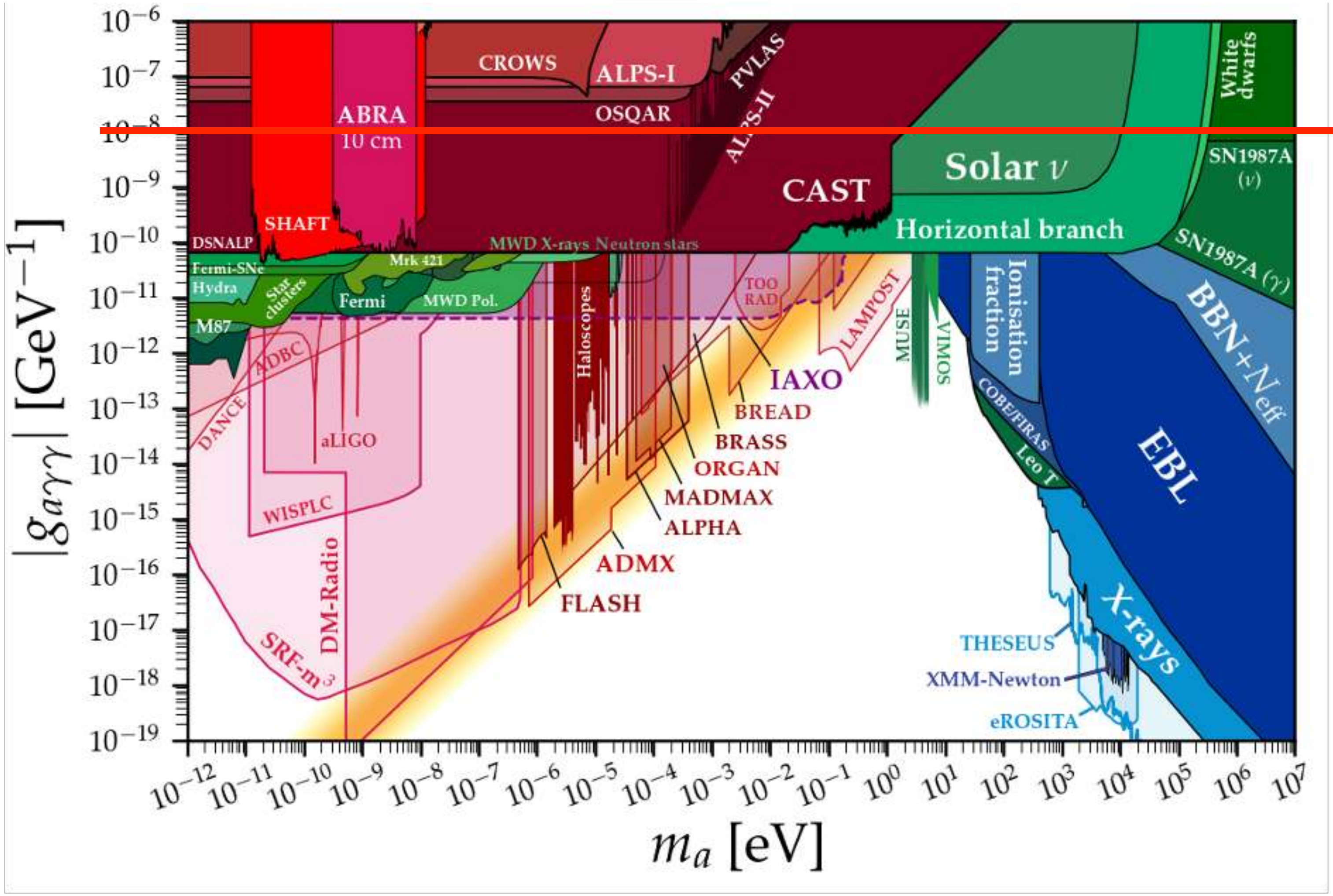
- A new data taking is ongoing for the pseudoscalar axion search

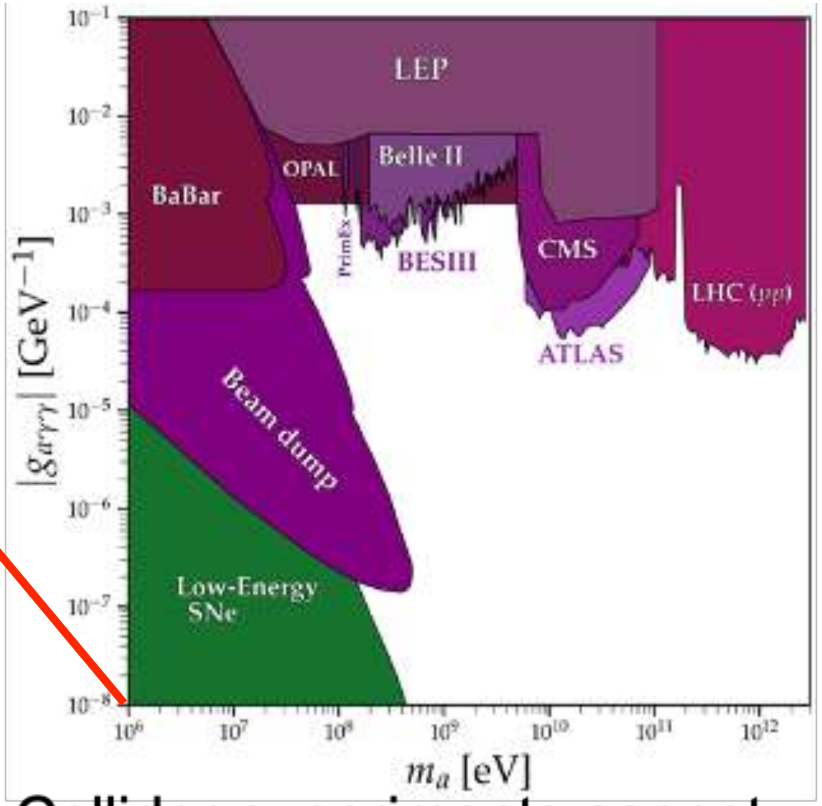
- The full setup installation of ALPS II will begin in the summer of 2024, design sensitivity will be reached in 2026

Backup

Axions: non-collider and colliders

Axion-photon coupling vs axion mass

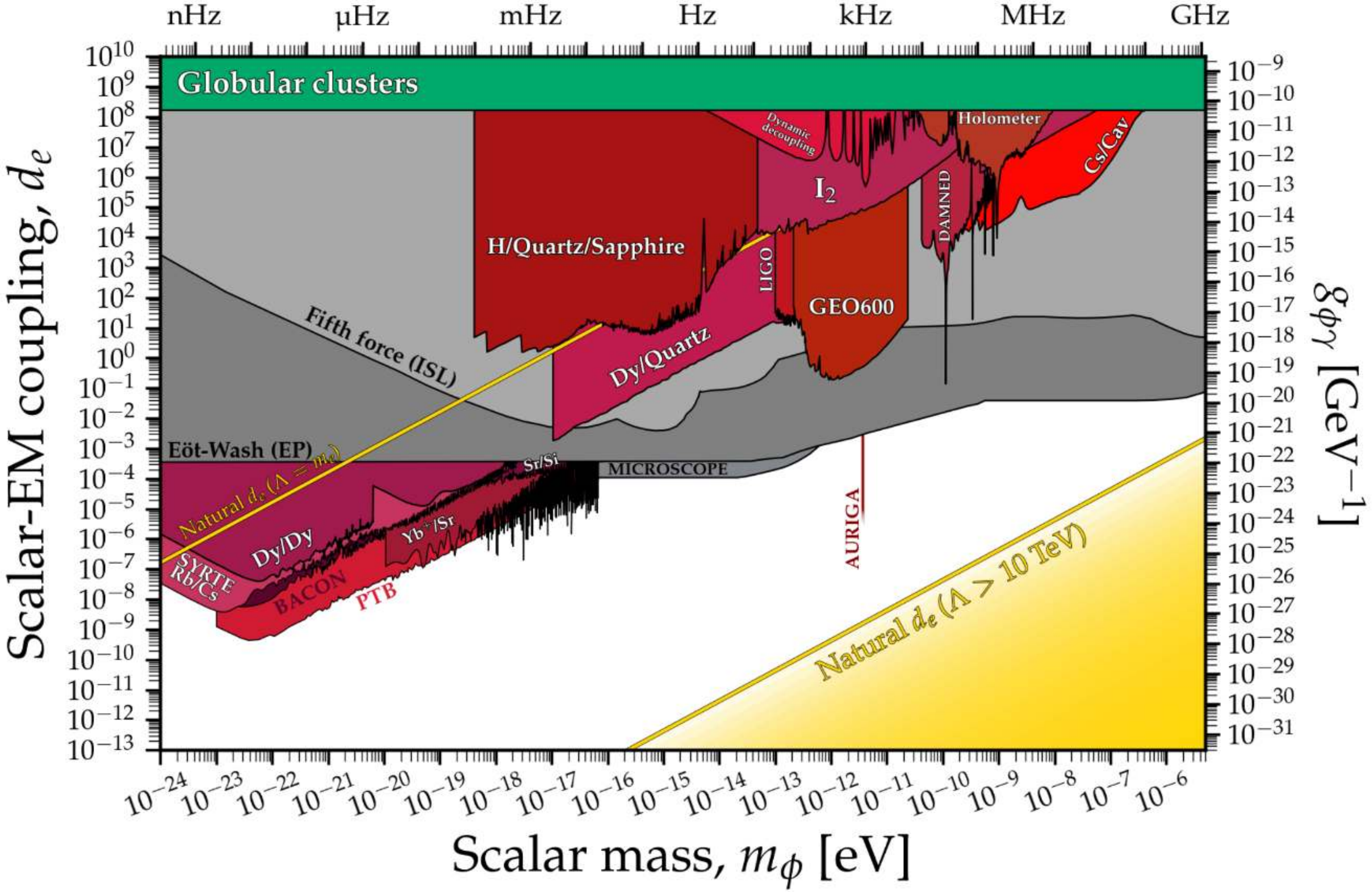




Collider experiments cannot probe directly for axions / ALPs motivated by astrophysics and cosmology.

Axions: non-collider and colliders - scalar case

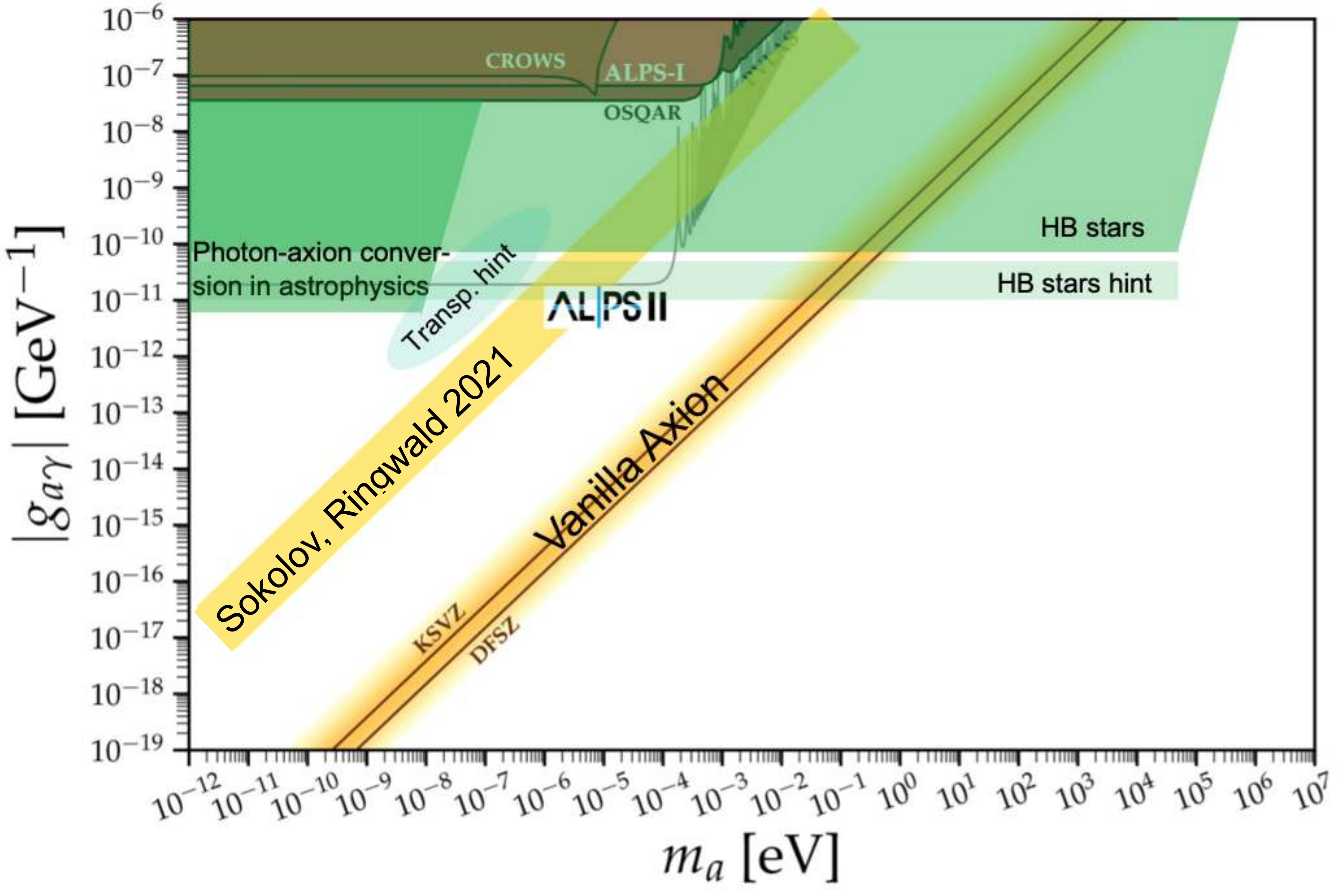
Axion-photon coupling vs axion mass



ALPS II

Strengths

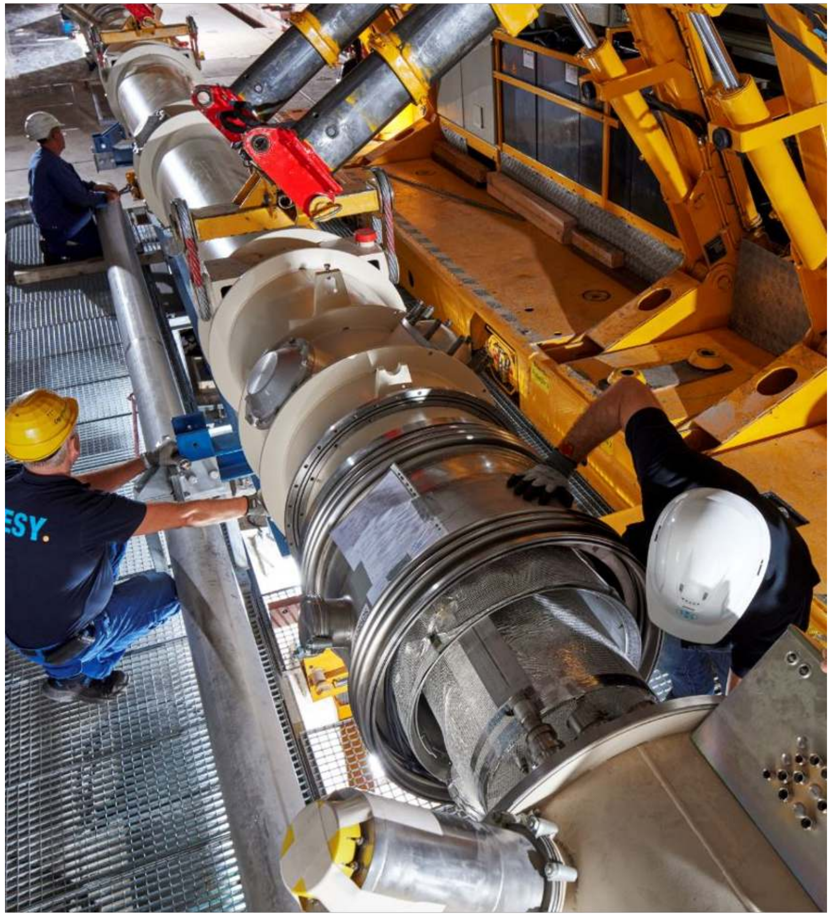
- ALPS II designed to improve sensitivity compared to ALPS I by a factor of ~3000
  - Exploring uncharted territory in parameter space, beyond astrophysical constraints
  - Checking axion explanation of astrophysical anomalies



- 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

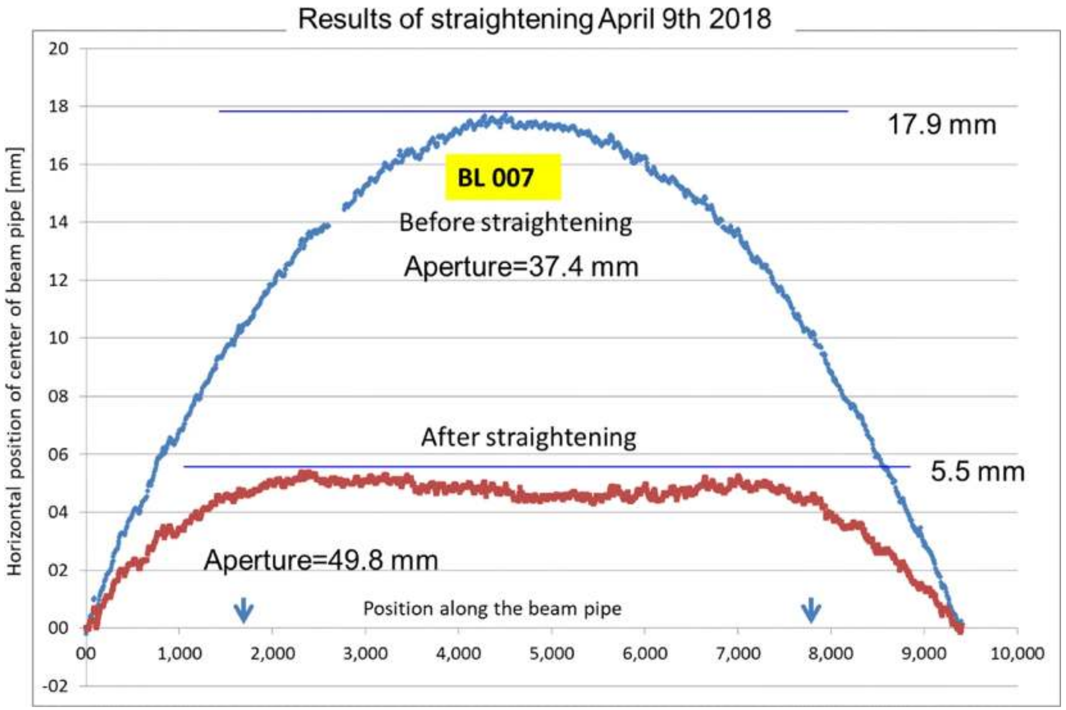
Magnets

The axion makers



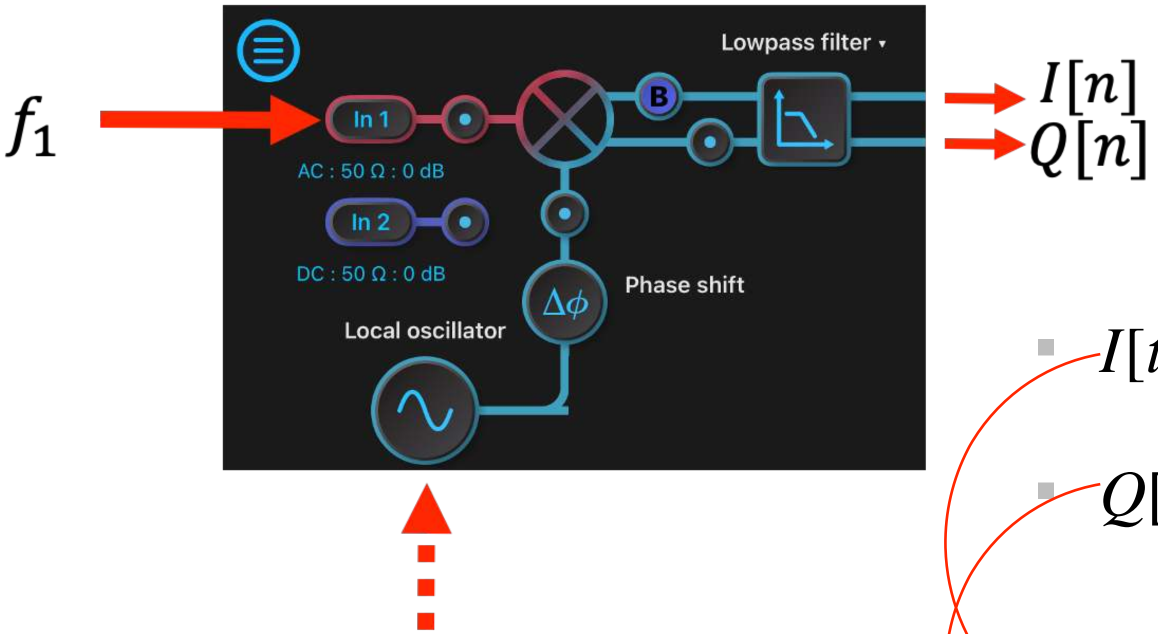
Albrecht, C., Barbanotti, S., Hintz, H. *et al.* Straightening of superconducting HERA dipoles for the any-light-particle-search experiment ALPS II. *EPJ Techn Instrum* 8, 5 (2021).

- 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



Signal extraction

In-phase and quadrature demodulation



$$f_{demod} = f_1 + f_0'$$

To recover amplitude information → **I/Q demodulation**

- $I[t] = 2G\sqrt{P_{sig}P_{LO}}cos(2\pi f_1 t + \Delta\phi) \times cos(2\pi f_{demod} t)$
- $Q[t] = 2G\sqrt{P_{sig}P_{LO}}cos(2\pi f_1 t + \Delta\phi) \times sin(2\pi f_{demod} t)$

$$\longrightarrow G\sqrt{P_{sig}P_{LO}}cos(2\pi f_0' t + \Delta\phi)$$

$$\longrightarrow G\sqrt{P_{sig}P_{LO}}sin(2\pi f_0' t + \Delta\phi)$$

If noise:

→ 0

→ 0

Sampling rate

- Nyquist frequency
  - $f_s > 2 \times f_0'$

Photon flux extraction

From I[n] and Q[n]

$$z[N] = \frac{(\sum_i^N I[n])^2 + (\sum_i^N Q[n])^2}{N^2}$$

Number of photons

$$N_\gamma/\mathrm{s} = \frac{\mathrm{z[N]}}{\mathrm{G^2 P_{LO} h}\nu}$$

Photon flux extraction

From I[n] and Q[n]

$$z[N] = \frac{(\sum_i^N I[n])^2 + (\sum_i^N Q[n])^2}{N^2}$$

Number of photons

$$N_\gamma/\mathrm{s} = \frac{\mathrm{z[N]}}{\mathrm{G^2 P_{LO} h}\nu}$$

If signal:

$$z[t] = \frac{(\sum_i^N G\sqrt{P_{sig}P_{LO}}cos(2\pi f_0' t + \Delta\phi))^2 + (\sum_i^N G\sqrt{P_{sig}P_{LO}}sin(2\pi f_0' t + \Delta\phi))^2}{N^2}$$

$$z \propto G^2 P_{sig} P_{LO}$$

If noise:

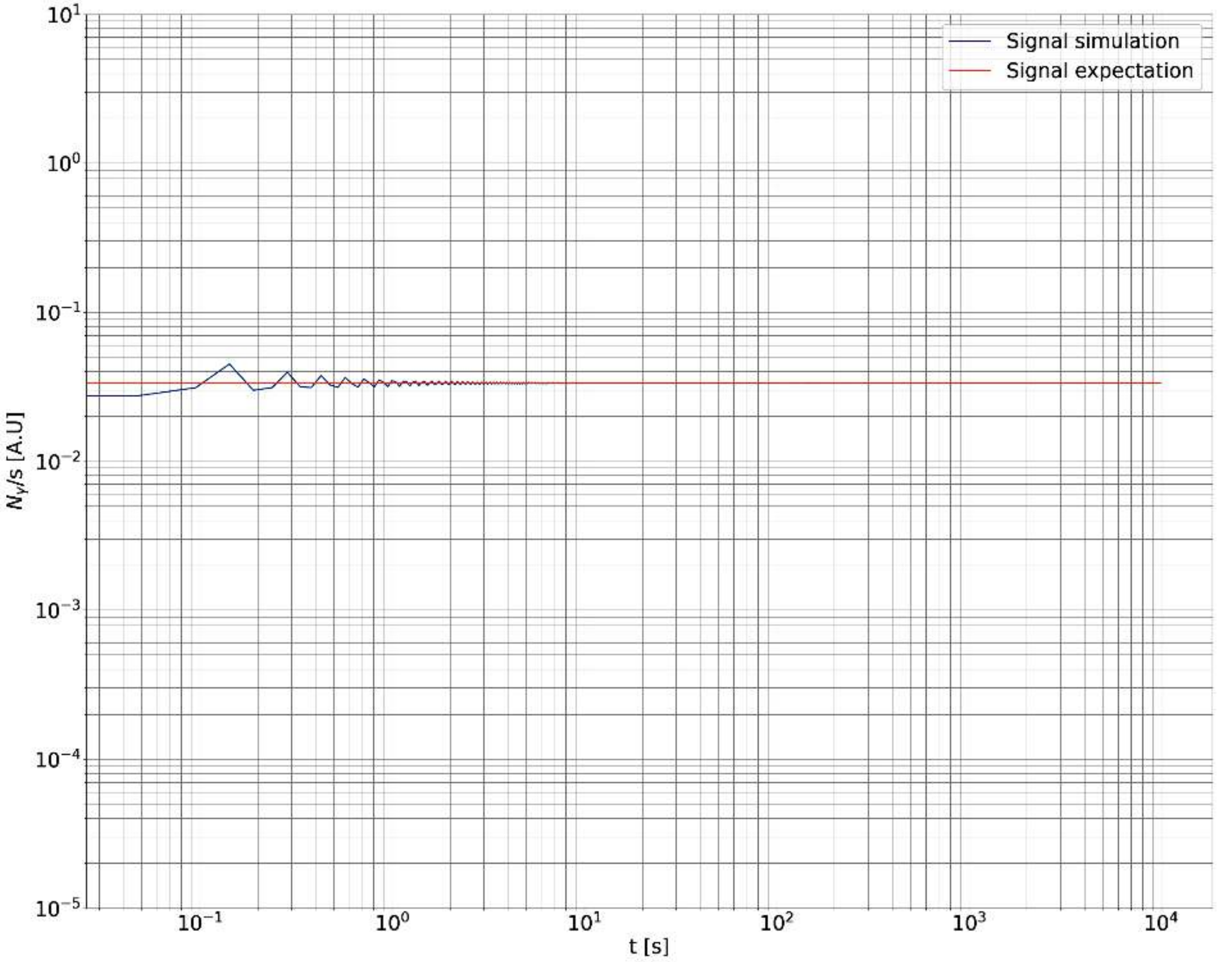
$$z \simeq 0$$

Photon flux extraction

Signal

Number of photons

$$N_\gamma/\mathrm{s} = \frac{\mathrm{z[N]}}{\mathrm{G^2 P_{LO} h}\nu}$$



No physical case

Signal

Will sum coherently

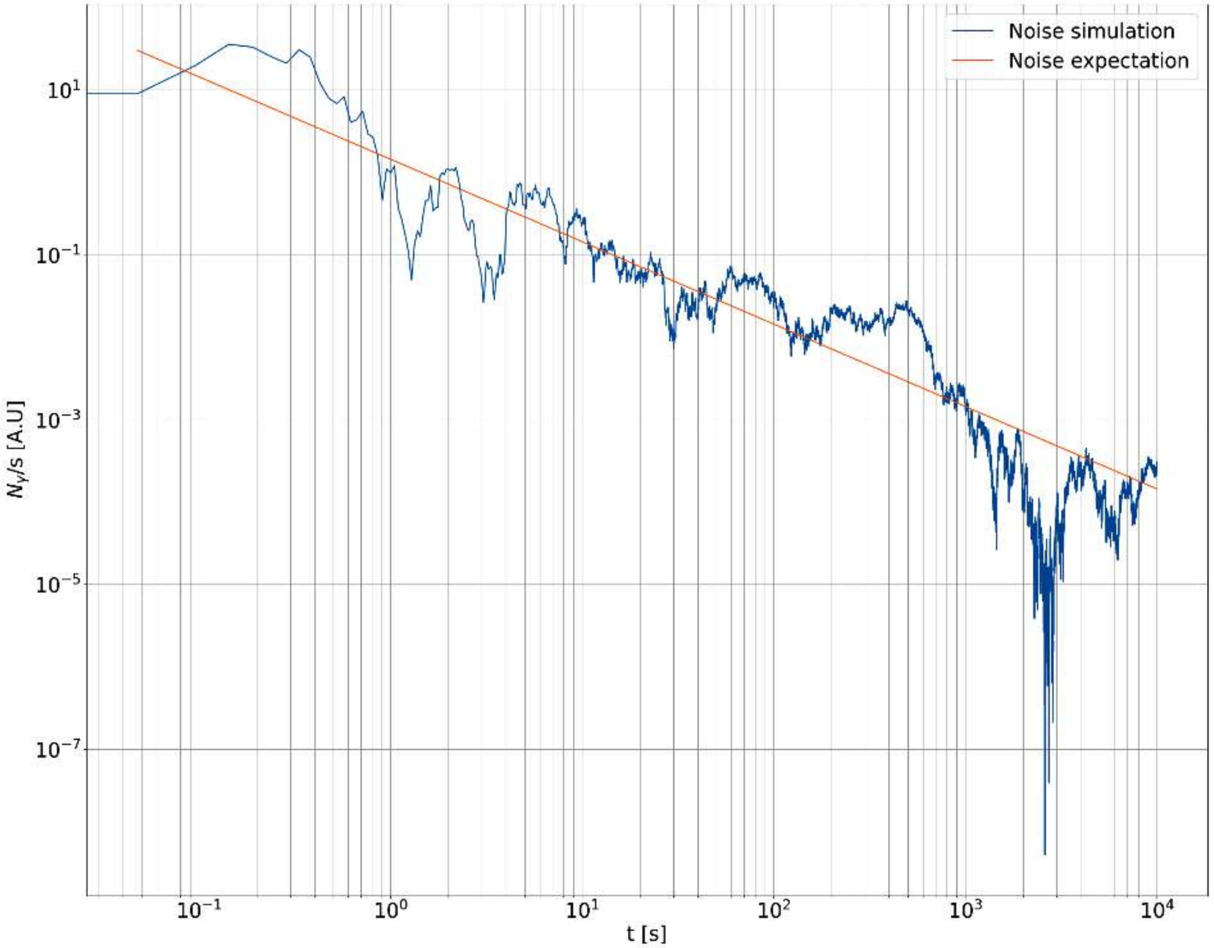
- $N_\gamma \propto P_{sig}$

Photon flux extraction

Noise

Number of photons

$$N_\gamma/\mathrm{s} = \frac{\mathrm{z[N]}}{\mathrm{G^2P_{LO}h}\nu}$$



Technical noises for HET mitigated by increasing the LO power

Shot- Noise

Will sum incoherently

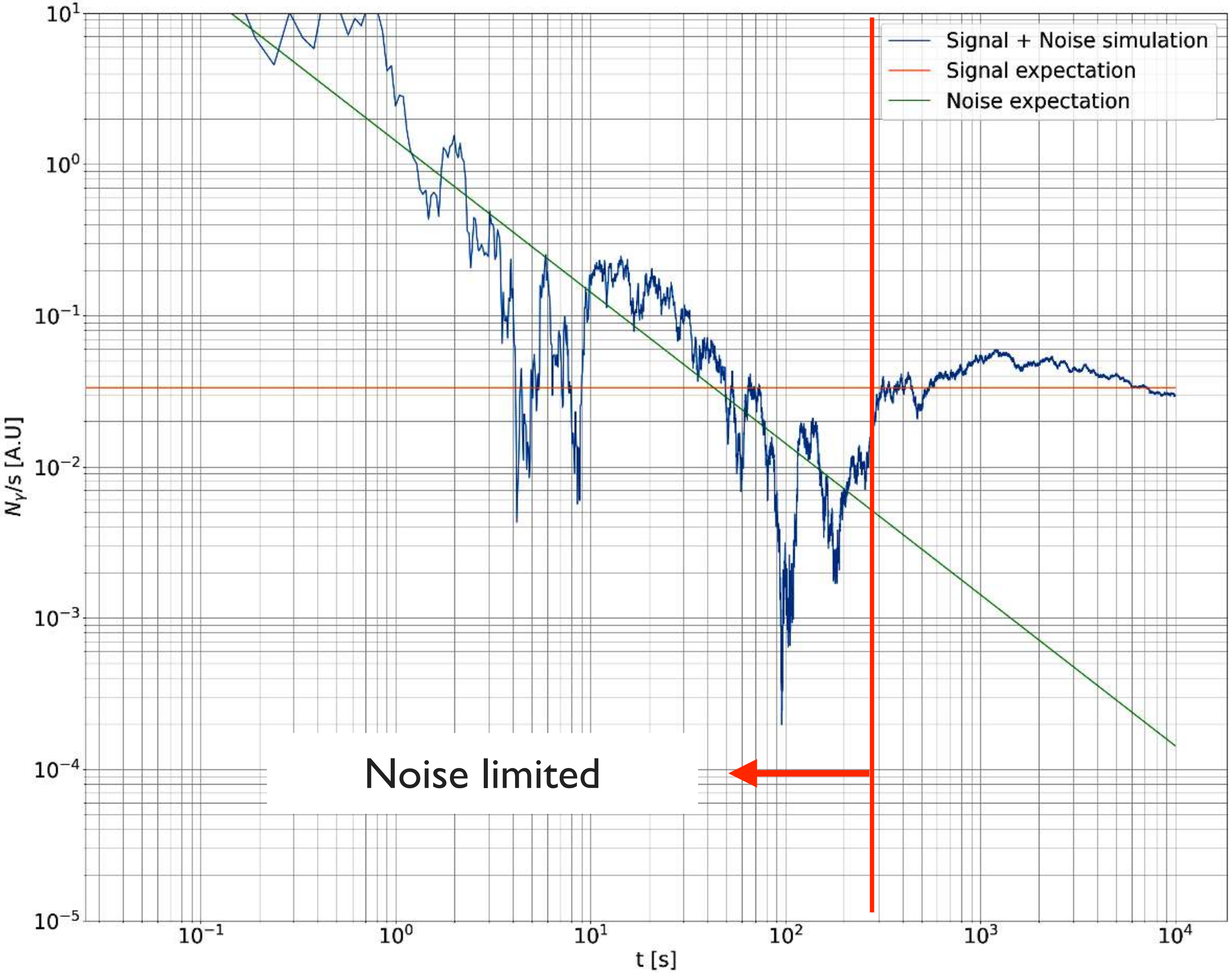
- $N_\gamma^{SN} = \dfrac{1}{\eta t}$

Photon flux extraction

Signal + Noise

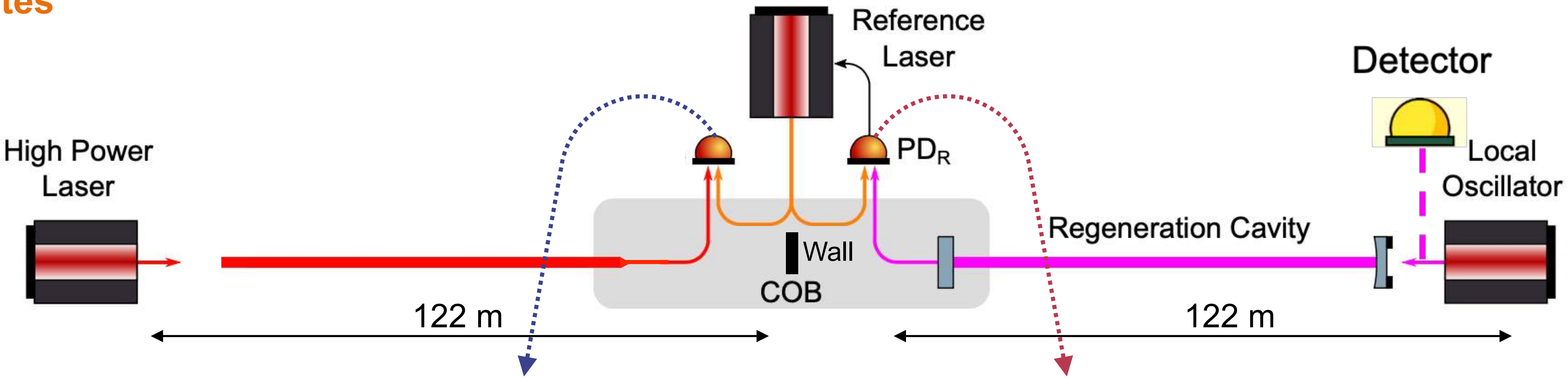
Number of photons

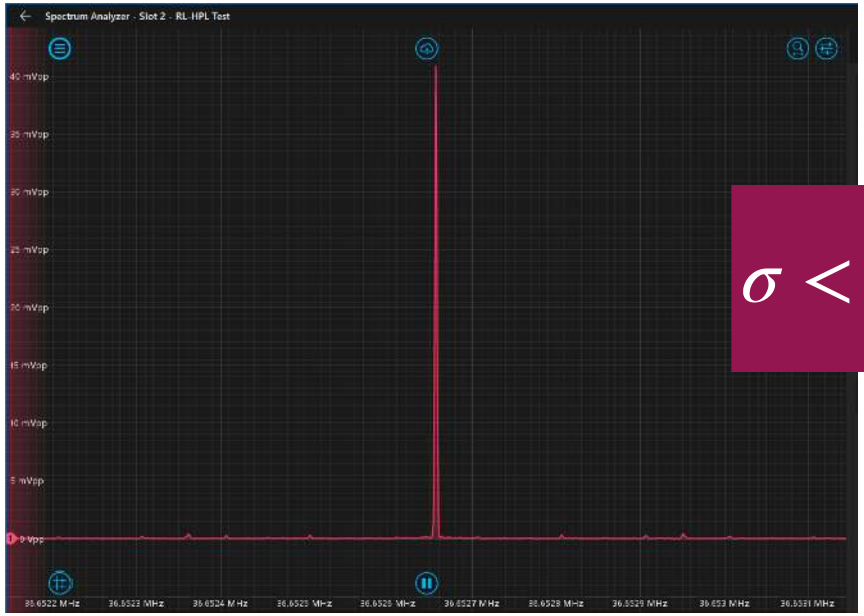
$$N_\gamma/\mathrm{s} = \frac{\mathrm{z[N]}}{\mathrm{G^2 P_{LO} h\nu}}$$



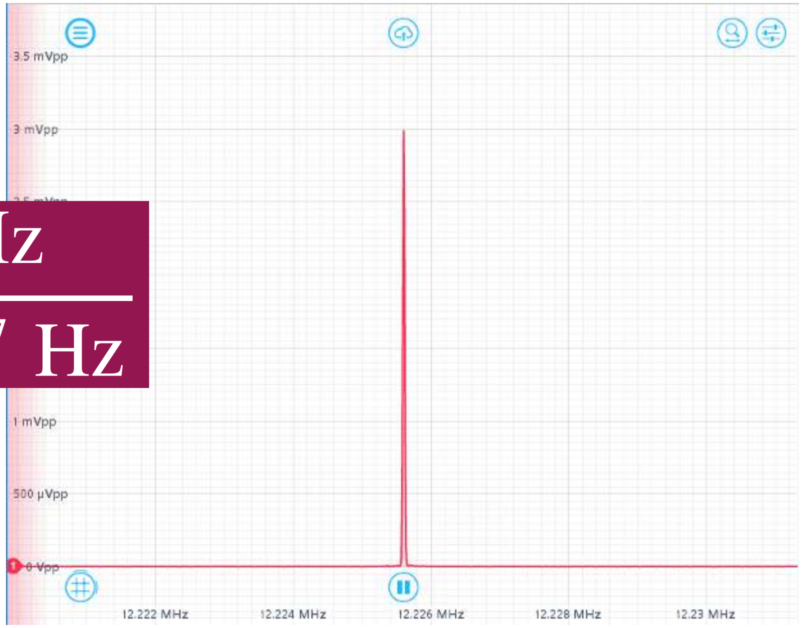
ALPS II’s initial science run scheme

Beat notes



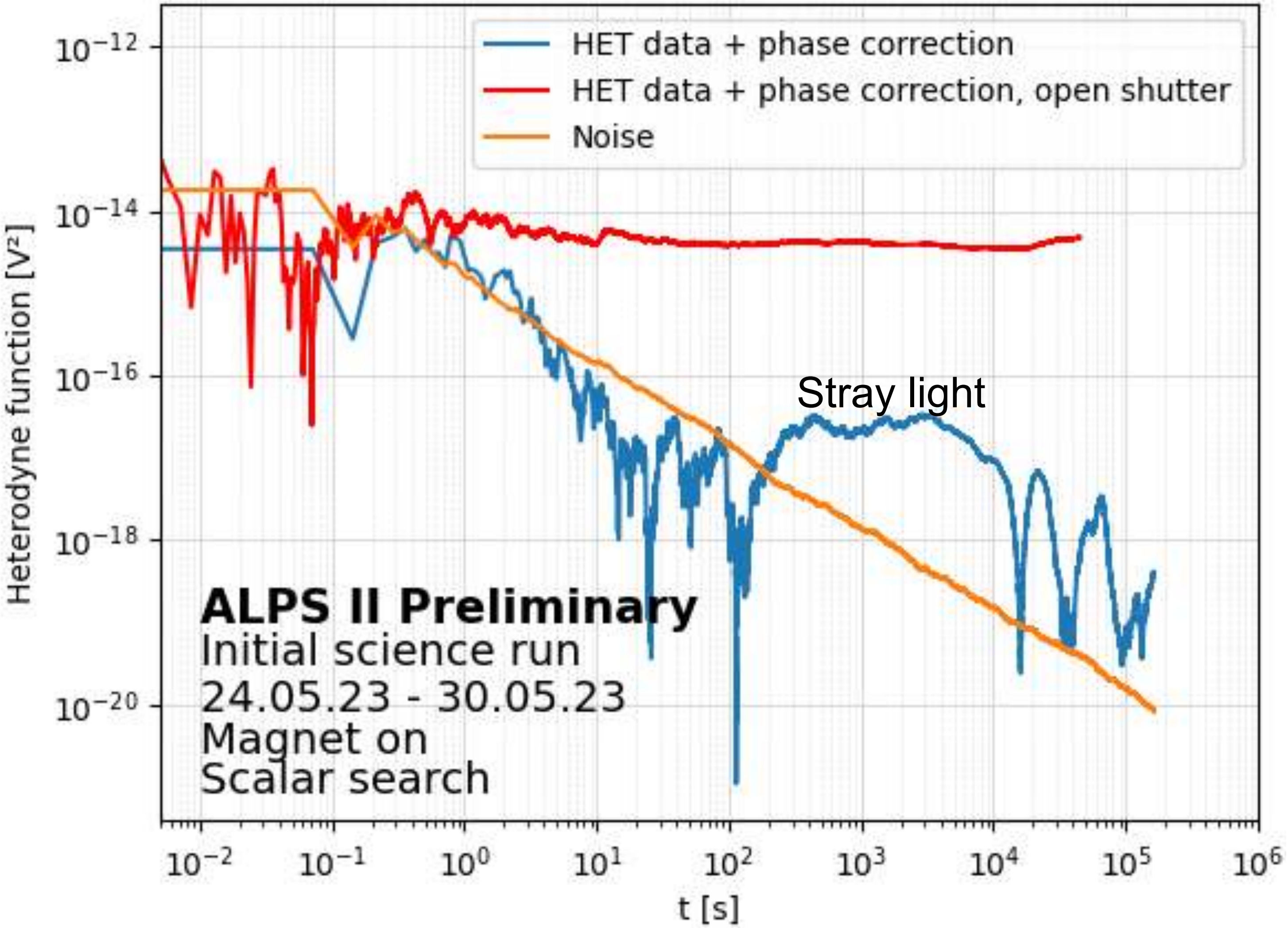


$$\sigma < \frac{\mu\ \mathrm{Hz}}{\sim 10^7\ \mathrm{Hz}}$$



Engineering run

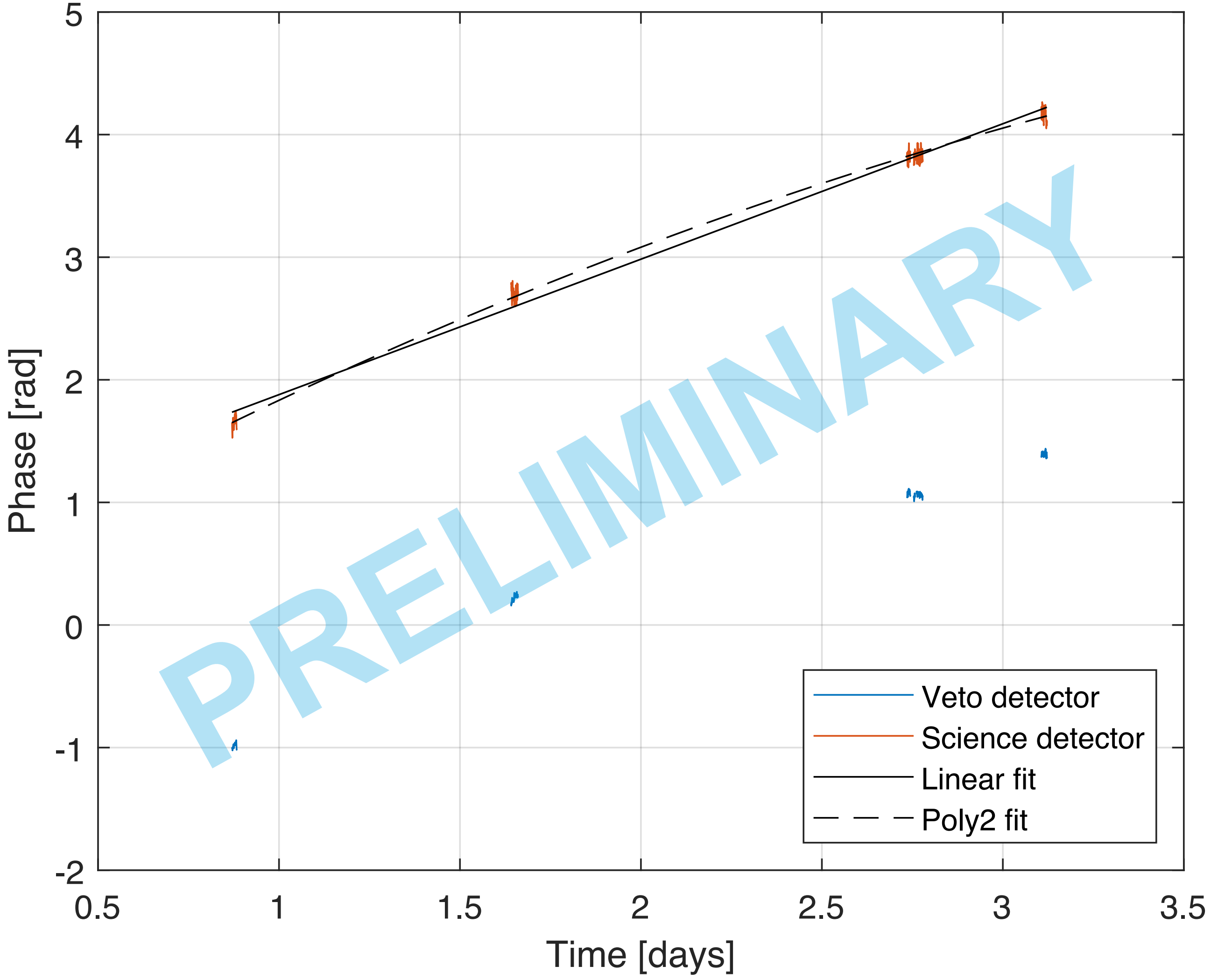
HET sensing



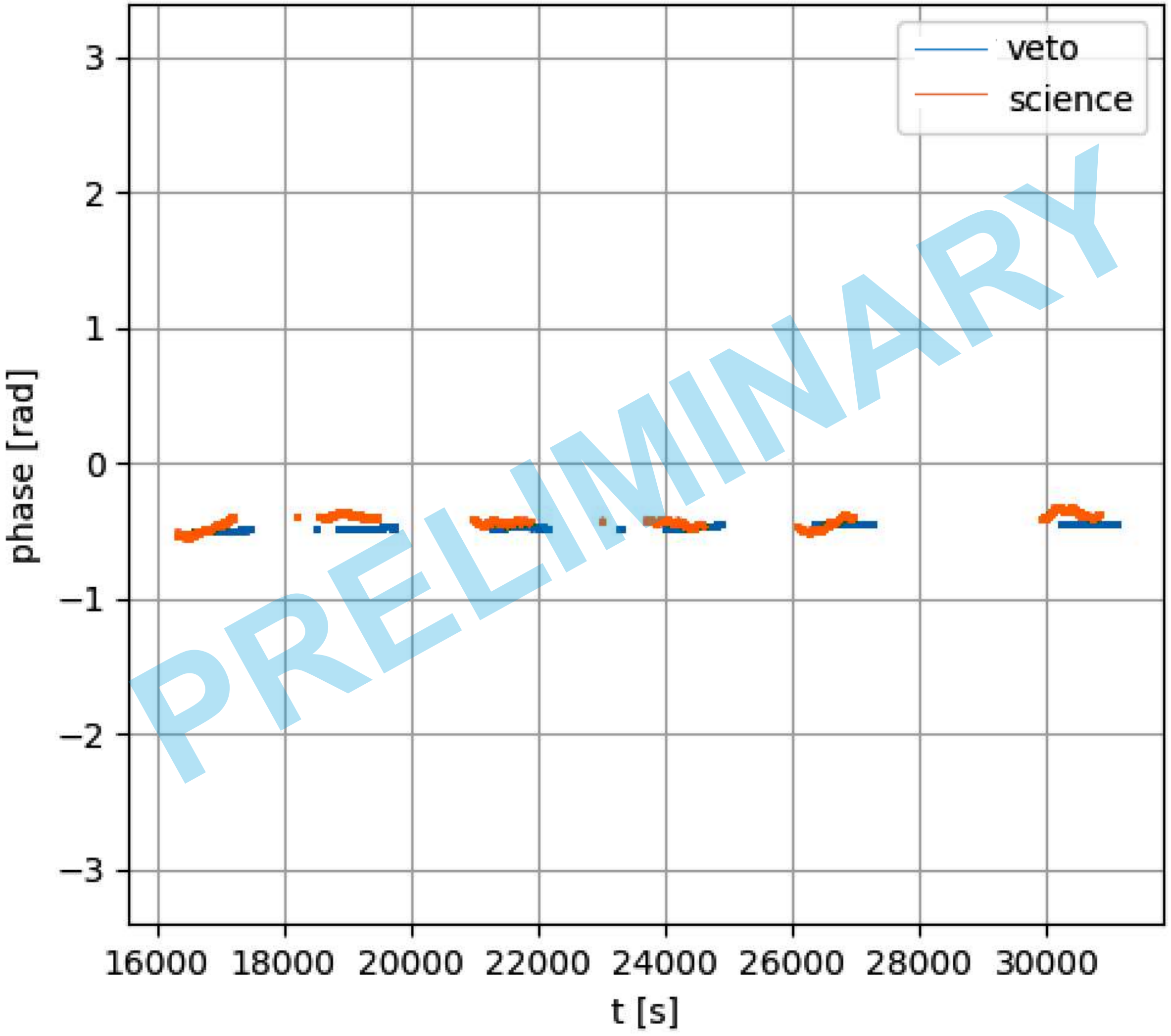
Fix the phase shift

Toward a new data taking

May 2023



November 2023

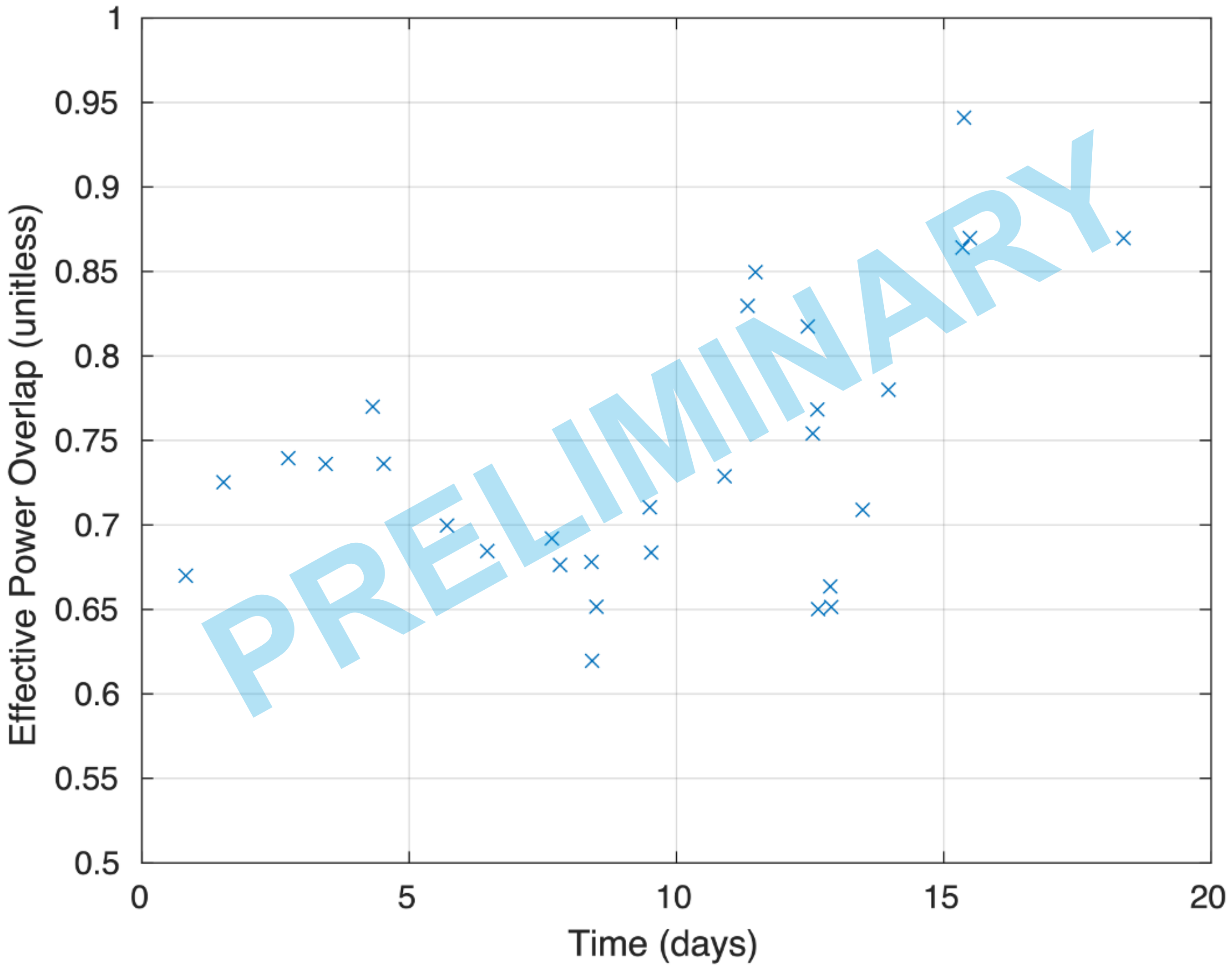


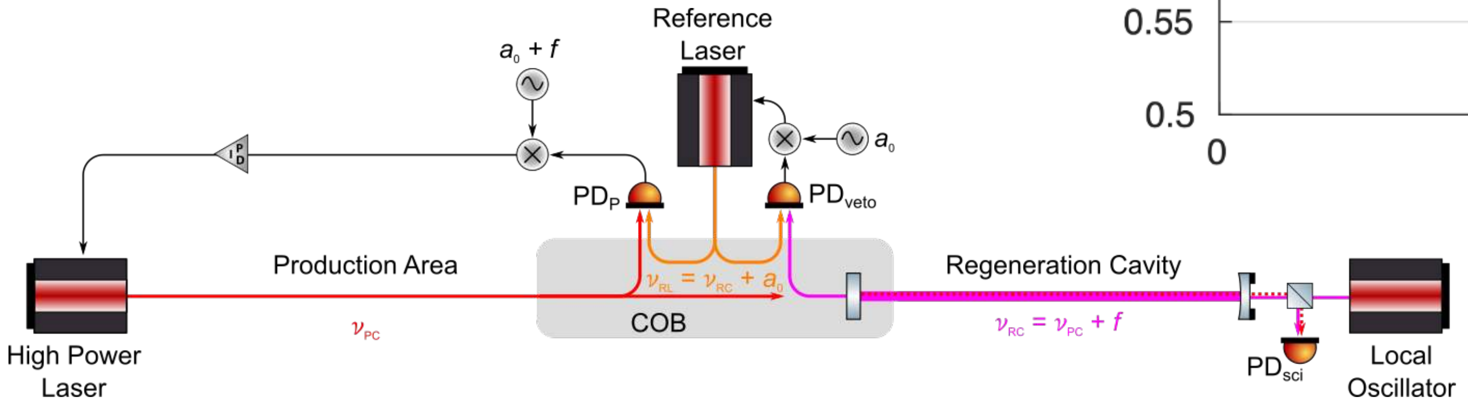
Open Shutter Runs 2024

Checking ALPS II performance

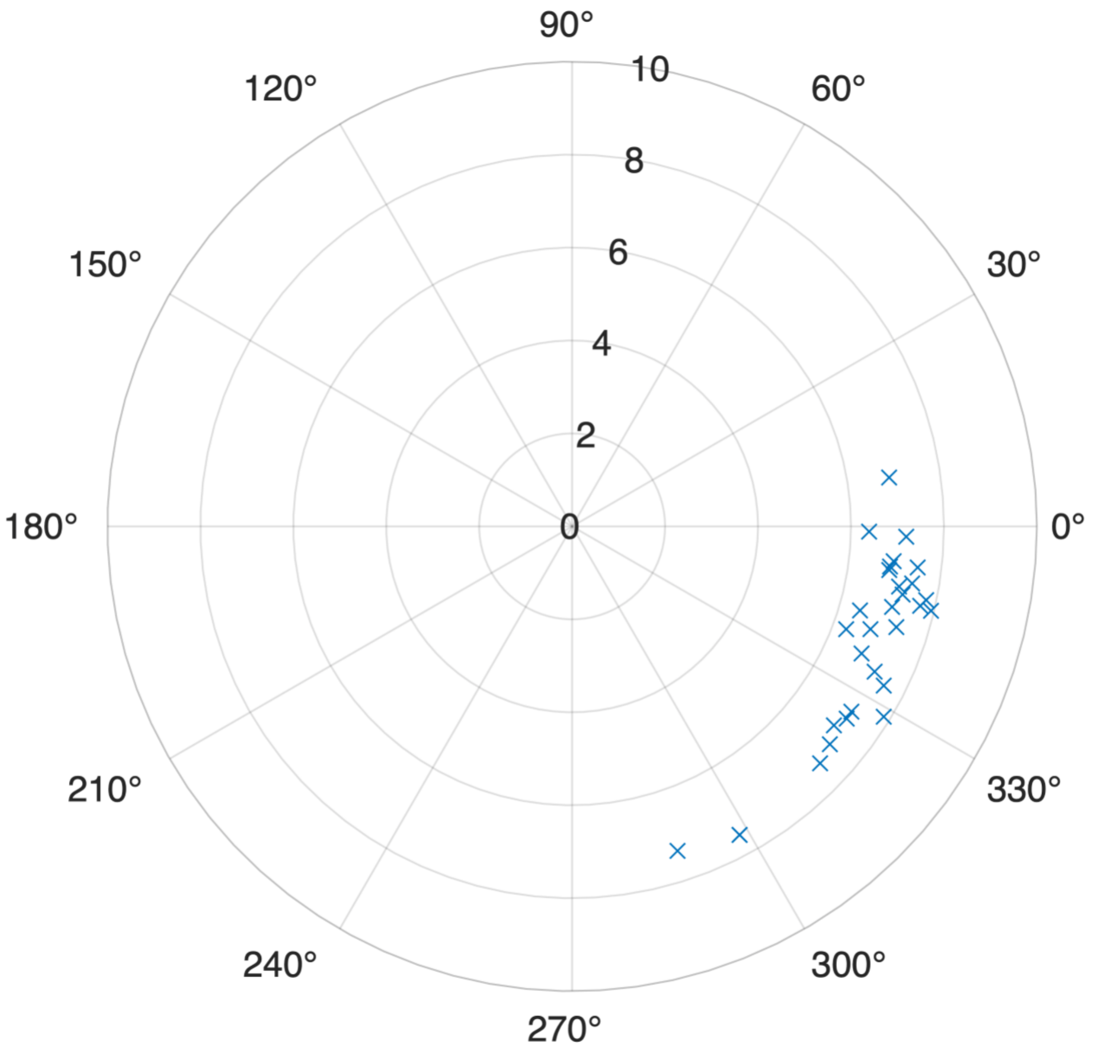
Assessing the HPL-RC coupling

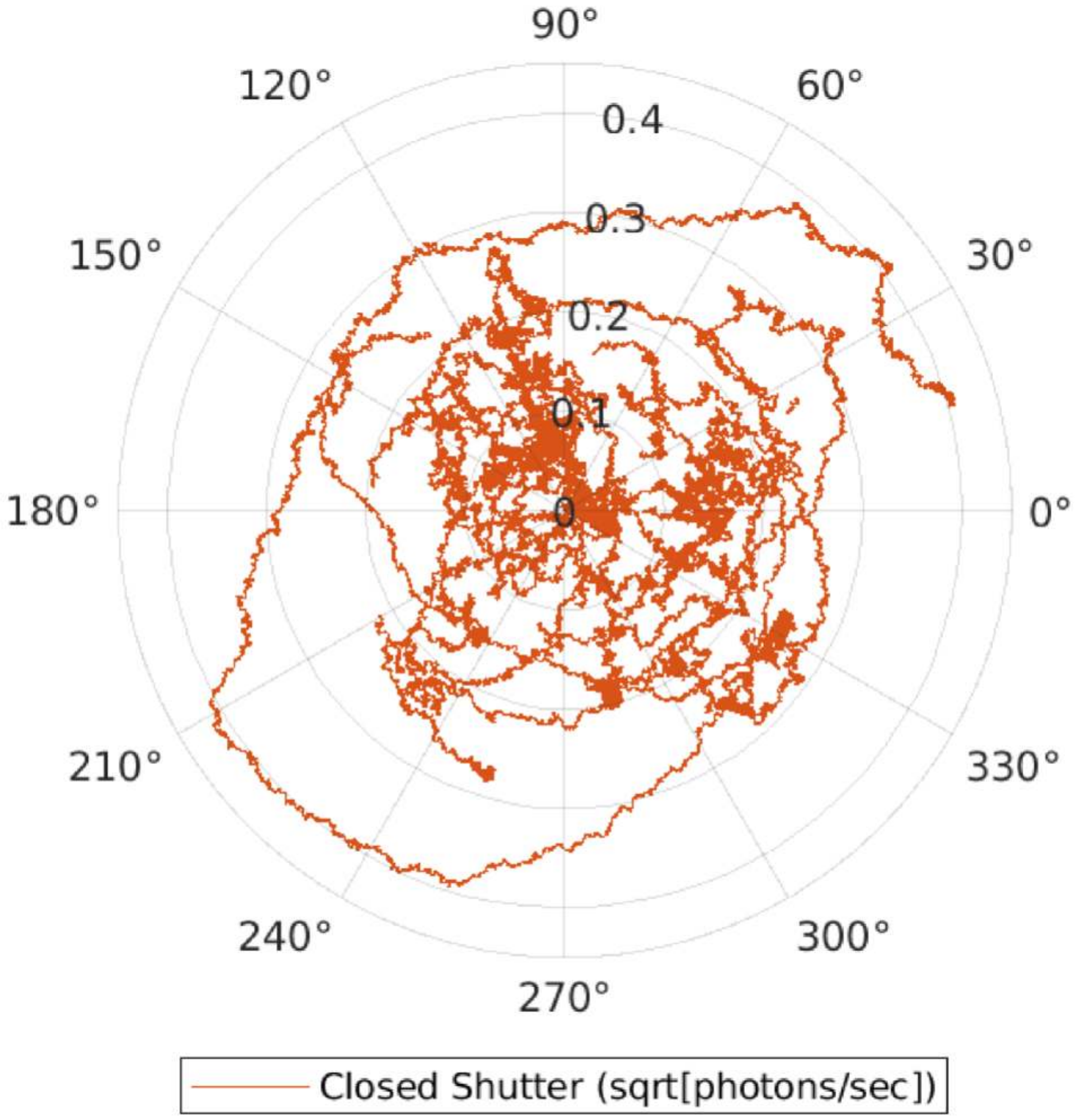
- Start with raw HET function data
- Scale in terms of photons/s





Phase evolution



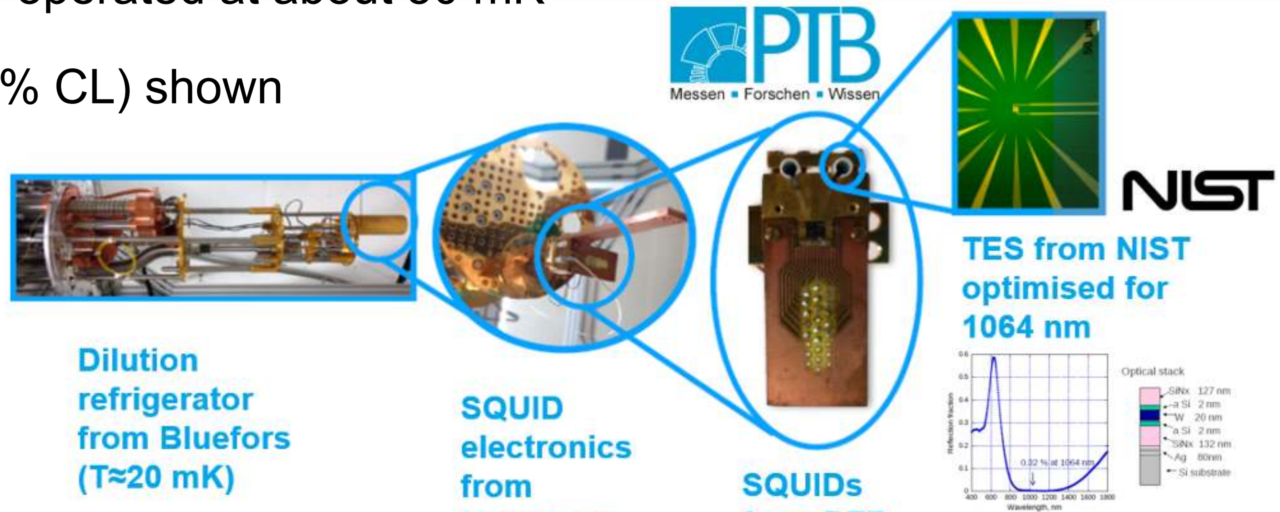


Photon Counting with a Cryogenic Transition Edge Sensor

Photon counting @ 1064 nm with low dark counts and high efficiency

Using a superconducting Transition Edge Sensor (TES) operated at about 50 mK

- Low **intrinsic dark counts** $(6.9^{+5.18}_{-2.93} \times 10^{-6}\ \mathrm{Hz}$, 95% CL) shown
- High efficiency of TES system reached
    - η = 0.931 ± 0.015
- Energy resolution below 10%
- Calibration setup with different wavelengths
- Promising also for direct searches for dark matter

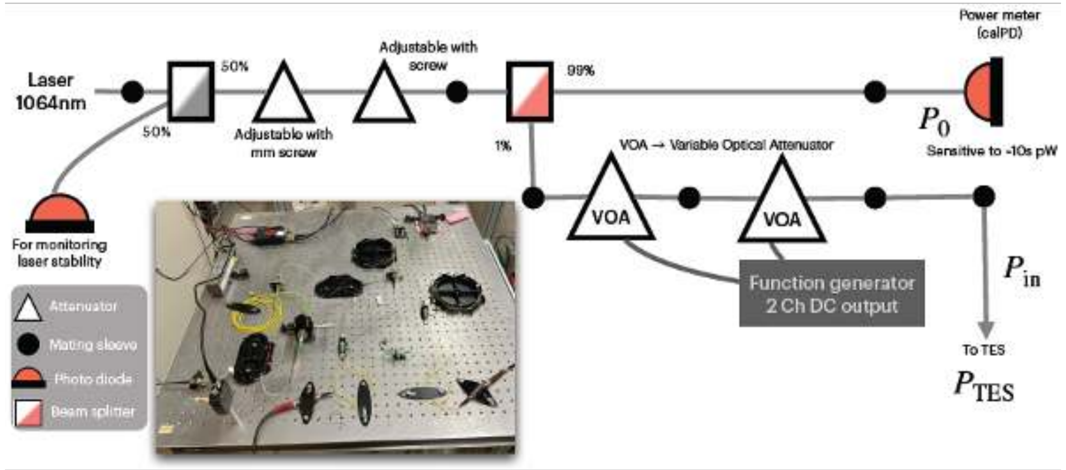


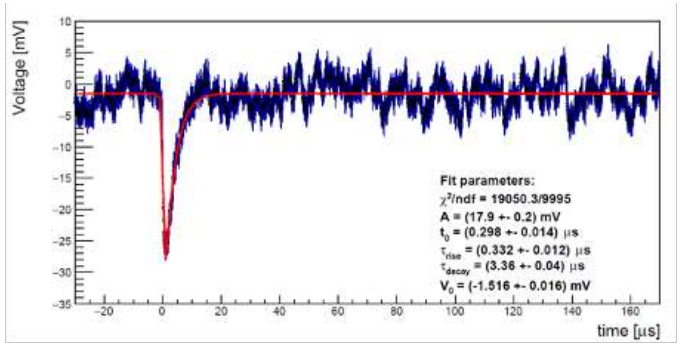
Dilution refrigerator from Bluefors (T≈20 mK)

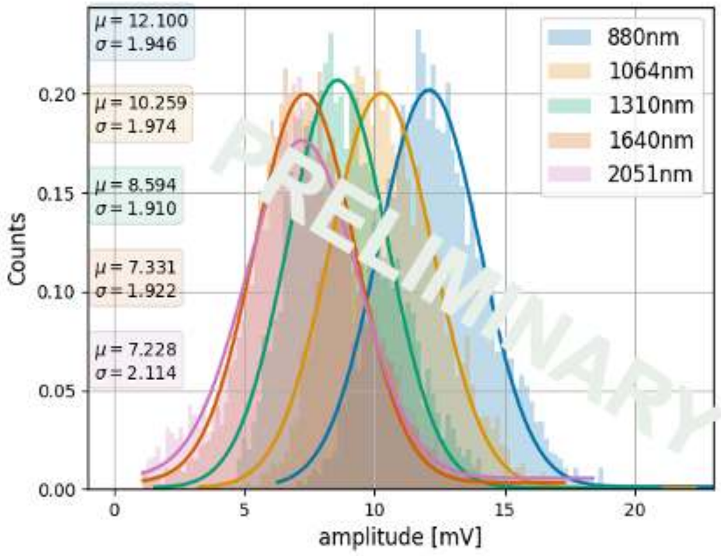
SQUID electronics from Magnicon

SQUIDs from PTB

TES from NIST optimised for 1064 nm







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