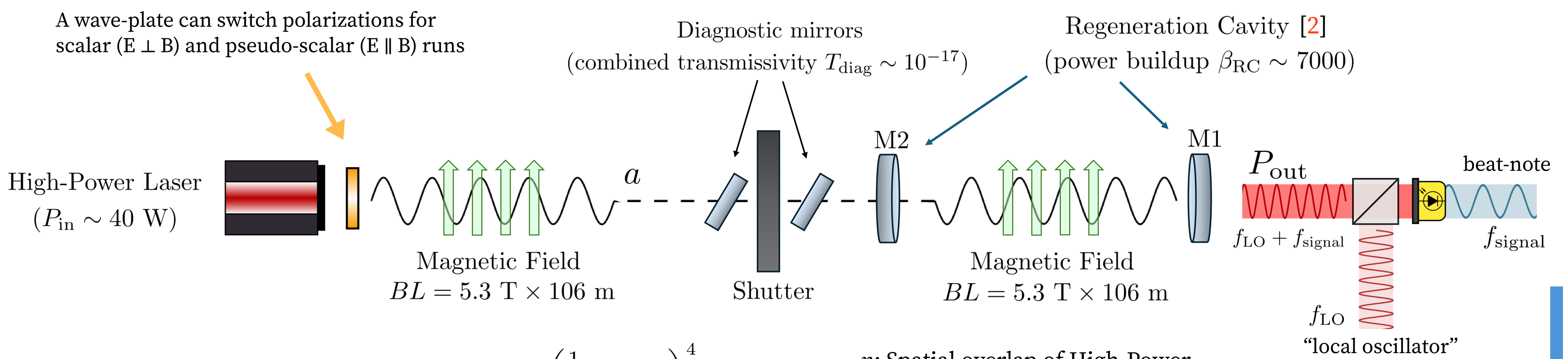
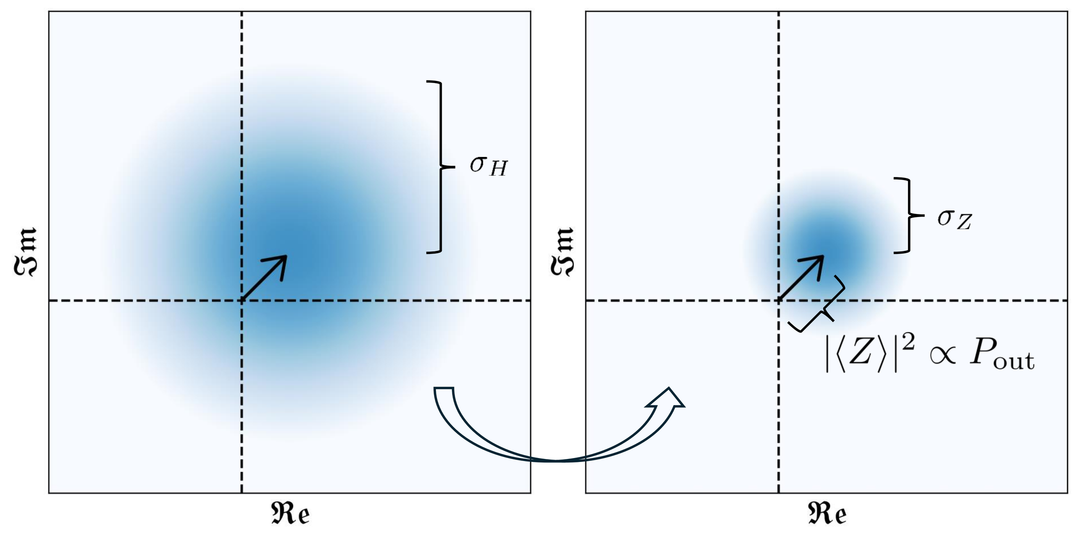
Data Analysis for ALPS II's Initial Science Campaign

20th Patras Workshop on Axions, WIMPs, and WISPs | Sep 22-26, 2025 | Daniel Brotherton

Light-Shining-Through-a-Wall Experiment





Re-converted Photon Rate: $P_{\rm out} = P_{\rm in}\left(\frac{1}{2} g_{a\gamma\gamma} BL\right)^4 \eta\, \beta_{\rm RC}$ ← η: Spatial overlap of High-Power Laser to Regeneration Cavity

Heterodyne detection [1]

1. regenerated light is interfered with a second field
2. produces a beat-note at a chosen frequency
3. beat-note is demodulated at the chosen frequency

$$H[n] = \underbrace{A\cos(2\pi f_{\rm signal} t[n] + \phi)}_{\text{beat-note}} \times \underbrace{e^{i2\pi f_{\rm signal} t[n]}}_{\text{demodulation}} = \frac{A}{2}\left(e^{-i\phi} + \cancel{\cdot}\right)$$ (filtered)

4. demodulated signal is a complex number H, which is averaged into Z:

$$Z = \frac{1}{N}\sum_n^N H[n], \quad |Z|^2 \propto P_{\rm out}$$

5. noise sums incoherently; signal-to-noise increases with longer averaging

Calibration

- When shutter is closed: $P_{\rm out} = P_{\rm in}\left(\frac{1}{2} g_{a\gamma\gamma} BL\right)^4 \eta\, \beta_{\rm RC}$
- When shutter is open: $P_{\rm open} = P_{\rm in}\, T_{\rm diag} T_{\rm M2}\, \eta\, \beta_{\rm RC}$
- Ratio of closed to open gives $g_{a\gamma\gamma}$
  - Systematics varying with time are eliminated:
    - $P_{\rm in}$, spatial overlap η, power buildup β, ...
    - $T_{\rm diag}$ and $T_{\rm M2}$ are static and easy to measure

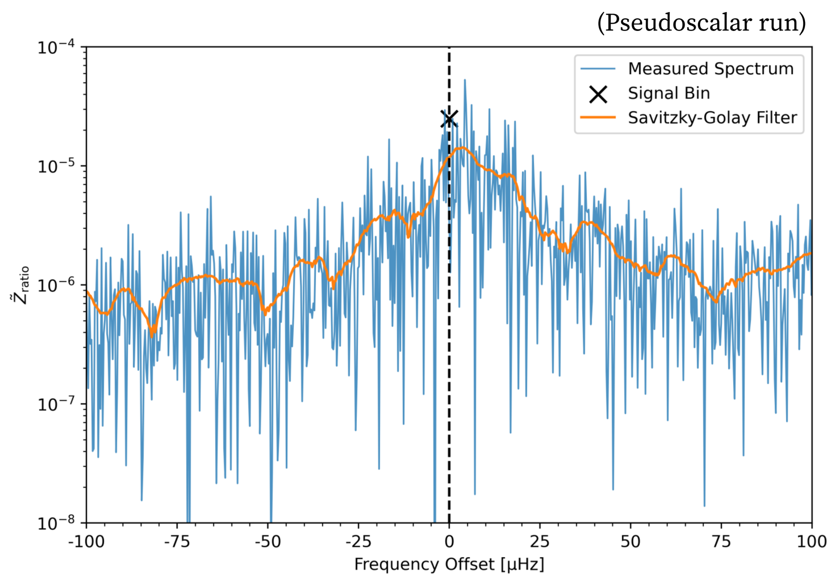
$$g_{a\gamma\gamma} = \frac{2}{BL}\left(T_{\rm diag} T_{\rm M2} \frac{P_{\rm out}}{P_{\rm open}}\right)^{1/4}$$

- Ratio of closed-to-open performed as complex numbers, removing phase changes:

$$\tilde{Z}_{\rm ratio} \equiv \frac{1}{N}\sum_n^N \frac{H[n]}{C[n]}$$

- Calibration array $C[n]$ made from open shutter Z-sums.

Stray-Light Behavior



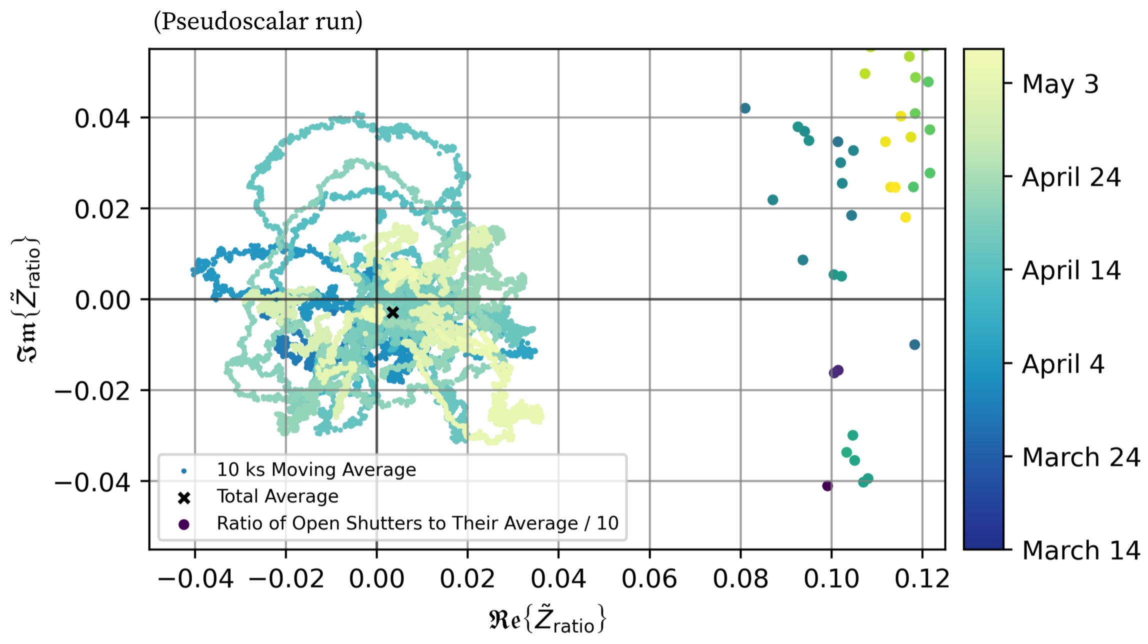
A power spectrum can be obtained for frequencies δf offset from the beat-note frequency.

$$S(\delta f) \equiv \left|\frac{1}{N}\sum_n^N \frac{H[n]}{C[n]} e^{2\pi i(\delta f)t[n]}\right|^2$$

Applying an averaging filter estimates the expected power in each frequency bin.

Why stray-light?

- broadened off-center peak around the signal bin (the beat-note frequency)
- no significant excess in signal bin relative to expectation in neighboring bins
- high fluctuations in phase and amplitude over time compared to open shutter



- A "moving-average" Z-sum reveals incoherent phase and amplitude evolution over the data run. $\tilde{Z}^{(10{\rm ks})}_{\rm ratio}[n] \equiv \frac{1}{10^4}\sum_{n-5000}^{n+5000}\frac{H[n]}{C[n]}$
- Open shutter Z-sums are divided by their average; values near 1 show they have stable phase and amplitude.

Stray-Light Statistics

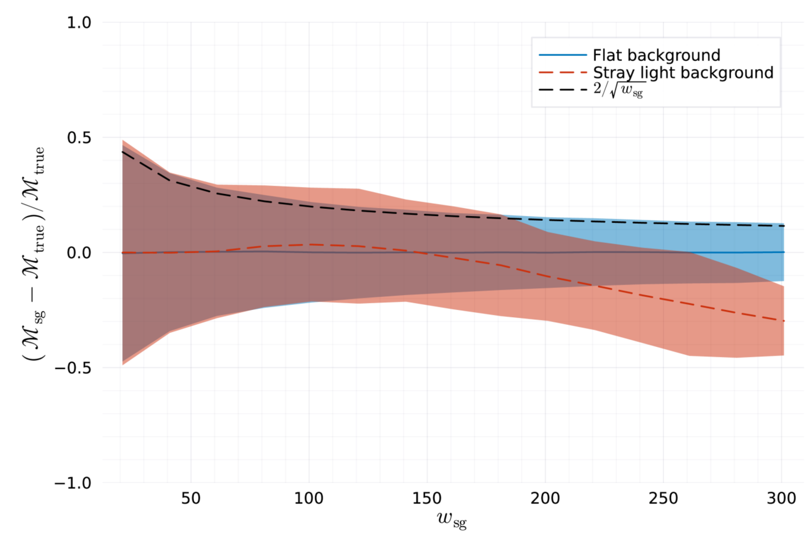
- Z follows a complex Gaussian distribution, so $|Z|^2$ follows a degree-2 non-central chi-square:

$$\mathrm{ncx2}(w\,|\,\lambda, s) = \frac{1}{2s} e^{-\frac{w+\lambda}{2s}} I_0\left(\frac{\sqrt{\lambda w}}{s}\right)$$

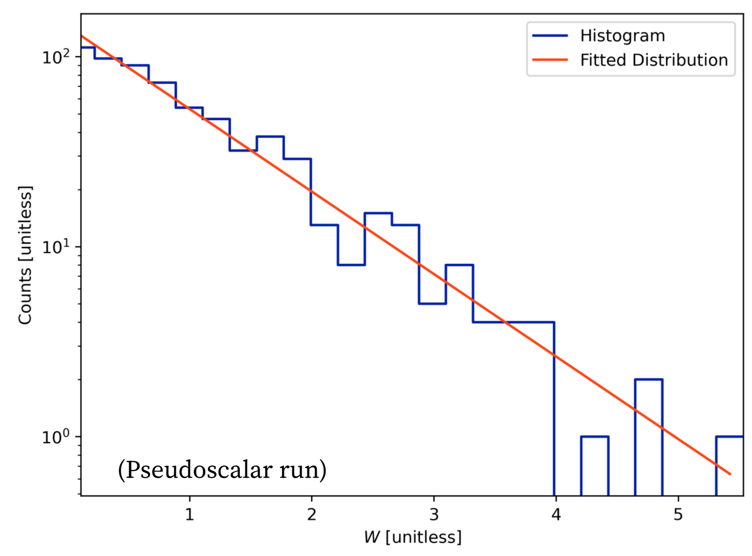
λ : non-centrality parameter, proportional to expected $P_{\rm out}$ (relates $g_{a\gamma\gamma}$)
s : scaling factor, related to noise expectation
I_0: modified Bessel function of the 1st kind

- using spectrum as a proxy for statistics on the signal bin:
  - assume the filtered spectrum estimates the mean of noise in each bin
  - normalize the spectrum by the filter (recovers the non-central chi-square distribution)

$$W(\delta f) = \frac{S(\delta f)}{S_{\rm filt}(\delta f)}$$



- Monte-Carlo simulations found optimal filter parameters (e.g. window size) that would not under-estimate the true mean.



- histogram of normalized spectrum $W(\delta f)$ follows the non-central chi-square distribution

	Power in signal bin*	Pearson test statistic	Non-centrality parameter*	5σ detection threshold*	95% confidence exclusion limit*
Pseudoscalar run	2.9×10^{-5}	0.92	0	1.5×10^{-4}	2.5×10^{-4}
Scalar run	1.9×10^{-5}	1.14	7.3×10^{-8}	3.6×10^{-4}	5.8×10^{-4}

*in same units as $|\tilde{Z}_{\rm ratio}|^2$

New Exclusion Limits

- neighboring frequencies used as proxy for statistics on signal bin
- statistics from spectrum calculates exclusion limits on $g_{a\gamma\gamma}$ such that
  - 95% probability to have not missed a 5σ detection
- For pseudo-scalar couplings:

$$g^{\rm ps}_{a\gamma\gamma} < 1.4 \times 10^{-9}\ \mathrm{GeV}^{-1}$$

  - ~20x better than previous light-shining-through-wall experiments
- For scalar couplings:

$$g^{\rm s}_{a\gamma\gamma} < 1.8 \times 10^{-9}\ \mathrm{GeV}^{-1}$$

References

1. A. Hallal, et al., "The heterodyne sensing system for the ALPS II search...", *Physics of the Dark Universe*, vol. 35, p. 100194, 2022.
2. T. Kozlowski, et al., "Design and performance of the ALPS II regeneration cavity", *Optics Express*, vol. 33, p. 11153, 2025.

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