Measuring VMB with ALPS II

Laura Roberts, DESY FH Particle Physics Seminar. Jan 31, 2026

Contents

Introduction

How does quantum electrodynamics manifest?

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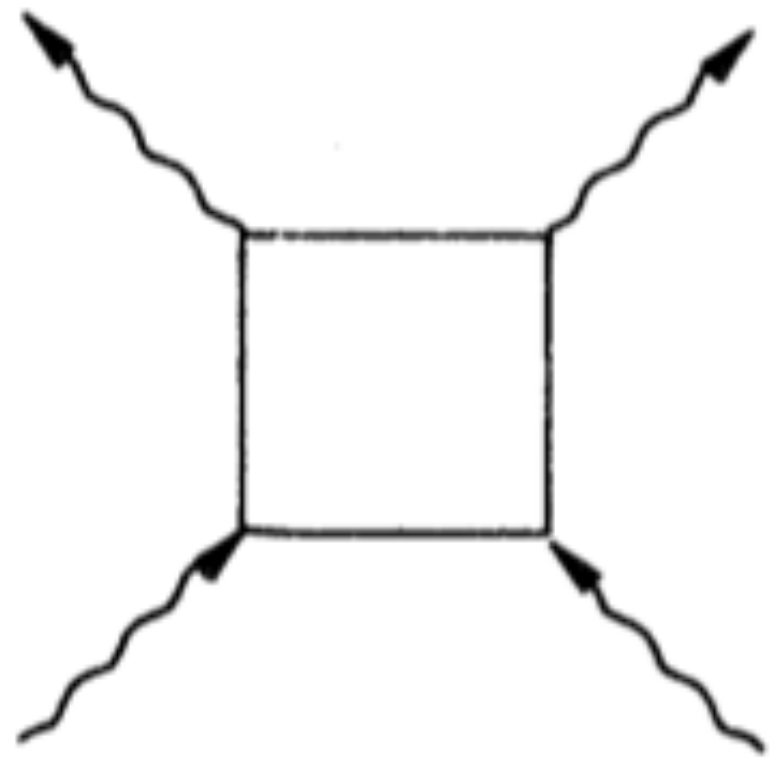
Light by Light scattering ($\gamma\gamma \rightarrow \gamma\gamma$):

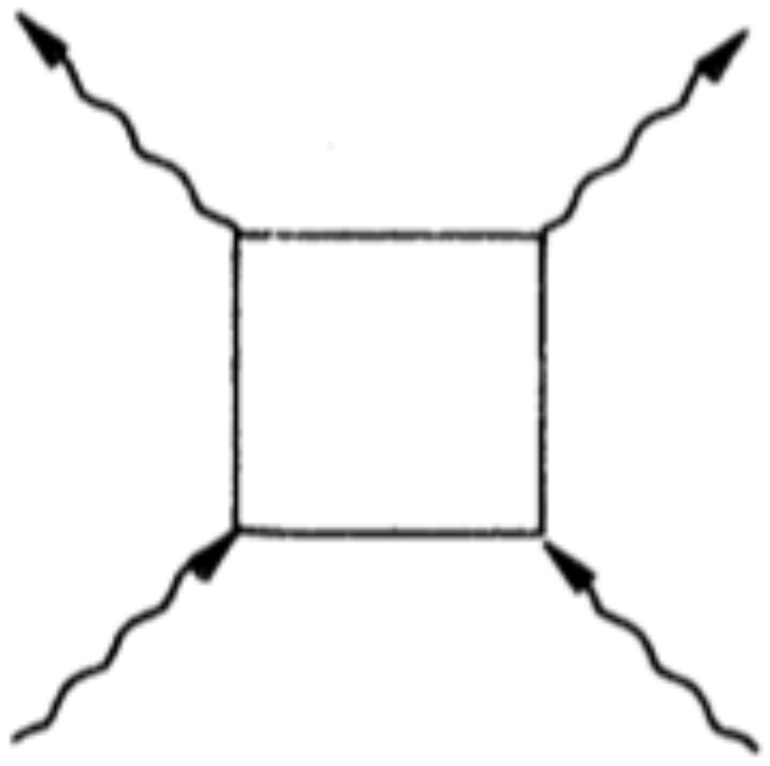
- Originally predicted by the four field interactions involving only photons, mediated by virtual particle loops

- The ATLAS collaboration at CERN LHC reported evidence of high energy light by light scattering- Later confirmed by CMS



Introduction

How does quantum electrodynamics manifest?



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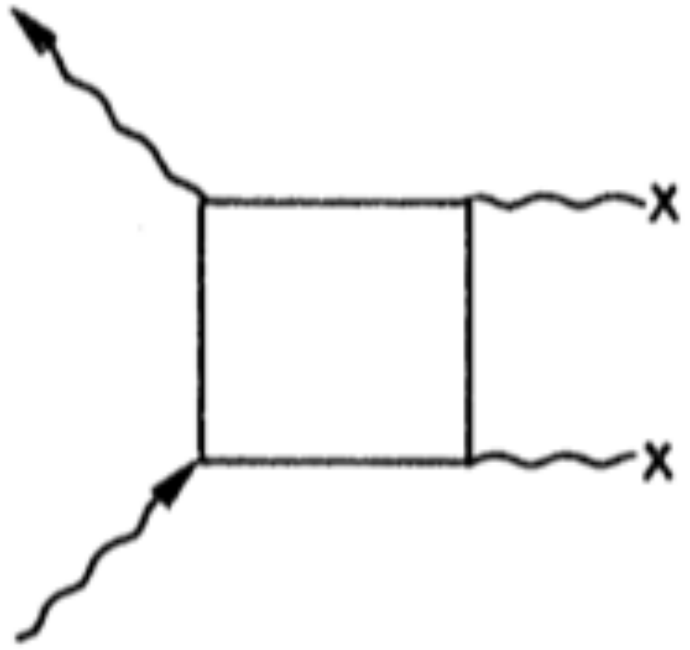


Delbrück Scattering:

- Scattering of photons in the Coulomb field of nuclei via virtual electron-positron pairs

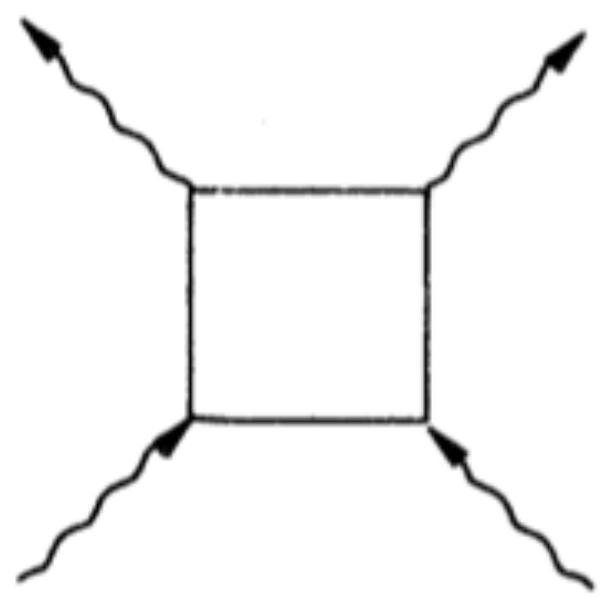
- First observation was achieved in a high-energy, small angle photon scattering experiment carried out at DESY in 1973

Introduction

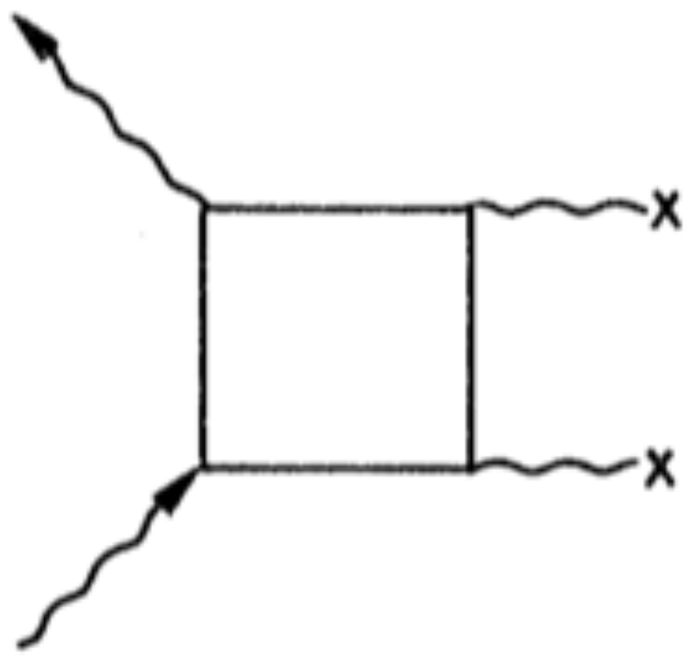
Experimental confirmation of QED Lagrangian:

$$\mathscr{L}_{QED} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\mathbf{E}}{c}\cdot\mathbf{B}\right)\right]$$

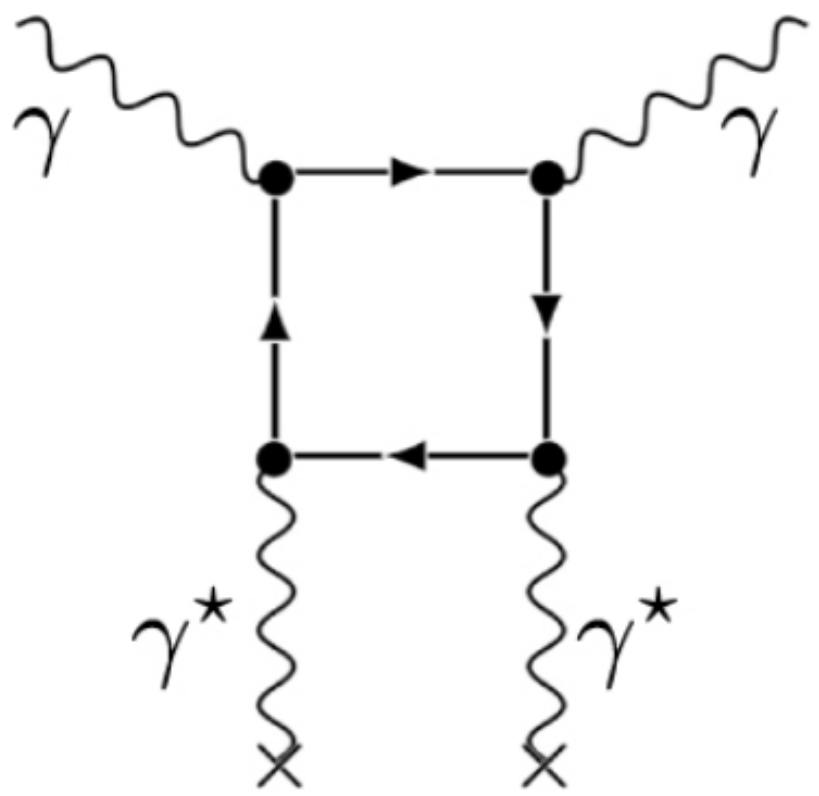
Light by Light scattering:



Delbrück Scattering:



Vacuum Birefringence:



Unmeasured for nearly 100 years

Introduction

Vacuum as a polarizable medium:

$$\mathscr{L}_{QED} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\mathbf{E}}{c}\cdot\mathbf{B}\right)^2\right]$$

In an external magnetic field:

$$n_{\parallel} = 1 + 7A_e B_{ext}^2$$

$$n_{\perp} = 1 + 4A_e B_{ext}^2$$

Where $A_e = \frac{2}{45\mu_0}\frac{\hbar^3}{m_e^4 c^5}\alpha^2 = 1.32 \times 10^{-}24\mathrm{T}^{-2}$

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Vacuum as a polarizable medium:

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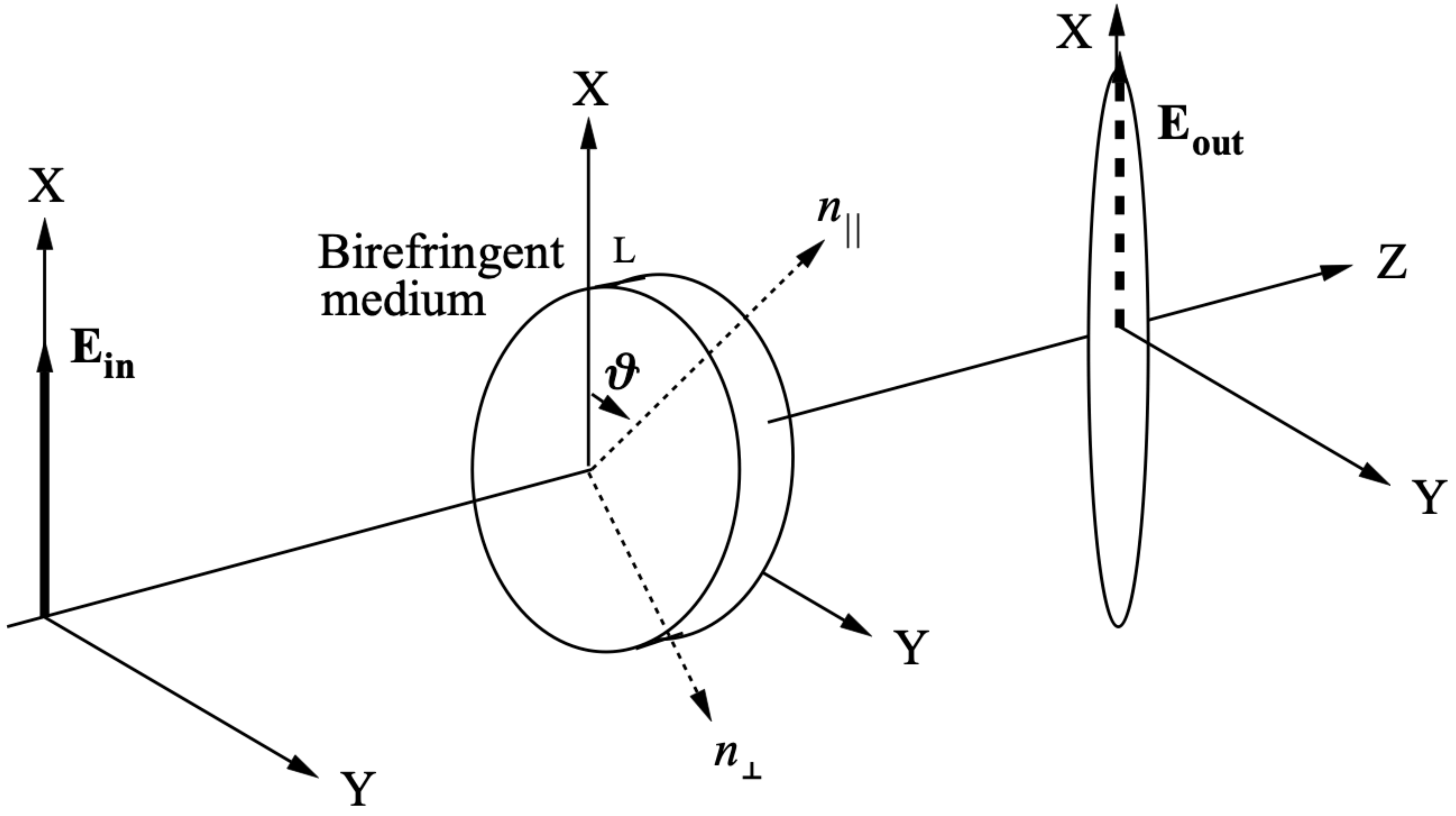
Vacuum Magnetic Birefringence (VMB):

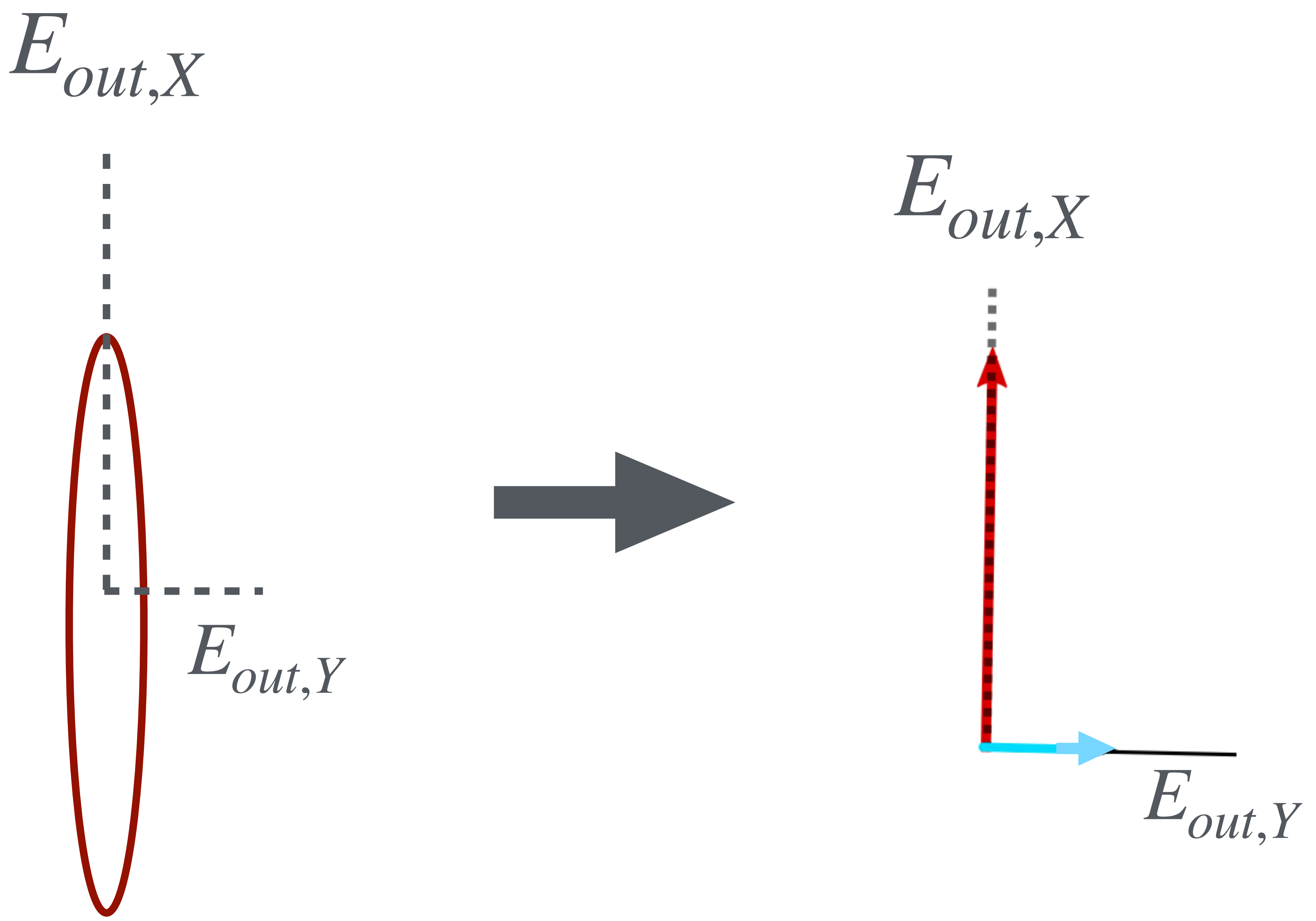
$$\Delta n_{vmb} = n_{\parallel}^{VMB} - n_{\perp}^{VMB} = 3A_e \times B^2 \approx 3.96 \times 10^{-24} \times B_{ext}^2$$

Measuring VMB

$$\Delta n_{vmb} = n_{\parallel}^{VMB} - n_{\perp}^{VMB} \approx 3.96 \times 10^{-24} \times B^2$$

Polarimetric Scheme::





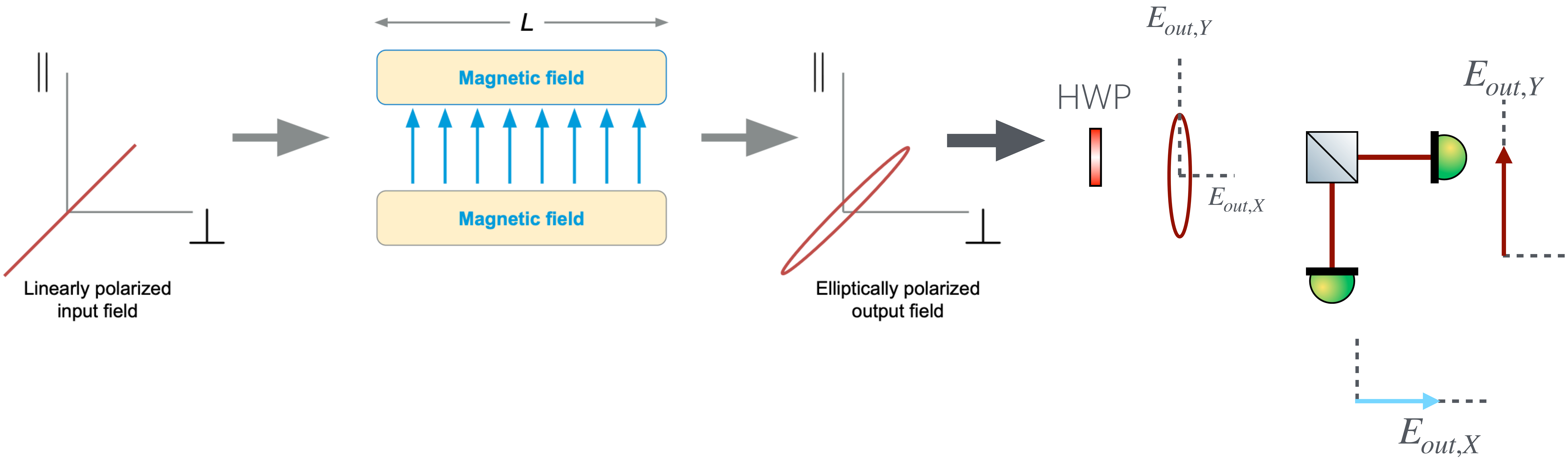
$$\Delta\phi = \phi_{\parallel} - \phi_{\perp} = \frac{2\pi}{\lambda}(n_{\parallel} - n_{\perp})L$$

Measuring VMB

Polarimetric Scheme::

VMB effect:

$$\Delta\phi_{VMB} = \frac{2\pi}{\lambda}(n_{\parallel}^{VMB} - n_{\perp}^{VMB})L \rightarrow \psi = \frac{\Delta\phi_{VMB}}{2} sin2\theta$$

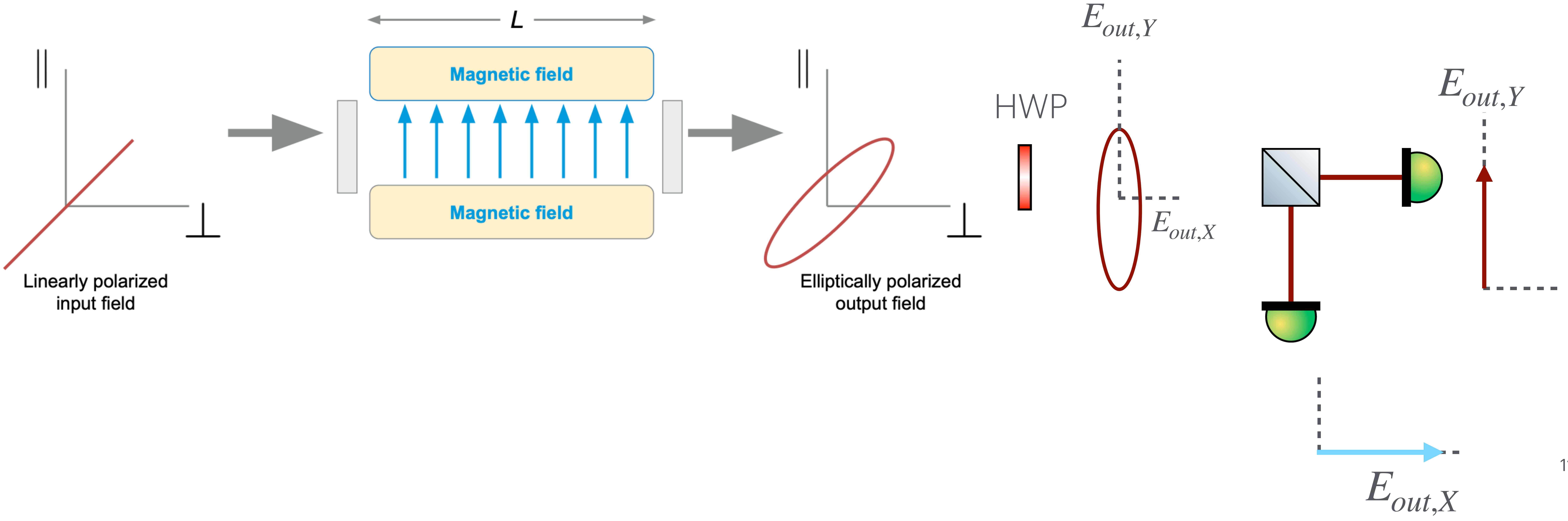


Measuring VMB

Polarimetric Scheme + optical cavity::

VMB effect:

$$\Delta\phi_{VMB} = \frac{2\pi}{\lambda}(n_{\parallel}^{VMB} - n_{\perp}^{VMB})L \times N_{cavity} \rightarrow \psi = \frac{\Delta\phi_{VMB}}{2} sin2\theta \times N_{cavity}$$

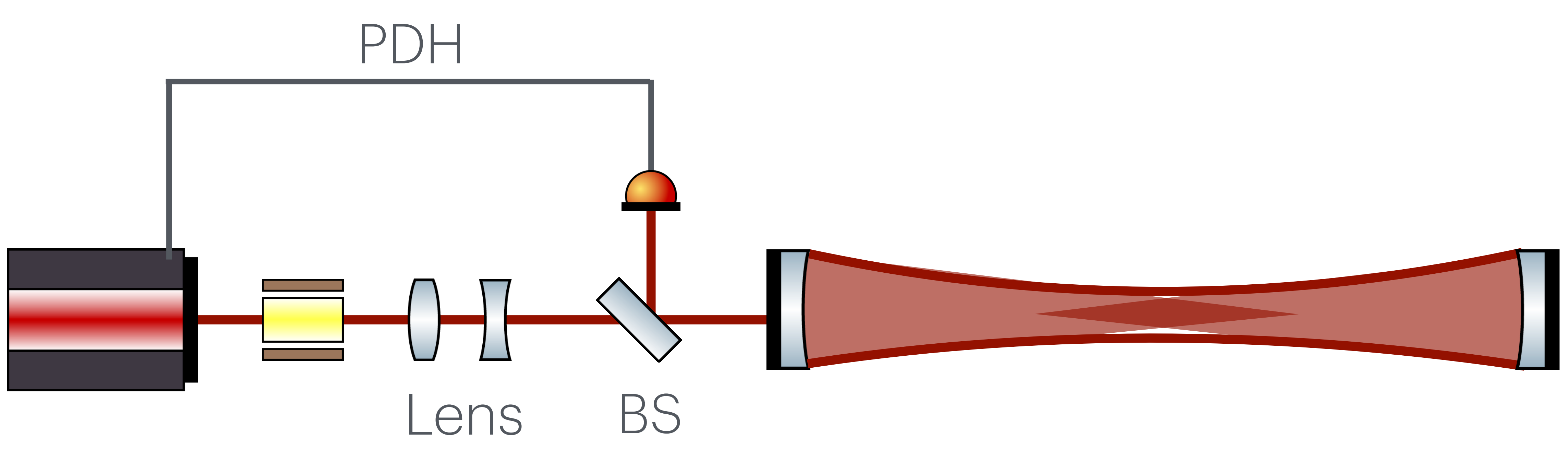


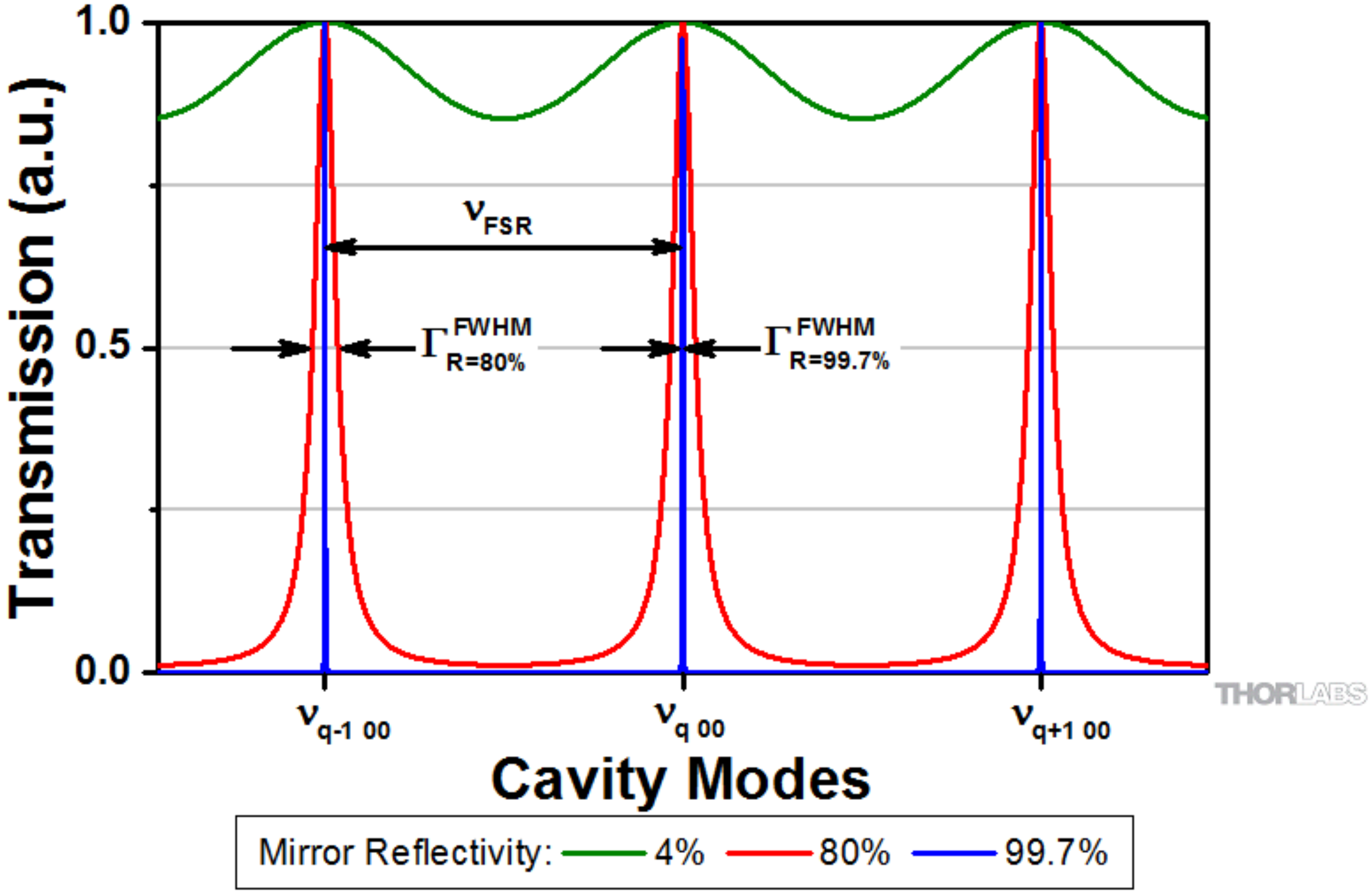
Measuring VMB

Brief Introduction to Optical Cavities:

When a laser is on resonance, the field makes an integer number of cycles per round trip.

The frequency spacing between the resonances of the cavity, known as the free spectral range (FSR): $f_{FSR} = \frac{c}{2L}$





Measuring VMB

Brief Introduction to Optical Cavities:

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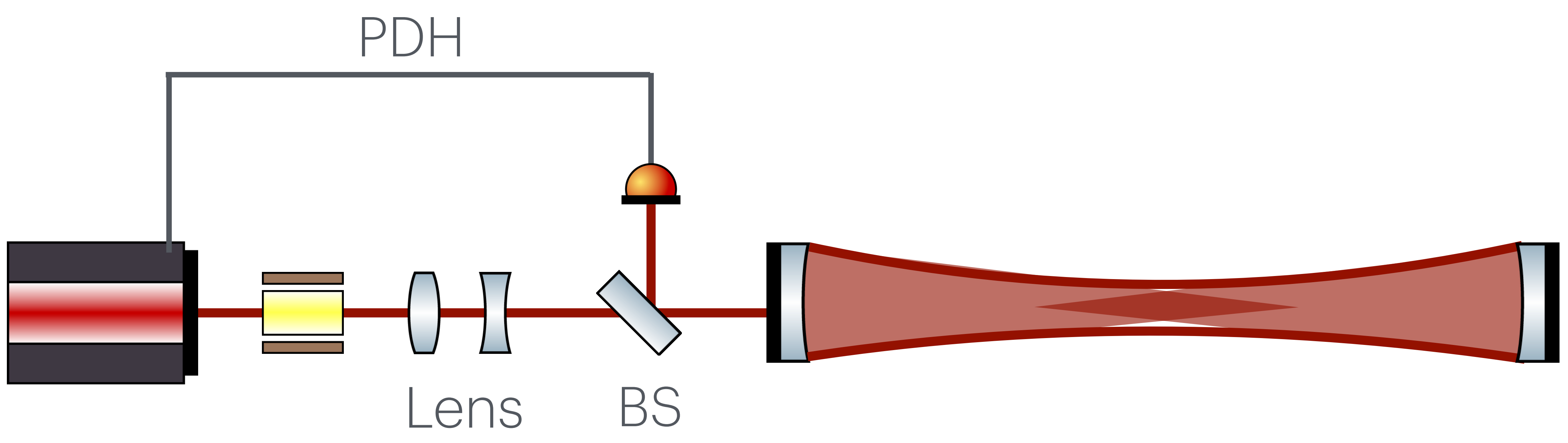
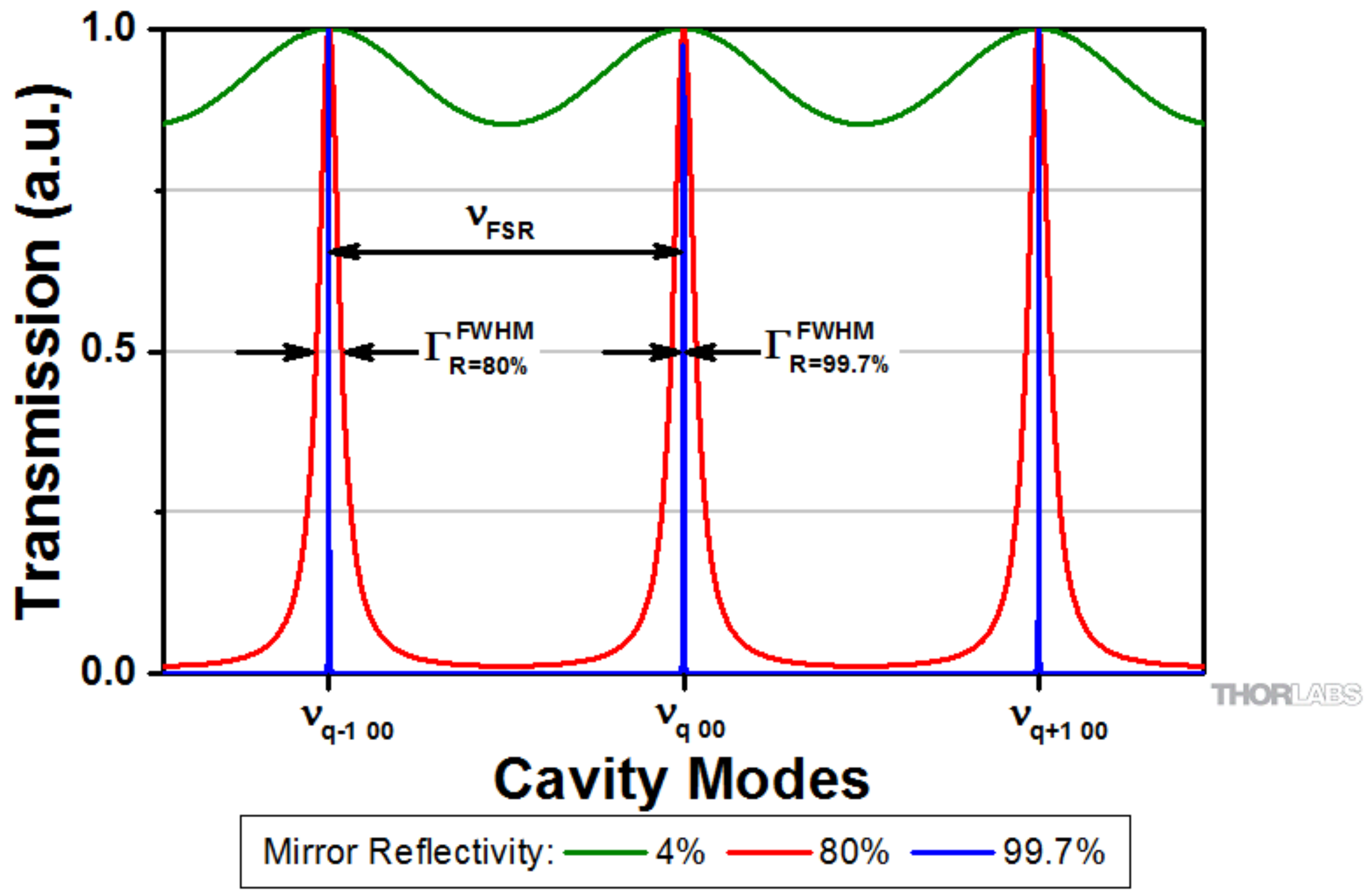
The frequency spacing between the resonances of the cavity, known as the free spectral range (FSR): $f_{FSR} = \frac{c}{2L}$

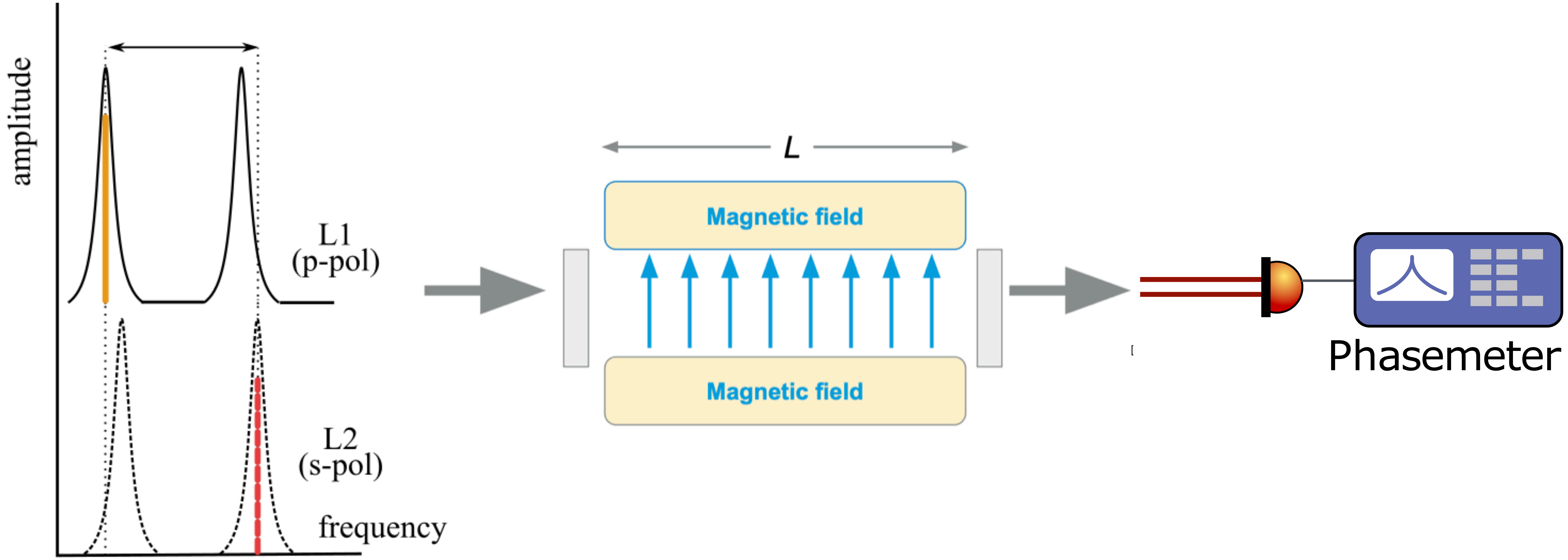
The finesse: $\mathscr{F} = \frac{f_{FSR}}{f_{FWHM}}$, describes the power buildup inside the cavity, and the amplification of the optical path length $N = 2\mathscr{F}/\pi$





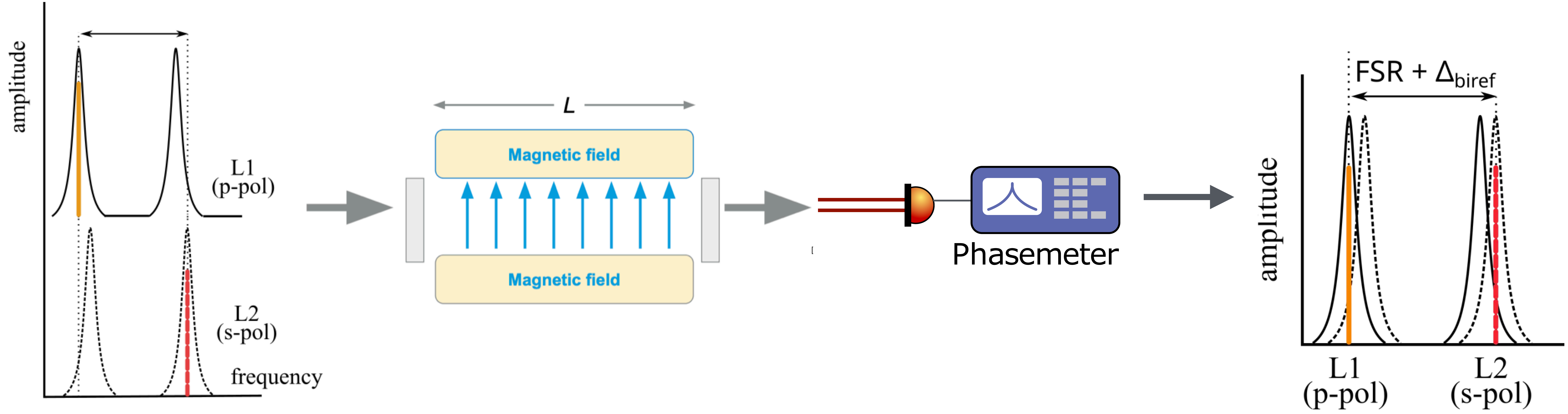
Measuring VMB

Interferometric:



Measuring VMB

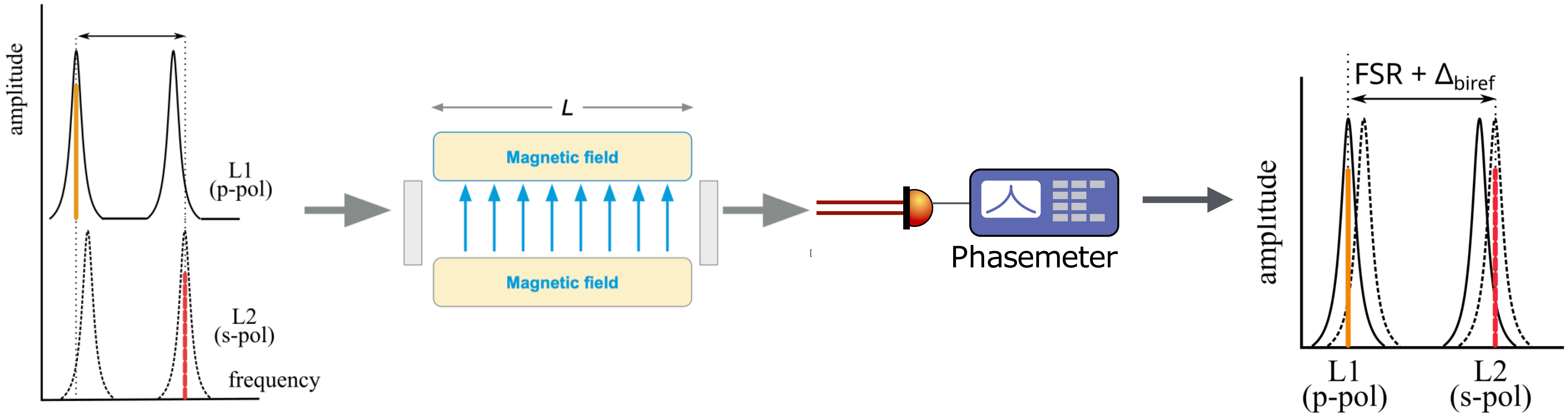
Interferometric:



- Cavity is birefringent, therefore orthogonal polarizations see resonances at slightly different cavity lengths, leading to Δ_{FSR}:
  - We are measuring the movement of the two sets of cavity resonances
- In the presence of VMB, only the s-polarized resonance will move w.r.t the magnet

Measuring VMB

Interferometric:



- Given some $\Delta\nu$ sensitivity, we translate this to optical path length sensitivity: $\Delta L = \dfrac{2L\lambda\Delta\nu}{c}$
- Noting that: $\Delta L_{VMB} = \Delta n_{VMB} \times L_{magnet}$

Previous VMB Experiments

VMB Figure of merit: $B^2 \times L$

Experiment	L_B [m]	N	Modulation	$\int B^2_{ext} dL$ [T^2 m]
OVAL (2017)	0.17	200,000	Pulsed magnet	13.8
BMV (2019)	0.31	270,000	Pulsed magnet	100
PVLAS-LNL (2008)	0.5	100,000	Rotating supercon. magnet	2.6
PVLAS-FE (2016)	1.64	446,000	Rotating permanent magnet	10.3

Previous VMB Experiments

Experiment	L_B [m]	N	Modulation	$\int B^2_{ext} dL$ [T^2 m]
PVLAS-LNL (2008)	0.5	100,000	Rotating supercon. magnet	2.6
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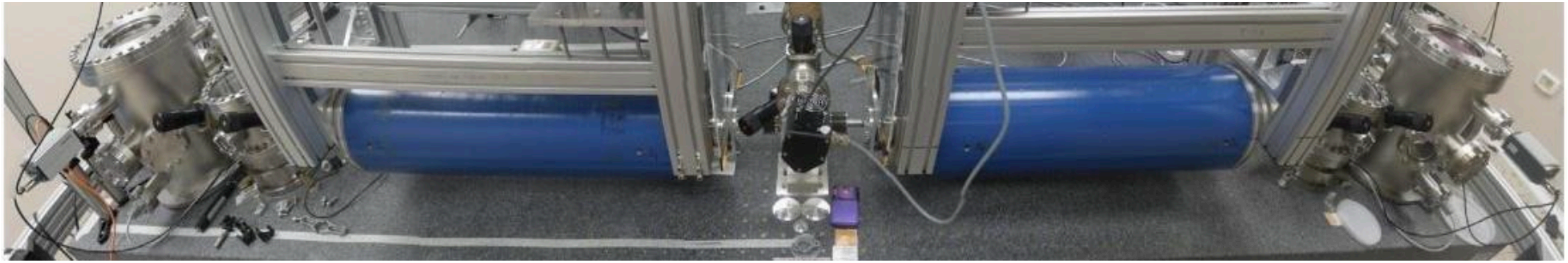
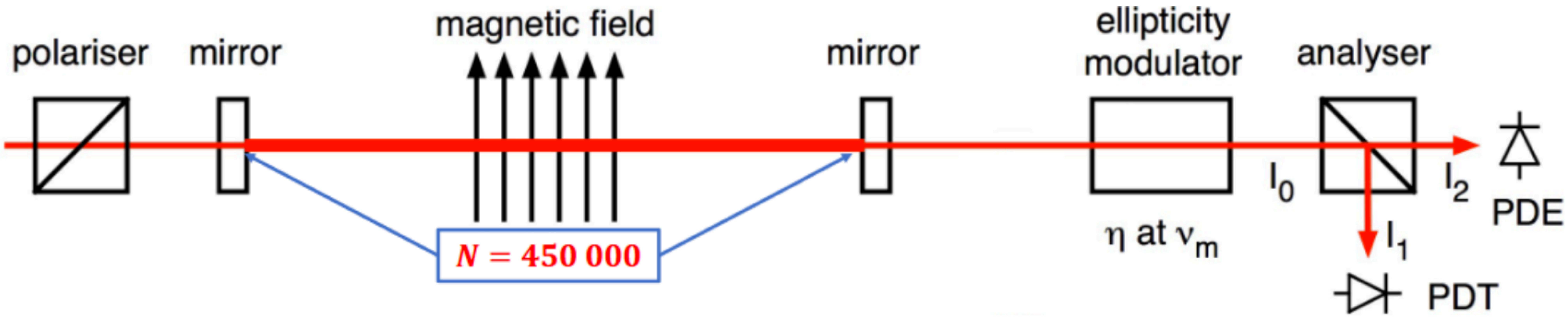




ALPS II Infrastructure

ALPS II Infrastructure

Magnets

- 24 superconducting HERA magnets, each 8.8m in length and 5.3 T in strength, straightened and aligned for the ALPS II experiment:

$$B = 5.3\ \text{T} \rightarrow \Delta B^2 = 27\ \text{T}^2$$

$$L_{\text{magnets}} = 212\ \text{m}$$

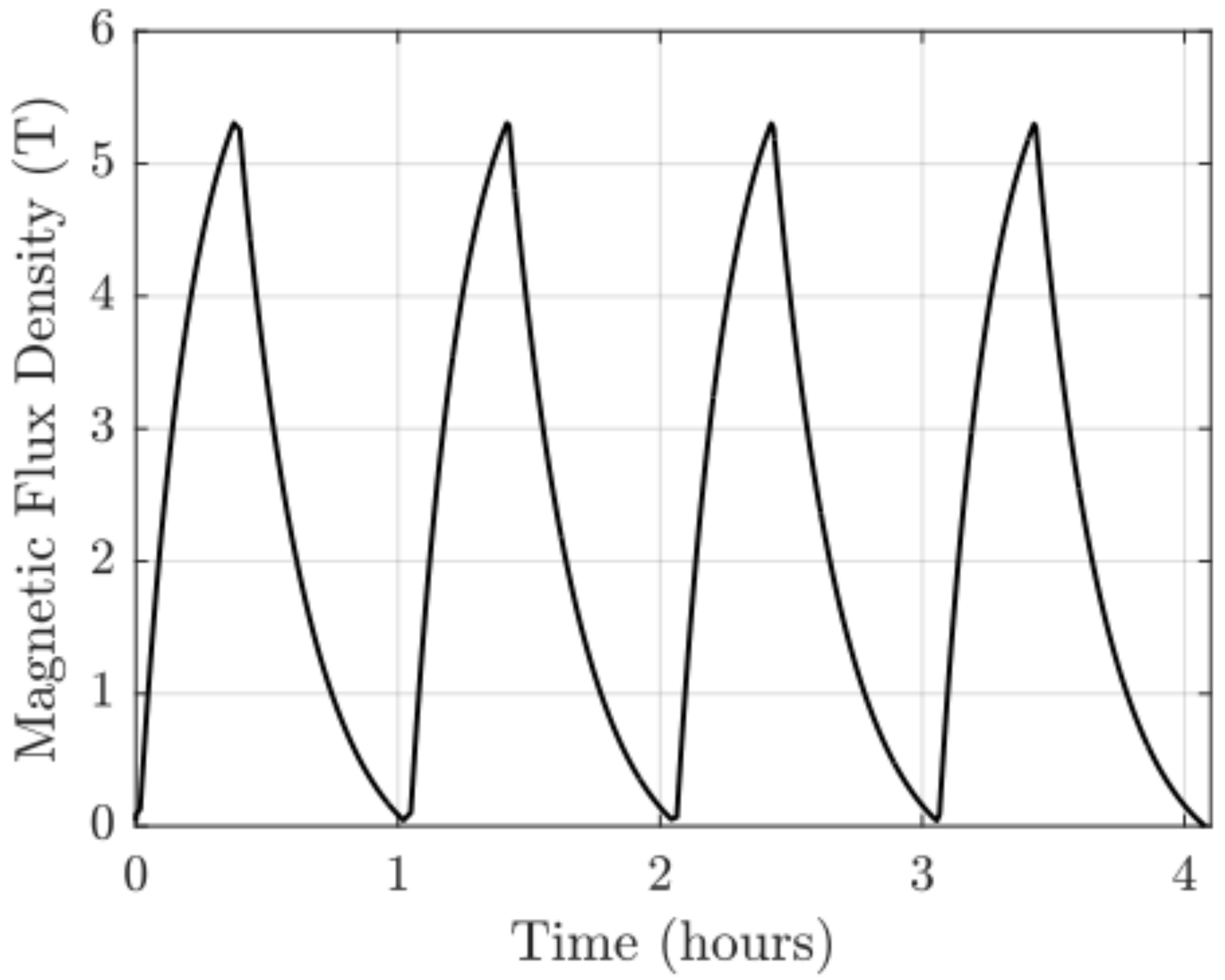
- Predicted amplitude in differential path length changes: $\Delta L_{VMB} = 2.37 \times 10^{-20}$meters.

ALPS II experiment at DESY is a light shining through a wall (LSW) axion dark matter search approaching final science runs. [2]

ALPS II Infrastructure

Magnets with modulation

- A characteristic modulation frequency of 0.3mHz was already demonstrated
    - Ramping and discharging the current to generate 4 pulses over the course of 4 hours
- Potential to increase this frequency up to 4mHz with upgrades to the system
    - Requires upgrades to the quench protection system



(a) Modulation of the ALPS II magnet string

ALPS II Infrastructure

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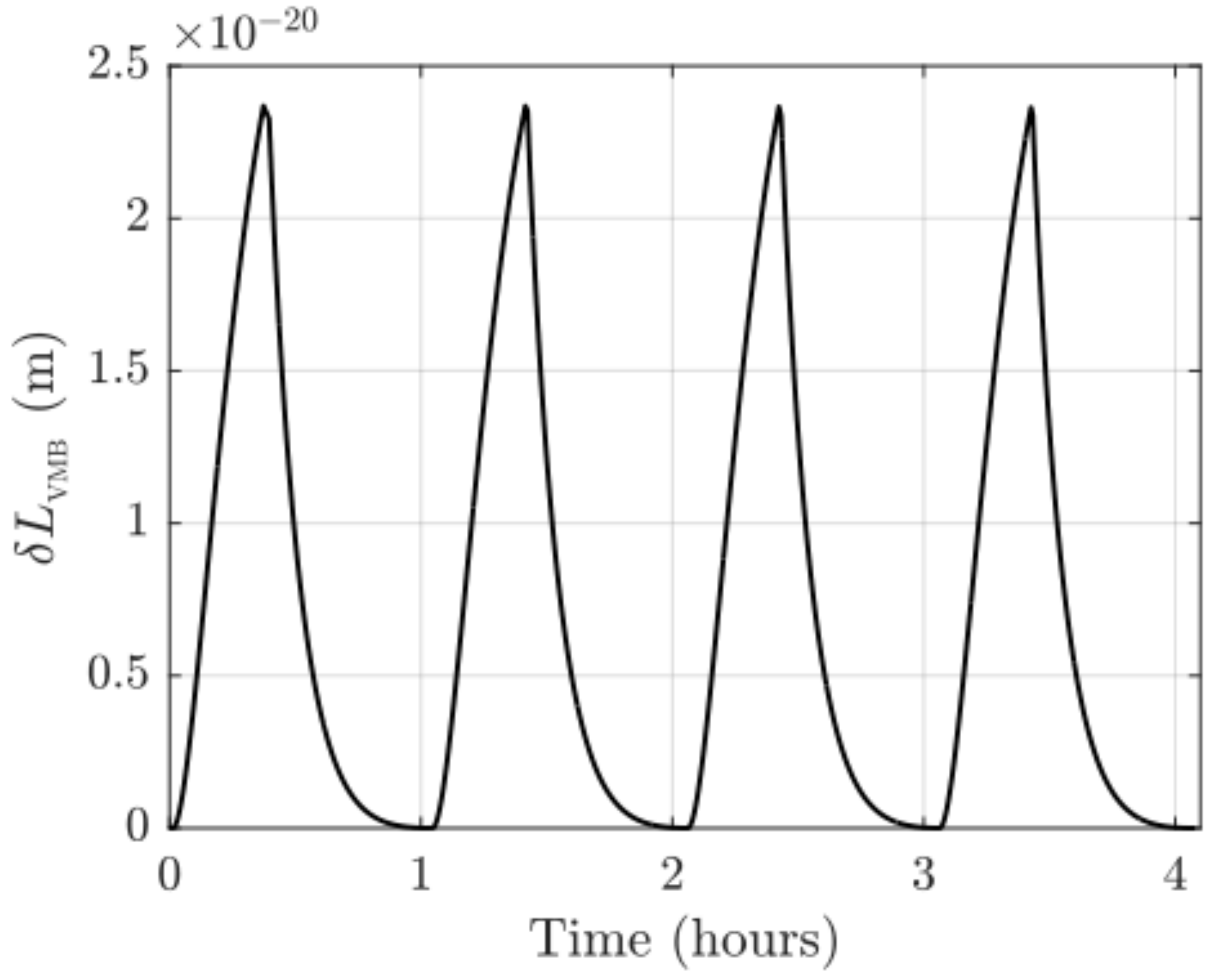


(b) Projected VMB signal

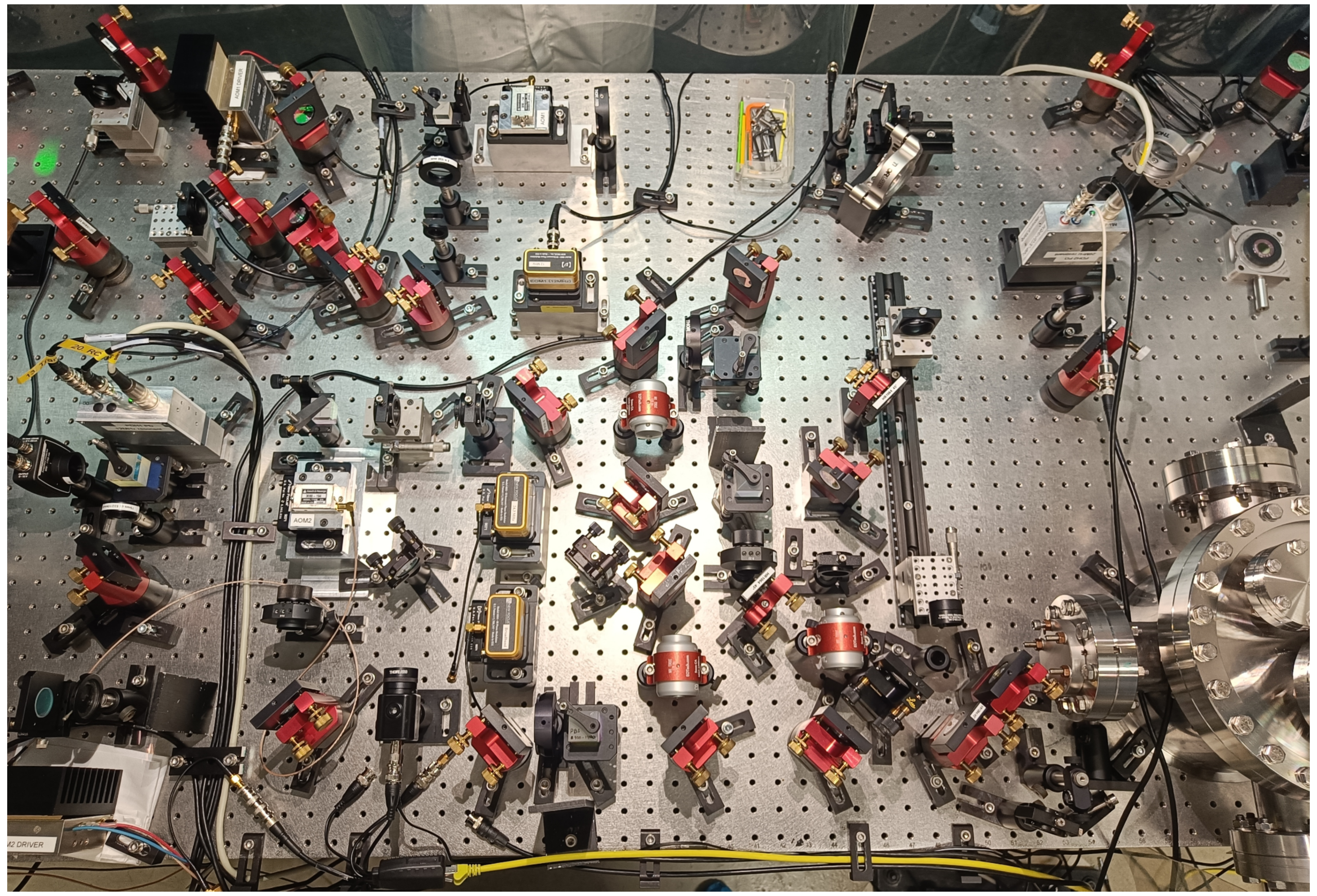
ALPS II Infrastructure

Optical Cavities

- Stable frequency lock of lasers to 123-meter high-finesse cavity inside magnet string
- World-record light storage time / narrow line width
- **19 meter high finesse cavity in HERA- West**
    - This is where we are developing VMB measurement techniques


Design and performance of the ALPS II regeneration cavity

TODD KOZLOWSKI,[1,*] LI-WEI WEI,[1] AARON D. SPECTOR,[1] AYMAN HALLAL,[2] HENRY FRÄDRICH,[1] DANIEL C. BROTHERTON,[3] ISABELLA OCEANO,[1] ALDO EJLLI,[2] HARTMUT GROTE,[4] HAROLD HOLLIS,[3] KANIOAR KARAN,[2] GUIDO MUELLER,[2,3] D. B. TANNER,[3] BENNO WILLKE,[2] AND AXEL LINDNER[1]



Hera-W prototype cavity injection optics

ALPS II Infrastructure

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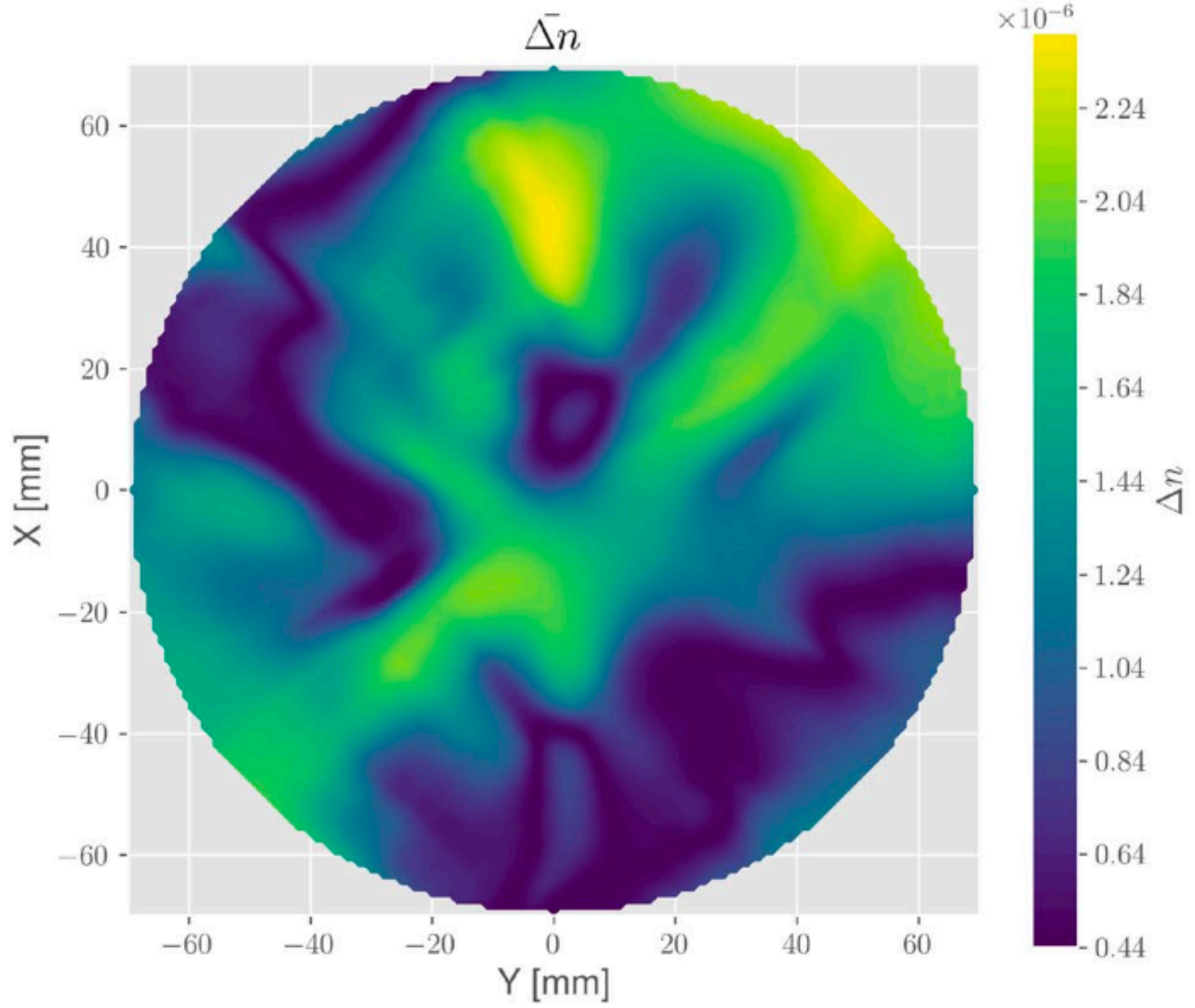
VMB in ALPS II (proposal)	**212**	**100,000**	**Ramped supercon. magnet**	**6000**

ALPS II can generate a larger VMB signal than any previous experiment !!

ALPS II Challenges

- Low modulation frequencies leaves us vulnerable to dynamic cavity birefringence noise
  - A low frequency noise arising from the mirrors of the cavity and is thought to be due to thermal and mechanical stress

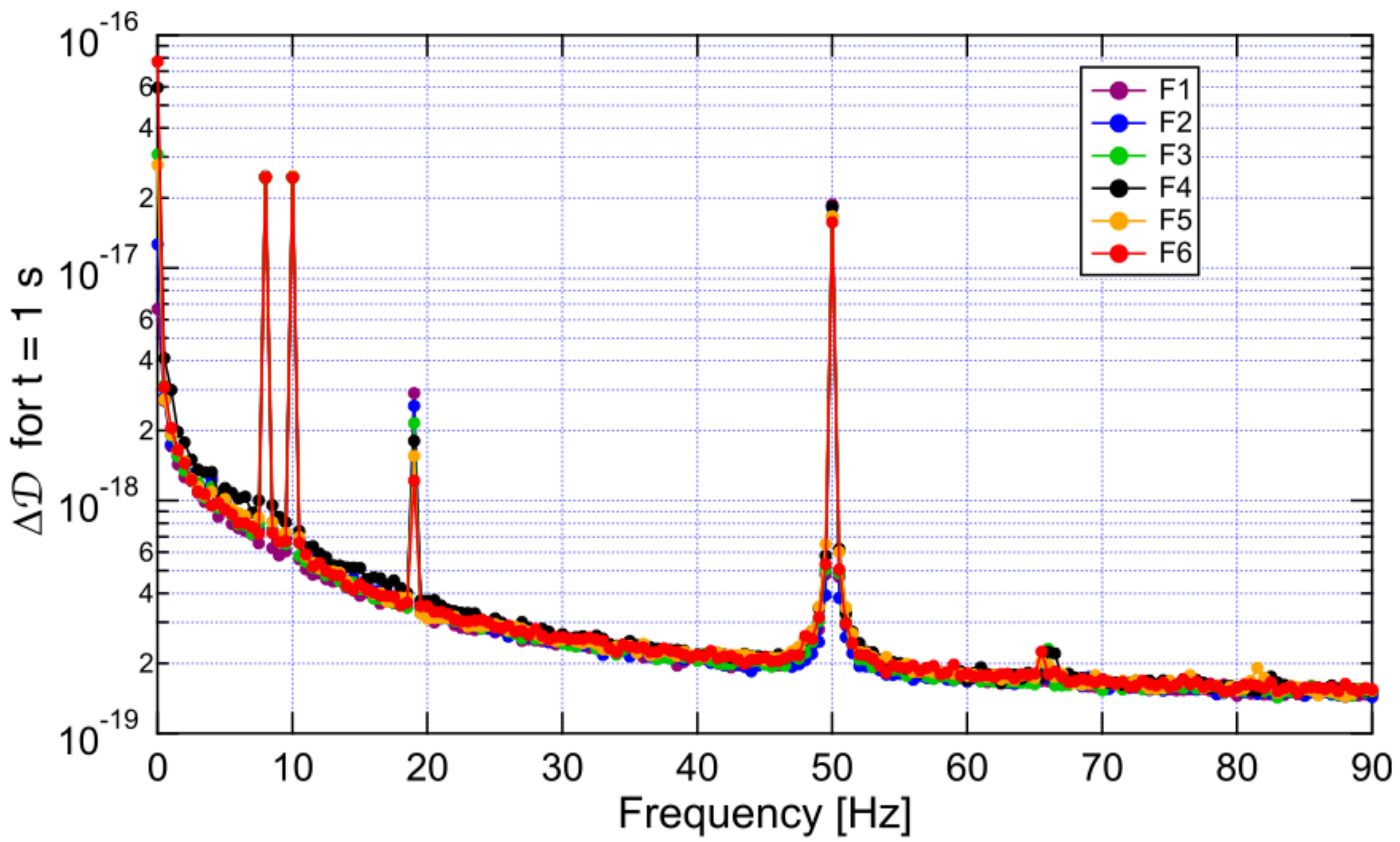


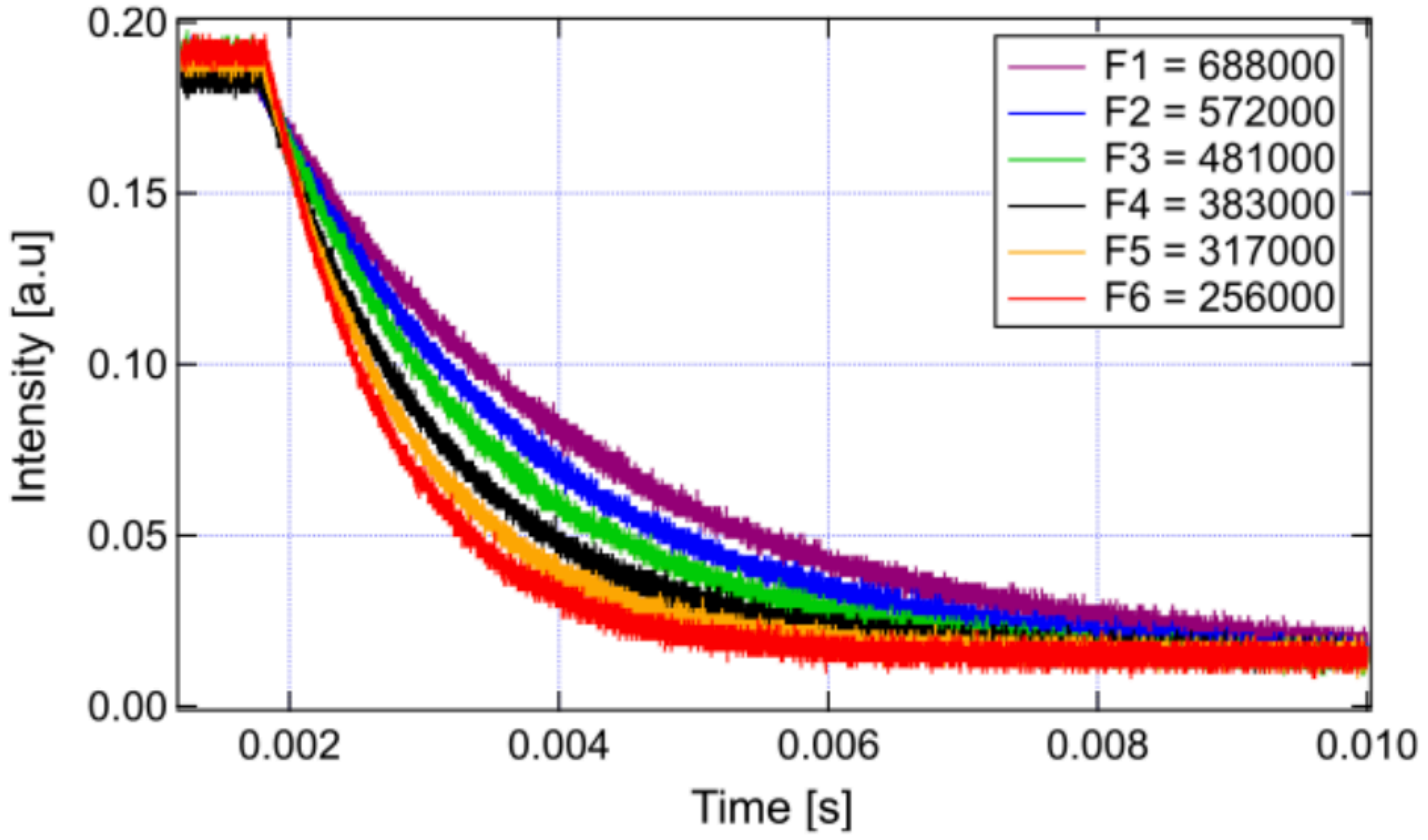
Birefringent map of KAGRA mirror coatings in [2]

ALPS II Challenges

- Low modulation frequencies leaves us vulnerable to dynamic cavity birefringence noise
  - A low frequency noise arising from the mirrors of the cavity and is thought to be due to thermal and mechanical stress
  - Increasing cavity finesse doesn't help - PVLAS
- We expect to reach this noise floor on both the prototype and final VMB experiment:
  - The estimation of this noise sets our sensitivity goals

A. Ejlli, F. Della Valle, U. Gastaldi et al. / Physics Reports 871 (2020) 1–74





The 19m Prototype

- We have a dedicated set up to develop the measurement system to be implemented in ALPS II for a VMB search
- 19m long, 30,000 finesse “test cavity” with no magnet in HERA-West Hall
- Our goal: precision cavity birefringence measurements

The 19m Prototype

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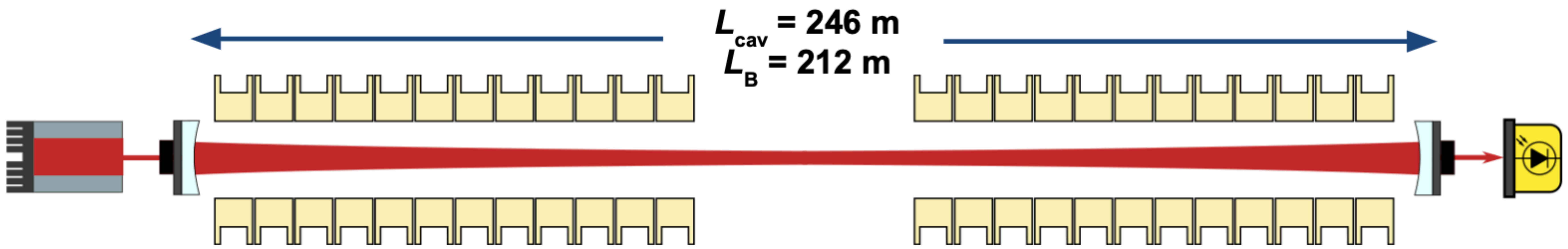
- 19m long, 30,000 finesse “test cavity” with no magnet in HERA-West Hall
- Our goal: precision cavity birefringence measurements
- **To demonstrate the sensing sensitivity required to detected VMB at ALPS II:**
    - For the prototype must achieve : $3.3 \times 10^{-17} m/\sqrt{Hz}$ for frequencies between 0.3 to 4 mHz
    - Laser stabilization system: 2ppm$/\sqrt{Hz}$ of a cavity linewidth

ALPS II Prospects

For a VMB search:

- If we achieve laser stabilization of $2\text{ppm}/\sqrt{Hz}$ of the cavity line width on the 245m long cavity with a finesse of 100,000 within the ALPS II magnet string, we would be able to reach the QED predicted value of VMB with a SNR of 3 after an integration time of roughly 22 days



$$B^2_{\text{ext}} \cdot L \approx 6,000$$

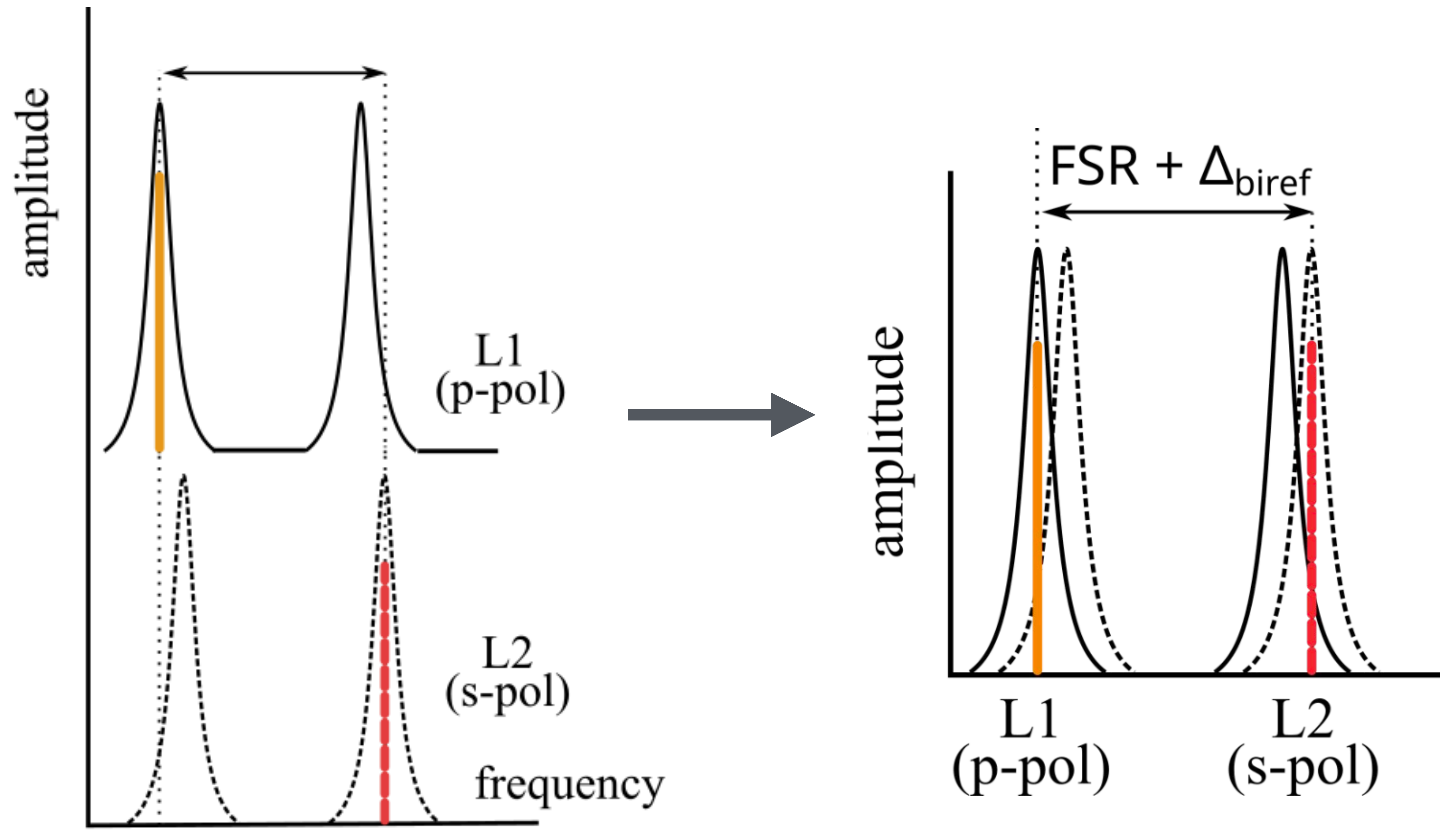
Relative path-length difference:

$$\Delta L \approx 2.37 \times 10^{-20}\ \text{m}$$

Measurement Techniques

Measurement Techniques

- Method devised by John L. Hall in 1995
- Individually lock two fields of orthogonal polarization to an optical cavity
- Read out the difference in the control signals of the two separate locks corresponding to cavity birefringence



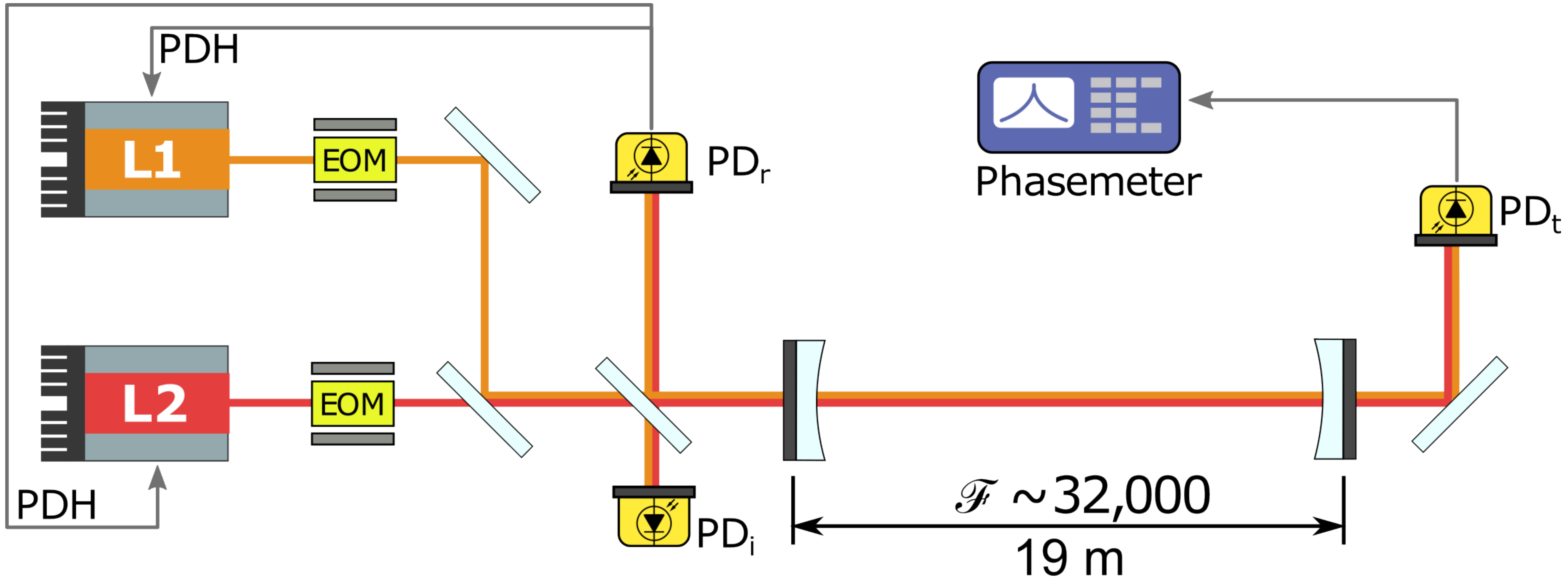
PHYSICAL REVIEW A, VOLUME 62, 013815

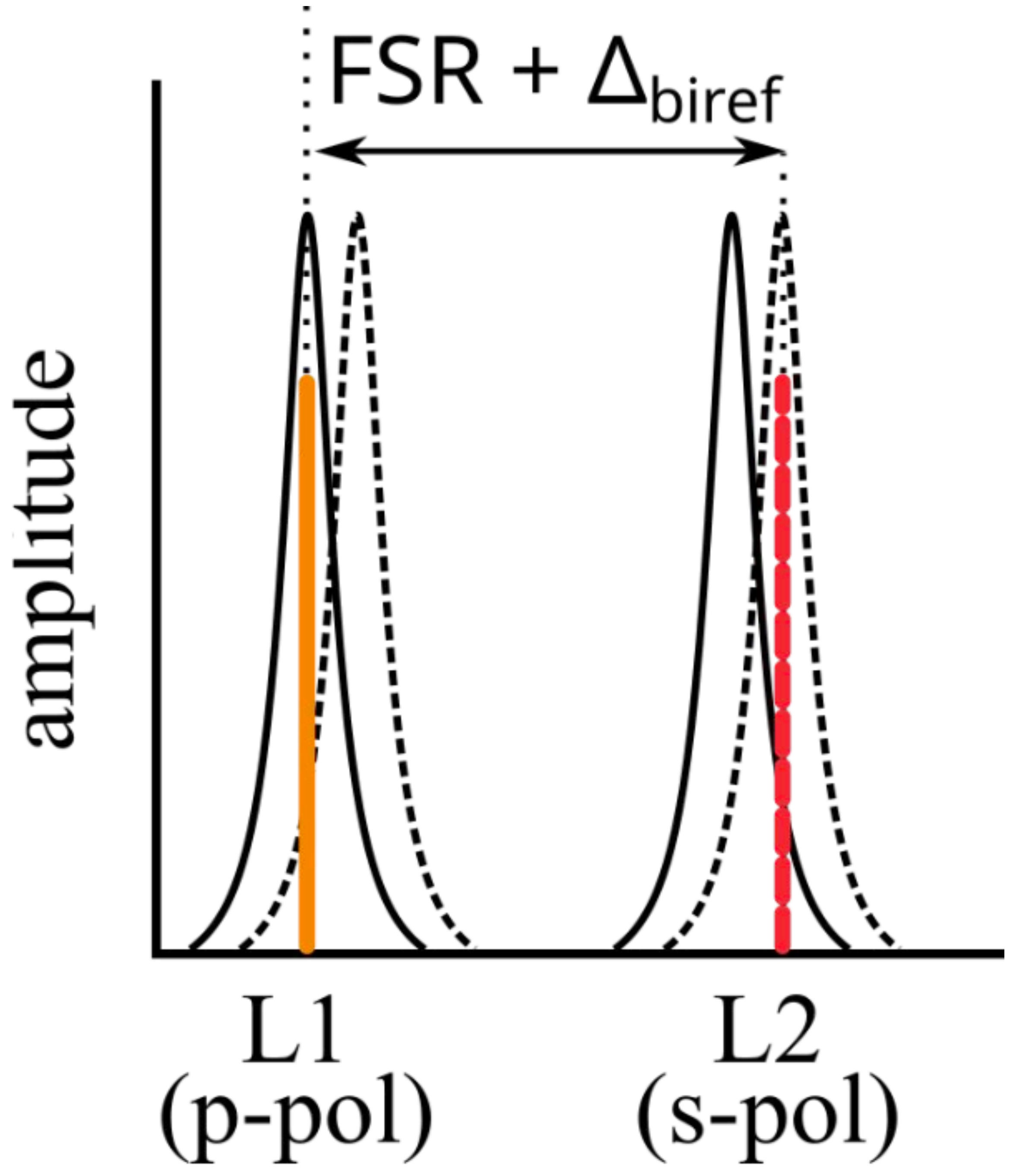
Measurement of mirror birefringence at the sub-ppm level: Proposed application to a test of QED

John L. Hall,* Jun Ye,* and Long-Sheng Ma†
JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440

(Received 6 January 2000; published 15 June 2000)

19m Prototype: measuring cavity birefringence





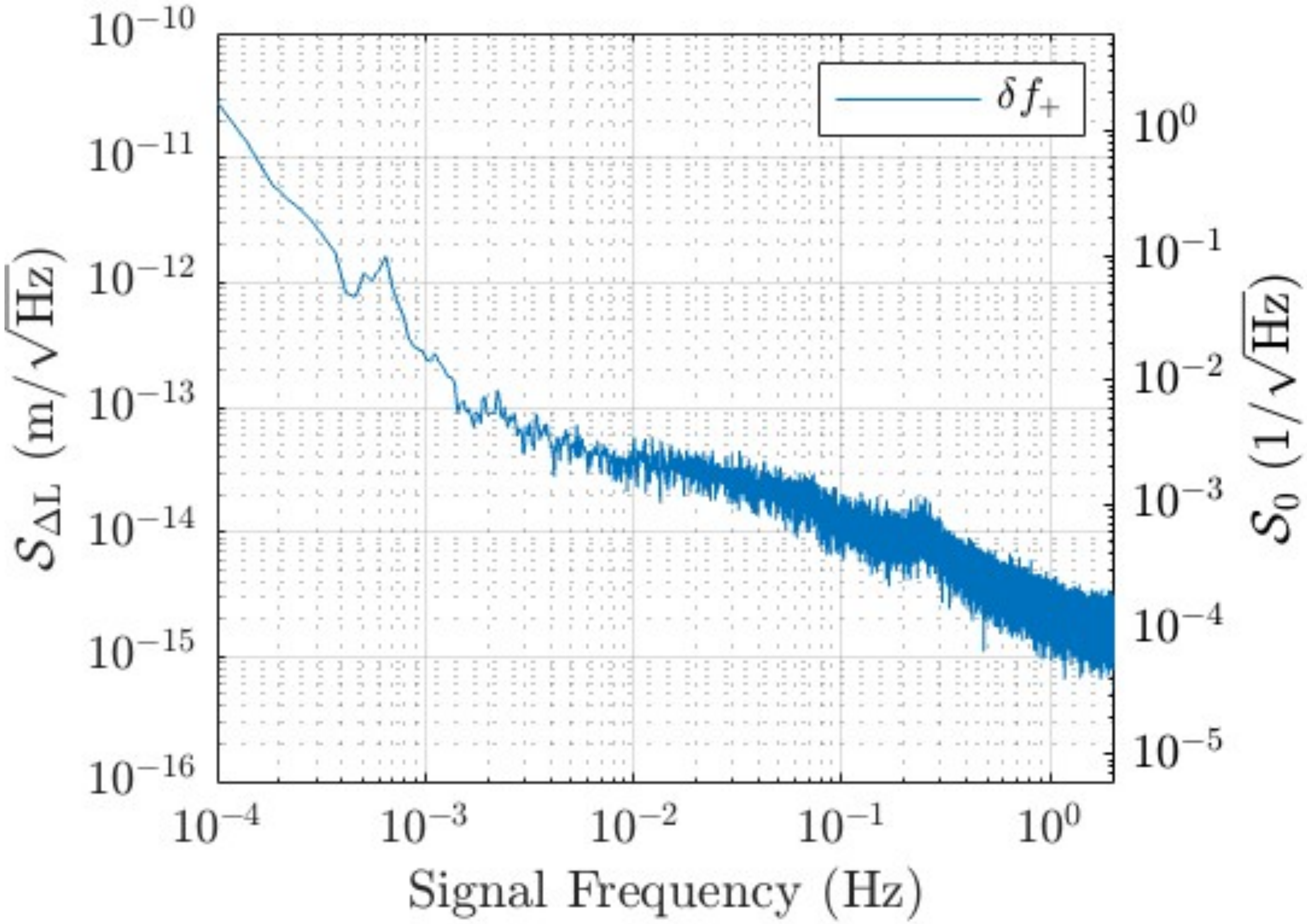
- **Our lab:**
  - Lock two fields separated by 2 FSRs to the 19m cavity
  - Measure their relative beatnote in transmission: Tracks the relative frequency between them, corresponding to FSR + Birefringence

Measurement Techniques

Prototype Results Pt. 1

- A weekend measurement of the same beat note between 2 fields of orthogonal polarizations

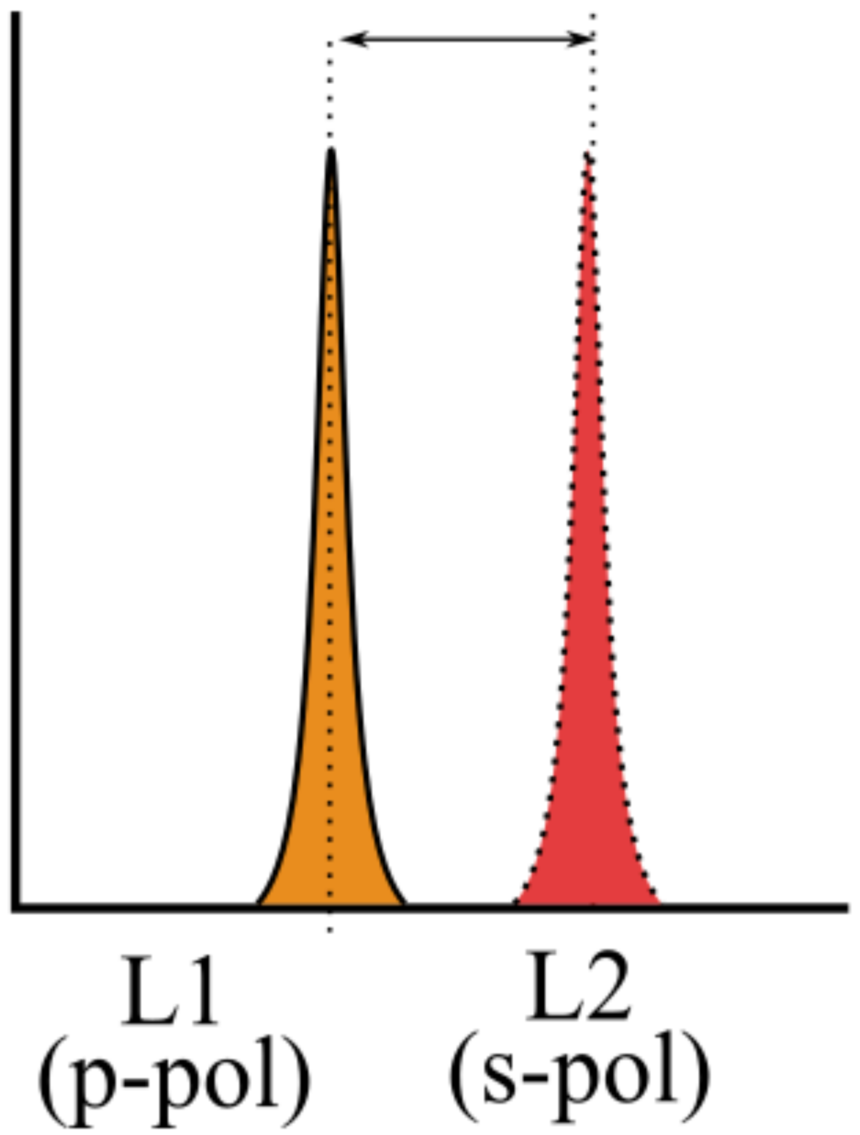
- Demonstrated a long stable lock of two lasers locked to the same cavity



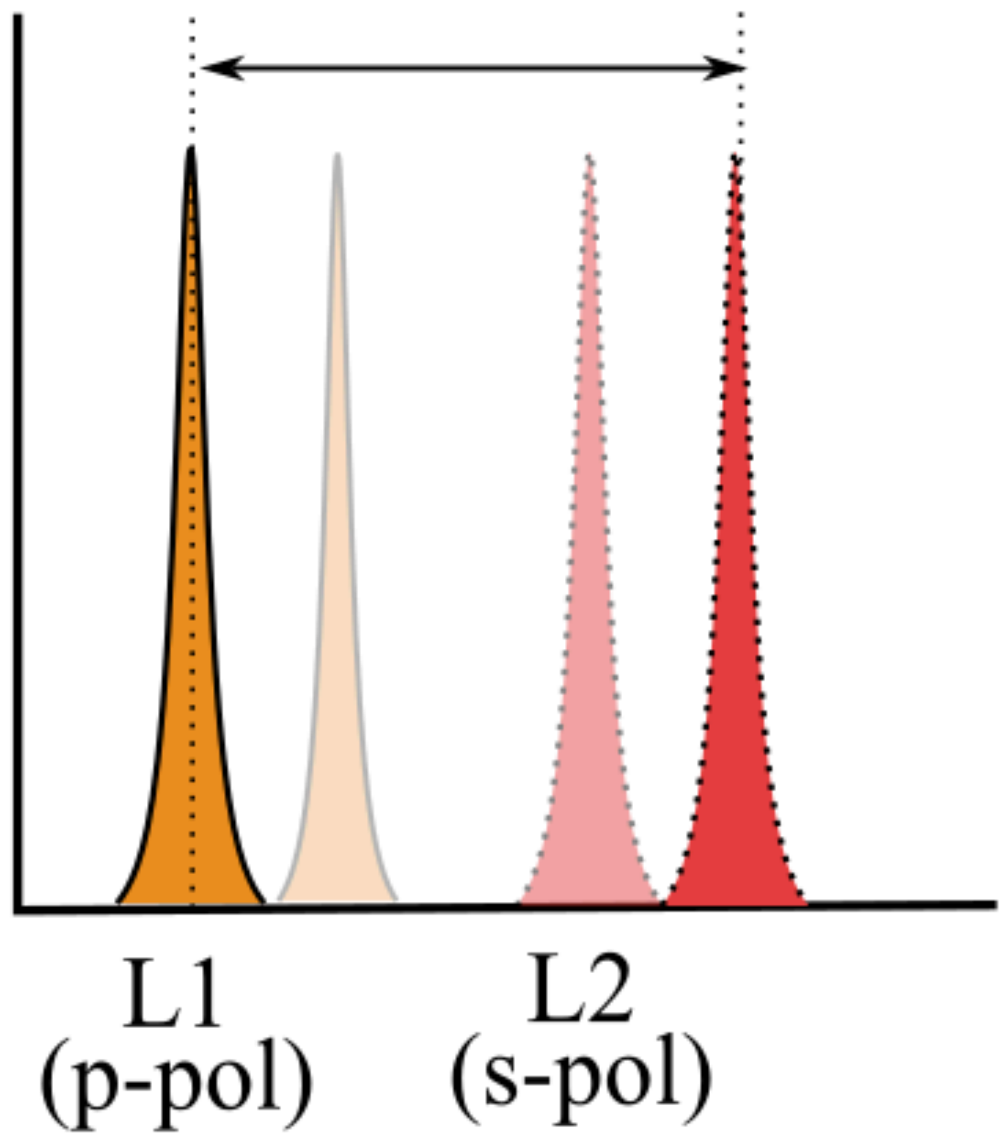
Prototype Results Pt. 1

- Cavity length drifts over time leads to a change in the free spectral range : ΔFSR
- Reminder: Free Spectral Range = $\dfrac{c}{2L_{cavity}}$
- The length of the cavity is not stable over time
- Length drifts couple into our measurement as frequency noise in the beat note of the two fields at ν_{FSR}

t=0

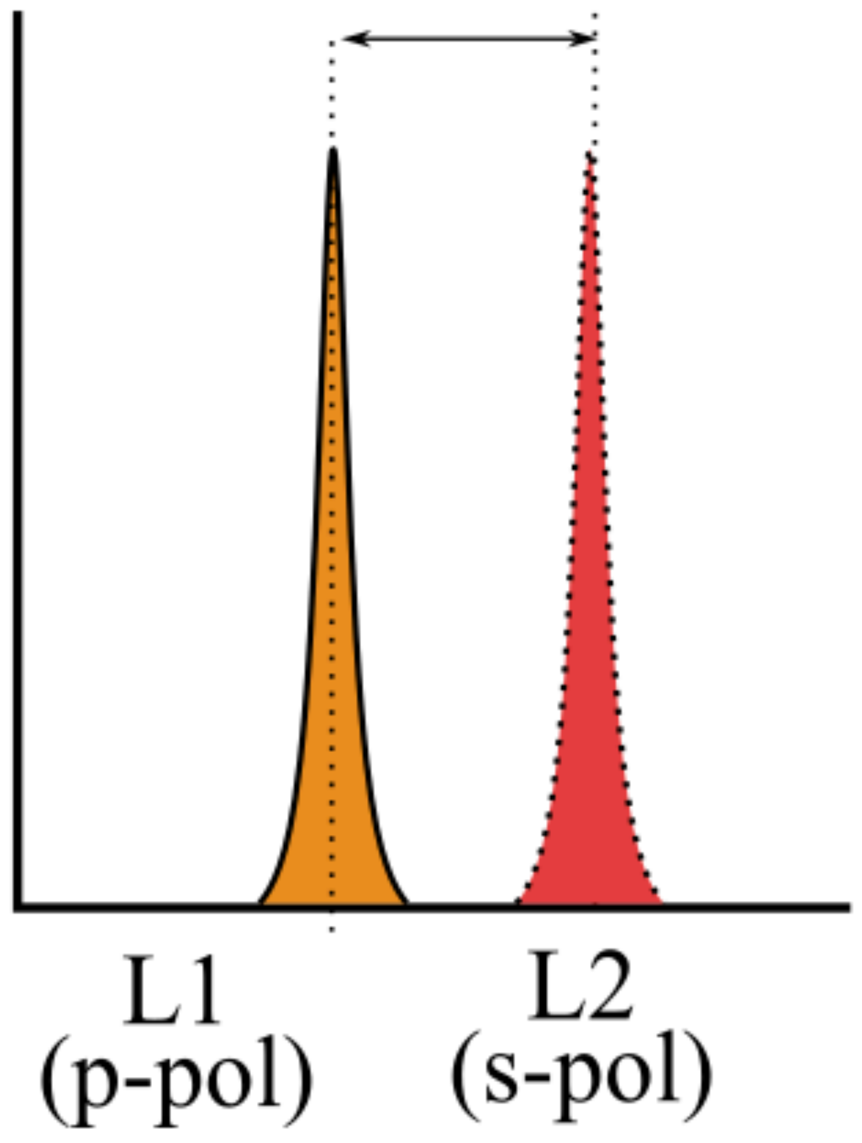


t=30min



Measurement Techniques

t=0



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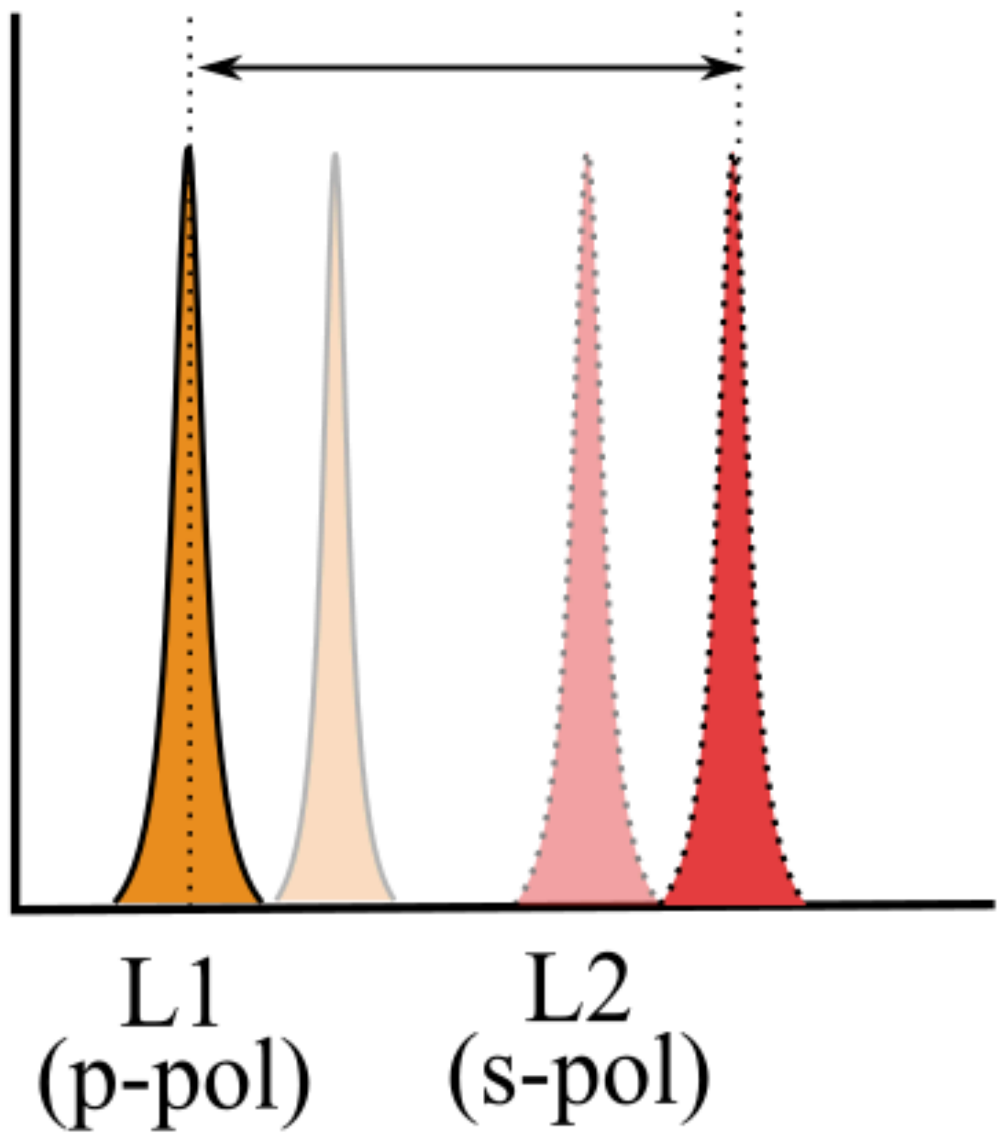
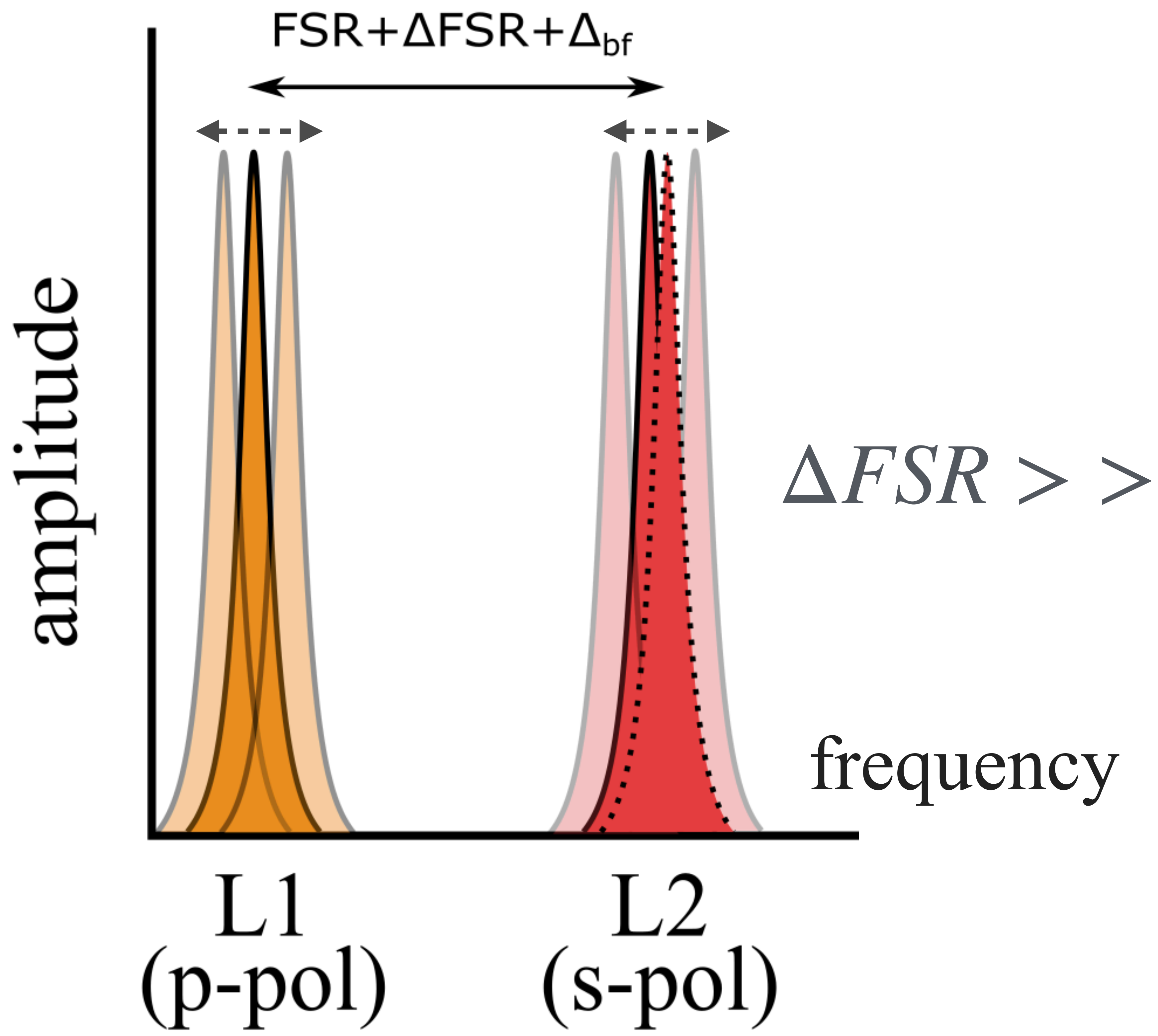


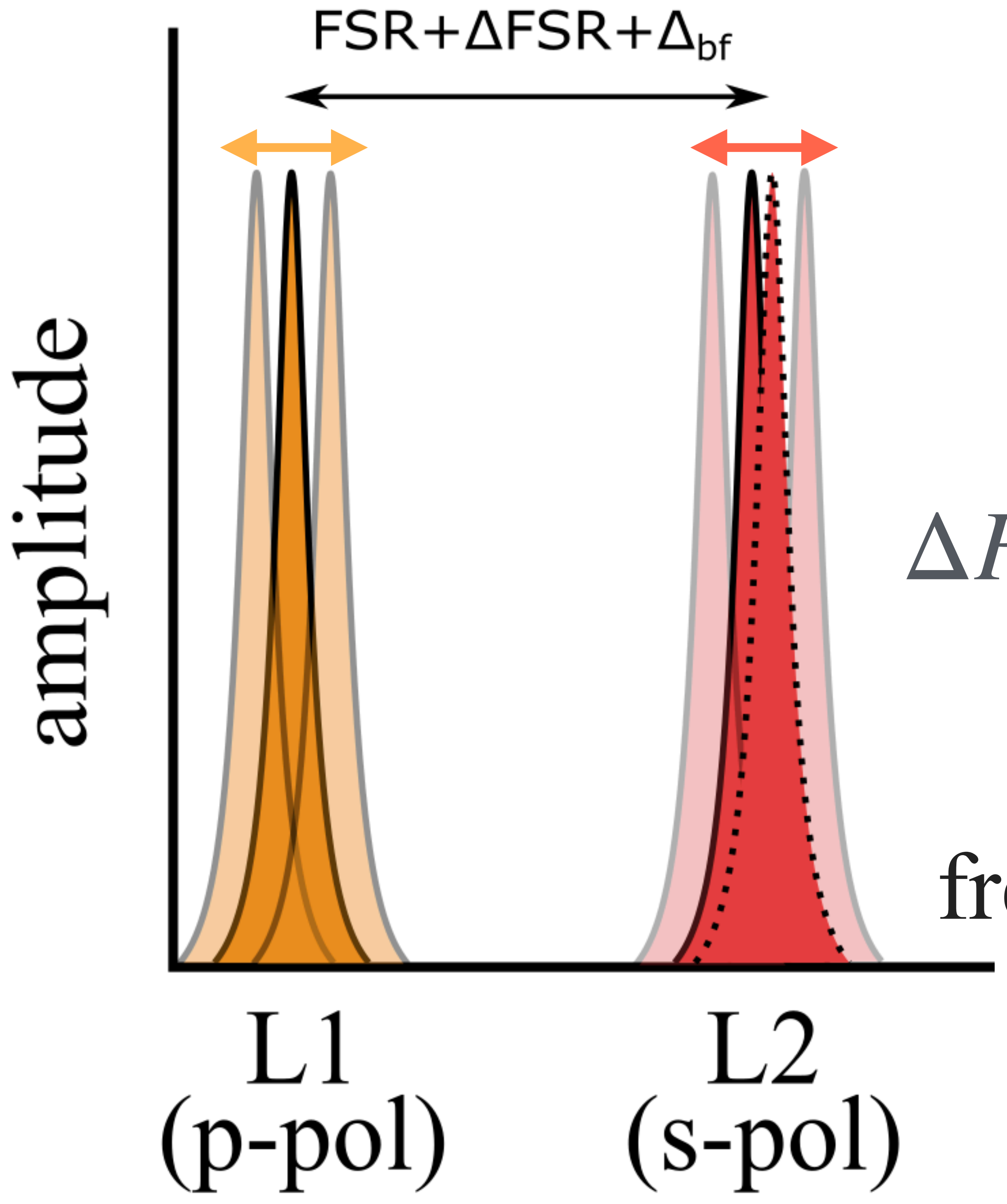


$\Delta FSR >> \Delta_{bf}$

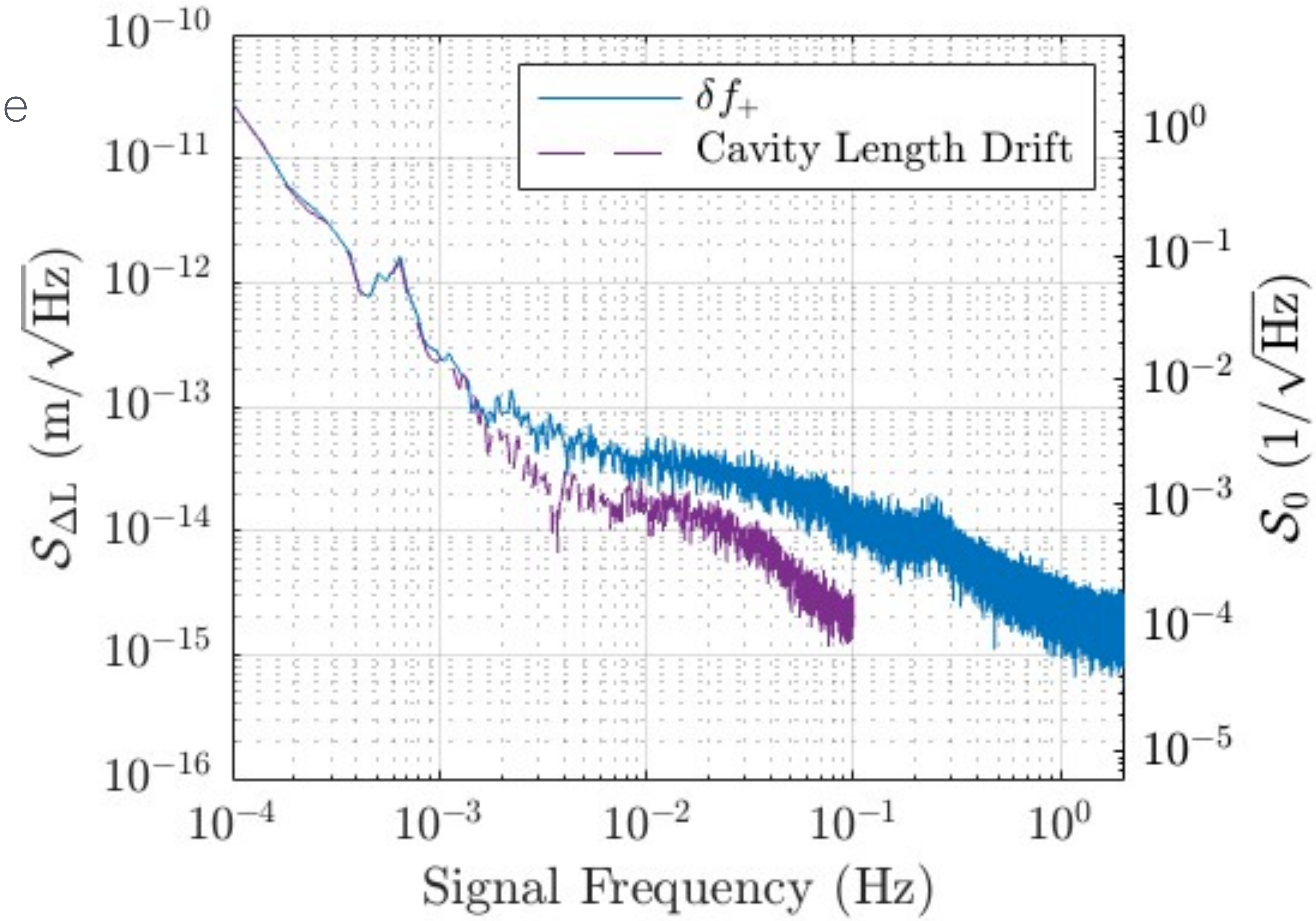
ALPS

Prototype Results Pt. 1

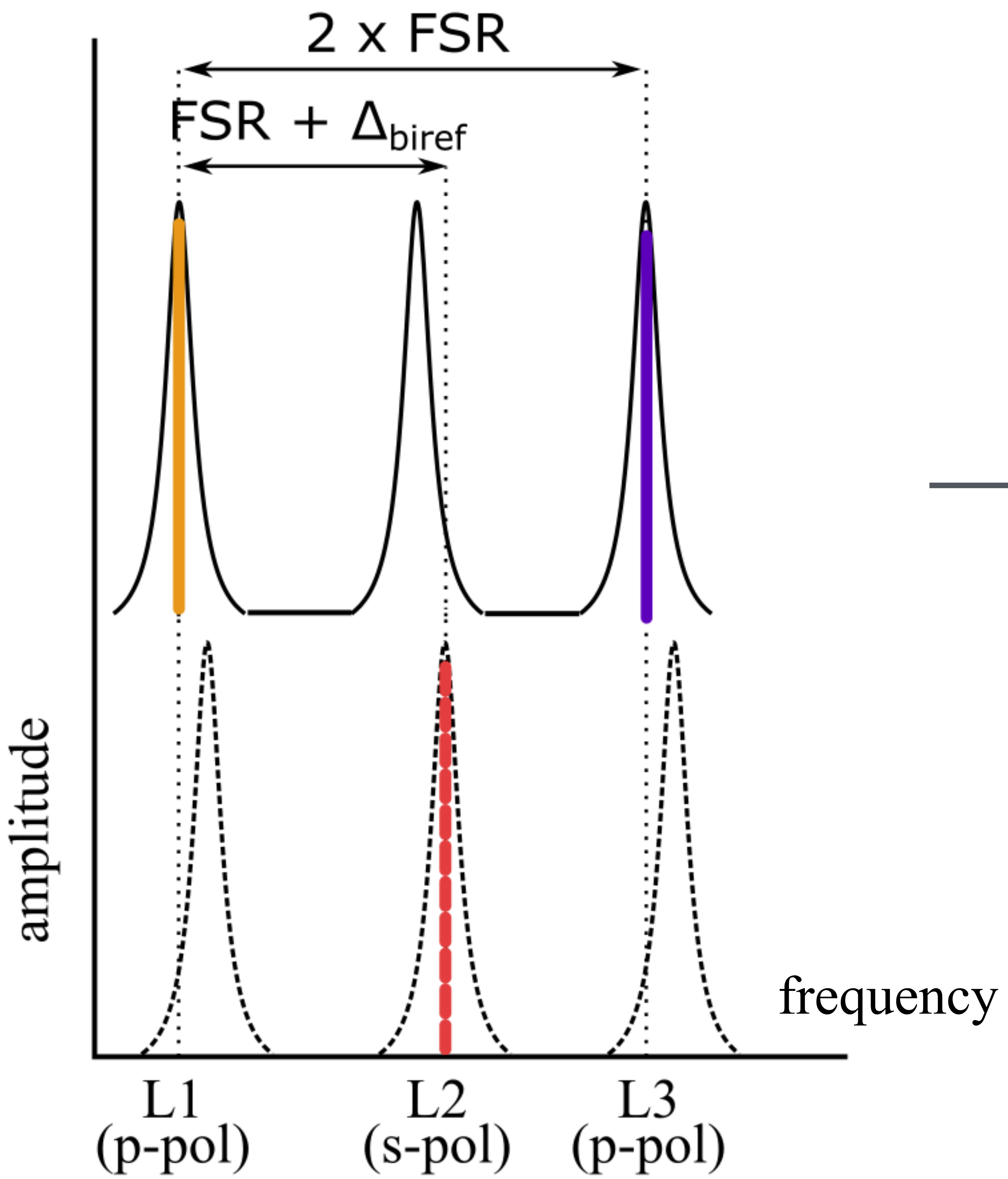
We can independently sense the drifts in the cavity length: **Purple**

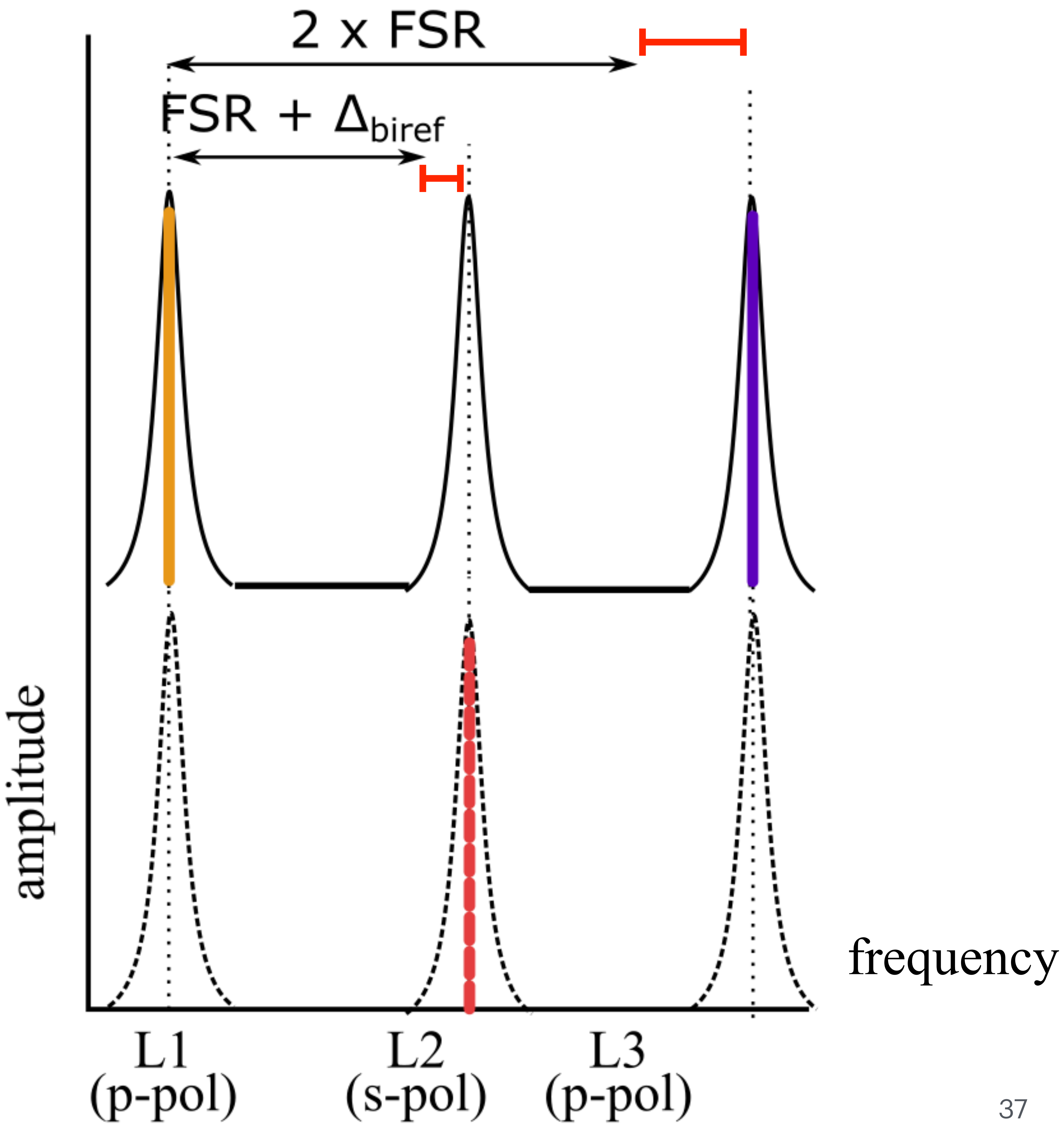


$\Delta FSR >> \Delta_{bf}$

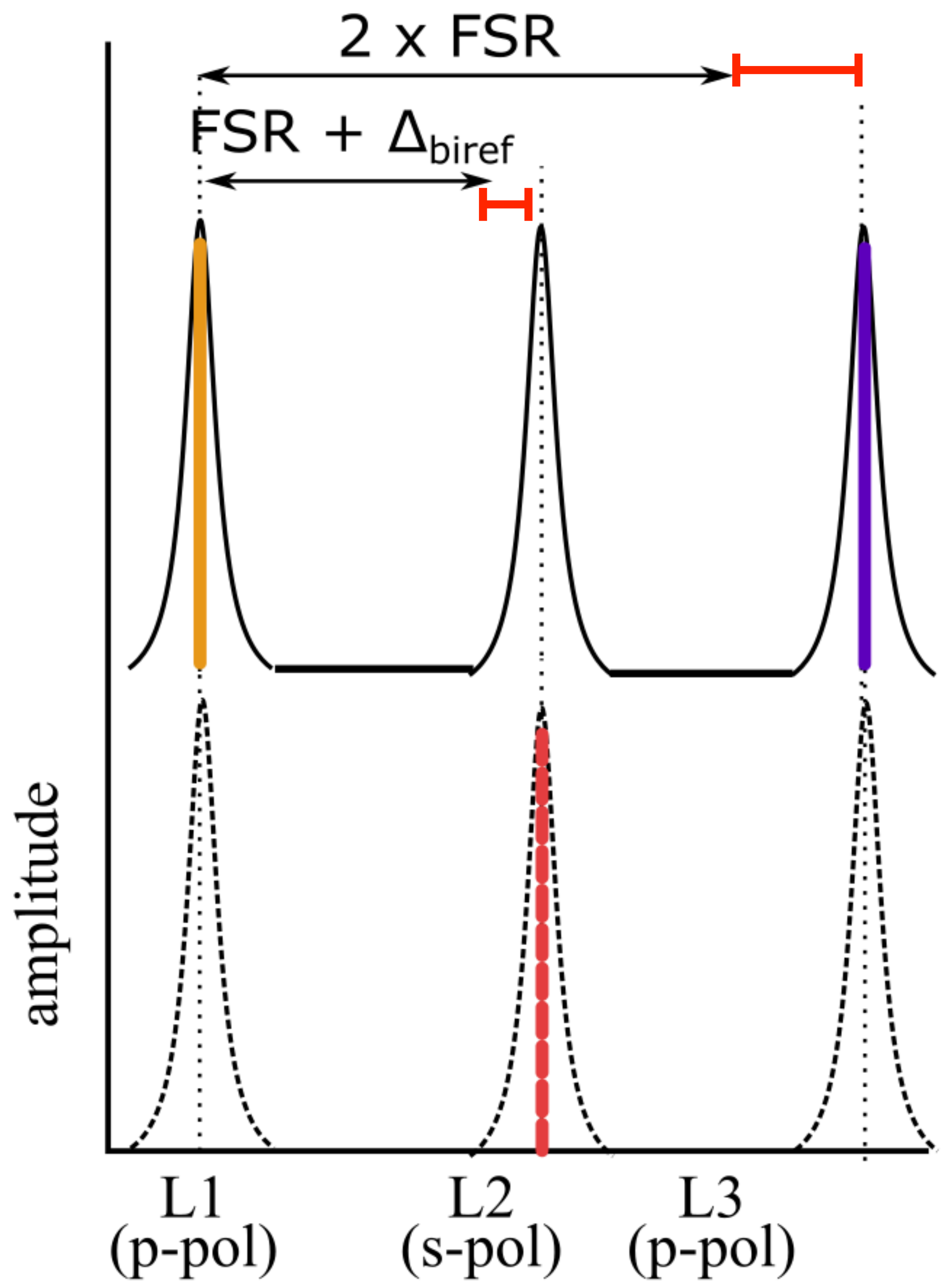


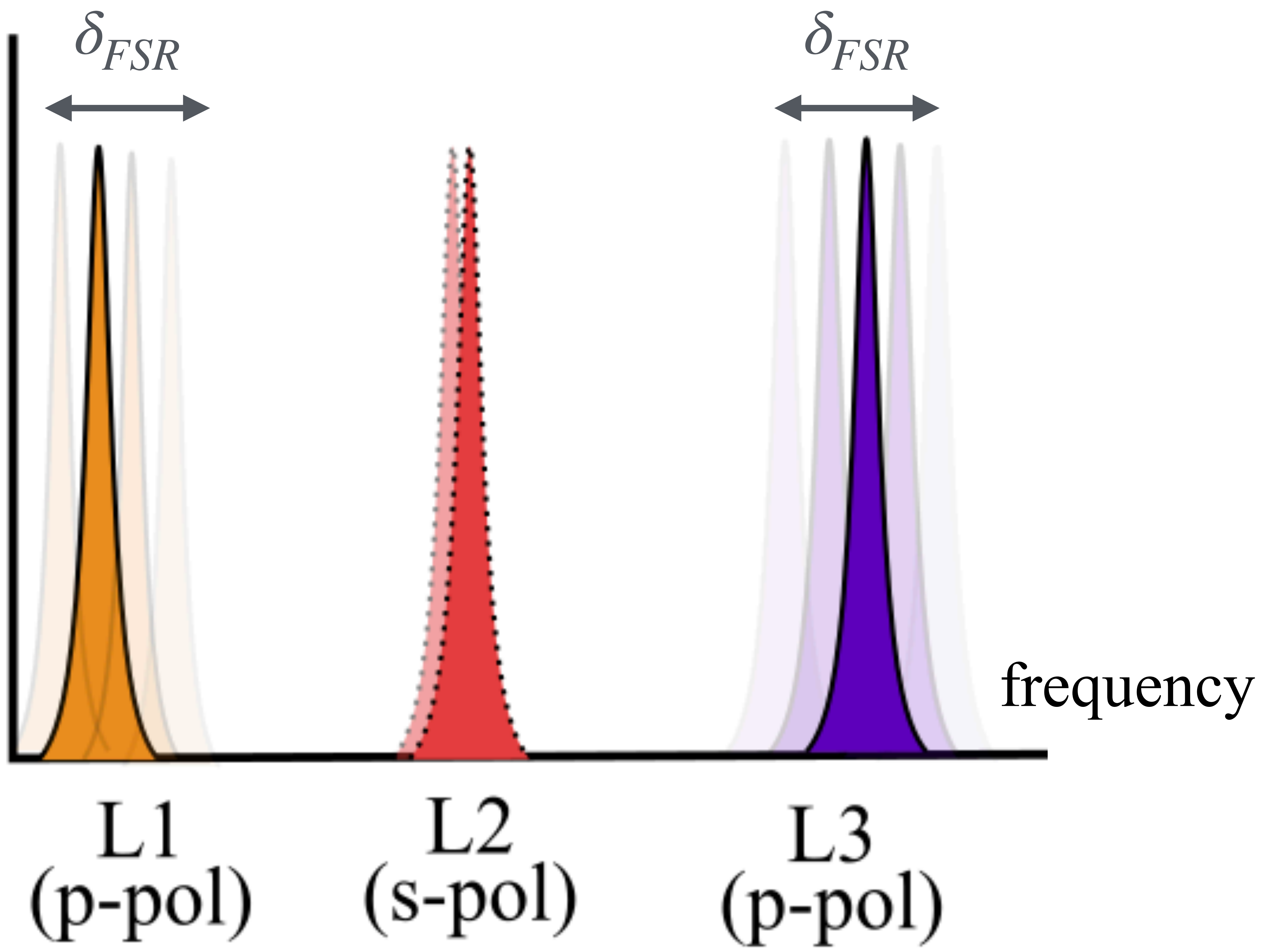
Measurement Techniques



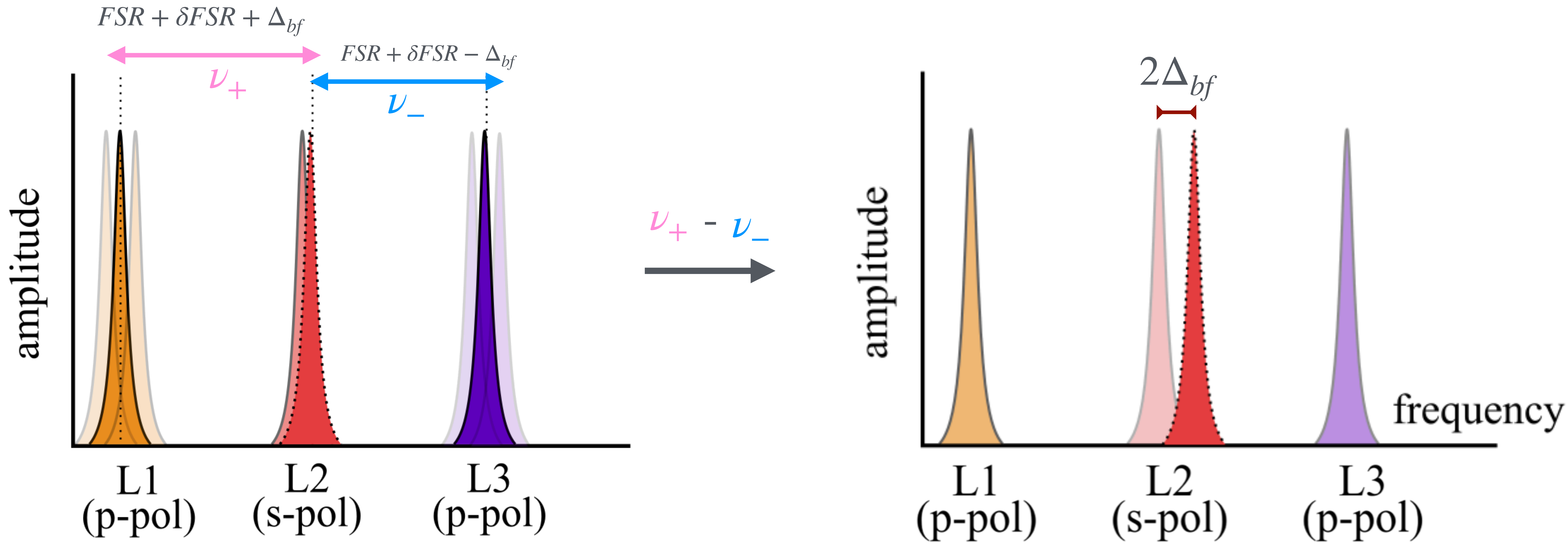


Measurement Techniques





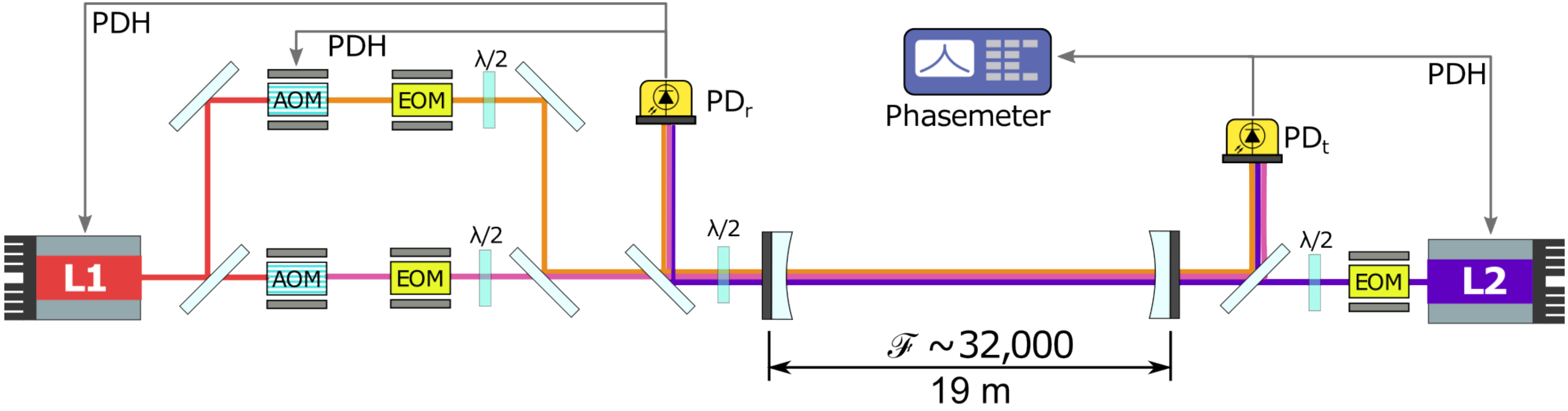
Measurement Techniques



- Lock 3 fields, spaced by 1 FSR wrt each other, 2 fields of the same polarization and one orthogonal
- We measure 2 beat notes and superimpose them to subtract the changes to the cavity FSR due to length noise

Measurement Techniques

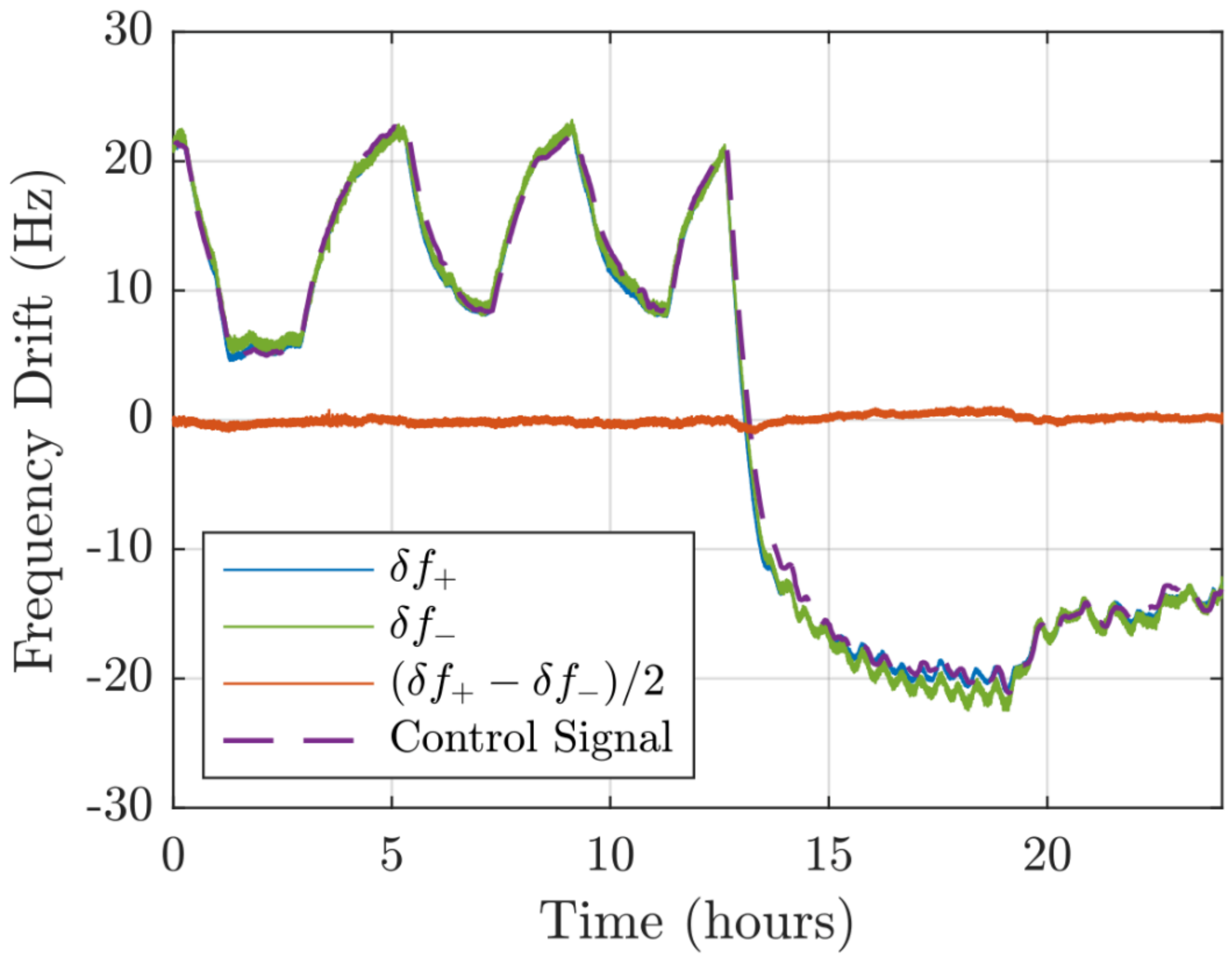
3 field Measurement:



- Lock 3 fields iduviduatlly to cavity, each spaced by 1 FSR
- 2 fields of the same polarization and one orthogonal centered between them

Prototype Results

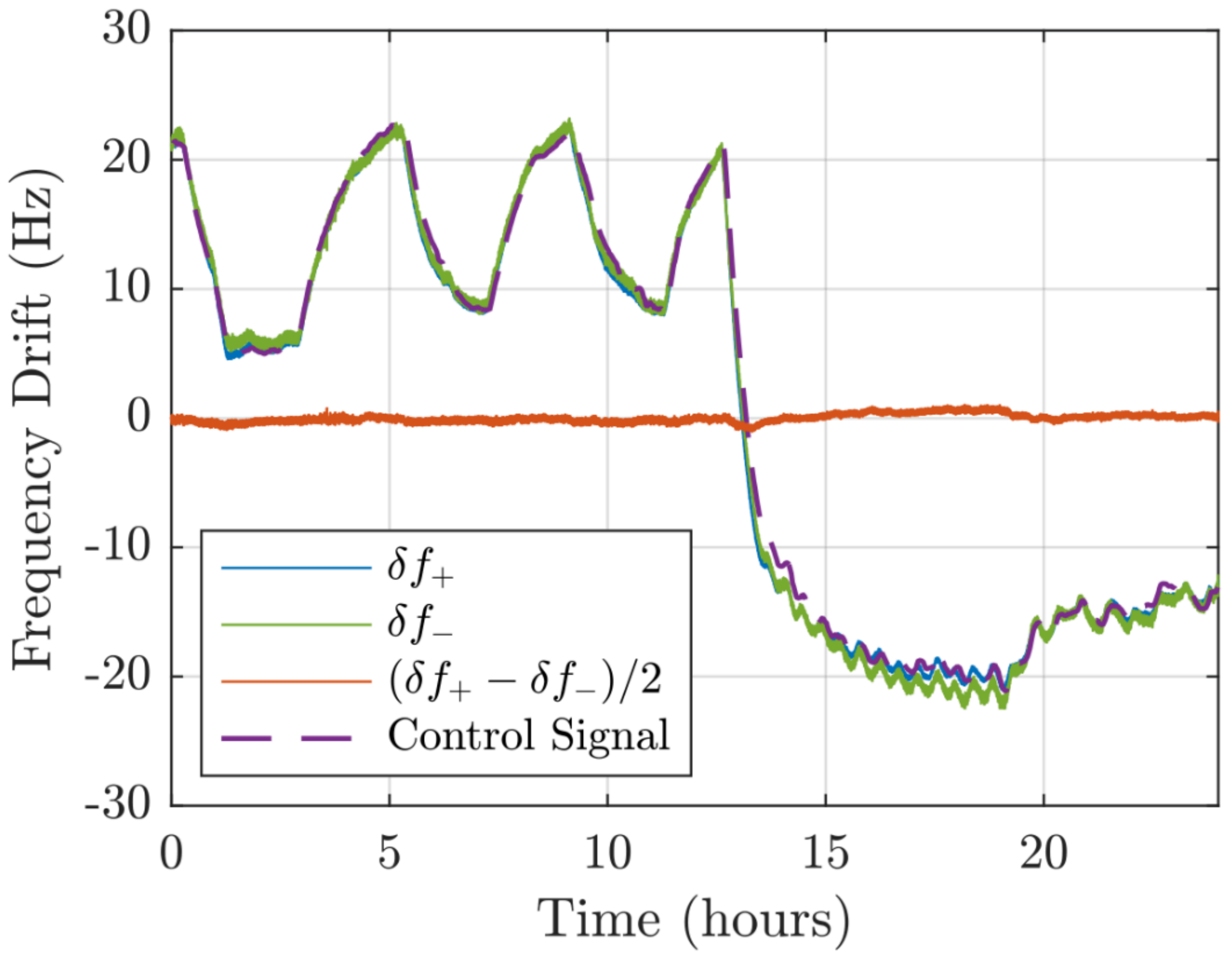
3 field: Cavity Length Noise Subtraction



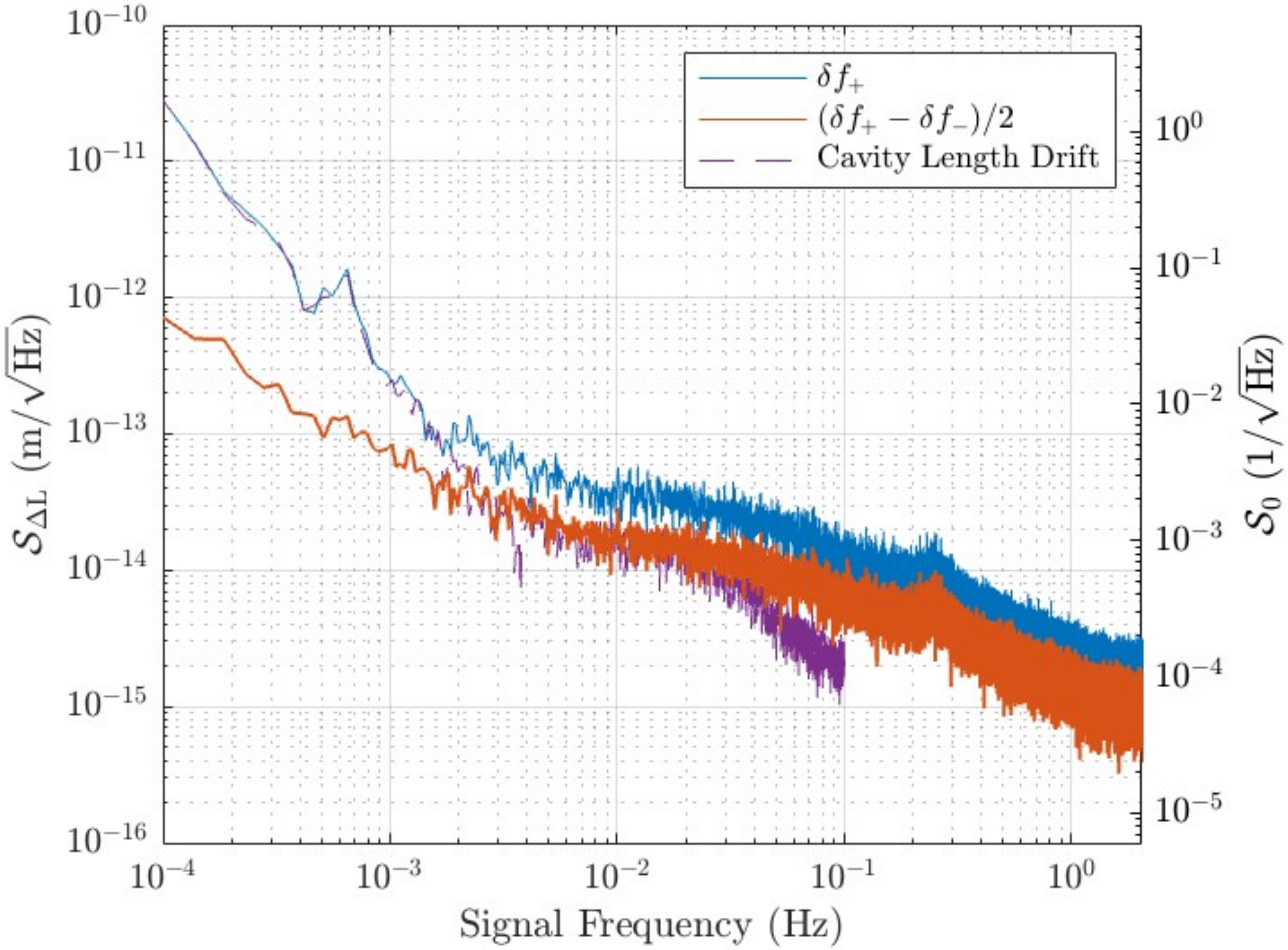
(a) Time series of the beatnote frequency drift

Prototype Results

3 field: Cavity Length Noise Subtraction



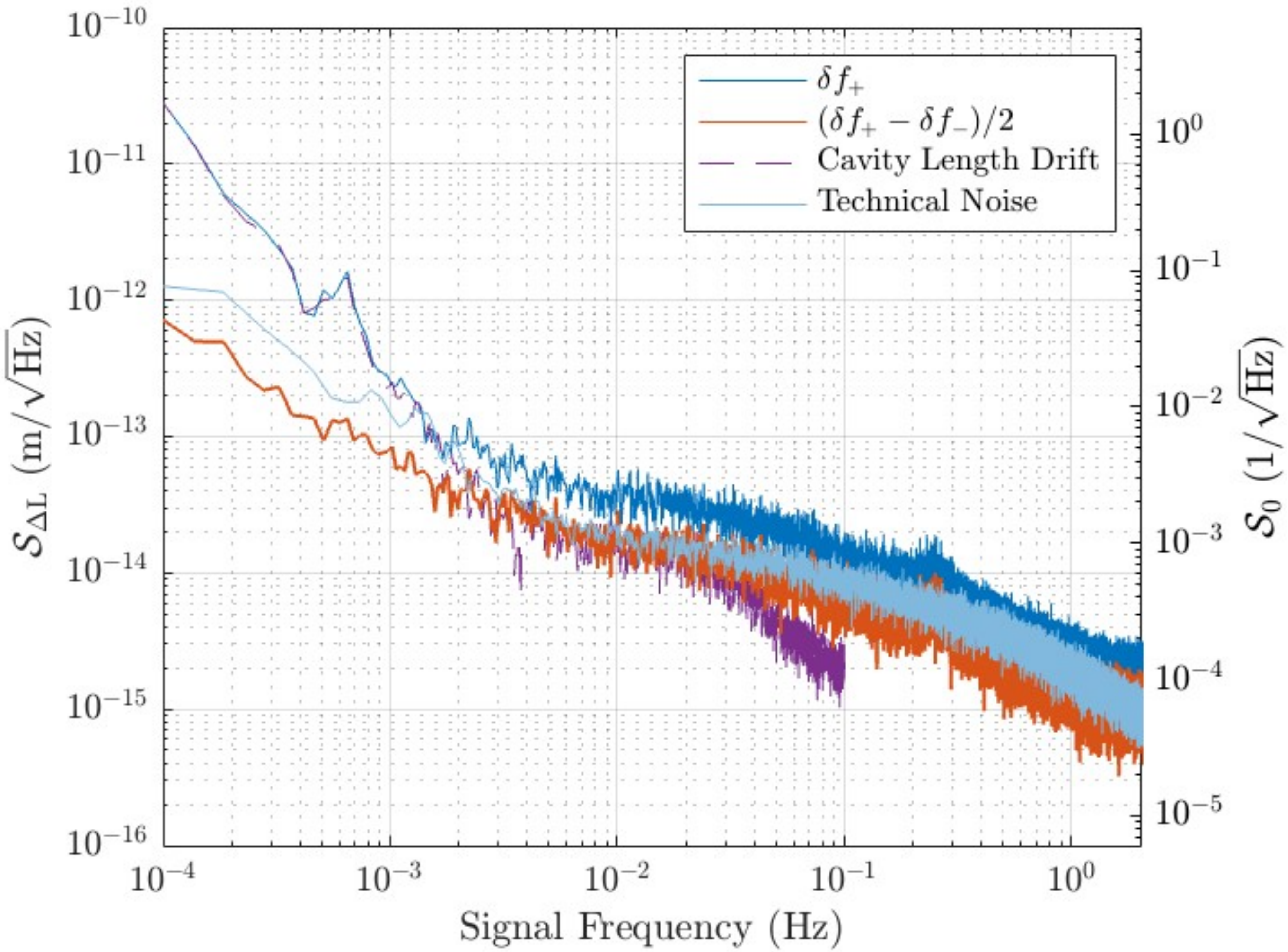
(a) Time series of the beatnote frequency drift



Prototype Results

Current Limitations:

Technical noise on the injection table of our lasers, that couple to the frequency stabilization loops



Prototype Results

Current Limitations:

Technical noise on the injection table of our lasers, that couple to the frequency stabilization loops

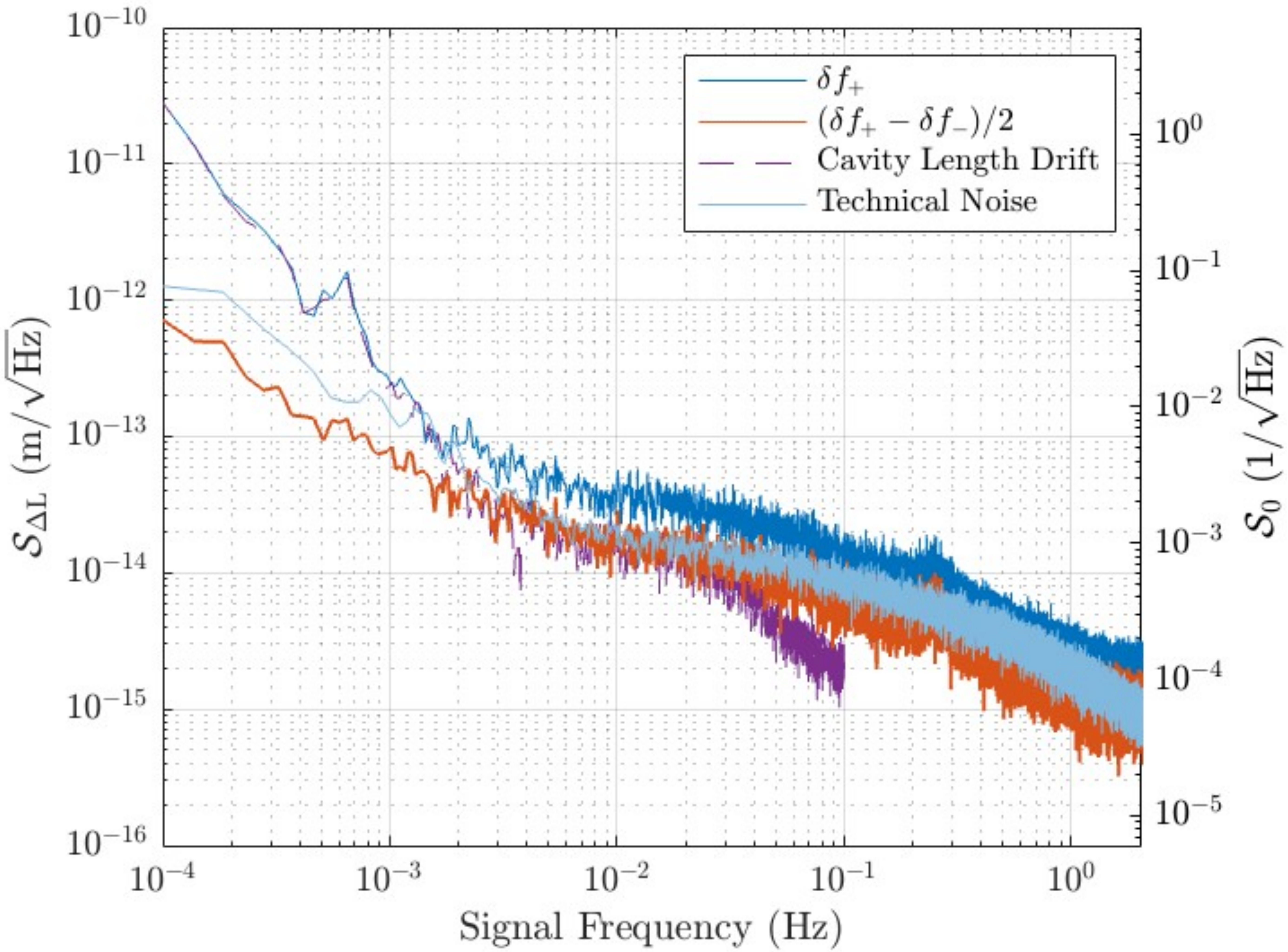
Demonstration of an interferometric technique for measuring vacuum magnetic birefringence with an optical cavity

Aaron D. Spector*[1], Todd Kozlowski[1], and Laura Roberts[2]

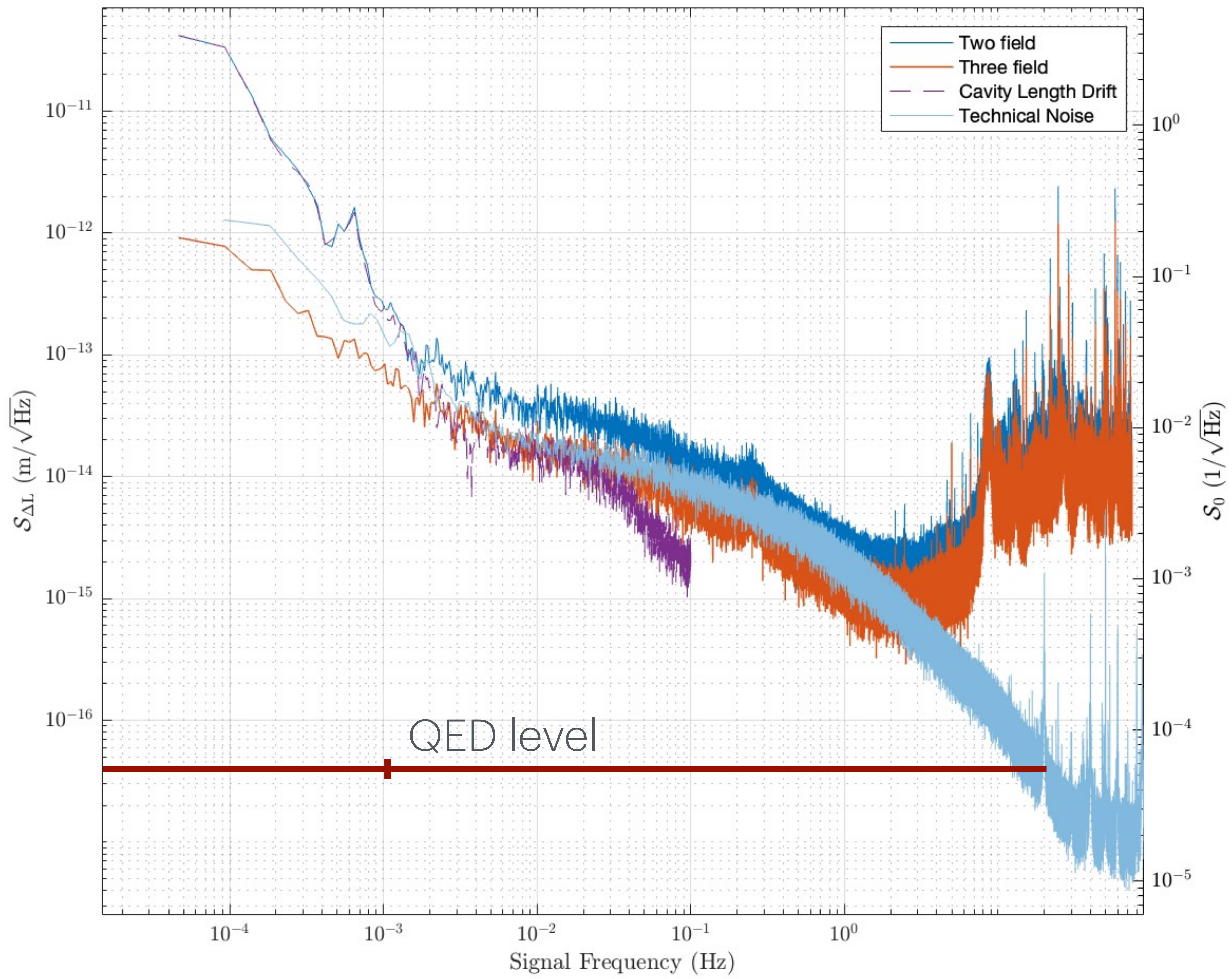
[1] *Deutsches Elektronen Synchrotron DESY, 22603 Hamburg, Germany*

[2] *Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut) and Leibniz Universität Hannover, 30167 Hannover, Germany*

https://doi.org/10.48550/arXiv.2510.14064



Quick Reality Check



Things to note:

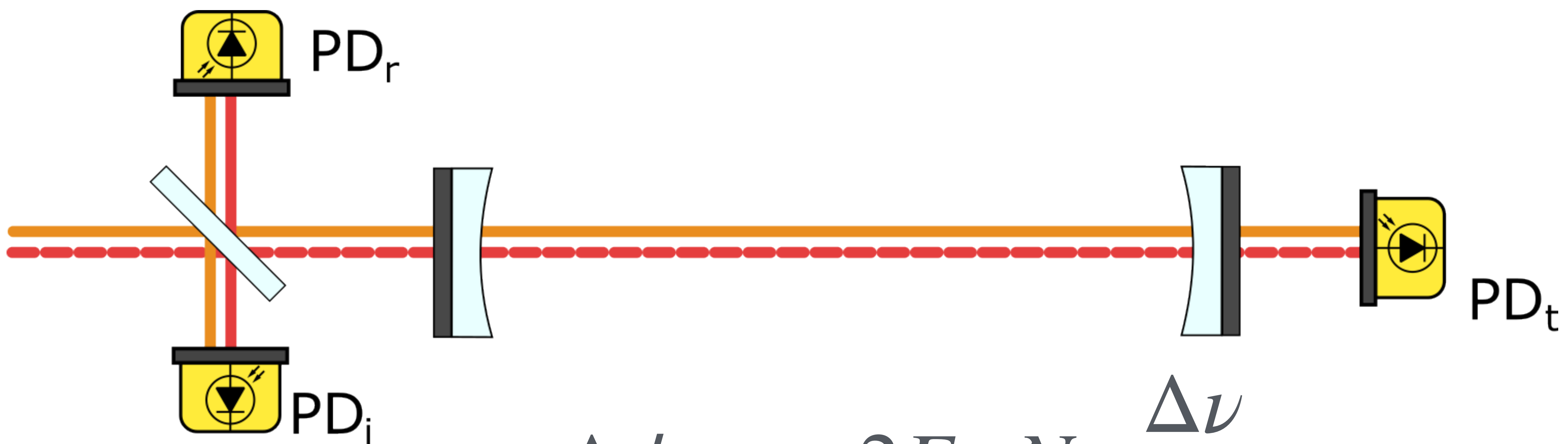
We are still 3 orders of magntide from our goal

But we have an understanding of the current limiting noise source and how to tackle it

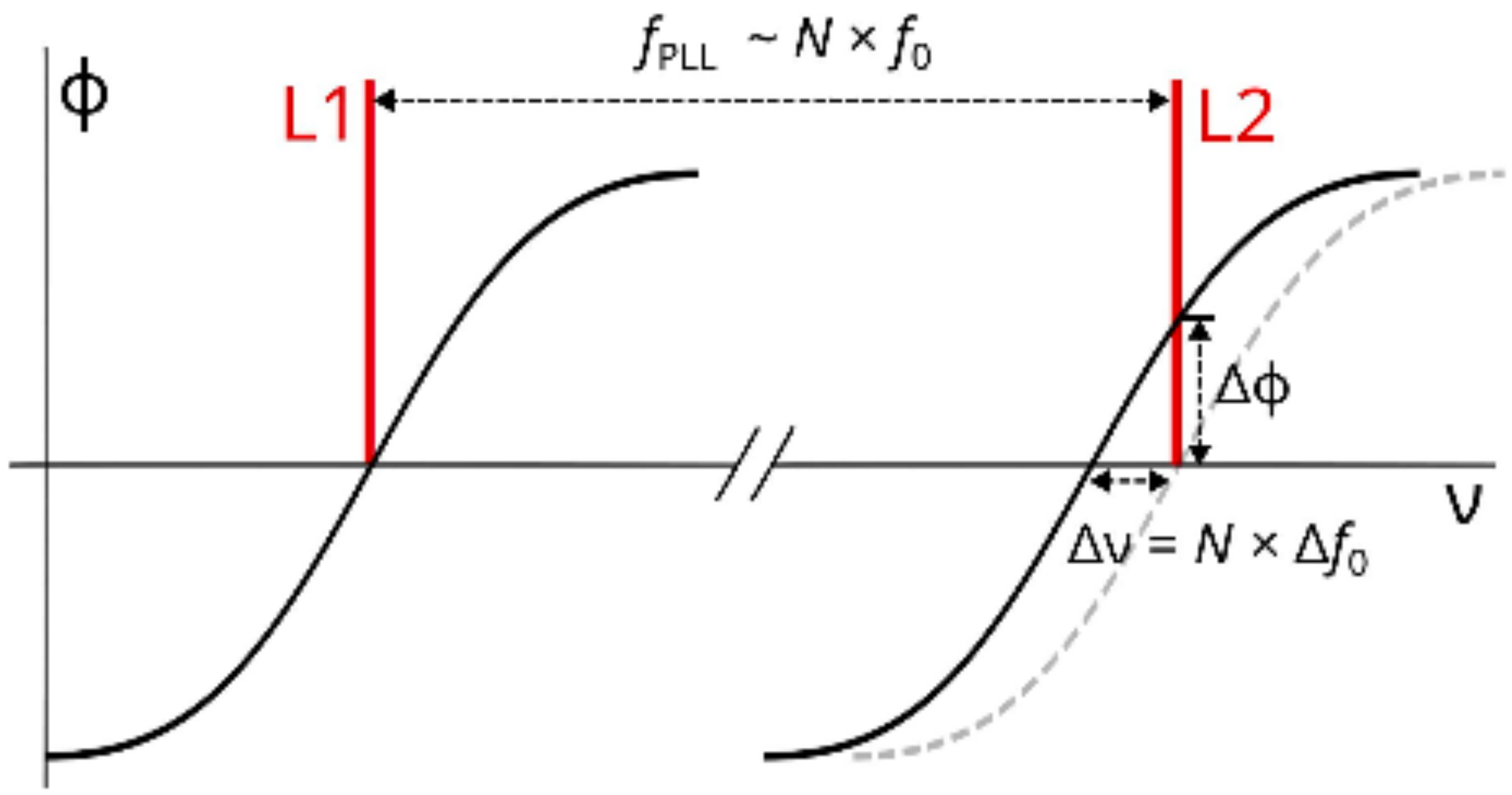
Subtracting Current Noise Floor

Subtracting Current Noise Floor

Measuring the offset induced into our control loops

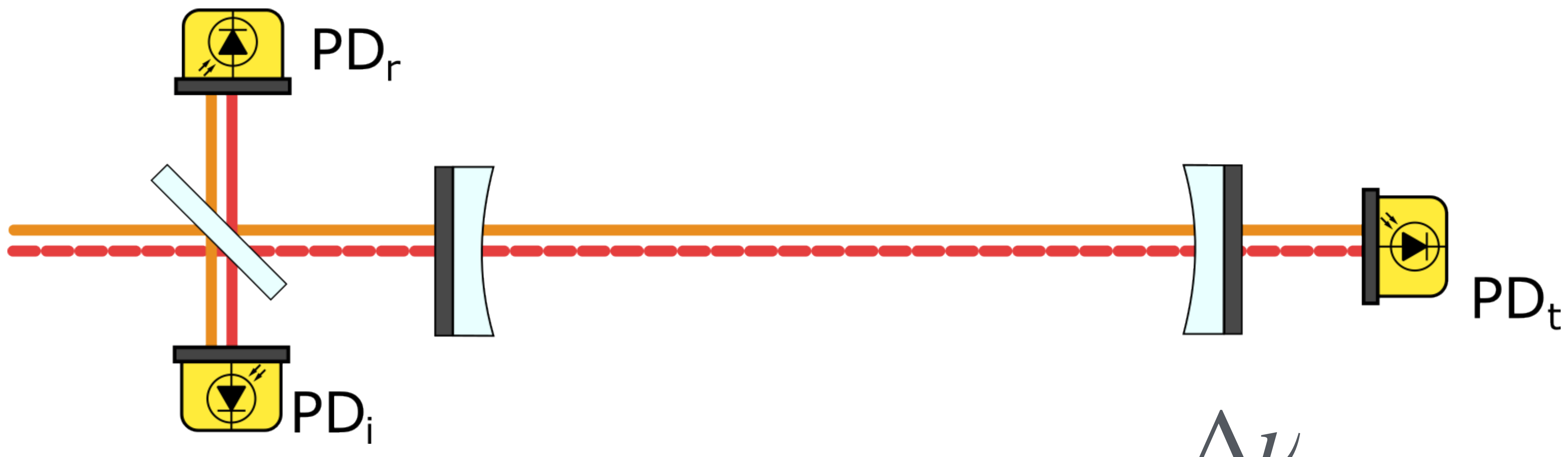


$$\Delta\phi \approx -2F \cdot N \cdot \frac{\Delta\nu}{\nu}$$



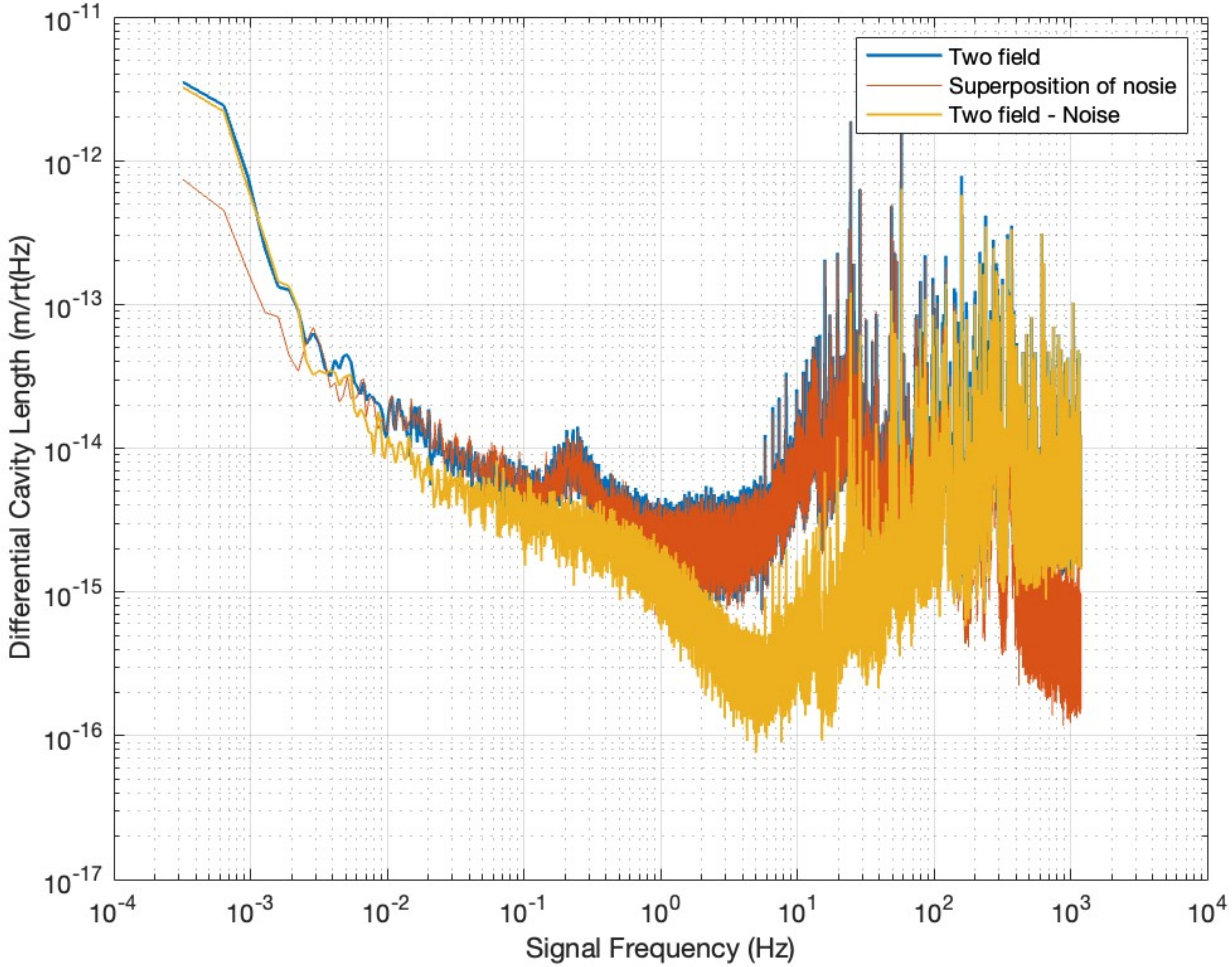
- Measure the relative phase of the beat notes at input PDi, transmitted PDt, and reflected PDr photodetectors
- Concept: Superimpose the differential phase measurements to extract the technical noise and subtract it in post processing

Subtracting Current Noise Floor



$$\Delta\phi \approx -2F \cdot N \cdot \frac{\Delta\nu}{\nu}$$

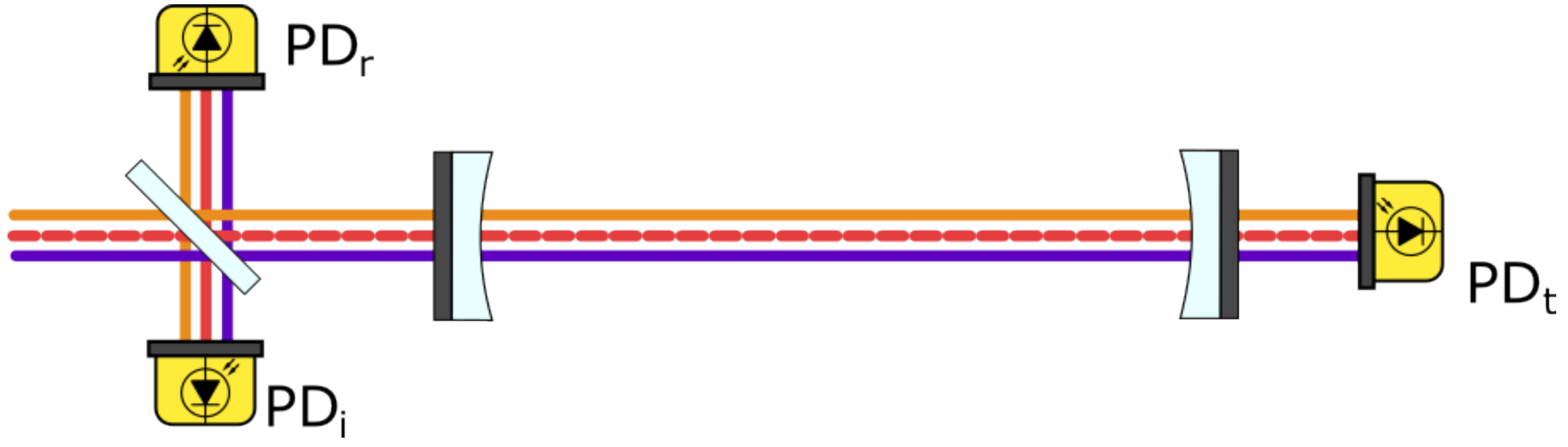
- **Blue:** Two field beat note measurement
- **Orange:** Superposition describing our noise
- **Yellow**: 2-field measurement with noise subtraction

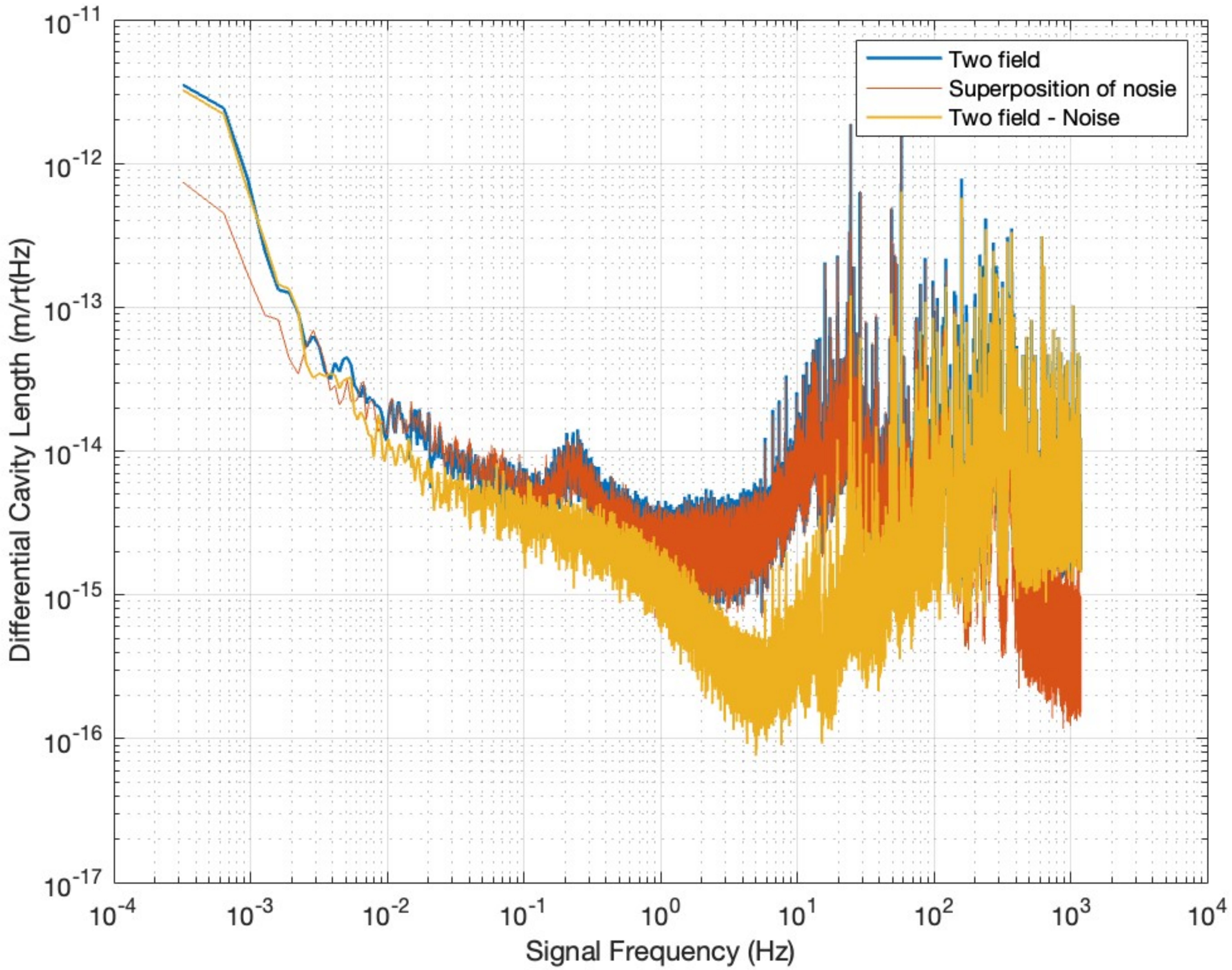


Subtracting Current Noise Floor

Next:

- Bettering our superposition of the noise
- Doing this with 3 fields





Comments on noise suppression

Multi-faceted approach:

- The control noise we are experiencing is a well studied phenomenon

Meaning, we have options

There are different sources & solutions:

- Source: Birefringence in the optics coupling to amplitude noise (RAM) in our locking system
    - Solution: control loops feeding back to EOM's used for frequency stabilization for active feedback of noise
- Source: Scattered light on the optical table
    - Solution: Alignment adjustments, baffles in vacuum system etc

Future Measurements

Future Measurements

For a hypothetical particle search:

- How they couple to our experiment:

  - **Mini Charged Particle's:**
    - Expected to modify the relative scaling of the VMB amplitude
    - Measuring VMB with ALPSII will constrain the MCP parameter space

Future Measurements

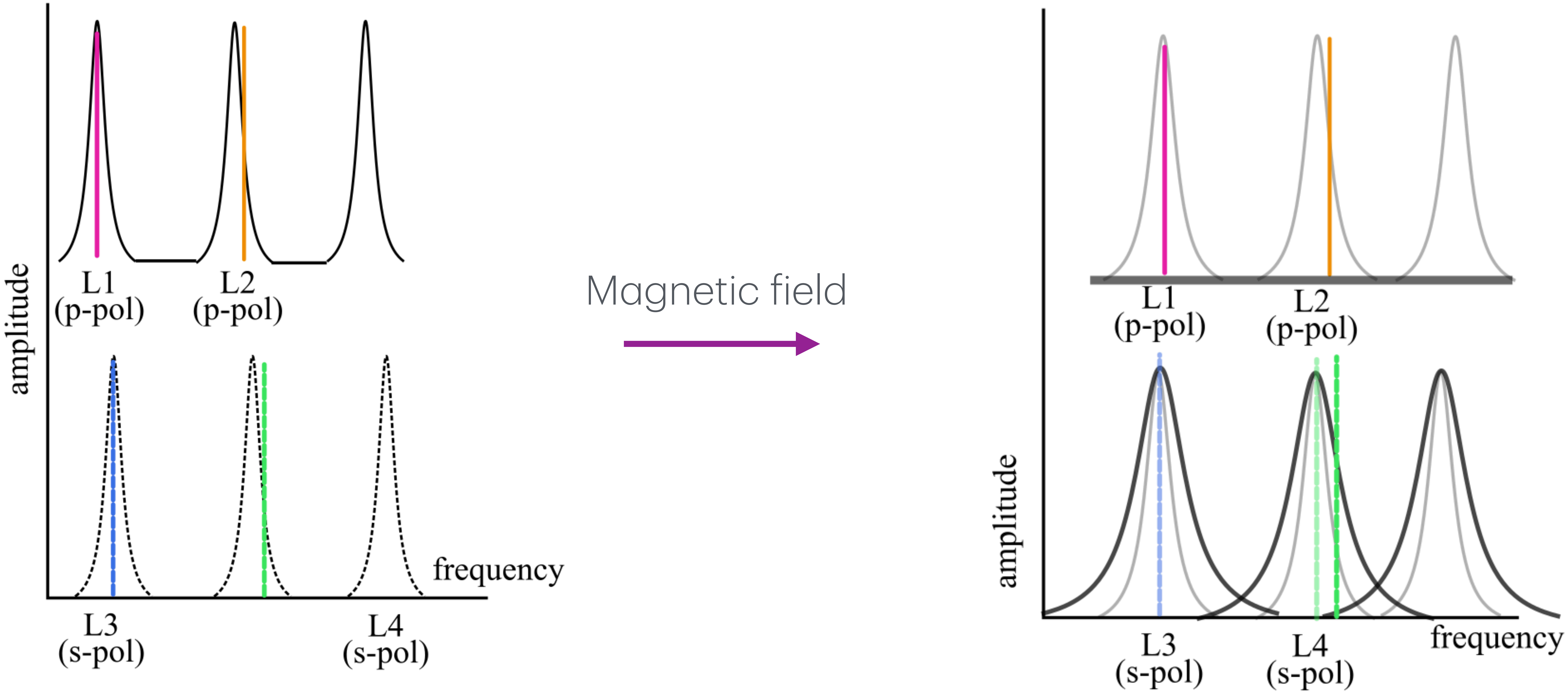
For a hypothetical particle search:

- How they couple to our experiment:

- **Mini Charged Particle's:**
  - Expected to modify the relative scaling of the VMB amplitude
  - Measuring VMB with ALPSII will constrain the MCP parameter space

- **Axion Like Particles:**
  - Couple to laser and magnetic field
  - Lead to a differential absorption in circulating field propagating through the cavity

Cavity Absorption Measurements:



- An absorption of light due to BSM particles would appear as an cavity loss - changing the HWHM of cavity line width

VMB at ALPS II Timeline

ALPS II (in HERA North)

19 meter Birefringence Lab (in HERA West)

Thank you :)

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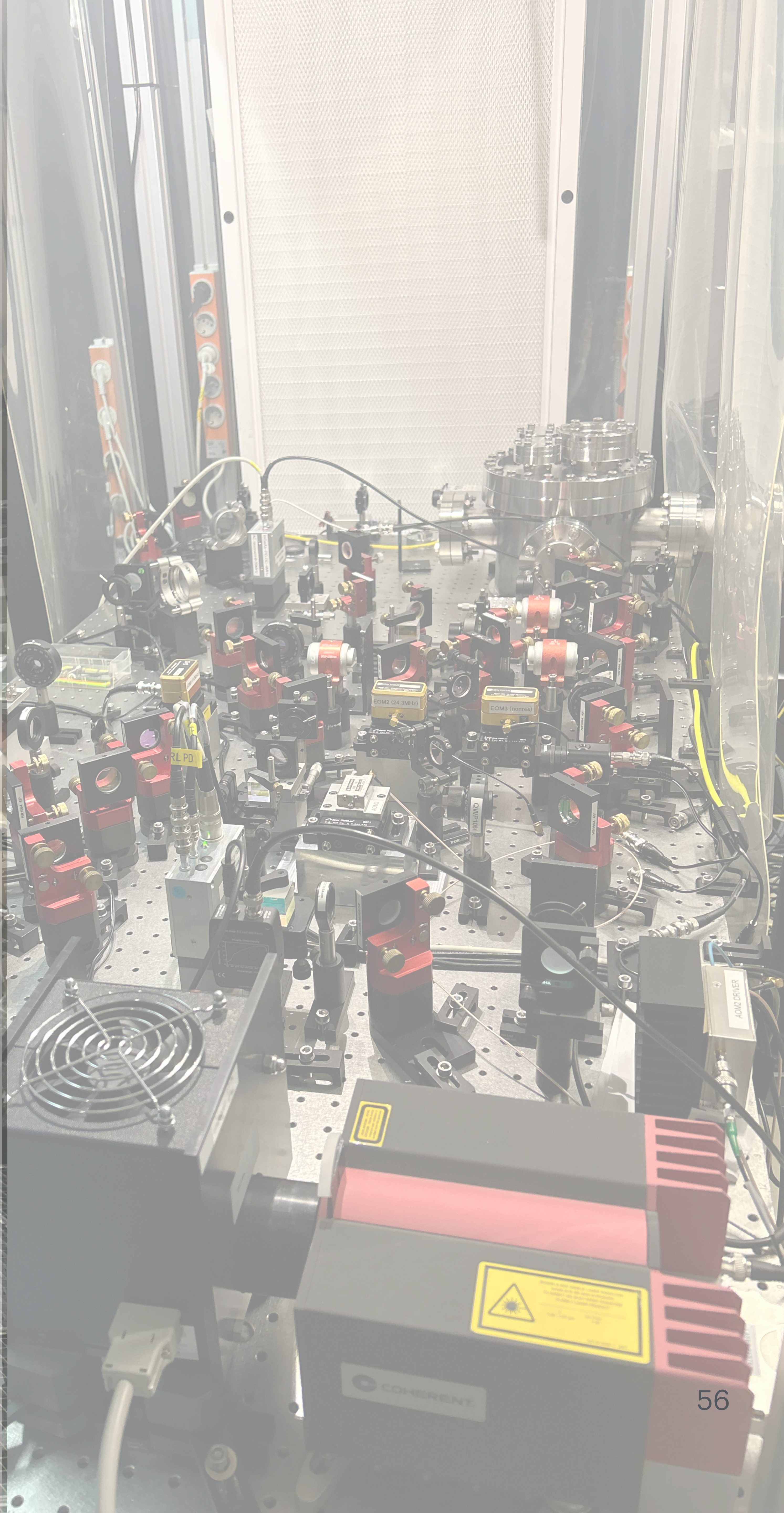
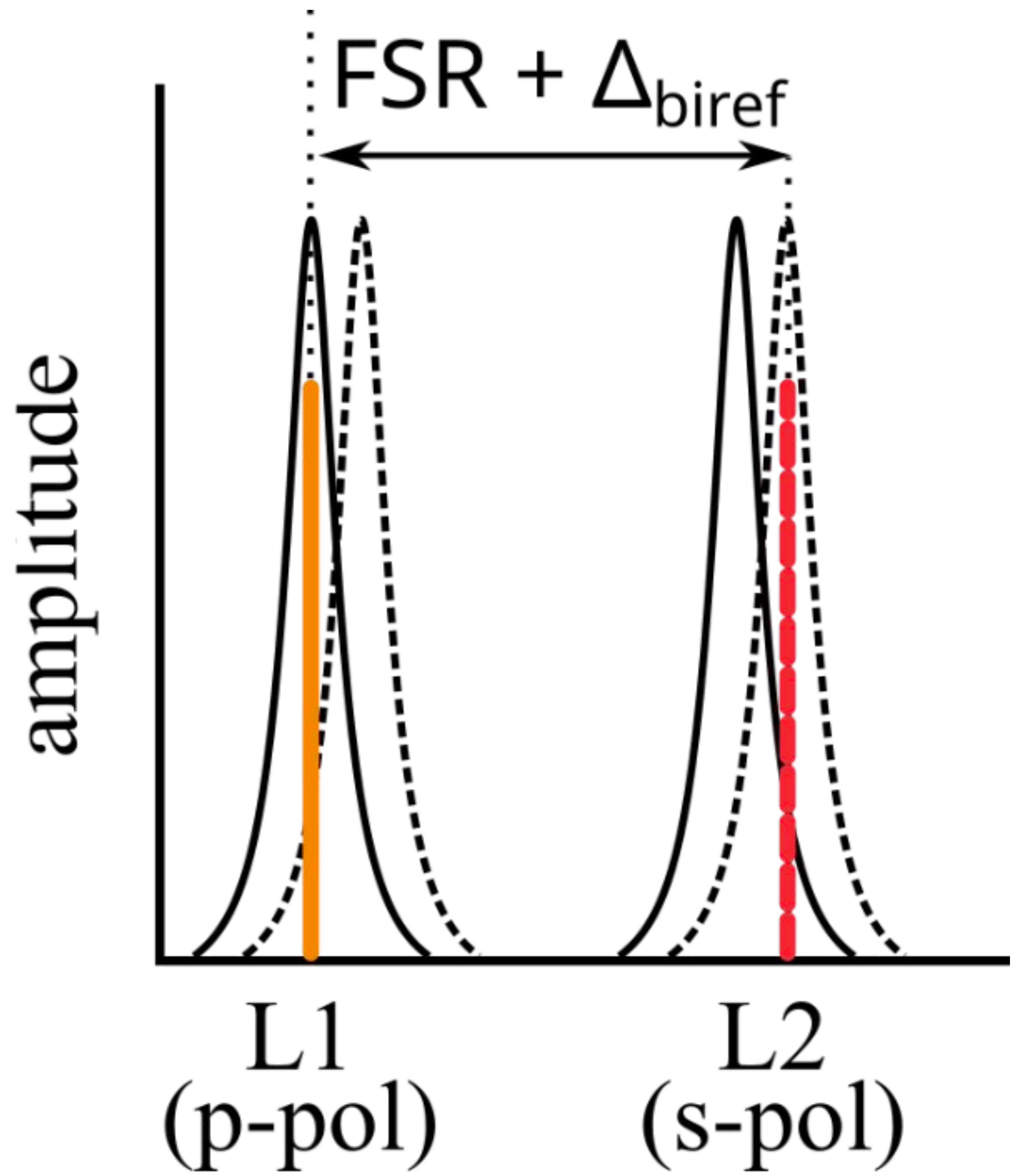
&
laura.roberts@desy.de

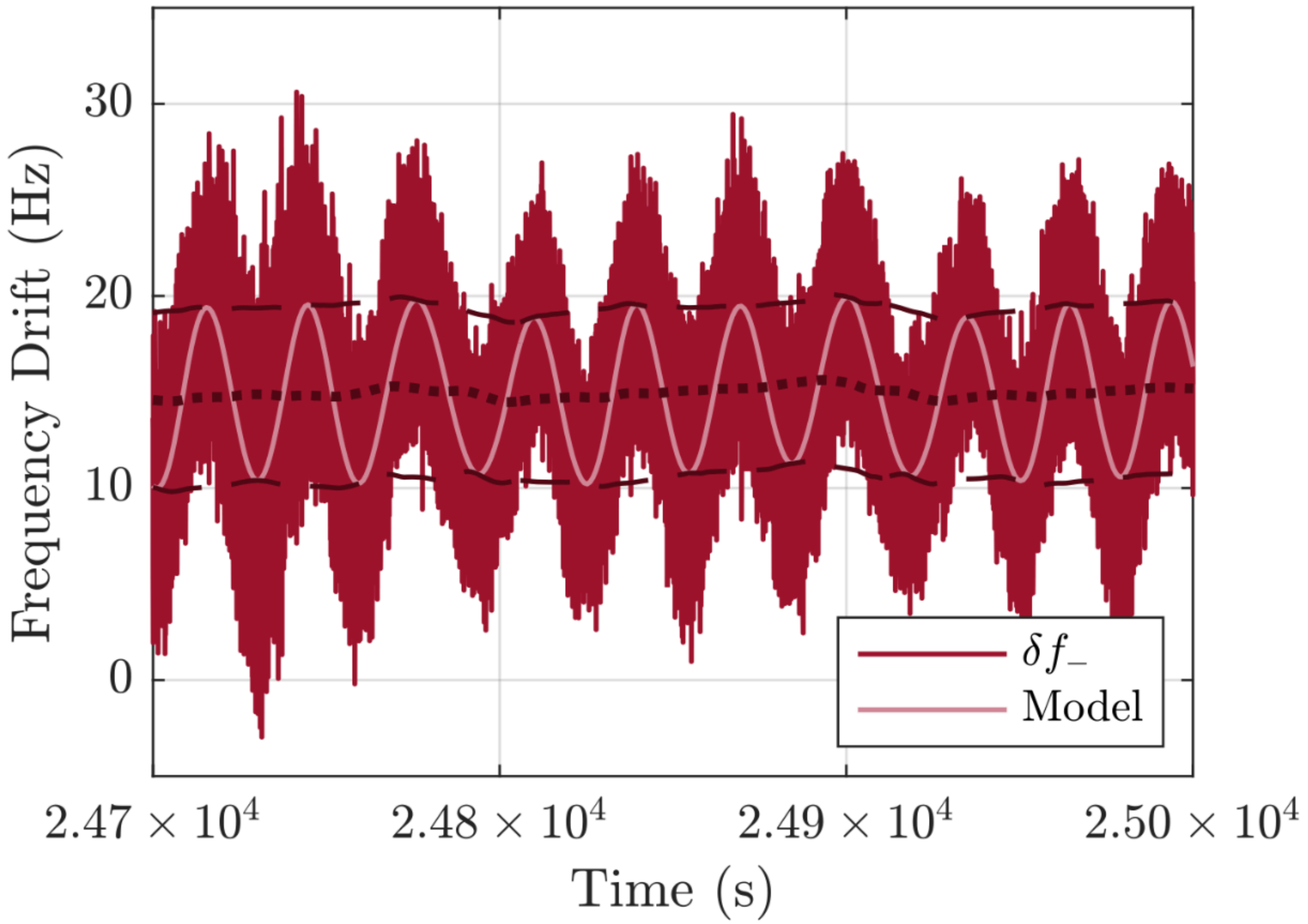


References

- [1] A. Ejlli et al. Physics Reports 871 (2020), pp. 1–74. issn: 0370-1573. url: https://www.sciencedirect.com/science/article/pii/S0370157320302428.
- [2] Zeidler, S., Eisenmann, M., Bazzan, M. *et al.* Correlation between birefringence and absorption mapping in large-size Sapphire substrates for gravitational-wave interferometry. *Sci Rep* **13**, 21393 (2023). https://doi.org/10.1038/s41598-023-45928-0
- [3]John L Hall et al. Physical Review A 62.1 (2000), p. 013815
- [4] Aaron D. Spector et al. 2025. arXiv: 2510.14064 [physics.optics]. url: https://arxiv.org/abs/2510.14064

Static Birefringence Measurement





(a) Oscillations in δf_{-} while rotating HWP

Here: $\Delta_{bf} = 8Hz$

Cavity Birefringence Noise

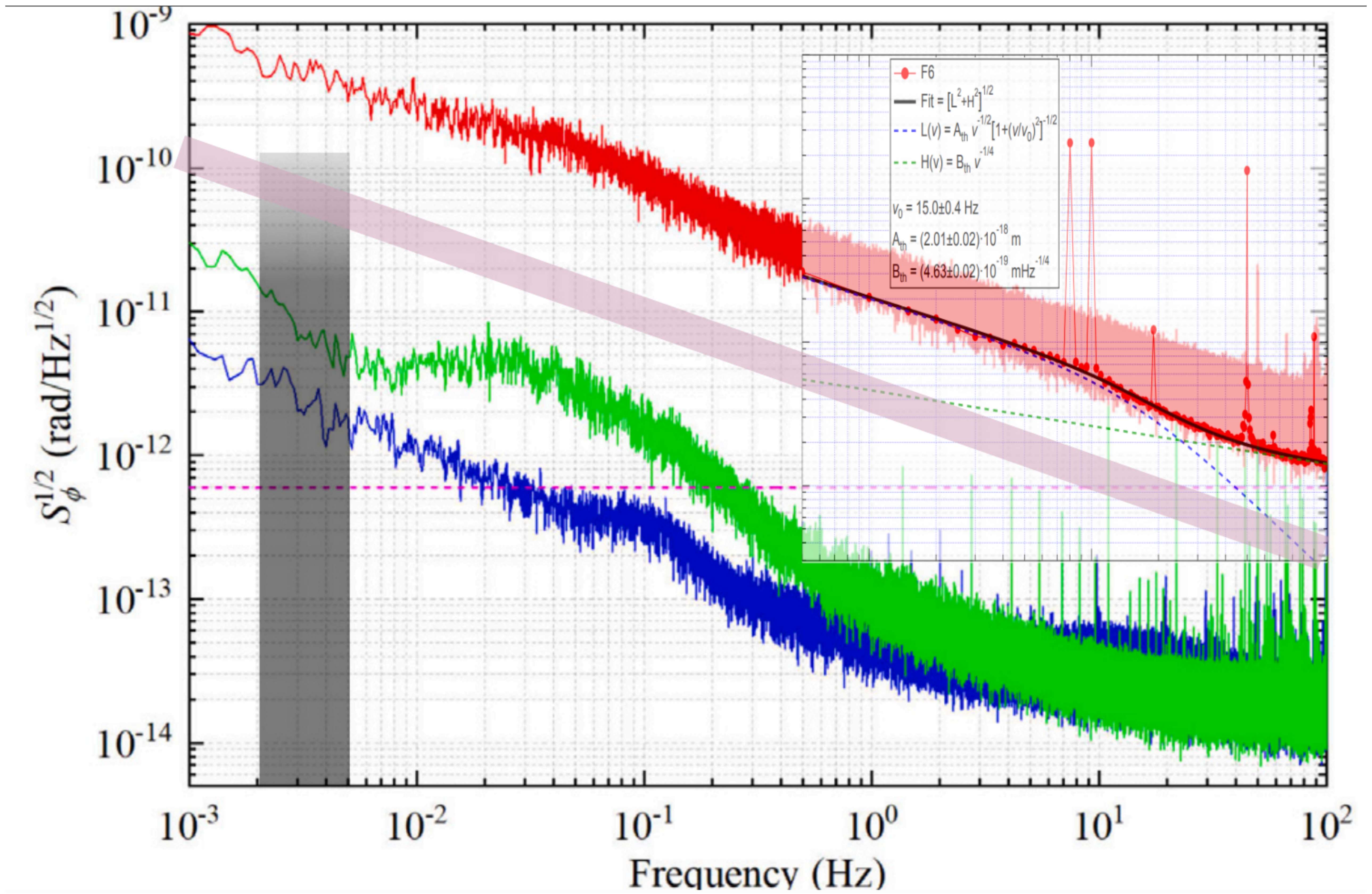


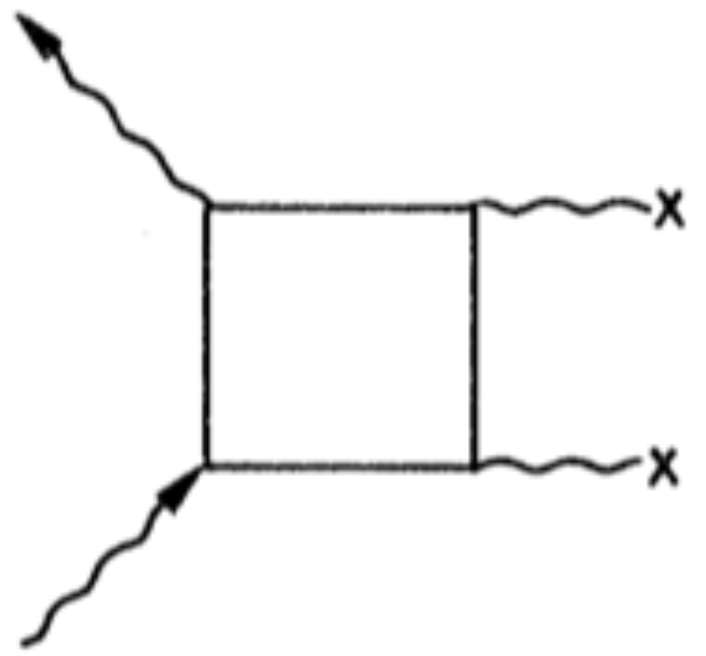
Figure: projection of ALPS signal and cavity BF noise

Credits: Todd Kozlowski

Introduction

How does quantum electrodynamics manifest?

Delbrück Scattering:



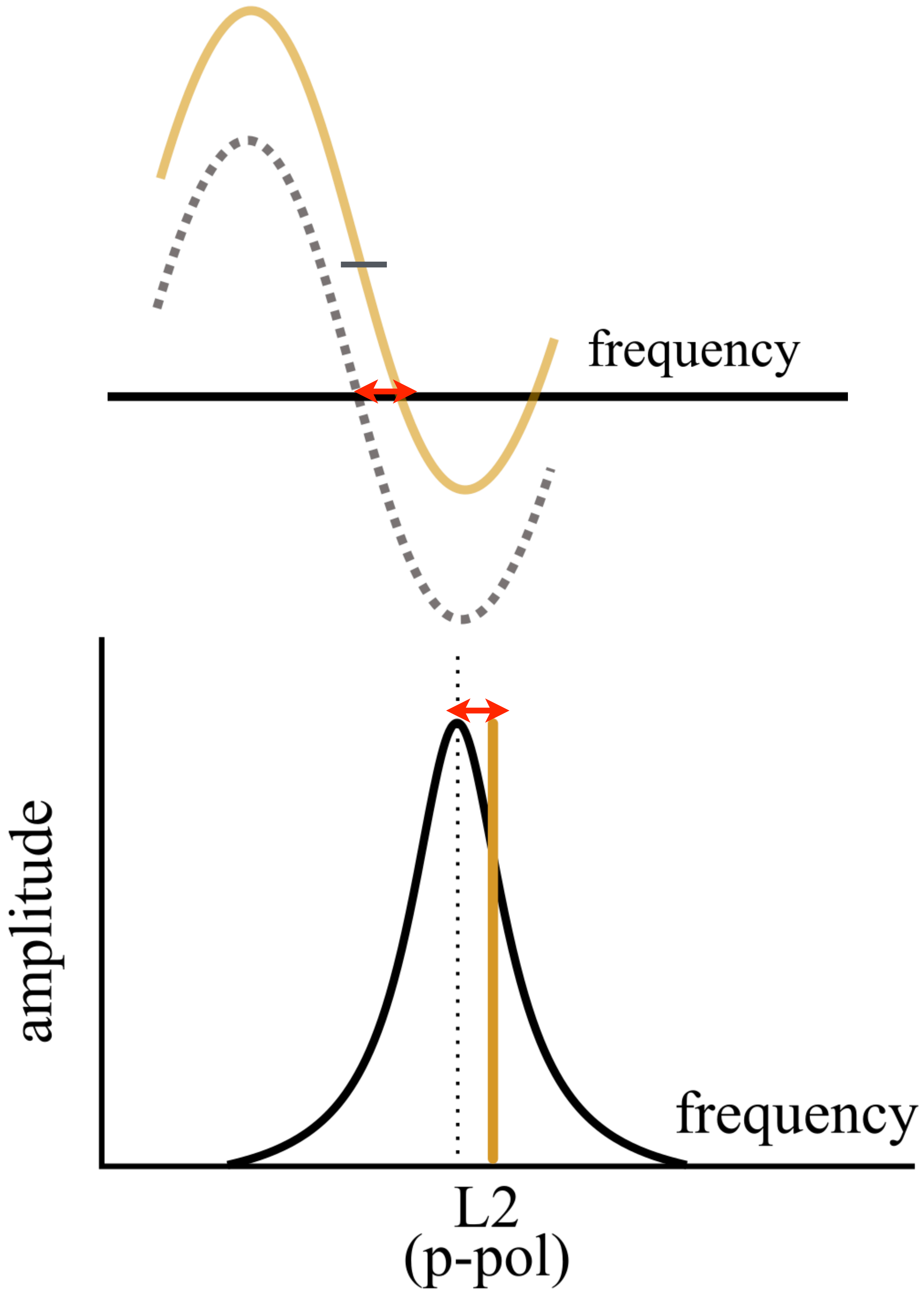
- Scattering of photons in the Coulomb field of nuclei via virtual electron-positron pairs
- First observation was achieved in a high-energy, small angle photon scattering experiment carried out at DESY in 1973

Others

- Muon g-2 experiment
- Lamb shift
- Casimir shift

Subtracting Current Noise Floor

- Out of loop noise couples to the offset of the error signals used to lock the individual fields
    - Leads to relative frequency noise with respect to the cavity resonance
- **Sources**:
    - Residual amplitude modulation
    - Scattered light



Cavity Absorption measurements

- Maybe a mild mention of how we plan to measure things that Felix talked abt: axion DM searches, mini charged particles
- A similar measurement scheme, but instead locking to the center of the cavity resonance were lock to the HWHM of the resonance and then changes in frequency are related to changes in the cavity losses which we can relate to differential absorption to dark sector physics

Cavity Birefringence Measurements

- Static and dynamic birefringence measurements

- What we do, results
- Projections of what we expect on 20m cavity
- Mention that reaching this level is actually our goal for the prototype

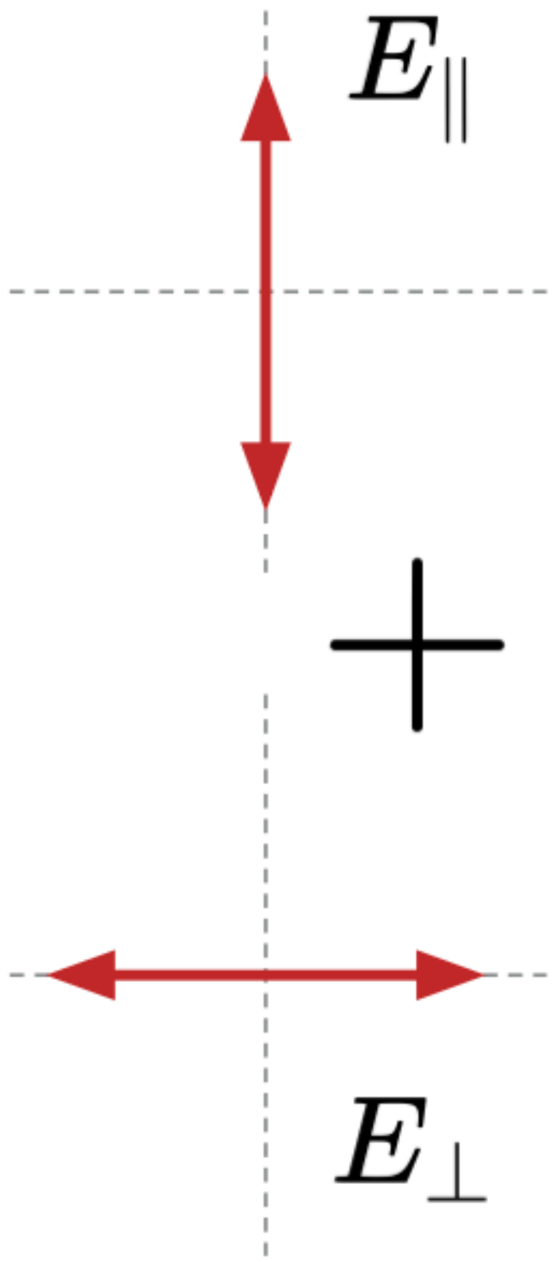
Measuring VMB

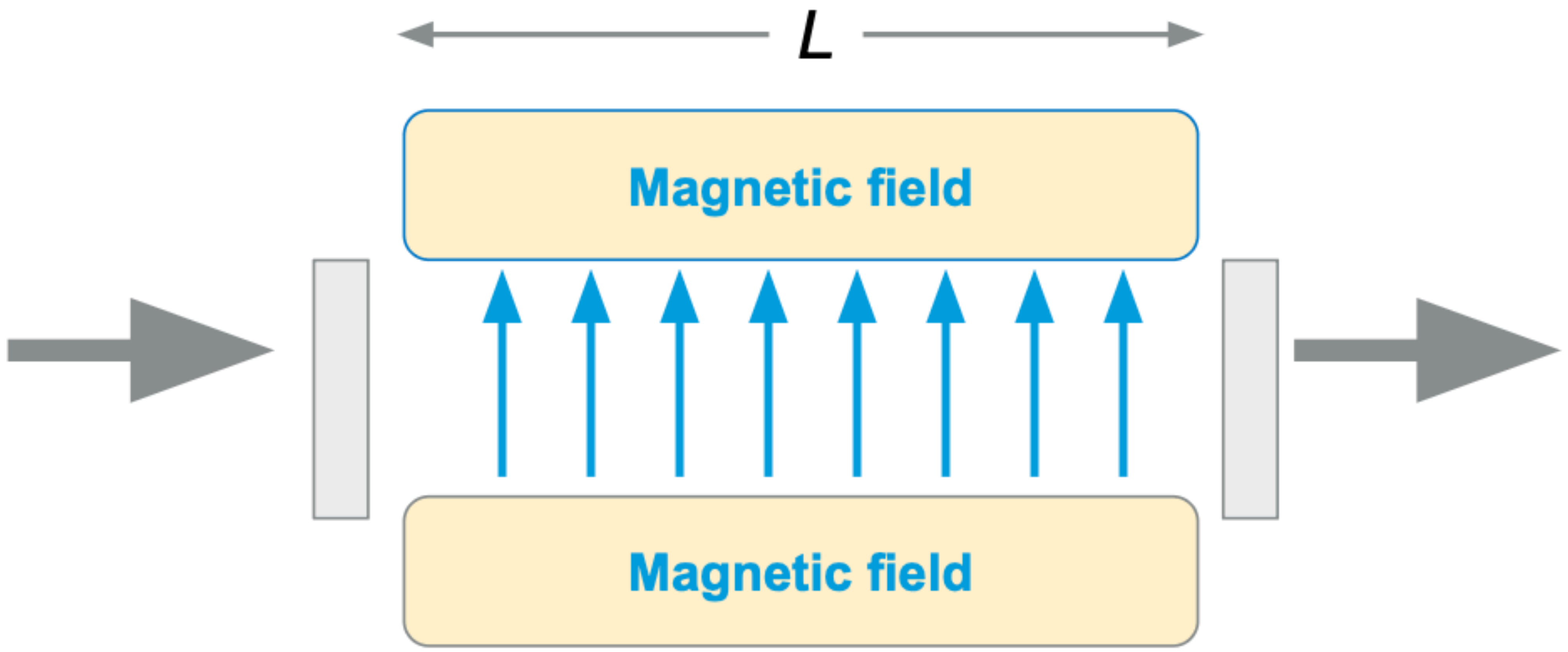
Generating VMB:

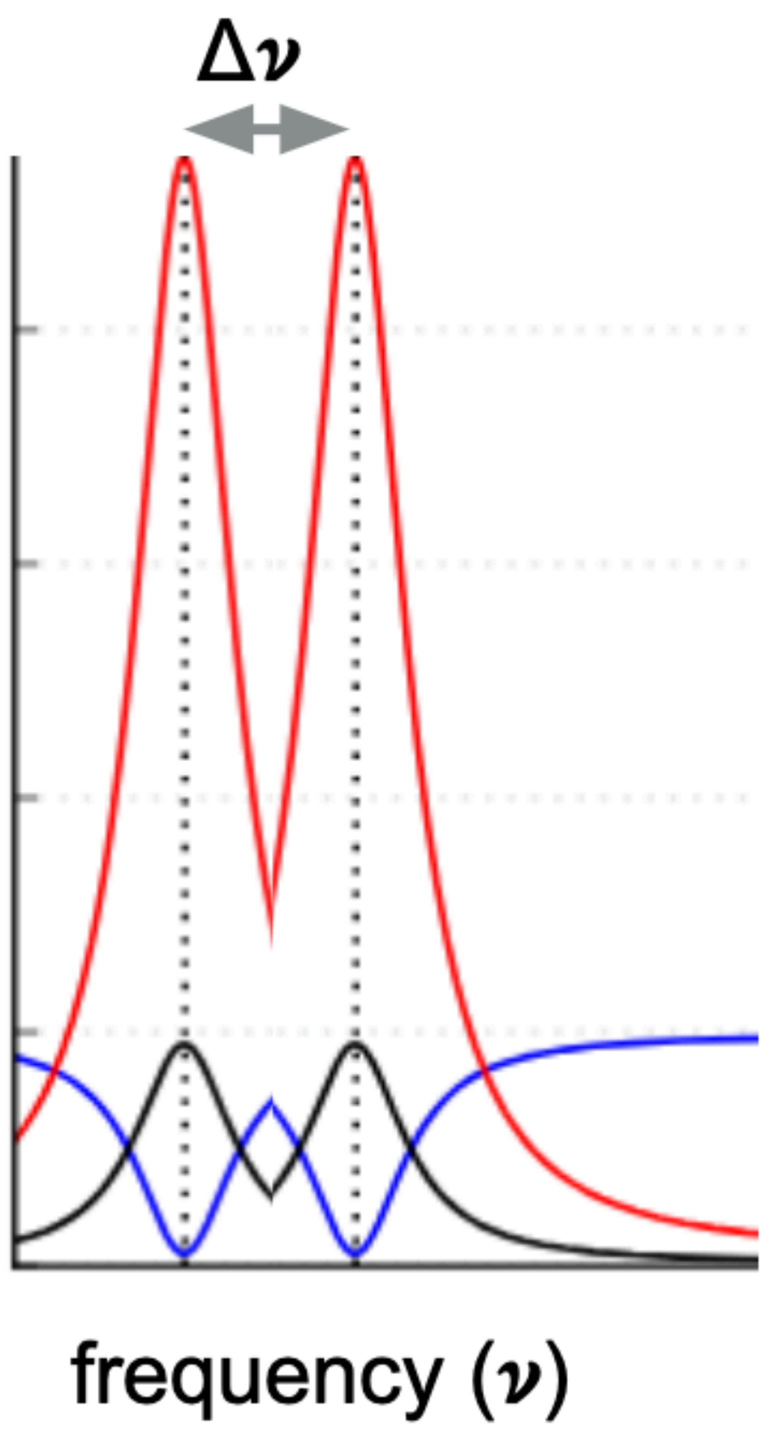
$$\Delta n_{vmb} = n_{\parallel}^{VMB} - n_{\perp}^{VMB} \approx 3.96 \times 10^{-24} \times B^2$$

Measuring VMB:

Interferometric:







$$\nu_{\parallel} = N \times \nu_{\mathrm{FSR},\parallel} = N \times \frac{c}{2L_{\parallel}}$$

$$\nu_{\perp} = N \times \nu_{\mathrm{FSR},\perp} = N \times \frac{c}{2L_{\perp}}$$