
# Towards a Measurement of the Vacuum Magnetic Birefringence in ALPS II

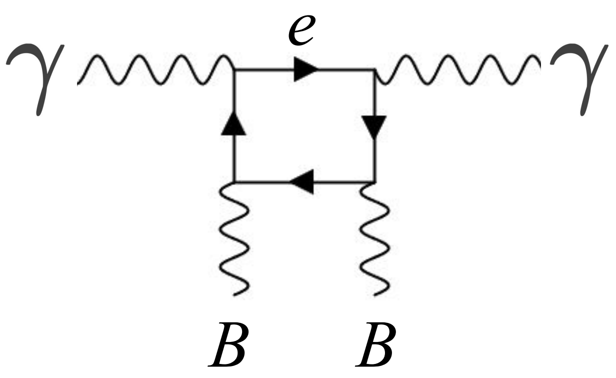
**Todd Kozlowski**, Aaron Spector, Laura Roberts

20th Patras Workshop, Tenerife

# Physics motivation

## 90 year old prediction of QED

- the result of light-by-light scattering, nonlinear corrections:
- **Euler-Heisenberg-Kockel Lagrangian**:




$$\mathcal{L}_{\mathrm{EH}} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{C_1}{\mu_0^2}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c}\cdot\vec{B}\right)^2\right]$$

H. Euler und B. Kockel, „Über die Streuung von Licht an Licht nach Diracs Theorie“, *Naturwissenschaften*, Bd. 23, 1935.

$$A_e \equiv \frac{1}{\mu_0} C_1 = 1.32 \times 10^{-24}\,\mathrm{T}^{-2}$$

$$\Delta n^{(\mathrm{VMB})} = n_{\parallel}^{(\mathrm{VMB})} - n_{\perp}^{(\mathrm{VMB})} = 3 A_e B_{\mathrm{ext}}^2$$

“The light in its passage through the electromagnetic fields will thus behave as if the vacuum took on a dielectric constant that differs from unity as a result of the action of the fields.” - V. Weisskopf, 1936

# Physics motivation

## Potential portal for testing new physics

### Test of alternative models of QED

- The **Born-Infeld model** predicts the absence of vacuum magnetic birefringence, providing an opportunity to definitely test the model

J. Math. Phys. 65, 012302 (2024); doi: 10.1063/5.0150790

### Experimental test of string theory

- ‘Minicharged particles’ predicted by many models of string theory modify the vacuum magnetic birefringence and introduce dichroism, providing a potential direct test [3]

J. Phys. Let. B 666, 66-70 (2008)
doi: 10.1016/j.physletb.2008.03.076

### A probe of the dark sector

- Photon mixing with the ‘dark sector’ neutrinos contributes to the overall VMB effect, making a precision measurement an effective probe

Prog. Theor. Exp. Phys. 2018 6 (2018); doi: 10.1093/ptep/pty059

**Would be the first laboratory observation of macroscopic nonlinear electrodynamics,** complementary to other DESY efforts to better understand the quantum vacuum.

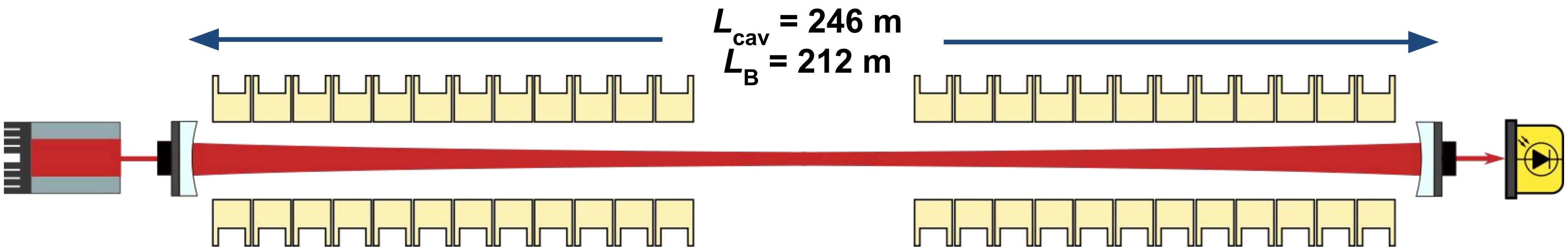
LUXE: https://doi.org/10.48550/arXiv.2205.06096
HED-HIBEF: https://doi.org/10.1017/hpl.2024.70

# VMB in the ALPS II infrastructure

$$\Delta n^{(\mathrm{VMB})} = n_{\parallel}^{(\mathrm{VMB})} - n_{\perp}^{(\mathrm{VMB})} = 3A_e B_{\mathrm{ext}}^2$$

$$\Delta L^{(\mathrm{VMB})} = \Delta n^{(\mathrm{VMB})} \cdot L_B$$

$$\propto B_{\mathrm{ext}}^2 \cdot L_B$$




$$B_{\mathrm{ext}}^2 \cdot L \approx 6,000$$

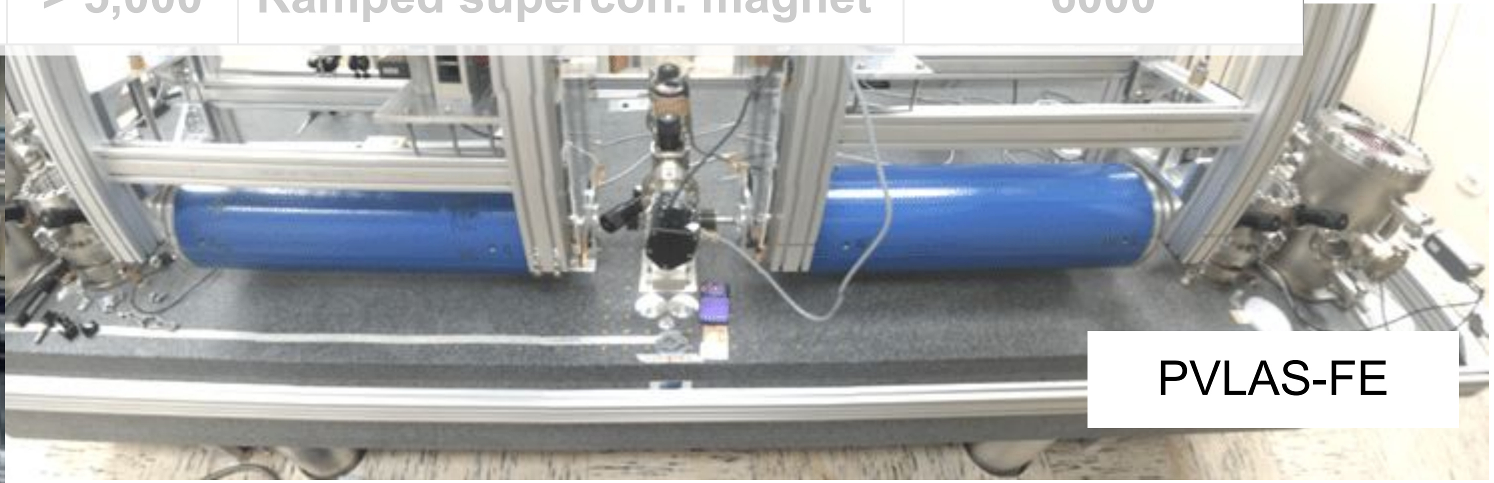
**Relative path-length difference:**

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

# VMB in the ALPS II infrastructure

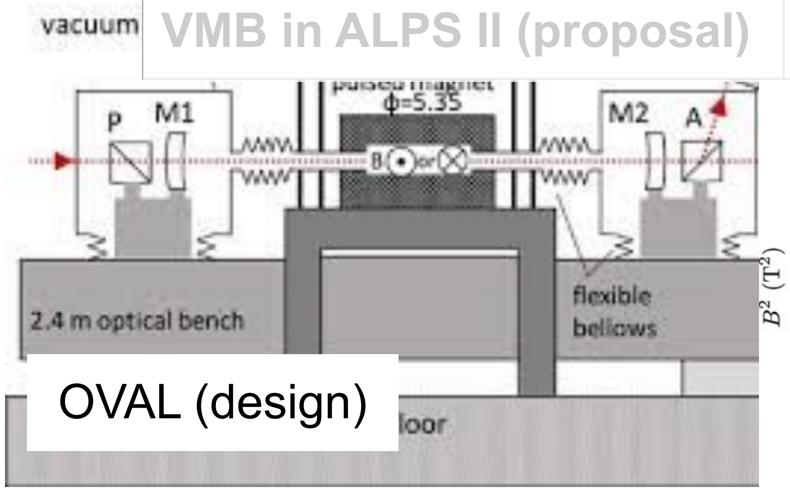
| Experiment | $L_B$ [m] | $N$ | Modulation | $\int B^2_{ext} dL$ [$T^2$ m] |
|---|---|---|---|---|
| PVLAS-LNL (2008) | 0.5 | 100,000 | Rotating supercon. magnet | 2.6 |
| PVLAS-FE (2016) | 1.64 | 446,000 | Rotating permanent magnet | 10.3 |
| OVAL (2017) | 0.17 | 200,000 | Pulsed magnet | 13.8 |
| BMV (2019) | 0.31 | 270,000 | Pulsed magnet | 100 |
| VMB@CERN (proposal) | 14.3 | ~1,600 | Rotating half-waveplates | 1290 |
| **VMB in ALPS II (proposal)** | **212** | **> 5,000** | **Ramped supercon. magnet** | **6000** |


PVLAS-LNL

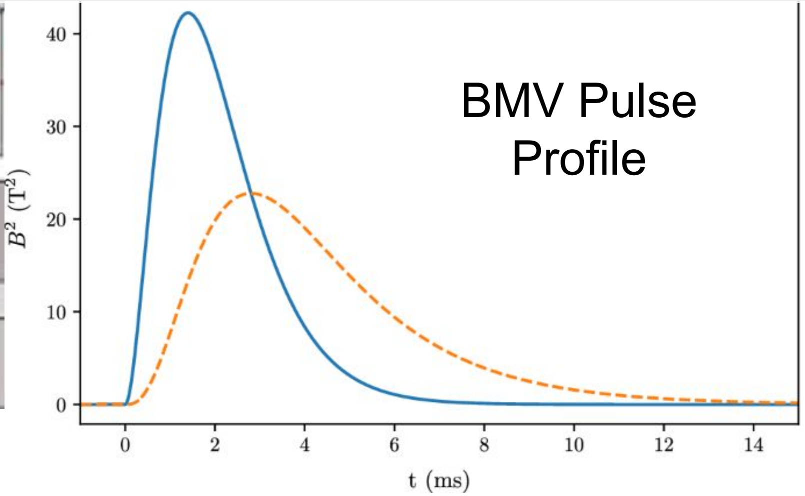

PVLAS-FE

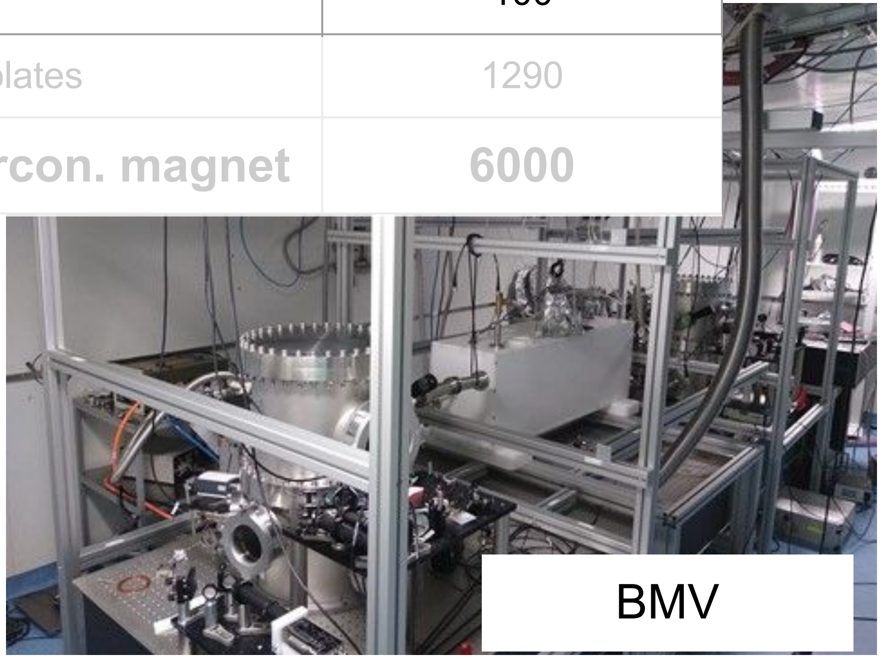
# VMB in the ALPS II infrastructure

| Experiment | $L_B$ [m] | $N$ | Modulation | $\int B^2_{ext} dL$ [T² m] |
|---|---|---|---|---|
| PVLAS-LNL (2008) | 0.5 | 100,000 | Rotating supercon. magnet | 2.6 |
| PVLAS-FE (2016) | 1.64 | 446,000 | Rotating permanent magnet | 10.3 |
| OVAL (2017) | 0.17 | 200,000 | Pulsed magnet | 13.8 |
| BMV (2019) | 0.31 | 270,000 | Pulsed magnet | 100 |
| VMB@CERN (proposal) | 14.3 | ~1,600 | Rotating half-waveplates | 1290 |
| **VMB in ALPS II (proposal)** | **212** | **> 5,000** | **Ramped supercon. magnet** | **6000** |



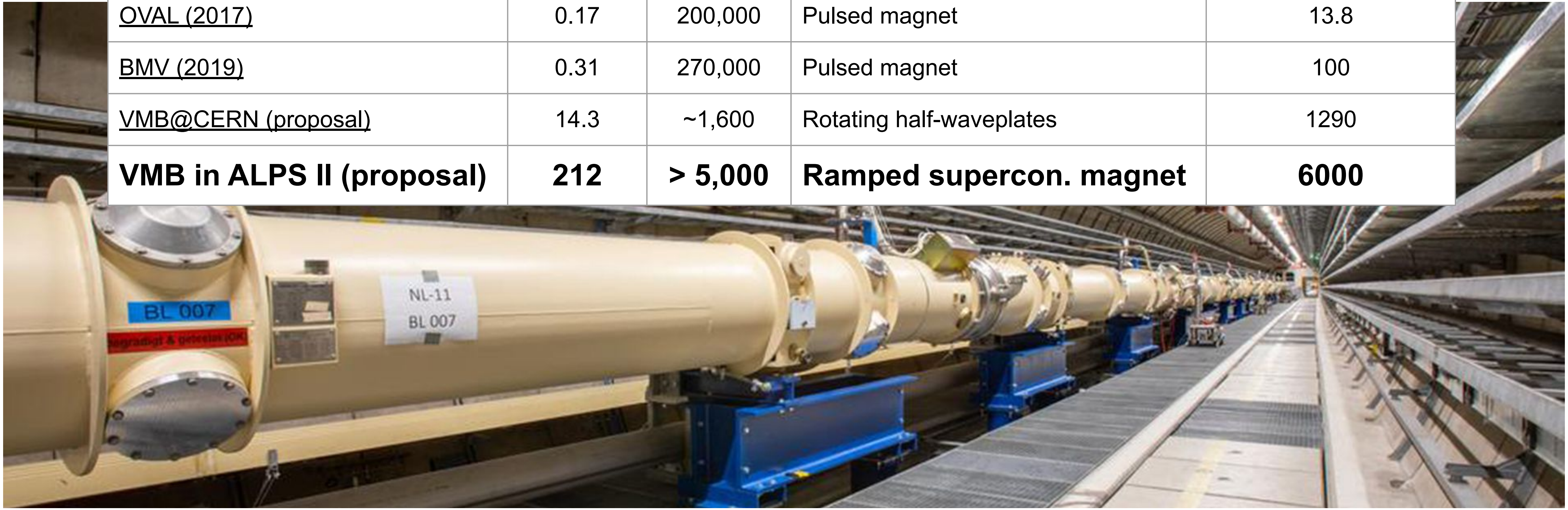
OVAL (design)





BMV

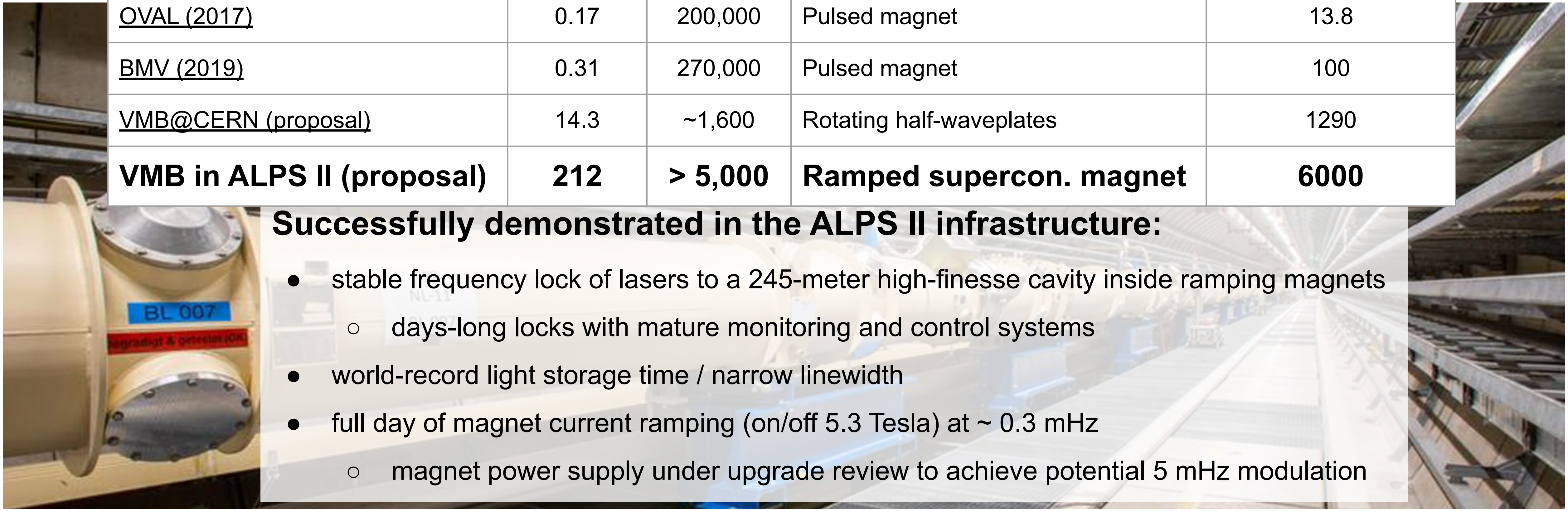
# VMB in the ALPS II infrastructure

| 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 |
| PVLAS-FE (2016) | 1.64 | 446,000 | Rotating permanent magnet | 10.3 |
| OVAL (2017) | 0.17 | 200,000 | Pulsed magnet | 13.8 |
| BMV (2019) | 0.31 | 270,000 | Pulsed magnet | 100 |
| VMB@CERN (proposal) | 14.3 | ~1,600 | Rotating half-waveplates | 1290 |
| **VMB in ALPS II (proposal)** | **212** | **> 5,000** | **Ramped supercon. magnet** | **6000** |



# VMB in the ALPS II infrastructure

| 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 |
| PVLAS-FE (2016) | 1.64 | 446,000 | Rotating permanent magnet | 10.3 |
| OVAL (2017) | 0.17 | 200,000 | Pulsed magnet | 13.8 |
| BMV (2019) | 0.31 | 270,000 | Pulsed magnet | 100 |
| VMB@CERN (proposal) | 14.3 | ~1,600 | Rotating half-waveplates | 1290 |
| **VMB in ALPS II (proposal)** | **212** | **> 5,000** | **Ramped supercon. magnet** | **6000** |

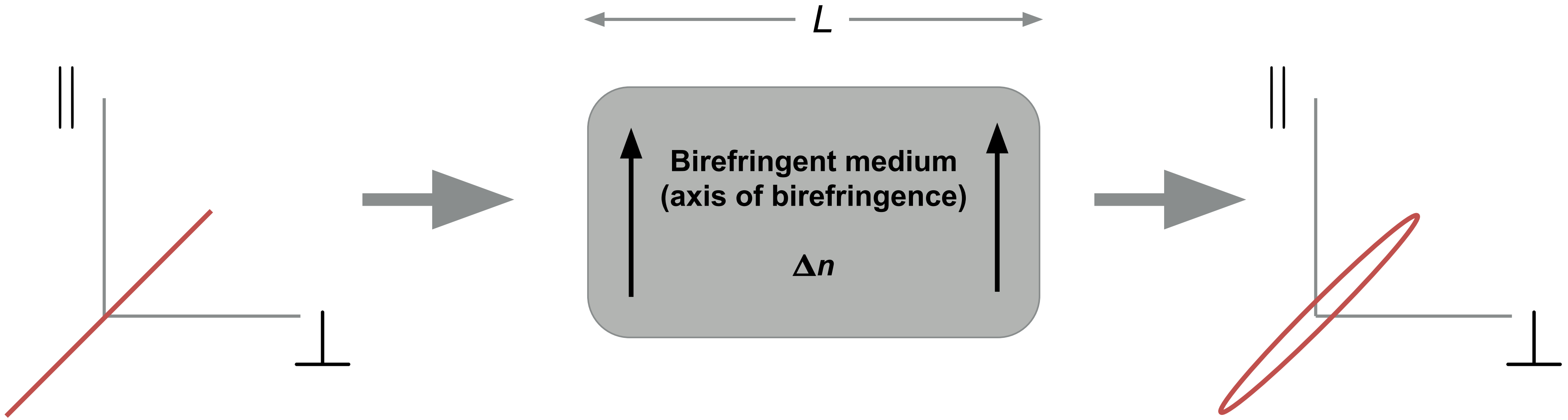



**Successfully demonstrated in the ALPS II infrastructure:**

- stable frequency lock of lasers to a 245-meter high-finesse cavity inside ramping magnets
  - days-long locks with mature monitoring and control systems
- world-record light storage time / narrow linewidth
- full day of magnet current ramping (on/off 5.3 Tesla) at ~ 0.3 mHz
  - magnet power supply under upgrade review to achieve potential 5 mHz modulation

# Experimental probes of the VMB

## Induce polarization ellipticity




Linearly polarized input field

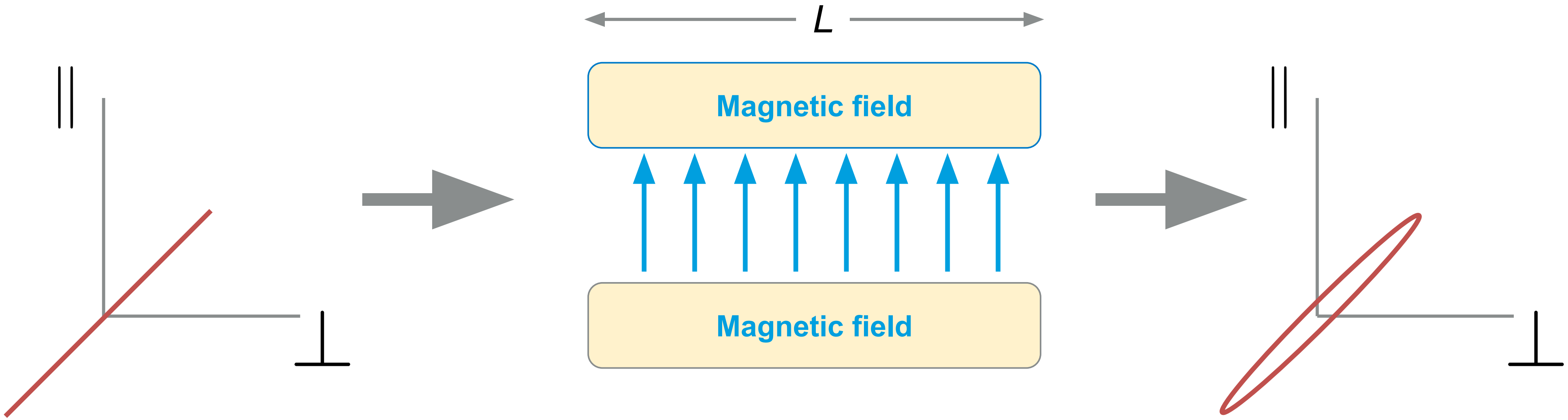
relative phase retardation:

$$\Gamma(L) = \frac{2\pi}{\lambda}\Delta n \cdot L$$

Elliptically polarized output field

# Experimental probes of the VMB

## Induce polarization ellipticity




Linearly polarized input field

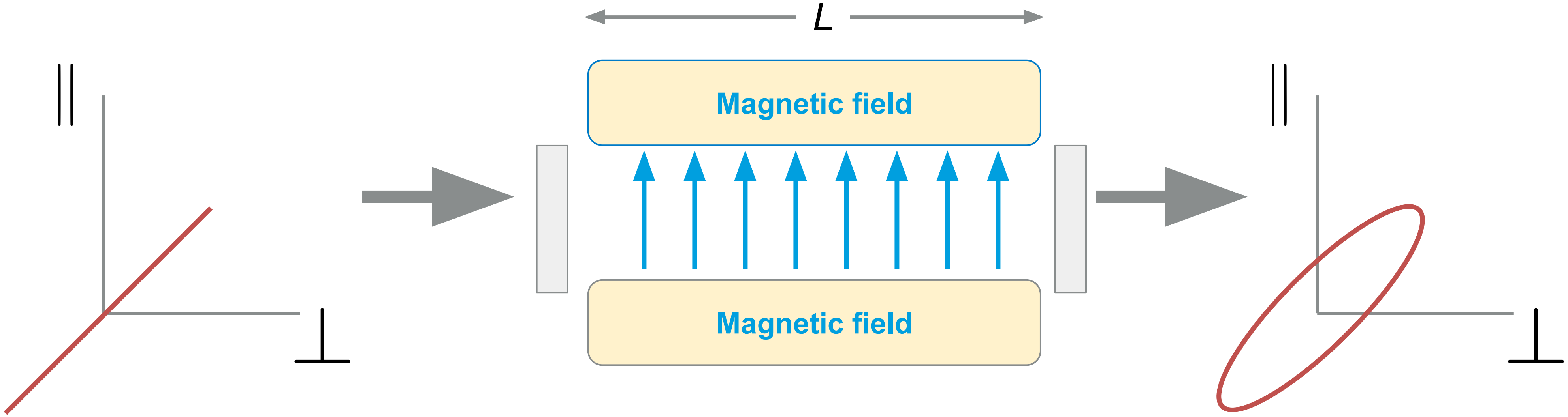
relative phase retardation:

$$\Gamma(L) = \frac{2\pi}{\lambda} 3A_e B_{\text{ext}}^2 \cdot L$$

Elliptically polarized output field

# Experimental probes of the VMB

## Induce polarization ellipticity




Linearly polarized input field

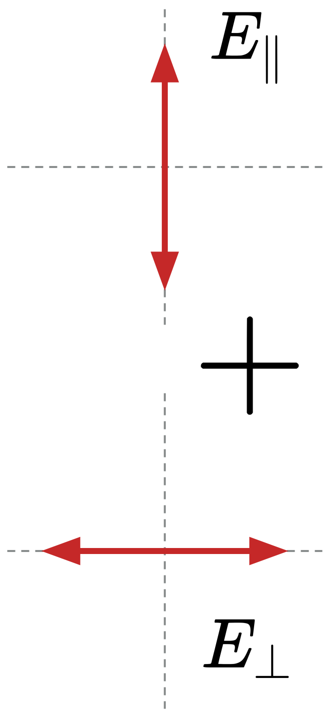
relative phase retardation:

Elliptically polarized output field

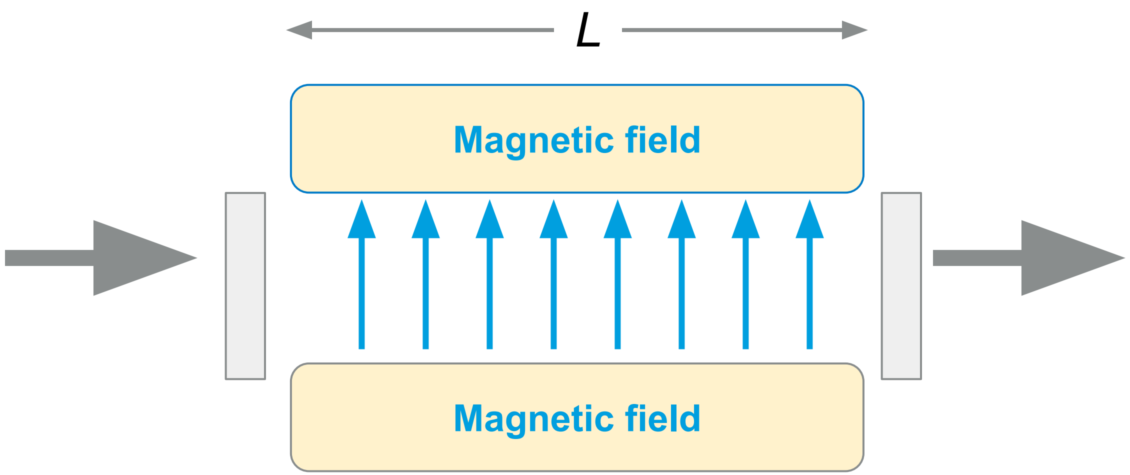
$$\Gamma(L) = \frac{2\pi}{\lambda} 3 A_e B_{\text{ext}}^2 \cdot N \cdot L$$

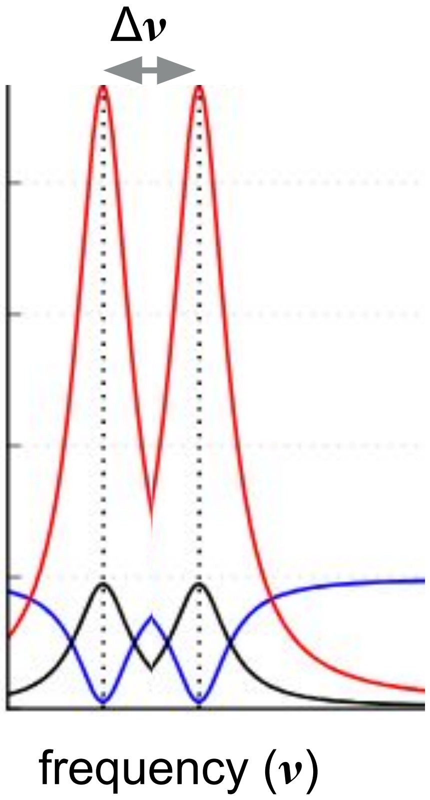
$$N \approx \frac{2 \cdot \mathcal{F}}{\pi} \approx \frac{\tau_{\text{storage}}}{L}$$

## Precision frequency metrology




- round-trip cavity length different for differently polarized fields of light
- can be read out as changes in relative frequency



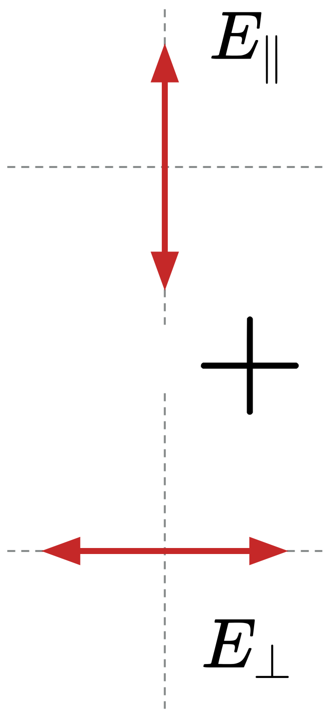

$$\nu_{\parallel} = N \times \nu_{\mathrm{FSR},\parallel} = N \times \frac{c}{2L_{\parallel}}$$

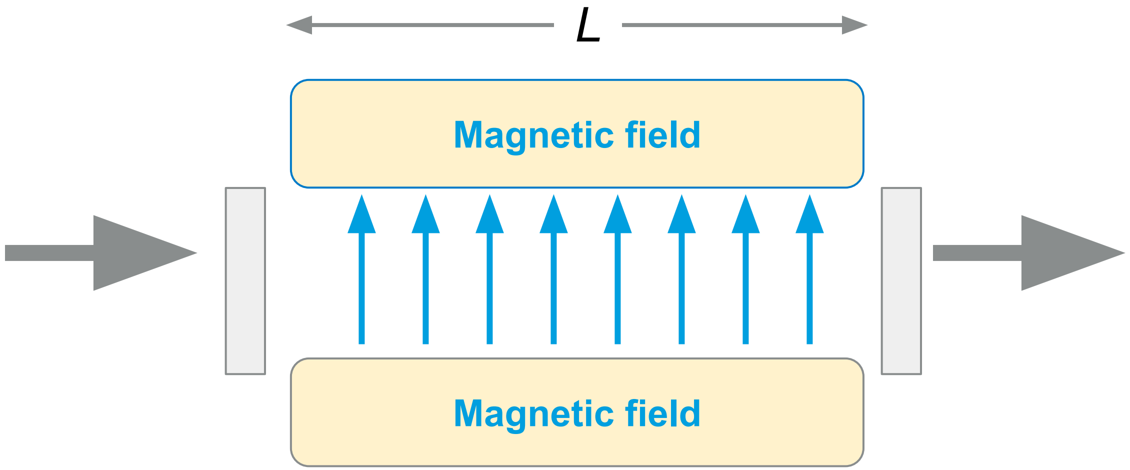
$$\nu_{\perp} = N \times \nu_{\mathrm{FSR},\perp} = N \times \frac{c}{2L_{\perp}}$$

# Experimental probes of the VMB

## Precision frequency metrology

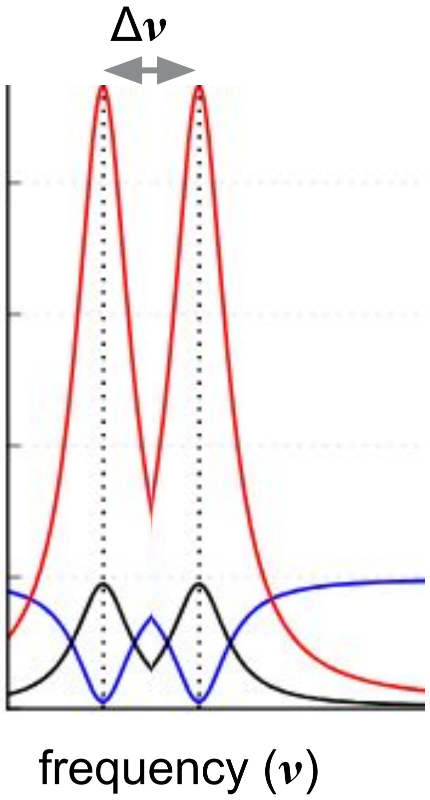
- round-trip cavity length different for differently polarized fields of light
- can be read out as changes in relative frequency




$$\Delta\nu = \frac{\Delta\phi_{\mathrm{rt}}}{2\pi}\nu_{\mathrm{FSR}}$$

$$= \frac{\Delta L}{\lambda_0}\nu_{\mathrm{FSR}}$$



# Experimental probes of the VMB

## Precision frequency metrology

Devised by John L. Hall in 1995 as a test of the VMB:

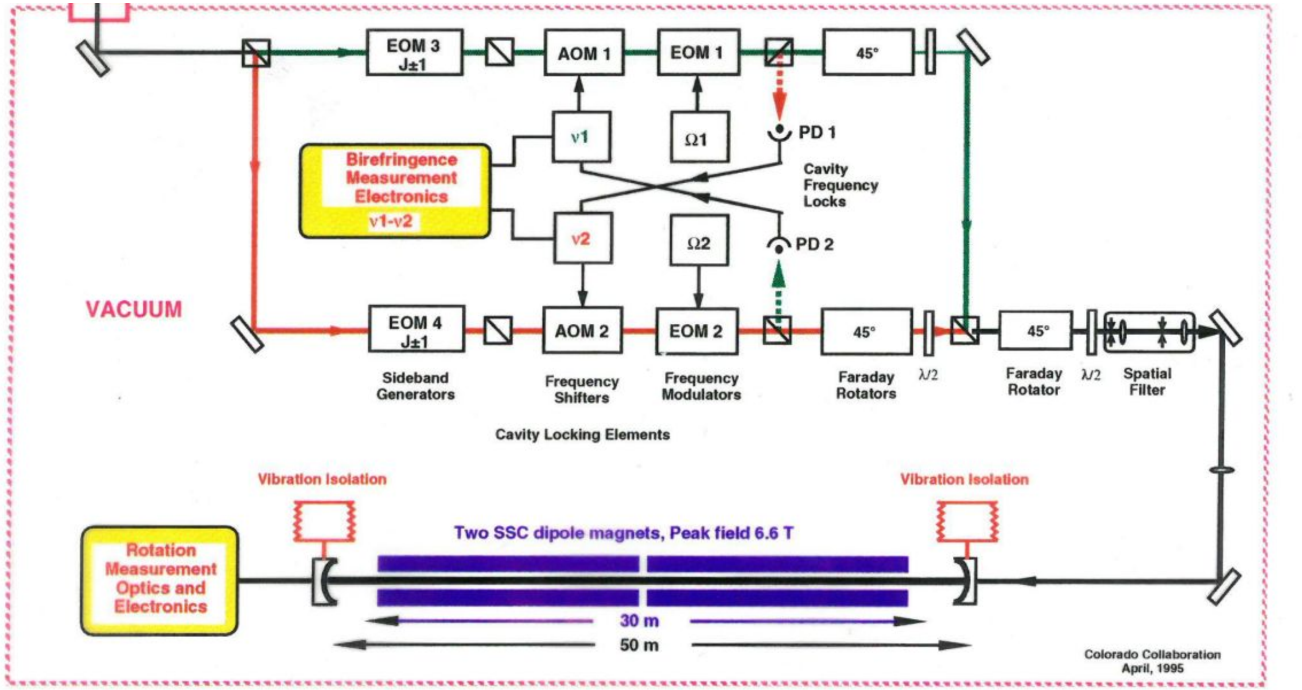
- **experimental principle:**
  - lock two orthogonal polarization states separately to the cavity
  - measure the relative **frequency splitting of two fundamental eigenmodes** caused by birefringence
  - birefringence signal is read out in the difference in the control signals of the two separate polarization state frequency locks
  - original experiment limited by cavity length noise

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)

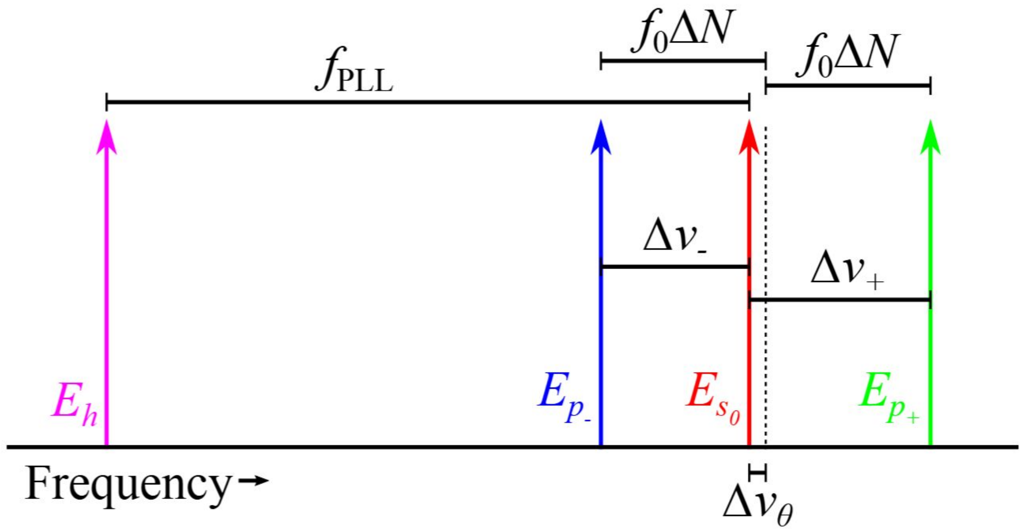
from Siu Au Li at the 2015 DESY VMB workshop (link)



# Experimental probes of the VMB

## Precision frequency metrology with heterodyne readout

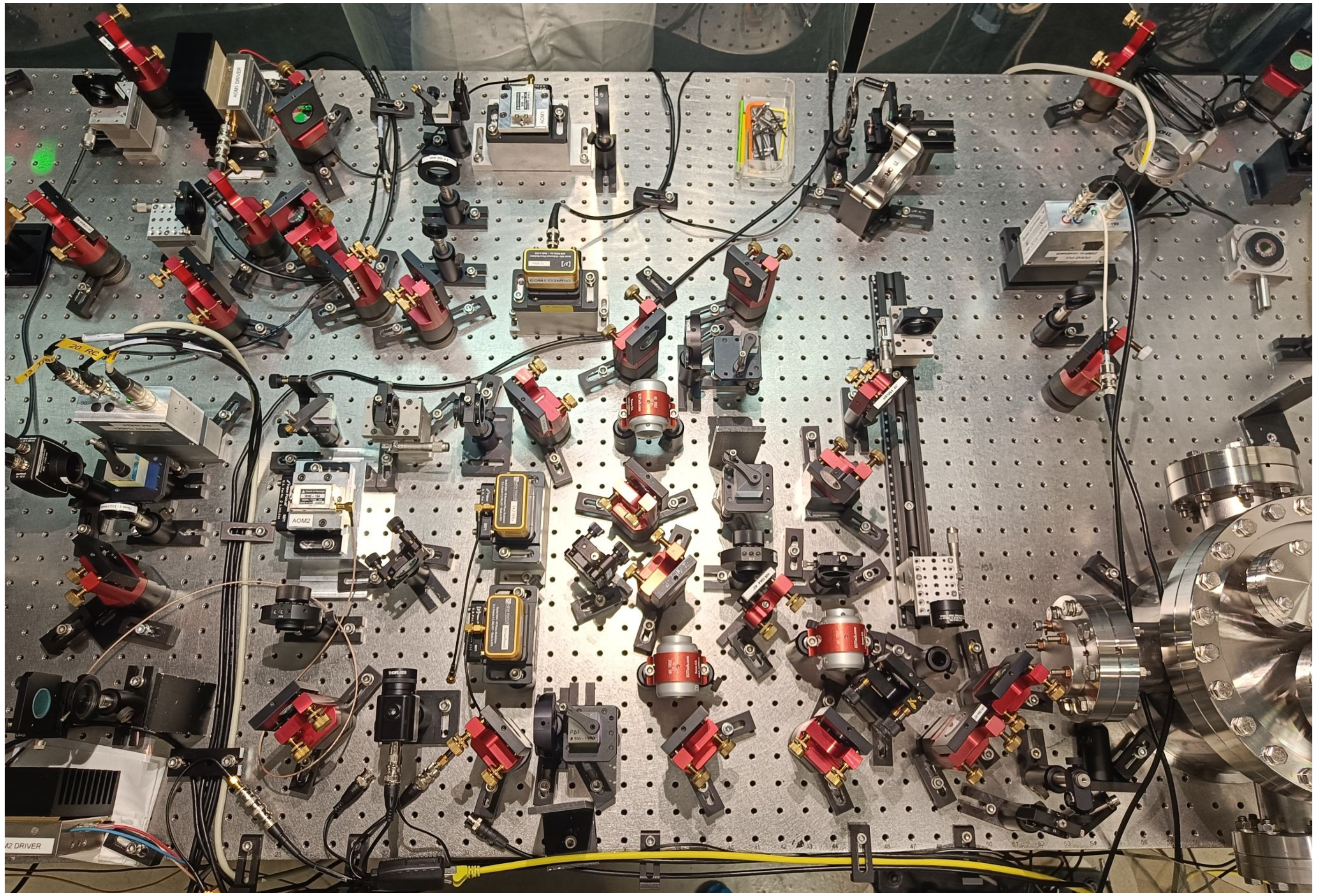
- lock *three fields* to cavity resonance in two orthogonal polarization states
- using an additional heterodyne local oscillator laser, read out the relative frequency differences between the upper and lower fields $E_{p+}$, $E_{p-}$
- a precision phasemeter measures the heterodyne beatnote frequencies, looking for any changes between the frequency of $E_{s0}$ and the "average" of the upper and lower p-polarized fields:




- changes in the absolute cavity length are common to **both beatnotes**, systematically excluded

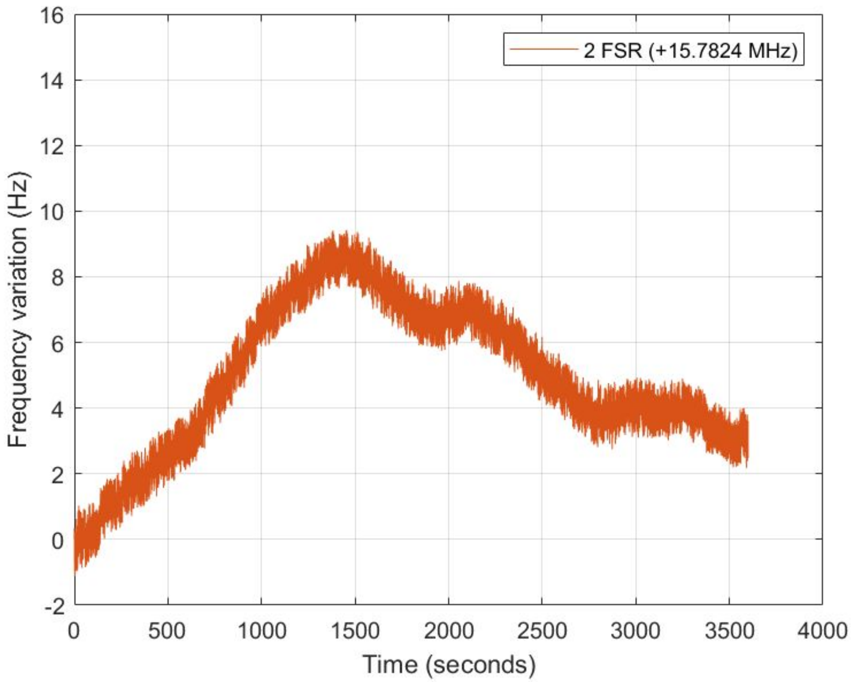
# ALPS 19 m birefringence prototype

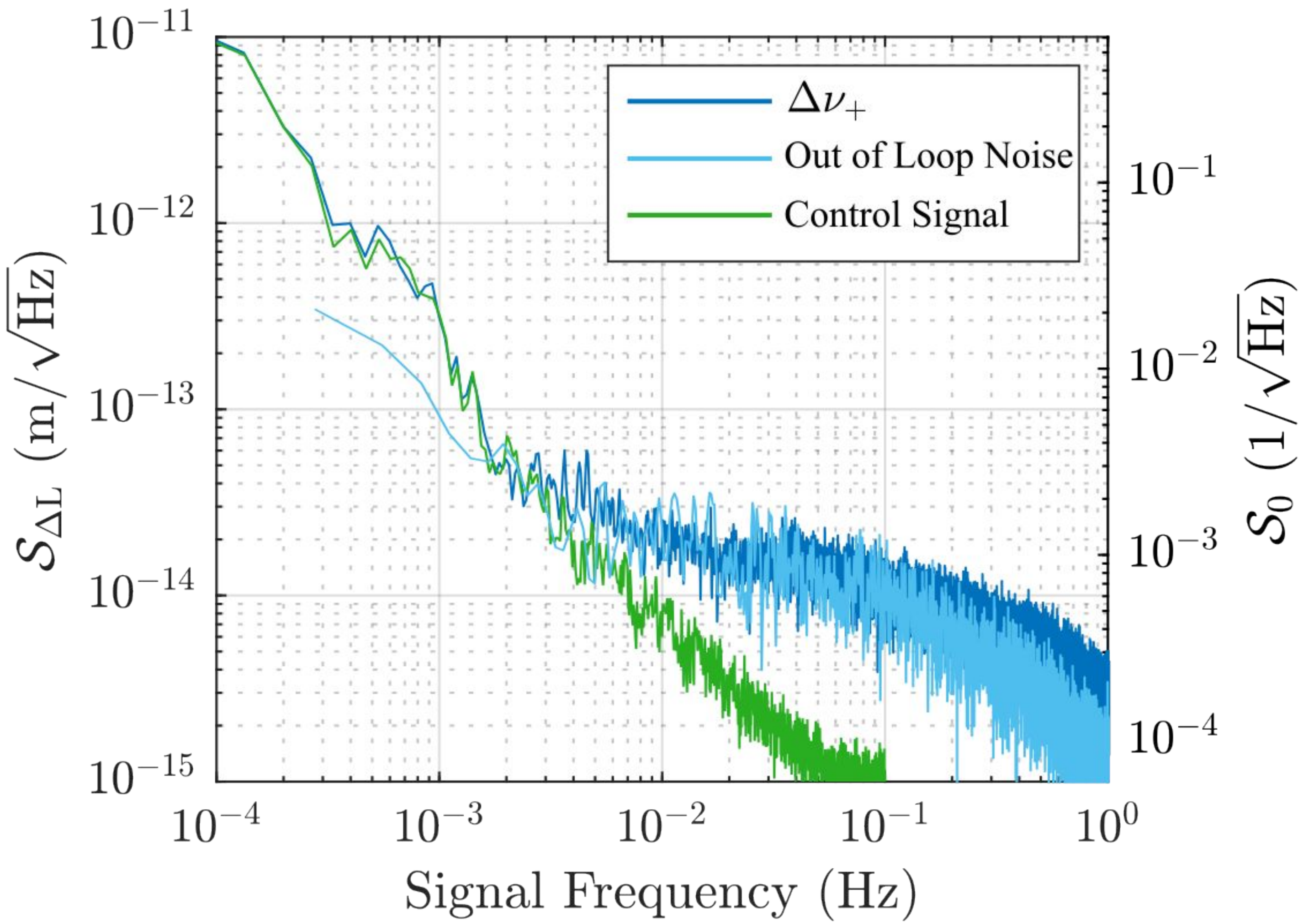
**Dedicated setup to demonstrate novel readout technique on a 19-meter long, 30000 finesse 'test cavity' (no magnets)**



# ALPS 19 m birefringence prototype

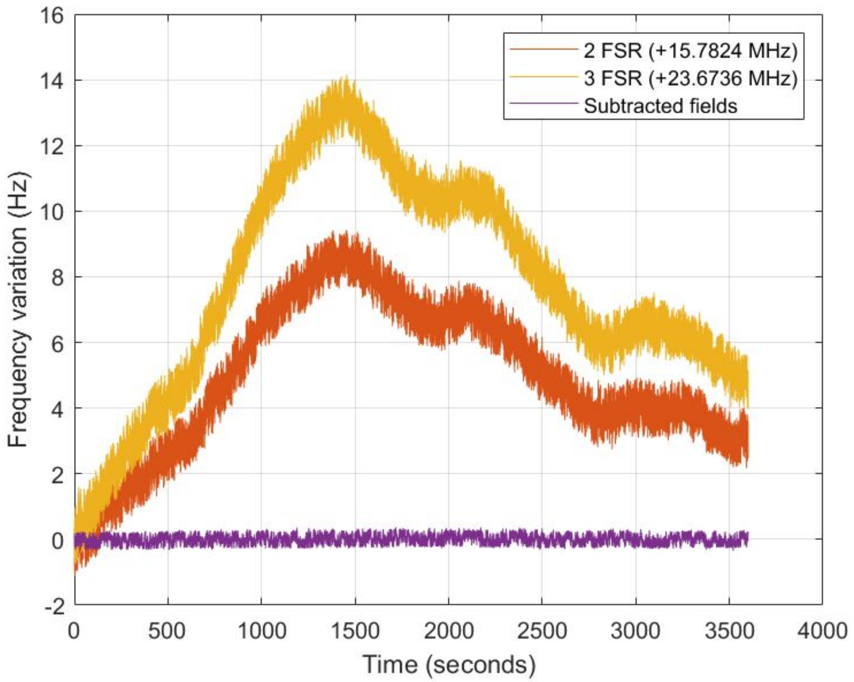
- **demonstrated**: simultaneous ‘symmetric’ locking of three fields to the cavity with arbitrarily adjustable polarizations
  - *suppression of cavity length noise* which is expected to dominate at our signal frequency

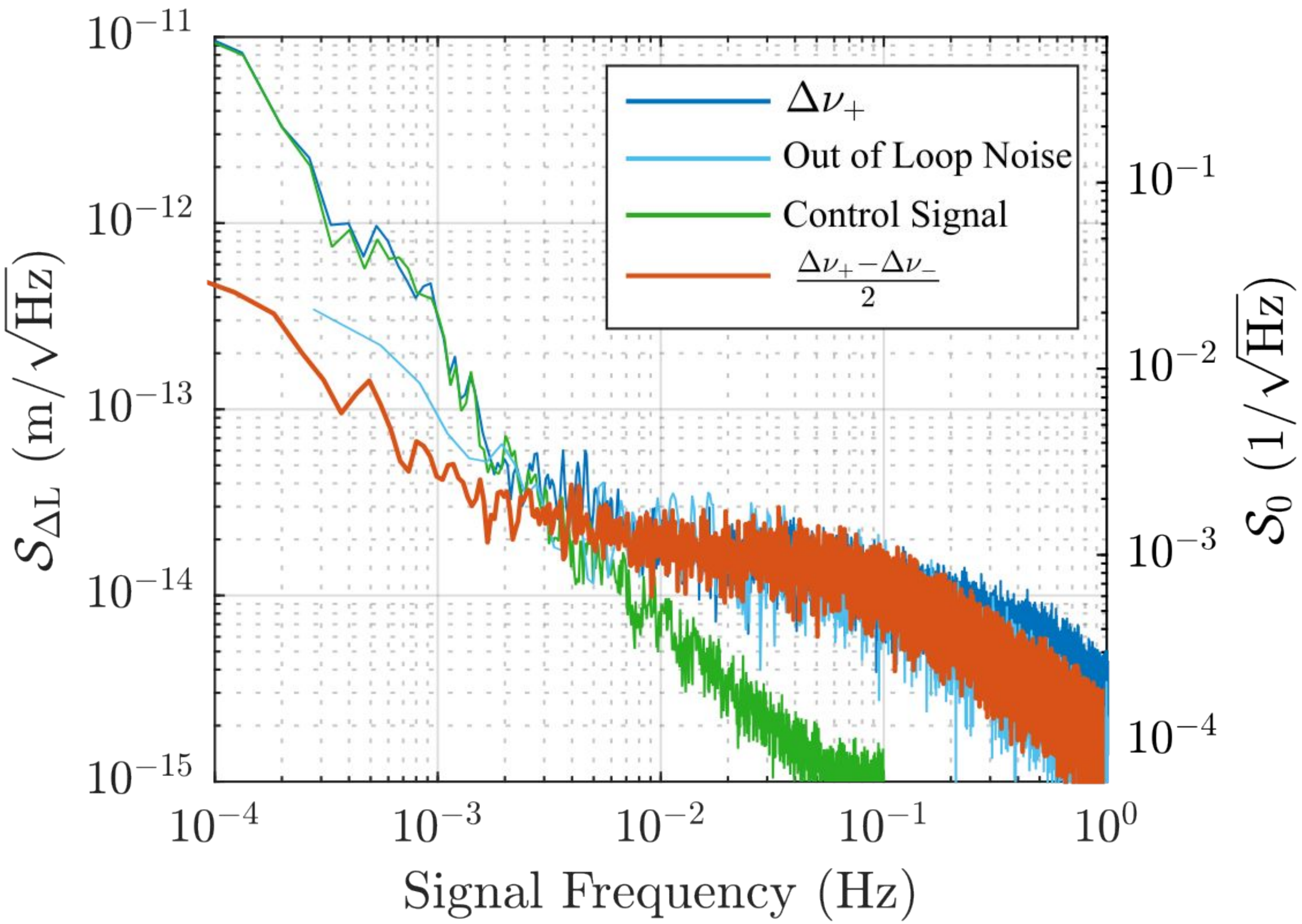


# ALPS 19 m birefringence prototype

- **demonstrated**: simultaneous ‘symmetric’ locking of three fields to the cavity with arbitrarily adjustable polarizations
  - *suppression of cavity length noise* which is expected to dominate at our signal frequency



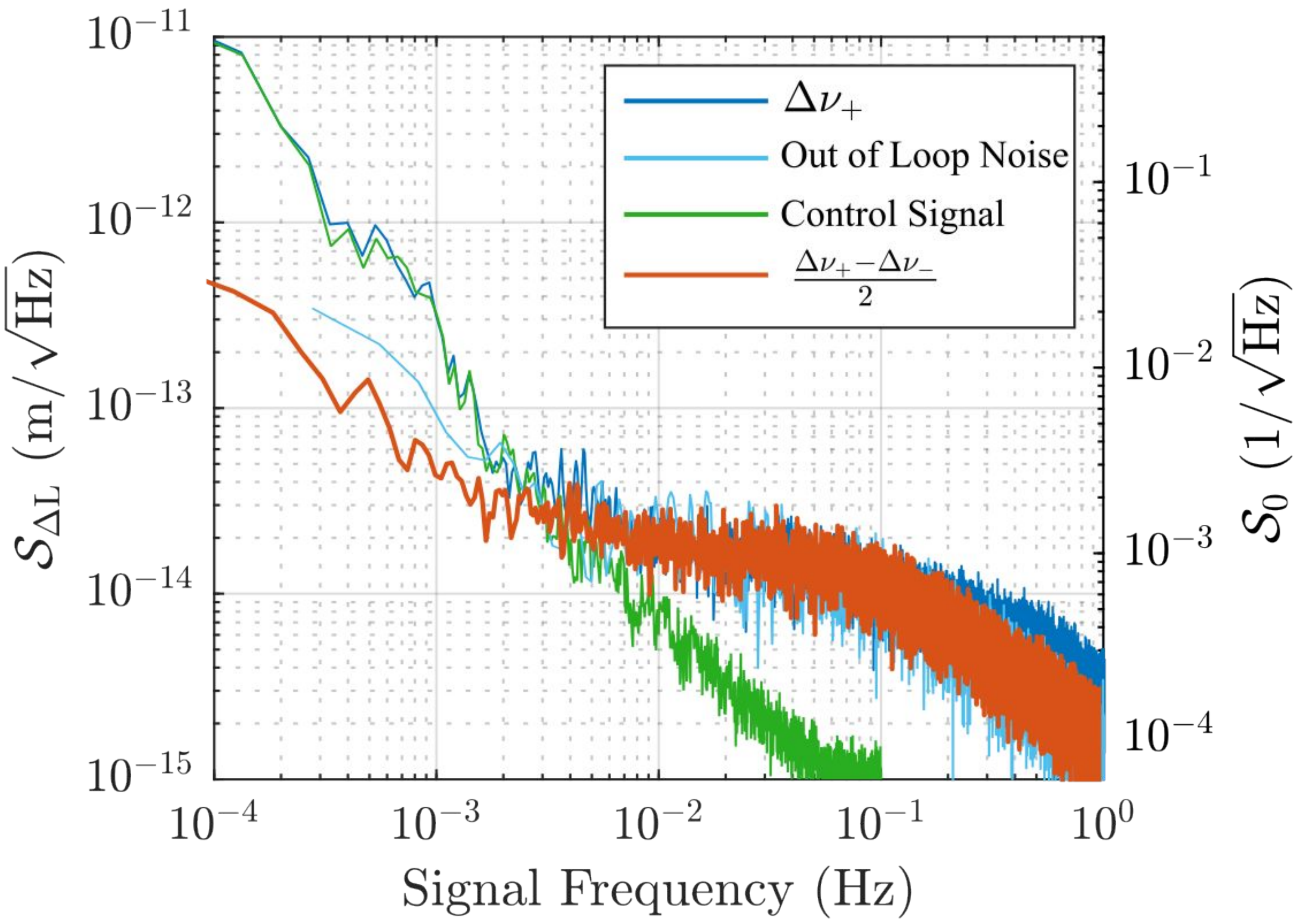



# ALPS 19 m birefringence prototype

- **demonstrated**: simultaneous ‘symmetric’ locking of three fields to the cavity with arbitrarily adjustable polarizations
  - *suppression of cavity length noise* which is expected to dominate at our signal frequency

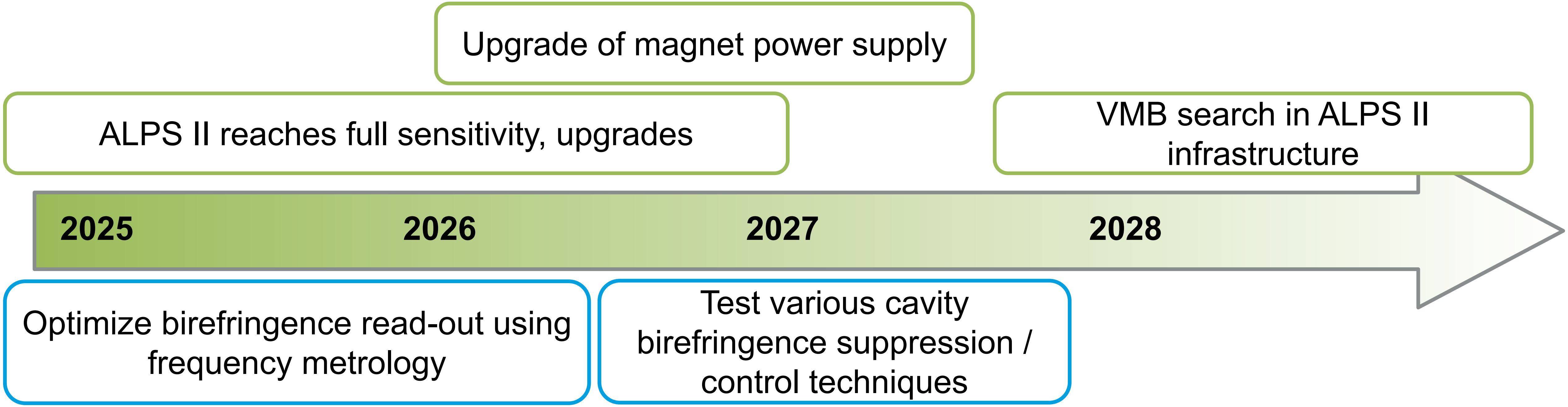
- **currently limiting noise source:** performance of the frequency stabilization
  - residual amplitude modulation / “out-of-loop” noise
  - suppression of this noise source has been demonstrated [1,2], will require modification to the setup

[1] https://doi.org/10.1364/OE.465597
[2] https://doi.org/10.1364/OPTICA.507655



# VMB in the ALPS II infrastructure

## **ALPS II** (in HERA North)




## **19 meter Birefringence Lab** (in HERA West)

# Backup Slides

# Back up: Intrinsic cavity birefringence noise

## Study of the birefringence noise in high-finesse ULE cavity

Shi-Xiang Yang [a], Yu-Pei Zhang [a], Wen-Hai Tan [b,*], Cheng-Gang Shao [a], Min-Kang Zhou [a], Shan-Qing Yang [b]

[a] *MOE Key Laboratory of Fundamental Physical Quantities Measurement, School of Physics, Huazhong University of Science and Technology, Wuhan 430074, People's Republic of China*

[b] *MOE Key Laboratory of TianQin Mission, TianQin Research Center for Gravitational Physics & School of Physics and Astronomy, Frontiers Science Center for TianQin, Gravitational Wave Research Center of CNSA, Sun Yat-sen University (Zhuhai Campus), Zhuhai 519082, People's Republic of China*

RESEARCH ARTICLE | DECEMBER 26 2017

## Noise characterization for resonantly enhanced polarimetric vacuum magnetic-birefringence experiments

M. T. Hartman; A. Rivère; R. Battesti; C. Rizzo

Check for updates

*Rev. Sci. Instrum.* 88, 123114 (2017)
https://doi.org/10.1063/1.4986871

## Intrinsic mirror noise in Fabry–Perot based polarimeters: the case for the measurement of vacuum magnetic birefringence

**G. Zavattini[1,a], F. Della Valle[2], A. Ejlli[1], W.-T. Ni[3], U. Gastaldi[1], E. Milotti[4], R. Pengo[5], G. Ruoso[5]**

[1] Sez. di Ferrara and Dip. di Fisica e Scienze della Terra, INFN, Università di Ferrara, via G. Saragat 1, Edificio C, 44122 Ferrara, FE, Italy
[2] Sez. di Pisa, gruppo collegato di Siena and Dip. di Scienze Fisiche, della Terra e dell'Ambiente, INFN, Università di Siena, via Roma 56, 53100 Siena, SI, Italy
[3] Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan, Republic of China
[4] Sez. di Trieste and Dip. di Fisica, INFN, Università di Trieste, via A. Valerio 2, 34127 Trieste, TS, Italy
[5] Lab. Naz. di Legnaro, INFN, viale dell'Università 2, 35020 Legnaro, PD, Italy

## Characterization of the Vacuum Birefringence Polarimeter at BMV: Dynamical Cavity Mirror Birefringence

M. T. Hartman[1], R. Battesti[1], and C. Rizzo[1]
[1]Laboratoire National des Champs Magnétiques Intenses (UPR 3228, CNRS-UPS-UGA-INSA)
F-31400 Toulouse Cedex, France
michael.hartman@lncmi.cnrs.fr

## On the effects of mirror birefringence and its fluctuations to laser interferometric gravitational wave detectors

Yuta Michimura,[1,2,3,*] Haoyu Wang,[2] Francisco Salces–Carcoba,[1] Christopher Wipf,[1] Aidan Brooks,[1] Koji Arai,[1] and Rana X Adhikari[1]

[1] *LIGO Laboratory, California Institute of Technology, Pasadena, California 91125, USA*
[2] *Research Center for the Early Universe (RESCEU), Graduate School of Science, University of Tokyo, Tokyo 113-0033, Japan*
[3] *PRESTO, Japan Science and Technology Agency (JST), Kawaguchi, Saitama 332-0012, Japan*
(Dated: August 2, 2023)

## Polarimetry for measuring the vacuum magnetic birefringence with quasi-static fields: a systematics study for the VMB@CERN experiment

**Guido Zavattini[1,2,a], Federico Della Valle[3,4,b], Alina Mariana Soflau[2,c], Lorenzo Formaggio[2,d], Giacomo Crapulli[2,e], Giuseppe Messineo[1,f], Emilio Mariotti[3,4,g], Štepan Kunc[5,h], Aldo Ejlli[6,i], Giuseppe Ruoso[7,j], Carmela Marinelli[3,4,k], Mirco Andreotti[1,l]**

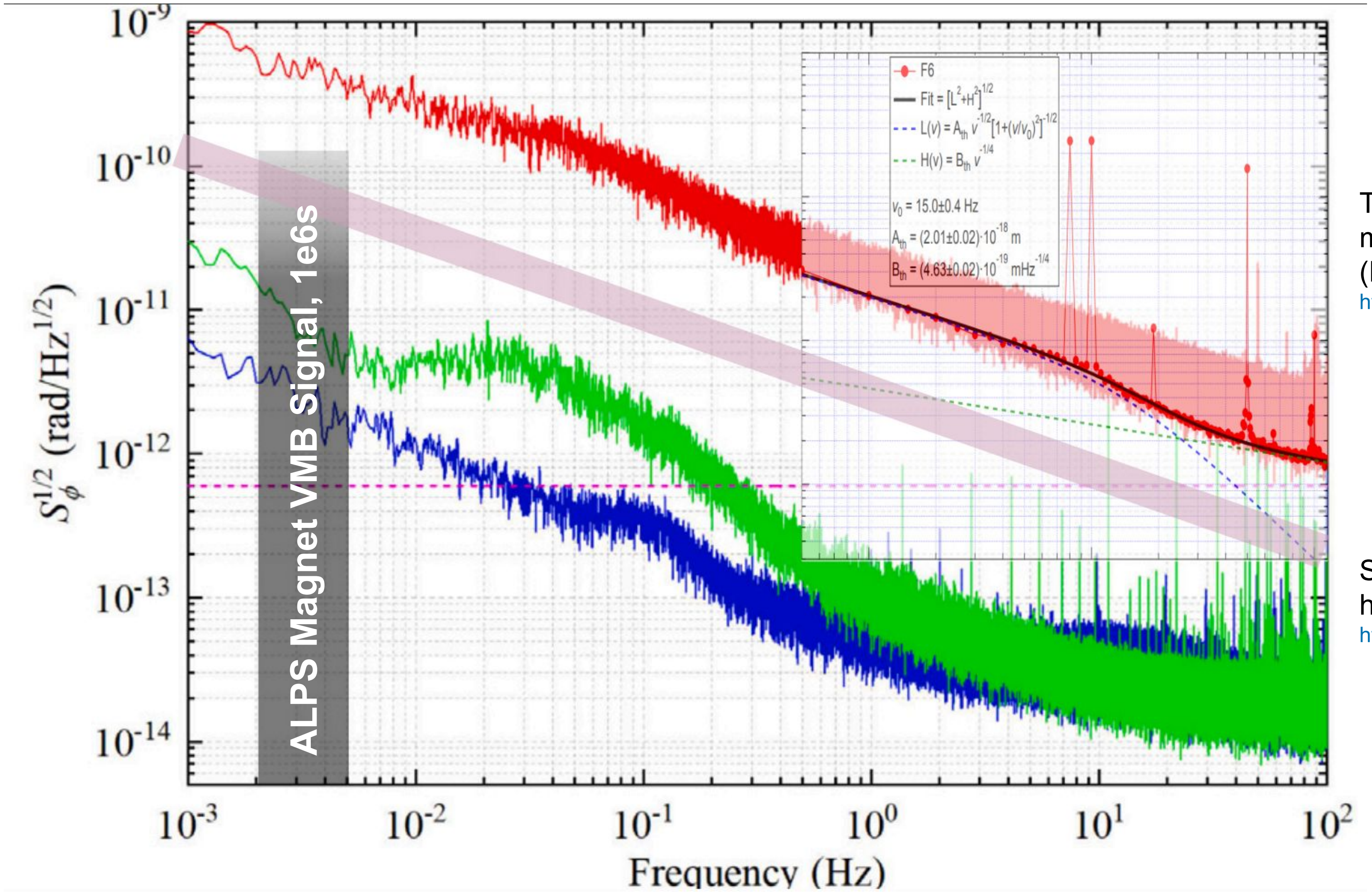
[1] INFN, Sez. di Ferrara, via G. Saragat 1, Edificio C, 44122 Ferrara, Italy
[2] Dip. di Fisica e Scienze della Terra, Università di Ferrara, via G. Saragat 1, Edificio C, 44122 Ferrara, Italy
[3] Dip. di Scienze Fisiche, della Terra e dell'Ambiente, Università di Siena, via Roma 56, 53100 Siena, Italy
[4] INFN, Sez. di Pisa, largo B. Pontecorvo 3, 56127 Pisa, Italy
[5] Technical University of Liberec, Studentská 1402/2, 46117 Liberec, Czech Republic
[6] School of Physics and Astronomy, Cardiff University, Queen's Building, The Parade, Cardiff CF24 3AA, UK
[7] INFN, Laboratori Nazionali di Legnaro, viale dell'Università 2, 35020 Legnaro, PD, Italy

## Vacuum birefringence experiments: optical noise

J. Agil[1,a], R. Battesti[2], and C. Rizzo[2]

[1] CNRS, LNCMI UPR 3228 (UGA, UT3, INSA-T, EMFL), F-31400 Toulouse Cedex, France
[2] Université Toulouse 3, LNCMI UPR CNRS 3228 (UGA, INSA-T, EMFL), F-31400 Toulouse Cedex, France

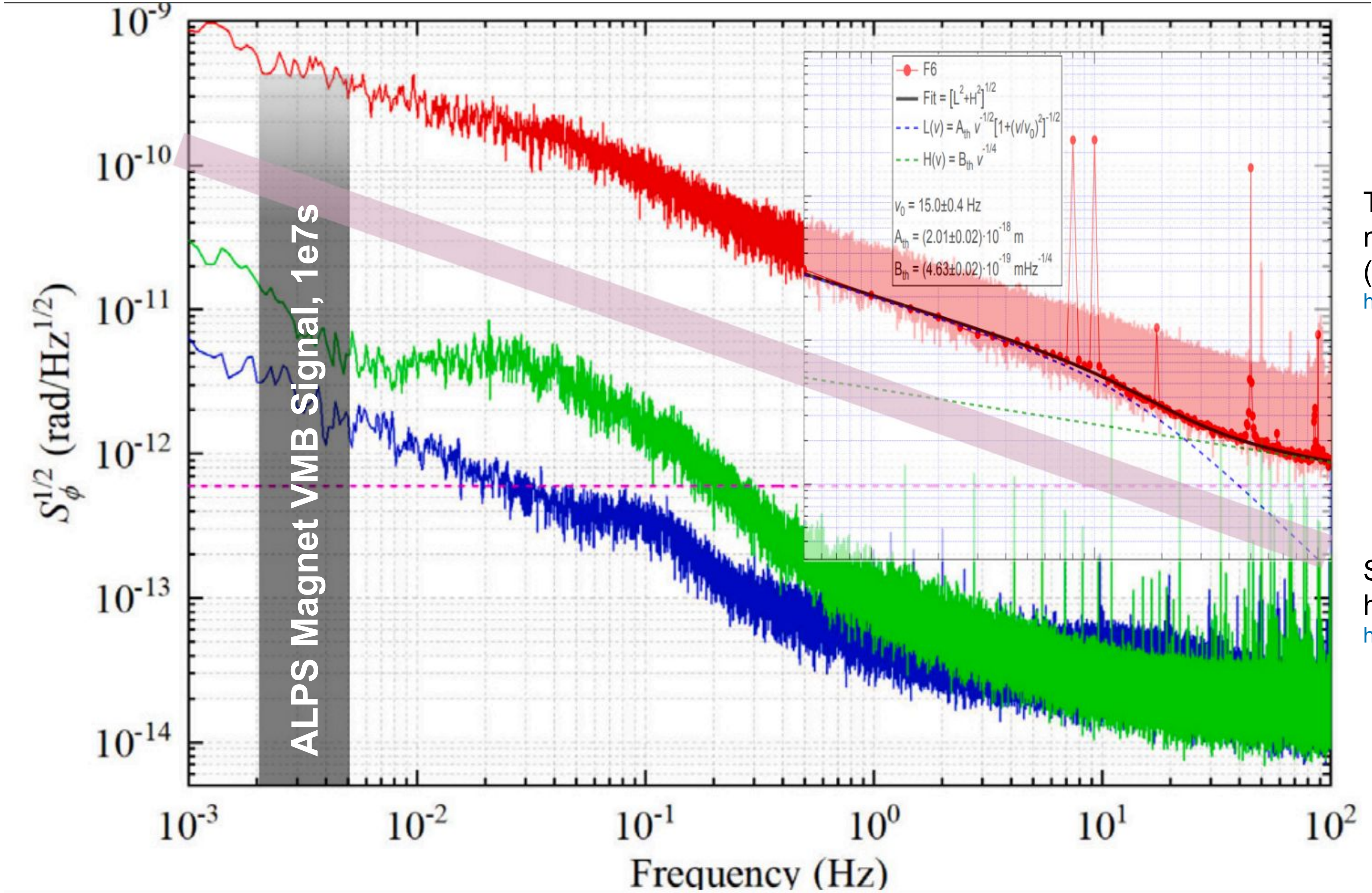
# Back up: Intrinsic cavity birefringence noise




The PVLAS experiment: A 25 year effort to measure vacuum magnetic birefringence (Ejlli et al. 2020) [INSET]
https://doi.org/10.1016/j.physrep.2020.06.001

Study of the birefringence noise in a high-finesse ULE cavity (Yang et al. 2025)
https://doi.org/10.1016/j.optlastec.2024.111660

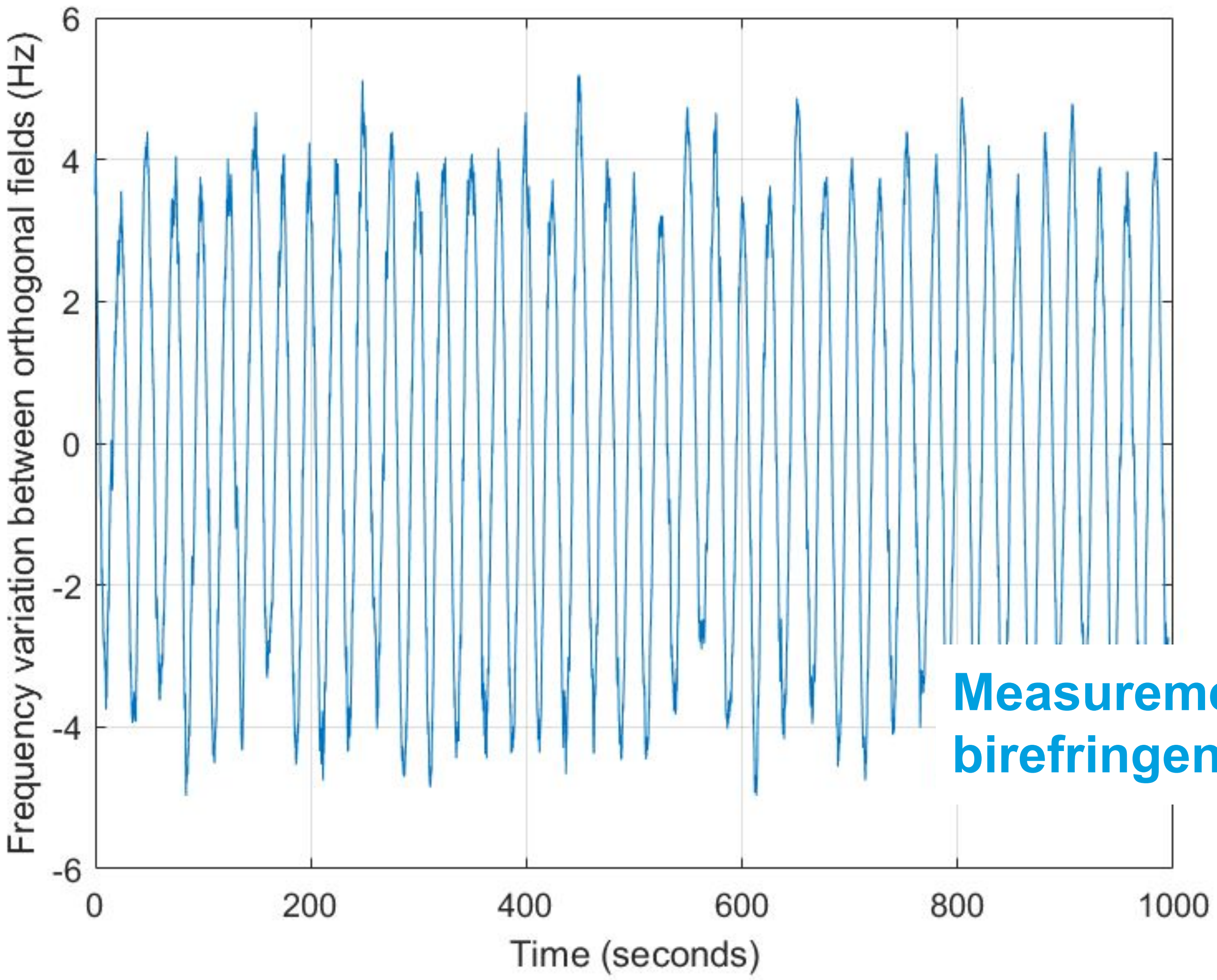
# Back up: Intrinsic cavity birefringence noise




The PVLAS experiment: A 25 year effort to measure vacuum magnetic birefringence (Ejlli et al. 2020) [INSET]
https://doi.org/10.1016/j.physrep.2020.06.001

Study of the birefringence noise in a high-finesse ULE cavity (Yang et al. 2025)
https://doi.org/10.1016/j.optlastec.2024.111660

# Back up: Static cavity birefringence measurement




**Measurement of the cavity static birefringence to ~ppb w/ rotating waveplate**

# Back up: Residual Amplitude Modulation reduction

**Reduction of residual amplitude modulation to 1 × 10-6 for frequency modulation and laser stabilization**
https://doi.org/10.1364/OL.39.001980