Probing the dark matter halo with long-baseline optical cavities

Using the ALPS II infrastructure to look for axions in the dark matter halo

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Axions in the Dark Matter Halo

Assumptions

- Dark matter energy density:
  - $\rho_a = a_0^2 m_a^2/2 \simeq 0.3\,\mathrm{GeV/cm^3}$
- Axion dark matter: $a(t) = a_0 \cos(m_a t + \delta_\tau(t))$
  - Dark matter local velocity: 10^{-3}
  - Coherence time:
    - $\tau = \frac{2\pi}{m_a v_a^2} \sim 1 \left(\frac{10^{-16}\,\mathrm{eV}}{m_a}\right)$ year

Tools at our disposal (within the ALPS group)

- Long baseline cavities
  - Hall North: 245 m baseline
    - World record cavity storage time
  - Hall West: 20 m baseline
    - Operate cavity with 100,000 finesse
    - Demonstrated pm length control
- Capable of shot noise limited detection in the MHz range

Phase velocity oscillation

Signal

- Axion field induces a circular birefringence in vacuum
  - Left vs. right handed circularly polarized states experience different phase velocity
  - $c^2_{L/R} = 1 \mp \frac{g_{a\gamma\gamma}\dot{a}}{k} \quad \rightarrow \quad c_{L/R} \simeq 1 \mp \frac{g_{a\gamma\gamma}\dot{a}}{2k}$
  - Phase oscillation over propagation length L:
  - $\phi_{\mathrm{L/R}}(t) = kL \mp \frac{g_{a\gamma\gamma}}{2} \int_{t-L}^{t} \dot{a}(t')\, dt' \quad \rightarrow \quad \phi_{\mathrm{L/R}}(t) = kL \mp \frac{g_{a\gamma\gamma}}{2} \{a(t) - a(t-L)\}$

Axion induced polarization rotation

Signal

- Relative phase oscillation between circularly polarized fields leads to polarization rotation:
  - $$\theta(t) = \frac{\phi_{\mathrm{R}}(t) - \phi_{\mathrm{L}}(t)}{2}$$
- Polarization state of linearly polarized fields:
  - $$\theta(t) = \frac{g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{a}}}}{m_{\mathrm{a}}} \sin\left(\frac{m_{\mathrm{a}}L}{2}\right) \sin\left(m_{\mathrm{a}}t + \delta_{\tau}(t) - \frac{m_{\mathrm{a}}L}{2}\right)$$

Projections for Gravitational Wave Interferometers

Idea pursued by Nagano et al for current/future GW observatories

PHYSICAL REVIEW D **104**, 062008 (2021)

Axion dark matter search using arm cavity transmitted beams of gravitational wave detectors

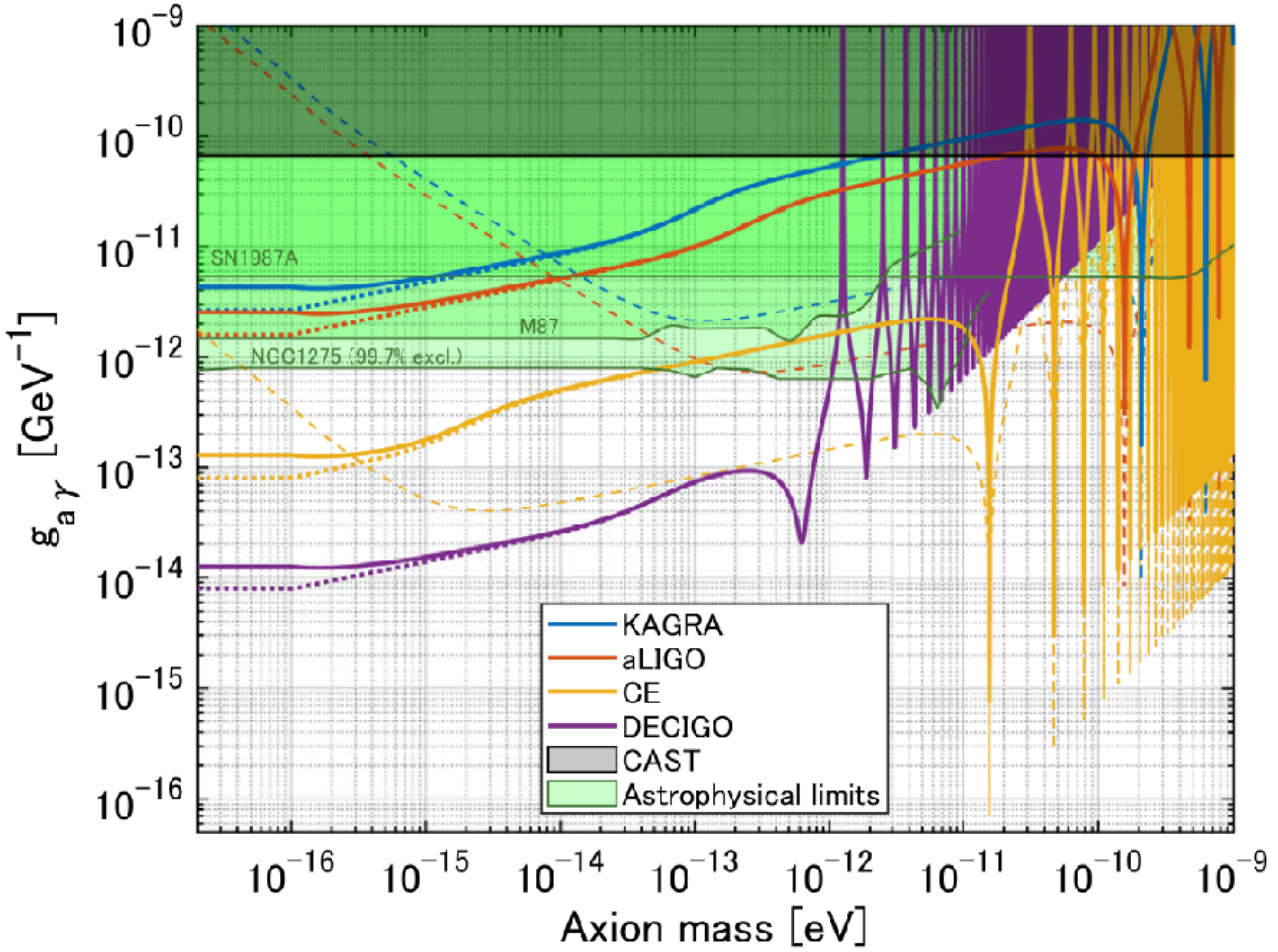
Koji Nagano,[1] Hiromasa Nakatsuka,[2] Soichiro Morisaki,[3] Tomohiro Fujita,[4,5] Yuta Michimura,[6,7] and Ippei Obata[8]

PHYSICAL REVIEW LETTERS **123**, 111301 (2019)

Axion Dark Matter Search with Interferometric Gravitational Wave Detectors

Koji Nagano,[1] Tomohiro Fujita,[2,3] Yuta Michimura,[4] and Ippei Obata[1]

Similar detector	L_{cav} [m]	P_0 [W]	λ [$\times 10^{-9}$ m]	(t_1^2, t_2^2) [ppm]
KAGRA [41]	3×10^3	335	1064	$(4 \times 10^3, 7)$
aLIGO [39]	4×10^3	2600	1064	$(1.4 \times 10^4, 5)$
CE [43]	4×10^4	600	1550	$(1.2 \times 10^3, 5)$
DECIGO [44]	10^6	5	515	$(3.1 \times 10^5, 3.1 \times 10^5)$



Accumulation of polarization rotation

Polarization rotation

- $$\theta(t) = \frac{g_{a\gamma\gamma}\sqrt{2\rho_\mathrm{a}}}{m_\mathrm{a}} \sin\left(\frac{m_\mathrm{a}L}{2}\right) \sin\left(m_\mathrm{a}t + \delta_\tau(t) - \frac{m_\mathrm{a}L}{2}\right)$$

- If $m_\mathrm{a}L \ll 1$:
- $$\theta(t) = g_{a\gamma\gamma}L\sqrt{\frac{\rho_\mathrm{a}}{2}} \sin\left(m_\mathrm{a}t - \frac{m_\mathrm{a}L}{2}\right)$$
- So amplitude of the oscillation is $g_{a\gamma\gamma}L\sqrt{\frac{\rho_\mathrm{a}}{2}}$
  - For L = 245 m, $g_{a\gamma\gamma}$ = 2×10^{-10} GeV^{-1}, ρ_a = 0.3 GeV/cm^3, the amplitude is ~10^{-13}

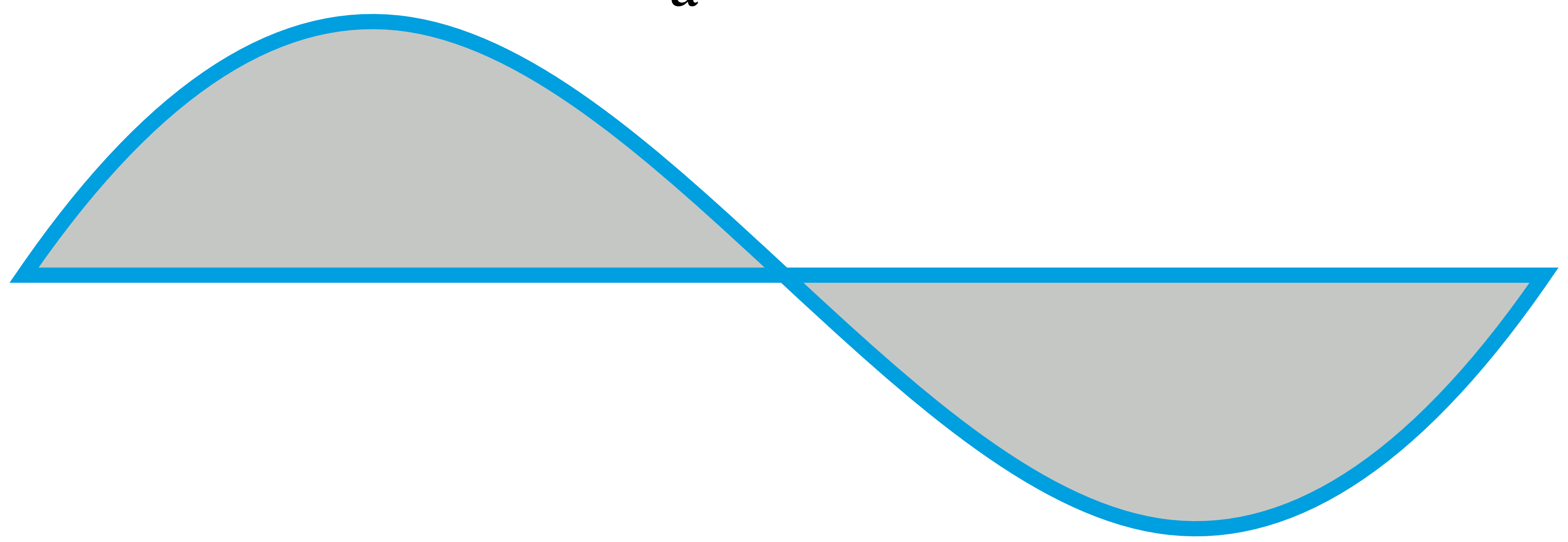
Accumulation of polarization rotation

Polarization rotation

- $$\theta(t) = \frac{g_{a\gamma\gamma}\sqrt{2\rho_{\mathrm{a}}}}{m_{\mathrm{a}}} \sin\left(\frac{m_{\mathrm{a}}L}{2}\right) \sin\left(m_{\mathrm{a}}t + \delta_\tau(t) - \frac{m_{\mathrm{a}}L}{2}\right)$$

  - If $m_{\mathrm{a}}L = 2N\pi$ for $N = 1,2,3...$
  - $\theta(t) = 0$
    - The oscillation in the phase velocity perfectly cancels itself

$m_{\mathrm{a}}L = 2\pi$



Accumulation of polarization rotation

Polarization rotation

- $$\theta(t) = \frac{g_{a\gamma\gamma}\sqrt{2\rho_\mathrm{a}}}{m_\mathrm{a}} \sin\left(\frac{m_\mathrm{a}L}{2}\right) \sin\left(m_\mathrm{a}t + \delta_\tau(t) - \frac{m_\mathrm{a}L}{2}\right)$$

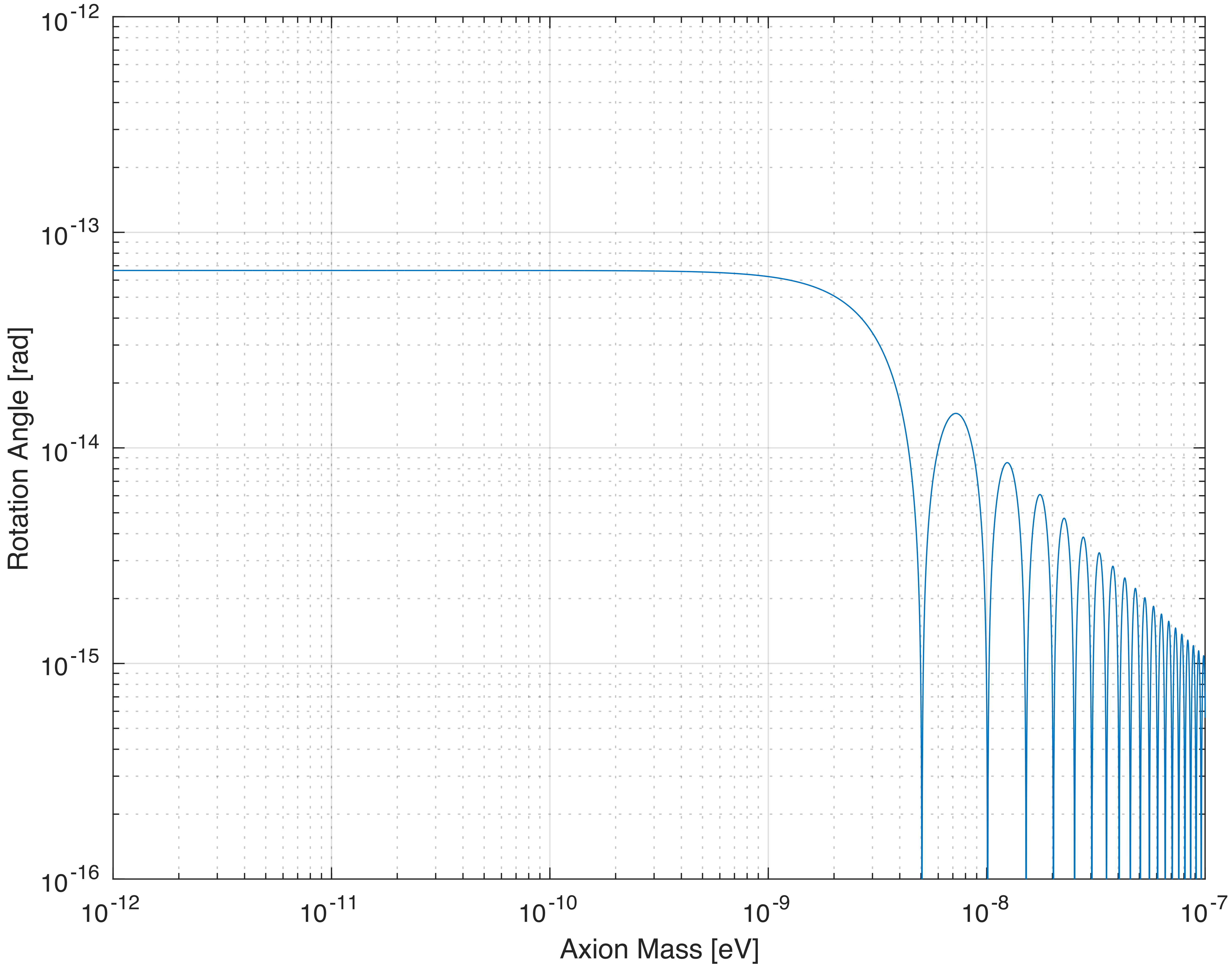
- If $m_\mathrm{a}L = (2N+1)\pi$ for $N = 0,1,2...$
- Amplitude of the oscillation is $\dfrac{g_{a\gamma\gamma}L\sqrt{2\rho_\mathrm{a}}}{(2N+1)\pi}$

$m_\mathrm{a}L = \pi$

Signal projection

Polarization rotation

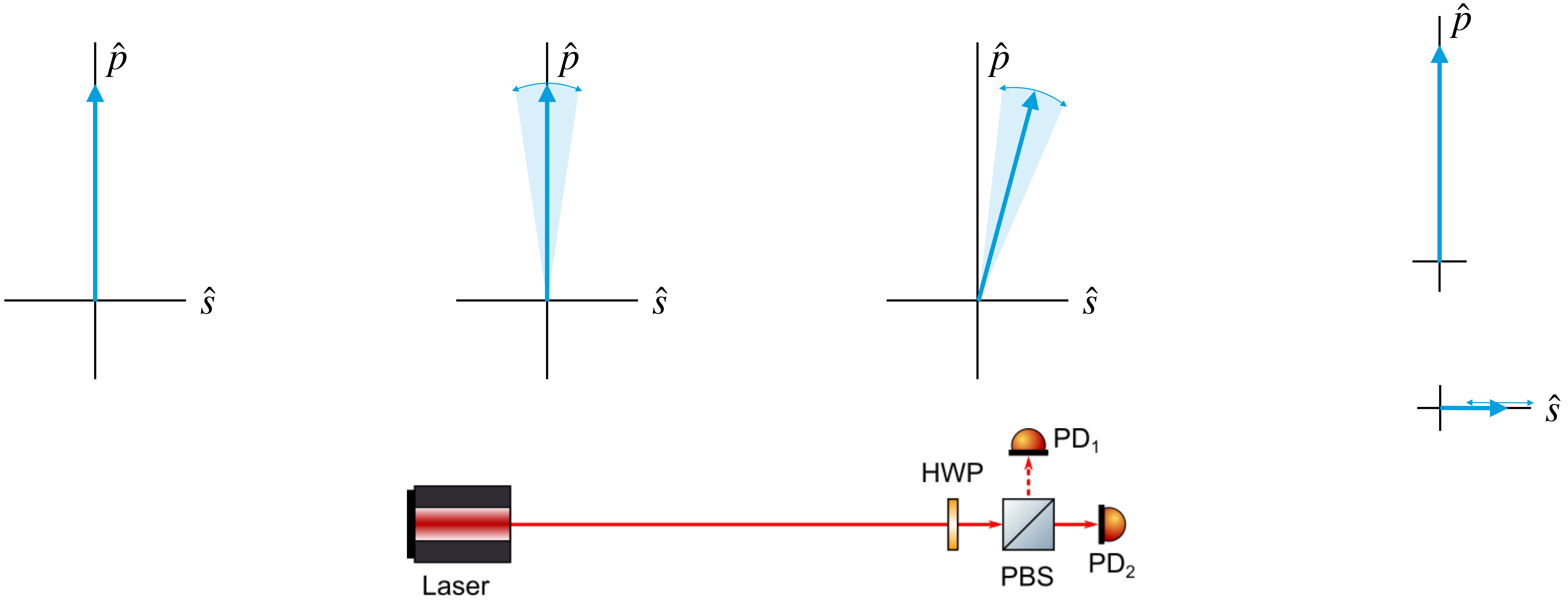
- L = 245 m
- $g_{a\gamma\gamma} = 2\times10^{-10}$ GeV^{-1}
- $\rho_a = 0.3$ GeV/cm^3



Measuring the effect

Single pass laser setup

- Measure polarization noise from laser propagating over long baseline
- Filter DC power with polarization optics to only measure modulation



Measuring the effect

Pushing the sensitivity with precision interferometry

Sensitivity

- Calculate the power spectral density of measured data
- If shot noise limited SNR:

$$\frac{\sqrt{T_{\rm obs}}}{2\sqrt{S_{\rm shot}(m)}}\delta c_0 \quad (T_{\rm obs} \lesssim \tau_{\rm a}) \qquad\qquad \frac{(T_{\rm obs}\tau_{\rm a})^{1/4}}{2\sqrt{S_{\rm shot}(m)}}\delta c_0 \quad (T_{\rm obs} \gtrsim \tau_{\rm a})$$

- Sensitivity to $g_{a\gamma\gamma}$ (SNR = 1, $T_{\rm obs} \gg \tau_a$)
- $$g_{\rm a\gamma\gamma}(m_{\rm a}) = 2\times 10^{-8}\,{\rm GeV}^{-1}\left(\frac{m_{\rm a}}{2.5\,{\rm neV}}\right)^{5/4}\left(\frac{1\,{\rm W}}{P_0}\frac{1064\,{\rm nm}}{\lambda}\right)^{1/2}\left(\frac{1\,{\rm day}}{T_{\rm obs}}\right)^{1/4}\left|\sin\left(\frac{m_{\rm a}L}{2}\right)\right|^{-1}$$

Measuring the effect

Sensitivity

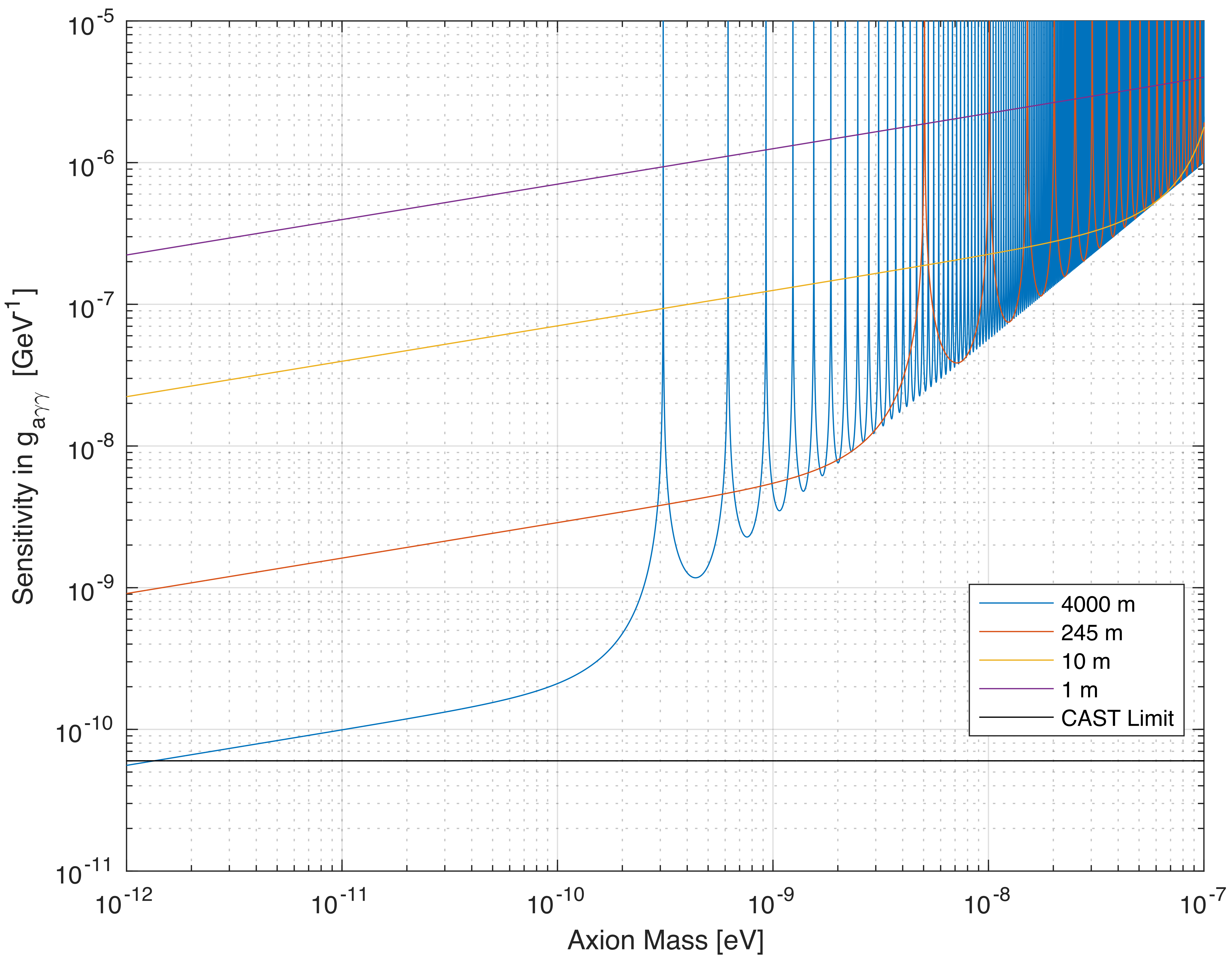
- Sensitivity to $g_{a\gamma\gamma}$ (SNR = 1, $T_{\mathrm{obs}} \gg \tau_a$, $m_{\mathrm{a}} L \ll 1$)
  - $$g_{a\gamma\gamma}(m_{\mathrm{a}}) \simeq 1 \times 10^{-8}\,\mathrm{GeV}^{-1} \left(\frac{m_{\mathrm{a}}}{2.5\,\mathrm{neV}}\right)^{1/4} \left(\frac{245\,\mathrm{m}}{L}\right) \left(\frac{1\,\mathrm{W}}{P_0}\frac{1064\,\mathrm{nm}}{\lambda}\right)^{1/2} \left(\frac{1\,\mathrm{day}}{T_{\mathrm{obs}}}\right)^{1/4}$$

- Sensitivity to $g_{a\gamma\gamma}$ (SNR = 1, $T_{\mathrm{obs}} \gg \tau_a$, $m_{\mathrm{a}} L = \pi$)
  - $$g_{a\gamma\gamma}(m_{\mathrm{a}}) = 2 \times 10^{-8}\,\mathrm{GeV}^{-1} \left(\frac{245\,\mathrm{m}}{L}\right)^{5/4} \left(\frac{1\,\mathrm{W}}{P_0}\frac{1064\,\mathrm{nm}}{\lambda}\right)^{1/2} \left(\frac{1\,\mathrm{day}}{T_{\mathrm{obs}}}\right)^{1/4}$$

Projecting the sensitivity

Sensitivity

- P = 2 W
- 1 day observation time
- 1064 nm wavelength



Using Fabry-Perot Cavities

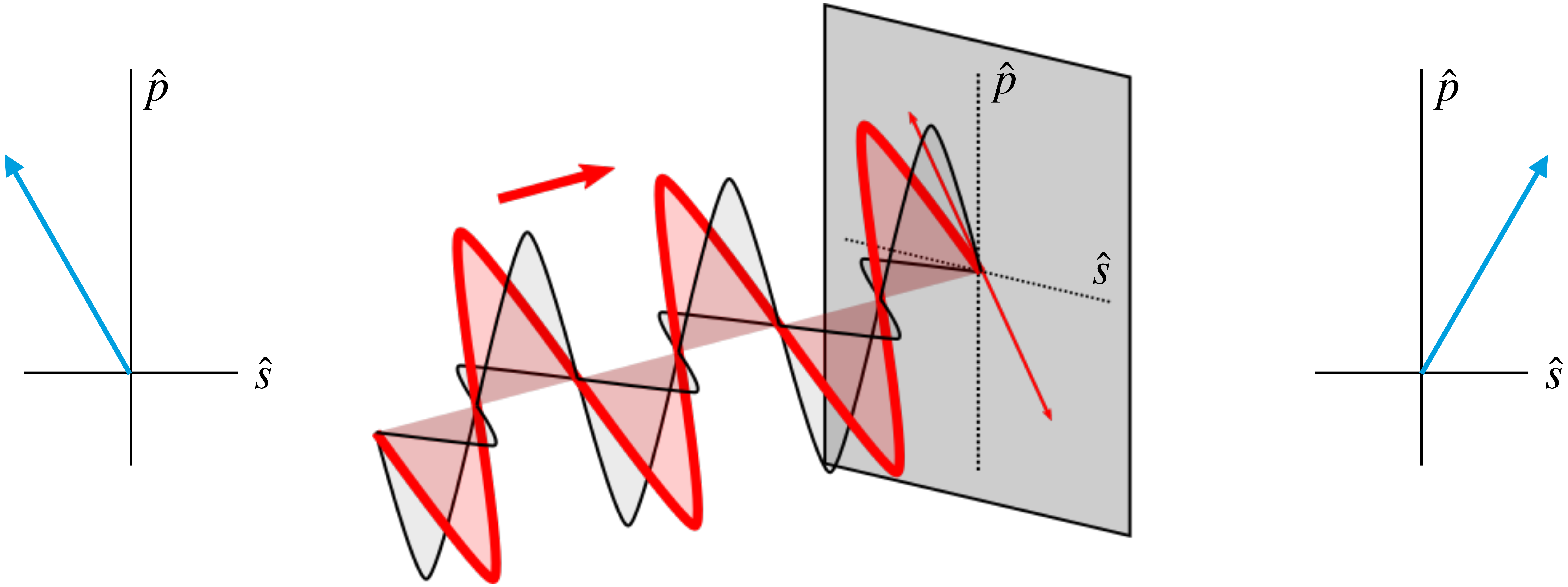
Boosting signal with optical cavity

- Each pass incurs polarization modulation
  - Coherent build up of polarization modulation for empty cavity when:
    $m_a L = \pi(2N + 1)$ for $N = 0, 1, 2...$

Using Fabry-Perot Cavities

Boosting signal with optical cavity

- Each pass incurs polarization modulation
  - Problem: no low mass sensitivity, incoming rotation cancels outgoing rotation, upon reflection



Using Fabry-Perot Cavities

Boosting signal with optical cavity

- Each pass incurs polarization modulation
  - Coherent build up of polarization modulation for empty cavity when:
    $m_a L = \pi(2N+1)$ for $N = 0, 1, 2...$
  - Polarization rotation enhanced by the finesse of the cavity

- $$\theta(t) = 2\frac{g_{a\gamma\gamma}\sqrt{2\rho_a}}{m_a}\beta(m_a L)\sin^2\left(\frac{m_a L}{2}\right)\sin\left(m_a t + \delta_\tau(t) - \frac{m_a L}{2}\right)$$

- $$\beta(m_a L) = \left|\frac{t_1 t_2}{1 - r_1 r_2}\frac{r_1 r_2}{1 - r_1 r_2 e^{-i2m_a L}}\right| \quad \text{with} \quad \beta(N\pi) = \beta_0 \simeq \frac{4t_1 t_2}{\left(t_1^2 + t_2^2 + l^2\right)^2}$$

Using Fabry-Perot Cavities

Boosting signal with optical cavity

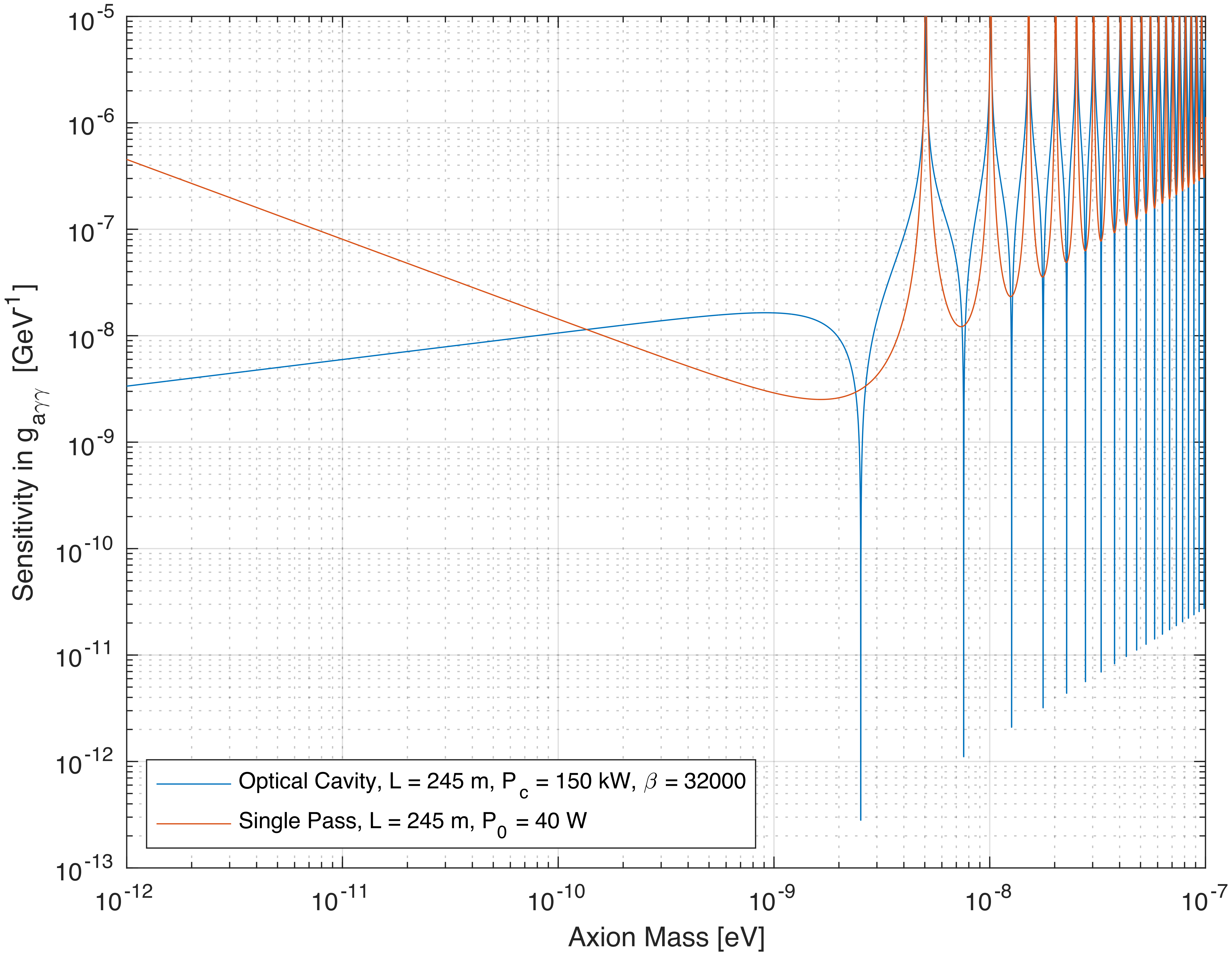
- Each pass incurs polarization modulation
  - Coherent build up of polarization modulation for empty cavity when: $m_\mathrm{a} L = \pi(2N+1)$ for $N = 0, 1, 2...$
  - Polarization rotation enhanced by the finesse of the cavity

- Sensitivity to $g_{a\gamma\gamma}$ (SNR = 1, $T_\mathrm{obs} \gg \tau_a$, $m_\mathrm{a} L = \pi$)
  - $g_{\mathrm{a}\gamma\gamma}(m_\mathrm{a}) = 2.5 \times 10^{-13}\,\mathrm{GeV}^{-1} \left(\frac{245\,\mathrm{m}}{L}\right)^{5/4} \left(\frac{\beta_0}{40{,}000}\right) \left(\frac{1\,\mathrm{W}}{P_0}\frac{1064\,\mathrm{nm}}{\lambda}\right)^{1/2} \left(\frac{1\,\mathrm{day}}{T_\mathrm{obs}}\right)^{1/4}$

Sensitivity using a cavity

Optical Cavity vs Single Pass

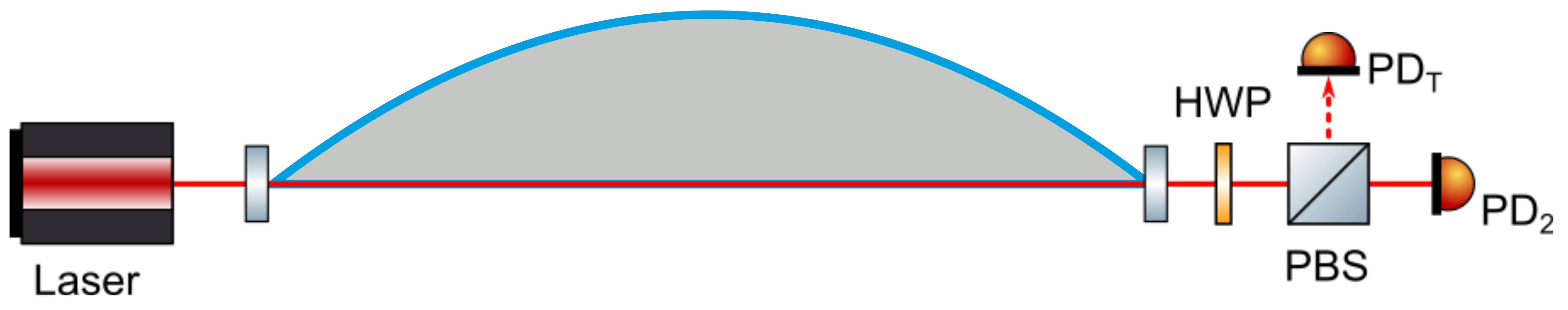
- Cavity likely limited to 150 kW
- Input power limited to 40 W
- Regions exist where single pass is more sensitive than the optical cavity (under these constraints)



Additional Challenges

Challenges

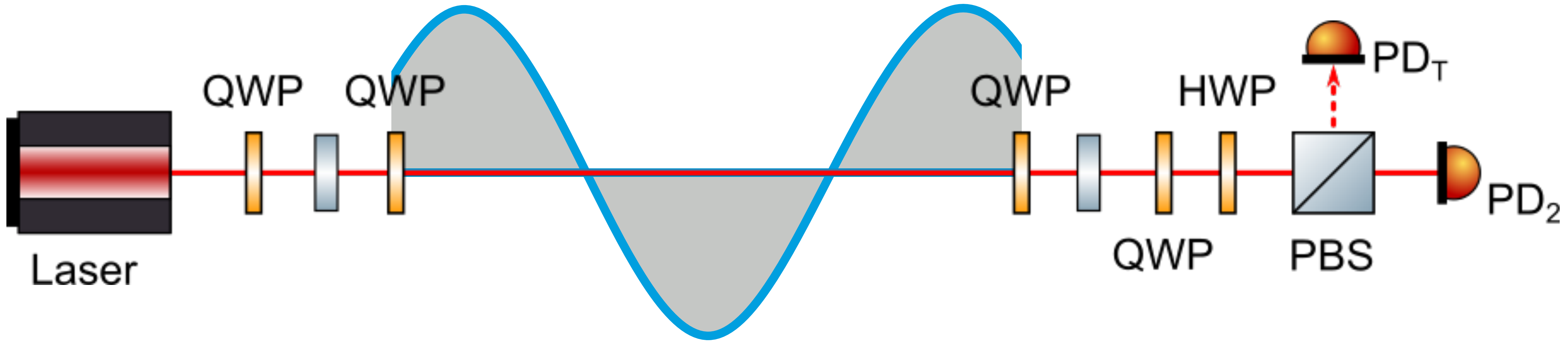
- Requires pm absolute length stability of the cavity
    - Relative length control demonstrated in ALPS II with pm precision
    - Must demonstrate absolute length sensing



Probing low mass axions

Other cavity configurations

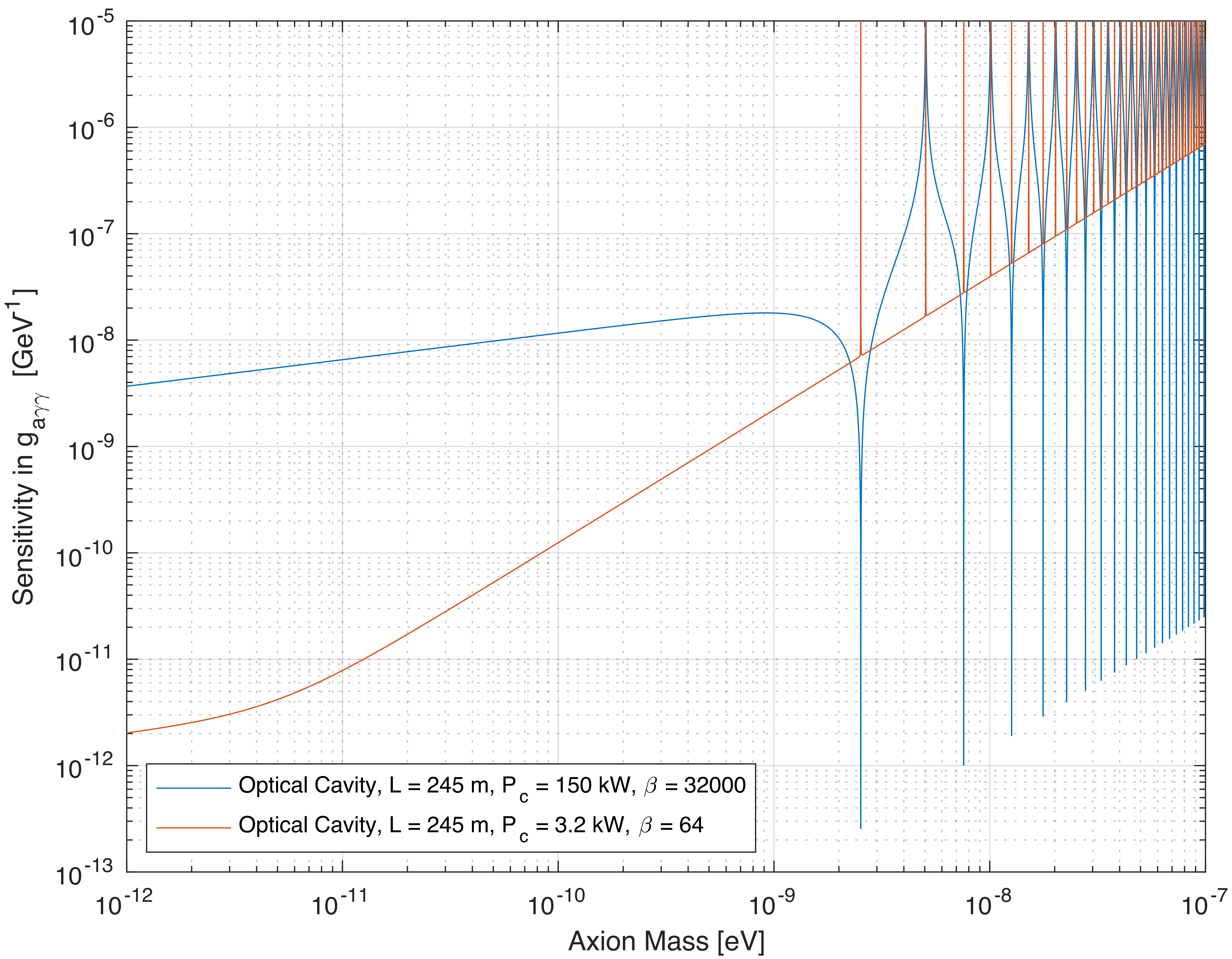
- Cavity with QWPs at each end
  - Ideal case:
    - Signal amplified for the 0-th order resonance (no other resonances amplified)
    - $$\theta(t) = 2\frac{g_{a\gamma\gamma}\sqrt{2\rho_\mathrm{a}}}{m_\mathrm{a}}\beta(m_\mathrm{a}L)\,\sin\left(m_\mathrm{a}L\right)\,\sin\left(m_\mathrm{a}t + \delta_\tau(t) - \frac{m_\mathrm{a}L}{2}\right)$$



Probing low mass axions

QWP cavity configuration

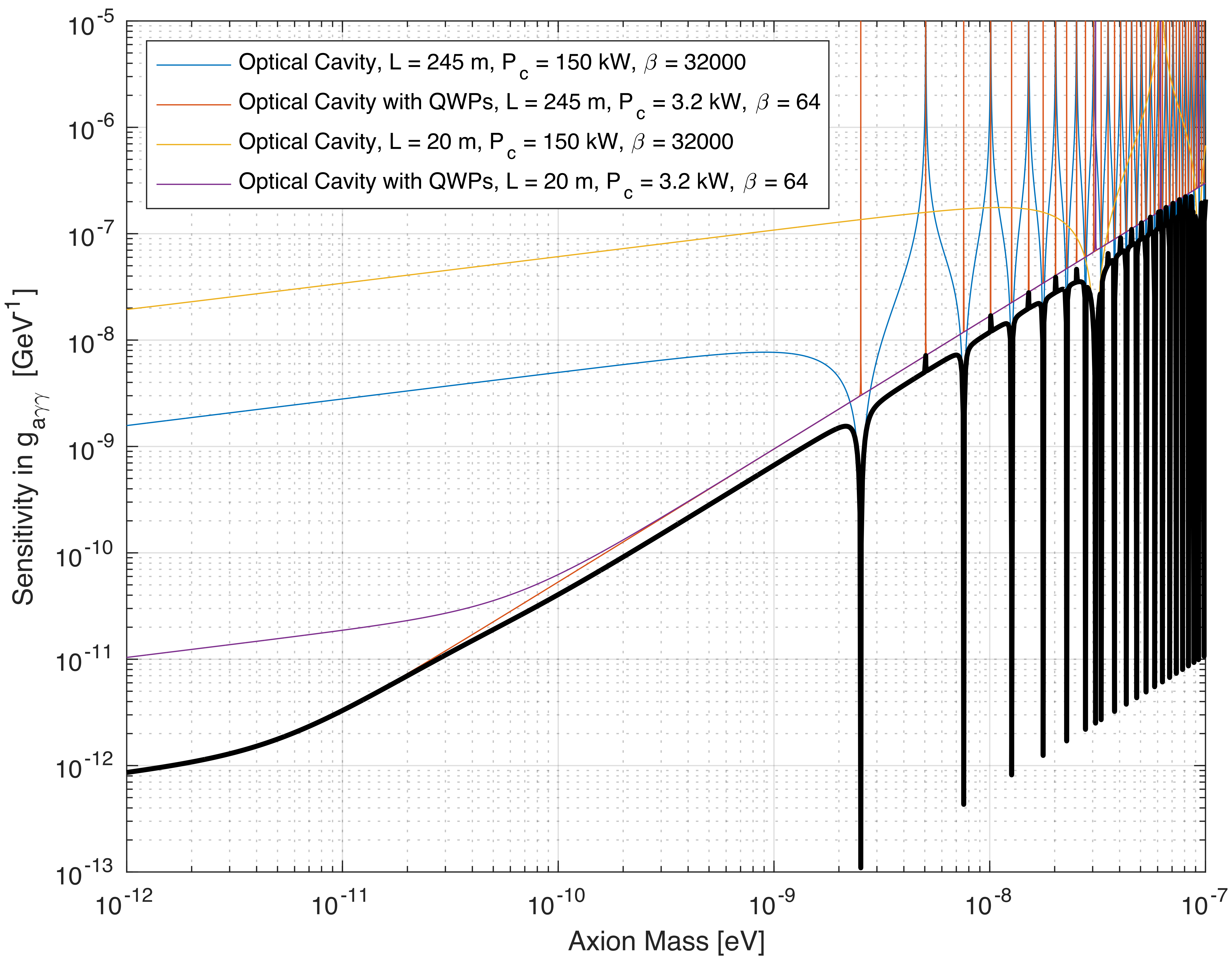
- Cavity with QWPs only resonance is at low masses
- Higher resonances
  - Cavity transfer function nearly canceled by sinusoidal axion mass response



Axion halo search potential at DESY using ALPS Cavities

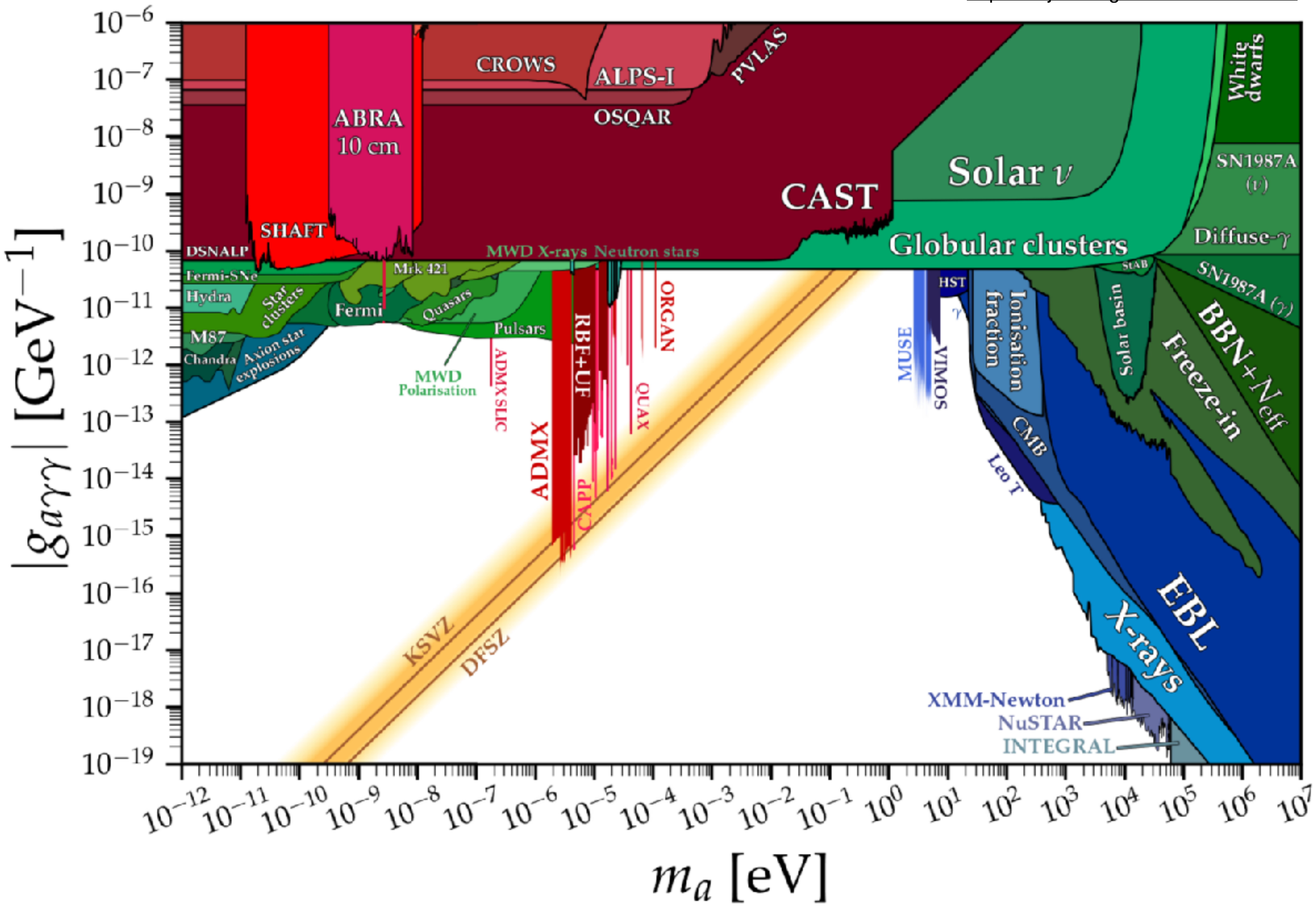
Potential search program

- 4 configurations
  - 245 m empty cavity
  - 245 m cavity with QWPs
  - 20 m empty cavity
  - 20 m cavity with QWPs
- 30 day observation time each
- Probe beyond the CAST limit



Axion parameter space

From Ciaran O'Hare: https://cajohare.github.io/AxionLimits/



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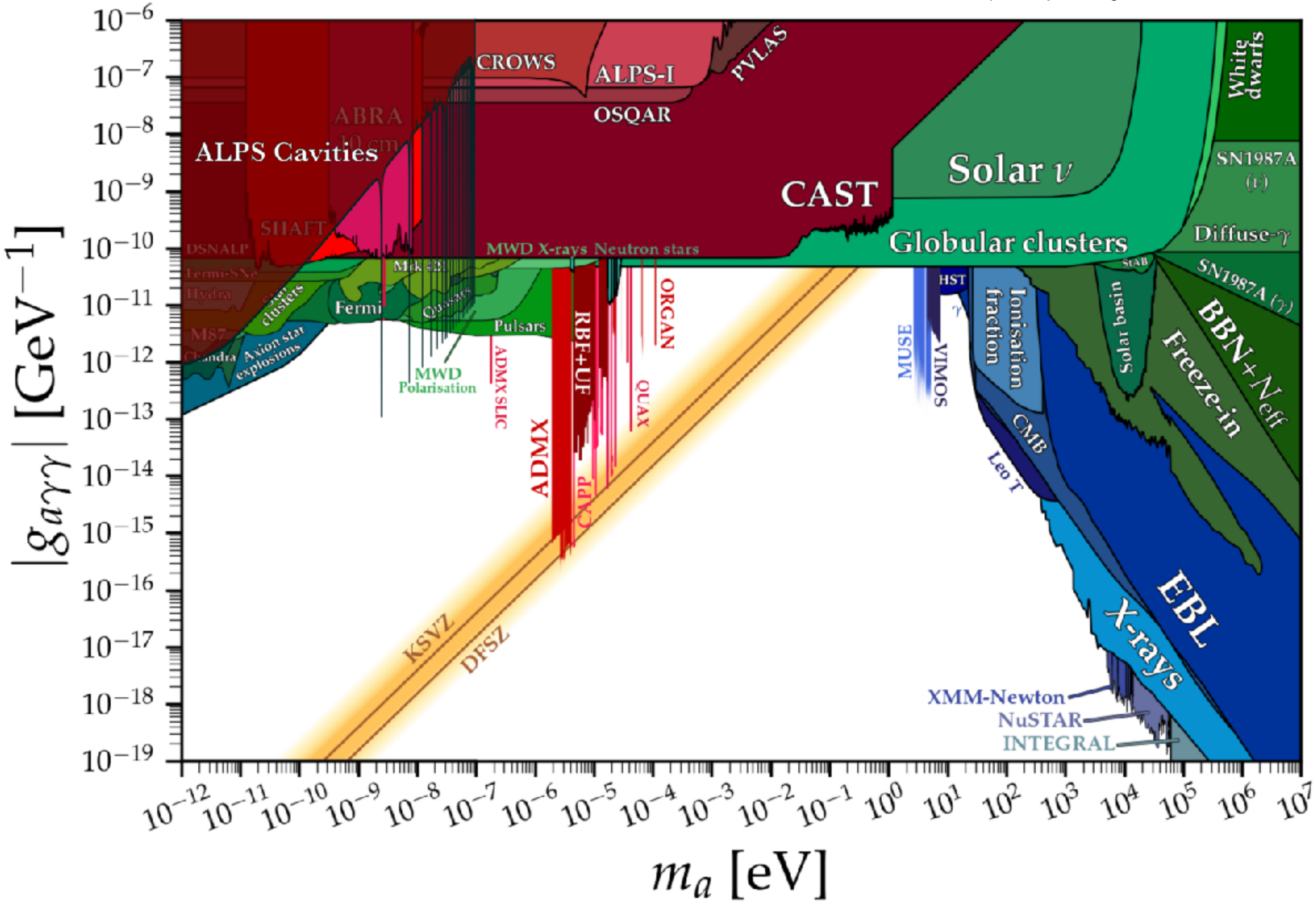

Applying new technologies

How to tune the resonances with respect to the axion mass

- 245 m cavities ~3 m of length tuning range (3% of the space between 1st and 2nd resonances)
  - Tuning by varying cavity FSR has limited range, not efficient
- Changing orientation of QWPs, different resonance for orthogonal polarization states
  - Not likely possible with high-finesse cavities
- Folding mirror setup

- Khalili cavity setup

Conclusions

We can search for axions in the dark matter halo using the optical cavities we built for ALPS II!

- Polarization modulation induced by axions would be a measurable signal
- Realistic to achieve sensitivities beyond the CAST limit with technology demonstrated at DESY
  - Mass range between 10^{-12} eV and 10^{-9} eV
  - Sensitivities down to $g_{a\gamma\gamma} > 10^{-13}$
- Tuning to fill the gaps between resonances is more complicated but we have some ideas

Infrastructure at DESY

Providing the foundation for experiments with precision interferometry

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Providing the foundation for experiments with precision interferometry

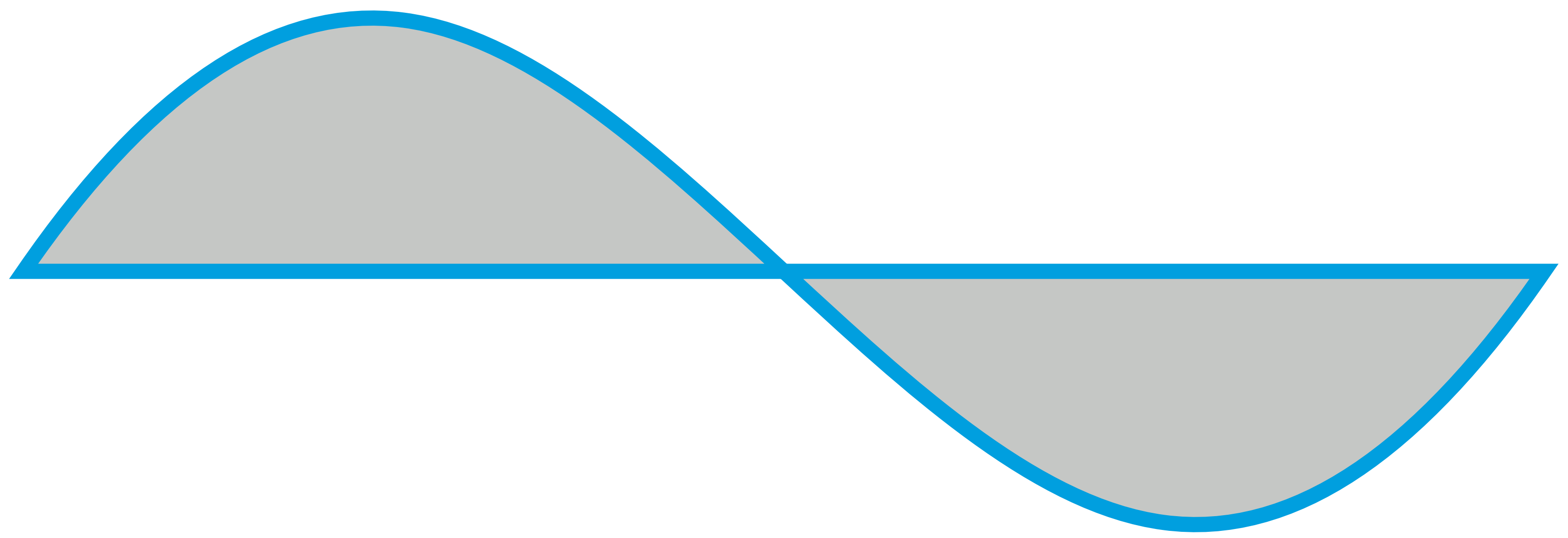
Accumulation of polarization rotation

Pushing the sensitivity with precision interferometry

Polarization rotation

- $$\theta(t) = \frac{2\Delta\theta}{m_a} \sin\left(\frac{m_a L}{2}\right) \sin\left(m_a t - \frac{m_a L}{2}\right)$$
  - If $m_a L$ is of order 1 or greater
    - Polarization rotation can cancel itself

$m_a L = 2\pi$



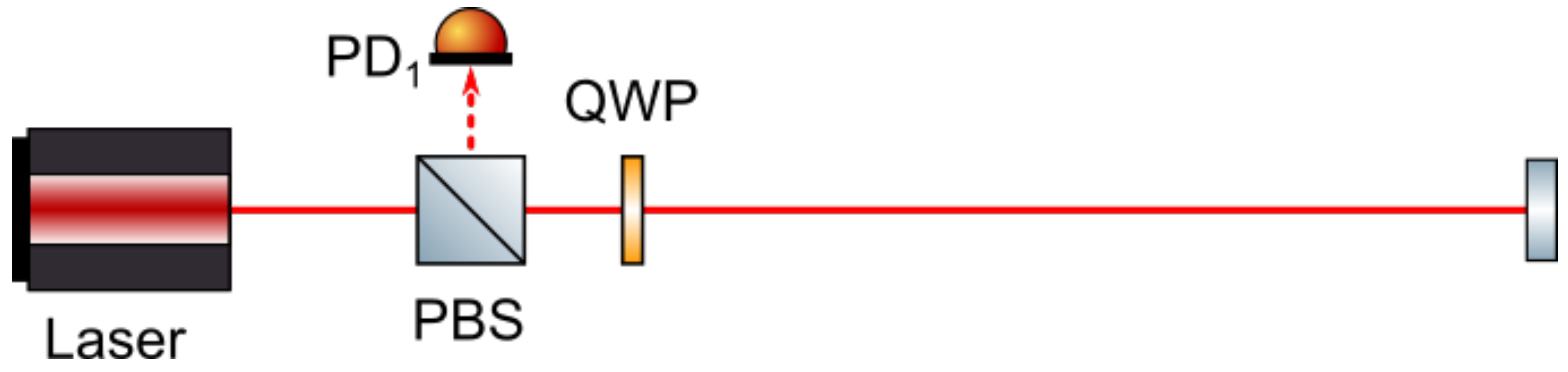
$m_a L = \pi$

Measuring the effect

Pushing the sensitivity with precision interferometry

Double pass laser setup

- Try to double baseline by reflecting back from a mirror, use QWP to filter DC power
- Problem: relative inversion between s and p polarized states upon reflection

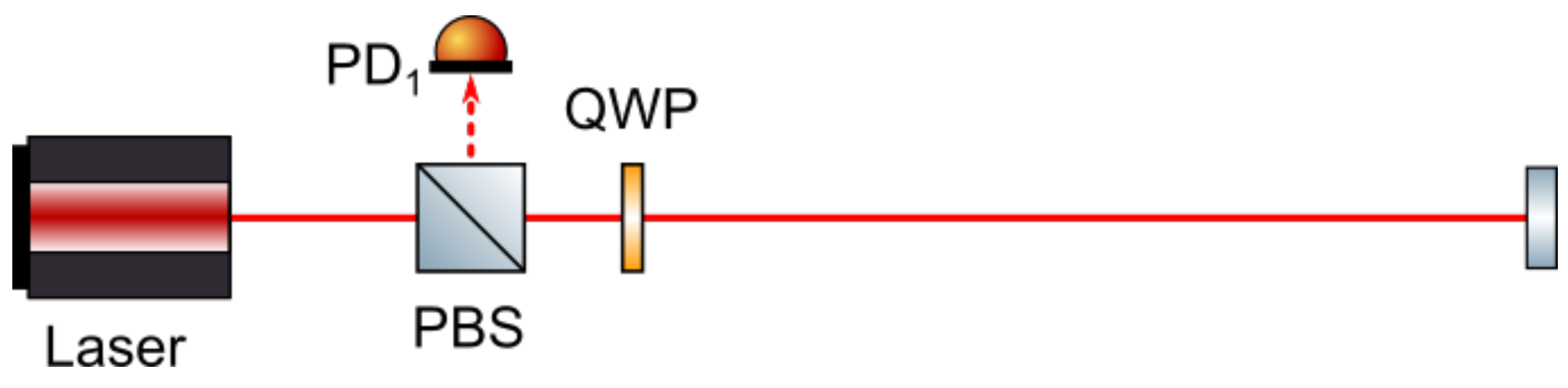


Measuring the effect

Pushing the sensitivity with precision interferometry

Double pass laser setup

- Try to double baseline by reflecting back from a mirror, use QWP to filter DC power
- Problem: relative inversion between s and p polarized states upon reflection
  - Response:
    - $$\theta(t) = 2\frac{g_{a\gamma\gamma}\sqrt{2\rho_\mathrm{a}}}{m_\mathrm{a}}\sin^2\left(\frac{m_\mathrm{a}L}{2}\right)\sin\left(m_\mathrm{a}t + \delta_\tau(t) - \frac{m_\mathrm{a}L}{2}\right)$$



Measuring the effect

Pushing the sensitivity with precision interferometry

Double pass laser setup with QWP

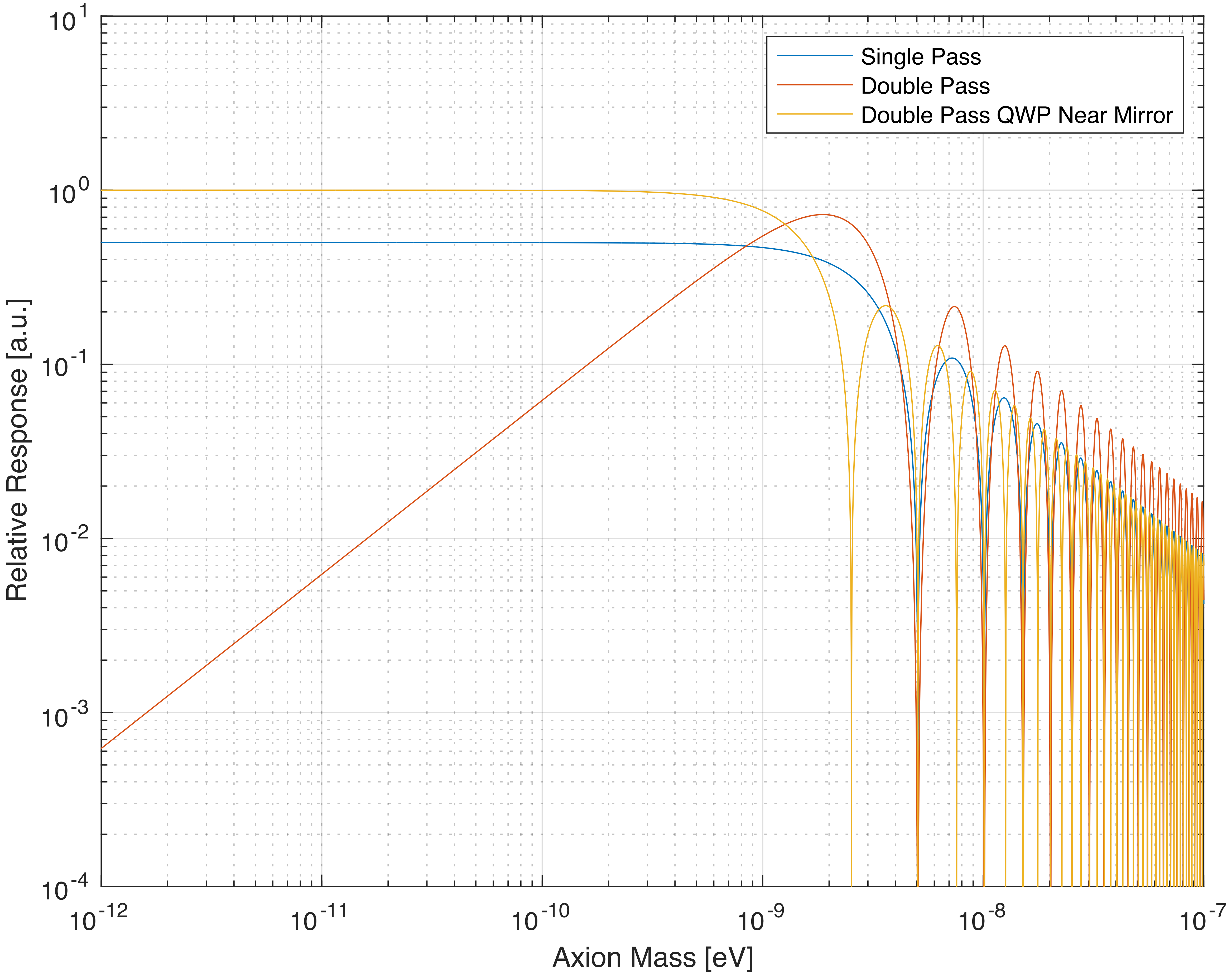
- Solution: change position of QWP to just before mirror
  - Leads to coherent sum of polarization modulation before and after reflection
  - Response:
    - $$\theta(t) = \frac{g_{a\gamma\gamma}\sqrt{2\rho_a}}{m_a} \sin\left(m_a L\right) \sin\left(m_a t + \delta_\tau(t) - \frac{m_a L}{2}\right)$$
    - For $mL \ll 1$ amplitude of polarization modulation $\simeq \dfrac{g_{a\gamma\gamma}\sqrt{2\rho_a}}{m_a}$

Measuring the effect

Pushing the sensitivity with precision interferometry

Comparing setups

- Response:



Measuring the effect

Pushing the sensitivity with precision interferometry

Comparing setups

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	Low mass resp.	Peak sens.	Peak locations	Zero locations
Single Pass	$\Delta\theta L$	$2\Delta\theta/m_a$	$m_a L = (2N+1)\pi$	$m_a L = 2N\pi$
Double Pass	none	$4\Delta\theta/m_a$	$m_a L = (2N+1)\pi$	$m_a L = 2N\pi$
Double QWP Pass	$2\Delta\theta L$	$2\Delta\theta/m_a$	$m_a L = (N+1/2)\pi$	$m_a L = N\pi$

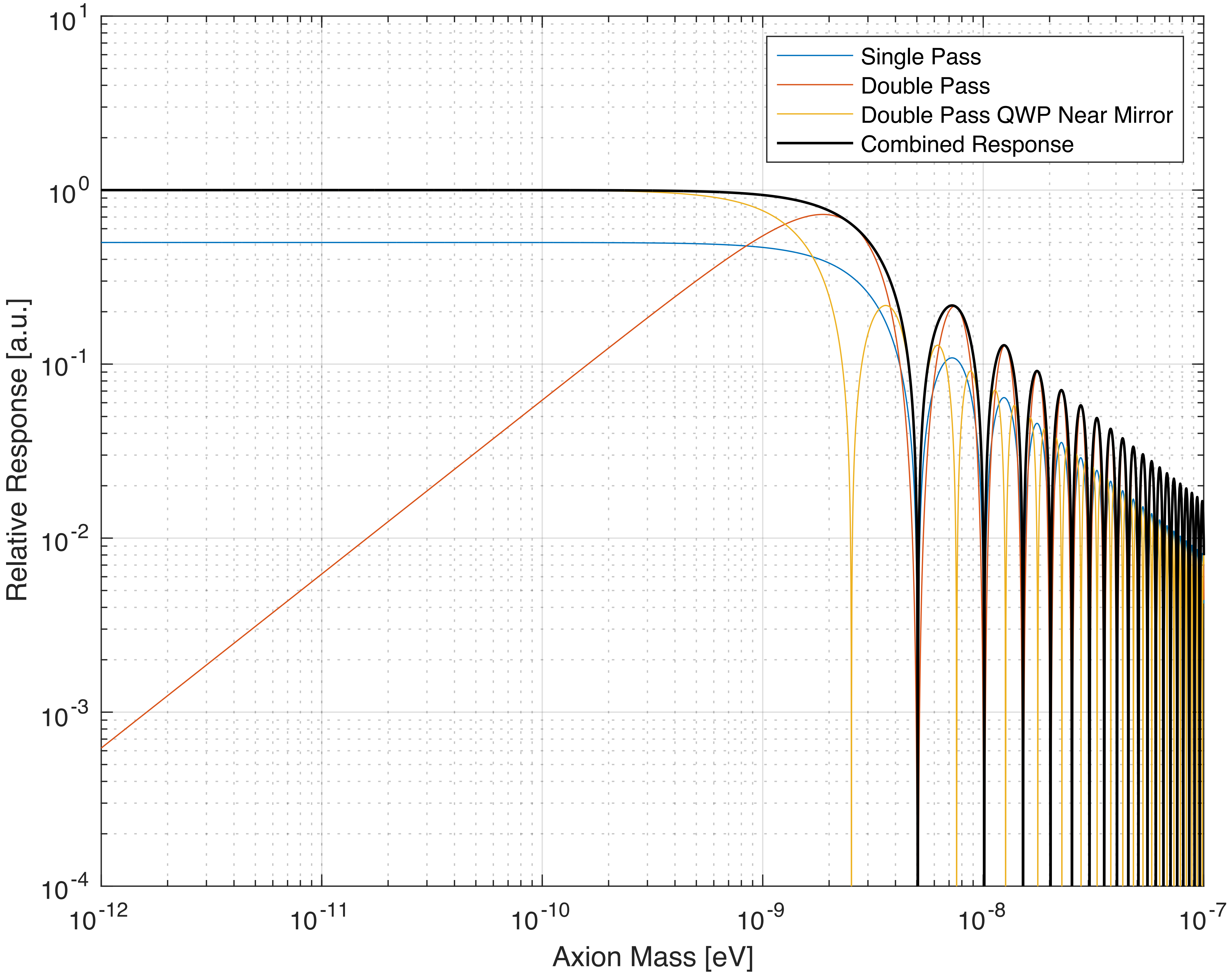
$(N = 0,1,2,\ldots)$

Measuring the effect

Pushing the sensitivity with precision interferometry

Comparing setups

- Response:



Measuring the effect

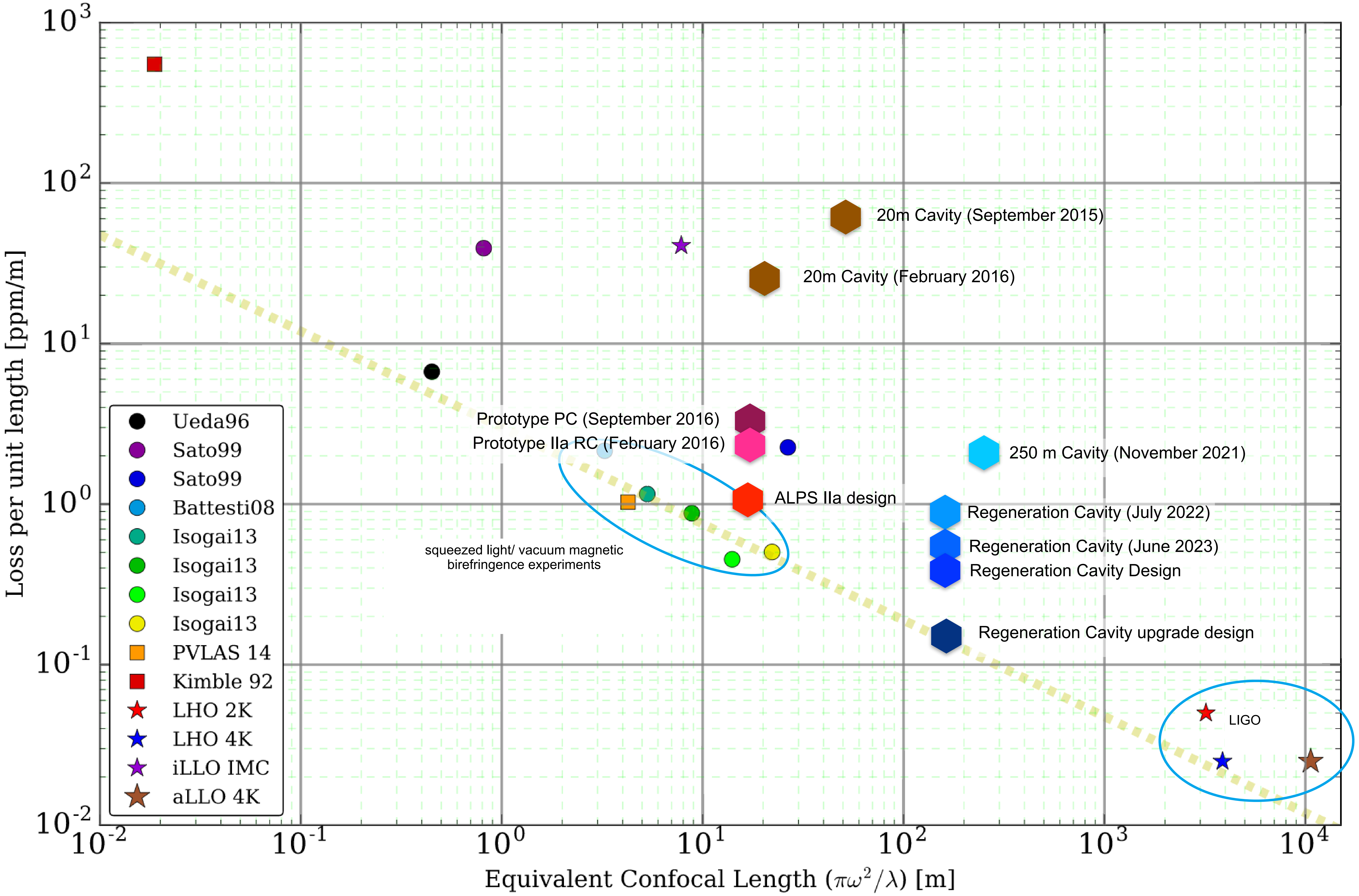
Pushing the sensitivity with precision interferometry

Boosting signal with optical cavity

- Each pass incurs polarization modulation
  - Empty cavity insensitive when $m_a L = 2\pi N$ for $N = 0, 1, 2...$
  - Peak sensitivity when $m_a L = \pi(2N + 1)$ for $N = 0, 1, 2...$
  - Response:
    - $\theta(t) = \frac{4\Delta\theta}{m_a} \sin\left(\frac{mL}{2}\right) \cos\left(\frac{mL}{2}\right) \sin(mt - mL) = \frac{2\Delta\theta}{m_a} \sin\left(m_a L\right) \sin(mt - mL)$
    - For $mL \ll 1$ amplitude of polarization modulation $\simeq 2\Delta\theta\, L$

Optical cavity loss per unit length

Learning from gravitational wave interferometers and VMB experiments



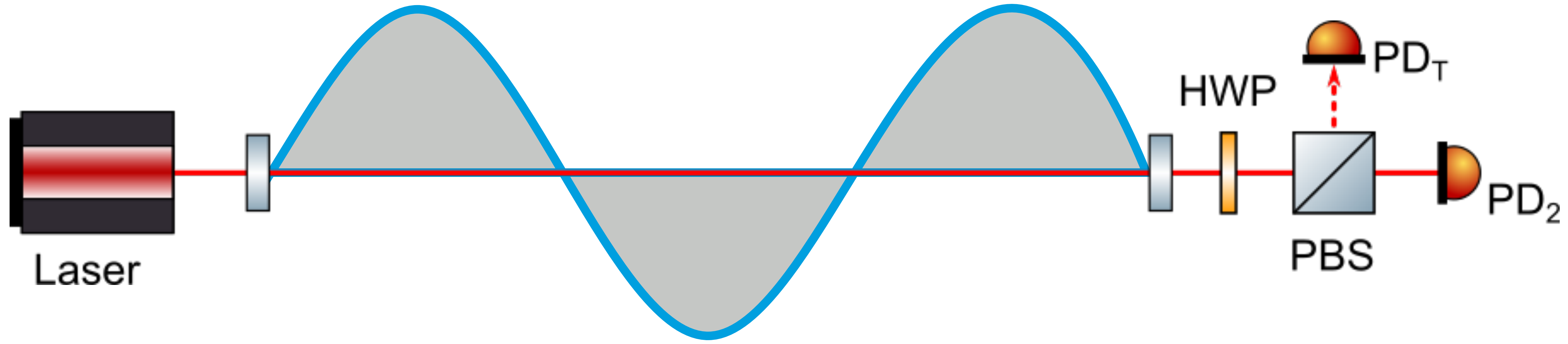
plot from LIGO T-1400226-v6

Using Fabry-Perot Cavities

Utilizing the ALPS II infrastructure

Boosting signal with optical cavity

- Each pass incurs polarization modulation
  - Coherent build up of polarization modulation for empty cavity when:
    $m_a L = \pi(2N + 1)$ for $N = 0, 1, 2...$
  - Polarization rotation enhanced by the finesse of the cavity
  - On 245 m baseline $\beta_0 = 40{,}000$ is possible
    - Requires pm length stability of the cavity (demonstrated in ALPS II)



Using Fabry-Perot Cavities

Utilizing the ALPS II infrastructure

Optical Cavity narrow band vs wide band

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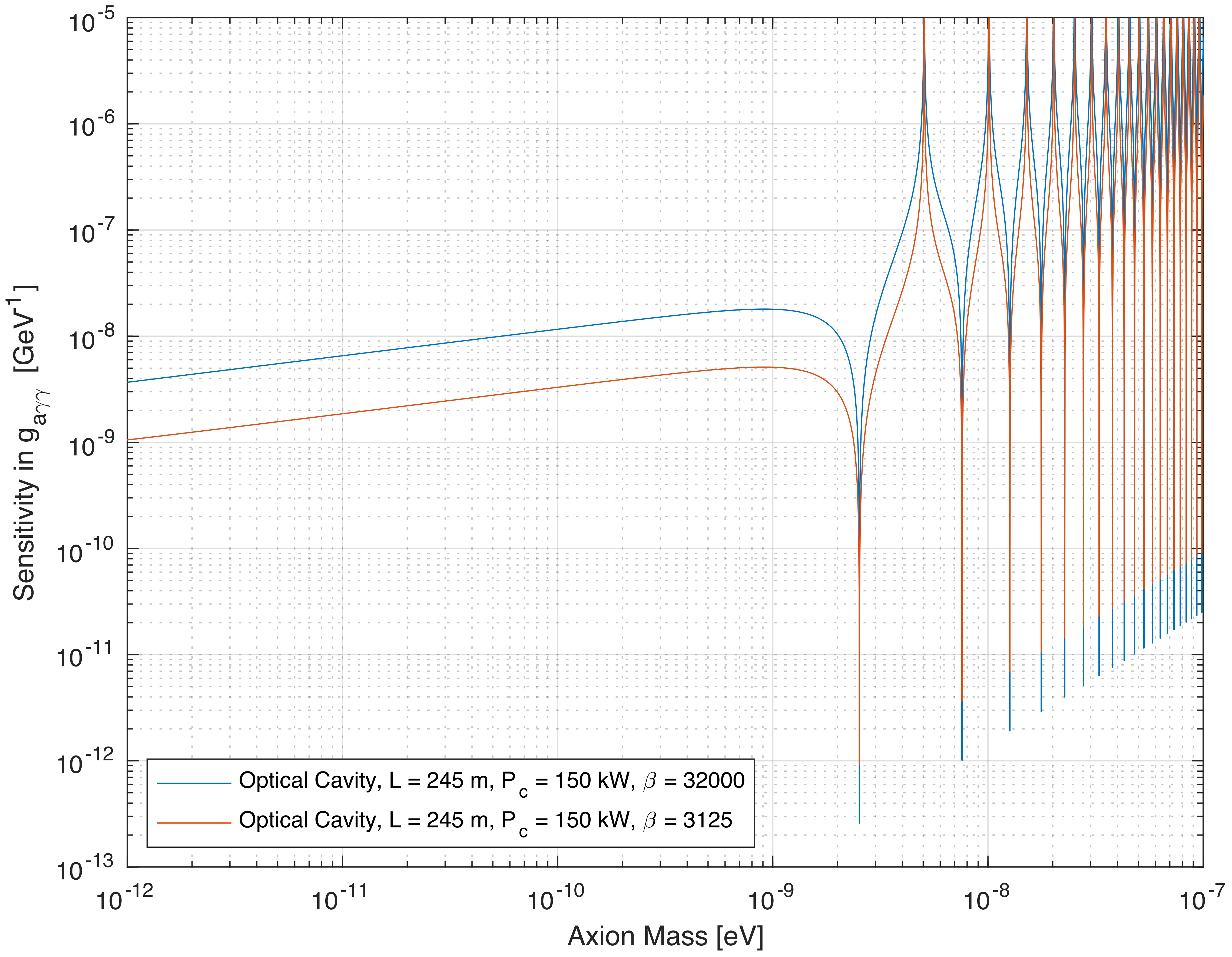

Using Fabry-Perot Cavities

Utilizing the ALPS II infrastructure

Boosting signal with optical cavity

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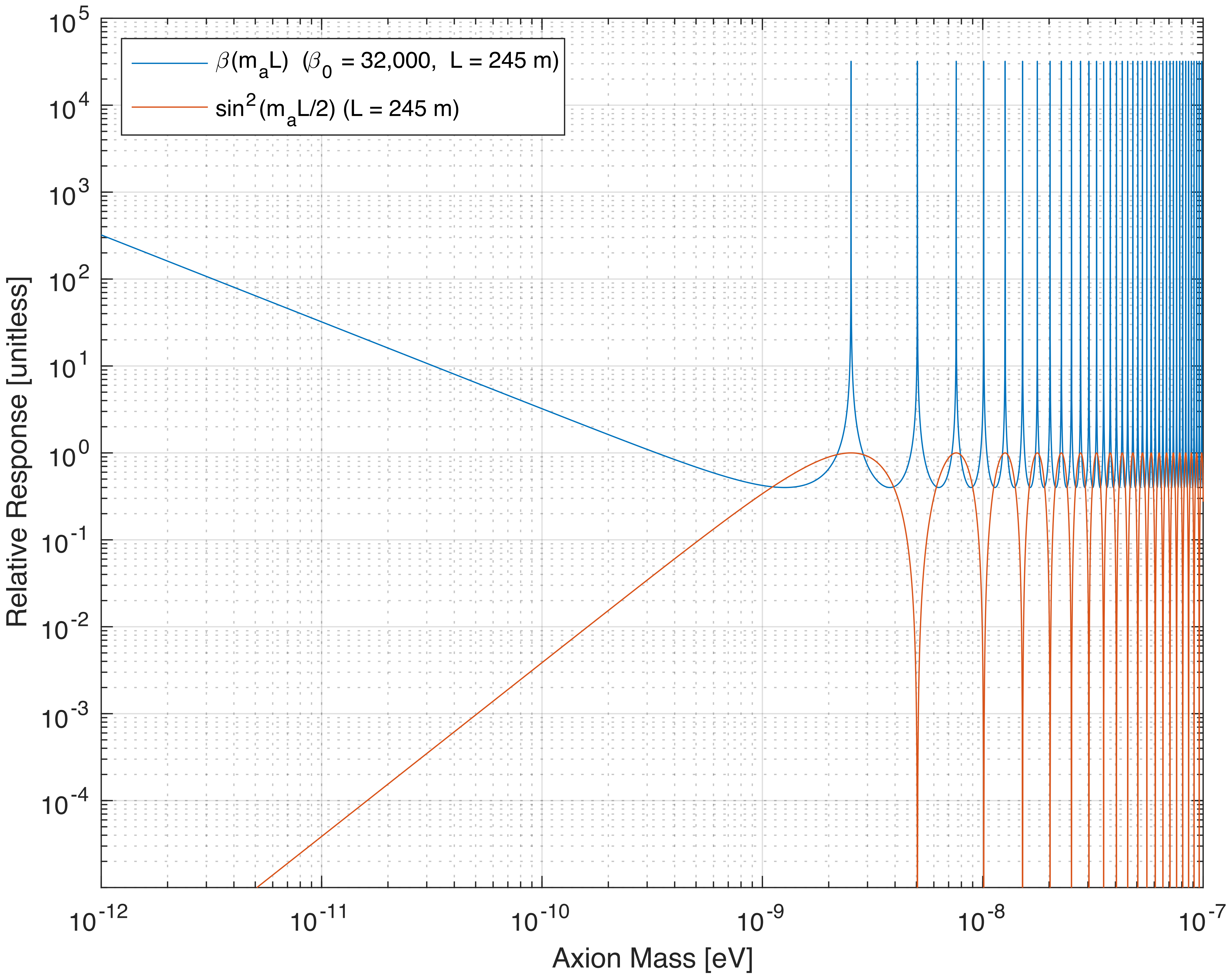
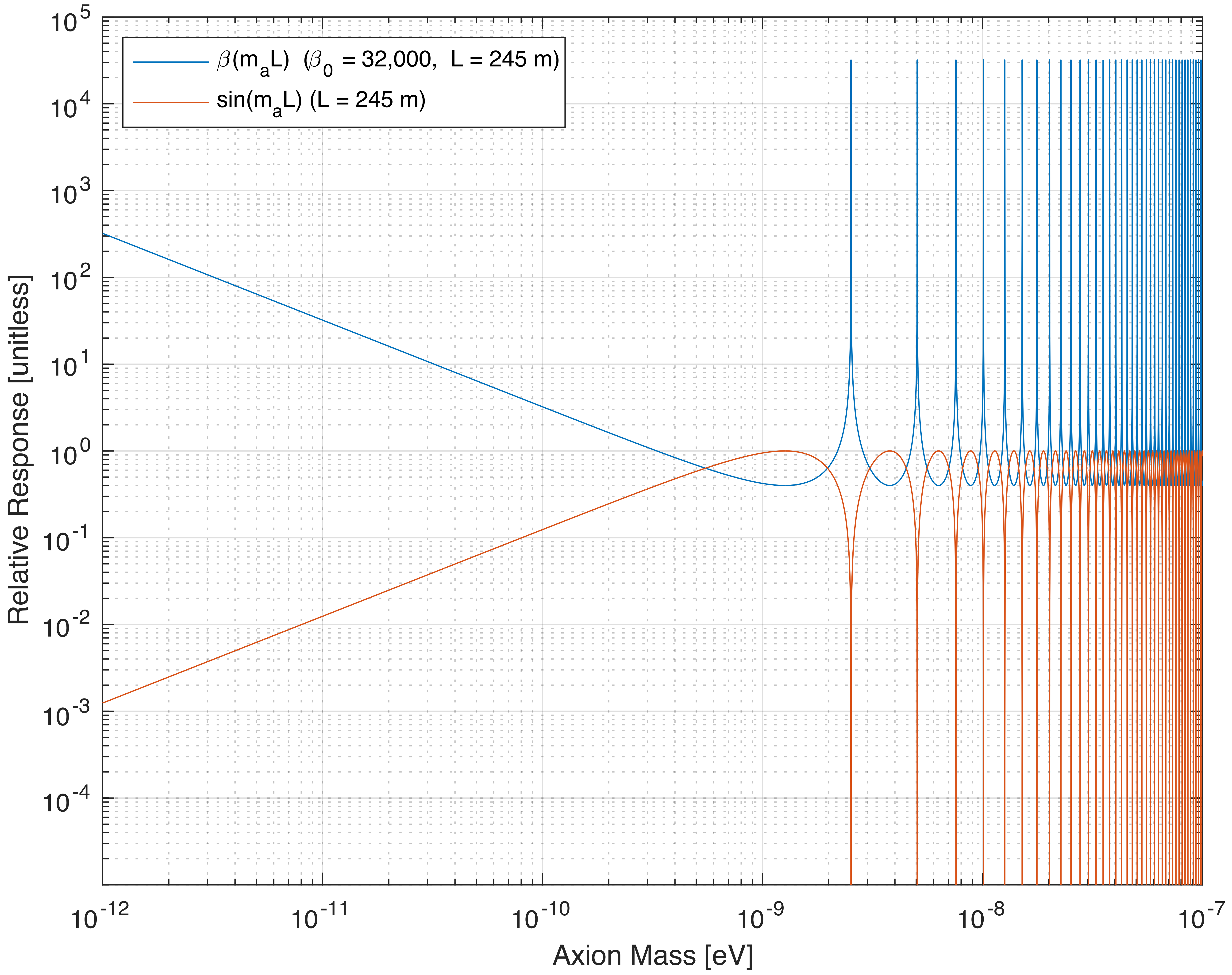


Probing low mass axions

Utilizing the ALPS II infrastructure

Other cavity configurations

- Cavity with QWPs at each end



Probing low mass axions

Utilizing the ALPS II infrastructure

Other cavity configurations

- Cavity with QWPs at each end
  - Ideal case:
    - If there is a non-zero integer number of wavelengths the polarization modulation cancels itself
    - Signal is only amplified for the 0-th order resonance
  - Challenges
    - Operating with QWPs inside a cavity