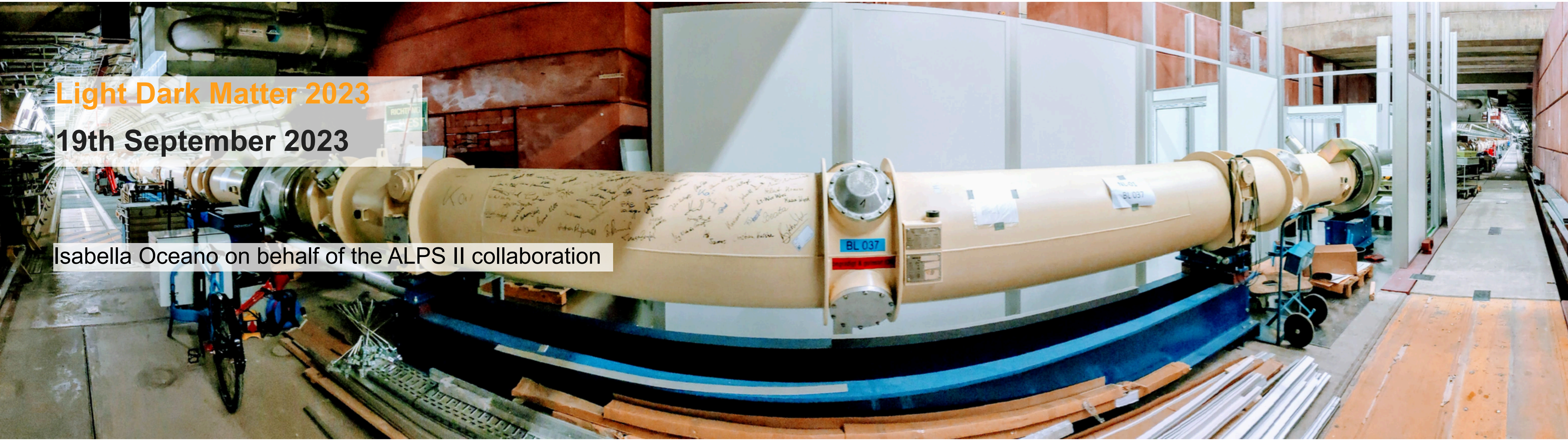
Status of the initial ALPS II science run



Light Dark Matter 2023

19th September 2023

Isabella Oceano on behalf of the ALPS II collaboration

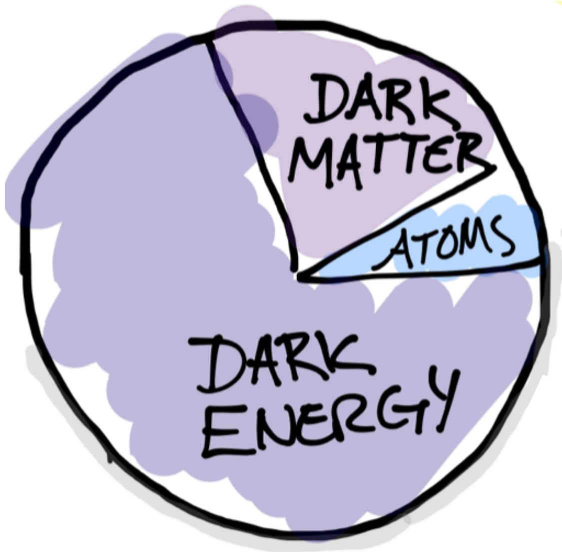
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

SDU University of Southern Denmark · Leibniz Universität Hannover · UF University of Florida · UHH · Cardiff University Prifysgol Caerdydd · JGU · DESY

Axion and Axion-Like particles

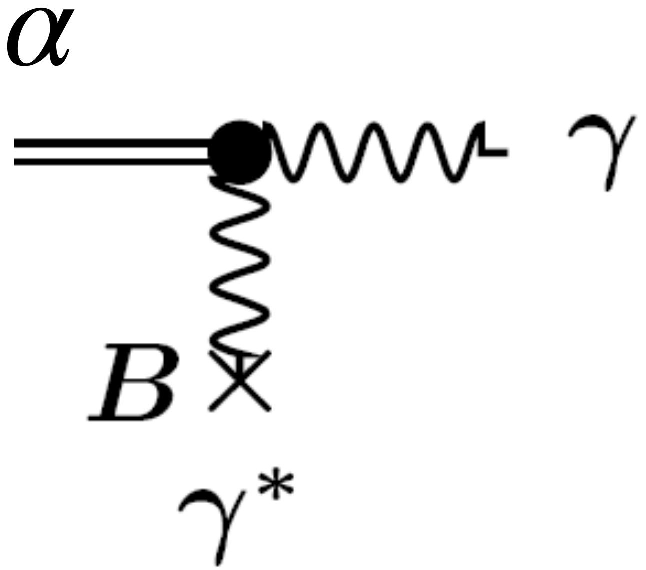
Motivation

- 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.



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

couplings to Standard
Model constituents

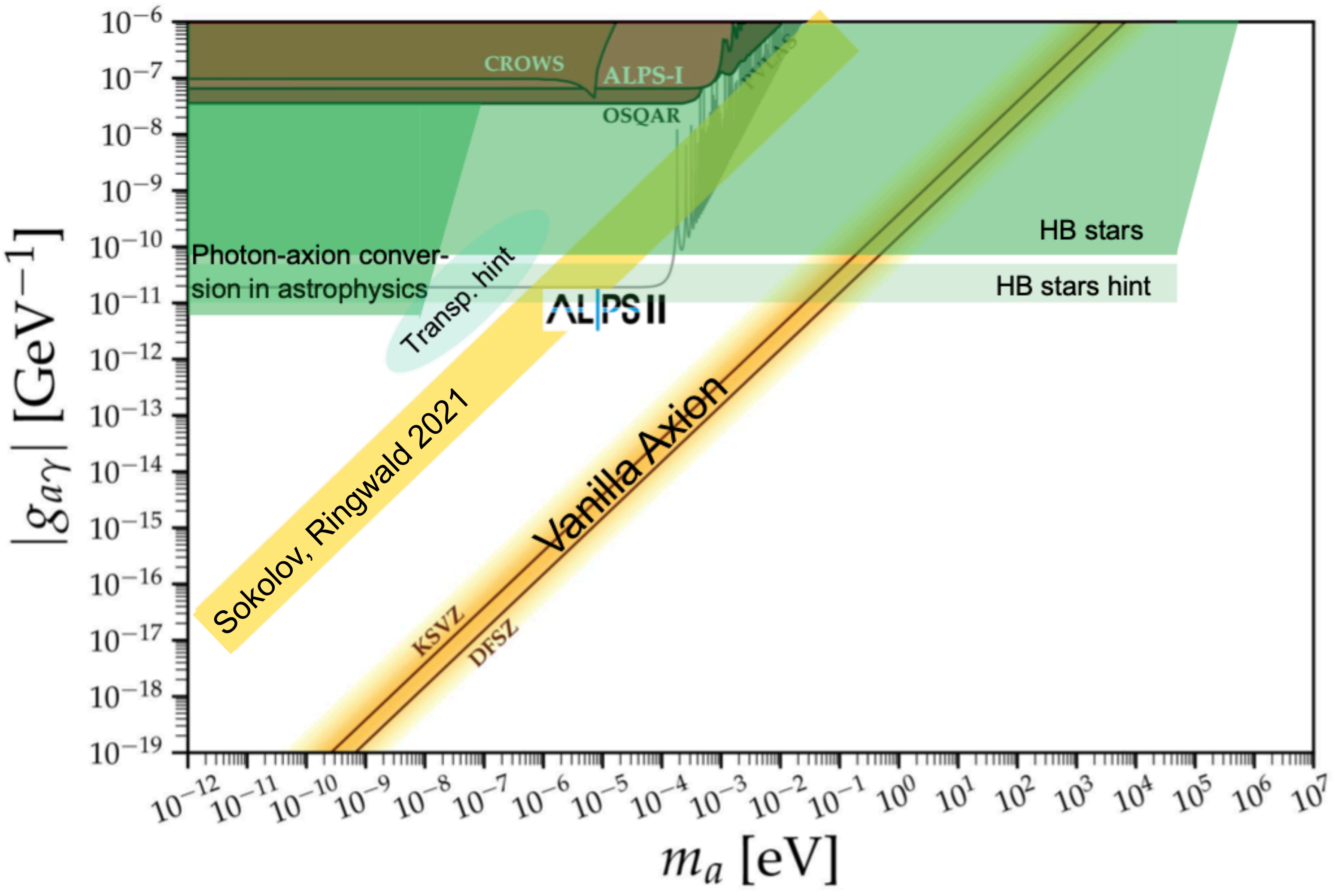


Sikivie effect

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

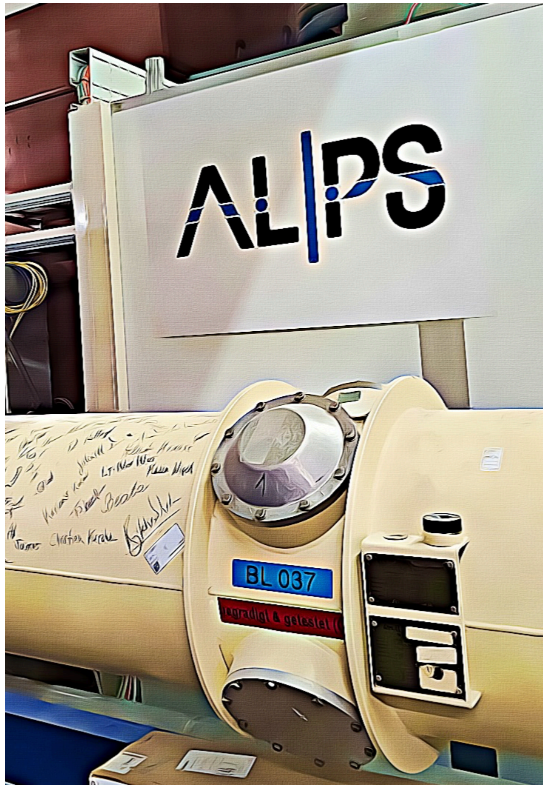
Any Light Particle Search II
Strengths

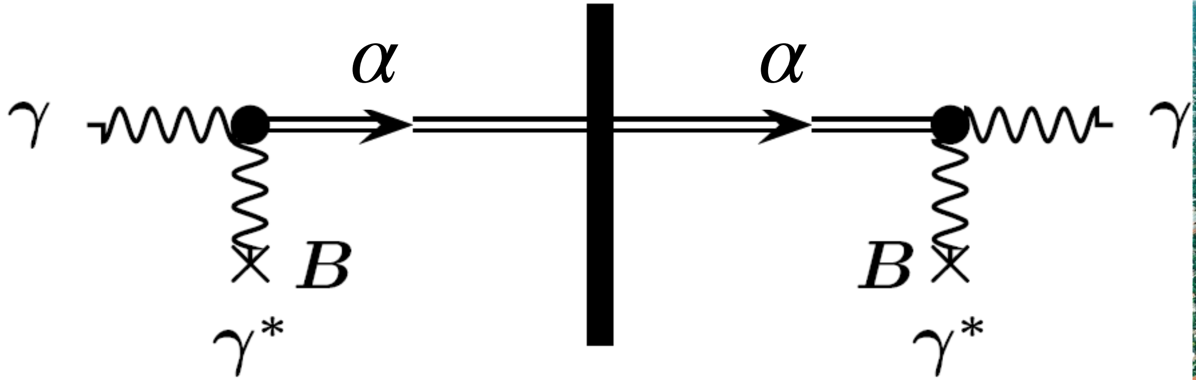
- ALPS II designed to improve sensitivity compared to ALPS I by a factor of ~3000
  - Exploring uncharted territory in parameter space, beyond astrophysical constraints
  - Checking axion explanation of astrophysical anomalies

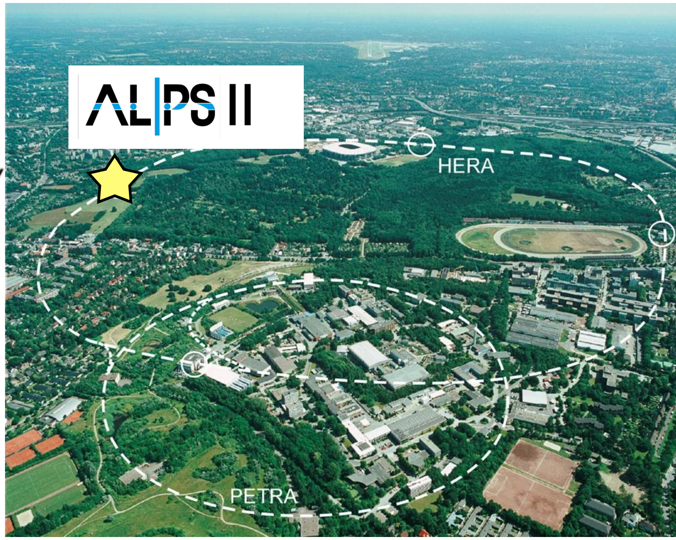


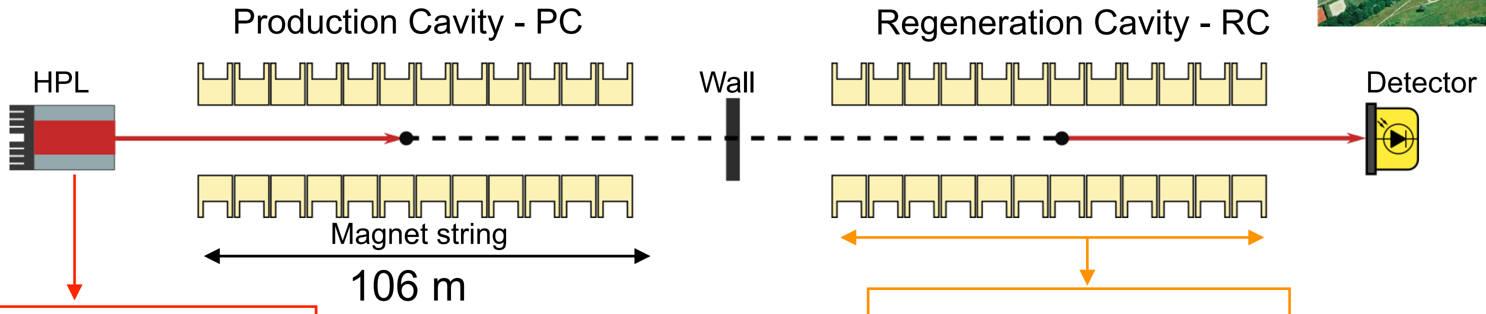
Any Light Particle Search II

The axion factory









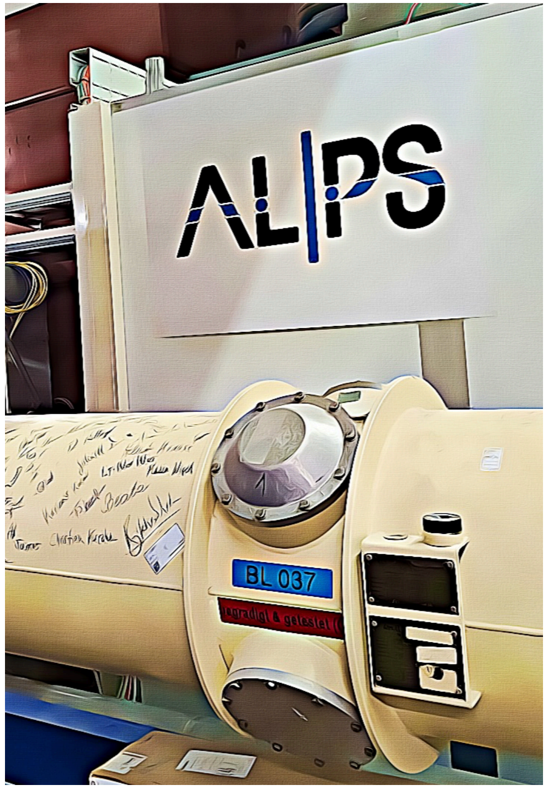
High power laser, 40W,
λ=1064 nm ~ 282 THz

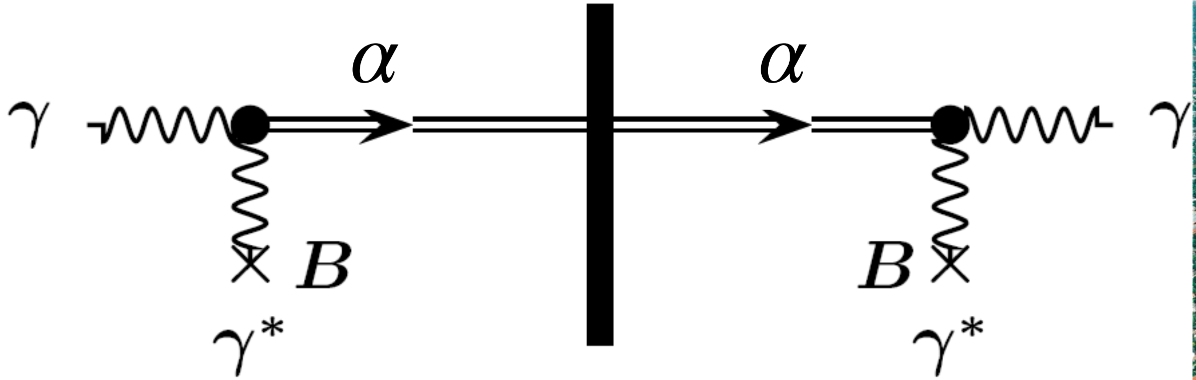
12 × 5.3 Tesla HERA
dipole magnets

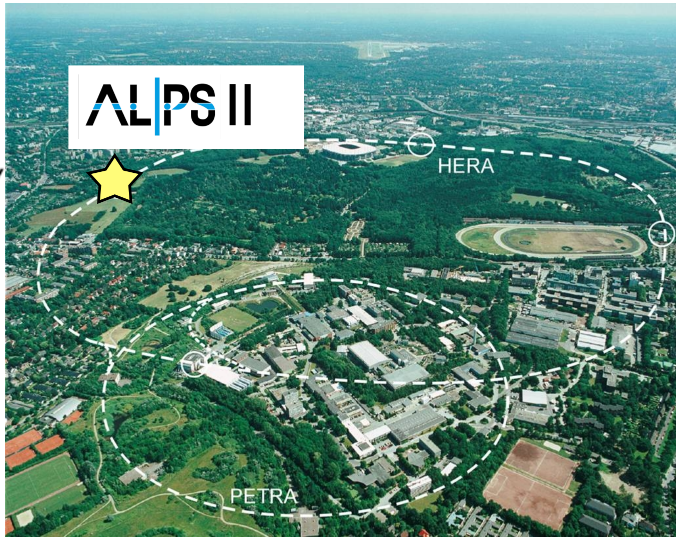
$$n_{\text{signal}} \approx \frac{1\ \text{photon}}{115{,}000\ \text{yr}} \cdot \left(\frac{P_{\text{laser}}}{50\ \text{W}}\right)\left(\frac{g_{a\gamma\gamma}}{2\times10^{-11}\ \text{GeV}^{-1}}\right)^4\left(\frac{B}{5.3\ \text{T}}\right)^4\left(\frac{L}{106\ \text{m}}\right)^4$$

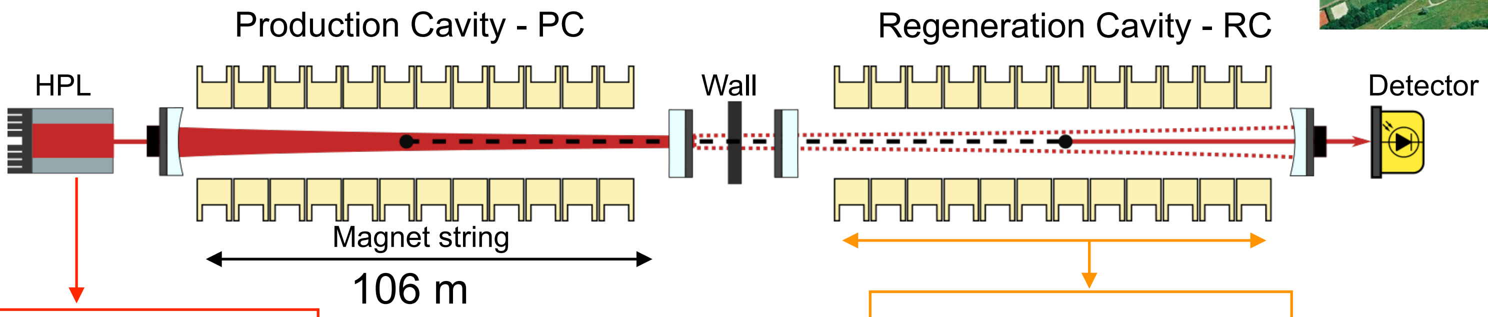
Any Light Particle Search II

The axion factory









High power laser, 40W, λ=1064 nm ~ 282 THz

12 × 5.3 Tesla HERA dipole magnets

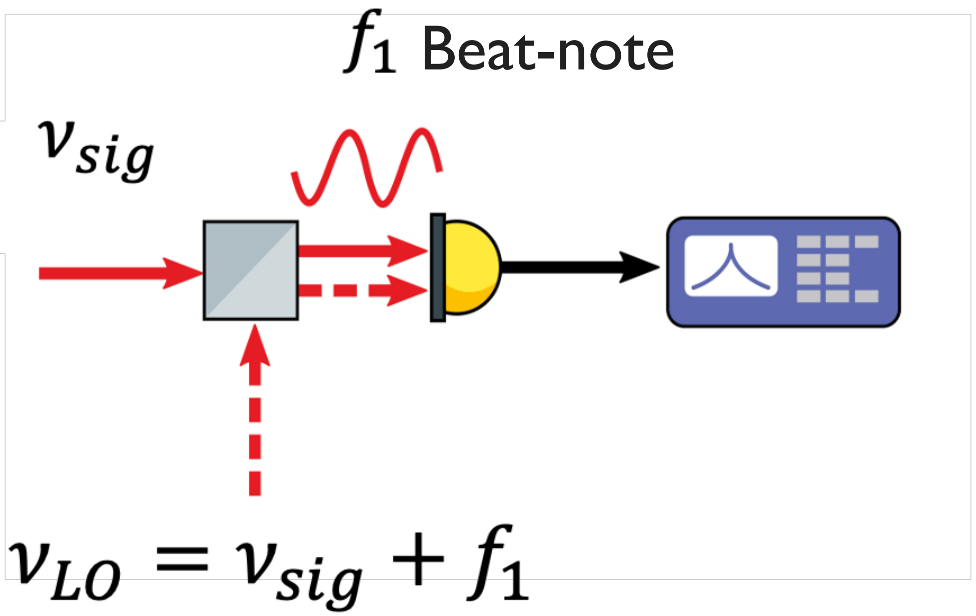
β: power buildup RC
η: quantum efficiency

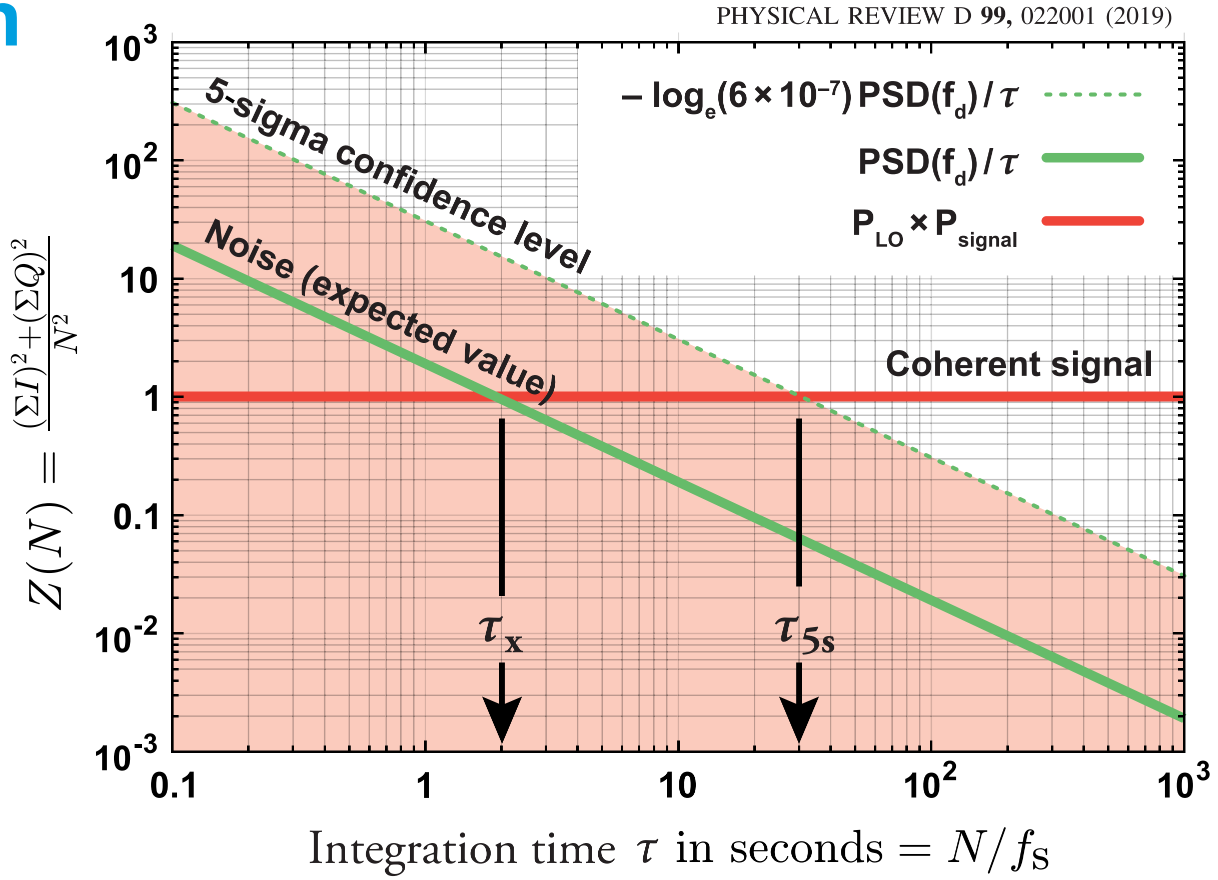
$$n_{\text{signal}} \approx \boxed{\frac{1\ \text{photon}}{37\ \text{hours}}} \cdot \left(\frac{P_{\text{PC}}}{150\ \text{kW}}\right)\left(\frac{\beta_{\text{RC}}}{10{,}000}\right)\left(\frac{\eta}{0.9}\right)\left(\frac{g_{a\gamma\gamma}}{2\times10^{-11}\ \text{GeV}^{-1}}\right)^4\left(\frac{B}{5.3\ \text{T}}\right)^4\left(\frac{L}{106\ \text{m}}\right)^4$$

HETerodyne: Coherent detection

A very sensitive technique

- 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





- 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}

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

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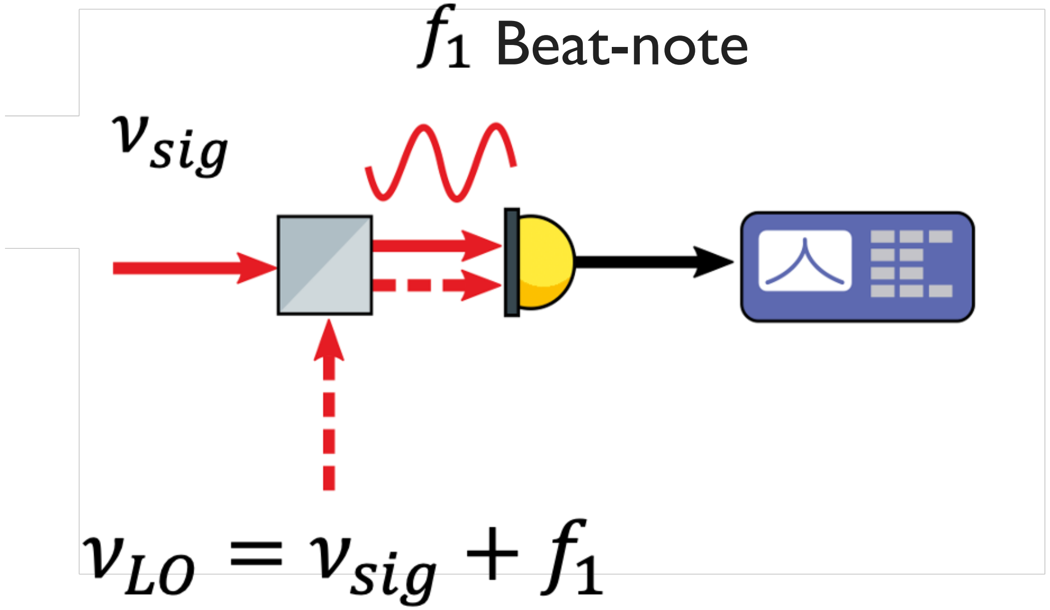

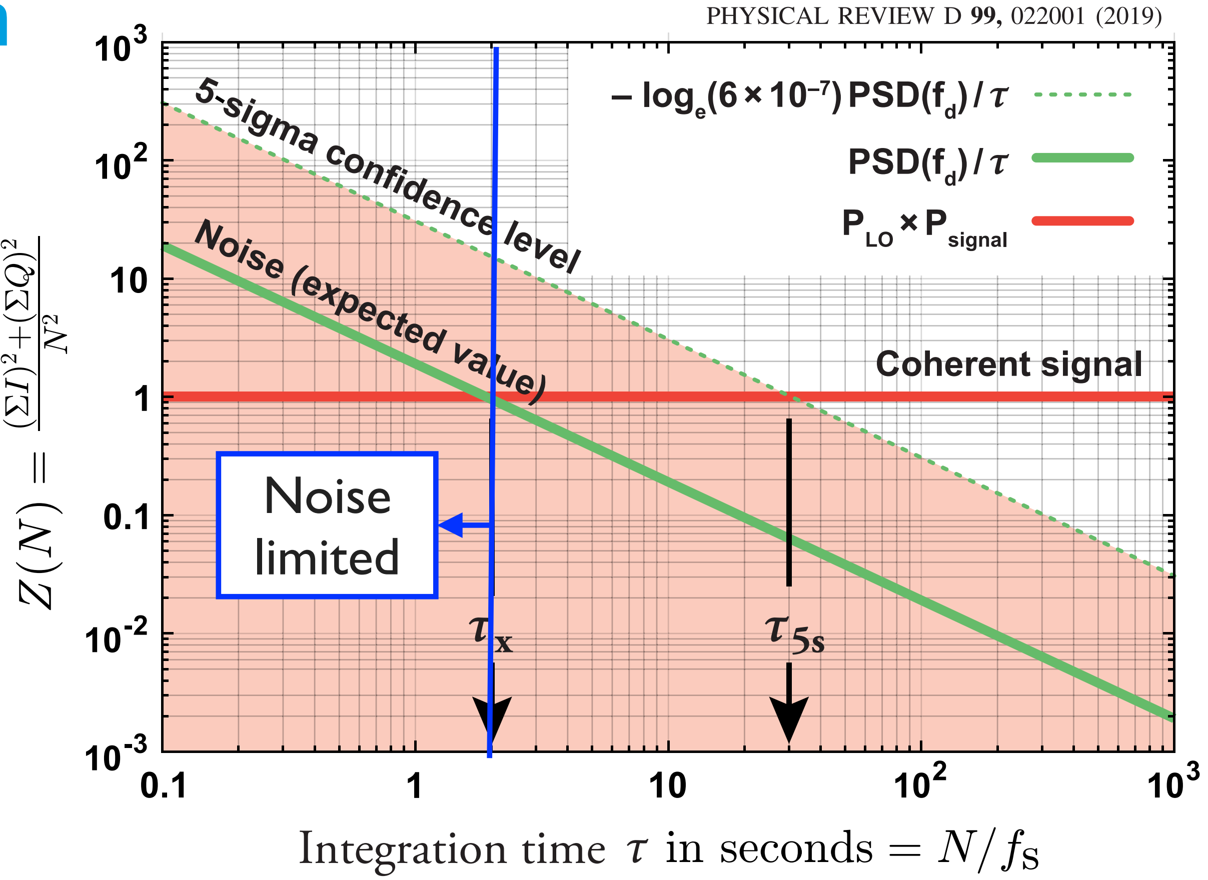

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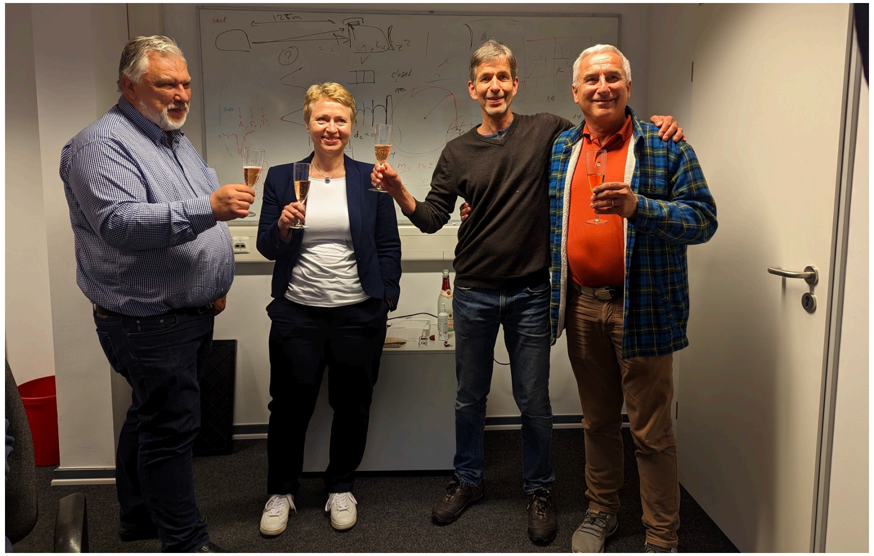
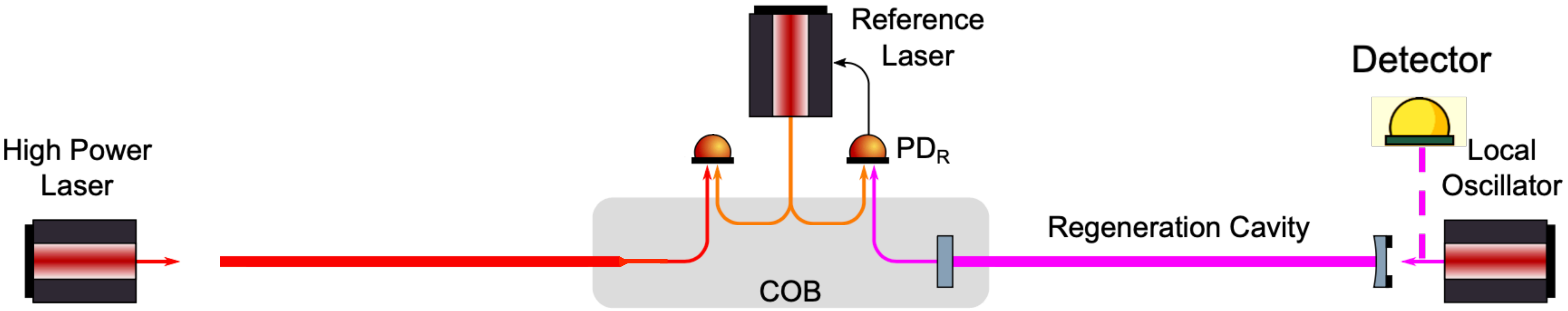
Initial science run

May 23rd to May 31st



ALPS II's initial science run scheme



- $5000 < \beta < 8000$
- $P_c = 40$ W

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

Phase stability as a **key detection point**

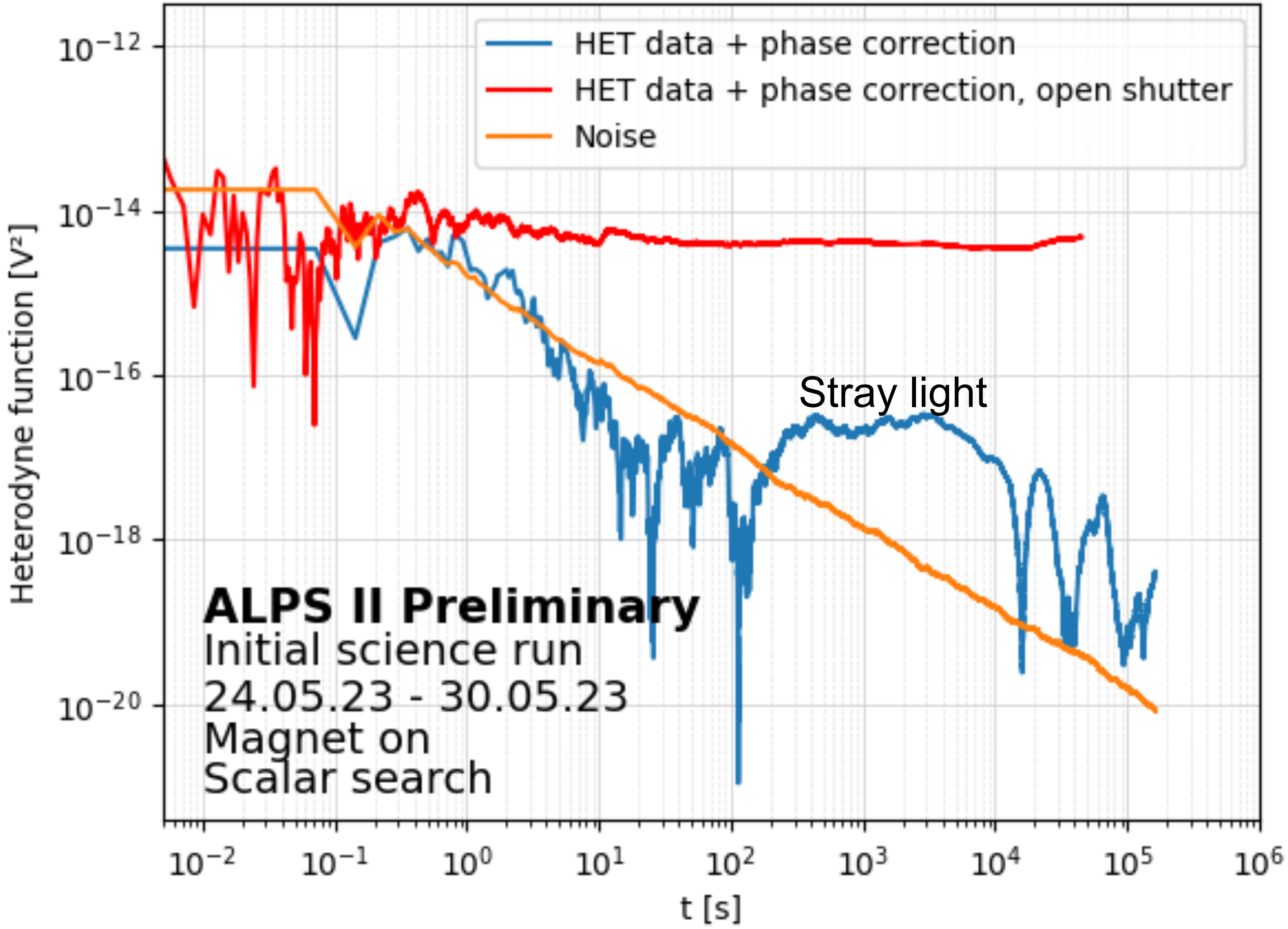
- Demodulation signal must be coherent with the measured signal
- LO must be coherent with regenerated field
  - HPL must be coherent with LO over the full run

Resonant Enhancement

- Power build-up only when the HPL frequency is resonant within the RC
- 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

Heterodyne function

Preliminary results

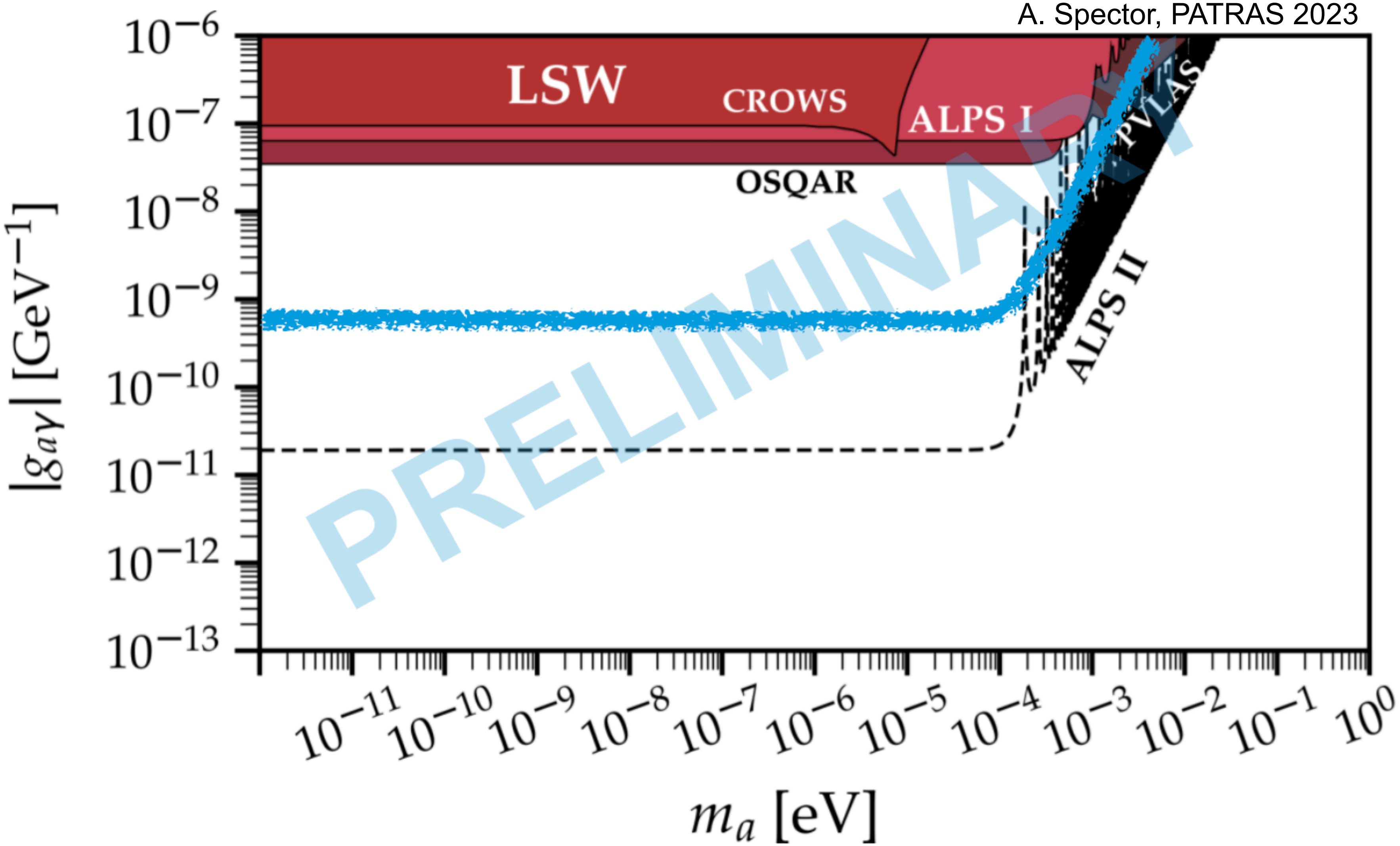


Successfully acquired data from May 23rd to 31st

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

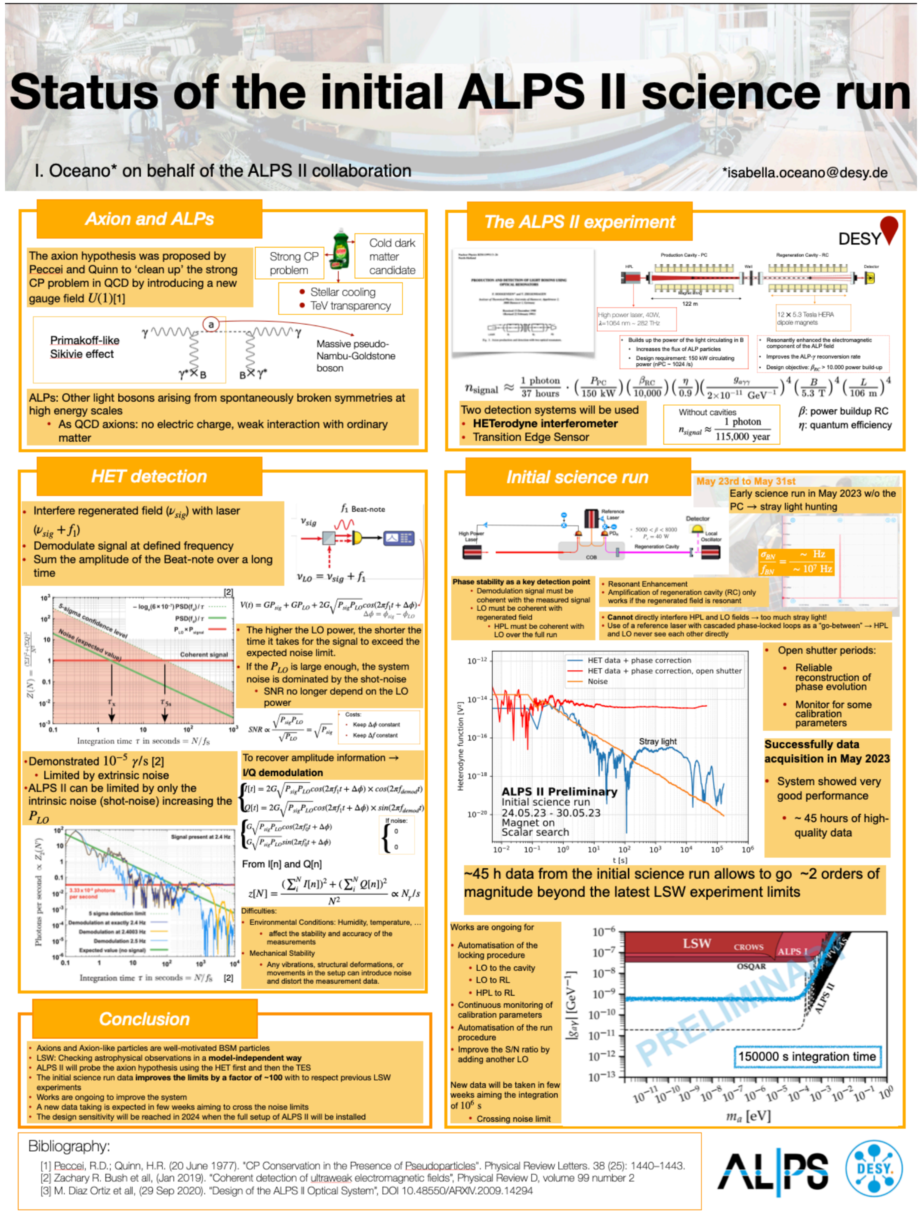
Preliminary sensitivity estimate

A. Spector, PATRAS 2023



150000 s integration time

Check our poster for more details!



Conclusion

- Axions and Axion-like particles are well-motivated BSM particles
- LSW: Checking astrophysical observations in a model-independent way
- ALPS II will probe the axion hypothesis using the HET first and then a photon counting approach
- The initial science run data improves the limits by a factor of 100 with to respect previous LSW experiments
- A new data taking is expected in few weeks aiming to be limited by shot-noise only

- The design sensitivity will be reached in 2024 when the full setup of ALPS II will be installed

Backup

ALPS II

Strengths

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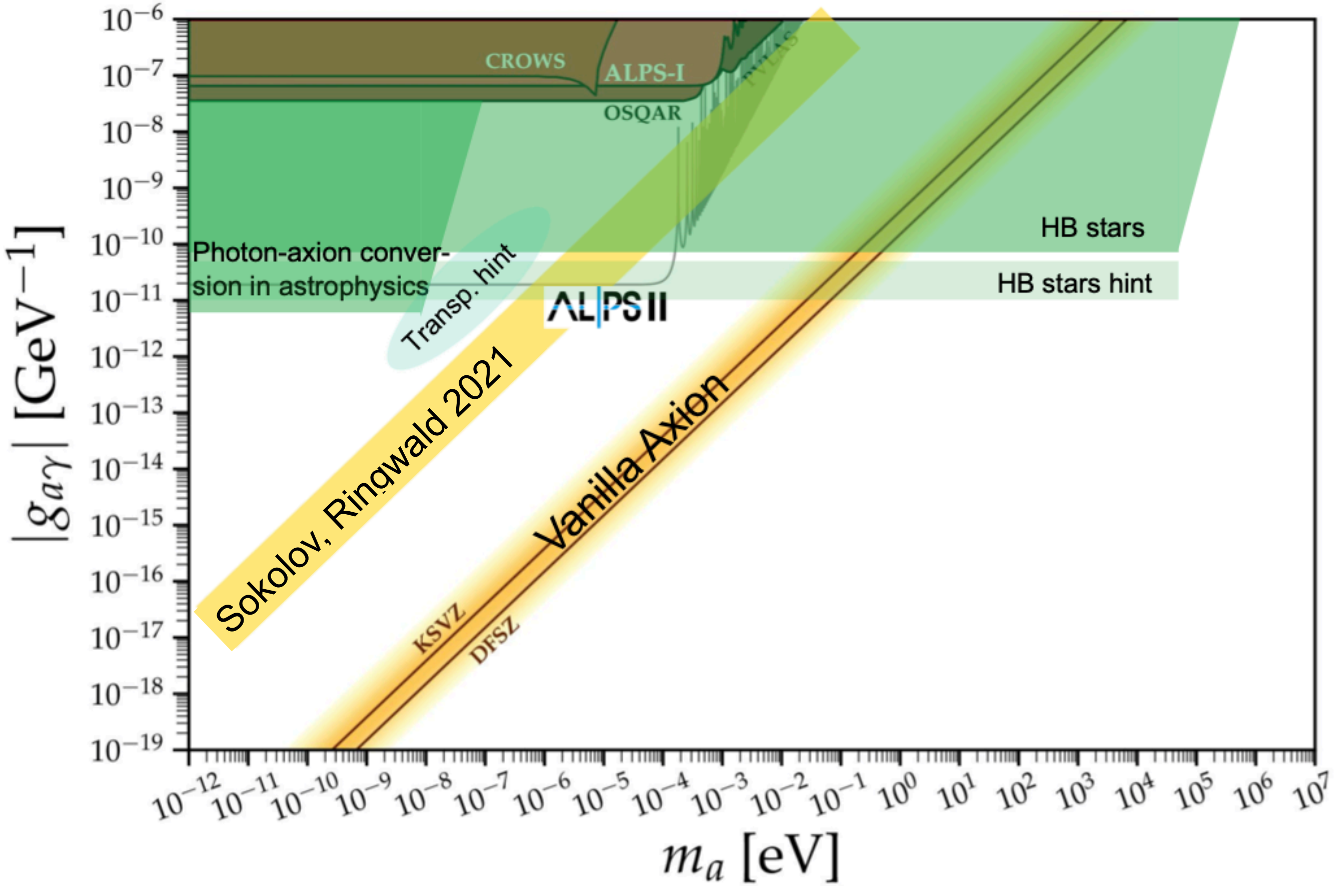
  - Exploring uncharted territory in parameter space, beyond astrophysical constraints
  - Checking axion explanation of astrophysical anomalies

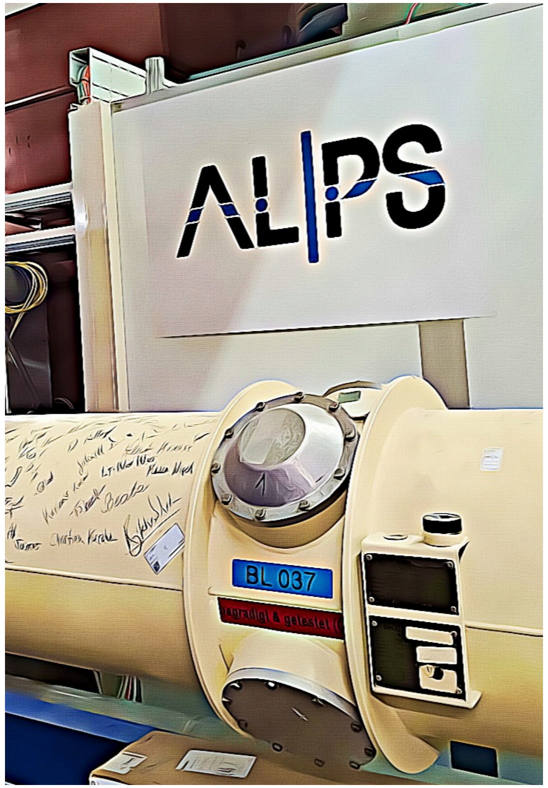


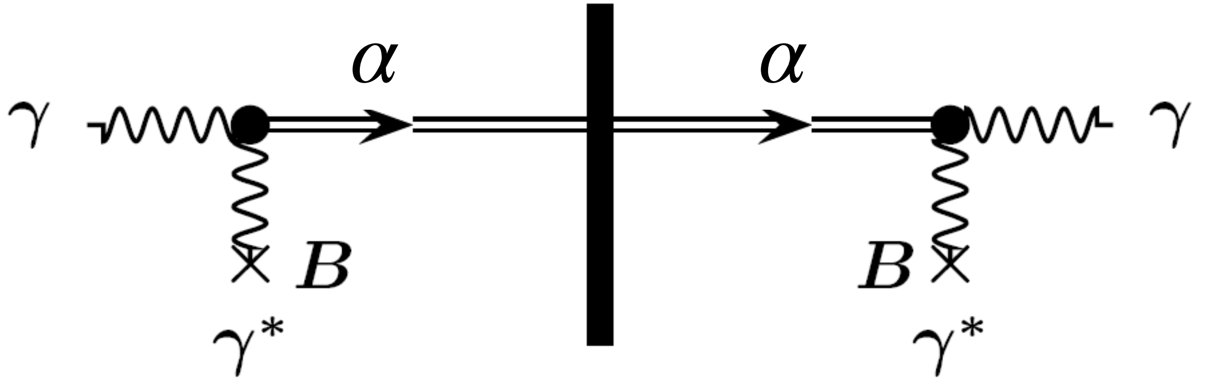
- Astrophysical constraints
  - Non-observation of BSM energy loss of Horizontal Branch (HB) stars in globular clusters
  - Non-observation of conversion photons into axions in astorophysical environments
- Astrophysical anomalies
  - Best fit of energy loss of (HB) starts hints at BSM contribution
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

Any Light Particle Search II

The axion factory

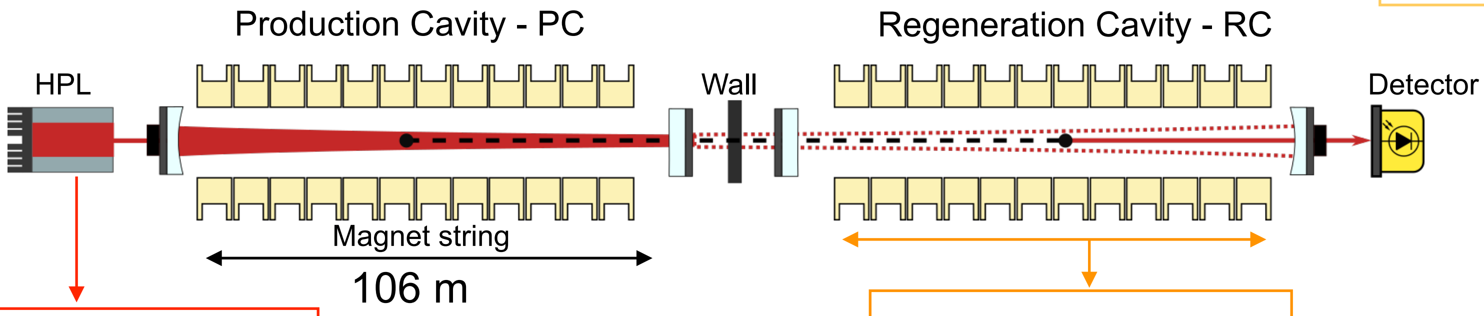
DESY





Two detection systems will be used

- HETerodyne interferometer
- Transition Edge Sensor



High power laser, 40W, λ=1064 nm ~ 282 THz

12 $\times$ 5.3 Tesla HERA dipole magnets

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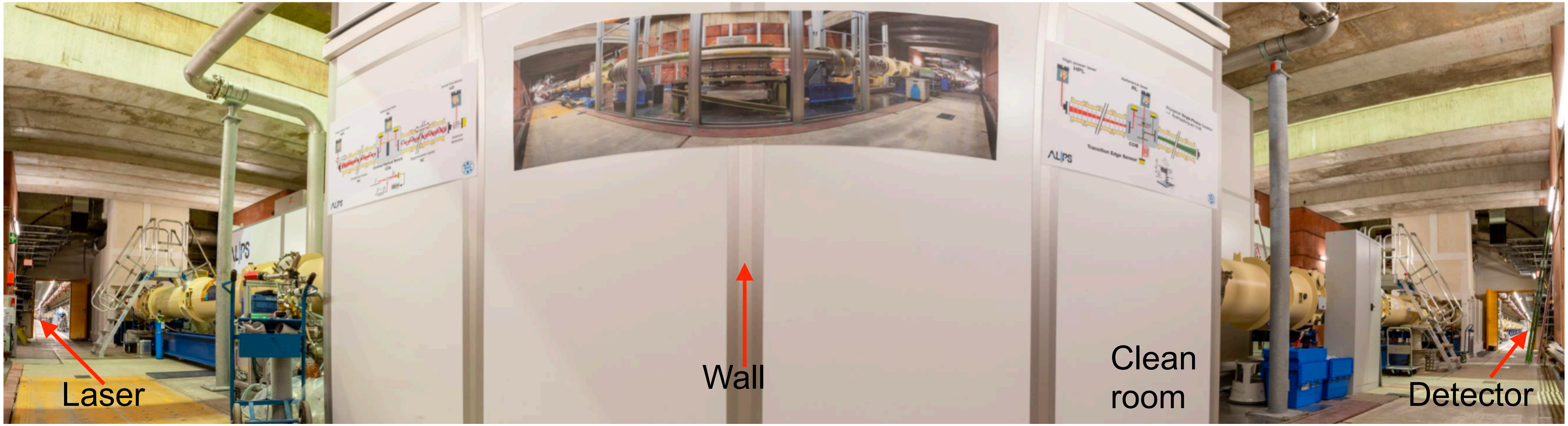
ALPS II achievement

- 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



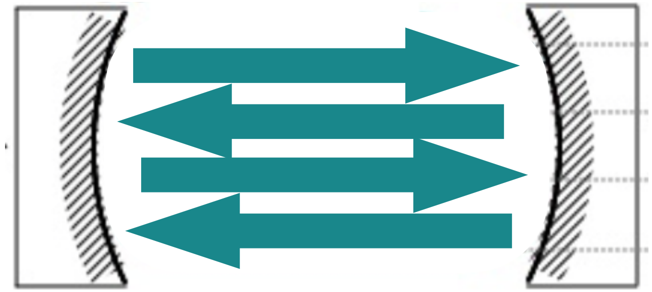
ALPS II achievement

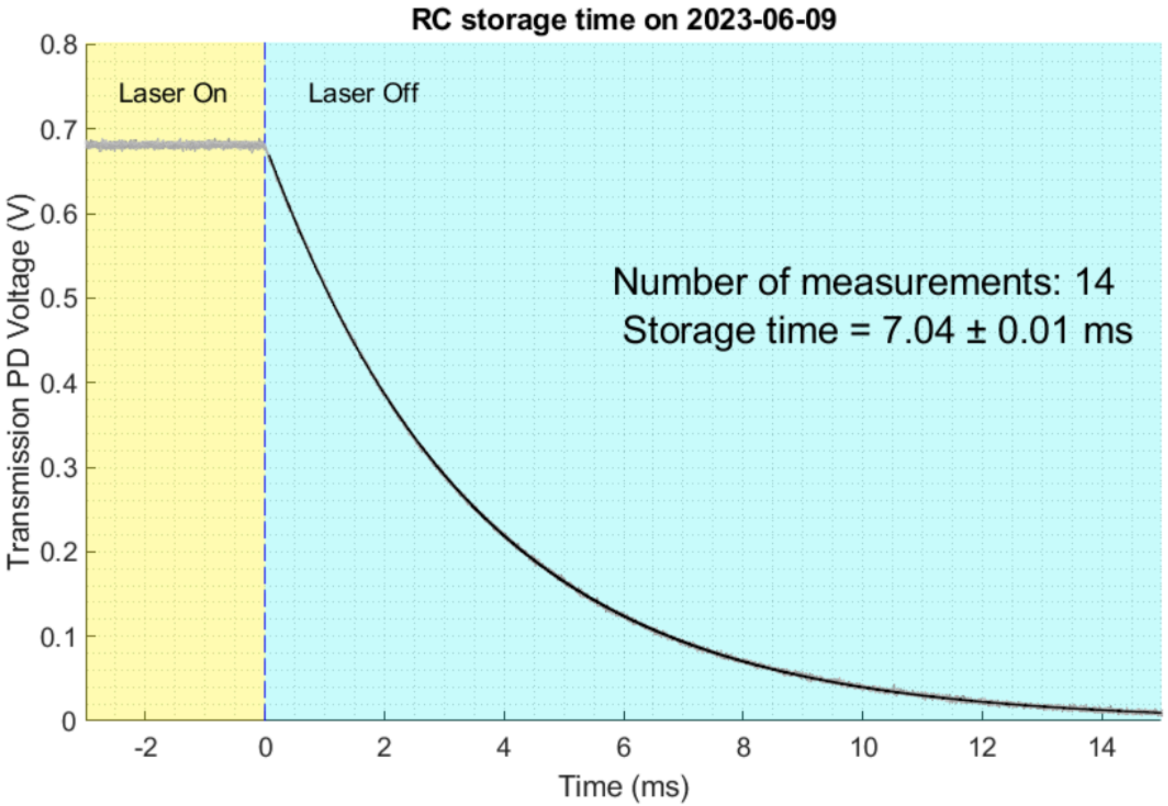
World-record

Leading precision interferometry!

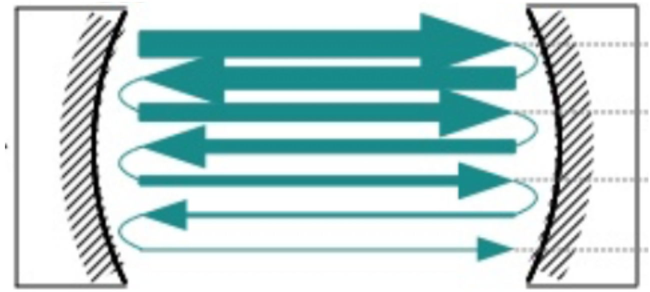
- Longest storage time Fabry Perot cavity ever!
- Length: 124.6m, FSR: 1.22 MHz
- Storage time: **7.04 ms**

Laser On





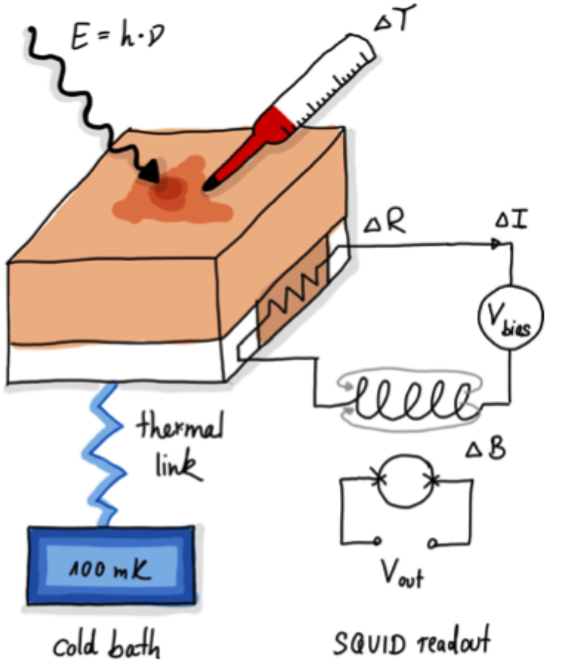
Laser Off

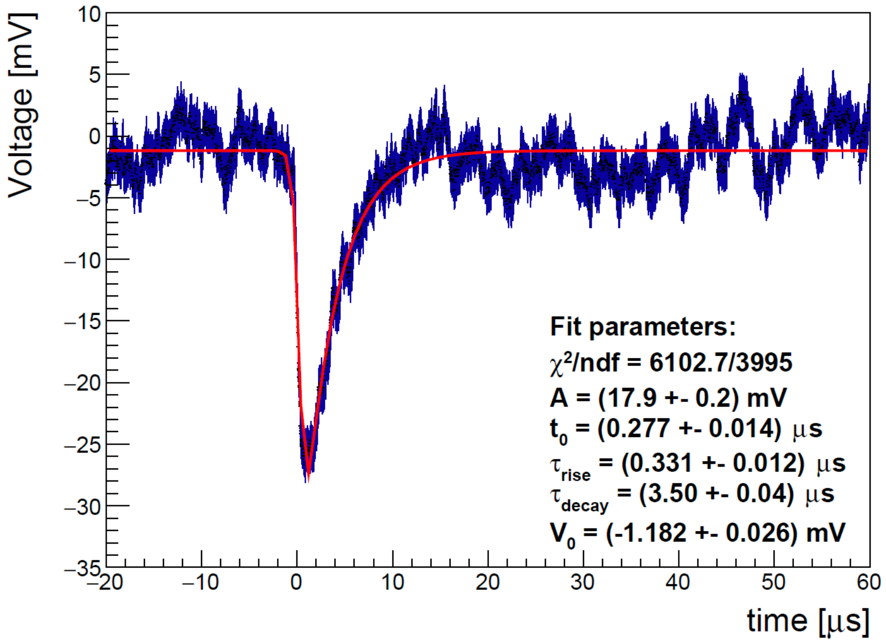


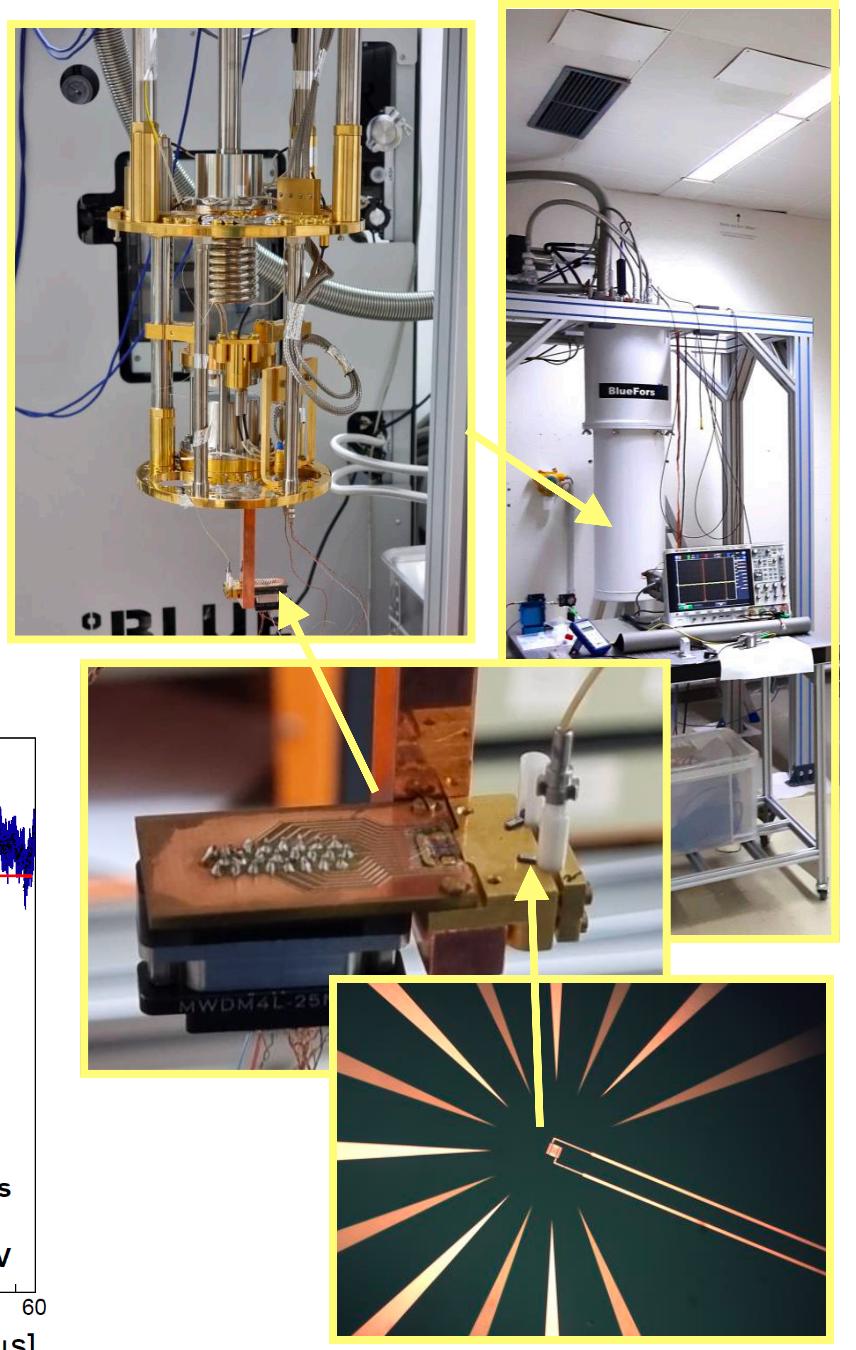
TES

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)

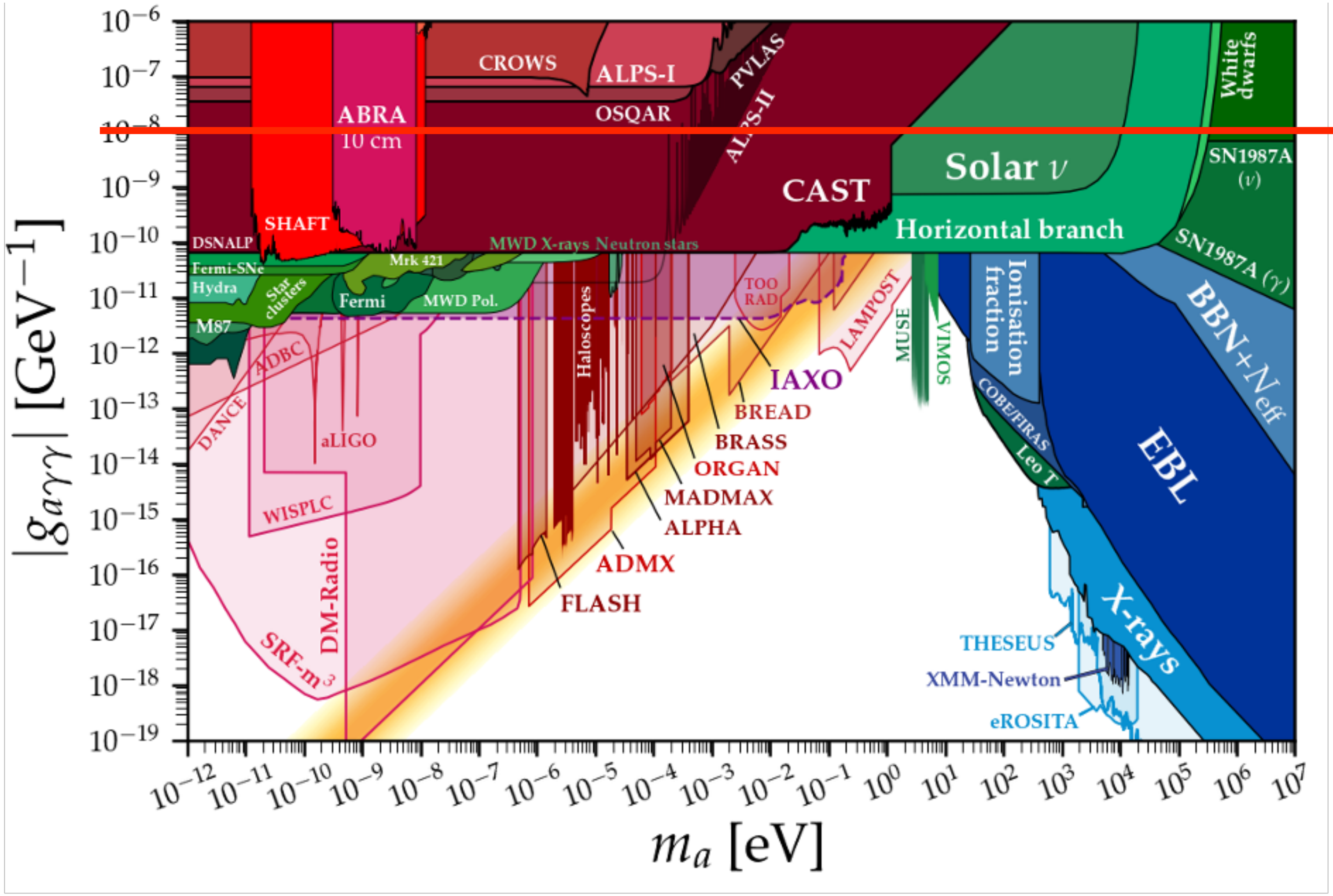


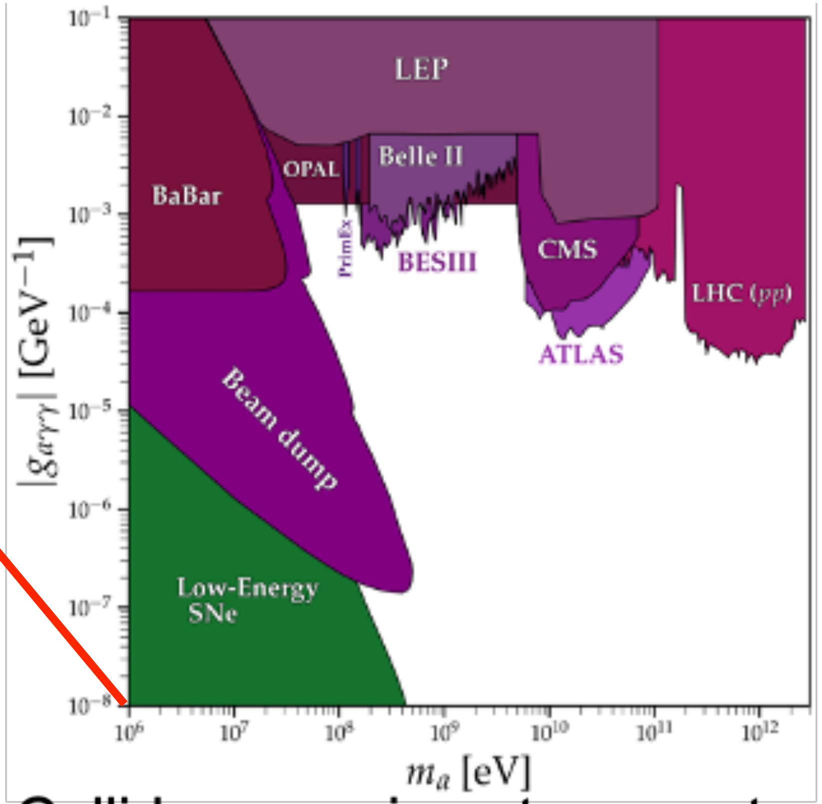




Axions: non-collider and colliders

Axion-photon coupling vs axion mass





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

HETerodyne: Coherent detection

Advantages & costs

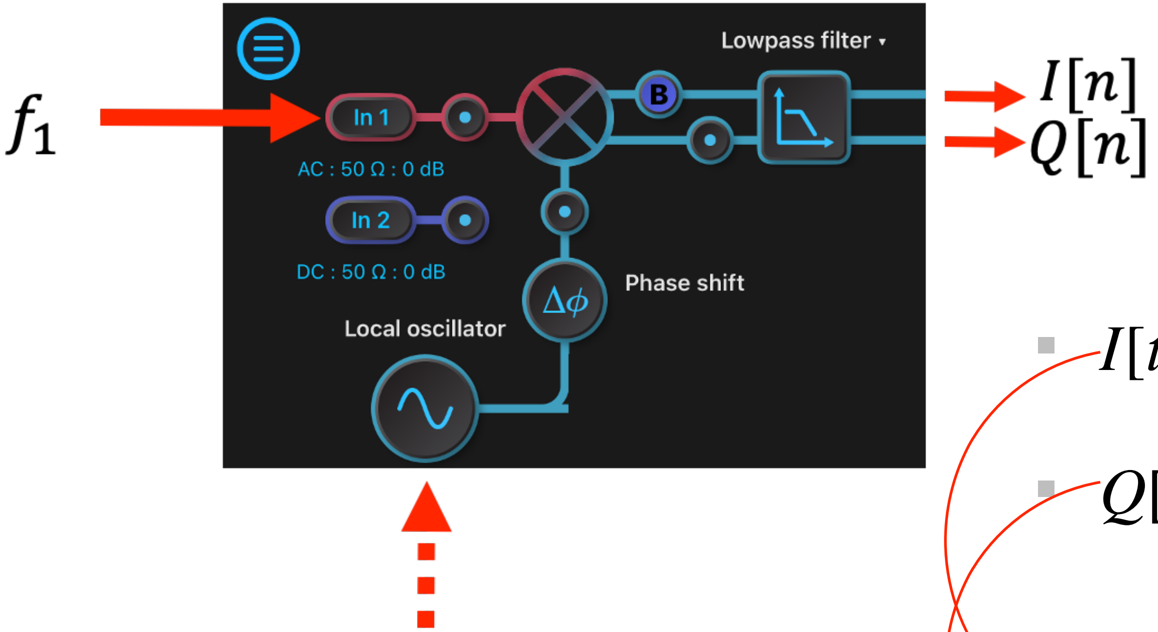
- The higher the LO power, the shorter the time it takes for the signal to exceed the expected noise limit.
- If the P_{LO} is large enough, the system noise is dominated by the shot-noise
  - SNR no longer depend on the LO power

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

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

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
  - $f_s > 2 \times f_0'$

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

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

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

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

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

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

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

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

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

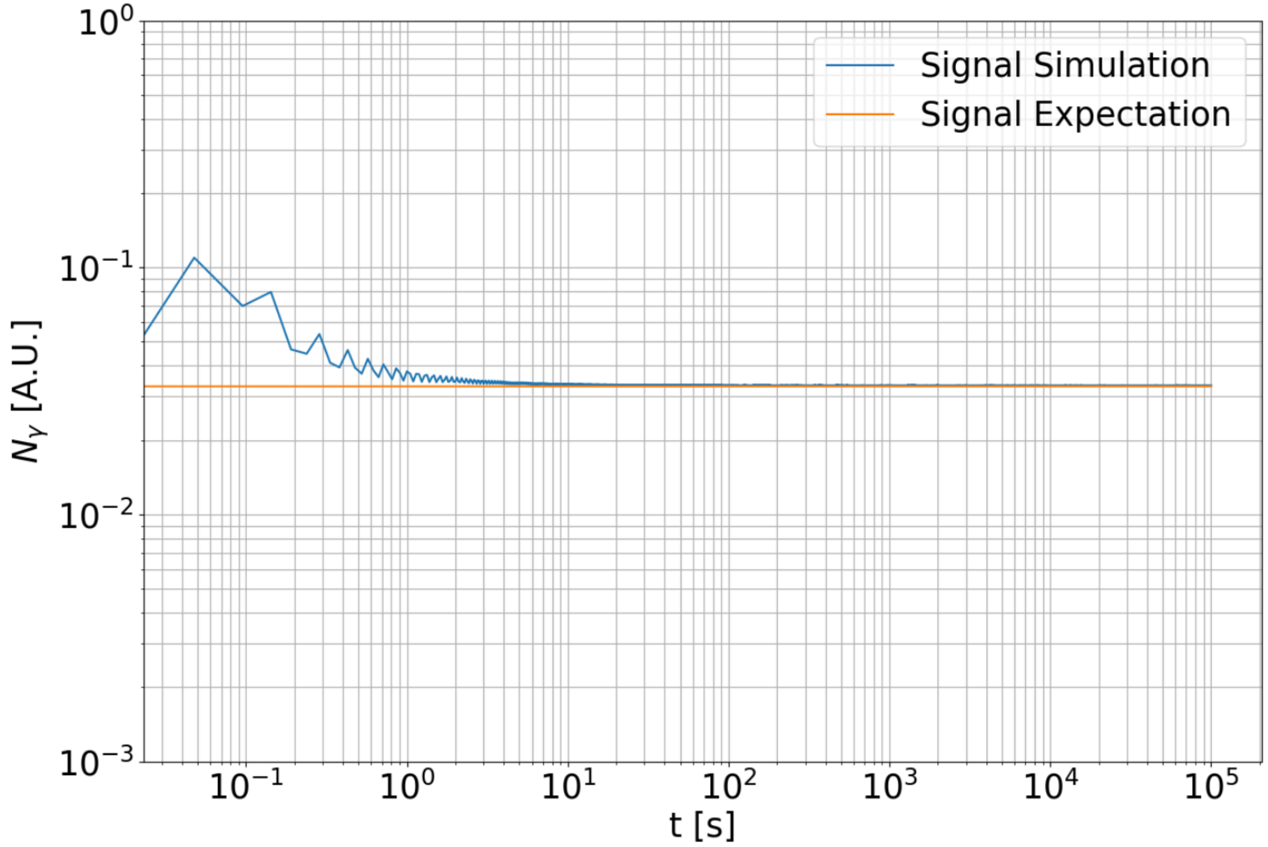
Number of photons

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

Signal

Will sum coherently

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



No physical case

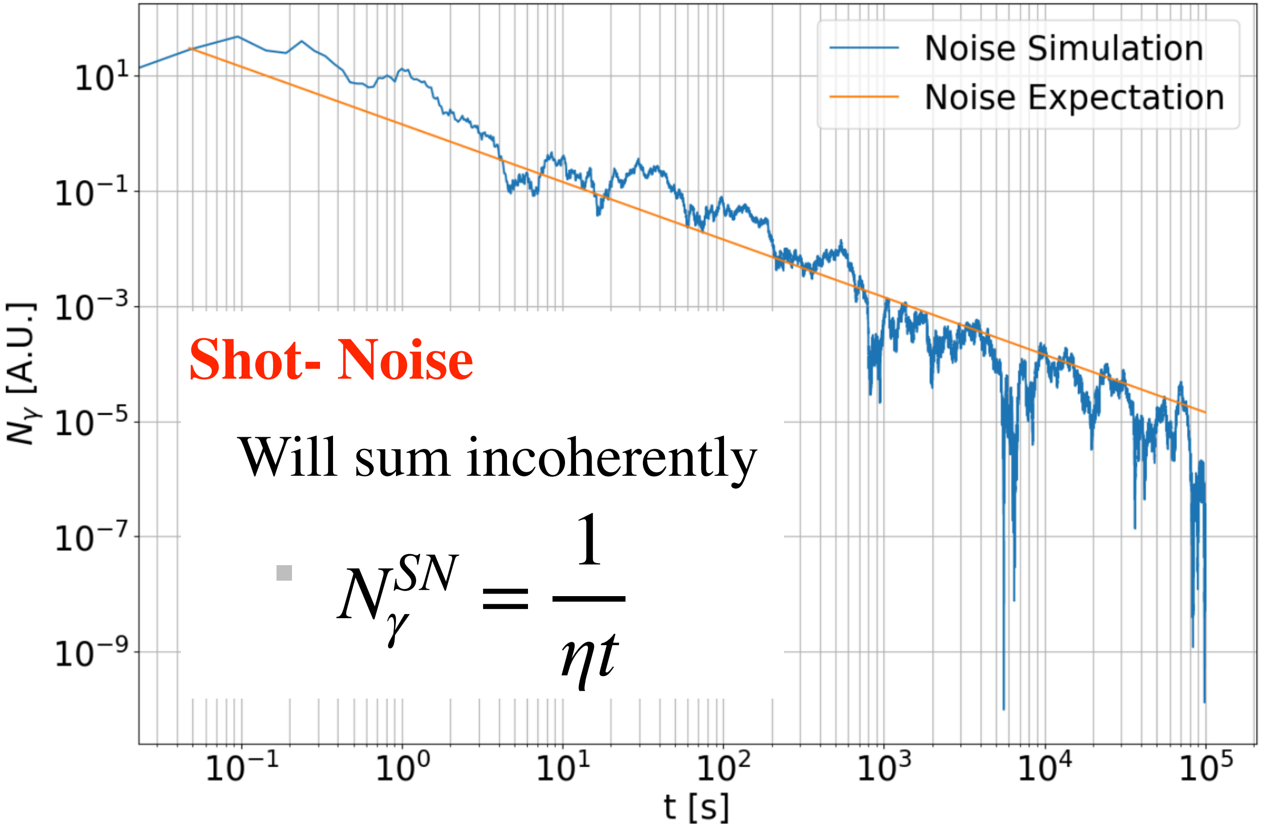
Photon flux extraction

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

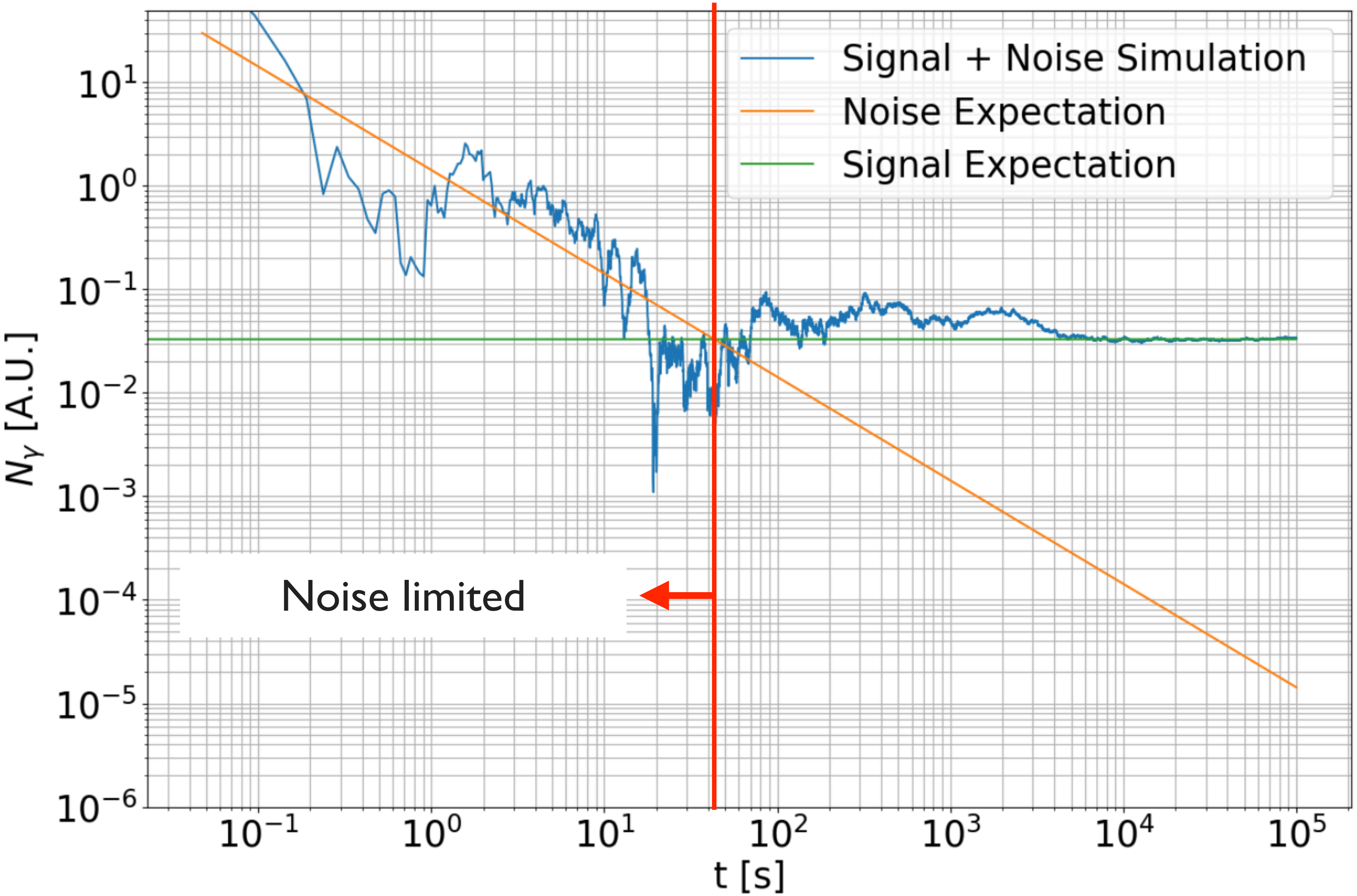
- $$N_\gamma^{SN} = \frac{1}{\eta t}$$

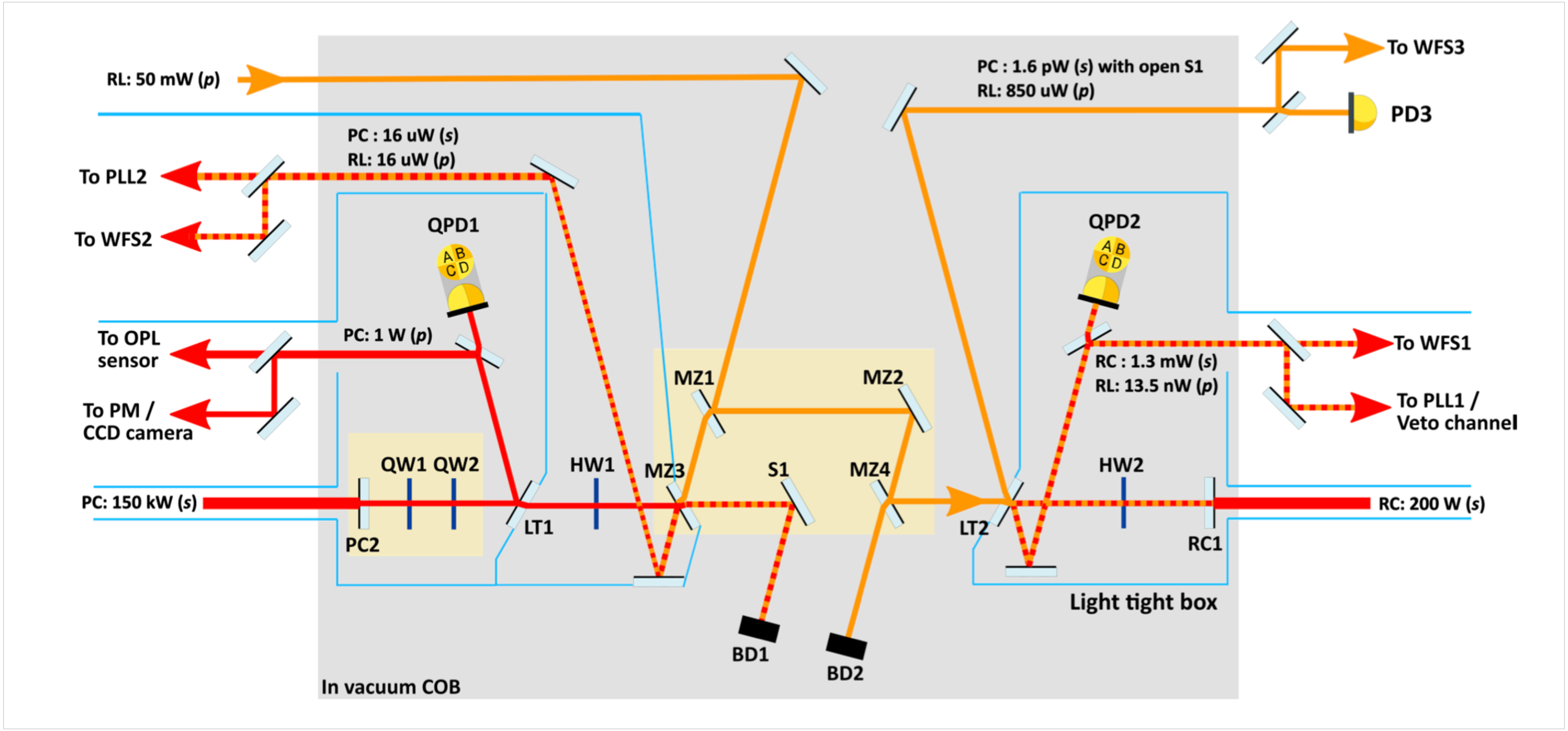
Photon flux extraction

Signal + Noise

Number of photons

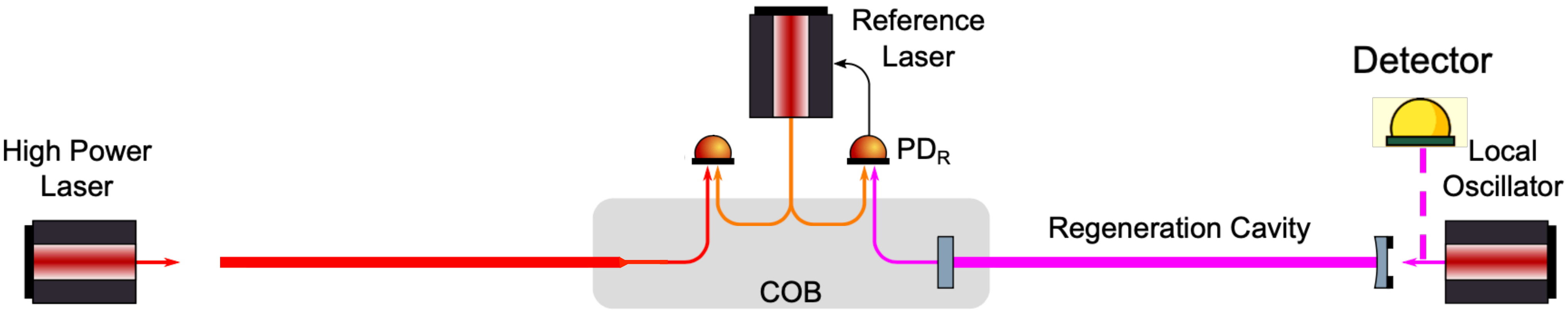
$$N_\gamma = \frac{z[n]}{G^2 P_{LO} h\nu}$$

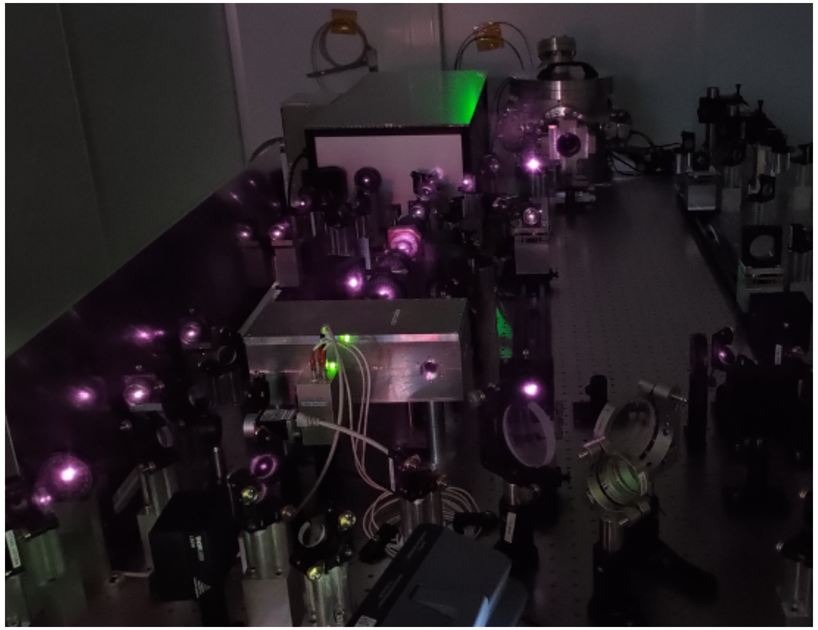


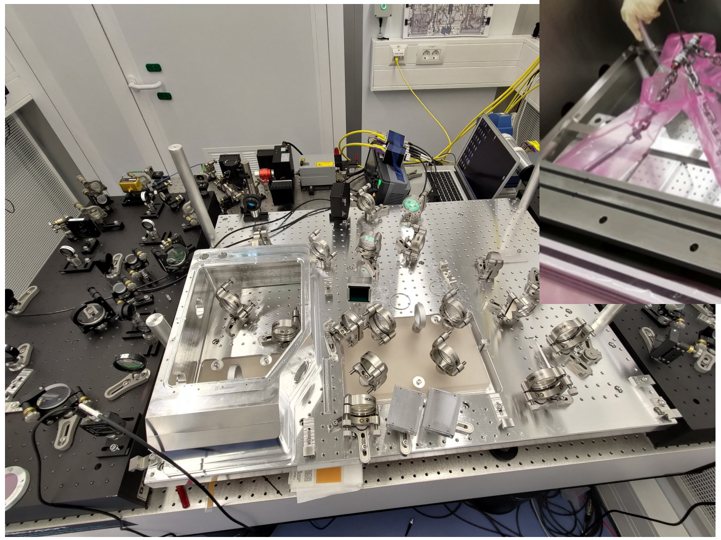


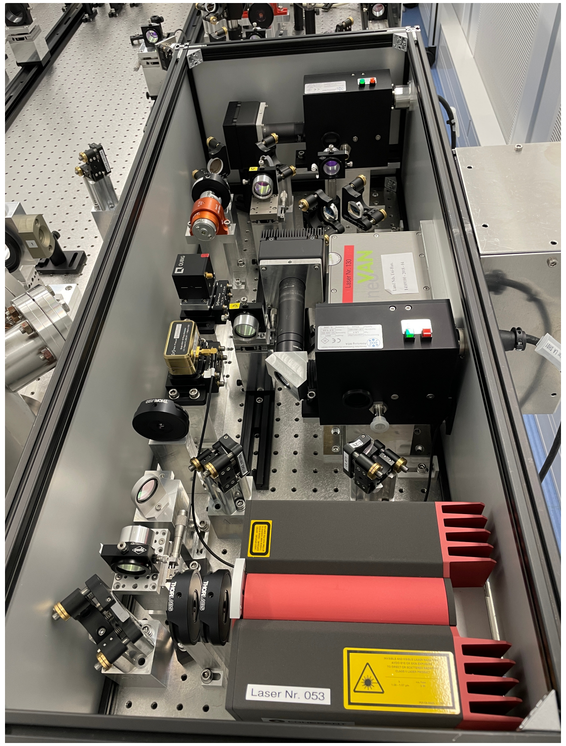
RL: 50 mW (p)
PC : 1.6 pW (s) with open S1
RL: 850 uW (p)
To WFS3
PD3
PC : 16 uW (s)
RL: 16 uW (p)
To PLL2
To WFS2
QPD1
QPD2
To OPL sensor
PC: 1 W (p)
To PM / CCD camera
To WFS1
RC : 1.3 mW (s)
RL: 13.5 nW (p)
To PLL1 / Veto channel
MZ1
MZ2
QW1 QW2
HW1
MZ3
S1
MZ4
HW2
PC: 150 kW (s)
RC: 200 W (s)
PC2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

ALPS II's initial science run scheme

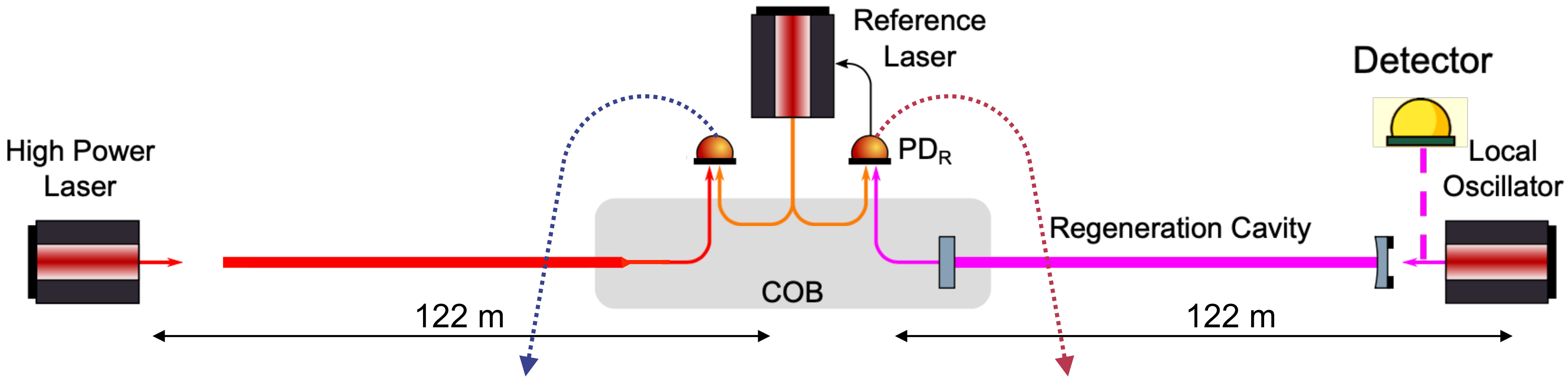


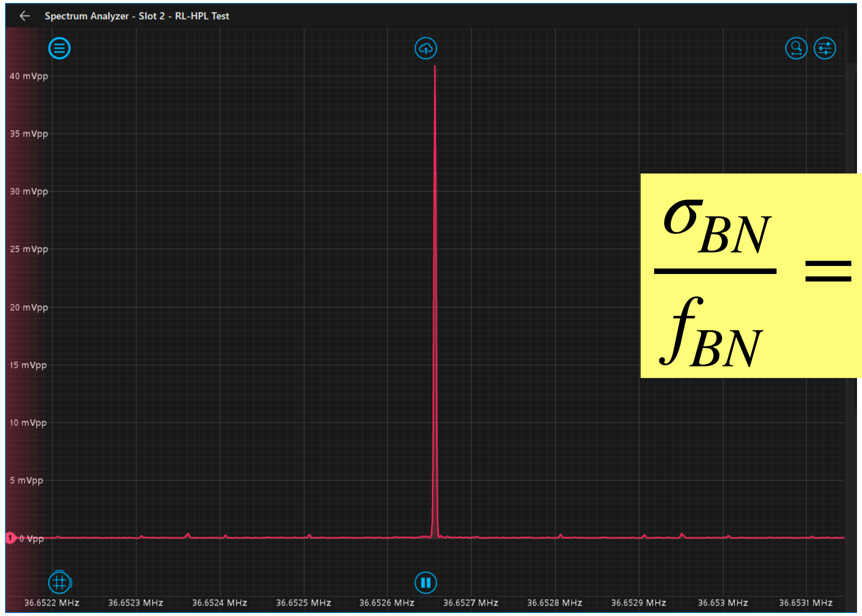




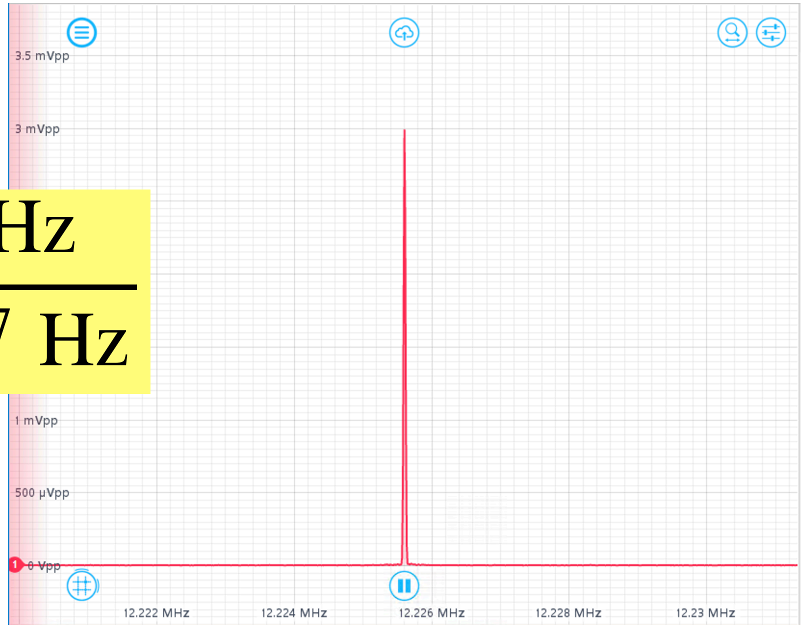


ALPS II's initial science run scheme





$$\frac{\sigma_{BN}}{f_{BN}} = \frac{\sim \text{ Hz}}{\sim 10^7 \text{ Hz}}$$



Open shutter data comparison