Polarimetry for Axion Search

Qazal Rokn

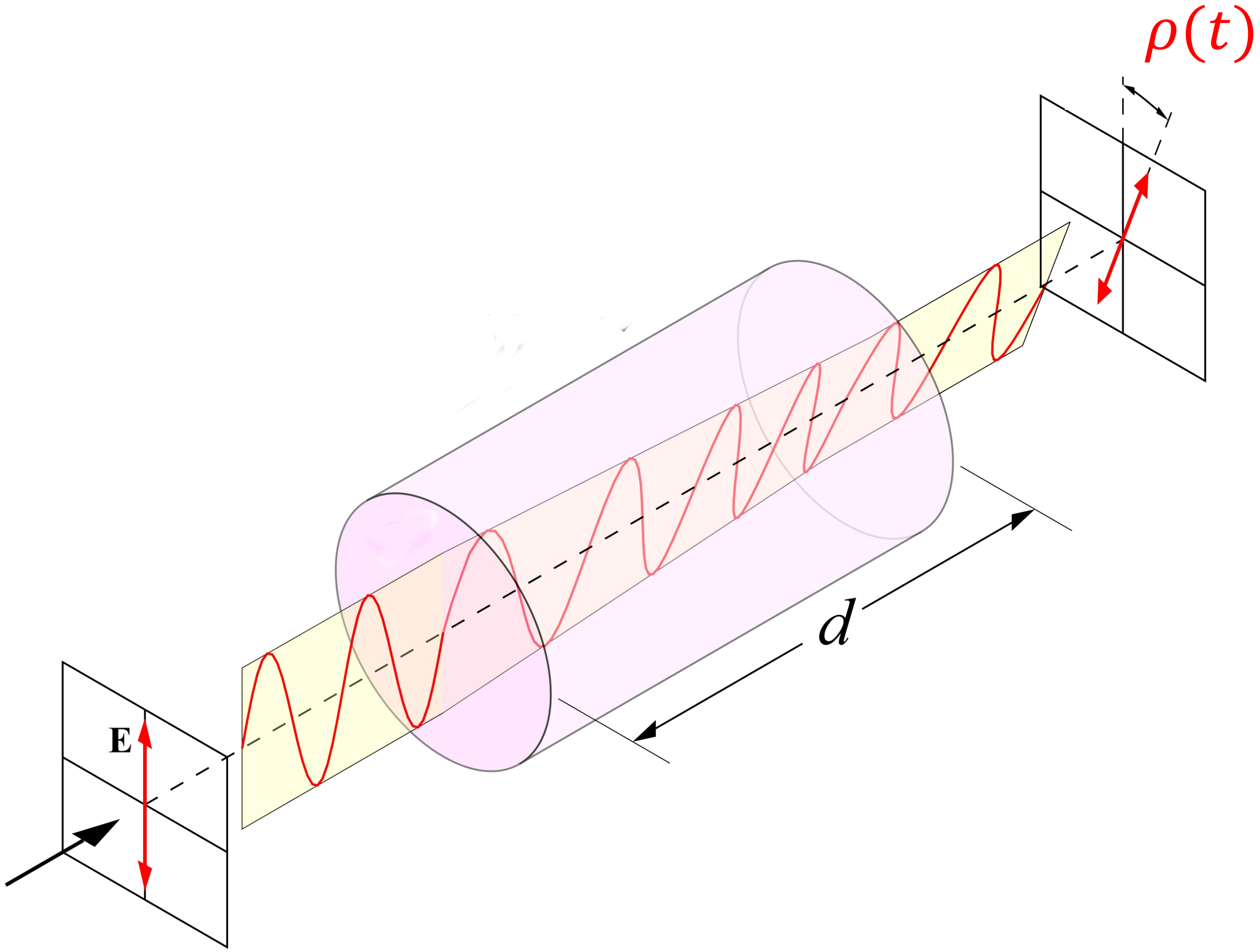
Max Planck Institute for Gravitational Physics/Leibniz Universität Hannover

12th June 2024

Ljubljana, Slovenia

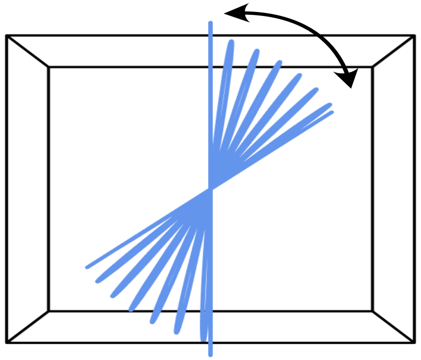
Qazal.rokn@aei.mpg.de

Effect of Axion Field on Polarization of Light



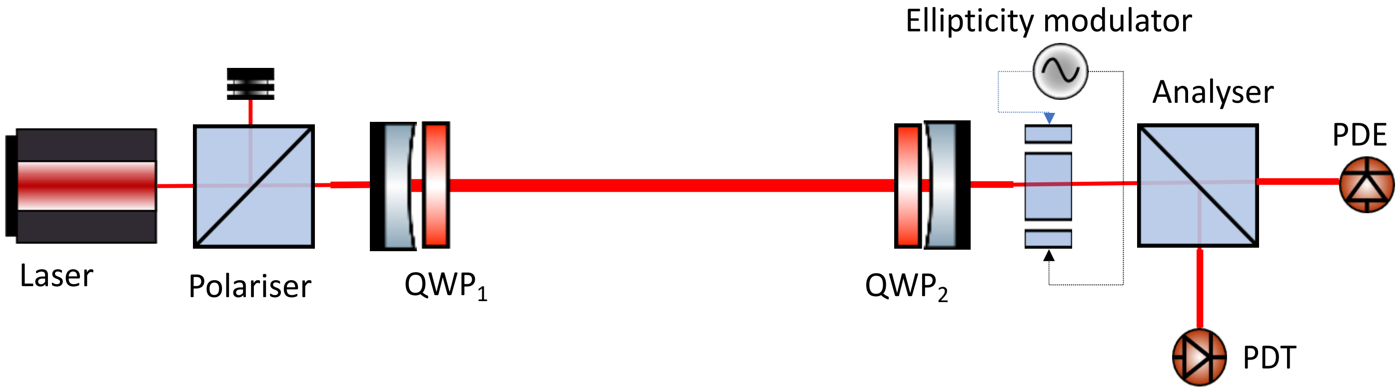
- Axion field rotates the polarization of linearly polarized light
- Angle of rotation oscillates with the frequency of Axion field

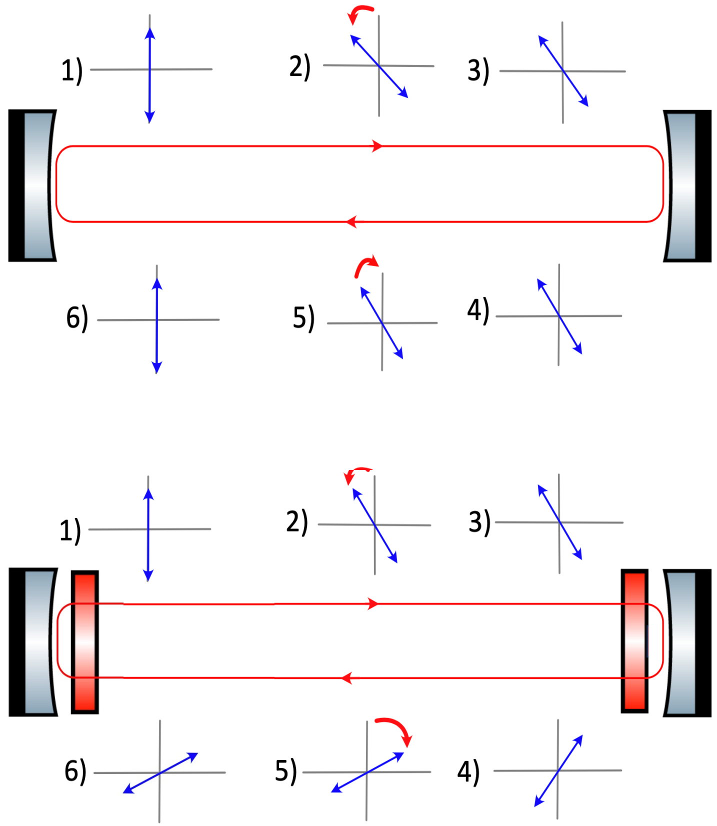
$$\rho(t) \propto \sin(\omega_{Axion} t)$$



Proposed set up for Axion Detection

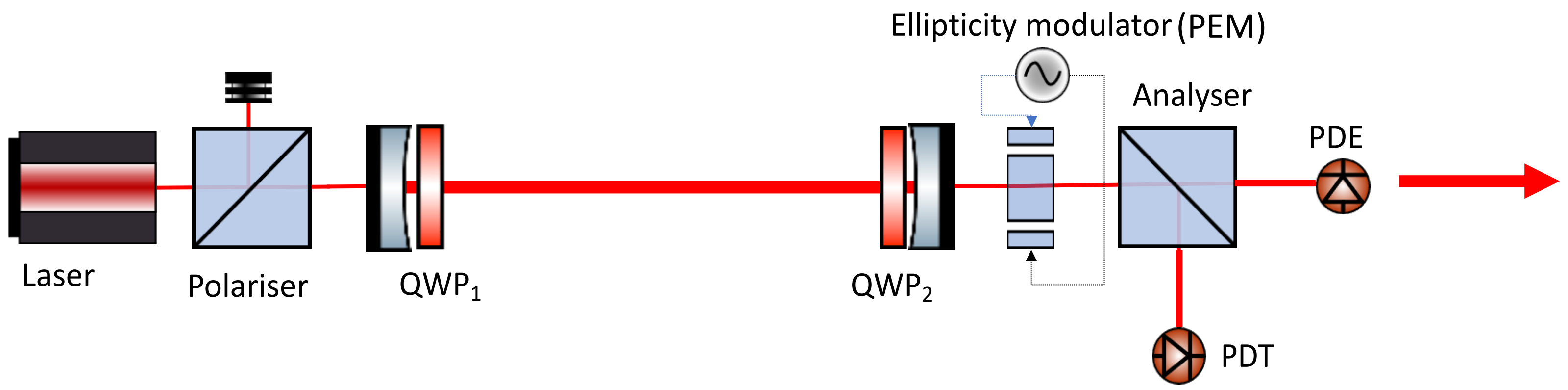
Function of the Quarter Wave Plates





- Axion-induced rotation direction depends on propagation direction
- The quarter wave plates prevent cancellation of the Axion effect
- QWP converts rotation modulation to ellipticity modulation

Detection using Heterodyne Technique



$$I_{\text{ext}}(\rho) \approx I_0(\sigma^2 + \eta^2 - 2N\eta\rho)$$

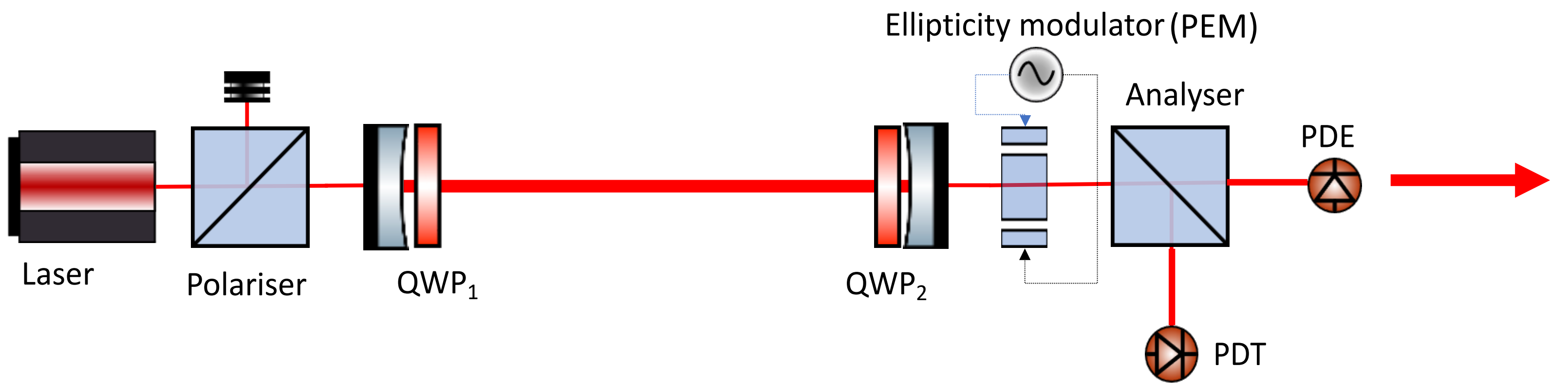
After demodulation @ ν_{PEM}

$$|\rho(\nu)| = \frac{\mathbb{I}\nu_{\text{PEM}}}{N\, h_T\, I_0\, \eta_0}$$

- Ellipticity-modulated light exits the cavity
- The light then passes through a Ellipticity Modulator ($\eta = \eta_0 \cos(\omega_{PEM} t)$)
- The resulting beat note is linearly proportional to the axion-induced rotation angle

Symbol	Definition
ρ	Rotation angle caused by the axion
η	PEM modulation depth
σ	Extinction ratio
N = $2\mathcal{F}/\pi$	Cavity buildup
I_0	The intensity of light leaving the cavity

Detection using Heterodyne Technique



$$I_{ext}(\rho) \approx I_0(\sigma^2 + \eta^2 - 2N\eta\rho)$$

After demodulation @ ν_{PEM}

$$|\rho(\nu)| = \frac{\mathbb{I}\nu_{PEM}}{N\ h_T\, I_0\, \eta_0}$$

- Ellipticity-modulated light exits the cavity
- The light then passes through a Ellipticity Modulator ($\eta = \eta_0 \cos(\omega_{PEM} t)$)
- The resulting beat note is linearly proportional to the axion-induced rotation angle

Symbol	Definition
ρ	Rotation angle caused by the axion
η	PEM modulation depth
σ	Extinction ratio
N = $2\mathcal{F}/\pi$	Cavity buildup
I_0	The intensity of light leaving the cavity

Noise Budget

$\frac{Noise\ (\mathbb{I}_{\nu PEM})}{I_0 \eta_0}$:

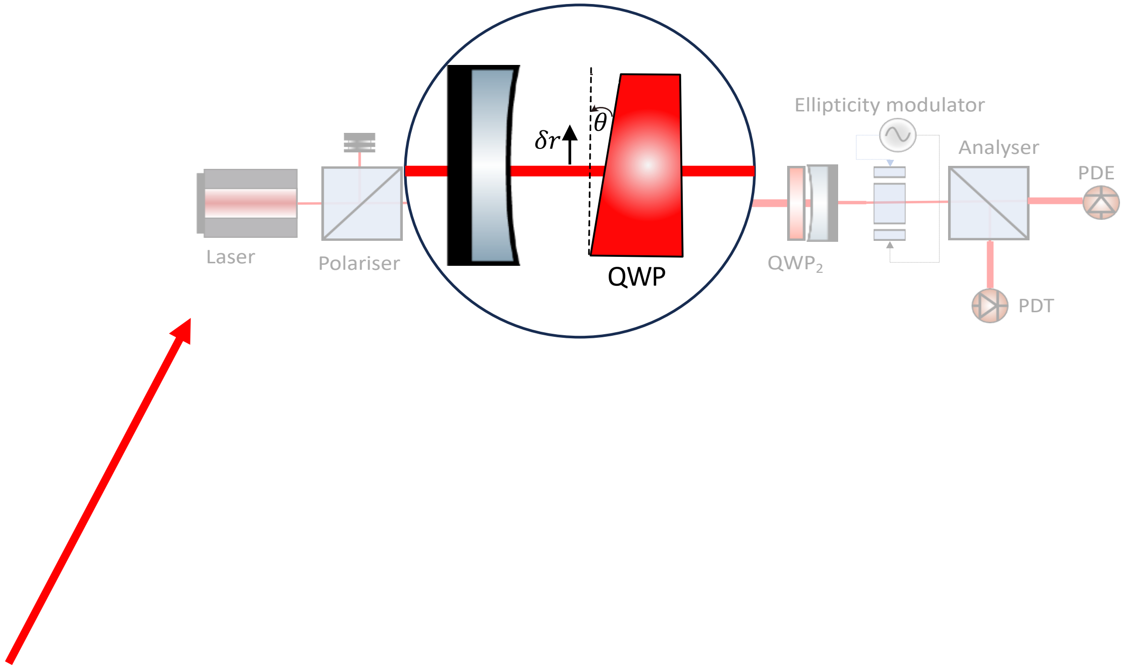
- Shot noise $= \sqrt{\frac{2e}{qI_0}\left(\frac{\sigma^2 + \eta_0^2/2}{\eta_0^2}\right)}$
- Dark noise $= \frac{i_{\text{dark}}}{qI_0\eta_0}$
- Thermal Johnson noise $= \sqrt{\frac{4k_BT}{G}}\frac{1}{qI_0\eta_0}$
- RIN $= N_{\nu_m}^{(\text{RIN})}\frac{\sqrt{(\sigma^2+\eta_0^2/2)^2+(\eta_0^2/2)^2}}{\eta_0}$
- Seismic/ pointing noise $= 2\pi\frac{N\,\delta r\,\theta}{\lambda}\Delta n\gamma(L,f)\ /I_0\eta_0$

COST EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Noise Budget

$\dfrac{Noise\ (\mathbb{I}_{\nu PEM})}{I_0\,\eta_0}$:

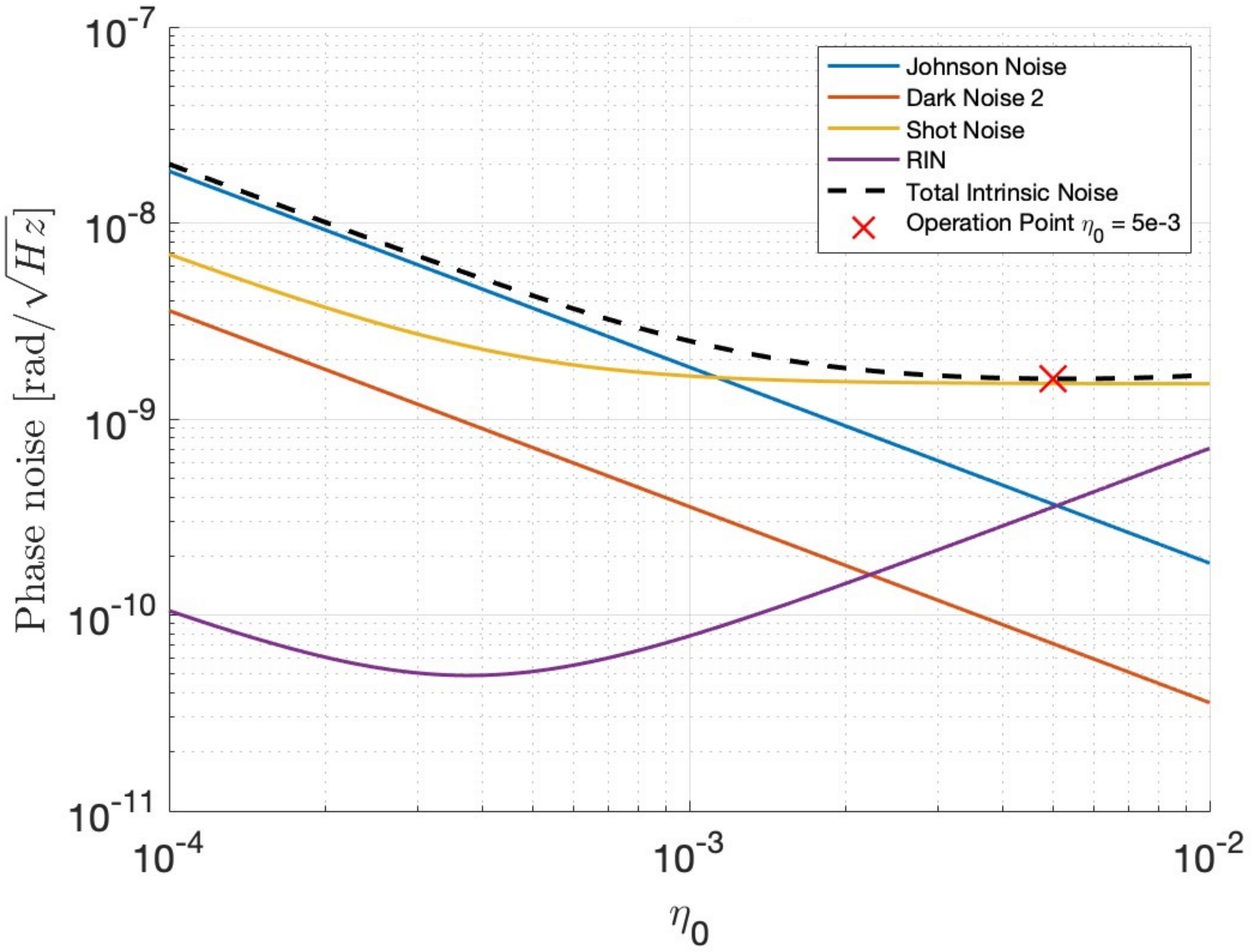
- Shot noise $= \sqrt{\dfrac{2e}{qI_0}\left(\dfrac{\sigma^2+\eta_0^2/2}{\eta_0^2}\right)}$
- Dark noise $= \dfrac{i_{\mathrm{dark}}}{qI_0\eta_0}$
- Thermal Johnson noise $= \sqrt{\dfrac{4k_BT}{G}}\dfrac{1}{qI_0\eta_0}$
- RIN $= N_{\nu_m}^{(\mathrm{RIN})}\dfrac{\sqrt{(\sigma^2+\eta_0^2/2)^2+(\eta_0^2/2)^2}}{\eta_0}$
- Seismic/ pointing noise $= 2\pi\dfrac{N\,\delta r\,\theta}{\lambda}\Delta n\gamma(L,f)\,/I_0\eta_0$



Noise Budget

- Shot noise $= \sqrt{\frac{2e}{qI_0}\left(\frac{\sigma^2+\eta_0^2/2}{\eta_0^2}\right)}$
- Dark noise $= \frac{i_{\text{dark}}}{qI_0\eta_0}$
- Thermal Johnson noise $= \sqrt{\frac{4k_BT}{G}}\frac{1}{qI_0\eta_0}$
- RIN $= N_{\nu_m}^{(\text{RIN})}\frac{\sqrt{(\sigma^2+\eta_0^2/2)^2+(\eta_0^2/2)^2}}{\eta_0}$

Symbol	Value
I_0	100 mW
σ^2	1e-7
T	300 k
G	1e6 Ω
q	0.7 A/W
$N_{\nu_m}^{(RIN)}$	1e-7/$\sqrt{Hz}$
i_{Dark}	25 $fA_{rms}/\sqrt{Hz}$



Sensitivity to the Axion-photon Coupling Coefficient

T	Transmitivity
R	Reflectivity
τ	Cavity round trip time
ρ_{local}	Dark matter local density
N	Cavity buildup
$\mathcal{F}$	Finesse

$$|\rho(\nu)| = \frac{S_P^{(tot)}}{N h_T(\nu)}$$

$$cavity\ build\ up:\ N = \frac{2\mathcal{F}}{\pi} \approx \frac{2}{T + loss}$$

$$h_T(\nu) = \frac{T}{\sqrt{1 + R^2 - 2R\cos 2\pi\nu\tau}} : Cavity\ transfer\ function$$

Sensitivity to ρ: $|\rho(\nu)| \approx S_p{}^{tot}\, \frac{\sqrt{loss^2 + 4\sin^2(\pi\nu_{Axion}\tau)}}{2}$

$$\rho \approx g_{a\gamma} a_0 \omega_a \tau \sin(\omega_a t)$$

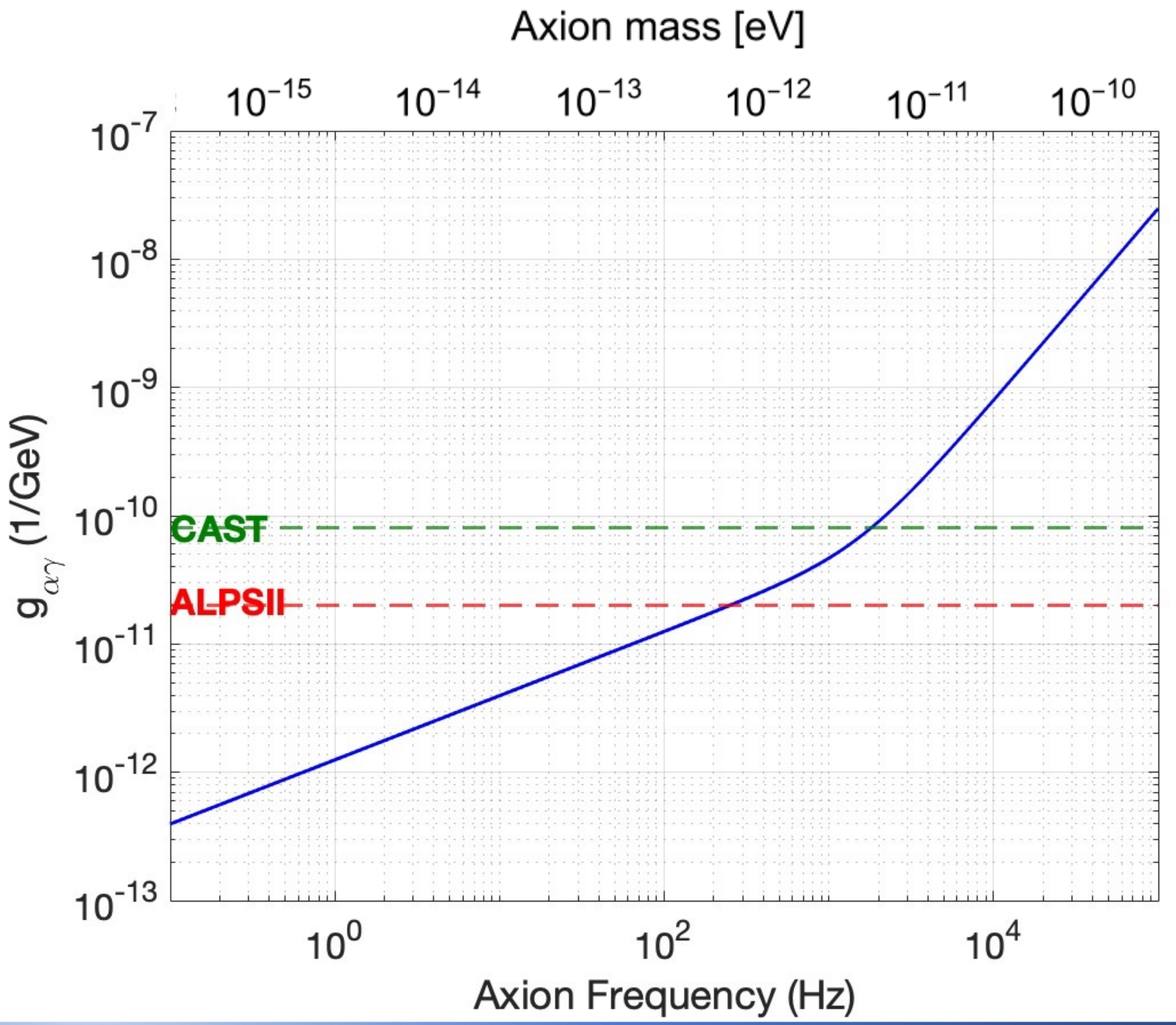
Sensitivity to $g_{a\gamma}$: $g_{a\gamma} = \frac{S_p{}^{tot}}{2\tau}\sqrt{\frac{loss^2 + 4\sin^2(\pi\nu_{Axion}\tau)}{2\rho_{local}}}$

Sensitivity to the Axion-photon Coupling Coefficient

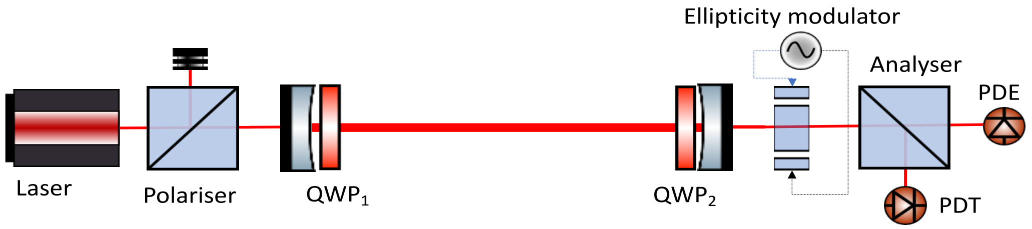
- The current sensitivity analysis does not include the effect of seismic noise

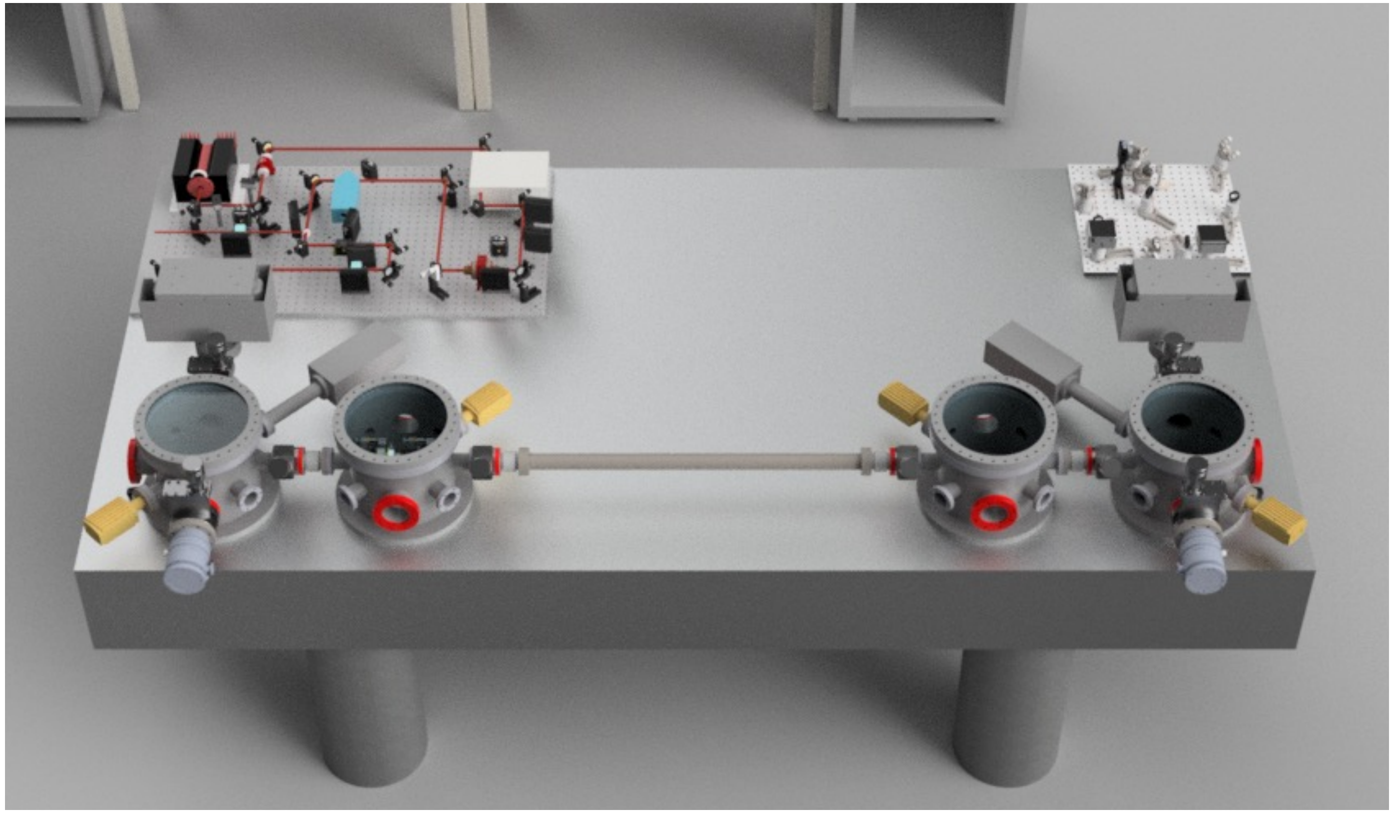
$$g_{\alpha\gamma} = \frac{S_p{}^{tot}}{2\tau}\sqrt{\frac{loss^2 + 4sin^2(\pi\nu_{Axion}\tau)}{2\rho_{local}}}$$

Symbol	Value
I_0	100 mW
σ^2	1e-7
T	300 k
G	1e6 Ω
q	0.7 A/W
$N_{\upsilon_m}^{(RIN)}$	1e-7/$\sqrt{Hz}$
i_{Dark}	25 $fA_{rms}/\sqrt{Hz}$
Loss	100 ppm
N	20,000



3D Design of Experimental Setup





Thank you!

Qazal.rokn@aei.mpg.de

cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY