



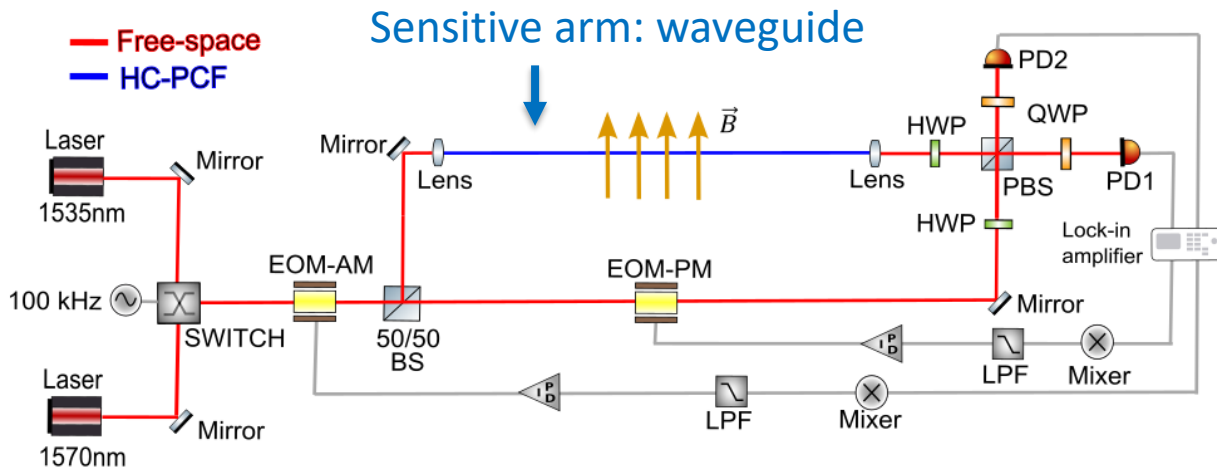
19TH PATRAS WORKSHOP ON AXIONS, WIMPS AND WISPS

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WISPFi: WISP Searches on a Fiber Interferometer

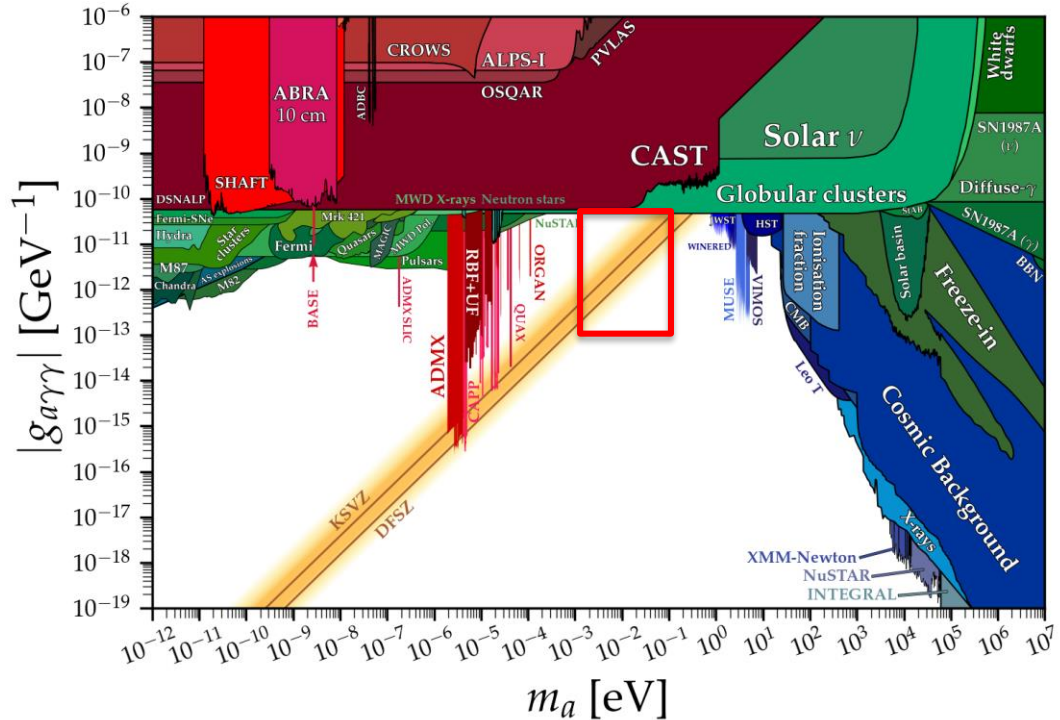
Introduction

- Table-top experiment.
- DM density independent.
- Photon disappearance.
- Room temperature.



Introduction

- Resonant conversion
- QCD band at meV range.



Resonant conversion

- Resonant condition: $m_\nu = m_a$ ($\theta = 45^\circ$).
- Conversion probability:

$$P_{\gamma \rightarrow a} = \underbrace{\sin^2(2\theta)}_{\text{Amplitude}} \underbrace{\sin^2(\pi L/L_{osc})}_{\text{Oscillations}} \quad [1]$$

- Axion mass in a medium with n_{eff} :

$$m_a = \omega \sqrt{1 - n_{\text{eff}}^2}$$

Mixing angle: $\tan(2\theta) = 2\omega \frac{g_{a\gamma\gamma} B}{m_\gamma^2 - m_a^2}$

$$P_{\gamma \rightarrow a} \approx 8 \times 10^{-19} \left(\frac{g_{a\gamma\gamma}}{10^{-12} \text{ GeV}^{-1}} \right)^2 \left(\frac{B}{9 \text{ T}} \right)^2 \left(\frac{L}{100 \text{ m}} \right)^2$$

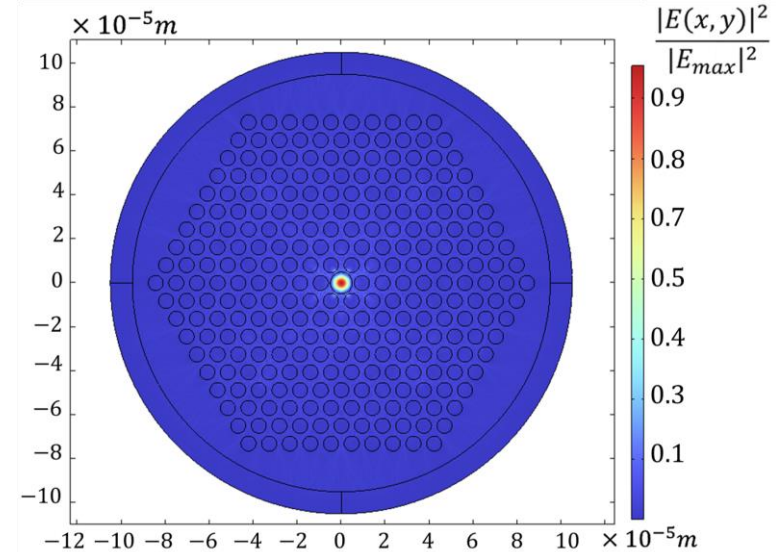
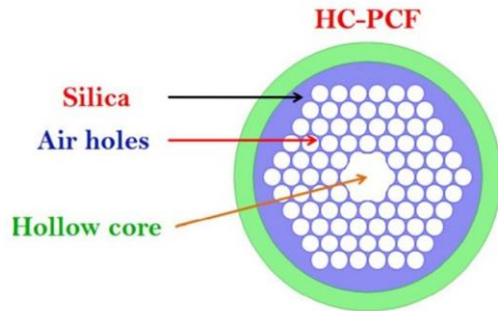
$$P_{\gamma \rightarrow a} \ll 1$$

Energy (ω) independent!

→ Required $n_{\text{eff}} < 1!$

Hollow-Core Photonic Crystal Fibers (HC-PCF)

- Low-refractive index hollow core.
- Hexagonal arrangement of holes in the cladding.
→ photonic-bandgap structure [2].
- The propagating mode can acquire $n_{\text{eff}} < 1$.



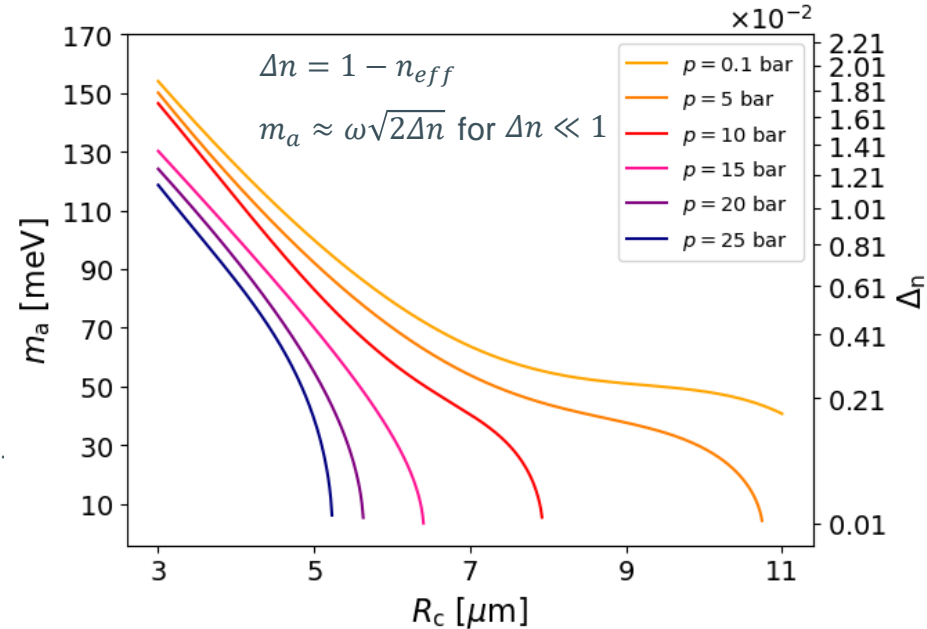
$$R_c = 5\mu\text{m}, p = 0.1\text{bar}, n_{\text{eff}} = 0.992, n_{\text{clad}} = 1.45$$

Effective mode index in HC-PCF

- Analytical approximation [3][4]:

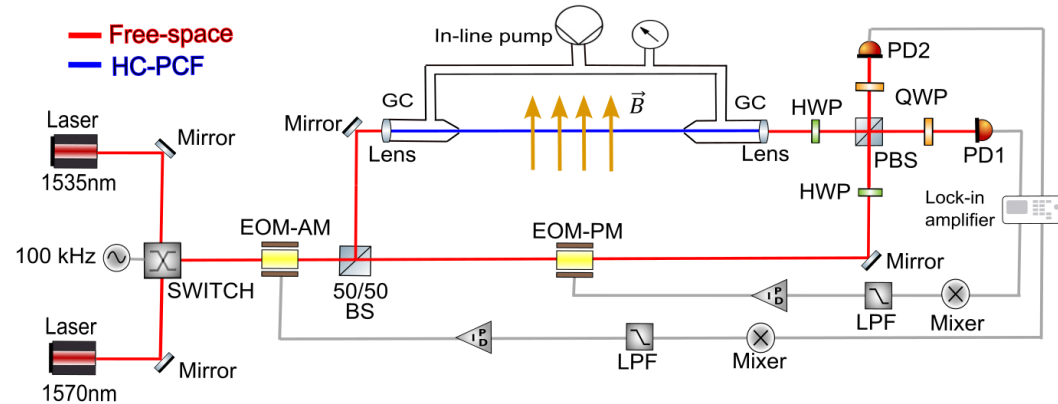
$$n_{eff} \approx \sqrt{n_{gas}^2(\lambda, p, T) - \left(\frac{u_{nm}}{k_{\gamma} R_c}\right)^2}$$

- Probed axion masses \sim **10 meV** to **100 meV**
 ($R_c = 5 \mu m$, $\lambda = 1550 nm$, $T = 20 \text{ }^{\circ}C$, $p = 0.1 \text{ bar}$ – 30 bar).

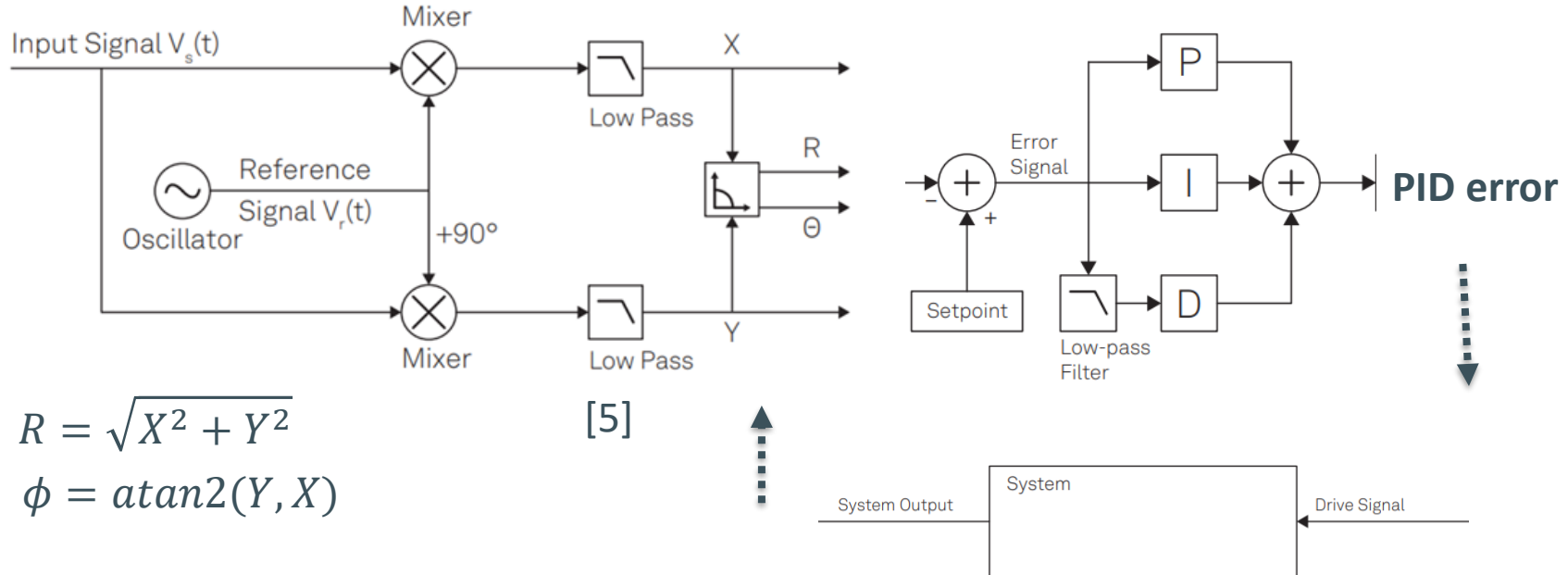


Experimental setup

- **Modulation:** In wavelength using two lasers and an optical switch.
- **Sensing arm:** HC-PCF placed in a magnet rail and pressurized for tuning.
- **Signal:** Demodulated at 100kHz in dark fringe (1%).
- **Lock-in:** In amplitude at 5MHz via PID.



Demodulated and Lock-in scheme



$$R = \sqrt{X^2 + Y^2}$$

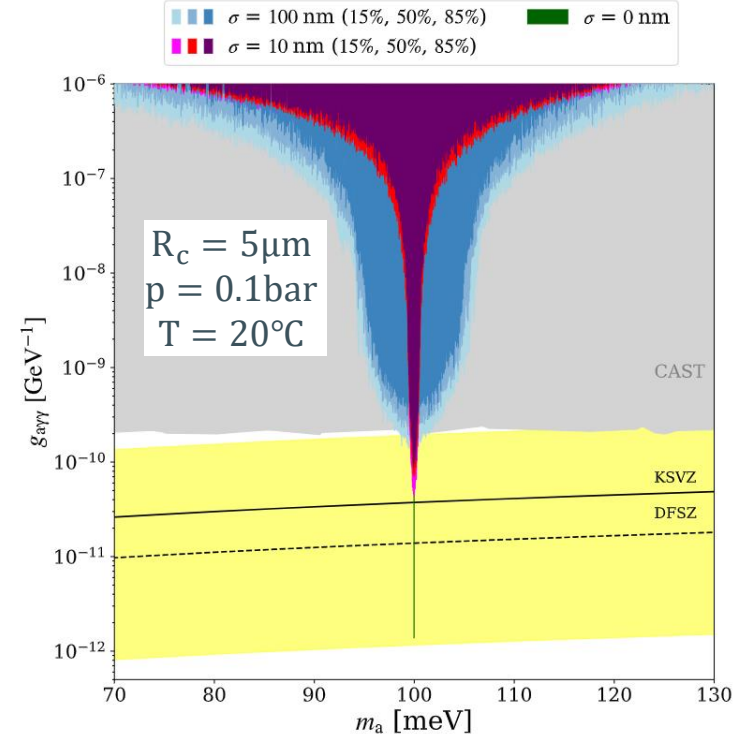
$$\phi = \text{atan2}(Y, X)$$

[5]

Sensitivity (I)

- Main noise sources:
 - Dark current of the photo-detector.
 - Noise power contribution from the sidebands.
- Straightness of the HC-PCF.
- Random variations in the core radius.

$$g_{\text{a}\gamma} \approx 1.2 \times 10^{-12} \text{GeV}^{-1} \left(\frac{\text{SNR}}{3}\right)^{1/2} \left(\frac{B}{9T}\right)^{-1} \left(\frac{L}{100\text{m}}\right)^{-1} \left(\frac{P_{\text{tot}}}{4W}\right)^{-1/2} \\
 \left(\frac{\beta_{\text{sig}}}{1}\right)^{-1/2} \left(\frac{t}{180\text{d}}\right)^{-1/4} \left(\frac{\text{NEPPD}+\text{SN}}{0.5\text{fW}/\sqrt{\text{Hz}}}\right)^{1/2}$$

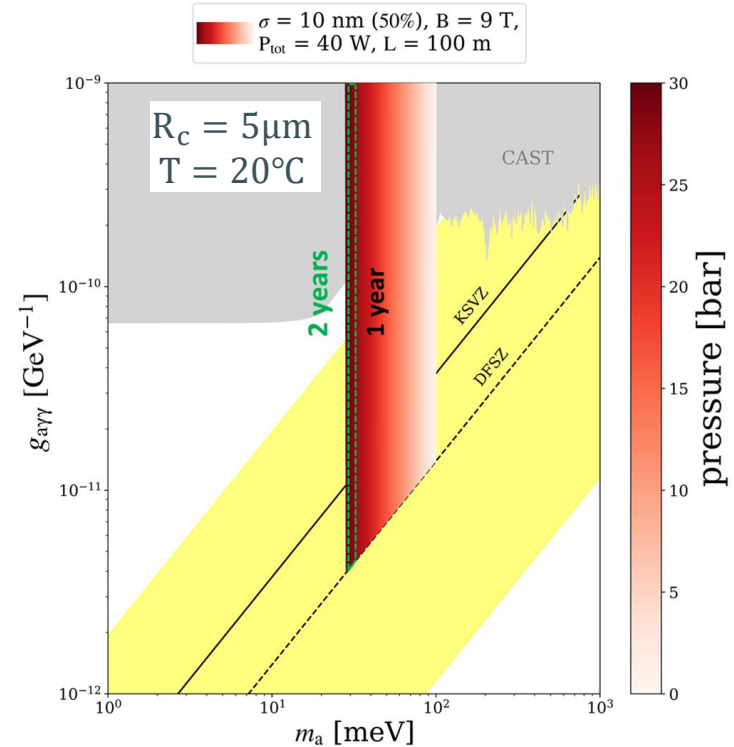


Sensitivity (II)

Long-term projection:

- 40 W laser @ 1535/1570 nm, $B = 9$ T, $L = 100$ m, straight HC-PCF with $\sigma = 10$ nm.
- Tuning from 0.1 – 27.9 bar in 210 steps of 0.6 meV between 28 – 100 meV.

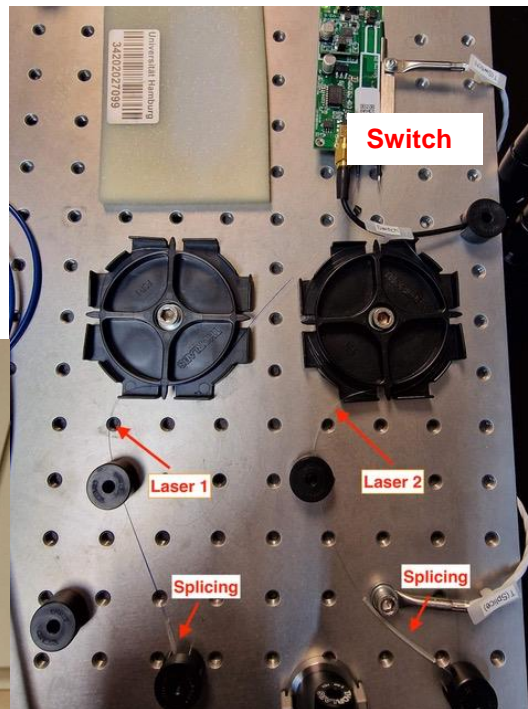
→ DFSZ sensitivity in a wide axion mass range!



WISPFI-prototype

- **Power:** 2W (using a booster amplifier)
- **Modulation:** Wavelength switching between 1535nm and 1570nm at 100kHz.

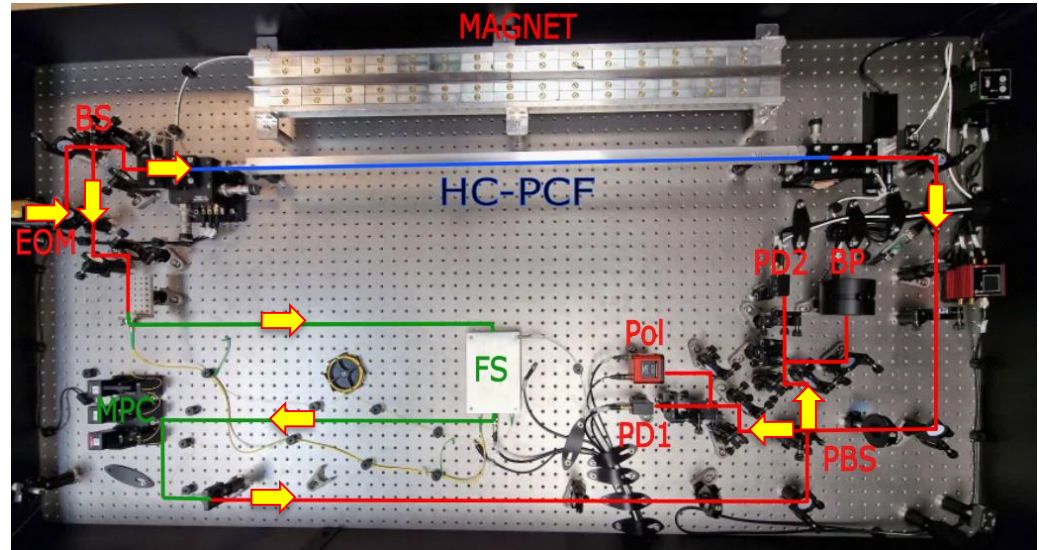
Axion!



WISPFI-prototype

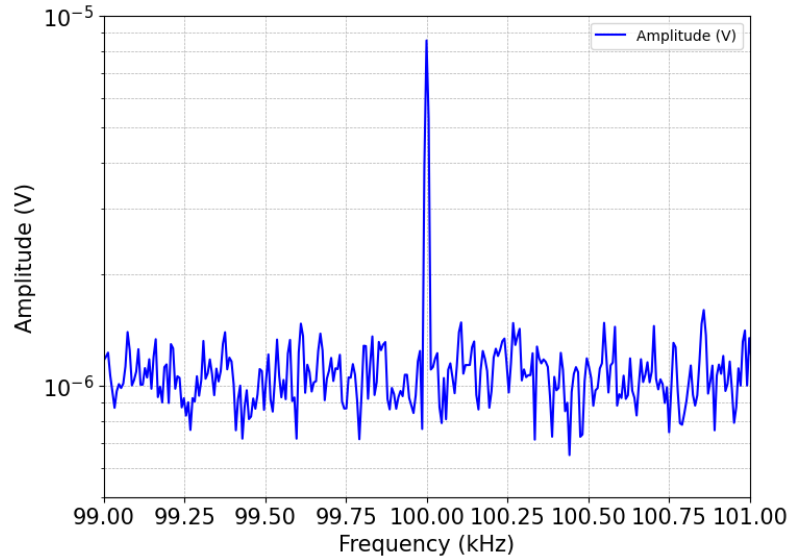
- **Sensing arm:** 1m long HC-PCF fiber (Rc=8.5 μ m) inside a 2.6T magnet rail.
- **Reference arm:** Fiber stretcher for phase matching.
- **Lock-in:** In amplitude at 5MHz using an EOM-AM (1% dark fringe).

- HC-PCF
- SMF
- Free-space

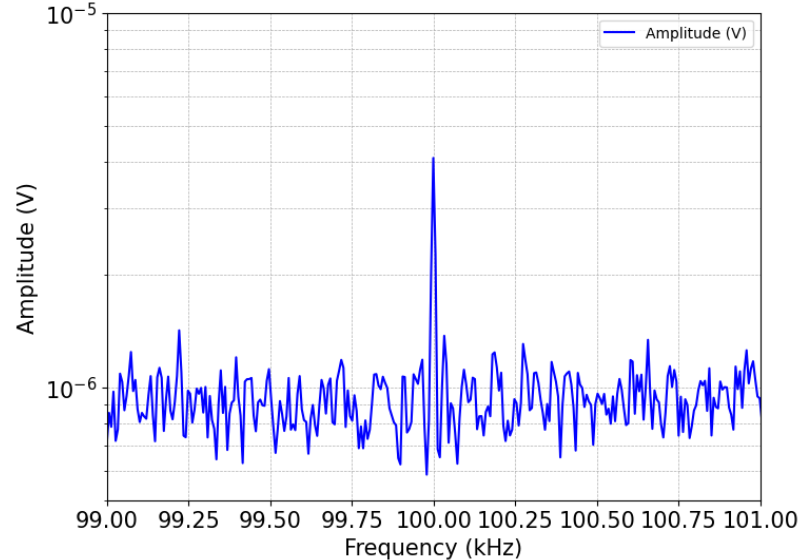


Adjusting power between the lasers

- Before adjusting power:

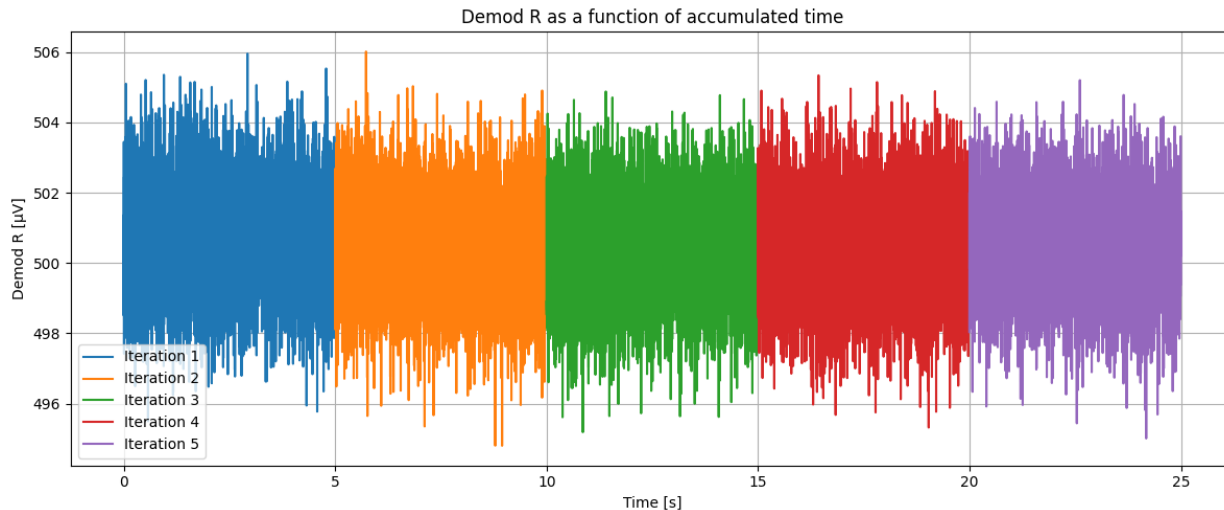


- After adjusting power:



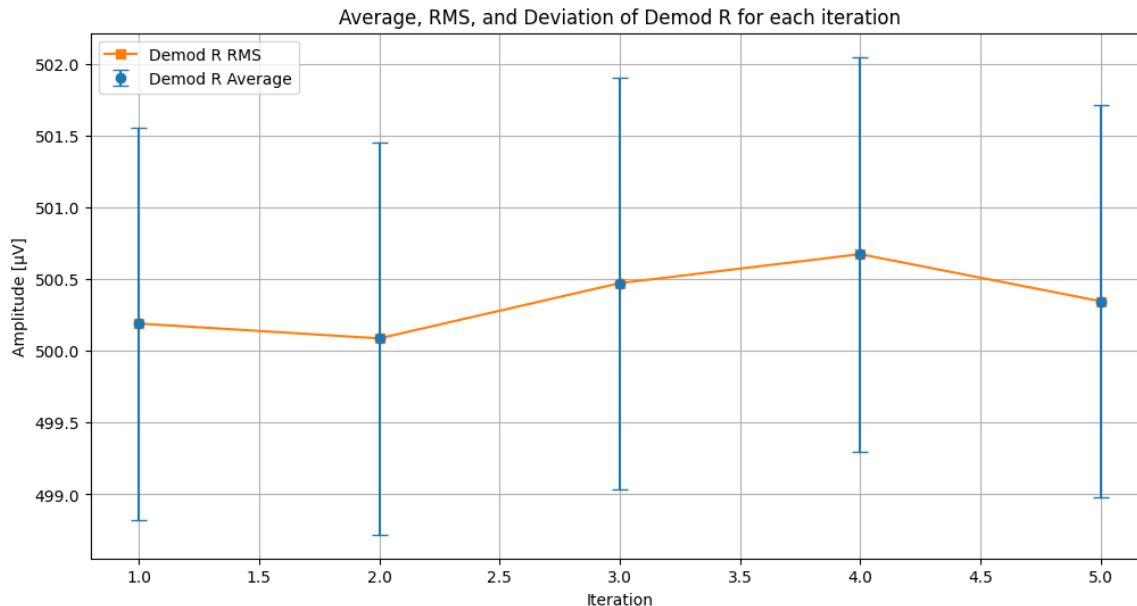
Locking (preliminary results)

- **Lock-in:** In amplitude at 5MHz (1% dark fringe).
- Time: 25s (5 iterations).



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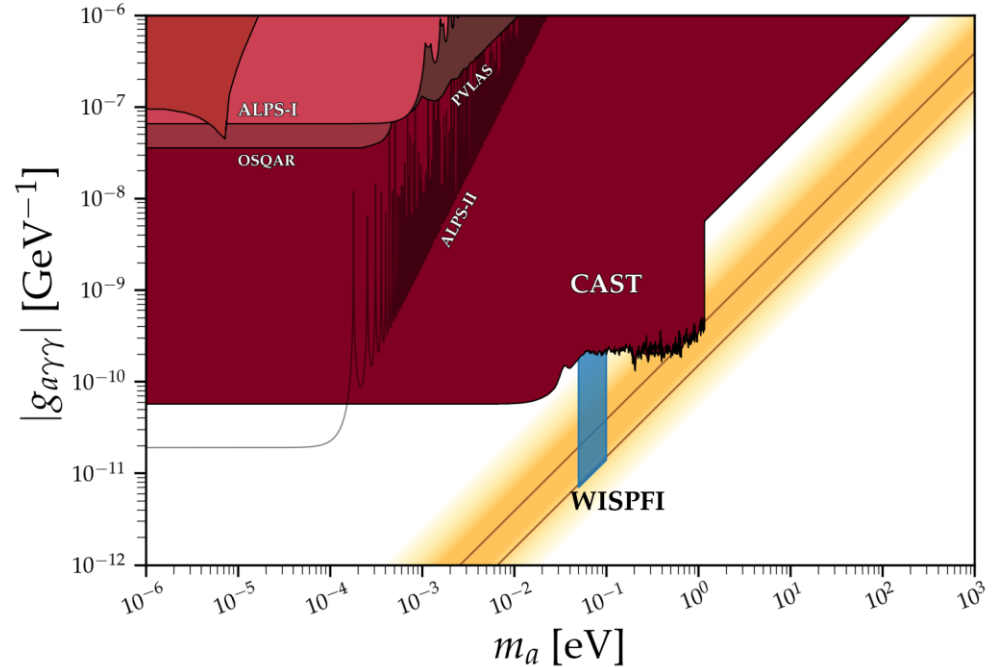
Future Steps

- Prototype built and ready for taking data in the following weeks!

Summary

- **Amplitude reduction** in the presence of $P_{\gamma \rightarrow a}$ resonant conversion using HC-PCF.
- **Tuning** in a wide axion mass range by regulating the **gas pressure** in the fiber.

<https://doi.org/10.1103/PhysRevD.109.123001>



Thanks for your attention!

**Find out more about the cluster:
www.qu.uni-hamburg.de**



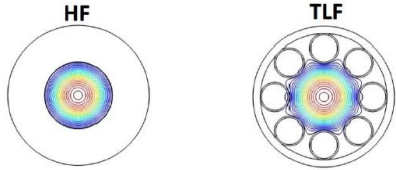
References

- (1) G. Raffelt, L. Stodolsky, Mixing of the photon with low-mass particles, Phys. Rev. D 37, 1237 (1988), <https://doi.org/10.1103/PhysRevD.37.1237>.
- (2) P. Russell, Photonic Crystal Fibers, Science 299, 5605 (2003), <https://doi.org/10.1126/science.1079280> .
- (3) E. A. J. Marcatili, R. A. Schmelzter, Hollow Metallic and Dielectric Waveguides for Long Distance Optical Transmission and Lasers, Bell System Technical Journal 43, 4, (1964), <https://doi.org/10.1002/j.1538-7305.1964.tb04108.x>.
- (4) L. Rosa et al., Analytical Formulas for Dispersion and Effective Area in Hollow-Core Tube Lattice Fibers, Fibers 9, 10, (2021), <https://doi.org/10.3390/fib9100058>.
- (5) “White Paper Principles of lock-in detection and the state of the art Zurich Instruments Release.” (2016), <https://api.semanticscholar.org/CorpusID:202682418>.

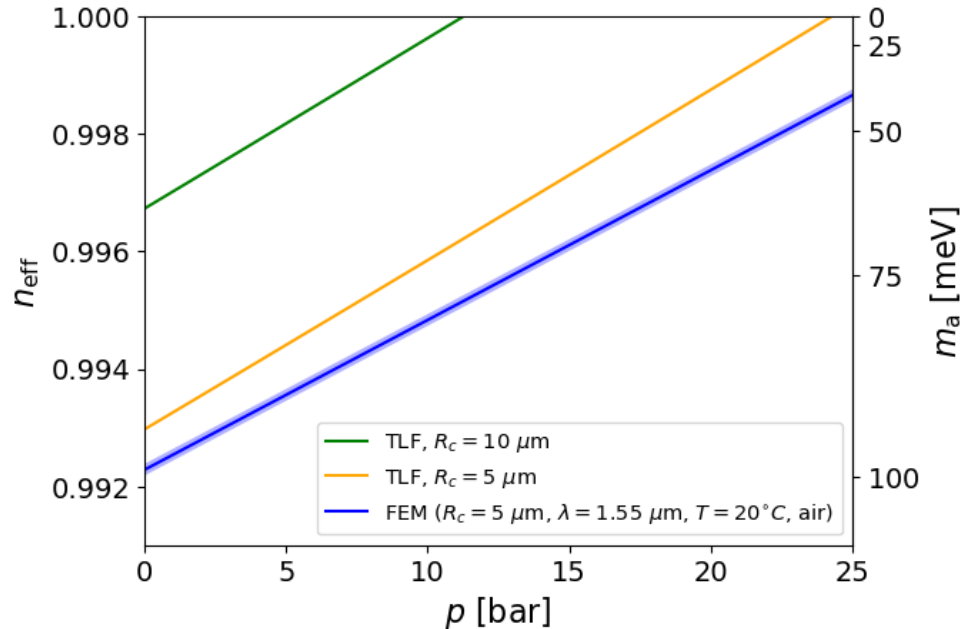


Backup Slides

Effective mode index in HC-PCF

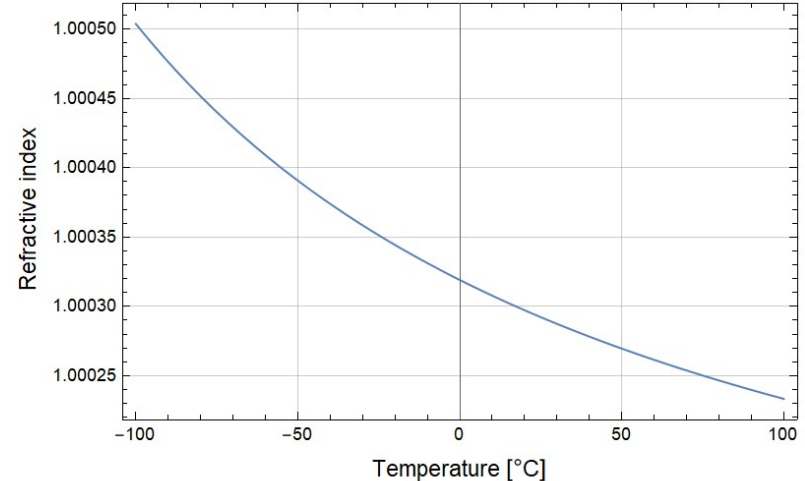
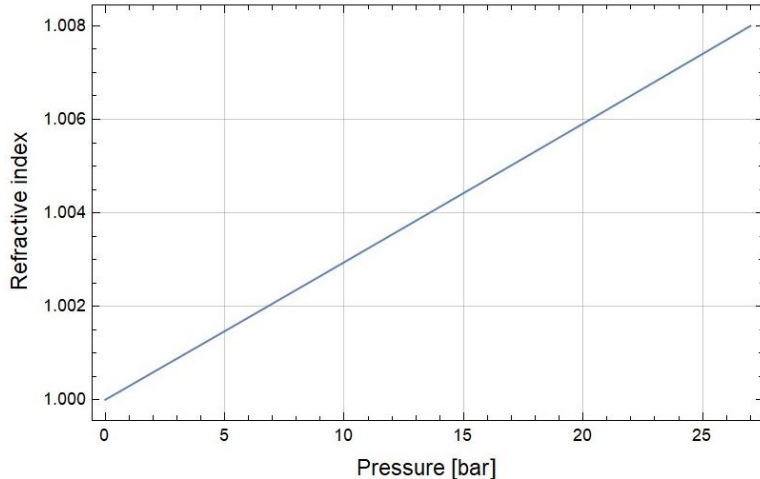


$$n_{eff} = \frac{k_{\gamma}}{k_0} = \sqrt{n_{gas}^2(\lambda, p, T) - \left(\frac{u_{nm}}{k_{\gamma} R_c}\right)^2}$$



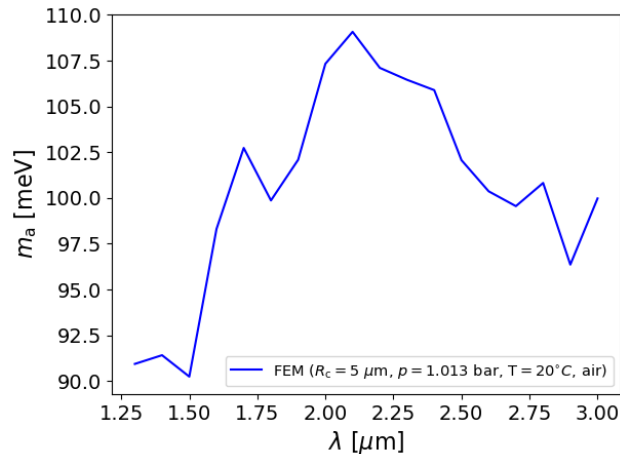
Refractive index of air

- Refractive index of air as a function of pressure and temperature for $T=20^{\circ}\text{C}$ and $P=1.013$ bar accordingly.

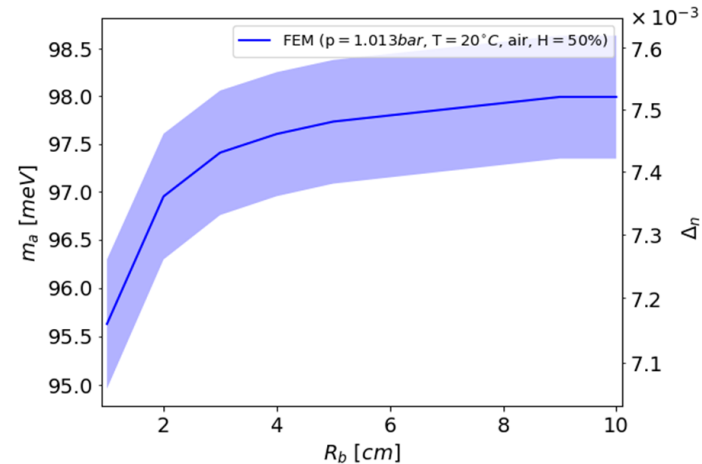


Effective mode index in HC-PCF (III)

- Wavelength of the propagating light and bending radius of the fiber also have an effect on the effective mode index.



$$\Delta n = 1 - n_{eff} \quad m_a \approx \omega \sqrt{2\Delta n}$$

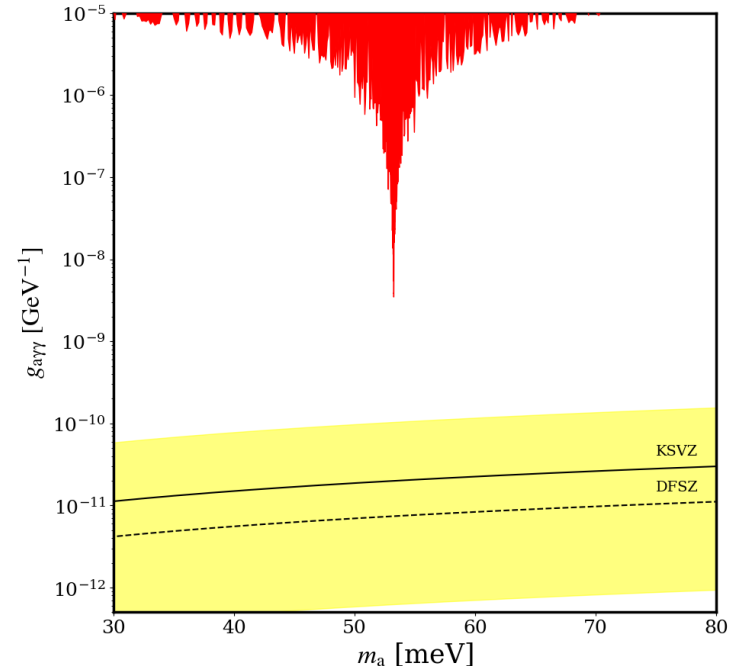


$$n'_{gas}(\lambda, p, T) = n_{gas}(\lambda, p, T) * n_{bend} = n_{gas}(\lambda, p, T) * \left(1 + \frac{c}{R_b}\right)$$

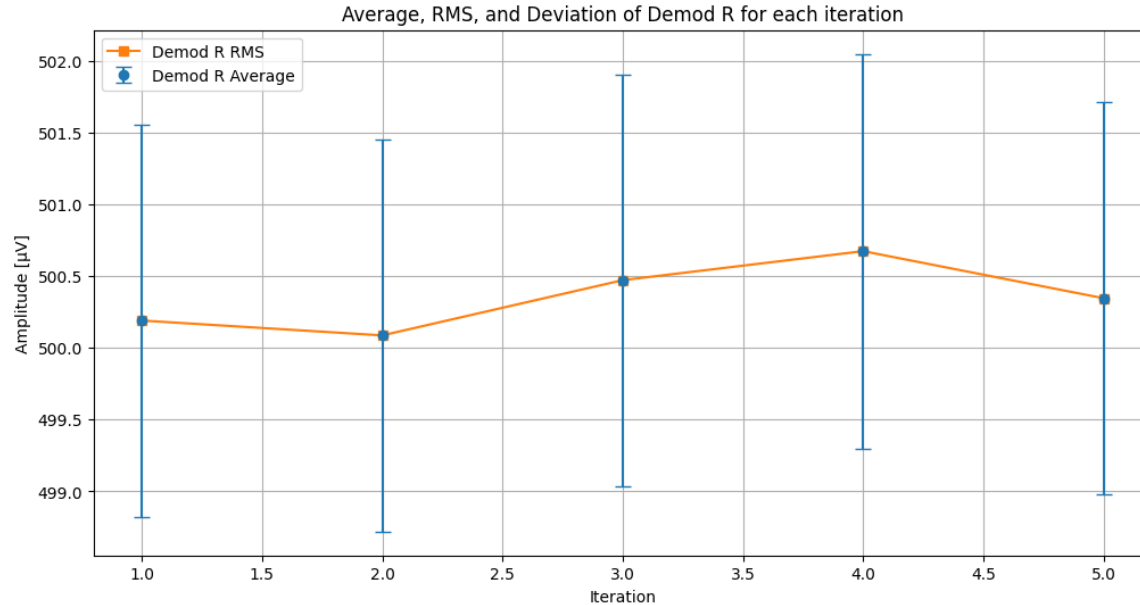
WISPF1-prototype (expected sensitivity)

- **Power:** 2W (using a booster amplifier)
- **Time:** 10days.
- **Pressure:** 0.1bar.
- **Temperature:** 20°C.
- **Core radius:** 8.5 μm .
- **Core radius variations:** 10nm

Expected amplitude reduction $\delta A \approx 1\text{nV}$



Demodulated signal and Locking (average)



Demodulated signal and Locking (preliminary results)

