Heterodyne detection of weak fields in ALPS II

DPG SMuK conference 2023

Isabella Oceano on behalf of the ALPS II collaboration

23th March 2023

Brief introduction to axions

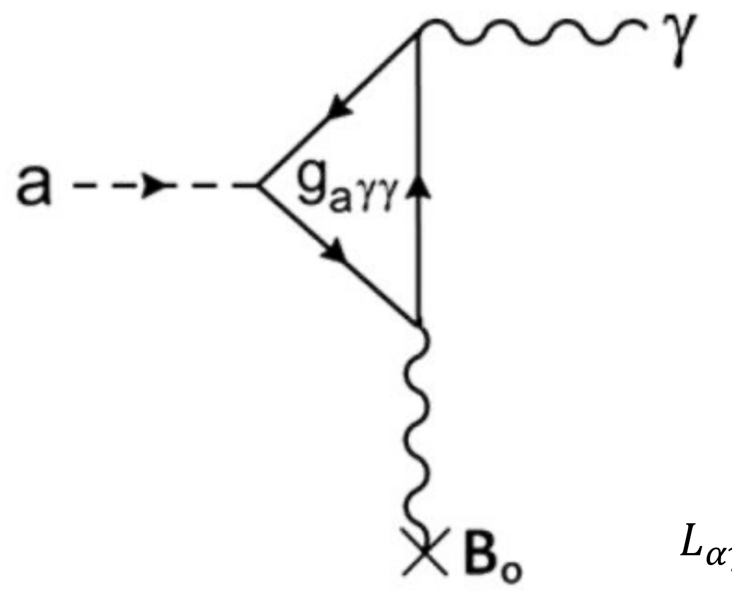
Motivation

- Axions to solve the riddle of CP-conservation in QCD
- Photon propagation in the universe
- Excessive stellar cooling
- Dark matter candidates

Searches strategy

- Haloscopes
- Helioscopes
- Light-shining-through-walls

Sikivie effect



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

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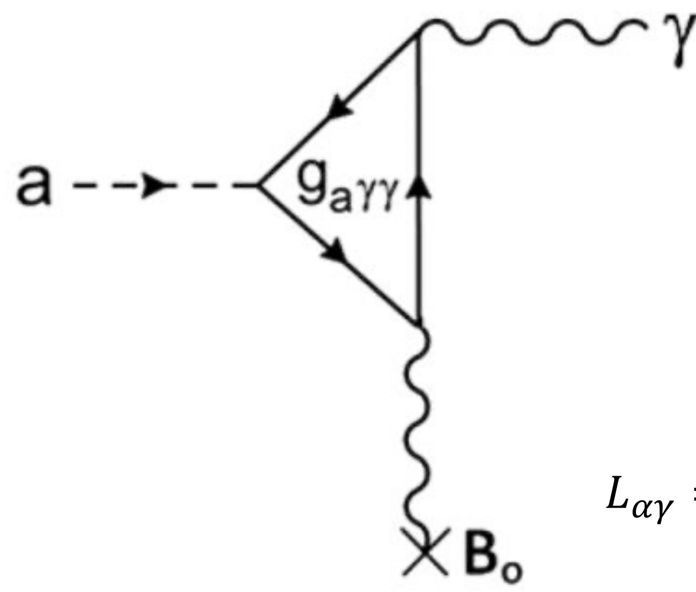
- **Light-shining-through-walls**

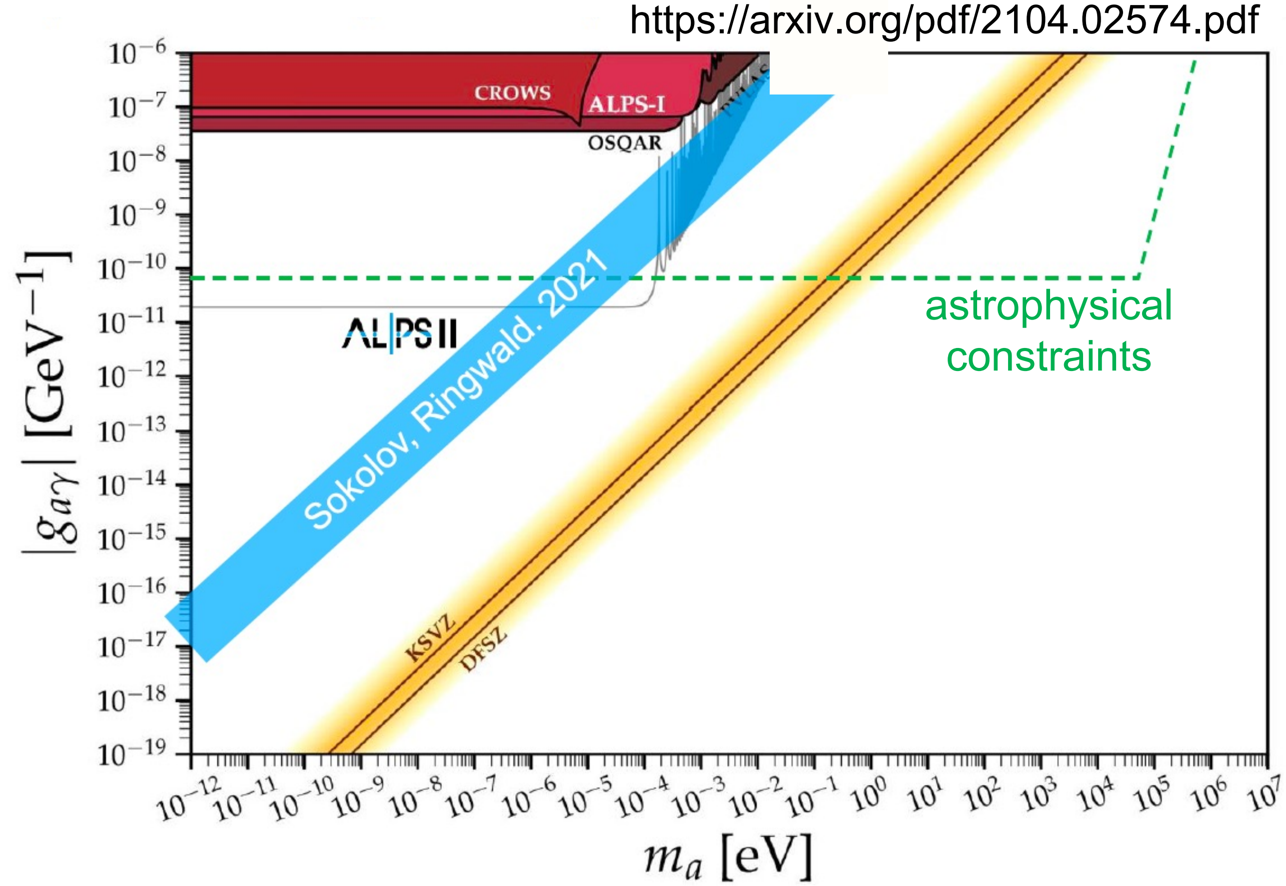
Not requiring cosmological or astrophysical assumptions → ALPS II

Sikivie effect



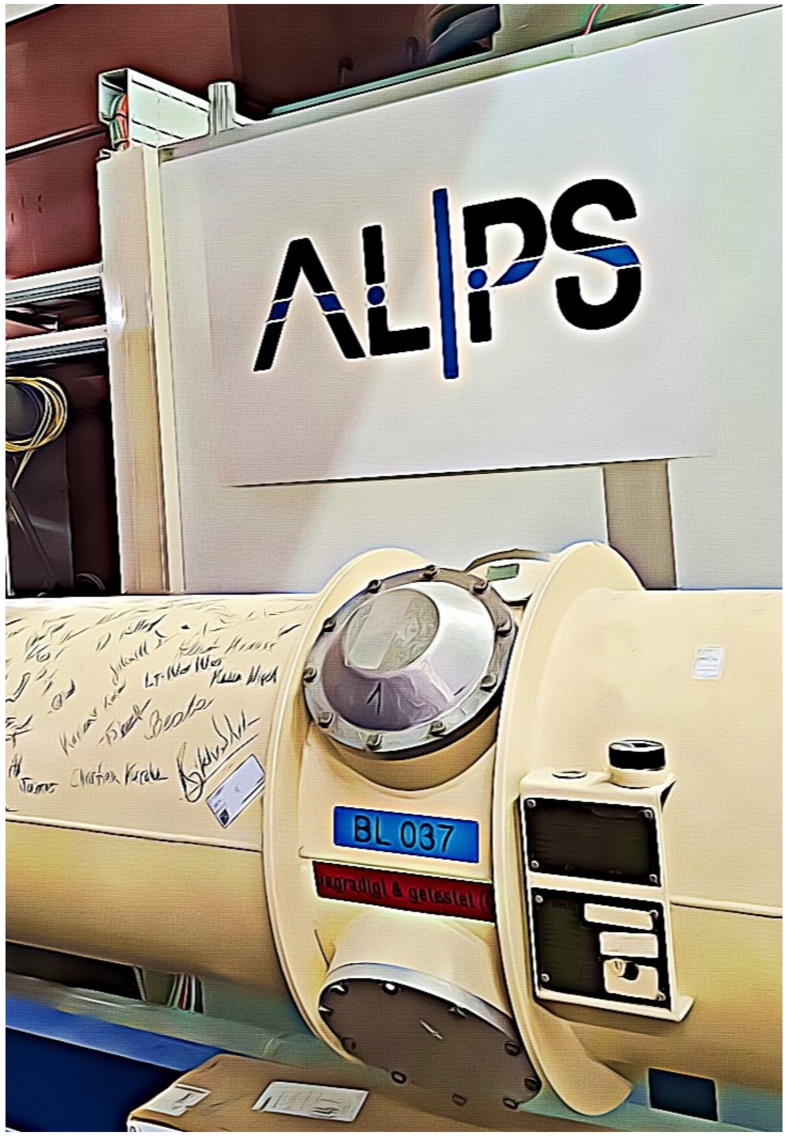
$$L_{\alpha\gamma} = g_{\alpha\gamma}\phi_\alpha \vec{E}\cdot\vec{B}$$

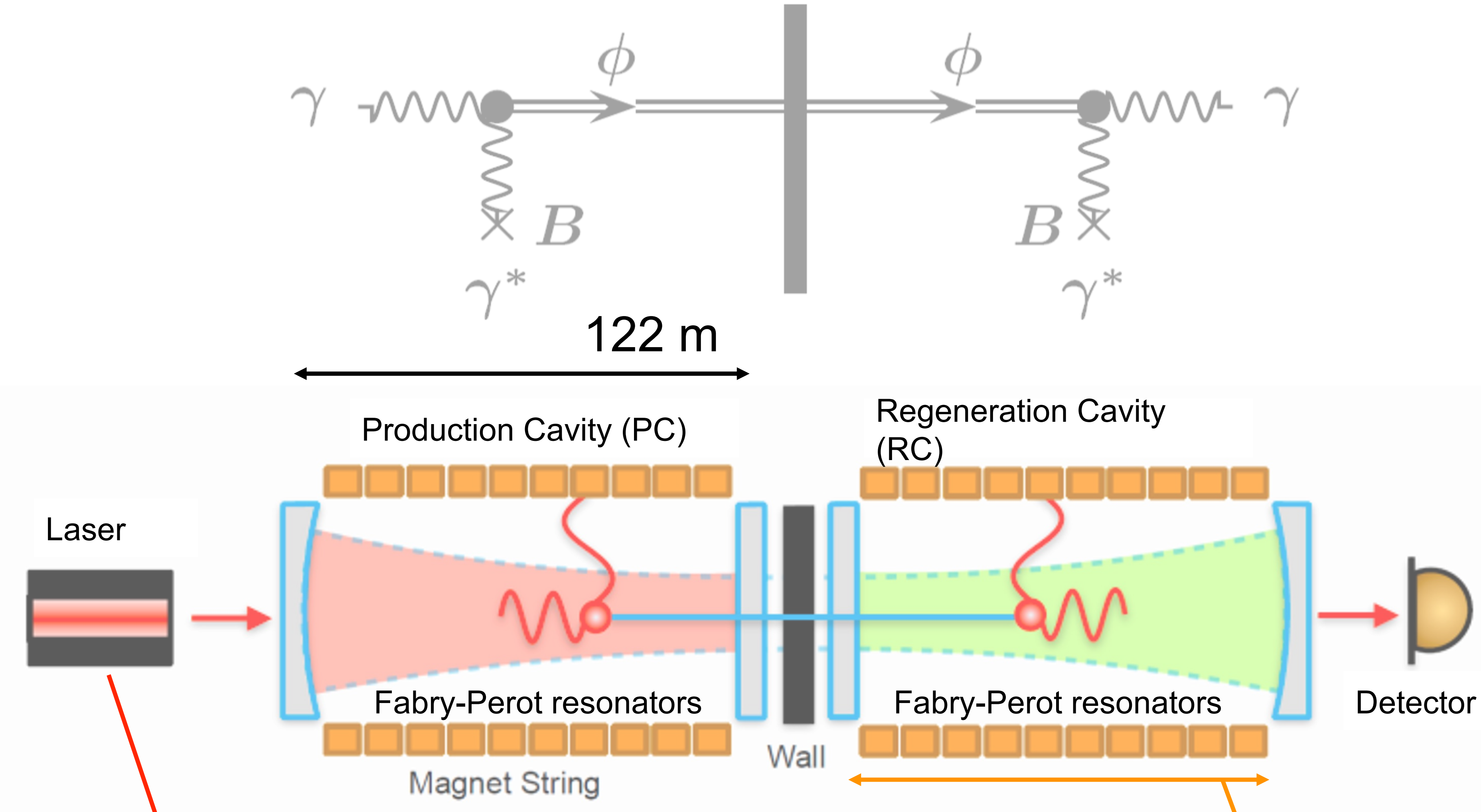
https://arxiv.org/pdf/2104.02574.pdf



Any Light Particle Search II

DESY





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

12 × 5.3 Tesla HERA dipole magnets

$$P(\gamma \rightarrow \alpha \rightarrow \gamma) = \left(\frac{g_{\alpha\gamma\gamma}\boxed{B_0 L_B}}{2}\right)^4 \boxed{\beta_{PC}}\boxed{\beta_{RC}}$$

Two detection systems will be used

- **HETerodyne interferometer**
- Transition Edge Sensor

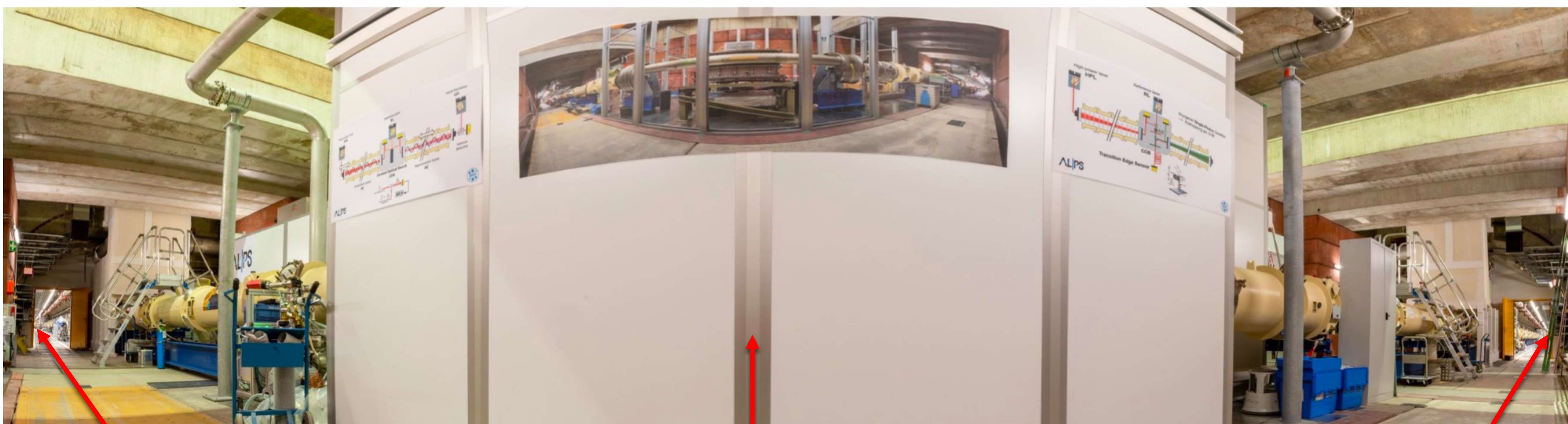
More details in:

- *"Recent Updates on the ALPS II experiment"* – Gulden Othman
- *"A TES for ALPS II – Status and Prospects"* – José Alejandro Rubiera Gimeno
- *"Further dark matter searches using ALPS II's TES detector "* – Christina Schwemmbauer

ALPS II achievements

- Installation of ALPS II began in 2019

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

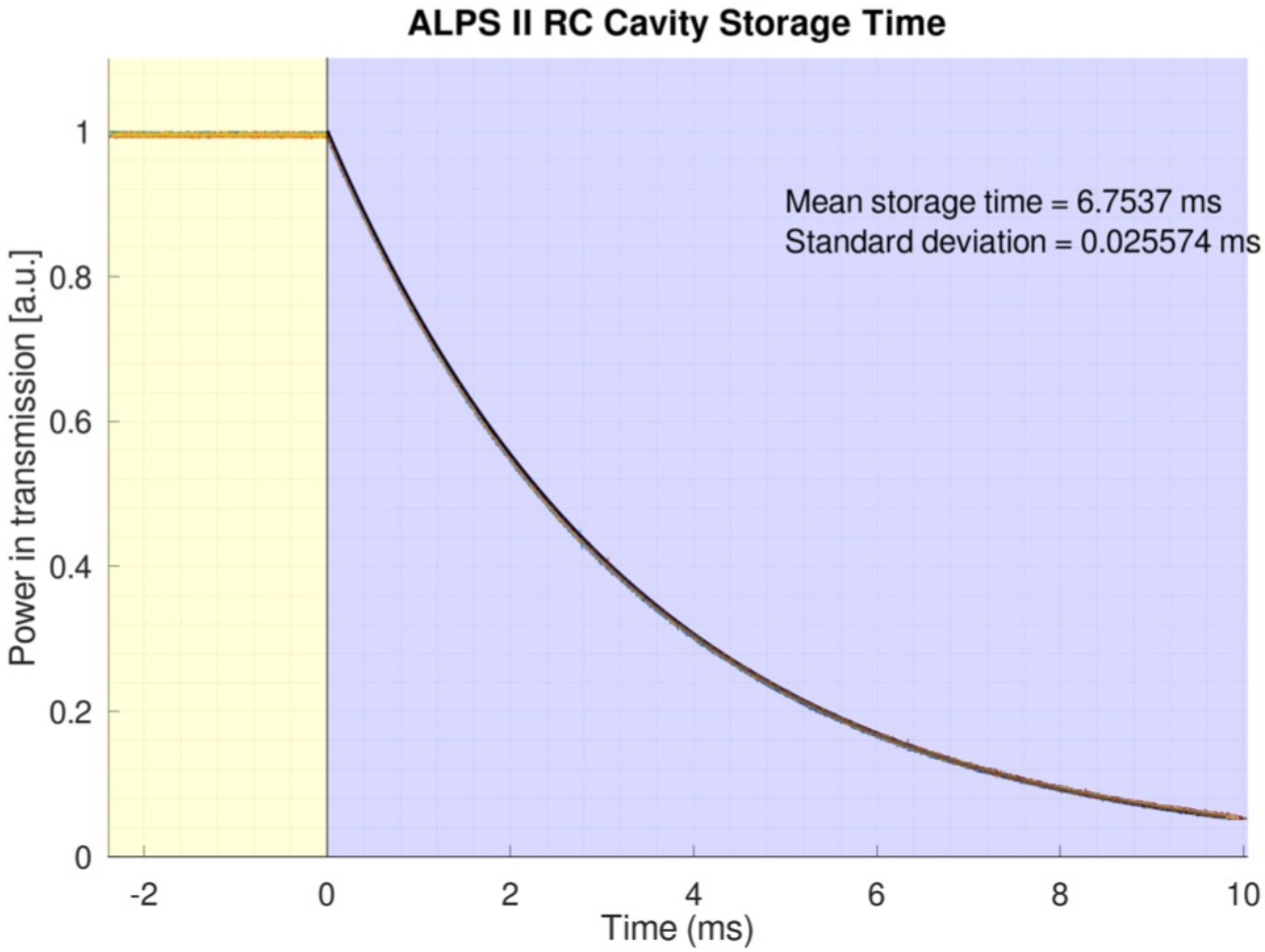


Laser Wall Detector

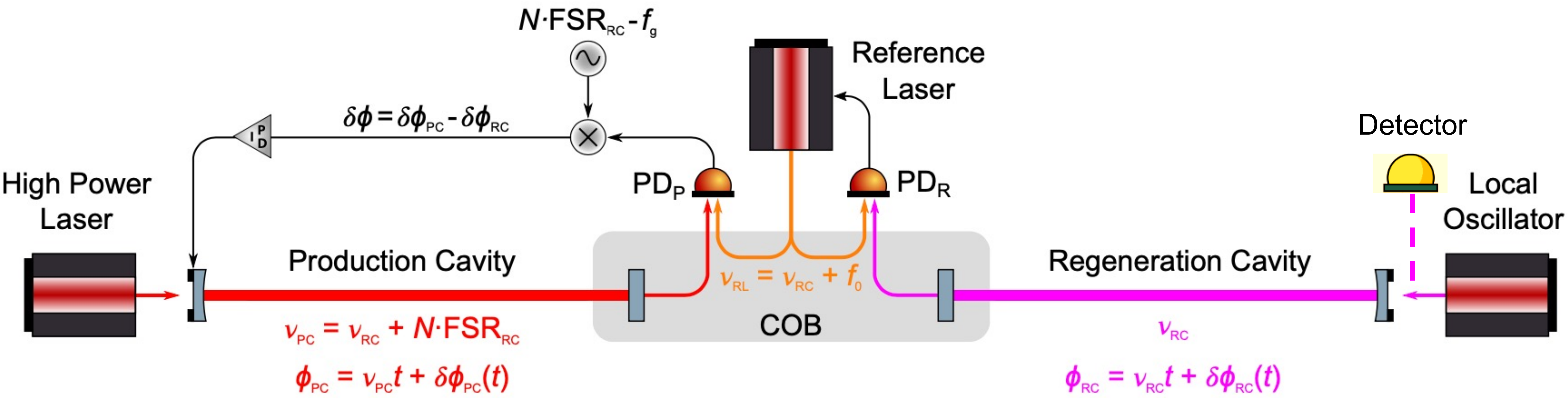
ALPS II achievements - World-record

Longest storage time Fabry Perot cavity ever!

- Length: 124.6m, FSR: 1.22 MHz
- Storage time: **6.75 ms**



ALPS II's first science run scheme

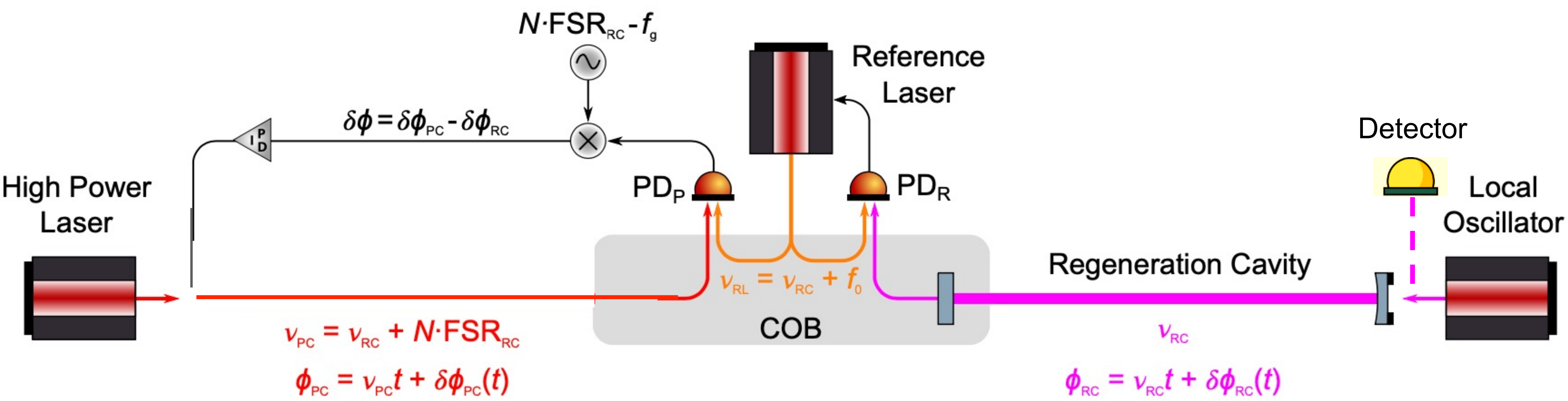


Amplifies circulating powerbefore the wall

Amplifies electromagnetic component of the axion field

ALPS II's early science run scheme

https://arxiv.org/pdf/2010.02334.pdf



Amplifies circulating powerbefore the wall

Amplifies electromagnetic component of the axion field

In ~a month the early science run will take place w/o the PC optimal for stray light hunting

!

Already a factor 100 beyond earlier LSW experiments!

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

- $g_{\alpha\gamma\gamma} = 2\times10^{-10}\mathrm{GeV}^{-1}$
- $5000 < \beta < 8000$
- $P_c = 40\mathrm{W}$

HETerodyne: Coherent detection

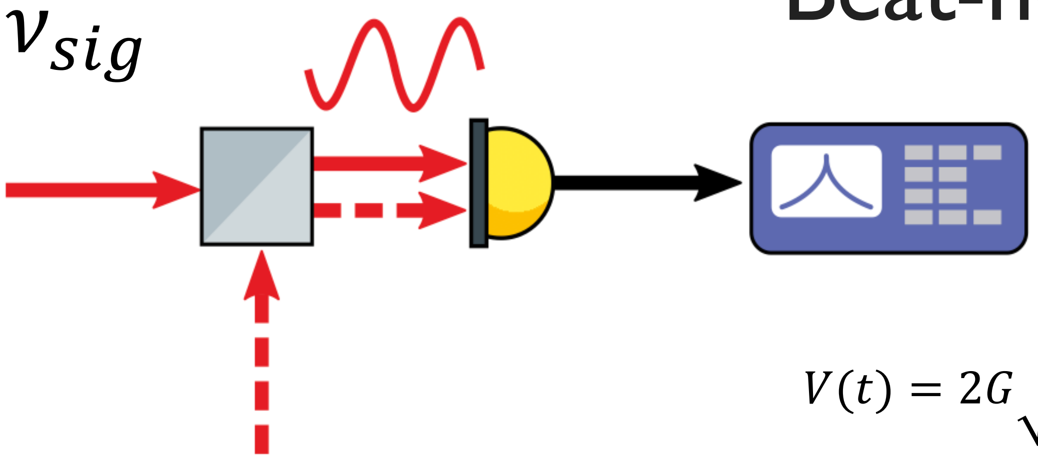
- The term has its root in the greek words ‘heteros’ (other) ‘dynamis’ (force)

New frequencies are created by mixing two frequencies

ν_1

Beat-note

ν_{sig}



$$V(t) = 2G\sqrt{P_{sig}P_{LO}}cos(2\pi\nu_0 t + \Delta\phi)$$

$$\nu_{LO} = \nu_{sig} + \nu_1$$

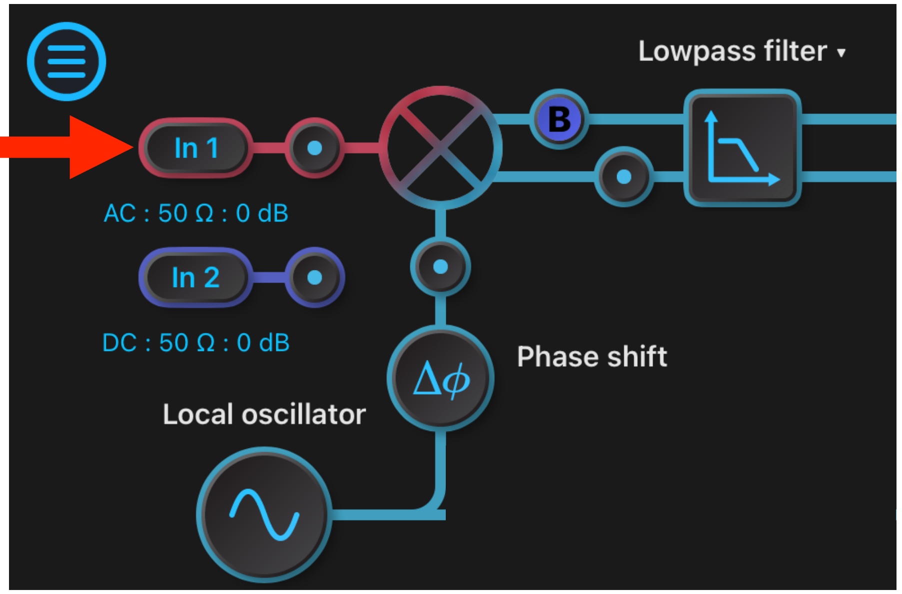
R. Fessenden

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

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

Signal extraction

f_1



$I[n]$

$Q[n]$

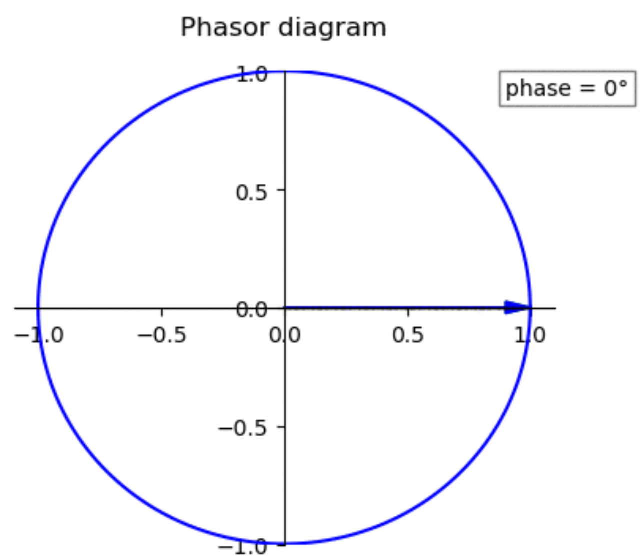
$$f_{dem} = f_1 + f_0'$$

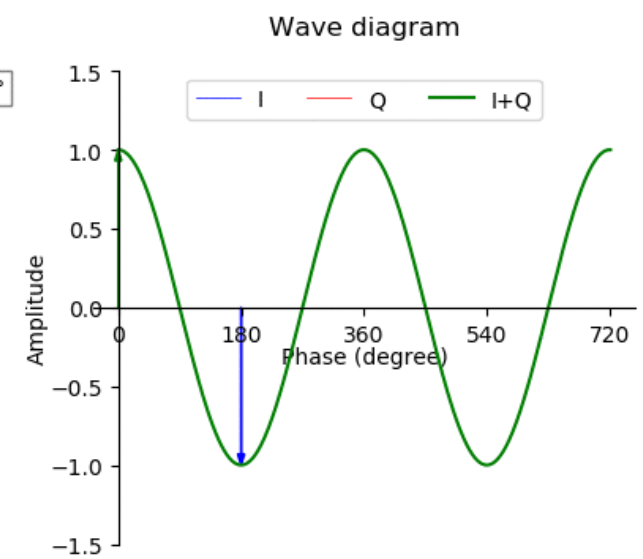
To recover amplitude information → **I/Q demodulation**

- $I[n] = x[n] \times cos(2\pi f_0' \cdot t)$
- $Q[n] = x[n] \times sin(2\pi f_0' \cdot t)$

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 - Signal

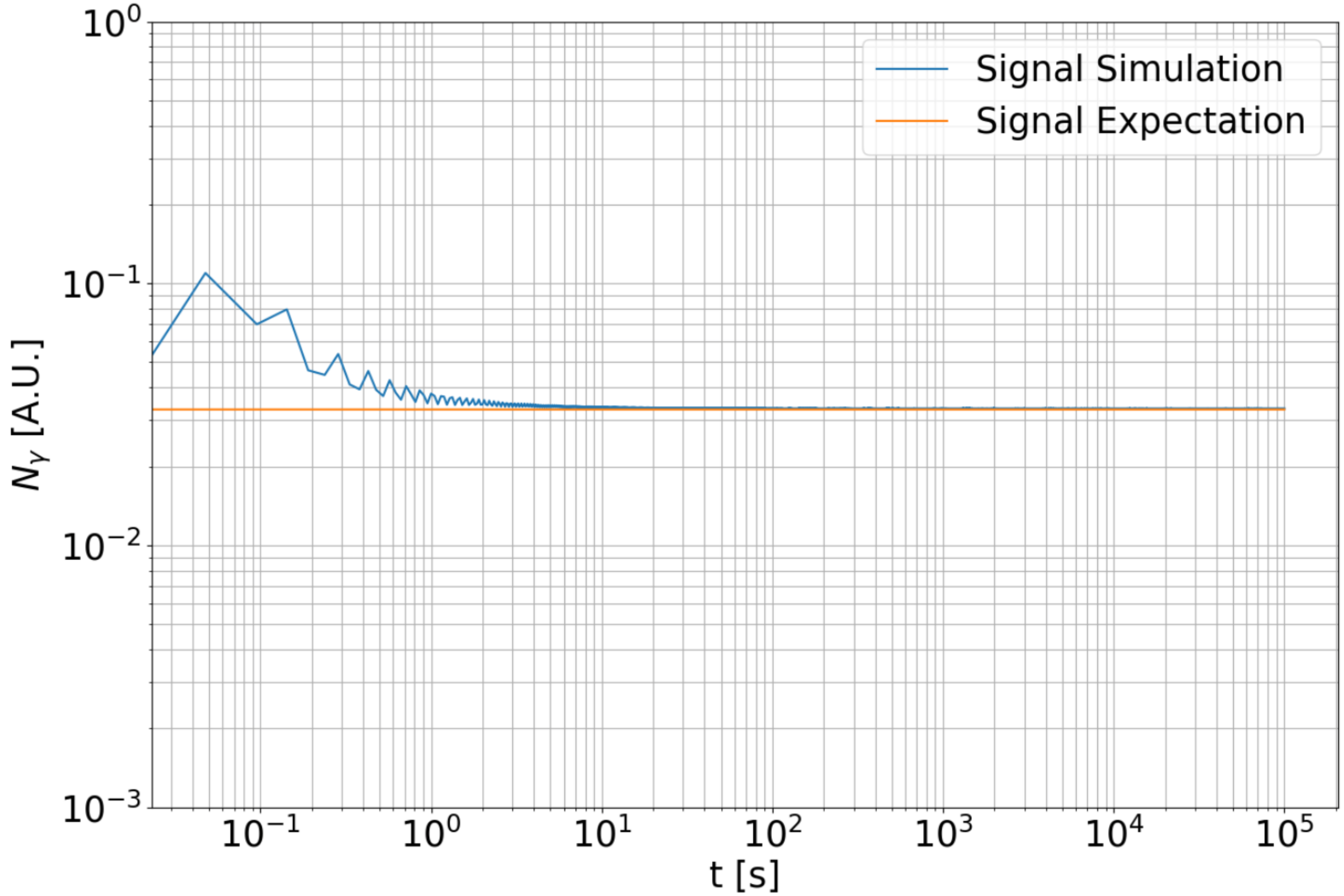
Number of photons

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

Signal

Will sum coherently

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

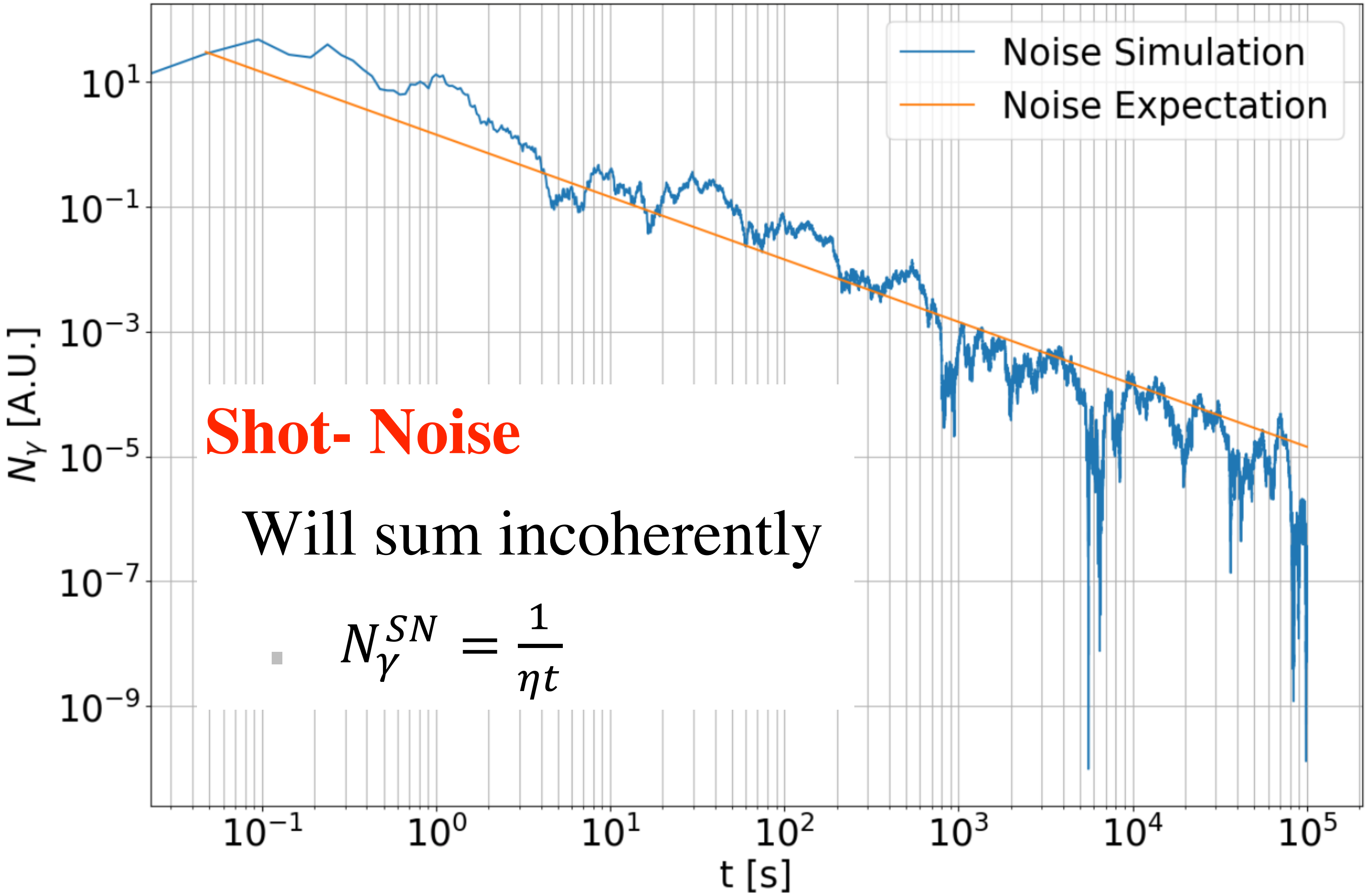


Photon flux extraction - Noise

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

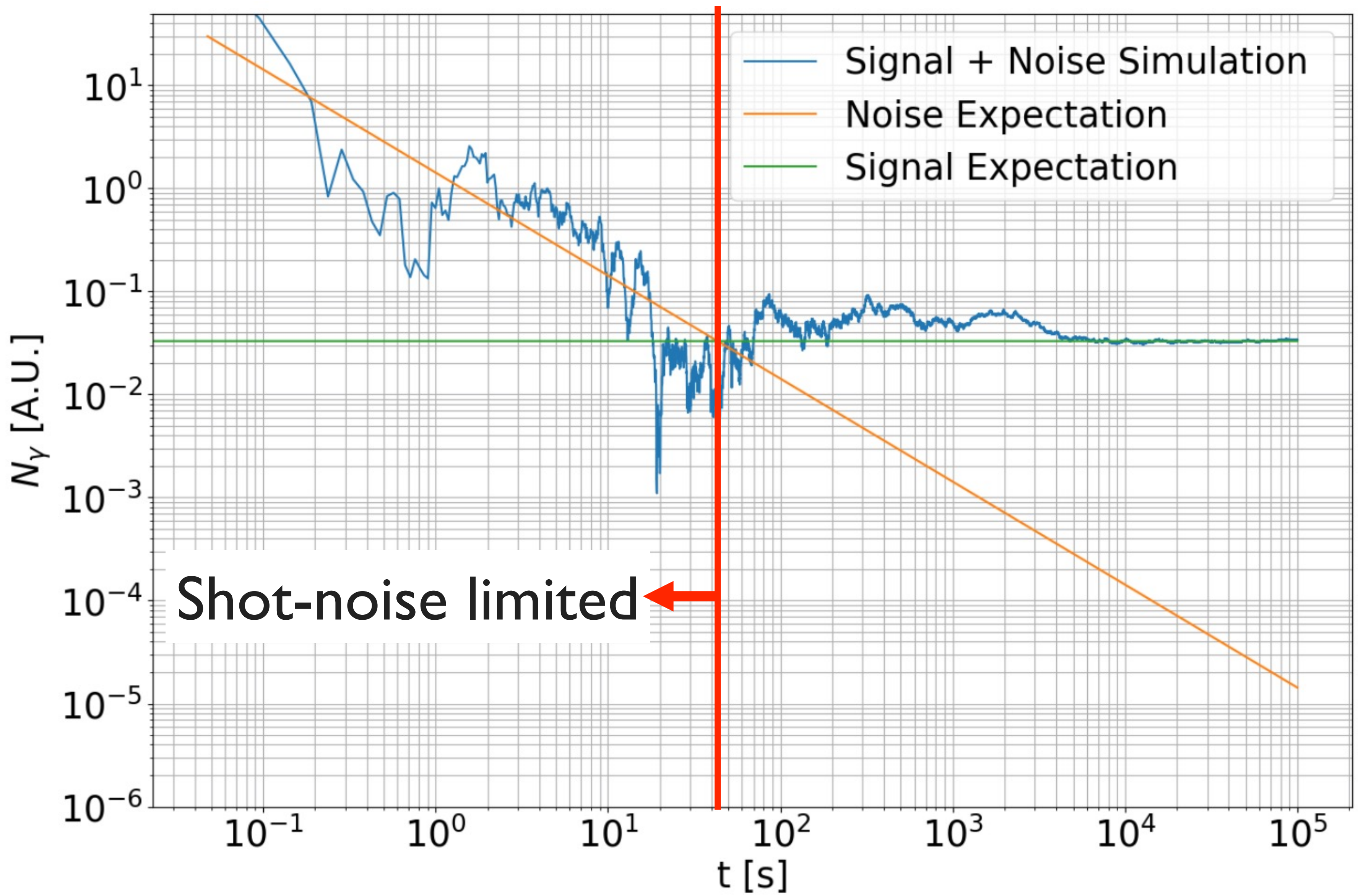
Will sum incoherently

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

Photon flux extraction - Signal + Noise

Number of photons

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

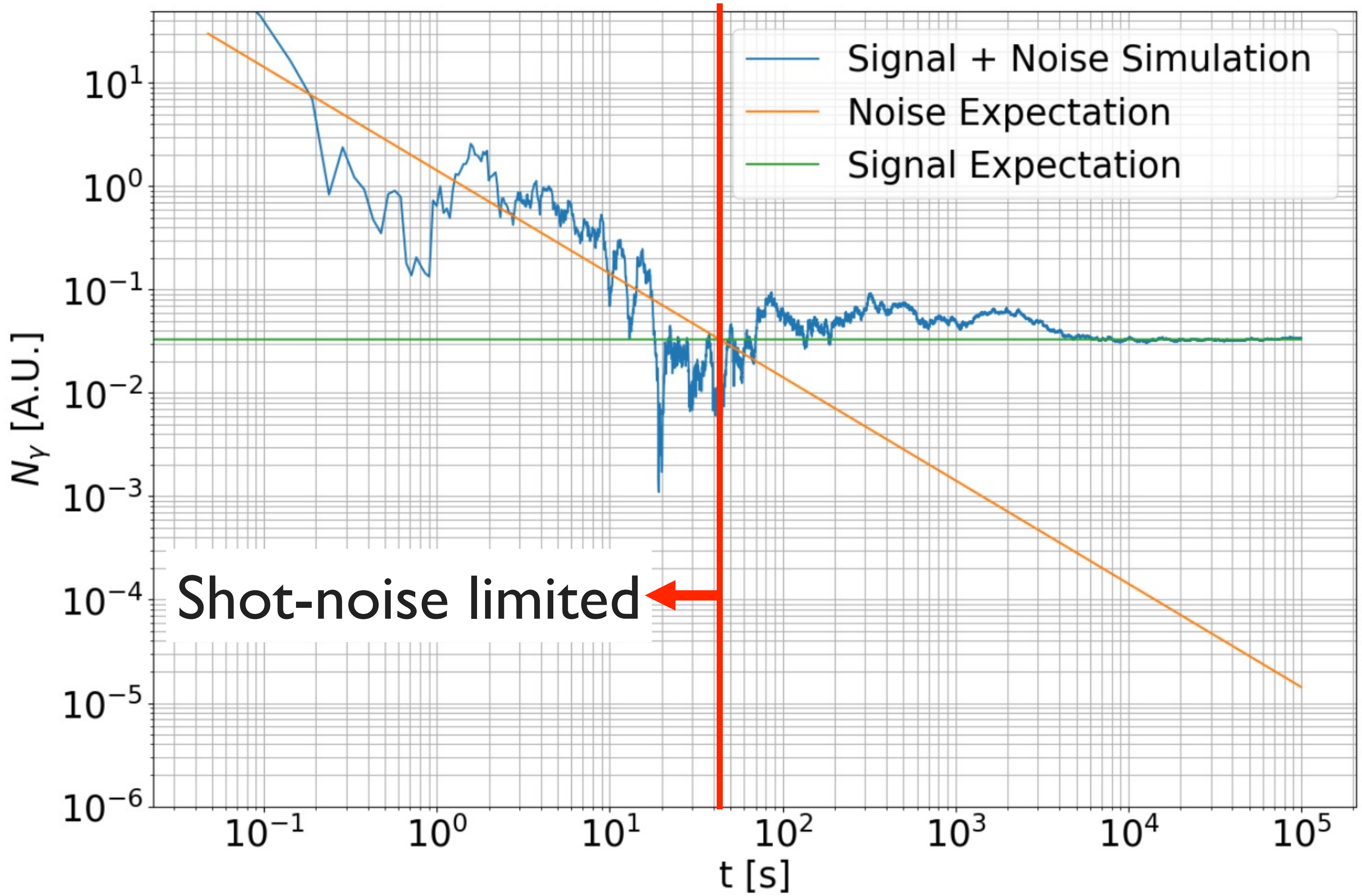


Photon flux extraction - Signal + Noise

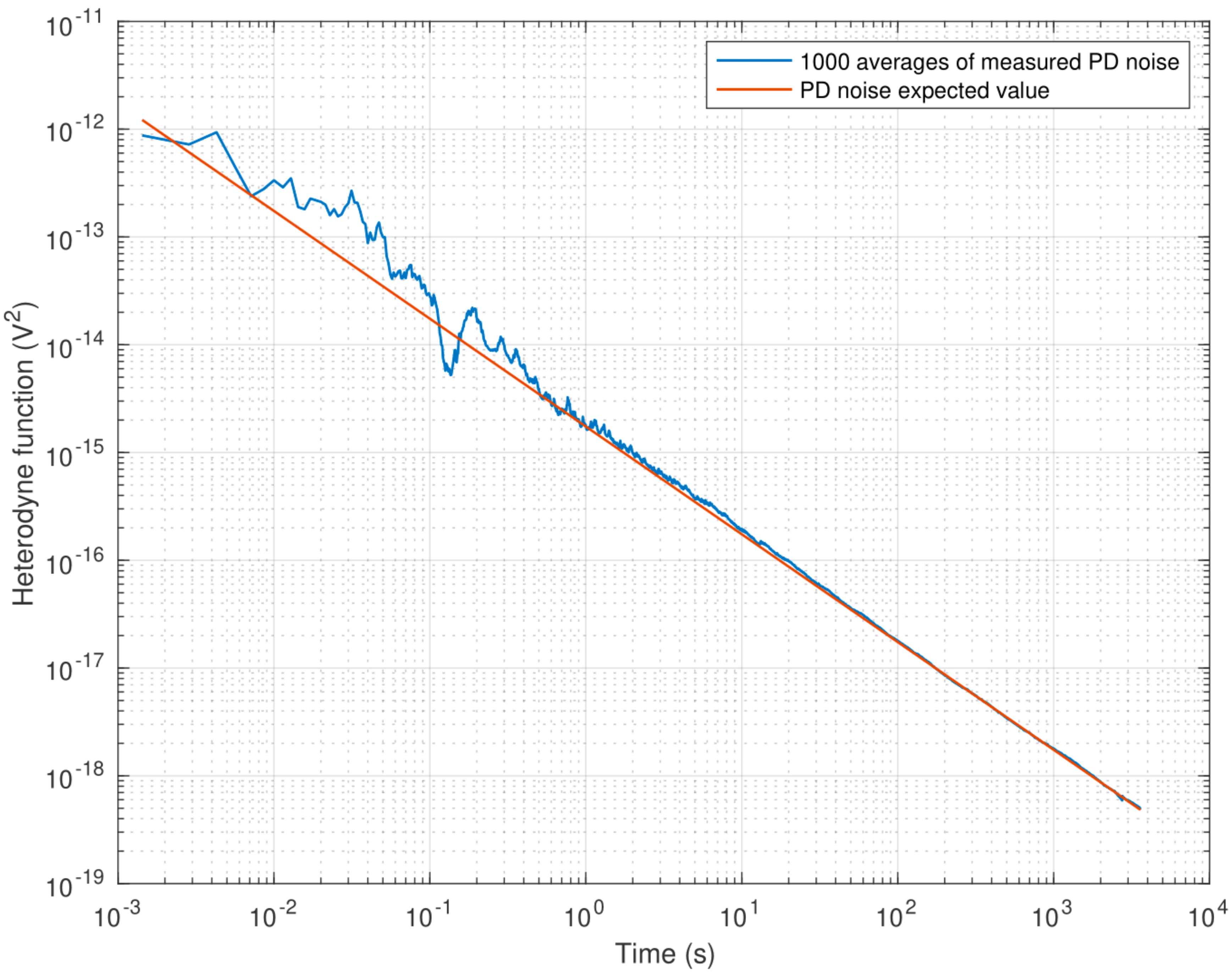
Number of photons

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

ALPS II integration time: ~**20 days**



Shot-noise measurement



Measurement agrees with expectation!!

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 **shot noise** is measured using the HET and demonstrated to **agree** with the expectation
- **First data taking** is expected in a **few months** and will take place with a reduced optical system to simplify operation and allow for more systematic tests

Backup

I/Q → N_γ

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

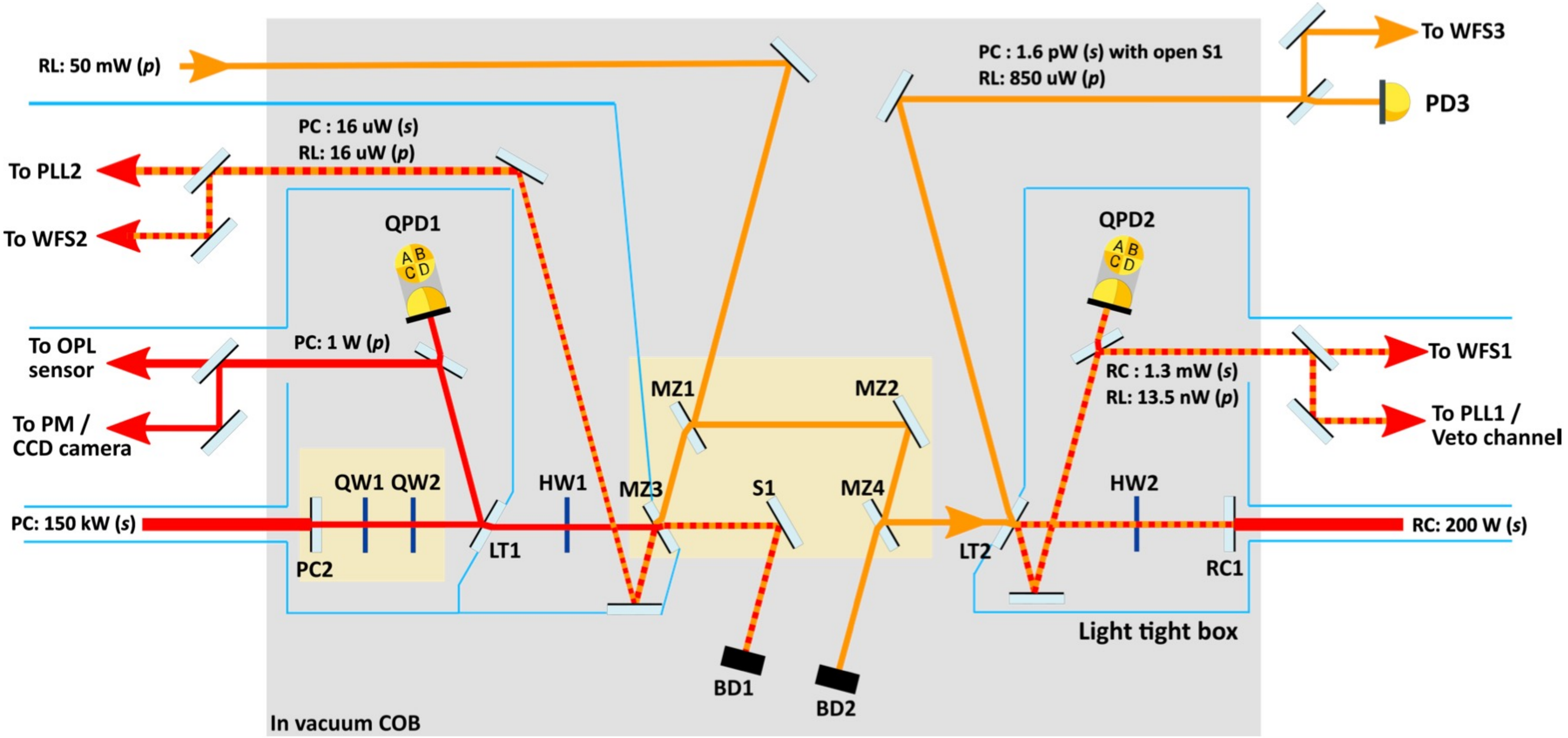
$$x_{sig}(t) = A\cos(2\pi f_{sig}t + \phi)$$

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

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

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

COB


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