Heterodyne detection of weak fields in ALPS II

PIER Workshop: Joint DESY and Universität Hamburg perspectives in detector research

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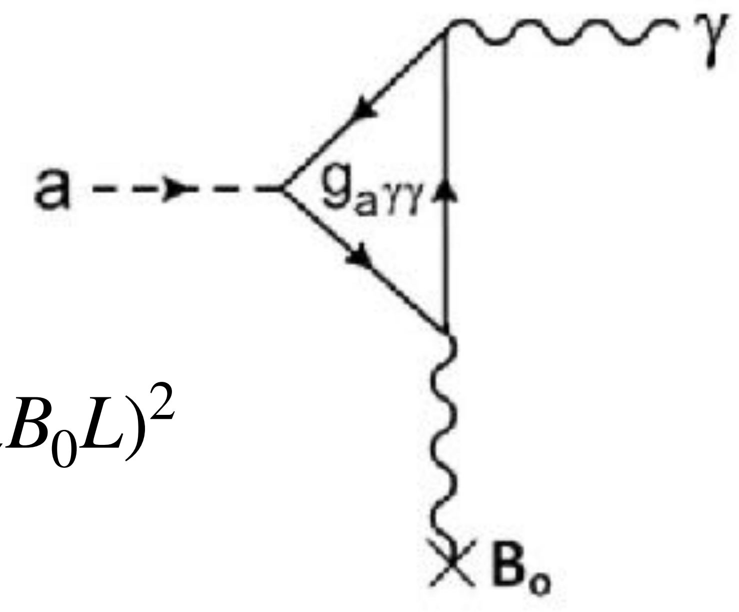
Axion and Axion-Like particles

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



$$L_{\alpha\gamma} = g_{\alpha\gamma\gamma}\phi_\alpha \vec{E} \cdot \vec{B_0}$$

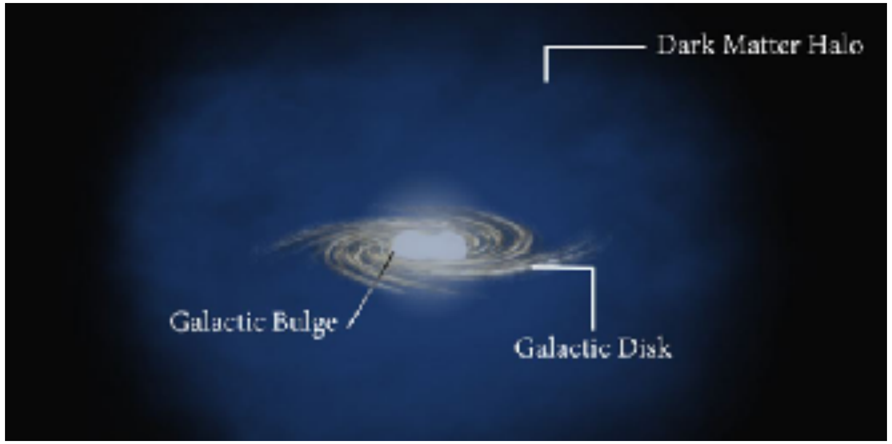
$$P(\alpha \to \gamma) \propto (g_{\alpha\gamma\gamma} B_0 L)^2$$

couplings to Standard Model constituents

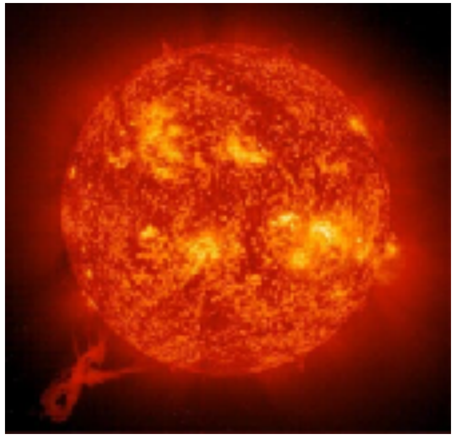
Axion and Axion-Like particles

Searches strategy

- Haloscopes

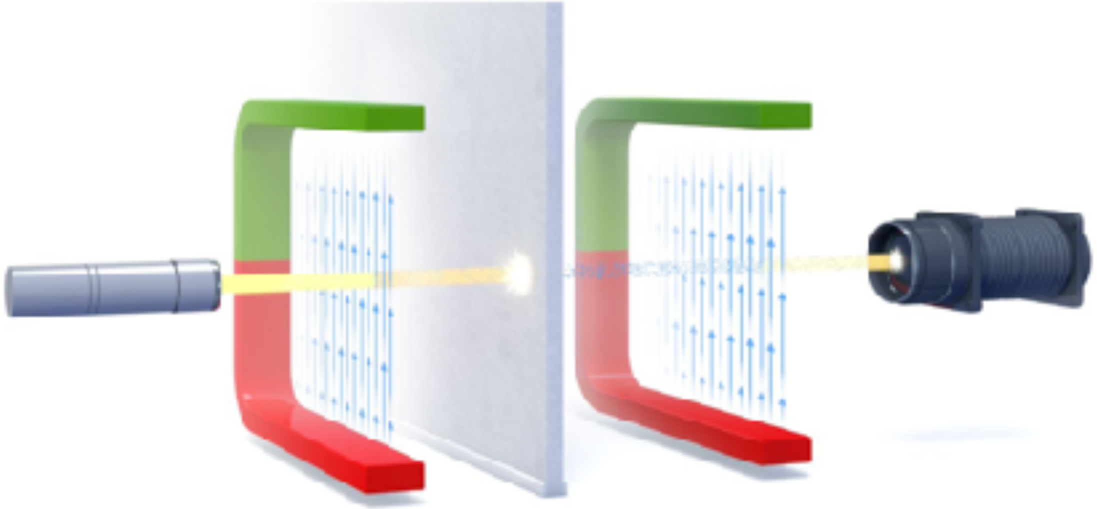


- Helioscopes



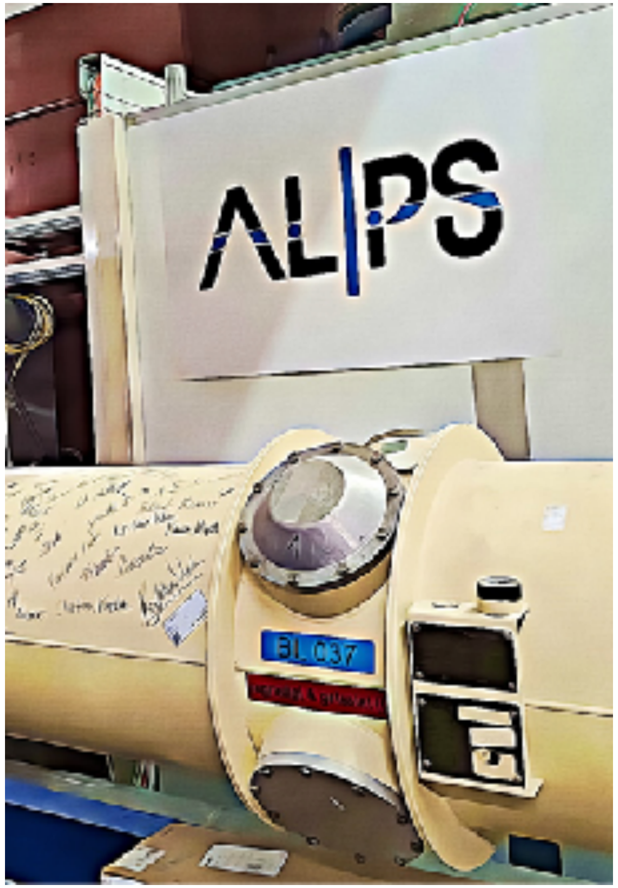
- **Light-shining-through-walls**

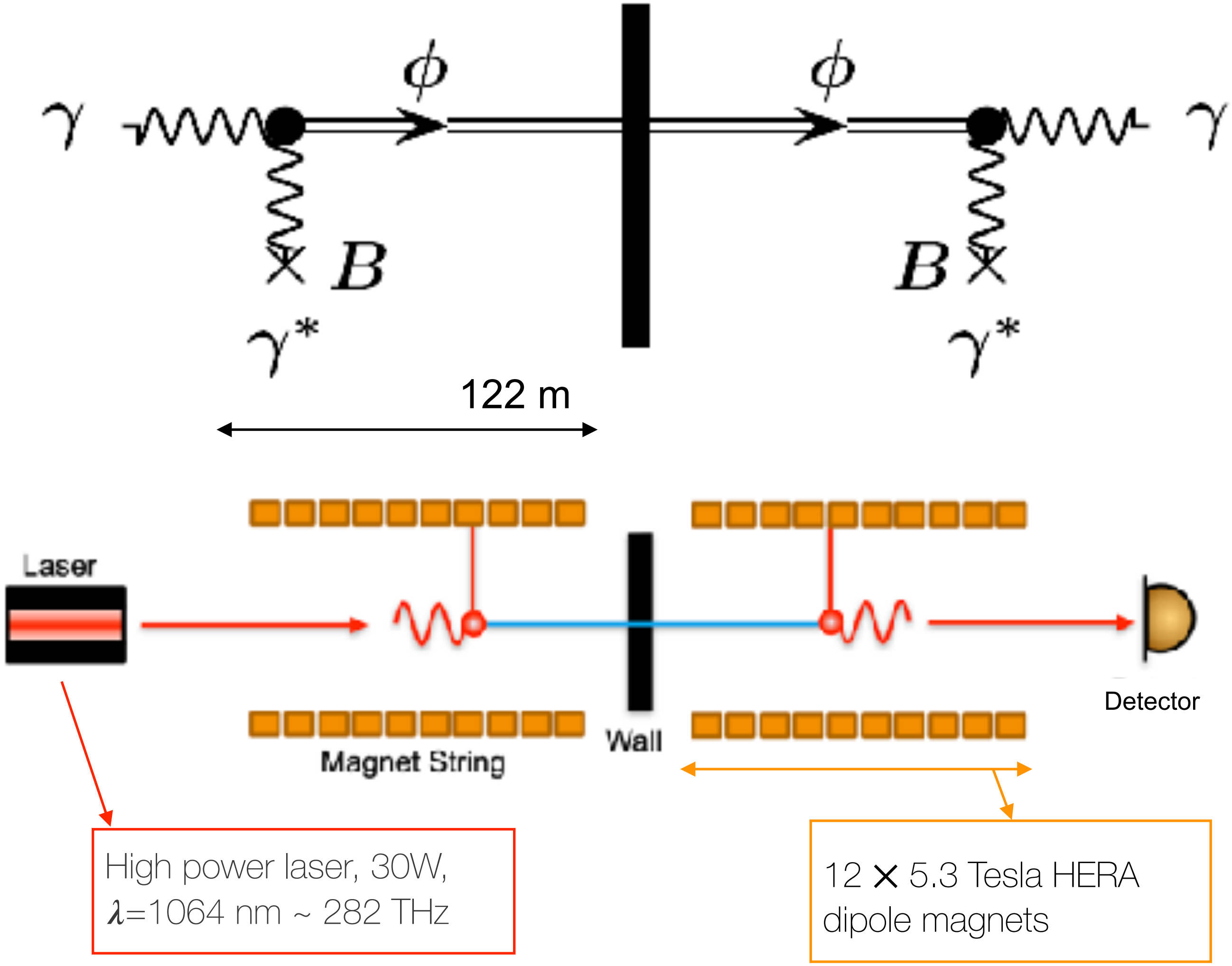
Not requiring cosmological or astrophysical assumption



Any Light Particle Search II

The axion factory





Two detection systems will be used

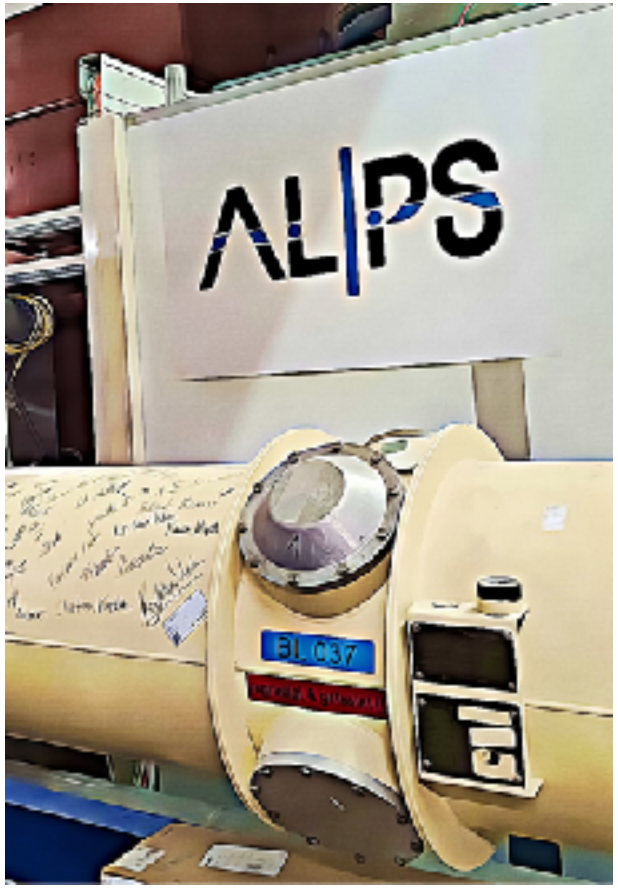
- **HETerodyne interferometer**
- Transition Edge Sensor

$$N_\gamma = \frac{1}{16}(g_{a\gamma\gamma}BL)^4 P_i \tau \sim 1\gamma/\ 150{,}000 \text{ yrs}$$

$$g_{a\gamma\gamma} = 2 \times 10^{-11}\ \text{GeV}^{-1}$$

Any Light Particle Search II

The axion factory



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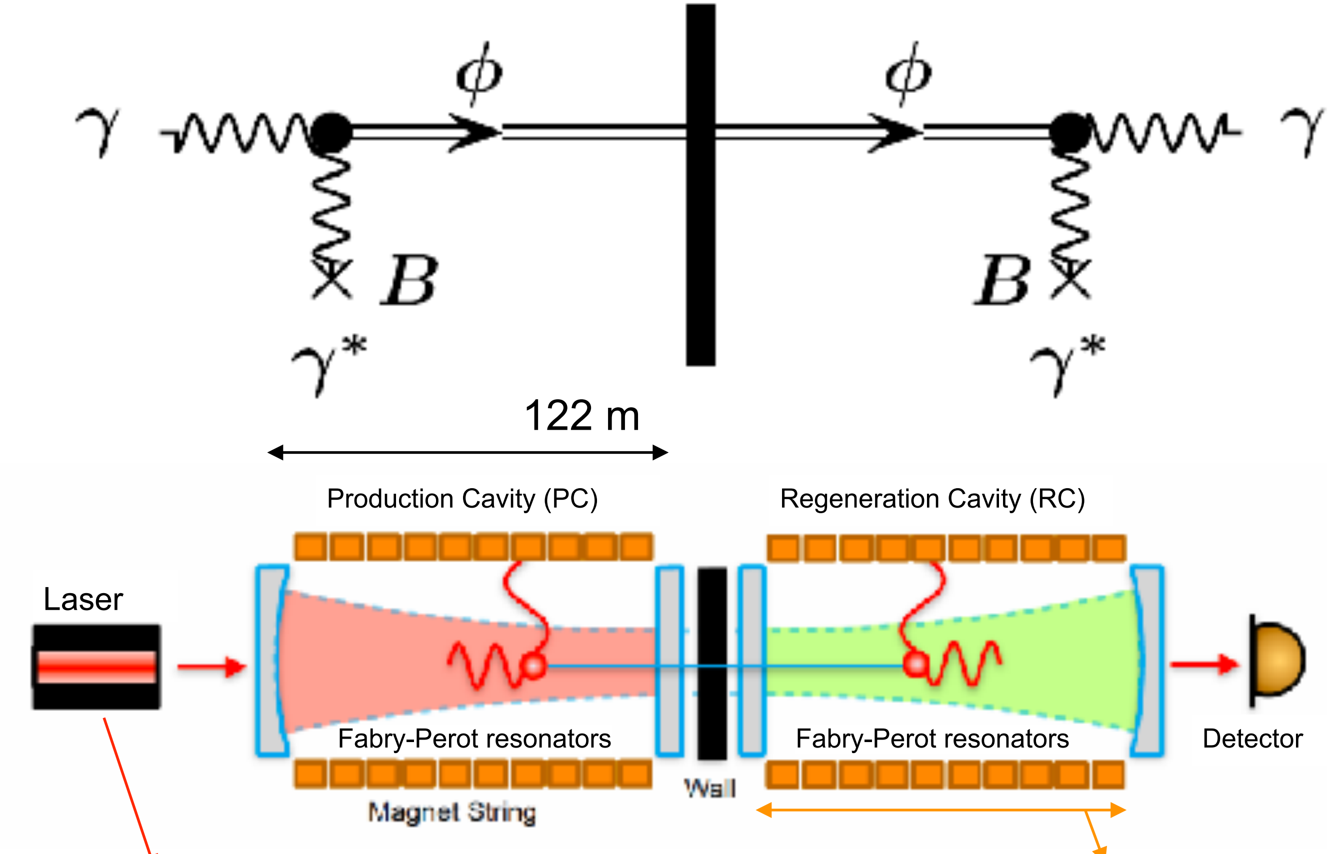


High power laser, 30W, λ=1064 nm ~ 282 THz

12 × 5.3 Tesla HERA dipole magnets

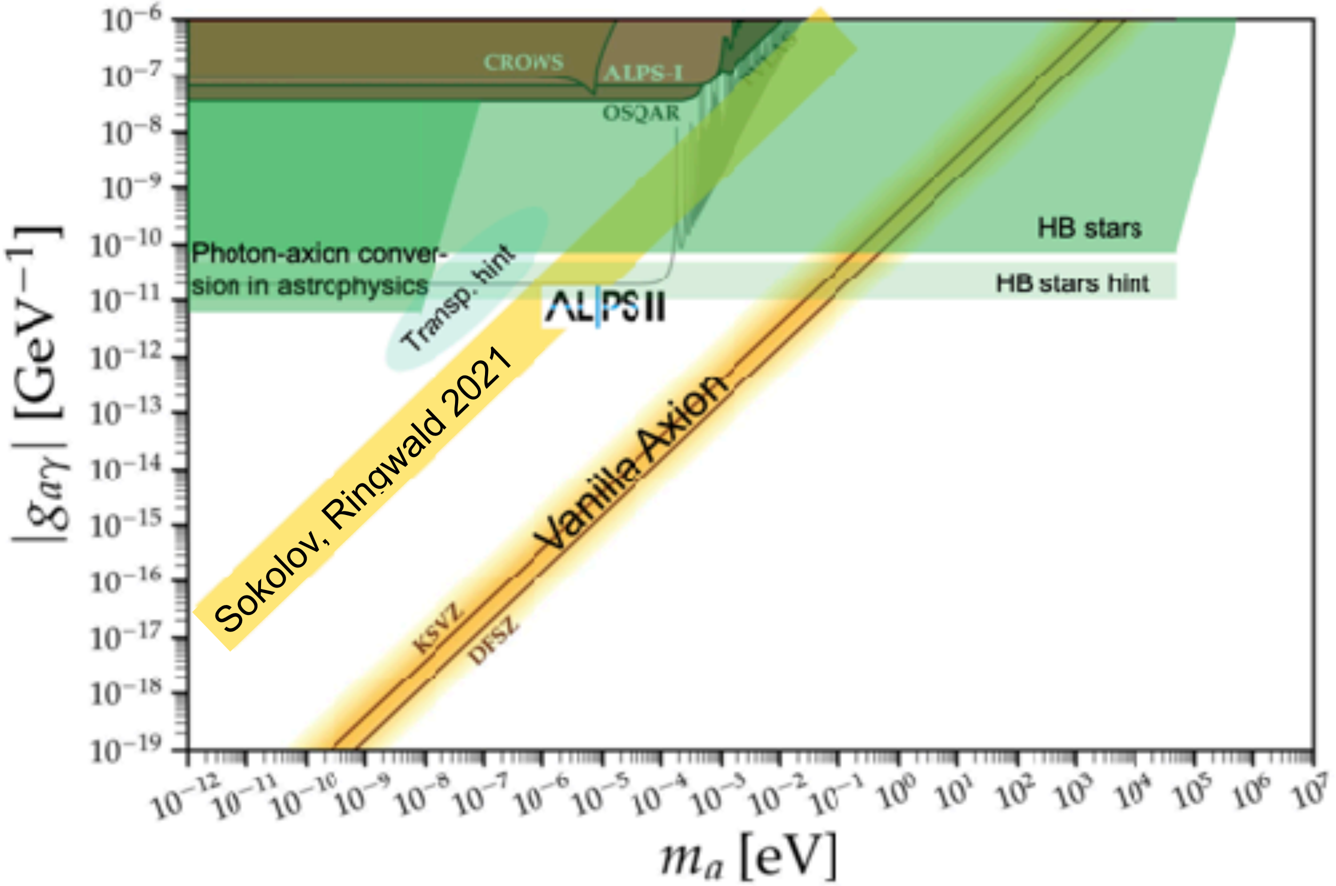
$$N_\gamma = \frac{1}{16}(g_{\alpha\gamma\gamma}BL)^4 \eta \beta_{PC} \beta_{RC} P_{RC} \tau \sim 1\gamma/\ \mathrm{day}$$

$$g_{\alpha\gamma\gamma} = 2 \times 10^{-11}\ \mathrm{GeV}^{-1}$$

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

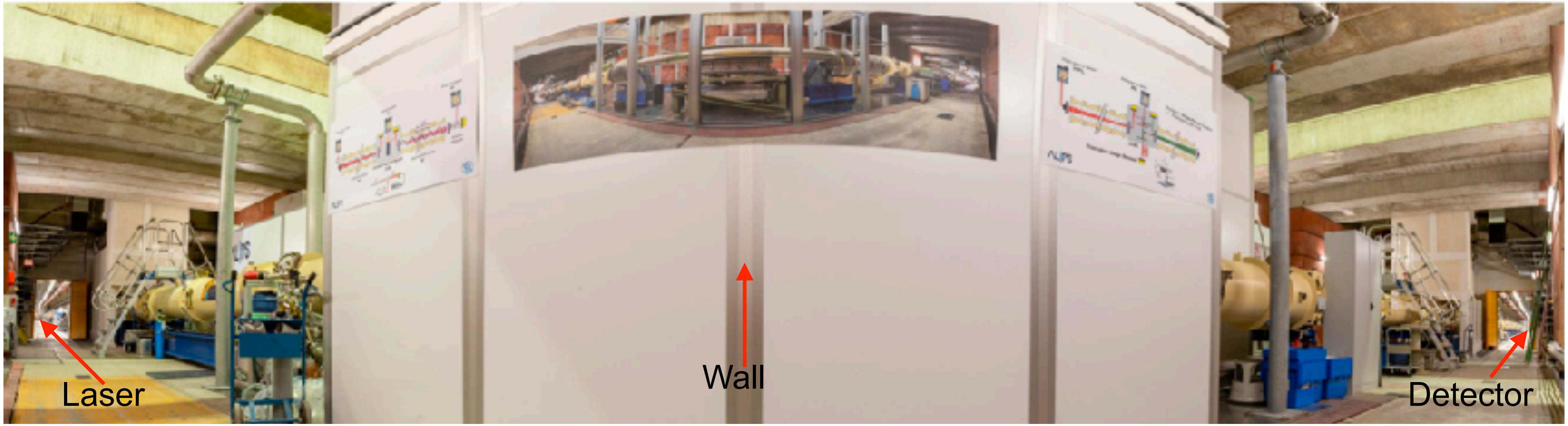


- Astrophysical constraints
  - Non-observation of BSM energy loss of Horizontal Branch (HB) stars in globular clusters
  - Non-observation of conversion photons into axions in astorophysical environments
- Astrophysical anomalies
  - Best fit of energy loss of (HB) starts hints at BSM contribution
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

ALPS II achievement

- Optic R&D from 2012
- Installation of ALPS II began in 2019

- In March 2022 the magnet string was successfully tested
- Completion of the whole installation in September 2022



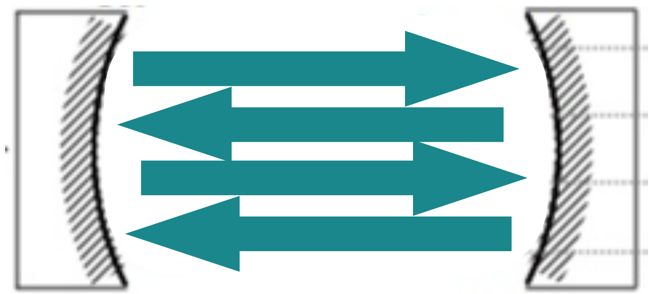
ALPS II achievement

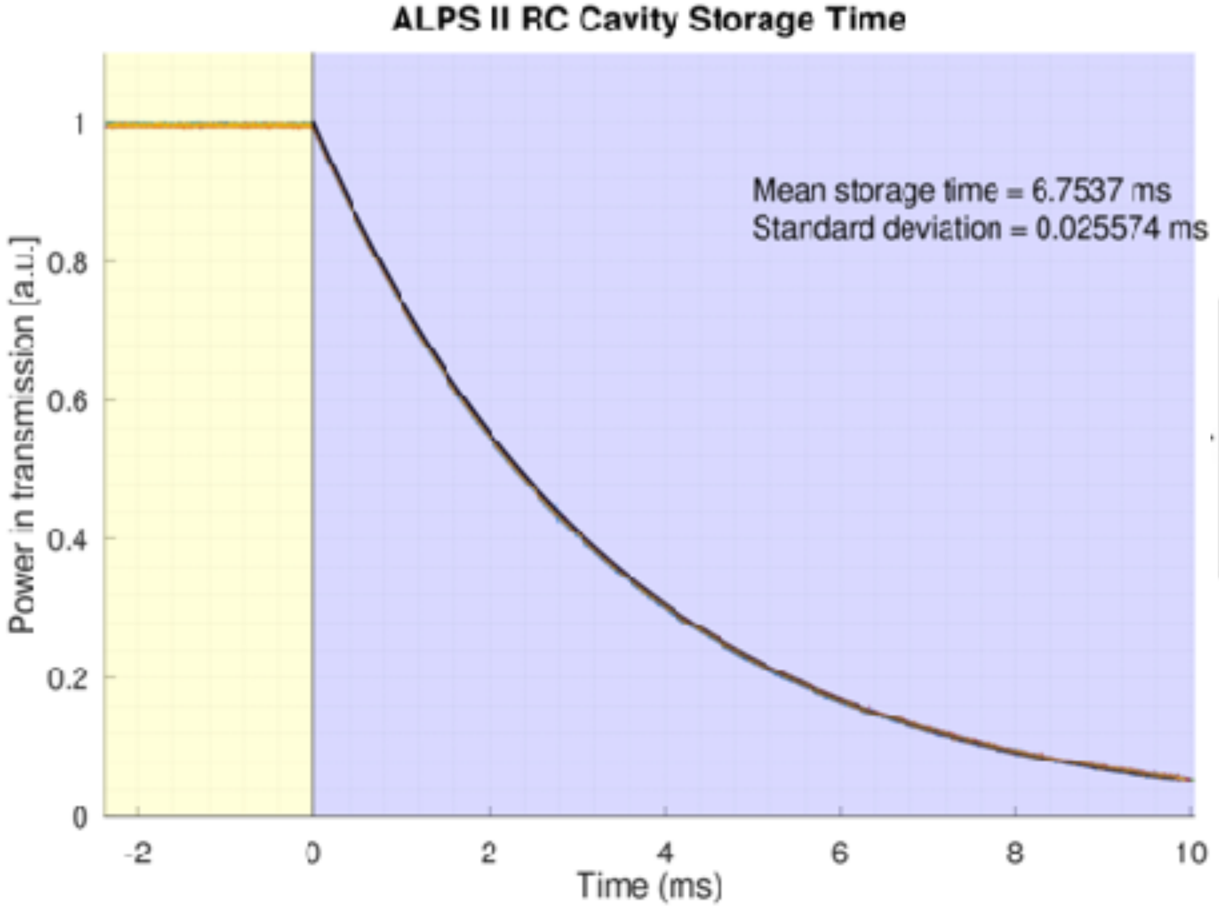
World-record

- Longest storage time Fabry Perot cavity ever!
- Length: 124.6m, FSR: 1.22 MHz
- Storage time: **6.75 ms**

Leading precision interferometry!

Laser On



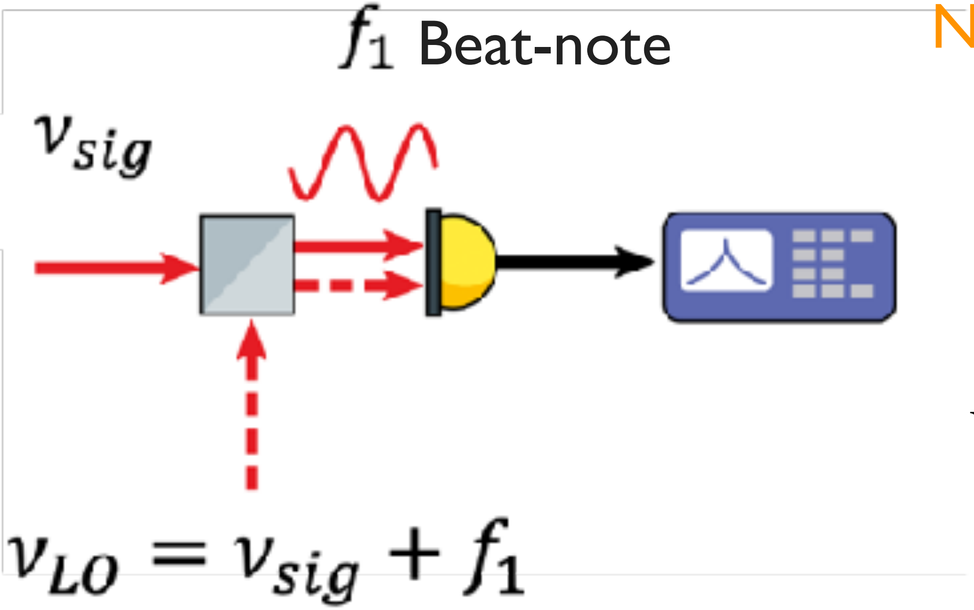


Laser Off

HETerodyne: Coherent detection

A very sensitive technique

- The term has its root in the greek words ‘heteros’ (other) ‘dynamis’ (force)



New frequencies are created by mixing two frequencies

R. Fessenden

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

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

Sum the amplitude of the beat-note over a long time.

HETerodyne: Coherent detection

Advantages & costs

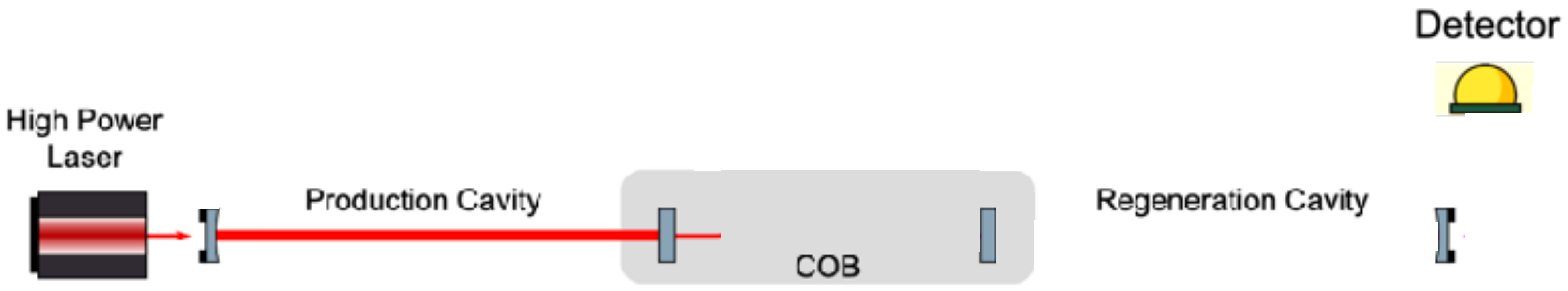
- The higher the LO power, the shorter the time it takes for the signal to exceed the expected noise limit.
- If the P_{LO} is large enough, the system noise is dominated by the shot-noise
  - SNR no longer depend on the LO power

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

- Costs:
  - Keep $\Delta\phi$ constant
  - Keep Δf constant

ALPS II's first science run scheme

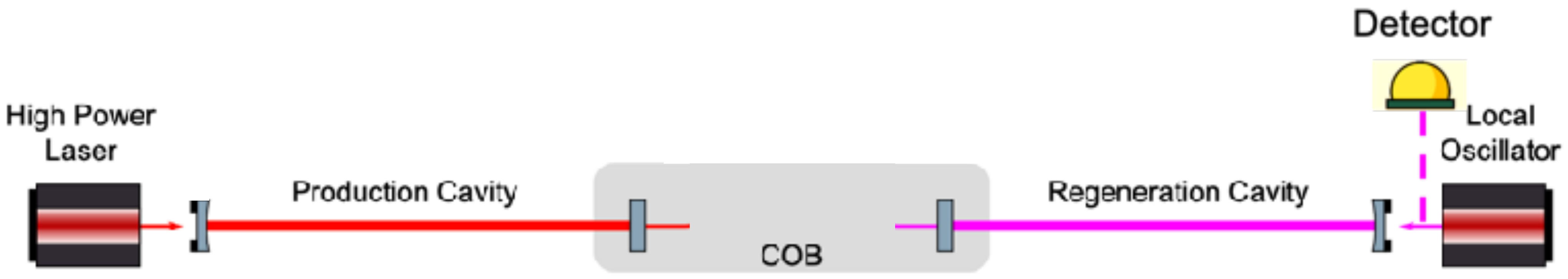
Axion production



Amplifies circulating
power before the wall

ALPS II's first science run scheme

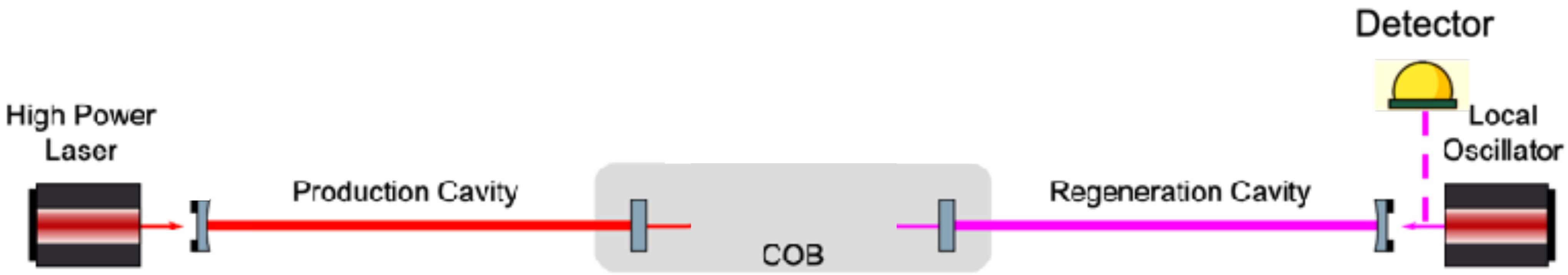
HET principle



Amplifies electromagnetic
component of the axion field

ALPS II's first science run scheme

HET principle

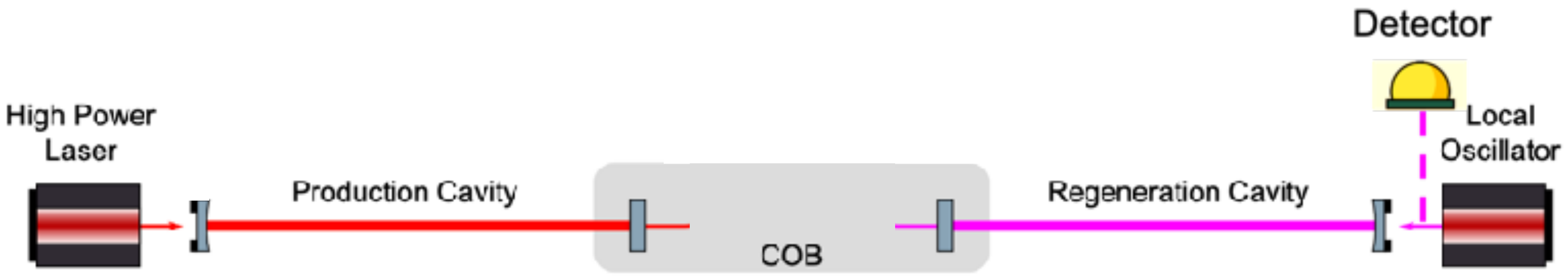


LO: $10^{20}\gamma/s$

Reconverted photons: $10^{-5}\gamma/s$

ALPS II’s first science run scheme

HET principle



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The idea: exploit the background to boost the signal!

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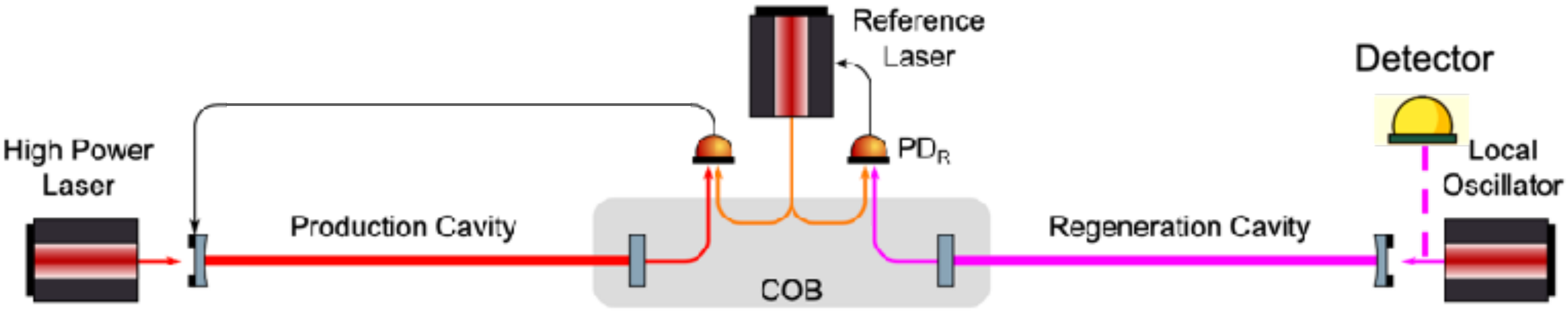
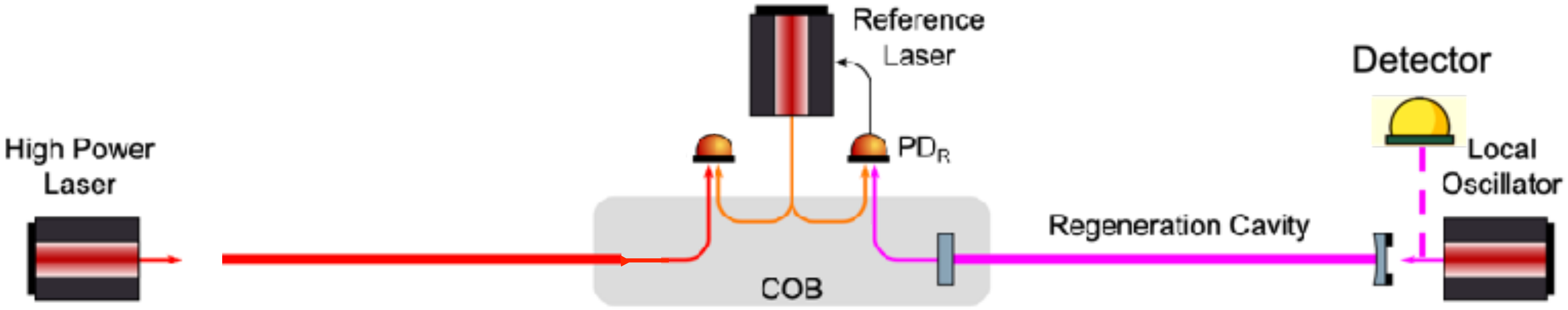


LO: $10^{20}\gamma/s$

Reconverted photons: $10^{-5}\gamma/s$

The idea: exploit the background to boost the signal!

ALPS II's initial science run scheme



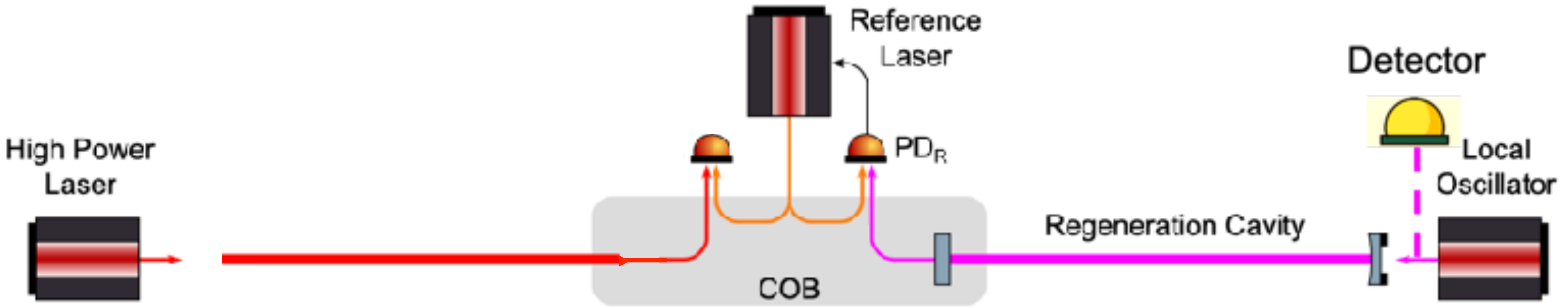
- $5000 < \beta < 8000$
- $P_c = 40\ \text{W}$

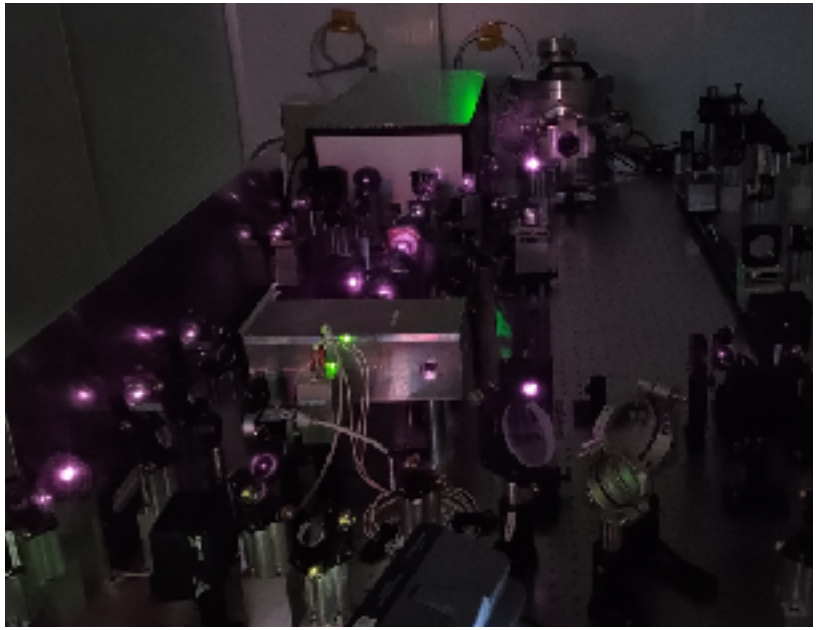
Early science run **ongoing** w/o the PC optimal for stray light hunting

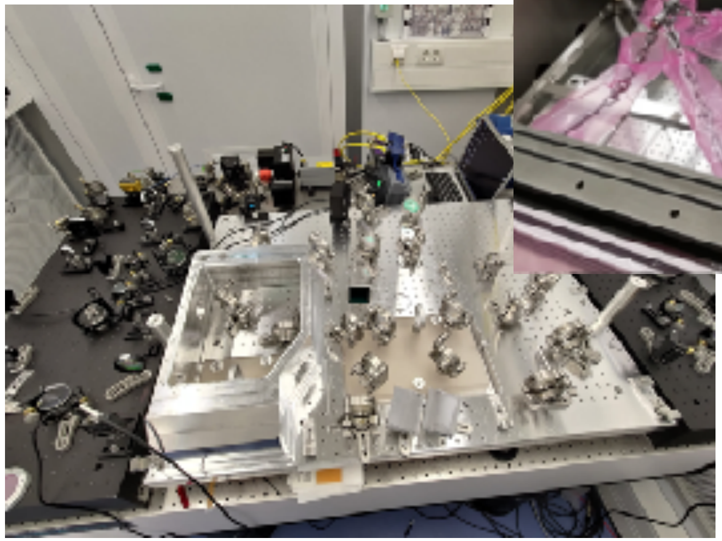
↓ !

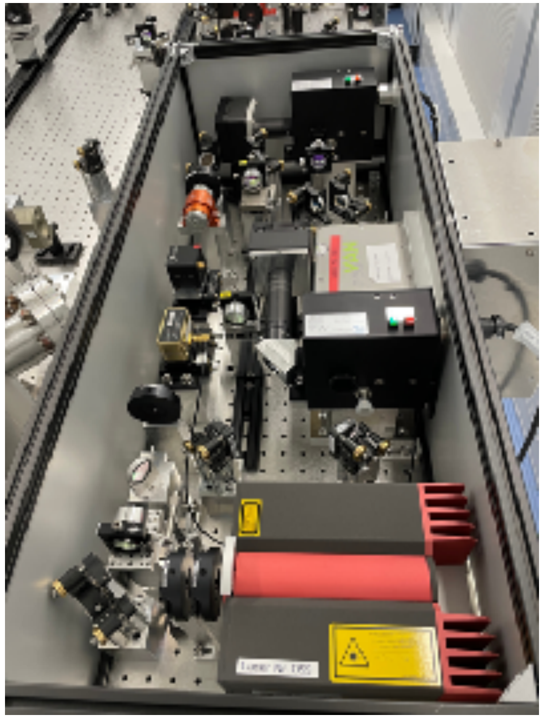
Already a factor **100** beyond earlier LSW experiments!

ALPS II's first science run scheme

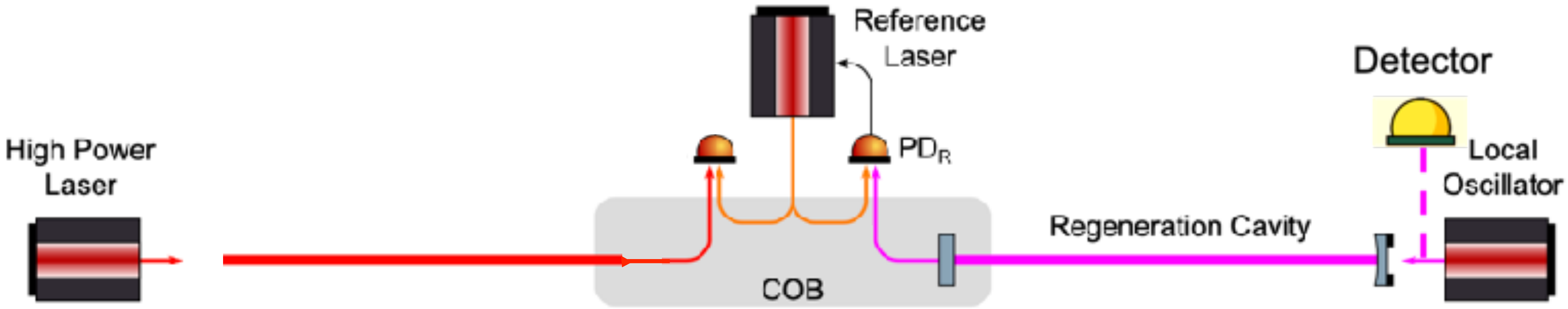






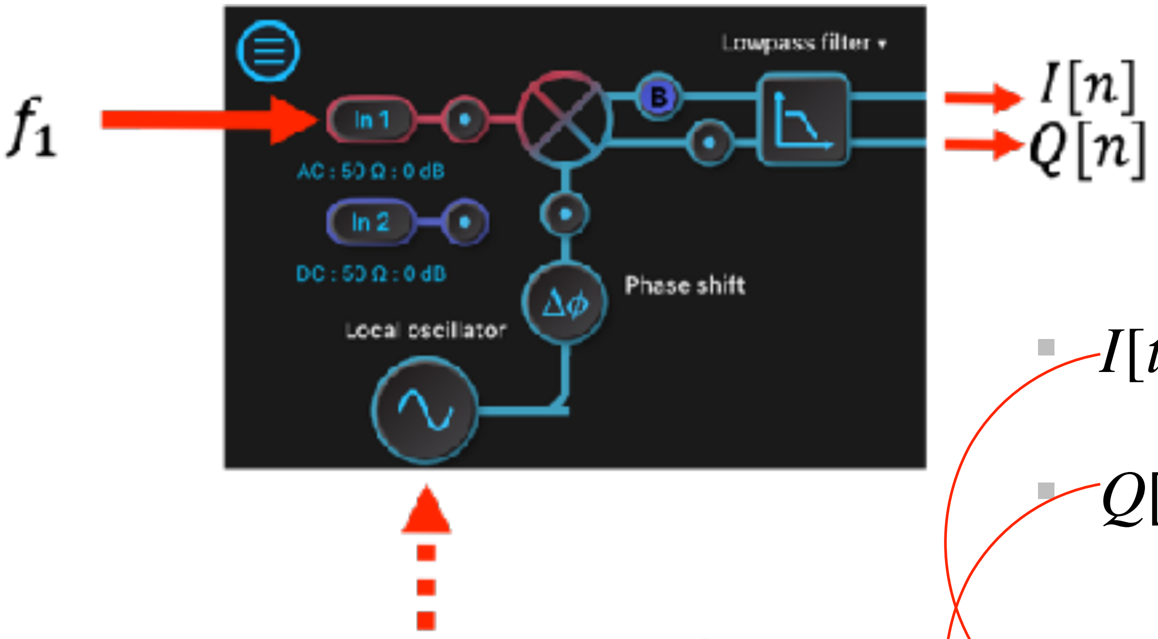


ALPS II's initial science run scheme



Signal extraction

In-phase and quadrature demodulation



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

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

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

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

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

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

$$N_\gamma = \frac{z[n]}{G^2 P_{LO} h\nu}$$

Photon flux extraction

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Number of photons

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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

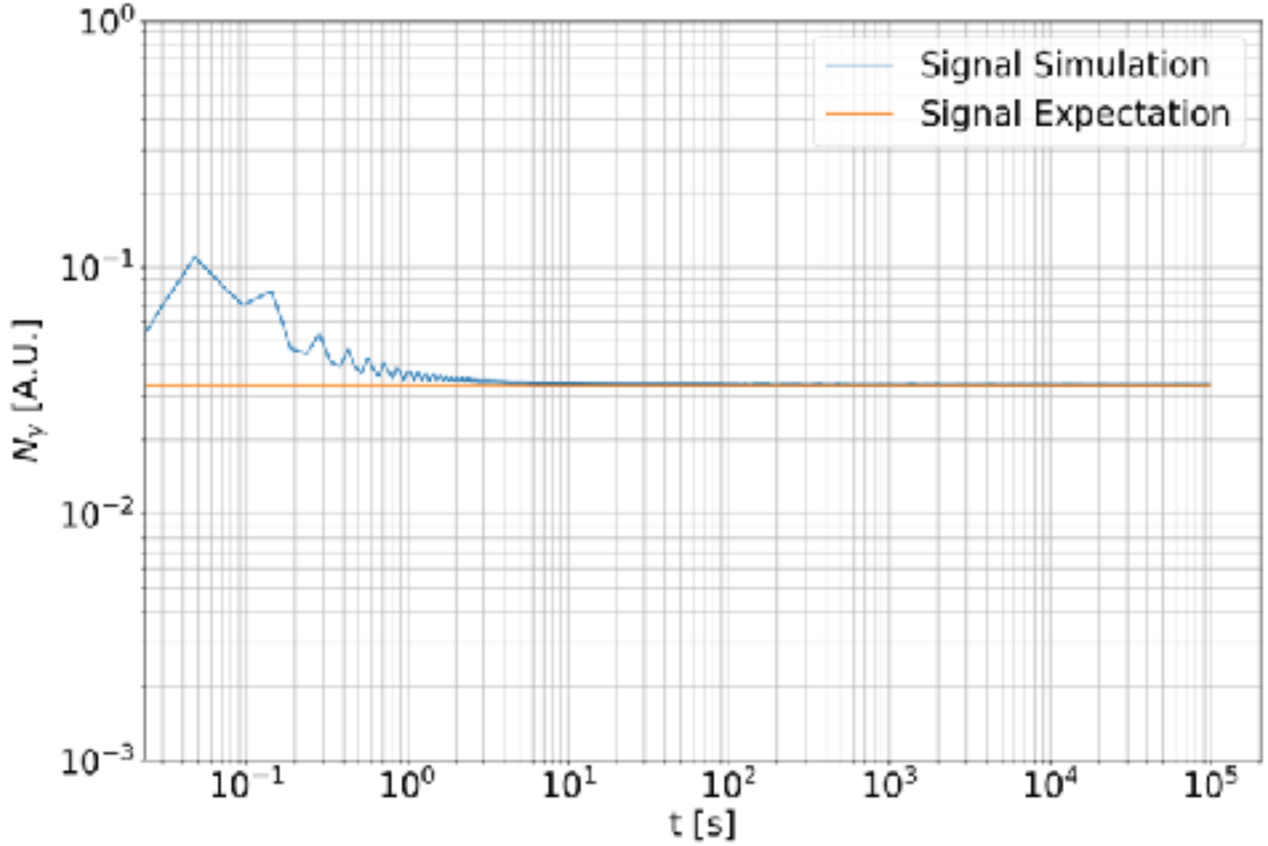
Number of photons

$$N_\gamma = \frac{z[n]}{G^2 P_{LO} h\nu}$$

Signal

Will sum coherently

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



No physical case

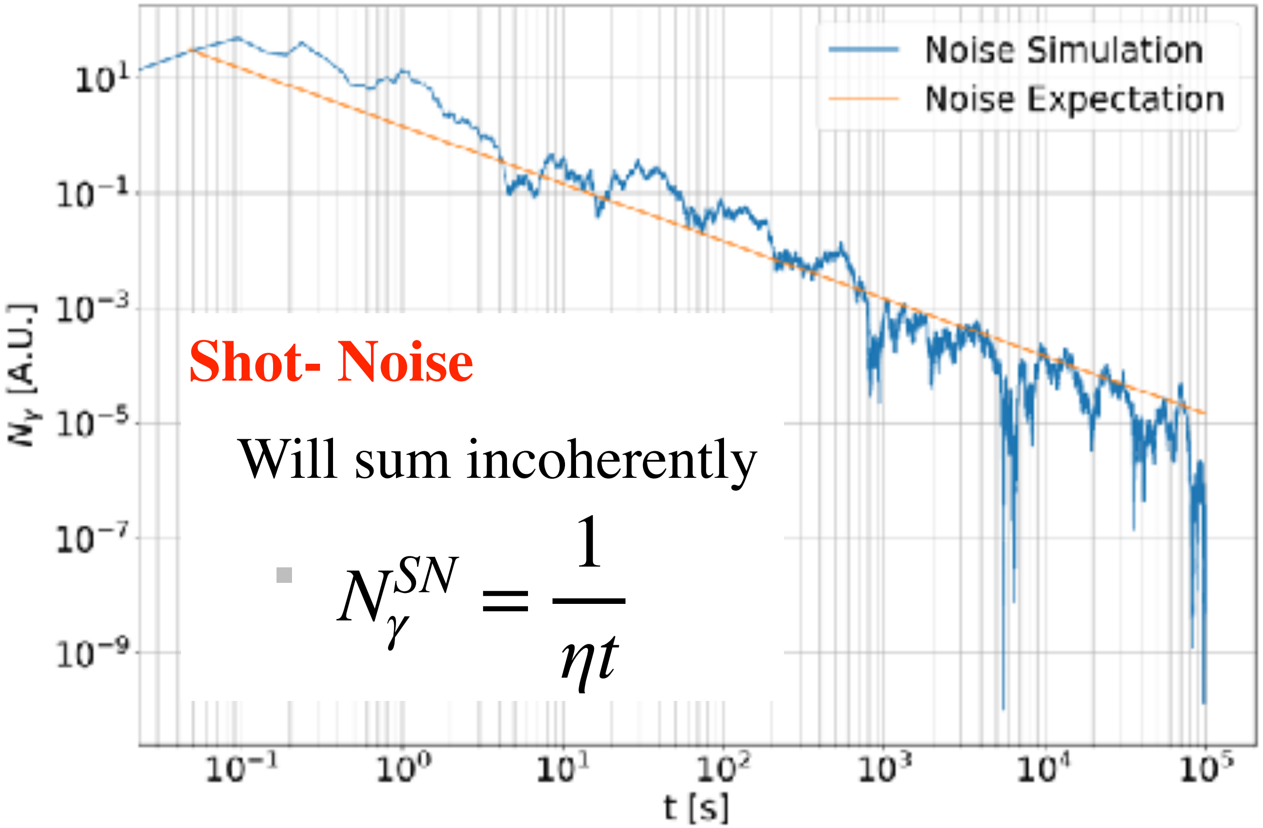
Photon flux extraction

Noise

Number of photons

$$N_\gamma = \frac{z[n]}{G^2 P_{LO} h\nu}$$

Technical noises for HET mitigated by increasing the LO power



Shot- Noise

Will sum incoherently

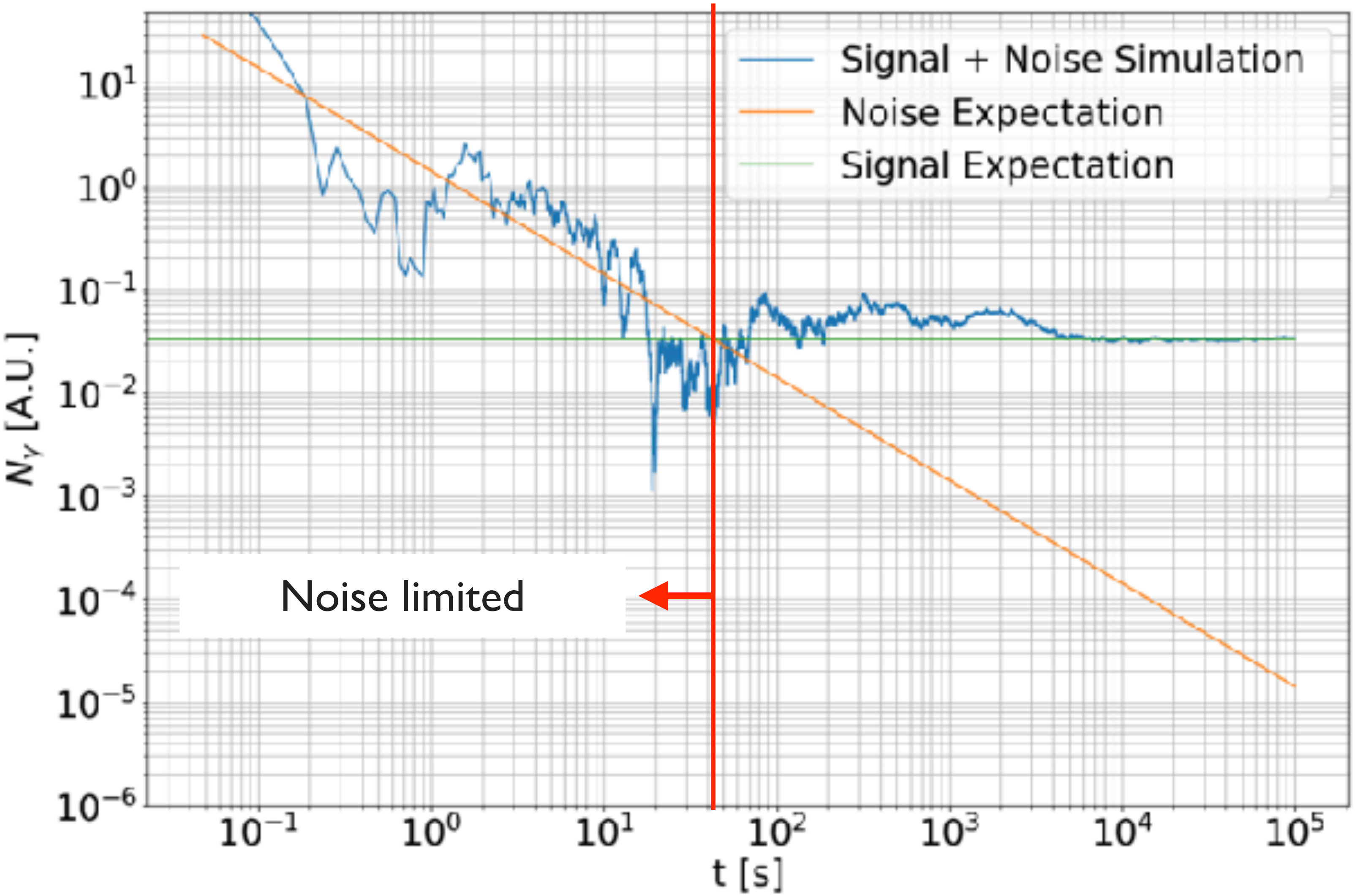
- $N_\gamma^{SN} = \frac{1}{\eta t}$

Photon flux extraction

Signal + Noise

Number of photons

$$N_\gamma = \frac{z[n]}{G^2 P_{LO} h\nu}$$



Photon flux extraction

Signal + Noise

Number of photons

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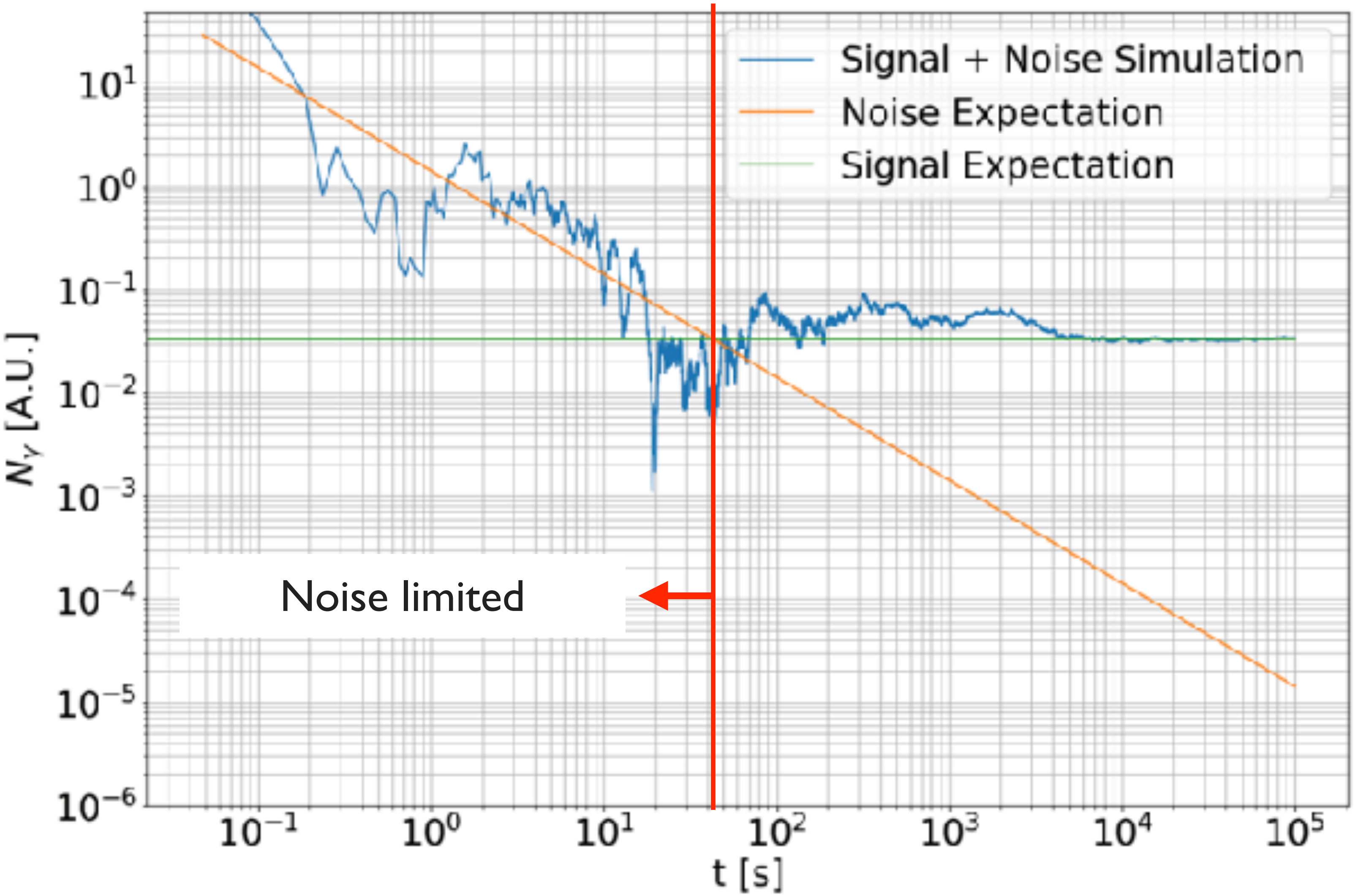


ALPS II integration time:
~20 days

What if we will observe a signal signature?

- Run with magnet off 😎

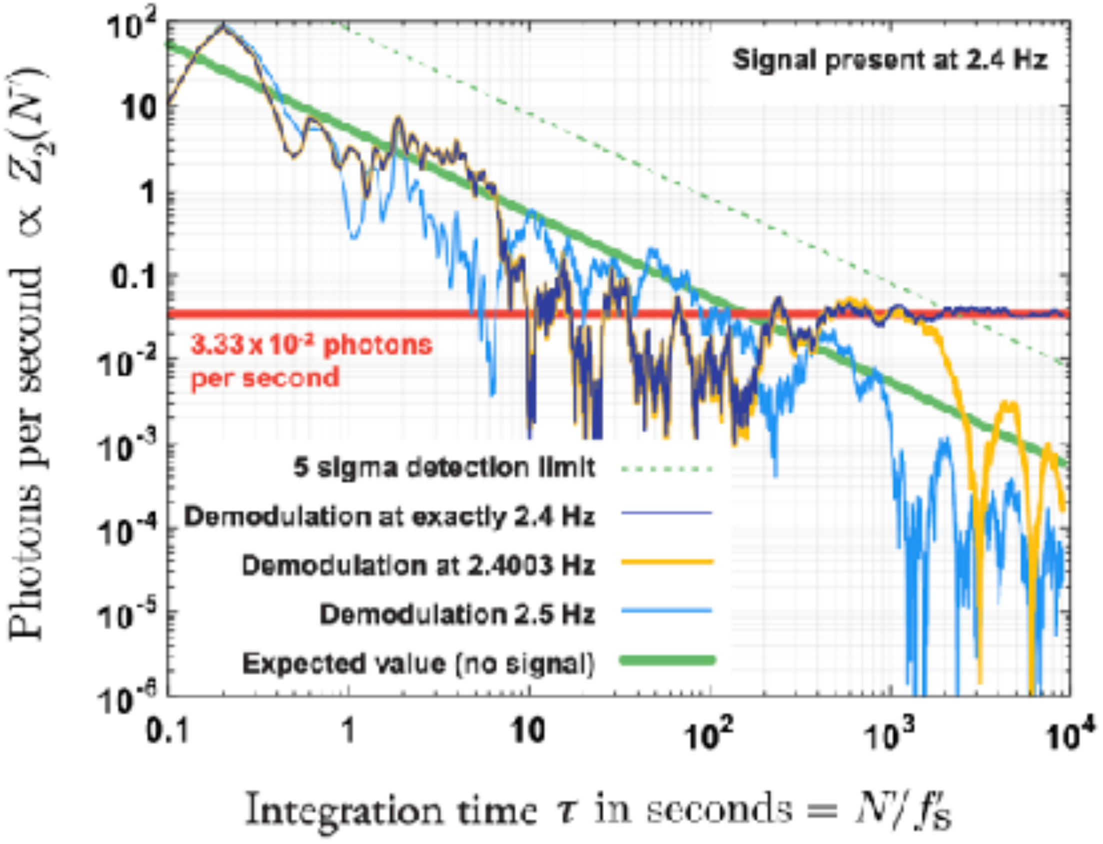
Difficulties in the measurement

A challenge in the challenges

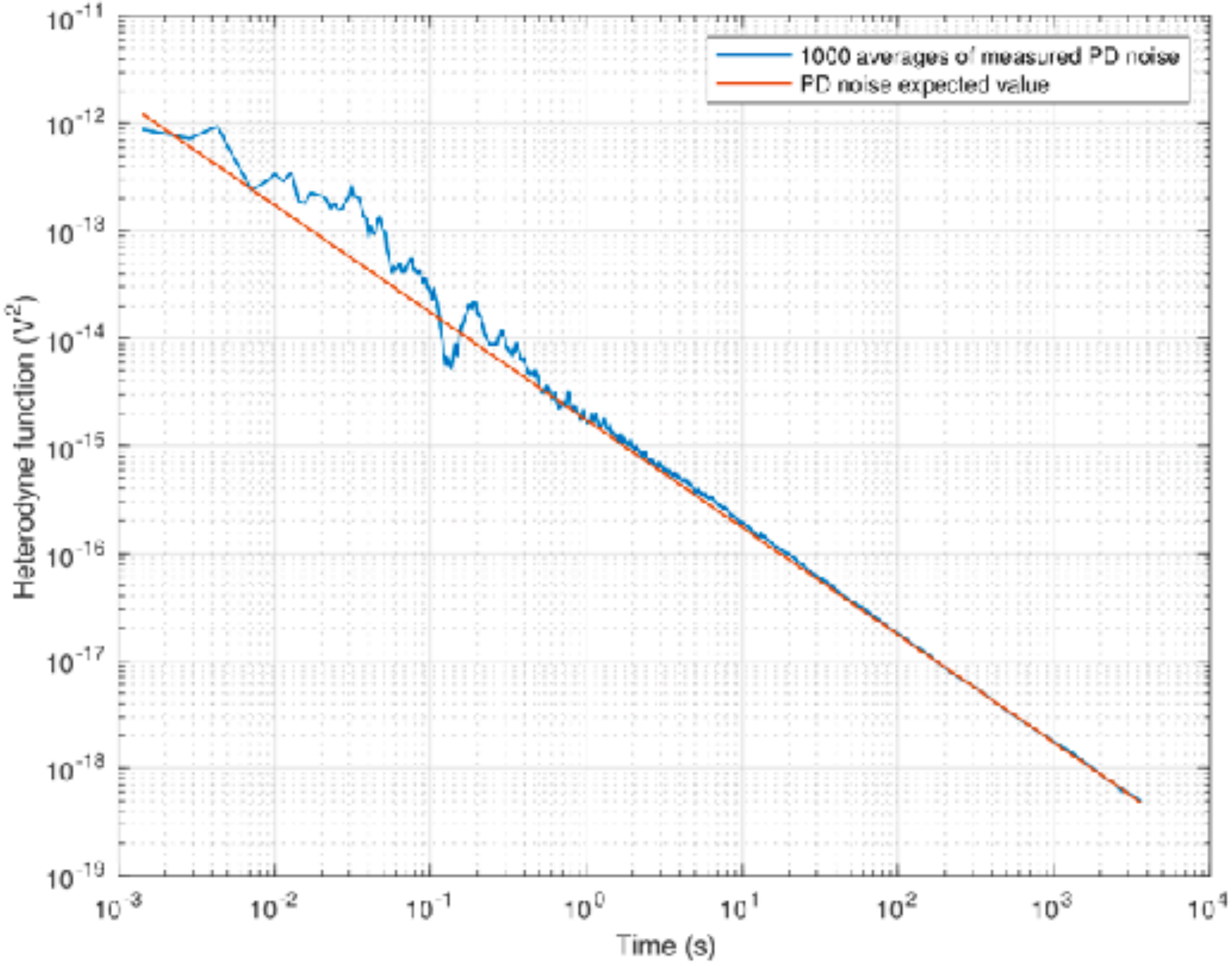
- Environmental Conditions: Humidity, temperature, …
  - affect the stability and accuracy of the measurements

- Mechanical Stability
  - Any vibrations, structural deformations, or movements in the setup can introduce noise and distort the measurement data.

arXiv:1710.04209v4

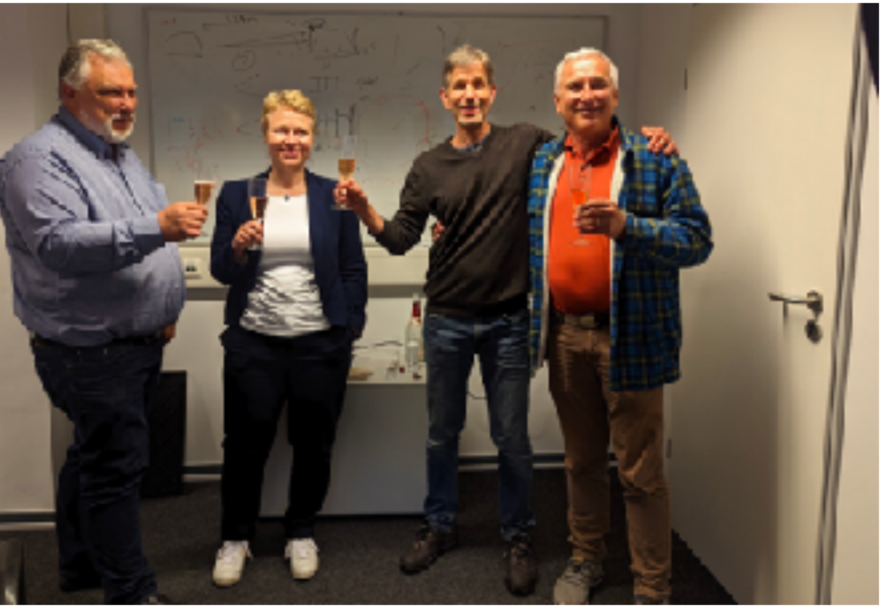


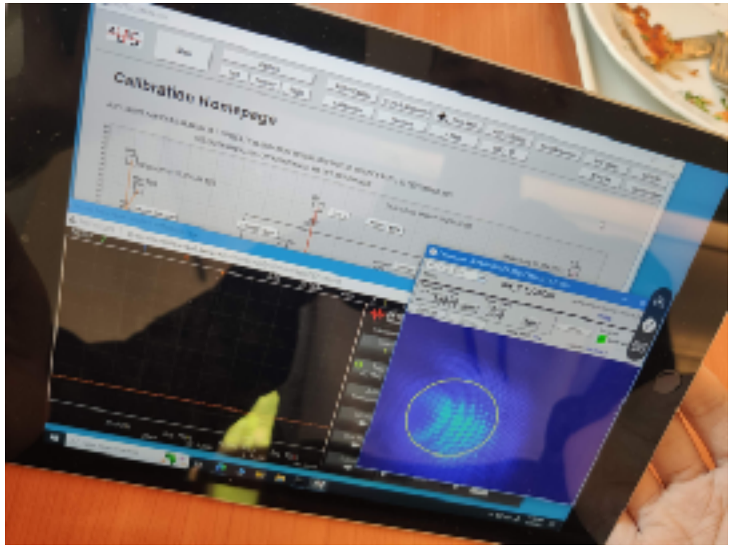
Photodiode noise measurement



Measurement agrees with expectation!!

Initial science run





Conclusion

- Axions and Axion-like particles are well-motivated BSM particles
- LSW: Checking astrophysical observations in a model-independent way
- ALPS II installation began in 2019 and was completed in September 2022
- The photodiode noise is measured using the HET and demonstrated to agree with the expectation
- First data taking is ongoing with a reduced optical system to simplify operation and allow for more systematic tests

- In future, the HET will be used in other axion experiments and to search for high-frequency GW!

Backup

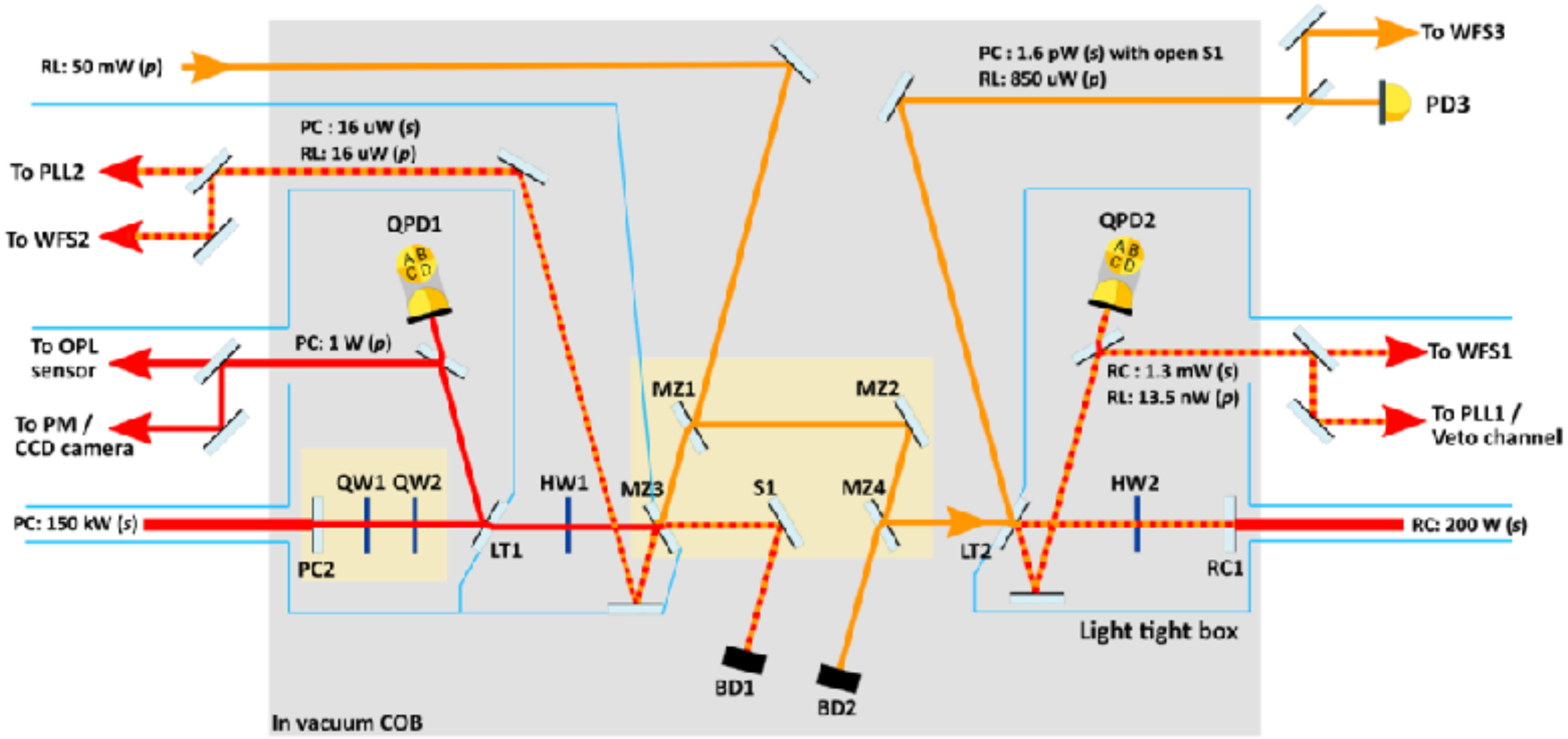
- A combination of the I and Q function measure the photon flux

$$x_{sig}(t) = A\cos(2\pi f_{sig}t + \phi)$$

$$\begin{cases} I = x_{sig}\cos(2\pi f_{sig}t) = A\cos(2\pi f_{sig}t + \phi)\cos(2\pi f_{sig}t) \\ Q = x_{sig}\sin(2\pi f_{sig}t) = A\cos(2\pi f_{sig}t + \phi)\sin(2\pi f_{sig}t) \end{cases}$$

$$\begin{cases} I = \frac{A}{2}[\cos(\phi) + \cos(4\pi f_{sig}t + \phi)] \\ Q = \frac{A}{2}[\sin(\phi) + \cos(4\pi f_{sig}t + \phi)] \end{cases}$$

$$z = I^2 + Q^2 = \frac{A^2}{4} \propto N_\gamma$$



RL: 50 mW (p)
PC : 1.6 pW (s) with open S1
RL: 850 uW (p)
To WFS3
PD3
PC : 16 uW (s)
RL: 16 uW (p)
To PLL2
To WFS2
QPD1
QPD2
To OPL sensor
PC: 1 W (p)
To PM / CCD camera
MZ1
MZ2
To WFS1
RC : 1.3 mW (s)
RL: 13.5 nW (p)
To PLL1 / Veto channel
QW1
QW2
HW1
MZ3
S1
MZ4
HW2
PC: 150 kW (s)
LT1
LT2
RC: 200 W (s)
PC2
RC1
Light tight box
BD1
BD2
In vacuum COB